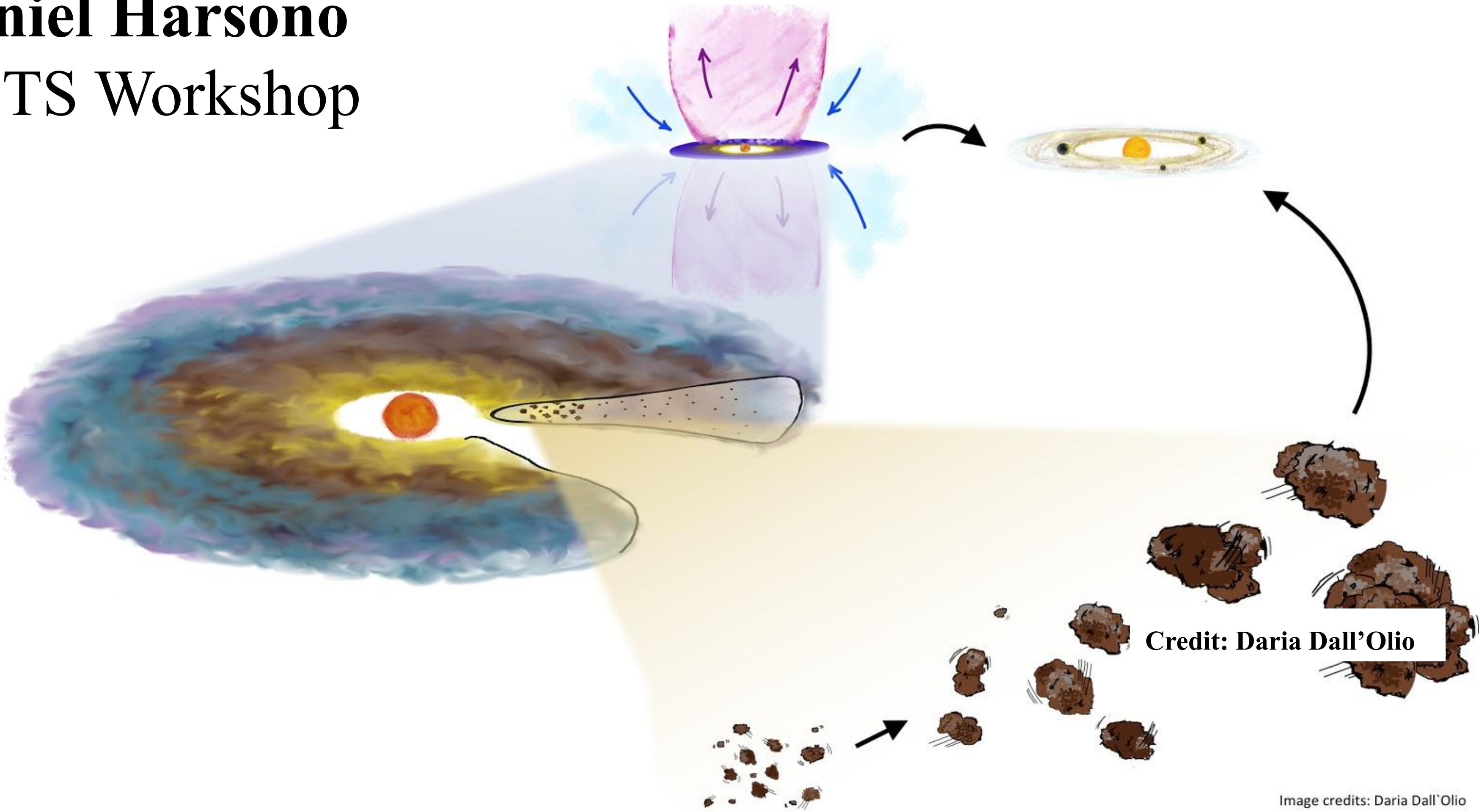
Star and Planet formation

Daniel Harsono

NCTS Workshop



Earth is covered by water on 70% of the surface.

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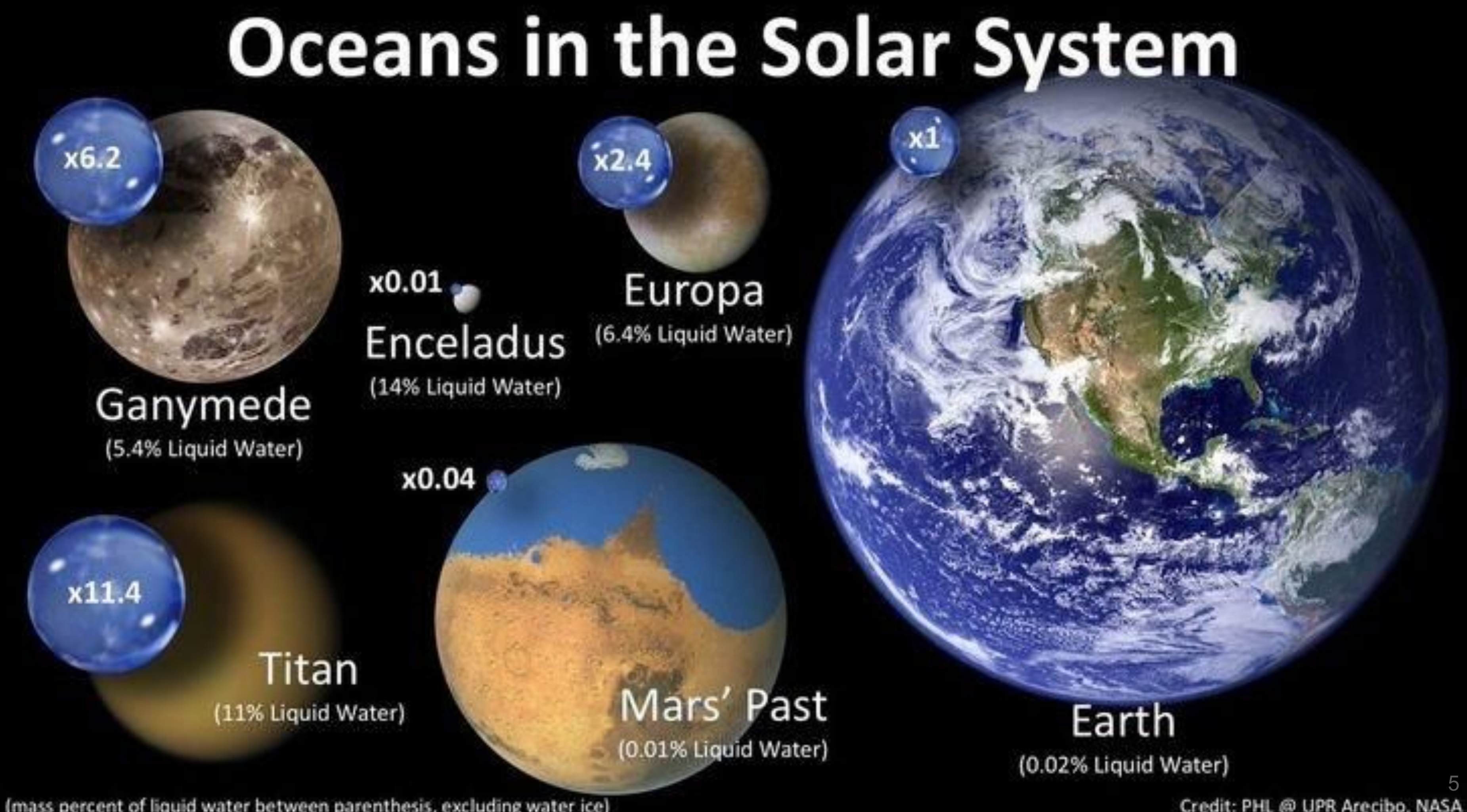
Liquid water is only 0.02% of the total mass.

Each of the bodies in the Solar System have different fraction of liquid water.

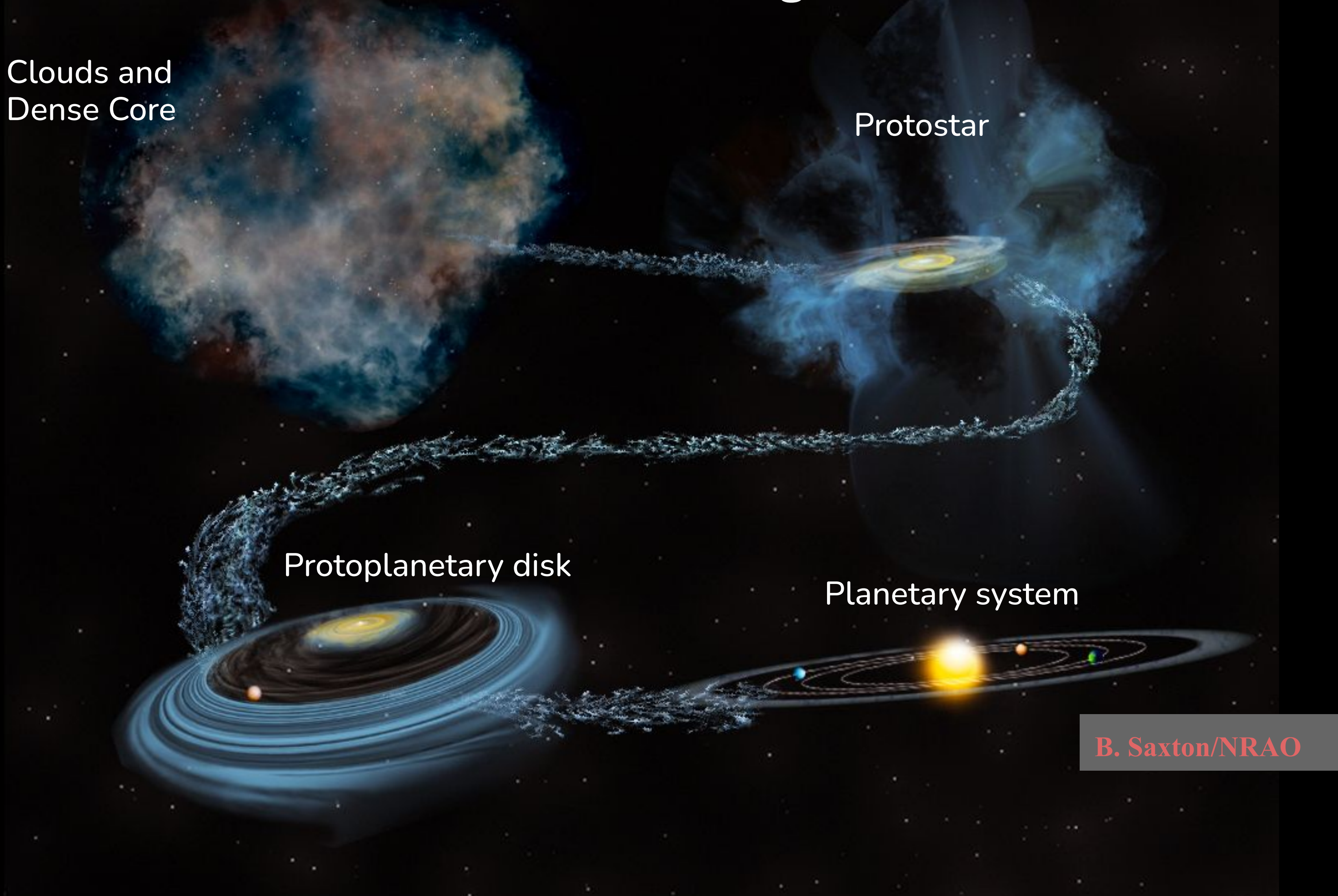


Earth is covered by water on 70% of the surface.

Liquid water is only 0.02% of the total mass.

How did the planets get their water?

Water evolution starts in the earliest stages of star formation.



We study star-forming regions:

- How did the Sun form?
- How do planets form?
- How did life begin?

ESO:DSS2/Davide de Martin

Dense cores

Taurus cloud by Lloyd Smith, Deep Sky West

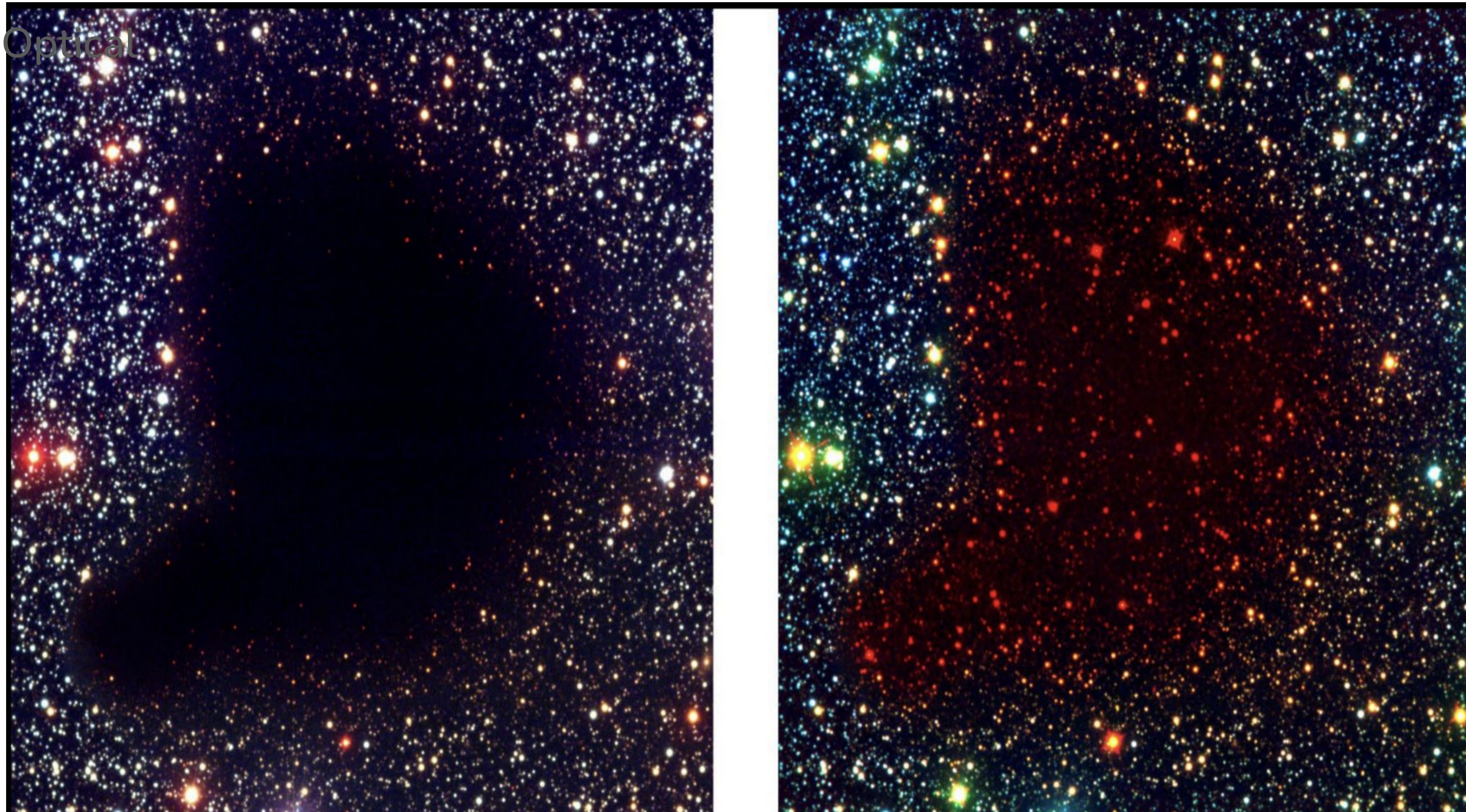
Dense cores

Stars form in the 'holes' of the sky.

These holes were discovered by Herschel and Barnard in the 1800s to 1900s.

In the 1900s, people noticed that these holes are full of gas and dust (also ices).

Dense core: Barnard 68



Optical

Infrared

Alves et al. 2001

Dense core: Barnard 68

This is a famous example of a core.

However, this core will not form a star because it does not have enough mass.

Not all dark regions in the universe will form a star.

Alves et al. 2001

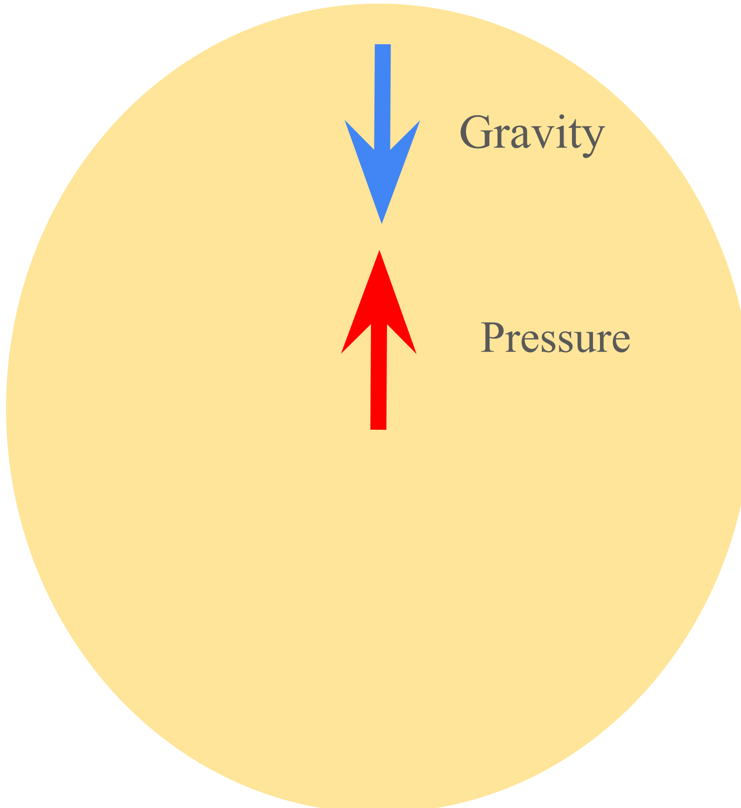
Support against collapse

These cores are hydrostatic: similar to stars but at much larger scales (0.1 parsecs ~ 20000 au)

Clouds do not collapse because it is supported by pressure: thermal motions of the gas.

$$K_{\mathrm{th}} = 3mn\sigma_{\mathrm{th}}^2$$

$$\sigma_{\mathrm{th}}^2 = \frac{\Delta v}{8\ln 2} = \frac{kT}{m}$$



Jeans mass

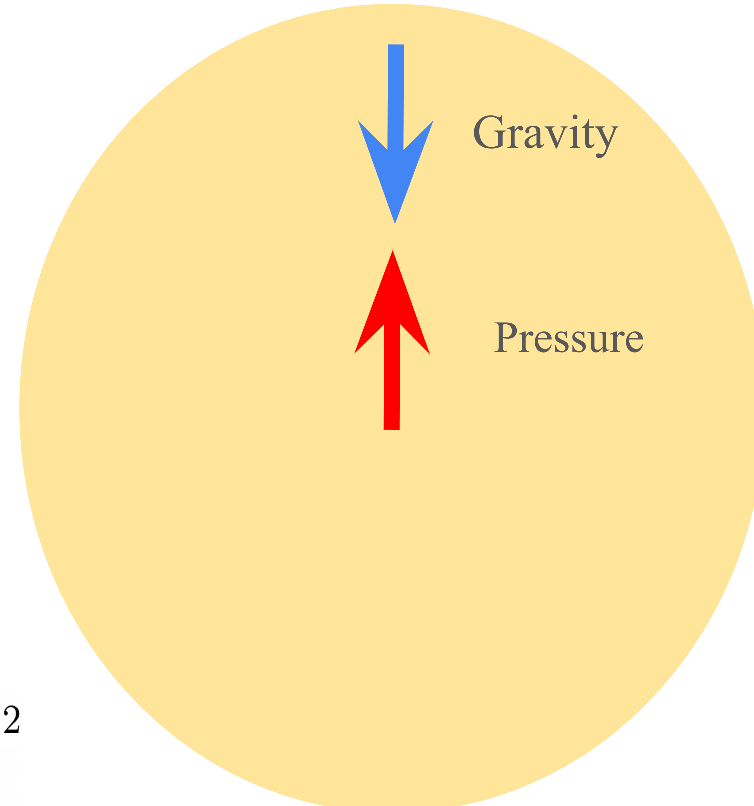
The dense core collapse if the mass exceeds the Jeans mass within a Jeans scale.

$$\frac{3MkT}{\mu m_h} < \frac{3}{5}\frac{GM^2}{R}$$

$$M_{\rm J} = \left(\frac{5kT}{G\mu m_{\rm H}}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

$$M = \frac{3}{4}\pi\rho_0 R^3$$

$$M_{\rm Jeans} = 10M_\odot\left(\frac{T}{10K}\right)^{3/2}\left(\frac{n}{10^4 cm^{-3}}\right)^{-1/2}$$



Jeans mass with magnetic field

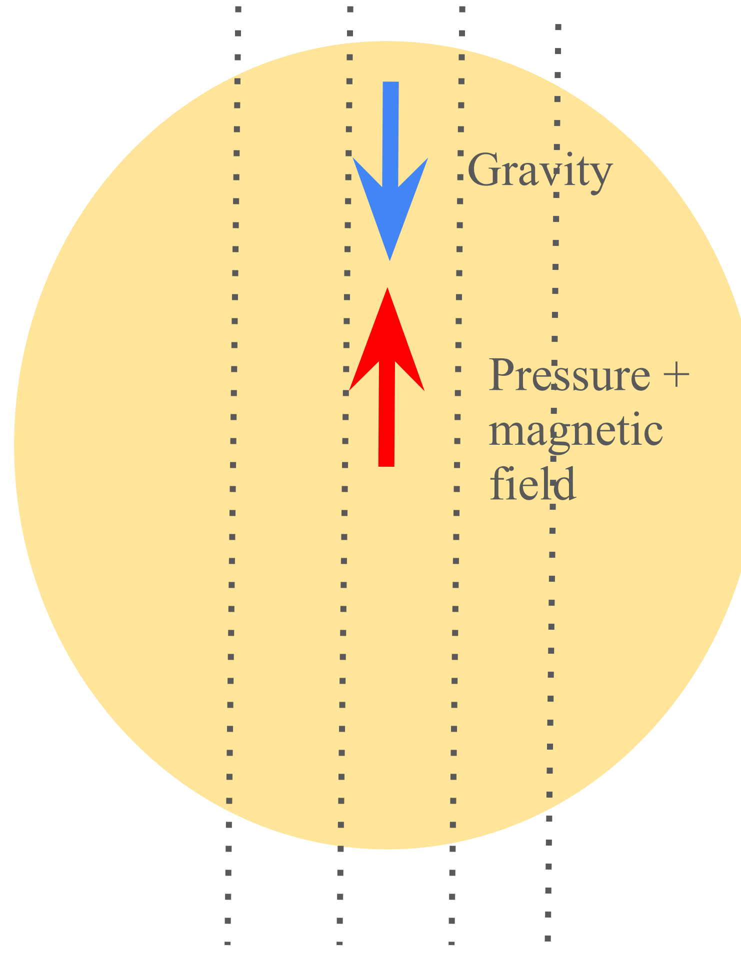
Magnetic field is typically around a few microGauss in star-forming regions.

Magnetic field supports against the collapse.

Gravity can take over the magnetic field forces as long as the mass is over the critical value:

$$M_{\rm cr} = 0.15\frac{\Phi}{G^{1/2}} = 10^3 M_\odot \left(\frac{B}{30\mu G}\right)\left(\frac{R}{2pc}\right)^2$$

With magnetic fields, the critical mass is now 1000 solar masses!



Bonnor Ebert mass (cylinder and sphere)

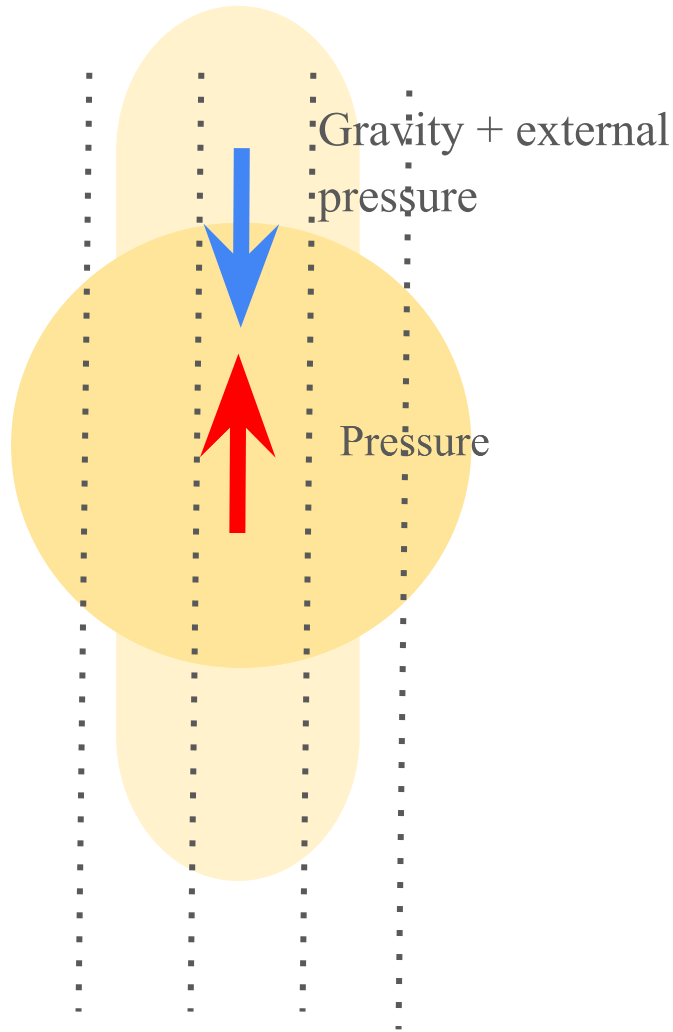
Dense cores are embedded in some cloud that still feeds that core.

The clouds also exert pressure on the dense core.

$$M_{\rm cr} = M_{\rm grav} + M_{\rm BE}$$

$$M_{\rm BE} = 1.18\frac{c_{\rm s}}{\sqrt{P_0 G^3}}$$

$$c_{\rm s} = \sqrt{\frac{kT}{\mu m_{\rm H}}}$$

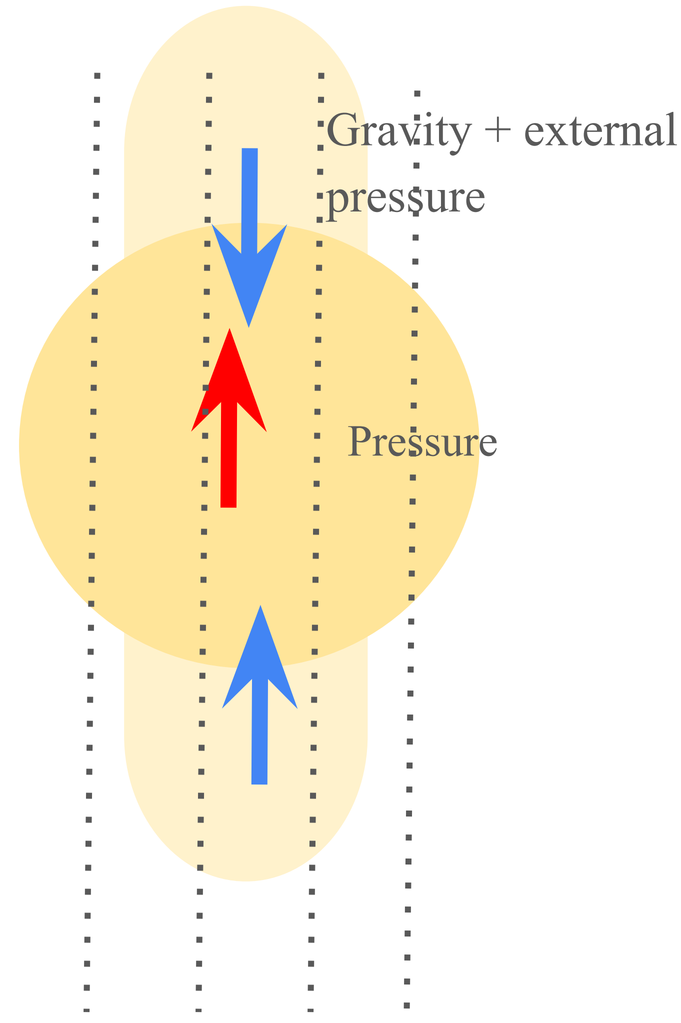


Isothermal collapse

Now, because of the surrounding cylinder of gas, the protostellar envelope is always evolving.

$$\frac{dP}{dr} = -G\frac{M\rho}{r^2}$$

$$\frac{dr}{dt}\frac{d^2r}{dt^2} = -\left(\frac{4\pi}{3}G\rho_0 r_0^3\right)\frac{1}{r^2}\frac{dr}{dt}$$



Free fall time

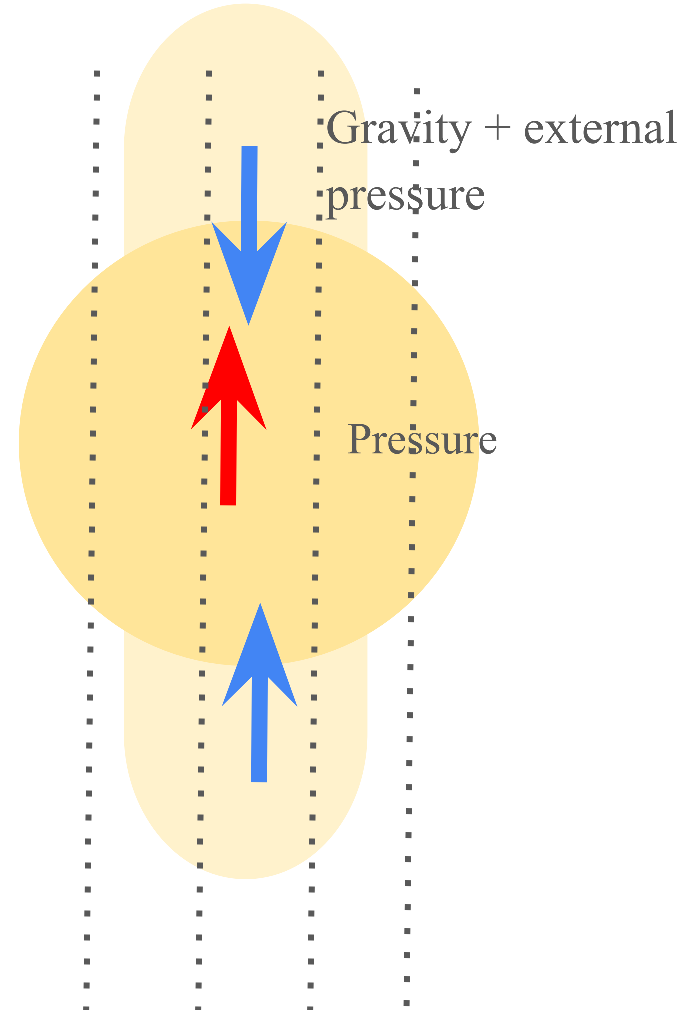
We can use this equation to define a free-fall time: the time for a sphere to collapse to 0.

$$t_{\mathrm{ff}} = \frac{\pi}{2\chi}$$

$$t_{\mathrm{ff}} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2}$$

$$\theta = \frac{r}{r_0}; \quad \chi = \left(\frac{8\pi}{3}G\rho_0\right)^{1/2}$$

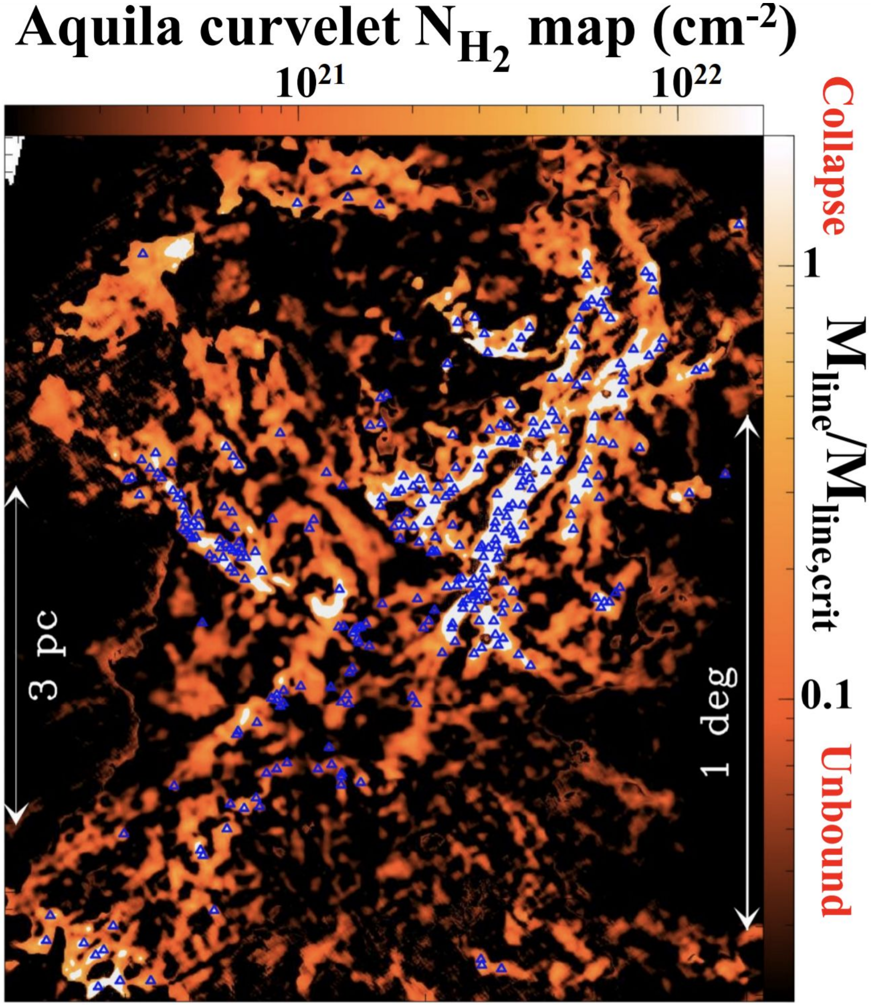
$$\frac{d\theta}{dt} = -\chi\left(\frac{1}{\theta} - 1\right)^{1/2}$$



Filaments

Filaments or cylinder mass can collapse if the mass in the line is larger than the critical value.

The typical temperature of these regions is 10 K so the mass is roughly about 16 solar mass per pc.



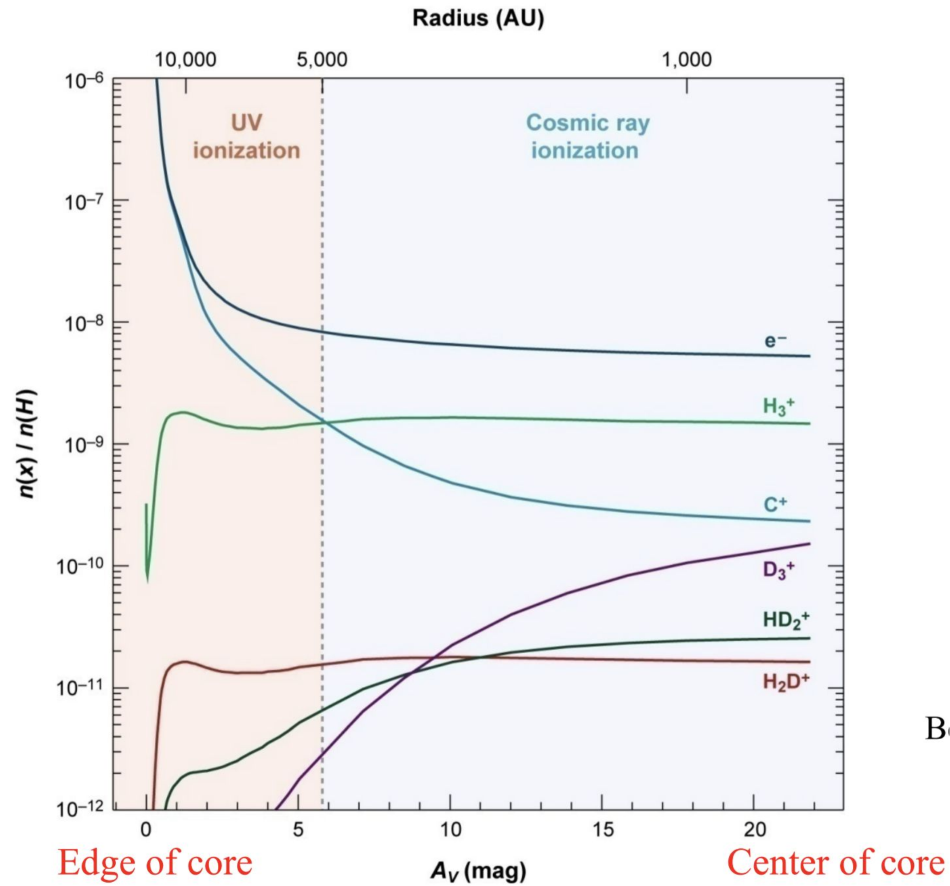
André et al. 2010

Magnetic fields

Magnetic forces can only act on the ions while neutrals can easily float into the high density regions.

Neutral gas continues to contract due to gravity so there is a different velocity between ions and neutrals.

Ambipolar diffusion



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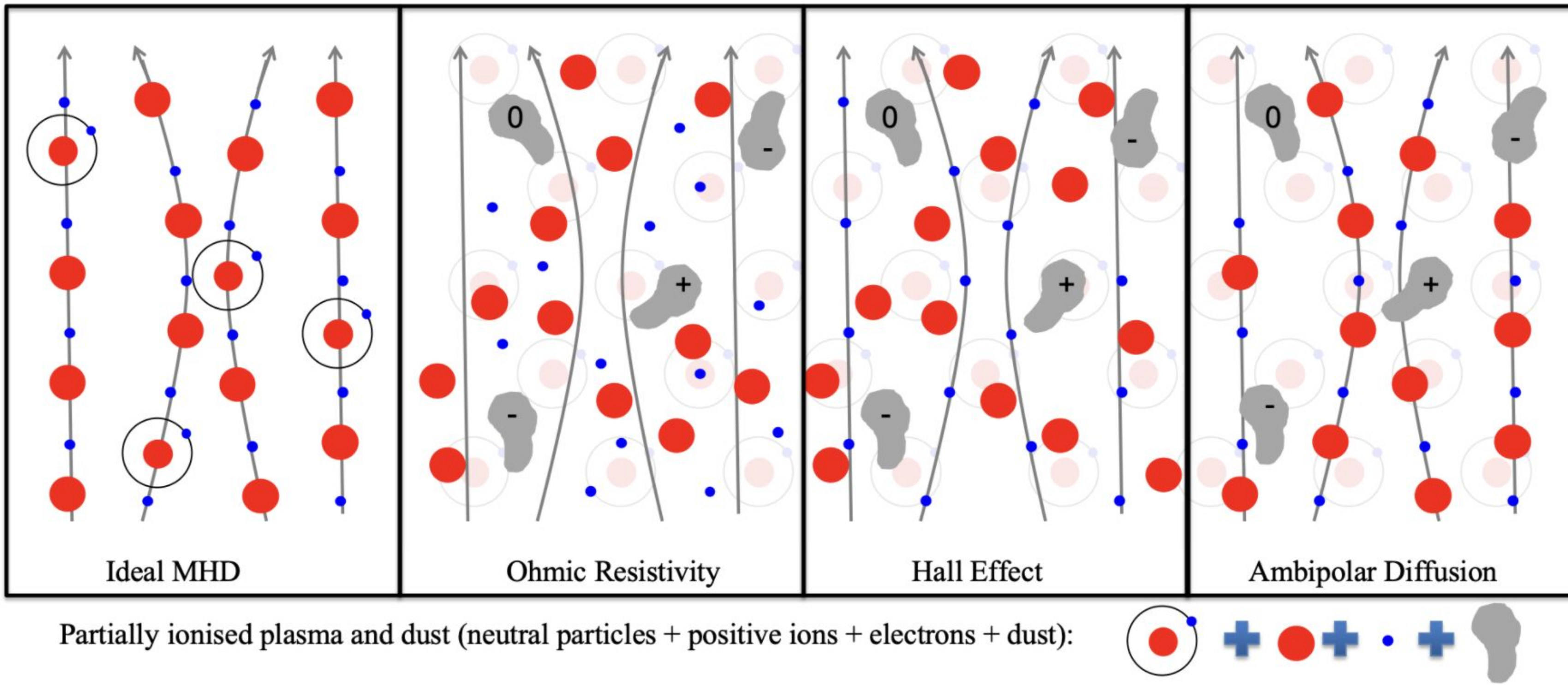
Bergin & Tafalla 2007

Ambipolar diffusion

Ions and electrons are stuck on the magnetic fields but the neutrals flow inward.

James Wurster



Timescales for star formation

The typical timescales that are important for star formation are:

- Free-fall
- Dynamical
- Ambipolar diffusion

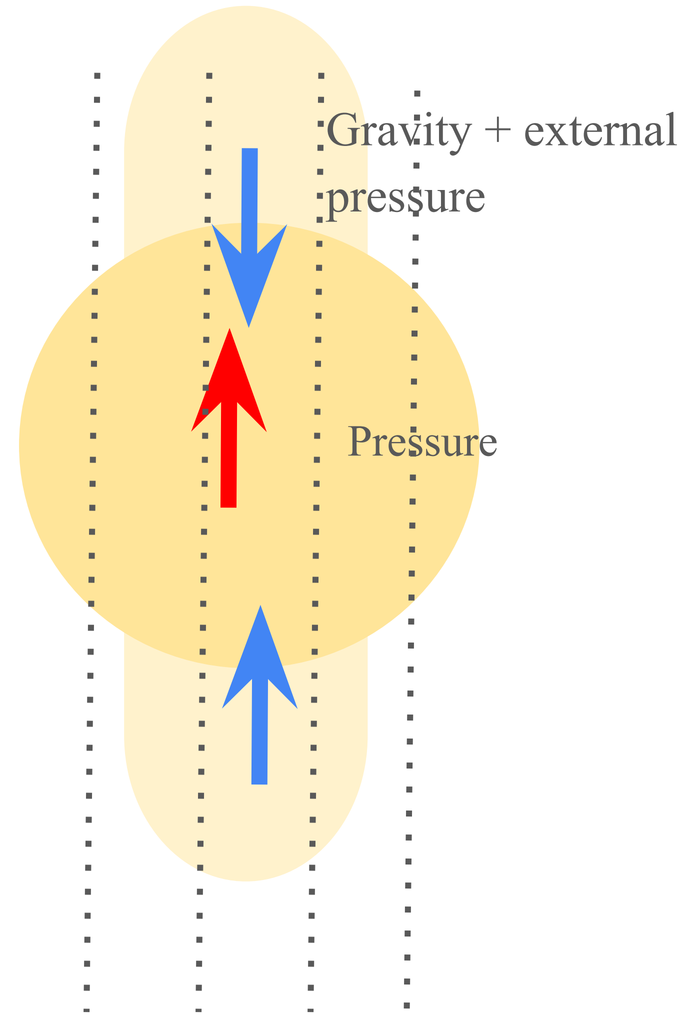
$$t_{\rm ff} \simeq 3.4 \times 10^5 \left(10^4/n\right)^{1/2} yr$$

$$t_{\rm dyn} = \frac{R}{v_{\rm A}} \simeq 3 \times 10^5 \frac{R}{0.1pc} \frac{30\mu G}{B} \sqrt{\frac{n}{10^4 cm^{-3}}} yr$$

$$\frac{t_{\rm AD}}{t_{\rm dyn}} \simeq \frac{\gamma_{\rm drag} c}{2\sqrt{2\pi G}} \simeq 8$$

$$t_{\rm AD} \simeq 2 \times 10^6 years$$

This delay in star formation is necessary to explain the observed low star formation rate.

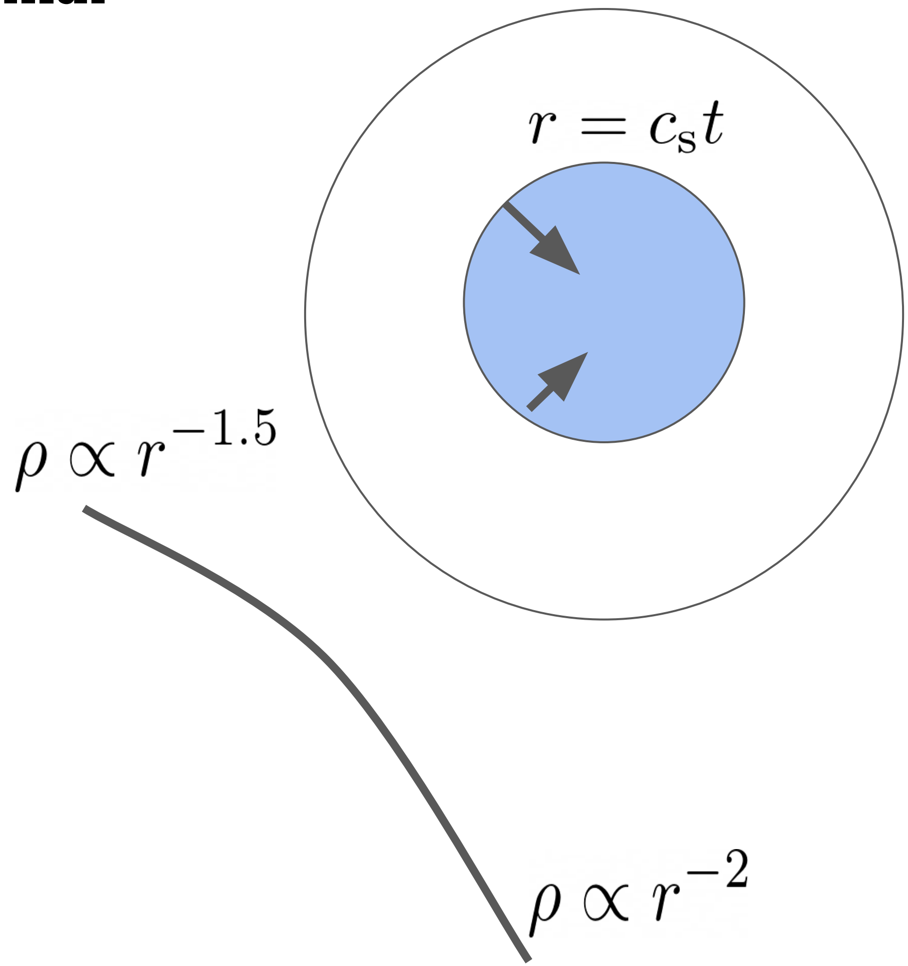


Analytical solutions: self-similar

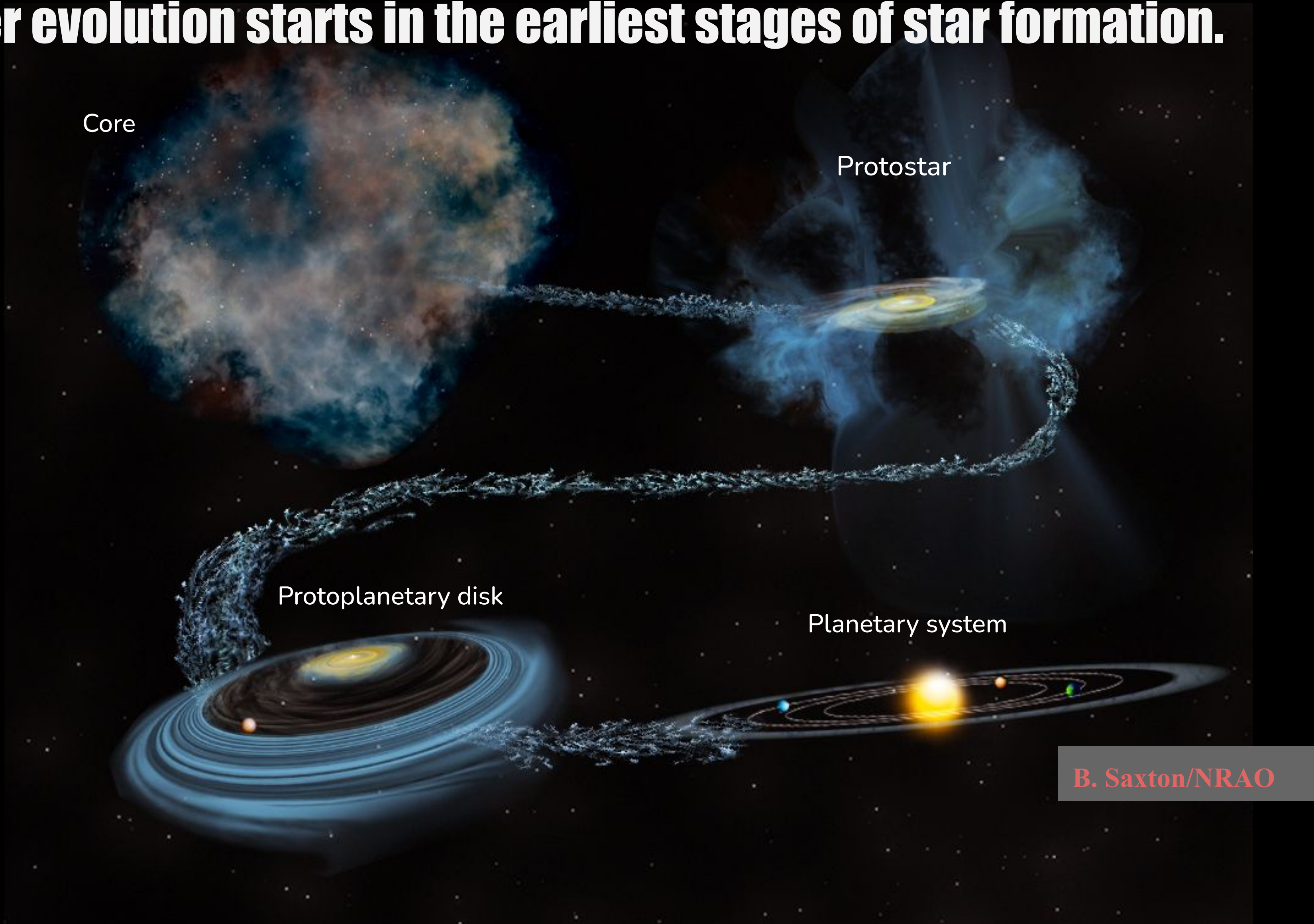
Self-similar collapse is an inside collapse as introduced by Shu 1977.

It is a special solution.

The outward going wave is letting know the gas outside that a star has formed.



Water evolution starts in the earliest stages of star formation.



Why a disk structure?

Typical dense cores have rotation rates of 10^{-13} Hz.

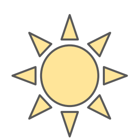
The specific angular momentum of the gas needs to be conserved:

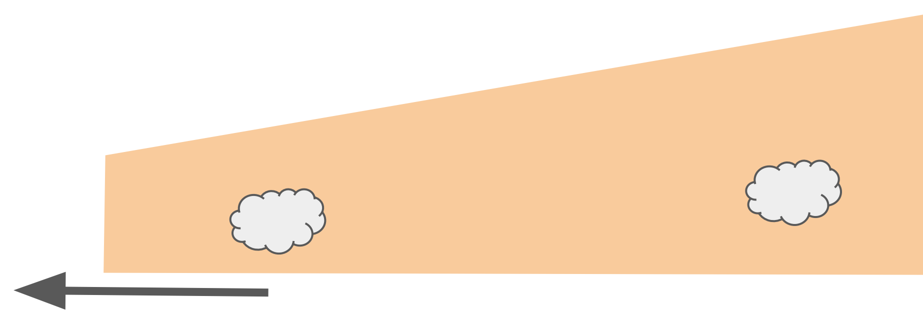
$$j = \Omega_{\mathrm{core}} R_{\mathrm{jeans}}^2 \approx 10^{21} cm^2/sec$$

$$j_{\mathrm{Keplerian}} = \sqrt{GMR}$$

$$R \approx 10^2 - 10^4 AU$$

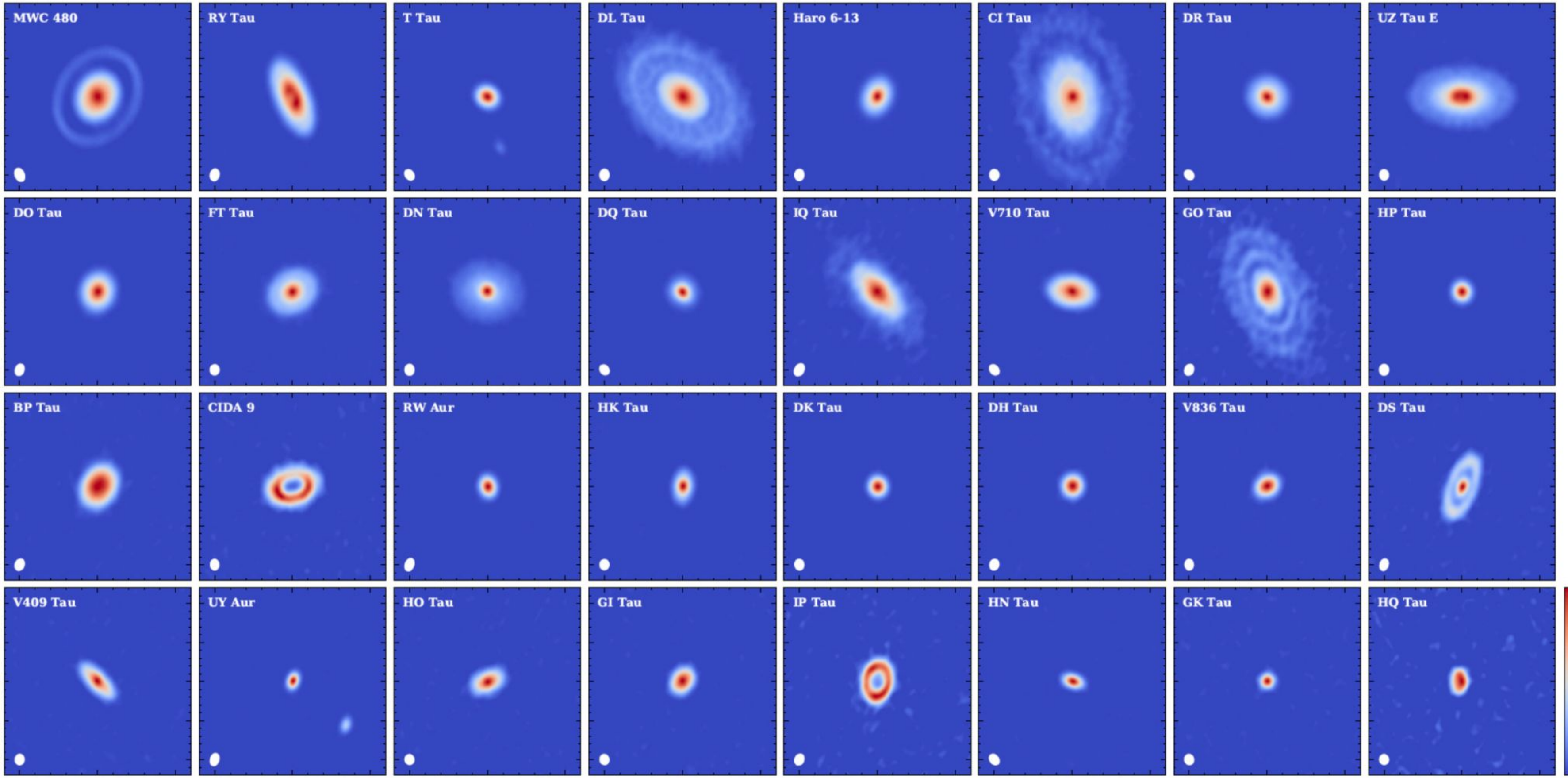
Much larger than a star -> disk





Disks as sites of planet formation

Long+ 2019



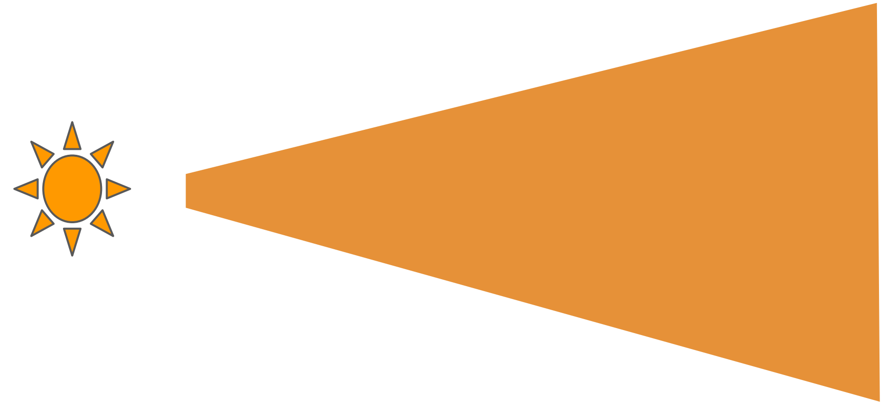
ALMA in Chile - sub-mm

High sensitivity and high spatial resolution instrument at sub-mm.

Disks as sites of planet formation

Disks are not geometrically thin because of stellar radiation.

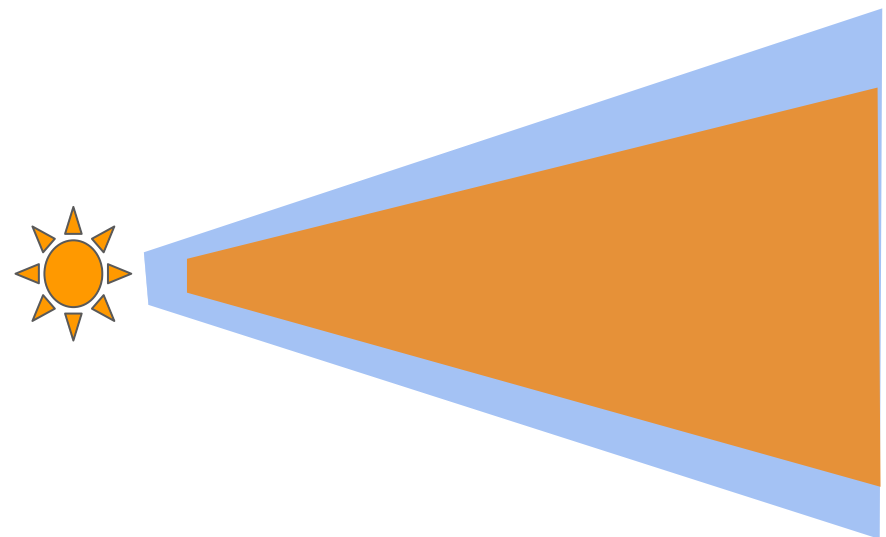
$$T(R) = T_0 \left(\frac{R}{1AU}\right)^{-0.75}$$



The observed disks are warmer than expected from simple balance of radiation and gravity.

$$T(R) = T_0 \left(\frac{R}{1AU}\right)^{-0.4--0.7}$$

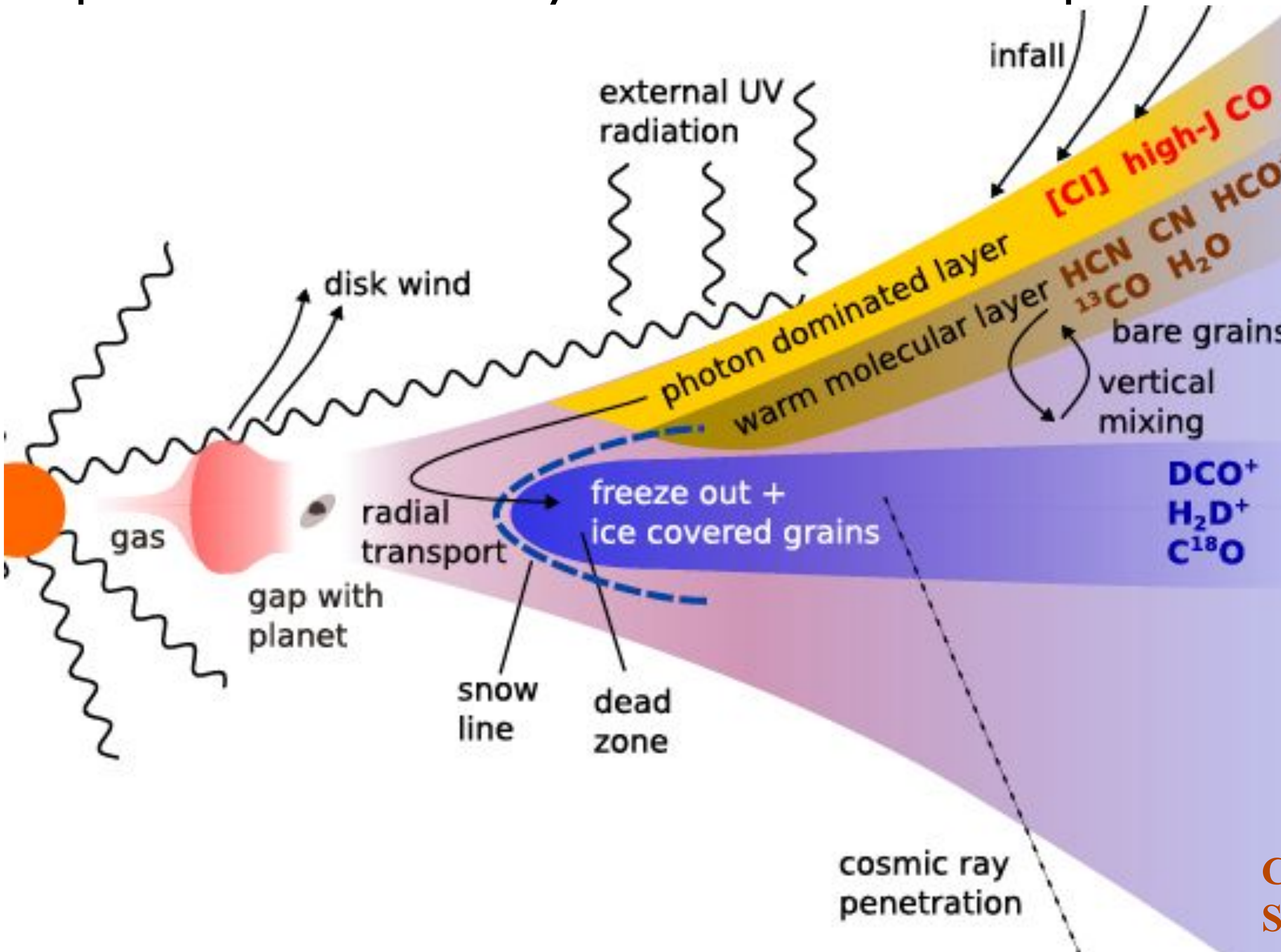
Disks must be flared and not flat.



The warm part of the disk expands into the vacuum.

Disk structure

It is very complex that is affected by internal and external processes.

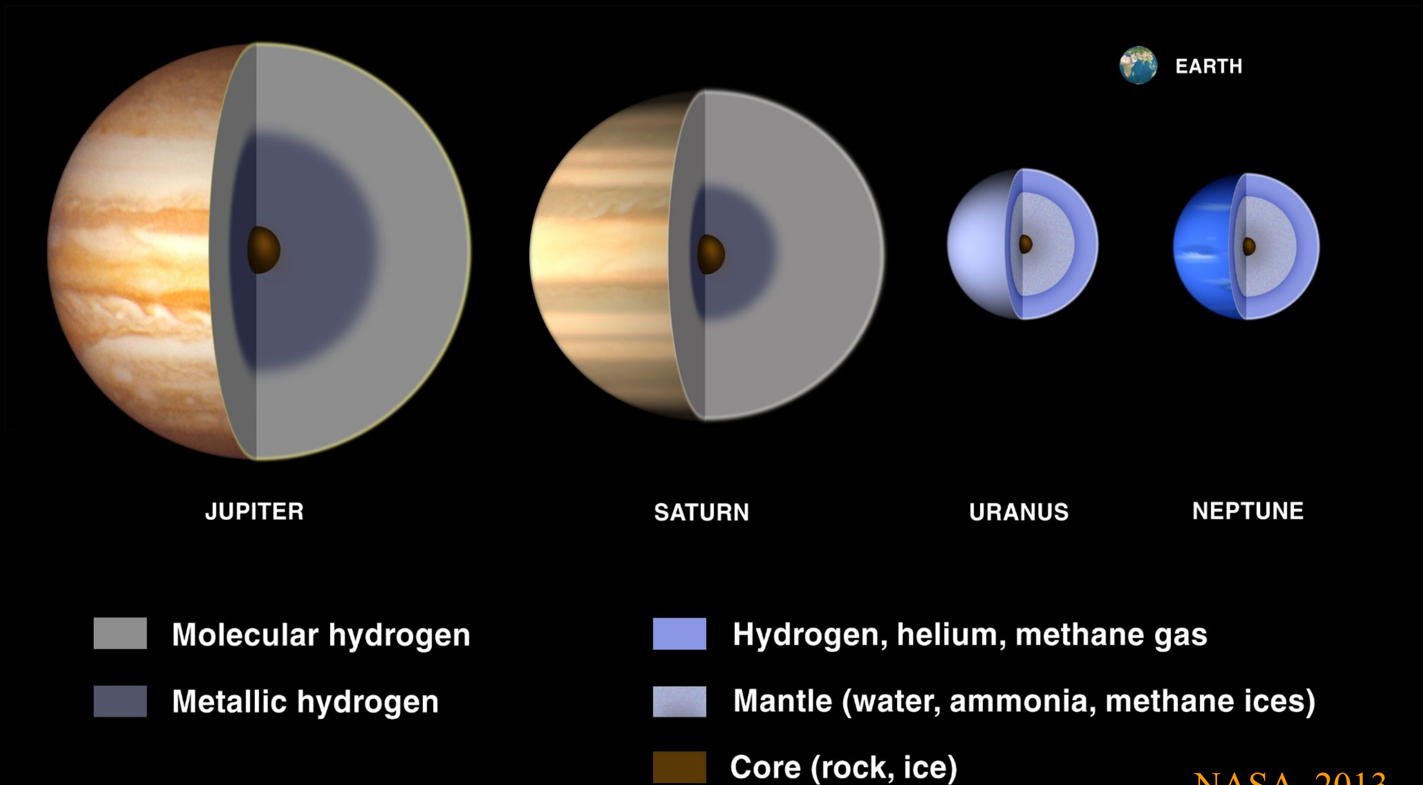


Credit:
Simon Bruderer

Disks lifetime

These planets must be formed in the gaseous disk so less than the disk age.

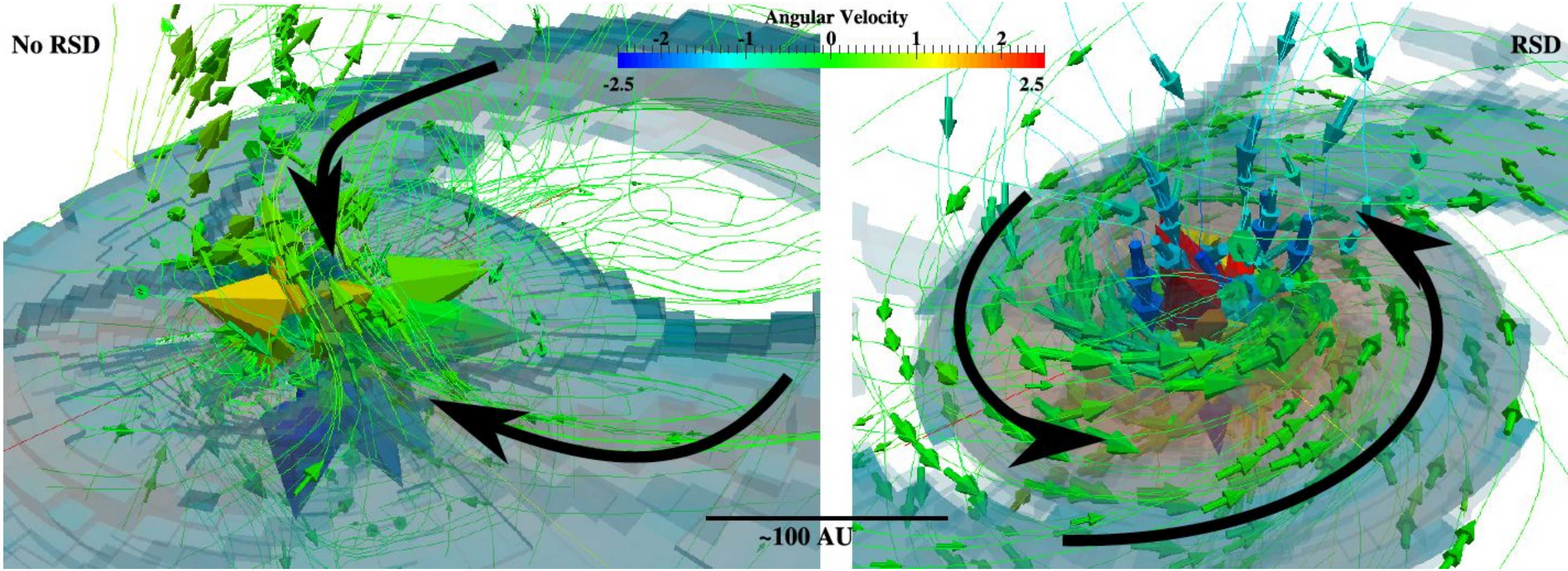
Disks lose their gas as they evolve within ~2 Myr.



NASA, 2013

Disk formation problem

Including magnetic fields, you can either form a disk that can form planets or it delays the protoplanetary disk formation.



No protoplanetary disk

Protoplanetary disk

Li+ 2013

Disk formation: Classical

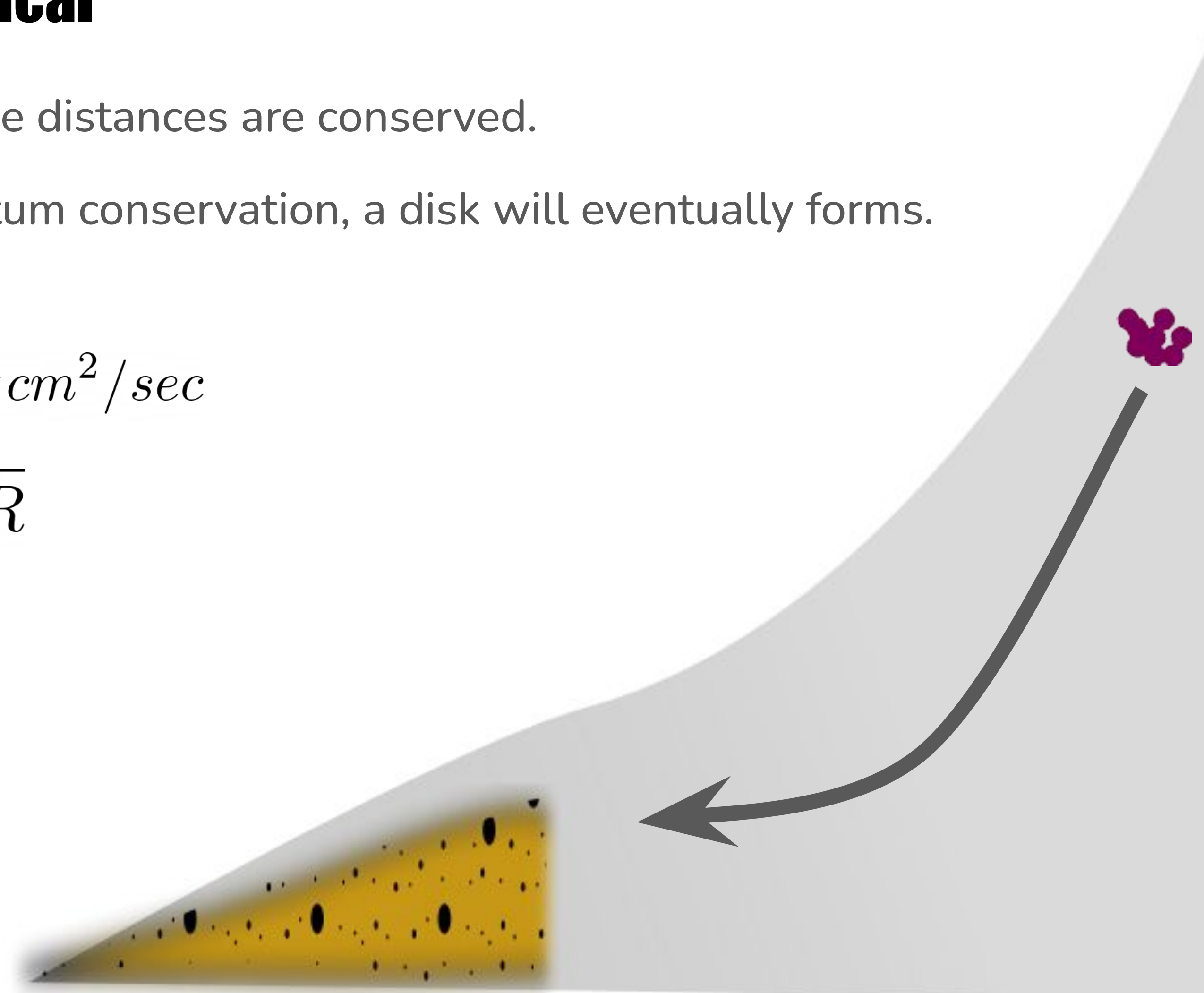
Any small rotation at large distances are conserved.

Through angular momentum conservation, a disk will eventually forms.

$$j = \Omega_{\text{core}} R_{\text{jeans}}^2 \approx 10^{21} cm^2/sec$$

$$j_{\text{Keplerian}} = \sqrt{GMR}$$

$$R \approx 10^2 - 10^4 AU$$



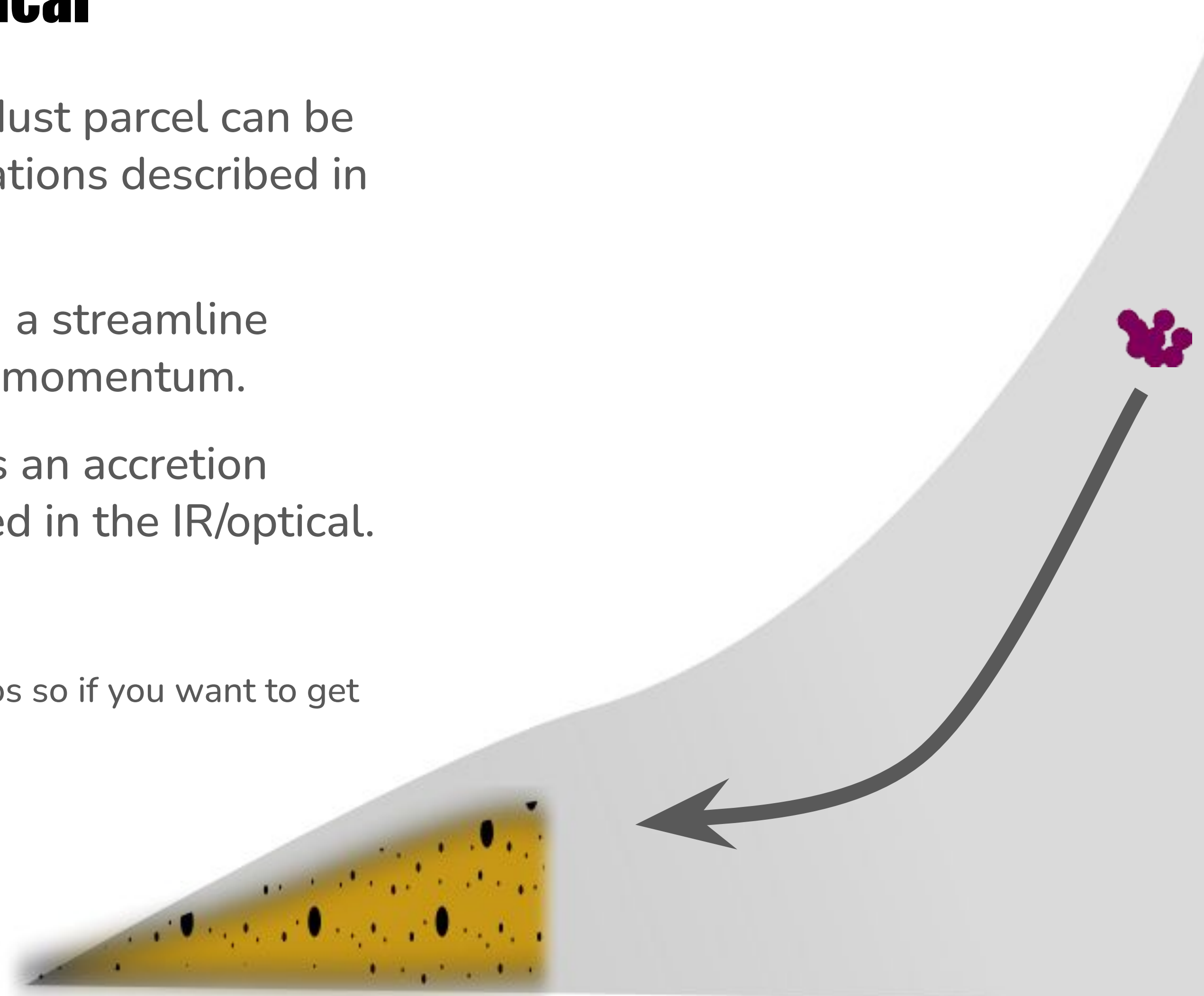
Disk formation: Classical

The motion of a gas and dust parcel can be described by a set of equations described in Ulrich 1976.

The parcel just falls along a streamline while conserving angular momentum.

It hits the disk and creates an accretion shock that can be observed in the IR/optical.

The original paper has some typos so if you want to get the right equations, you need
to solve it again.



Disk formation: Classical

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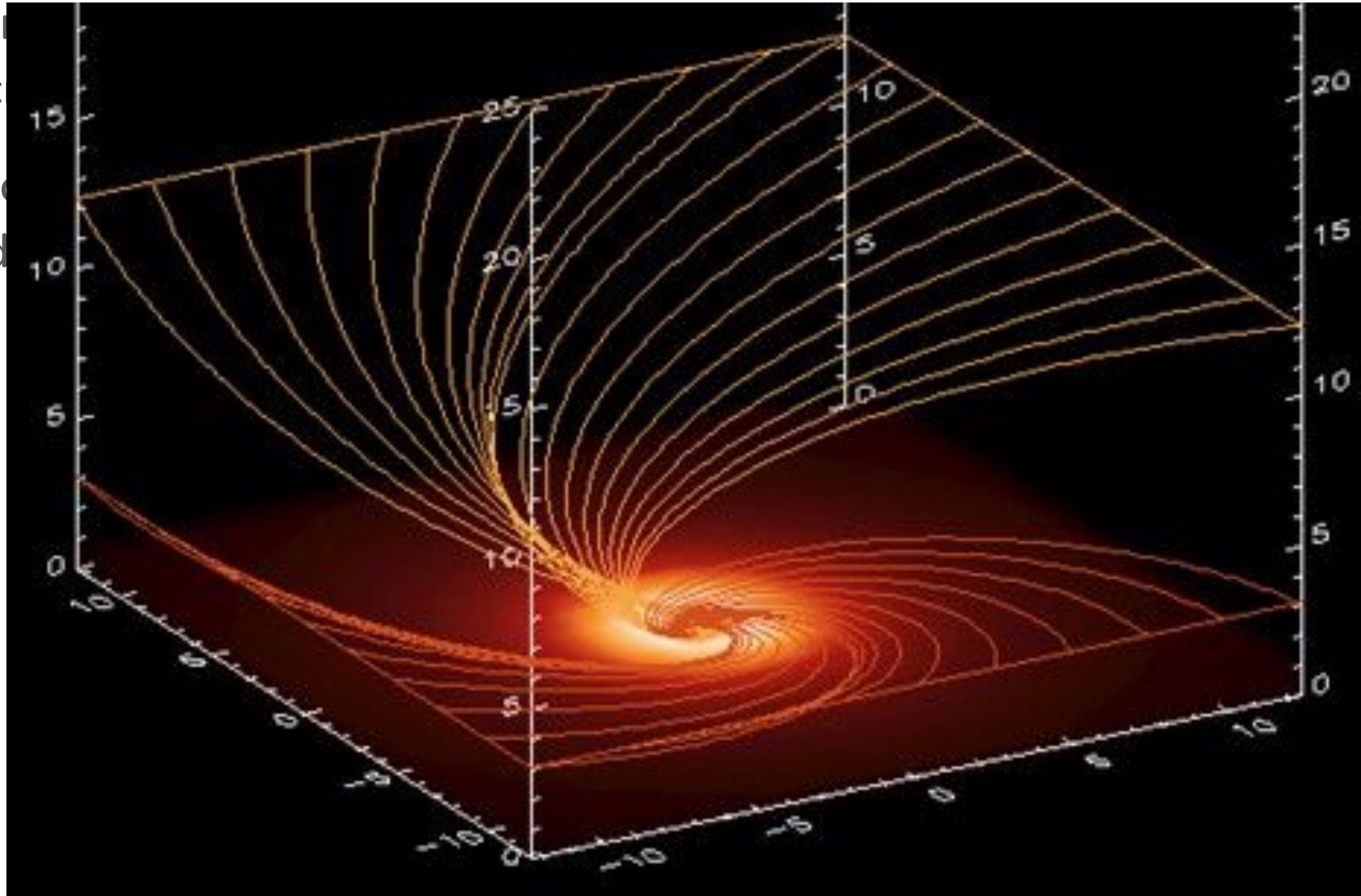
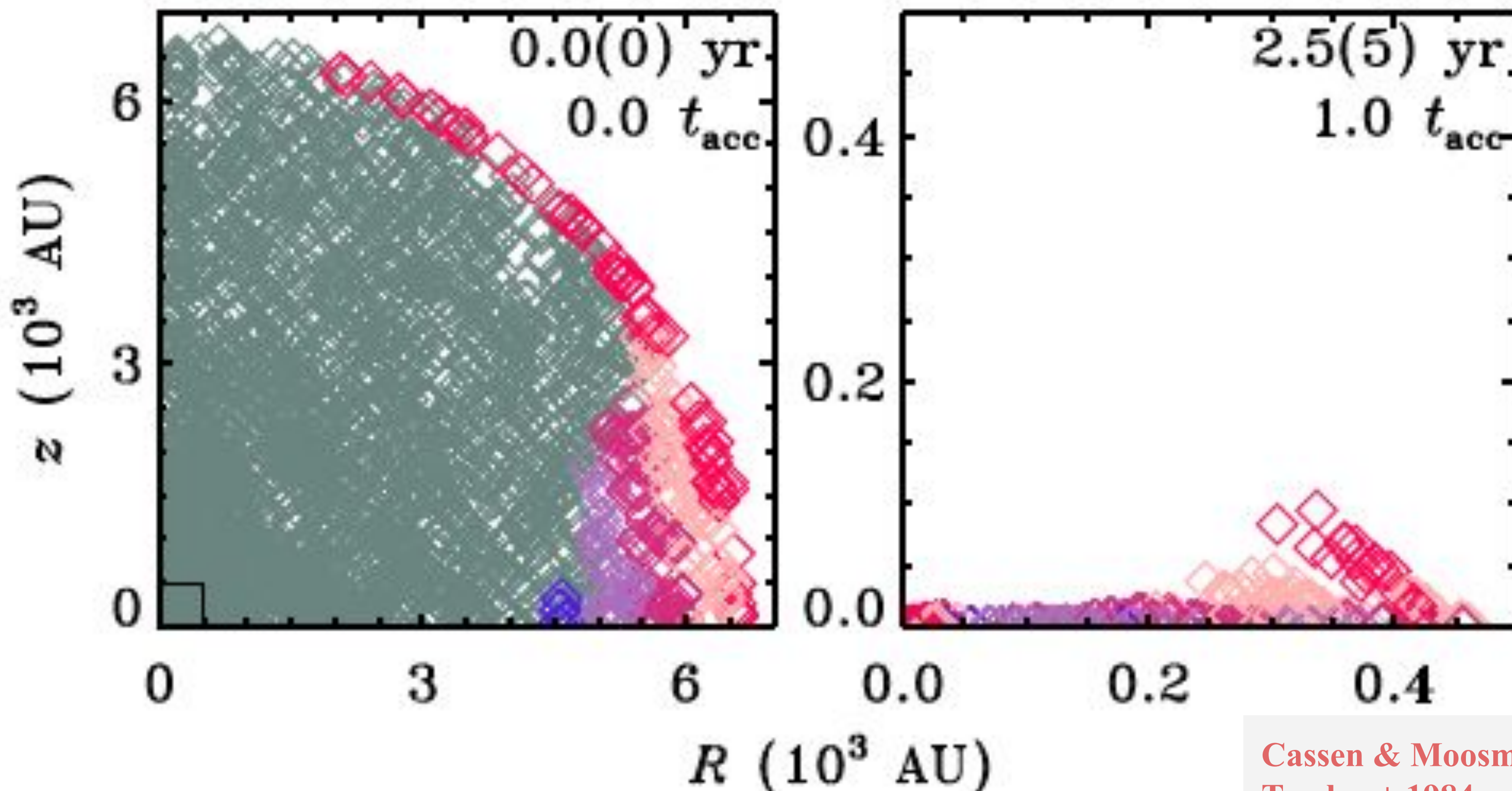


Disk formation: Classical

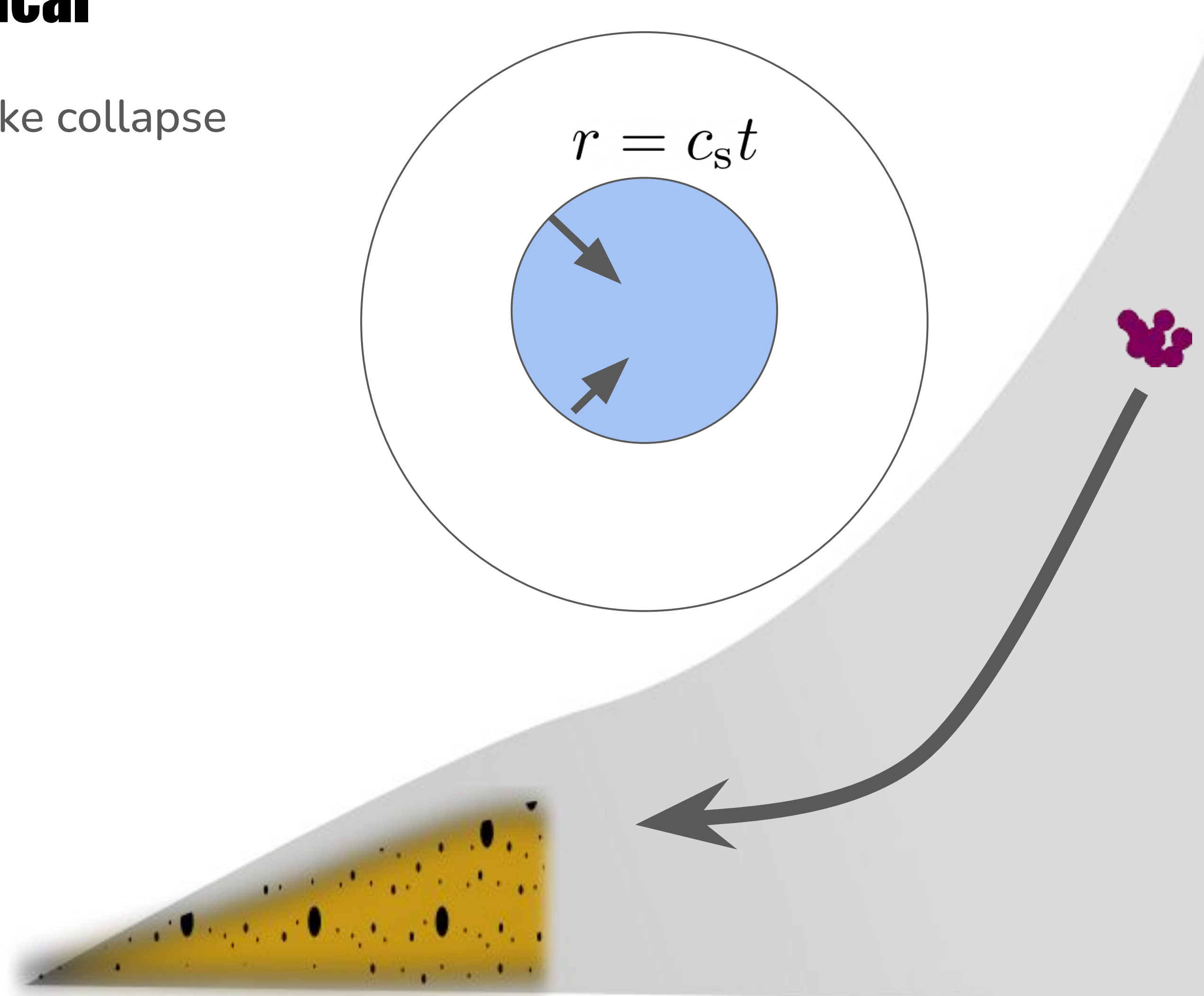
We can take a step further to simulate the whole collapse and disk formation using a set of differential equations.



Cassen & Moosman 1981
Terebey+ 1984
Visser+ 2009

Disk formation: Classical

Large-scale: isothermal-like collapse

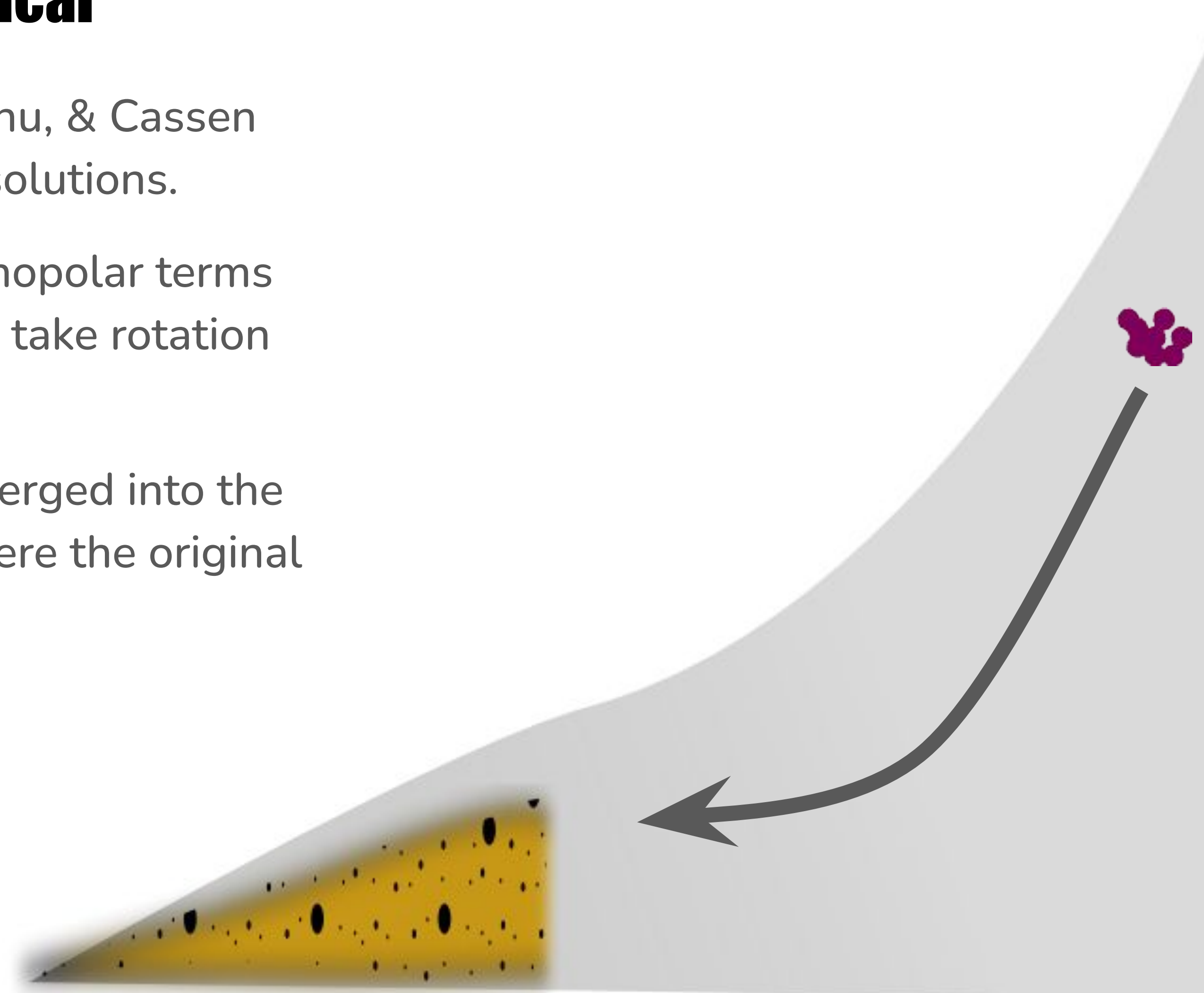


Disk formation: Classical

Medium scale: Terebey, Shu, & Cassen and Cassen & Moosman solutions.

These solutions have monopolar terms and quadrupolar terms to take rotation into account.

These solutions can be merged into the Ulrich 1976 solutions where the original solutions breakdown.

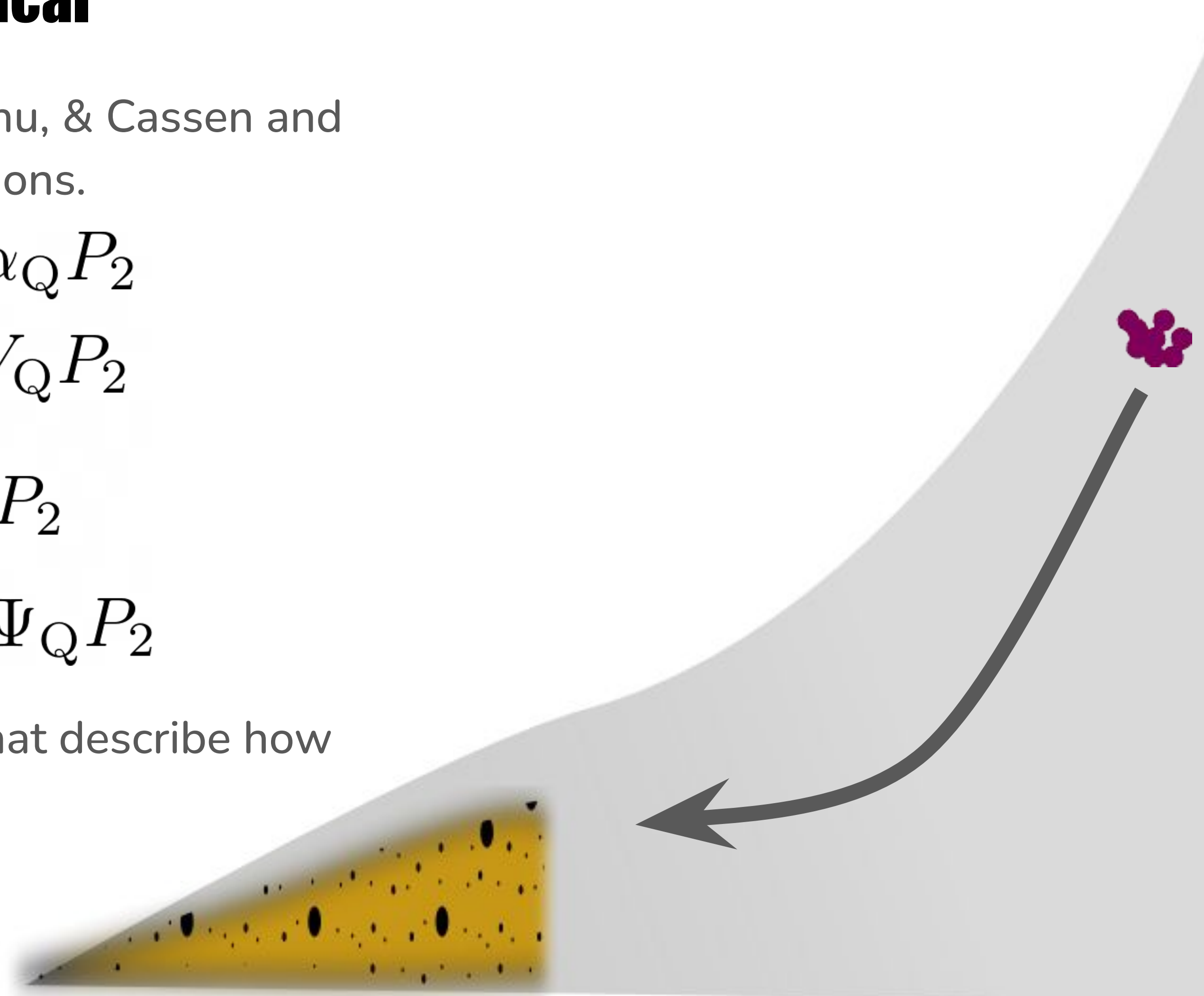


Disk formation: Classical

Medium scale: Terebey, Shu, & Cassen and Cassen & Moosman solutions.

$$
\begin{aligned}
\alpha &= \alpha_{\mathrm{M}} + \alpha_{\mathrm{Q}} P_2 \\
V &= V_{\mathrm{M}} + V_{\mathrm{Q}} P_2 \\
W &= W_{\mathrm{Q}} \frac{d}{d\theta} P_2 \\
\Psi &= \Psi_{\mathrm{M}} + \Psi_{\mathrm{Q}} P_2
\end{aligned}
$$

These are the solutions that describe how matter enters the disk.

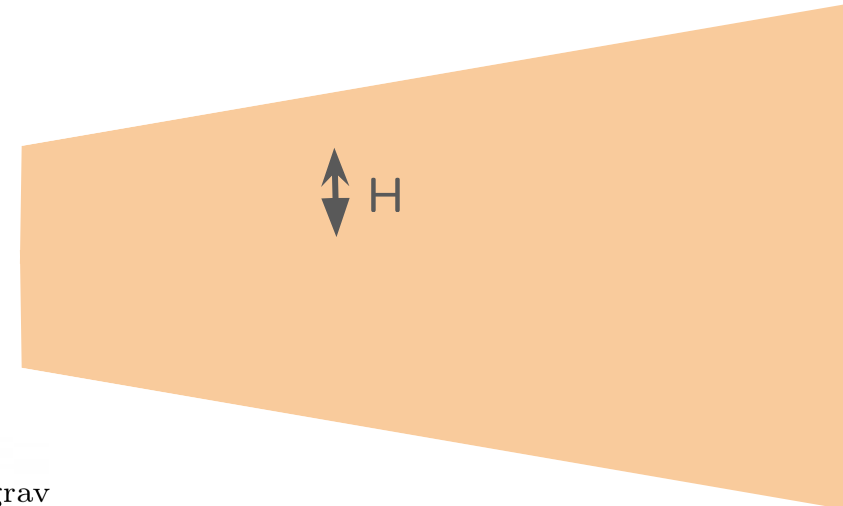


Disk motion

A very thin disk behaves such as :

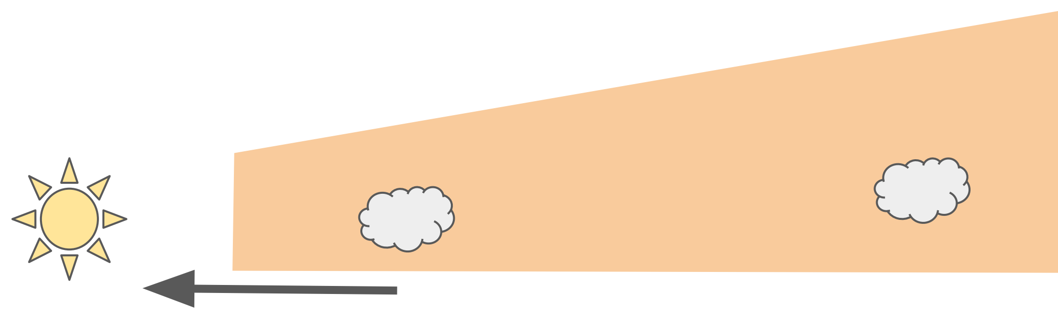
$$\partial_t \Sigma + \frac{1}{R}\partial_{\mathrm{R}} R\Sigma v_{\mathrm{R}} = 0$$

$$\partial_t \vec{v} = -\frac{1}{\rho}\vec{\nabla}\vec{P} + \eta\nabla^2\vec{v} + (\eta+\xi)\vec{\nabla}\left(\vec{\nabla}\cdot\vec{v}\right) - \nabla\Phi_{\mathrm{grav}}$$



The disk must be in equilibrium
where the gas is usually barotropic

$$c_{\mathrm{s}}^2 = \frac{dP}{d\rho}$$



Disk formation: Classical

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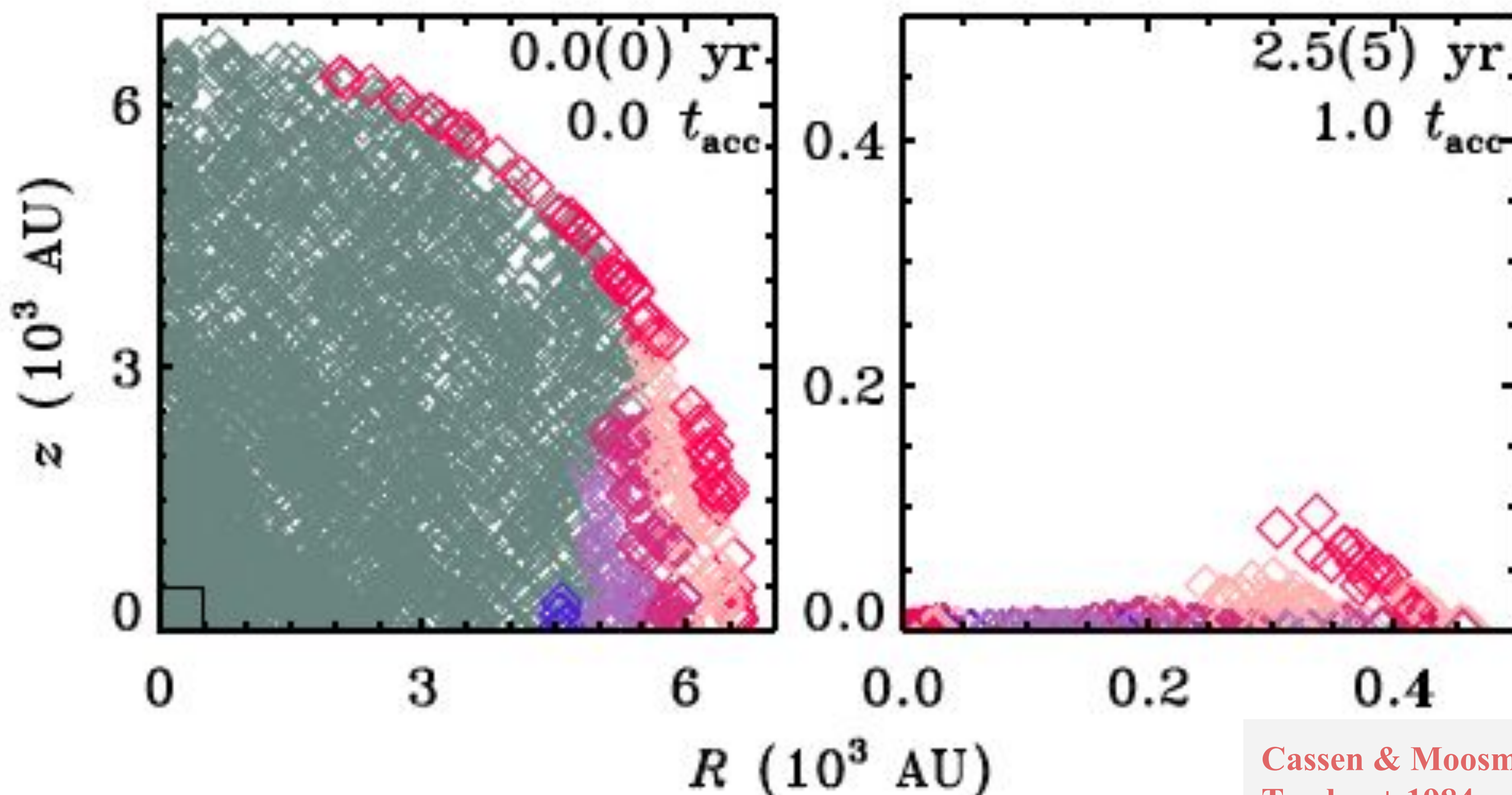
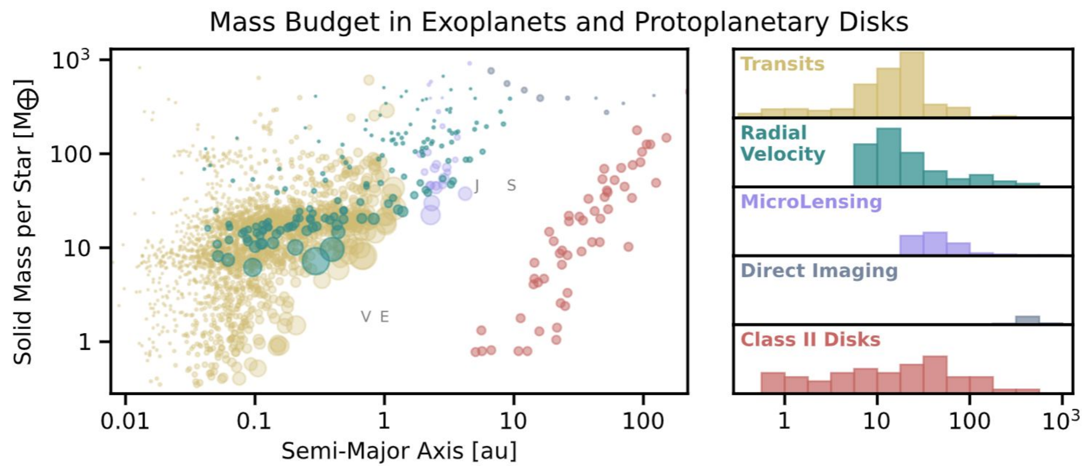


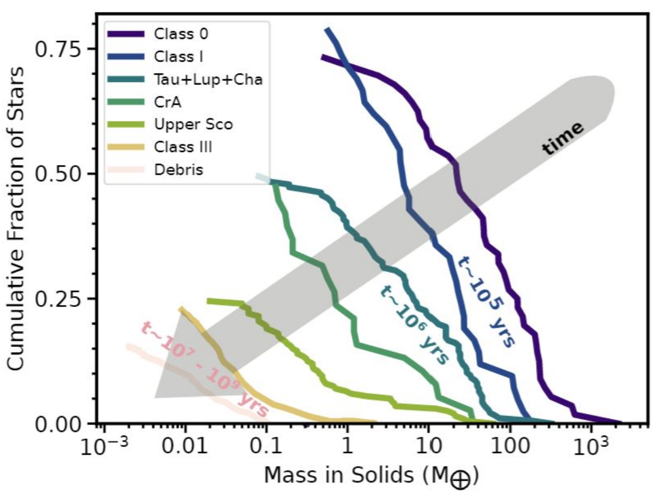
Cassen & Moosman 1981
Terebey+ 1984
Visser+ 2009

Mass budgets

We need to know how much mass can we start with.

With sub-mm telescopes, we can compare the masses of disks to planets.





Mulders+ 2020
Drazkowska+ 2022

Mass budgets

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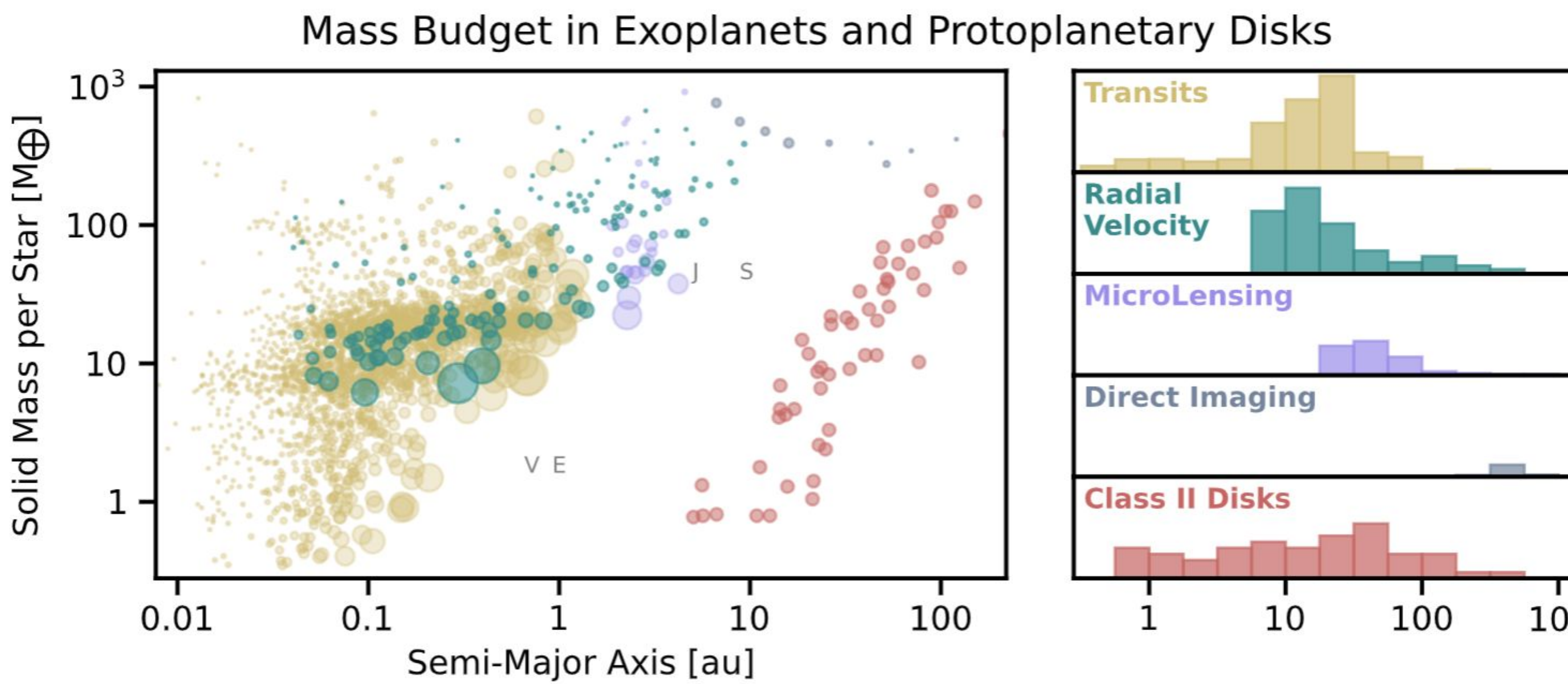
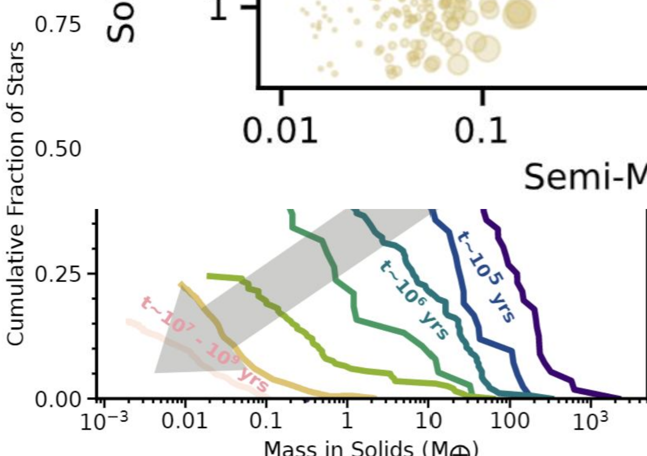
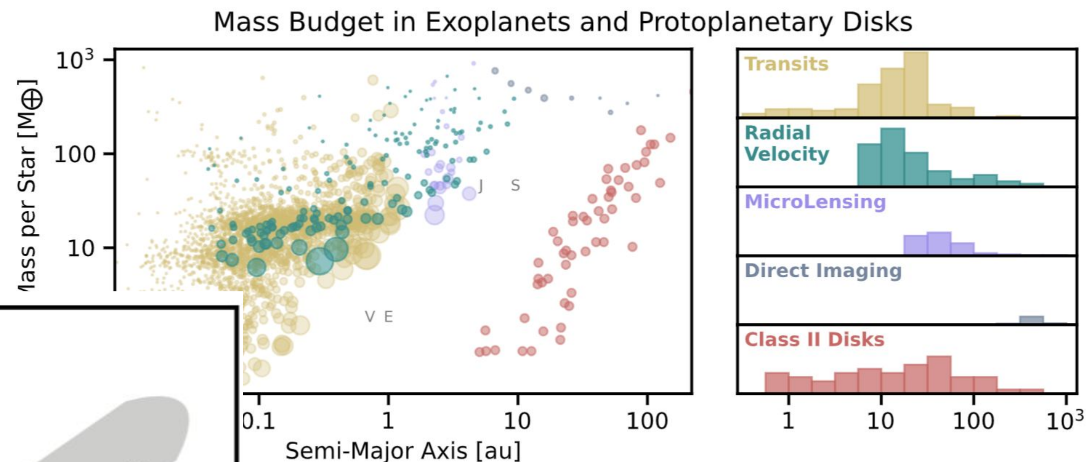


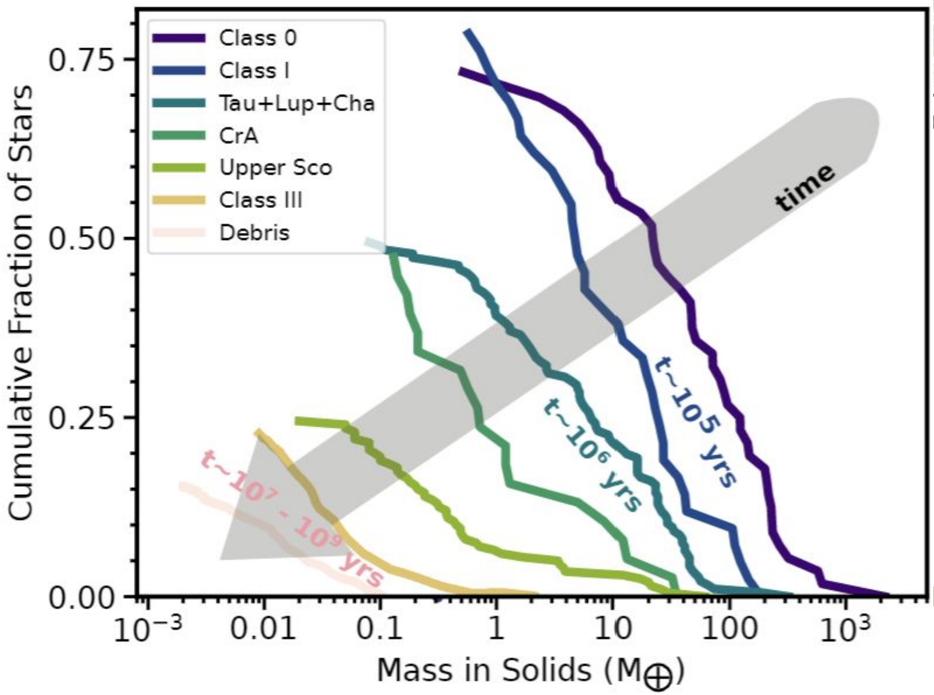


Mulders+ 2020
Drazkowska+ 2022

Mass budgets

We only have enough solid mass to form planets in the early stages of star formation.





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Interstellar ices

Dust grains coagulate and create larger dust grains

They can acquire mantles of ices as long as it is big enough with H_2O, CO, CO_2, CH_3OH, …

You can observe the ices in the infrared against dark clouds with strong IR sources.

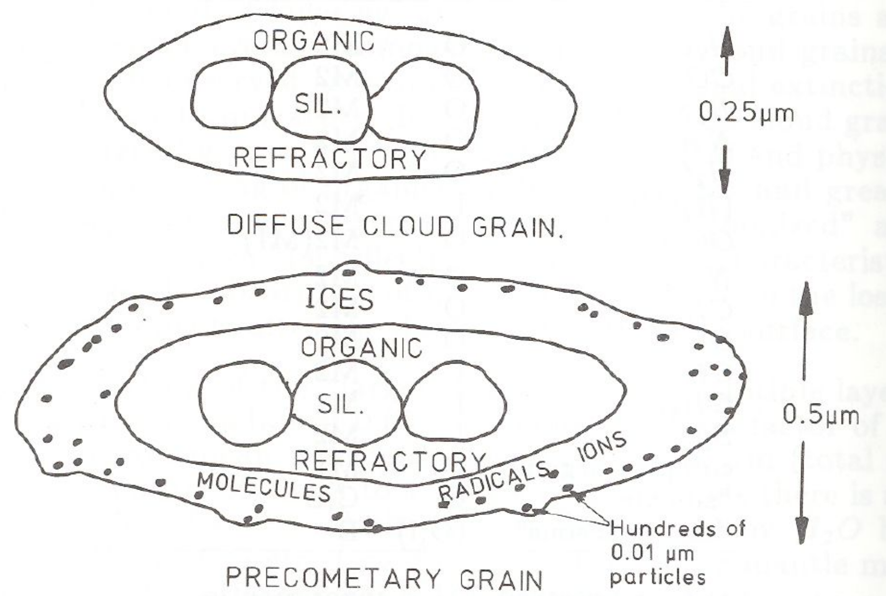


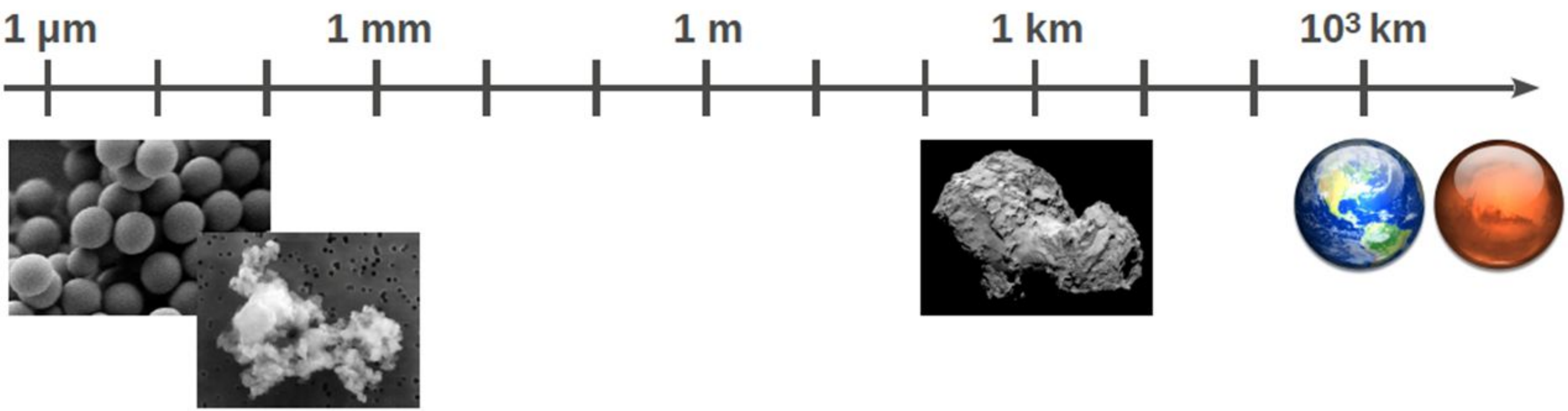
Fig. 1. Interstellar grains as core-mantle structures.

The start of planet formation

Dust grains start off at around 0.1 microns.

Smaller dust grains exist in the diffuse ISM but they tend to be iceless.

Planetesimals: small solid bodies that orbit around a star (moons, asteroids, Pluto...), they are the planetary embryos.



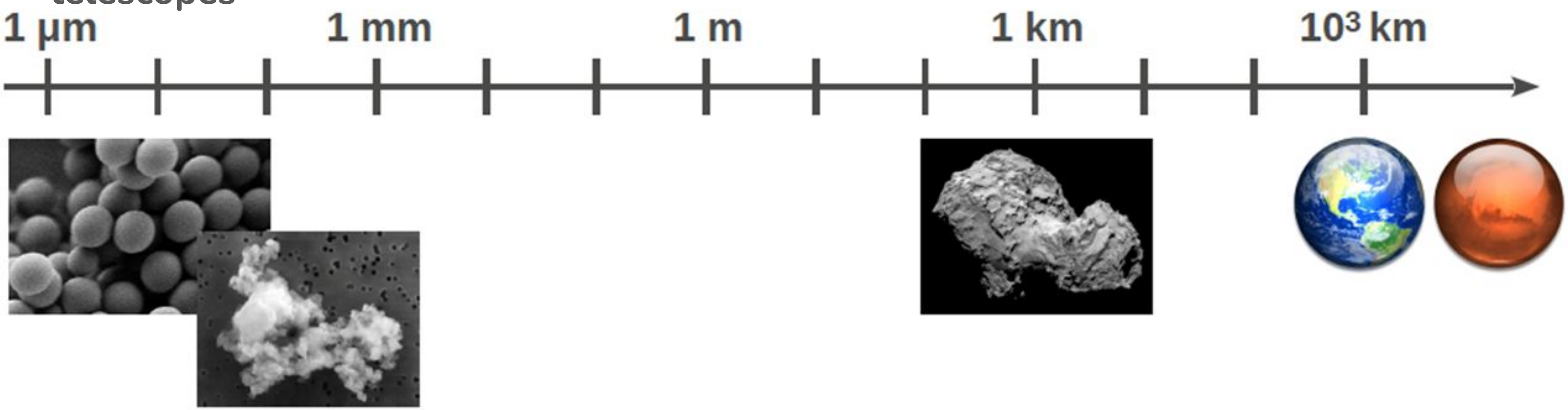
The start of planet formation

Protoplanets: large planetesimals that have heavy elements in their core and probably can hold its own atmosphere that is gaseous.

Observation with IR and sub-mm telescopes

?

30-m telescopes,



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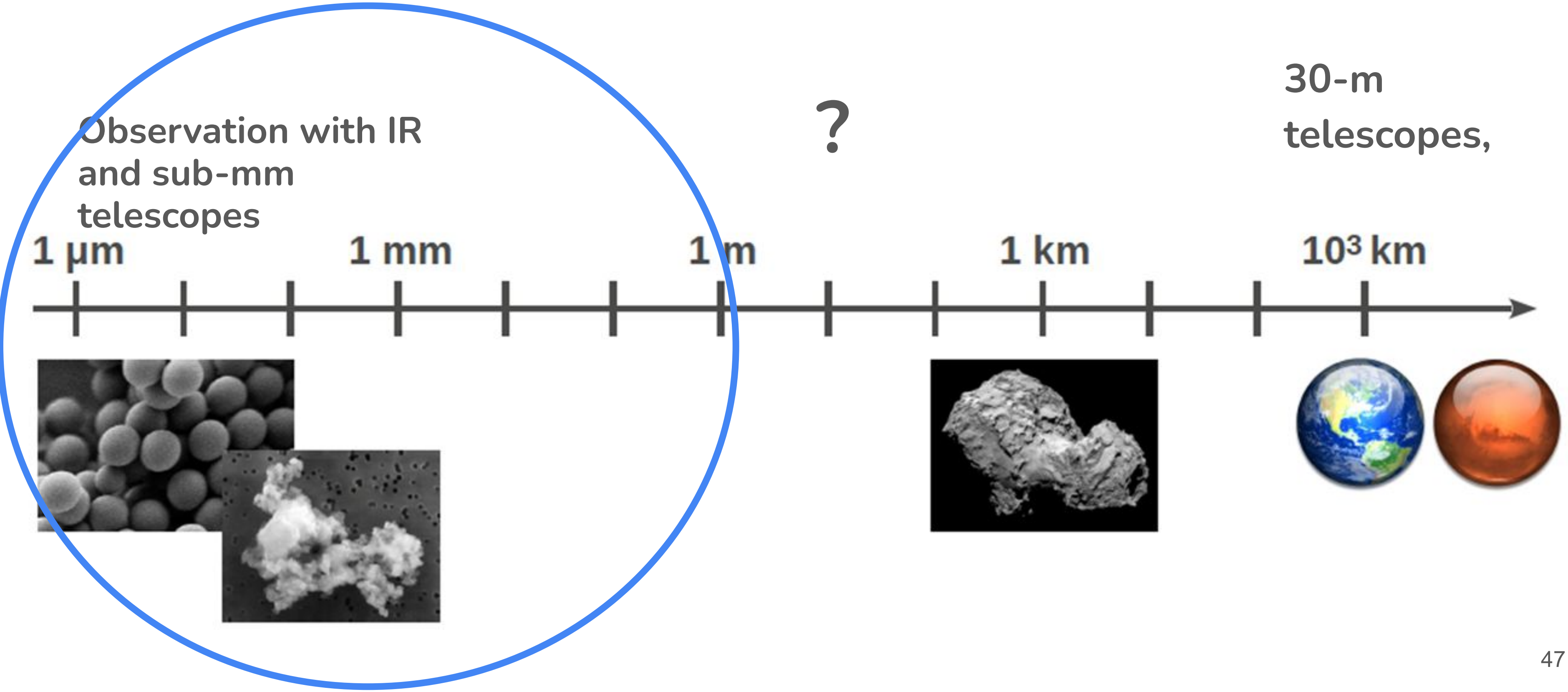
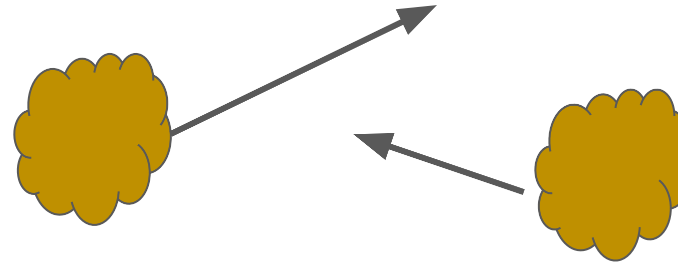


The start of planet formation

When the dust particle meets another dust particle, it can collide and merge.

This success rate of merging depends on turbulence.



$$\frac{dm}{dt} = \sigma_{\mathrm{ij}} \rho j \delta v$$

Collisional cross section that depends on the size and fluffyness

Density: particle concentrates through physical processes

Collisional speed: turbulence and location of merging in the disk: merging, fragmentation, bouncing

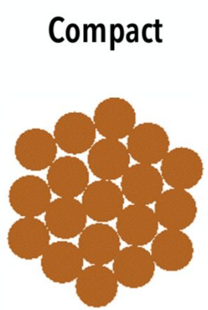
The start of planet formation

This growth produced by aggregation of monomers (the smallest grain)

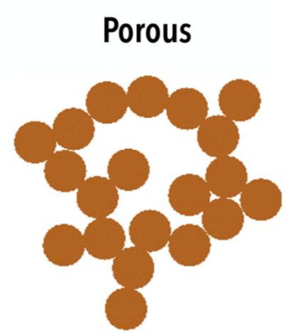
The size over mass increases with each aggregation.

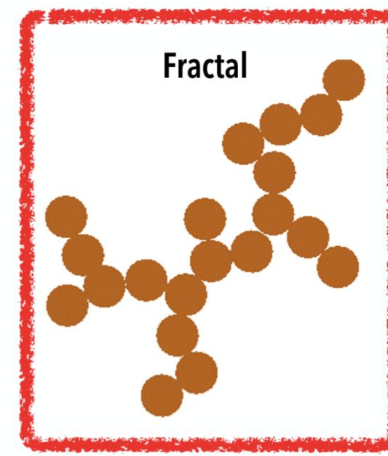
High size/mass -> not easy to settle

Floats in the gas



Low size/mass -> settles

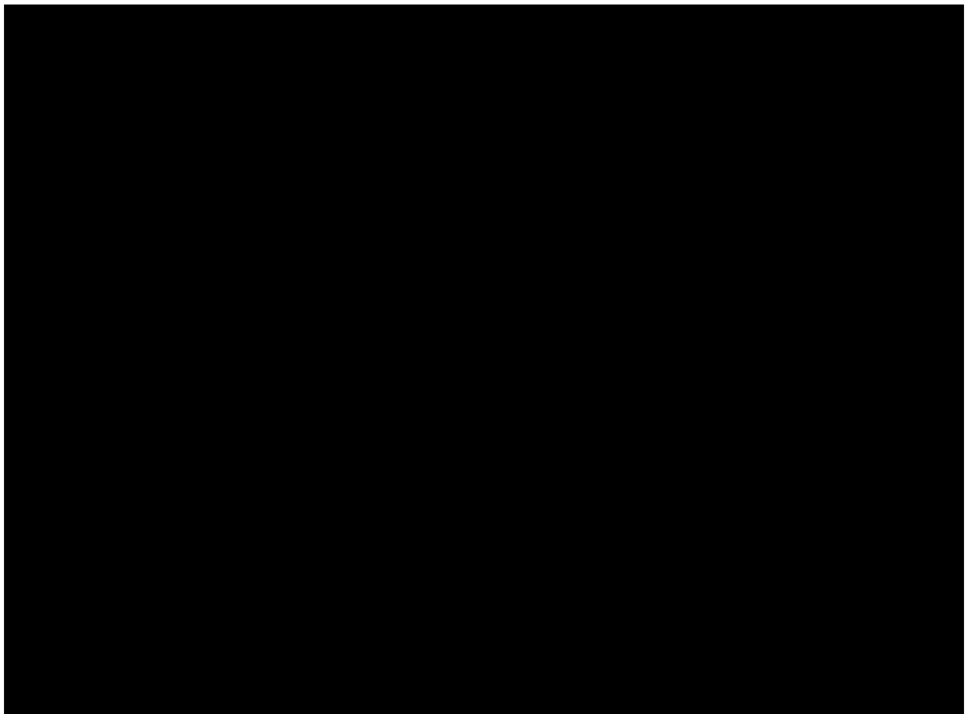


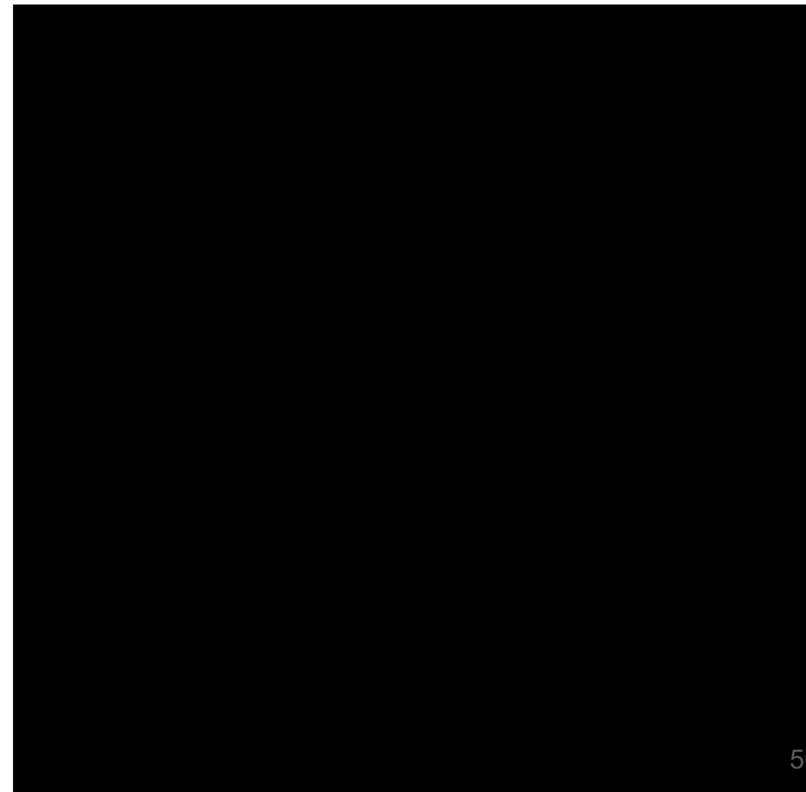


The start of planet formation

For small particles, we know that they can stick.

These are from drop towers experiments and flying experiments.

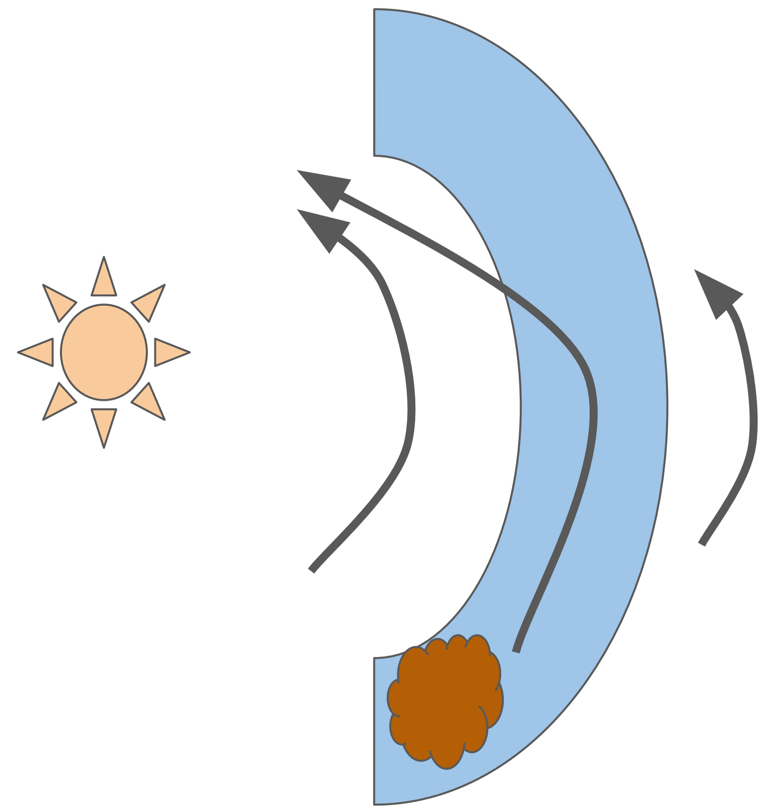




Problem of drifting

Dust grains interact with the gas in the disk.

The gas drags the dust grains to slower velocities so that they fall into the star.

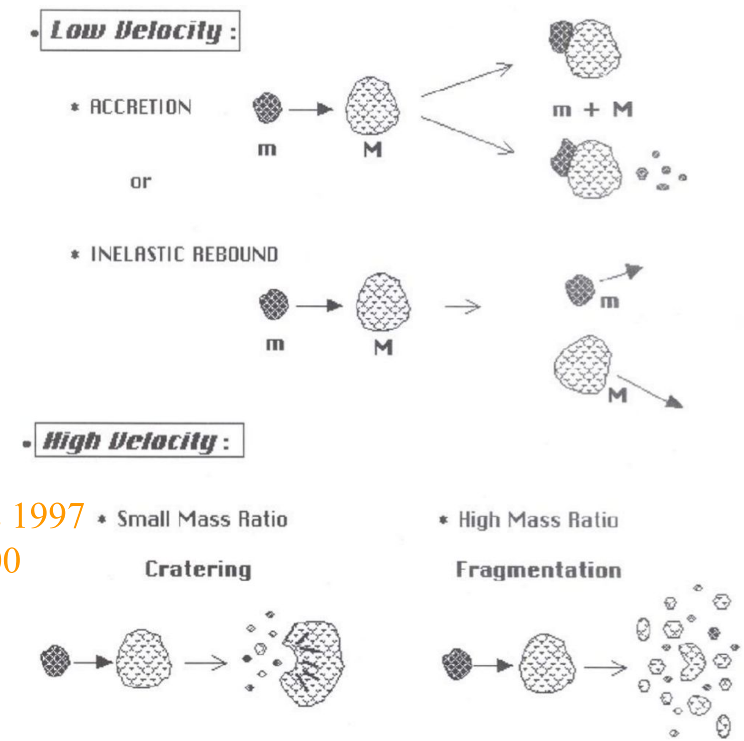


$$F_{\mathrm{drag}} = 0.5 C_{\mathrm{D}} \pi a^2 \rho V^2$$

$$t_{\mathrm{stop}} = \frac{mv}{F_{\mathrm{drag}}}$$

The start of planet formation

The outcome depends on the velocity and the differences between the two particles that are colliding.



Dominik & Tielens 1997
Blum & Wurm 2000
Beckwith+ PPIV

Sticking (*total mass gain*)

Mass transfer (*some mass gain*)

Bouncing (*neutral*)

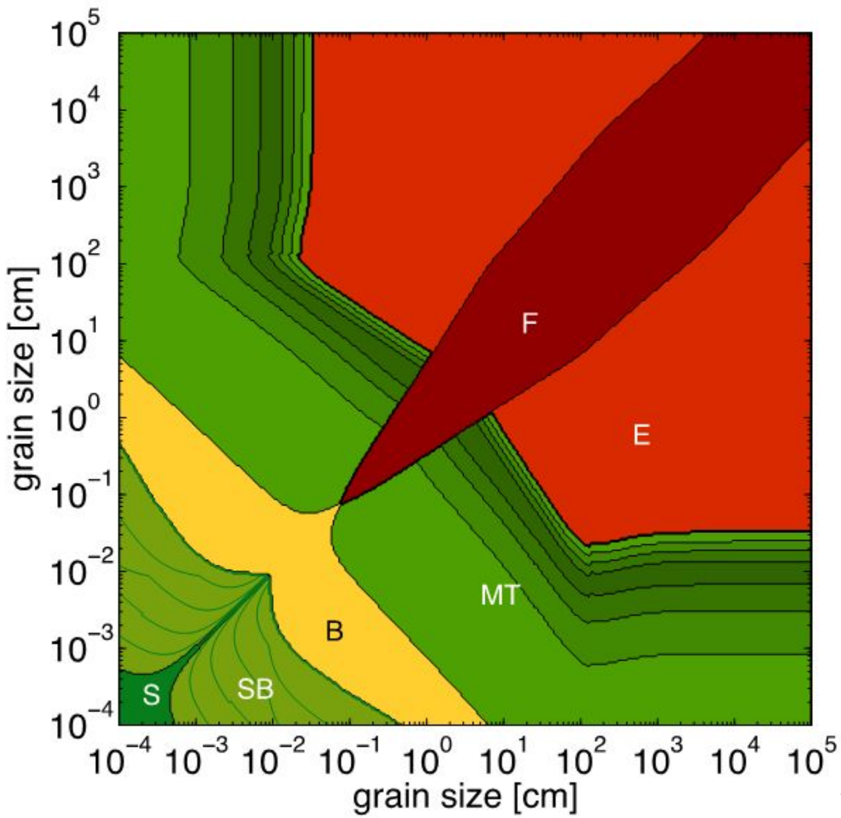
Cratering (*some mass loss*)

Fragmentation (*catastrophic mass loss*)

The start of planet formation

The outcome depends on the velocity and the differences between the two particles that are colliding. Everything is stuck at 1 m.

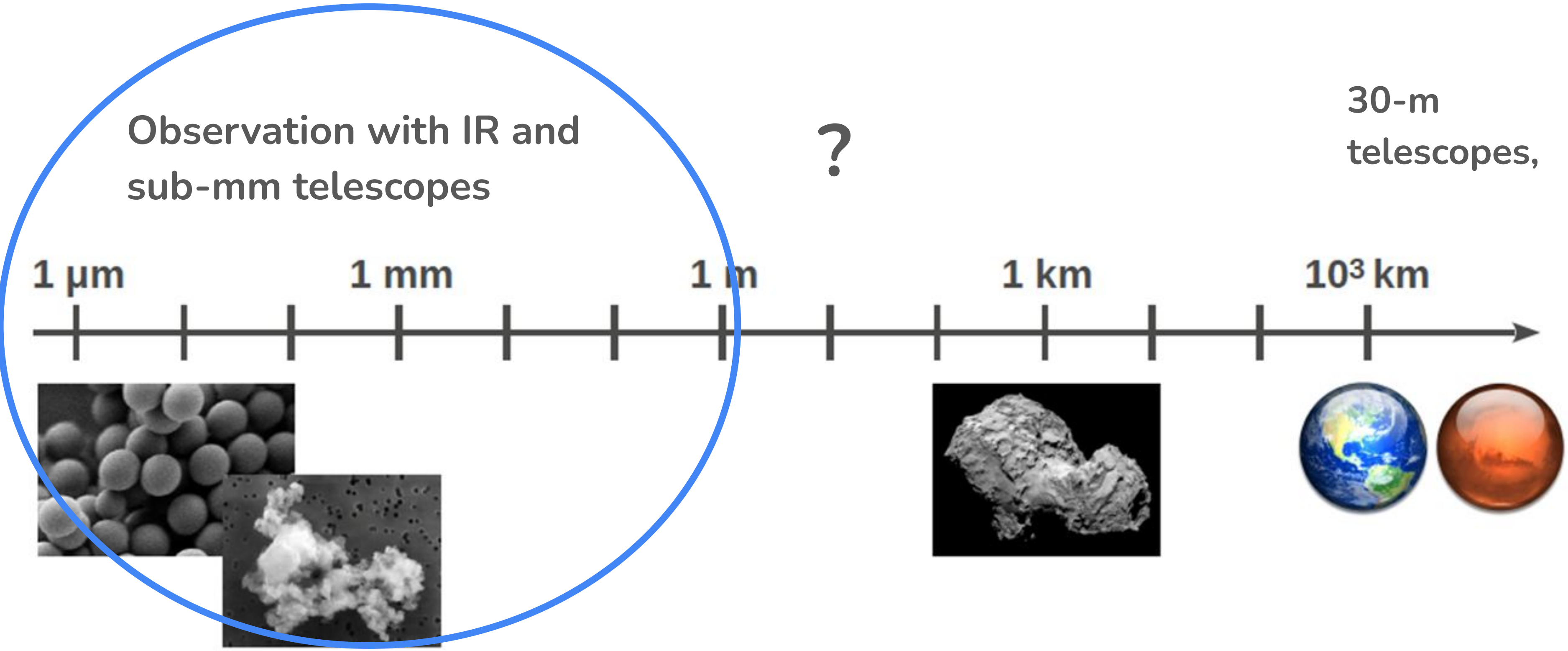
Sticking (S)
Bouncing (B)
Mass Transfer (MT)
Fragmentation (F)
Erosion (E)



Dominik & Tielens 1997
Blum & Wurm 2000
Beckwith+ PPIV

The start of planet formation

Protoplanets: large planetesimals that have heavy elements in their core and probably can hold its own atmosphere that is gaseous.



Problem of settling

Dust grains fall due to the gravity of the disk.

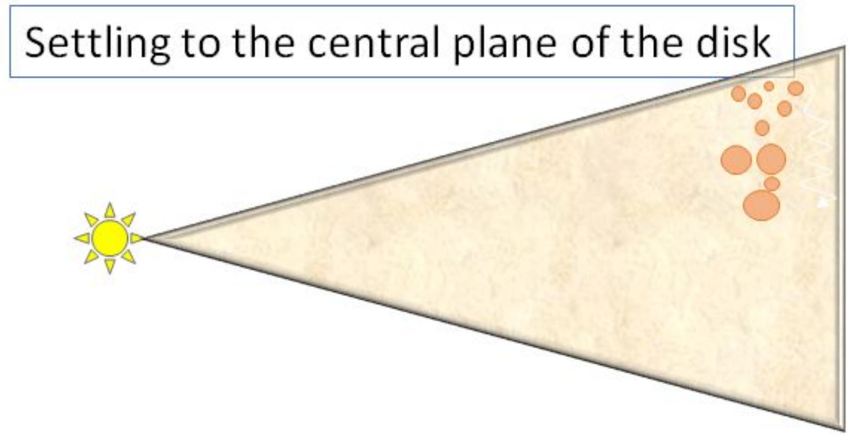
They settle to the midplane of the disk.

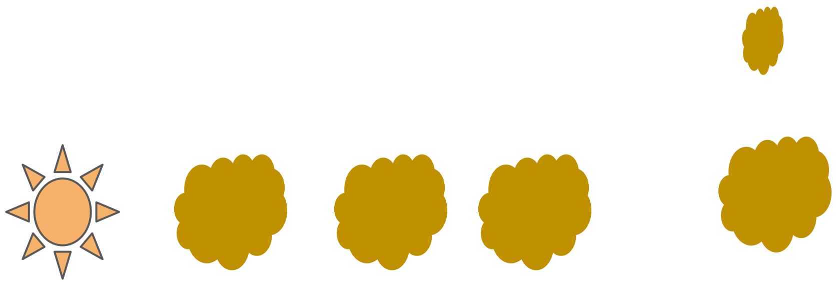
$$t_{\mathrm{settle}} \approx \frac{H}{v_{\mathrm{set}}} \approx \frac{1}{\Omega^2 t_{\mathrm{stop}}}$$

For typical disks,

1 cm dust: 100 years

1 micron: 10^6 years





Problem of drifting

We know settling is fast so the problem is back to the radial component.

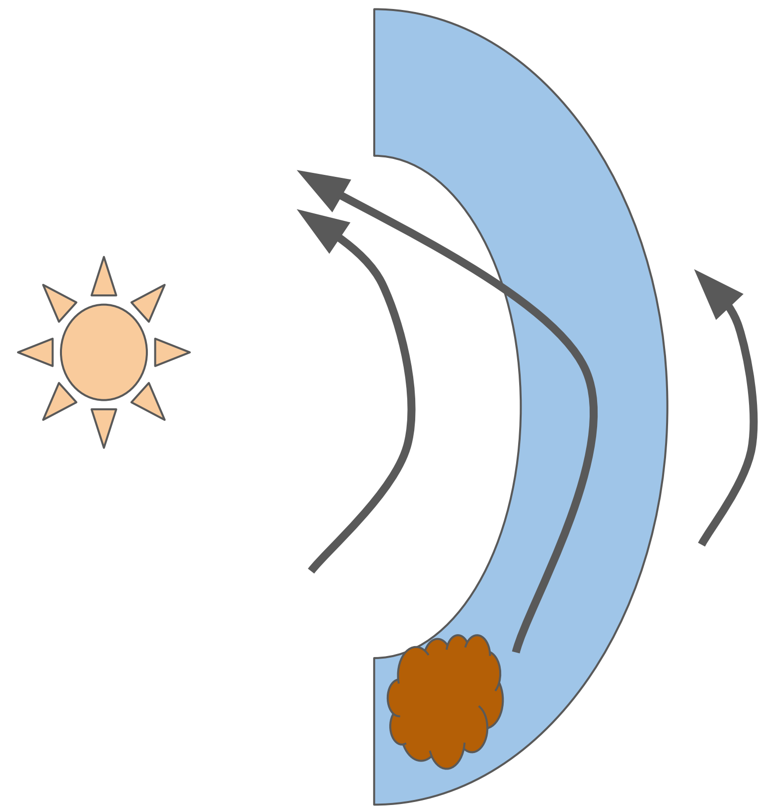
Can the dust survive?

Small grains: coupled to gas

$$t_{\text{stop}} << \frac{1}{\Omega}$$

Large grains feel the headwind so it gets slowed down more...

$$t_{\text{stop}} >> \frac{1}{\Omega}$$



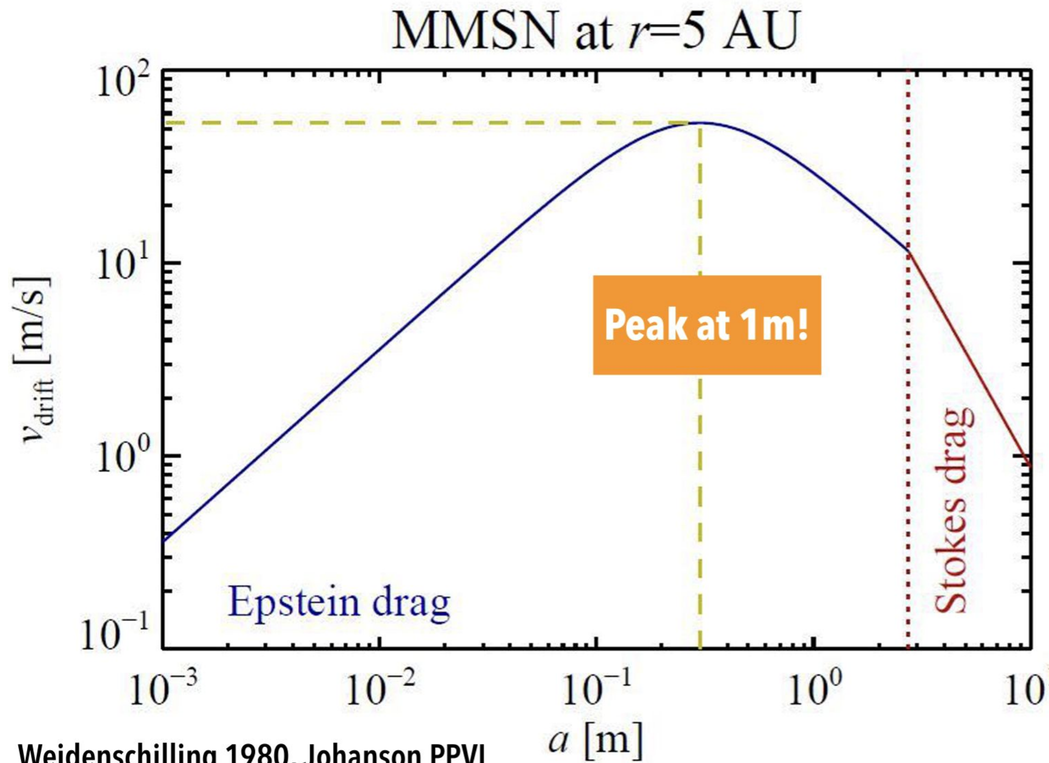
Problem of drifting

Drift velocity is maximum at 1m.

So, this is called the meter-size problem because no grains can grow beyond 1 meter.

$$V_{\mathrm{drift}} = \frac{-2\Delta V}{\Omega t_{\mathrm{stop}} + (\Omega t_{\mathrm{stop}})^{-1}}$$

Any 1 meter dust grain will be lost within 100 -- 1000 years at 1 AU.



Weidenschilling 1980, Johanson PPVI

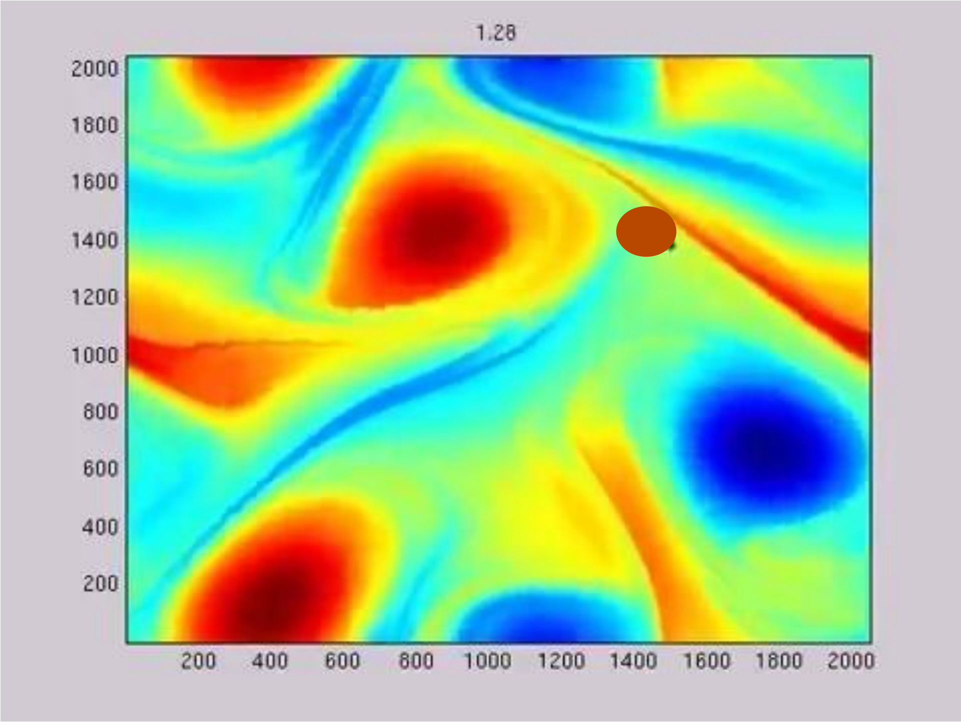
Pressure trapping

This is the pressure in the gas.

Dust particle as shown in black tends to follow the gas pressure.

Dust particles tend to be stuck at high pressure environment and cannot get out.

In this region, the velocity difference between two grains are small so they can grow.



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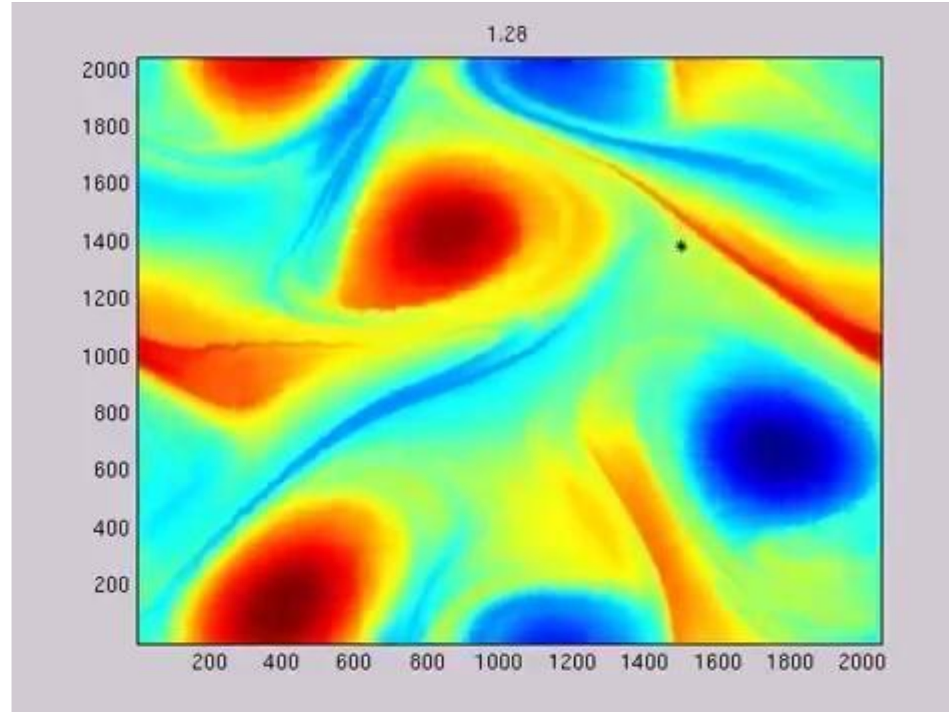


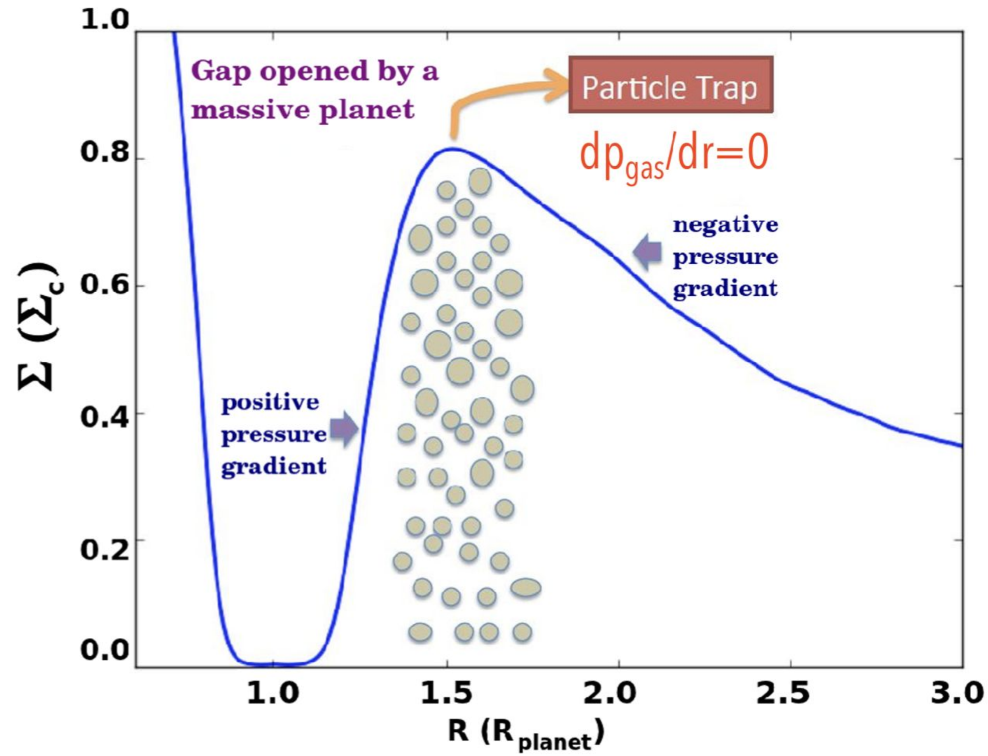
Pressure trapping

A companion or a planet can create a gap in the disk.

The gap means that there is a huge gas pressure difference between the outside and inside.

Large dust grain will be trapped inside of this pressure bump.

Causes: snowline, zonal flows, and hydro instabilities



Whipple 1972
Pinilla et al. 2012

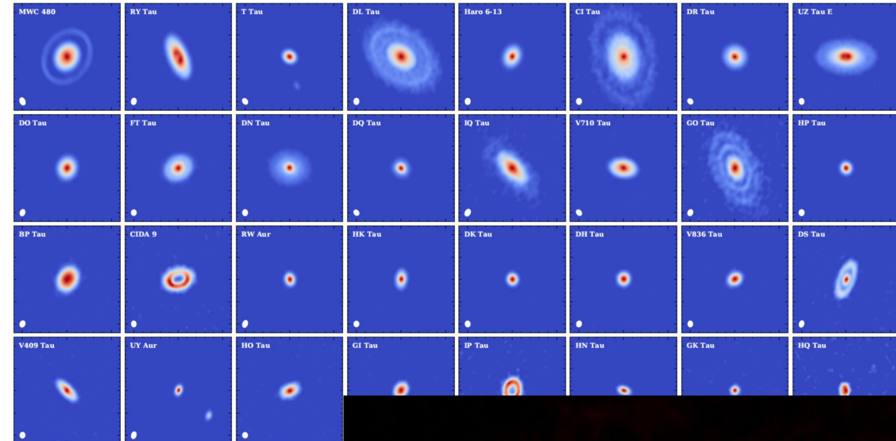
Pressure trapping

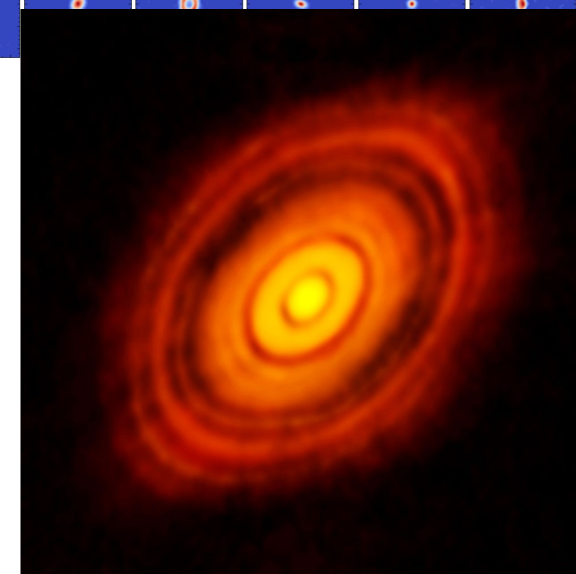
We see a lot of gaps in disks with ALMA.

This is an evidence of ongoing planet formation that leads to overcoming the meter-size barrier.

ALMA cannot see meter size bodies and it will be difficult to see such big bodies in observations.

A depletion of small grains mean that a large one must be there -> indirect.



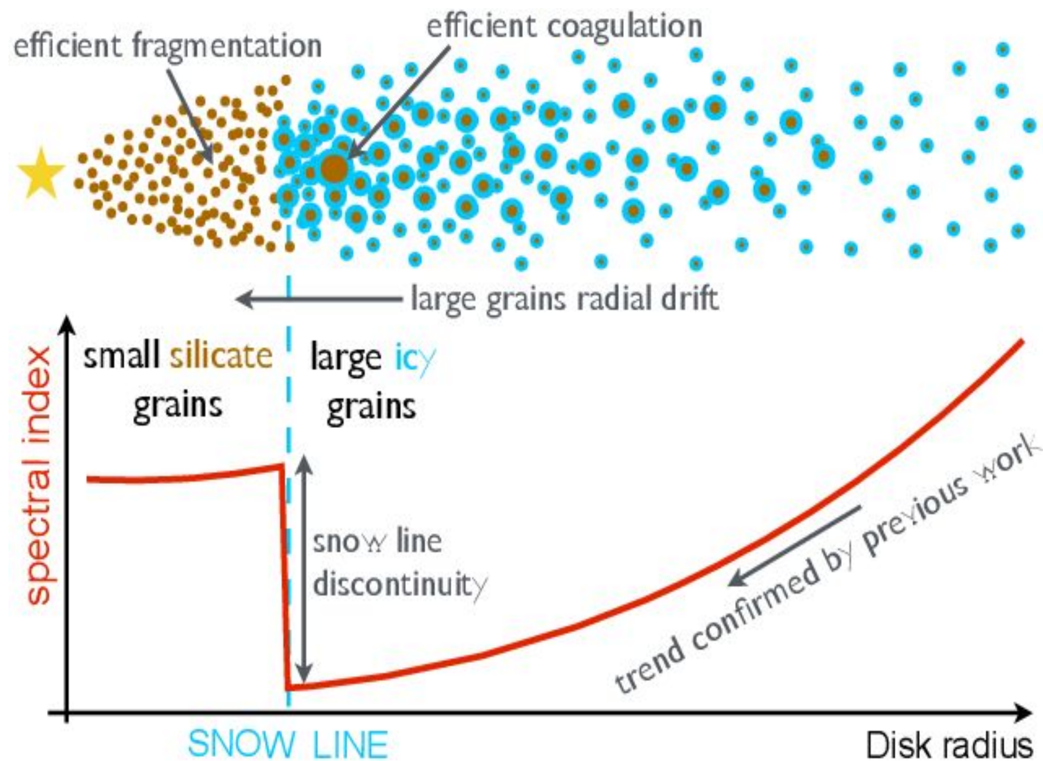


Pressure trapping: snowline

Snowlines refer to a region or a line where the temperature is high enough for ices to evaporate.

Since the ices evaporate, the gas pressure increases in total and this slows down the migration of dust grains and let them grow.

Water snowline is very important for this mechanism at < 1 au.



Banzatti+ 2015

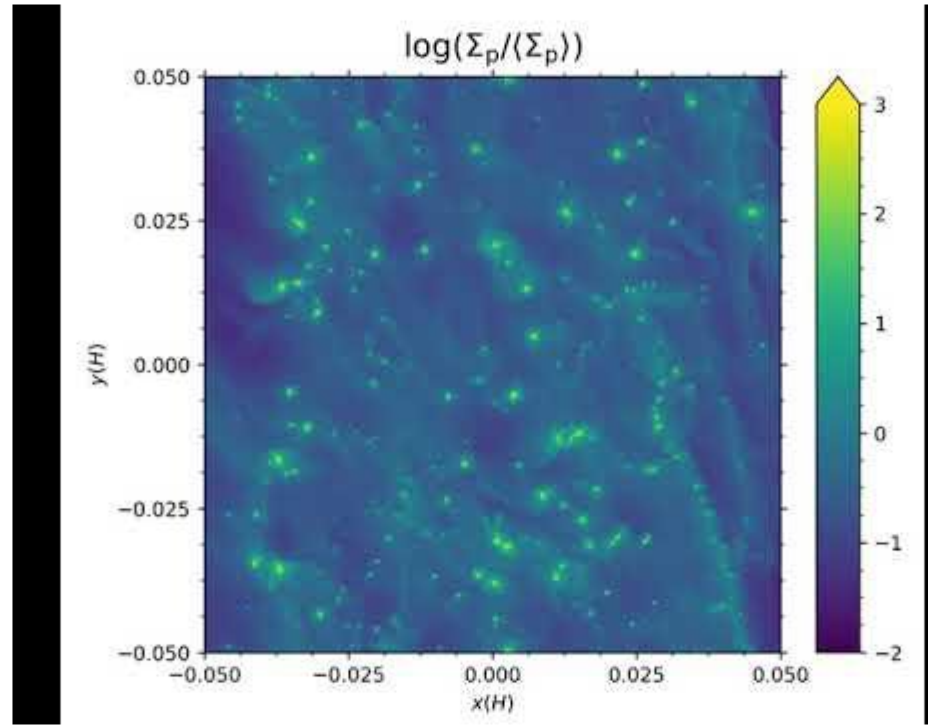
Streaming instability

In the midplane, the dust mass is so large compared to the gas.

Dust can clump and collapses like the Jeans mass idea.

This leads to instabilities to the flow of the gas and lead to higher concentration of dust grains.

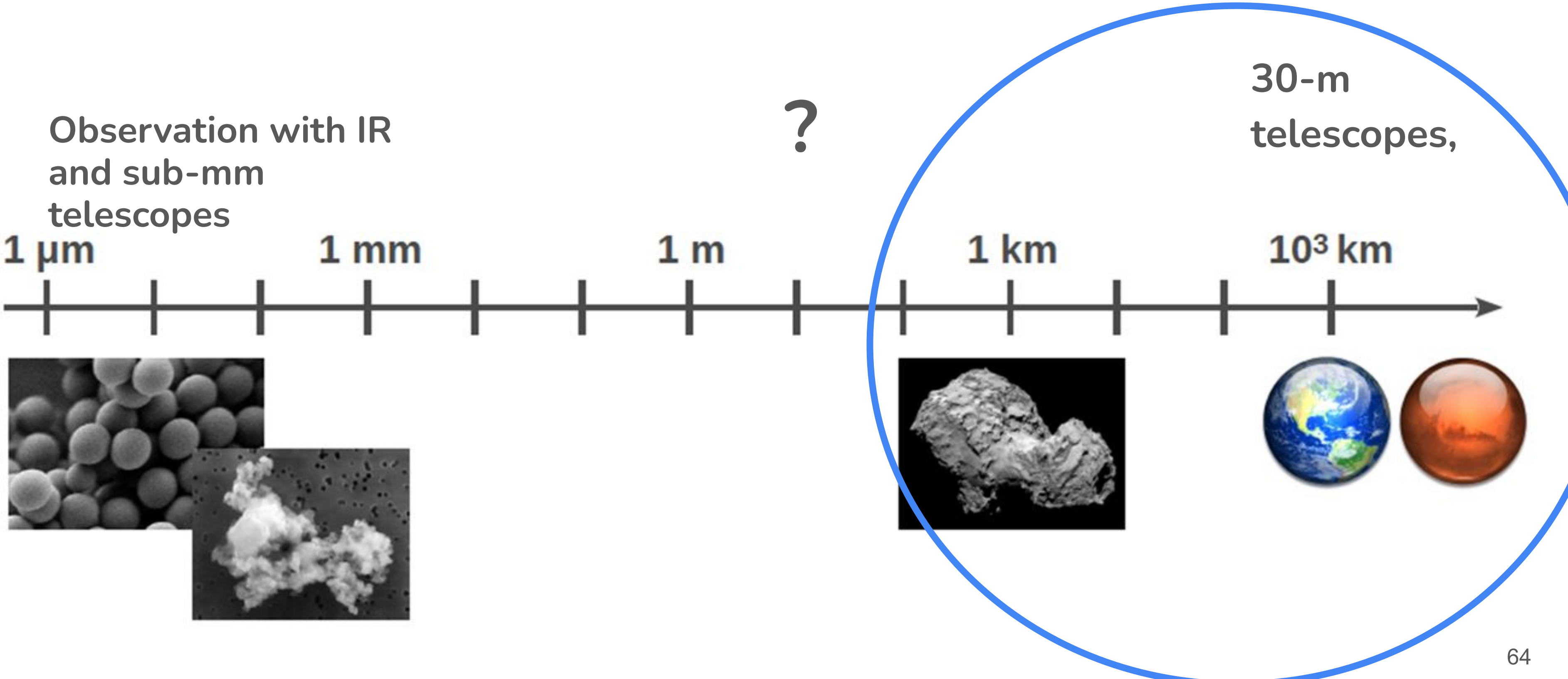
Streaming instability can easily form Earth or Neptune like planes.



Nesvorny+
Johansen+ 2014

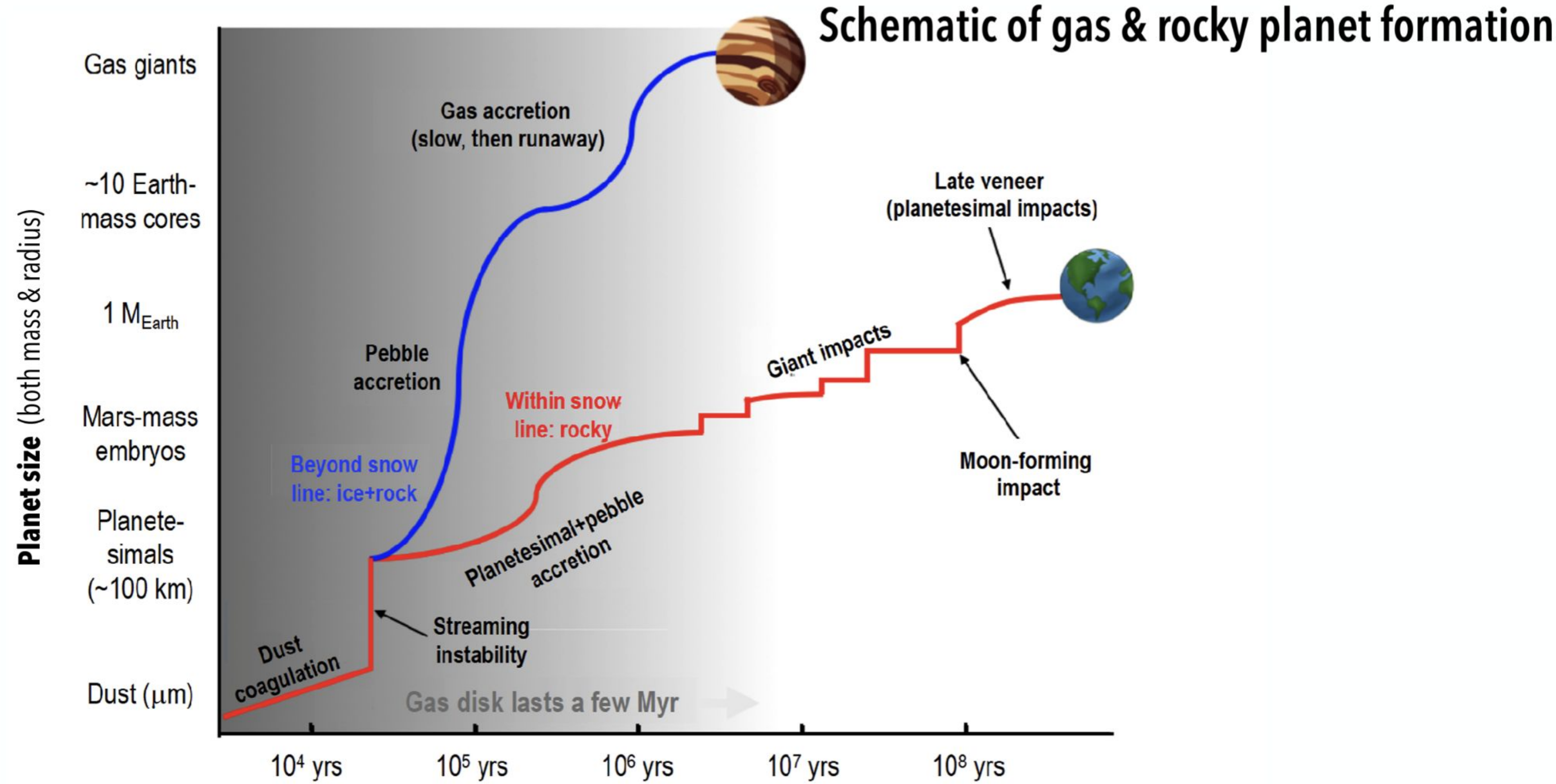
The start of planet formation

Now, we can overcome the meter barrier. The meter barrier can be skipped by instabilities in the disk.



Big bodies formation

Gravity and N-body interactions take over.



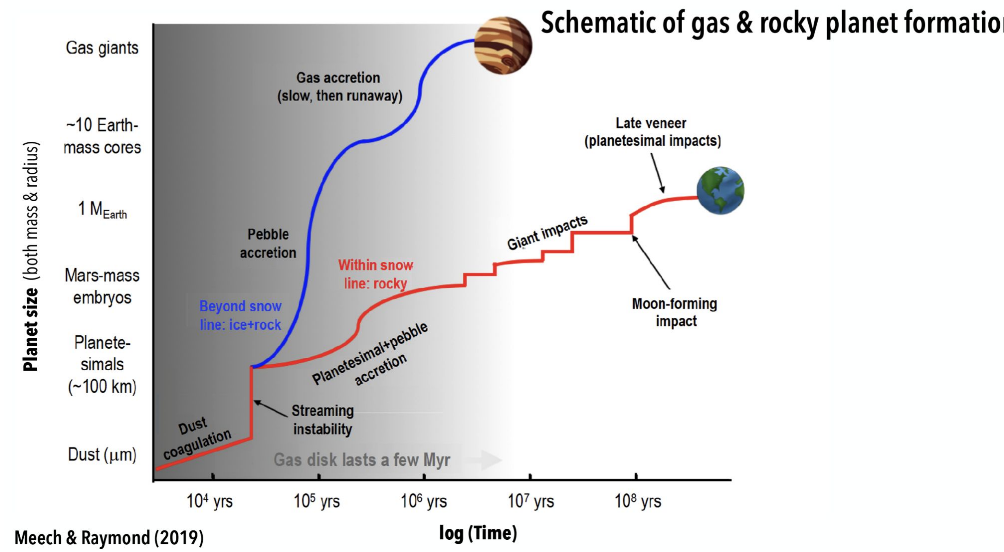
Meech & Raymond (2019)

Embryo formation

Km-size bodies are stirred by the gravitational forces of the central star and other bodies.

Planetesimals now behave more like N-body.

We look at the statistics of the planetesimals with eccentricity e and inclination i.



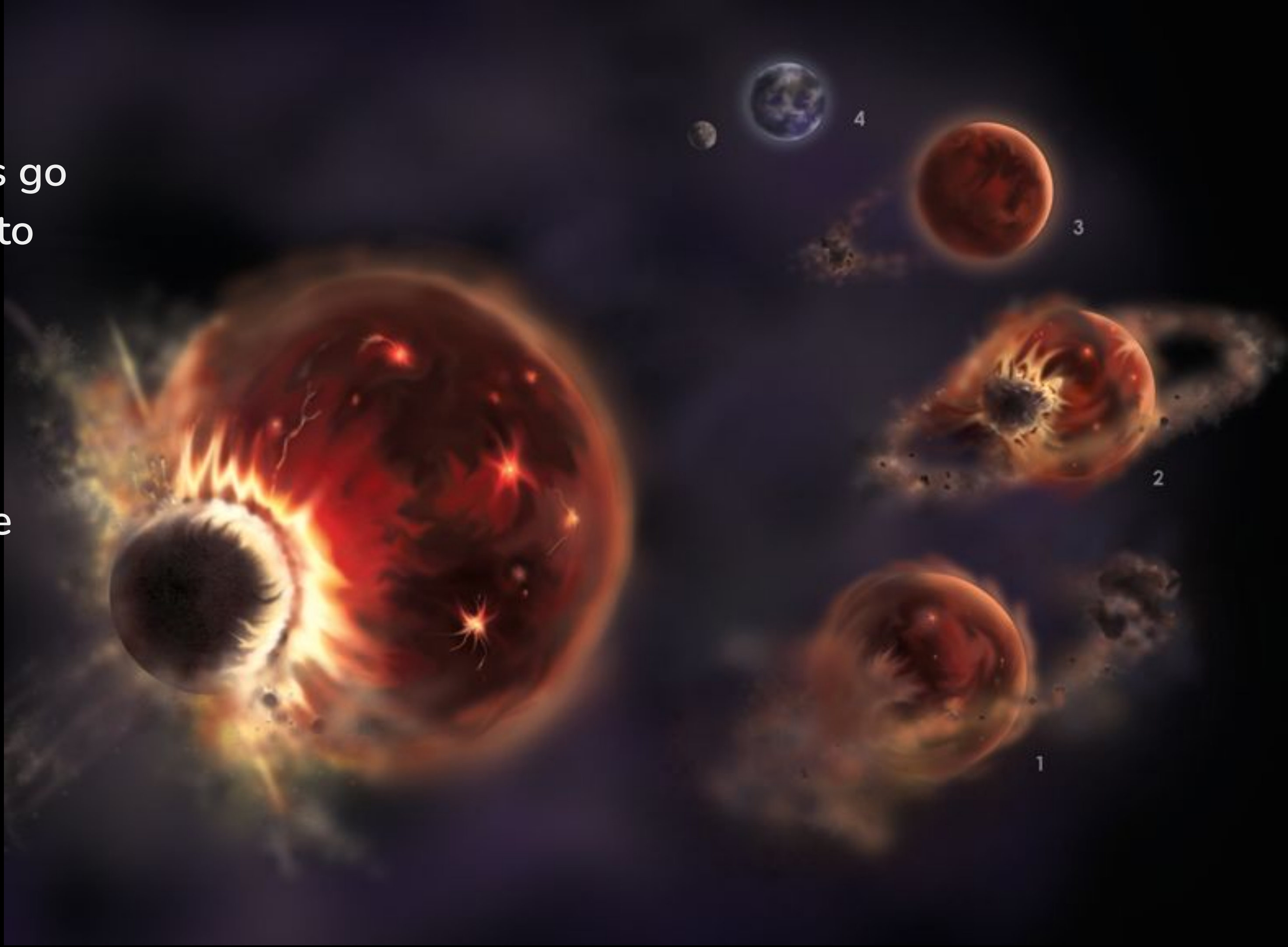
$$f(e,i) = 4\frac{\sigma}{m}\frac{e \times i}{<e^2><i^2>}\exp\left[-\frac{e^2}{<e^2>}-\frac{i^2}{<i^2>}\right]$$

Giant impacts

Earth like planets go through impacts to grow.

Similar to moon formation.

Not all moons are formed this way.



Big bodies formation

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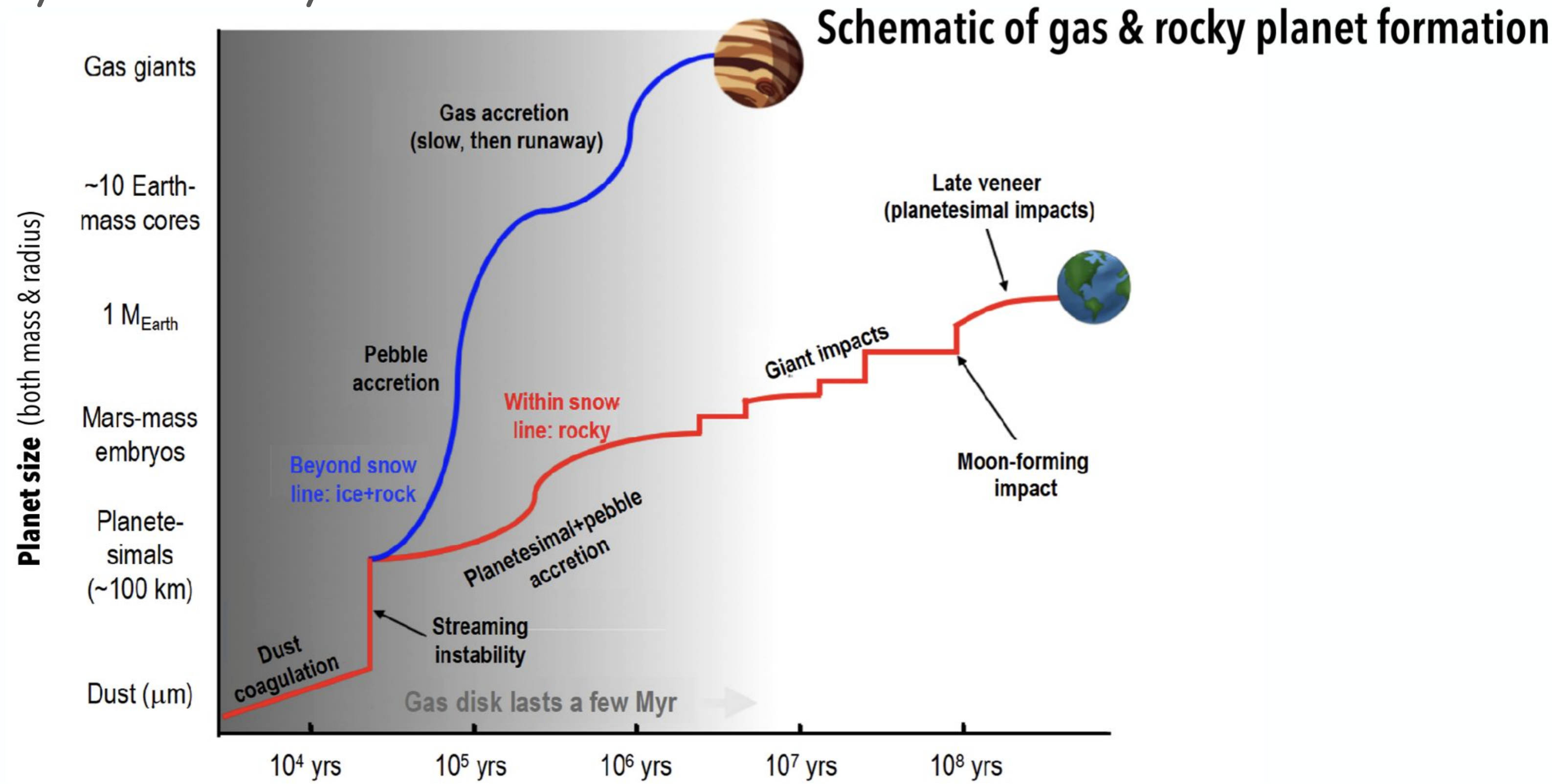


Meech & Raymond (2019)

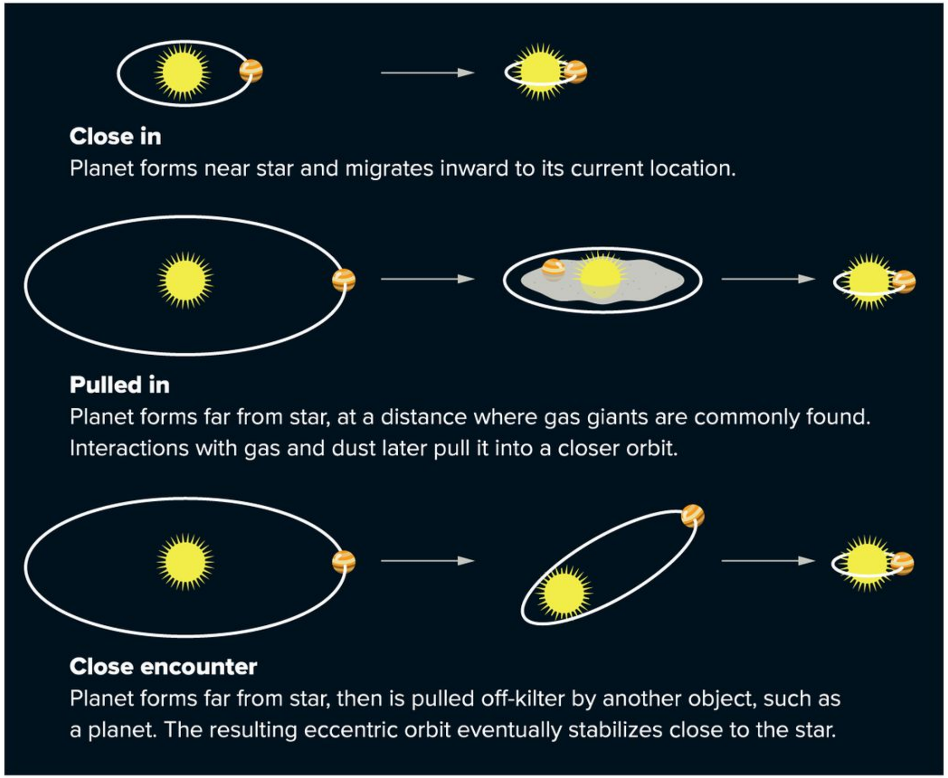
Migration of planets

Hot jupiters: jupiter-like gas giants that orbit very close to their stars.

This suggests that planets migrate during their lifetime.

This is complicated and not all of the models agree.

Three origin theories for hot Jupiters



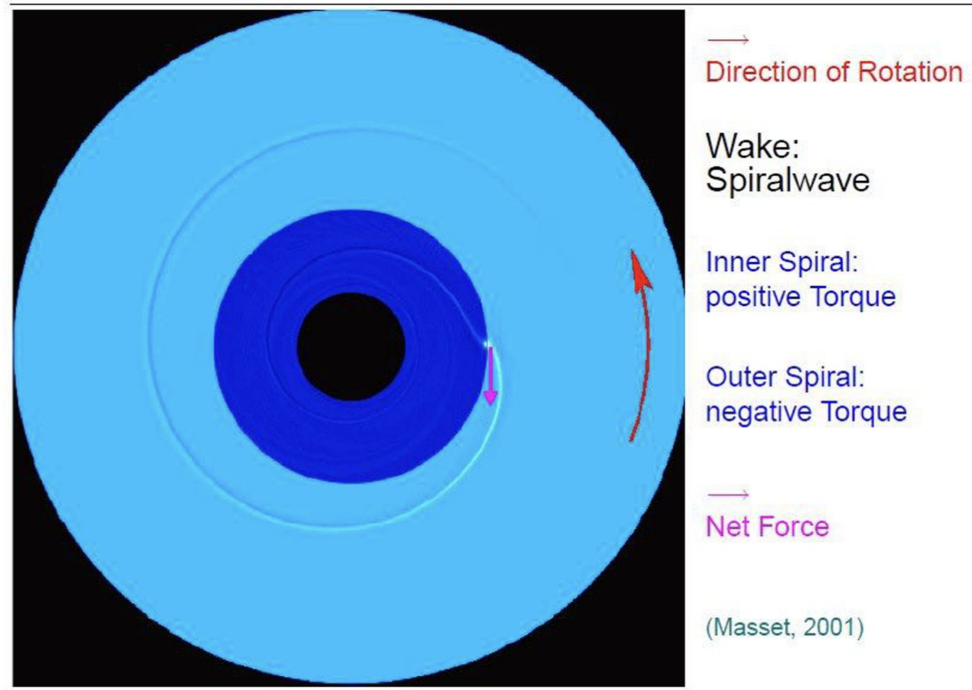
SOURCE: R.I. DAWSON AND J.A. JOHNSON / *AR ASTRONOMY AND ASTROPHYSICS* 2018 KNOWABLE MAGAZINE

Migration of planets

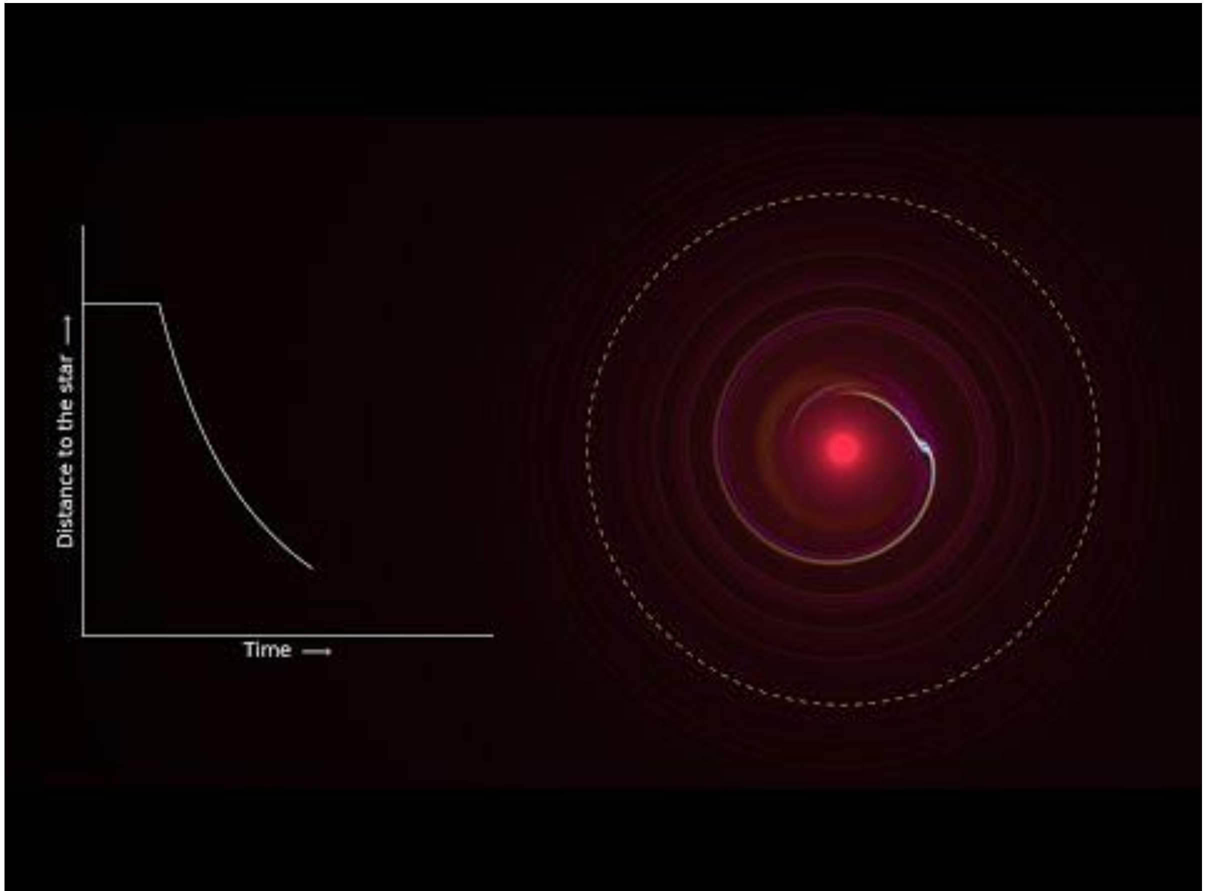
Type I: Low mass planets that are torqued by disk + protoplanet gravity. Inward migration.

Type II: Higher mass planets (~Neptune or Saturn). Non-linear perturbations with gap opening.

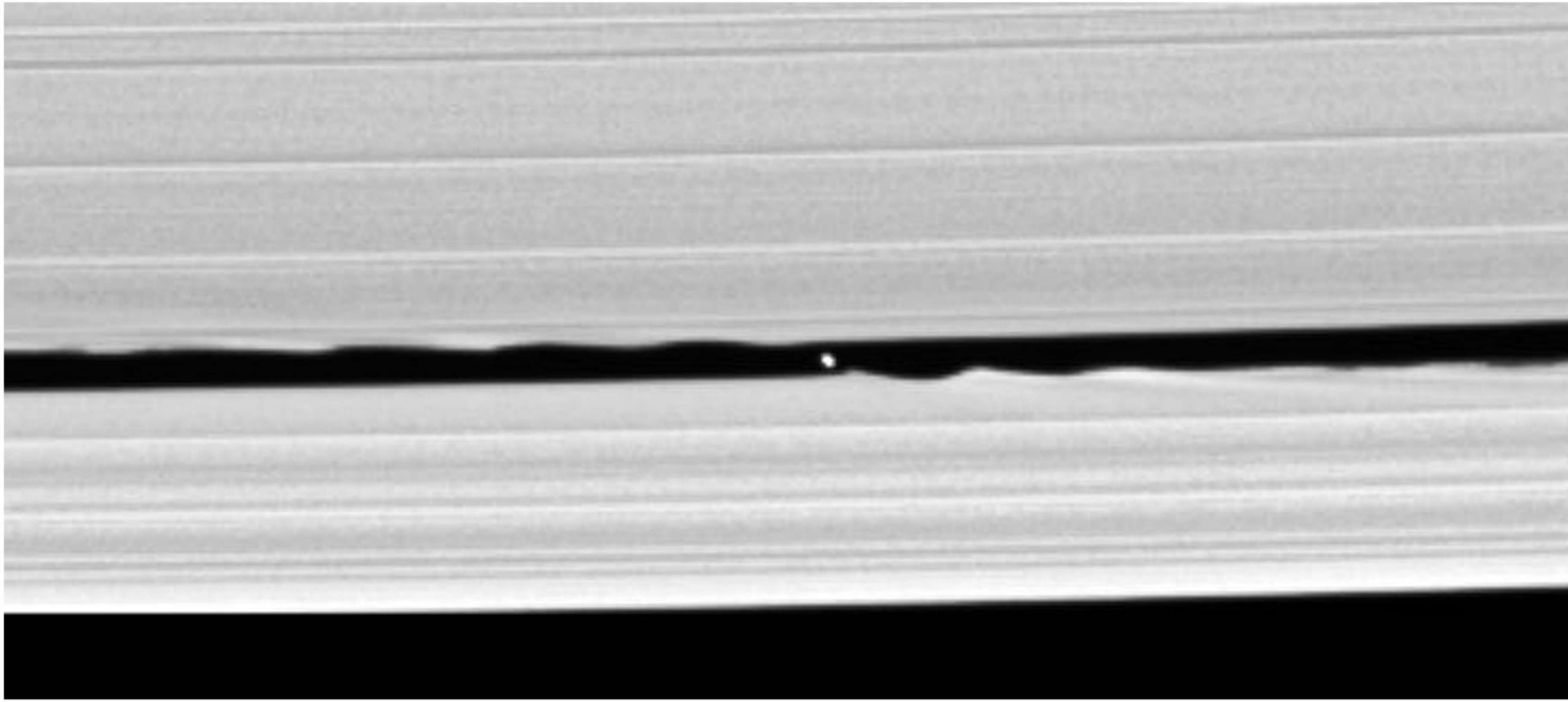
Type III: Anything that does not fit. It requires a massive disk and it can moves inward and outward depending on the disk.



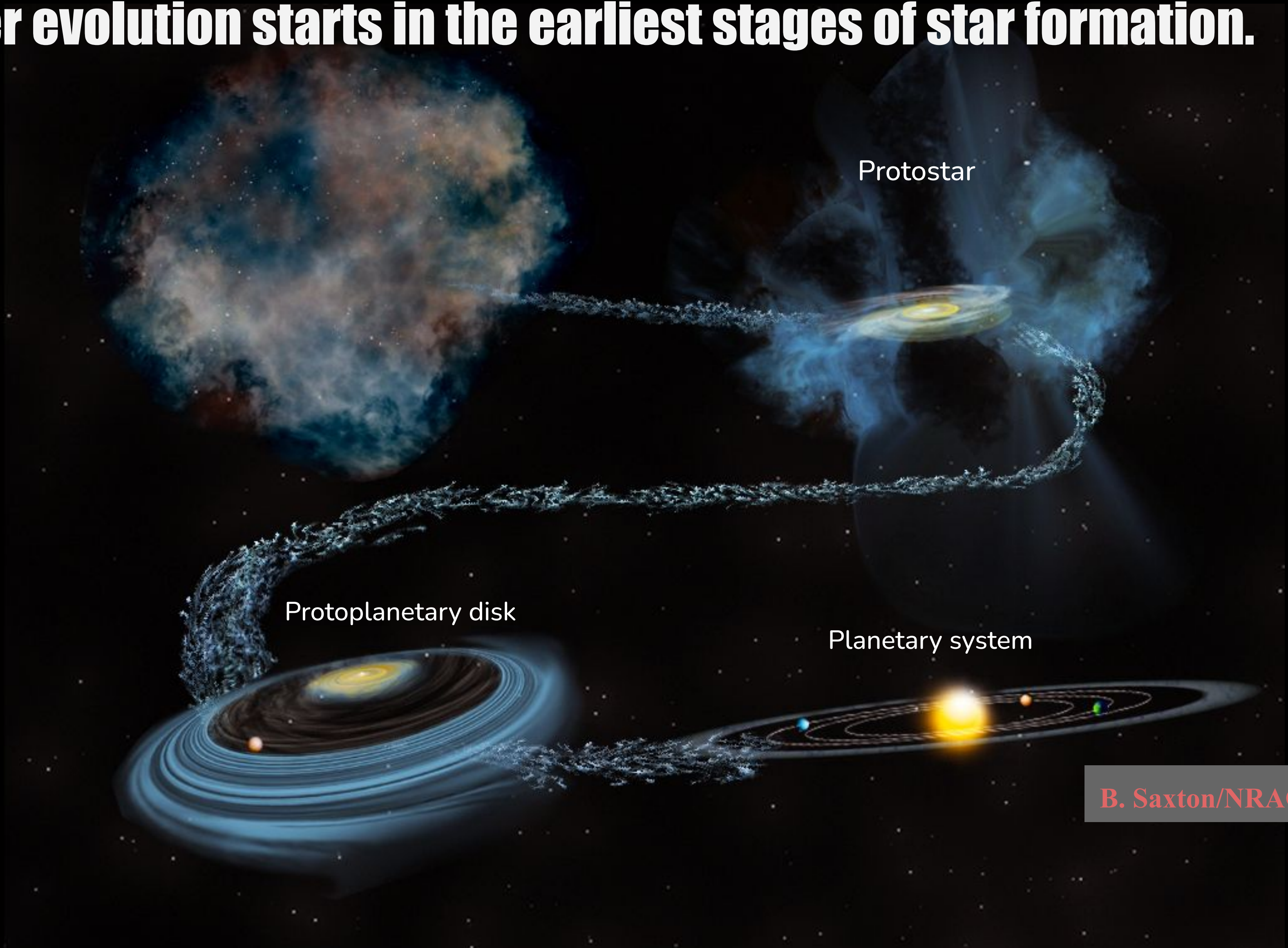
Type I migration



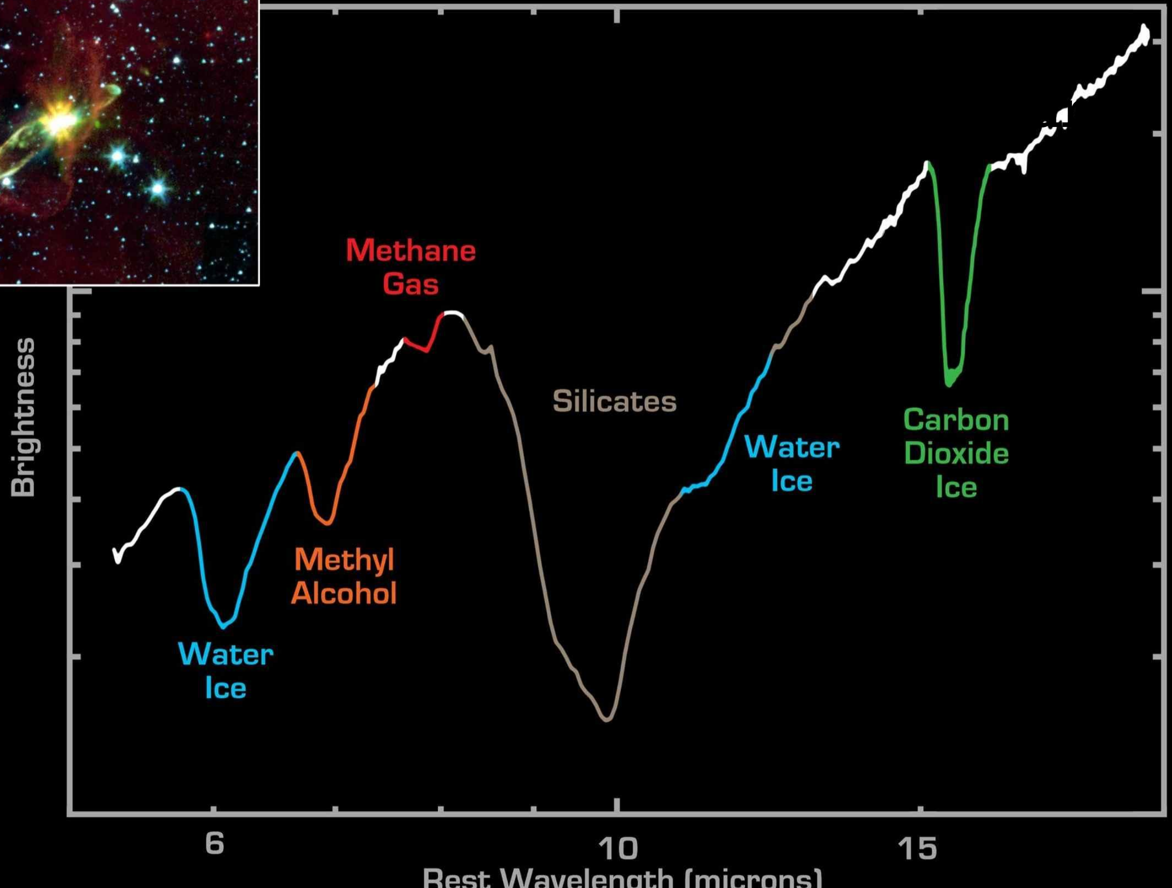
Type II migration



Water evolution starts in the earliest stages of star formation.



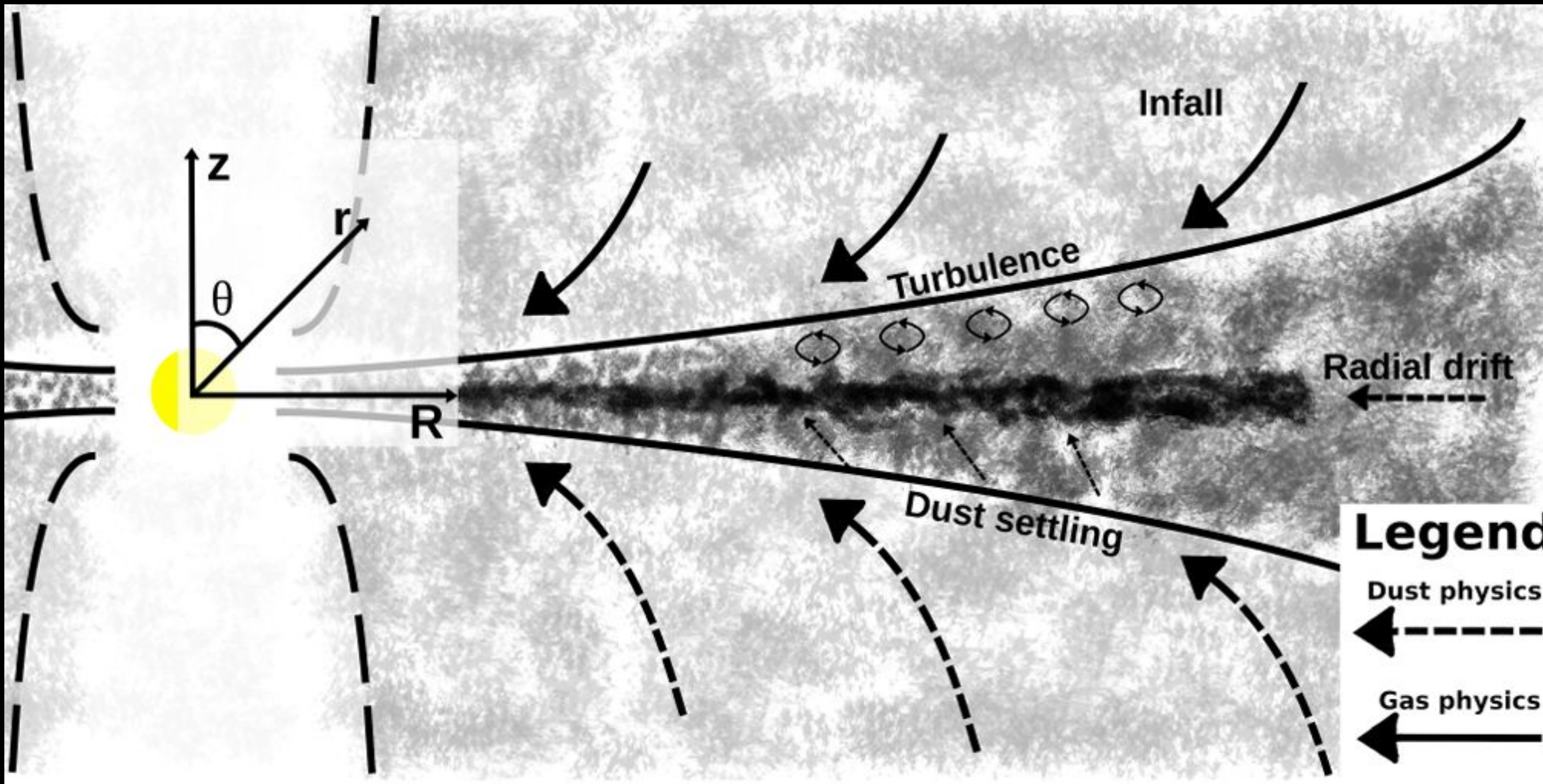
JWST programs



Coming in November!

NASA/JPL/Caltech
Boogert et al. 2015

Dusty disk formation



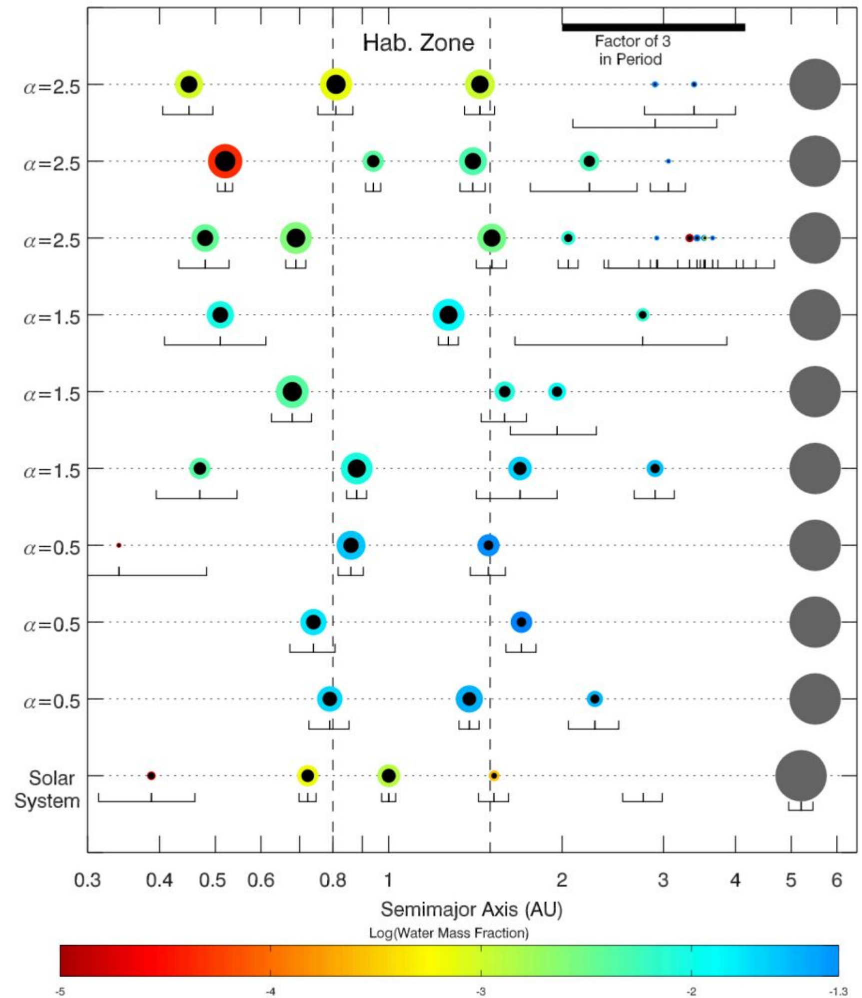
Putting this together with the dust: dusty disk forms first > decoupled gas and dust disk.

Cridland+ 2021

Objective: from clouds to planets

By following the trails of material from star formation to planets, we can try to understand whether or not our model of the Earth formation should have a lot of water.

These models can be tested against future observations of planets around other stars.



Summary

Planet formation happens early during the star formation process.

Star and planet formation happens together and they affect each other.

Most of these things can be understood analytically without sophisticated simulations but need hydro to see all of the details.