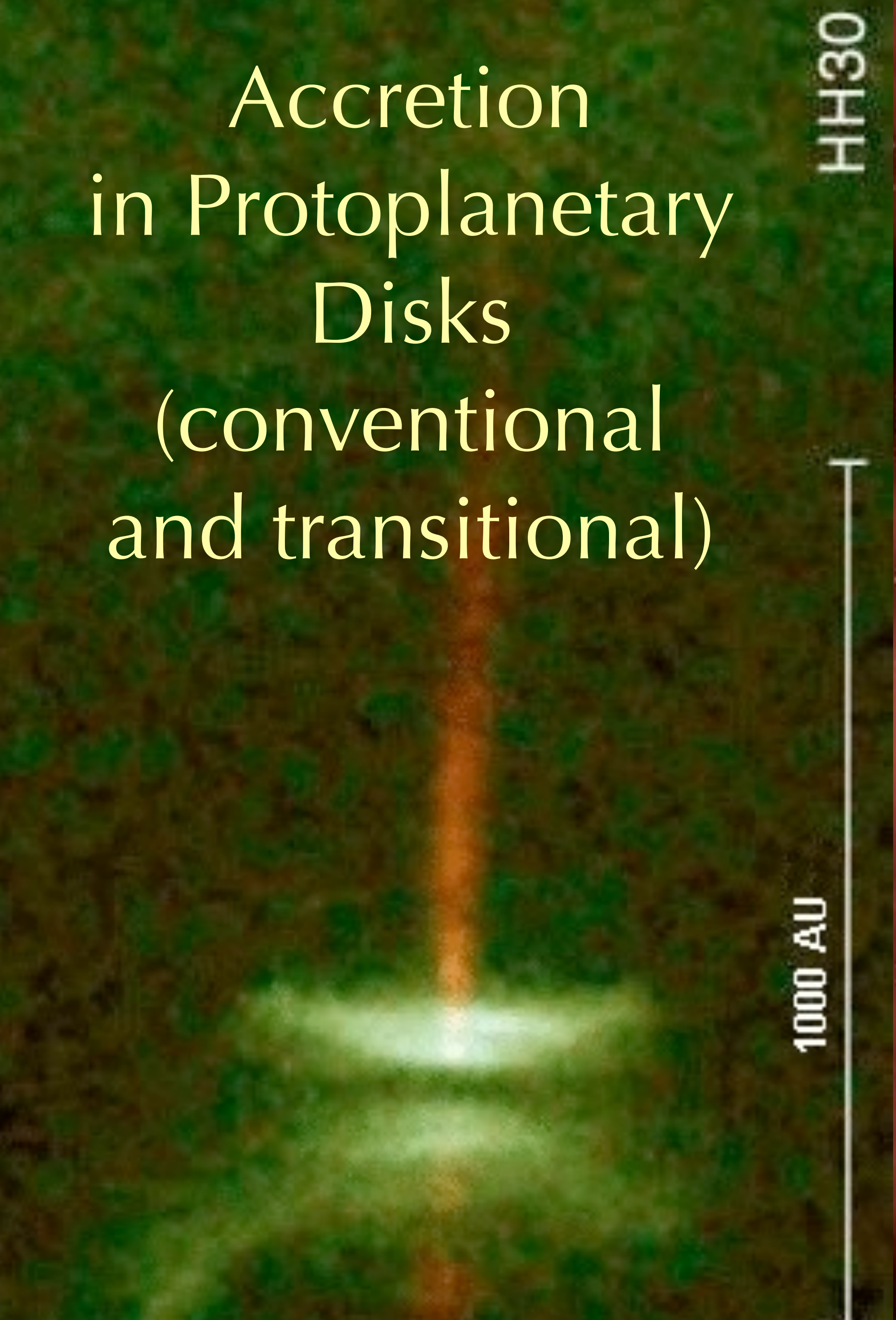
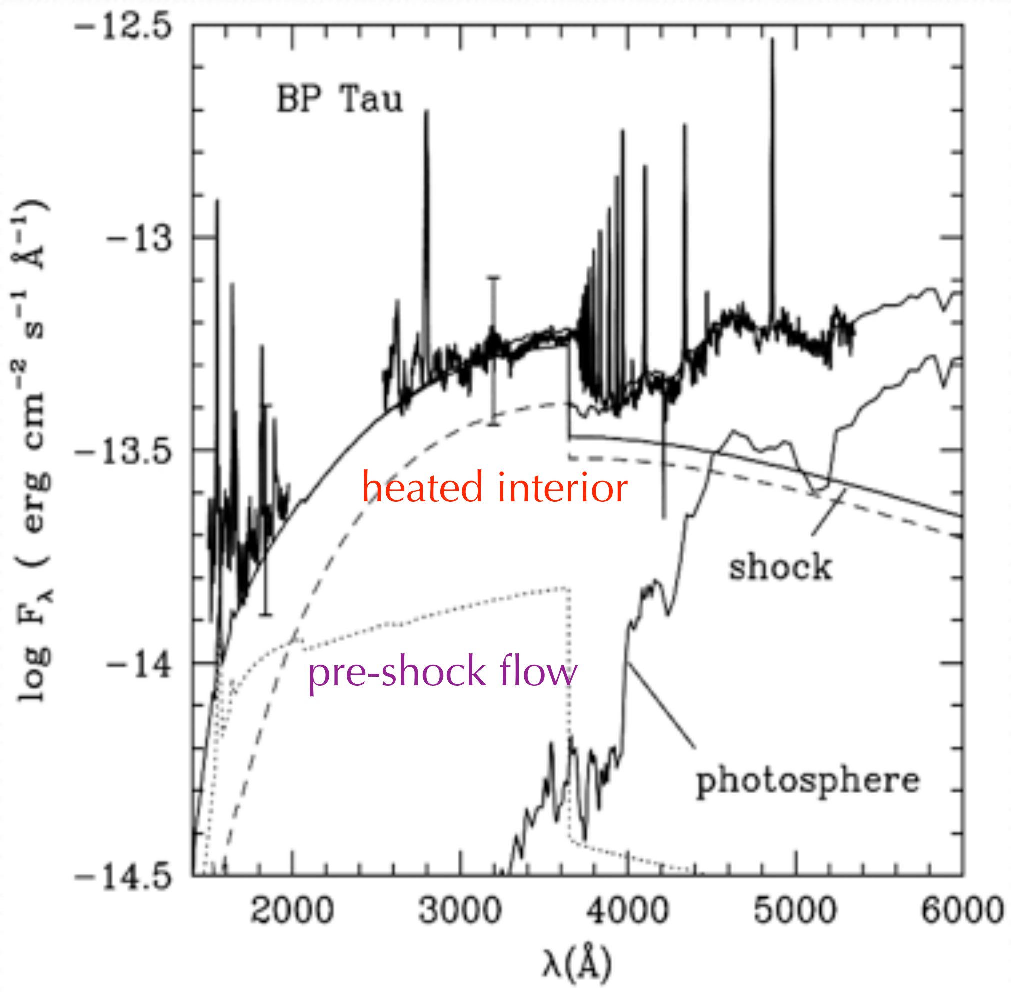
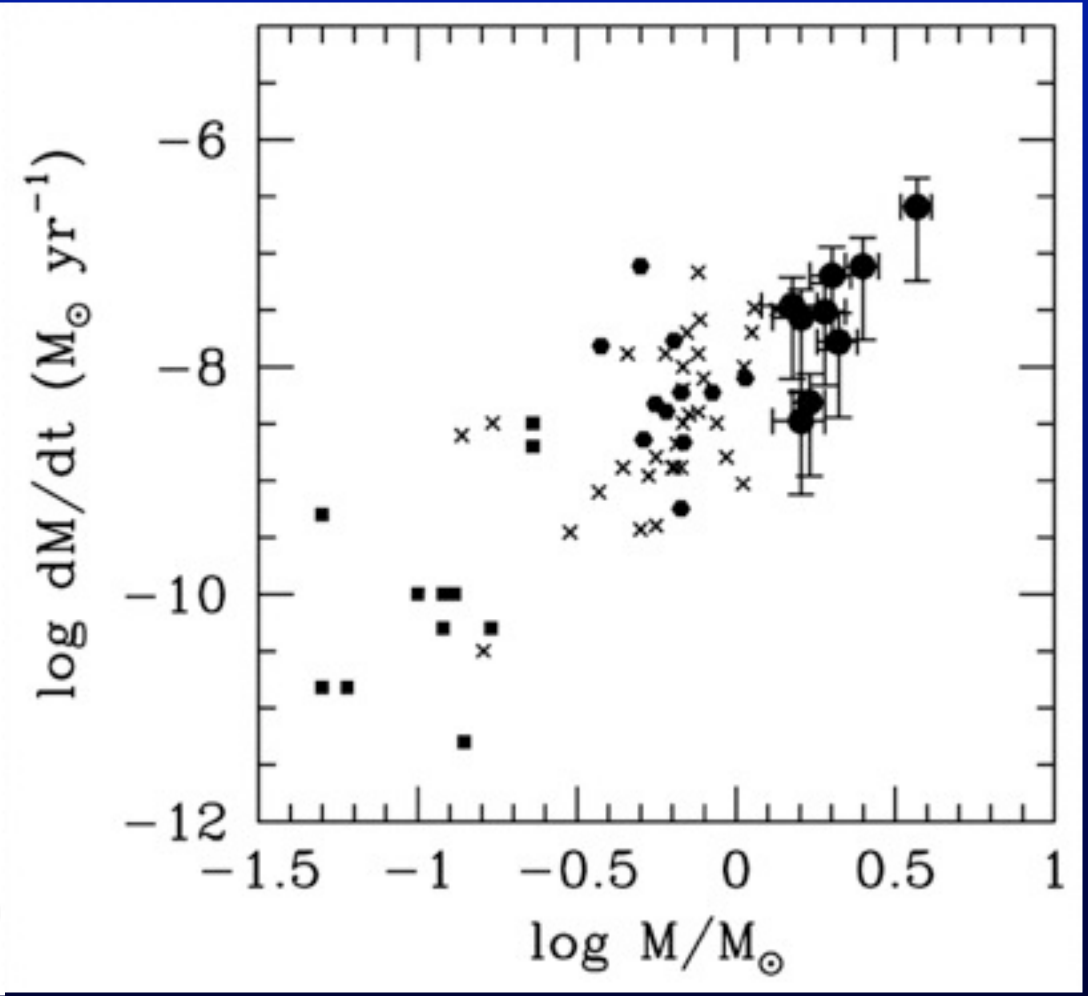
Accretion in Protoplanetary Disks (conventional and transitional)



EC
Daniel Perez-Becker
(Berkeley)

Pre-main-sequence stars accrete

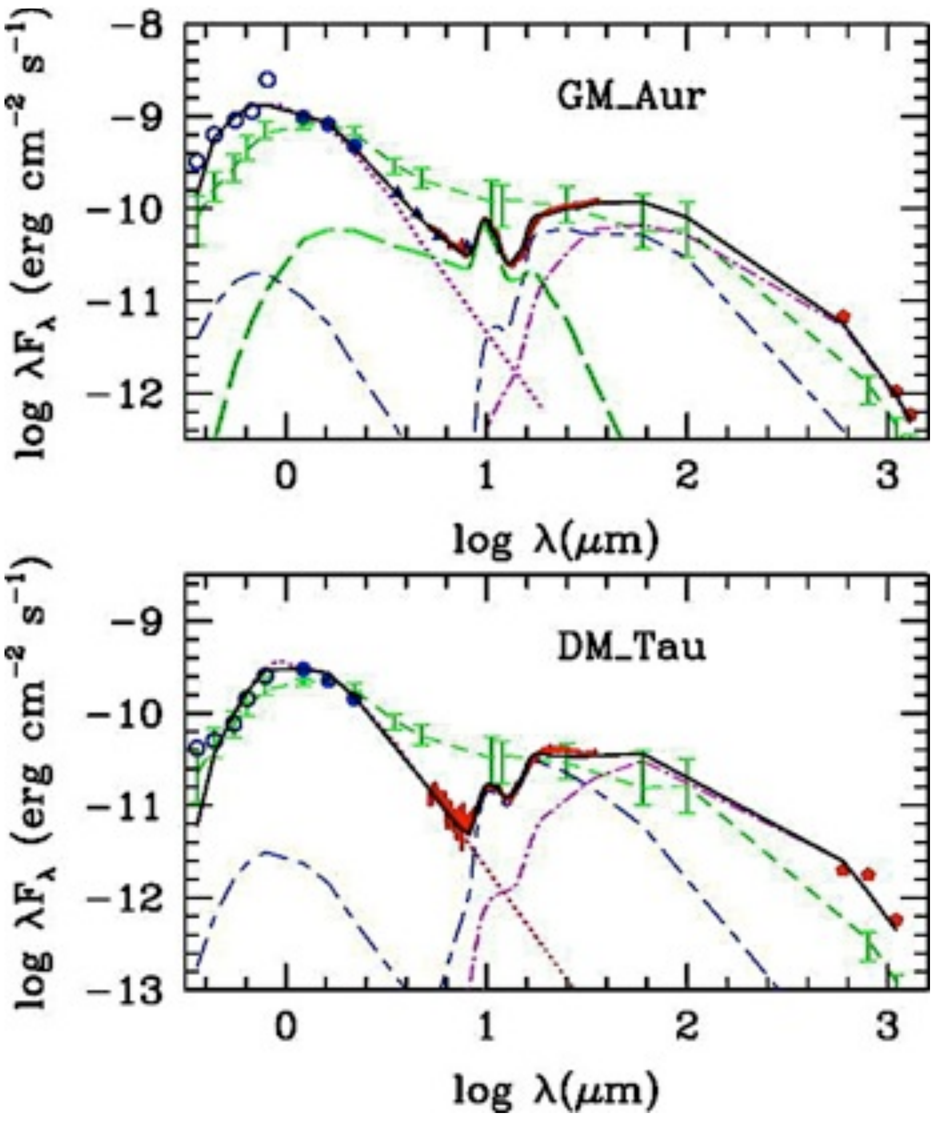




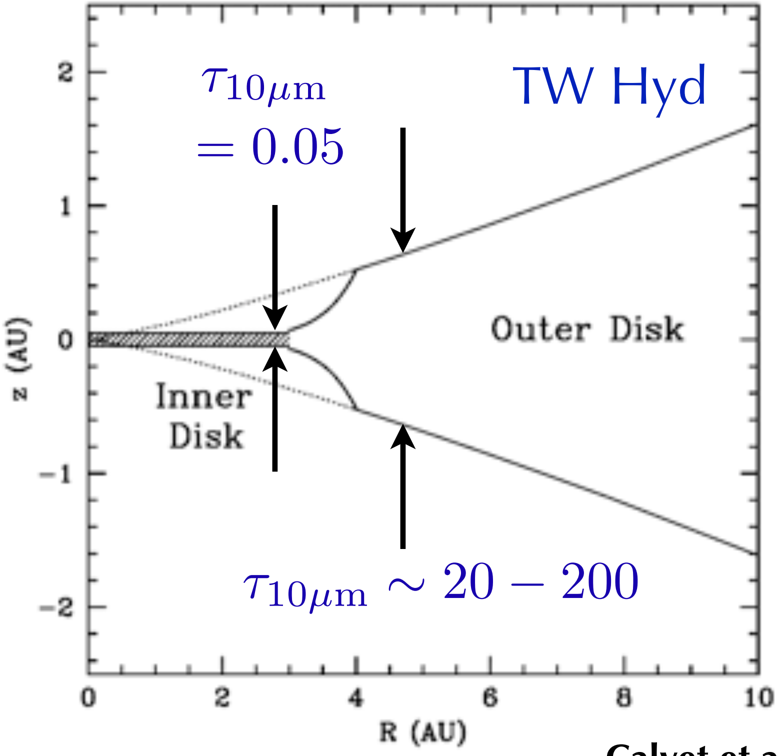
Blue excess powered by accretion

Calvet & Gullbring 98
Muzerolle et al. 05
Hartmann et al. 06
Herczeg & Hillenbrand 08

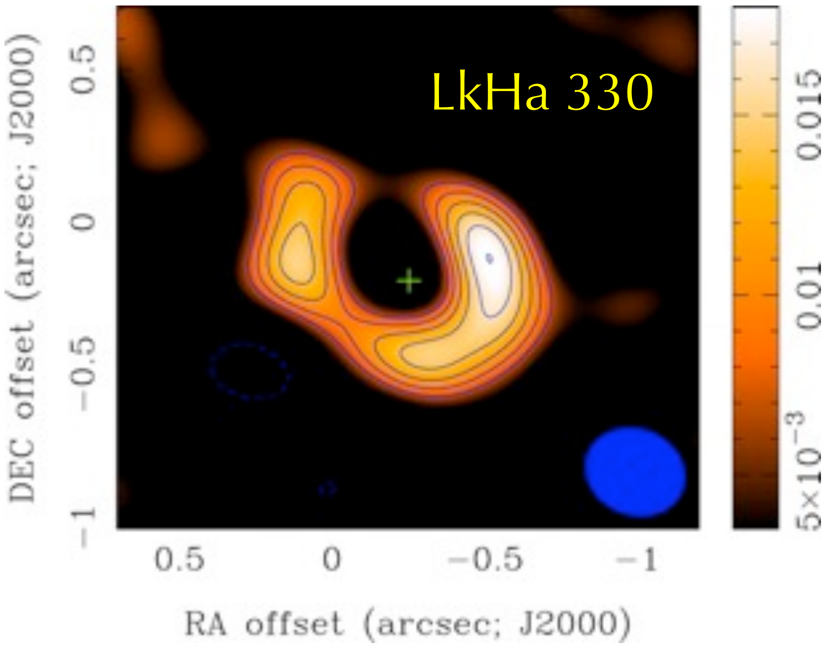
Transitional Disks



Calvet et al. 05



Calvet et al. 02



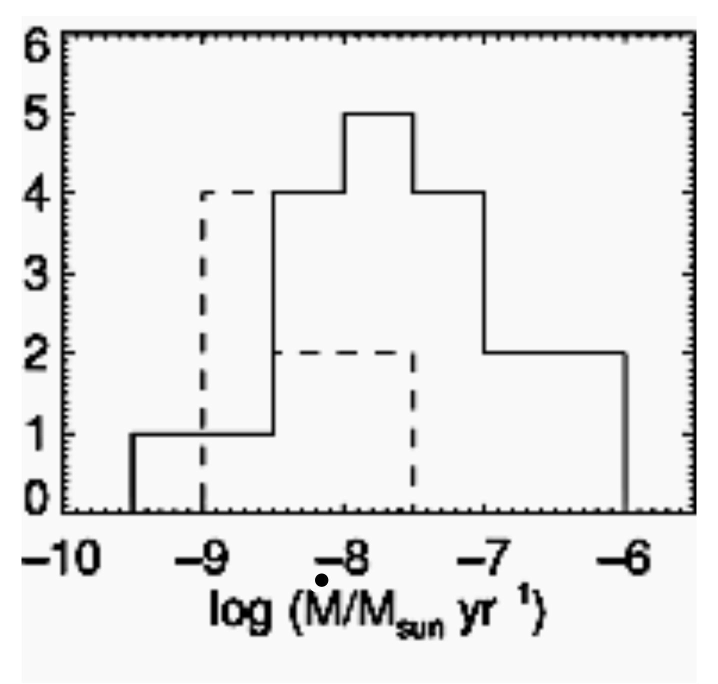
Brown et al. 08

Holes are not empty

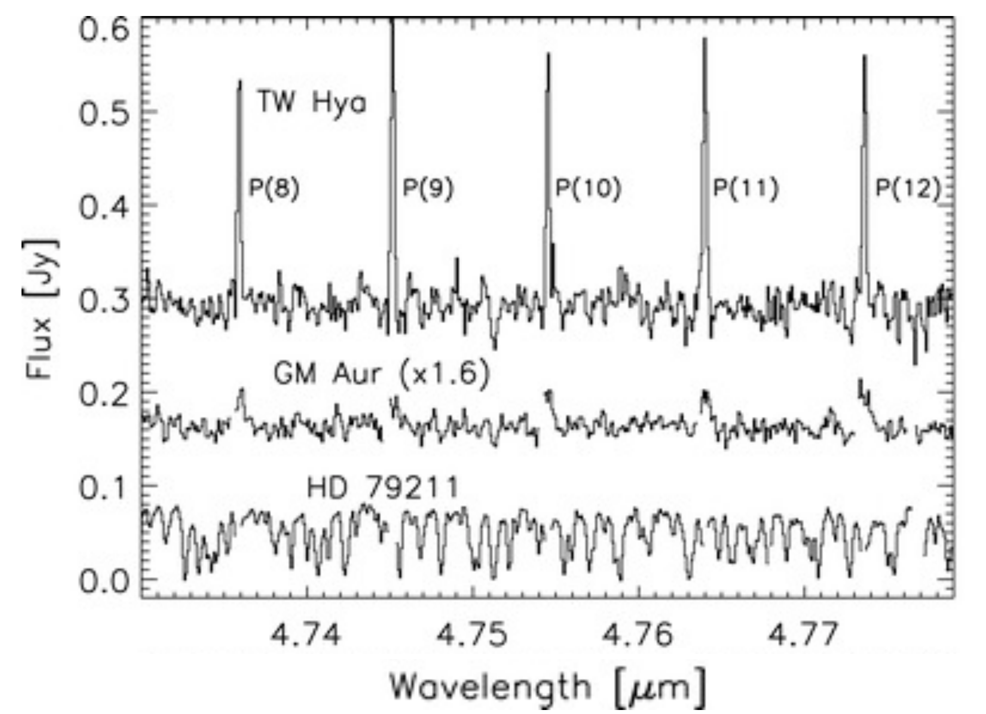
- Mild near-IR excesses in some sources
  $\tau_{10\mu\mathrm{m}} \sim 0.002 - 0.05$

- Many accrete
  $\dot{M} \sim 0.1 \times \mathrm{median\,T\,Tauri}$

- Inner molecular gas disks
  $\Sigma(\mathrm{H}_2) > 0.1\,\mathrm{g\,cm}^{-2}$ at $\sim 0.2\mathrm{AU}$



Najita et al. 07



Salyk et al. 07

Puzzle: $1000 \times$ smaller τ but comparable $\dot{M}$

Theories:

- Grain growth
- Clearing by companion

Not mutually exclusive

Clearing by companion (Transitional = Circumbinary)

Binary separation

$a_{\rm binary} \approx 8$ AU

$\approx$ Hole radius

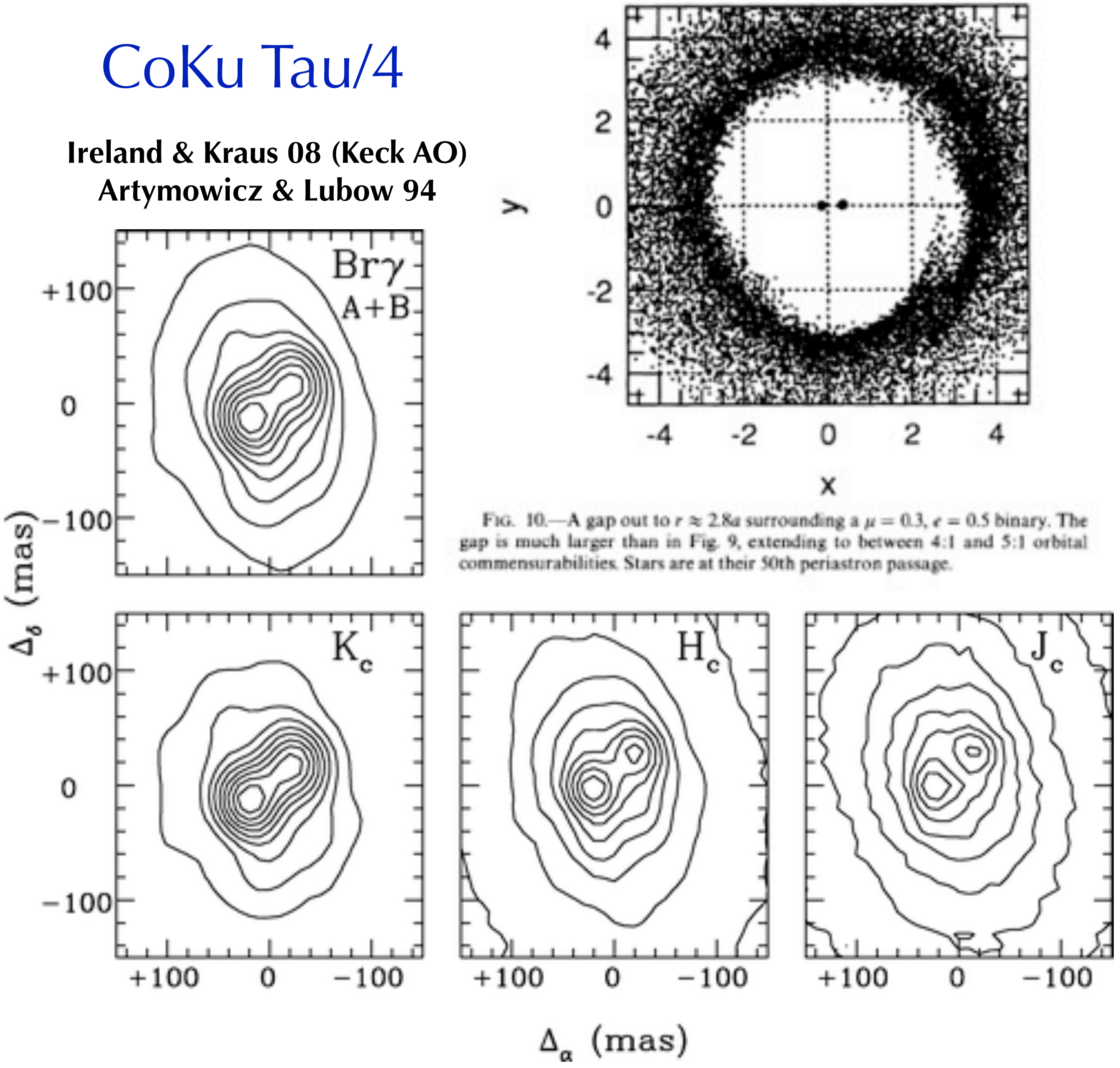
$a_{\rm rim} \approx 10$ AU

$\tau_{10\mu m} < 0.002$

$\dot{M}_* < 10^{-10} M_\odot/{\rm yr}$

No CO gas out to 2 AU

D'Alessio et al. 05
Najita et al. 07
Blake, Salyk, personal comm.

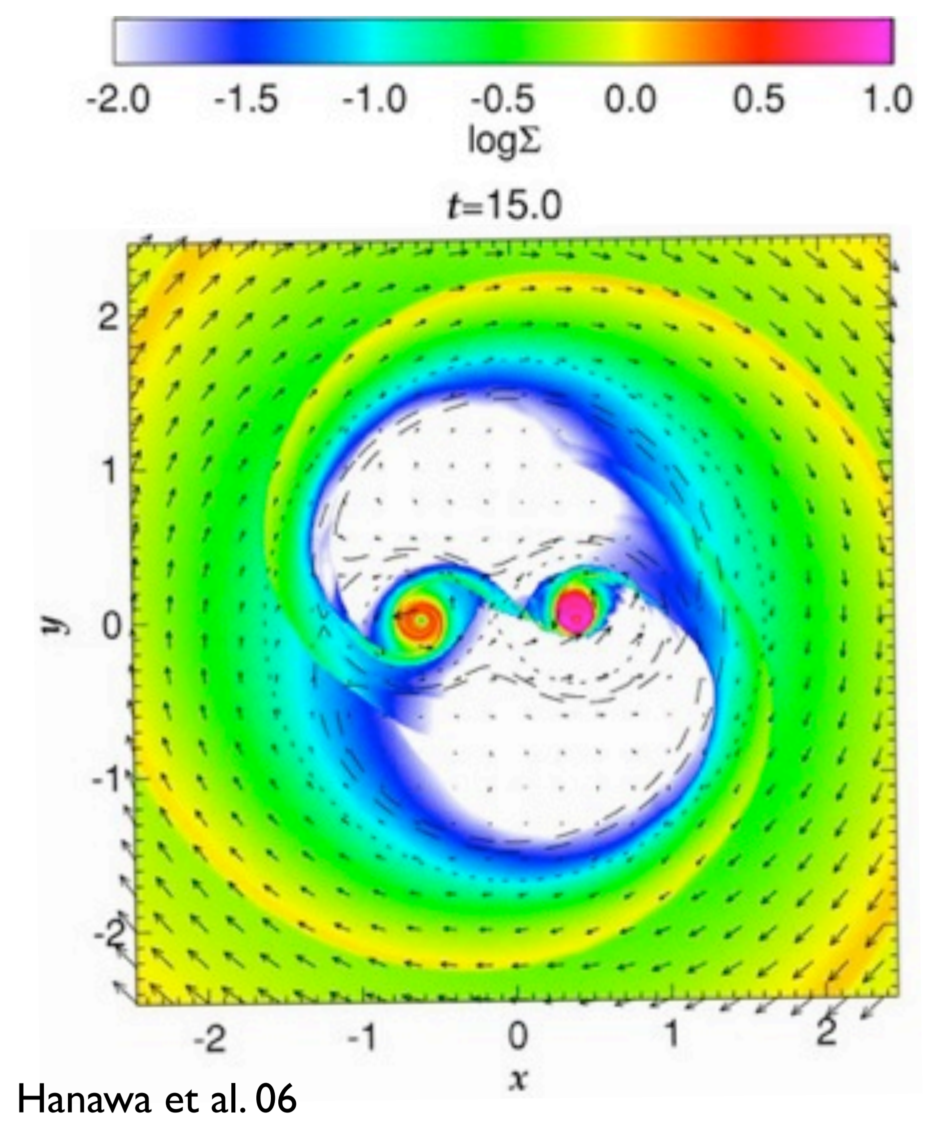


CoKu Tau/4

Ireland & Kraus 08 (Keck AO)
Artymowicz & Lubow 94

FIG. 10.—A gap out to $r \approx 2.8a$ surrounding a $\mu = 0.3$, $e = 0.5$ binary. The gap is much larger than in Fig. 9, extending to between 4:1 and 5:1 orbital commensurabilities. Stars are at their 50th periastron passage.

Clearing by companion (Transitional = Circumbinary)



Hanawa et al. 06

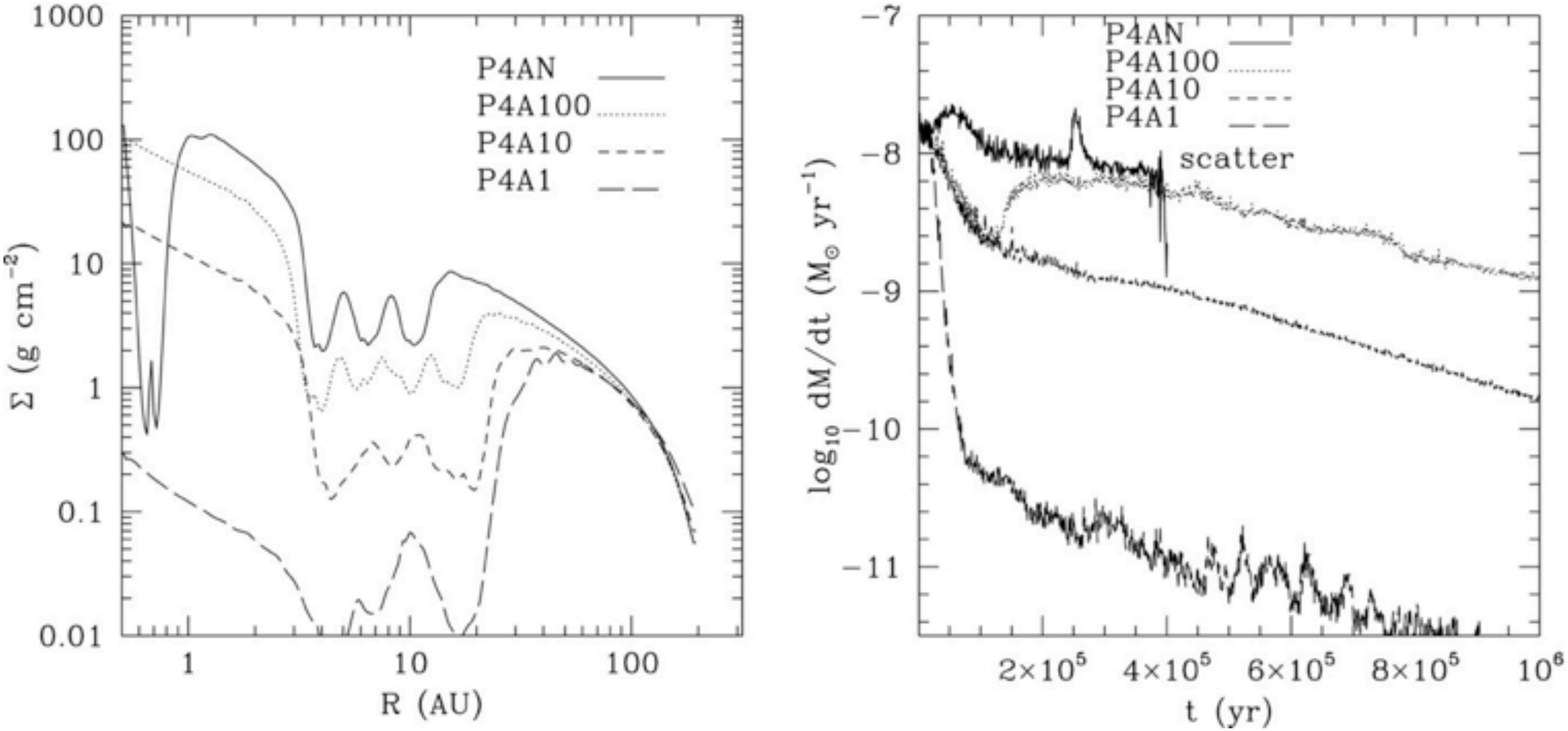
Mass can still accrete onto star (viscosity / pressure / eccentricity / mass ratio)

Fast flow (up to radial free-fall) implies low surface density

Resolves the puzzle of
similar $\dot{M}$ but
1000x lower optical depth

Clearing by multiple planets

Simulation of 4-planet system in viscous disk



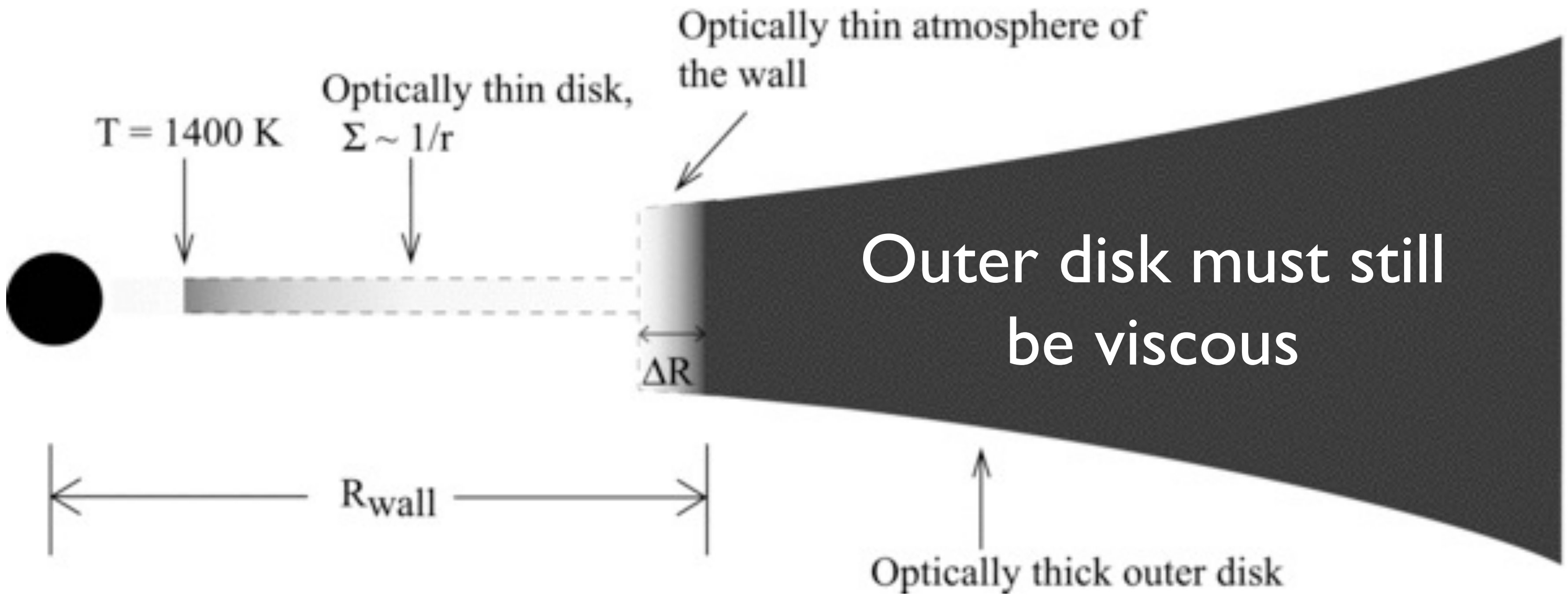
2D FARGO

Zhu et al. 11

Right sign, too small magnitude

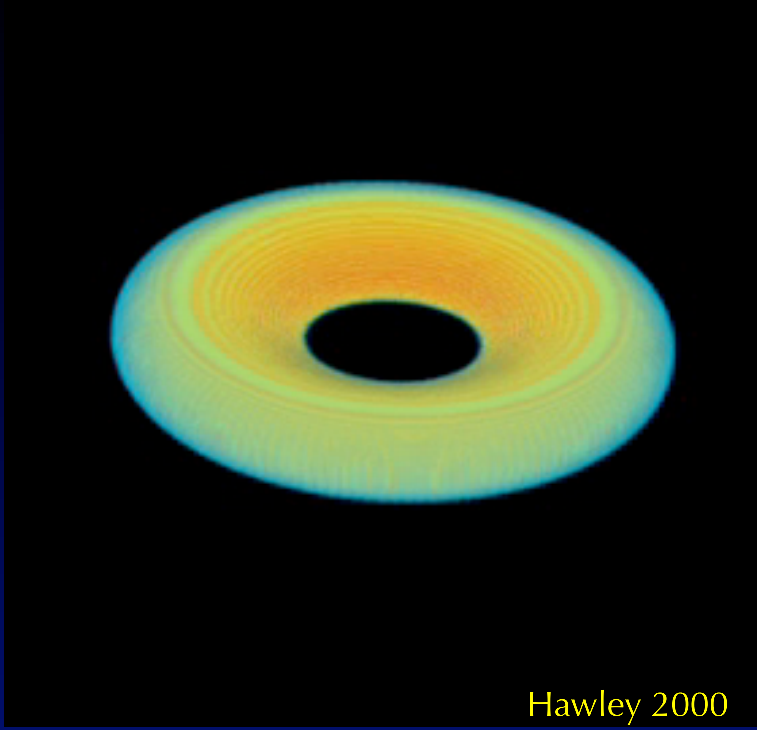
– unless dust is also depleted

Planets inside the hole do not explain disk accretion



Outer disk must still be viscous

Disk accretion


Hawley 2000

Magneto-rotational instability (MRI)
= linear instability
which drives turbulence
in weakly magnetized,
outwardly shearing flows

Requirements

1. Magnetic flux freezing
   (defeat Ohmic dissipation)
   (Fleming, Stone, & Hawley 00)

$$\mathrm{Re_M} \equiv \frac{c_s h}{\eta} \propto \frac{n_e}{n}$$

$$> \mathrm{Re_M^*} \approx 10^2 - 10^4$$

2. Good neutral-ion coupling
   (defeat ambipolar diffusion)
   (Blaes & Balbus 94;
   Hawley & Stone 98; Bai & Stone 11)

$$\mathrm{Am} \equiv \frac{n_i \langle \sigma v \rangle_{in}}{\Omega} > \mathrm{Am}^* \approx \text{1-100}$$

Surface Layer Accretion by the MRI

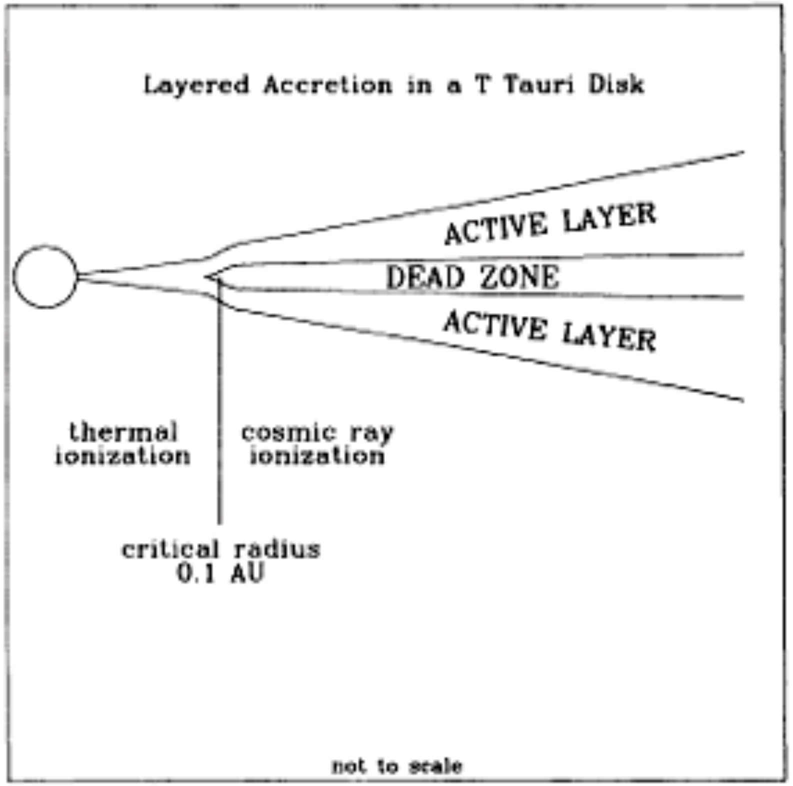
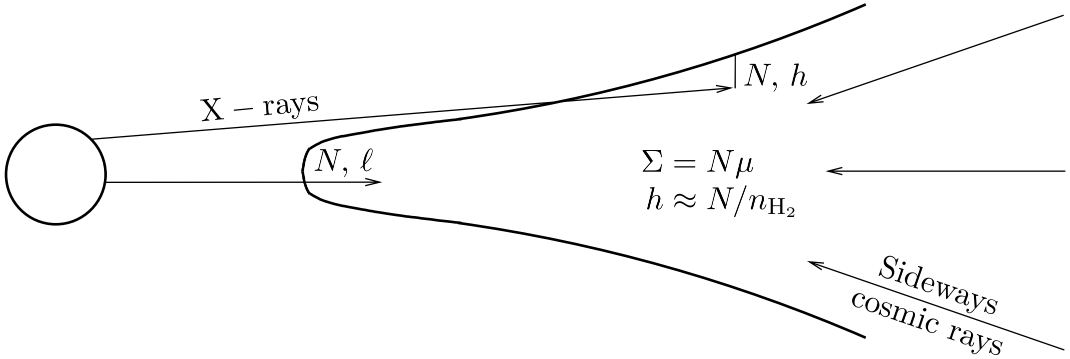


FIG. 1.—Sketch showing the key features of a layered accretion disk. Inside $\simeq 0.1$ AU, where $T \simeq 10^3$ K, collisional ionization is sufficient to couple the magnetic field to the gas. Outside this critical radius cosmic rays ionize a layer of thickness $\simeq 100\ \mathrm{g\ cm^{-2}}$ on either side of the disk. Sandwiched between these active layers is a dead zone where no accretion occurs.

Gammie 96



Sources of ionization

1. Cosmic rays
2. Stellar X-rays
3. Stellar UV

Glassgold et al. 97
Sano et al. 00
Ilgner & Nelson 06
Bai & Goodman 09
Turner et al. 10
Perez-Becker & EC 11a
Perez-Becker & EC 11b

Galactic cosmic rays blocked by stellar wind

cosmic ray flux

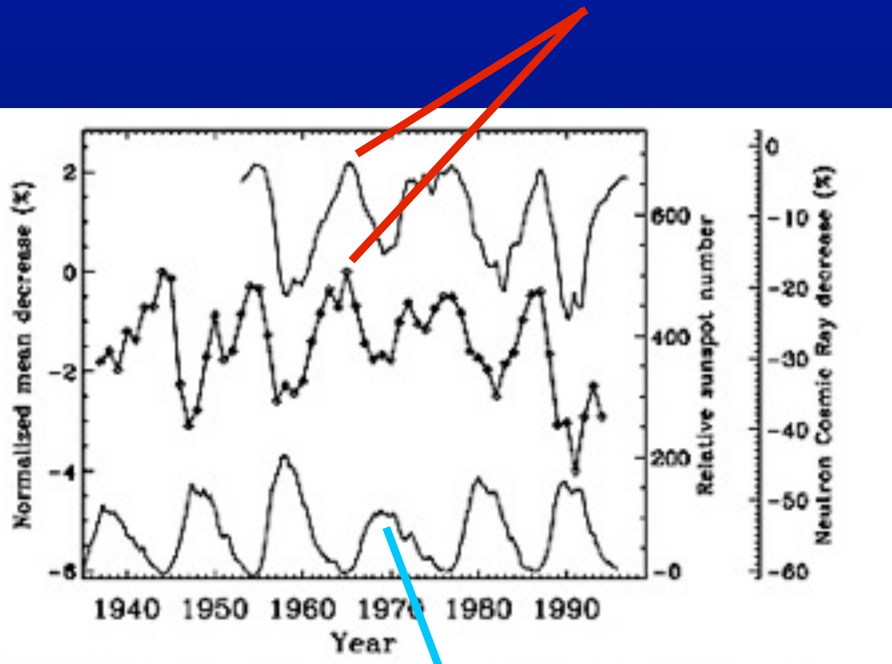


FIG. 2. Top curve is cosmic ray flux from the neutron monitor in Climax, Colorado (1953–1996). Middle curve is annual mean variation in cosmic ray flux as measured by ionization chambers (1937–1994). The neutron data have been normalized to May 1965, and the ionization chamber data have been normalized to 1965. Bottom curve is the relative sunspot number.

sunspot number

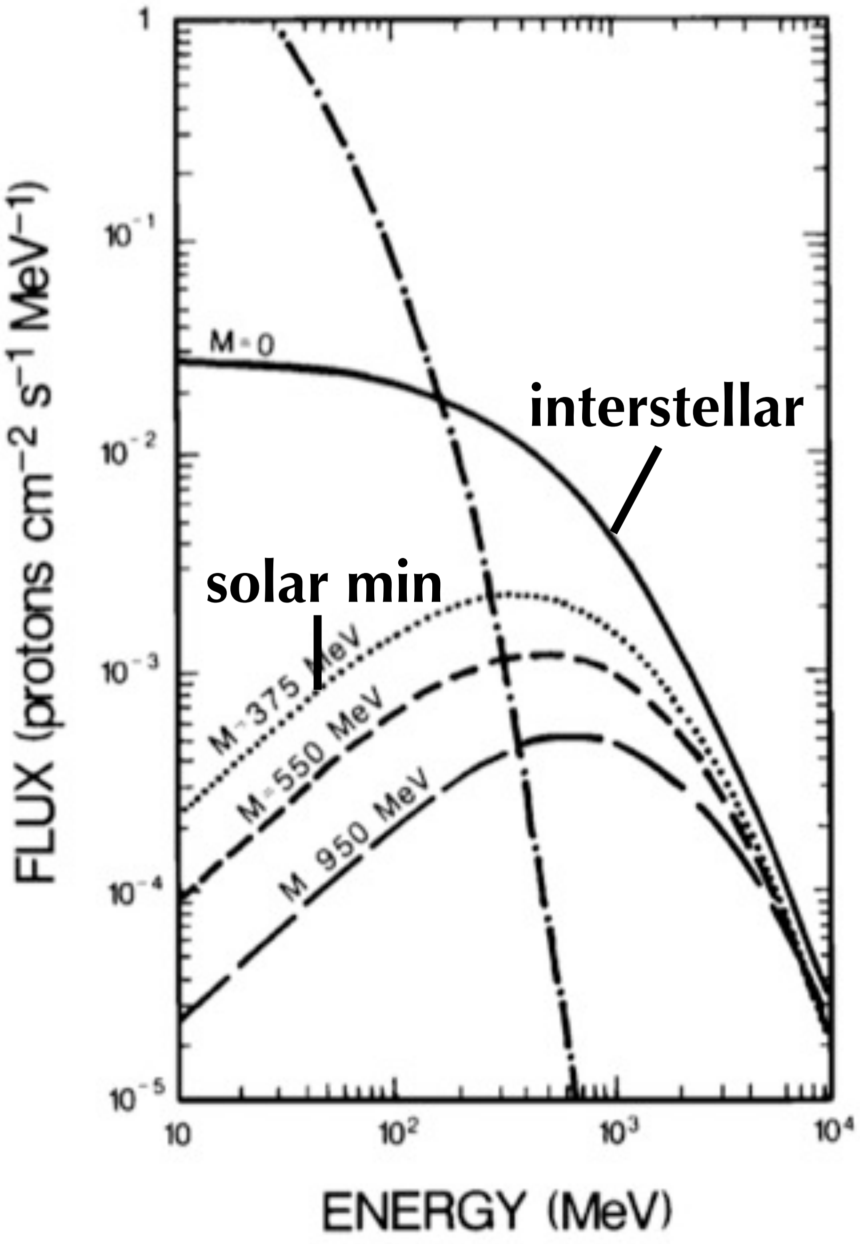
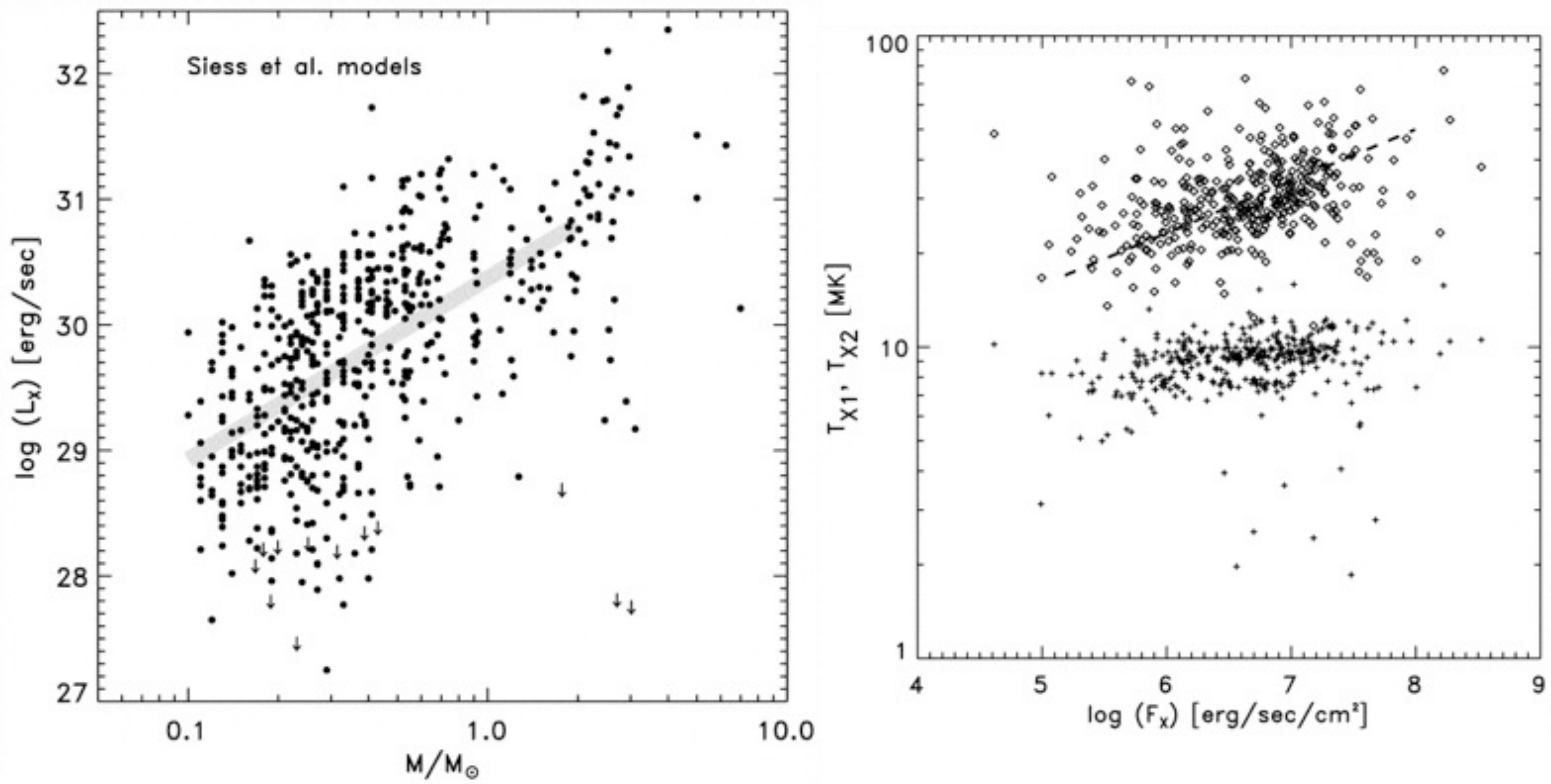


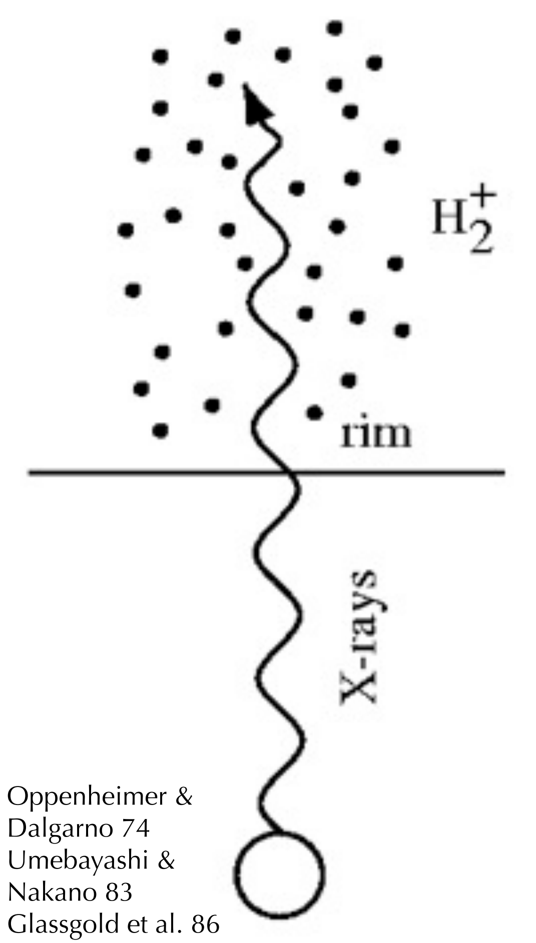
Fig. 1. The omnidirectional fluxes as a function of kinetic energy of solar protons with R_o = 100 MV (the dot-dashed line) and of GCR protons in the solar system (using equation (1)), for no modulation (M = 0) and for three levels of modulation: solar maximum (M = 950 MeV), the 11-year average (M = 550 MeV), and solar minimum (M = 375 MeV).

Svensmark 98
Reedy 87

Pre-main sequence stars are X-ray luminous



Preibisch et al. 05
Chandra COUP Orion survey



Oppenheimer &
Dalgarno 74
Umebayashi &
Nakano 83
Glassgold et al. 86

$$H_2^+ + H_2 \longrightarrow H_3^+ + H$$

$$H_3^+ + CO \longrightarrow \boxed{HCO^+} + H_2$$

free
metal
Mg

charge
transfer

$\beta_t \sim 10^{-9}\,\mathrm{cm^3\,s^{-1}}$

Mg^+

e^-

dissociative
recombination

$\beta_{\rm diss} \sim 3 \times 10^{-7}\,\mathrm{cm^3\,s^{-1}}$

$H + CO$

e^-

radiative
recombination

$\beta_{\rm rec} \sim 4 \times 10^{-12}\,\mathrm{cm^3\,s^{-1}}$

Mg

grain$^-$

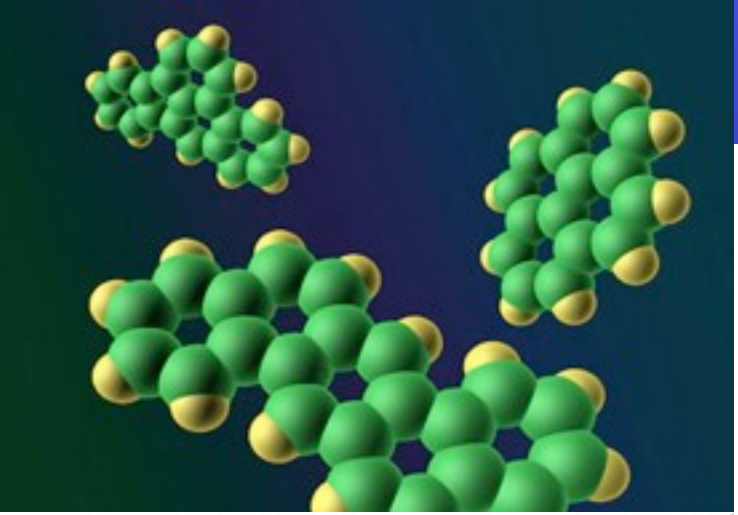
PAH$^-$

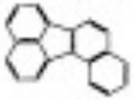
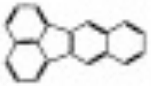
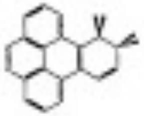
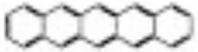
neutralization onto charged particles

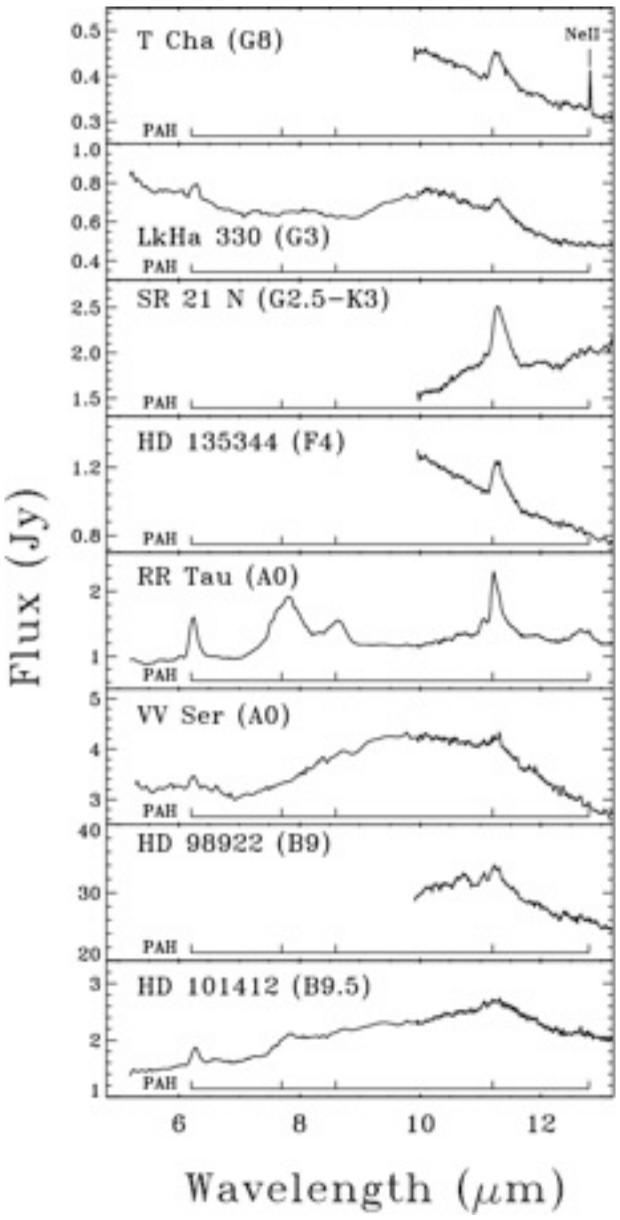
Mg

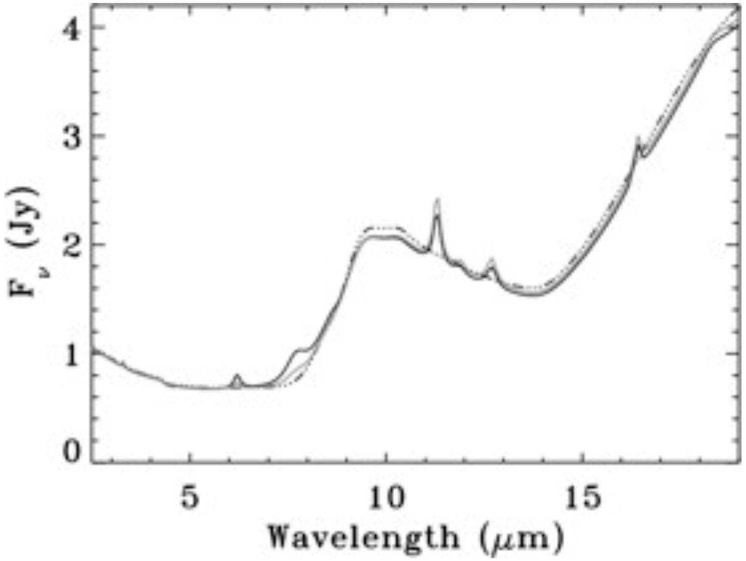
Mg

Polycyclic Aromatic Hydrocarbons (PAHs)



Formula	Name	Structure
$C_{20}H_{12}$	Benzo(j)fluoranthene	
	Benzo(k)fluoranthene	
	Benzo(e)pyrene	
	Perylene	
$C_{20}H_{14}$	9,10-Dihydrobenzo(e)pyrene	
$C_{22}H_{12}$	Benzo[ghi]perylene	
$C_{22}H_{14}$	Pentacene	
$C_{24}H_{12}$	Coronene	
$C_{42}H_{18}$	Hexabenzocoronene-A	





PAH abundance ~ 0.01-10 ppb H_2

(in diffuse ISM ~1 ppm H)

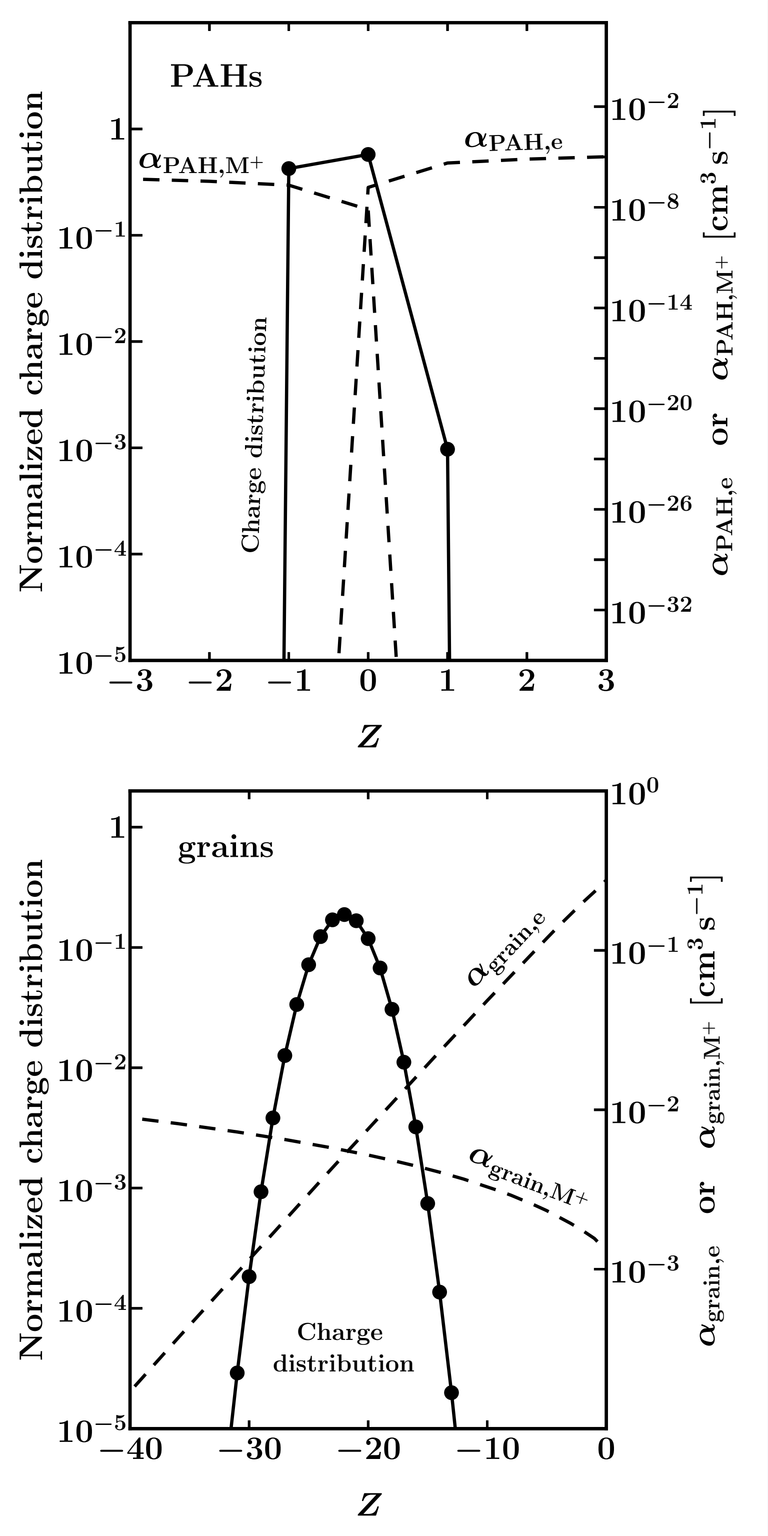
Allamandola et al. 99
Geers et al. 06

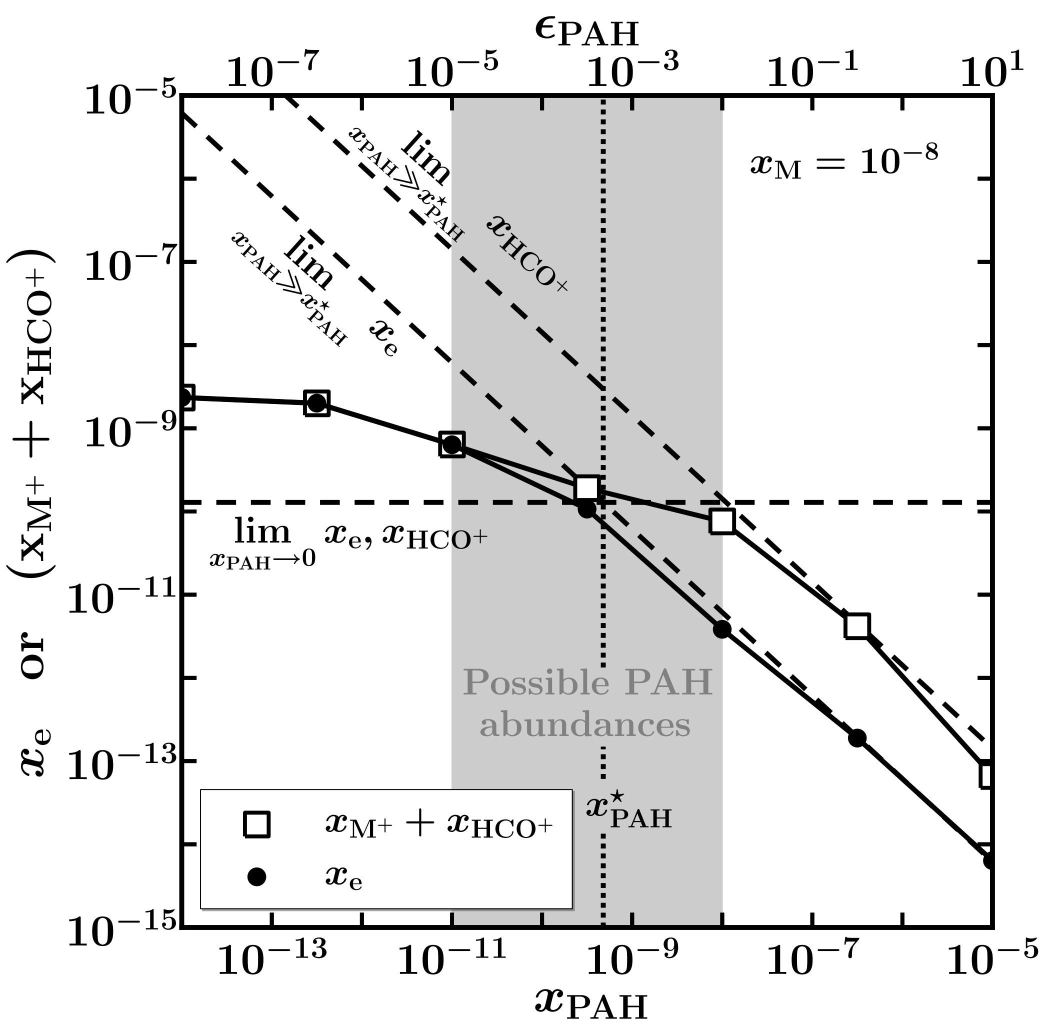
Charge Balance

X-rays ⇒ HCO⁺, Mg⁺ — e⁻

grain⁻ (1 μm)

PAH⁻ (6 Å)

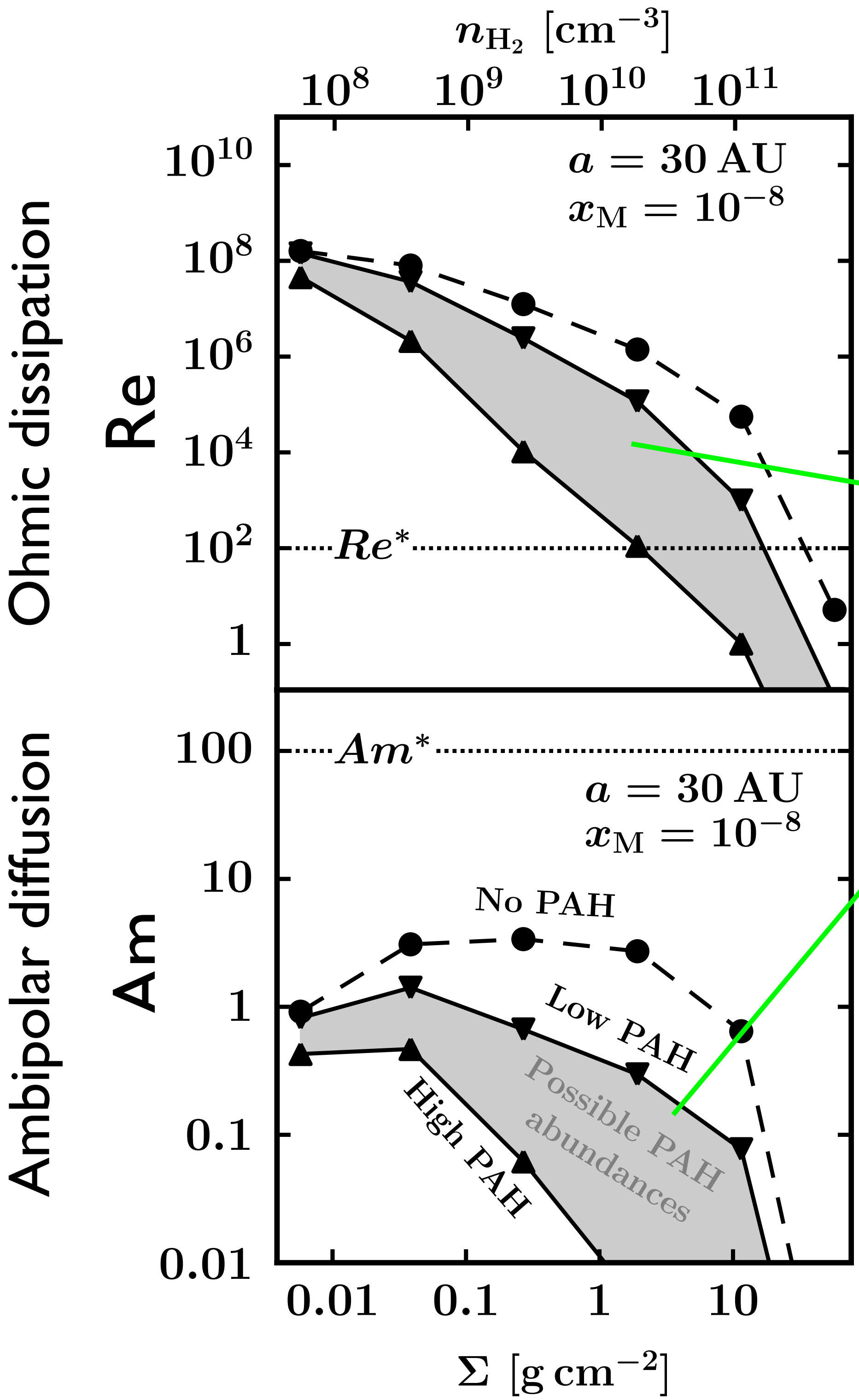




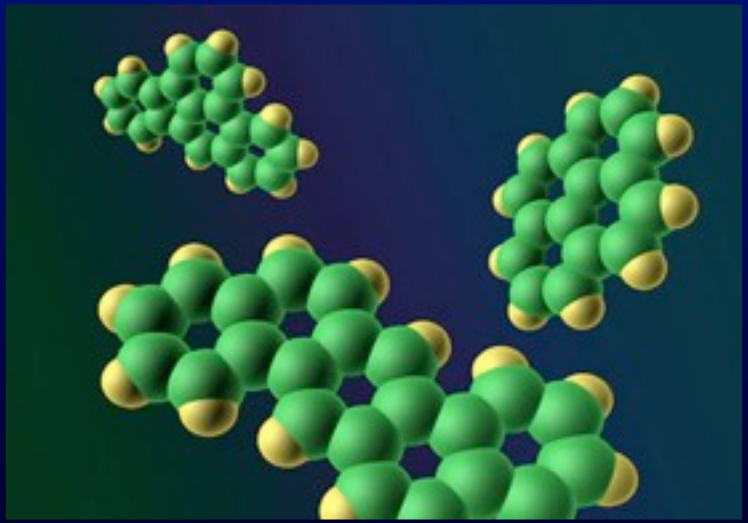
X-ray ionization only

Field may be frozen to plasma ✔

But ions decoupled from neutrals ✗



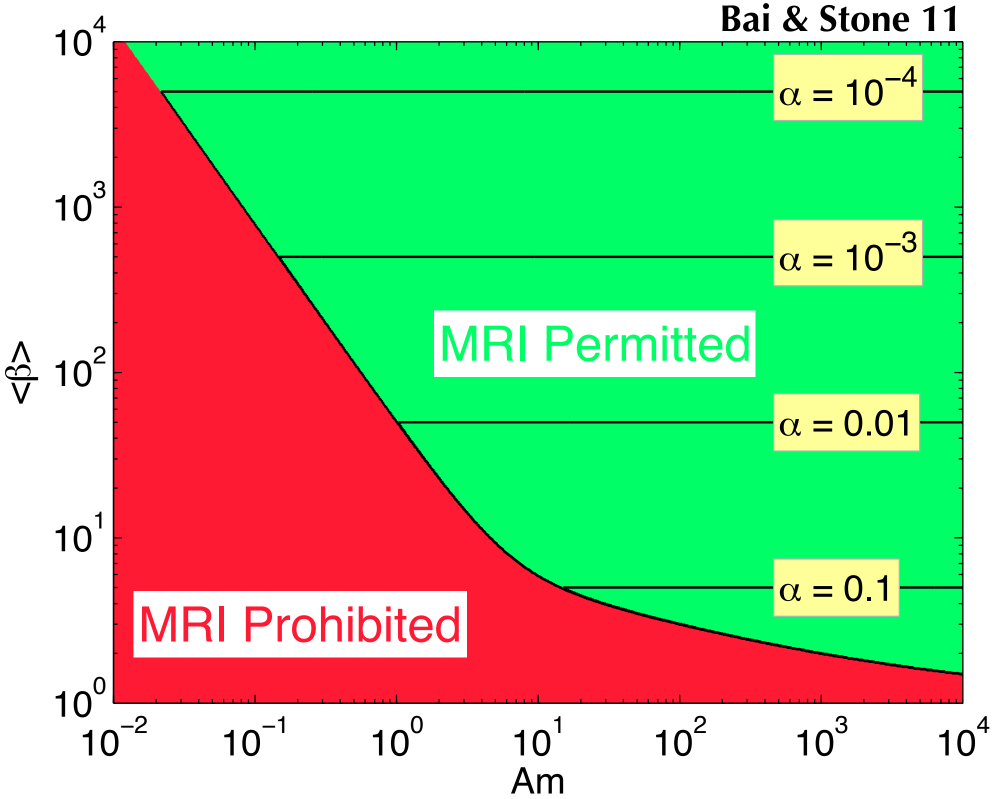
region allowed by PAHs



(0.01-10 ppb H_2)

Perez-Becker & EC 11a
see also Mohanty, Ercolano, and Turner 11, in prep.

MRI with ambipolar diffusion



$\alpha \approx 1/(2\beta)$

and $\beta_{\min}(\mathrm{Am})$

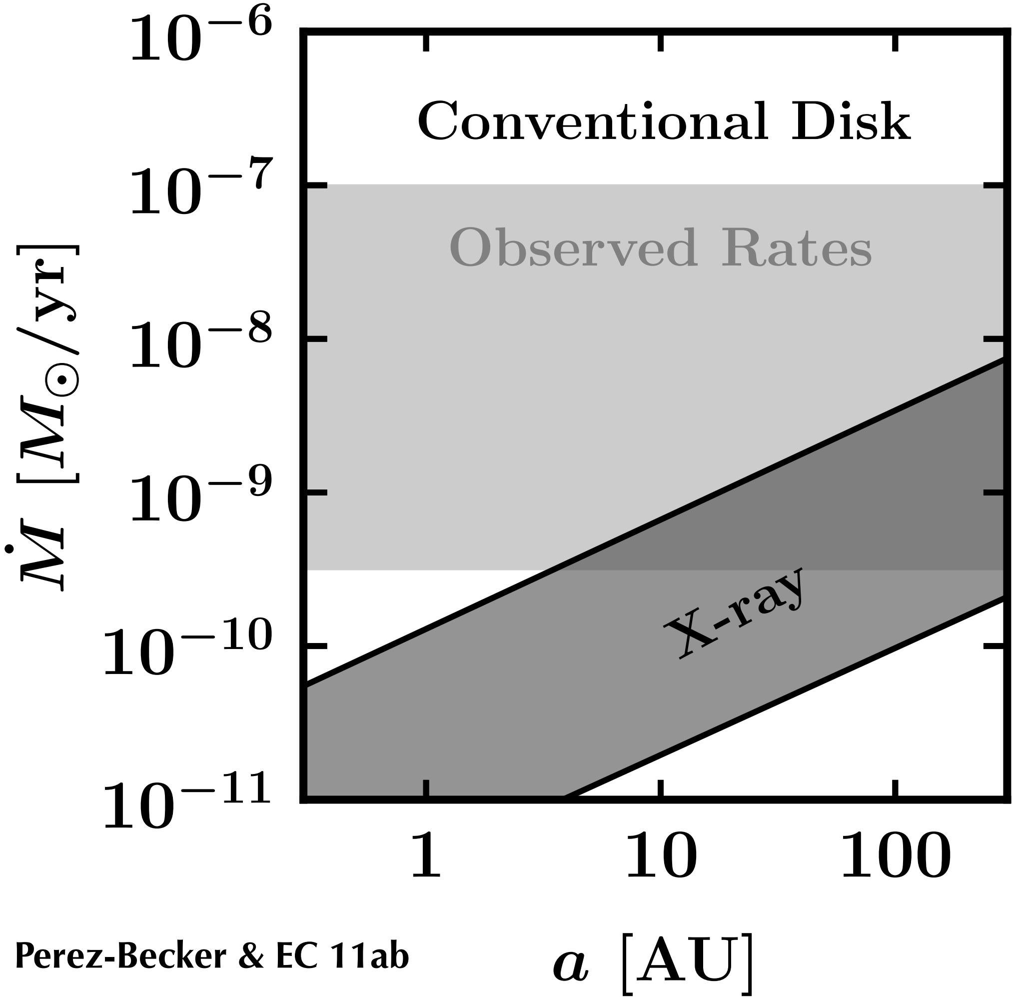
$\Rightarrow \alpha_{\max}(\mathrm{Am})$

Kunz & Balbus 94
Hawley et al. 95
Desch 04
Pessah 10
Bai & Stone 11

$\alpha_{\max}(\mathrm{Am})$ and $\mathrm{Am}(\Sigma)$

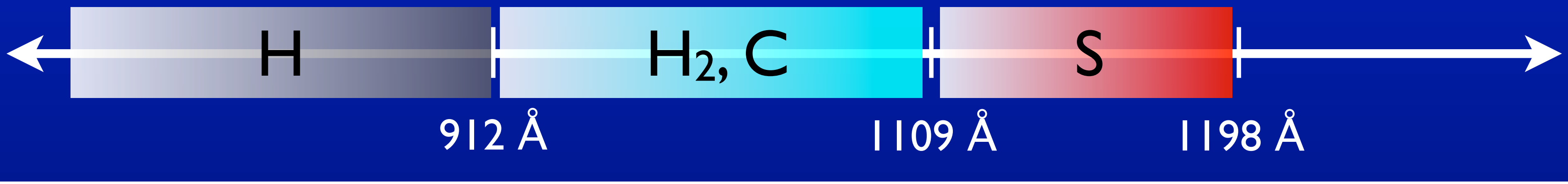
$\Rightarrow \dot{M}$

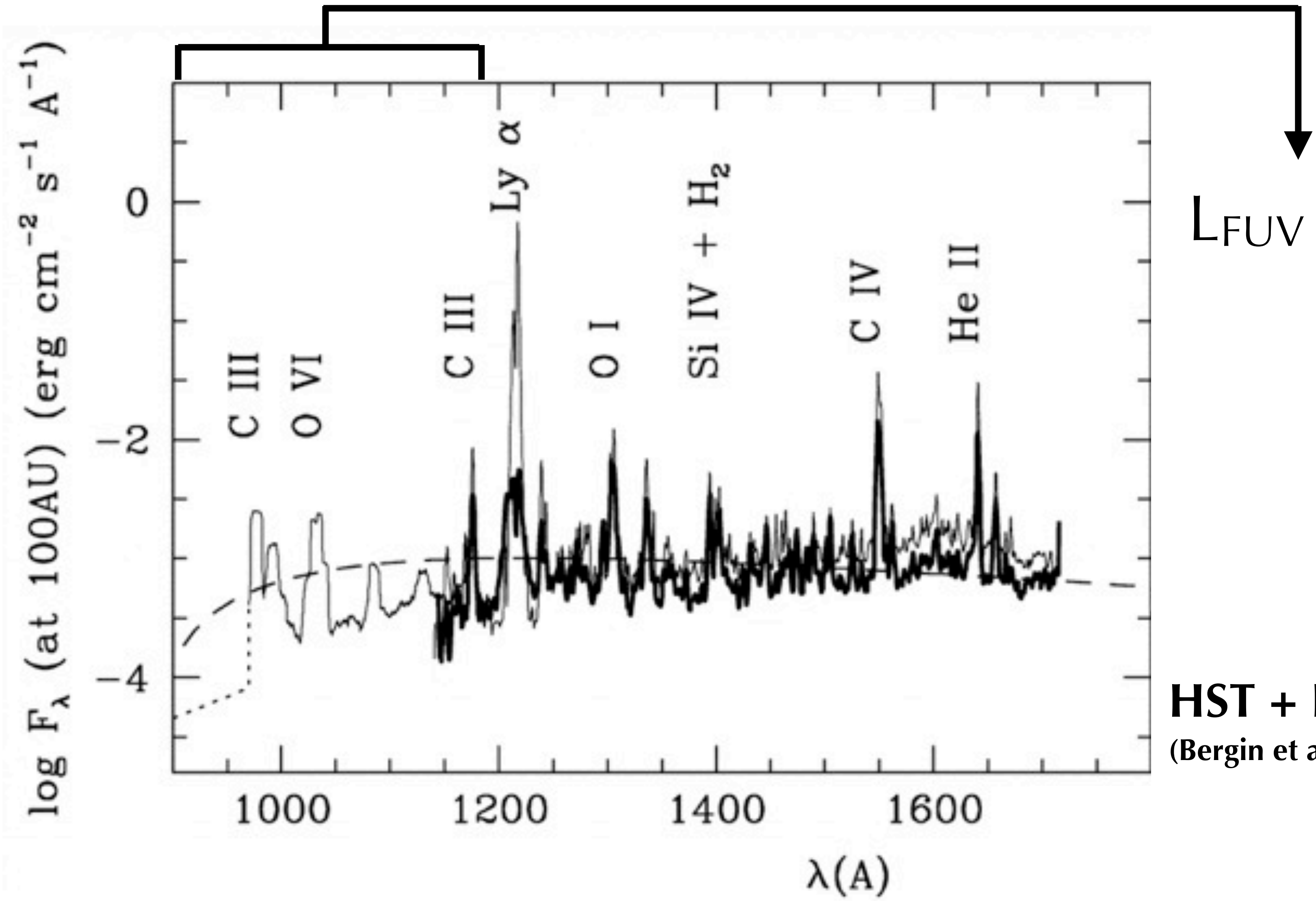
X-rays + PAHs =
weak accretion



Perez-Becker & EC 11ab

Far-Ultraviolet (FUV) Ionization



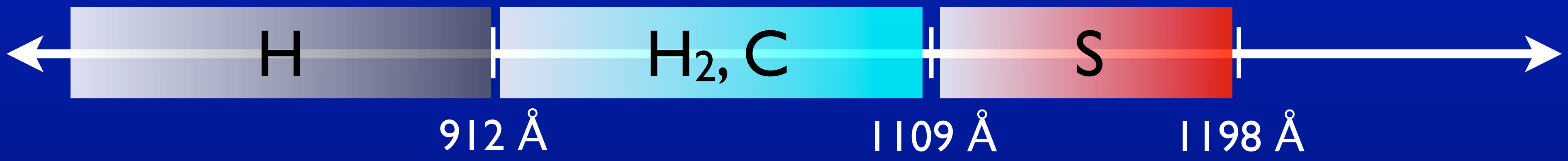


$L_{FUV} \sim 10^{30}\text{-}10^{32}$ erg/s

HST + FUSE

(Bergin et al. 03; Herczeg et al. 02)

FUV Ionization



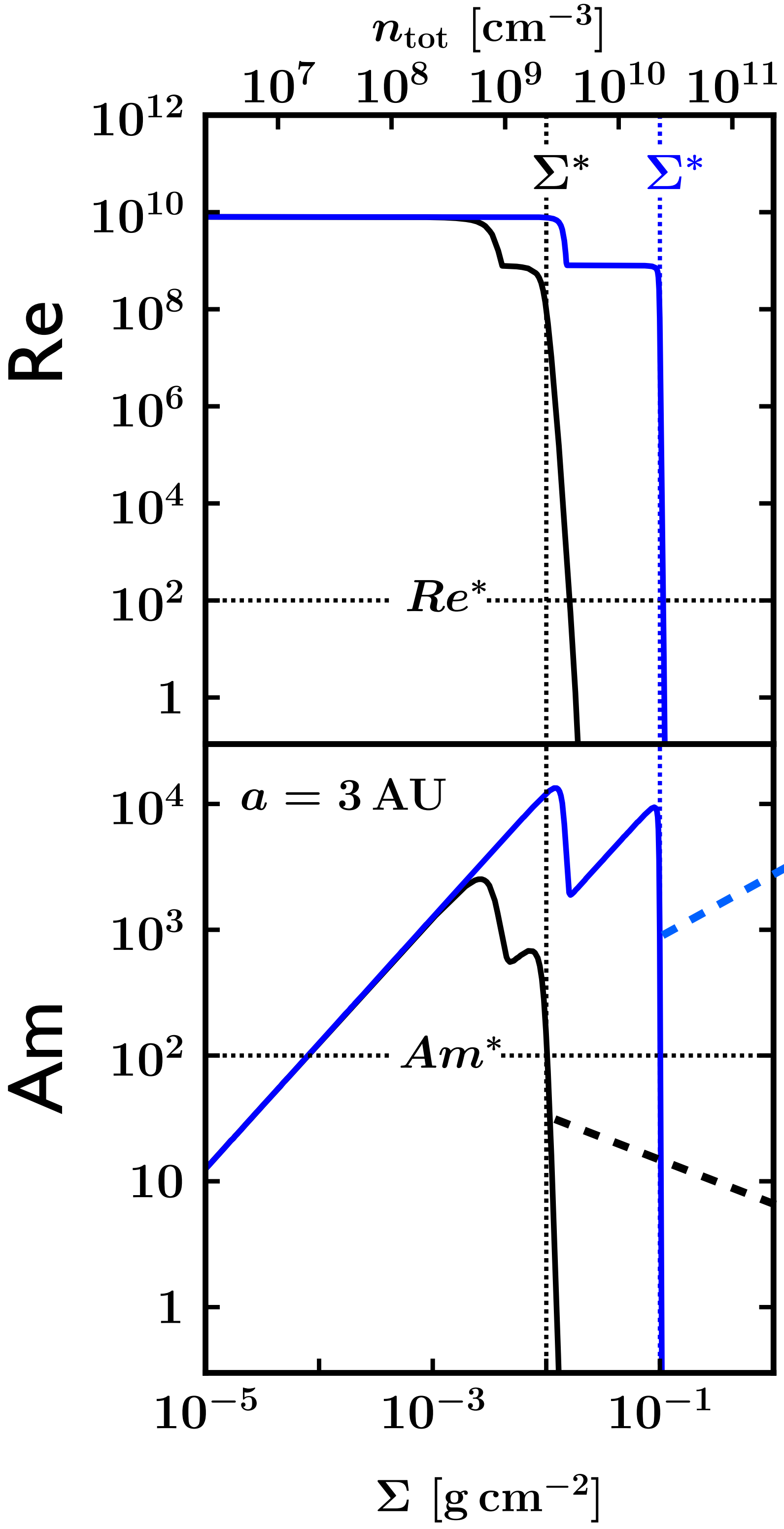
Strömgren slab

$$\left.\begin{array}{l} \quad\text{photoionizations} \qquad\qquad \text{recombinations} \\ \dfrac{L_{\rm FUV}}{h\nu\, 4\pi a^2} \cdot \dfrac{h}{a} \sim n_i n_e \alpha_{\rm rec} \cdot h \\ \\ n_i = n_e = f n_{\rm H_2} \;\; \text{(cosmic abundance)} \end{array}\right\} \quad n_{\rm H_2}$$

$$\Rightarrow \Sigma_{\rm MRI} \sim n_{\rm H_2} \mu h$$

$$\sim 0.1 \left(\frac{L_{\rm FUV}}{10^{30}\ {\rm erg/s}} \right)^{1/2} \left(\frac{10^{-5}}{f} \right) {\rm g/cm^2}$$

Perez-Becker & EC 11ab



$N_{\tau=1}$ = 10^{24} cm^{-2} [S/H] = -1

$N_{\tau=1}$ = 10^{22} cm^{-2} [S/H] = 0

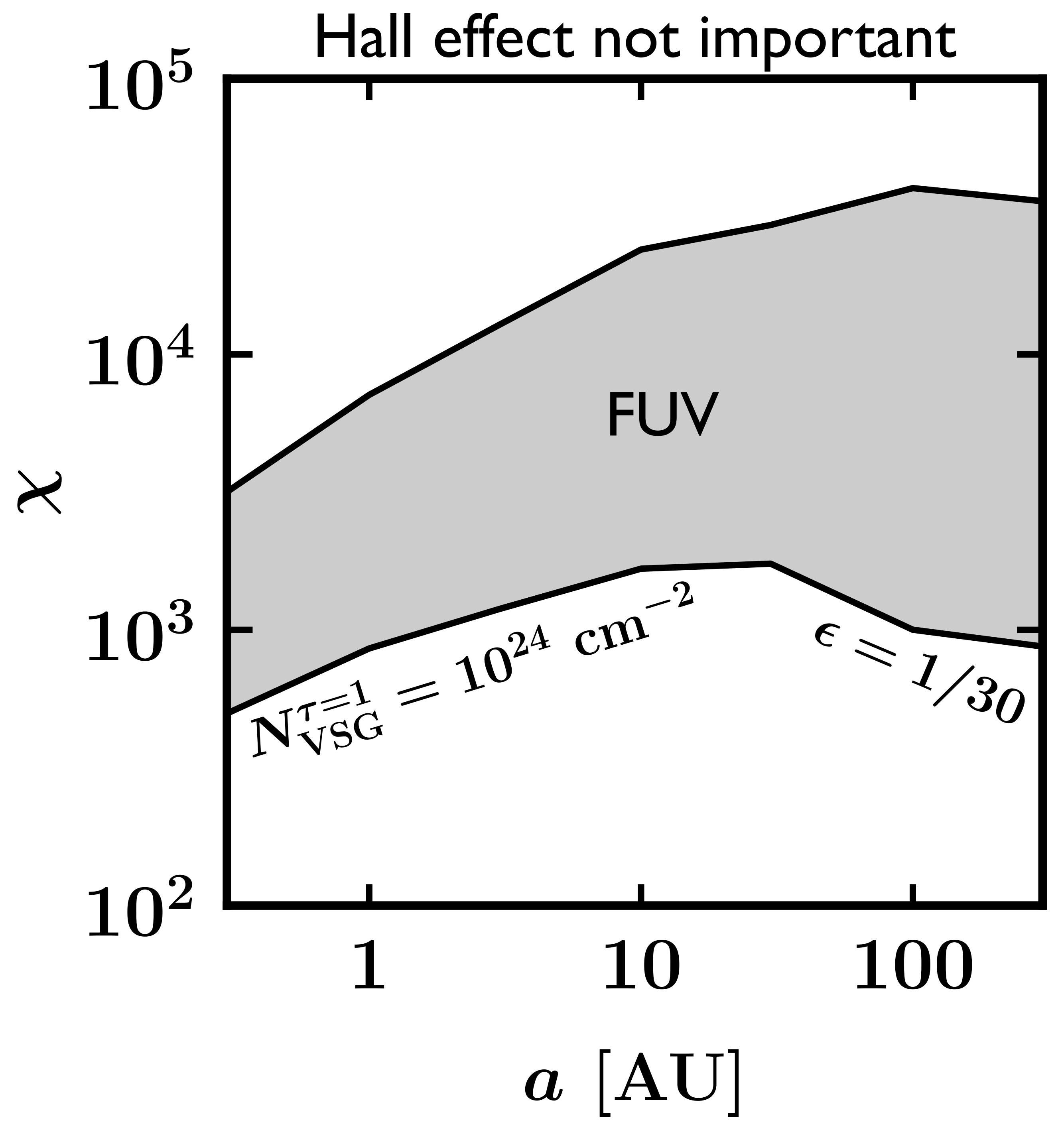
FUV ionization only

Field is frozen to plasma ✔
Good ion-neutral coupling ✔

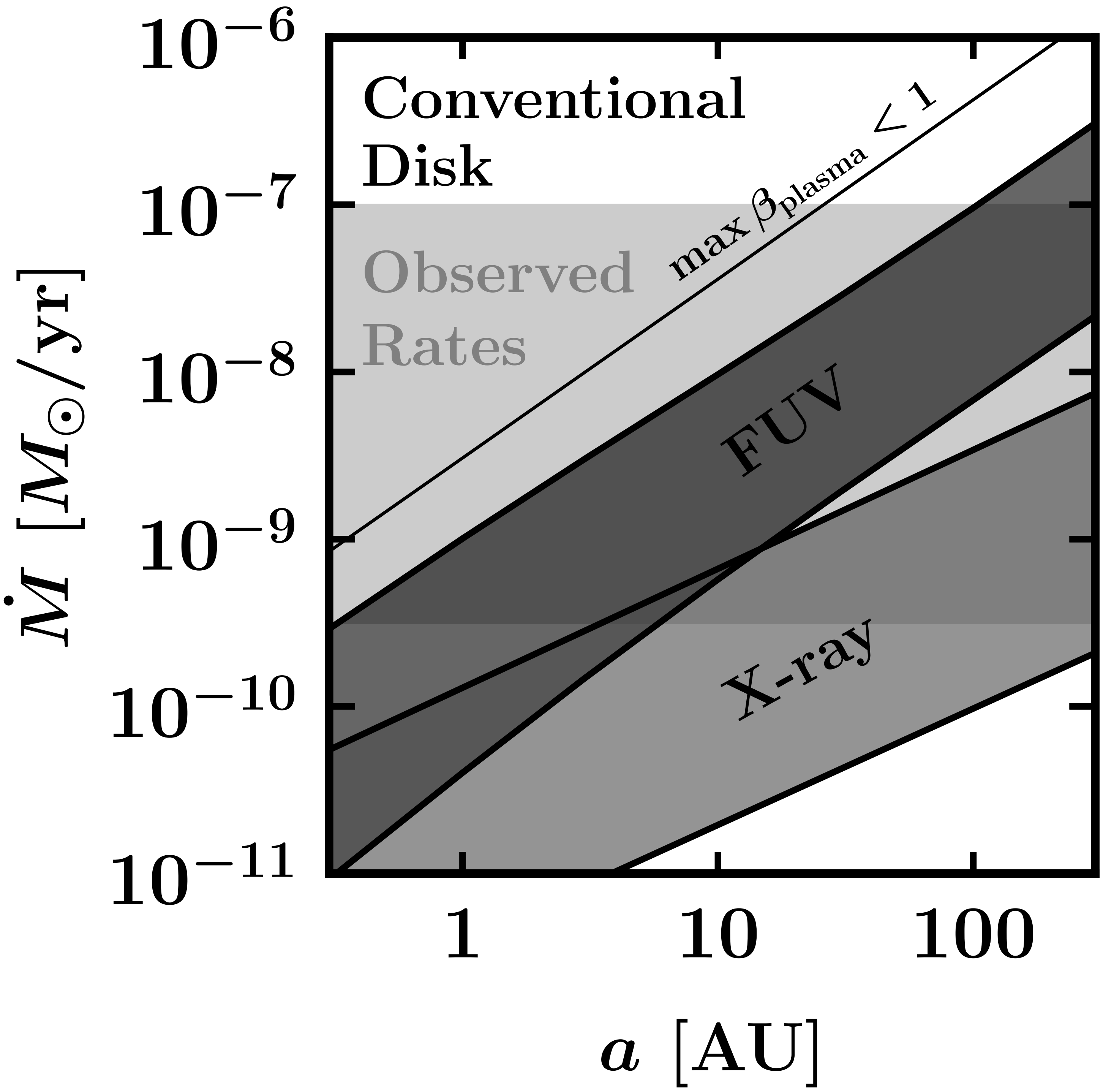
robust against PAHs (PAHs included at maximum abundance)

sensitive to dust-to-gas ratio (vertical settling of dust)

Perez-Becker & EC 11b



Wardle & Salmeron 11



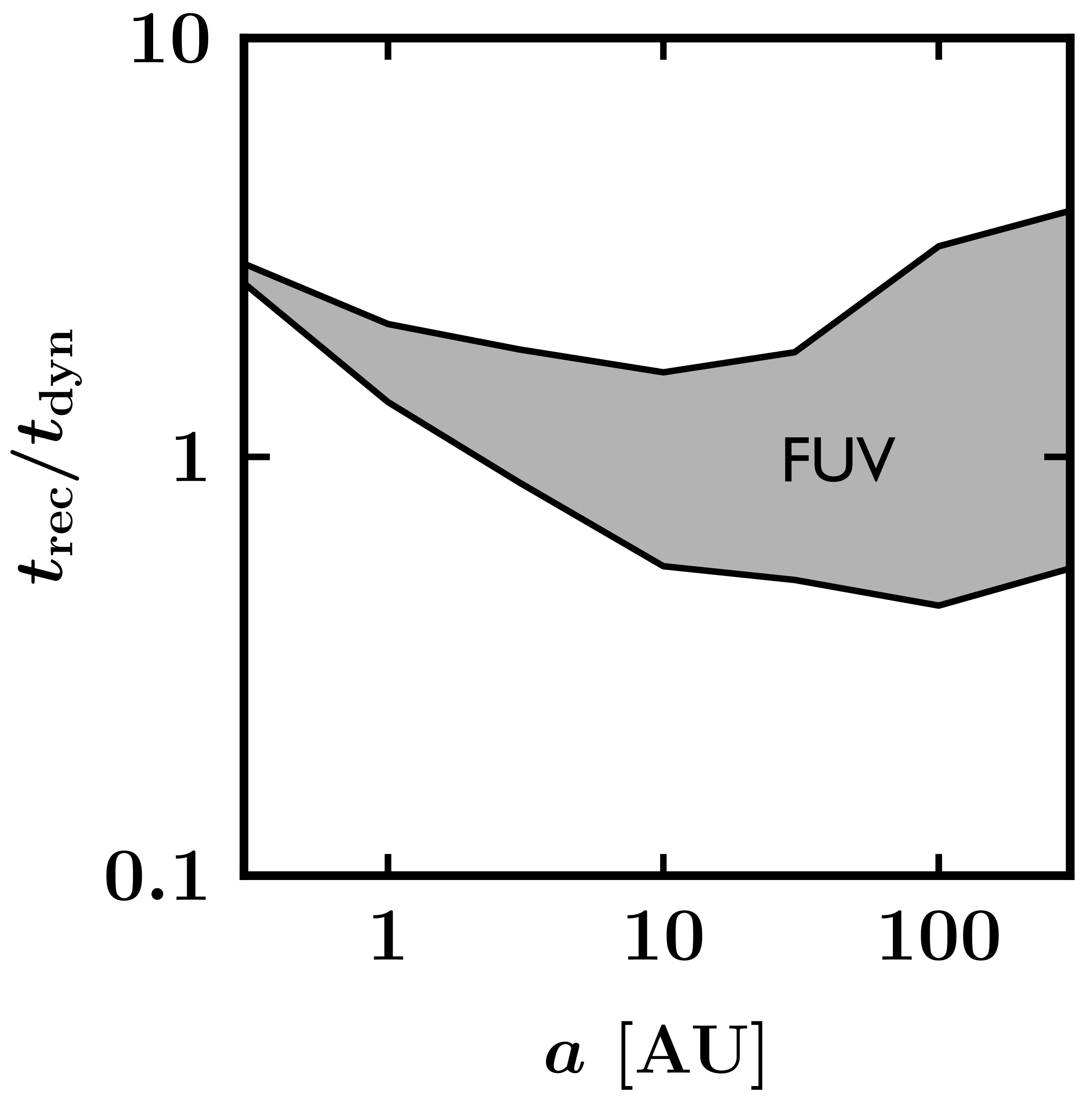
$$\dot{M} \sim 2 \times 3\pi\Sigma^*\nu$$

$$\sim 6\pi\Sigma^*\alpha\frac{kT}{\mu\Omega}$$

FUV-ionized surface layers can reproduce accretion rates at large radius but not small radius

Perez-Becker & EC 11b

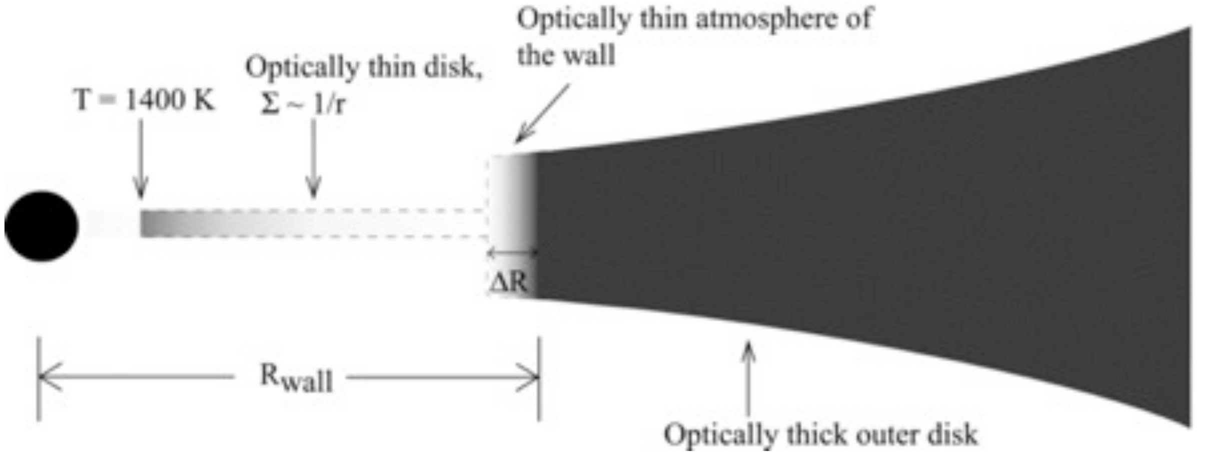
Ion recombination
time
vs.
dynamical time

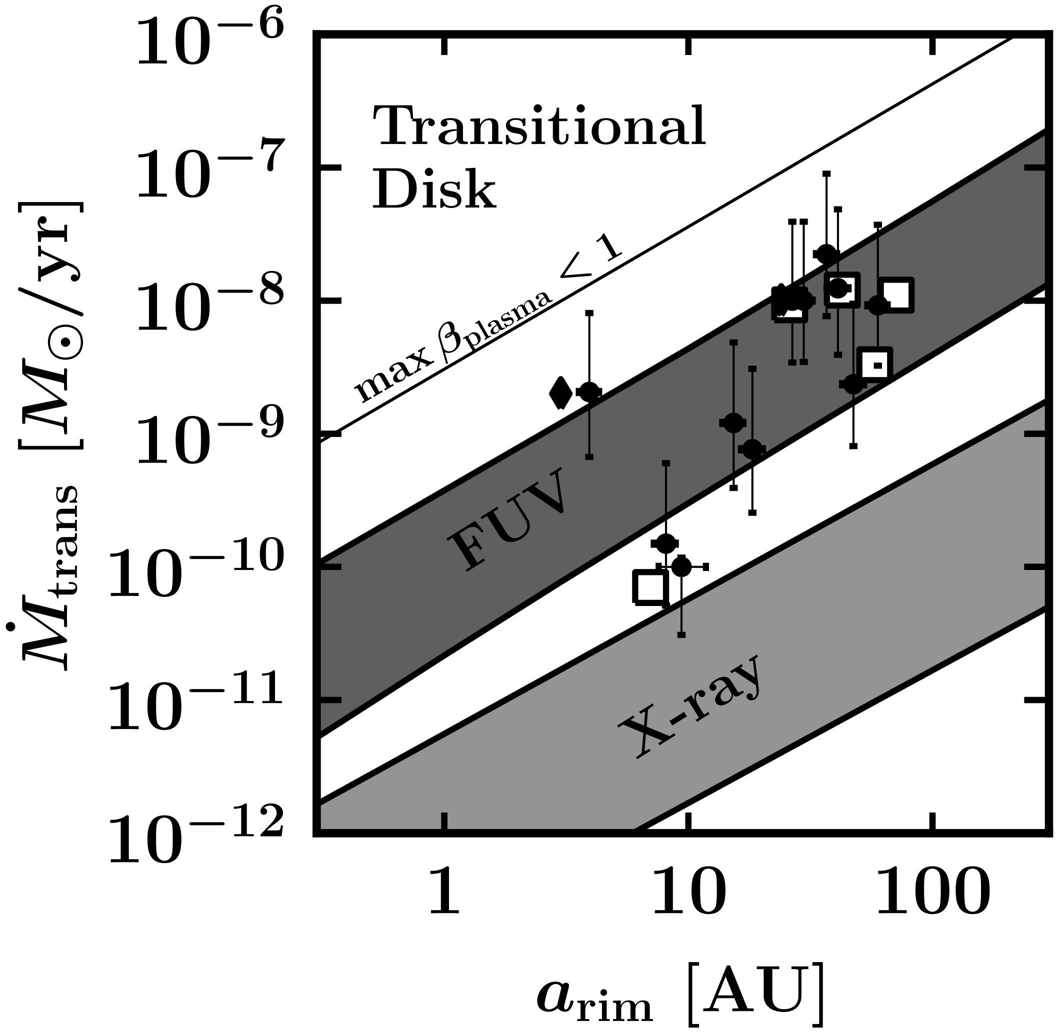


Turbulent mixing
of plasma to
greater depths
can extend
MRI-active layer

Ilgner & Nelson 06b

FUV-driven MRI in Transitional Disks





Rim accretion rate reproduces observations

Transport problem at small radii could be solved by companions

Murray-Clay & EC 07
Kim et al. 09
Perez-Becker & EC 11ab
Zhu et al. 11

Extra Slides

Is the required field super-equipartition?

On the one hand, the field must be strong enough:

$$\dot{M} \sim \langle B_r B_\phi \rangle h/\Omega$$

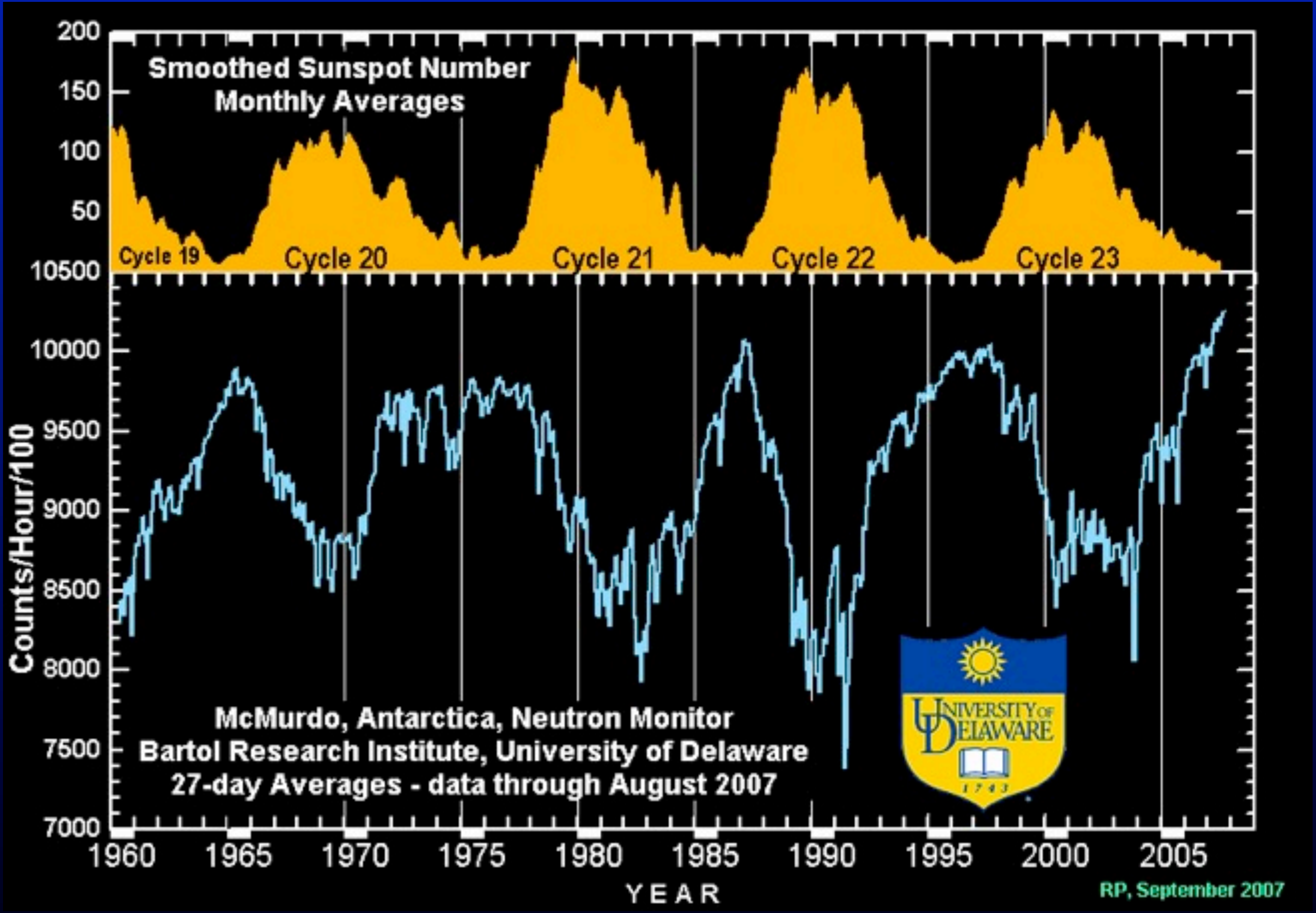
$$\Rightarrow \min B > 1\,\mathrm{G} \left(\frac{\dot{M}}{10^{-8} M_\odot/\mathrm{yr}} \right)^{1/2} \left(\frac{r}{\mathrm{AU}} \right)^{-5/4}$$

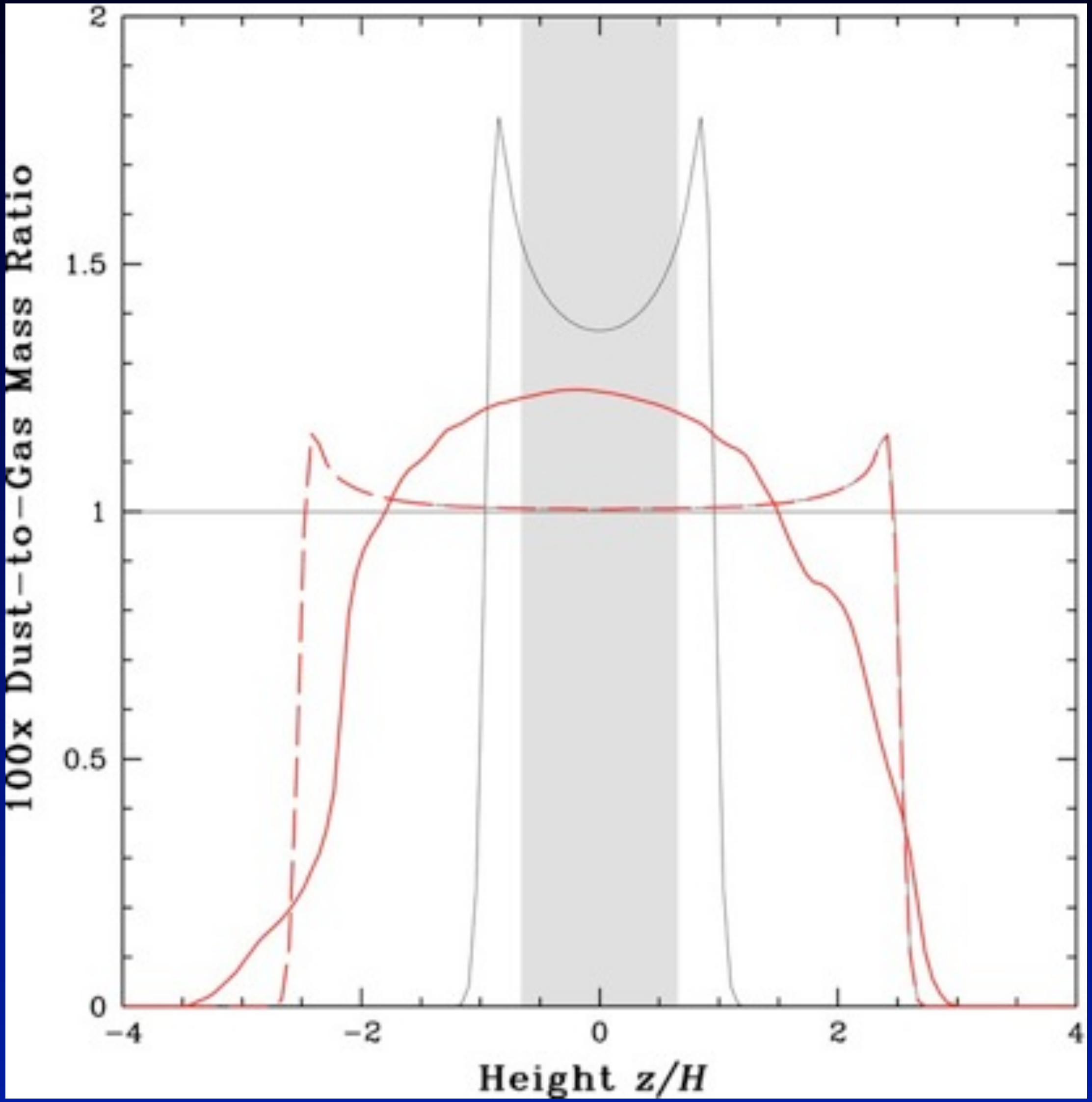
$$\beta \equiv \frac{P_{\mathrm{gas}}}{P_{\mathrm{mag}}} = \frac{8\pi nkT}{B^2} < 1 \left(\frac{\Sigma}{0.1\,\mathrm{g/\,cm^2}} \right) \left(\frac{10^{-8} M_\odot/\mathrm{yr}}{\dot{M}} \right) \left(\frac{r}{1\,\mathrm{AU}} \right)$$

On the other hand the field cannot be too strong: $\beta > 1$

Possible for r > 1 AU

e.g., Bai & Goodman 09

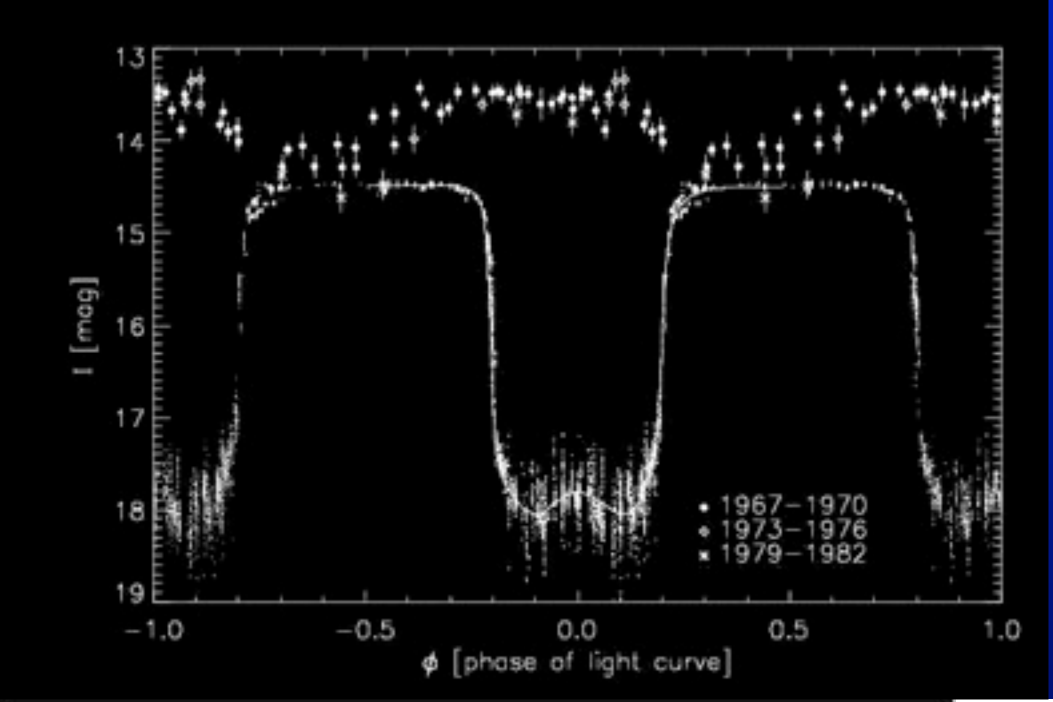
Smoothed Sunspot Number
Monthly Averages
200
150
100
50
Cycle 19
Cycle 20
Cycle 21
Cycle 22
Cycle 23
10500
10000
9500
9000
8500
8000
7500
7000
Counts/Hour/100
McMurdo, Antarctica, Neutron Monitor
Bartol Research Institute, University of Delaware
27-day Averages - data through August 2007
University of Delaware
1743
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
YEAR
RP, September 2007

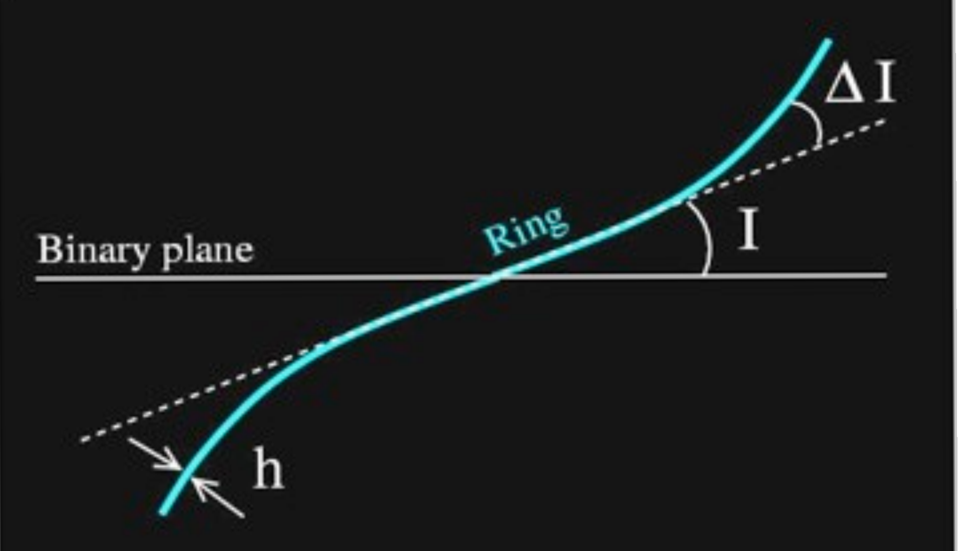

100x Dust-to-Gas Mass Ratio
2
1.5
1
0.5
0
−4
−2
0
2
4
Height z/H

Inside-Out Accretion of Transitional Disks

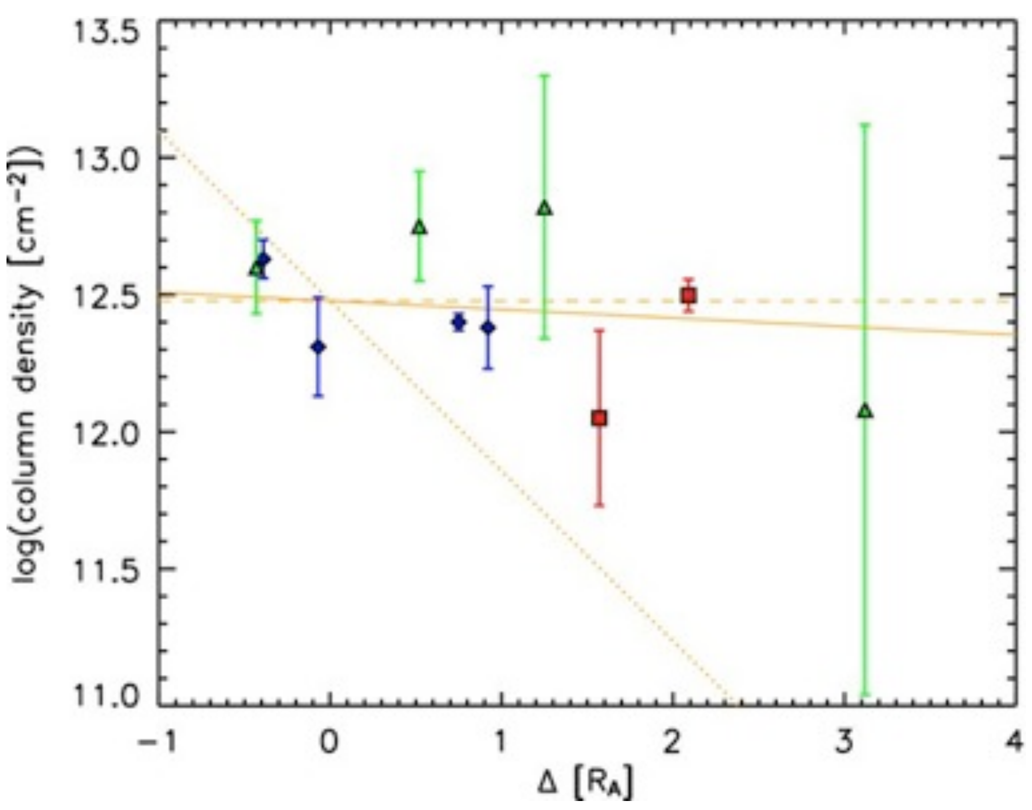
Measuring dust layer thicknesses

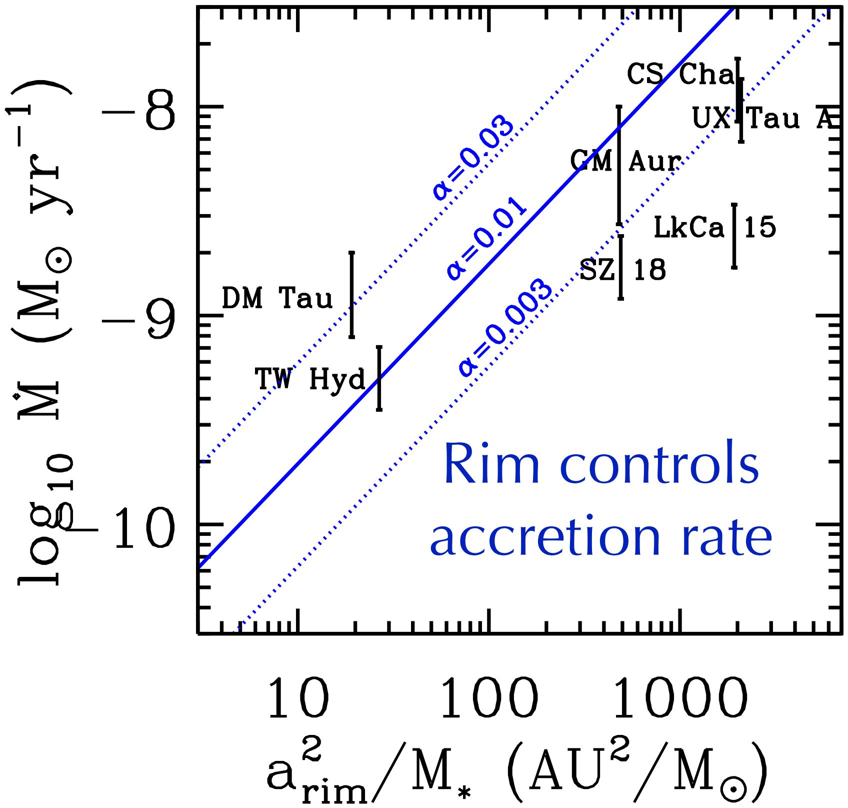
(e.g., occulting circumbinary disk of KH 15D)

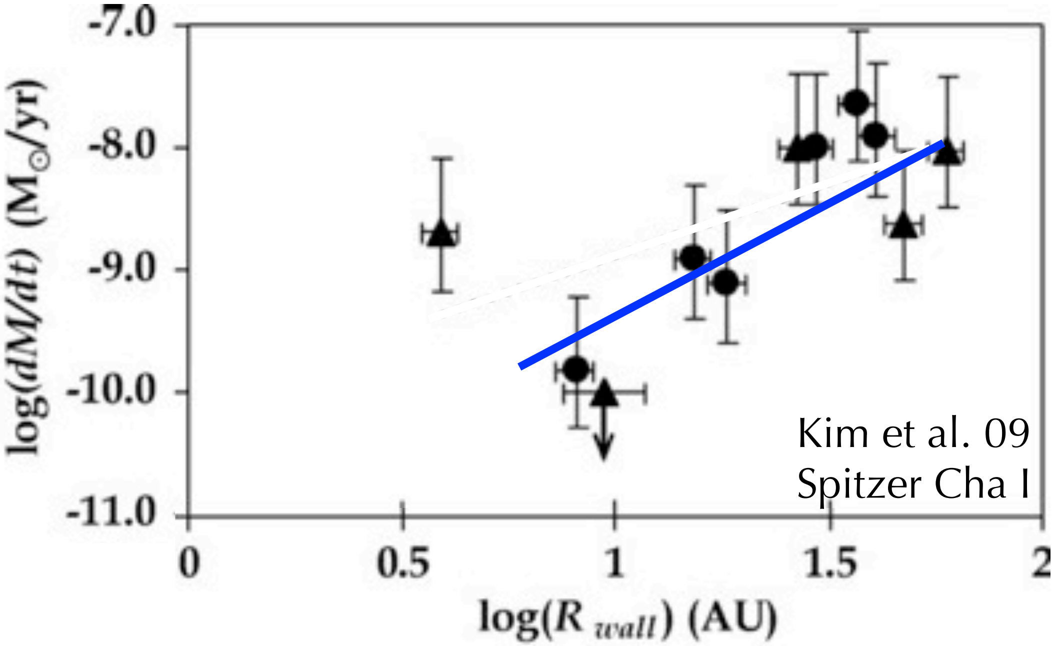




- Dust thickness $h/r \leq R_{\odot}/r \sim 10^{-2}$
- Inclination $I \sim 10^{-1}$
- Warp $\Delta I / I < 10^{-1}$ (self-gravity)
  $\Delta I / I \sim -10^{-1}$ (gas pressure)







Kim et al. 09
Spitzer Cha I

X-ray driven MRI

$$\dot{M} \sim \frac{12\pi\alpha N^* a_{\rm rim}^2 (kT^*)^{3/2}}{GM_*\mu^{1/2}}$$

For constant **α**,

$\Sigma_{\rm gas} \sim 10 - 100\,{\rm g\,cm^{-2}}$

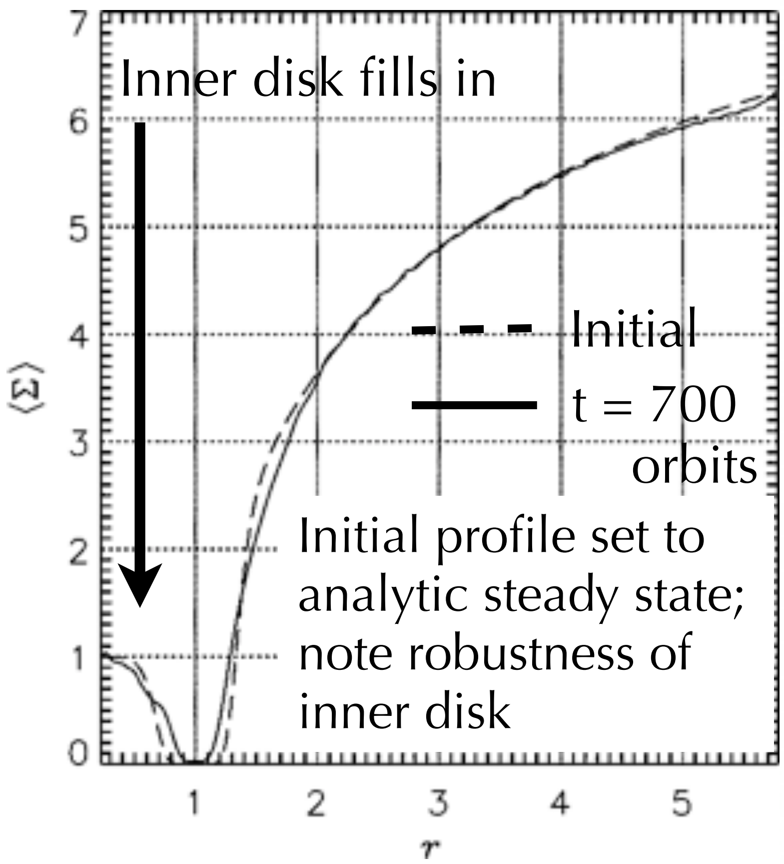
@ 1 AU

- 10-100 x lower density than MMSN
- Satisfies CO lower limits
- Type II migration slower than usual

But cannot explain origin of hole

EC & Murray-Clay 07

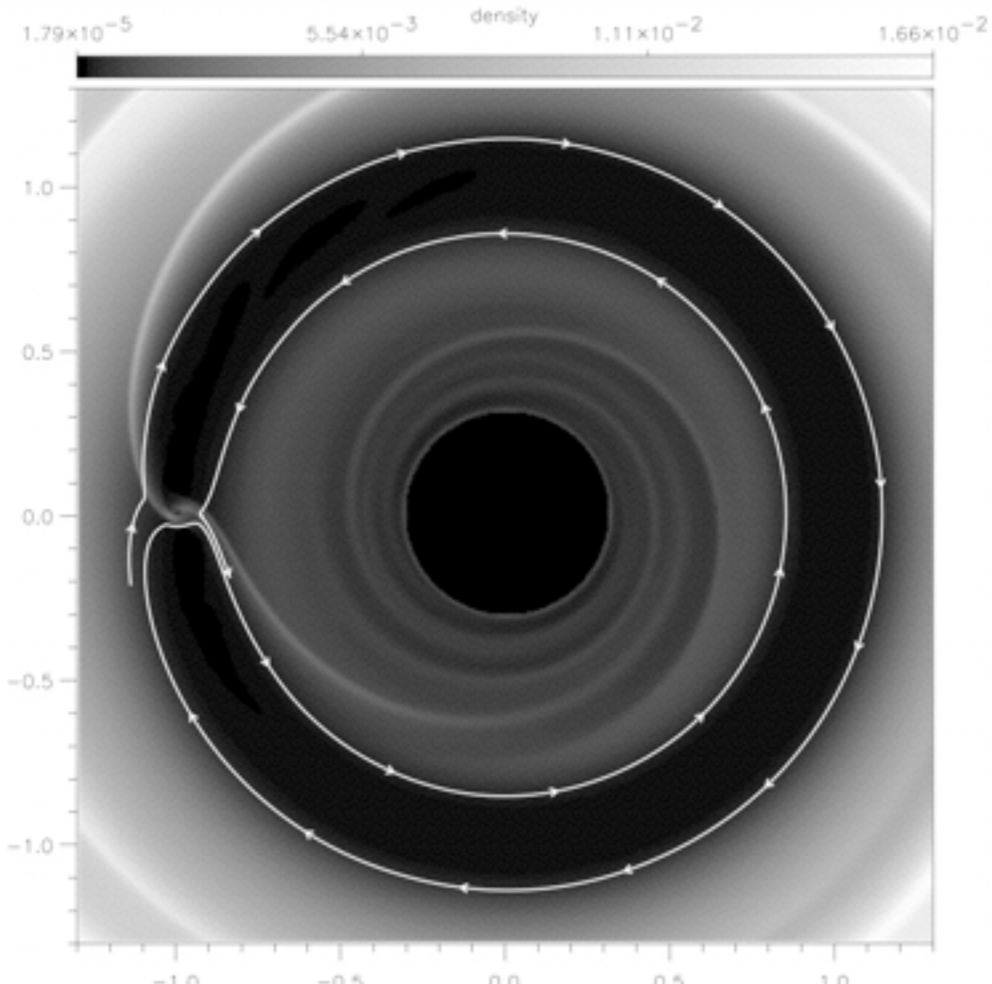
Planet Clearing



Inner disk fills in

Initial profile set to analytic steady state; note robustness of inner disk

Lubow & D'Angelo 06



Lubow et al. 99

$\dot{M}_{\rm inner} \approx 0.1\dot{M}_{\rm outer}$
neglecting
migration

- But planetary migration reduces clearing efficiency
- Short-lived solution ($t_{\rm diffusion} \sim r^2 / \nu \sim 10^4$ orbits)
- Perhaps multiple planets can help

But deeper correlations may exist …

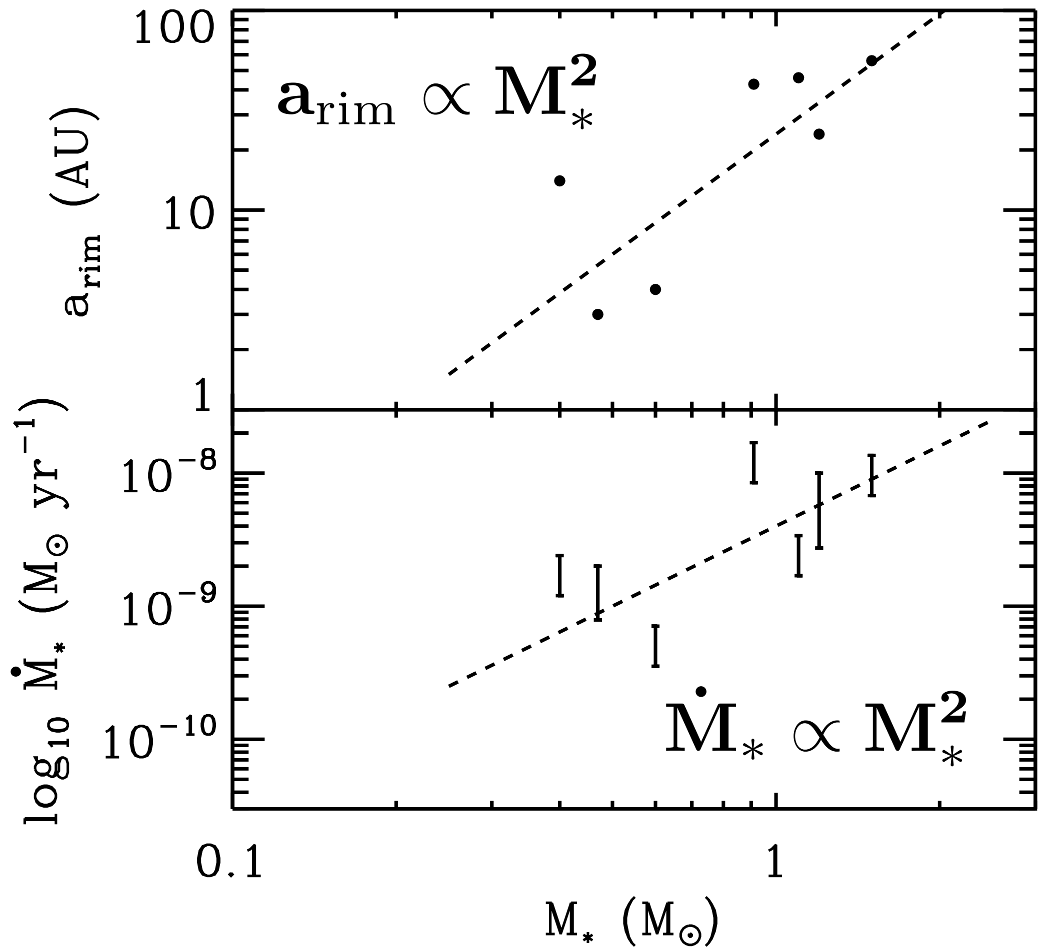
Same

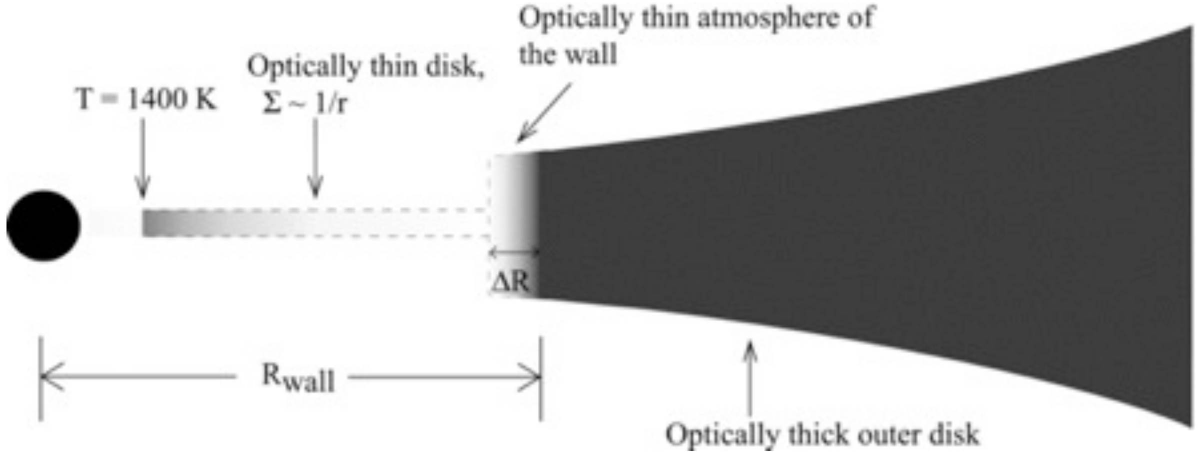
$\dot{M}_* \propto M_*^2$

holds for non-transitional disks

How to keep the inner hole clear of dust?

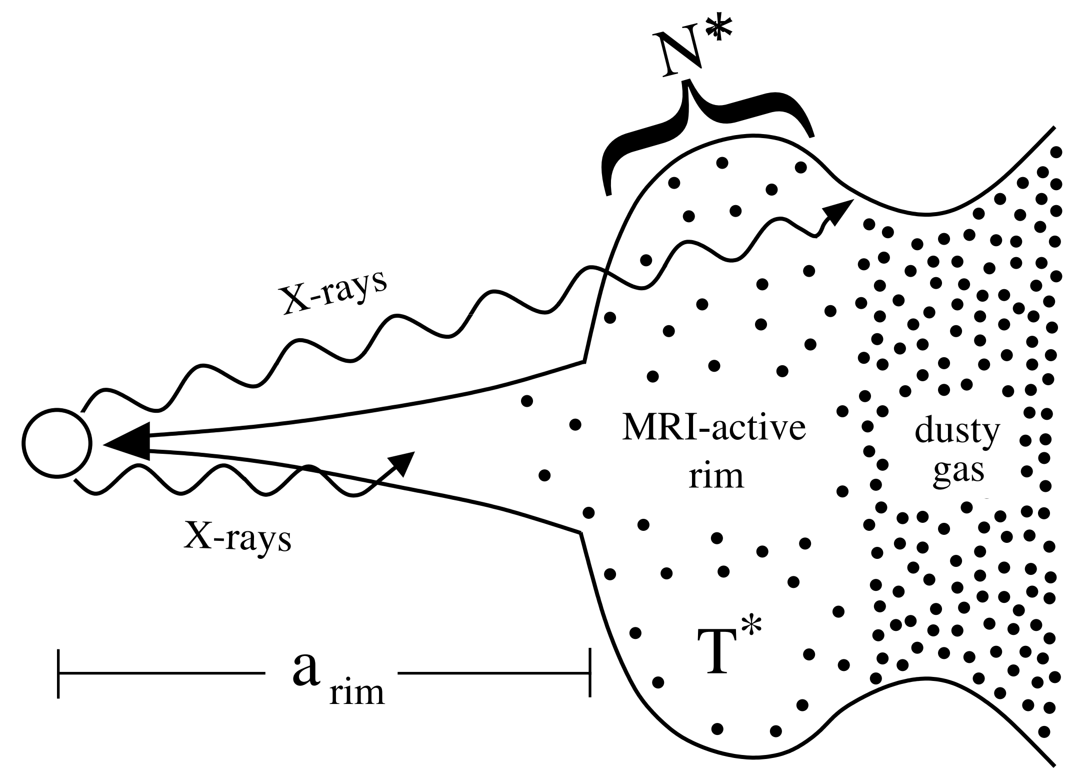
Leaked dust might concentrate at $a \ll a_{\rm rim}$, restoring $\tau_{10\mu m} > 1$: Gapped (“pre-transitional”) disk possible





Kim et al. 09

Inside-Out MRI



10^{23} cm^{-2}

$$M_{\rm rim} = 2\pi a_{\rm rim} \times 2h \times \boxed{N^*}\ \mu$$

$$t_{\rm diff} \sim a_{\rm rim}^2 \,/ \boxed{\nu}$$

$$\nu = \boxed{\alpha} c_s h$$

MRI simulations give 10^{-4}-10^{-1}

$$\dot{M} \sim \frac{M_{\rm rim}}{t_{\rm diff}} \sim \frac{12\pi\alpha N^* a_{\rm rim}^2 (k \boxed{T^*}\ )^{3/2}}{G M_* \mu^{1/2}}$$

230 K

$$\frac{L_X \sigma_X e^{-N^* \sigma_X} f_{\rm heat} n}{4\pi a_{\rm rim}^2} \sim \Lambda_{\rm CO}(T^*)$$

photo-ionization heating

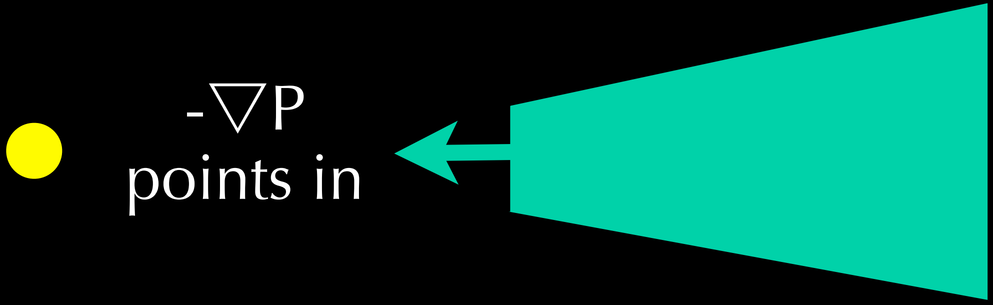
CO ro-vibrational cooling

Glassgold, Najita, & Igea 04

EC & Murray-Clay 07

Keeping inner hole clear of dust

Aerodynamic filter



-∇P
points in

Gas is super-Keplerian

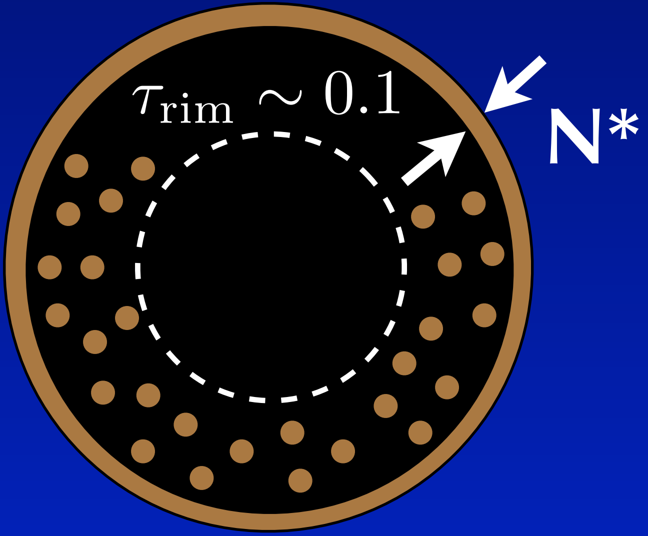
Dust is Keplerian ∴ dragged out

Rice et al. 06

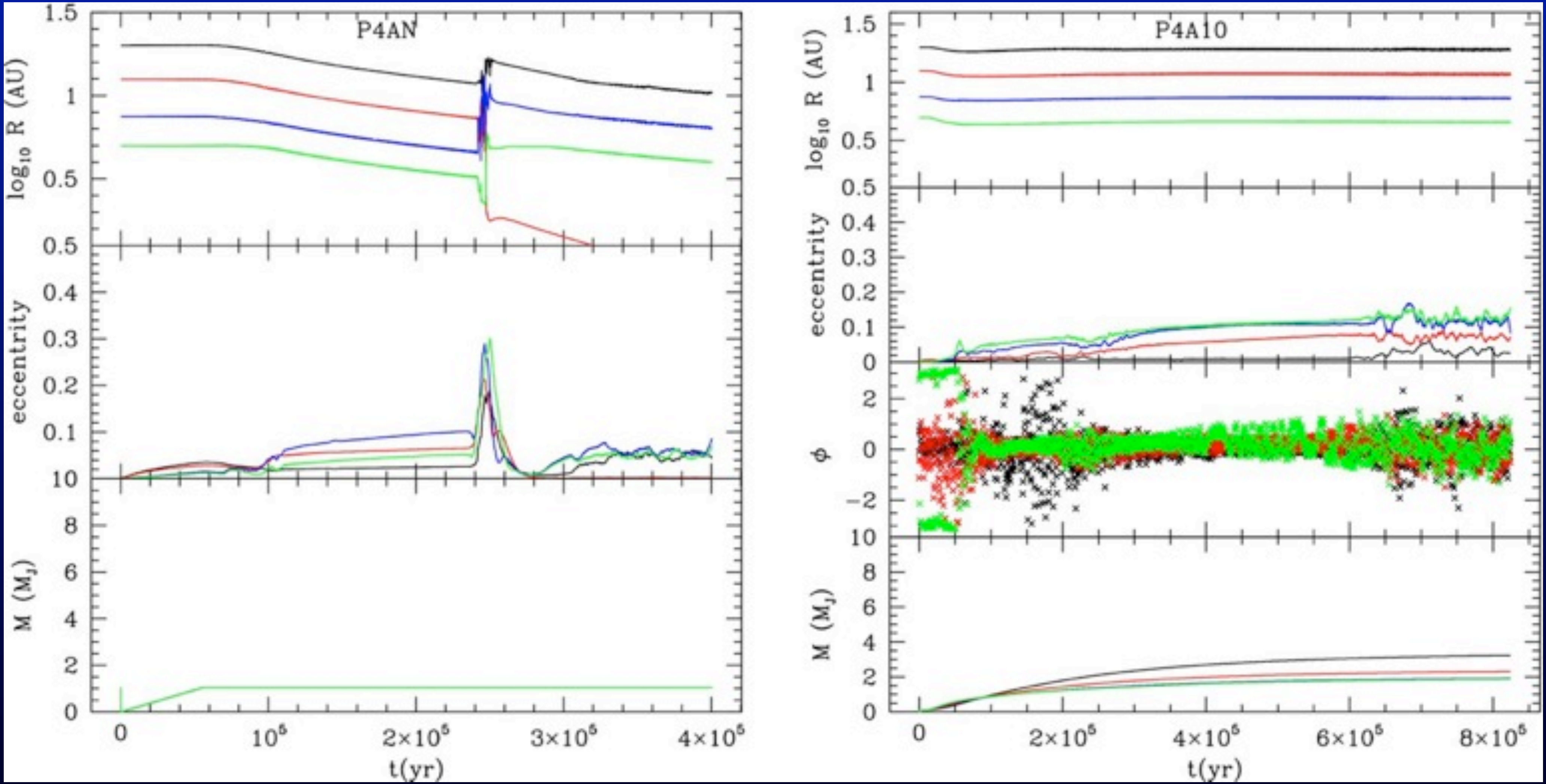
Radiation pressure

$$t_{\rm blow} \sim \frac{1}{\Omega}\left(\frac{1}{\Omega t_{\rm stop}}\right)$$

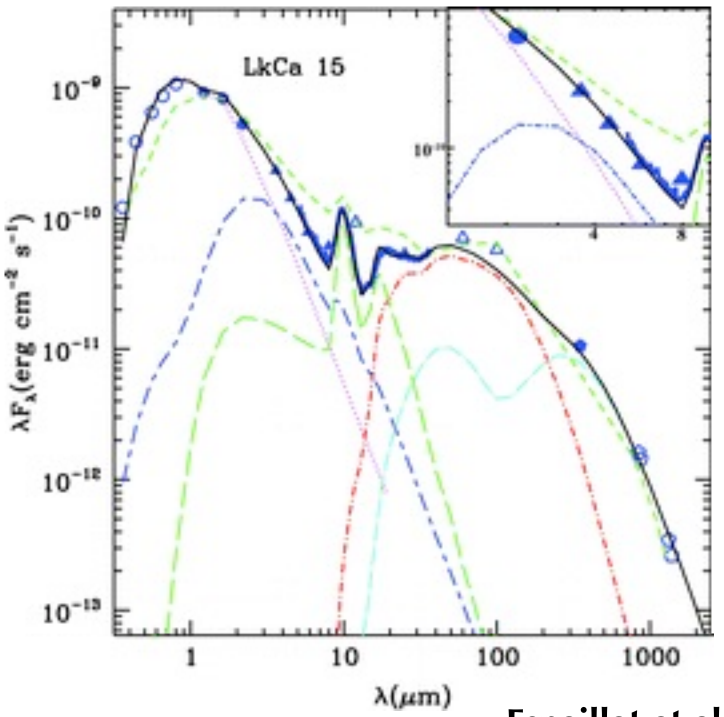
EC & Murray-Clay 07



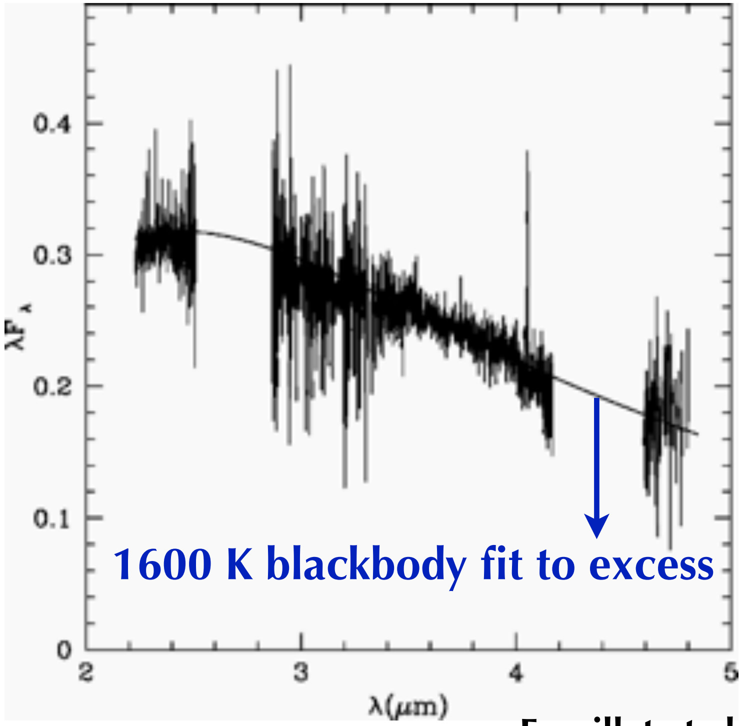
- Filtering is inefficient
- Leaked dust might concentrate at $a \ll a_{\rm rim}$, restoring $\tau_{10\mu{\rm m}} > 1$:
  Gapped ("pre-transitional") disk possible


P4AN
log₁₀ R (AU)
1.5
1
0.5
eccentricity
0.5
0.4
0.3
0.2
0.1
10
8
6
4
2
0
M (M_J)
0
10⁵
2×10⁵
3×10⁵
4×10⁵
t(yr)
P4A10
log₁₀ R (AU)
1.5
1
0.5
eccentricity
0.5
0.4
0.3
0.2
0.1
0
ϕ
2
0
−2
10
8
6
4
2
0
M (M_J)
0
2×10⁵
4×10⁵
6×10⁵
8×10⁵
t(yr)

“Pre-Transitional” Gapped Disks

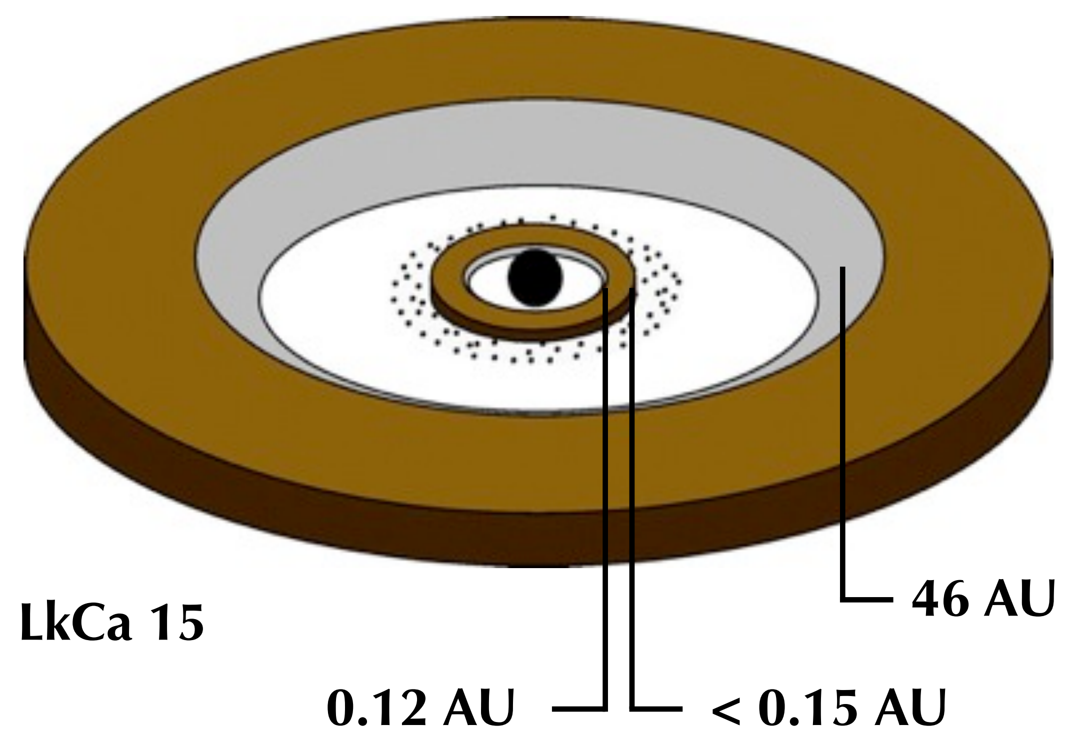


Espaillat et al. 07

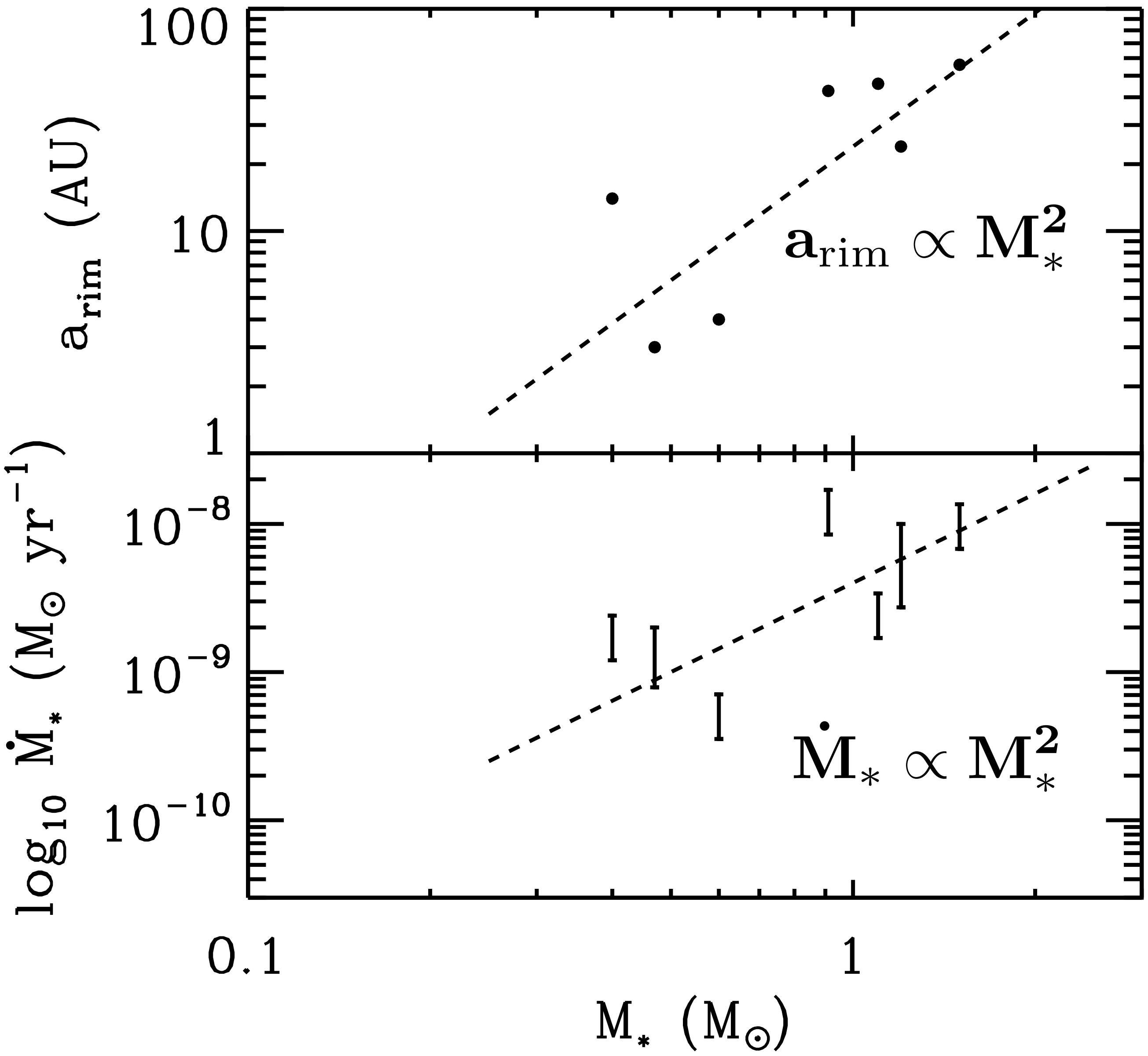


1600 K blackbody fit to excess

Espaillat et al. 08



But deeper correlations may exist …



Why?

And does similar relation hold for debris disks?

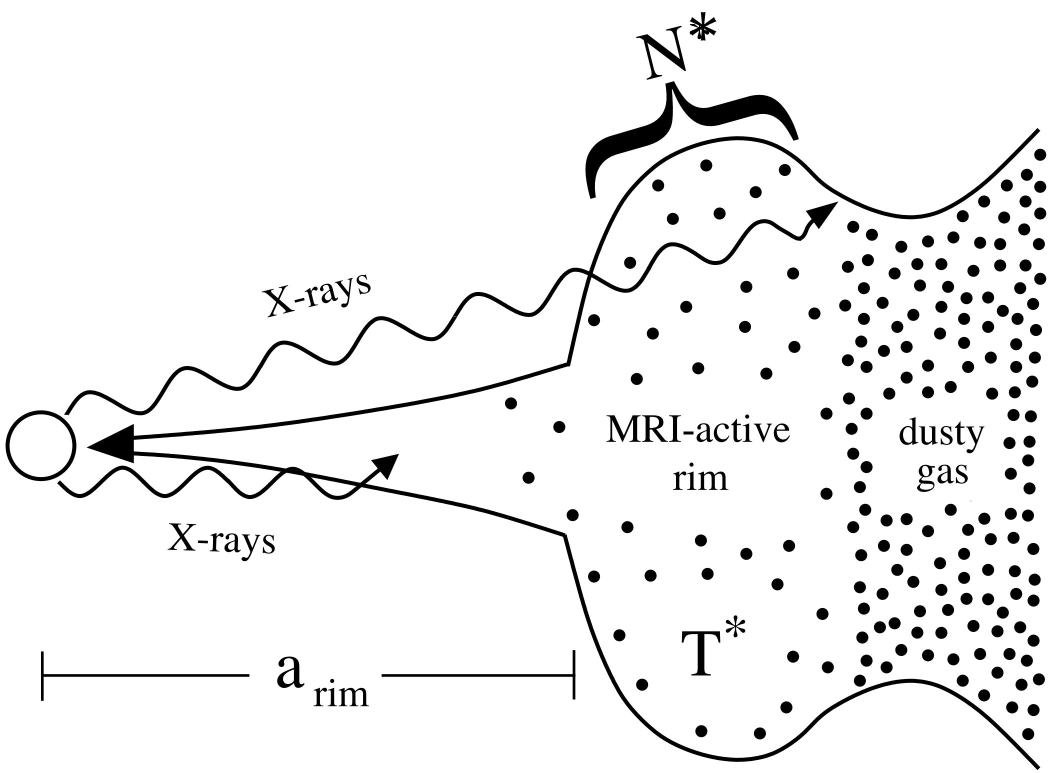
Same
$\dot{M}_* \propto M_*^2$
holds for non-transitional disks

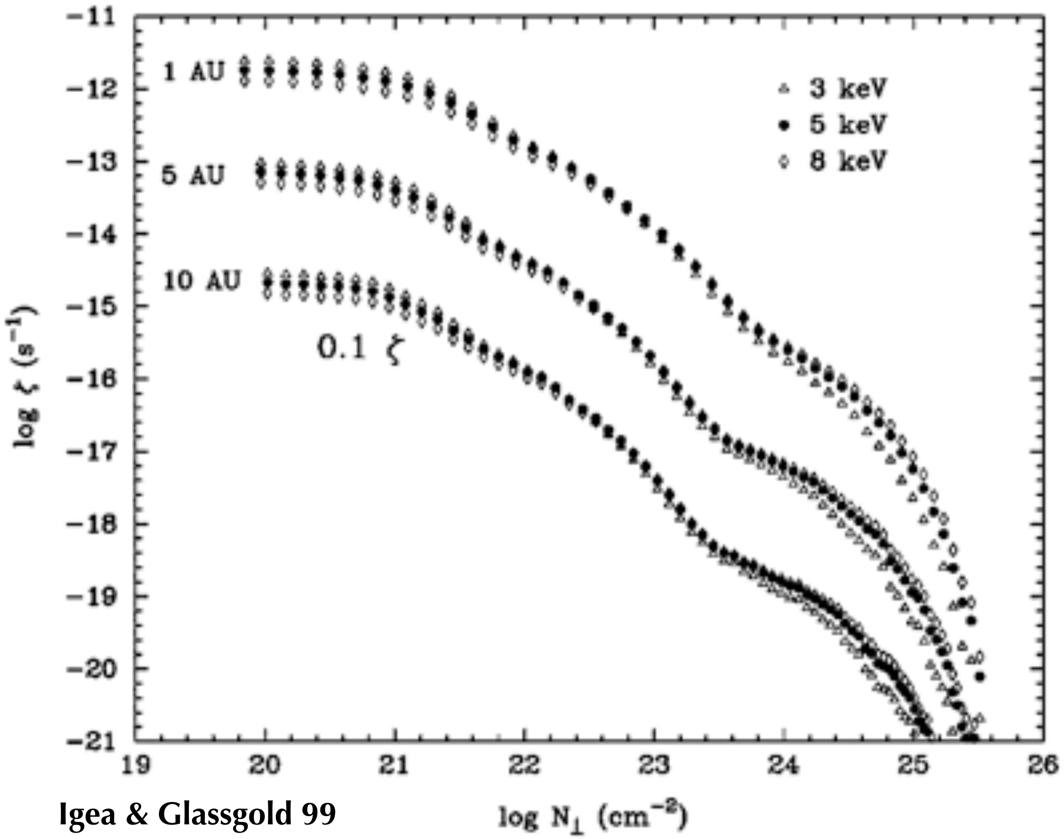
Sustaining MRI at a << $a_{\rm rim}$

Scale to minimum temperature (blackbody)

$$T = 50\,{\rm K}\; a_{\rm AU}^{-3/4}\; \dot{M}_{-9}^{1/4}\; \widehat{T} \qquad (\widehat{T} > 1)$$

$$N_{\perp} = 10^{25}\,{\rm cm}^{-2}\; a_{\rm AU}^{-3/4}\; \alpha_{0.01}^{-1}\; \dot{M}_{-9}^{3/4}\; \widehat{T}^{-1}$$





Igea & Glassgold 99

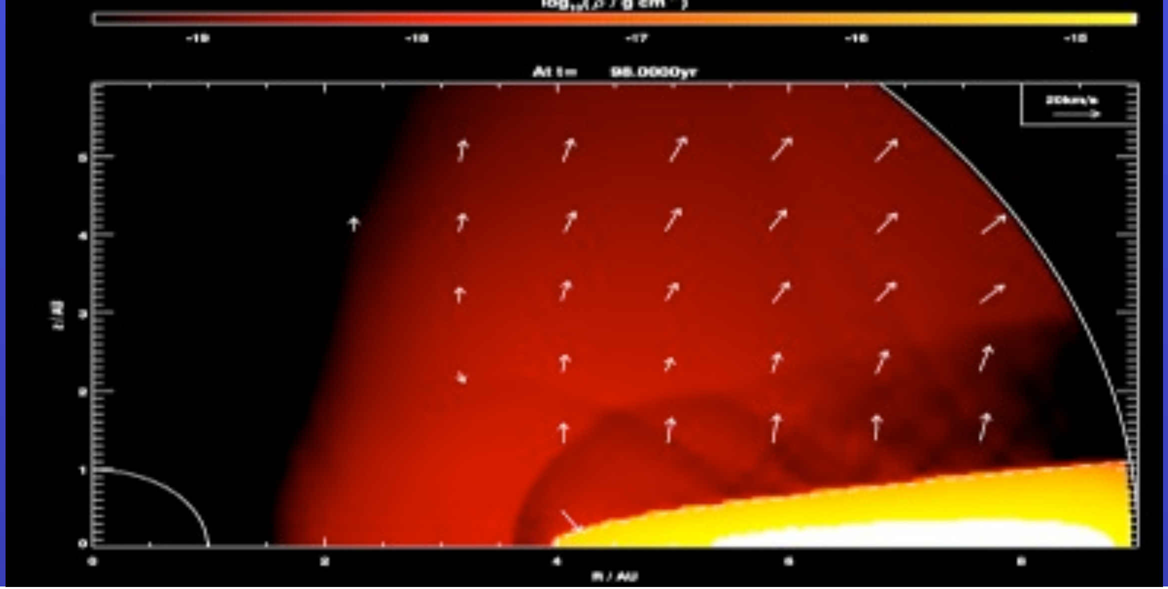
ζ (Igea & Glassgold 99)

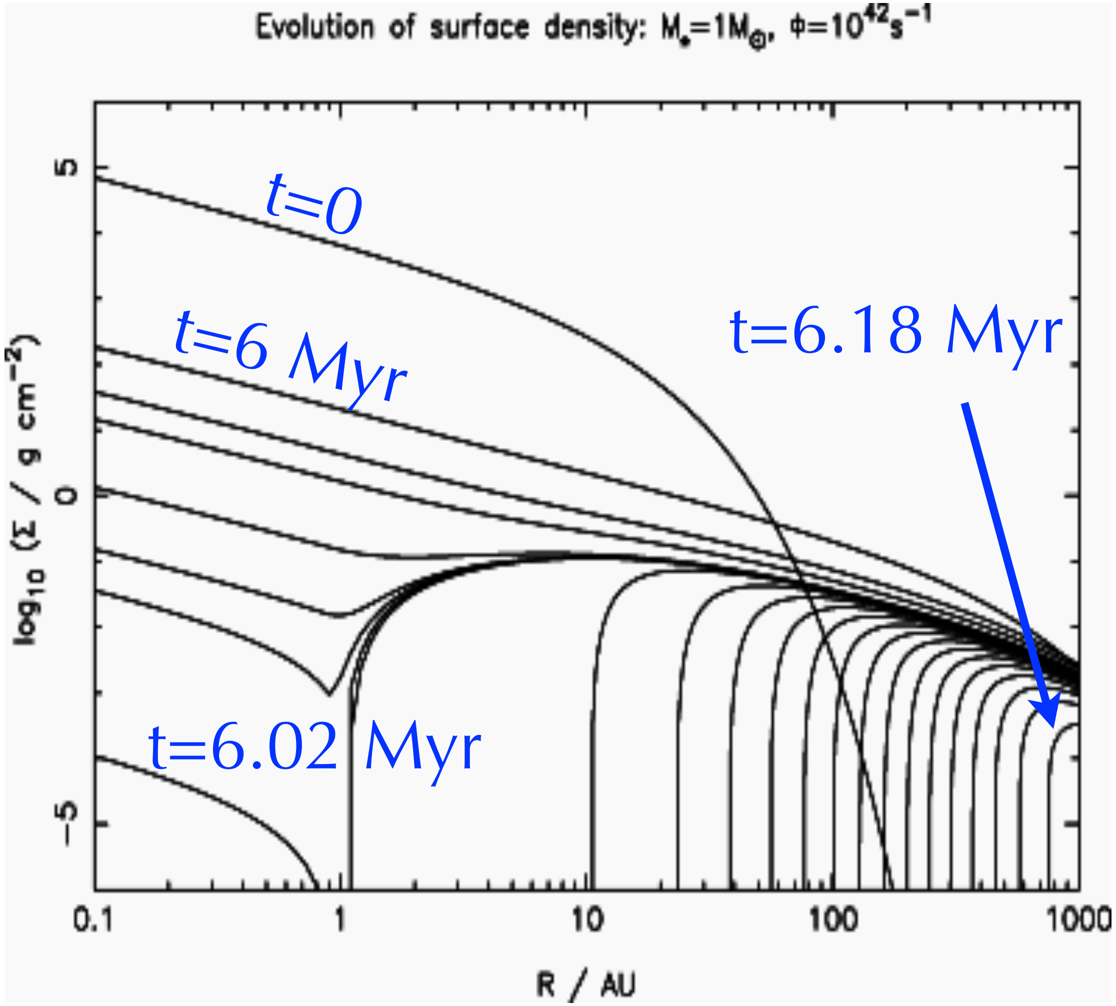
$\downarrow$ quartic

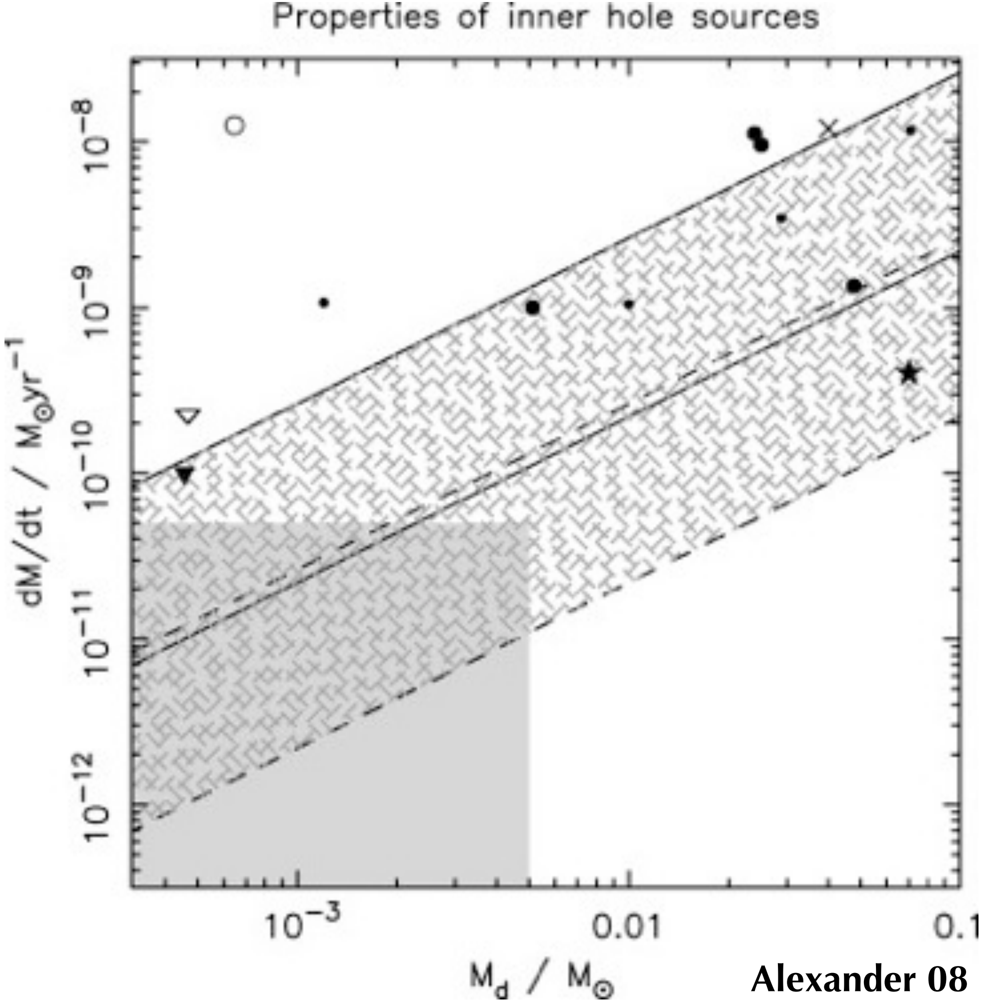
$$\begin{aligned} {\rm Am} &\approx 90 \,@\, 1\,{\rm AU} \\ {\rm Am} &\approx 120 \,@\, 0.1\,{\rm AU} \end{aligned} \quad \text{vs.} \quad {\rm Am}^* \approx 100$$

∴ Even midplane is MRI-active

Outer disk photoevaporation starves inner disk

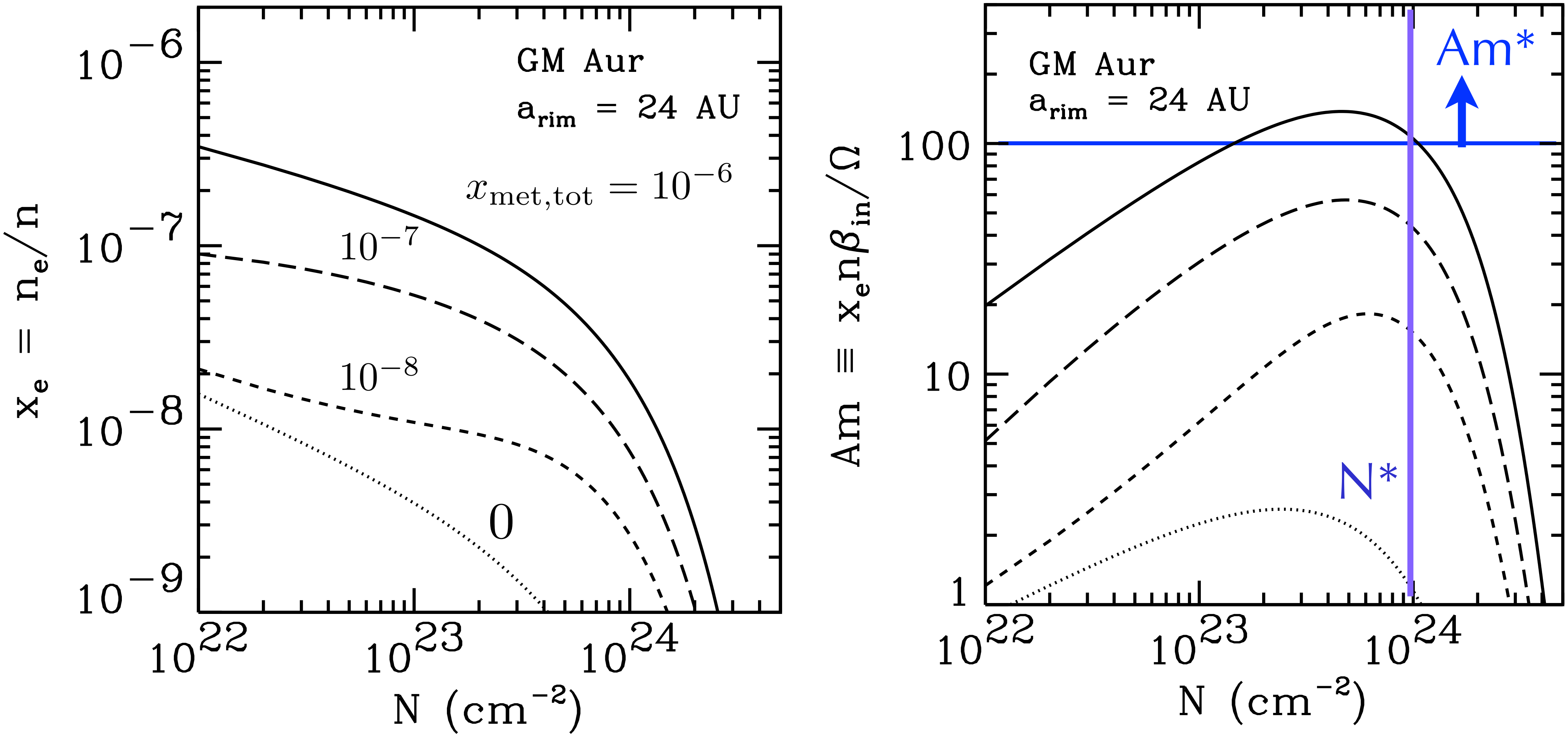






Alexander 08

Estimating N*



$$x_e^4 + \left(\frac{\beta_{gr}}{\beta_{rec}}\right) x_e^3 + \left(\frac{\zeta}{n\beta_{diss}}\frac{\beta_t}{\beta_{rec}}\right) x_e^2 - \left(\frac{\zeta}{n\beta_{diss}}\frac{\beta_t}{\beta_{rec}}\right)\left(\frac{\beta_{gr}}{\beta_t} + x_{met,tot}\right) x_e - \frac{\beta_t}{\beta_{rec}}\left(\frac{\zeta}{n\beta_{diss}}\right)^2 = 0$$

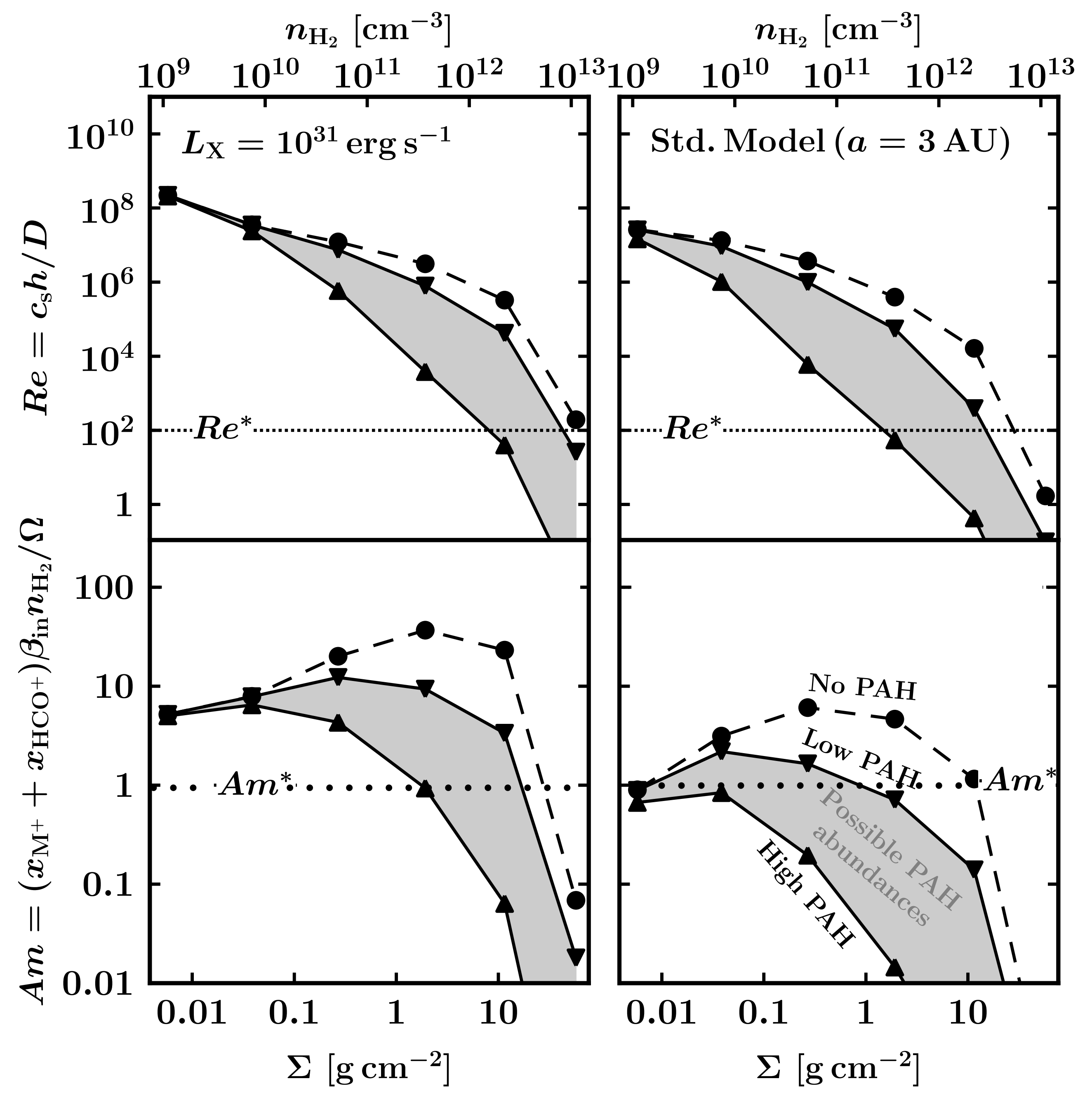
$$n = 2N/a_{rim} \qquad \zeta = \frac{L_X \sigma_X e^{-N\sigma_X} \xi_{secondary}}{4\pi E_X a_{rim}^2}$$

EC & Murray-Clay 07

Theories for transitional disks are not mutually exclusive

Planets	+	Grain growth	+	MRI	+	Radiative / aerodynamic blowout
smaller $\dot{M}_*$		smaller $\tau_{10\mu\mathrm{m}}$		origin of viscosity		smaller $\tau_{10\mu\mathrm{m}}$
Multiple planets might explain factor of 10 and prolong Type II migration						Imperfect clearing can lead to gapped disks (e.g. LkCa 15)

X-ray ionized MRI-active surface layer



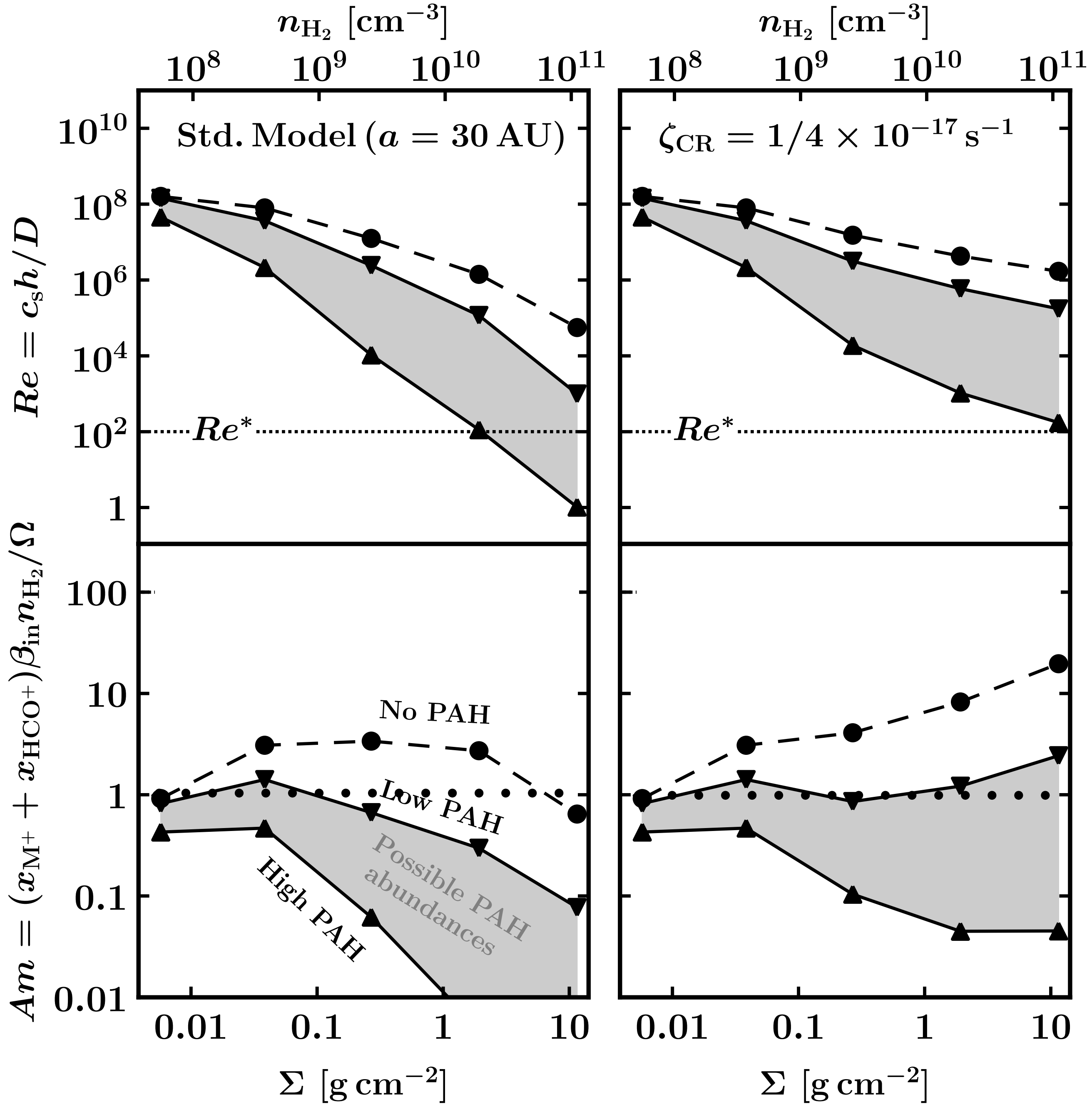
At 3 AU,

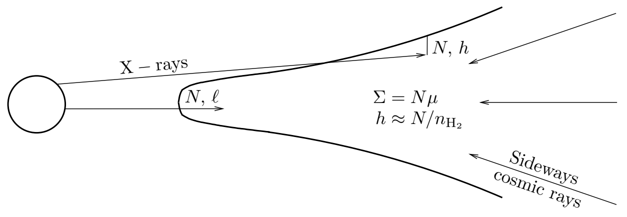
Am ~ 1 (α ~ 10^{-3})

Σ_{active} ~ 1 g cm^{-2}

Perez-Becker & EC 10

X-ray ionized MRI-active surface layer





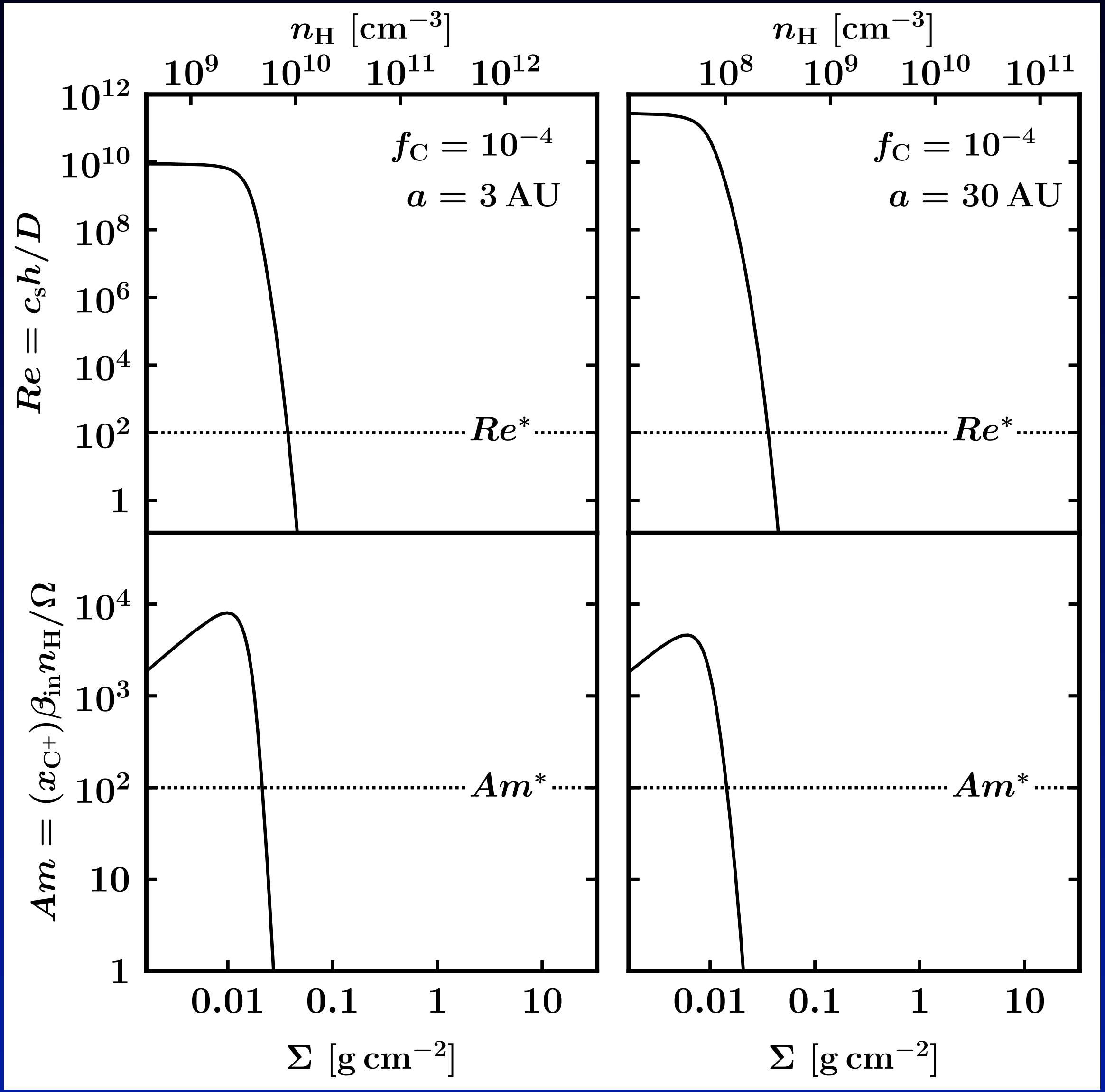
At 30 AU,

Am ~ 1 ($\alpha \sim 10^{-3}$)

Σ_{active} ~ 0.1 g cm^{-2}
if no cosmic rays

Σ_{active} ~ 10 g cm^{-2}
if cosmic rays

Far-UV (912-1100 Å) ionized MRI-active surface layer



$$H_2 + h\nu \rightarrow H + H$$

$$H + H + \text{grain} \rightarrow H_2 + \text{grain}$$

$$C + h\nu \rightleftarrows C^+ + e^-$$

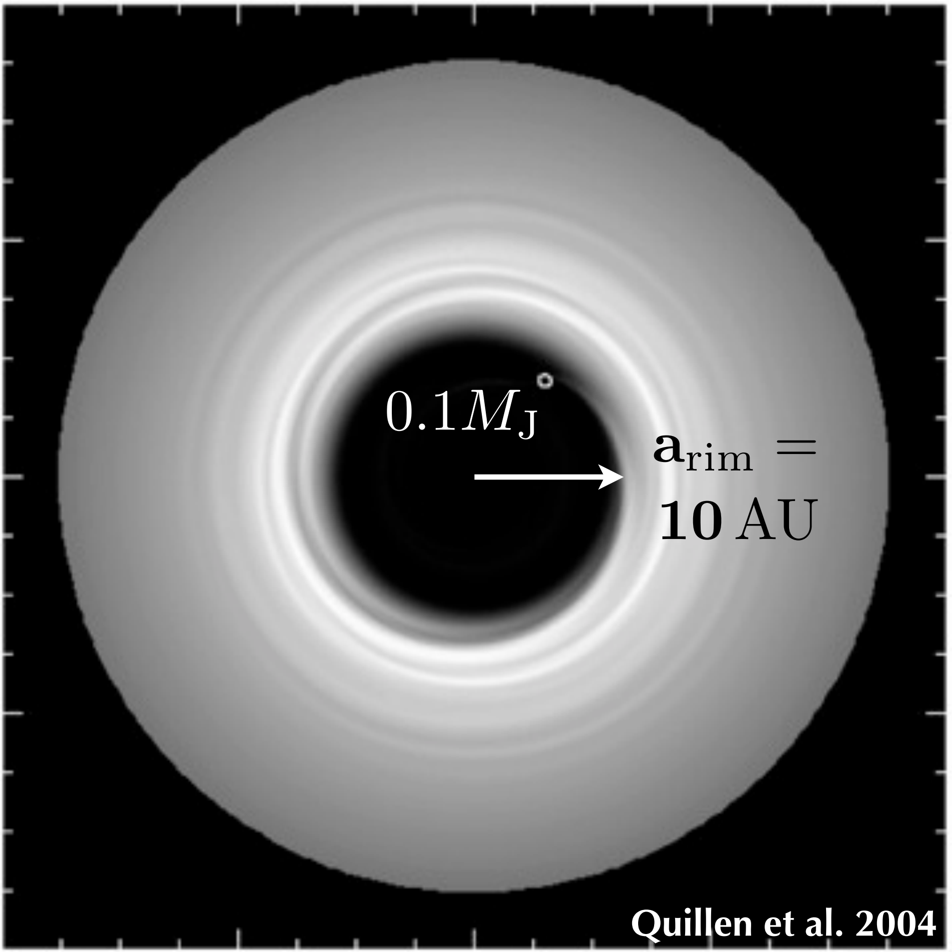
$$x_{CO} = 10^{-4}$$

At 3-30 AU,

$Am > 10^2$ ($\alpha \sim 0.1$)

$\Sigma_{active} \sim 0.01$ g cm^{-2}

Planet Clearing



Quillen et al. 2004

Initial $\Sigma_{\rm inner} / \Sigma_{\rm outer} = 0.01$

Run duration = 100 orbits
≪ Viscous time $t_{\rm diff}$ ~ 10000 orbits

$$t_{\rm diff} \sim a_{\rm rim}^2 / \boxed{\nu}$$

$$\nu = \boxed{\alpha} c_s h$$

0.004 (assumed)

∴ Hole in simulation reflects assumed initial conditions

	Σ active (g/cm^2)	α	T (K)	$\dot{M}$ ($M_\odot$/yr)
3 AU X-ray	1	10^{-3}	80	10^{-11}
3 AU Far-UV	0.01	0.1	300	4×10^{-11}
30 AU X-ray+CR	0.1-10	10^{-3}	30	10^{-11}-10^{-9}
30 AU Far-UV	0.01	0.1	300	10^{-9}

Protoplanetary Disks

disk mass ~ 0.001-0.1 stellar mass