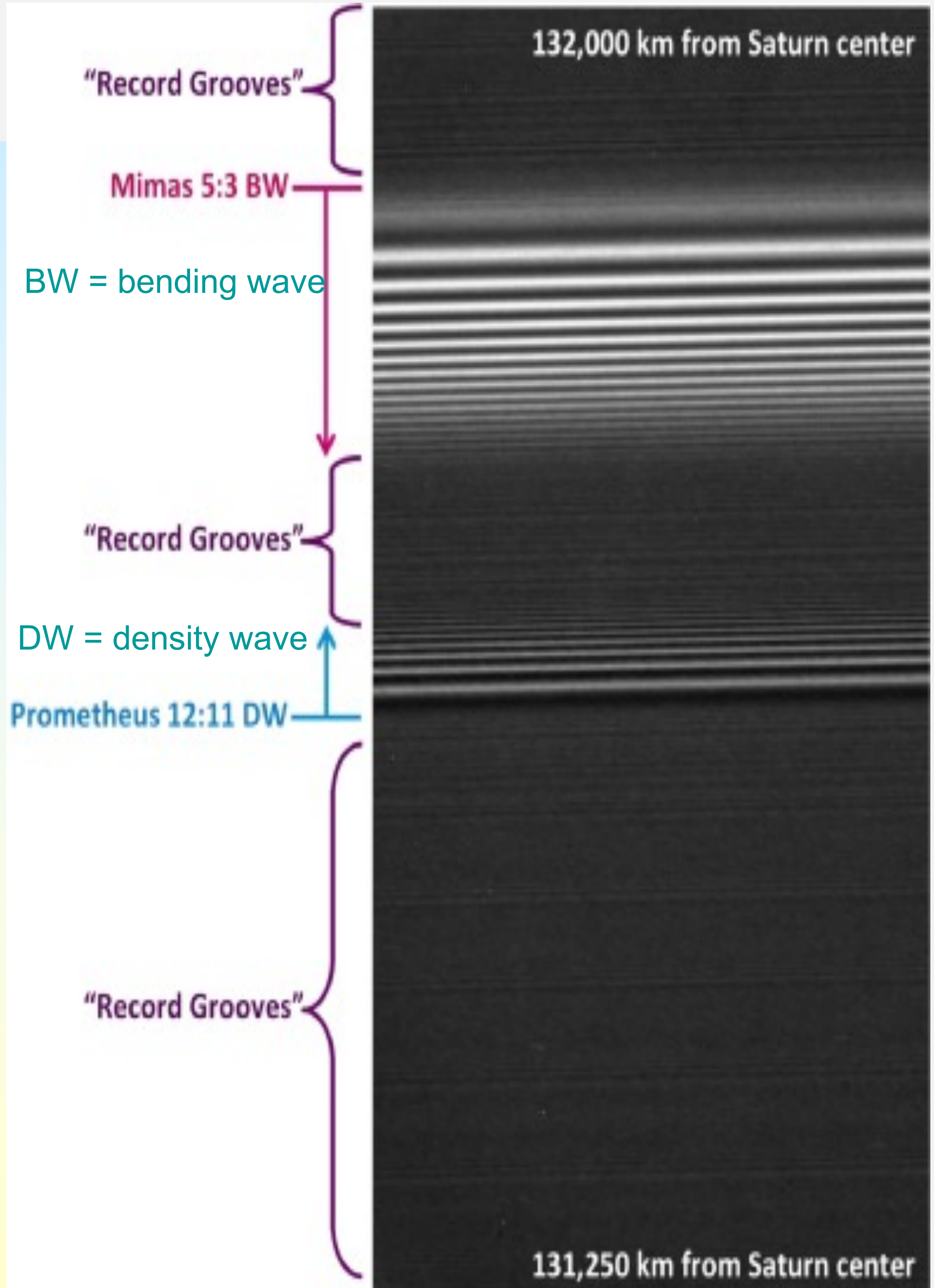
Lecture 19-20 ASTC25

Migration of protoplanets

1. Mechanisms of disk-planet interaction: migration

- resonances → waves
- corotational torques

2. Numerical simulations of migration
3. High performance computing of flow around a small embeded planet



Disk-planet interaction:

- ☑ observed in nature
- ☑ understood analytically
- ☑ studied in detail numerically

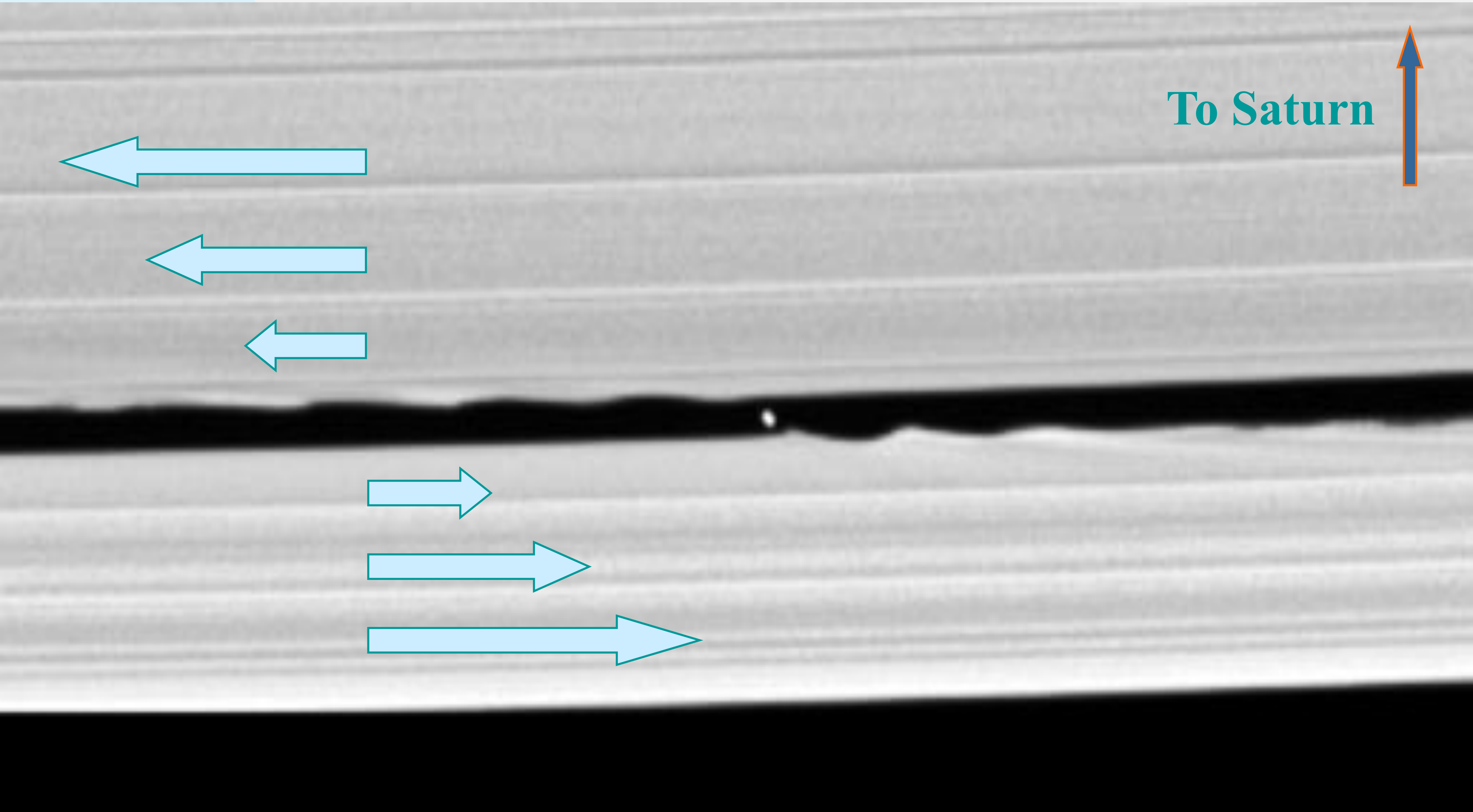
Some of the structure in planetary rings and galaxies is due to long-distance gravitational interaction with satellites:

Waves are excited at mean-motion resonances (Lindblad resonances).

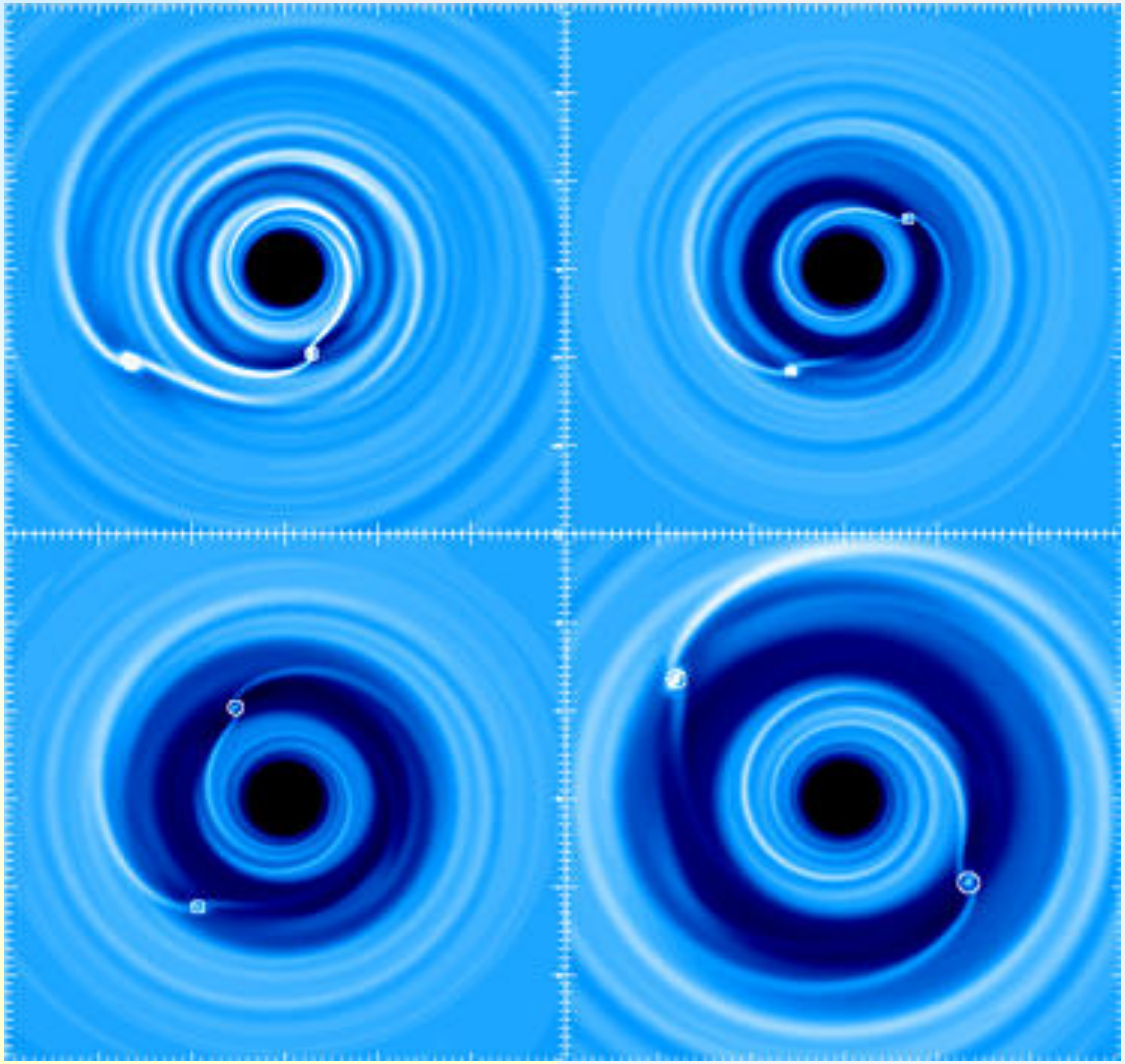
Such interaction effectively repels the disk from the object

A gap-opening body (Daphnis) in a disk:
Saturn rings, Keeler gap region (width =35 km)

This 7-km satellite of Saturn was announced on 11 May 2005.

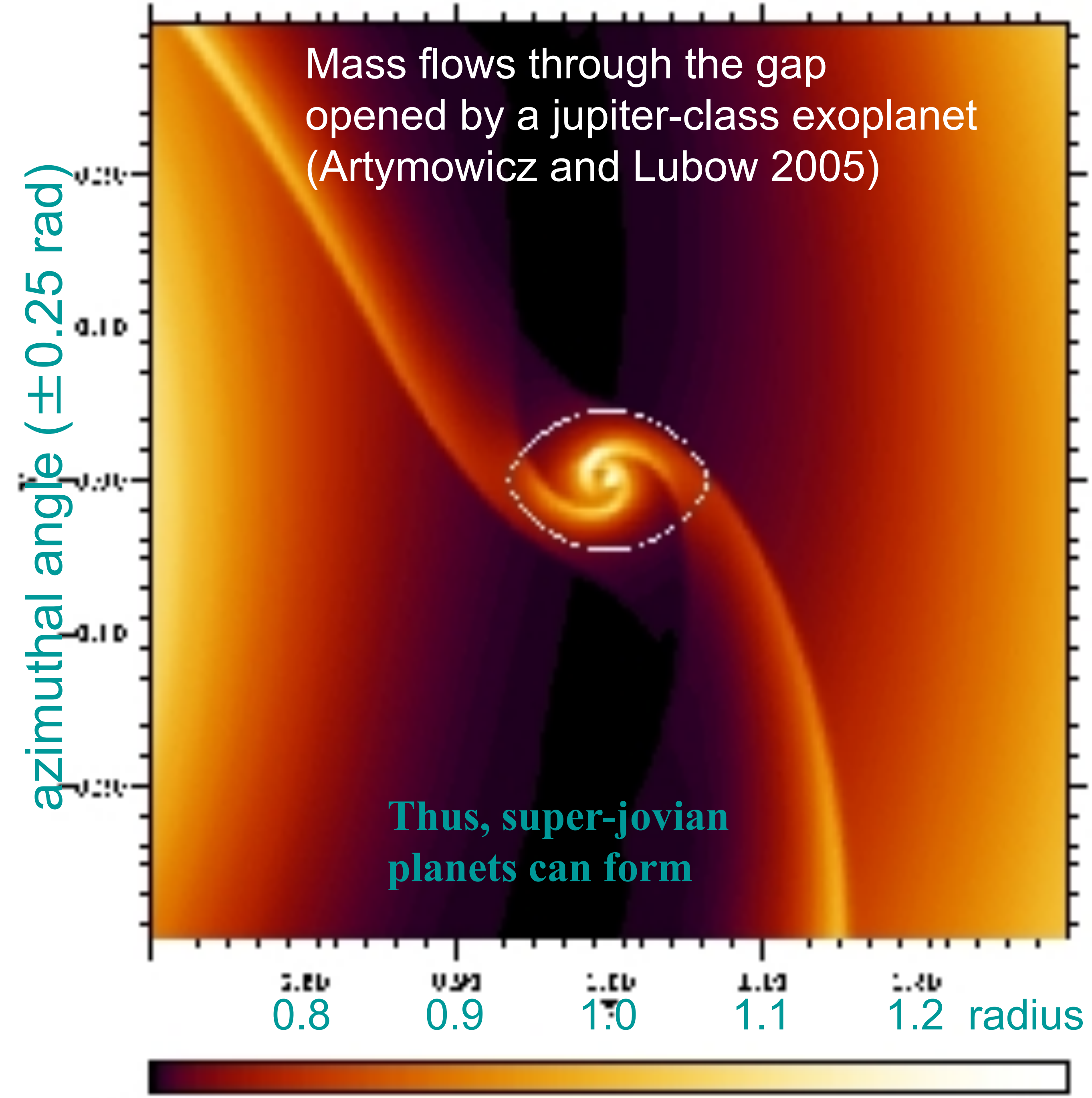


Simulations reproduce the density wave excitation at resonances.
Those are mean motion resonances between the planet and disk material.



Pairs of exoplanets may be caught in a mutual 2:1 resonance

A substantially different mechanism of interaction is mass flow through gap, happening in the CR (corotational) region around planet’s orbit



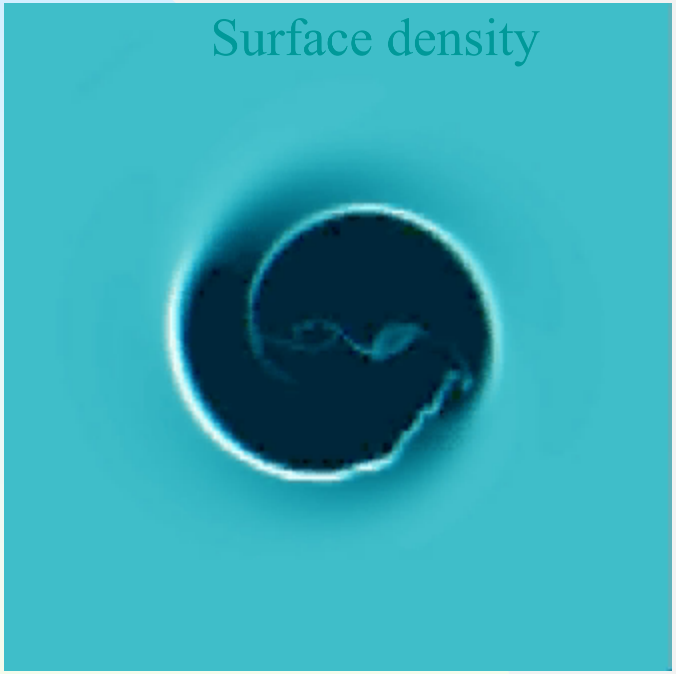
The dotted oval is the Roche lobe of Jupiter (horizontal extent (1 ± 0.07) a

Growth of a giant gaseous planet starts when solid core exceeds a critical mass ~10 M_E (~core mass in J,S,U,N)

Prior to these calculations it was thought that gap opening stops the growth of a giant planet. It does not.

An example of calculations withRiemann-solver hydrocode.

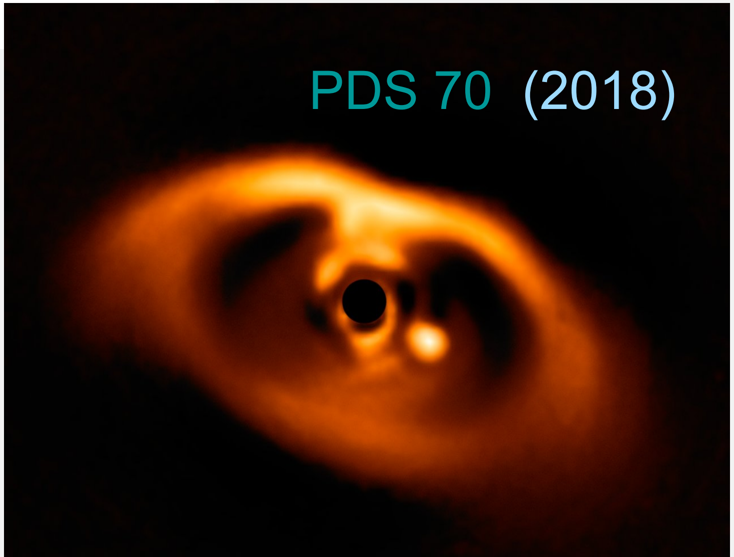
PPM = Piecewise parabolic method [of reconstruction of variables]



Log(surface density)

Artymowicz (2004)

Binary star on a circular orbit,
accreting gas from a circumbinary disk
through the circumbinary gap (above)



Mass flows through a wide and deep gap
in a young object PDF 70.

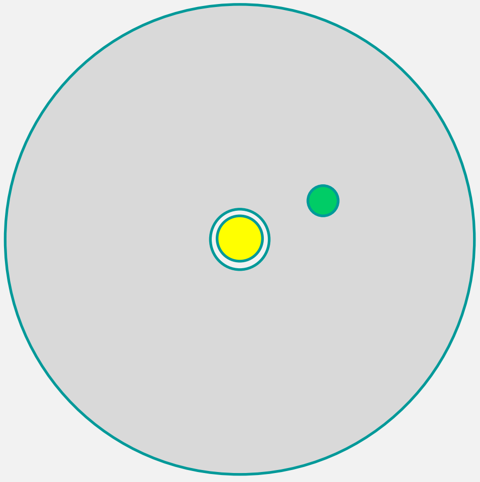
What the permeability of gaps teaches us about our Solar System's origin

- Jupiter was potentially able to grow to 5-10 m_J, if left accreting from a standard solar nebula for ~1 Myr

The most likely reason why it did not grow larger is that the nebula was already disappearing & not enough gas mass was available

Migration Type I :
embedded in fluid
(moderate speed)

There are three types of planet migration



Neptune trying to open a gap

Horizontal axis shows radius in the range (0.5-5) a.

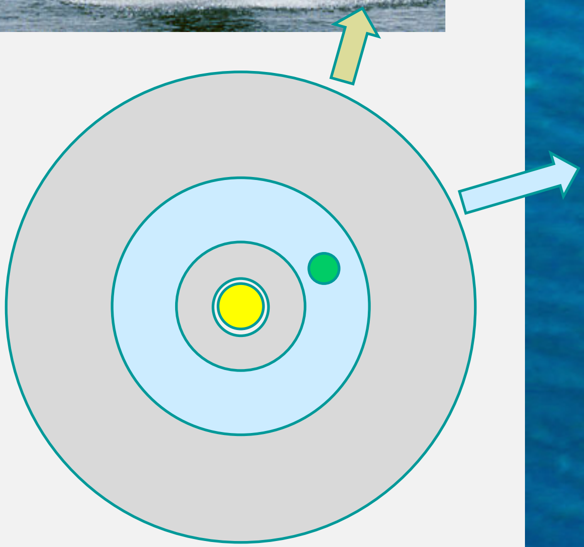
Full range of azimuths 0^{o}-360^{o} on the vertical axis.

Time is displayed in units of initial orbital period.

colors show the gas surface density $\Sigma(x,y)$

Migration Type I :
embedded in fluid
(moderate speed)

Migration Type II :
in the open, empty gap
Slow, since it is proportional to disk viscosity



Migration Type III
partially open (gap)
and very fast

Gap opening by a Jupiter-class planet

Variable-resolution, adaptive grid Lagrangian PPM.

Polar coordinates. Horizontal axis shows radius in the range $r = (0.5\text{-}5)\ a$. Full range of azimuthal angle ($\theta = 0^o\text{-}360^o$) on the vertical axis.

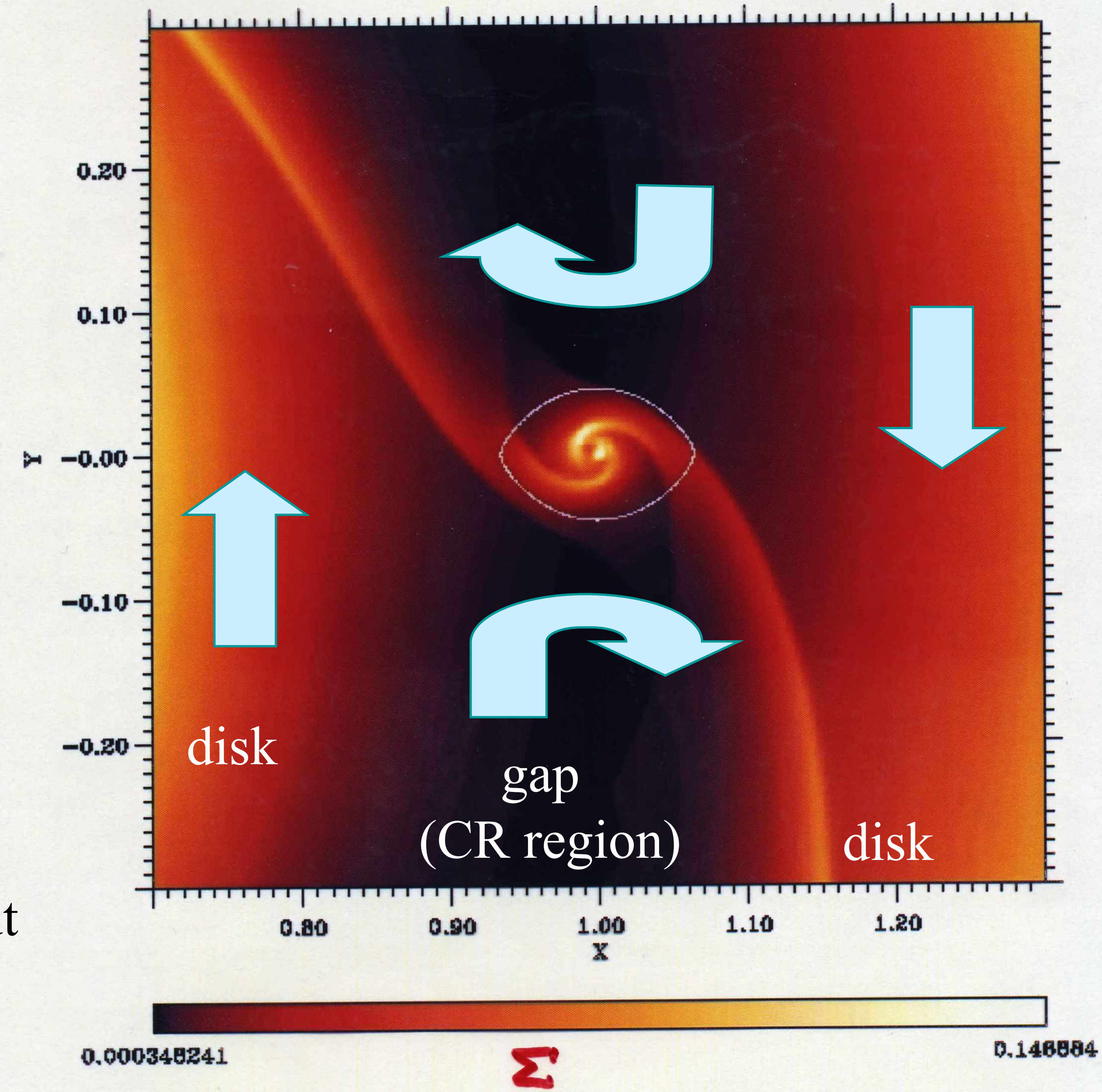
Time in units of initial orbital period is shown in the corner of the animation.

High resolution hydrocode.

Jupiter-mass planet, fixed orbit *a=1, e=0*

White oval = Roche lobe, radius r_L= 0.07

Corotational region out to $x_{CR} = \pm 0.17$ from the planet's orbit



Initially inner disk only.

The rapid **inward migration** is OPPOSITE to the expectation based on shepherding & tidal waves (due to mean-motion res. a.k.a. Lindblad resonances.)

colors show gas surface density Σ(x,y)

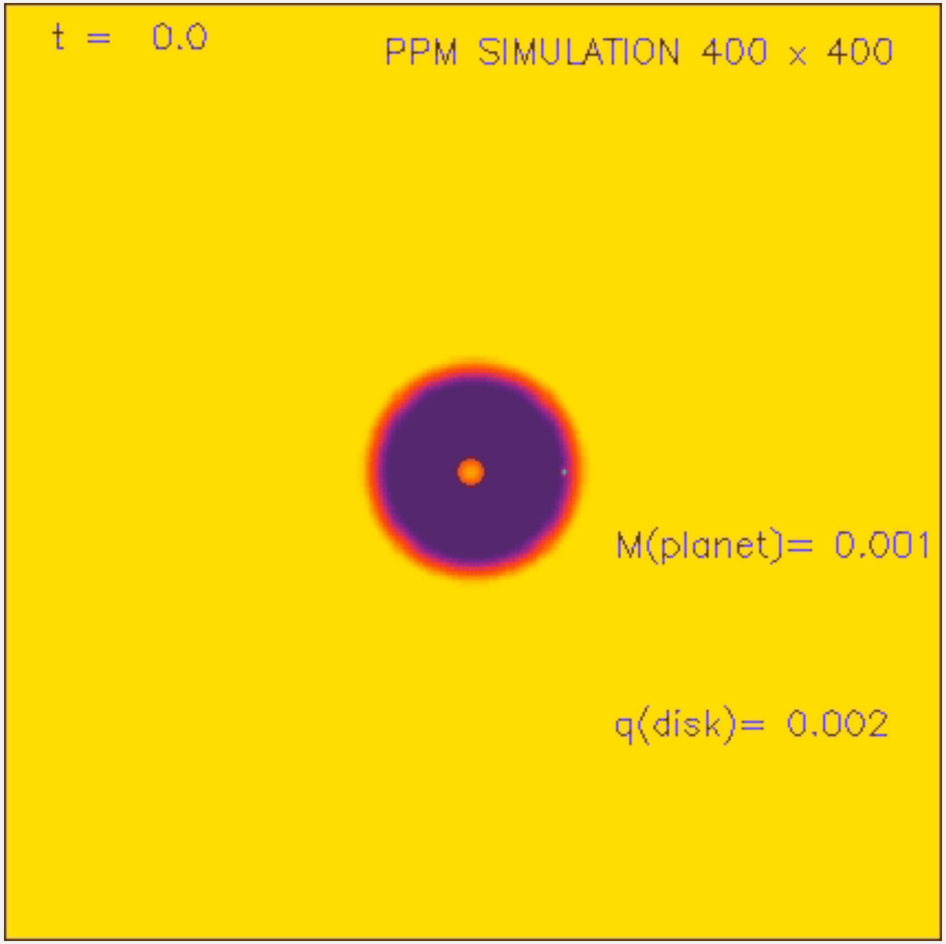
migration type III

Corotational torques cause rapid inward sinking of a planet.
(Gas is transferred outward from orbits inside to those outside the protoplanet, along horseshoe orbits. To conserve angular momentum, satellite moves in.)

Now consider the opposite case of an inner hole in the disk (initially)

Against the prediction of shepherding satellite theory, the planet rapidly migrates outwards, toward the disk.

migration type III



Here, the situation is an inverse of the previous slide: gas is initially outside the planet. Disk gas traveling on hairpin/horseshoe orbits fills the inner void. By moving in, the gas rapidly drives the planet out. Lindblad resonances in the outer disk produce the spiral waves and try to move the planet in, but are too weak compared with the CR torques.

Simulation of **outward migration** (type III) of a Jupiter-class protoplanet

Variable-resolution, high-order adaptive grid code (following the planet).

Horizontal axis shows the radius in the range (0.5-5)a

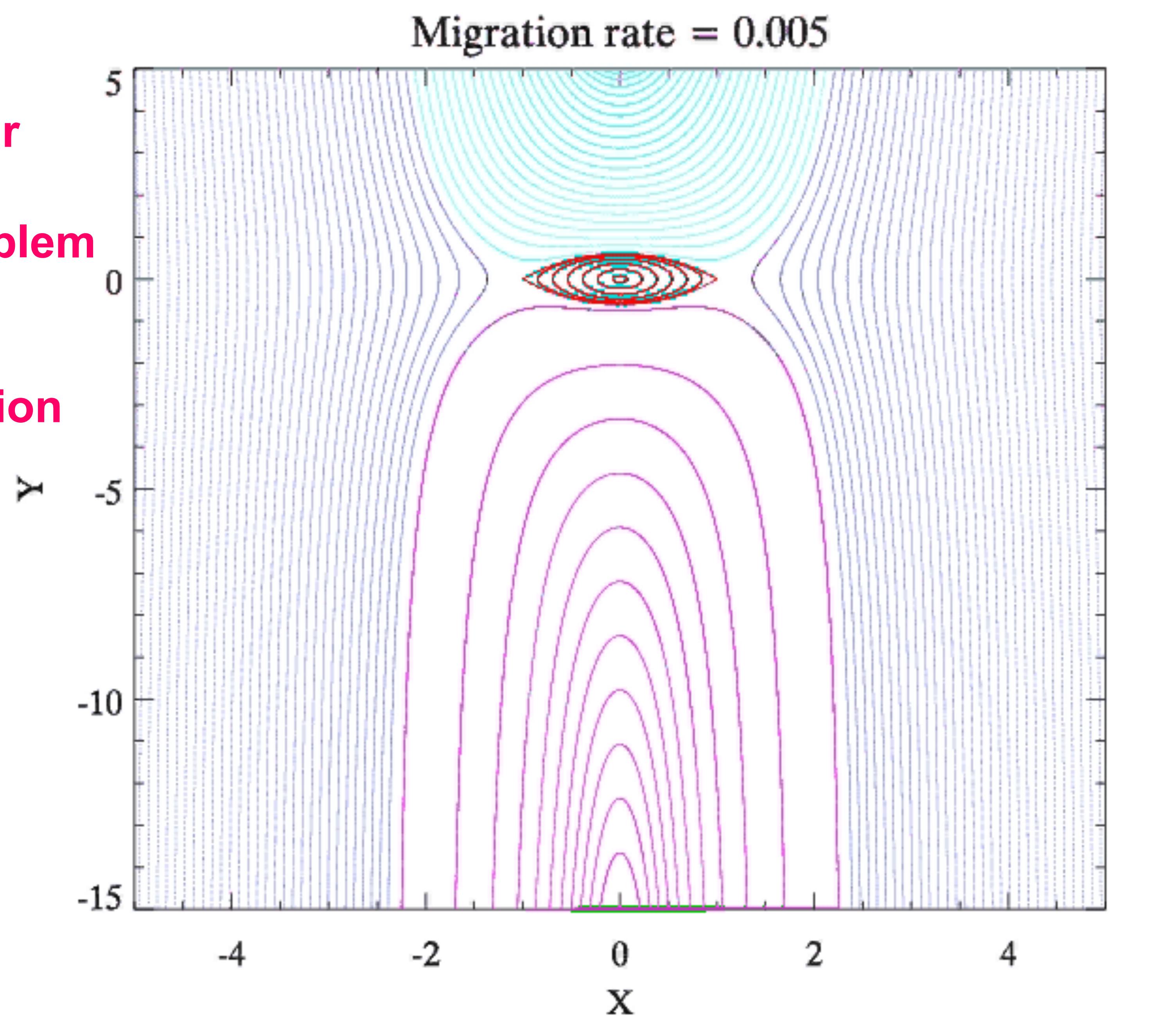
Full range of azimuth
$\theta = 0^o$-360^o
is shown on the vertical axis
Time is displayed in units of initial orbital period.
Peplinski, Mellema and Artymowicz (2007, 2008)

Guiding center trajectories in the Hill problem can explain features of type III migration

Unit of length = Hill sphere

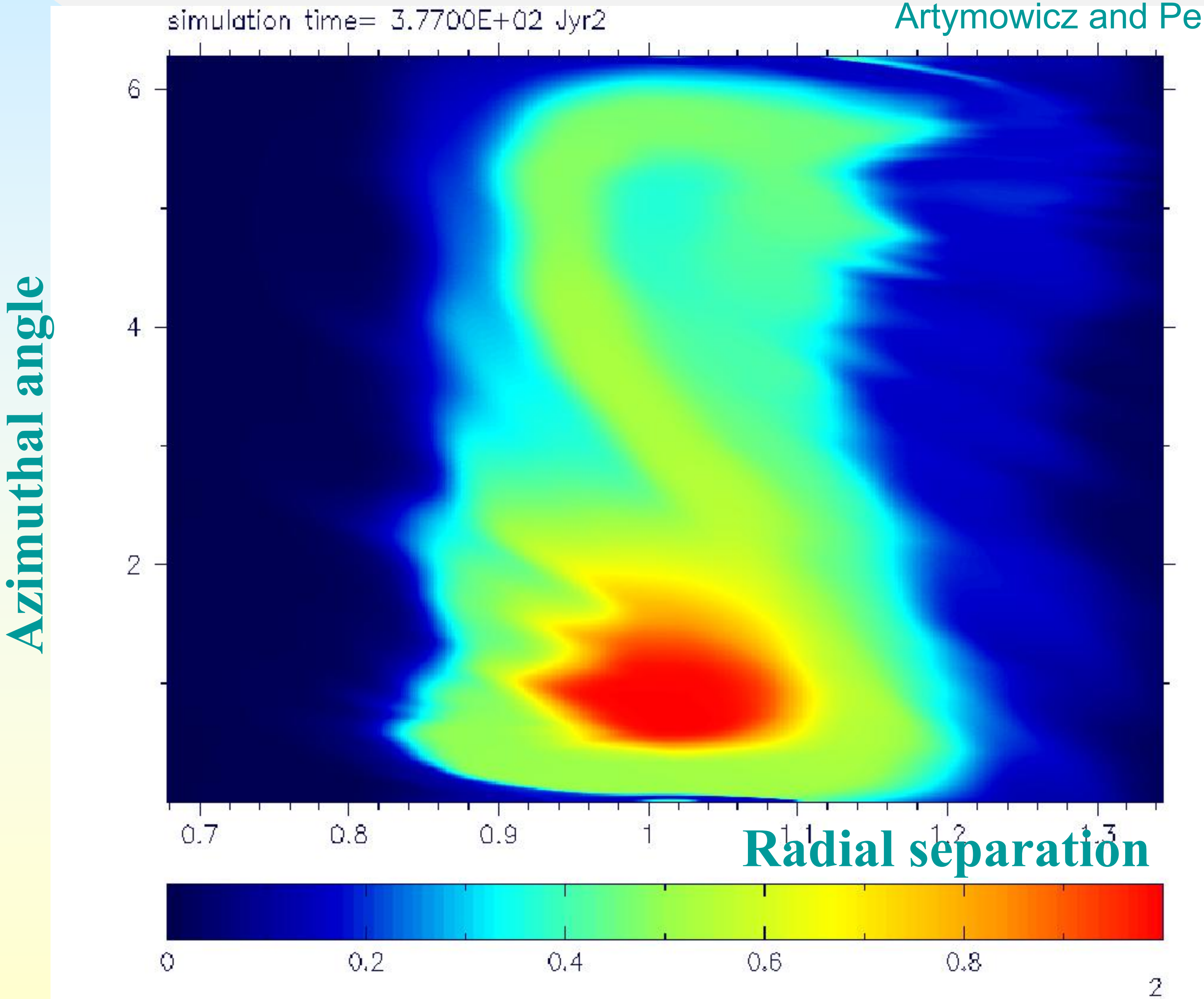
Unit of da/dt = Hill sphere radius per dynamical time.

Animation: Eduardo Delgado



Slow migration, density of gas (PPM code FLASH on a CPU cluster)

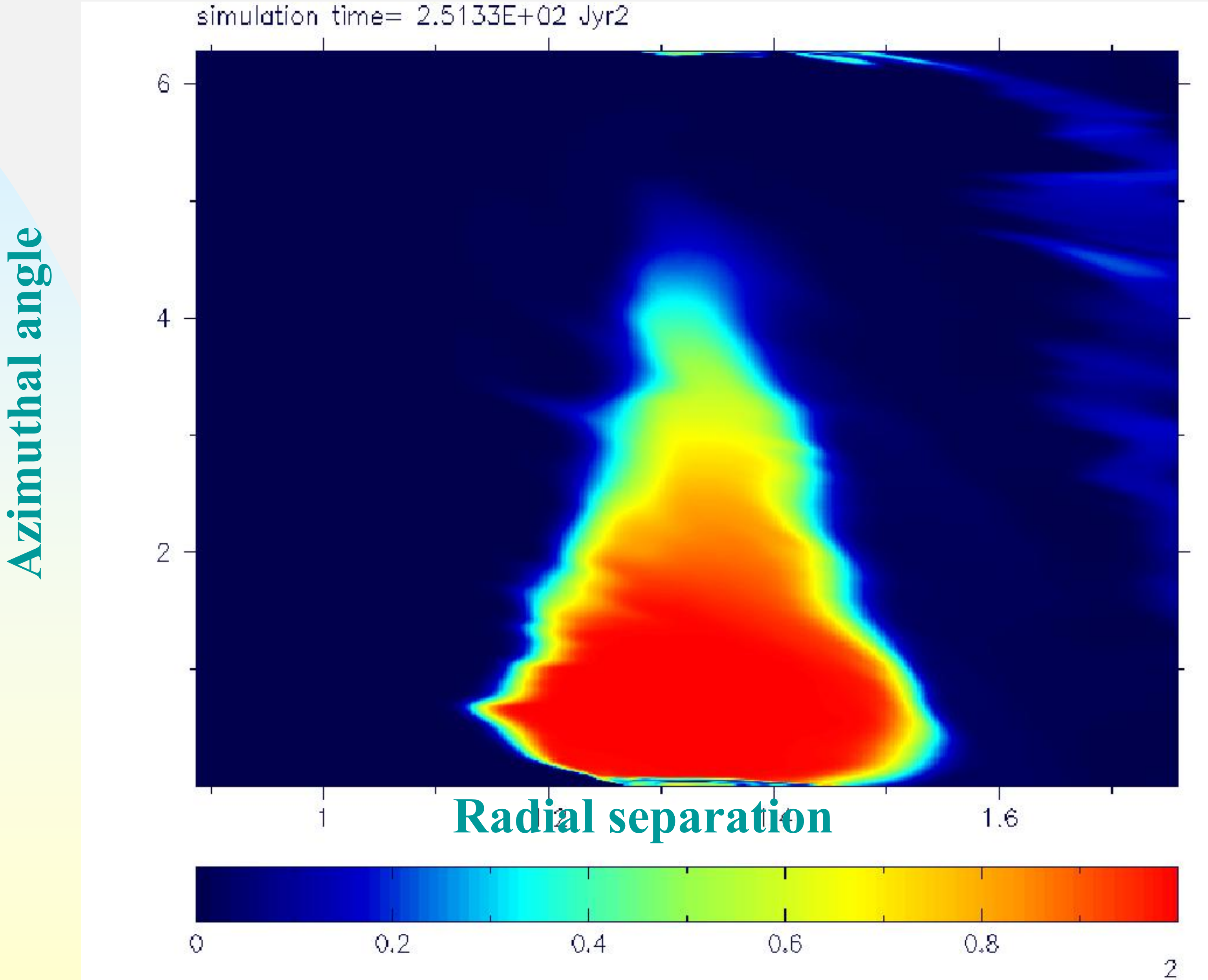
Artymowicz and Peplinski (2012)



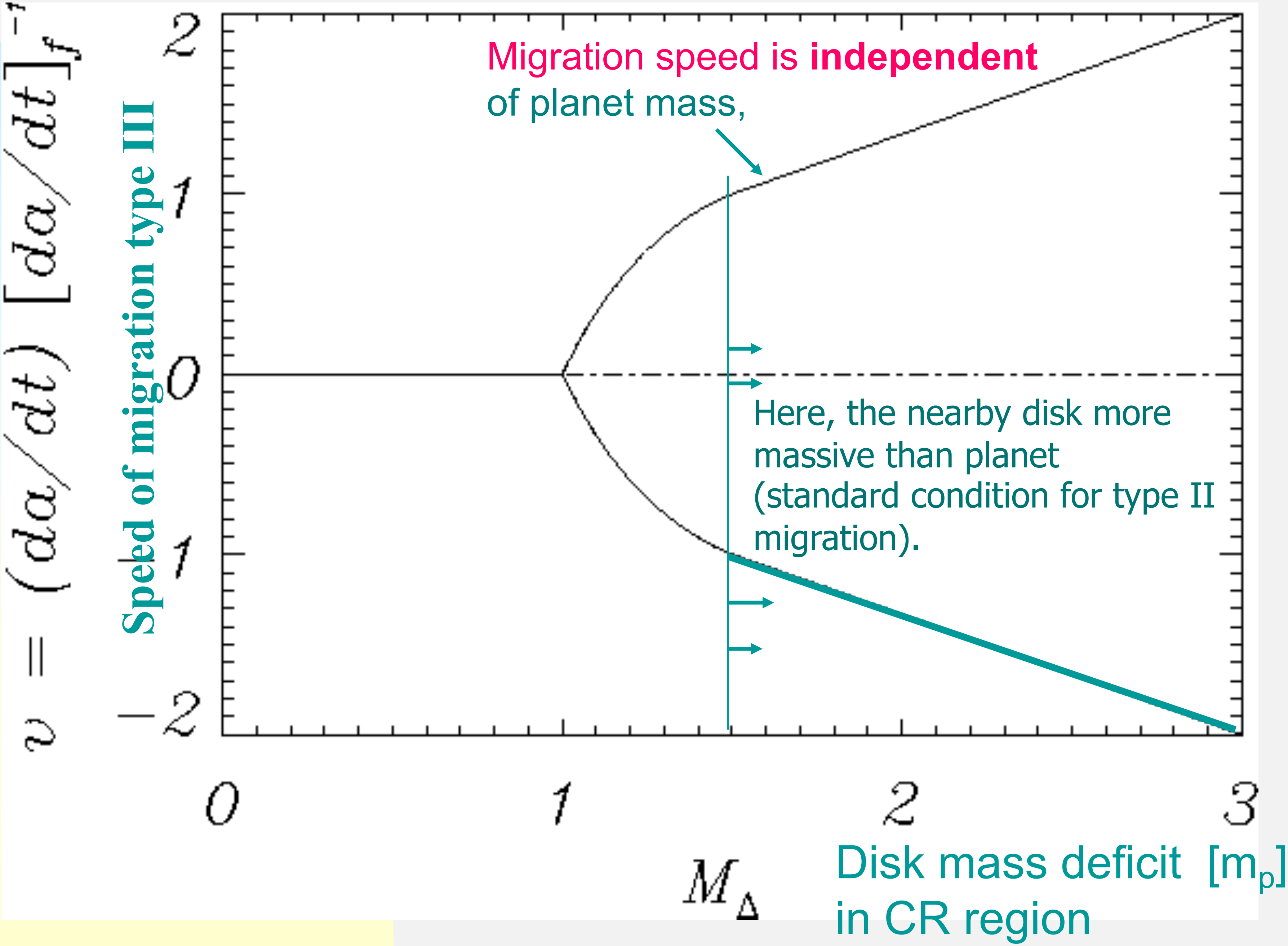
The annulus of circulating flow is called Corotational Region (CR)

In fluid disks, it spans $\pm 2.5\ r_L$ from planet's orbit

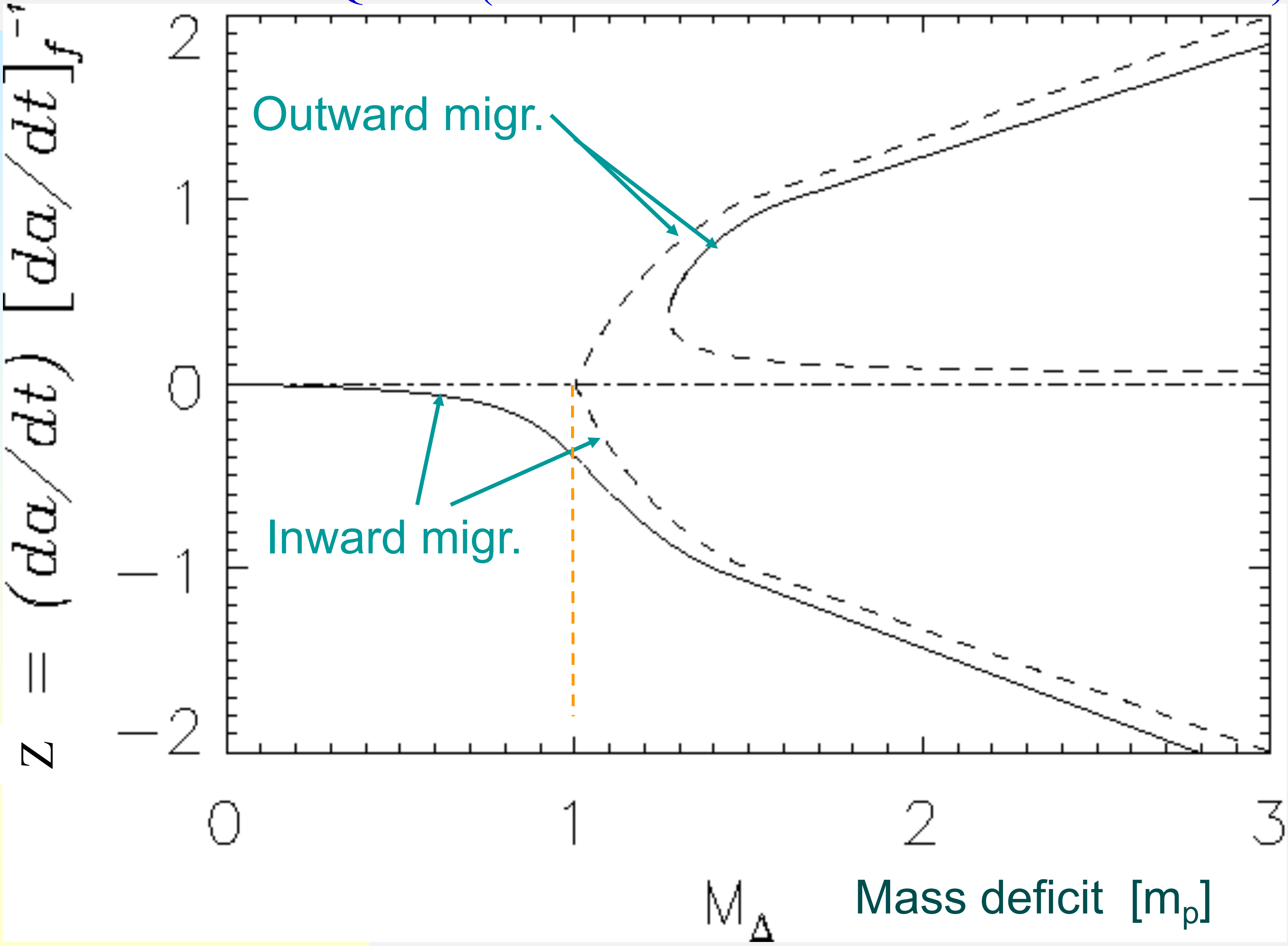
Fast migration



Migration type III, neglecting resonant wave generation viscosity



ALL TORQUES (Corotational + Lindblad/waves + viscous)



Type III migration is unusual:

- It acts very rapidly (e.g., 44 periods for standard disk + Jupiter) does not much depend on the mass of the planet & disk viscosity, just on the disk mass.

- It stops when the approximate criterion of migration is violated.
  Criterion for self-sustaining migration:
  M_{planet} **<** $M_{deficit}$ in the corotation region

So the standard, gap-centered-on-planet migration (called type II) is really in an unstable equilibrium in most cases.
This is easy to check numerically by pushing the planet off-center.
The planet then transitions to type III migration.

Summary of type-III migration

- Rapid (timescale can be < ~100 orbits).
- Mass flow through the gap dominate wave excitation in far-away disk by mean-motion (Lindblad) resonances
- Inward migration explains 'hot jupiters' class of exoplanets (described in the next lecture)
- Its direction depends on prior history, not just on disk properties.
- Migration stops on disk features (rings, edges and/or substantial density gradients.) Such edges seem natural (dead zone boundaries, magnetospheric inner disk cavities, formation-caused radial disk structure)
- Offers possibility of survival of giant planets at intermediate distances (0.1 - 1 AU),
- and of terrestrial planets during the passage of a giant planet on its way to the star (slower migration of giant planet would destabilize Earths)

Disks and the eccentricity of orbits of exoplanets:

As long as there is some gas in the corotational region (say, +- 20% of orbital radius of a jupiter), eccentricity is strongly damped by the disk.

Only if and when the gap becomes so wide that the near-lying LRs are eliminated, eccentricity is excited. (planets larger than 10 M_{Jup} were predicted in 1992 to be on eccentric orbits).

In practice, disks may account for intermediate-e exoplanets.

For extremely high eccentricities, we need N-body explanations: perturbations by stars, or other planets.

SUPERCOMPUTING in the study of the origins of planets

„The 3-D flow around a small, embedded planet"

Fung, Artymowicz and Wu (2015)

Simulating a small, 5-Earth mass planet orbiting inside an accretion disk is challenging: resolution must be much better than the Roche size of the protoplanet (~0.01 orbital radius).

* * *

Code: PenGUIn on GPUs (Graphical Processing Units)

Computer: 3 graphics cards or GPUs in one box

Language: CUDA C++, an extension of C language for massively parallel computations on GPUs

Calculation must be done in 3-D, cover all the disk

2-D

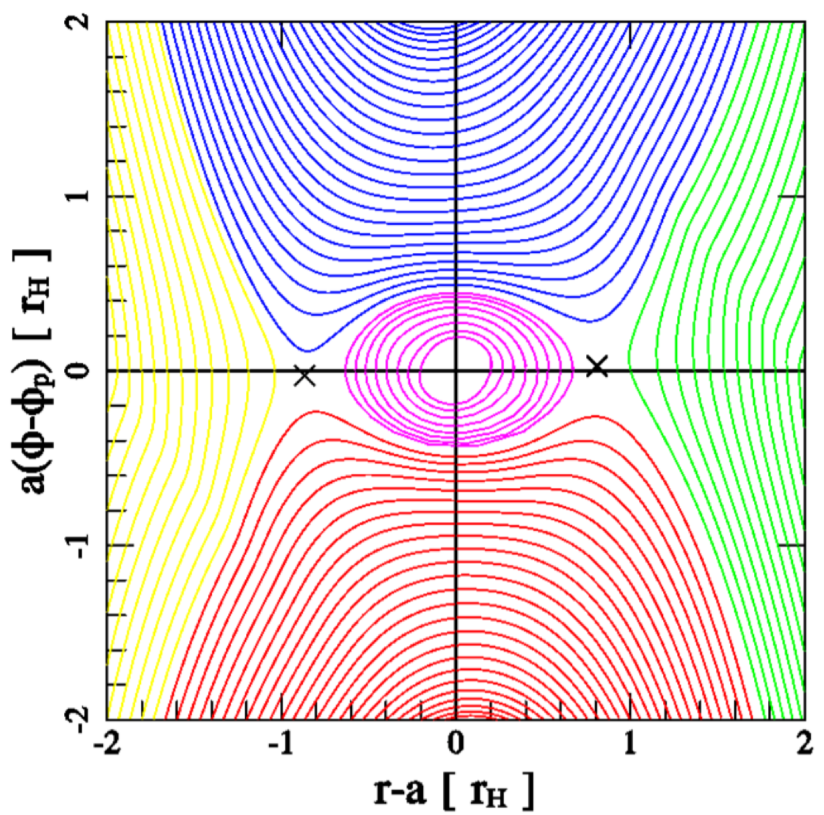


FIG. 1.— Streamlines around a planet in 2D, plotted in the corotating frame

3-D

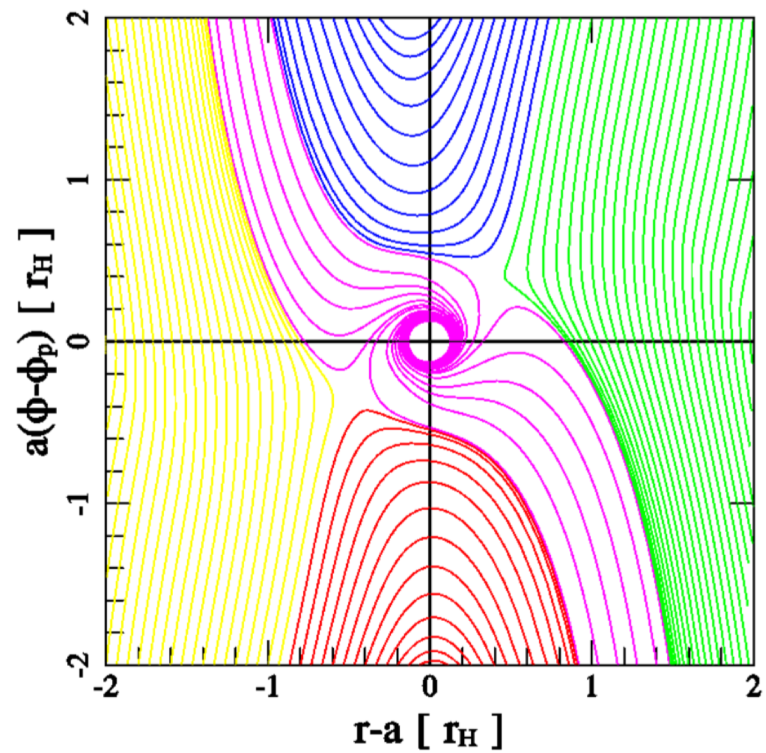
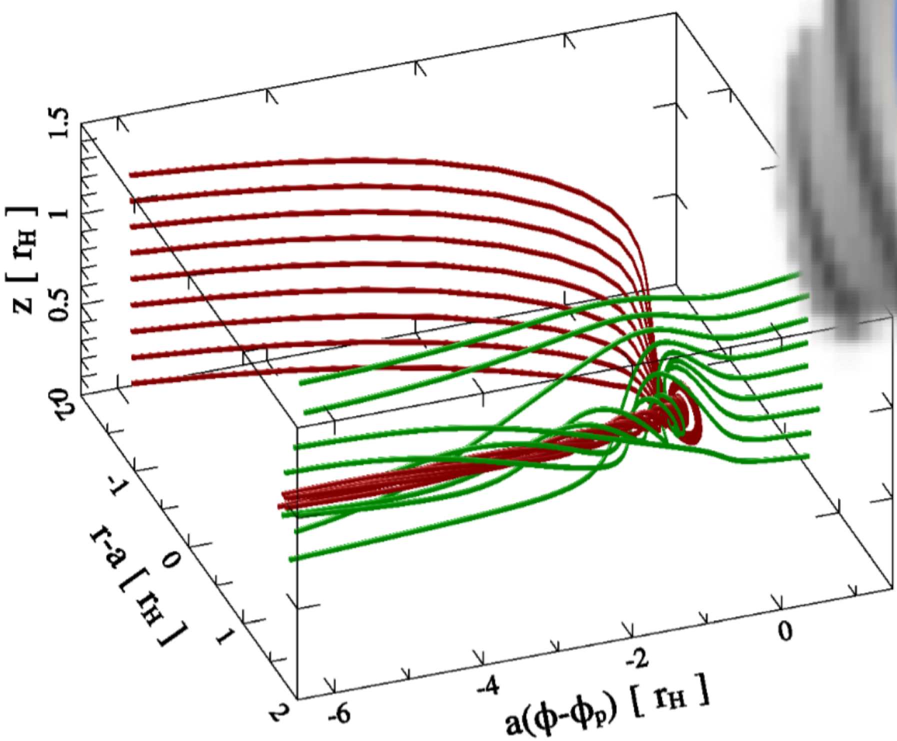
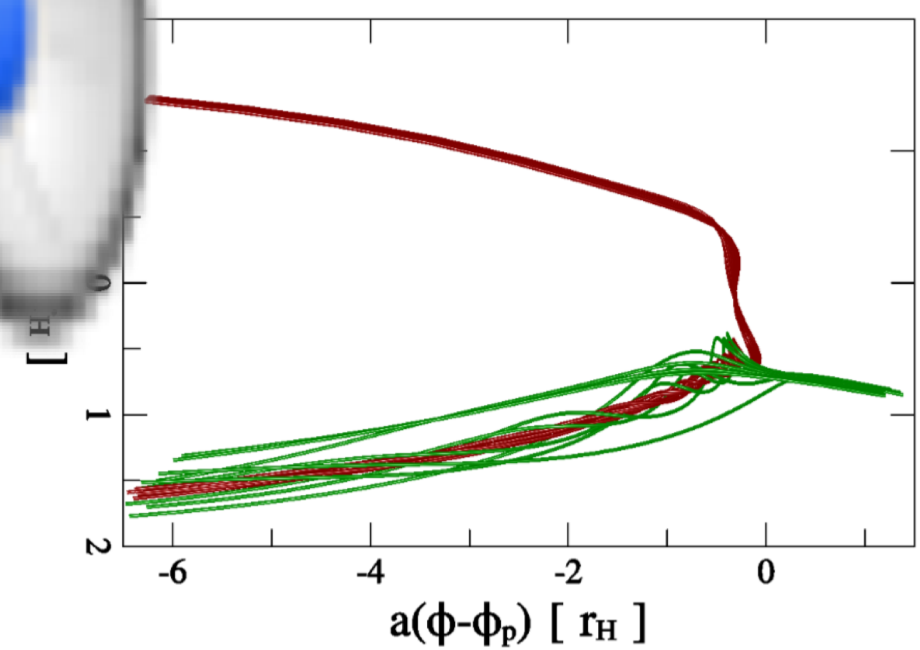
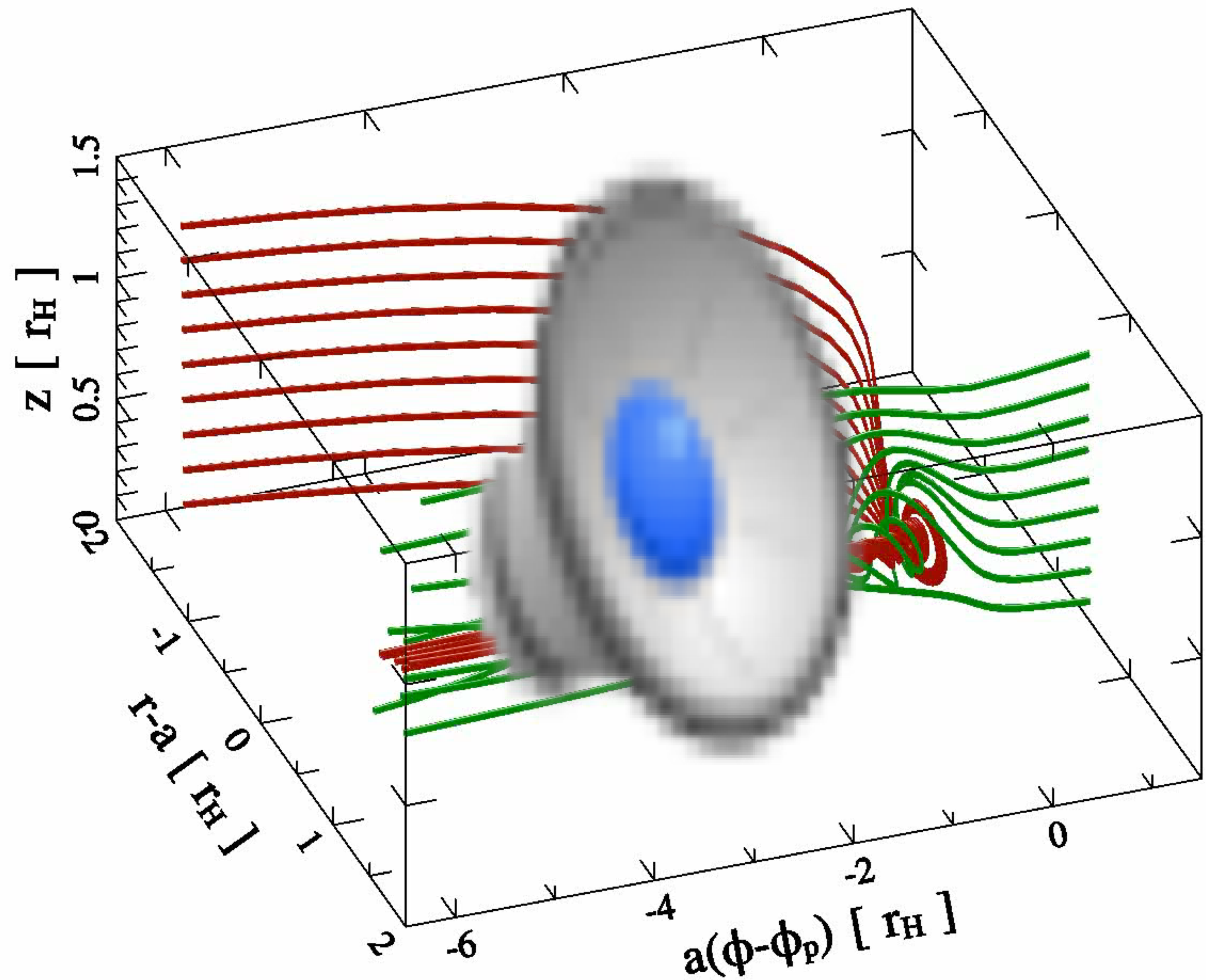


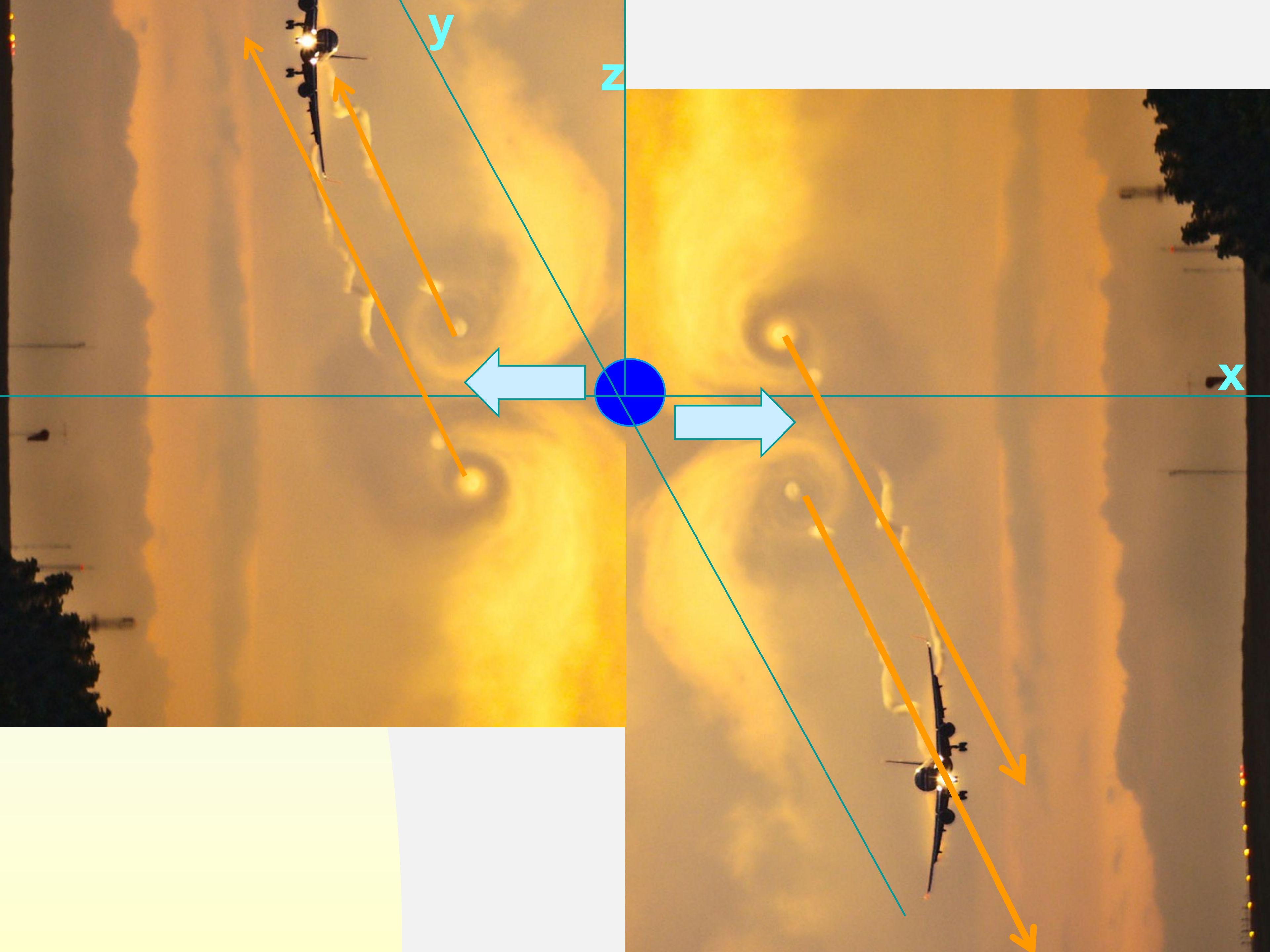
FIG. 8.— Streamlines in the disk midplane. Compare with Figure 1 for differences between 2D and 3D flow. Yellow, red, green, and blue streamlines are assigned in the same manner as Figure 1. Unlike Figure 1, magenta lines are outflows away from the planet, pulled down from initially higher altitudes. They reach as close as $1.5 r_s$ from the planet and are unbound.


z [r_H]
r-a [r_H]
$a(\phi-\phi_p)$ [r_H]


$a(\phi-\phi_p)$ [r_H]



z [r_H]
0
0.5
1
1.5
r-a [r_H]
-2
-1
0
1
2
a(ϕ-ϕ_p) [r_H]
-6
-4
-2
0


y
z
x

Migration & growth of objects in disks (disk-satellite interaction) is one of the most fundamental & timely subjects in dynamical astronomy

Very often the complexity of fluid motions forces us to develop numerical solutions.

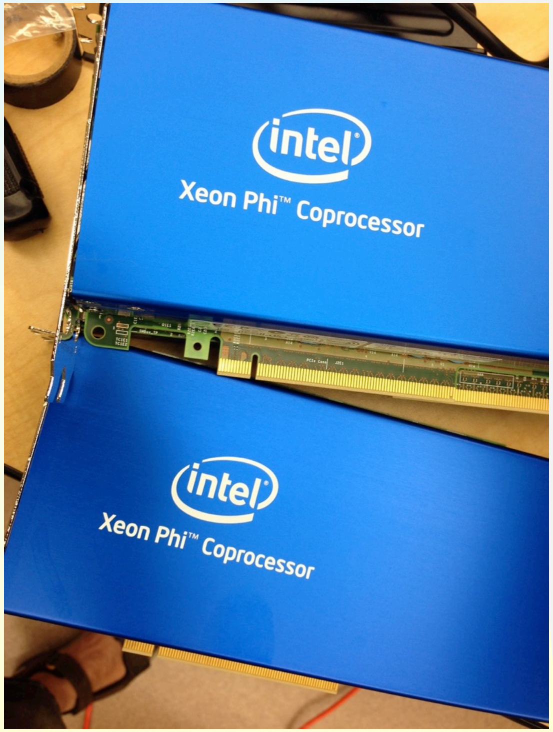
HPC (High Performance Computing) becomes a necessity.
It is done on supercomputers:
Linux-equipped workstations with numerical processors, networked to do parallel computations.

Preferred languages: C/C++, Fortran, plus Python scripts for I/O

HPC

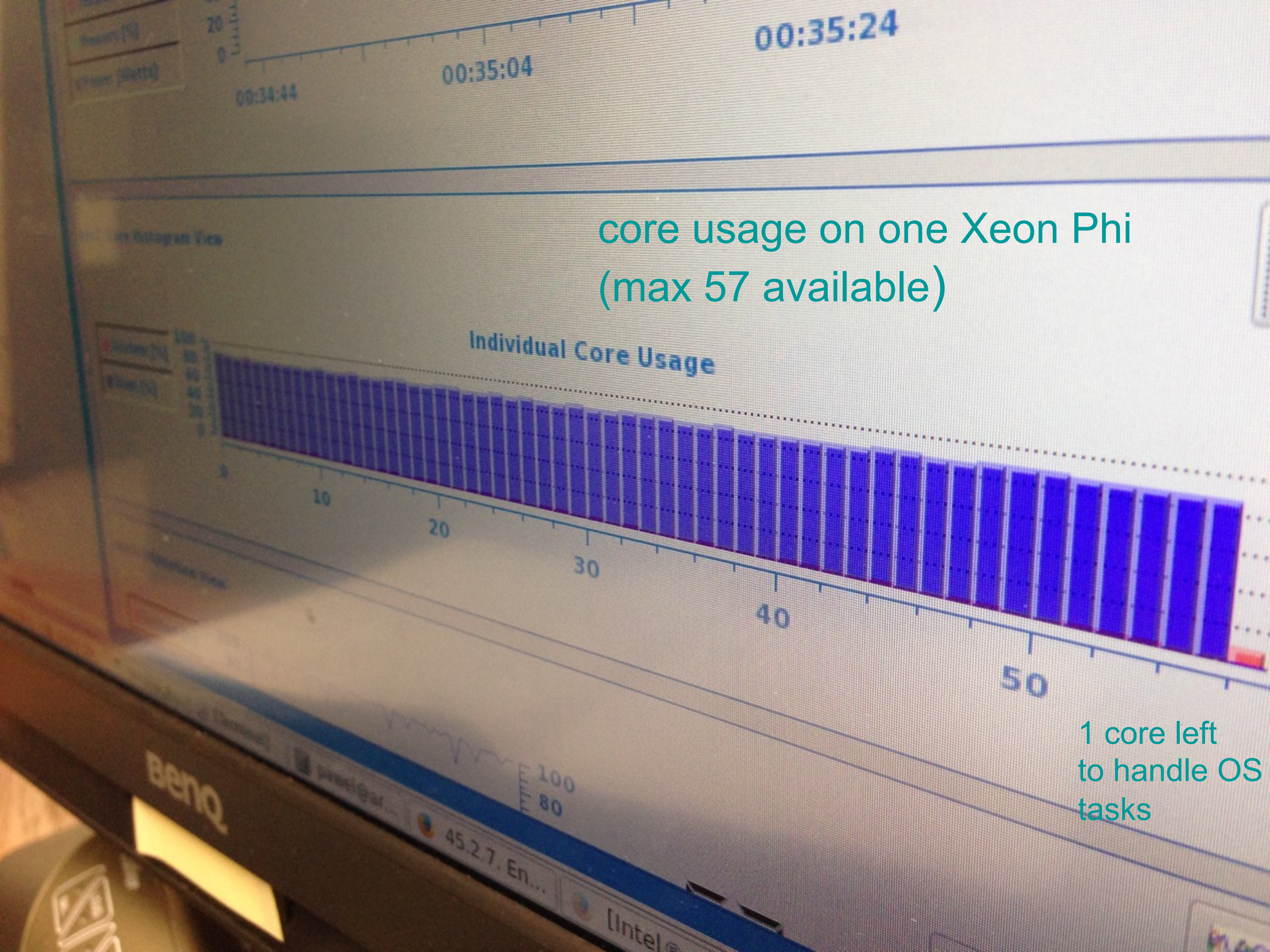
CPU-like
(incl. XeonPhi)

GPU
(graphics processors)



+ quantum computing in.... 20 yrs?


UTSC
EVGA GTX 480



core usage on one Xeon Phi (max 57 available)

1 core left to handle OS tasks

Art cluster is featured on a banner outside DPES office

If you are interested in supercomputing (HPC), take PHYD57 course Advanced Computational Methods in Phys.

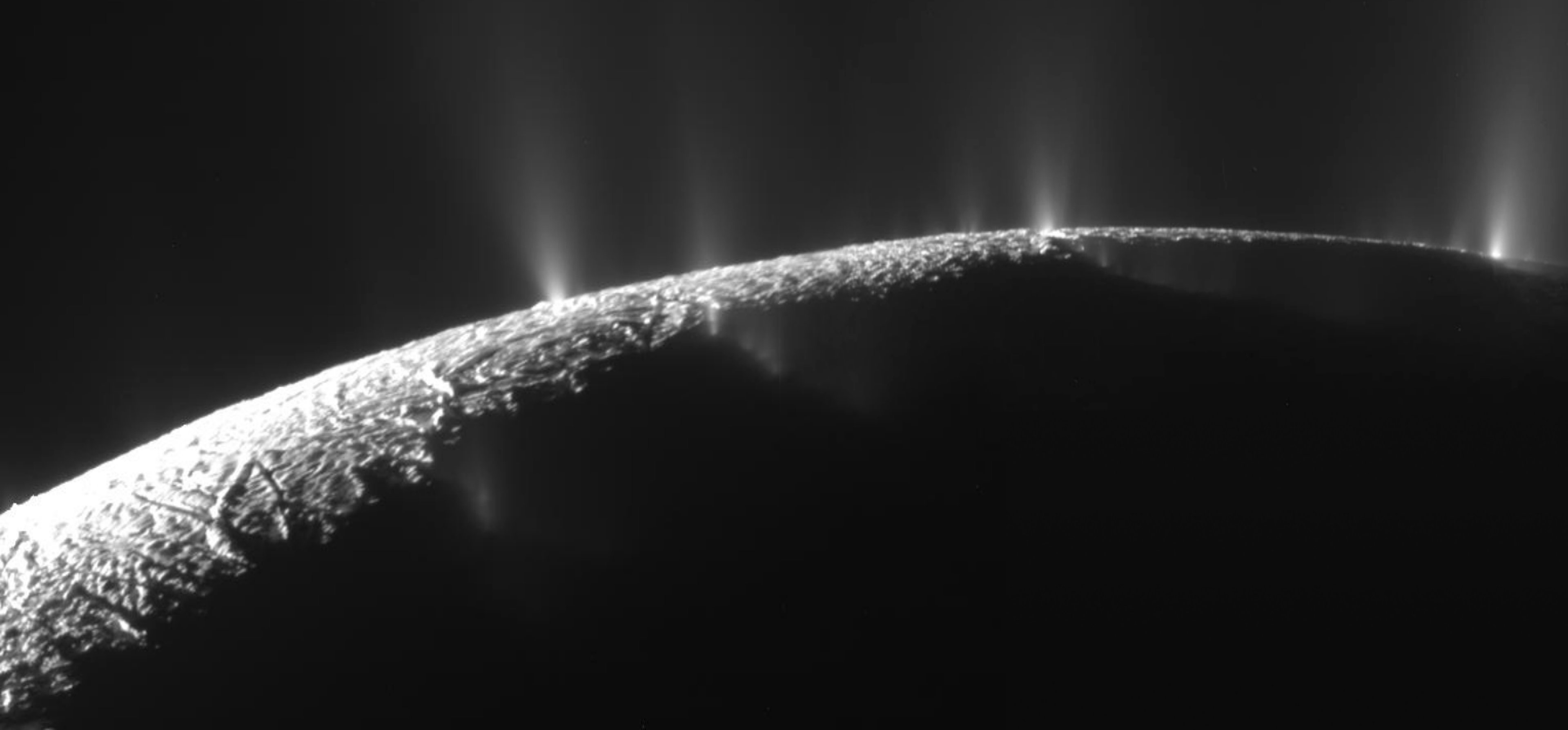
Lecture 21-23 ASTC25

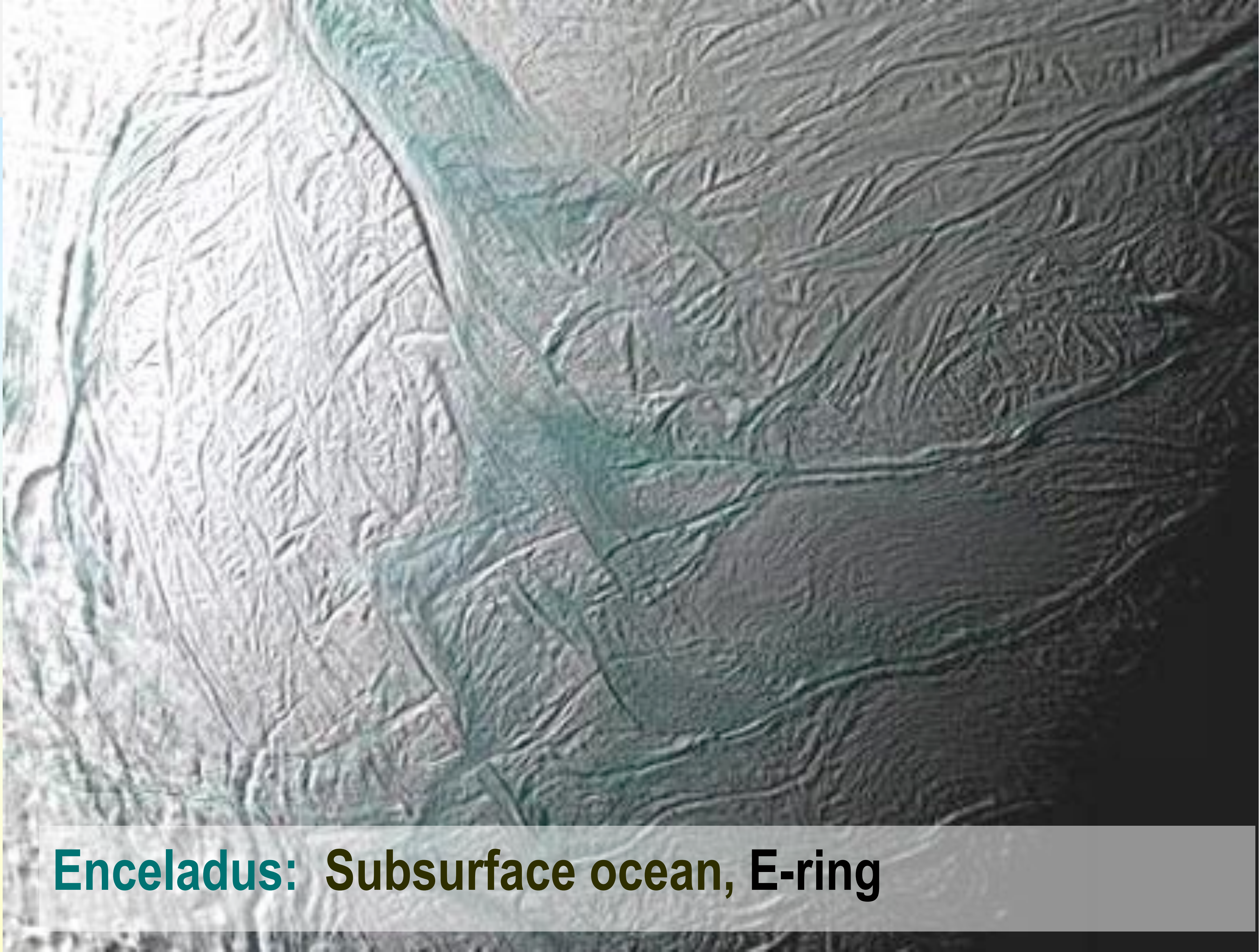
Discovery of Extrasolar planets

- Solar system vs. extrasolar systems.
- Discovery of diversity & uniformity
- Pulsar planets
- Radial velocity planets
- Transiting and microlensing planets
- Direct imaging

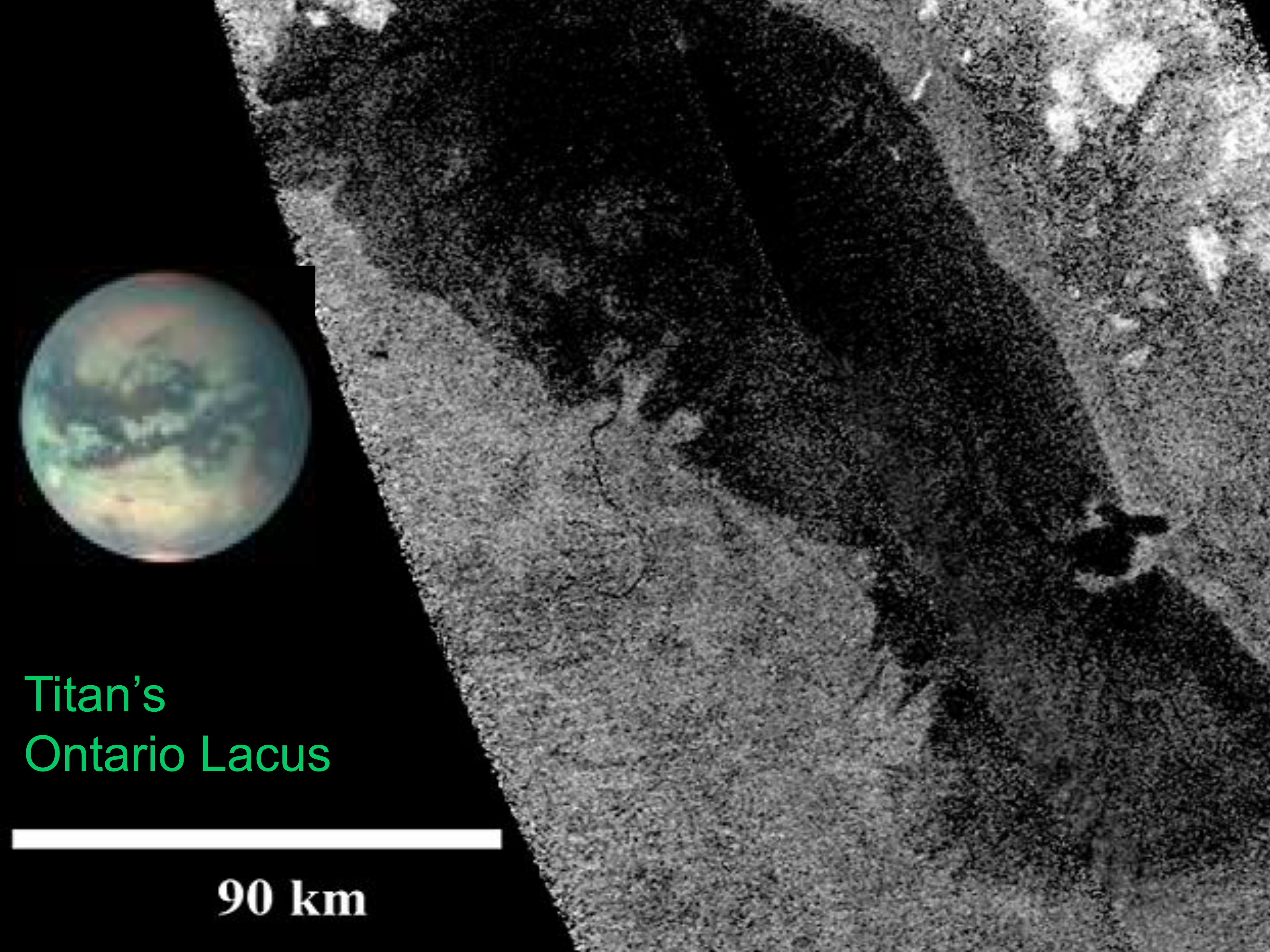
Some day we will see the other worlds as clearly as we now see our amazing solar system planets and satellites (e.g. Saturn’s system)

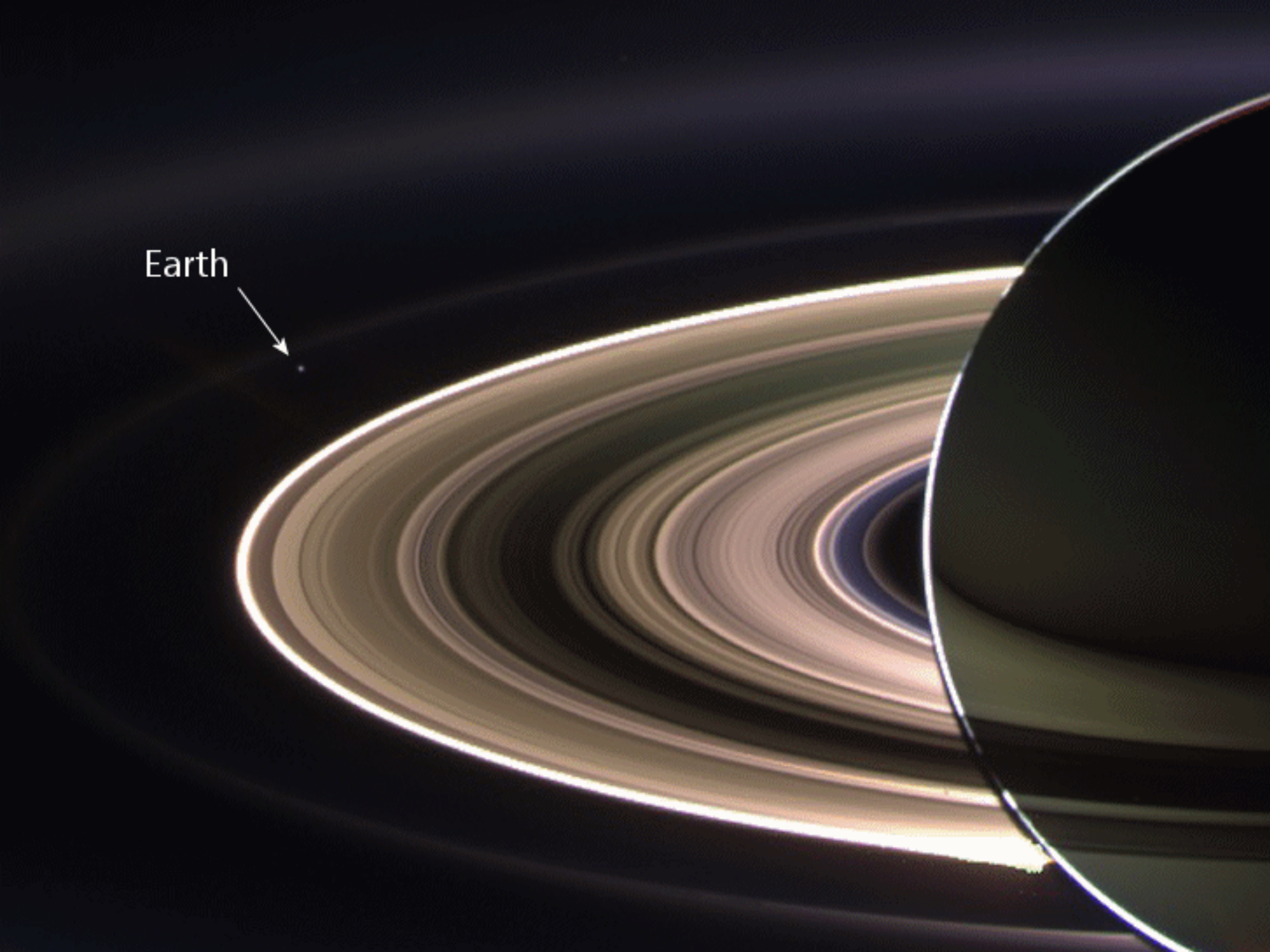
Enceladus with geysers

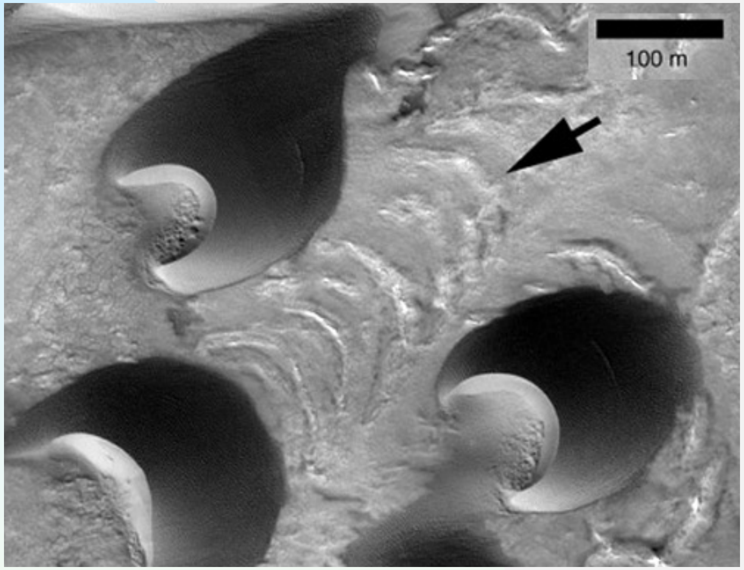


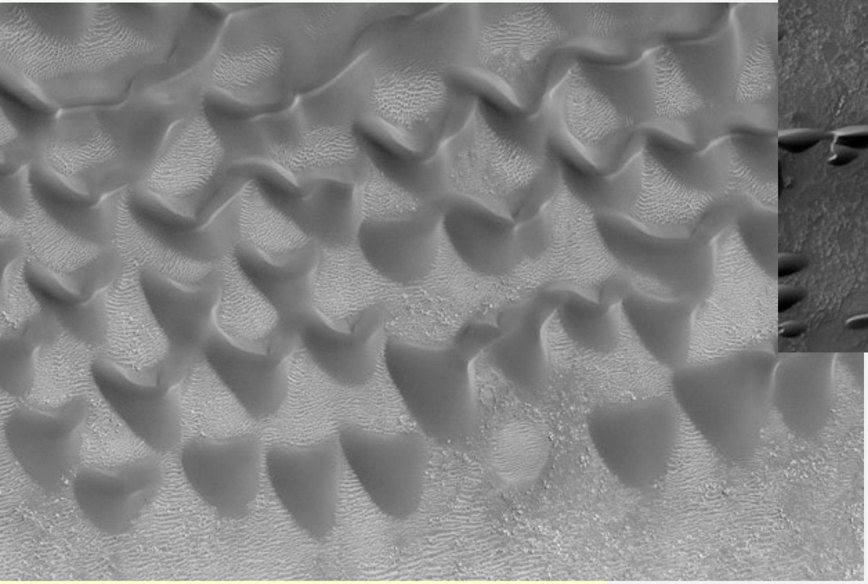


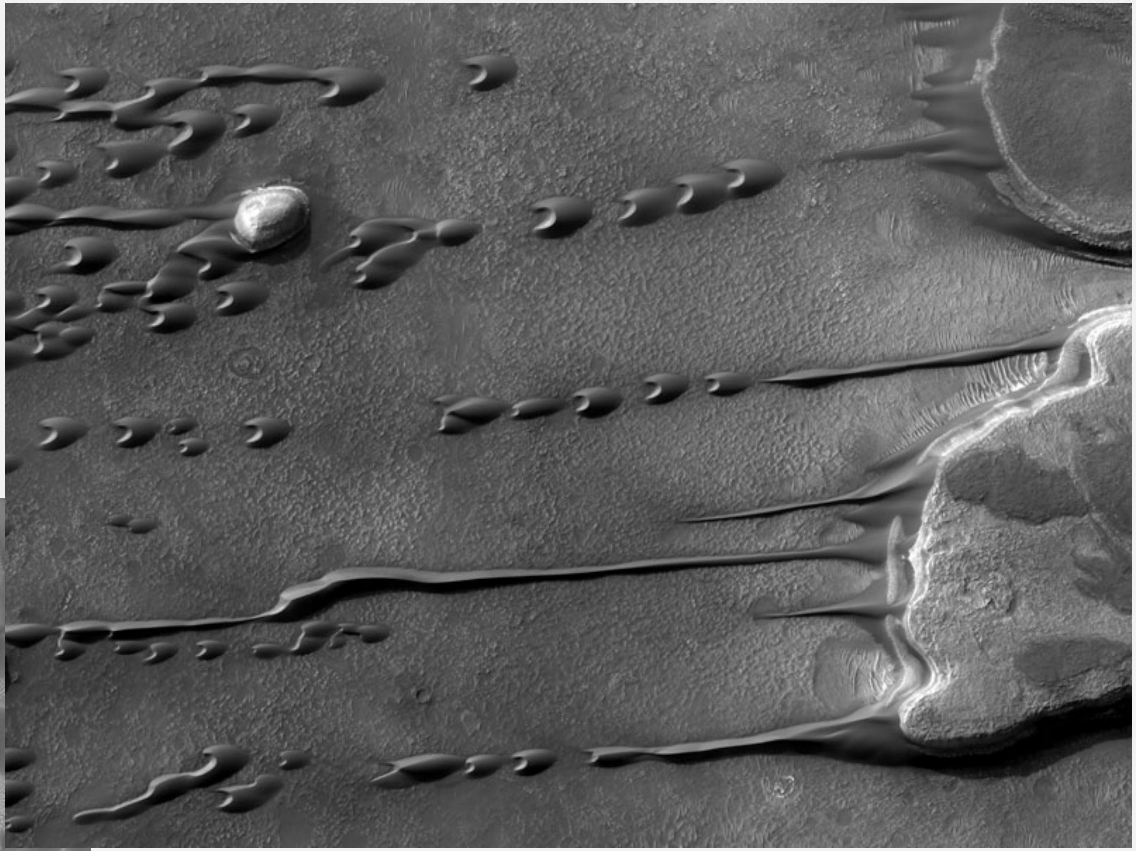
Enceladus: Subsurface ocean, E-ring


Titan’s
Ontario Lacus
90 km


Earth

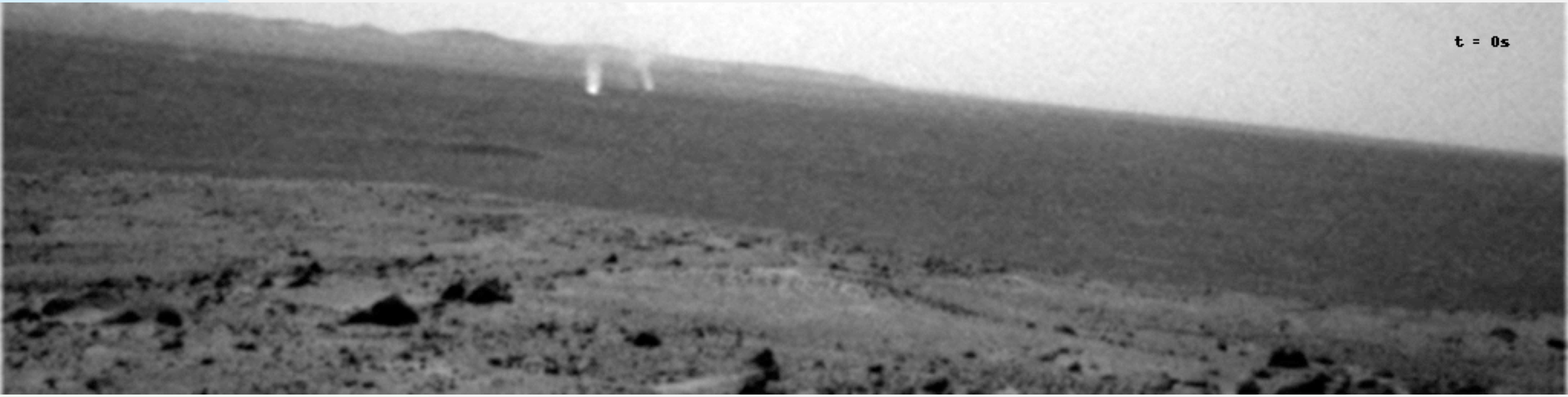




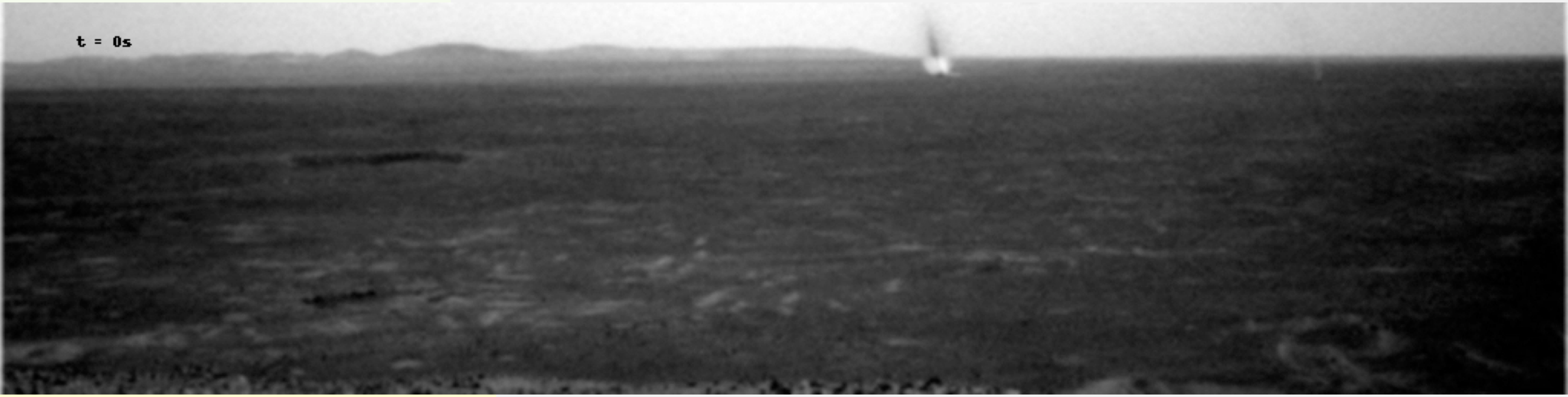


Can you guess which body that is?

Before we see such dust devils on extrasolar planets…

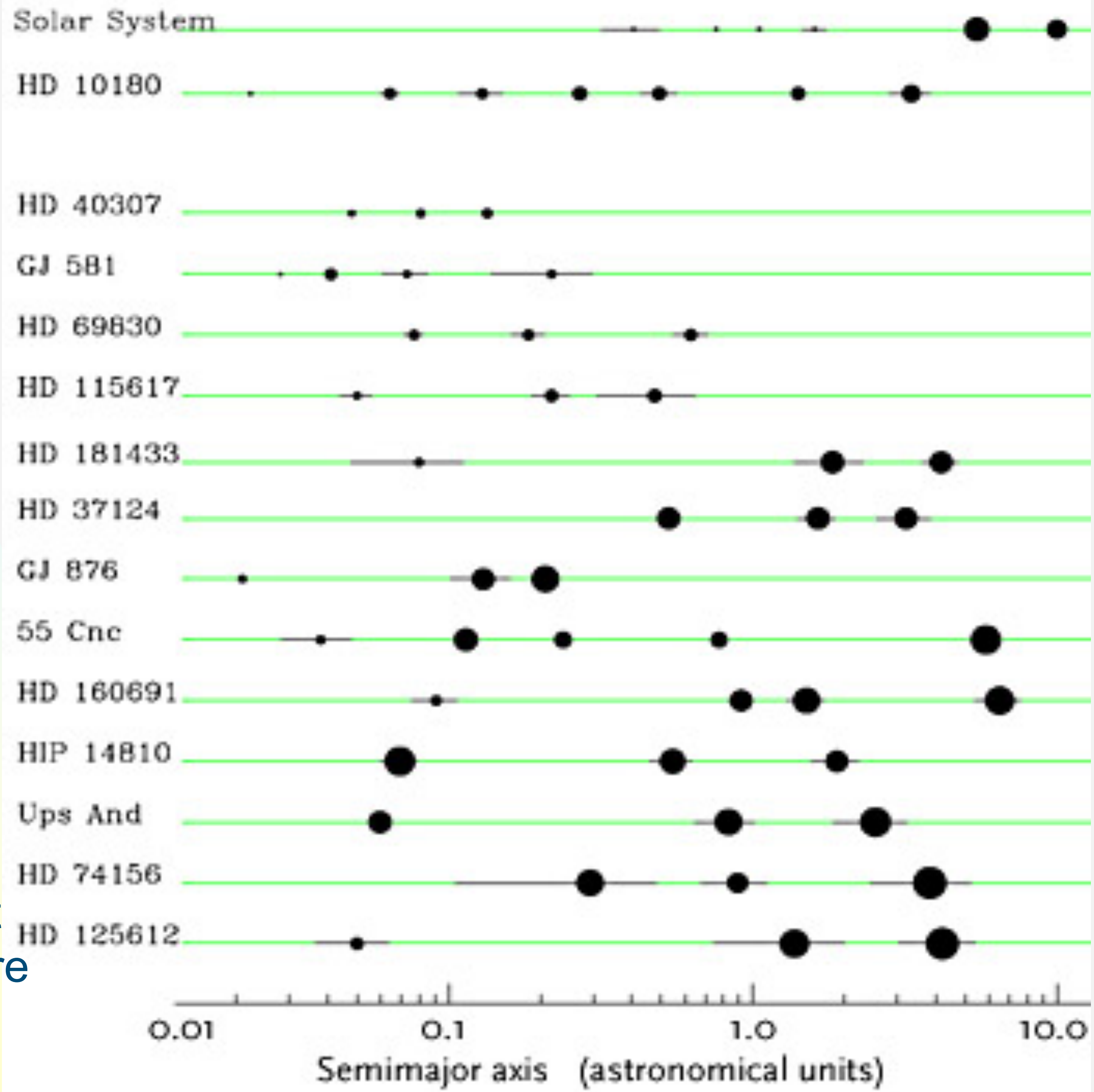


(surface of Mars)



...we have to learn to remotely observe

and theoretically figure out the nature and origin of exoplanets



Some multi-planet system architecture is shown here (we know many more)

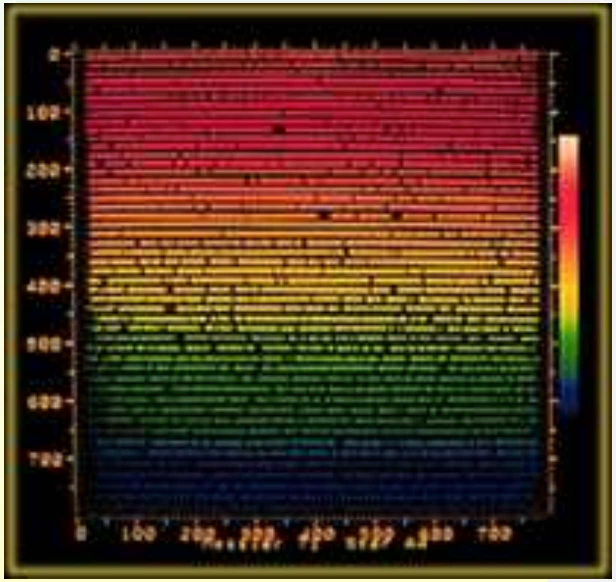
450 B.C.E: Extrasolar systems predicted (Leukippos, Demokritos).
Formation in disks described.

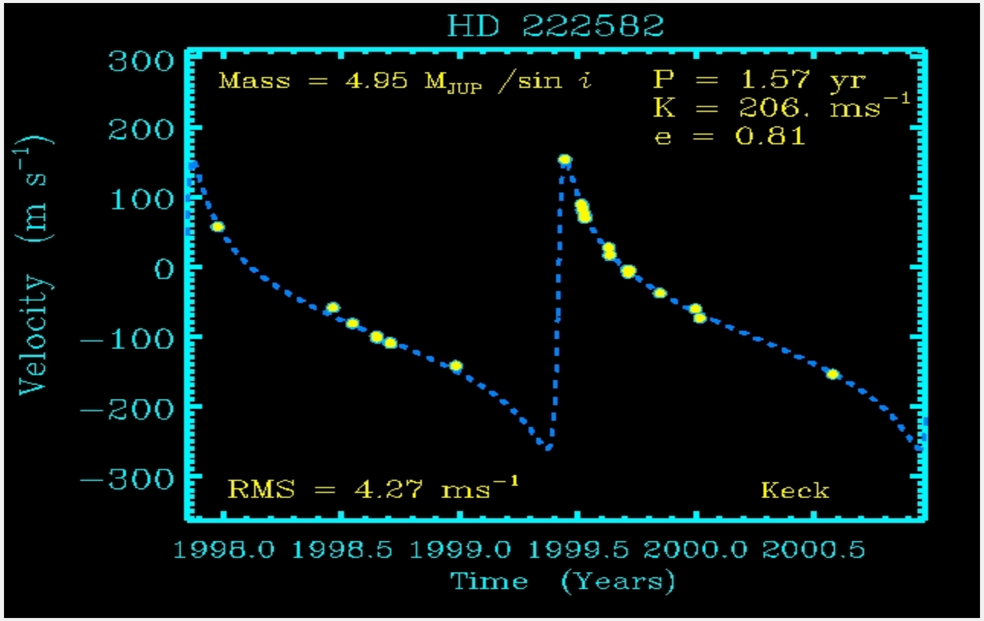
325 B.C.E.: “Disproved” by Aristoteles (a.k.a. Aristotle)

1983: First dusty disks in exoplanetary systems discovered by IRAS

1992: First exoplanets found around a millisecond pulsar (Aleksander Wolszczan)

1995: Radial velocity planets found around normal, nearby stars, via Doppler spectroscopy of the host starlight, starting with Mayor & Queloz, continuing with Marcy & Butler, and many other astronomers





From: Diogenes Laertius, Φιλοσοφοι βιοι (3rd cn. A.D.), IX.31

"The worlds come into being as follows: many bodies of all sorts and shapes move from the infinite into a great void; they come together there and produce a single whirl, in which, colliding with one another and revolving in all manner of ways, they begin to separate like to like."

Leucippus

(Solar nebula of Kant & Laplace A.D. 1755-1776? Accretion disk?)

"There are innumerable worlds which differ in size.
In some worlds there is no Sun and Moon, in others they are larger than in our world, and in others more numerous. (...) in some parts they are arising, in others failing.
They are destroyed by collision with one another. There are some worlds devoid of living creatures or plants or any moisture."

Democritus

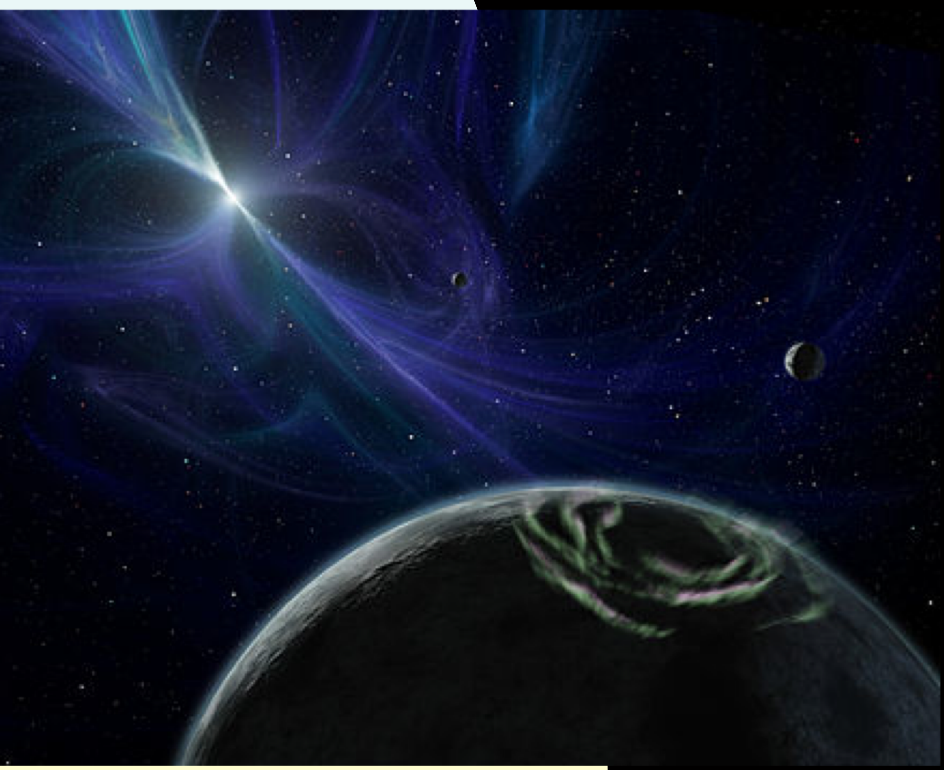
(Planets predicted: **around pulsars**, binary stars, close to stars **?**)

There are infinite worlds both like and unlike this world of ours. *For the atoms being infinite in number (...) there nowhere exists an obstacle to the infinite number od worlds.*

Epicurus (341-270 B.C.)

PULSAR PLANETS

In 1990-1992 a new era in the planetary astronomy began thanks to one unassuming millisecond pulsar named PSR B1257+12, observed in Arecibo by a Polish radio-astronomer Alexander Wolszczan [VOLsh-chan] (who studied in Copernicus' birthplace, Toruń) :



Arecibo radio telescope-
was then the largest on Earth
(300 m fixed dish)

Pulsar planets: PSR 1257+12 B (a millisecond pulsar)

Two Earth-mass planets and one Moon-mass planet were the first extrasolar planets, or exoplanets.

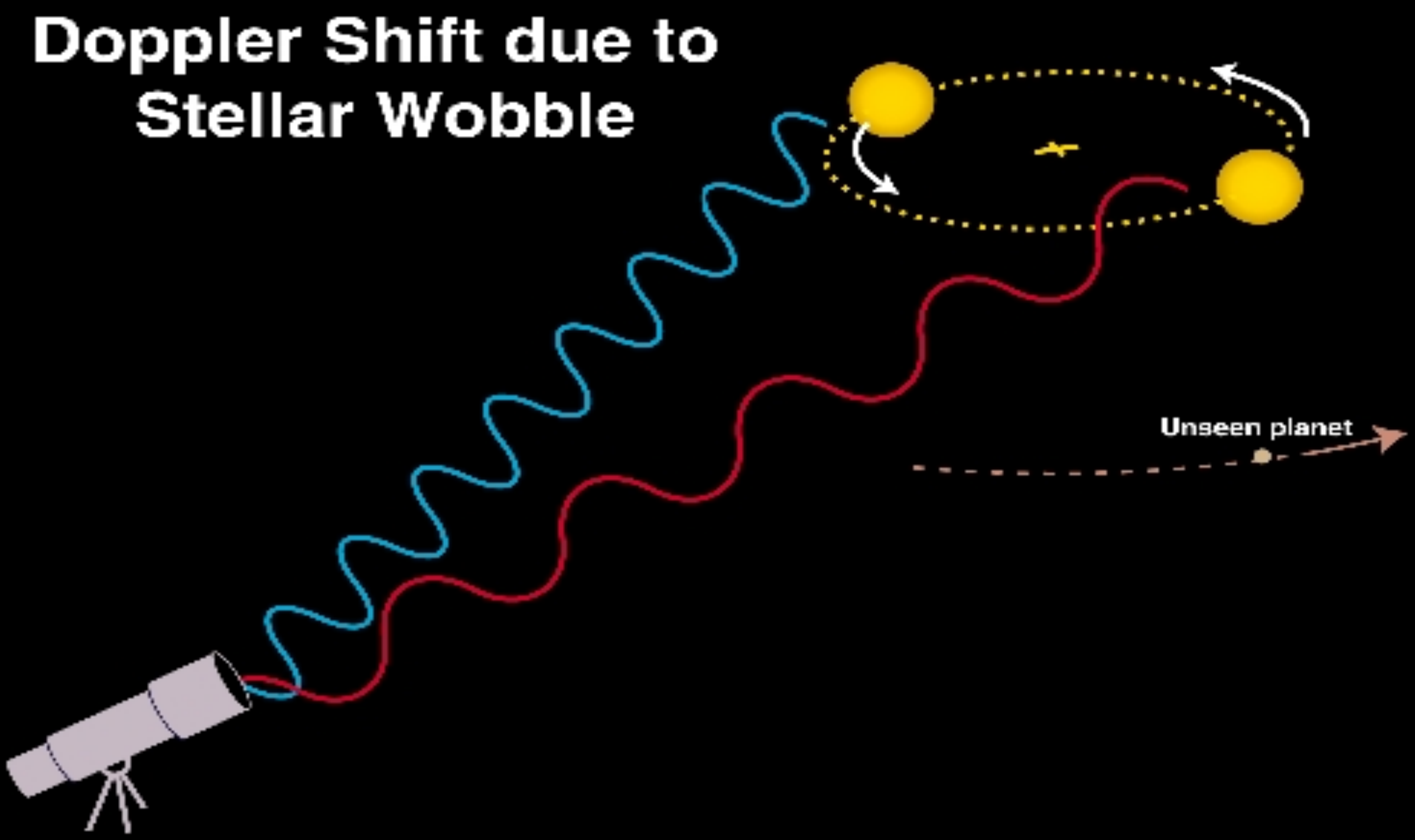
Discovered by Alex Wolszczan in his search for millisecond pulsars in 1991, they were announced in 1992. The circumstances were dramatic, as shortly before that astronomer Andrew Lyne (UK) made a similar but erroneous discovery of a planet around another pulsar! Lyne's conference talk in 1992 with *retraction* of his group's discovery preceded the talk by Wolszczan. Lyne's group mistakenly left a signature of Earth's motion in observations of another pulsar. [At the conference, theorists gave talks explaining how Lyne's "planet" was likely formed.]. Imagine the hesitant reception of Wolszczan's claim..

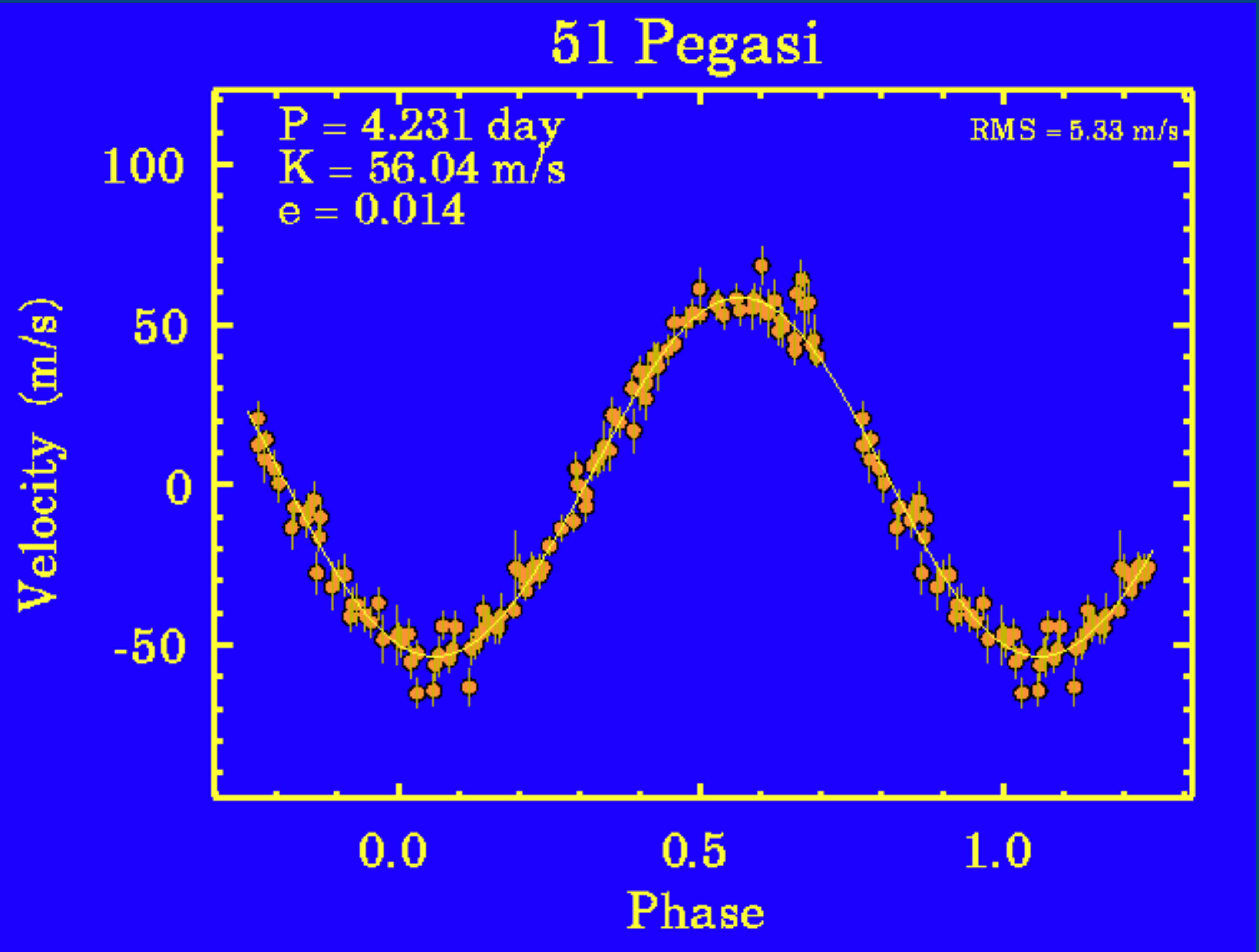
Planet	PSR 1257+12 A	PSR 1257+12 B	PSR 1257+12 C
M.sin [M_E]	0.020 ± 0.002	4.3 ± 0.2	3.9 ± 0.2
Semi-maj axis:	0.19 AU	0.36 AU	0.46 AU
P(days):	25.262 ± 0.003,	66.5419 ± 0.0001	98.2114 ± 0.0002
Eccentricity:	0.0	0.0186 ± 0.0002	0.0252 ± 0.0002
Name:	*Draugr*	*Poltergeist*	*Phobetor*

Pulsar timing is so exact that observers now suspect having detected a comet (unconfirmed!)

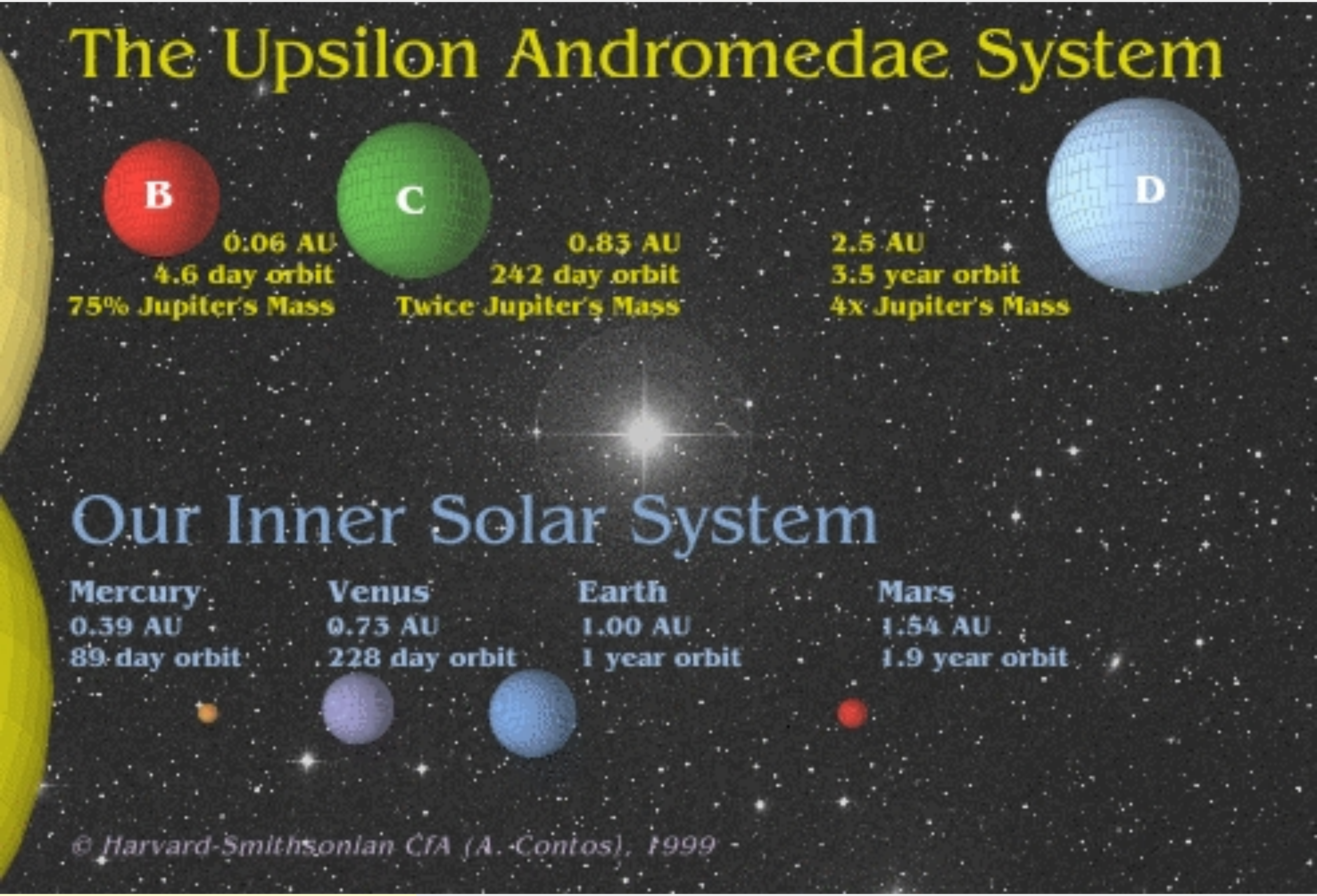
pulsar PSR B1957+12 and its planets may be a result of a merger of two white dwarfs.

Radial-velocity planets

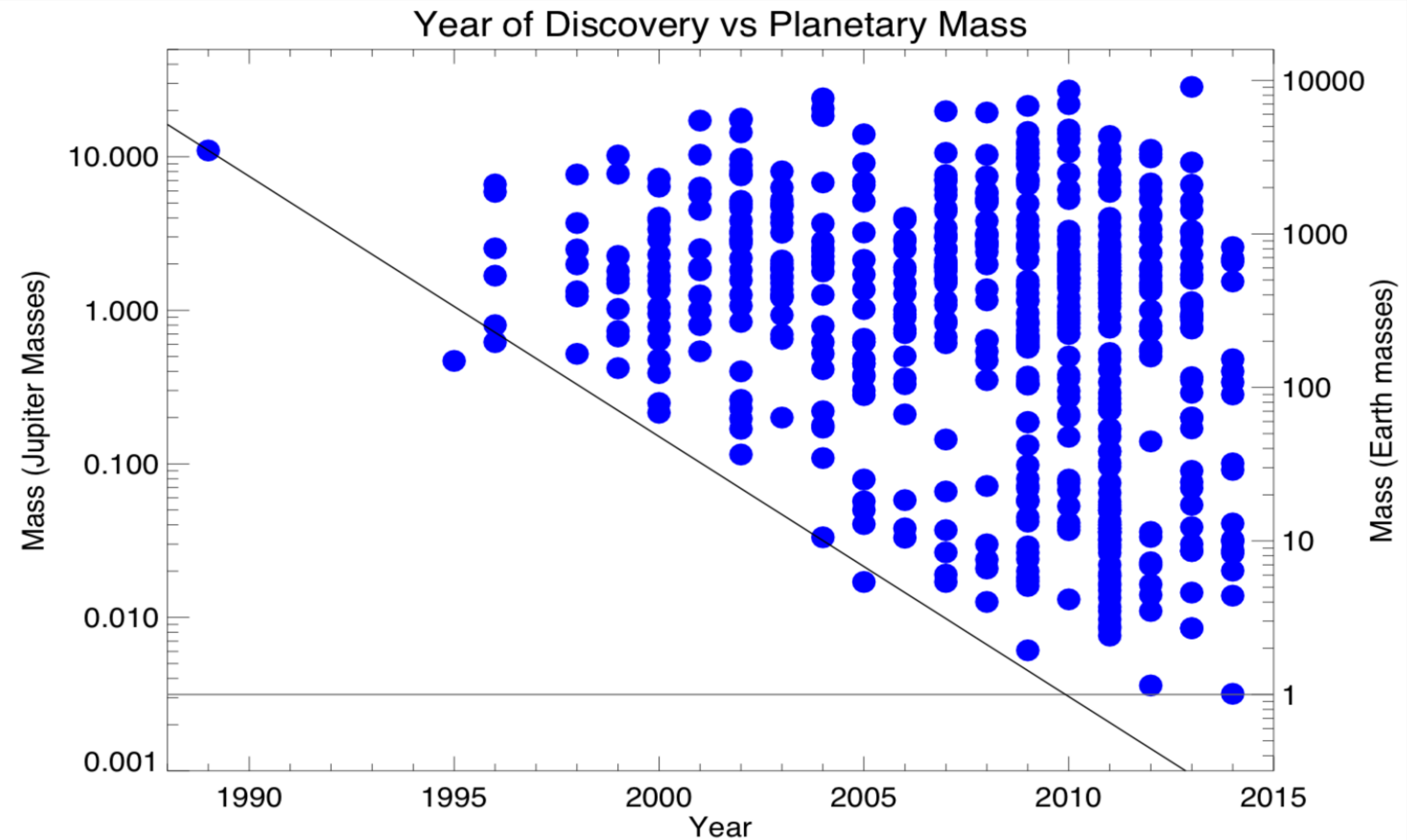




51 Pegasi
P = 4.231 day
K = 56.04 m/s
e = 0.014
RMS = 5.33 m/s
100
50
0
-50
Velocity (m/s)
0.0
0.5
1.0
Phase

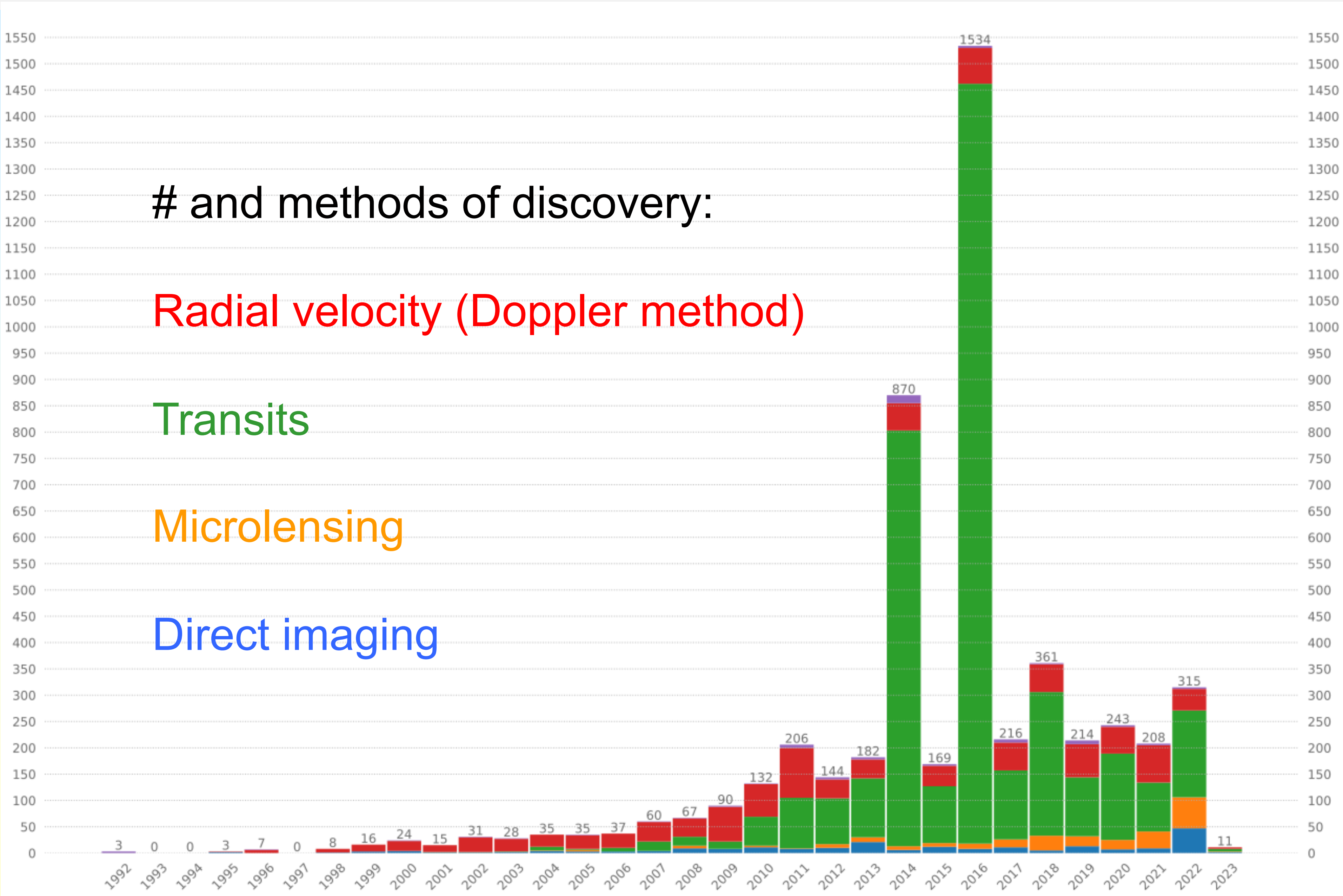


Planet B saved from falling onto the star by relativistic precession of its orbit



Technical capability has been increasing, resulting in many super-Earth and then Earth-mass planet discoveries. Planets below the sloped line could not be detected

Limit of ~1 Earth mass detection (horizontal line) is set by the physical variability of the stellar surface, mimicking the radial velocity of the whole star.

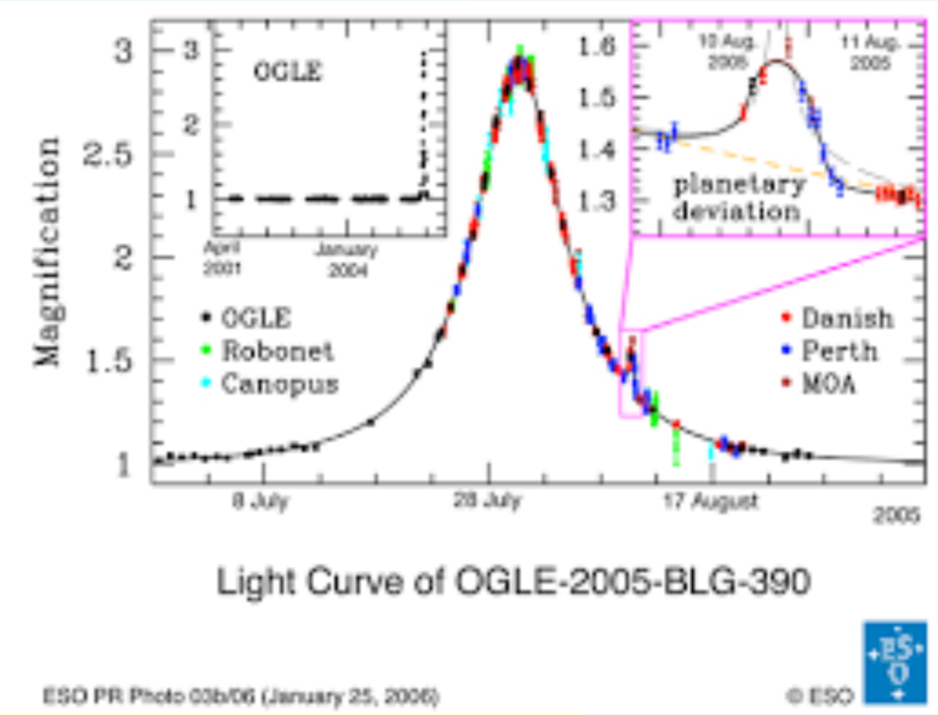


and methods of discovery:
Radial velocity (Doppler method)
Transits
Microlensing
Direct imaging
3 0 0 3 7 0 8 16 24 15 31 28 35 35 37 60 67 90 132 206 144 182 870 169 1534 216 361 214 243 208 315 11
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

Microlensing

= Using a star+planet as a gravitational lens.

Observations during the temporary, chance alignment of the planetary system with a far-away star always leads to the increase of brightness of the distant source/star.
The planet causes its separate little peak of brightness.

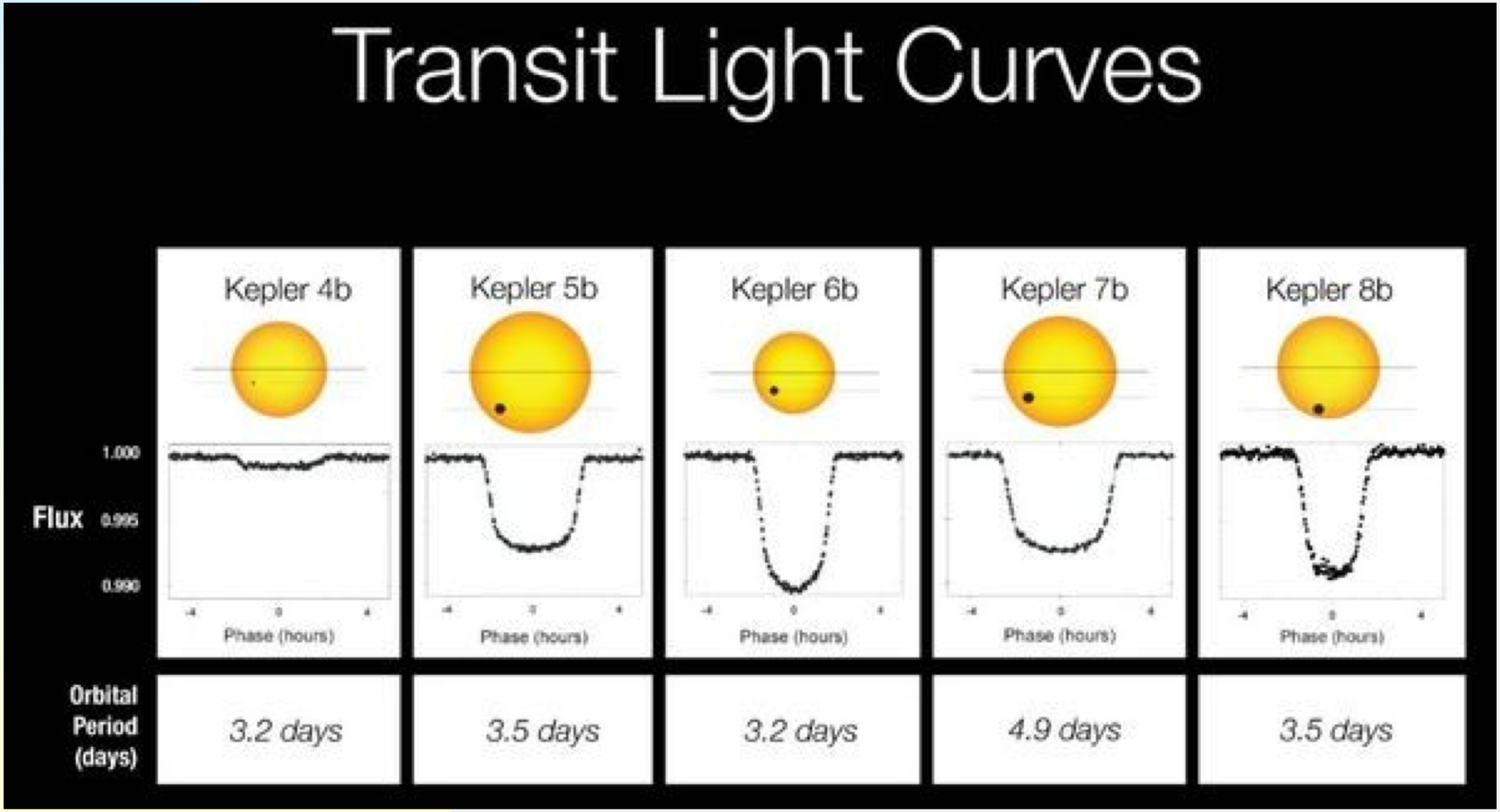


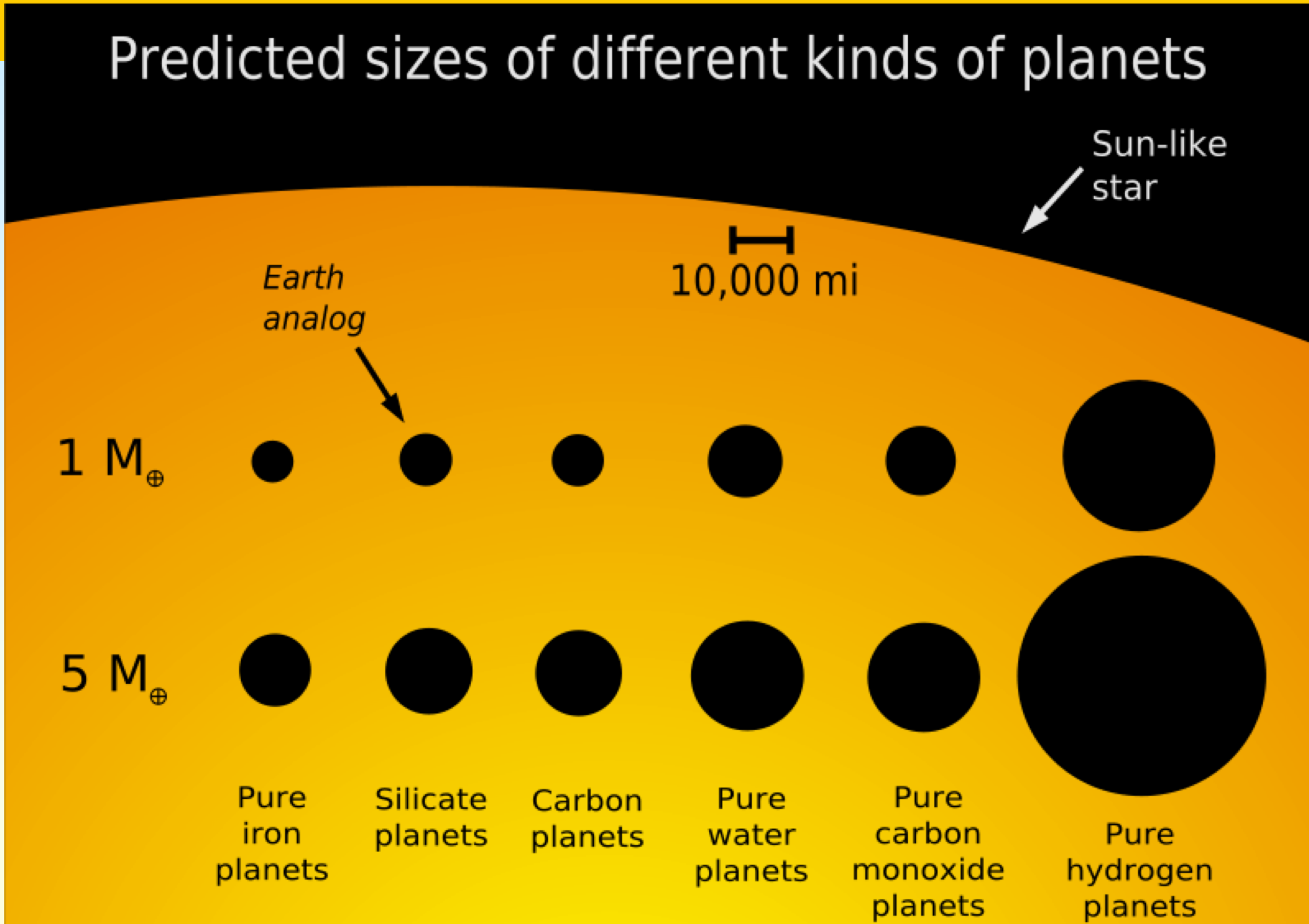
Light Curve of OGLE-2005-BLG-390

late 1990s: first microlensing planets found (the lensed image was of a star in the Galaxy center)

Microlensing transit does not repeat, it's a one-time observation.

OGLE is a collaboration using dedicated small Warsaw Telescope in Chile.


Transit Light Curves
Kepler 4b
Kepler 5b
Kepler 6b
Kepler 7b
Kepler 8b
1.000
Flux
0.995
0.990
Phase (hours)
Orbital Period (days)
3.2 days
3.5 days
3.2 days
4.9 days
3.5 days

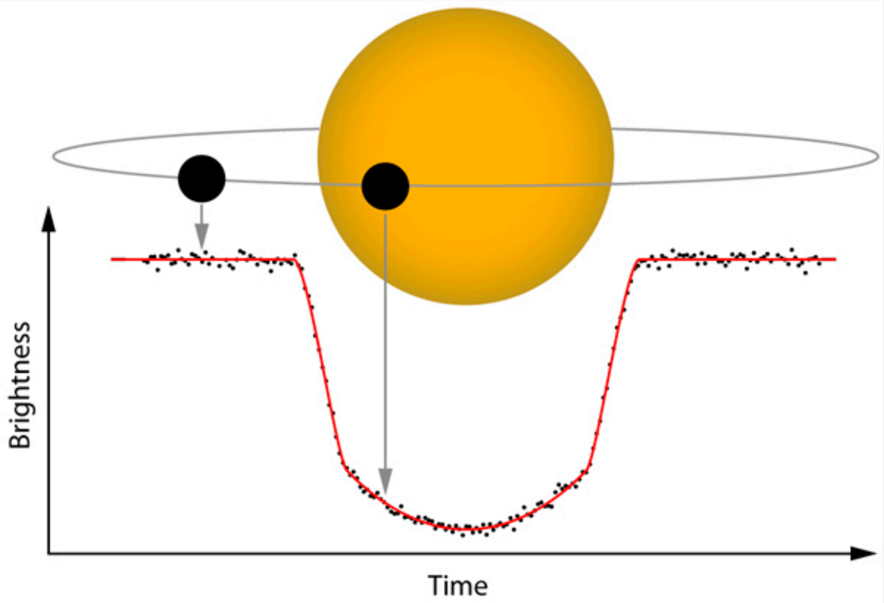


If the planet blocks 10^{-4} to 10^{-2} of the star's light, then it is about 10^{-2} to 10^{-1} times the radius of the star (area ~ radius^2).

Star-planet distance and star-Earth distance are of no importance.

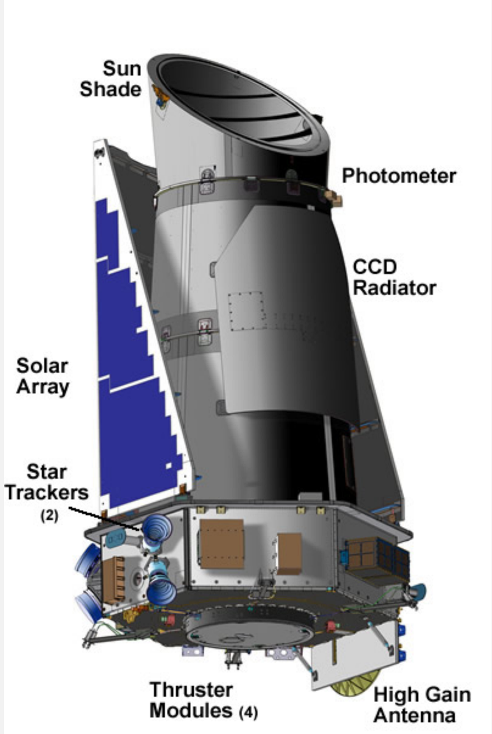
2000s: transit discoveries (stellar partial eclipses)

WASP 10b giant planet

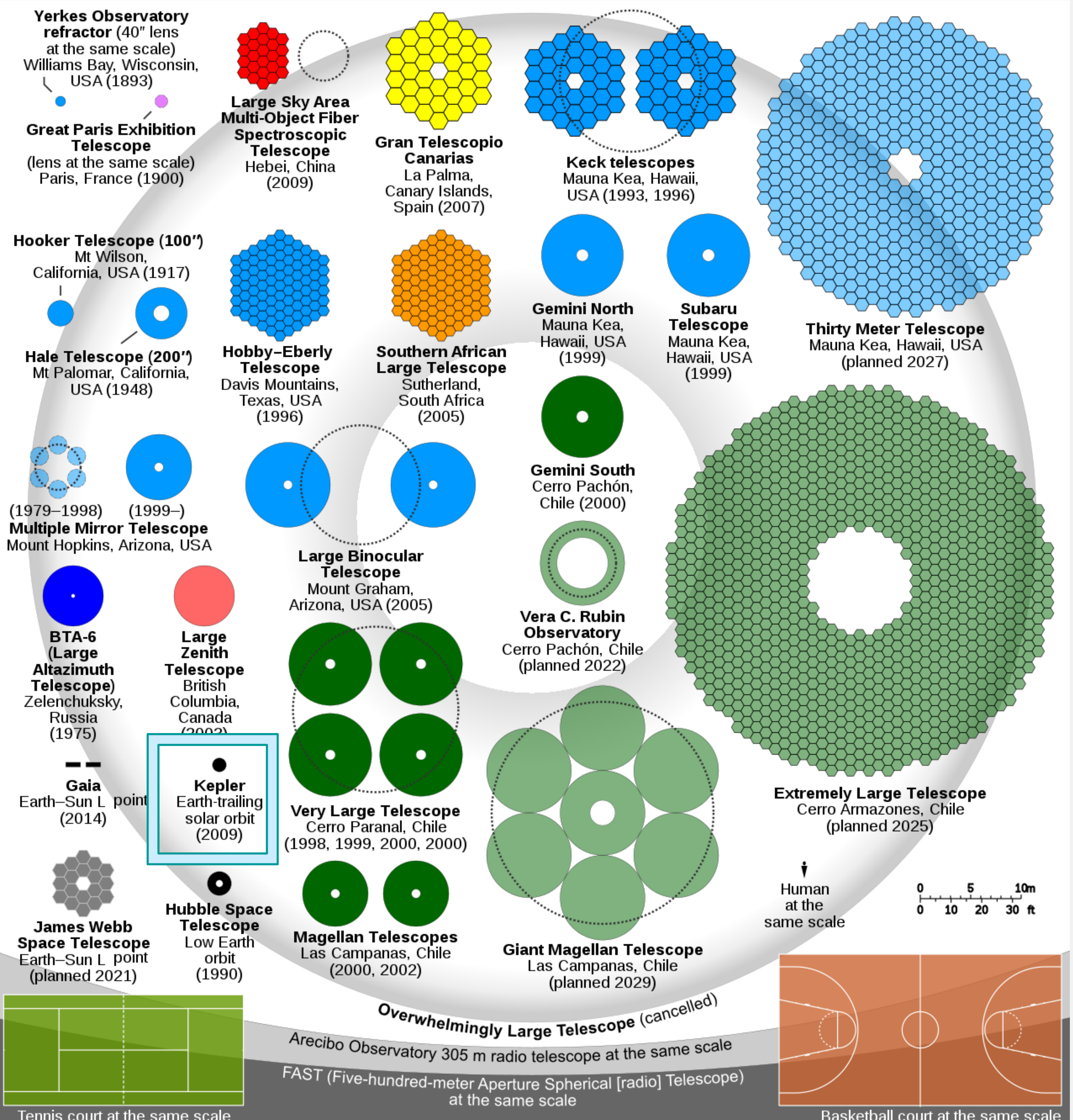


Method's advantage:

Telescopes used for transit studies do not have to be very large



KEPLER: satellite observatory to find transiting Earth-like exoplanets



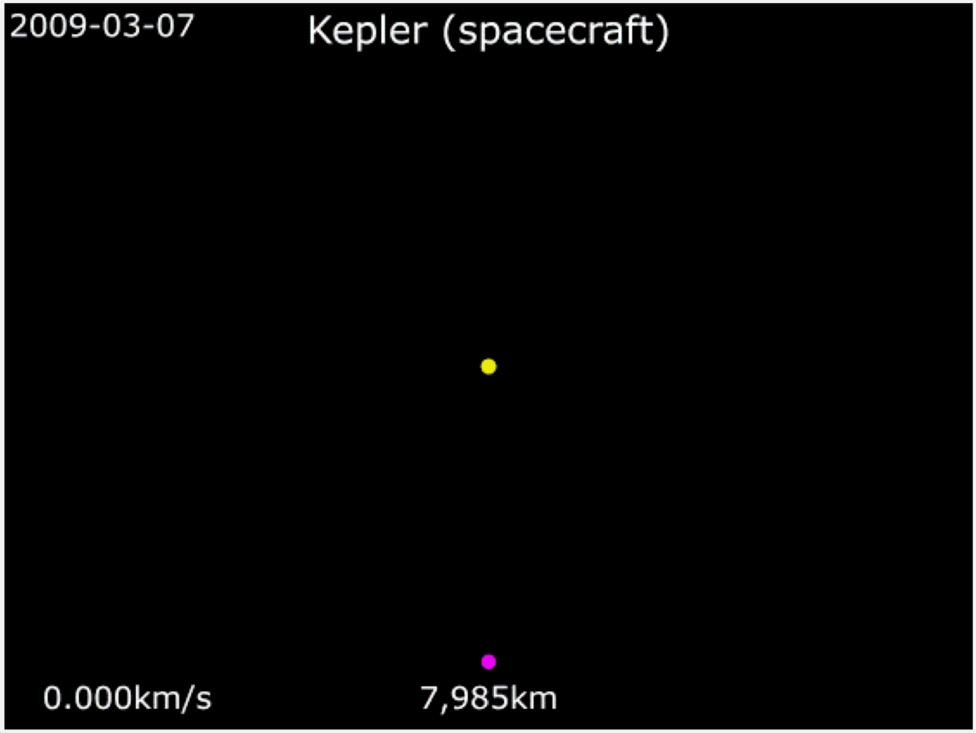
TELESCOPES in 2021

- sensitivity
- angular resolution
- spectral resolution

>2000 exoplanets were found by the Kepler space observatory (2009-2016)

Kepler space telescope
0.95 m diameter

cost $650m

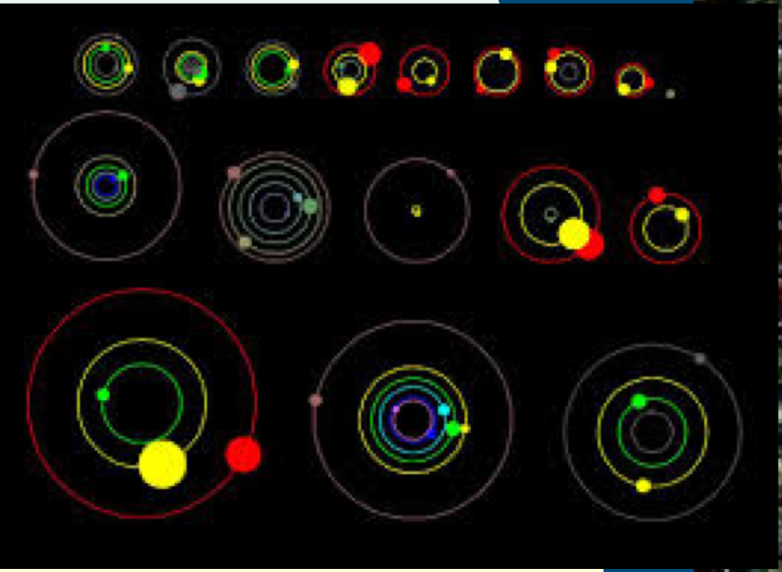


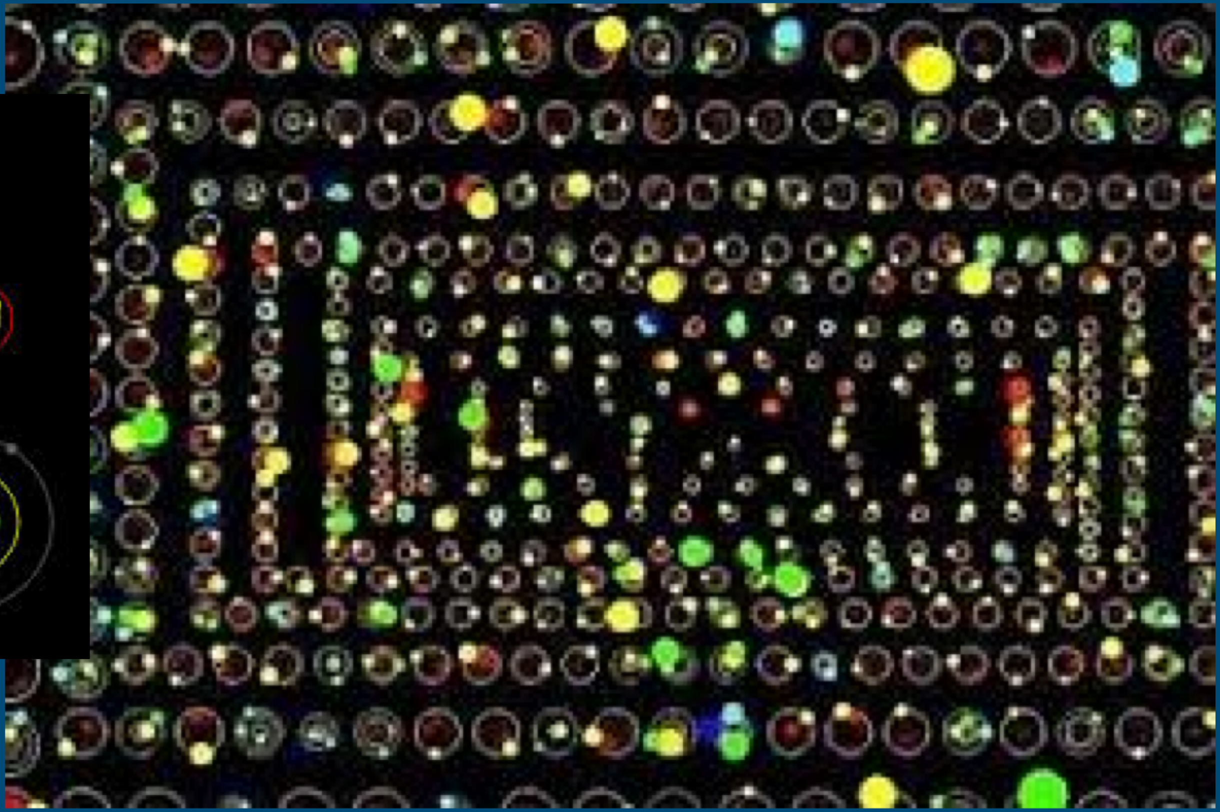
This NASA observatory was launched in 2009 and functioned OK for 3.5 yrs, and then a bit crippled for another 5.5 yrs (2/4 reaction wheels failed). It could find the size but not the mass of thousands of transiting exoplanets.

EXPLORATION OF SOLAR AND EXTRASOLAR SYSTEMS – 21st CENTURY

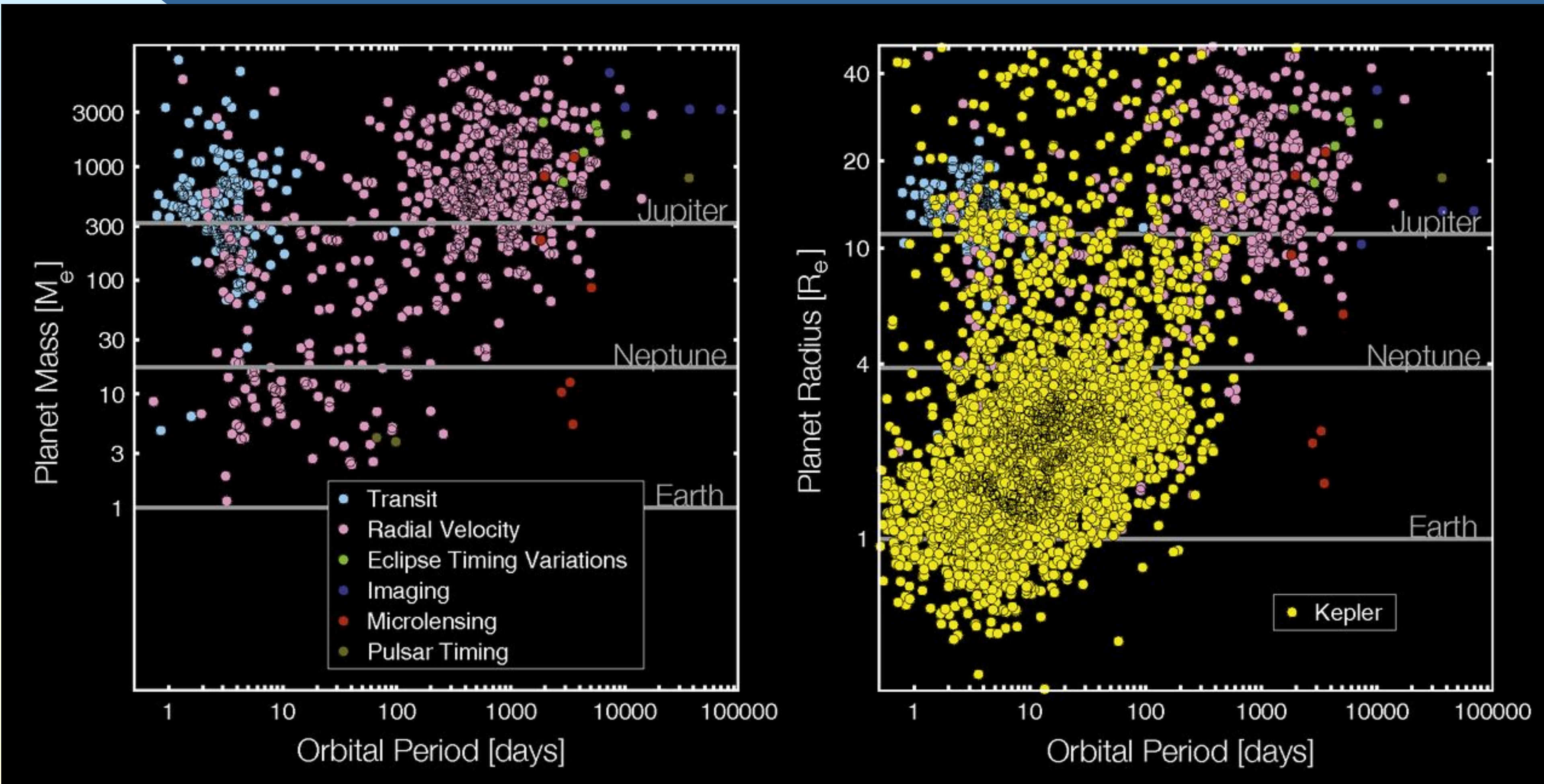
Kepler and Kepler2

(2nd phase of operation) discovered thousands of planetary systems





Kepler’s planets. Statistics.



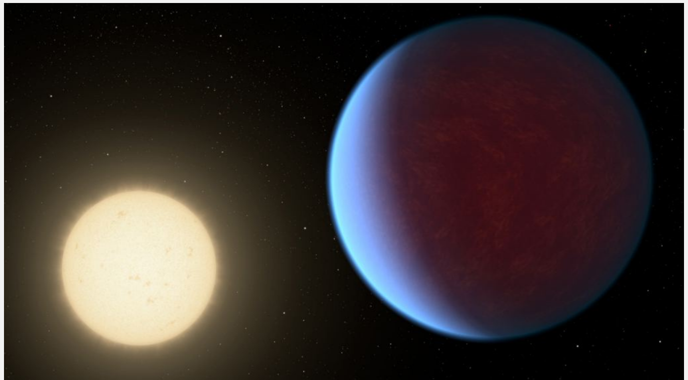
This nice diagram shows how many planets Kepler telescope (2009-2016) has found, and that only could find the physical radius (but not the mass) of a planet ***close to its star*** https://www.universetoday.com/138017/two-new-super-earths-discovered-around-red-dwarf-star/

In 2018 UTSC announced a work of a PhD student Ryan Cloutier and his collaborators from U. of Montreal.

They have measured radial velocity curve of K2-18b (a planet discovered as transiting before by Kepler K2 mission) and also found a 2nd non-transiting planet on inclined orbit.

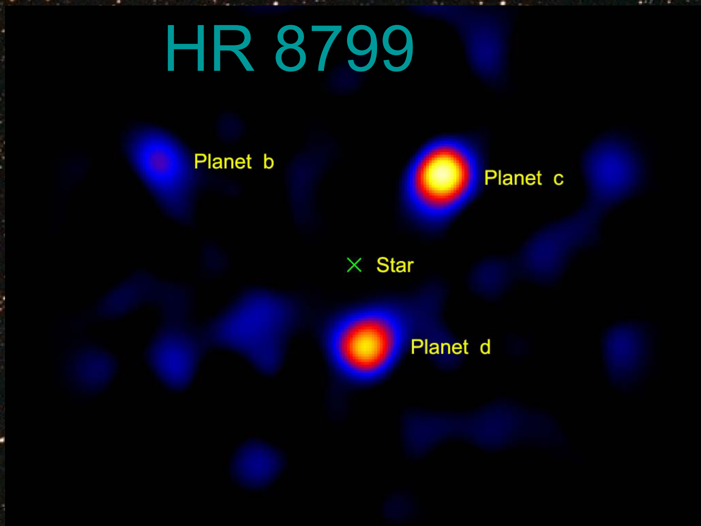
The K2-18b planet has 8 ± 1.9 Earth masses, and is either a rocks+gas planet or a water-world. Mid-IR Spitzer space telescope found H_2O signature. Density = 3.3 ± 1.2 g/cm^3. Finding density is a great advantage of the combined use of v_r and transits.

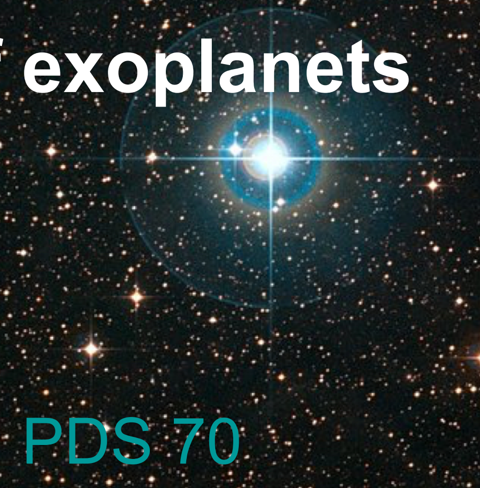
K2-18c is 7.5 ± 1.3 Earth's masses and 2.4 times closer to the star than K2-18b. It's period is 9 days, so it is a pretty warm super-Earth with currently unknown density. Some publications treat is as a still unconfirmed tentative signal, which may due to stellar activity.

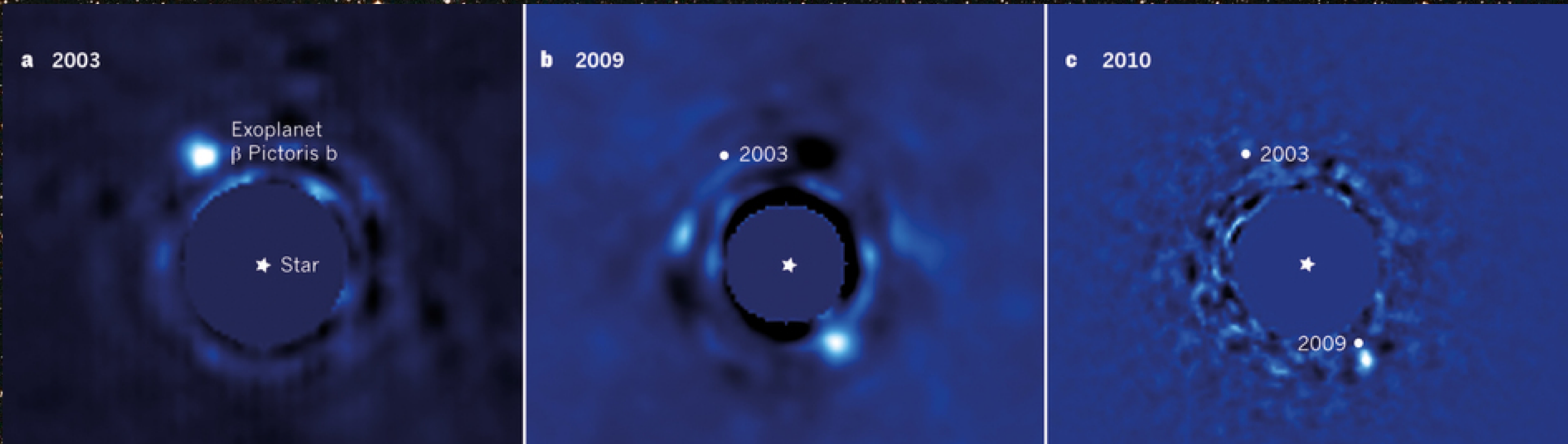


The star K2-18 is type-M dwarf, 0.82 $M_{\odot}$

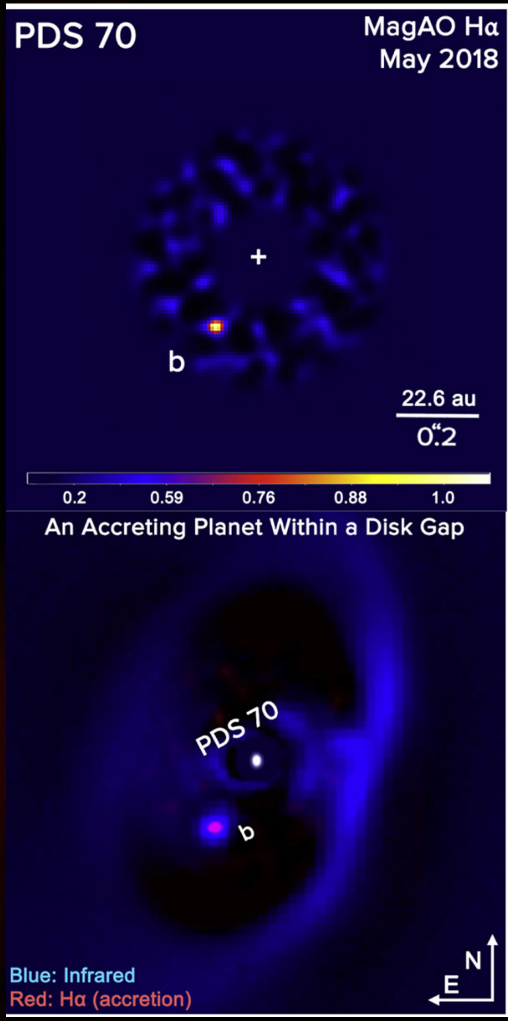
Direct imaging of exoplanets



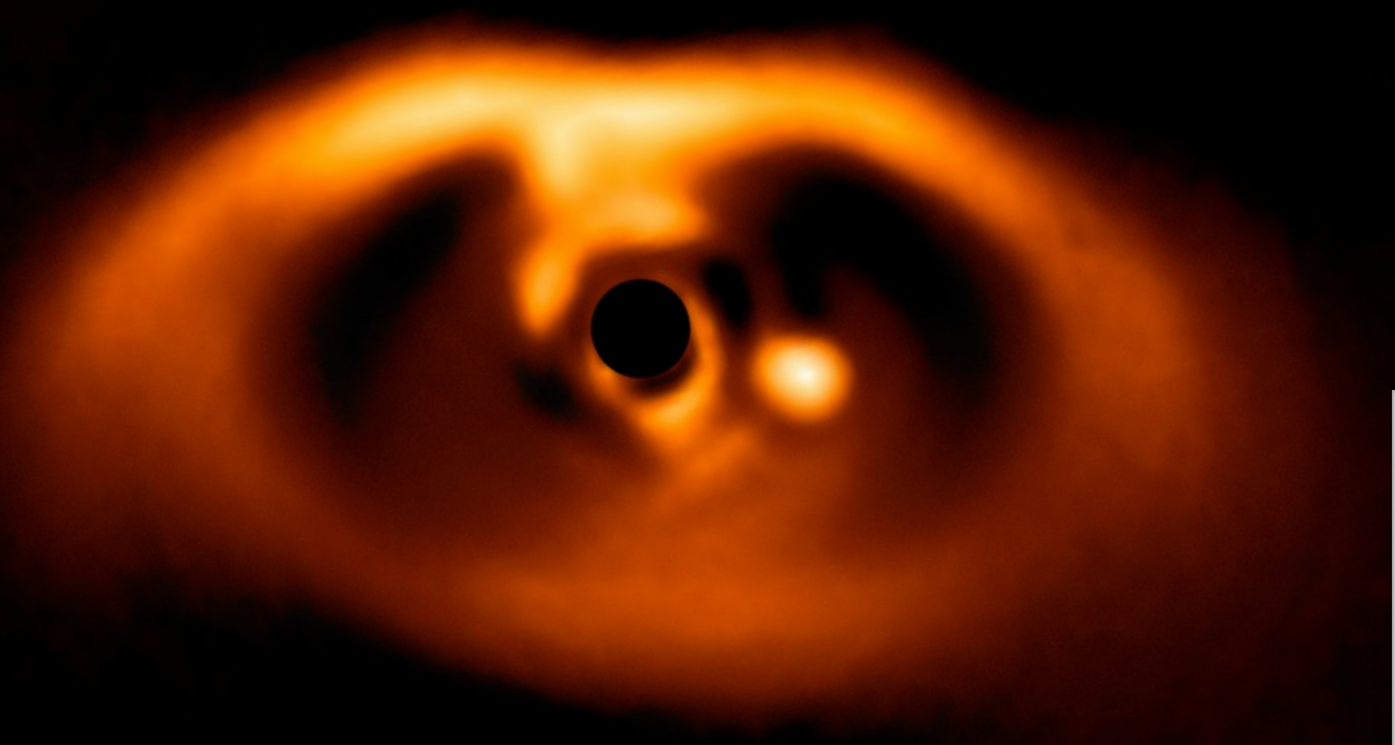


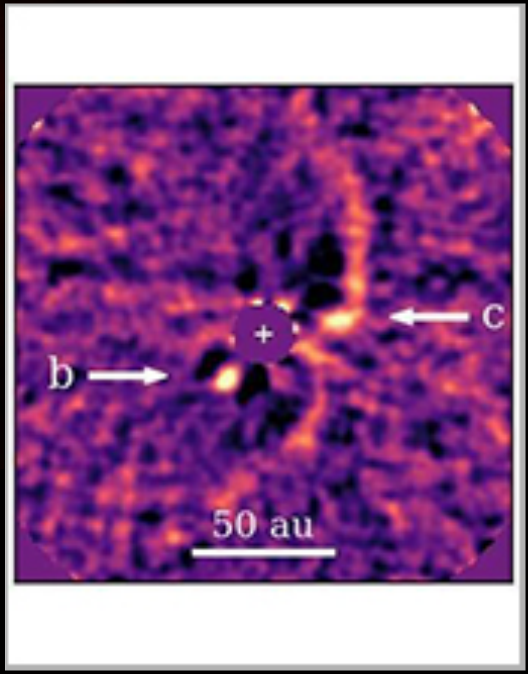


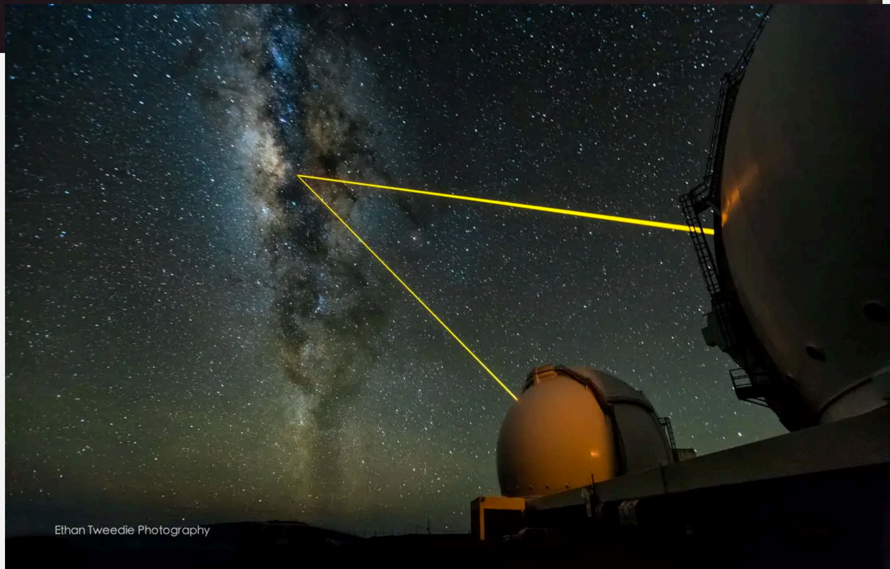
Newly formed giant planet in a disk gap of a T Tau star PDS 70 (discovered at ESO in 2018)



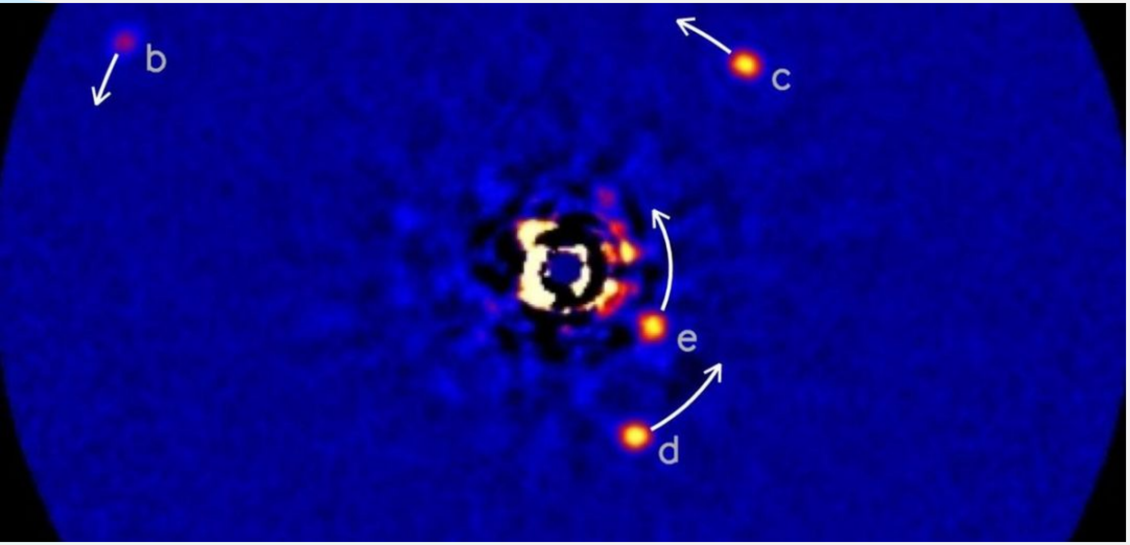
Or... newly formed *TWO* giant planets in a disk gap of PDS 70?
Different interpretations have been proposed.

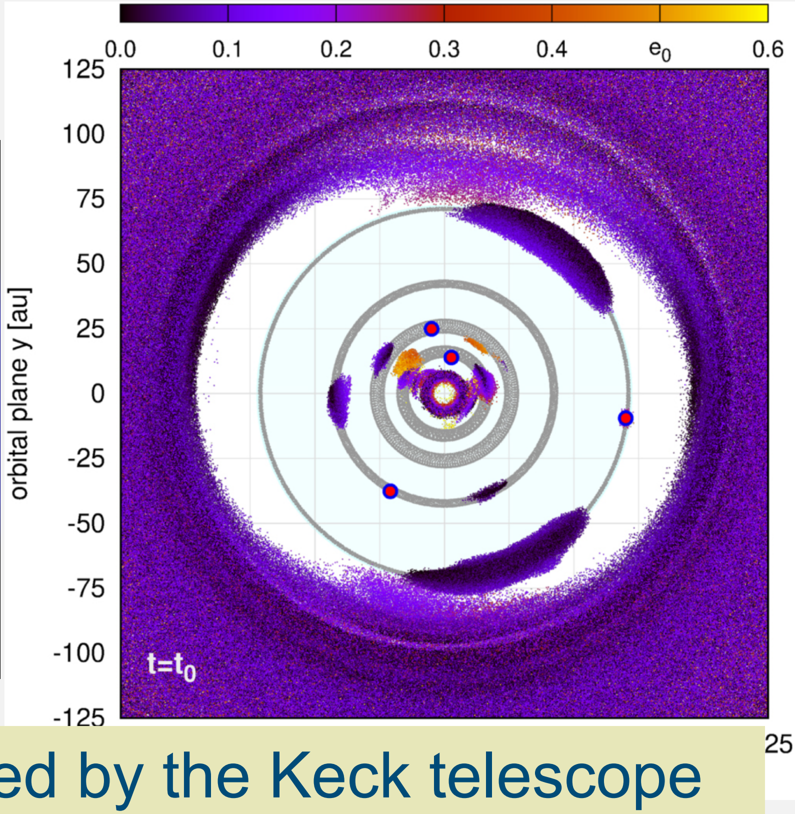






W.M. Keck telescope pair on Mauna Kea, Hawaii - the largest & one of the best multi-mirror telescopes,
36 hexagonal units making a 10 m mirror ea. Weighs 300 tons, but operates with nm precision (mirror’s shape and position must be < wavelength)

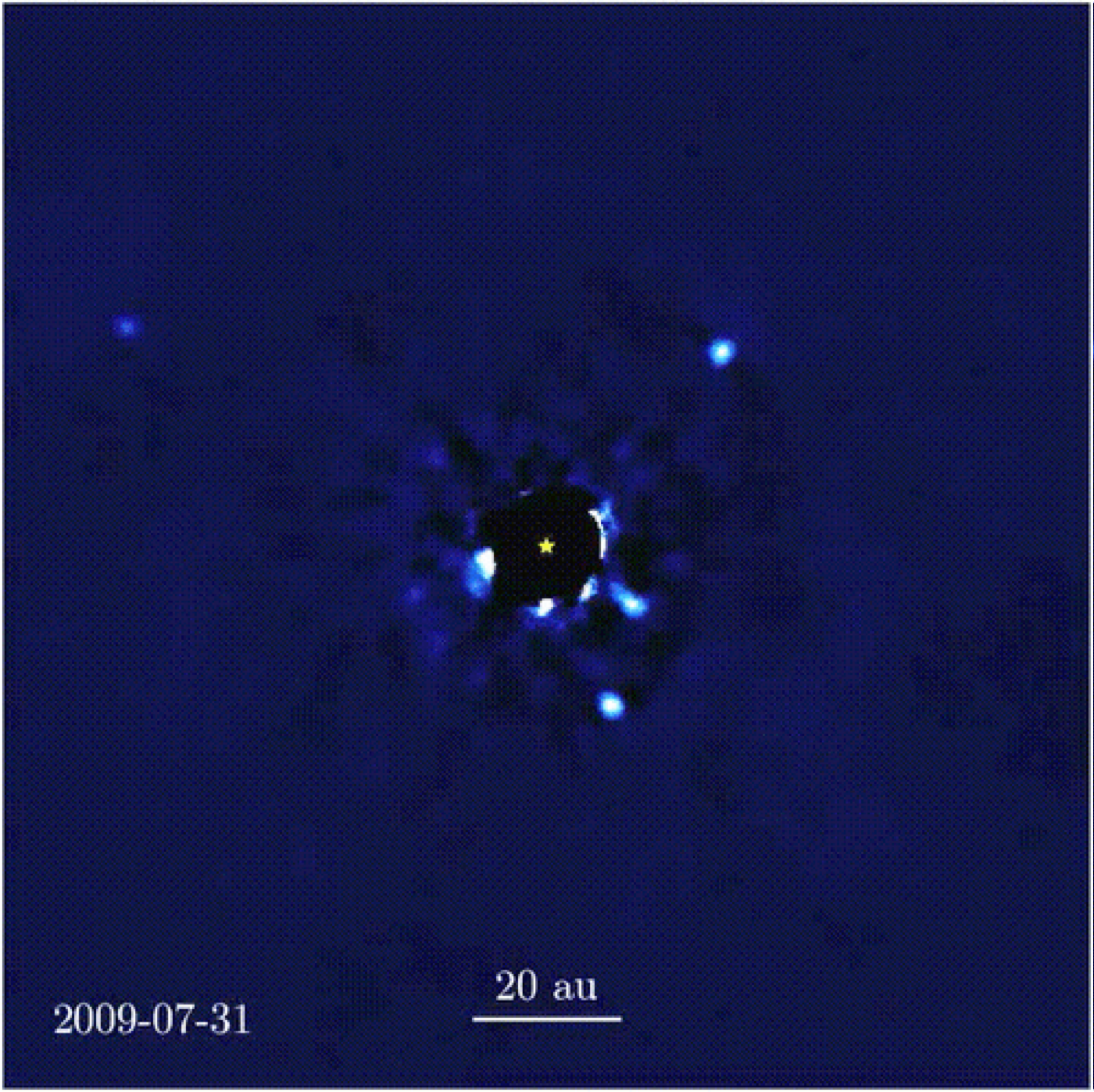




HR 8799 system of four planets, imaged by the Keck telescope and modeled as interacting with a dusty planetesimal disk.

This system was imaged because of its wide orbits (it is very hard to see planets closer to the stars than ~10 AU (for typical stellar distances > 20 pc).

Some early simulations suggested it may be unstable dynamically. More recent studies suggest a 8:4:2:1 mean-motion resonance. (Io, Europa and Ganymede are in 4:2:1 MMR.)

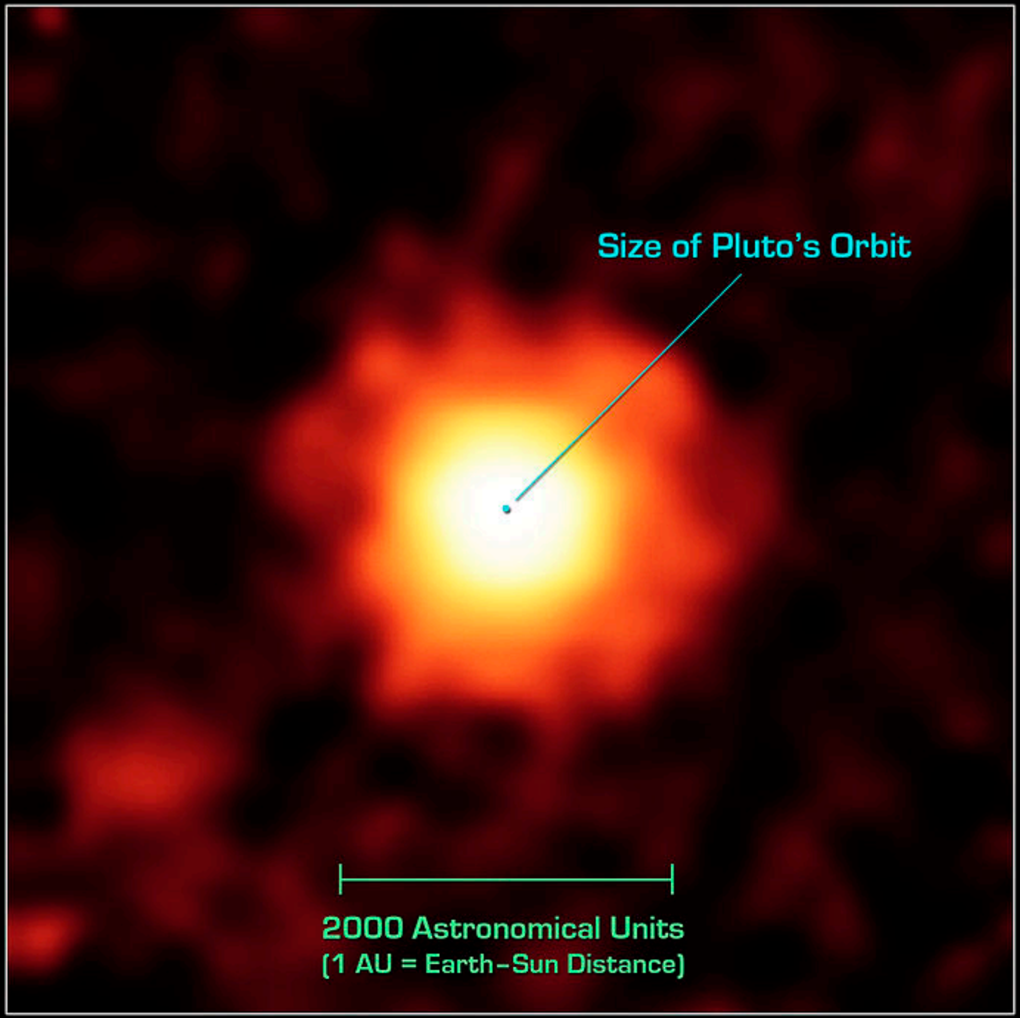


HR 8799

four planets discovered by imaging

40 pc away in Pegasus

20-50 Myr old ϒ Dor star (pulsating) and λ Boo star (lower iron-group abundances)



Debris Disk around Star HR 8799
Spitzer Space Telescope • MIPS

NASA / JPL-Caltech / K. Su (Univ. of Arizona) sig09-008

IR imaging reveals that HR 8799 has a disk of dust, which implies asteroid collisions and dust release from comets in this system.

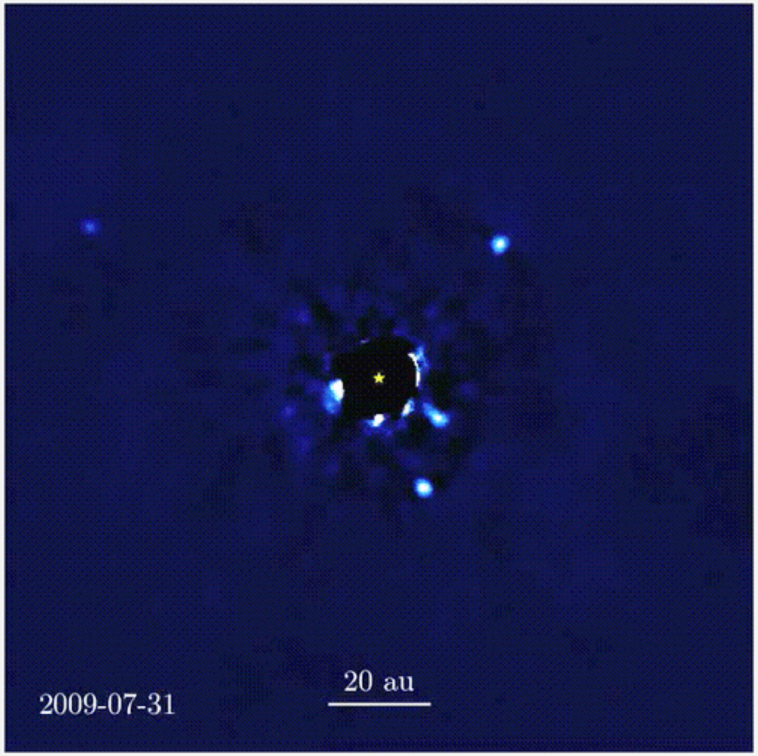
So this planetary system is like beta Pic or Vega,

or like the Solar System when it was less than 50 Myr old.

HR 8799 planetary system (age 20-50 Myr). The star is a blue-ish, 1.47 $M_\odot$, 4.9 $L_\odot$ main-sequence star of type F0 (or A5 when looking at metal lines).

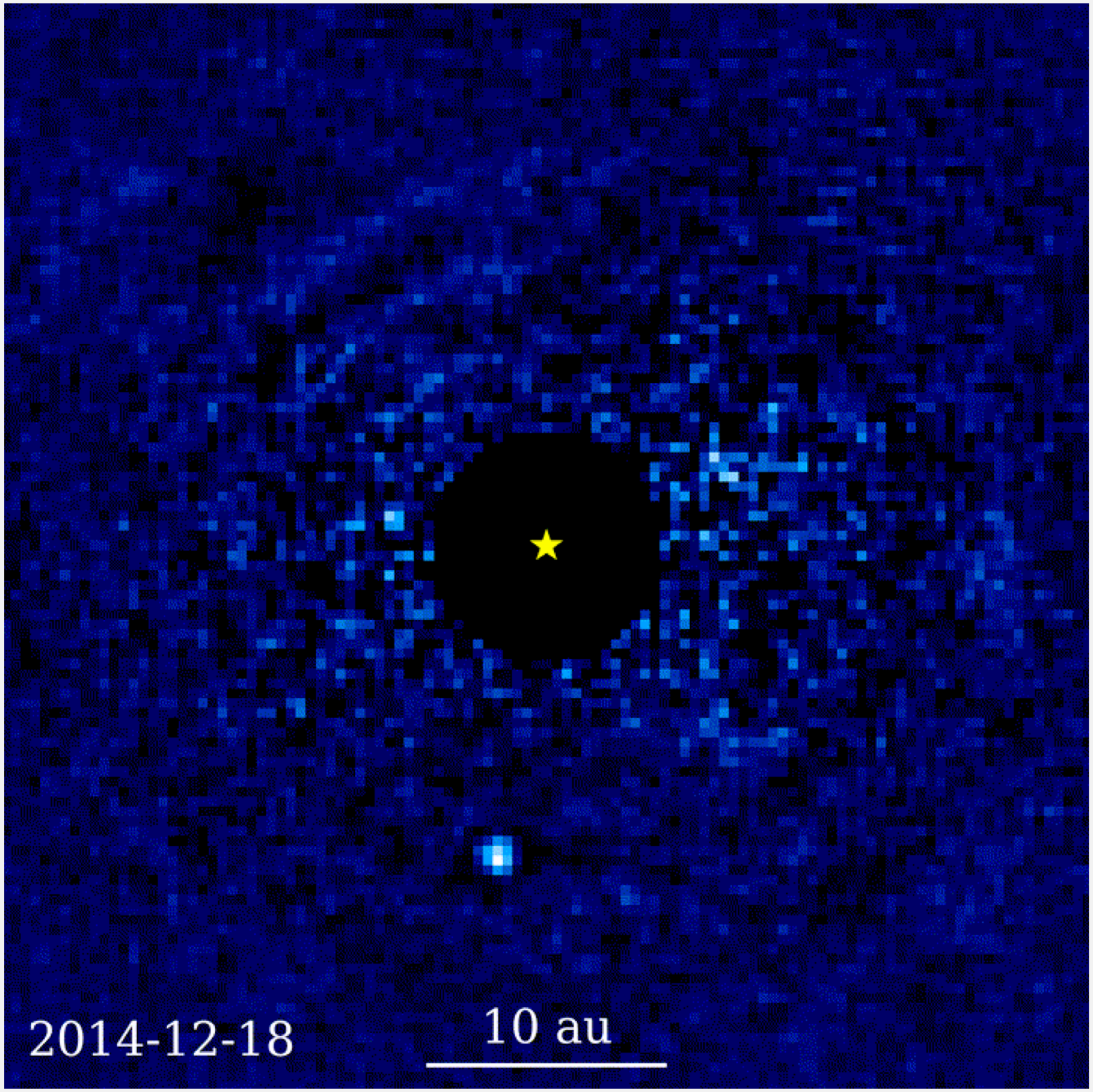
Planet	Mass	a(AU)	P(yr)	*e*	*i*	Radius (R_J)
e	7.4±0.6 M_J	16.25±0.04	~45	0.1445±0.0013	25±8°	1.17+0.13−0.11
d	9.1±0.2 M_J	26.67±0.08	~100	0.1134±0.0011	28°	1.2 +0.1−0
c	7.8±0.5 M_J	41.39±0.11	~190	0.0519±0.0022	28°	1.2 +0.1−0
b	5.7±0.4 M_J	71.6±0.2	~460	0.016±0.001	28°	1.2 +0.1−0.1
Dust disk		6–1000				

The 4 planets are red-hot due to their young age (have not yet cooled down)

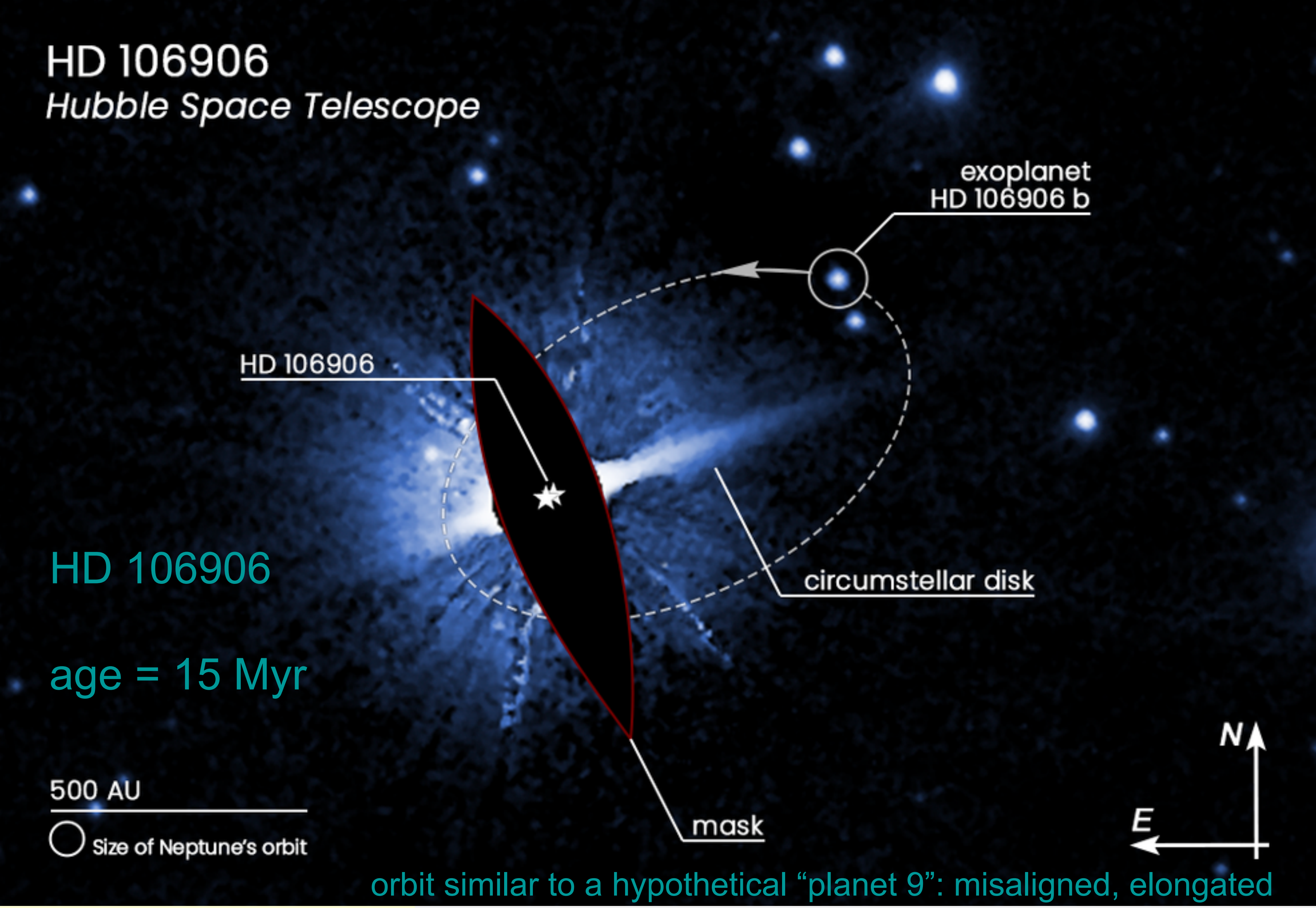


Another imaged planet: 51 Eri b (51 Eridani b)

The star is 1.75 $M_{\odot}$, 1.45 $R_{\odot}$, 6.7 $L_{\odot}$ F-type, member of a moving β Pic group, thought to be 20 Myr old.



The planet is a bit larger than Jupiter:
mass = 2.6±0.3 M_J,
radius 1.1 R_J



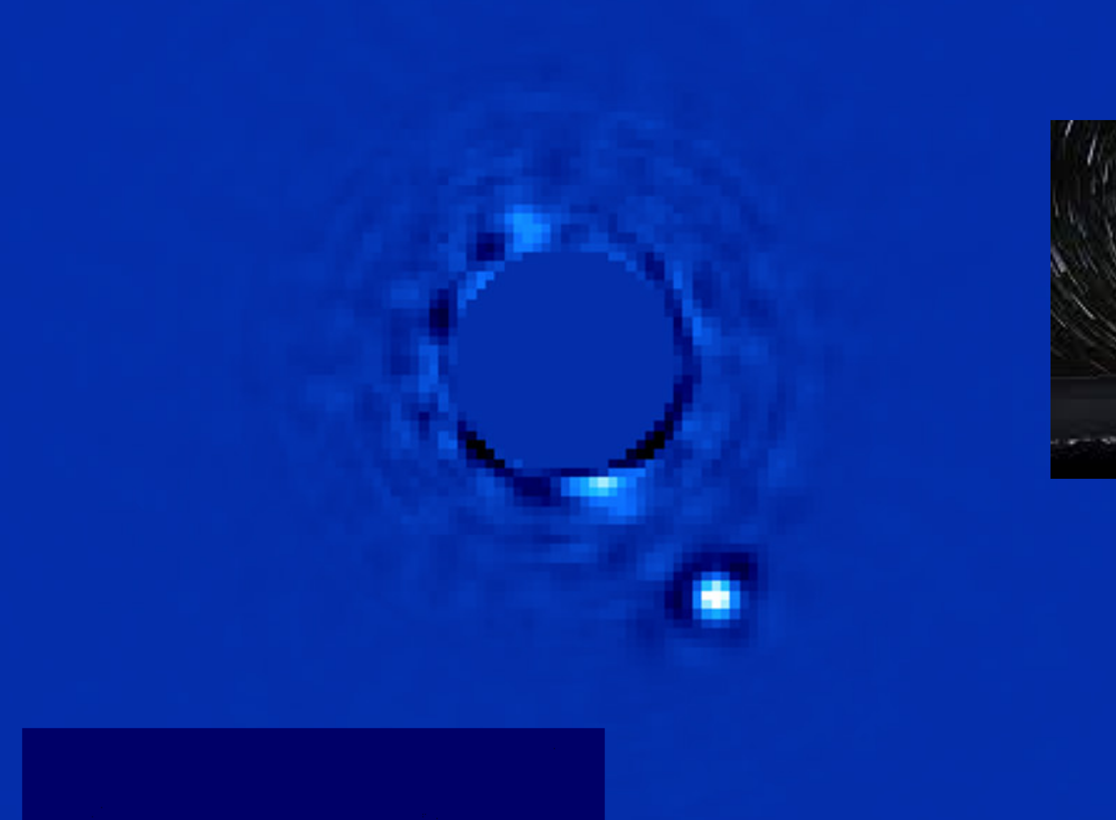
HD 106906

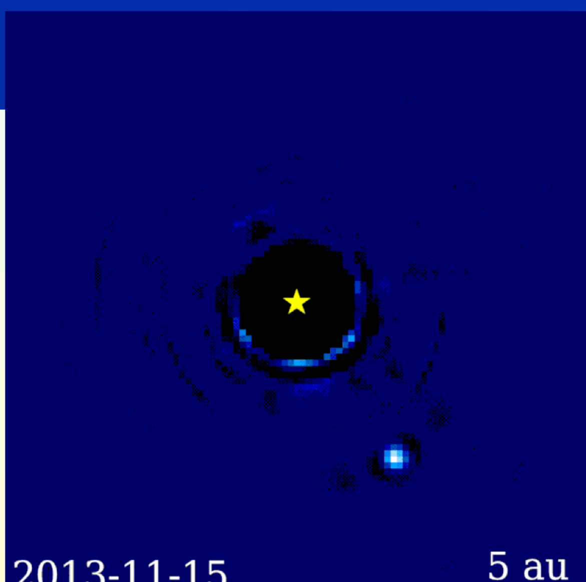
age = 15 Myr

orbit similar to a hypothetical “planet 9”: misaligned, elongated

$m_p = 11\ m_J$

one of the possible orbits around this double star (dashed)





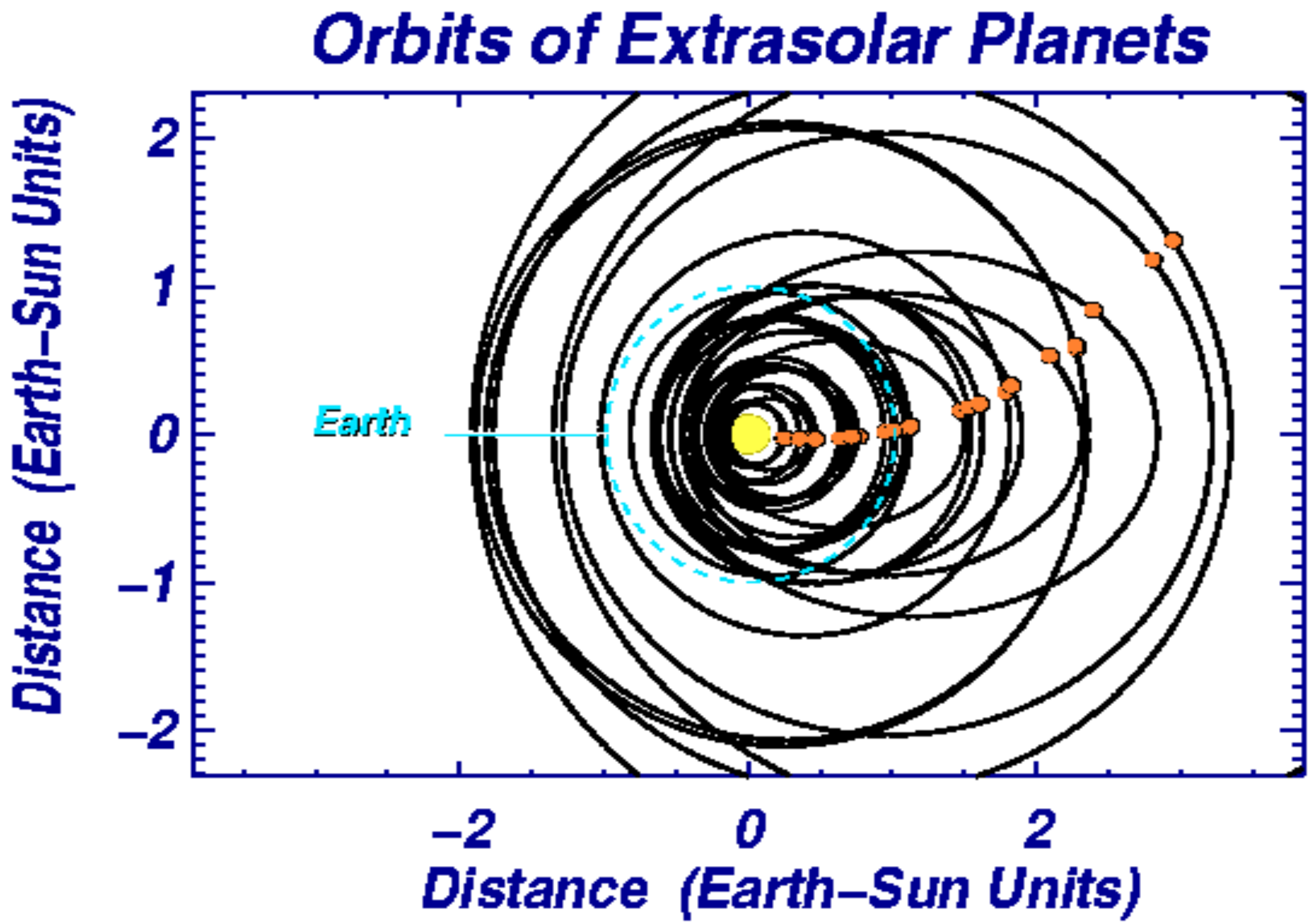
β Pic planet

see nice animations
of observations of b Pic
and 51 Eri in 2013-2018
on wiki or our course page

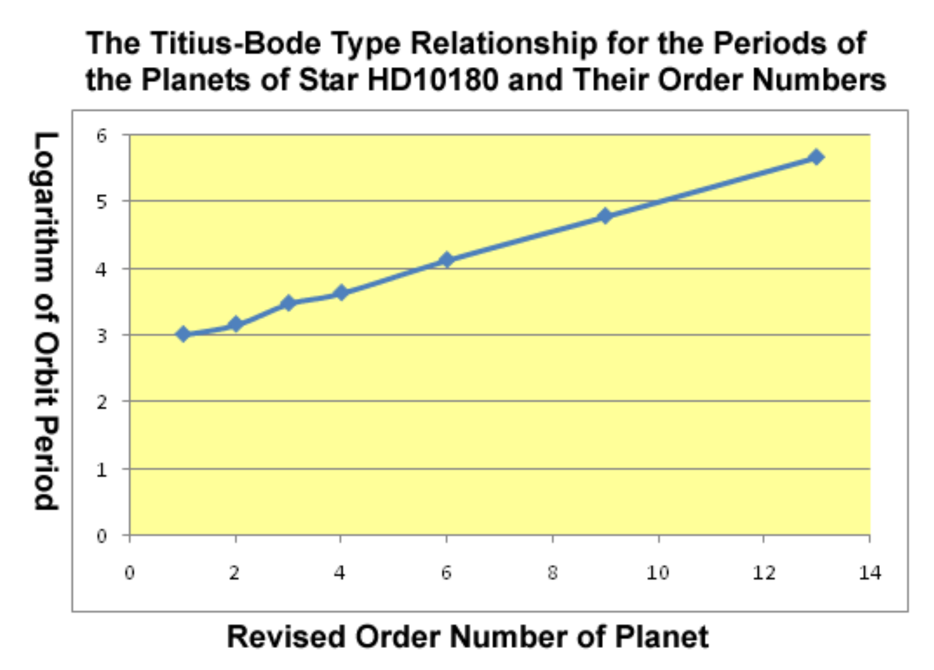
imaged by Gemini Planet Imager on
Cerro Pachon mountain in Chile (8 m)

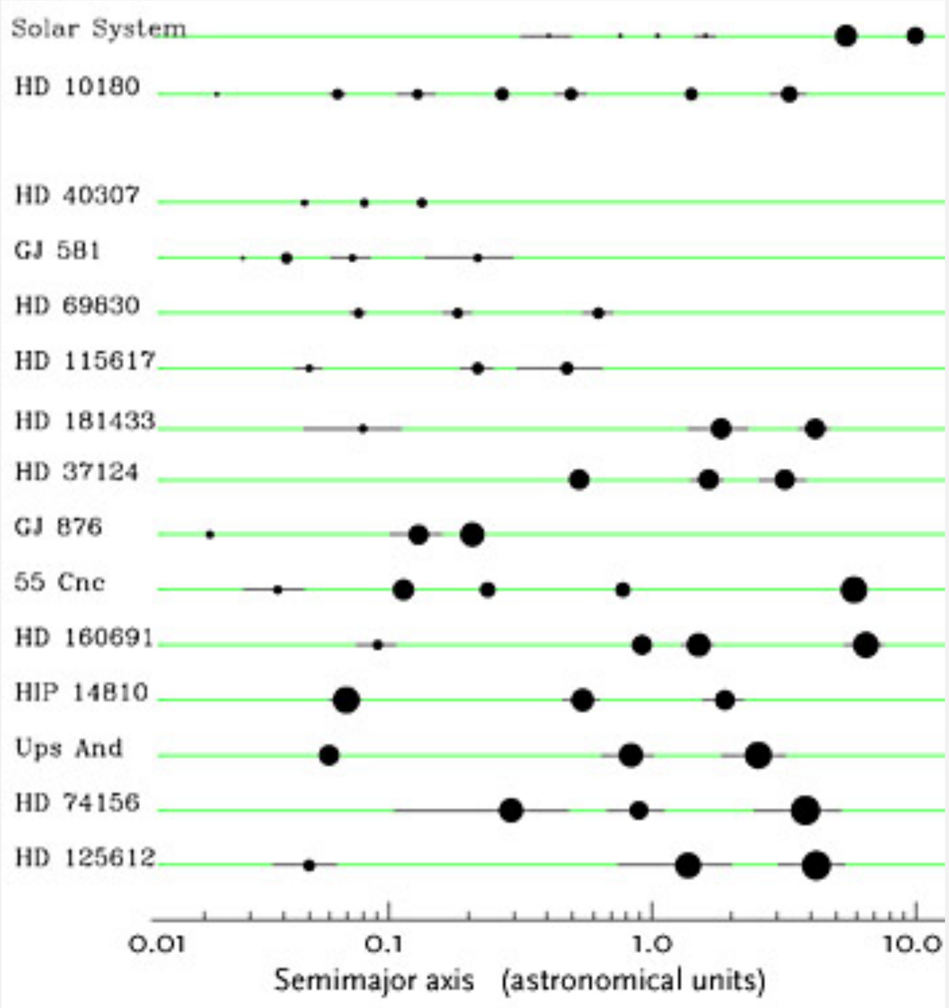
Regularities found:
Noticeable eccentricity is quite common

Exoplanet orbits superimposed in one plot, made to scale:

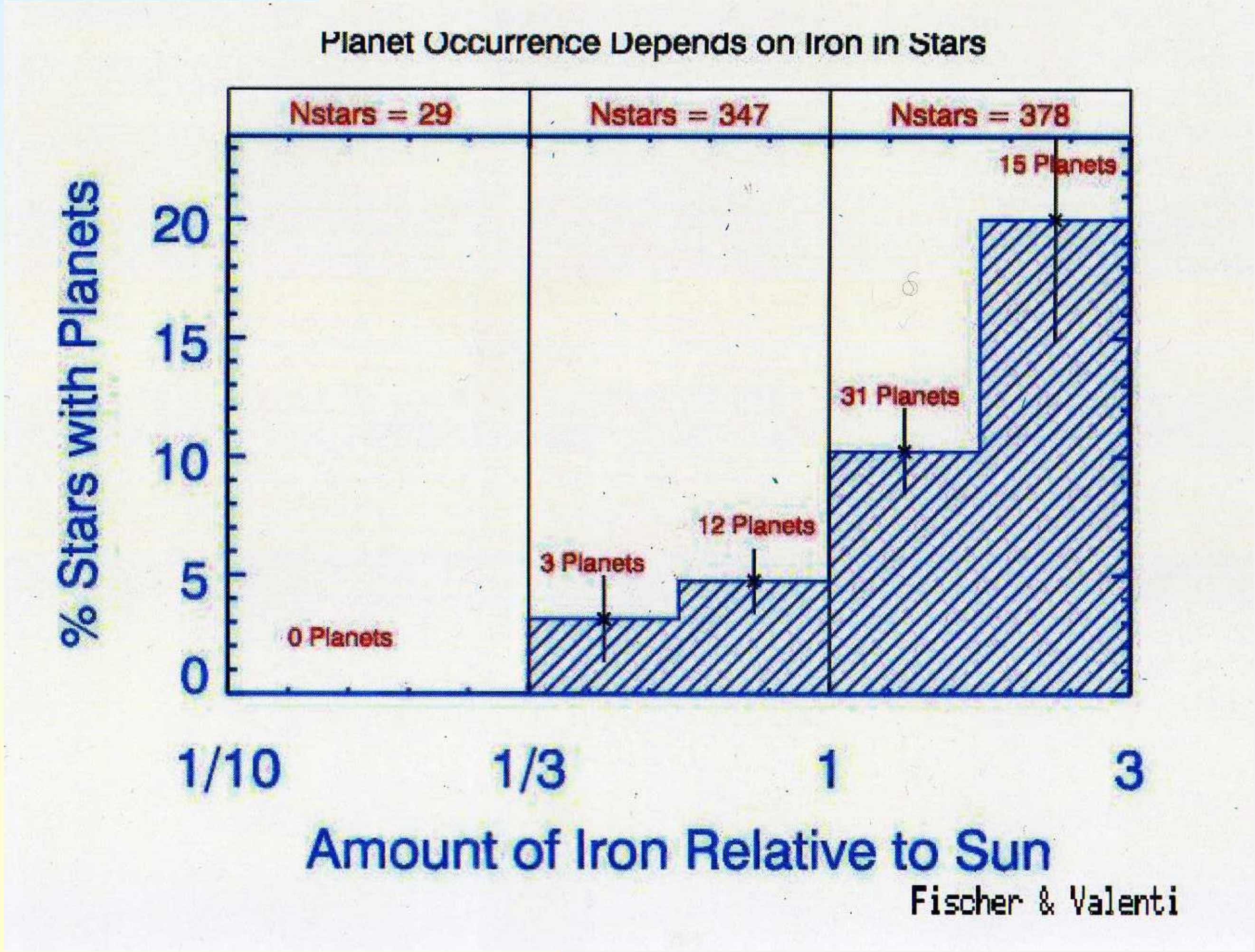


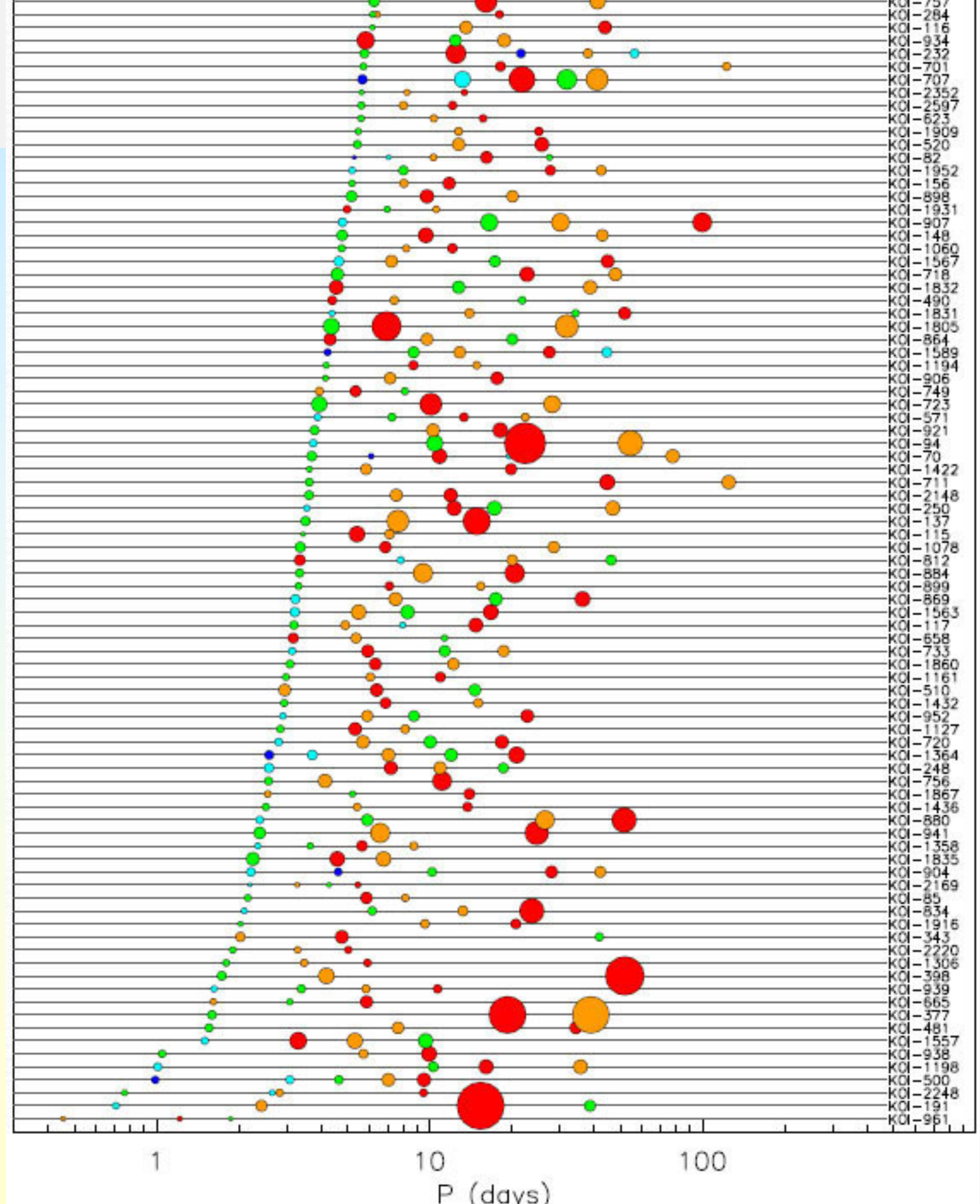
Titius-Bode-like rules (e.g., $r_n \sim 1.73^n$) are obeyed by some exoplanetary systems. Some other systems are resonant – planets show commensurabilities of orbital motion periods





Regularities found:
stars of higher metallicity have more planets





We have found that:

Planetary systems are common

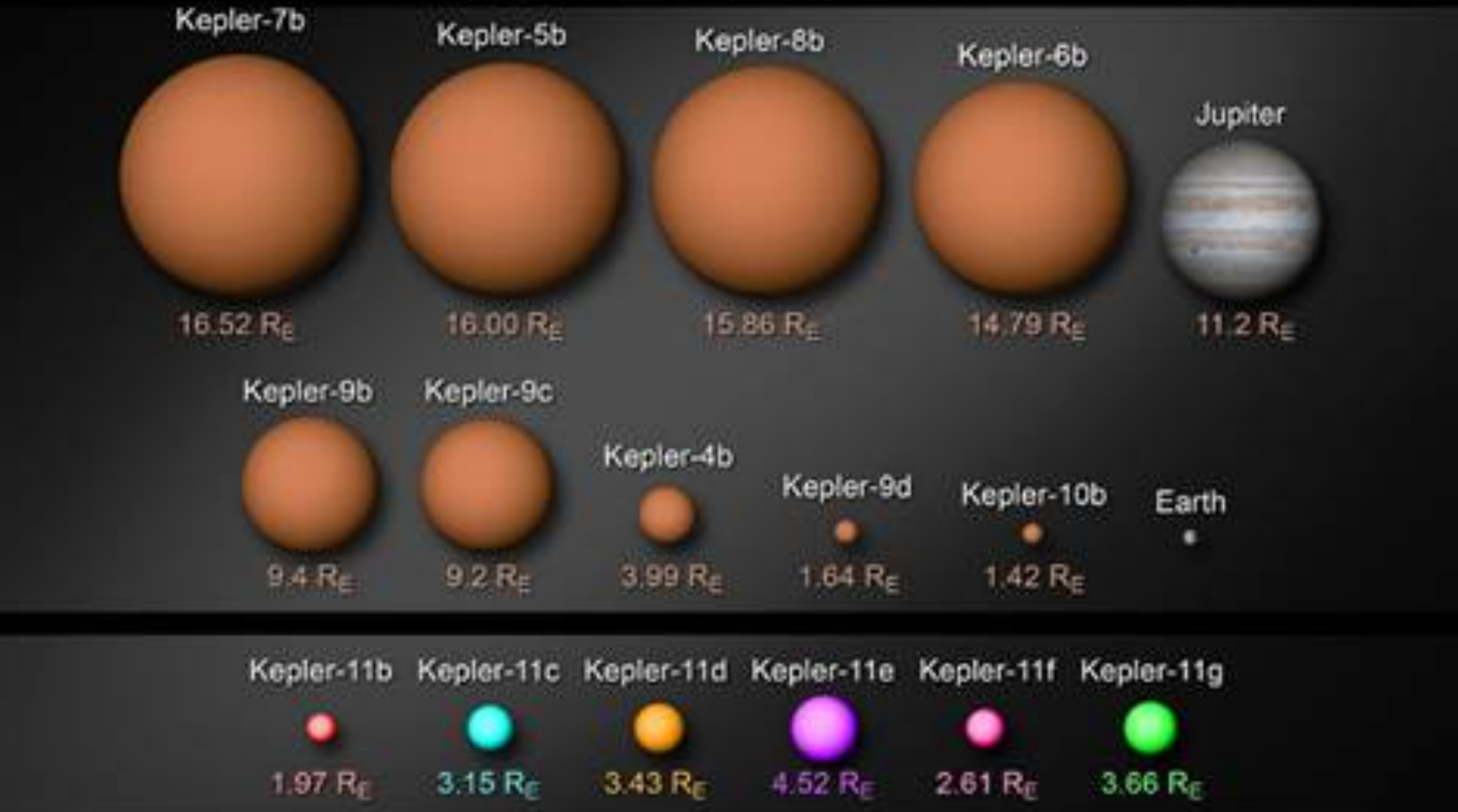
There is about 1:1 star:planet frequency in the universe

Multiplanetary systems are common too

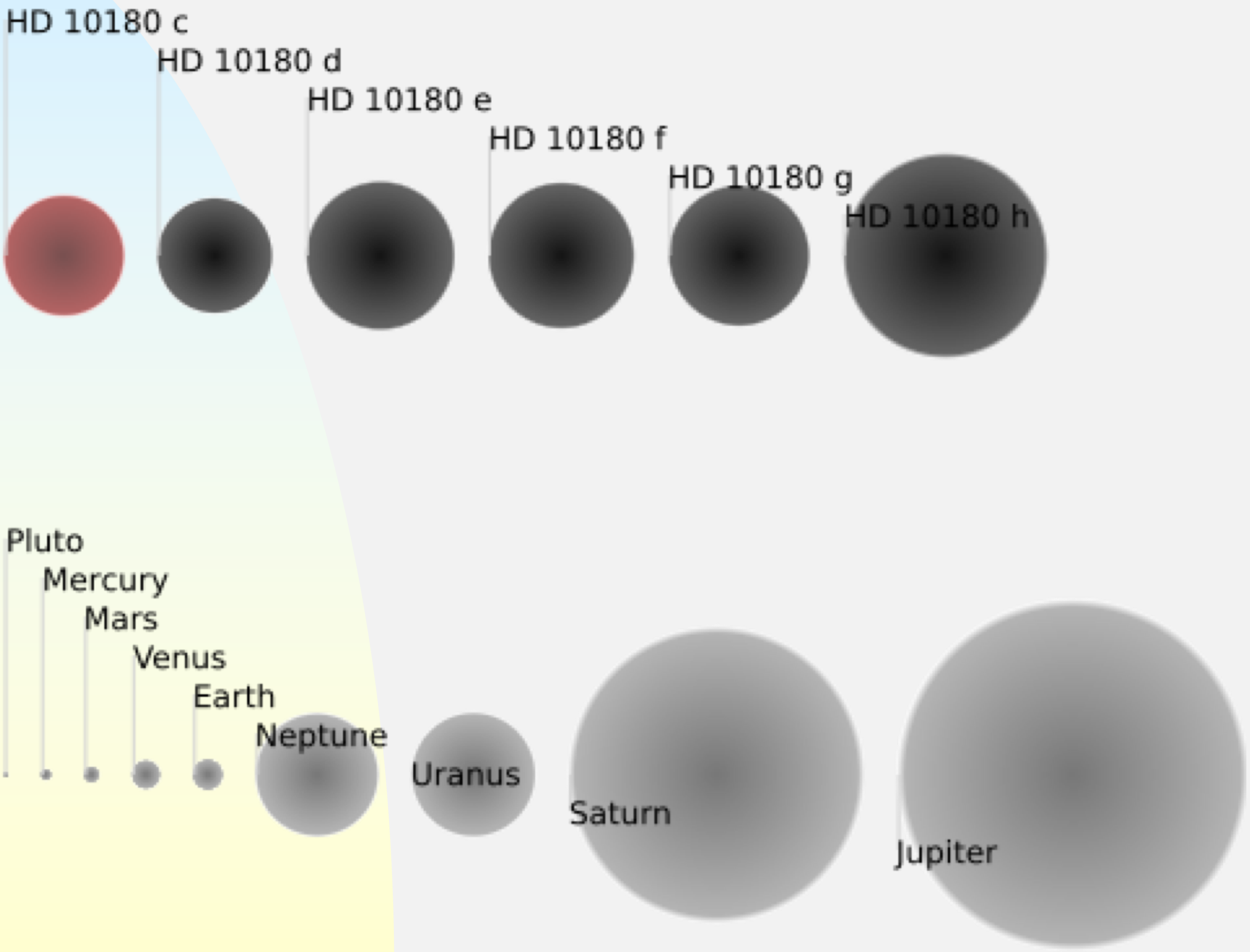
KOI - Kepler space observatory planets

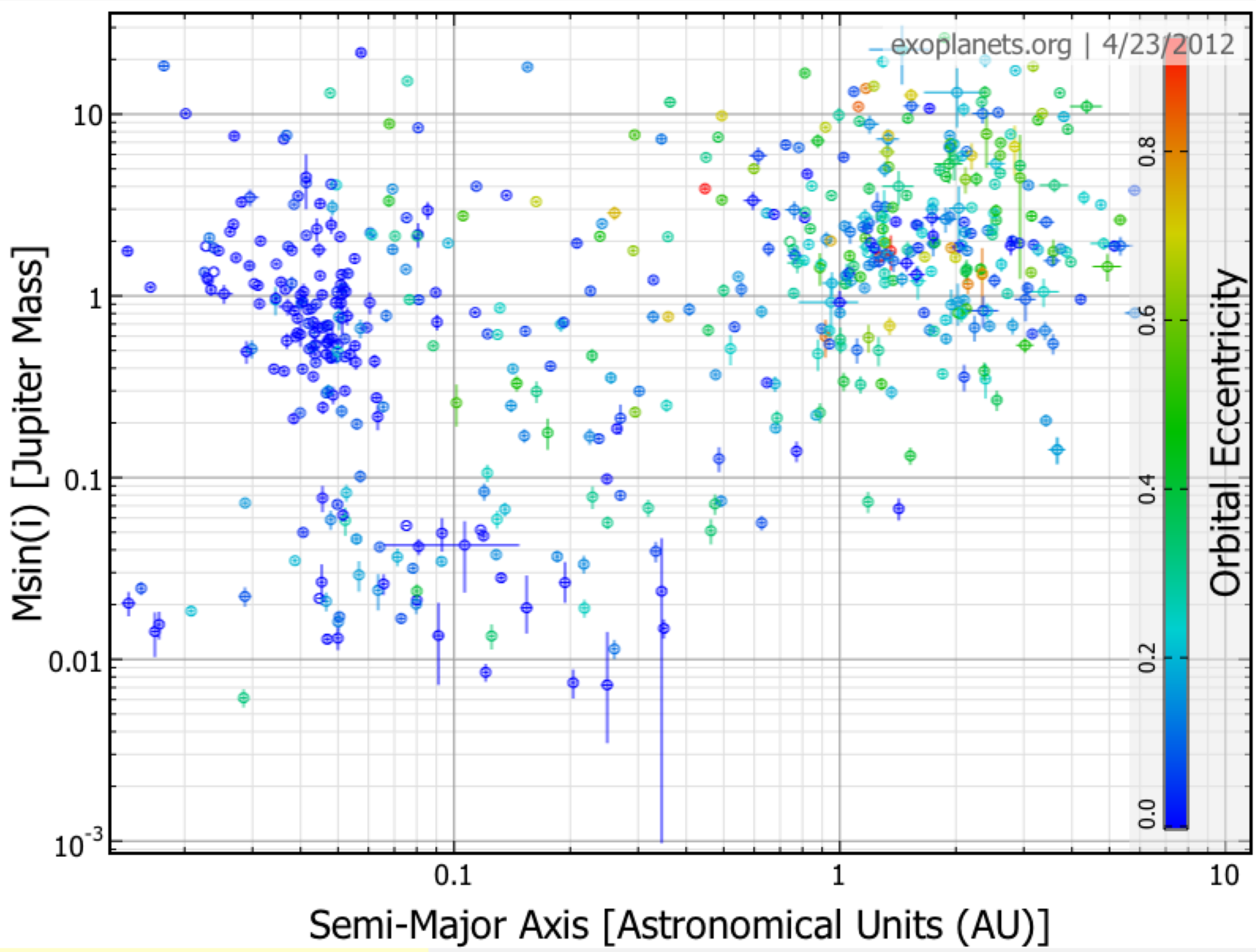
(OI = Objects of Interest, before confirmation)

Planet Sizes



HD 10180 – system of 9 planets (more than in the solar system)




exoplanets.org | 4/23/2012
Msin(i) [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
0.1
1
10
Semi-Major Axis [Astronomical Units (AU)]
Orbital Eccentricity
0.0
0.2
0.4
0.6
0.8

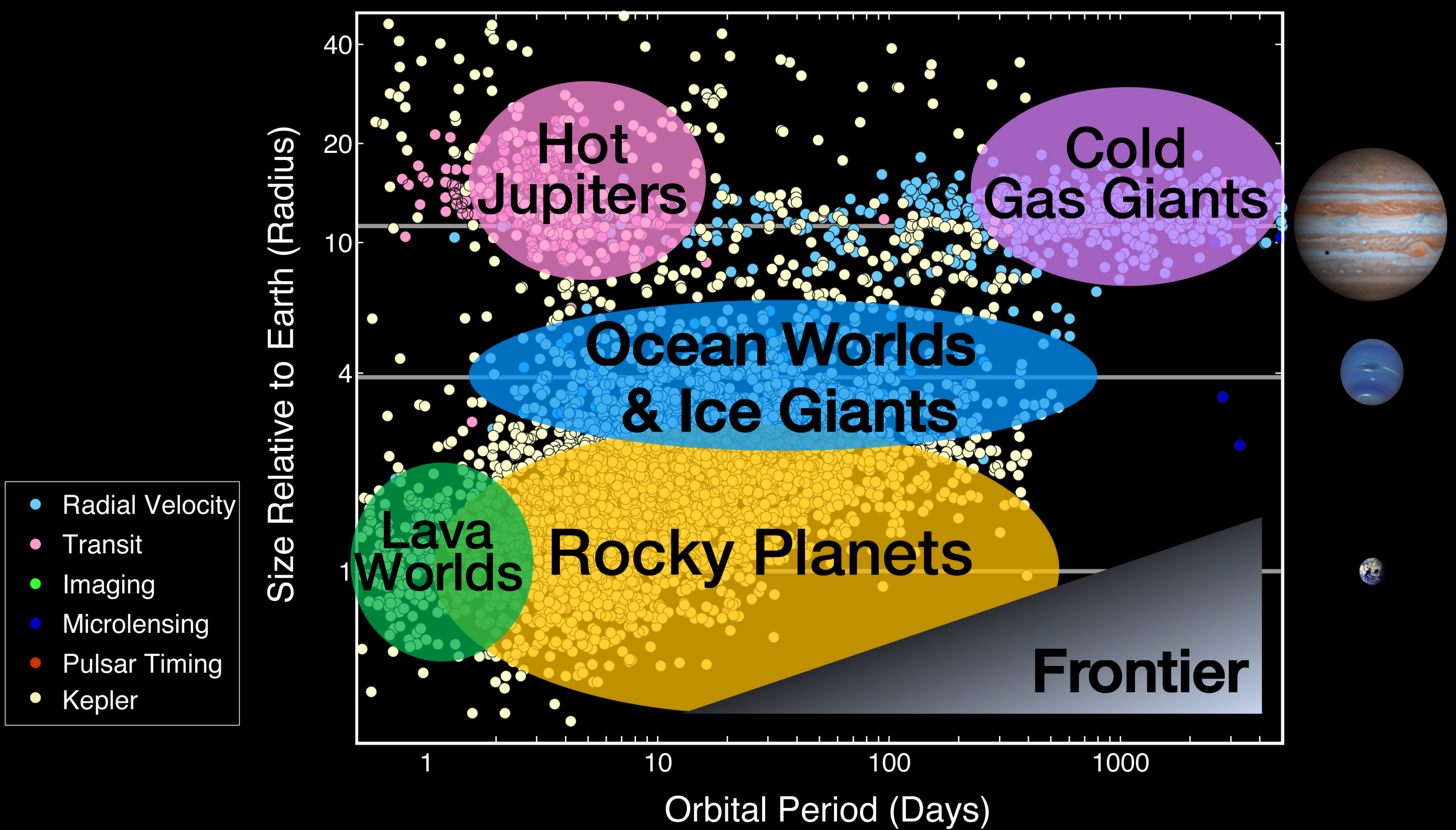
Major surprise of the 1990s: Hot jupiters

(the blue dots = low eccentricity, on the left = short-period end of the previous diagram)

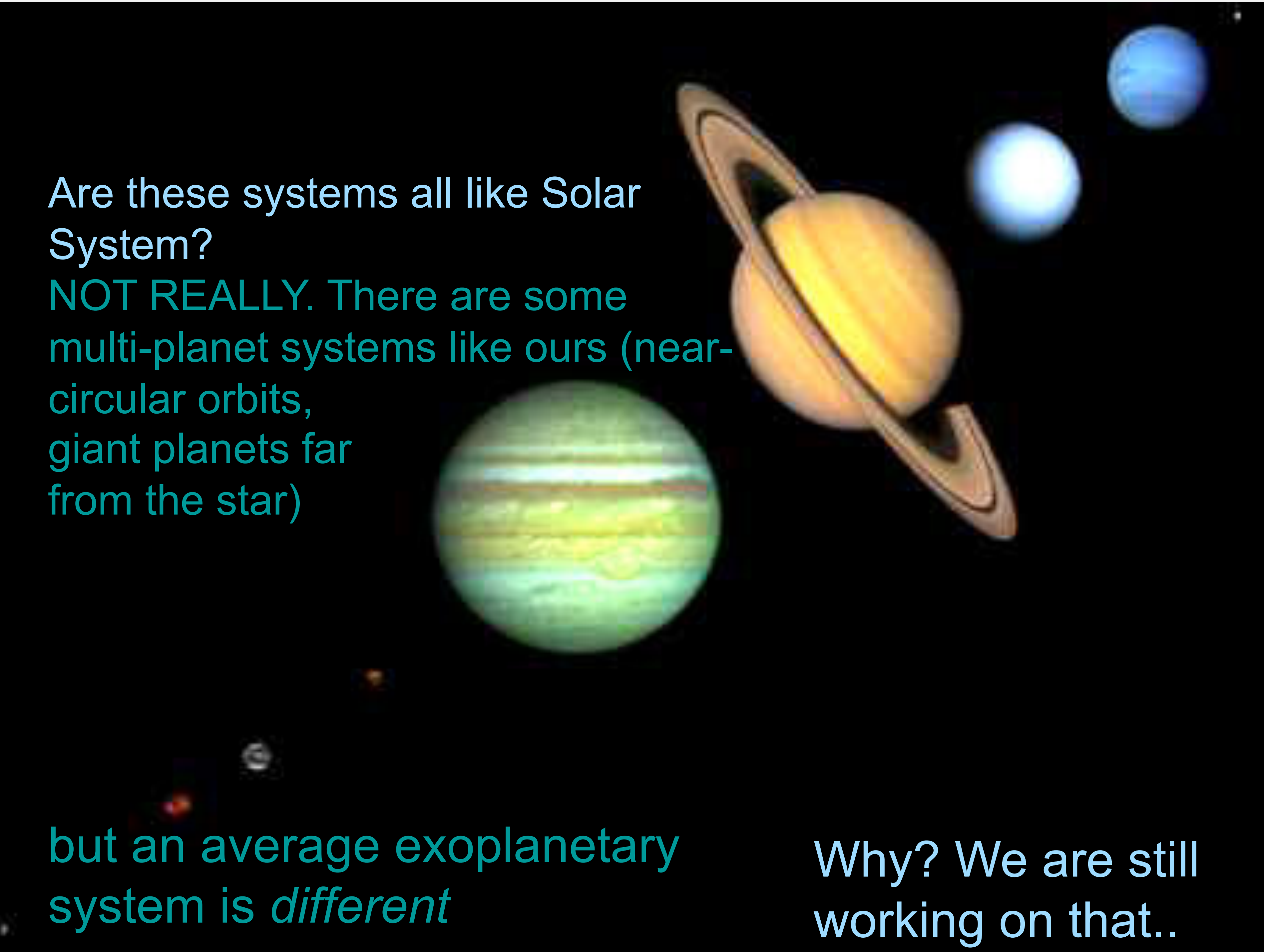
Planets similar to our giant planets but located extremely close to their stars and therefore hot at the surface (up to ~1000 K)

We think that their presence is not because they formed there (conditions not right) but that they have migrated there from further regions of the protoplanetary disk

Exoplanet Populations



https://en.wikipedia.org/wiki/List_of_exoplanets_discovered_in_2023



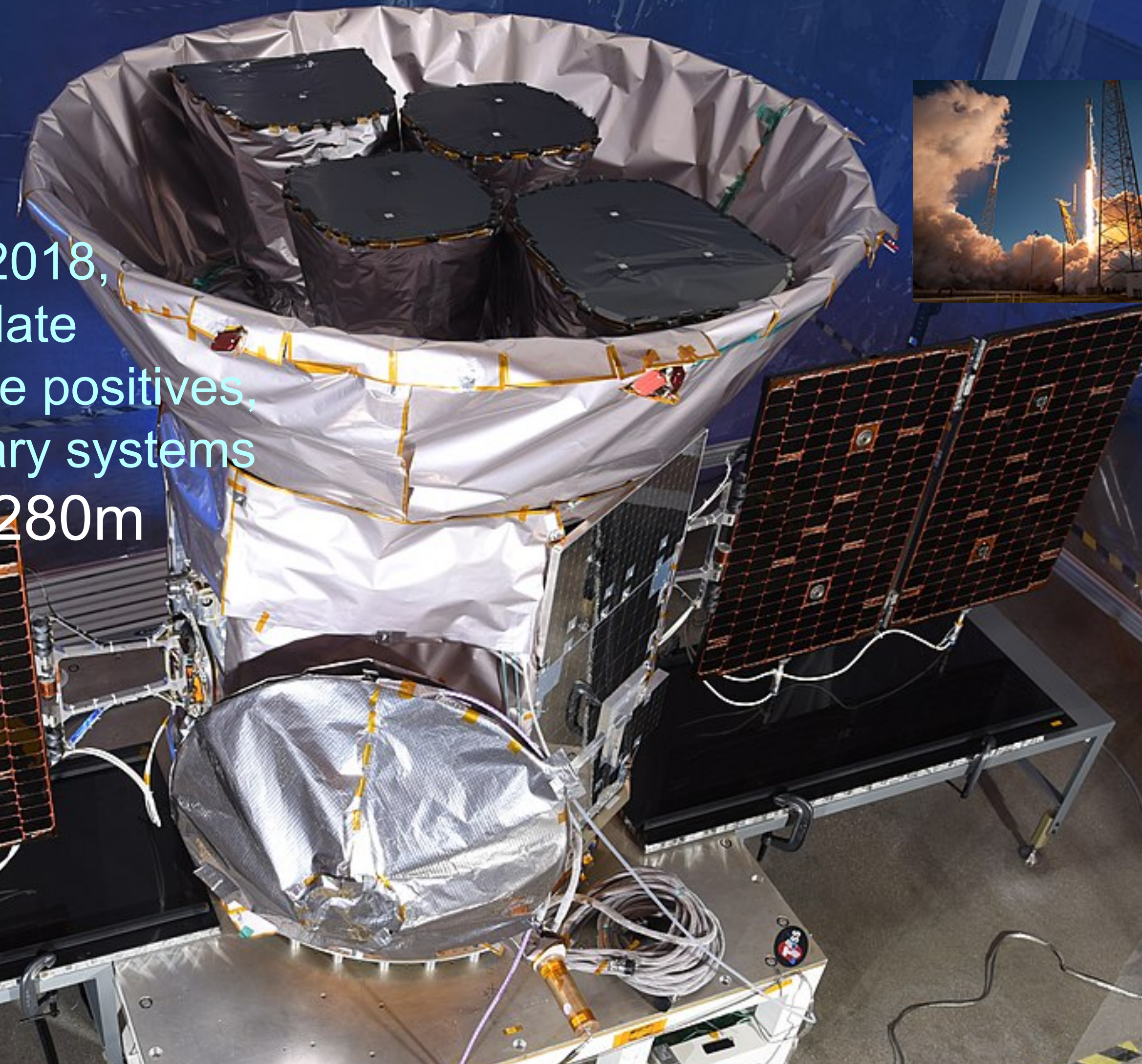
Are these systems all like Solar System?

NOT REALLY. There are some multi-planet systems like ours (near-circular orbits, giant planets far from the star)

but an average exoplanetary system is *different*

Why? We are still working on that..

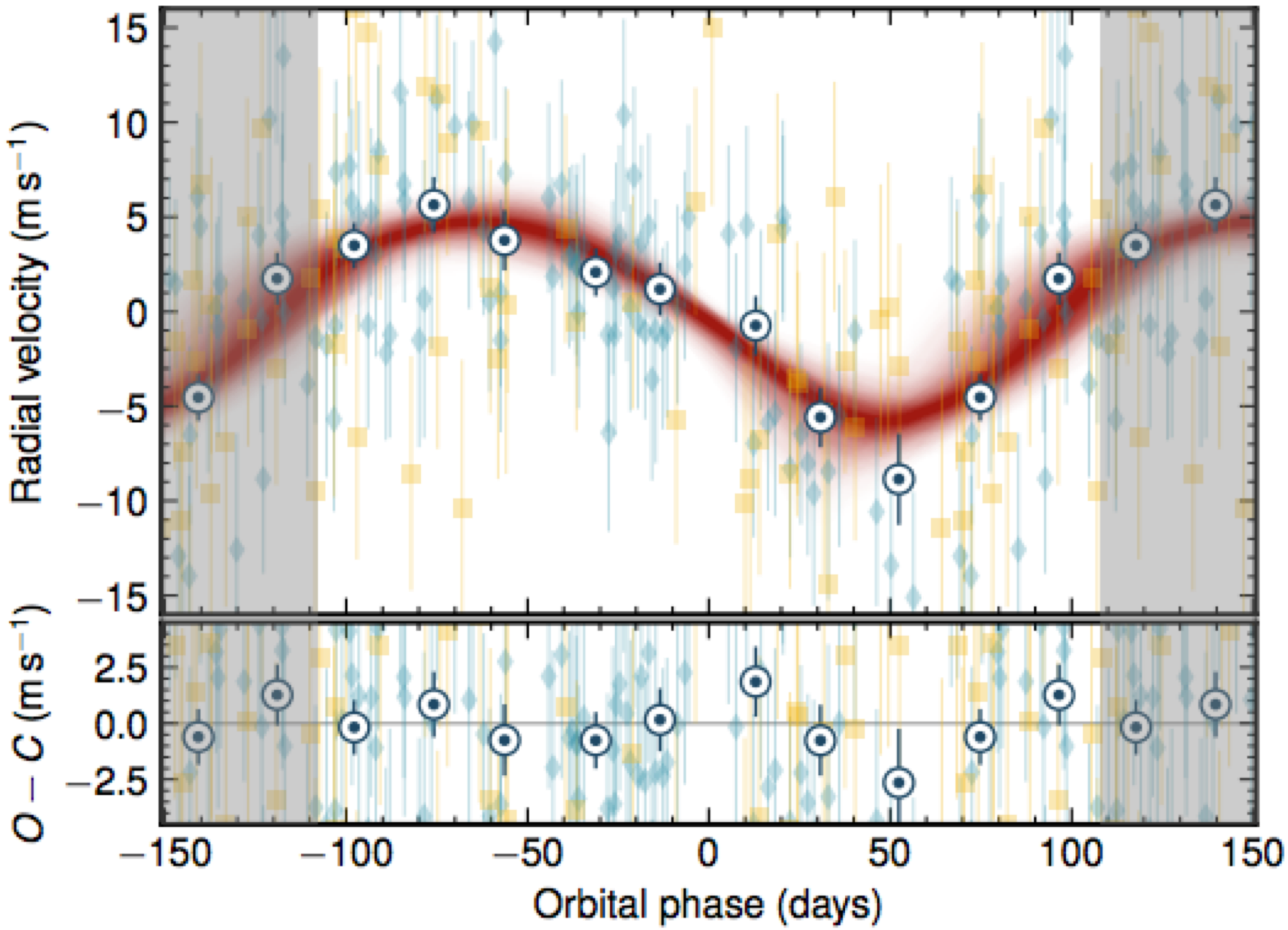
TESS: Designed mostly at MIT,
constructed in 2016-2018,
launched by SpaceX rocket in 2018,
still working. Found ~6k candidate
systems, of which ~¼ were false positives,
and ~270 confirmed exoplanetary systems
by April 2023, cost \$280m



An interesting exoplanetary system, in which the 1st planet was discovered by a high-school student W. Cukier in TESS data, and is very low density super-Neptune, and the 2nd planet was found in 2023: **TOI-1338** (TESS object of interest no. 1338).
TESS = Transit Exoplanet Survey Satellite (covers 85% of sky).

radial velocity variations method in practice

compare: $v_* = \pm 76$ km/s



TOI-1338

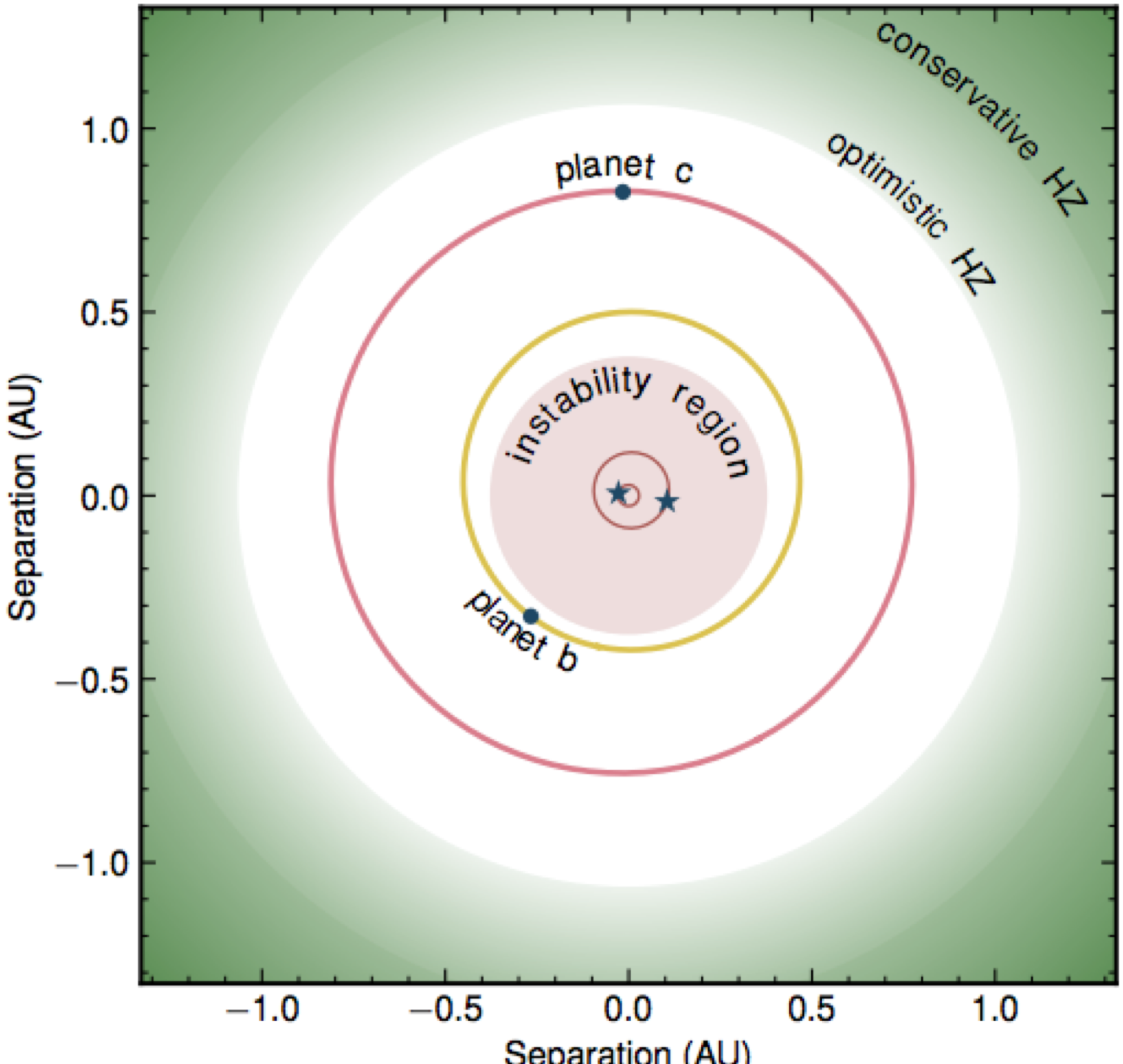
single-lined spectroscopic system

type F8
a = 0.13 AU
P =14.6^d
age 4.4 Gyr

Figure 2: Phased Keplerian Radial-Velocity (RV) models of TOI-1338/BEBOP-1c with ESPRESSO (blue diamonds) and HARPS (orange squares) data along with associated residuals after removing the binary signal. RV data is binned by 0.1 phase units (~21.6 days) and illustrated by the circular points. Red Keplerian models are based on 500 randomly drawn posterior samples from a `kima` run, shaded from the 50th to 99th percentiles. The shaded regions display the repeating signal.

Nearly coplanar, circumbinary planetary system

TOI-1338



star A:

$M_A = 1.127\ M_\odot$

$R_A = 1.331\ R_\odot$

star B:

$M_B = 0.313\ M_\odot$

$R_B = 0.309\ R_\odot$

---

2 super-Neptunes:

planet ***b***

$M_b = 33 \pm 20\ M_{Earth}$

$a = 0.461$ AU (95^d)

$e = 0.088 \pm 0.004$

$R_b = 6.85 \pm 0.19\ R_E$

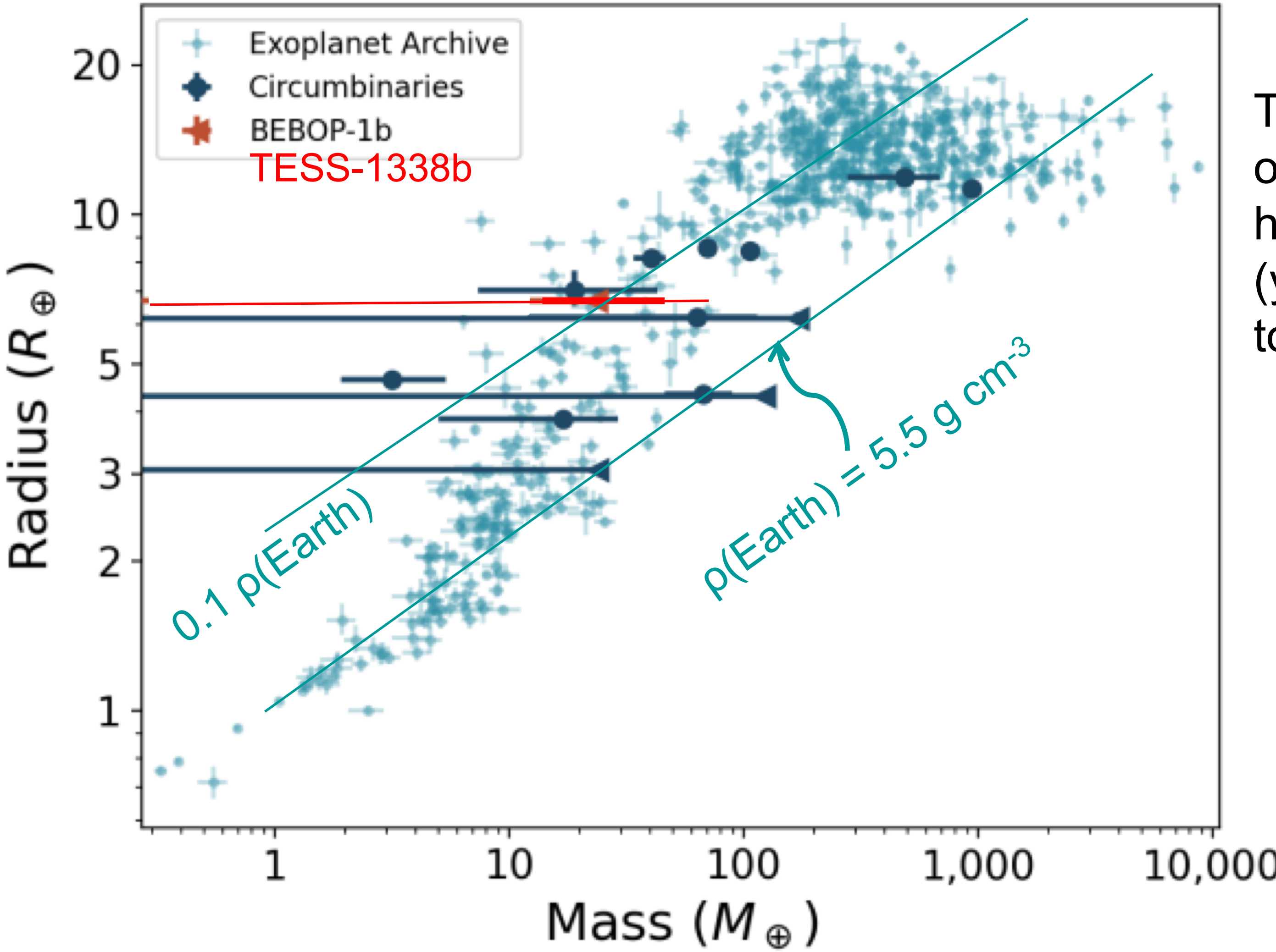
planet ***c***

$M_c = 65 \pm 12\ M_E$

$a = 0.79$ AU (216^d)

$e < 0.16$

cf. "The First Circumbinary Planet Discovered with Radial Velocities", Standing et al. (2023)



The inner planet of TOI-1338 system has very low density (you should be able to find out how low!)

Figure 3: Radius vs Mass plot of all transiting circumbinary planets (dark blue) and planets orbiting single stars (light blue). TOI-1338/BEBOP-1b is highlighted in orange, with one of the lowest densities known. The newly-discovered TOI-1338/BEBOP-1c is not on the graph since