Chapters 7,8: 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

Chapters 7,8 – Key Points

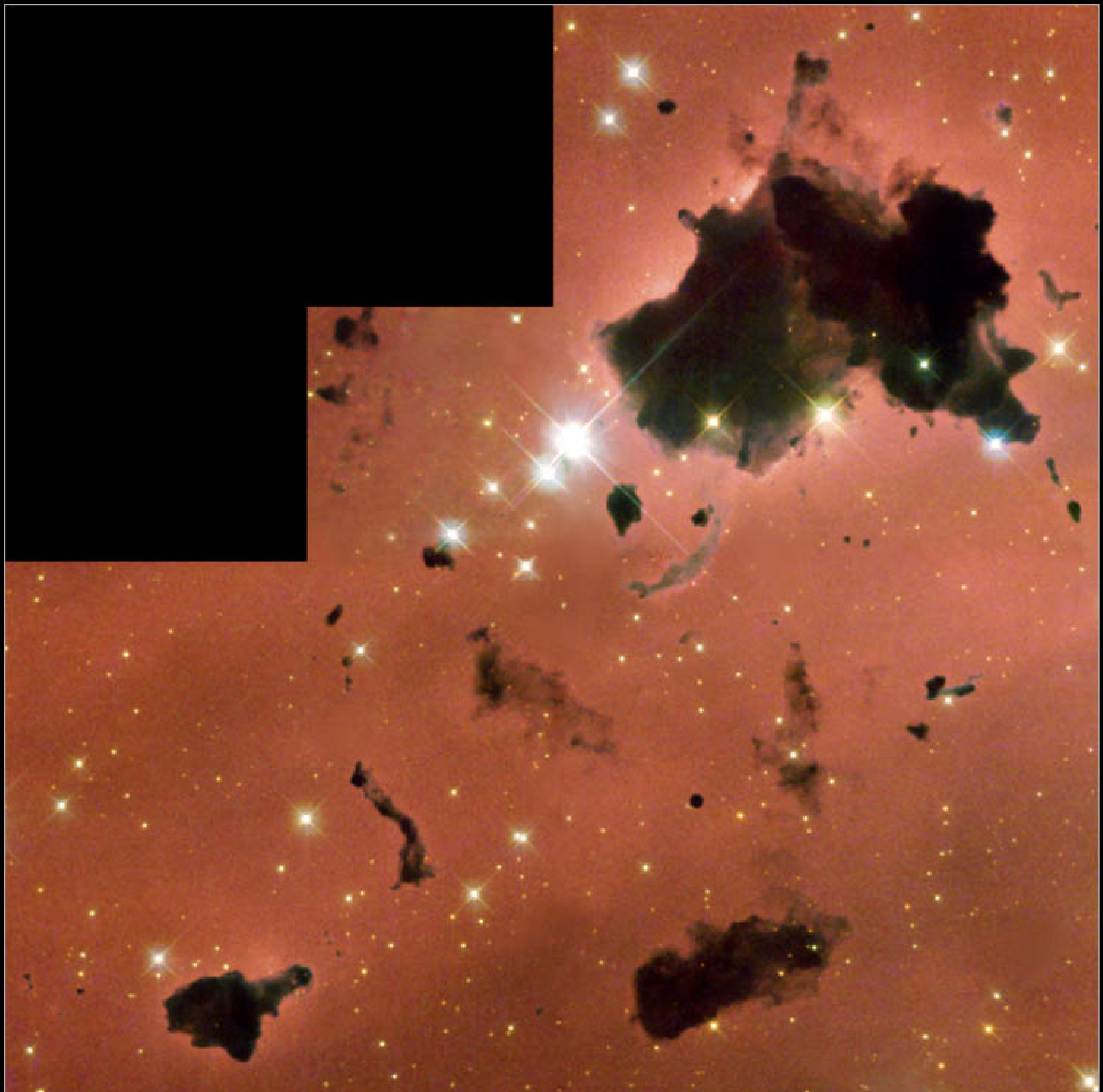
- Our solar system: a by-product of star formation within a giant molecular cloud
- Need HIGH density, and LOW temperature to favor star and planet formation.
- Planets form in the disk of high angular momentum material, pulled offline by gravity of neighboring protostars
- A supernova likely triggered the collapse of the proto-solar cloud (excess Mg 26 inside meteorites is one of key evidences)
- Angular momentum came from gravitational pull from nearby other stars in our cluster, as proto-solar nebula collapsed
- This angular momentum only allowed collapse to a certain size disk, so not 100% could fall onto central star. Friction caused material to settle into a disk
- Gravity caused proto-planets to form, coalesce into planets which inherit the motion of the disk material
- This mechanism explains the large scale patterns of our solar system. Details are still an active area of research
- Inner planets – formed by rocky material inside "frost line"
- Outer planets – formed by hydrogen compound ices as "starter seeds", and since H is most of the proto-solar system, these planets are large
- Beyond, is Kuiper Belt of 10's of thousands of giant ice cores
- 100x further away is the Oort Cloud, size limited by tidal forces from other stars in our Galaxy to about ½ light year outer radius, of more ice cores.

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

Reflection Nebula NGC 1999

The Following 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

The "Close Encounters" Hypothesis - Fails

- Perhaps two stars orbiting the galaxy pass, by chance, so close together that tidal forces pull off the outer layers and add angular momentum and that provides the proto-planetary disk?
- Back decades ago, this older idea could not yet be ruled out
- It was never favored, but now it can be conclusively ruled out – because we observe that solar systems are found around almost all stars, yet the statistical calculations show that close encounters must be extremely rare

So how do the planets themselves form in these disks 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 (much more mass here). The growth rate would be much faster as gravity would kick in right away for such massive objects.

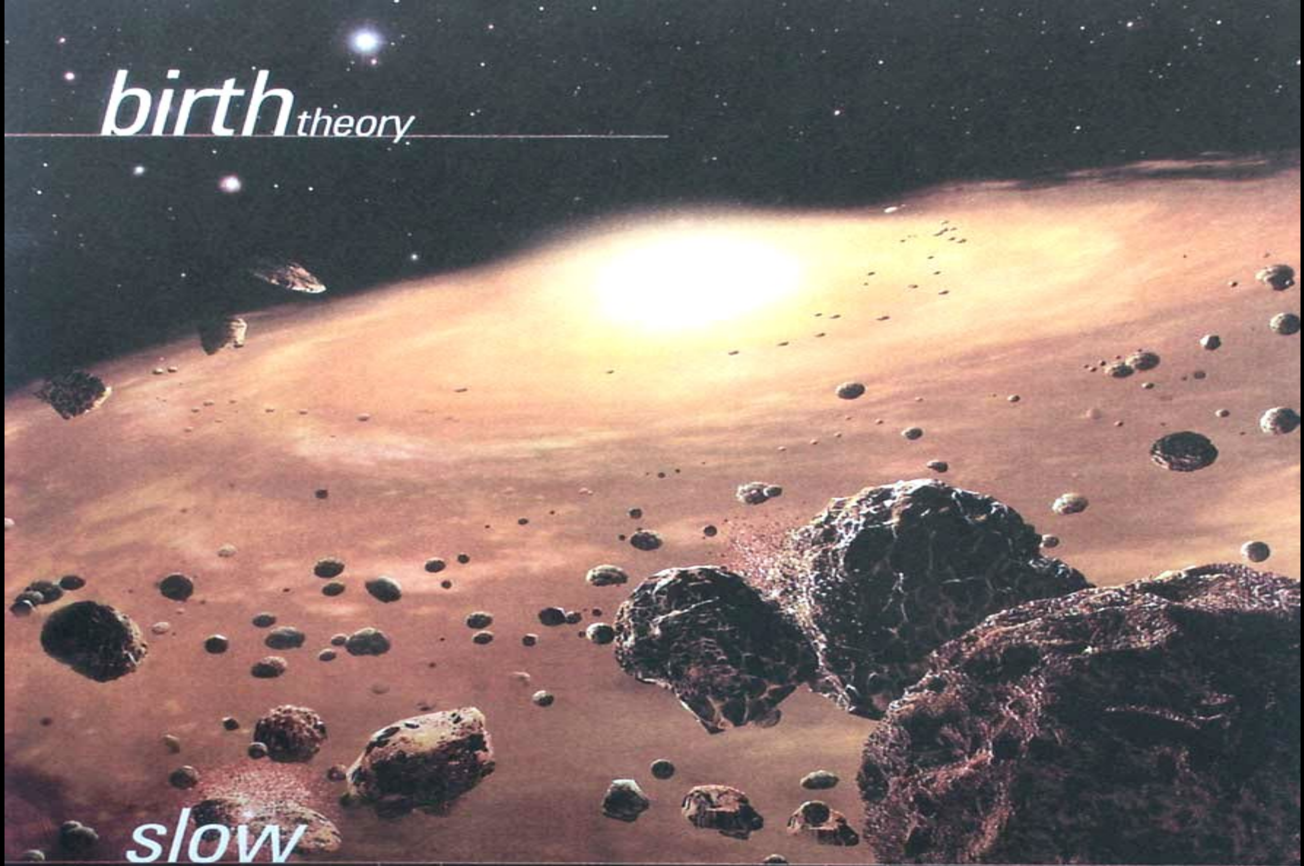
But… there's a Race Here

- 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.

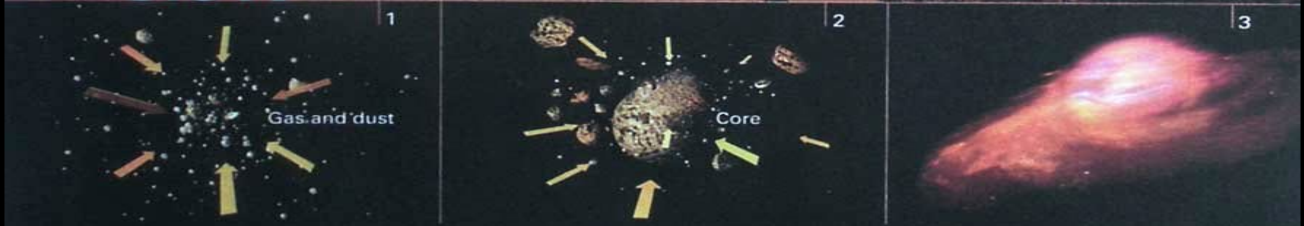
The Slow Scenario: Basic idea…

- Friction between dust grains rubs electrons to other grains, resulting in charged grains which attract each other, building "dust bunnies", to larger
- Process continues till resulting proto-planet is a half mile across, at which point self-gravity begins to accelerate accretion, until a planet is formed
- Ice, gas, water-bearing micro-meteoroids add the volatiles which become the atmosphere

birth theory



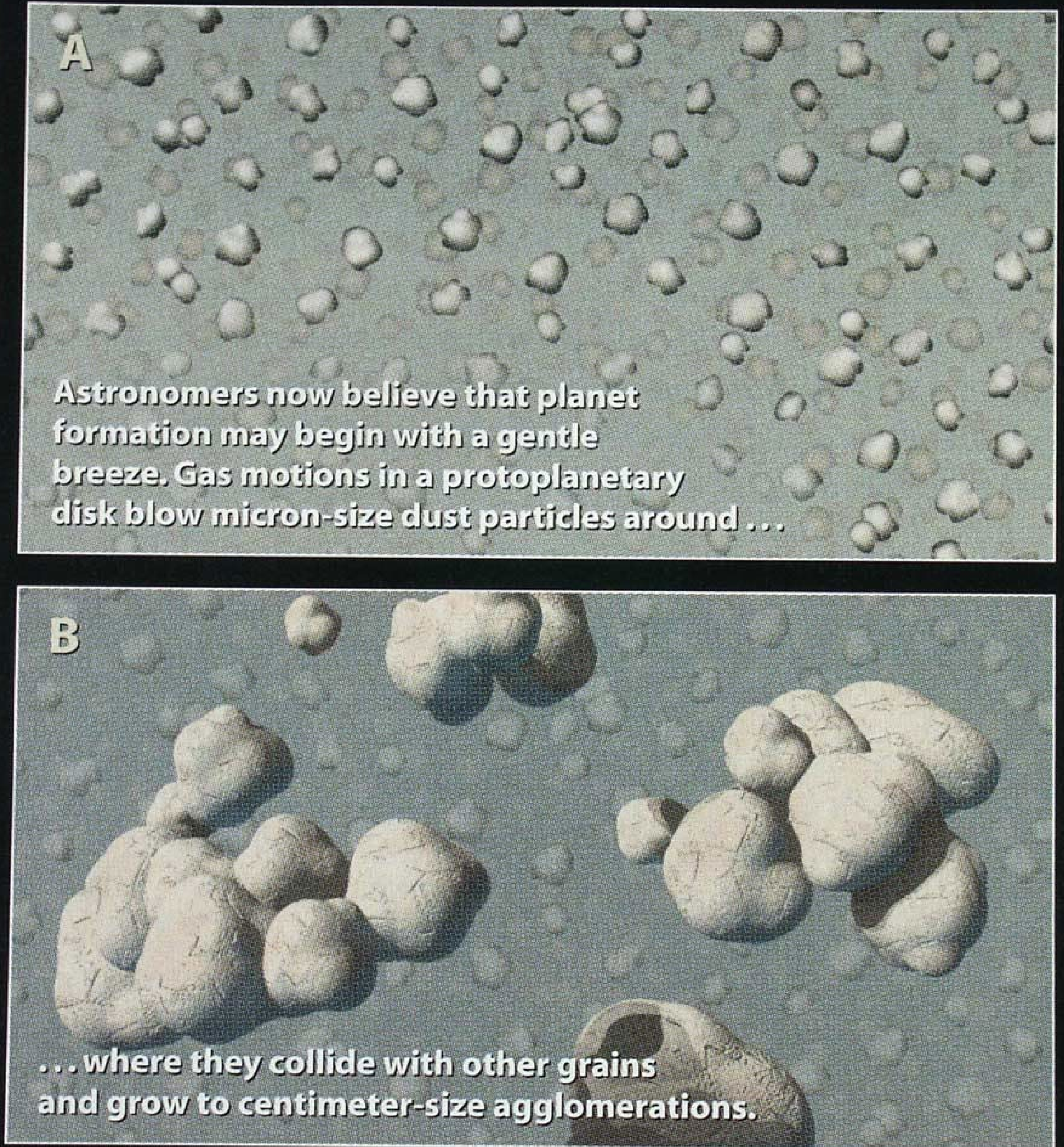
slow

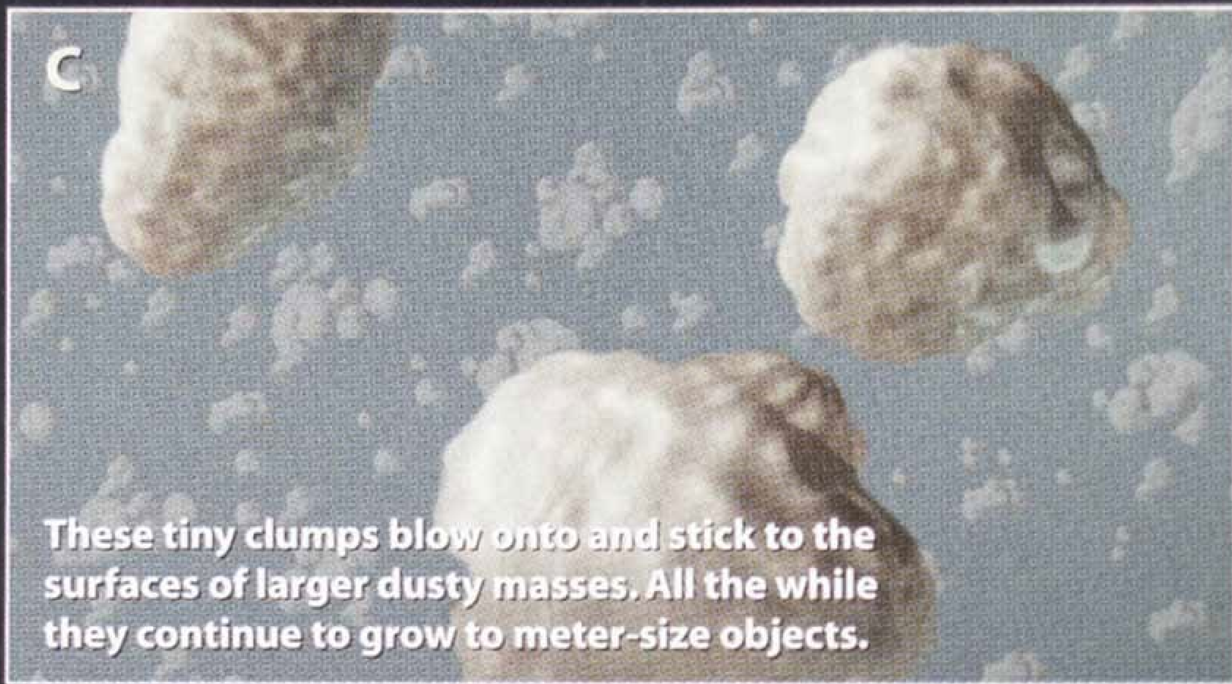


Core Accretion

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).

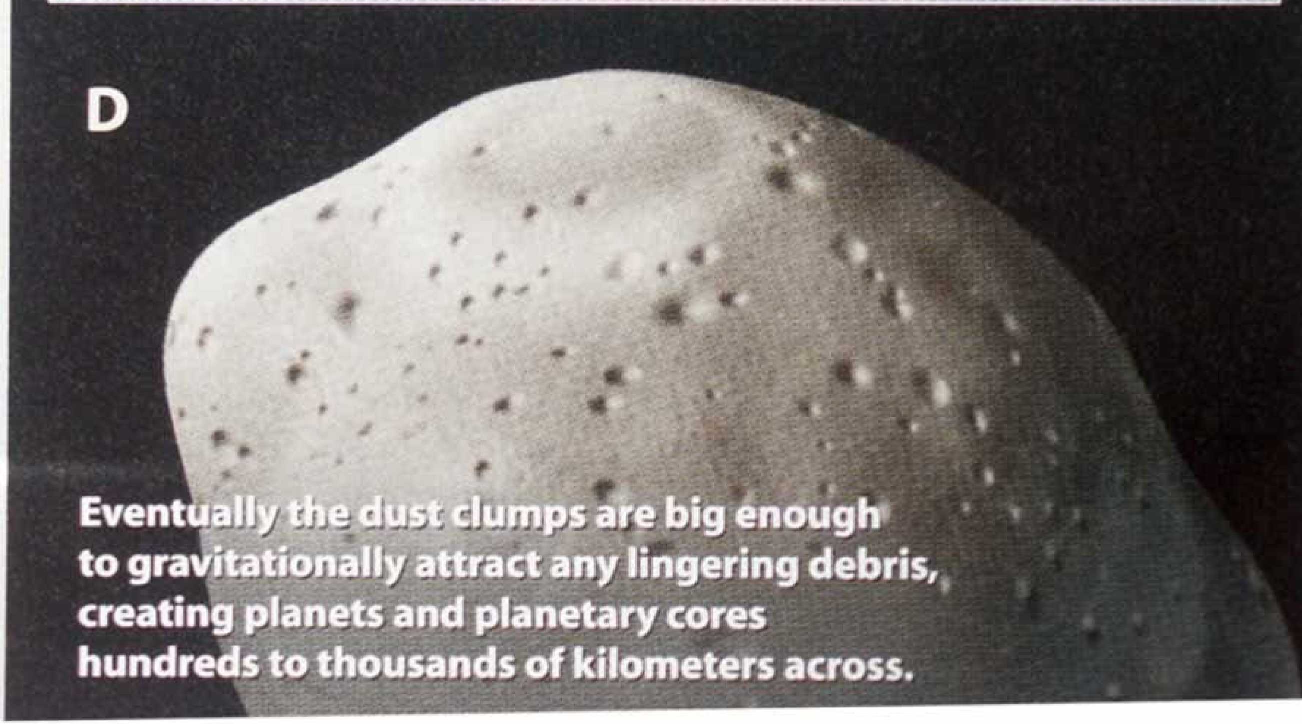
Making a planet this way could take several million years. That's too slow, say some theorists, who argue that the gas needed for planet growth may not linger that long in the disk. They favor a fast alternative (facing page). Either way, smaller, Earth-size planets would form much later, from the leftover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


A
Astronomers now believe that planet formation may begin with a gentle breeze. Gas motions in a protoplanetary disk blow micron-size dust particles around . . .
B
. . . where they collide with other grains and grow to centimeter-size agglomerations.



C

These tiny clumps blow onto and stick to the surfaces of larger dusty masses. All the while they continue to grow to meter-size objects.



D

Eventually the dust clumps are big enough to gravitationally attract any lingering debris, creating planets and planetary cores hundreds to thousands of kilometers across.

Late in Planet Formation…(artist's idea)

The “Fast” Scenario; Eddy’s form and the entire eddy of gas too, collapses to make a planet

- As the mass of the system gets concentrated into the central star, orbital speeds in close are fast, and farther out much slower
- This causes friction; differential rotation, and this generates eddys of spinning vortices
- These may run into each other and combine, eventually being large enough and dense enough to gravitationally collapse and make a planet

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

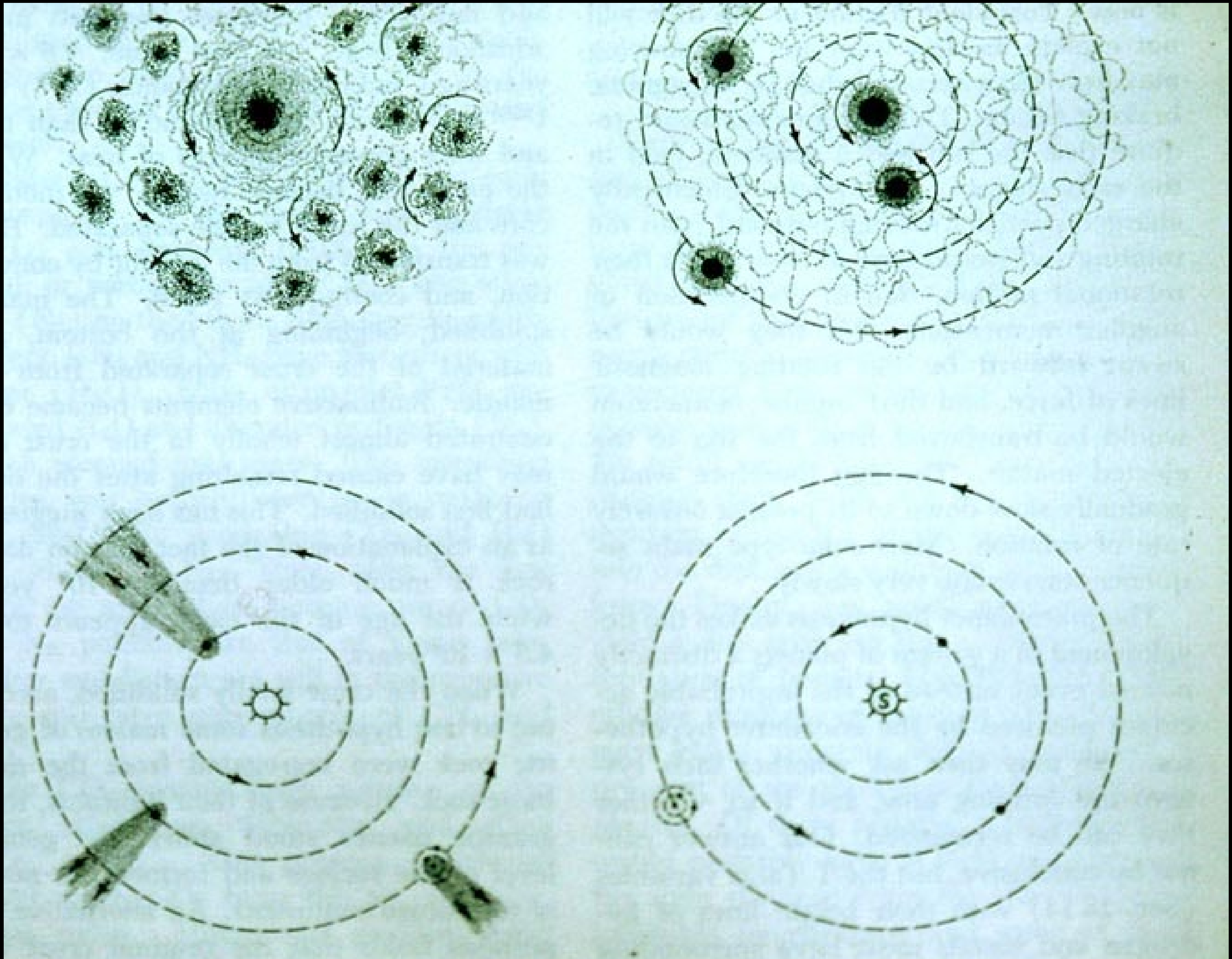


Figure 24.6 Origin of the solar system from a turbulent cloud of gas and dust, according to the protoplanet hypothesis.

fast

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.

A key to the mystery is measuring the masses of proto-planetary disks.

- Do disks stay massive enough for long enough to form planets?
- Tough to answer, because atomic hydrogen cools to form molecular hydrogen, which is very hard to detect.
- Clever astronomers have used a new clue; measure the hydrogen isotope deuterium, whose abundance is directly proportional to ordinary hydrogen. They've done this for a young star TW Hydrae, which is only 3-10M yrs old, and find the disk is much more massive than they had guessed.
- Maybe at least many disks stay massive long enough for the "slow" method to work?
- But still….

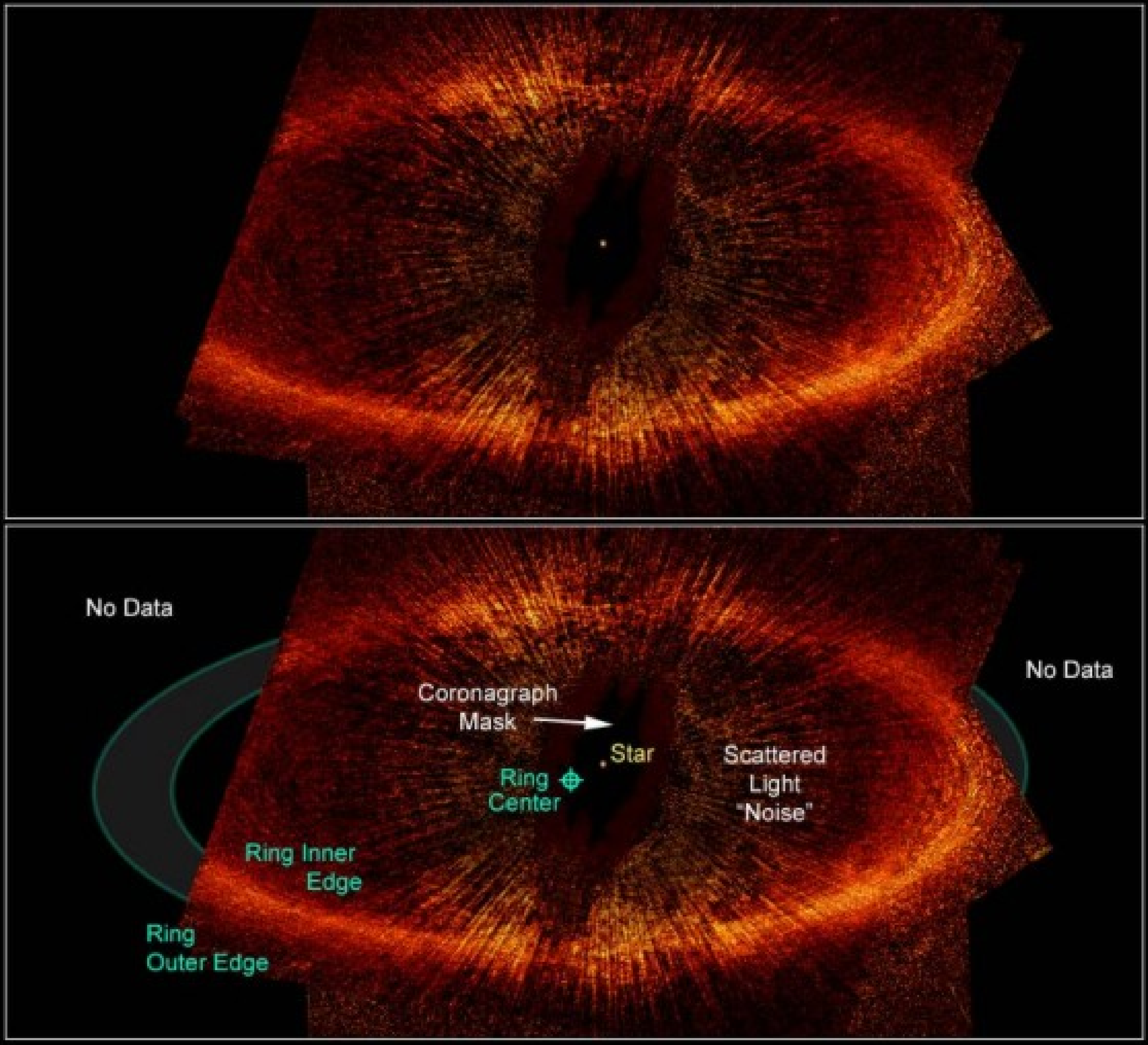
We’re beginning to see…

- … 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.

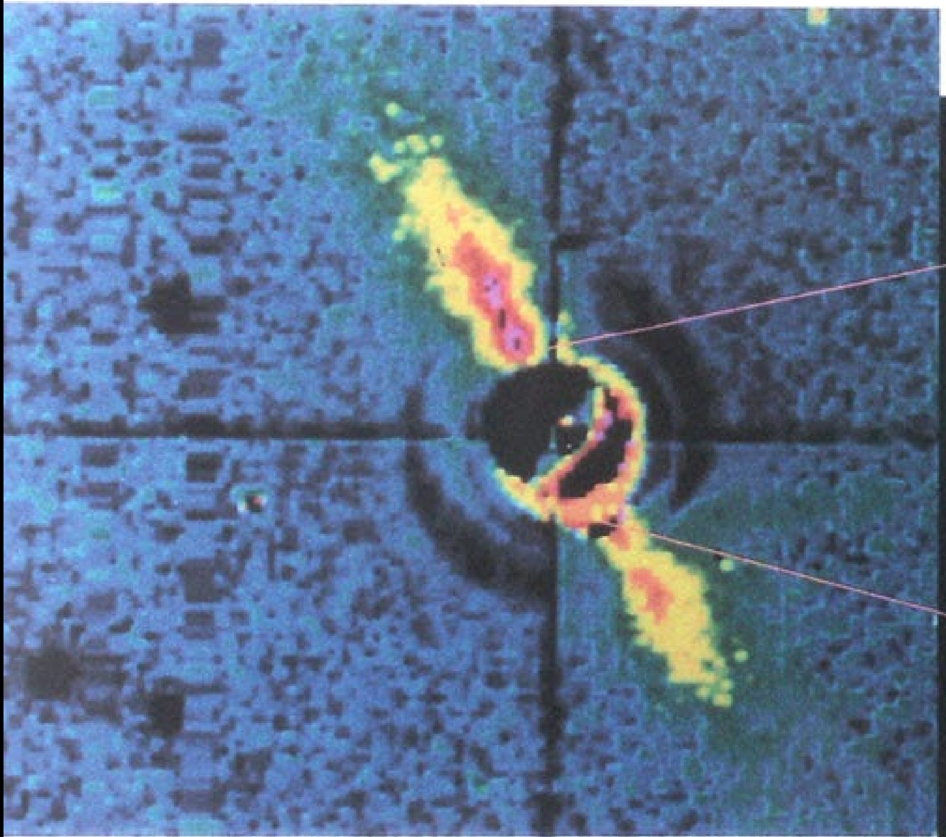
"Slow" Core Accretion goes faster when gravity gets strong enough, but…

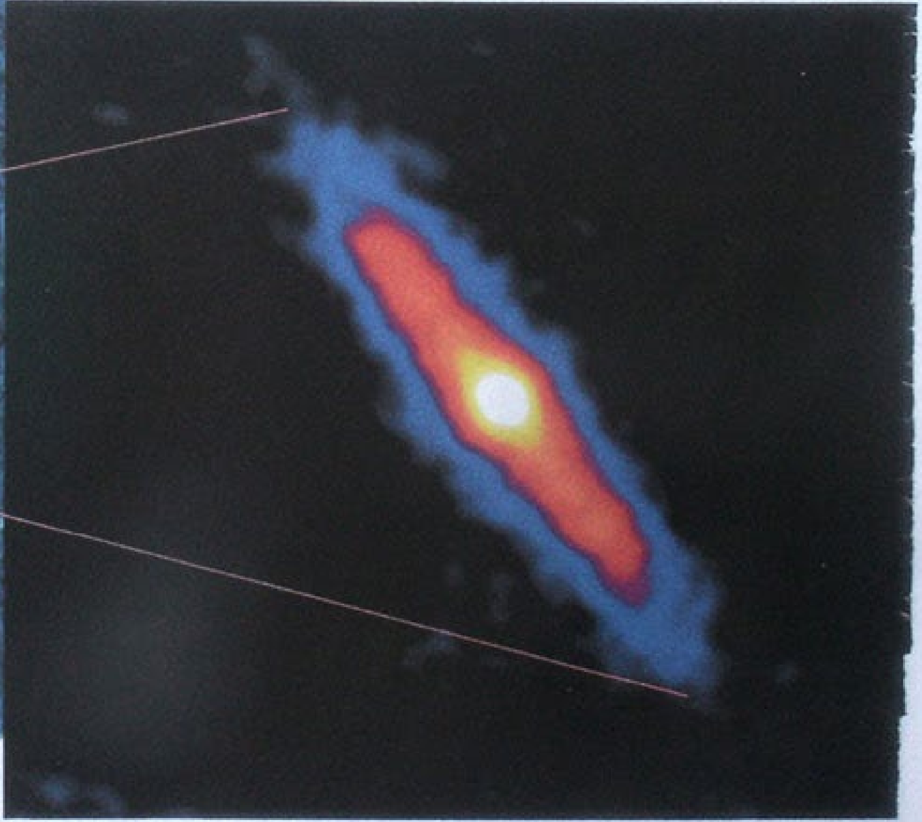
- Once the core grows past ~0.5-1 mile across, gravity becomes significant and accelerates the process.
- Growth rate goes as radius to the 4^{th} power (for constant density).
- So, those cores which get to the self-gravity point first, quickly run away and dominate the growth, accreting the rest. These 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 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.
- This is not yet solved to our satisfaction

Some real disks…Fomalhaut's

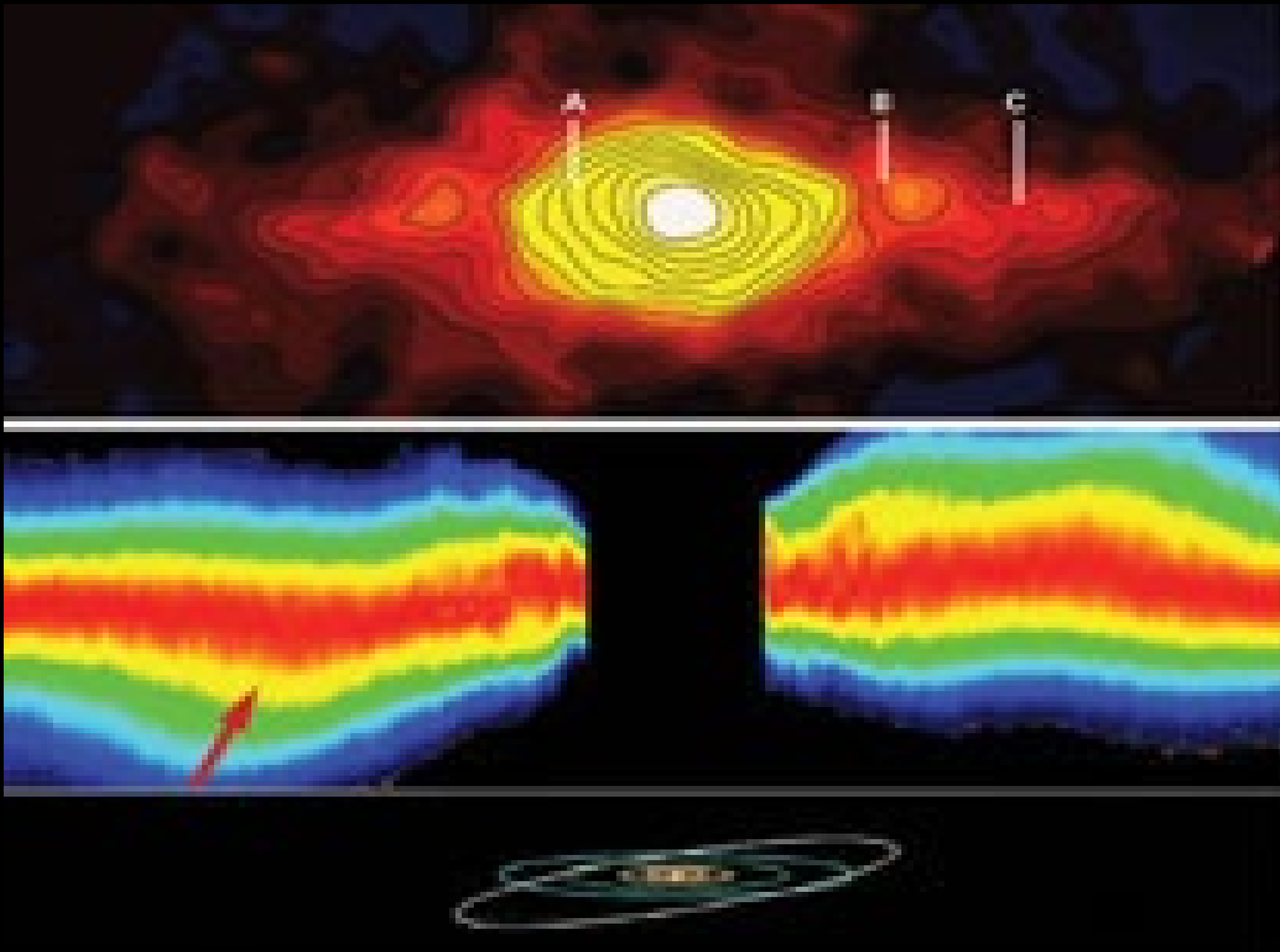


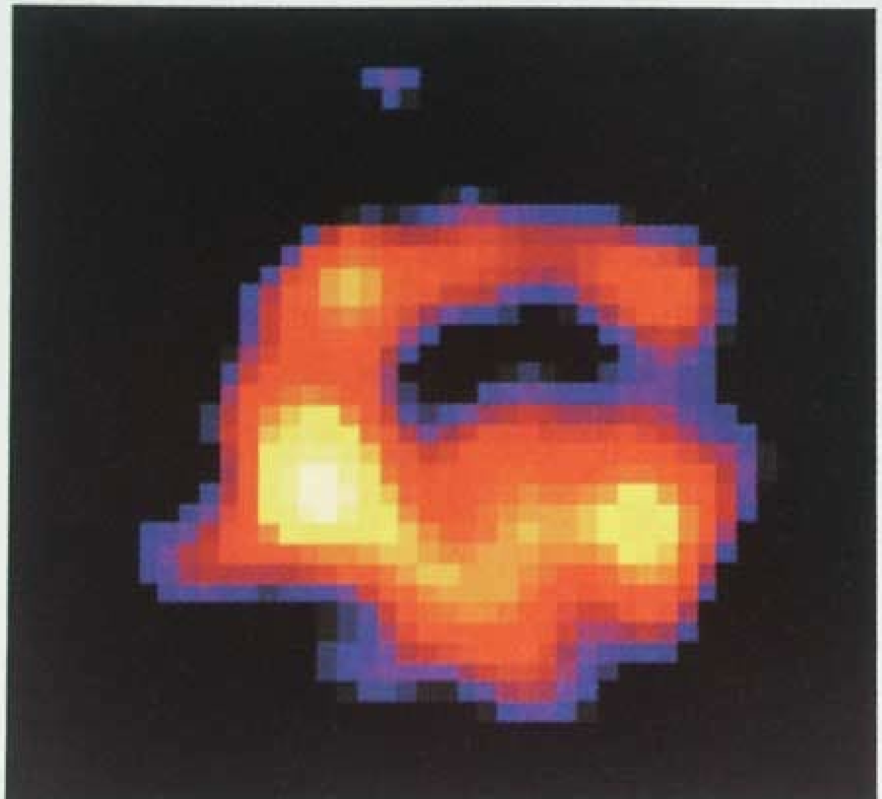
A vast cloud of dust, perhaps kicked up by colliding asteroids, envelops the young star Beta Pictoris in images from 1984 (left) and last January. Both images give a side view of the disk-shaped cloud and indicate brightness with false color. The earlier one, made in visible light, reveals only the disk's 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.

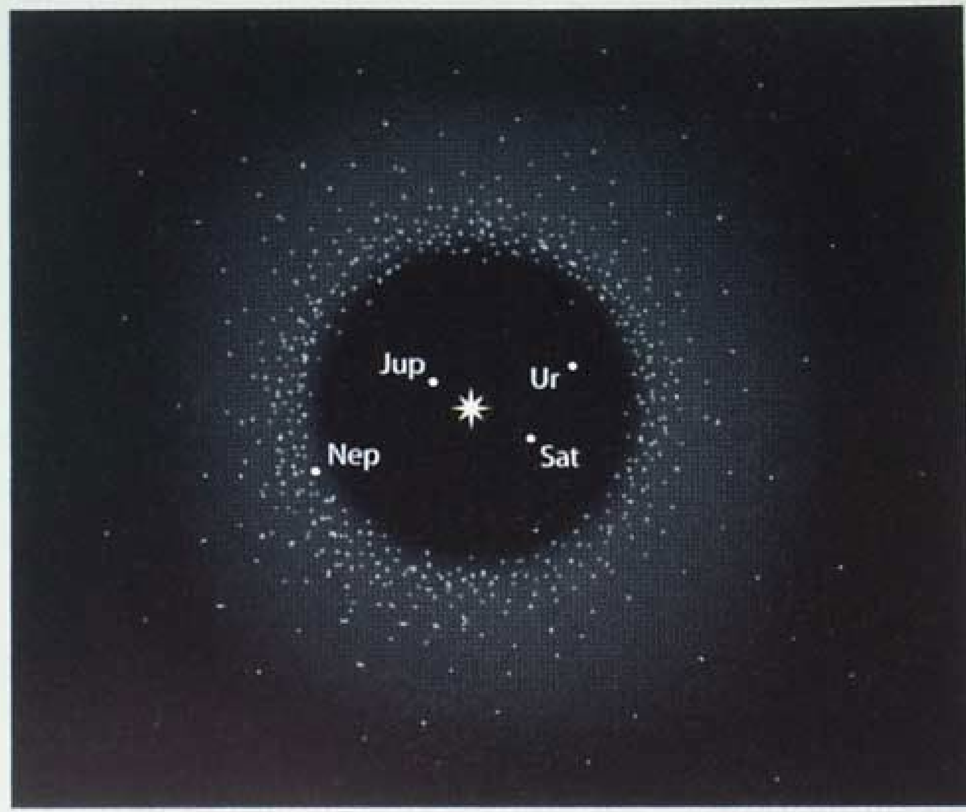




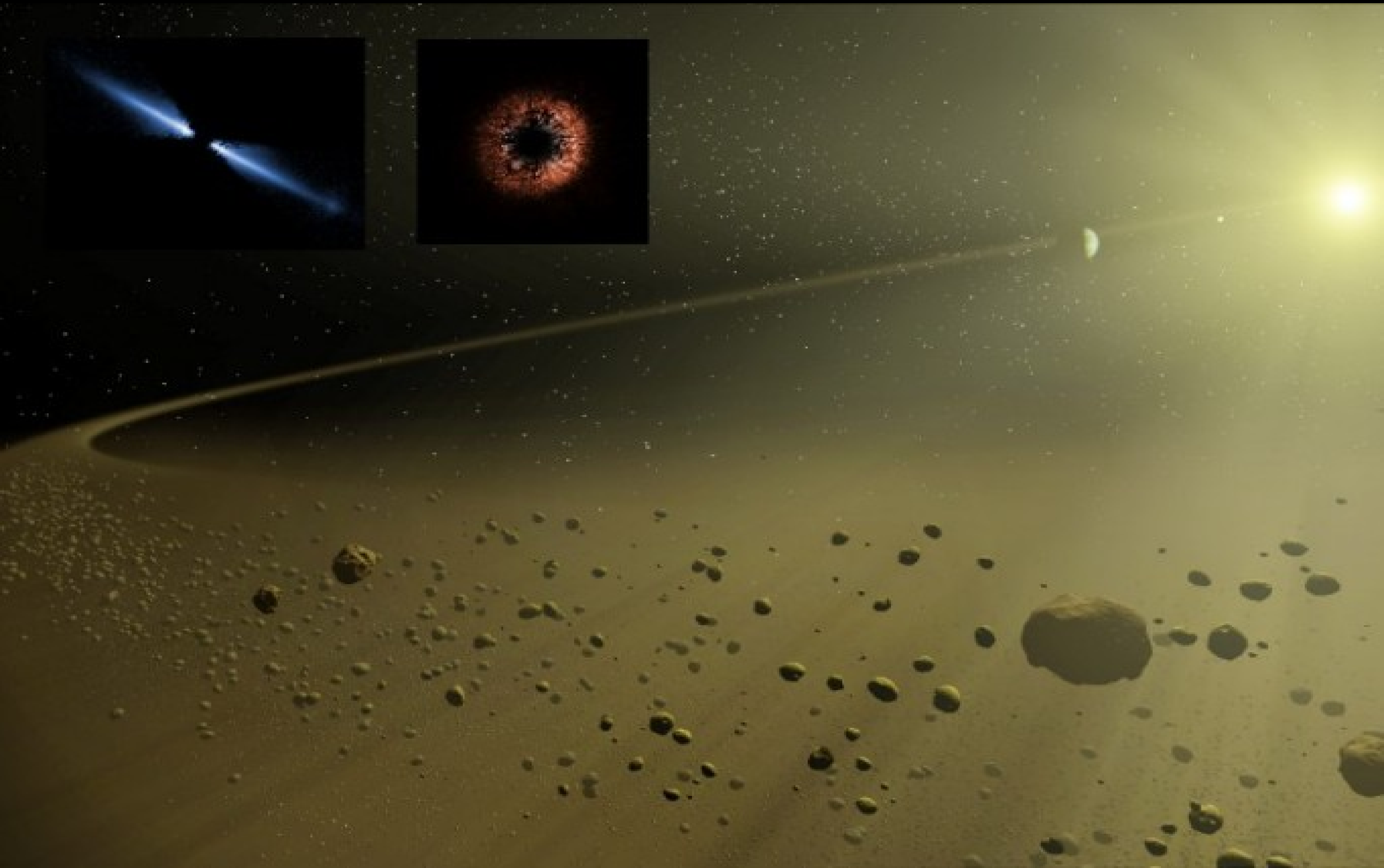
BRADFORD SMITH, UNIVERSITY OF ARIZONA, AND RICHARD TERRILE, JET PROPULSION LABORATORY (ABOVE); CHARLES TELESCO, UNIVERSITY OF FLORIDA, AND SCOTT FISHER, GEMINI OBSERVATORY


A
B
C




Jup
Ur
Nep
Sat

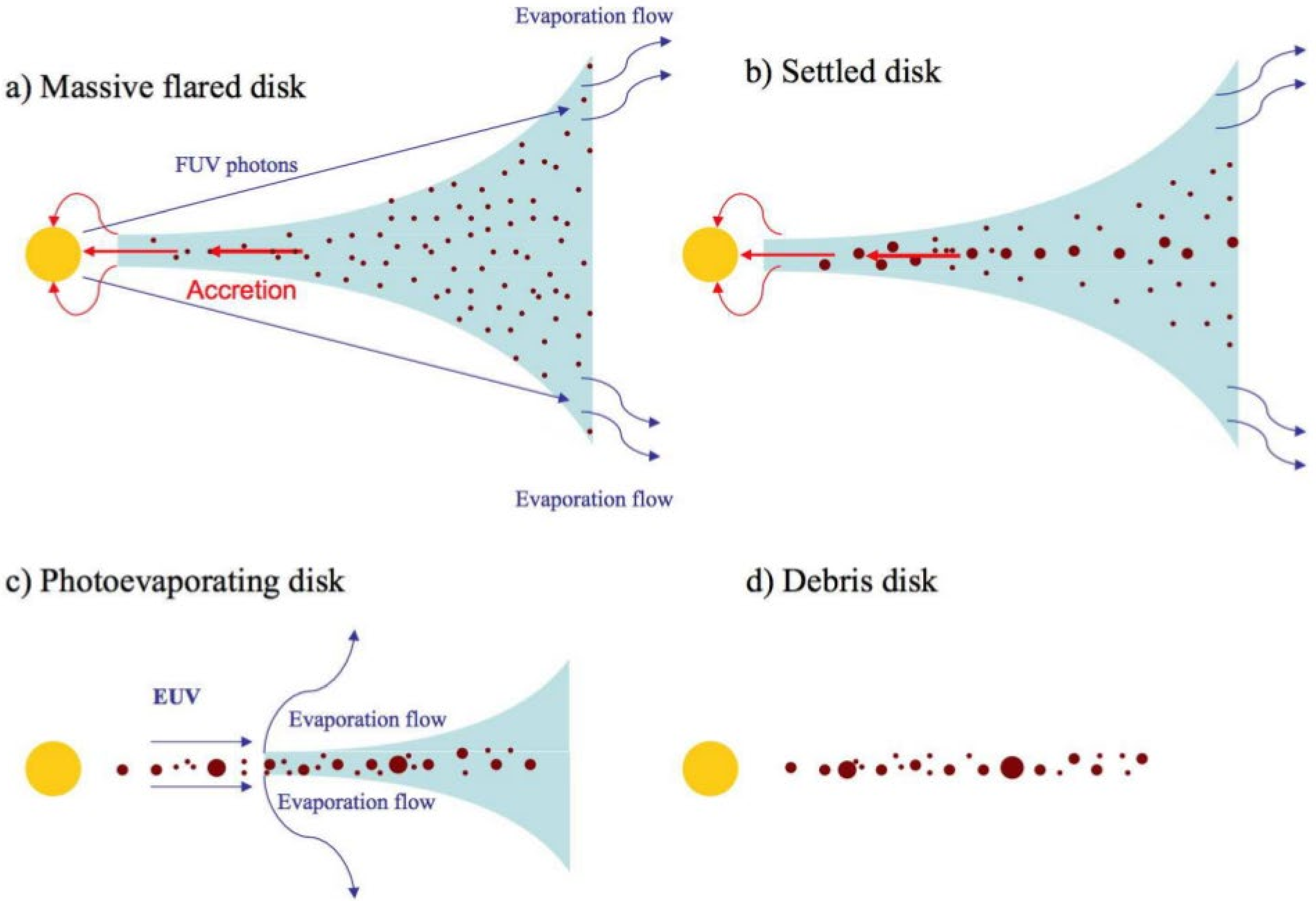
Probably you have some mix of both processes happening at the same time. Dirt clods within eddys or rings



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).

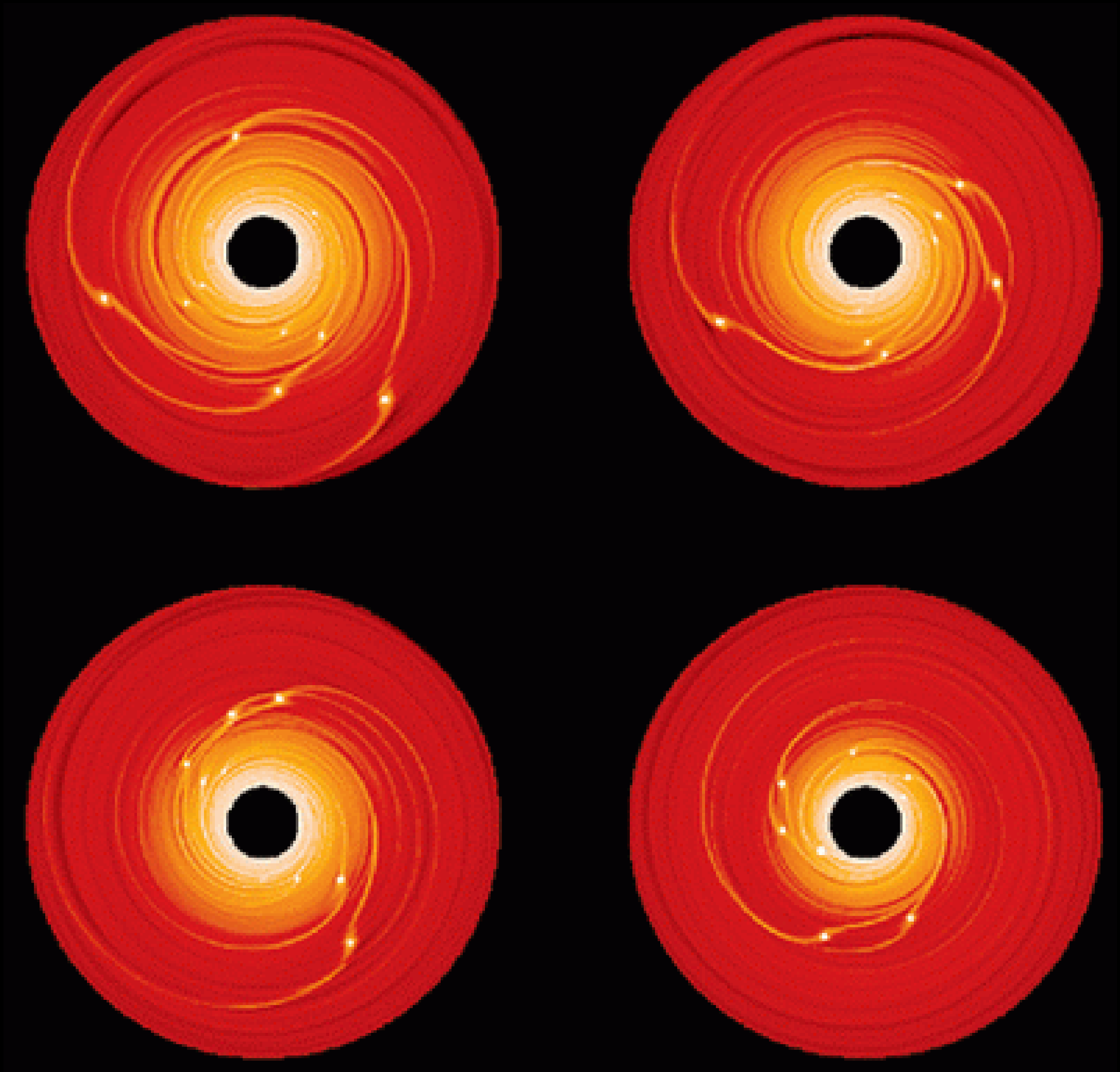
ART BY MOONRUNNER DESIGN. CONSULTANT: DEREK C. RICHARDSON, UNIVERSITY OF MARYLAND

Young Proto-stars in Dusty Environments

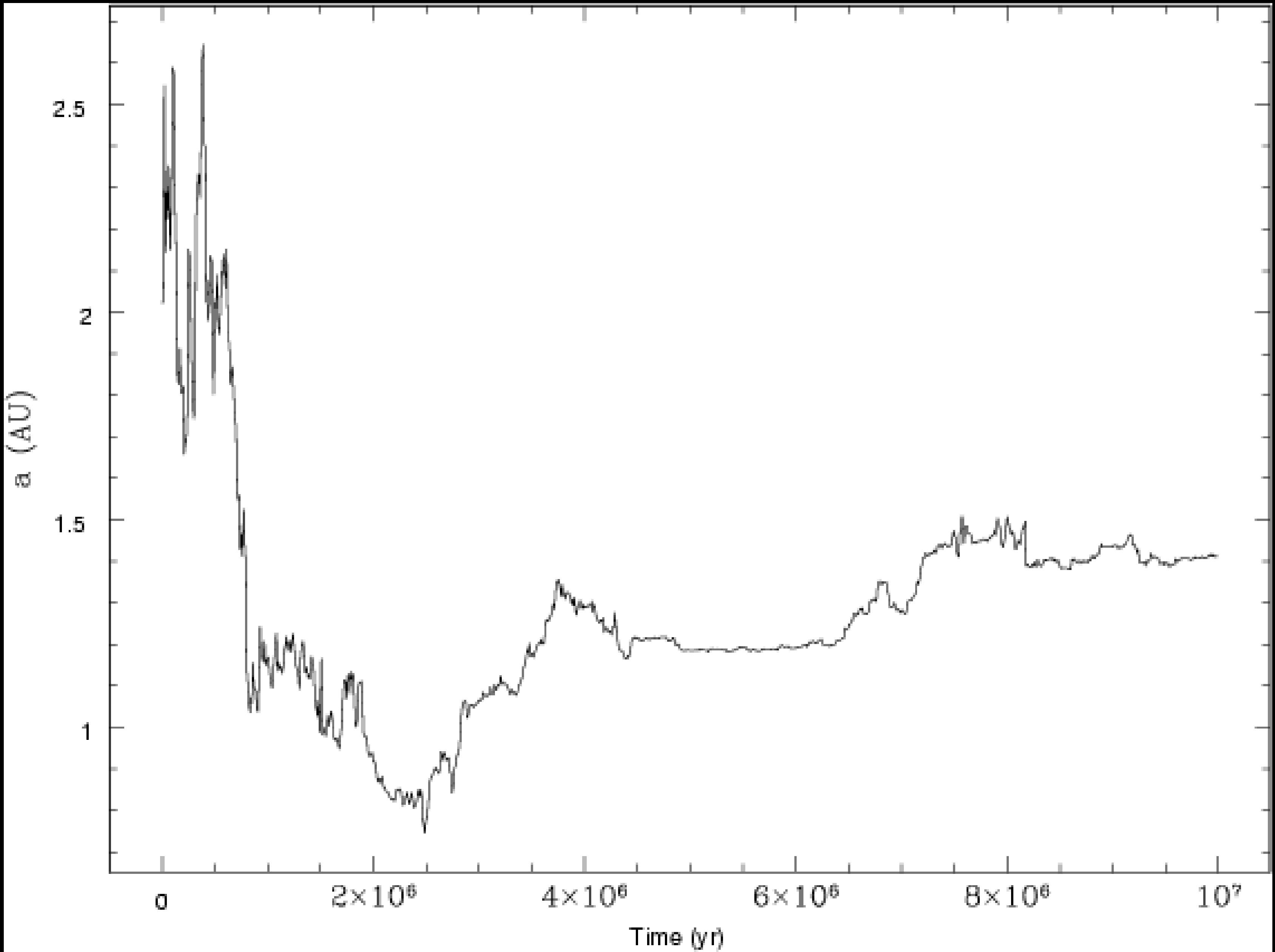


a) Massive flared disk
Evaporation flow
FUV photons
Accretion
Evaporation flow
b) Settled disk
c) Photoevaporating disk
EUV
Evaporation flow
Evaporation flow
d) Debris disk

Numerical Simulation 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



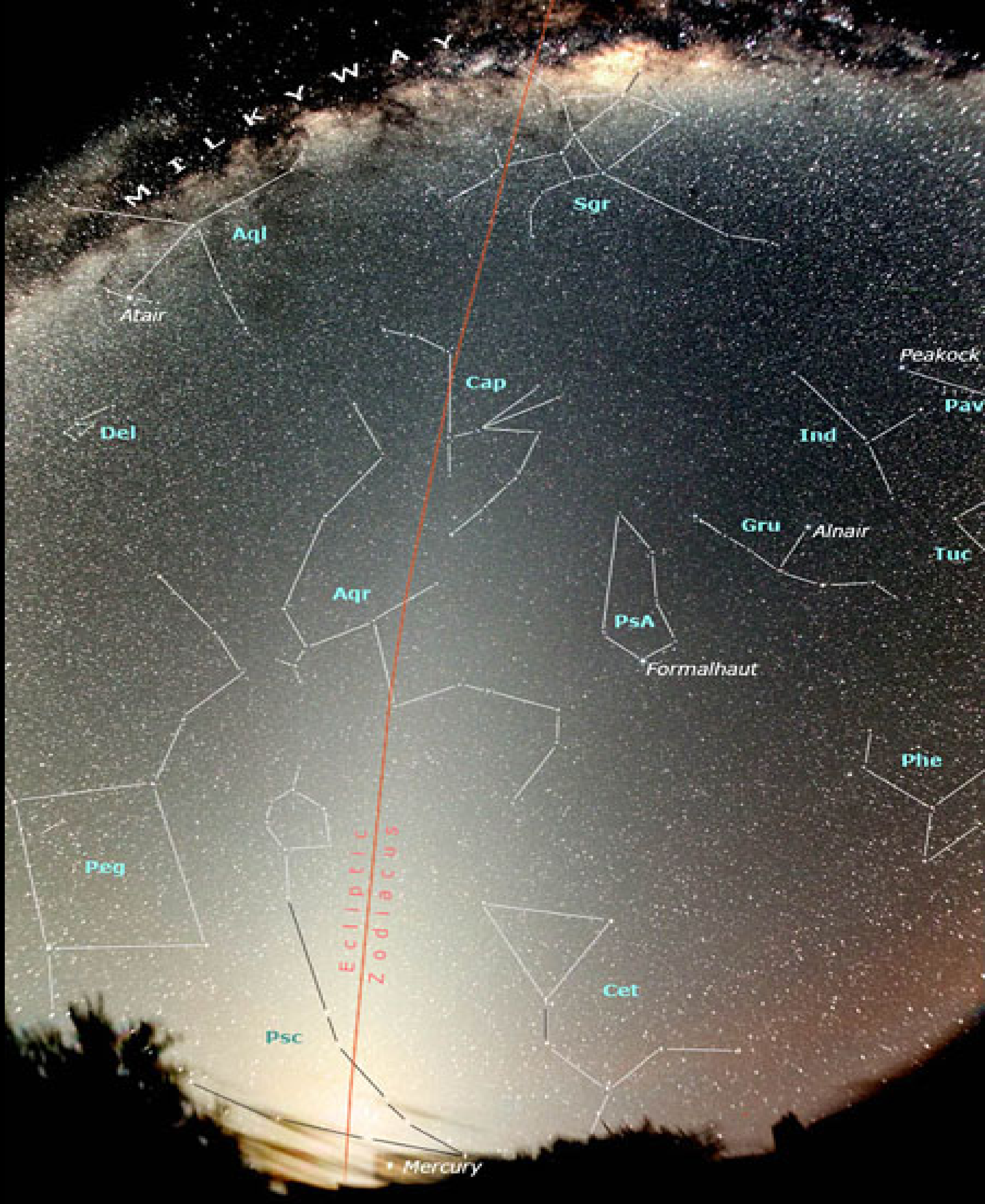
“Strafing” on Some Moons Shows Prior Dust Disk Evidence

Is There Any Visible Remnant of our 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. Maybe most is fresher.

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



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

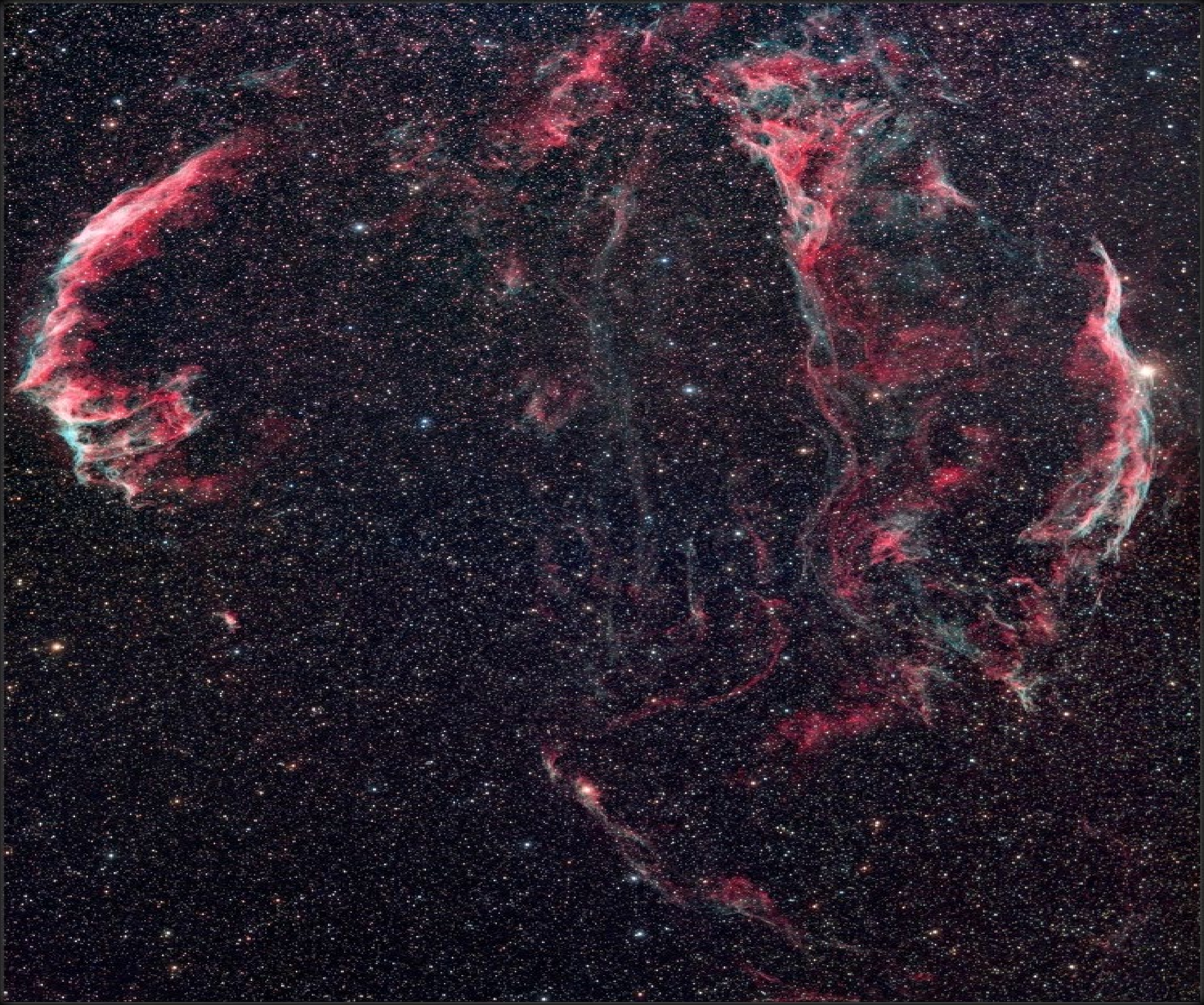
Gritschneder *et.al.* (2011) (summarized here), and UCSC pdf here, did hydrodynamic simulations, and find a type II supernova 5 parsecs away would produce the evidence we see – Mg 26 (from decayed Al 26) uniformly spread through the solar nebula in the abundances seen.

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 Giant 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.

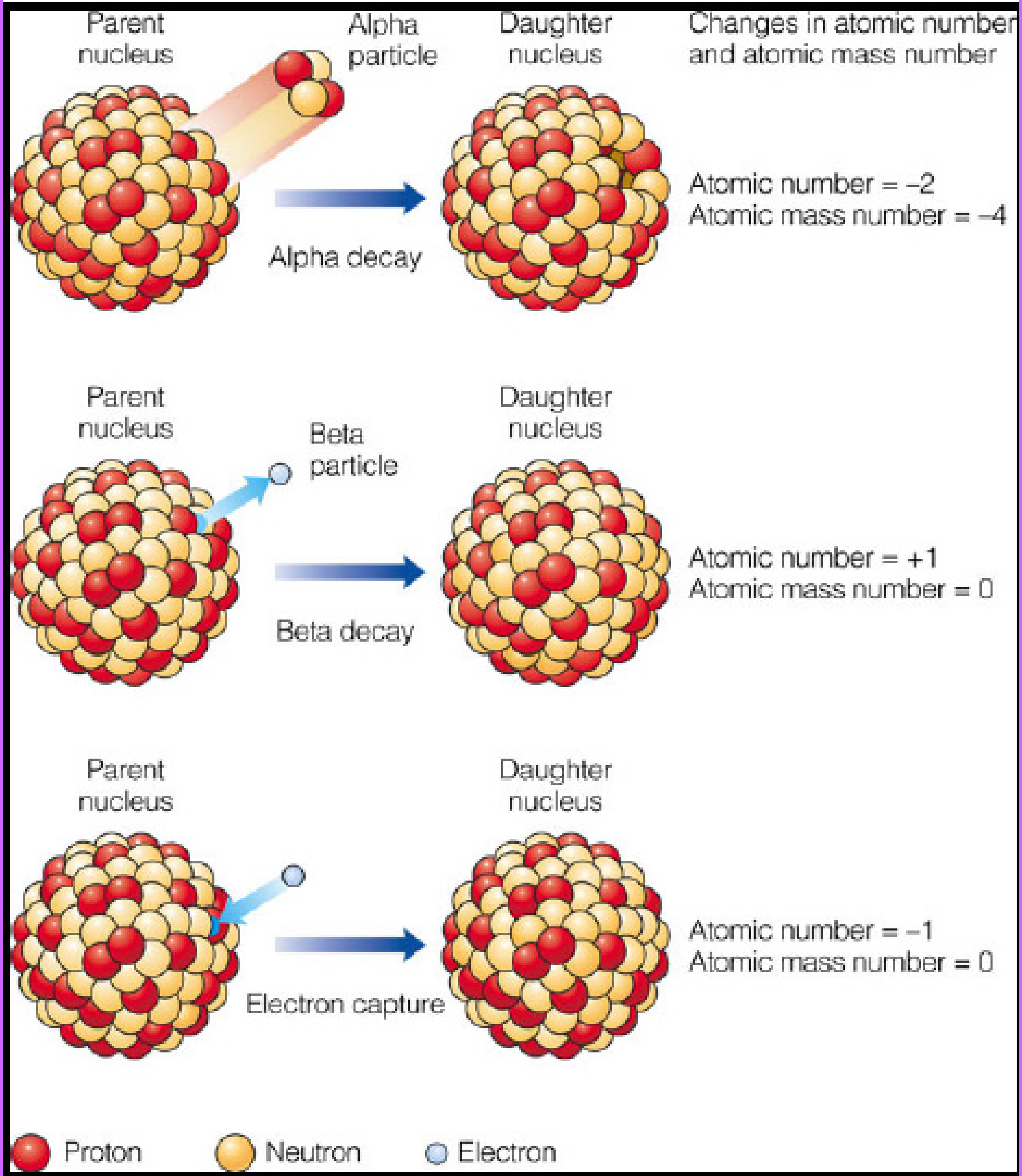


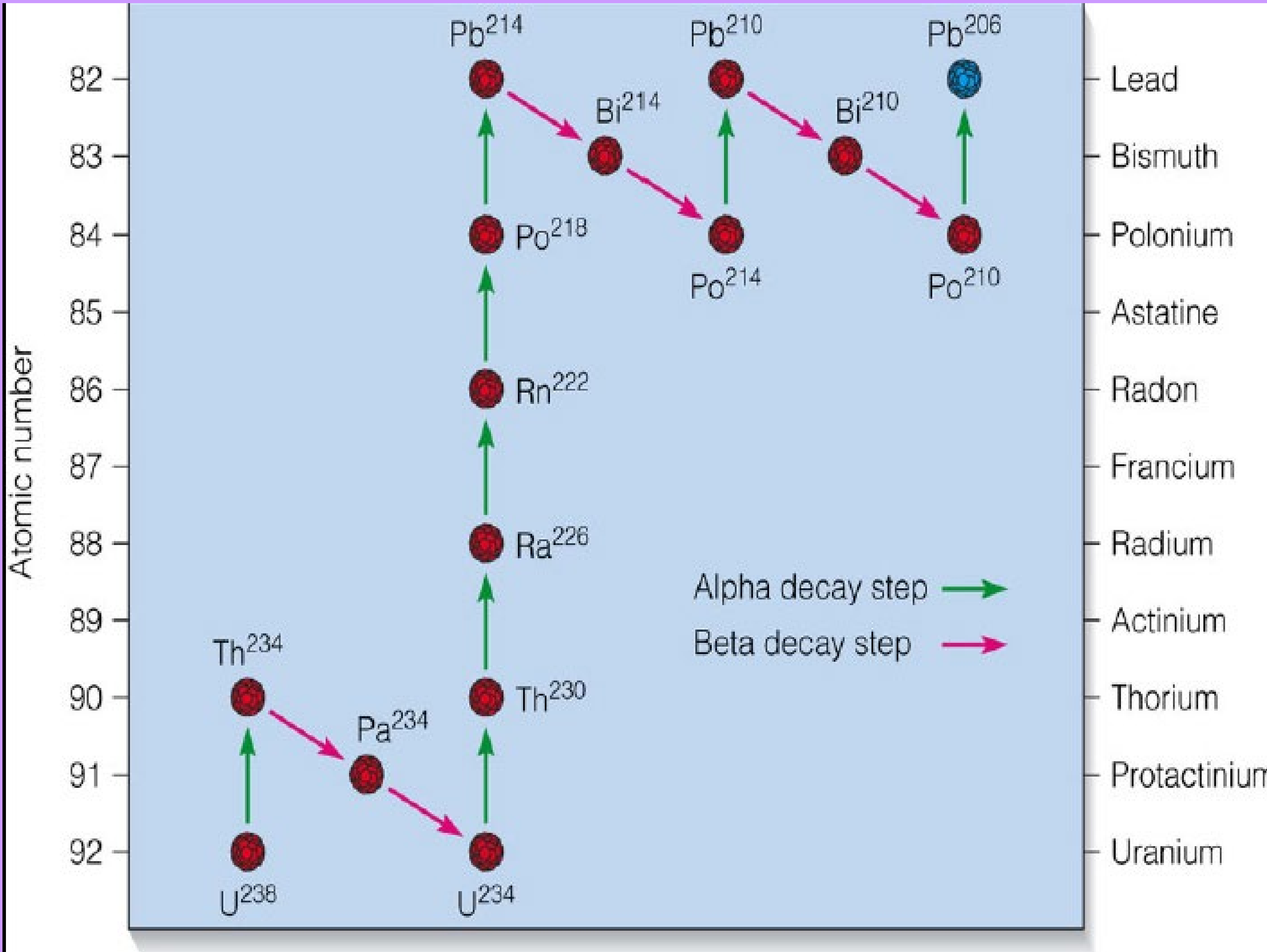
The Veil Nebula Complex in Cygnus

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


Atomic number
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83
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Pb214
Bi214
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Bi210
Pb206
Po218
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Po210
Rn222
Ra226
Th234
Th230
Pa234
U238
U234
Lead
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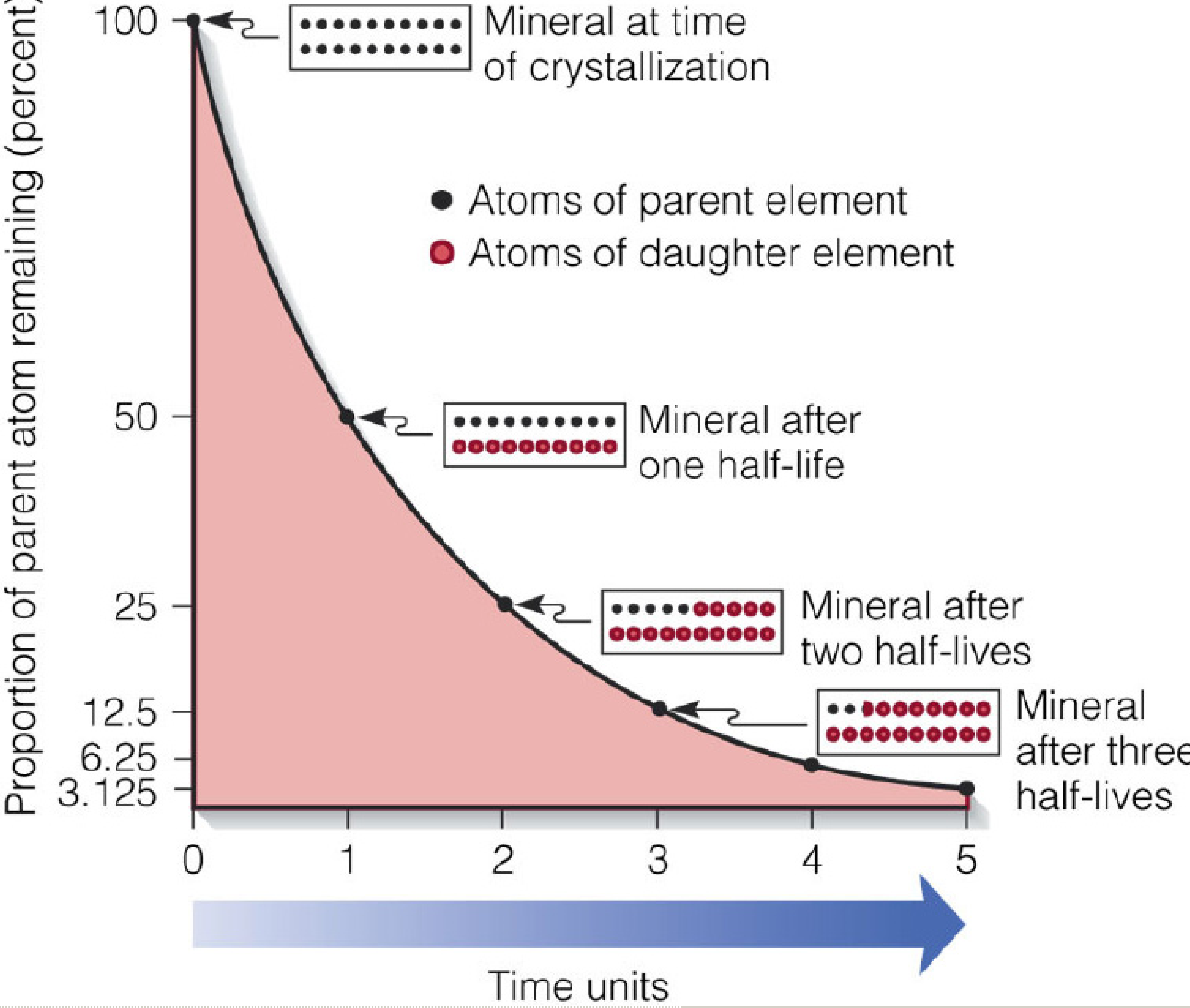
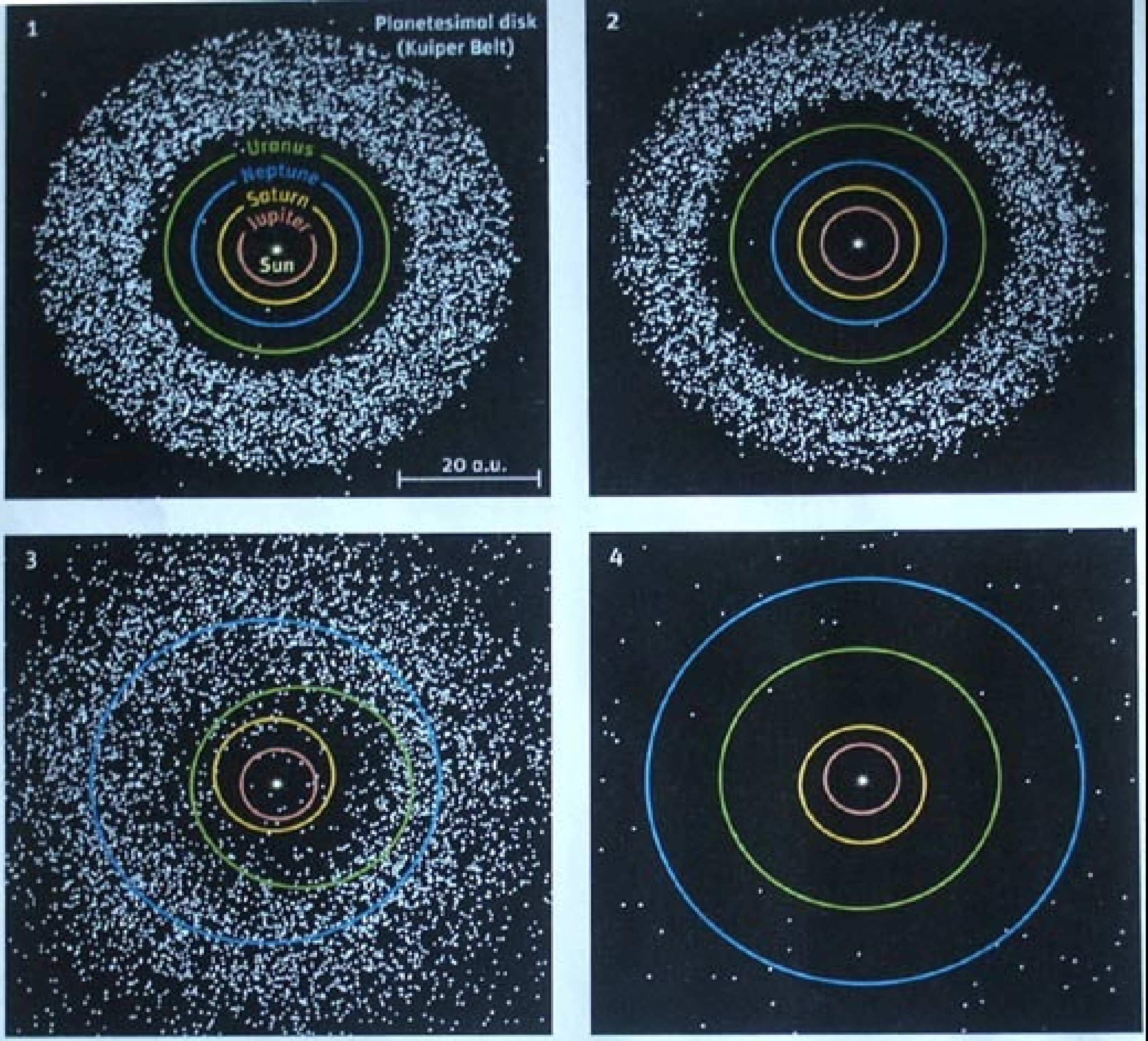
Protactinium
Uranium
Alpha decay step
Beta decay step



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 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 a bit farther out, to their current positions.**



(1) In a recent computer simulation, Jupiter and Saturn start off on circular orbits at 5.5 and 8.2 astronomical

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

The Story

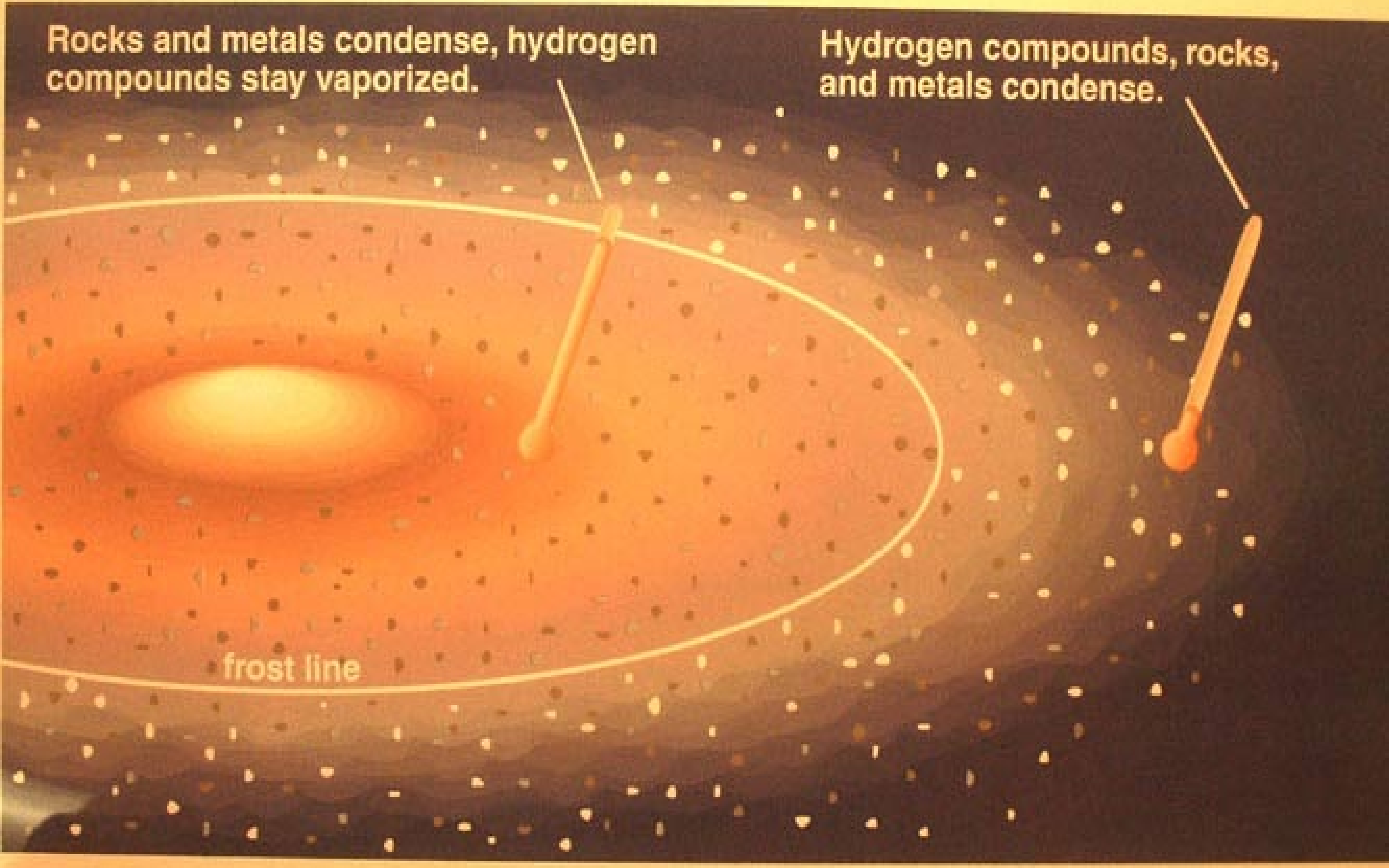
- The formation sequence we laid out fits well known physics and accounts for all of these features. It's the odds-on favorite for "The Truth", albeit no doubt there's details which are yet to be fully worked out
- Many of these details will no doubt become clearer as we discover new planets around other stars and puzzle out their characteristics. That's a story very much in today's news and today's active research

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

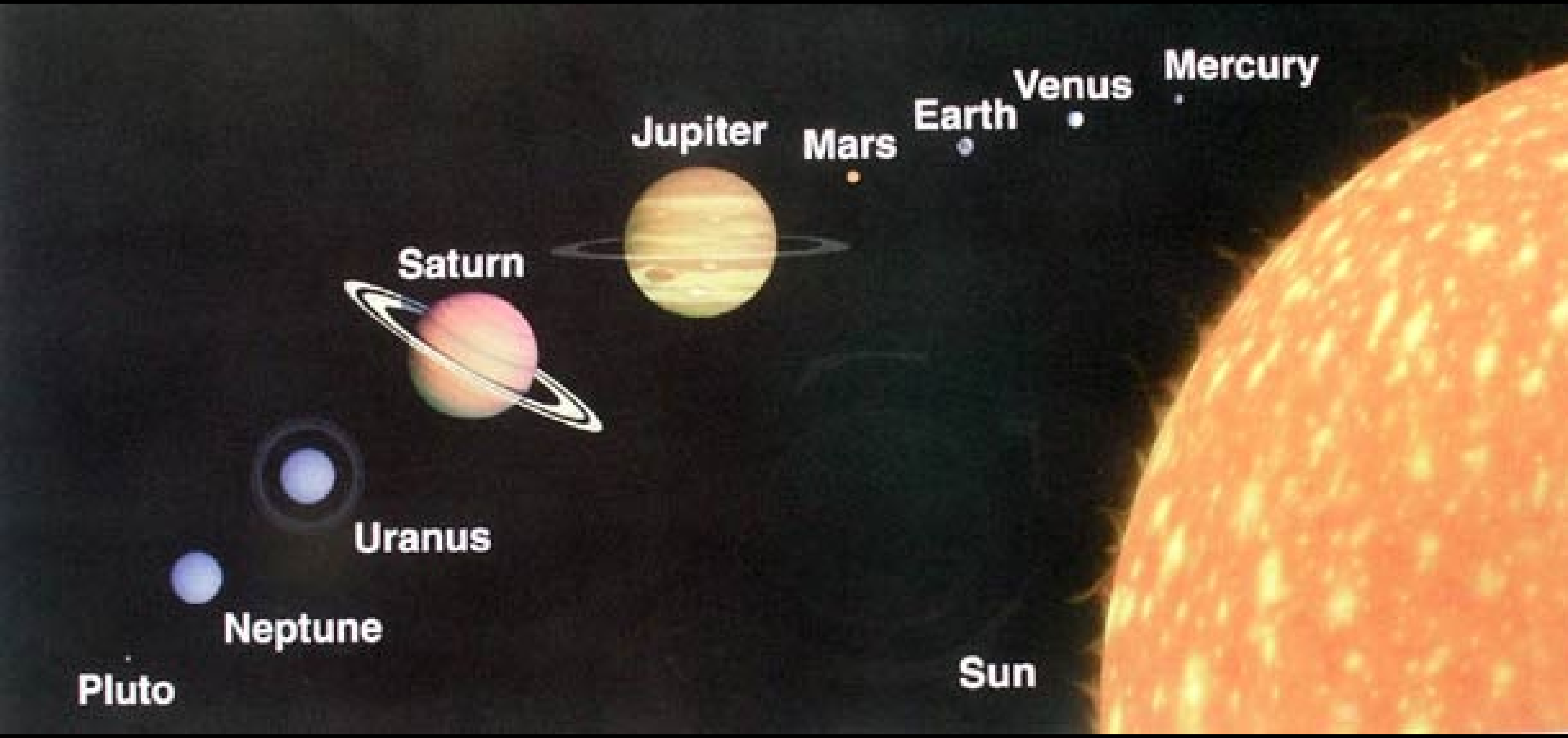
Beyond the Frost Line…

- 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

Ergo – 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 Kuiper Belt stand-in)

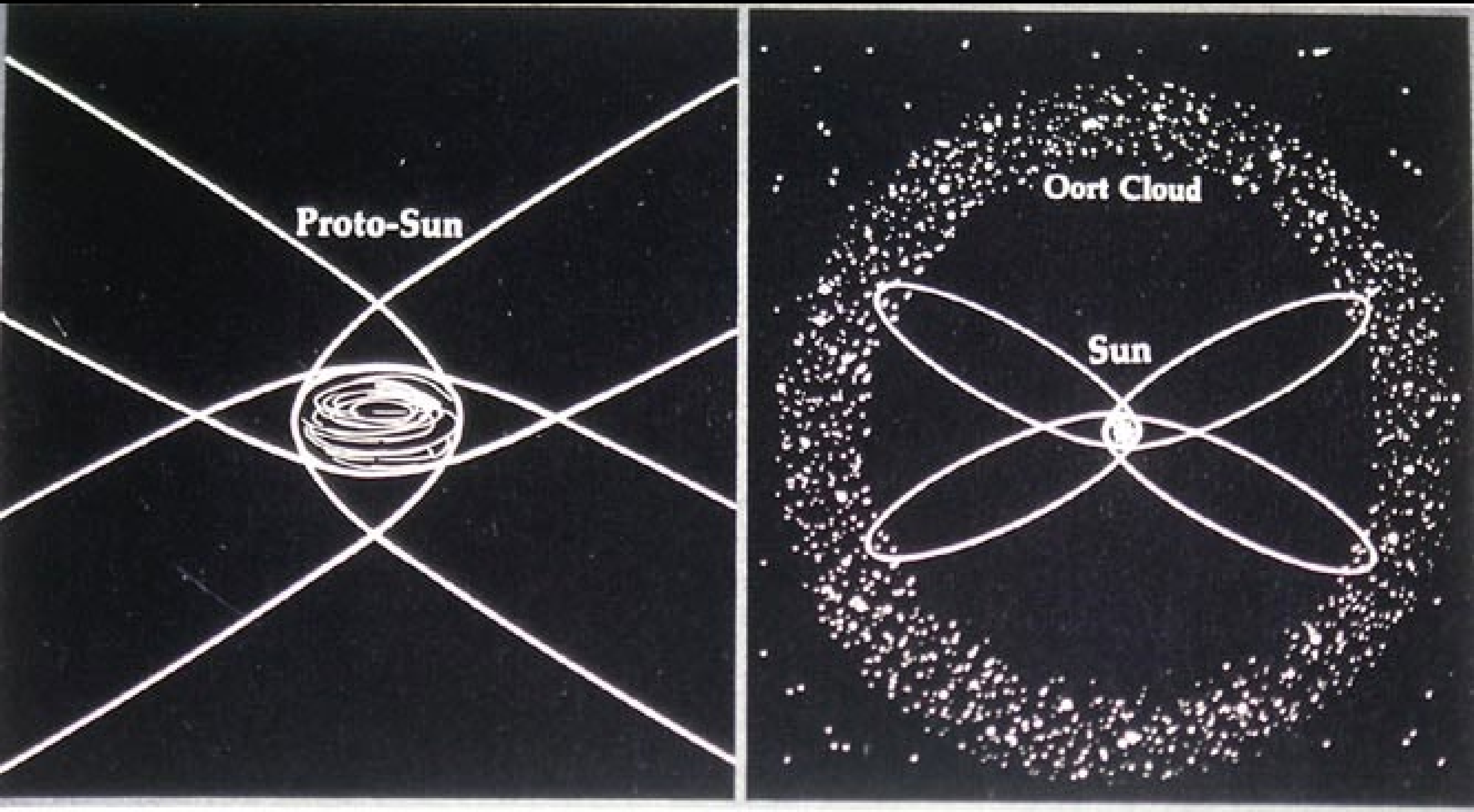


Beyond Neptune… the Kuiper Belt of Giant Ice Balls!

- 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 **Oort Cloud** of comets
- Inferred from the observed orbits of comets which have their farthest points vastly farther away than Pluto.
- About 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.

Chapters 7,8 – Key Points

- Our solar system: a by-product of star formation within a giant molecular cloud
- Need HIGH density, and LOW temperature to favor star and planet formation.
- Planets form in the disk of high angular momentum material, pulled offline by gravity of neighboring protostars
- A supernova likely triggered the collapse of the proto-solar cloud (excess Mg 26 inside meteorites is one of key evidences)
- Angular momentum came from gravitational pull from nearby other stars in our cluster, as proto-solar nebula collapsed
- This angular momentum only allowed collapse to a certain size disk, so not 100% could fall onto central star. Friction caused material to settle into a disk
- Gravity caused proto-planets to form, coalesce into planets which inherit the motion of the disk material
- This mechanism explains the large scale patterns of our solar system. Details are still an active area of research
- Inner planets – formed by rocky material inside "frost line"
- Outer planets – formed by hydrogen compound ices as "starter seeds", and since H is most of the proto-solar system, these planets are large
- Beyond, is Kuiper Belt of 10's of thousands of giant ice cores
- 100x further away is the Oort Cloud, size limited by tidal forces from other stars in our Galaxy to about ½ light year outer radius, of more ice cores.