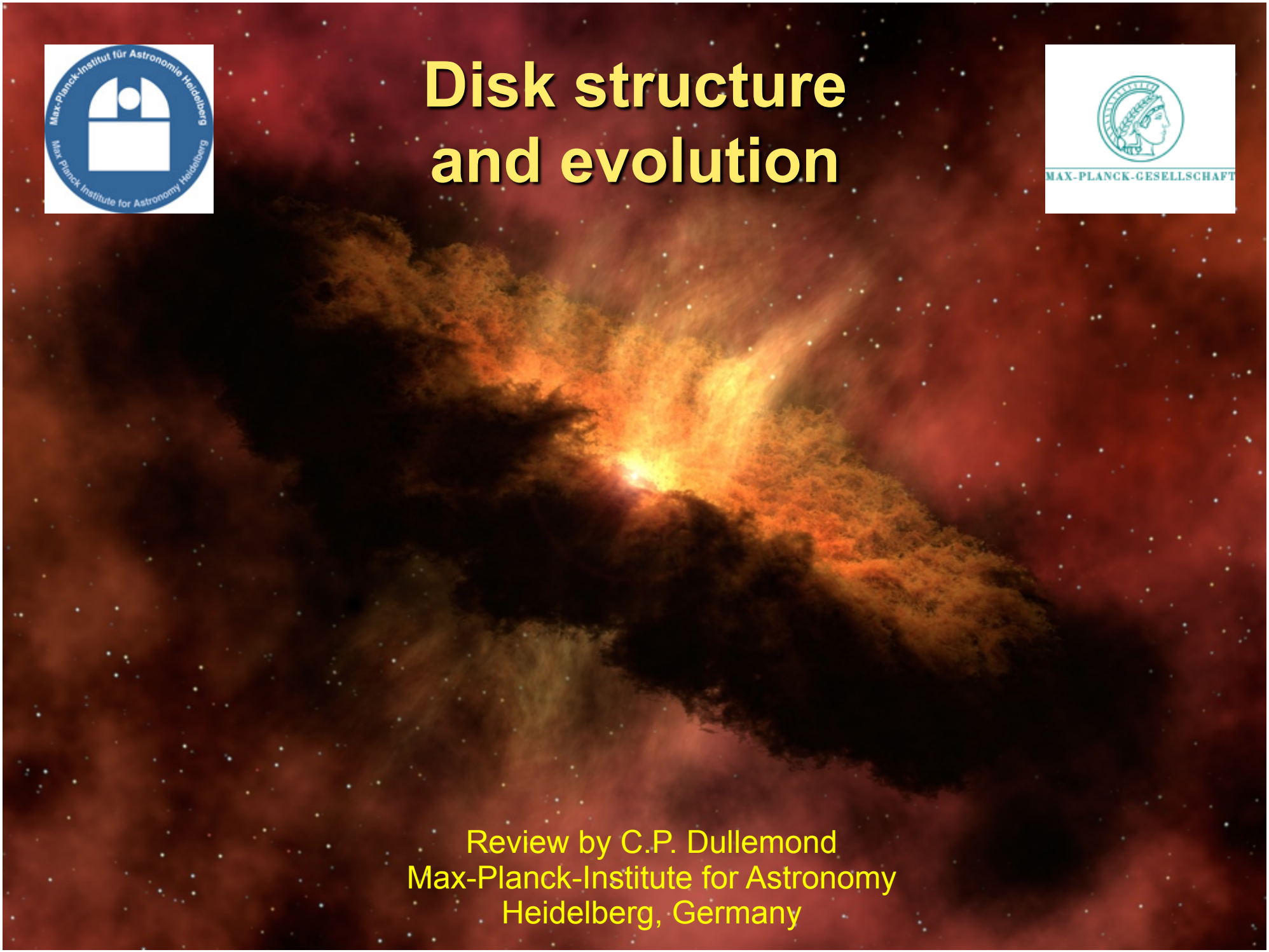
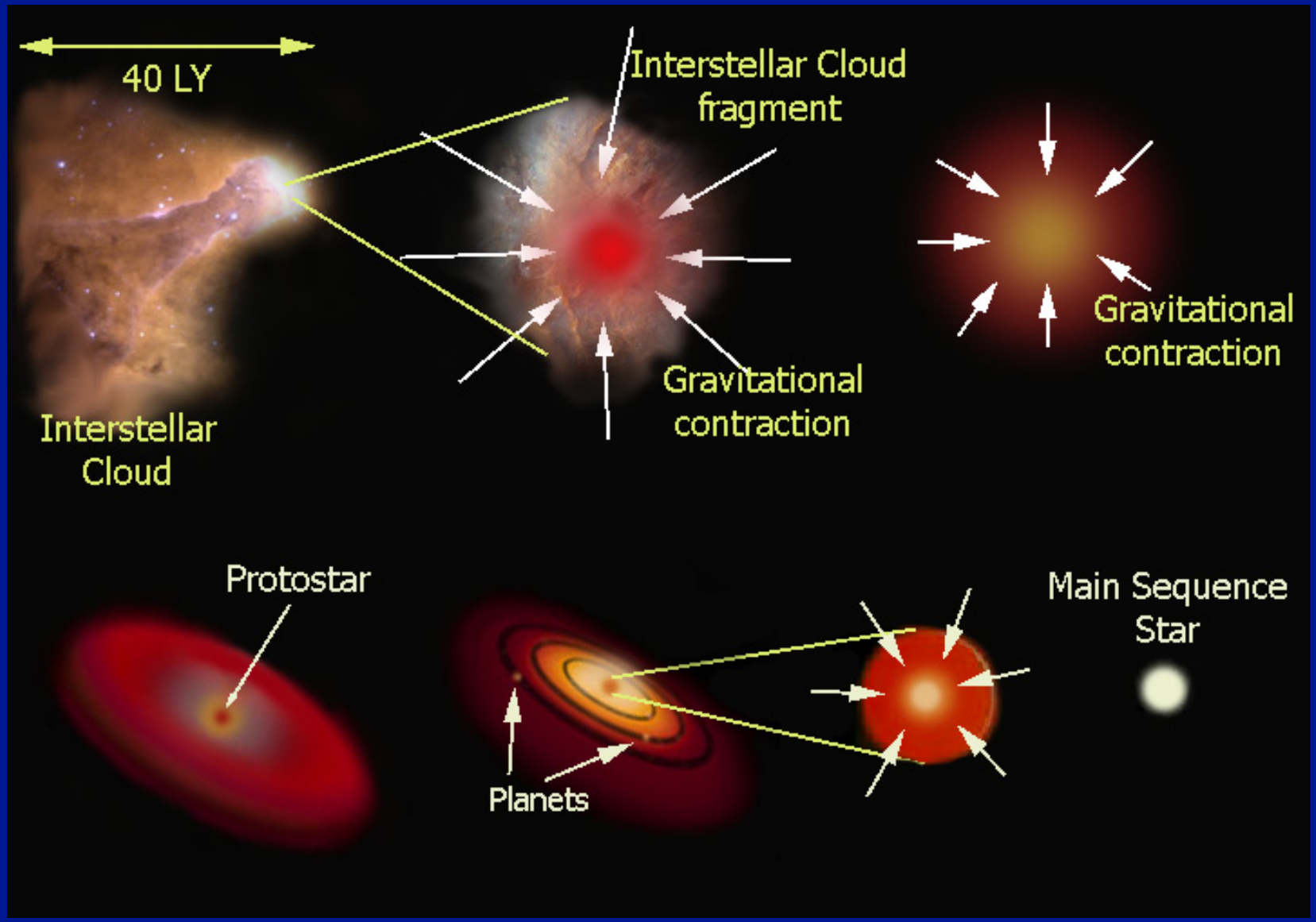


Disk structure and evolution

Review by C.P. Dullemond
Max-Planck-Institute for Astronomy
Heidelberg, Germany

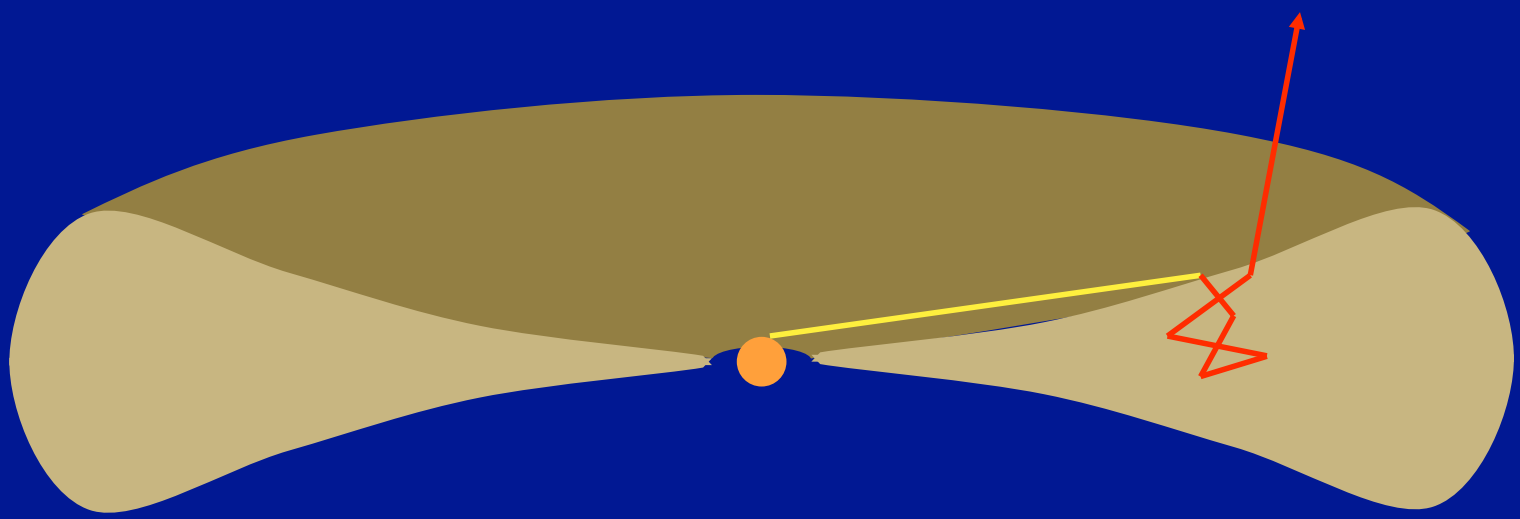
Introduction

Introduction: Star + Planet Formation

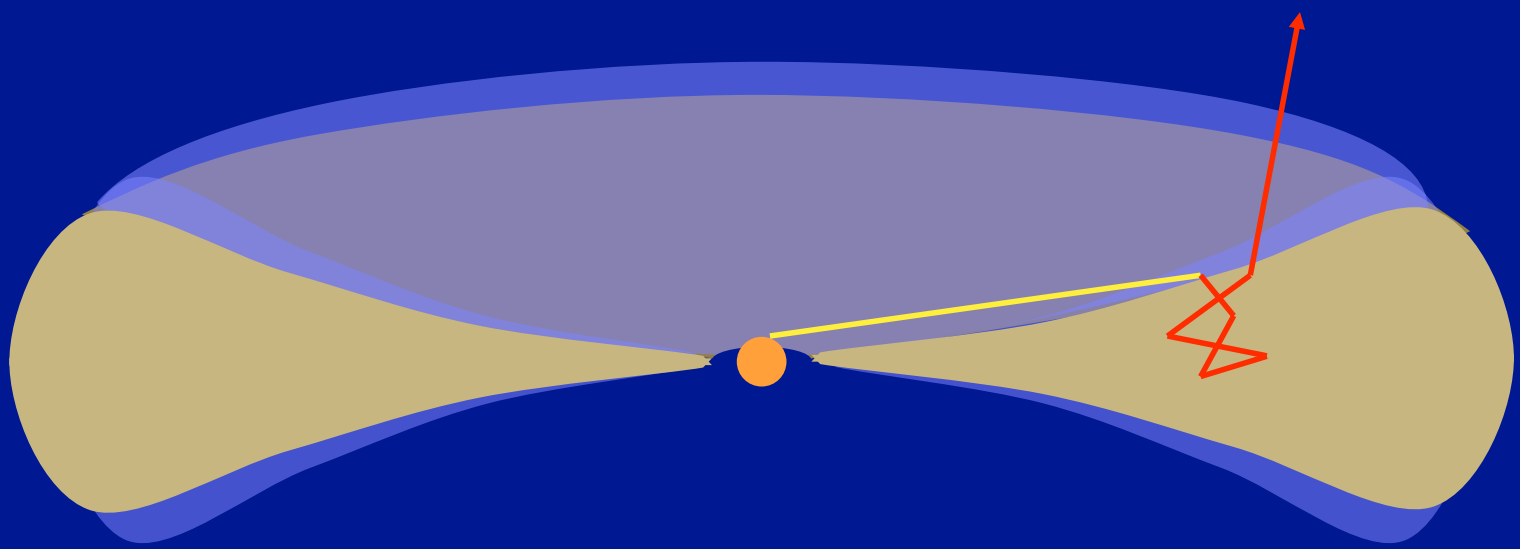


Still one of the nicest disk images:

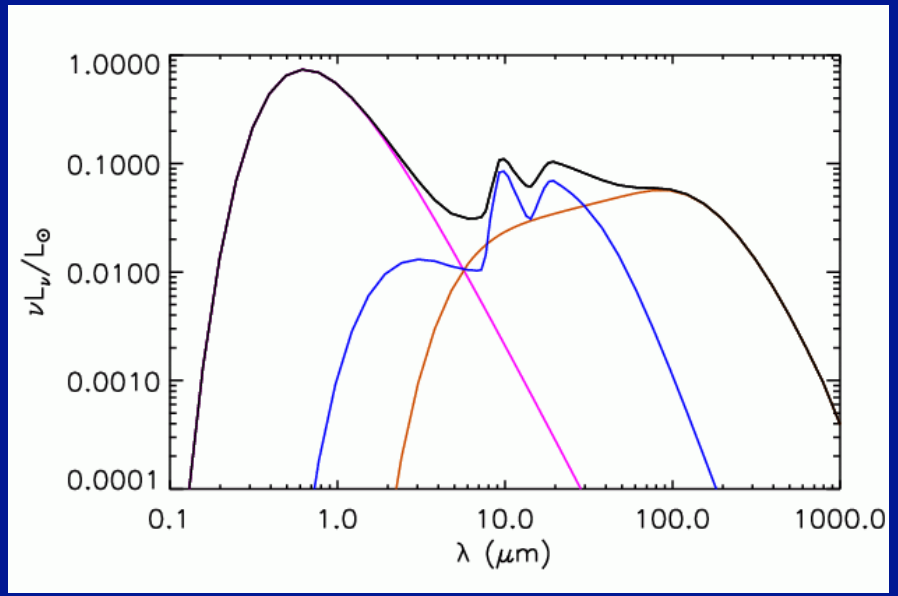
Flaring disk structure: irradiation



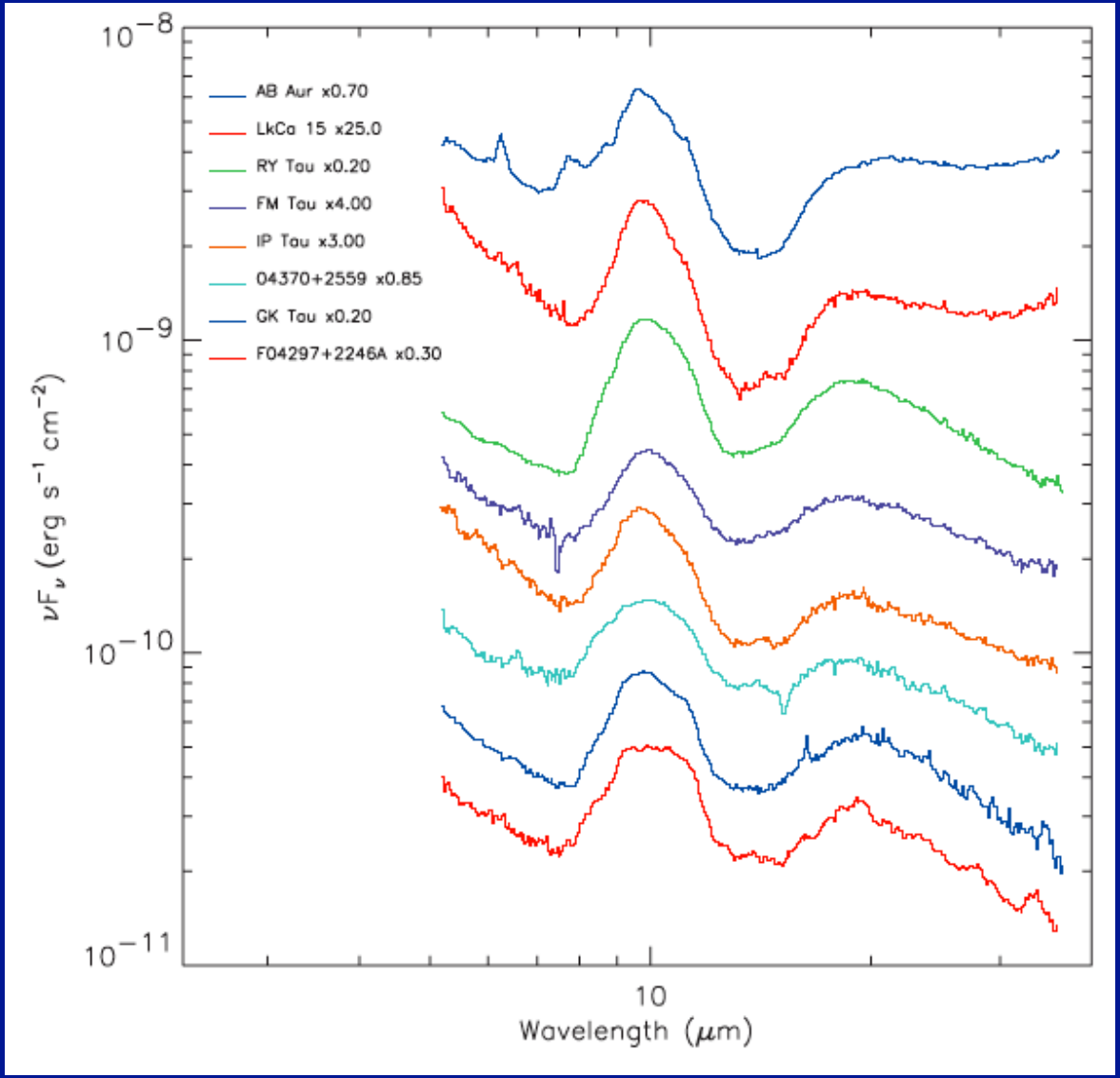
Creation of a warm surface layer



Calvet et al. 1991
Malbet & Bertout 1991
Chiang & Goldreich 1997



T Tauri Star SEDs:

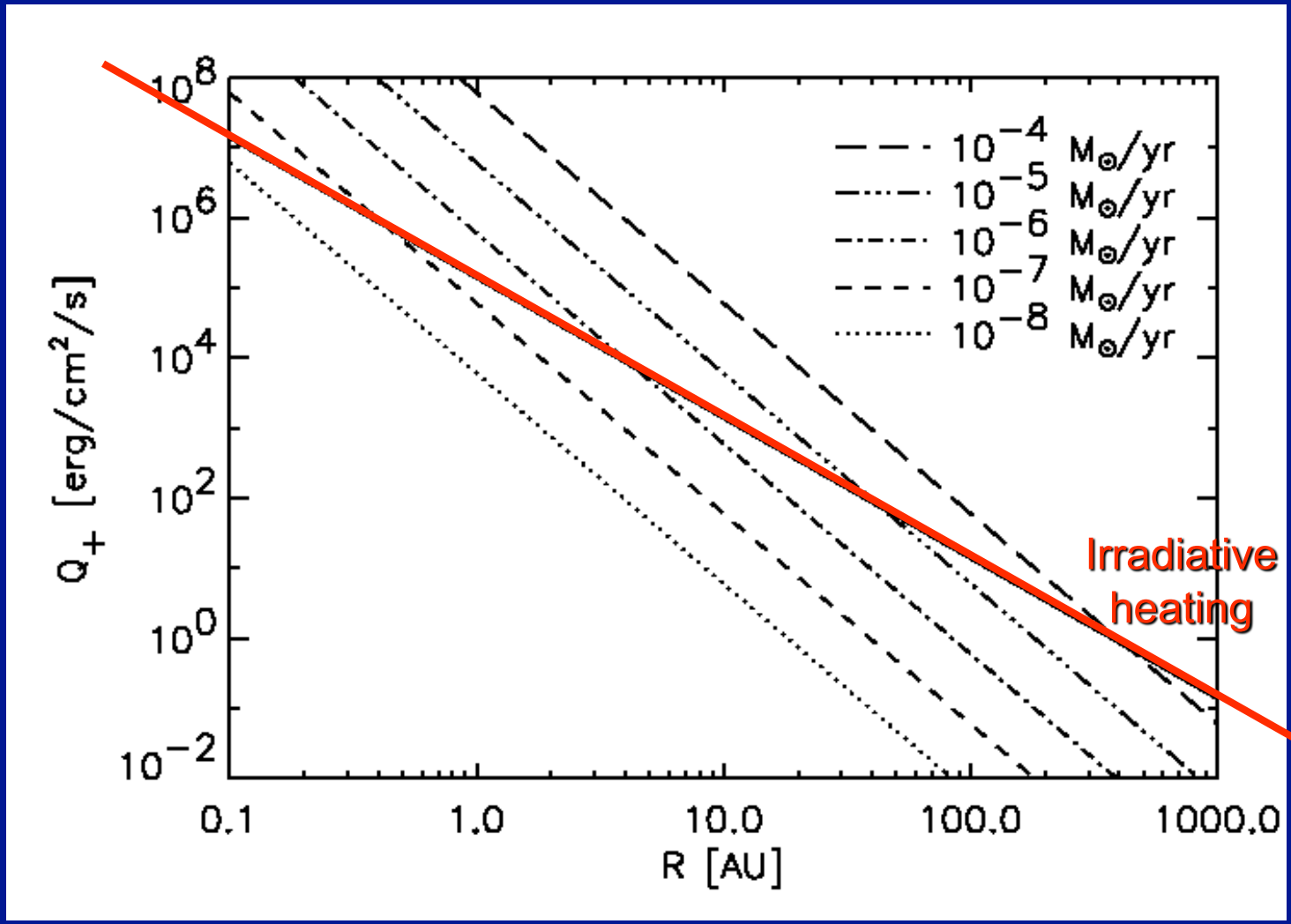


Furlan et al. 2006

Spitzer IRS spectra of large sample of class II sources. Furlan et al. 2006

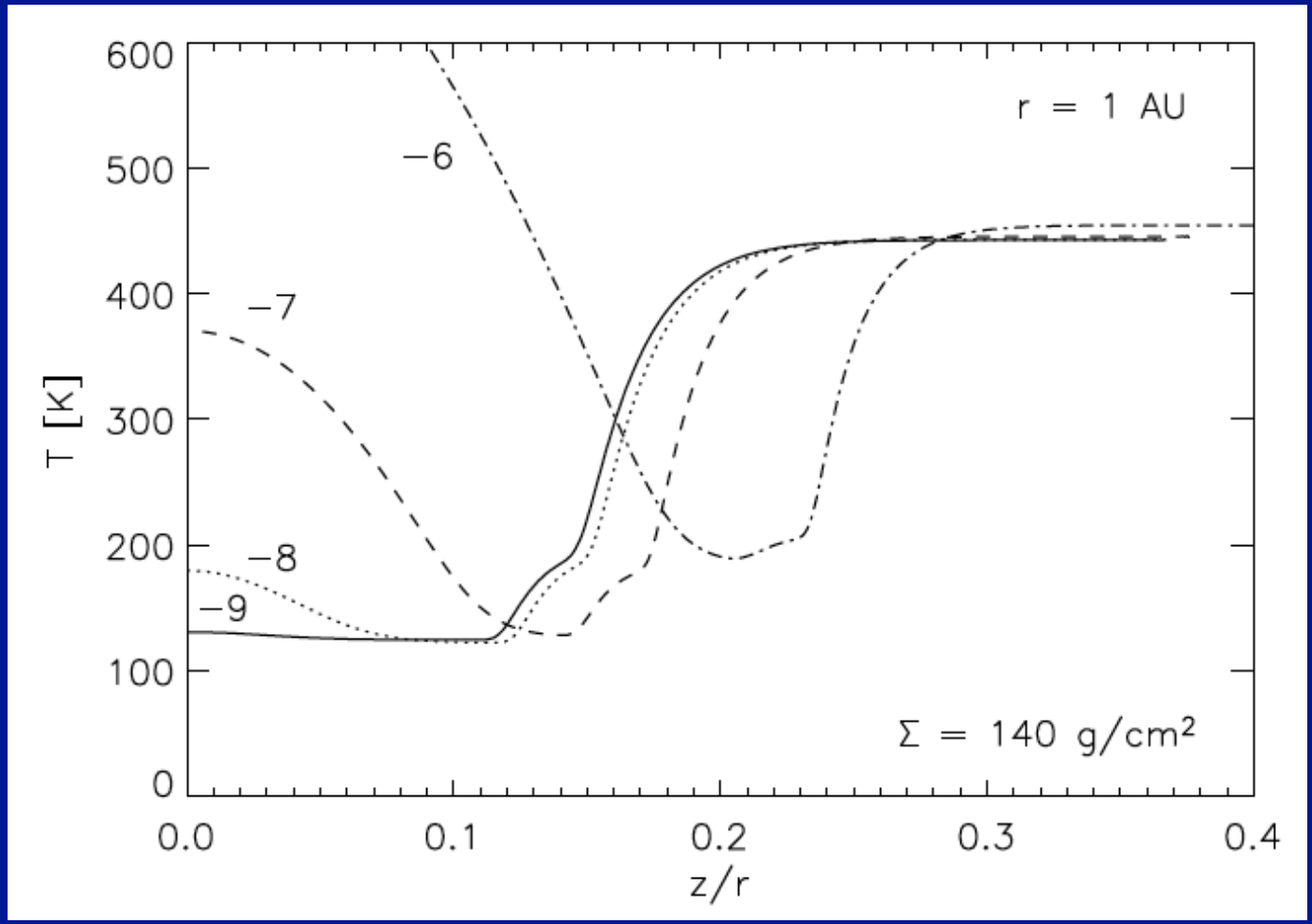
Shown here: the sources with the flattest SEDs, i.e. strongest disk flaring.

Accretional heating vs. Irradiation



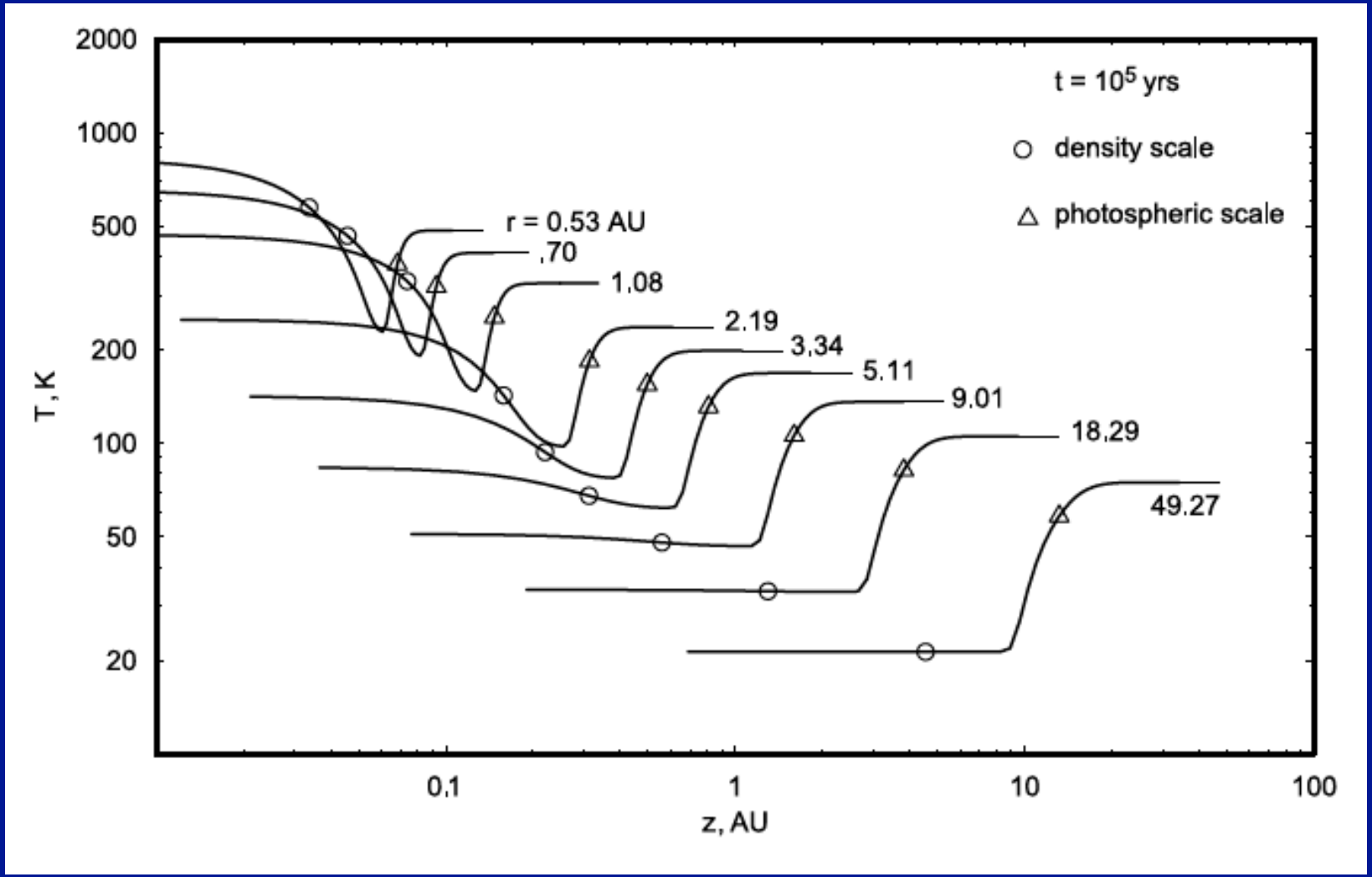
Disk around a T Tauri star

Vertical temperature structure: detail



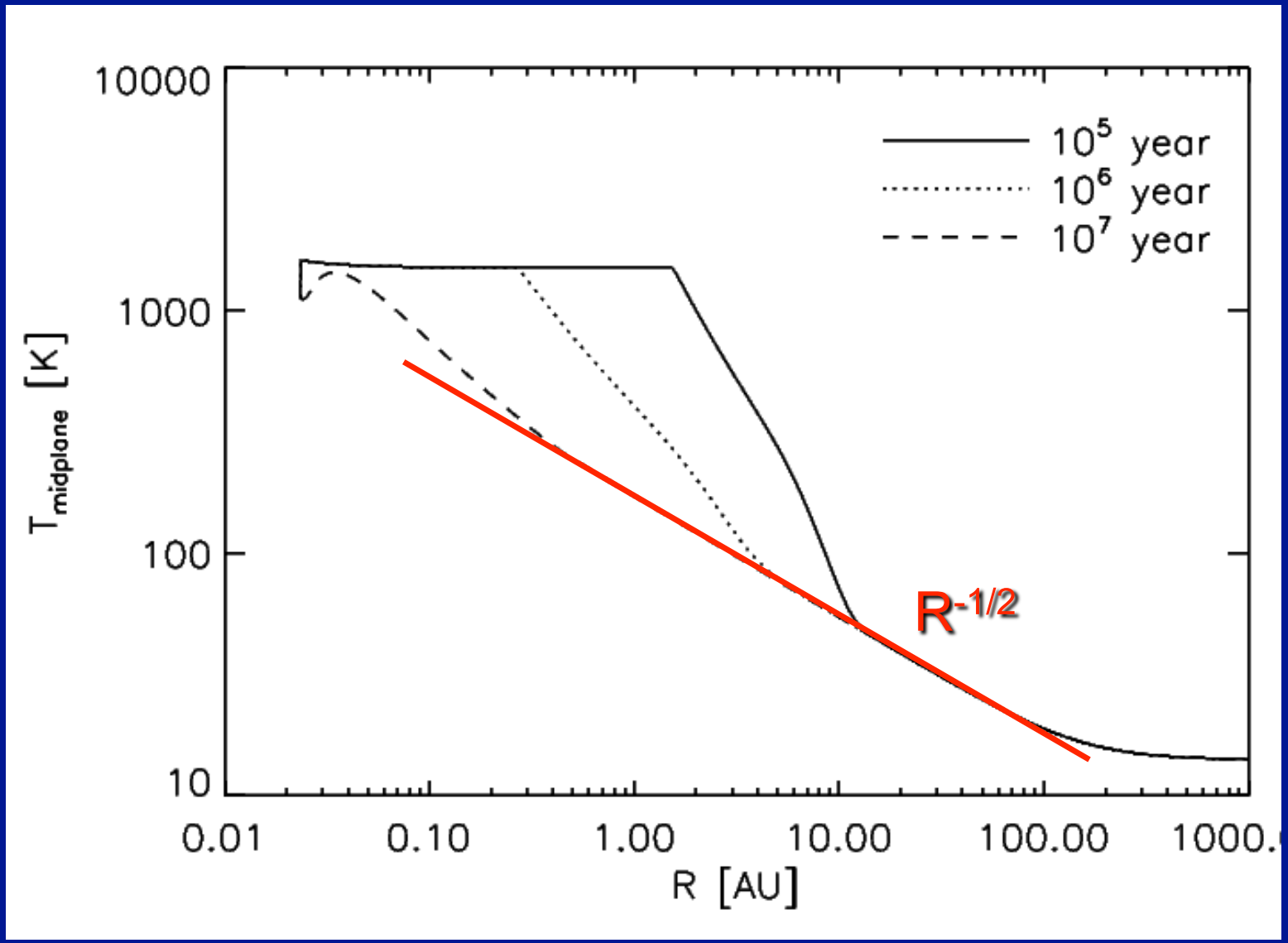
Vertical structure of a protoplanetary disk
(Model: P. D'Alessio)

Vertical temperature structure: detail



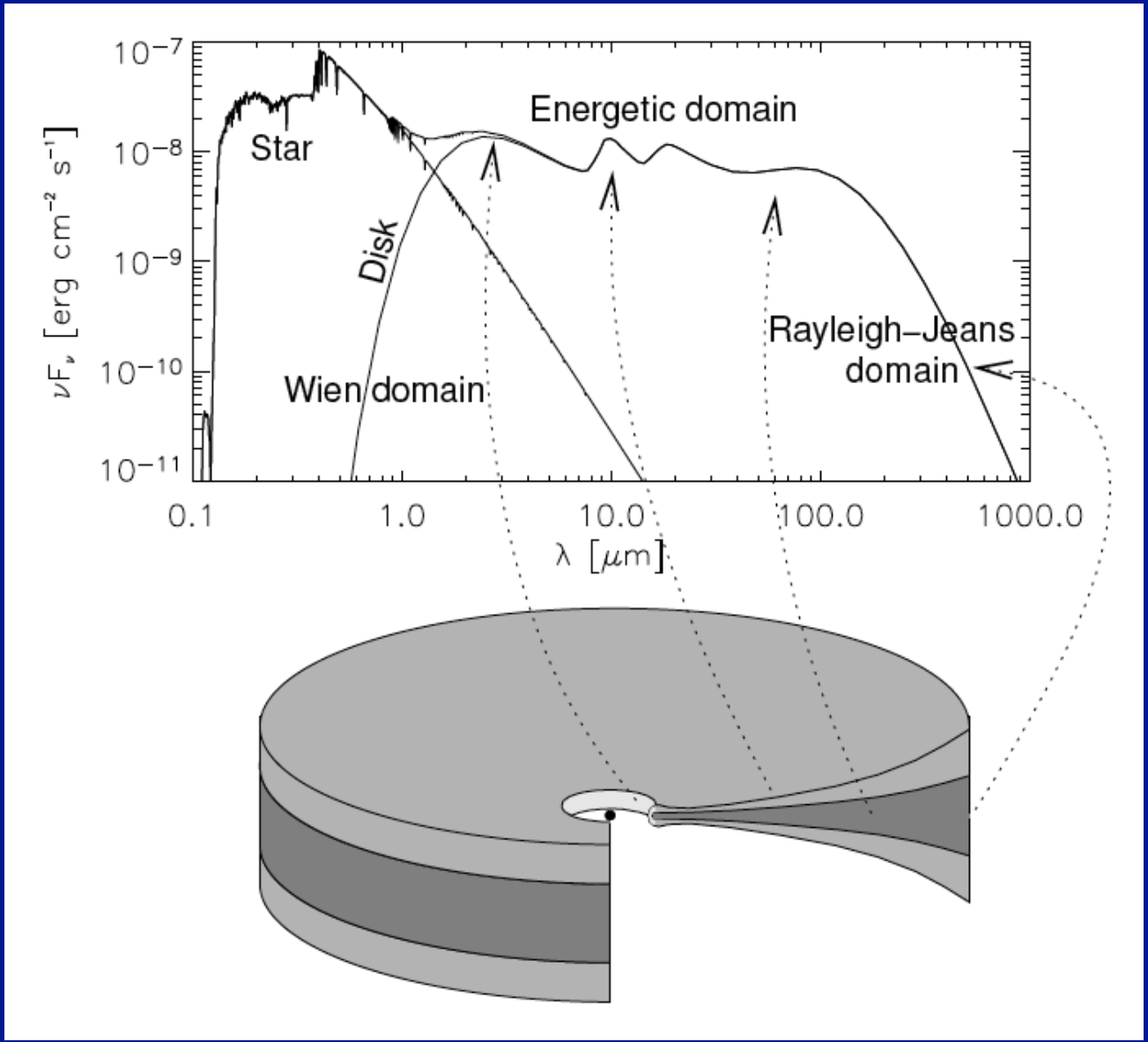
Davis (2005)

Vertical temperature structure: detail



Quick-n-dirty model

Where does the radiation come from?



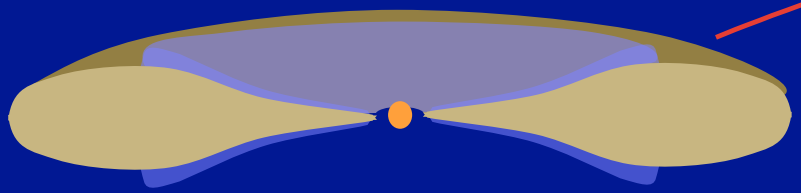
Disk geometry:

Flaring disks and flat (self-shadowed?) disks

Degree of flaring: shape of SED

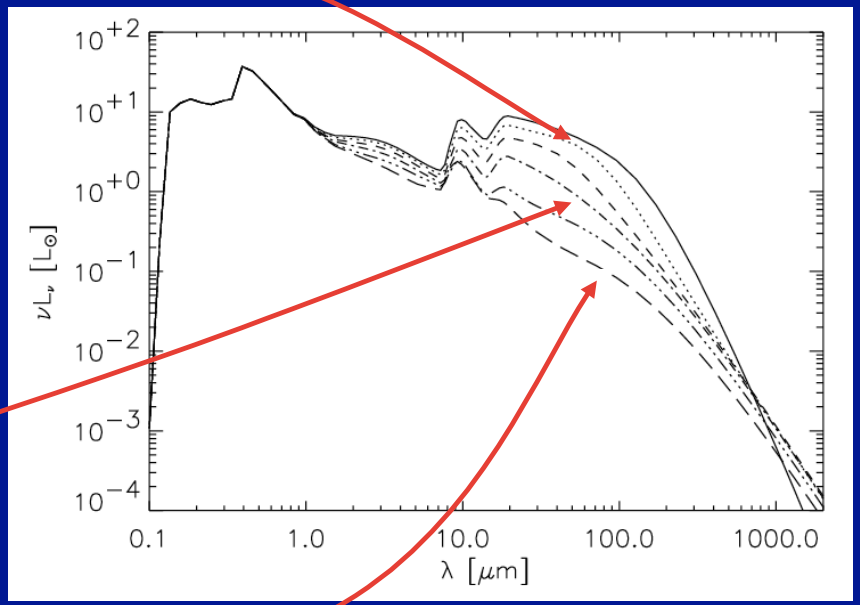
strong flaring

weak flaring



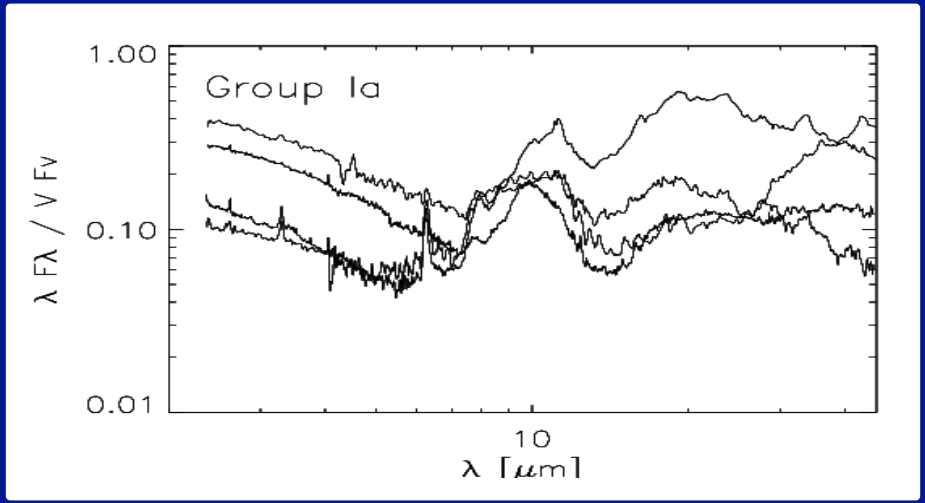
shadows?

?

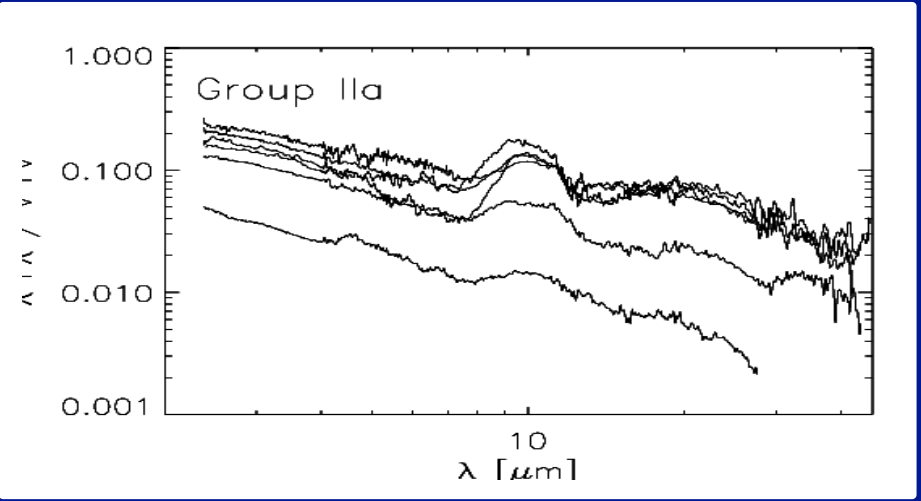


Herbig Ae Star SEDs:

Group I

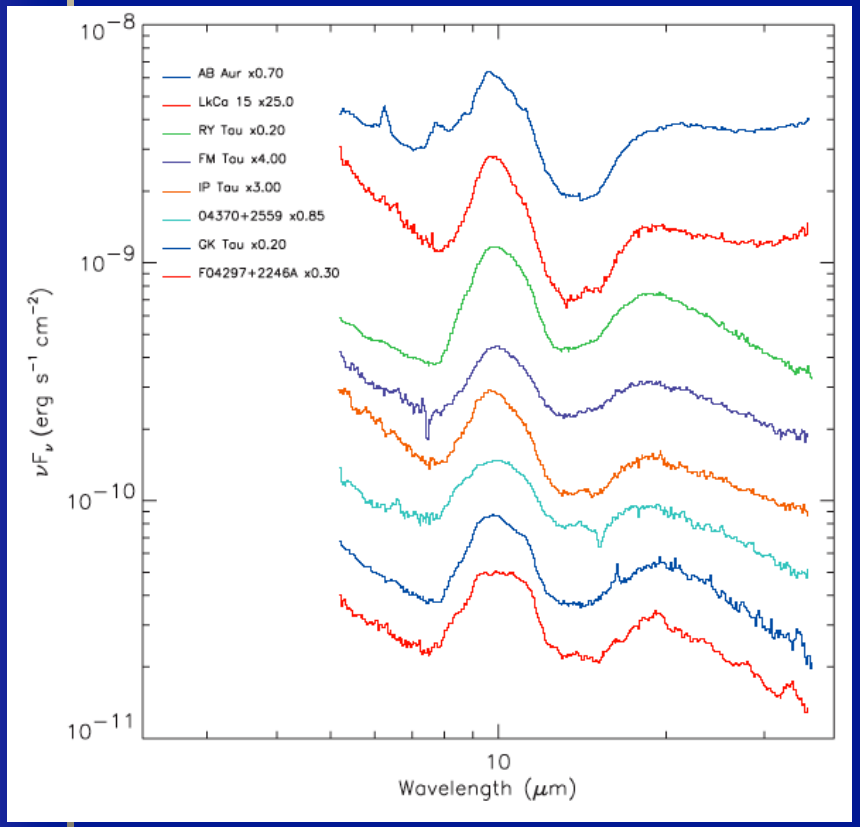


Group II

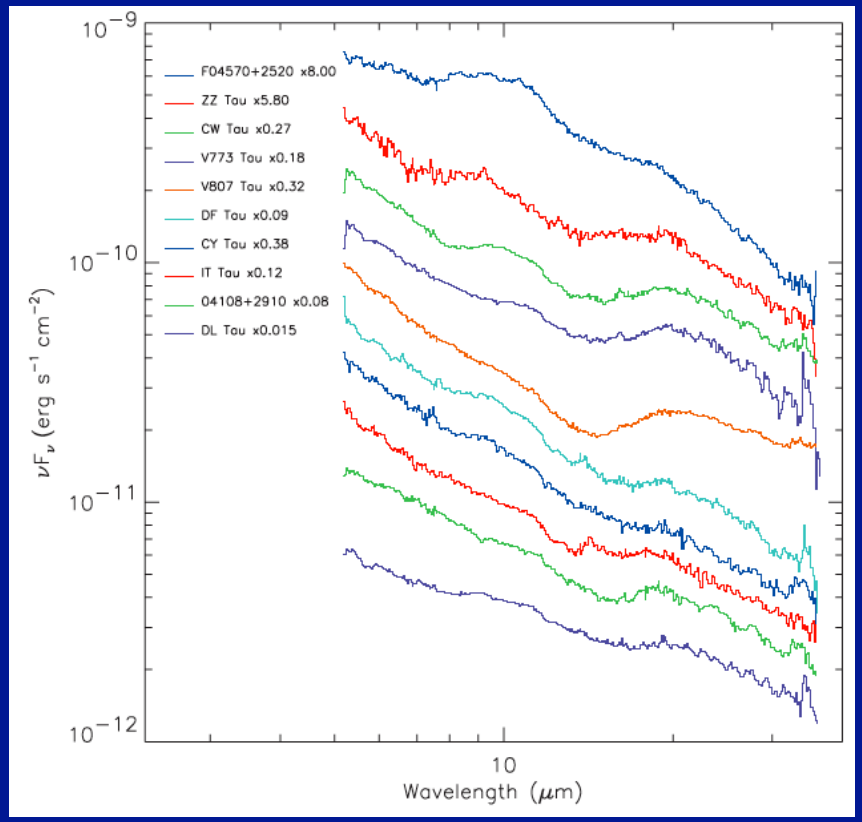


Meeus et al. (2001)

T Tauri Star SEDs:



Flaring?



Weak flaring?
Self-shadowed?

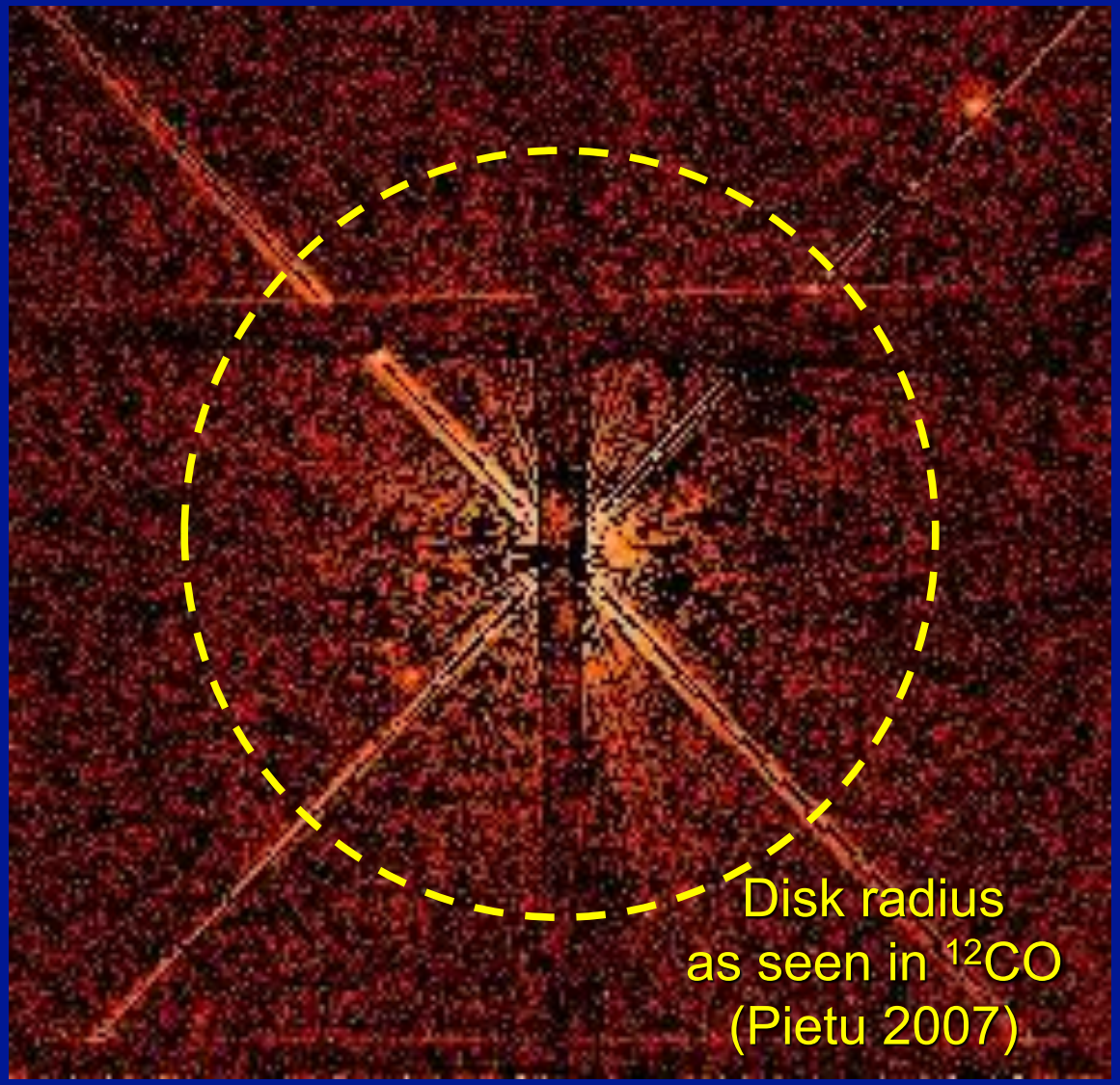
Furlan et al. 2006

The debate about
“self shadowing”

Does it exist?

Hiding a disk by shadowing

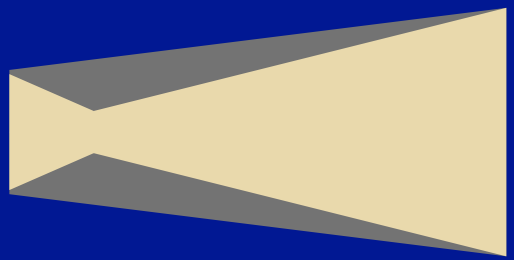
MWC 480:



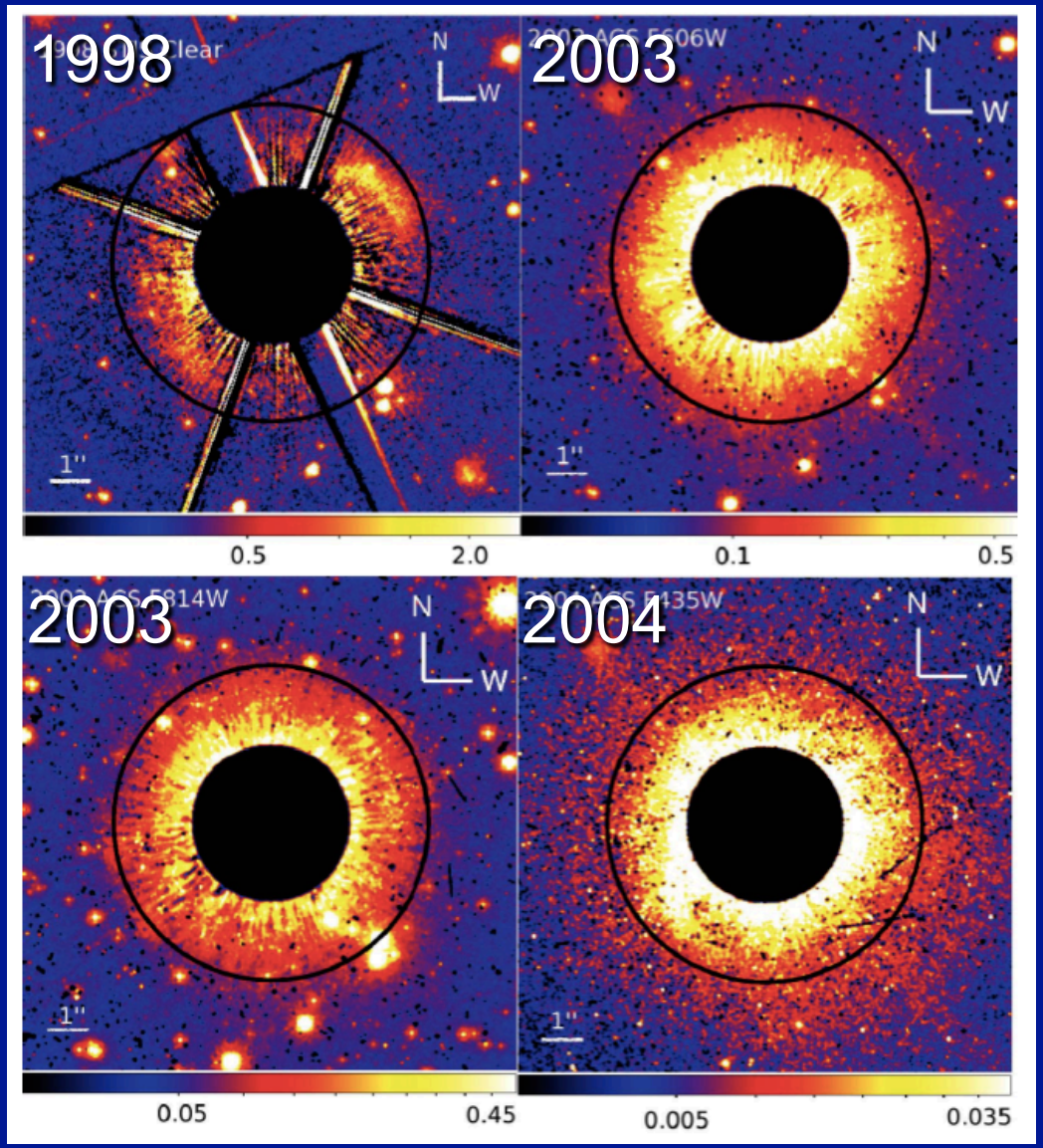
Courtesy of
C. Grady

Evidence for self-shadowing?

Time-variable scattered light on “short” time scale



Wisniewski, Grady et al. 2008



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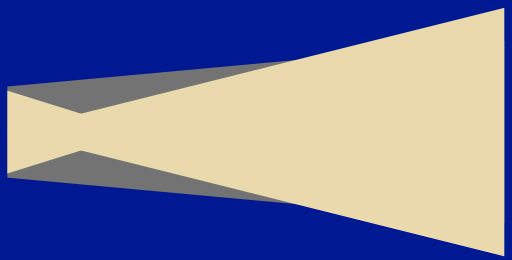
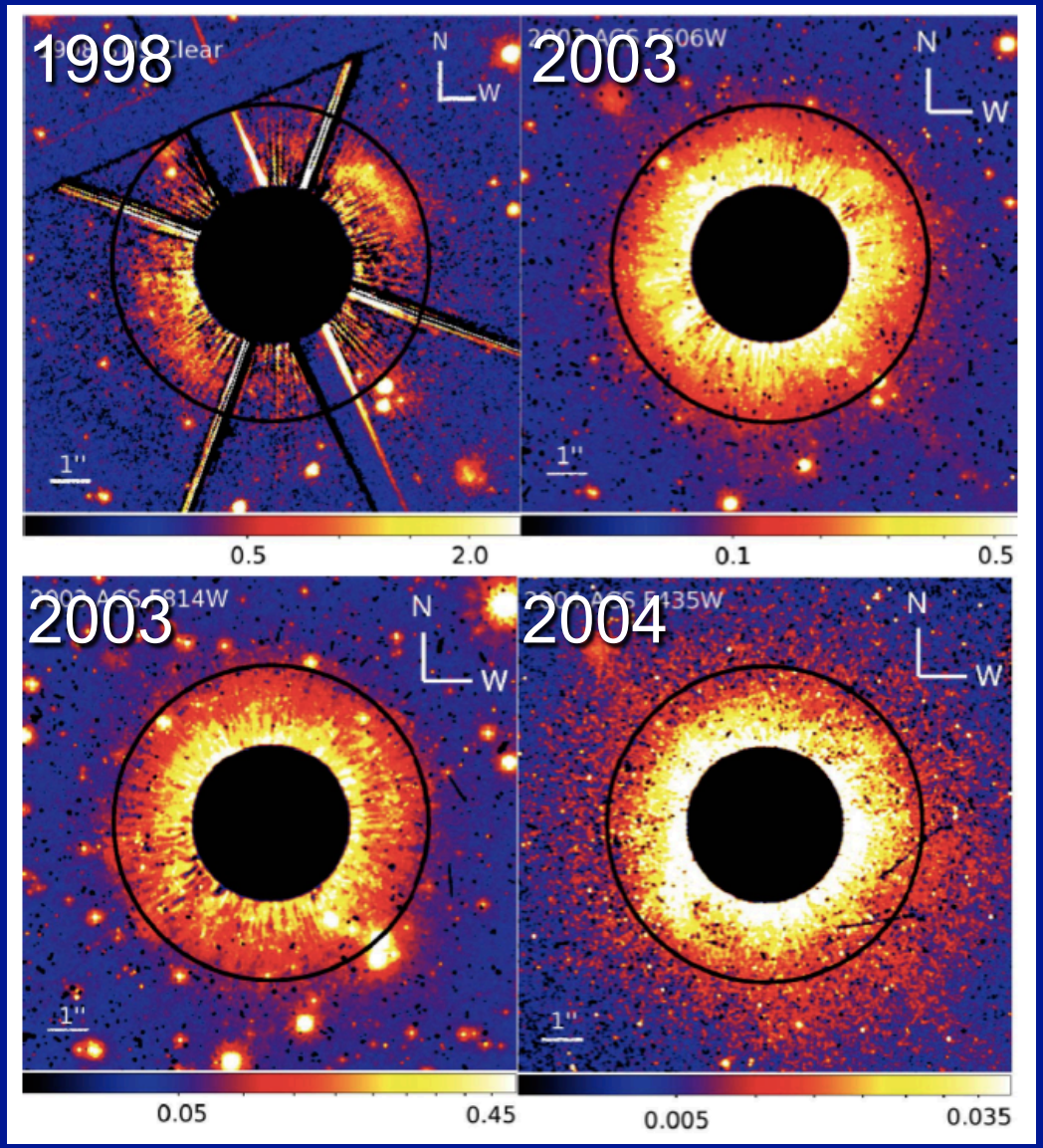


Wisniewski, Grady et al. 2008



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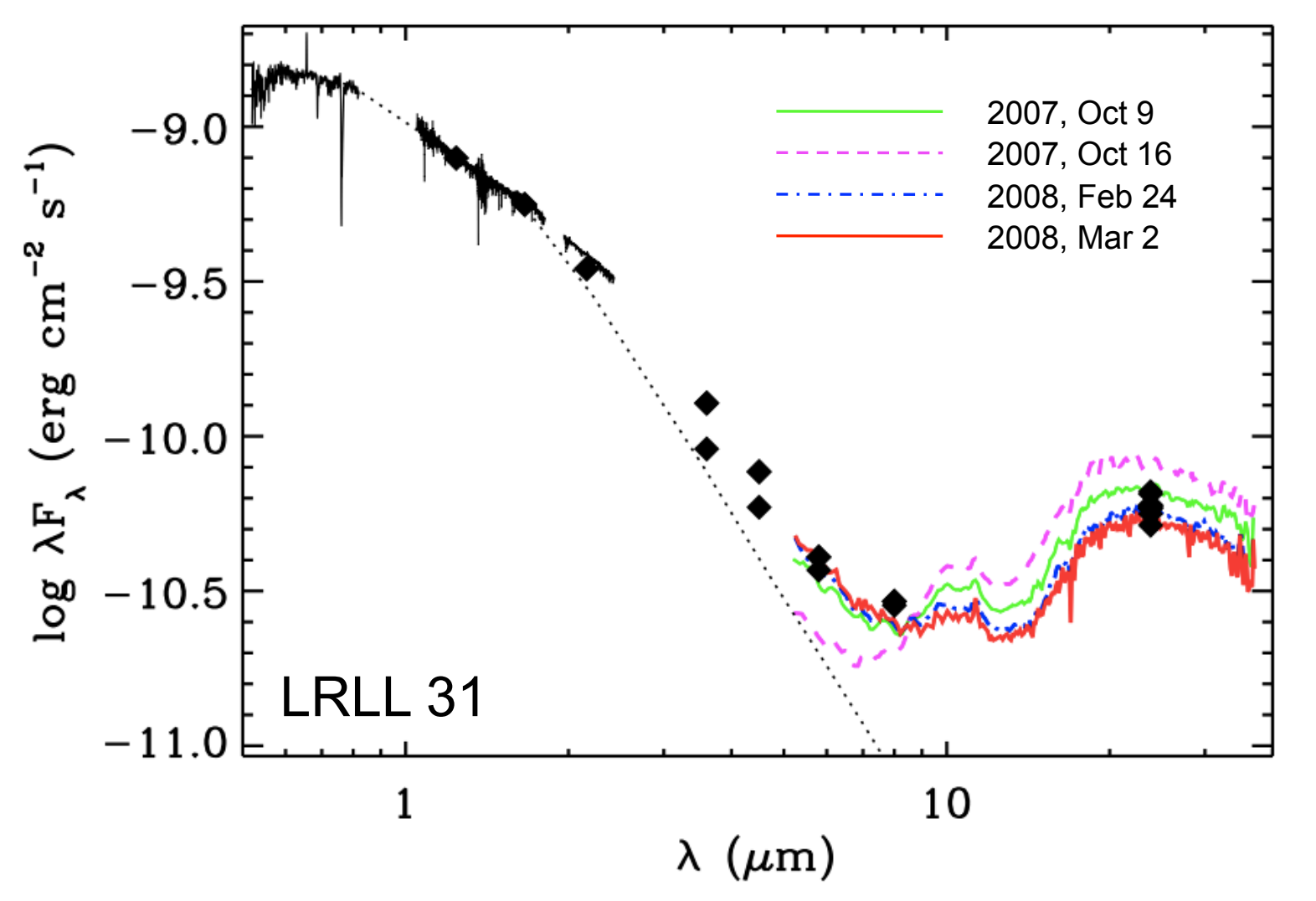


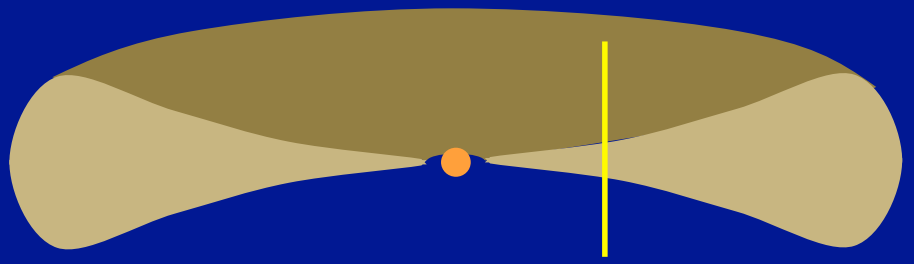
Muzerolle et al. 2009

Disk formation and viscous evolution

Disk evolution: a 1-D approach

Vertically integrated density: Σ

$$\Sigma(r) = \int \rho(r,z),dz$$

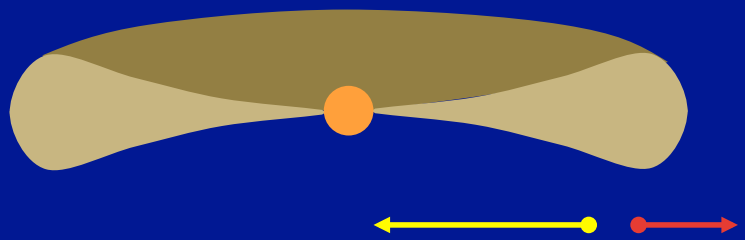


Shakura & Sunyaev 1973
Lynden-Bell & Pringle 1976

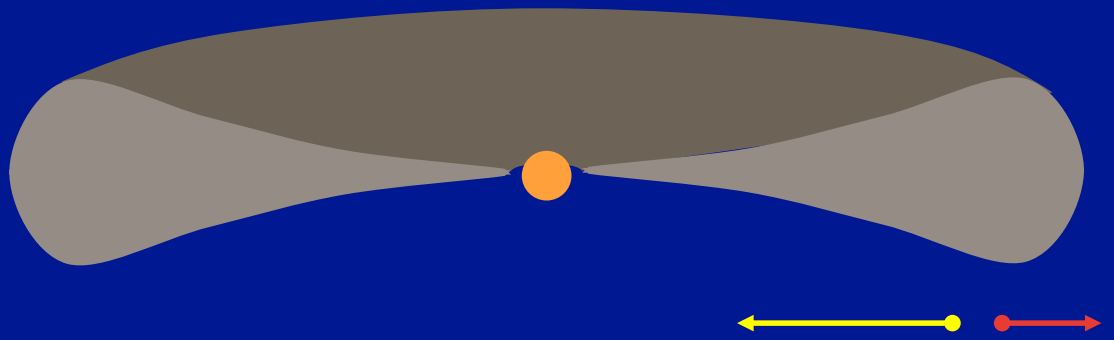
Time evolution of Σ

$$\frac{\partial \Sigma(r,t)}{\partial t} - \frac{3}{r}\frac{\partial}{\partial t}\left[\sqrt{r}\frac{\partial}{\partial t}\left(\sqrt{r}\nu(r,t)\Sigma(r,t)\right)\right] = S(r,t)$$

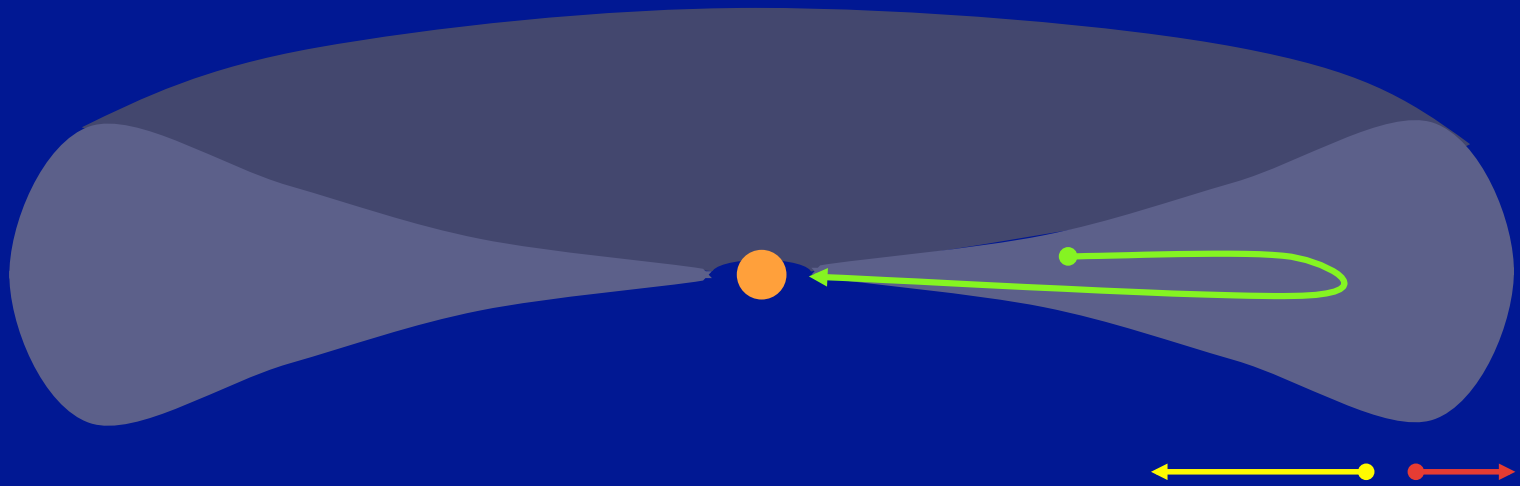
Disk accretion and spreading



Disk accretion and spreading

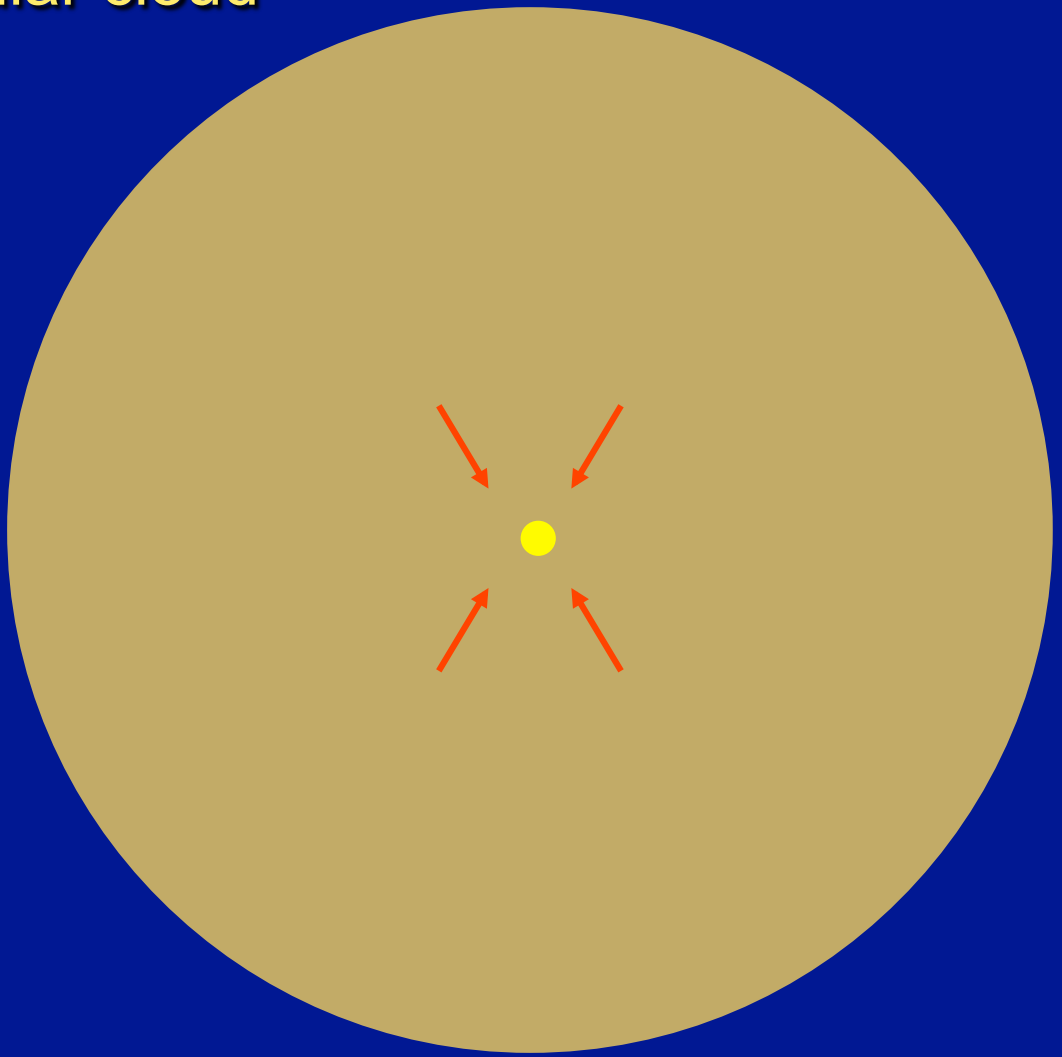


Disk accretion and spreading



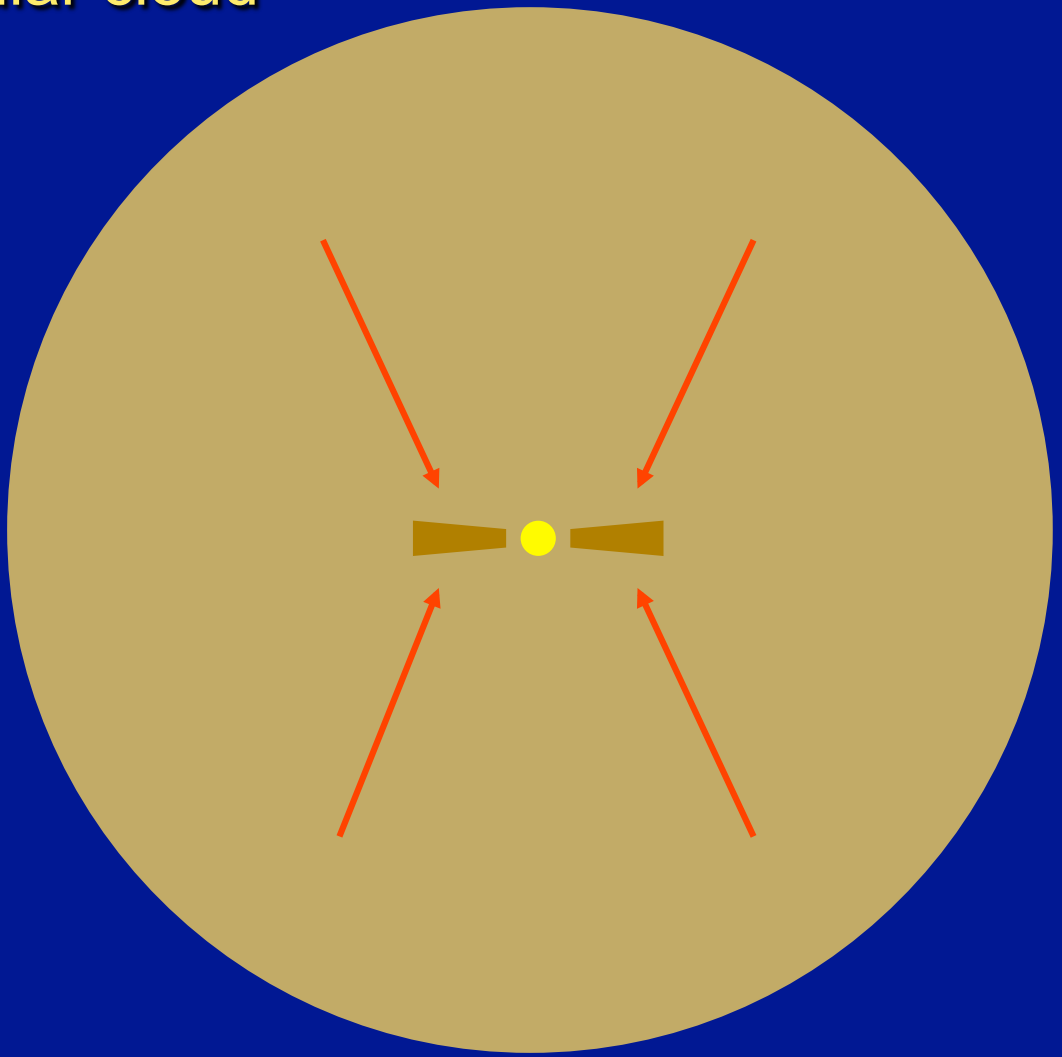
Disk formation and spreading

Molecular cloud core:



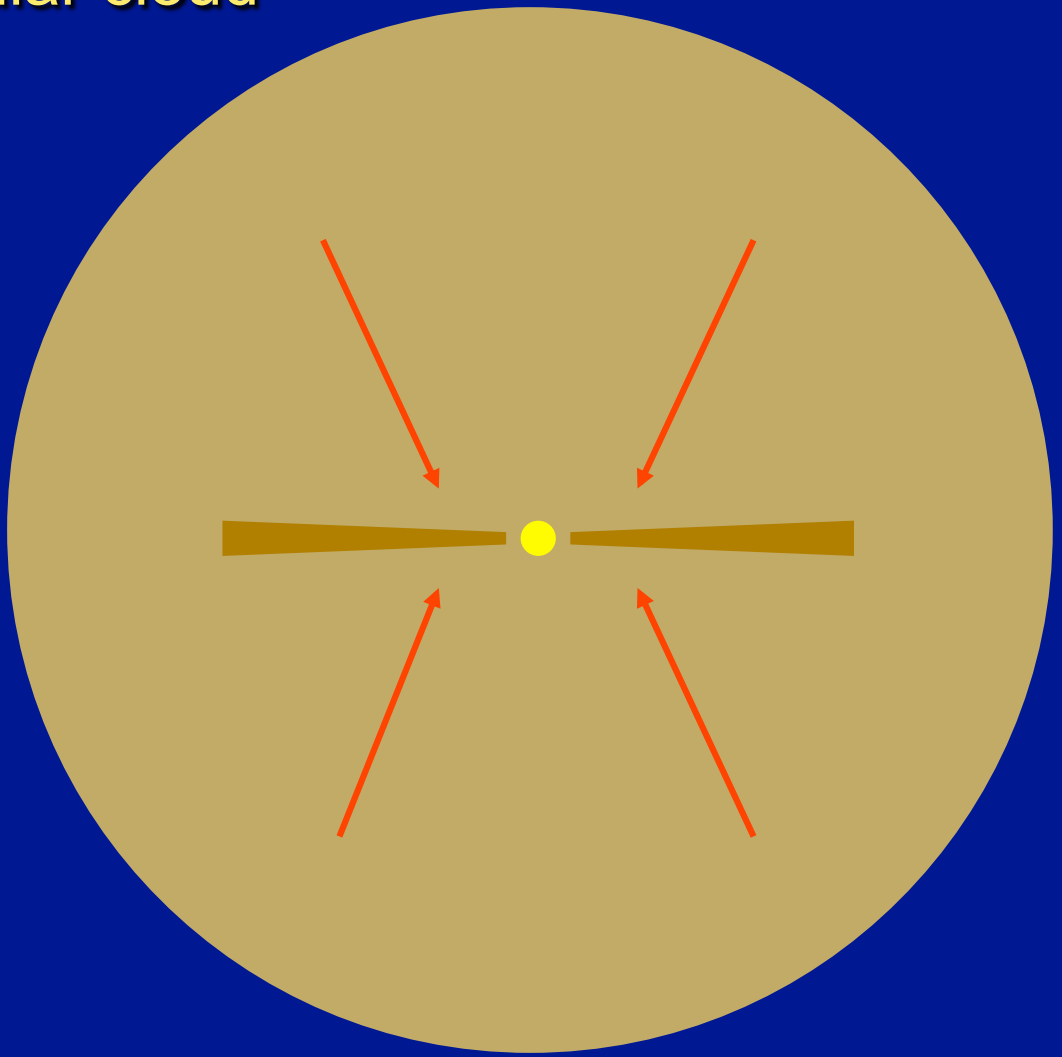
Disk formation and spreading

Molecular cloud core:



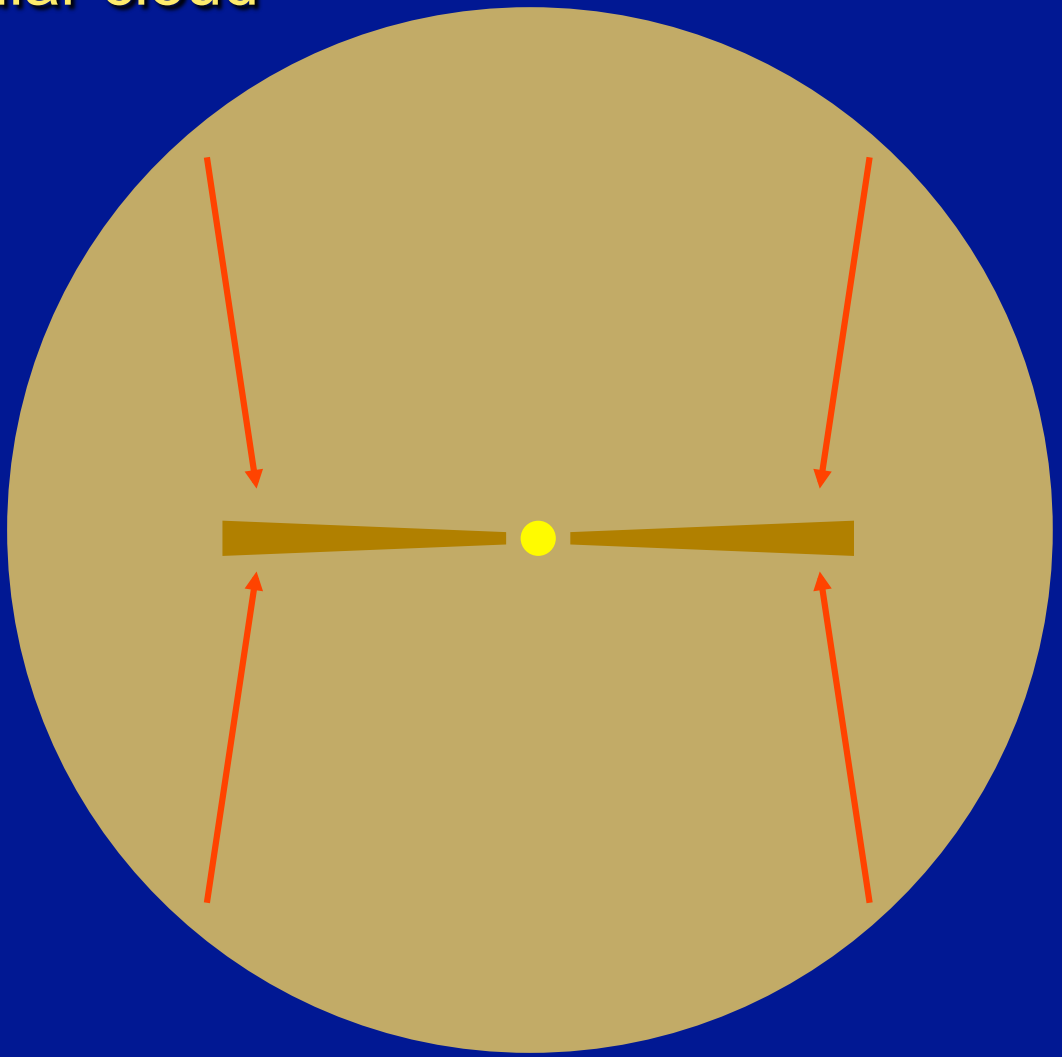
Disk formation and spreading

Molecular cloud core:



Disk formation and spreading

Molecular cloud core:



Disk formation and spreading

Molecular cloud core:

Simple model for cloud collapse

- Simple Shu-type model, but with rotation
- Assume E_{rot}/E_{grav} does not correlate with M_{cloud}.

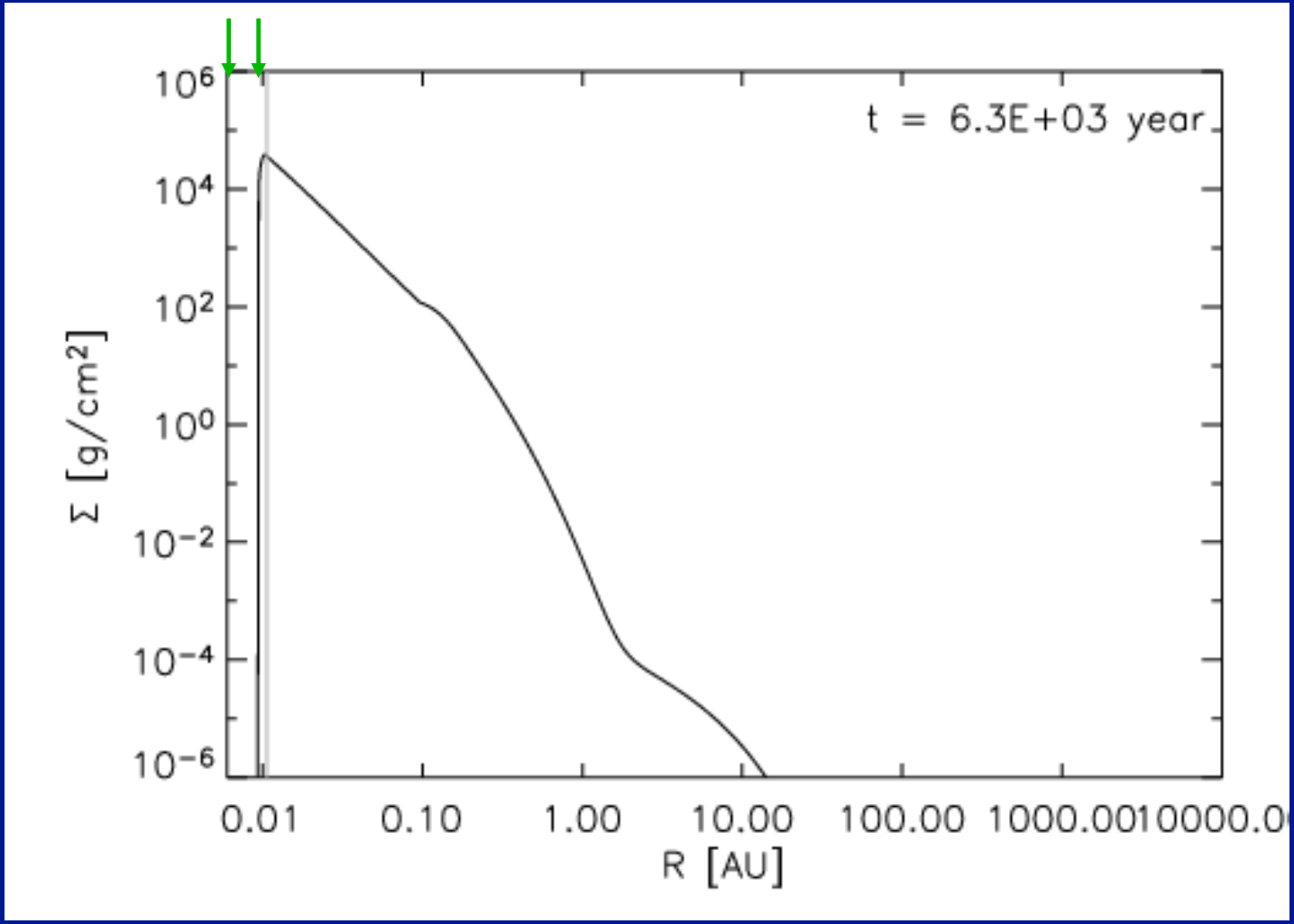
Initial Parameters:
1. Cloud rotation ω
2. Cloud mass

$$\Omega / \sqrt{GM / R_{\rm core}^3}$$

- ω, M_{cloud} determine centrifugal radius. Viscous evolution then determines:
  - M_{disk} at end of Class I (infall) phase
  - R_{disk} at end of Class I (infall) phase

Disk formation and spreading

Dullemond, Natta & Testi (2006)
Hueso & Guillot (2005)



Disk formation and spreading

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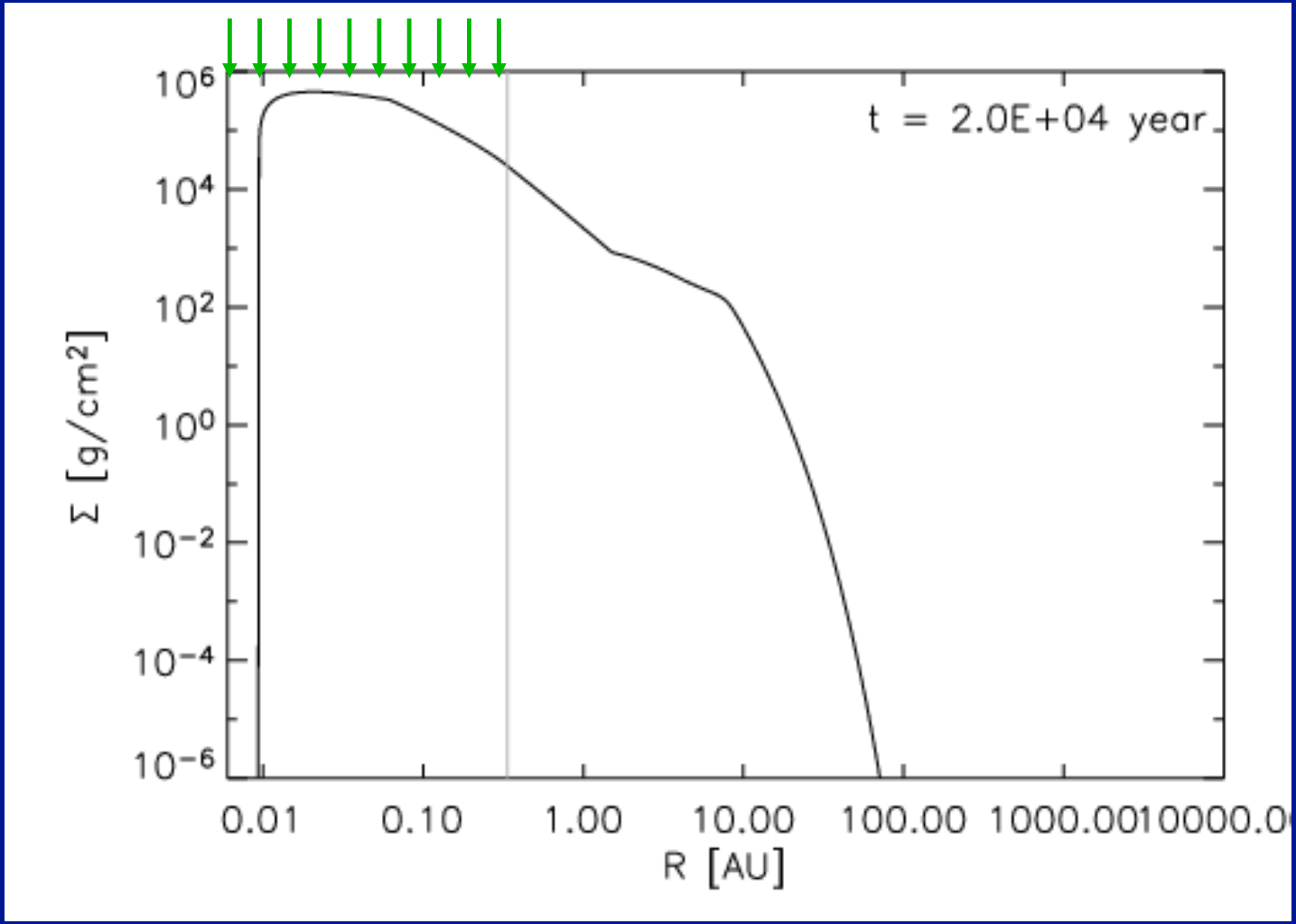

Disk formation and spreading

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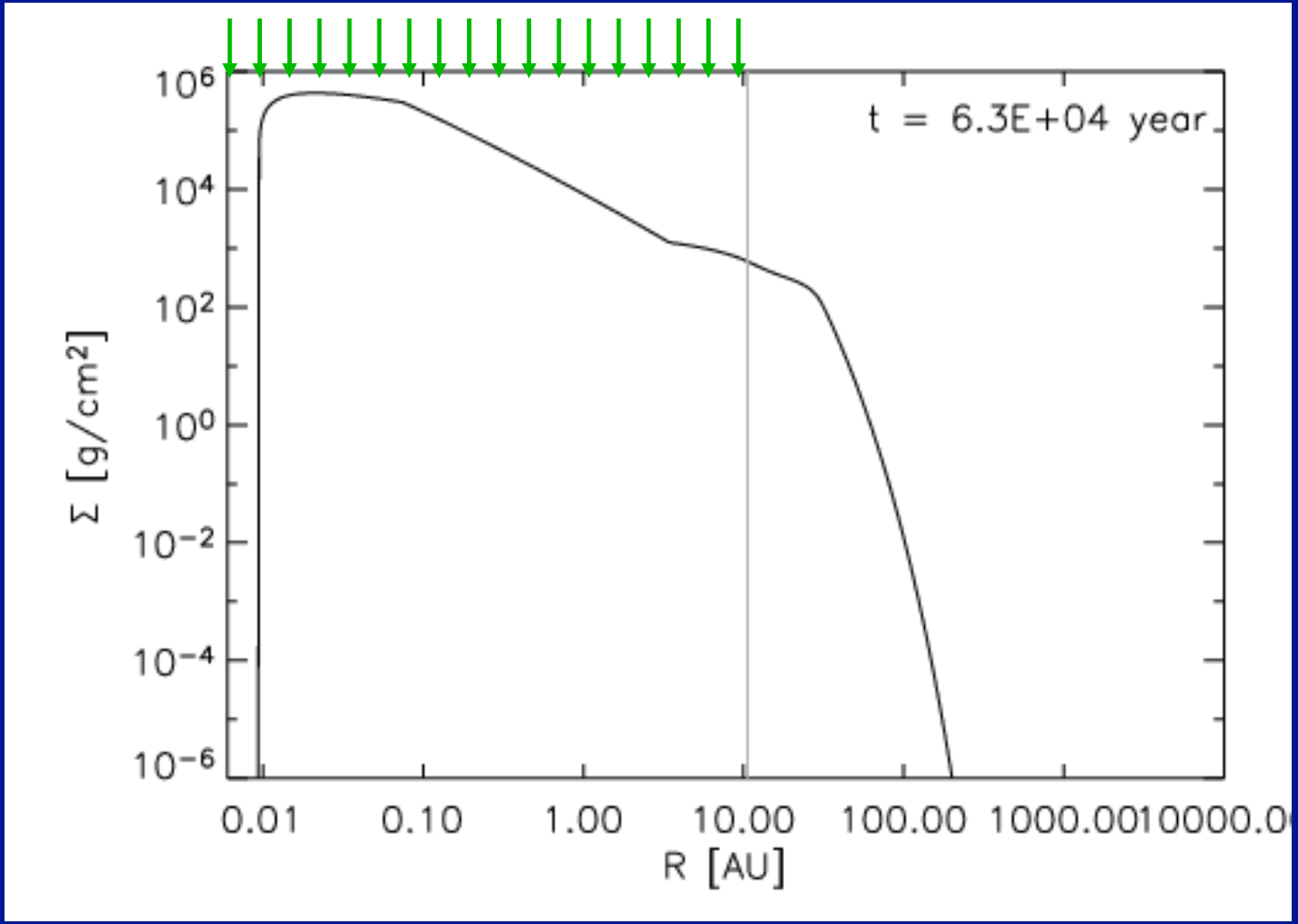

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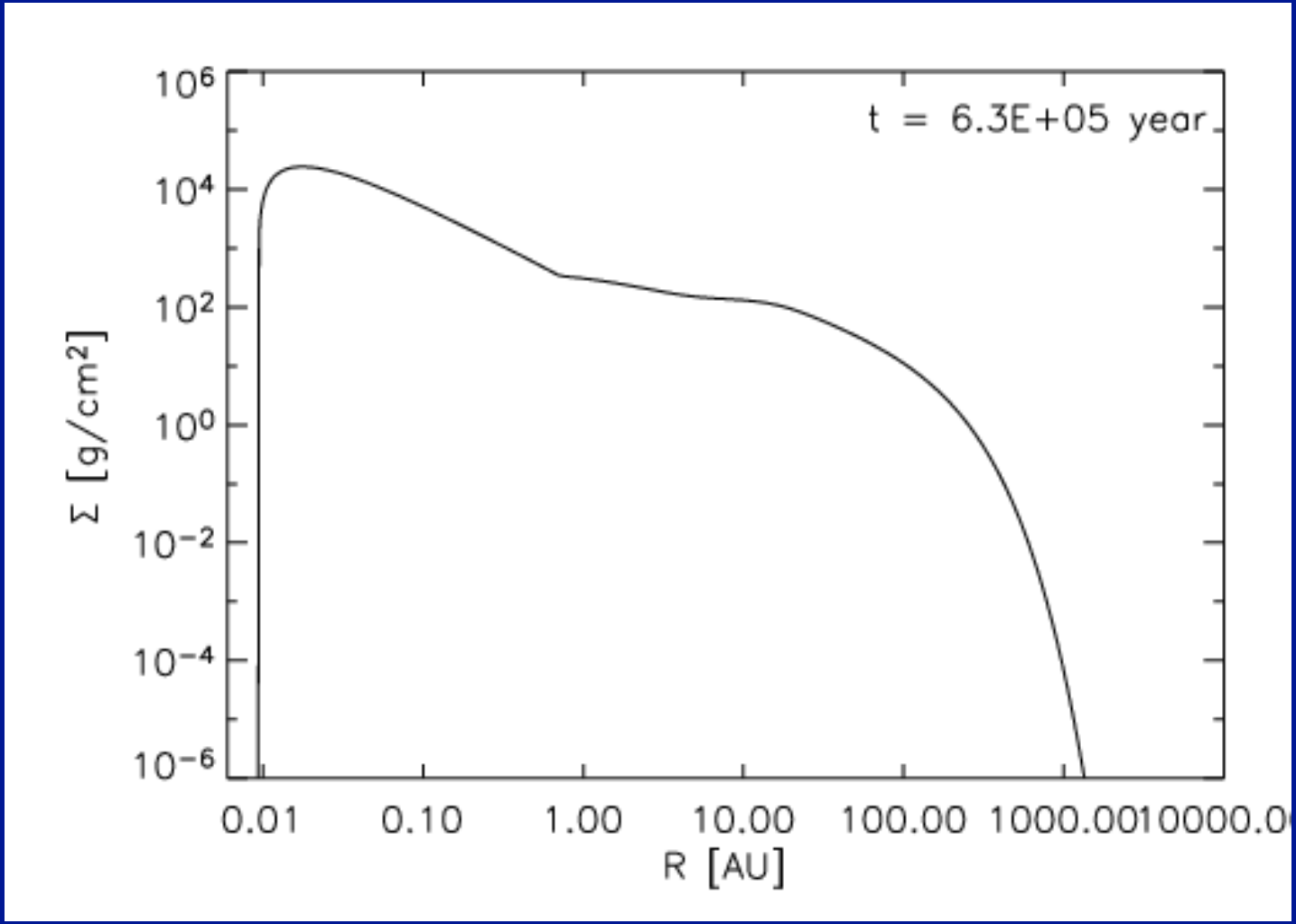

Disk formation and spreading

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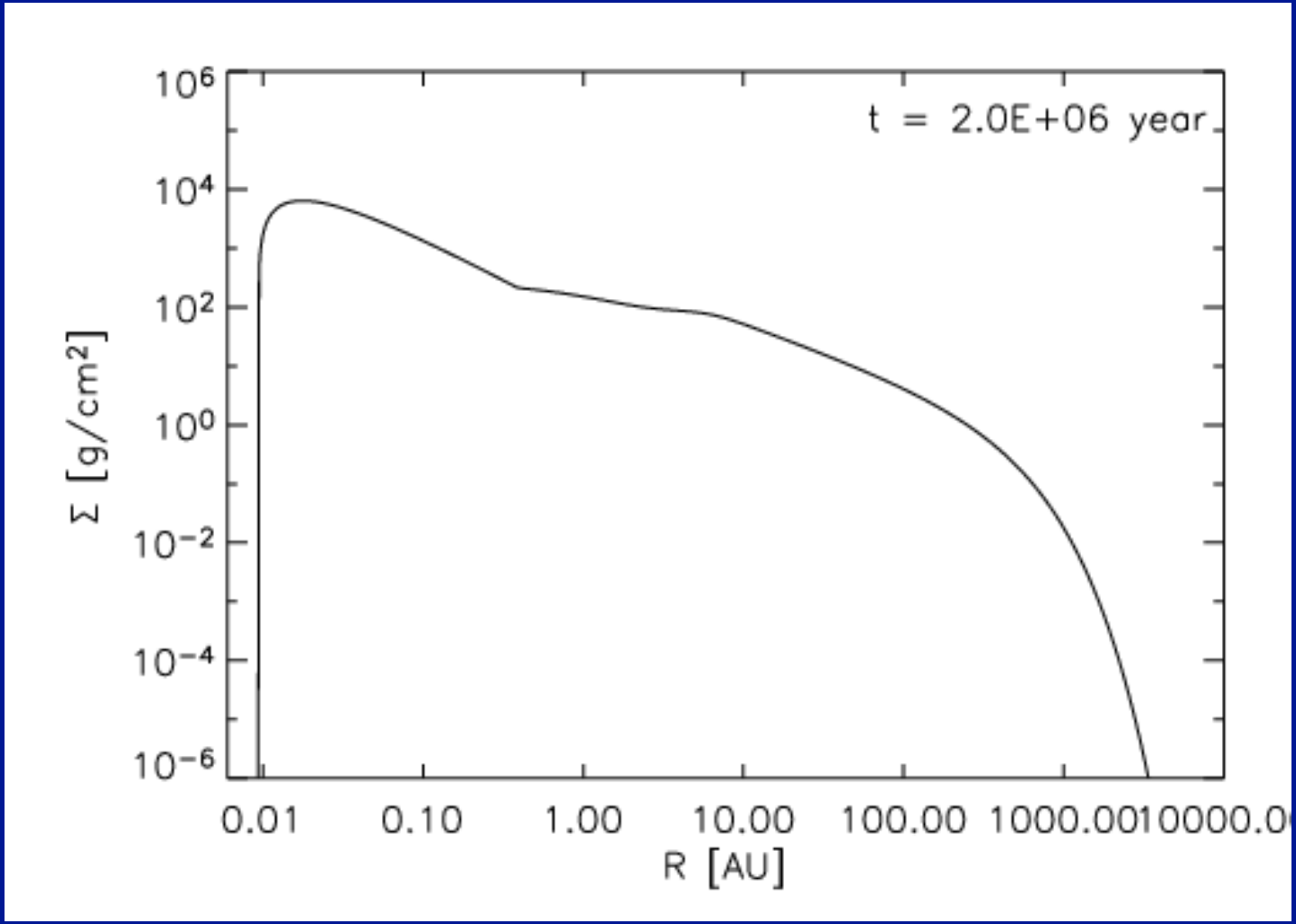
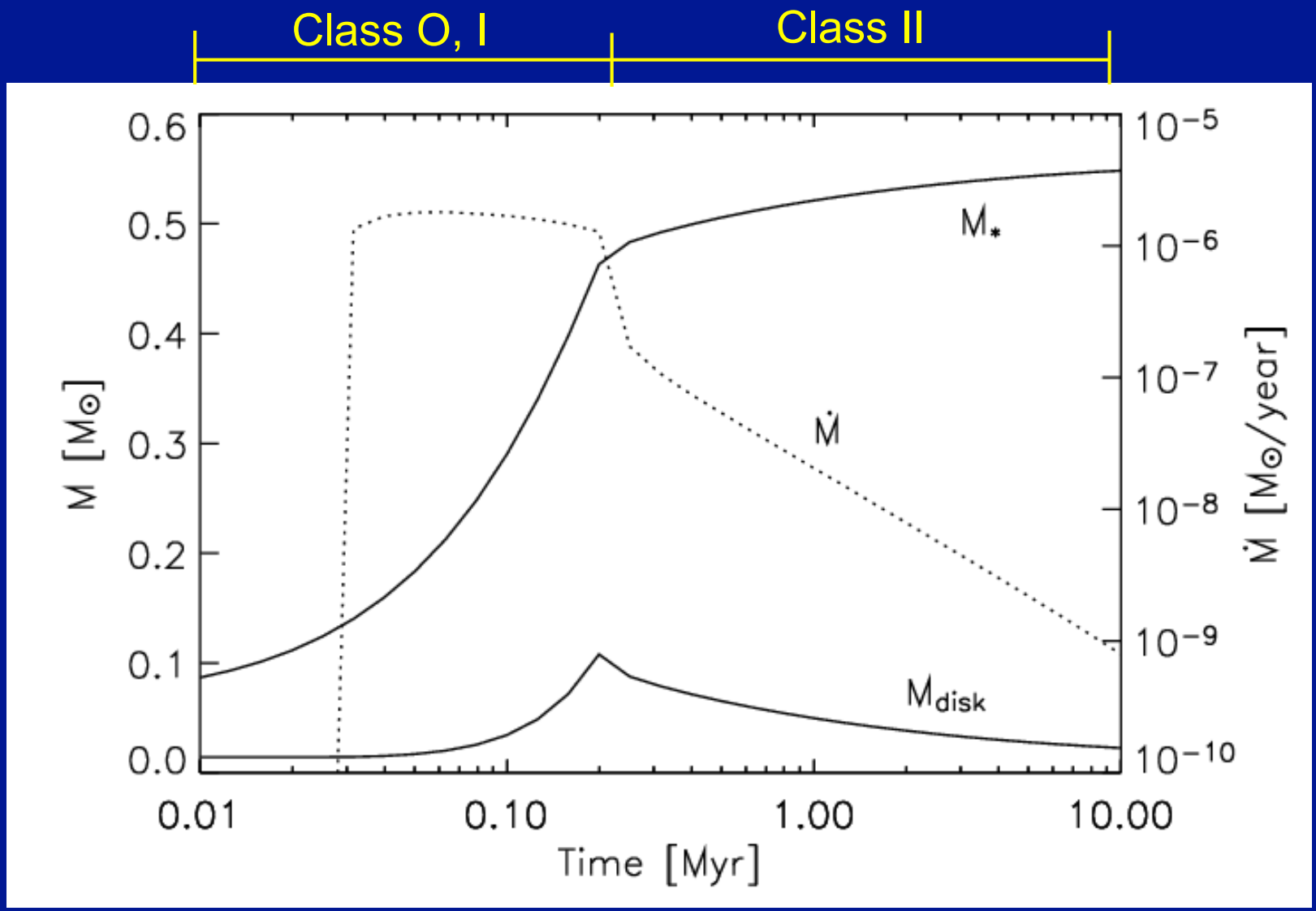
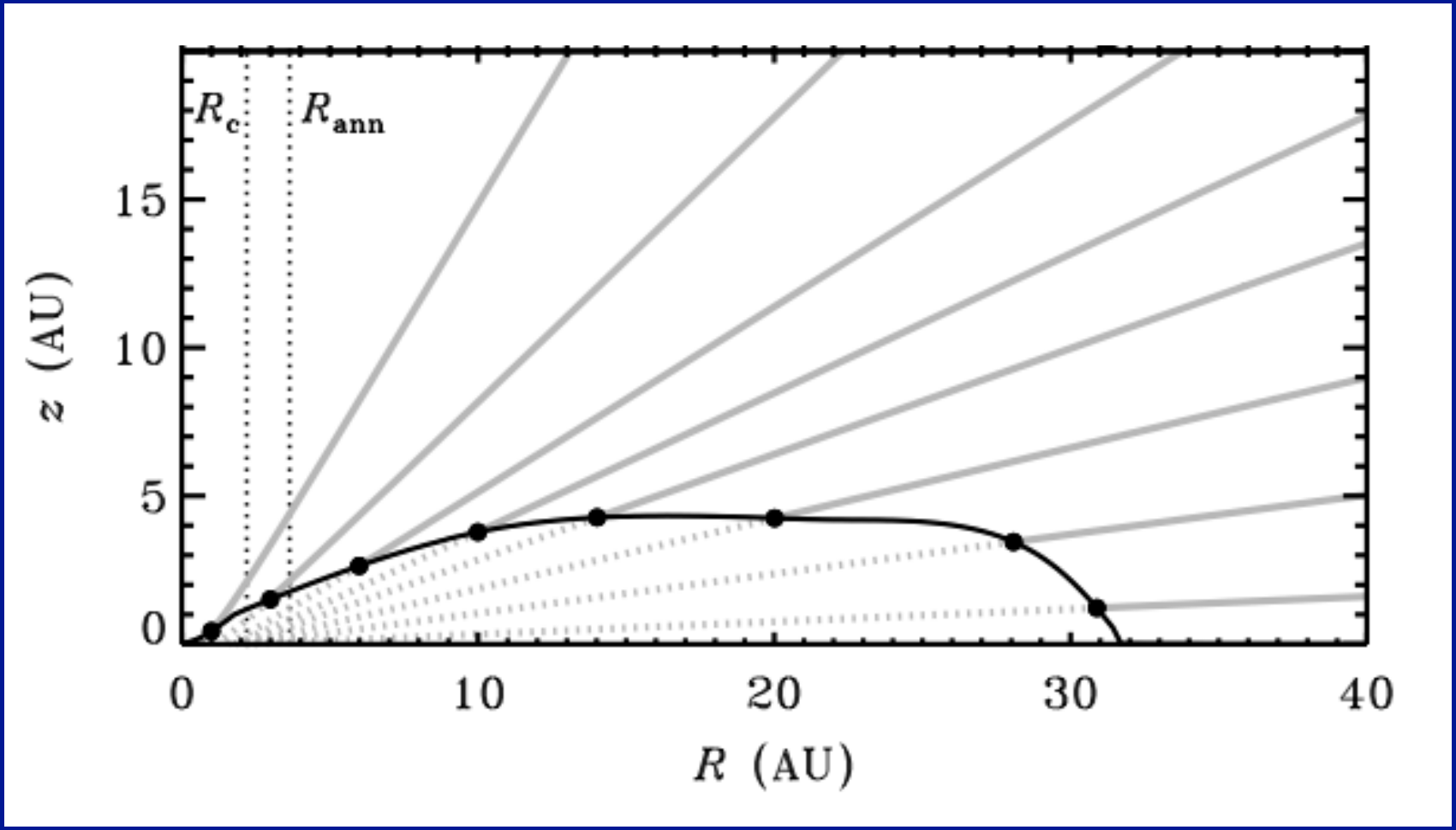


Evolution of disk parameters



(after Hueso & Guillot 2005)

Effect of finite disk thickness



Visser, van Dishoeck, Doty & Dullemond 2009
Visser & Dullemond 2010

Testing viscous accretion with observations

Shakura & Sunyaev model

Suppose we *know* that c_s^2 is a given power-law:

Ansatz: surface density is also a powerlaw:

$$c_s^2 \sim r^{-\xi} \qquad \Sigma \sim r^{-\eta}$$

$$\nu \equiv \alpha \frac{c_s^2}{\Omega_K} \sim r^{-\xi+3/2}$$

The radial velocity then becomes:

$$v_r \equiv -\frac{3}{\Sigma\sqrt{r}} \frac{\partial}{\partial r}\left(\Sigma \nu \sqrt{r}\right) = 3(\xi+\eta-2)\frac{\nu}{r} \longrightarrow v_r = -\frac{3}{2}\frac{\nu}{r}$$

Stationary continuity equation:

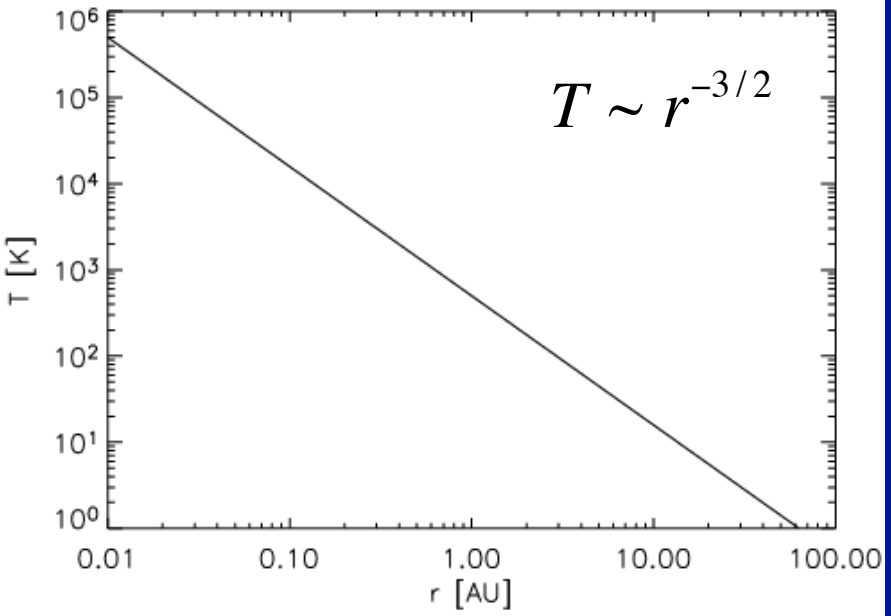
$$\frac{\partial(\Sigma r v_r)}{\partial r} = 0$$

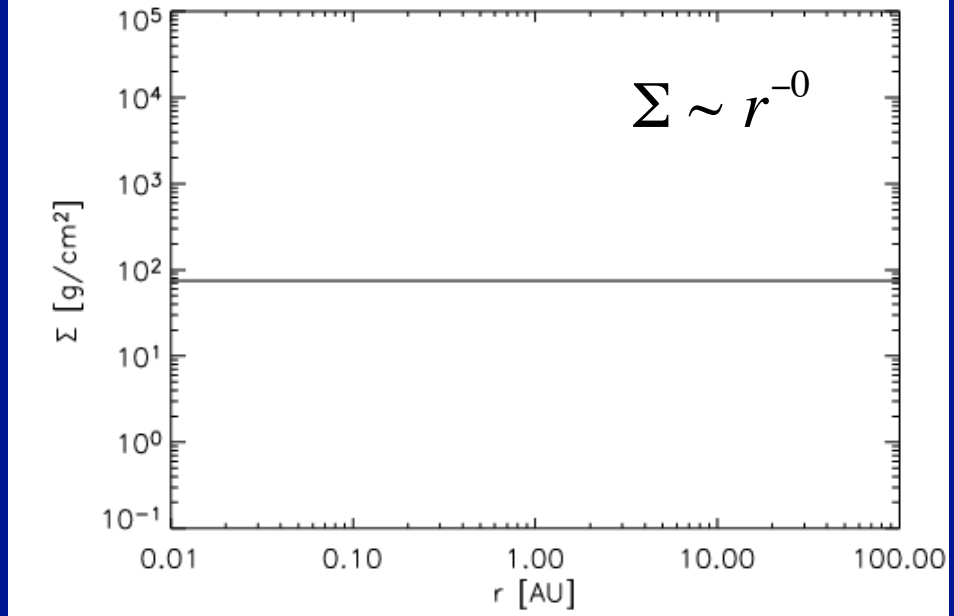
from which follows:

$$\Sigma \sim r^{\xi-3/2}$$

$$\eta = -\xi + 3/2$$

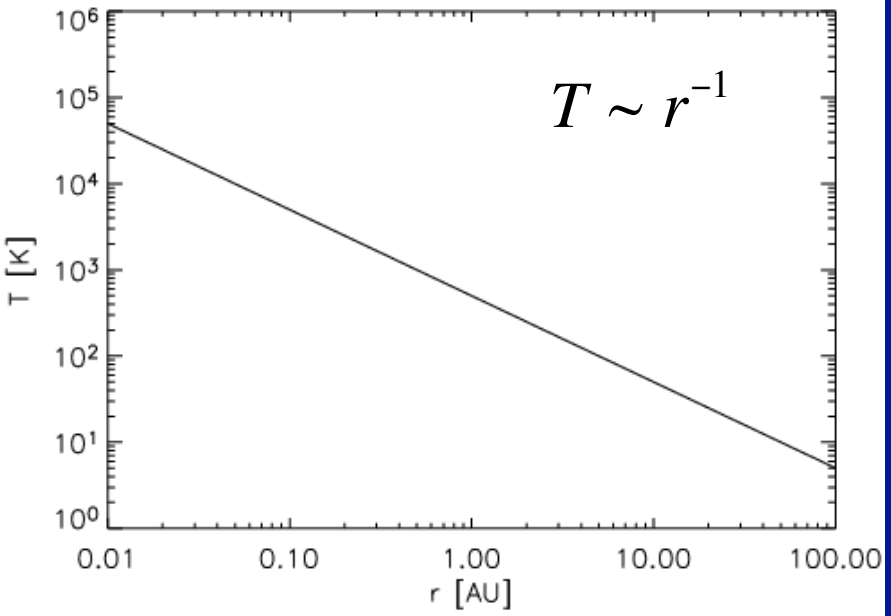
Shakura & Sunyaev model

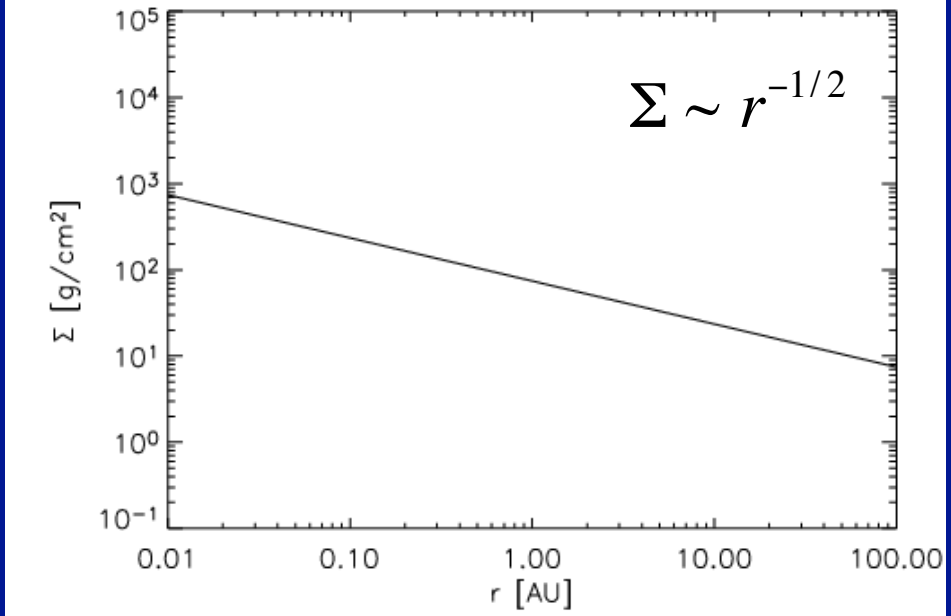




$$\Sigma T \propto R^{-3/2}$$

Shakura & Sunyaev model





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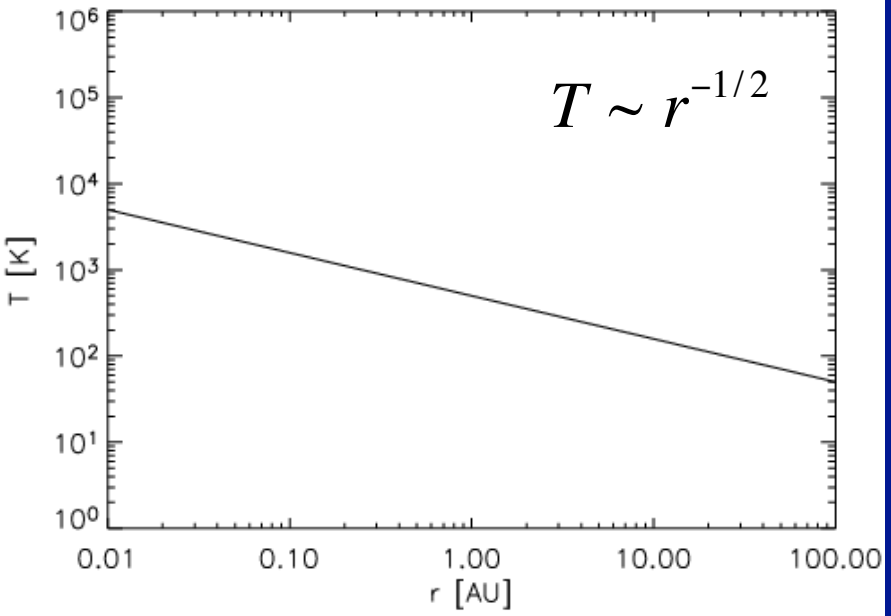
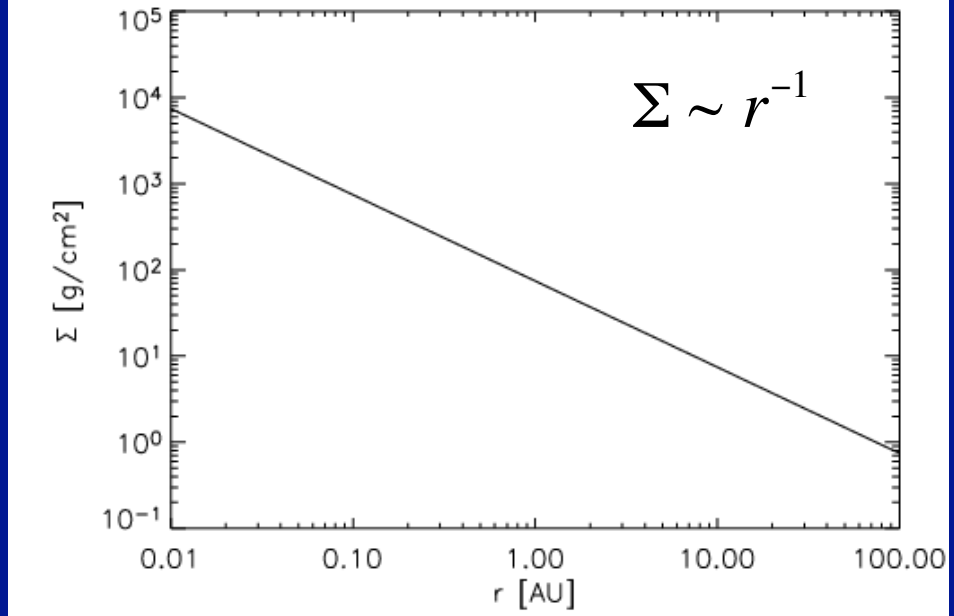
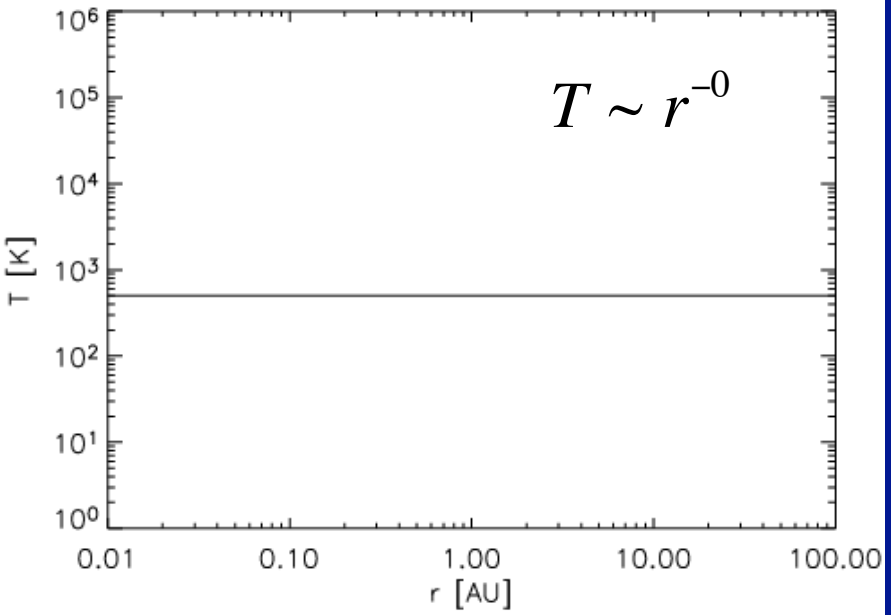
Shakura & Sunyaev model

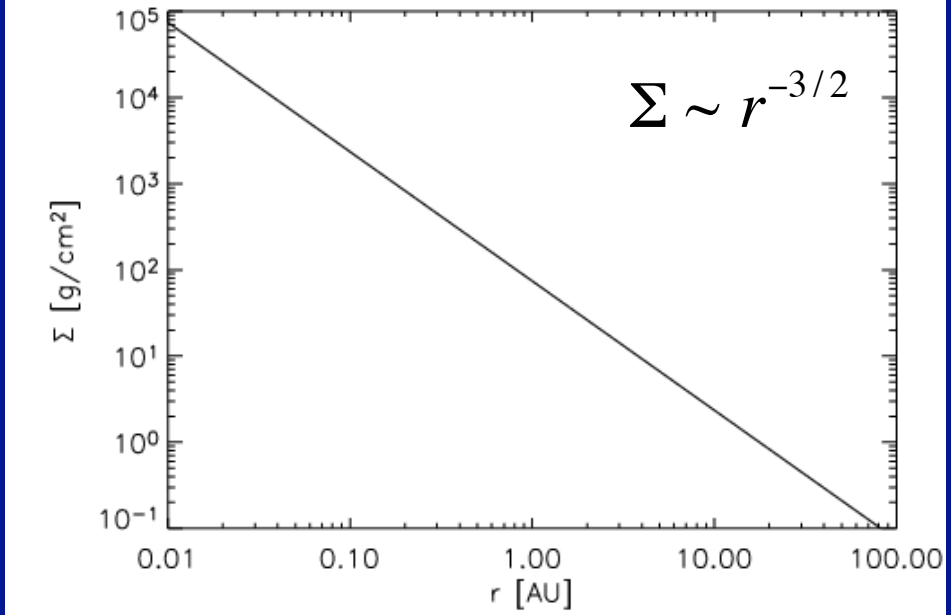




$$\Sigma T \propto R^{-3/2}$$

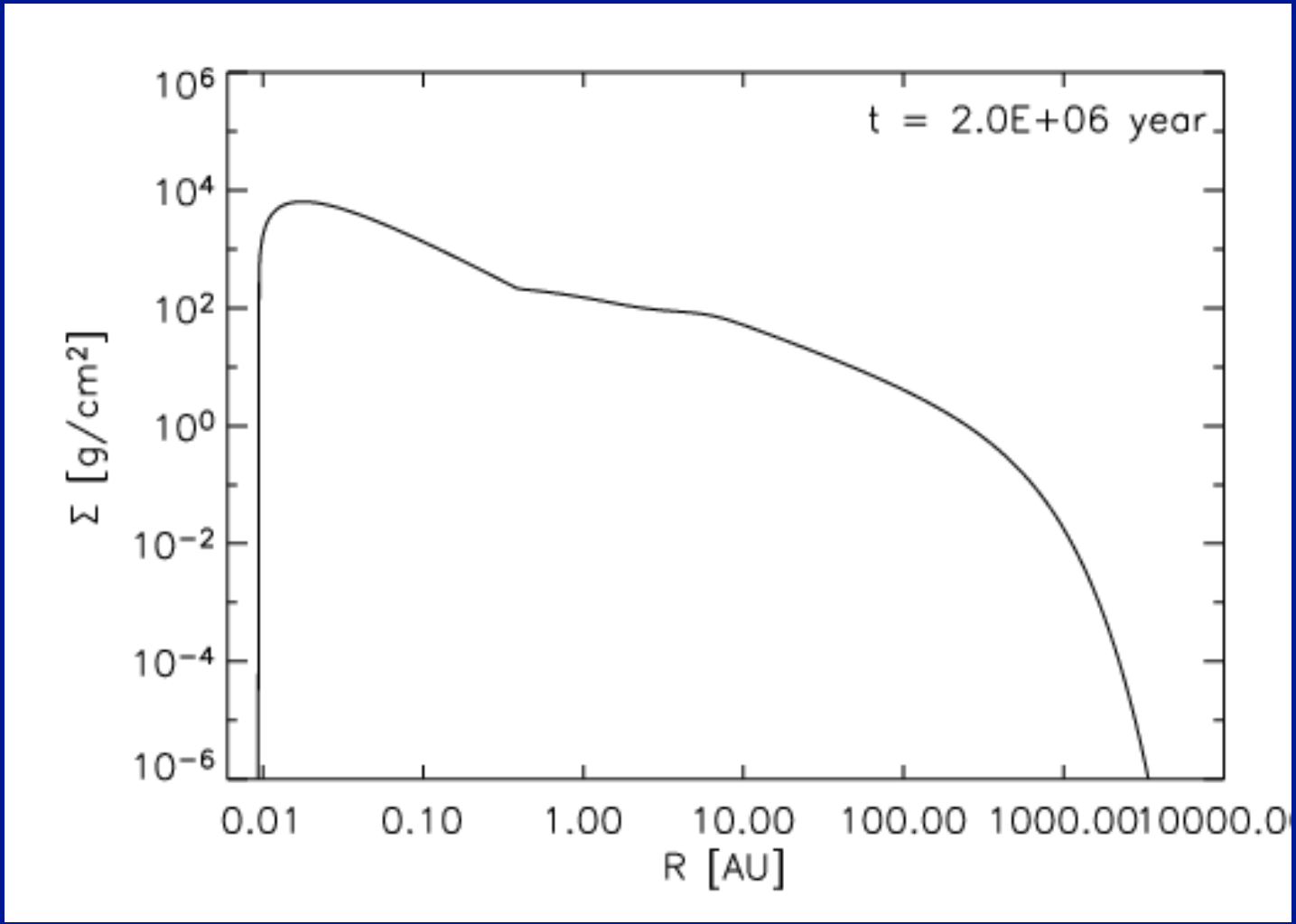
Shakura & Sunyaev model





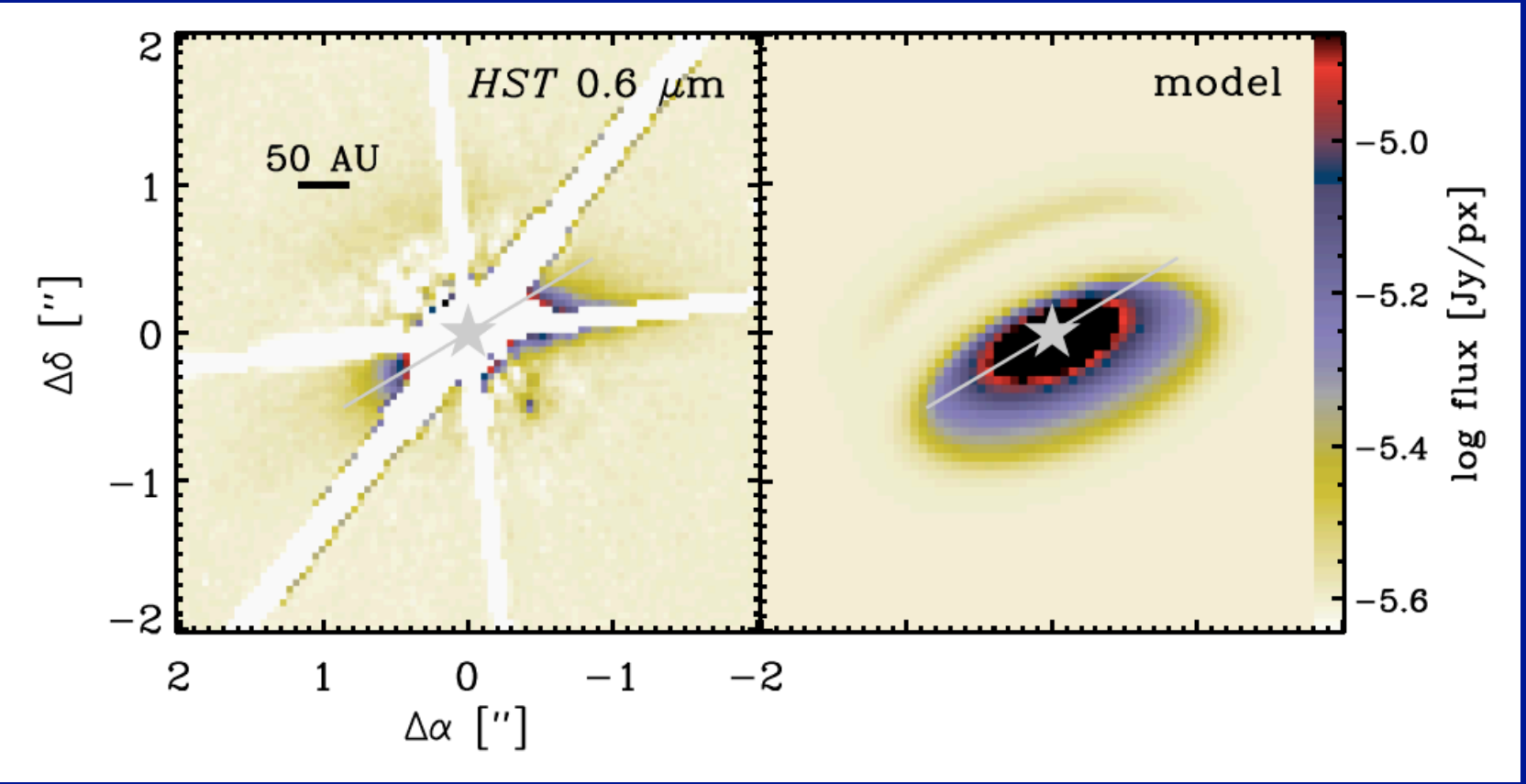
$$\Sigma T \propto R^{-3/2}$$

Time-dependent disk



Radial distribution of matter

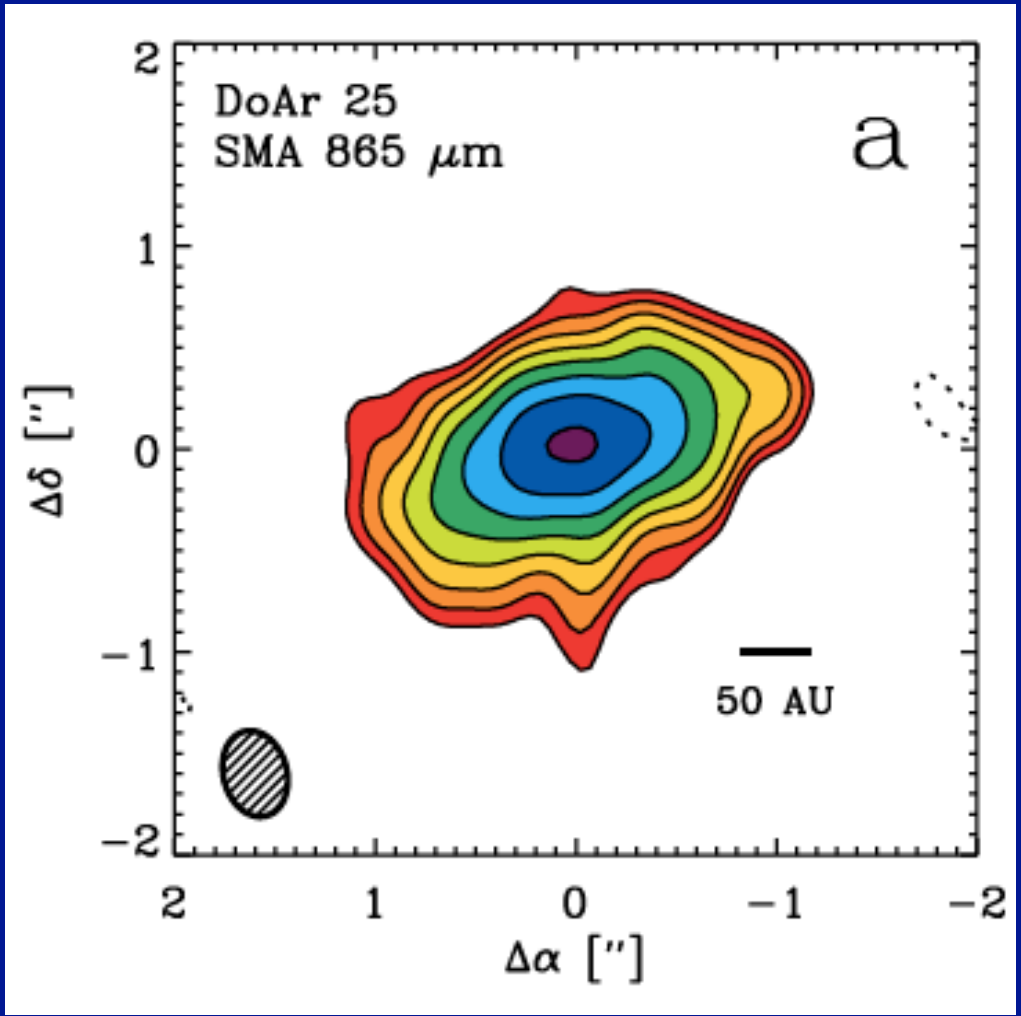
The case of DoAr 25



Andrews, Hughes, Wilner & Qi (2008)

Radial distribution of matter

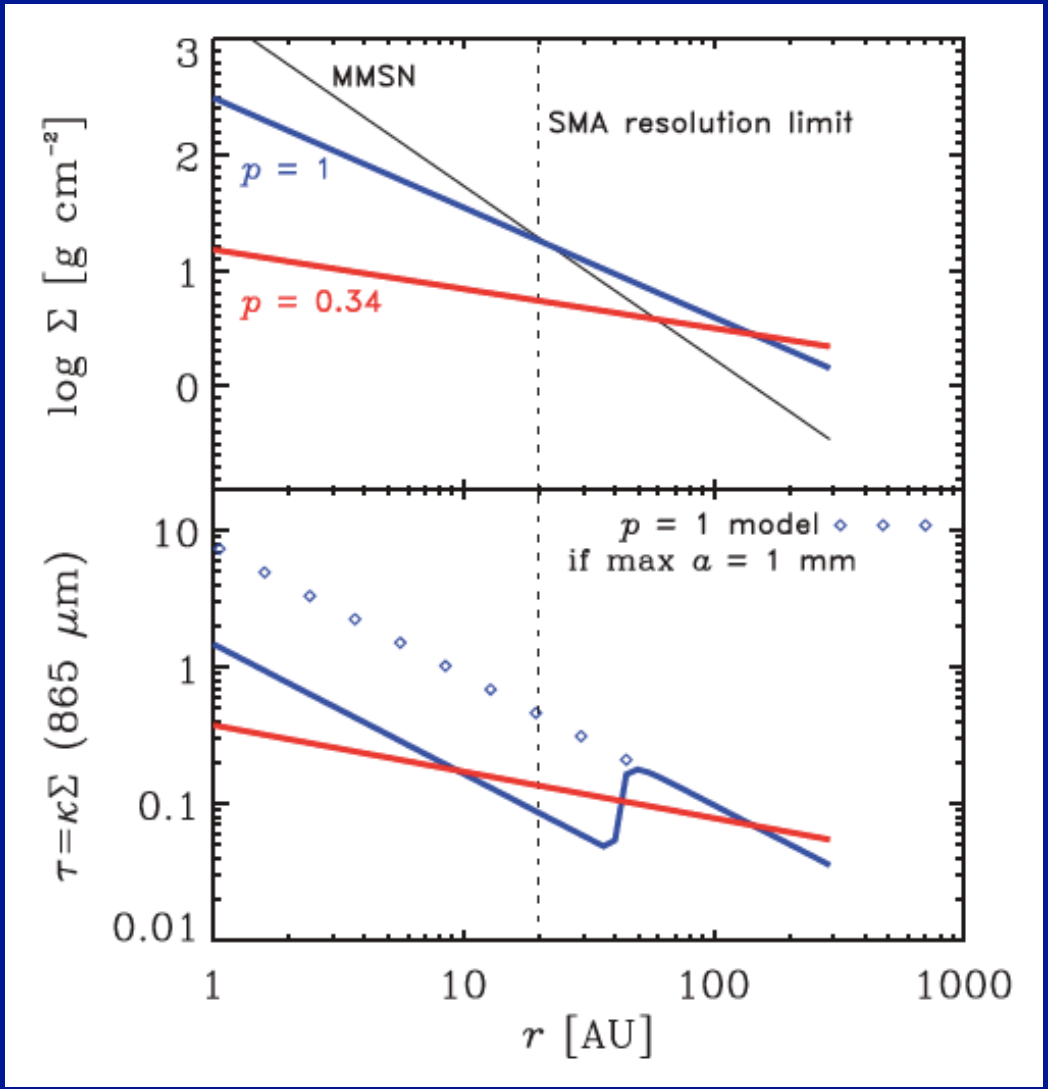
The case of DoAr 25



Andrews, Hughes, Wilner & Qi (2008)

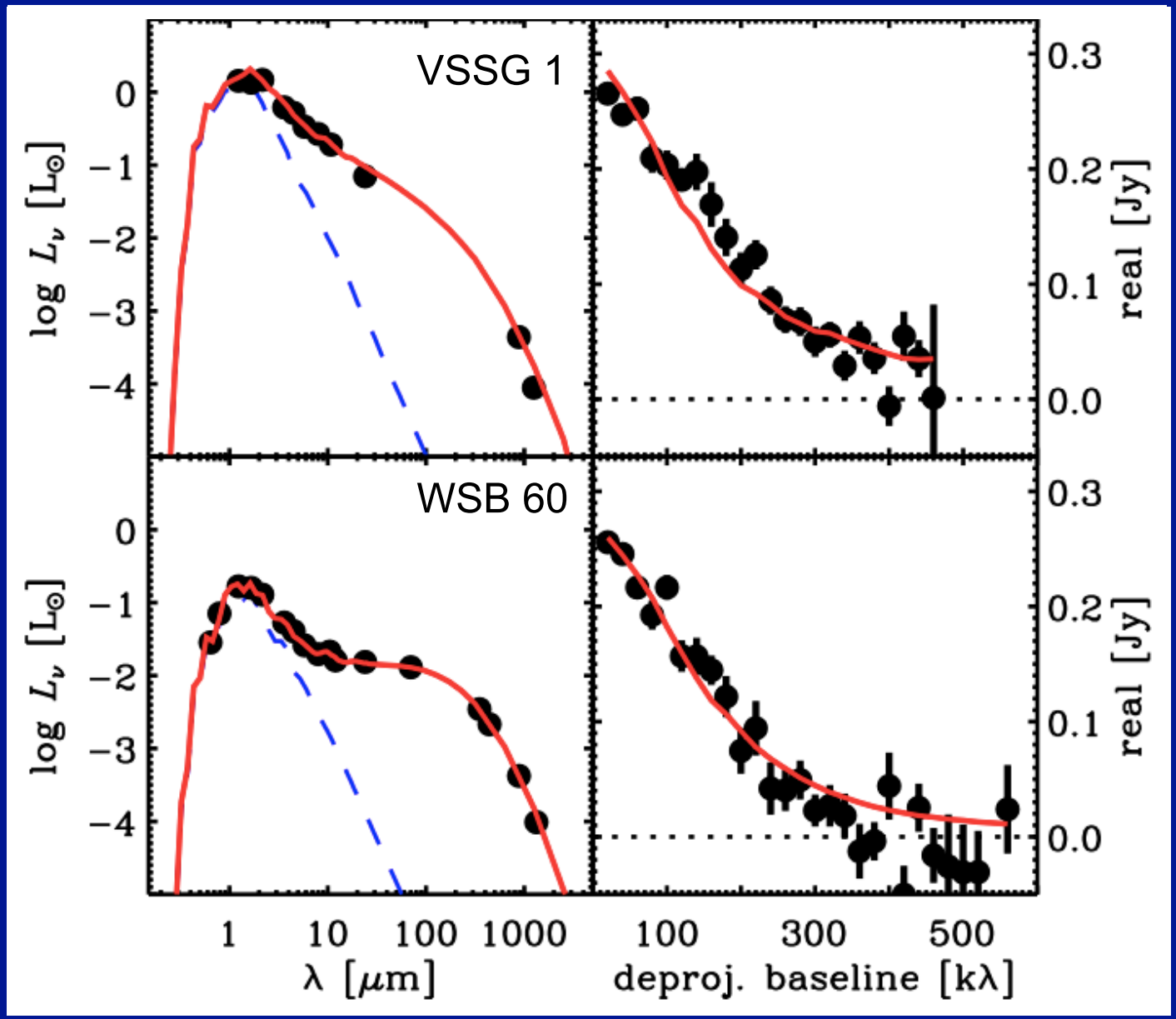
Radial distribution of matter

The case of DoAr 25



Andrews, Hughes, Wilner & Qi (2008)

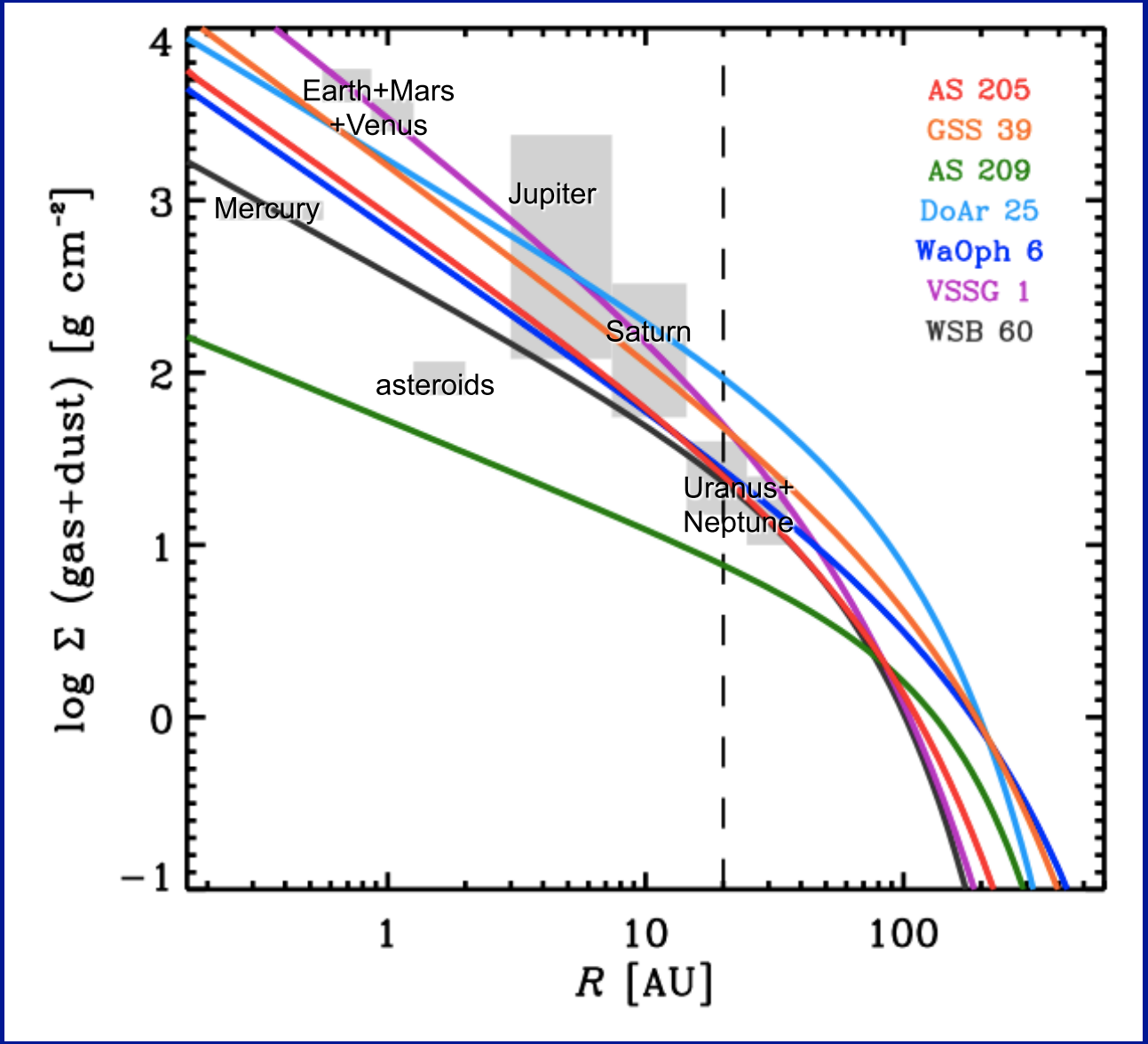
Radial distribution of matter



SED + millimeter resolved maps (=visibility values)

Andrews et al. (2009)

Radial distribution of matter



See also:

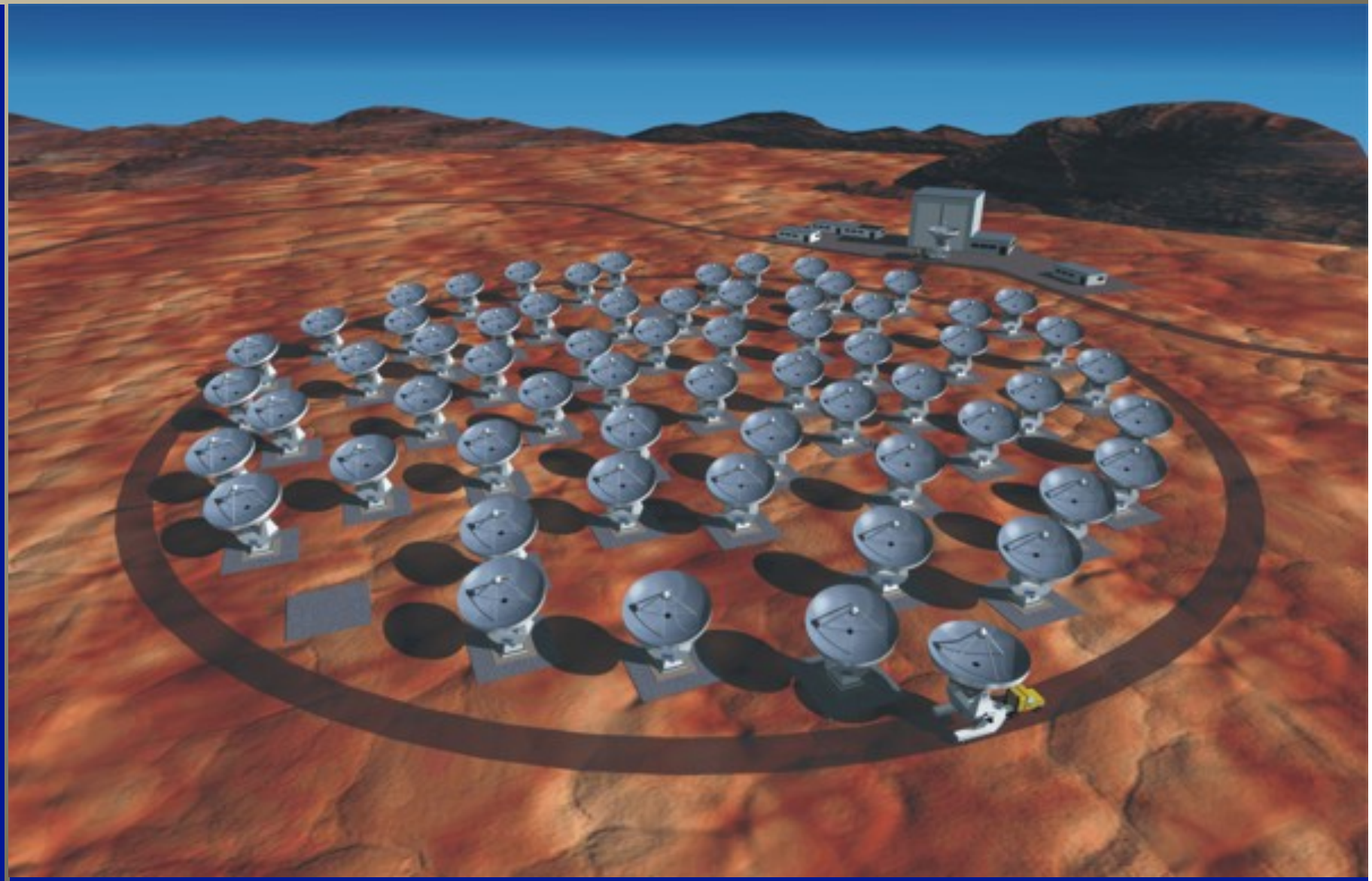
Kitamura et al. 2002

Pietu et al. 2007

Isella, Carpenter & Sargent 2009

Andrews et al. (2009)

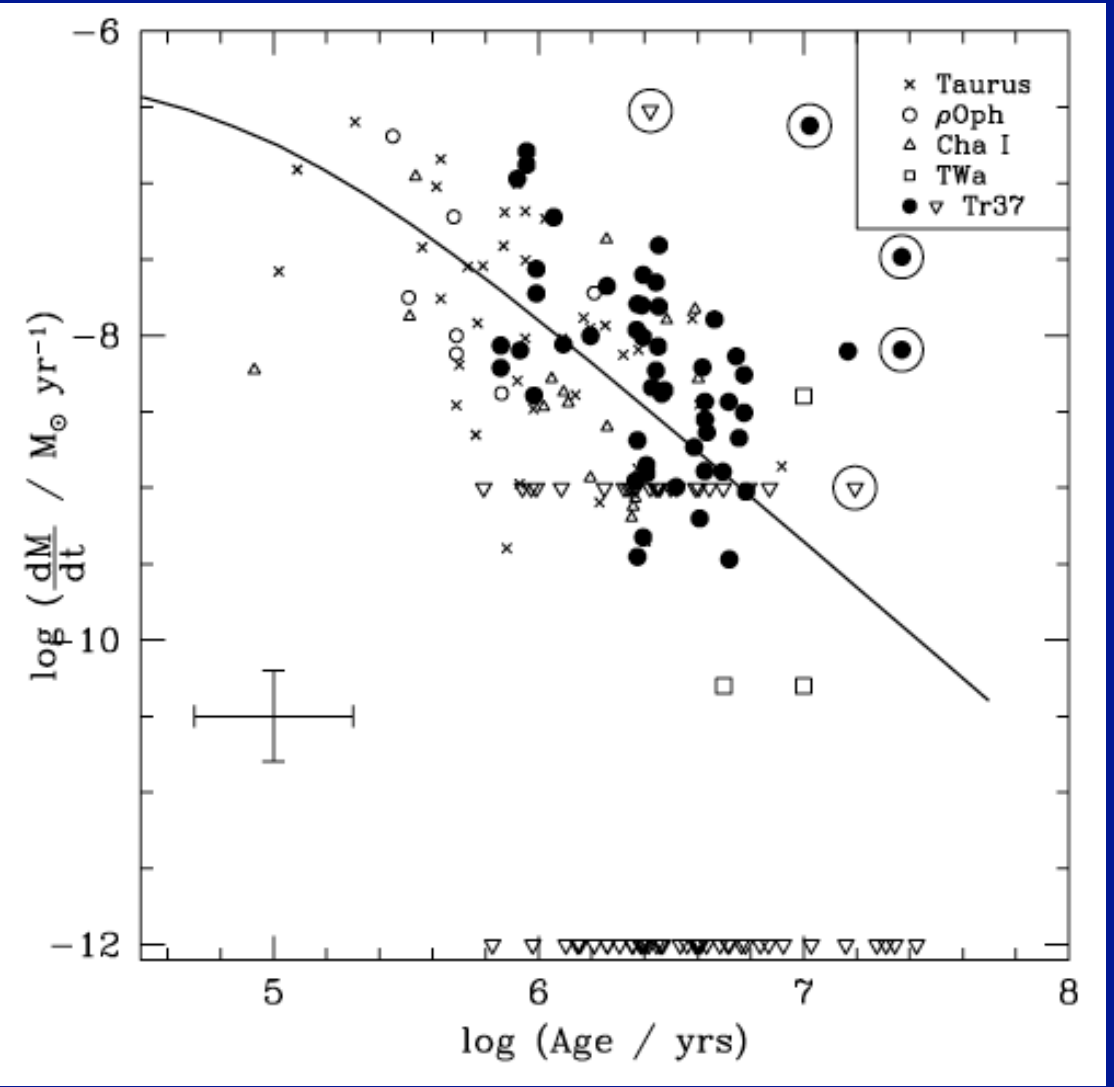
Looking forward to this toy:



Coming soon...

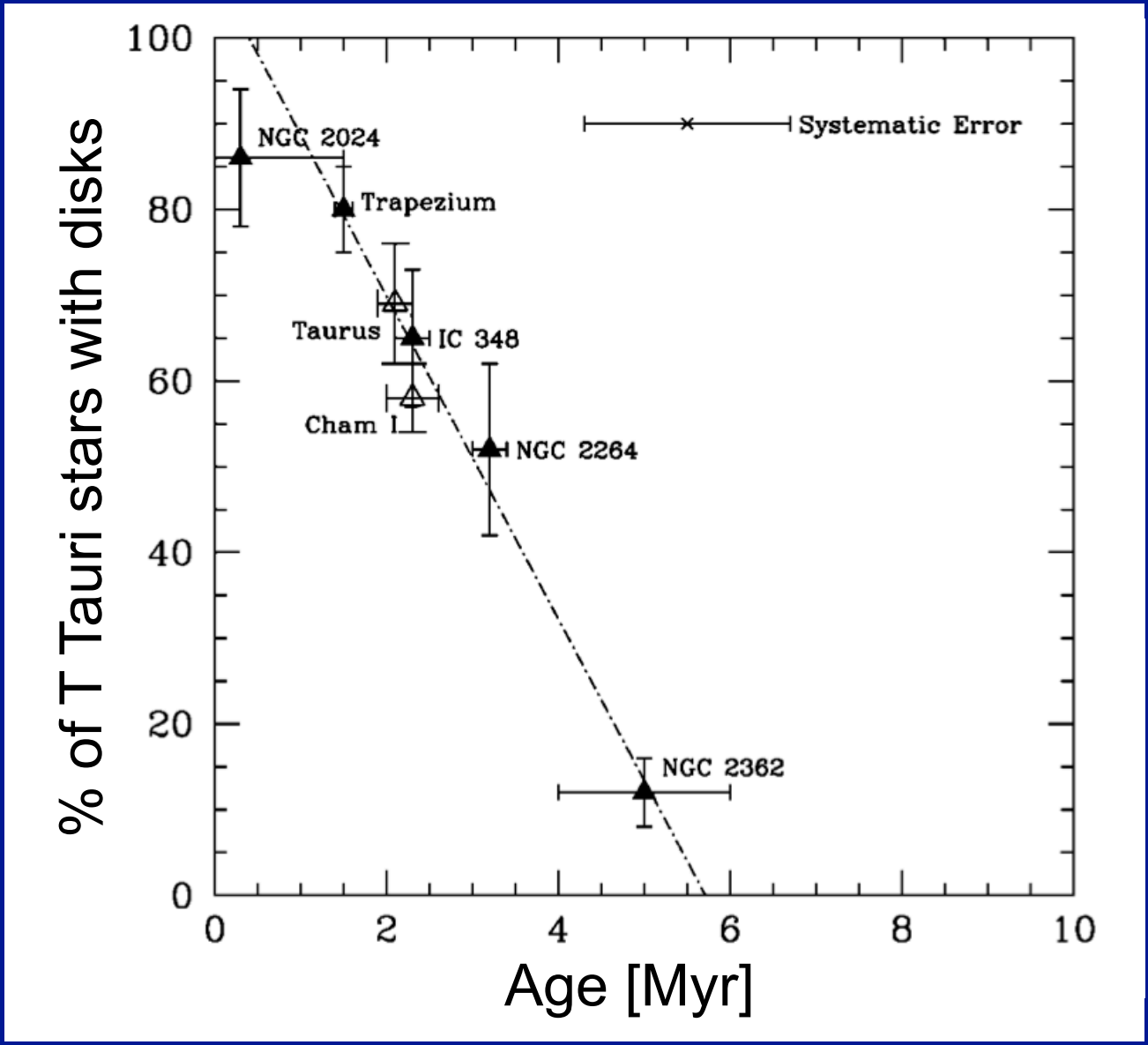
Disk destruction through photoevaporation

Statistics of disk accretion rates



Sicilia-Aguilar et al. 2006

Disk presence vs. Age

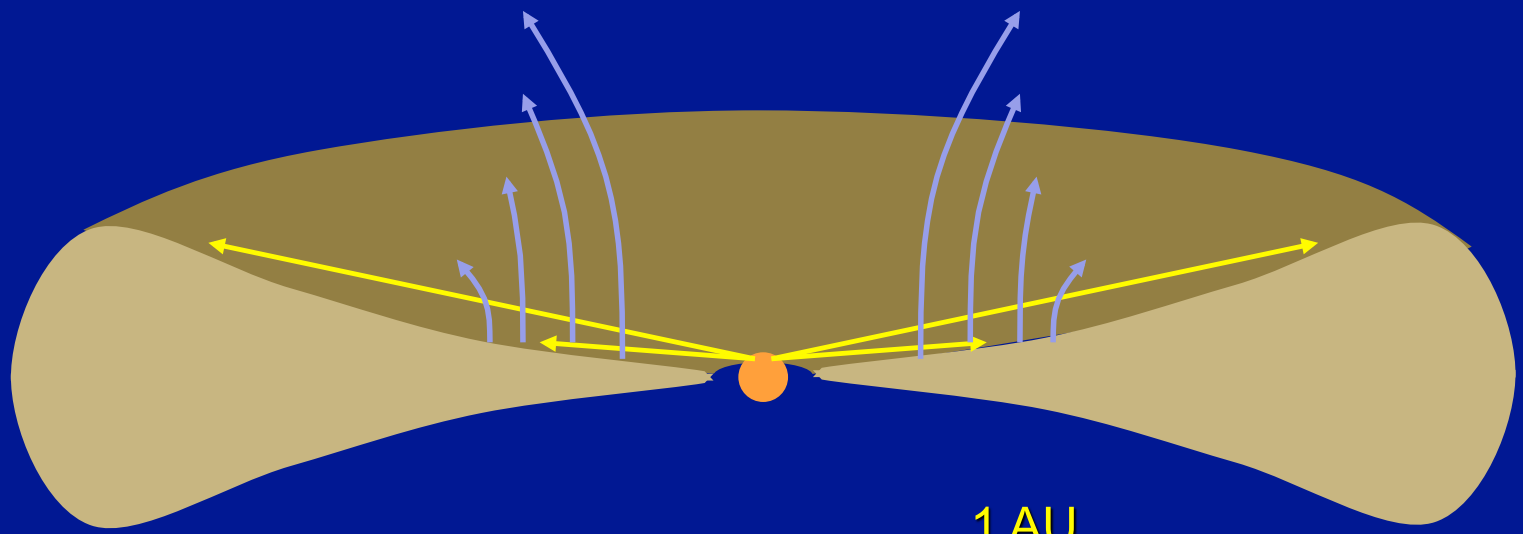


Haisch et al. 2001

EUV-driven Photoevaporation

EUV = Hydrogen-ionizing radiation (hv>13.6 eV)

EUV Photoevap:
- Weak, but
- Works around 1 AU



Hollenbach et al. 1994; Clarke et al. 2002;
Alexander et al. 2006; Ercolano et al. 2008;
Gorti & Hollenbach 2007

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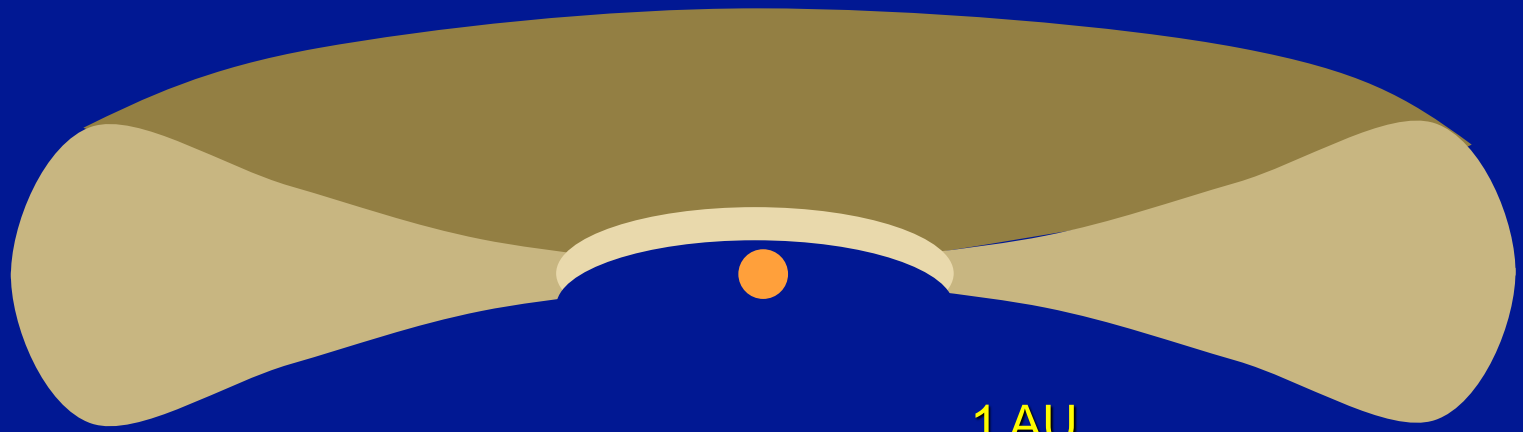

Hollenbach et al. 1994; Clarke et al. 2002;
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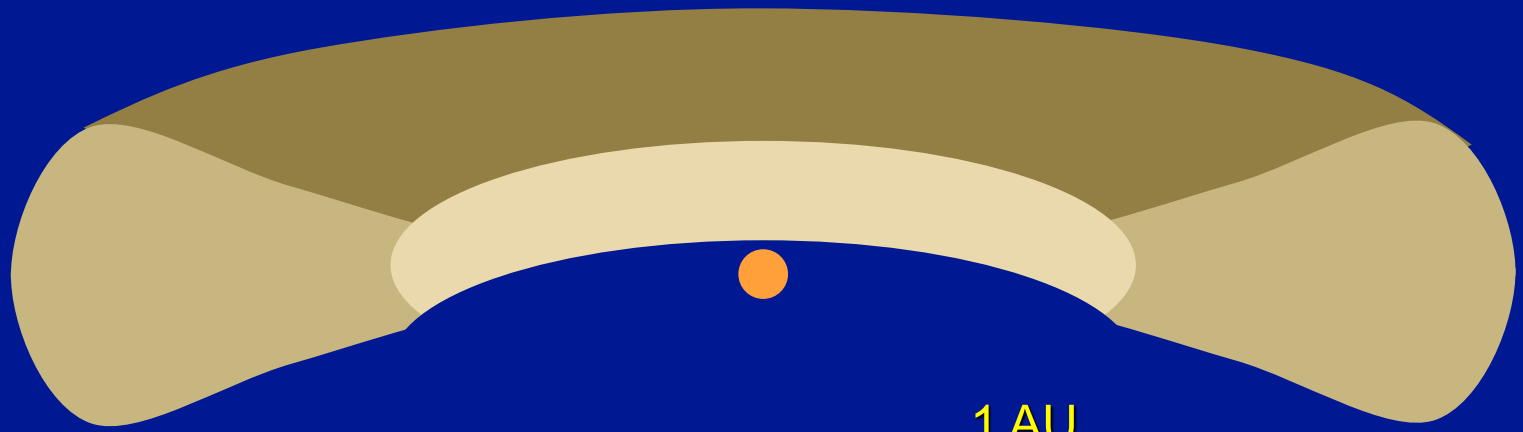

Hollenbach et al. 1994; Clarke et al. 2002;
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Gorti & Hollenbach 2007

EUV-driven Photoevaporation

EUV = Hydrogen-ionizing radiation (hv>13.6 eV)

EUV Photoevap:
- Weak, but
- Works around 1 AU

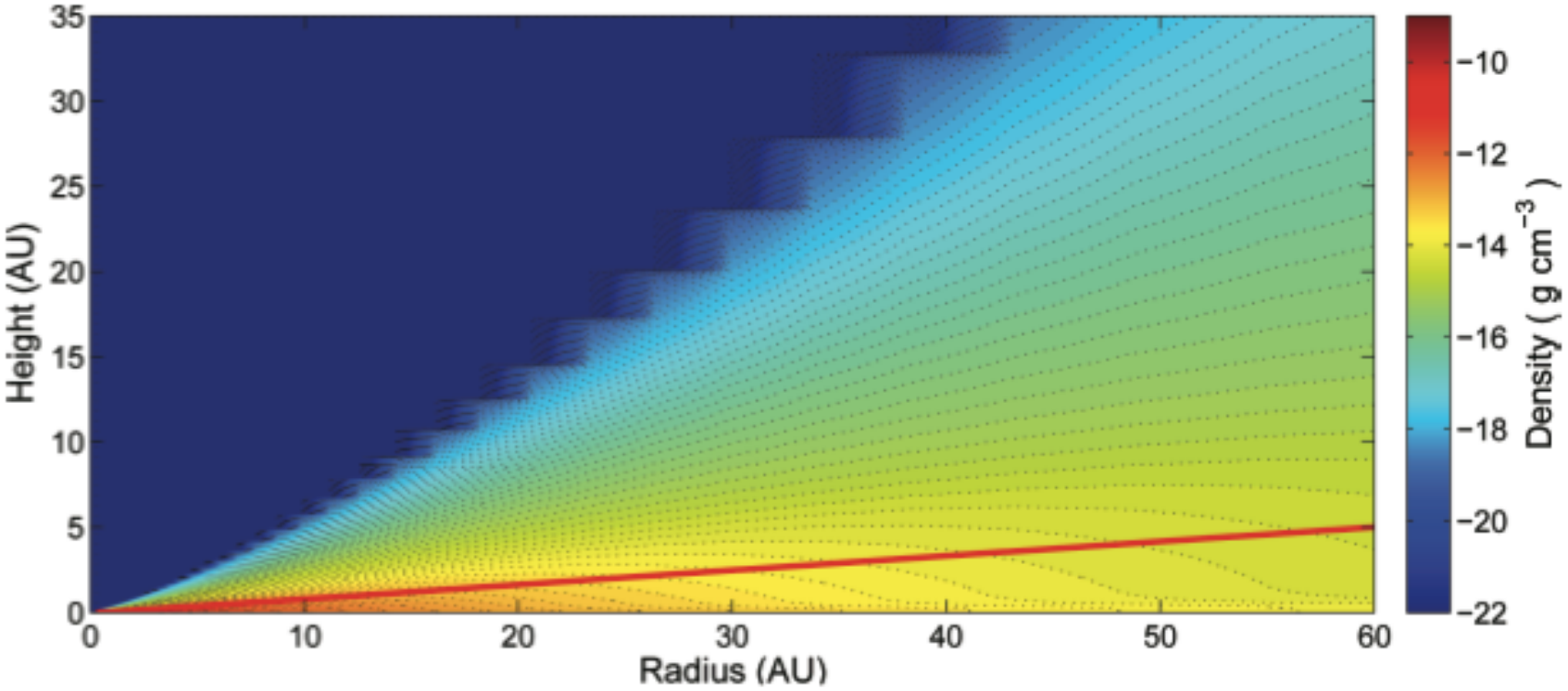
1 AU

50 AU

Hollenbach et al. 1994; Clarke et al. 2002;
Alexander et al. 2006; Ercolano et al. 2008;
Gorti & Hollenbach 2007

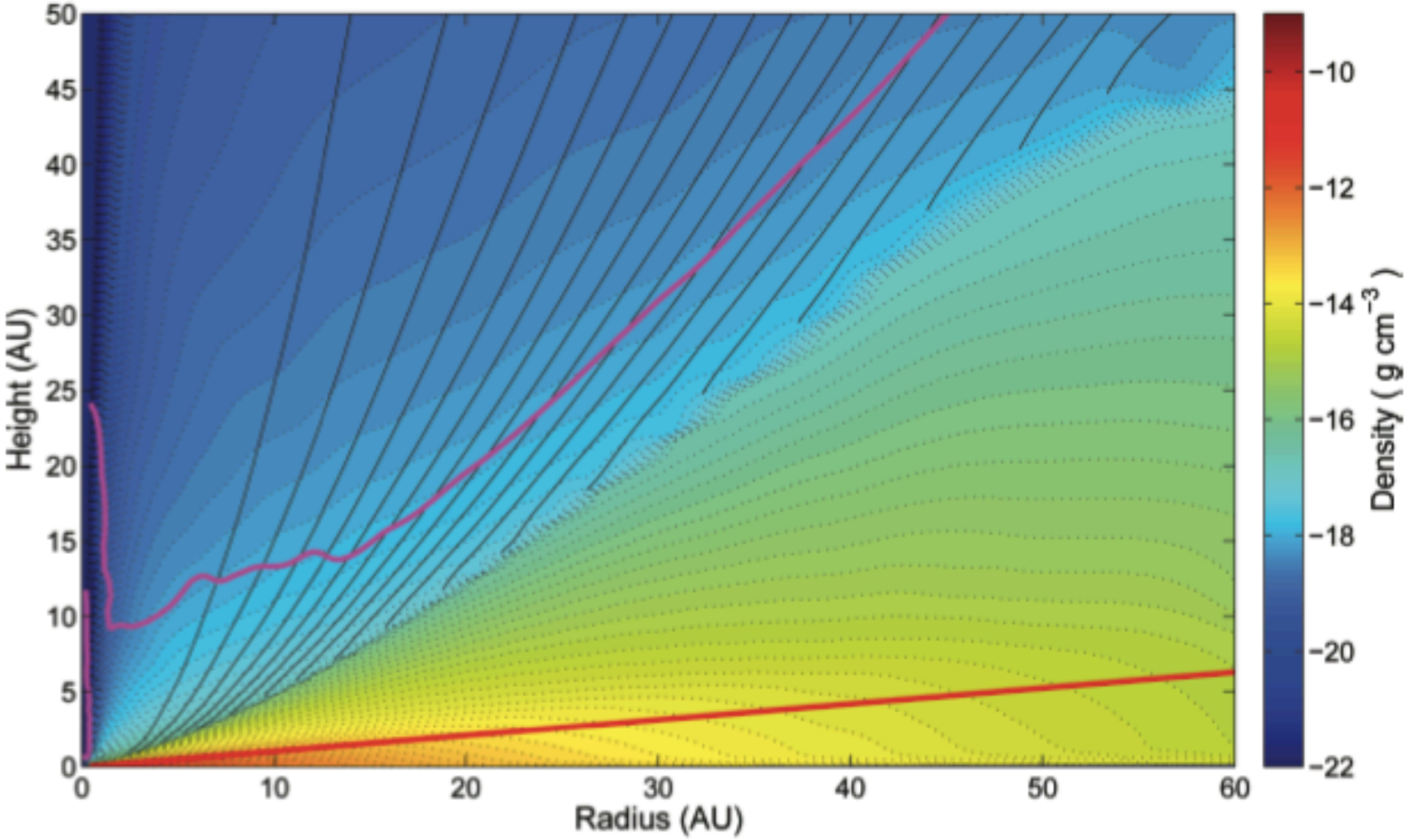
2-D models of photoevaporation

Starting model



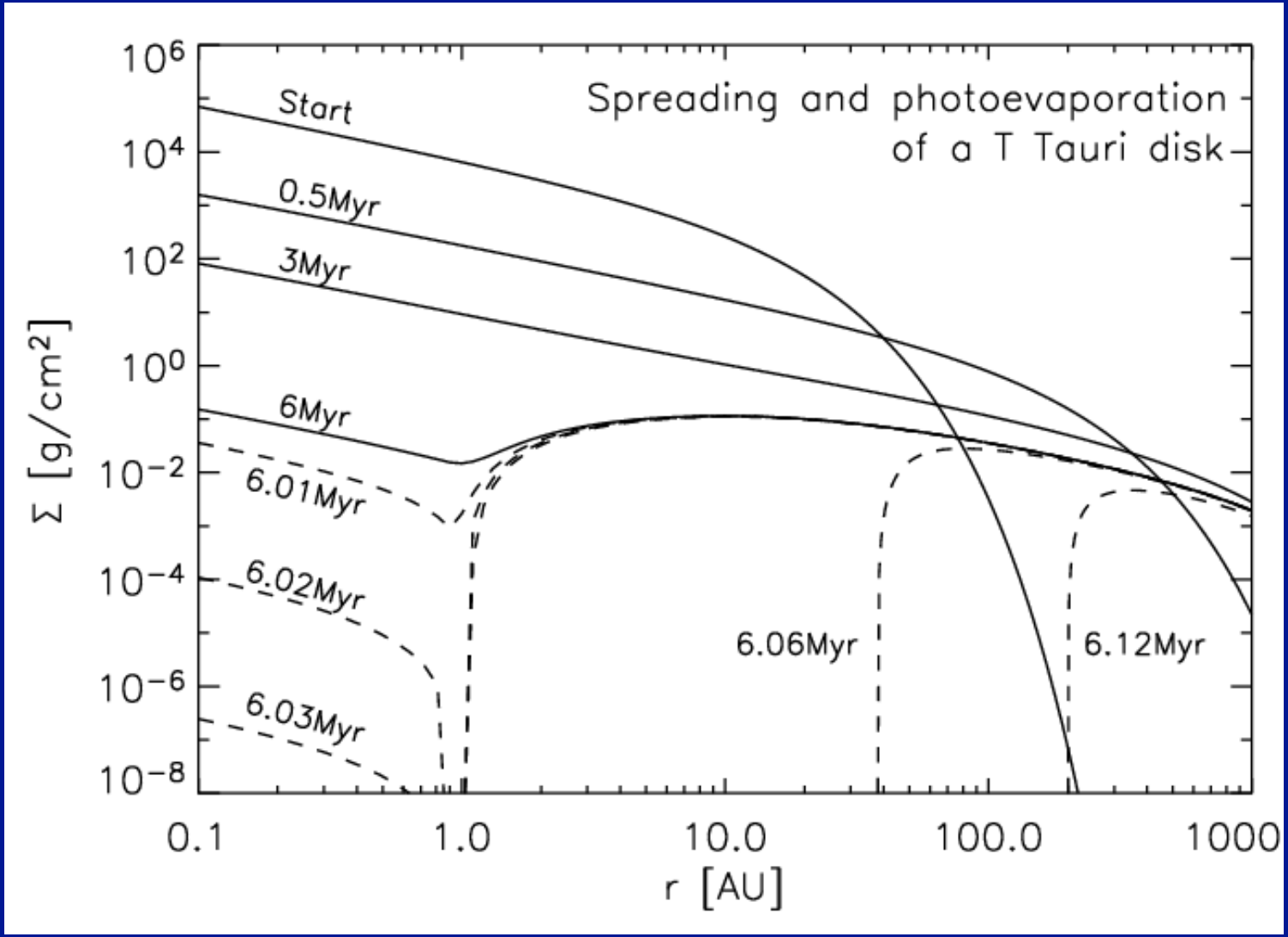
Owen, Ercolano, Clarke & Alexander 2010

2-D models of photoevaporation



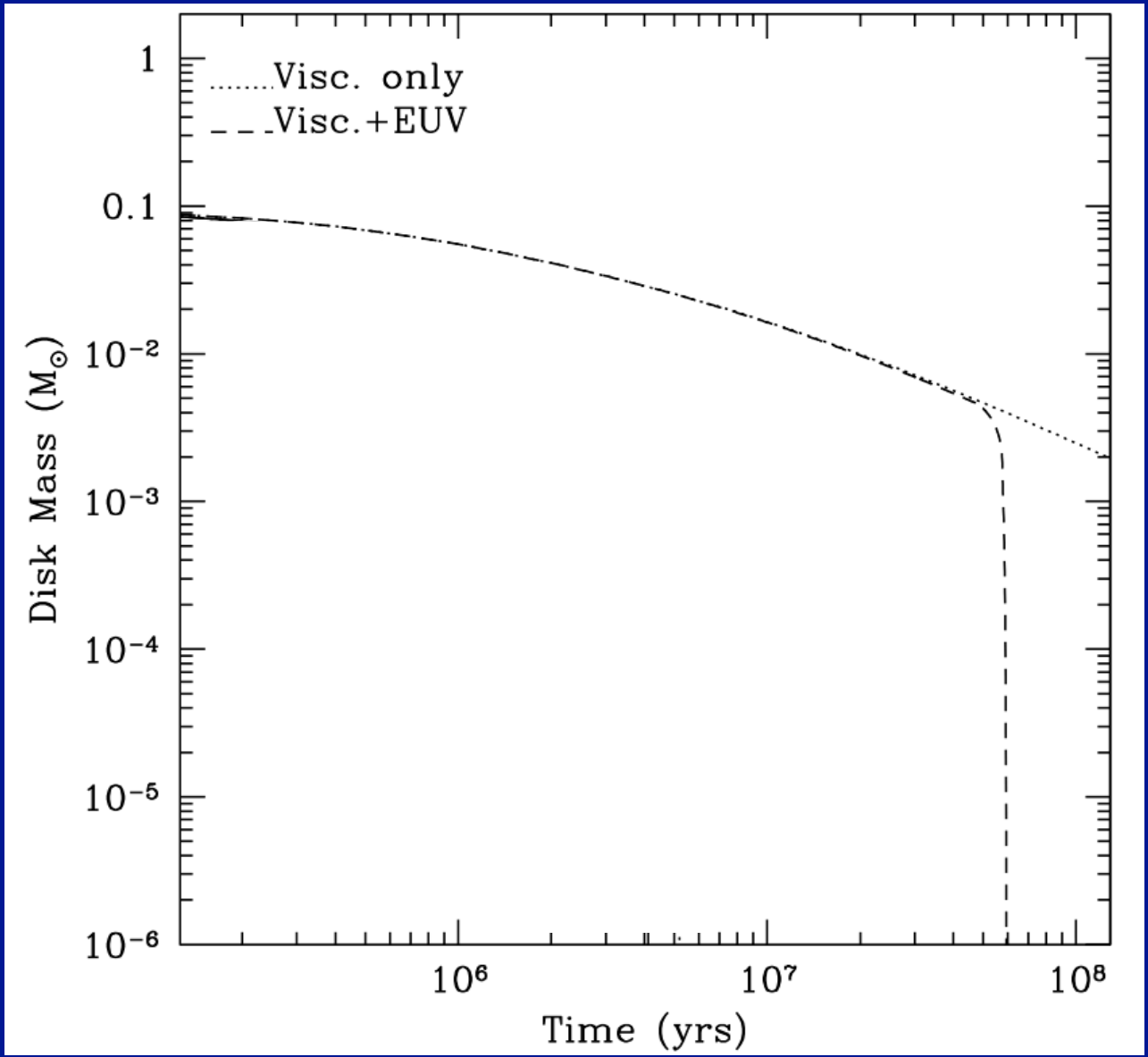
Owen, Ercolano, Clarke & Alexander 2010

Extreme-UV Photoevaporation



Hollenbach 1994; Clarke et al. 2001
Alexander, Clarke & Pringle 2006

But with more realistic (=larger) initial disk mass:

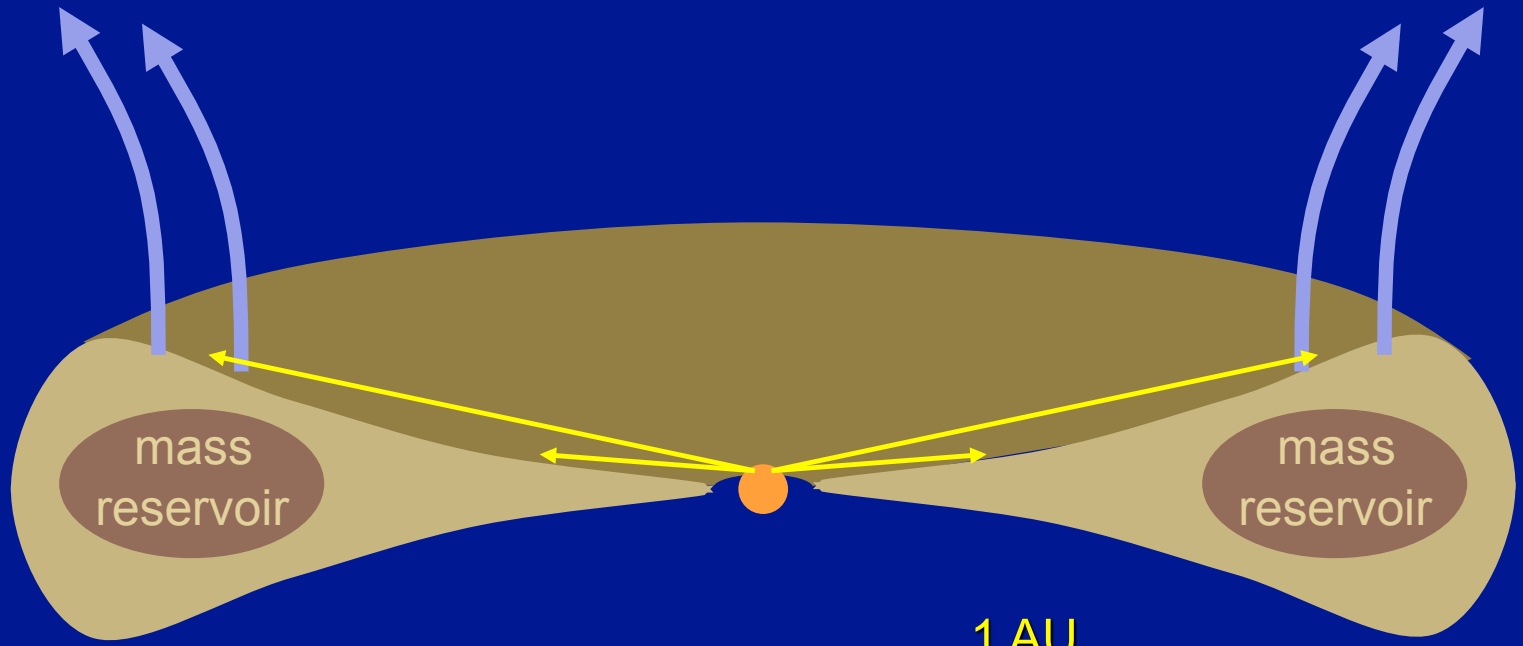


Gorti, Dullemond & Hollenbach (2009)

But: there is also FUV radiation!

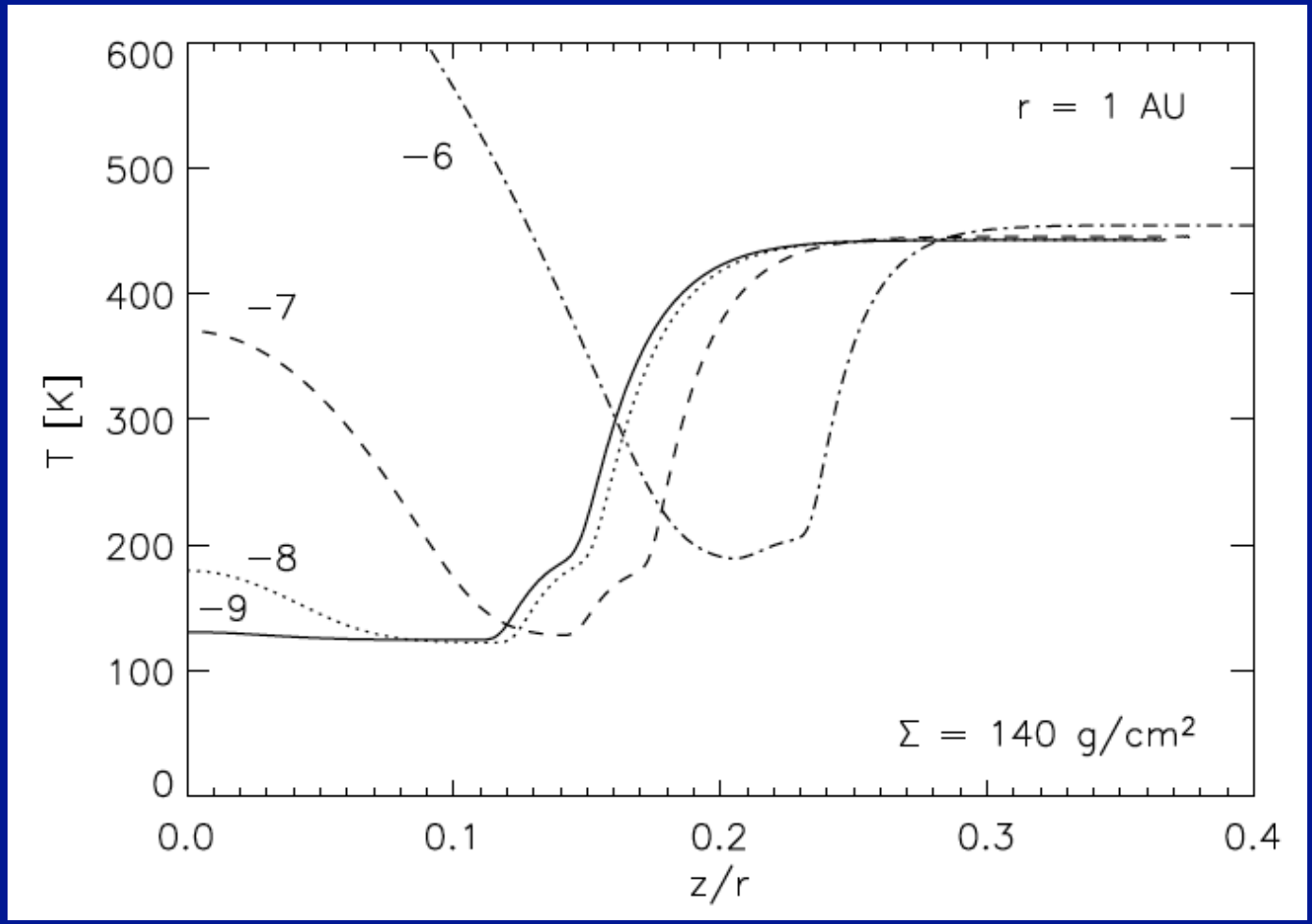
FUV = Photochemistry-driving radiation (hv<13.6 eV)

FUV Photoevap:
- Strong, but
- Works > 50 AU



Gorti & Hollenbach 2007

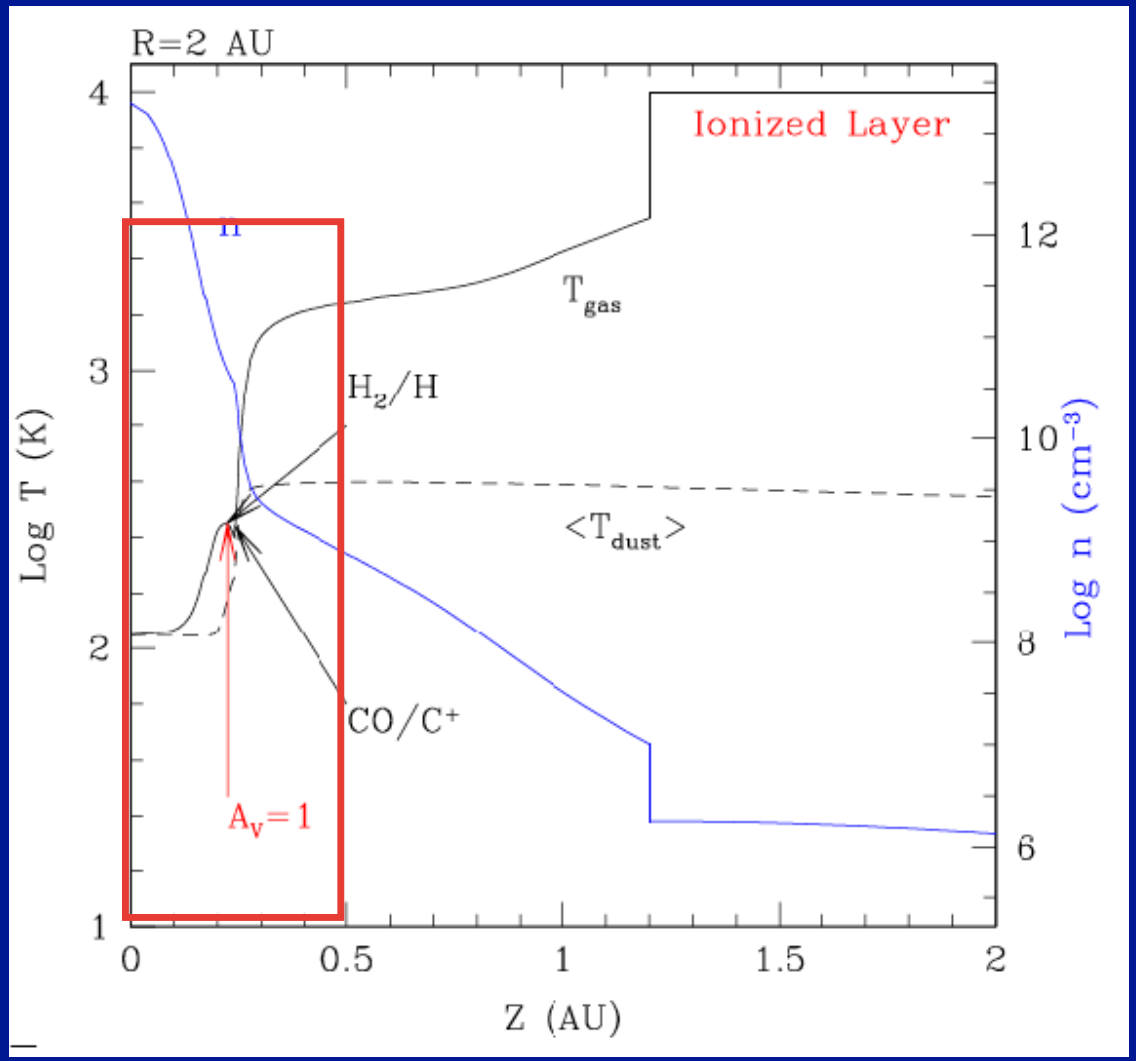
Photoevaporation: Vertical structure revisited



Vertical structure of a protoplanetary disk
(Cf. PPV Review Dullemond, Hollenbach, Kamp & D'Alessio)

Photoevaporation: Vertical structure revisited

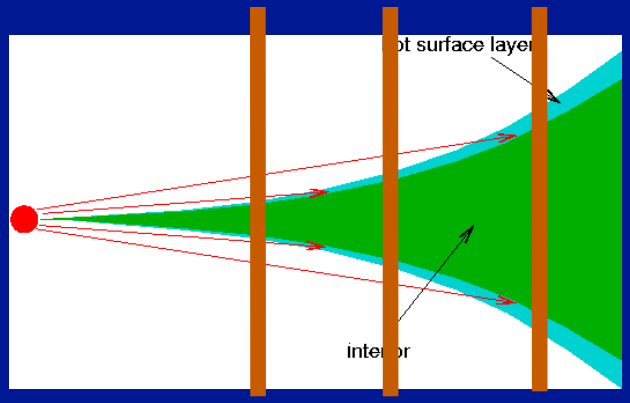
Gas-dust temperature decoupling



Gorti & Hollenbach 2008

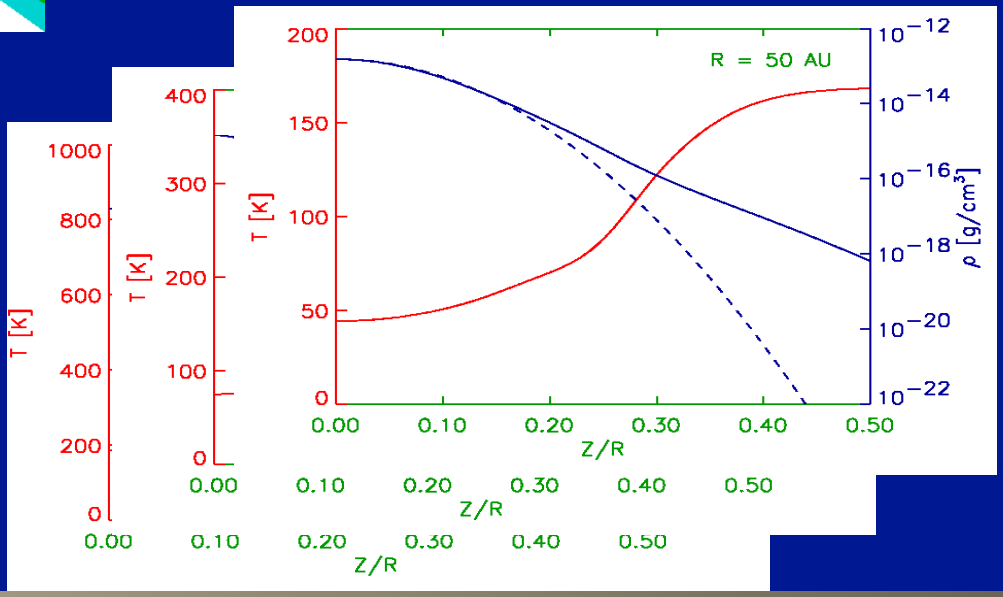
EUV + FUV Photoevaporation

- Solve full 2-D (=1+1D) structure of disk on-the-fly while doing disk evolution and compute from this the mass loss at each radius.

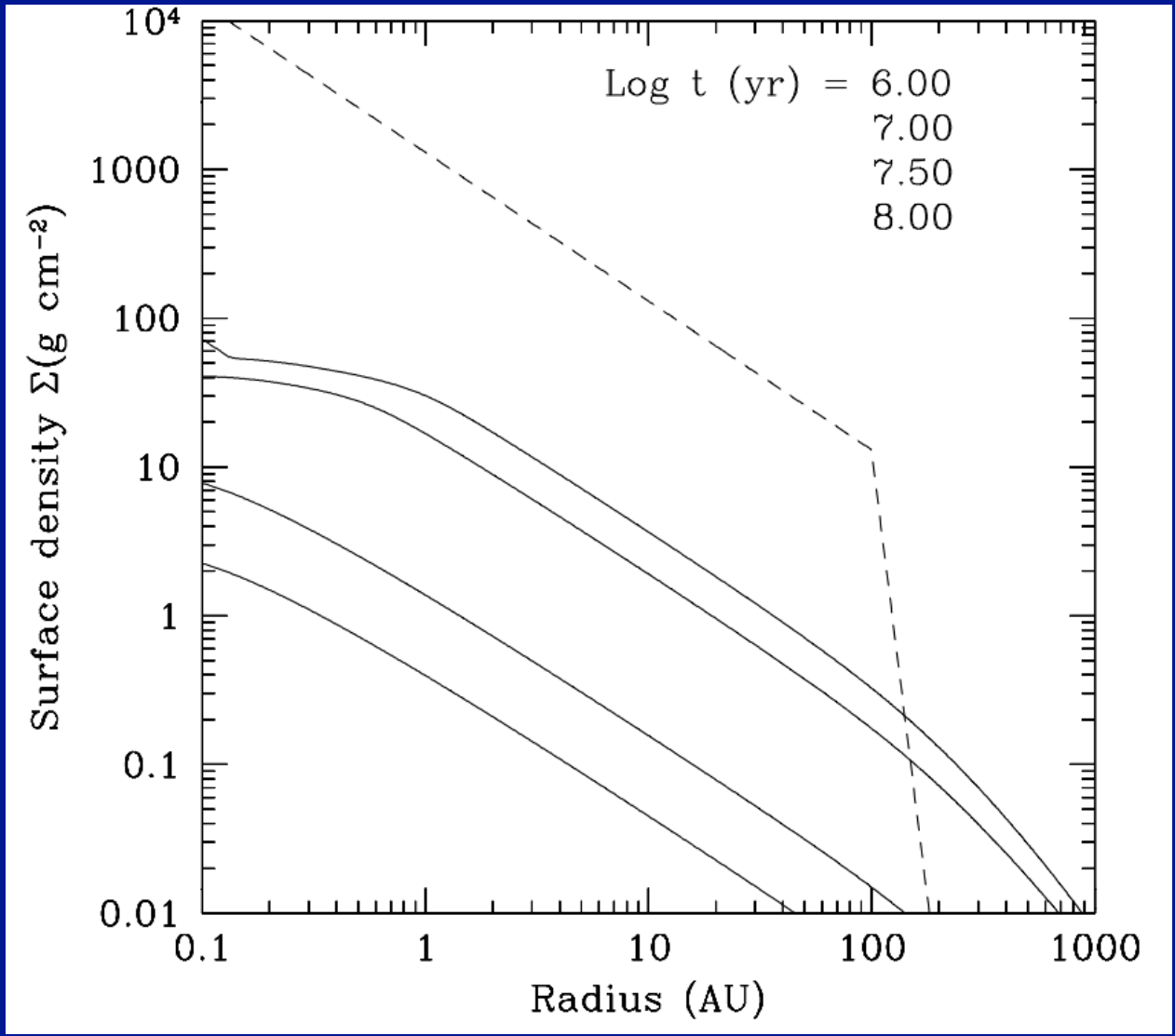


Gorti & Hollenbach (2007)

Gorti, Dullemond & Hollenbach (2009)

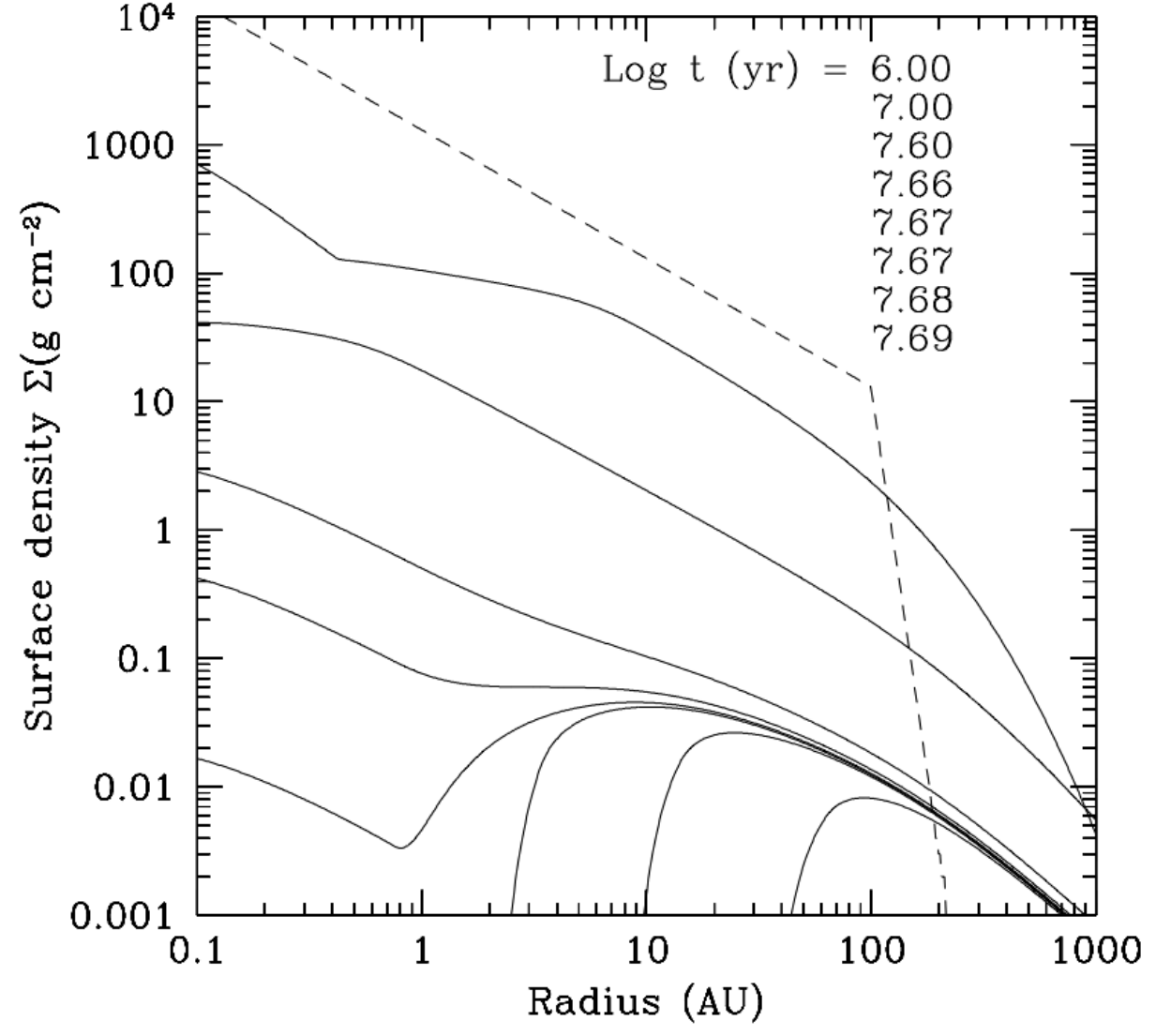


No photoevaporation...



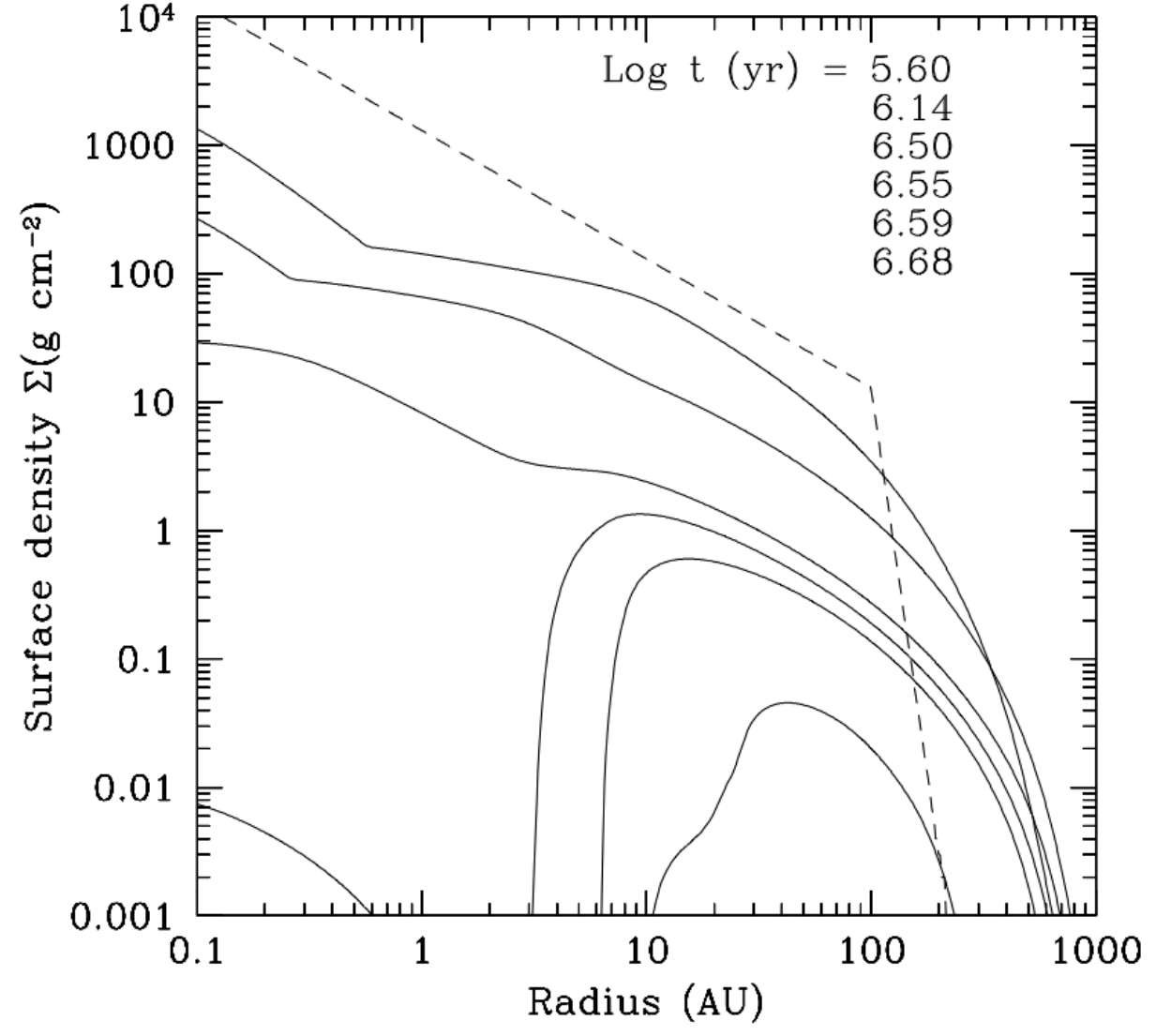
Gorti, Dullemond & Hollenbach 2009

EUV photoevaporation...



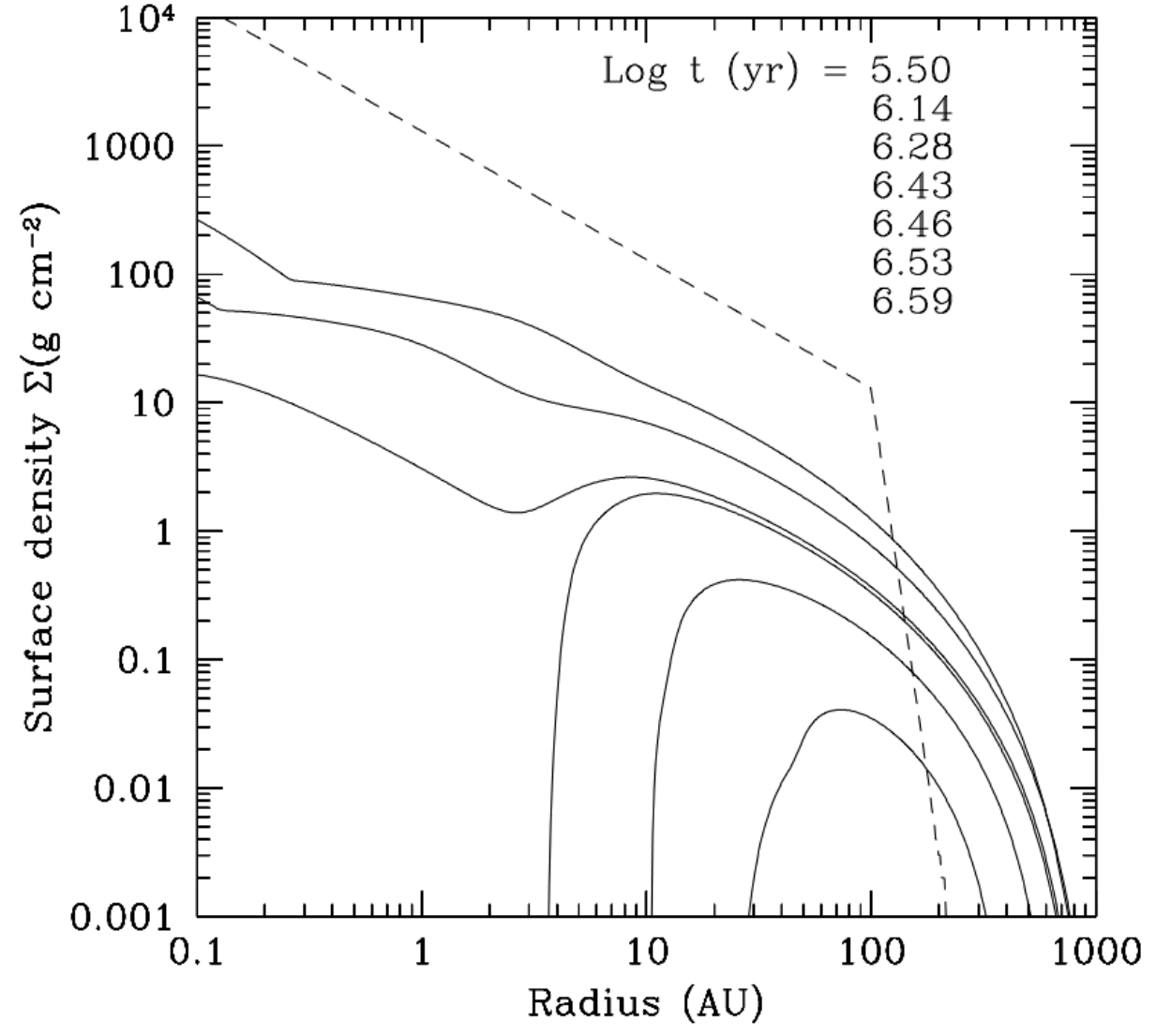
Gorti, Dullemond & Hollenbach 2009

FUV photoevaporation...



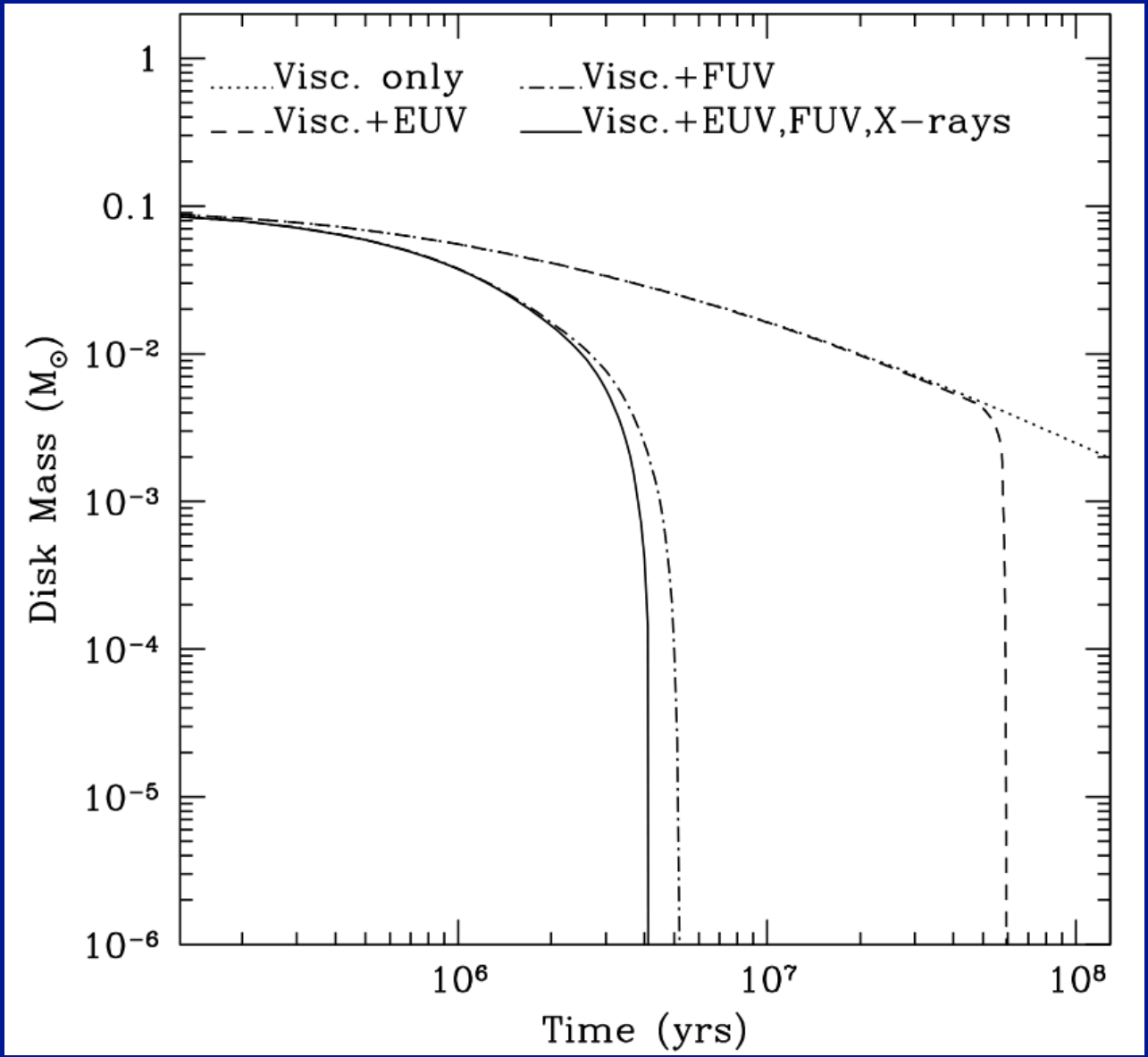
Gorti, Dullemond & Hollenbach 2009

EUV+FUV photoevaporation...



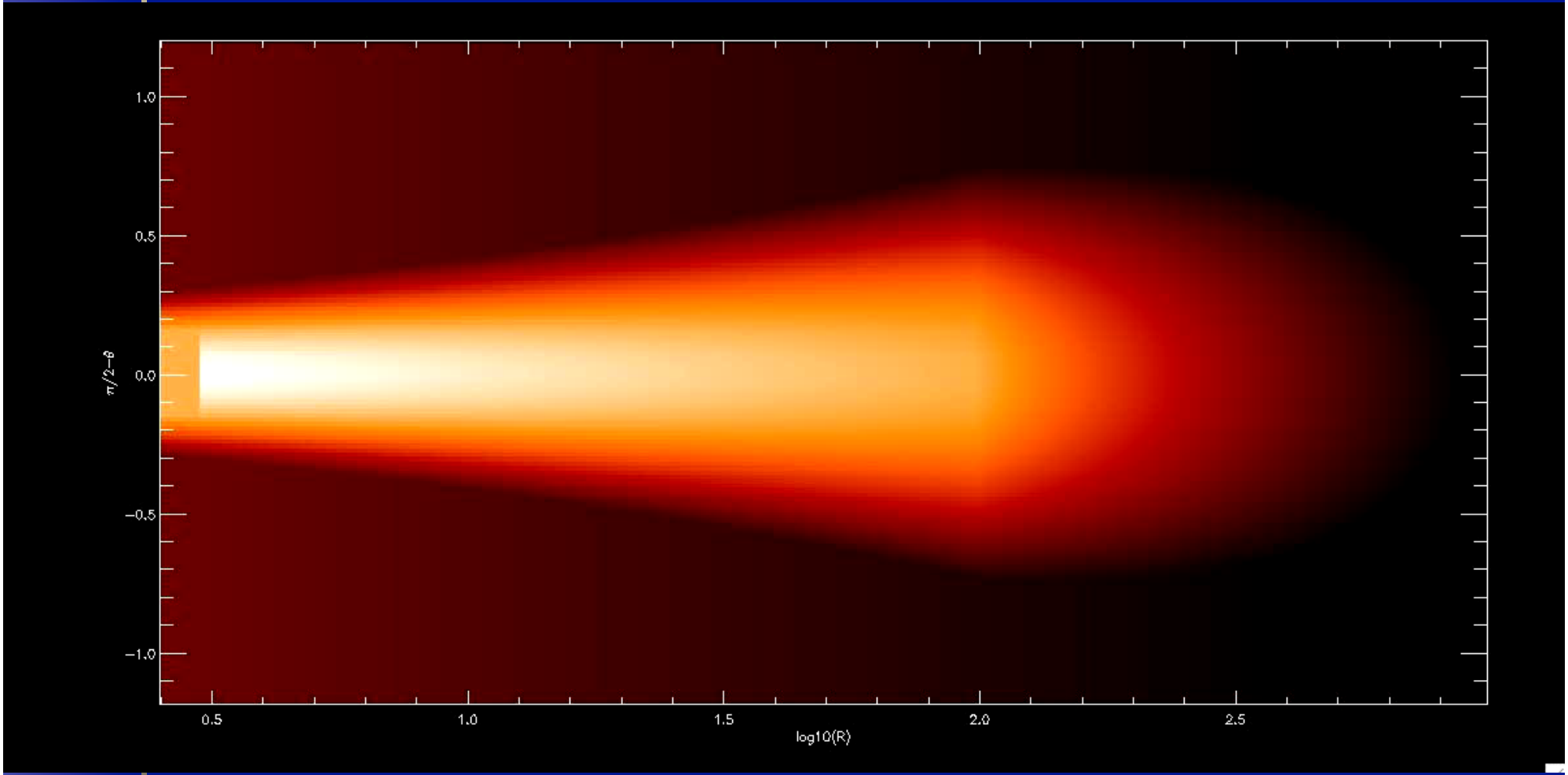
Gorti, Dullemond & Hollenbach 2009

FUV can photoevaporate even massive disks



Gorti, Dullemond & Hollenbach (2009)

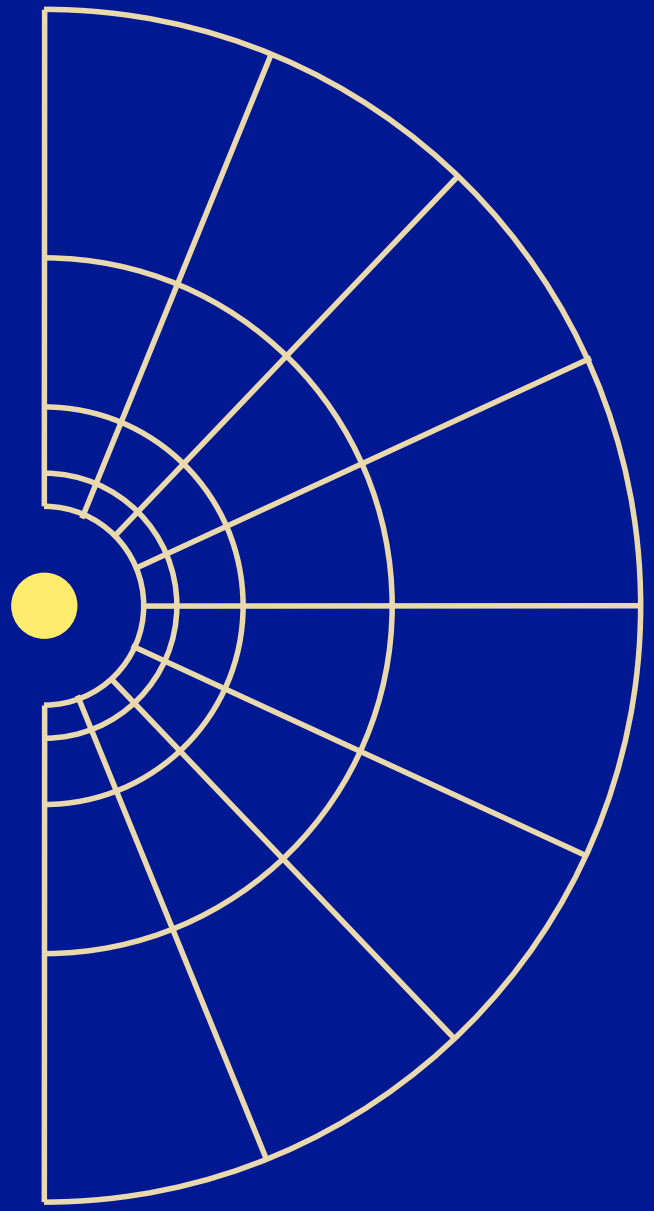
FUV PhotEvap: 2-D Radiation Hydro



10 AU 100 AU 1000 AU

Dullemond, Gorti & Hollenbach in prep.

FUV PhotEvap: 2-D Radiation Hydro



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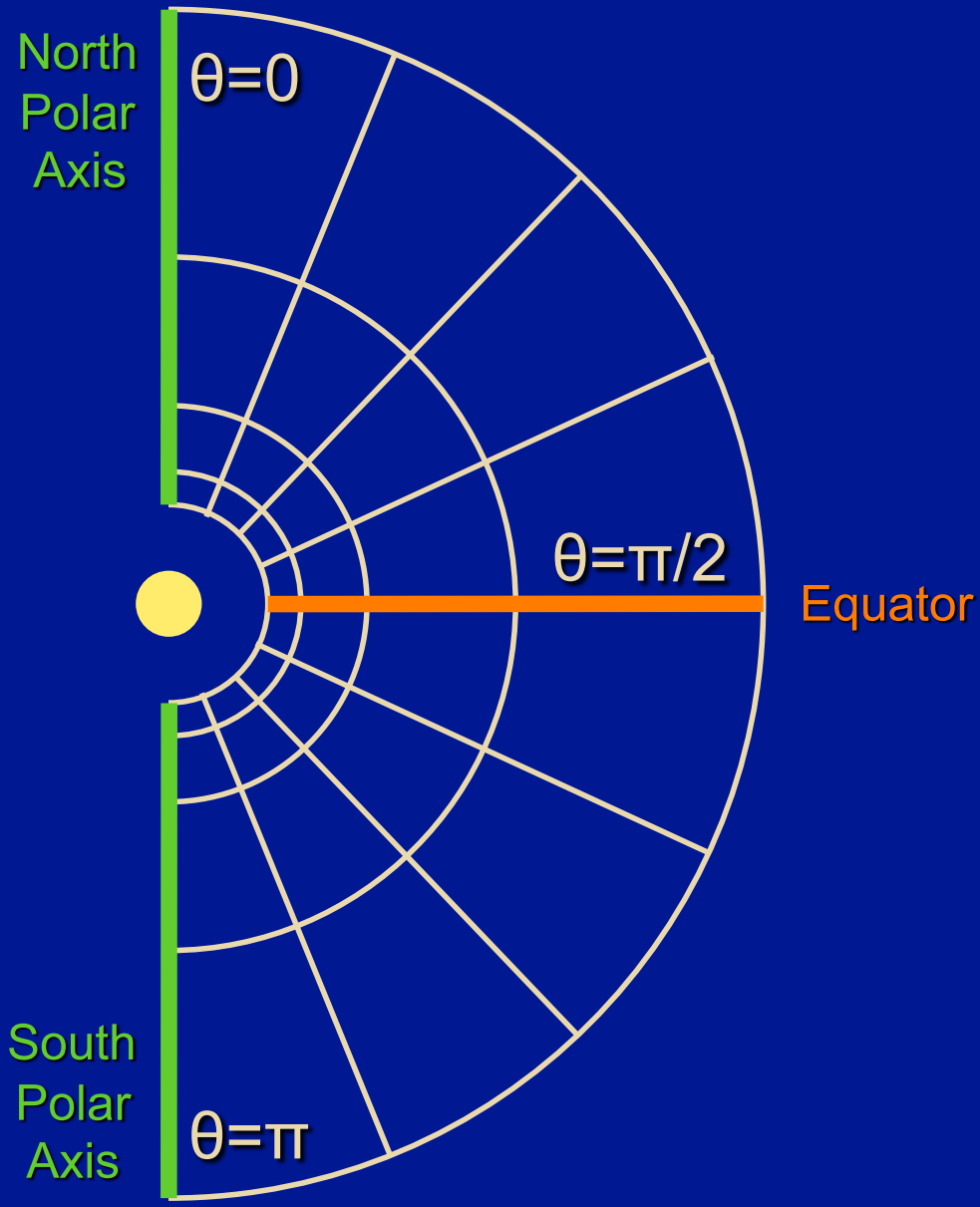

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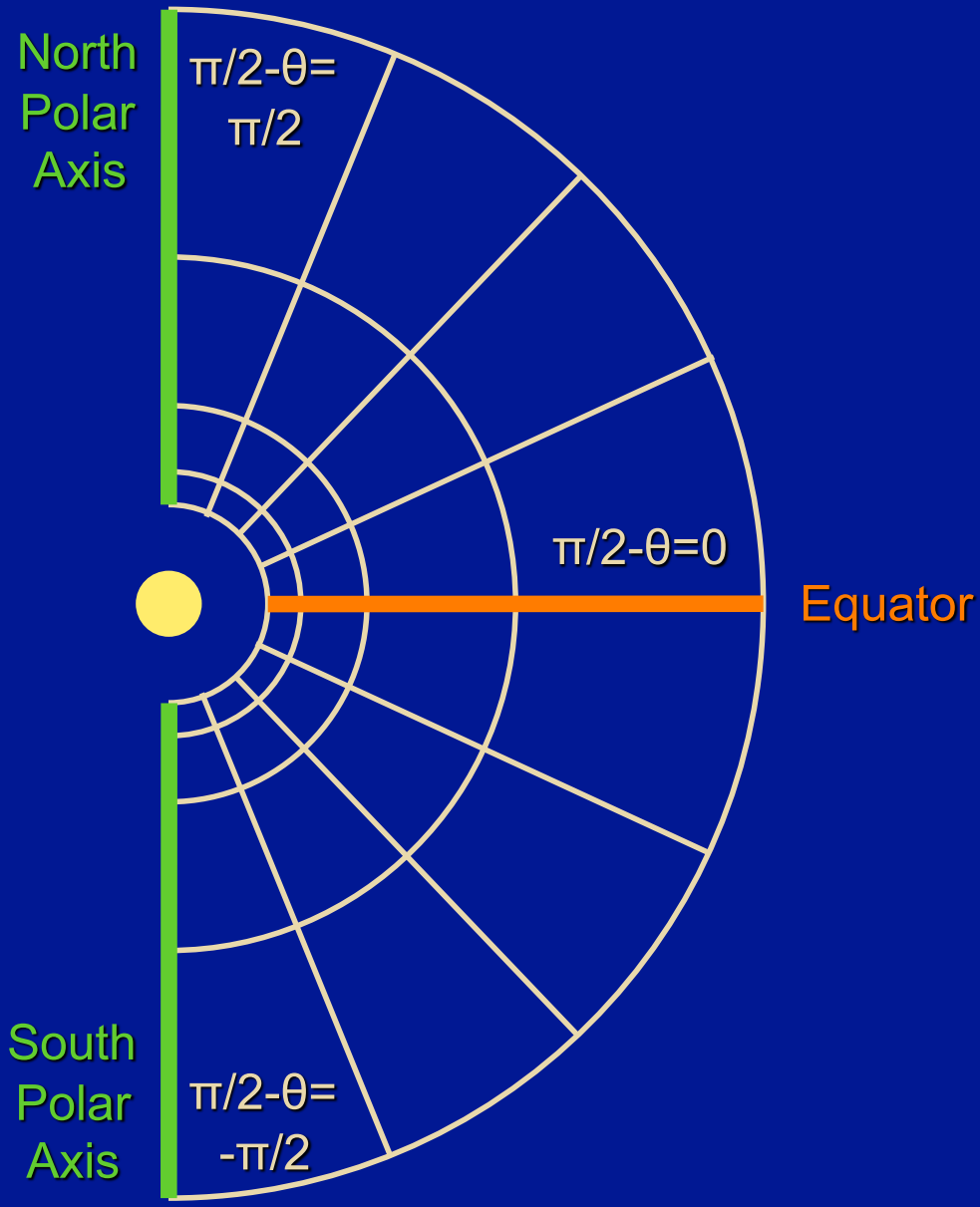
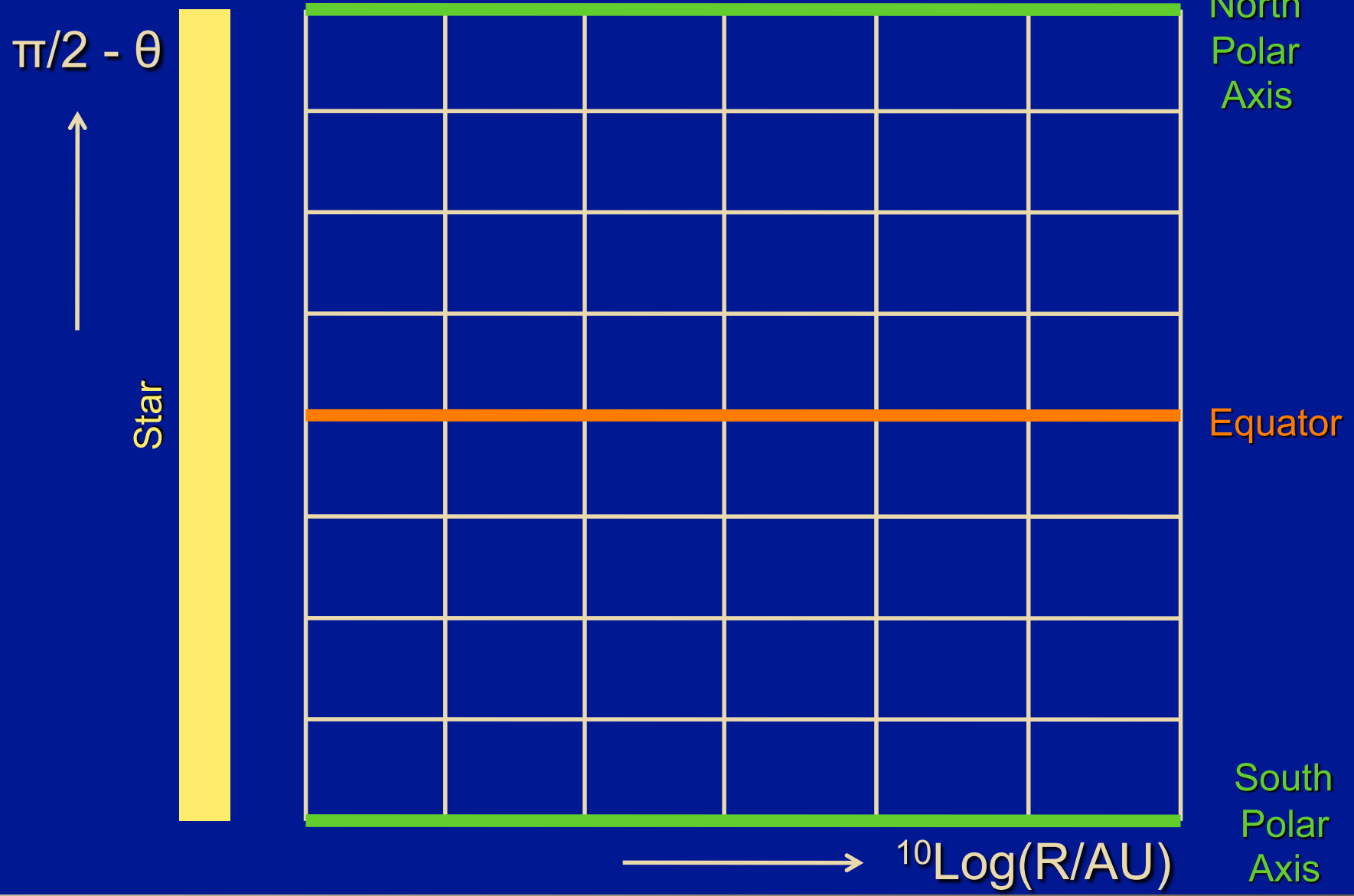
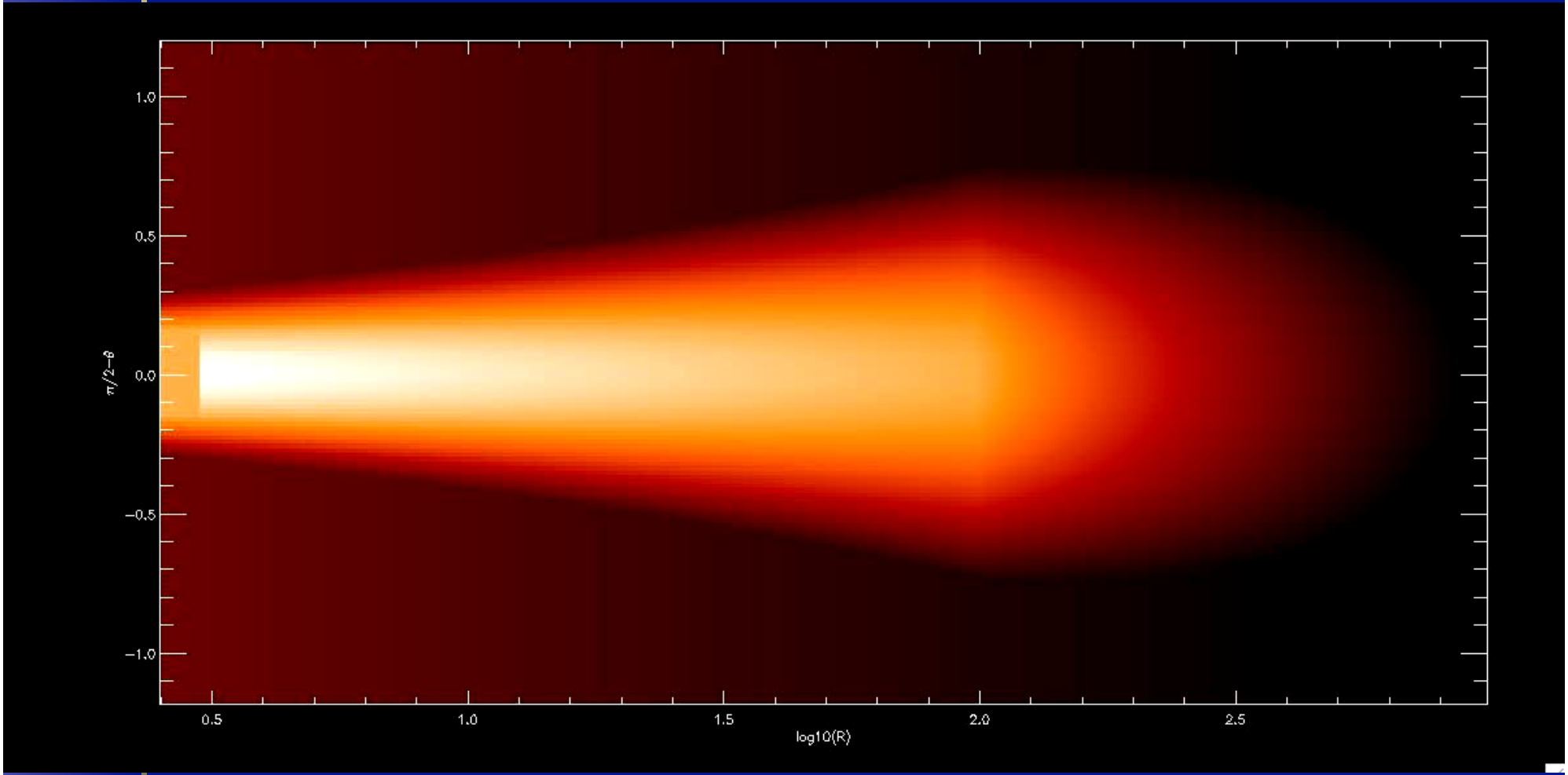


FUV PhotEvap: 2-D Radiation Hydro



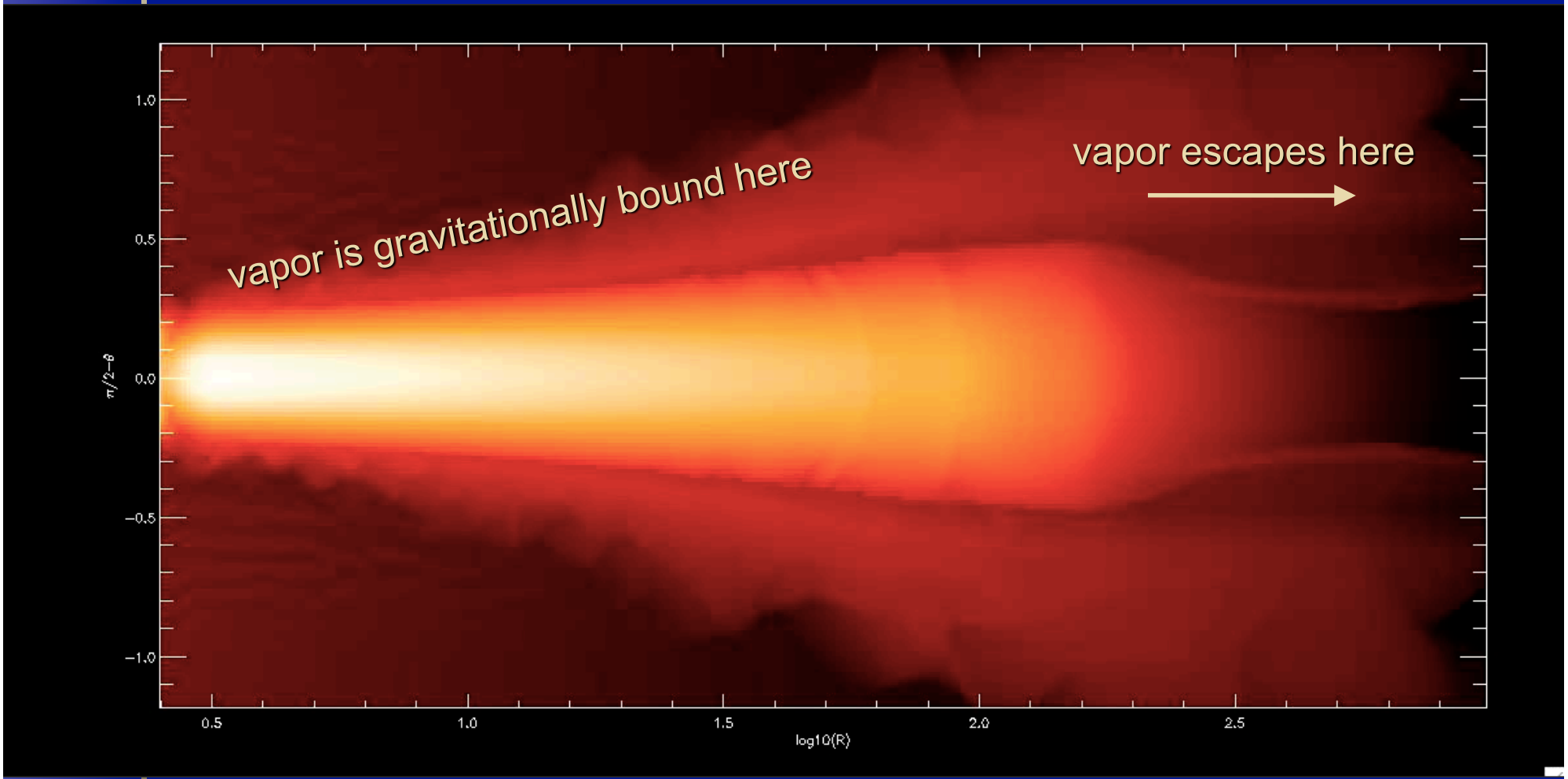
FUV PhotEvap: 2-D Radiation Hydro



10 AU 100 AU 1000 AU

Dullemond, Gorti & Hollenbach in prep.

FUV PhotEvap: 2-D Radiation Hydro



10 AU 100 AU 1000 AU

Dullemond, Gorti & Hollenbach in prep.

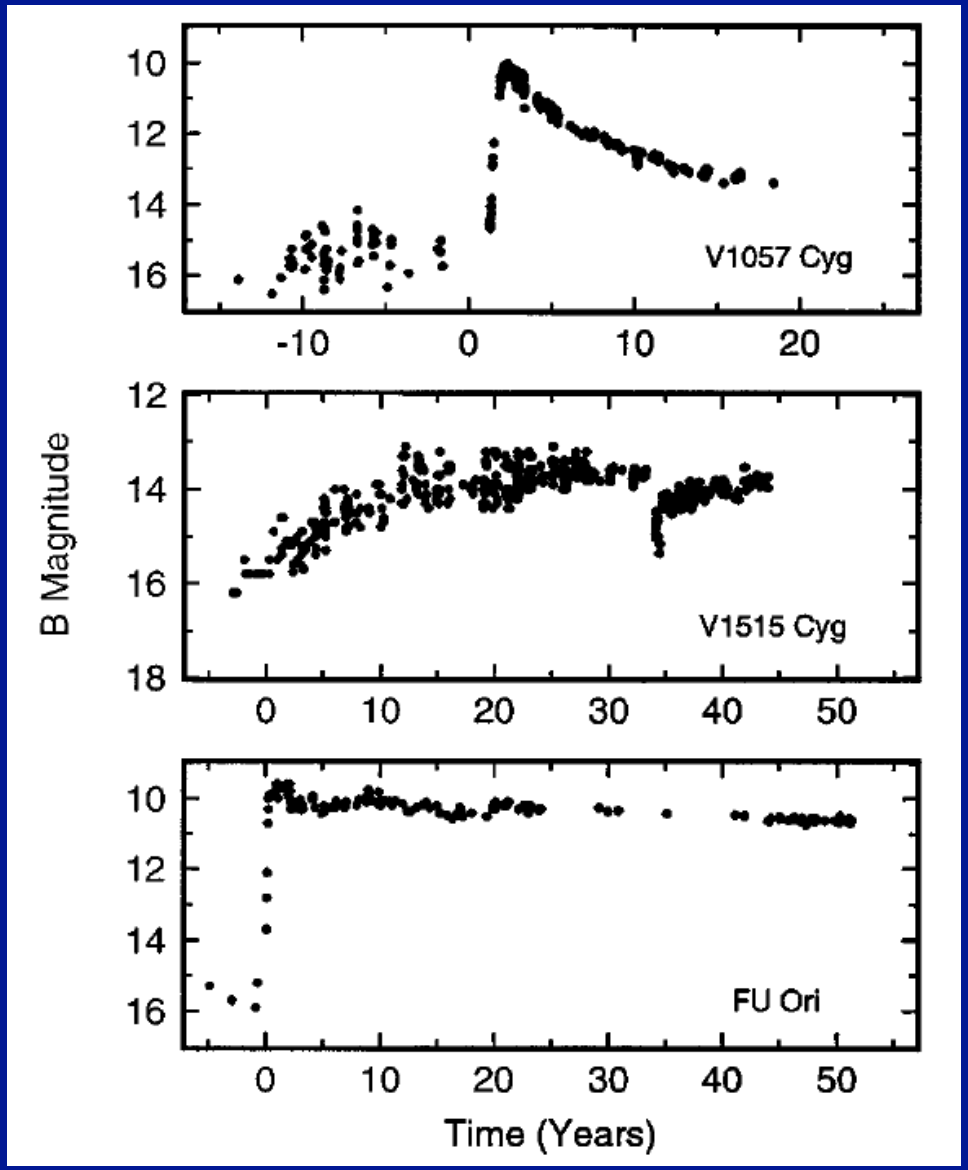
Variability:

Outbursting disks

Two main types

- Long term outbursts: *FU Orionis type (FUORs)*
  - Duration: 10 – 100 year (?)
  - Duty cycle: ??
- Short term outbursts: *EX Lupi type (EXORs)*
  - Duration: months
  - Duty cycle: (tens of) years

FU Orionis outbursts

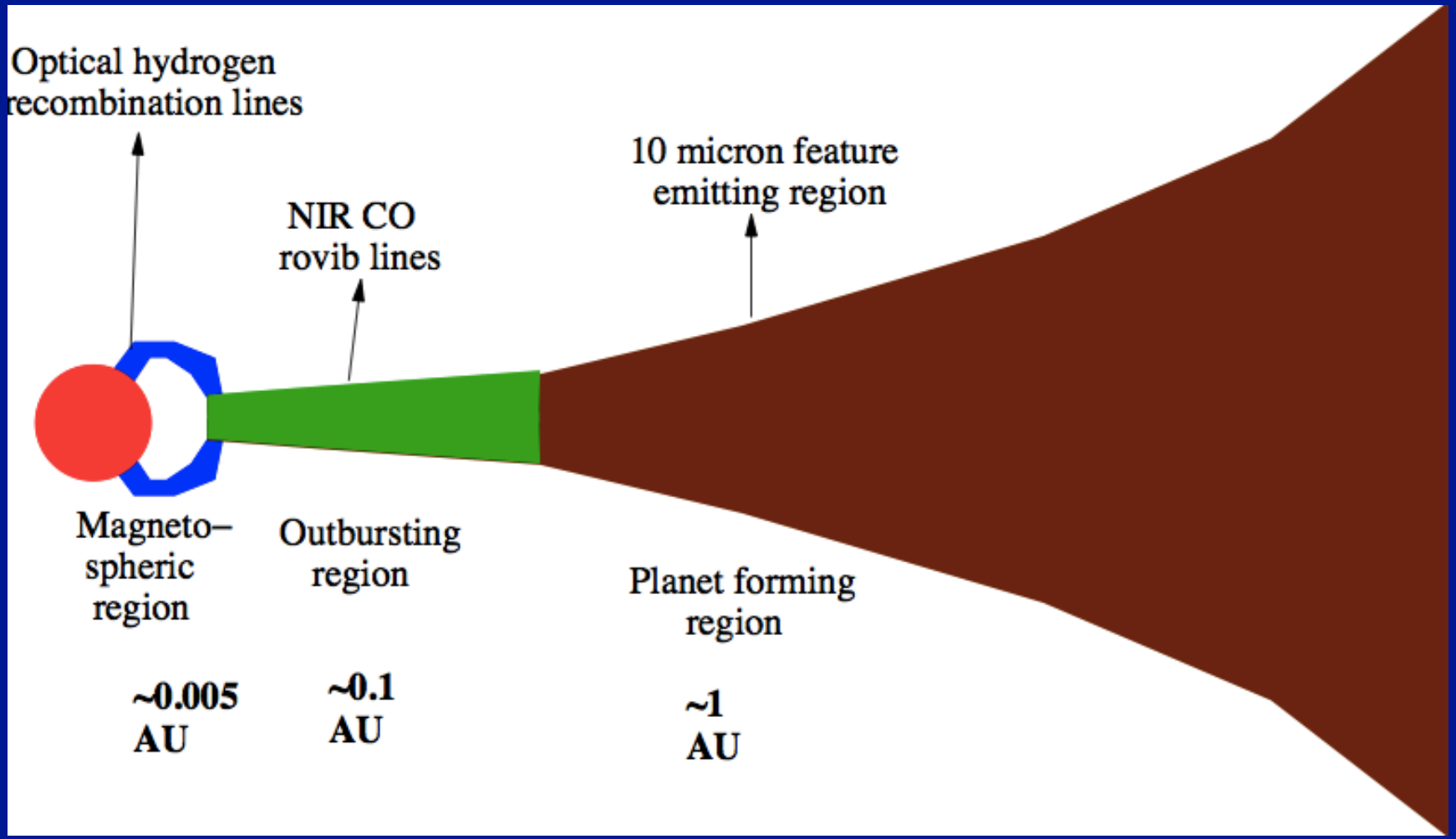


Hartman & Kenyon (1996)

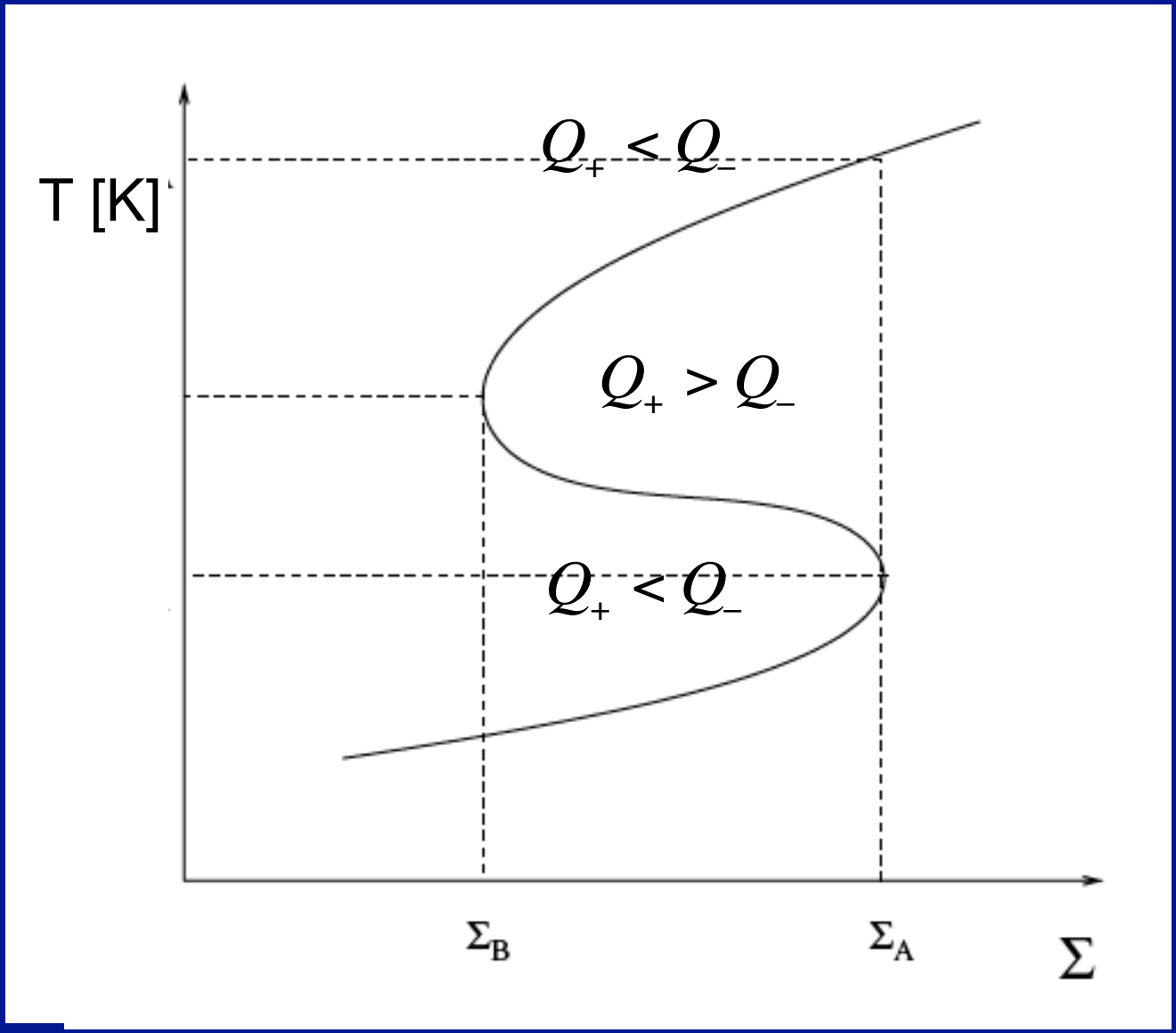
EX Lupi outbursts

Mc Neal's nebula

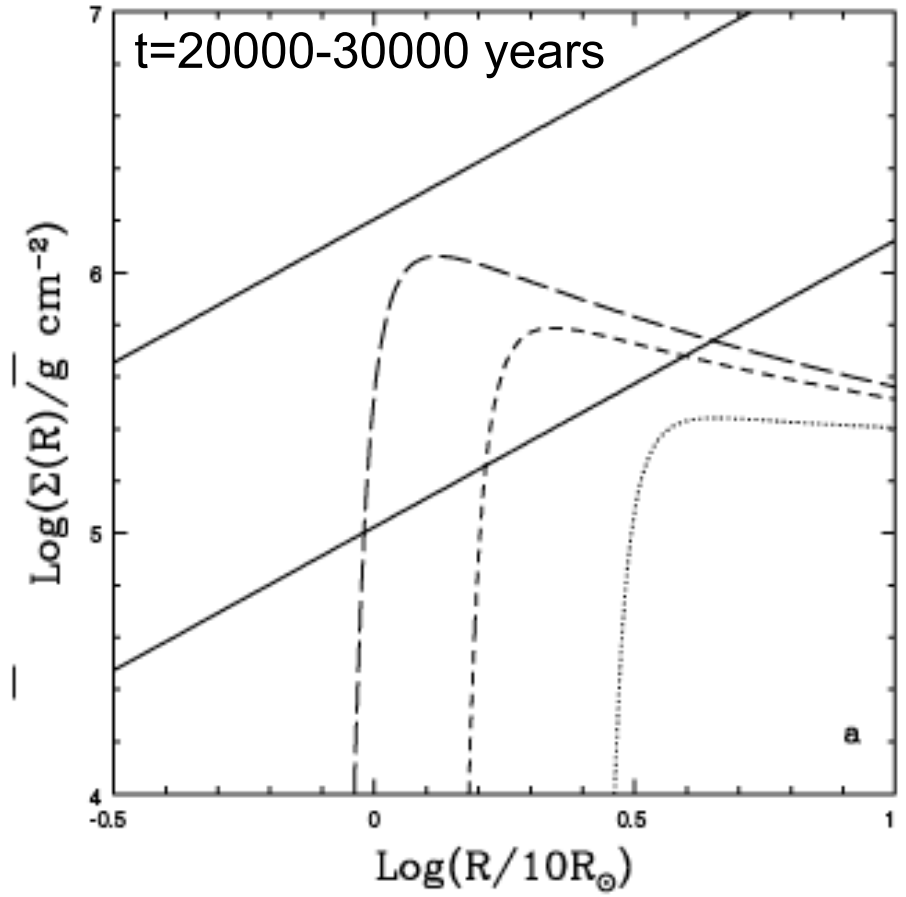
Thermal instability in the disk

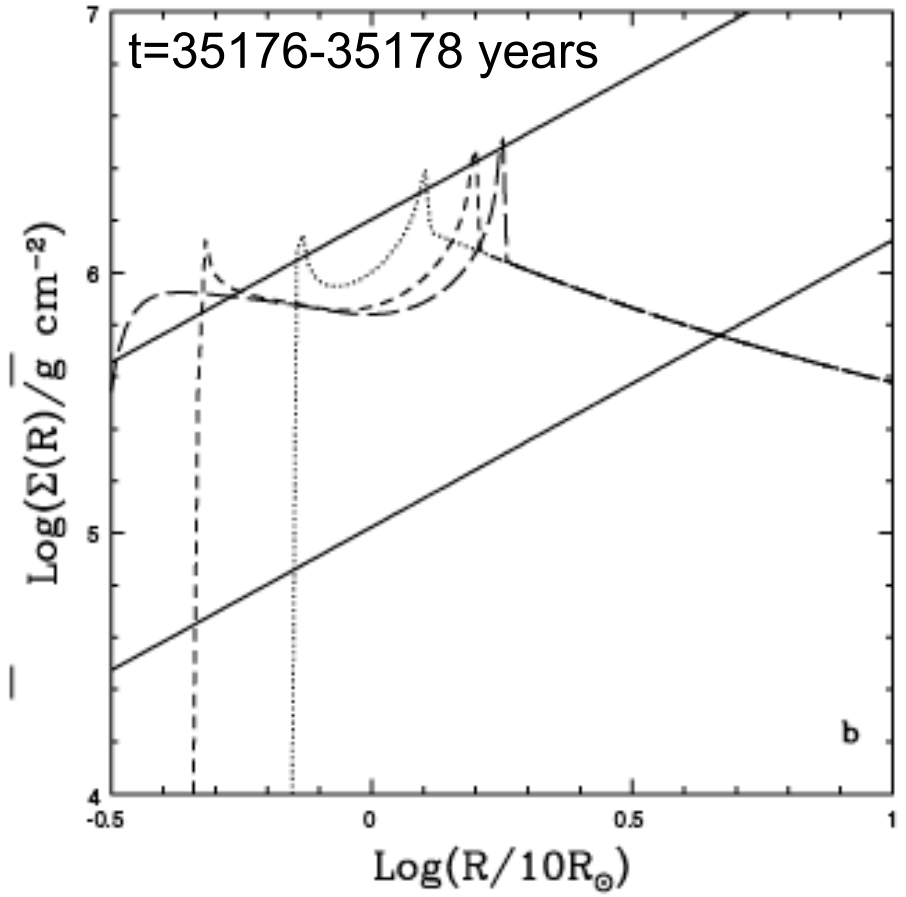


Thermal instability in the disk



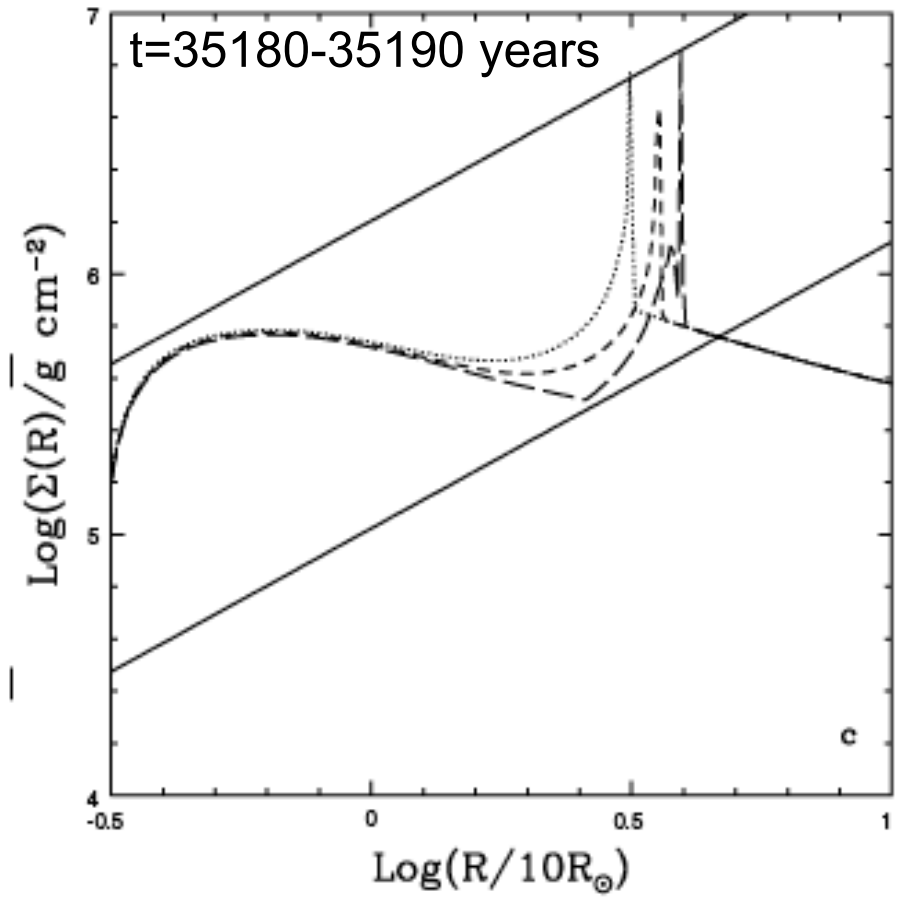
Thermal instability in the disk

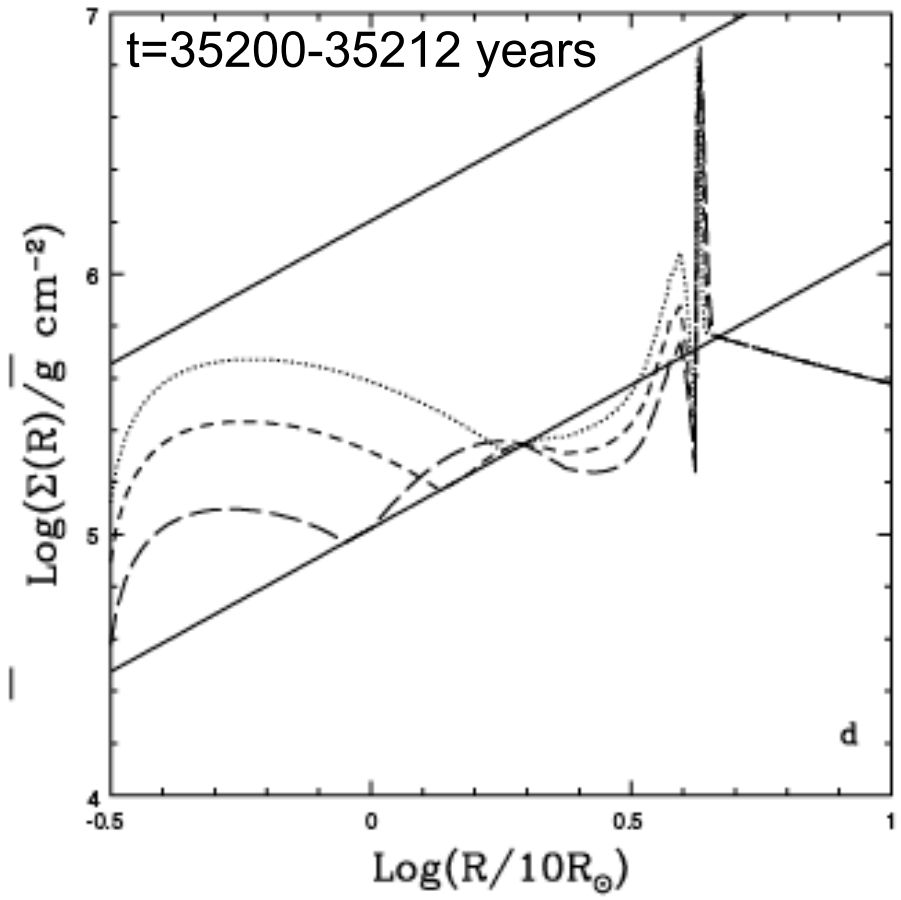




Lodato & Clarke (2004)

Thermal instability in the disk





Lodato & Clarke (2004)

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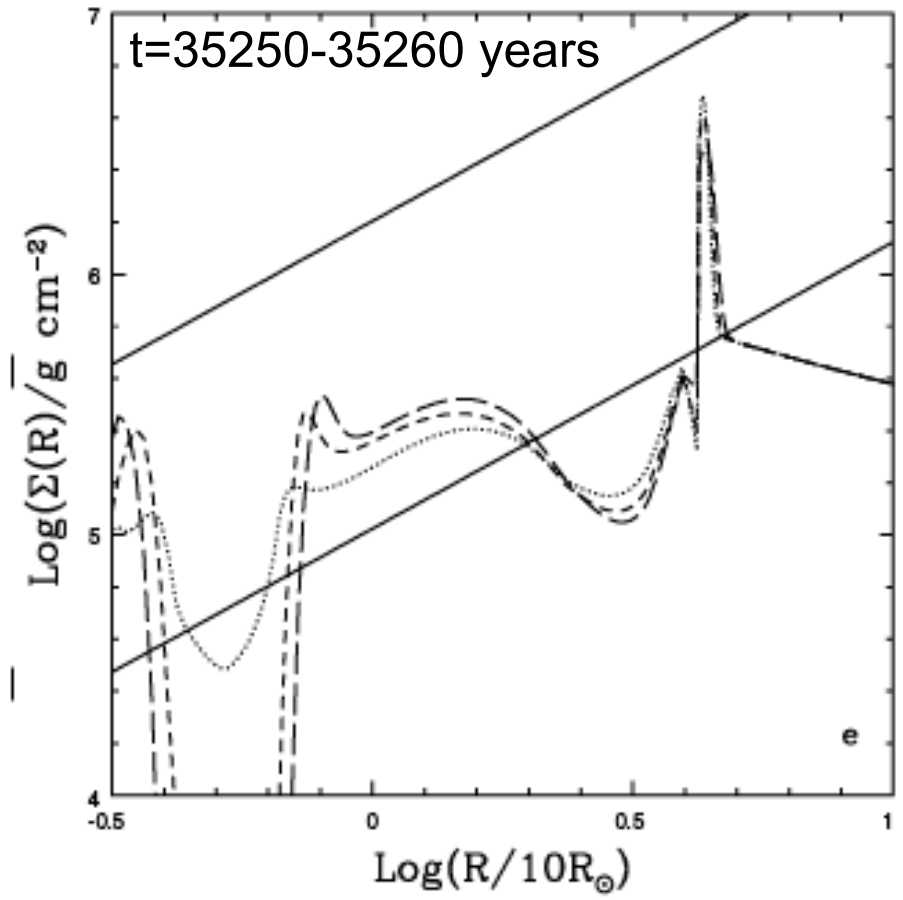

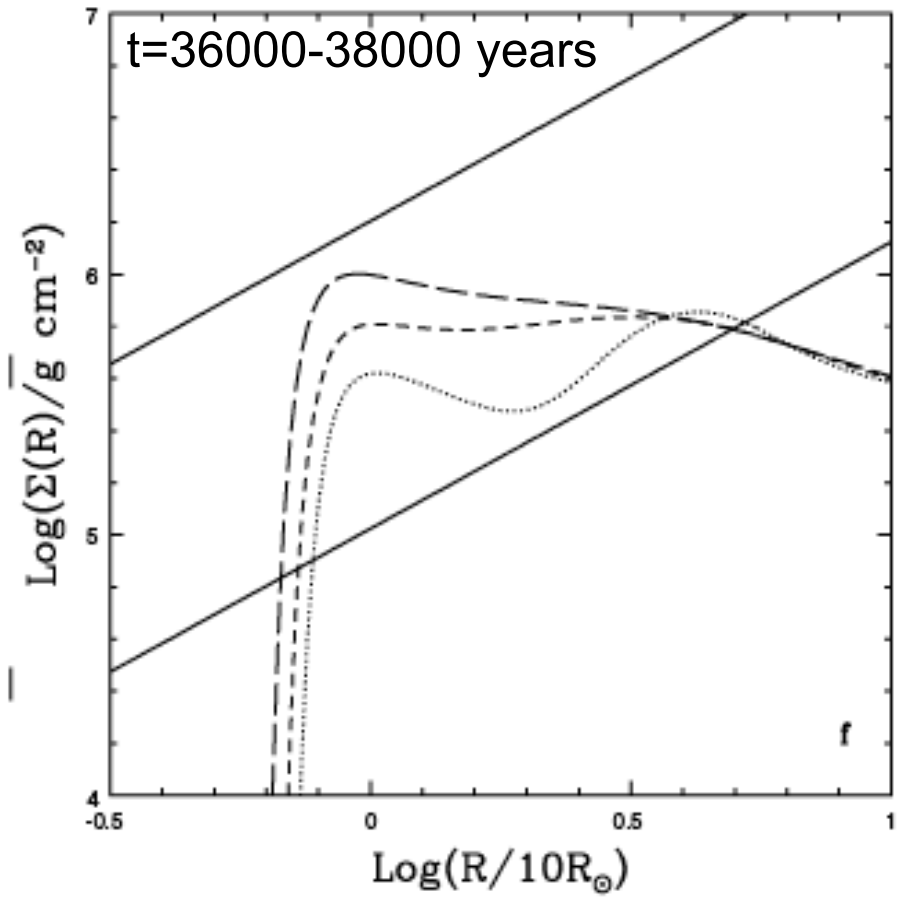

Lodato & Clarke (2004)

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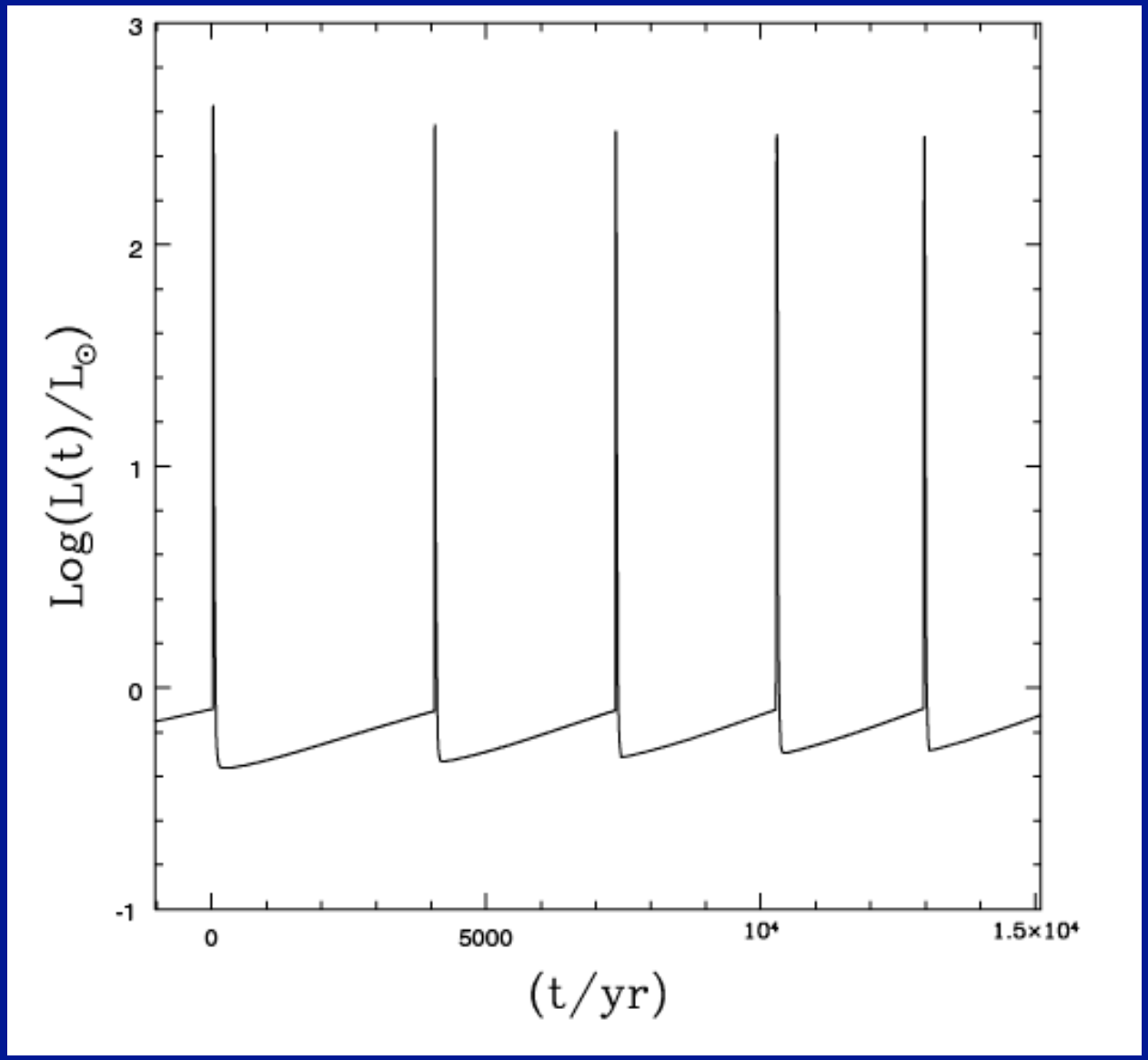
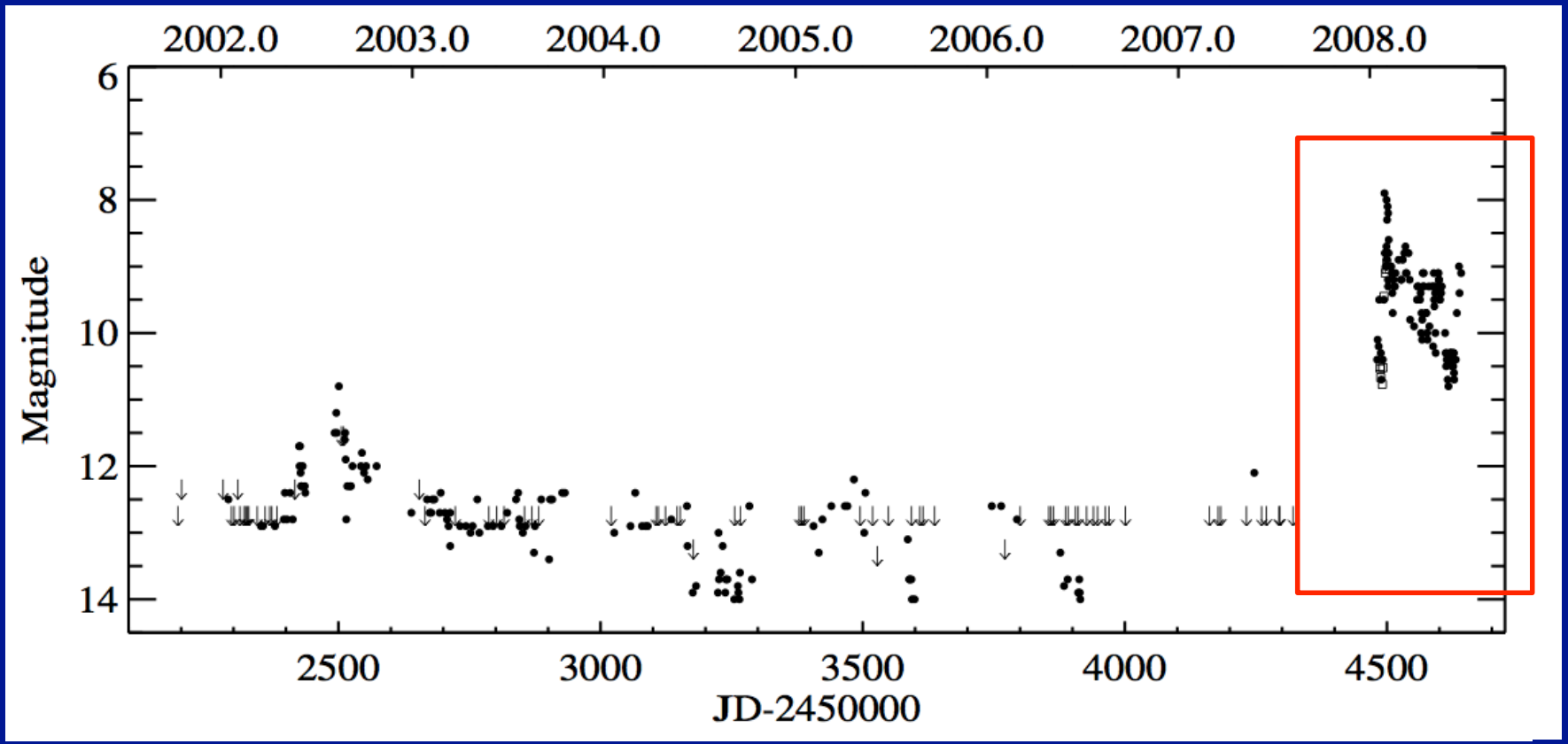


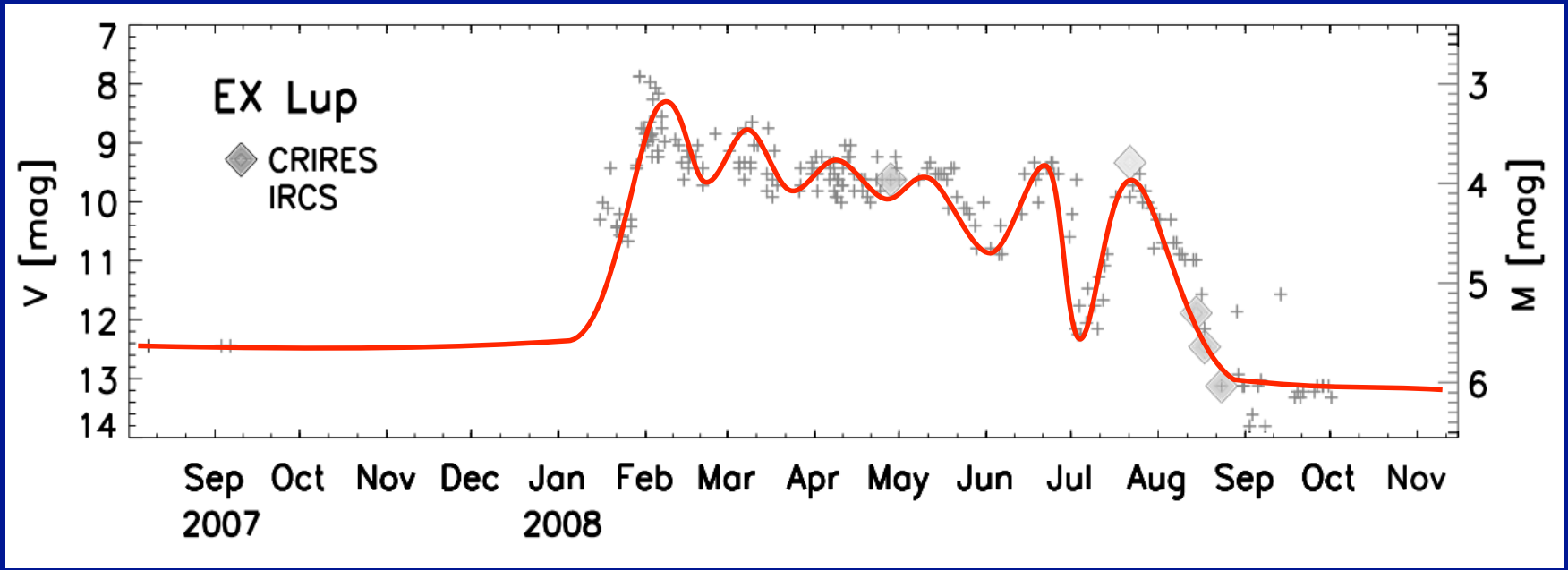
Model for FU Orionis outburst

Lodato & Clarke (2004)

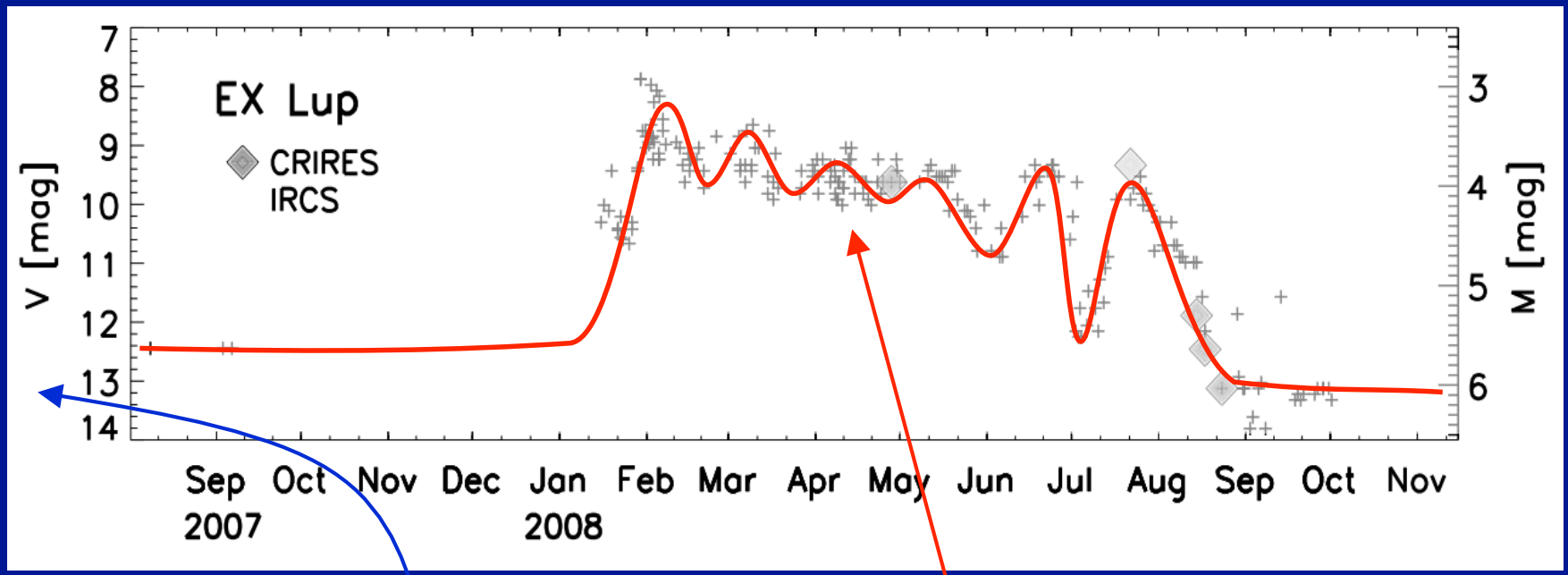
The recent outburst of EX Lupi

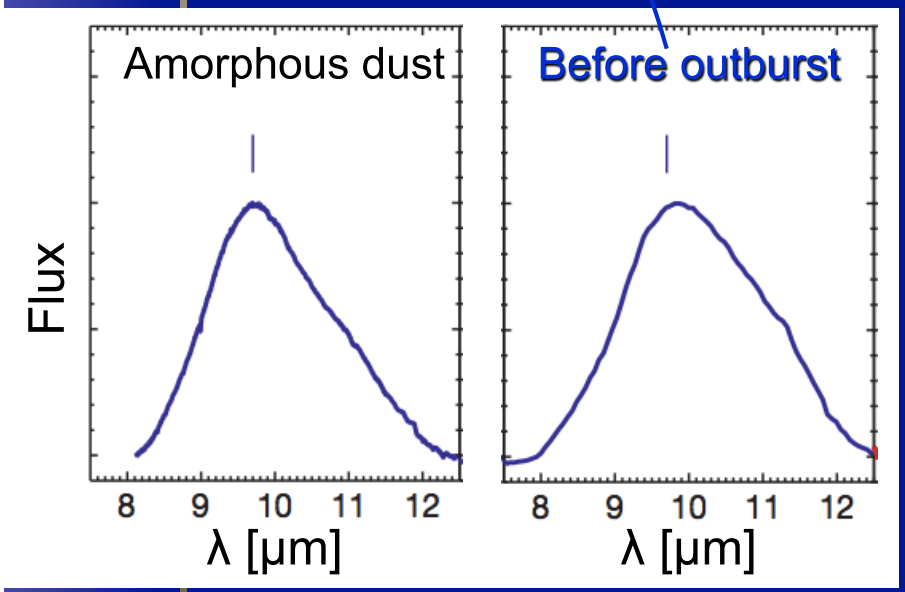


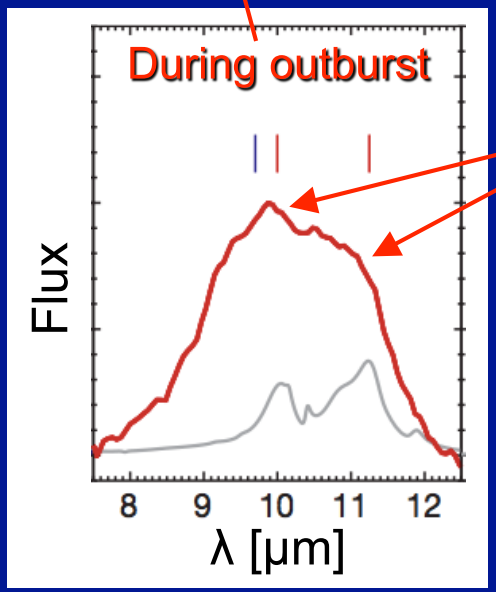
The recent outburst of EX Lupi



Watching dust processing happen!







Peaks indicative of crystalline dust

Abraham, Juhasz et al. Nature, 2009

More on multi-wavelength variability

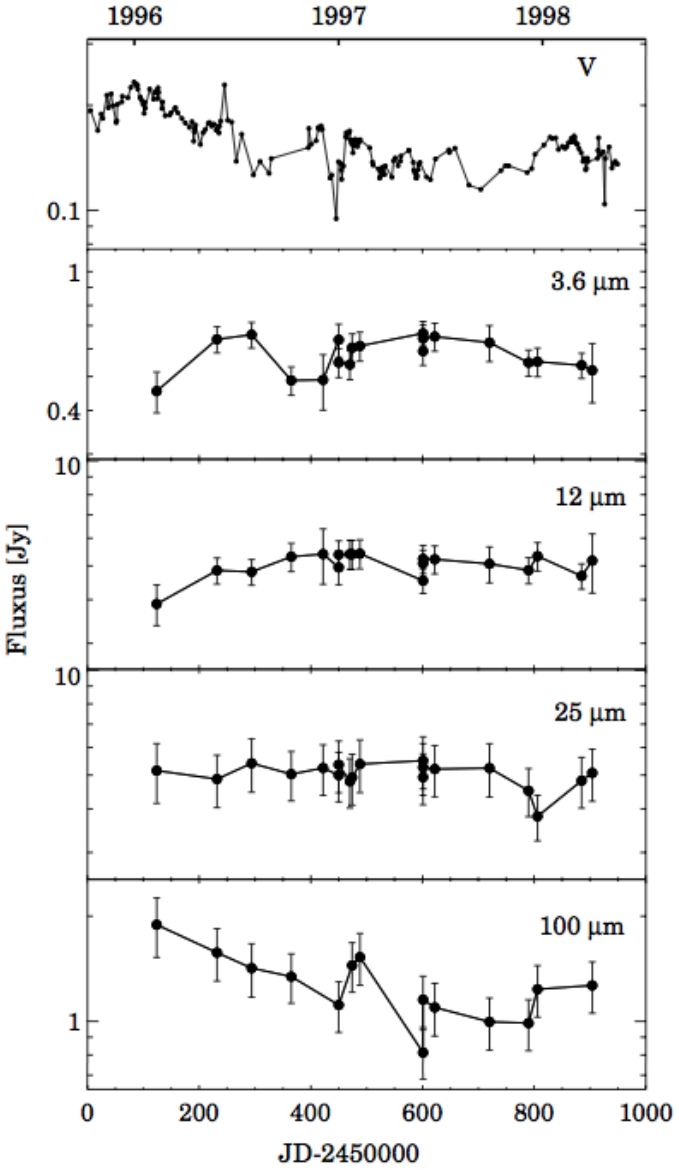
5 μm

3.6 μm

12 μm

25 μm

100 μm



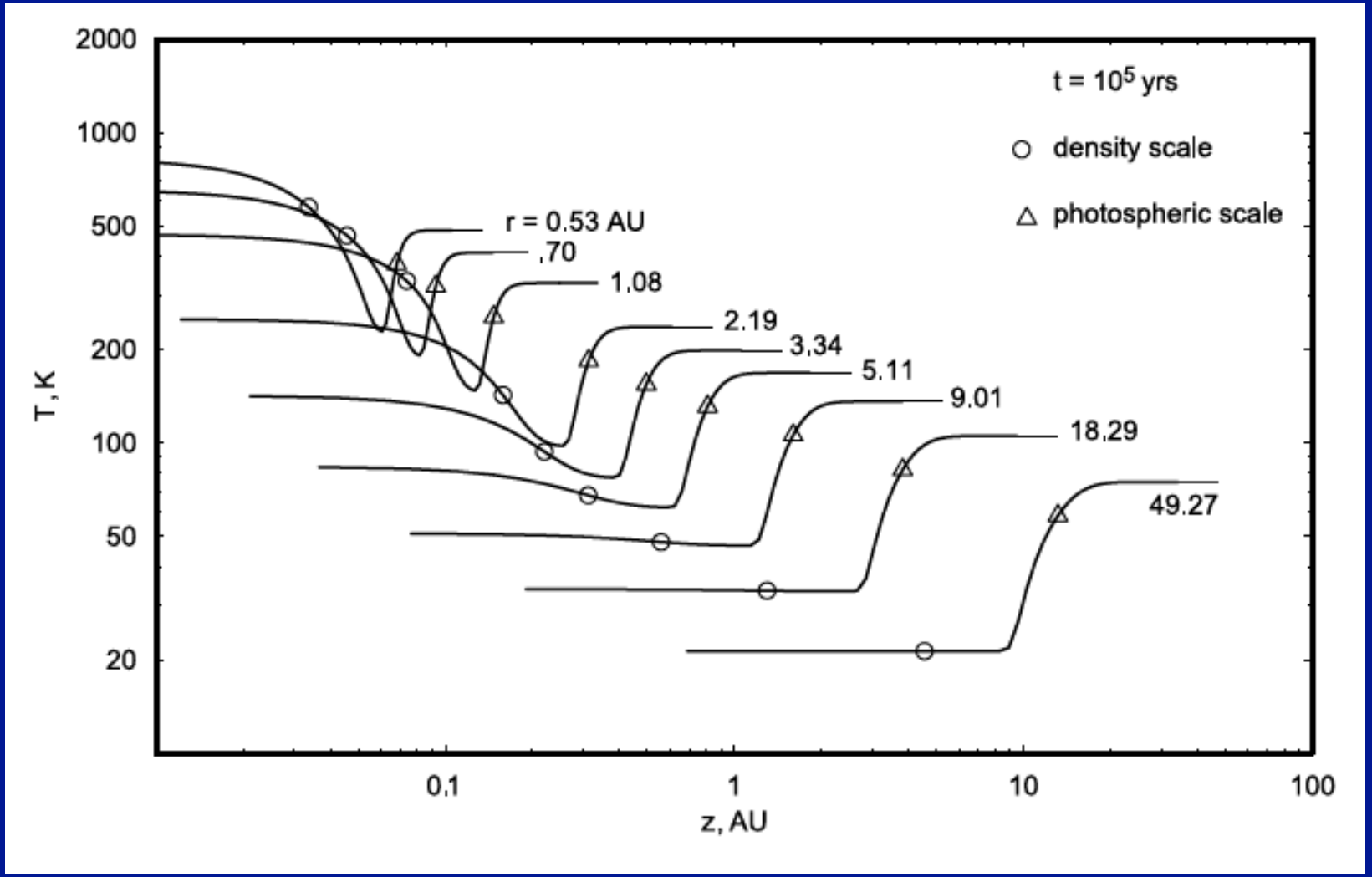
Juhasz, Abraham et al. 2007

Some conclusions

- There is some evidence of “self-shadowing” in disks
- Recent mm observations start probing the radial distribution of matter in the disk in the planet forming region
- FUV-driven photoevaporation is likely to be important in addition to EUV-driven and X-ray-driven photoevaporation

Where is the snow line?

Where is the ‘snow line’?



Davis (2005)

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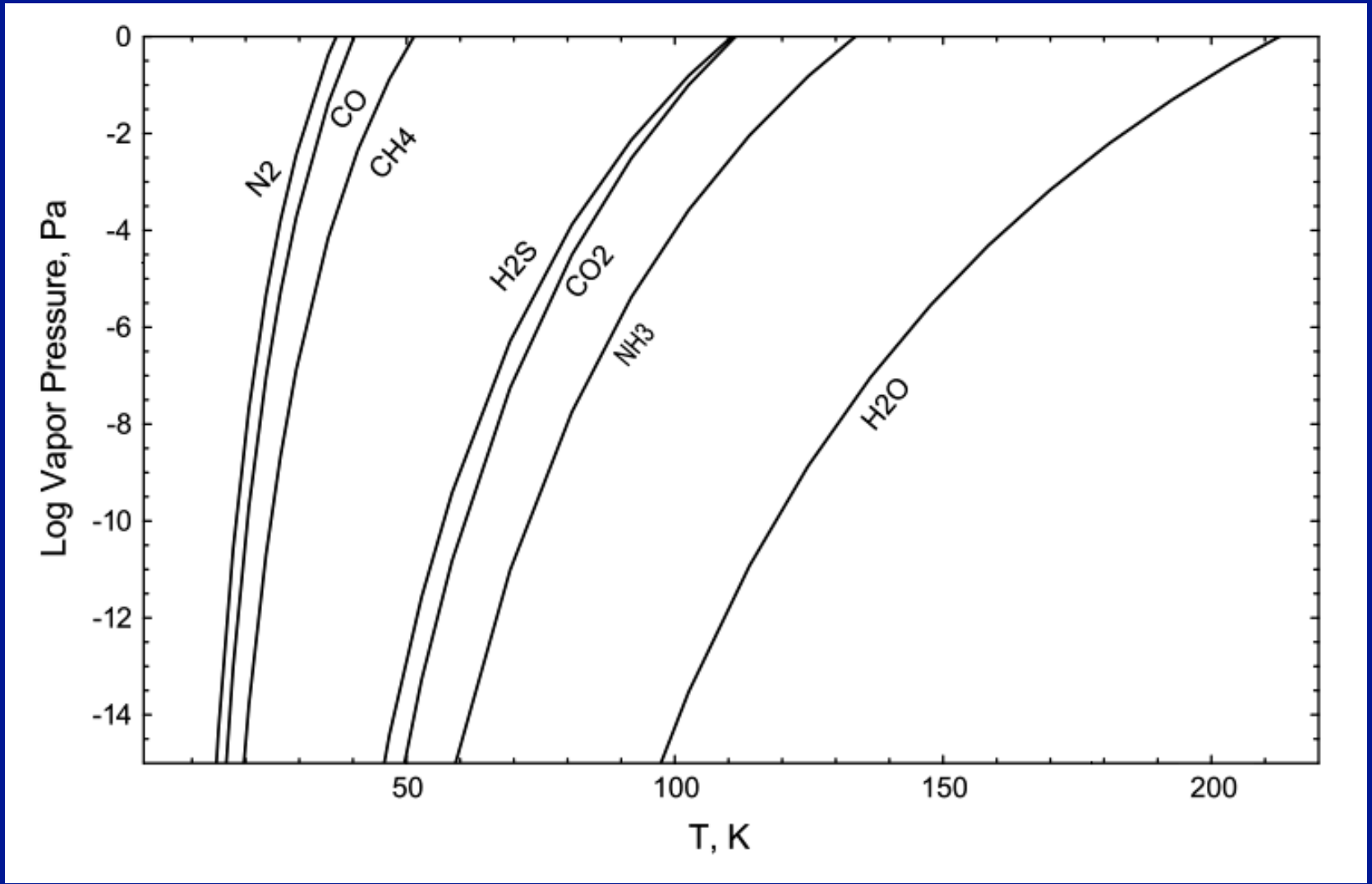

Davis 2005
Lecar, Podolak, Sassalov & Chiang 2006

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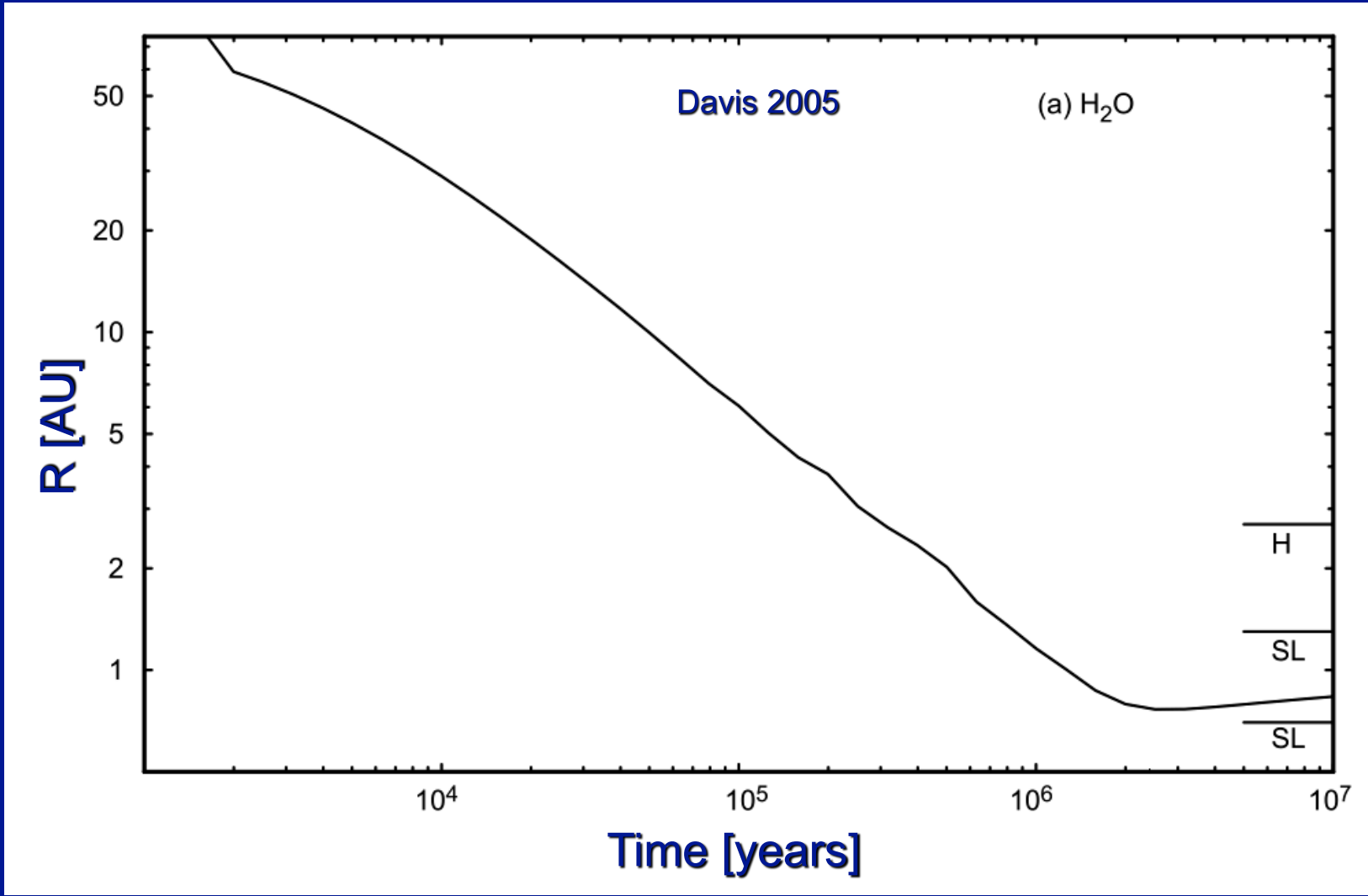
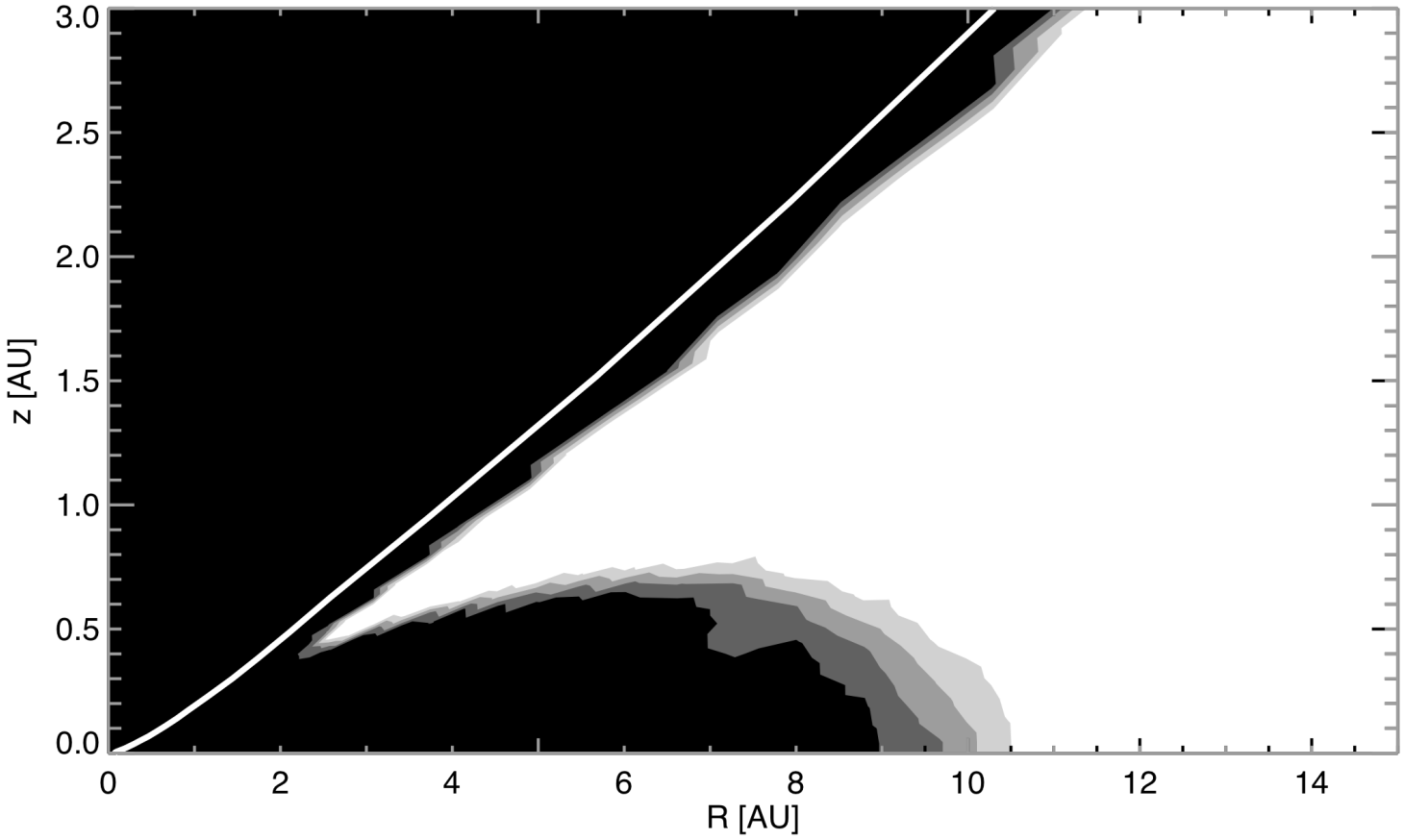


Davis 2005
Lecar, Podolak, Sassalov & Chiang 2006

Where is the ‘snow line’?

First fully 2-D/3-D radiative transfer model of snow line

$dM/dt = 10^{-7}\ M_{\odot}/yr, \qquad \alpha=0.01$

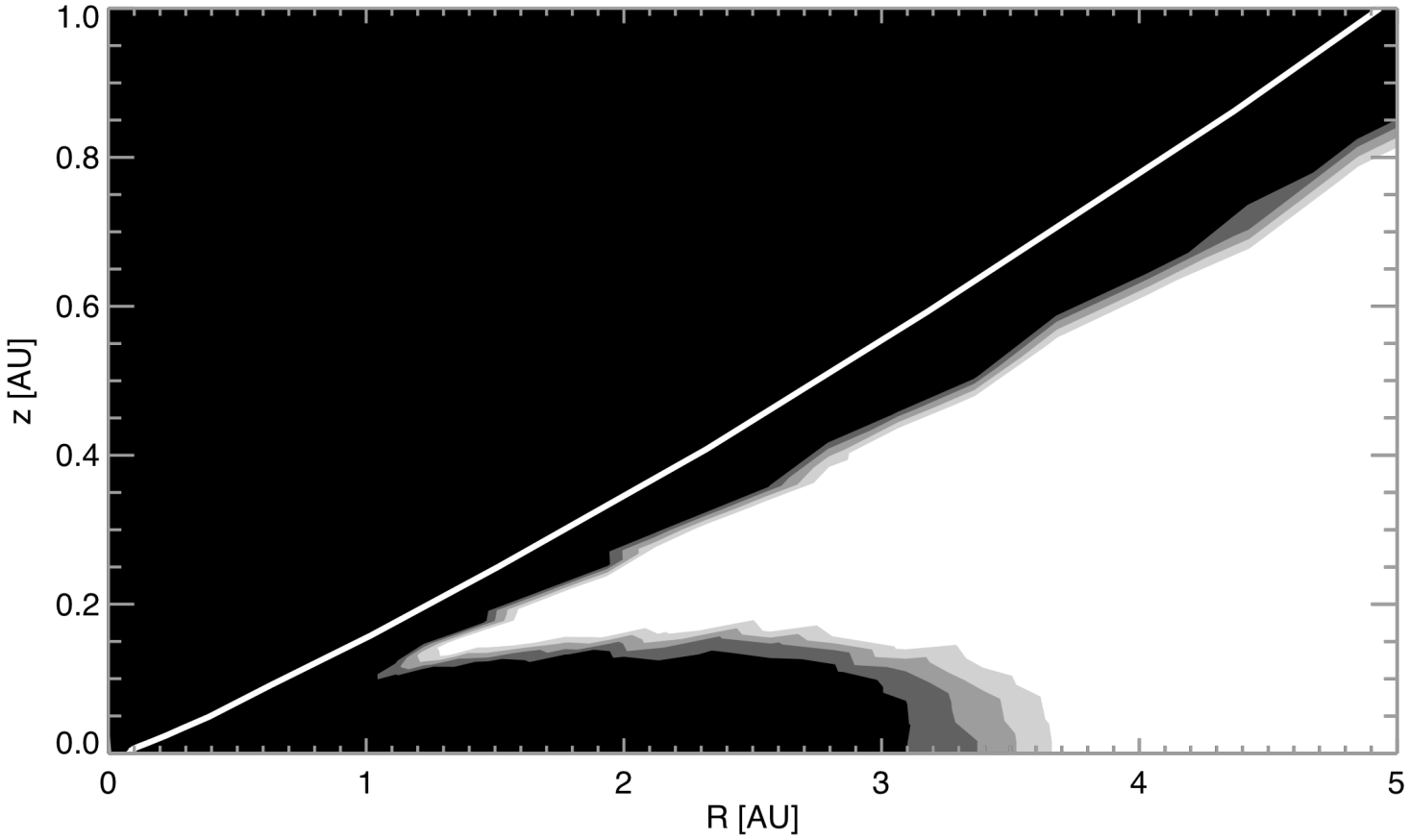


Min, Dullemond, Dominik & Kama in prep.

Where is the ‘snow line’?

First fully 2-D/3-D radiative transfer model of snow line

$dM/dt = 10^{-8}\ M_{\odot}/yr, \qquad \alpha=0.01$

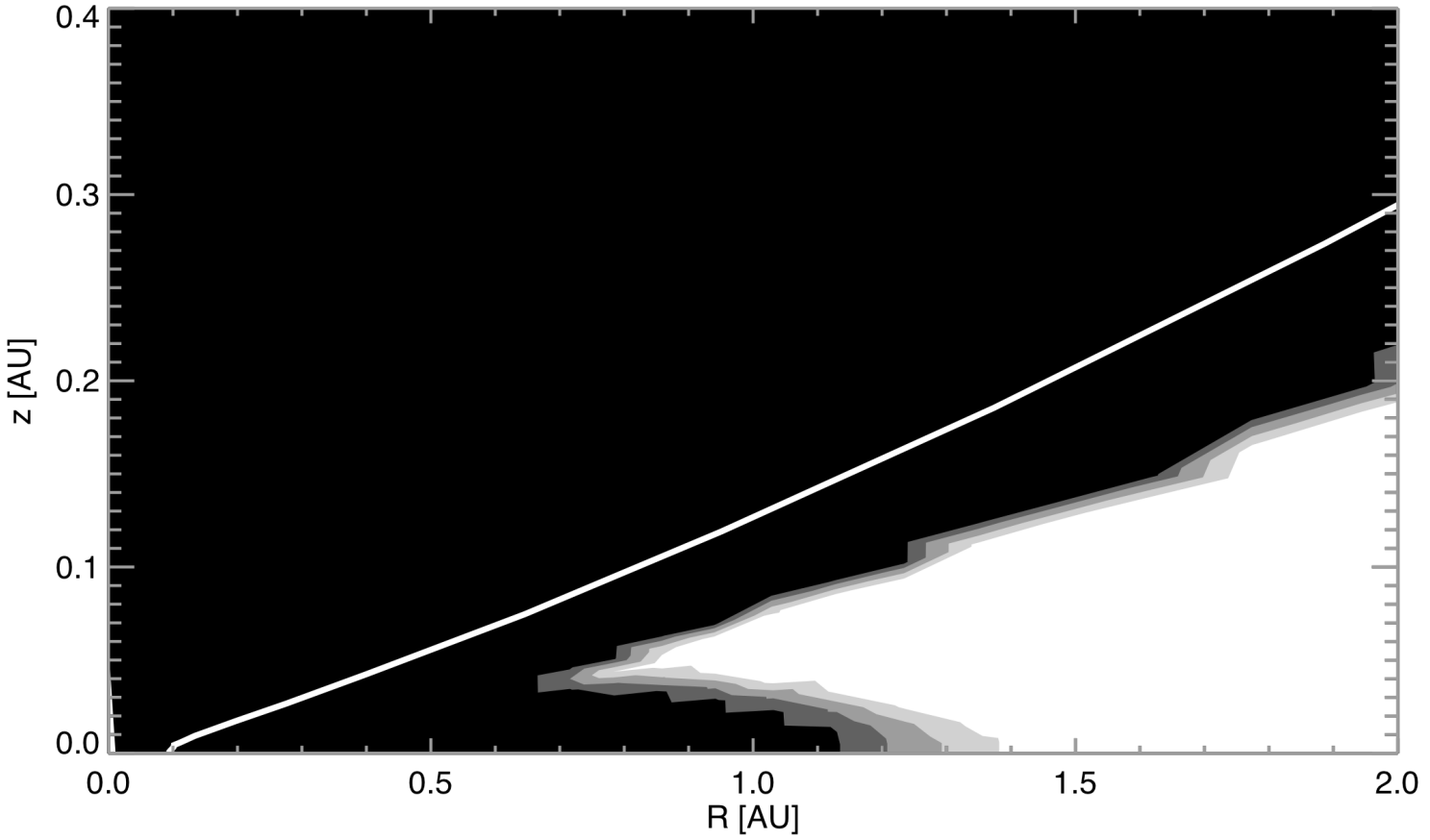


Min, Dullemond, Dominik & Kama in prep.

Where is the ‘snow line’?

First fully 2-D/3-D radiative transfer model of snow line

$dM/dt = 10^{-9}\ M_{\odot}/yr, \qquad \alpha=0.01$



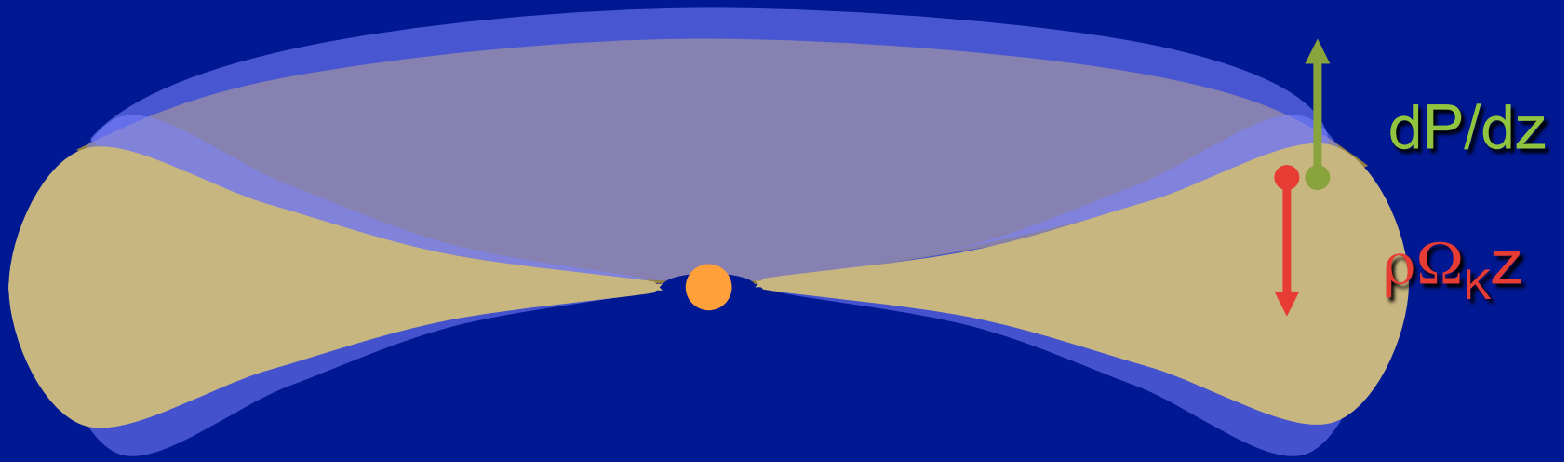
Min, Dullemond, Dominik & Kama in prep.

Disk winds as the driving force for accretion

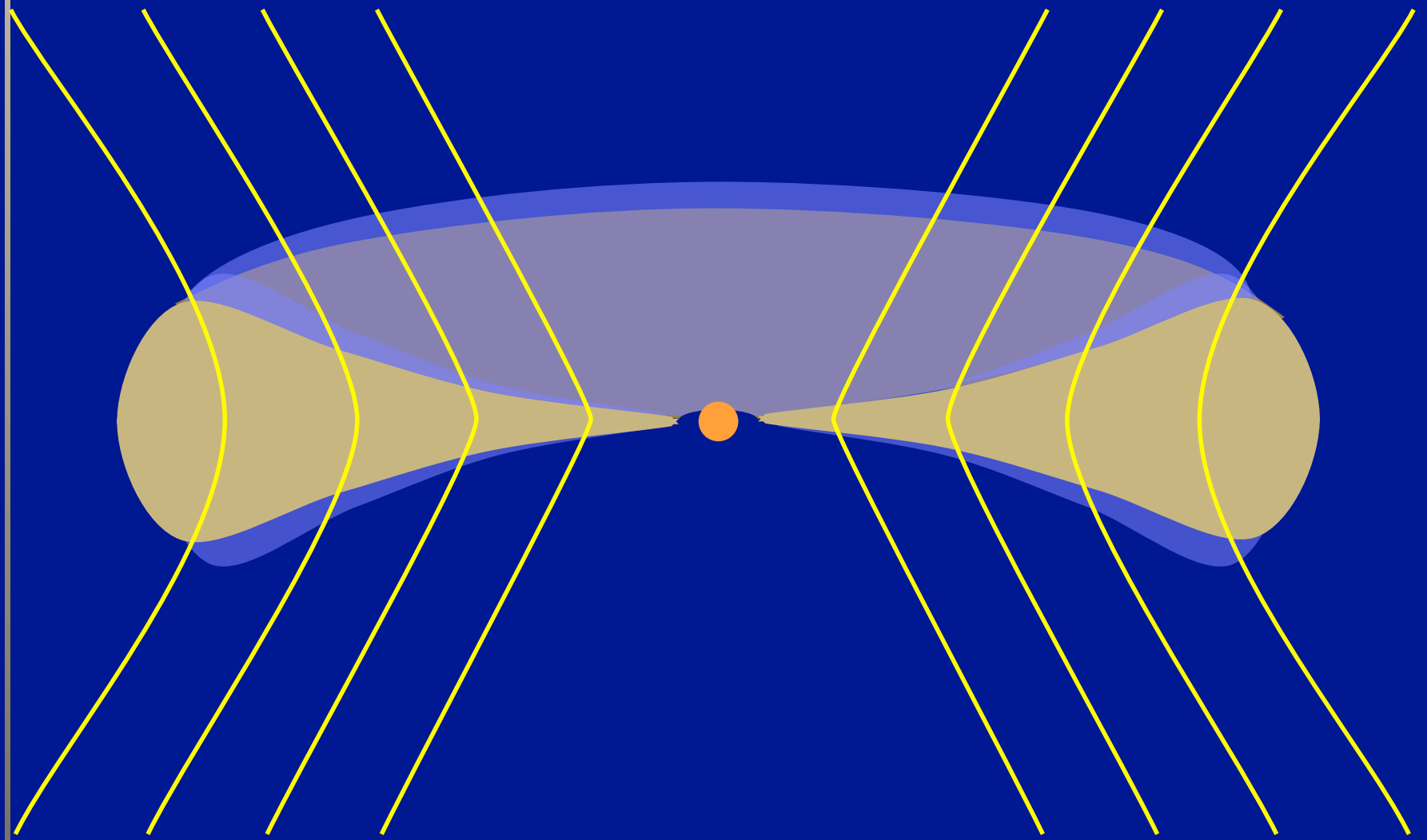
Removing ang-mom by outflows

- Outflows can remove angular momentum
- Often jets are being considered best at this, but they are launched from close to star.
- A “true” jet can only remove last bit of angular momentum from disk.
- Disk wind is slower, but removes more angular momentum.
- Requirements:
  - Global (not stellar) magnetic field threading the disk
  - B^2/8pi > P_gas (according to some models)

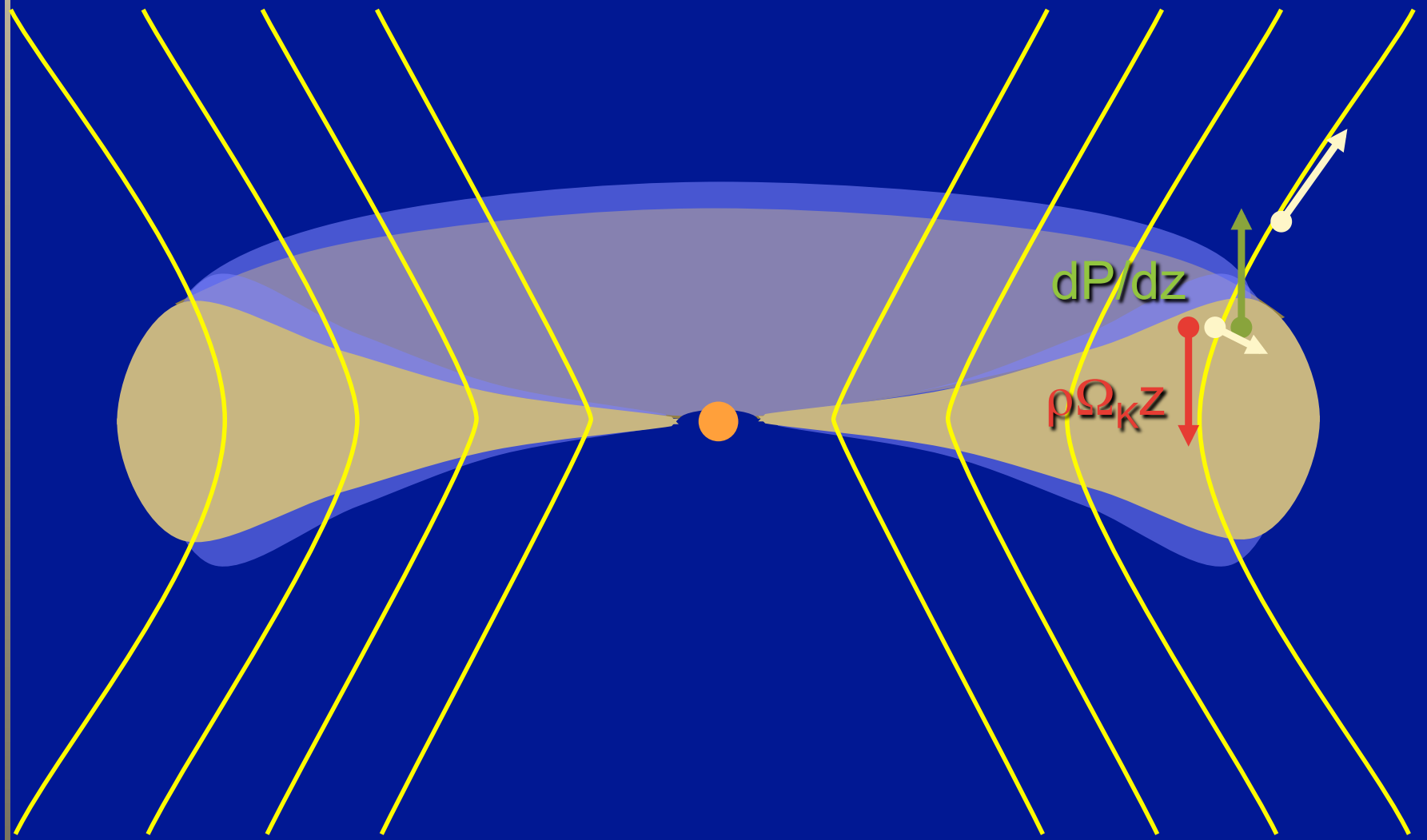
Geometry: only gravity vs pressure



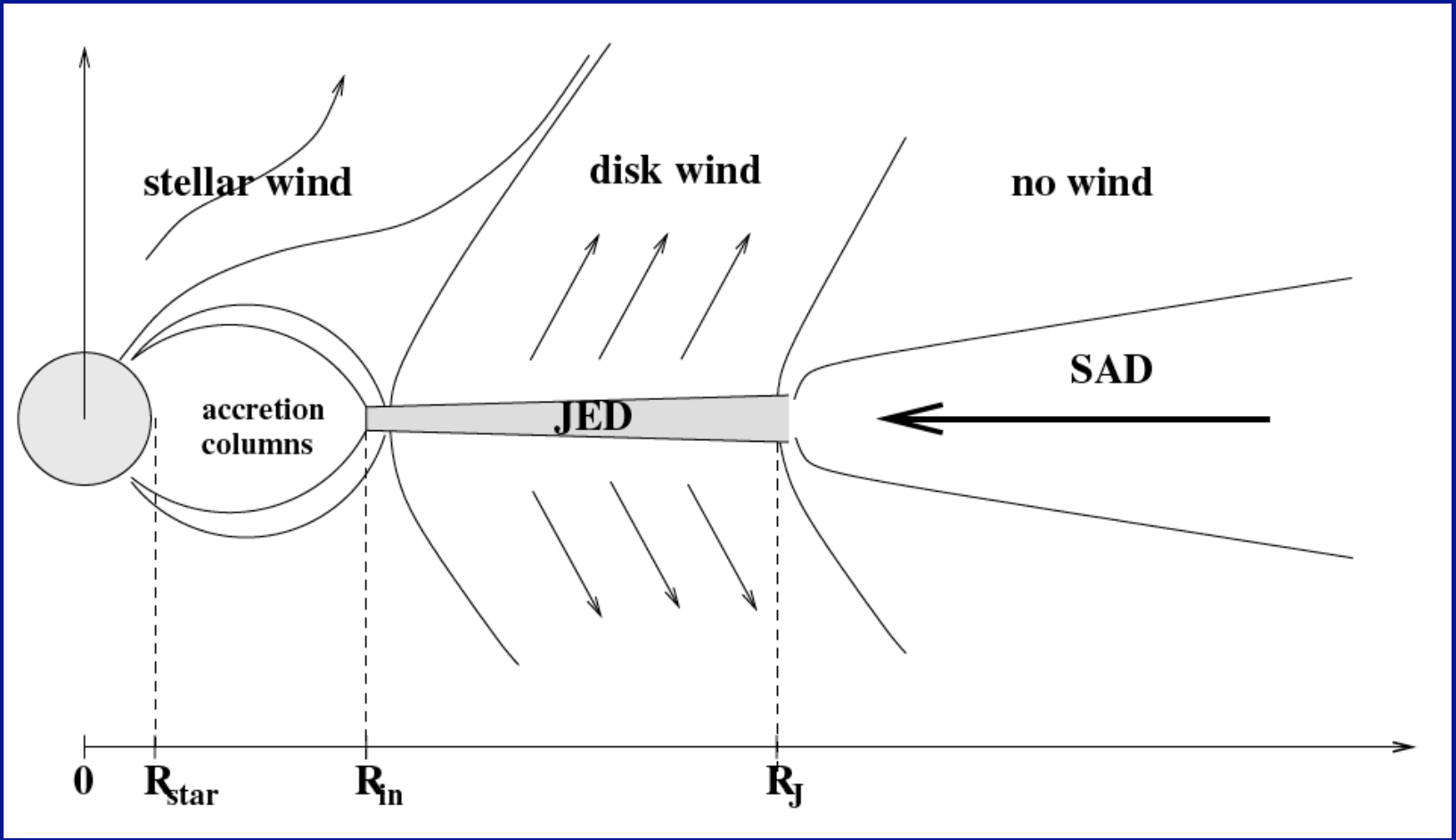
Geometry: adding vertical B-field



Geometry: adding vertical B-field



Disk evolution through global B-field

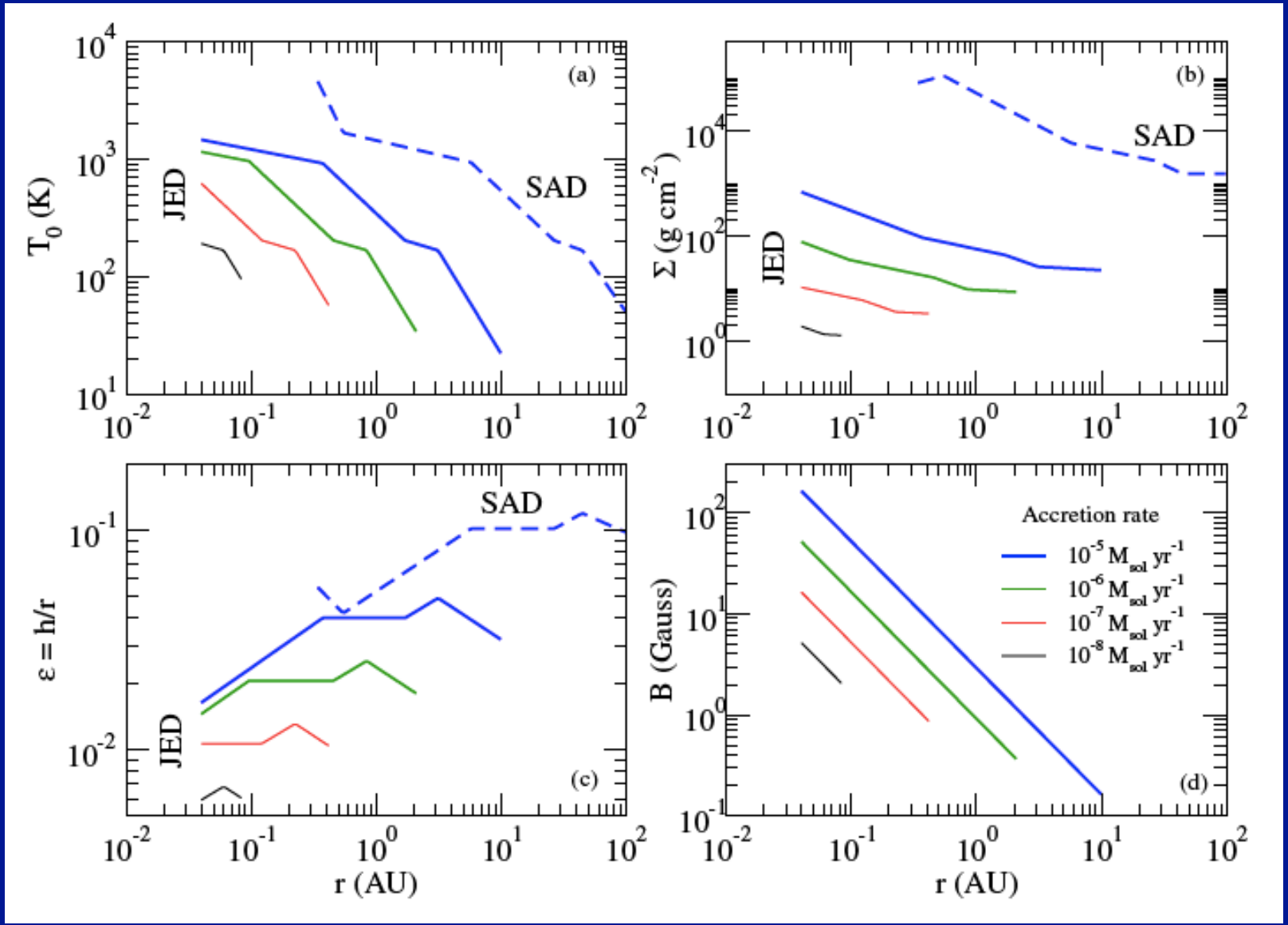


Combet & Ferreira (2008)

Consequences of wind-driven accretion

- accelerate accretion
- may cause optically thin inner disks (Combet & Ferreira 2007)
- drive slow dense outflows
- modify dust-to-gas ratio in disk: consequence for planet formation
- cause accretion WITHOUT mixing: consequence for thermal history of solar system primitive material

Disk evolution through global B-field

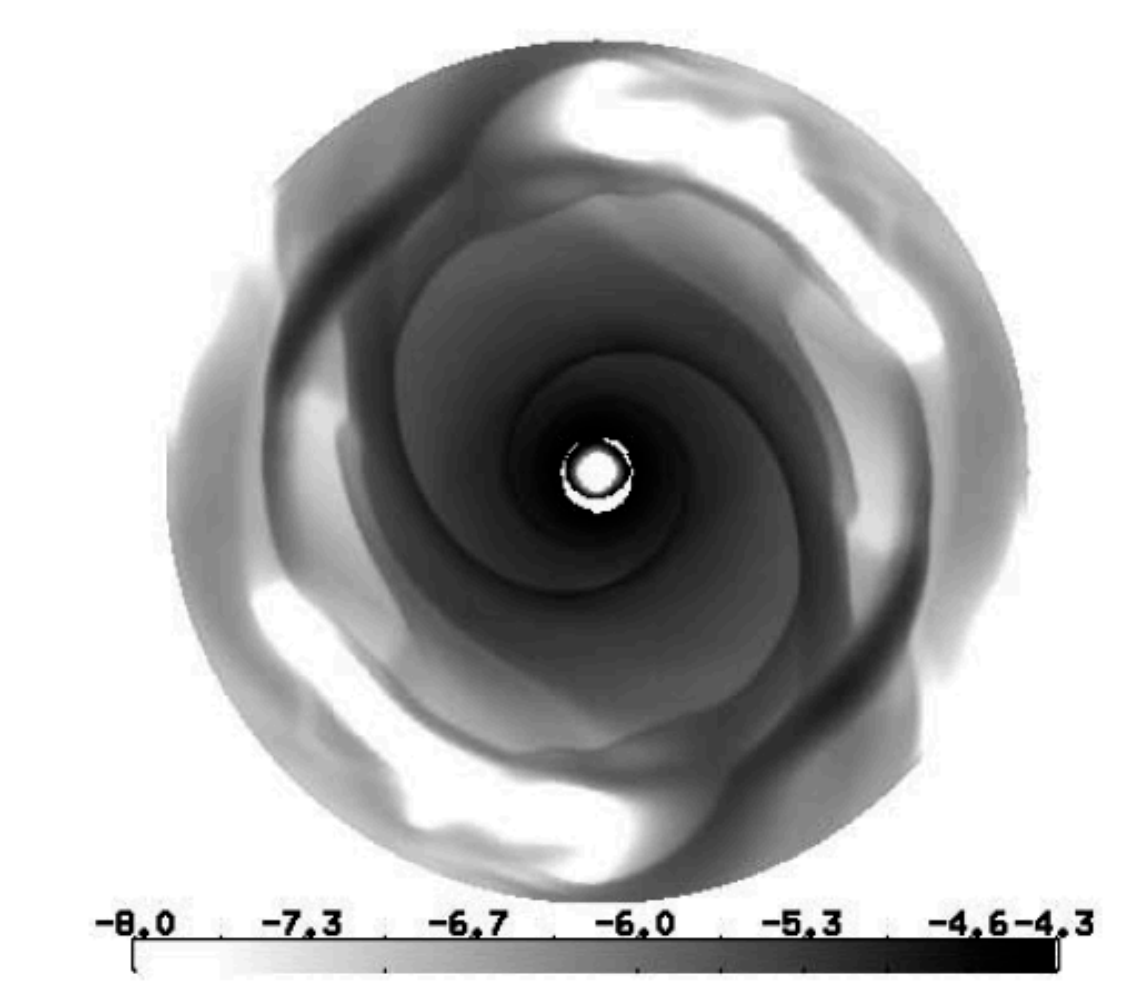


Combet & Ferreira (2008)

Moving away from the steady accretion picture:

Gravitational instabilities

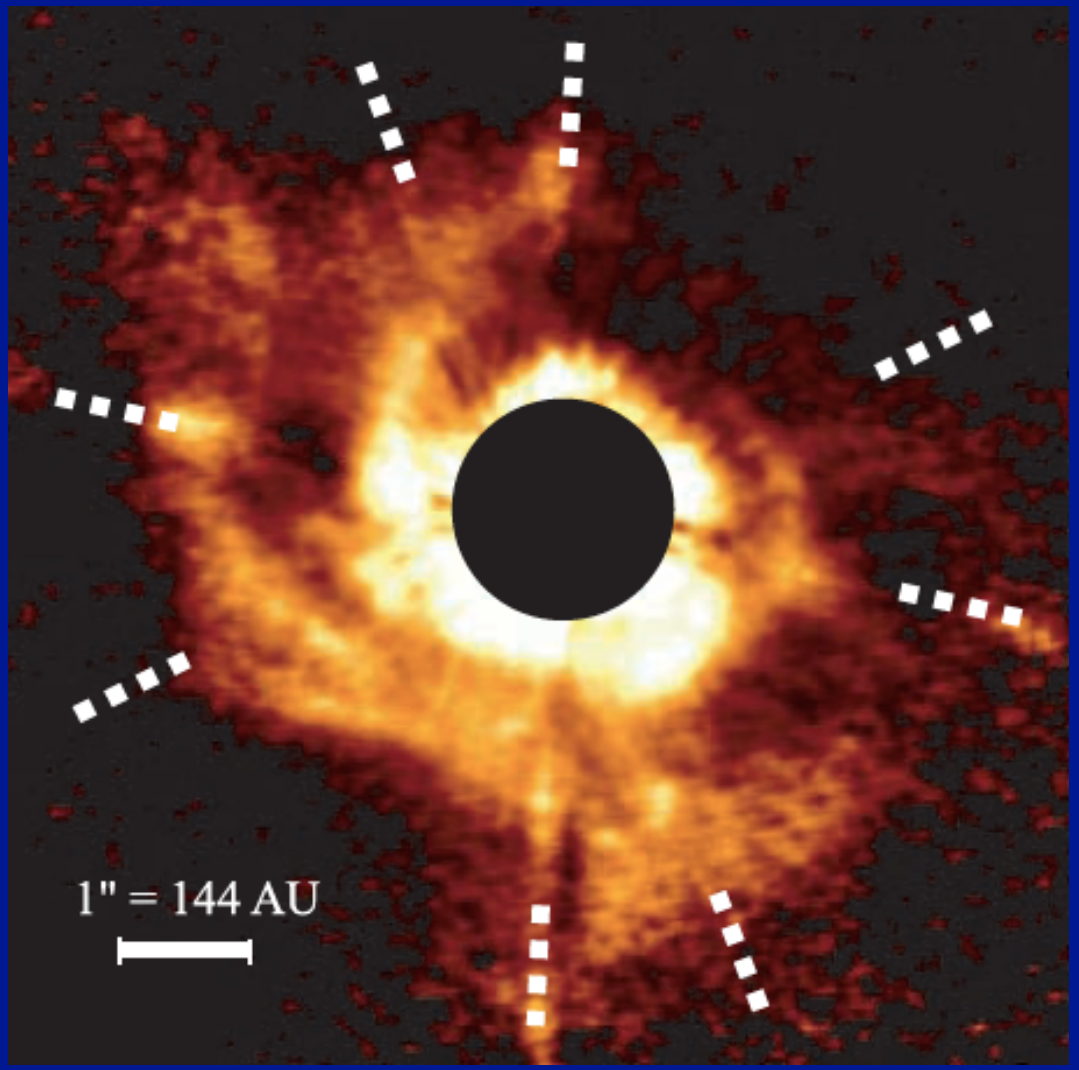
Gravitational instabilities



Boley et al. 2006

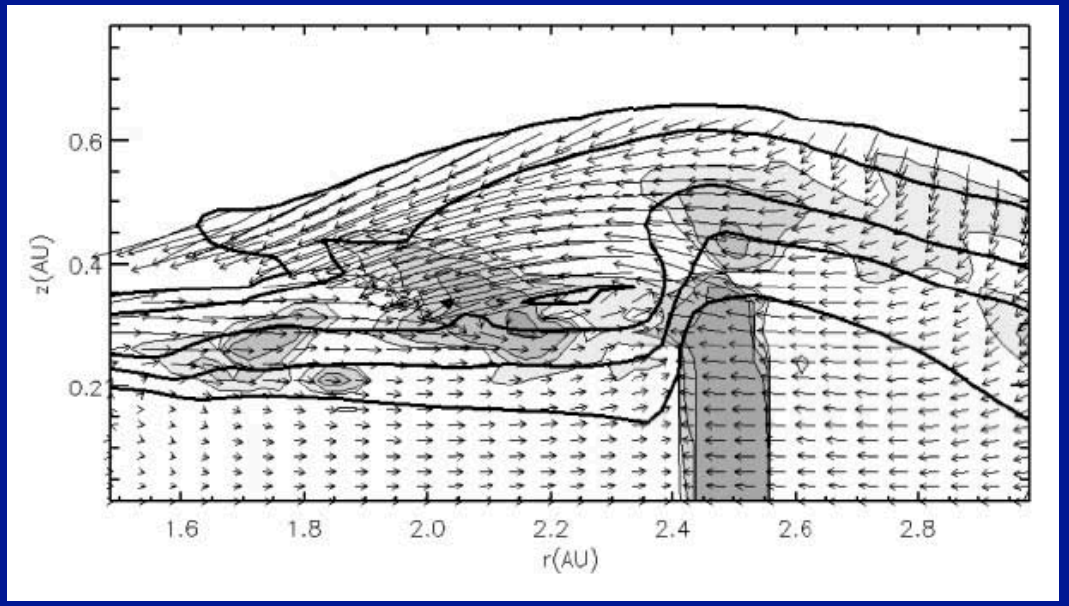
Observed spiral structure?

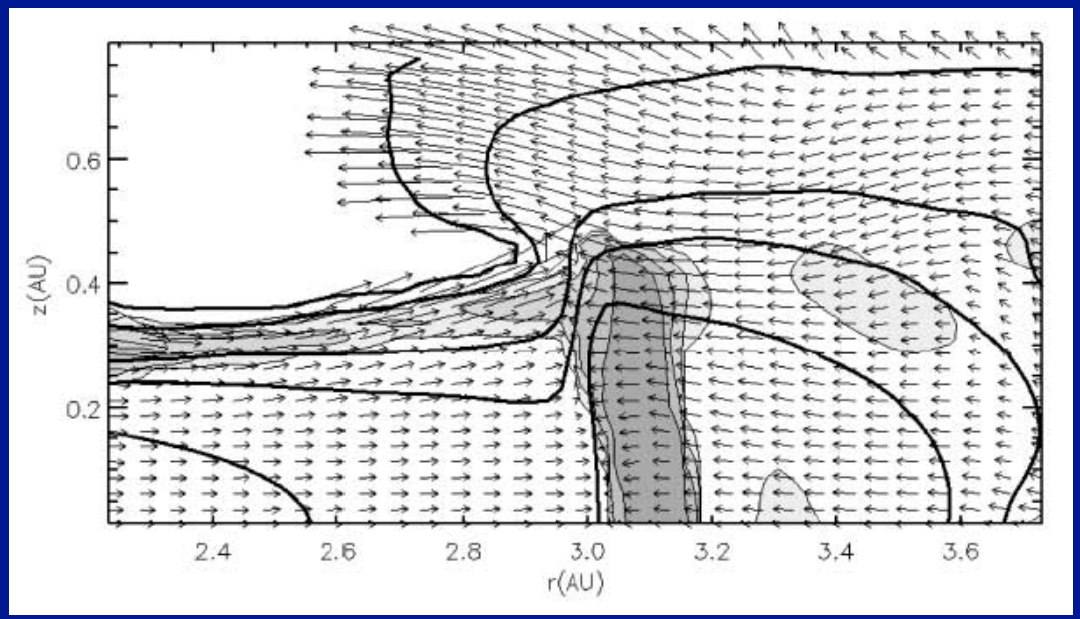
Disk around
AB Aurigae



Fukagawa et al. 2004

Crashing waves





Boley et al. 2006