# Stellar Siblings: How Multiple Star Systems Form

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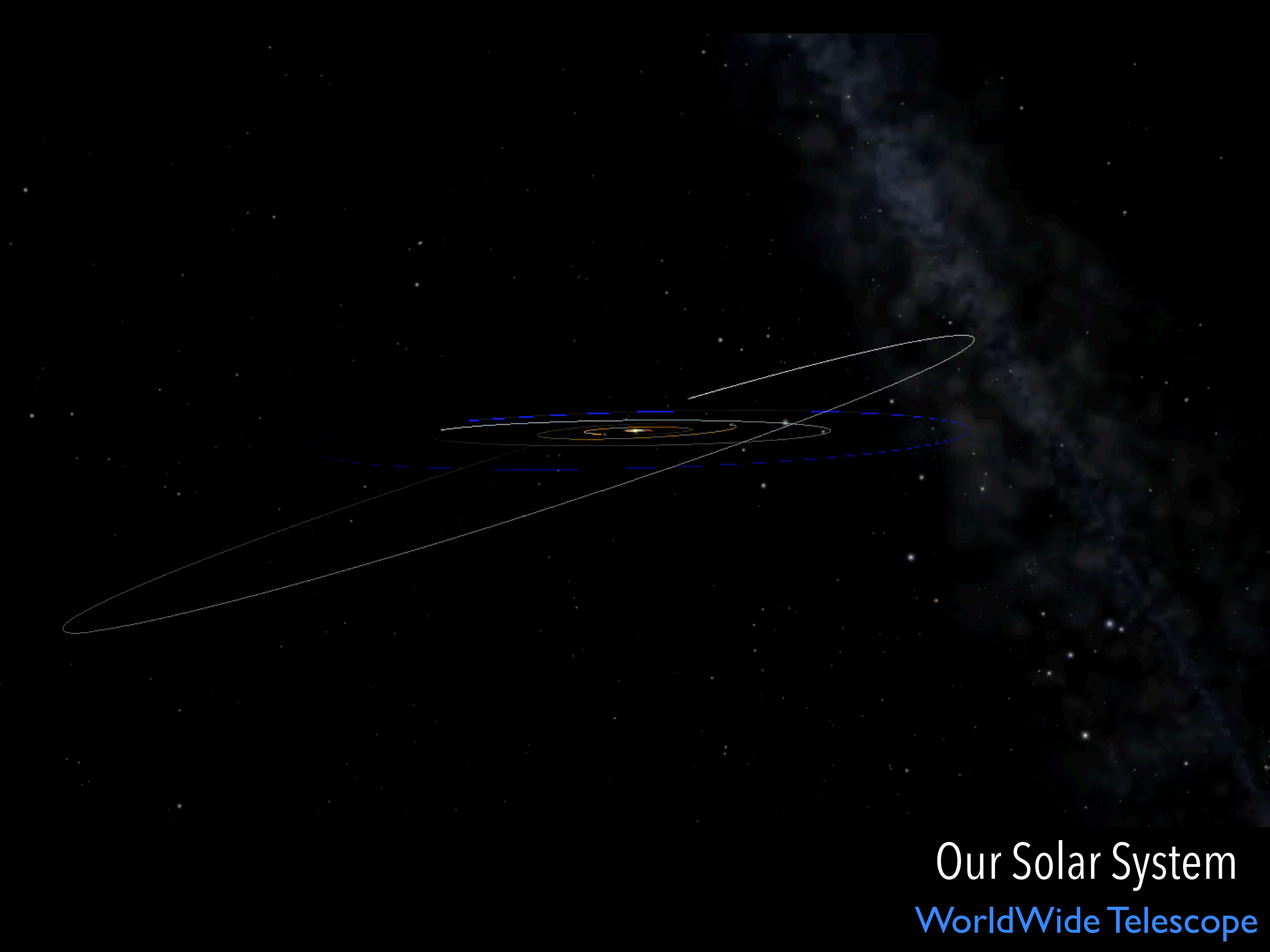
The University of Texas at Austin

恆星的兄弟姐妹：多星系統如何形成

Work is supported by:
RESEARCH CORPORATION for SCIENCE ADVANCEMENT
NASA
NSF

Artist's Impression of HD 98800B


Our Solar System
WorldWide Telescope

# Outline

- Some Examples of Multiple Star Systems
- How Stars Form 恆星如何形成
- How Multiples Form Differently 多星系統呢？
- Observation Challenges and Discoveries
  觀測的挑戰與發現
- What does it all mean for Planets?
  這對於行星意味了什麼？

# Our Sun is lonely

If the sun were only 17 inches across, the next closest star....

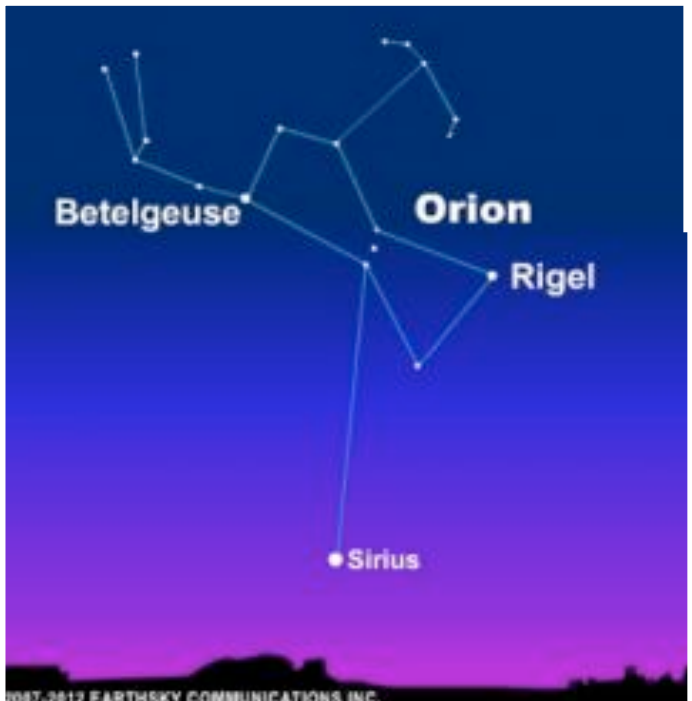
如果太陽直徑比喻成43公分

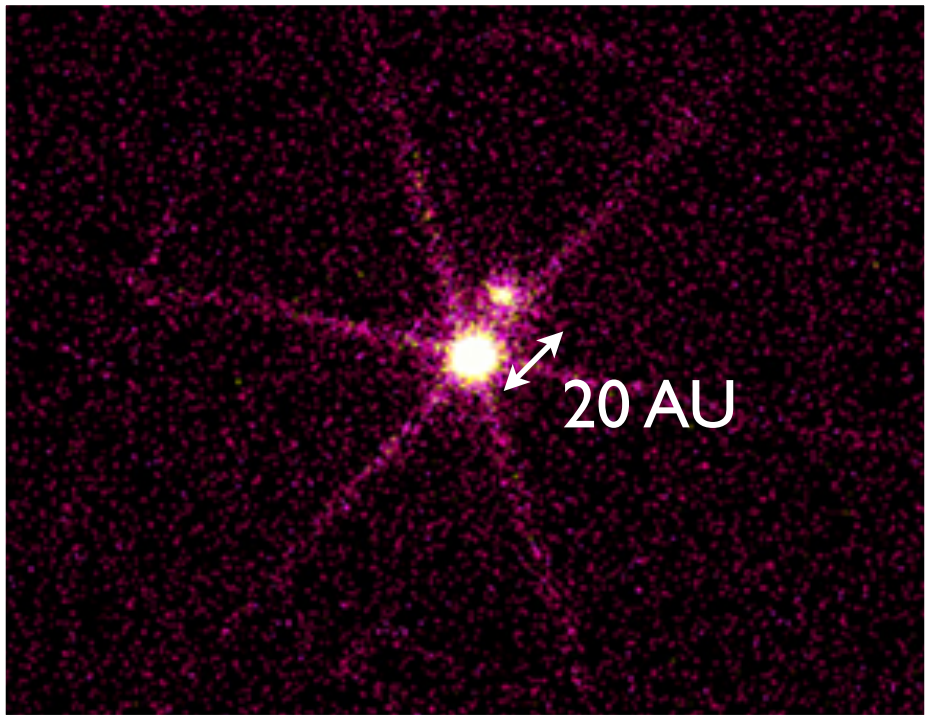
... would be on the other side of the earth!

那麼最鄰近的恆星，相當於地球的另外一邊

# Many stars have siblings...

Two stars =
"Binary" system




**Sirius AB**, Chandra X-ray Observatory Image
*Credit: NASA/SAO/CXC*

天狼星的雙星A、B
在X射線波段的影像

AU＝天文單位
＝地日平均距離
AU = Astronomical Unit

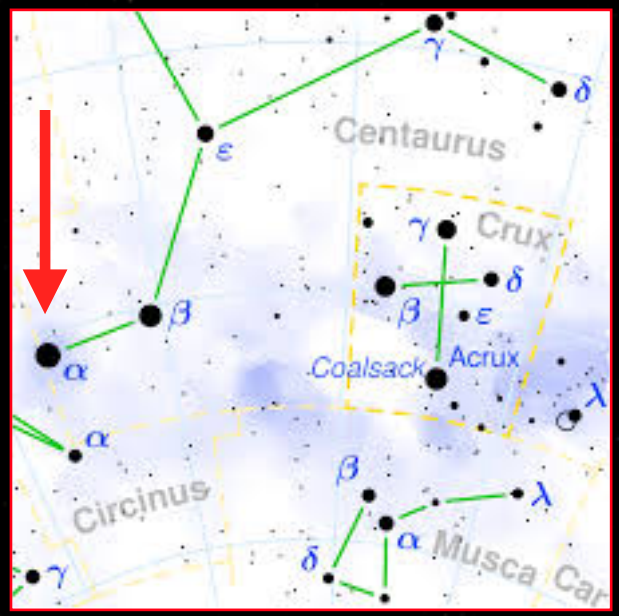
# Most Famous Binary System

星際大戰裡的雙星

Tatooine system (Star Wars)

# Many stars have siblings...

Three stars =
"Triple" system




α Centauri AB

Alpha Cen = 南門二

11-35 AU

13,000 AU

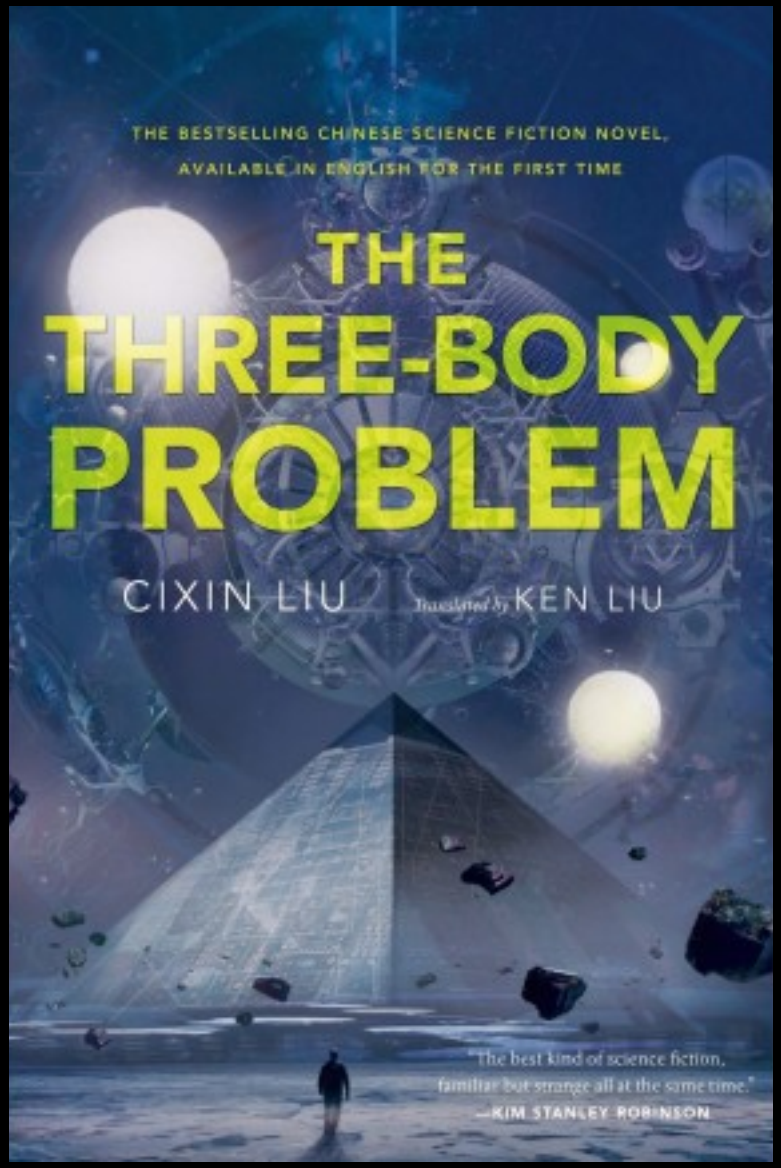
α Centauri C
also known as
Proxima Centauri

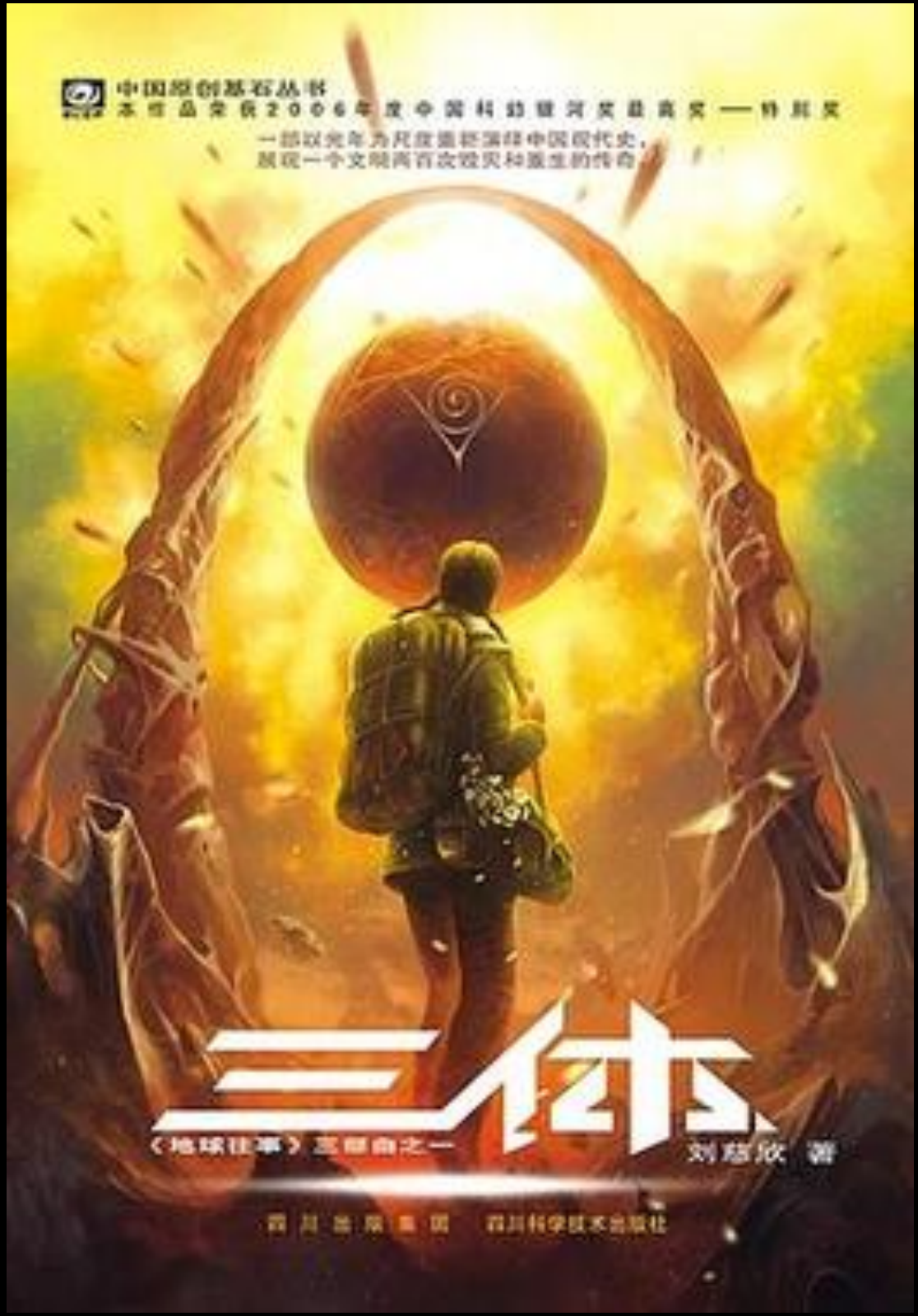
Alpha Centauri C = 毗鄰星

離太陽最近的恆星，是個三星系統：A、B、C

**Closest star system to our own!**

# Most Famous Triple System

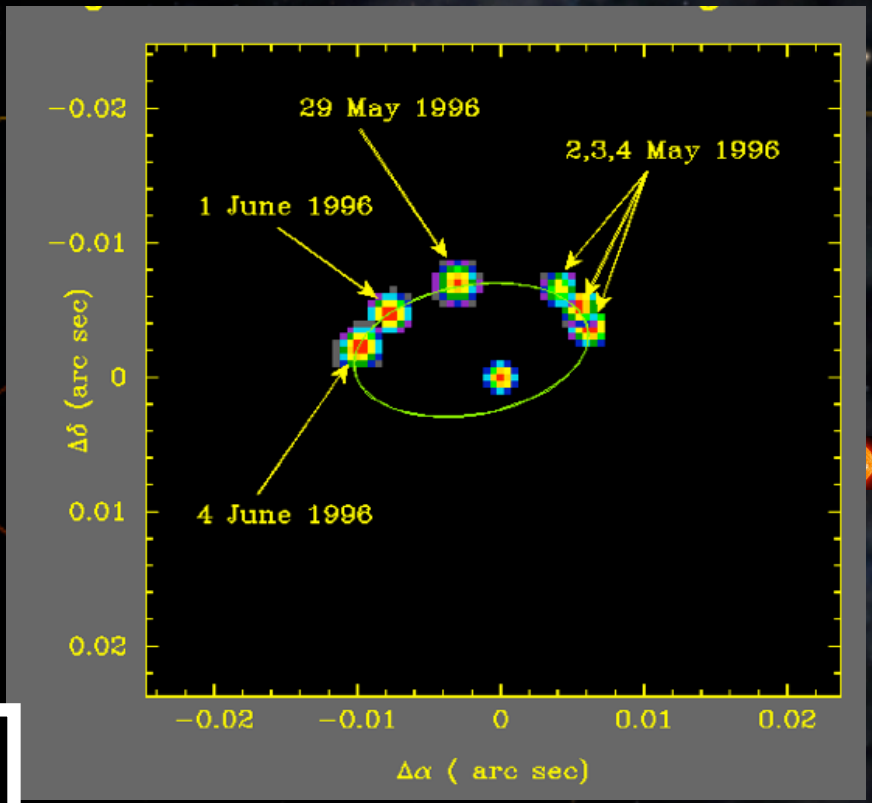


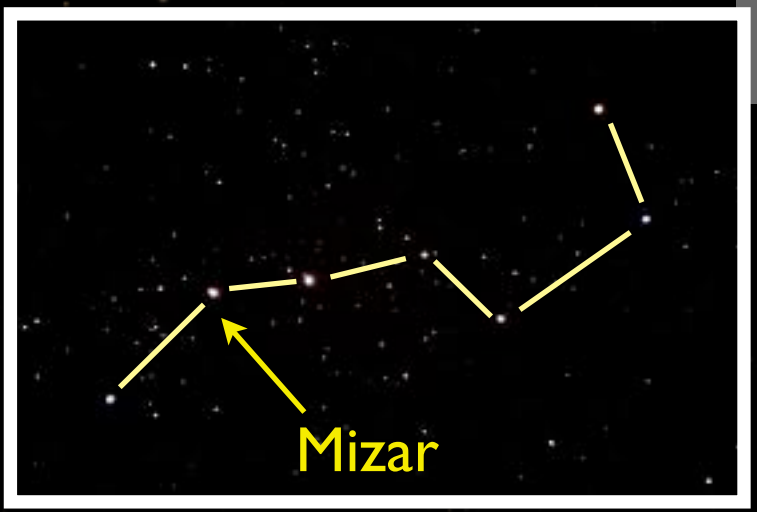
# Many stars have siblings...

Four stars = "Quadruple" system

四星系統



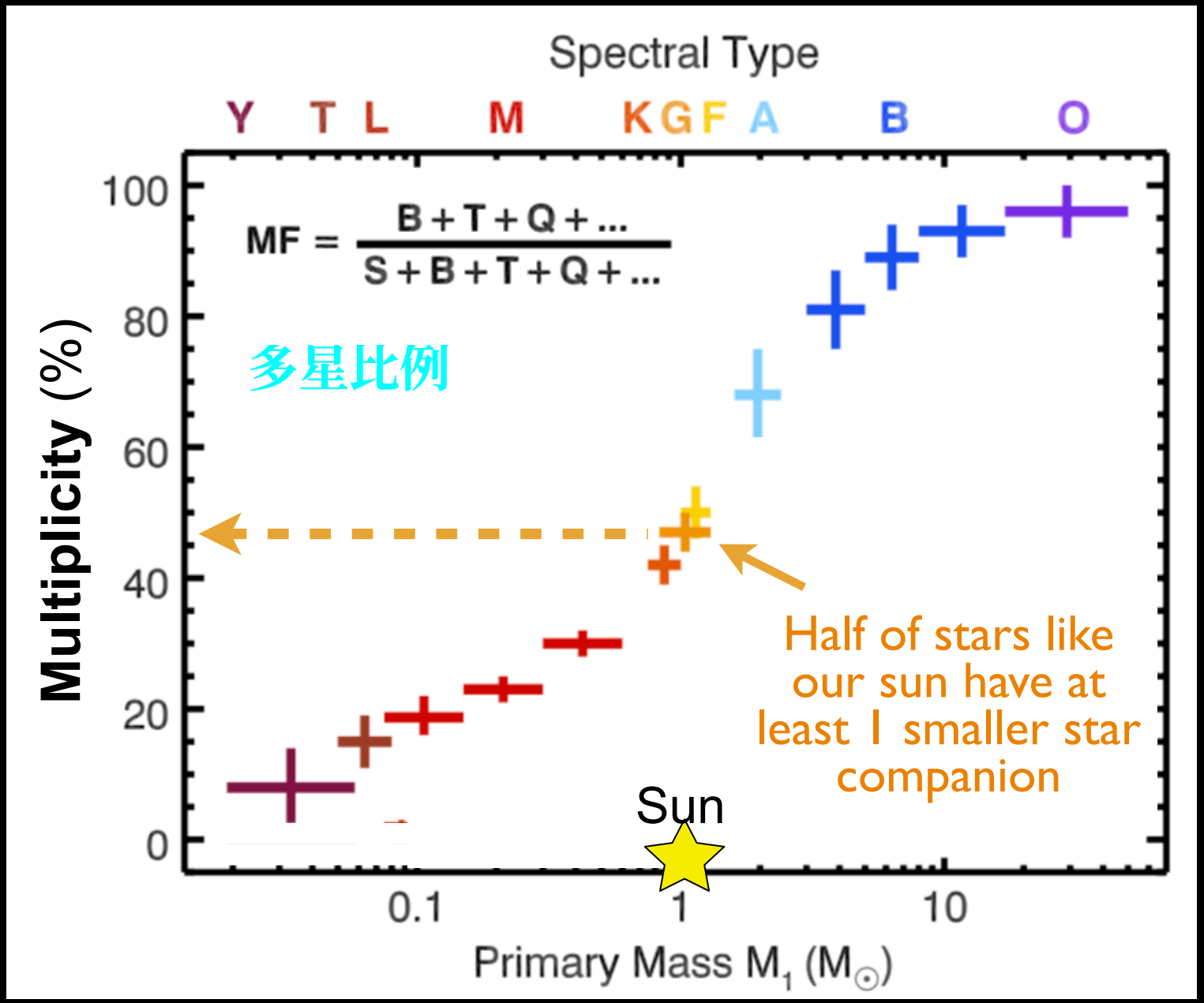

MizarA + Companion

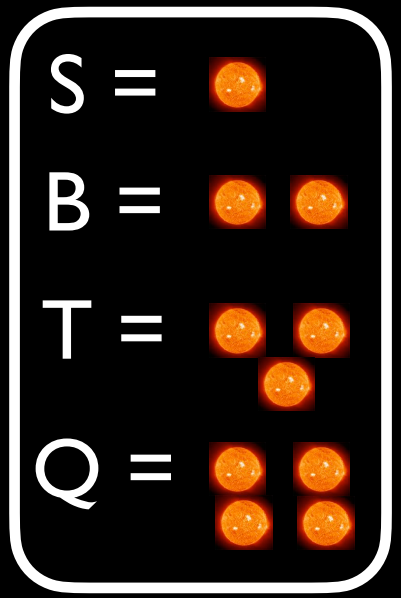



開陽雙星：北斗七星

斗杓外端第二顆；各自又是雙星

# How special is our sun?

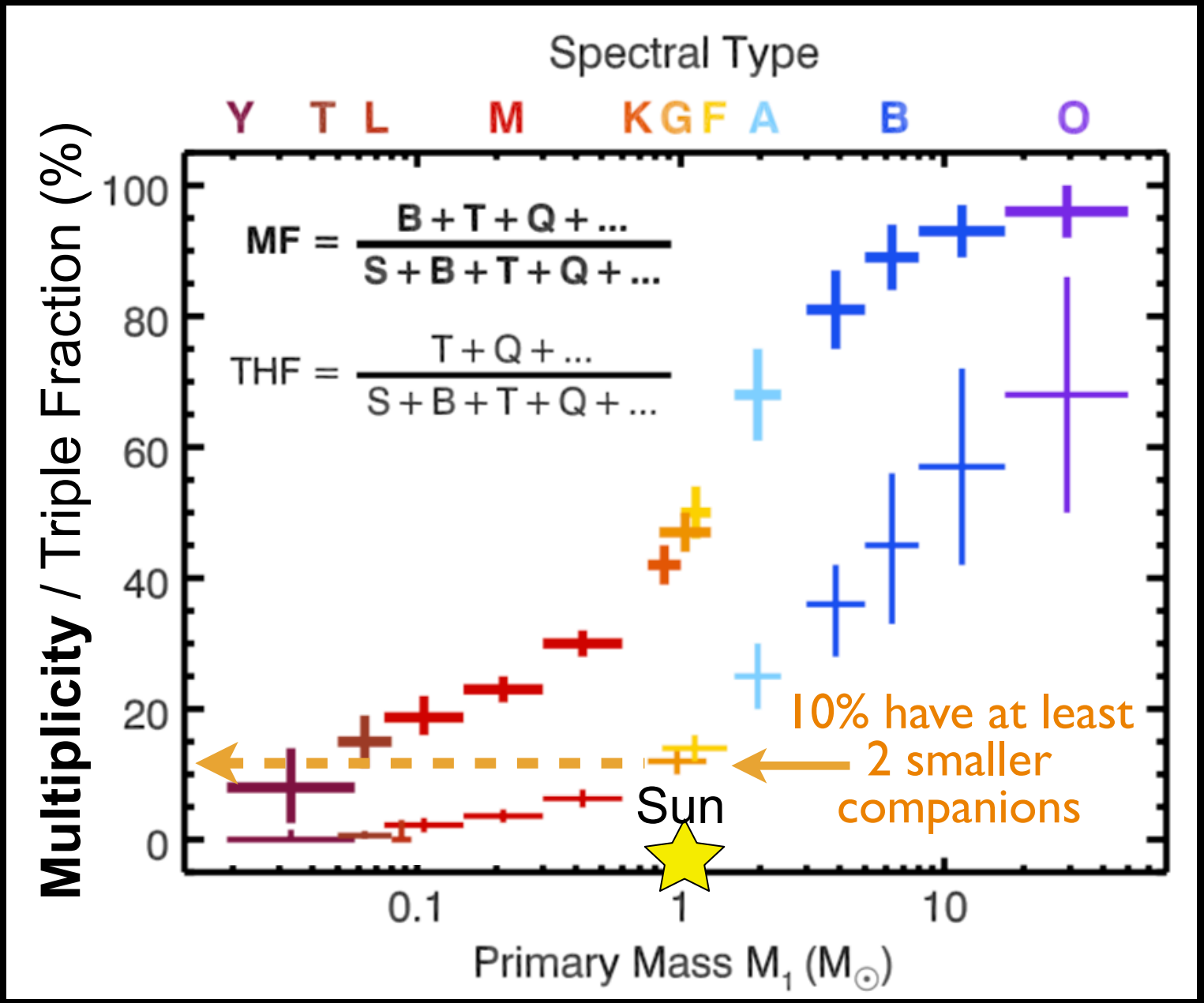


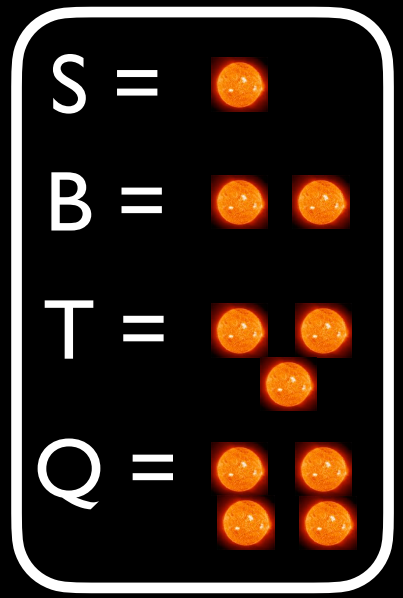




類似太陽的恆星有半數至少有顆小伴星

Offner et al. 2022 sub.

# How special is our sun?




有10%至少有2顆小伴星

Offner et al. 2022 sub.

# How do two stars end up close together?

這些雙星怎麼湊在一起的？

. . . they were born that way!

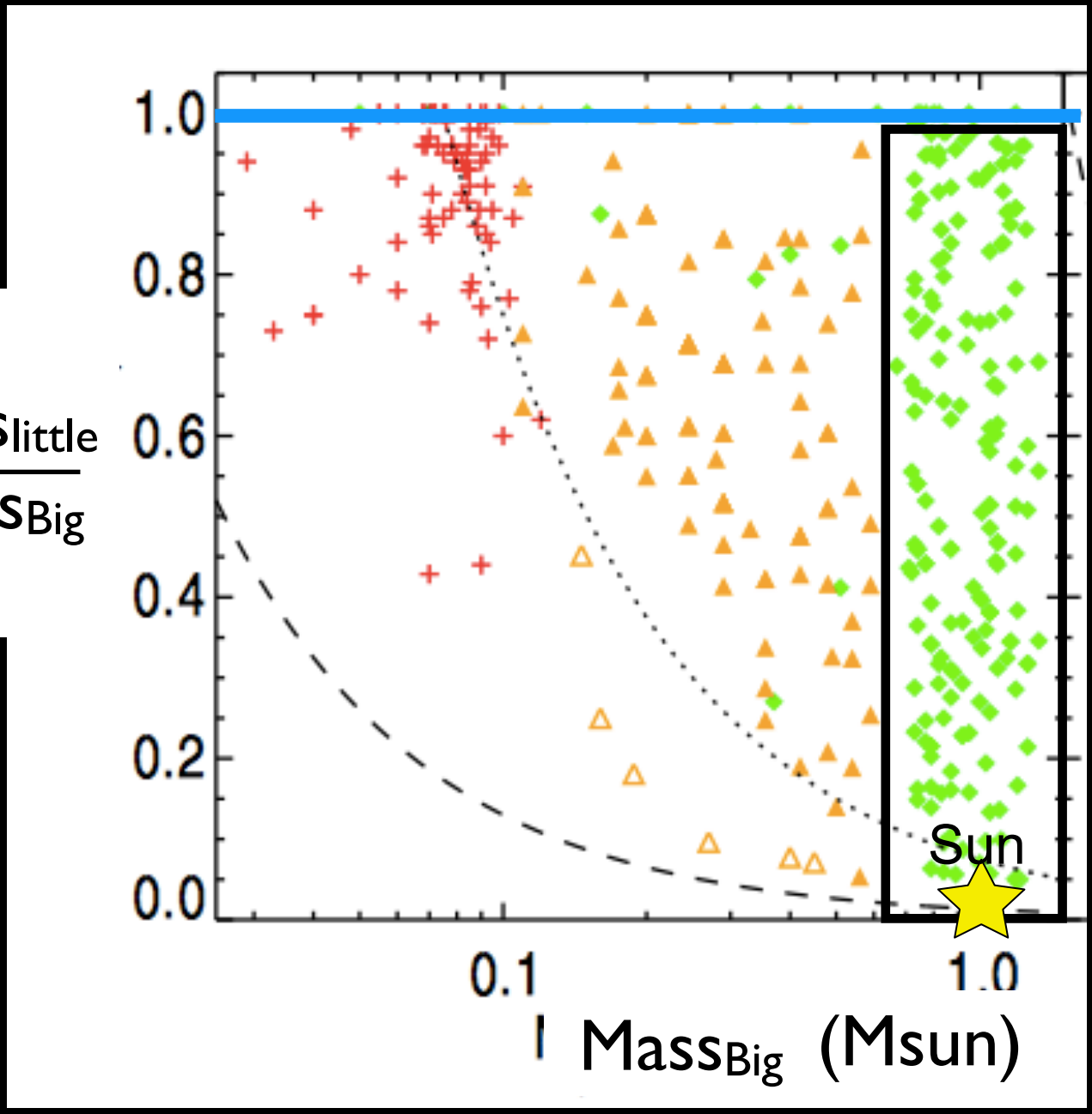
它們生來如此

# How do two stars end up close together?

Often they are very different sizes!

但它們常常大小不一樣

# Sibling sizes are usually different




Equal mass stars: "twins"

雙星質量一樣者：孿生星

Duchene & Kraus 2013

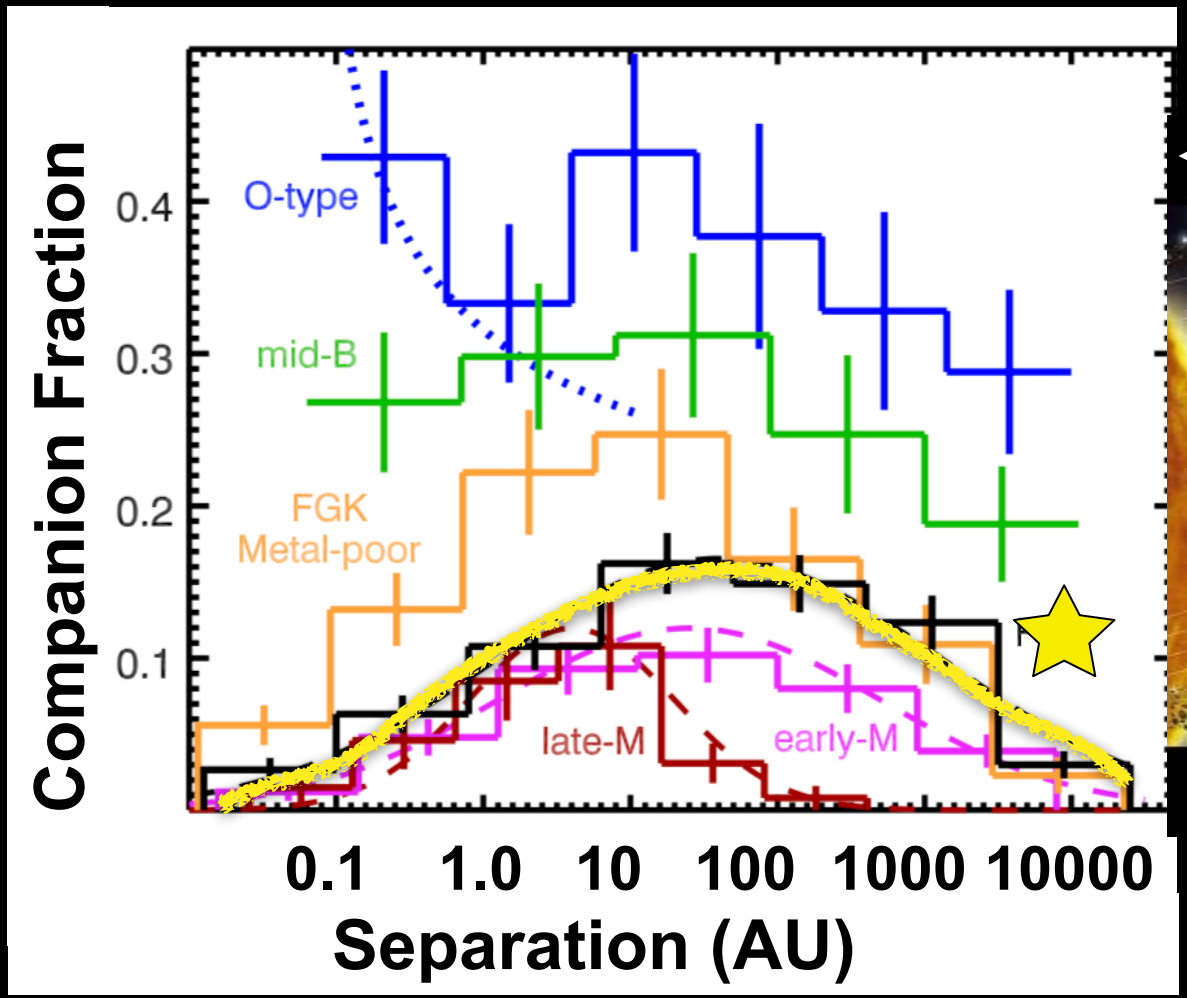
# Typical Separation of Sun-like stars is 50 AU

雙星彼此相距：~50 au


50 AU

相比之下，冥王星跟太陽的距離大約是 40 au

40 AU (Sun/Pluto)

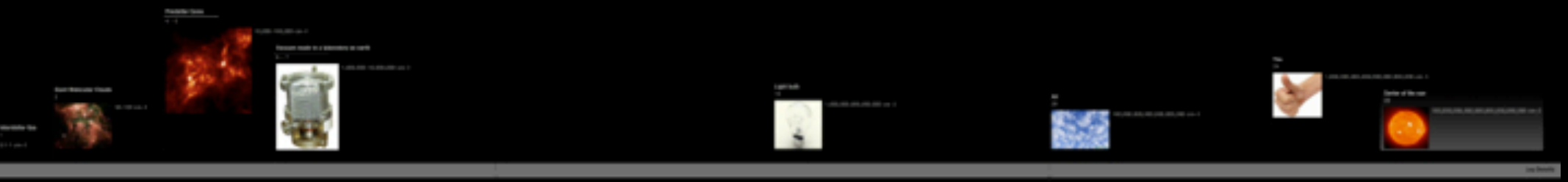



Offner et al. 2022 sub.

# Problem: How to make a star?

# Problem: How to make a star?

恆星誕生過程：密度增加20個數量級（10自乘20次）



20 orders of magnitude in density

此處密度指的是單位體積內的原子數量

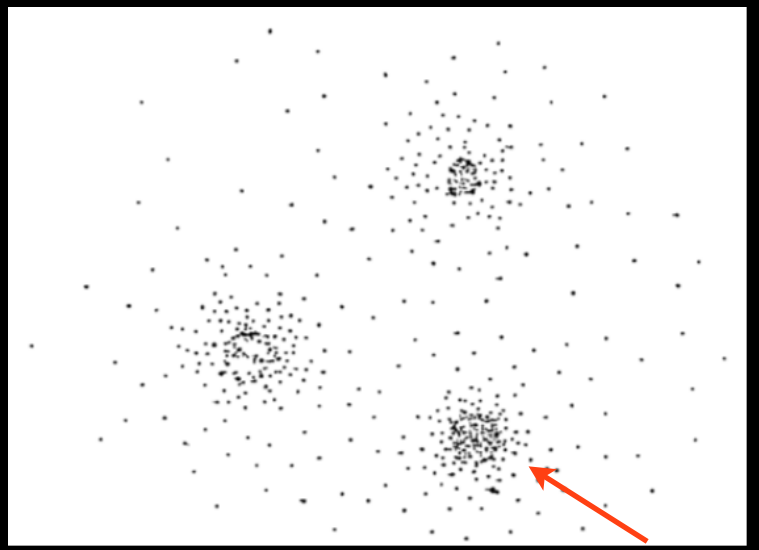
"Gas density" = # of atoms per volume

# Gravity!

# Gravity!

Once a certain density is reached, the gas contracts due to its own gravity.

靠引力。一旦達到某個密度，氣體自我的引力造成收縮



# Gravity!

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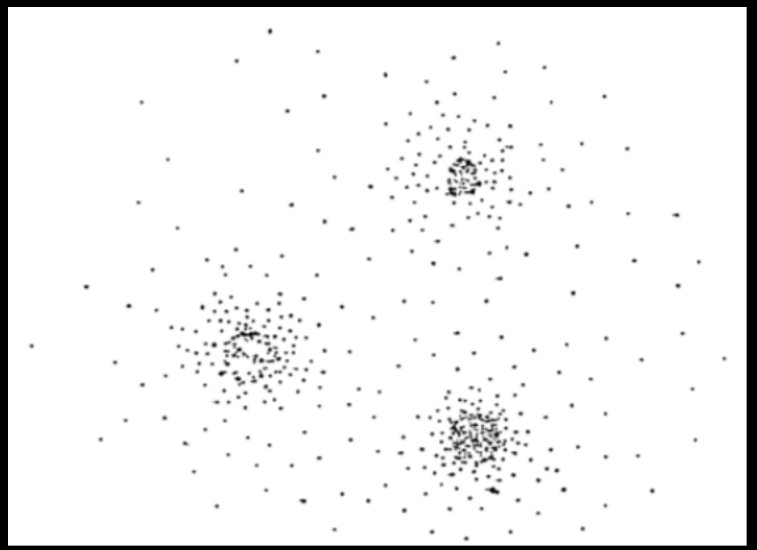


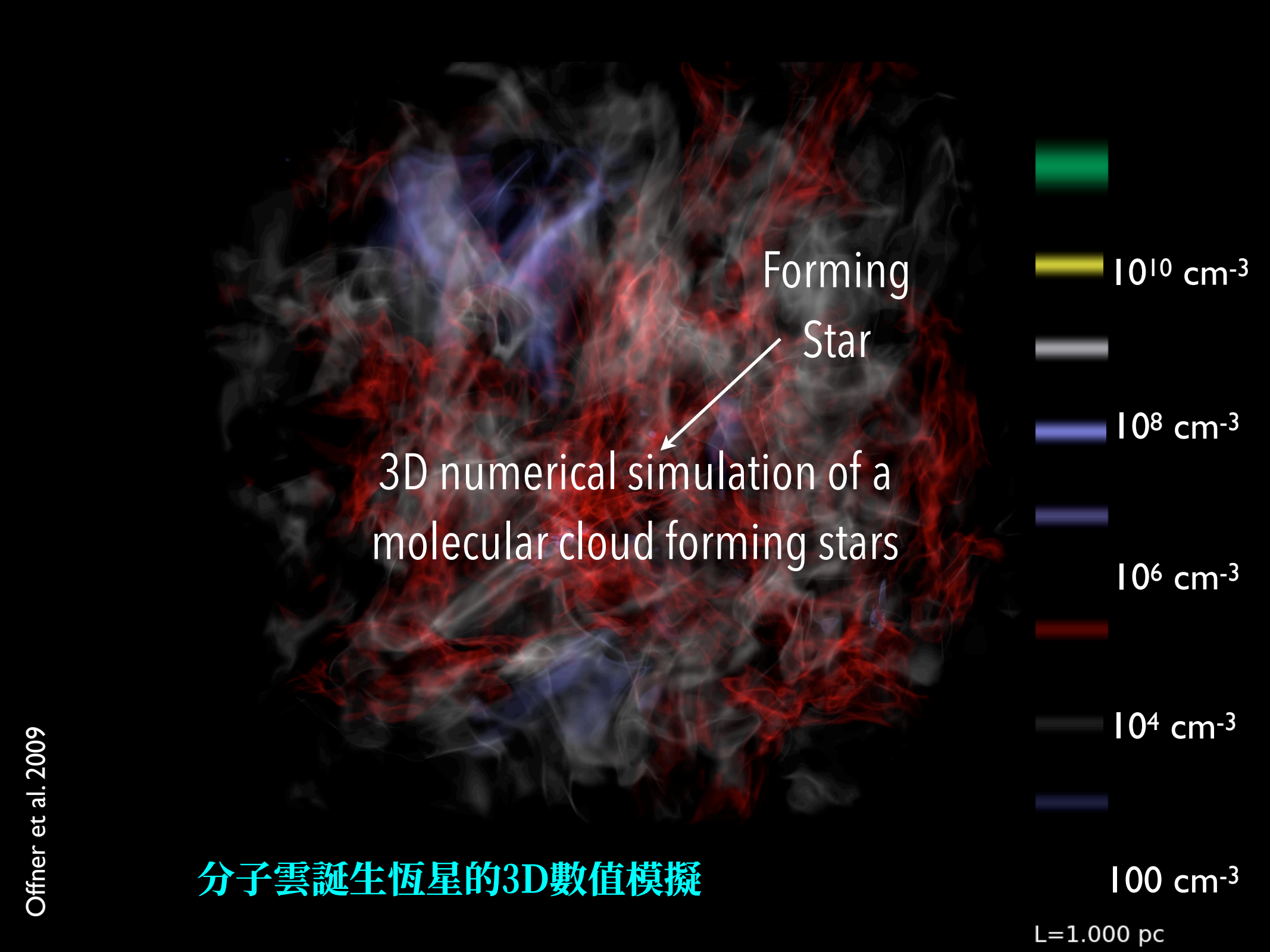
"**Gravitational Instability**" causes runaway collapse.

**超過該密度，收縮一發不可收拾**

For air: size is

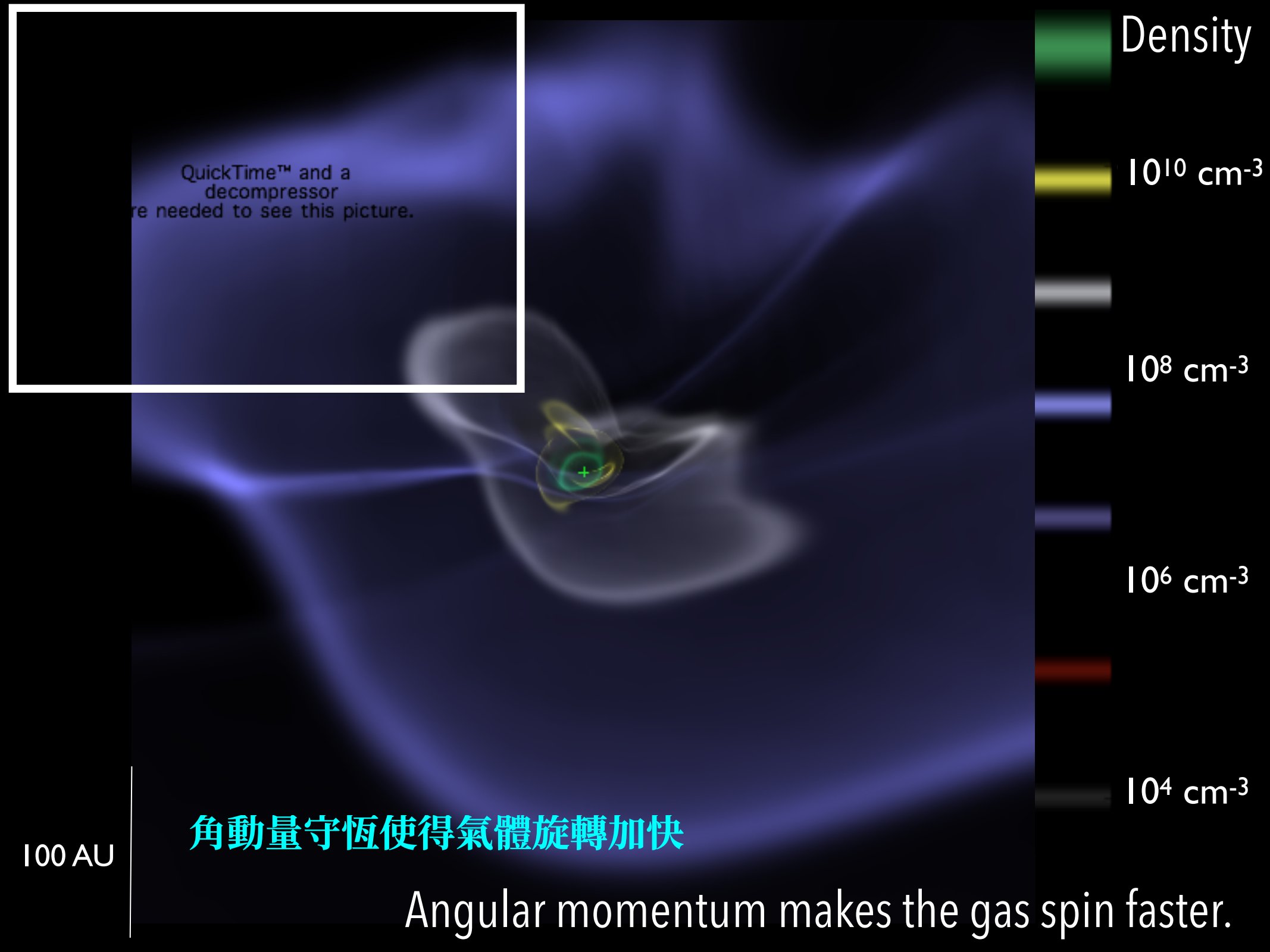
~10 $R_{Earth}$

**以空氣來說，大小差不多為10個地球半徑**




分子雲誕生恆星的3D數值模擬

Offner et al. 2009

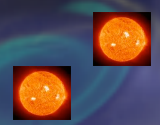

QuickTime™ and a
decompressor
re needed to see this picture.
Density
10^10 cm^-3
10^8 cm^-3
10^6 cm^-3
10^4 cm^-3
100 AU
角動量守恆使得氣體旋轉加快
Angular momentum makes the gas spin faster.

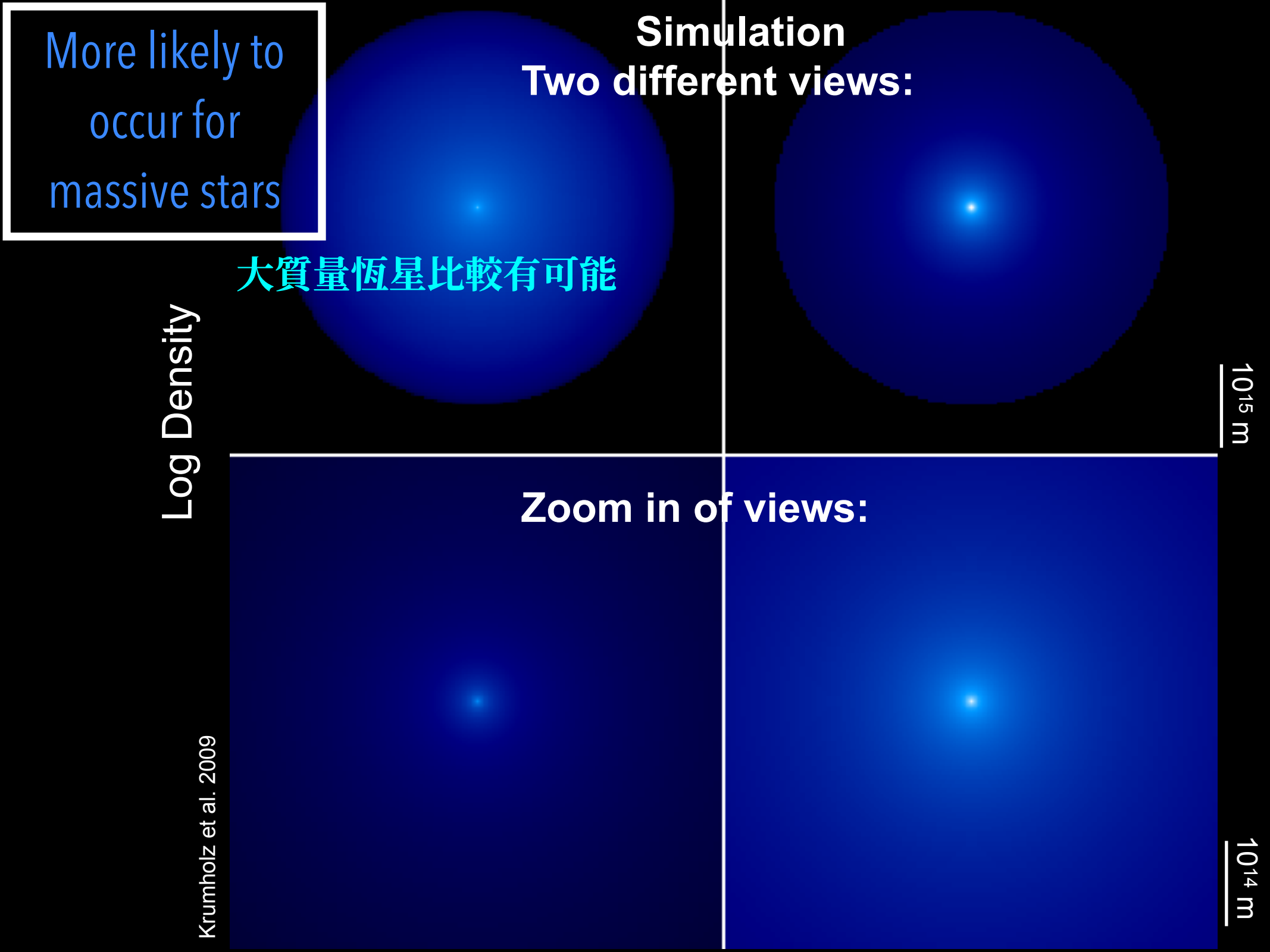
# How to form Multiplies?

## 怎麼製造多星系統？

Option 1: "Disk Fragmentation"

第一種可能：環星盤分裂

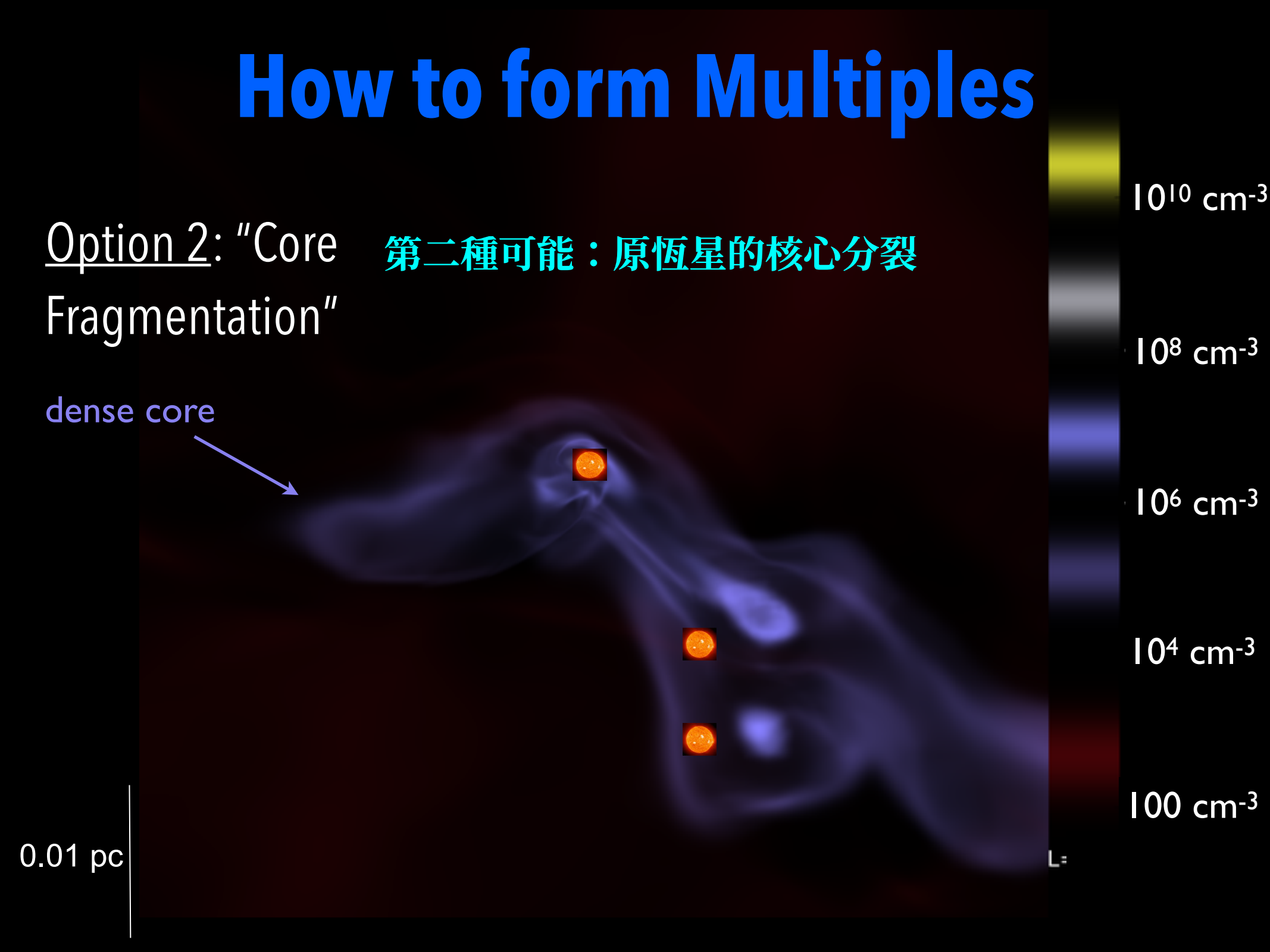



More likely to occur for massive stars
大質量恆星比較有可能
Simulation
Two different views:
Log Density
$10^{15}$ m
Zoom in of views:
$10^{14}$ m
Krumholz et al. 2009

# How to form Multiples

Option 2: "Core Fragmentation"

第二種可能：原恆星的核心分裂



# How to form Multiples

Option 3:
"Capture"

第三種可能：恆星彼此擄獲

*Neither disk fragmentation*
nor core fragmentation
nor capture
happened in the dense gas that
formed our Sun and planets.

**形成我們太陽與行星的那團雲氣中，這些可能性都不對**

# Observations Challenges

觀測的挑戰

# Gas density is high

## 氣體濃密

Eagle Nebula
HST /NASA

# Young stars are far away

## 年輕恆星距離遙遠

66 antennas (54 12m + 12 7m)

Atacama Large Millimeter - submillimeter Array (**ALMA** Interferometer)

ALMA 干涉儀（位於智利的毫米／次毫米陣列望遠鏡）

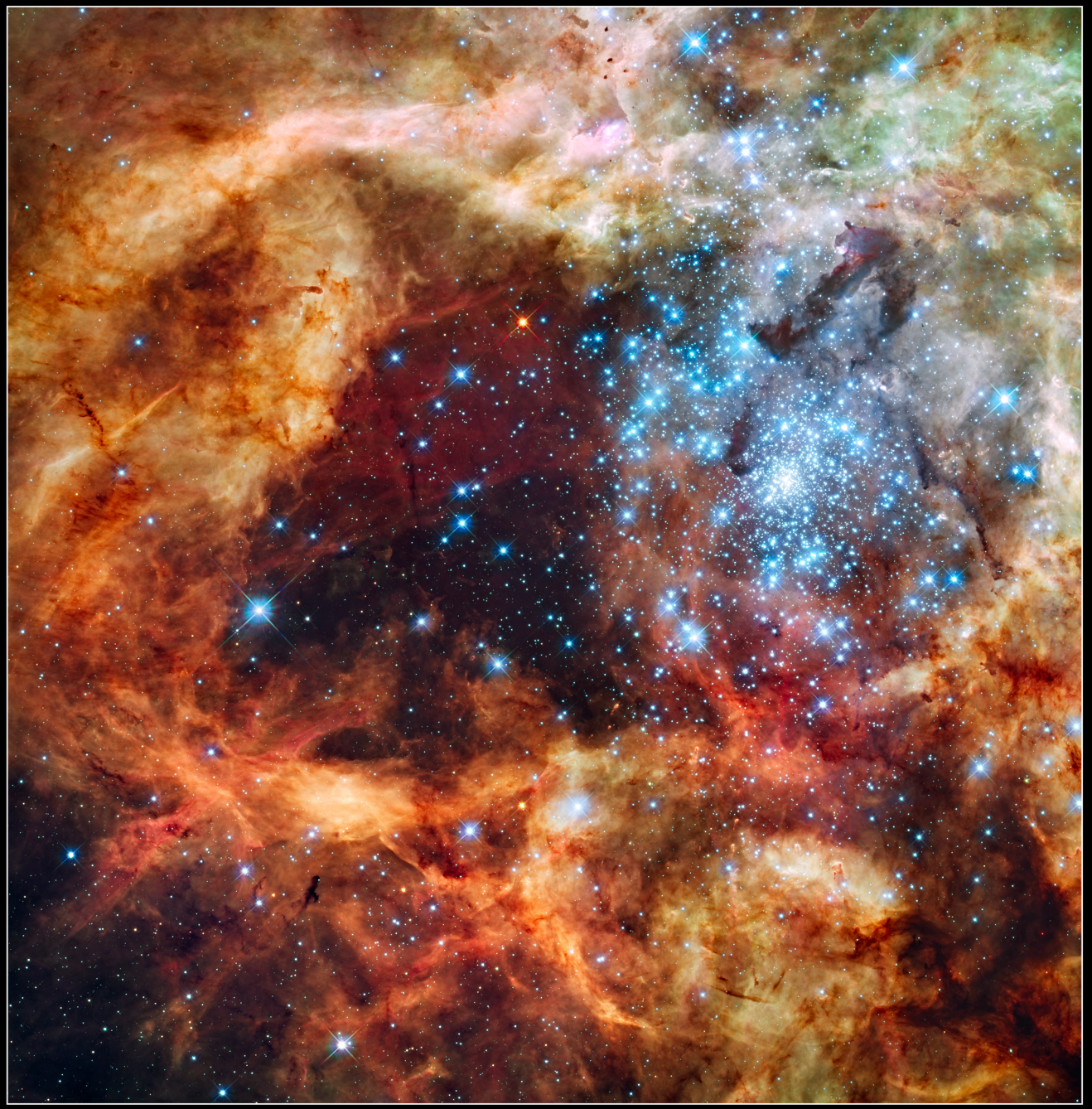
# Long Timescales

(Millions of years)

**時間尺度長（百萬年）**

We can't observe stars forming in real time

**我們無法看著它進行**



**Star-Forming Region 30 Doradus**

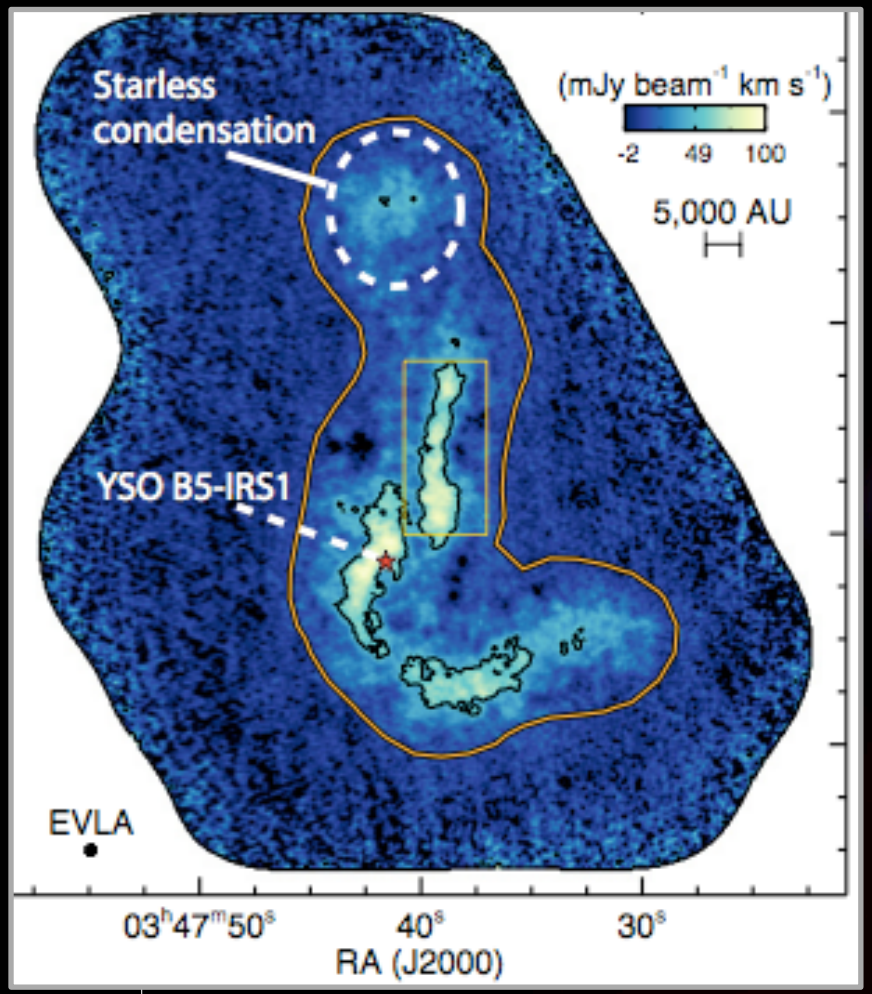
*Hubble Space Telescope* • WFC3/UVIS

NASA, ESA, F. Paresce (INAF–IASF, Italy), and the WFC3 Science Oversight Committee STScI-PRC09-32a

# Discoveries!

# Quadruple Star System Caught in Formation! 實際觀測到四星系統正在形成

Core Fragmentation 星核分裂




B5, Pineda et al. 2011 B5恆星形成區

Simulation Prediction

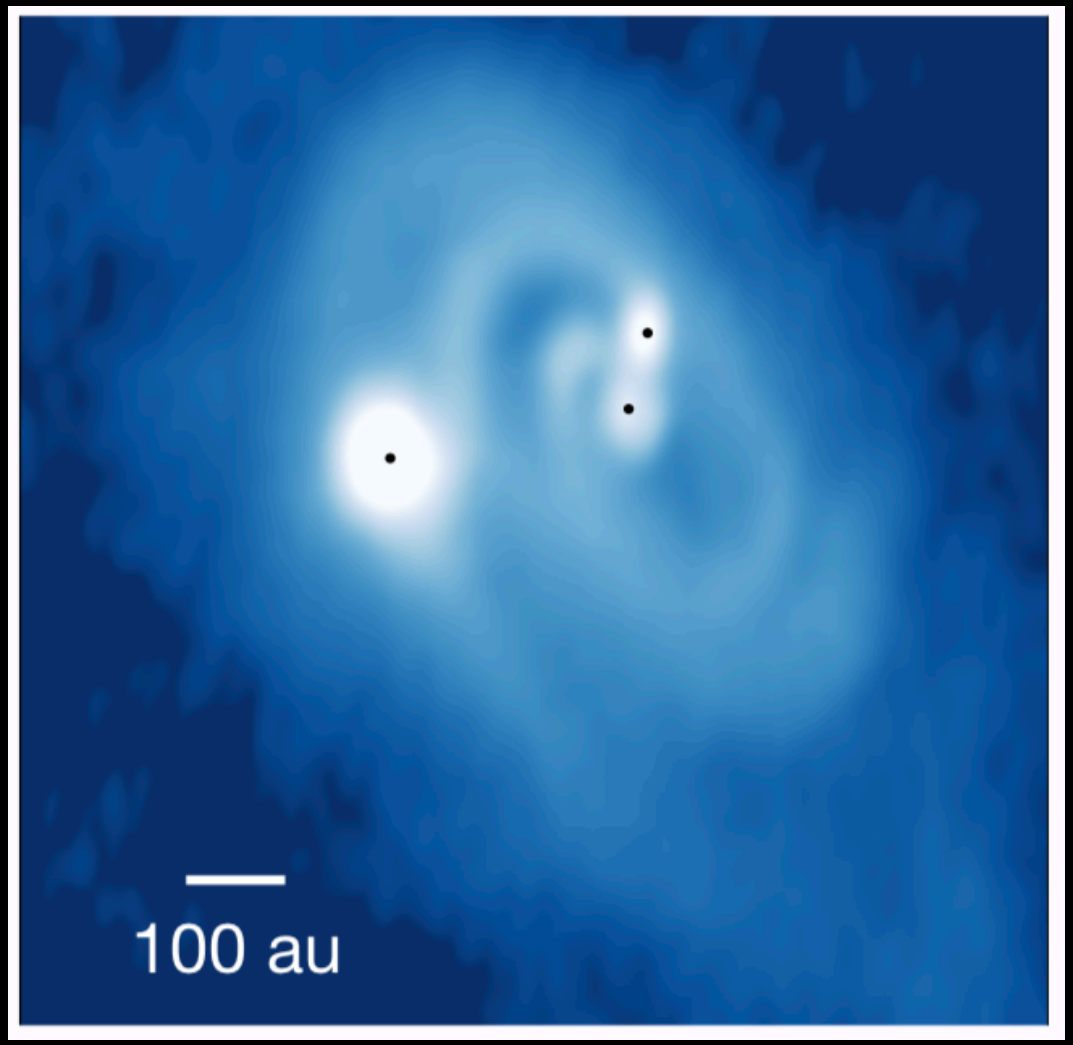
電腦模擬的預測

Offner et al. 2010

# Triple Star System Caught in Formation!

## 實際觀測到三星正在形成

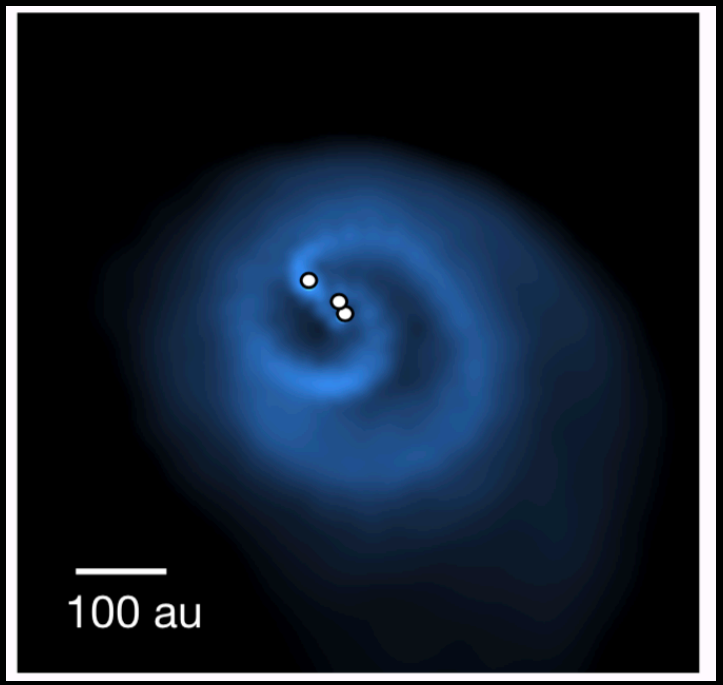
Disk Fragmentation 環星盤分裂




Very Large Array (VLA) Observation 新墨西哥州的 VLA 望遠鏡

Reynolds et al. 2021, Tobin et al. 2016, Nature

電腦模擬



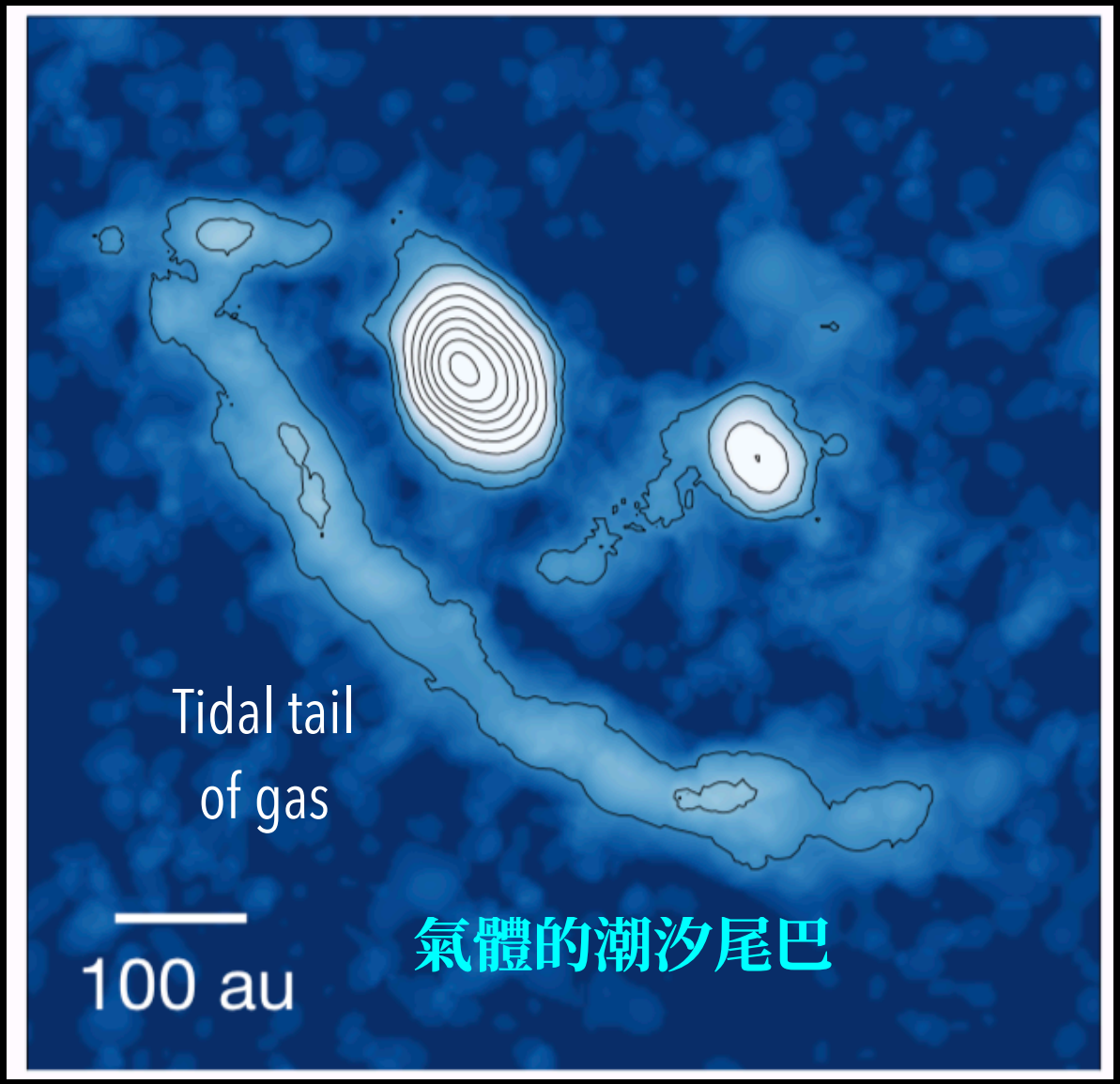

Simulation Prediction

Bate 2018

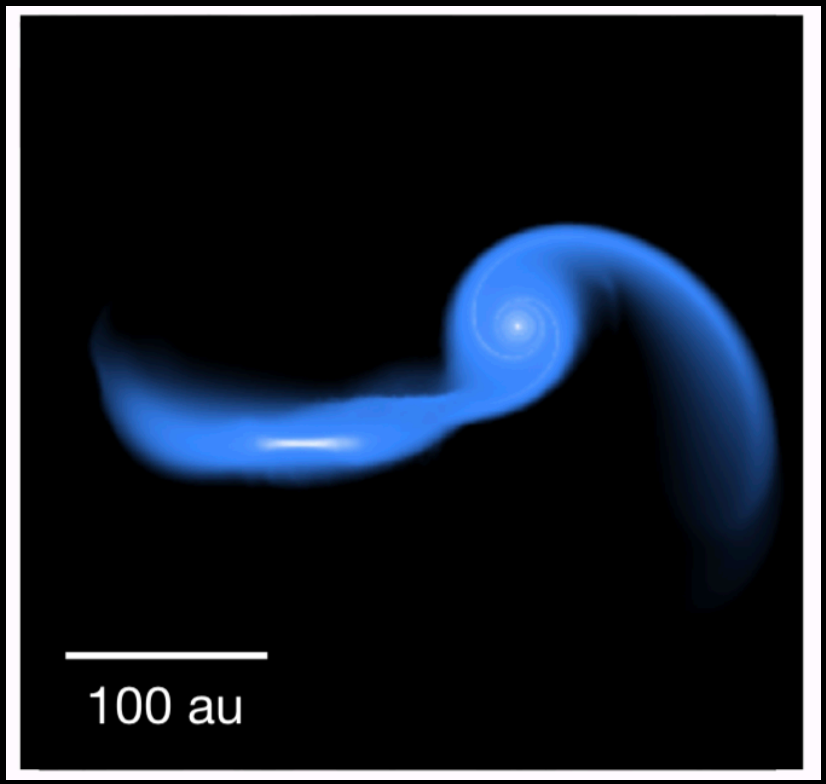
# Possible Formation by Capture!

也可能由擄獲形成

Dynamical Interaction 動力互動




ALMA Observation, Rodriguez et al. 2018




Simulation Prediction

Munoz et al. 2015

電腦模擬

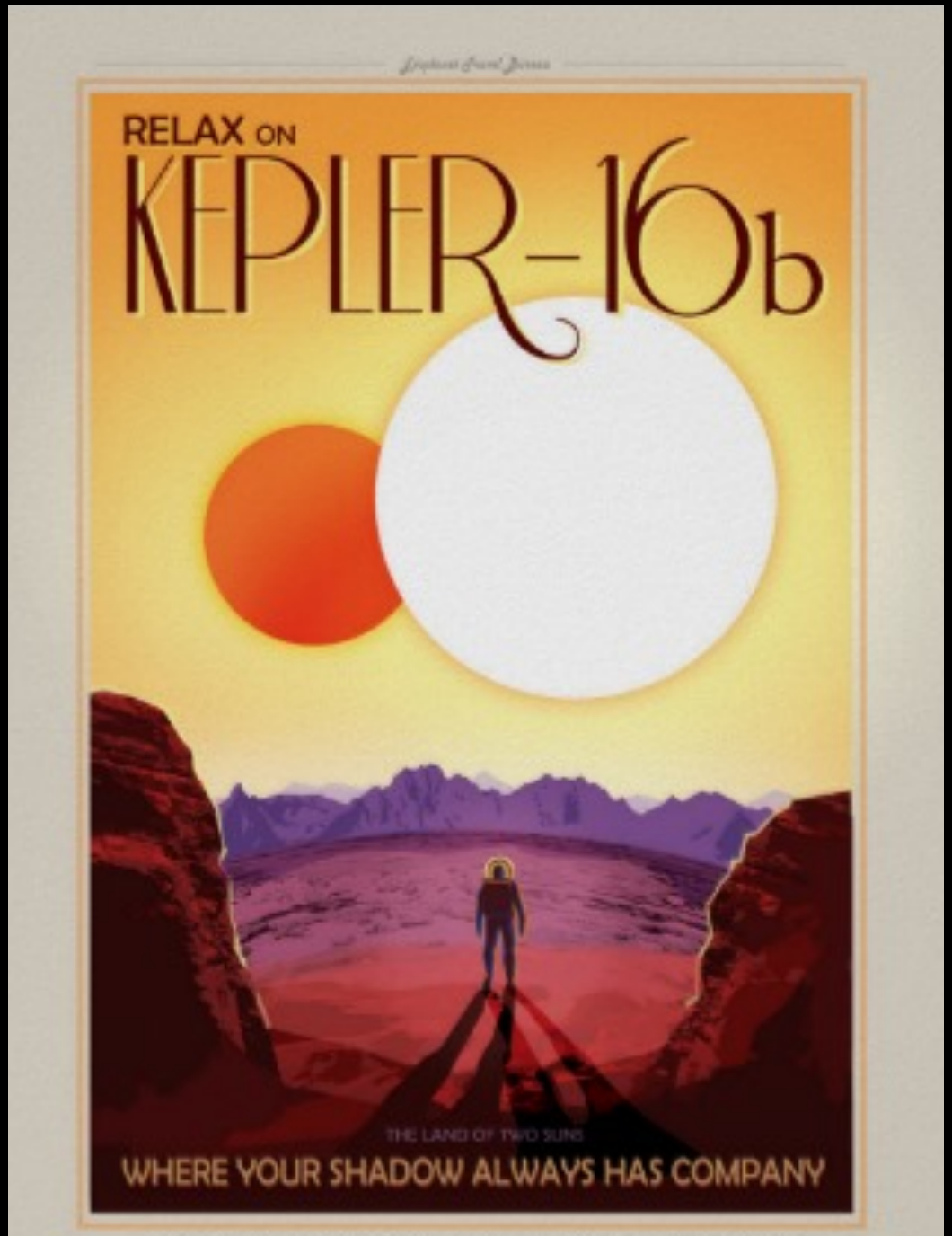
# Implications for Other Planetary Systems

對於行星系統的形成有何啟發呢？

Tatooine System (Star Wars)

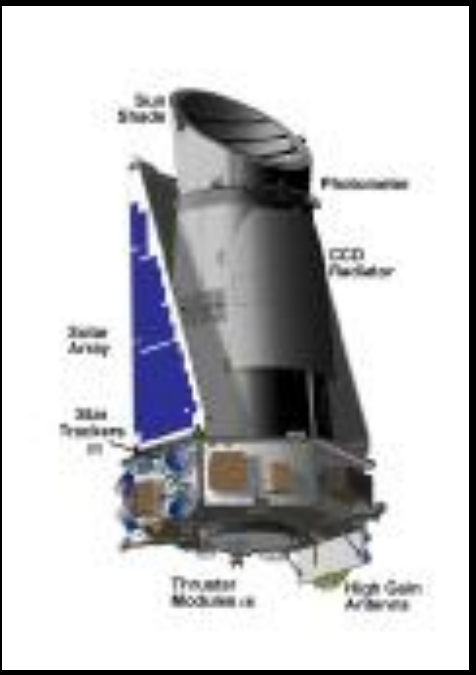
# Not just Sci Fi anymore…

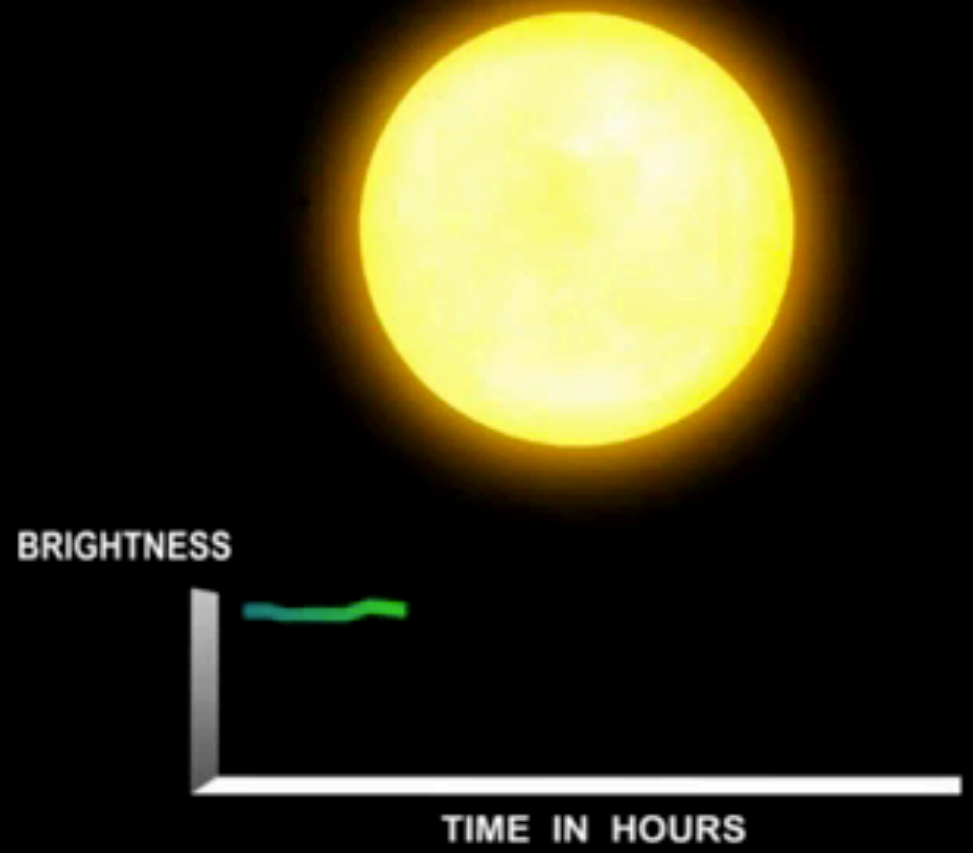
不再只是科幻



# Kepler Mission

## 克卜勒太空望遠鏡



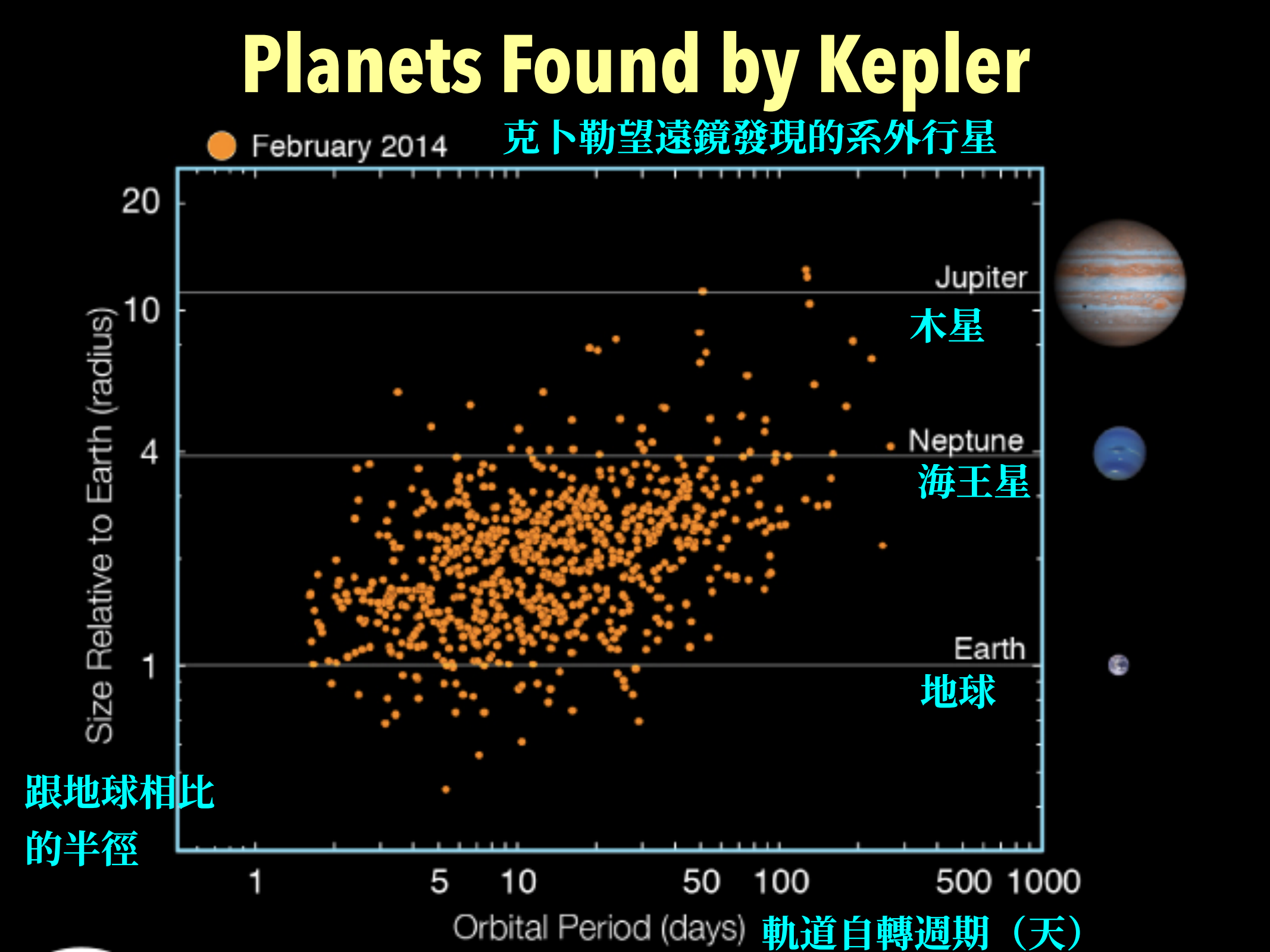



當（我們看到）行星凌越其母恆星，會稍微擋住星光

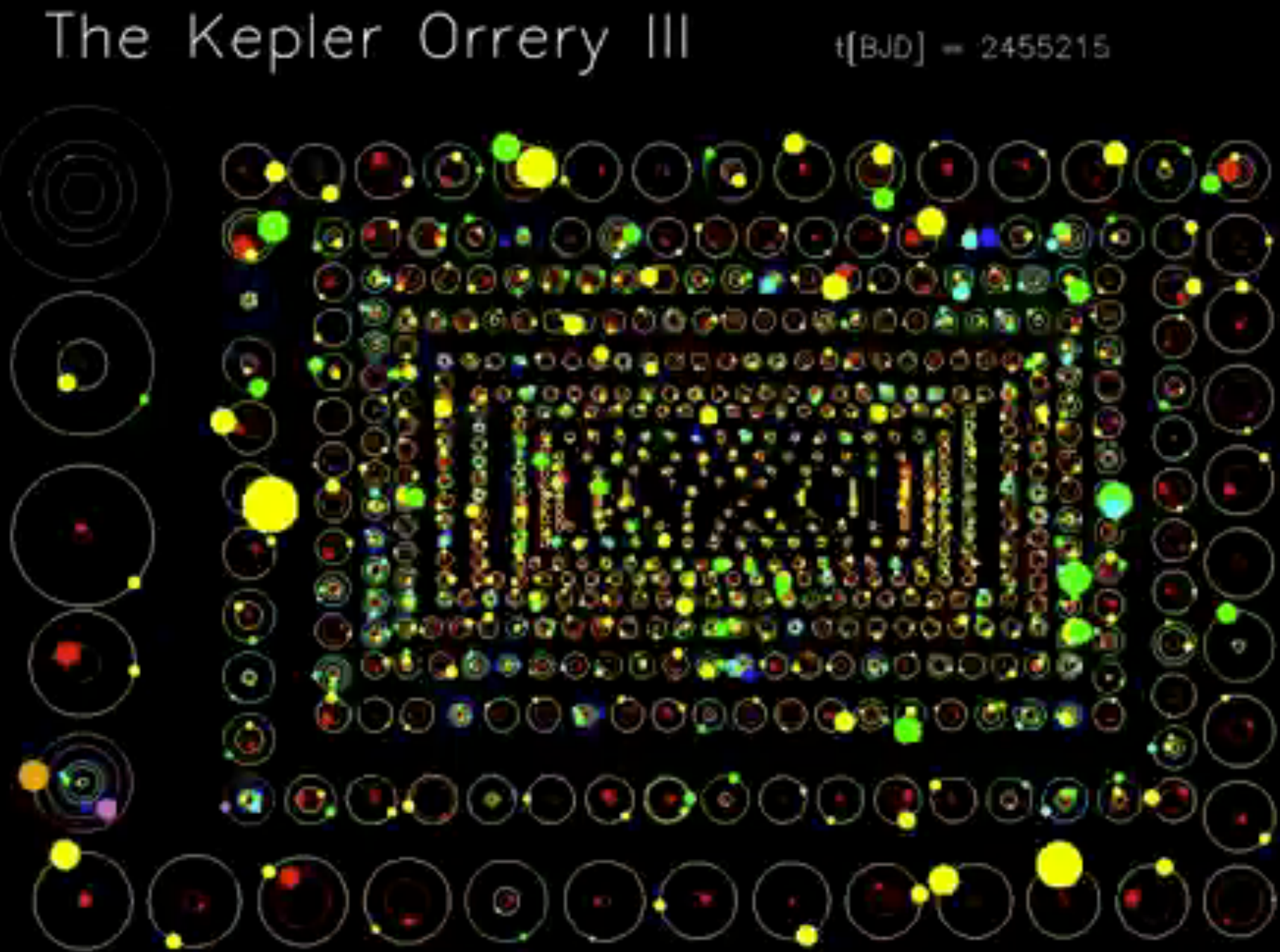
As the planet crosses in front of the star it blocks some of the star's light

# Planets Found by Kepler

克卜勒望遠鏡發現的系外行星

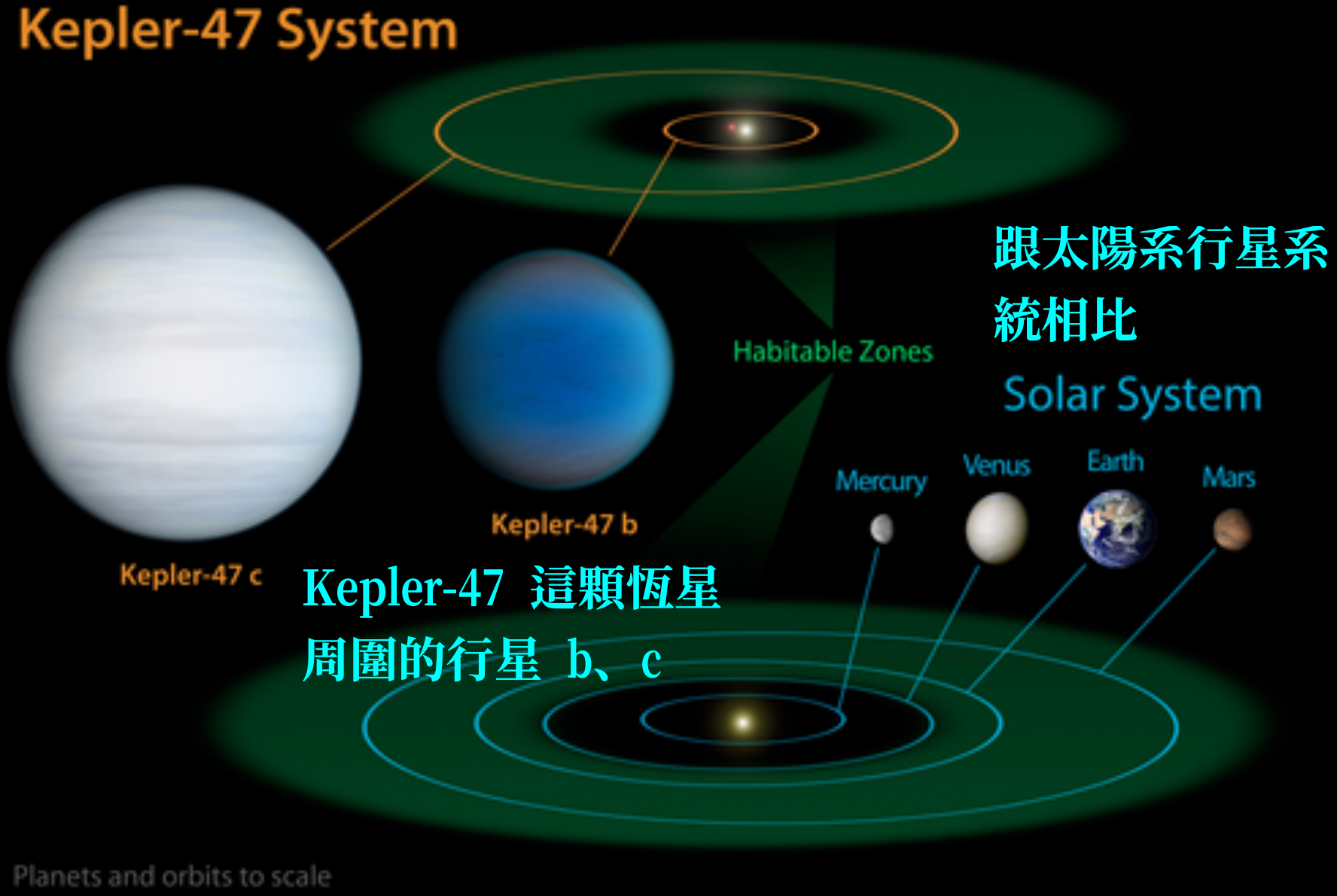


# Systems with More than 1 Planet



# "Circumbinary" Planets

繞著雙星系統的行星



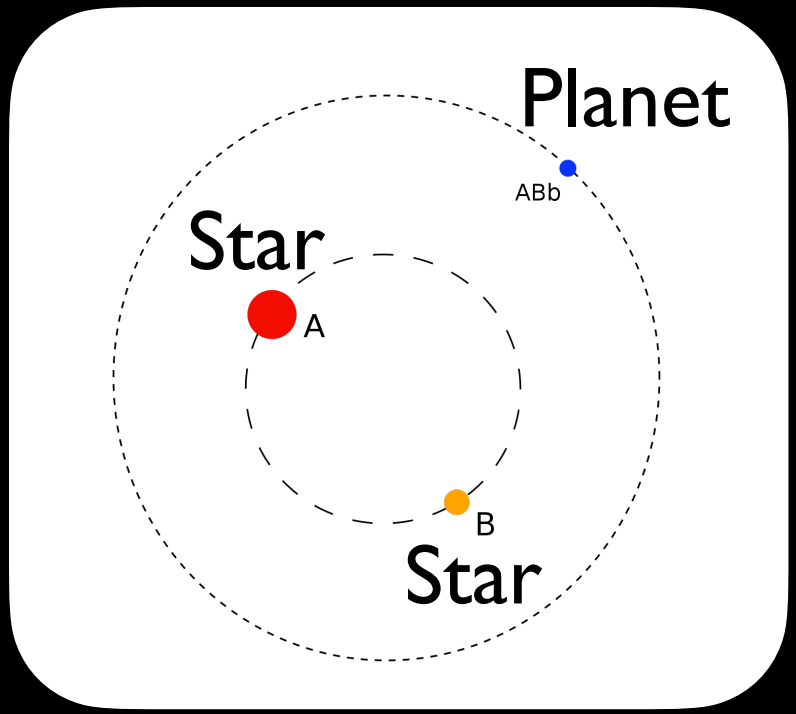

跟太陽系行星系統相比

Kepler-47 這顆恆星周圍的行星 b、c

# Current Census of Circum-binary Planets

23 and counting…

繞雙星的行星，已經發現23個了




| Star system | Mass ($M_J$) | Semimajor axis (AU) | Discovered |
|---|---|---|---|
| PSR B1620-26 | 2 ± 1 | 23 | 1993[4] |
| HD 202206 | 2.179 | 2.4832 | 2005[6] |
| DP Leonis | 6.05 ± 0.47 | 8.19 ± 0.39 | 2010[35] |
| NN Serpentis | 6.91 ± 0.54 | 5.38 ± 0.20 | 2010[36] |
| NN Serpentis | 2.28 ± 0.38 | 3.39 ± 0.10 | 2010[36] |
| Kepler-16 | 0.333 ± 0.016 | 0.7048 ± 0.0011 | 2011[37] |
| Kepler-34 | 0.220 ± 0.0011 | 1.0896 ± 0.0009 | 2012[38] |
| Kepler-35 | 0.127 ± 0.02 | 0.603 ± 0.001 | 2012[38] |
| NY Virginis | 2.85 | 3.457 | 2012[40] |
| RR Caeli | 4.2 ± 0.4 | 5.3 ± 0.6 | 2012[41] |
| Kepler-38 | < 0.384 | 0.4644 ± 0.0082 | 2012[42] |
| Kepler-47 | 0.027 ± 0.005 | 0.2956 ± 0.0047 | 2012[43] |
| Kepler-47 | 0.07 ± 0.061 | 0.989 ± 0.016 | 2012[43] |
| PH1 | < 0.532 | 0.634 ± 0.011 | 2013[44] |
| FW Tau AB | 10 ± 4 | 330 ± 30 | 2014[46] |
| ROXs 42B | 9 ± 3 | 140 ± 10 | 2014[45] |
| HD 106906 | 11 ± 2 | 650 | 2014 [A] |
| Kepler-413 | $0.21^{+0.07}_{-0.07}$ | $0.3553^{+0.0020}_{-0.0018}$ | 2014[49] |
| Kepler-453 | < 0.05 | 0.7903 ± 0.0028 | 2014[13] |
| Kepler-1647 | 1.52 ± 0.65 | 2.7205 ± 0.0070 | 2016 |
| OGLE-2007-BLG-349 | 0.25 ± 0.041 | 2.59 | 2016 |
| MXB 1658-298 | 23.5 ± 3.0 | 1.6 ± 0.1 | 2017 |
| KIC 5095269 | 7.70 ± 0.08 | 0.795 - 0.805 | 2017 |

# Environment in Young Systems Sets Planet Formation

行星在年輕恆星的周圍環境裡誕生

NASA, Artist's image of a protoplanetary disk

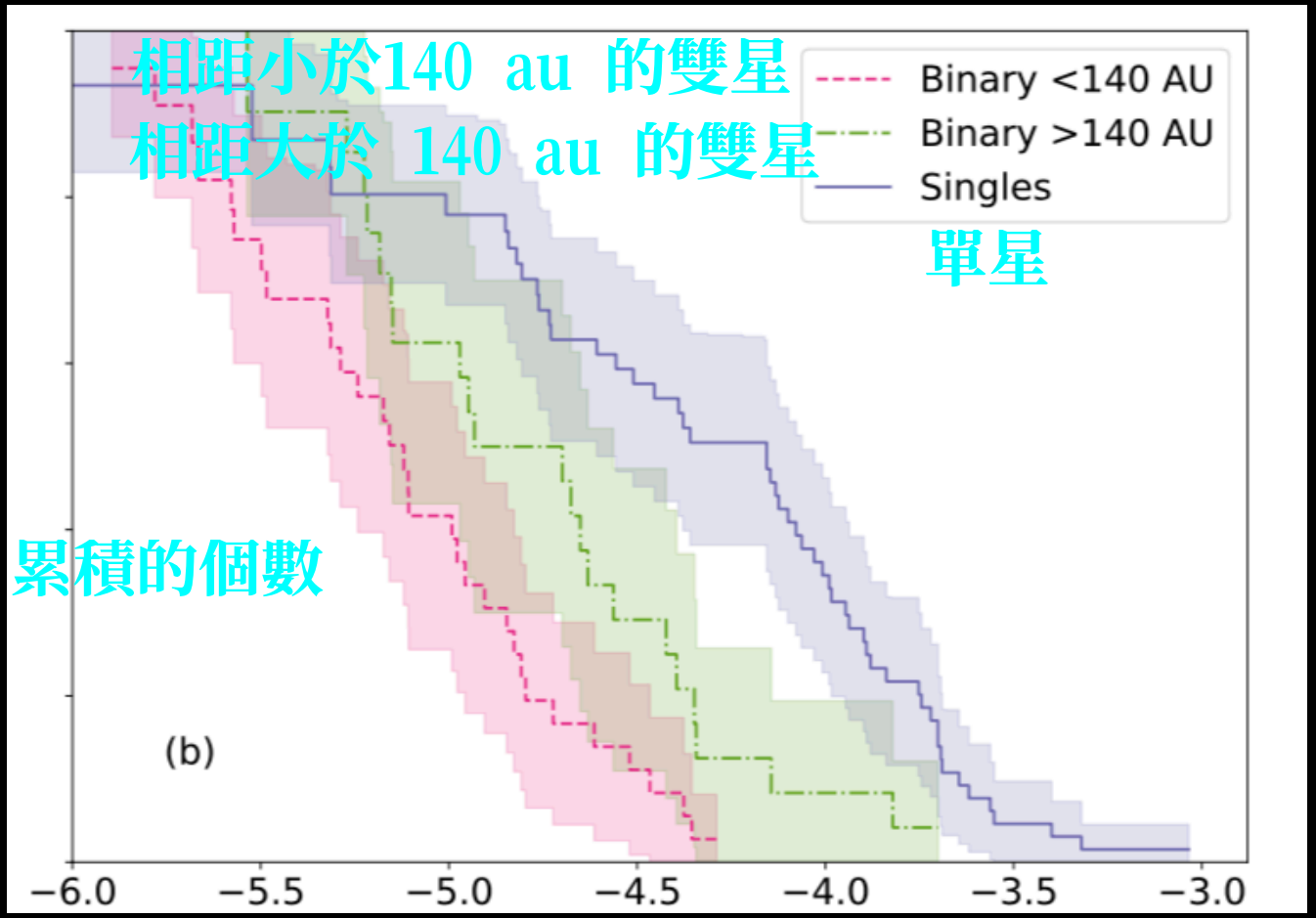
# What Planet Formation Might Be Like In a Multiple System

## 在多星系統裡，行星怎麼誕生呢？

四星系統環境的想像圖

Artist's Impression of quadruple system HD 98800B

# Planet Forming Disks in Multiple Systems 多（恆）星系統的環星盤




Fraction Greater Than X

Log (Mdust/M*) 環星盤中塵埃質量

- Single stars have the largest disks
- Close binaries have the smaller disks

單星環星盤大
緊密雙星環星盤最小

Akeson et al. 2019

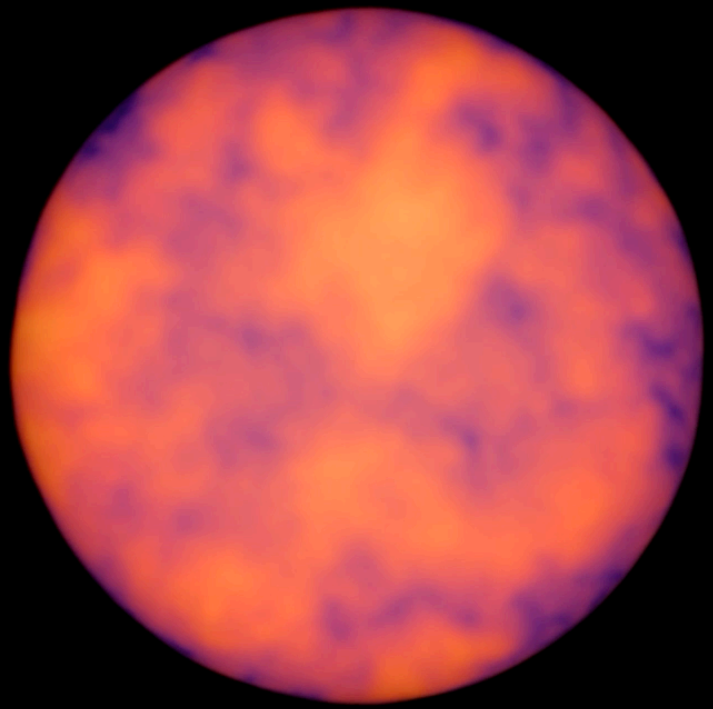
# Open Questions

待回答的問題

- What fraction of multiple systems form from each mechanism? 多星系統依照各自形成機制的比例
- How do the system properties change with time? 性質如何隨時間而變化
- How is planet formation different in multiple systems? 多星系統中行星形成的機制如何不同

# Simulations fill the gaps in our knowledge

## 讓電腦模擬提供解答



**STAR FOR**mation in **G**aseous **E**nvironments (**STARFORGE**)

Grudic et al. 2021, Guszejnov et al. 2021, Grudic ea 2022

# Conclusions:

- Our lonely Sun is a little unique – most stars like it *do* have a stellar sibling. 恆星多有兄弟姐妹，太陽是例外
- Most stellar siblings probably form from disk or core fragmentation – we now have evidence of this in nature. 這些伴星多半來自環星盤或原恆星核分裂
- Some multiple star systems have orbiting planets! 有些多星系統周圍居然也有行星
- Discoveries of star and planet formation are ongoing! 這仍是積極研究的課題