Star Clusters

--- Links between Galaxies and Stars

- Star clusters as stellar birth places
- Open clusters, globular clusters, and others
- Star clusters as targets of investigation
- Star clusters as tools in stellar & galactic studies
- Latest and outstanding issues

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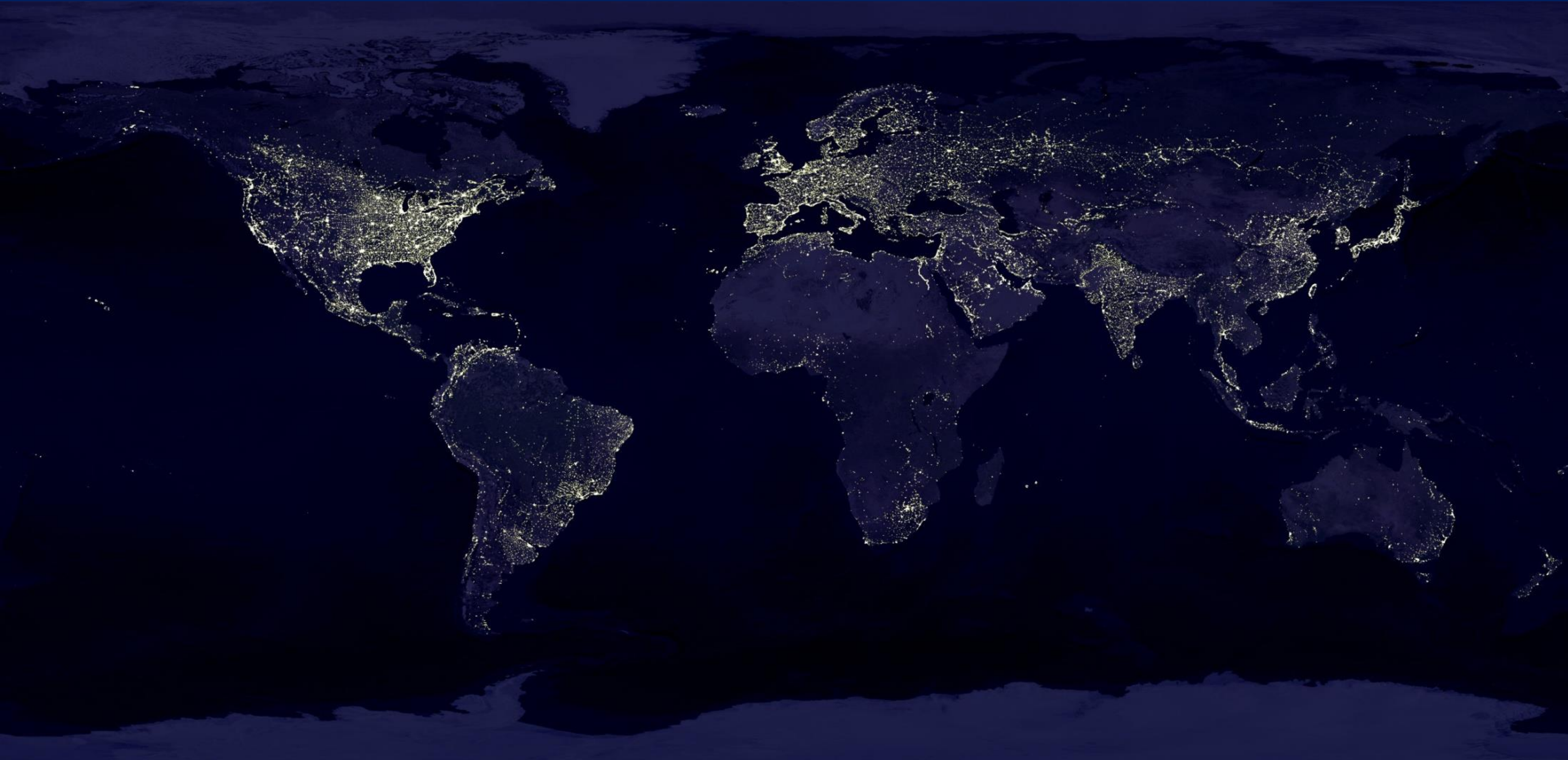
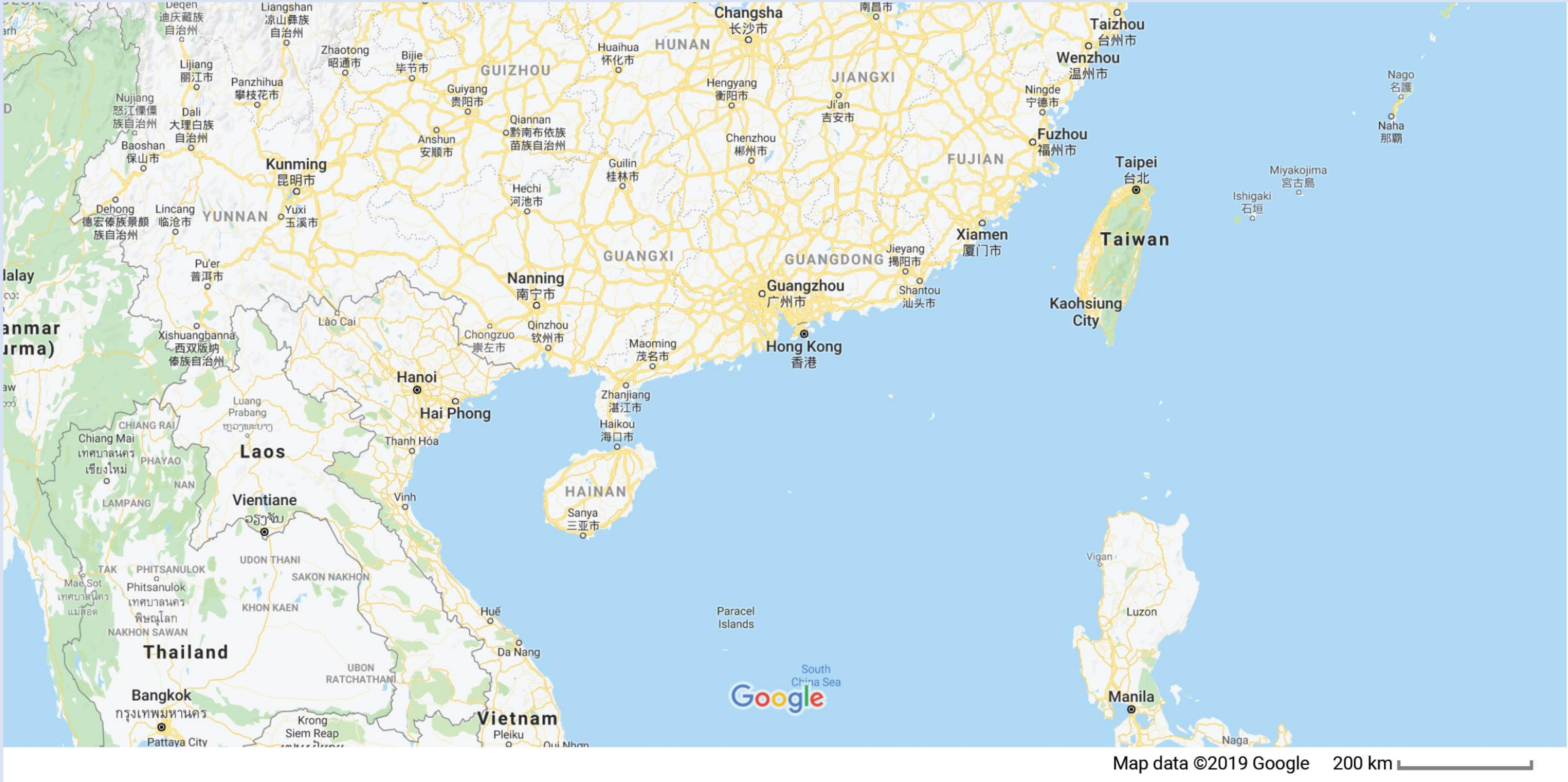
http://ps1tw.astro.ncu.edu.tw/ps1sc/tmp_20191028/StarClusters2019ISYA42Yunnan.pdf

https://bit.ly/2BRlp7K

Earth at Night




Changsha
长沙市
Taizhou
台州市
Wenzhou
温州市
HUNAN
JIANGXI
GUIZHOU
Huaihua
怀化市
Hengyang
衡阳市
Ji'an
吉安市
Zhaotong
昭通市
Bijie
毕节市
Guiyang
贵阳市
Liangshan
凉山彝族
自治州
Deqen
迪庆藏族
自治州
Lijiang
丽江市
Panzhihua
攀枝花市
Nujiang
怒江傈僳
族自治州
Dali
大理白族
自治州
Baoshan
保山市
Qiannan
黔南布依族
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Anshun
安顺市
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Ningde
宁德市
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Nago
名護
Naha
那覇
Kunming
昆明市
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Hechi
河池市
Taipei
台北
Miyakojima
宮古島
Ishigaki
石垣
Dehong
德宏傣族景颇
族自治州
Lincang
临沧市
YUNNAN
Yuxi
玉溪市
Xiamen
厦门市
Taiwan
GUANGXI
GUANGDONG
Jieyang
揭阳市
Pu'er
普洱市
Nanning
南宁市
Guangzhou
广州市
Shantou
汕头市
Kaohsiung
City
Lào Cai
Chongzuo
崇左市
Qinzhou
钦州市
Maoming
茂名市
Hong Kong
香港
Xishuangbanna
西双版纳
傣族自治州
Hanoi
Hai Phong
Zhanjiang
湛江市
Haikou
海口市
Luang
Prabang
CHIANG RAI
Chiang Mai
PHAYAO
Thanh Hóa
Laos
NAN
LAMPANG
HAINAN
Vientiane
Vinh
Sanya
三亚市
Vigan
UDON THANI
TAK
PHITSANULOK
SAKON NAKHON
Mae Sot
Phitsanulok
KHON KAEN
Luzon
Huế
Paracel
Islands
NAKHON SAWAN
Thailand
Da Nang
UBON
RATCHATHANI
South
China Sea
Bangkok
Manila
Krong
Siem Reap
Vietnam
Pleiku
Pattaya City
Naga
Map data ©2019 Google
200 km

Siding Spring, Australia, 3.9 m

Devasthal, India, 3.6 m

Gaomeigu, China 2.4 m

Doi Inthanon, Thailand 2.4 m

Xinglong, China, 2.16 m

Hanle, India 2.0 m

Okayama, Japan, 1.88 m

Bohyunsan, Korea, 1.8 m

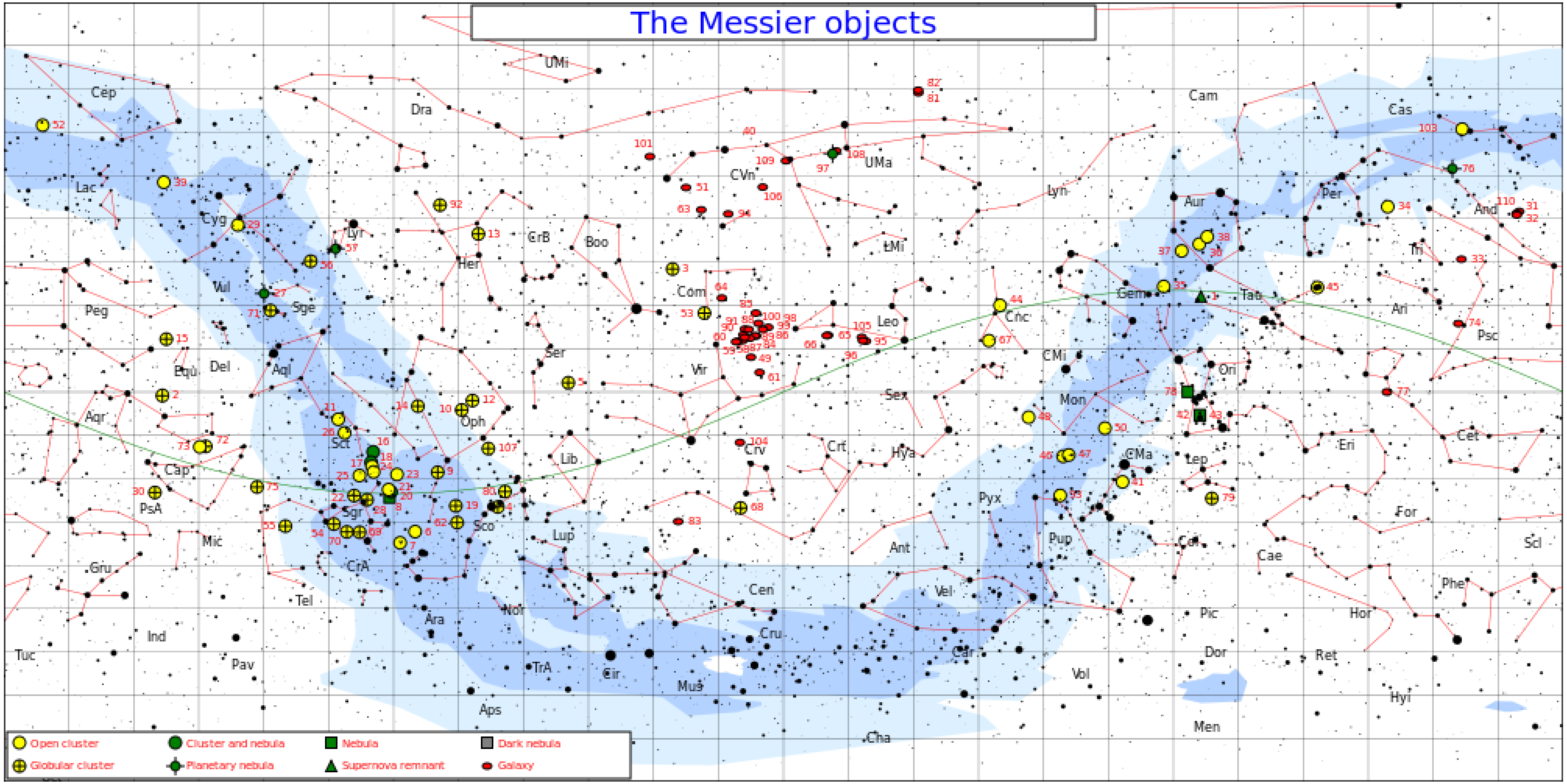
Mt John, New Zealand, 1.8 m

Study of Star Clusters

- Historically one of the oldest subjects in astronomy, next to stars and planets, e.g., the Messier objects …
- Progress paused for a few decades because CCD sizes did not catch up
- Interest revived because of sky surveys and OIR wide-field imaging, and *Gaia* measurements
- Current Milky Way census: 3000+ open clusters,
100+ globular clusters
- Latest interests mainly in massive star clusters, dissolving/dissolved (extended clusters, moving groups), and extragalactic systems

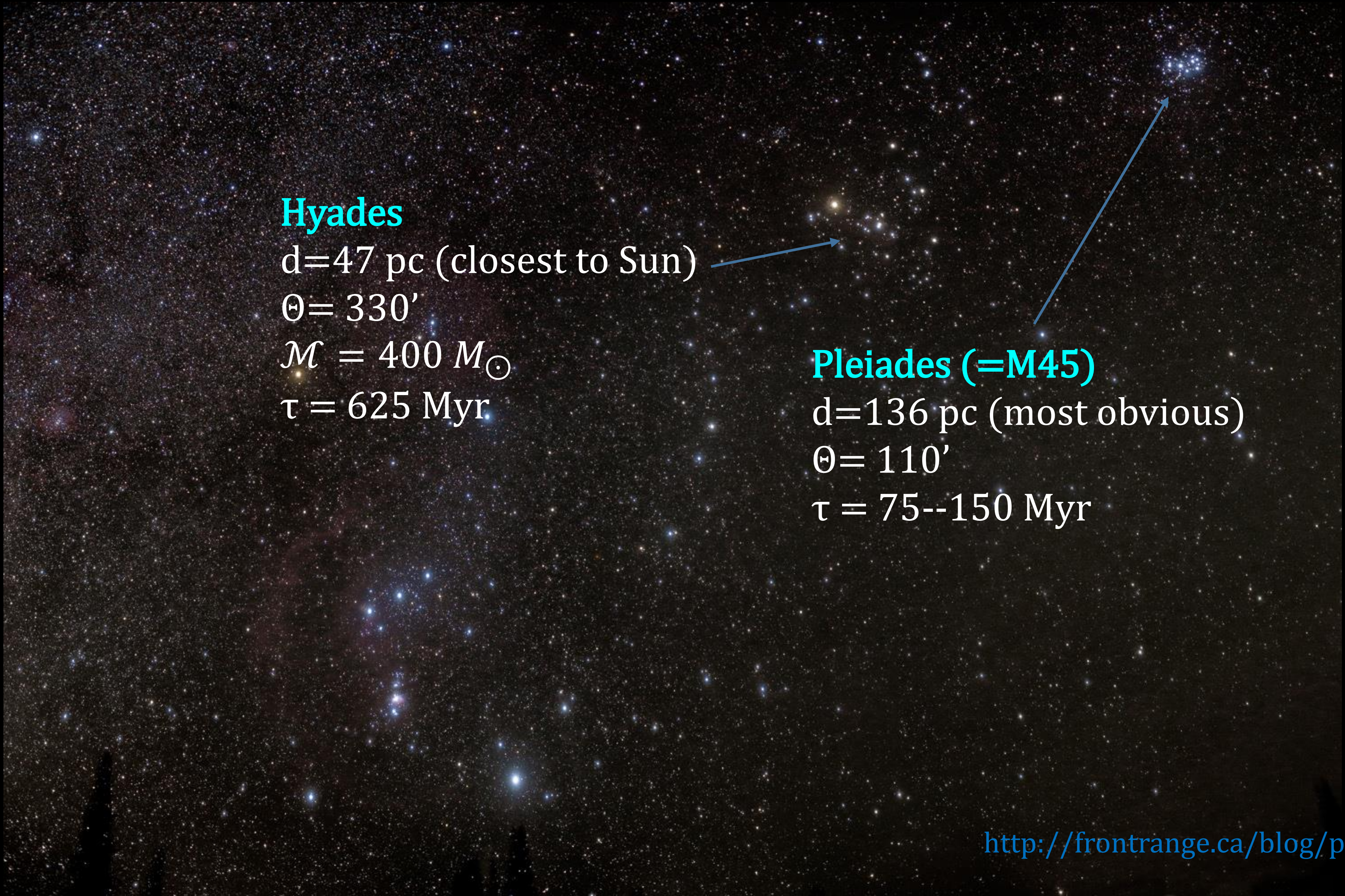
Star Clusters

- Long recognized by naked eyes in the night sky



OCs: 26
GCs: 29

Messier "*Catalogue des Nébuleuses et des Ams e'Étoiles*" ("Catalogue of Nebulae and Star Clusters" (1771)


Hyades
d=47 pc (closest to Sun)
$\Theta = 330'$
$\mathcal{M} = 400\ M_{\odot}$
$\tau = 625$ Myr
Pleiades (=M45)
d=136 pc (most obvious)
$\Theta = 110'$
$\tau = 75$--150 Myr
http://frontrange.ca/blog/page/6/

Praesepe (=M44=Beehive)

d=177 pc

Θ= 95’

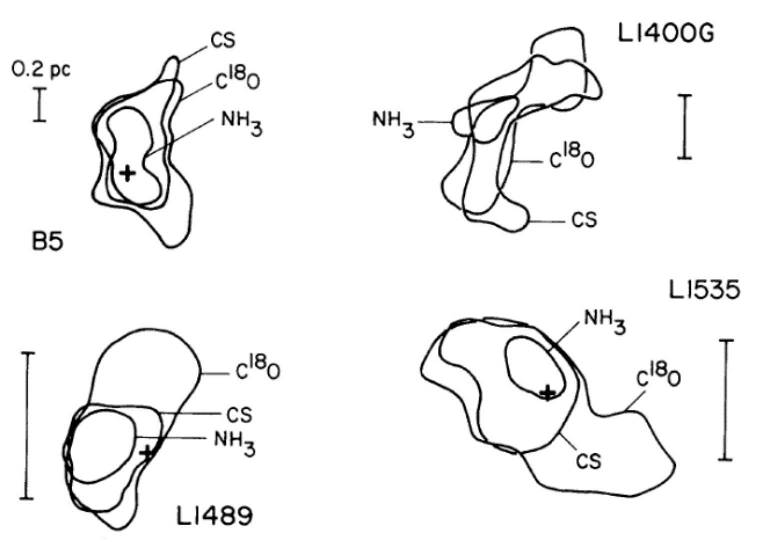
$\mathcal{M} = 500 - 600\ M_{\odot}$

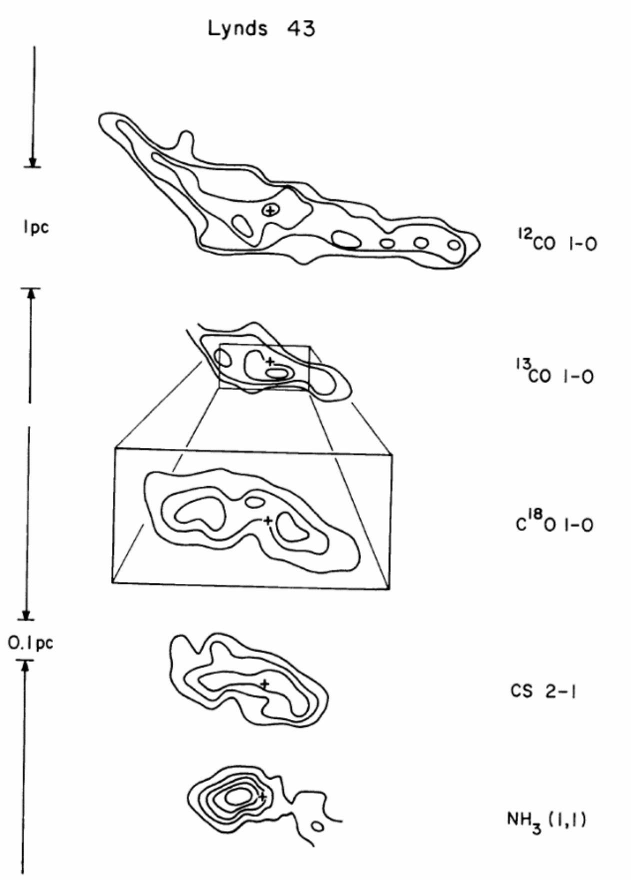
$\tau = 600 - 700$ Myr

Formation of Stars

Stars are formed <u>in groups</u> out of dense molecular cloud cores, and planets are formed, at the same time as the stellar birth, in circumstellar disks.

Star Formation = Cluster Formation





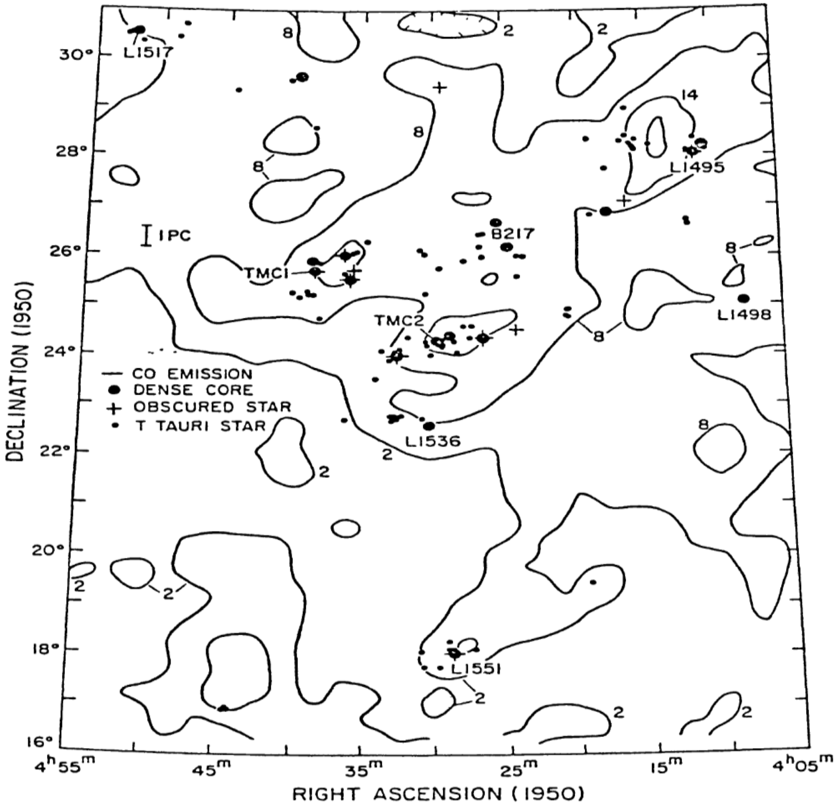
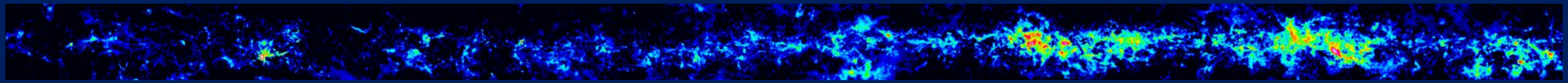
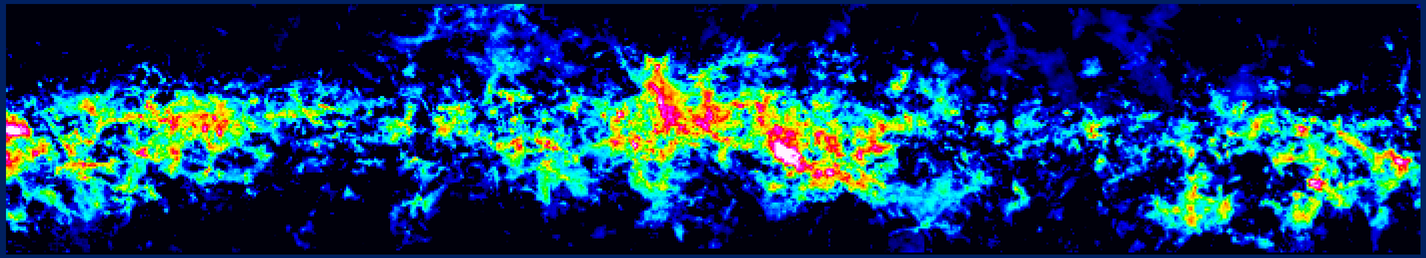


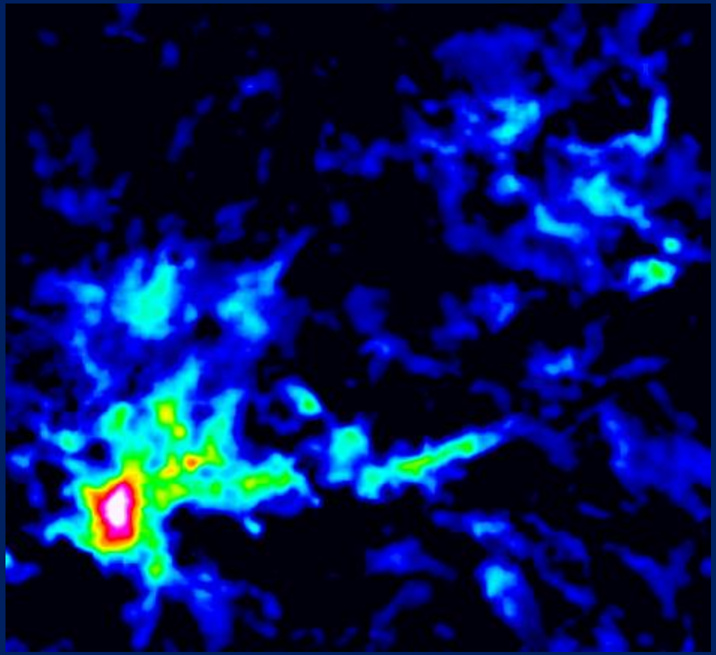
Figure 2 CO contour map of the Taurus molecular cloud with positions of dense NH_3 cores, embedded infrared sources, and visible T Tauri stars (from Myers 1986).

Molecular clouds observed by different tracers …

Filamentary Molecular Clouds







Giant Molecular Clouds

D=20~100 pc

$\mathcal{M} = 10^5 \sim 10^6\ \mathcal{M}_\odot$

$\rho \approx 10 \sim 300\ \mathrm{cm}^{-3}$

$T \approx 10 \sim 30$ K

$\Delta v \approx 5 \sim 15\ \mathrm{km}^{-1}$

Molecular clumps/ clouds/condensations

$n \sim 10^3\ \mathrm{cm}^{-3}$, $D \sim 5$ pc,

$M \sim 10^3\ \mathrm{M}_\odot$

Dense molecular cores

$n \geq 10^4\ \mathrm{cm}^{-3}$, D ~ 0.1 pc,

$M \sim$ 1-2 $\mathrm{M}_\odot$

http://www.bu.edu/galacticring/outgoing/PressRelease/

GMCs are short lived → Most young stellar groups are not gravitational bound at birth (“high infant fatality rates”).

Those that survive and remain gravitational bound are the **star clusters** we see today: **open clusters** and **globular clusters**

Those recently dissolved with then-members still sharing similar space motion: **stellar associations** or **moving groups** (e.g., Beta Pictoris MG, AB Doradus MG)

Similar properties: OB associations or T association;
Reflection nebulae: R associations (e.g., Mon R2)

Disintegrated star clusters supply the field stars.

Nearby Examples

Massive Star-Forming Region

- *Orion OB Association* (350-400 pc) OMC 05:56 -01:48

Low-Mass Star-Forming Regions

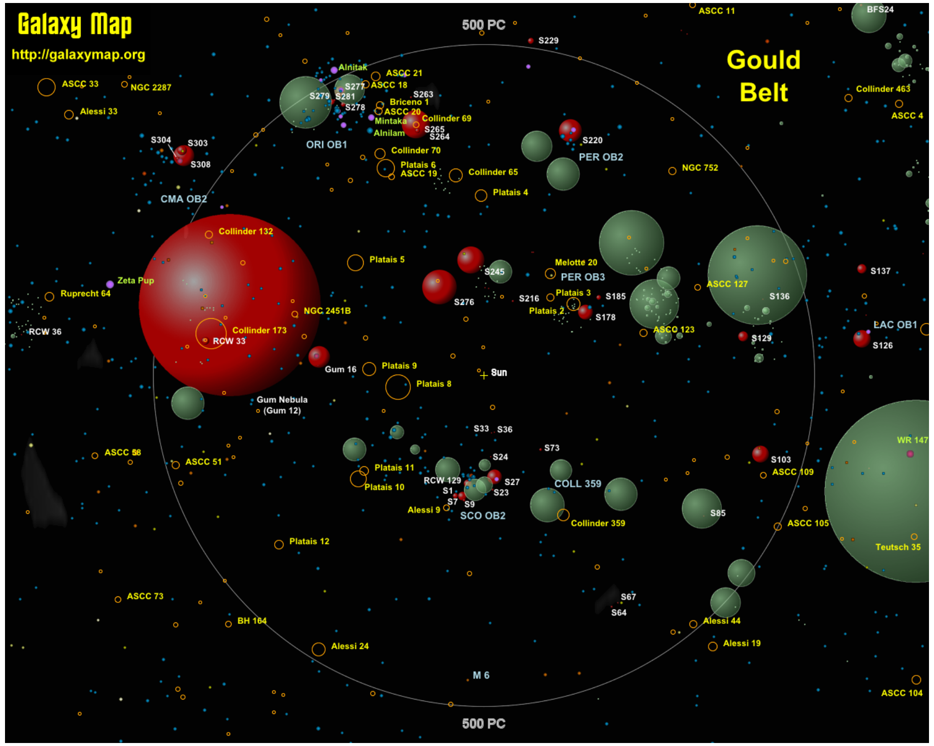
- *Taurus Molecular Cloud (TMC-1)* (140 pc) TMC 04:41 +25:52
- *Rho Ophiuchi cloud* (130 pc) Oph 16:28 -24:32
- *Lupus* (140 pc)
- *Chamaeleon* (160 pc)
- *Corona Australis* (130 pc) CrA 19:01 -36:59

4/5 in the southern sky …

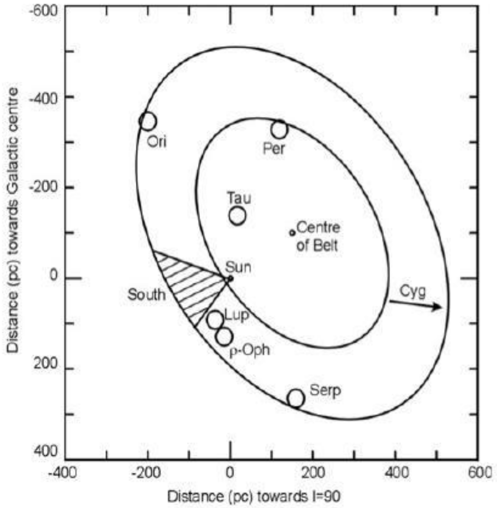
why?

The **Gould Belt**, a (partial) ring in the sky, ~1 kpc across, centered on a point 100 pc from the Sun and tilted about 20 deg to the Galactic plane, containing star-forming molecular clouds and OB stars (OMC, Sco-Cen OB, Cepheus OB2, Perseus OB2, TMC, parts of Serpens clouds) = local spiral arm

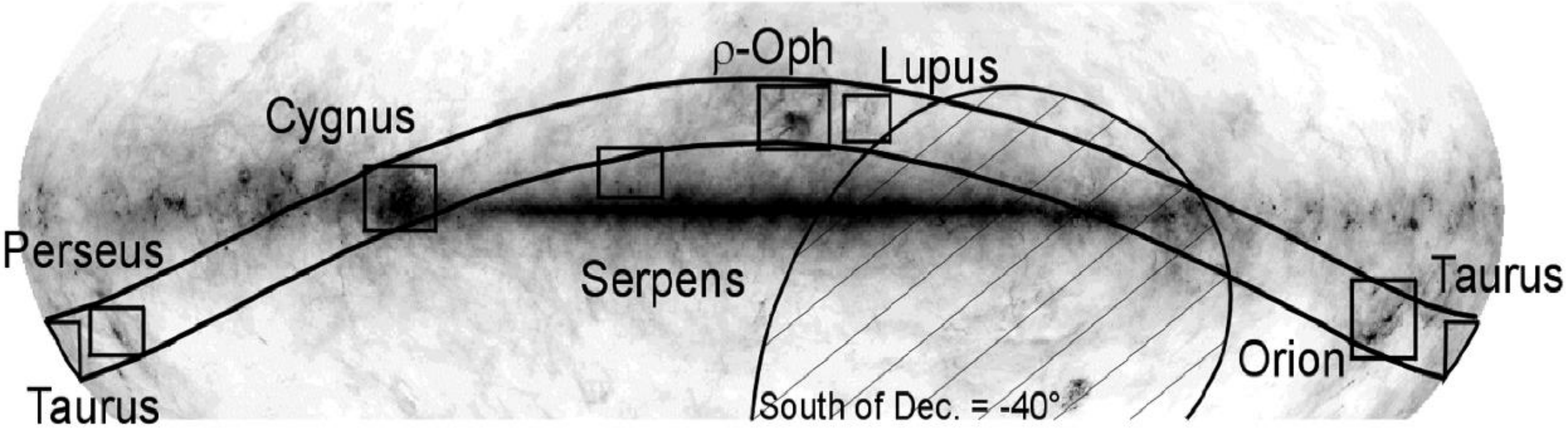
Origin unknown (dark matter induced star formation 30 Myrs ago?)



http://galaxymap.org/detail_maps/download_maps/gould.png

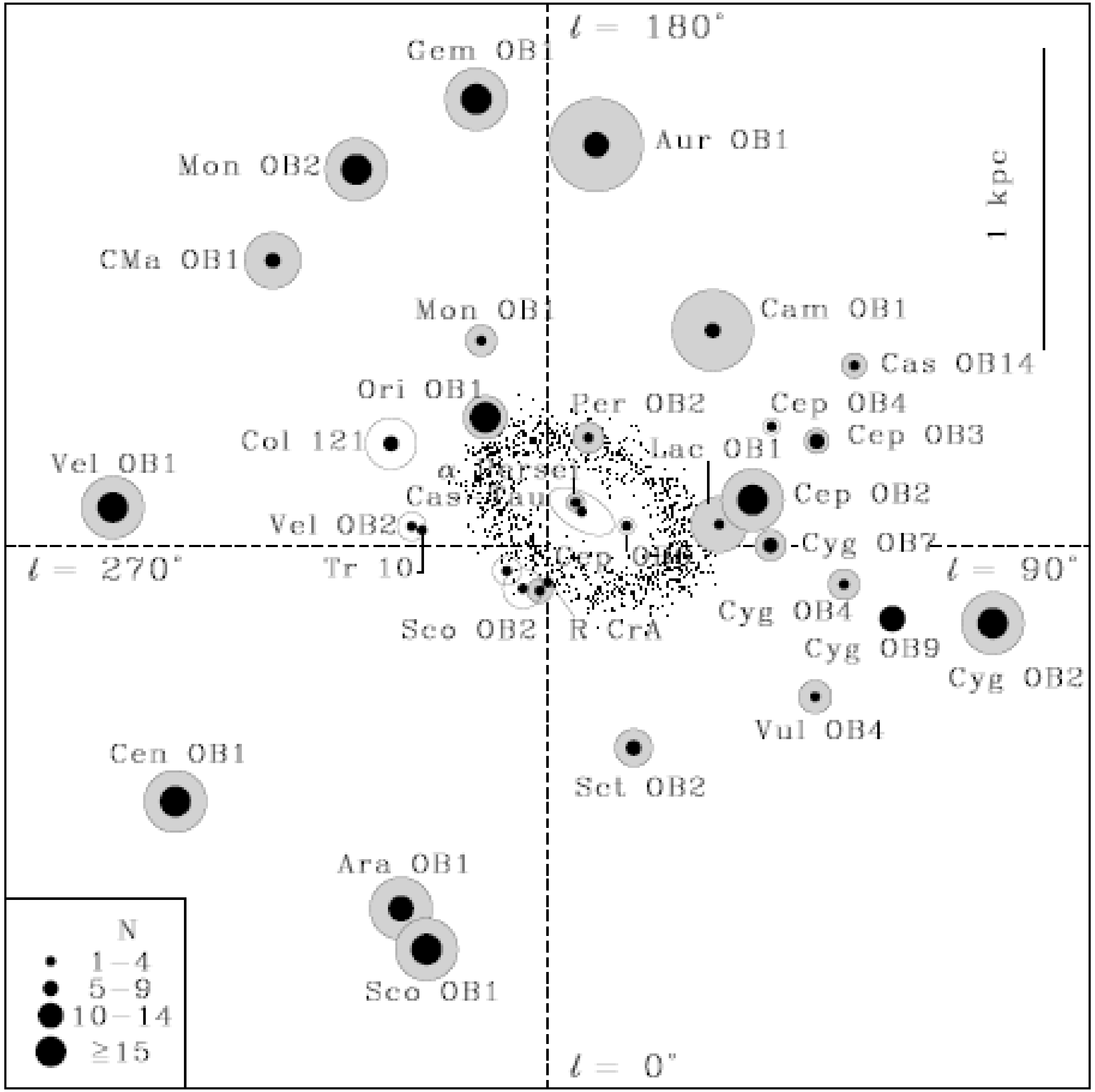


http://www.jach.hawaii.edu/JCMT/surveys/gb/



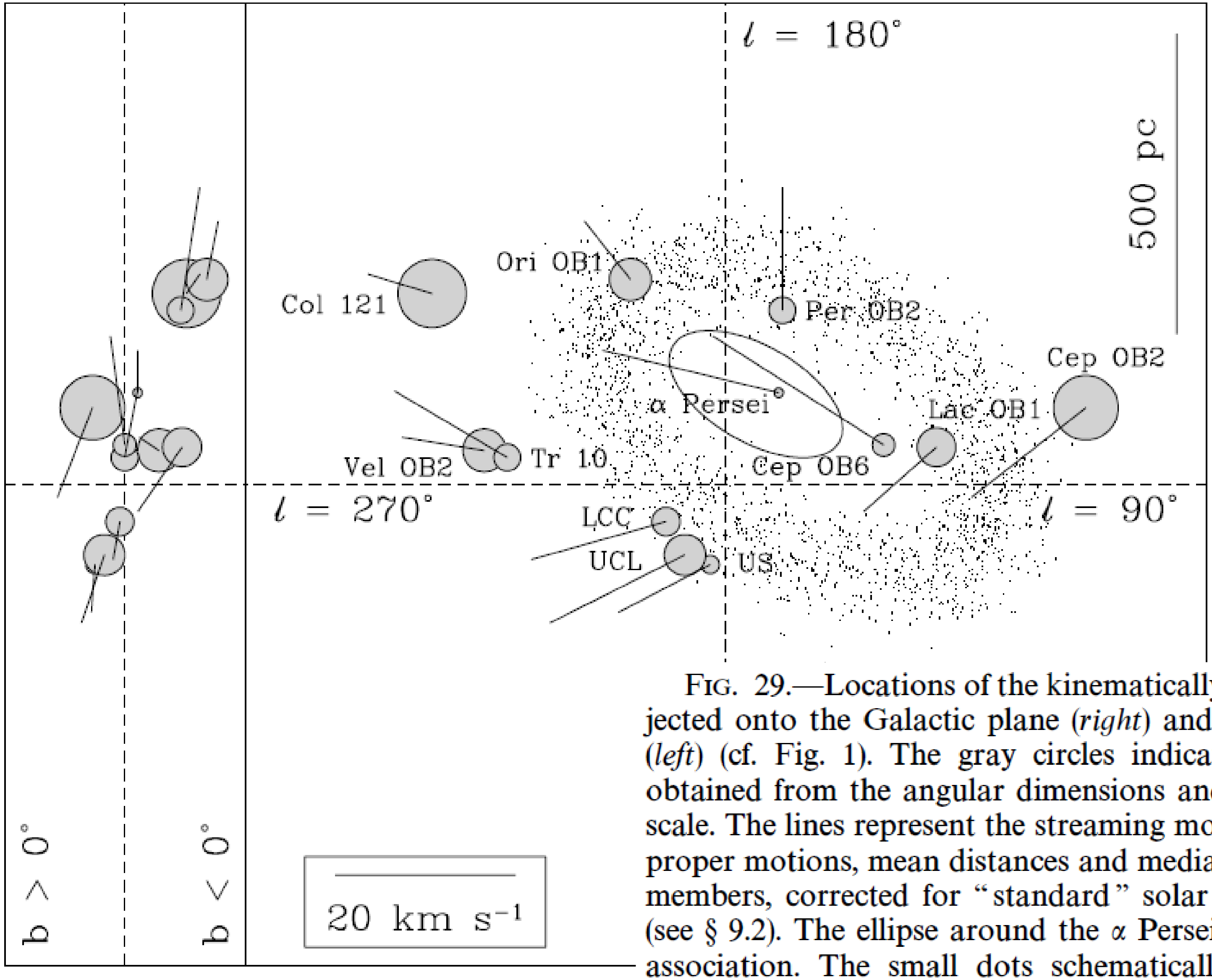
Gould's Belt superimposed on to an IRAS 100 micron emission map

Gould belt



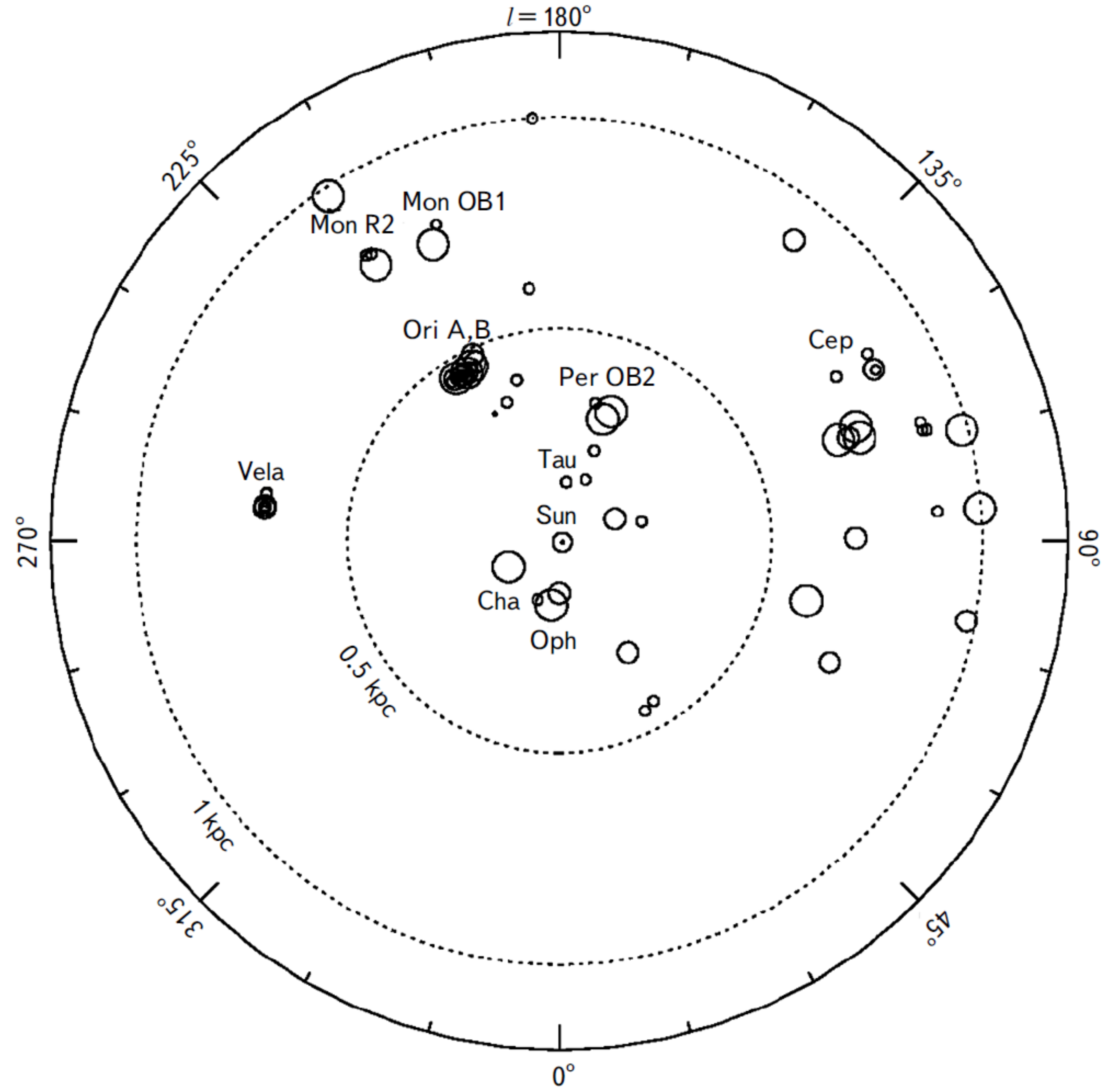
http://hera.ph1.uni-koeln.de/~heintzma/All/OB_stars.htm

Gould belt

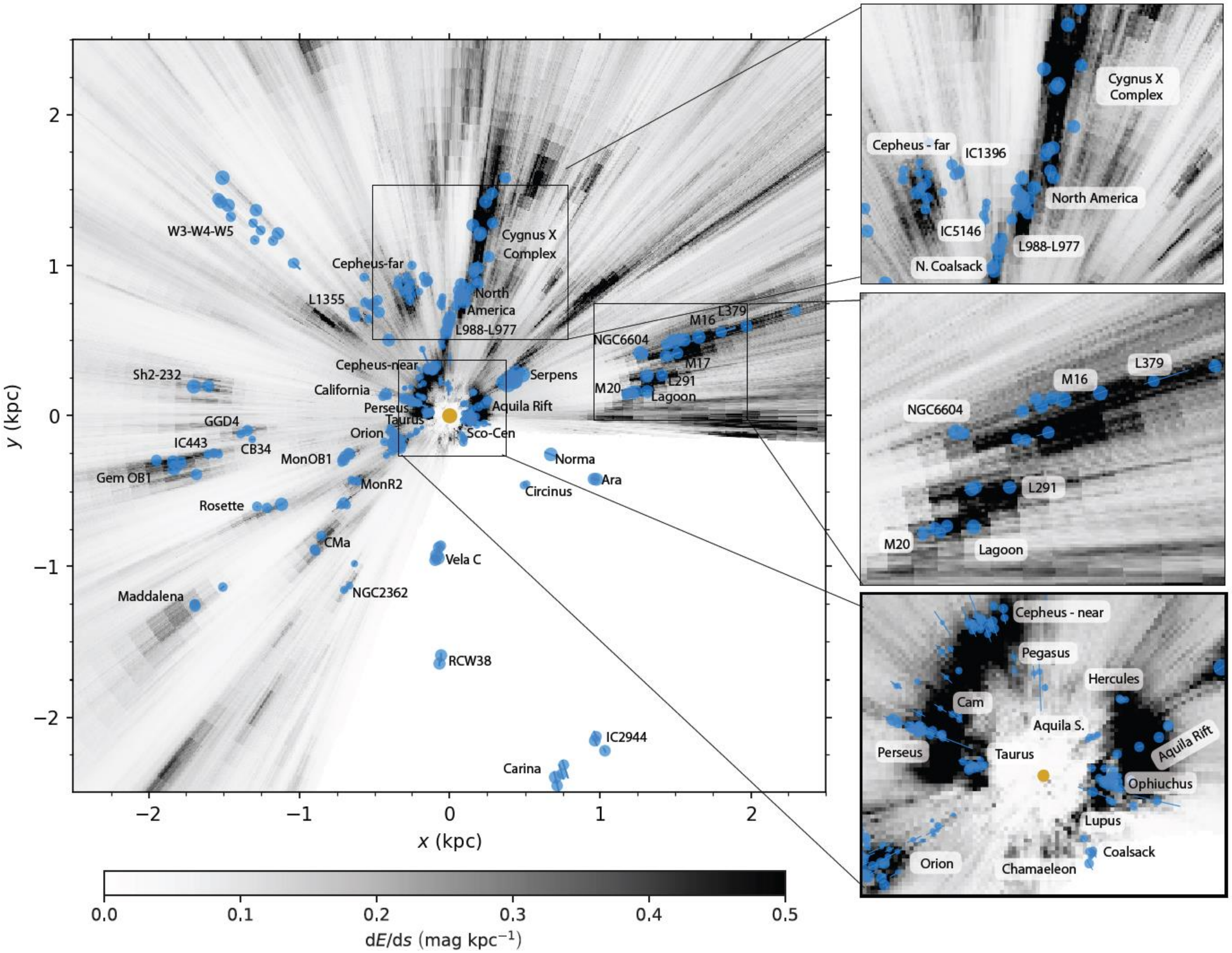


de Zeeuw+99?

FIG. 29.—Locations of the kinematically detected OB associations projected onto the Galactic plane (*right*) and a corresponding cross section (*left*) (cf. Fig. 1). The gray circles indicate the physical dimensions as obtained from the angular dimensions and mean distances, on the same scale. The lines represent the streaming motions, derived from the average proper motions, mean distances and median radial velocities of the secure members, corrected for "standard" solar motion and Galactic rotation (see § 9.2). The ellipse around the α Persei cluster indicates the Cas–Tau association. The small dots schematically represent the Olano (1982) model of the Gould Belt.



Bobylev 2014



W3-W4-W5
Cepheus-far
Cygnus X Complex
North America
L988-L977
L1355
Cepheus-near
California
Perseus
Taurus
Orion
Sh2-232
GGD4
IC443
CB34
MonOB1
Gem OB1
MonR2
Rosette
CMa
Maddalena
NGC2362
Vela C
RCW38
Carina
IC2944
Norma
Ara
Circinus
Sco-Cen
Aquila Rift
Serpens
NGC6604
M16
L379
M17
L291
M20
Lagoon
x (kpc)
y (kpc)
dE/ds (mag kpc^{-1})
Cepheus - far
IC1396
IC5146
N. Coalsack
Cepheus - near
Pegasus
Hercules
Cam
Aquila S.
Ophiuchus
Lupus
Coalsack
Chamaeleon

Zucker 2020

Fig. 2. Bird's-eye view of the Star Formation Handbook cloud catalog (colored blue points), looking down on the Galactic disk with the sun (orange circle) at the center. The catalog is overlaid on the 3D "Bayestar19" dust map from Green et al. (2019) integrated from $z = \pm 300$ pc off the plane. The points have been arbitrarily scaled according to their dust extinction (between $A_V = 0$ mag and $A_V = 9$ mag), so larger scatter points indicate more extinguished sightlines. The statistical errors (corresponding to the 16th/84th percentile of the cloud distances) are indicated via the line segments; an additional systematic uncertainty is expected, as reported in Table A.1. *Right-hand panels*: zoom-ins of the clouds towards $l = 90°$ (*top*), clouds near the Sagittarius arm (*middle*), and clouds within the nearest 375 pc of the sun (*bottom*). In case this 3D figure does not render, an interactive 3D version is also accessible online and at `https://faun.rc.fas.harvard.edu/czucker/Paper_Figures/handbook_distances.html`.

Barnard 72 in Ophiuchus

http://www.robgendlerastropics.com/B72JMM.jpg

Maddalena+86

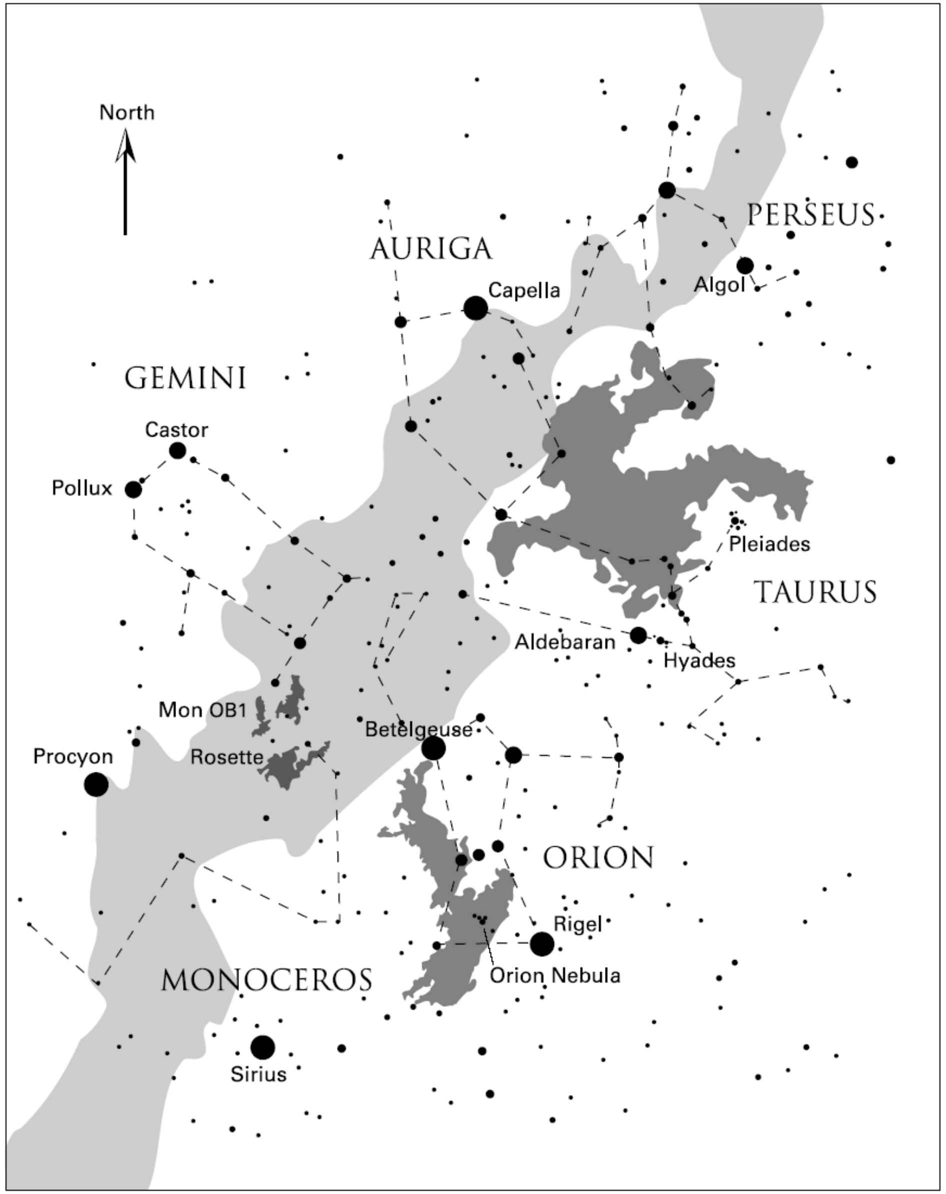


Figure 1.1 A portion of the Northern sky. The Milky Way is depicted as light grey, while the darker patches indicate giant molecular clouds. Also shown, according to their relative brightness, are the more prominent stars, along with principle constellations.

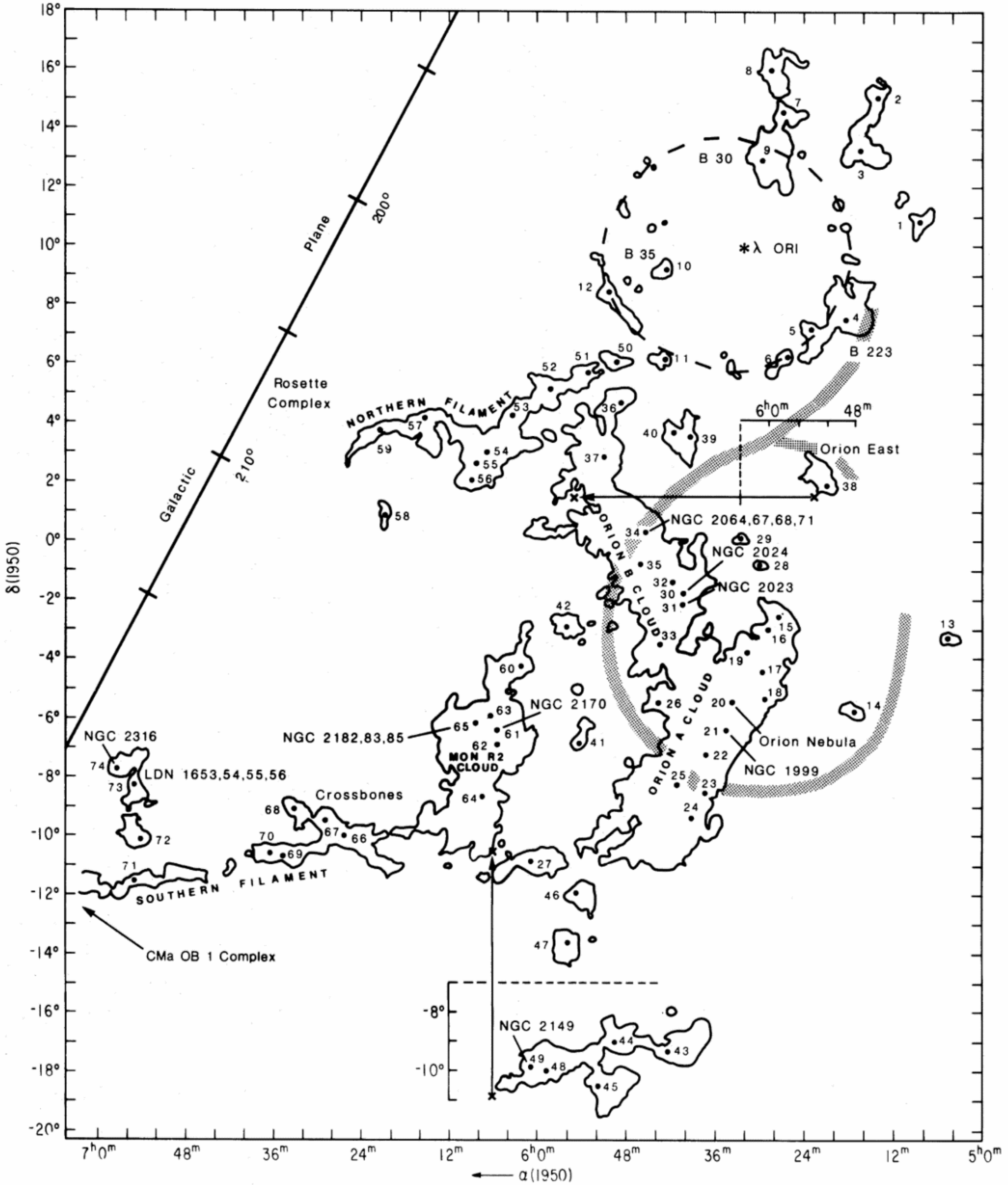
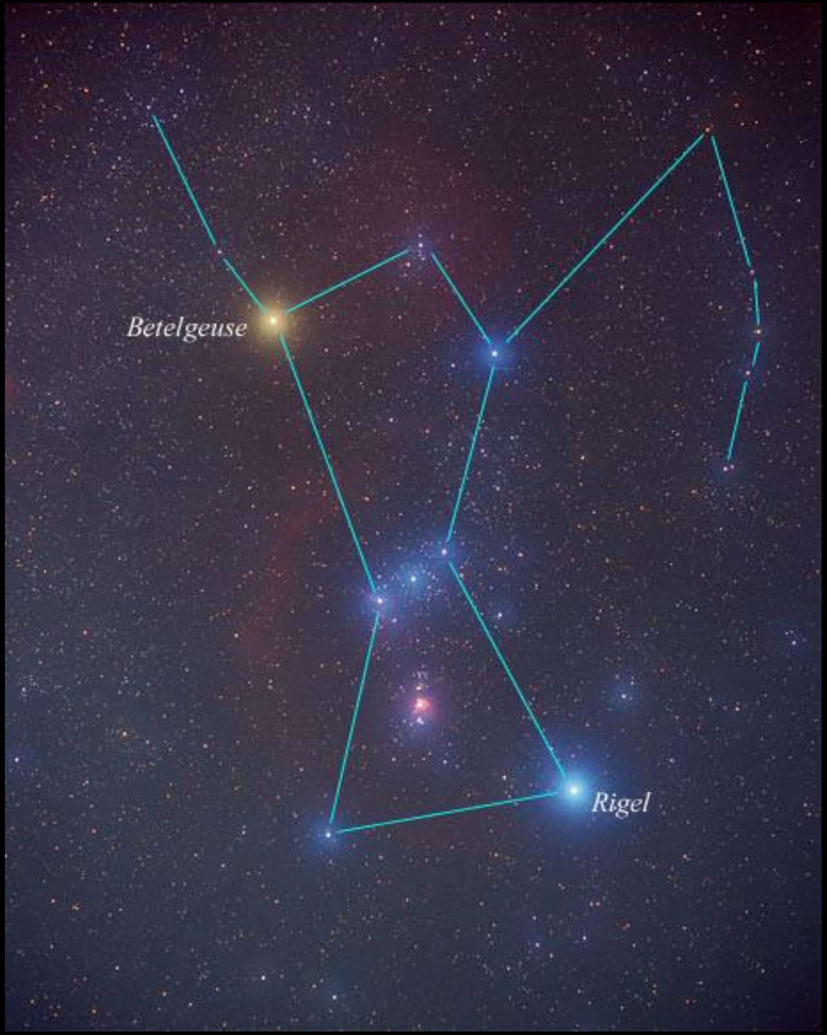
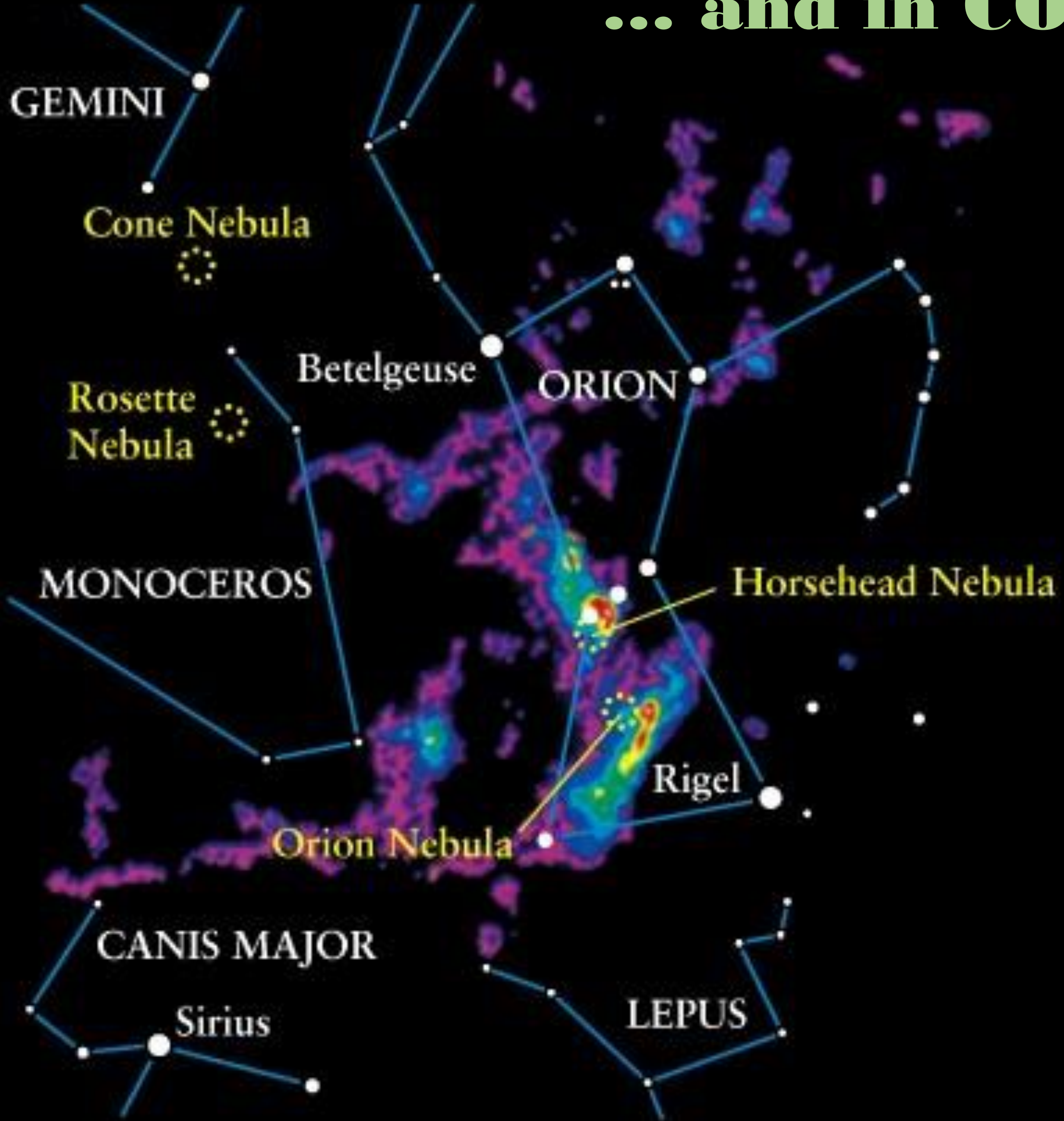


FIG. 3.—Schematic diagram of the molecular clouds: the lowest contour from Fig. 2. Dots with numbers, corresponding to those in Table 1, indicate locations of CO emission peaks. Some NGC numbers indicate the optically prominent objects coincident with CO peaks. The extent of UV emission from Barnard's loop is indicated by the shaded arc (from O'Dell, York, and Henize 1967; Isobe 1973). The dashed line roughly indicates the extent of the λ Ori ring of clouds.

Orion in visible light



… and in CO



(Bok) Globules silhouetted against emission nebulosity

© Anglo-Australian Observatory   Photograph by David Malin

A dark cloud core seen against a star field

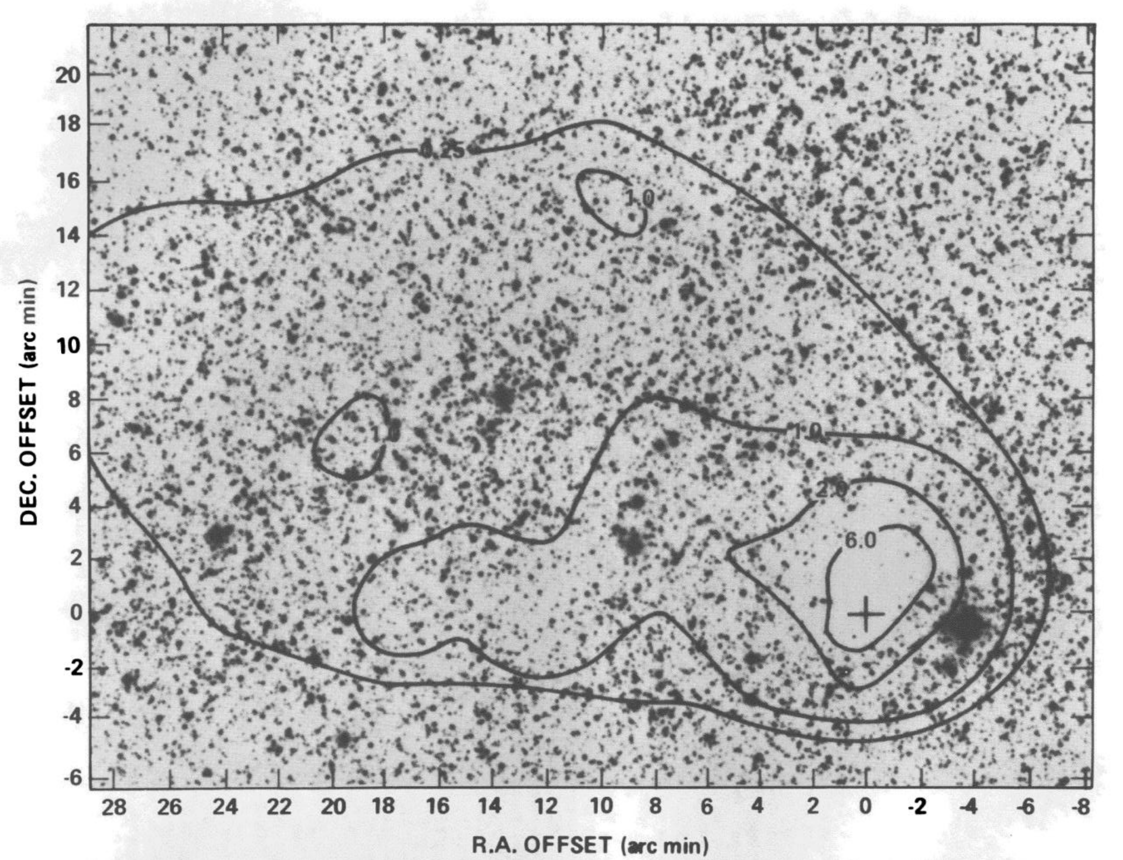
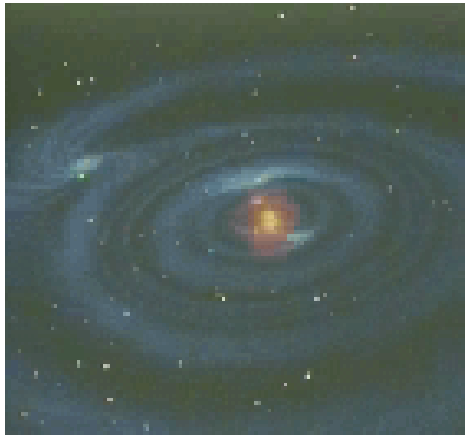


FIG. 1.—The optical image of B335 on the blue POSS print. Superposed on it are the $N(H_2)$ contours in units of 10^{21} cm^{-2}; the derivation of $N(H_2)$ is discussed in § IIIa(i). In the SW corner there is a highly obscured core region ~2′ × 3′ surrounded by an extended envelope covering ~34′ × 20′.

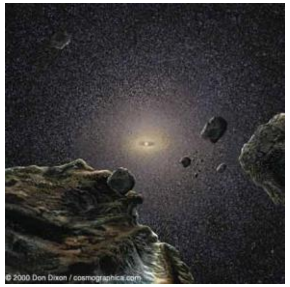
Frerking et al. (1987)

Star Formation in a Nutshell

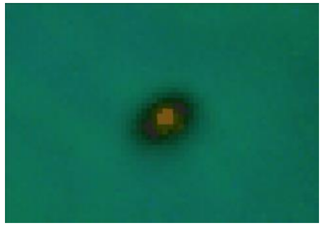


Interstellar Dark Cloud —**Contraction** / **Rotation**→ Protostar + Accretion Disk + Surplus Gas & Dust

Protostar ↓ - - → **Stellar Radiation, Wind**

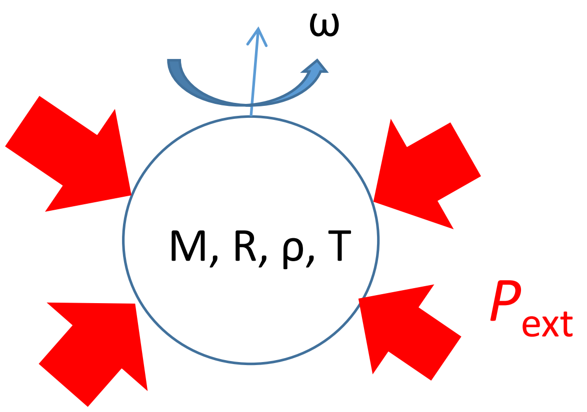


Young Star + Planetary Disk



Planetary Disk ↓

IS dust → Rocks → Planetesimals → Planets



Cloud of mass $\mathcal{M}$, radius R, temperature T, density ρ rotating at ω

$$E_{rot} = \frac{1}{2} I \omega^2 \qquad I = \frac{2}{5} M R^2$$

$$\Omega = -\frac{3}{5}\frac{GM^2}{R}$$

$$\frac{mv^2}{r} = \frac{GmM}{r^2}$$

Onset of spontaneous cloud collapse --- **Virial Theorem** 2 K + U =0

If ω=0, $P_{\text{ext}} = 0$

$$2 \cdot \frac{3}{2} \frac{M}{\mu m_H} kT - \frac{3}{5}\frac{GM^2}{R} = 0$$

$$\mathcal{M}_J = \left(\frac{\pi k_B T}{4 \mu m_H G}\right)^{3/2} \sqrt{\frac{1}{\rho}} \approx 1.0 \left(\frac{T}{10\ \text{K}}\right)^{3/2} \left(\frac{n_{H_2}}{10^4\ \text{cm}^{-3}}\right)^{-1/2} [\mathcal{M}_\odot]$$

If $\mathcal{M}_{\text{cloud}} > \mathcal{M}_{\text{J}}$ (Jeans critical mass) ➔ cloud collapse

Virial theorem

Equation of motion (in the Lagrangian form)

$$\varrho \frac{d^2\vec{r}}{dt^2} = \vec{f} - \nabla P \qquad (1)$$

In hydrostatic equilibrium, $\frac{d^2\vec{r}}{dt^2} = 0$, so $\vec{f} = \nabla P$, and assuming spherical symmetry and the force is self-gravitation

$$\frac{dP}{dr} = -\frac{G\, m(r)\, \varrho(r)}{r^2}$$ (Hydrostatic equilibrium)

and $m(r) = \int_0^r 4\pi r^2\, \varrho\, dr$ (mass continuity/distribution)

$$\varrho \frac{d^2\vec{r}}{dt^2} = \vec{f} - \nabla P$$

Take vector dot of $\vec{r}$ of (1), divide by ϱ, define $\boldsymbol{F} = \boldsymbol{f}/\varrho$ (force per unit mass, and integrate, using the boldface for vectors

$$\int dm\, \boldsymbol{r} \cdot \frac{\boldsymbol{d^2r}}{\boldsymbol{dt^2}} = \int \boldsymbol{r} \cdot F\, dm - \int \boldsymbol{r} \cdot \nabla P\, \frac{dm}{\varrho} \qquad (2)$$

Given $\frac{d}{dt}\left(\boldsymbol{r} \cdot \frac{d\boldsymbol{r}}{dt}\right) = \boldsymbol{r} \cdot \frac{d^2\boldsymbol{r}}{dt^2} + \left(\frac{d\boldsymbol{r}}{dt}\right)^2 = \frac{1}{2}\frac{d^2}{dt^2}\boldsymbol{r}^2$

So, $\displaystyle \int dm\, \boldsymbol{r} \cdot \frac{\boldsymbol{d^2r}}{\boldsymbol{dt^2}} = \frac{1}{2}\frac{d^2}{dt^2}\int \boldsymbol{r}^2\, dm - \int \left|\frac{d\boldsymbol{r}}{dt}\right|^2 dm$

$$= \frac{1}{2}\frac{d^2 I}{dt^2} - 2\mathcal{E}_{\text{kin}}$$

I: moment of inertia
$\mathcal{E}_{\text{kin}}$: kinetic energy

Because $dm = \varrho\, dV$, the last term in (2),

$$\int \boldsymbol{r} \cdot \nabla P \, \frac{dm}{\varrho} = \int \boldsymbol{r} \cdot \nabla P \, dV = \int \nabla \left(\boldsymbol{r} P\right) dV - 3 \int P \, dV$$

$$= \oint P\boldsymbol{r} \cdot d\boldsymbol{S} - 3 \int P \, dV$$

Assuming spherical symmetry,

$$= 4\pi R^3 P_s - 3 \int P \, dV$$

Note:

$$\int \nabla \left(\boldsymbol{r} P\right) = (\nabla \cdot \boldsymbol{r}) P + \boldsymbol{r} \cdot \nabla P$$

$$\nabla \cdot \boldsymbol{r} = 3$$

Gauss's theorem → volume integral of the divergence to surface integral

Putting together, we have

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 2\mathcal{E}_{\mathrm{kin}} + 3\int P\, dV + \int \boldsymbol{r} \cdot F\, dm - \oint P\boldsymbol{r} \cdot d\boldsymbol{S}$$

where $\boldsymbol{r} \cdot F$ (work) is virial;

or

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 2\,\mathcal{E}_{\mathrm{kinetic}} + 3\int P\, dV + \mathcal{E}_{\mathrm{potential}} - 4\pi R^3 P_{\mathrm{external}}$$

For stars, under hydrostatic equilibrium and $P_{\mathrm{ext}} = 0$,

$$2\,\mathcal{E}_{\mathrm{k}} + \mathcal{E}_{\mathrm{p}} = 0$$

$$\frac{1}{2}\frac{d^2I}{dt^2} = 2\,\mathcal{E}_\mathrm{k} + \mathcal{E}_\mathrm{p}$$

LHS = 0 → stable

LHS < 0 → collapsing

LHS > 0 → expanding

$\mathcal{E}_\mathrm{k}$: a variety of kinetic energies

- ✓ Kinetic energy of molecules
- ✓ Bulk motion of clouds
- ✓ Rotation
- ✓ …

$\mathcal{E}_\mathrm{p}$: a variety of potential energies

- ✓ Gravitation
- ✓ Magnetic field
- ✓ Electrical field
- ✓ …

$\mathcal{E}_\mathrm{total} = \mathcal{E}_k + \mathcal{E}_p$, governs if the system is <u>bound</u> ($\mathcal{E}_\mathrm{total} < 0$)

For stars, mostly $\mathcal{E}_p = \Omega$ (gravitational energy; negative)

If $P_{\text{ext}} \neq 0$ **(Bonnor – Ebert sphere)** $2K + U - 3\,P_{\text{ext}}\,V = 0$

Typical parameters for molecular dense cores or Bok globules
→ OK to collapse

In reality, resistance by $\vec{\mathcal{B}}$, $\vec{\boldsymbol{\omega}}$, turbulence, etc.
→ low star formation efficiency (a few %) in typical clouds

For GMCs → $\mathcal{M}_J \approx 100 \sim 1000\ \mathcal{M}_\odot$

But stars have masses ≈0.08 $\mathcal{M}_\odot$ to 150 $\mathcal{M}_\odot$.   (*What if not?*)

So what happens?

Formation of Star Clusters

Recall $\mathcal{M}_J \propto \frac{T^{3/2}}{\rho^{1/2}}$, and a smaller $\mathcal{M}_J$ favors cloud collapse

Cloud collapse → ρ always ↑, if gravitational energy radiated away → optically thin → cooling → $T \approx$ const (**isothermal collapse**)

denser → more collisions → more excitations and line emission → if photons escape → cooling

→ $\mathcal{M}_J \propto \rho^{-1/2} \longrightarrow \mathcal{M}_J$ ↓, i.e., easier to exceed the threshold

→ **fragmentation** to fragments or cores → a **star cluster**

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cloud opaque → photons do not escape

When a dense core becomes very dense → optically thick (**adiabatic collapse**) → $T \propto \rho^{3/2}$ ↑, and $\mathcal{M}_J \propto \rho^{1/2}$ ↑ with time, i.e., ever more difficult to collapse → individual stars

Barnard 86

NGC 6520

Types of Star Clusters

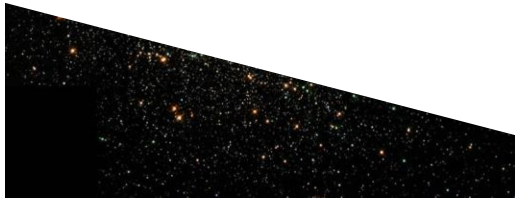
Morph… there are two general kinds of star clusters

The division is not always clear. There are some clusters with properties of both kinds, and there are yet some falling in between.

- Gala…
  - ✓Lo…
  - ✓1(…
  - ✓Y…
  - ✓/…

…2 m

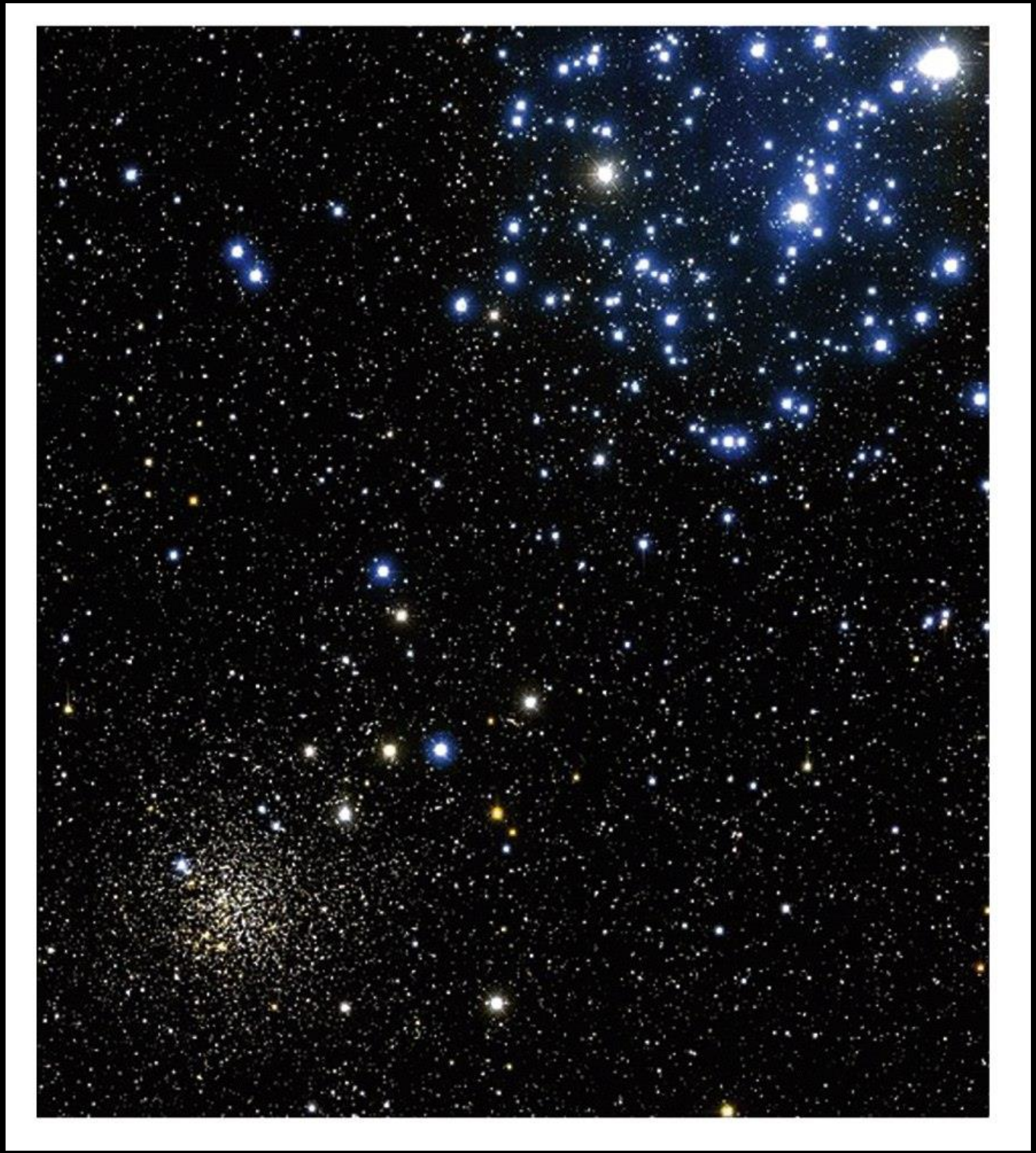
- Globular…
  - ✓Spherically shaped, … concentrated
  - ✓10^4 to 10^6 members
  - ✓Old members; Pop II ("metal" poor)
  - ✓100s known; mostly in the halo , orbiting/concentrated toward the GC



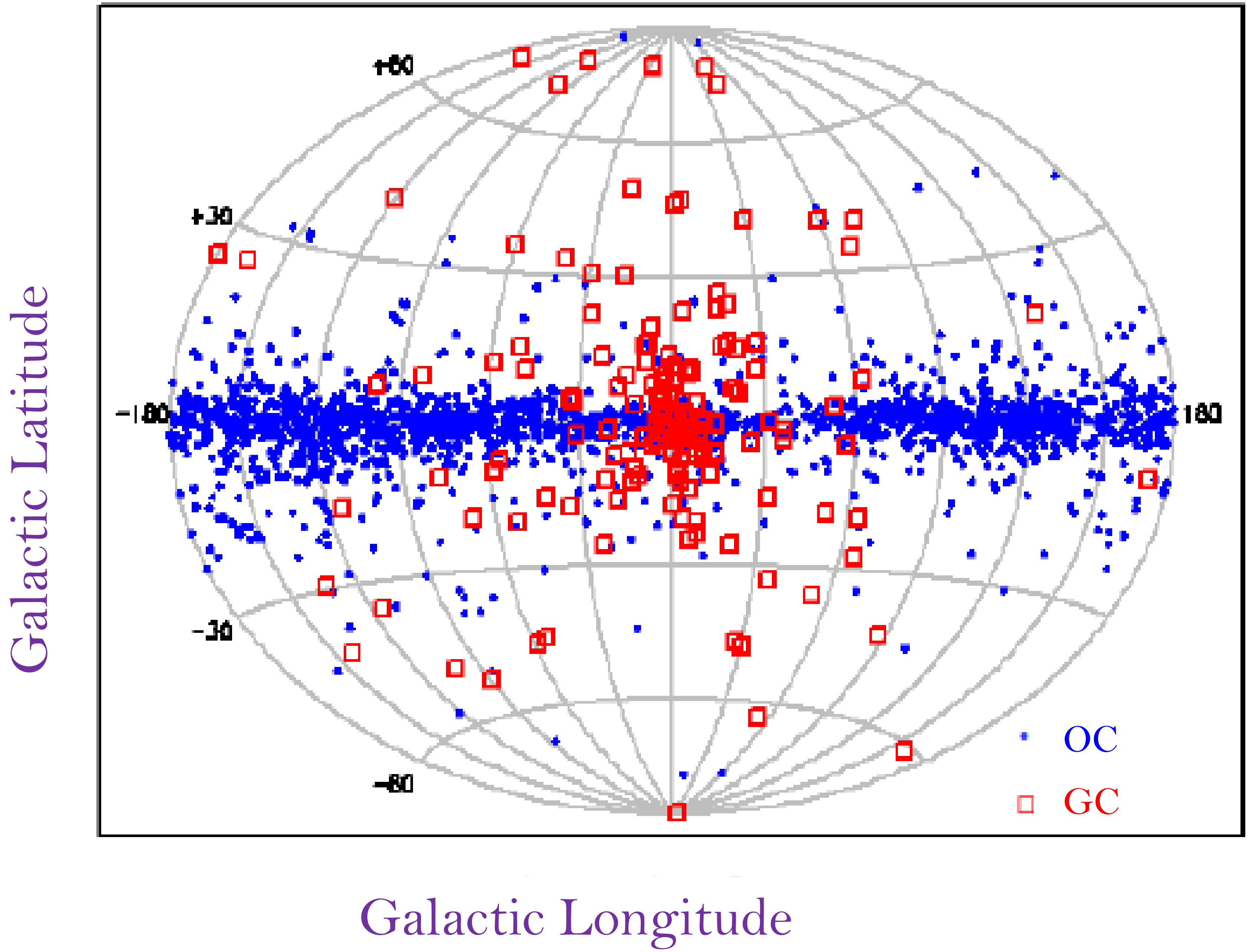
M80 HST

M31-G1 HST

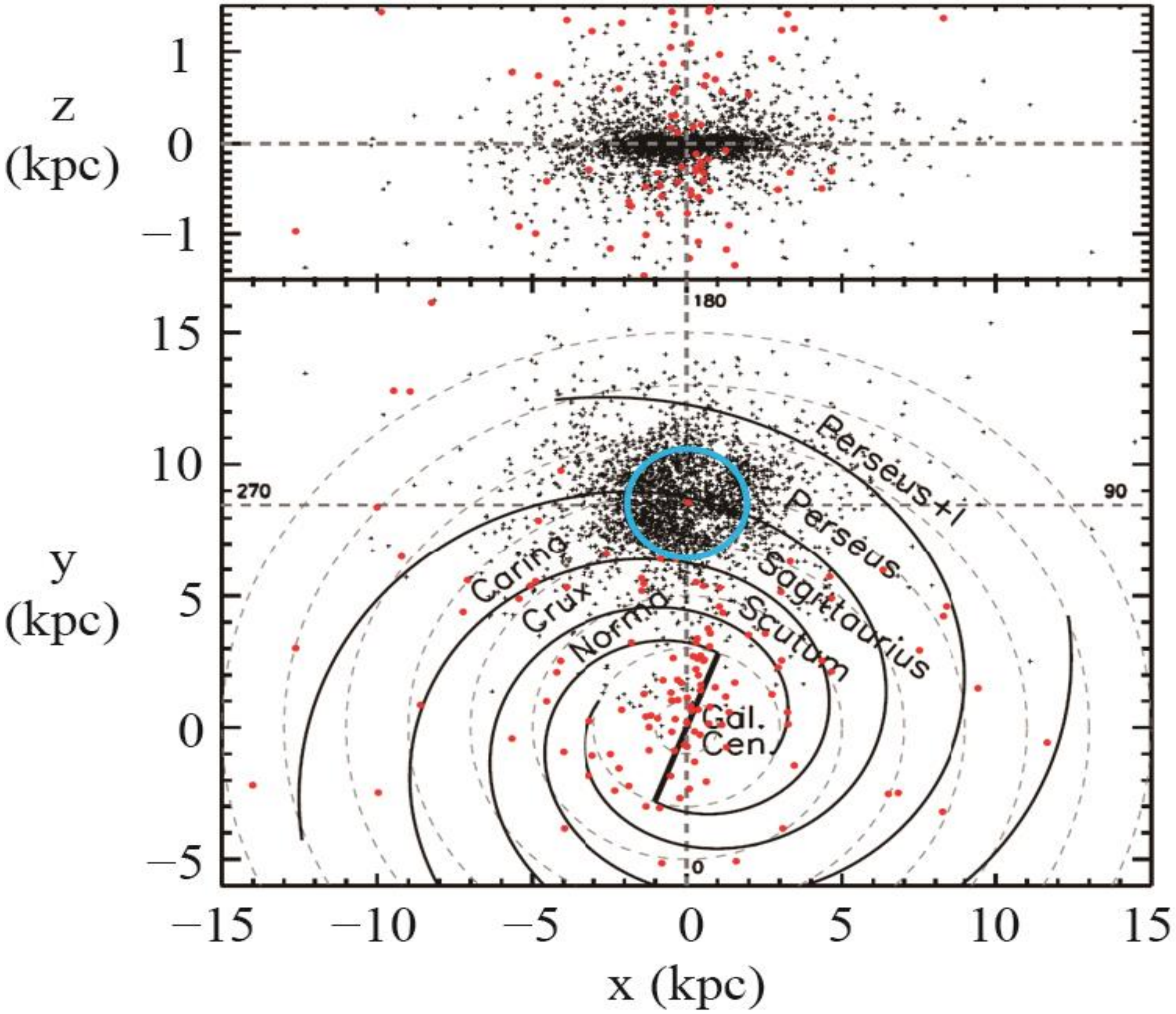
M35
$d = 860$ pc
$\tau = 150$ Myr



NGC 2158
$d = 5200$ pc
$\tau = 1.05$ Gyr



+60
+30
-180
180
-30
-60
OC
GC
Galactic Latitude
Galactic Longitude

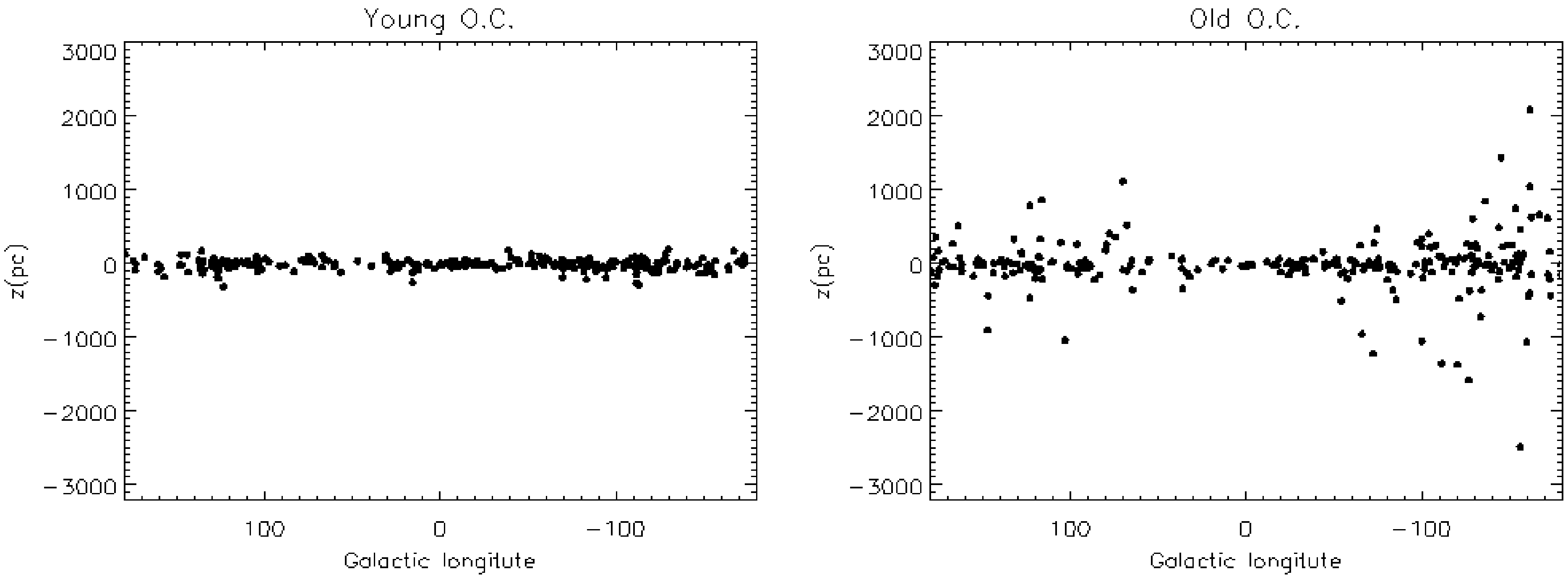


OCs preferentially on the disk plane

GCs preferentially away from the disk in the halo; centering around the Galactic center

Most known star clusters within 1-2 kpc (*why*?)

Spatial Distribution of Galactic Open Clusters



Young open clusters (< 100 Myr) are located near the Galactic plane.
Older systems are more scattered above and below the plane.

Metallicity gradients

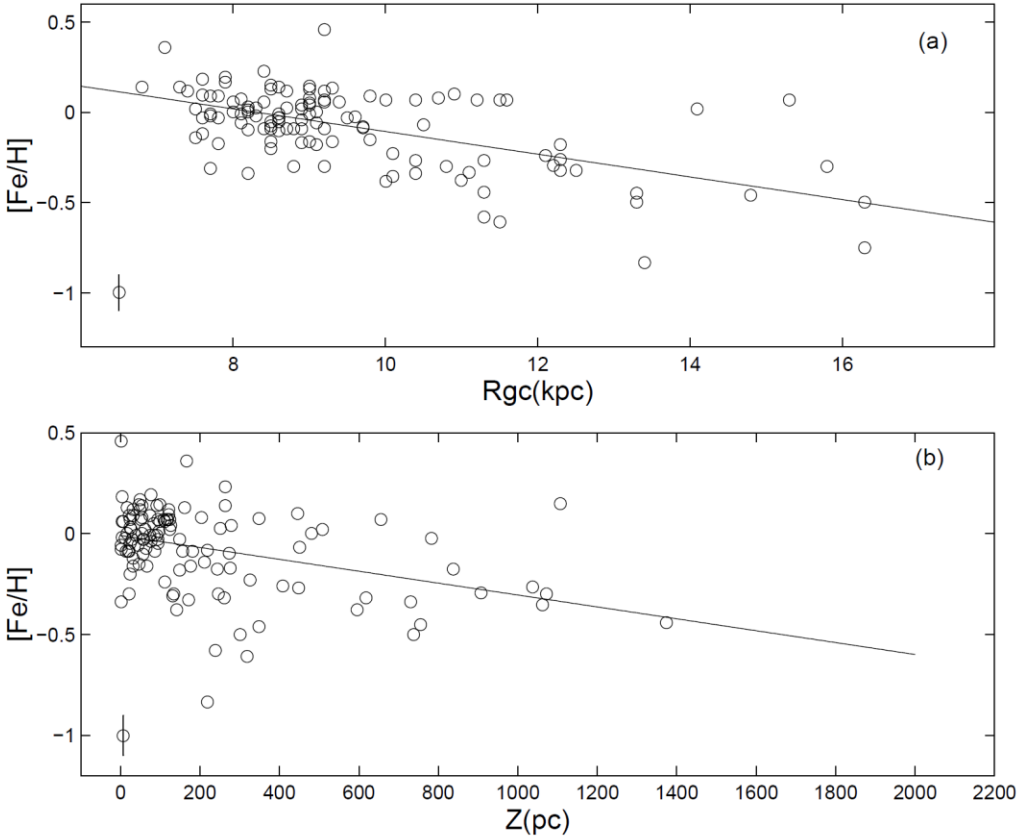


FIG. 8.—(*a*) Radial and (*b*) vertical abundance gradient for 118 open clusters. The least-square fitting results in a gradient of -0.063 ± 0.008 and -0.295 ± 0.050 dex kpc^{-1}, respectively. The typical error bar for [Fe/H] is about 0.1 dex, as shown in the lower left corner of the figures. In deriving the vertical gradient, the radial gradient has been corrected.

Age-Metallicity Relation

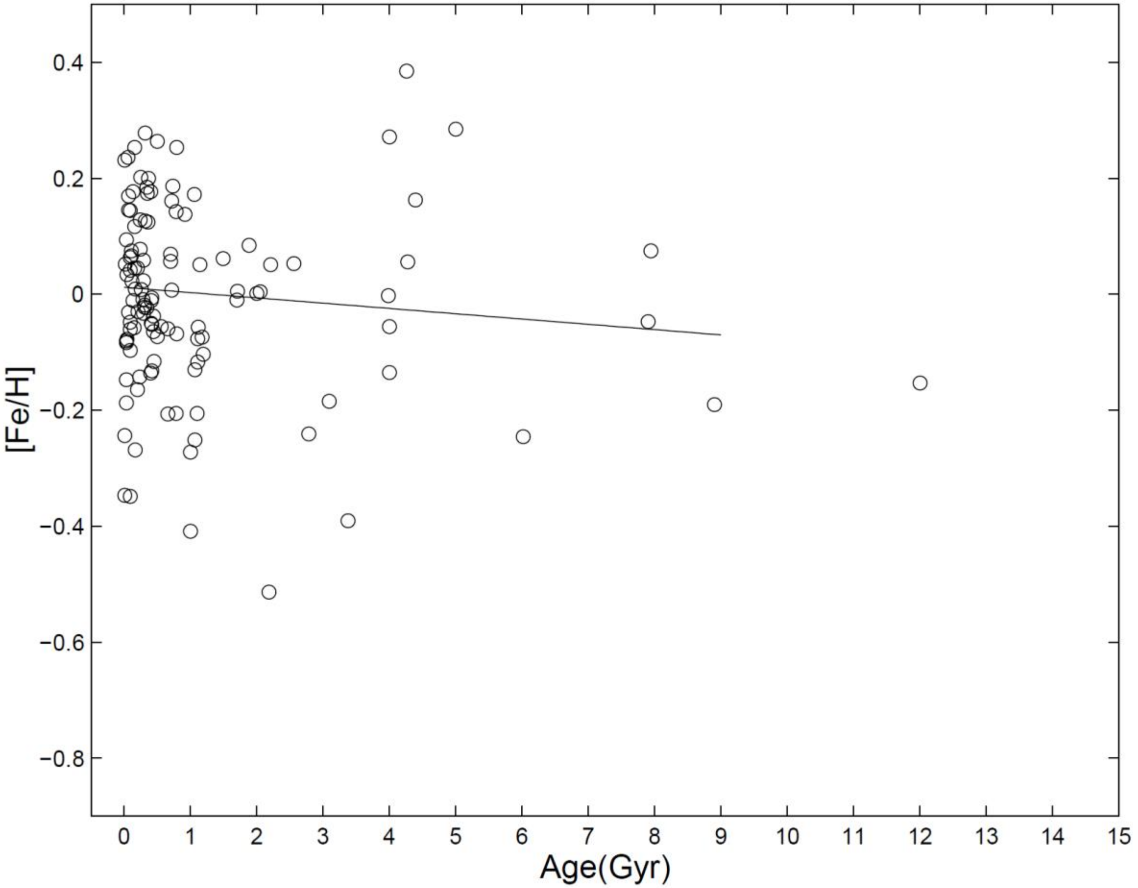
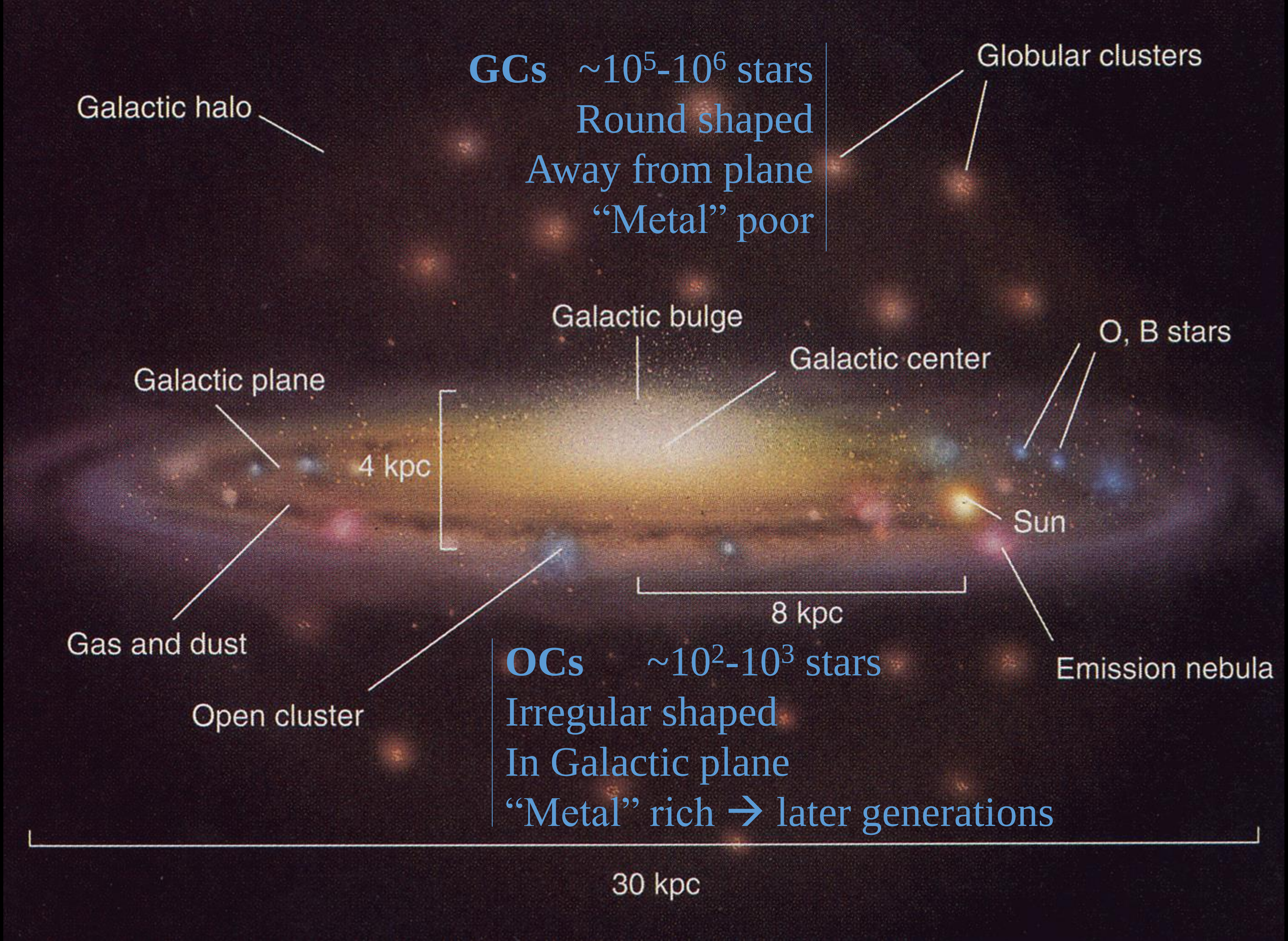


FIG. 10.—Age-metallicity relation (AMR) for the 118 open clusters after correcting for the radial gradient. The solid line is a least-square fit for the open cluster data.

Chen, L. + 2003

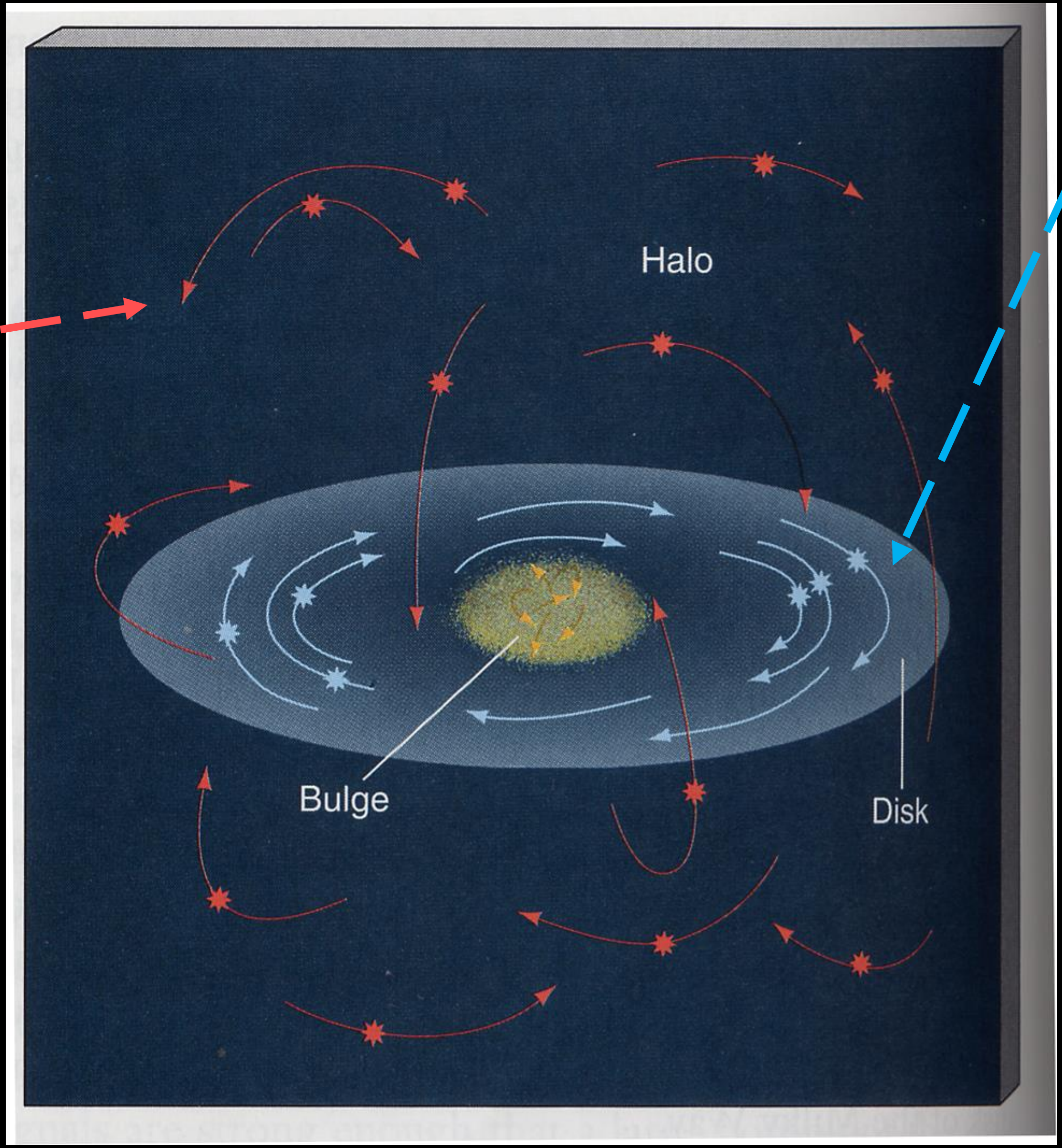


GCs ~10^5-10^6 stars
Round shaped
Away from plane
"Metal" poor

OCs ~10^2-10^3 stars
Irregular shaped
In Galactic plane
"Metal" rich → later generations

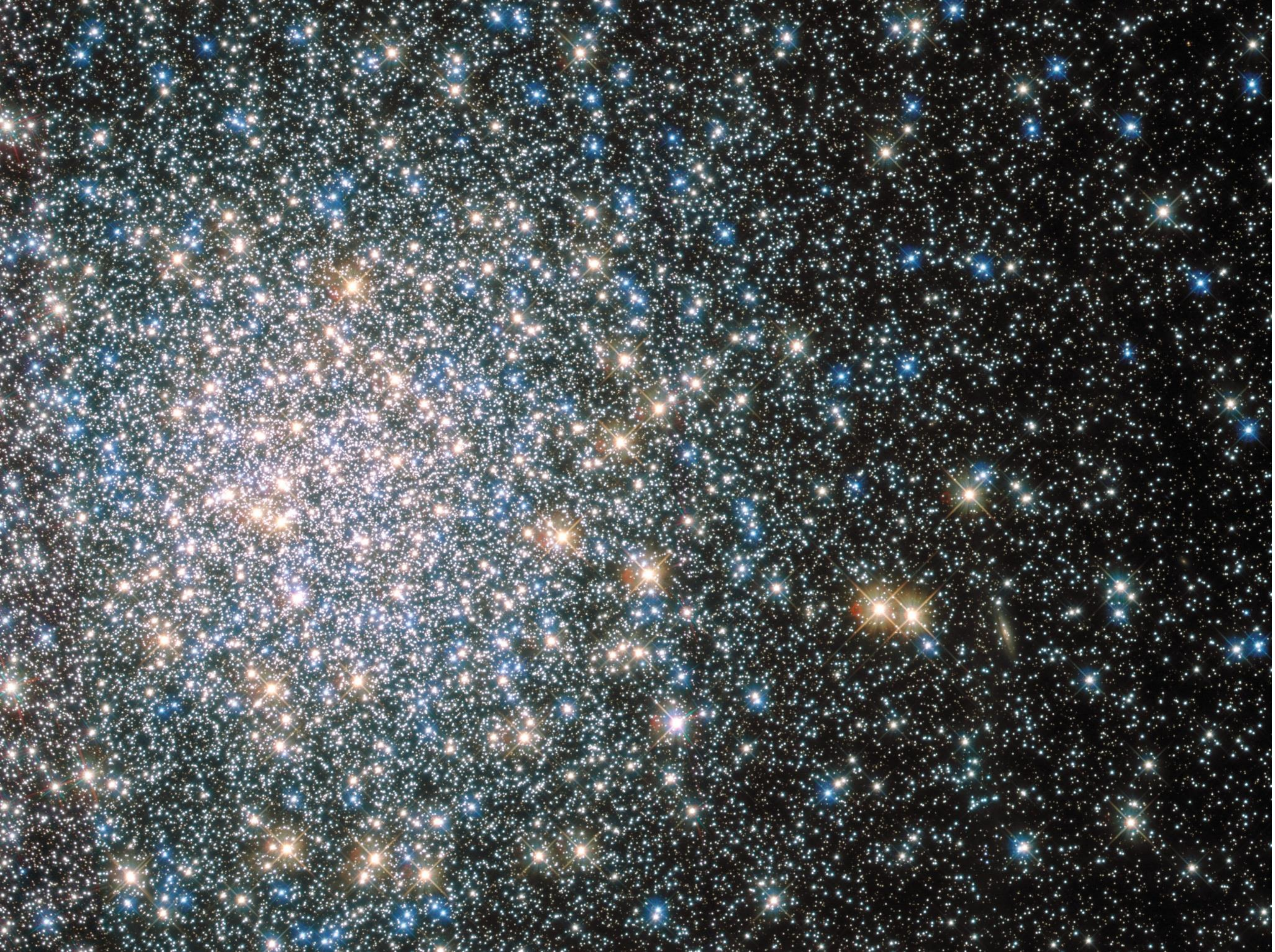
Stars in the halo and globular clusters move at random orientations

→ Star clusters remain self-gravitating and relatively intact



Stars and open clusters in the disk move in the plane of the disk

→ shear force tears a star cluster apart



A globular cluster is very compact that even the *HST* cannot resolve individual stars near the core.

Messier 5 by HST
APOD 2014.04.25

Star Clusters
as
Targets of Investigation

How to determine the luminosity and surface temperature, chemical composition, etc., of a star? How to determine its distance and age of a star?

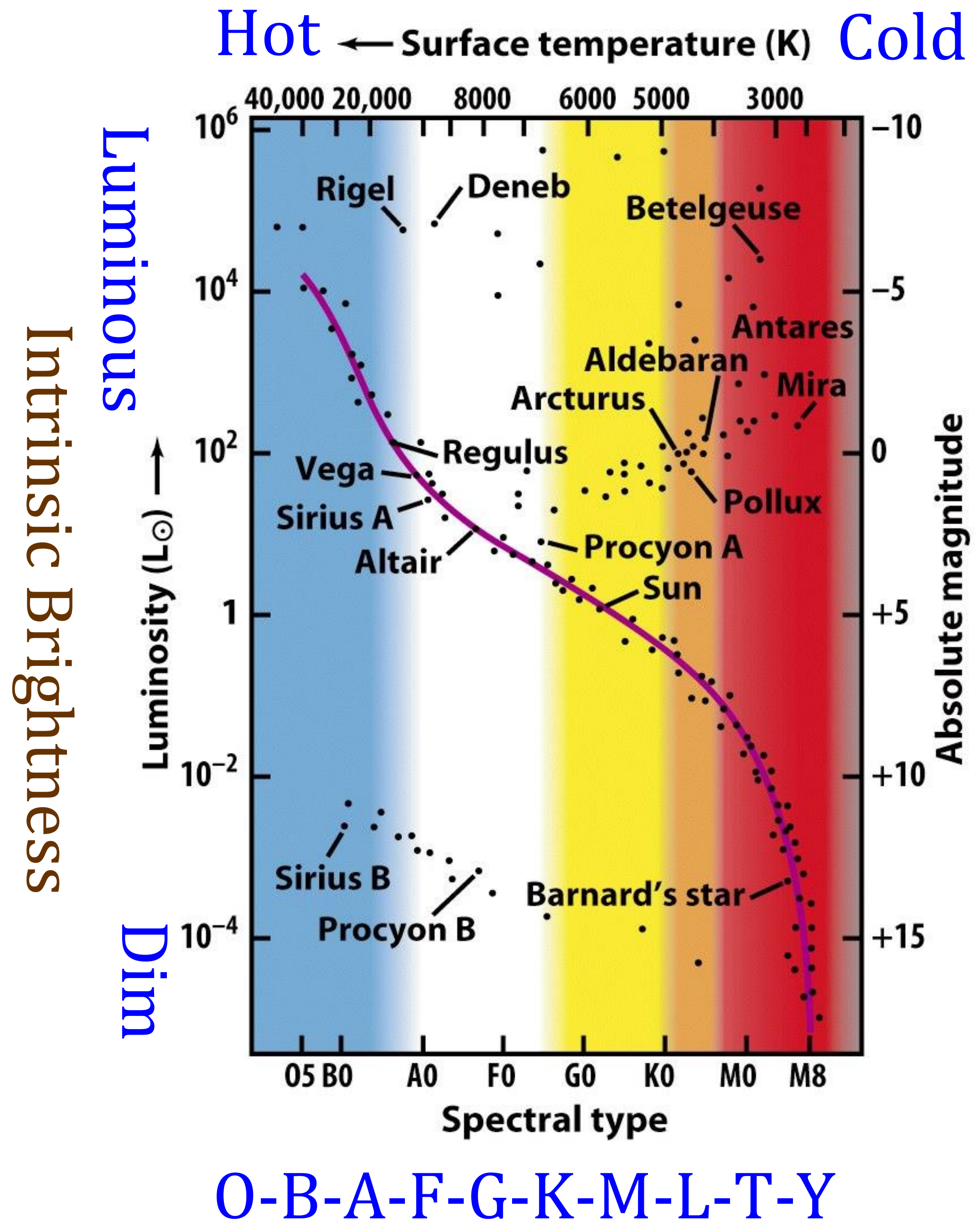
It is much easier if the star is a cluster <u>member</u>, because all the members were formed at the same time (coeval) out of the same molecular cloud, and at the same distance from us.

Stellar Properties in a Nutshell

A star generates energy by thermonuclear fusion reactions at its core → (outward) thermal pressure (gradient) to counteract (inward) gravitational pull

➔ **hydrostatic equilibrium** in every part of a star

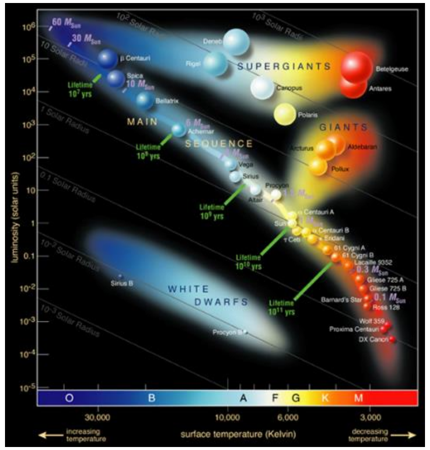
Stars with stable supply of H as nuclear fuel → **main sequence stars** = normal stars



$$\mathcal{L} = 4\,\pi\,\mathcal{R}^2\,\sigma\,T^4$$

Stellar luminosity | Stellar surface area | Blackbody radiation per unit area

$\uparrow$ $\mathcal{L}$



$\leftarrow T$

$$\mathcal{L} \propto \mathcal{M}^{3.5\sim5.5}$$

Main-sequence stars

- ◻ core hydrogen fusion; a stellar mass sequence
- ◻ MS stars have similar radii.
- ◻ Massive stars → fusion rate ↑↑↑ at the core → luminous $\mathcal{L}$ ↑↑↑ → large energy flux through stellar surface $4\,\pi\,\mathcal{R}^2$ → T↑

  Low-mass stars → moderate fusion rate → luminous $\mathcal{L}$ ↓ → smaller flux through surface → T↓

→ A diagonal band in the **Hertzsprung-Russell (HR) diagram**

Stellar Evolution in a Nutshell

$\tau \propto \mathcal{M}/\mathcal{L} \propto \mathcal{M}^{-2.5}$

- Massive MS stars → fusion rate ↑↑↑ → luminous $\mathcal{L}$ ↑↑↑
  → nuclear fuel (H) used up rapidly → lifetime τ ↓↓

  Low-mass MS stars → moderate fusion rate → luminous $\mathcal{L}$ ↓
  → fuel used up slowly → τ ↑
- When central hydrogen exhausted (~10% for the Sun)
  → core contracts until being stopped
  - ✓ by next rounds of fusion — Nuclear waste (e.g., He) → nuclear fuel
  - ➢ by electron degenerate pressure (a white dwarf)
  - ➢ by neutron degenerate pressure (a neutron star)
  - ➢ by spacetime singularity (a black hole)
- Disruptive/explosive ending → complex nuclei to ISM

Member stars in a star cluster are formed out of the same molecular cloud, so should have the same age, same chemical abundances, and at the same distance from us.

But ...

What if there is significant time lapse in star formation?

→ different ages

For nearby systems, the depth may no longer be negligible

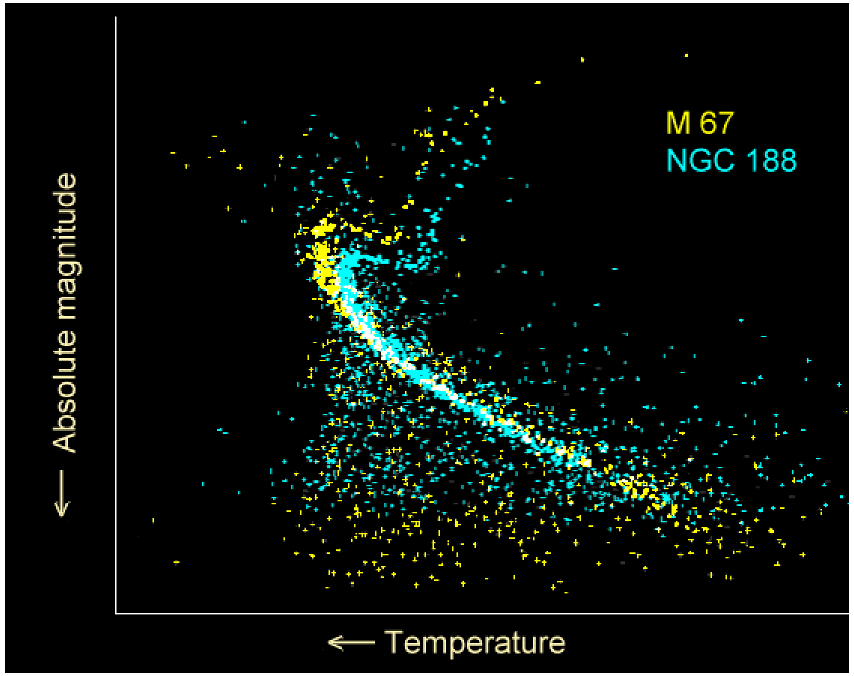
→ different distances

What if member stars are not from the same cloud?

→ different abundances

Hertzsprung-Russell Diagram
(physical)

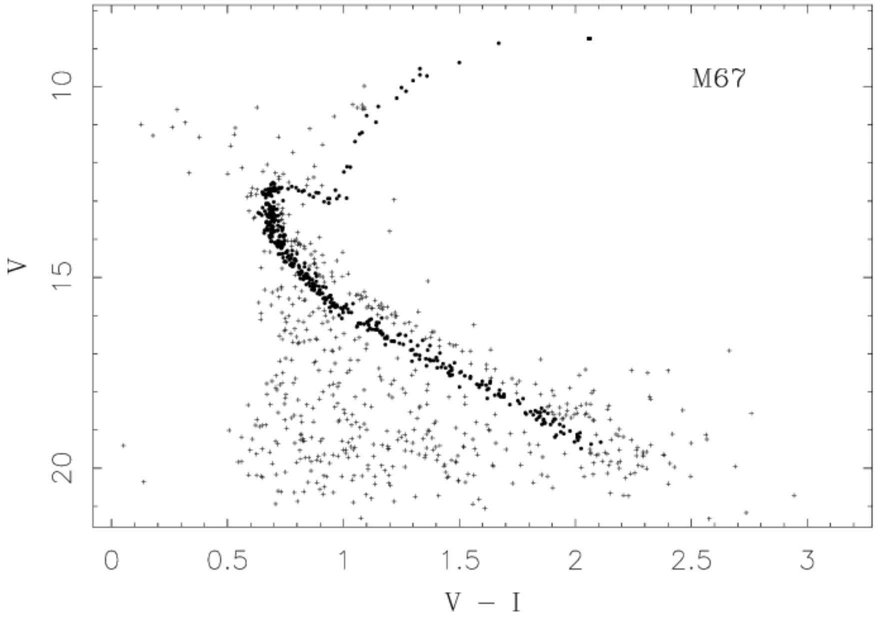
Brightness (Luminosity or Absolute Magnitude)



Spectral Type or surface Temperature

Color-Magnitude Diagram (CMD)
(observational, a proxy of the HRD)

Apparent or Absolute Magnitude



"Color" $(m_1 - m_2)$

To Determine the Distance of a cluster

Main Sequence Fitting

$$m_\lambda - M_\lambda = 5\log d_{\rm pc} - 5 + A_\lambda$$

$$(m_{\lambda 1} - m_{\lambda 2}) = (M_{\lambda 1} - M_{\lambda 2}) + E(\lambda 1 - \lambda 2)$$

$$E(\lambda 1 - \lambda 2) \equiv A_{\lambda 1} - A_{\lambda 2}$$

ISM (dust) reddening

More distant → fainter and redder

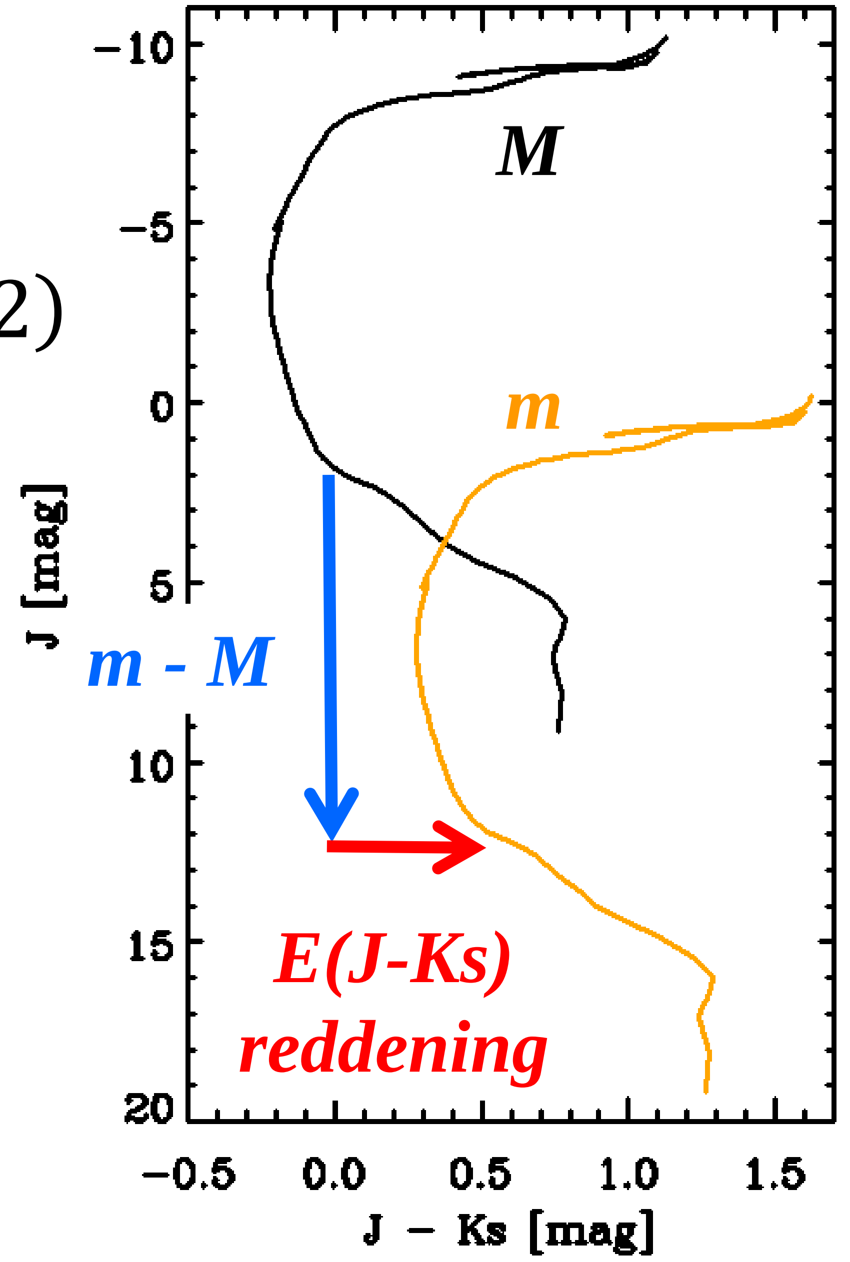
ISM "**Reddening law**" (Rieke & Lebofsky 1985)

$$A_B = 1.324\, A_V$$

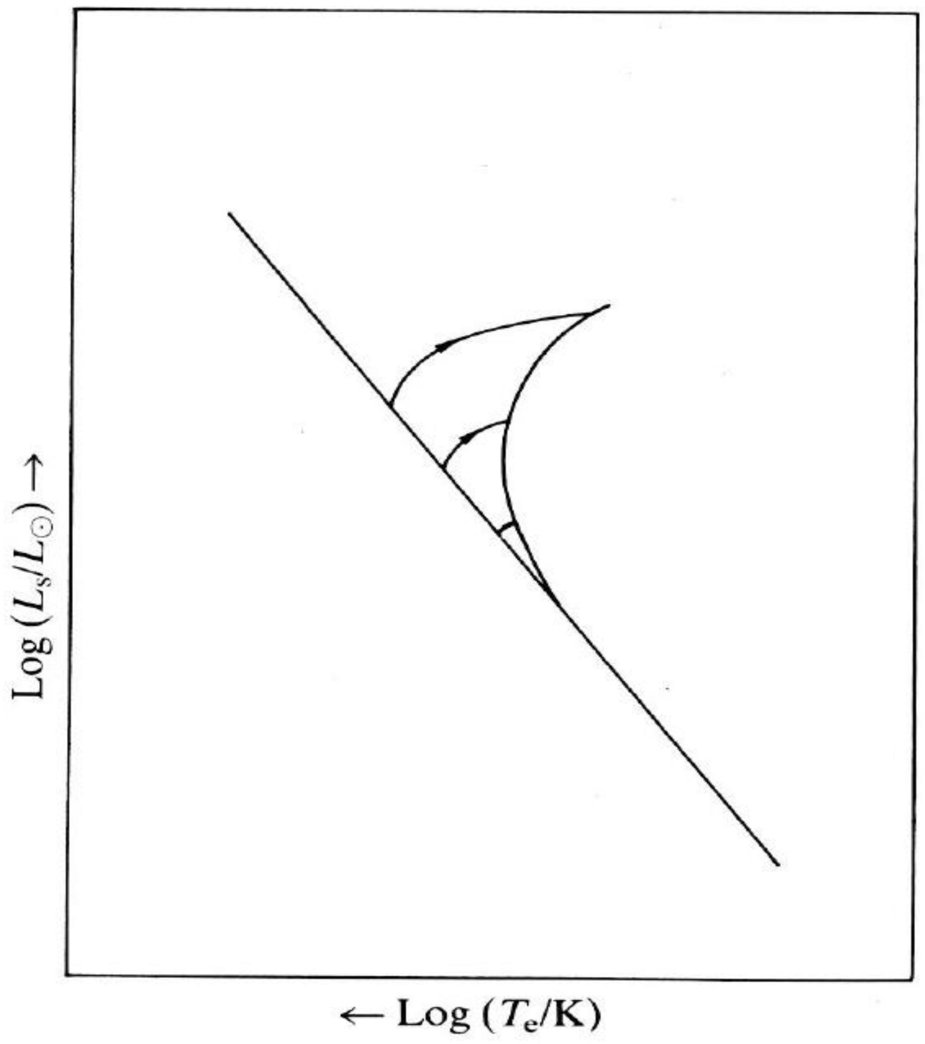
$$A_J = 0.282\, A_V$$

$$A_K = 0.112\, A_V$$

$$R \equiv A_V/E(B-V) \approx 3.1$$



To Determine the Age of a Star Cluster

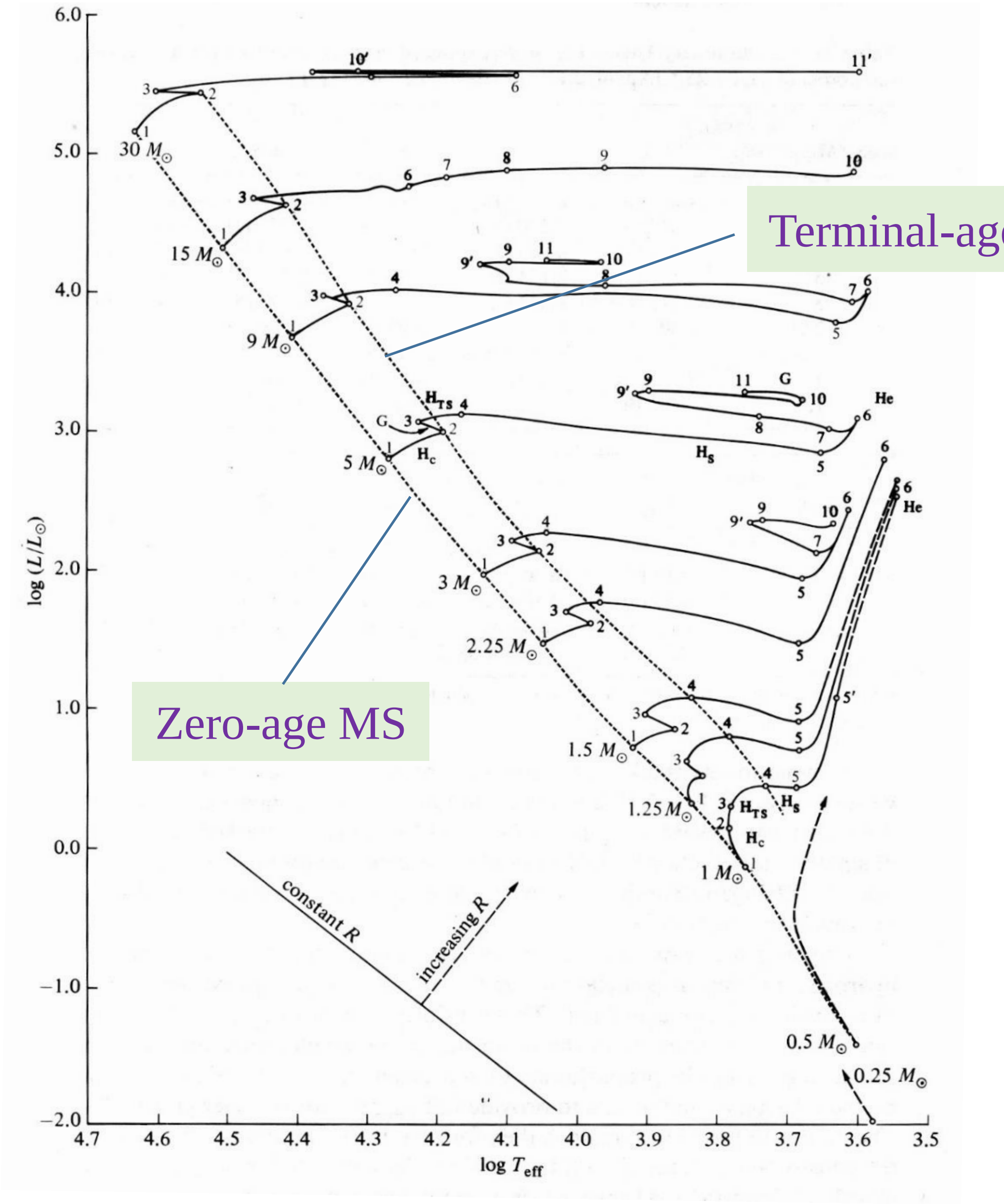


As a cluster (its member stars) ages, massive stars leave the MS first and evolve to the post-main sequence phase, then progressively followed by lower-mass members.

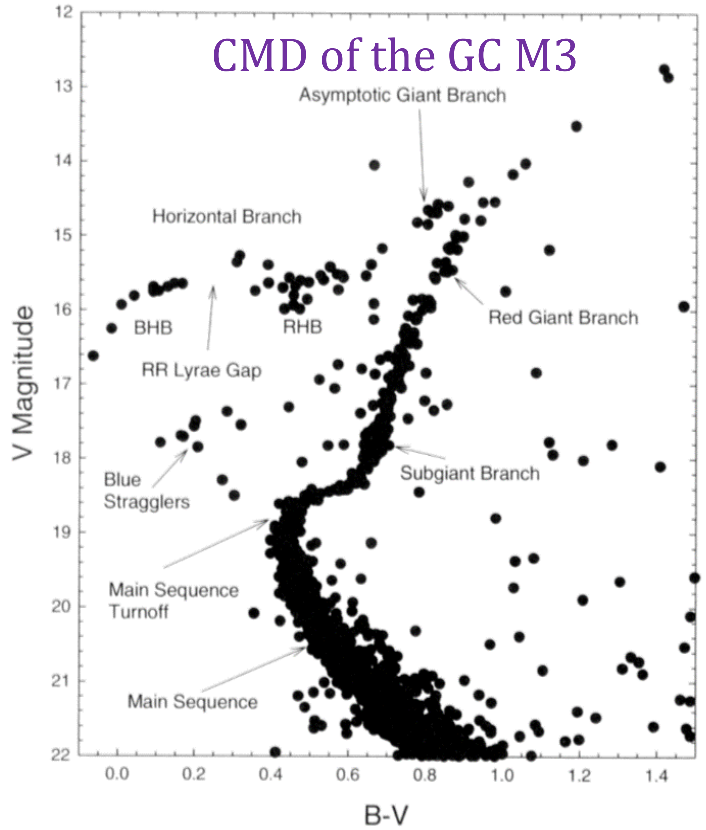
The MS is "peeled off" from the top (upper MS) down.

Only the low-mass stars remain on the MS.

Evolution of individual stars of different masses

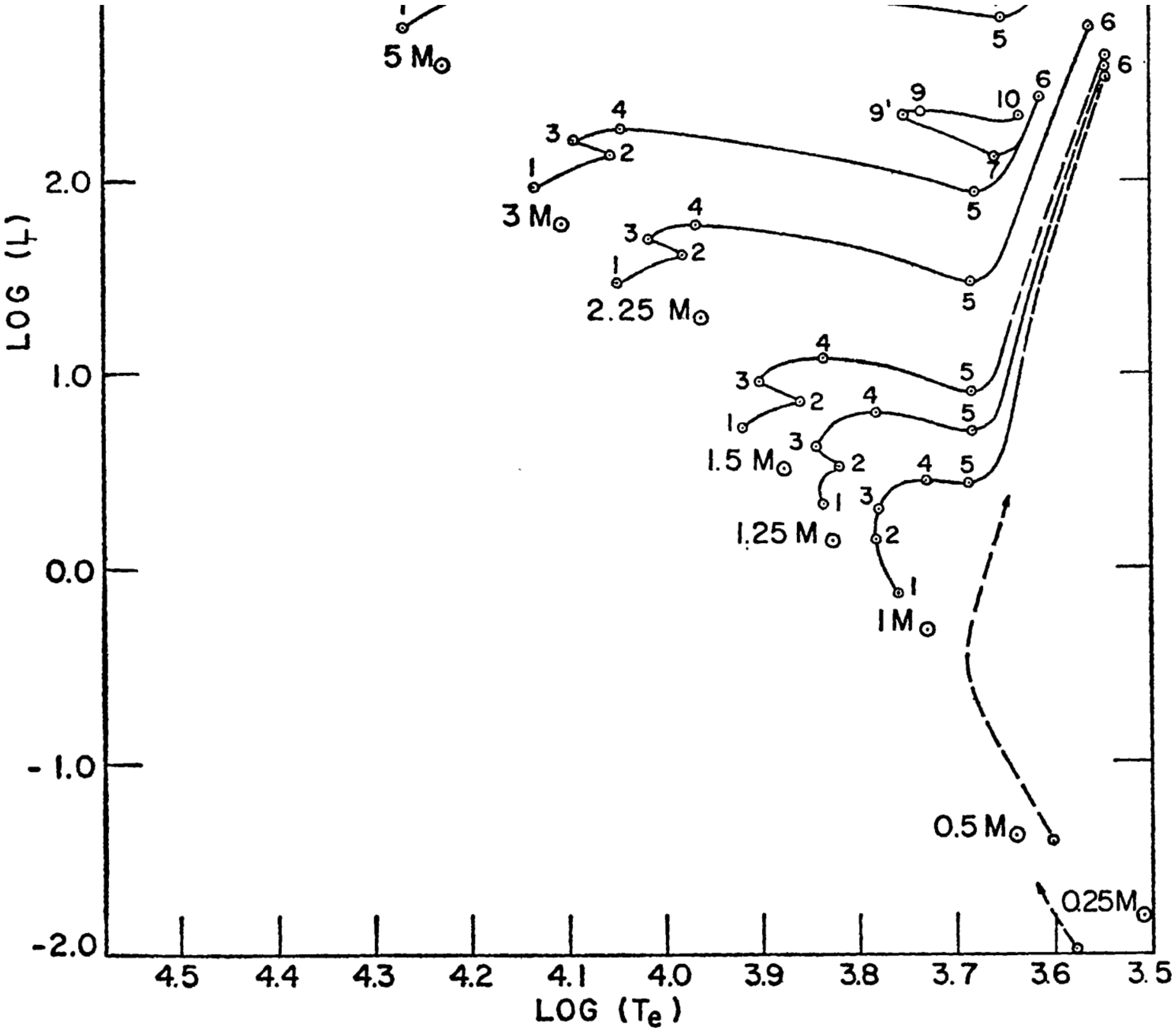


A collection of stars at different evolutionary stages

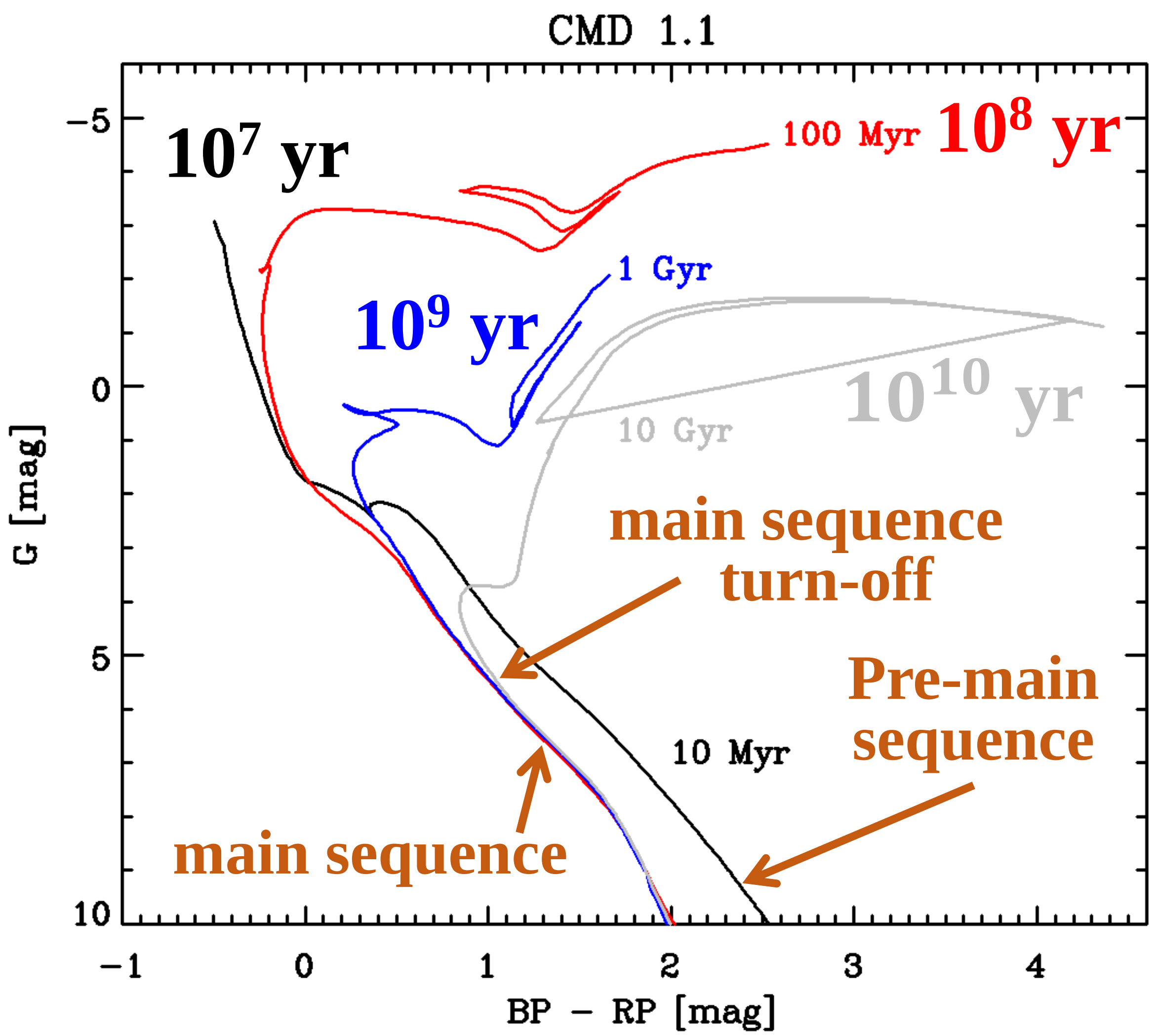


- Snapshot of different stellar masses at this age
- Star clusters at different ages → **theory of stellar evolution**

1-2 main sequence
2-3 overall contraction
3-4 H <u>thick</u> shell burning
5-6 H <u>thin</u> shell burning
6-7 red giant
7-10 core He burning
8-9 envelope contraction



Theoretical isochrones



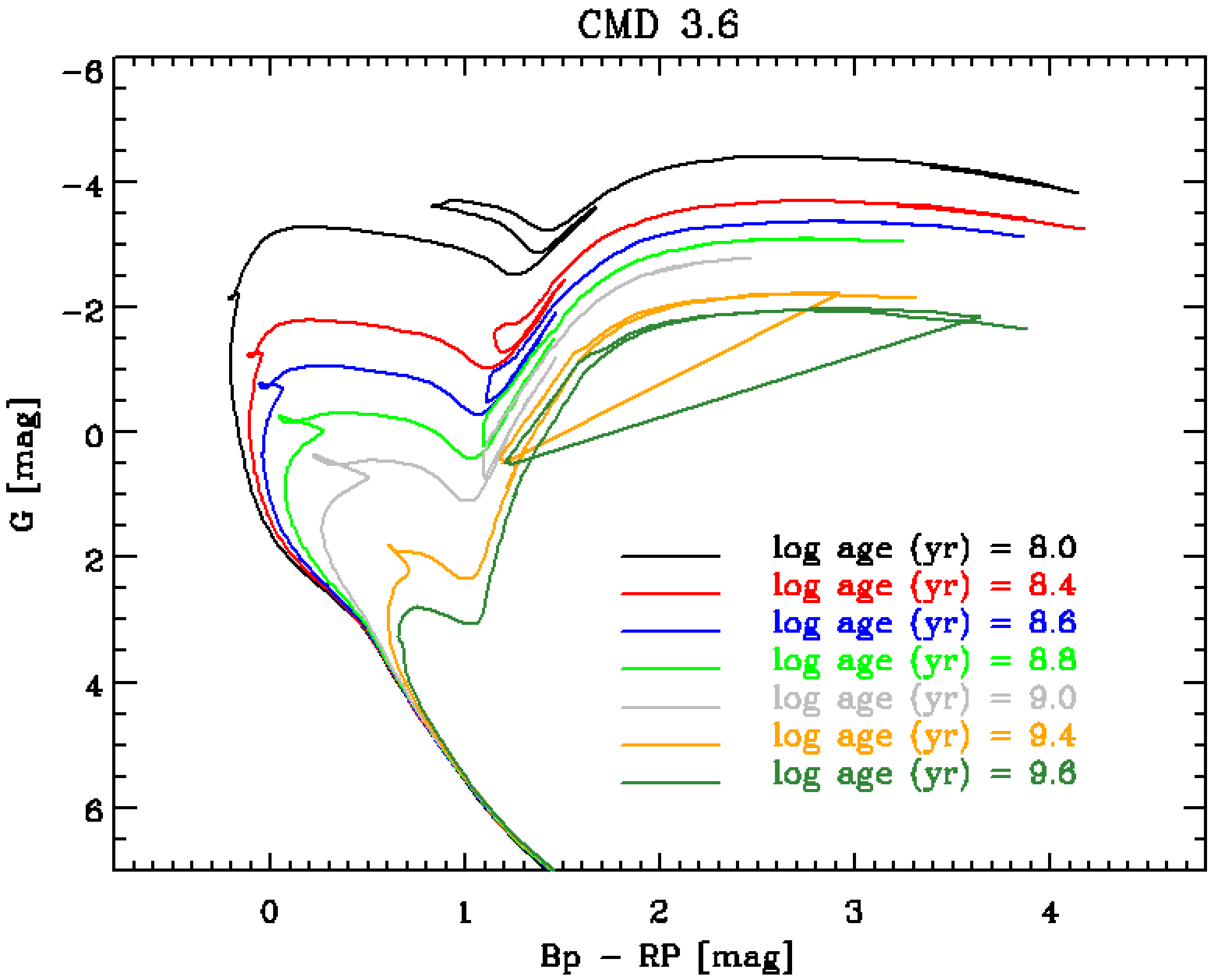
<u>Assumptions</u>:

✓coeval star formation
✓same metallicity
✓same distance

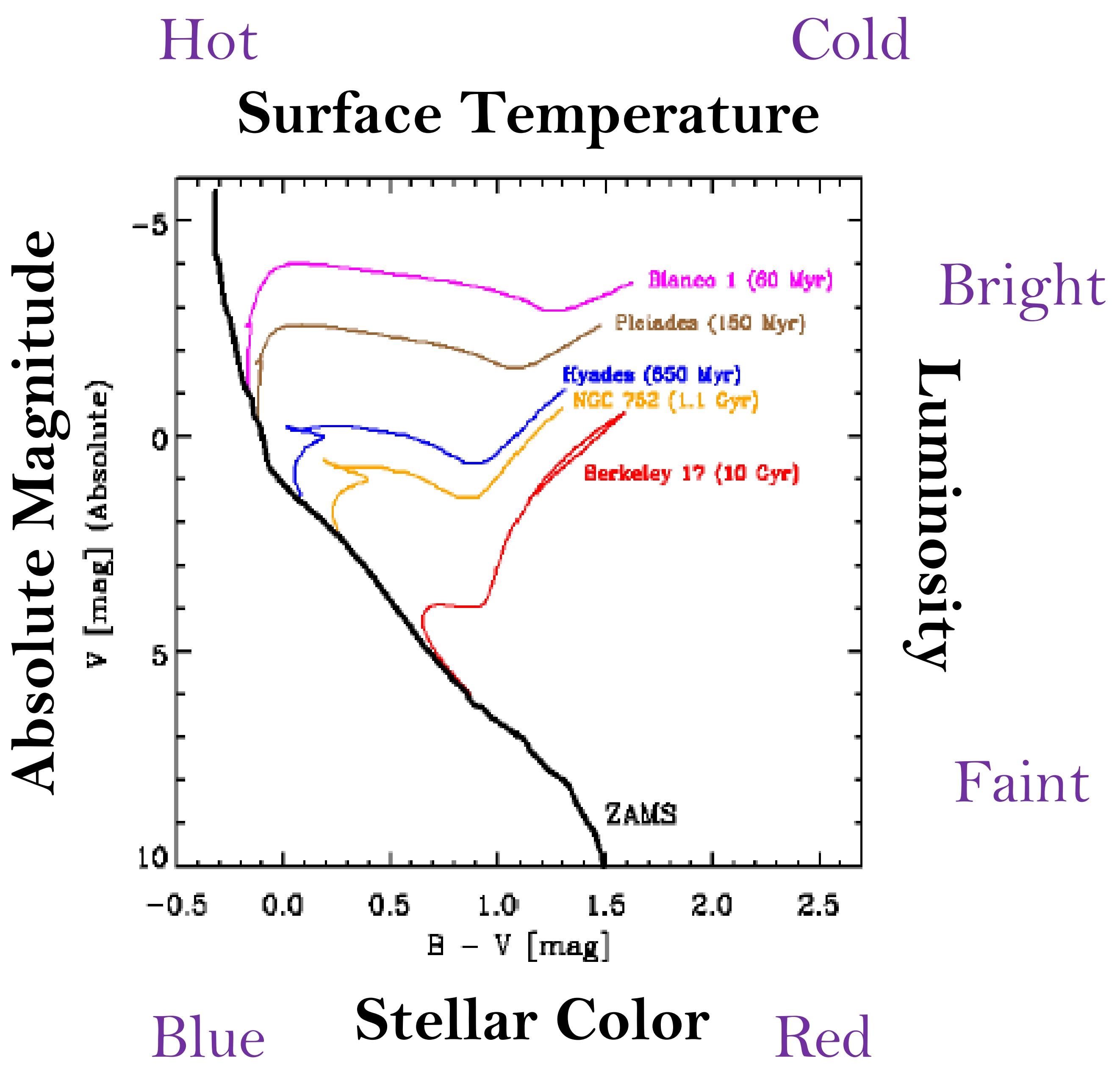
How good are these …

Age of the cluster
= the main sequence lifetime of stars at the MSTO

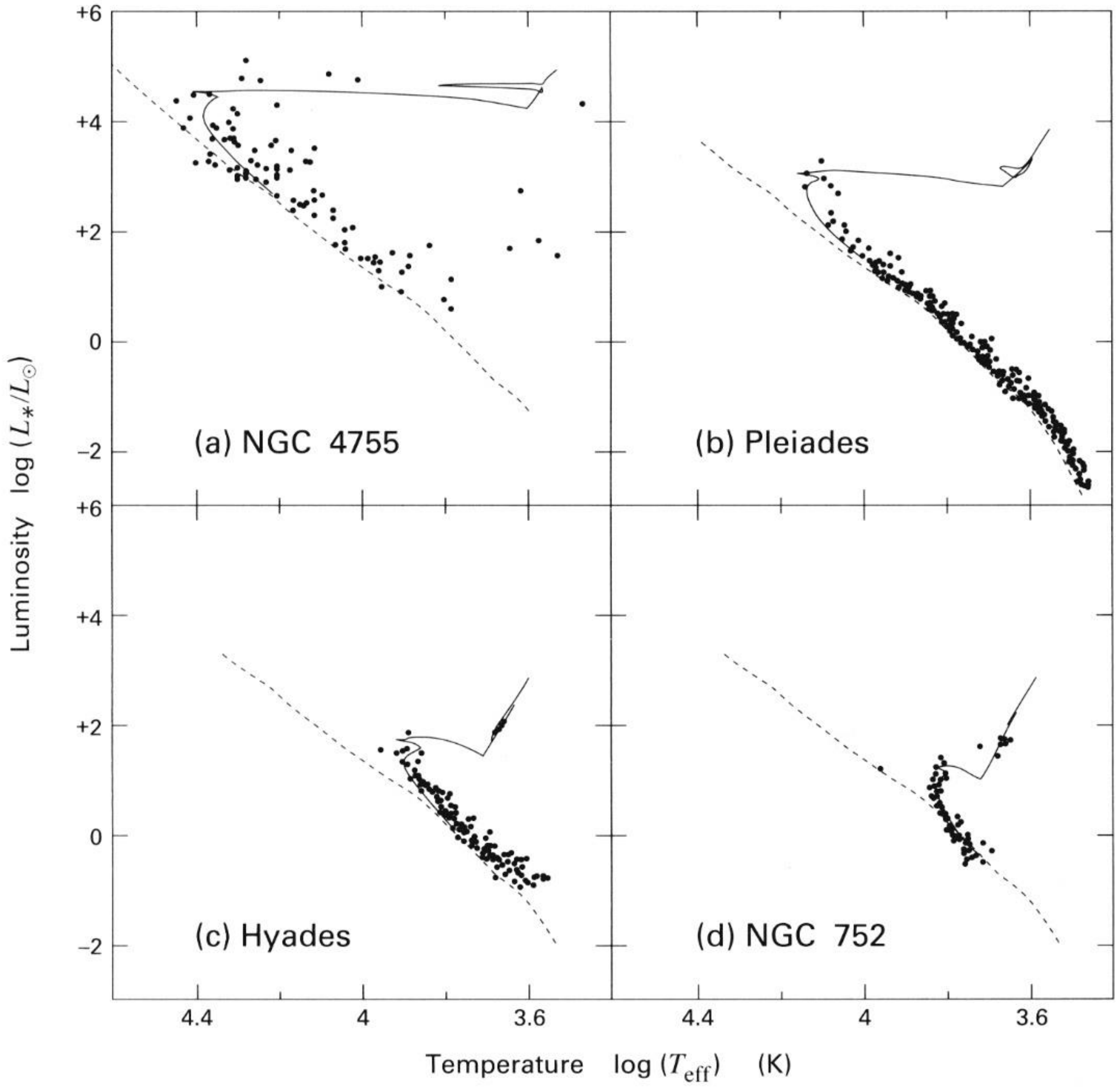
Post-MS members, while rarer than MS, are useful.


CMD 3.6
G [mag]
Bp – RP [mag]
−6
−4
−2
0
2
4
6
0
1
2
3
4
log age (yr) = 8.0
log age (yr) = 8.4
log age (yr) = 8.6
log age (yr) = 8.8
log age (yr) = 9.0
log age (yr) = 9.4
log age (yr) = 9.6

Observed CMDs



Test of Stellar Evolution by Star Clusters



Examples of HR diagrams of four open clusters, arranged by age, each showing the zero-age main sequence (ZAMS) and the best-fit isochrone.

Stahler & Palla (2004)

Effect of Metallicity

"metals" → low ionization/excitation potentials → effective coolants

Given the same mass, a metal poorer star is bluer and brighter.

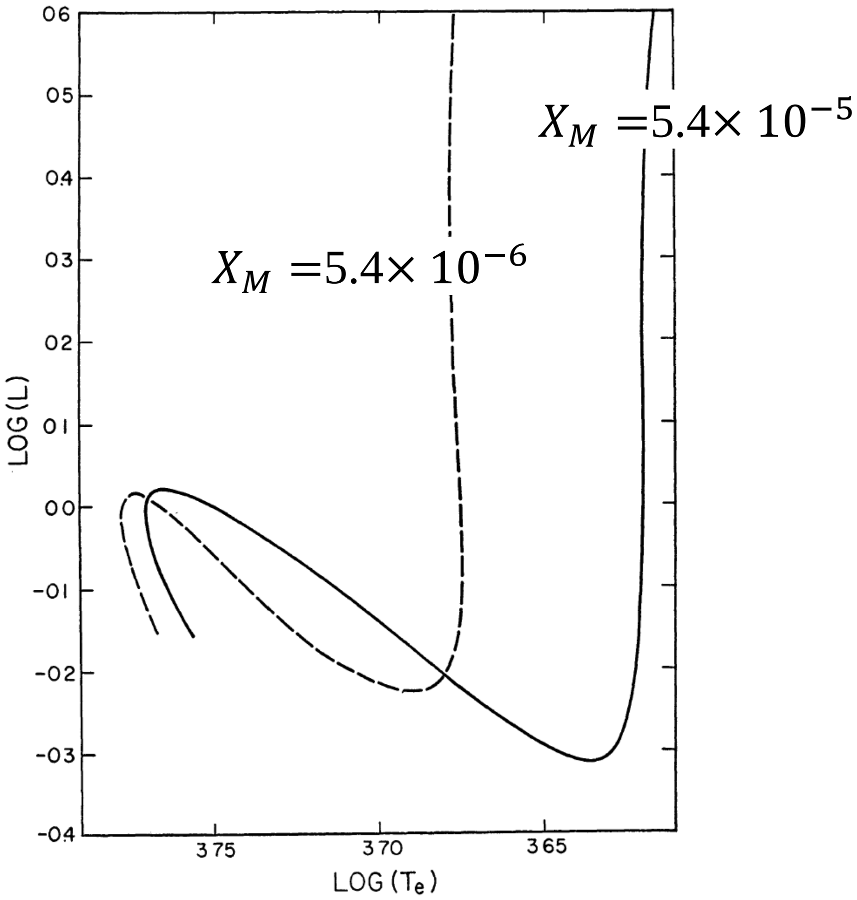
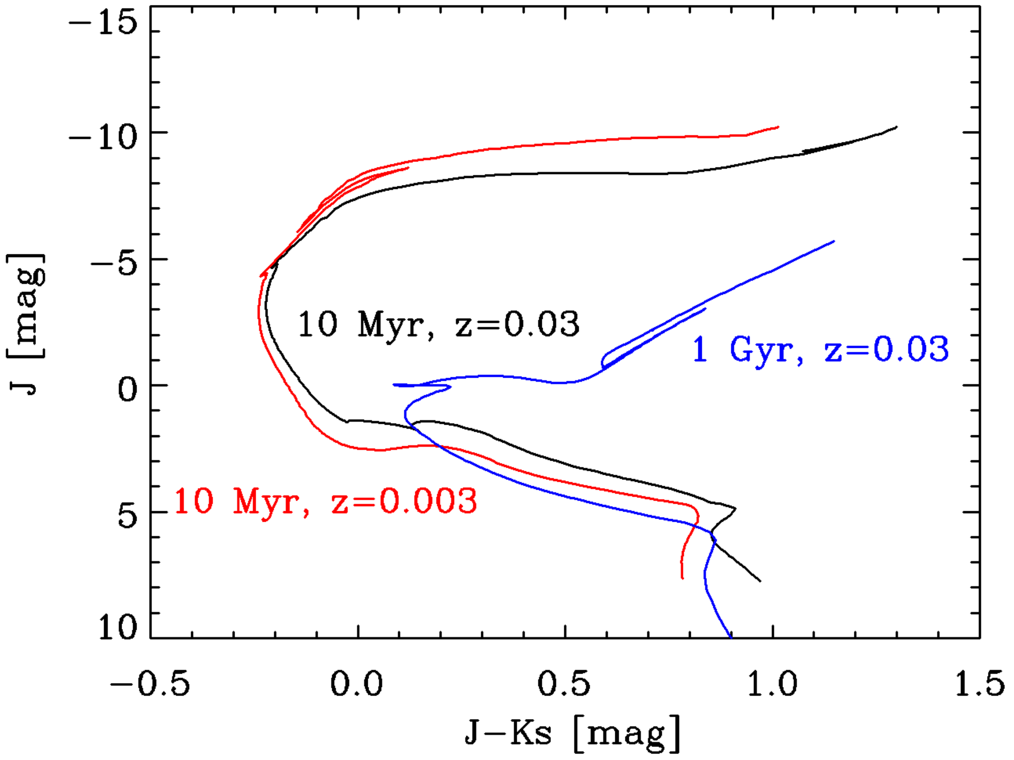


FIG. 1.—Paths in the theoretical Hertzsprung-Russell diagram for $M = M_\odot$. Luminosity in units of $L_\odot = 3.86 \times 10^{33}$ erg/sec and surface temperature T_e in units of ° K. Solid curve constructed using a mass fraction of metals with 7.5-eV ionization potential, $X_M = 5.4 \times 10^{-5}$. Dashed curve constructed with $X_M = 5.4 \times 10^{-6}$.

Iben (1965)

A metal poorer cluster → bluer



A younger cluster retains a longer upper MS, and even contains some PMS stars.

HB stars:
He core burning,
RR Lyrae variables

Blue stragglers:
An extension of MS beyond the MSTO. They should not exist according to “standard” stellar evolution theory.

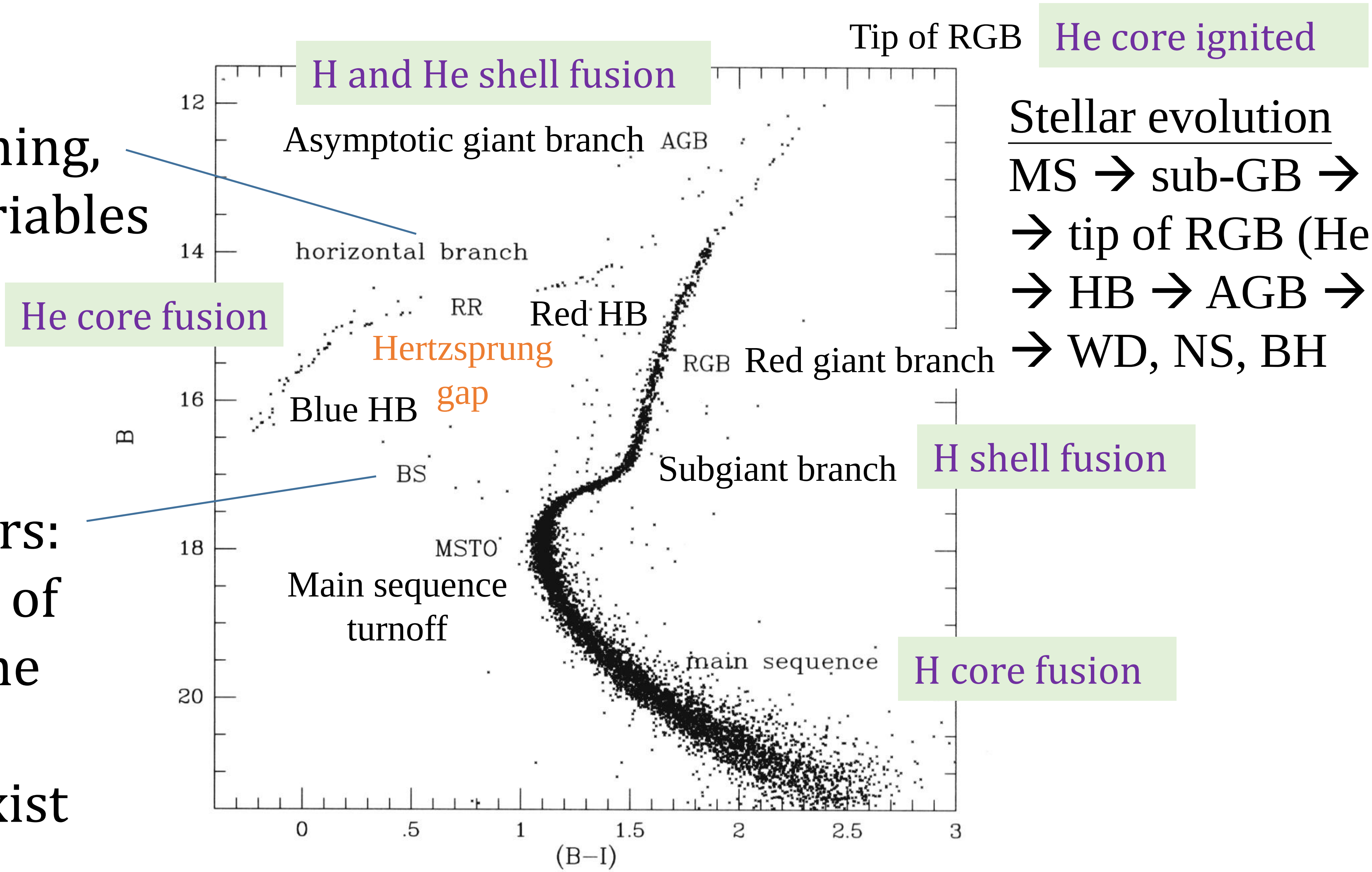
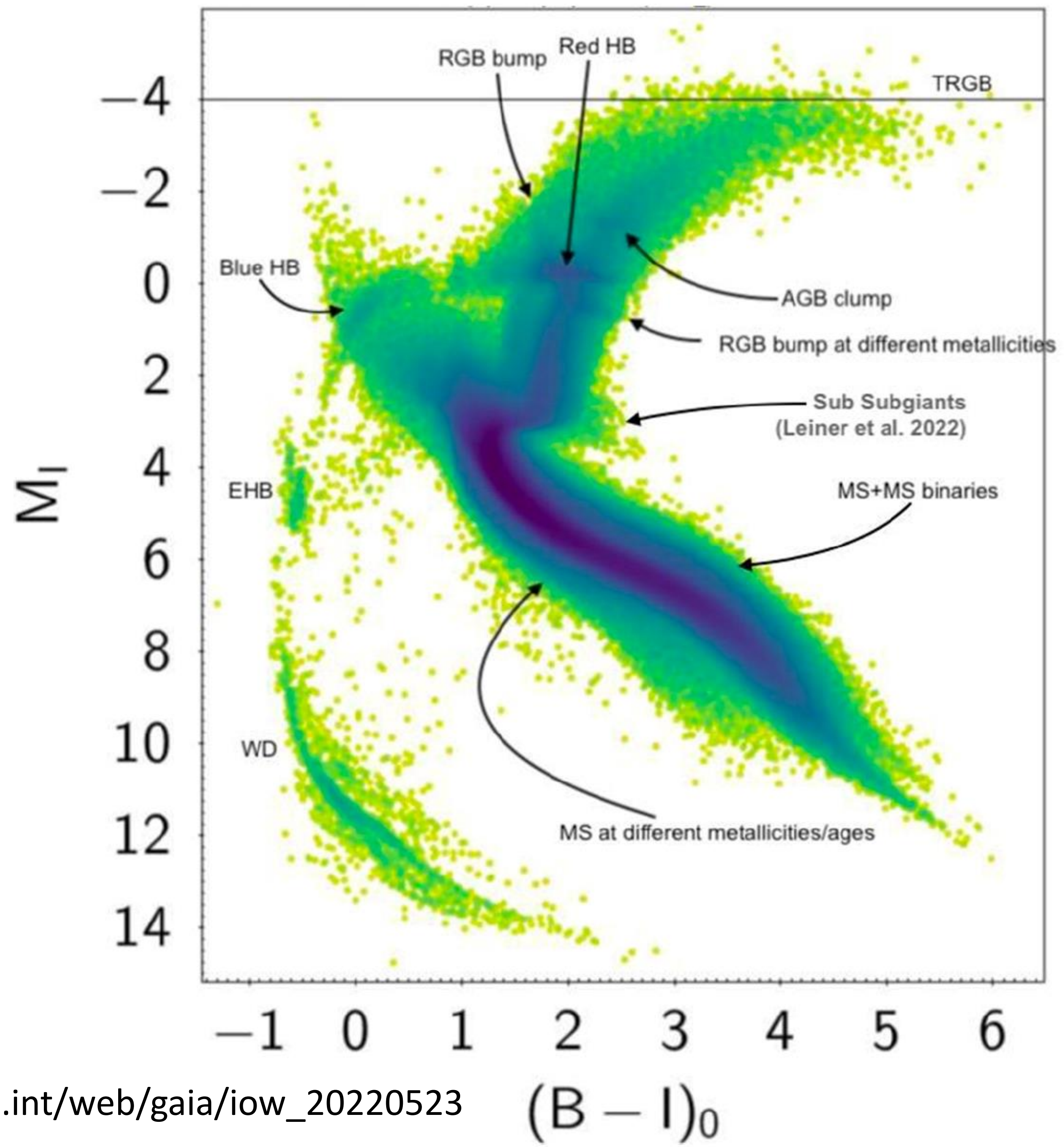


Fig. 2.1. The color–magnitude diagram of M5. The horizontal branch and main sequence are labeled. Also shown are: the RR Lyrae gap or instability strip (RR); the Red Giant Branch (RGB); the asymptotic giant branch (AGB); the main-sequence turn-off (MSTO); and blue stragglers (BS). (From data supplied by M. Bolte.)

Stellar evolution

MS → sub-GB → RGB
→ tip of RGB (He flash?)
→ HB → AGB → (PN, SN)
→ WD, NS, BH

Ashman & Zepf (1998)



Gaia

https://www.cosmos.esa.int/web/gaia/iow_20220523

Blue Stragglers

Common among GCs, even in some OCs.

Possible mechanisms of formation

- ✓ They formed later, therefore live longer (Roberts 1960)?

  But the age difference would have been large, and GCs do not seem to contain much gas.

- ✓ Binary merging as a result of mass transfer between equal-mass components (Iben 1986) ?
- ✓ Stellar collisions (Hills & Day 1976) ?
- ✓ Prolonged MS lifetimes due to rotation or ***B*** field (Wheeler 1979) ?
- ✓ Do not suffer as much mass loss as normal stars (slow rotators) ?

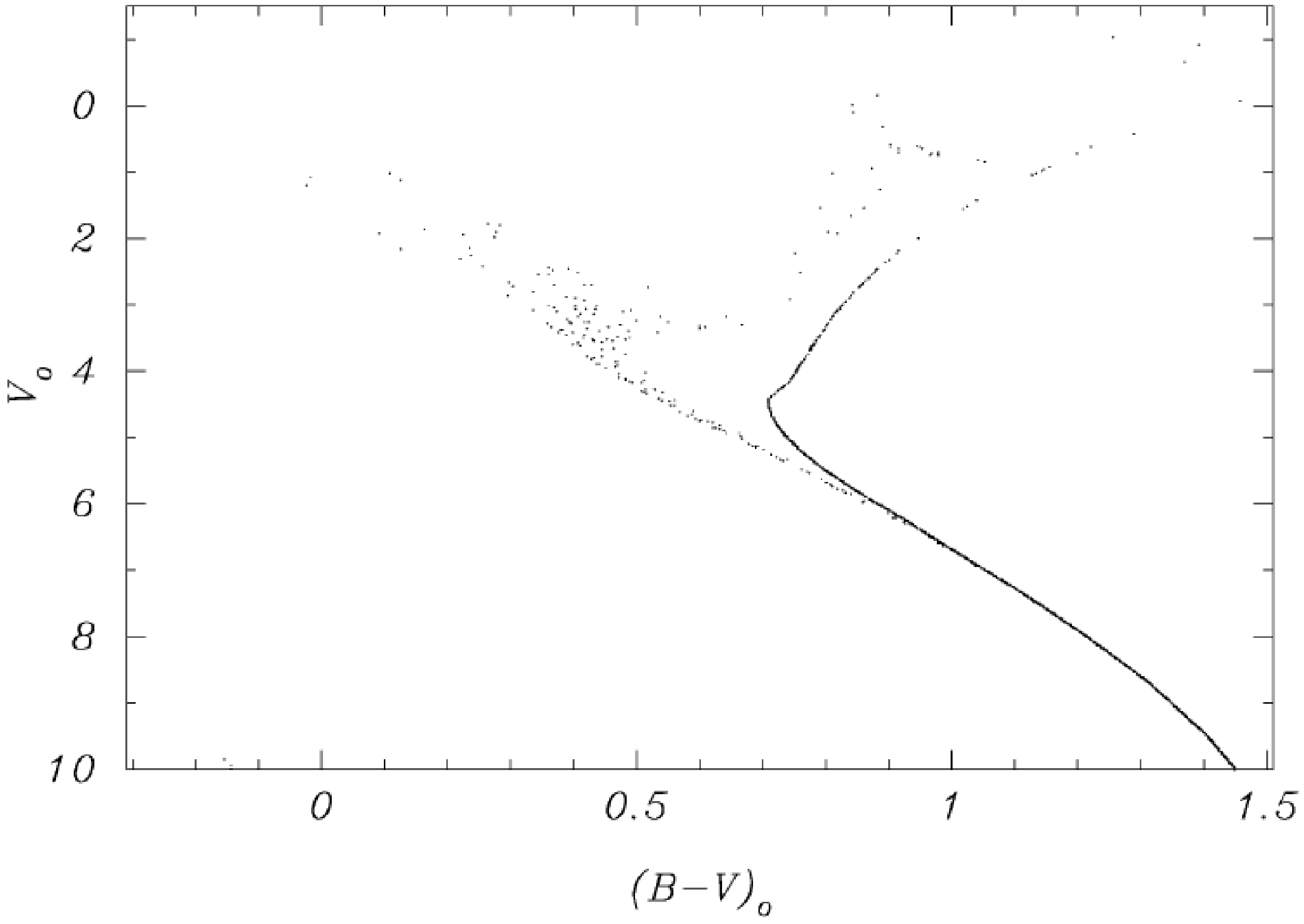



Fig. 5. Hertzsprung-Russell diagram of model C, at ca. t = 12 Gyr. 10^4 stars (corresponding to about the total number of stars in the core) were selected randomly from all stars involved in the simulation.

Stellar collisions between evolving stars.

A synthetic CMD at 12 Gyr, with the simulation starting at 10 Gyr, with a population of MS (single) stars with a flat mass spectrum, plus white dwarfs and neutron stars

Note the blue stragglers and yellow stragglers

(Portegies Zwart+97)

Horizontal Branch

Bright and distinct
→ extragalactic distance indicator

Different morphologies of GCs …

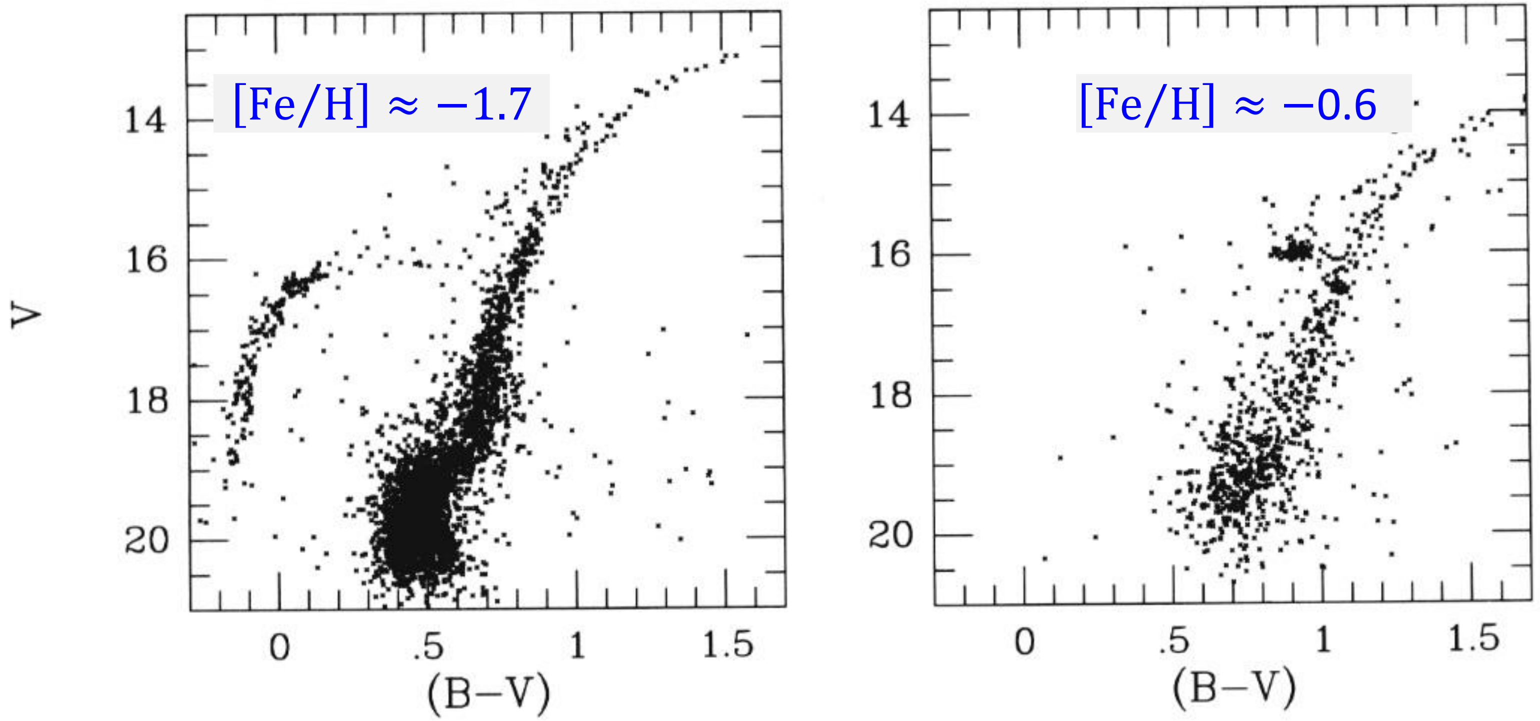


Fig. 2.2. The color–magnitude diagrams of NGC 1904 (left) and NGC 6637 (right) illustrating differences in horizontal branch morphology and the location of the main-sequence turn-off. (From data supplied by R. Buonanno and A. Sarajedini.)

Metallicity as the "first parameter"; higher z → redder

But not every metal-poor GC has an extended blue HB tail!

All [Fe/H] ≈ −1.6

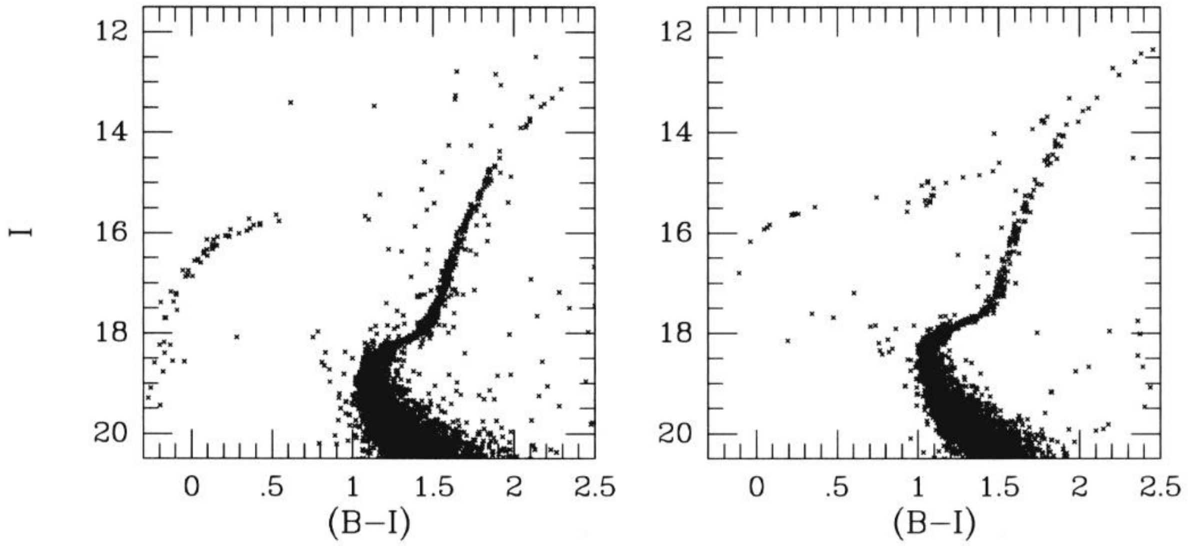


Fig. 2.3. The color–magnitude diagrams of M2 (left) and M3 (right). (From data supplied by P. Stetson.)

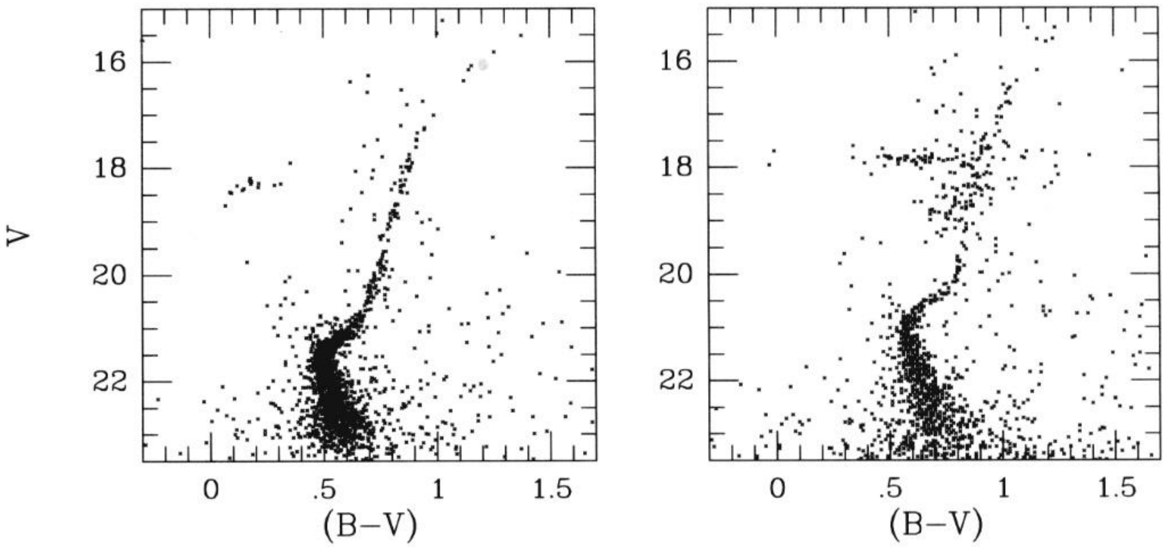
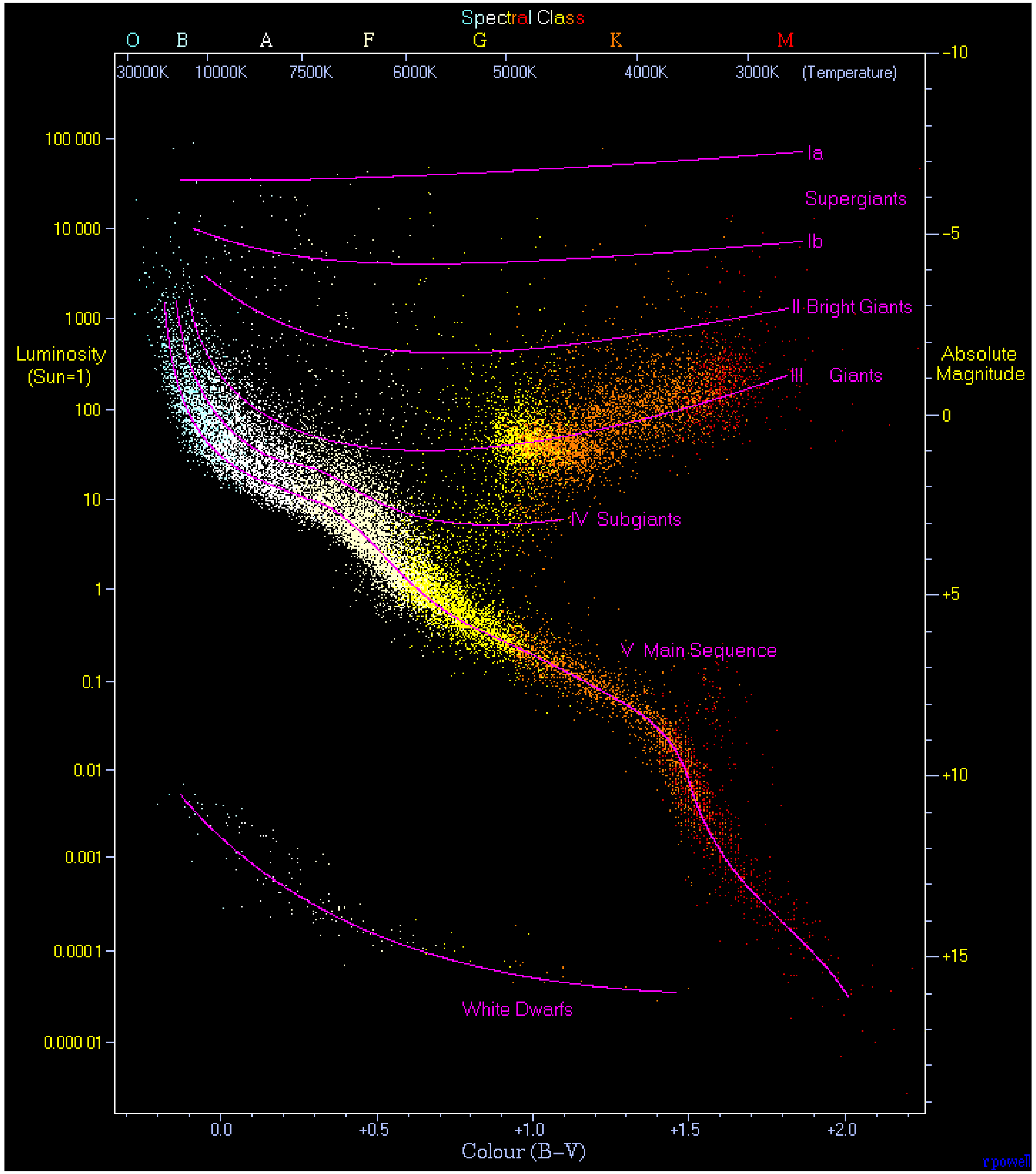


Fig. 2.4. The color–magnitude diagrams of Arp 2 (left) and Ruprecht 106 (right). (From data supplied by R. Buonanno.)

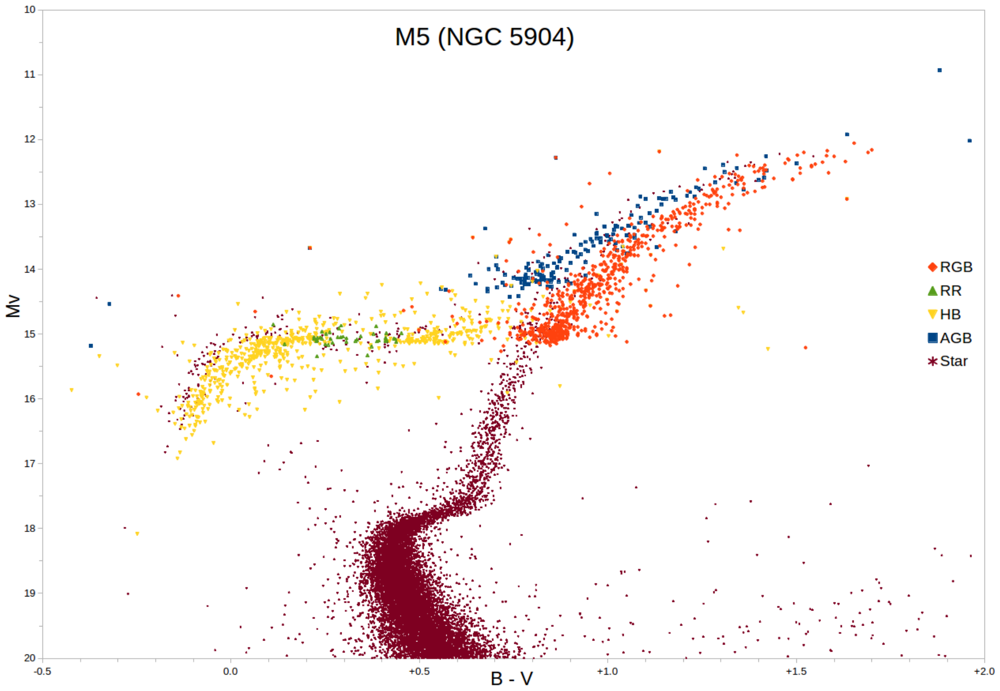
The "**second parameter**"
- ✓ age (older → bluer)?
- ✓ mass loss on RGB?
- ✓ He abundance??



Red Clump

Clustering of cool horizontal-branch giants (core He fusion, metal-rich)

… 5,000 K and $M_V \sim 0.5$



https://en.wikipedia.org/wiki/Subgiant#/media/File:M5_colour_magnitude_diagram.png

Distance to M31 With the *HST* and *Hipparcos* Red Clump Stars (1998)

K. Z. Stanek & P. M. Garnavich

Using the red clump stars to determine the distance to M31

$M_I = -0.23$

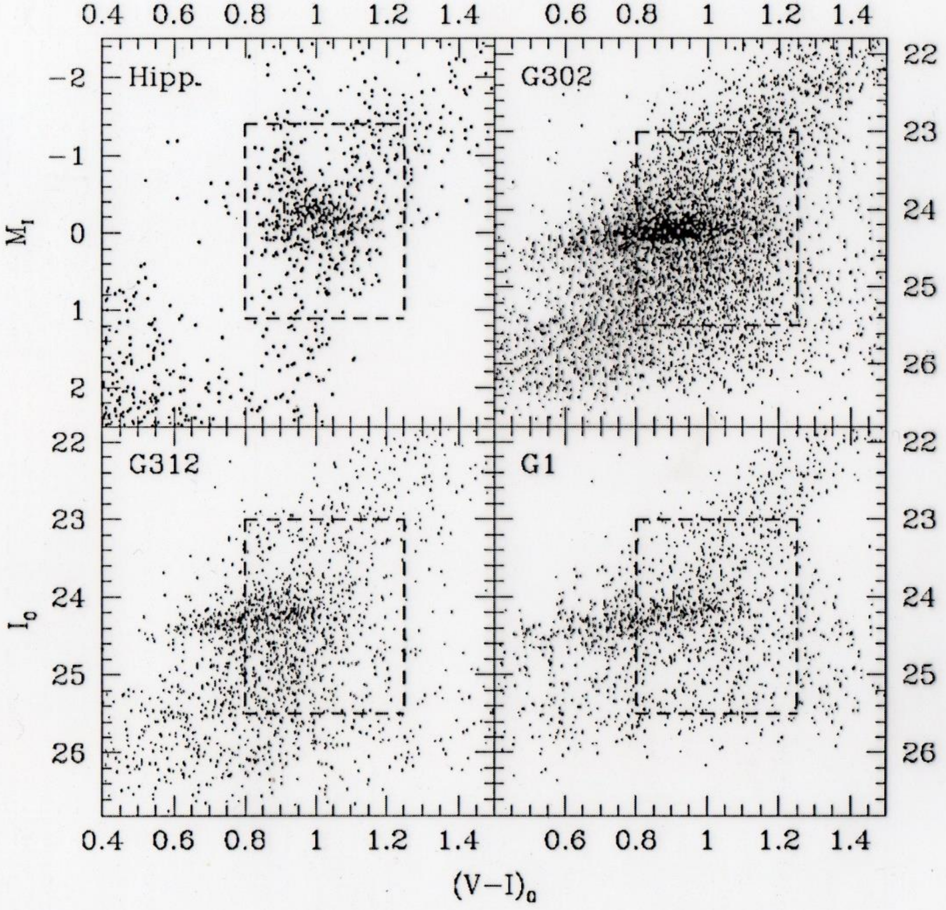
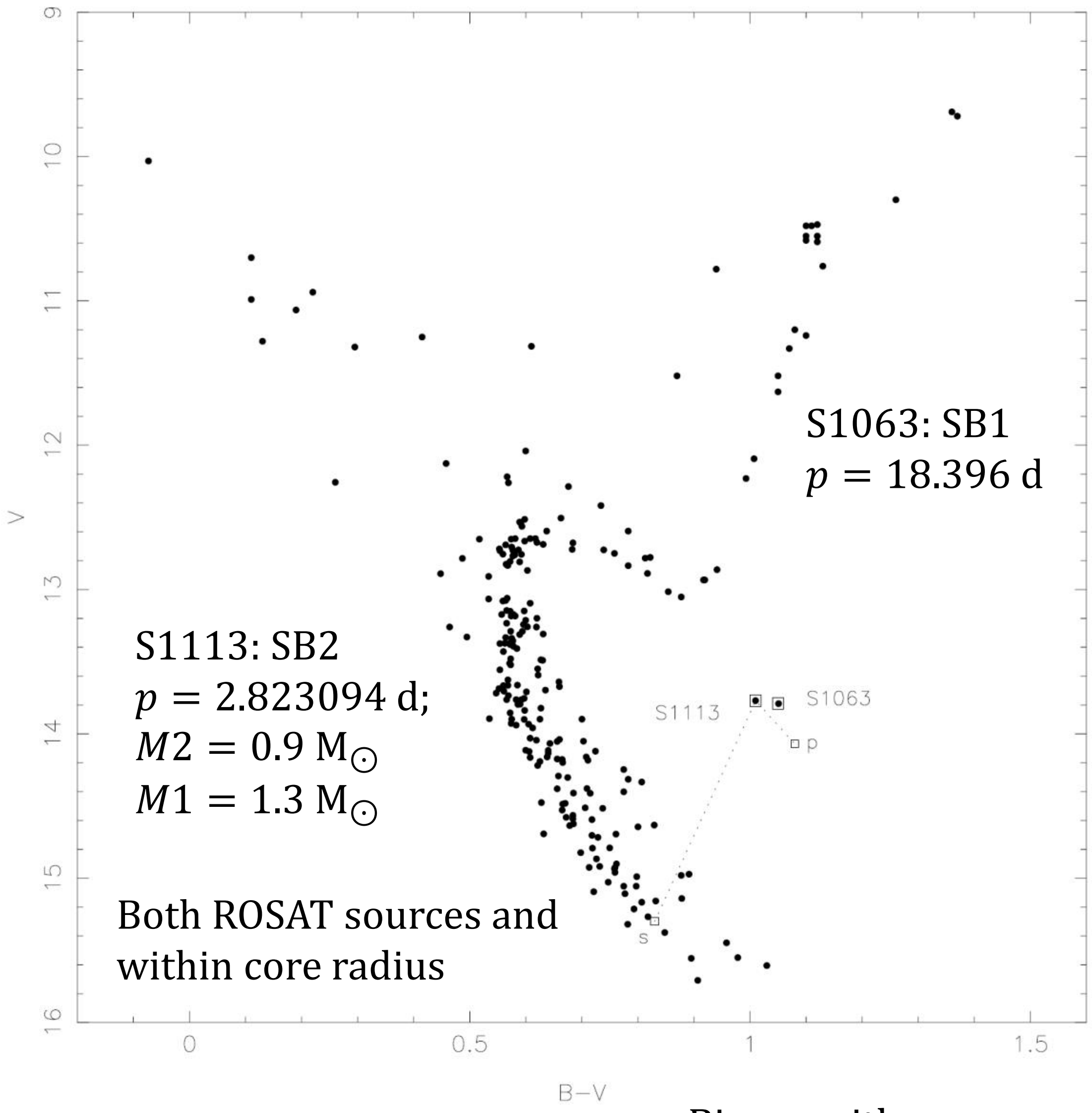


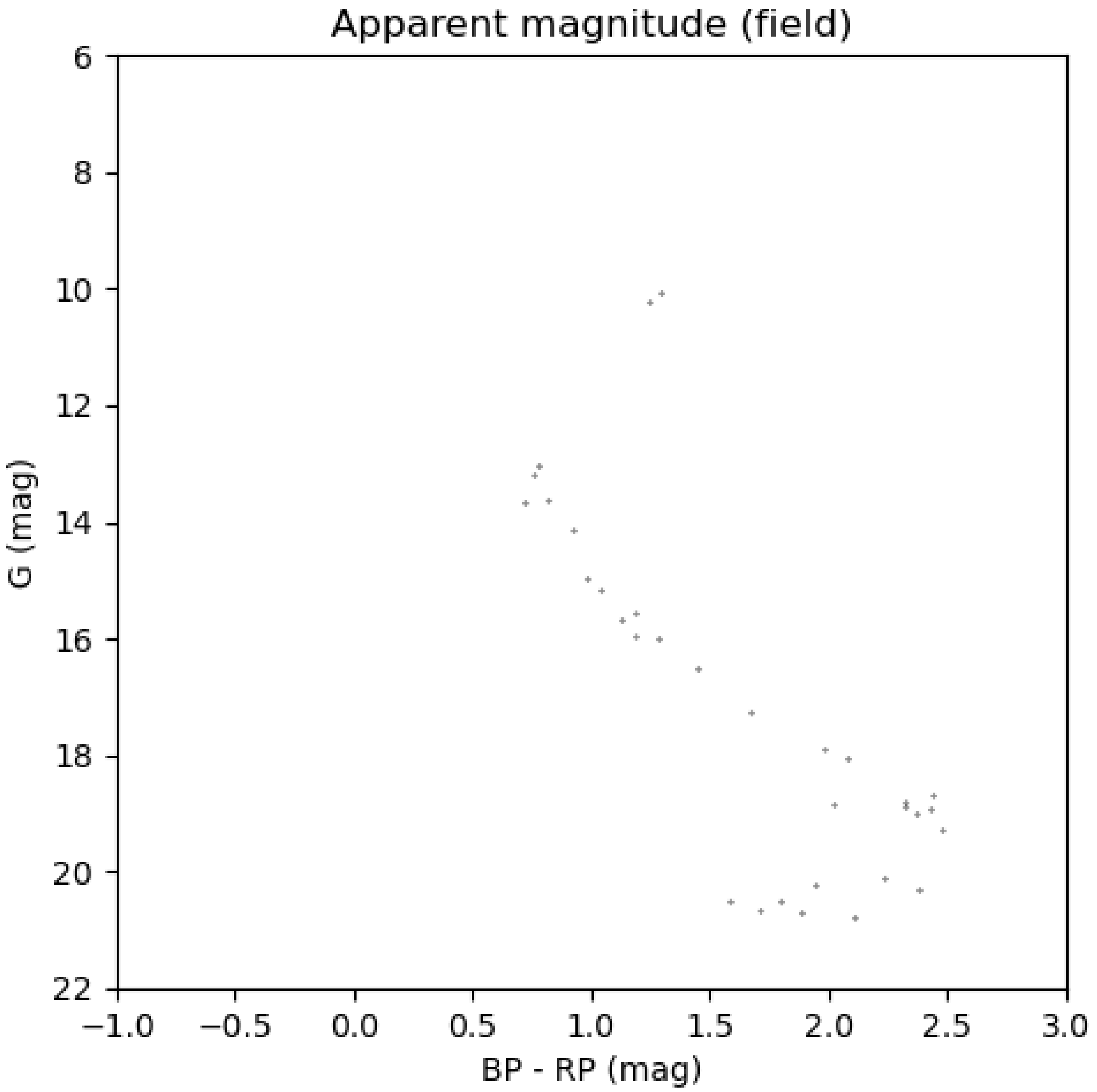
Fig. 2.— The red clump dominated parts of CMDs for the *Hipparcos* stars (upper-left panel) and for three fields in M31 observed with the HST. The dashed rectangles surround the red clump regions used for the comparison between the local and the M31 red clump stars.

$$R_{M31} = 784 \pm 13 \pm 17 \ kpc$$

13: statistical error; 17: systematic

Sub-subgiants = red stragglers

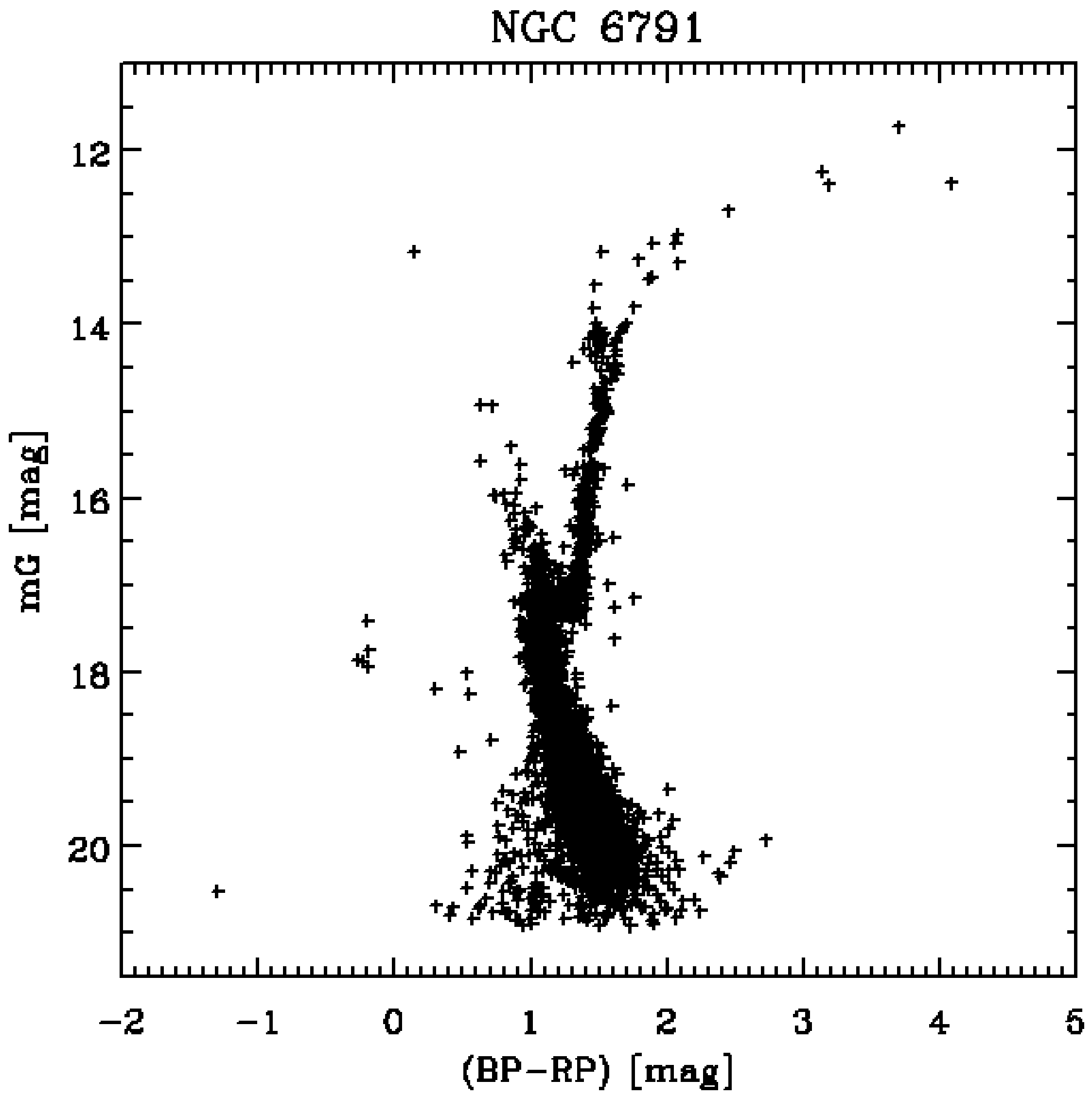


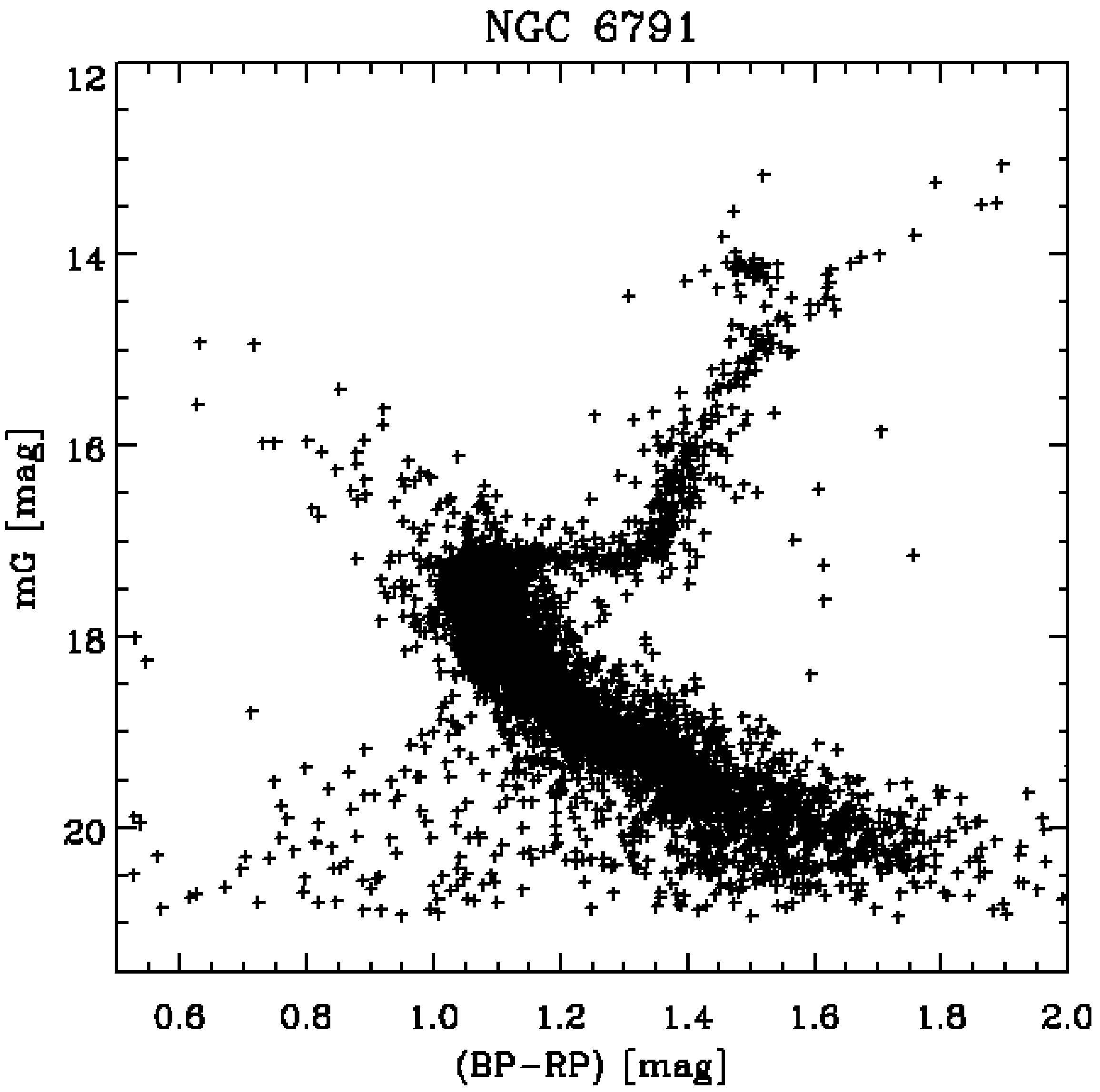


Mathieu+03 on M67

Binary with mass transfer; merger, dyn stellar exchanges?

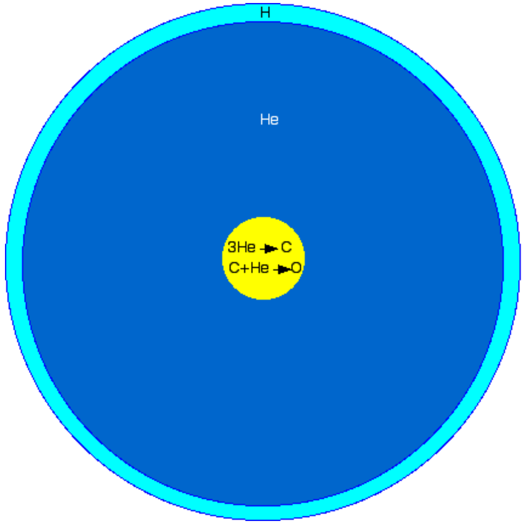
NGC 6791





More oddities

Blue sub-dwarfs: sdB, sdO



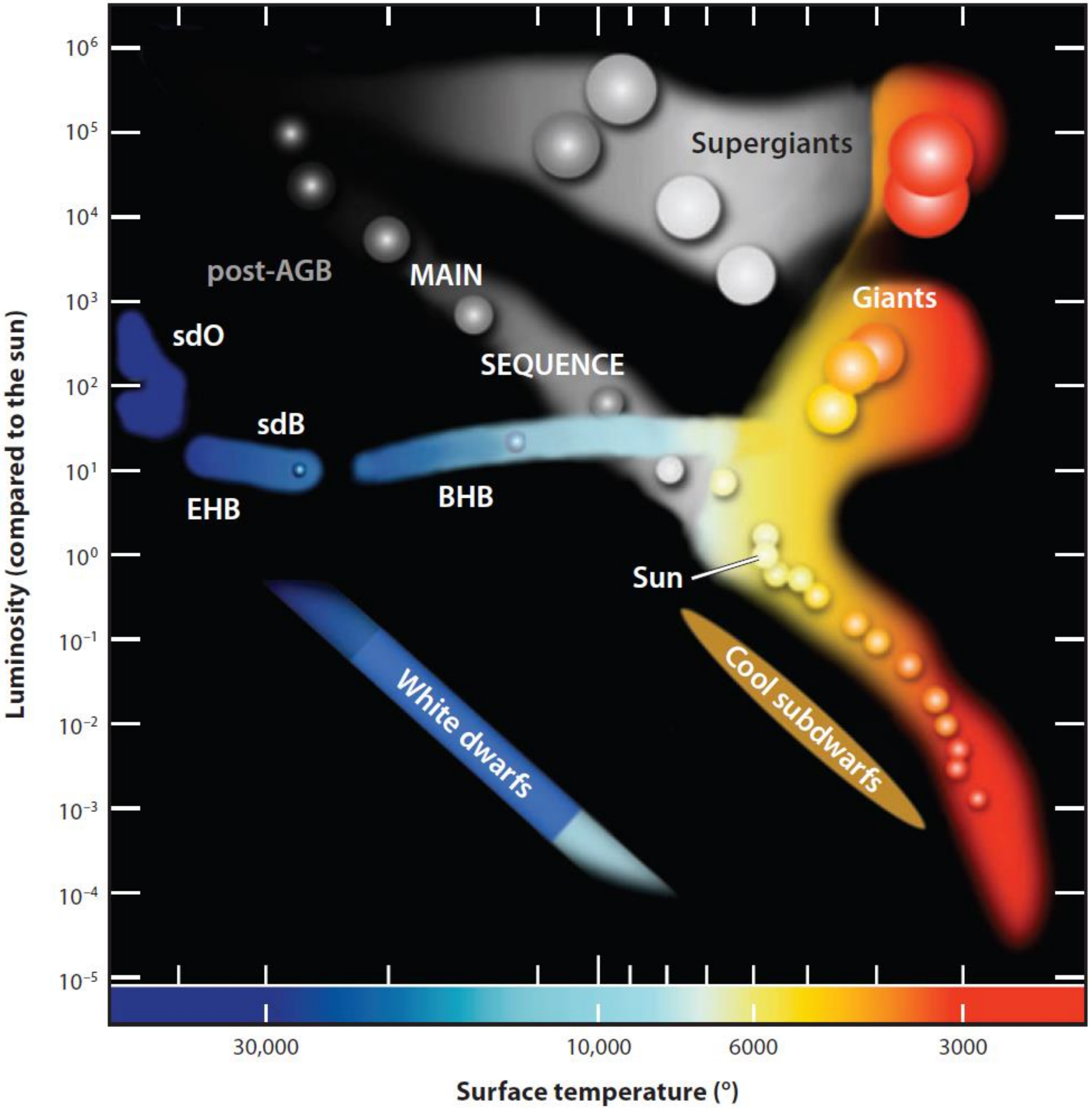


Figure 1

Sketch of a Hertzsprung-Russell diagram highlighting the position of hot subdwarf (sdB and sdO) stars and the extreme horizontal branch (EHB) located to the left and below the hot end of the main sequence but above the white dwarf cooling sequence. The EHB is separated from the blue horizontal branch (BHB). The location of stars having evolved from the postasymptotic giant branch is shown for comparison. The hot subdwarf stars have nothing in common with traditional cool subdwarfs found below the lower main sequence. Courtesy of ESO, with modifications by S. Geier and K.S. de Boer.

Star Clusters --- Lecture 2

Star Clusters

--- Links between Galaxies and Stars

- Star clusters as stellar birth places
- Open clusters, globular clusters, and others
- Star clusters as targets of investigation
- Star clusters as tools in stellar & galactic studies
- Latest and outstanding issues

Wen-Ping Chen
Graduate Institute of Astronomy
National Central University
Taiwan

Theorists believe in their own results, while others don't. Observer do not believe in their own results, but others do.

A theoretician develops theories to confront with observations.
An observer acquires data to compare with theories.
An experimentalist conducts experiments to compare with

It is all what <u>you do</u> to answer the question. You should know it all, though usually master on one aspect for now.

Yes, you should concentrate on what you are doing, and do not stretch yourself too thin. You may decide to do only one thing in your life and do it well. But you should not decide what it is now.

Is this what my adviser is doing (asked me to do)? Why am I doing it? Is it challenging? Am I excited?

Do not limit yourself.

Practicality

A hands-on exercise

Catalogues of galactic open clusters

- ✓ Lynga (1987)
- ✓ WEBDA (originally by Mermilliod, latest 2013) compilation MW and LMC+SMC
- ✓ Catalog of Open Cluster Data
- ✓ Dias+ (2002..2015), Sampedro et al. (2017), $N = 1876$
- ✓ Kharchenko et al. (2005) based on ASCC-2.5, a few 100s
- ✓ Cantat-Gaudin et al. 2018, Gaia/DR2, N=1229 w/ members

Catalogues of galactic globular clusters

- ✓ Harris (1996, 2010) $N = 157$

VizieR B/ocl

cdsarc.u-strasbg.fr/viz-bin/cat/B/ocl

YouTube 地圖

Portal Simbad VizieR Aladin X-Match Other Help

Optically visible open clusters and Candidates : B/ocl

Access to VizieR FTP ReadMe TAP Xmatch

Authors : Dias W.S. , Alessi B.S., Moitinho A. et..al

Bibcode : 2002A&A...389..871D (ADS)
Cite

UAT : Proper motions, Metallicity, Chemical abundances, Radial velocity, Open star clusters

Compilation (CCC)

Records : 2134 clusters

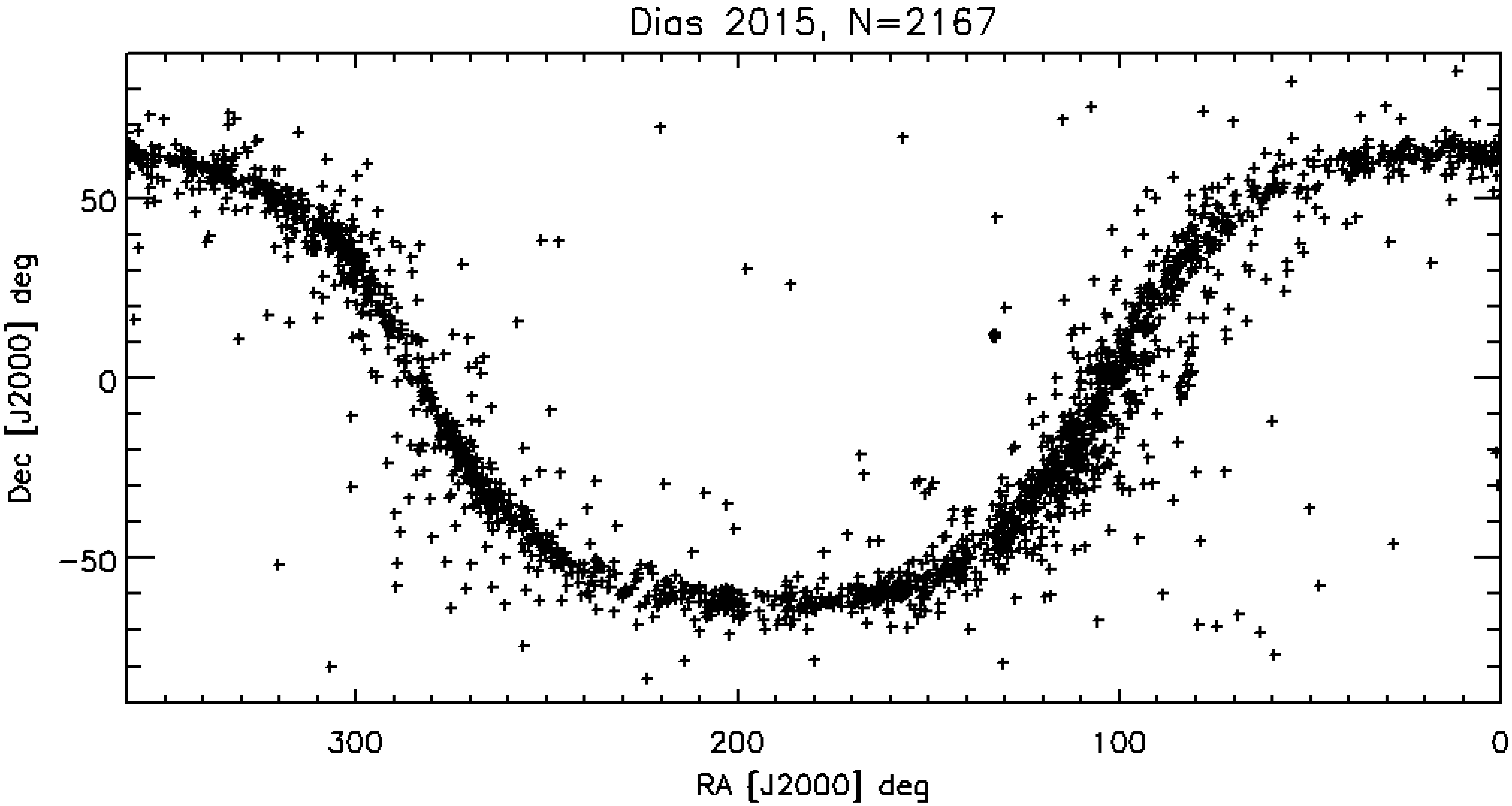
Article Origin | Description | See also | Prov | FTP | VizieR

New catalog of optically visible open clusters and candidates (V3.5) (2015)
Go to the original article (10.1051/0004-6361:20020668)

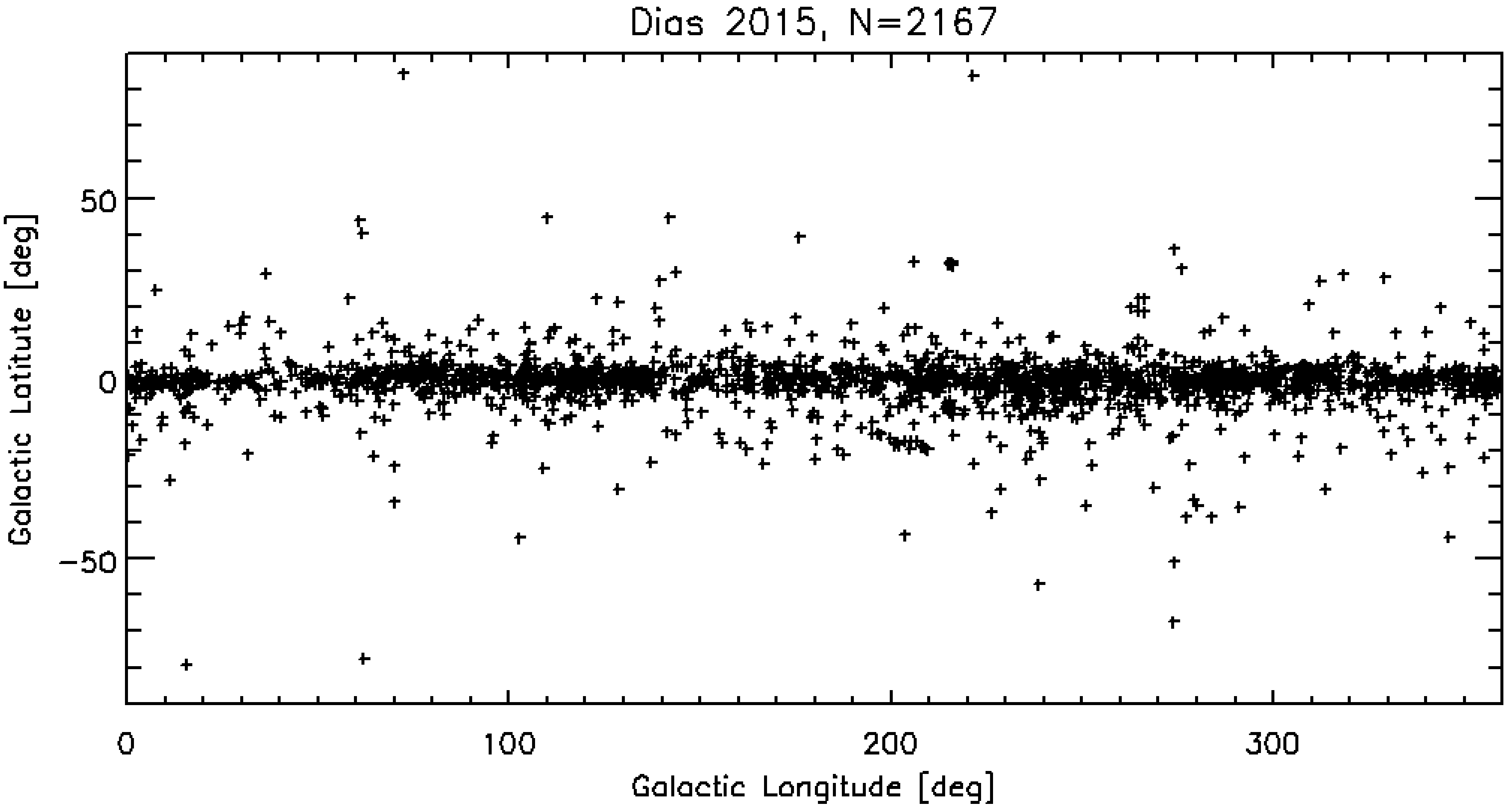
Keywords : galaxy open clusters and associations: general - catalogs

Abstract: We have compiled a new catalogue of open clusters in the Galaxy which updates the previous catalogues of Lynga (1987, Cat. VII/92) and of Mermilliod (1995, in Information and On-Line Data in Astronomy, ed. D. Egret & M. A. Albrecht (Dordrecht: Kluwer), 127) (included in the WEBDA database, http://obswww.unige.ch/webda). New objects and new data, in particular, data on kinematics (proper motions) that were not present in the old catalogues, have been included. Virtually all the clusters (2167) presently known were included, which represents an increment of about 986 objects relative to the Lynga (1987, VII/92) catalogue. The catalogue is presented in a single table containing all the important data, which makes it easy to use. ...(more)

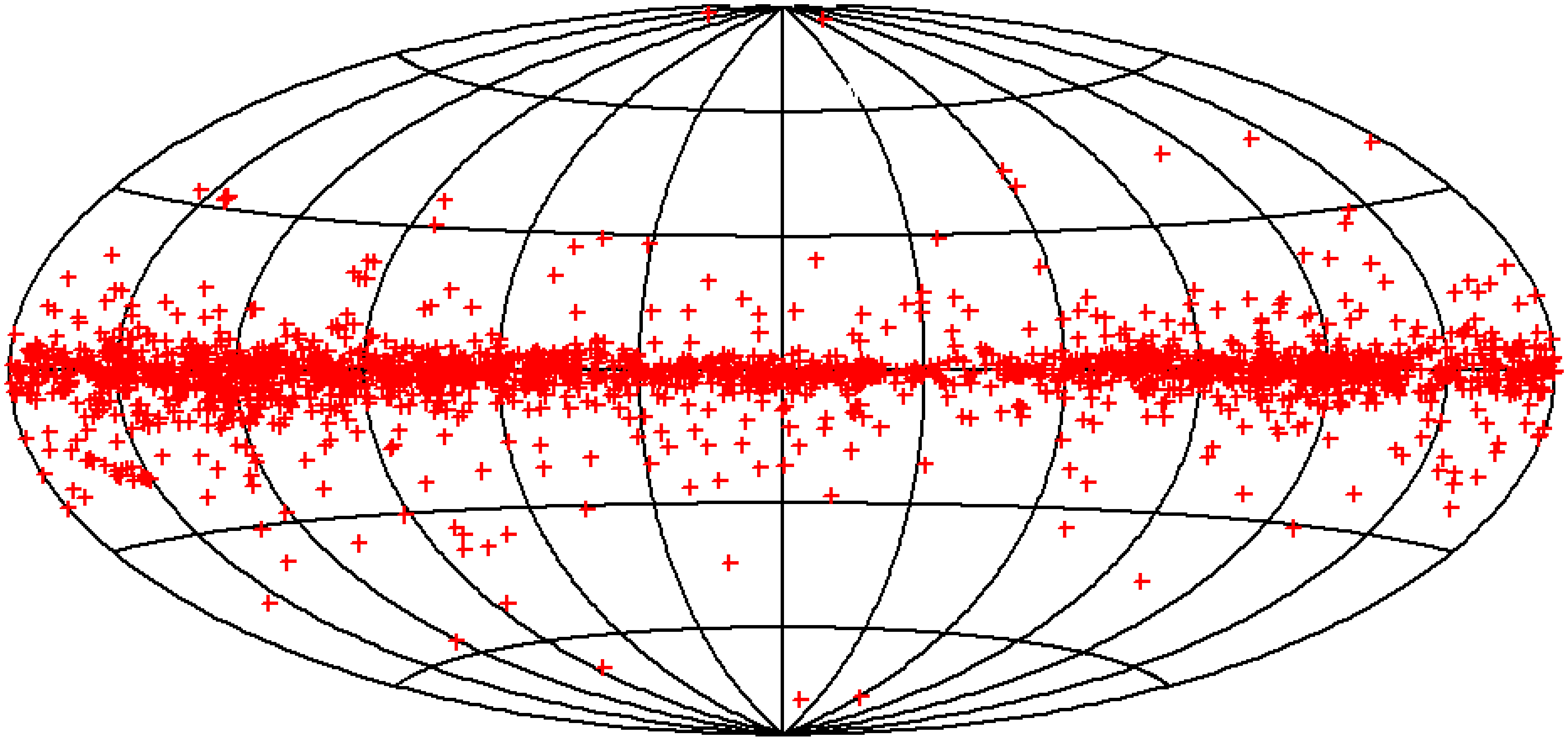
Inserted into VizieR : 12-Jul-2002
Last modification : 22-Jun-2018

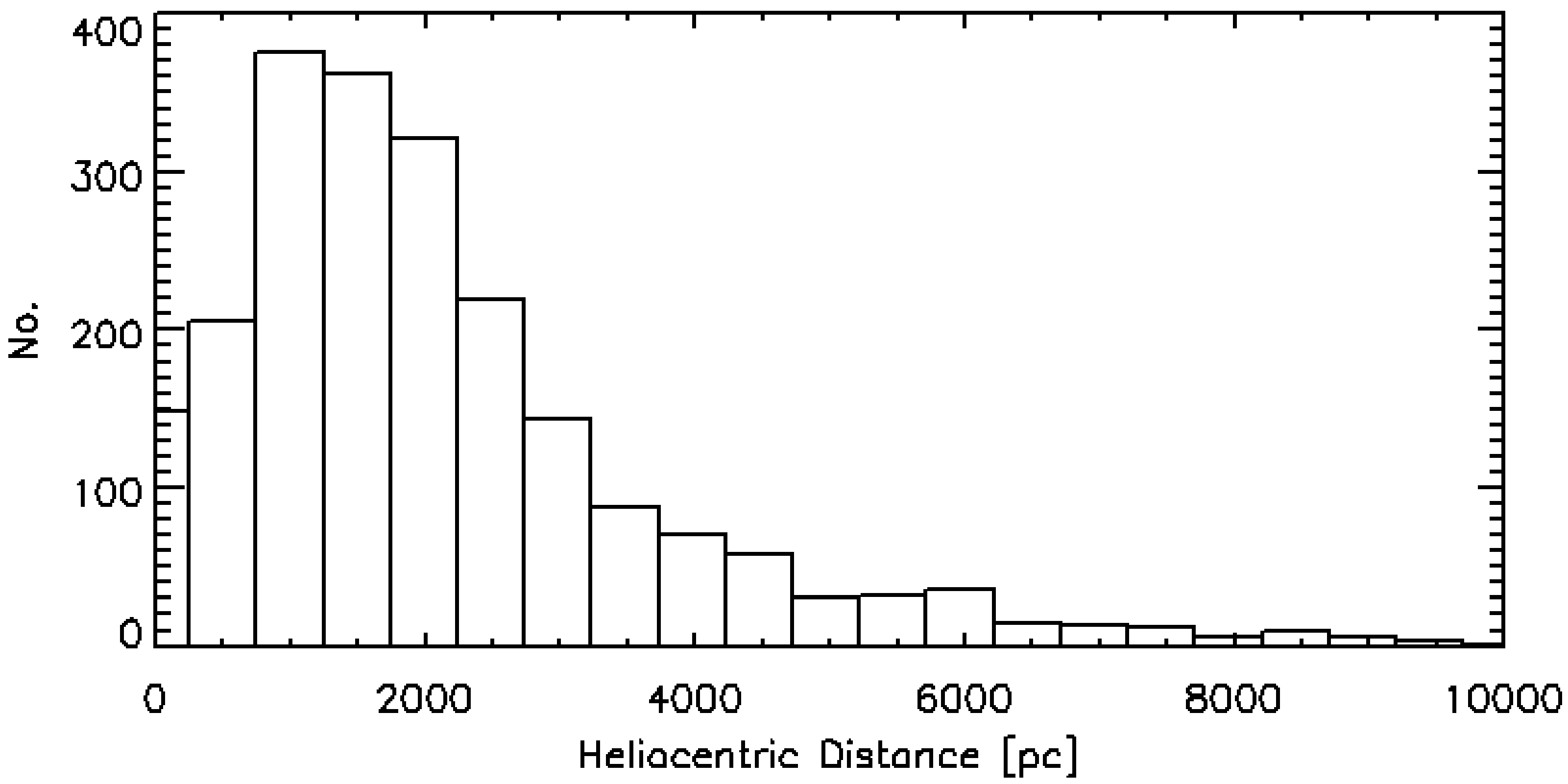


Dias 2015

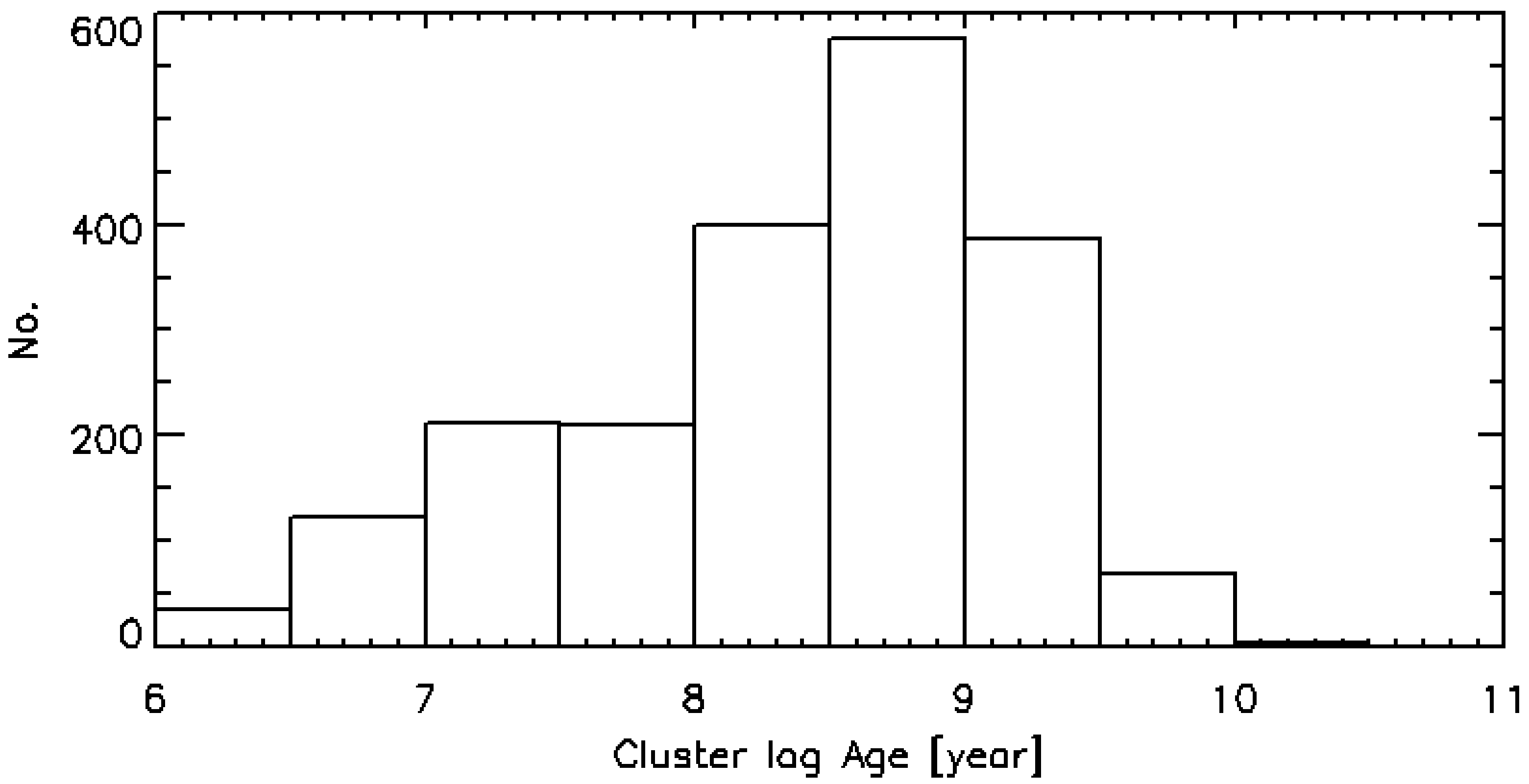


Dias 2015, N=2167
Galactic Latitude [deg]
50
0
−50
0
100
200
300
Galactic Longitude [deg]

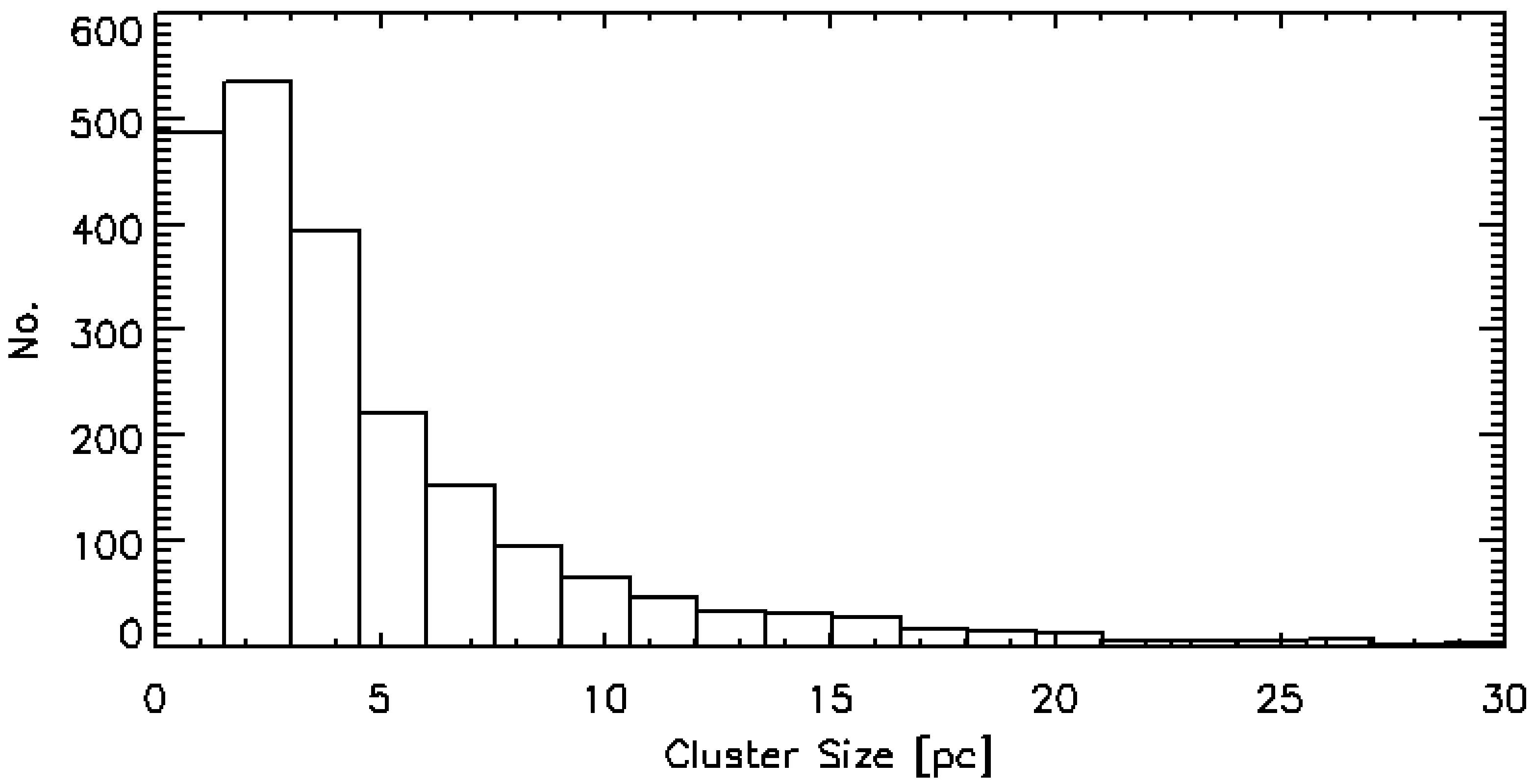




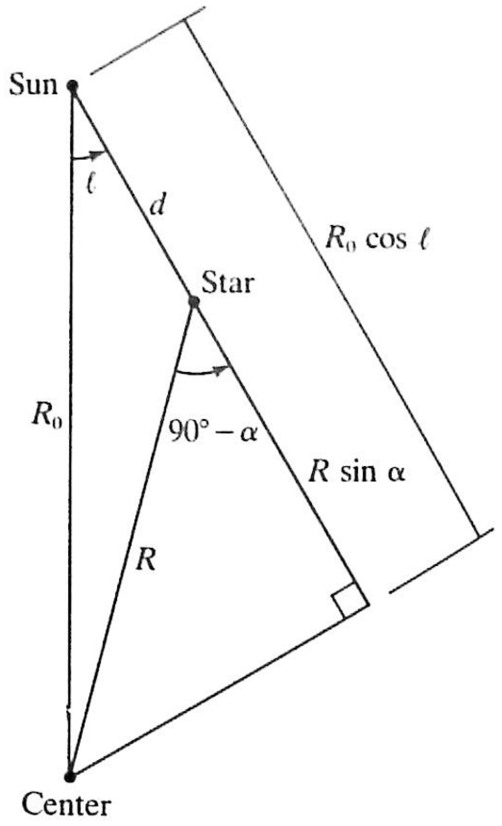
No.
400
300
200
100
0
0
2000
4000
6000
8000
10000
Heliacentric Distance [pc]



600
400
200
0
No.
6
7
8
9
10
11
Cluster log Age [year]



600
500
400
300
200
100
0
No.
0
5
10
15
20
25
30
Cluster Size [pc]


Sun
ℓ
d
$R_0 \cos \ell$
Star
R_0
$90° - \alpha$
$R \sin \alpha$
R
Center

To Identify Members in a Star Cluster

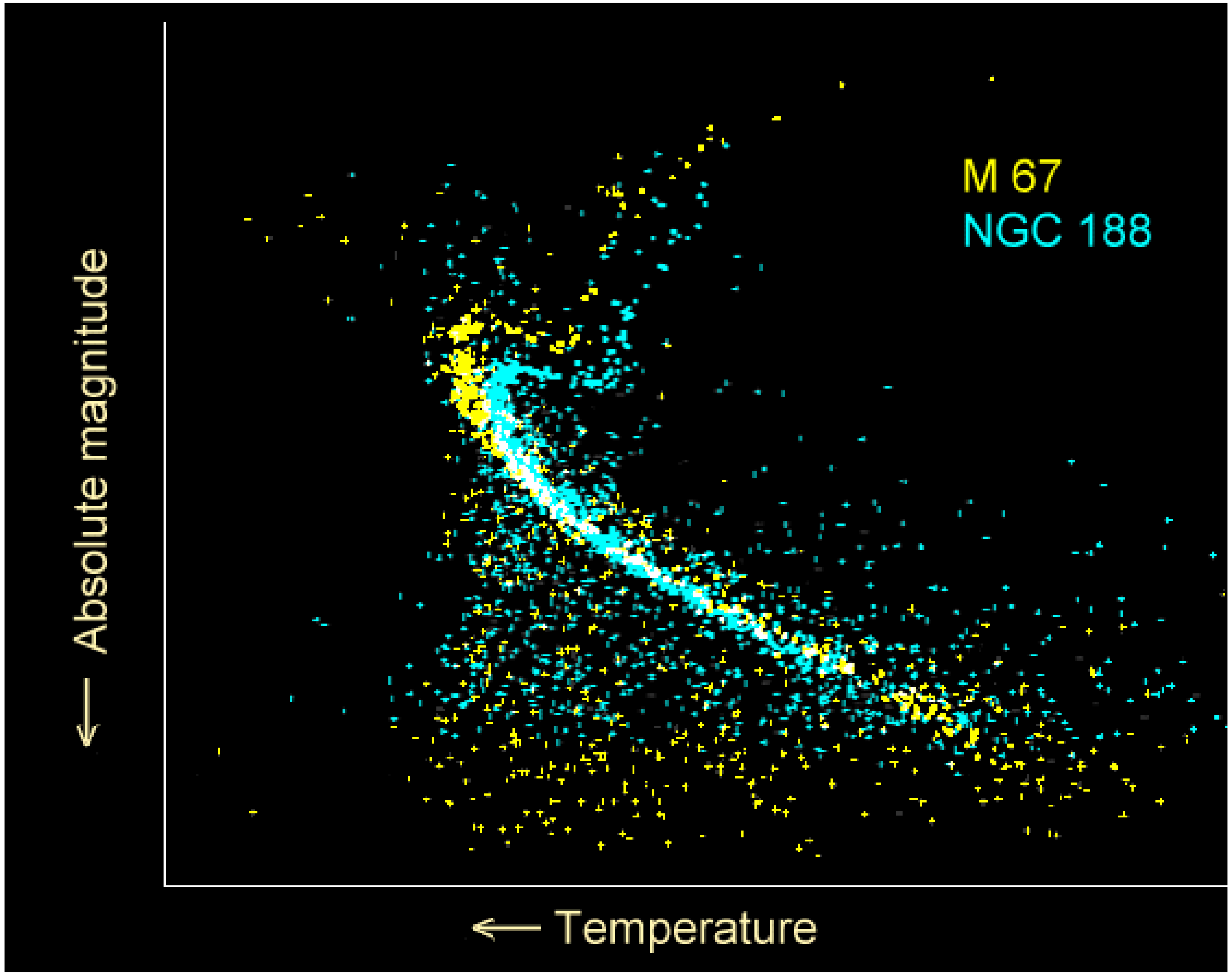
Member stars are grouped in at least 6-dimensional space, 3 in location (position and distance) and 3 in motion (proper motion and radial velocity) (and in metalicity, etc.)

➔ To secure the member list, find

- grouping in space (sky coordinates + distance)
- grouping of proper motions (and radial velocity)
- grouping along the main sequence/isochrone (CMD)

Members: similar in positions and in space motions …

A Case Study M67 an OC ~4 Gyr old (i.e., solar age), [Fe/H] = −0.1, distance 800 to 900 pc, an apparent angular diameter > 30’



2 old OCs

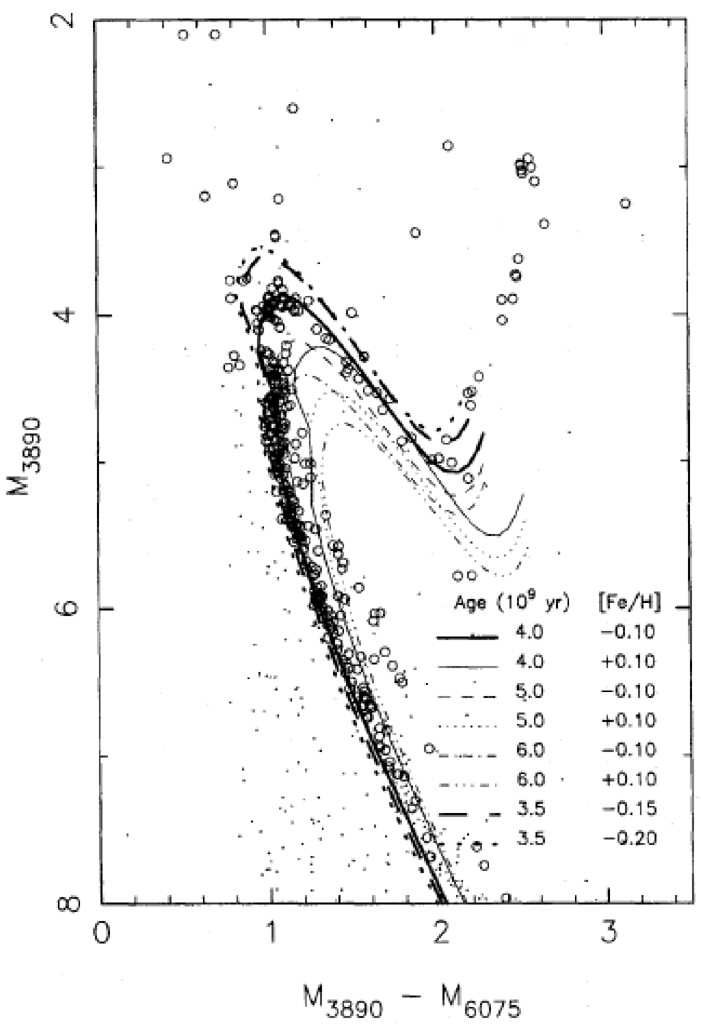


FIG. 10. Worthey-VandenBerg-Kurucz isochrone models fit to the observed $(m_{3890}-m_{6075})$ vs m_{3890} CMD. $(m-M)_0=9.47$ and $E(B-V)=0.05$ are assumed; see text for details. The values of age and [Fe/H] of each isochrone are shown in the graphs. Data for stars with known membership probabilities $\geq 80\%$ are plotted as open circles; all other stars are plotted as dots.

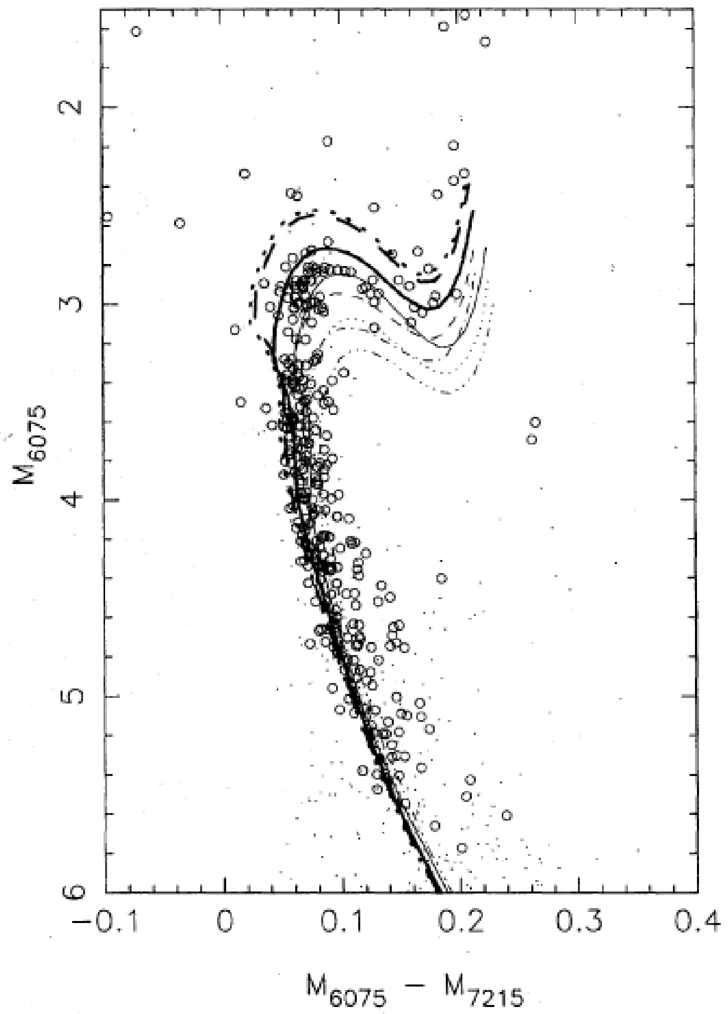
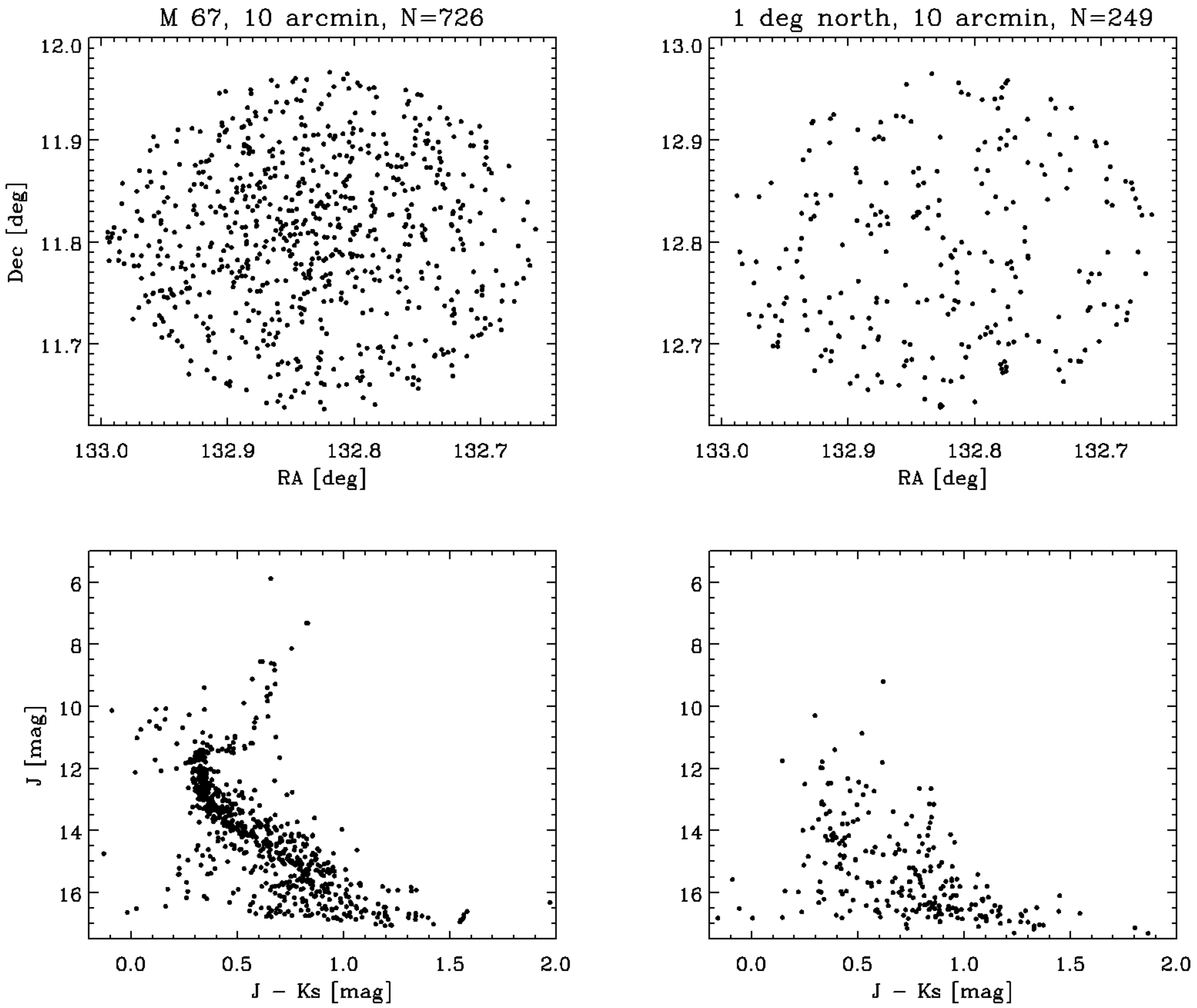


FIG. 11. Worthey-VandenBerg-Kurucz isochrone models fit to the observed $(m_{6075}-m_{7215})$ vs m_{6075} CMD. Same models, distance modulus and [Fe/H] as for Fig. 10.

Fan+96 BATC

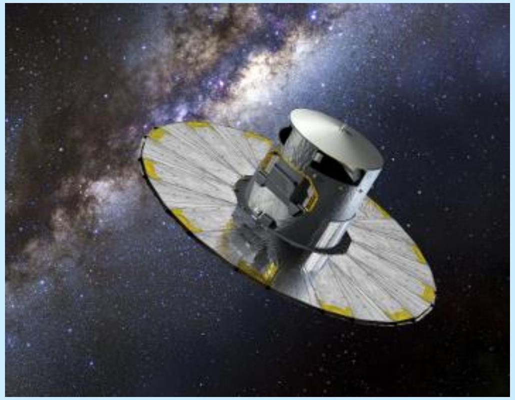
Two Micron All Sky Survey (2MASS) data

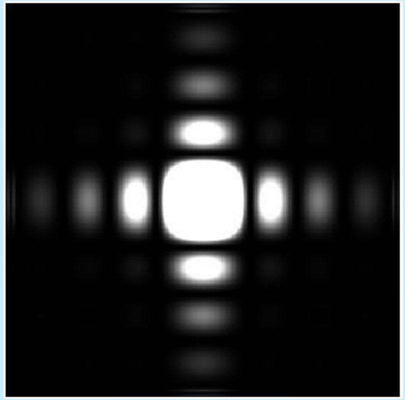
M67 field vs a Galactic field



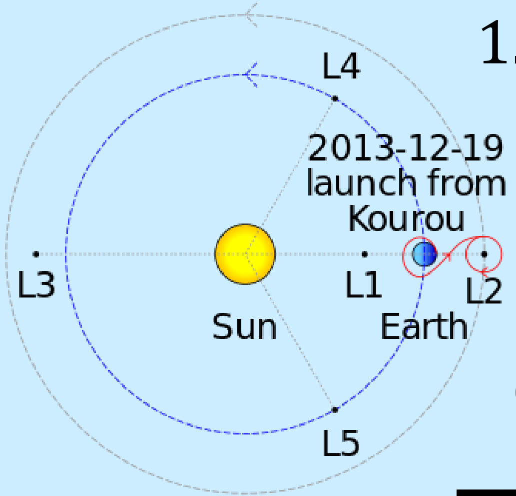
Gaia (Space Telescope)

- ✓ 2013 to 2022? by ESA
- ✓ High-precision astrometry (position) → distance + motion → 3D map of MW and beyond; quasars, exoplanets
- ✓ < 20 mag (1% MW)
- ✓ G, BP, RP photometry + spectroscopy → $L, T_{\mathrm{eff}}, g,\ [M/H]$, and RV
- ✓ Latest DR3 in 2022.06

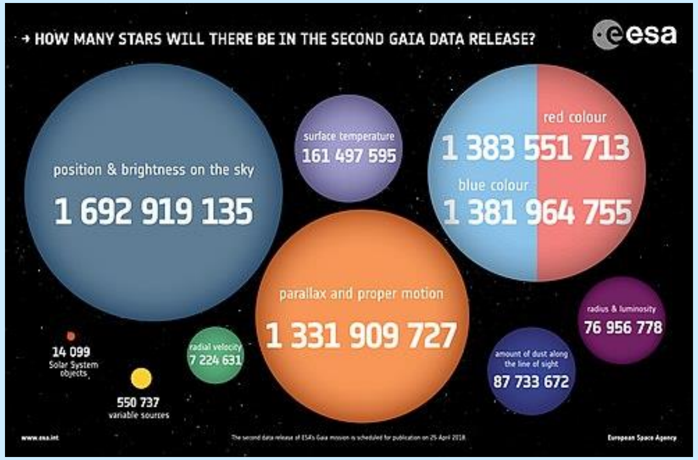




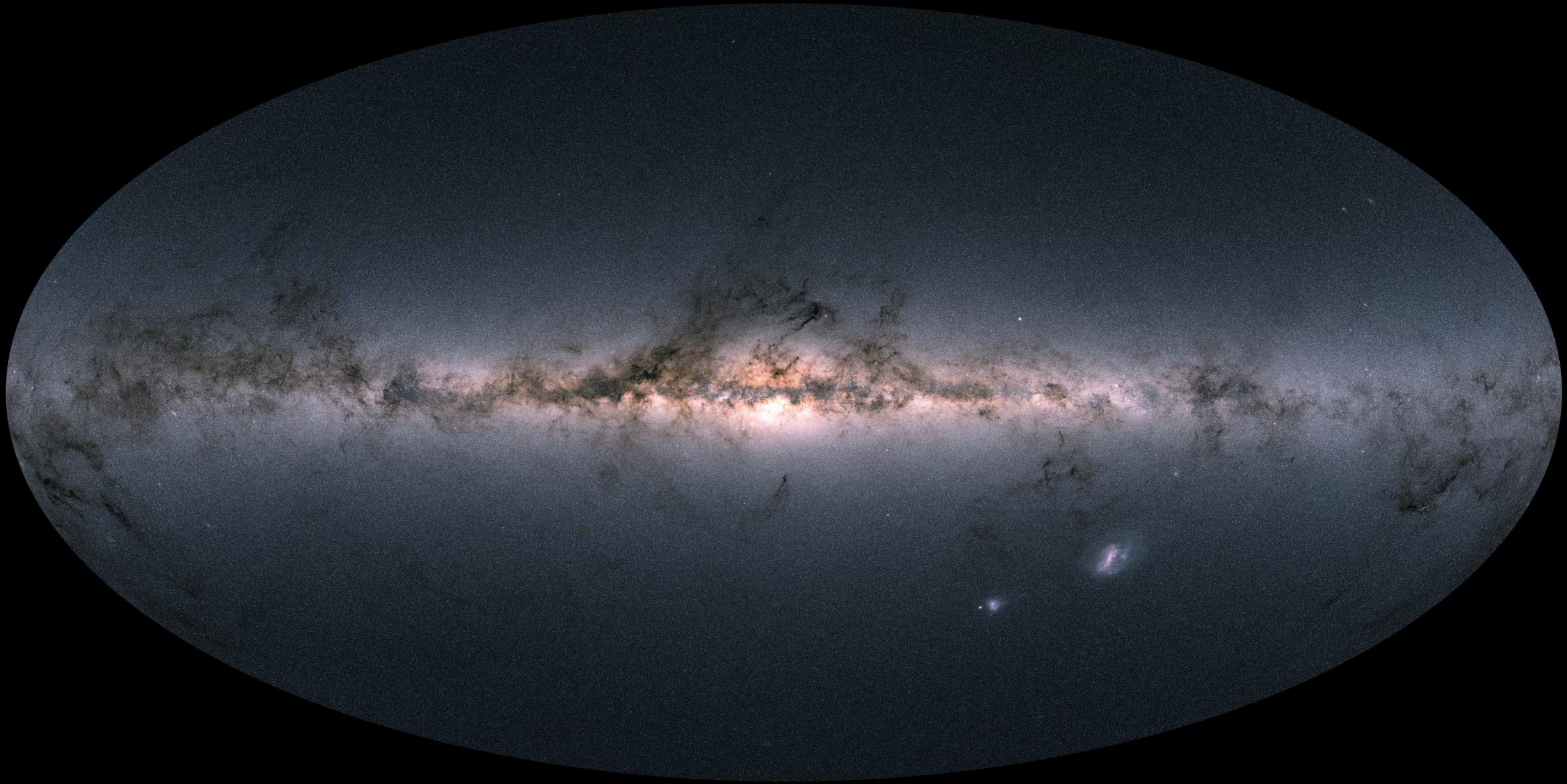
1.45 m × 0.5 m primary

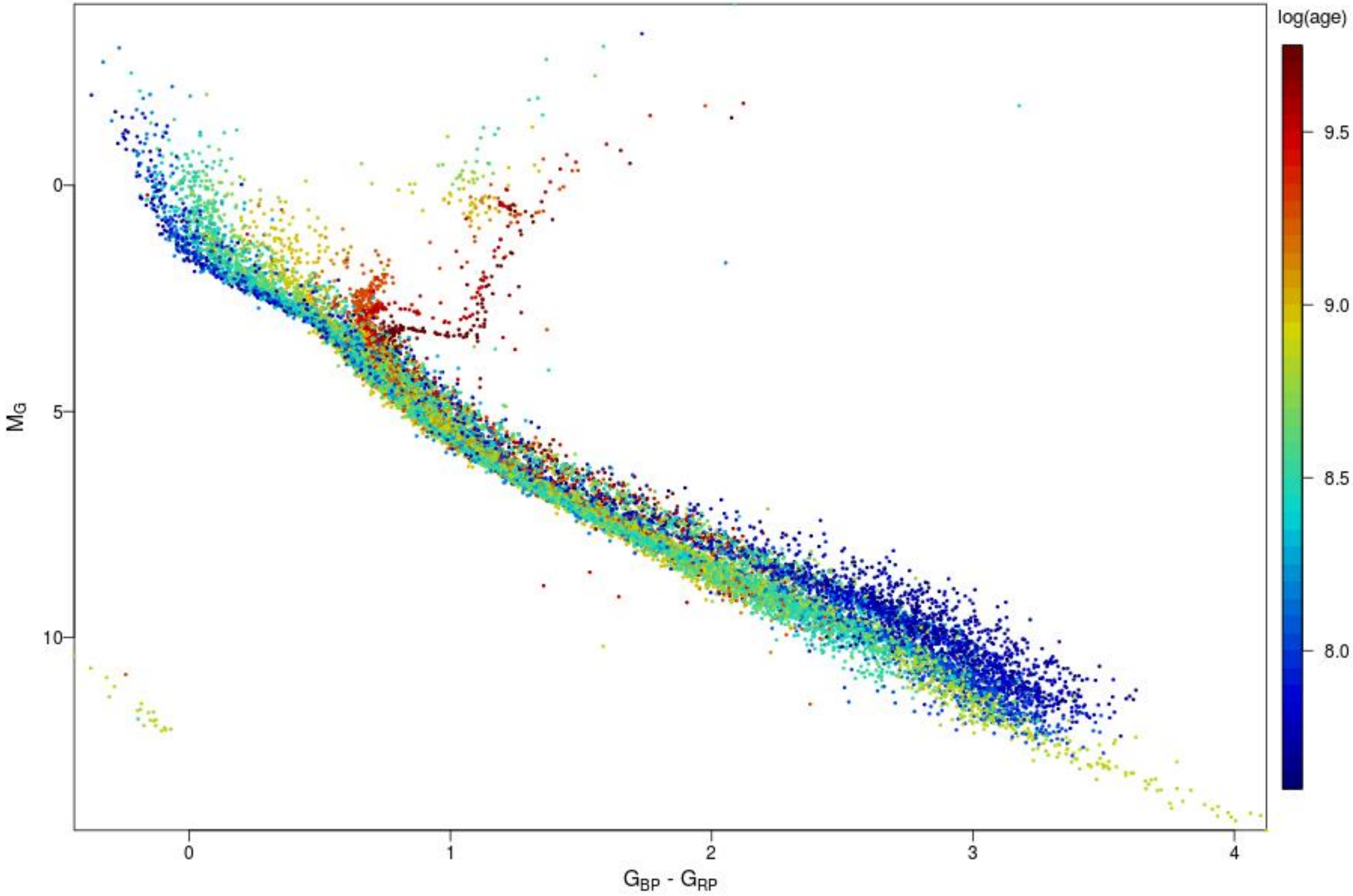


Orbit @Sun-Earth L2



Gaia's Sky in Color

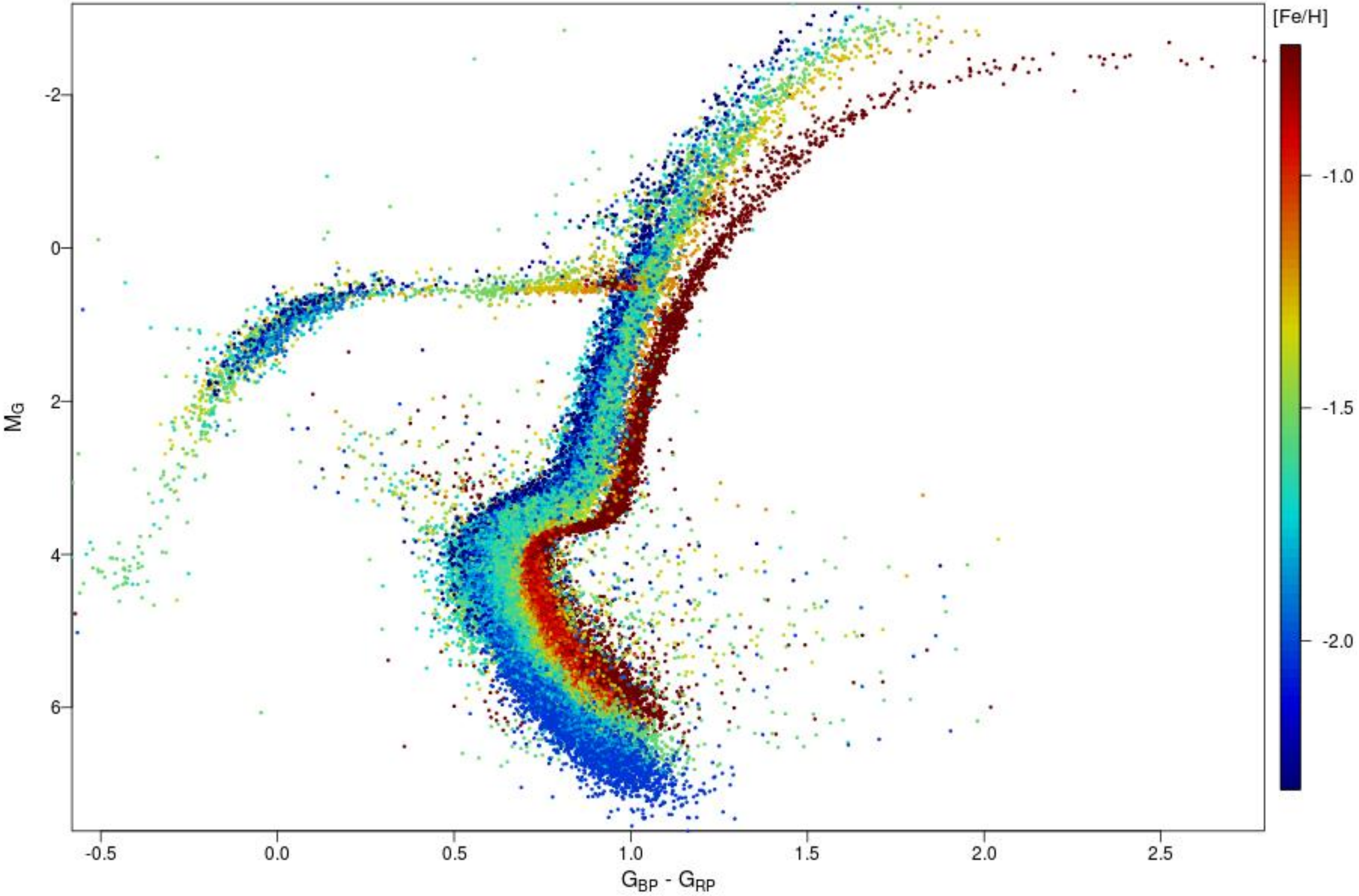


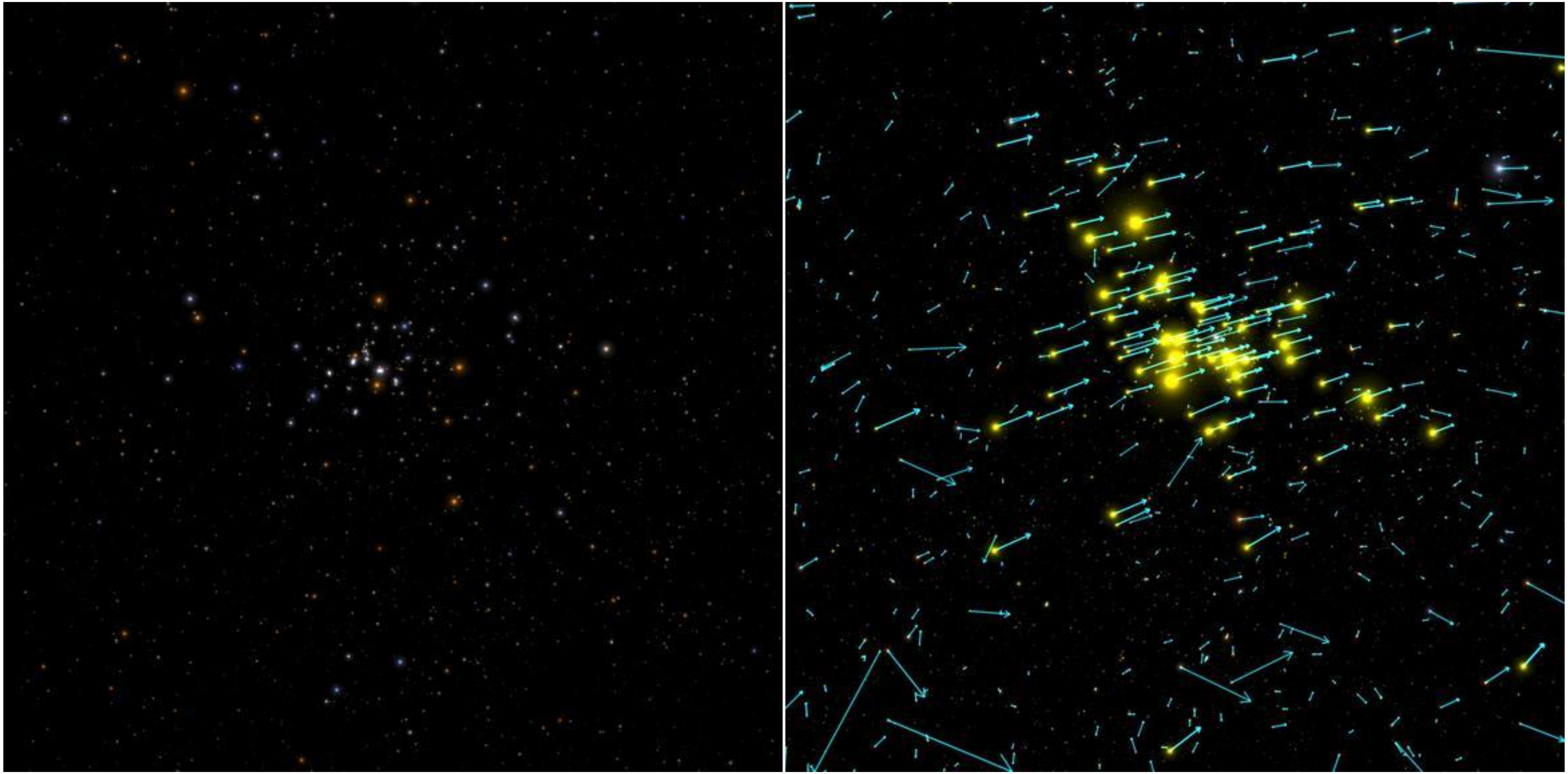


32 OCs

Gaia Collaboration 2018+

14 GCs





https://www.dlr.de/content/en/images/2020/4/gaia-hyades-star-cluster.html

Portal | Simbad | VizieR | Aladin | X-Match | Other | Help

Gaia DR3 Part 1. Main source : I/355

Access to: VizieR | FTP | ReadMe | TAP | Xmatch

Authors : Gaia collaboration

VizieR DOI : 10.26093/cds/vizier.1355 *Cite*
Bibcode : 2022yCat.1355....0G (ADS)

UAT : Proper motions, Surveys, Asteroids, Astronomical object identification, Trigonometric parallax, Astrometry, Variable stars, Radial velocity, Photographic photometry, Photometry, Standard stars, Optical astronomy

Observation (OC)

Records : 1811709771 sources

Article Origin | Description | Acknowledgment | See also | Prov | FTP | VizieR

Gaia Data Release 3 (Gaia DR3) Part 1 Main source. (2022)

Keywords : catalogs - astrometry - parallaxes - proper motions - techniques photometric - techniques: radial velocities

Abstract: Gaia Data Release 3 (Gaia DR3) will be released on 13 June 2022. The Gaia DR3 catalogue builds upon the Early Data Release 3 (released on 3 December 2020) and combines, for the same stretch of time and the same set of observations, these already-published data products with numerous new data products such as extended objects and non-single stars.

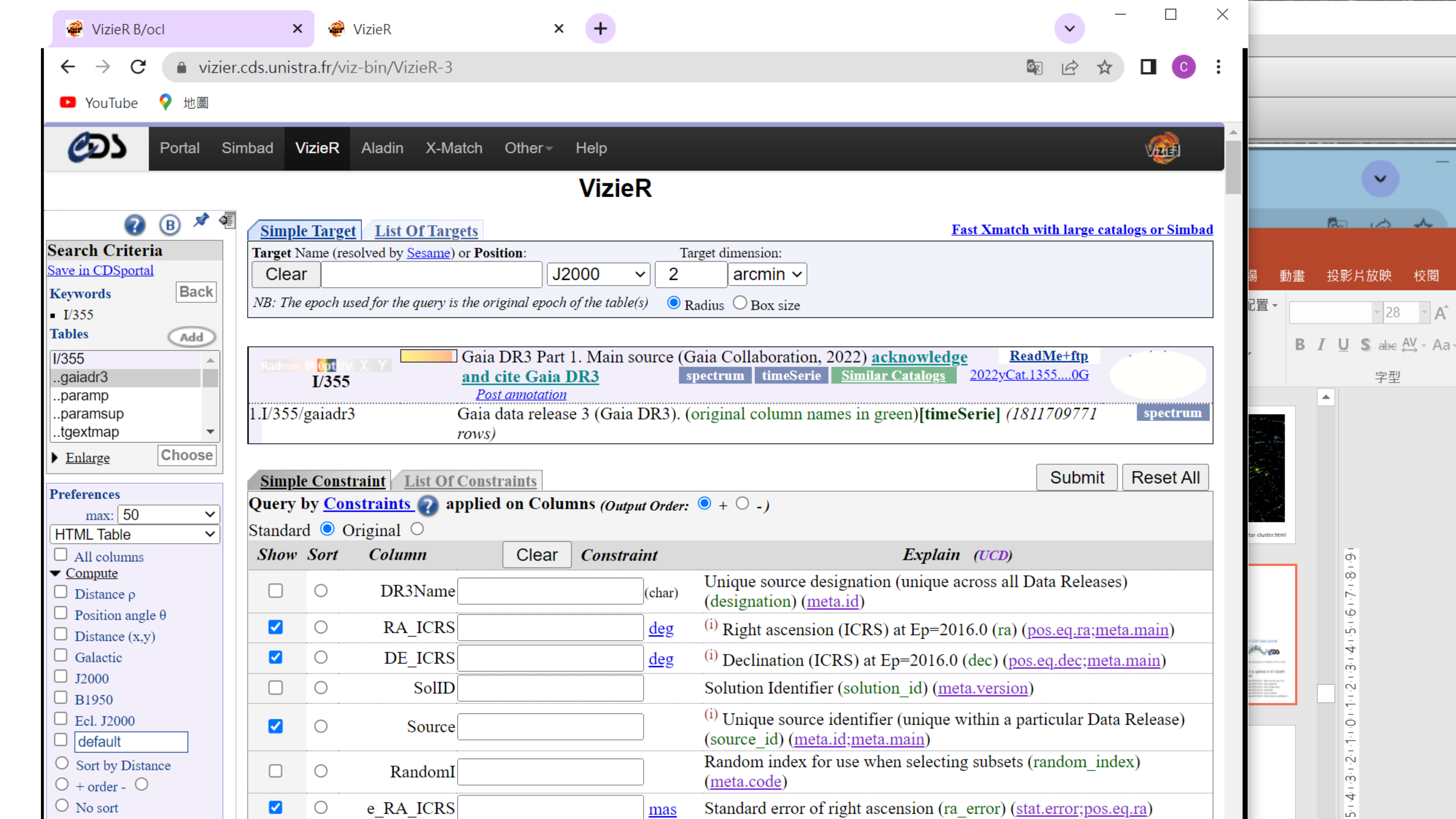
Go to the CDS Gaia portal

Download all Gaia Sources as VOTable, FITS or CSV here.

Gaia DR3 is splited in 6 VizieR catalogues

- I/355 : Gaia DR3 Part 1. Main source (tap/sql)
- I/356 : Gaia DR3 Part 2. Extra-galactic
- I/357 : Gaia DR3 Part 3. Non-single stars
- I/358 : Gaia DR3 Part 4. Variability
- I/359 : Gaia DR3 Part 5. Solar System
- I/360 : Gaia DR3 Part 6. Performance verification

https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=I/355


VizieR B/ocl
VizieR
vizier.cds.unistra.fr/viz-bin/VizieR-3
YouTube
地圖
Portal
Simbad
VizieR
Aladin
X-Match
Other
Help
VizieR
Simple Target
List Of Targets
Fast Xmatch with large catalogs or Simbad
Search Criteria
Save in CDSportal
Keywords
Back
I/355
Tables
Add
I/355
..gaiadr3
..paramp
..paramsup
..tgextmap
Enlarge
Choose
Target Name (resolved by Sesame) or Position:
Target dimension:
Clear
J2000
2
arcmin
NB: The epoch used for the query is the original epoch of the table(s)
Radius
Box size
Gaia DR3 Part 1. Main source (Gaia Collaboration, 2022) acknowledge and cite Gaia DR3
ReadMe+ftp
I/355
spectrum
timeSerie
Similar Catalogs
2022yCat.1355....0G
Post annotation
1.I/355/gaiadr3
Gaia data release 3 (Gaia DR3). (original column names in green)[timeSerie] (1811709771 rows)
spectrum
Simple Constraint
List Of Constraints
Submit
Reset All
Preferences
Query by Constraints applied on Columns (Output Order: + -)
max: 50
Standard
Original
HTML Table
All columns
Show
Sort
Column
Clear
Constraint
Explain (UCD)
Compute
Distance ρ
DR3Name
(char)
Unique source designation (unique across all Data Releases) (designation) (meta.id)
Position angle θ
RA_ICRS
deg
(i) Right ascension (ICRS) at Ep=2016.0 (ra) (pos.eq.ra;meta.main)
Distance (x,y)
Galactic
DE_ICRS
deg
(i) Declination (ICRS) at Ep=2016.0 (dec) (pos.eq.dec;meta.main)
J2000
SolID
Solution Identifier (solution_id) (meta.version)
B1950
Ecl. J2000
Source
(i) Unique source identifier (unique within a particular Data Release) (source_id) (meta.id;meta.main)
default
Sort by Distance
RandomI
Random index for use when selecting subsets (random_index) (meta.code)
+ order -
No sort
e_RA_ICRS
mas
Standard error of right ascension (ra_error) (stat.error;pos.eq.ra)
動畫
投影片放映
校閱
字型
28

- ✓ Try to query “m67” (What is it?)
- ✓ Start out with 2’
- ✓ Uncheck all entries; then select those needed

- ✓ Column-wise data format; empty fields? NAN?

- ✓ Preferences: try “999-filled“?, “;-separated-Values”

- ✓ Then download stars within a radius of 30’ (i.e., 1-deg FOV), unlimited, ;-separated m67GaiaDR3r30m.tsv - 記事本

檔案(F) 編輯(E) 格式(O) 檢視(V) 說明

```
#Column RA_ICRS (F15.11)       Right ascension (ICRS) at Ep=2016.0 (ra)       [ucd=pos.eq.ra;meta.main]
#Column e_RA_ICRS       (F7.4)  Standard error of right ascension (ra_error)    [ucd=stat.error;pos.eq.ra]
#Column DE_ICRS (F15.11)       Declination (ICRS) at Ep=2016.0 (dec)   [ucd=pos.eq.dec;meta.main]
#Column e_DE_ICRS       (F7.4)  Standard error of declination (dec_error)       [ucd=stat.error;pos.eq.dec]
#Column Plx     (F9.4)  ? Parallax (parallax)   [ucd=pos.parallax.trig]
#Column e_Plx   (F7.4)  ? Standard error of parallax (parallax_error)   [ucd=stat.error;pos.parallax.trig]
#Column pmRA    (F9.3)  ? Proper motion in right ascension direction, pmRA*cosDE (pmra) [ucd=pos.pm;pos.eq.ra]
#Column e_pmRA  (F6.3)  ? Standard error of proper motion in right ascension direction (pmra_error)     [ucd=stat.error;pos.pm;pos.eq.ra]
#Column pmDE    (F9.3)  ? Proper motion in declination direction (pmdec)        [ucd=pos.pm;pos.eq.dec]
#Column e_pmDE  (F13.10)        ? Standard error of proper motion in declination direction (pmdec_error)        [ucd=stat.error;pos.pm;pos.eq.dec]
#Column Gmag    (F9.6)  ? G-band mean magnitude (phot_g_mean_mag)       [ucd=phot.mag;em.opt]
#Column e_Gmag  (F9.6)  ? Error on G-band mean magnitude (added by CDS) (phot_g_mean_mag_error) [ucd=stat.error;phot.mag;stat.mean]
#Column BPmag   (F9.6)  ? Integrated BP mean magnitude (phot_bp_mean_mag)       [ucd=phot.mag;em.opt.B]
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#Column RV      (F7.2)  ? Radial velocity (radial_velocity)     [ucd=spect.dopplerVeloc.opt;em.opt.I]
#Column e_RV    (F5.2)  ? Radial velocity error (radial_velocity_error) [ucd=stat.error;spect.dopplerVeloc.opt;em.opt.I]
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#Column GLAT    (F15.11)        Galactic latitude (b)   [ucd=pos.galactic.lat]
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deg;mas;deg;mas;mas;mas;mas/yr;mas/yr;mas/yr;mas/yr;mag;mag;mag;mag;mag;mag;km/s;km/s;deg;deg
--------------;-------;--------------;-------;---------;-------;---------;------;---------;-------------;---------;---------;---------;---------;---------;---------;-------;-----;---------------;---
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132.95522365017; 0.4227;+11.35801105862; 0.2219;   1.5343; 0.5074;  -17.491; 0.540;  -15.398; 0.4230279326;19.856251; 0.004723;21.111031; 0.123293;18.726480; 0.031837;       ;     ;216.23129639606; 3
132.94448609465; 0.0707;+11.36581785856; 0.0371;   0.2816; 0.0833;   -0.449; 0.088;   -3.538; 0.0687142834;17.101488; 0.002844;17.482079; 0.008929;16.555628; 0.006974;       ;     ;216.21773281010; 3
132.94652719872; 0.0838;+11.35387628734; 0.0452;   1.2375; 0.0997;  -10.848; 0.106;   -3.124; 0.0798023641;17.412605; 0.002899;18.451990; 0.015721;16.407856; 0.006849;       ;     ;216.23146452316; 3
132.93896782686;27.3164;+11.35632101421;12.6933;         ;       ;         ;      ;         ;             ;21.976078; 0.052303;20.707281; 0.600357;19.163086; 0.103546;       ;     ;216.22517034321; 3
```

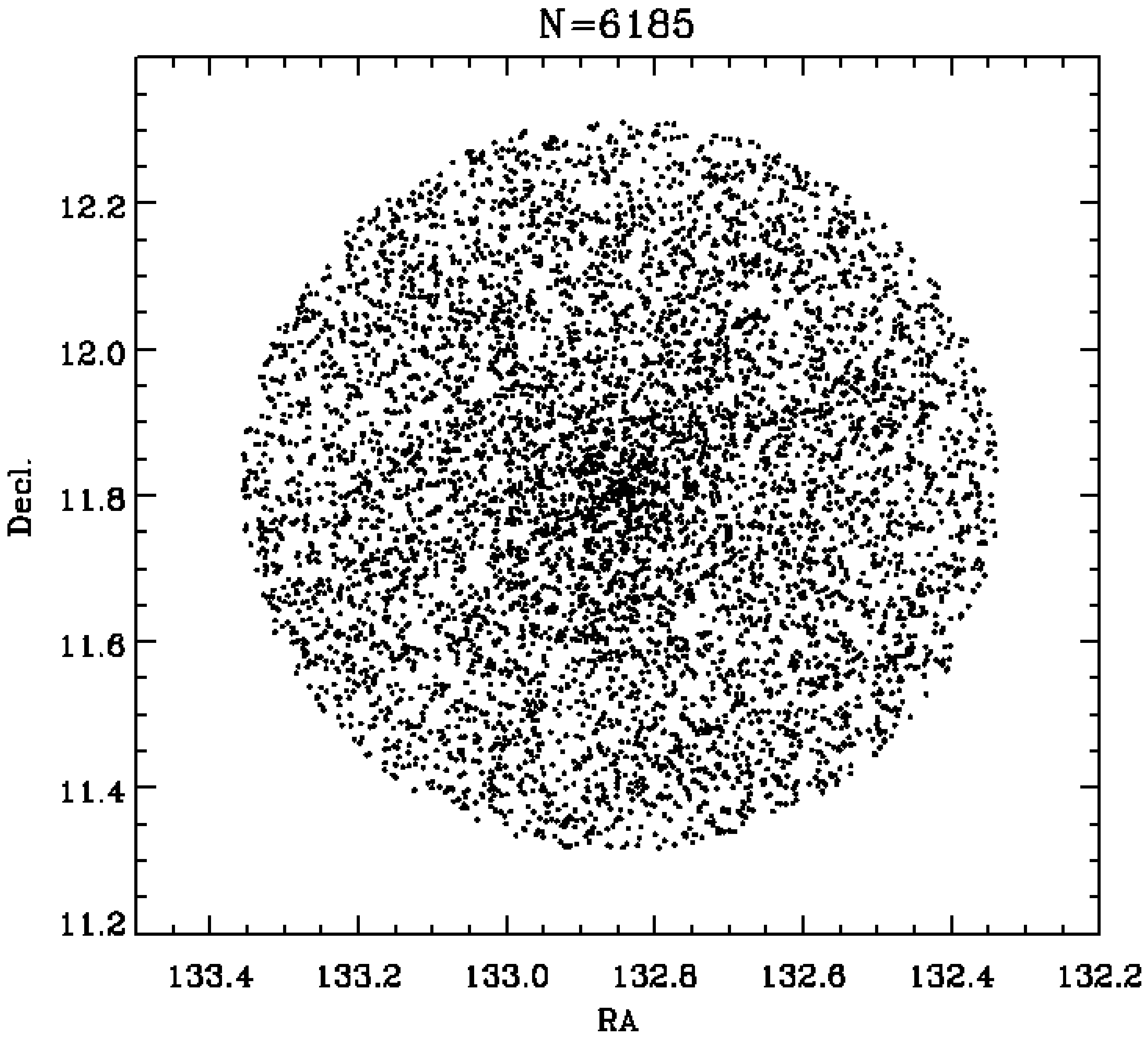
第 1 列，第 1 行 100% Unix (LF) UTF-8

Gaia positions

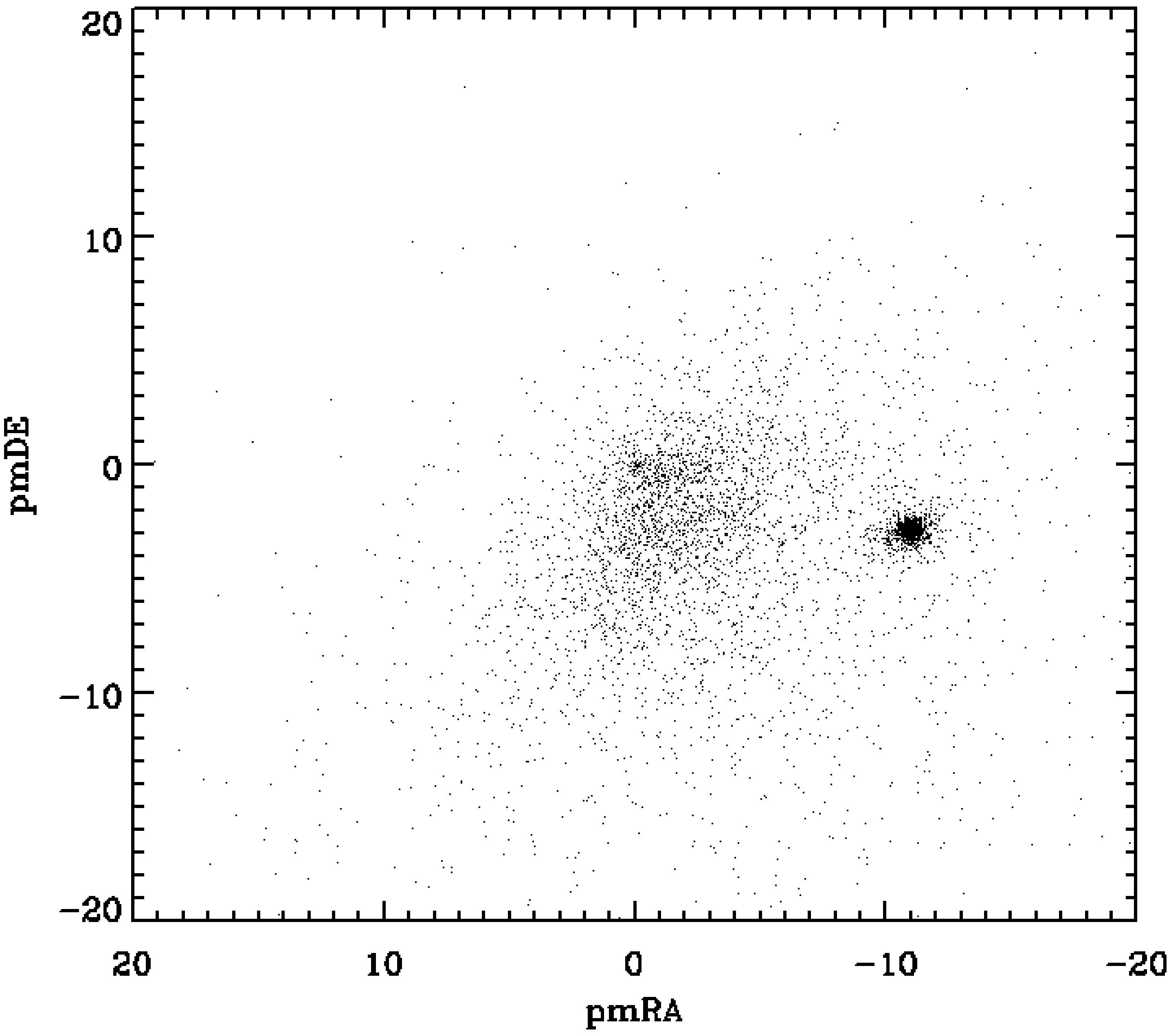
All stars within 1 deg field …

Concentration at center (the cluster) obvious

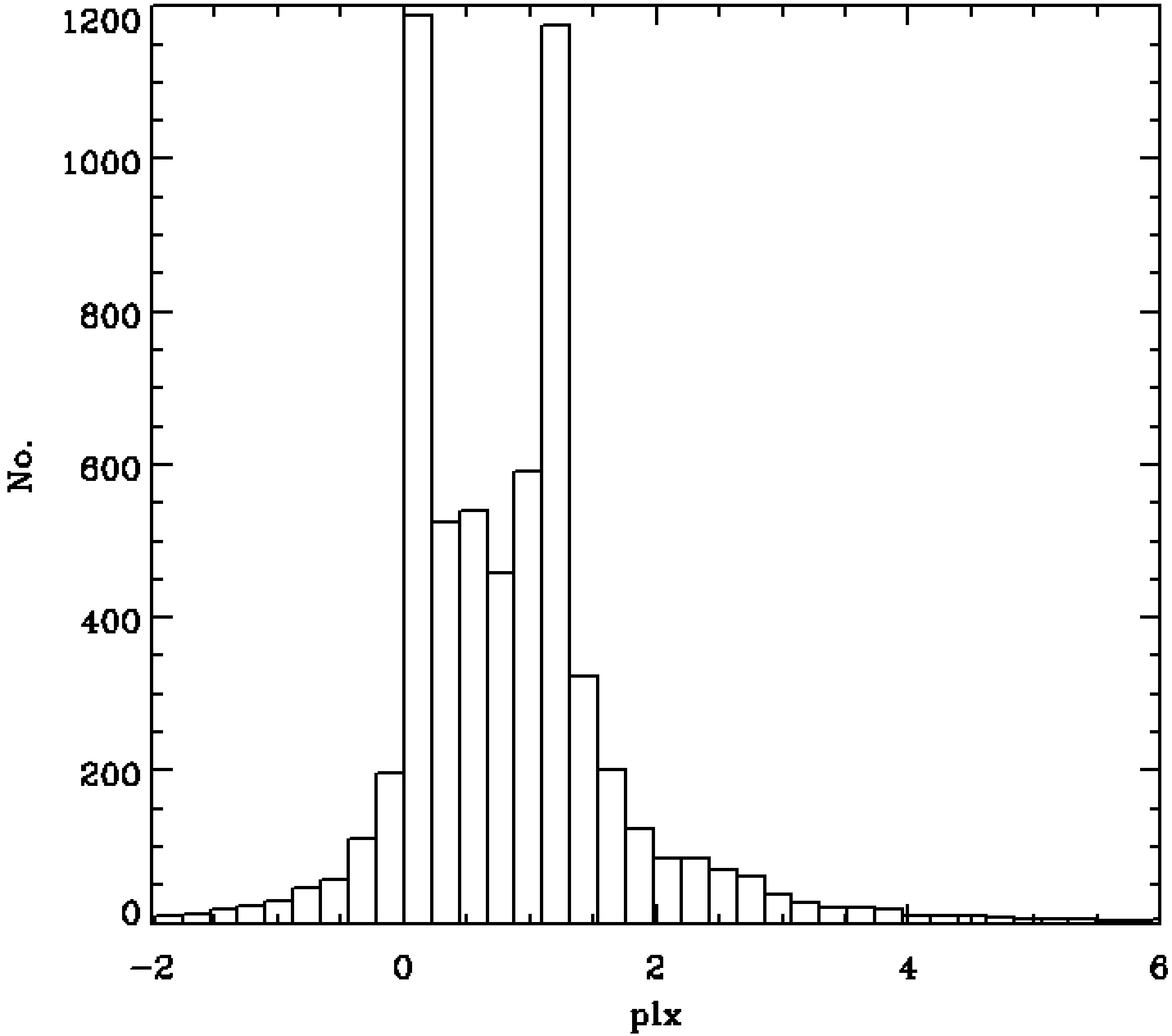
Extended shape?

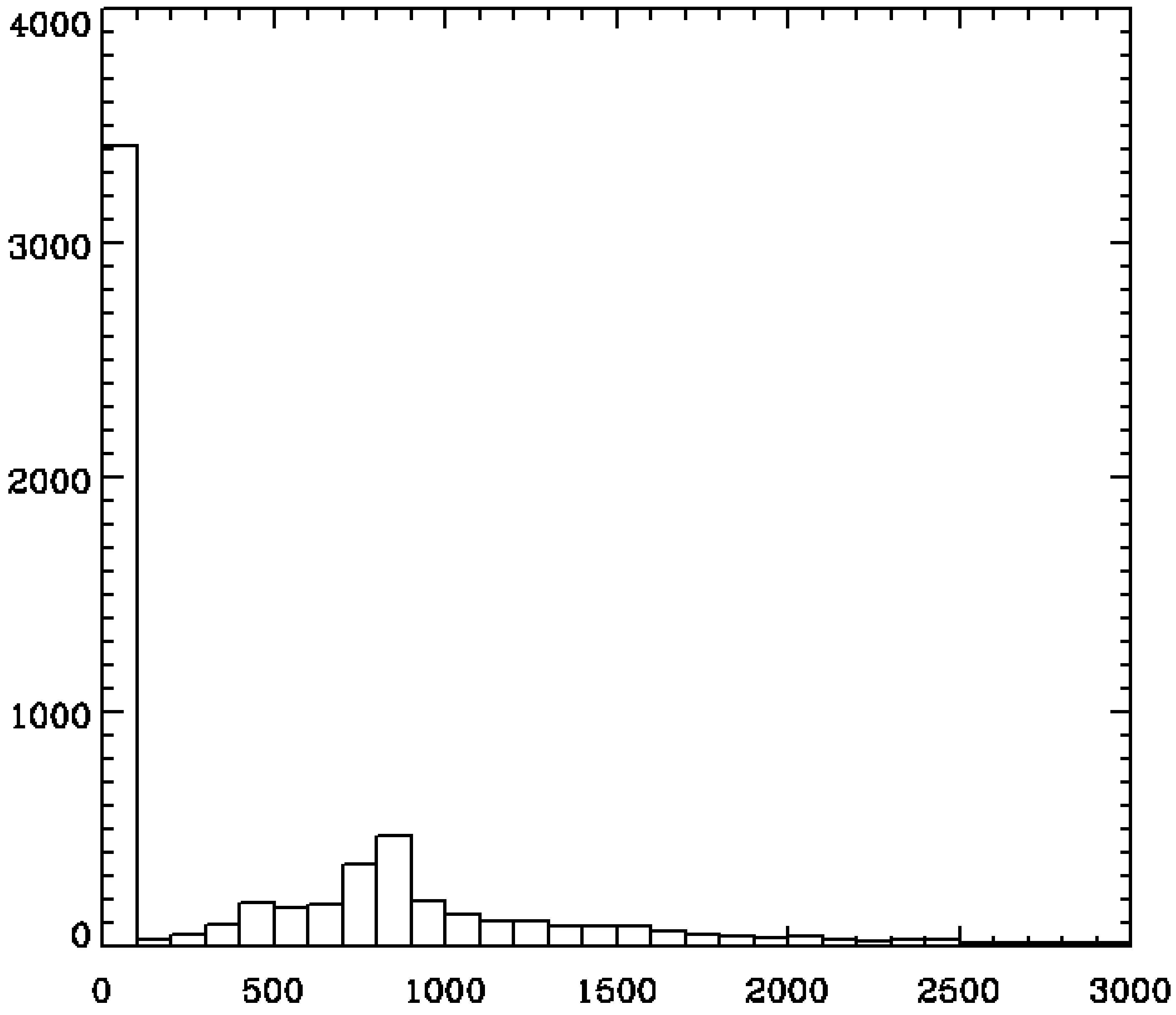


Cluster members move differently from field stars (solar motion)

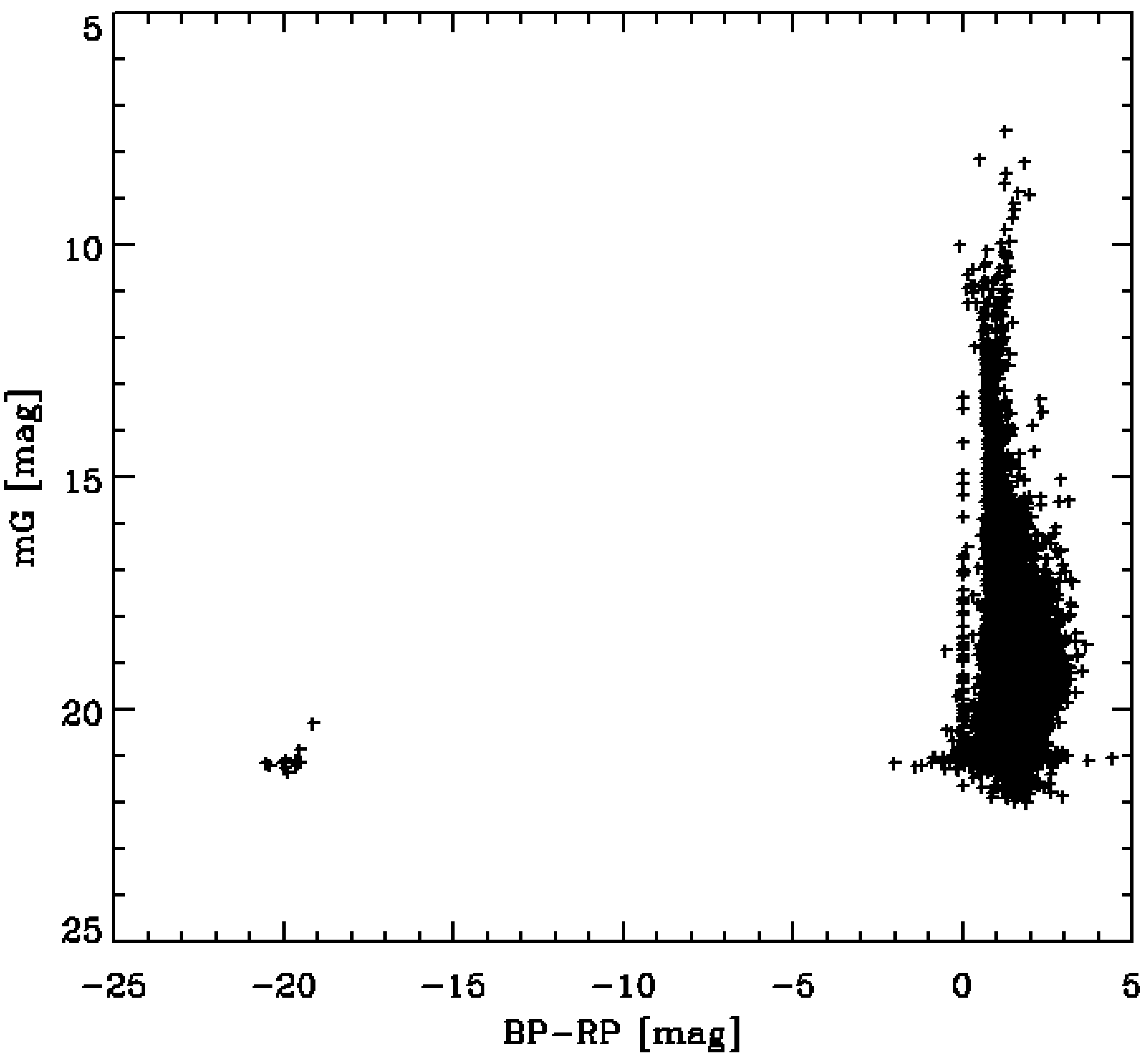


Parallax distribution

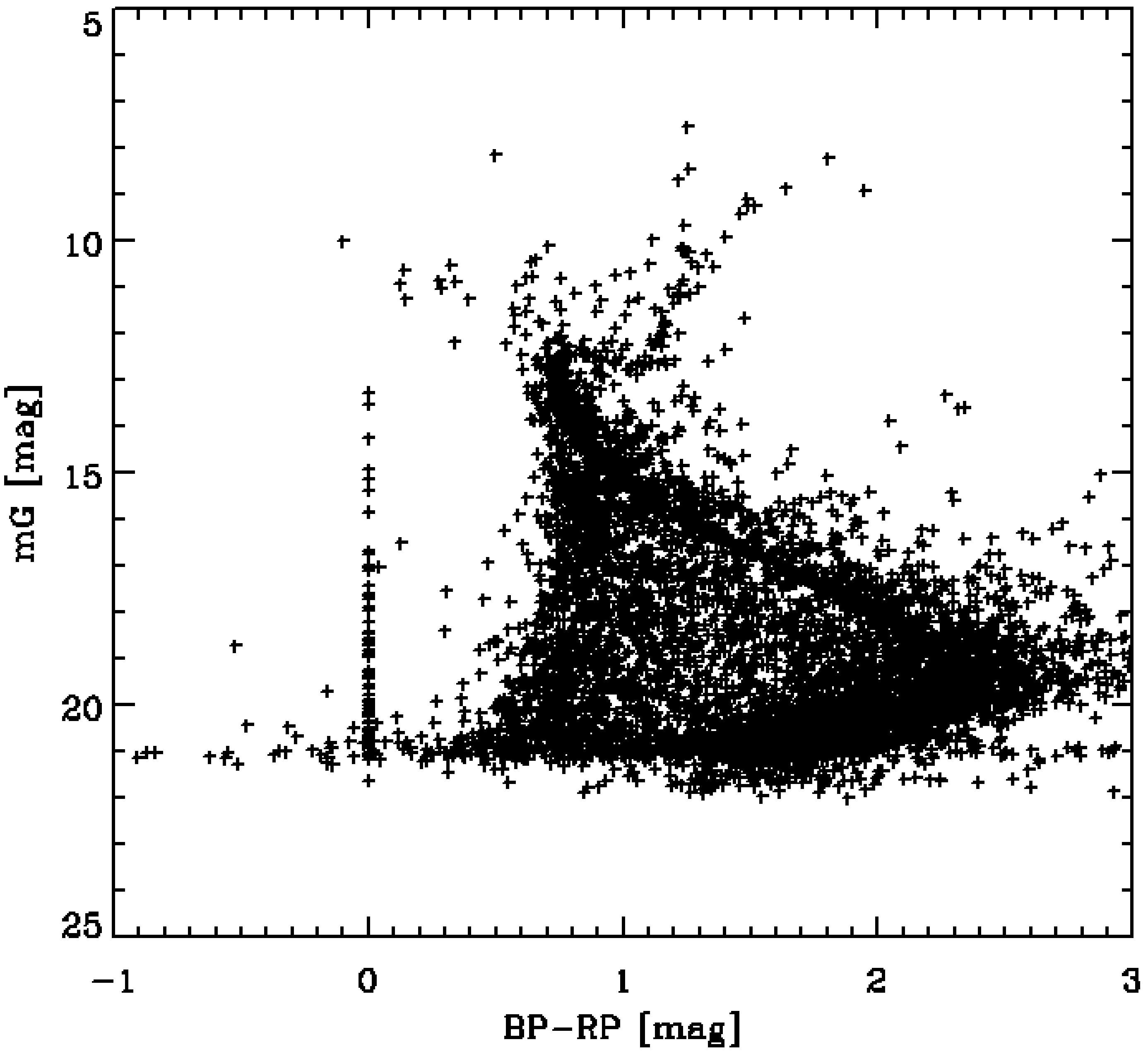




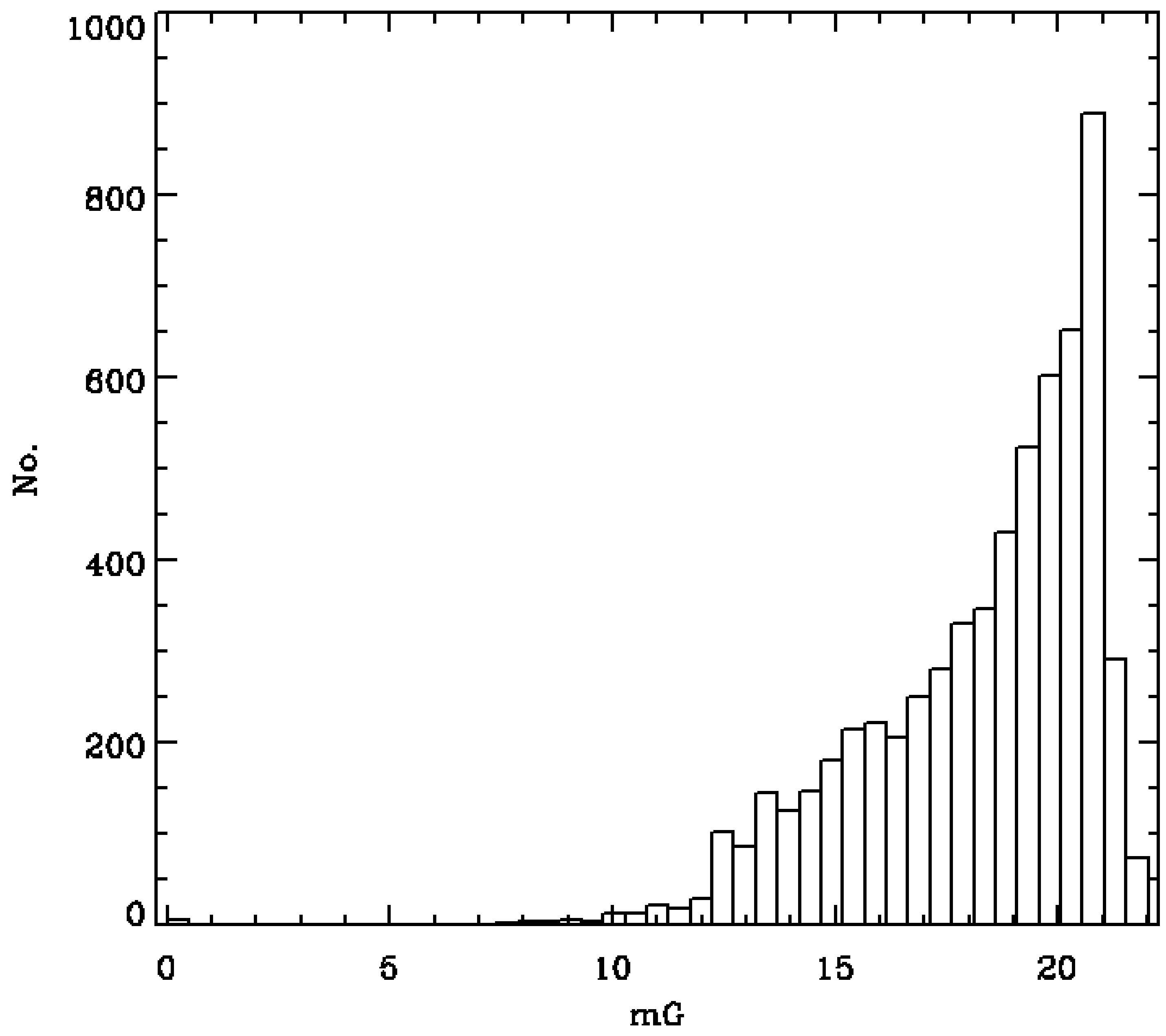
4000
3000
2000
1000
0
0
500
1000
1500
2000
2500
3000



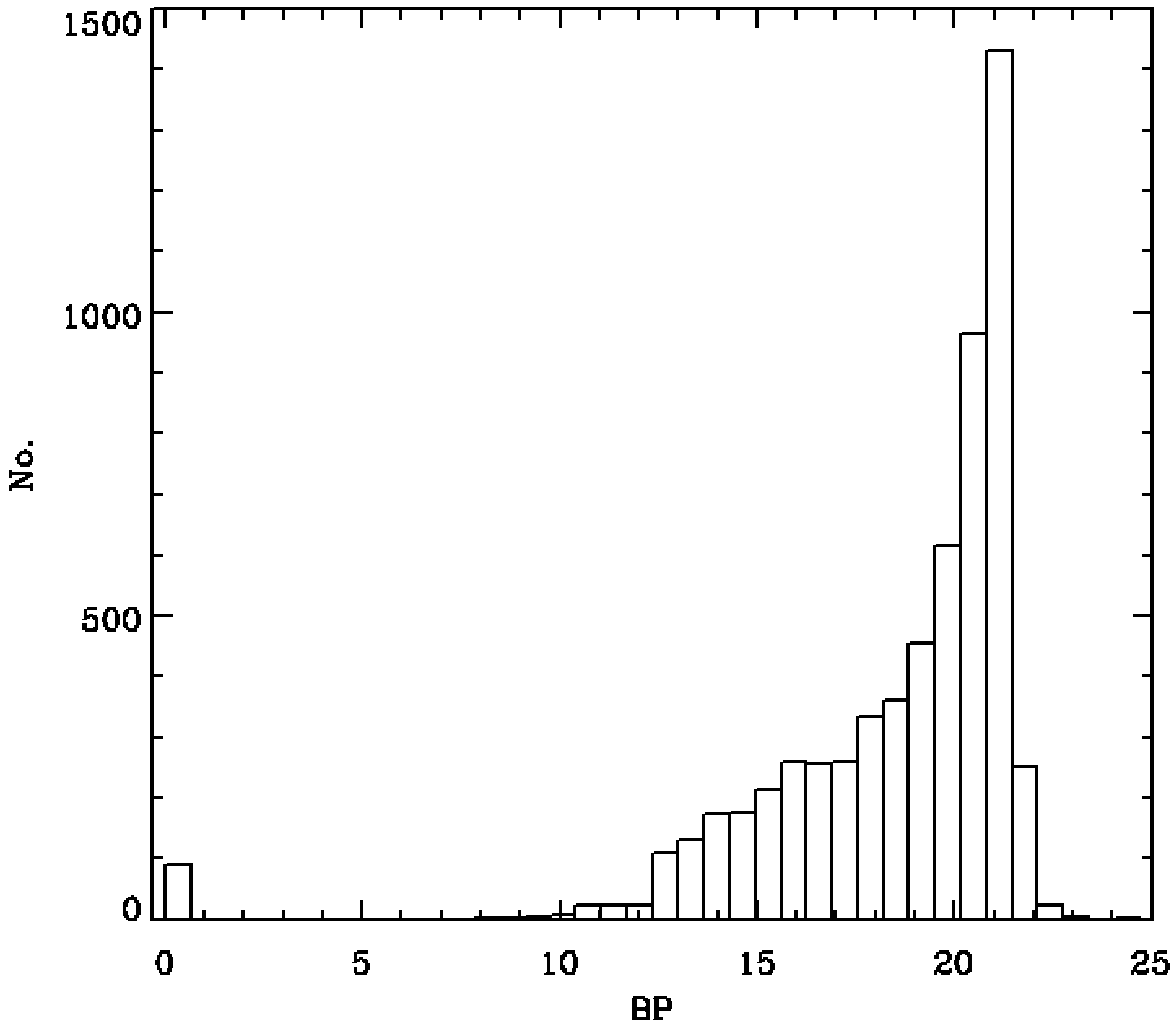
5
10
15
20
25
mG [mag]
−25
−20
−15
−10
−5
0
5
BP−RP [mag]

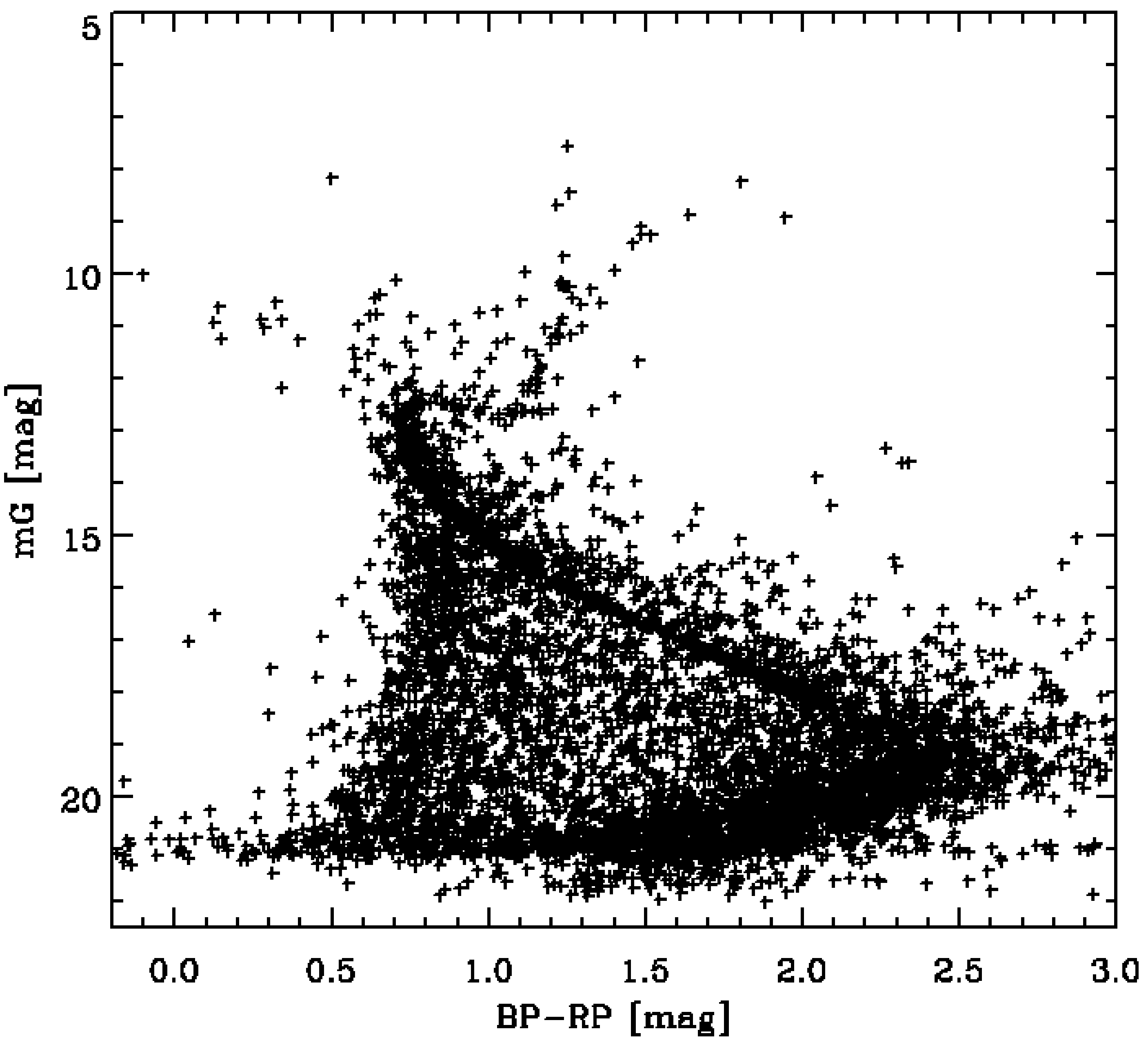


mG [mag]
BP−RP [mag]
5
10
15
20
25
−1
0
1
2
3

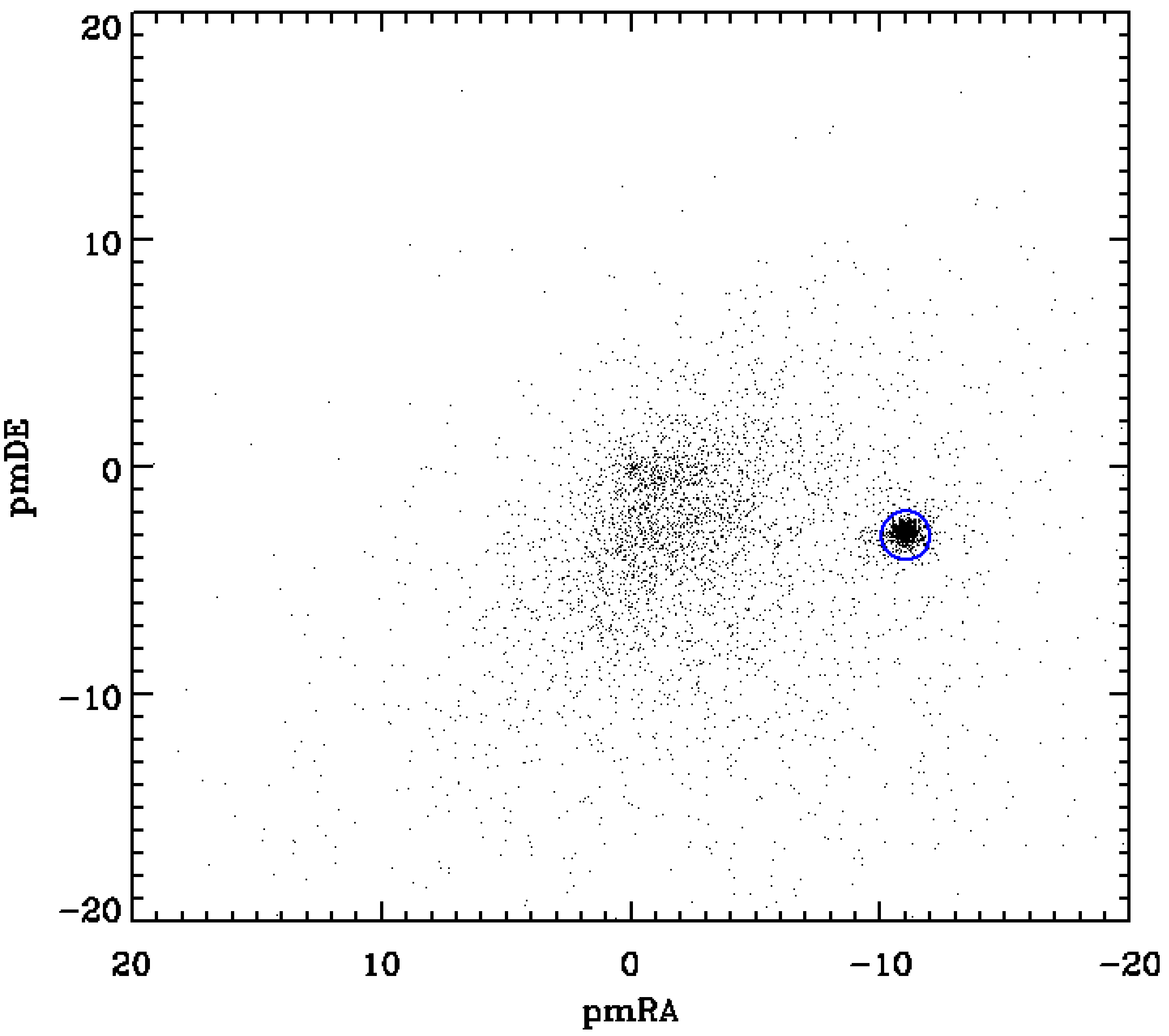


1000
800
600
400
200
0
No.
0
5
10
15
20
mG


1500
1000
500
0
No.
0
5
10
15
20
25
BP

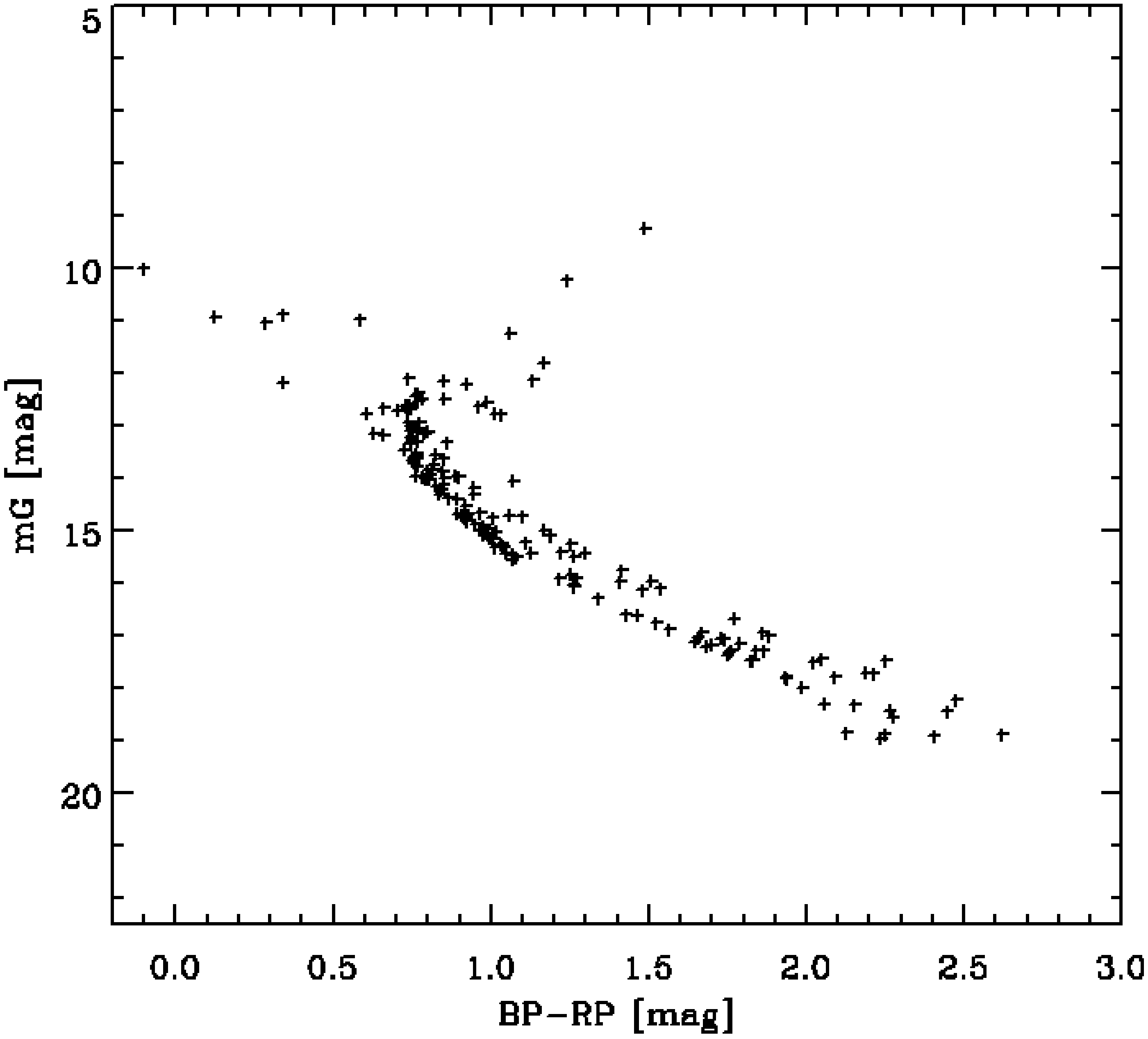


5
10
15
20
mG [mag]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
BP−RP [mag]

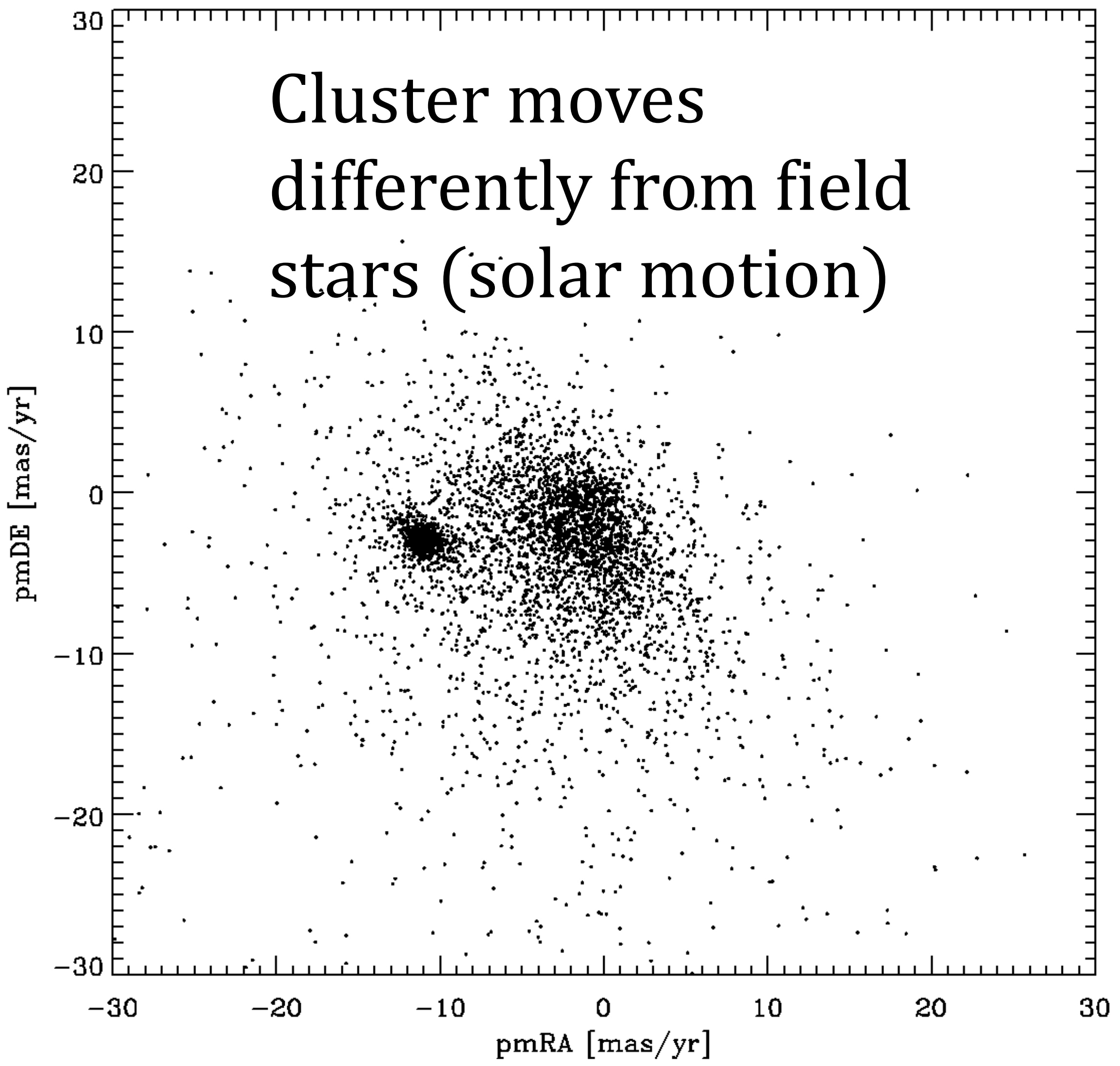


20
10
0
−10
−20
pmDE
20
10
0
−10
−20
pmRA

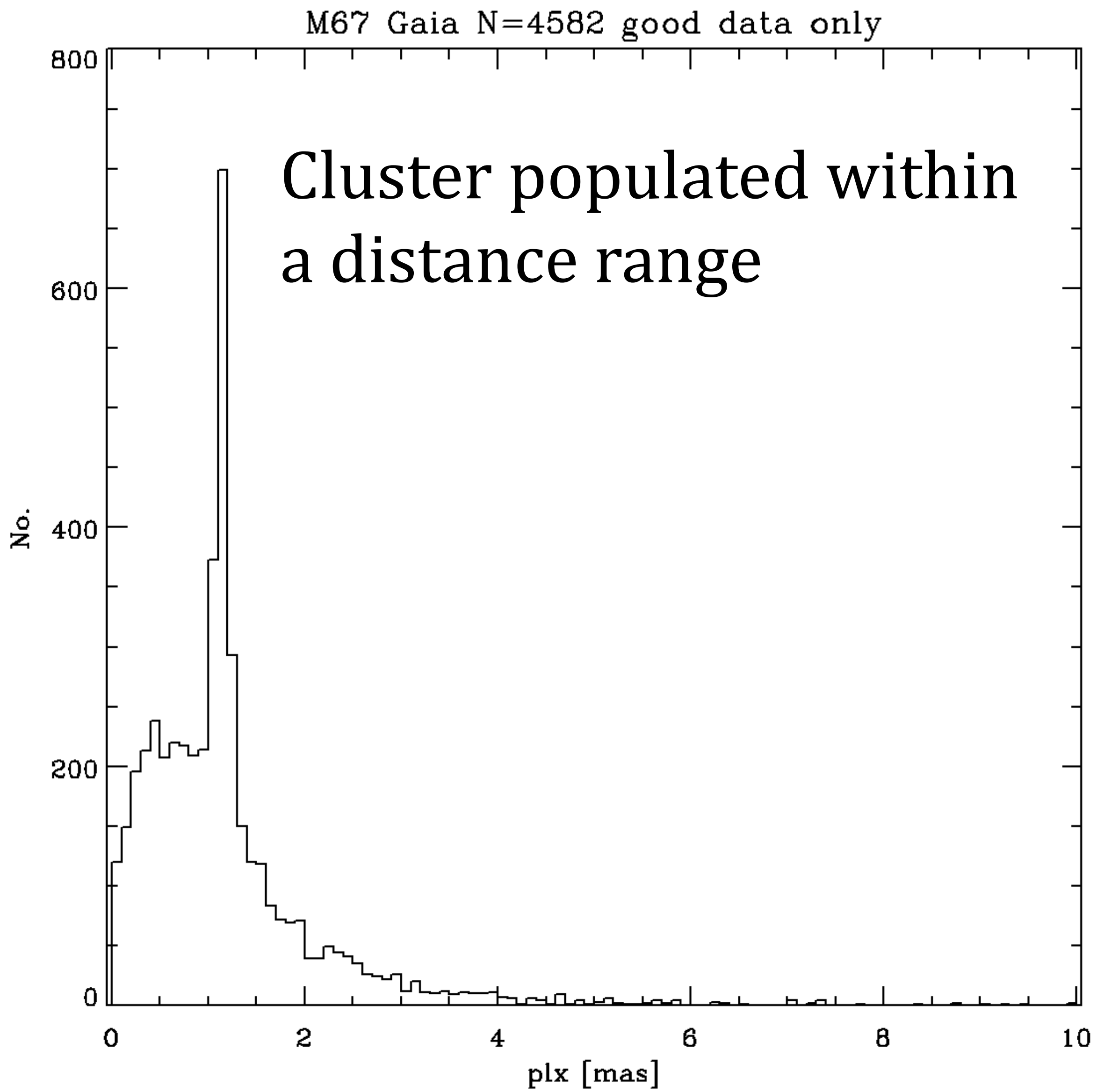
```
allOK=WHERE( gmag ne 0 and
bpmag ne 0 and rpmag ne 0 and
rad lt rad0 and pmRAD lt
pmRAD0 and dis GT 200)
```



Gaia proper motions

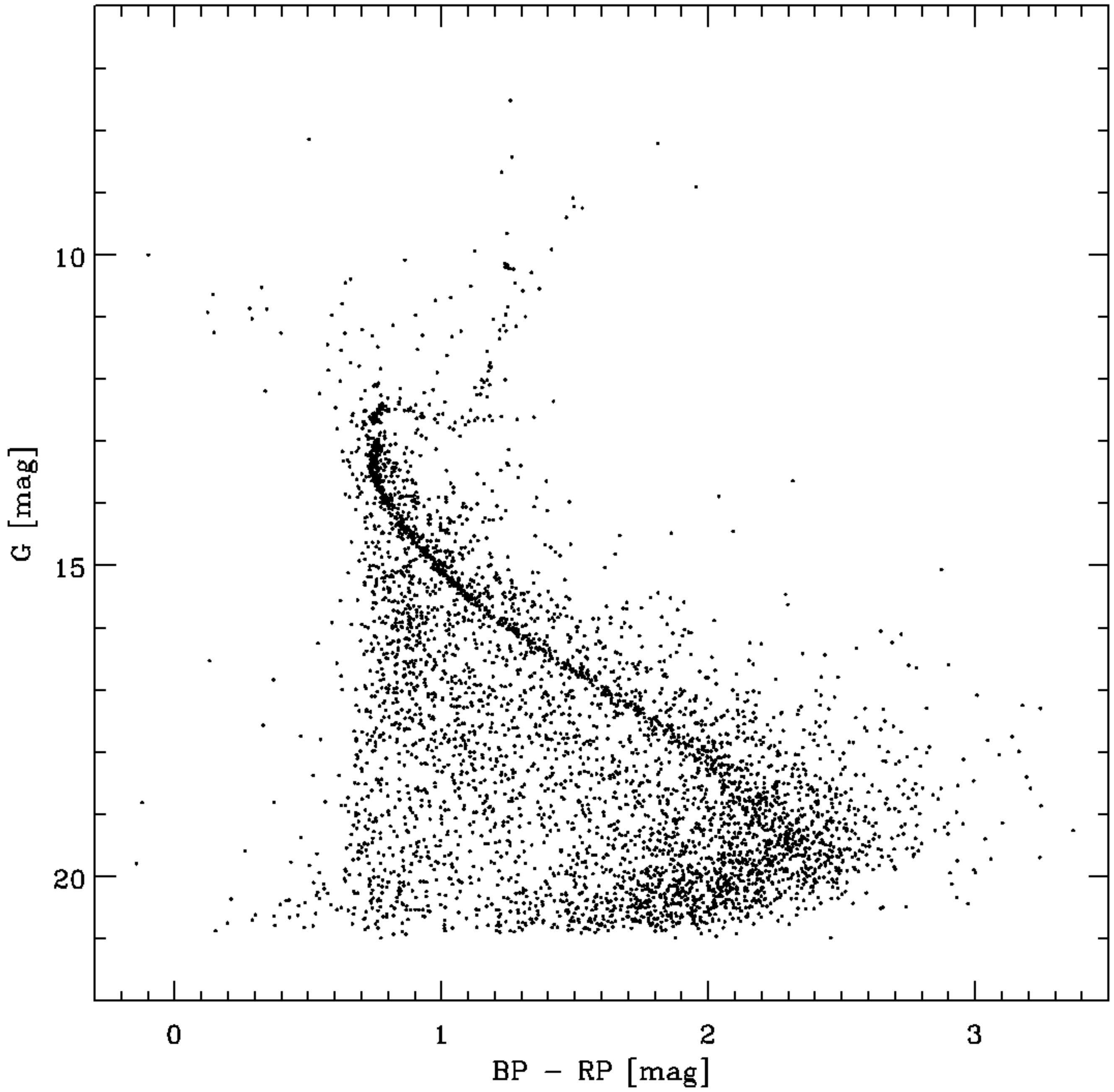


Gaia parallaxes



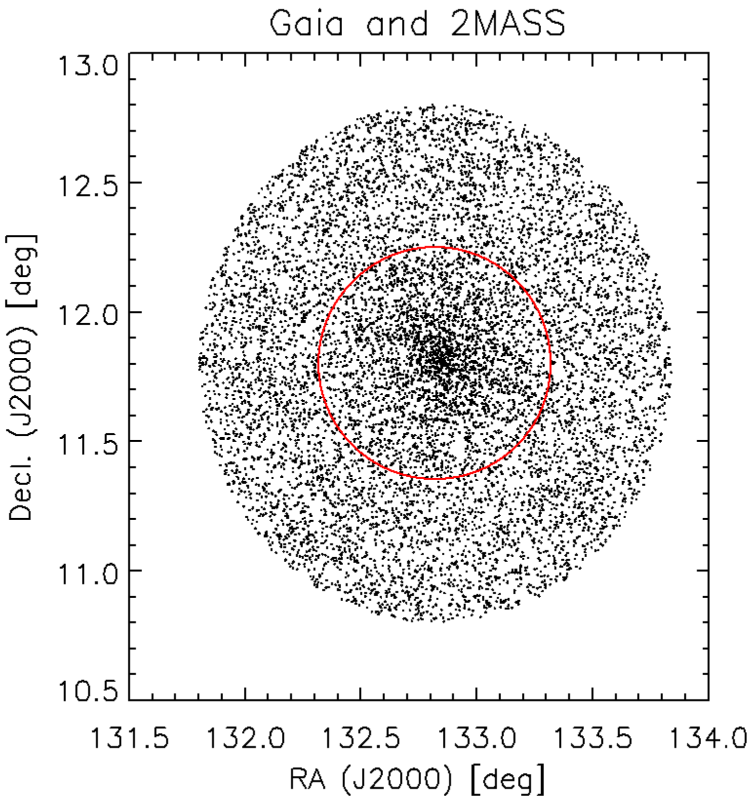
Gaia CMD

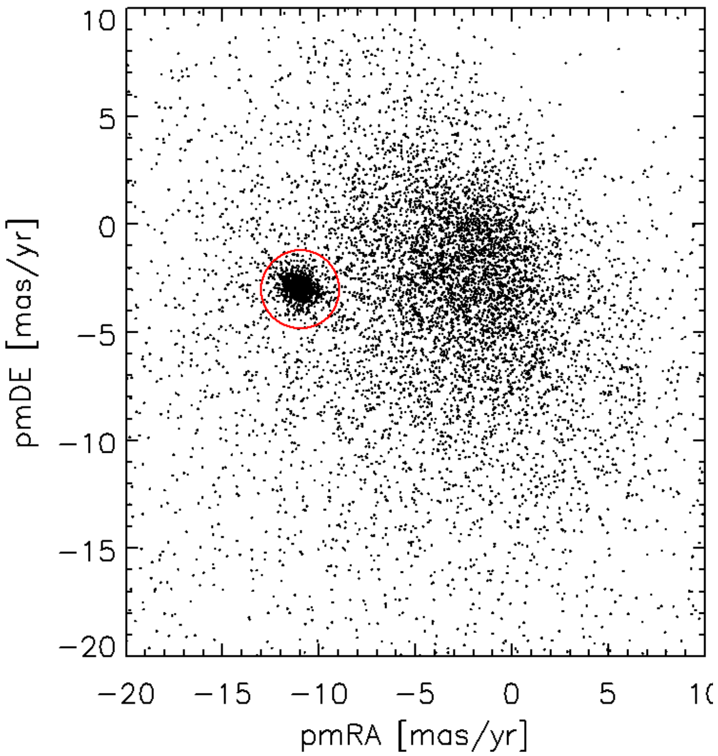
The cluster sequence stands out clearly in the CMD, though there are many contaminations, i.e., non-members.

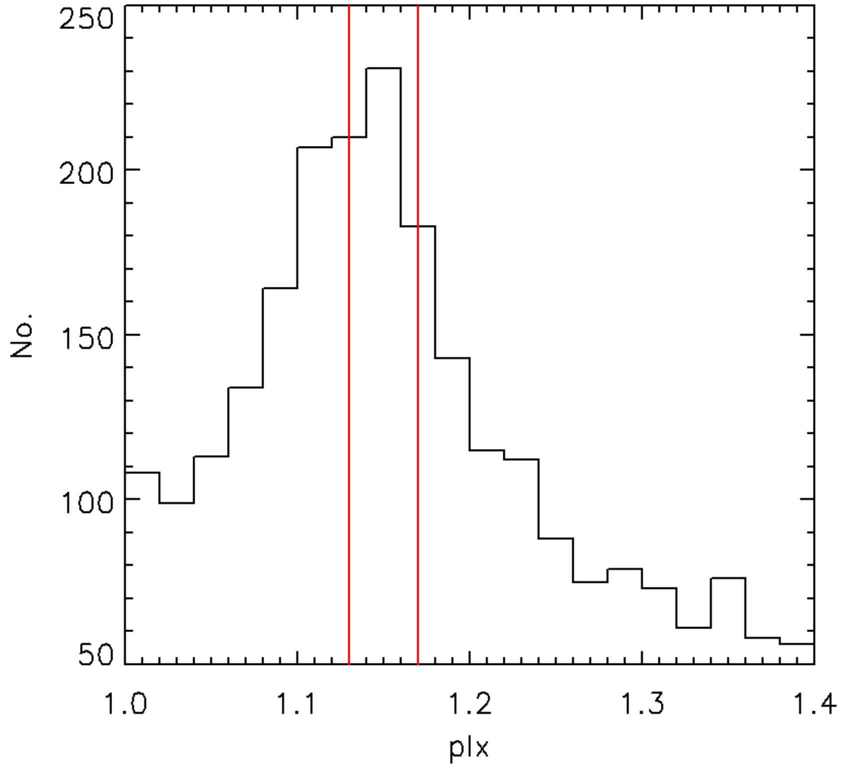


With some preliminary selection criteria in sky coordinates, proper motion, and parallax …

```
ok=WHERE( plx LT 10 and plx
GT 0 and plx LT 1.5 and plx
GT 0.5 and  ABS(pmra+12) LT
5 and ABS(pmde+4) LT 5 )
```



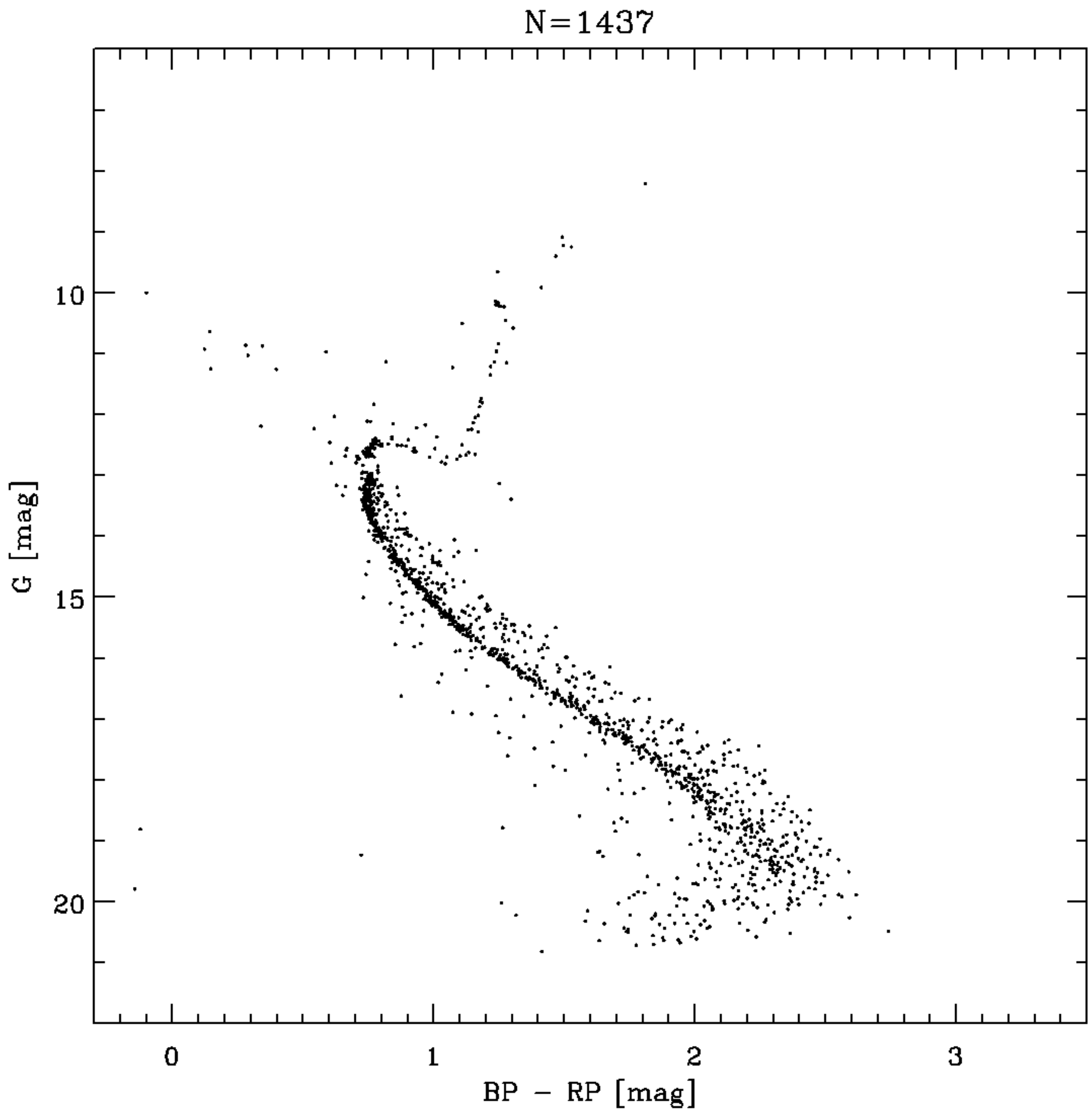




plx(max)=1.15 → d=870 pc

Iterative membership selection

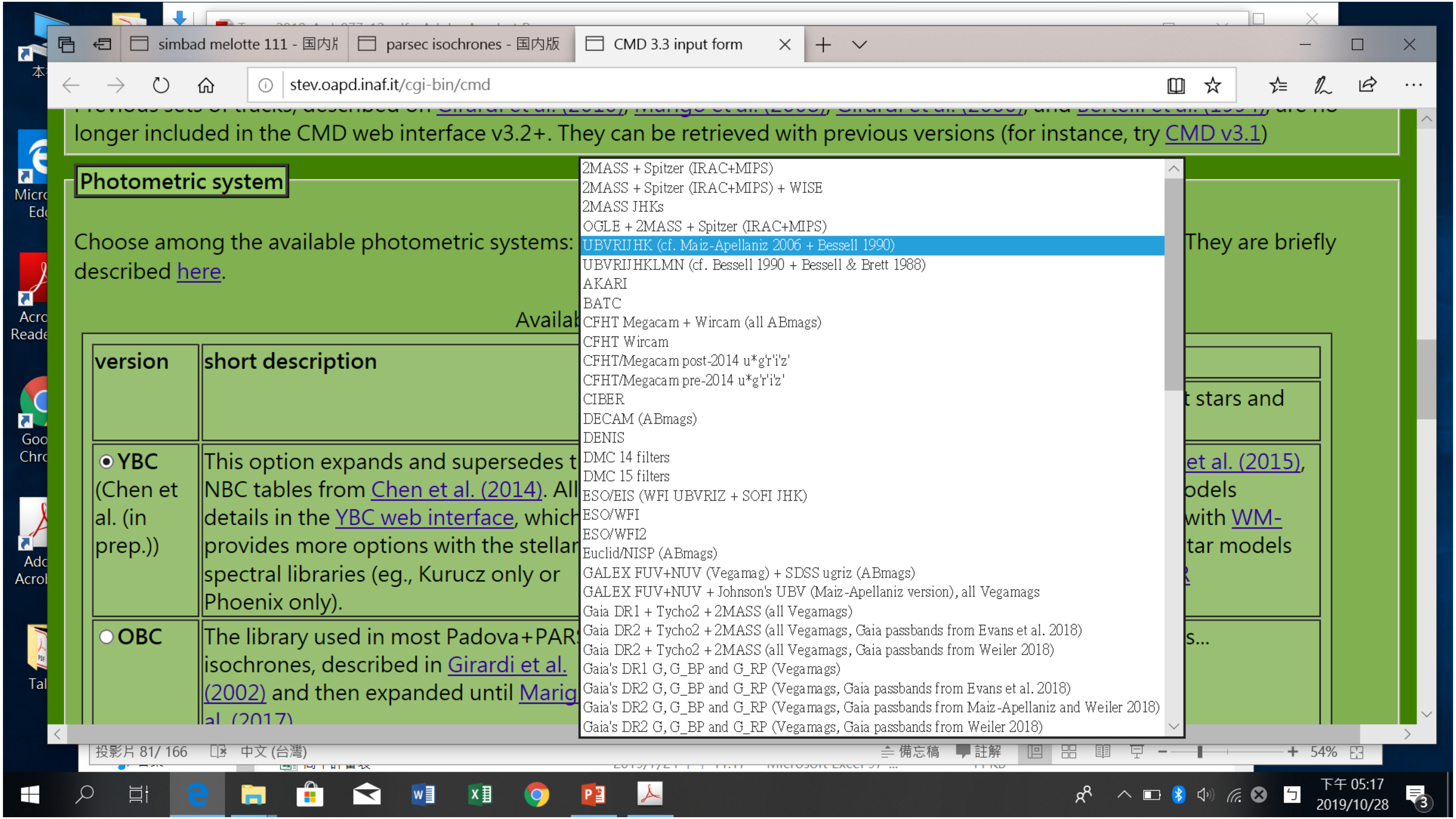
- ✓ Age and distance
- ✓ Blue stragglers
- ✓ Red clump giants
- ✓ "Blue clump"?
- ✓ Binaries
- ✓ White dwarfs?
- ✓ Brown dwarfs?



An Example Stellar Isochrone on Demand: The “Padova” tracks

http://stev.oapd.inaf.it/cgi-bin/cmd

Key word: “PARSEC isochrones”



simbad melotte 111 - 国内版
parsec isochrones - 国内版
CMD 3.3 input form
stev.oapd.inaf.it/cgi-bin/cmd
longer included in the CMD web interface v3.2+. They can be retrieved with previous versions (for instance, try CMD v3.1)
Photometric system
Choose among the available photometric systems:
They are briefly described here.
Availab
version
short description
YBC (Chen et al. (in prep.))
This option expands and supersedes t
NBC tables from Chen et al. (2014). All
details in the YBC web interface, which
provides more options with the stellar
spectral libraries (eg., Kurucz only or
Phoenix only).
OBC
The library used in most Padova+PARS
isochrones, described in Girardi et al.
(2002) and then expanded until Marig
2MASS + Spitzer (IRAC+MIPS)
2MASS + Spitzer (IRAC+MIPS) + WISE
2MASS JHKs
OGLE + 2MASS + Spitzer (IRAC+MIPS)
UBVRIJHK (cf. Maiz-Apellaniz 2006 + Bessell 1990)
UBVRIJHKLMN (cf. Bessell 1990 + Bessell & Brett 1988)
AKARI
BATC
CFHT Megacam + Wircam (all ABmags)
CFHT Wircam
CFHT/Megacam post-2014 u*g'r'i'z'
CFHT/Megacam pre-2014 u*g'r'i'z'
CIBER
DECAM (ABmags)
DENIS
DMC 14 filters
DMC 15 filters
ESO/EIS (WFI UBVRIZ + SOFI JHK)
ESO/WFI
ESO/WFI2
Euclid/NISP (ABmags)
GALEX FUV+NUV (Vegamag) + SDSS ugriz (ABmags)
GALEX FUV+NUV + Johnson's UBV (Maiz-Apellaniz version), all Vegamags
Gaia DR1 + Tycho2 + 2MASS (all Vegamags)
Gaia DR2 + Tycho2 + 2MASS (all Vegamags, Gaia passbands from Evans et al. 2018)
Gaia DR2 + Tycho2 + 2MASS (all Vegamags, Gaia passbands from Weiler 2018)
Gaia's DR1 G, G_BP and G_RP (Vegamags)
Gaia's DR2 G, G_BP and G_RP (Vegamags, Gaia passbands from Evans et al. 2018)
Gaia's DR2 G, G_BP and G_RP (Vegamags, Gaia passbands from Maiz-Apellaniz and Weiler 2018)
Gaia's DR2 G, G_BP and G_RP (Vegamags, Gaia passbands from Weiler 2018)
t stars and
et al. (2015),
odels
with WM-
tar models
s...
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中文 (台灣)
備忘稿
註解
54%
下午 05:17
2019/10/28

simbad melotte 111 - 国内版 | parsec isochrones - 国内版 | CMD 3.3 input form

stev.oapd.inaf.it/cgi-bin/cmd

Ages/metallicities

Choose your metallicity values using the approximation [M/H]=log(Z/X)-log(Z/X)$_\odot$, with (Z/X)$_\odot$=0.0207 and Y=0.2485+1.78Z for PARSEC tracks.

Input form for multiple values of ages/metallicities (up to a maximum of 1e4 isochrones):

		initial value	final value	step (use 0 for a single value)
ages	◉ linear age (yr) =	1.0e9 yr	1.0e10 yr	0.0 yr
	○ log(age/yr) =	6.6 dex	10.13 dex	0.0 dex
metallicities	◉ metal fraction Z =	0.0152	0.03	0.0
	○ [M/H] =	-2 dex	0.3 dex	0.0 dex

Output

Kind of output:

◉ Isochrone tables: stellar parameters as a function of initial mass

○ Luminosity functions: star counts expected, in the interval from -15 to 20 mag, with bins 0.5 mag wide, per 1 Msun of stellar population

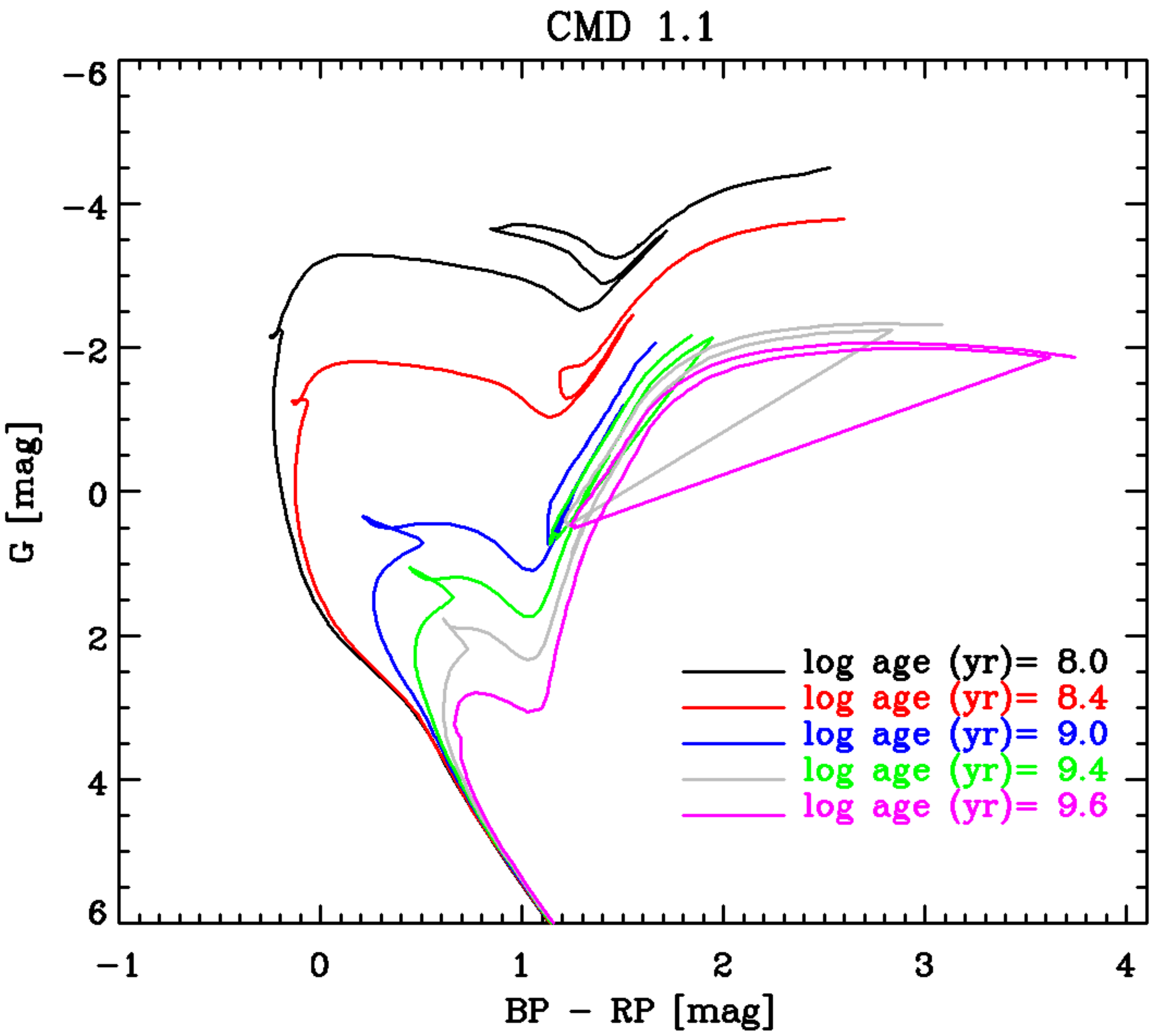
○ Simulated populations with a total mass of 1.0e4 Msun

投影片 82/ 167 中文 (台灣) 備忘稿 註解 54%

下午 05:18 2019/10/28

Exercises

- ☐ Using Gaia photometric measurements (G, G_{BP}, G_{RP}), download and compare the isochrones of different ages.
- ☐ Check out the effect of metallicity.
- ☐ How would the extinction/reddening affect a theoretical isochrone?



CMD 1.1
G [mag]
−6
−4
−2
0
2
4
6
BP − RP [mag]
−1
0
1
2
3
4
log age (yr)= 8.0
log age (yr)= 8.4
log age (yr)= 9.0
log age (yr)= 9.4
log age (yr)= 9.6

Star Clusters
as
Tools for Investigation

Infant Star Clusters

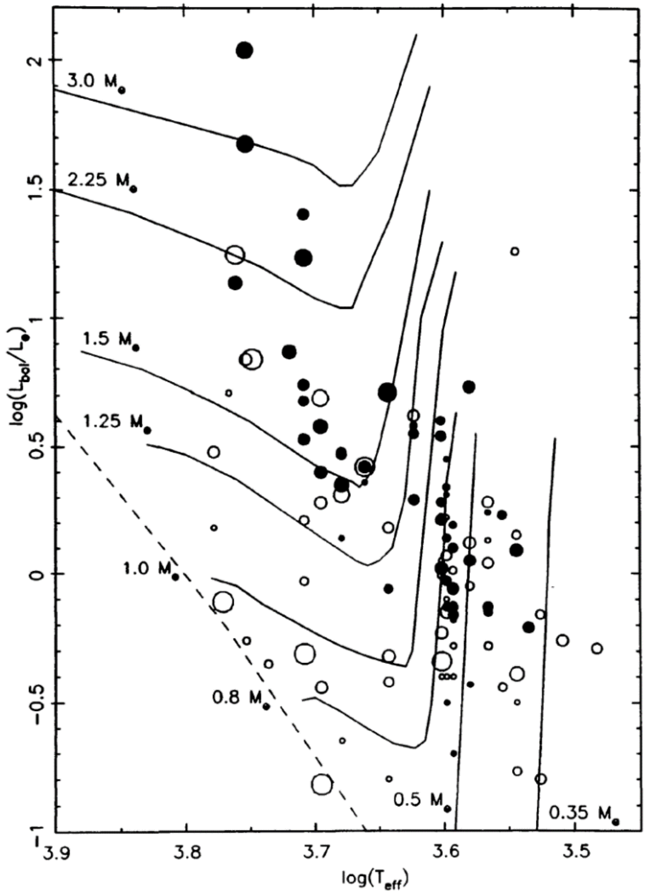
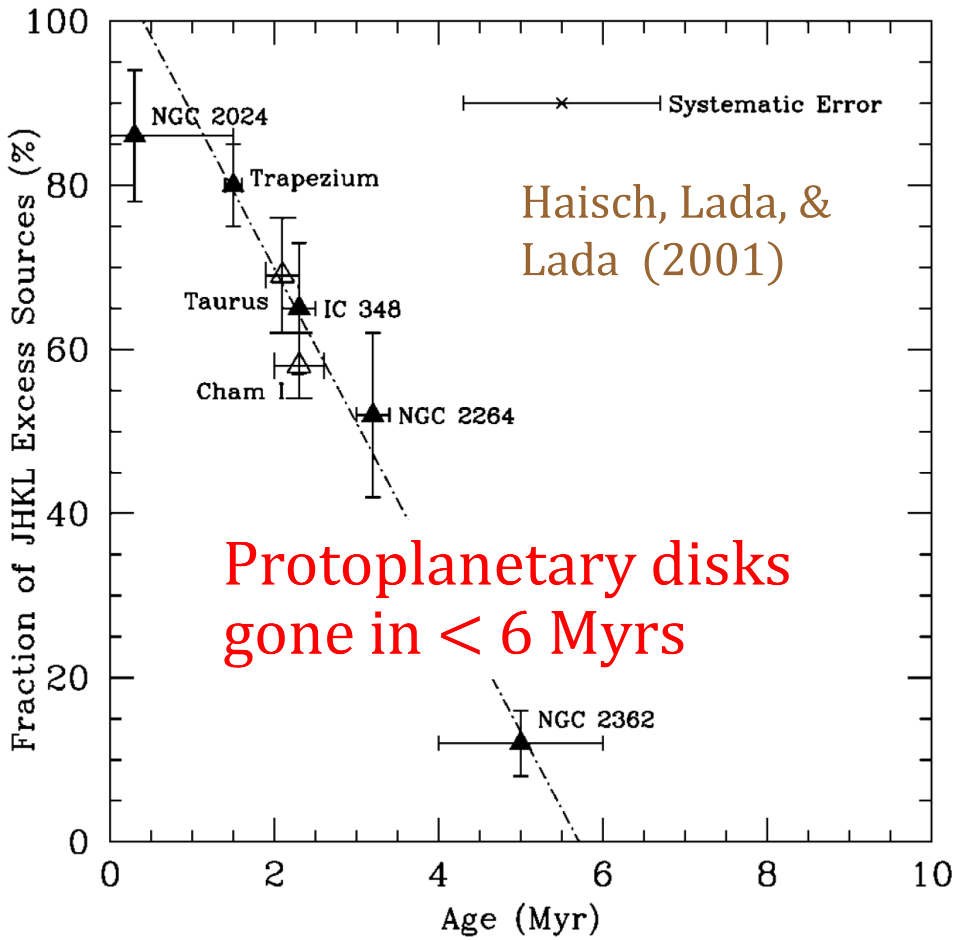


Figure 4 Position in the Hertzsprung-Russell diagram of all CTTSs and WTTSs with known $v \sin i$. WTTSs are represented by open circles, and CTTSs by dark circles. In both cases, the circle area is proportional to the stellar $v \sin i$. Approximate pre-main-sequence quasi-static evolutionary tracks for various masses are also plotted together with the zero-age main sequence (dashed line).

PMS stars contracting toward the ZAMS

Bertout (1989)



Fraction of PMS stars with IR excess → age of a star cluster too young to have an MSTO

Formation of Massive Stars

Not as well known as for low-mass (sun-like) stars

- **Competitive accretion (of cloud cores)?**

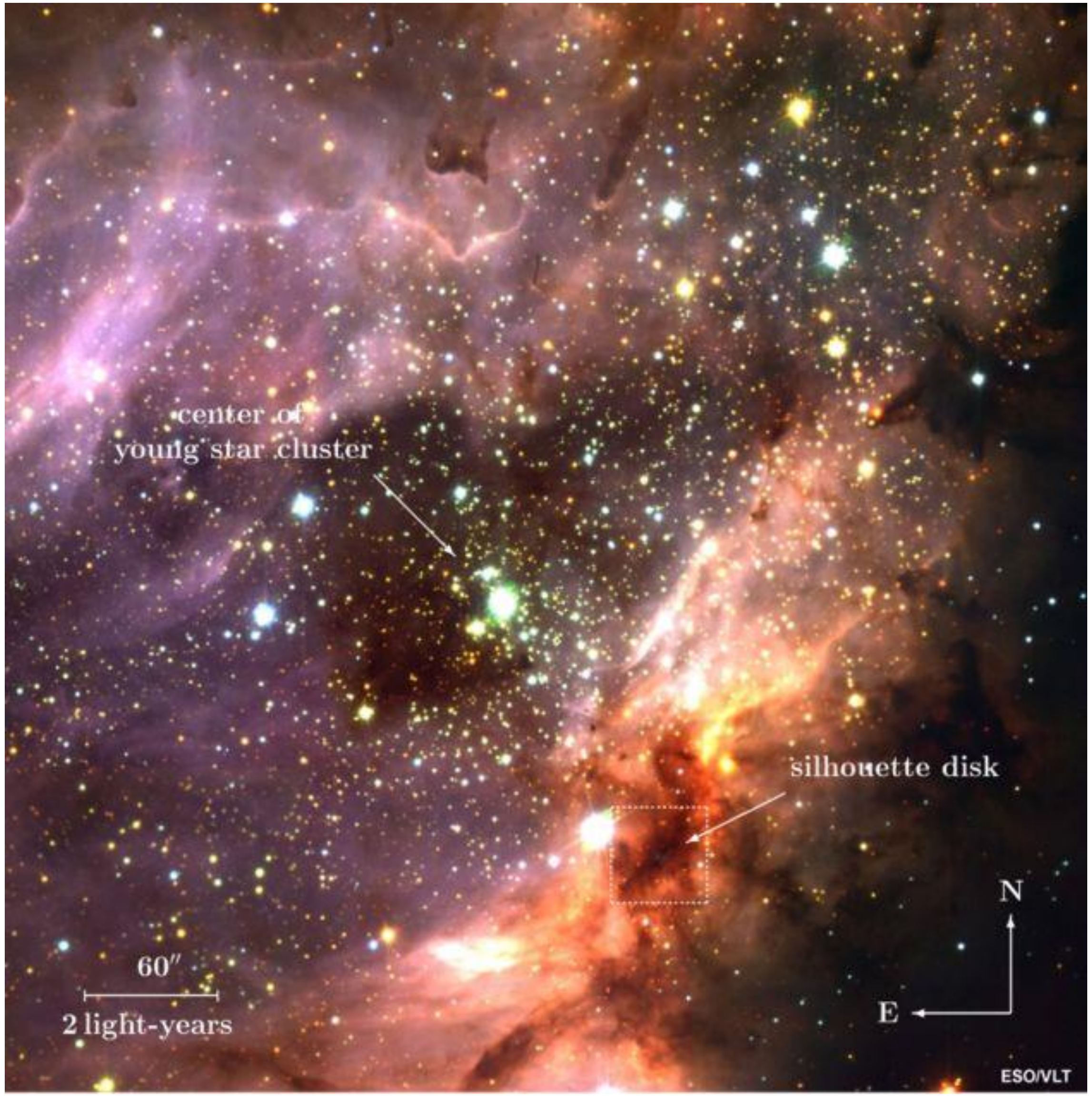
  ... low-mass protostars competing with each other, and accrete matter from the parent molecular cloud

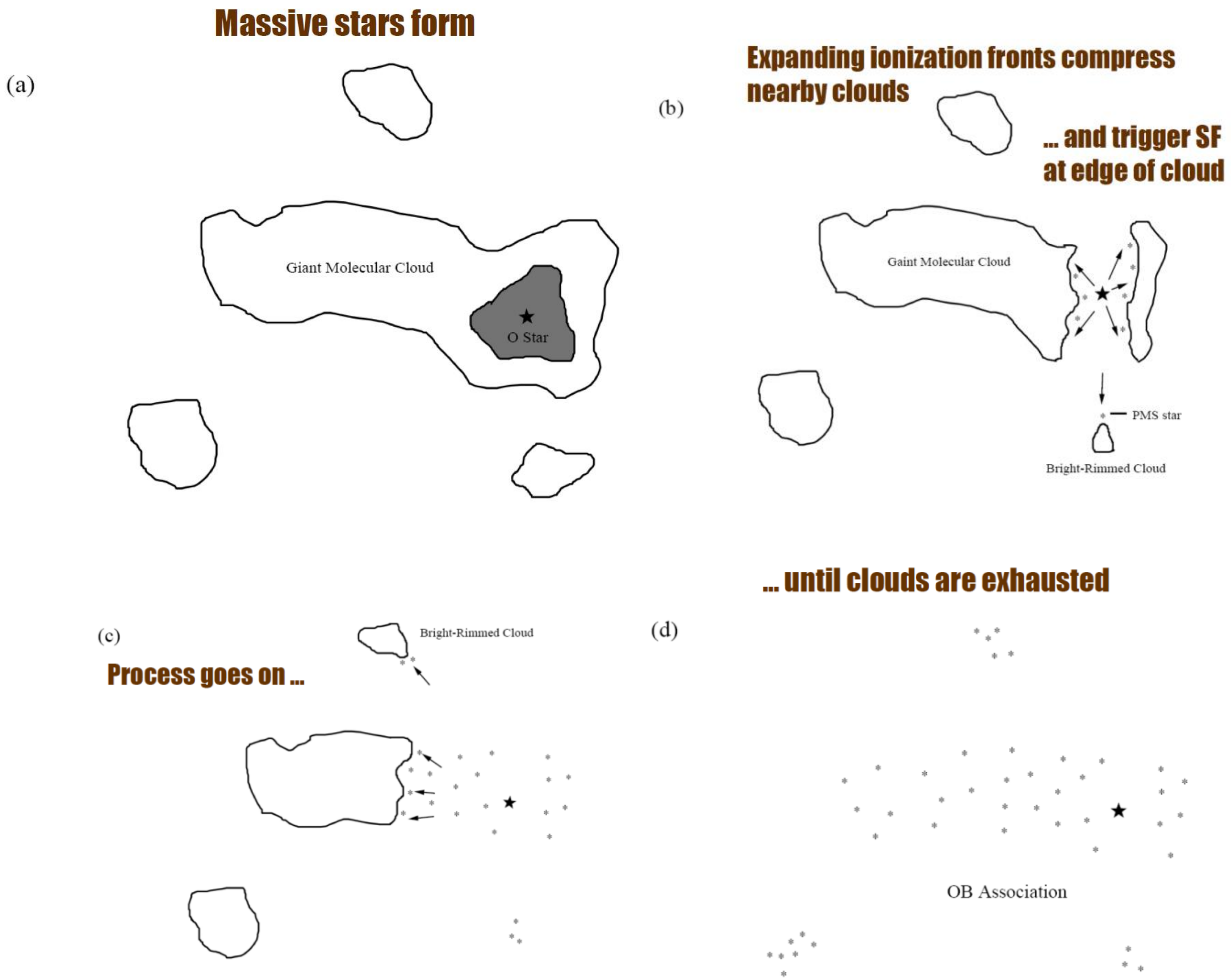
- **Coalescence of two or more stars with lower masses?**

Massive stars strong influence on the environment via fierce winds and radiation.

But which are formed first, high-mass or low-mass stars?

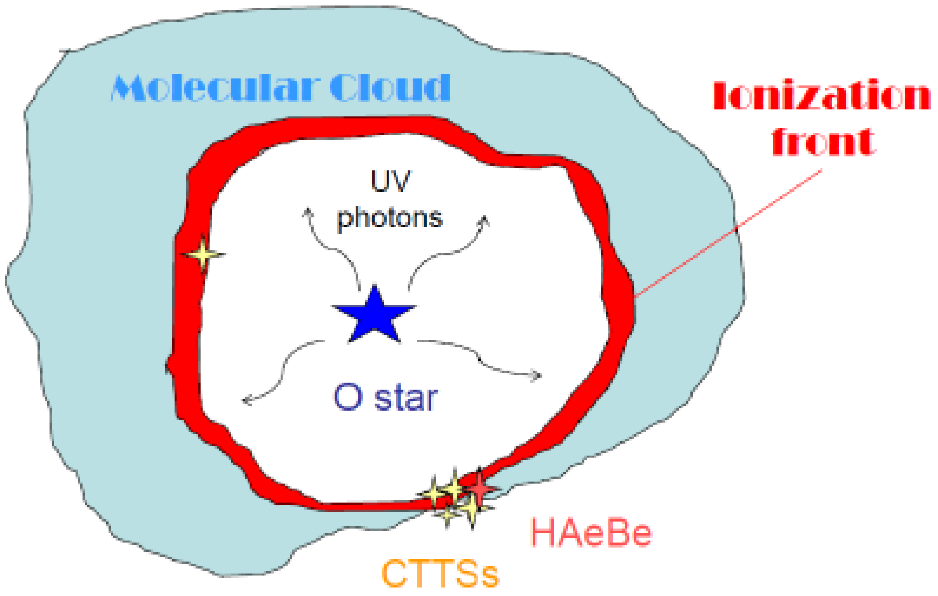
Triggered Star Formation



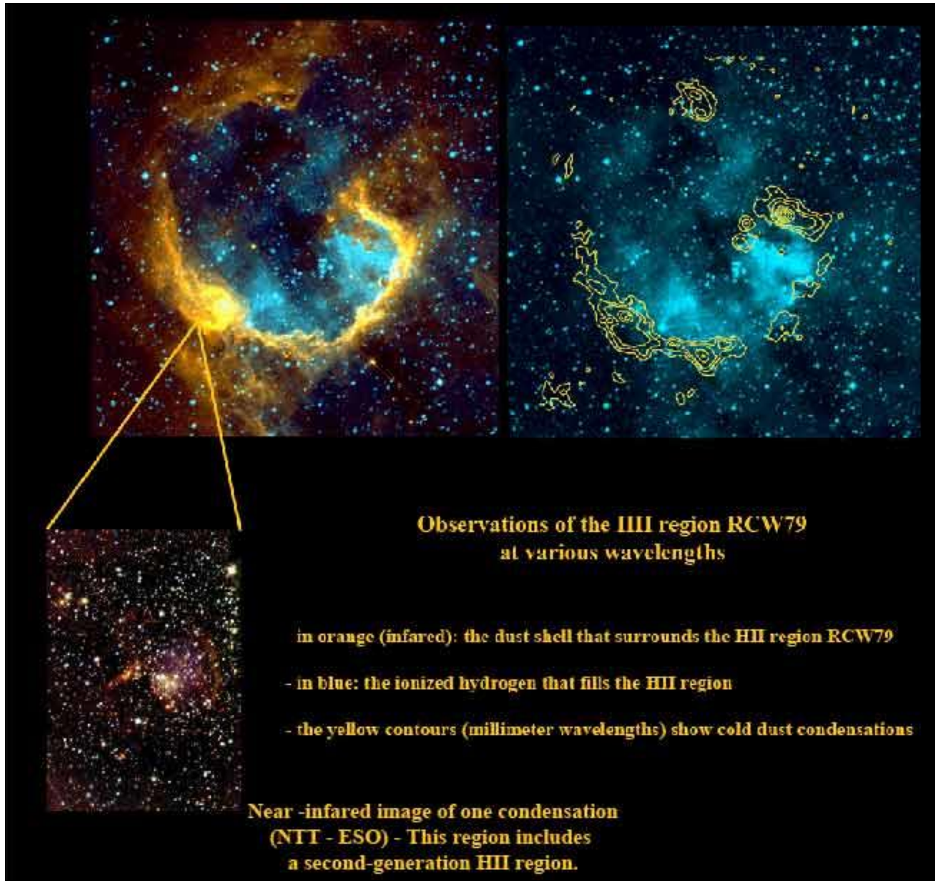


Collect-and-Collapse

OB stellar wind (ramp pressure) + radiation pressure on a <u>surrounding</u> molecular cloud
→ Formation of stars at the cavity boundary

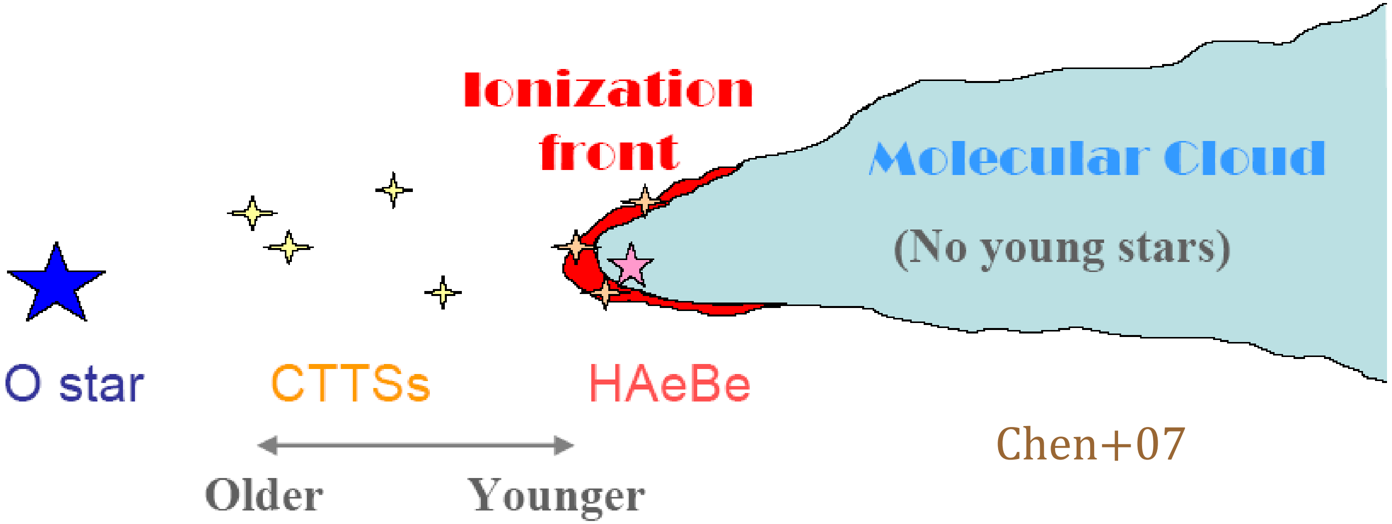


Chen 2010

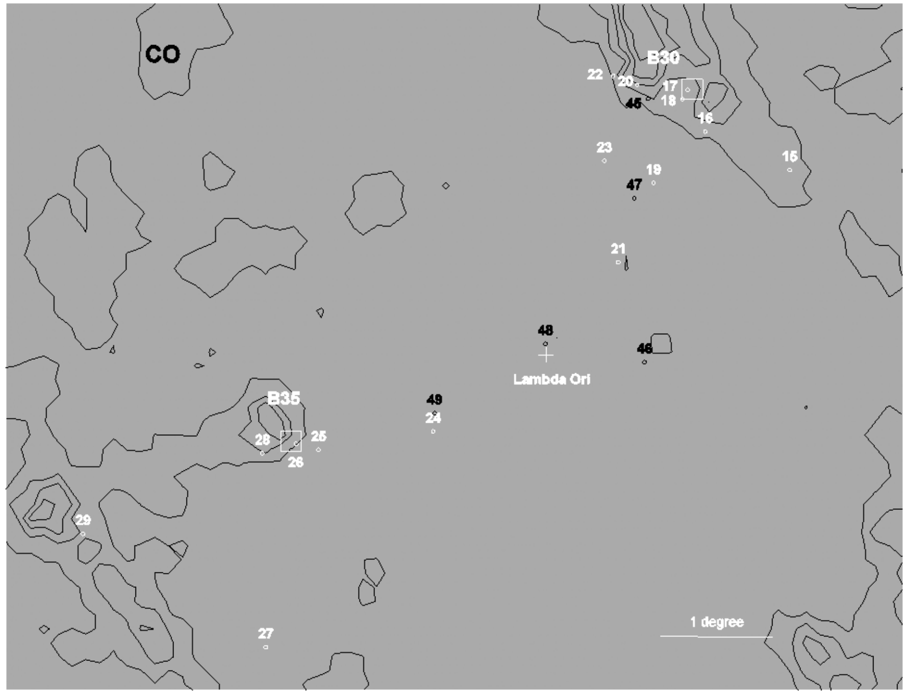


Radiation-Driven Implosion

OB stellar radiation ionizes the edge of a nearby cloud (bright-rimmed cloud) → inward shock to induce cores which may not otherwise collapse spontaneously.



Chen+07



Lee+05, 07, 09

Cloud Morphology remnant cloud points to the massive stars

Stellar Group Sequence YSOs line up in between, in an age sequence: younger toward the cloud, youngest at the interface (the BRC); no SF inside the cloud (yet)

Rotation vs Spectral Type

- Higher-mass stars faster
- Much slower after ~F5
- Slowing down with age

→ angular momentum evolution diagnosed by star clusters with known ages

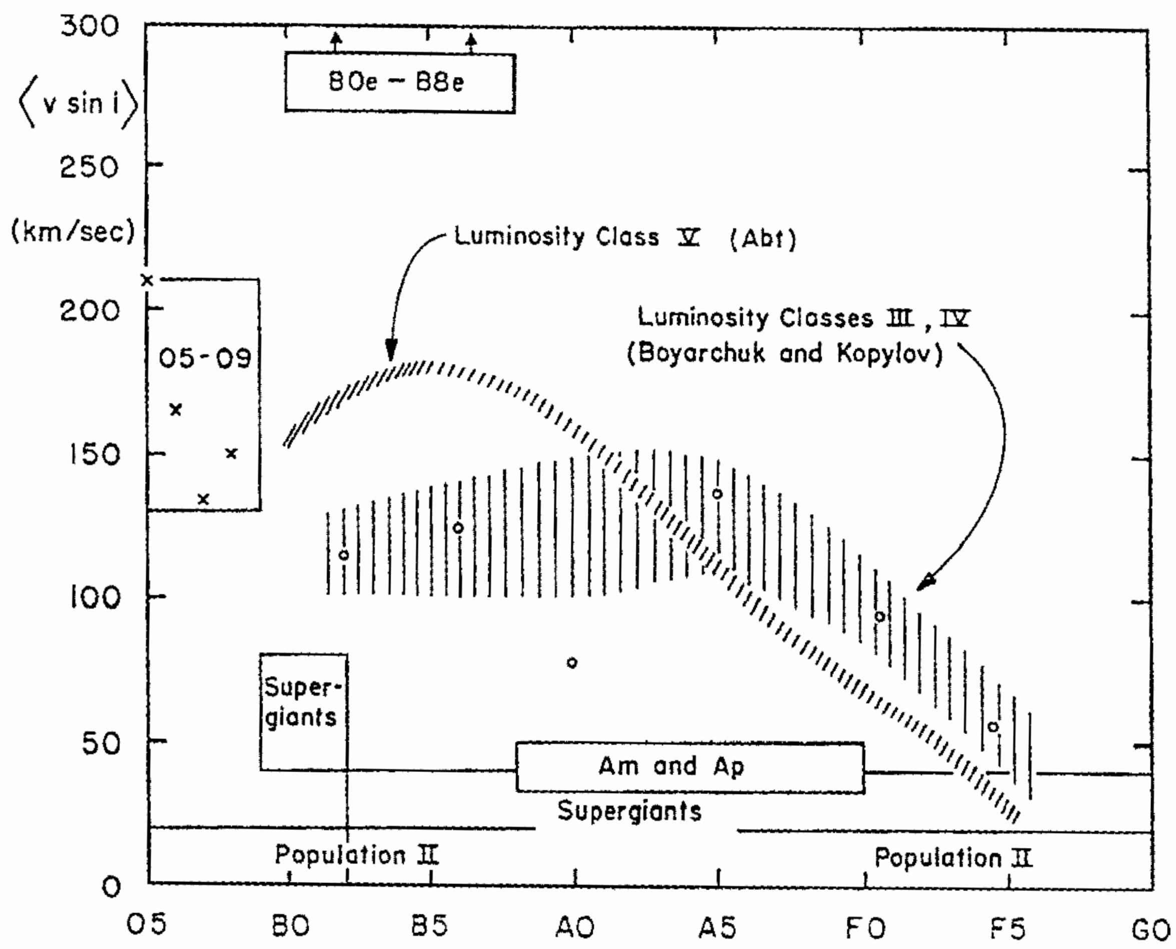


Fig. 3. Projected equatorial velocities, averaged over all possible inclinations, as a function of spectral type. On the main sequence (luminosity class V), early-type stars have rotational velocities that reach and even exceed 200 km/s; these velocities drop to a few km/s for late-type stars, such as the Sun (type G2) (Slettebak [20]; courtesy Gordon & Breach)

Effect of Rotation
→ star cooler and fainter

$\frac{\Omega}{\Omega_{crit}} \nearrow \Rightarrow L \searrow$

- More so for lower-mass stars
- Rotation effectively lowers the stellar mass.

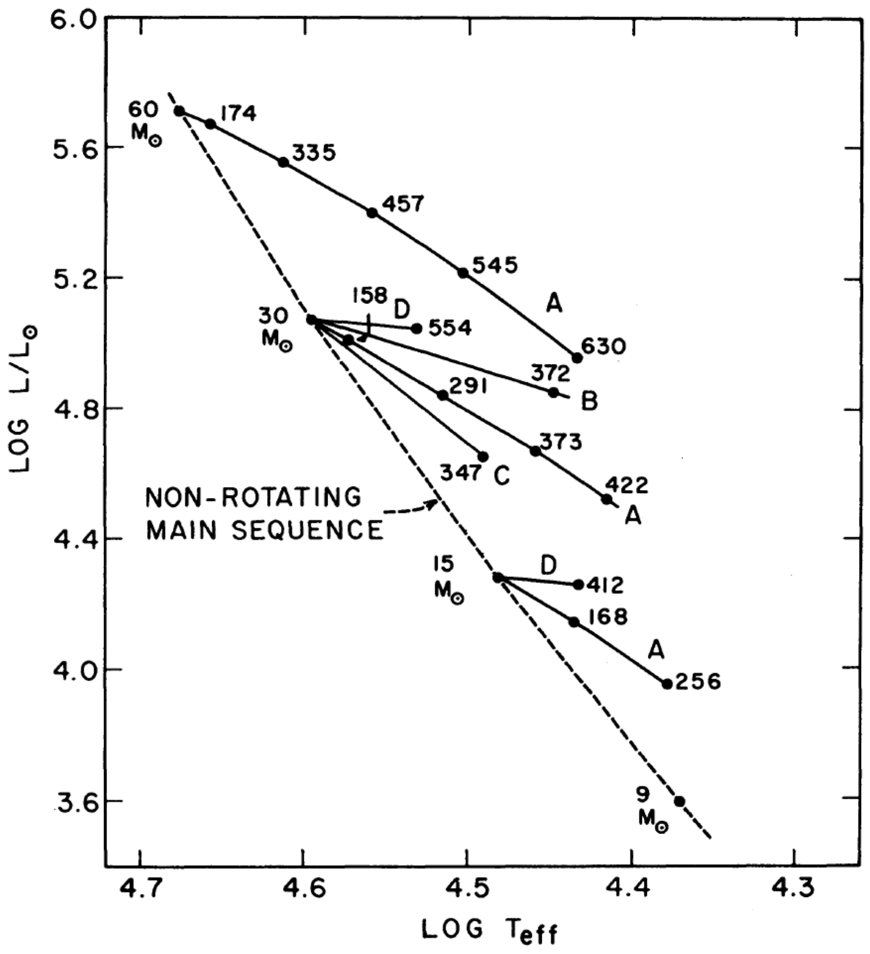
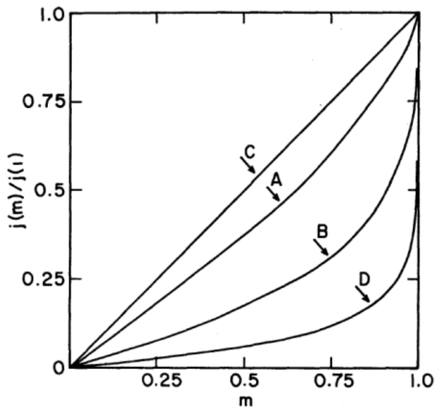


Fig. 2.—Theoretical H-R diagram showing model sequences of increasing angular momentum (*solid curves*). Numbers on curves give calculated velocities at the equator in km sec^{-1}. The distribution of angular momentum for each sequence is indicated by the letter A, B, C, or D.

Bodenheimer (1971) ApJ, **167**, 153

<u>Rotation law</u>:
angular momentum distribution $j(m_{\varpi})$ as a function of m_{ϖ}, the mass fraction interior to the cylinder of radius ϖ about the rotation axis.



D: solid body rotation

Fig. 1.—Angular momentum per unit mass, as a function of mass fraction interior to a given cylinder about the axis of rotation, for three assumed laws of differential rotation (Cases A, B, and C) and for a uniformly rotating model (Case D) of 30 $\mathfrak{M}_{\odot}$, log J = 52.73.

Modified CMD/isochrone

Effect of Binarity

- ☐ Most stars in solar neighborhood in binary, triple or multiple systems (Duquennoy & Mayor 1991)
- ☐ Stars born in groups
- ☐ YSOs binary rate comparable to MS population

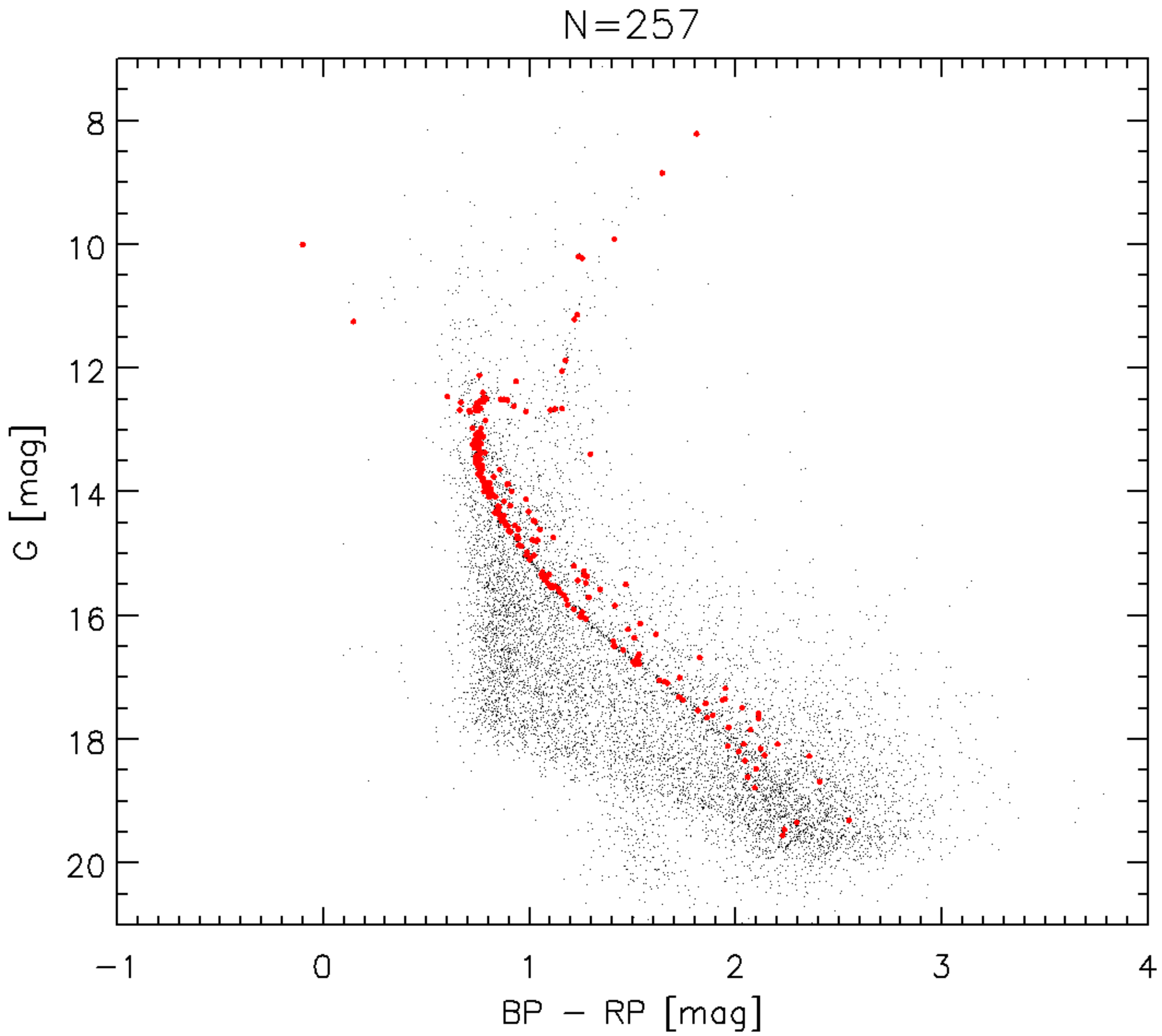
➔ Binaries unlikely to form by encounters; chances too low

Star Formation = Planet Formation

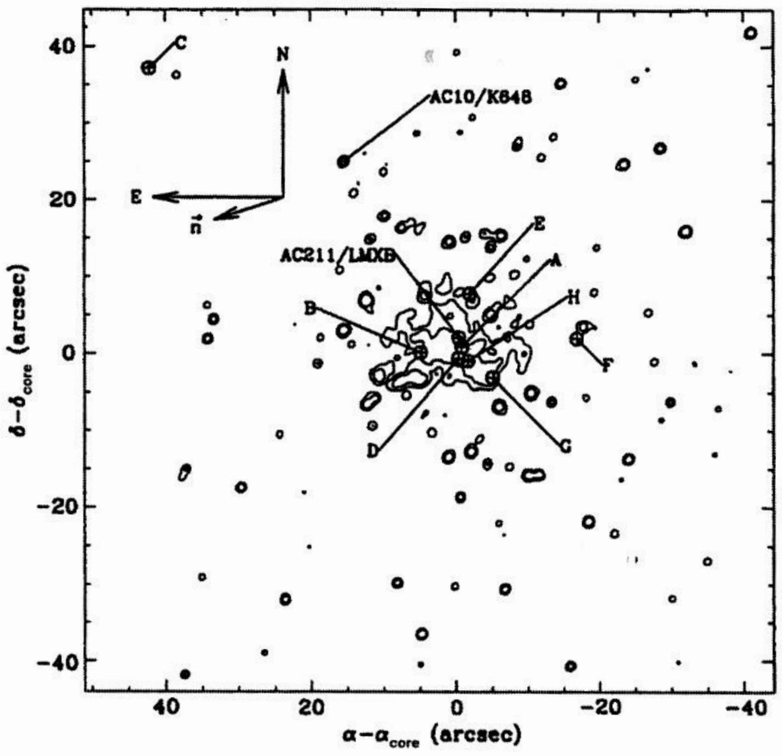
= Cluster Formation

= Binary Formation

Cluster binary rate ⇔ mass, age, environments?



- GCs very crowded → wide pairs stripped off;
  close pairs: NS accreting from companion X-ray sources;
  eventually merged → GW
- Binaries more massive → sink to the center

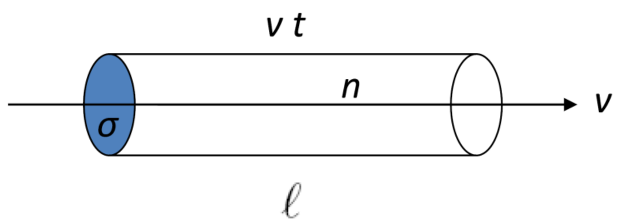


High-energy phenomena

GCs account for 0.1% of MW stars but 10% number of of low-mass X-ray binaries

Heggie & Hut

Stellar encounter rate $n\sigma v$



Volume V= (Area) (length)
= cross section $\sigma \cdot \ell = \sigma\, vt$

n: number density
σ: cross section
v: relative speed

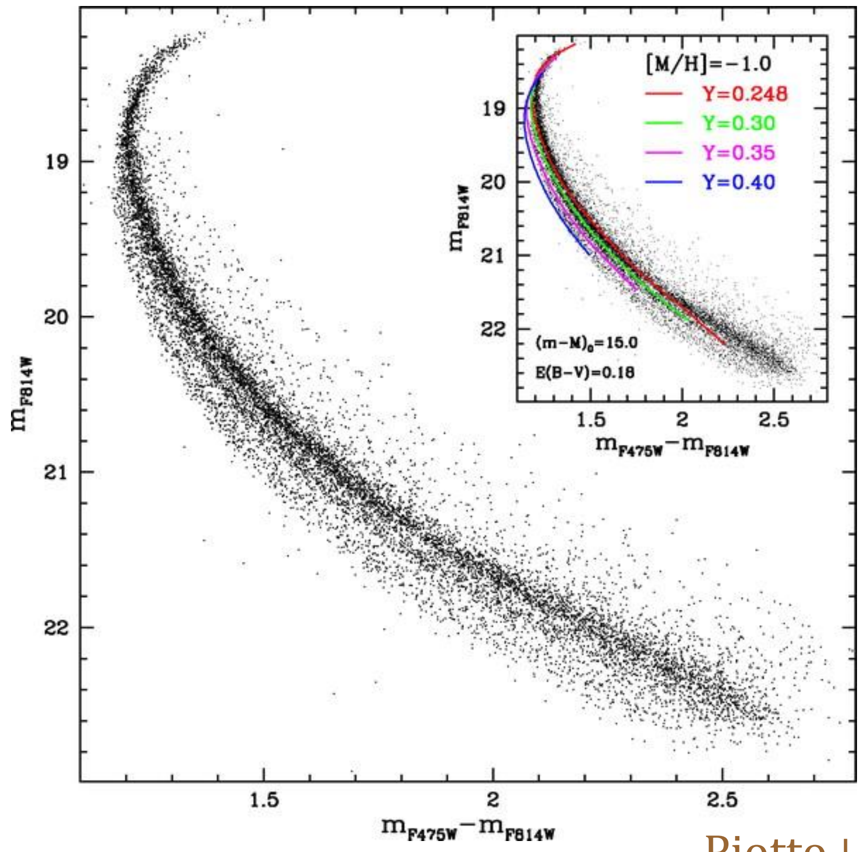
In solar neighborhood, $n = 1\ \mathrm{pc}^{-3}$;
$\sigma = 5\ \mathrm{au}$; $v = 50\ \mathrm{km\ s^{-1}}$
Probability= $10^{-13}\ \mathrm{yr}^{-1}$

Only the widest pairs, with separations $10^3 - 10^4$ au vulnerable

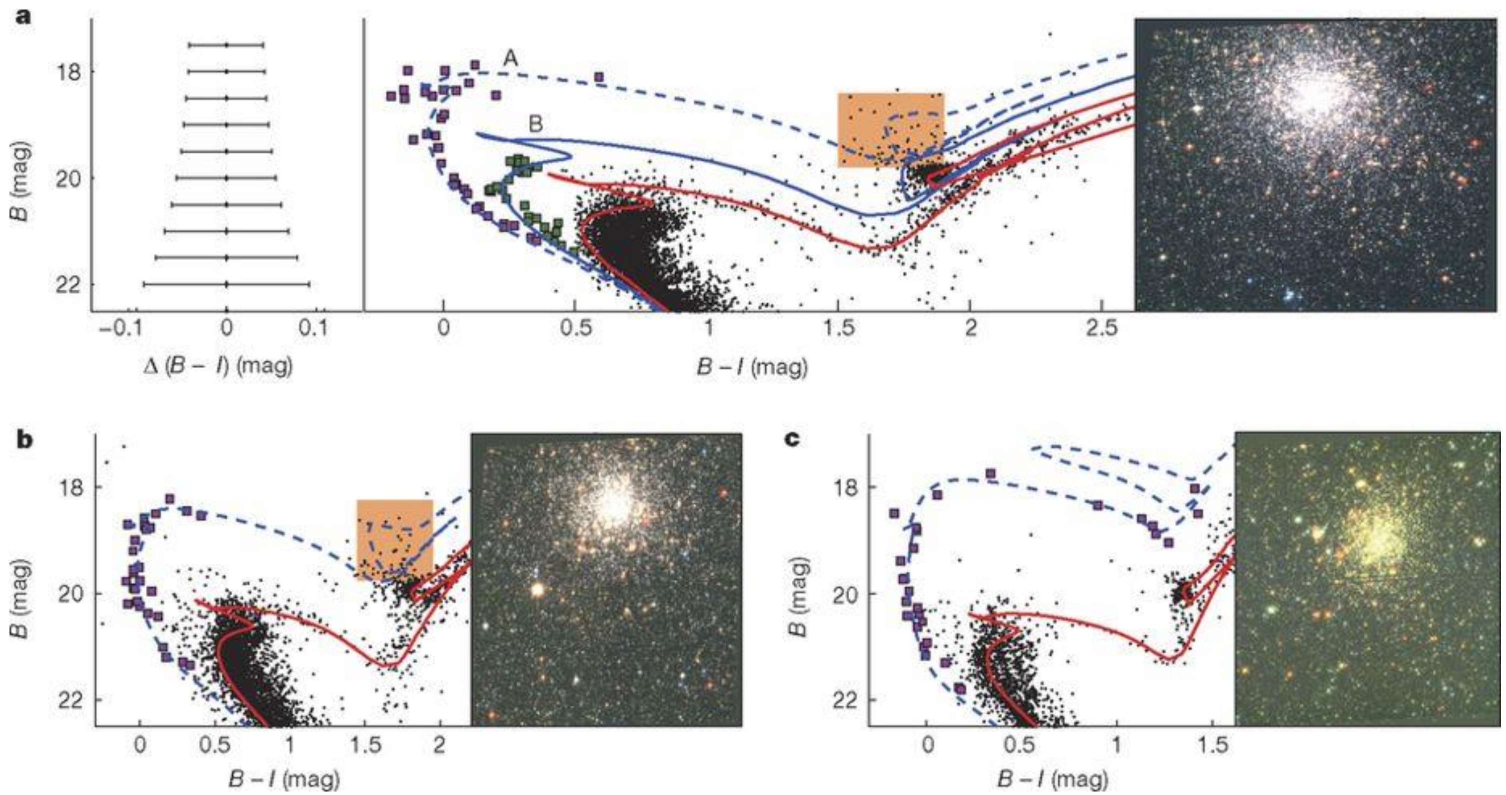
In star clusters $\Delta v = 1 - 2\ \mathrm{km\ s^{-1}}$, $n \uparrow$
Encounters frequent
→ binary formation and dissolution
→ $\mathcal{E}_{\mathrm{binding}}$ important as energy reservoir in cluster dynamics

Heggie & Hut

Effect of Noncoevality



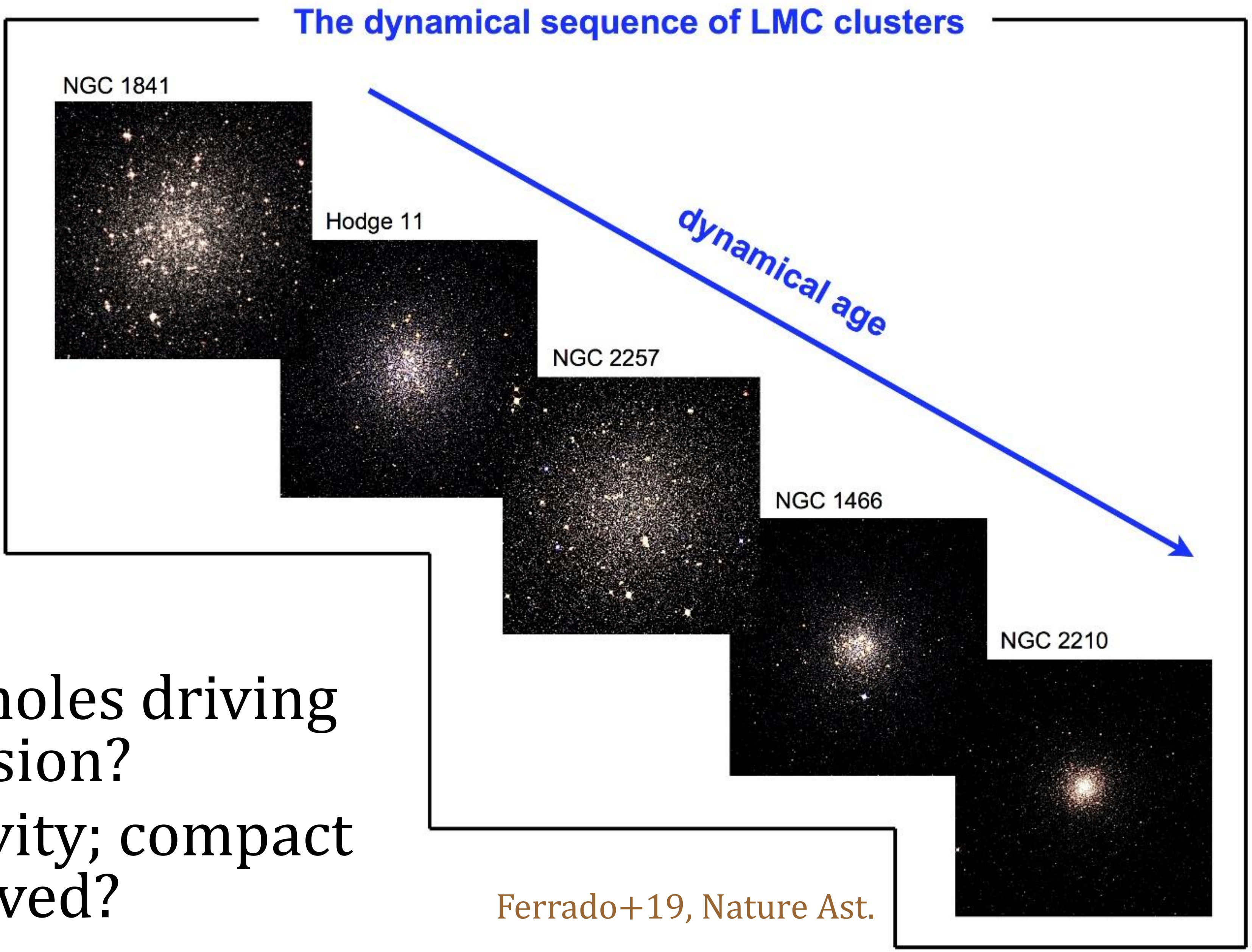
Piotto+07, ApJL



Distinct PM-selected MS branches in the GC NGC 2808, signifying successive rounds of star formation

Generations of stars in each of the 3 massive young (1 to 2 Gyr) star clusters, NGC 1783 (LMC), NGC 1806 (LMC), and NGC 411 (SMC) Li+16, Nat

In the LMC, young clusters compact; old system small or large



- † Binary black holes driving cluster expansion?
- † Latest SF activity; compact systems survived?

Ferrado+19, Nature Ast.

Star Clusters --- Lecture 3

CTTSs characterized by infrared excess in the SEDs

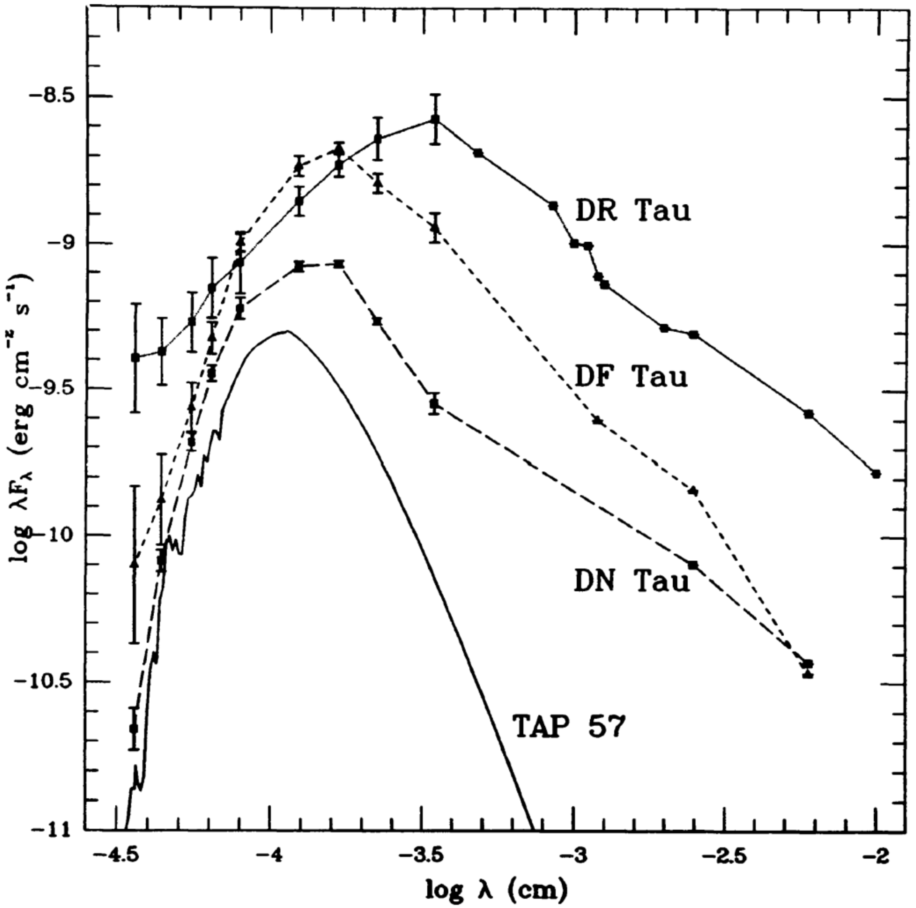


Figure 3 Observed spectral energy distributions from 3600 Å to 100 μm of the stars whose spectra are shown in Figure 2. The energy distribution of the K7V WTTS TAP 57, shown as a solid line, has been displaced downward by 0.3 dex. The filled symbols are simultaneous (for DN Tau and DF Tau) or averaged (for DR Tau) photometric data (cf. Bertout et al. 1988) supplemented by *IRAS* data (Rucinski 1985). When available, observed variability is indicated by error bars. When compared with WTTSs such as TAP 57, CTTSs display prominent ultraviolet and infrared excesses. Excess continuum flux and optical emission-line activity are often correlated.

… and also <u>UV excess</u>
→ spectral “veiling”

Bertout (1989)

Star Clusters

--- Links between Galaxies and Stars

- Star clusters as stellar birth places
- Open clusters, globular clusters, and others
- Star clusters as targets of investigation
- Star clusters as tools in stellar & galactic studies
- **Latest and outstanding issues**

Wen-Ping Chen
Graduate Institute of Astronomy
National Central University
Taiwan

(Initial) Mass Function --- Origin of Stellar Masses

Birthrate function $B(M,t) =$ the number of stars per unit volume, with masses between M and $M + dM$ that are formed out of ISM during time interval t and $t + dt$.

$$B(M,t)\,dM\,dt = \psi(t)\,\xi(M)\,dM\,dt,$$

where ψ(t) is the **star formation rate** (SFR),
and ξ(M) is the **initial mass function** (IMF).

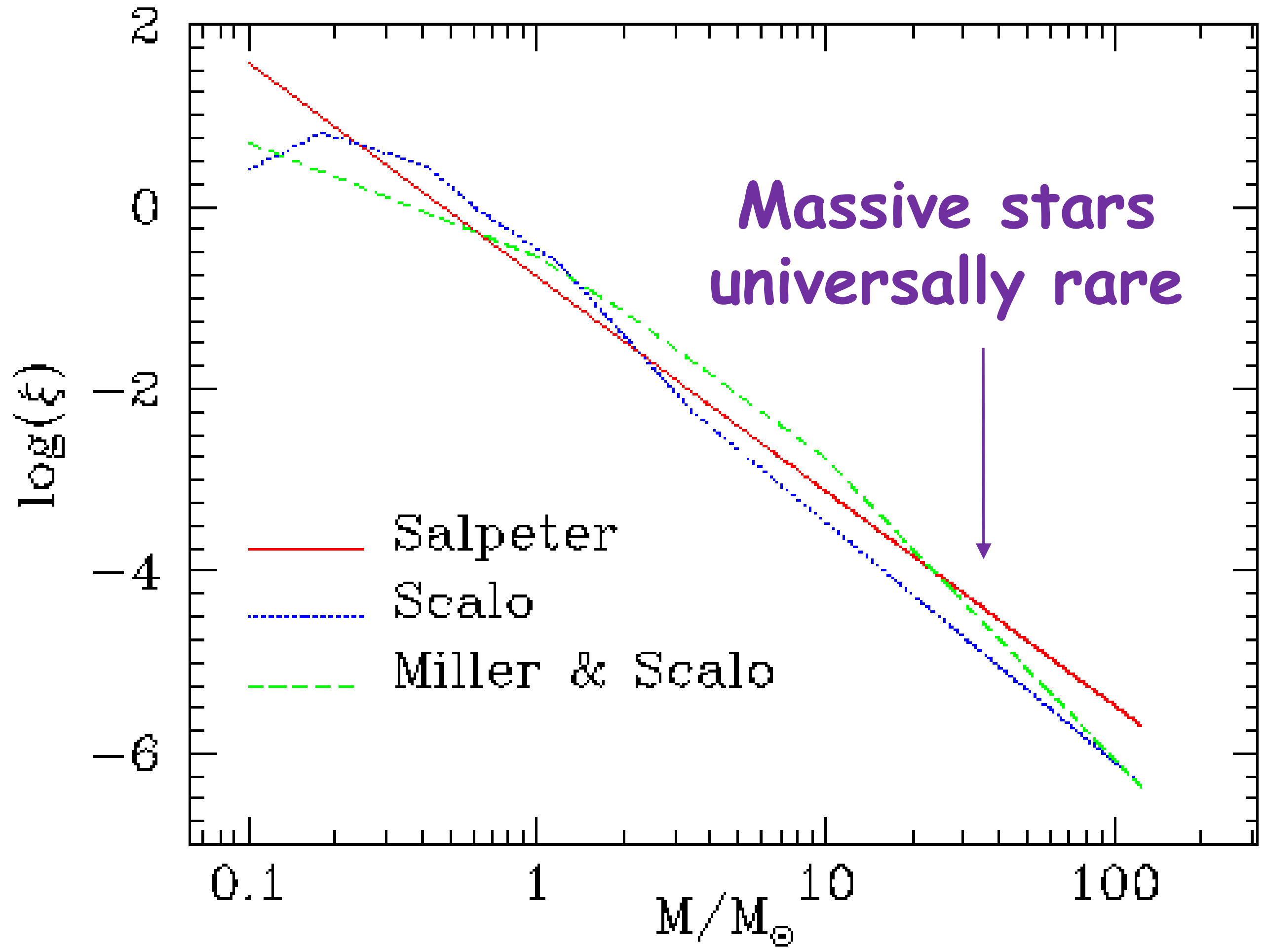
For the Galactic disk, SFR is $5.0 \pm 0.5\ M_\odot\ \mathrm{pc}^{-2}\ \mathrm{Gyr}^{-1}$ integrated over the z direction.

The IMF: the fractional distribution in mass of a newly formed stellar system; often assumed a simple power law

$$\xi(\mathcal{M}) \propto \mathcal{M}^{-\alpha} = \mathcal{M}^{-(1+\Gamma)}$$

In general, $\xi(\mathcal{M})$ extends from a lower to an upper cutoff, e.g., from 0.1 to 125 solar masses.

Commonly used IMFs are those of Salpeter (1955), Scalo (1986), and Miller & Scalo (1979).



http://webast.ast.obs-mip.fr/hyperz/hyperz_manual1/node7.html

- Salpeter (1955) on solar-neighborhood stars
  Present-day LF → mass-luminosity relation → present-day mass function → stellar evolution → initial mass function $\boldsymbol{\alpha = 2.35}$ or $\boldsymbol{\Gamma = 1.35}$

- Miller and Scalo extended work below 1 $M_\odot$ (1979)
  $\alpha \approx 0$ for $M < 1\ M_\odot$

- Pavel Kroupa (2002)
  $\alpha = 2.3$ for $M > 0.5\ M_\odot$
  $\alpha = 1.3$ for $0.08\ M_\odot < M < 0.5\ M_\odot$
  $\alpha = 0.3$ for $M < 0.08\ M_\odot$

- A universal IMF among stellar systems (SFRs, star clusters, galaxies) (Bastian+10) → Many more low-mass stars than higher mass stars → Cloud fragmentation? Self-regulated accretion?

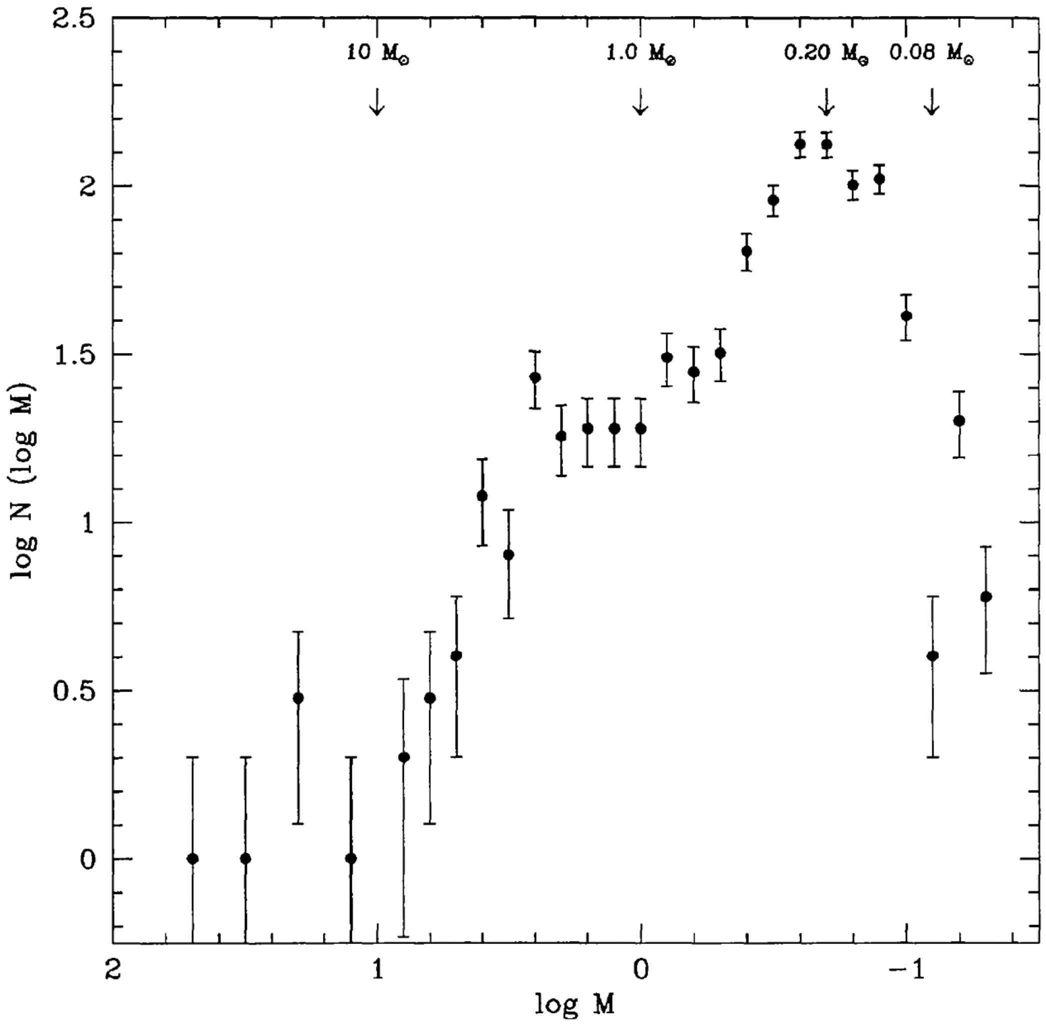
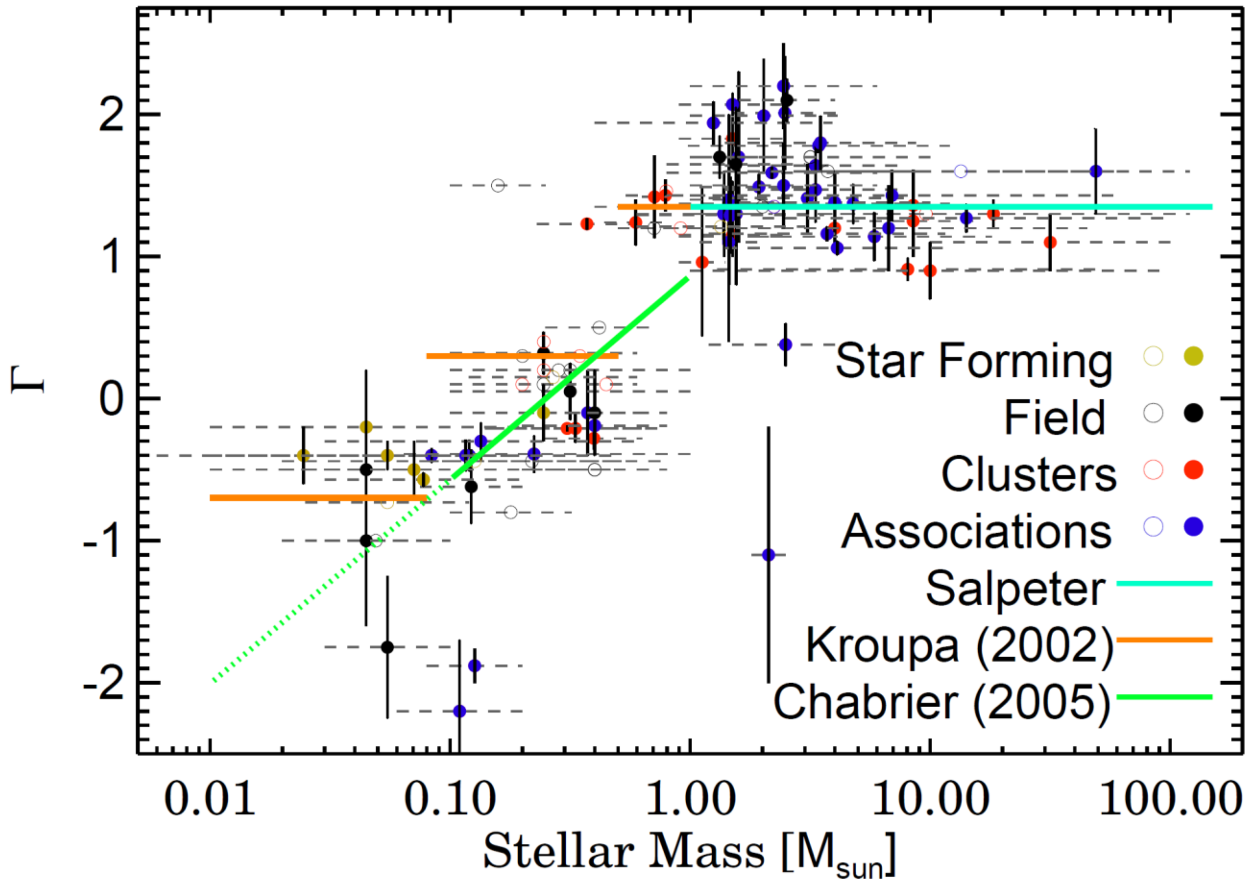
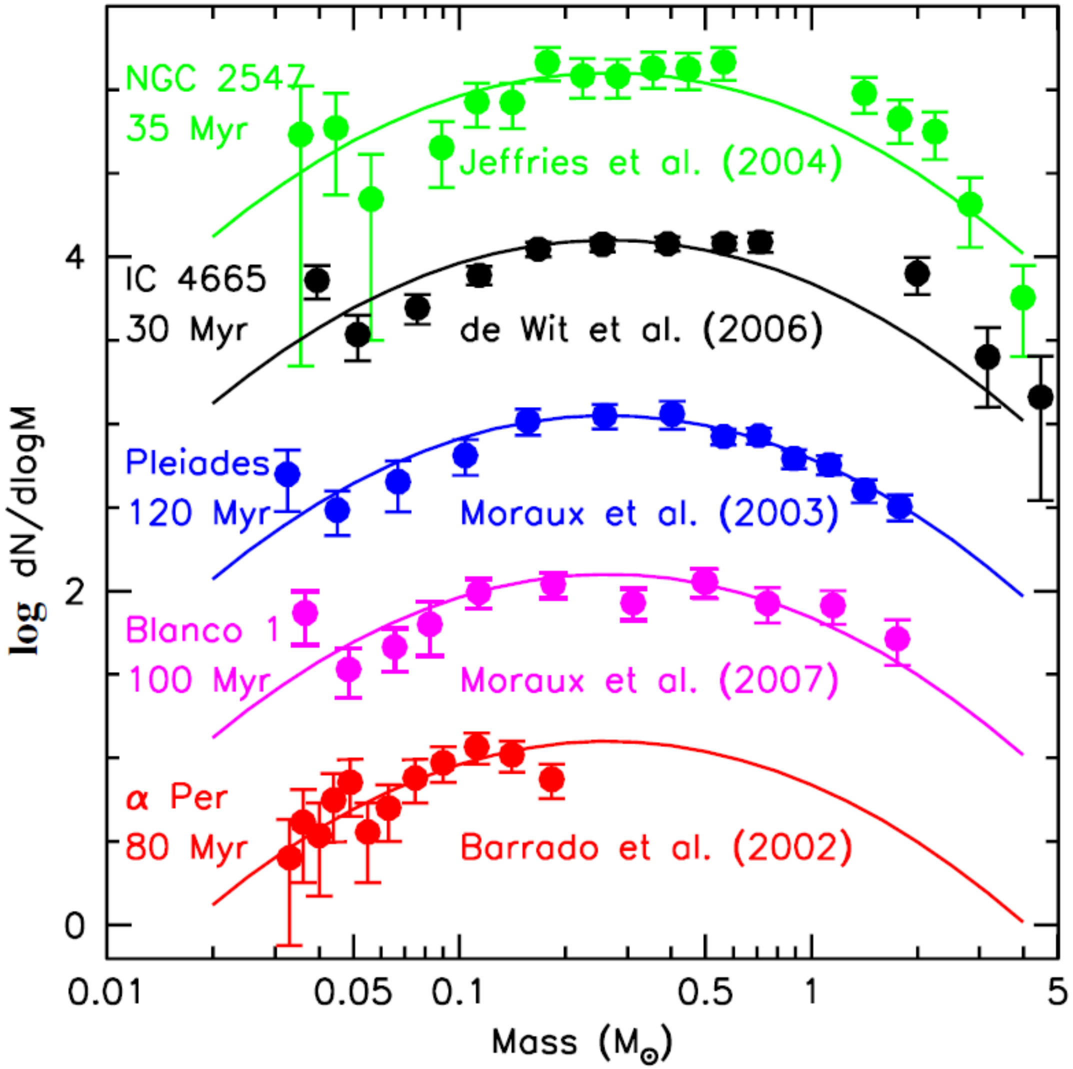


FIG. 17. *The Initial Mass Function as measured in the Orion Nebula Cluster.*

Hillenbrand 1997, AJ, 113, 1733

Peaking 0.2—0.3 Msun?



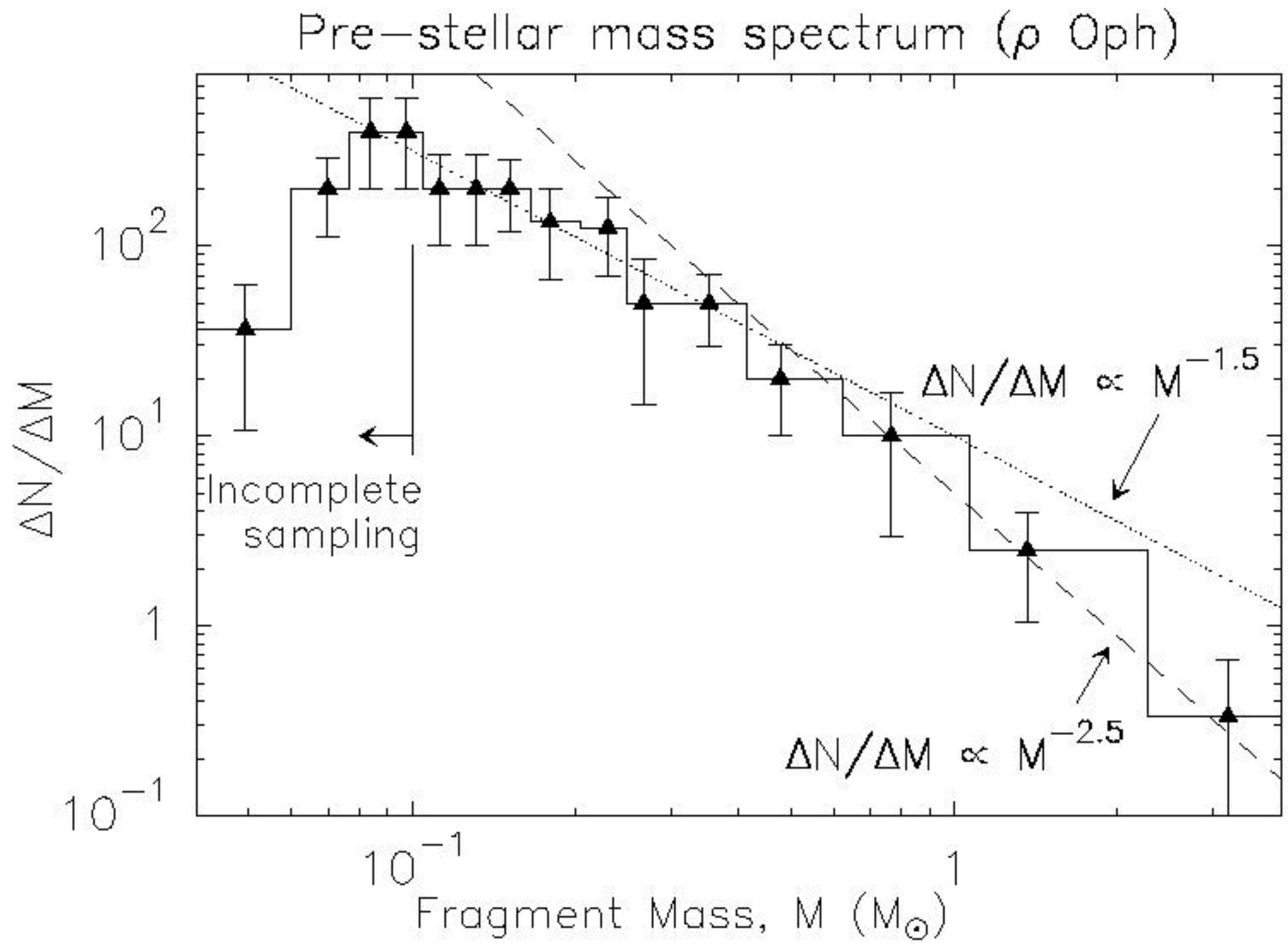


Bastian et al. 2010, ARAA

OCs 30—120 Myr

Jeffries 2012

Stellar Initial Mass Function and Dense Core Mass Function



Andre et al. (2000)

Structure of a (Globular) Cluster

Core radius r_c

surface brightness to half

$$I(r) = \frac{I_c}{1 + (r/r_c)^2}$$

Half-light/mass radius r_h

containing half of the light/mass

Tidal (limiting) radius r_t

density to zero

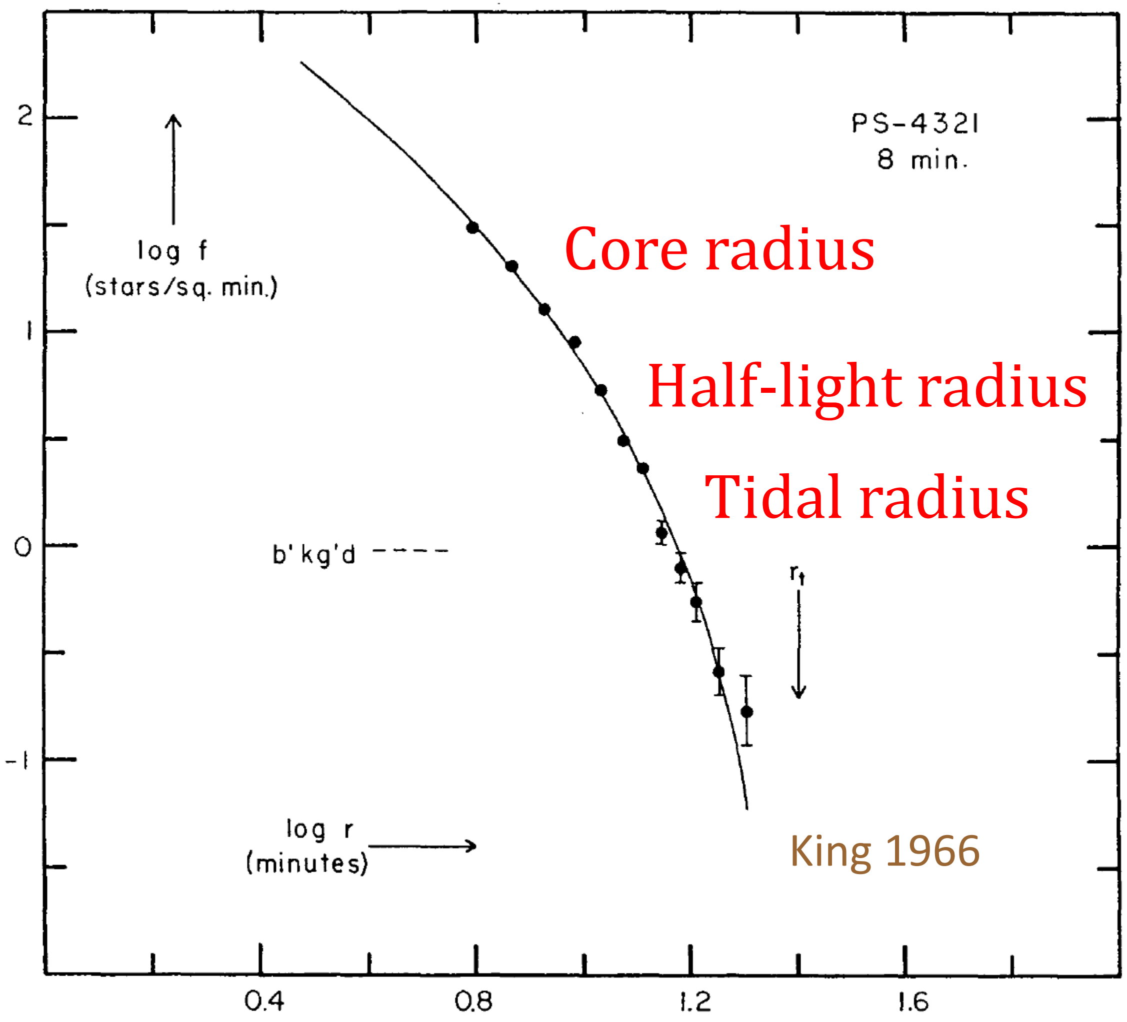


FIG. 2. Comparison of star counts in M13 with theoretical curve for $\log(r_t/r_c) = 1.50$. Maximum-exposure 48-in. Schmidt plate.

The King model

The surface brightness profile

(King 196; Michie 1963)

$$f(E) = \begin{cases} 0 & (E > E_0) \\ K[e^{-\beta(E-E_0)} - 1 & (E < E_0) \end{cases}$$

$$E = (1/2)\, v^2 + \phi(r)$$

$$r_c = \sqrt{\frac{9}{4\pi G\, \rho_0\, \beta}}$$

r_t where $\phi = 0$

K, β, E_0 all constants;

$\phi(r)$: potential

ρ_0: central density

Table 1-3. Parameters of globular and open clusters

	Globular	Open
Central density ρ_0	$8 \times 10^3\, M_\odot\, pc^{-3}$	$100\, M_\odot\, pc^{-3}$
Core radius r_c	1.5 pc	1 pc
Median radius r_h	10 pc	2 pc
Tidal radius r_t	50 pc	10 pc
Central velocity dispersion σ_0 (line-of-sight)	$7\, km\, s^{-1}$	$1\, km\, s^{-1}$
Mass-to-light ratio Υ	$2\Upsilon_\odot$	$1\Upsilon_\odot$
Mass M	$6 \times 10^5\, M_\odot$	$250\, M_\odot$
Lifetime	10^{10} yr	2×10^8 yr

NOTES: Values for globular clusters are medians from the compilation of Peterson and King (1975). Values for open clusters are typical values from the literature. The central densities are especially uncertain: individual clusters may have central densities that differ by a factor of 100 from the values quoted.

r_h / r_t --- "Strength" against tidal disruption

r_c / r_h --- Status of dynamical "evolution"

M3

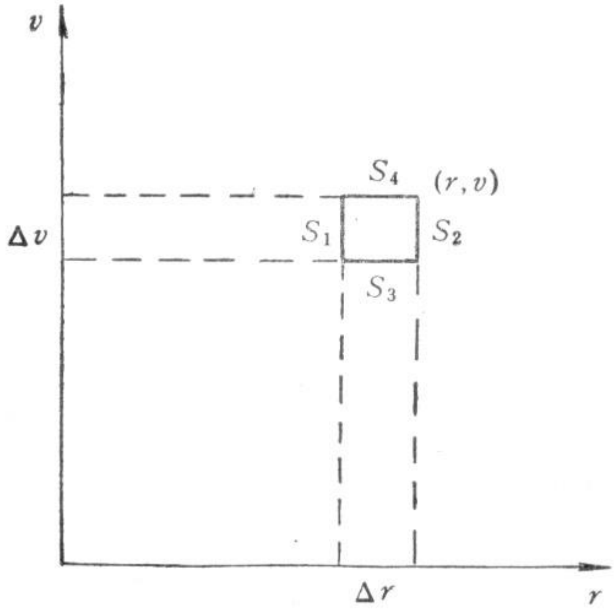
$r_{\text{vis}} \approx 18'$

$r_{\text{half-mass}} \approx 1.1'$

i.e., very dense

$\mathrm{r}_{\text{tidal}} \approx 38'$

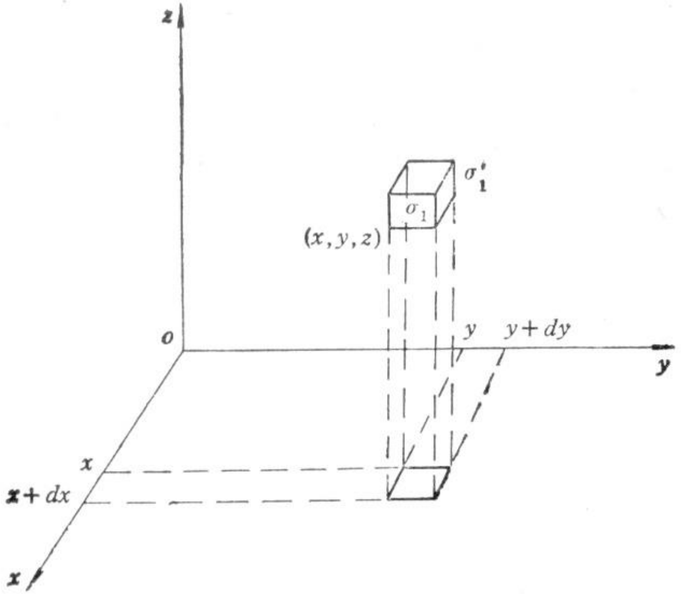
Cluster Dynamics



The distribution function (phase-space density) $f(r, v, t)$: number of particles within dr, dv, dt. For a system of a single species of particles, each of mass m, the total mass in a 6-d phase volume

$$M(t) = \; m\, f(r, v, t)\, dv\, dr$$

$$dM = M(t + dt) - M(t) = m\, \frac{\partial f}{\partial t} dv\, dr\, dt$$



NOT an analogy of an ideal gas system, because of the infinite-range attractive gravitational force

Under the influence of the smooth potential $\phi(x)$, the distribution function (phase-space density) $f(x, v, t)$ obeys the **Collisionless Boltzmann equation**

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \nabla \phi \cdot \frac{\partial f}{\partial \mathrm{v}} = 0$$

Stellar encounters → velocity distribution

Fokker-Planck equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \nabla \phi \cdot \frac{\partial f}{\partial \mathrm{v}} = \Gamma[f]$$

need a treatment of the collision term Γ

Binney & Tremaine (1987)
Spitzer (1987)

Jacobi limit (Binney & Tremaine 1987) ; almost the tidal radius

$$r_t = \pm d \left[\frac{m_c}{M_G\,(3+m_c/M_G)} \right]^{1/3} \approx \left[\frac{m_c}{3\,M_G(d)} \right]^{1/3}$$

if $m_c \ll M_{\mathrm{G}}$ and $r_t \ll d$

m_c: mass of cluster
d: Galactic orbital radius
$M_{\mathrm{G}} = M_{\mathrm{G}}(d)$: Galactic mass interior to the orbit

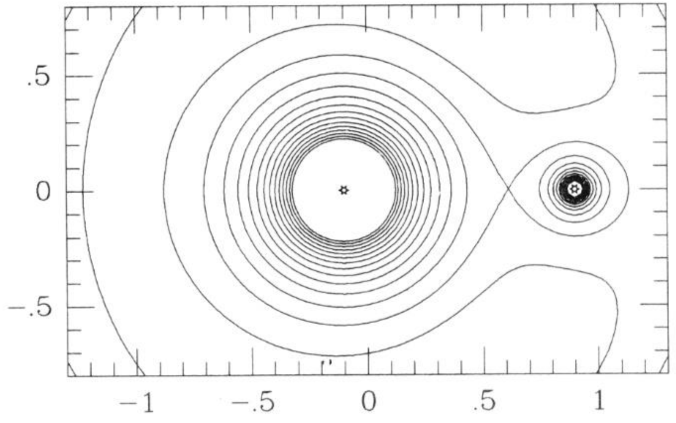


Figure 7-8. Contours of equal effective potential Φ_{eff} defined by equation (7-81) for two point masses, m and $M = 9m$, in circular orbit about one another. The particles are unit distance apart. The center of mass is at the origin, and the central Lagrange point is located near (0.6,0).

Dynamical Evolution of Star Clusters

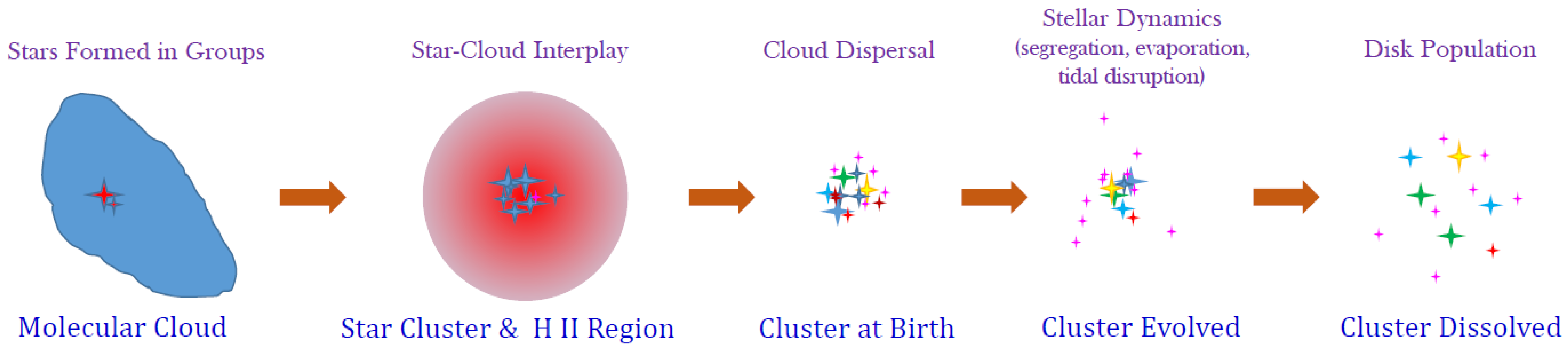
Gas dynamics, stellar dynamics, stellar evolution (and mass loss), and Galactic environments (e.g., gravitational potential)

Dynamical Evolution of a Star Cluster

Chen+04, Chen & Chen 2010

- (Initial) Molecular clouds are clumpy and filamentary; so are the youngest star clusters.
- (Internal) Gas dispersal (stellar winds, SN explosions) + Mutual gravitational interaction between members → spherical shape (relaxation), with more massive stars concentrating more toward the center (mass segregation). Lowest-mass members are vulnerable to ejection out from the system (stellar evaporation).
- (External) Eventually Galactic perturbations (tidal forces, differential rotation) distort and rip apart the star clusters. Then-members supply the Galactic disk population.
- A recently dissolved system in the solar neighborhood may be recognized as a moving (star) group.

All star formation takes place in GMCs, when local clouds become gravitationally unstable and collapse.



- ☐ Stellar mass loss → shallowing gravitation potential
- ☐ Two-body relaxation → mass segregation

  → core collapse (density cusp)

  → intermediate-mass black holes

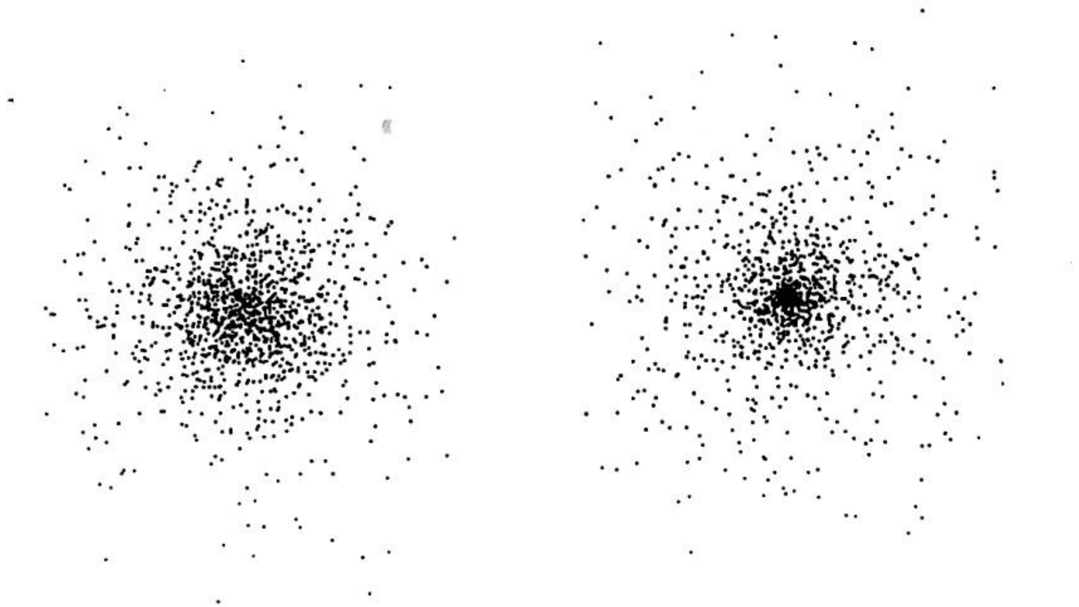


Fig. 18.1. Core collapse from a King model with $W_0 = 3$, $N = 1285$. The initial model is shown on the left, and the view on the right shows the same model to the same scale after core collapse. The model has a tidal cutoff.

Heggie & Hut

Dynamical Relaxation of a Stellar System

$$\tau_{\text{cross}} = D/v$$

$$N_{\text{cross}} = \frac{0.1N}{\ln N}$$

$$\tau_{\text{relax}} = \tau_{\text{cross}} \cdot N_{\text{cross}}$$

Massive stars "sink" to center.
Low-mass stars occupy a larger volume.
Lowest-stars are ejected.
Cluster disintegrates.

where

τ_{cross} ... the time for a member (star) to move across the system (cluster) = dynamical time scale

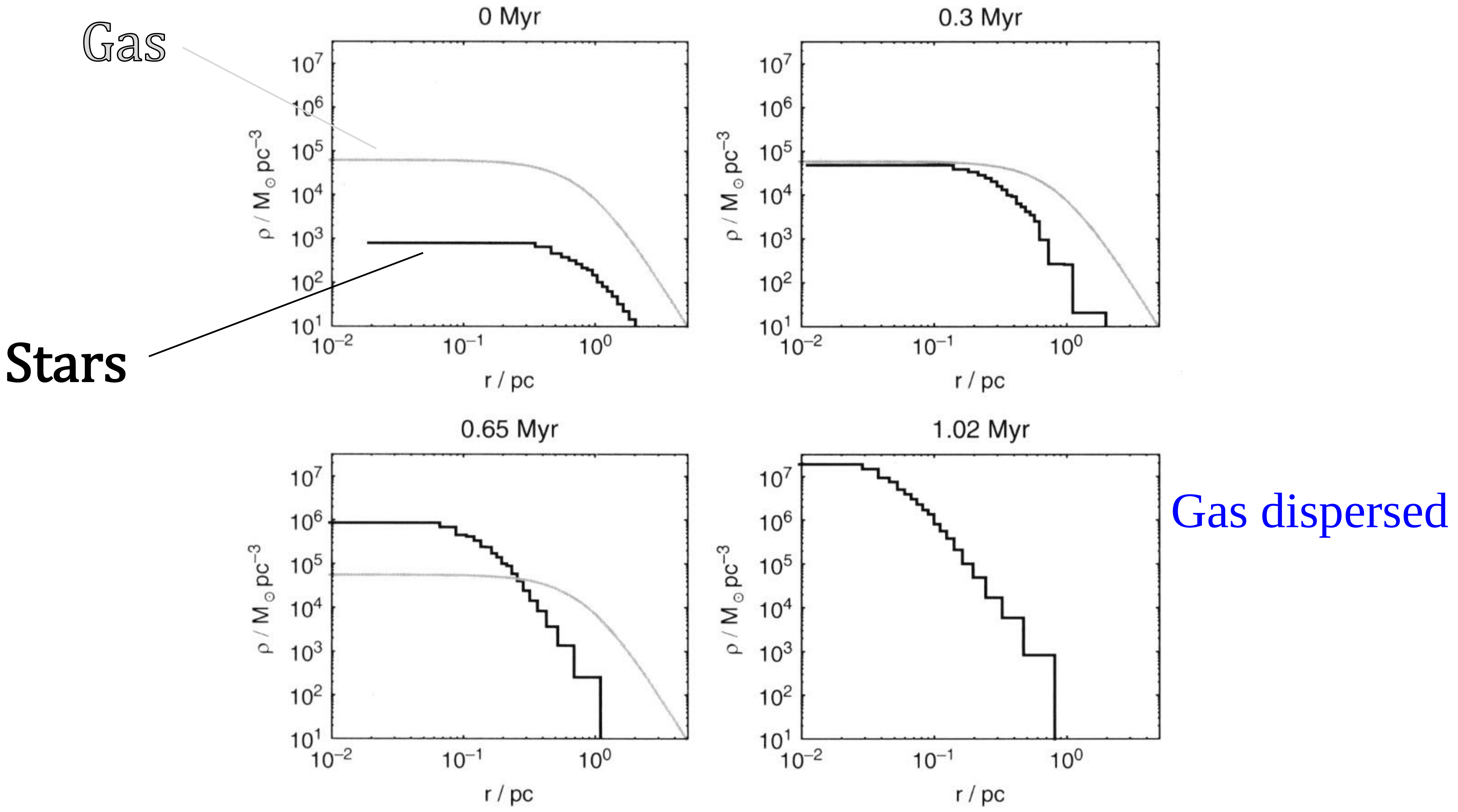
D ... diameter of the cluster

v ... velocity of the star

N ... number of stars in the cluster

N_{cross} ... number of crossings

When more than half of the mass of a virialized system is lost within τ_{cr} → the system dissolves (Hills 1980)



Moeckel & Clarke 2011

For a typical globular cluster, $\tau_{\rm relax} \approx \; 10^8 \sim 10^9 \; {\rm yr}$

Most GCs have been relaxed.

Present MW GCs gone in 10 Gyr

For a typical open cluster, $\tau_{\rm relax} \approx \; 10^6 \sim 10^7 \; {\rm yr}$

Young OCs are being relaxed.

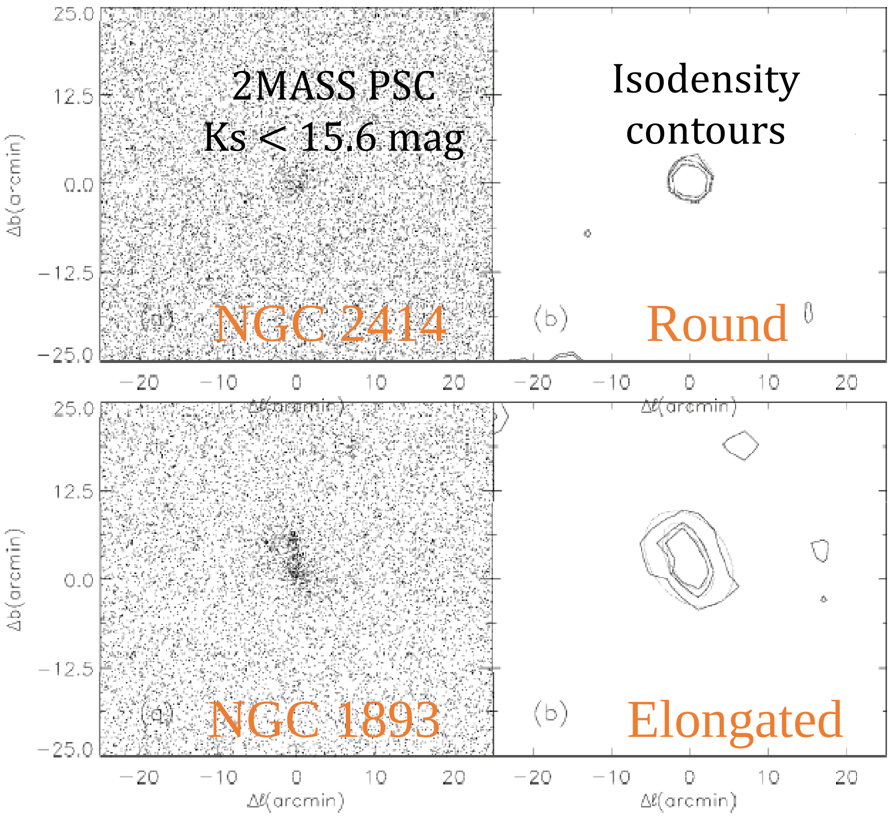
Some very young clusters (a few Myr= a few crossing times) display mass segregation.

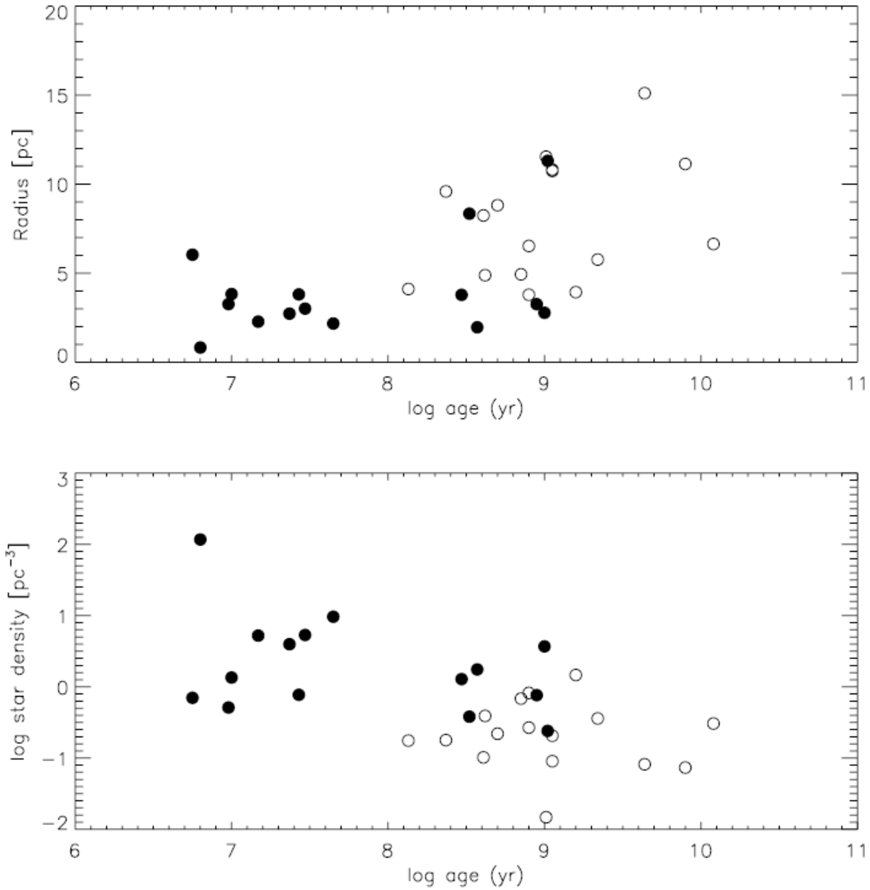
Lower-mass stars are more vulnerable to be thrown out
→ Stellar evaporation

$$\tau_{\rm evaporation} \approx 96 \; \tau_{\rm relax}$$ (Shu 1984)

OCs are flattened in general, even among the youngest systems (1-2 Myr) that have no time to relax ← filaments of parental cloud

As an OC evolves, its core becomes circularized by stellar dynamics, whereas the overall size expands and stellar density drops.



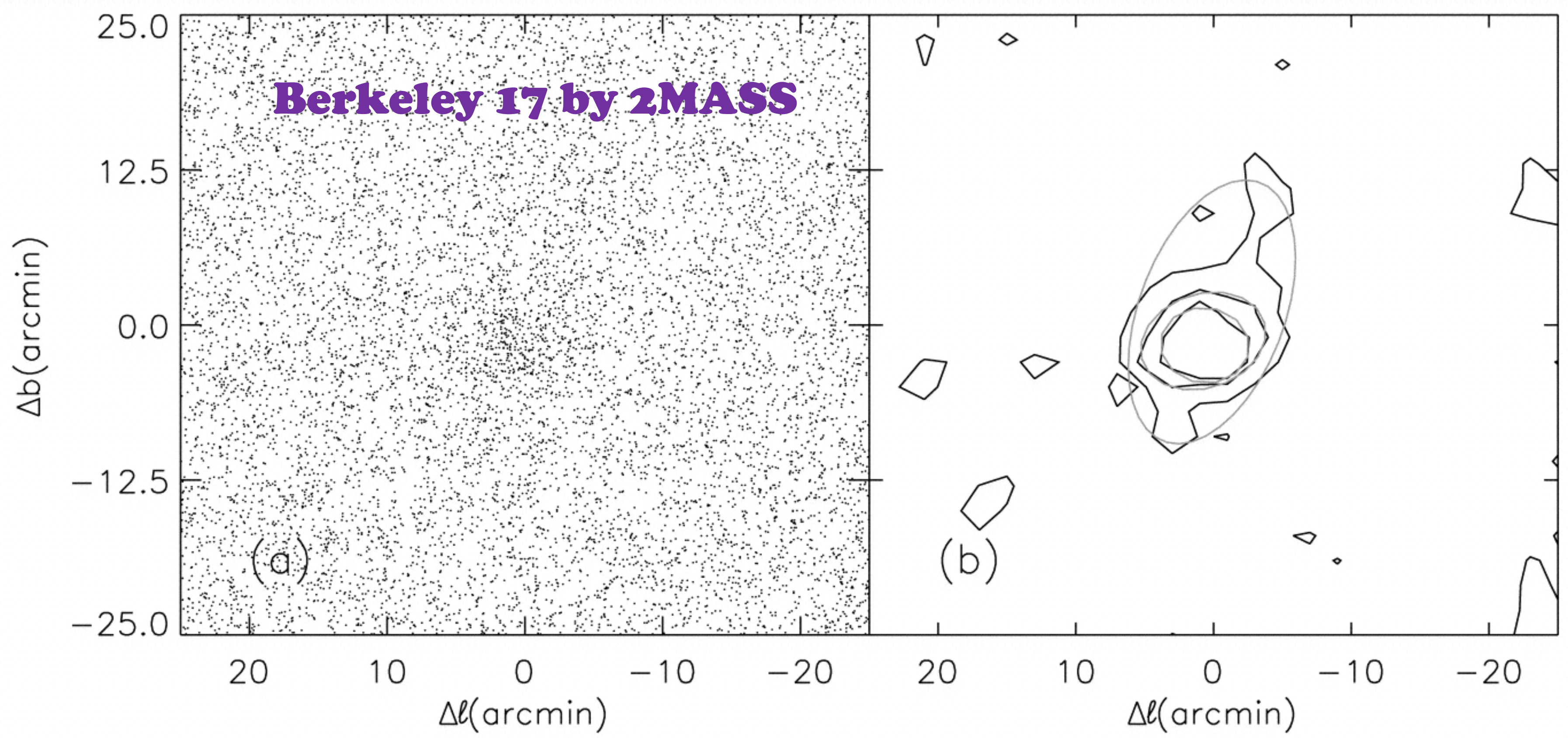


Probabilistic star counting by weighting each star by the number of neighbors

Chen+04

Tidal Distortion of Star Clusters

Eventually tidal force and Galactic differential rotation tear the cluster apart.

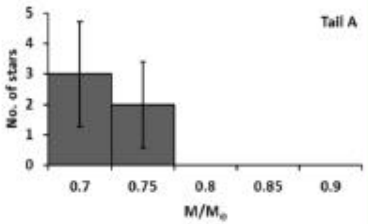


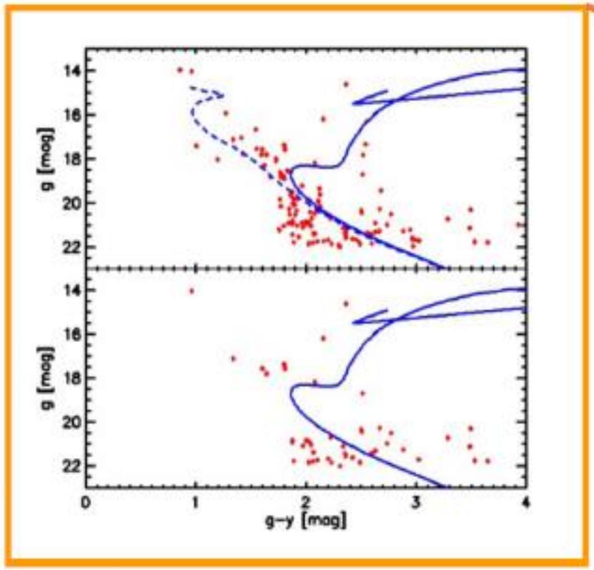
Berkeley 17, among the oldest (~10 Gyr) MW open clusters, and located at the outer edge of the disk, shows evidence of elongation …

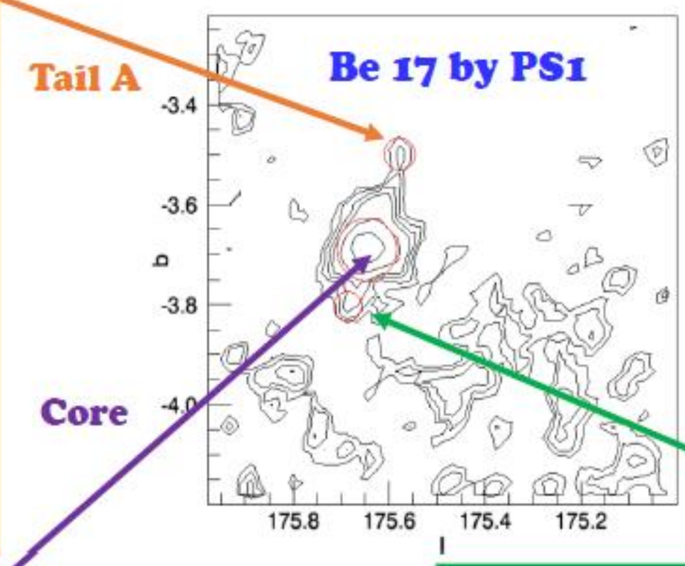
Chen+04

Escape of Low-Mass Members

Typically low-mass members outnumber massive ones.





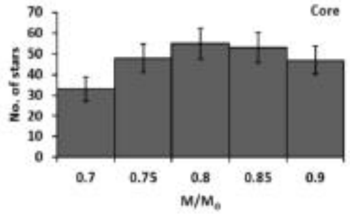


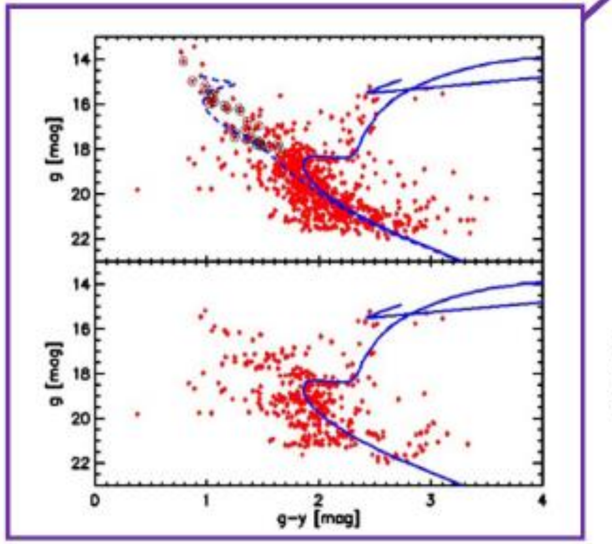
10 Gyr

d_{GC}=11.2 kpc

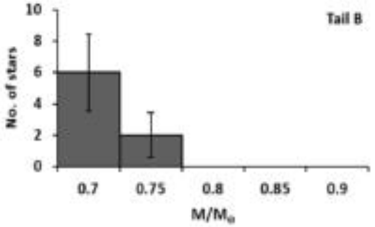
To $g_{P1} \leq 21.5$ mag or $\geq 0.6\ M_\odot$

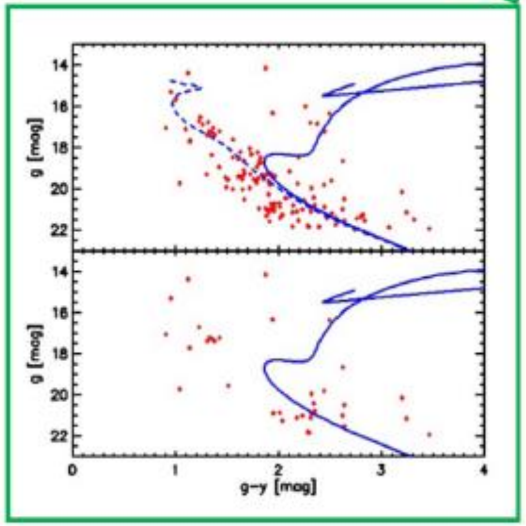
… relative shortage of lower-mass members in the core





… paucity of more massive members in the tails



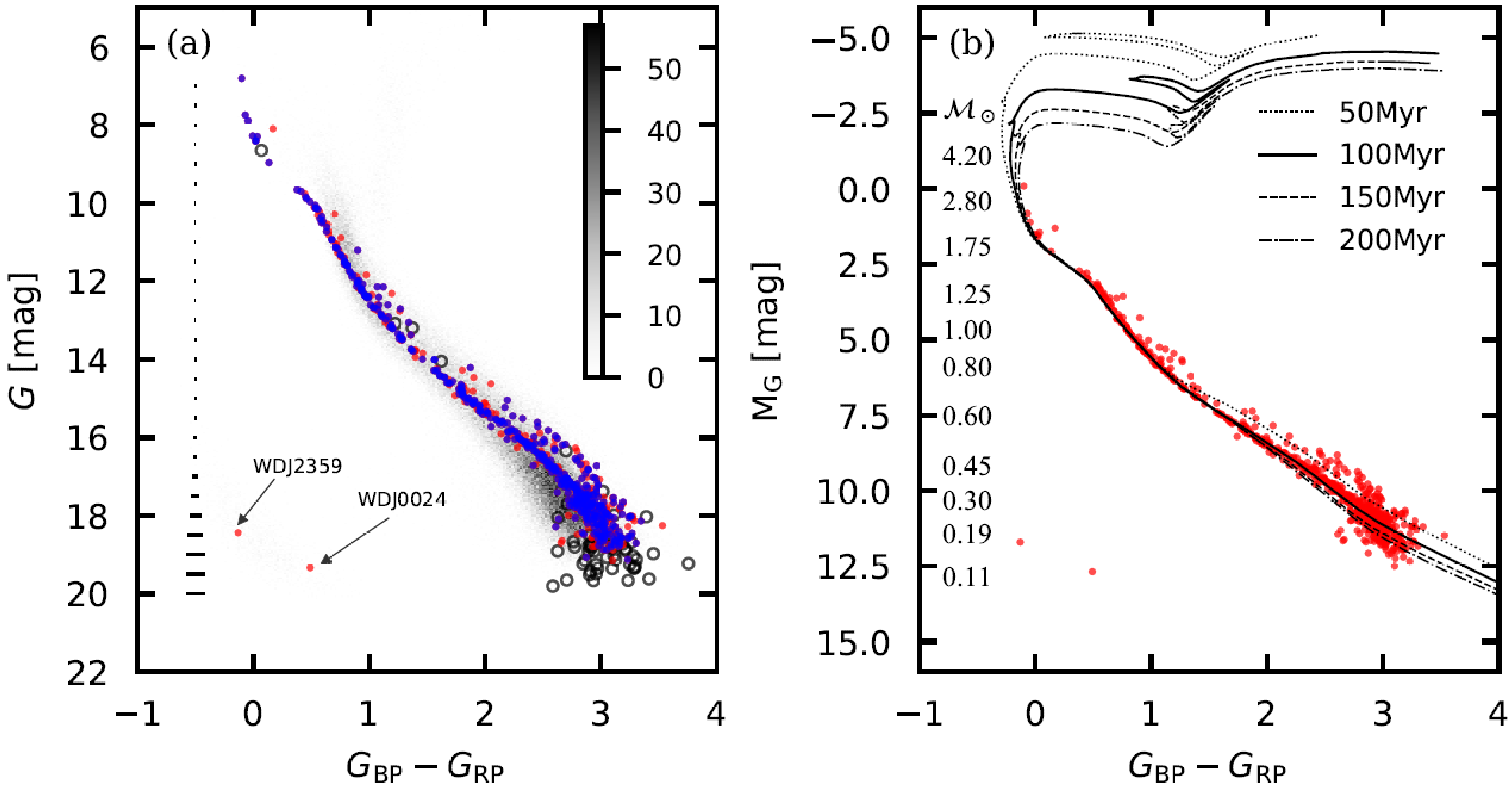


… mass segregation and stellar evaporation.

Bhattarcharya+17

Membership of Blanco 1

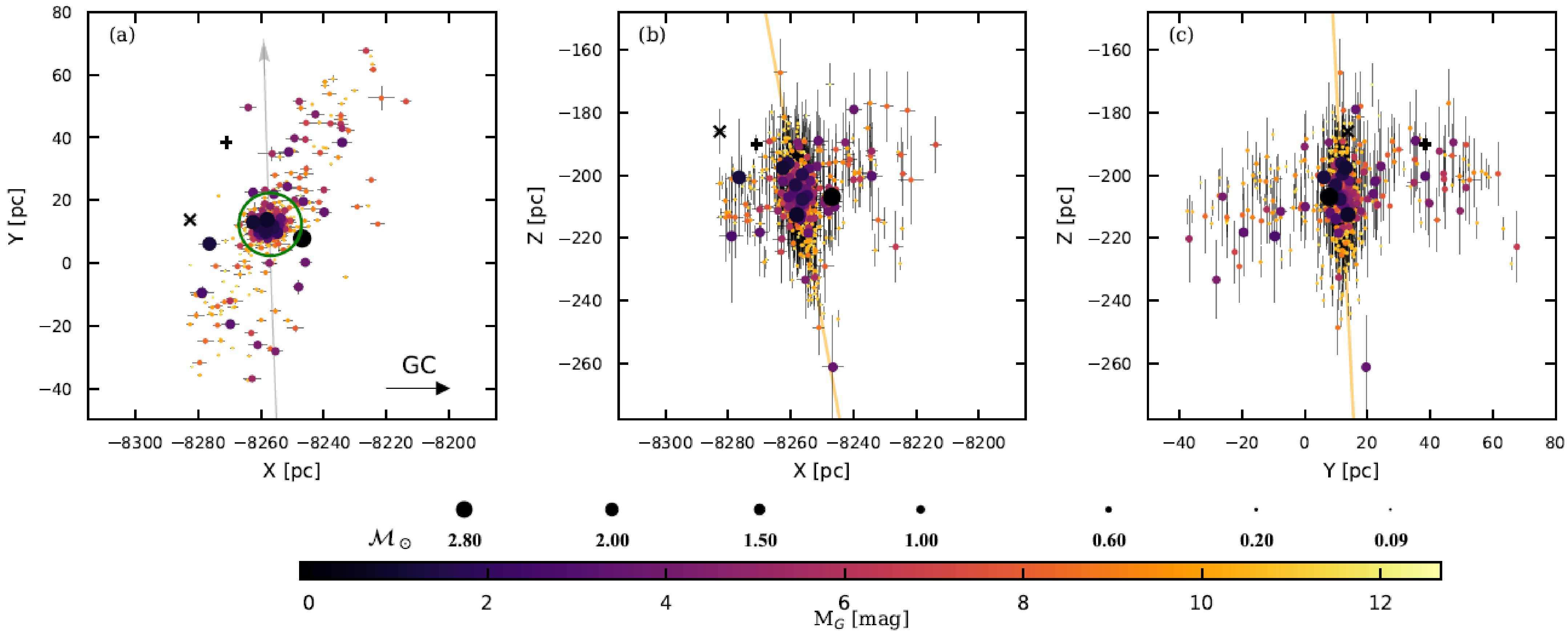
Young (100 Myr), nearby (230 pc), seen near the Gal. South Pole ($\ell = 15^o, b = -79^o$)



Gaia/DR2 data + STARGO (clustering of $\alpha, \delta, \varpi, \mu_\alpha, \mu_\delta$)

Zhang+19

A leading and a trailing tail found on the orbital plane → differential rotation shear?



Zhang+19

Globular Clusters not perfectly round

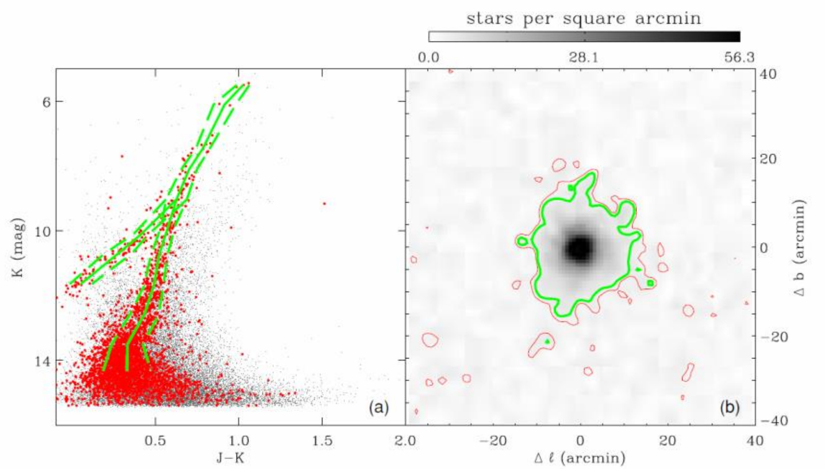


Figure 5. (a) CMD of the NGC 6121 field, with the red dots indicating highly probable cluster members, i.e., stars within $0.5\langle\theta\rangle$ radius from the cluster center. A giant branch and an HB can be clearly seen in the CMD. The green solid-line and dashed-line mark respectively the biweight mean and deviation of the red dots in each color–magnitude bin. (b) Density distribution of CMD-selected cluster members, i.e., stars located between the two green-dashed lines in (a). The thick (green) and thin (red) curves represent the 3σ and 2σ isodensity contours, respectively.

Morphology (Axial ratio) of 116 GCs

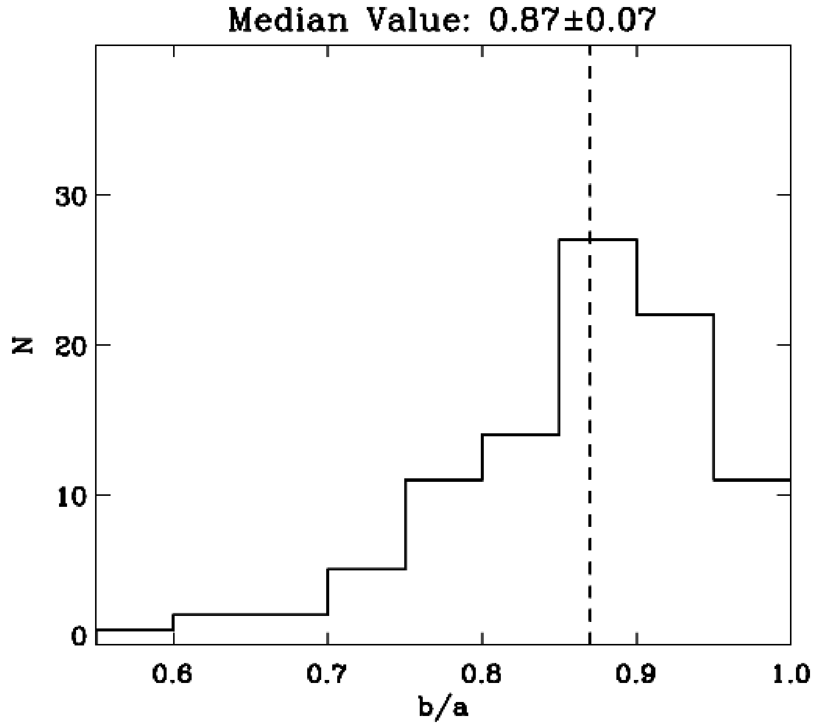
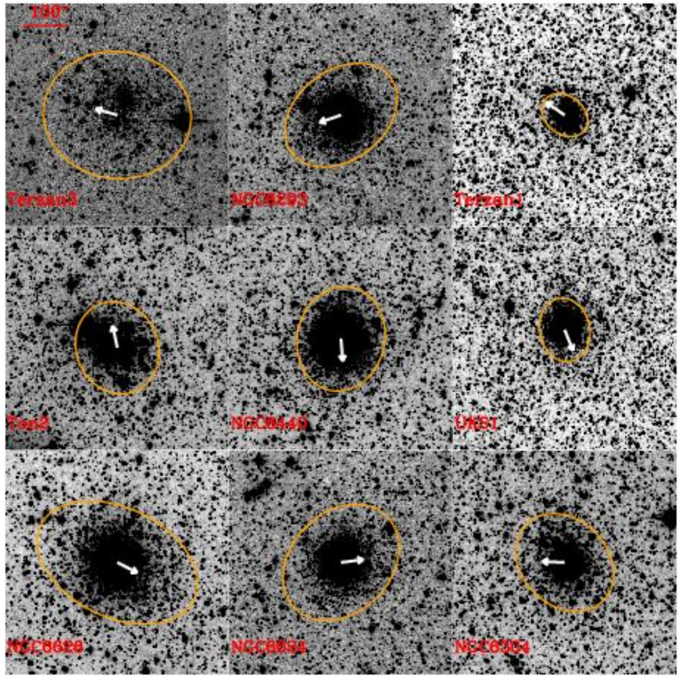


Fig. 6.— The distribution of the axial ratios of the 95 Galactic globular clusters with reliabile measurements. The dashed line indicates the median value of 0.87 of the sample.

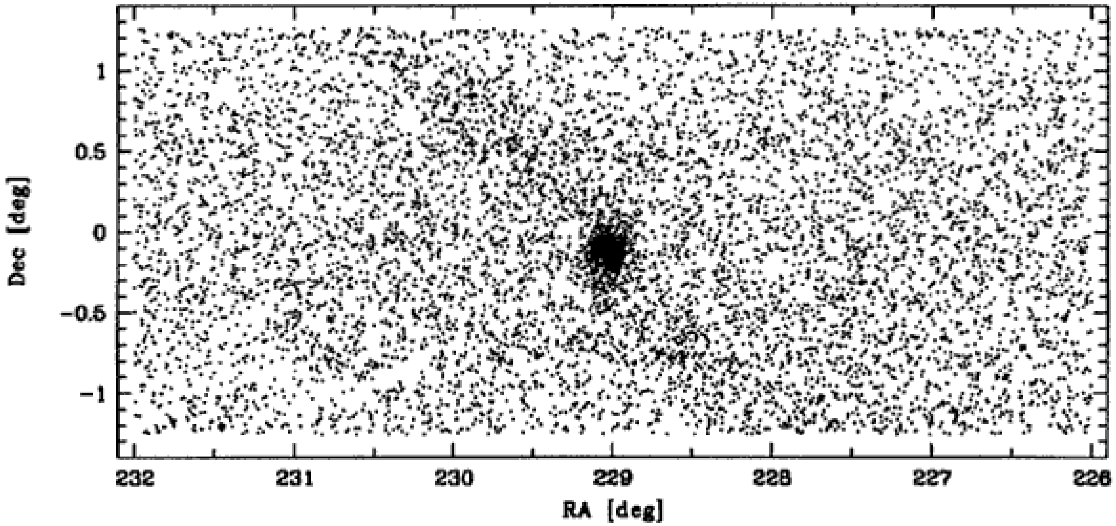
Mostly due to tidal force from the Galactic bulge; some with debris tails

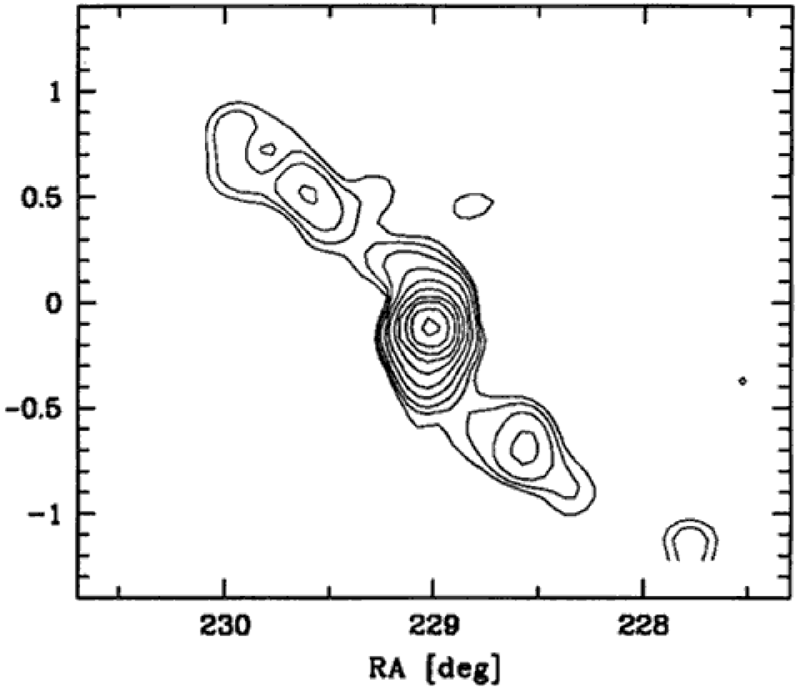


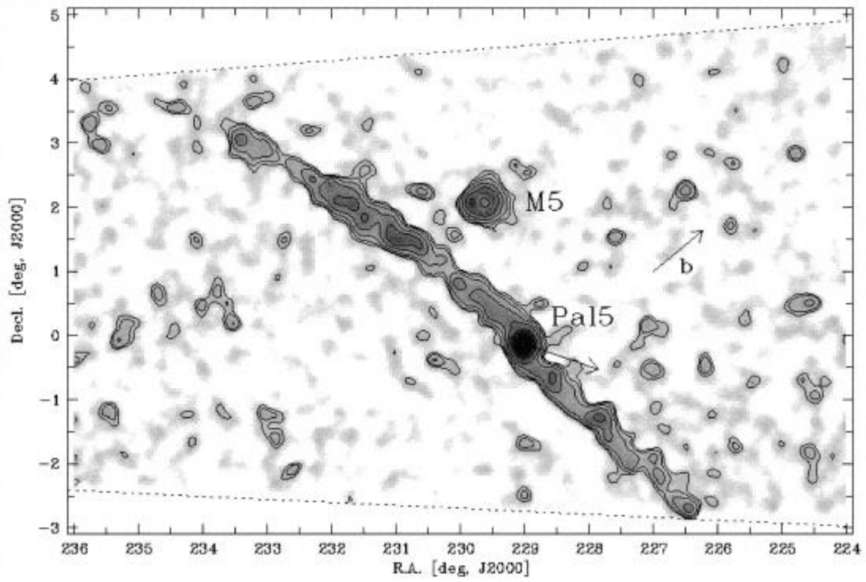
Chen, CW, et al. (2010)

Tidal Tails

Odenkirchen+01







10 deg tails from SDSS Odenkirchen+03

The "archetype" of globular cluster **tidal tails** --- those found by the digital sky survey on the globular cluster **Palomar 5**.

Tidal Tails of Globular Clusters

Chen, CW, et al. (2010)

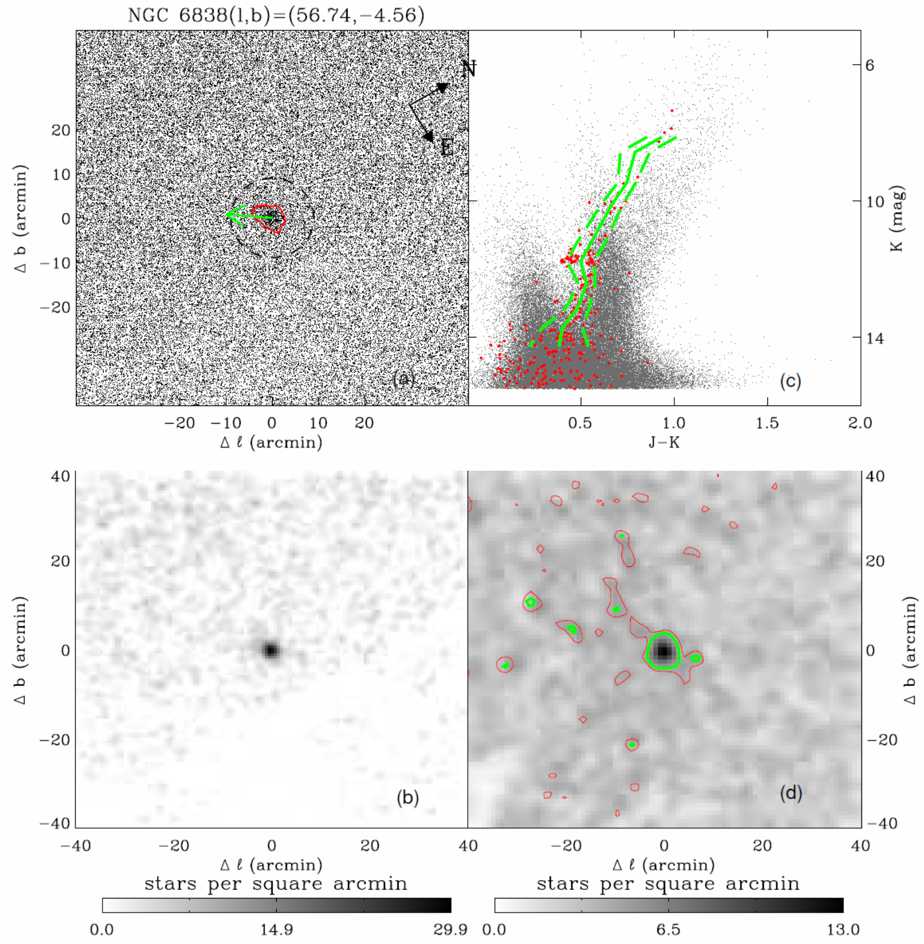


Figure 30. Same as Figure 19 but for the halo GC NGC 6838, for which the axial ratio is determined to be 0.68 ± 0.02.

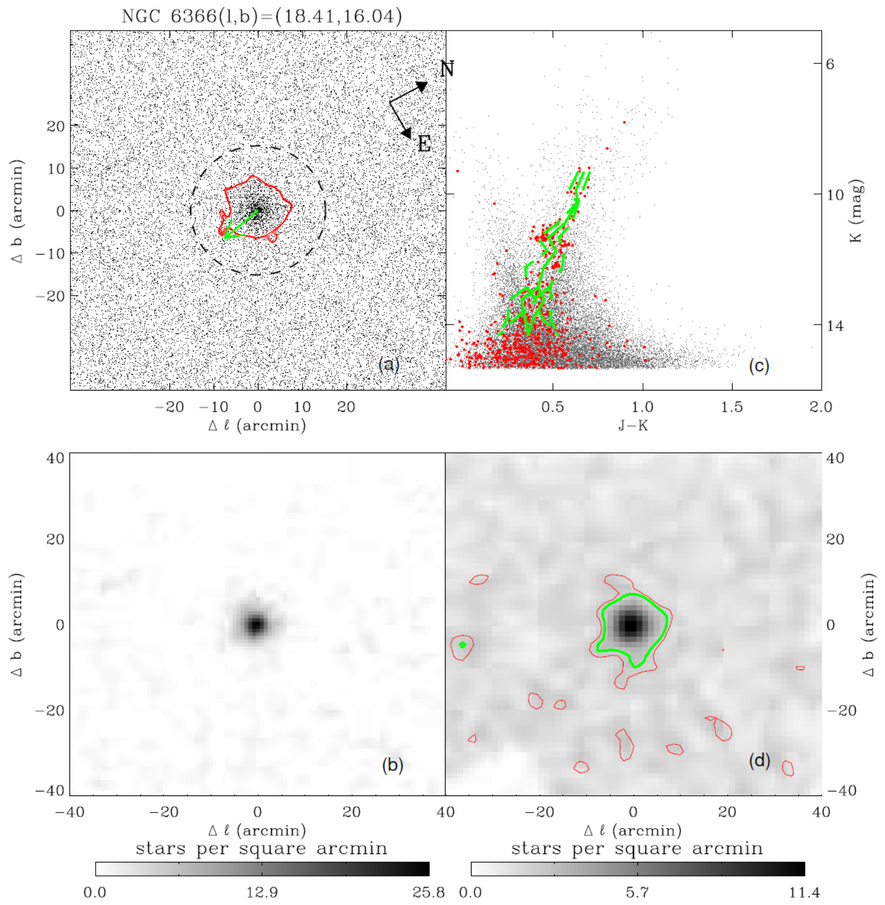
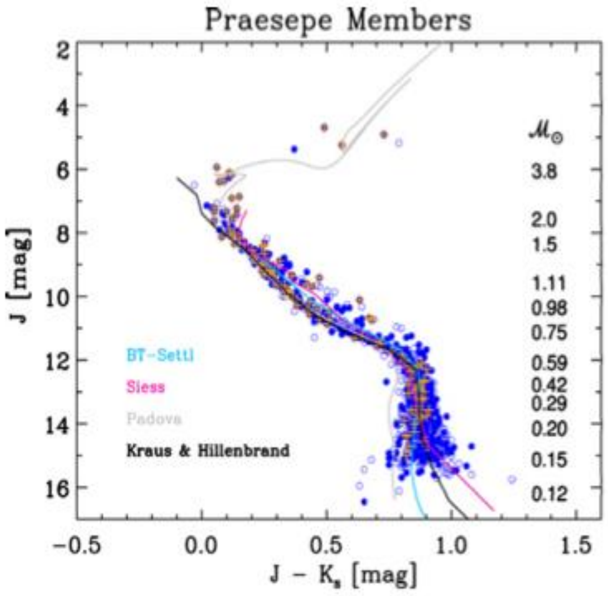


Figure 35. Same as Figure 19 but for the bulge GC NGC 6366, whose probable member stars selected by the color–magnitude method (see the text) show clumpiness around the cluster.

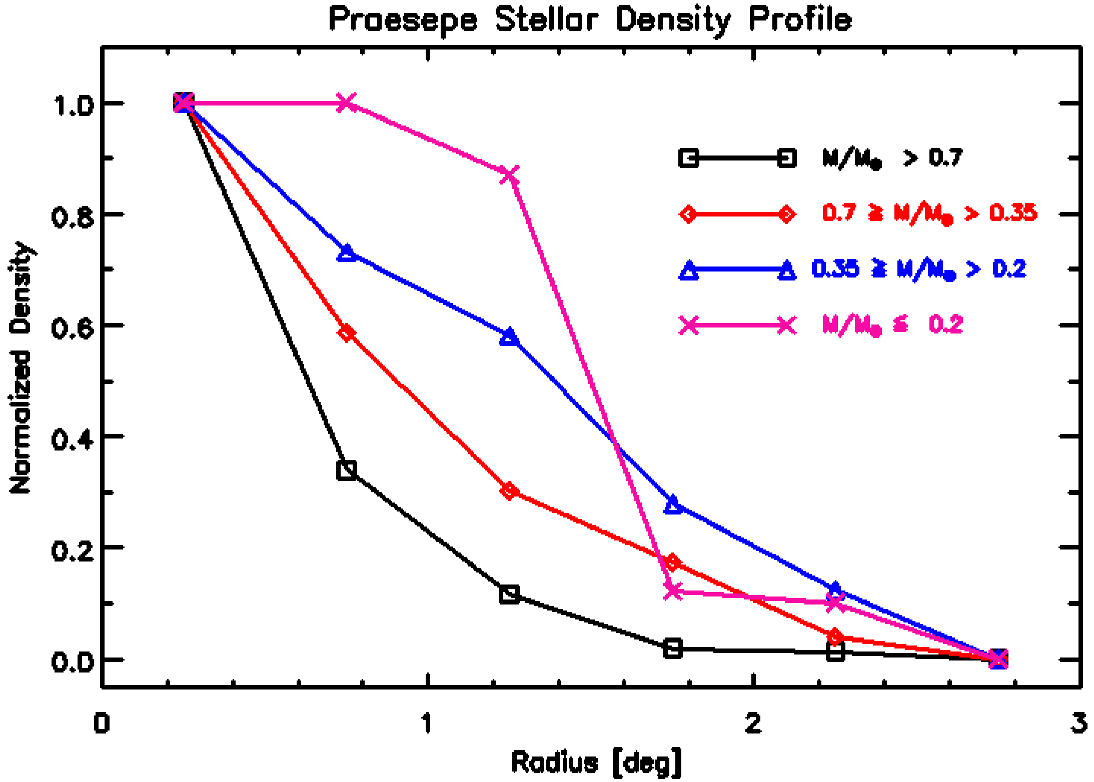
As a GC ages, high-mass stars have died, and low-mass stars have escaped, leaving behind binaries, WDs, etc.

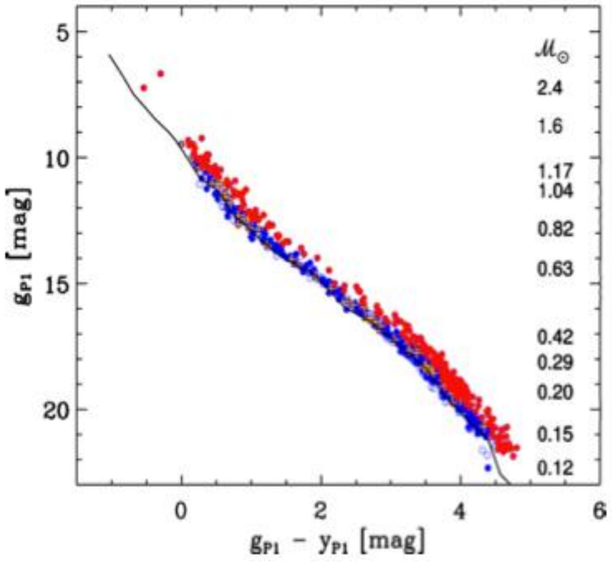
Dissolving Star Clusters



Praesepe
(M44, 750 Myr, 179 pc)

2MASS, PS1, PPMXL
→ 1040 member candidates



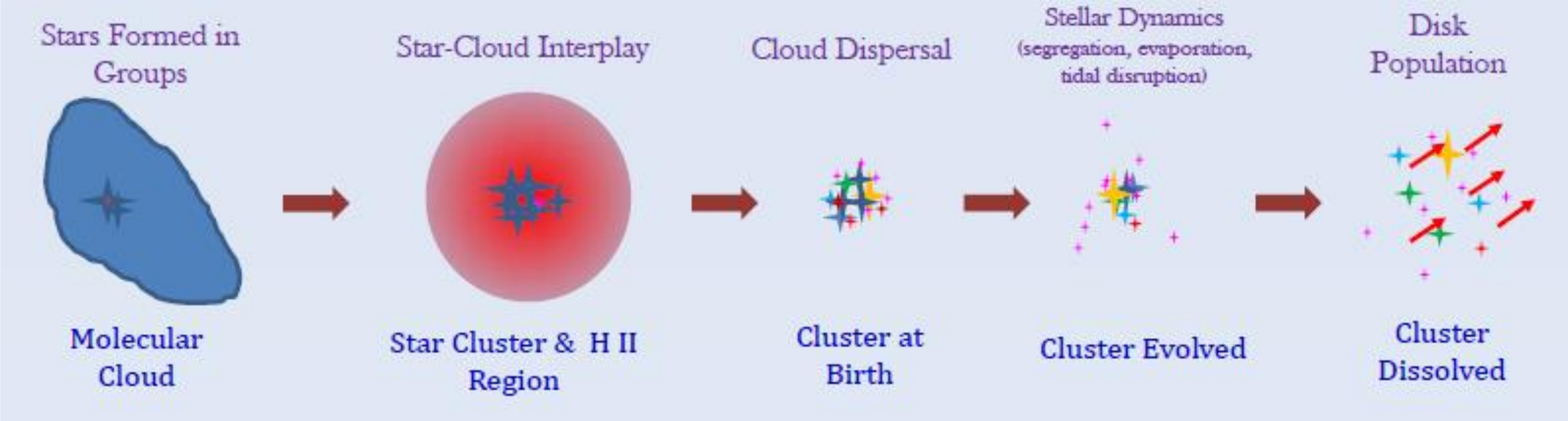


- ◆20-40% binary rate with a preference of similar-mass pairs
- ◆Mass segregation with the lowest mass members (< 0.2 $M_\odot$) being stripped

➔ The cluster is being dissolved.

Wang+13

Dissolved Star Clusters

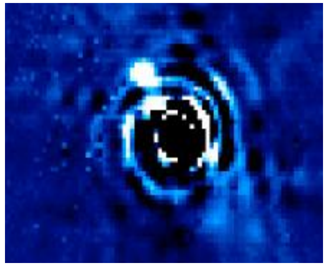


Recently dissolved star clusters recognizable if young and in the solar neighborhood → **stellar moving groups**

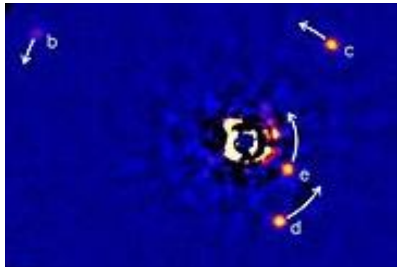
Then-members share the same space volume and motion, (and abundance, age, etc.)

So far 9 MGs known within 150 pc, with ages 10–100 Myr

Known Moving Groups



β Pic in BPMG
Lagrange et al. 2009



HR 8799 in Columba
Marois et al. 2010

Known nearby moving groups, adapted from Torres et al. (2008)						
Name	D[T] [pc]	Age[M] [Myr]	U[T] [kms^{-1}]	V[T] [kms^{-1}]	W[T] [kms^{-1}]	N[T]
β Pictoris (BP)	40±18[T,S]	12-22	-10.1±2.1	-15.9±0.8	-9.2±1.0	55[T,S]
AB Doradus (AB Dor)	51±29[T,S]	50-120	-6.8±1.3	-27.2±1.2	-13.3±1.6	97[T,S]
Tucana/Hologinm (Tuc-Hor)	48±7	10-40	-9.9±1.5	-20.9±0.8	-1.4±0.9	44
TW Hydrae (TWH)	59±22[D]	8-20	-10.5±0.9	-18.0±1.5	-4.9±0.9	31[D]
Columba (Col)	82±30	10-40	-13.2±1.3	-21.8±0.8	-5.9±1.2	41
Carina (Car)	85±35	10-40	-10.2±0.4	-23.0±0.8	-4.4±1.5	23
Argus (Arg)	106±51	30-50	-22.0±0.3	-14.4±1.3	-5.0±1.3	64
ϵ Chamaeleontis (ϵ Cha)	108±9	~6[T]	-11.0±1.2	-19.9±1.2	-10.4±1.6	30[M2]
Octans (Oct)	141±34	~20[T]	-14.5±0.9	-3.6±1.6	-11.2±1.4	15

D: Ducourant et al. 2014, M: Malo et al. 2013 , M2: S: Schlieder et al. 2012, T: Torres et al. 2008, M2: Murphy et al. 2013

Chen, CY (2016)

Outstanding Issues of Star Cluster Studies

Substellar Populations

Stars are formed in groups out of dense molecular cloud cores, and planets are formed, at the same time as the stellar birth, in circumstellar disks.

What about brown dwarfs?

Do they form like stars (and evolve like planets, i.e., ever cooling), or do they form like planets?

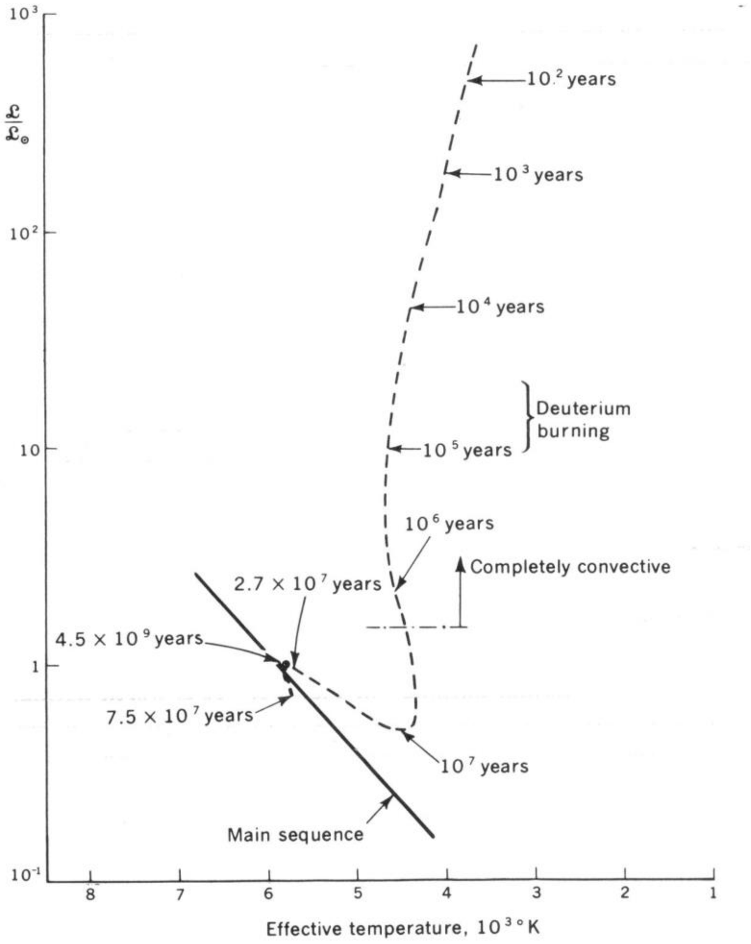
Free-floating substellar objects (brown dwarfs or planets)?

Sloppy nomenclature

Giant → relatively large in size; Dwarf → relatively small

e.g., yellow dwarf, red dwarf, brown dwarf, white dwarf
dwarf planet, dwarf galaxy

Stars	$\mathcal{M}/\mathrm{M}_{\odot} > 0.08$, core H fusion Spectral types O, B, A, F, G, K, M
Brown Dwarfs	$0.065 > \mathcal{M}/\mathrm{M}_{\odot} > 0.013$, core D fusion $0.080 > \mathcal{M}/\mathrm{M}_{\odot} > 0.065$, core Li fusion Spectral types M6.5–9, L, T, Y Electron degenerate core ✓$10\ \mathrm{g\ cm^{-3}} < \rho_c < 10^3\ \mathrm{g\ cm^{-3}}$ ✓$T_c < 3 \times 10^6$ K
Planets	$\mathcal{M}/\mathrm{M}_{\odot} < 0.013$, no fusion ever



Pre-main-sequence evolution of the Sun

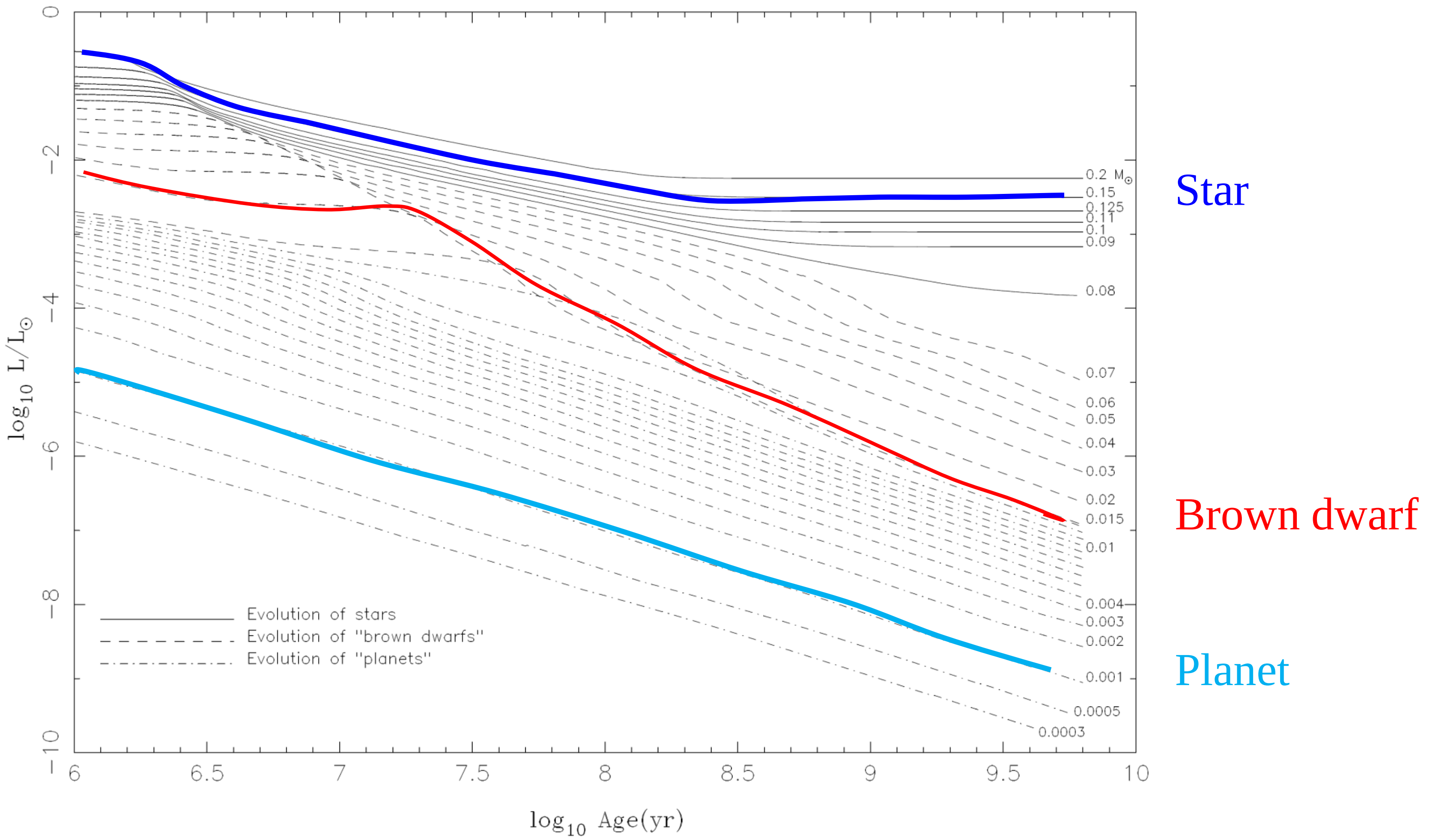


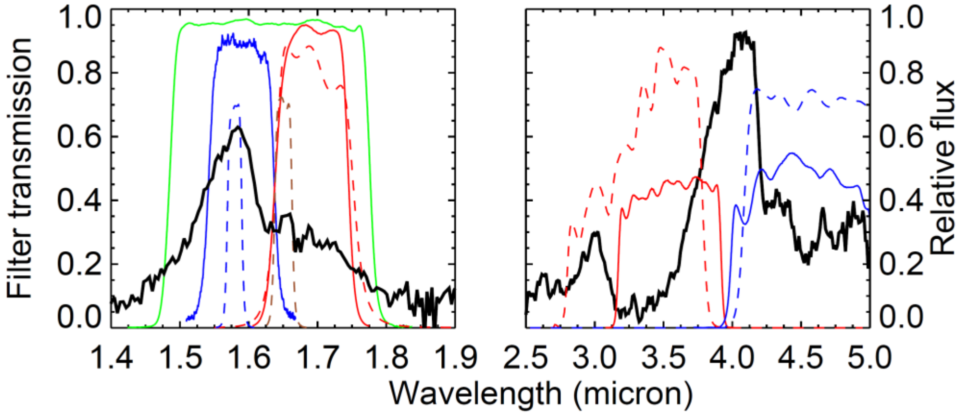
FIG. 7.—Evolution of the luminosity (in $L_\odot$) of solar-metallicity M dwarfs and substellar objects vs. time (in yr) after formation. The stars, "brown dwarfs" and "planets" are shown as solid, dashed, and dot-dashed curves, respectively. In this figure, we arbitrarily designate as "brown dwarfs" those objects that burn deuterium, while we designate those that do not as "planets." The masses (in $M_\odot$) label most of the curves, with the lowest three corresponding to the mass of Saturn, half the mass of Jupiter, and the mass of Jupiter.

Burrows

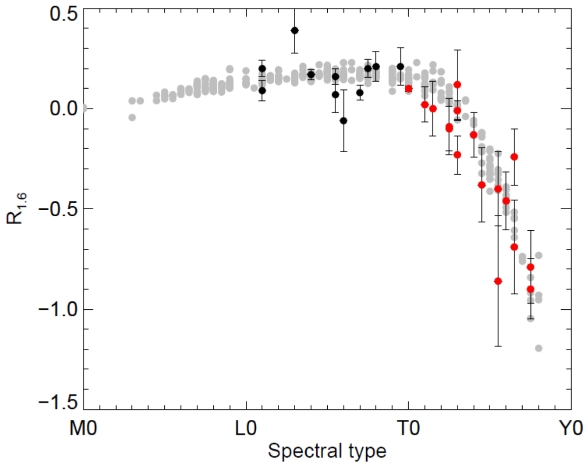
Young Methane T Dwarfs in Star Clusters

- Almost all known BDs in the field
- Substellar brighter when younger
- BDs in young star-forming regions
  → T dwarfs in L1688 in ρ Oph (130 pc, 1 Myr)
- T dwarf spectra are characterized by <u>methane</u> absorptions
  → Narrow-band on-off imaging
  and by <u>cool</u> atmospheres
  → IR colors

Chiang+ 2014

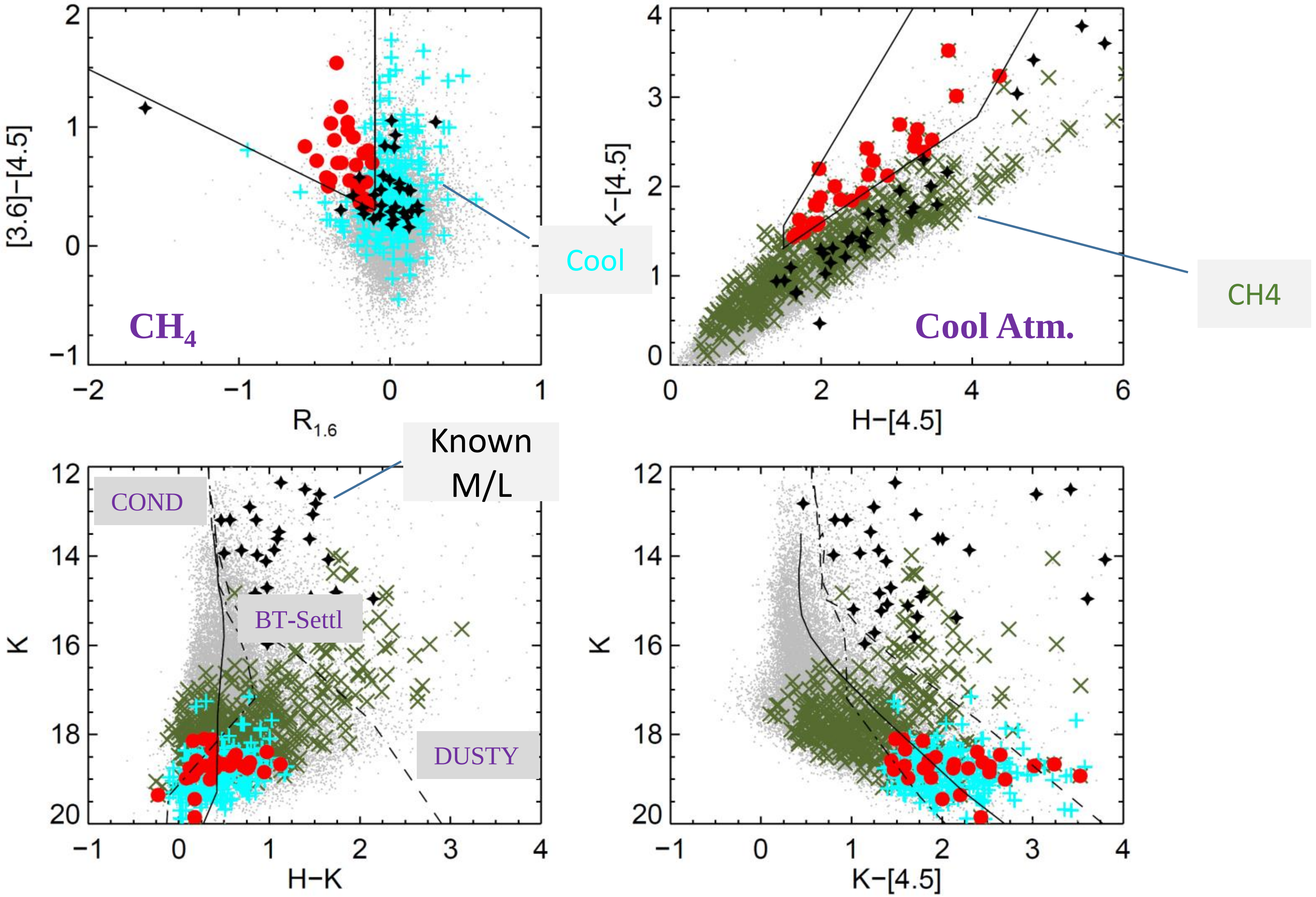


A typical L4 dwarf (black) and the transmission curves of CFHT/WIRCam H, CH4ON, CH4OFF, Gemini Hcon, [Fe II], and Spitzer IRAC bands



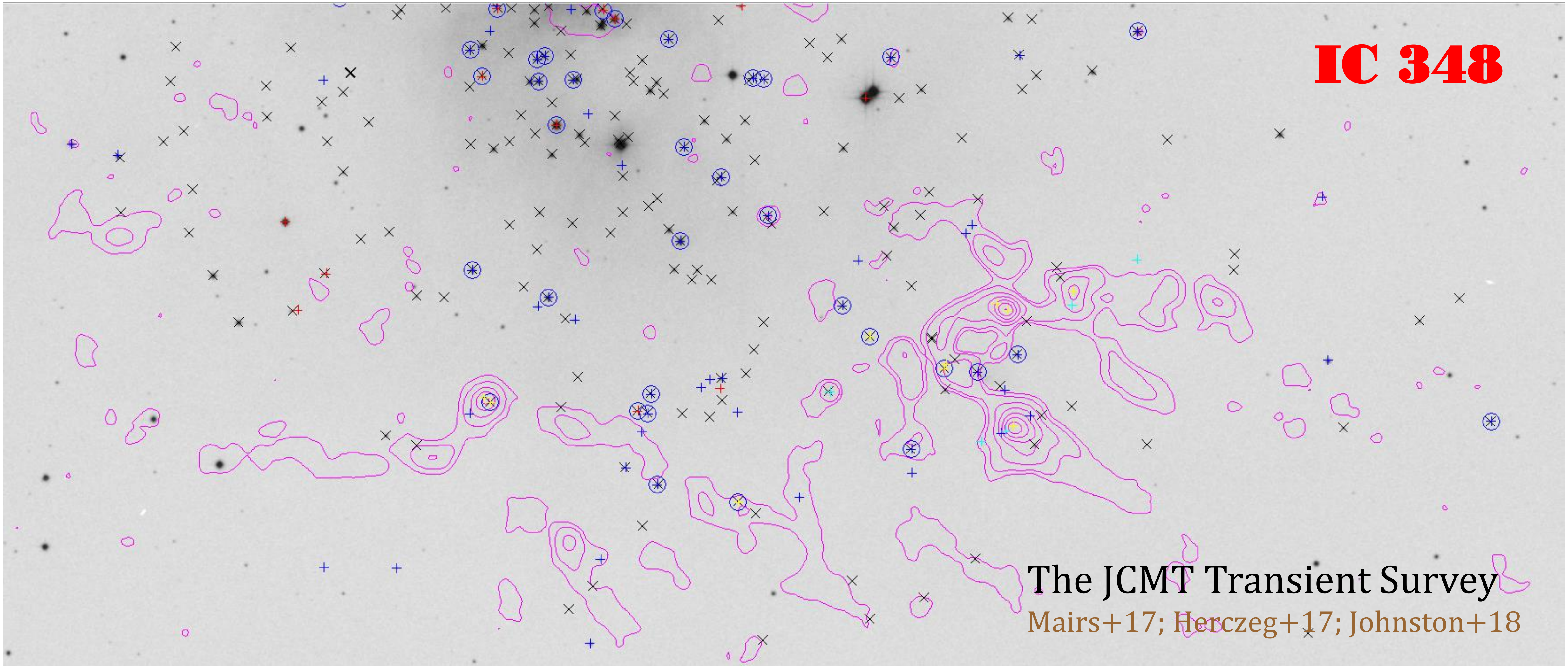
On-off 1.6 μm imaging photometry of the "training" data set of known L and T dwarfs in the field

Brown Dwarfs at Birth



Chiang+ 2014

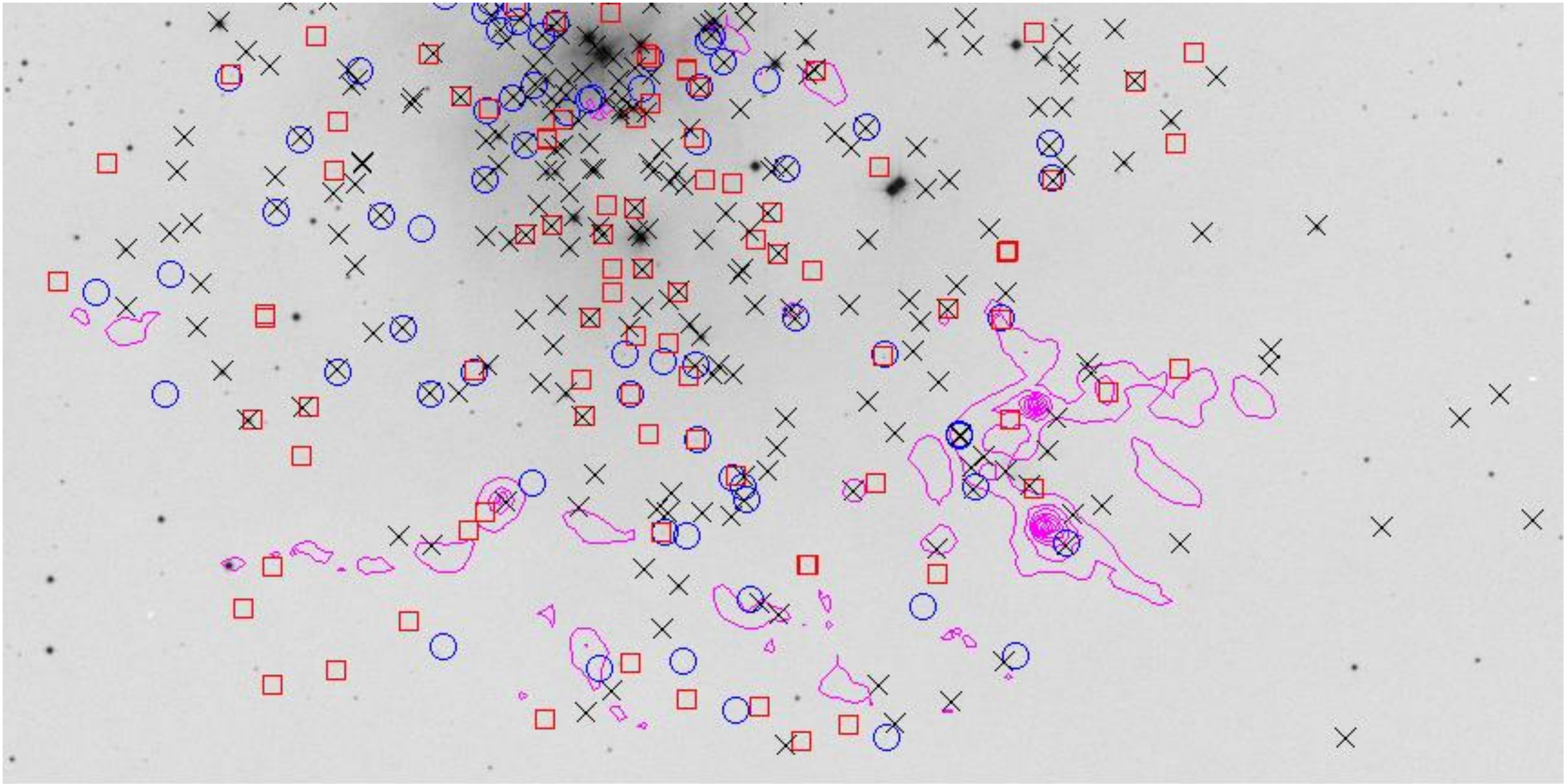
A total of 28 T dwarf candidates found (1) with methane features, (2) with cool atmospheres, (3) not detected by *Spitzer* MIPS, (4) with consistent PMs.



X x-ray sources
+ Class II YSOs
+ Class 0/I protostars
+ Class III YSOs
+ Flat Spectrum Objects
◯ X-ray emitting protostar

850 μm emission (JCMT/SCUBA2), X-ray sources, And YSOs

X-ray Brown Dwarfs at Birth



X-ray sources (crosses), confirmed (red boxes) and candidate (blue circles) BDs, and smm dust clumps (contours)

BDs convective
+ fast rotation
→ chrom. active
until too cold
→ charge neutral
→ no dynamo;
but aurorae

JCMT/SCUBA-2

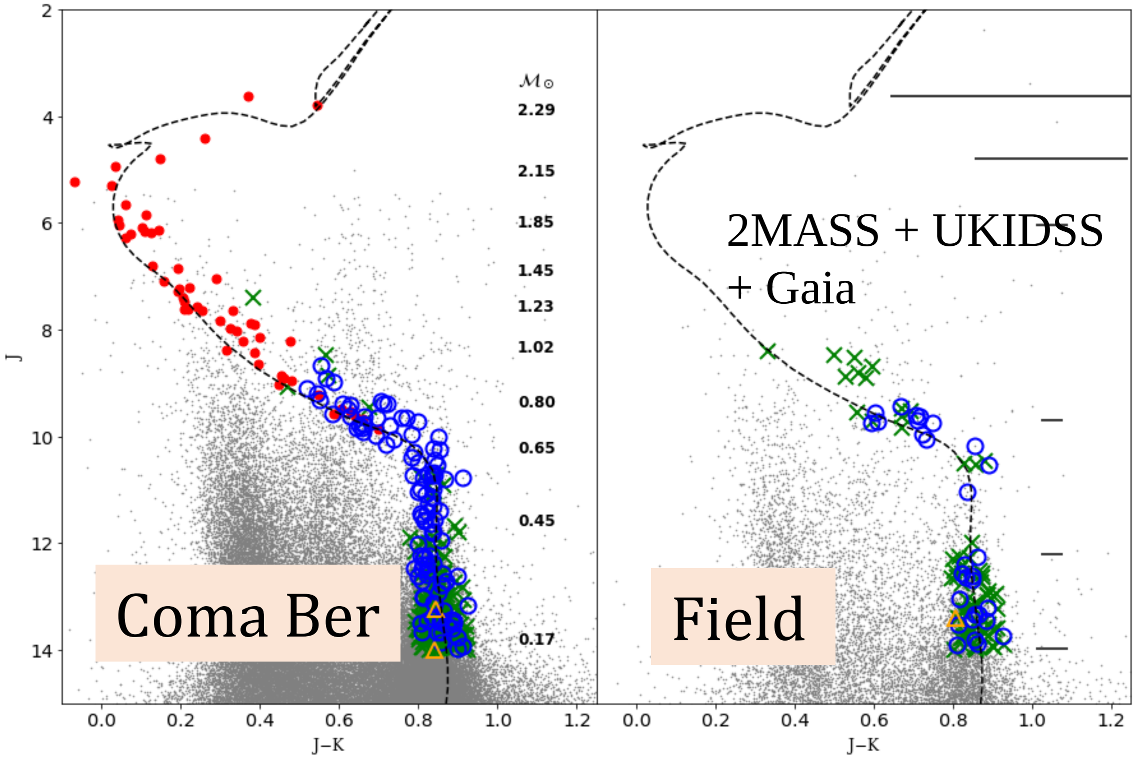
Transient Survey for prostellar var.

IC348 19+ epochs

Lalchand+20

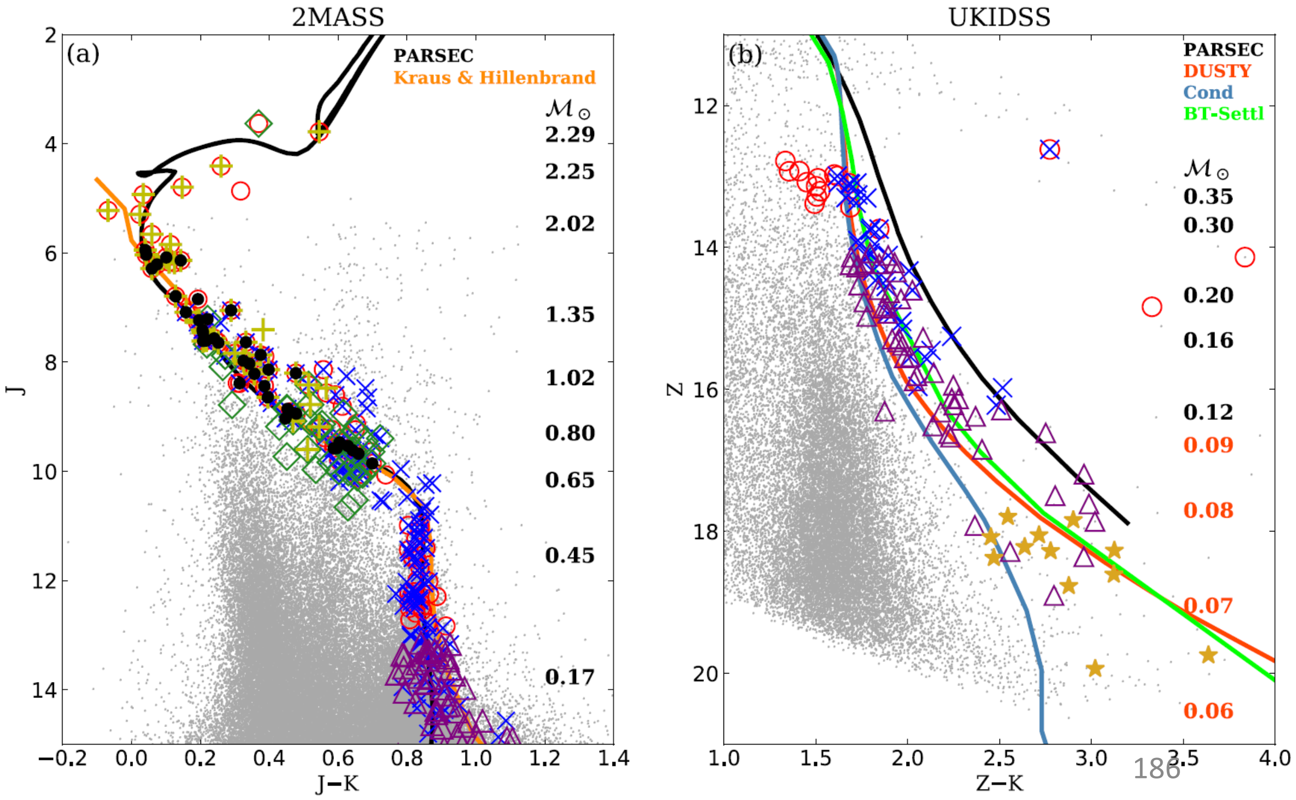
Aged Brown Dwarfs

Coma Berenices star cluster (Melotte 111)

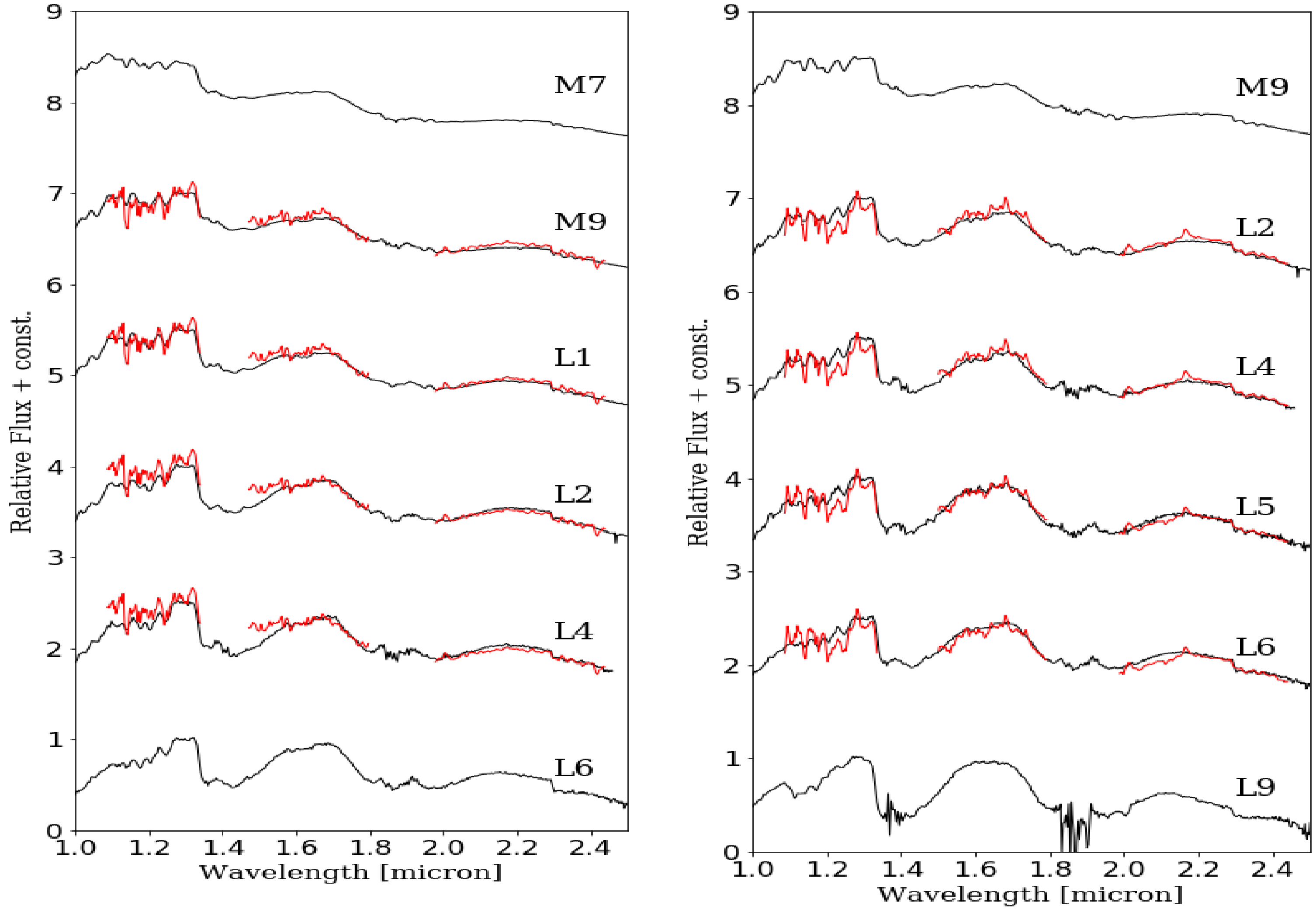


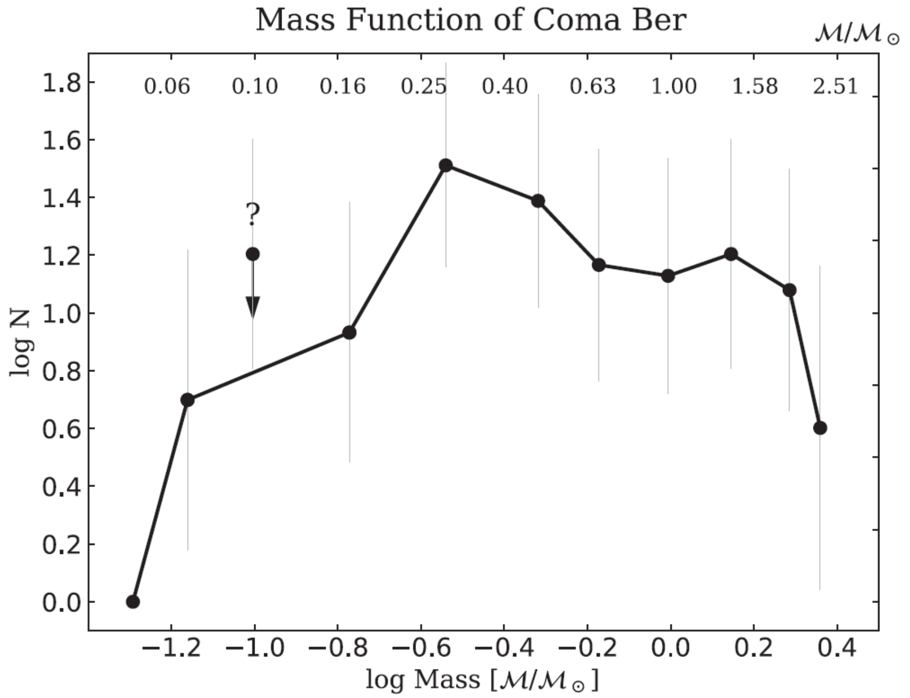
"Decontamination"

Intermediate-aged (800 Myr), nearby (87 pc, nearest next to Pleiades), seen near the GNP ($\ell = 221°, b = +84°$)



Tang+18

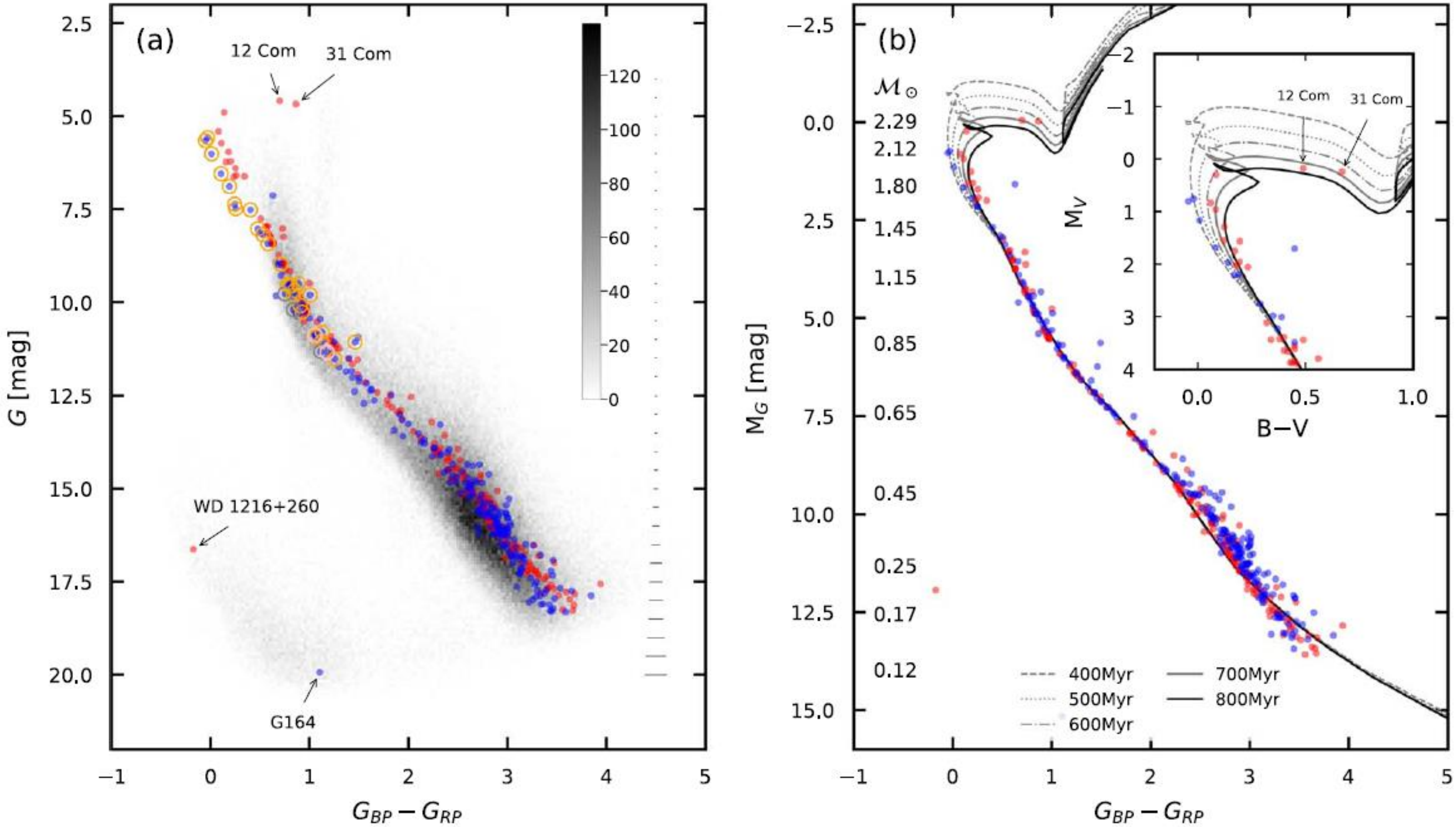




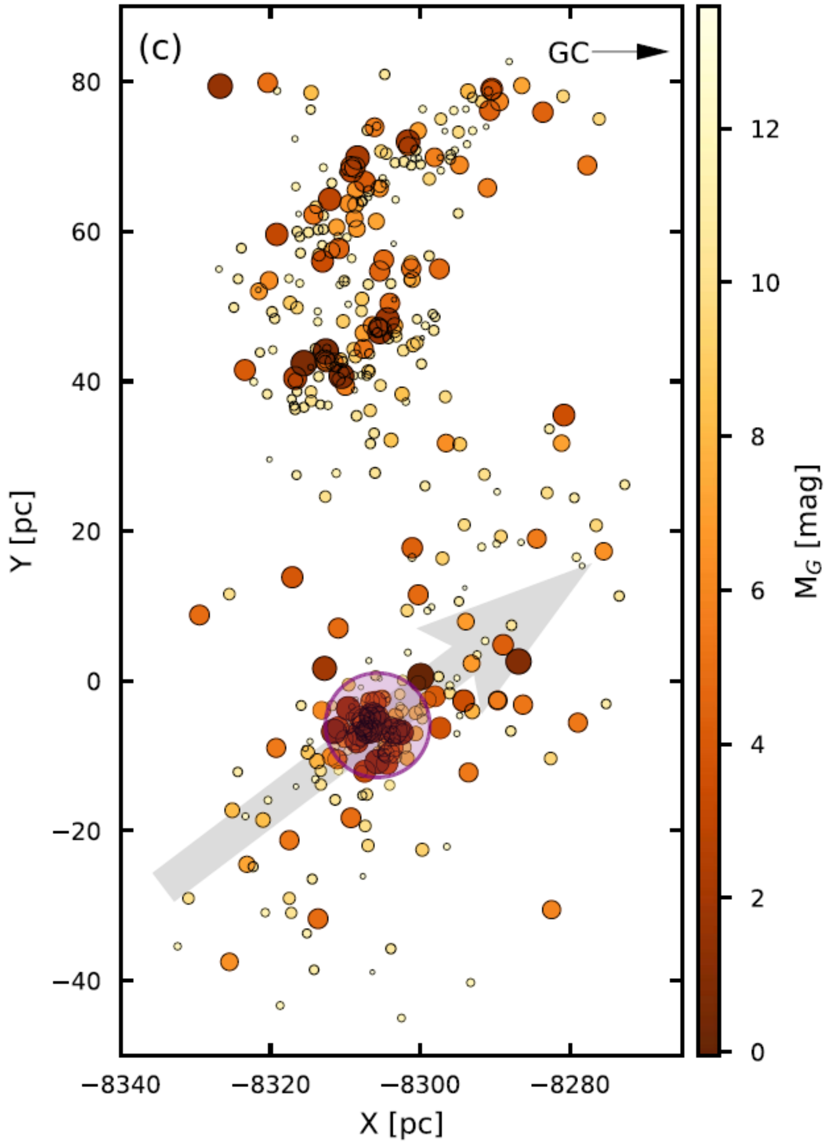
Previously coolest known member: M9.

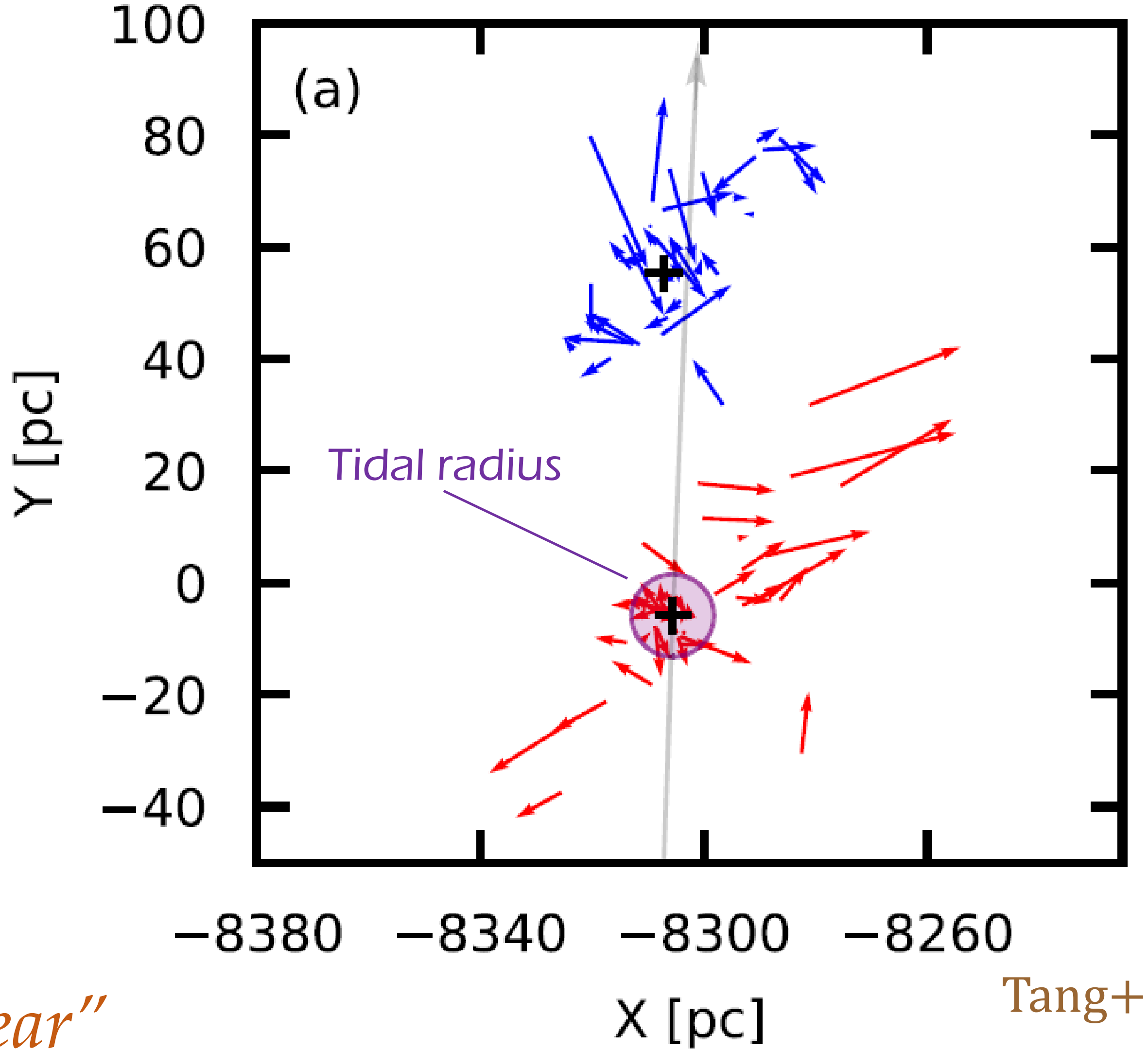
We found an L2 and an L4 BDs

Tang+18


(a)
12 Com
31 Com
WD 1216+260
G164
G [mag]
$G_{BP} - G_{RP}$
(b)
$\mathcal{M}_\odot$
2.29
2.12
1.80
1.45
1.15
0.85
0.65
0.45
0.25
0.17
0.12
M_G [mag]
M_V
B−V
400Myr
500Myr
600Myr
700Myr
800Myr

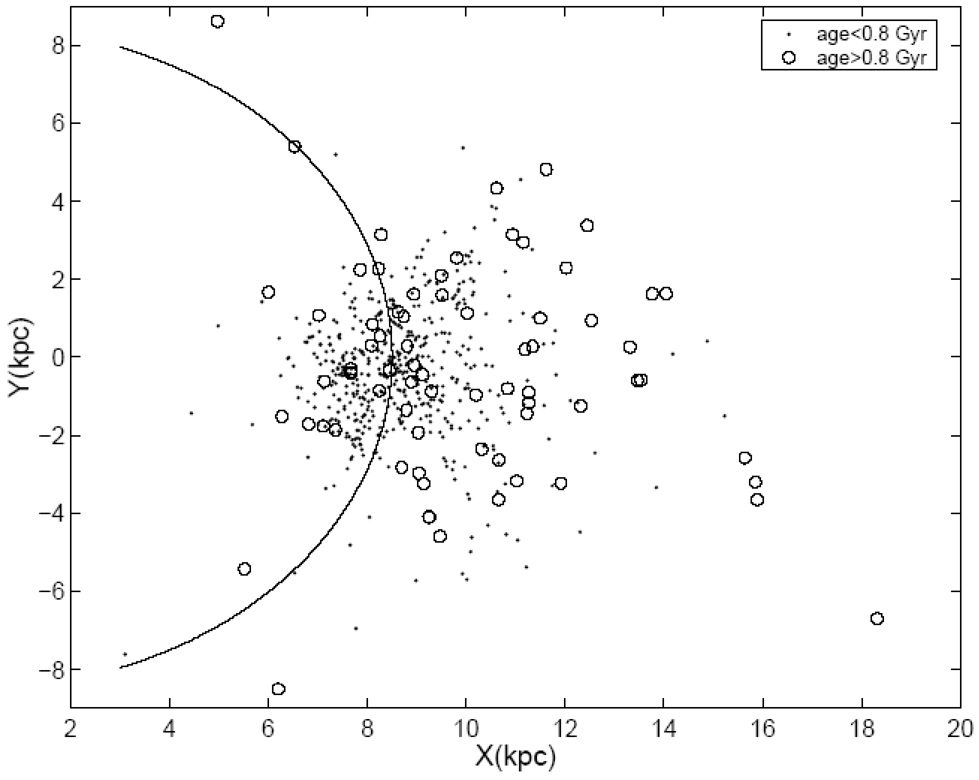
Velocities of "tail" members relative to the cluster mean (U, V, W)

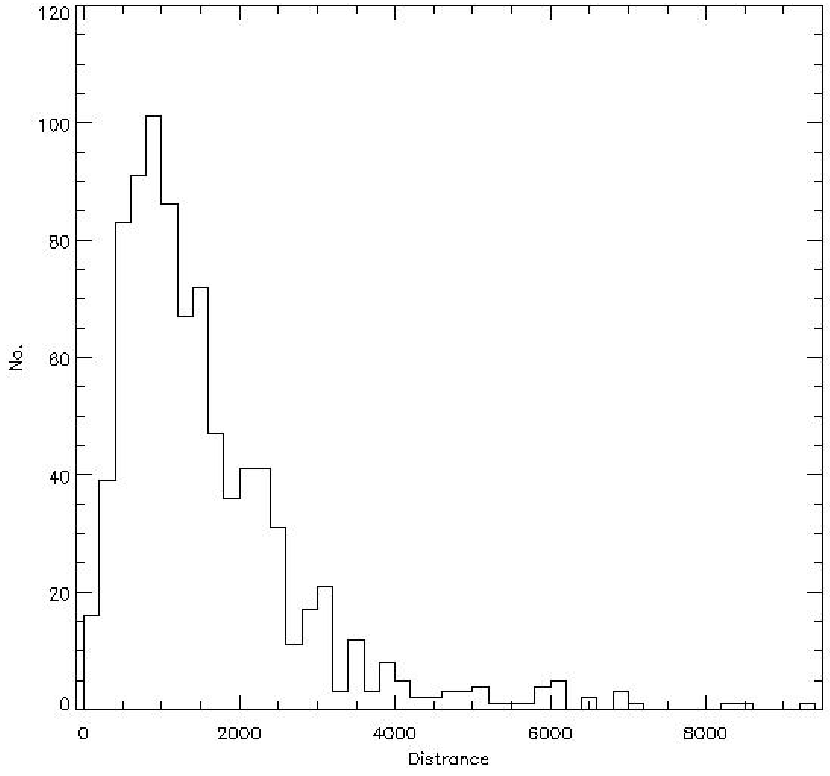




Tang+19

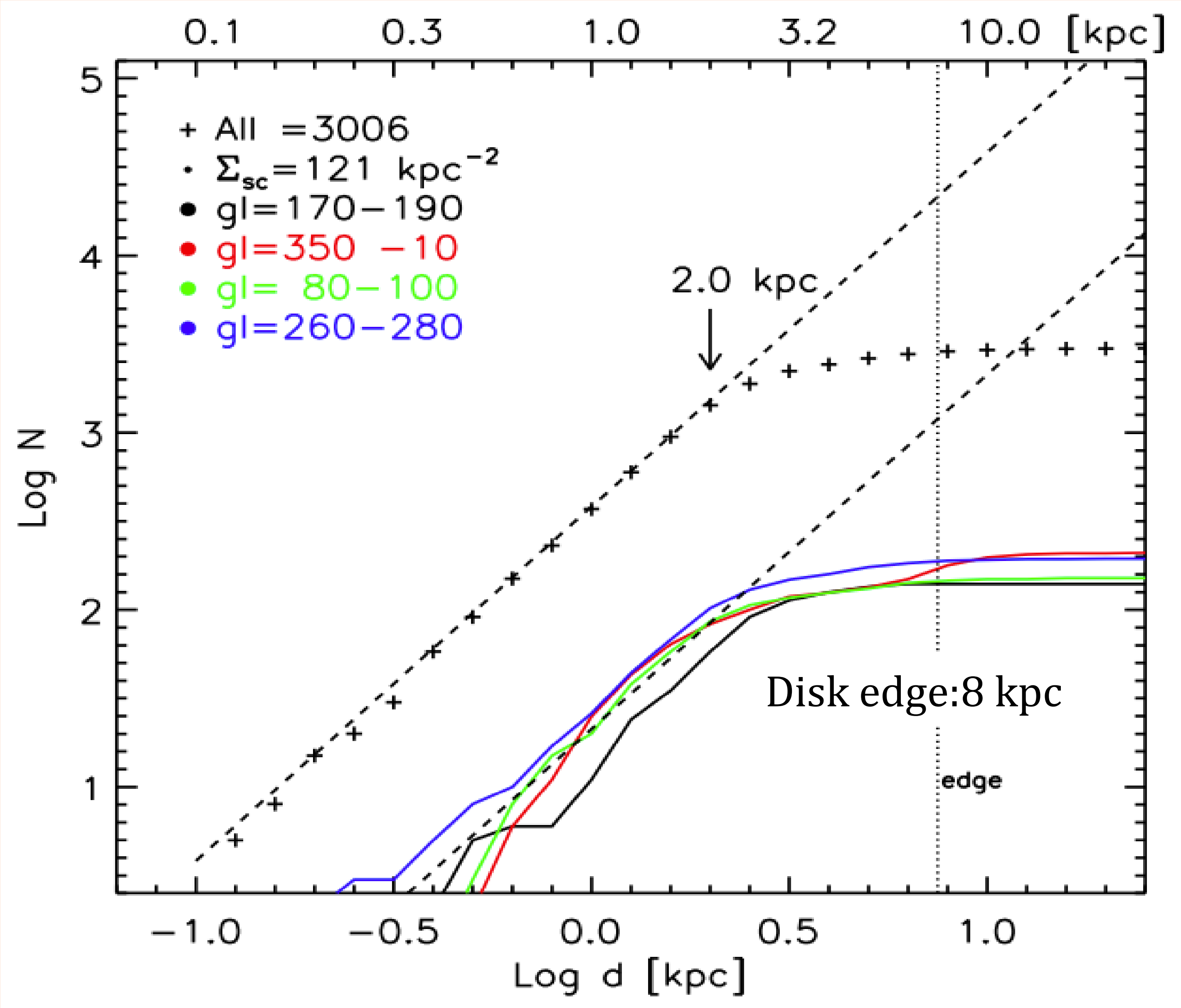
"Tail, Tail, Everywhere;
Find Them Distant, Find Them Near"





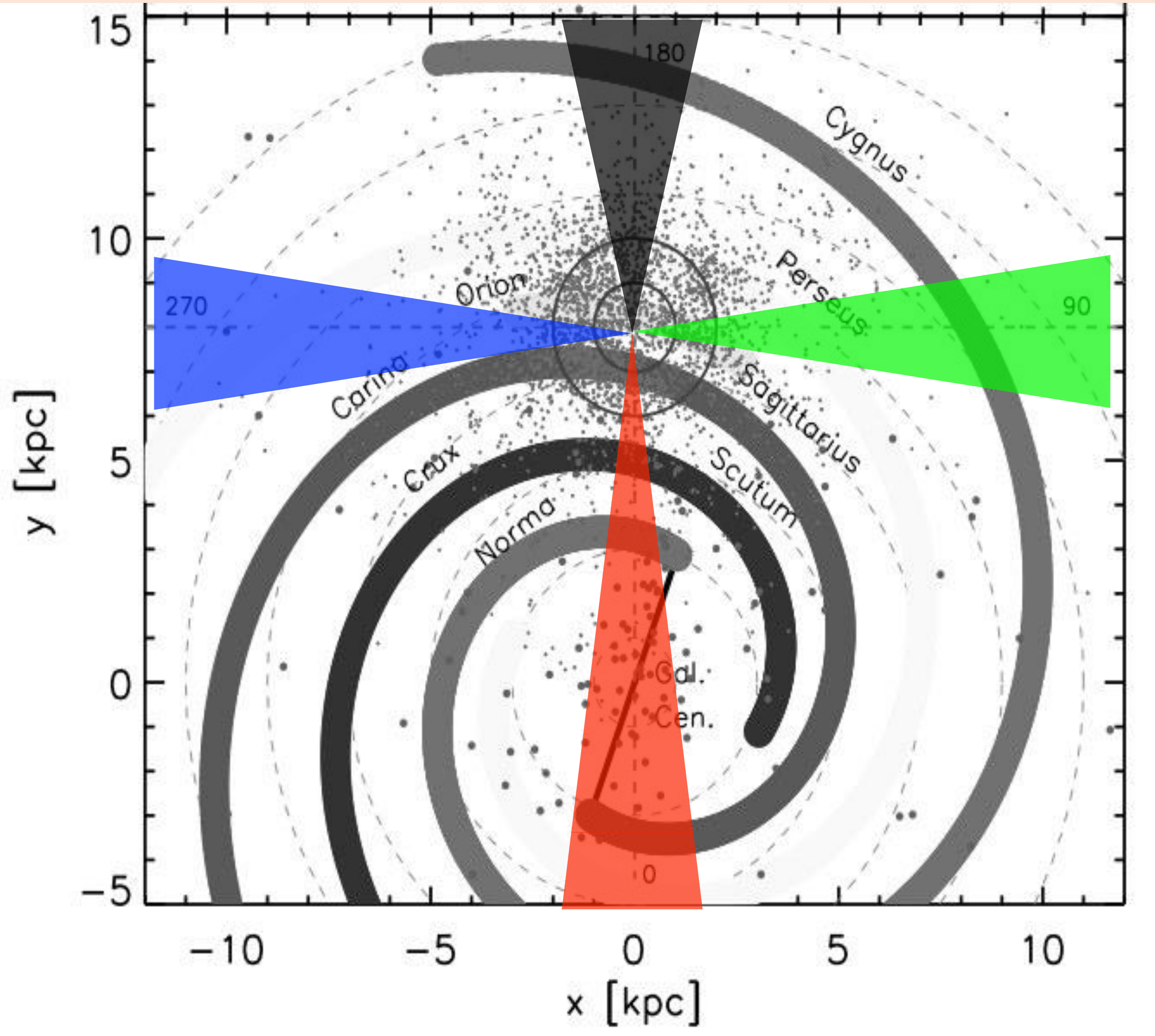
Chen, L. et al. (2003)

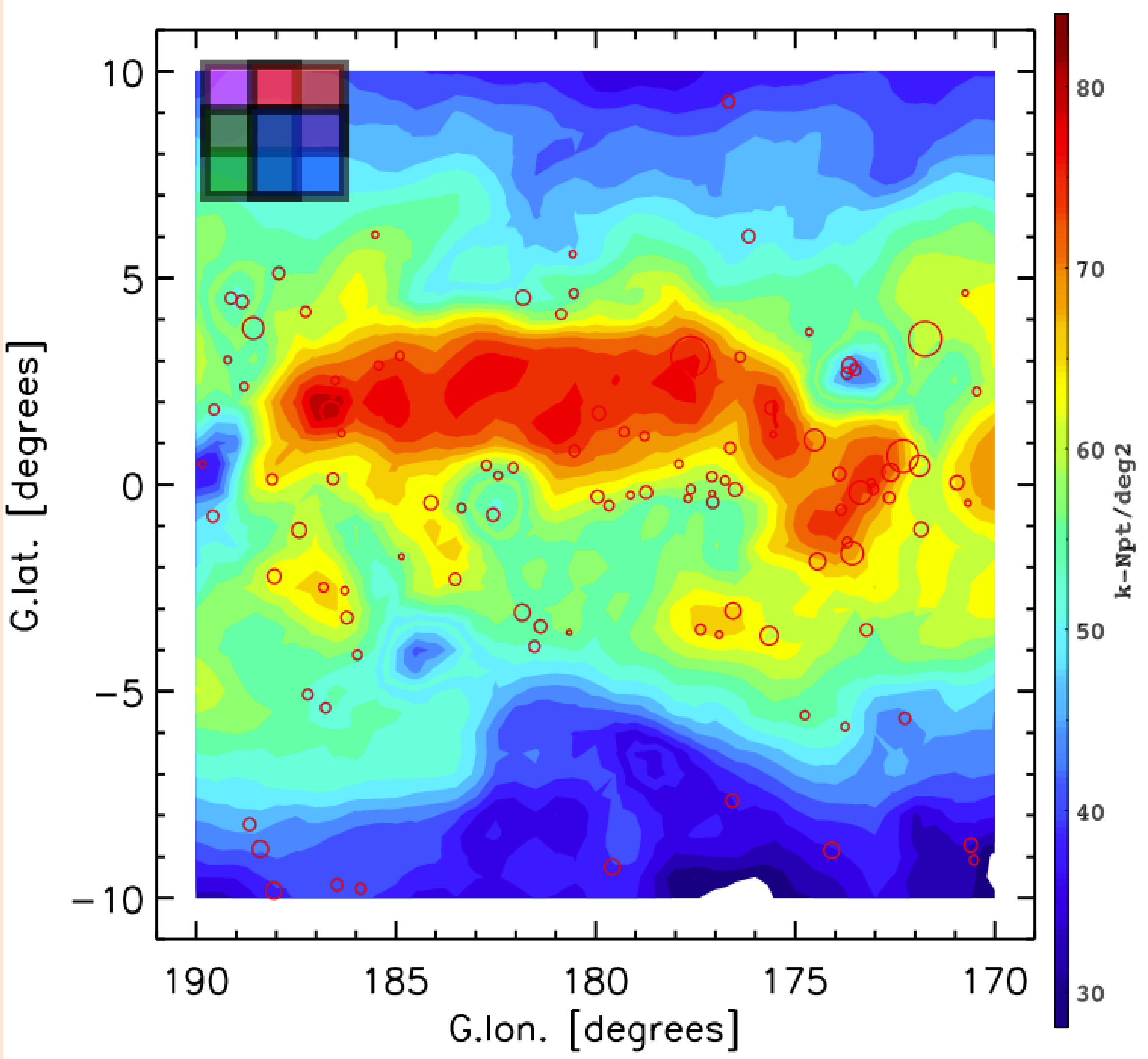
- The Galactic OC sample is **highly incomplete**.
- Some10^5 expected (Piskunov et al. 2006) ***vs*** a few 10^3 catalogued (Kharchenko et al. 2013, mostly < 2 kpc)
- Largely because of dust extinction in the solar neighborhood and lacks of systematic search



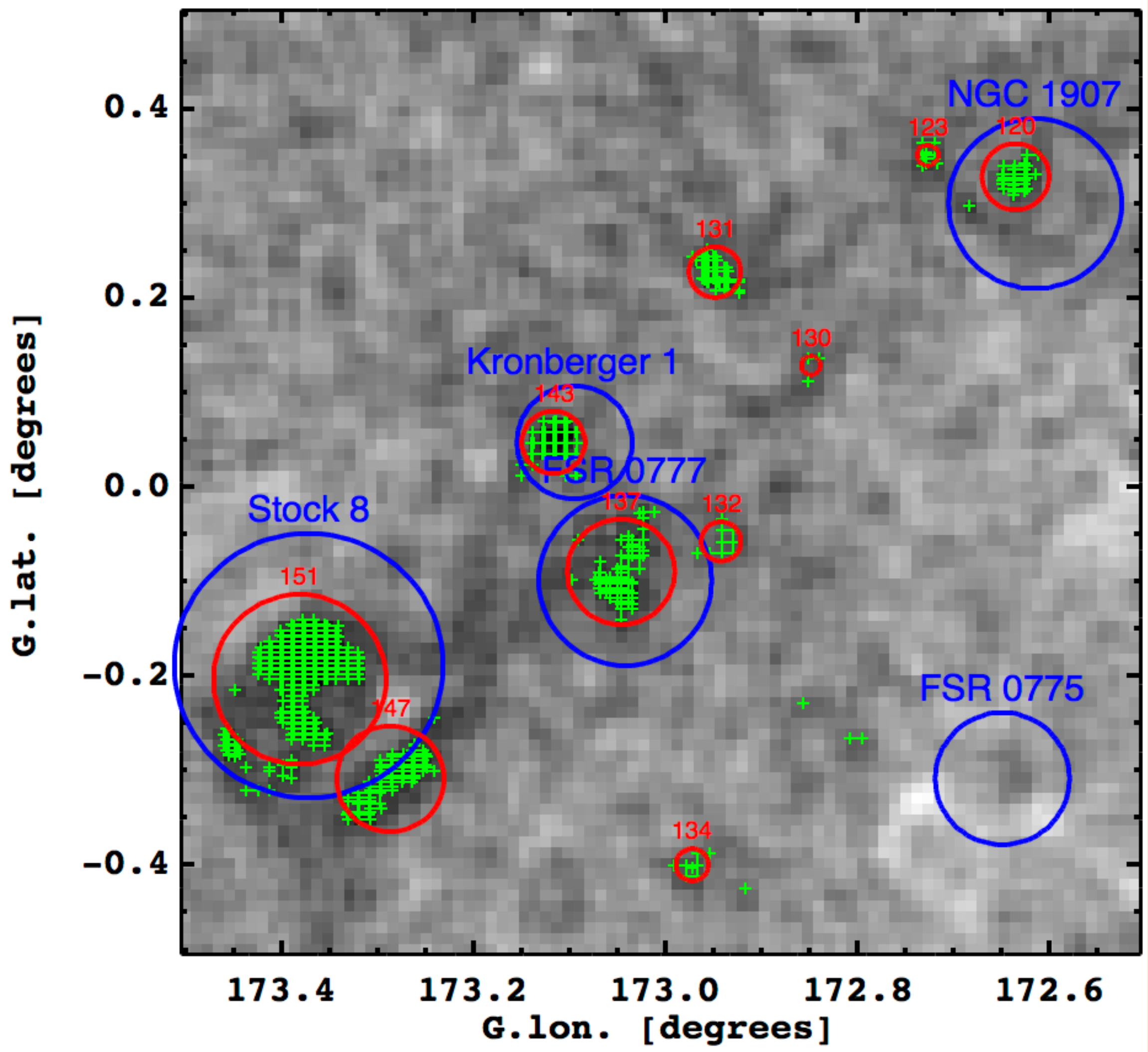
Lin et al. (2014)

Finding Uncatalogued Clusters

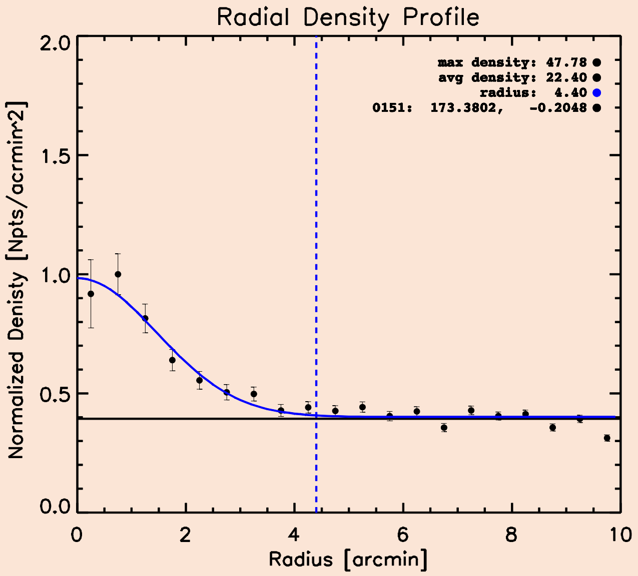




1 deg field; 0.5 deg shift
4 times overlap



- Star counting PS1 3π data to identify density enhancements as star cluster candidates
- Matched with known clusters
- Characterization (size, $N_{members}$, distance, age, spatial structure, etc.)



Stock 8
d = 1731 pc
log t = 7.05 yr
E(B-V) =0.6

1x1 deg field, each grid of 10 stars; 3 sigma above background; 3 adjacent grids

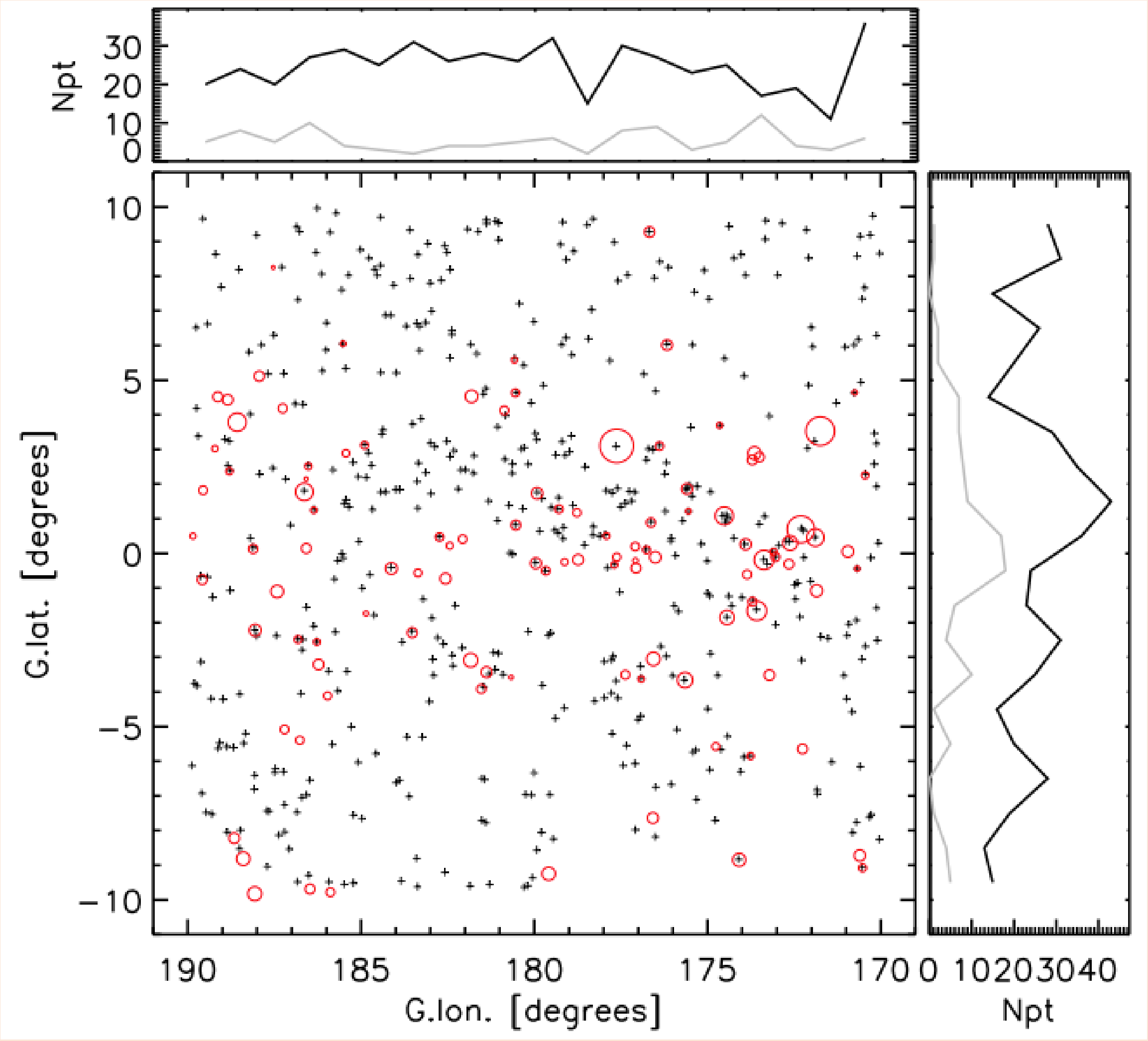
Search Results

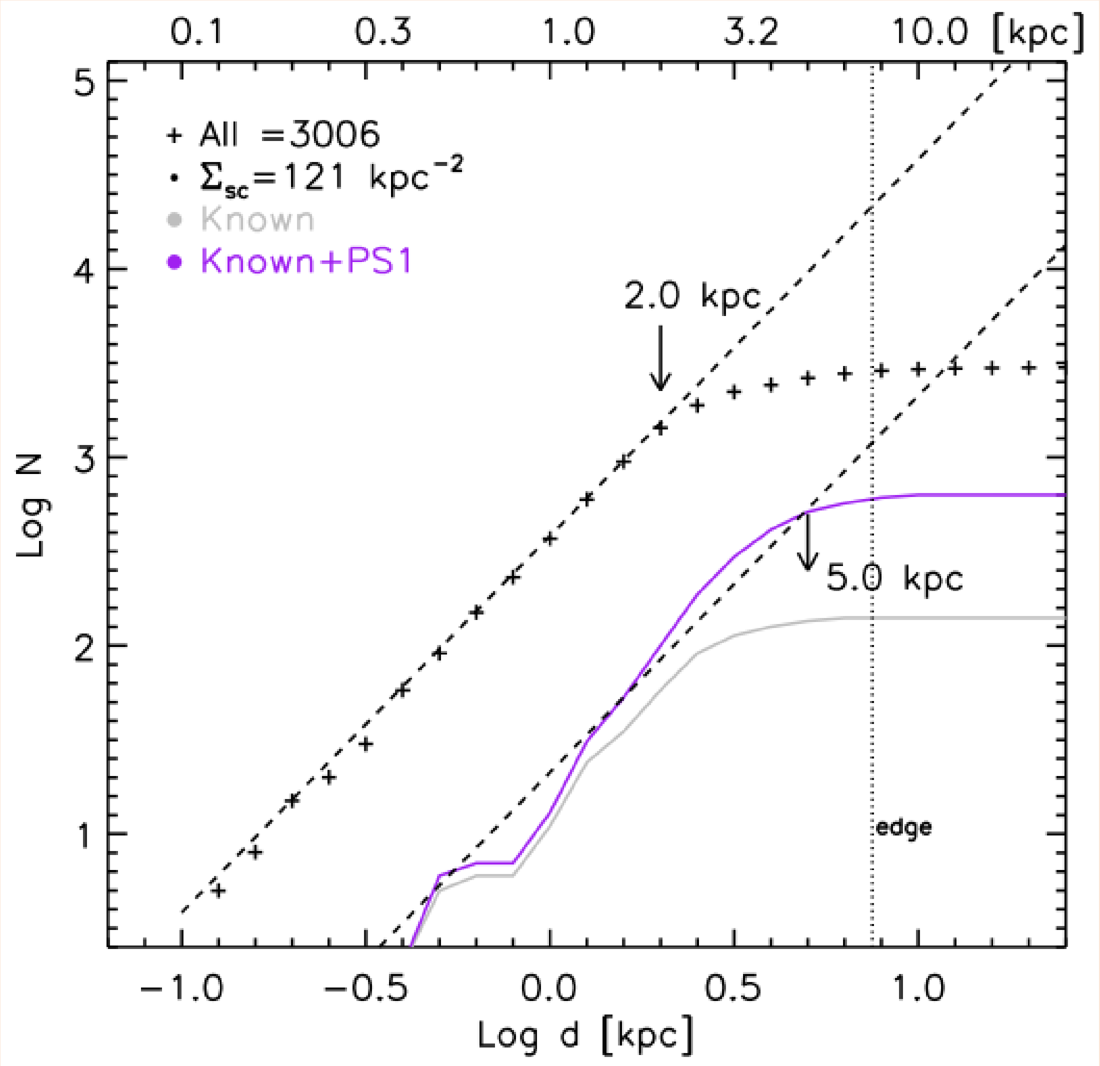
- 50 of 109 known star clusters rediscovered
  - ✓ 30 probably not real star clusters (X)
  - ✓ 13 too large > 10’ (nearby, well known) (X)
  - ✓ 2 embedded clusters (X)
  - ✓ 4 in H II regions (X)
  - ✓ 10 detected only in two dithering (3 required)
  - ➔ Detection rate 50/60 ~ 83%

Limiting mass:
$0.25\ M_\odot$ at 1 kpc
$0.7\ M_\odot$ at 4 kpc

- Additional 491 candidates identified
  - ✓ Preliminary characterization
  - ✓ Detailed follow-up studies underway

The revised open cluster sample toward the Galactic anti-center is complete from current 1-2 kpc up to ~5 kpc



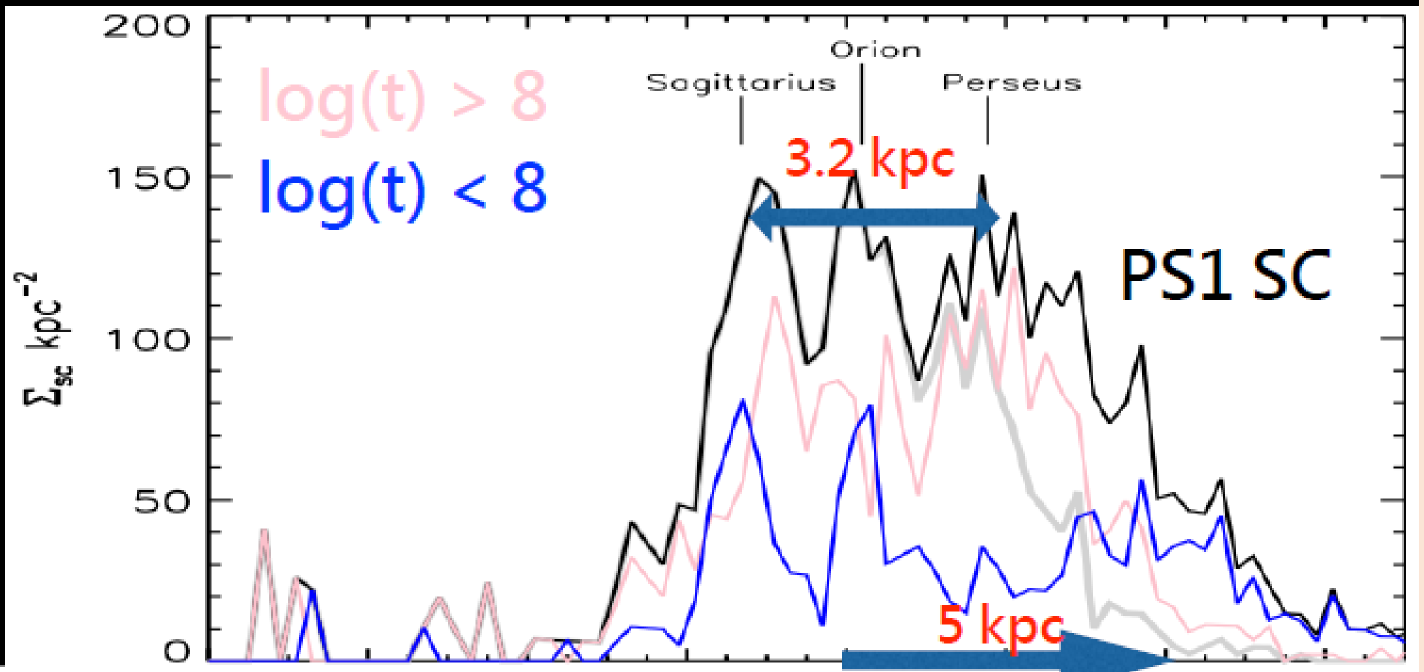


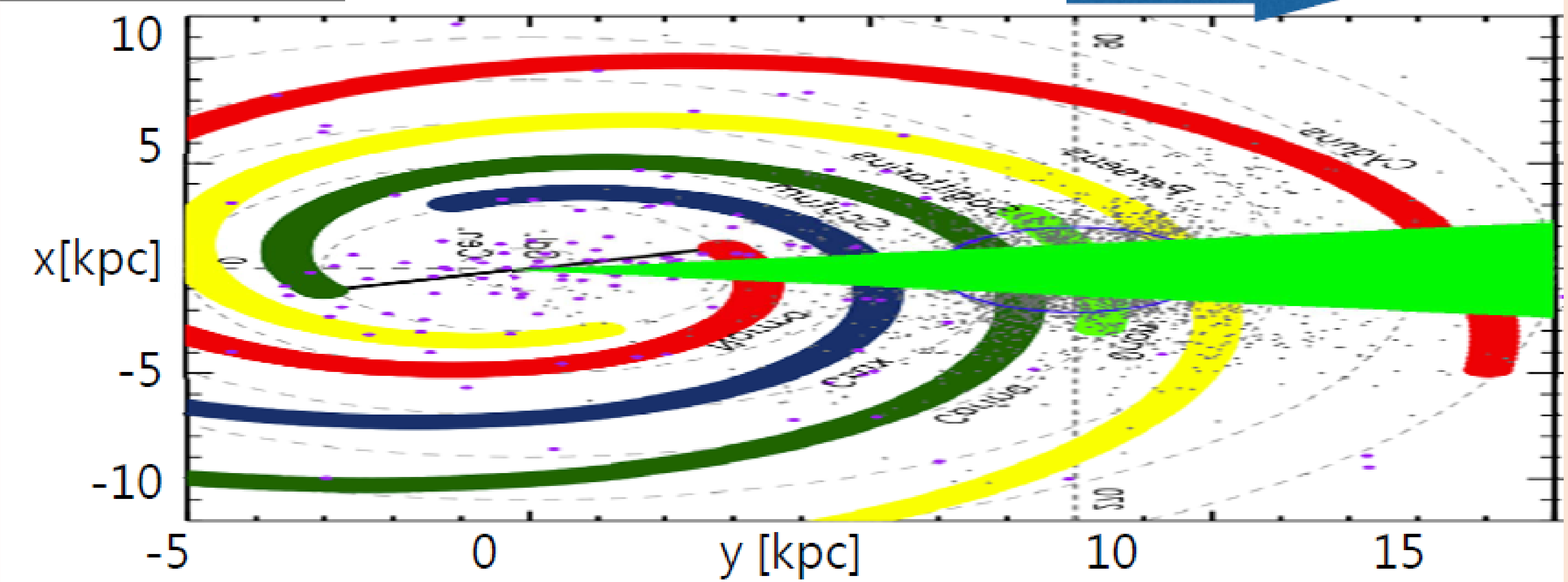
Probing Spiral Arms

Sagittarius:
450±50 pc

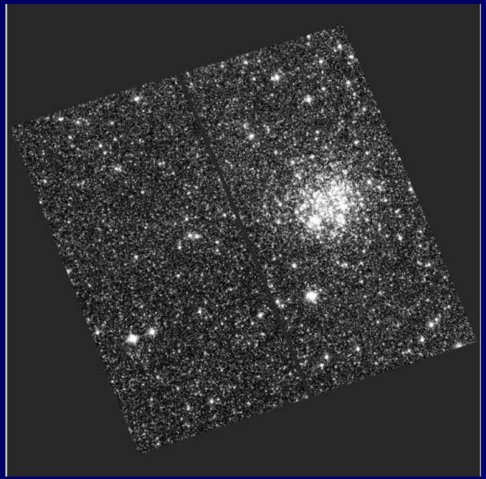
Orion:
400±50 pc

Perseus:
800±100 pc

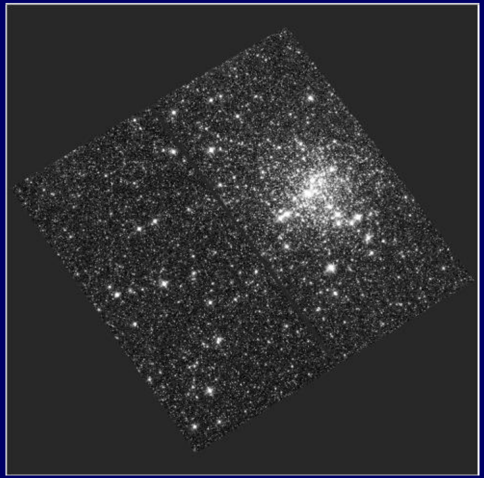




Star Clusters in LMC



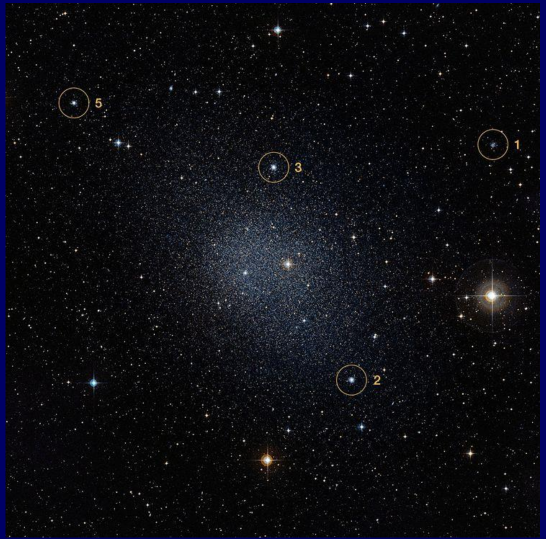
NGC2107 (e_{k89}=0.88)

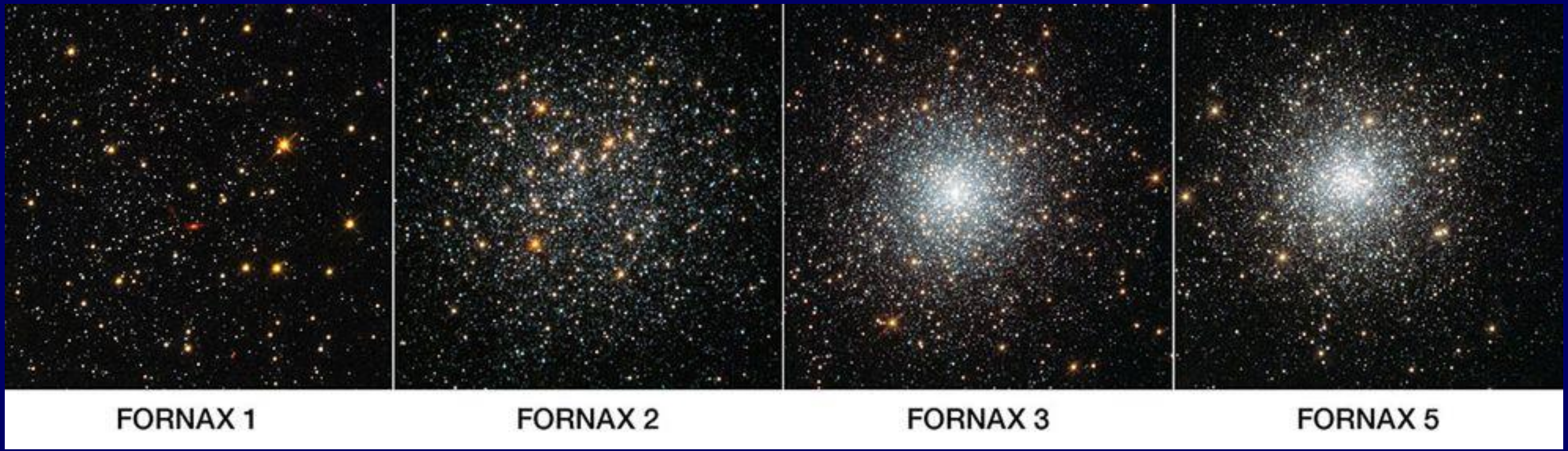


NGC1751 (e_{k89}=0.85)

Globular Clusters in the Fornax Dwarf Galaxy

Where are the old stars?





Super Star Clusters

- ✓d =8500 pc
- ✓τ = 4~5 Myr
- ✓Many peculiar stars: 6 yellow supergiants, 4 red supergiants, 24 Wolf-Rayet stars, 1 luminous blue variable, 1 supergiant sgB[e] (a recent merger?)
- ✓Precursor of a globular cluster?

Westerlund 1 (= Ara Cluster) in Milky Way

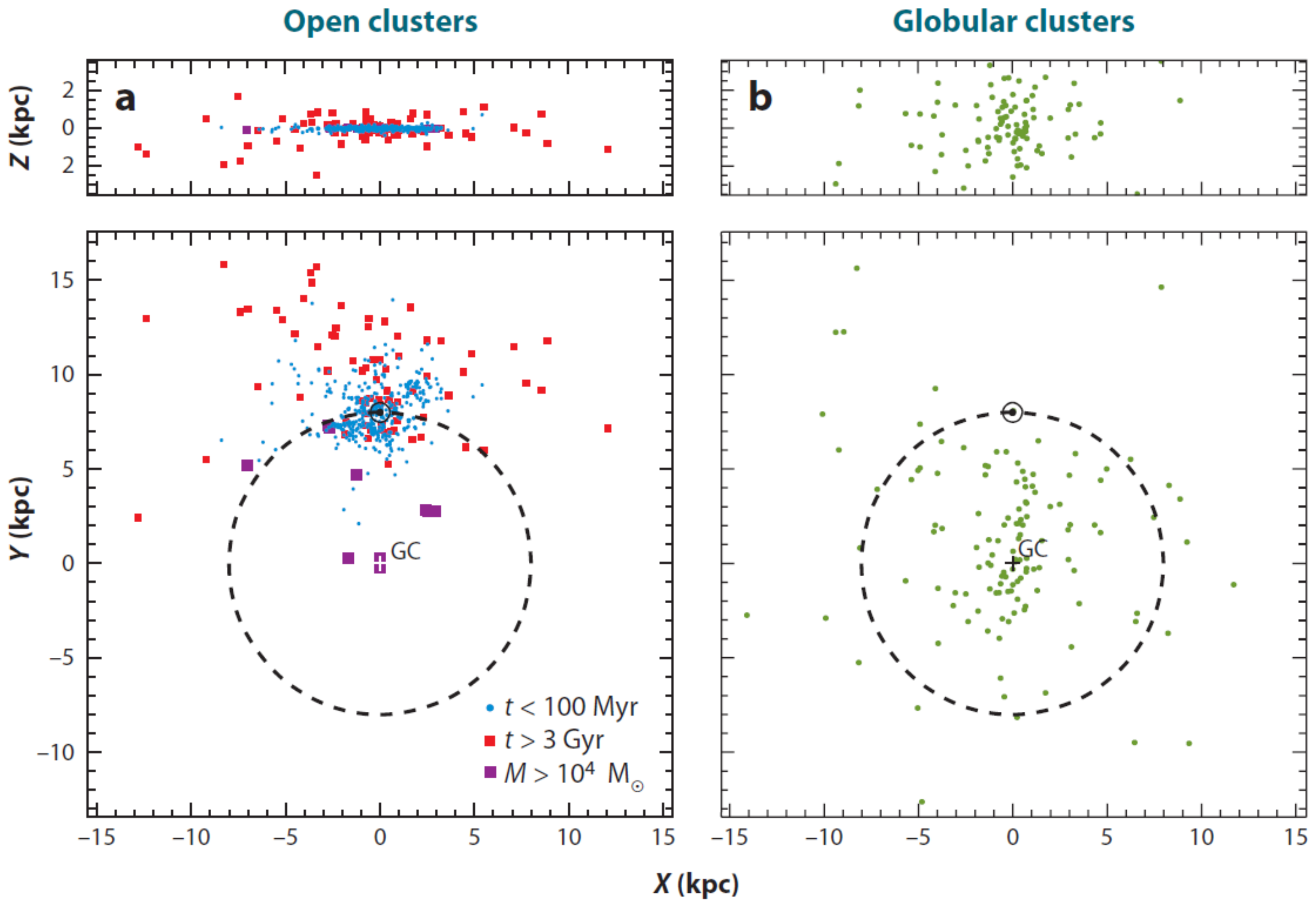


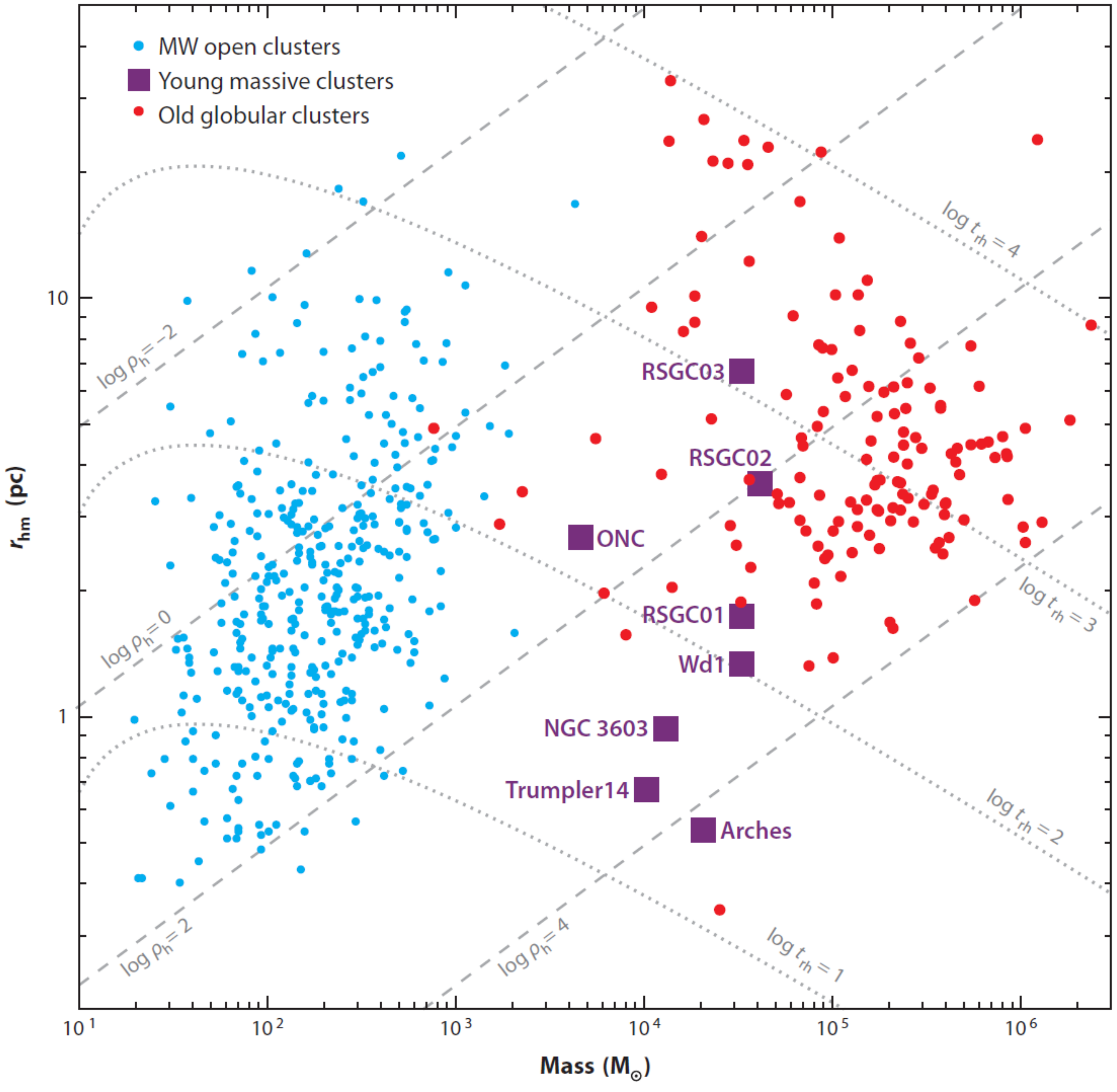
Figure 1

(*a*) Distribution of young (<100 Myr, *filled blue circles*) and old (>3 Gyr, *filled red squares*) open clusters in the Galactic plane, based on the catalog of Dias et al. (2002). The old open clusters are found preferentially toward the Galactic anticenter and above the plane compared to the young open clusters. The young massive clusters (*purple squares*) are located within the solar circle, which is probably a selection effect caused by the higher star-formation rate (per unit area) toward the Galactic center. (*b*) Distribution of old globular clusters; data from the Harris (1996) catalog.

Young massive clusters are like

disk population
↔ Open clusters

Portegies Zwart+10, ARAA

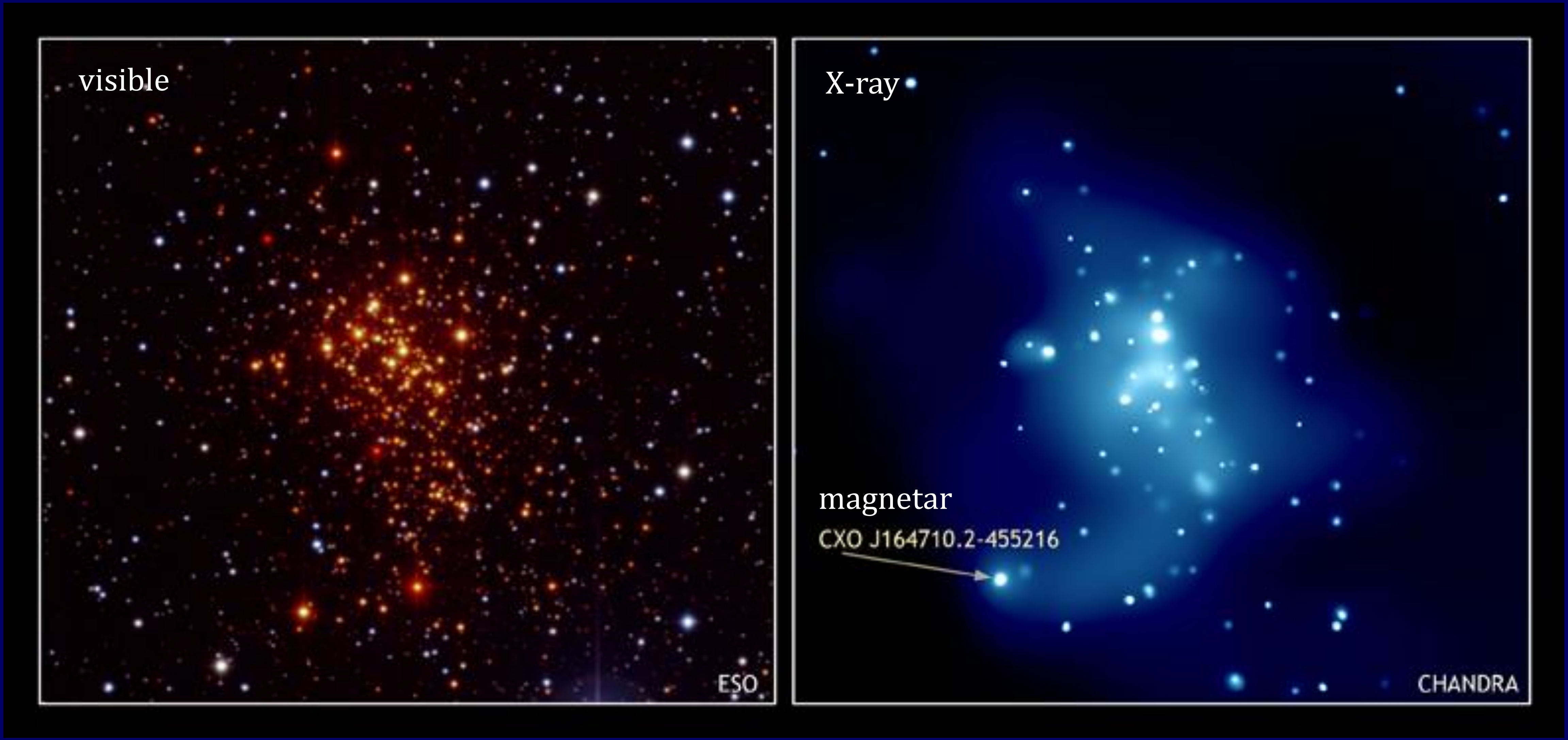


Young massive clusters behave like,
in mass-radius
↔ Globular clusters

Default mode of cluster formation?

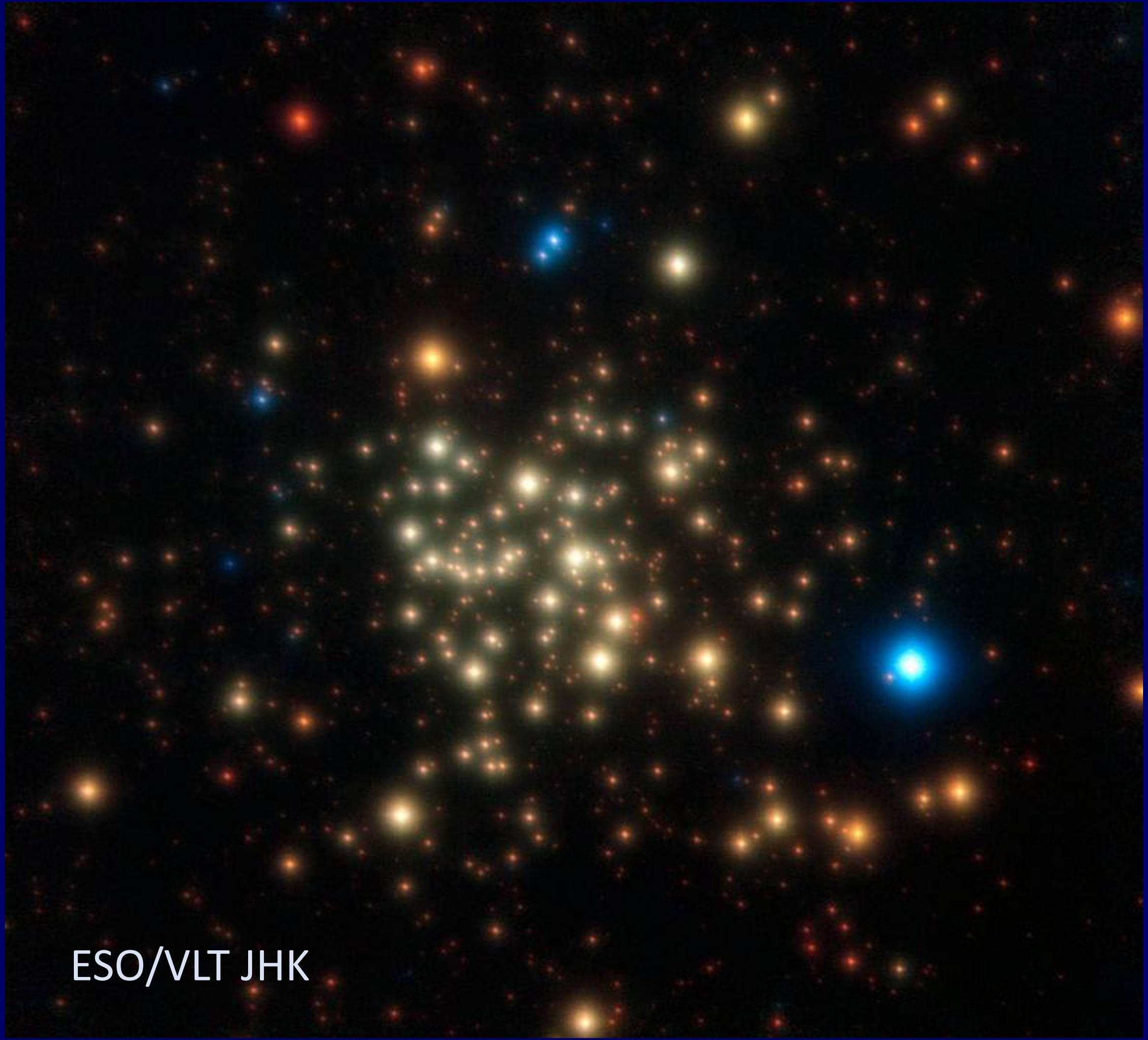
Figure 2

Radius-mass diagram of Milky Way open clusters, young massive clusters, and old globular clusters. Open cluster half-mass radii $r_{\rm hm}$ (see Section 1.3.2) and masses are taken from studies by Dias et al. (2002) and Lamers et al. (2005, and private communication), respectively. Data for the young massive clusters are discussed in more detail in Section 2. Globular cluster data are taken from the Harris catalog. Gray dashed and dotted lines represent constant half-mass density $\rho_{\rm h} = 3M/8\pi r_{\rm hm}^3$ and half-mass relaxation time $t_{\rm rh}$ (Equation 17), respectively.



The hot OB supergiants in Wd1 primarily emit blue light – however they appear as red stars in the visible light image on the left, as all the blue light from the stars has been absorbed due to the large interstellar reddening.

Survivor Star Clusters



- ✓$\alpha = 17^h\,45^m\,50.5^s$
- ✓$\delta\ = 28°\,49'\,28''$
- ✓d =8500 pc
- ✓Optically obscured
- ✓100 ly from the GC
- ✓$\tau\ = 2\sim4$ Myr
- ✓Many young, massive stars
- ✓Stars $> 150\ \mathcal{M}_\odot$?

Arches Cluster toward the Galactic center

Extended Globular Clusters

There is a new kind of star clusters in addition to open clusters and globular cluster …

- ☐ similar to globular clusters in number of members and metallicity
- ☐ but with much larger sizes
- ☐ so not as dense as globular clusters.

For example, in M31:

M31WFS C1, M31WFS C2, and M31WFS C3

Nuclear Star Clusters

5.6 Properties of the Milky Way nuclear star cluster

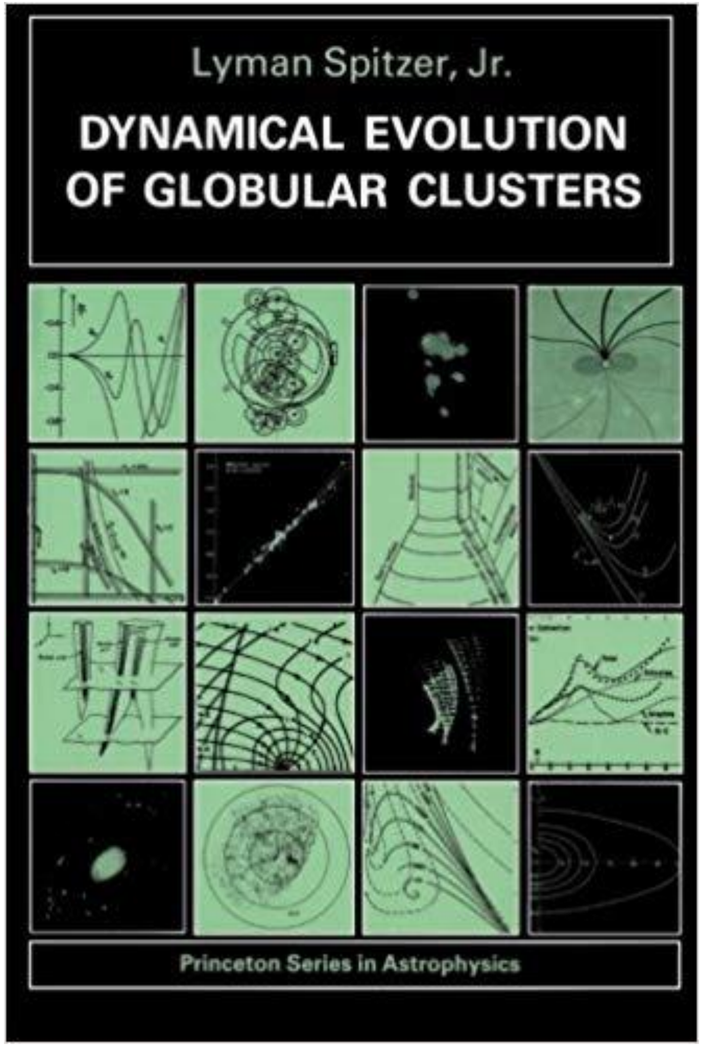
The NSC at the heart of the Milky Way warrants a special attention, because its proximity ($d = 8.1 \pm 0.1$ kpc, Gravity Collaboration et al. 2019; Do et al. 2019) offers a unique opportunity to study physical processes on scales that are impossible to resolve in external NSCs (at $d = 8.1$ kpc, $1'' = 0.04$ pc). In this section, we, therefore, provide a brief summary of the properties of the Milky Way NSC. For a more comprehensive overview, we refer the reader to the recent reviews by Genzel et al. (2010) and Schödel et al. (2014b).

Neumayer+2020

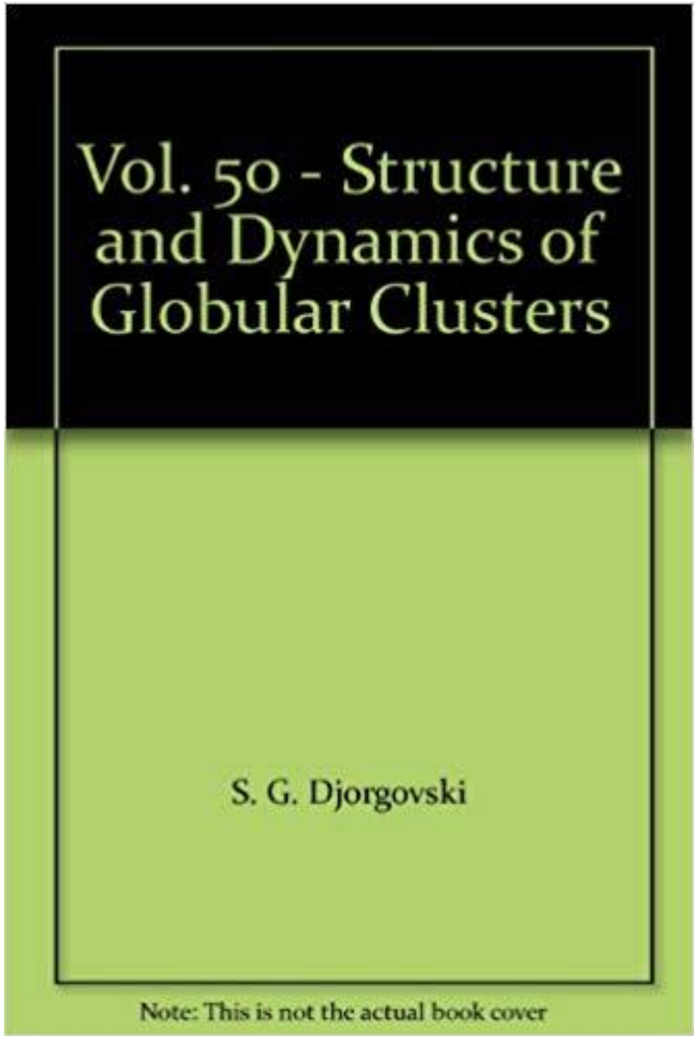
- Star clusters serve as a good test bed for star formation and evolution theories. ***Which theory is more favorable? Under what conditions?***
- Star clusters serve to probe the Galactic structure and evolutionary history. ***How did the formation of thick/thin disks proceed?***
- Star clusters are born big; youngest star clusters bear the imprint of molecular cloud structure. ***Why do massive stars tend to be centrally concentrated?***
- Low-mass stars are 'evaporated' as the result of mutual gravitational interactions among members (+ external tidal perturbation) ***How did a star cluster shape up/down?***
- A cluster eventually dissolves. ***Do they die young?***
- Do galactic environments influence the origin of stellar masses? ***How is the IMF influenced by the environments?***

Conclusion

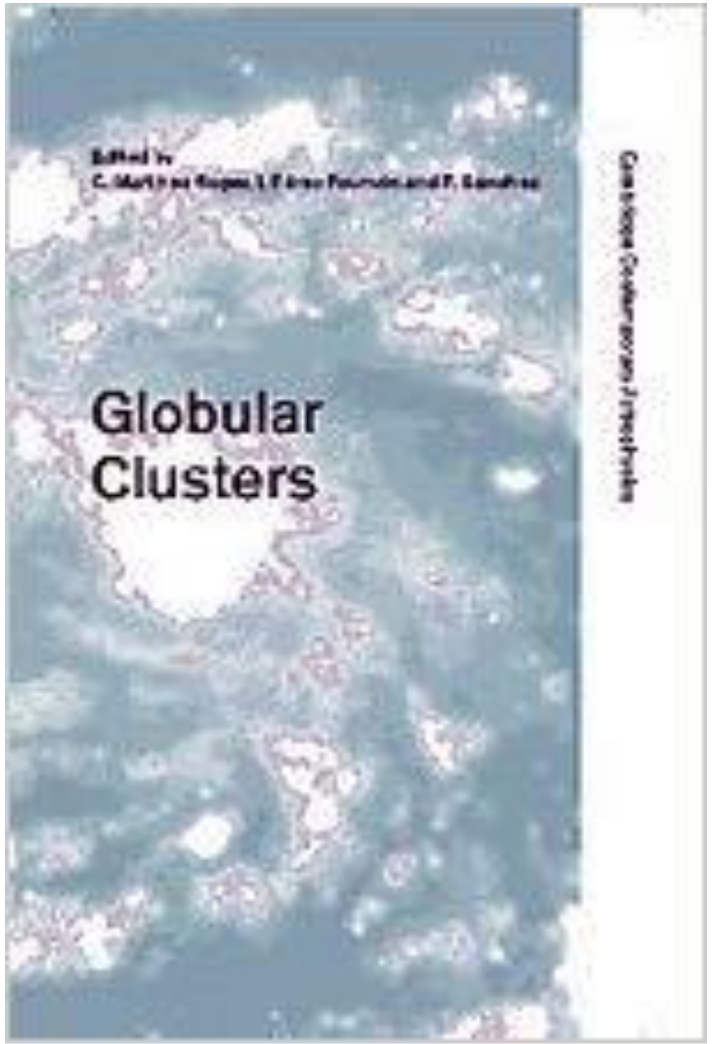
- Nothing of an “old” topic
- Time ripe to study star clusters in quality and in quantity
- Gaining ever more knowledge than before of the long known and studied star clusters, with new answers and new questions---larger vs smaller systems; much massive vs very low-mass members; systems in MW vs beyond.
- Expanding the sample of star clusters, including in nearby galaxies; useful in studies of stellar evolution, and Galactic structure/evolution



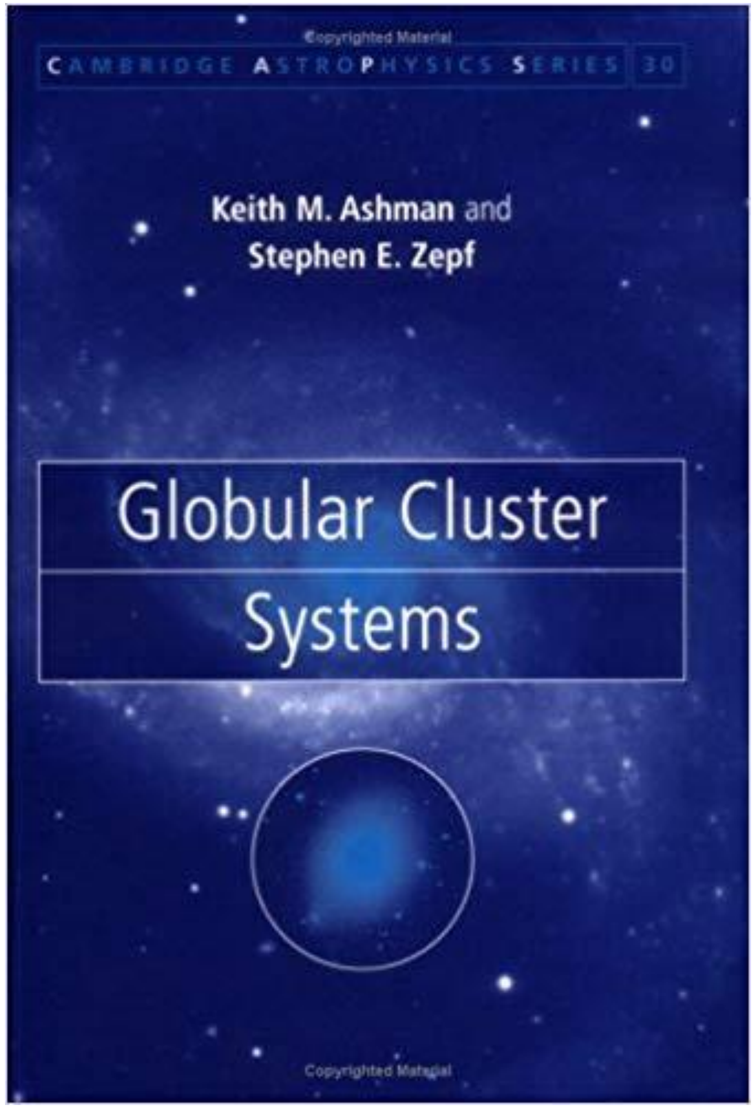
1988



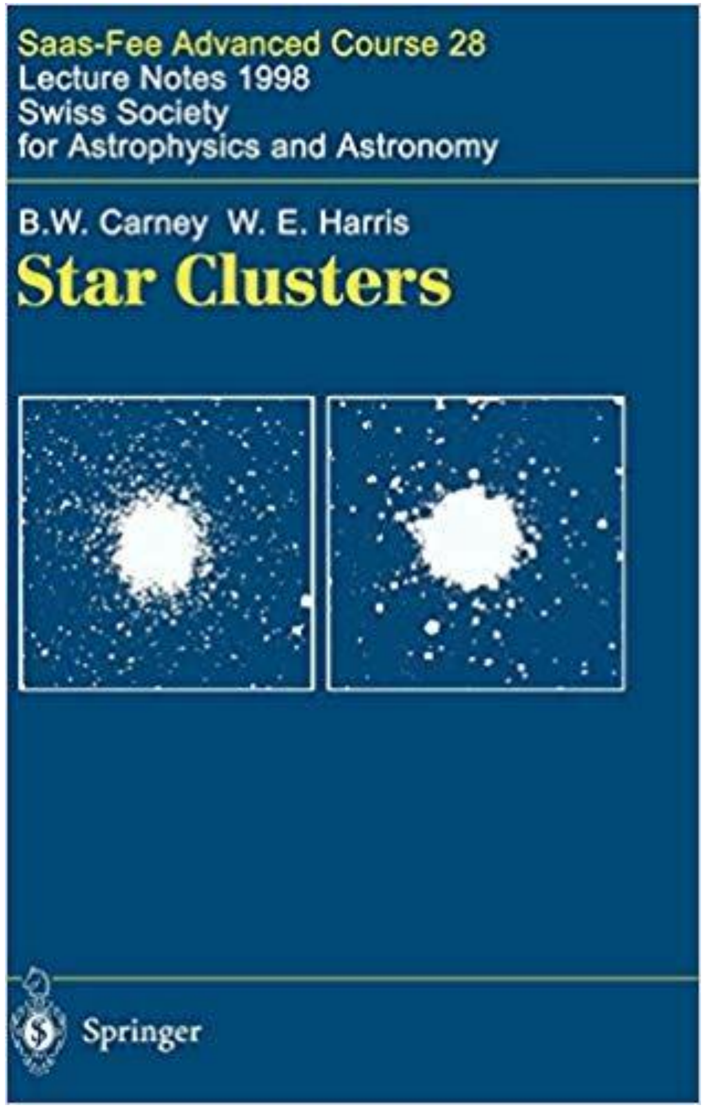
1993



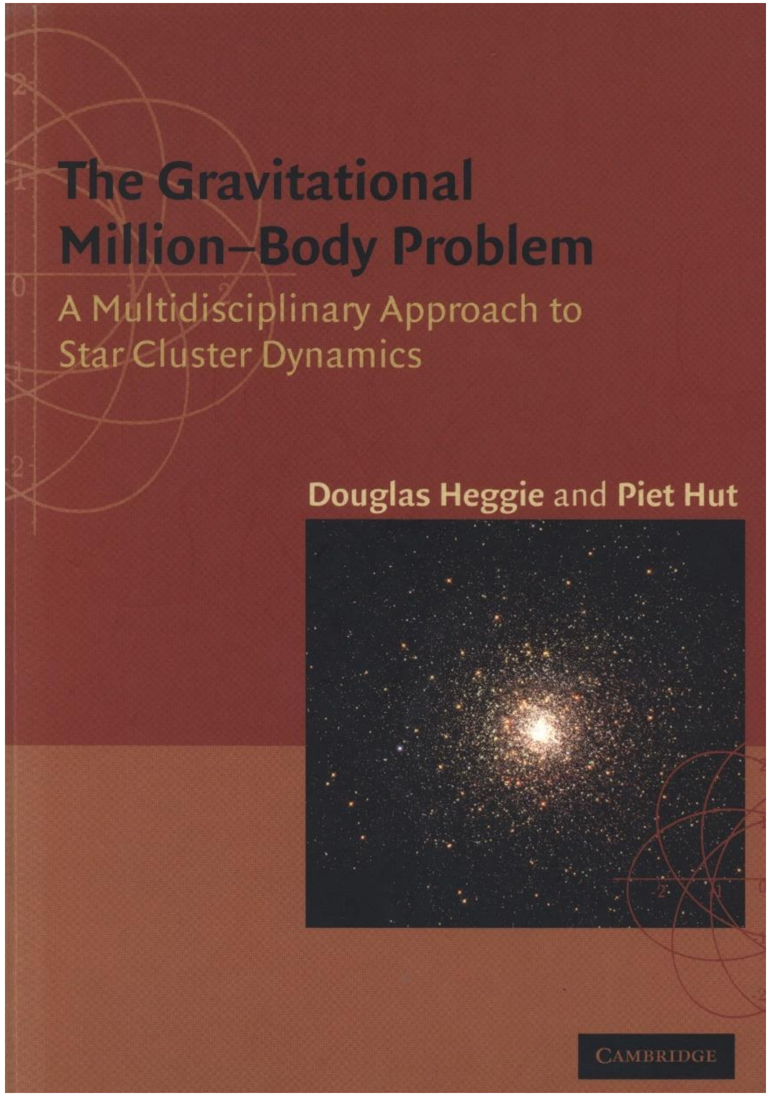
1999



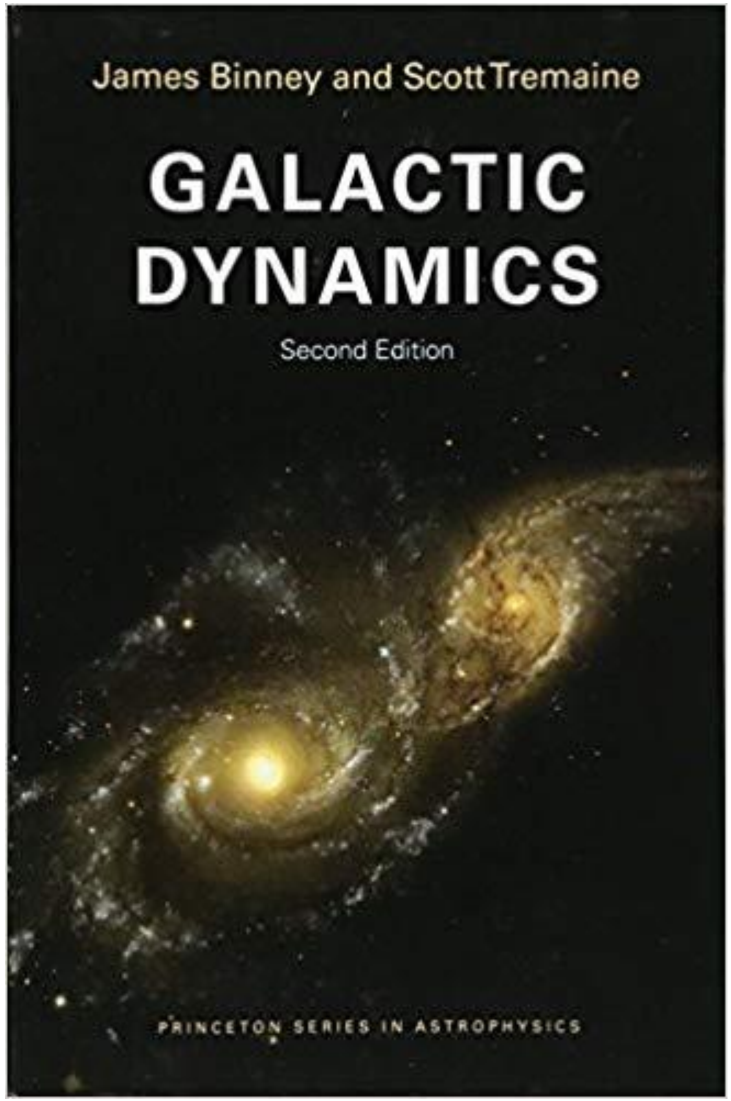
2001



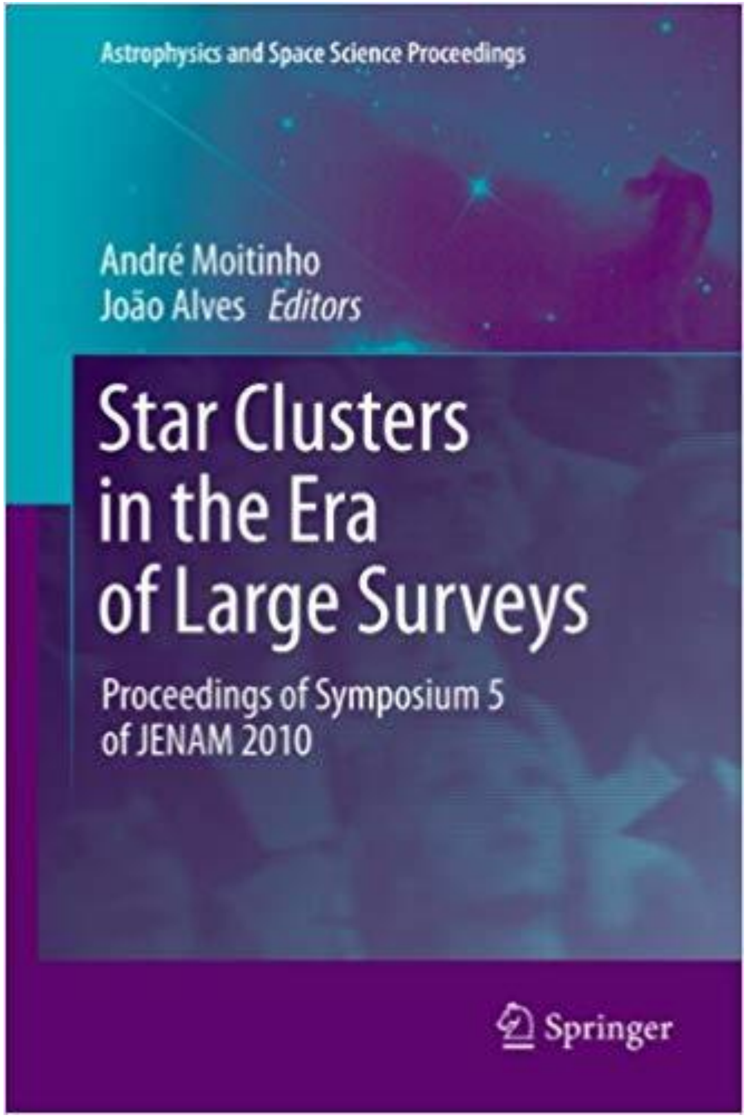
2001



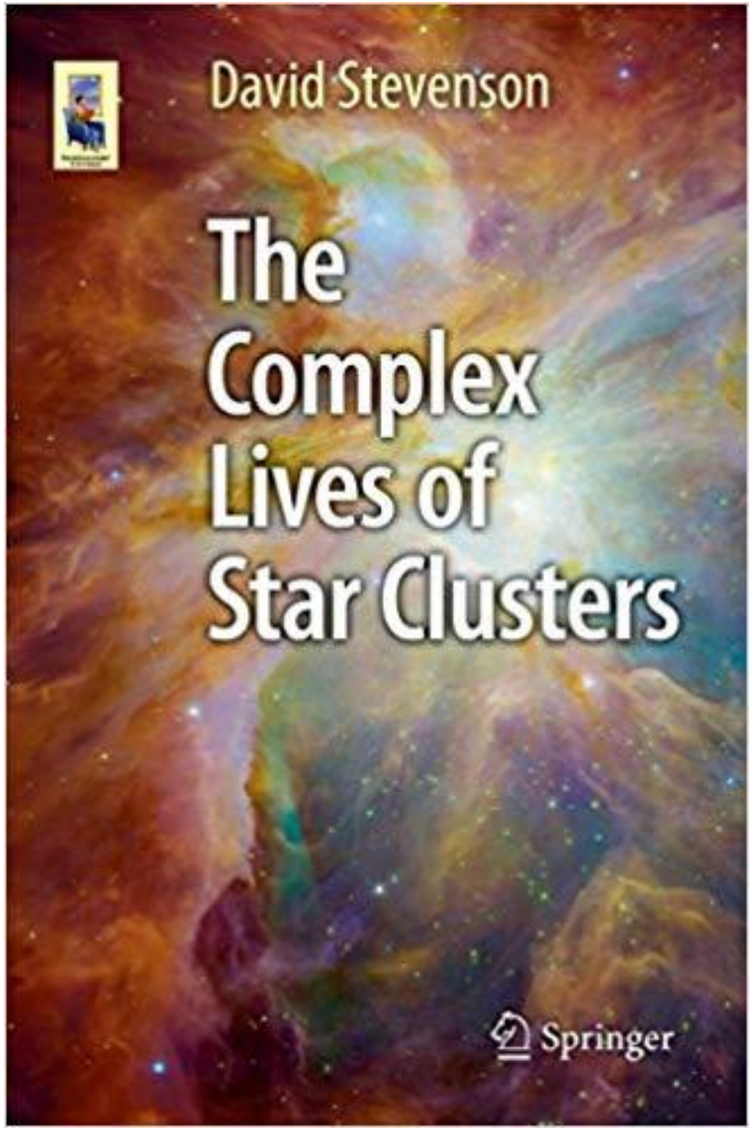
2003


James Binney and Scott Tremaine
GALACTIC DYNAMICS
Second Edition
PRINCETON SERIES IN ASTROPHYSICS

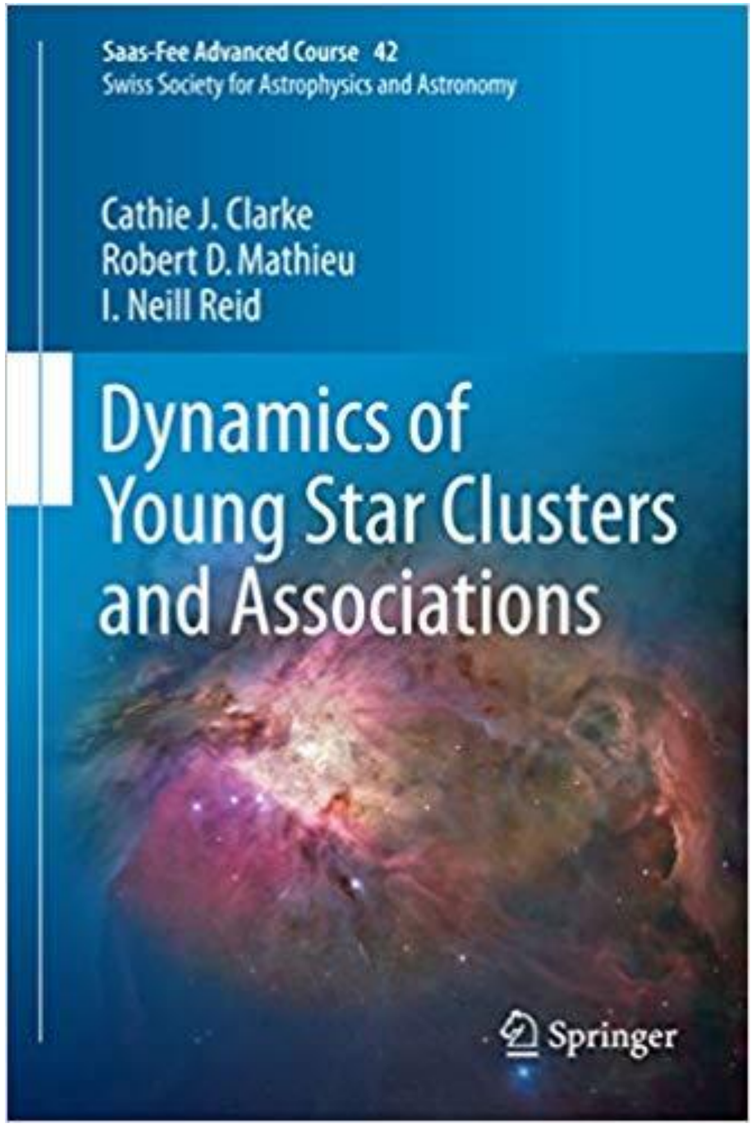
2008


Astrophysics and Space Science Proceedings
André Moitinho
João Alves Editors
Star Clusters in the Era of Large Surveys
Proceedings of Symposium 5 of JENAM 2010
Springer

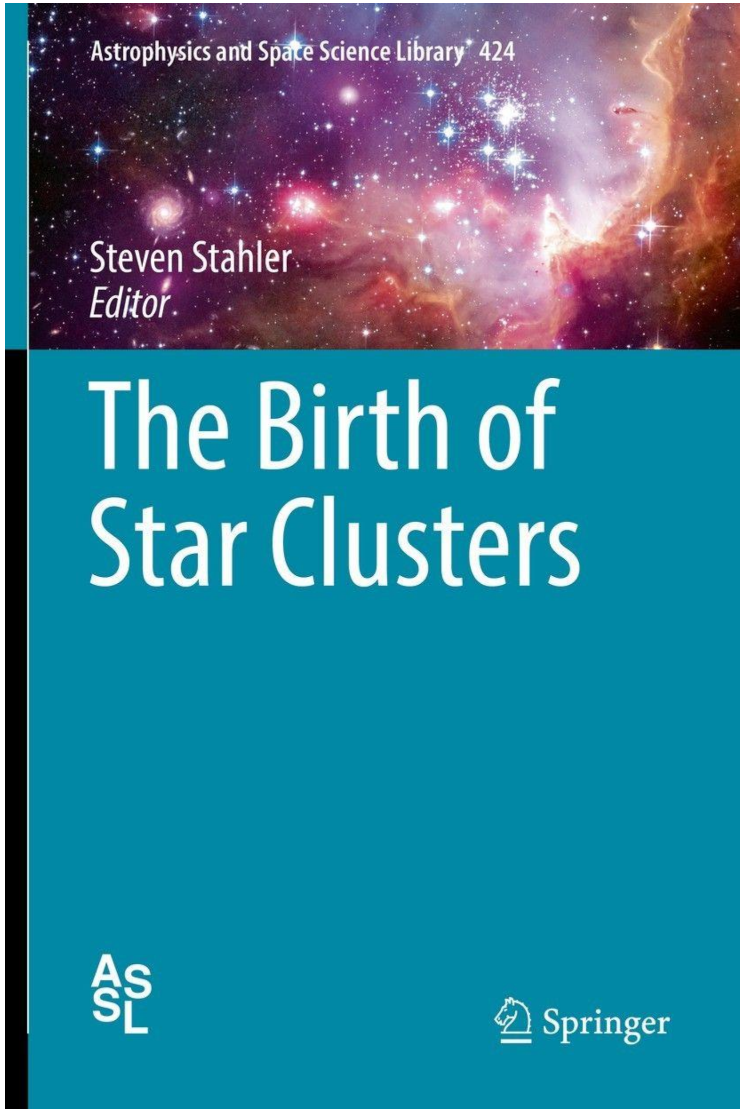
2012



2015



2015



2018

Lulin Observatory

Lon: 120° 52' 25" E
Lat: 23° 28' 07" N
Alt: 2,862 m
in central Taiwan
Sky 21.28 mag/sq"
Data: 1,450 hrs/yr

. One-Meter
. (TAOS 50 cm × 4)
. SLT 40
. LWT40
. L35

+ Experiments of meteorology, space and earth sciences

Panoramic Survey Telescope And Rapid Response System (Pan-STARRS)

DR2@MAST

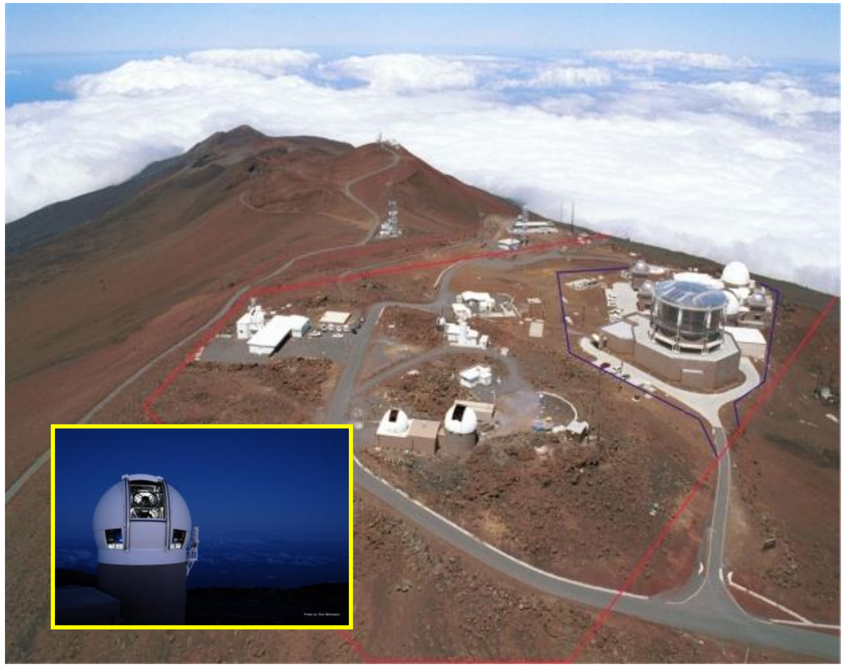
PS1 + PS2

Haleakala, HI, USA

D=1.8 m; 1.4 Gpix

Etendue=50 $m^2 deg^2$

(84 for Subaru/HSC; 319 for LSST)



Zwicky Transient Facility (ZTF)

DR1@IPAC

Palomar, CA, USA

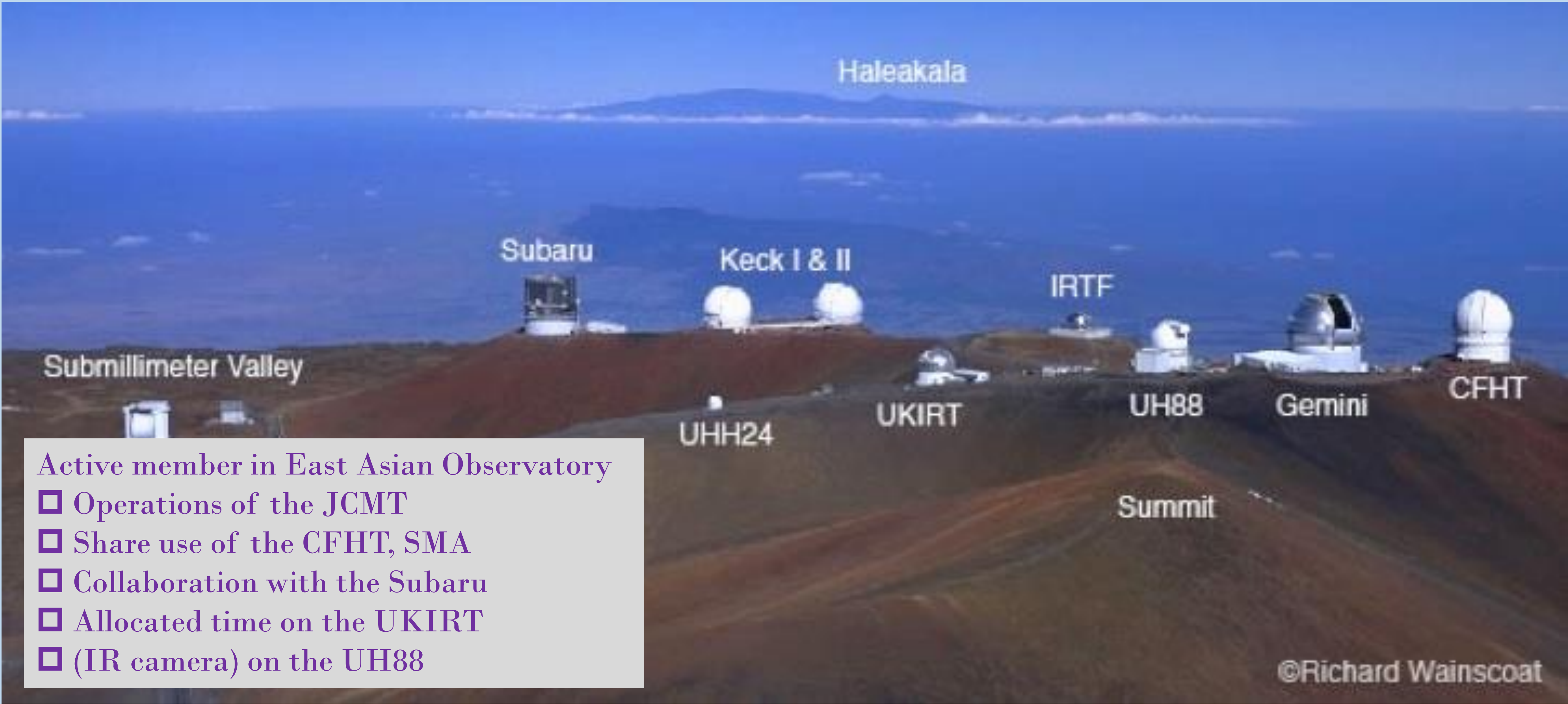
3750 sq deg an hour to 20.5 mag

48” (1.2 m) sky survey 47 sq deg

60” (1.5 m) classification SEDM

200” (5 m) spectroscopy

Maunakea Observatory



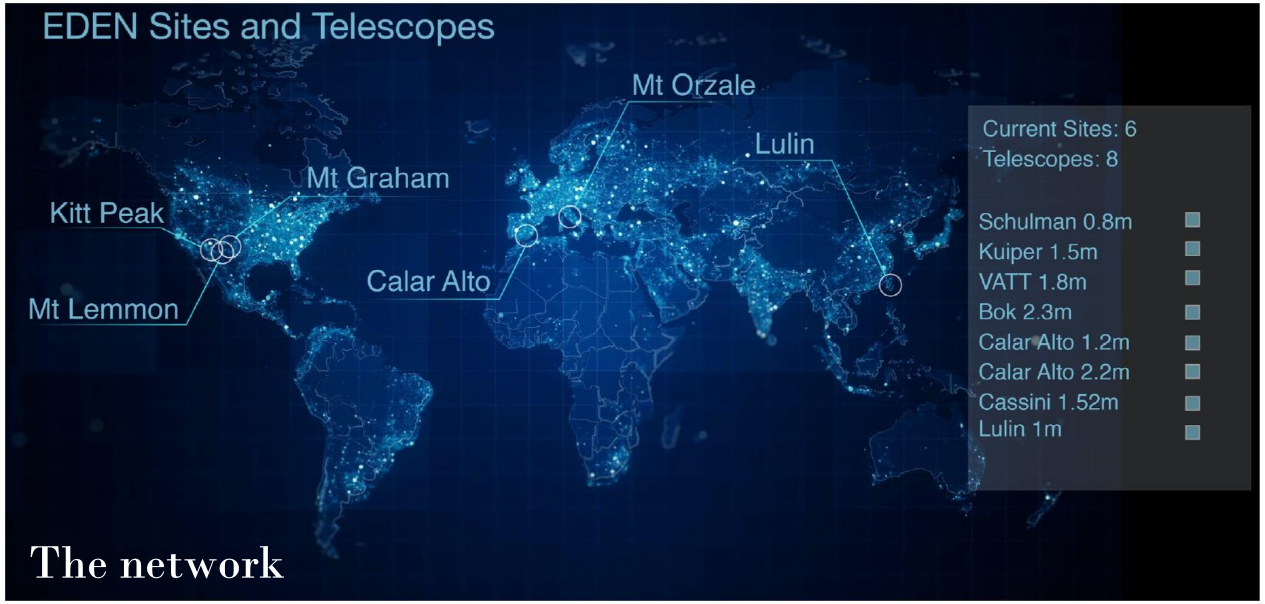
Active member in East Asian Observatory

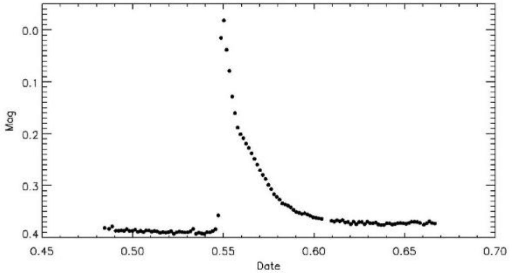
- Operations of the JCMT
- Share use of the CFHT, SMA
- Collaboration with the Subaru
- Allocated time on the UKIRT
- (IR camera) on the UH88

Exoearth Discovery and Exploration Network (EDEN)

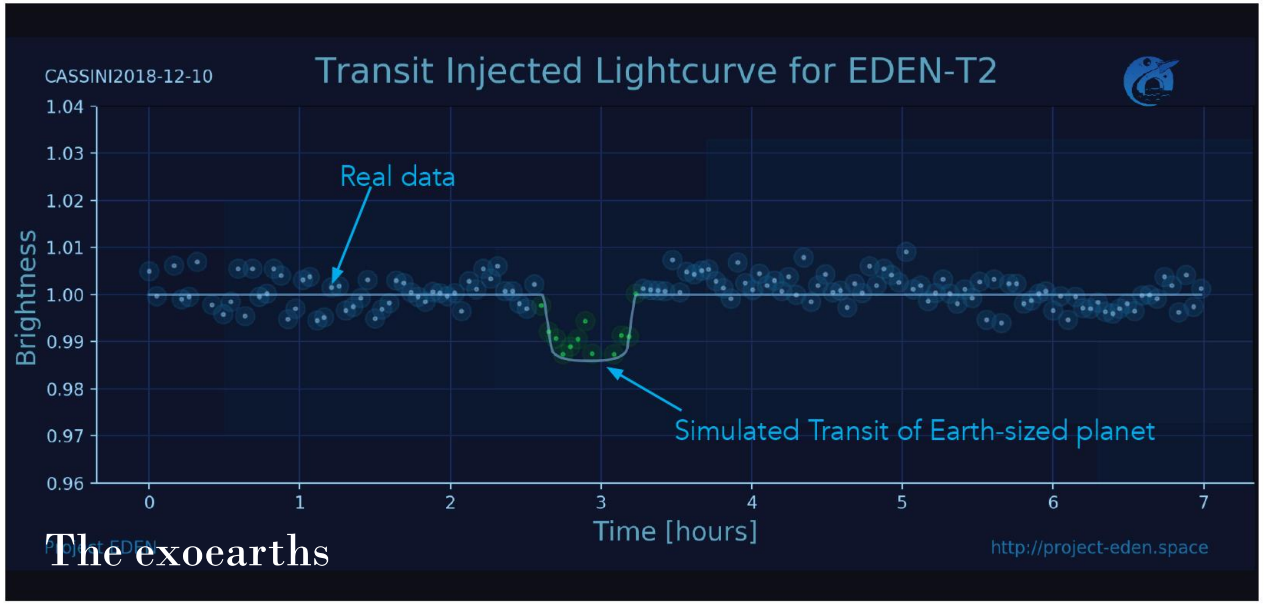
… habitable exoearths around nearby M dwarfs

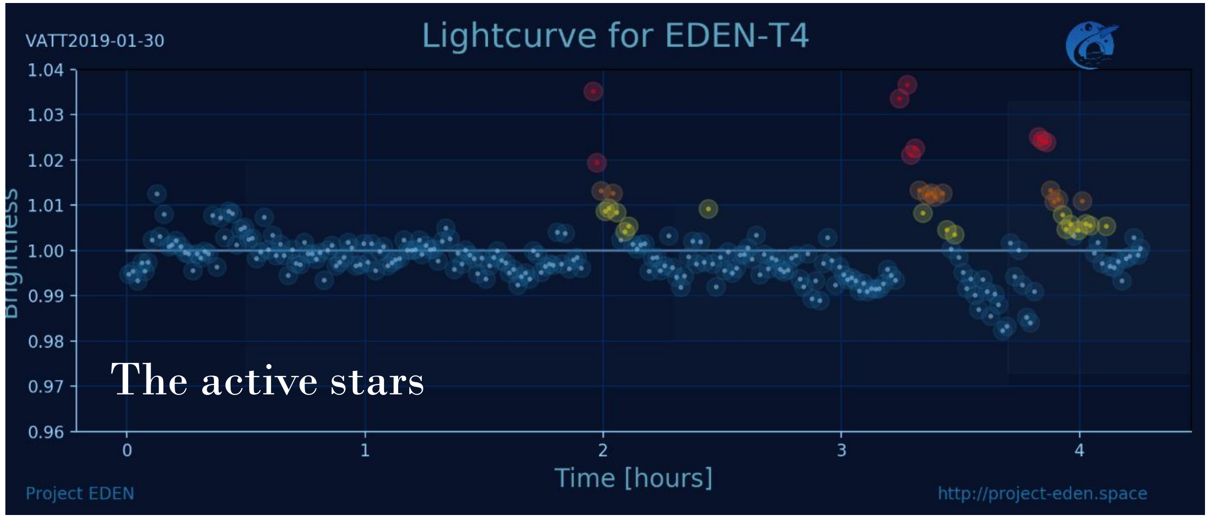
Exploring our neighborhood one paradise at a time …





PI: Daniel Apai
(U Arizona)





NCU Two-Meter Telescope **By 日本西村公司 (Nishimura)**

- ◆ Planned to install @Lulin, to secure the discoveries of PS1 6 hours lead time; with first-light instruments: (1) a 4-color (*rizy*) simultaneous imager, (2) a *JHK* imager
- ◆ Hampered by the environment impact study, construction permit, budget cycles …
- ◆To be installed at VRTS in Chile with ShAO（上海天文台）, CAS South America Center for Astronomy （中智中心）and UCN

2010/03

2019/01

Seeing 0.5”

Clear nights 85%

On the short list as one of the potential sites for the ESO ELT

Overall considerations

- ✓ Sky quality
- ✓ Accessibility, water and power supply
- ✓ political stability