News and Reminders

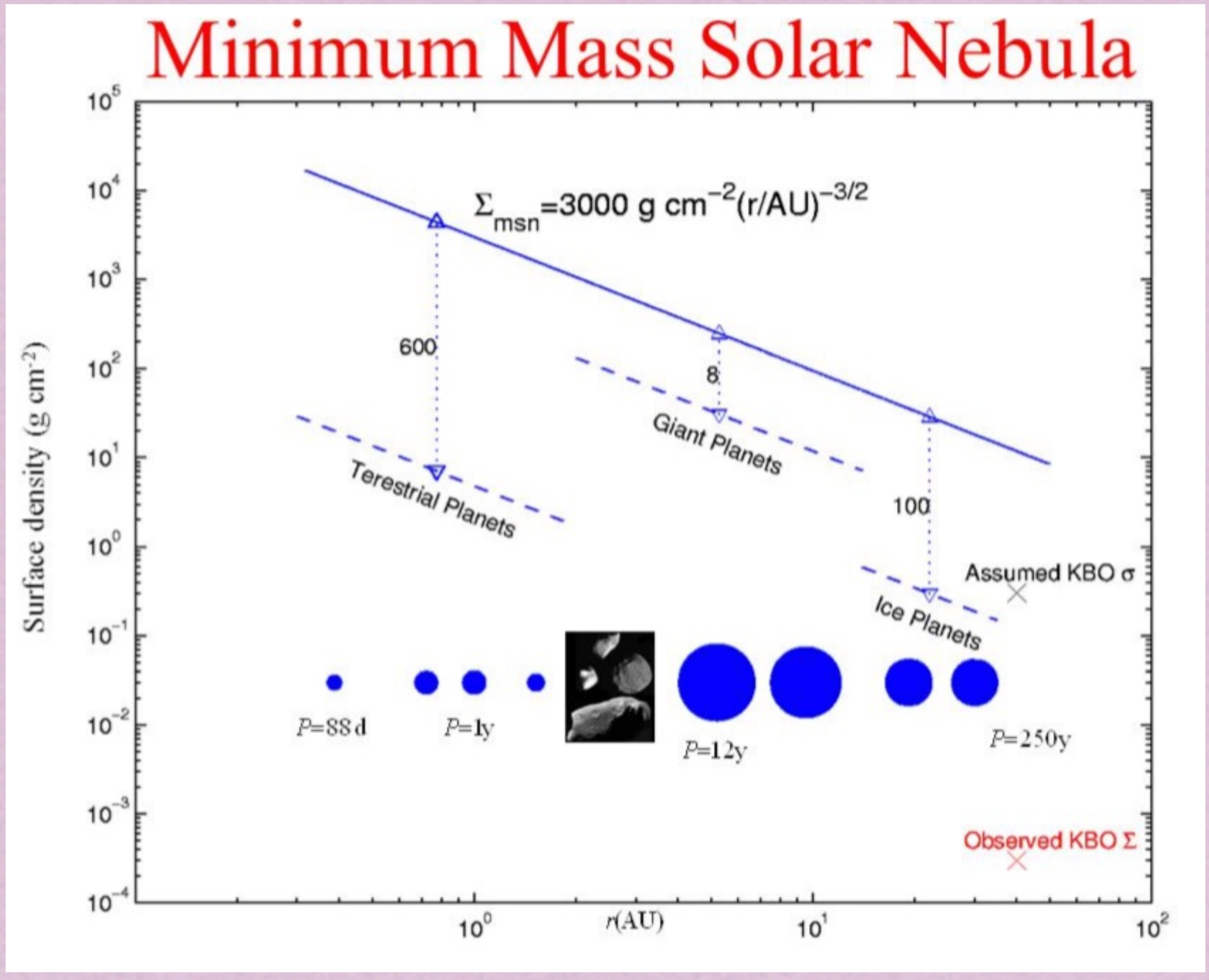
Homework 5 - due Monday, Nov. 18

Wednesday - guest lecture by Dominic Oddo

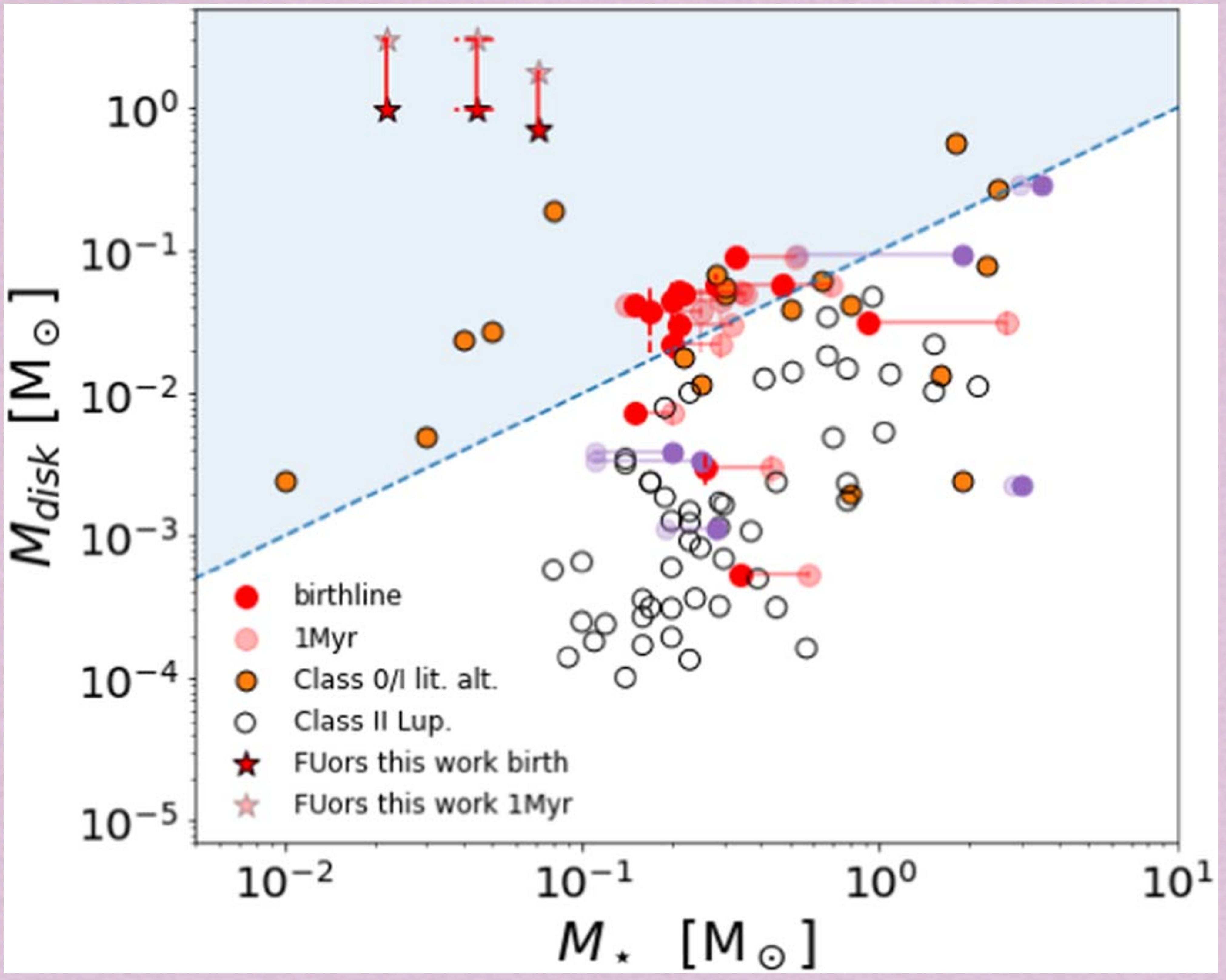
End of semester proposal due dates:

- Abstract due: today
- Proposal due: Monday, Dec. 2

Minimum-Mass Solar Nebula (MMSN)



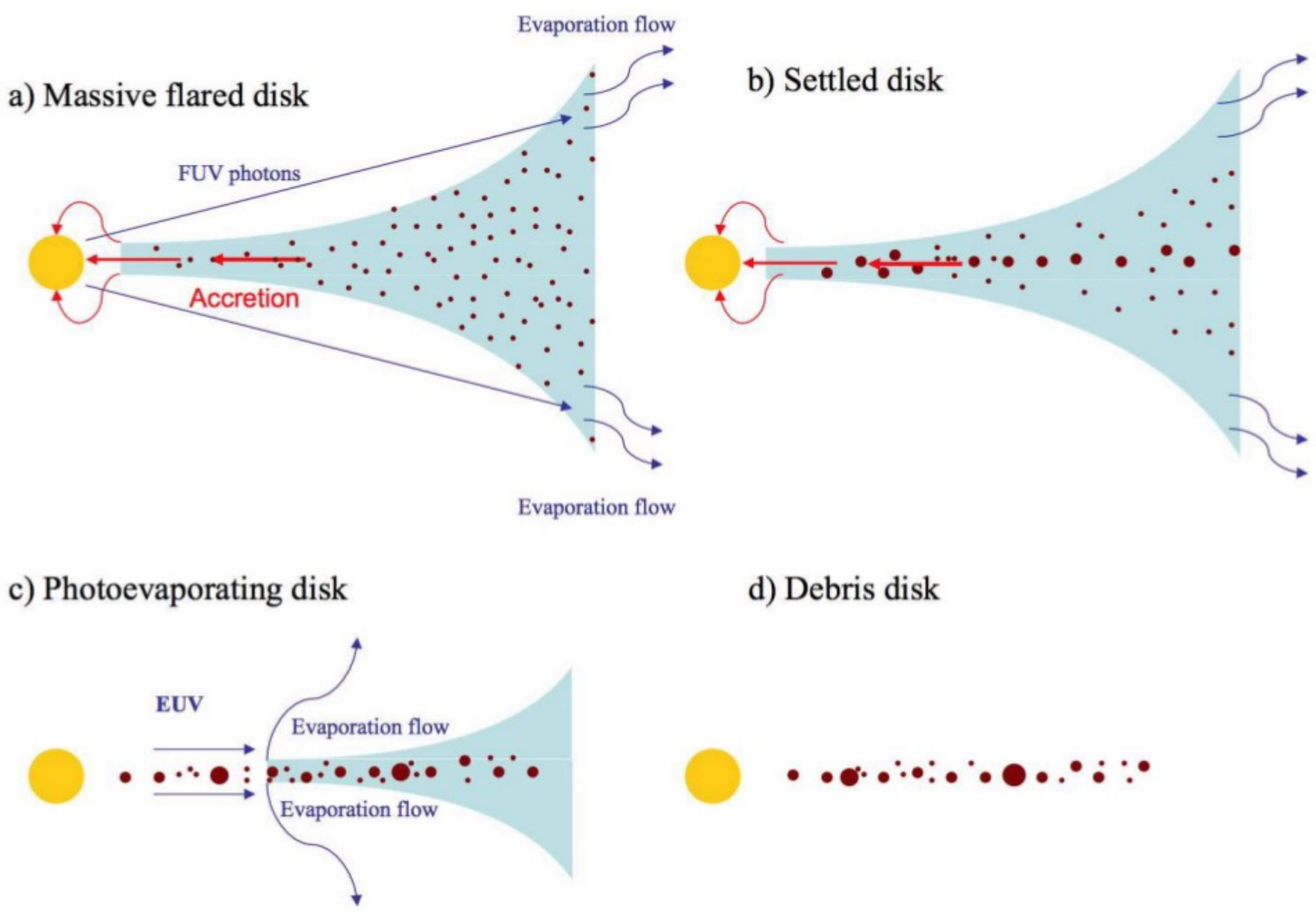
Disk Masses



M_{disk} [$M_\odot$]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-2}
10^{-1}
10^0
10^1
$M_\star$ [$M_\odot$]
birthline
1Myr
Class 0/I lit. alt.
Class II Lup.
FUors this work birth
FUors this work 1Myr

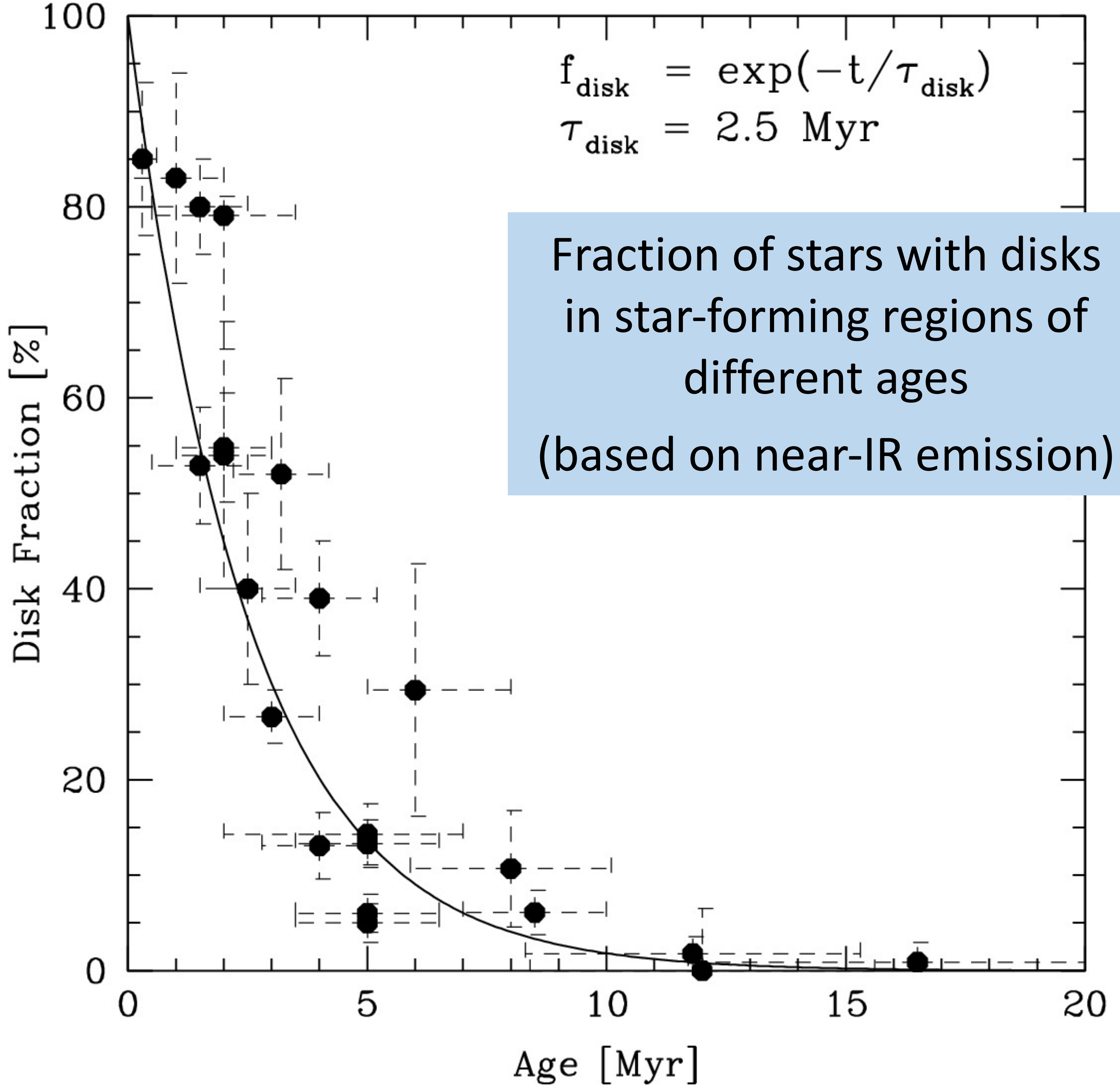
Disk Evolution

Gas is cleared from the disk mainly by a combination of:
accretion onto the central star,
accretion into gas-giant planets,
and photoevaporation



Williams & Cieza 2011

Disk Lifetimes



Fraction of stars with disks in star-forming regions of different ages

(based on near-IR emission)

Mamajek 2009

Planetesimal Formation

It all starts with dust…

Dust grains (<1 micron) are present in atmospheres of giant stars

-> but their formation is still debated

Planetesimal Formation

At this early stage, motion of grains is coupled to gas

Fractals form, held together by van der Waals force (short-range force from interaction of dipole moments at surface of grains that are in contact)

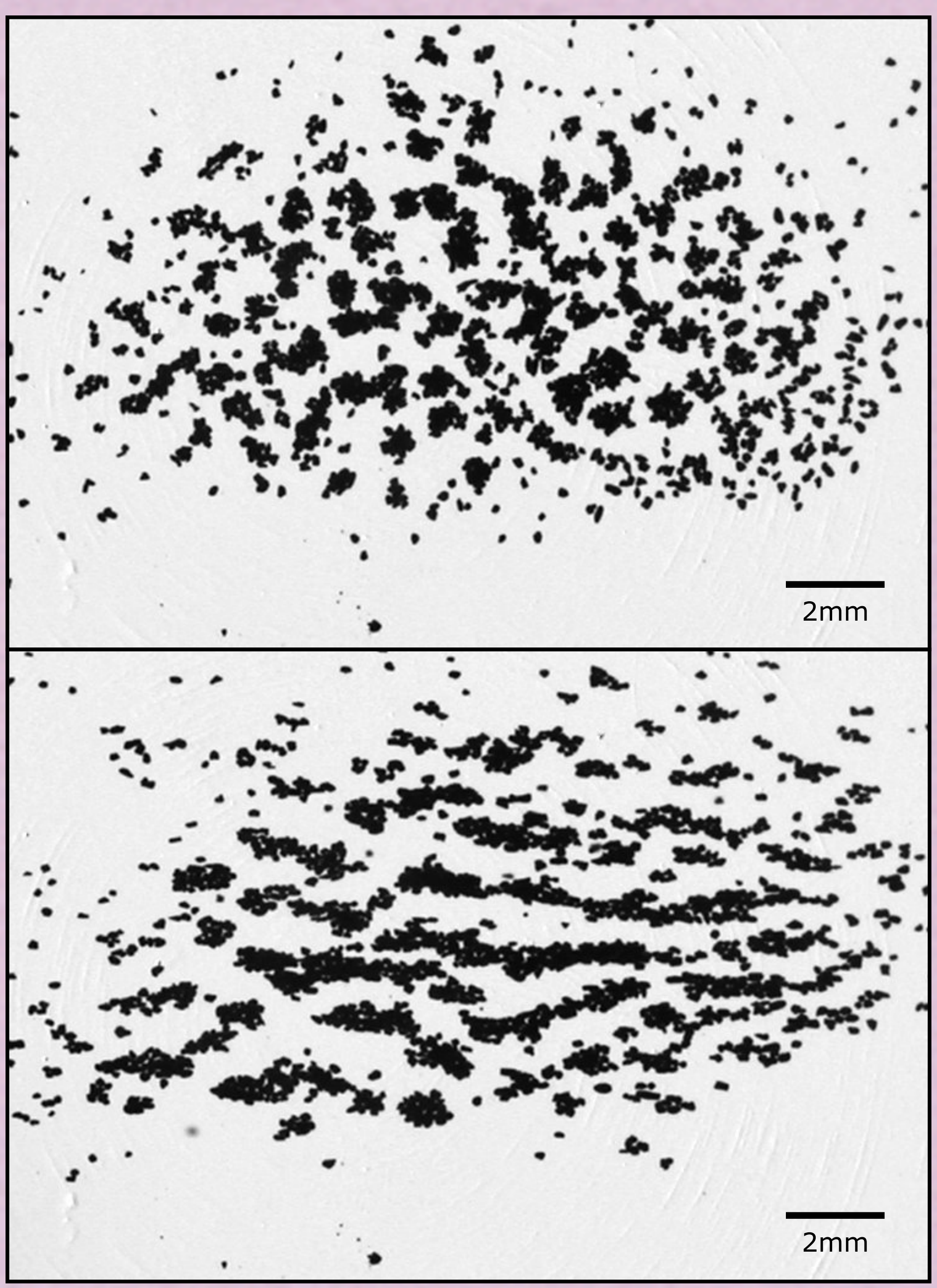
At ~1 mm: bouncing/fragmentation barrier!

-> but need sticking for growth

-> ongoing research

-> magnetic fields could shift bouncing barrier to larger sizes -> magnetic aggregation

Krus & Wurm (2018)



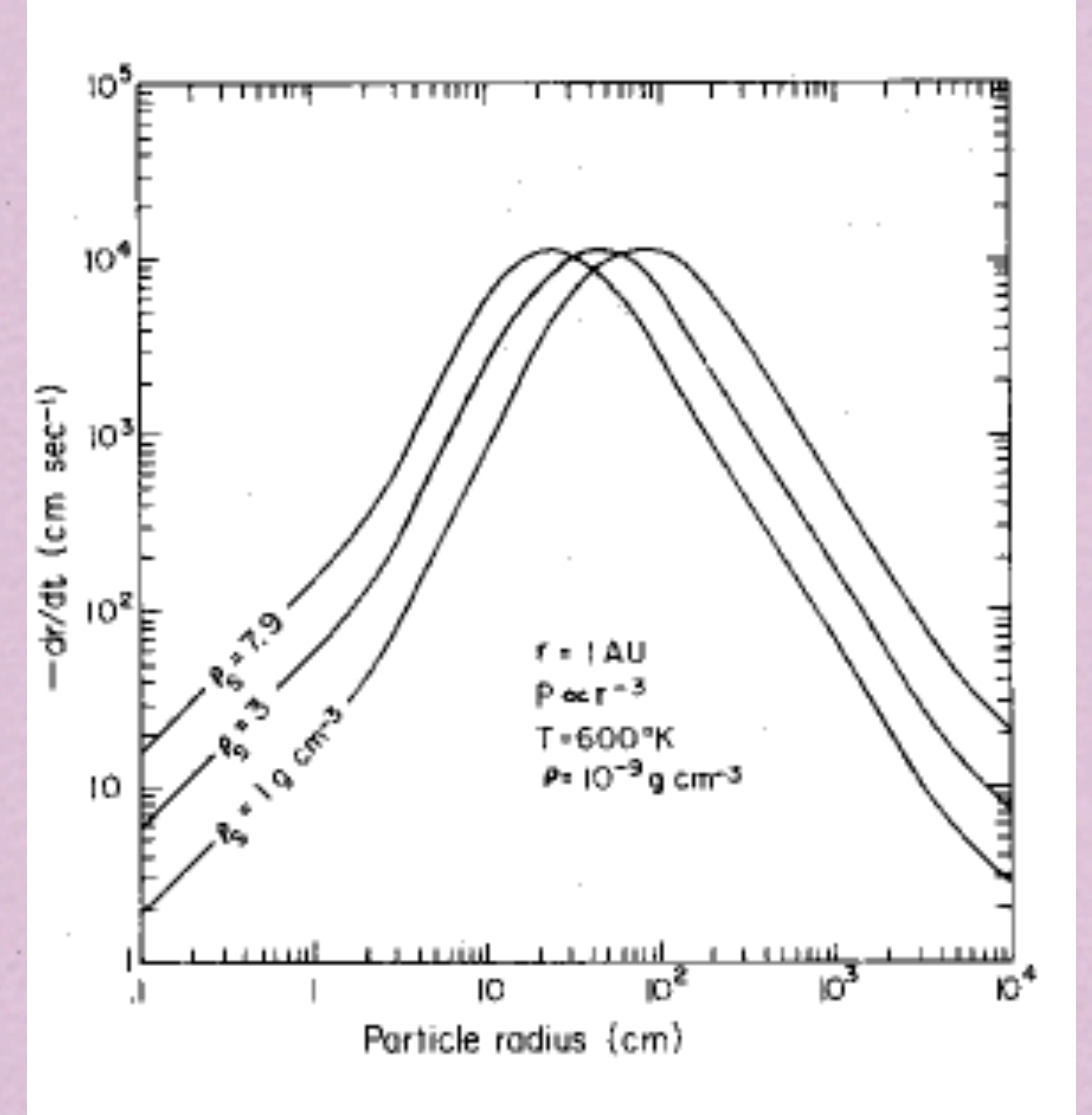
Magnetic field on

Magnetic field off

The Drift Barrier

As particles grow in mass, they decouple from the gas and begin to settle toward the mid-plane of disk

Consider: gas is partially supported against stellar gravity by pressure in radial direction, so gas moves *slower* than Keplerian rate.



Smaller grains are coupled to the gas, but:

Larger particles (mm - cm) move at speeds closer to Keplerian and thus feel a headwind from the slower gas.

-> some angular momentum is removed from particle -> they drift inward

Very large bodies (km-sized) have low surface area to mass ratio, so feel less headwind -> no drift

"Effective gravity" felt by gas:

$$g_{eff} = \frac{-GM_\odot}{r^2} - \frac{1}{\rho_g}\frac{dP}{dr}$$ ← have you seen this before?

↑ acceleration produced by the pressure gradient

but also: $g_{eff} = -r\Omega_g^2$ (for a circular orbit)

centrifugal acceleration → $-r\Omega_g^2$

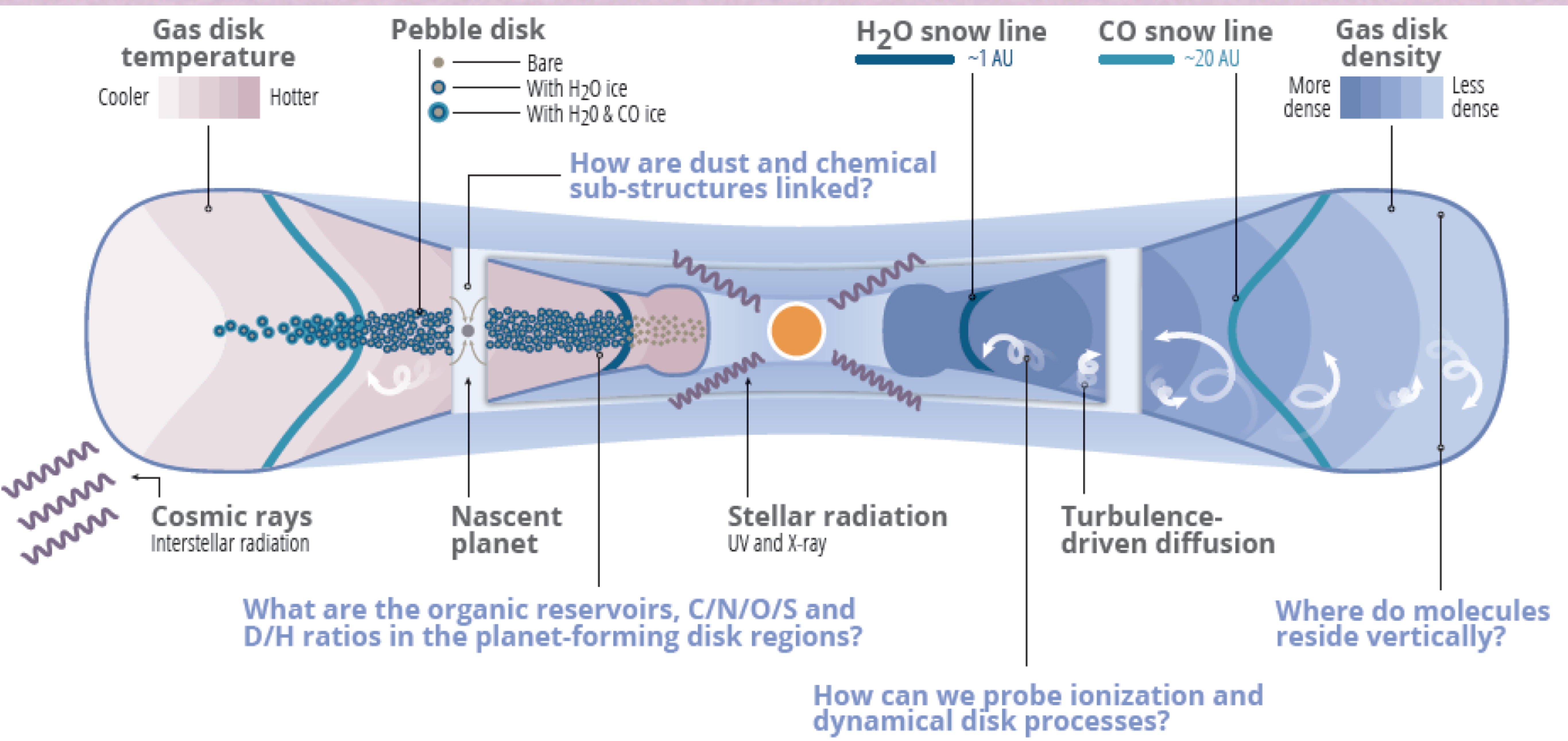
Ω_g ← angular velocity

$$\Omega_g = \sqrt{\left(\frac{GM}{r^2} + \frac{1}{\rho_g}\frac{dP}{dr}\right)\frac{1}{r}}$$

$$= \sqrt{\frac{GM}{r^3}\left(1 + \frac{r^2}{GM\rho_g}\frac{dP}{dr}\right)}$$

$$= \sqrt{\frac{GM}{r^3}}\left(1 - \underbrace{\left(\frac{-r^2}{2GM\rho_g}\frac{dP}{dr}\right)}_{\sim 5\times10^{-3}}\right)$$

so disk rotates 0.5% slower than Keplerian speed



Gas disk temperature
Cooler
Hotter
Pebble disk
Bare
With H_2O ice
With H_2O & CO ice
H_2O snow line
~1 AU
CO snow line
~20 AU
Gas disk density
More dense
Less dense
How are dust and chemical sub-structures linked?
Cosmic rays
Interstellar radiation
Nascent planet
Stellar radiation
UV and X-ray
Turbulence-driven diffusion
What are the organic reservoirs, C/N/O/S and D/H ratios in the planet-forming disk regions?
Where do molecules reside vertically?
How can we probe ionization and dynamical disk processes?

Planetesimal Formation

Gravitational instability planetesimal formation:

- if dust settles in very thin disk that is also nearly perfectly free of turbulence, then dust disk may fragment into clumps that collapse under own gravity;
- problem: turbulence prohibits these circumstances from being reached.

Streaming instability:

- bodies drift in (from loss of angular momentum), encounter another one and accumulate into a cluster
    - *local* gas is sped up a little by cluster and rotates closer to Keplerian speed
    - headwind on cluster is reduced, and drifts more slowly toward the star
- slower drifting clusters are overtaken and joined by isolated particles from further away, increasing the local density and further reducing radial drift
- -> exponential growth of the clusters

From Planetesimals to Planetary Embryos

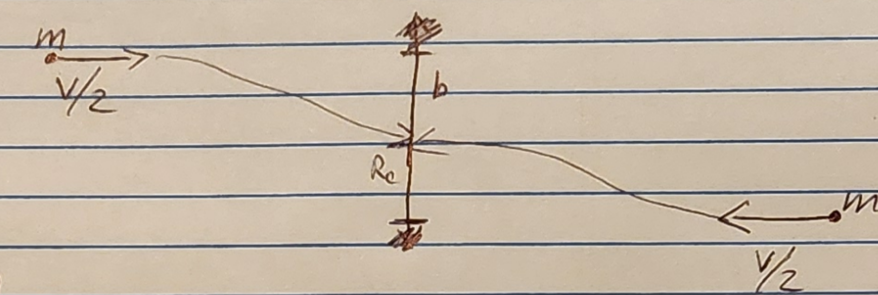
Lots of planetesimals floating around.
These **O(1 km)**-sized bodies feel much less headwind from the gas.

Collisions abound:

- can be mostly inelastic -> accretion
- elastic -> fragmentation
- elastic -> rebound
    - “semi”-Keplerian orbits are changed to random motions

From planetesimals to planetary embryos:

b: impact parameter
(distance of closest approach without gravity)



Collisions + accretion

relative velocity of each body at infinity is $V/2$

at closest approach, they have velocity V_{max} and separation R_c.

Energy conservation:

$$\frac{1}{2} m \left(\frac{v}{2}\right)^2 + \frac{1}{2} m \left(\frac{v}{2}\right)^2 = \frac{1}{8} m v^2 \times 2 = \frac{1}{4} m v^2$$

$$= \frac{1}{2} m V_{max}^2 \times 2 - \frac{Gmm}{R_c}$$

$$= m V_{max}^2 - \frac{Gmm}{R_c}$$

Conservation of angular momentum:

$$-m \frac{v}{2} r + m \frac{v}{2} (r+b) = 2 m V_{max} \frac{R_c}{2}$$

(since no radial component of velocity at point of closest approach)

$$\frac{vb}{2} = V_{max} R_c \implies \boxed{V_{max} = \frac{vb}{2R_c}}$$

Let R_s = sum of radii of the two bodies

if $R_c < R_s \Longrightarrow$ collision

if $R_c > R_s \Longrightarrow$ flyby

$$b^2 = \frac{4 V_{max}^2 R_c^2}{V^2} = \frac{4 R_c^2}{V^2}\left(\frac{1}{4} m v^2 + \frac{G m^2}{R_c}\right)\frac{1}{m}$$

$$= R_c^2 + \frac{4 R_c}{V^2} G m$$

So the largest value of b that gives a collision is:

$$b = \sqrt{R_s^2 + \frac{4 R_s G m}{V^2}}$$

if b is larger than this, it means that $R_c > R_s$

can write as function of V_{esc} $\left(V_{esc} = \sqrt{\frac{4Gm}{R_s}}\right)$:

$$b = R_s \sqrt{\left(1 + \frac{V_{esc}^2}{V^2}\right)}$$

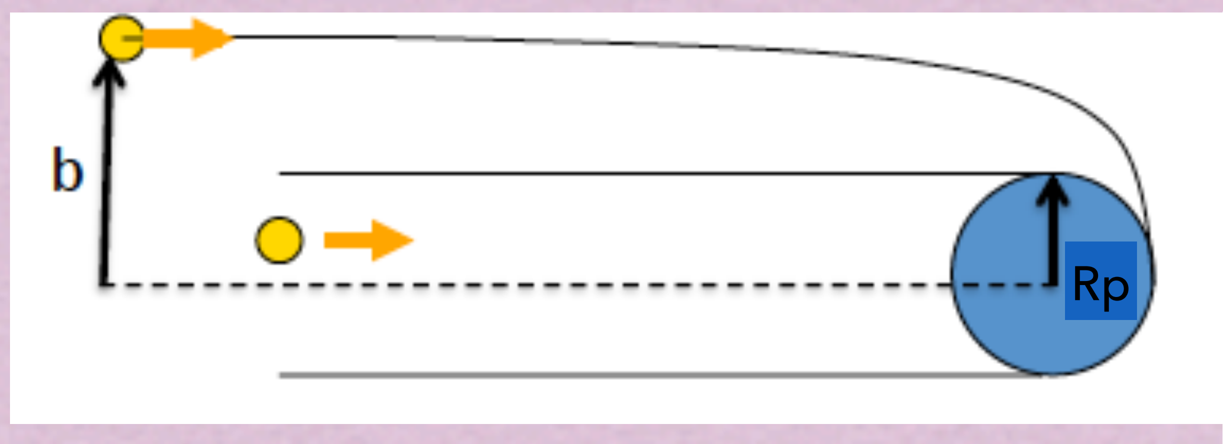
Can define a gravitational focusing factor:

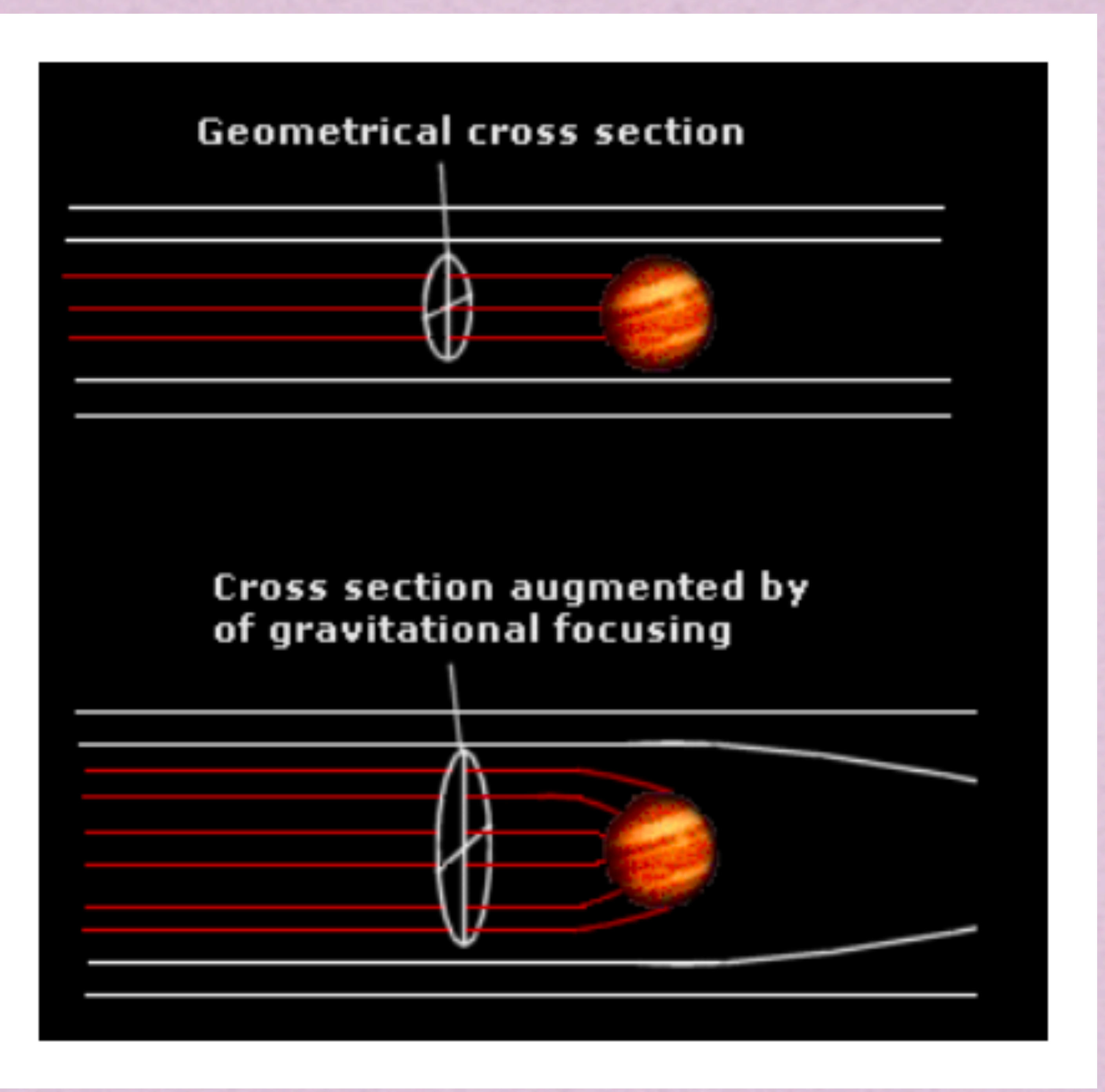
$F_g = 1 + \left(\frac{V_{esc}}{V}\right)^2$ and a cross-section for collisions

$$\Gamma = \pi R_s^2 \left(1 + \left(\frac{V_{esc}}{V}\right)^2\right) = \pi R_s^2 F_g$$

When $v \ll V_{esc}$, growth is much faster due to gravitational focusing

Gravitational Focusing





Without gravitational focusing:

$\Gamma = \pi \ R_p^2$

With gravitational focusing:

$\Gamma = \pi \ b^2 = \pi \, (R_c^2 + 4R_cGm/v^2)$

Growth rate:

$$\frac{dM}{dt} = \rho_{sw} V_{rms} \Gamma$$

where ρ_s is the density of the planetesimal swarm and V_{rms} is the dispersion velocity

$$= \rho_{sw} V_{rms} \pi R_s^2 F_g \propto M^{2/3}$$