Astro 27 – Field Astronomy First Lecture: Planets

Formation of the Solar System

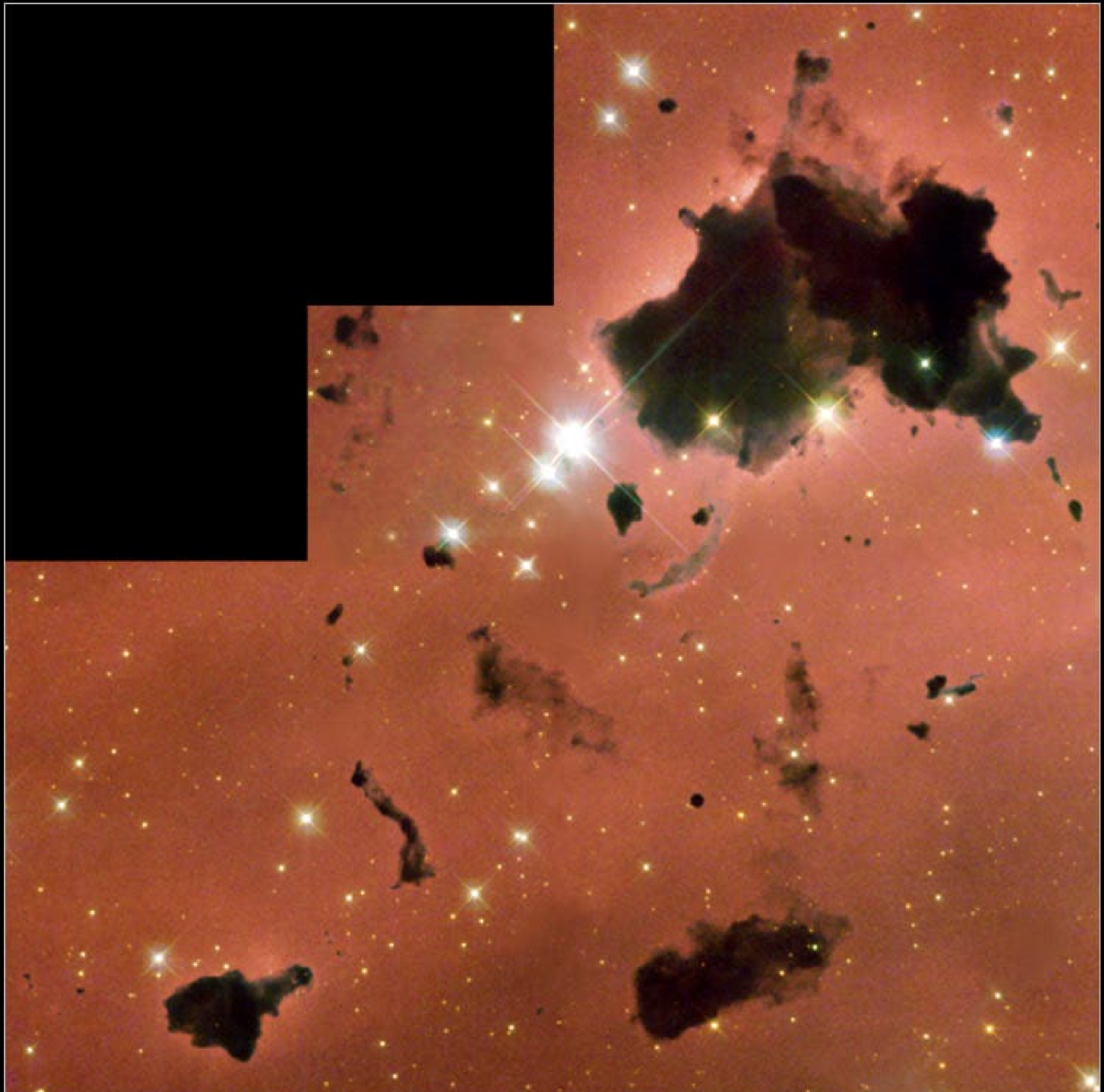
- •Stars, solar systems form within giant molecular clouds
- •Requires **high density**, **dust, and low temperatures** to initiate gravitational collapse
- •Our solar system apparently formed after blast wave from a supernova compressed a giant molecular cloud, forming hundreds or thousands of stars; sun was one of them
- •Tidal torque produces angular momentum
- •Gravitational collapse then flattens to a disk
- •Eddy formation, merging, proto-planets gravitational collapse to form planets

To Get Planets, You Need Stars: Conditions for Star Formation…

- Stars form in giant clouds of gas and dust
- Often called "Giant Molecular Clouds" because the conditions also favor formation of molecules like water, CO, etc.
- Need **HIGH density** areas
- Need **COLD temperatures**
- Cold temperatures mean low pressure so gravity can overcome it and cause the proto-star to collapse

And, Need DUST

- Why? Because dust will block all hot radiation and keep the area cool. Your protostar doesn’t like to be bombarded by high energy radiation from nearby stars!
- It likes to be inside a nice cold “dust cocoon”, where it can slowly bring together the gas and dust and make a star
- Cold dust will be dark, silhouette’ing in the photos to come…



N11B in the Large Magellanic Cloud

Hubble Heritage

The Next Slide is a Classic Hubble Photo…

- The Orion Nebula is the nearest rich star formation region, with hundreds of new stars still forming
- Inside the Orion Nebula, we see **new solar systems forming!**
- We see proto-planetary dusty disks surrounding many newly forming stars
- The neighboring stars compete gravitationally for infalling material, so it can’t fall STRAIGHT in, and hence you have angular momentum, and it is THIS material which remains outside the star and can collapse into planets

How do the planets themselves form in this disk of dust and gas?

- We're still working on it – a very tough problem… Do we have all the right physics?
- Magnetic fields? Gravity, pressure, radiation transport, cooling mechanisms and rates, collision histories, migrations, "million body problem" for sure, rate of evolution of the proto-sun *vs.* the proto-planets important and uncertain, need numerical codes with huge dynamic range – dust bunnies to planets!
- Big Brains running Big Computers needed!
- There are **Two basic scenarios**, with variations possible within these two…

Slow *vs.* Fast: While variations are many, the basic ideas are…

- **The "Slow" scenario**: the "seeds" of planet formation are dust grains, into dust bunnies, growing until large enough to be self-gravitating (about ½ mile across) and accelerate growth. Beyond "frost line", "seeds" would be ices (hydrogen compounds with low melting points). Since H dominates mass, these planets would grow faster and bigger.
- **The "Fast" scenario**: eddys form, merge. Eddys include not just dust (which is only ~2% of total mass recall), but hydrogen and helium as well 98% of the total mass). The growth rate would then be much faster as gravity would kick in right away for such massive objects.

But… there's a Race Here

- The star itself is gravitationally collapsing, heating up, initiating fusion, generating a hot stellar wind of hydrogen and helium nuclei, and luminosity, all of which have momentum and provide pressure which blow away the surrounding disk of proto-planetary material. Can planets form (thus being dense, stable against this pressure) quickly enough so that the material isn't simply blown away first?
- That's the race, and it happens over a time scale of just a few million years at most. Observations suggest disks last roughly 6 million years around newly formed solar-type stars.
- So, we need a mechanism which forms planets quickly.

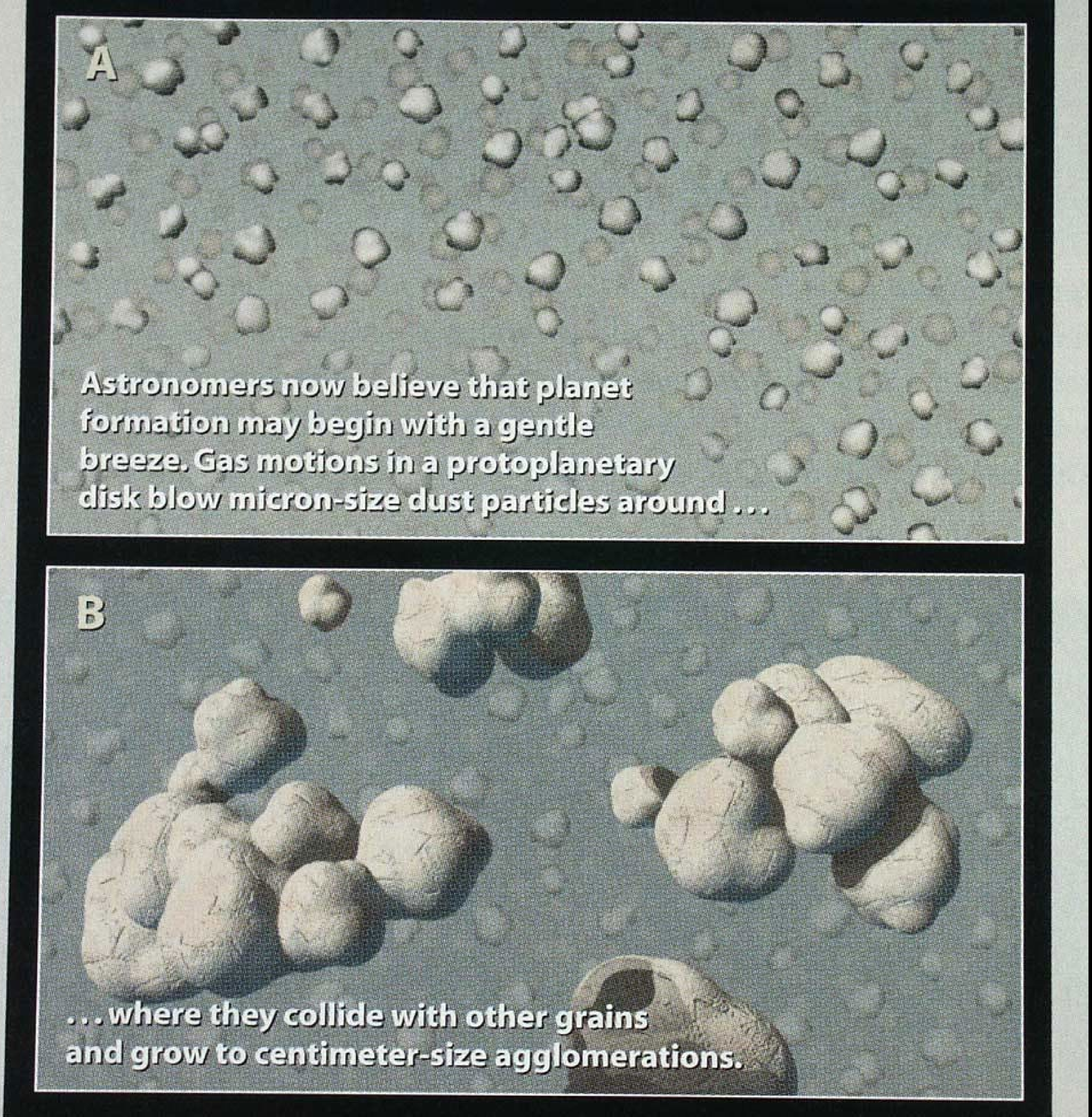
birth theory

slow

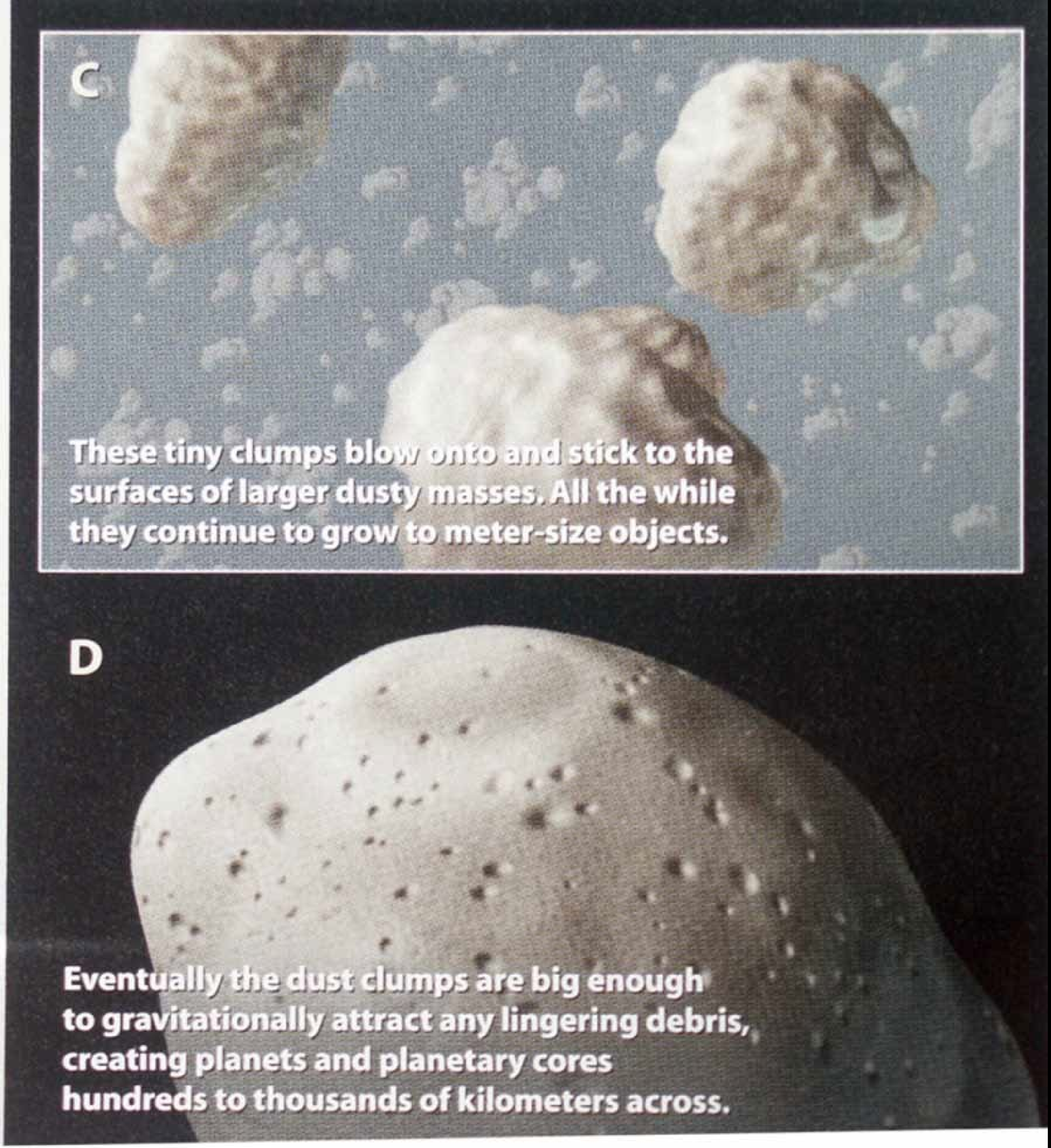
Core Accretion

The first planets to emerge from the whirling disk of gas and debris that surrounds a newborn star are gas giants like our Jupiter and Saturn. Most astronomers think they take shape slowly by growing step by step from the rocky material in the disk (top). First, tiny dust grains stick together (1), forming larger grains that collide to form still larger lumps. The growth process eventually yields solid cores roughly ten times the mass of the Earth (2). Their powerful gravity sucks in gas from the disk to create a giant, gas-cloaked planet (3).

Making a planet this way could take several million years. That's too slow, say some theorists, who argue that the gas needed for planet growth may not linger that long in the disk. They favor a fast alternative (facing page). Either way, smaller, Earth-size planets would form much later, from the leftover disk material.



Dust grain making dust bunnies



…Dust bunnies into proto-planets

Late in Planet Formation

The "Fast" Scenario: Eddys into Proto-Planets, into Planets

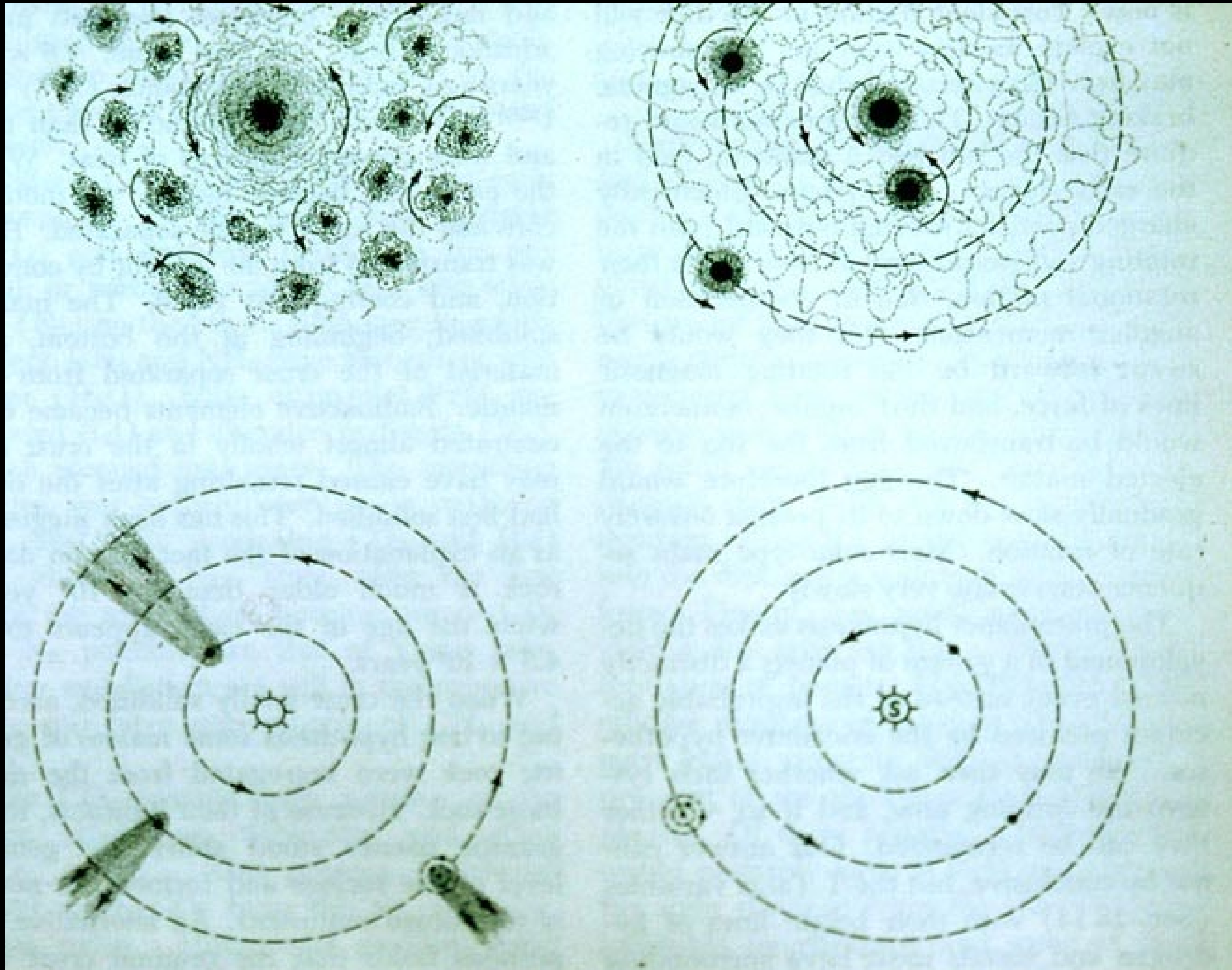


Figure 24.6 Origin of the solar system from a turbulent cloud of gas and dust, according to the protoplanet hypothesis.

ART BY MOONRUNNER DESIGN. CONSULTANT: ALAN BOSS, CARNEGIE INSTITUTION OF WASHINGTON

Gravitational Instability

Many young stars have bright neighbors whose intense radiation can strip gas from a planet-forming disk. That would force giant planets to form faster than the gas disappears. "I don't think core accretion can do that," says astrophysicist Alan Boss, lead supporter of a speedier recipe for planet formation. In this theory, gravity causes the disk of gas and dust to collapse into dense clouds, shown at top as bright clumps. Each cloud shrinks (1) and solid material falls to the center, creating a core within a few thousand years (2). Then the rest of the cloud contracts, forming the gas giant (3). The process could take less than a million years. "It's a pretty picture," says Boss, though he admits, "it's still just a fairy tale." That could change if giant planets (now known to orbit some 10 percent of sunlike stars) turn out to be much more common, implying that they regularly win the race against disk erosion.

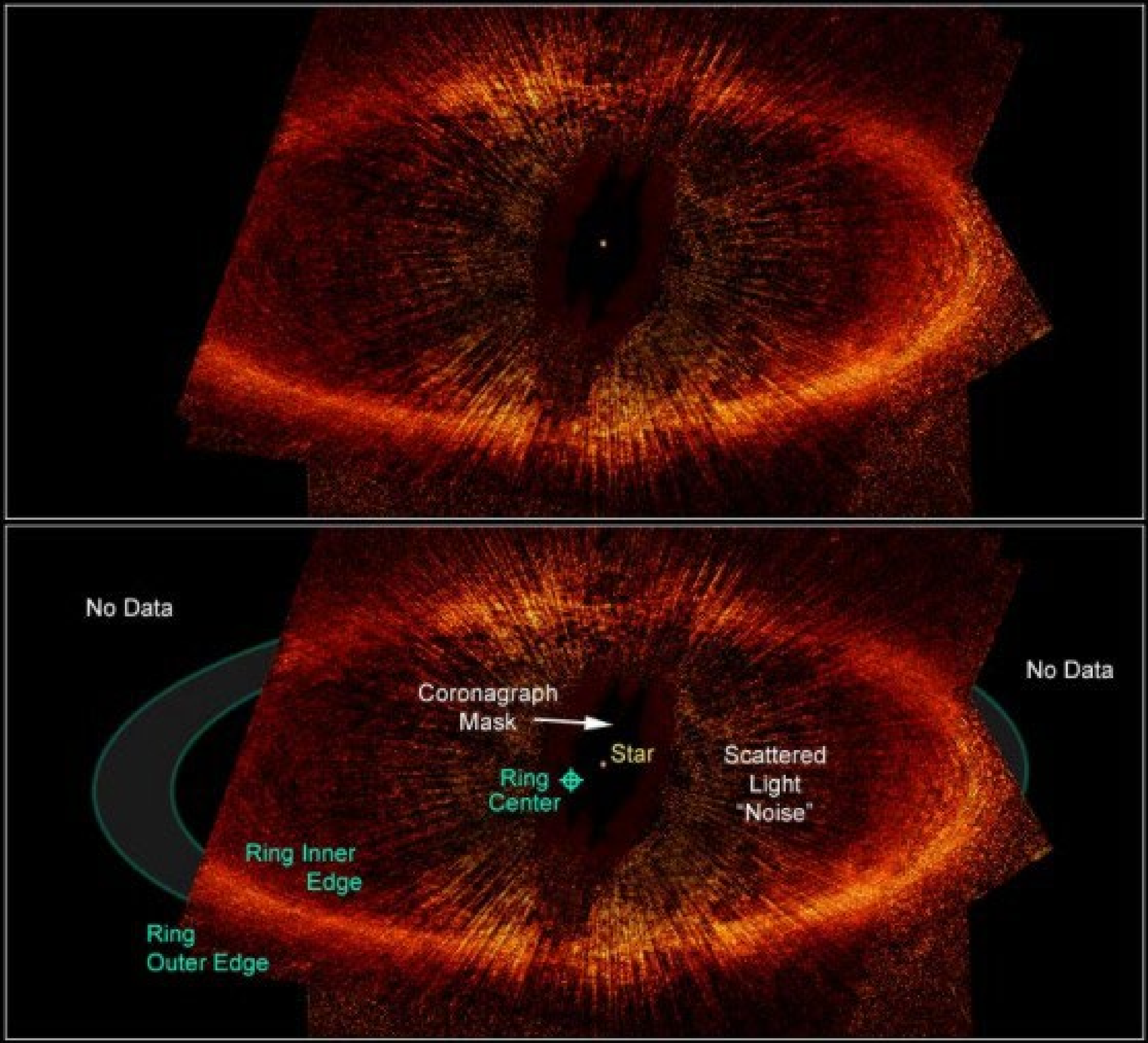
We’re beginning to see…

- … planets around stars that are too young and with disks too young to be well fit by the ‘slow accretion’ idea.
- So the “Fast” scenario is gaining some “weight of evidence” here
- Most likely, however, is that a mixture of both processes happen within different environments. Large *vs*. small stars, crowded *vs*. empty environments, etc. Alas - Occam’s Razor doesn’t always win the day.

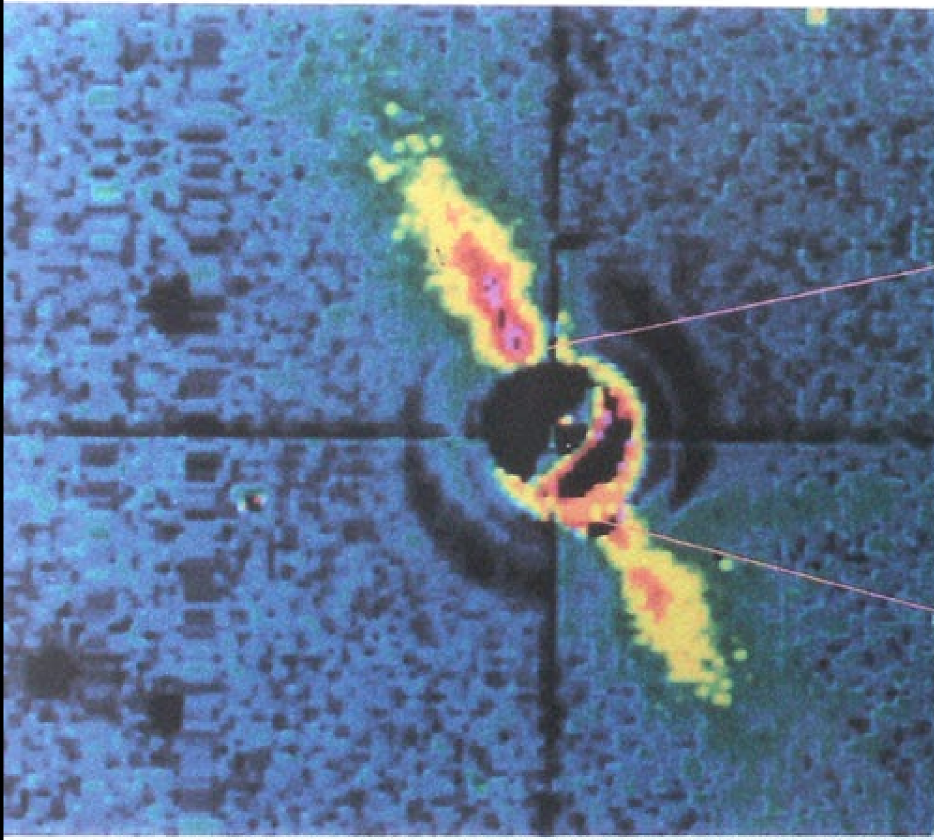
"Slow" Core Accretion goes faster when gravity gets strong enough, but…

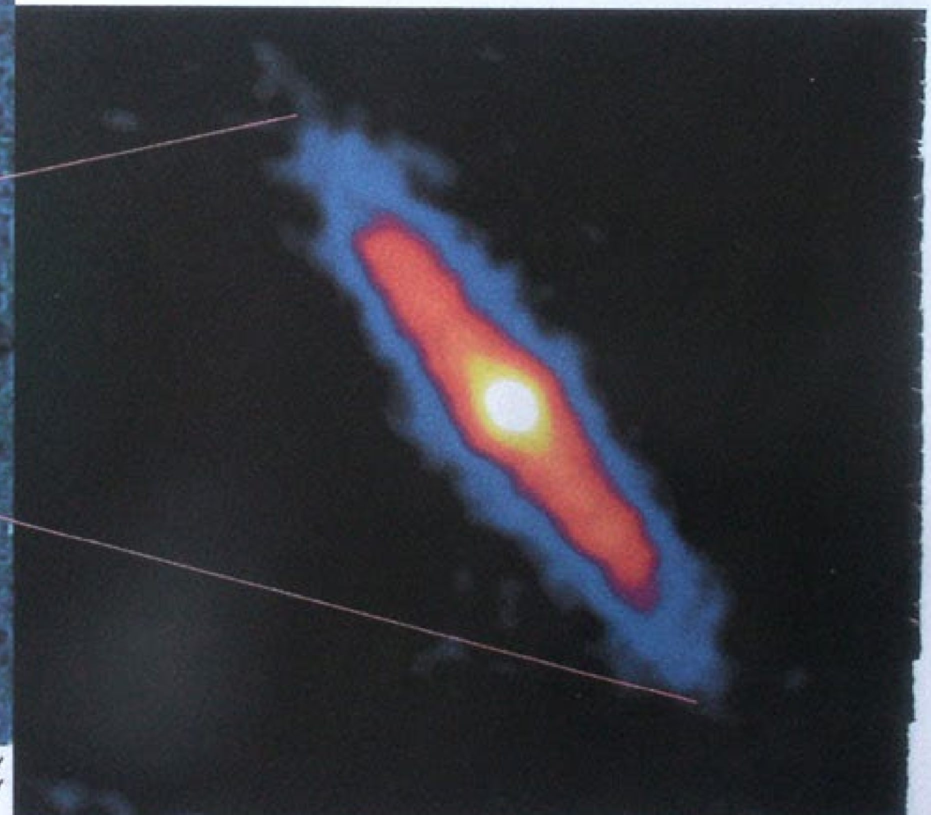
- Once the core grows past ~0.5-1 mile across, gravity becomes significant and accelerates the process.
- Growth rate goes as radius to the 4^{th} power (for constant density).
- So, those cores which get to the self-gravity point first, quickly run away and dominate the growth, accreting the rest.
- These become the true planets. Further orbital collisions likely consolidate these into a fewer number of planets now in long-term stable orbits.
- **But, the key mystery is getting from dust bunnies to ~mile across**. How this happens is still not well-understood. It would seem that collisions would knock these planetesimals apart and halt or significantly slow growth so that getting to the self-gravitation size would be difficult.
- Magnetic fields help?? Viscosity slows local relative velocity dispersions??
- This is not yet solved to our satisfaction

Some real disks…Fomalhaut's

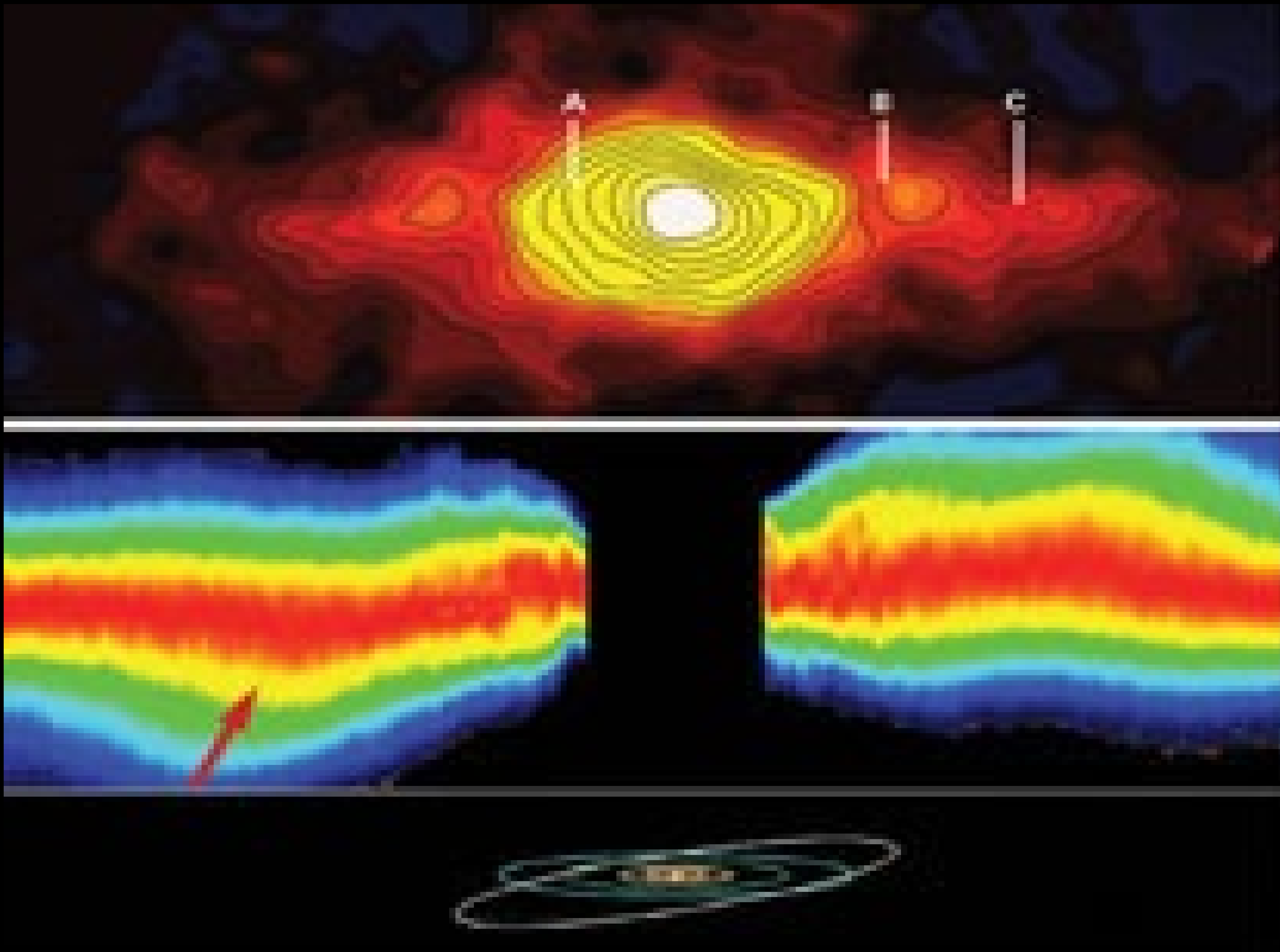


A vast cloud of dust, perhaps kicked up by colliding asteroids, envelops the young star Beta Pictoris in images from 1984 (left) and last January. Both images give a side view of the disk-shaped cloud and indicate brightness with false color. The earlier one, made in visible light, reveals only the disk's edges, but the new infrared view homes in on a smaller region about twice the size of our planetary system. The part of the disk colored red looks lumpy, perhaps because unseen planets are displacing the dust.

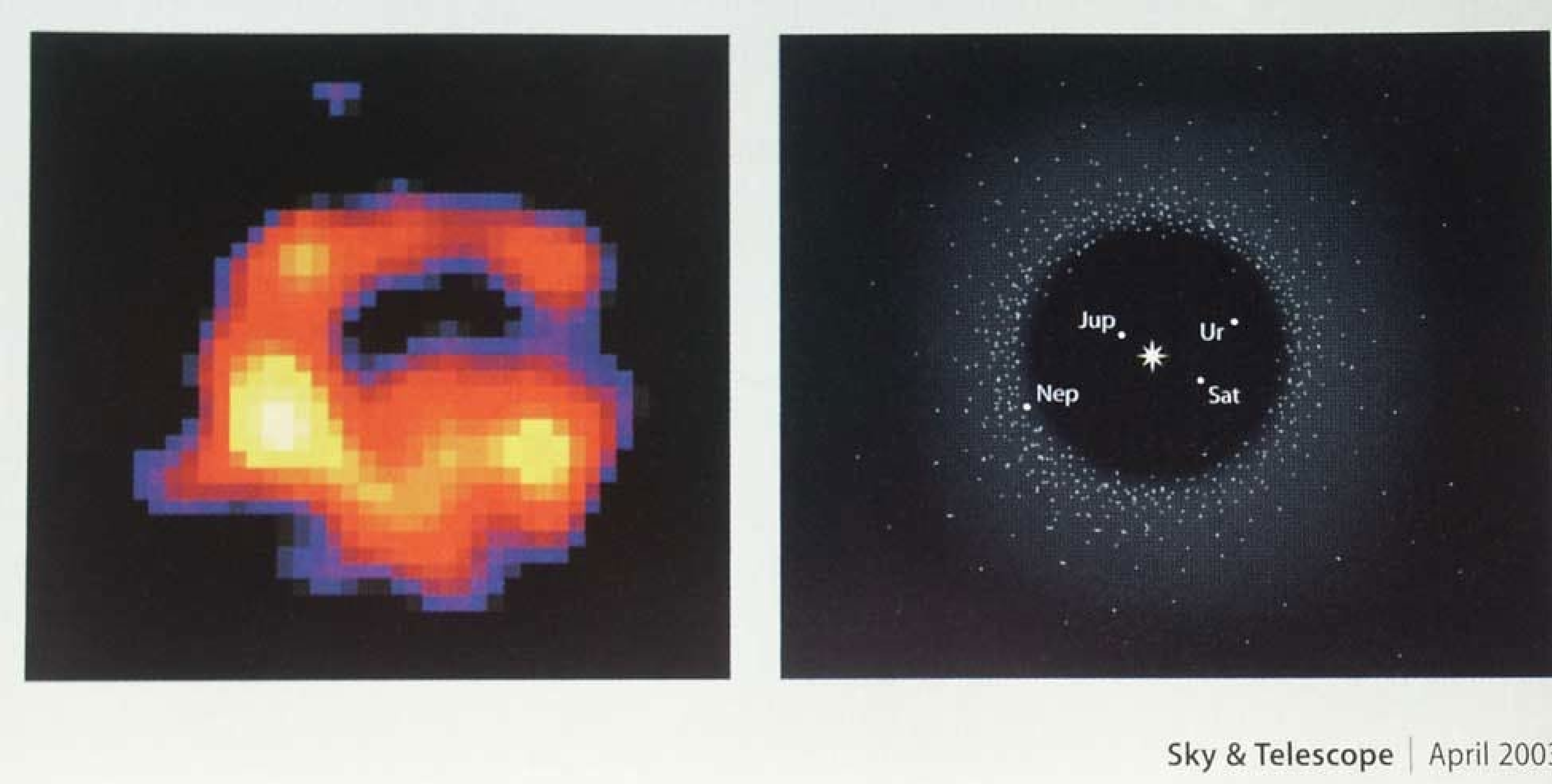




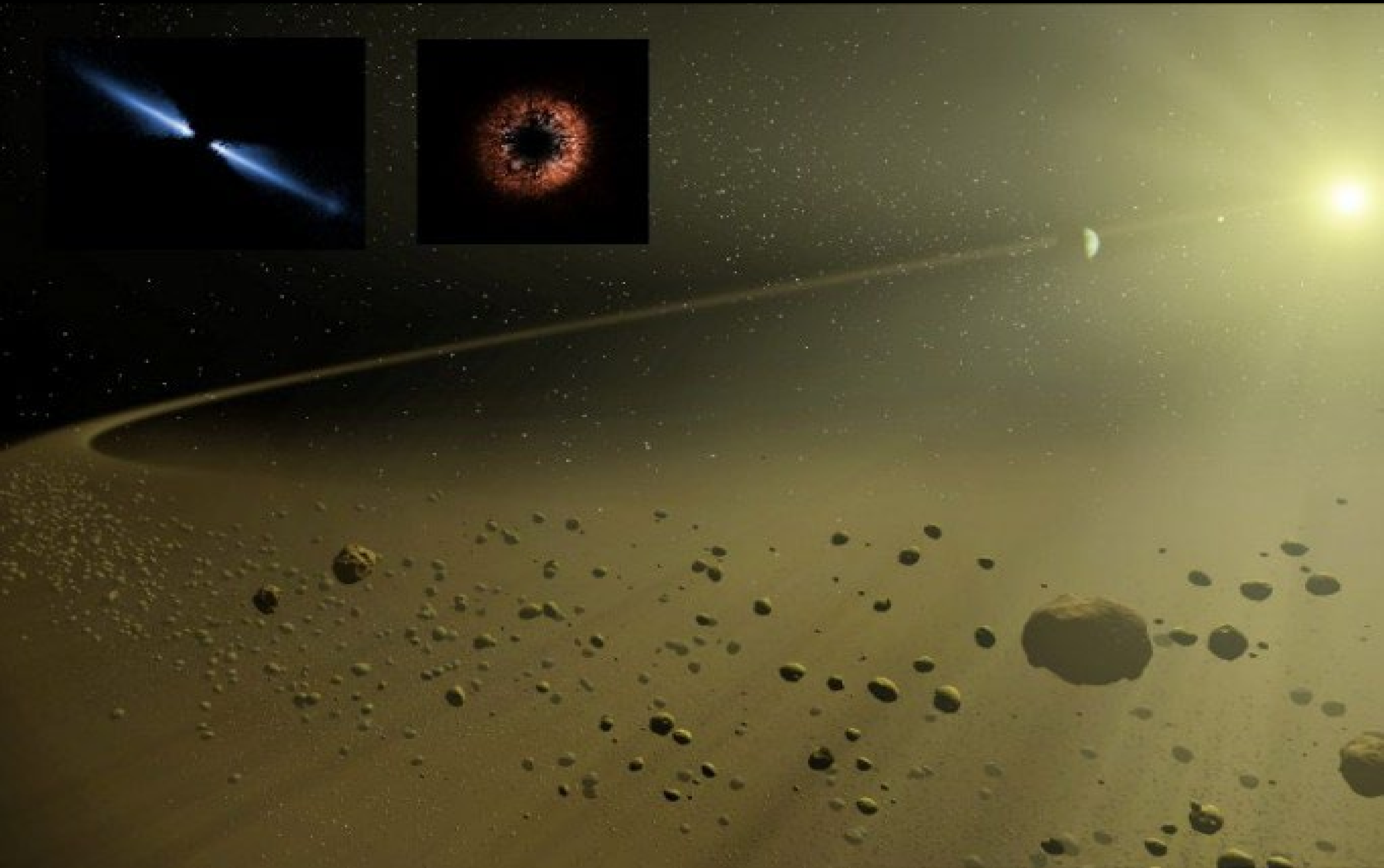
BRADFORD SMITH, UNIVERSITY OF ARIZONA, AND RICHARD TERRILE, JET PROPULSION LABORATORY (ABOVE); CHARLES TELESCO, UNIVERSITY OF FLORIDA, AND SCOTT FISHER, GEMINI OBSERVATORY


A
B
C

Epsilon Eridani System; early images a decade ago already show proto-planetary globs

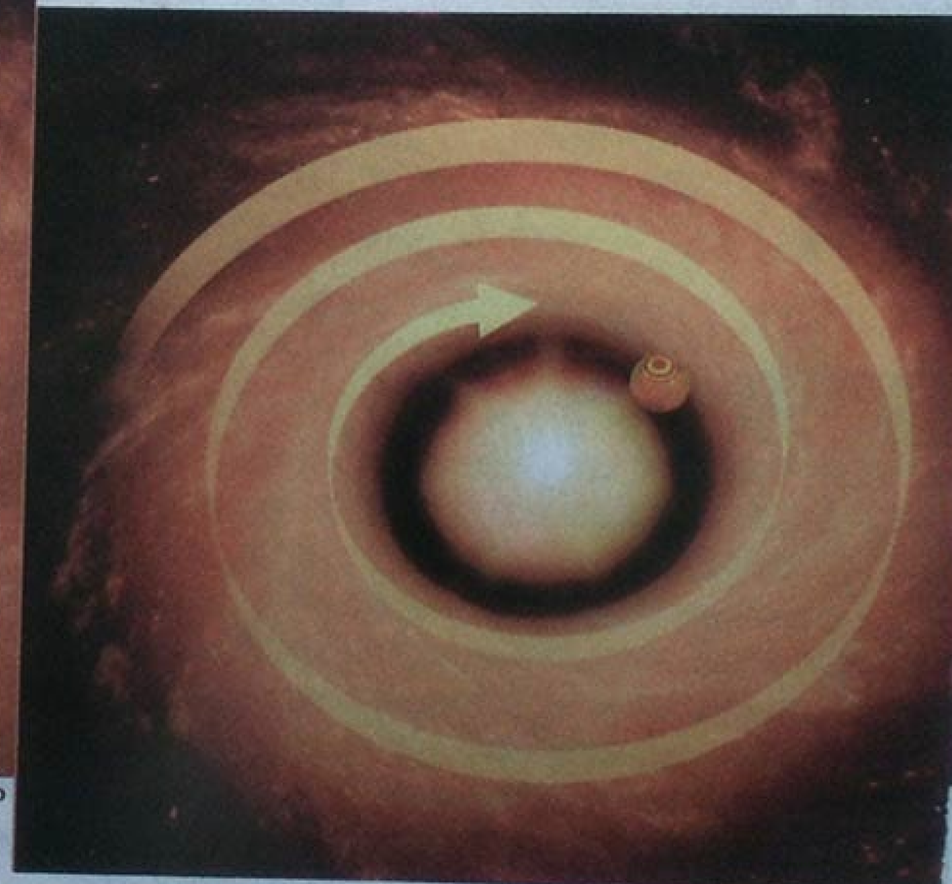


Probably you have some mix of both processes happening at the same time. Dirt clods within eddys or rings

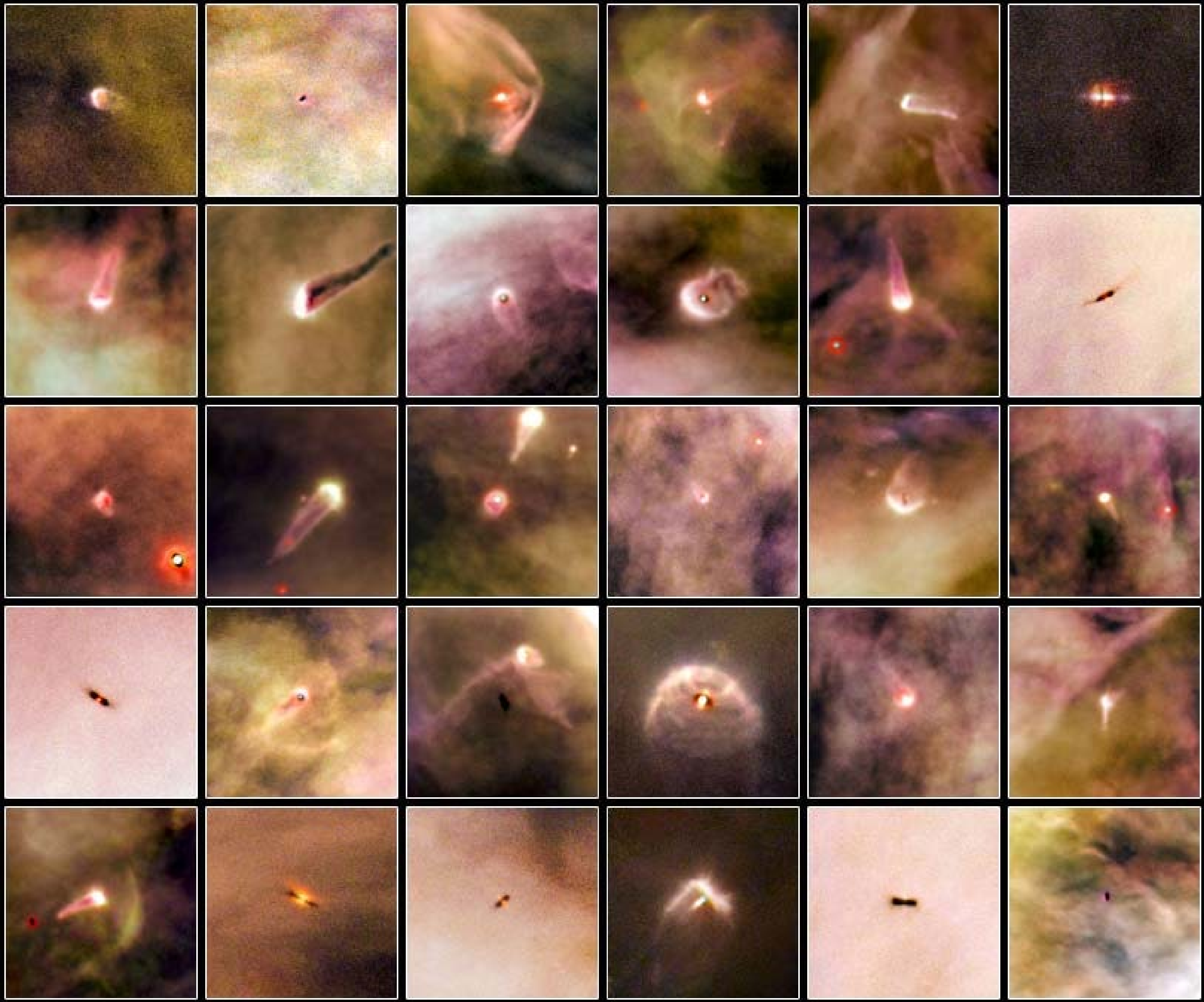


Giant planets take shape far from their star, where raw material is abundant. But astronomers have found scores of giants that apparently migrated inward after forming. In one theory, the process begins as a newborn giant carves a gap in the disk of gas and dust swirling around a young star (below left). The gap doesn't stay put: Friction between particles and gas molecules gradually slows down the disk. The material spirals inward, carrying the gap—and the planet—with it (below).

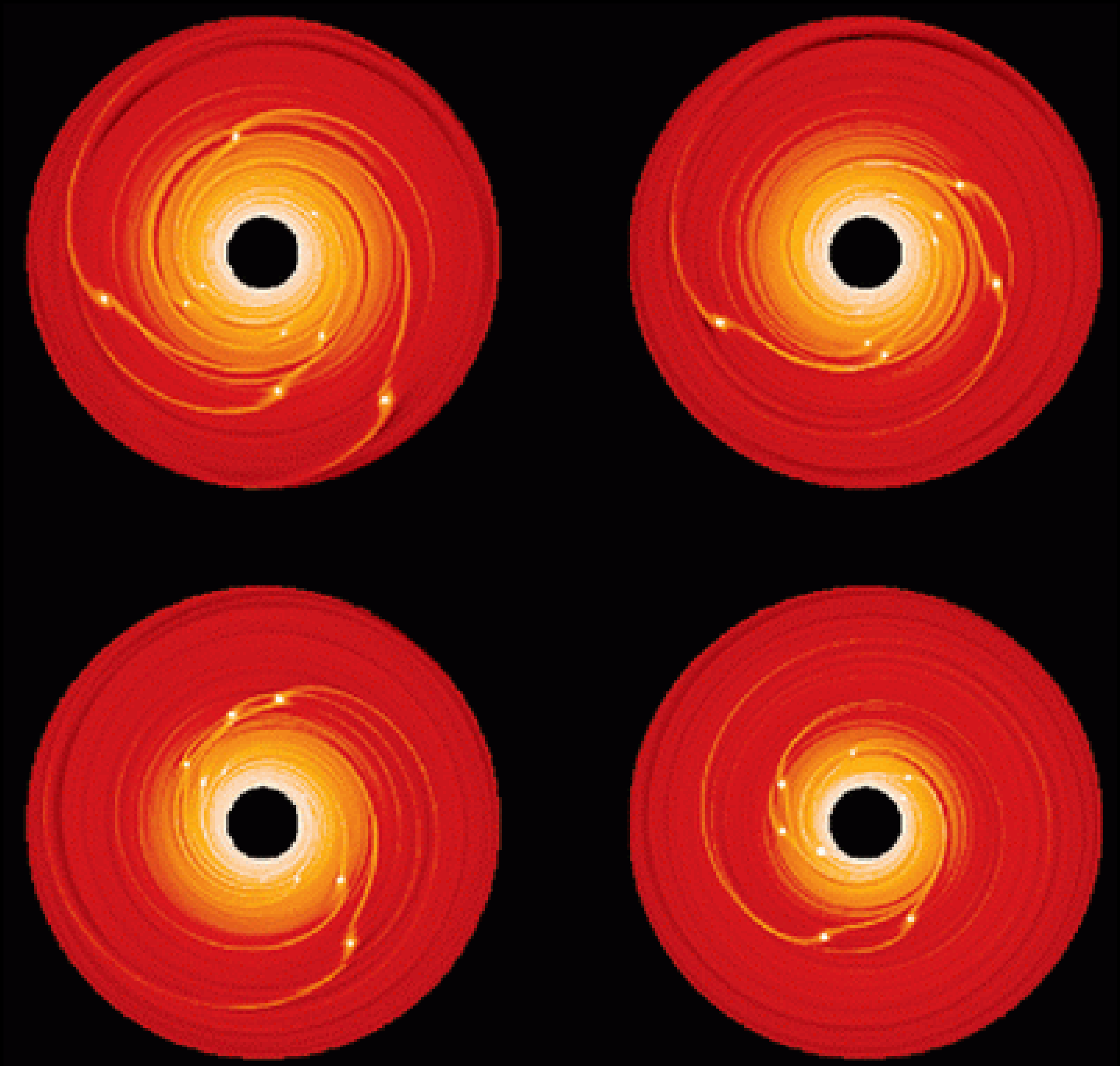
ART BY MOONRUNNER DESIGN. CONSULTANT: DEREK C. RICHARDSON, UNIVERSITY OF MARYLAND



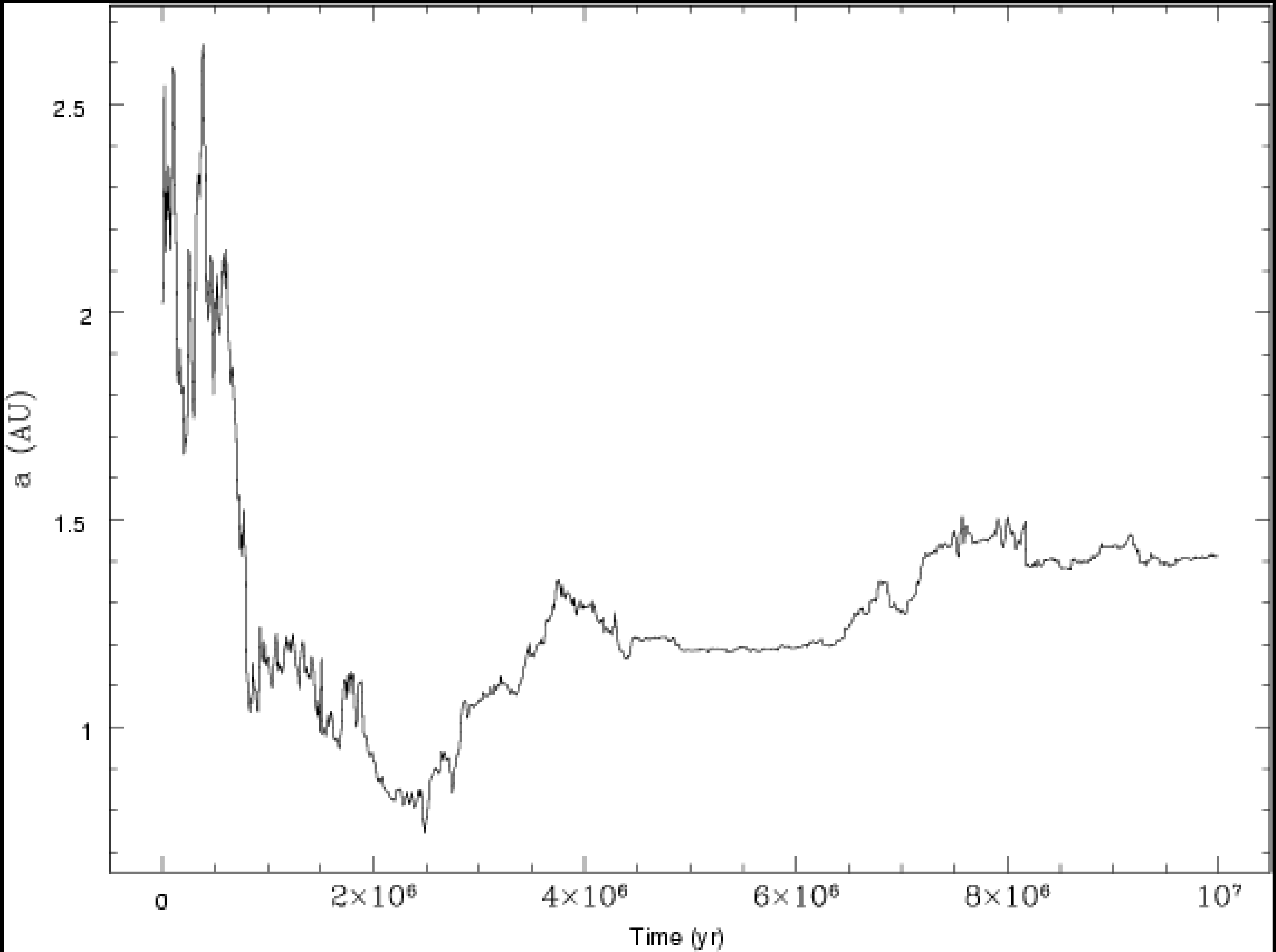
Young Protostars in Dusty Environments



Numerical Sim Showing Locked Migration Inward



This Simulation planet migrated from 2.5AU to 0.6AU and then out to 1.4 AU where it settled, in 10 million years



“Strafing” Shows Evidence of Early Dusty Disk

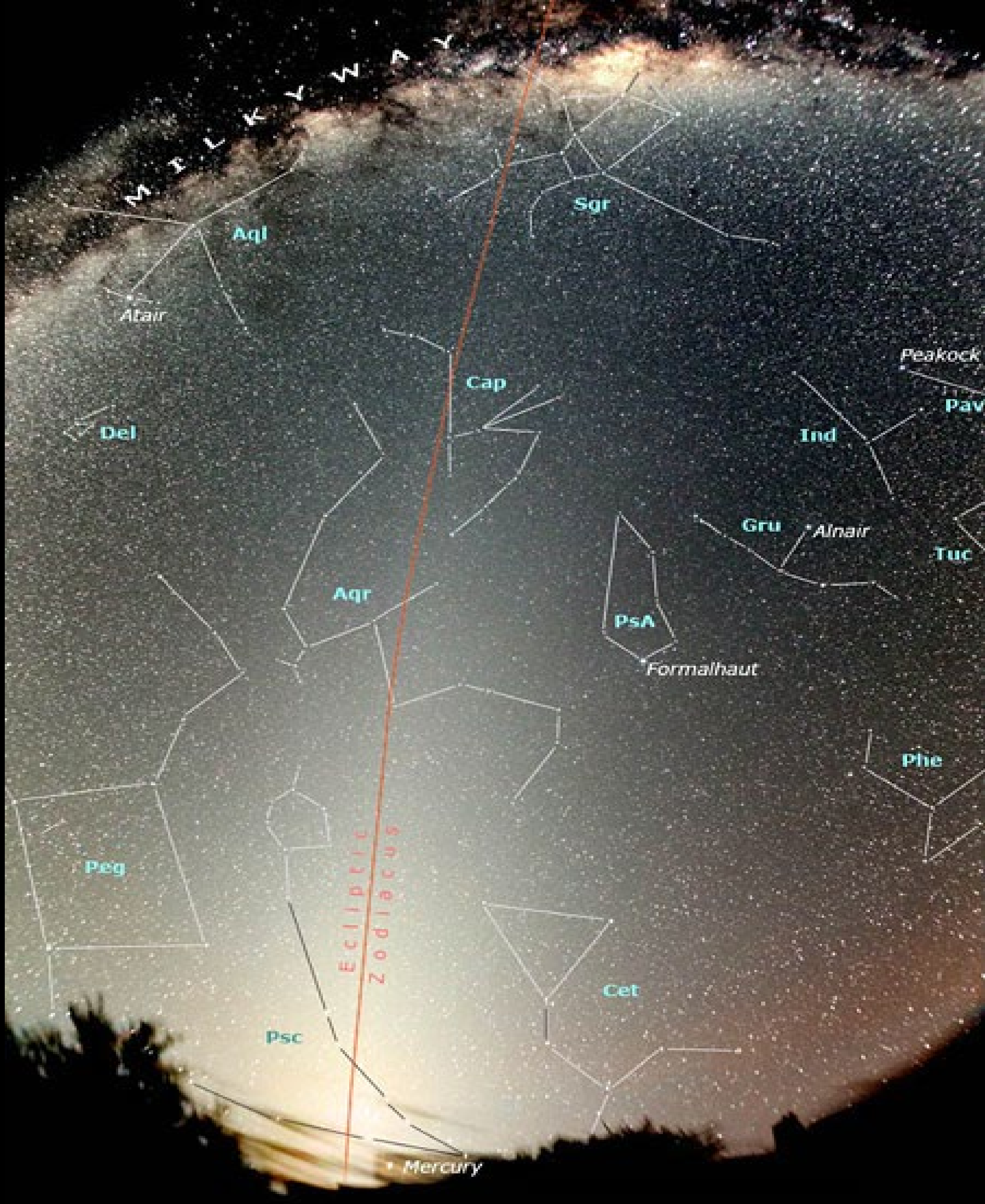
Is There Any Visible Remnant of <u>Our</u> Dusty Disky Beginnings?

- **Yes** – it's written in the structure of our Solar system! Planets all orbit in the same plane (pretty much), and all in the same direction, and all in nearly circular orbits

- And… You can see a pale echo of our dusty disk as the **Zodiacal Light**
- However, much of the Zodiacal Light is due to fresher dust made by collisions with existing asteroids, calculations indicate – so, it's not all primordial.

Zodiacal light – a faint band of light seen just after sunset or before sunrise, due to forward scattering of sunlight off dust in the plane of the solar system

We'll look for this on our field trip



What Actually Triggered the start of the collapse to OUR Solar System?

- Evidence favors a supernova explosion nearby did the job…
- SN blast wave compresses interstellar cloud rapidly, and the debris of that explosion is contained in the first objects to solidify in our solar system. Meteoroids.
- Aluminum 26 has a half-life of only 700,000 years, decays to Magnesium 26. And Mg-26 is INSIDE meteorites
- That says Al-26 was put into the meteoroid when it was still molten and since they age-date almost all to the same date – 4.56 billion years ago – that looks like the formation date. (Ergo, a supernova went off nearby less than a million years before the solar system formed. Co-incidence? Probably not. We see supernova-induced star formation elsewhere in our Galaxy

Isotopic Abundances Are Evidence of our Supernova-triggered Beginning

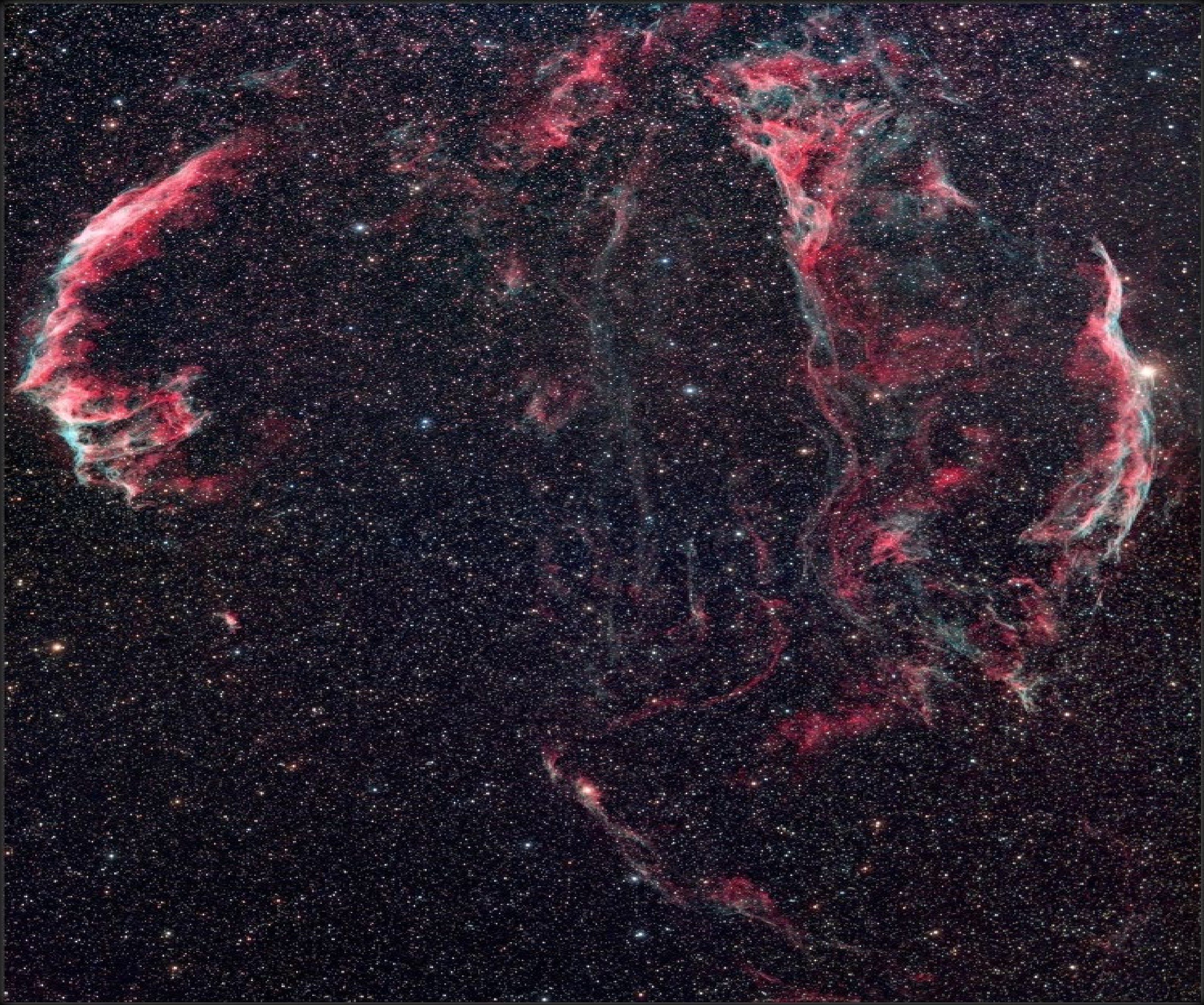
Gritschneder *et.al.* (2011) (summarized here), and UCSC pdf here, did hydrodynamic simulations, and find a Type II supernova 5 parsecs away would produce the evidence we see – Mg 26 (from decayed Al 26) uniformly spread through the solar nebula in the abundances seen.

More detail for the Curious: Argument for a Supernova-Triggered Solar System

- **Key observations…**
- 1. Mg 26 is uniformly distributed throughout the solar system and throughout studied meteorites.
- 2. CAI's (calcium rich inclusions) within meteorites have a very narrow (~1600K) temperature range within which they solidify, and this corresponds to a very narrow time range when they could incorporate Al-26. Time scale <~20,000 yrs very early in formation.
- 3. CAI's are enriched in Mg-26 relative to the other parts of the meteorite which cooled later and that enrichment is consistent across wide range of meteorites studied.
- 4. The abundance of Mg-26 correlates closely with that of Aluminum 27 (Al-27) and Al-26 is expected to correlate well with Al-27 as well (Gritschneder *et al.* 2011).
- 5. Freefall time for a solar system massed cloud is ~100,000 years, much too long to account for the CAI's which cool within 20,000 years and all have uniform enrichment: Need fast, forceful compression, not freefall.
- These observations indicated that Al-26 was injected rapidly, within 20,000 years, into the young solar nebula while it was hot enough (>1600K) for CAI material to not yet have solidified.
- Gritschneder *et.al.* 2011 hydro simulations show a massive star supernova (type II SN) within a Gian Molecular Cloud, and 5pc away from a reasonble overdensity, would both compress the overdensity cloud to initiate star formation of the sun, and seed the overdensity material uniformly with Al-26, which would decay within a few million year entirely into Mg-26. All consistent with observations.
- **Alternate ideas don't work as well**

-- cosmic ray induced transformations of Ar40->Al-26->Mg-26 over long periods in the solidified rock would not produce the uniform distribution seen since the required cosmic ray energies to produce Al-26 are low and penetrate poorly into rock.

-- Asymptotic Giant Branch stars, and massive Wolf Rayet stars can produce Al-26 into the new solar system, given enough time, but this time scale is much too long to be consistent with the uniform distribution in CAI's, which cooled in only 20,000 years.

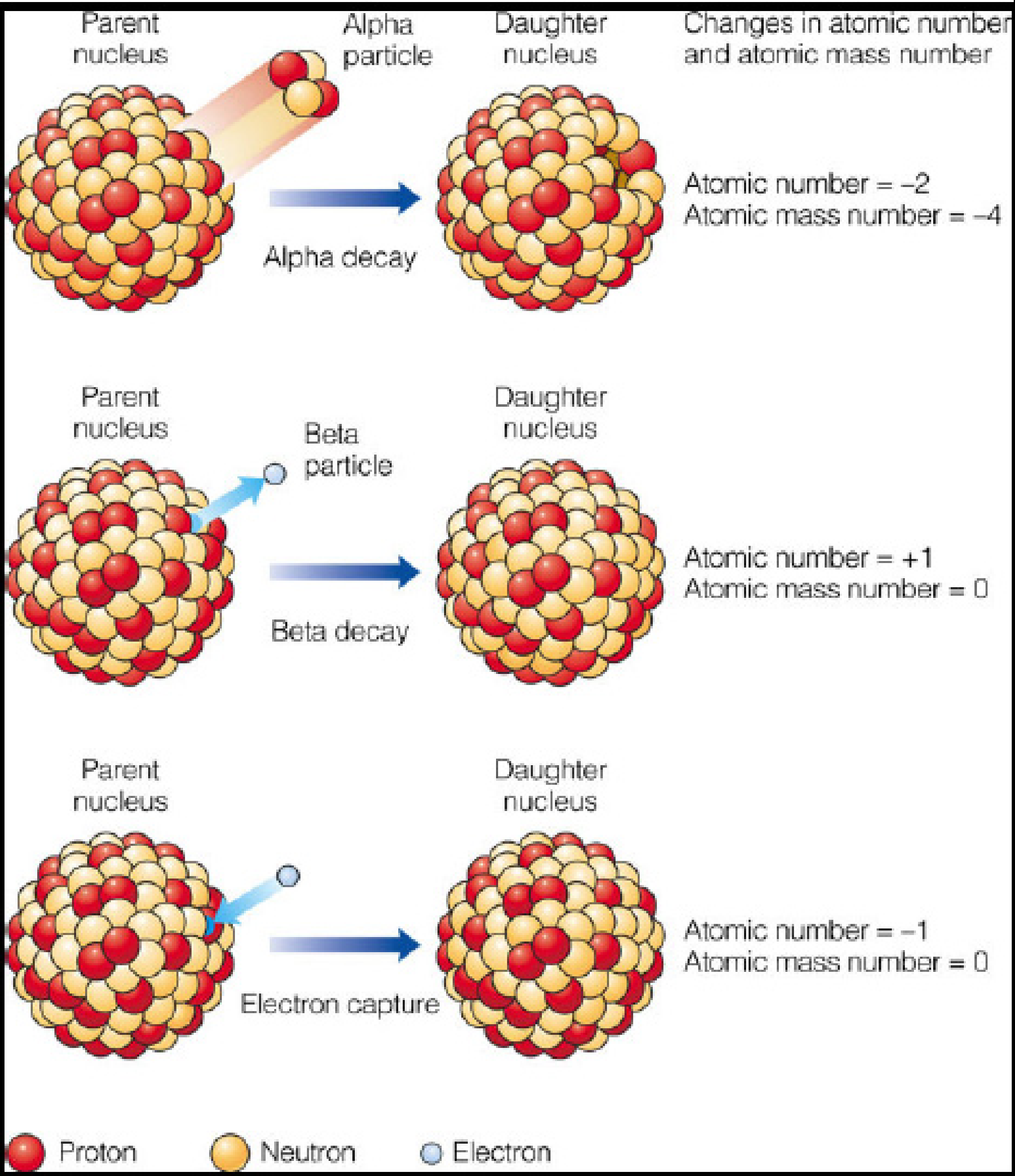


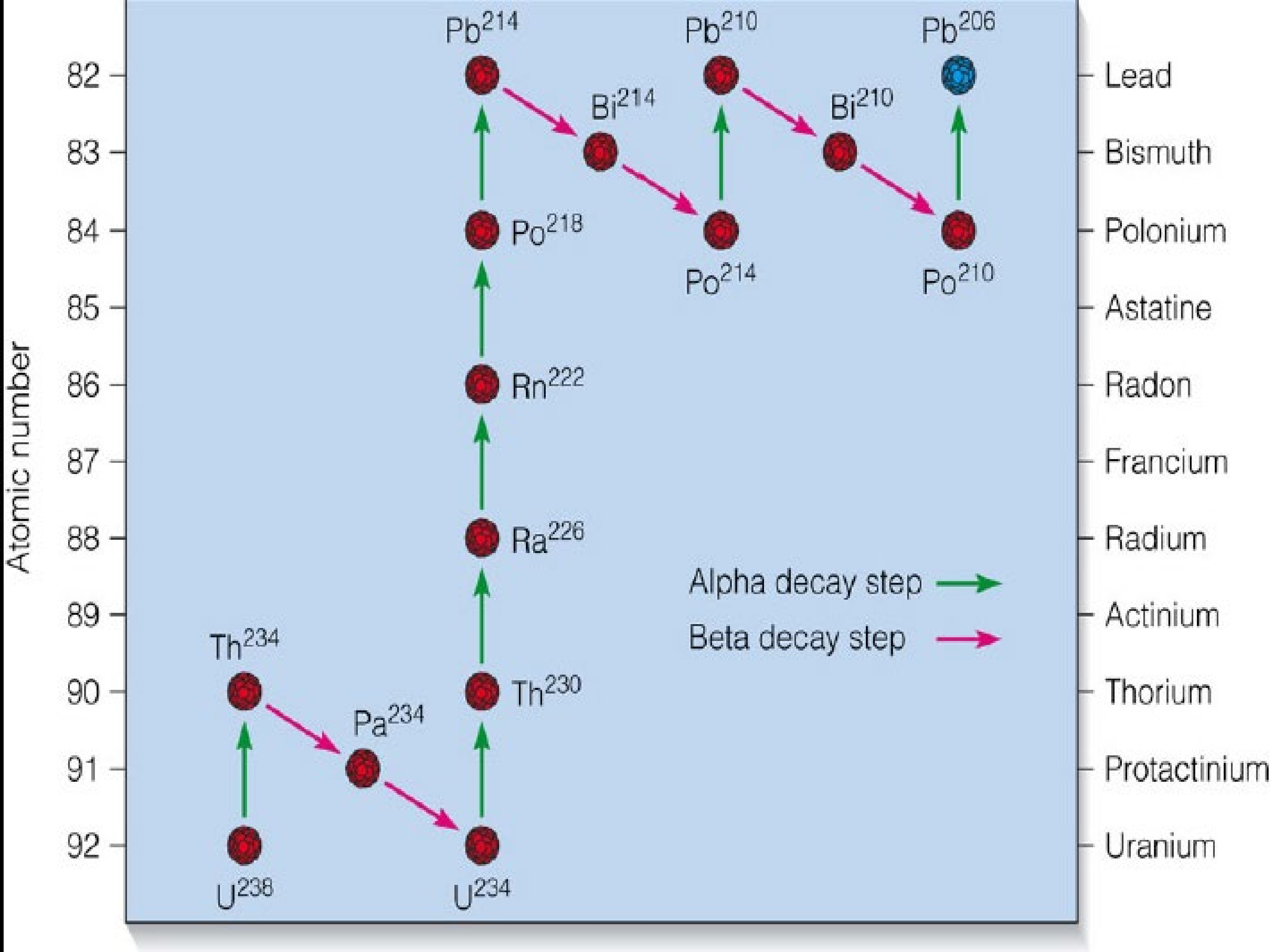
The Veil Nebula Complex in Cygnus

Acquired by Greg Parker
Processed by Noel Carboni

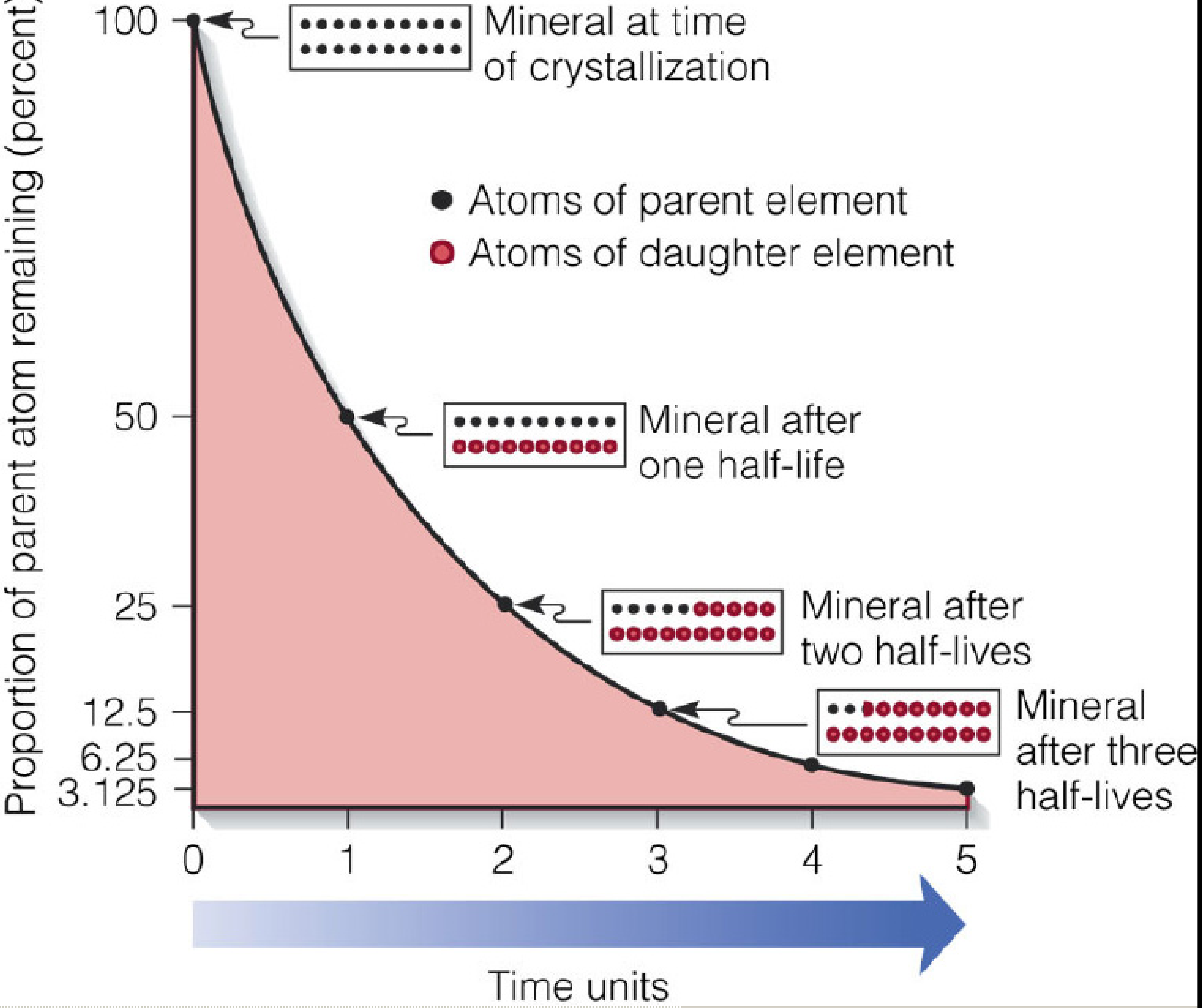
When Did This Happen?

- 4.567 billion years ago! How did we figure this out? Radioactive decay "clocks"…
- Zircon crystals crystallize out of molten rock while still at high temperature. Within their structure, they admit U (uranium) and Th (thorium) atoms, but strongly exclude Pb (Lead) during the crystallization process.
- So the Pb in these crystals could only have gotten there by radioactive decay of Uranium at the corresponding spots in the crystal.
- This makes them ideal crystals for age-dating any rock which contains them. The ratio of Pb-206 to U-238 tells the tale.


Parent nucleus
Alpha particle
Daughter nucleus
Changes in atomic number and atomic mass number
Alpha decay
Atomic number = –2
Atomic mass number = –4
Parent nucleus
Beta particle
Daughter nucleus
Beta decay
Atomic number = +1
Atomic mass number = 0
Parent nucleus
Daughter nucleus
Electron capture
Atomic number = –1
Atomic mass number = 0
Proton
Neutron
Electron



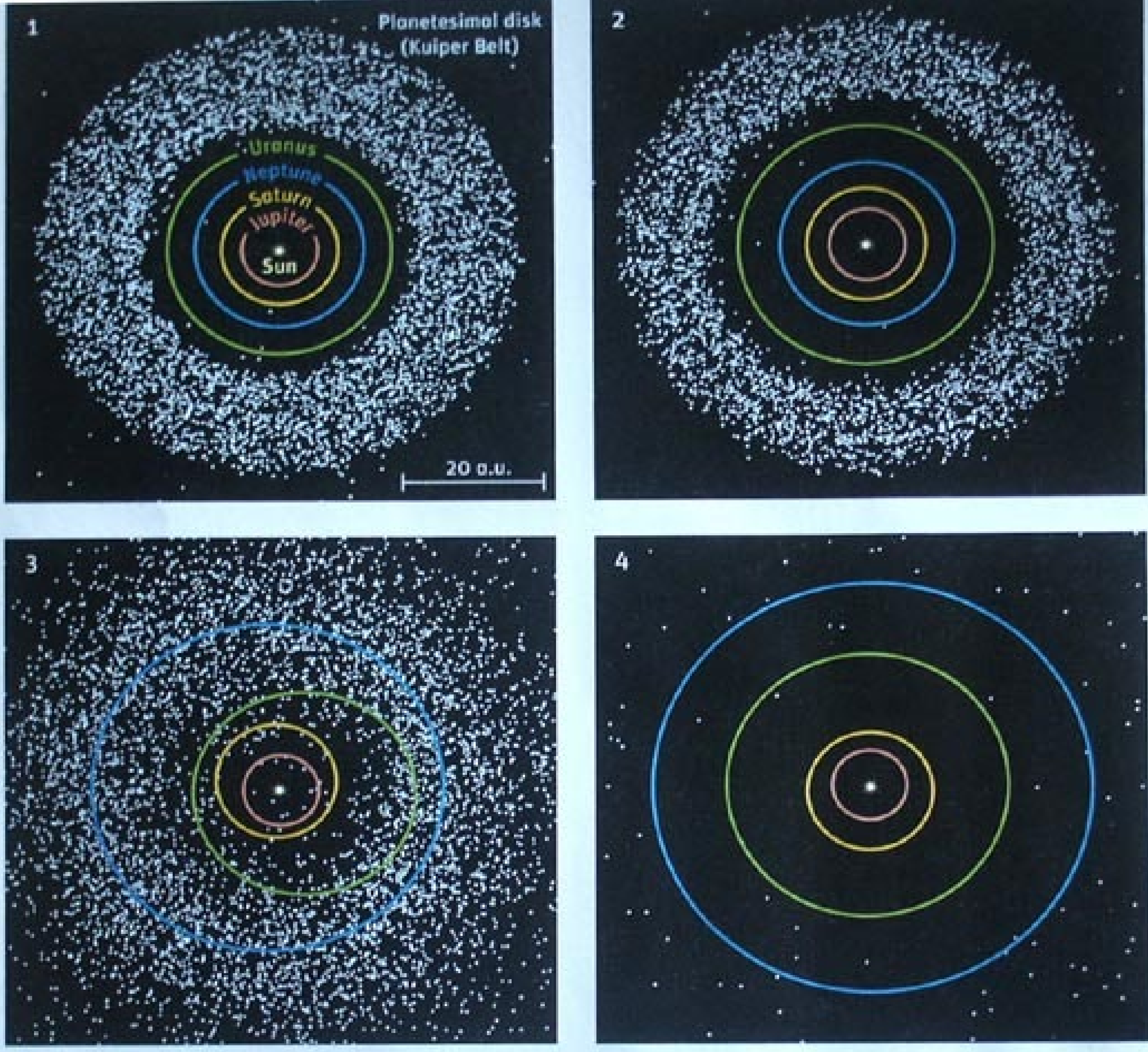
Atomic number
82
83
84
85
86
87
88
89
90
91
92
Lead
Bismuth
Polonium
Astatine
Radon
Francium
Radium
Actinium
Thorium
Protactinium
Uranium
U238
Th234
Pa234
U234
Th230
Ra226
Rn222
Po218
Pb214
Bi214
Po214
Pb210
Bi210
Po210
Pb206
Alpha decay step
Beta decay step



Proportion of parent atom remaining (percent)
100
50
25
12.5
6.25
3.125
Mineral at time of crystallization
Atoms of parent element
Atoms of daughter element
Mineral after one half-life
Mineral after two half-lives
Mineral after three half-lives
0
1
2
3
4
5
Time units

Other Early Excitement: Some Planet Swapping

- **Problem:** Gravity/Hydro computer codes and the distributed solar nebula inferred from current planet positions, will not allow a outer planets to grow as massive as they are in the ~10 million year time available.
- Desch *et.al.* (2008) show that packing the solar nebula tighter and evolving that forward can produce all the planets and Kuiper Belt observed in the time (~10 million years) needed to avoid major losses of the planetary material due to the solar wind.
- His simulations show the solar nebula mass migrating outwards, in general.
- The work also shows that Uranus and Neptune switched places, scrambling the KBO's and also pulling Jupiter and Saturn farther out, to their current positions.



Early migration of planets and scattering of the Kuiper Belt

Any successful Solar System Formation theory must explain some key patterns…

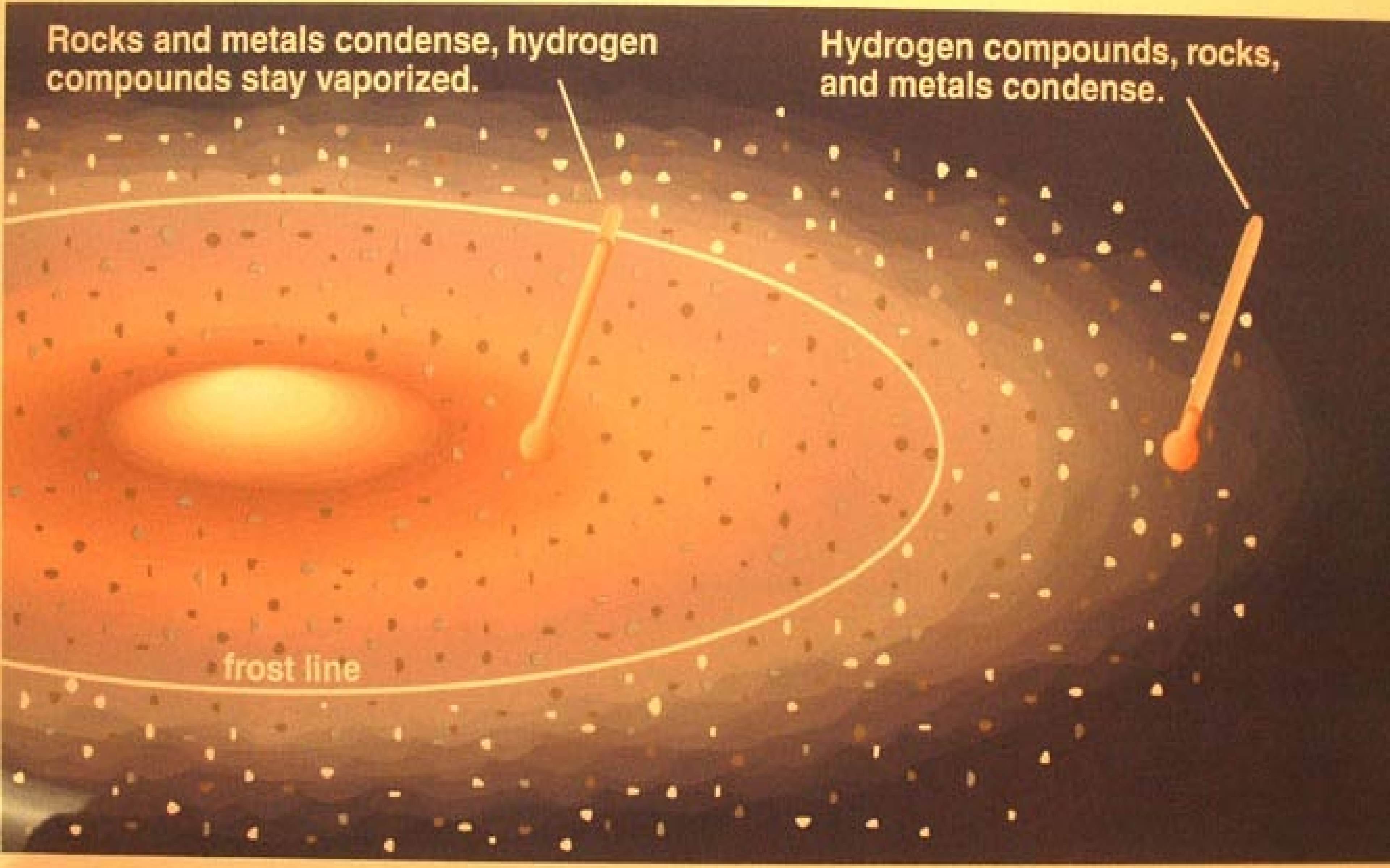
- 1. All planets orbit in the same plane
- 2. All planets orbit in the same direction
- 3. All planets have nearly circular orbits
- 4. Planet orbits are non-intersecting and with fairly regular spacings

Some General Features of Our Solar System

- Inner planets – Mercury, Venus, Earth, Mars –
- --small
- -- made almost completely of rock
- -- no natural moons or rings
- -- thin (or no) atmospheres, mostly of carbon dioxide (except Earth).

…Then the Asteroid Belt

- ~ a million rocks or rock/ice boulders, up to a few hundred miles across
- The large majority orbit between Mars and Jupiter
- Probably formed from the collisional breakup of several small planets which had unstable orbits due to Jupiter's strong gravity nearby


Rocks and metals condense, hydrogen compounds stay vaporized.
Hydrogen compounds, rocks, and metals condense.
frost line

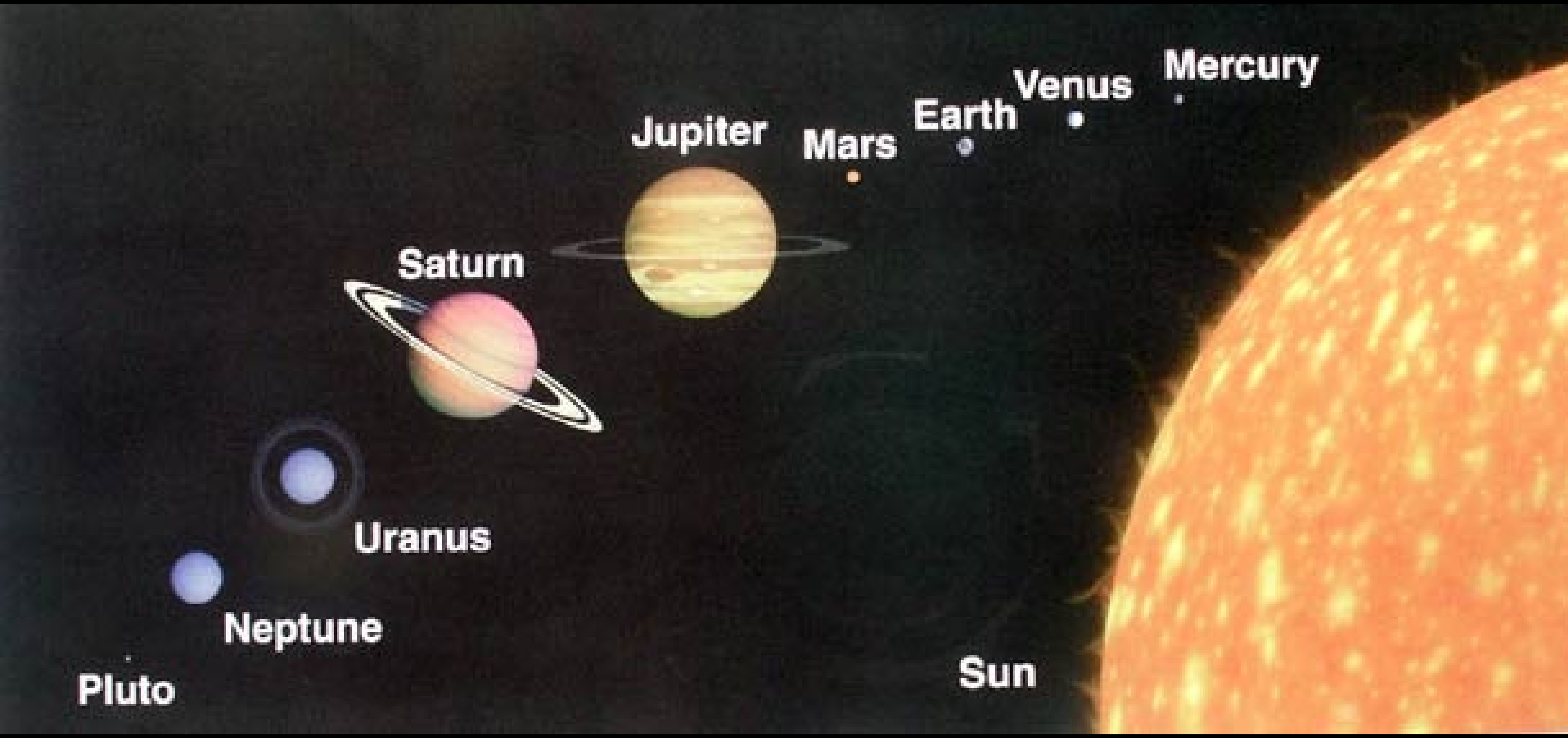
Beyond the Frost Line…

- Hydrogen compounds (mainly water) able to form snow flakes, then snow balls, and hang together to make self-gravitating proto planets
- Since hydrogen is the vast majority of ALL the mass in the solar nebula disk, being able to hang on to H and He means MASSIVE planets beyond the Frost Line

These Massive Planets are the Outer Planets

- Jupiter (2.5 times the mass of ALL other planets put together), with enough mass to make enough pressure to form liquid hydrogen, and rocky core at the bottom
- Saturn – small rocky core surrounded by a little liquid hydrogen and then deep layer of H and He
- Uranus and Neptune – smaller, small rock core and H, He envelope
- All have large natural moon systems
- All have rings of icy and/or dusty material

All the planets (Pluto is the Kuiper Belt stand-in)

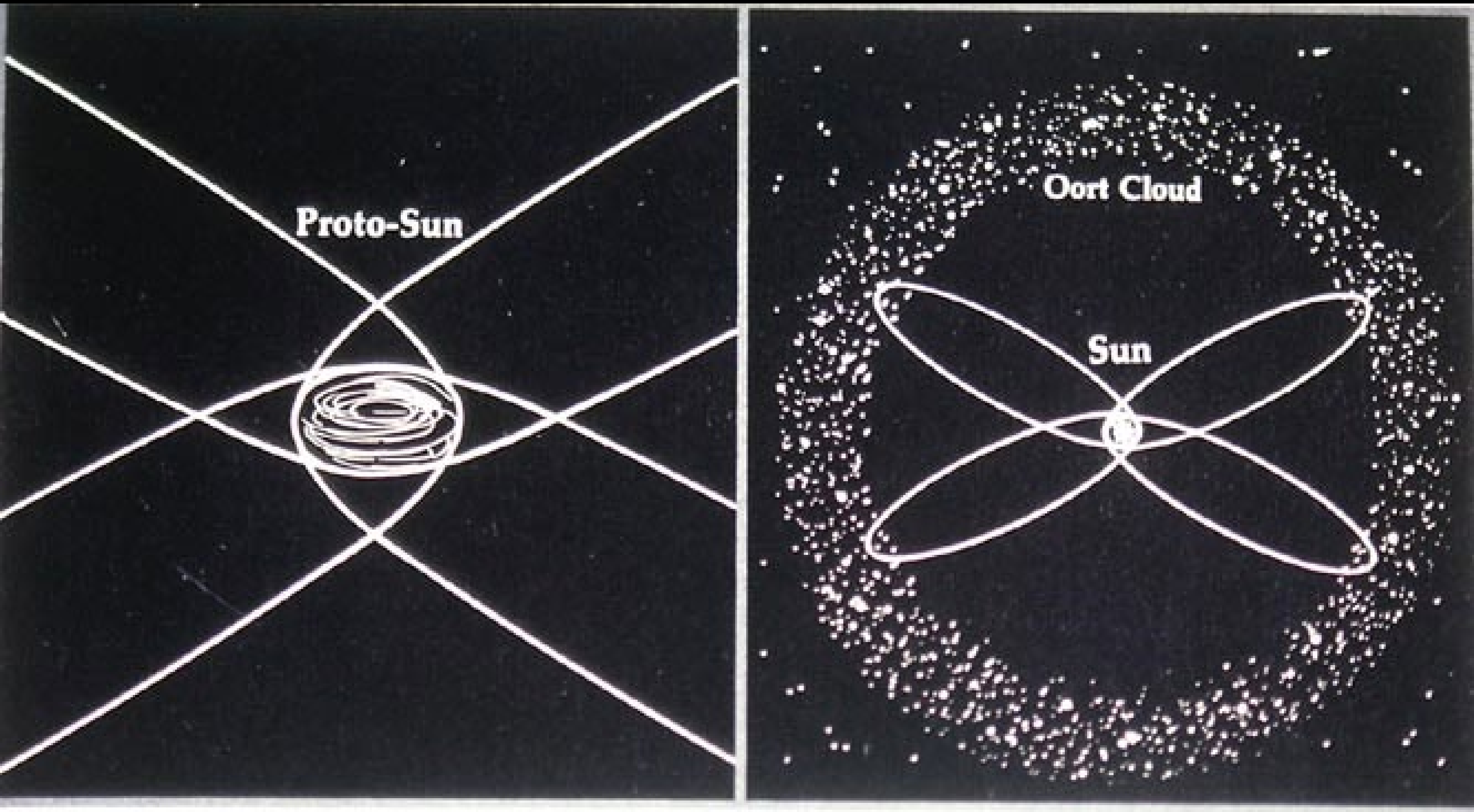


Beyond Neptune… the "Kuiper Belt" of Giant Ice Balls!

- Thousands or tens of thousands of balls of ice up to a few hundred miles across.
- Possibly the remnant of a once much larger reservoir of icy objects which were scattered by planetary migrations of Uranus and Neptune
- Perhaps out here the solar nebula was too sparse and collisions were too rare to pull together material into large planets

Finally, 100 times farther still…

- The **<u>Oort Cloud</u>** of comets
- Inferred from the observed orbits of comets which have their farthest points vastly farther away than Pluto.
- Ends ~½ light year from the sun – pretty much at the theoretical limit that objects can remain gravitationally bound to the sun for 5 billion years without getting tidally yanked off by other stars passing by.
- No flattened shape to the distribution of these objects – too little angular momentum to settle the material into a disk (or "belt"), so it's a roughly spherical "cloud"



Comets approaching a rapidly shrinking proto-Sun would be drawn into elongated elliptical orbits as the proto-Sun decreased in size. Stellar perturbations could then alter these orbits to form the Oort Cloud.

Other Solar Systems Around Other Stars

- Stars form around other stars in Open Star Clusters, leading to angular momentum in infalling material, disks, and solar systems expected therefore to be common
- Exoplanets = planets around other stars
- How do we discover them?
- How do selection effects bias our results?
- What are these exoplanets like?
- Can we detect their atmospheres, climate?

Discovering Other Solar Systems

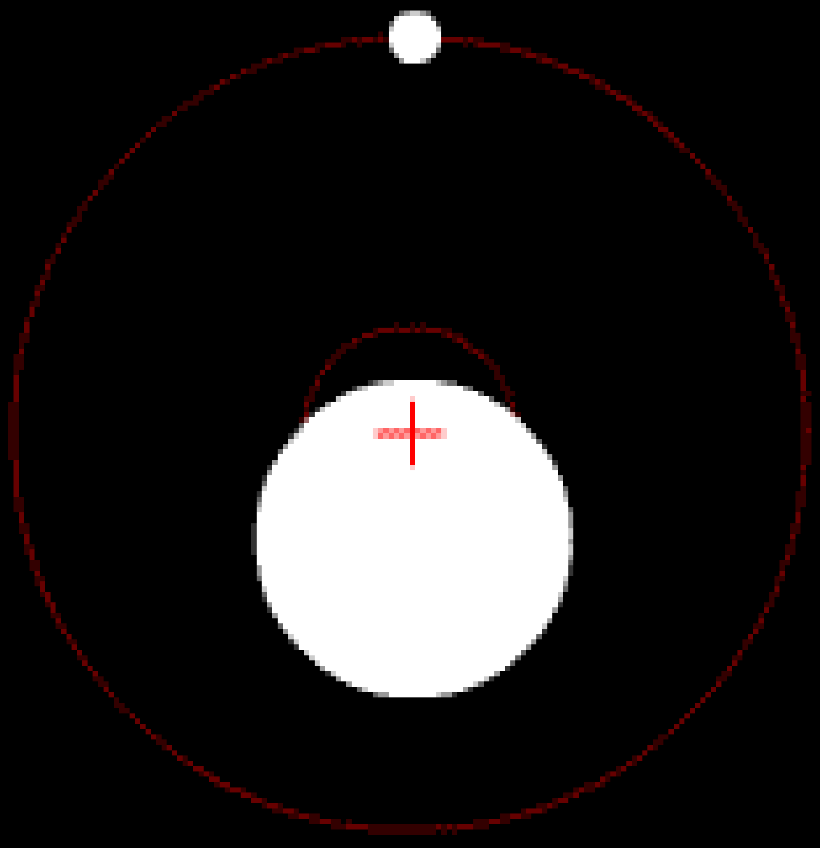
- How do we find planets around other stars? It's hard!!
- Planets are too faint, too close to parent star to actually "see", except in a tiny handful of cases. Must be clever (as always! Astronomers are good at that)
- There are **3 methods of finding exoplanets** today…

- **1. Periodic Doppler shifts in parent star's spectral lines show Newton's 3rd Law (action/reaction) reflex motion of the star as the planet orbits**
- **2. Transits of planet in front of star result in tiny drop in star's brightness.**
- **3. Direct Imaging: By far the hardest!**

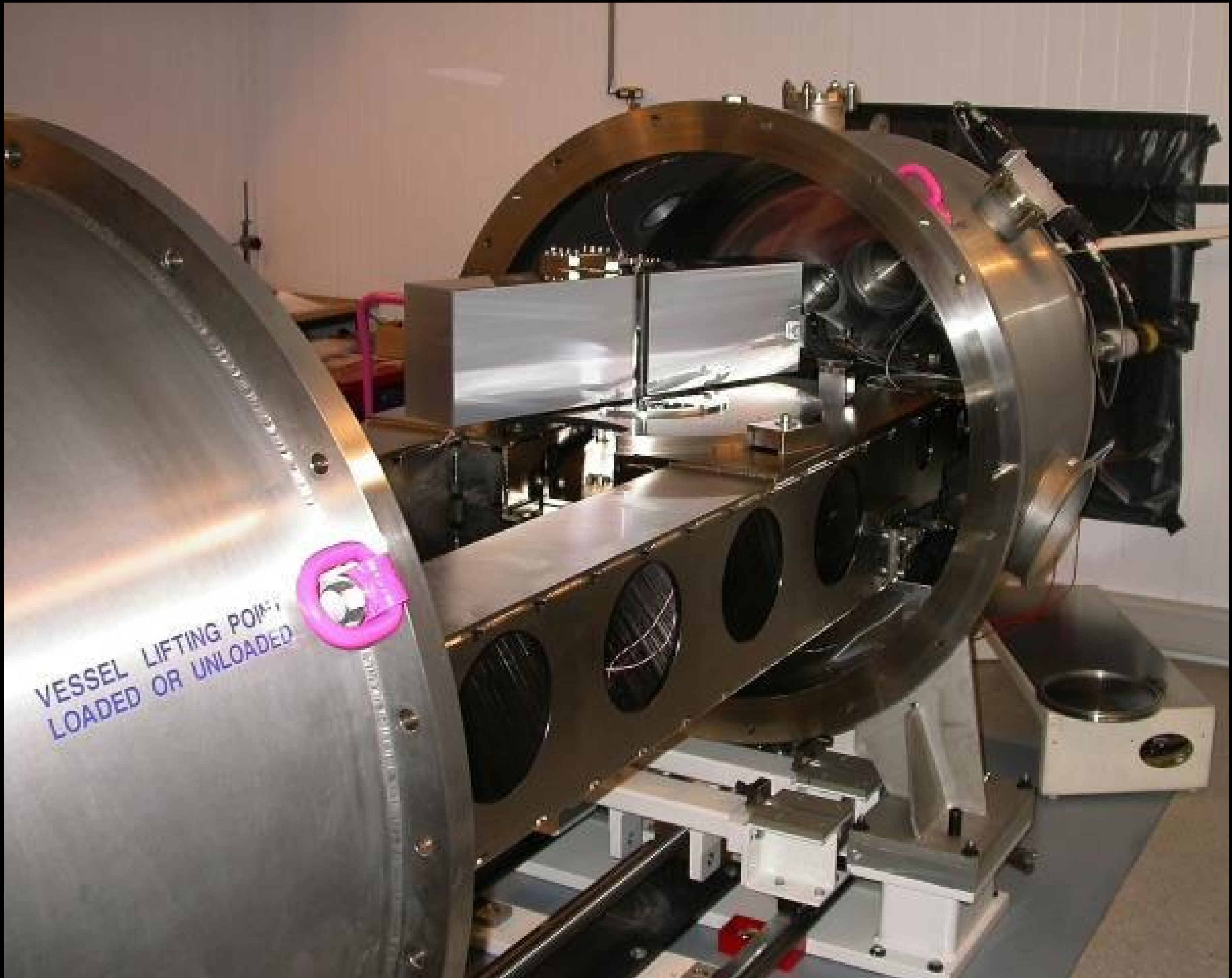
<u>Doppler Method</u>: From the Ground, this is the least-hardest Way to Find Solar Systems - Observing Periodic Doppler Shifts in the Parent Star

- Stars are massive, planets are not…
- So, the Doppler Shifts of the parent star would be tiny.
- Even mighty Jupiter is only 1/1000 the mass of the sun.
- It moves at a speed of 12.7 km/sec in its orbit, so the sun moves only 1/1000 of that, or 13 meters/sec
- So v/c is 4×10^{-8} or 40 billionths or 1 part in 25 million!!
- Wavelength shifts of only 1 part in 25 million, even assuming the orbital plane allows all of that to be line-of-sight and so detectable by the Doppler shift. Very hard!
- It means we're going to bias the kinds of solar systems we can find
- Need high precision, expensive **<u>spectrographs…</u>**

Orbiting Planet's Gravity Makes the Star Orbit too: Doppler Effect Makes That Detectable



The HARPS Spectrograph

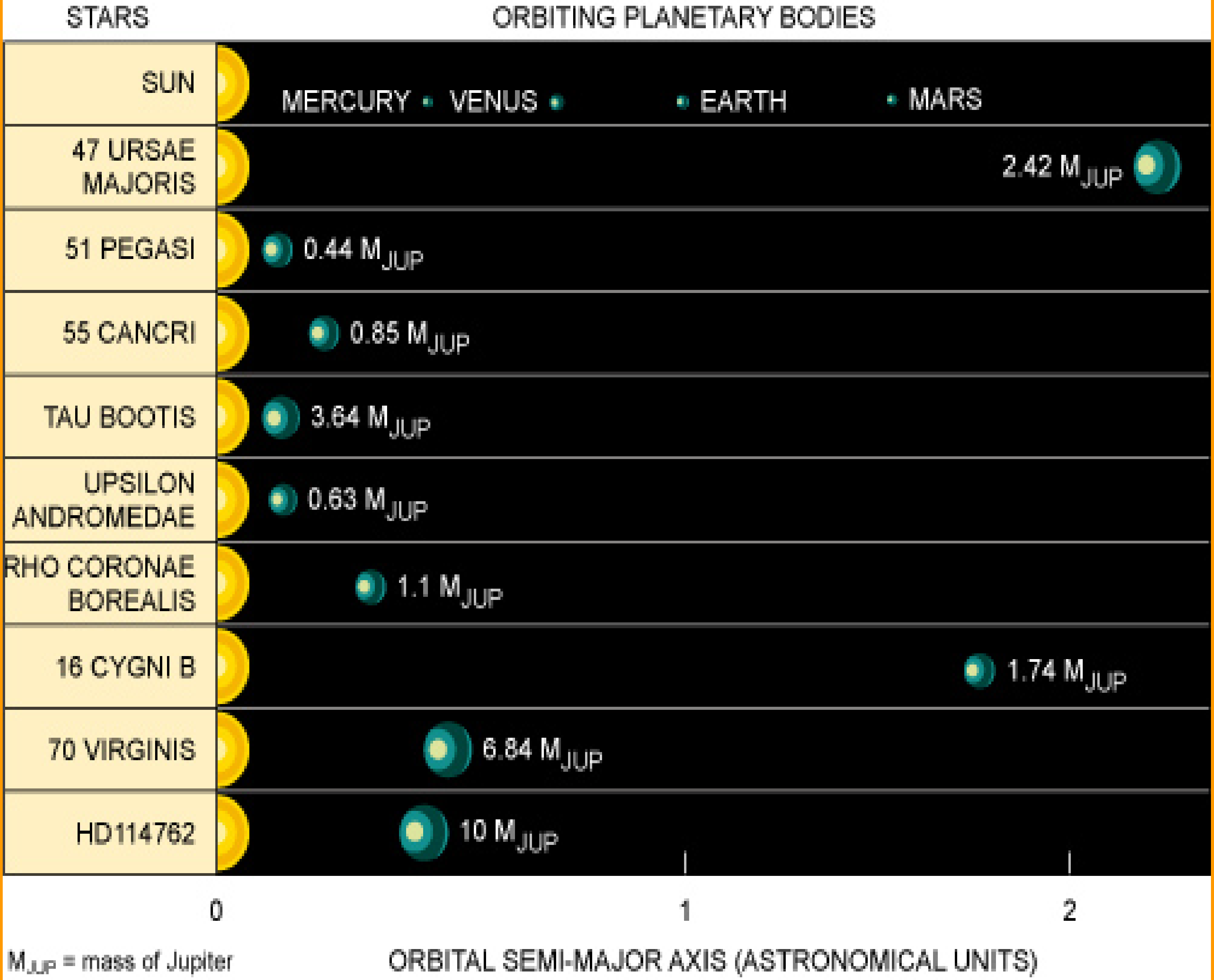


Strong Selection Effect from the Doppler Method

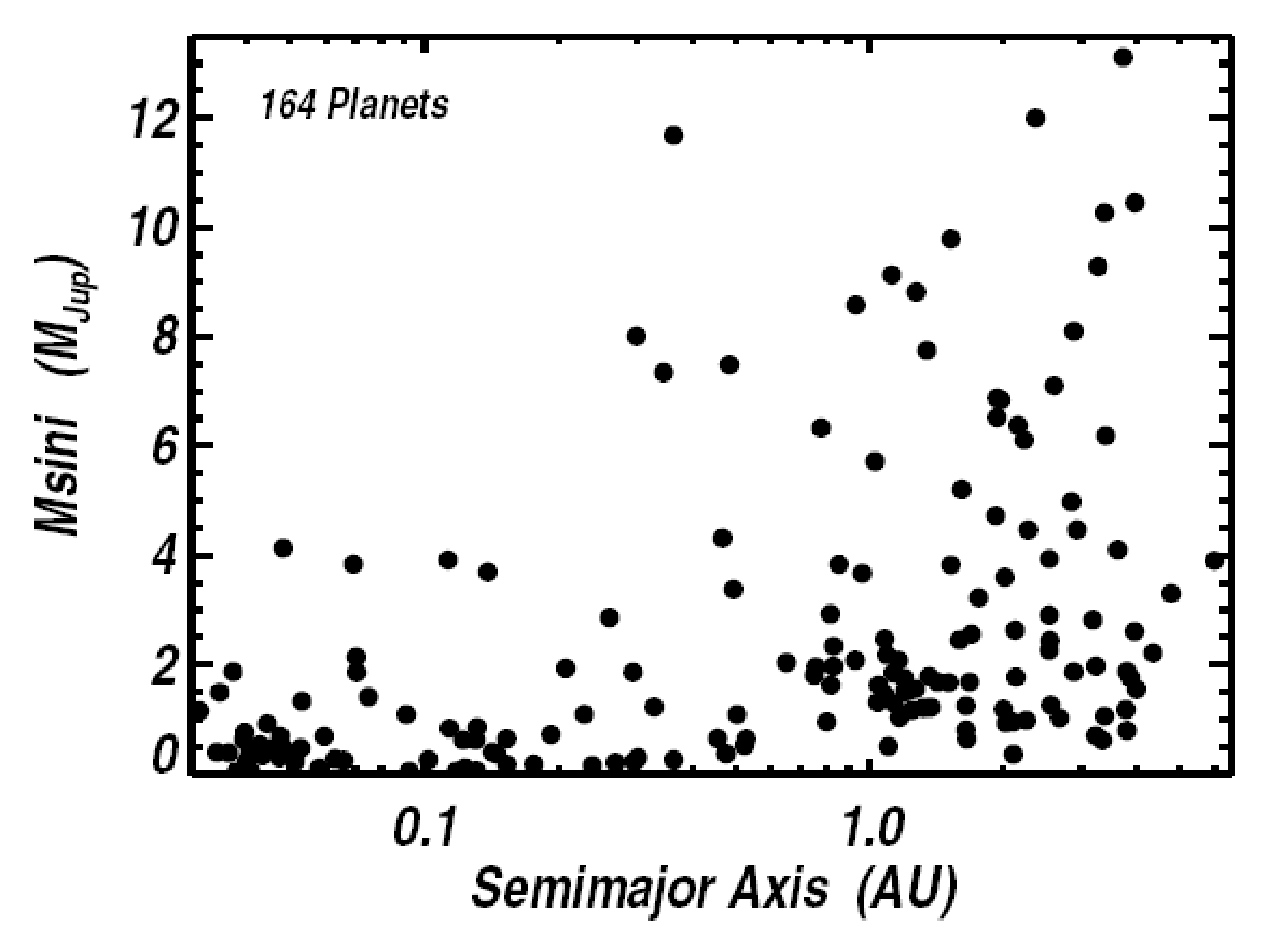
- The signal-to-noise ratio will be too small to detect unless the planet is MASSIVE and the planet is CLOSE to the parent star, so that the parent star is reaction'ing as FAST AS POSSIBLE
- That means the method is highly biased to find BIG Jupiter-like planets in orbits well inside the equivalent of Mercury's orbit.
- "**Hot Jupiters" is what we call such exoplanets**
- From what we've learned in class, this sounds like a pretty unlikely situation! Heavy elements are rare, massive planets must be made mostly of the dominant chemical elements – hydrogen and helium. These would evaporate away on a time scale which is likely short compared to the age of the system.

But Perseverance Pays!

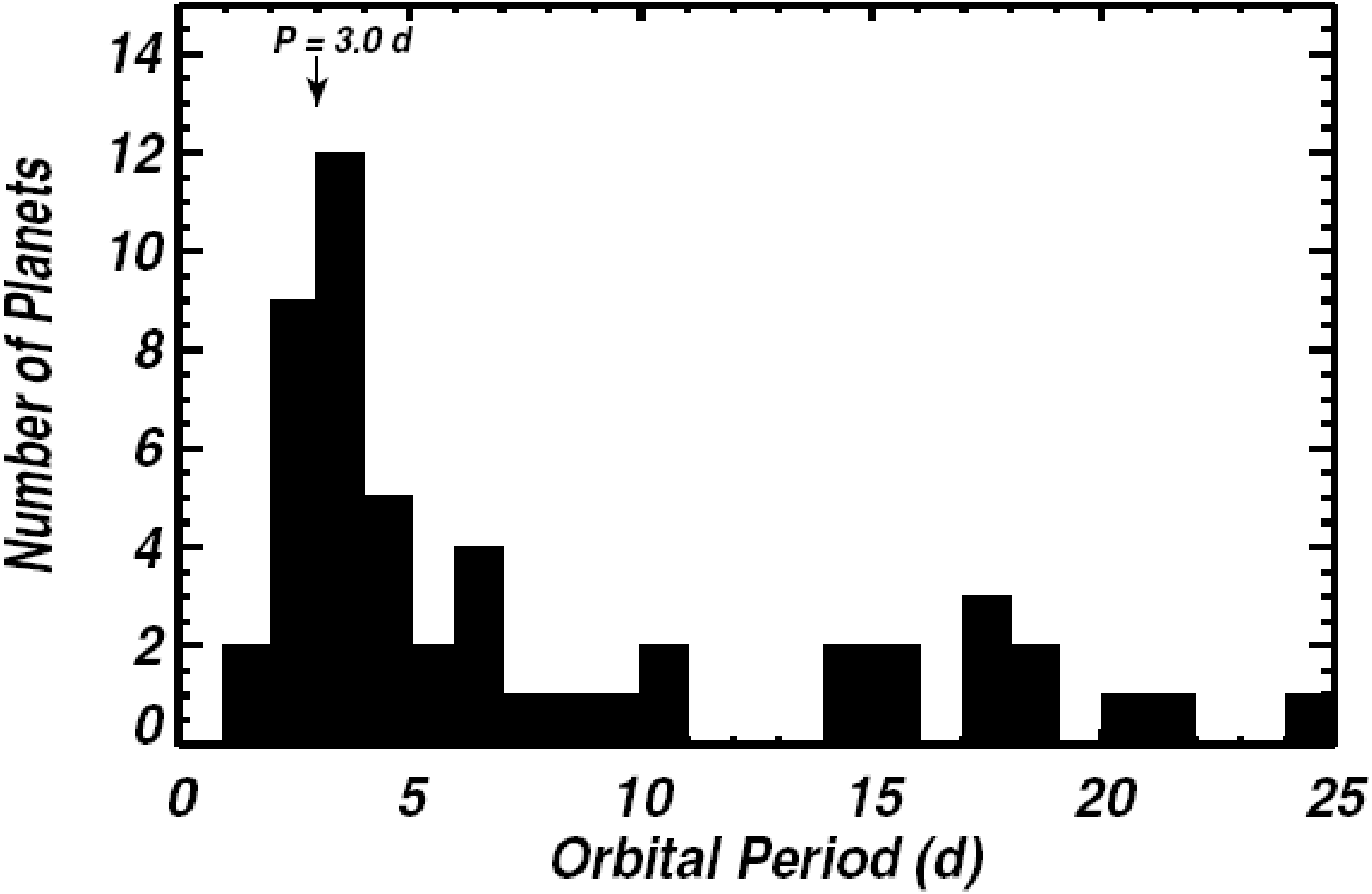
- So, we were not optimistic about finding ANY planets with 1990's technology. But Queloz and Mayor in Europe, and Marcy and Butler in the U.S., initiated searches
- They carefully monitored the position of spectral lines for a large number of bright stars, taking frequent observations over years, and….. **found tiny Doppler shifts... Planets!**
- As of Sept 2013, about 800 nearby stars have had planetary systems discovered around them, 150 by Kepler Mission via transit method, the rest by Doppler method.
- Today, 4200 Kepler Mission likely solar systems discovered by transit method, 1000 confirmed. More than by Doppler Method.
- Calculated implications: **over 90% of sun-like stars are have planetary systems around them!**


STARS
ORBITING PLANETARY BODIES
SUN
MERCURY
VENUS
EARTH
MARS
47 URSAE MAJORIS
2.42 M JUP
51 PEGASI
0.44 M JUP
55 CANCRI
0.85 M JUP
TAU BOOTIS
3.64 M JUP
UPSILON ANDROMEDAE
0.63 M JUP
RHO CORONAE BOREALIS
1.1 M JUP
16 CYGNI B
1.74 M JUP
70 VIRGINIS
6.84 M JUP
HD114762
10 M JUP
0
1
2
M JUP = mass of Jupiter
ORBITAL SEMI-MAJOR AXIS (ASTRONOMICAL UNITS)

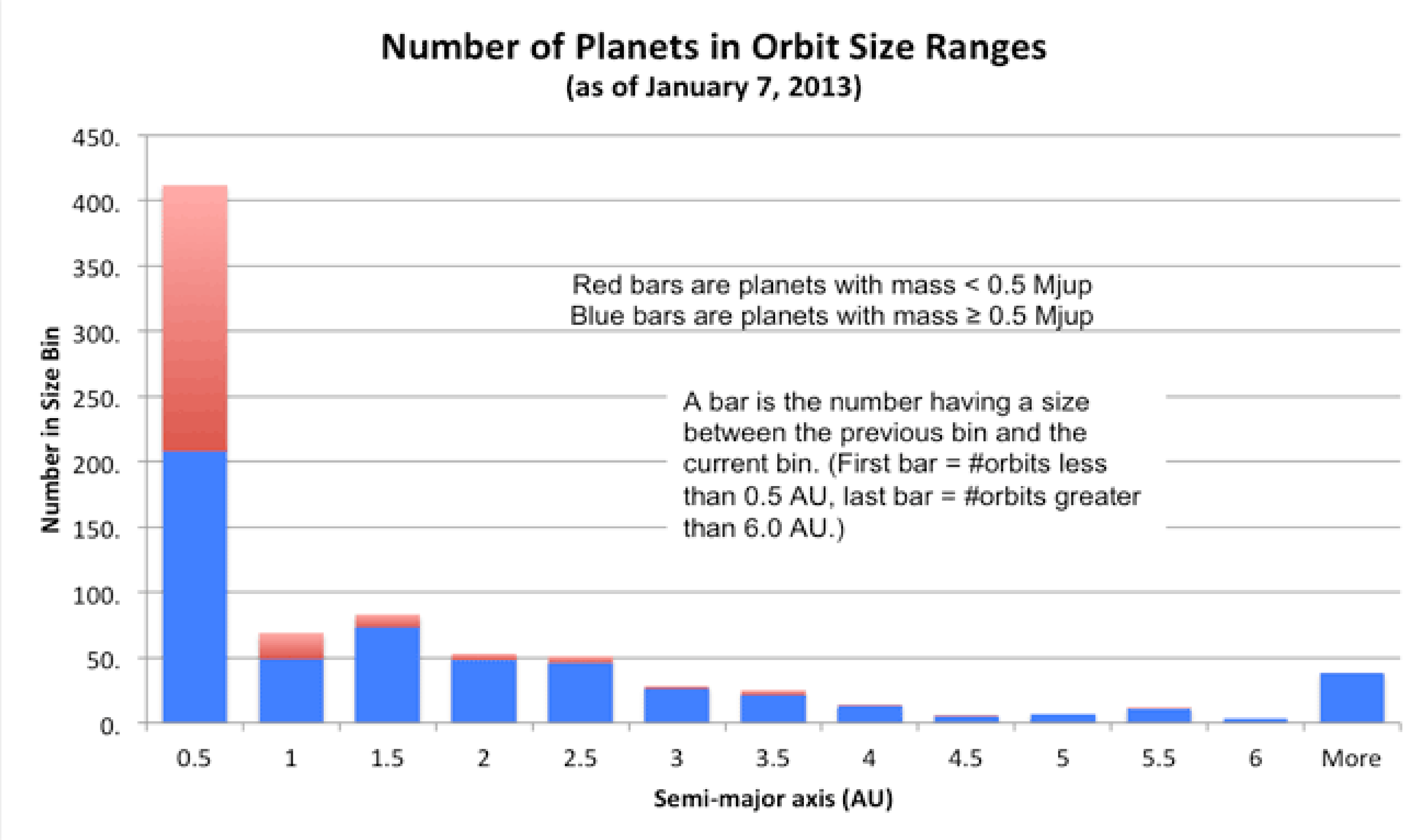
The Large Majority of Early Discoveries by Doppler Method: Lots of “Hot Jupiters” Found



Orbital Periods of a Month or Less Give the Strongest, Easiest Signal; First to be Found



Even Transit method is biased Towards Close-in Discoveries. Most Discoveries Correspond to Inside Venus' Orbit



Clearly, We Don't Think Such "Jupiters" Can Form So Close to Stars

- It's too hot, and the amount of rocky material is always a tiny fraction of the total mass – which is mostly Hydrogen and Helium and would not collect onto such a massive small rocky core to make a "hot Jupiter".

But Then How Can There be So Many Hot Jupiter Systems?

- **<u>Planetary Orbit Migration!</u>**
- What if Jupiter's can MIGRATE inward from their cold distant birth place, and find themselves in close to their star for a reasonable amount of time before they evaporate?
- Two Prime Mechanisms can cause planetary migration…

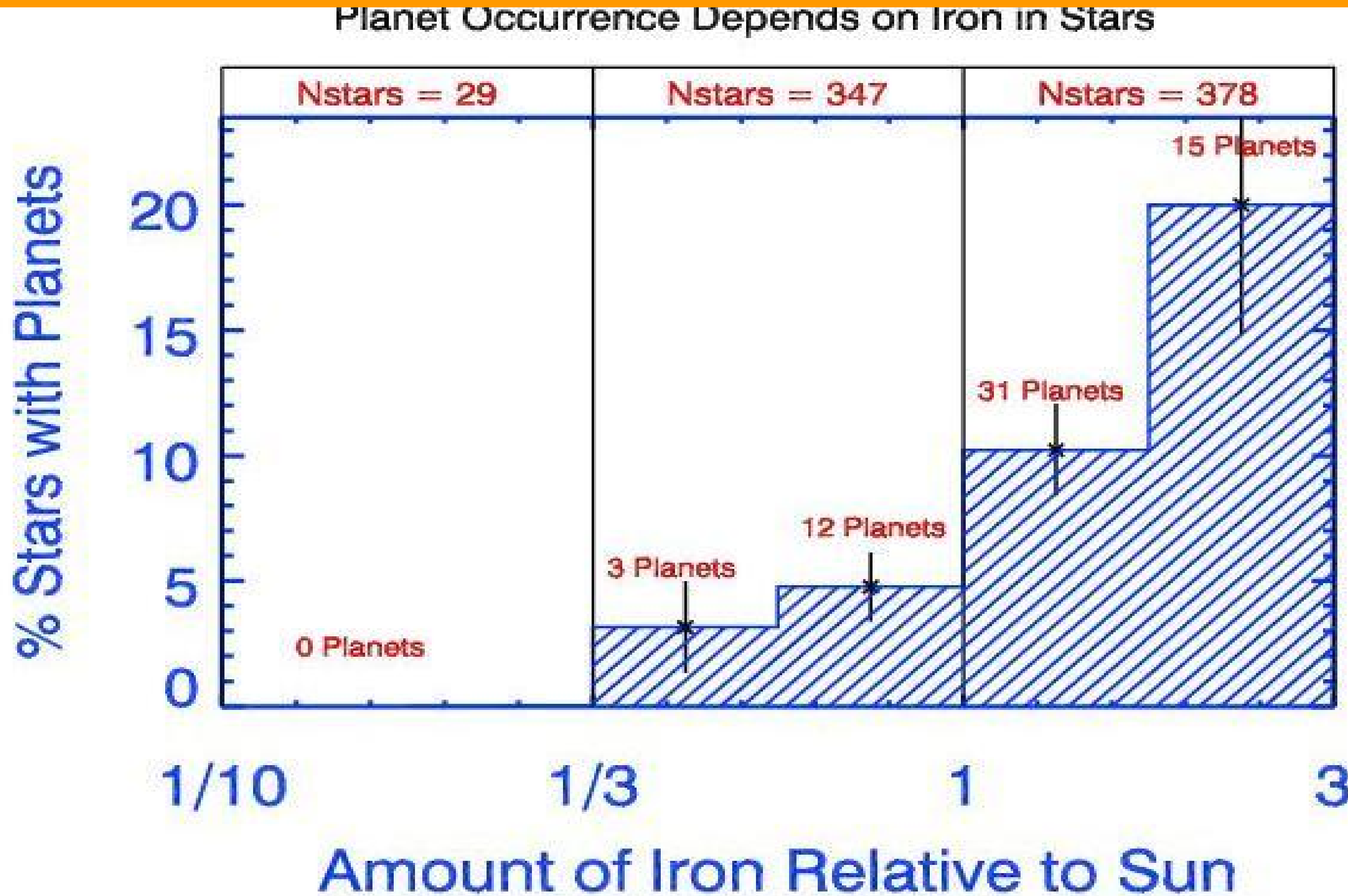
1. Disk Friction Drags Planet Inward

- A disk of dust will feel much internal friction due to the differing rotation speeds at neighboring radii.
- Friction turns to heat, radiated away, and the energy loss is subtracted from the orbital motion energy of the disk particles.
- Gas is lightweight enough that it'll more tend to be blown away by the stellar winds and radiation pressure.
- But dust will not feel nearly so much, and a thick dust disk will instead tend to fall towards the star as this frictional energy dissipation of orbital energy proceeds
- So this mechanism requires dust, and dust is made of "metals" (elements heavier than helium).
- ***Do high-metallicity stars have planets? Yes!***

Giant planets take shape far from their star, where raw material is abundant. But astronomers have found scores of giants that apparently migrated inward after forming. In one theory, the process begins as a newborn giant carves a gap in the disk of gas and dust swirling around a young star (below left). The gap doesn't stay put: Friction between particles and gas molecules gradually slows down the disk. The material spirals inward, carrying the gap—and the planet—with it (below).

ART BY MOONRUNNER DESIGN. CONSULTANT: DEREK C. RICHARDSON, UNIVERSITY OF MARYLAND

Stars with High Metallicity Are More Likely to Have Planets…

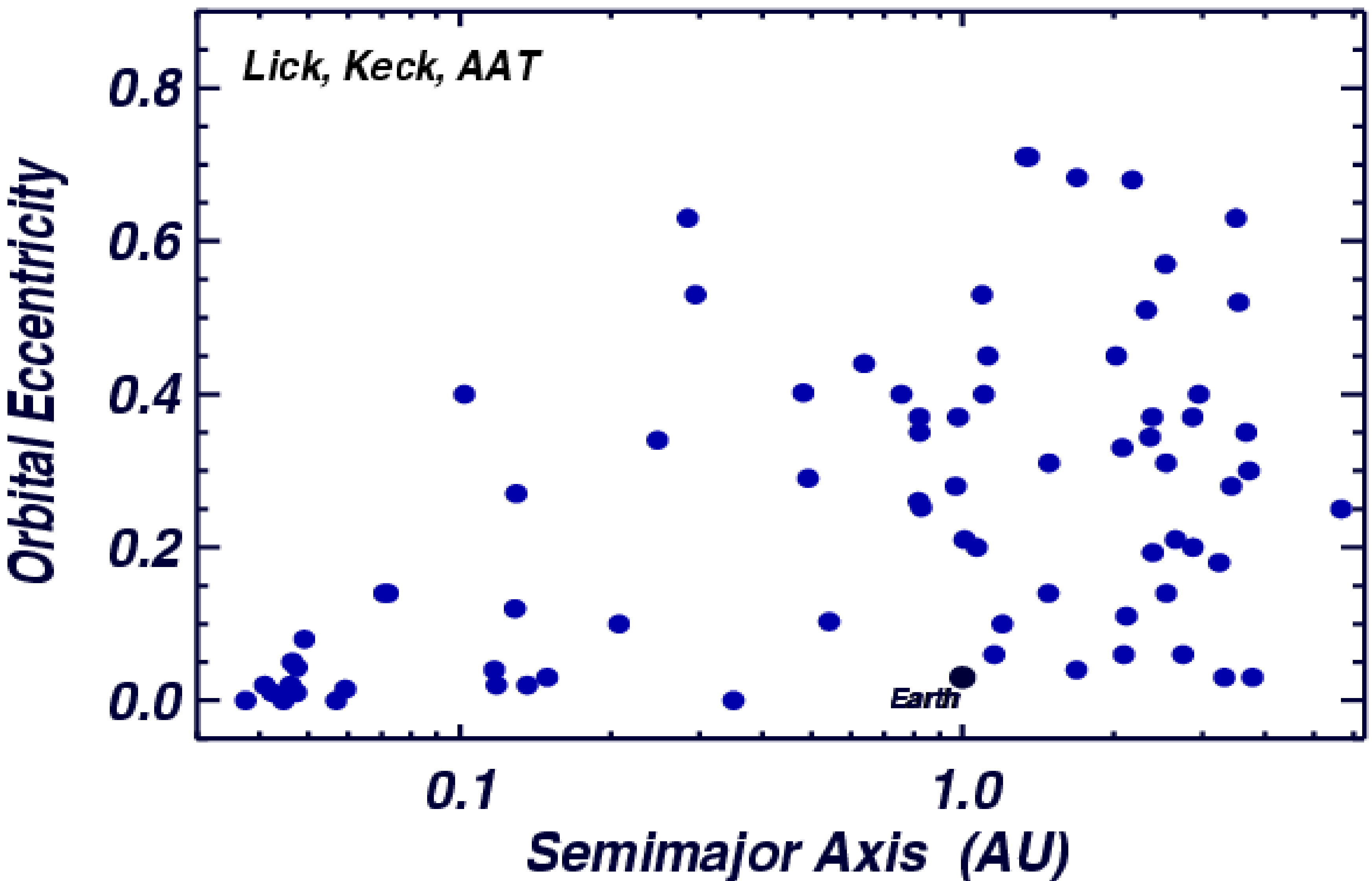


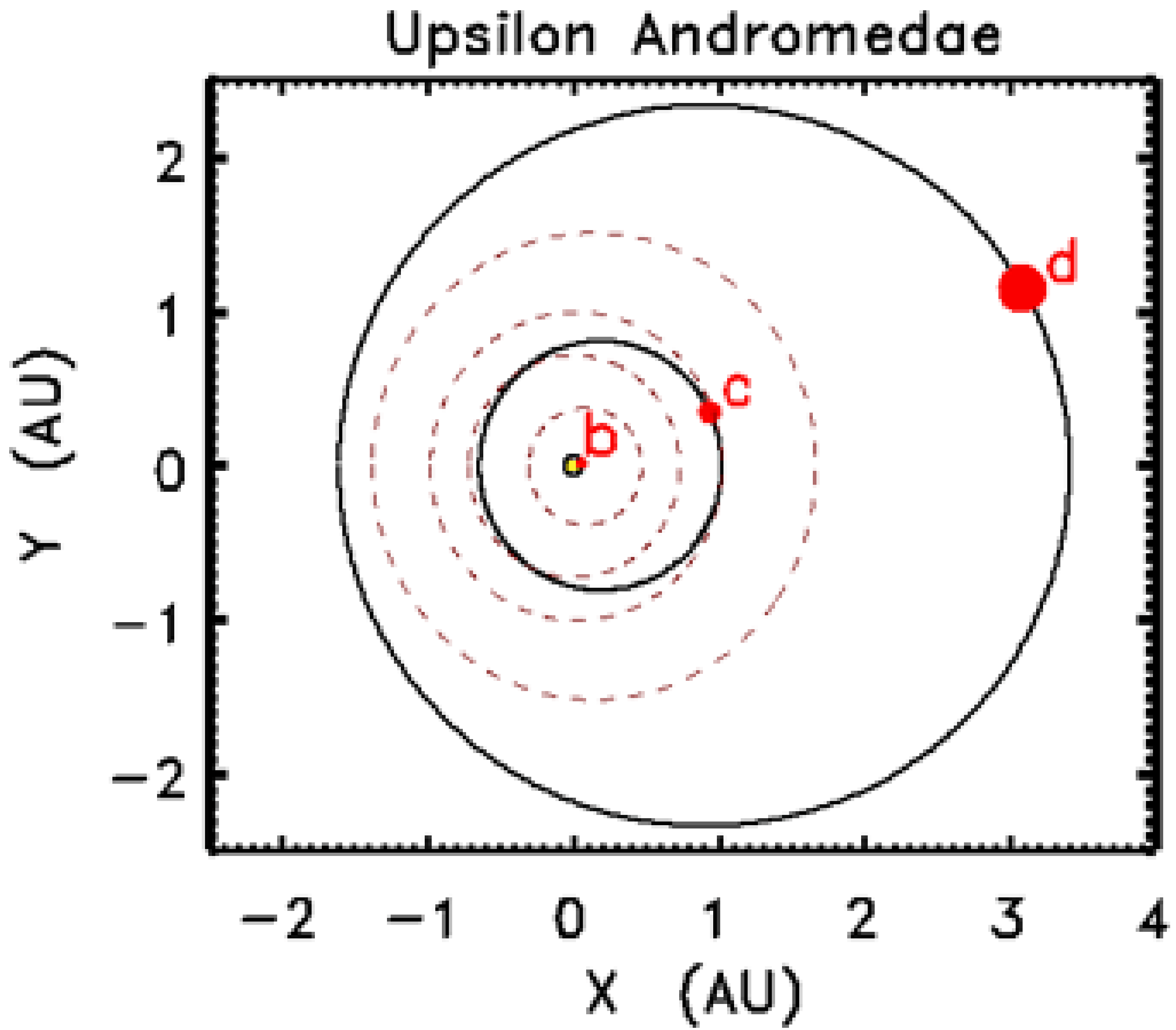
Fischer & Valenti

2. Resonance-induced Close Encounters w/ Other Planets

- Planets should, by physics, form in fairly circular orbits since the disk gas/dust will be in circular motion, with plenty of space between planets by the time formation is about done.
- But resonances can amplify eccentricity of an orbit, to the point of orbit-crossing (close encounter possible!), and then the two planets could end up almost ANYwhere, and very likely on fairly eccentric orbits.
- The older a solar system is, the more time for even weak resonances to build up to this point.
- Computer simulations show eccentric orbits should be the rule, which would argue that our own solar system is very unusual (our system has most planets in pretty circular orbits, and no evidence of migration for any planets except Neptune and Uranus.

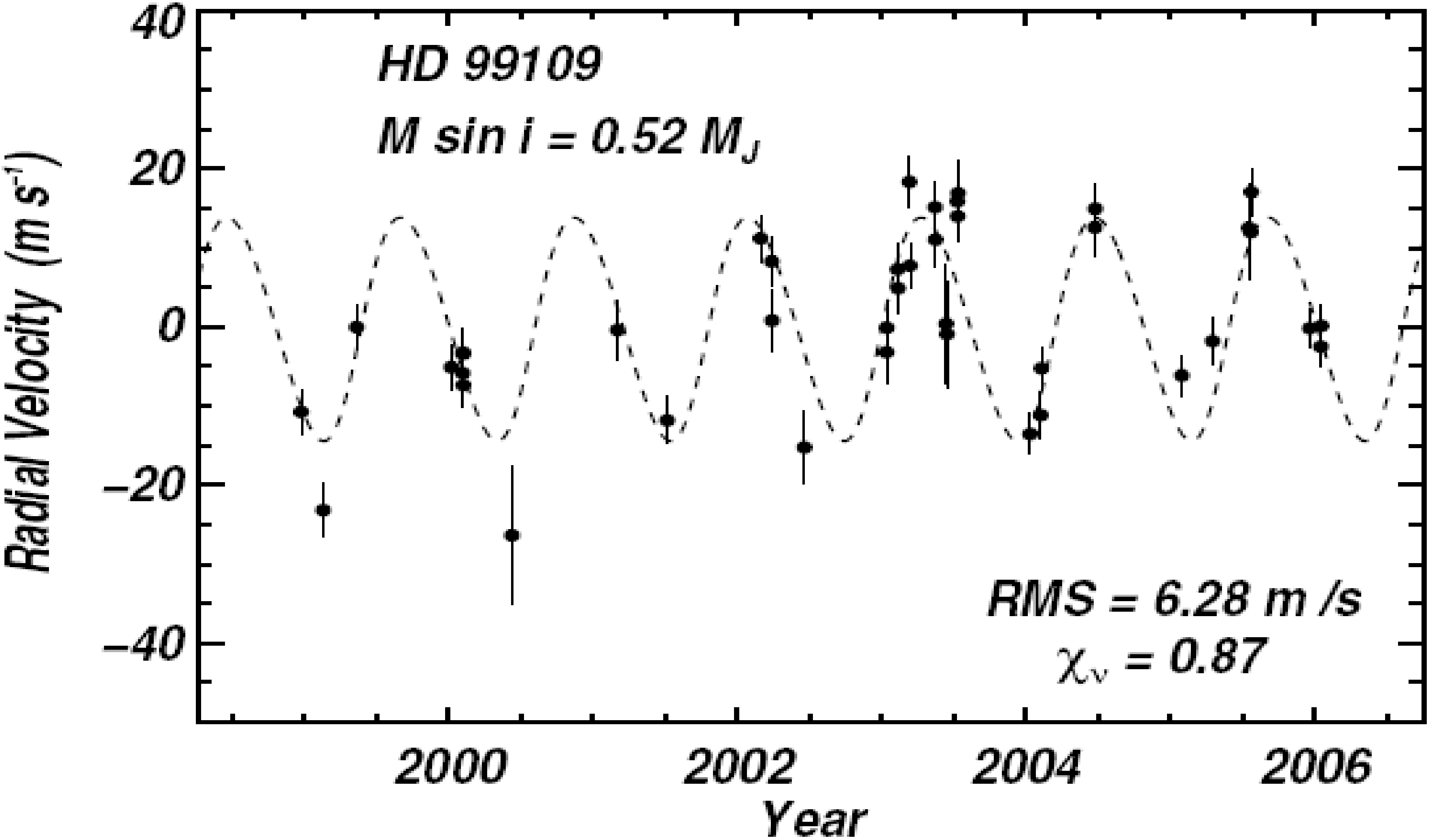
We see… lots of planets have very eccentric orbits, unlike the circular orbits of our own Solar System. Dynamics indicates this is caused by migration



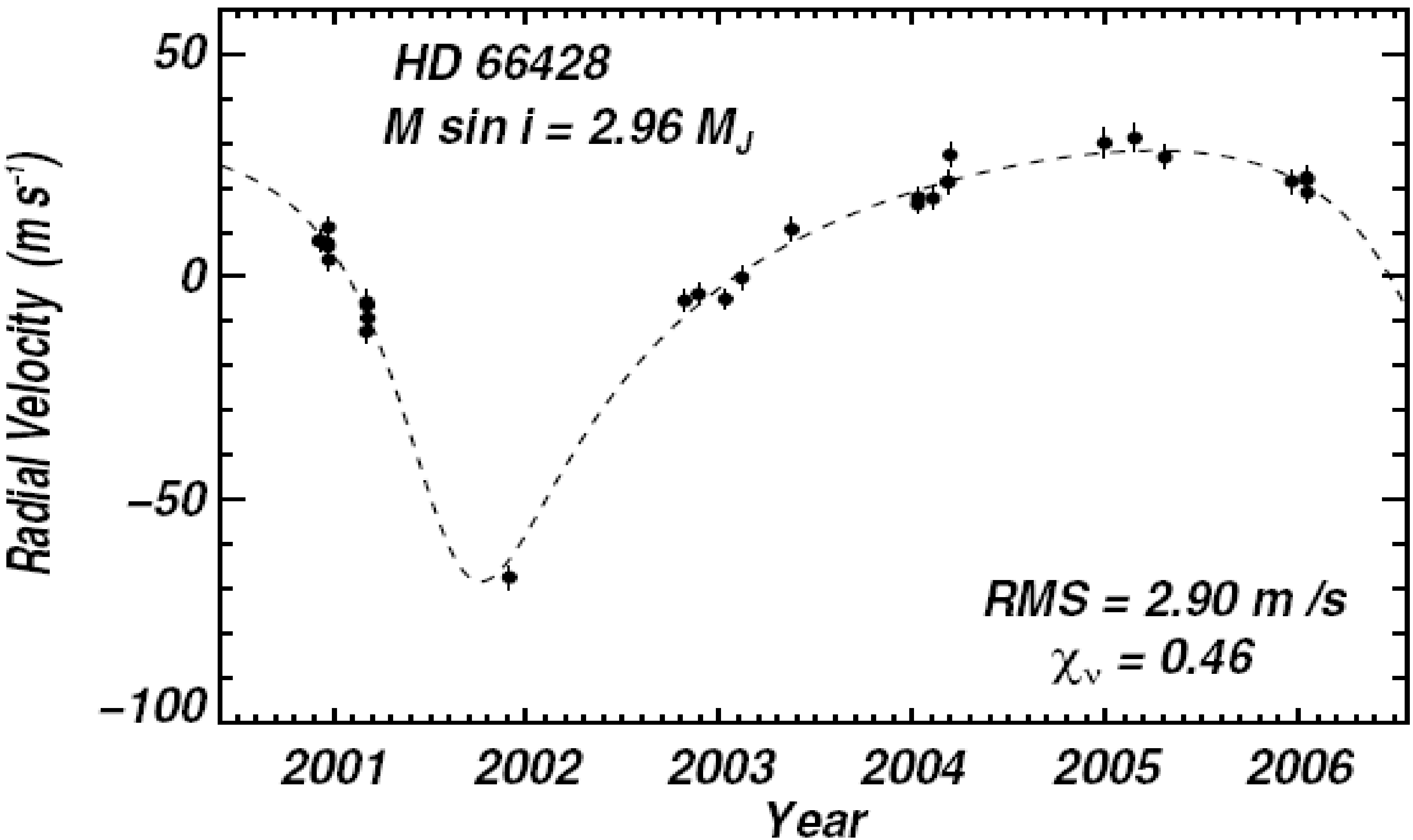


Upsilon Andromedae
b
c
d
Y (AU)
X (AU)
2
1
0
−1
−2
−2
−1
0
1
2
3
4

A Fairly Circular Orbit Fits For This One



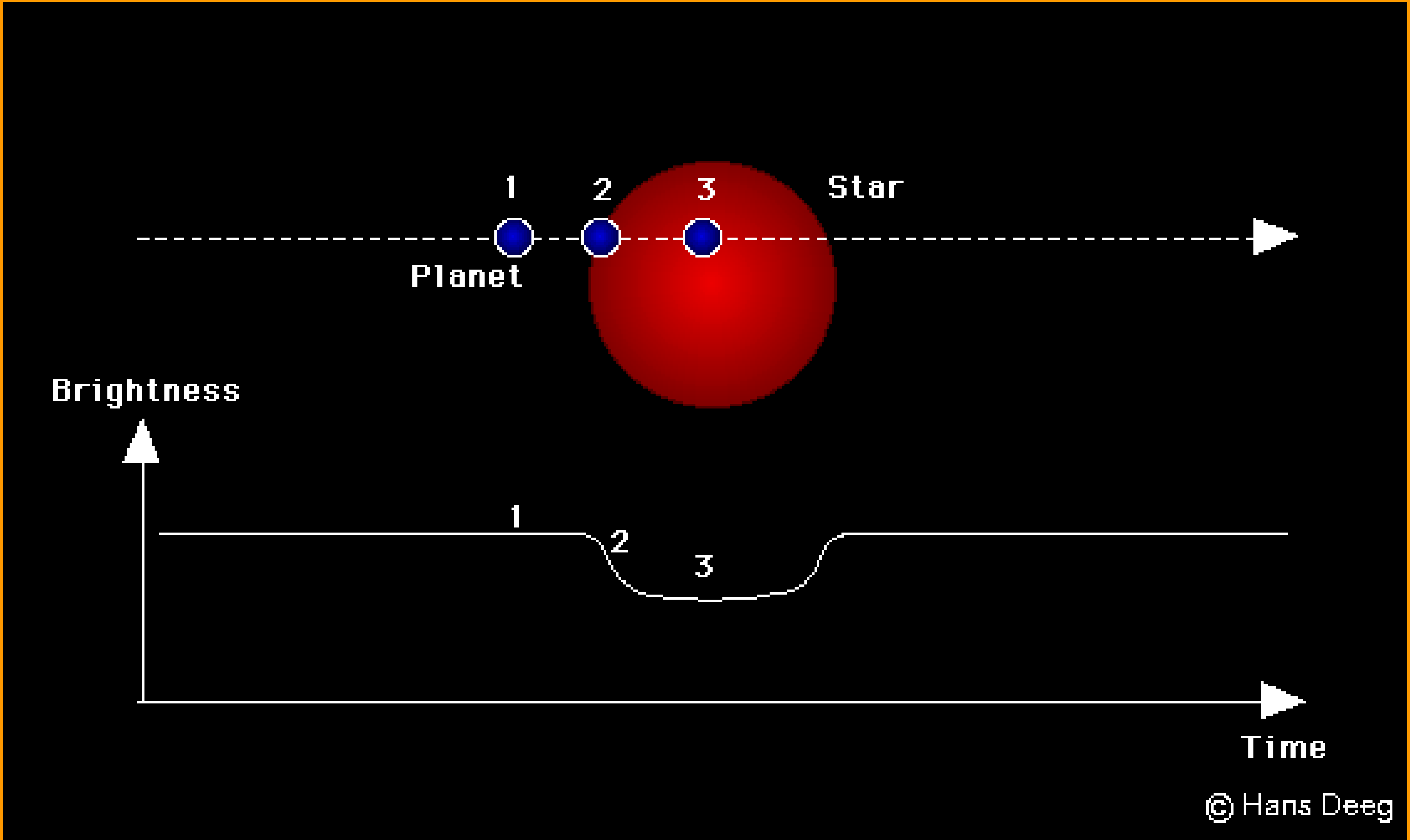
But A Very Elliptical Orbit Needed for a Good Fit Here



So far, No Truely Earth-like Planets Have Been Discovered

- In part that's because Earth is so tiny even Kepler has a hard time detecting such small planets.
- In part, we do think Earth-like planets (vs. just Earth-*sized* planets) are rare.
- But interest is high – we want to find planets which may have life. We want to know we're not alone out here!
- Discovery of Earth-like planets requires **transit** data to measure their size and therefore get their density (rock? Ice? Gas?).

The Transit Method: Transiting Planets Discovered by Precision Monitoring of Star’s Brightness



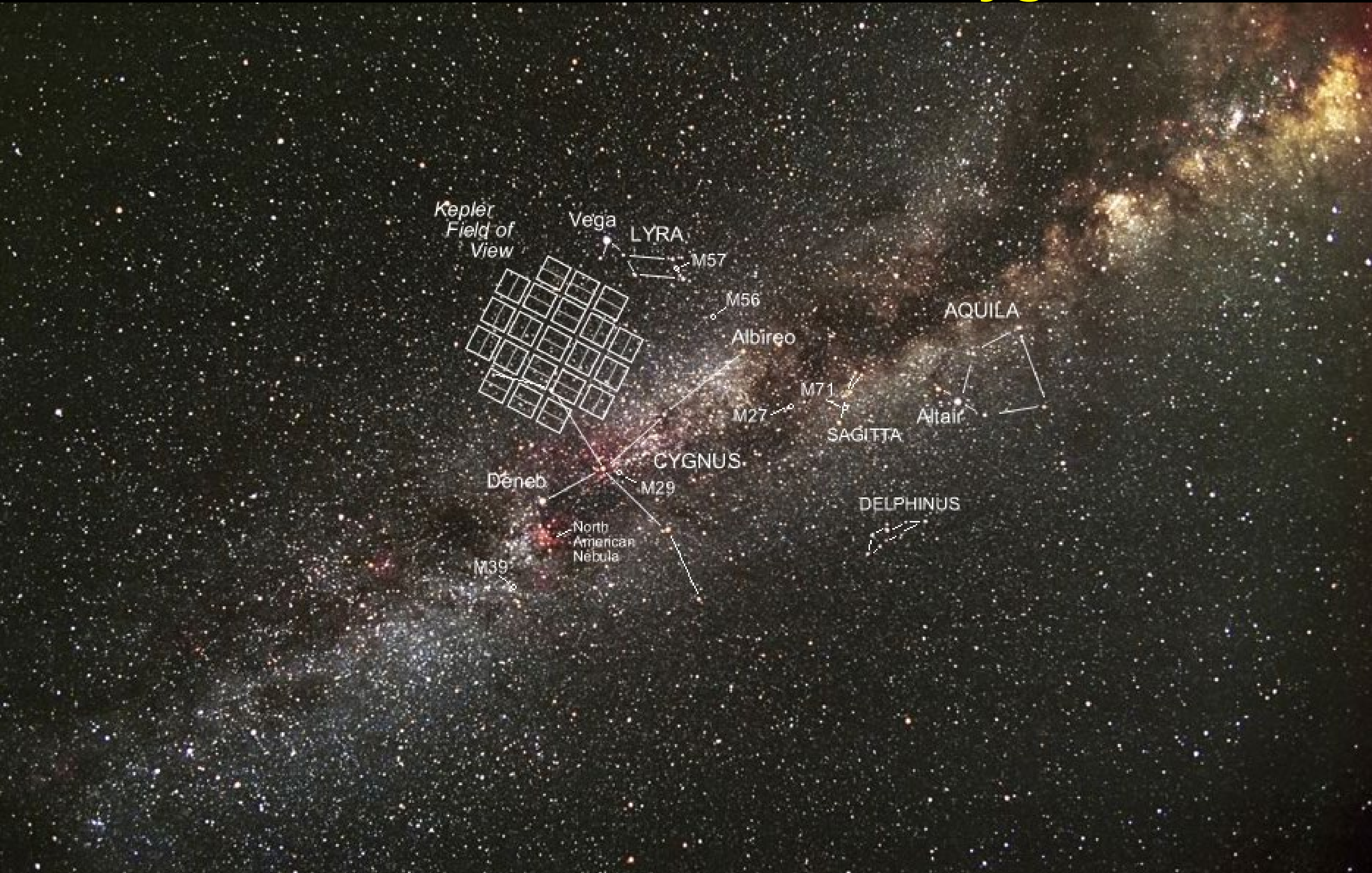
Transits are HARD to Detect!

- Planets are tiny and stars are large.
- Must be able to do accurate photometry (the science of measuring the brightness of an object) down to the level of a few thousandths of a magnitude, or a few hundredths of 1 percent of the total light.

A Specialized Satellite Launched in 2009 – The Kepler Mission

- Kepler monitored many tens of thousands of stars in the constellation Cygnus for transits, down to 14th magnitude
- Has discovered 1000 confirmed and over 4,000 unconfirmed planets around other stars, most of them "Super-Earths" between 1-2 Earth diameters.
- (**confirmed** means have been seen over enough transits to determine orbital nature. Unconfirmed are likely/possible transits but might yet turn out to be starspots, etc. Need more transits to confirm. But Kepler team estimates ~80% are real)
- But, Kepler only studies stars in a small square in the constellation of Cygnus, not the entire sky
- And alas, In summer 2013 – **Kepler died**, victim of failed gyros. Much data still to be analyzed though. Very productive mission.

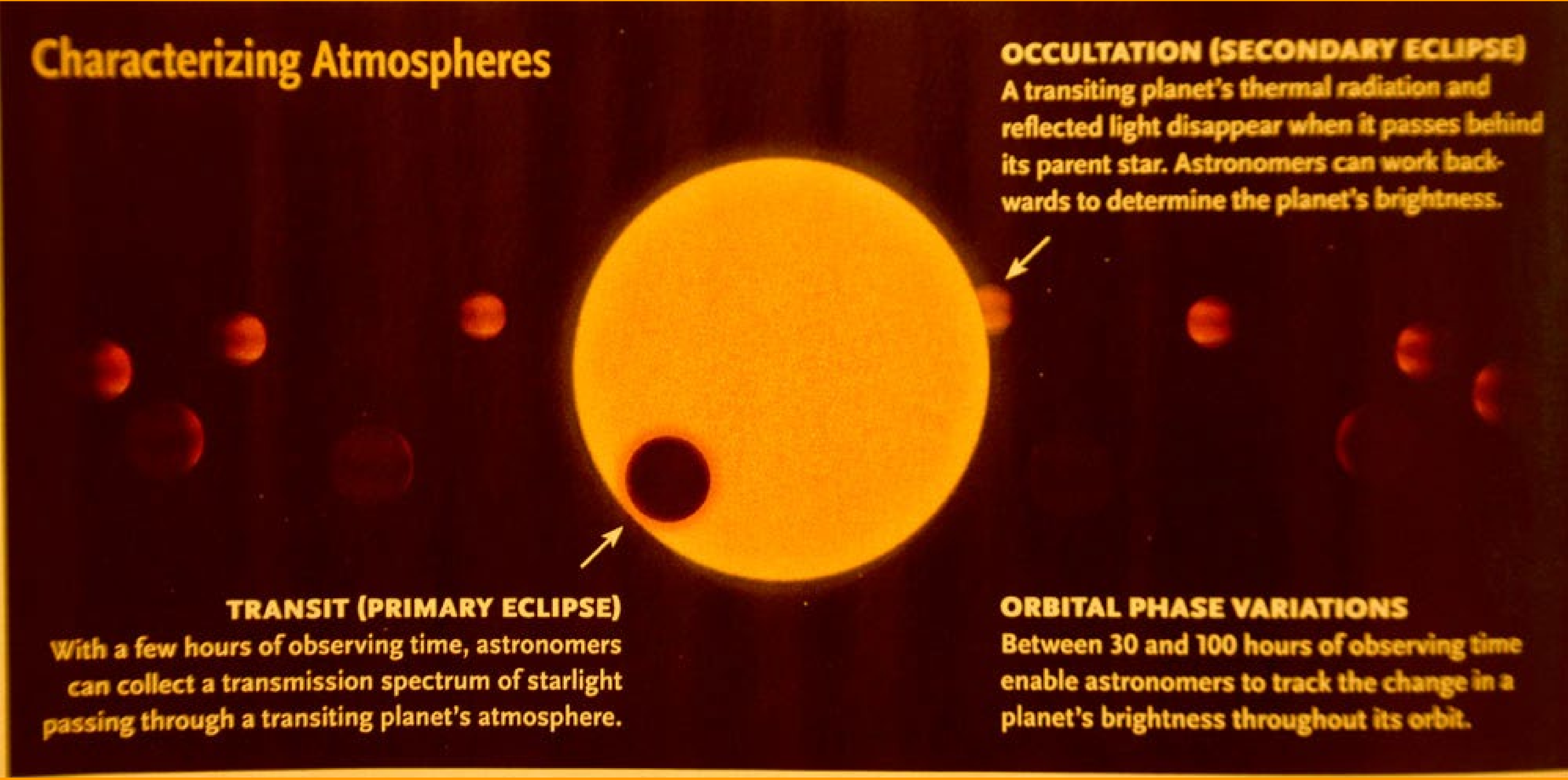
The Kepler Mission – Targeted on A Corner of Constellation Cygnus



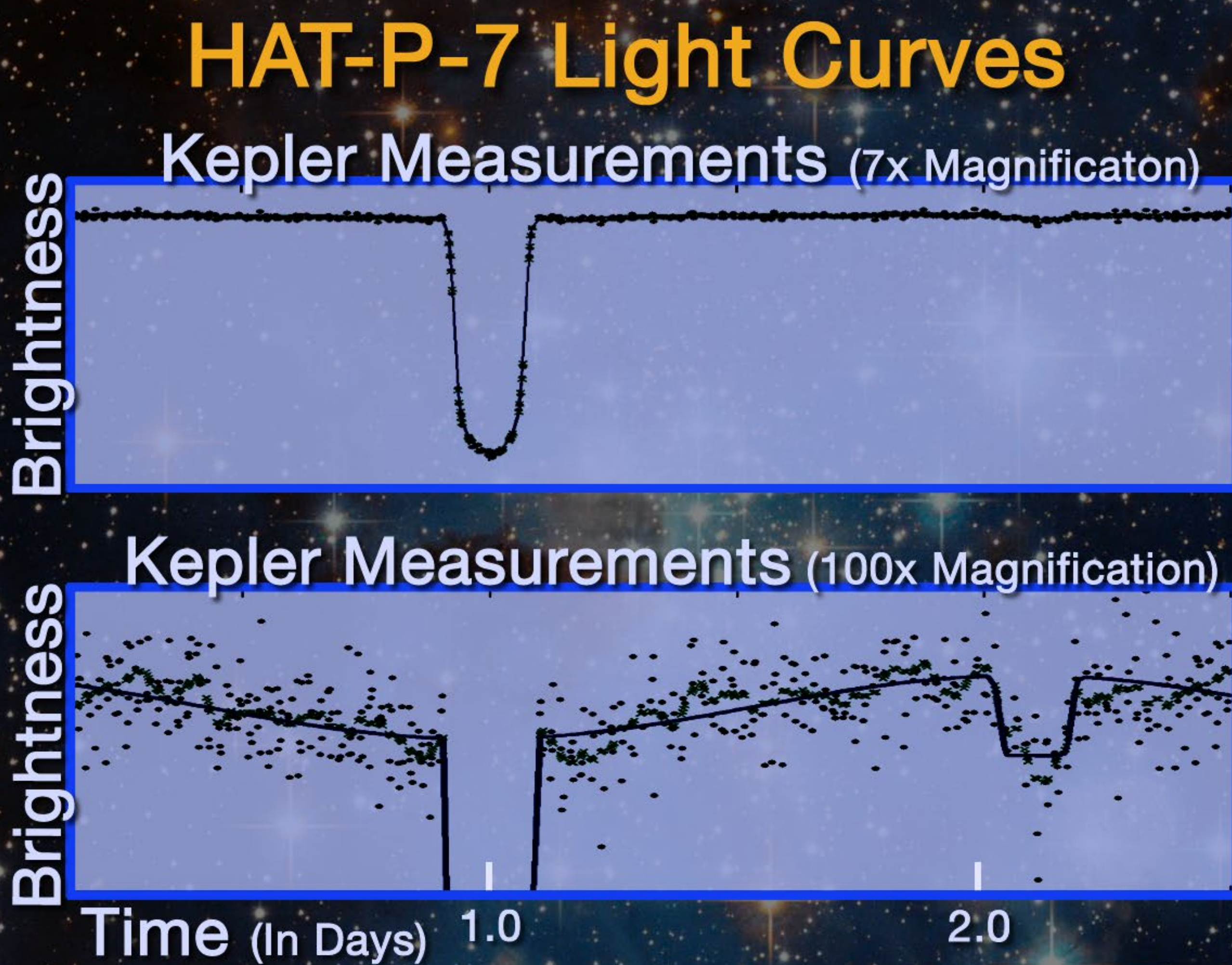
Transit Method Provides Crucial Data Not Possible from Doppler

- The method is being pushed hard at this time – because it has one key advantage which other methods do not:
- **We get the *size of the planet*, since that's what determines the observed light loss**
- The **mass** of the planet then comes from Doppler Method measurements on parent star
- Combining these gives the **density** and, together with distance from the star and star luminosity, the approximate **chemical composition can be guessed**
- And, if we're lucky and careful, we can see absorption in the star's spectrum due to the planetary atmosphere's varying opacity at different wavelengths during the transit. This tells us directly what the planet's atmosphere is made of, via this "**transmission spectrum**"
- Over 4200 possible transiting planets have now been found in Kepler data. 1000 have been confirmed as of December 2014.

Transit Light Curve – What's Happening to Cause the Light Variations



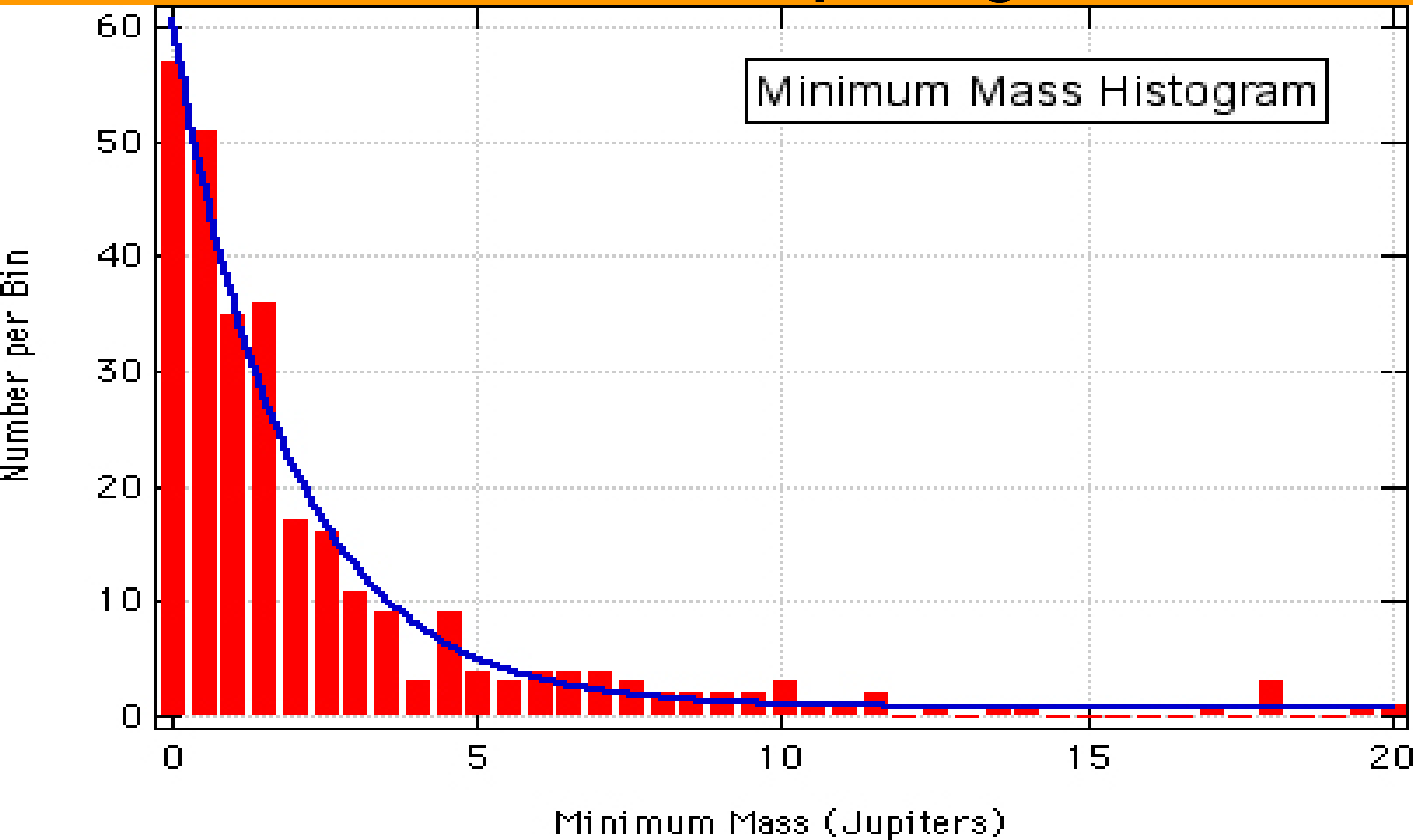
That's a Beautifully Noise-free Light Curve!



Some Kepler Findings…

- First, that there is micro-level variations in stellar luminosities more commonly than we had guessed.
- This makes transits harder to detect, but good software and humans (see citizen science Zooniverse website) have mostly overcome this.
- **Planets are common! Well over 90% of solar-type stars calculated to have planetary systems**
- Small planets are the most common, but very tough to pull out of the data because transit light loss is so tiny and the "twinkle" of other causes of light variation (pulsations, star spots, etc) are possible.

Correcting for Observational Bias Shows Small Planets More Common Than Big Ones, Not Surprising

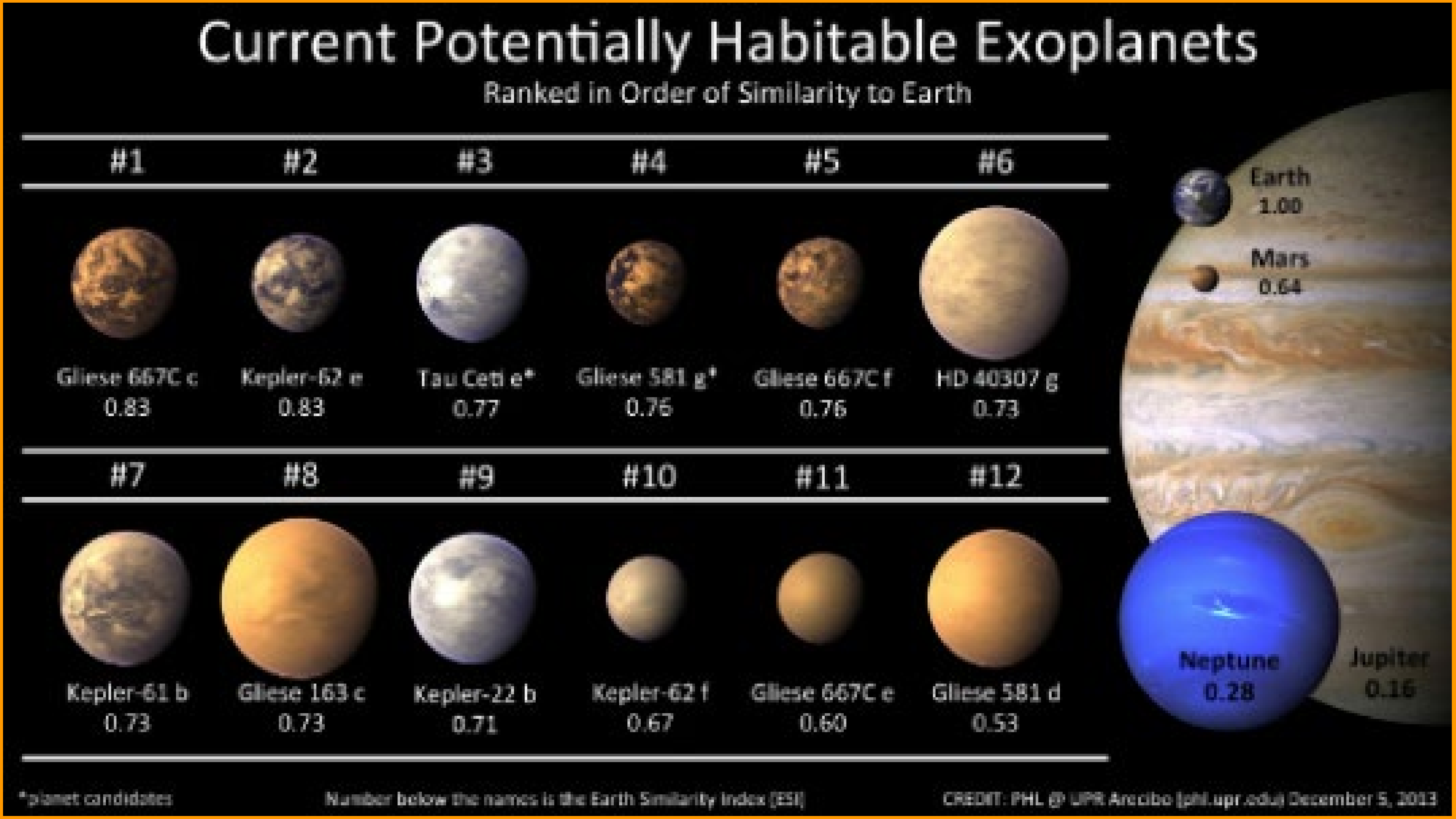


Some Small Kepler Planets *vs.* Our Own Solar System's Small Planets

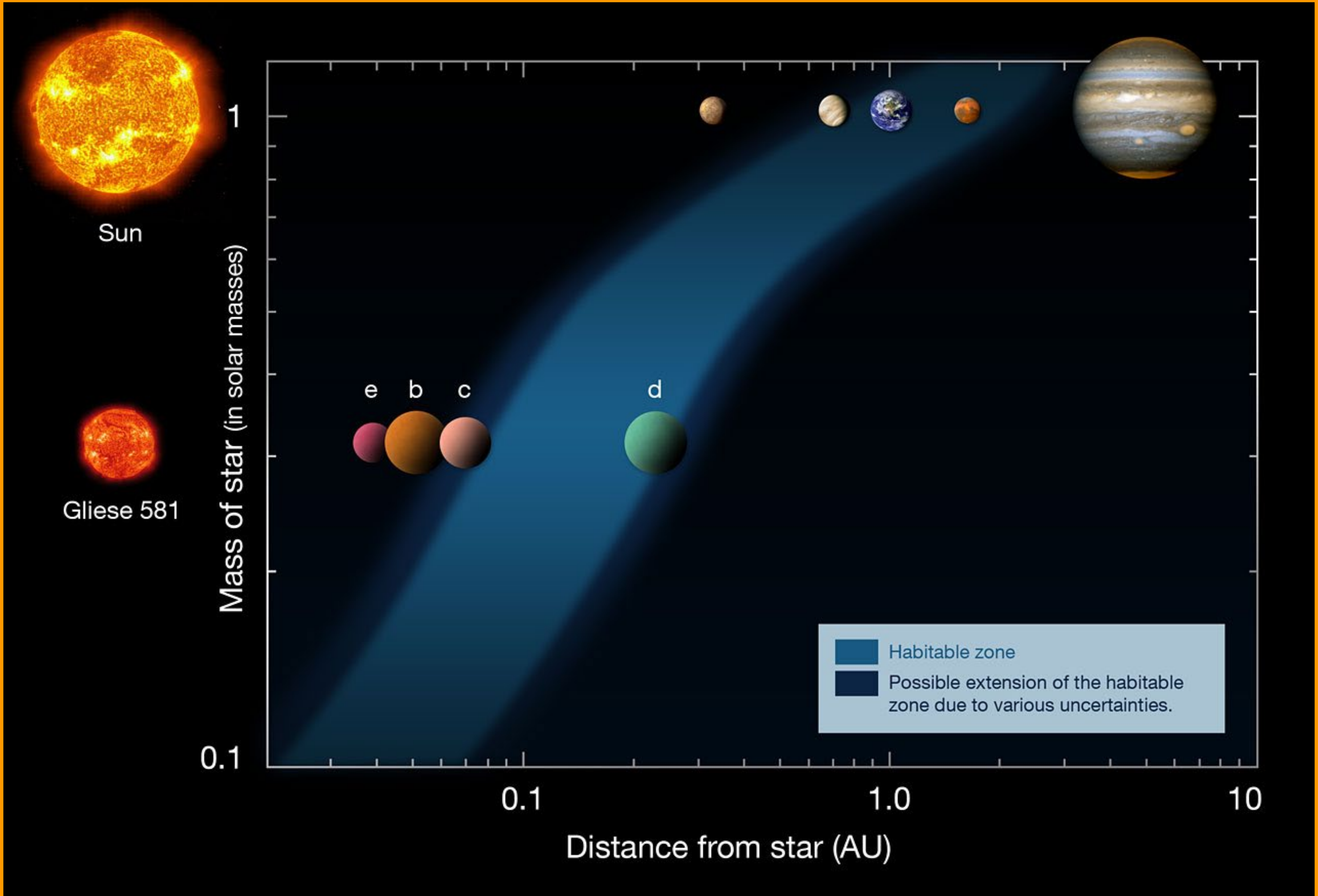
The Definition of the "Habitable Zone"

- No, it doesn't mean there are probably civilizations here
- And it doesn't even mean life is likely here
- It means only that the calculated equilibrium temperature in this region, for a planet, can permit liquid water to exist. BUT, even this requires the right atmospheric composition and density so that greenhouse heating permits liquid water. We believe life requires liquid water.

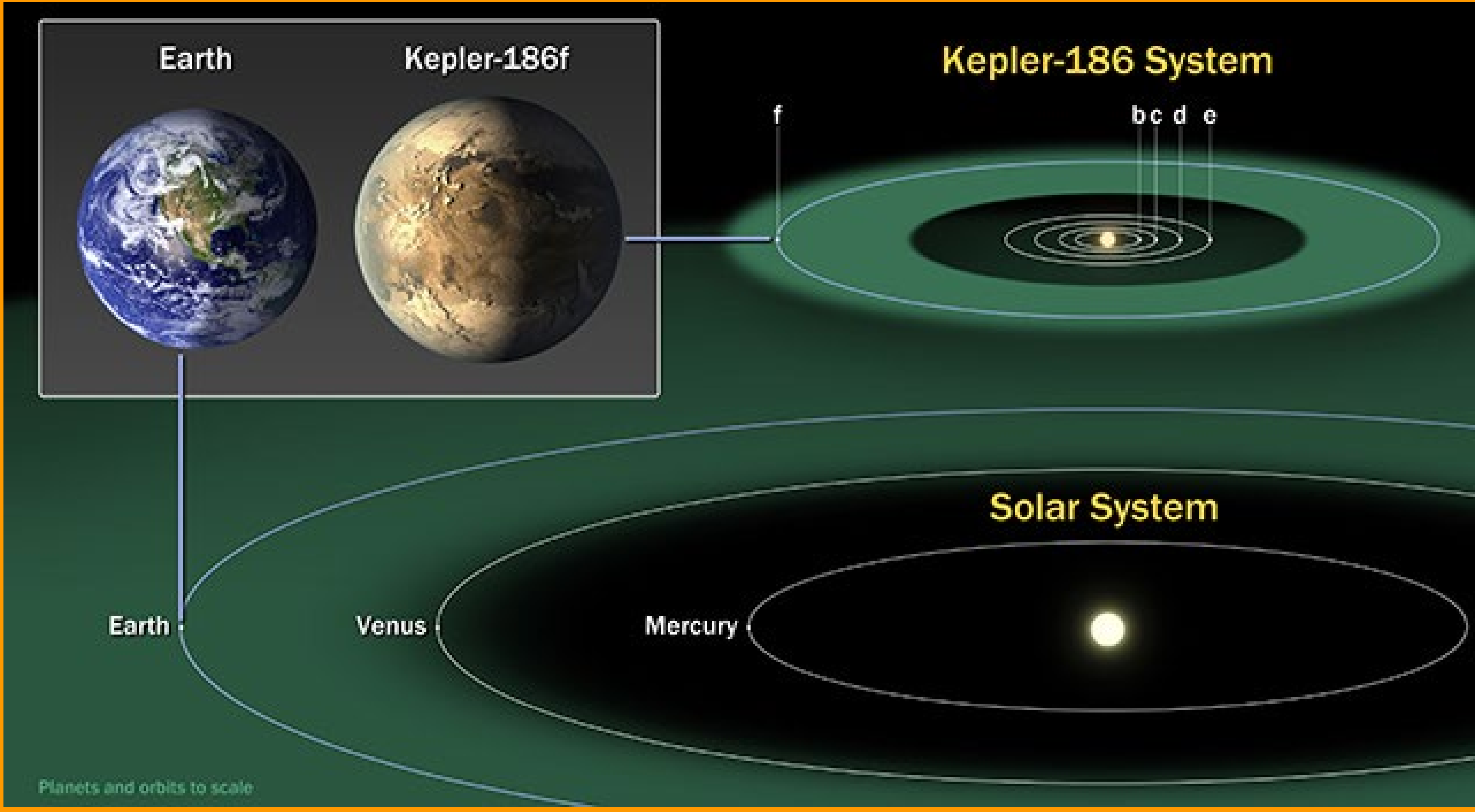
No True Earth's, but Some SuperEarth's in Roughly Habitable Zone



The Habitable Zone: Solar System *vs.* Gliese 581 System



Kepler 186f: Closest Earth Analog So Far?



Kepler 186f: What Do We Know?

- First Earth-sized planet in habitable zone, but…
- Orbits a red dwarf (often have strong UV flares)
- Orbit has ~50% odds of being tidally locked (day=year). Even if not, day likely months long – not good for life
- Mass unknown and unmeasurable (~0.3-3.8$M_{\mathbf{earth}}$),
- Atmosphere unknown and unmeasurable. If 0.5 to 5 bars of CO2, Greenhouse could warm it enough for liquid water
- Orbit circular, that's good – but SETI has listened since Apr. '14 – no intelligent signals

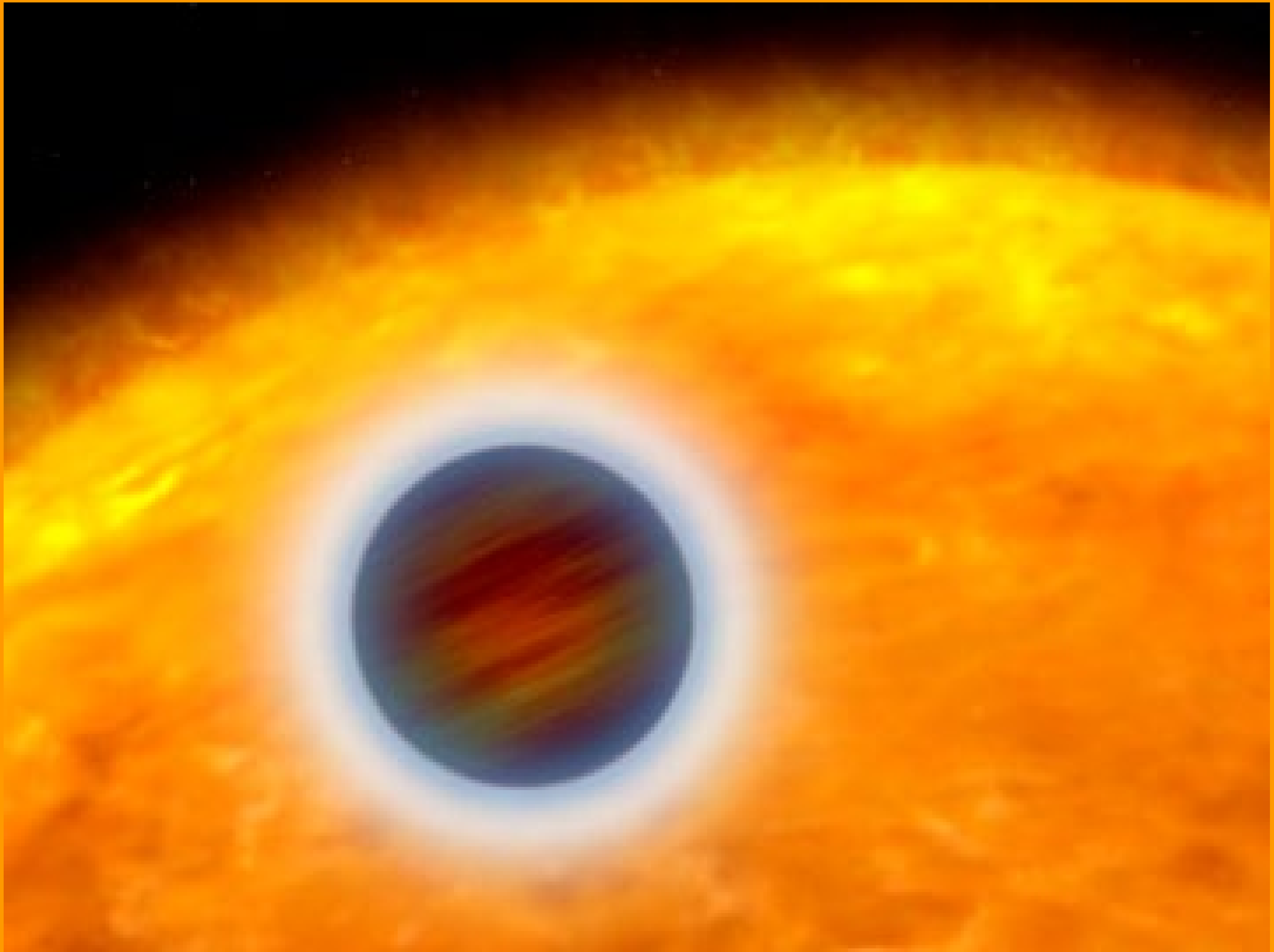
Key Kepler Findings

- ~20% of all stars have Earth-sized planets
- Small planets (rocky?) are equally common around both small dim and large luminous stars
- **Almost all stars (at least ~90%) have planets!**
- 43% of Kepler planets have other planet(s) in the same system (which is NOT saying that 43% of all stars have multiple planets)

How to Discover and Characterize the Atmospheres, Climate of Exoplanets?

- During a transit, some of the light of the parent star is filtering through the atmosphere of the planet before making it into our telescopes.
- Measuring the depth of the transit light loss in narrow wavelength bands results in a low-resolution spectrum of the outer atmosphere of the exoplanet…
- …this is a "**transmission spectrum**"
- But this amount of filtered light is TINY!
- We have a few detections now – like Carbon monoxide and water detected in HR 8799's planet's atmosphere
- HAT-P-12b shows no water vapor absorption, which was surprising. Most likely explanation is the water vapor layer is beneath opaque high clouds which masked the signal

Transmission Spectra- Tough, But CanTell Us Atmospheric Composition



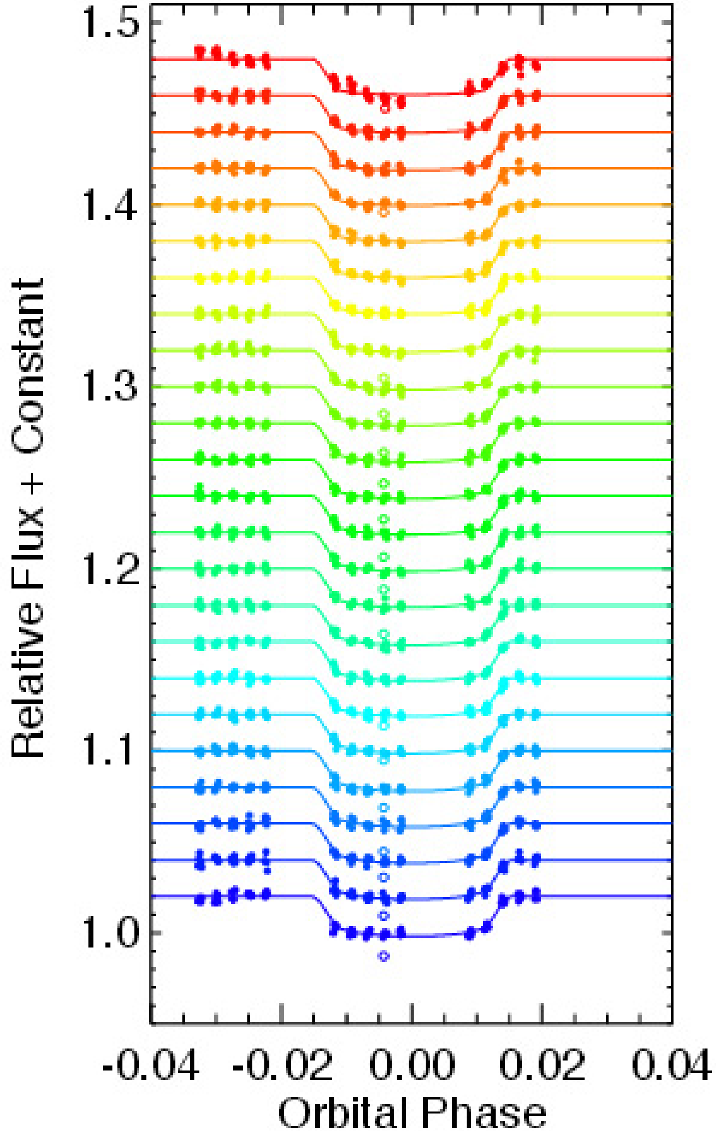
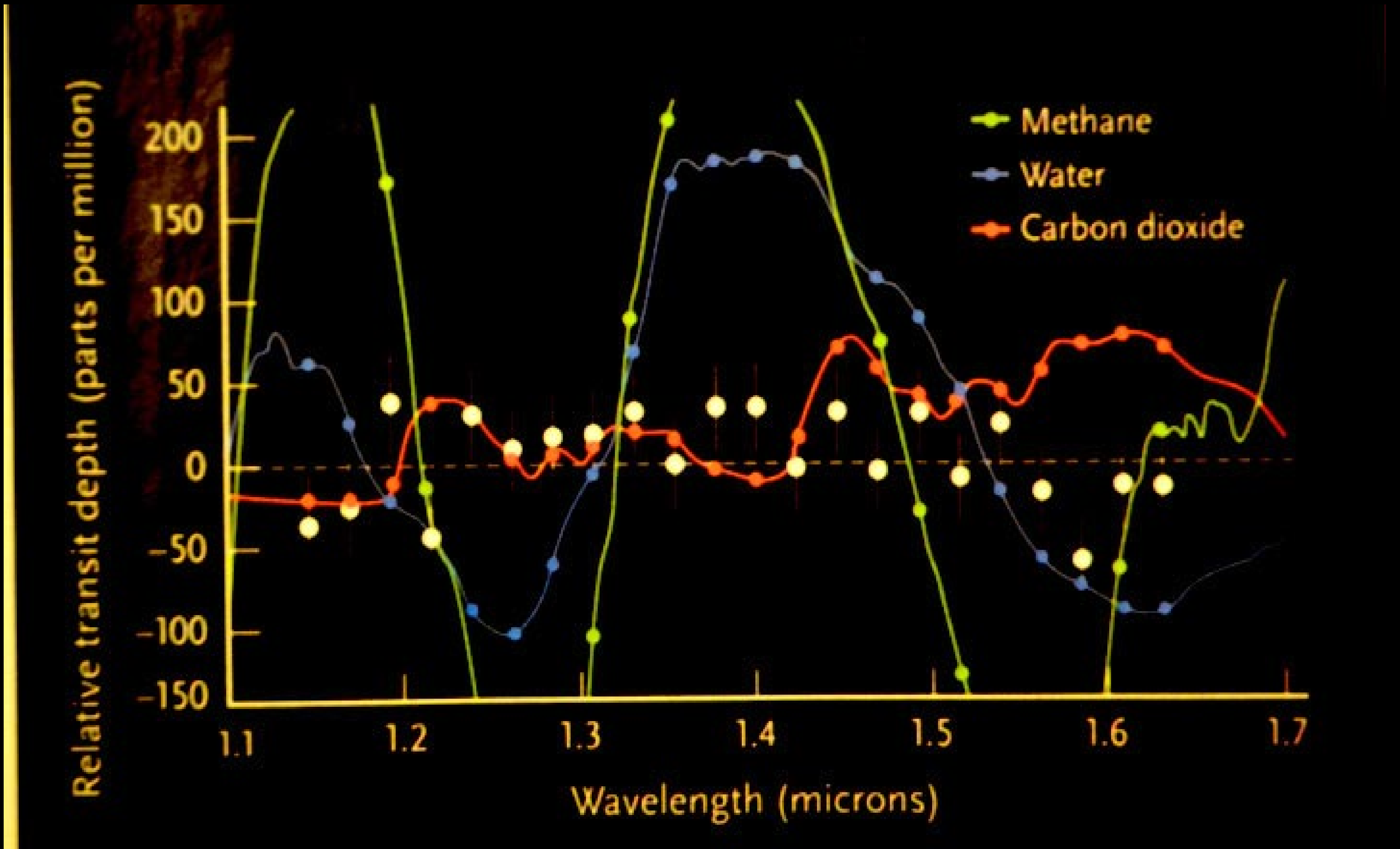


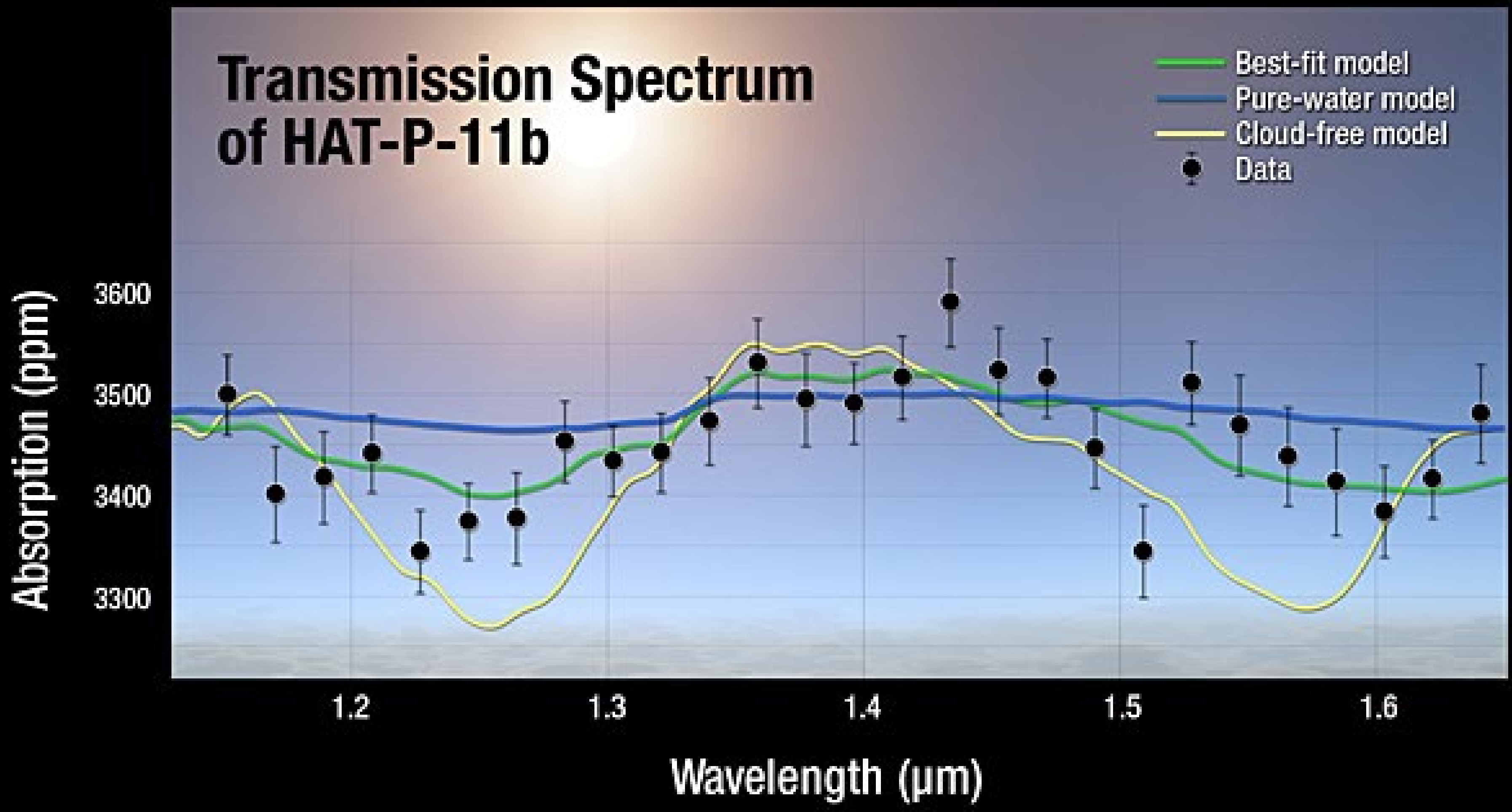
FIG. 3.— Transit model fit to each spectral bin. The systematics are removed from the data (round points with error bars). The solid curves are the best fit light curve models for each bin. Transit eclipse depths for the shorter wavelengths are denoted by blue near the bottom and the longer wavelengths are shown in red near the top. The hollow circles are the outlier point that we exclude from the fits.

- **Different transit depth at different wavelengths (colors) tell us what the atmosphere opacity is and therefore what the atmosphere's chemical composition is.**

By taking the known spectral signatures of common molecules, and fitting them to an observed spectrum, you can find roughly how much of each there is in the atmosphere



Water Discovered on Planet HAT-P-11b

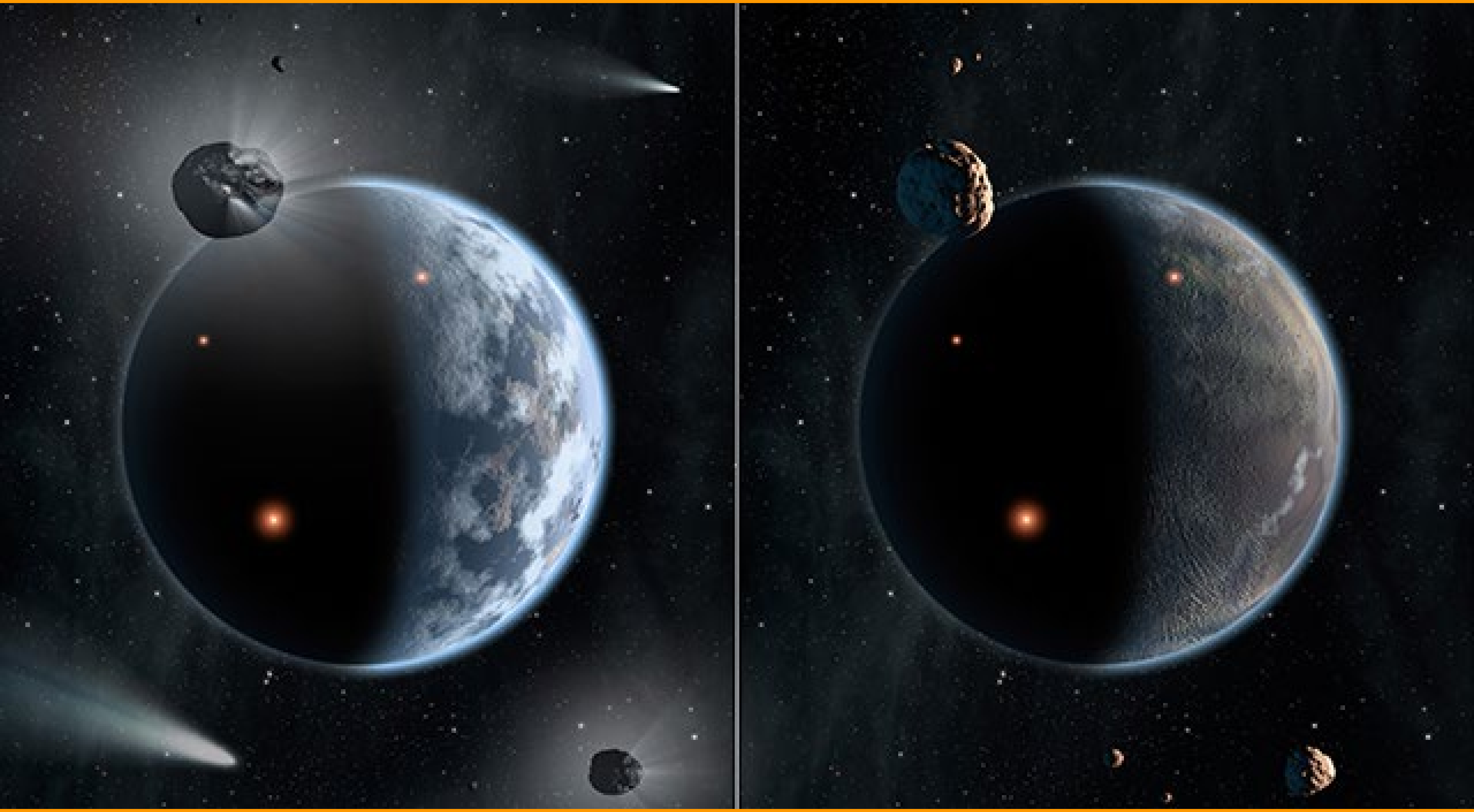



POD

Infrared Light from Hot Jupiters Directly Detected in Favorable Cases

- This allows a crude estimate of how the day / night temperature differs on such a planet, as “Hot Jupiters” are expected by elementary physics to be tidally locked with their parent star
- It also gives us a direct measure, not just inferred, of the planet’s temperature
- http://arxiv.org/abs/0705.0993

Solar Systems Rich in Carbon – Don't have Oceans, Says New Study in '13



We were Lucky!

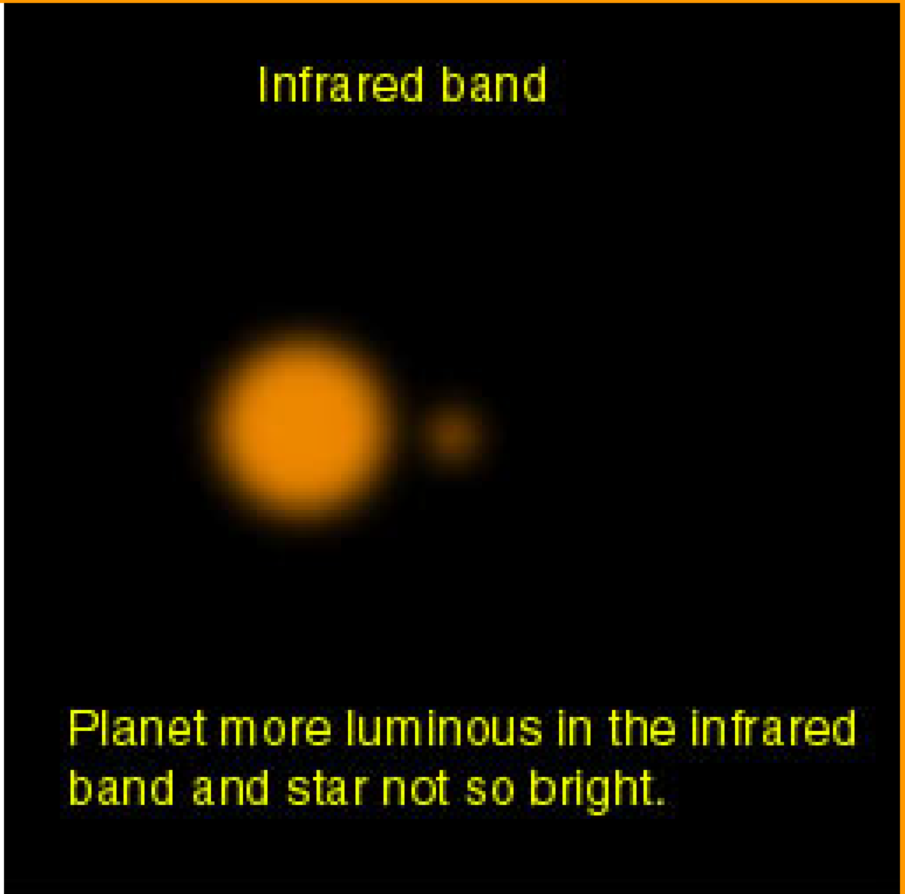
- Excess carbon will grab the oxygen and lock it into CO and CO_2, or in crystalline form as diamond, if mass and pressure is high enough
- That leaves no oxygen left to bind with hydrogen and make water
- Bummer. But, our own solar nebula happened to be low in carbon, hence we have an oxygen left to bind with hydrogen and make an ocean-dominated planet and life. We were lucky!
- You want carbon for life, but just some, not a lot, or you get no water or oceans, which are also required for life.
- This is yet another argument that planets which are favorable for 4 billion years of life are rare – you need just the right amount of carbon: too little, or too much, and you cannot have a living planet

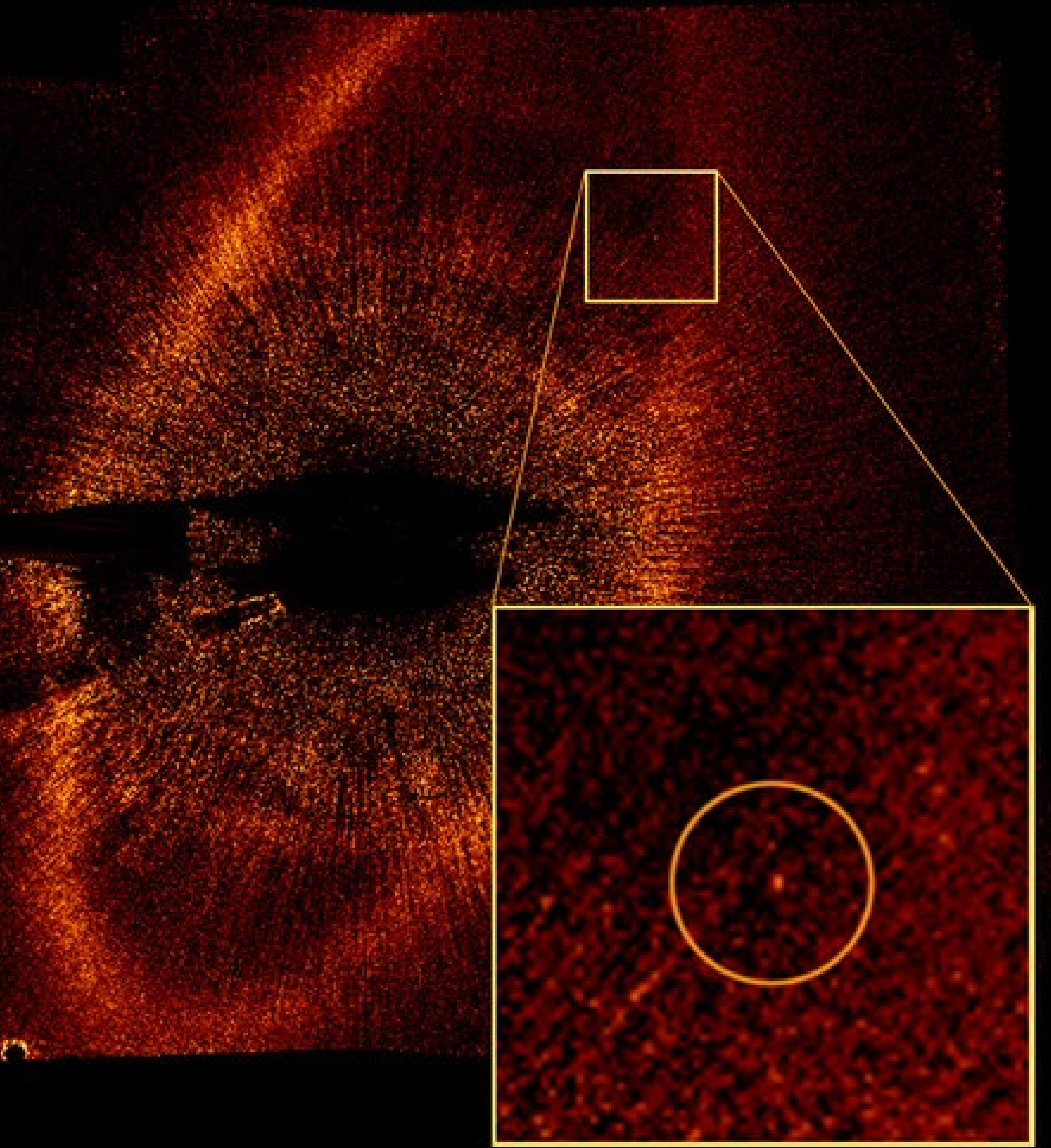
And in the year - 2008…

- ***The first image of planets around another star…. !***

- ***But this is by far the least likely way to find planets.***
- ***Stars are BRIGHT and planets are DIM and too CLOSE, for the most part***

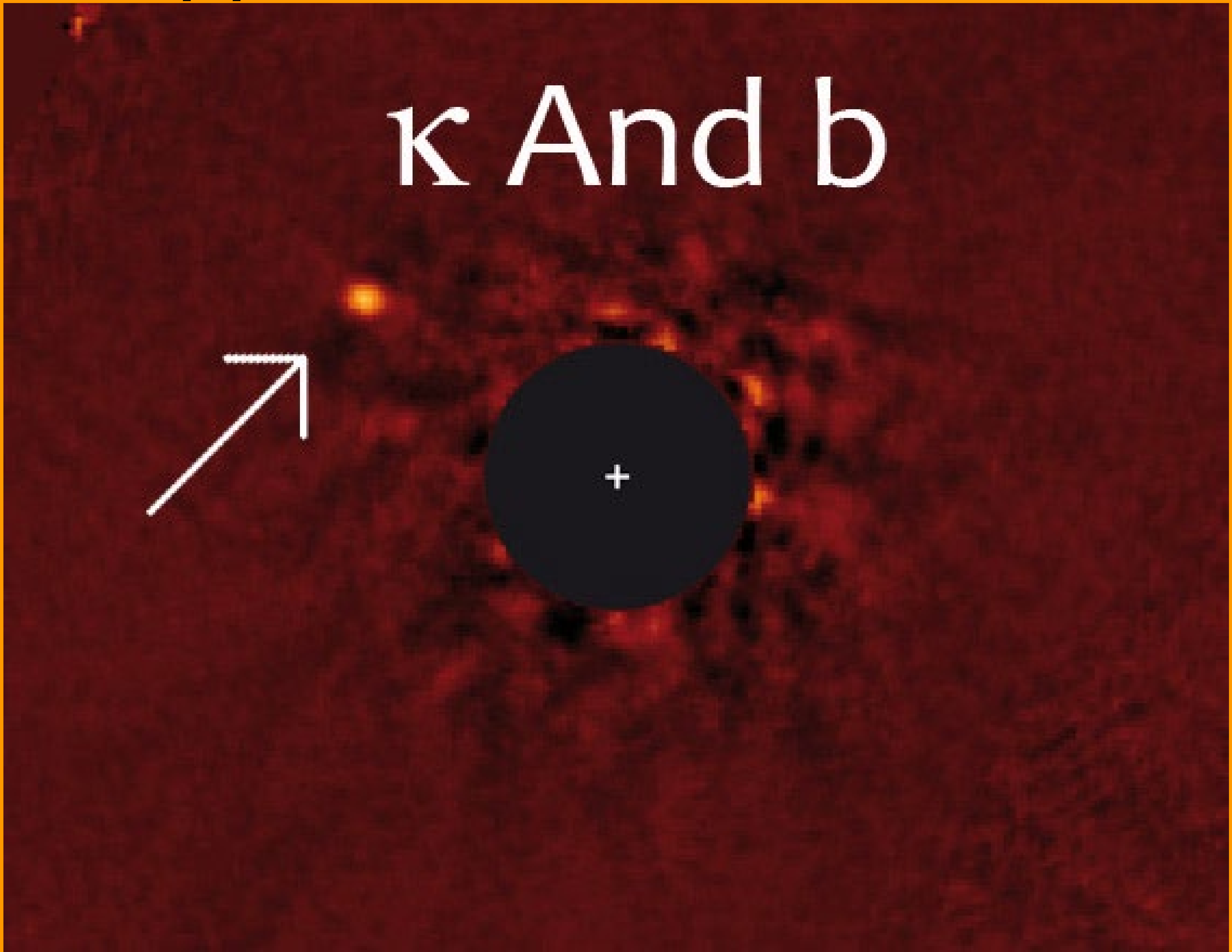
Much Easier to See Planets (but still very tough) in the Infrared, Where Planet Puts Out ~All of it's Light



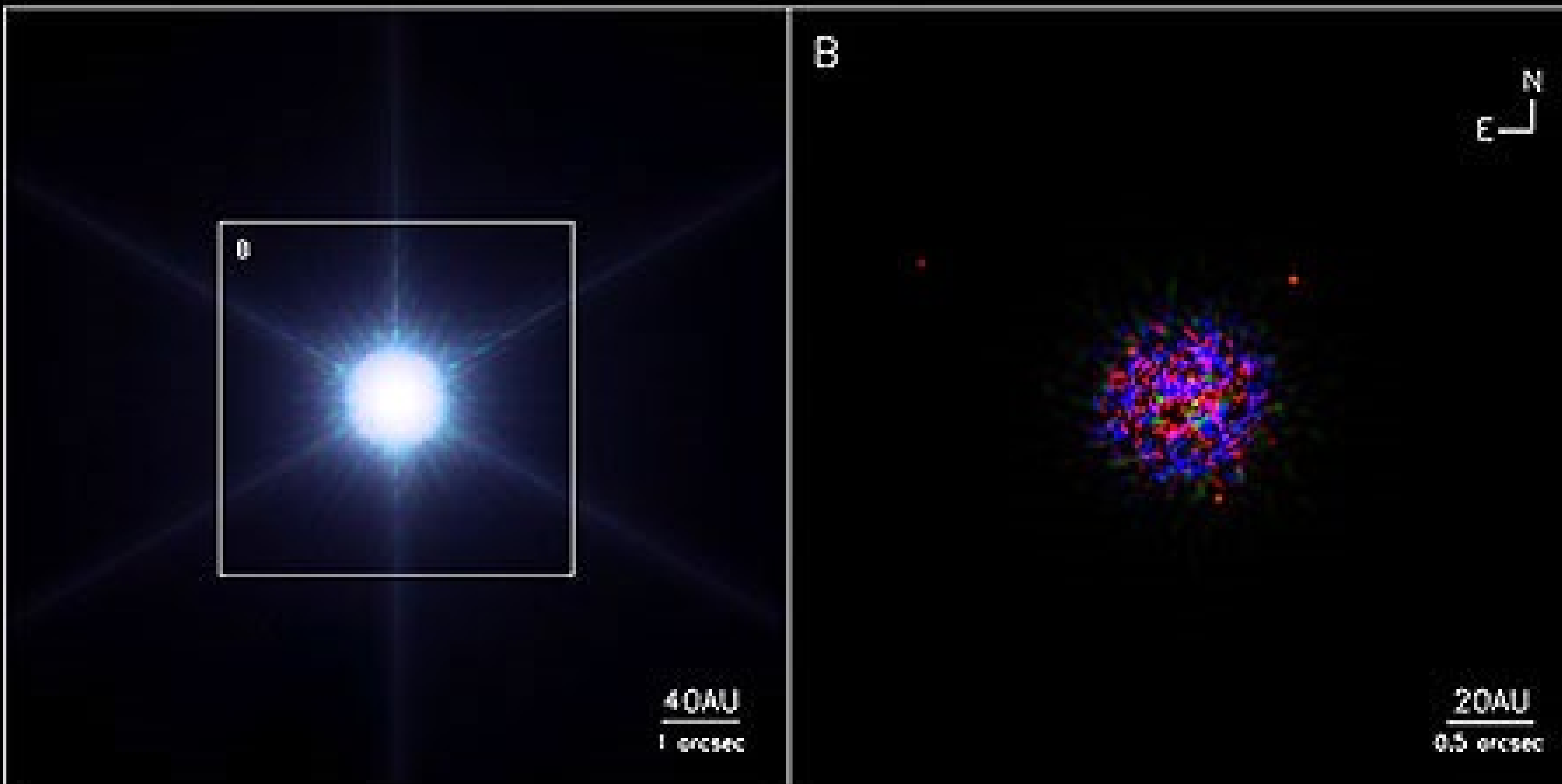


- This particular speck was NOT digital noise; it followed the laws of gravity, and must be a planet!

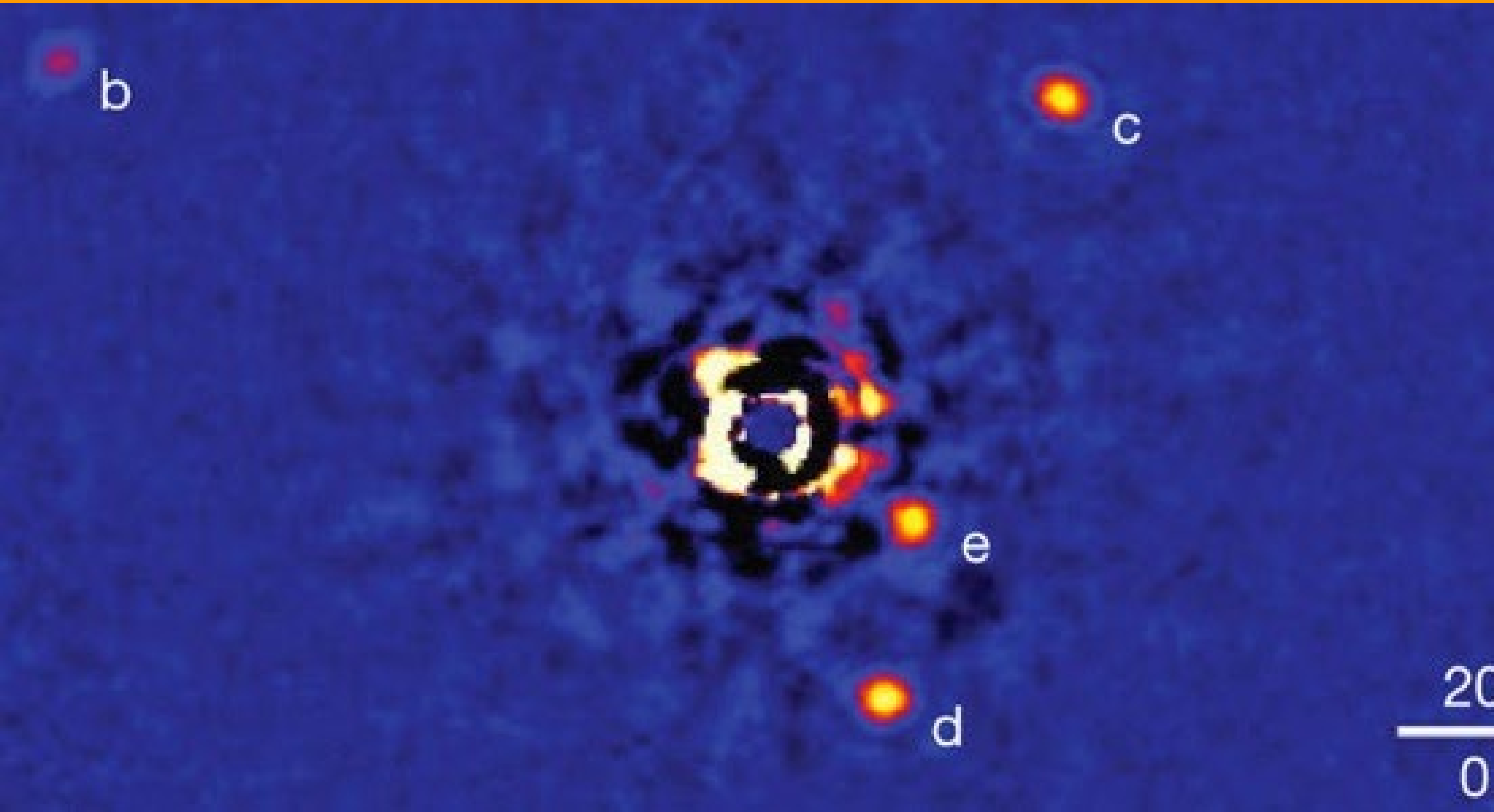
Kappa Andromedae’s Planet

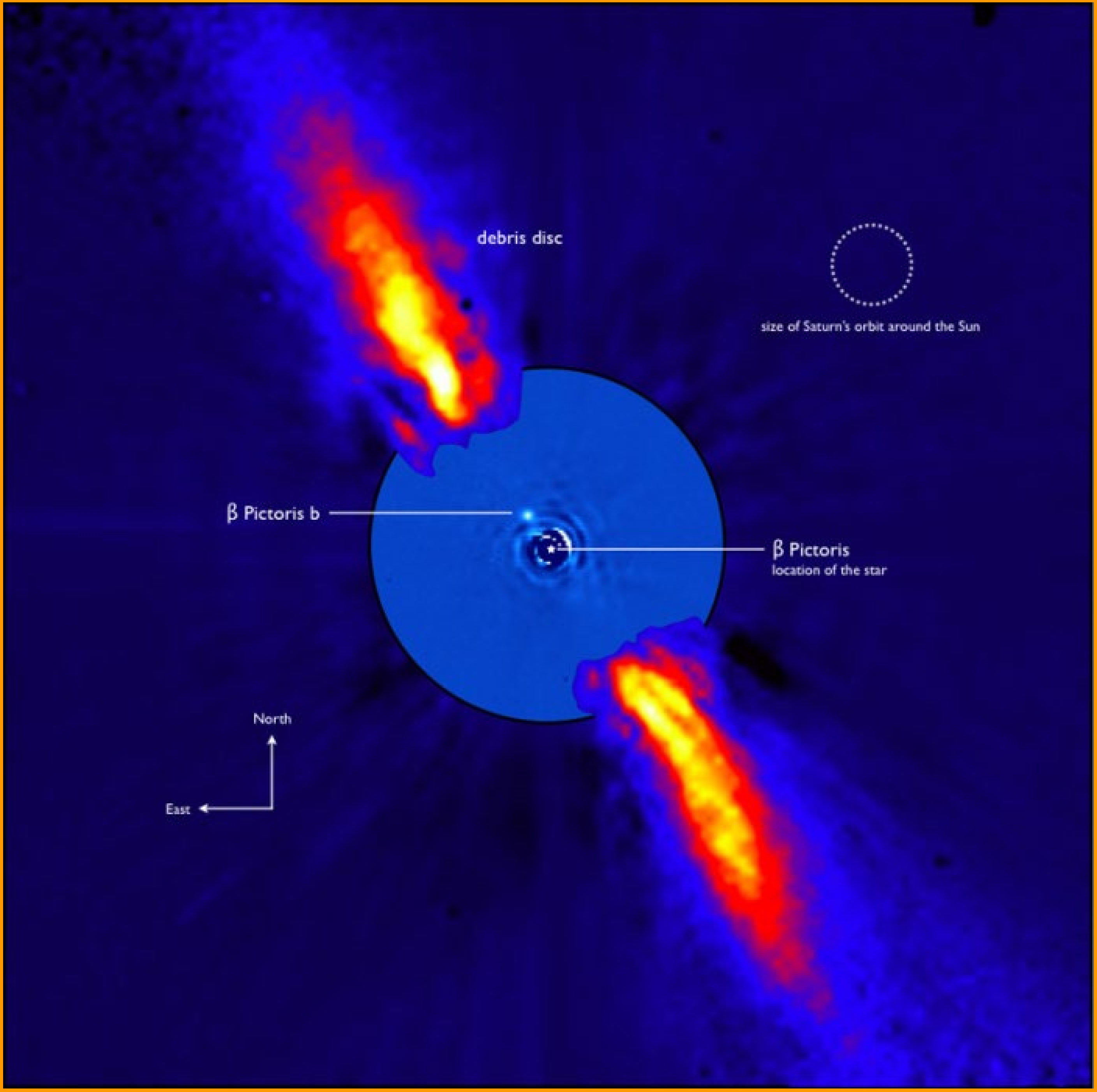


HR 8799 Planetory System



20 AU Is About the Size of Neptune's Orbit, So These are Distant, Cold Exoplanets

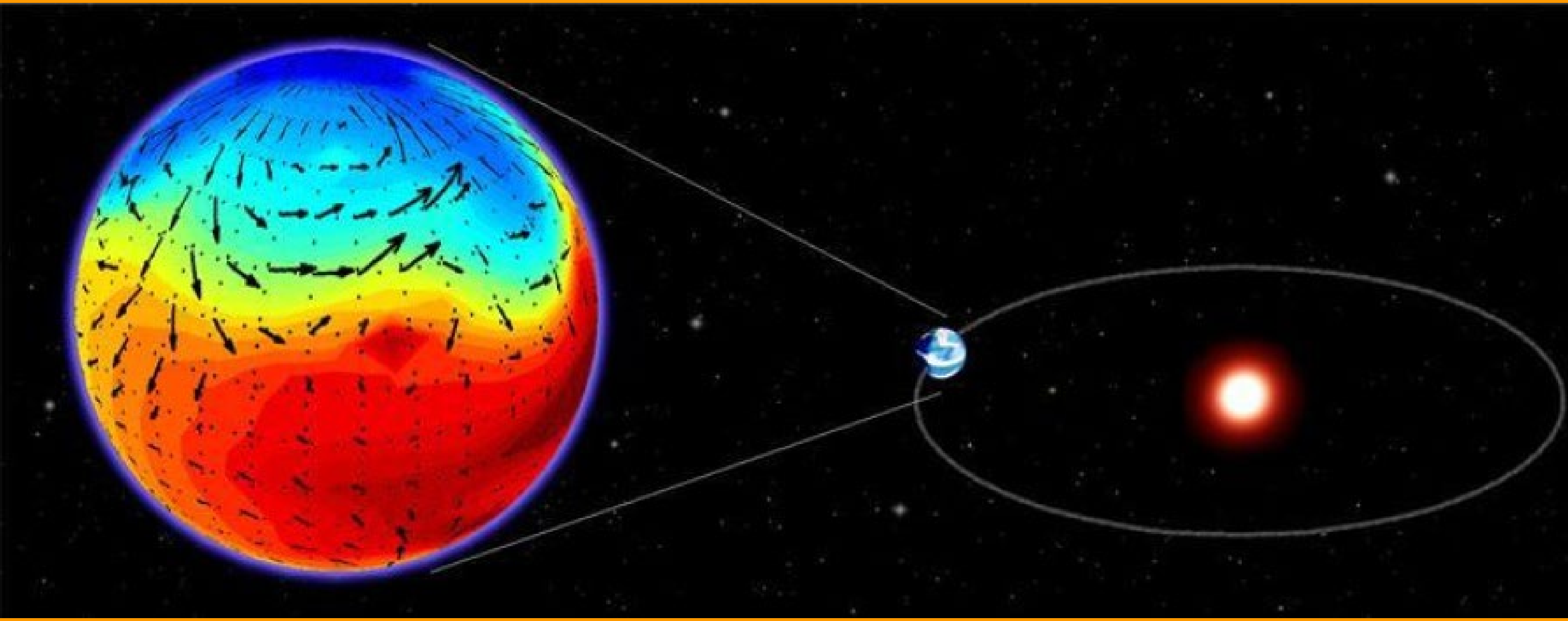



debris disc
size of Saturn's orbit around the Sun
β Pictoris b
β Pictoris
location of the star
North
East

Kepler Discovers: Red Dwarfs Have Planets Too

- They're the most common of all stars, so planets common too.
- But Red Dwarfs are so cool and so dim, planets need to be so close to be warm and in the "habitable zone", that tidal stretching would grab hold of the planet's rotation and halt it – **"Tidally Locked"**
- Sunny side would be permanently sunny, night side cold and permanently night
- Tough on climate!!

Tidally Locked Planet, makes for permanent very High Winds from Cold side to Hot Side



For More on Planetary Climate And Especially on **Earth Climate and Current/Future Climate Change**

- …. Sign up for **Astro 7 “Planetary Climate Science” !**
- I offer it every year, **2:45-5:50pm Tuesdays**.
- It satisfies the GE lab science lecture class just like Astro 3, 4, 5 do.