Planet Formation Theory

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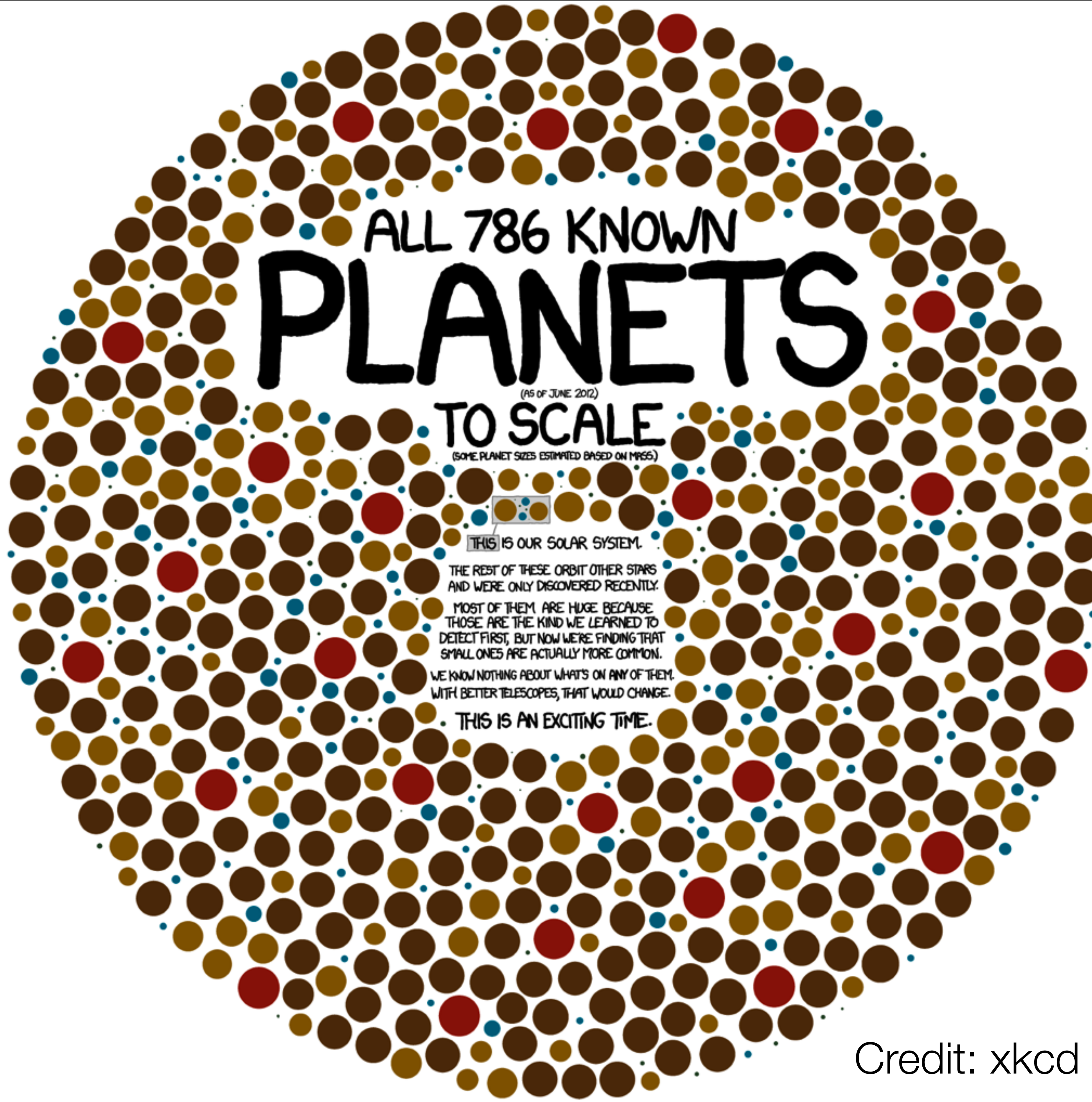
Image via: io9

Outline

- Protostellar Discs:
  - The Initial Conditions for Planet Formation
  - A Hard Time Limit for Planet Formation

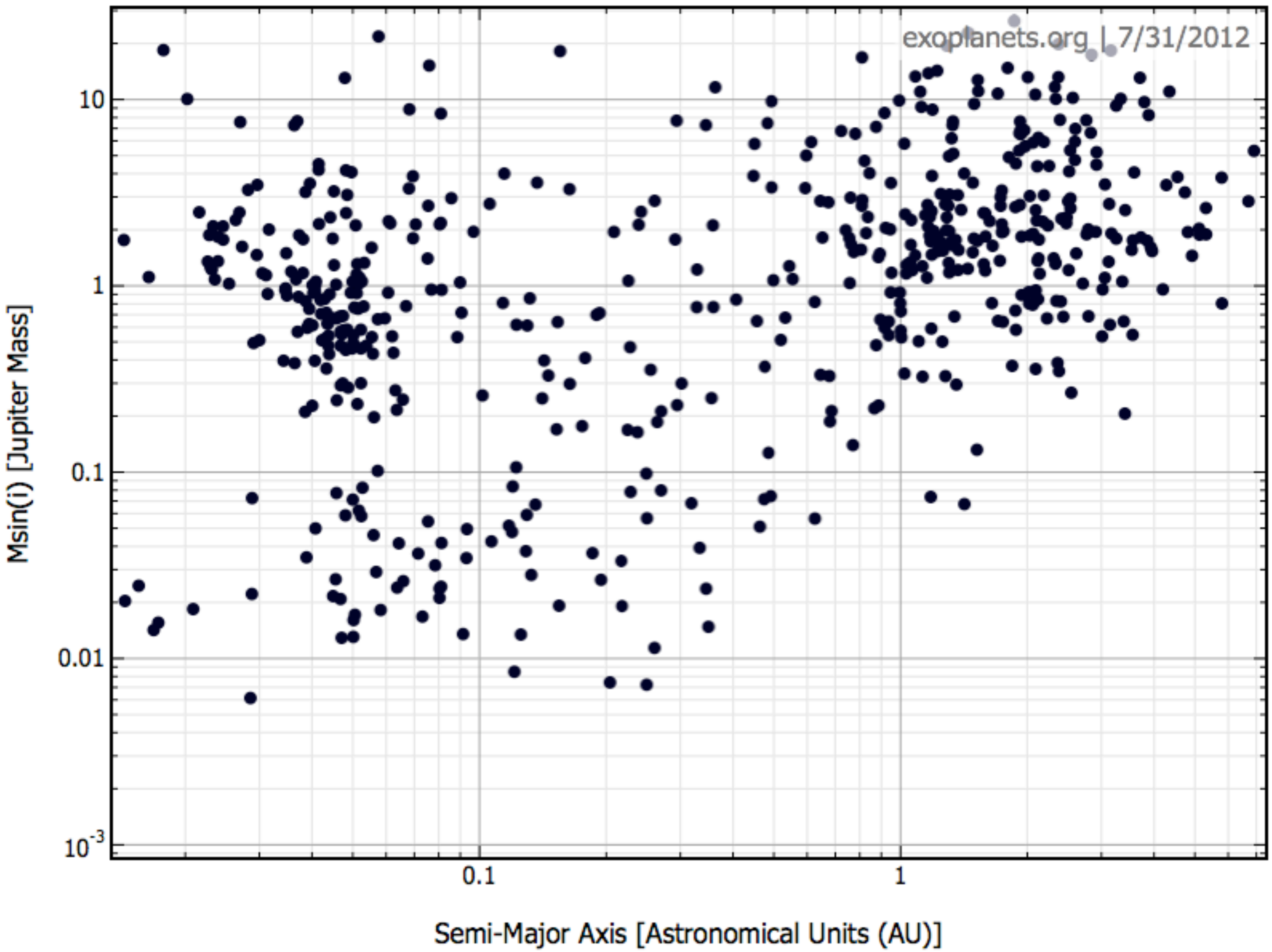
- The Core Accretion Model:
  - Planetesimal Formation
  - Terrestrial Planet Formation
  - Giant Planet Formation
  - Dynamical Evolution

- The Gravitational Instability Model:
  - Conditions for Disc Fragmentation
  - Tidal Downsizing of Disc Fragments


ALL 786 KNOWN
PLANETS
(AS OF JUNE 2012)
TO SCALE
(SOME PLANET SIZES ESTIMATED BASED ON MASS.)
THIS IS OUR SOLAR SYSTEM.
THE REST OF THESE ORBIT OTHER STARS AND WERE ONLY DISCOVERED RECENTLY.
MOST OF THEM ARE HUGE BECAUSE THOSE ARE THE KIND WE LEARNED TO DETECT FIRST, BUT NOW WE'RE FINDING THAT SMALL ONES ARE ACTUALLY MORE COMMON.
WE KNOW NOTHING ABOUT WHAT'S ON ANY OF THEM. WITH BETTER TELESCOPES, THAT WOULD CHANGE.
THIS IS AN EXCITING TIME.

Credit: xkcd

Motivation


exoplanets.org | 7/31/2012
10
1
0.1
0.01
10^{-3}
Msin(i) [Jupiter Mass]
0.1
1
Semi-Major Axis [Astronomical Units (AU)]

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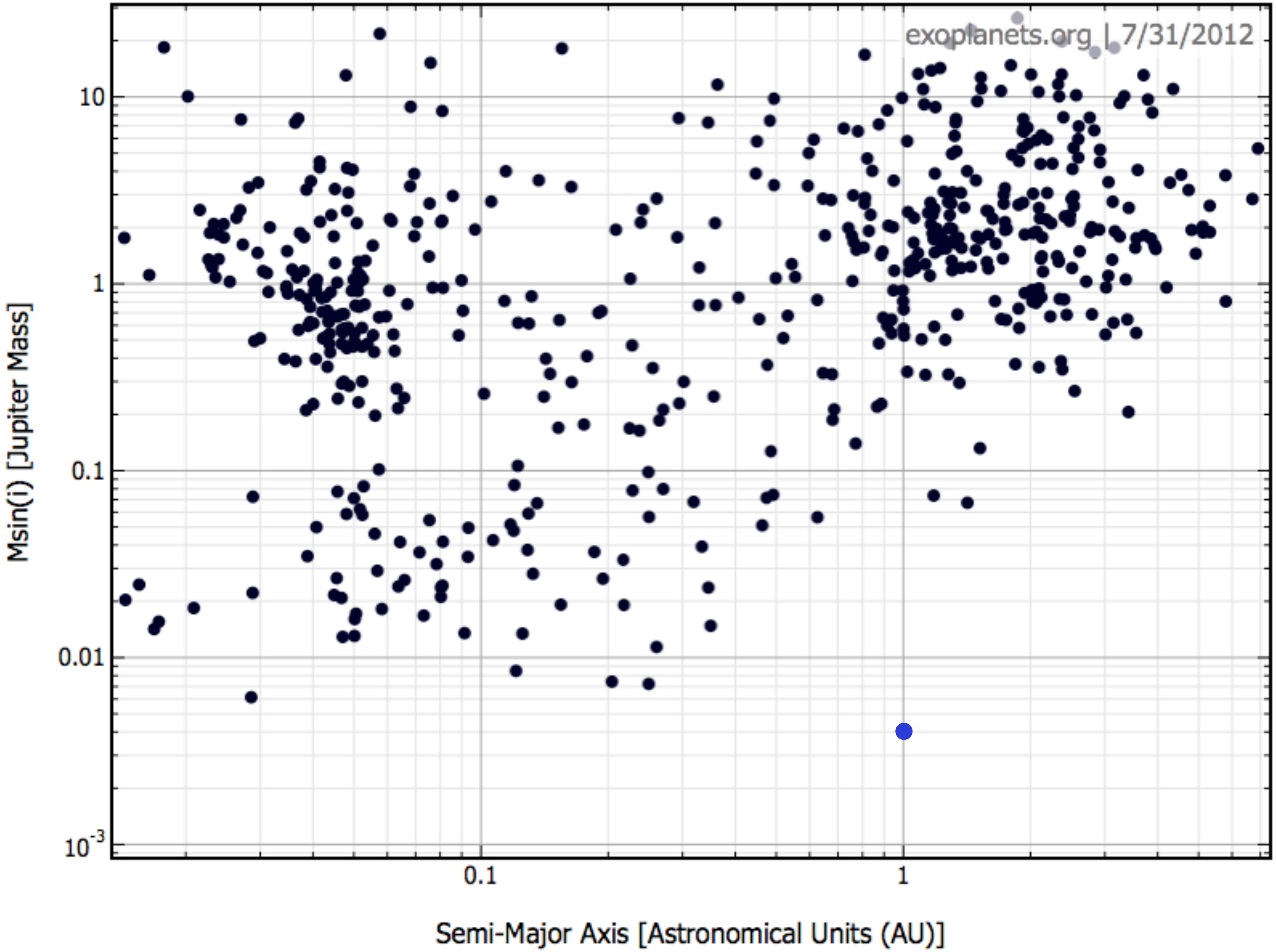
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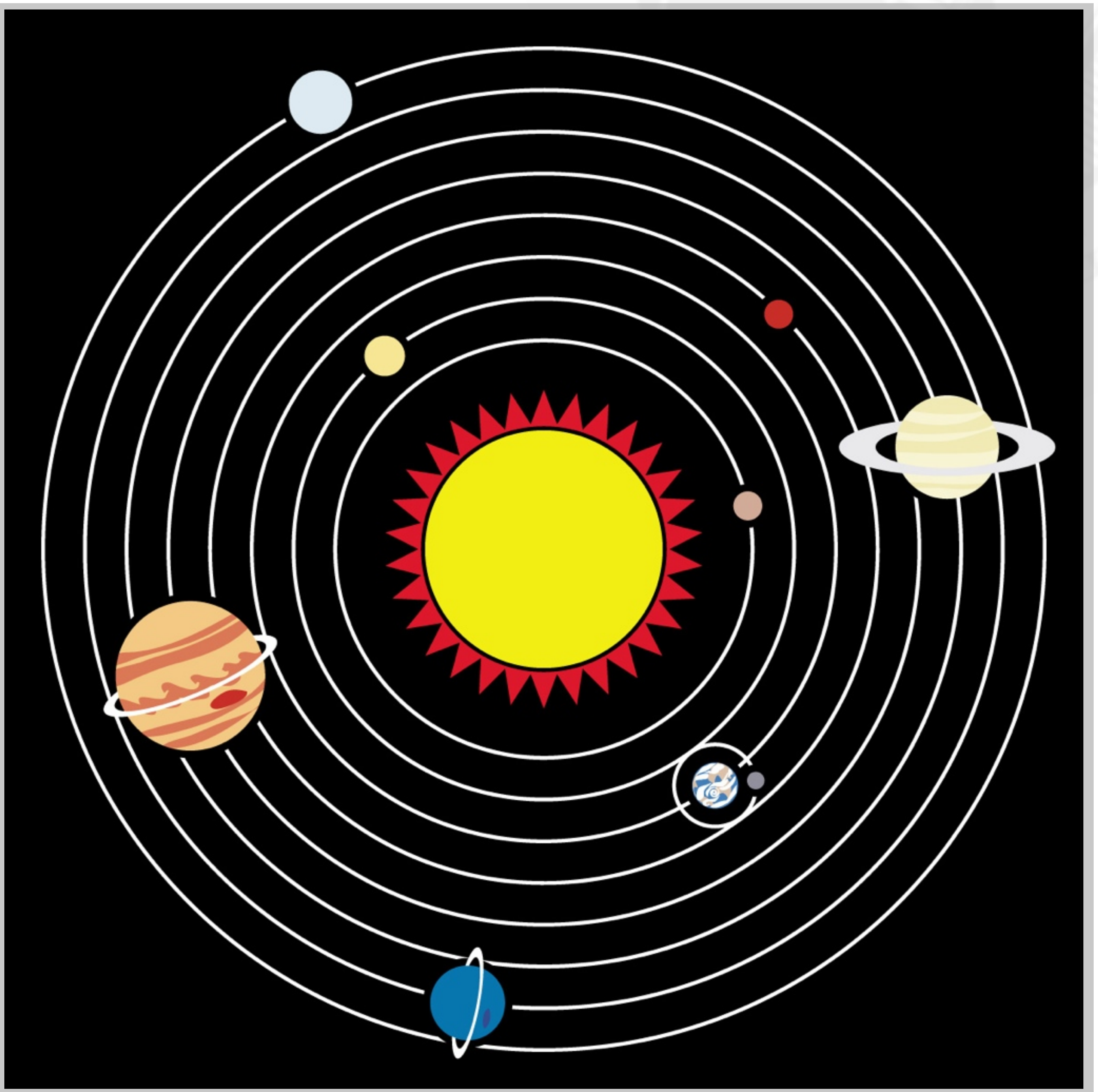
Lessons from the Solar System

The Solar System is coplanar

Most of the mass is in the Sun

Most of the angular momentum is in the planets and debris

Radionuclide dating constrains ages and formation eras



Lessons from Star Formation

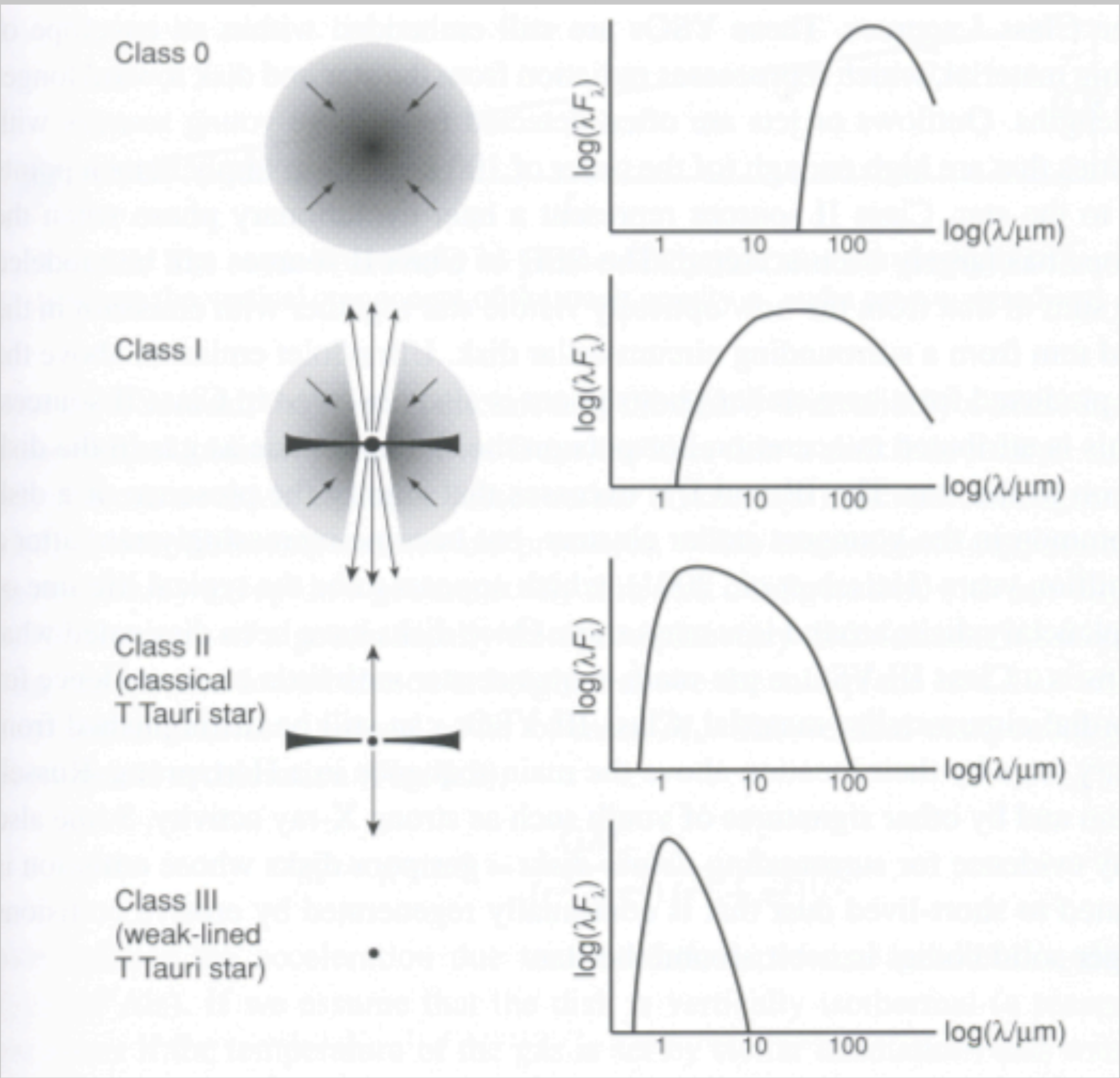


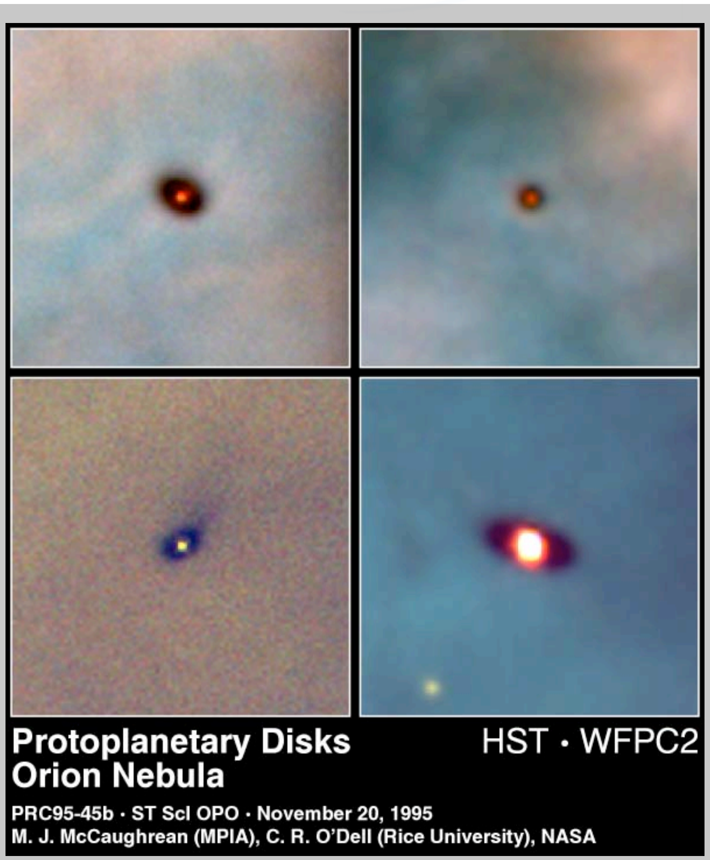
Figure from Armitage (2010)
Astrophysics of Planet Formation

Excess angular momentum produces **discs** around young stars

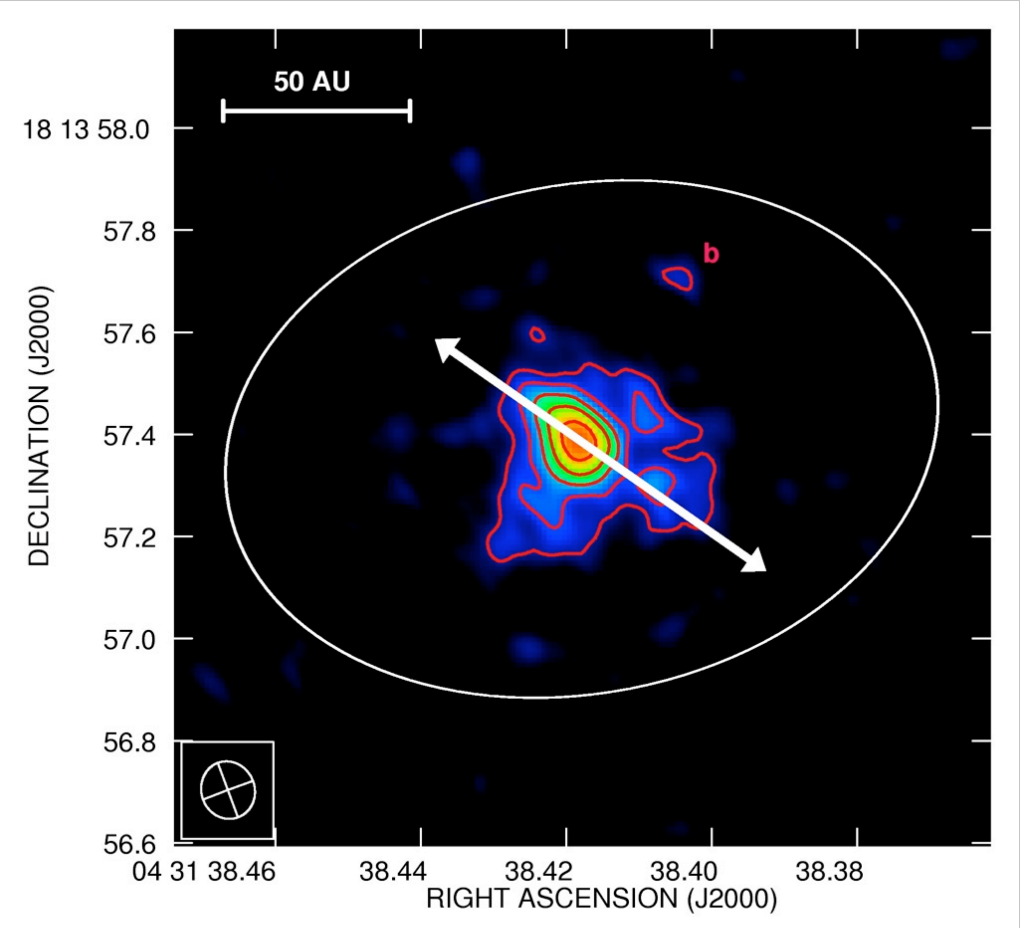
These discs are ~99% gas, ~1% dust

They are the feedstock for planet formation

Lessons from Star Formation



"Proplyds" imaged with HST (optical) McCaughrean et al (1995)



HL Tau at 1.3cm using VLA, with a protoplanetary candidate ("b") (Greaves et al 2008)

Fomalhaut imaged by Herschel at 70 microns (Acke et al 2012)

The Initial Conditions

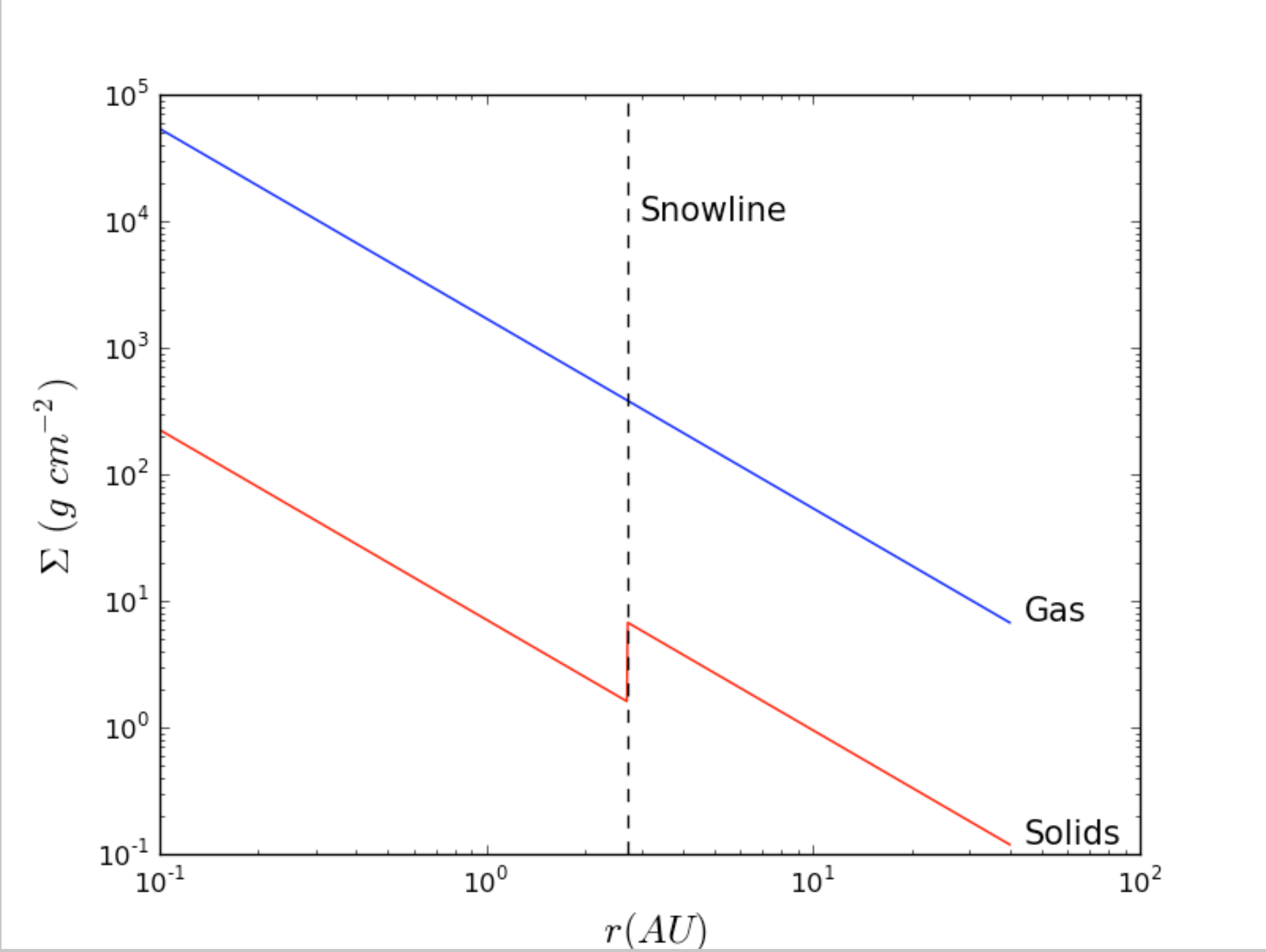
An educated guess: Solar System ingredients distributed in a disc
We infer a **Minimum Mass Solar Nebula** by:

1. Smearing out the planets according to their spacing

2. Topping this mass up with H and He

3. Converting this smeared mass into a surface density

The Initial Conditions



Hayashi (1981)

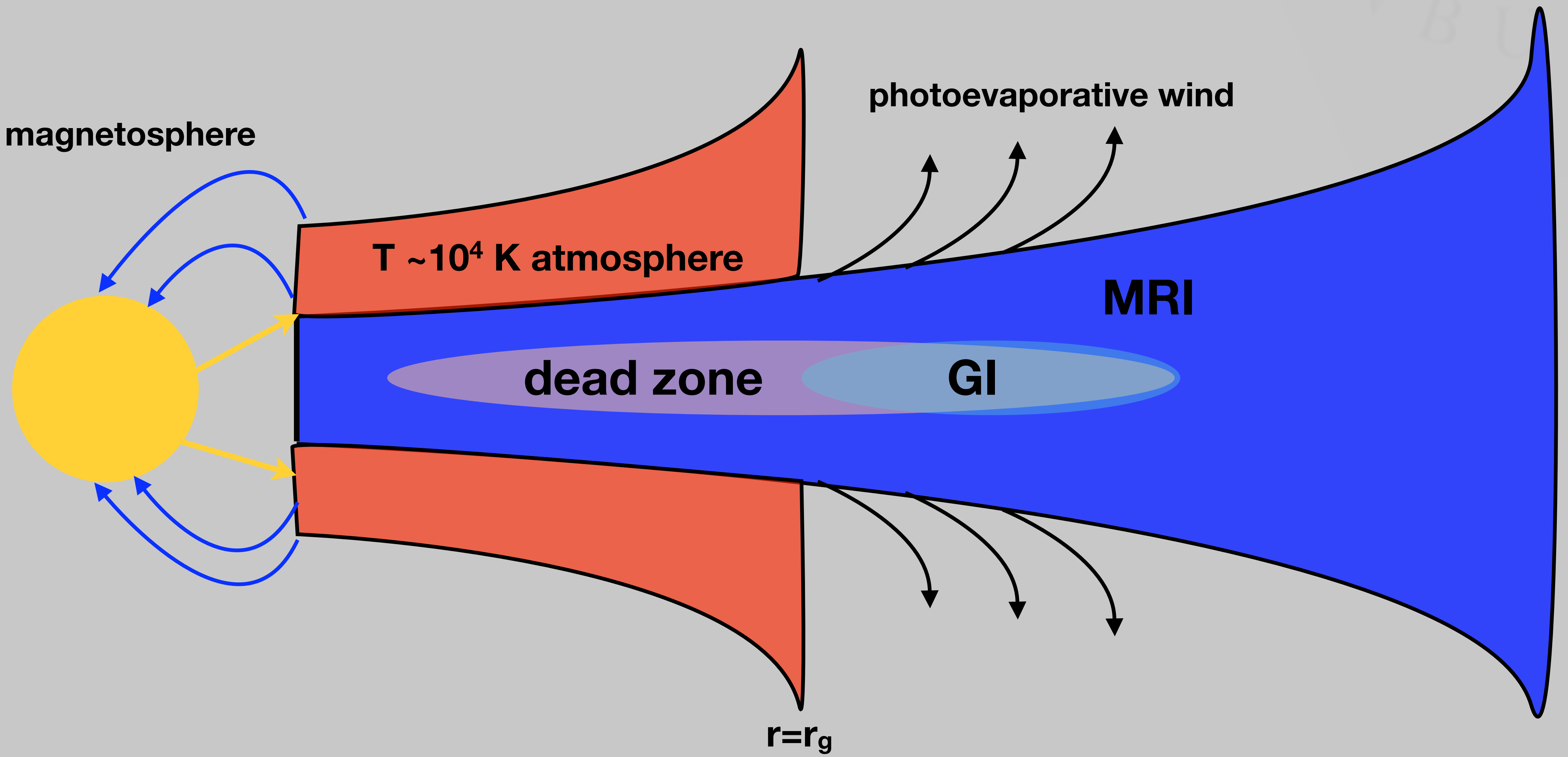
The total disc mass is approximately 0.01 solar masses

Disc Evolution

Vertical hydrostatic equilibrium gives discs a **flared** structure

Stellar irradiation of the upper disc strongly affects the **chemistry**

Evolution - **angular momentum transport** and **evaporation**



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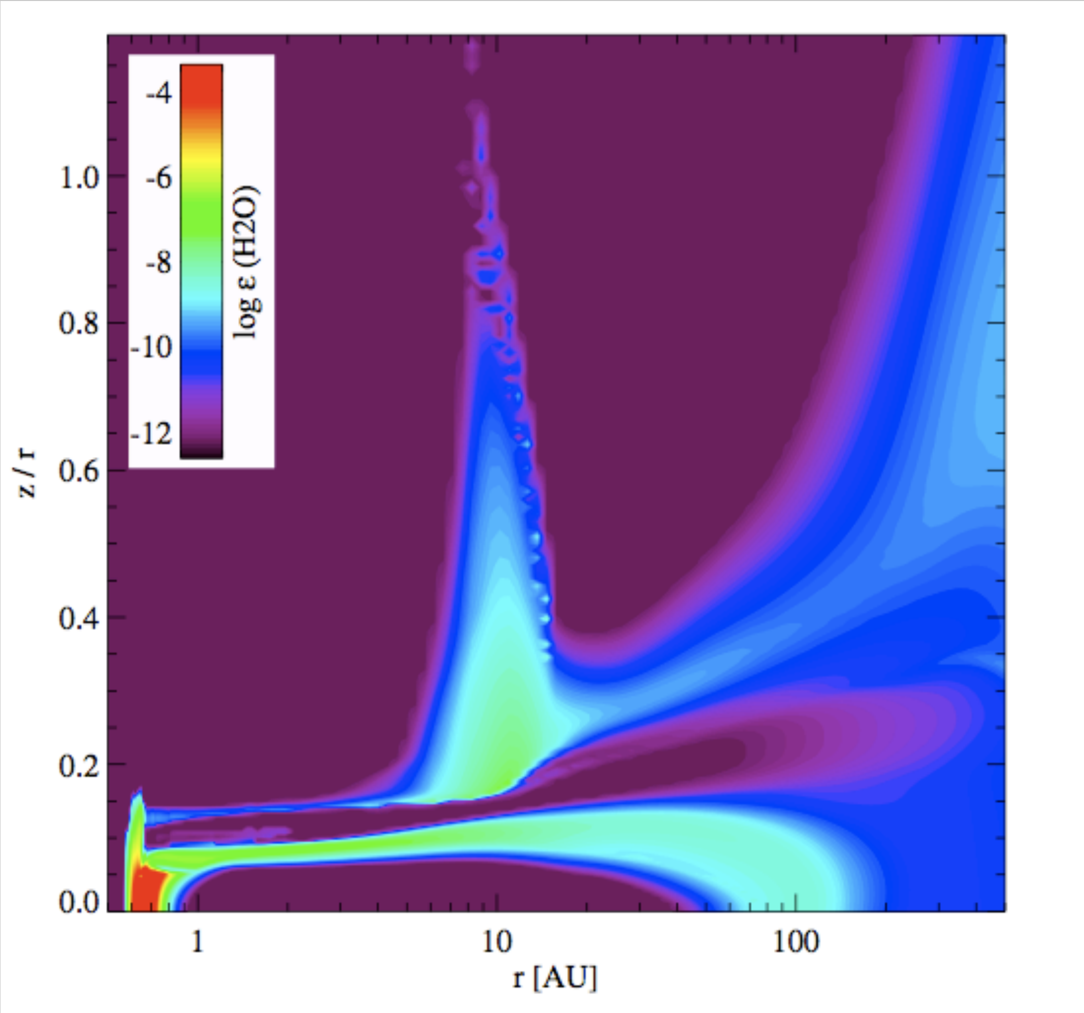
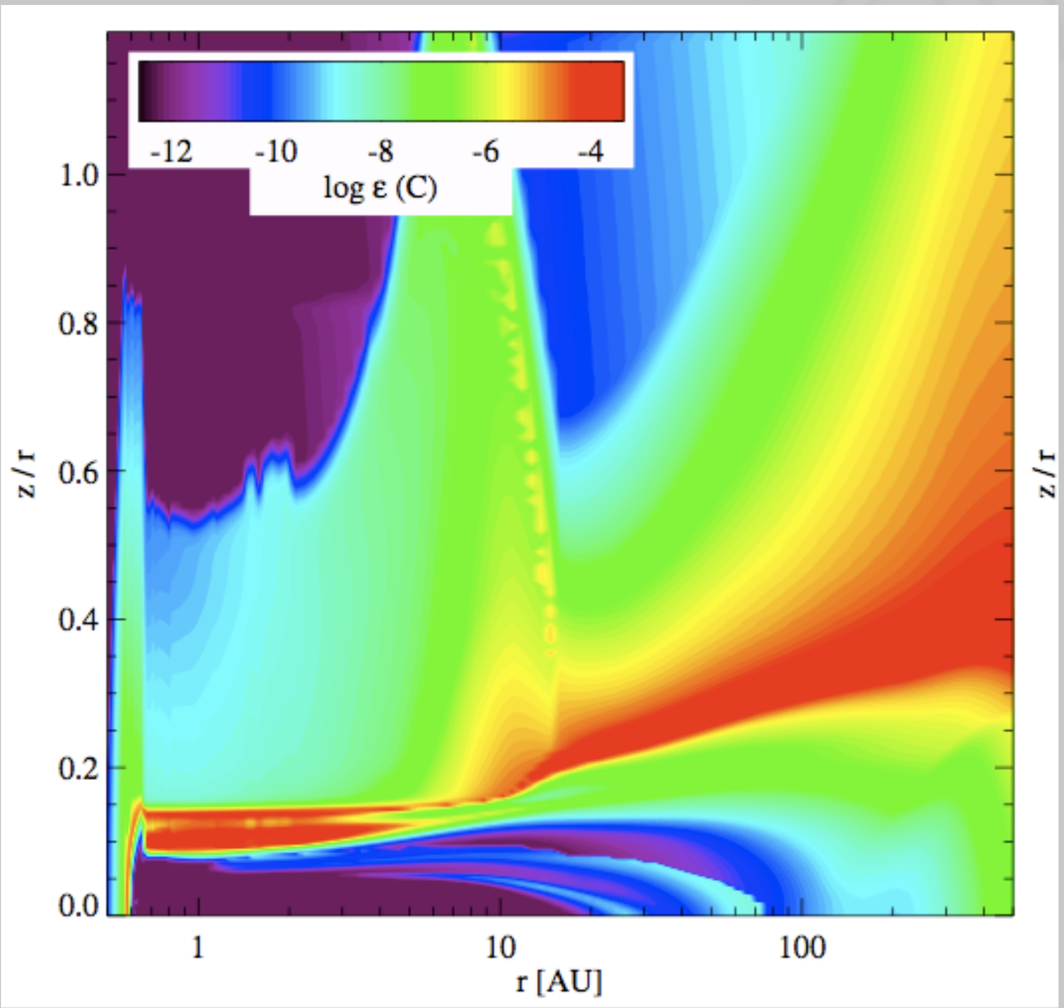
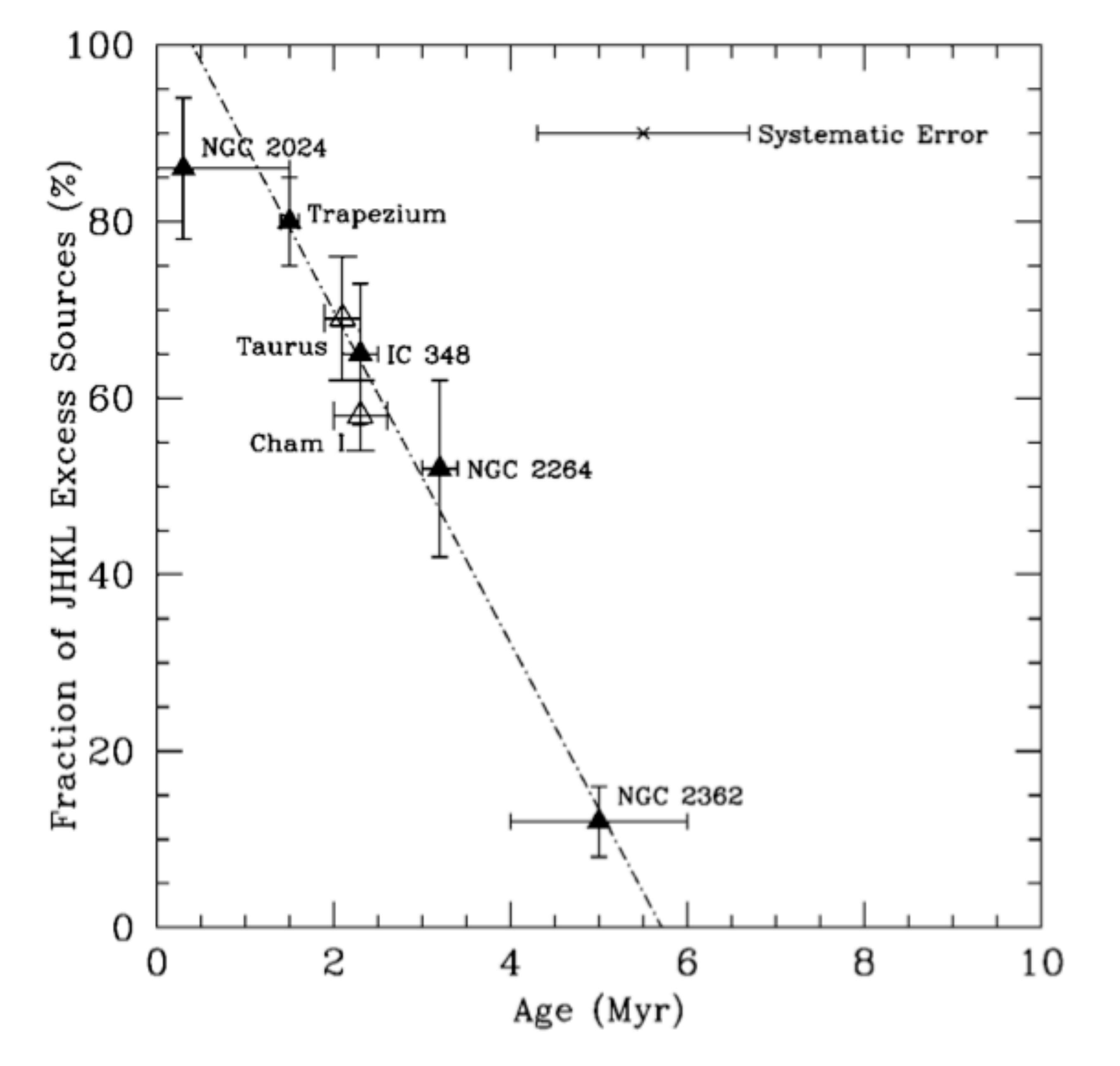




ProDiMo, Woitke et al (2009)

A Hard Time Limit



Observations show that optically thick discs are rare after a few million years

Planets must be able to form before discs are dispersed

Haisch, Lada & Lada (2001)

The Core Accretion Model

In short:

1. The dust in the disc (1% of the total mass) collides and grows to form **planetesimals**

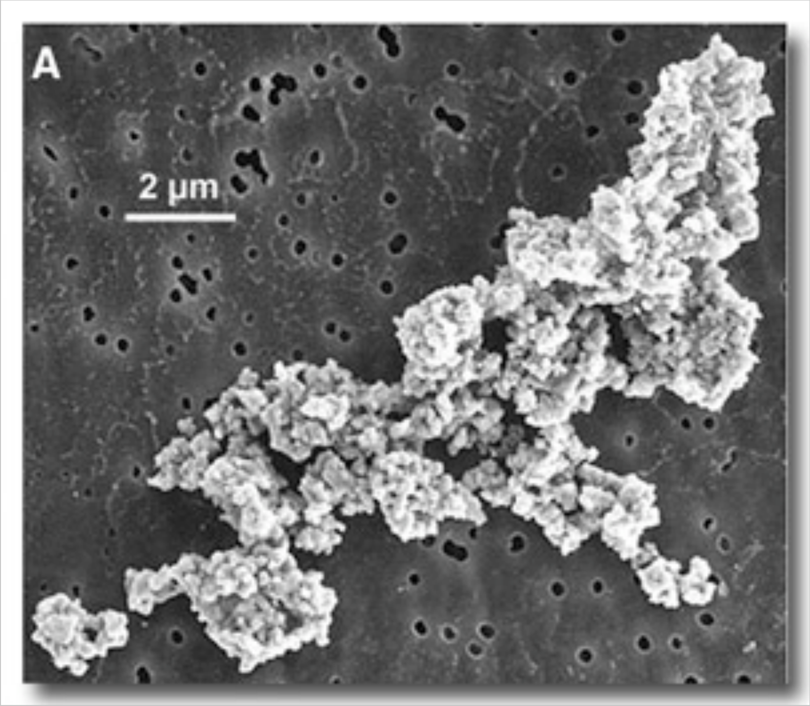
2. These planetesimals collide to form **protoplanetary cores**

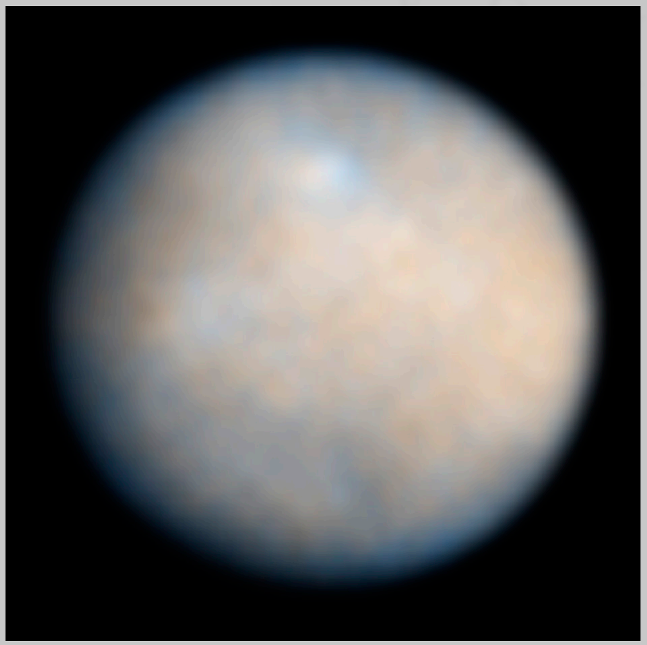
3. If these cores are massive enough, then they can accrete large amounts of gas and become **giant planets**

4. If not, they become **terrestrial planets**

Planetesimal Formation

- This is probably the hardest step in the core accretion process
- Grains begin at sub-micron sizes, and must grow to a few km





Ceres (HST)
(500 mi)

- Initially, growth is easy, and assisted by electrostatic forces
- As the grains grow, they feel aerodynamic drag from the gas

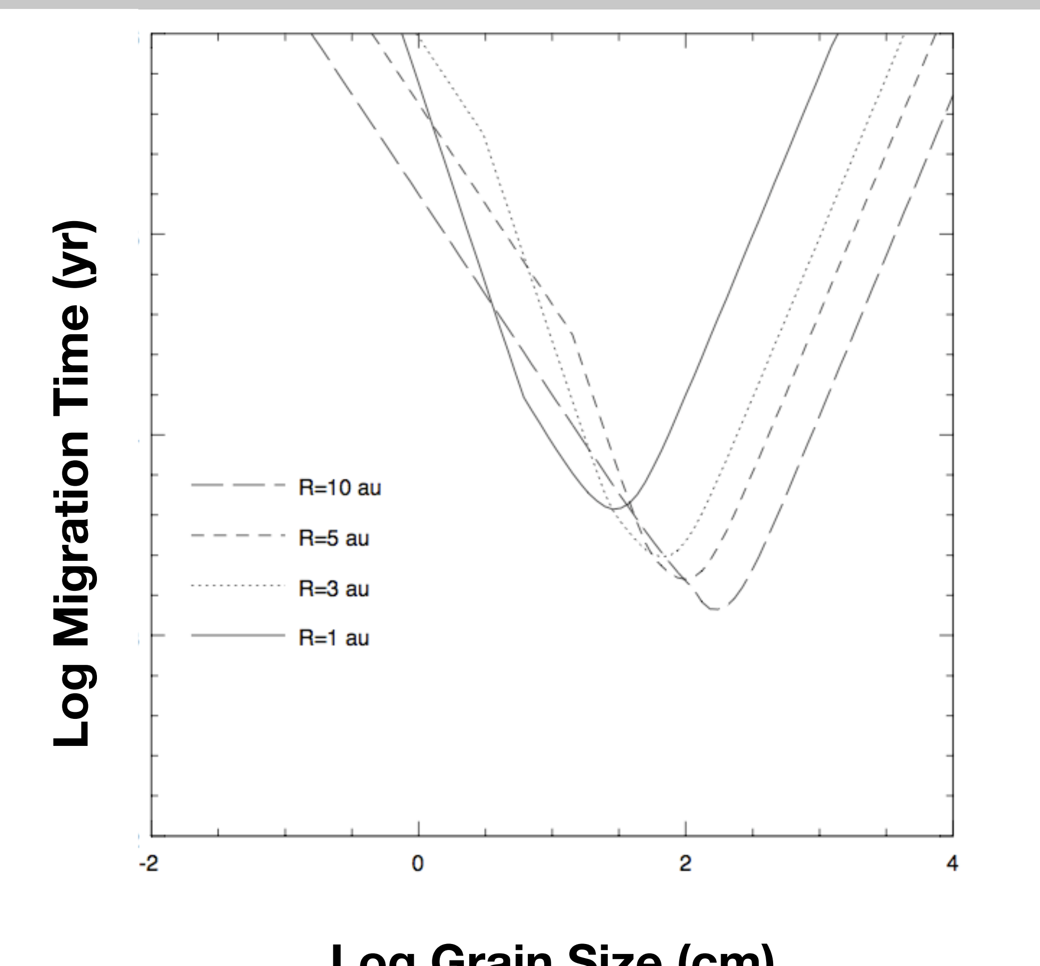
The Metre Barrier to Grain Growth

Aerodynamic drag pulls dust towards pressure maxima

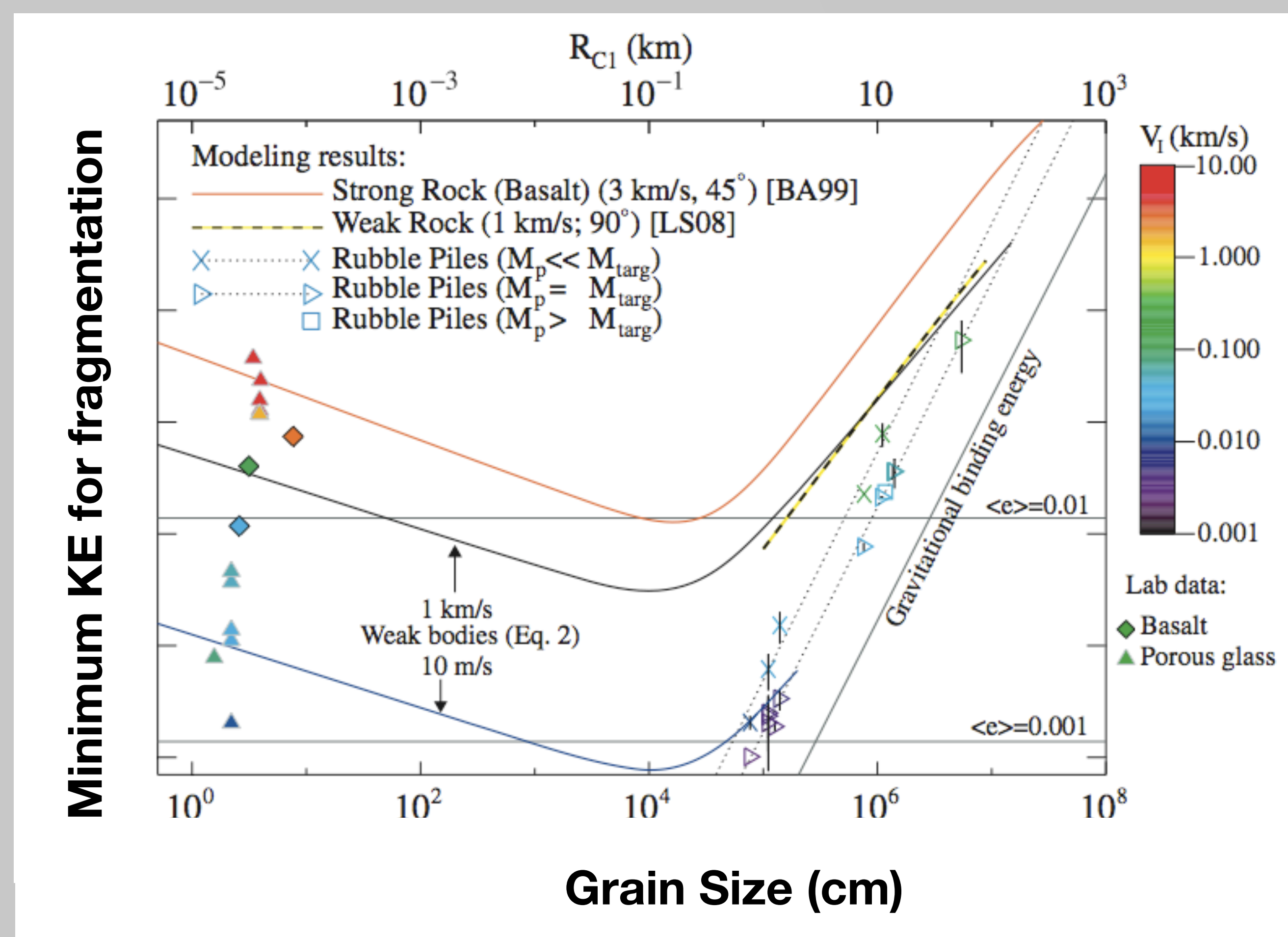
→ Settling to the disc midplane (**good**) and radial drift inward (**bad**)

Higher relative velocities, highly porous grains → **fragmentation**

Rice et al (2004)

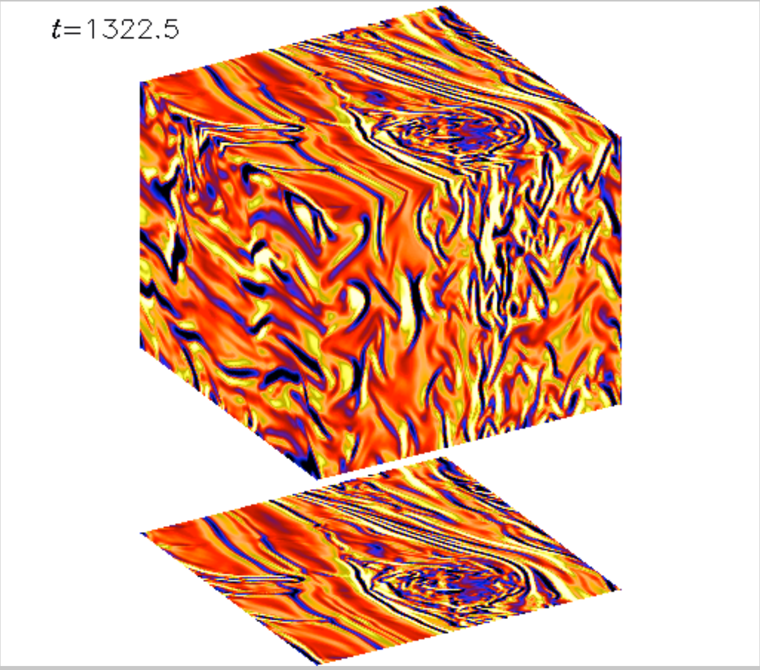


Stewart and Leinhardt (2009)



Solutions to the Metre Barrier

Trap dust at the edges of disc “dead zones”
Use disc turbulence to scoop up grains
Vortices could also trap grains
The streaming instability can reduce drift



Credit: Wladimir Lyra

Johansen et al (2007)

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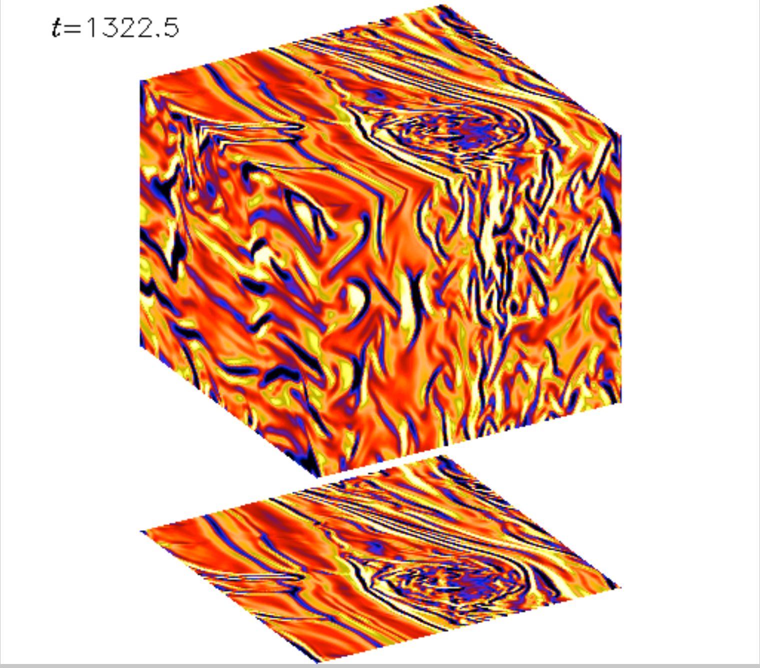

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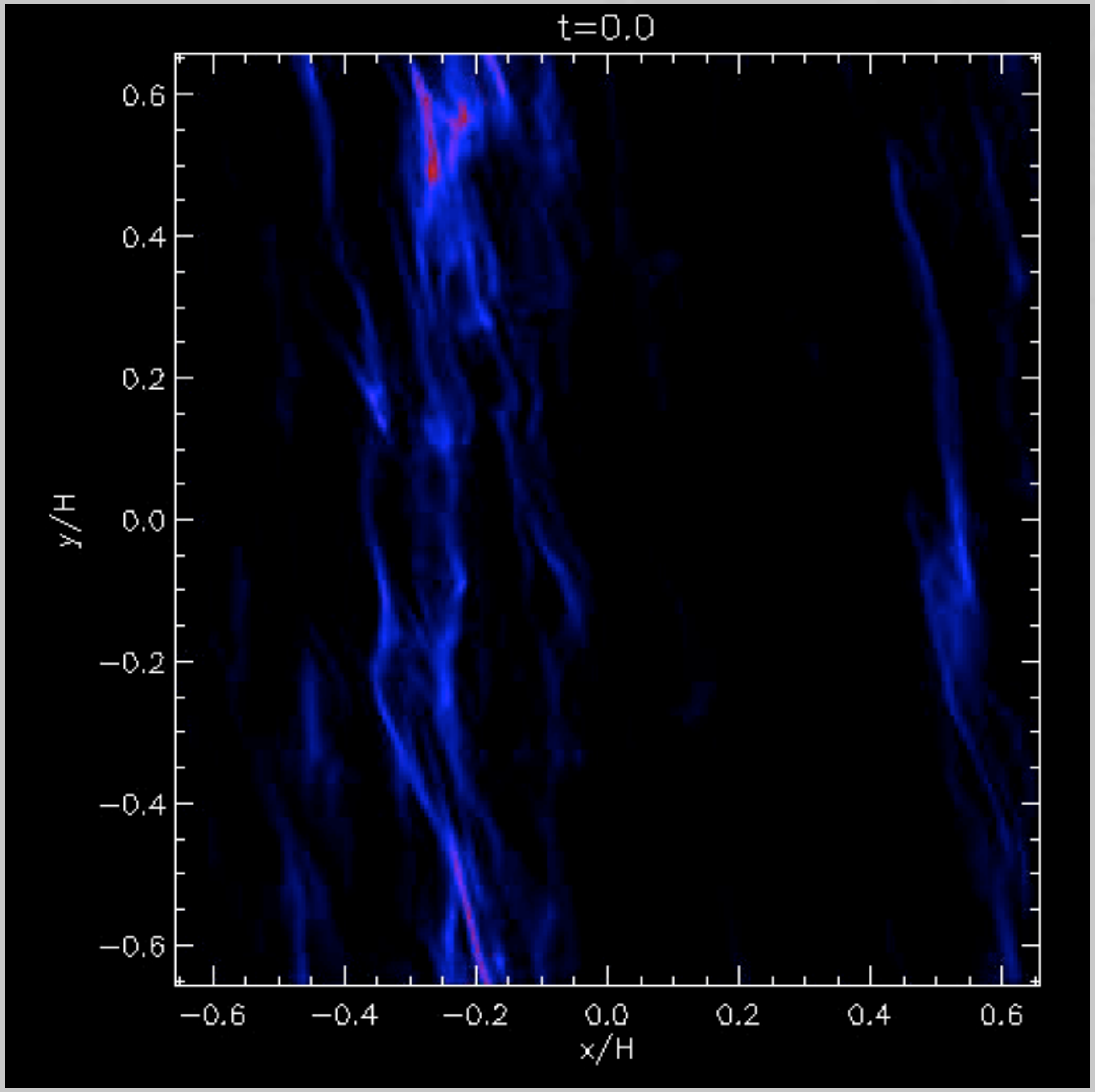
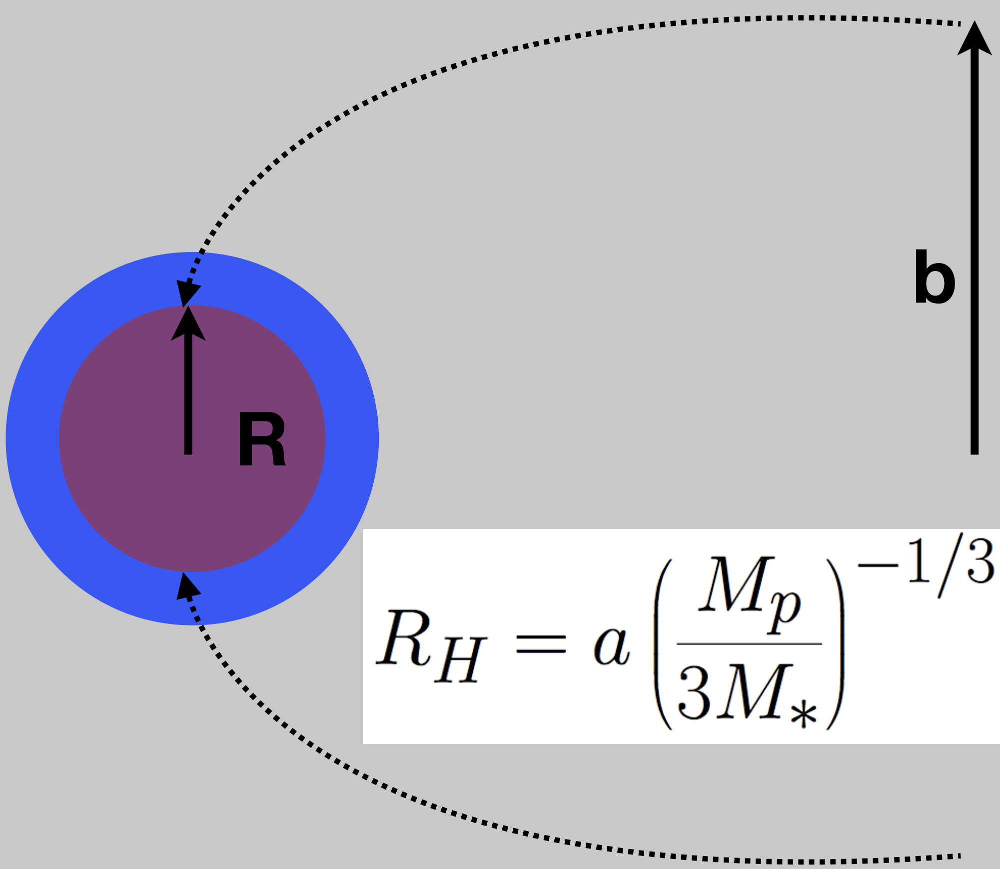


Johansen et al (2007)

Core Growth: The Runaway Phase

- Once the planetesimals have formed, they grow by mutual collision
- Gravitational focusing soon becomes important



$$R_H = a\left(\frac{M_p}{3M_*}\right)^{-1/3}$$

$$\dot{M} = \pi R^2 \rho v \left(1 + \frac{2GM}{Rv^2}\right)$$

$$\frac{\dot{M}}{M} \propto M^{-1/3}$$

fractional growth rate

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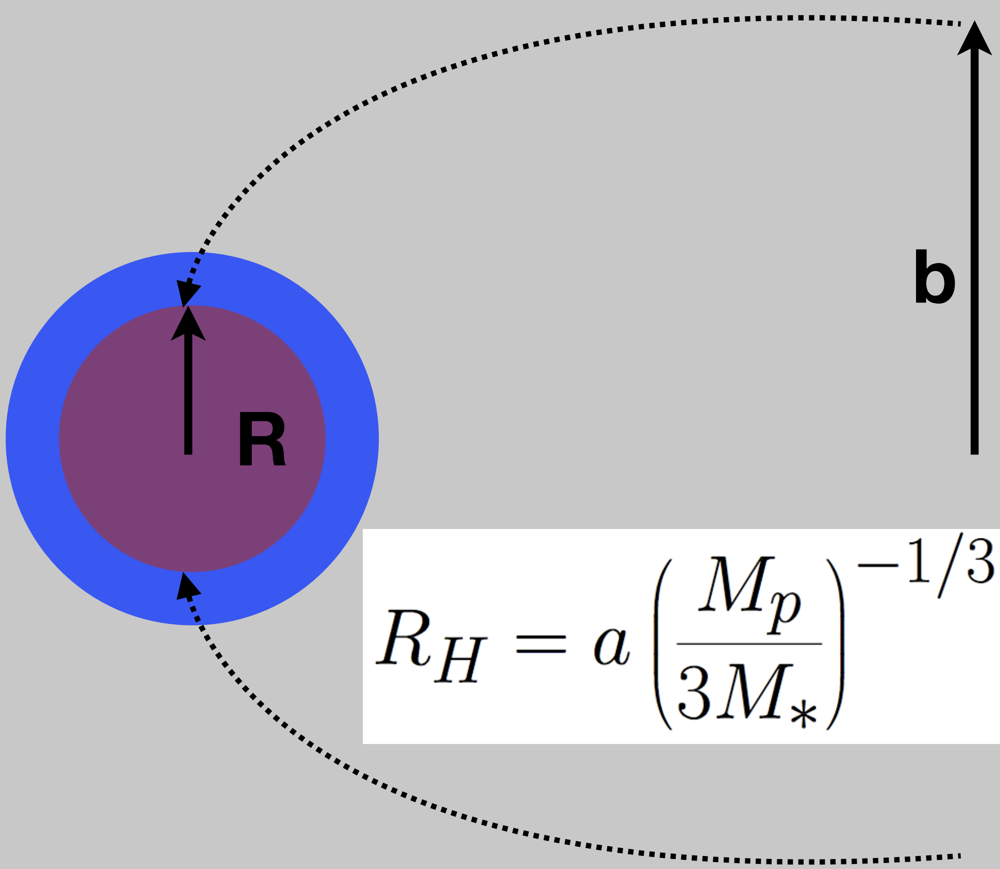

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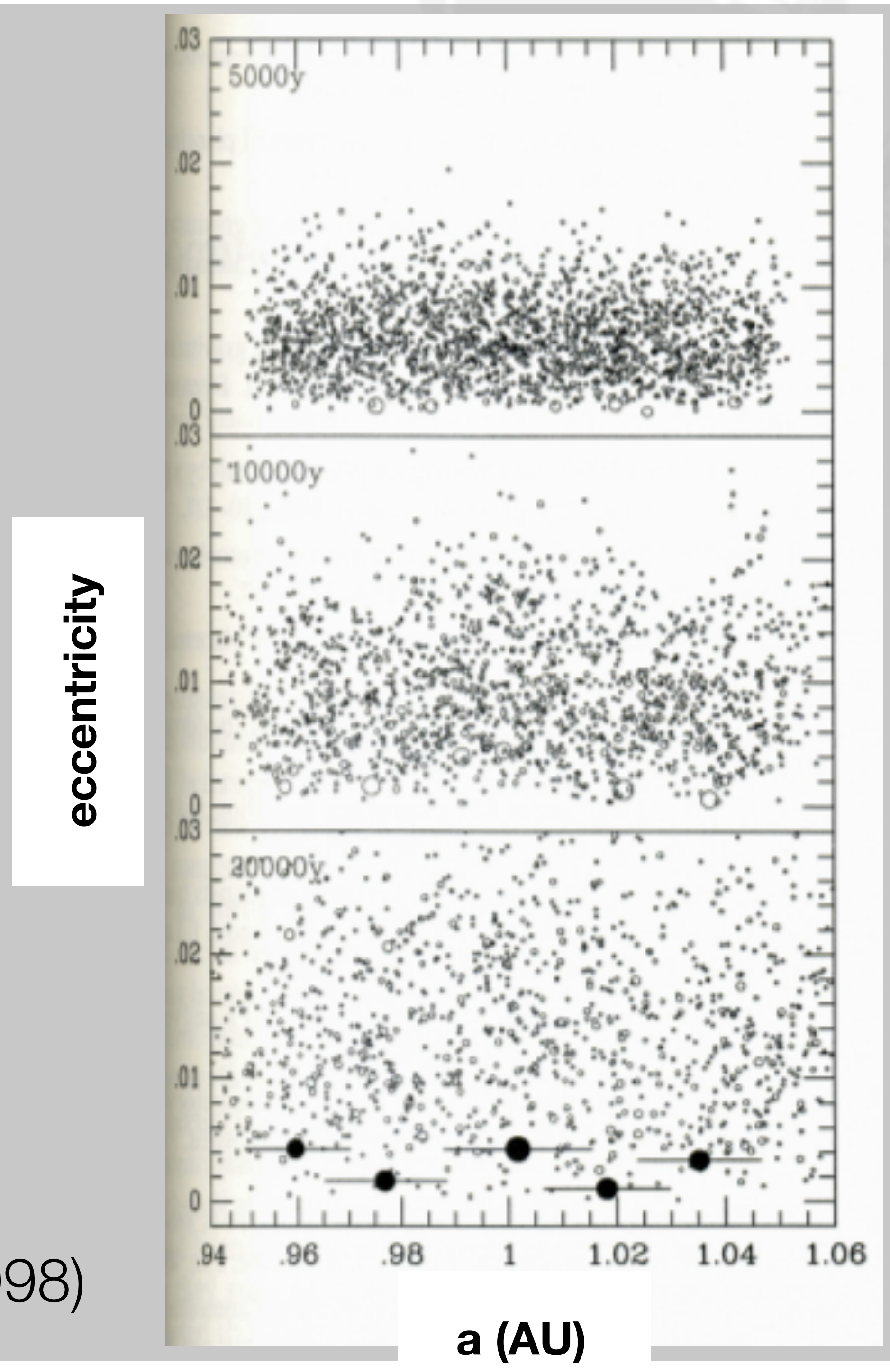
fractional growth rate

- When the body's escape velocity is large, **runaway growth** begins

Rise of the Oligarchs

- Runaway growth of cores "stirs" the planetesimals
- This increases the velocity dispersion, limiting further growth
- Planetesimals which grow to the mass of ~ Vesta (10^{-5} $M_\oplus$) become "Oligarchs"
- Adjacent oligarchs regulate each other's growth



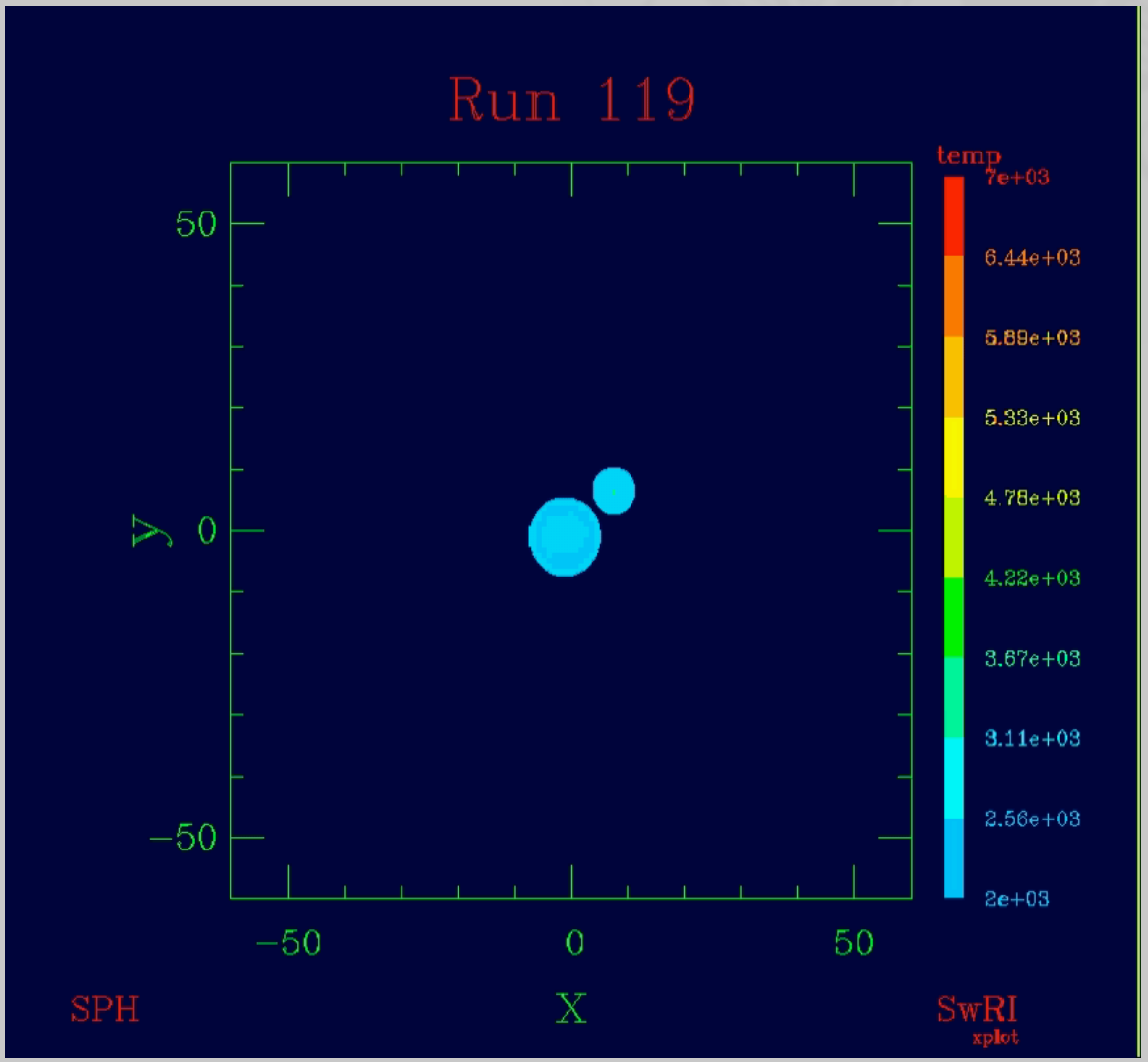
(Kokubo and Ida 1998)

The Terrestrial Planets

- Protoplanets can only accrete material that enters their "**feeding zone**"
- The feeding zone is a few Hill Radii in size:

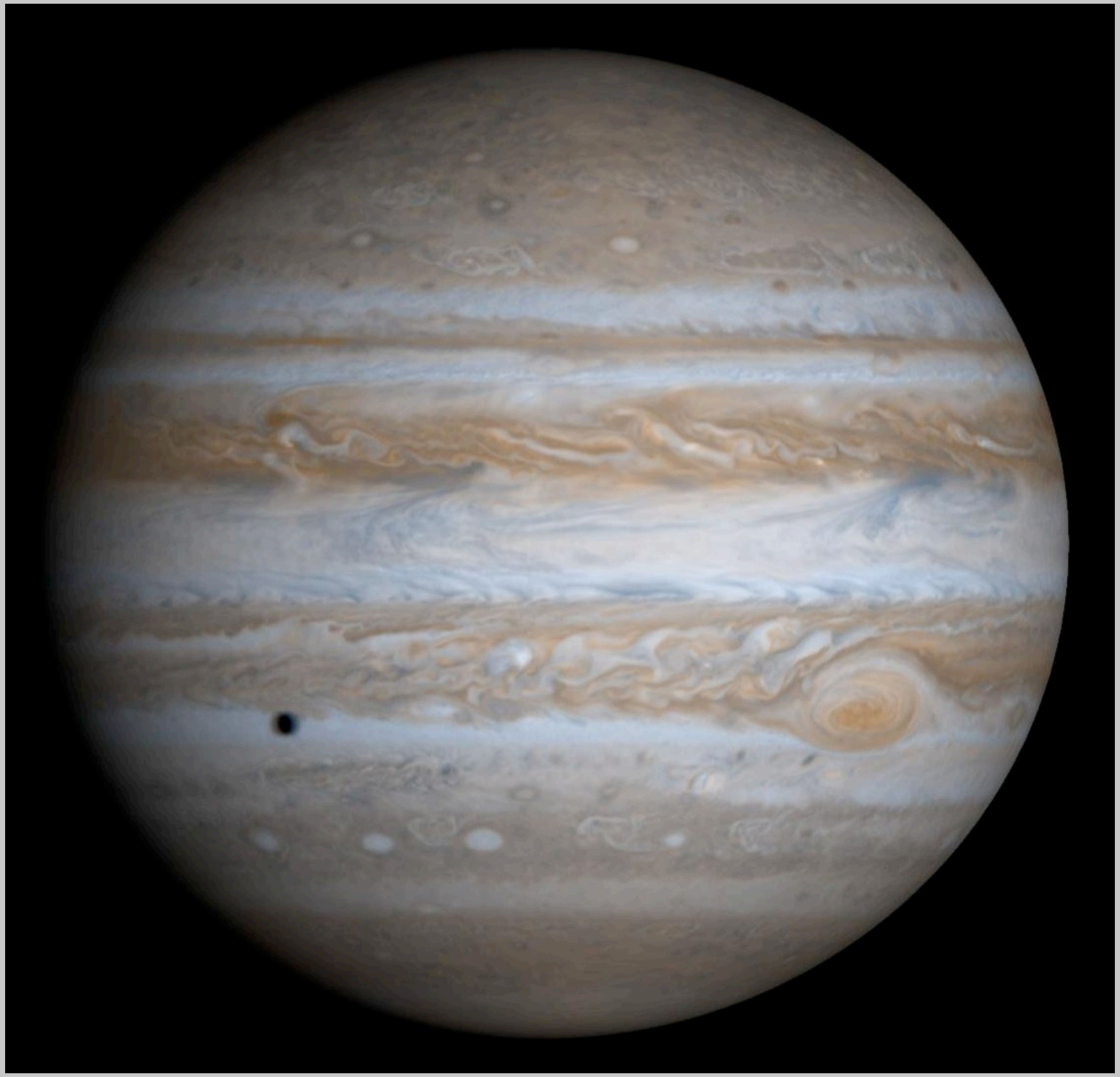
$$R_H = a\left(\frac{M_p}{3M_*}\right)^{-1/3}$$

- Eventually, the protoplanet will reach an **isolation mass**
- At 1 AU, this is of order 0.1 $M_\oplus$, further out it can be large as 9 $M_\oplus$
- The final assembly involves **protoplanetary collisions**



Canup (2003)

The Giant Planets

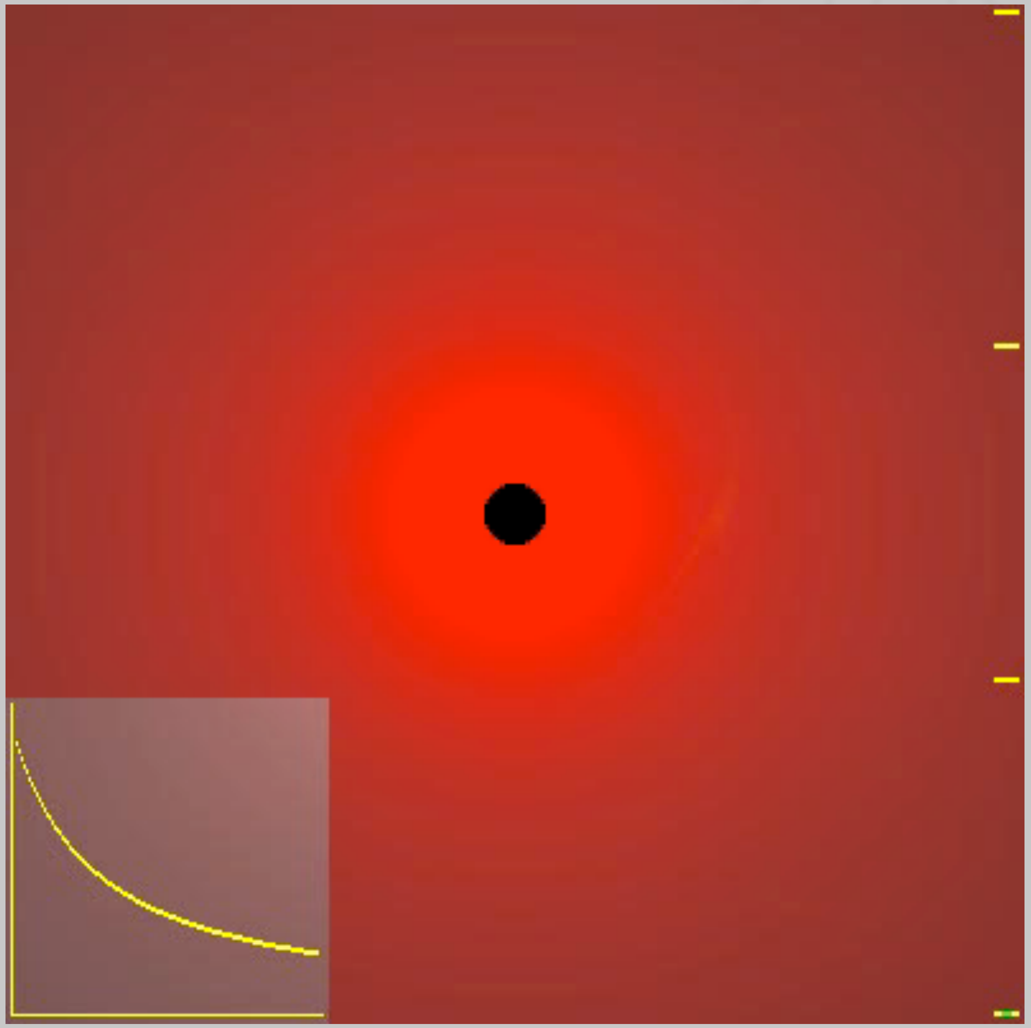


- While the core is growing, it accretes gas hydrostatically from the disc
- If the core mass exceeds 10 $M_\oplus$, then **runaway gas accretion** begins
- The core then gobbles up gas until:
  1. There is no gas left
  2. Tidal forces prevent further gas from becoming bound
- The formation timescale (start to finish) is close to the disc lifetime

Planet Migration

- The protoplanetary disc is not a stage: it is an actor
- The protoplanet excites **density perturbations** which create **torques**
- These torques are generated at **resonances** between the planet and disc

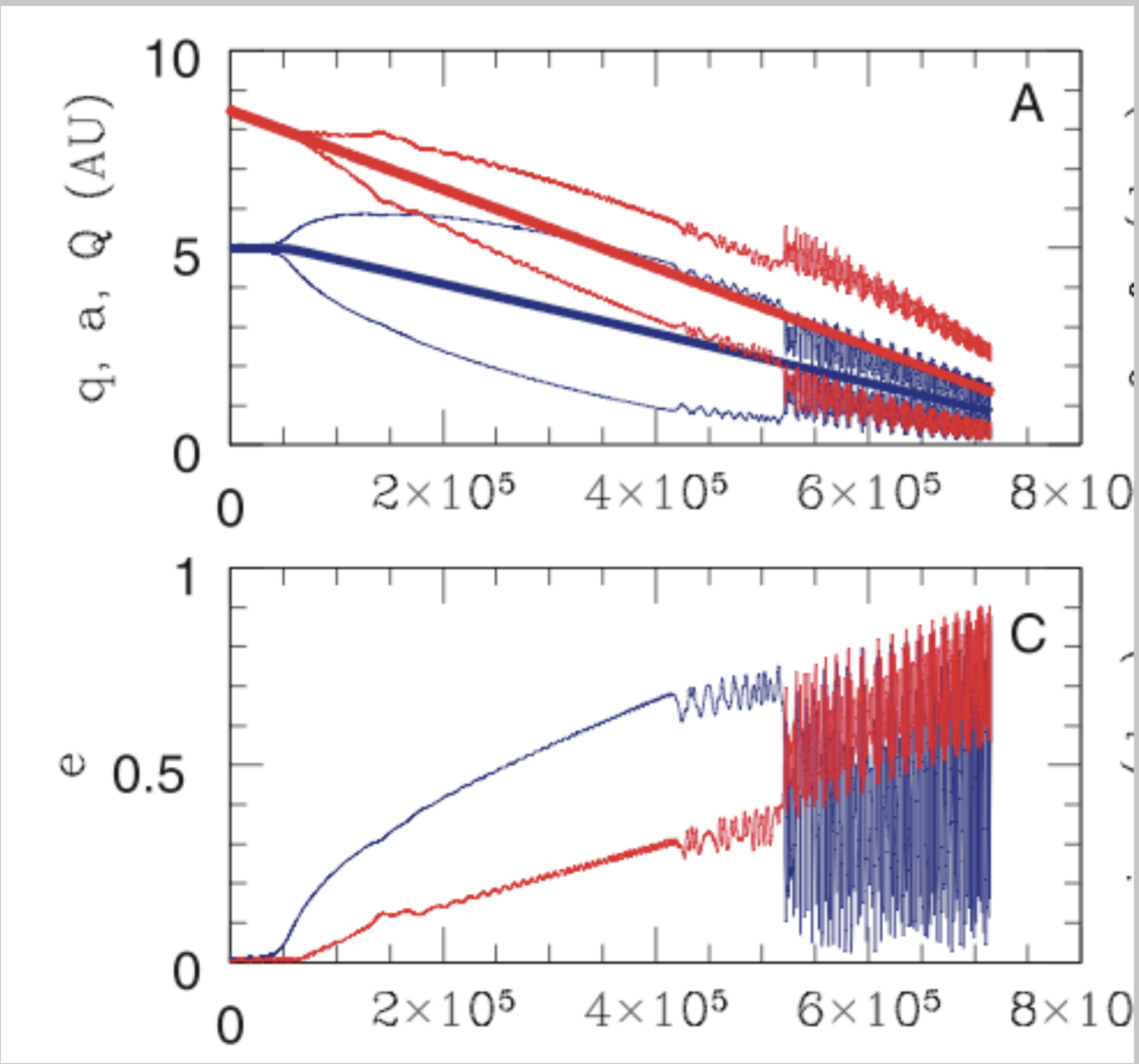
- **Type I** migration occurs when interior and exterior torques are out of balance
- **Type II** migration occurs when the planet carves a gap in the disc
- Both are inward for **laminar** discs
- **Planetesimal scattering** can create outward migration



Credit: Phil Armitage

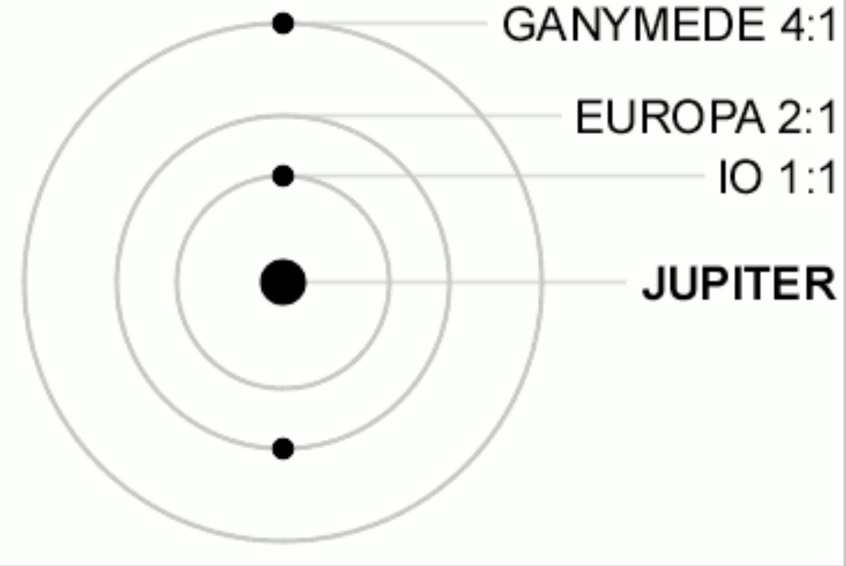
Dynamical Evolution II: Resonant Capture

- Planets are resonant if they share a **commensurate characteristic frequency**



Thommes and Lissauer (2003)

- e.g. the Mean Motion Resonance (MMR, below)
- Migration can result in capture into a resonance



Dynamical Evolution III: Planet-Planet Scattering

Raymond et al (2012)

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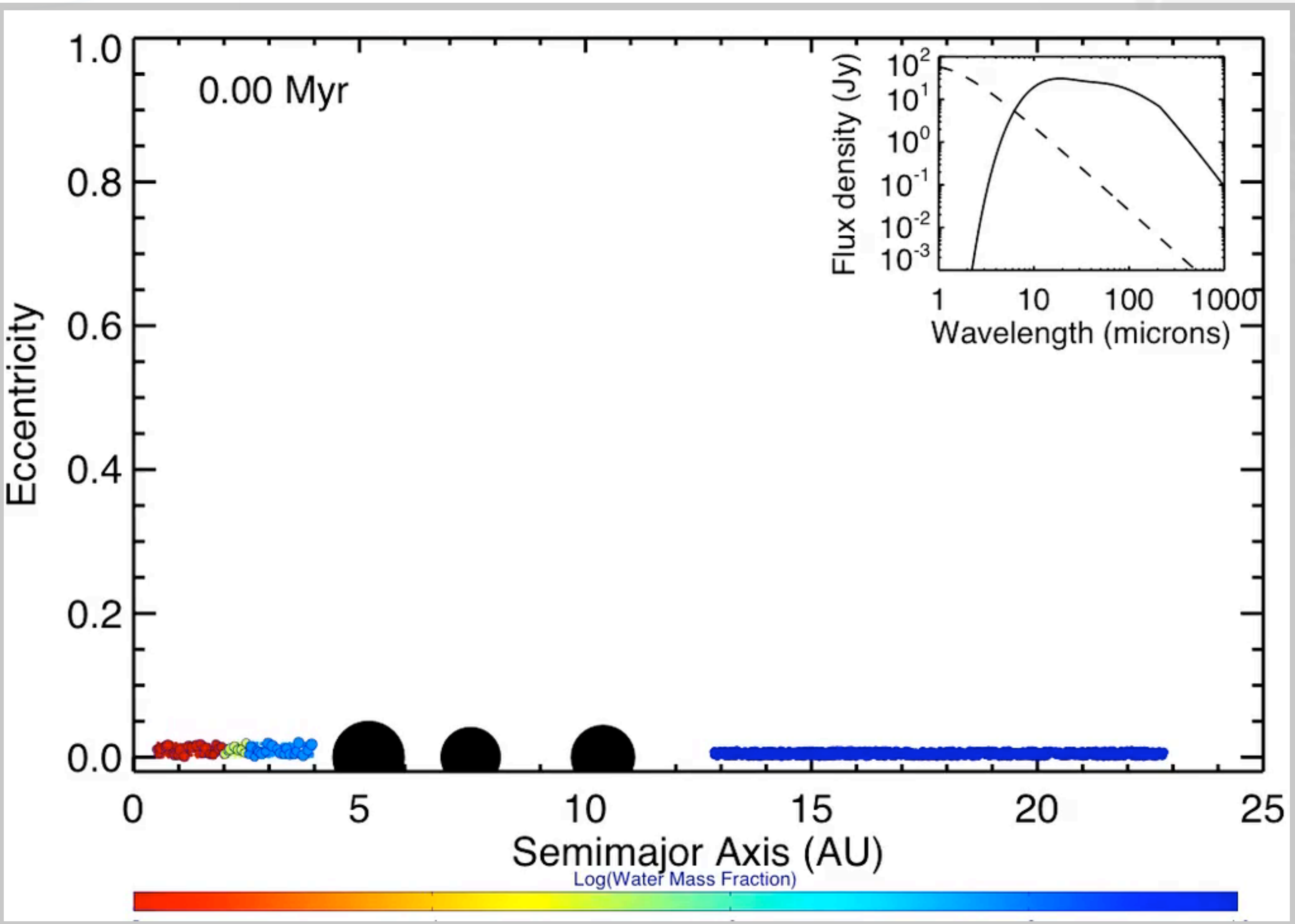
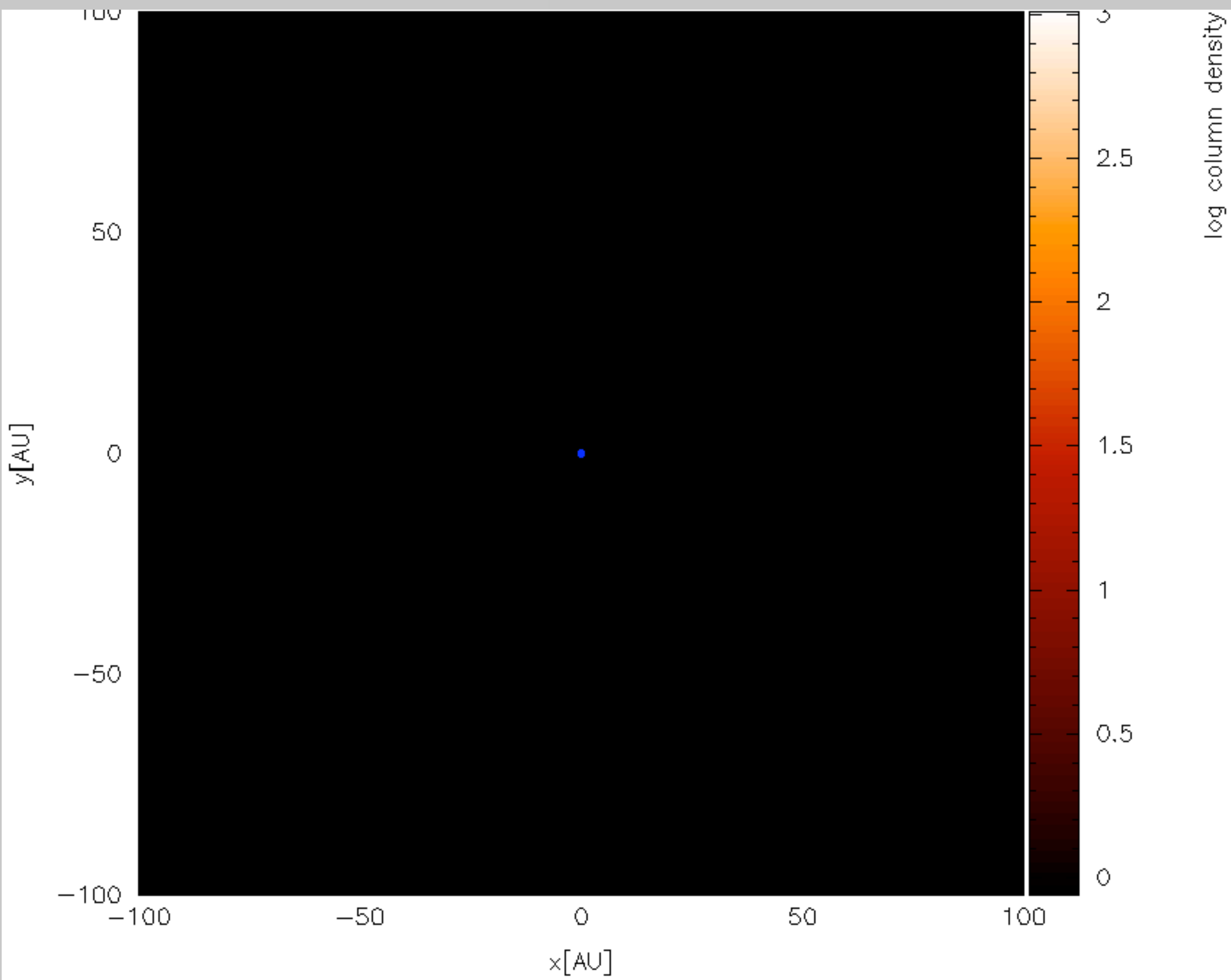


Raymond et al (2012)

An Alternative Model: Formation by Gravitational Instability



$$Q = \frac{c_s \Omega}{\pi G \Sigma} \sim 1.5 - 1.7$$

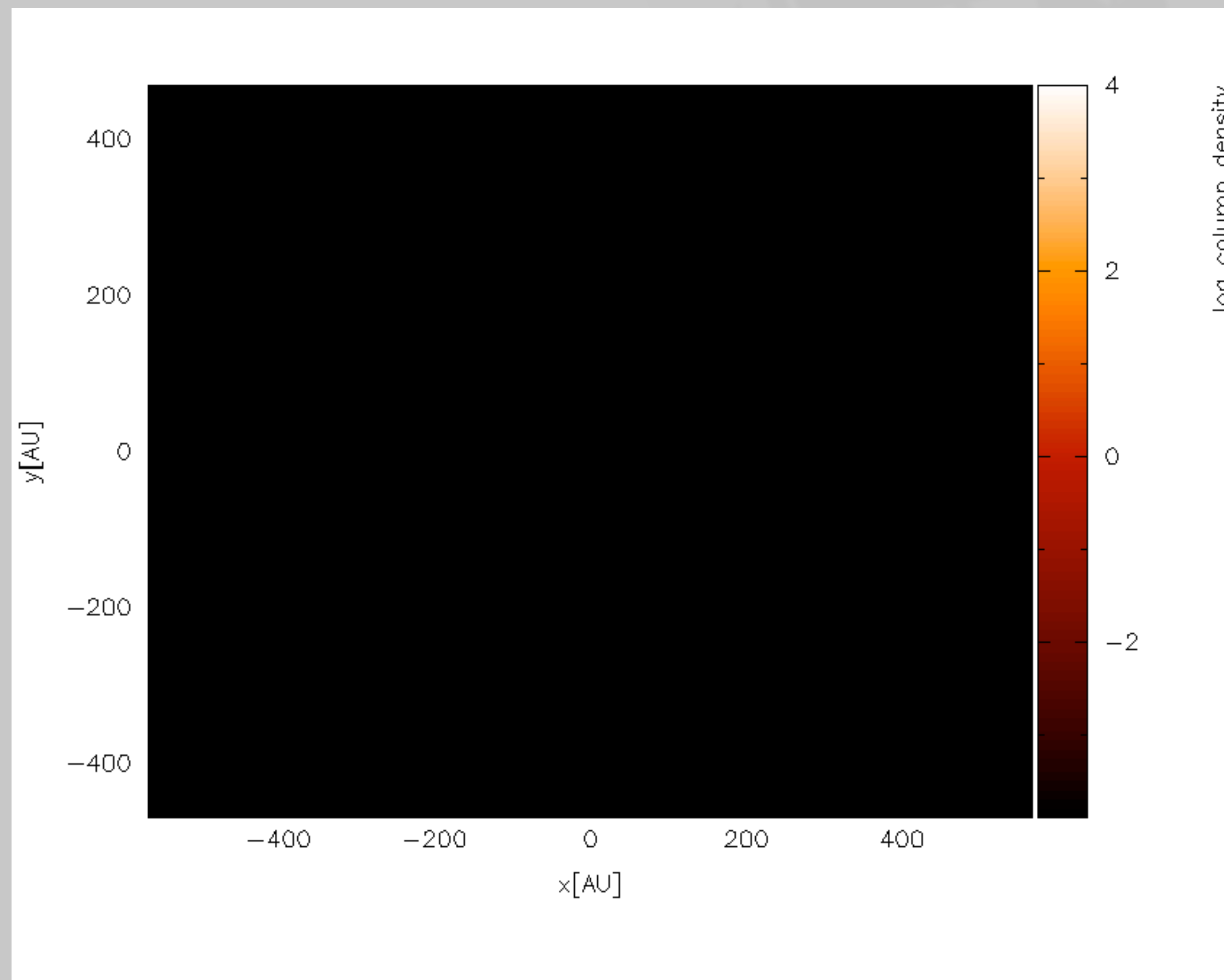
- Early on, protostellar discs can be gravitationally unstable
- This produces non-axisymmetric perturbations: **spiral waves**
- If the density perturbations are strong enough: **fragmentation**

Conditions for Disc Fragmentation

- Typically, self-gravitating discs maintain a **quasi-steady state**
- The heating produced by the instability is balanced by cooling
- To make a disc fragment, this thermostat must be broken

$$\beta_c \leq \beta_{crit}$$

$$\alpha \geq \alpha_{max} \approx 0.06$$



$$\beta_c = t_{cool}\Omega$$

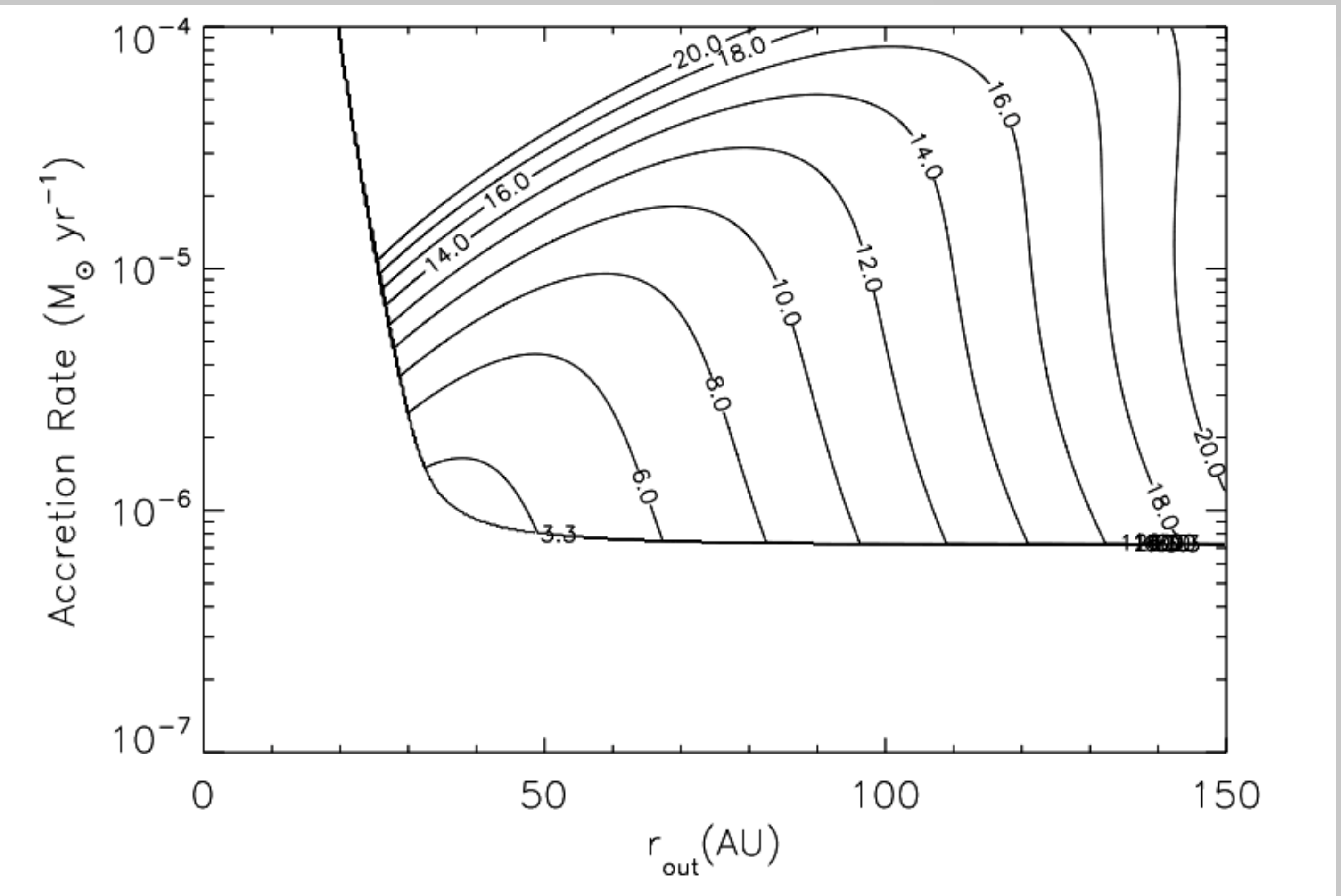
$$\alpha_{eq} = \frac{4}{9\gamma(\gamma-1)\beta_c}$$

Typical Fragment Masses

- These criteria were built for isolated discs
- They don't take into account envelope accretion and other phenomena
- I rewrote the criteria in terms of the Jeans mass inside the spiral arm
- This also allows us to calculate fragment masses (Forgan and Rice 2011)

$$M_J = \frac{4\sqrt{2}\pi^3}{3G} \frac{Q^{1/2} c_s^2 H}{\left(1 + \frac{\Delta\Sigma}{\Sigma}\right)}$$

$$\Gamma_J = \frac{M_J}{\dot{M}_J}$$



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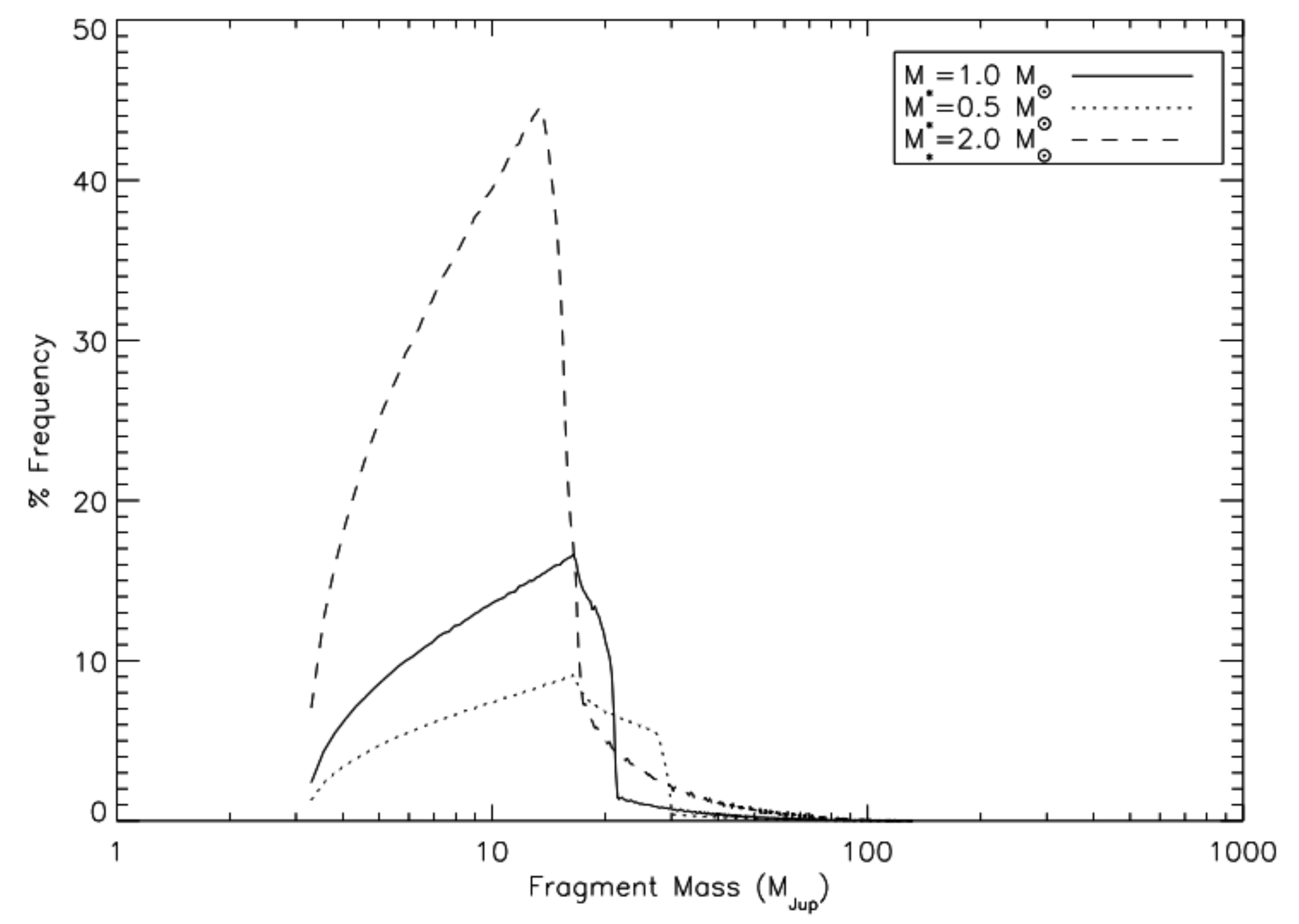

The Tidal Downsizing Hypothesis

- Gravitational Instability only produces massive objects - or does it?
- **Dust sediments** to the centre, forming a solid core
- Embryo migrates inward, fills its Roche lobe and is **tidally stripped**
- Presto! Lower mass planets (possibly terrestrial planets)

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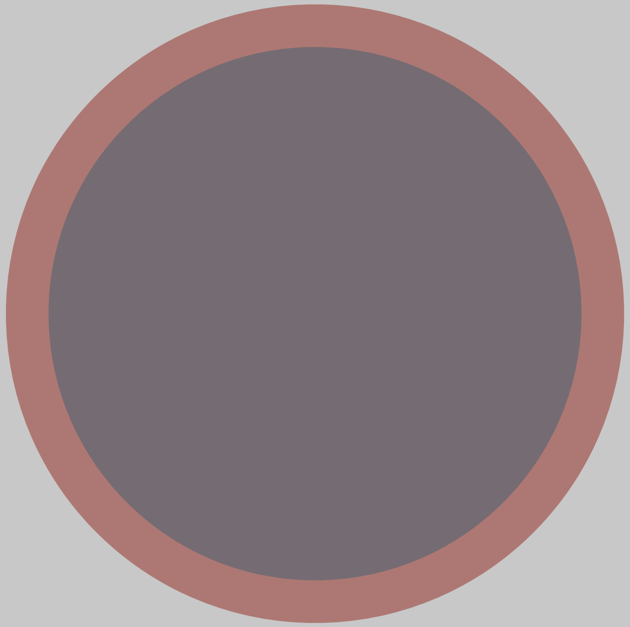

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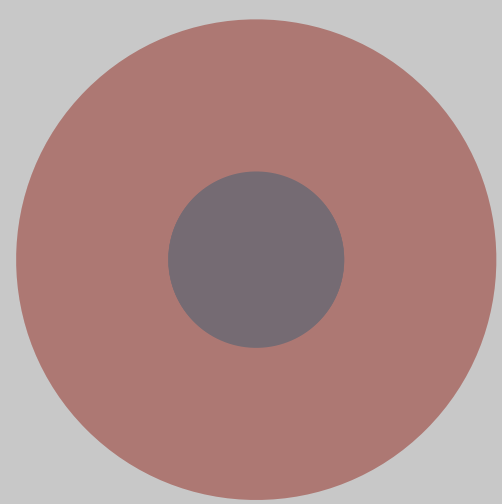

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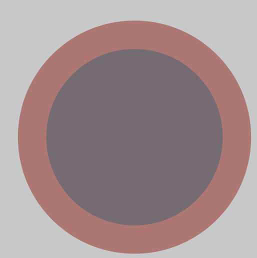


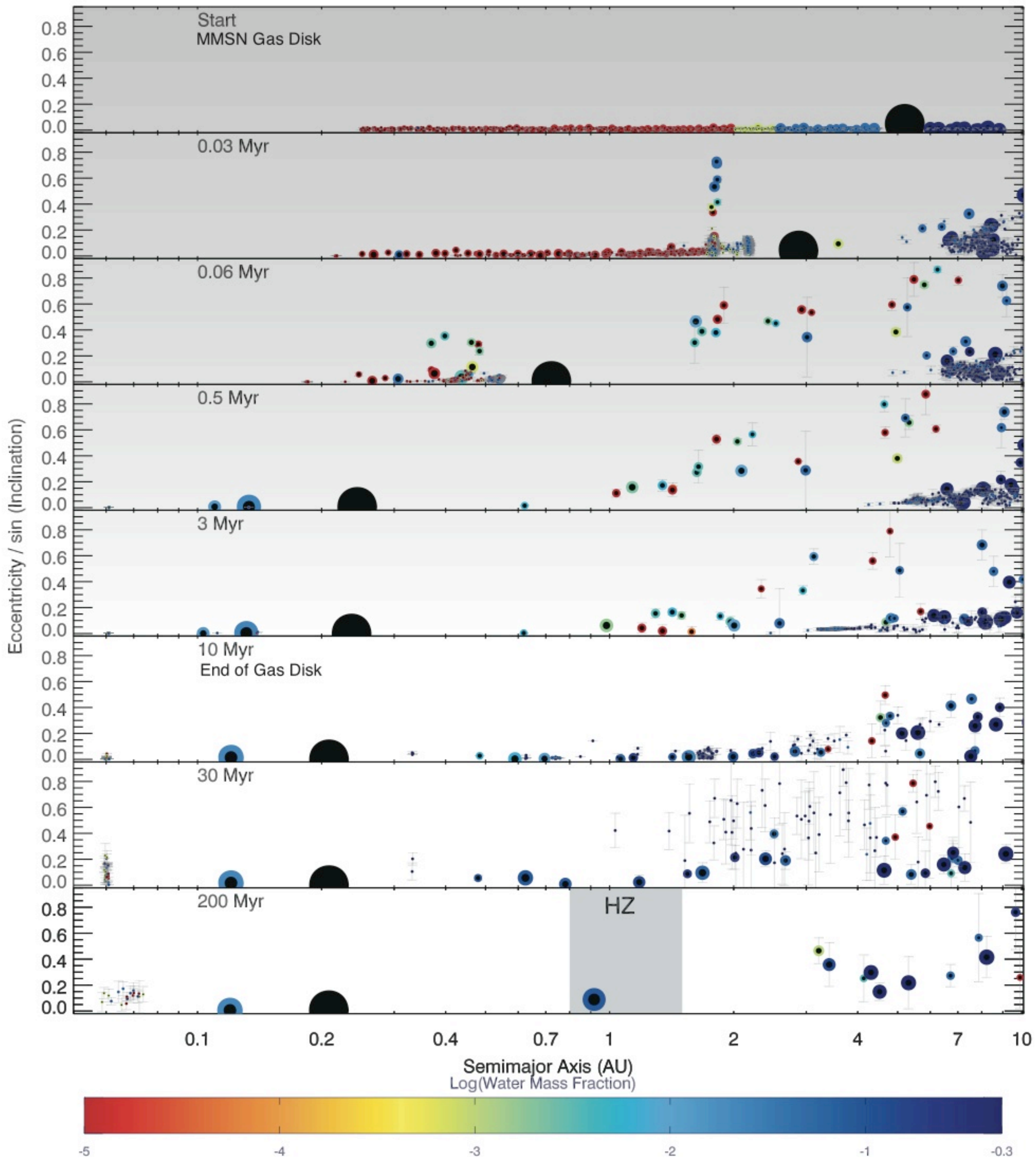
Two Modes of Planet Formation

- Chances are both work together in at least one system (Boley 2009)

- Gravitational Instability forms massive planets quickly at large radii

- Core accretion forms low mass planets slowly at low radii

Mandell et al (2007)



Conclusions

- The processes of planet formation and star formation are intimately connected (via the protostellar disc)

- Physics: gravity, magnetohydrodynamics, radiation + Chemistry

- **Core Accretion** forms planets < a few M_{Jup} slowly, at low radii

- **Gravitational Instability** forms objects > a few M_{Jup} quickly at large radii

- Both could work together