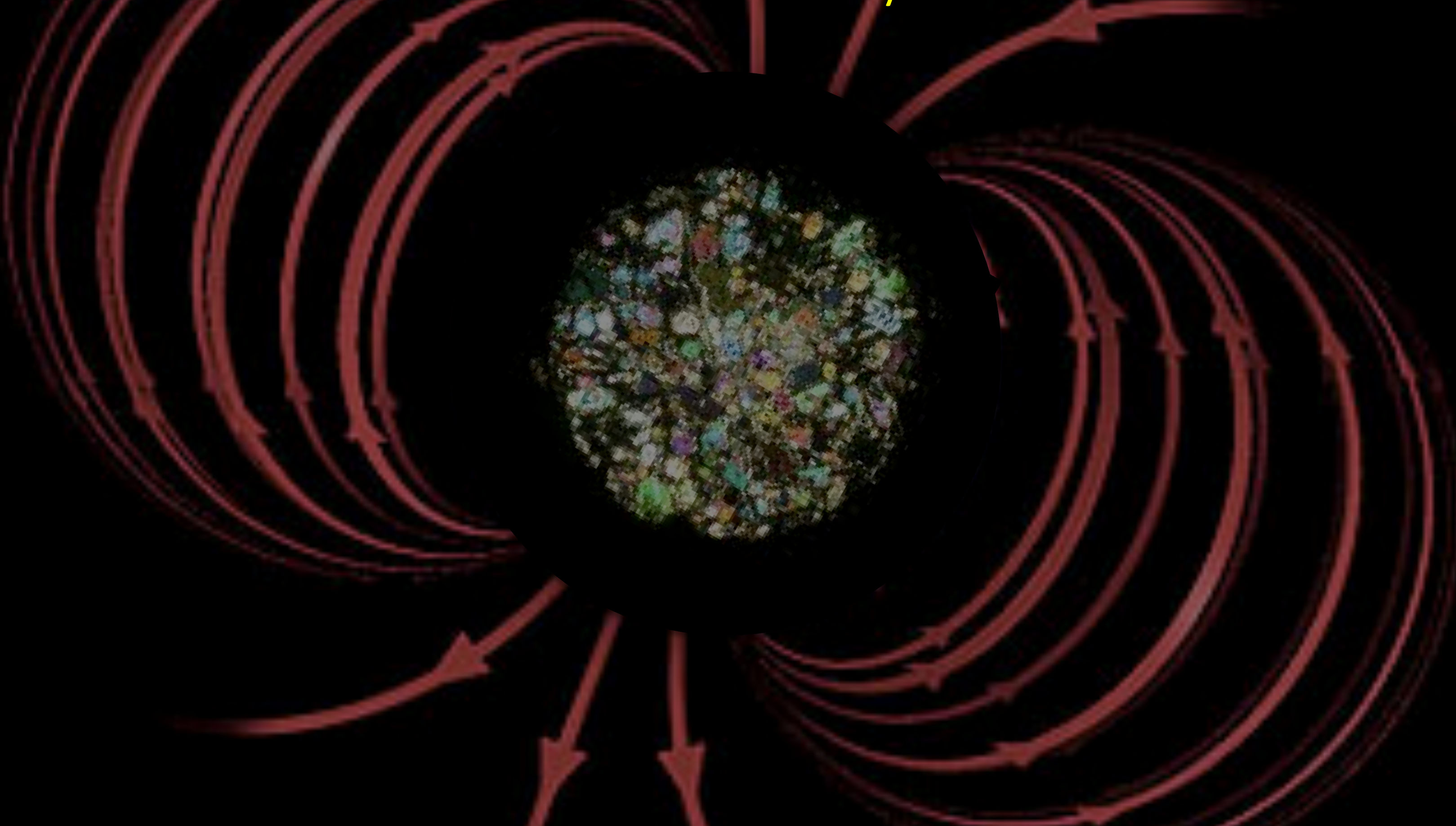
Meteoritic and Planetary Constraints on our Protoplanetary Disk

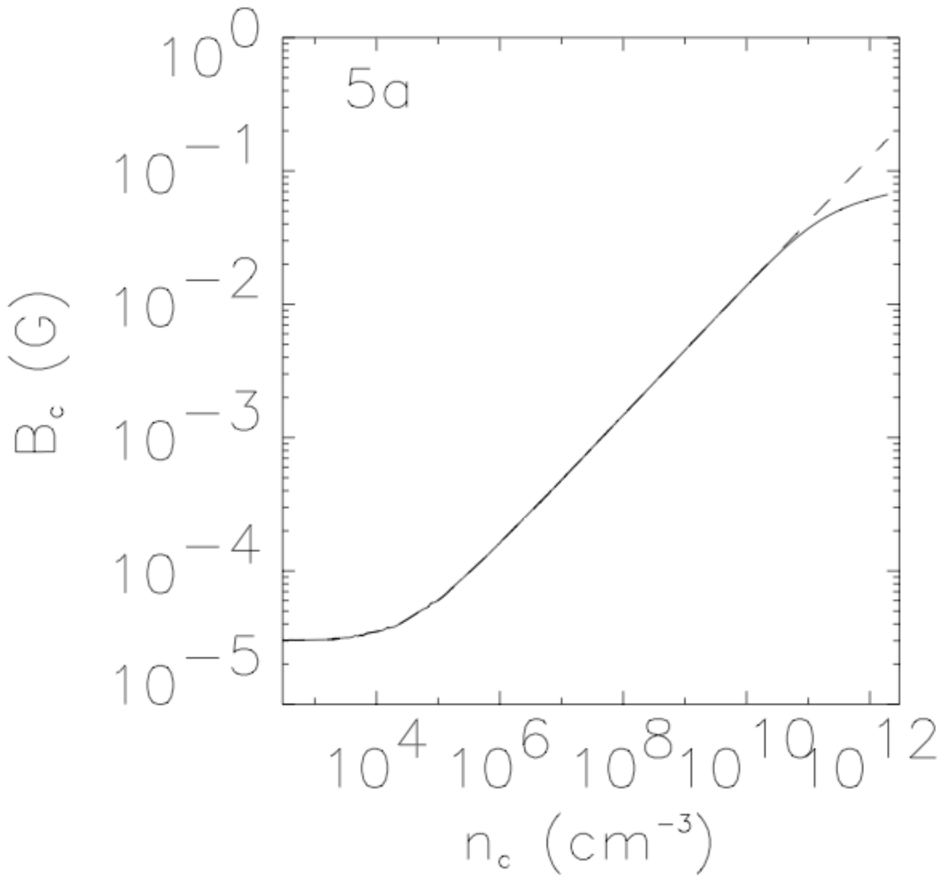
Steve Desch
Arizona State University

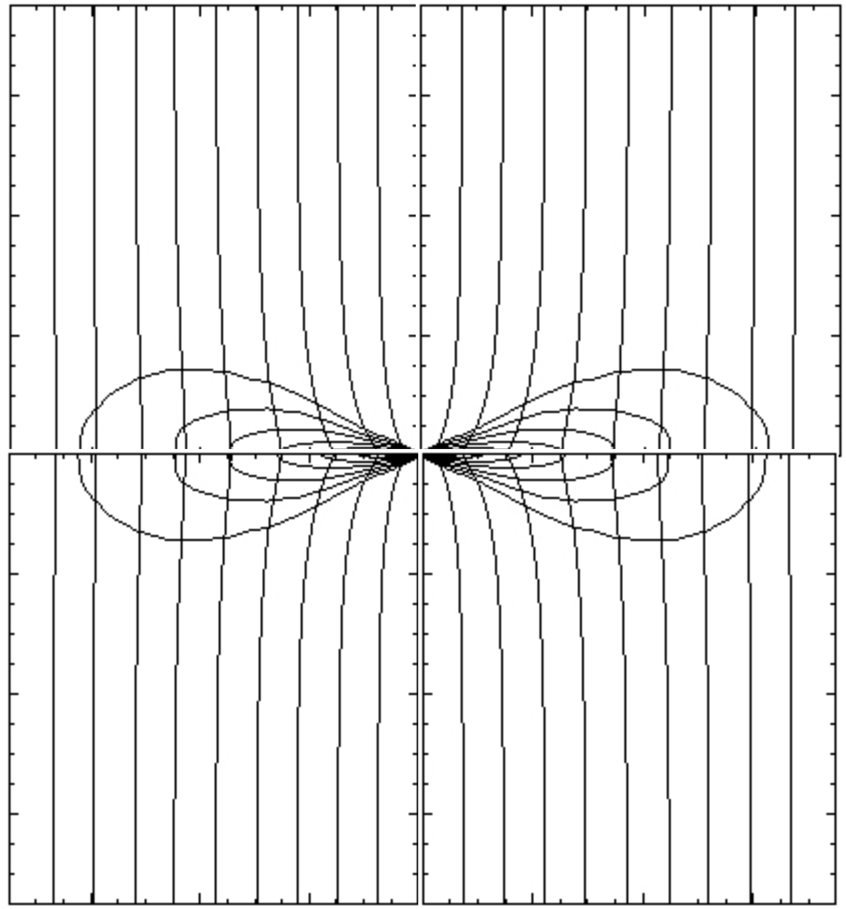


Non-Ideal MHD in Protoplanetary Disks / NBIA
August 7, 2013

When I Started Studying Protoplanetary Disks...

From my (1998) PhD thesis:
During molecular cloud collapse, once $n_H > 10^{10}$ cm^{-3}, field lines no longer dragged in.
B ~ 85 mG within 20 AU. Protoplanetary disk forms in this background field.





Desch & Mouschovias (2001)

When I Started Studying Protoplanetary Disks...

From Desch (2004):

Linear stability analysis of (axisymmetric MRI) including arbitrary B field geometry, arbitrary wave direction, Ohmic dissipation, ambipolar diffusion, and Hall terms

Also proved maximum growth rate always = Oort A-value

$$\sigma^4 + (\omega_{\rm OD} + \omega_{\rm AD} + \omega_T)\sigma^3 + \mathcal{C}_2\sigma^2 + (\omega_{\rm OD} + \omega_{\rm AD} + \omega_T)\left(\kappa^2 \cos^2\theta + \omega_{\rm A}^2 \cos^2\iota\right)\sigma + \mathcal{C}_0 = 0, \tag{35}$$

where

$$\mathcal{C}_2 = \kappa^2 \cos^2\theta + 2\omega_{\rm A}^2 \cos^2\iota + (\omega_{\rm H}\cos\iota)\left[\cos\theta \frac{d\Omega}{d\ln r} + (\omega_{\rm H}\cos\iota)\right] + (\omega_{\rm OD} + \omega_{\rm AD})\omega_T + \omega_{\rm AD}\left(\frac{d\Omega}{d\ln r}\right)g, \tag{36}$$

$$\mathcal{C}_0 = \left[\omega_{\rm A}^2 \cos^2\iota + 2(\Omega\cos\theta)(\omega_{\rm H}\cos\iota) + \frac{d\Omega^2}{d\ln r}\cos^2\theta\right] \times \left[\omega_{\rm A}^2\cos^2\iota + \frac{\kappa^2\cos\theta}{2\Omega}(\omega_{\rm H}\cos\iota)\right] + \kappa^2\cos^2\theta \times (\omega_{\rm OD} + \omega_{\rm AD})\omega_T + \omega_{\rm AD}\left(\frac{d\Omega}{d\ln r}\right) \times \left(\kappa^2\cos^2\theta + \omega_{\rm A}^2\cos^2\iota\right)g, \tag{37}$$

But what are the inputs?

Ionization rate?

Density?

Grain settling?

Magnetic field strength and geometry?

Meteoritics /planetary science provide such constraints!

Some things I have learned about protoplanetary disks using meteoritic and planetary data:

1. Our disk formed in a high-mass star-forming region and experienced external photoevaporation with $G_0 \approx 1000$.

2. Our disk was far more massive and dense than the Minimum Mass Solar Nebula, with a much steeper profile: $\Sigma(r) \sim r^{-2.2}$.

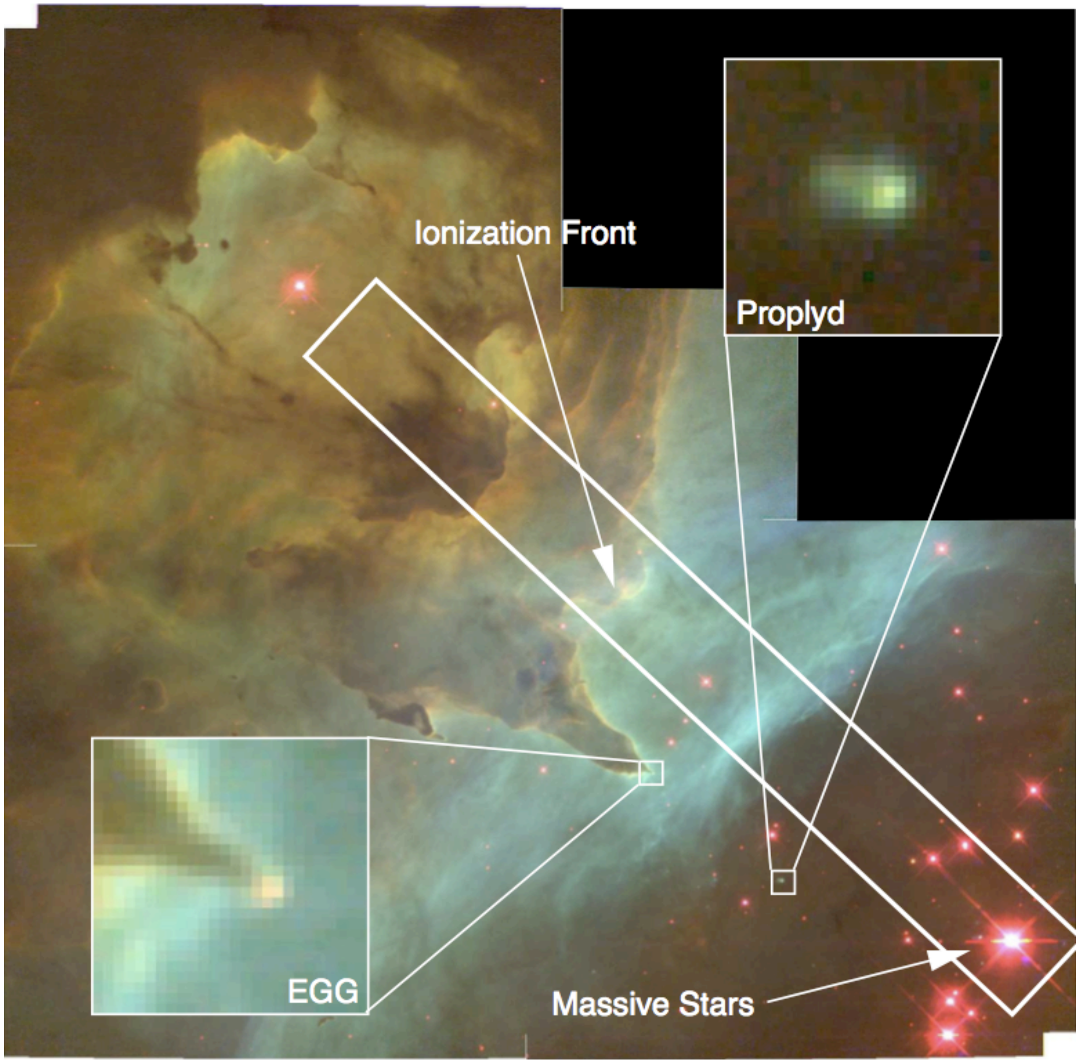
3. Alpha had to increase with heliocentric distance.

4. The field strength in the disk was $B \sim 0.1$ G.

#1. The Sun formed in an H II region:

1. **It would be very common**
   About 50% of Sun-like stars form in cluster with O star (Lada & Lada 2003; Myers & Adams 2001; Hester & Desch 2005)
2. **Orbit of Sedna (and 2000 CR_{105} and 2012 VP_{113})**
   Perihelion at 76 AU requires lifting by stellar encounter only probable in cluster with > 10^3 stars (Kenyon & Bromley 2004; Morbidelli & Levison 2004)
3. **Short-lived ($t_{1/2} \sim 10^6$ yr) radionuclides in meteorites**
   ^{26}Al, ^{41}Ca, ^{60}Fe probably require WR winds and/or core-collapse supernova to inject material into molecular cloud (Wadhwa et al. 2007; Pan et al. 2012). Internal processes (e.g., X-winds) insufficient (Desch et al. 2010). => Disk saw massive stars' FUV
4. **Truncation of the classical Kuiper Belt**
   Observed edge at 47 AU (Trujillo & Brown 2001) strongly suggests photoevaporation with $G_0 \sim 1000$ (Adams et al. 2004)
5. **Mass-independent oxygen isotope fractionation in meteorites**
   Oxygen isotope anomalies most easily explained by UV photochemistry (Lyons & Young 2005) with $G_0 \sim 1000$ (Lyons et al. 2009).
6. **Structure (surface density profile) of the disk**
   updated minimum mass solar nebula shows $\Sigma(r) \sim r^{-2.2}$, apparently requires photo-evaporated outer edge (Desch 2007; Kalyaan & Desch, in prep; next slides), $G_0 \sim 1000$.

See also Hester et al. (2004); Adams et al. (2010); Pfalzner (2012)

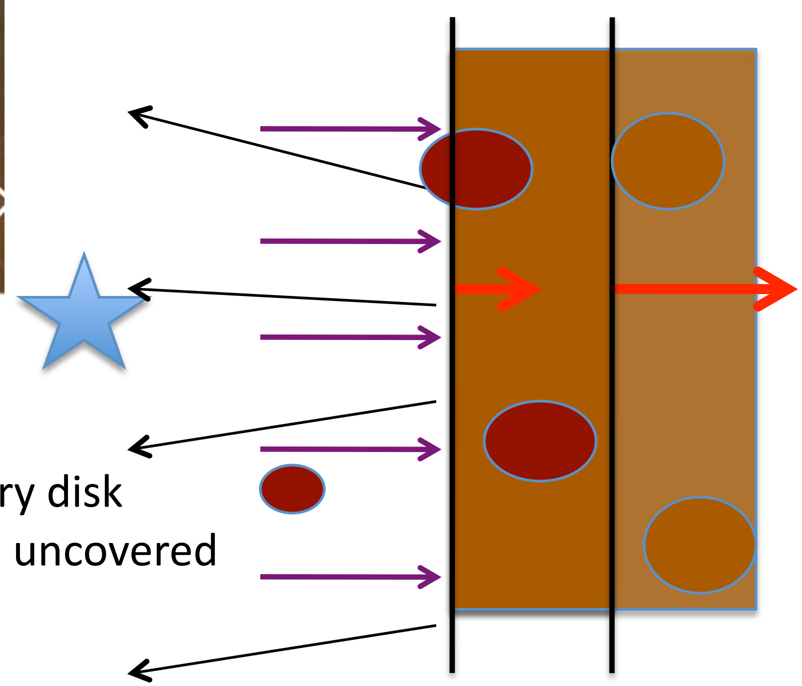


NGC 6357: Hester & Desch (2005)

Shocks are driven into molecular clouds, about few x 0.1 pc and 10^5 – 10^6 yr ahead of the (D-type) ionization fronts (Osterbrock 1989).

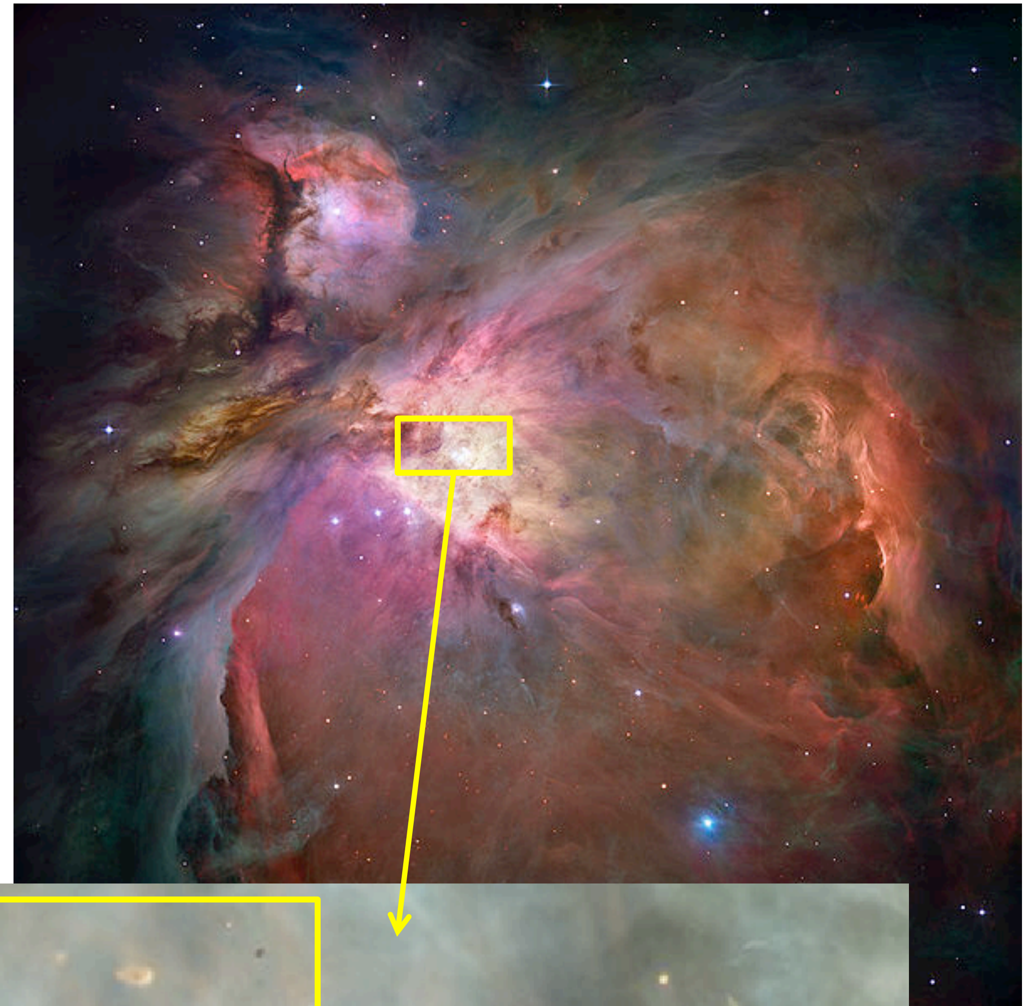
Star formation is triggered by this shock (Hester et al. 1996).

Strong evidence for prompt triggering (Snider et al. 2009).



This is the Sun's birth environment: our protoplanetary disk formed in the molecular cloud, then ~ 10^5 yr later was uncovered by ionization front, exposed to G_0 ~ 1000 FUV fields.

Protoplanetary disks in massive star-forming regions are subject to FUV photoevaporation --- and you can't ignore it!



Hubble Space Telescope images of "proplyds" in Orion (McCaughrean & O'Dell 1996).

#2. The disk was more massive, and steeper, than MMSN:

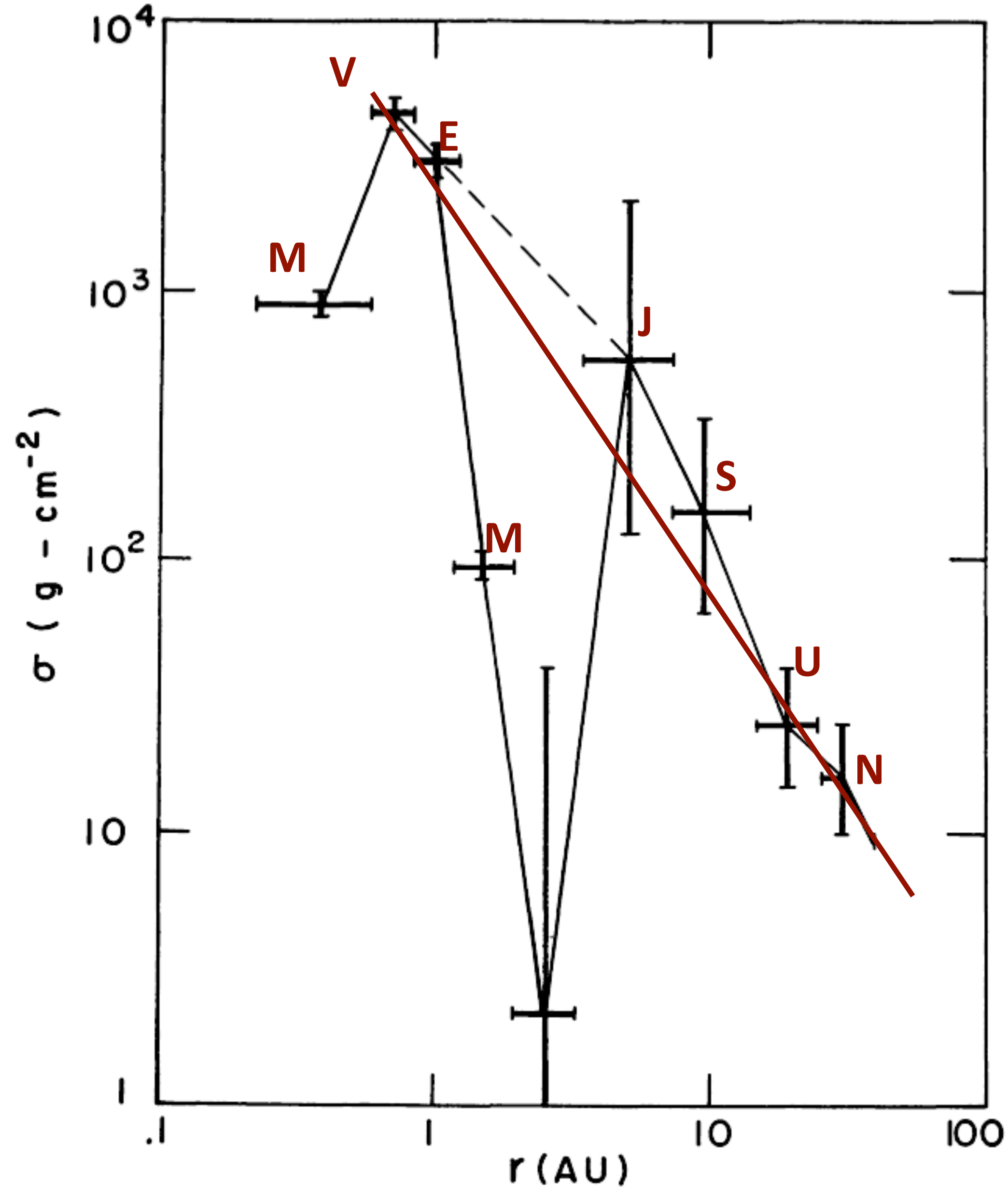
"Minimum Mass Solar Nebula"

Weidenschilling (1977) and Hayashi (1981) derived a rough power law:

$$\Sigma(r) \sim 1700\ (r/AU)^{-1.5}\ g\ cm^{-2}$$

Total mass in disk ~ 0.013 $M_\odot$

A *bad* model, but still the best approach for constraining Σ(r)... (until ALMA?)



Weidenschilling (1977)

Problems with the MMSN

1. The planets did not form where they are today

Neptune long known to have migrated outward > 10 AU to explain orbits of Pluto (Malhotra 1993) [and other 3:2 KBOs].

'Nice' model starts giant planets between 5 and 15 AU.

Other models (Walsh et al. 2011) suggest even closer.

=> Solar nebula was more compact than MMSN.

2. By construction it ignores lots of solids not in planets

Planet formation was not 100% efficient; 50% of solids likely in dust (Weidenschilling 2000) and lost with gas. Nice Model says primordial Kuiper Belt was ~ 35 M_E.

=> Solar nebula was more massive than MMSN.

3. Planet Formation requires higher densities

Jupiter's core requires 5x MMSN (Pollack et al. 1996; Lissauer et al. 2013).

No way to form Uranus and Neptune in disk lifetime (Lissauer & Stewart 1993).

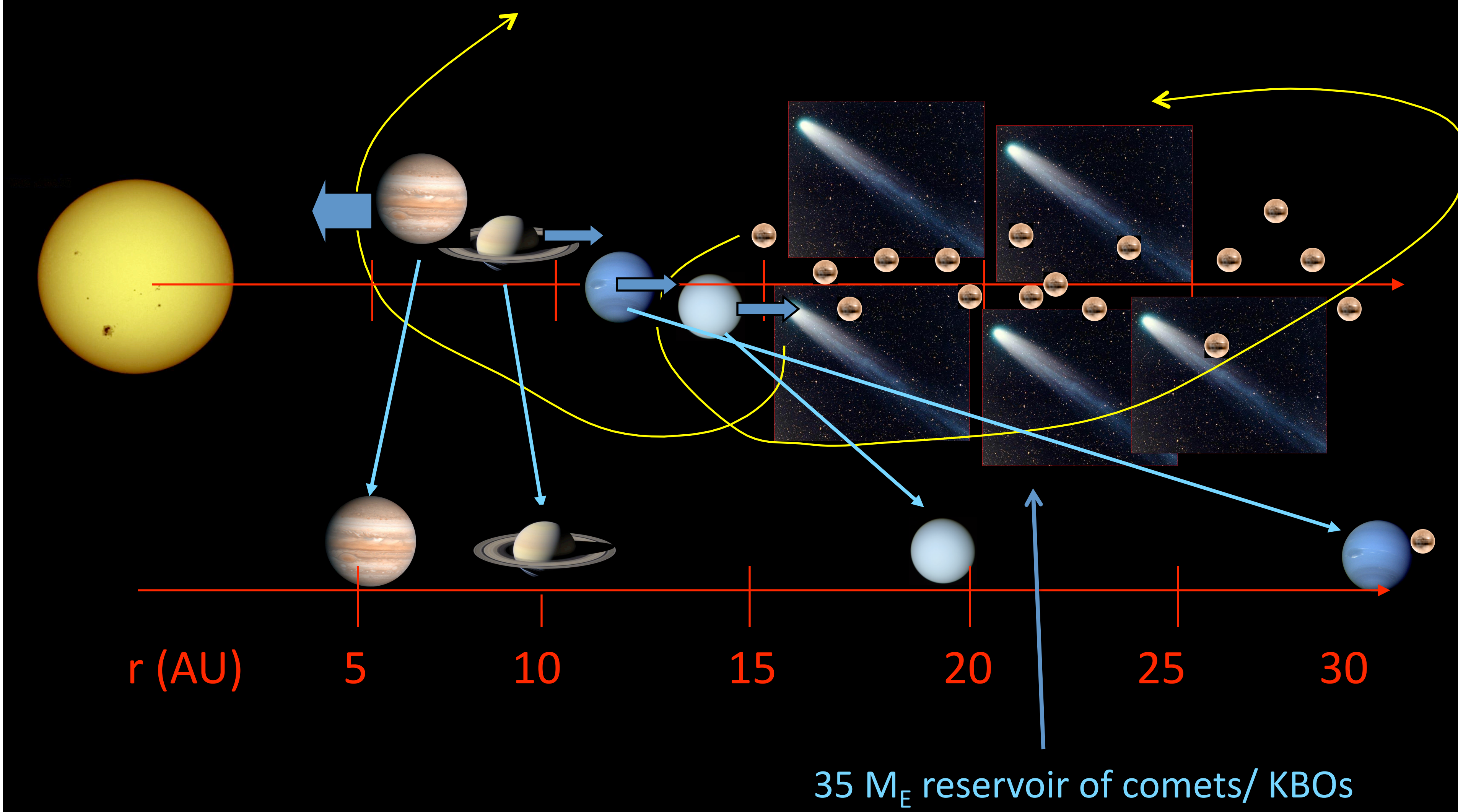
4. Chondrule formation requires higher densities at 2-3 AU

Most chondrules formed by shocks (Desch & Connolly 2002; Desch et al. 2012).

Melting requires $\rho > 10^{-9}$ g cm^{-3} (10 x MMSN) even for highest shock speeds (8 km/s).

The Nice Model (Tsiganis et al. 2005; Gomes et al. 2005; Morbidelli et al. 2005)

2:1 resonance crossing occurs about 650 Myr after solar system formation



Updated MMSN: $\Sigma(r) \sim r^{-2.2}$

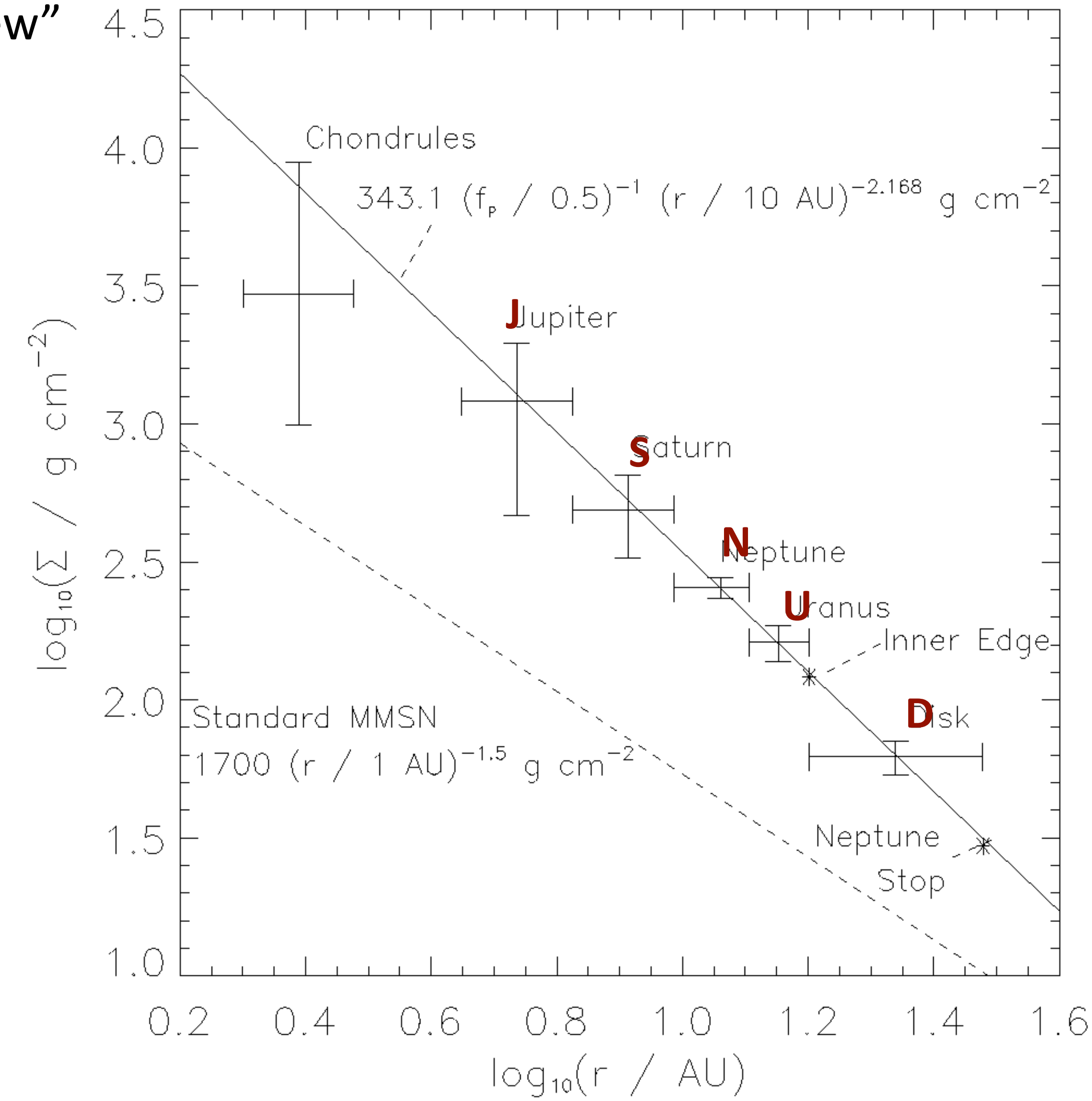
Desch (2007) derived $\Sigma(r)$ of "new" MMSN using Nice model results

Much higher surface densities:
- More compact configuration
- Includes extra 35 M_E

Higher overall mass ~ 0.09 $M_\odot$

Steeper profile in outer disk (> 3 AU): $\Sigma(r) \sim r^{-2.2}$

Still subject to caveats:
- Planets may not have formed at these locations, either.
- Planets need not accrete locally.



#3: Alpha was non-uniform:

$\Sigma(r) = r^{-p}$ is expected from equations of steady-state protoplanetary disks (Lynden-Bell & Pringle 1974), but usually p ≈ 1.

$$\frac{\partial}{\partial t}(\Sigma r^2 \nu) = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\dot{M}}{2\pi}r^2\Omega + r^3\Sigma\nu\frac{\partial\Omega}{\partial r}\right) \qquad \frac{\partial\Sigma}{\partial t} = \frac{1}{2\pi r}\frac{\partial\dot{M}}{\partial r}$$

$$\frac{-\dot{M}}{2\pi}r^2\Omega - r^3\Sigma\nu\frac{\partial\Omega}{\partial r} = \text{const.}$$

Now ignore outer boundary and assume $d\Omega/dr = 0$ at $r=R_\star$:

$$\Sigma(r) = \frac{\dot{M}}{3\pi\nu(r)}\left[1 - \left(\frac{R_\star}{r}\right)^{1/2}\right] \approx \frac{\dot{M}}{3\pi\nu(r)}$$

If $\nu(r) = \alpha\, C\, H = \alpha\, C^2 / \Omega$, then $\nu(r) \sim \alpha\, T\, r^{3/2} \sim \alpha\, r^{3/2-q}$.

Typically $T(r) \sim r^{-q}$, $q \approx ½$.

If α = constant and dM/dt = uniform, then $\Sigma(r) \sim r^{-p}$., $p = 3/2 - q \approx 1$

Protoplanetary Disk Evolution --- Why is $\Sigma(r) \sim r^{-2.2}$?

Desch (2007) used same equations

$$\frac{\partial}{\partial t}(\Sigma r^2 \nu) = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\dot{M}}{2\pi} r^2 \Omega + r^3 \Sigma \nu \frac{\partial \Omega}{\partial r}\right) \qquad \frac{\partial \Sigma}{\partial t} = \frac{1}{2\pi r}\frac{\partial \dot{M}}{\partial r}$$

$$\frac{-\dot{M}}{2\pi} r^2 \Omega - r^3 \Sigma \nu \frac{\partial \Omega}{\partial r} = \mathrm{const.}$$

Now ignore ***inner*** boundary and assume $d\Omega/dr = 0$ at ***outer*** disk edge $r=r_d$:

$$\Sigma(r) = \frac{(-\dot{M})}{3\pi\nu(r)}\left[\left(\frac{r_{\rm d}}{r}\right)^{1/2} - 1\right]$$

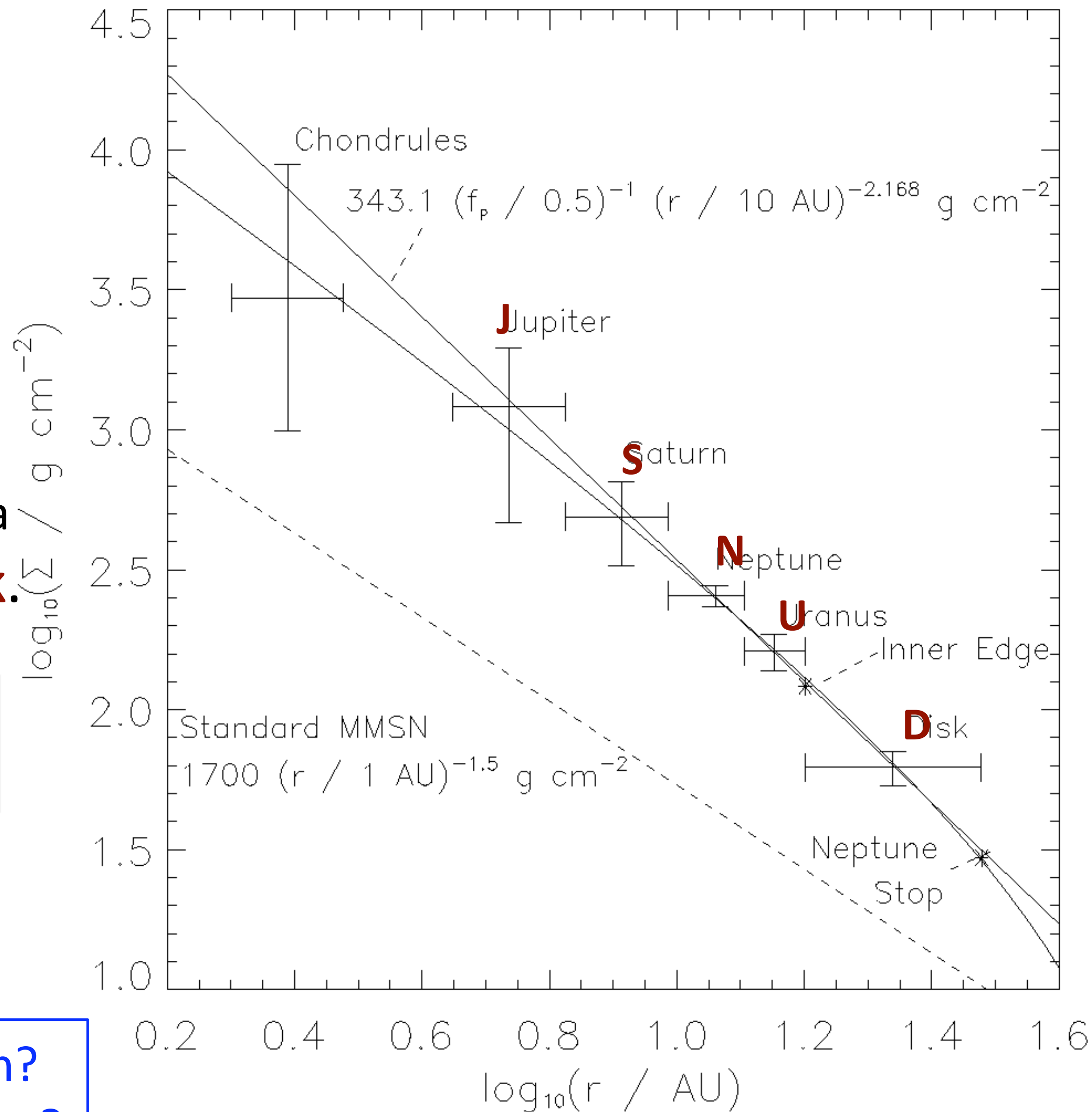
Disk marked by outward transport ($dM/dt < 0$).
Takeuchi & Lin (2002): if $p+q > 2$, net transport must be outward.
Steady-state ***decretion*** disk.
Similar solution derived by Canup & Ward (2002) for circumjovian disk.

Protoplanetary Disk Evolution --- Why is $\Sigma(r) \sim r^{-2.2}$?

Fits with r_d = 40 -100 AU provide very good match to constraints from planet masses, chondrule formation, disk erosion, and Neptune's migration.

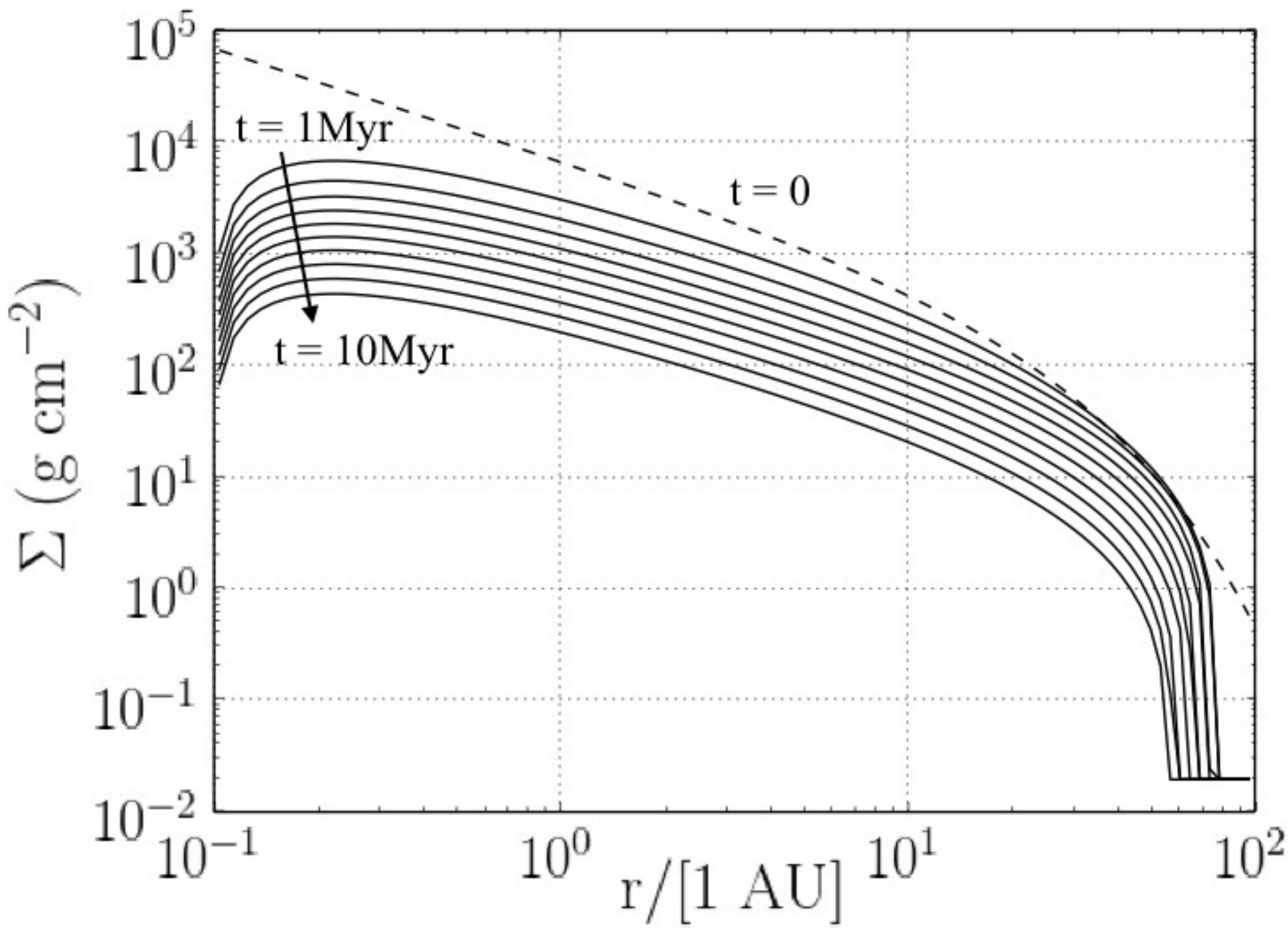
Solar nebula surface density profile could be consistent with a **steady-state decretion disk**.

$$\Sigma(r) = \frac{(-\dot{M})}{3\pi\nu(r)} \left[\left(\frac{r_\mathrm{d}}{r} \right)^{1/2} - 1 \right]$$



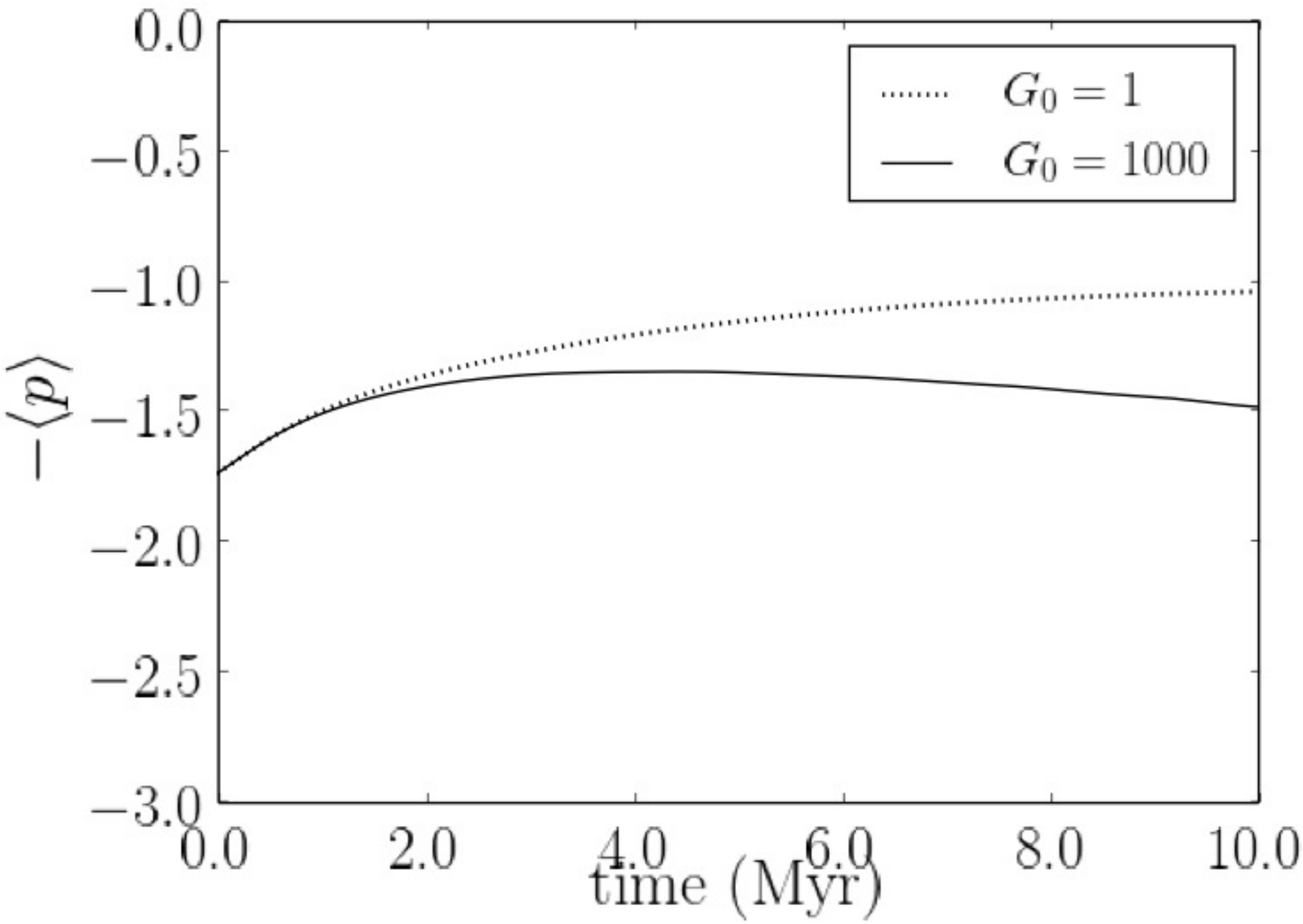
Is steady state a valid assumption?
Do *evolving* disks reach -2.2 slopes?

Photoevaporated Disks with Uniform Alpha



Surface density vs. heliocentric distance, using uniform alpha = 10^{-3}.
Disk evolution nearly self-similar.

Photoevaporated Disks with Uniform Alpha



Slope of surface density profile between 5 and 30 AU: p = -d log Σ / d log r.
Slope nearly constant, -1, if G_0 = 1; slope nearly constant, -1.5, if G_0 = 1000.
Similar results founds by Mitchell & Stewart (2010).

Photoevaporated Disks with Non-Uniform Alpha

Assume turbulent viscosity due to magnetorotational instability.

Bai and Stone (2011) simulations suggest that if magnetic turbulence is saturated, magnetic field is maximally amplified, and $\langle\beta\rangle = \beta_{min}$, then local value of alpha given by

$$\alpha = \frac{1}{2\beta_{\rm min}} \qquad \mathbf{Am} \equiv \frac{\gamma \rho_i}{\mathbf{\Omega}}$$

$$\beta_{\rm min}({\rm Am}) = \left[\left(\frac{50}{{\rm Am}^{1.2}} \right)^2 + \left(1 + \frac{8}{{\rm Am}^{0.3}} \right)^2 \right]^{1/2}$$

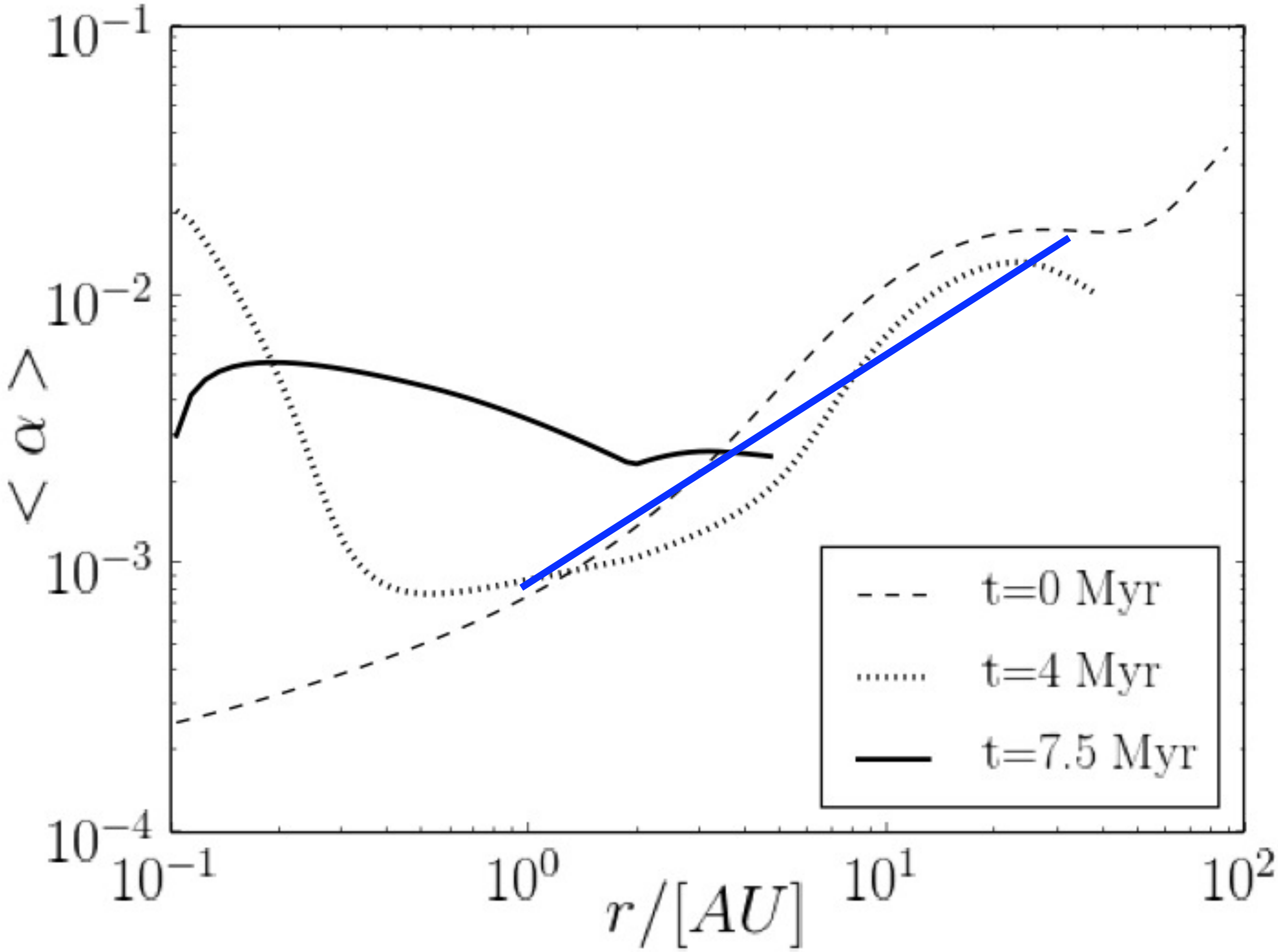
For now we determine local n_i by balancing cosmic-ray and X-ray ionizations against gas-phase recombinations (dust-free case):

$$(\zeta_{\rm cr} + \zeta_{\rm xr})\, n_{\rm H} = \beta_{\rm dr}\, n_{\rm e}\, n_{\rm i}$$

We account for attenuation of X-ray ionization (Glassgold et al. 1997, 1999) and cosmic rays (Umebayashi & Nakano 1986).

Alpha is vertically averaged, weighted by mass.

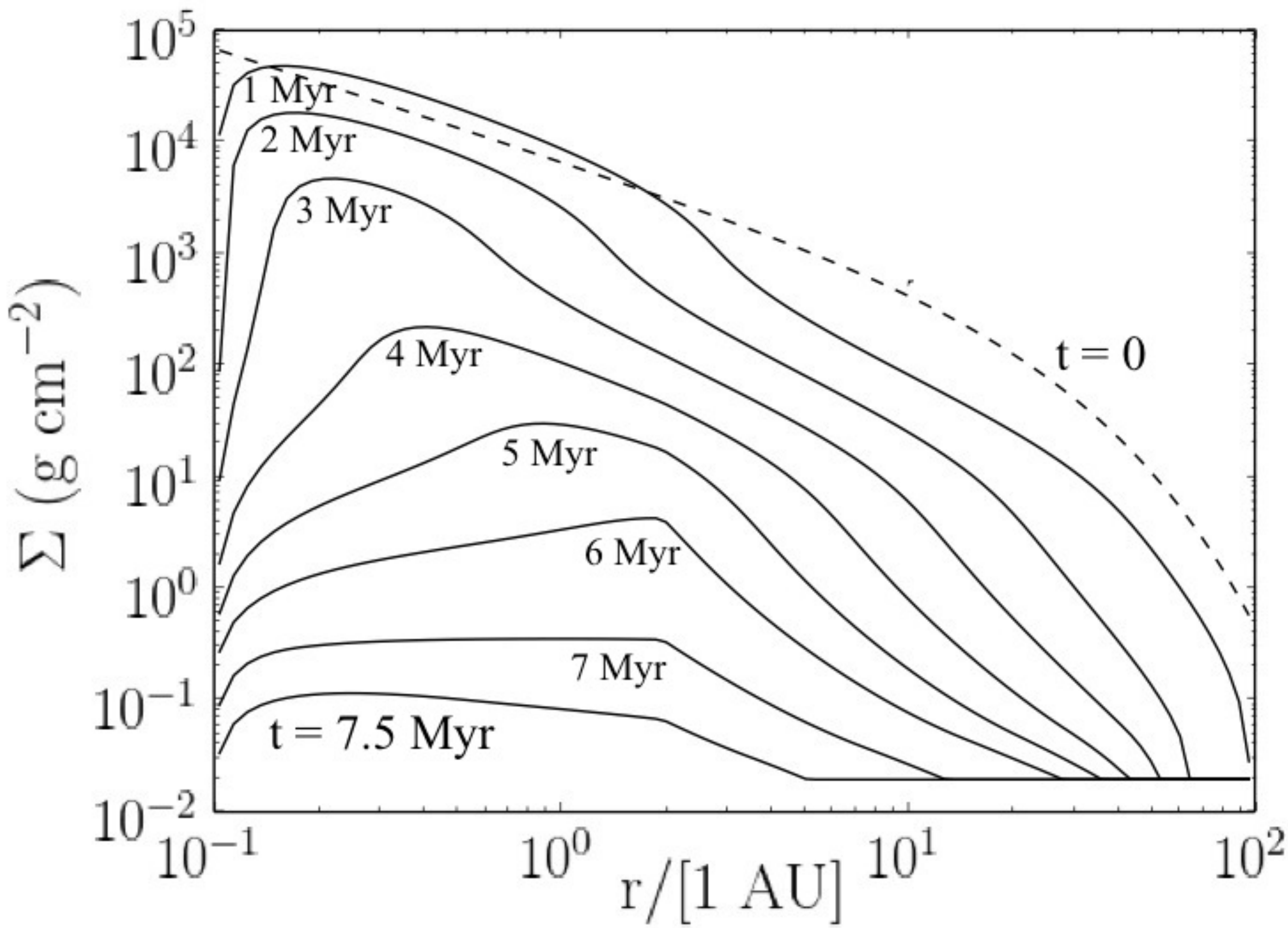
Photoevaporated Disks with Non-Uniform Alpha



Vertically averaged alpha vs. heliocentric distance, assuming Bai & Stone (2011) formulation and dust-free ionization chemistry.

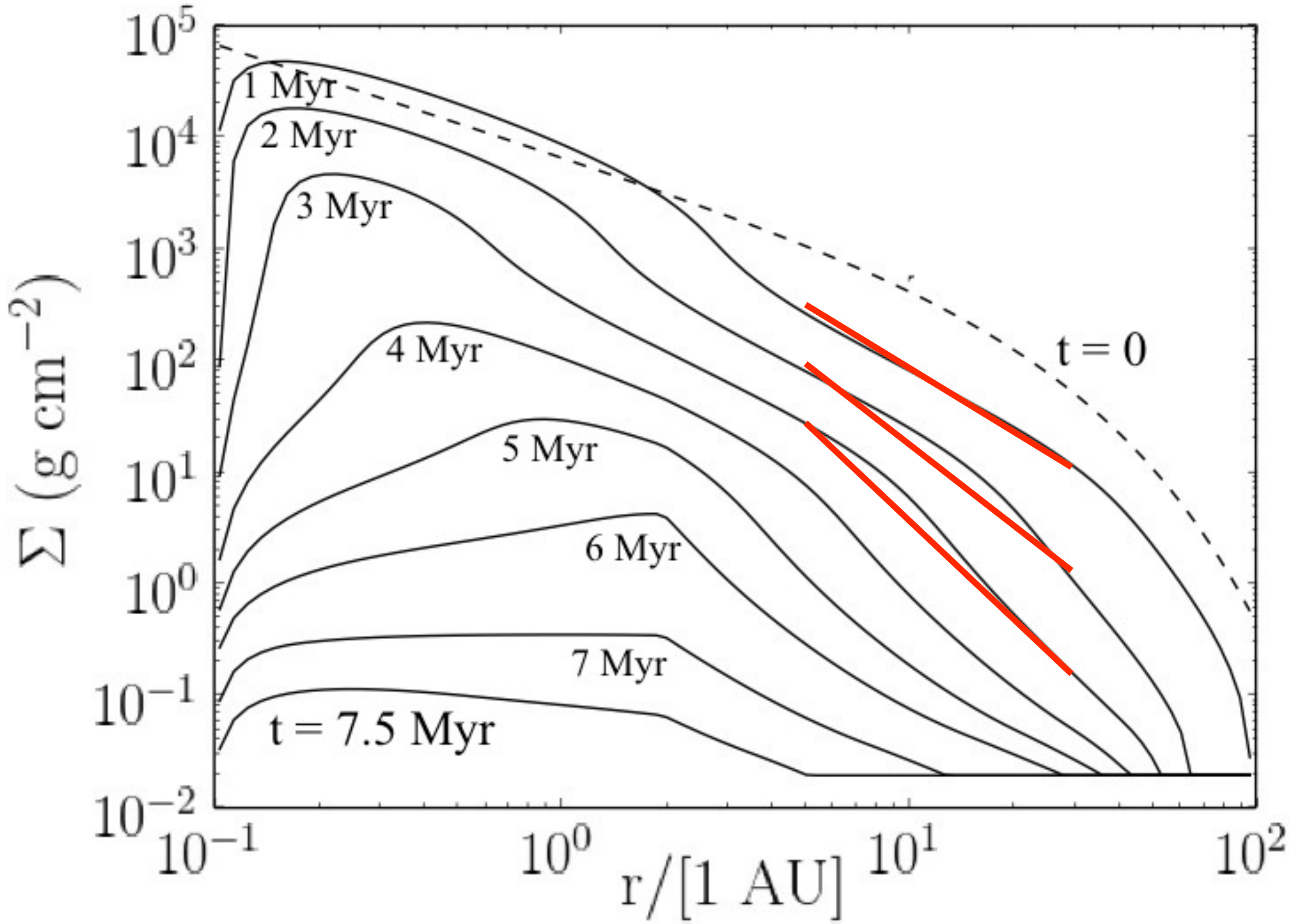
Outer annuli (> 10 AU) very turbulent ($\alpha \sim 10^{-2}$), inner annuli less so ($\alpha \sim 10^{-3}$).

Photoevaporated Disks with Non-Uniform Alpha



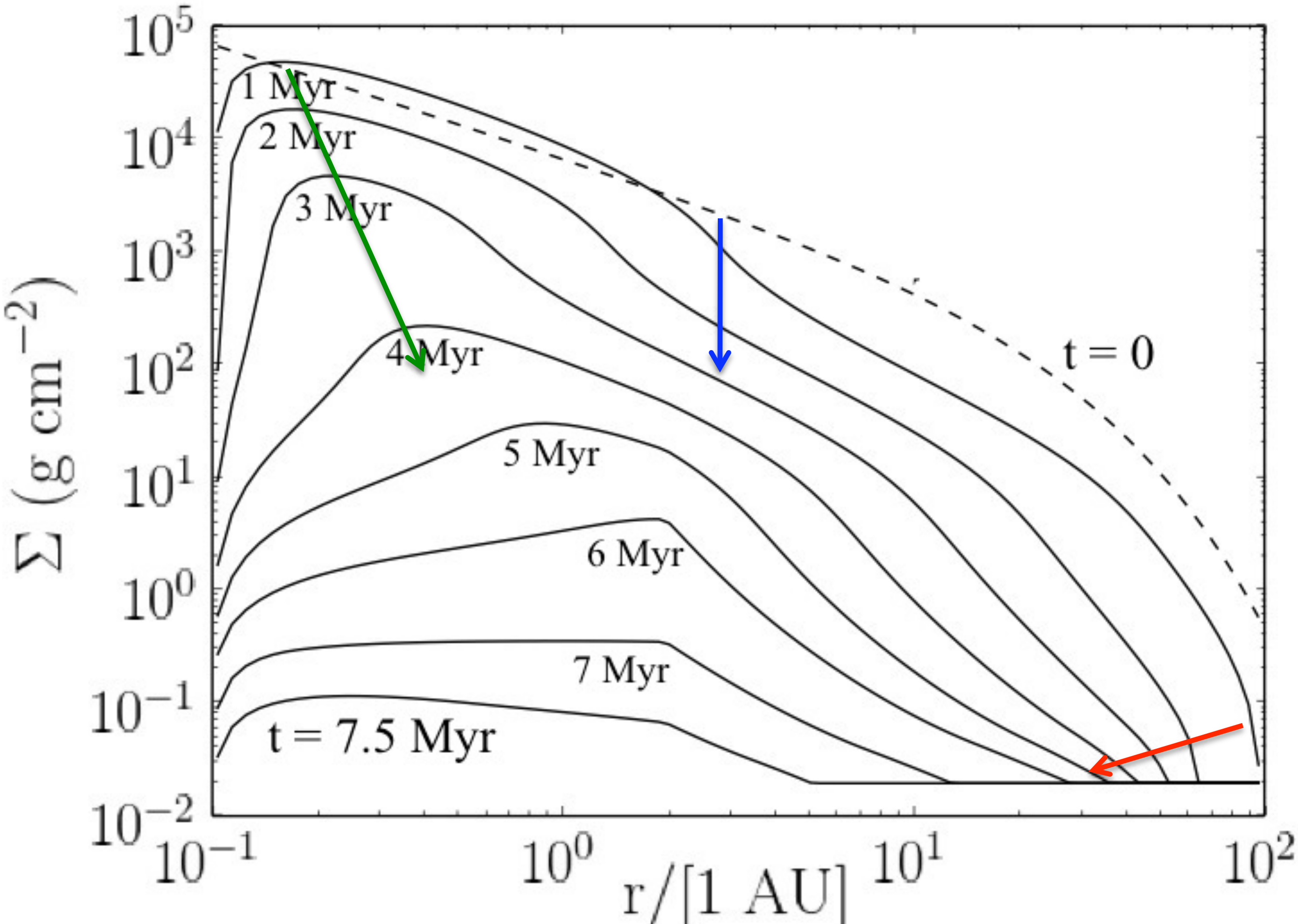
Surface density vs. heliocentric distance, using spatially varying alpha defined above. Outermost annuli lost more quickly. Far from a power law!

Photoevaporated Disks with Non-Uniform Alpha



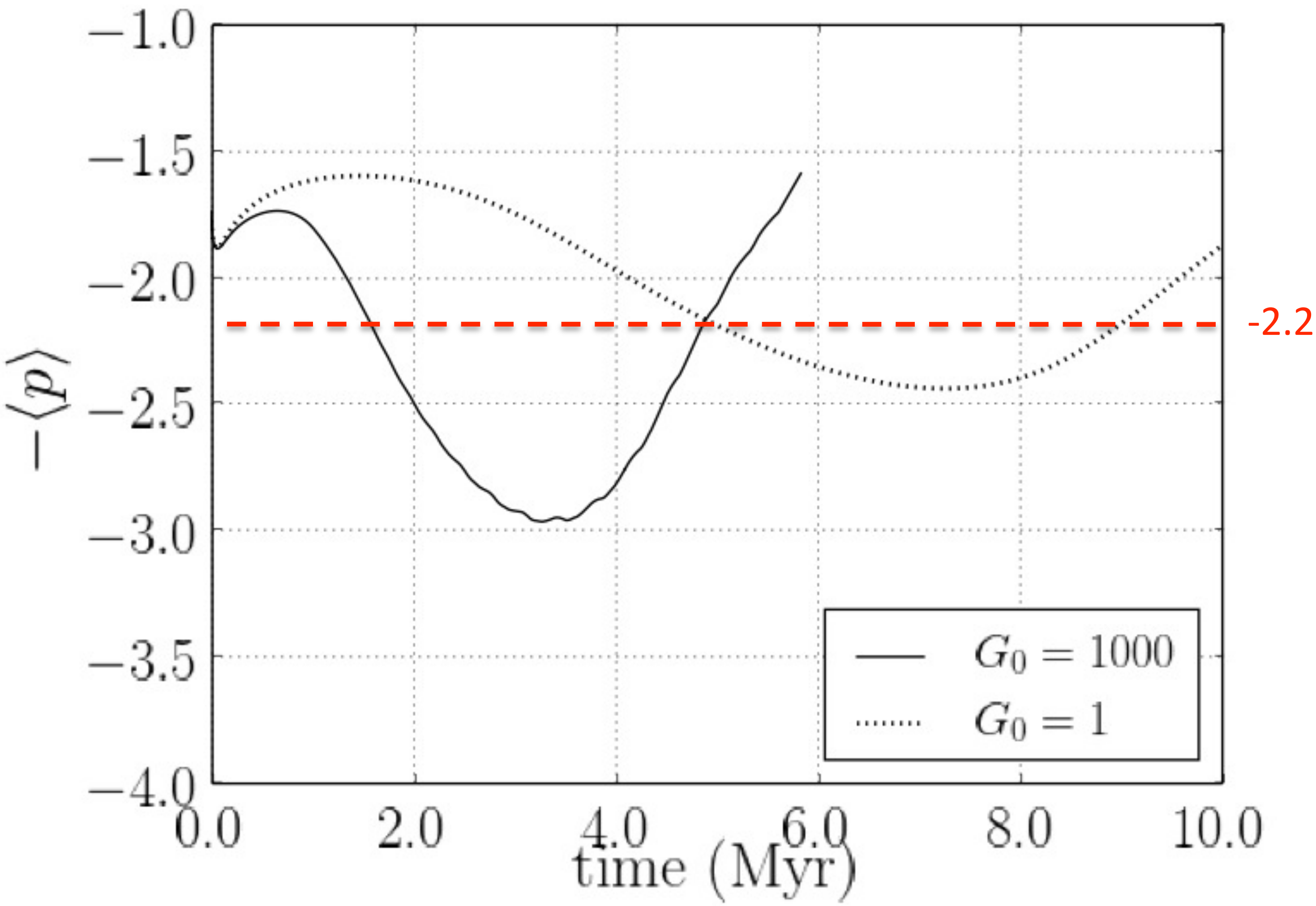
Surface density vs. heliocentric distance, using spatially varying alpha defined above. Outermost annuli lost more quickly. Slope grows more negative.

Photoevaporated Disks with Non-Uniform Alpha



Surface density vs. heliocentric distance, using spatially varying alpha defined above. Unfortunately, this disk evolved too quickly: chondrules formed at 2-3 AU, at 3 Myr. But disk outer edge is about right. Note surface density (and pressure?) maximum.

Photoevaporated Disks with Non-Uniform Alpha

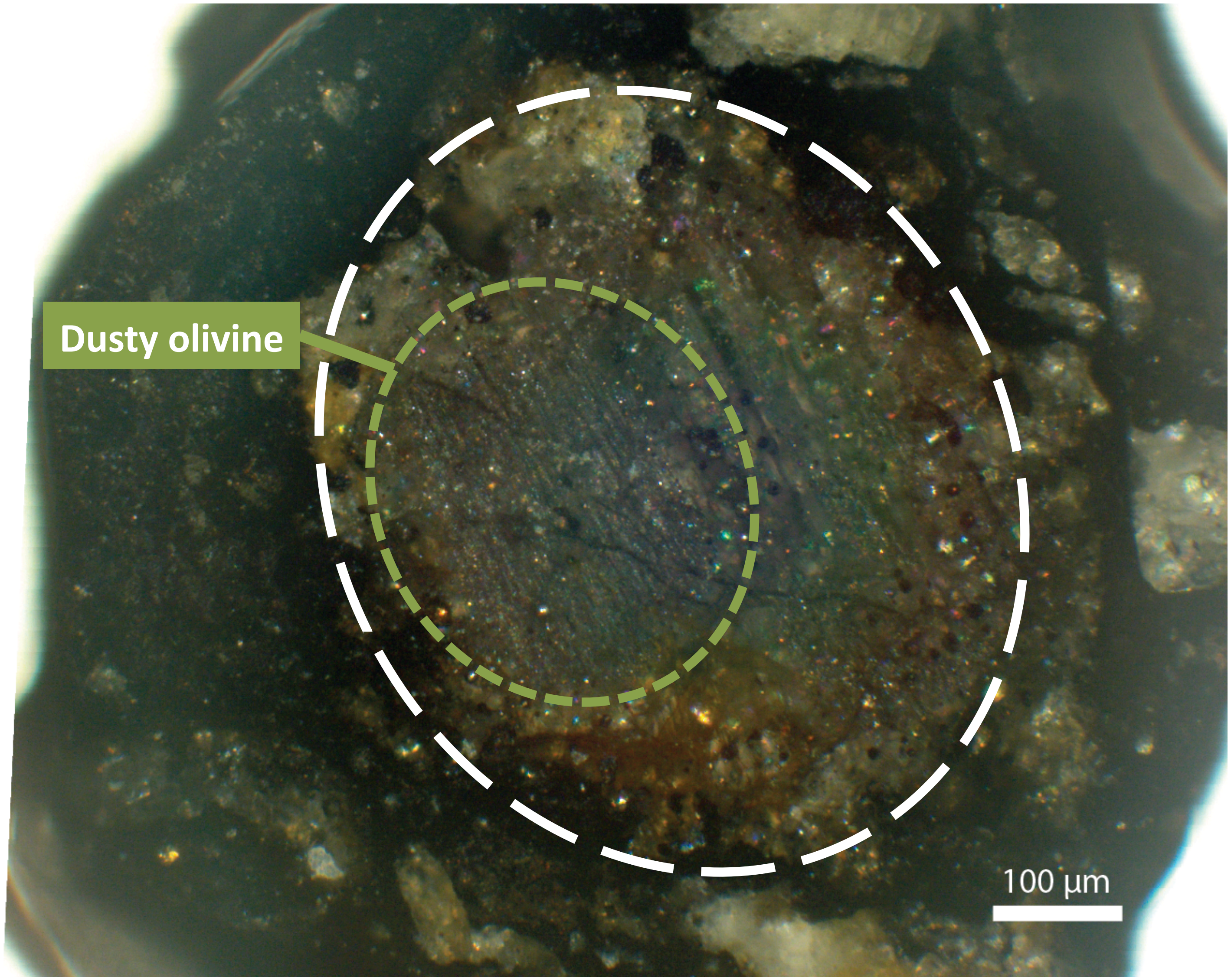


Slope of surface density profile between 5 and 30 AU. If G_0 = 1000, slope centers on -2.2 during first 2 Myr of disk evolution (while planets are forming).

#5: B was ~ 0.1 G in the disk:

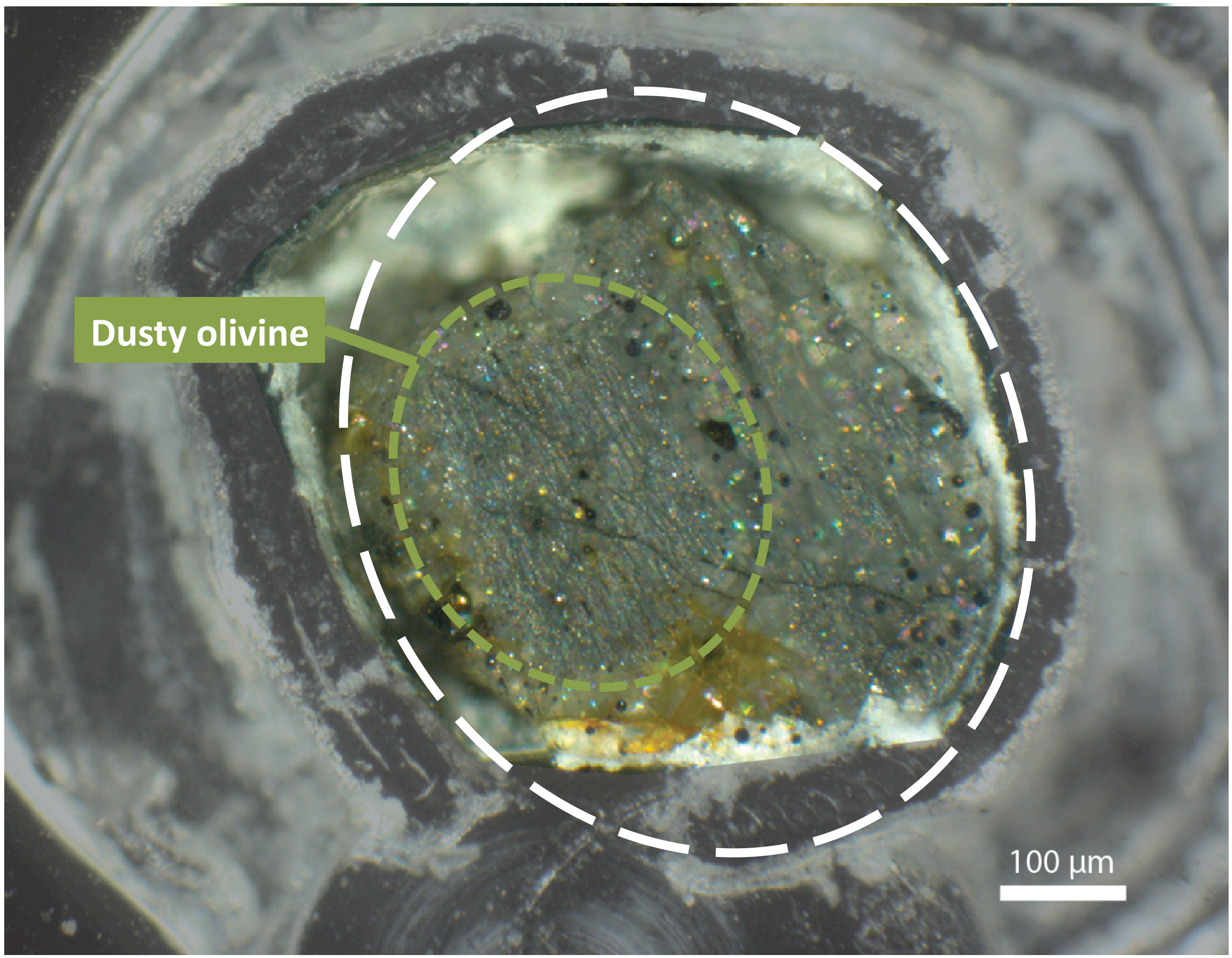
Semarkona chondrule in slab cut by magnetically clean wire saw at AMNH.

Dusty olivine = olivine crystal in a chondrule, with single-domain kamacite (FeNi) inclusions, Curie points 1038 K.



Chondrules record magnetic fields existing during chondrule formation

Matrix and metal- and sulfide–rich rim removed by magnetically clean micromill in MIT Paleo-magnetism Lab.



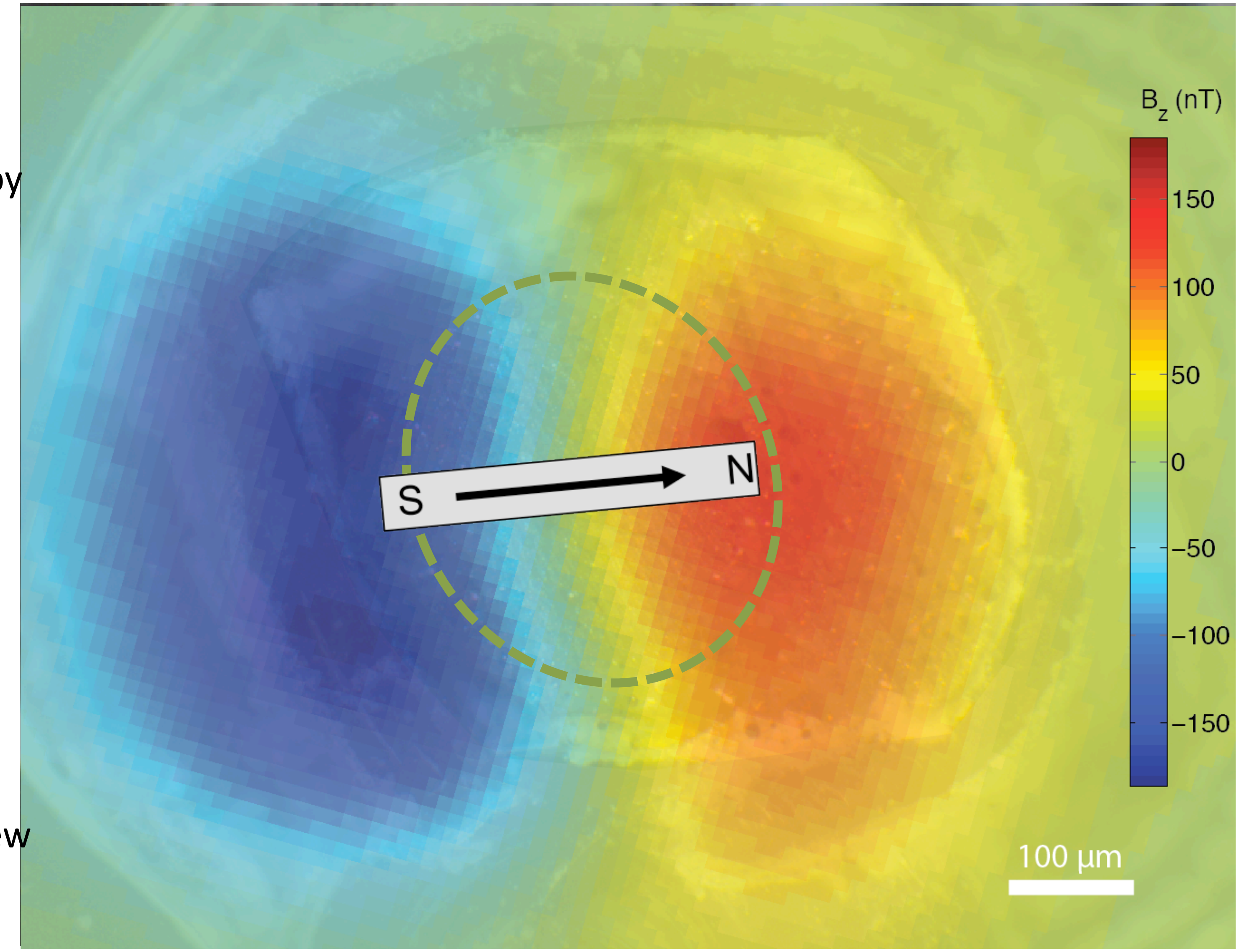
Chondrules record magnetic fields existing during chondrule formation

New magnetic map of dusty olivine-rich chondrule

Magnetic fields measured by SQUID microscopy at MIT Paleo-magnetism Lab.

Chondrules are tiny (randomly oriented) bar magnets

Paleofield=
71 ± 40 μT.
= 0.71 ± 0.40 G
(Fu et al., in review at *Science*)



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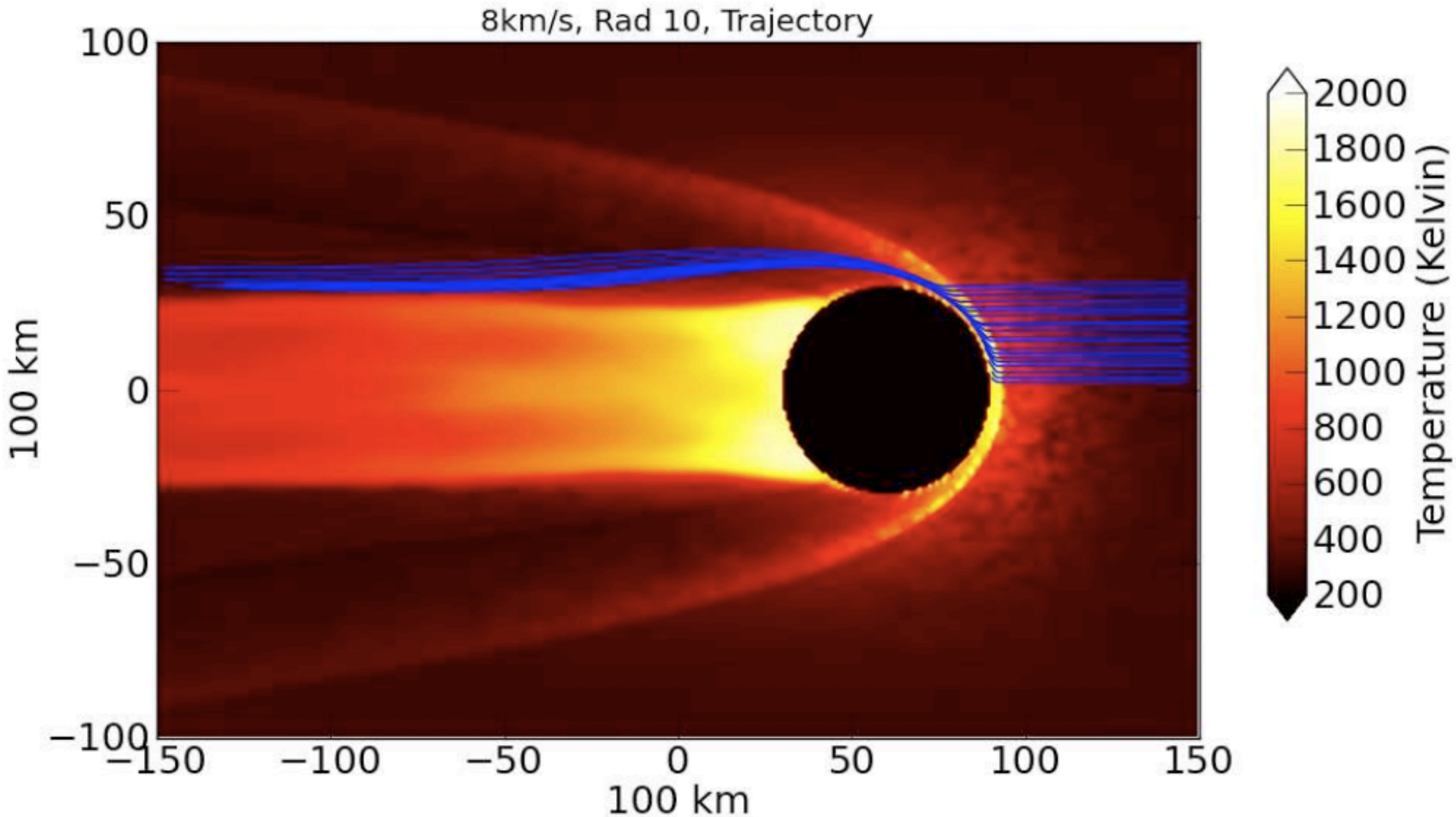
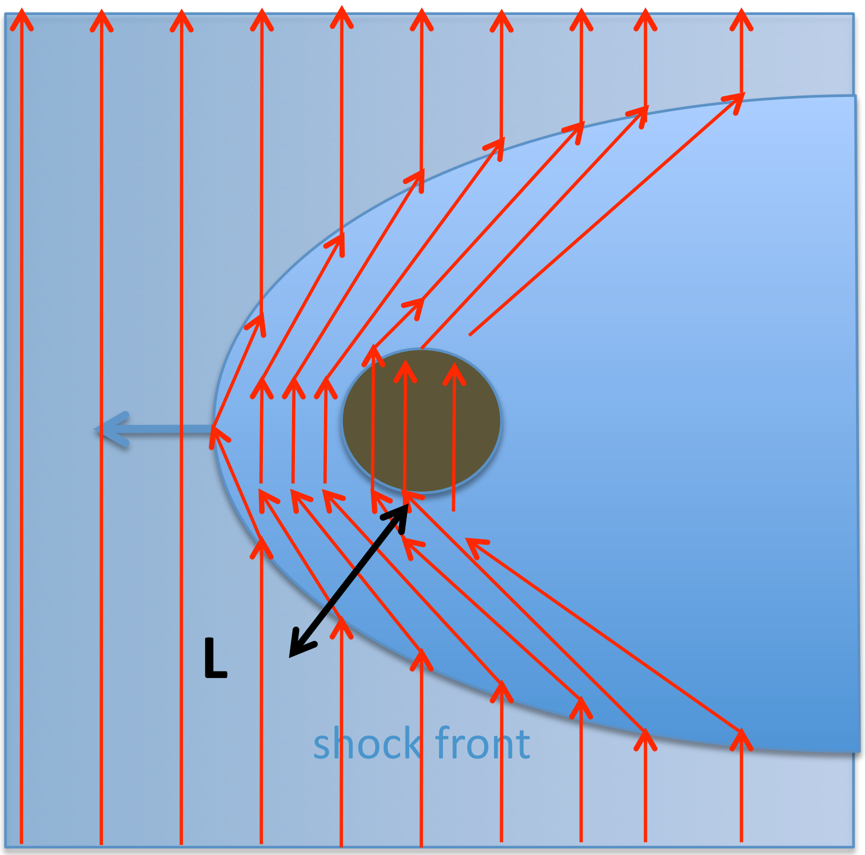


Boley et al. (2013)

Magnetic Fields in Planetary Bow Shocks with Magnetic Diffusion



In planetary embryo bow shock model (Morris et al. 2012; Boley et al. 2013), compressed B can diffuse out of shocked region on timescale $t_{diff} \sim L^2 / D$,

$$\mathcal{D} = \frac{c^2}{4\pi} \frac{1}{\sigma_e}$$

$$= 1.4 \times 10^{18} \left(\frac{T}{1000\,\mathrm{K}}\right)^{1/2} \left(\frac{n_e/n_n}{10^{-13}}\right)^{-1} \mathrm{cm}^2\,\mathrm{s}^{-1}$$

If t_{diff} << hours, B = 1 x background field

If t_{diff} >> hours, B ≈ 10 x background field.

Much (MHD) work needs to be done to translate B during chondrule formation (700 mG) to B in solar nebula (70 – 700 mG ?).

Sure looks like B ~ 0.1 G! (see: Desch & Mouschovias 2001)

Some things I have learned about protoplanetary disks using meteoritic and planetary data:

1. Our disk formed in a high-mass star-forming region and experienced external photoevaporation with $G_0 \approx 1000$.

2. Our disk was far more massive and dense than the Minimum Mass Solar Nebula, with a much steeper profile: $\Sigma(r) \sim r^{-2.2}$.

3. Alpha had to increase with heliocentric distance.

4. The field strength in the disk was $B \sim 0.1$ G.

One more thing I've (just) learned about protoplanetary disks:

I just realized that **thermionic emission** should dominate charging in PPDs for T above ≈ **700 K**.

This has nothing to do with thermal ionization or potassium (which I contend is not in eqbm).

The same grains that remove electrons from the gas also put electrons in the gas, so n_e is independent of density or grains (so long as they dominate).

n_e depends only on temperature, but rises steeply with T, because (effective) work functions of silicates likely to be only ≈ 2.5 eV (Desch & Cuzzi 2000).

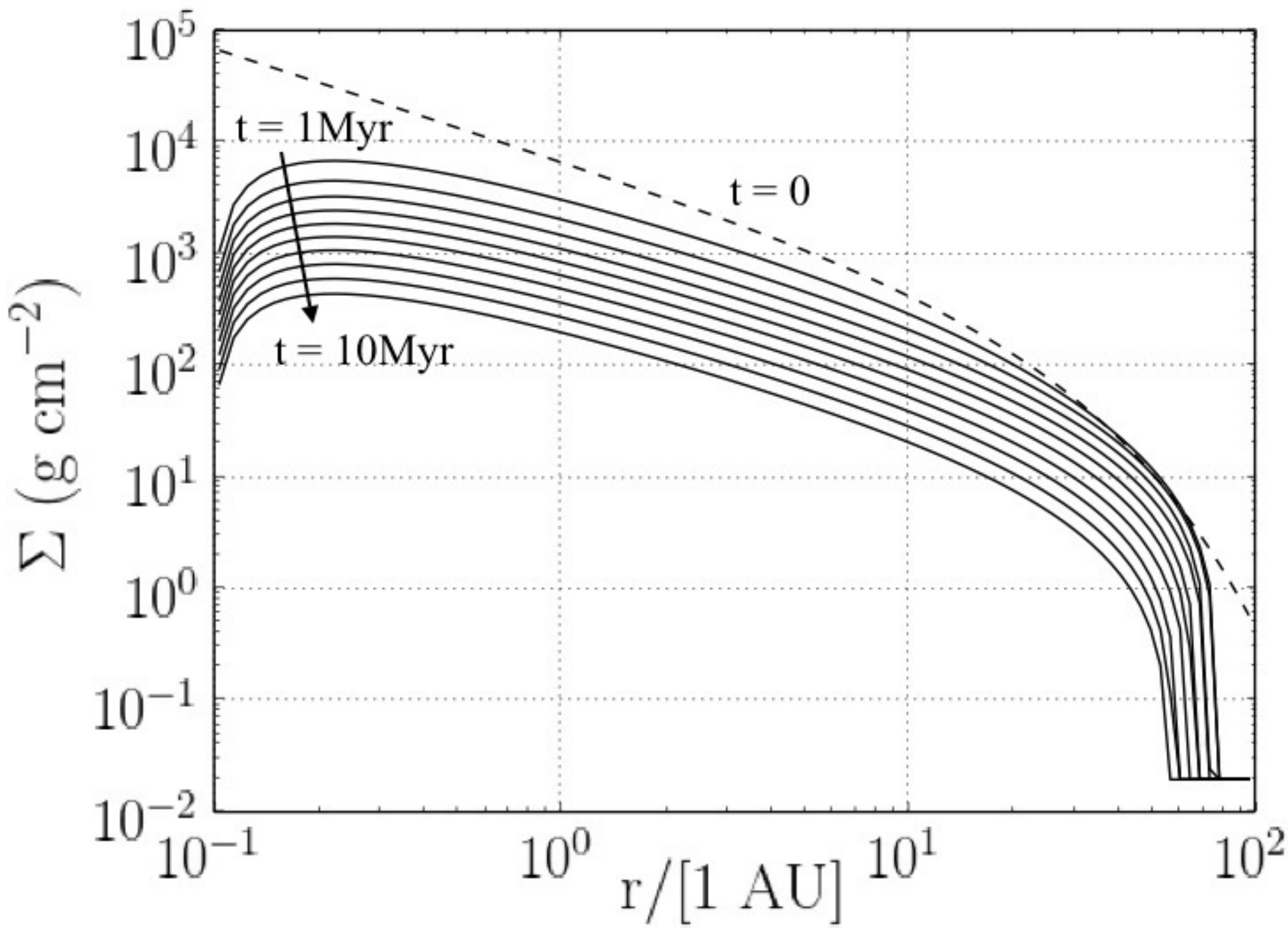
$$n_{\rm e} = 1.2 \times 10^{15}\, T^{3/2}\, \exp\left(-\frac{W/k}{T}\right)\ {\rm cm}^{-3}$$

Dust grains positively charged, but not severely; $x_e = 10^{-13}$ means Z ≈ +10 [1 μm grains, d/g=0.01]

Yes, n_e increases with T, but kinetics may still take a long time (1 year at 1000 K ?)

Extra slides = disk evolution models with uniform alpha and variable alpha

Photoevaporated Disks with Uniform Alpha



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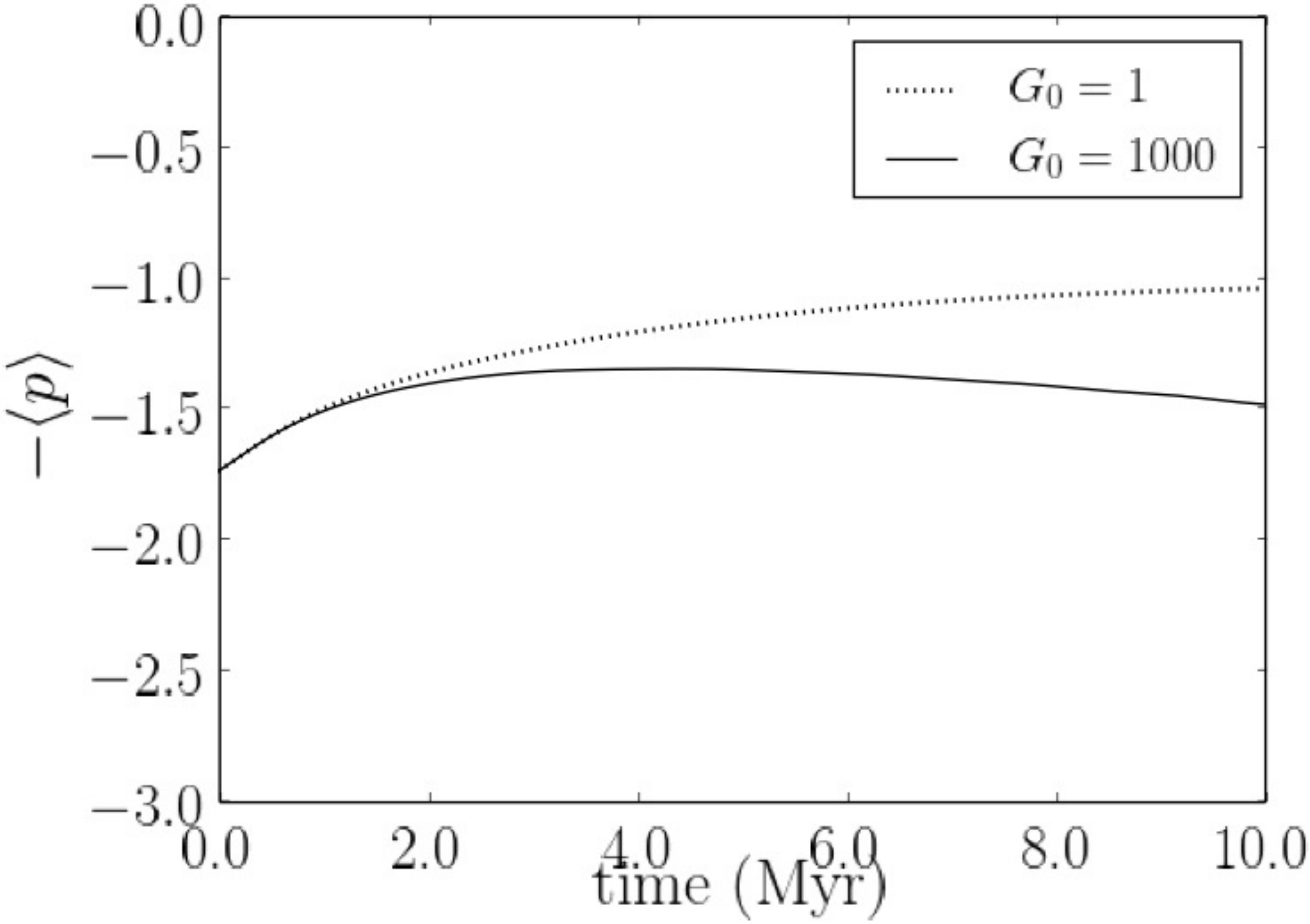

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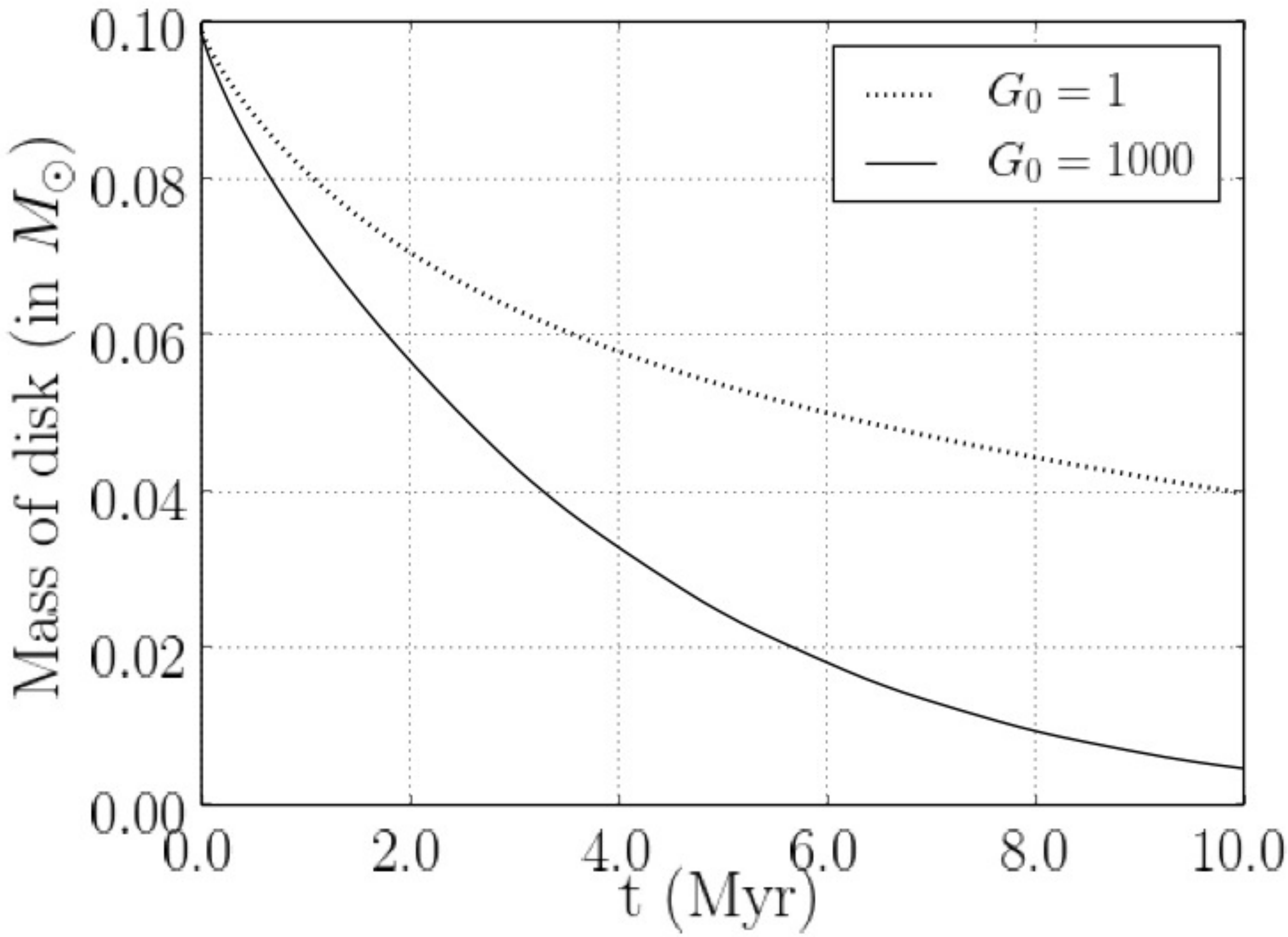
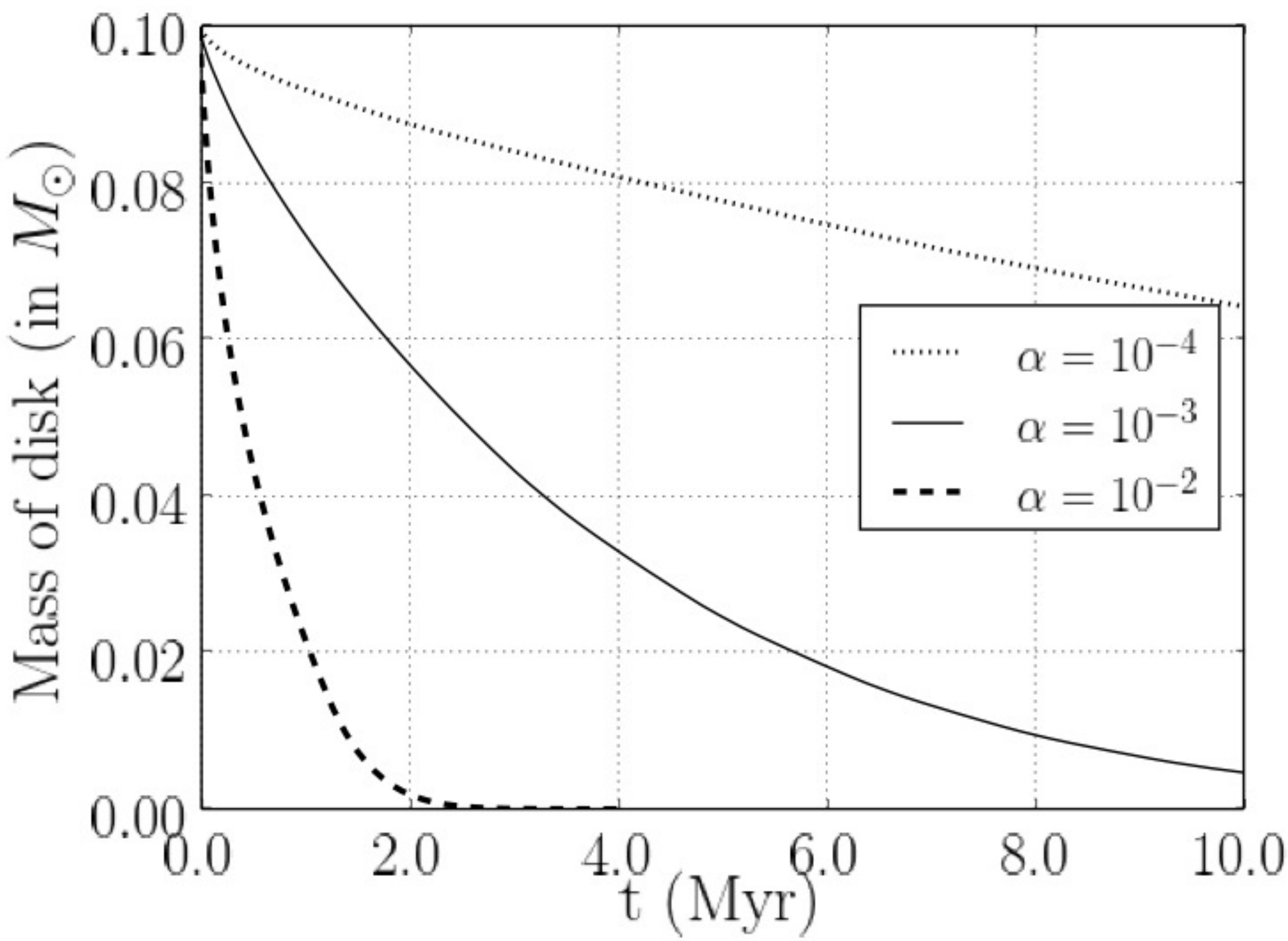


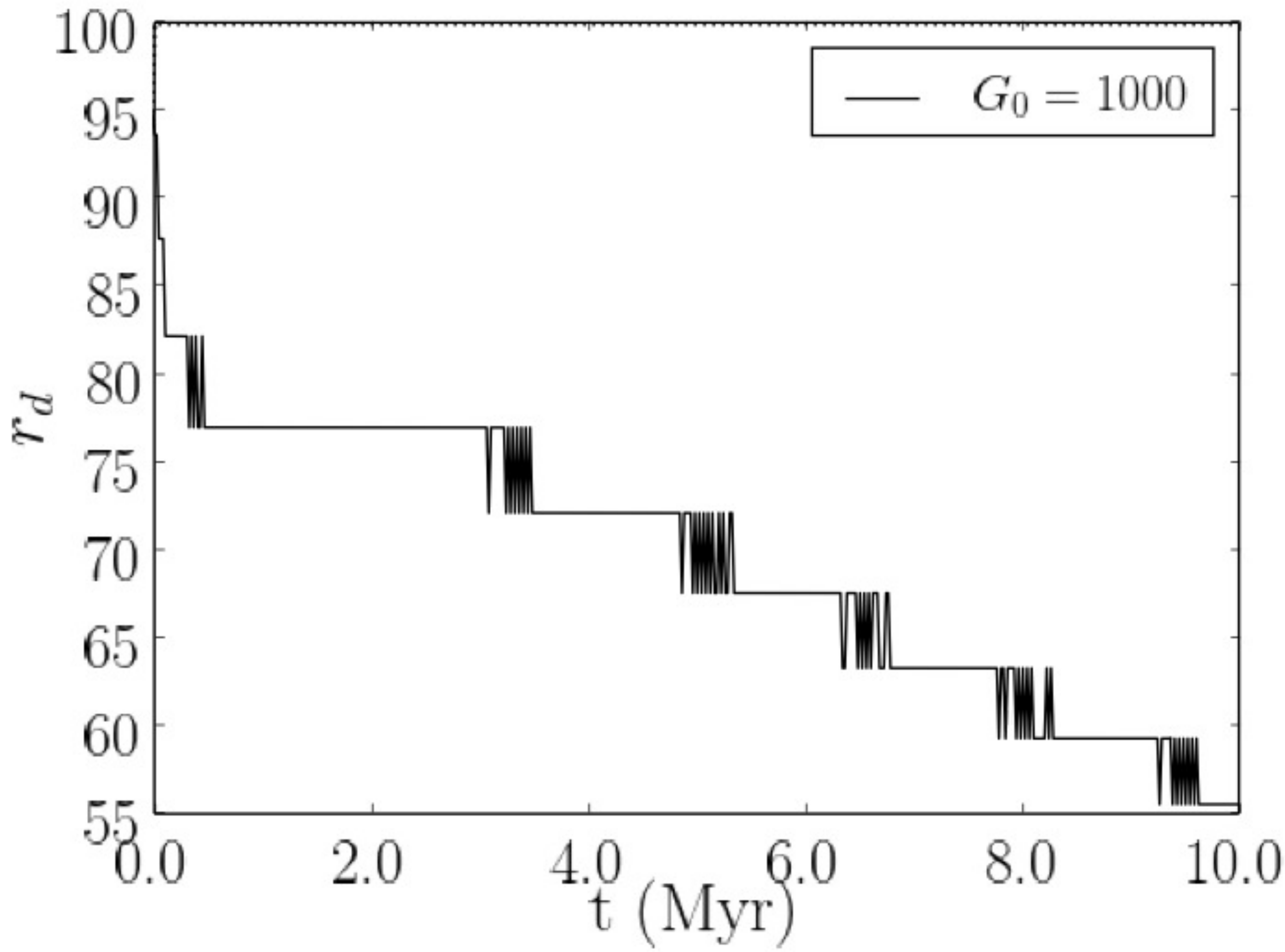
Photoevaporation removes mass from the disk:
Mass in disk falls by half in 6 Myr if G_0 = 1, in 2.5 Myr if G_0 = 1000.

Photoevaporated Disks with Uniform Alpha



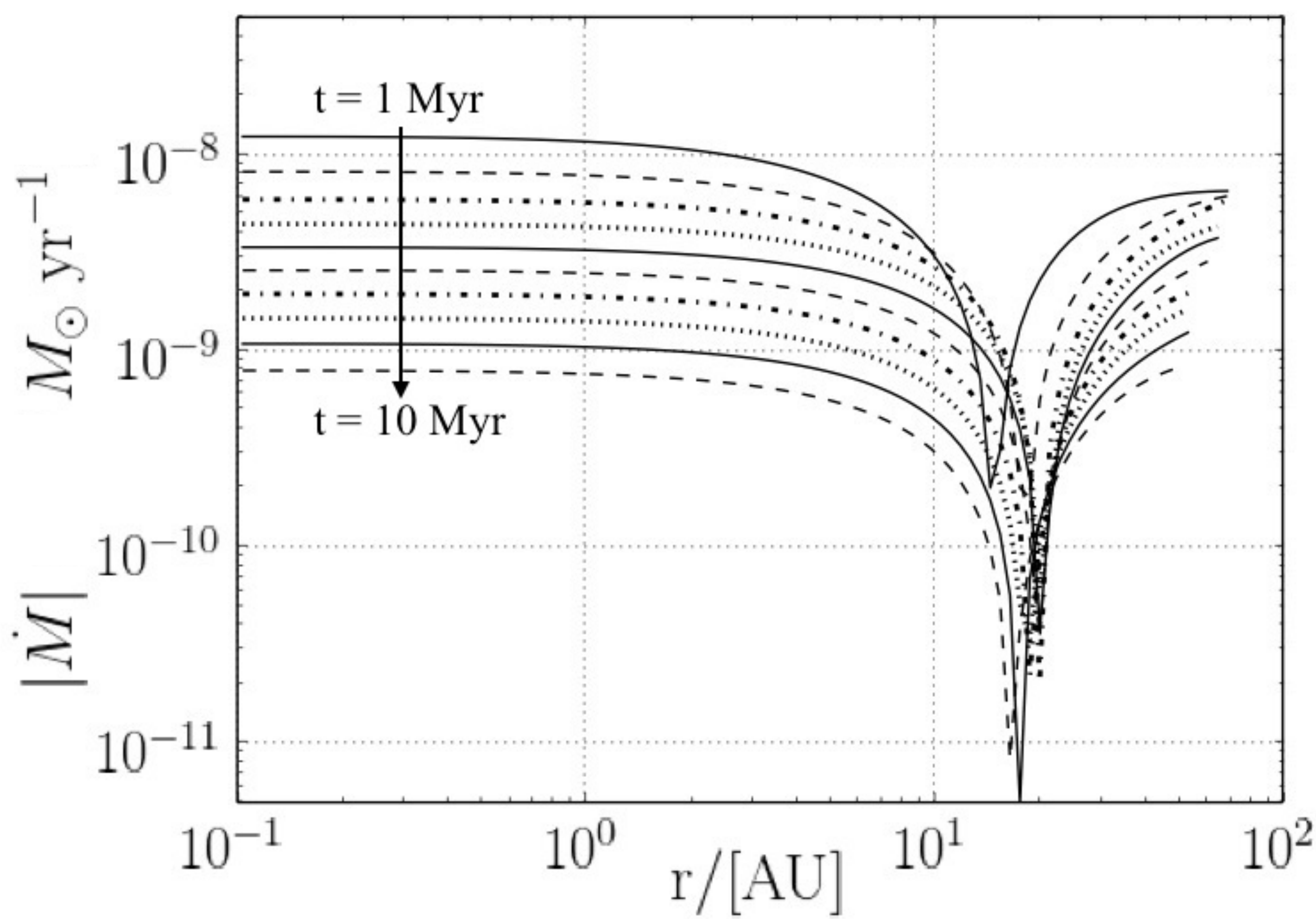
Larger alpha means faster delivery of mass to outer edge.
Assuming G_0 = 1000, mass in disk falls by half in 2.5 Myr if $\alpha = 10^{-3}$, < 0.3 Myr if $\alpha = 10^{-2}$.

Photoevaporated Disks with Uniform Alpha



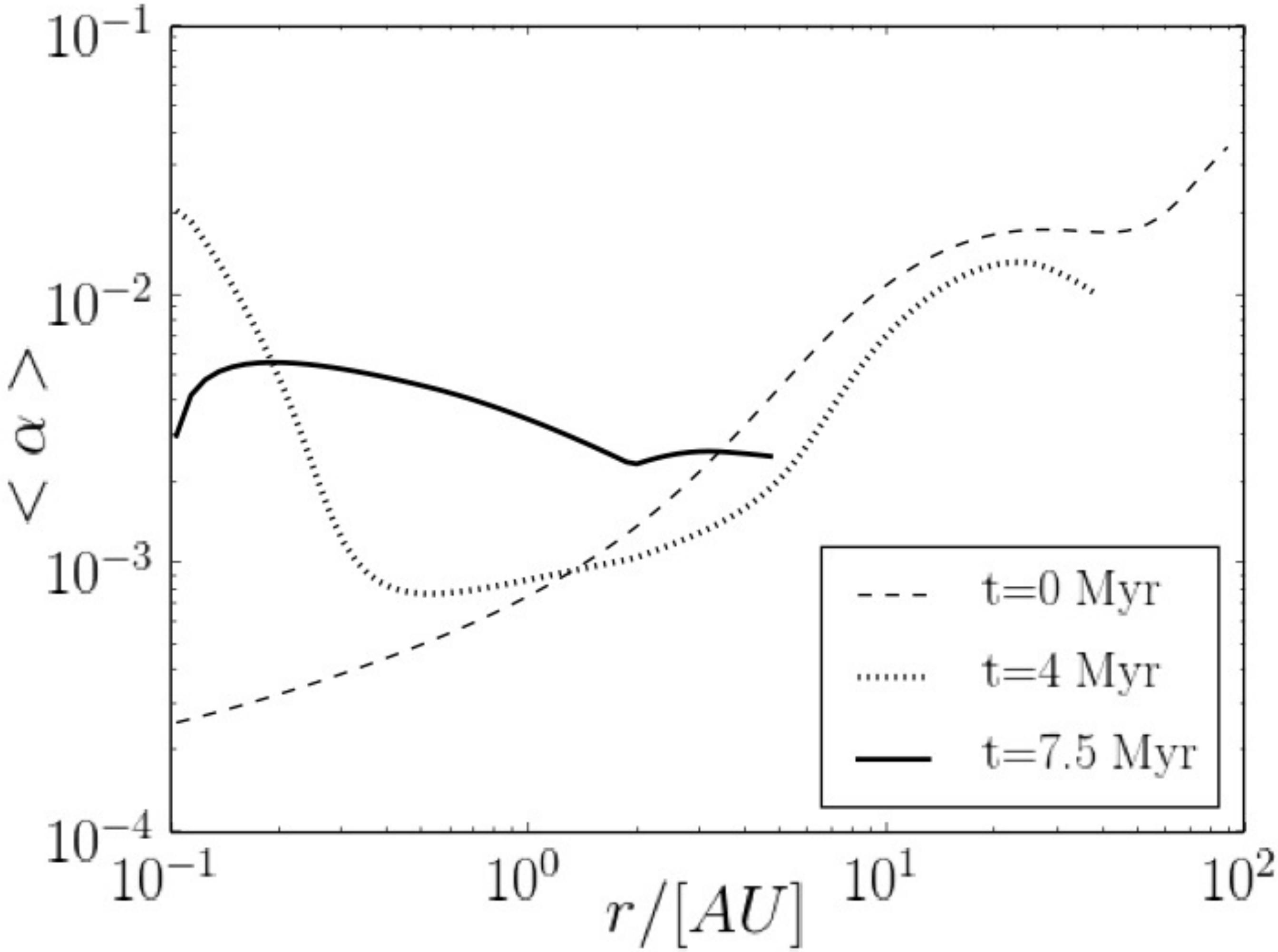
Outer edge of disk decreases from ≈ 80 AU to 60 AU if $\alpha = 10^{-3}$ and $G_0 = 1000$.

Photoevaporated Disks with Uniform Alpha



Mass inside 15 or 20 AU moves inward.
Mass beyond 20 AU moves outward to disk edge at 60 to 80 AU.

Photoevaporated Disks with Non-Uniform Alpha



Vertically averaged alpha vs. heliocentric distance, assuming Bai & Stone (2011) formulation and dust-free ionization chemistry.

Outer annuli (> 10 AU) very turbulent ($\alpha \sim 10^{-2}$), inner annuli less so ($\alpha \sim 10^{-3}$).

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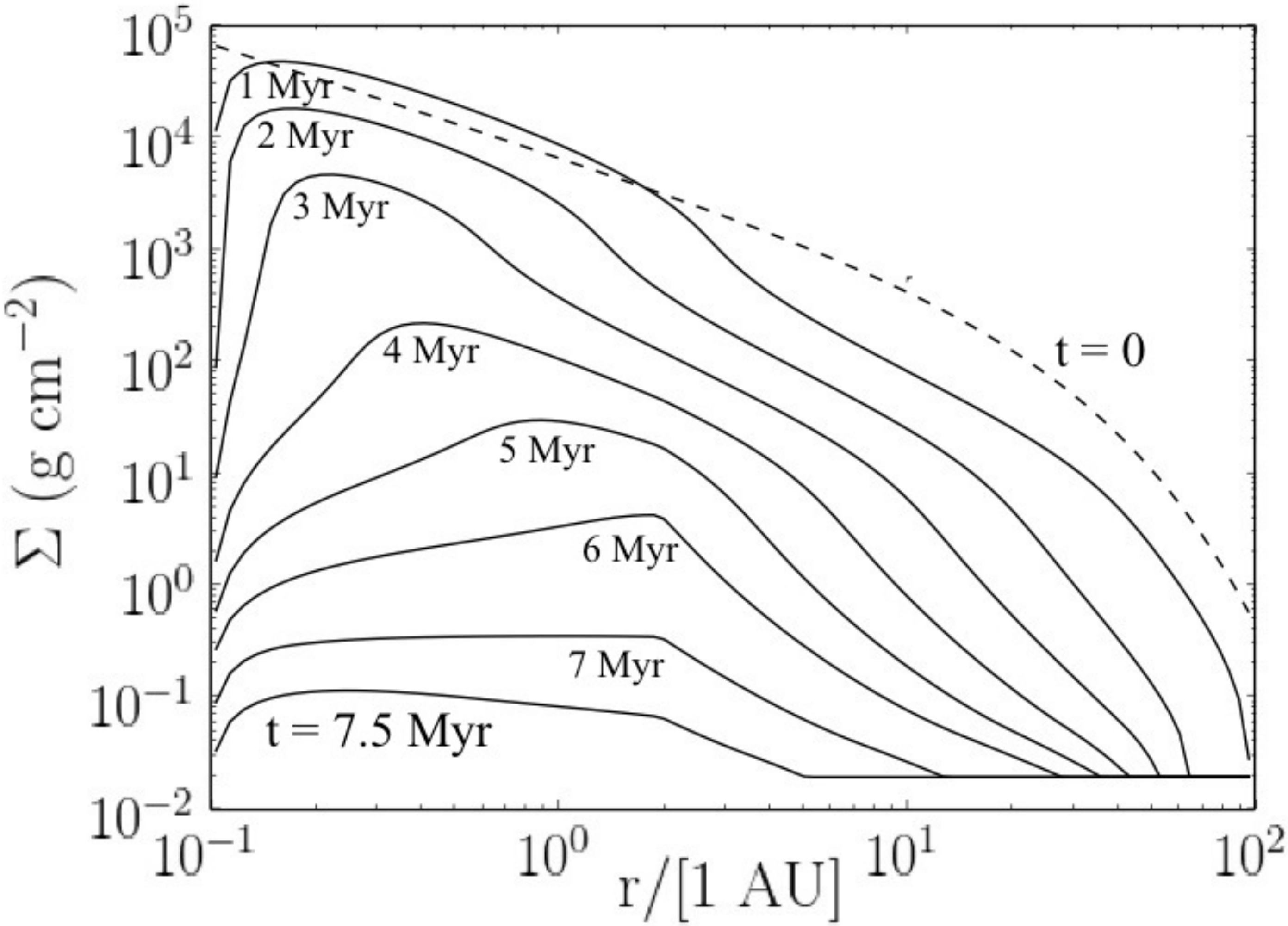
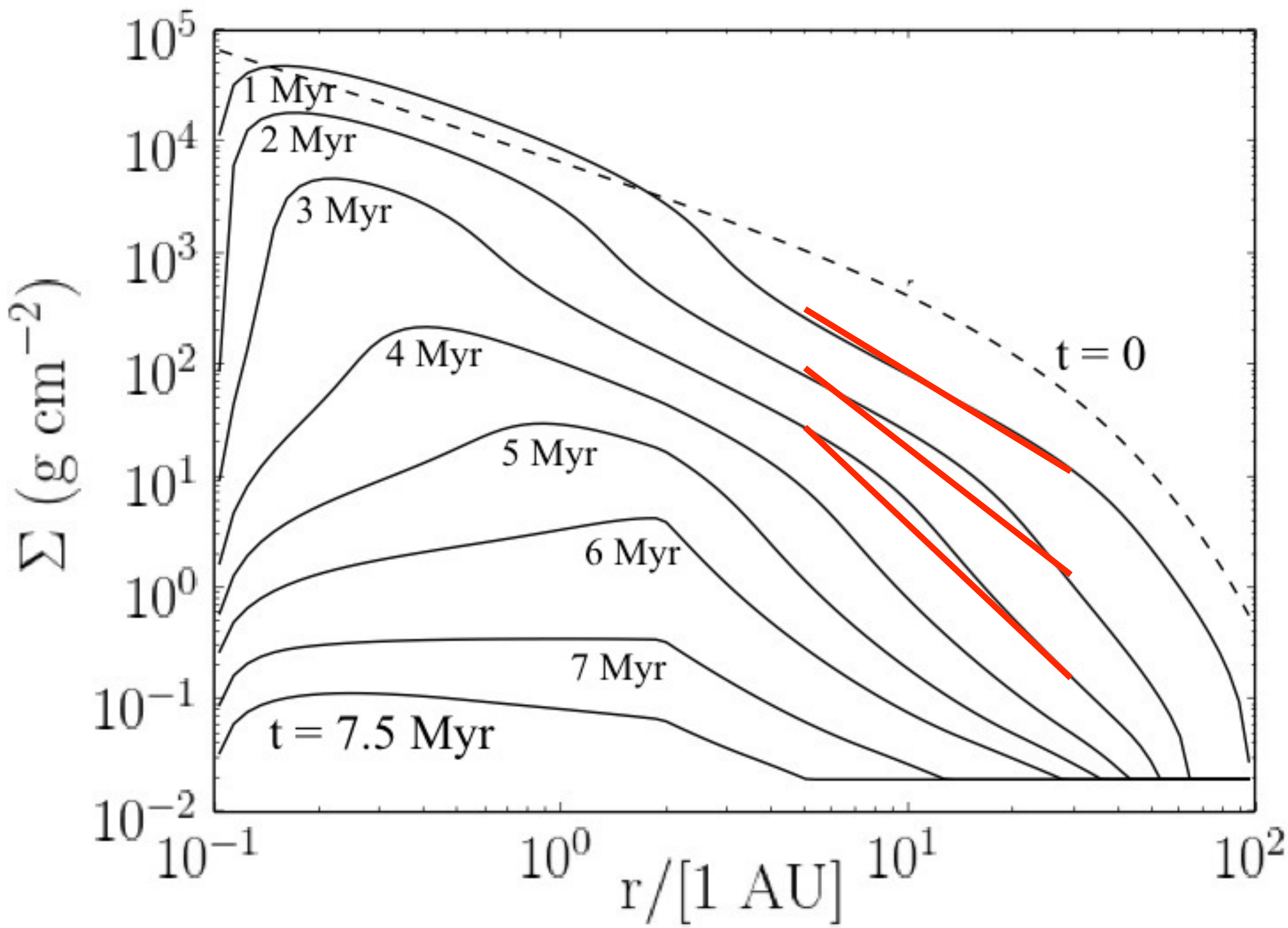


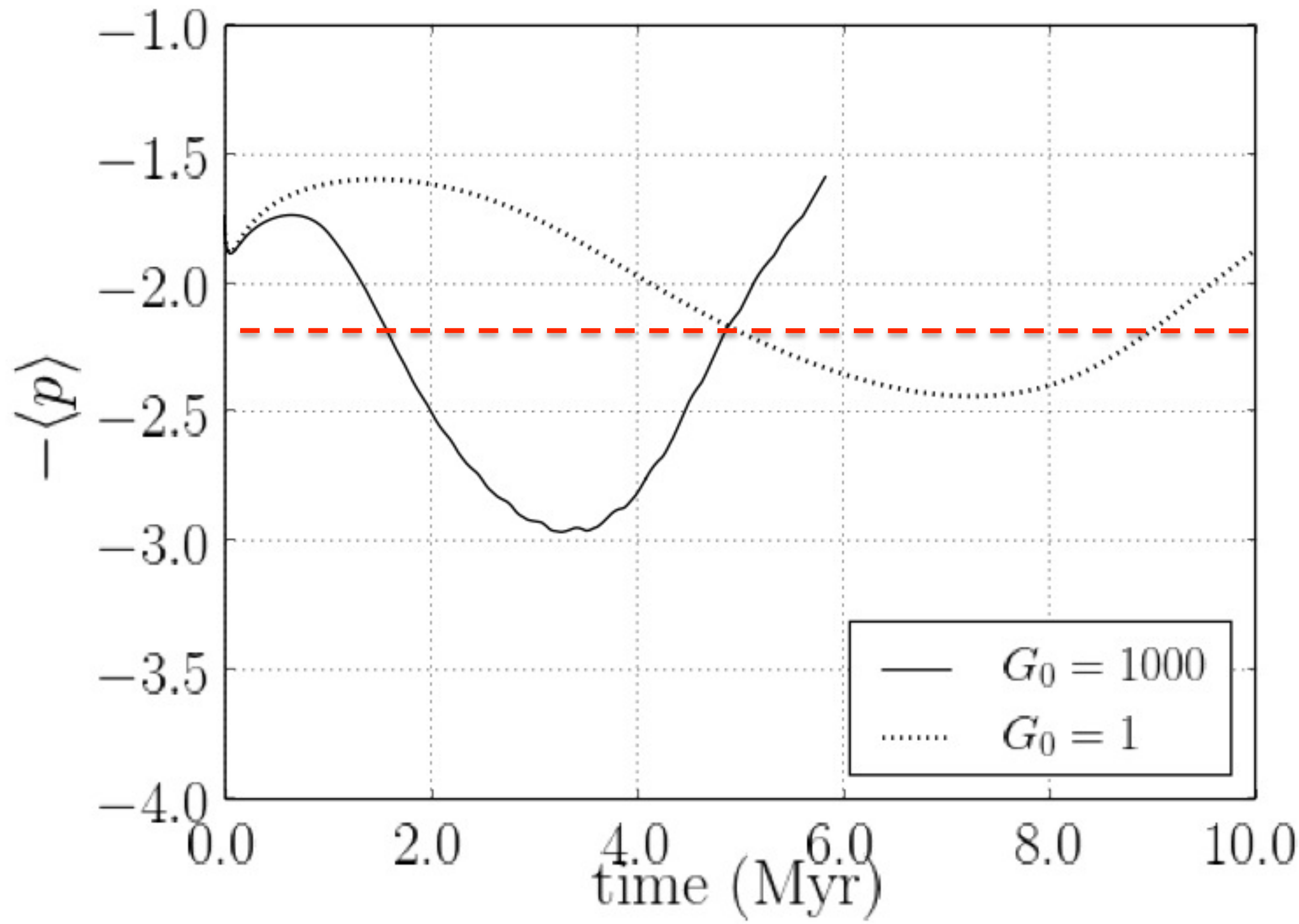
Surface density vs. heliocentric distance, using spatially varying alpha defined above. Outermost annuli lost more quickly. Far from a power law!

Photoevaporated Disks with Non-Uniform Alpha



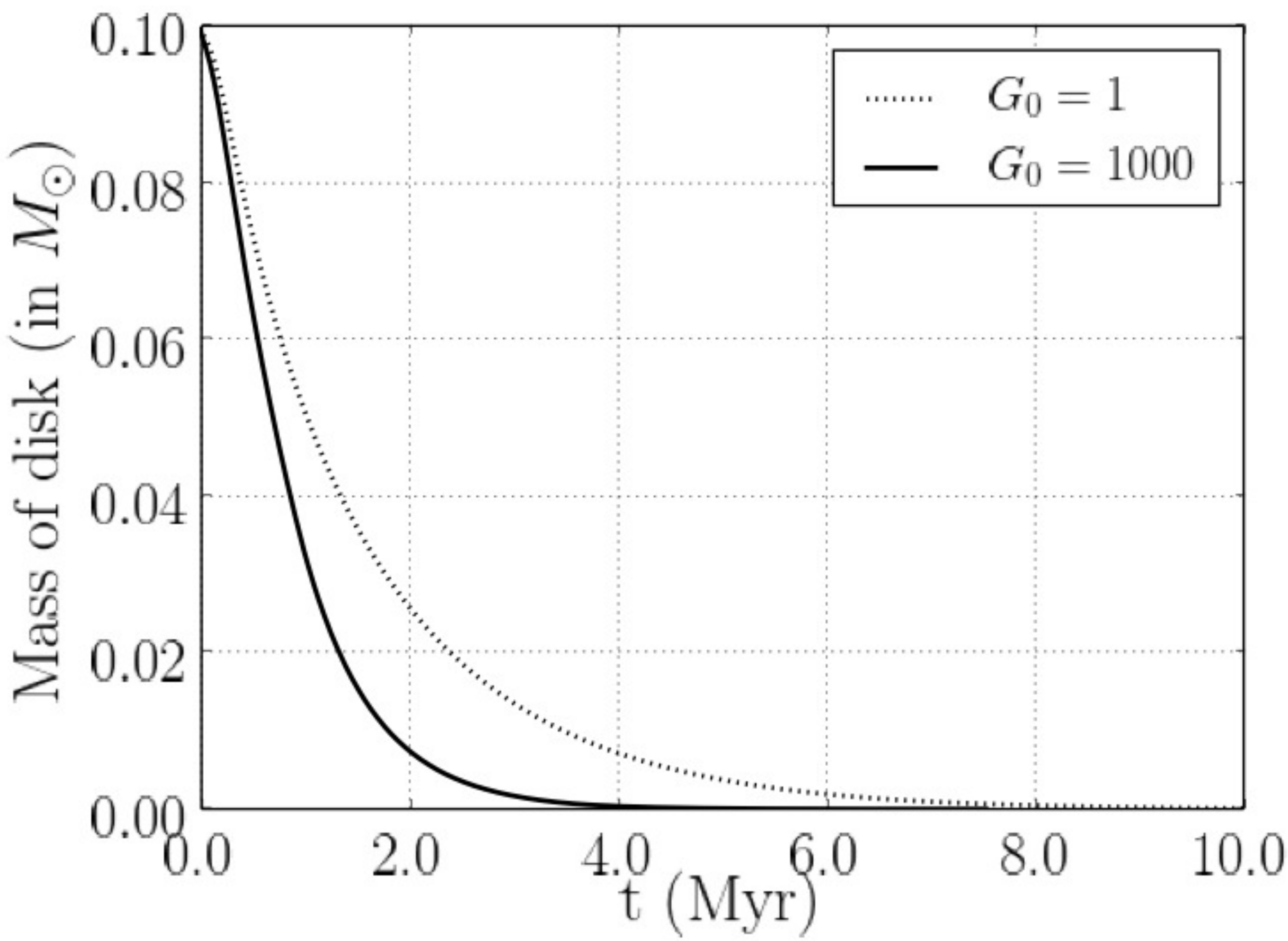
Surface density vs. heliocentric distance, using spatially varying alpha defined above. Outermost annuli lost more quickly. Slope grows more negative.

Photoevaporated Disks with Non-Uniform Alpha

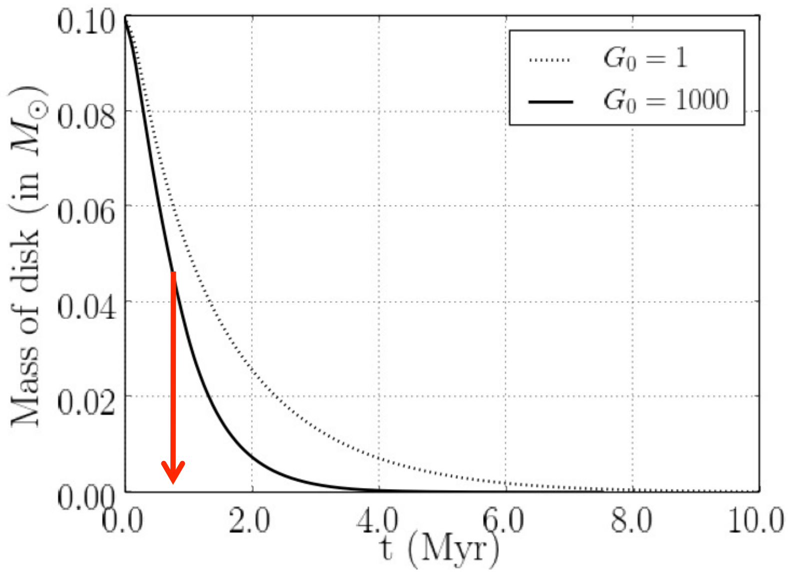


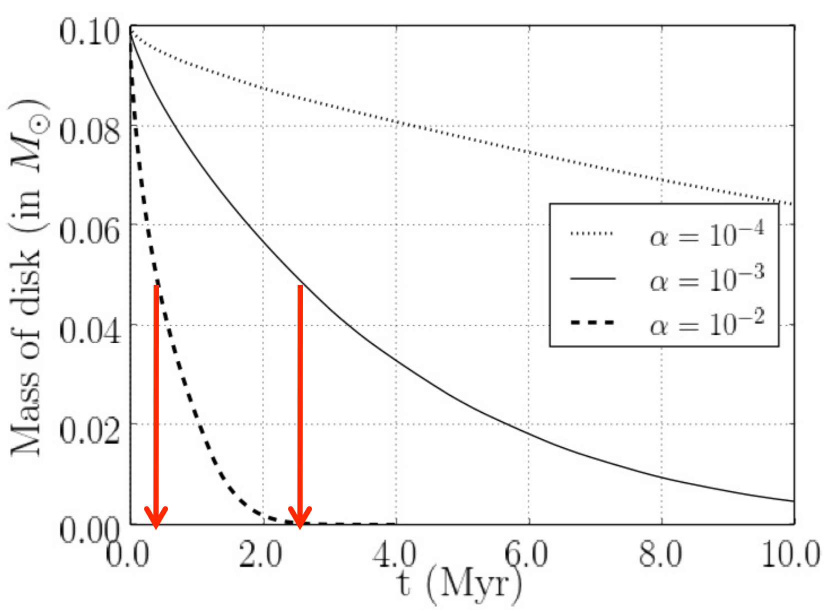
Slope of surface density profile between 5 and 30 AU. If G_0 = 1000, slope centers on -2.2 during first 2 Myr of disk evolution (while planets are forming).

Photoevaporated Disks with Non-Uniform Alpha



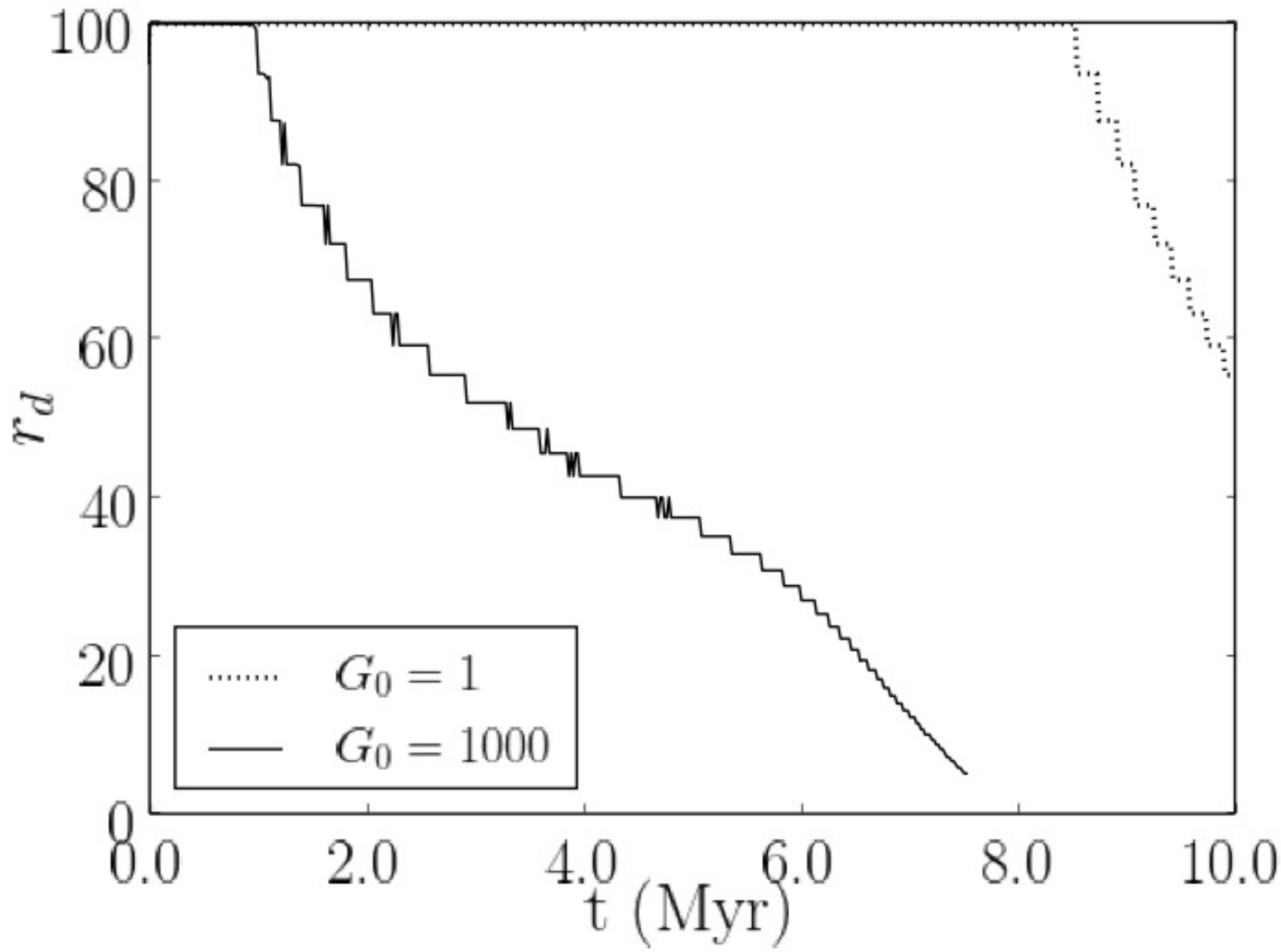
Photoevaporated Disks with Non-Uniform Alpha





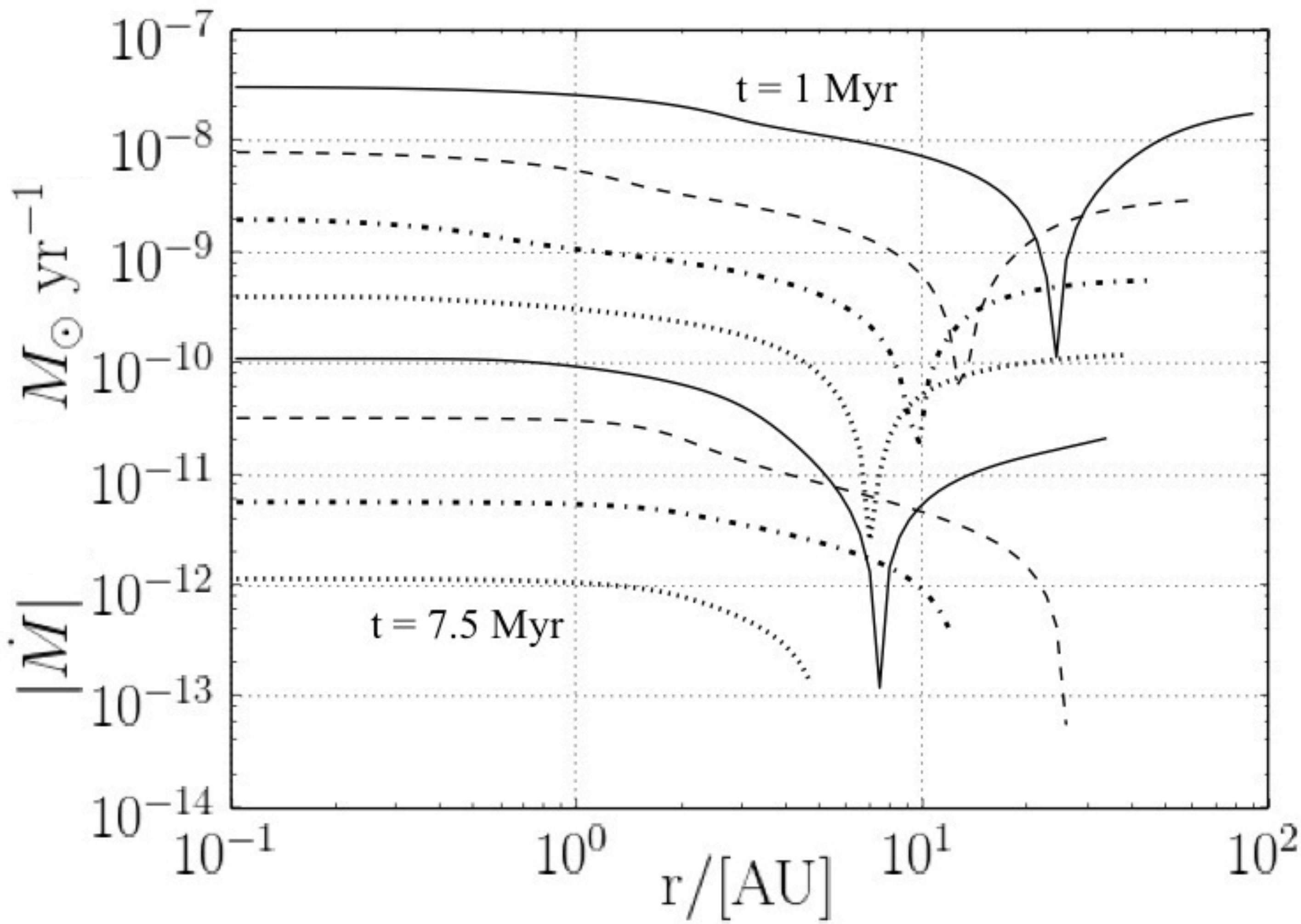
Disk survival / mass loss equivalent to uniform alpha between 10^{-3} and 10^{-2}.

Photoevaporated Disks with Non-Uniform Alpha



Outer edge of disk decreases to < 60 AU (G_0 = 1000) by 2 Myr .

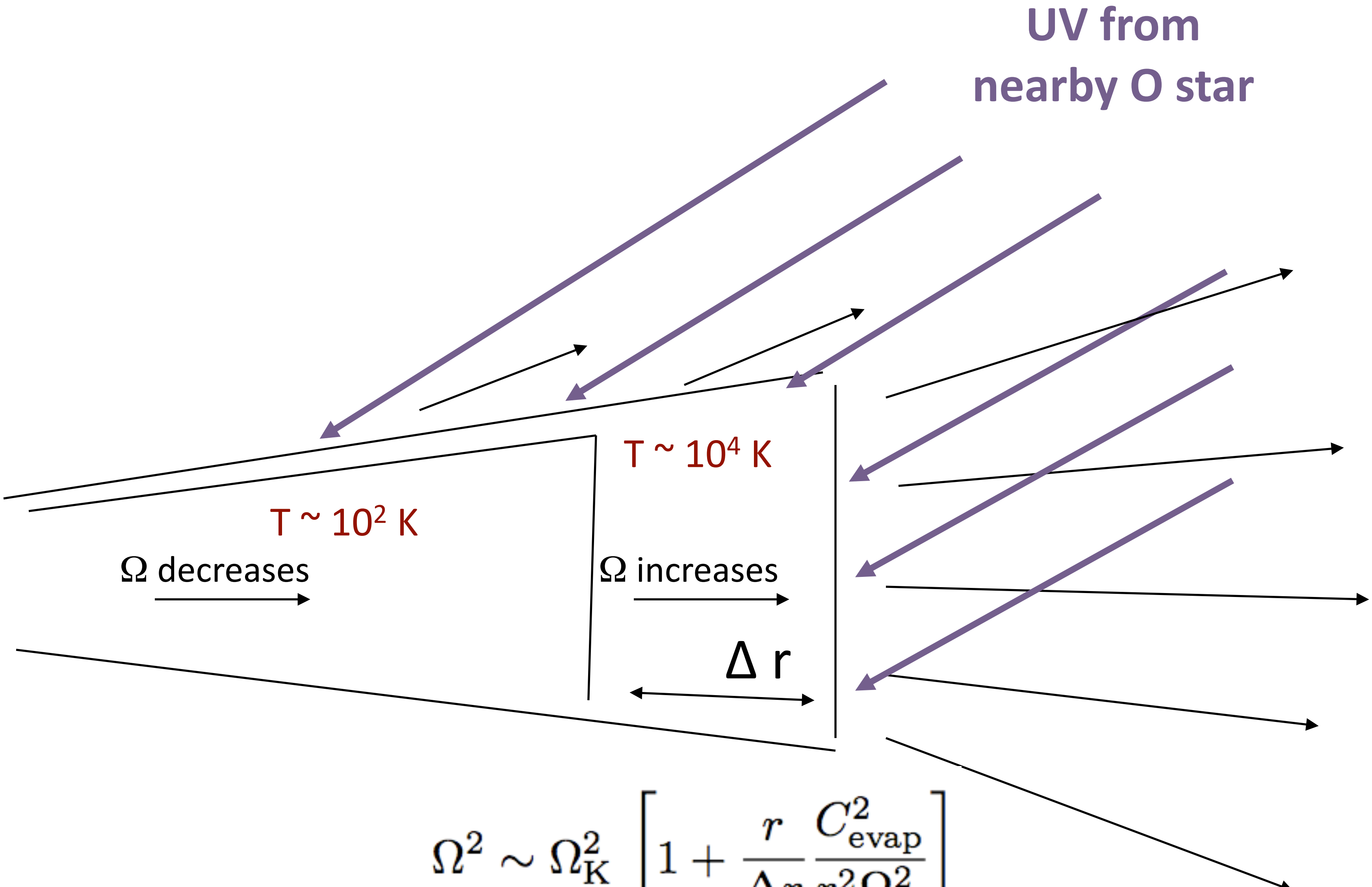
Photoevaporated Disks with Non-Uniform Alpha



Mass inside 10 or 20 AU moves inward.

Mass beyond 15 AU moves outward to disk edge beyond about 50 AU.

Photoevaporation imposes dOmega/dr=0 at outer edge



$$\Omega^2 \sim \Omega_{\rm K}^2 \left[1 + \frac{r}{\Delta r} \frac{C_{\rm evap}^2}{r^2 \Omega_{\rm K}^2} \right]$$