
(Lucas et al. 1977)

Is there a Tatooine?

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University of Arizona
March 14th, 2017, KITP

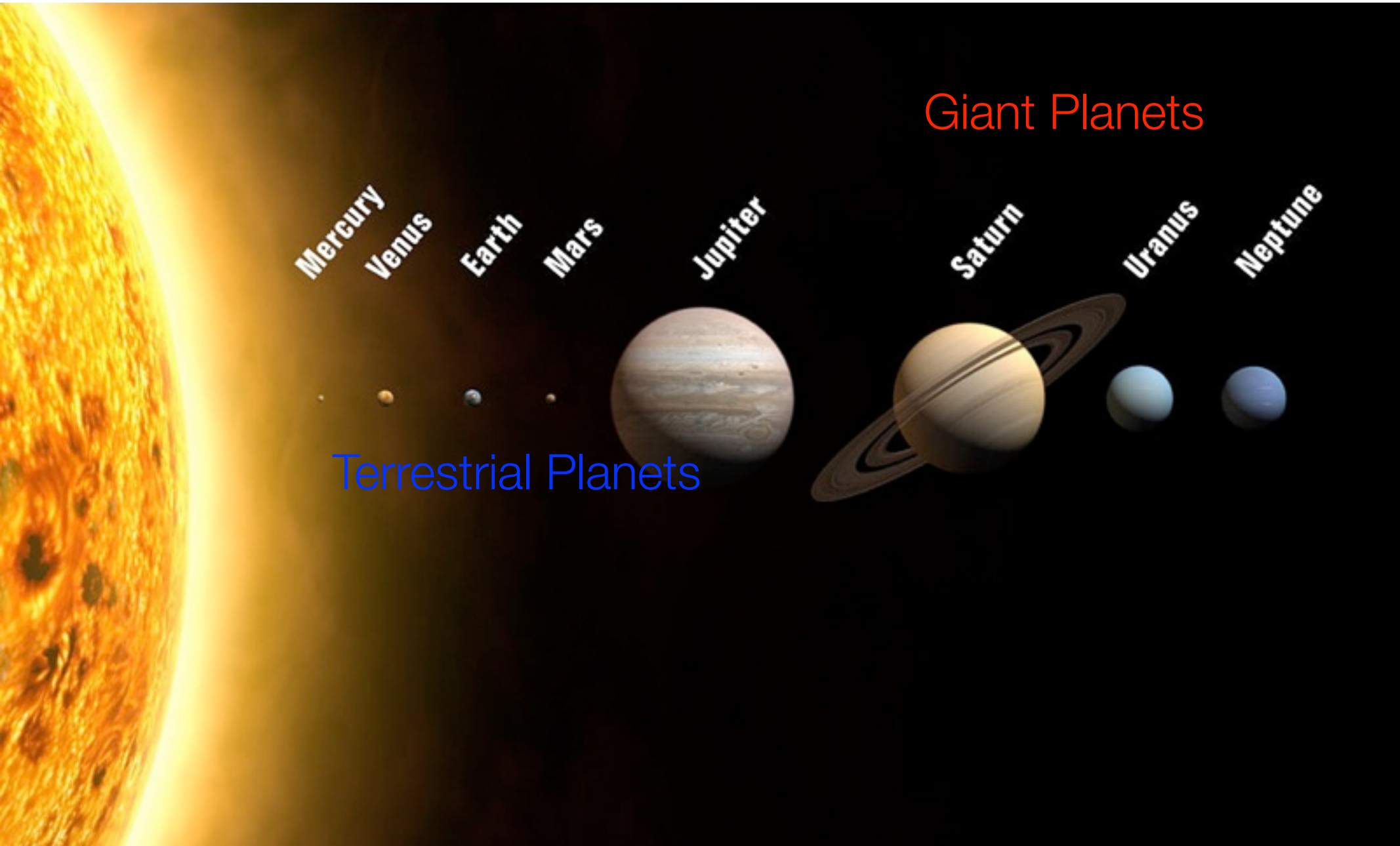
Tobin, Kratter et al, Nature 2016

From 18th century problems to exotic exoplanets

- The observational **exoplanet revolution**
- How do we model the **gravitational interactions** of systems containing more than two massive bodies?
- How can we use **celestial mechanics** to gain new insight into the mysteries of planet formation?

Pierre-Simon Laplace (1749–1827). Posthumous portrait by Jean-Baptiste Paulin Guérin, 1838.

Our Solar System



Kepler Space Telescope

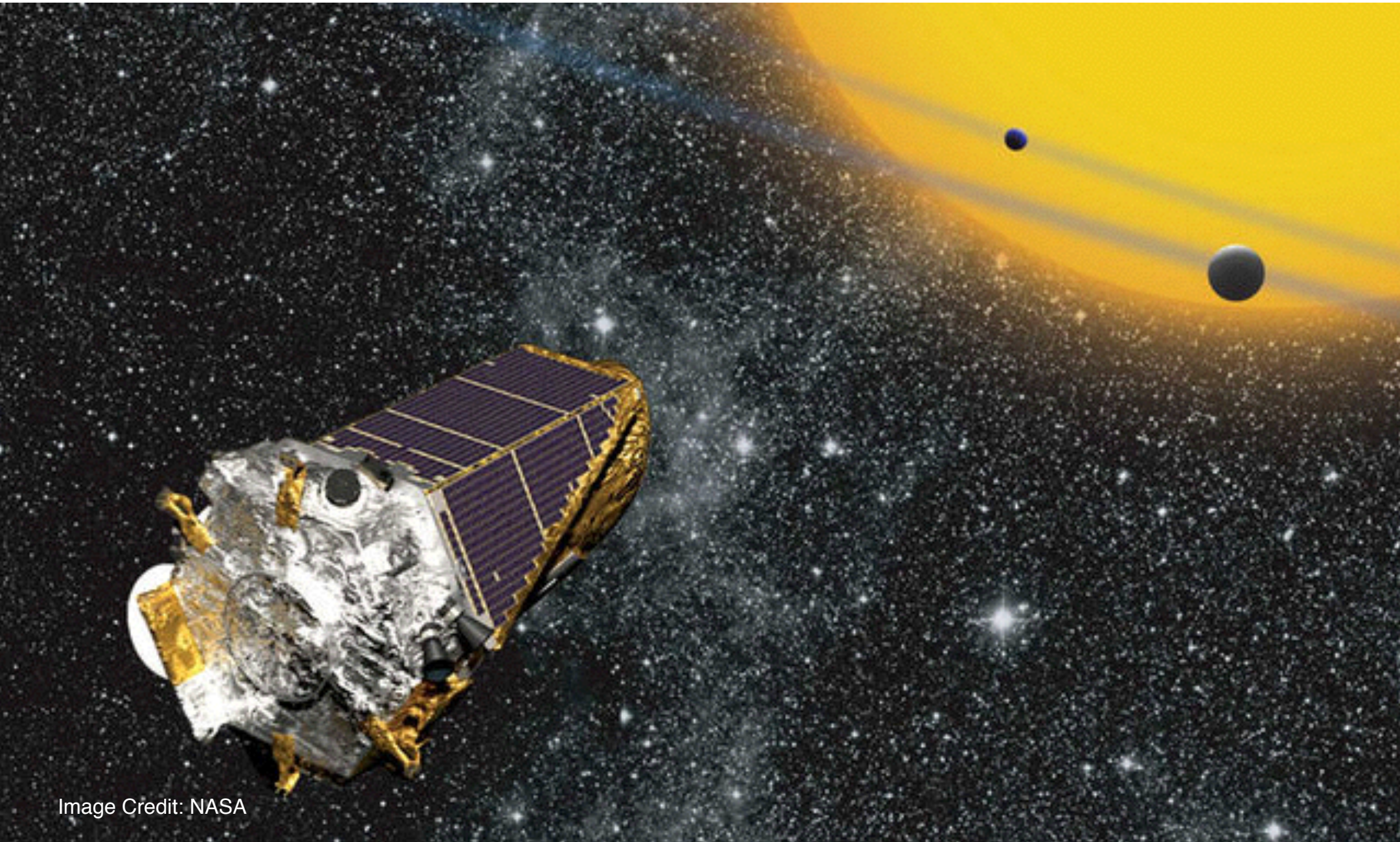
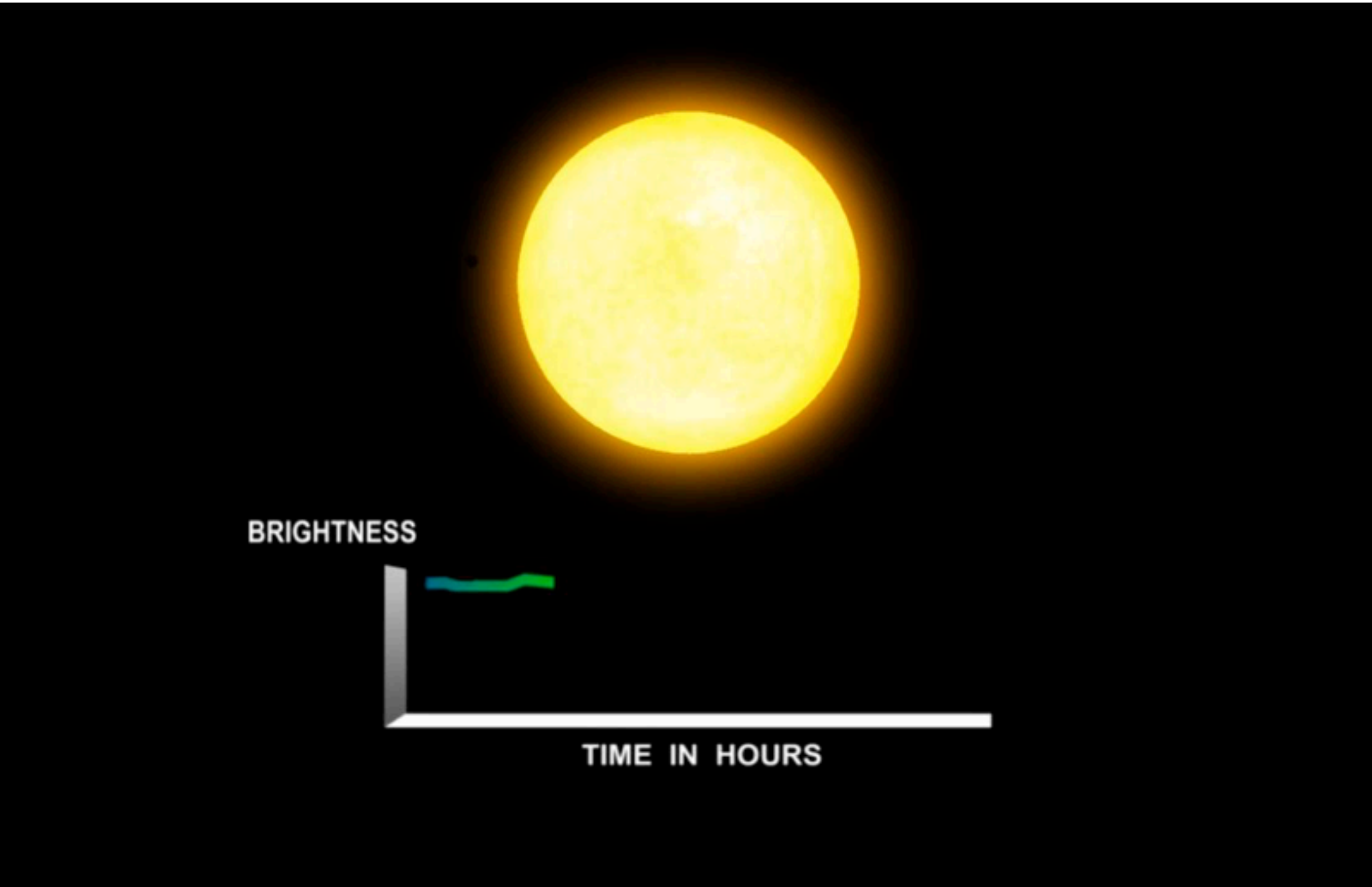


Image Credit: NASA

Exoplanet Detection: Transits



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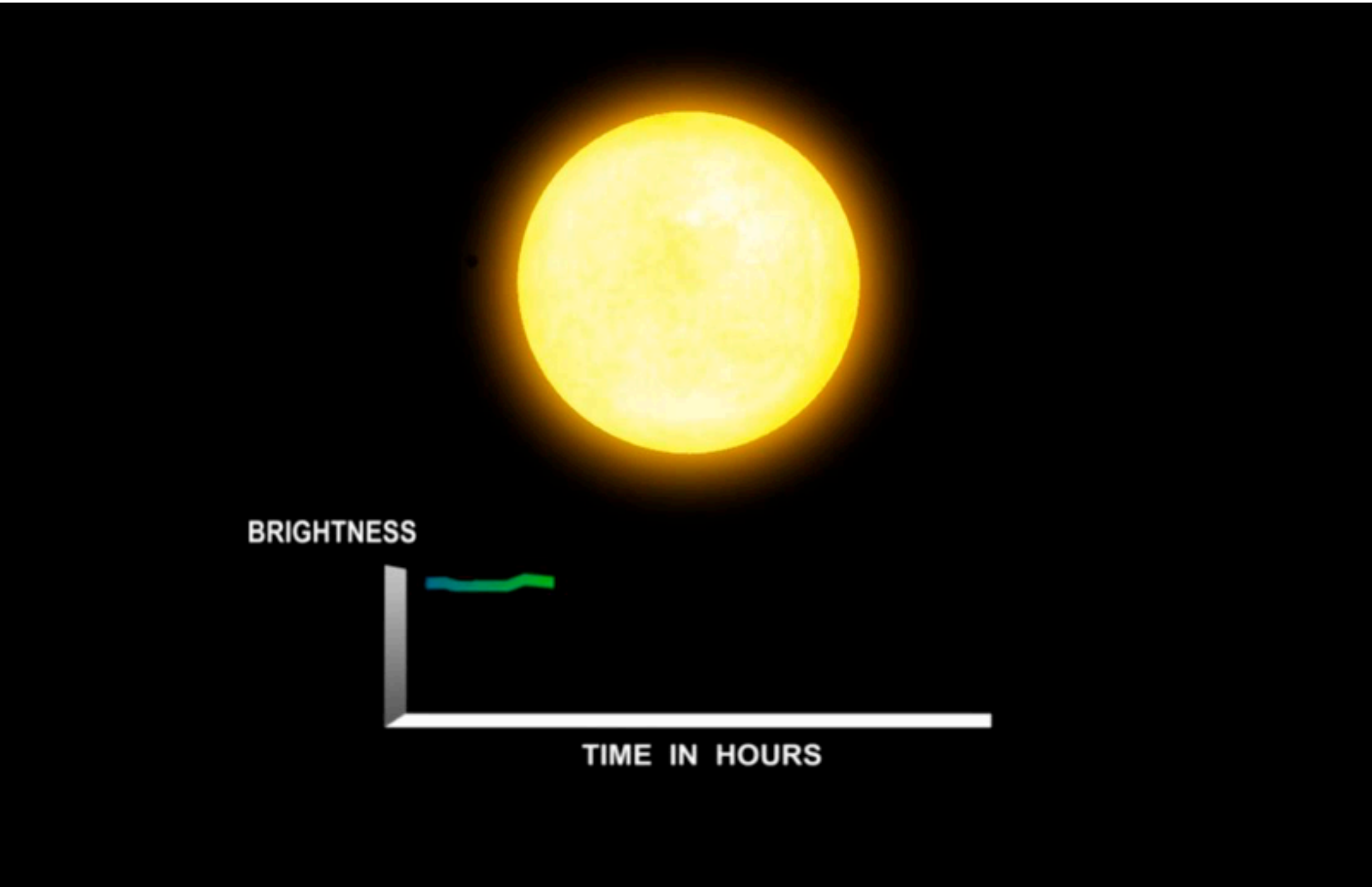
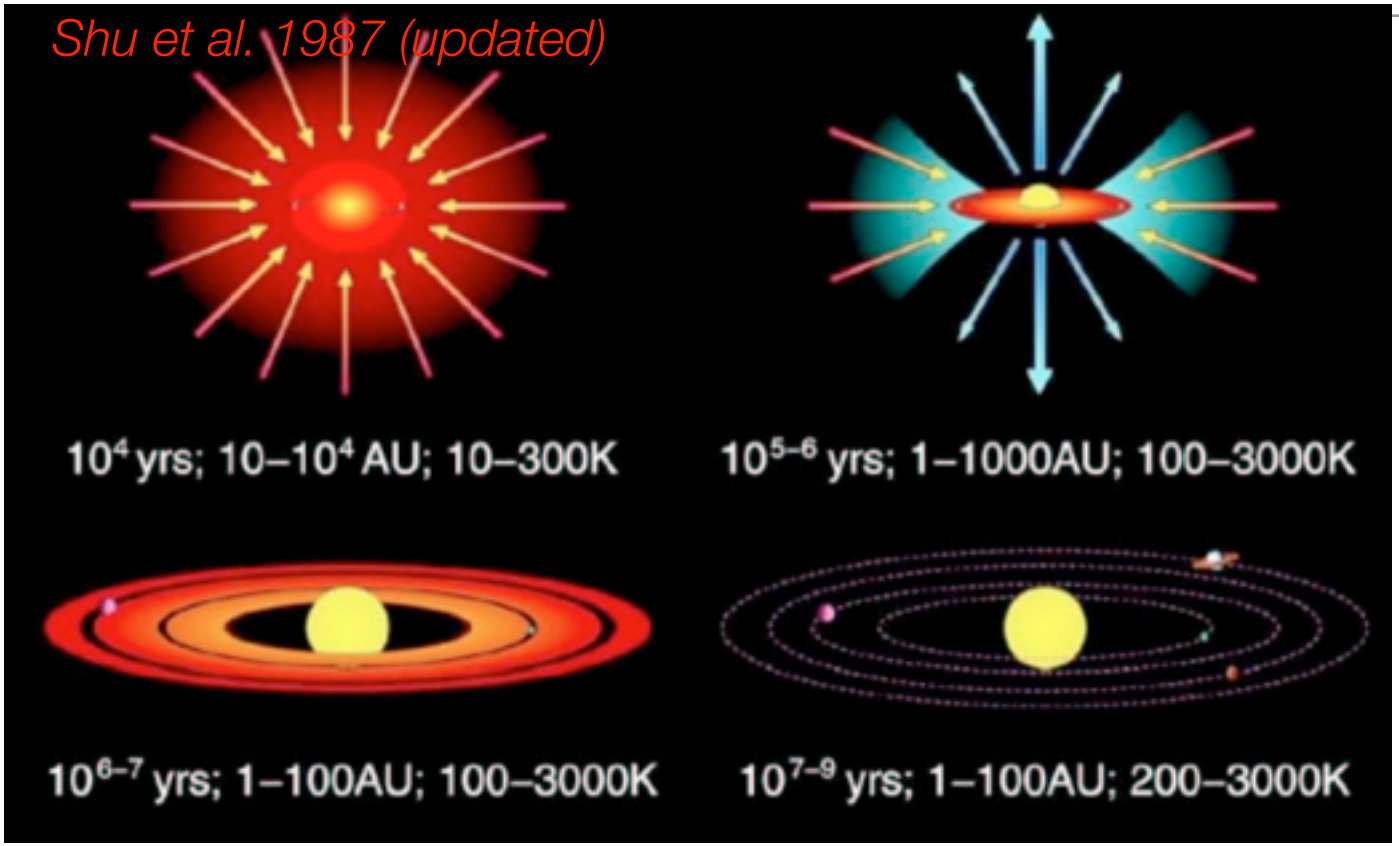


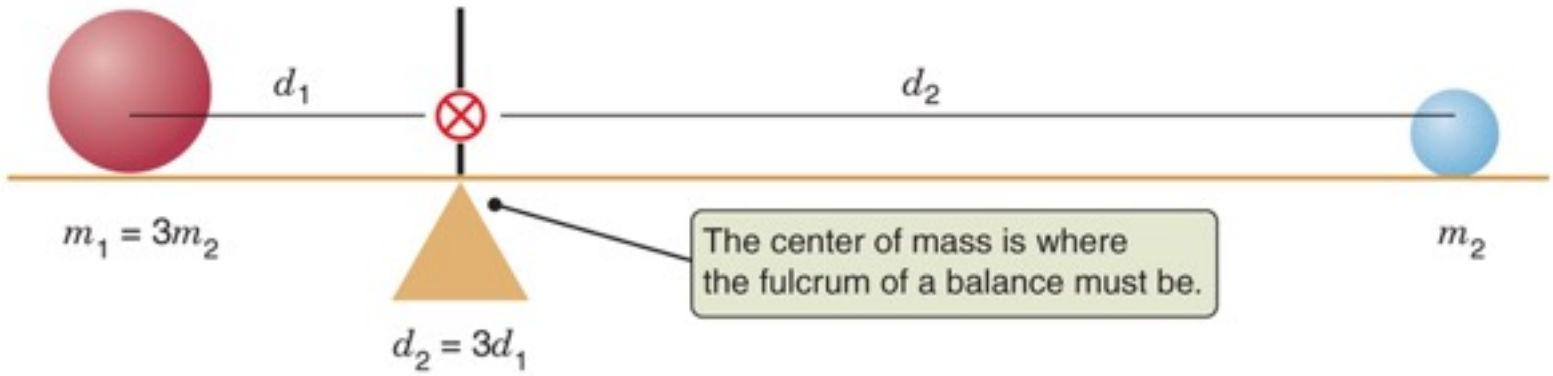
The Exoplanet Revolution

Movie by Alex Parker

How do we extract meaning from all of this data?



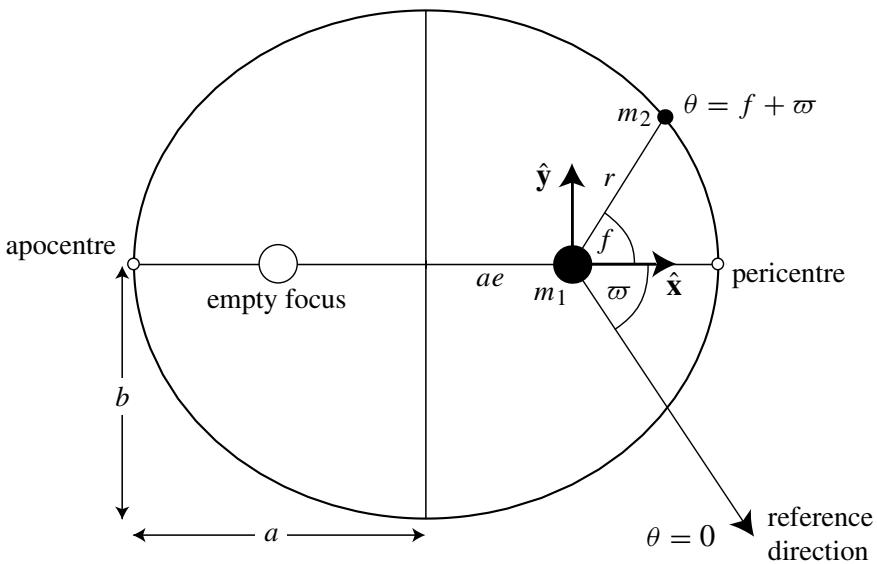
An end-to-end model for planet formation is still out of reach.
We can make progress by trying to model orbital evolution and dynamics

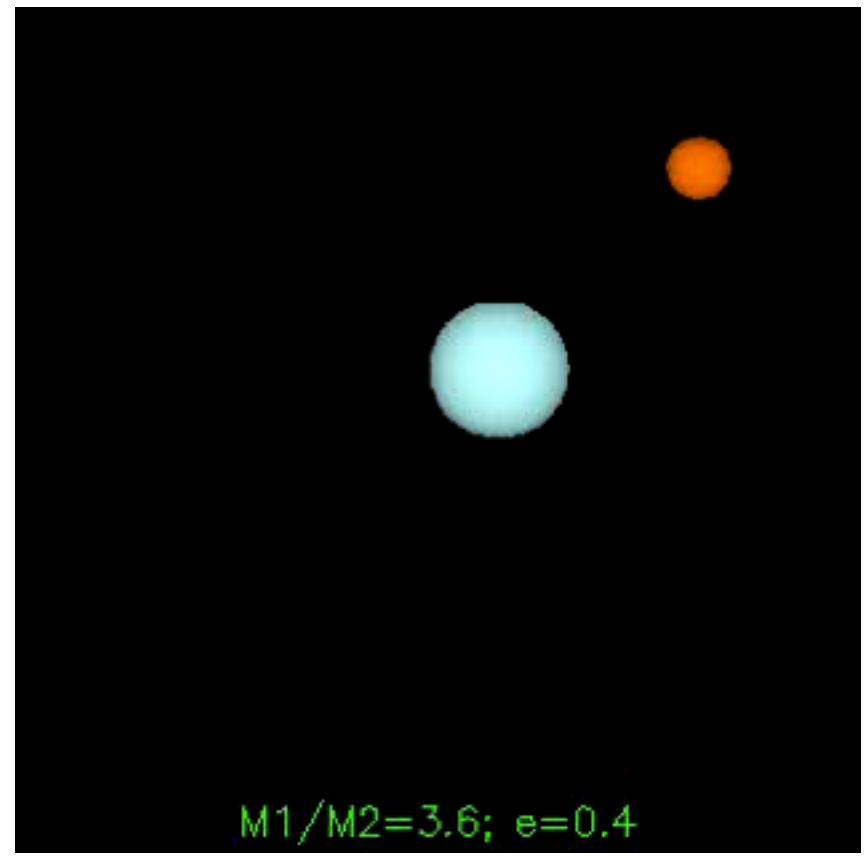


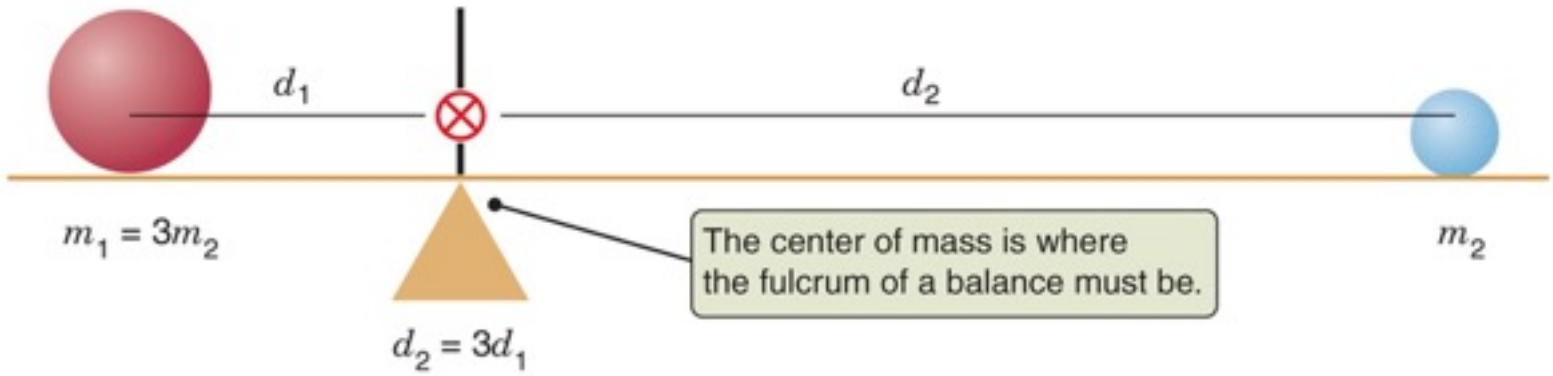
The two-body problem

There exists an analytic orbital solution for any two massive bodies.

Given the positions and velocities at any instant in time, we know the future (and past) behavior







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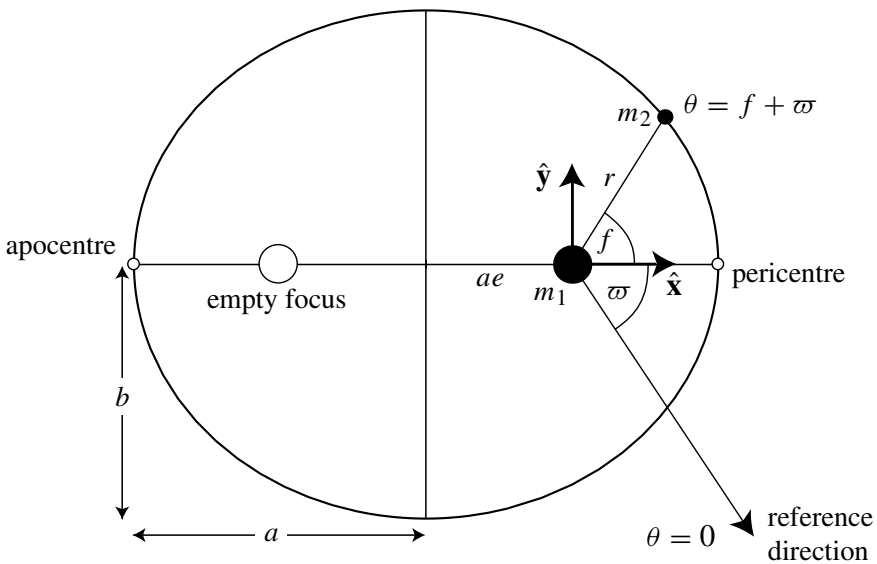
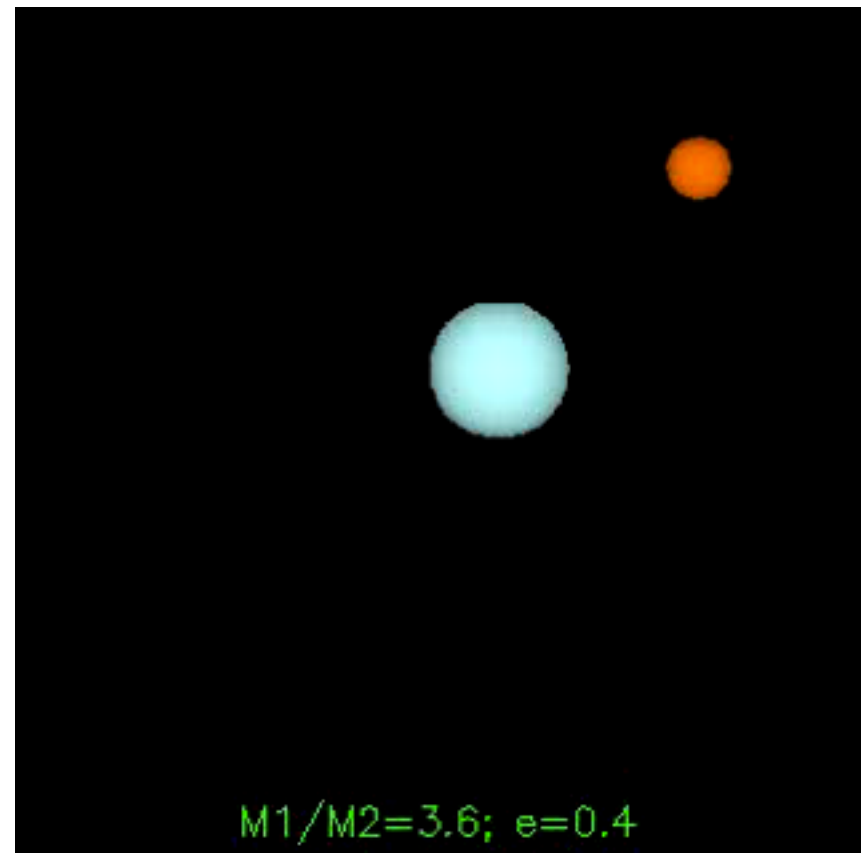
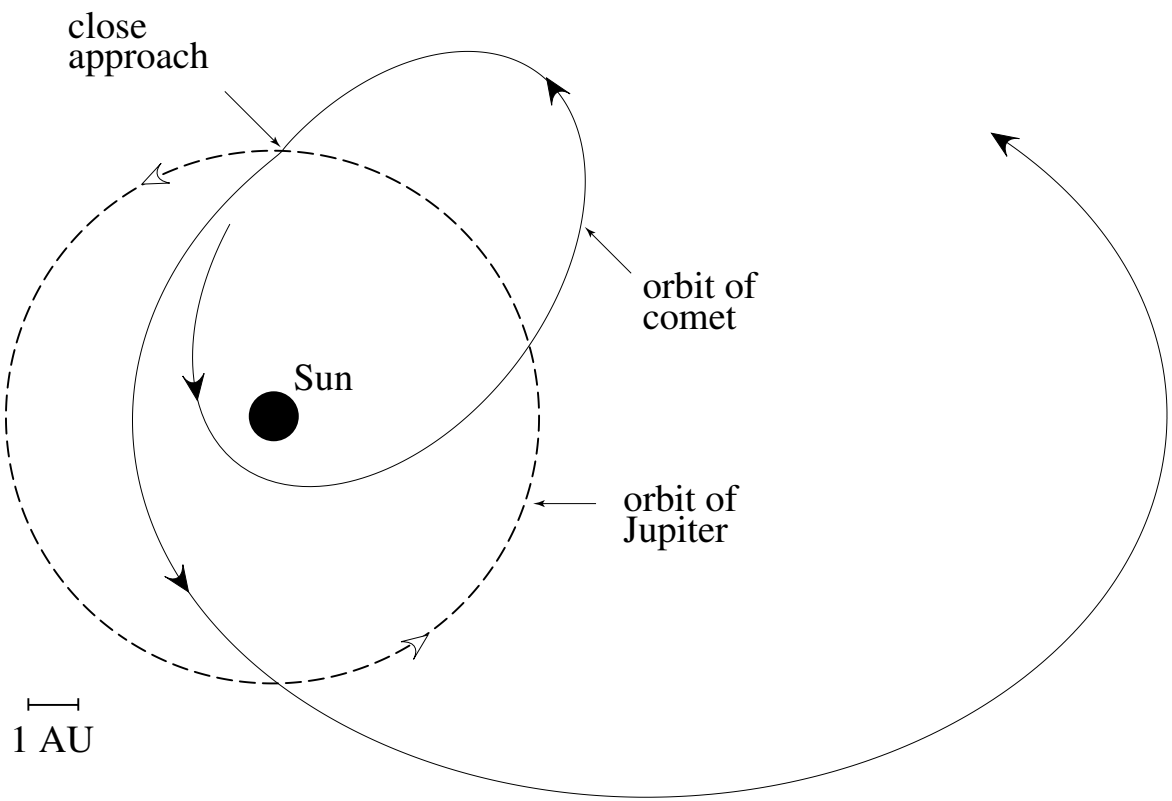




Next step up: the restricted three body problem



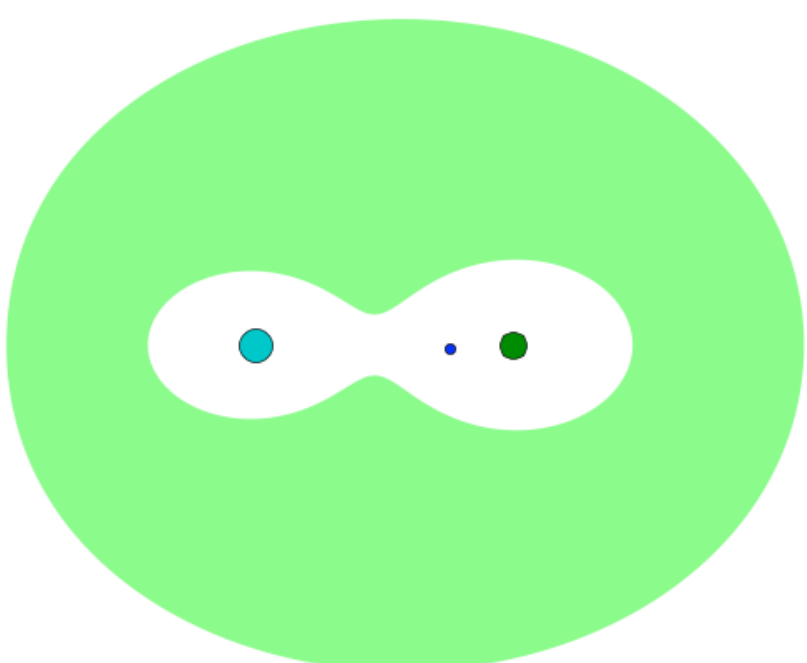
- Three bodies, but we only count the mass of two. The third is a so-called “test particle”
- Like the two body problem, we can make some statements about how the objects orbit each other with a few simple equation
- Classic example is the Sun, Jupiter and an asteroid, moon, or comet

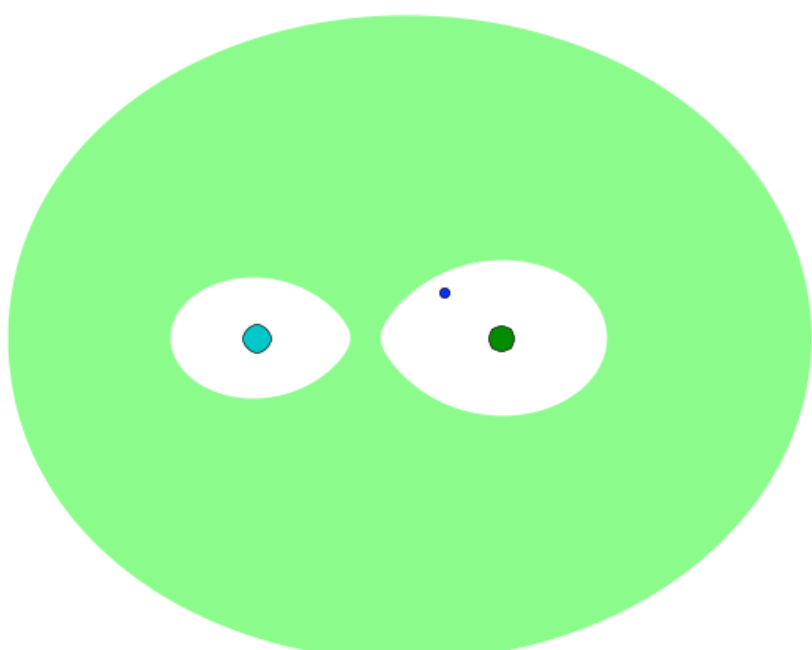
The circular restricted 3-body problem

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} x + 2\dot{y} - \frac{1-\mu}{r_1^3}[x+\mu] - \frac{\mu}{r_2^3}[x-(1-\mu)] \\ y - 2\dot{x} - \frac{1-\mu}{r_1^3}y - \frac{\mu}{r_2^3}y \\ -\frac{1-\mu}{r_1^3}z - \frac{\mu}{r_2^3}z \end{bmatrix}$$

$$r_1 = \sqrt{(x+\mu)^2 + y^2 + z^2} \qquad r_2 = \sqrt{(x-(1-\mu))^2 + y^2 + z^2}$$

$$C_J = n^2(x^2+y^2) + 2\left(\frac{\mu_1}{r_1} + \frac{\mu_2}{r_2}\right) - \left(\dot{x}^2 + \dot{y}^2 + \dot{z}^2\right)$$

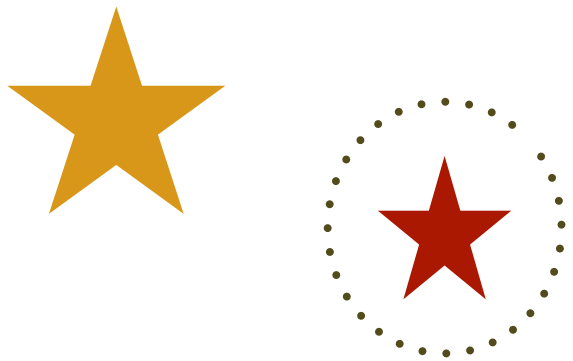




Many stars are in pairs (or triples!)

Planets are found at a range of distances and masses in these systems

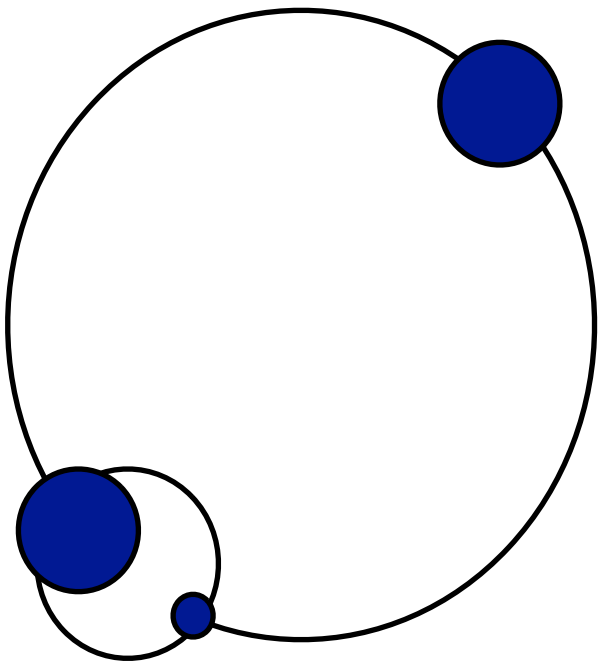
A modern example, planets in binaries



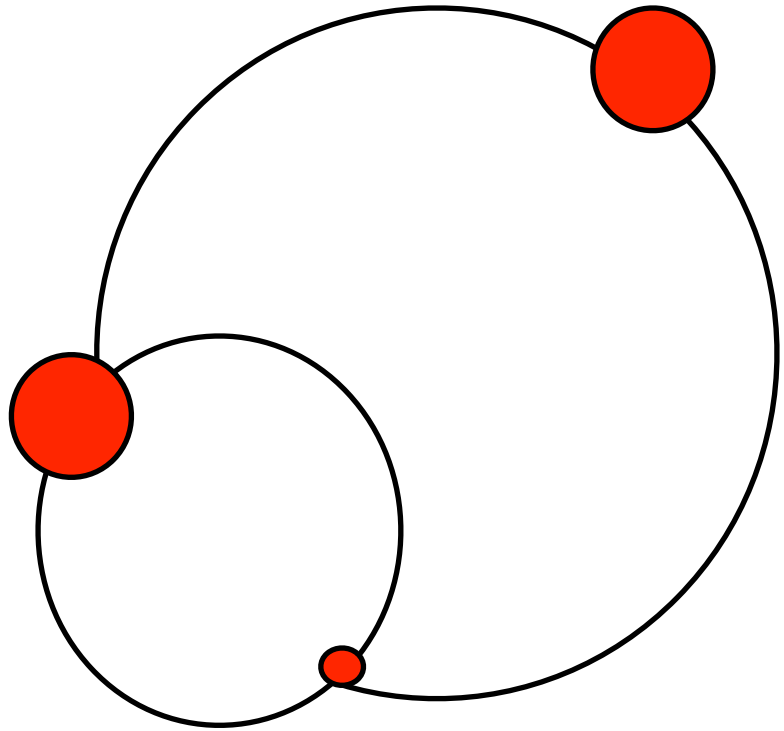
Satellite-Type

Planetary-Type
"Tatooines"

Planet stability requires well separated orbits



$a_{\rm in} << a_{\rm out}$



$a_{\rm in} \leq a_{\rm out}$

Holman and Wiegert 1999, Mudryk & Wu 2007

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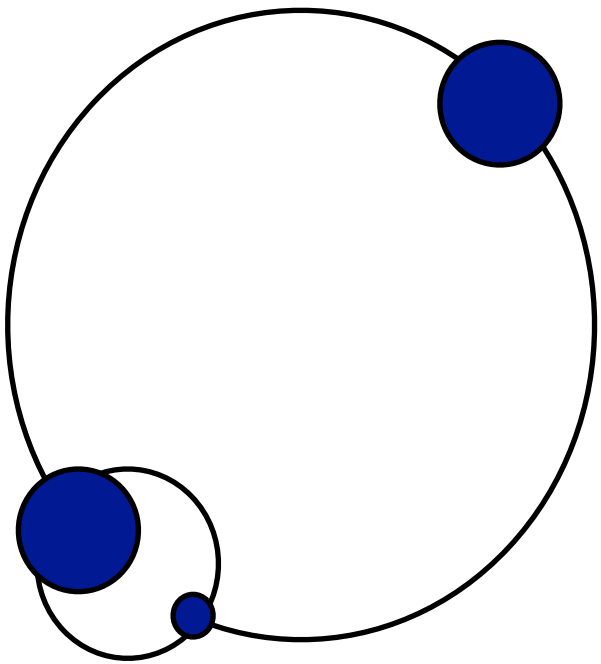

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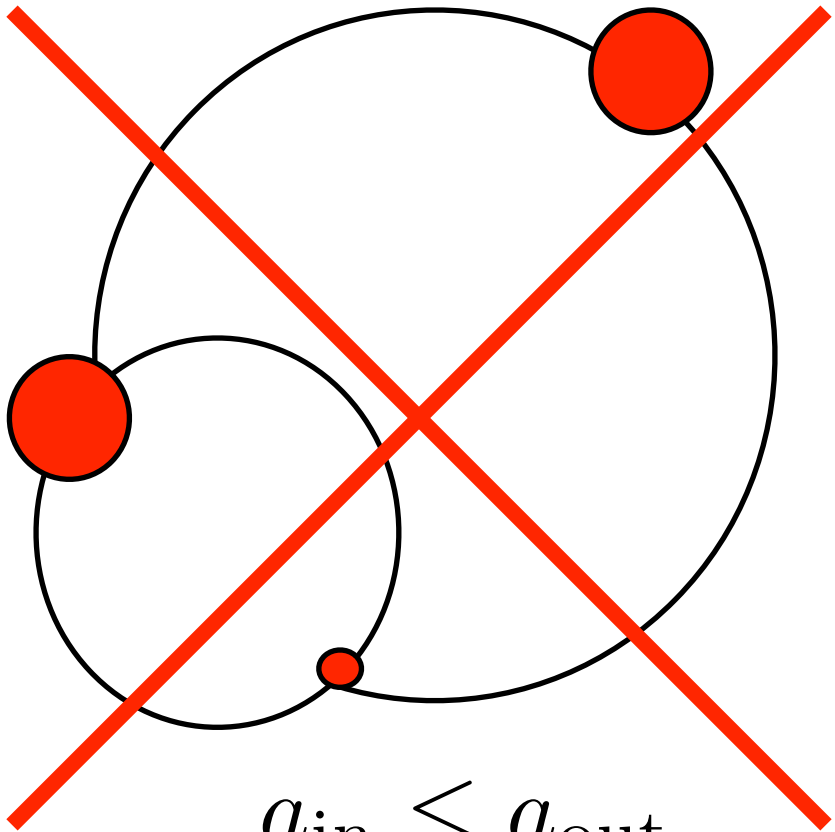

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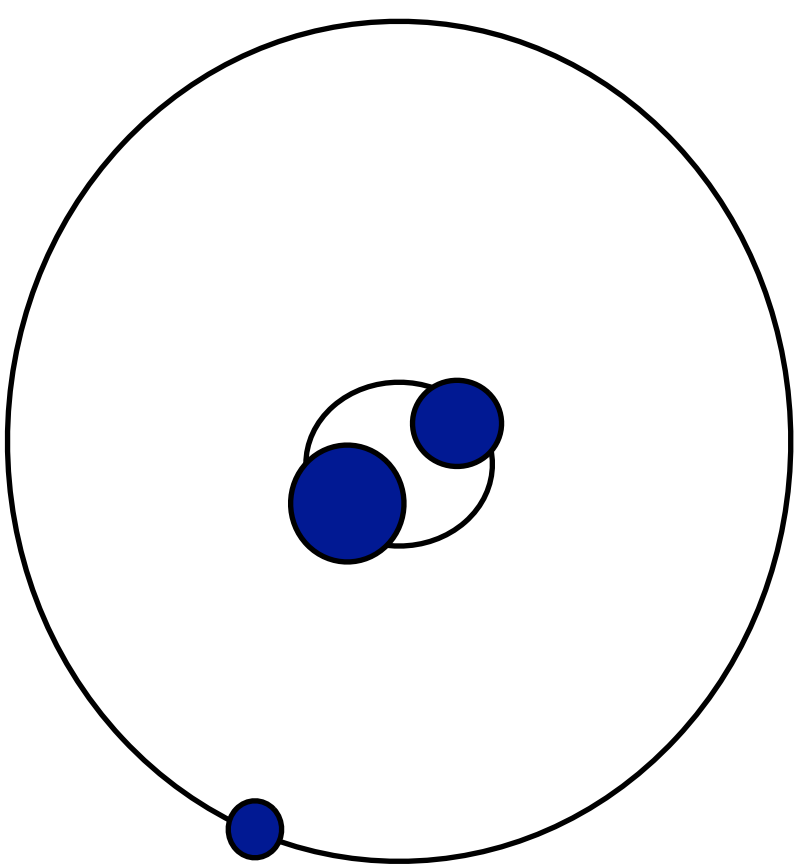

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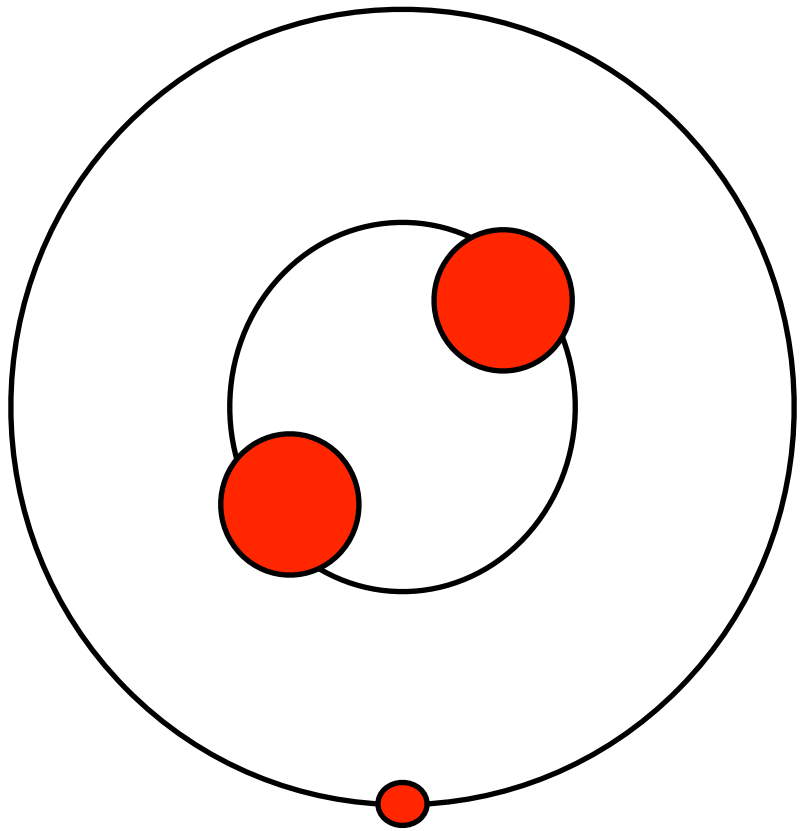

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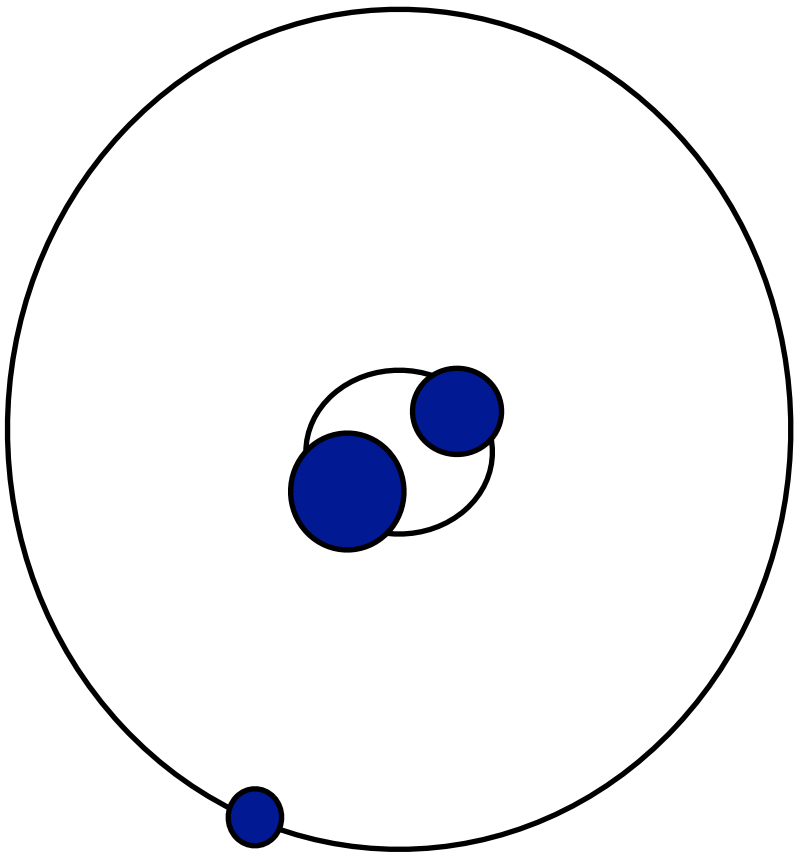

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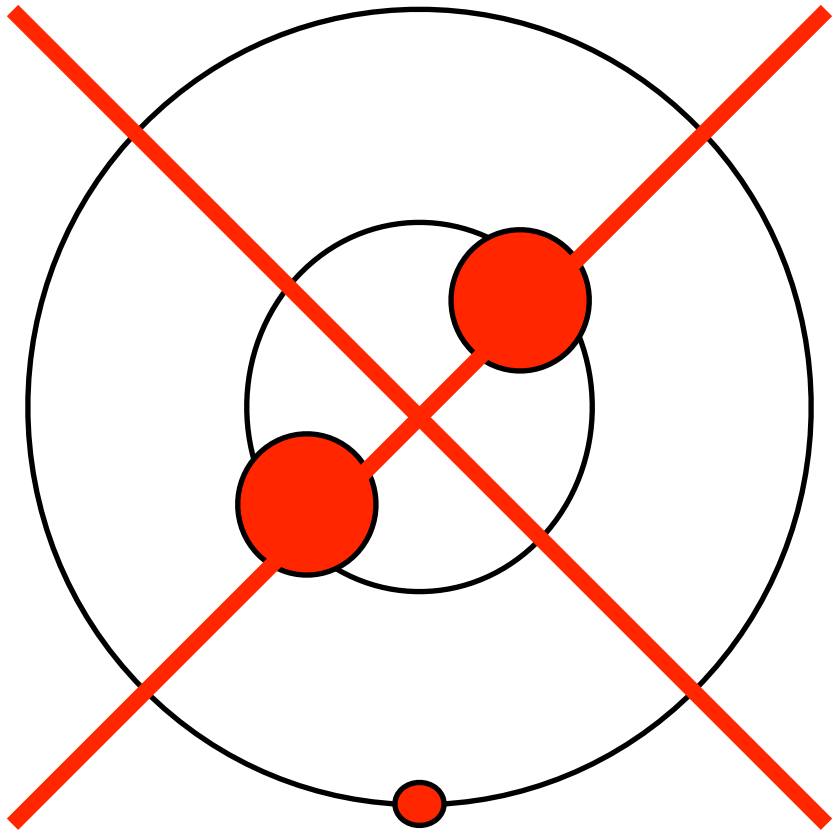

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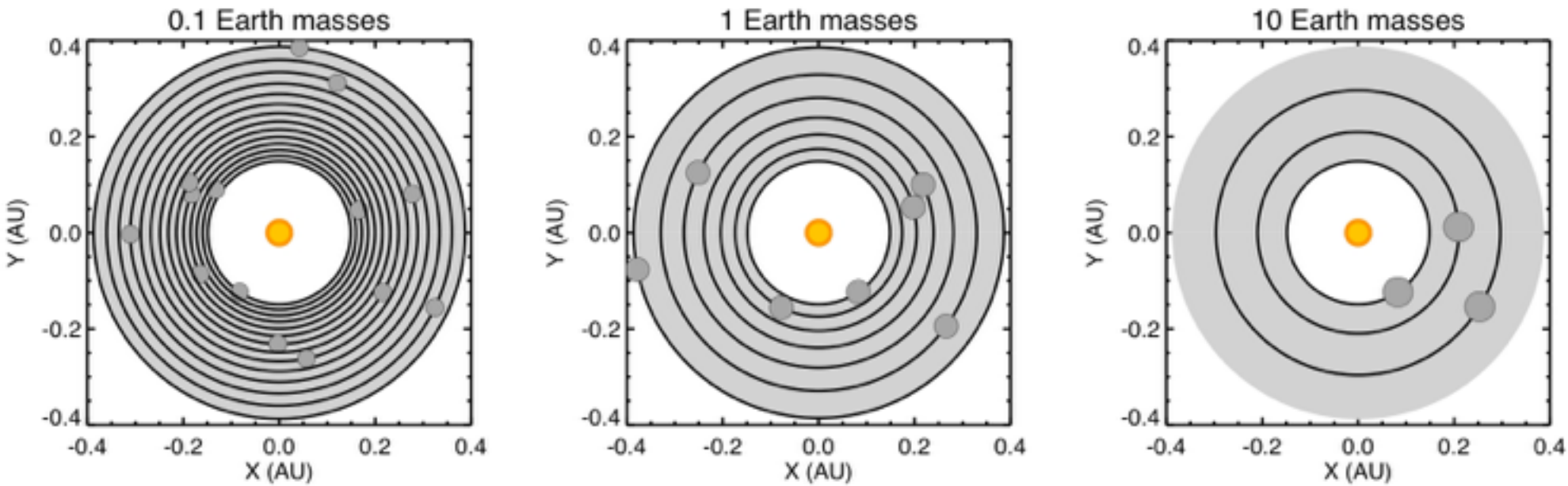
Stability is an issue even in systems with only 1 sun

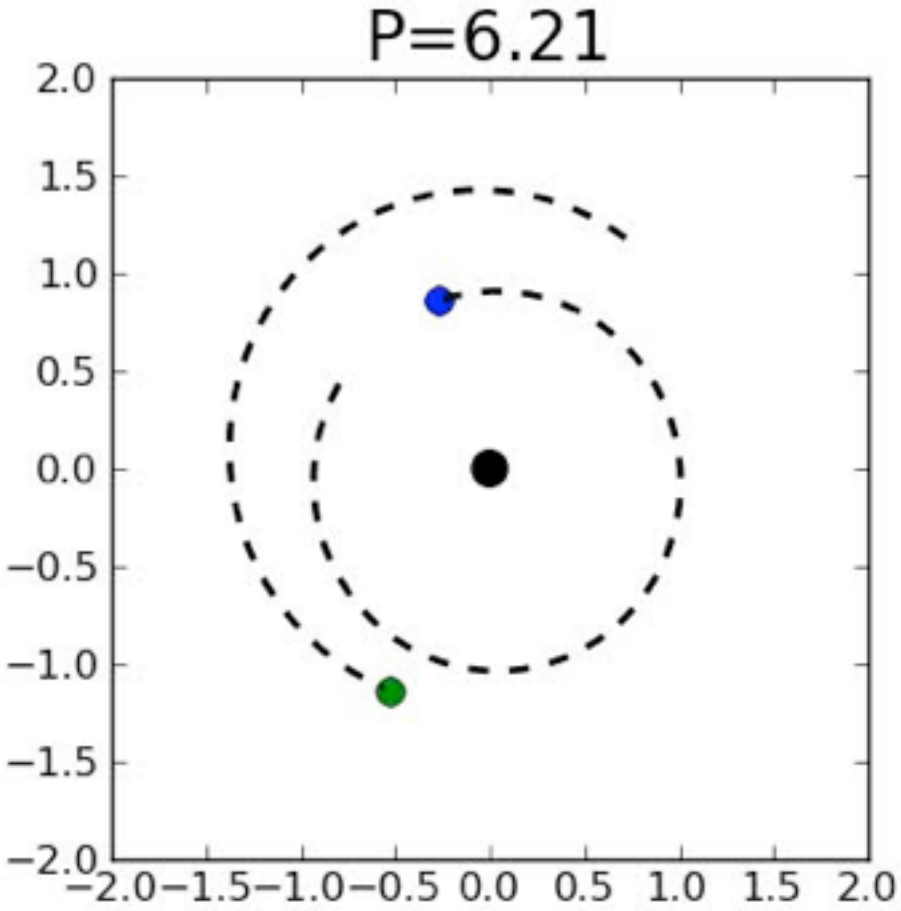


- Minimum planet spacing depends on distance from the sun and planet mass.
- More massive, or more tightly packed planets exert stronger gravitational tugs on each other, readily causing instabilities
- When they are closer to the star, its gravity dominates more, making the planet tugs less important

Chaos vs Stability?

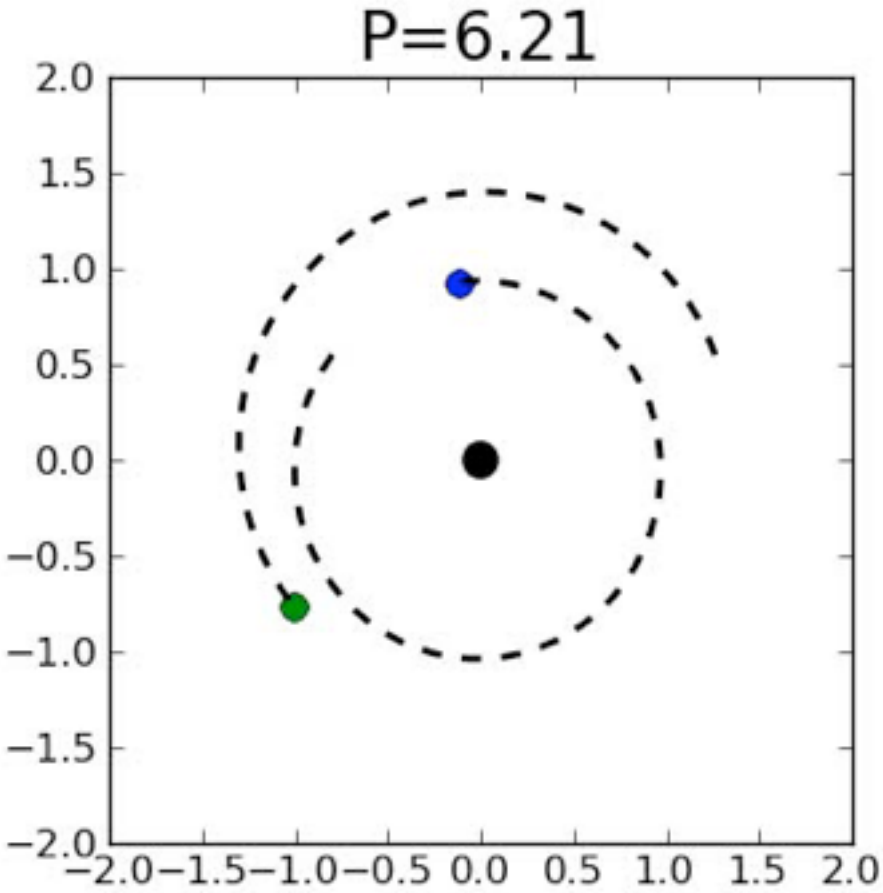
System 1:

1.0 AU, 1.067 AU



System 2:

1.0 AU, 1.073 AU



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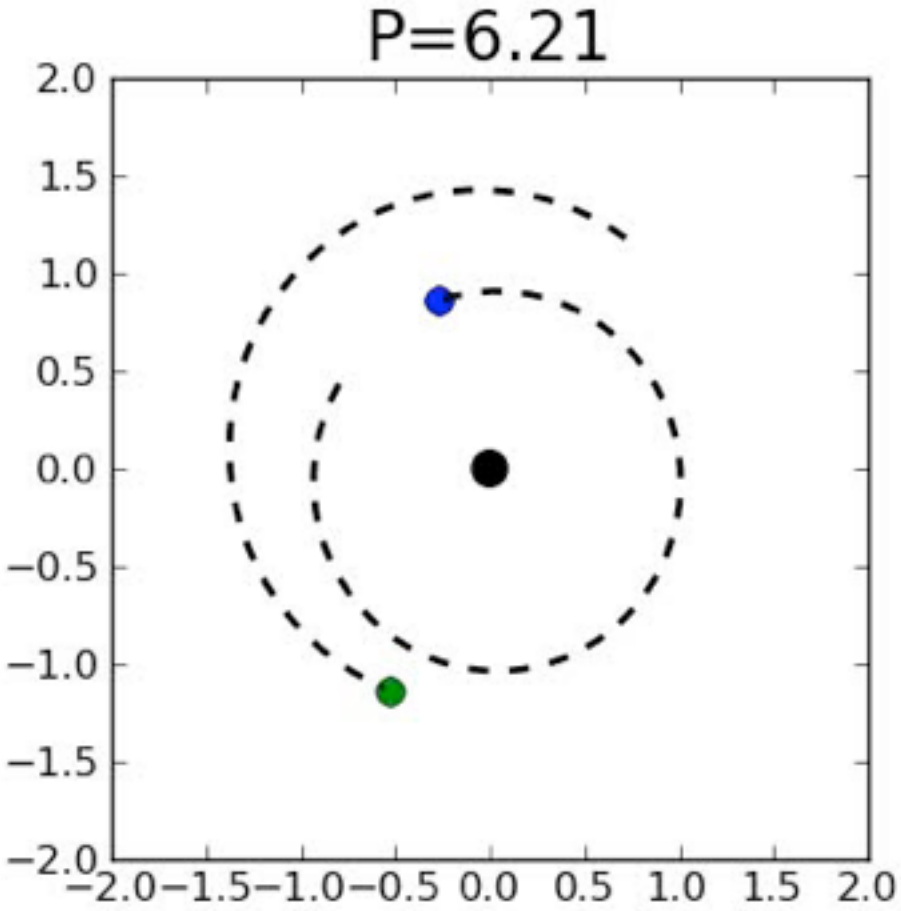

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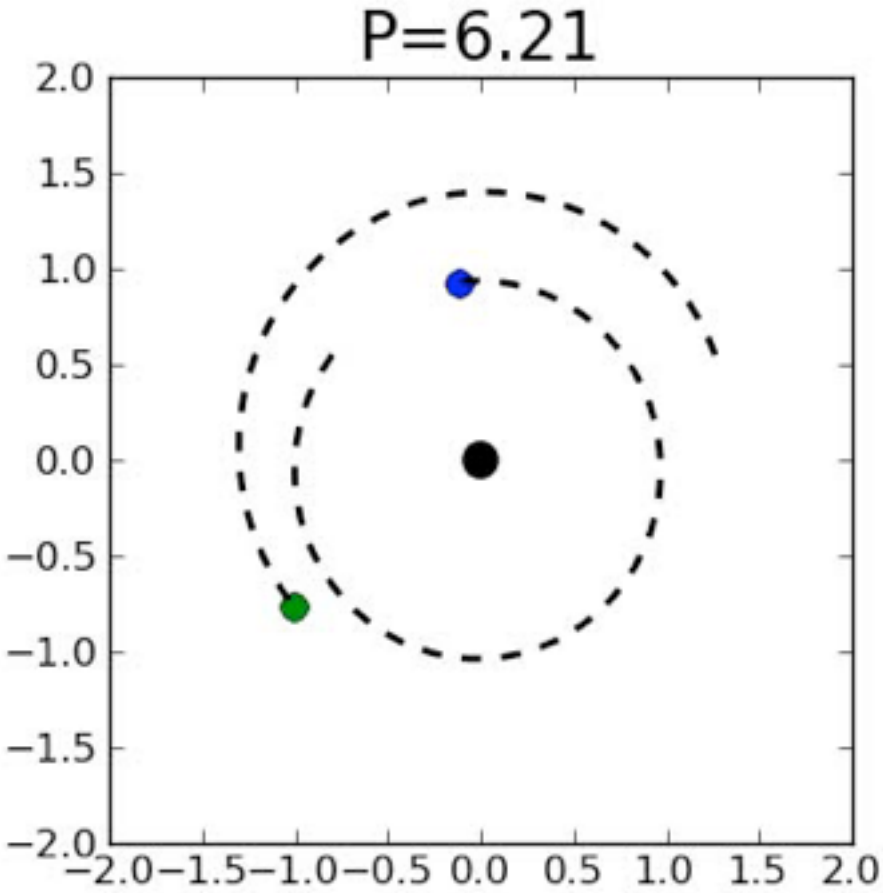

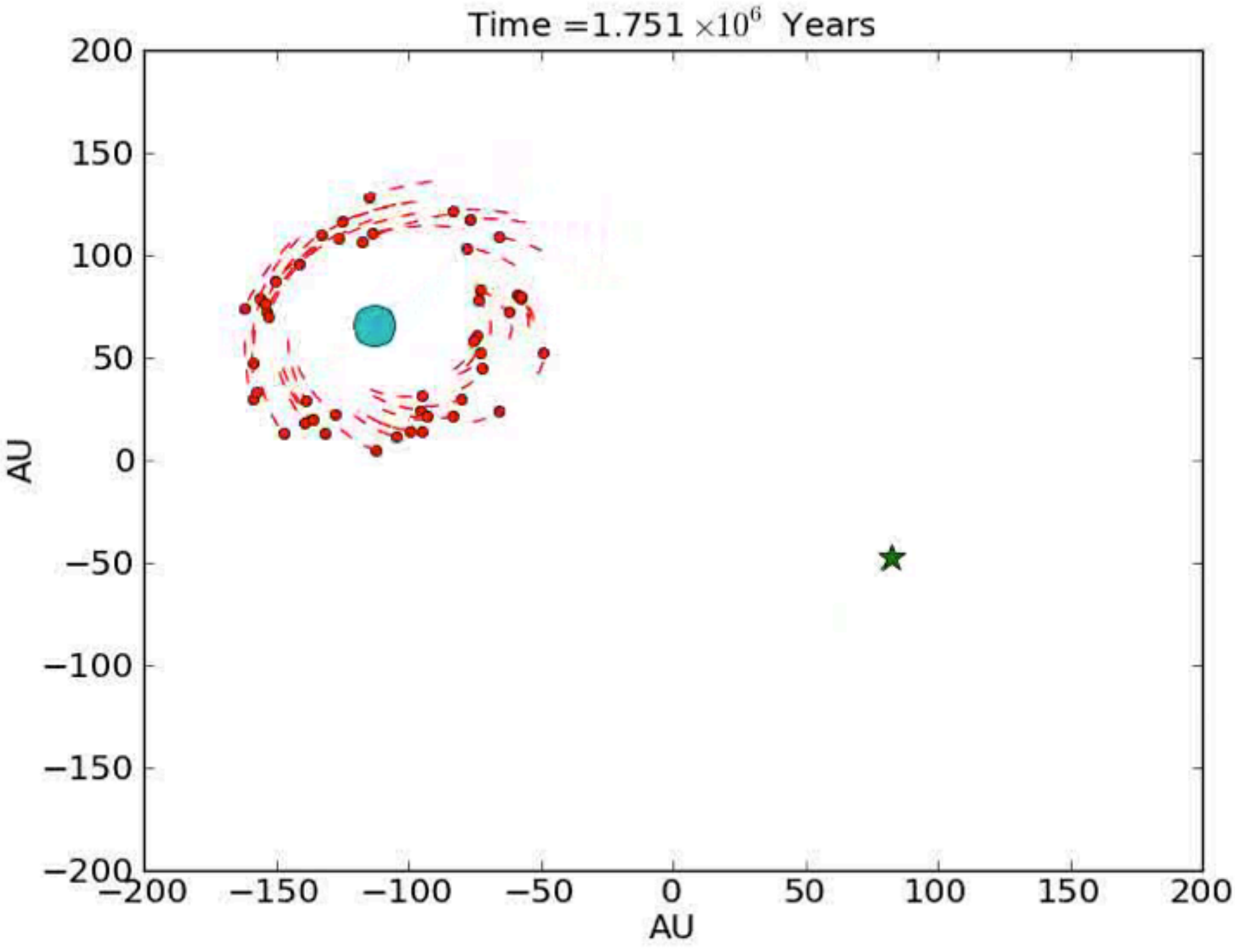
Time =1.751 $\times 10^6$ Years
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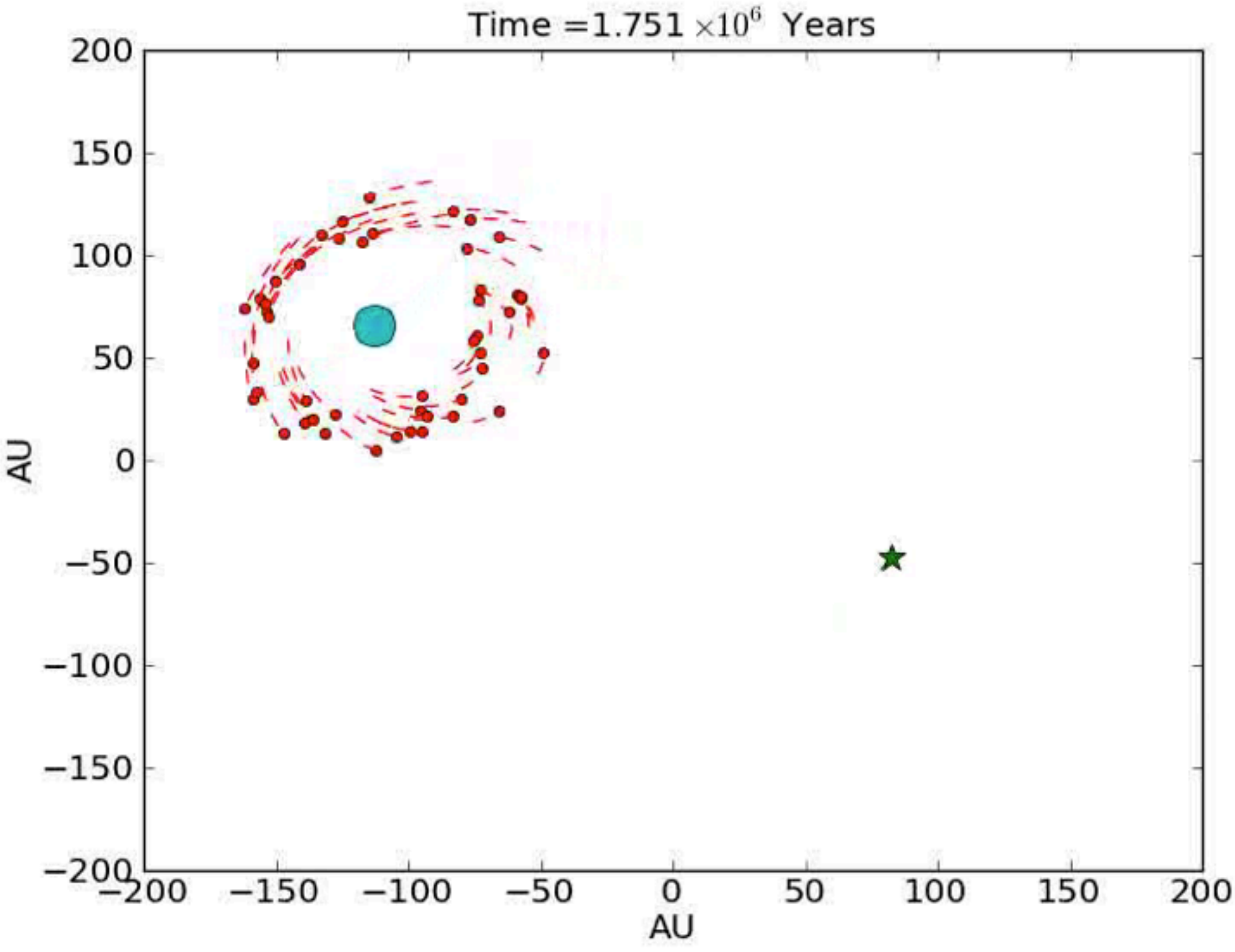
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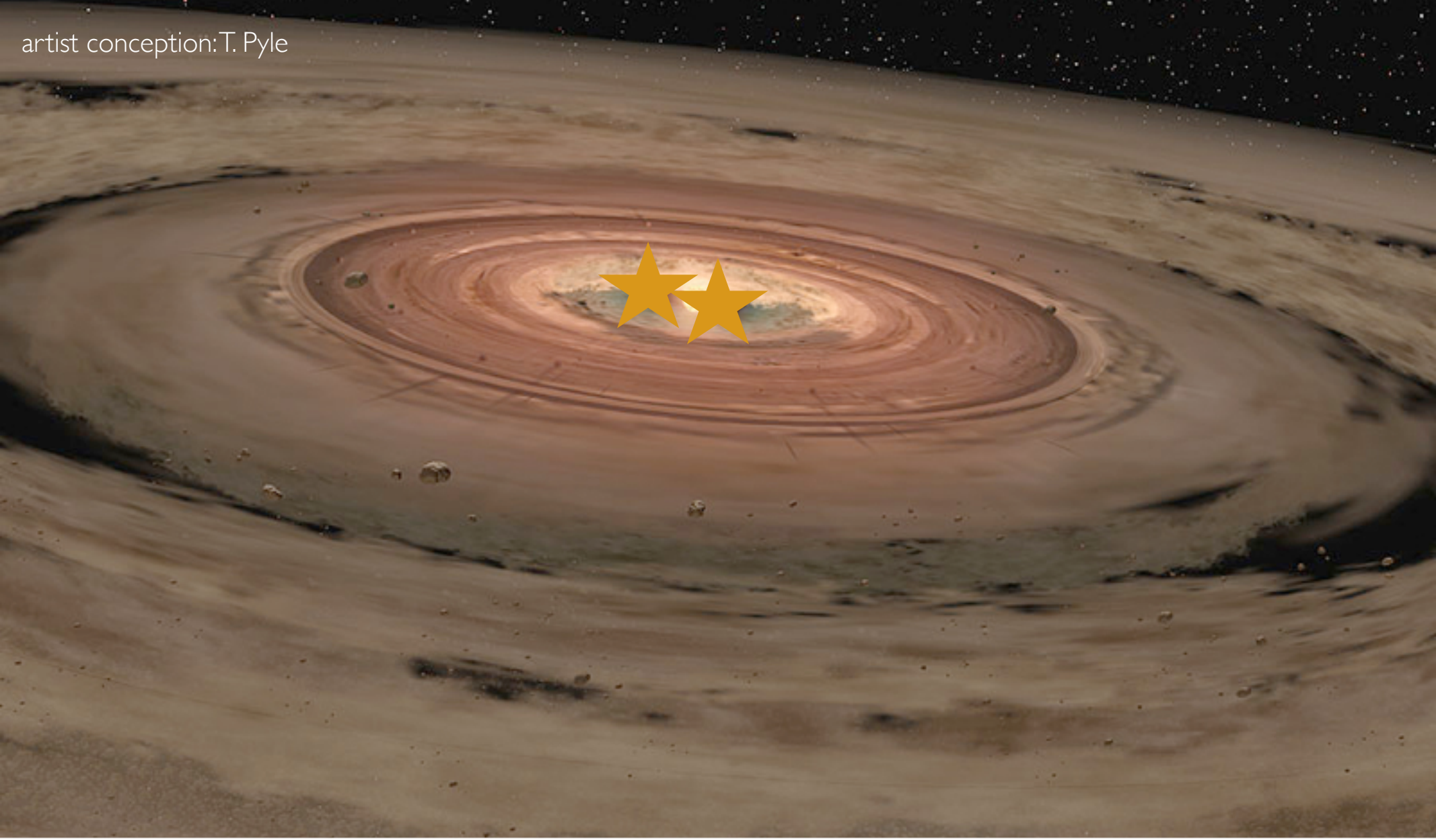
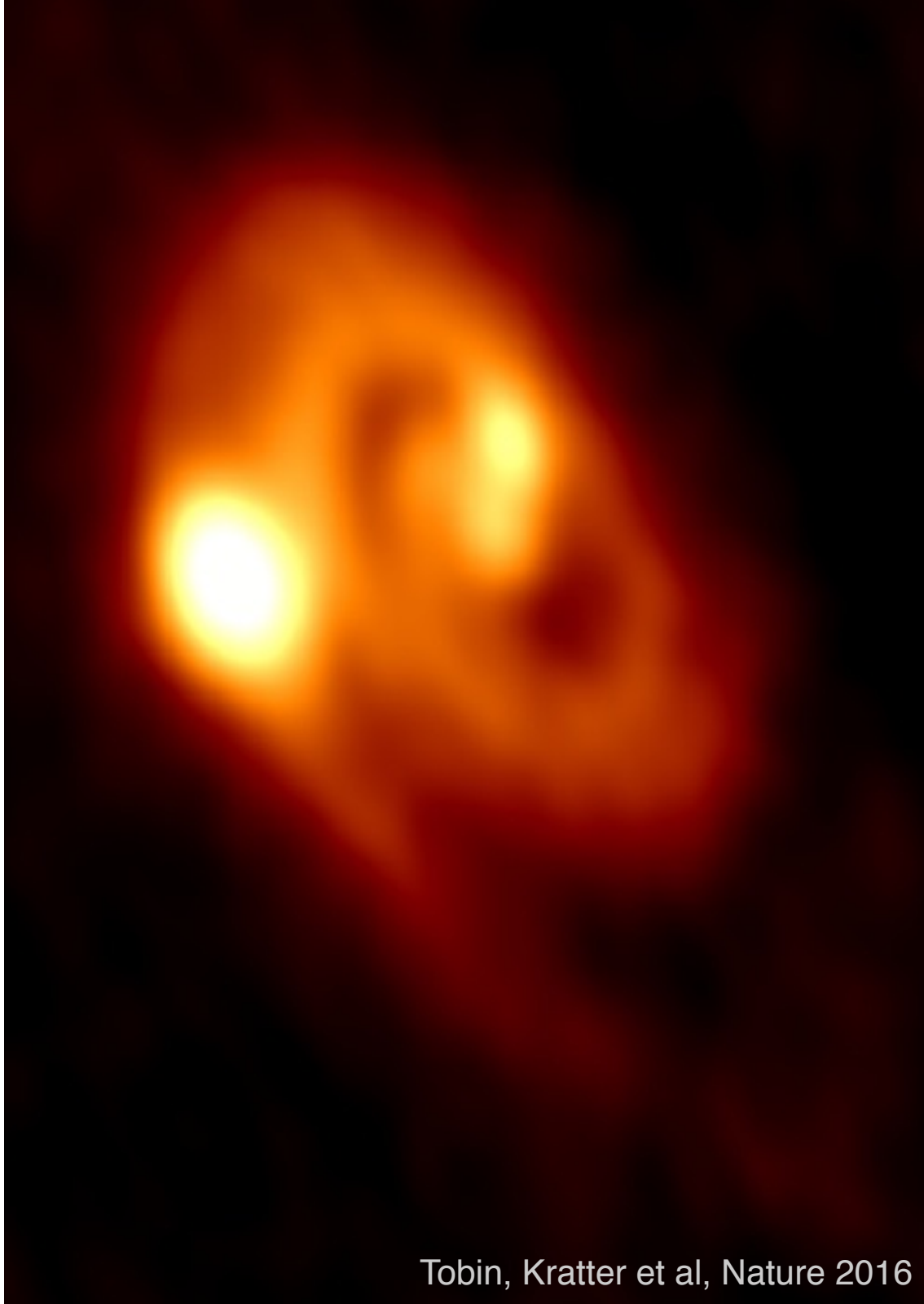


Why study planets in binaries?

We learn about the stars and planets!

The Planet Clock!

- Planets form in the disks of gas and dust out of which stars are born
- These disks only survive for a few Myr
- Tatooine systems tell us that at least some binary stars must assume their current system position within ~Myr
- This lets us rule out many previous theories of binary formation!



Tobin, Kratter et al, Nature 2016

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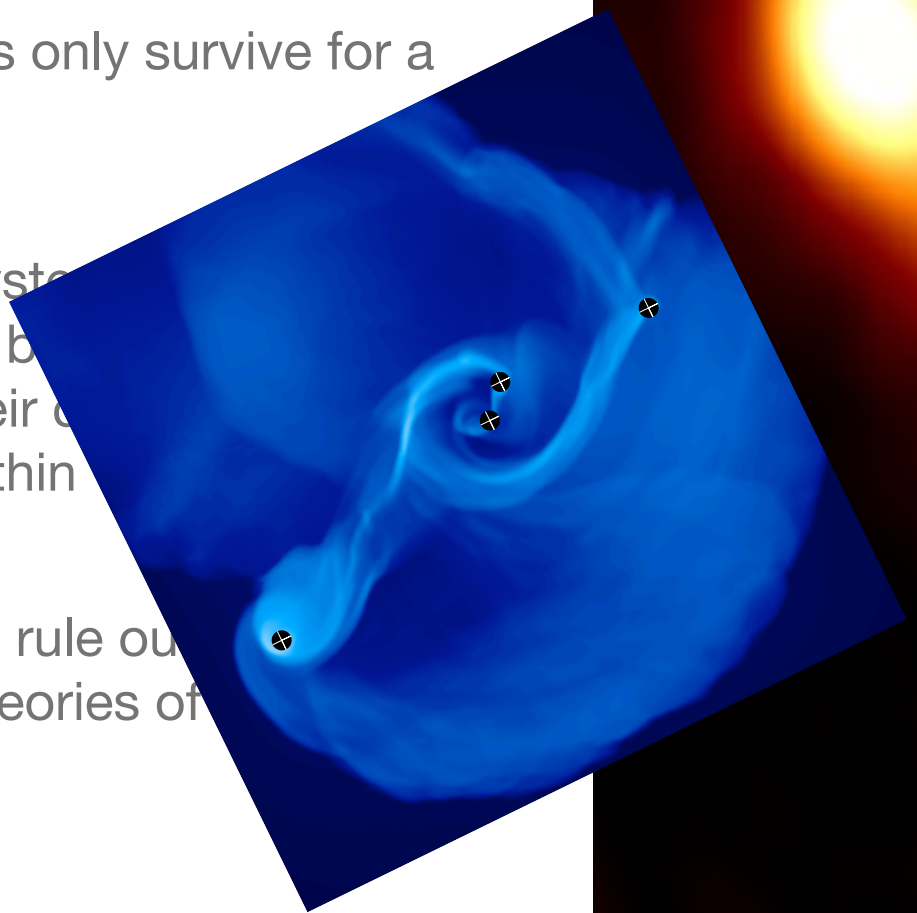

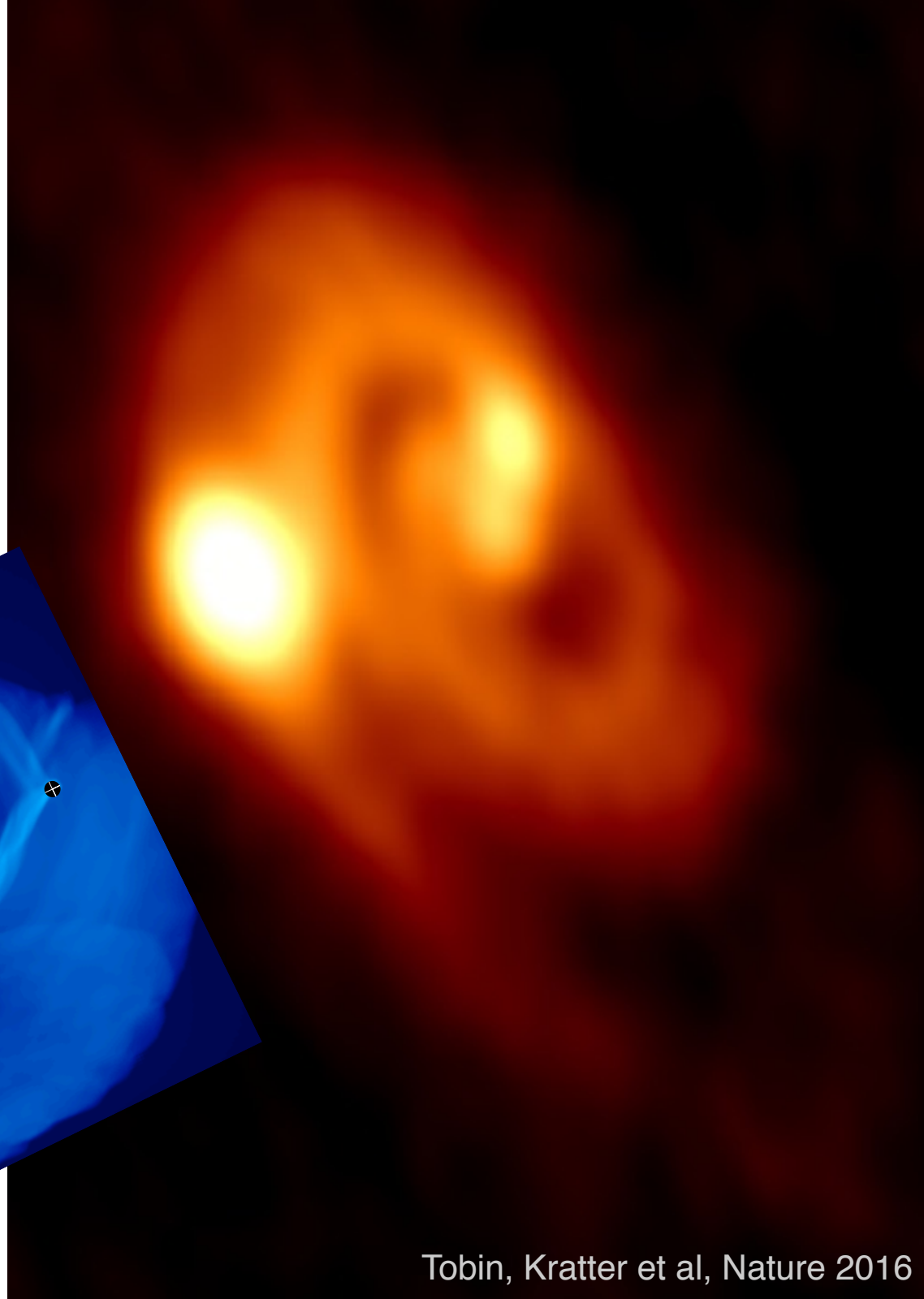

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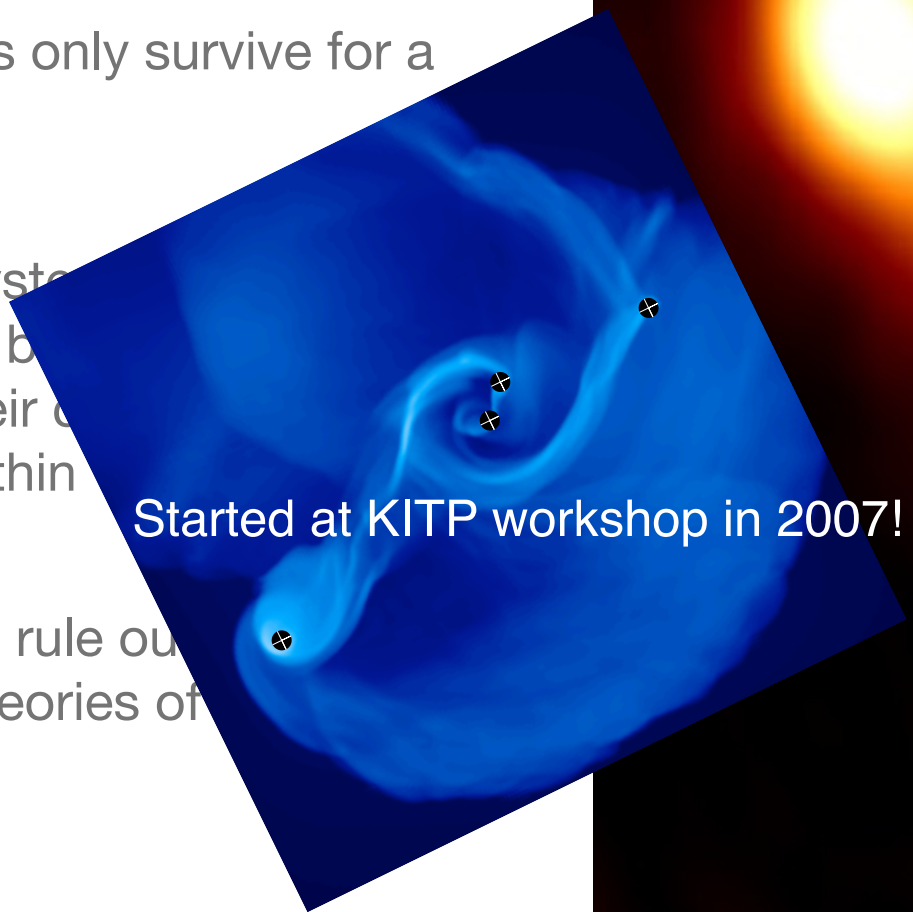

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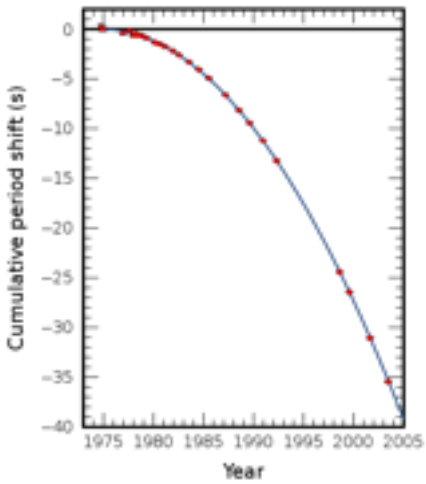
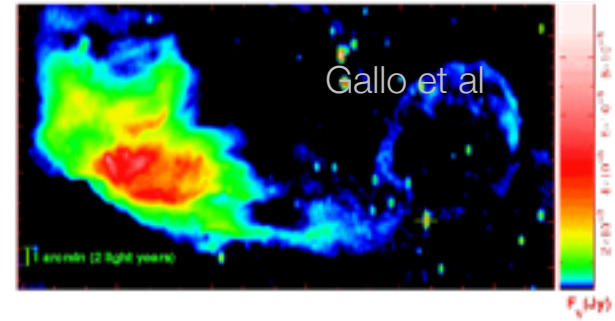
Binaries are fundamental to all of astrophysics



GR confirmation

Type Ia supernovae / dark energy



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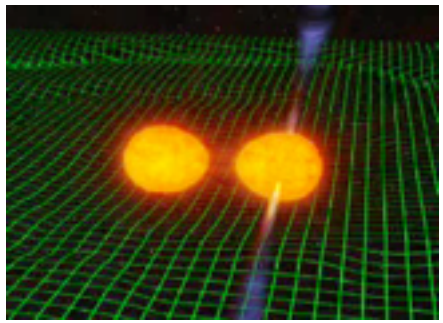
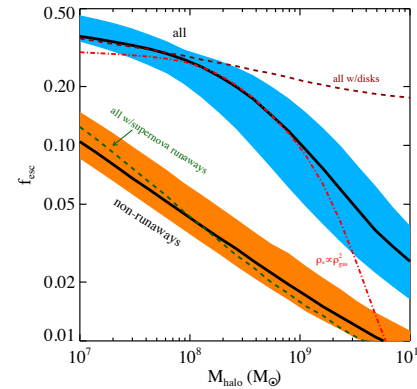


GW signal

Exoplanet characterization



Reionization

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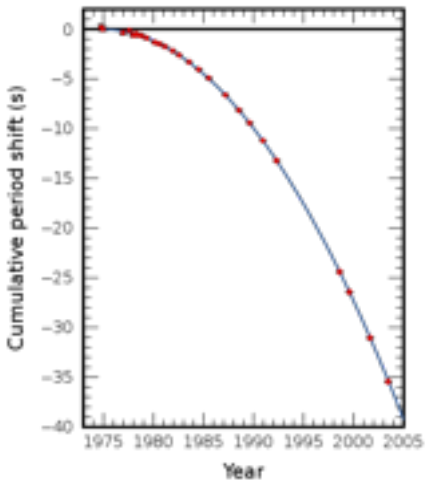

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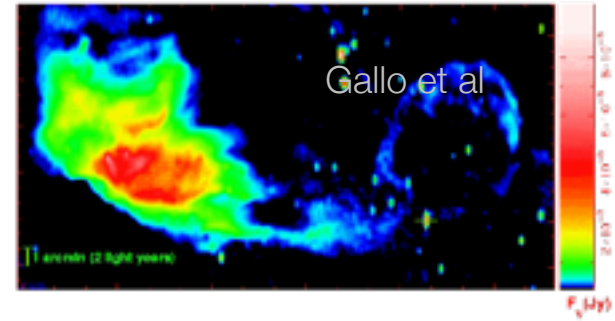

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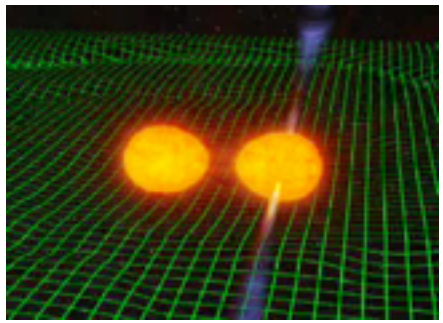

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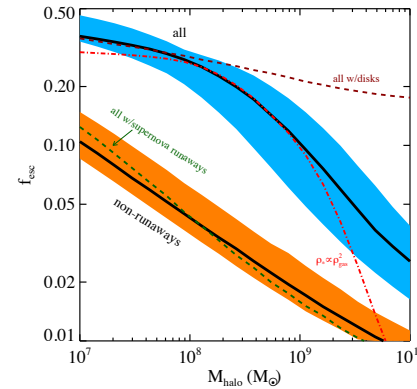

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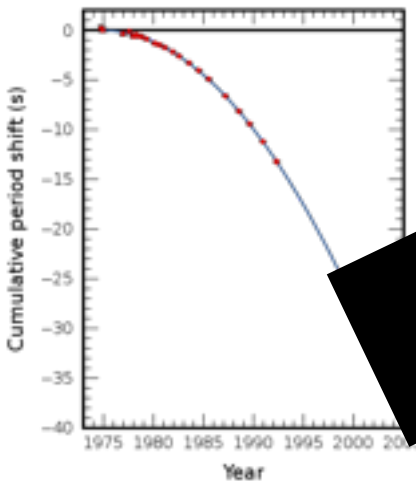

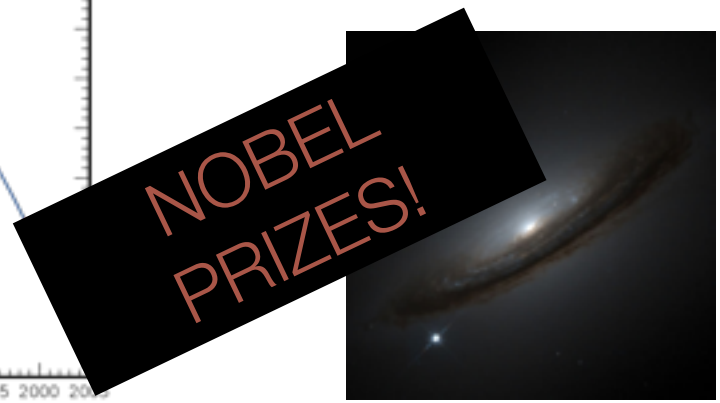

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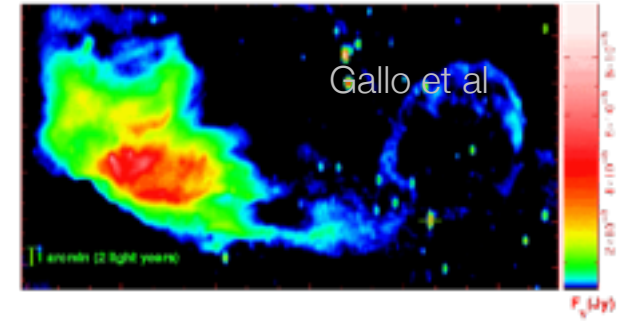

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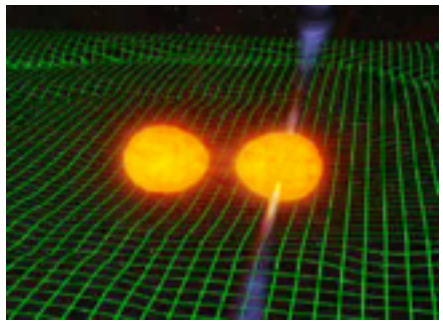

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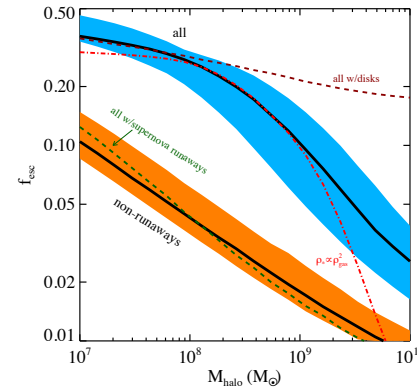

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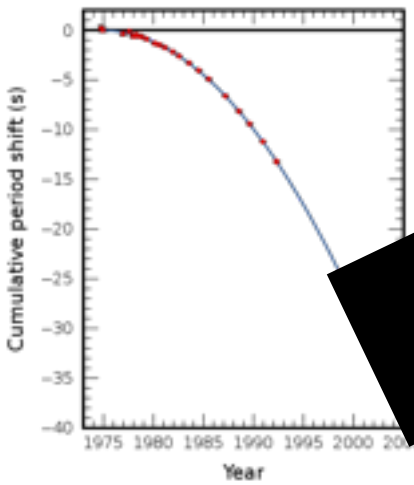
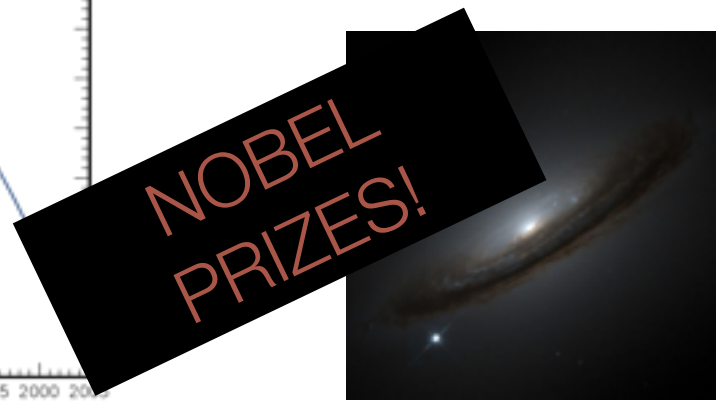
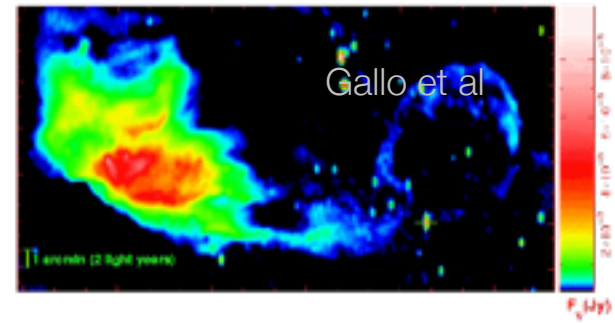
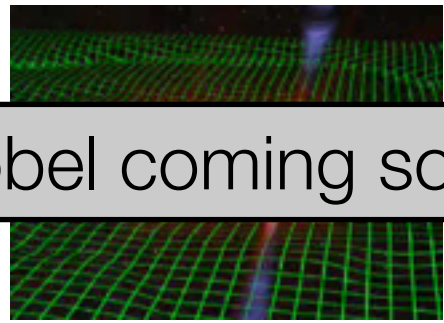




GR confirmation

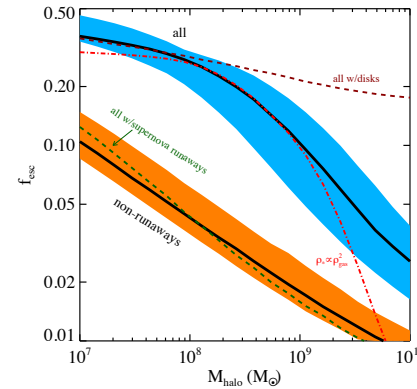


Confirmed BH



GW signal

Exoplanet characterization



Reionization

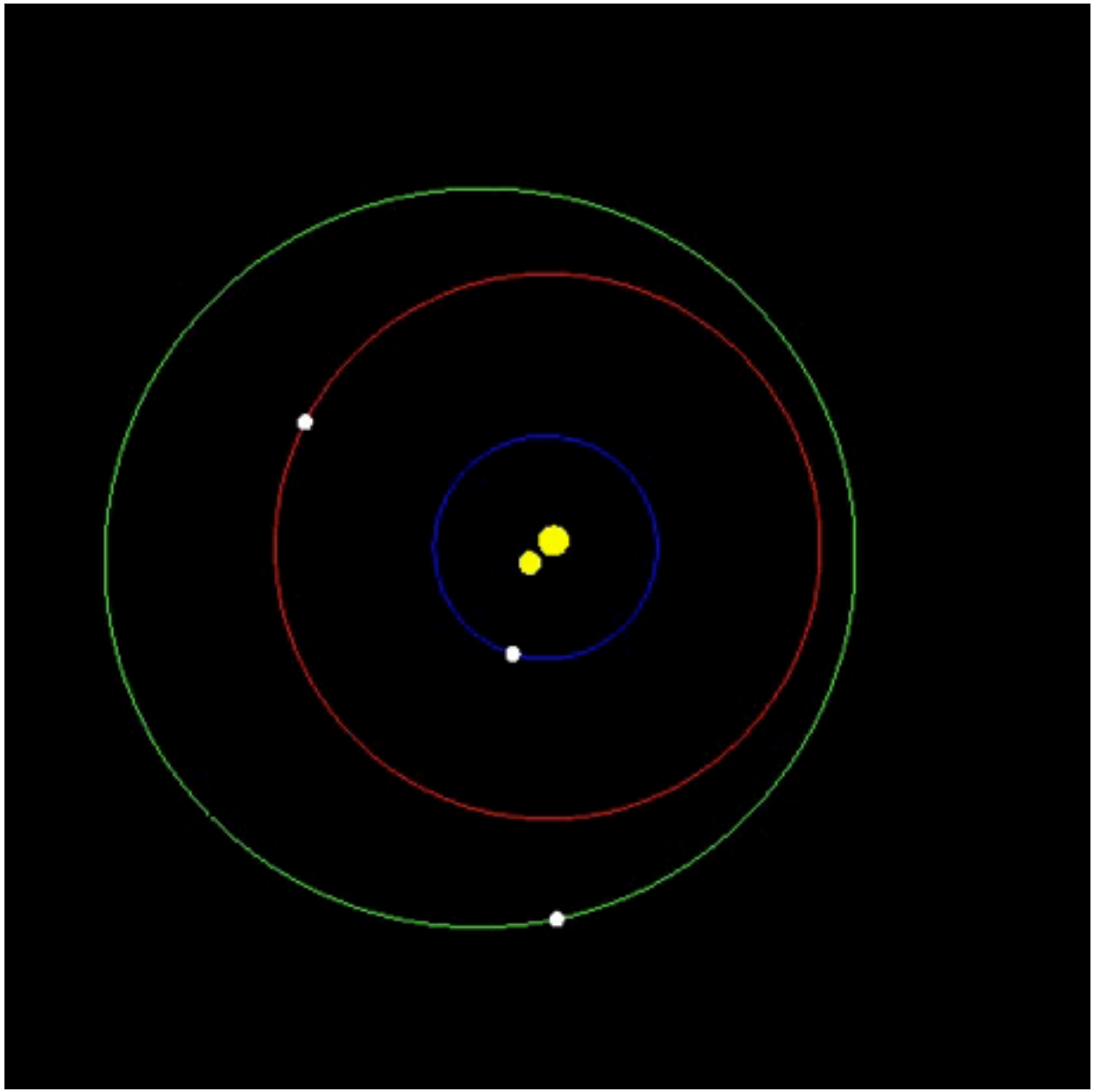
Formation Extremes

- Planets around binaries are subject to extra kicks and tugs
- The properties of the natal disk can be highly constrained
- Serve as excellent mode to falsify planet formation models

A triple star system containing a super-Jupiter on a nearly unstable orbit

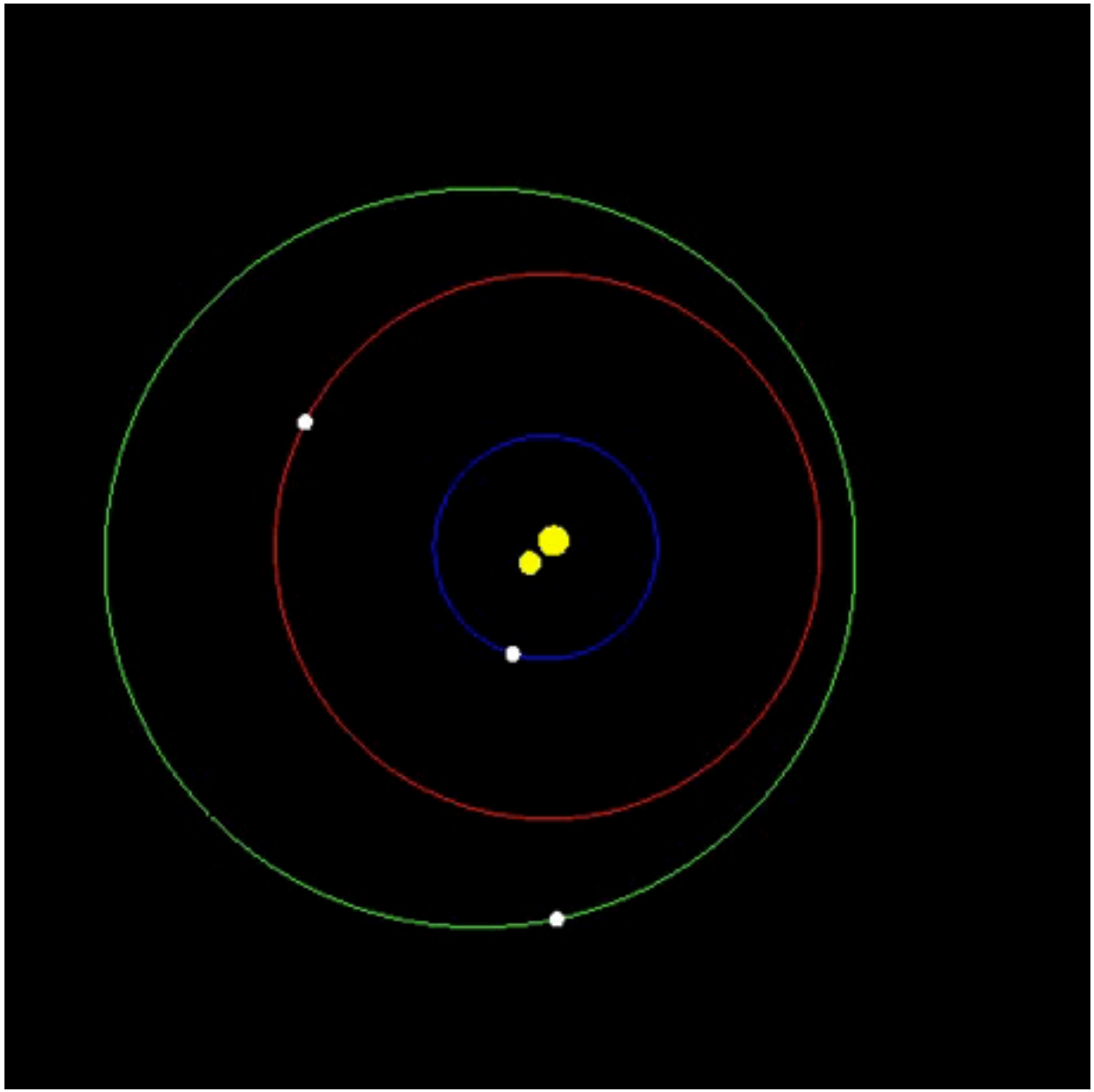
HD 131399
Wagner, Apai, Kasper, Kratter et al, 2016, Science

Kepler 47: a (stable) Tatooine type system



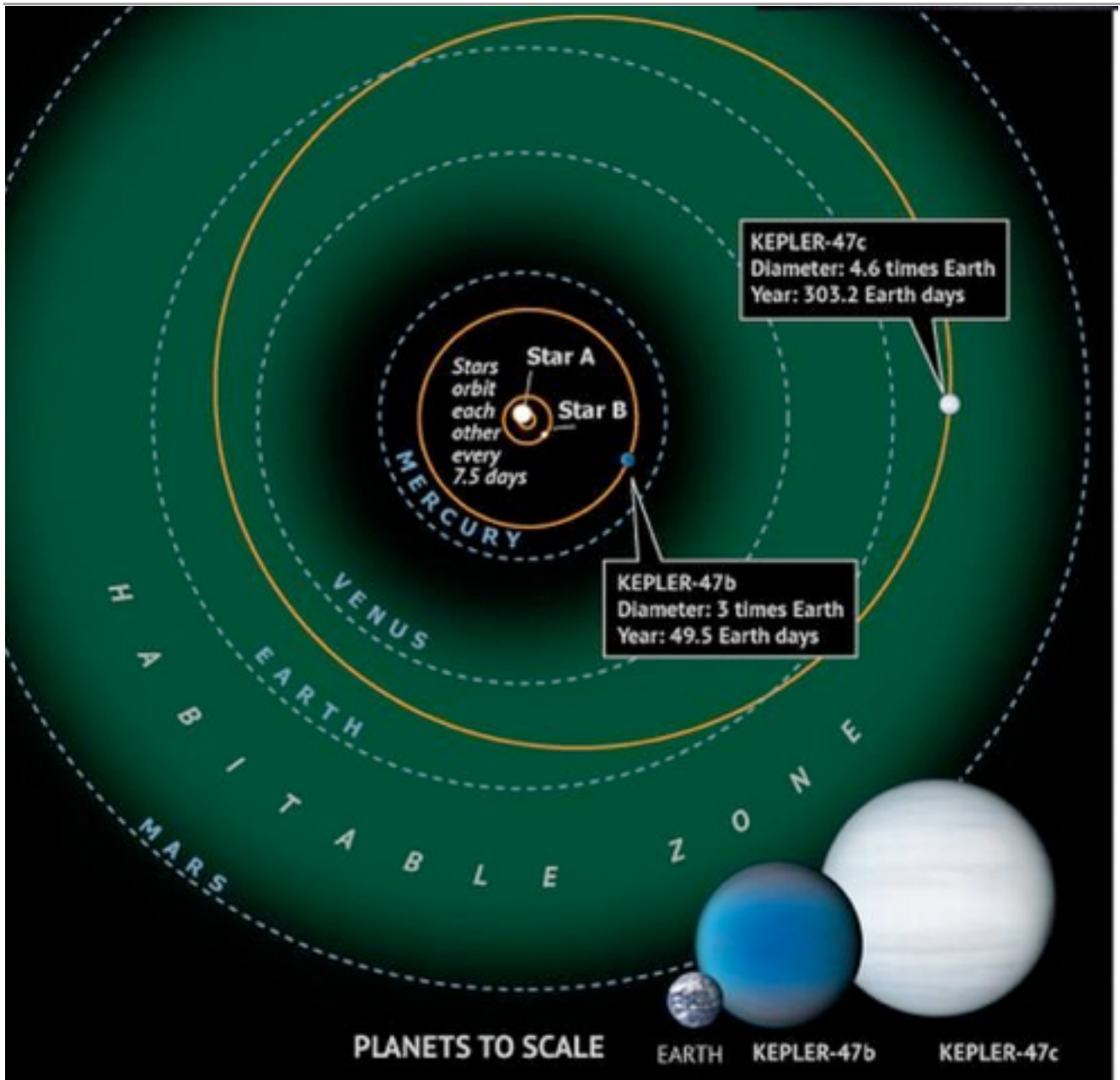
Credit: R. Smullen

Kepler 47: a (stable) Tatooine type system



Credit: R. Smullen

Circumbinary planets are easier to find in “habitable zone”

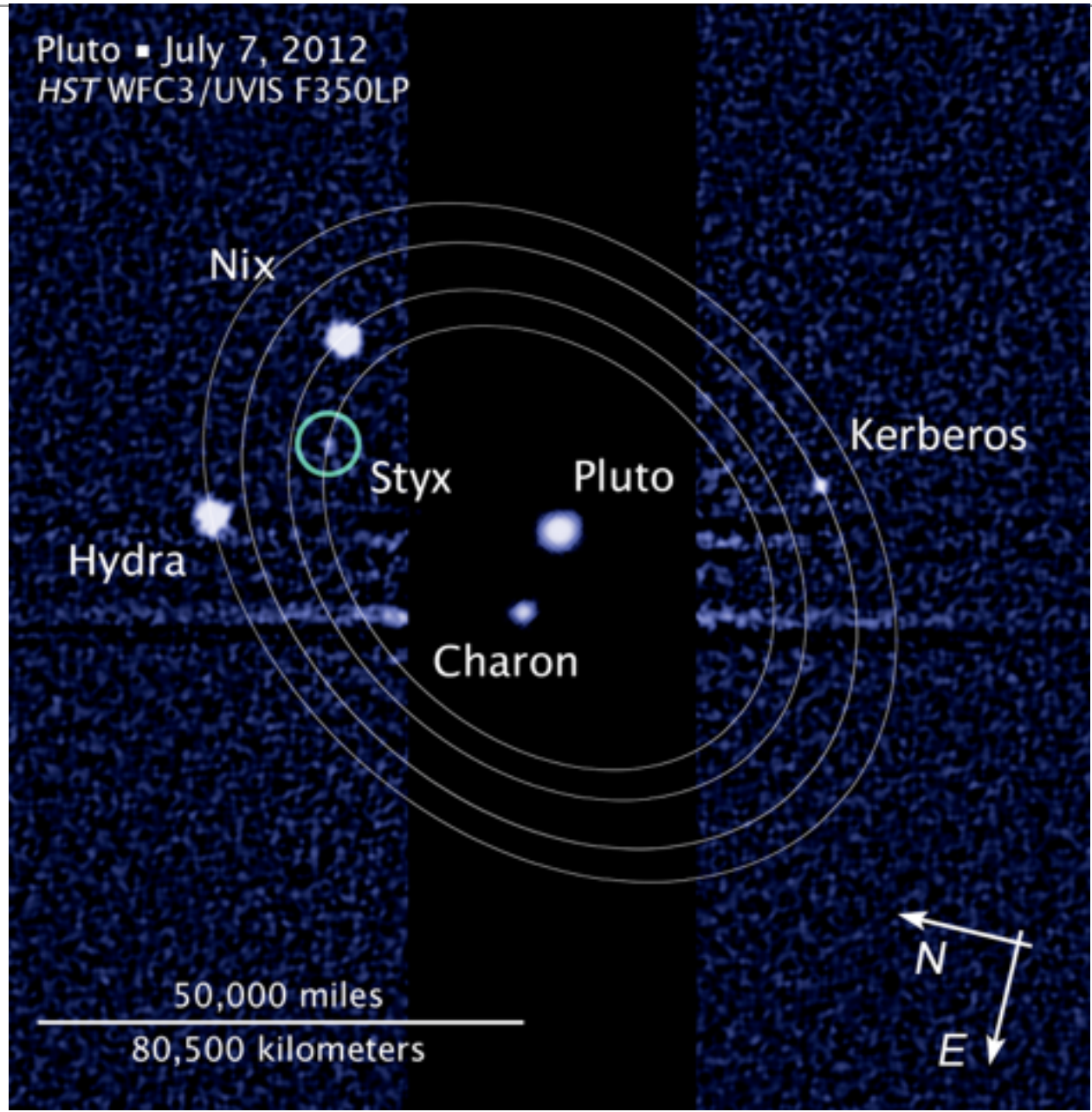


In theory, this bodes well for finding Tatooines.

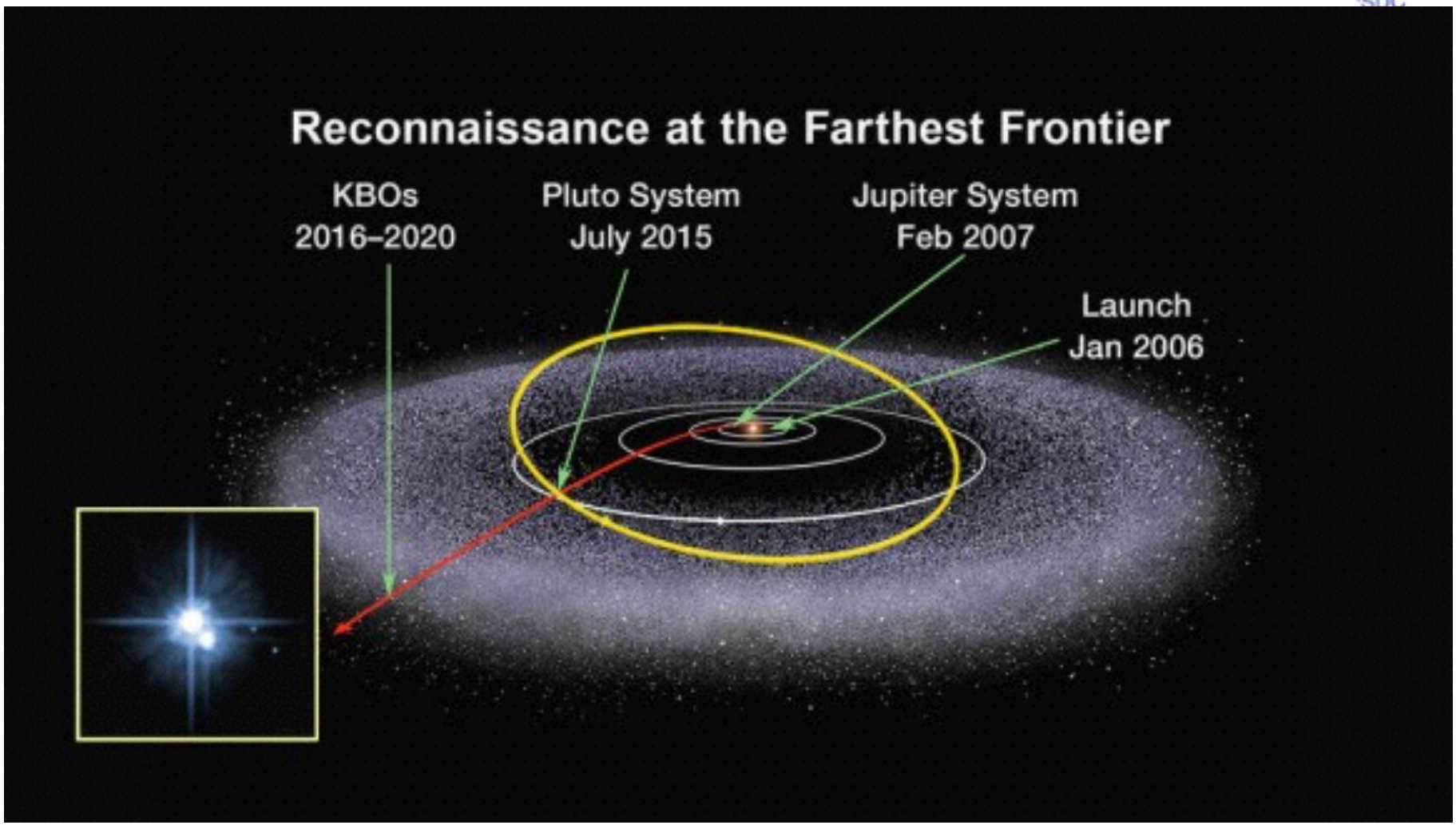
So far, all of the circumbinary planets are massive gas giants.

Kepler 47 b,c
(Orosz et al. 2012)

Local Example: Pluto not a Planet ...
a Mini Circumbinary Multi-Planet System!

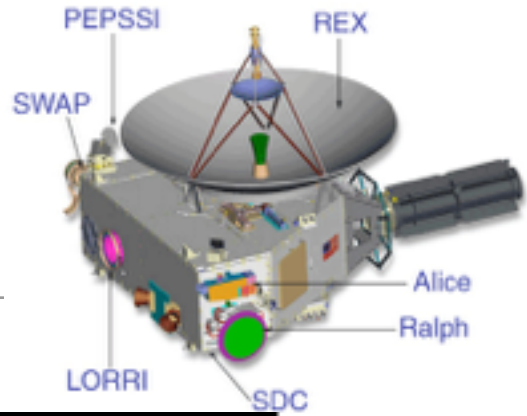


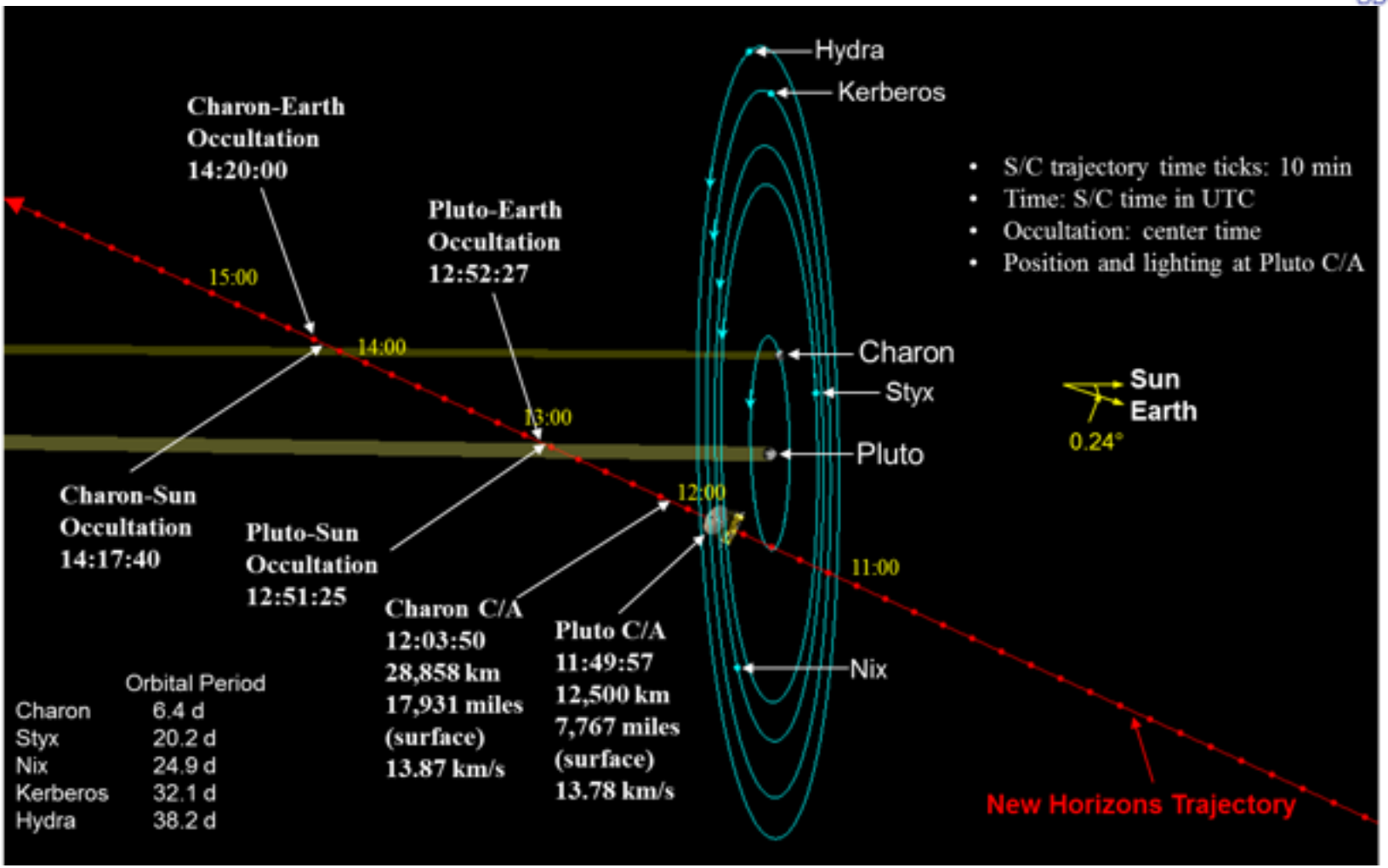
Local Example: Pluto not a Planet ...
a Mini Circumbinary Multi-Planet System!



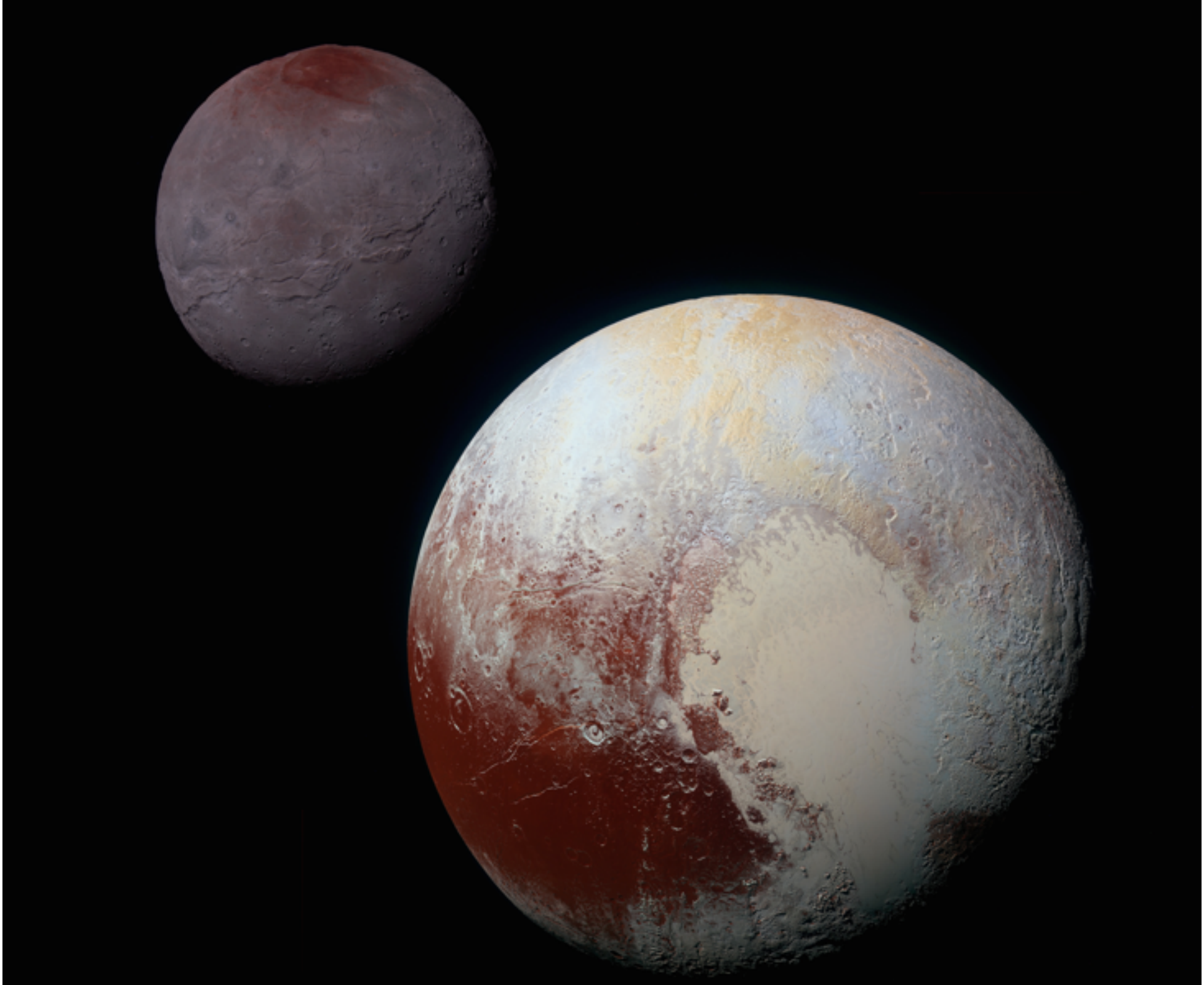
New Horizons Mission

Local Example: Pluto not a Planet ...
a Mini Circumbinary Multi-Planet System!

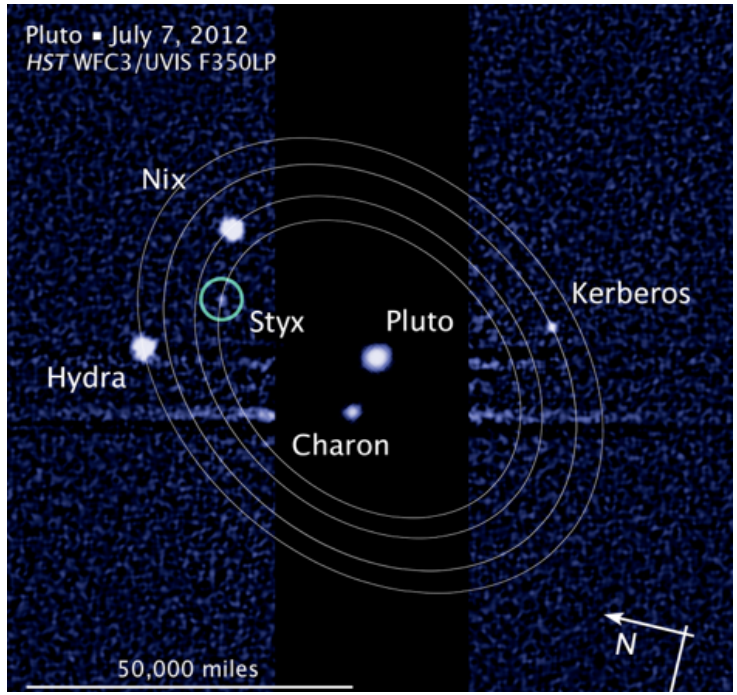


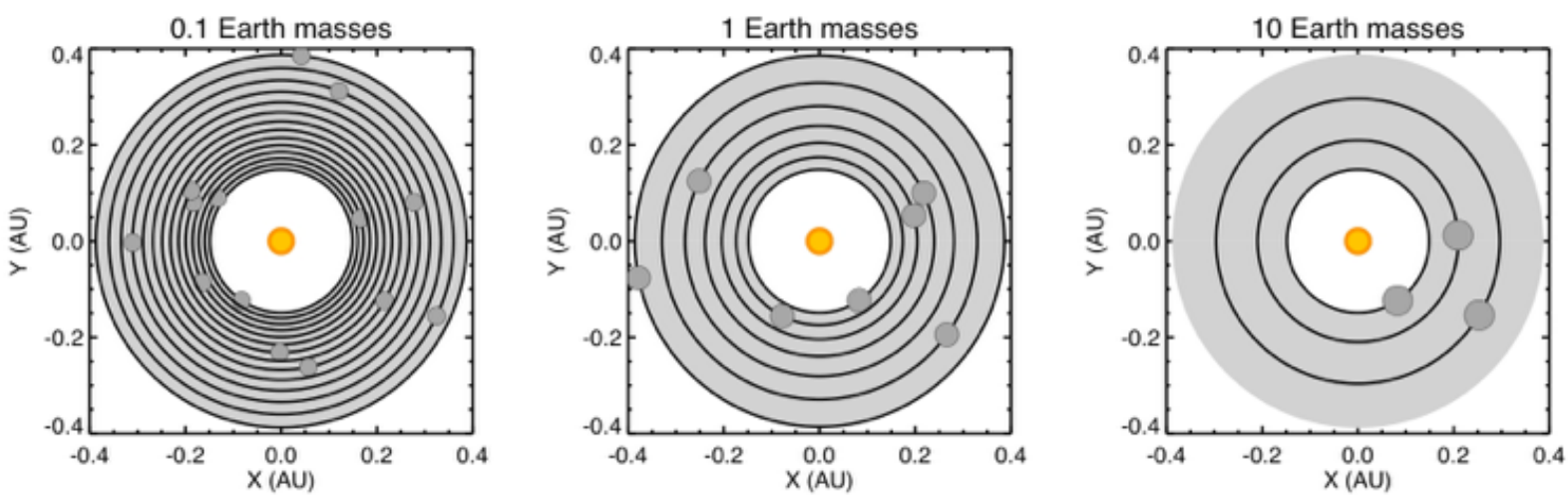


New Horizons Mission

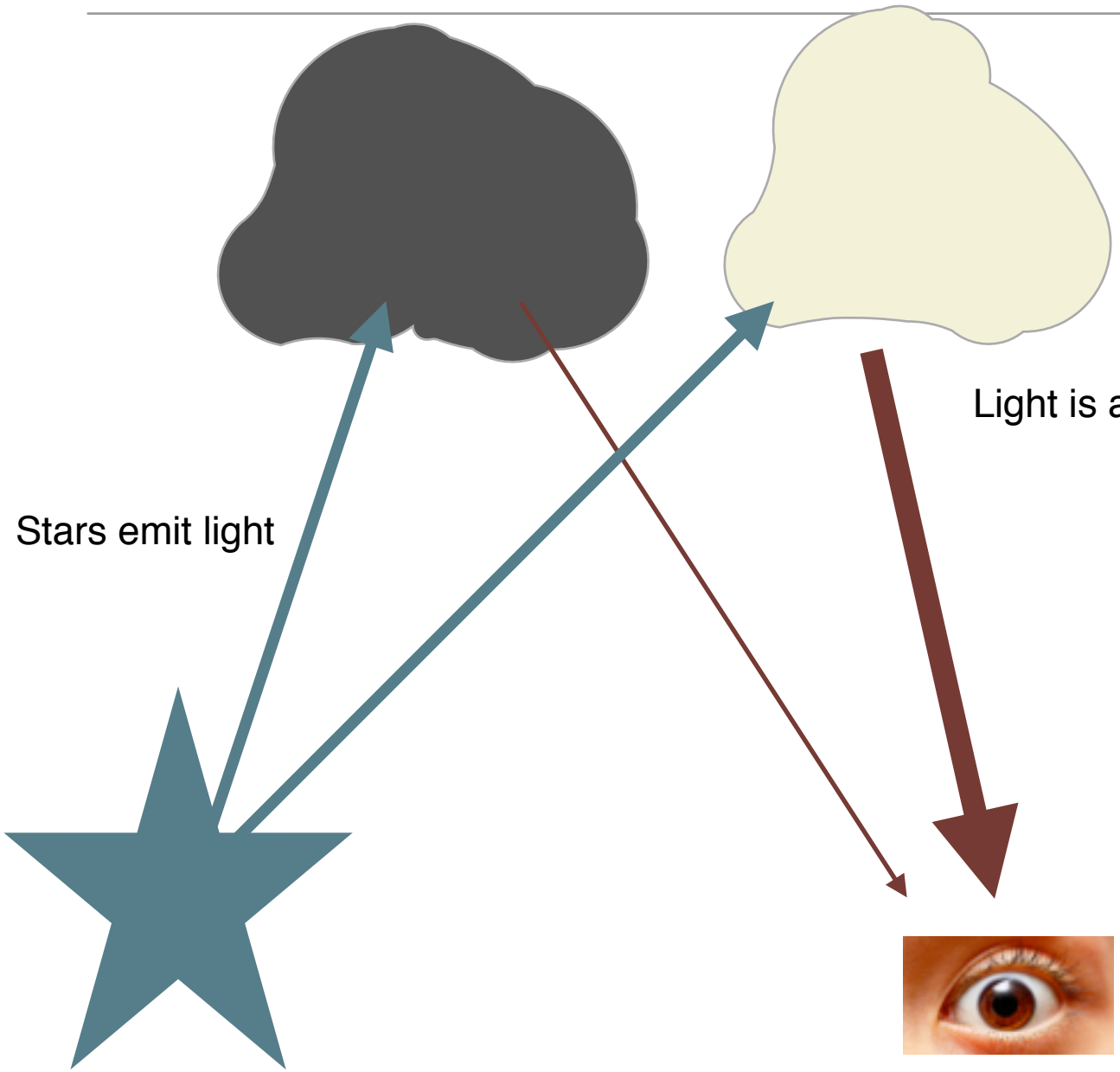


We can discern the properties of the system using dynamical stability





Observing “Rocks” vs “Stars”

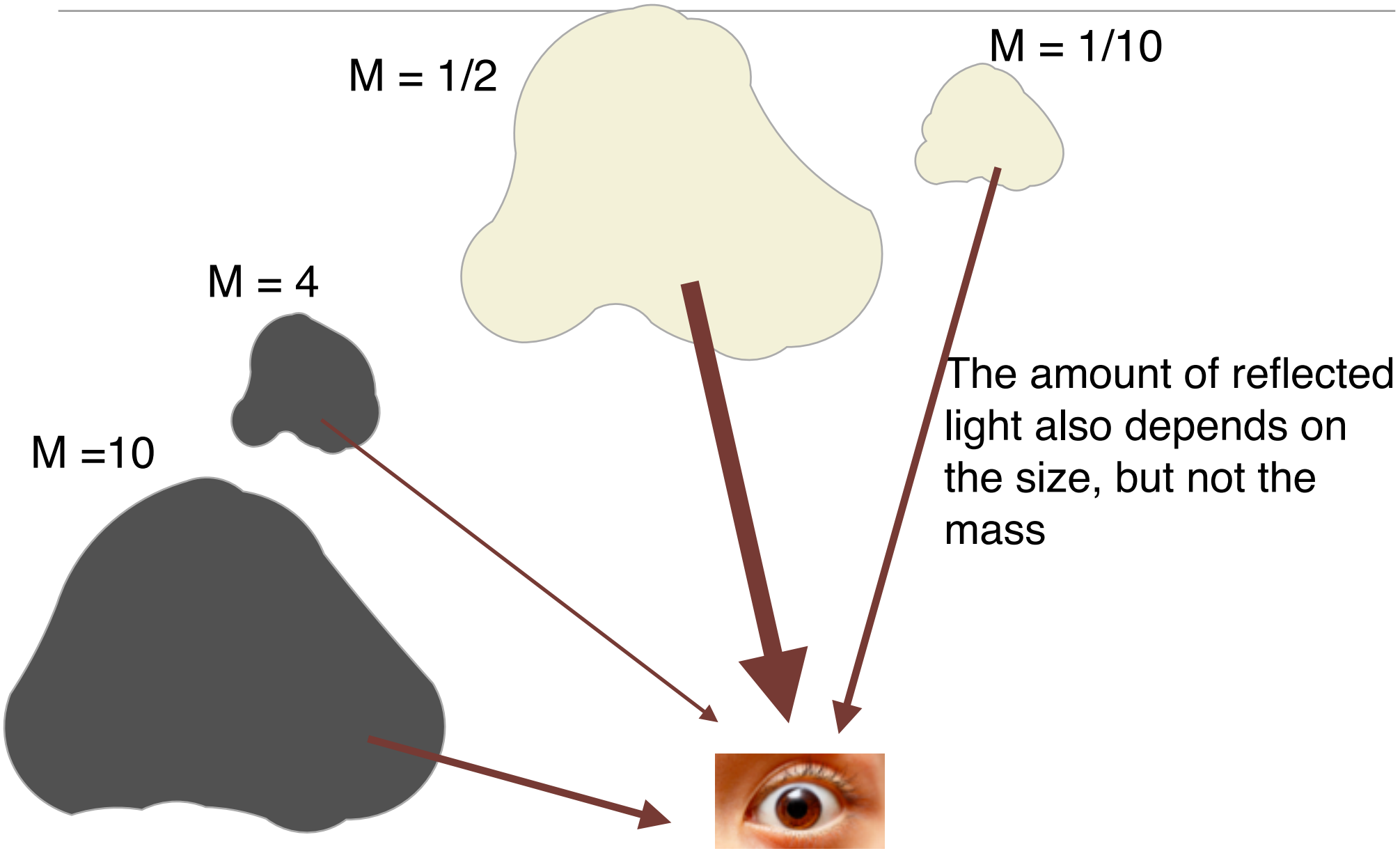


Light is absorbed / reflected by rocky bodies

Stars emit light

What we see depends on how reflective it is, its **ALBEDO**

Observing “Rocks” vs “Stars”

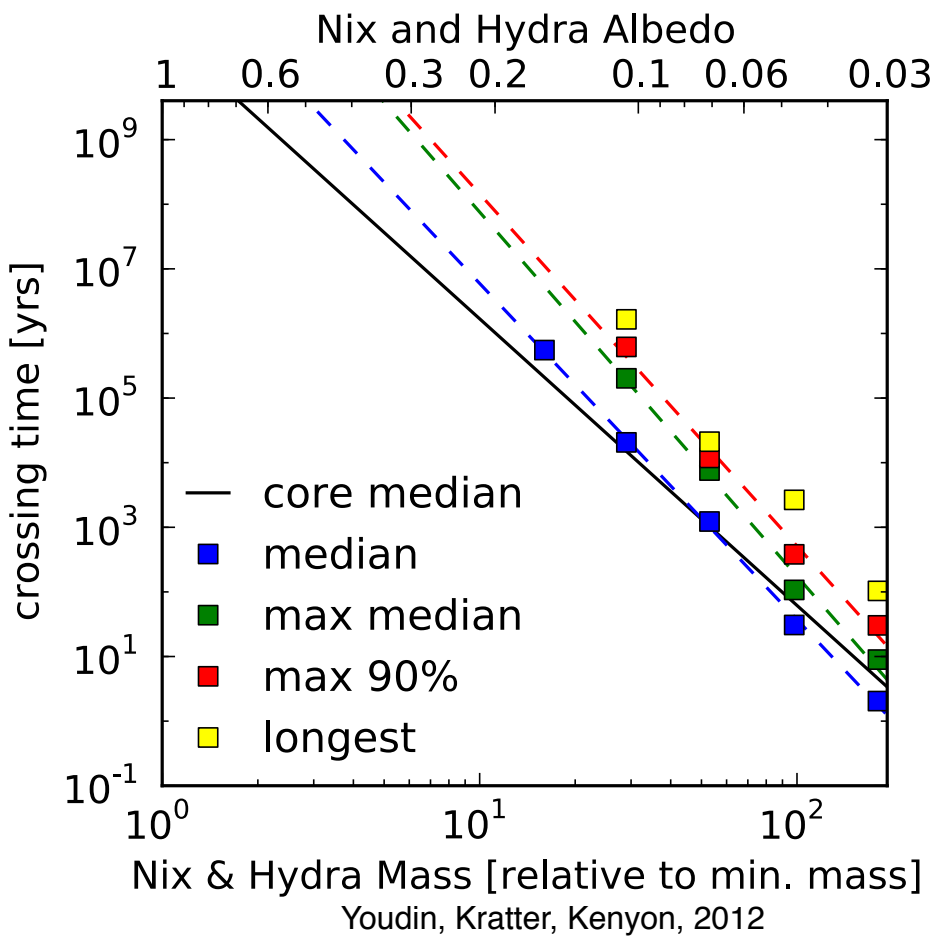


We can conclude that Pluto's moons are icy!

- Our dynamical estimates of the masses and albedos have been validated by New Horizons

- This shows the strength of this method for systems we can't go visit

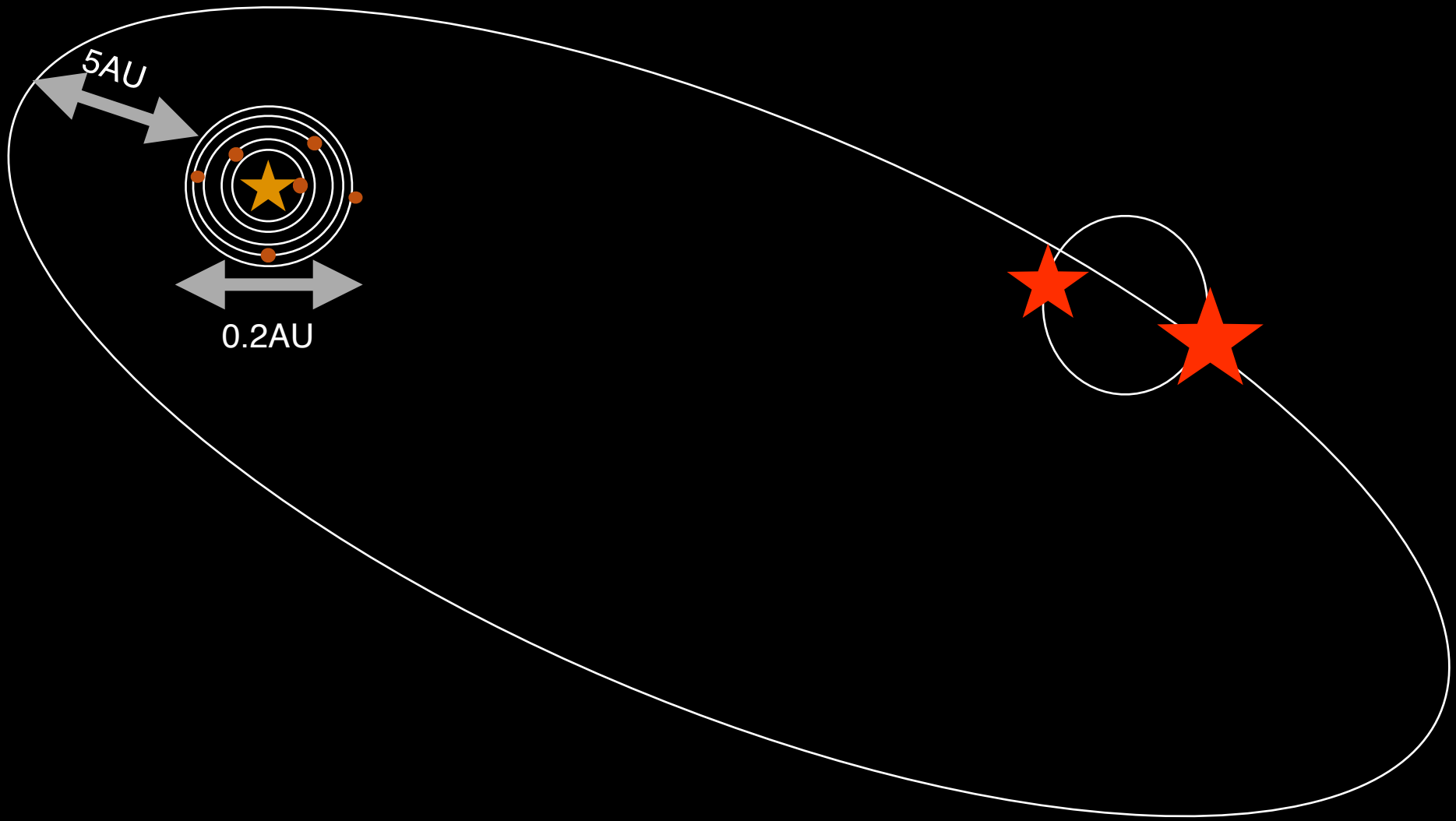
Fresh asphalt	0.04
Worn asphalt	0.12
Bare soil	0.17
Green grass	0.25
Desert sand	0.40
New concrete	0.55
Ocean Ice	0.5–0.7
Fresh snow	0.80–0.90
Enceladus	0.9
Pluto	0.49-0.66
Charon	0.36-0.39



Youdin, Kratter, Kenyon, 2012

Dupuy, Kratter et al 2016

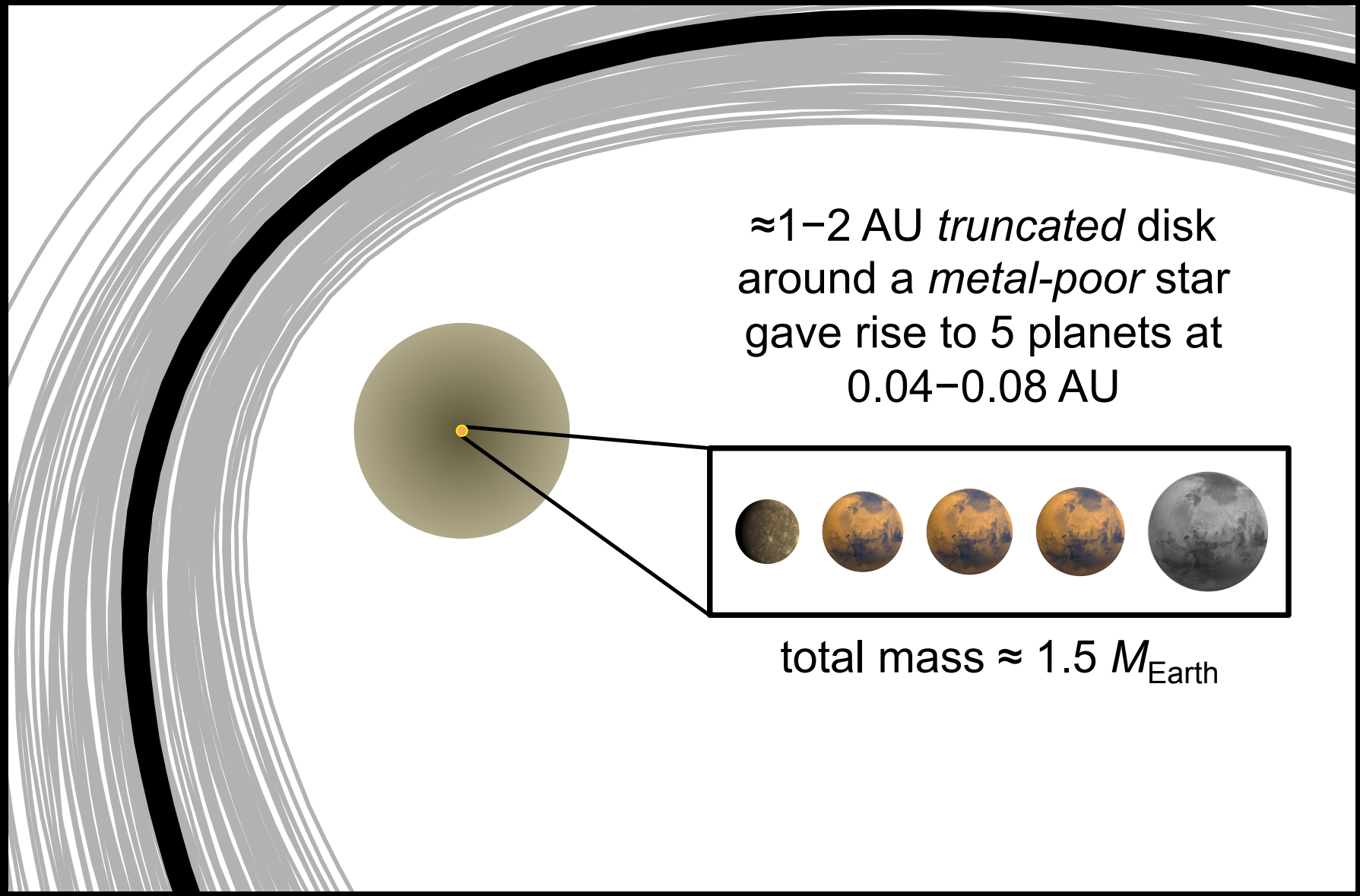
KEPLER 444: 5 SUB-EARTH PLANETS IN A TRIPLE STAR SYSTEM

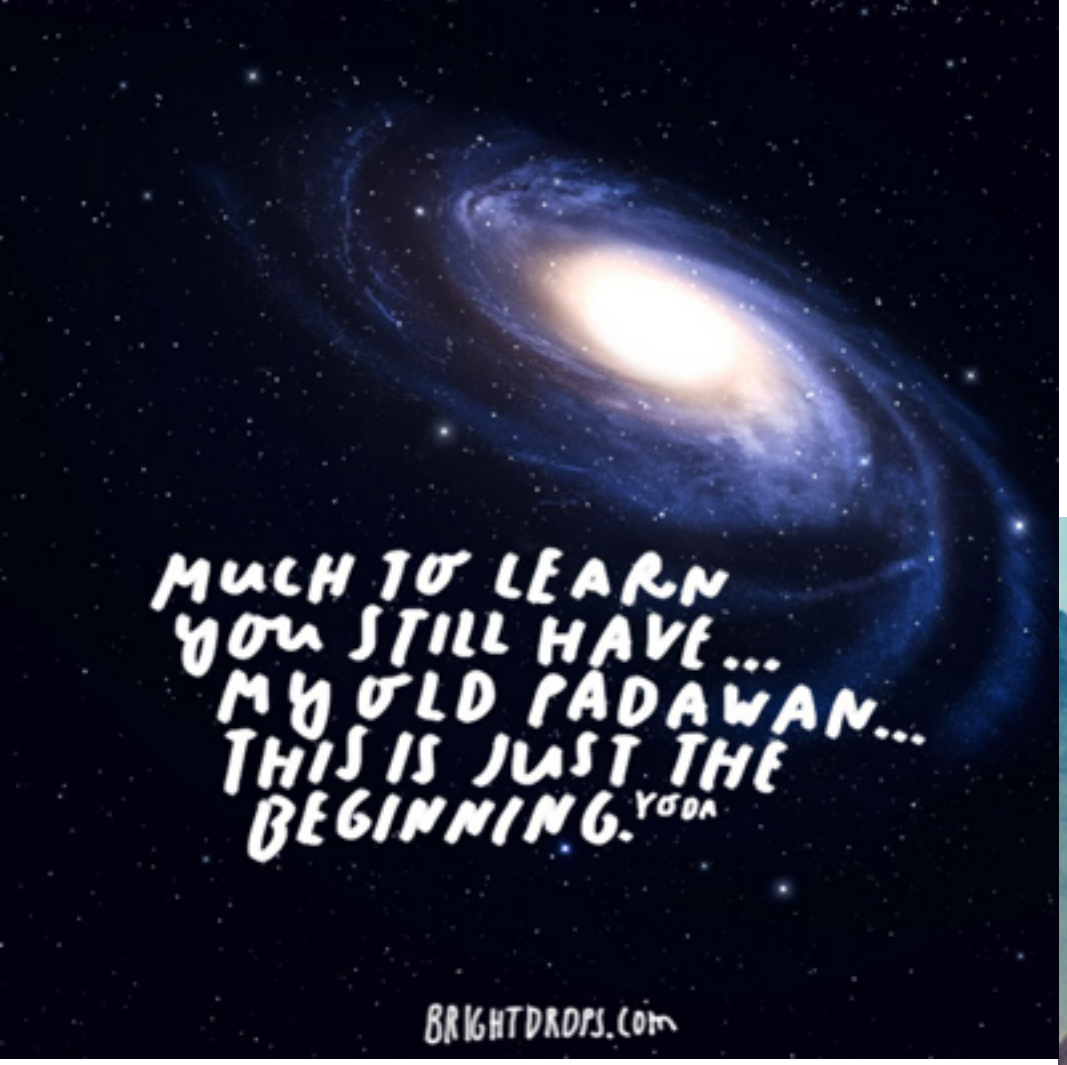


Another extreme system that constraints planet formation

Dupuy, Kratter et al 2016

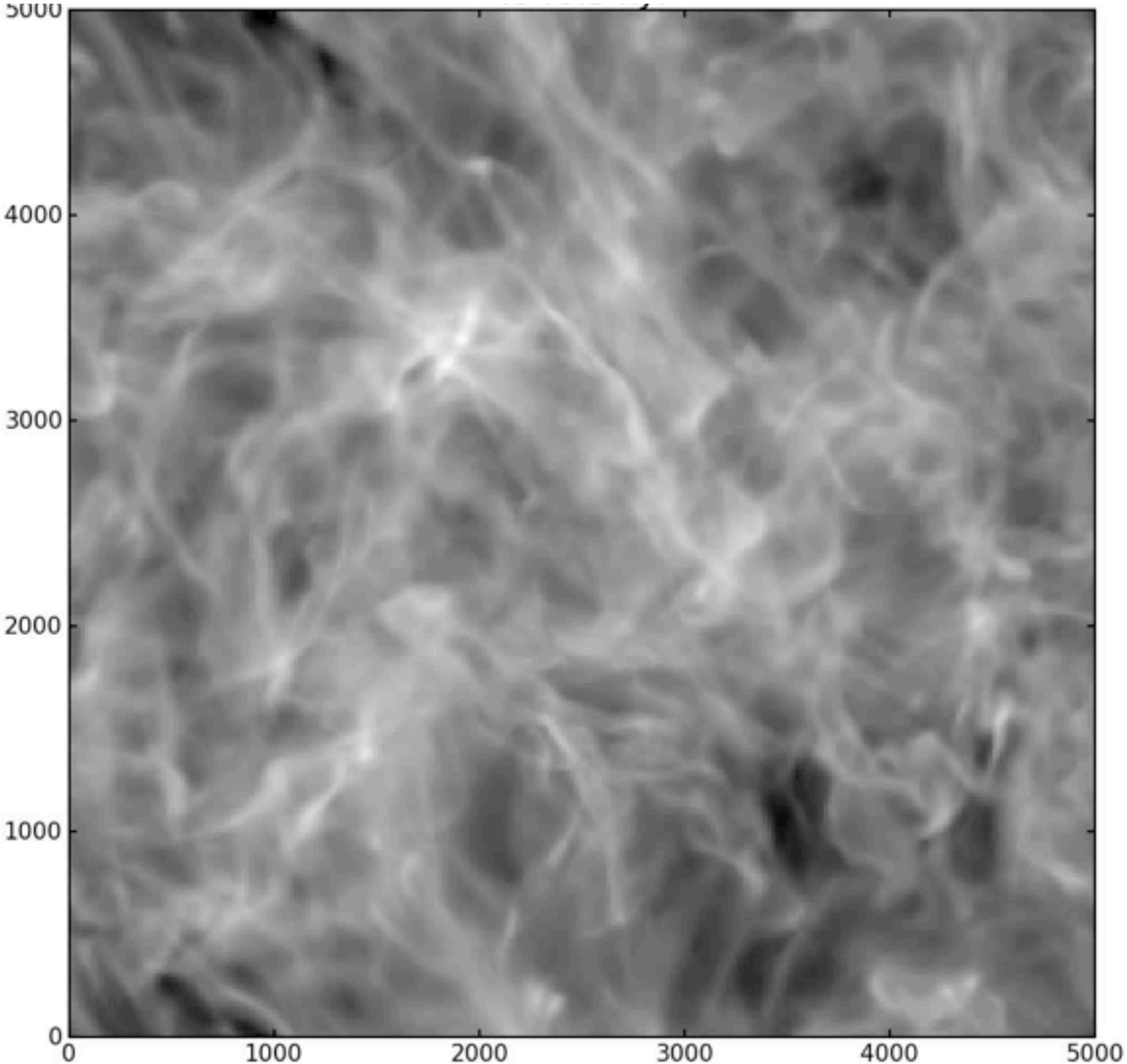
PLANET FORMATION MUST BE VERY EFFICIENT IN SOME SYSTEMS




MUCH TO LEARN
YOU STILL HAVE...
MY OLD PADAWAN...
THIS IS JUST THE
BEGINNING.
YODA
BRIGHTDROPS.COM


ALWAYS PASS ON
WHAT YOU HAVE
LEARNED.
YODA
BRIGHTDROPS.COM

Thank you



Thank you