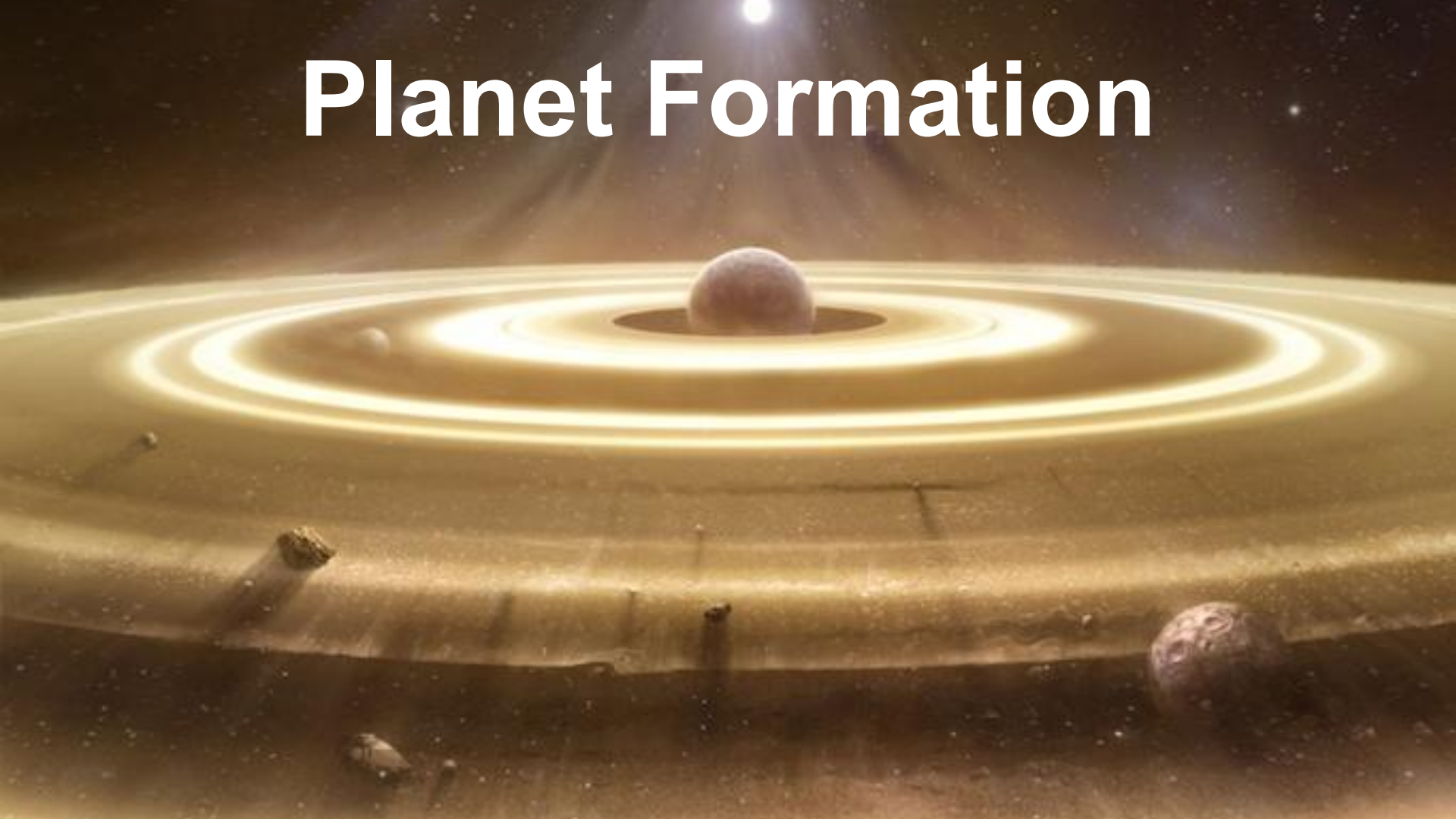
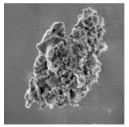
Planet Formation



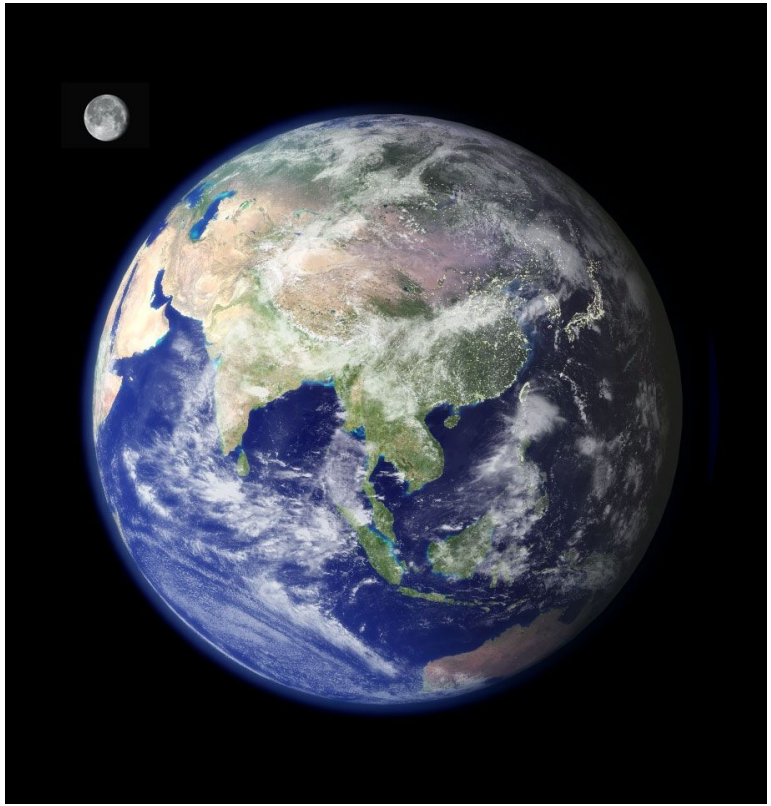
Growing solid bodies is a problem that spans ~37 orders of magnitude



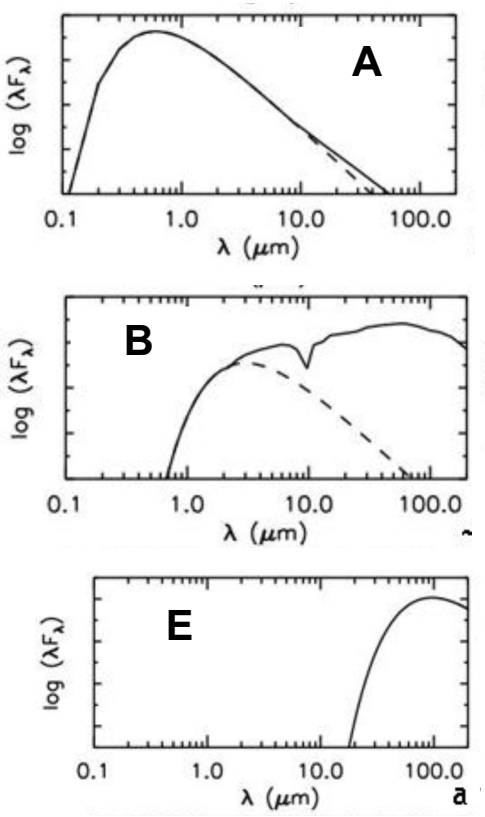
Mass growth x10^{37}

from dust to planets

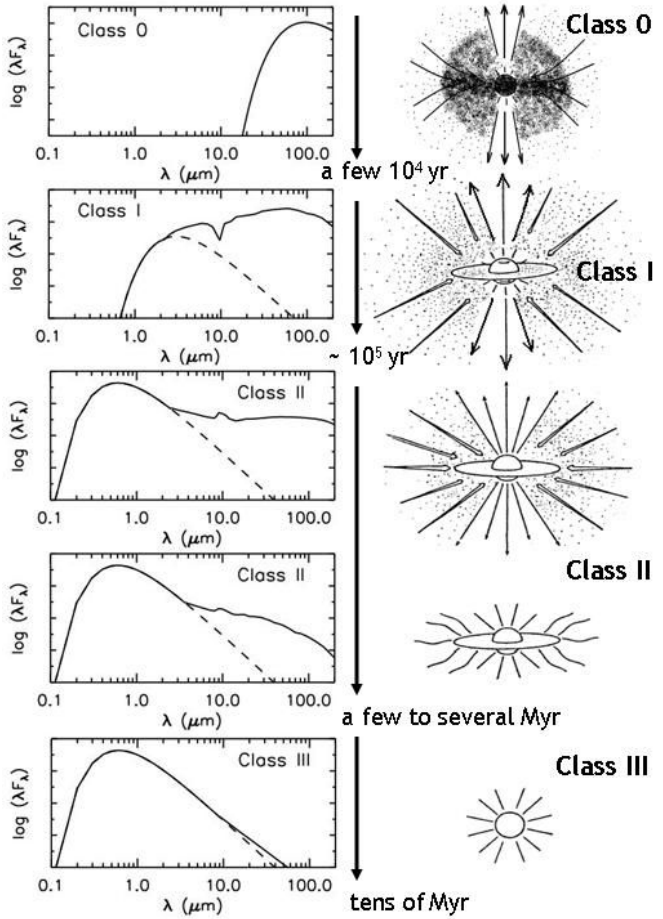
(terrestrial or cores for gas giants)



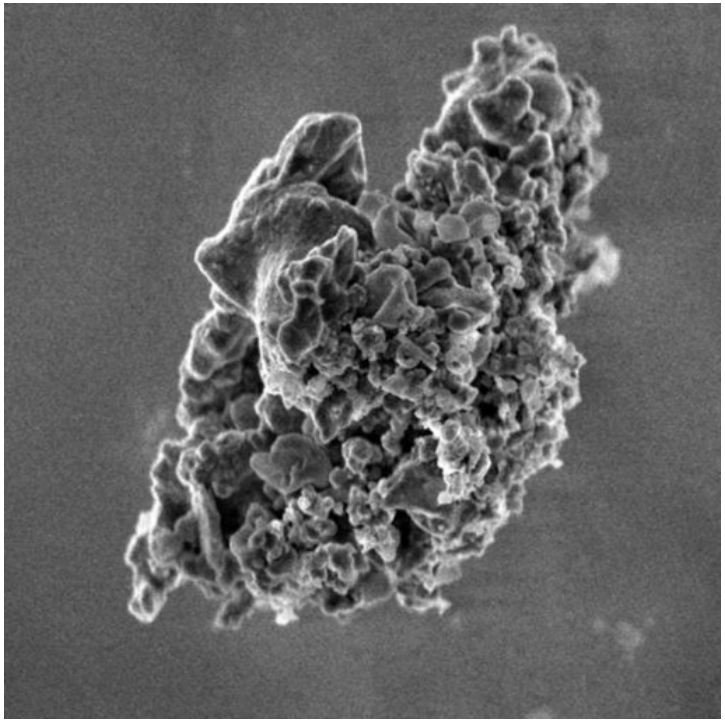
Put these SEDs in order by age (young to old)



Answer:
E → B → D → C → A



Planet(esimal) Formation



Dust particles coagulate to form bigger objects:

- Dust grains
- Pebbles
- Boulders
- Planetesimals
- …. Planets?

Building Block: Dust Grains

They are coupled to the gas in the proto-planetary environment, and move in Brownian motions.

Relative velocities ~1-10 m/s

From here, the story is competing growth vs fragmentation.

The “Meter Barrier”

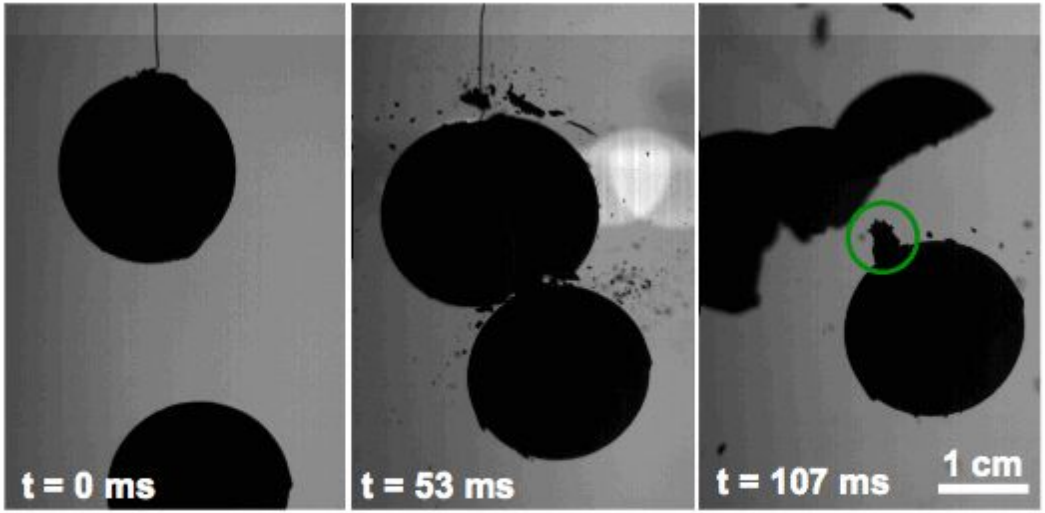


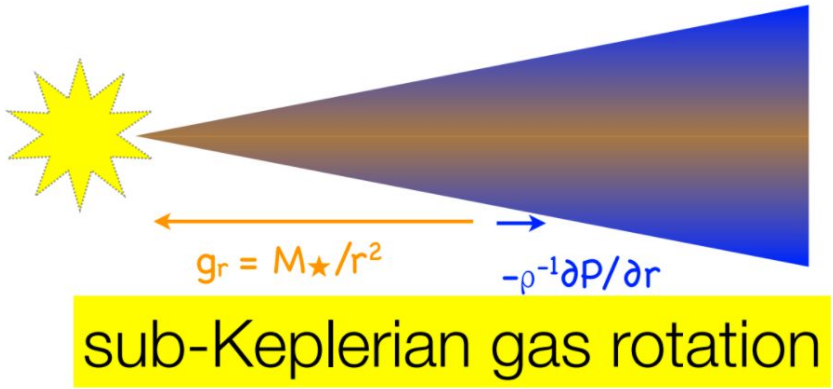
FIG. 7.— An image sequence of a fragmenting collision at a velocity of 47 cm s^{-1}. The upper aggregate is destroyed while the lower one gains 0.6 percent of its original volume.

As sizes approach meters (i.e., boulders), objects decouple from the gas and relative velocities grow, while the weakest bond in the aggregate becomes weaker.

➡ **Fragmentation should win.**

How can small pebbles grow to planet size?

Material drift in the disk



Gas rotates slower than Keplerian velocity because of pressure support.

Let's derive this!

$$\frac{v_{\phi,gas}^2}{r} = \frac{GM_*}{r^2} + \frac{1}{\rho}\frac{dP}{dr}$$

For small dust particles:

$$t_{\rm fric} = \frac{m\ v}{|F_D|}$$

Relative velocity of gas and dust

Drag force

Drag force:

$$F_D = mv\frac{\rho_g}{\rho_d}\frac{c_s}{a}$$

$$t_{\rm fric} = \frac{\rho_d}{\rho_g}\frac{a}{c_s}$$

Poll!

What size objects will radially drift from 10 AU into the star within the lifetime of the disk?

A. Micron and km size particles

B. mm, cm, and m size particles

C. micron sized particles only

D. No particles

E. All particles

Poll!

What size objects will radially drift from 10 AU into the star within the lifetime of the disk?

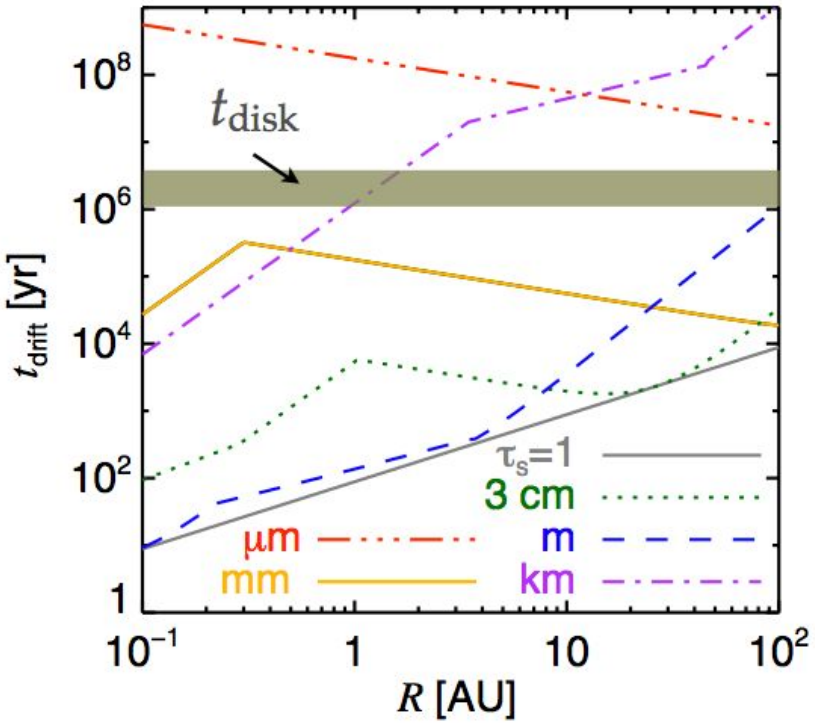
A. Micron and km size particles

B. mm, cm, and m size particles

C. micron sized particles only

D. No particles

E. All particles



Material drift in the disk

This means that ~pebble sized particles drift inwards radially.

Dust (a < mm) moves with the gas

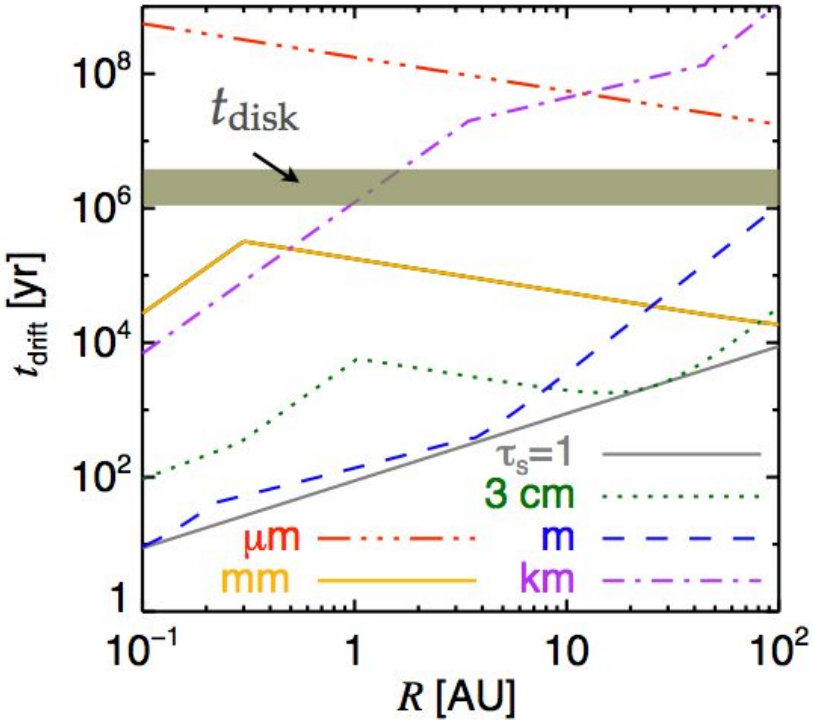


Dust (a > mm) feels a head wind



➡ Loss of angular momentum

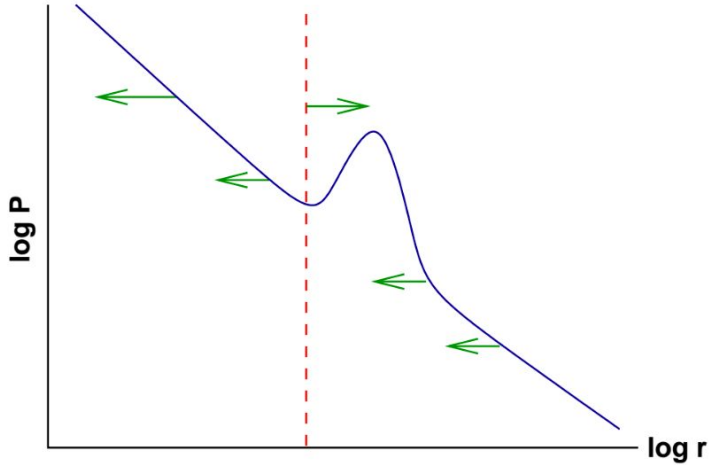
➡ Spirals inward

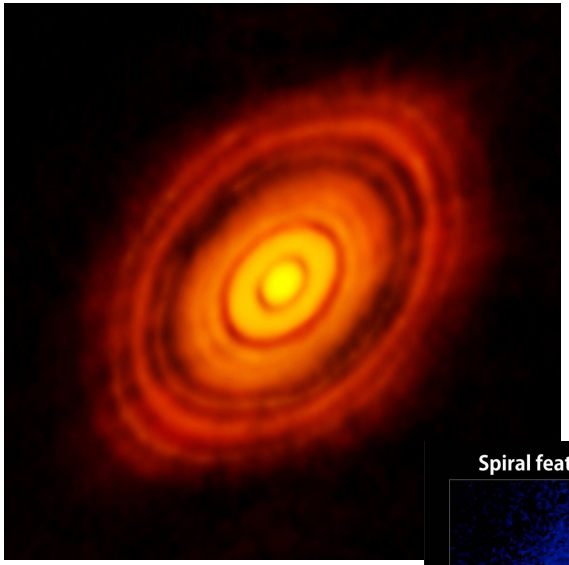


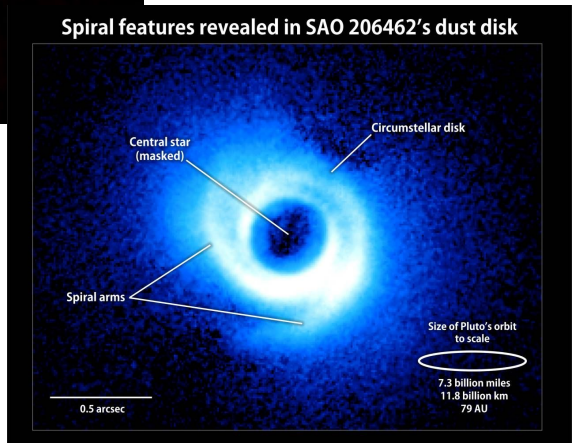
Material drift in the disk

How to stop the drift?

➡ Local pressure maxima?



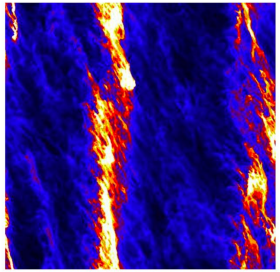




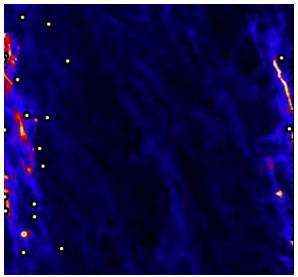
Material drift in the disk

Streaming Instability

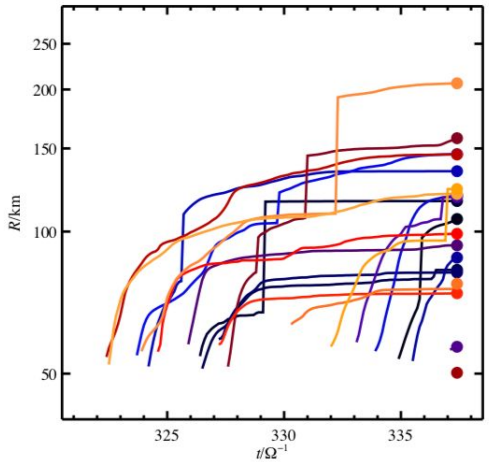
Particles concentrate due to streaming instabilities



Gravitational collapse to form planetesimals



Final Sizes

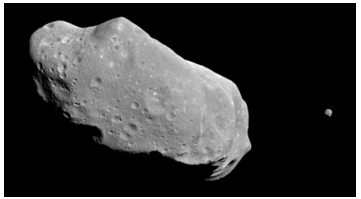


Current thinking is that we go straight from “pebbles” to planetesimals in our gas-rich disk

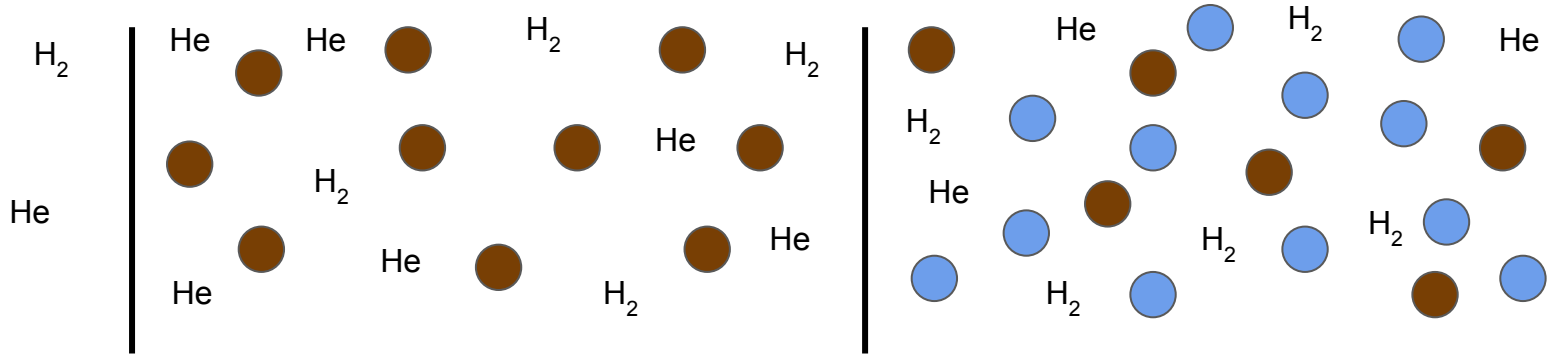
1 - 10 cm



1 - 1000 km

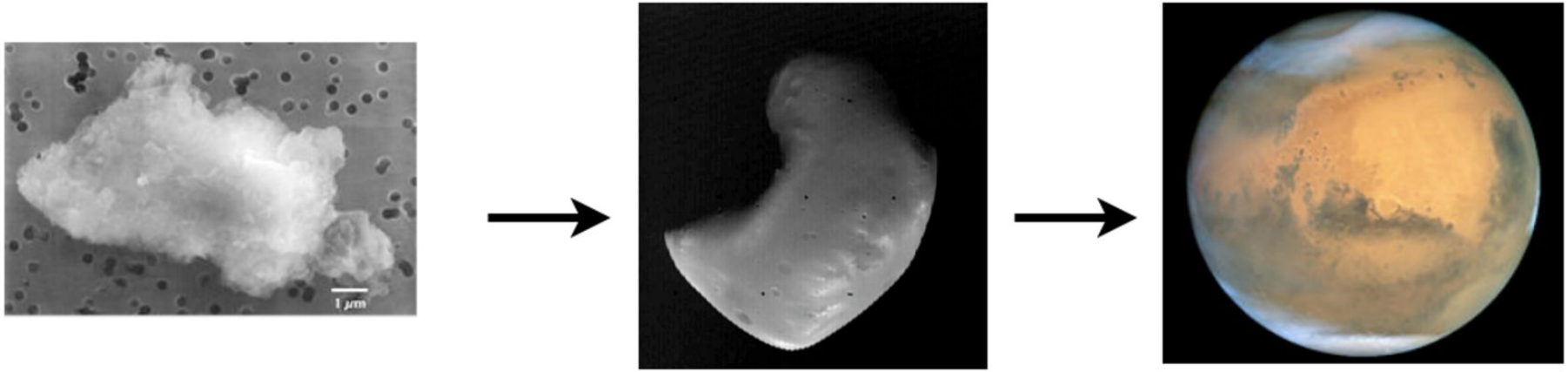


Planet formation across the disk



Too hot, rocks vaporize	Water vaporized closer to the star	Water is frozen at further distances

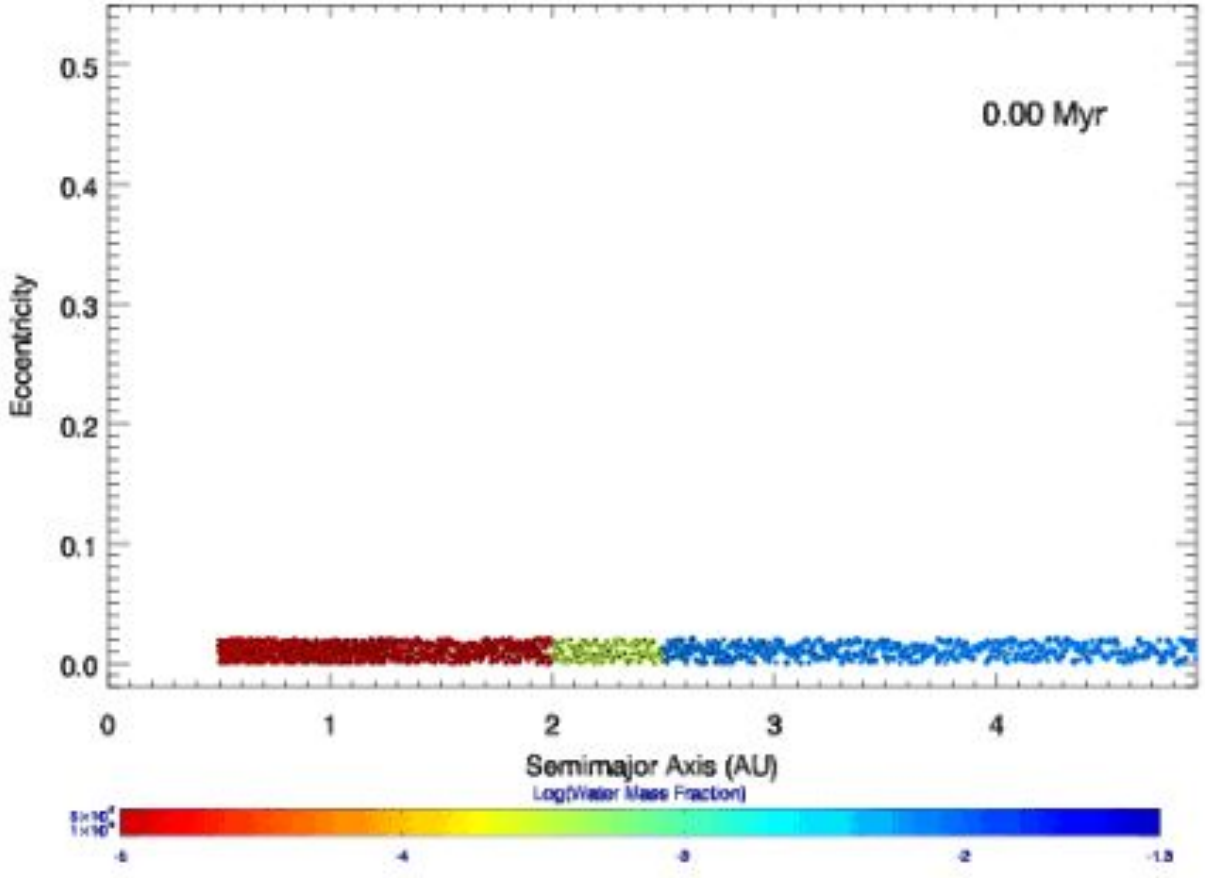
Terrestrial planet formation



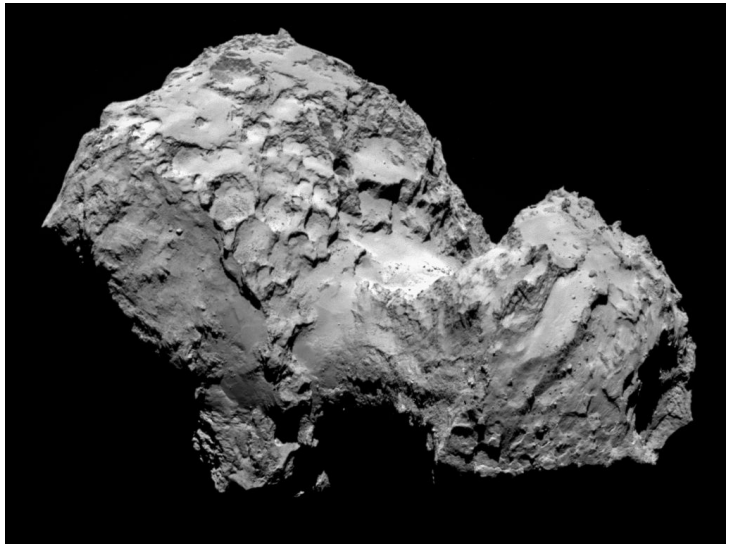
1. Dust particles → planetesimals
2. Growth via collisions (aided by gravitational focusing)
3. Growth via perturbations of orbits* and collisions of very large planetesimals

*from giant planets

Terrestrial planet formation



Gravitational Binding

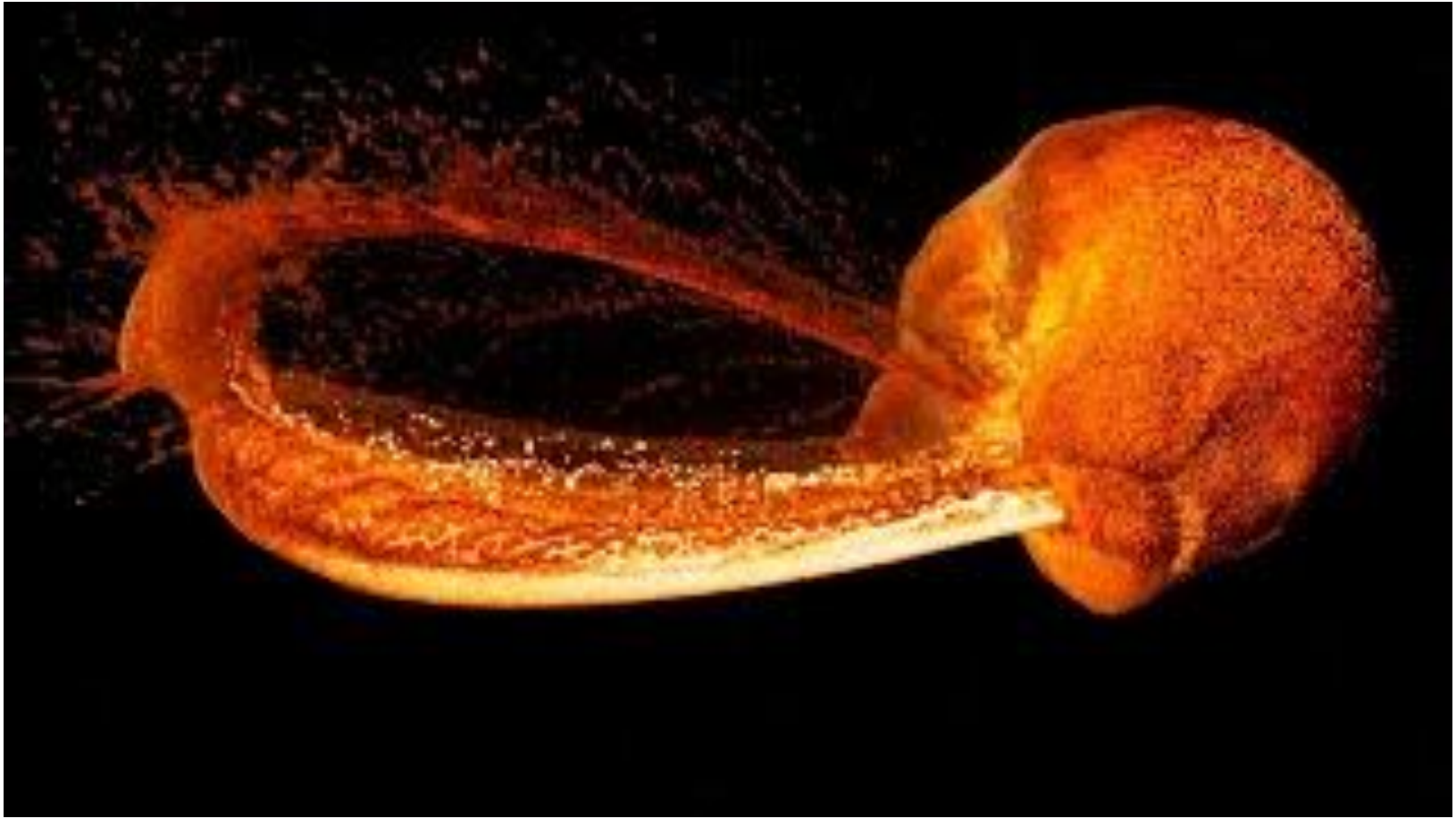


Beyond 100s of meters, gravitational binding energy becomes significant, most impactors are small, and bodies can grow more easily.

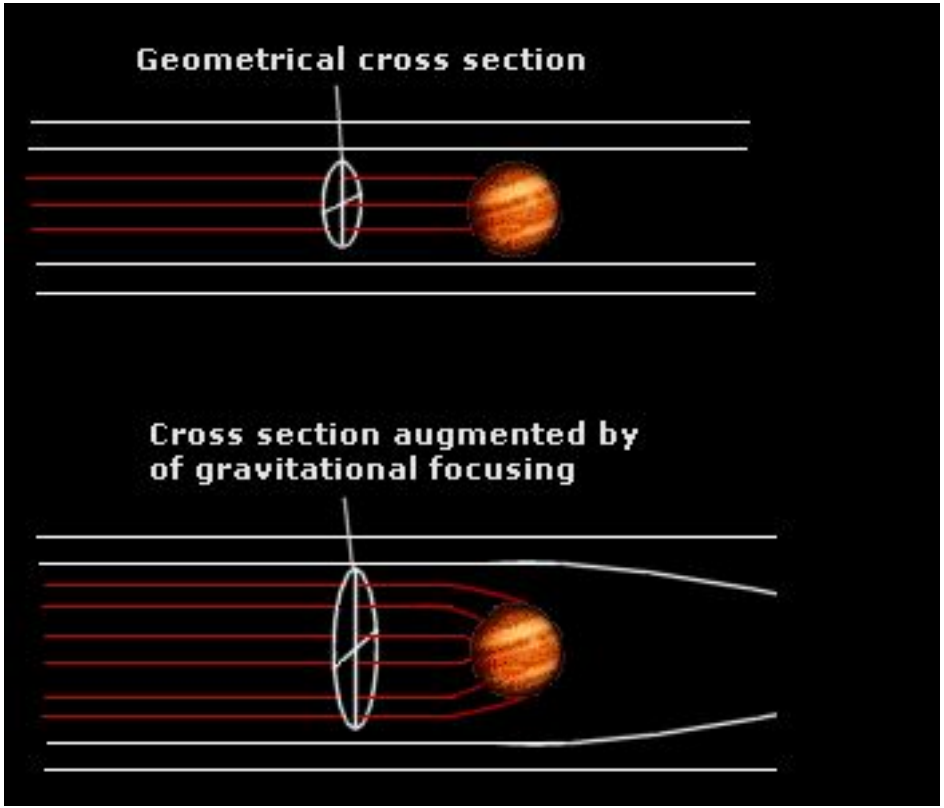
The gravitational binding can be seen during the sampling of the asteroid Bennu by OSIRIS-REx



Example: The Moon forming collision



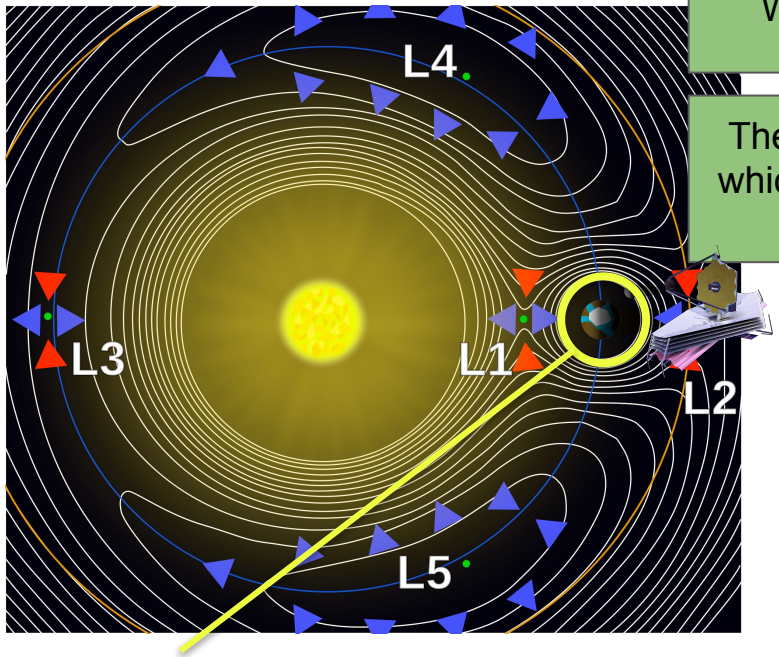
Gravitational Focusing & Runaway Growth



Above a critical mass, gravity further assists growth by increasing the effective collection area.

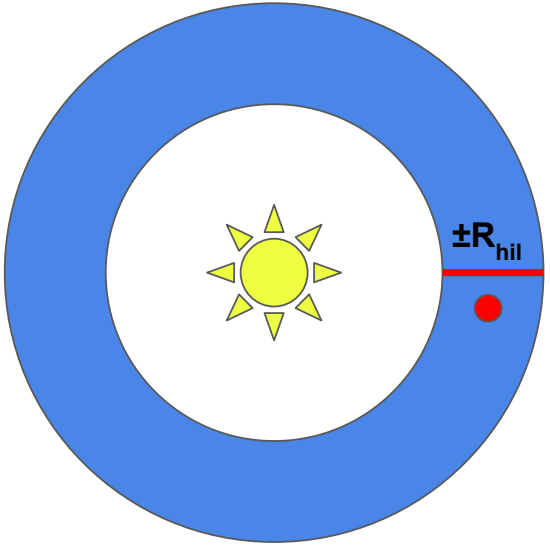
➡ **Hill Radius**

The Hill Radius (or Hill Sphere)



What are L1, L2, L3 & L4?

The Lagrange points which are metastable. JWST is in L2!



Hill Radius: volume of space over which the planet(esimal)s are gravitationally important

The total mass of planetesimals in an annulus defined by the Hill radius of a planet.

➡ **Isolation mass**

Once the planet has absorbed all those planet-esimals, it runs out of easy fuel for growth.

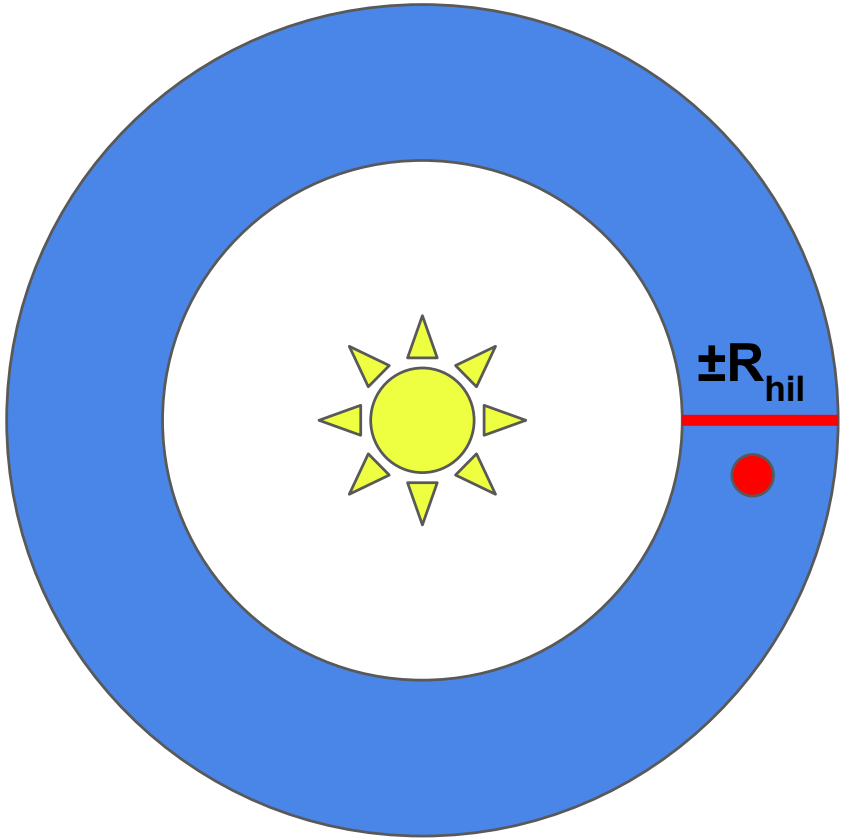
Isolation Mass

At 1 AU, planets:

- grow to M_{Mars},then stall.
- further growth from colliding with proto-Marses.

At 5 AU, planets:

- grow to 40 M_{earth} … and
- don’t stall. Why?



Poll!

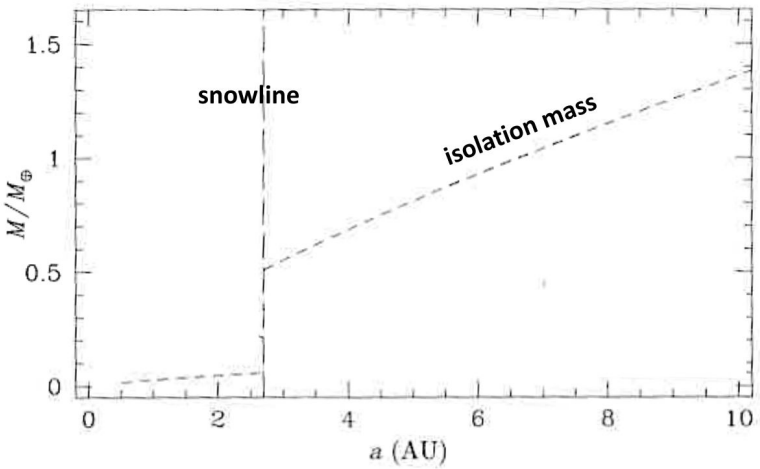
In the outer regions of the solar nebula where temperatures were low,

A. only rock and iron could condense, decreasing the isolation mass
B. only ice could condense, decreasing the isolation mass
C. hydrogen and helium gases were able to condense, increasing the isolation mass
D. in addition to rock and iron, ices also condensed, increasing the isolation mass

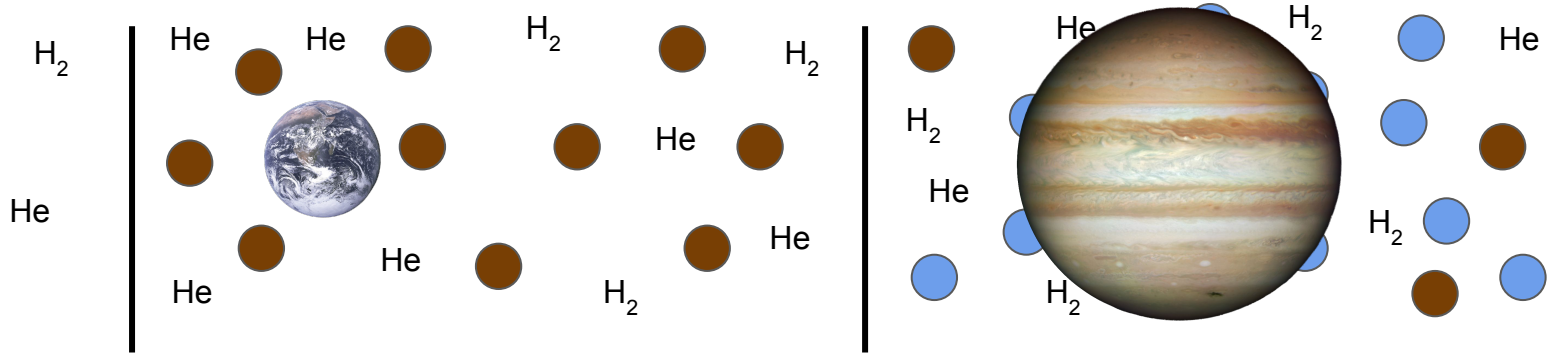
Poll!

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D. in addition to rock and iron, ices also condensed, increasing the isolation mass



Planet formation across the disk



What material is available at different distances to the star?

➡ When enough solids (rocks, ice, or both) stick together, they attract H2/He gas

➡ Need ~5 - 10x mass of Earth

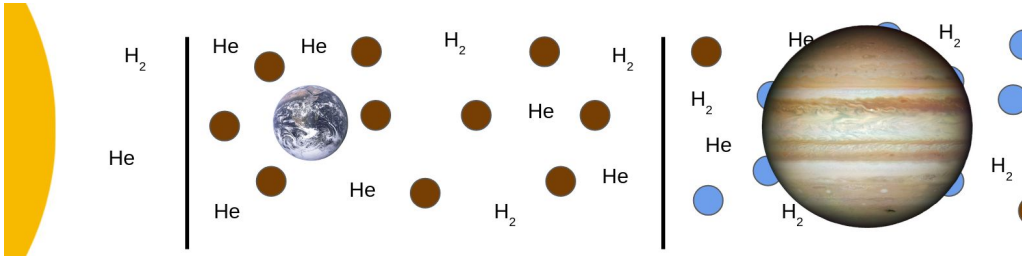
➡ H2/He gas is available everywhere for ~10 million years…. until blown away by the star

➡ when the planets aren't formed large enough, or are formed too slowly (H2/He is gone)

Poll!

Earth likely did NOT form with a massive H/He atmosphere (like Jupiter and Saturn) because:

A. Earth formed in a region where H/He were never available
B. Jupiter and Saturn formed first and used up all the H/He gas
C. Earth formed too small and/or too slowly to accrete H/He
D. Earth was too hot for ice to condense, so it was impossible for H/He to accrete



Poll!

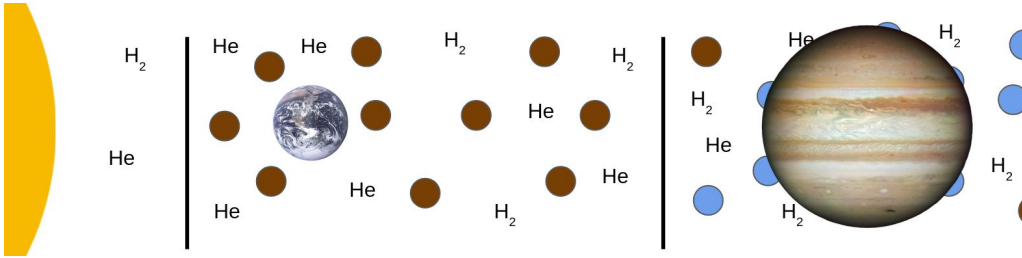
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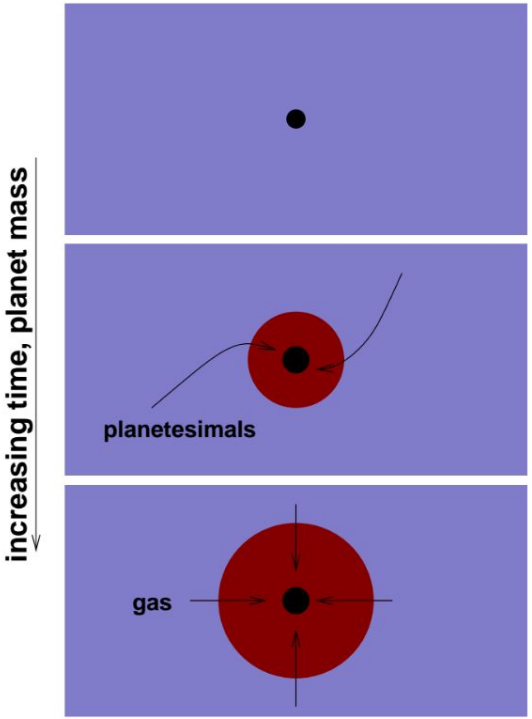
D. Earth was too hot for ice to condense, so it was impossible for H/He to accrete



Giant planet formation

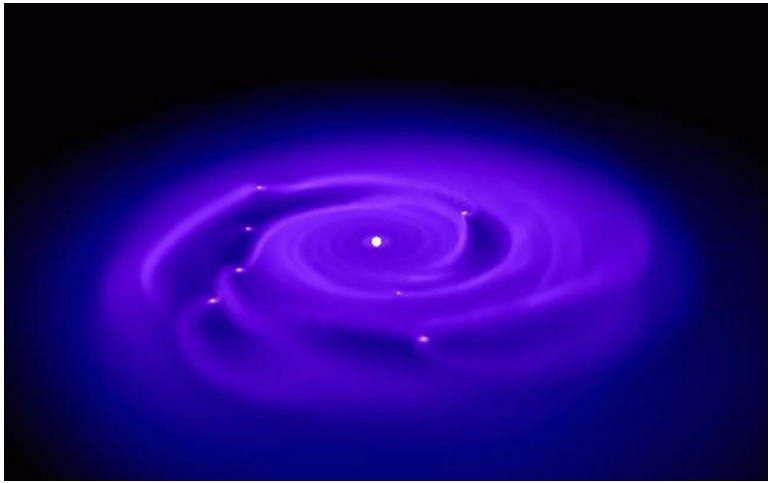
Core accretion

(favored for most planets)

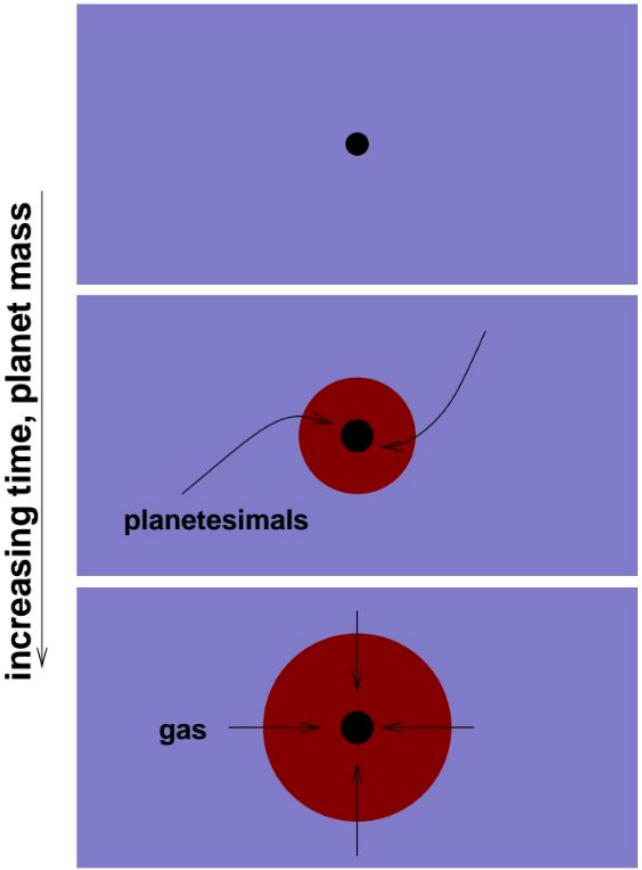


Disk fragmentation

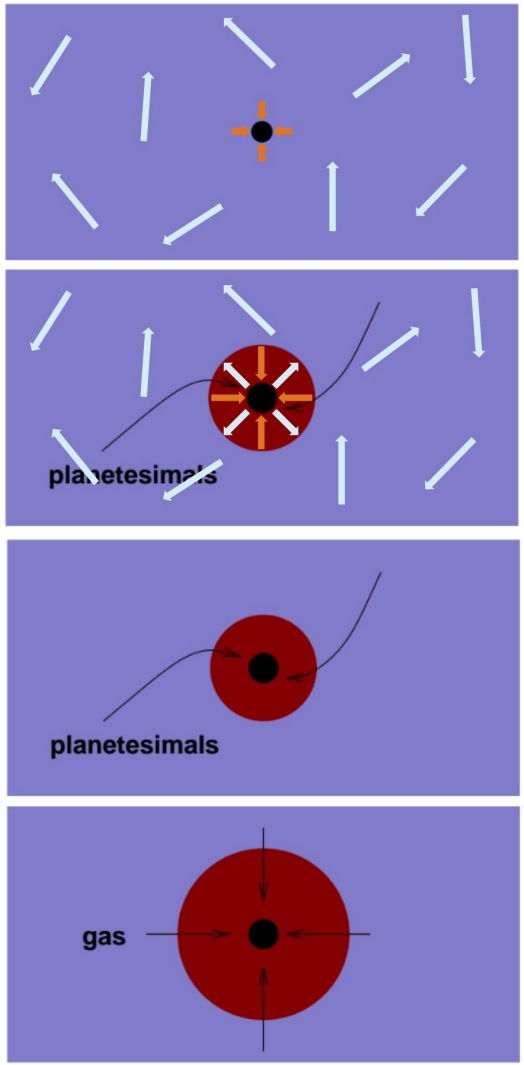
Gravitational instability



Core accretion



1. **Core formation**
   (same process as for terrestrial planets)
2. **Hydrostatic growth**
   (slow gain of gas + planetesimals until core reaches a critical mass)
3. **Runaway growth**
4. **Termination of growth**
   (material used up; planet begins to cool and contract)



Core accretion

A core can hold onto an atmosphere when the gravity of the planet dominates over the gas dynamics of the disk.

Apply equations of [stellar/planetary] structure to core, use conditions of disk as outer boundary:

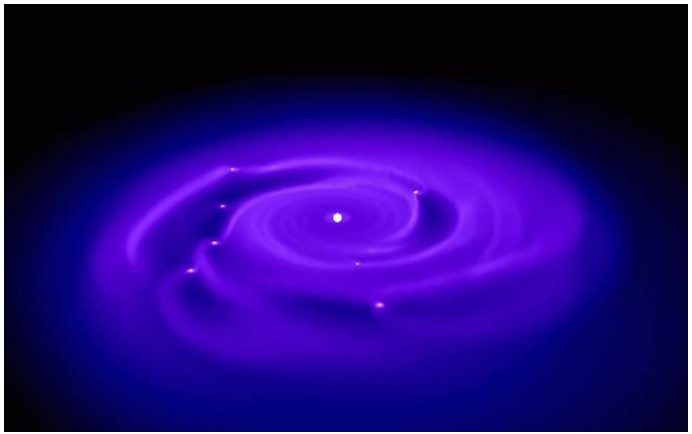
$$M_{p,\,min} \;\alpha\; \frac{c_s^3}{\sqrt{\rho_p}} \left[\ln\left(\frac{\rho_p}{\rho_{\rm gas}} \right) \right]^{3/2}$$

Eventually it grows massive enough that it can no longer maintain hydrostatic balance

➡ **Runaway growth**

Disk instability

Disk instability
Top Down: Overdensities directly, (nearly) instantaneously collapse



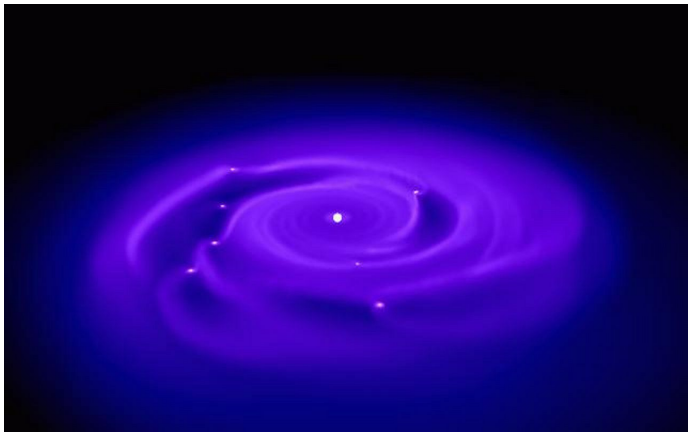
Predictions: Early formation at at larger orbital radii, with higher planetary luminosities



Disk instability vs. core accretion

Disk instability

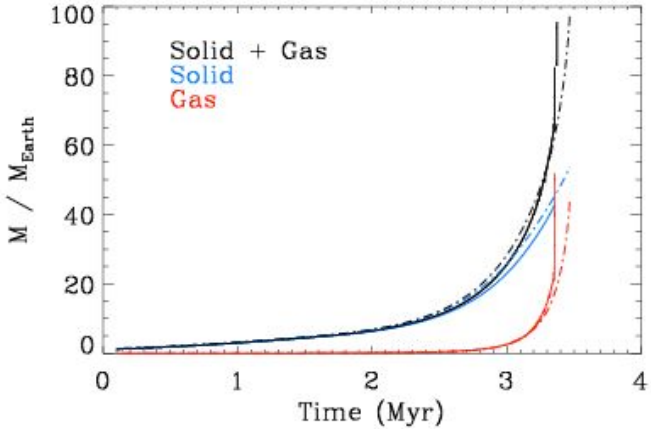
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Predictions: Early formation at at larger orbital radii, with higher planetary luminosities

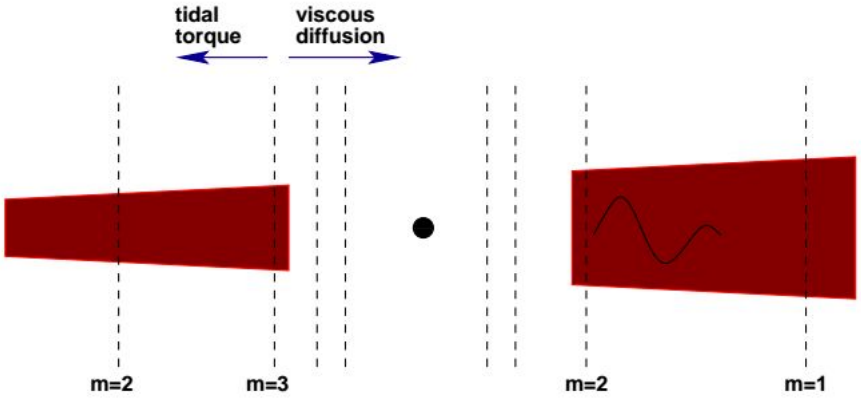
Core Accretion

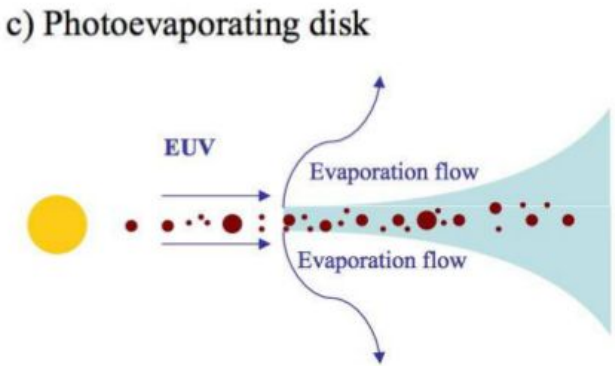
Bottom Up: Dust, Pebbles, Boulders, Planetesimals, Planets, Gas Giants



Predictions: Late formation at smaller orbital radii, with lower planetary luminosities

Runaway growth





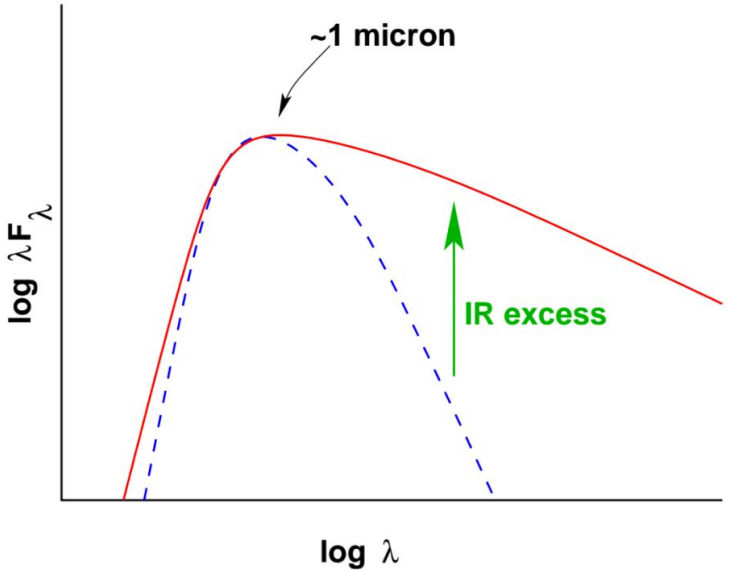
Runaway growth stops when:

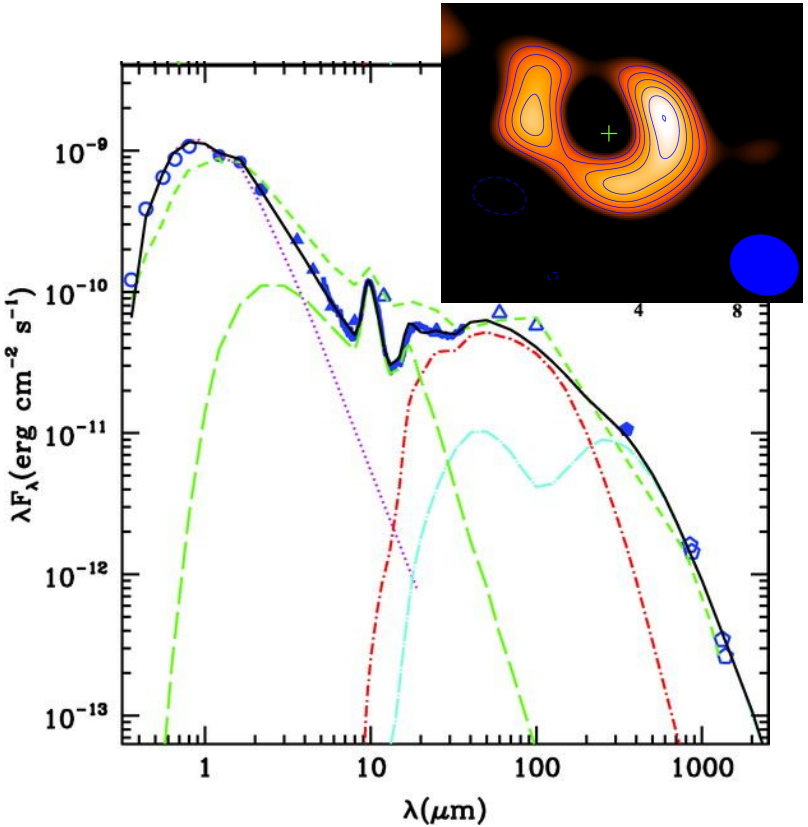
- all nearby gas is gone (annulus cleared)
- or all gas is gone (disk dissipates)

Whatever is faster determines how large the planet can grow.

Question:

What would the spectral energy distribution of a disk with a gap in it look like, qualitatively?





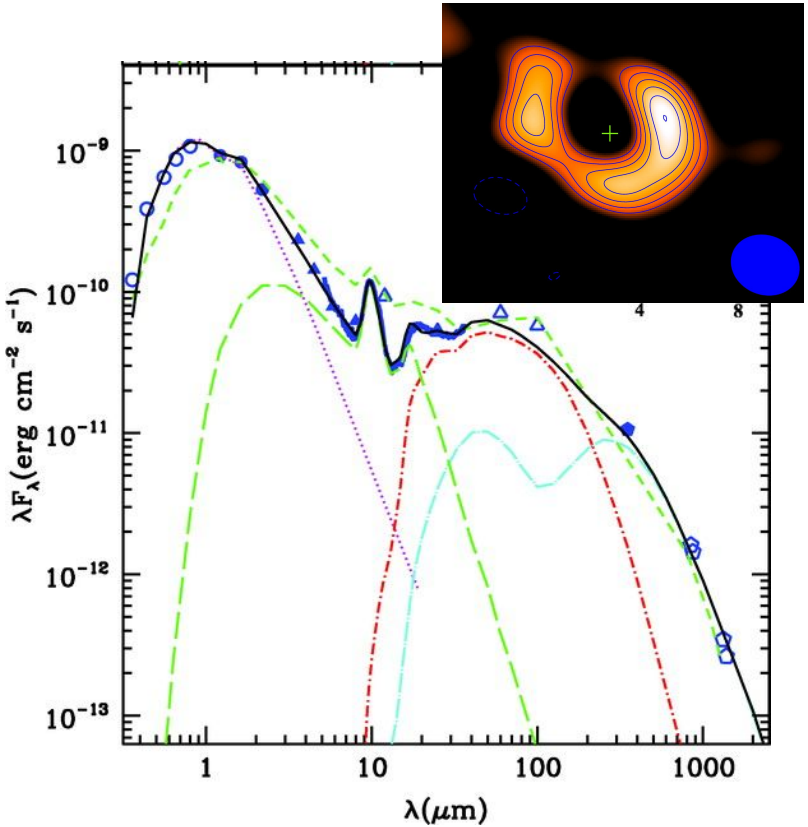
Sites of Ongoing Planet Formation

What would the spectral energy distribution of a disk with a gap in it look like, qualitatively?

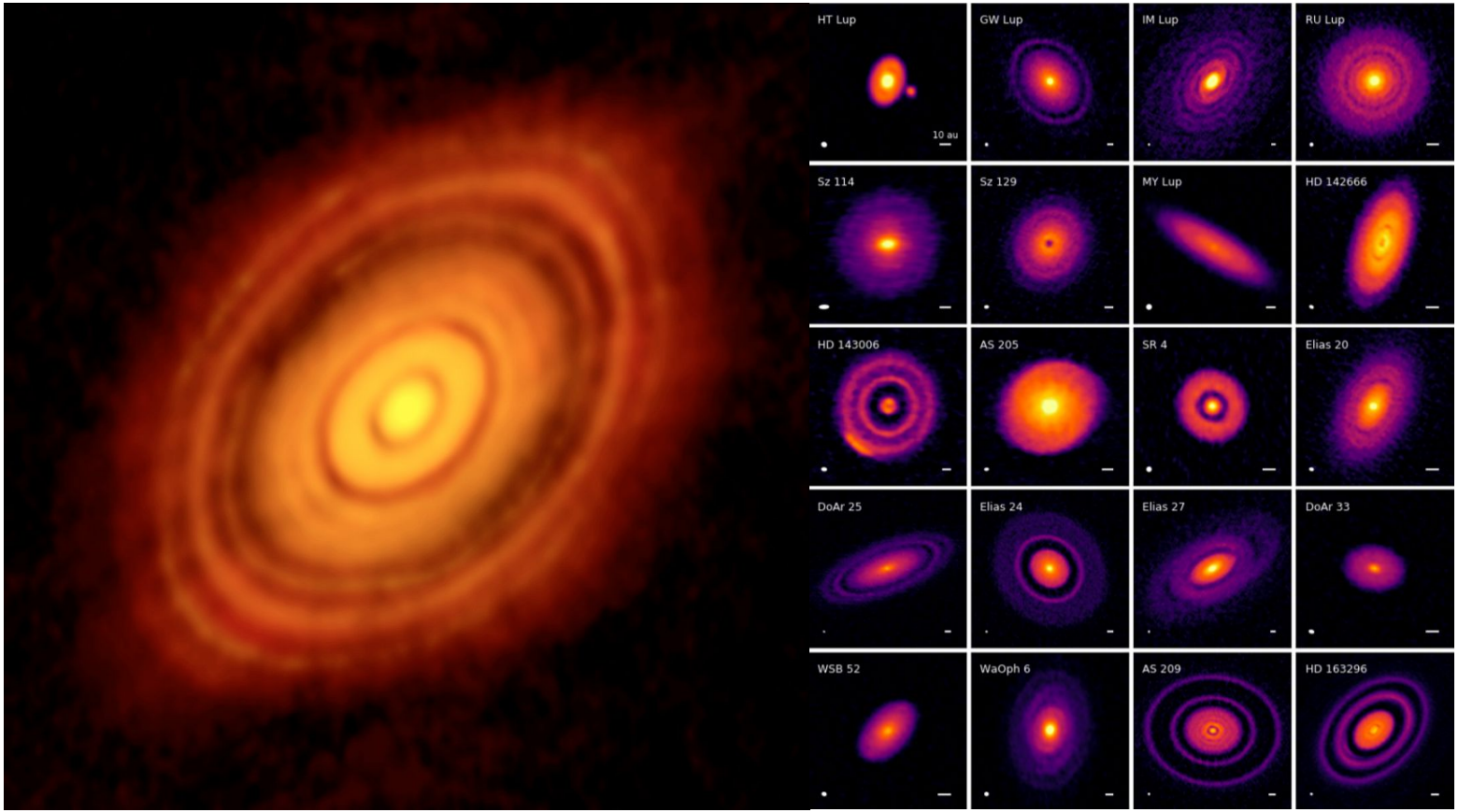
Transitional Disks

Some protoplanetary disks have large cleared gaps – perhaps signposts of ongoing planet formation?

First inferred from SED fits, now imaged throughout the infrared

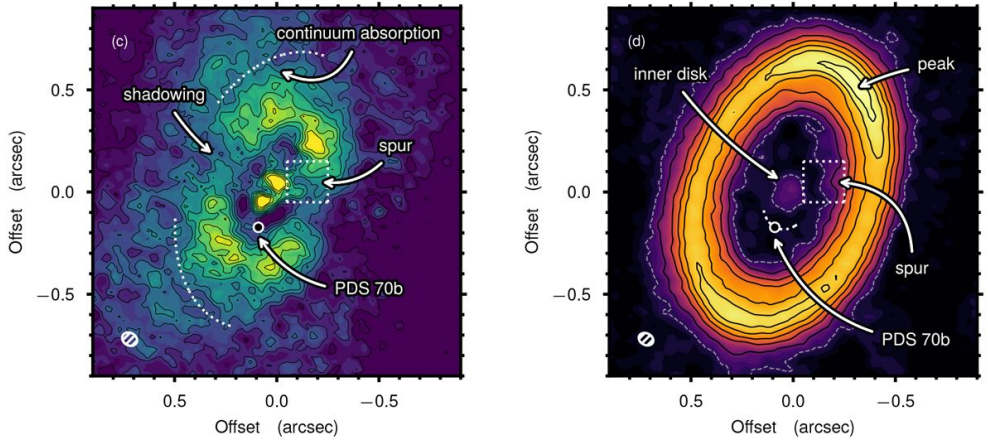


Sites of Ongoing Planet Formation



Transitional disks as viewed by ALMA, Andrews et al. 2018

Sites of Ongoing Planet Formation



ALMA images of PDS 70 disk show central inner disk, outer disk, gap in the middle

VLT images show two accreting protoplanets

