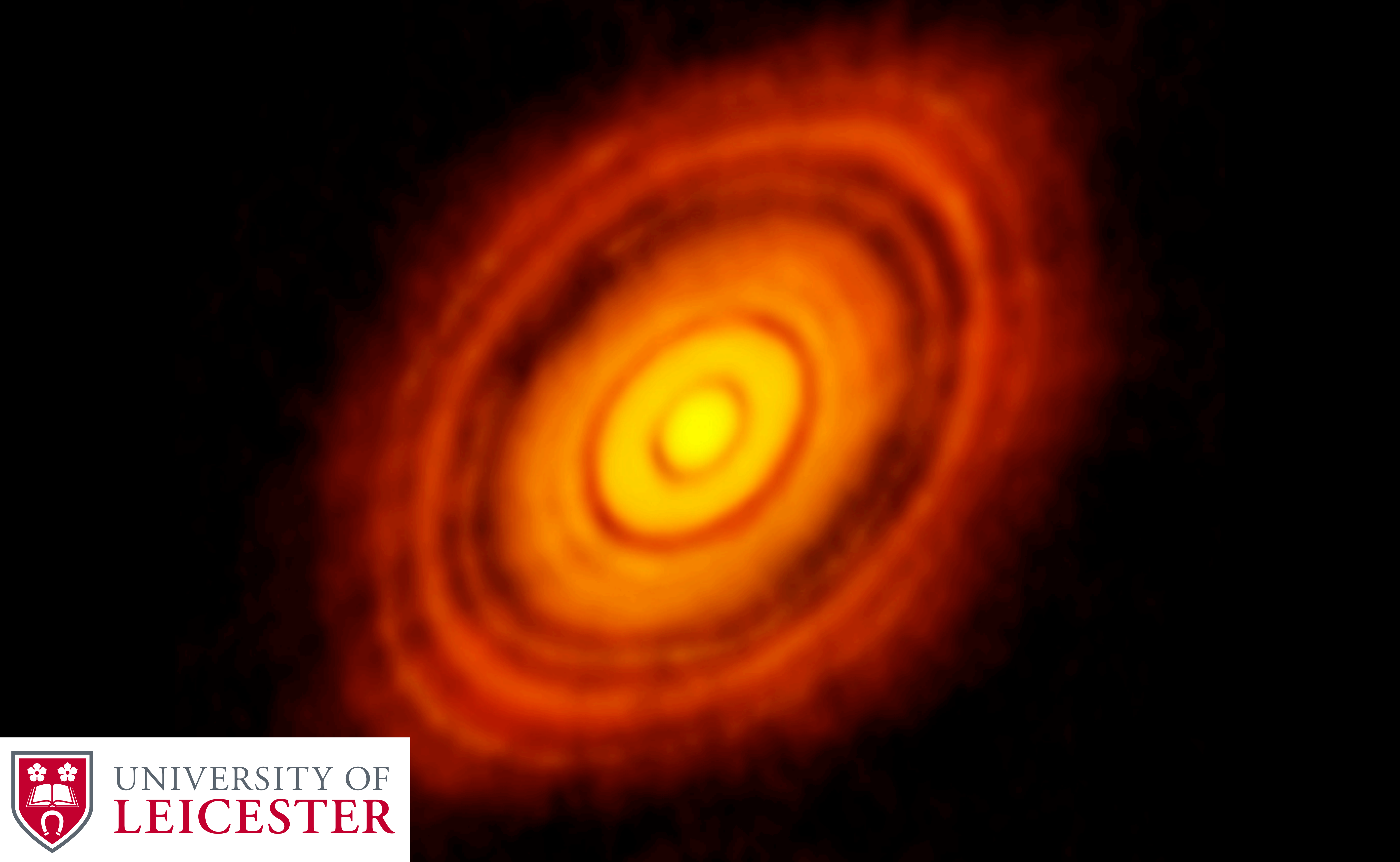
Formation of Planetary Systems

Lecture 2 - Protoplanetary discs



UNIVERSITY OF LEICESTER

Course Outline

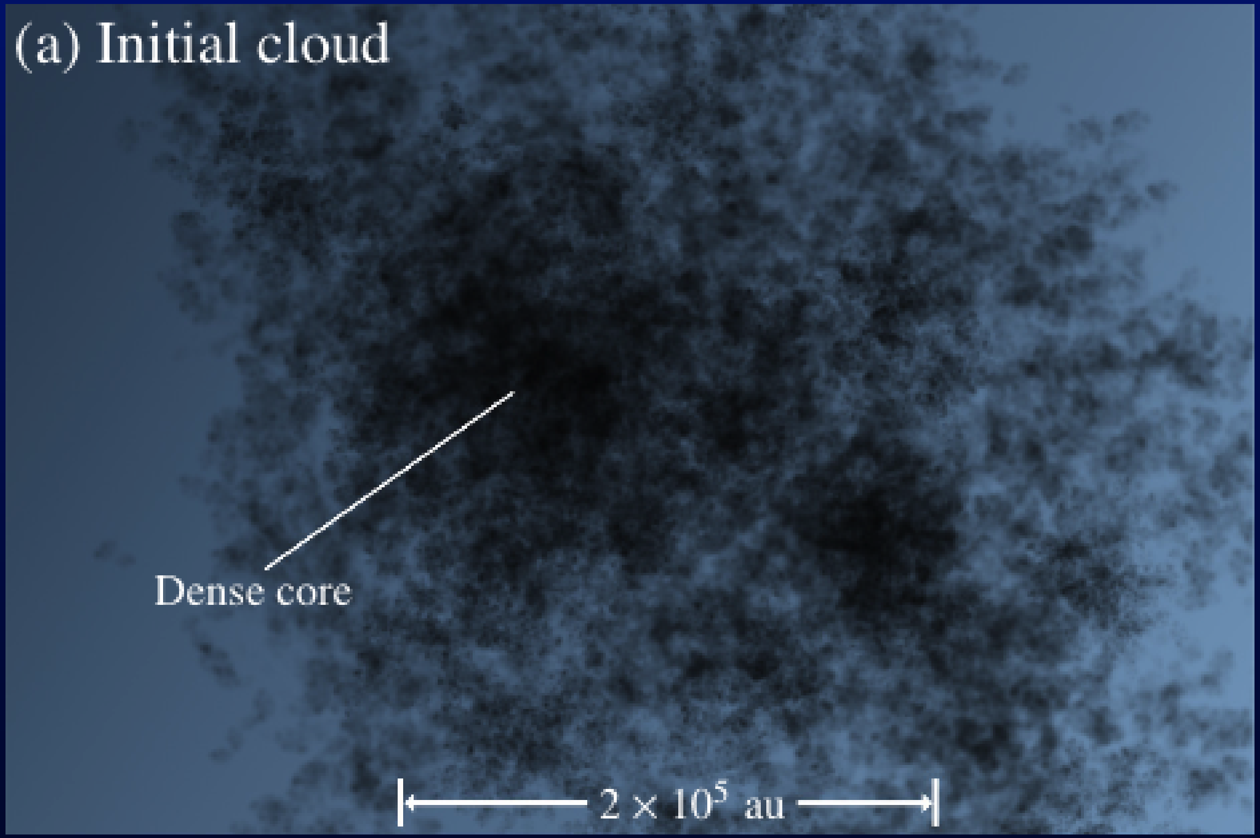
- 5 Lectures, 2 hours each (with a break in the middle!).
  1) Observations of planetary systems
  2) Protoplanetary discs
  3) Dust dynamics & planetesimal formation
  4) Planet formation
  5) Planetary dynamics
- Notes for each lecture will be placed on the course home page *in advance* - you may find it useful to annotate these as we go.
- These slides will also be posted online.
- Textbooks: Armitage - *Astrophysics of planet formation* (CUP).

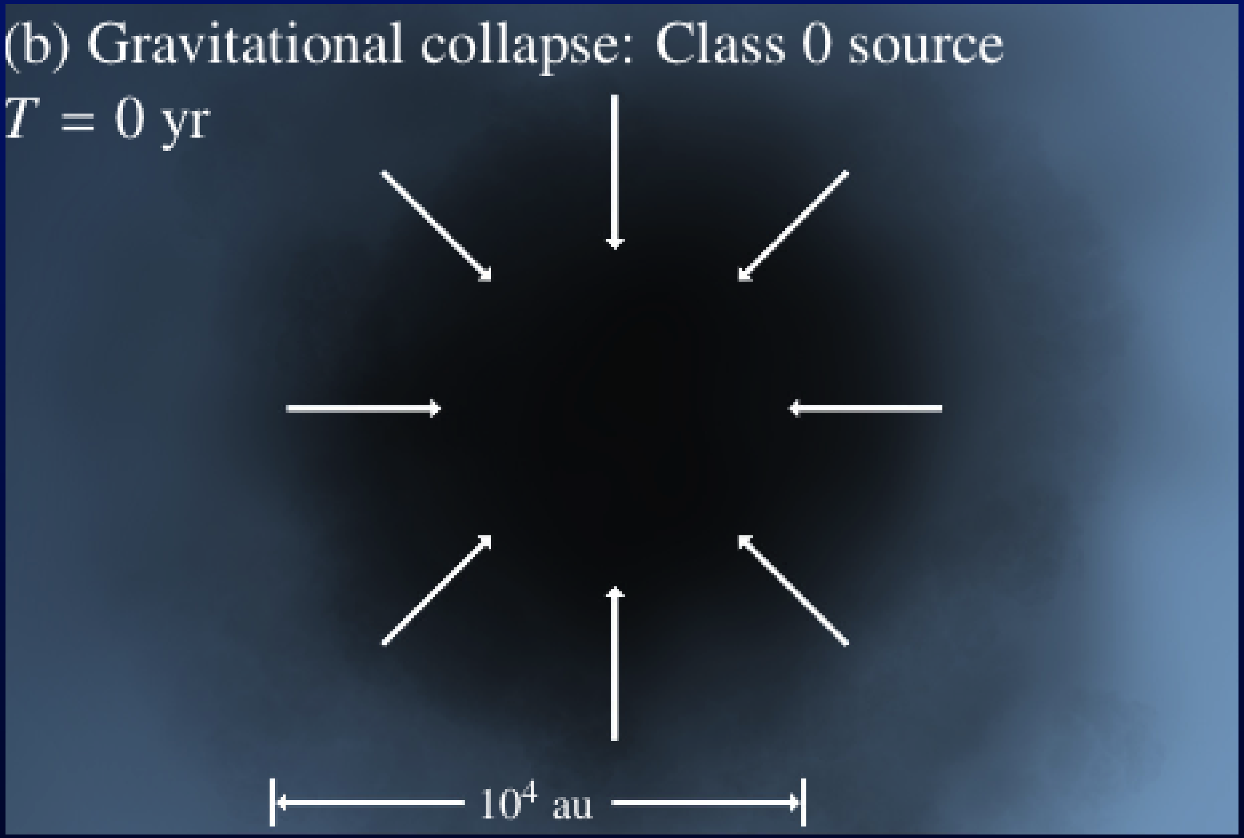
  Protostars & Planets series (*V* - 2007; *VI* - 2014)

Course home-page: `rdalexander.github.io/planets_2023.html`

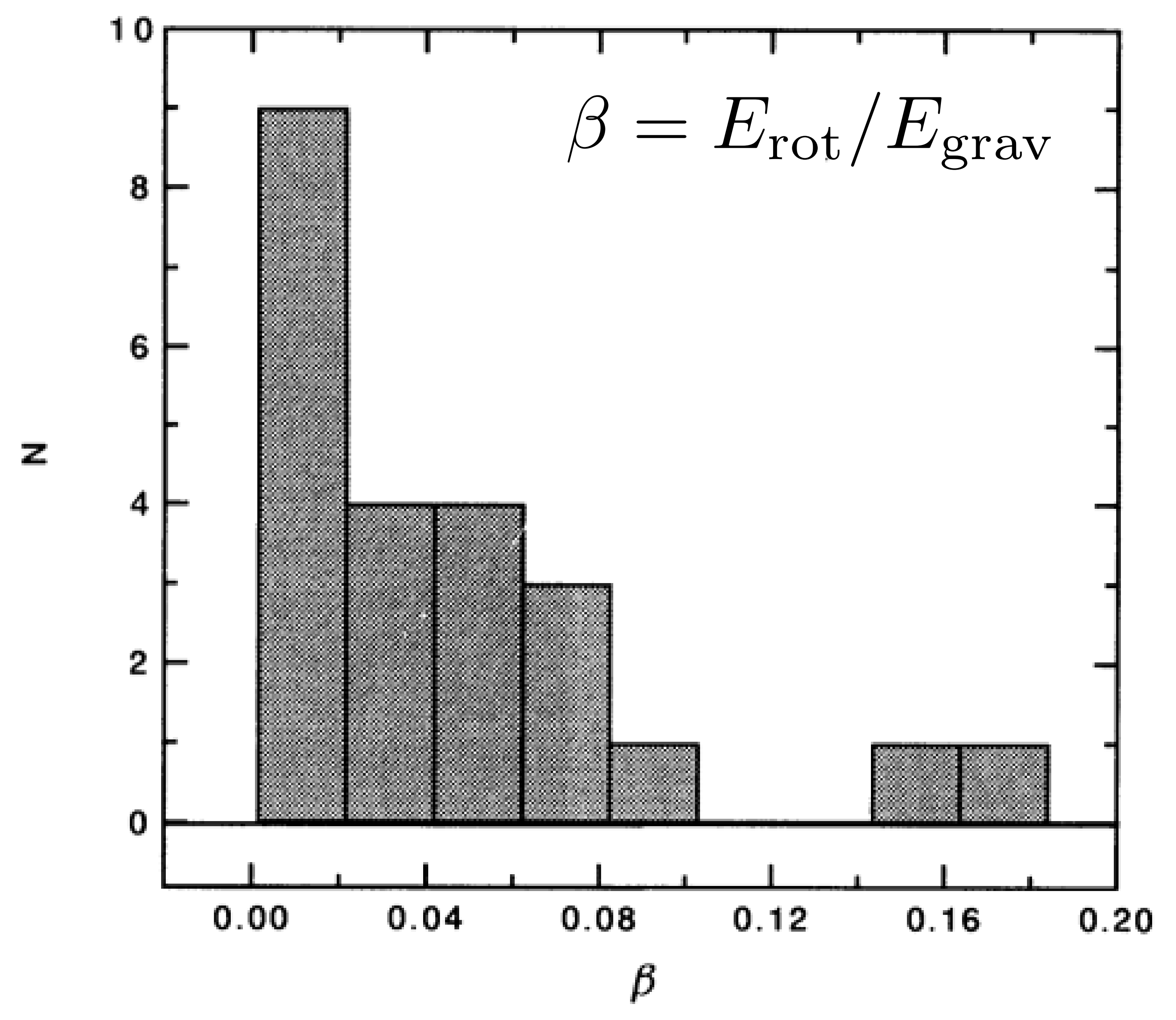
Gravitational collapse

Figures from Alex Dunhill (PhD thesis, 2013), after Shu et al. (1987)

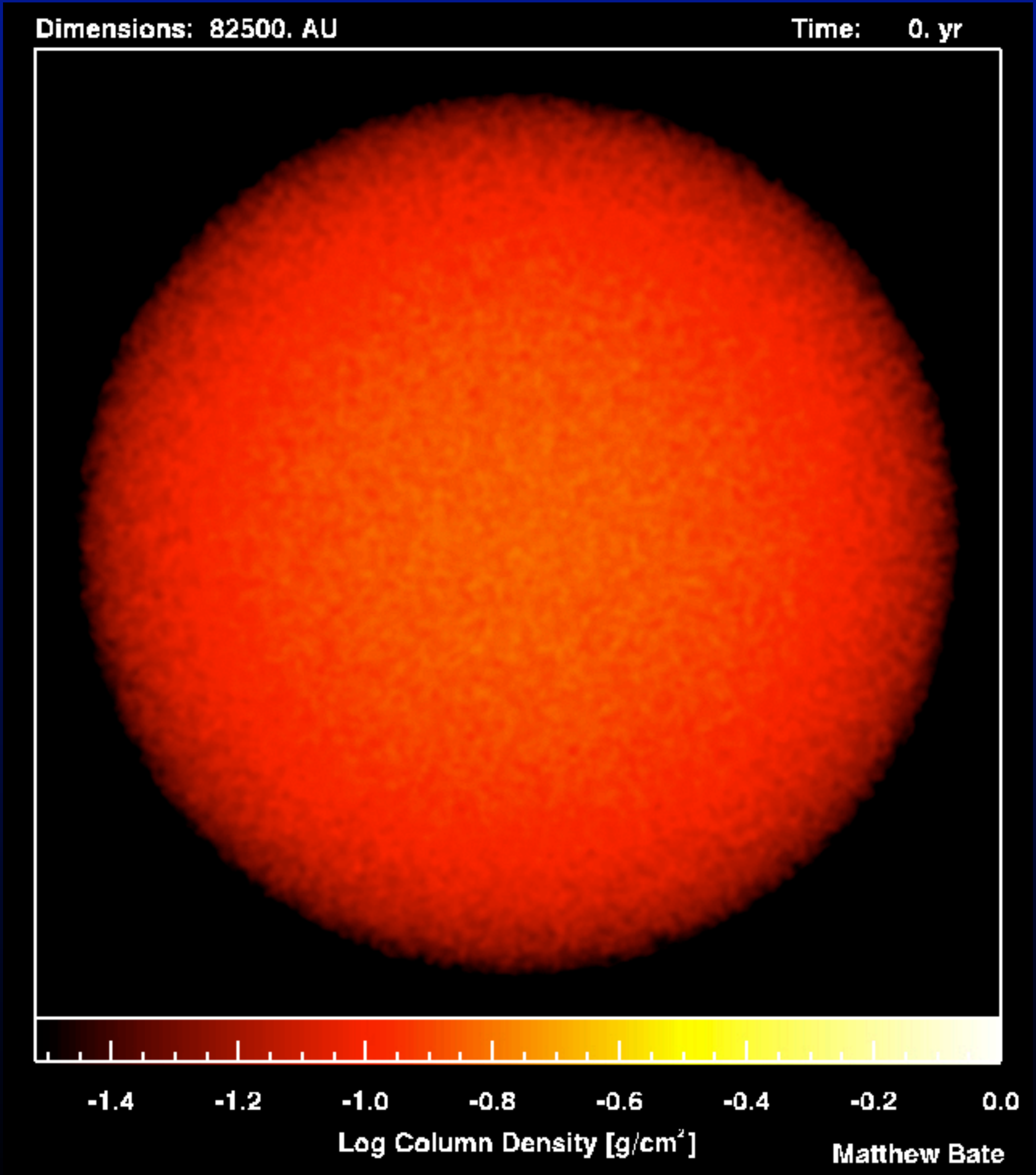




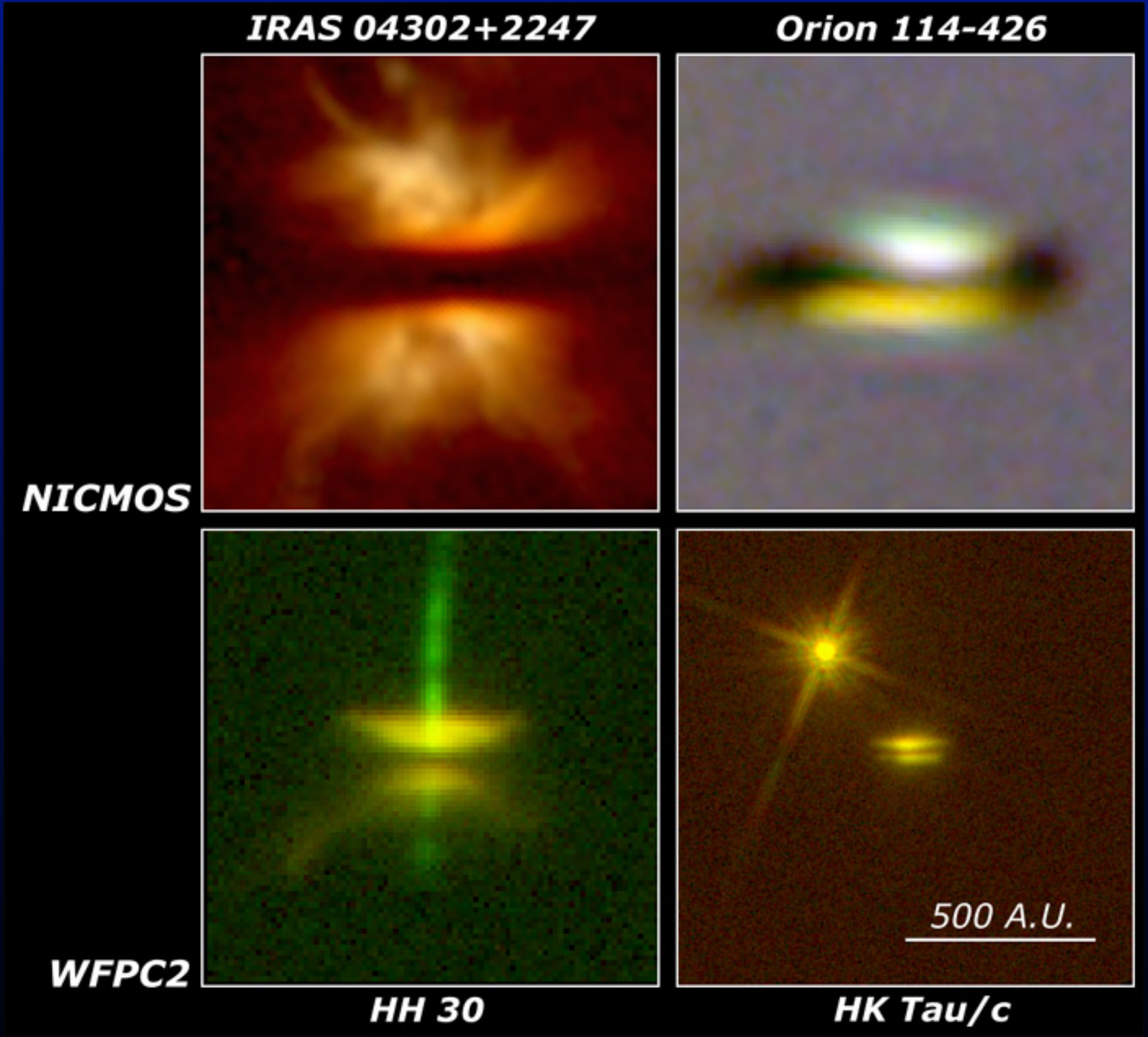
Measuring rotation

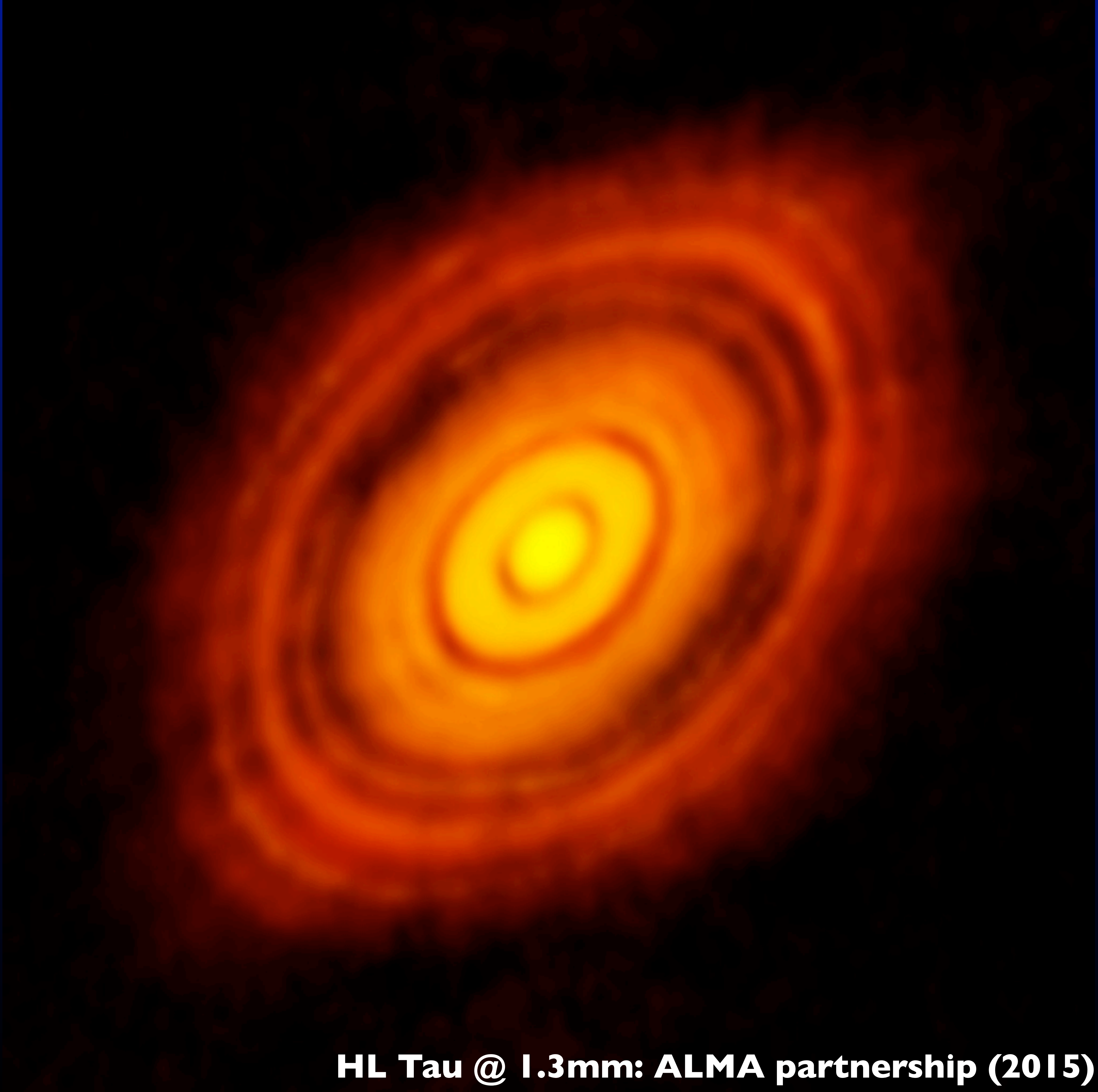


Goodman et al. (1993)

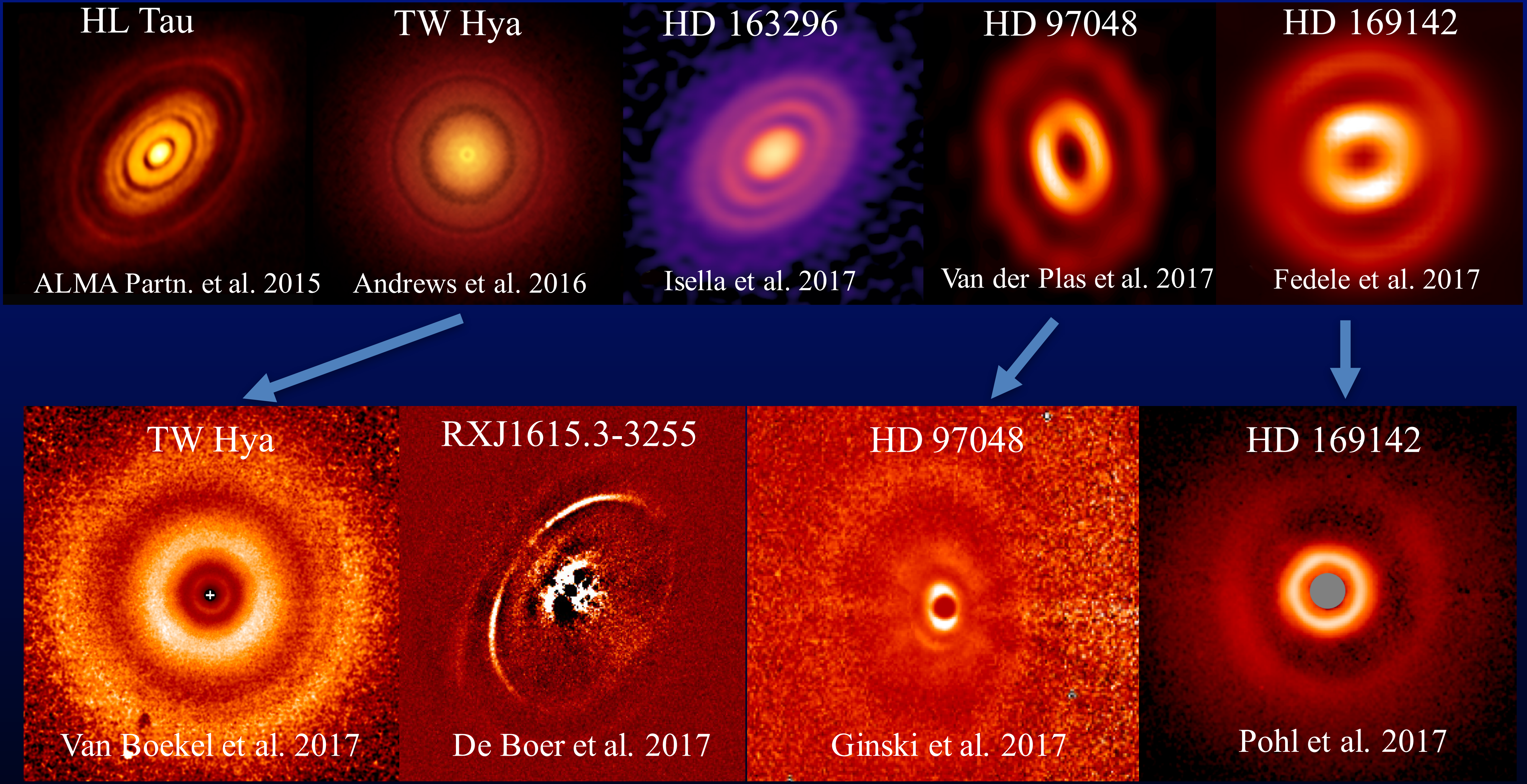


Bate et al. (2002, 2003)


IRAS 04302+2247
Orion 114-426
NICMOS
WFPC2
500 A.U.
HH 30
HK Tau/c



HL Tau @ 1.3mm: ALMA partnership (2015)



HL Tau
ALMA Partn. et al. 2015

TW Hya
Andrews et al. 2016

HD 163296
Isella et al. 2017

HD 97048
Van der Plas et al. 2017

HD 169142
Fedele et al. 2017

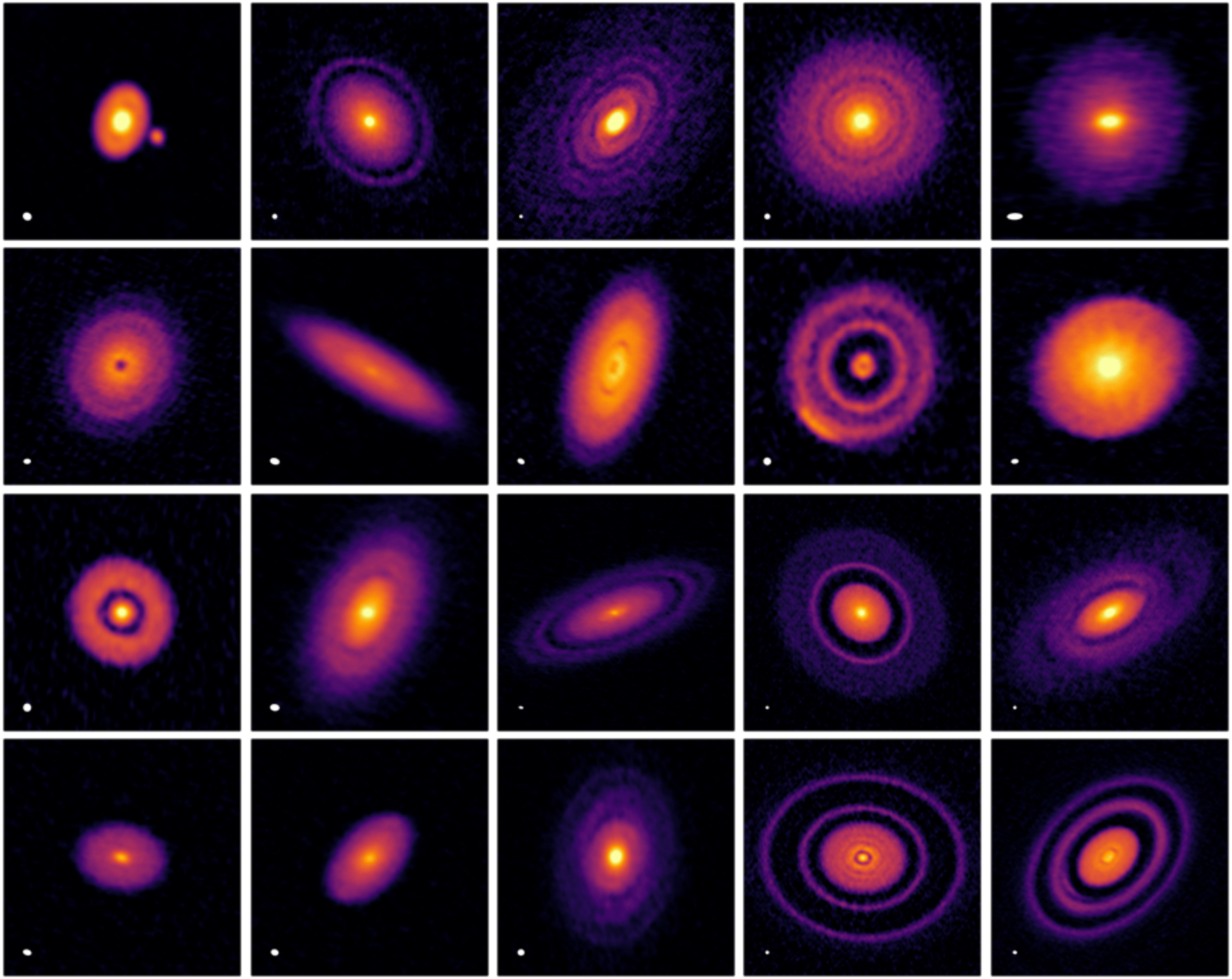
TW Hya
Van Boekel et al. 2017

RXJ1615.3-3255
De Boer et al. 2017

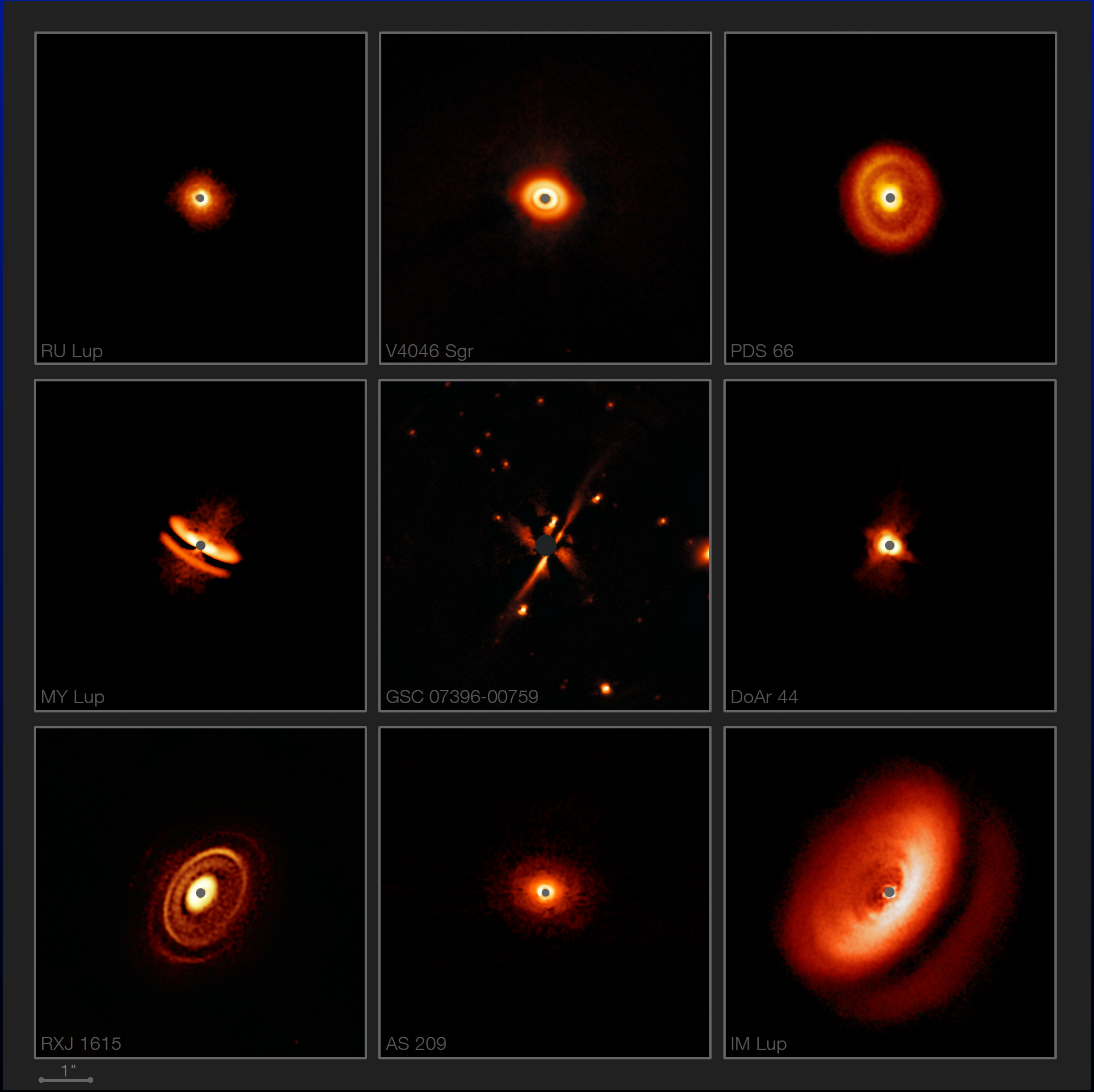
HD 97048
Ginski et al. 2017

HD 169142
Pohl et al. 2017

Compilation slide courtesy of Giovanni Dipierro

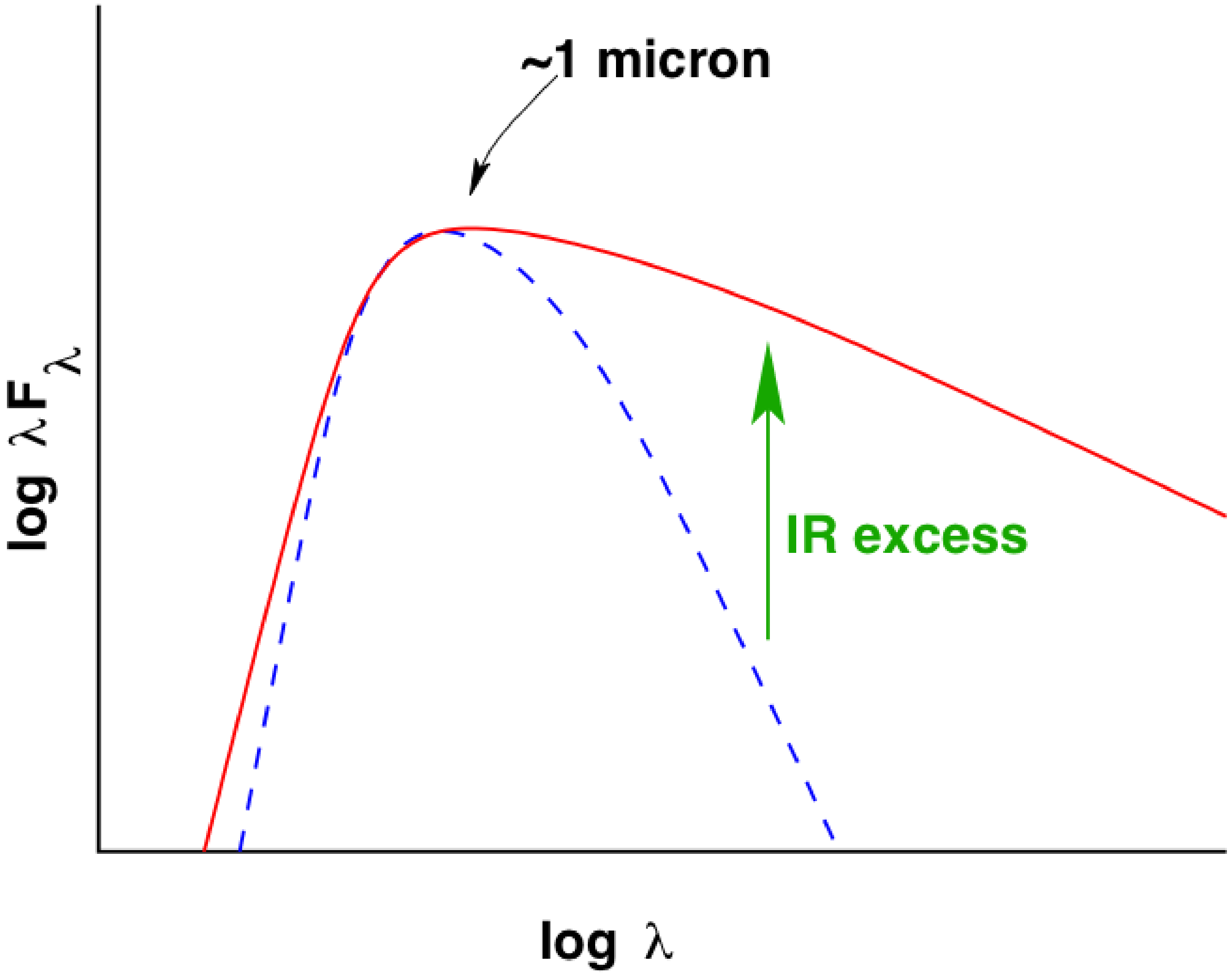


ALMA “DSHARP” survey; Andrews et al. (2018)



VLT-SPHERE “DARTTS” survey (1.6μm); Avenhaus et al. (2018)

SED Classification Scheme

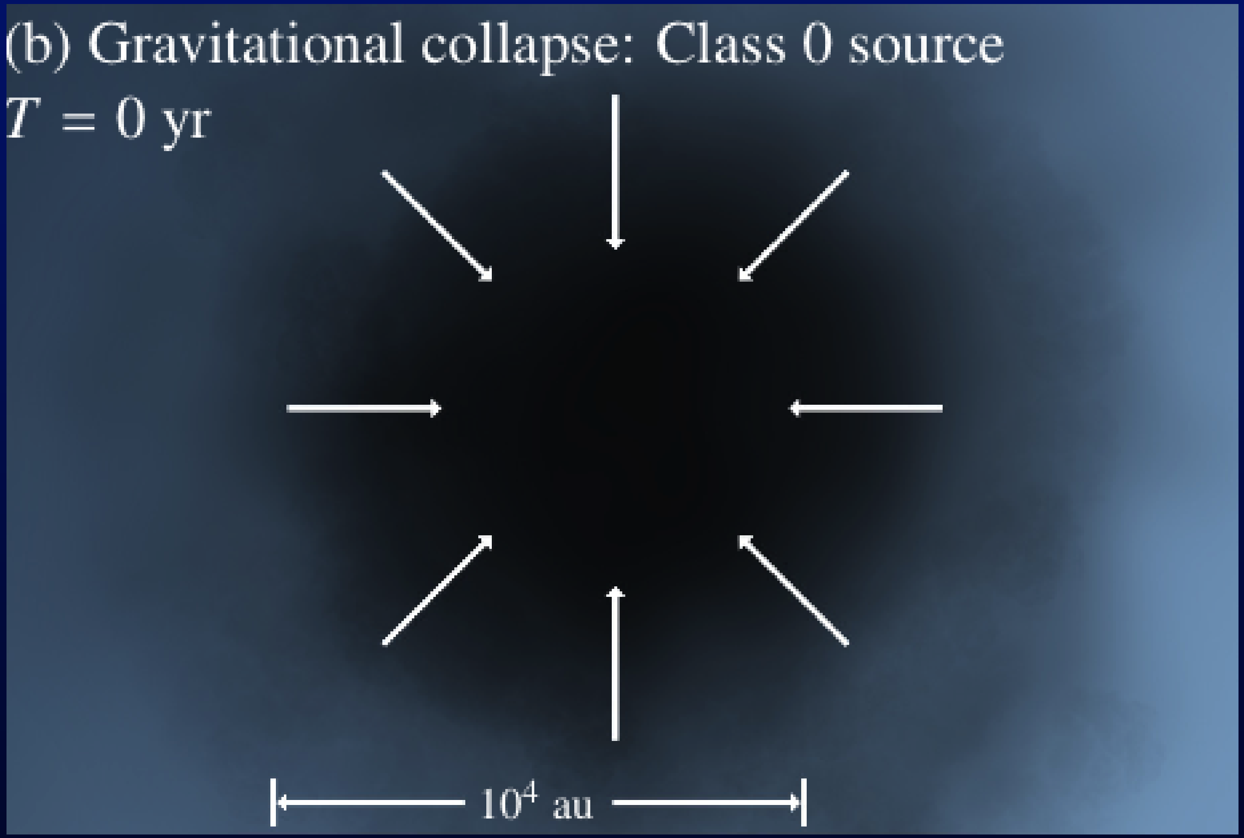


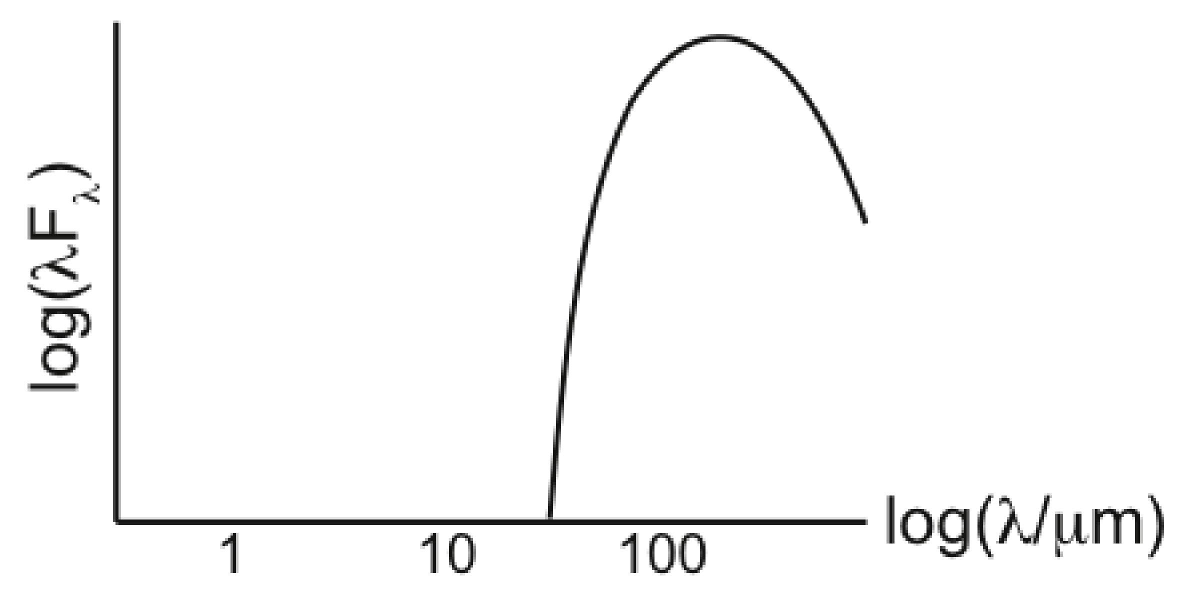
Armitage (2007)

$$\alpha_{\rm IR} = \frac{d\log\left(\lambda F_\lambda\right)}{d\log\lambda}$$

SED Classification Scheme

Figures from Alex Dunhill (PhD thesis, 2013) & Armitage (2010)

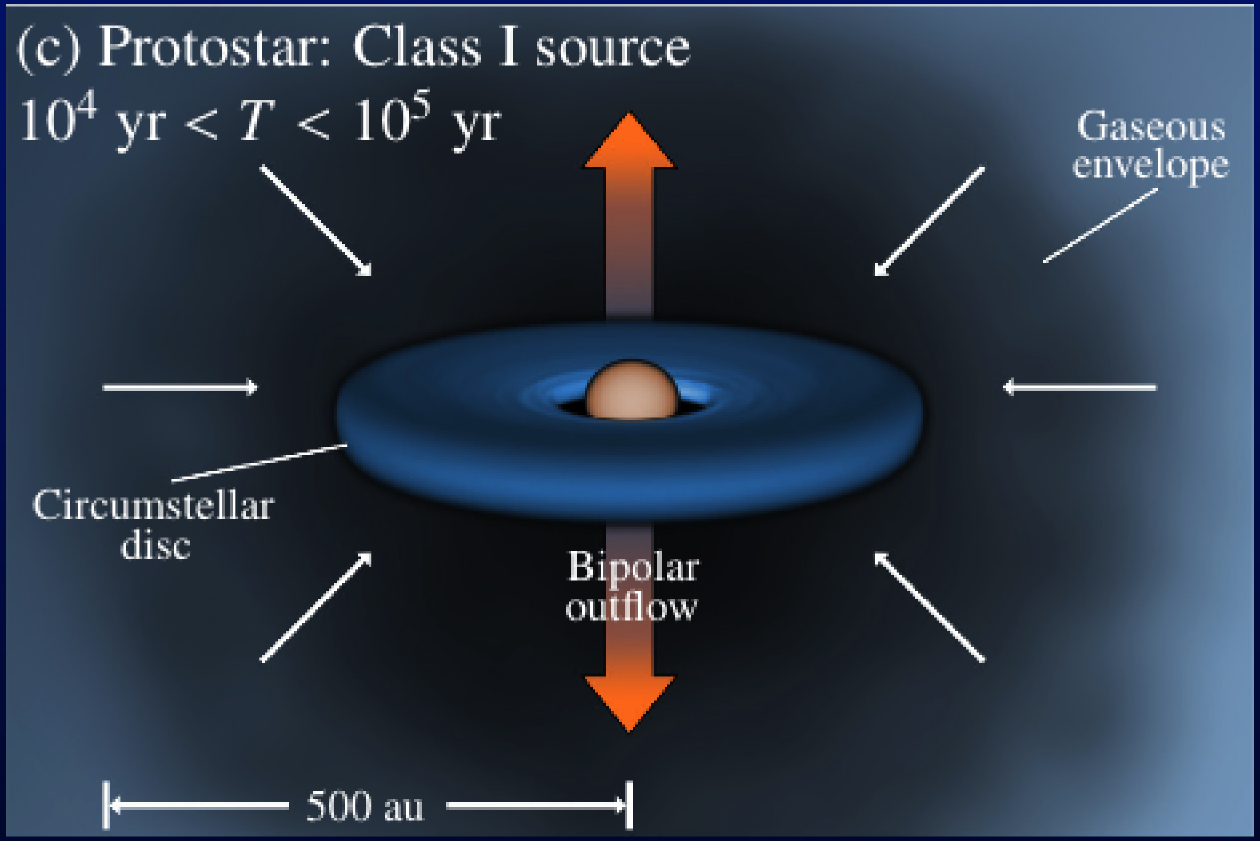


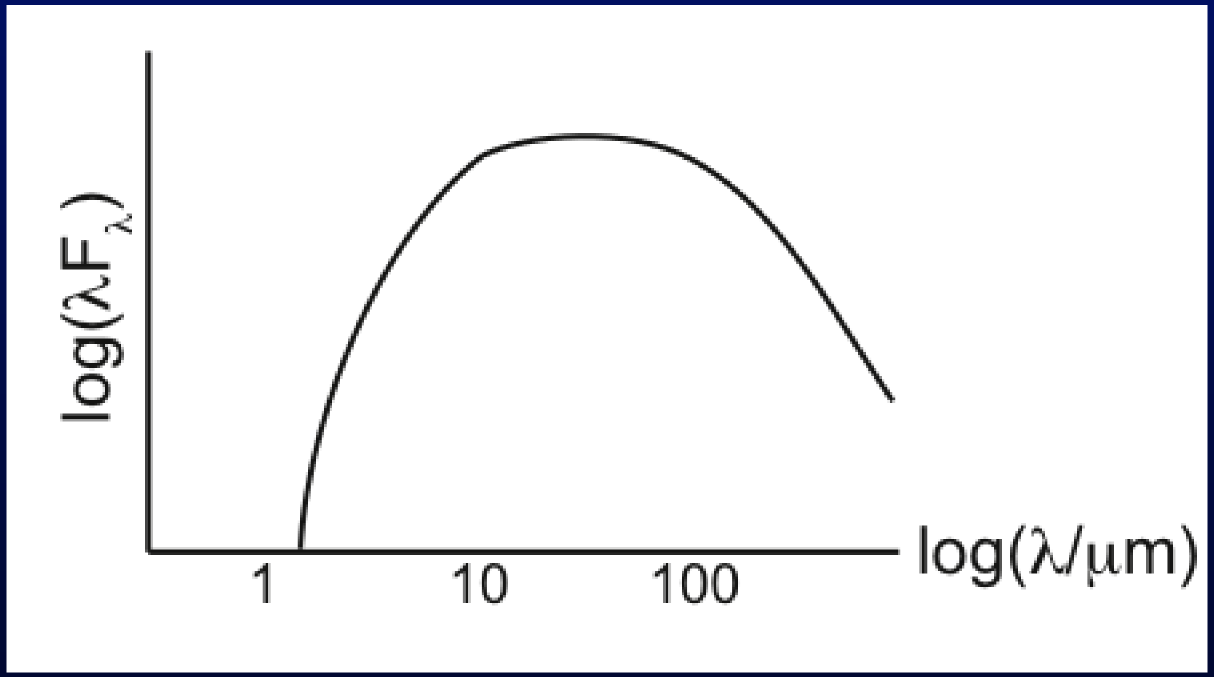


Class 0: sub-mm sources, no detectable IR emission

SED Classification Scheme

Figures from Alex Dunhill (PhD thesis, 2013) & Armitage (2010)

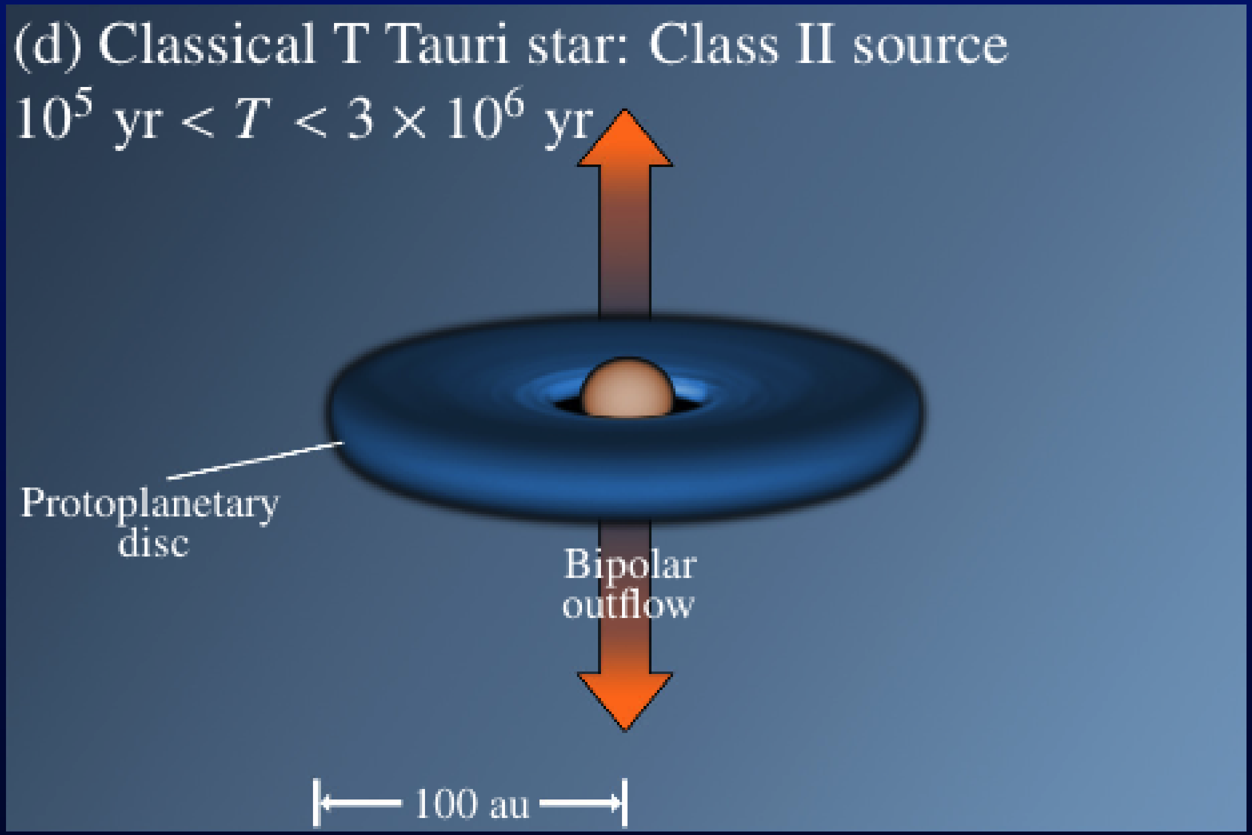


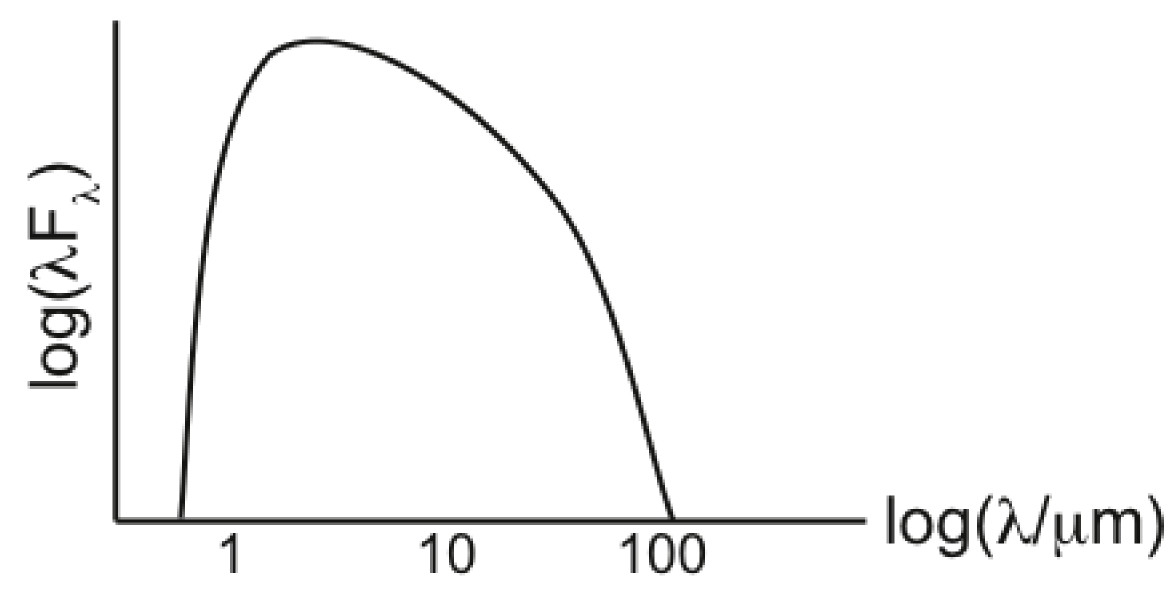


Class I: $\alpha_{\mathrm{IR}} \gtrsim 0.0$

SED Classification Scheme

Figures from Alex Dunhill (PhD thesis, 2013) & Armitage (2010)

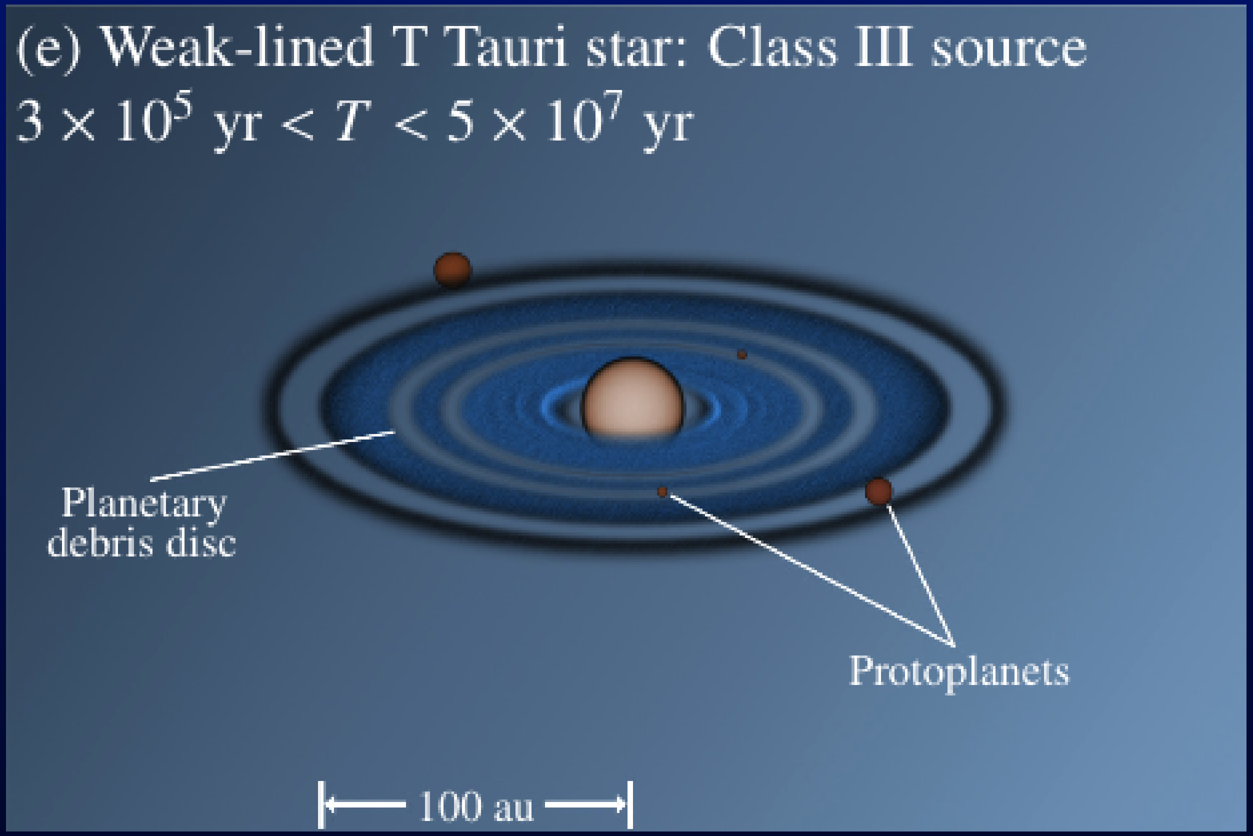


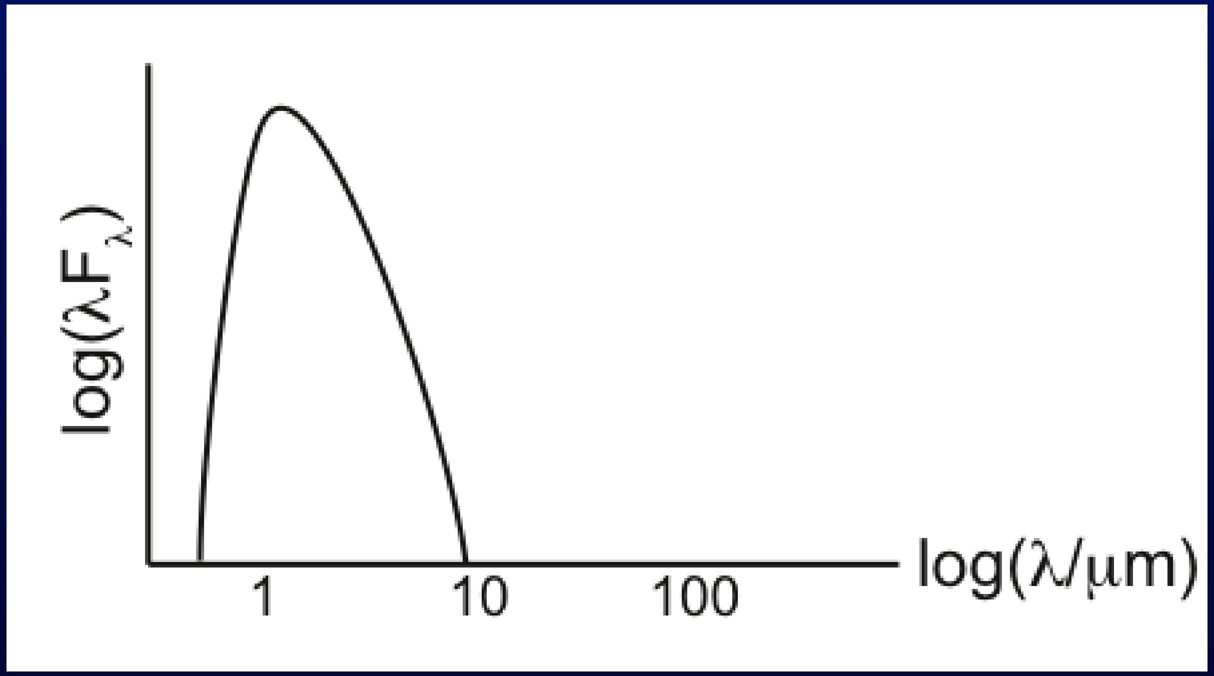


Class II: $-1.5 \lesssim \alpha_{\rm IR} \lesssim 0.0$

SED Classification Scheme

Figures from Alex Dunhill (PhD thesis, 2013) & Armitage (2010)



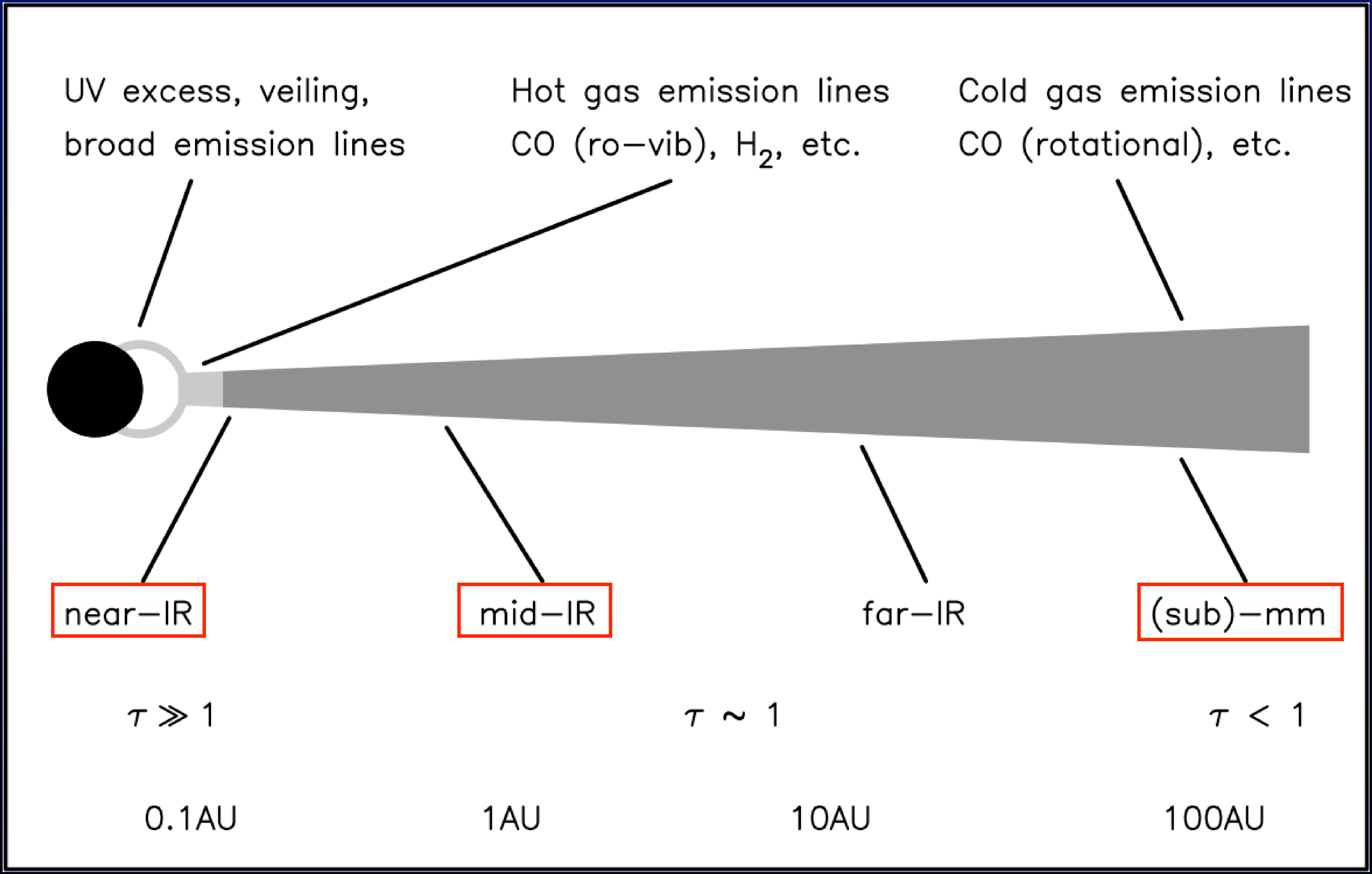


Class III: $\alpha_{\rm IR} \sim -1.5$

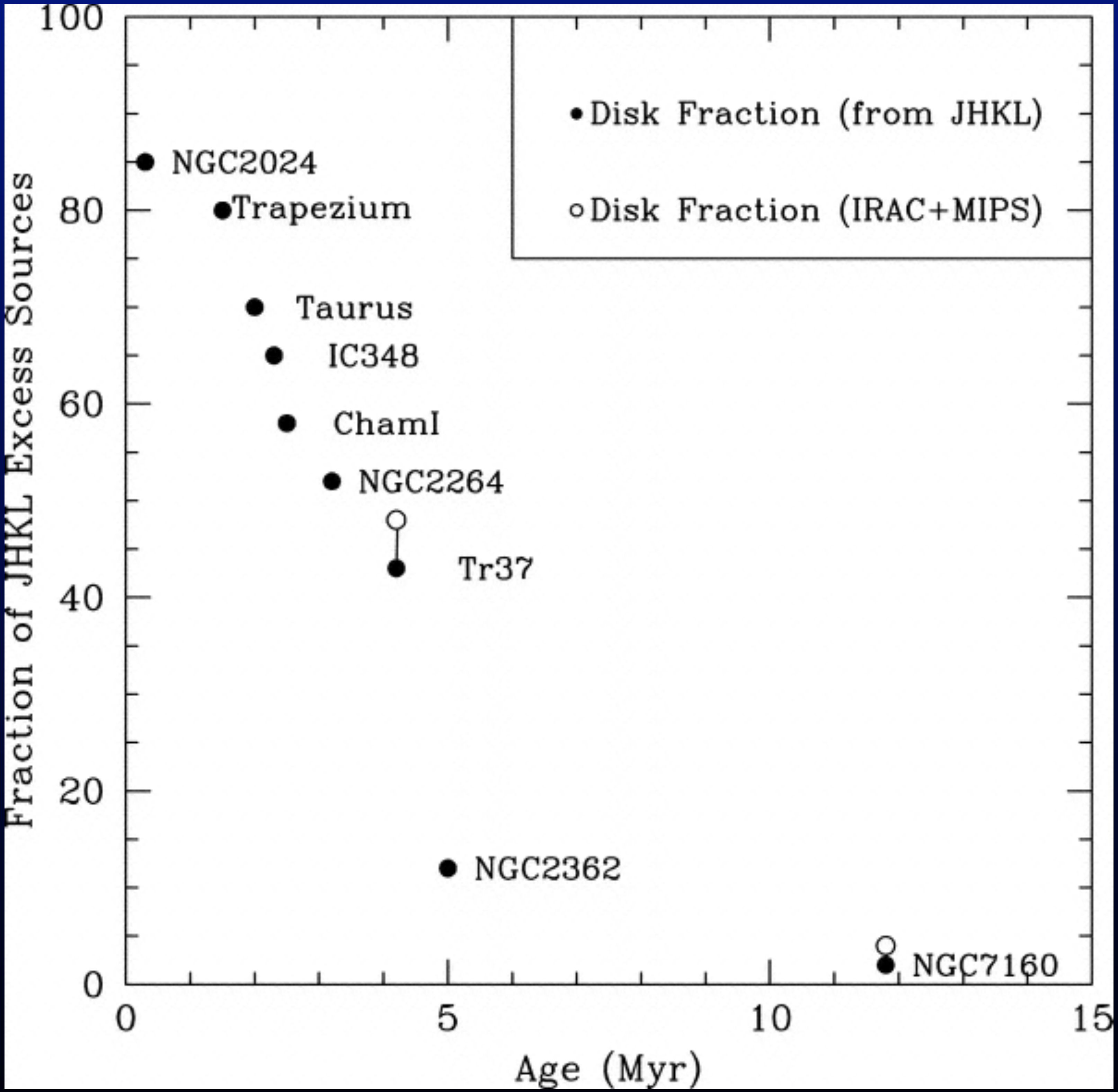
Observations of protoplanetary discs

GAS

DUST

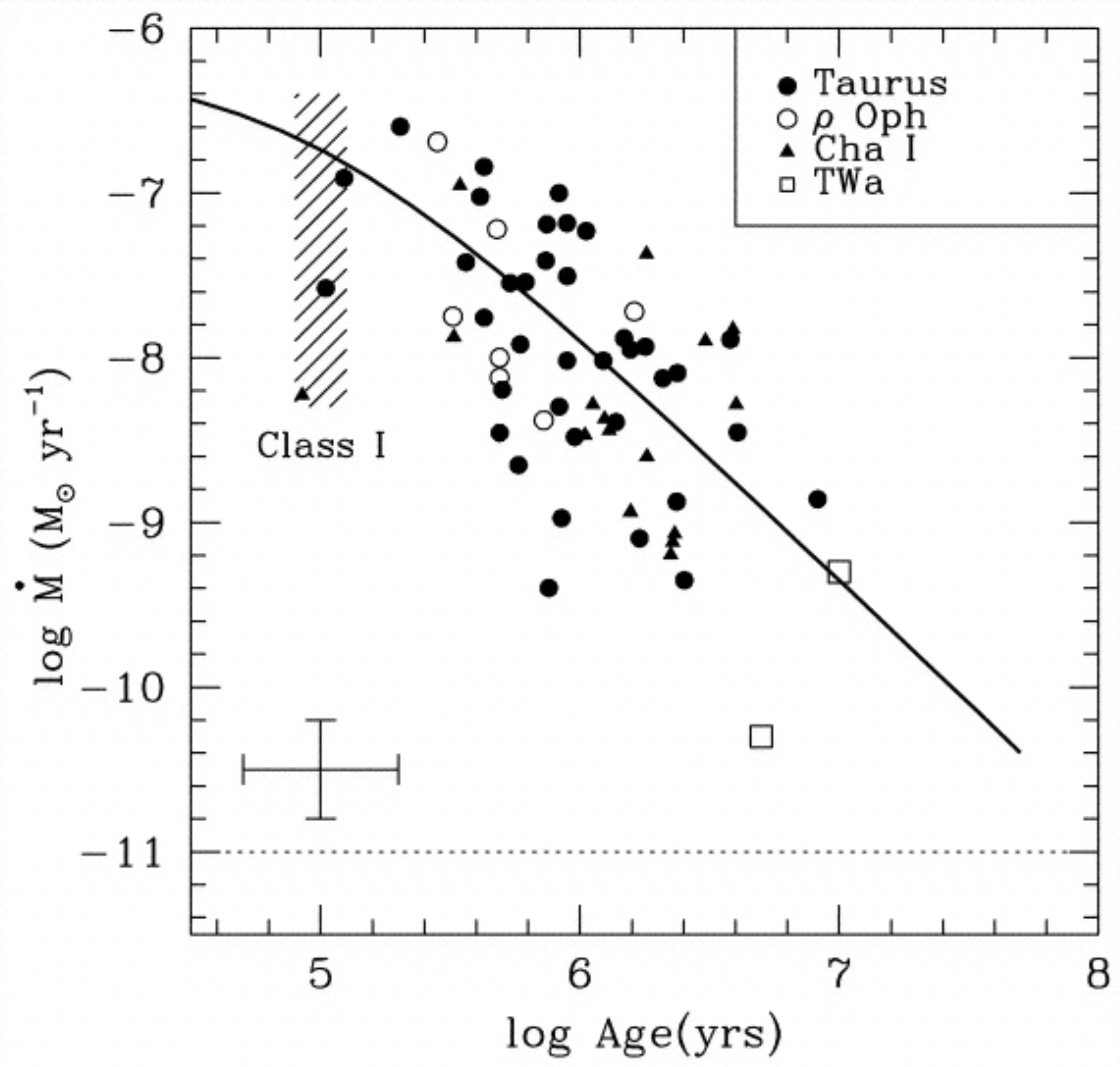


Disc lifetimes



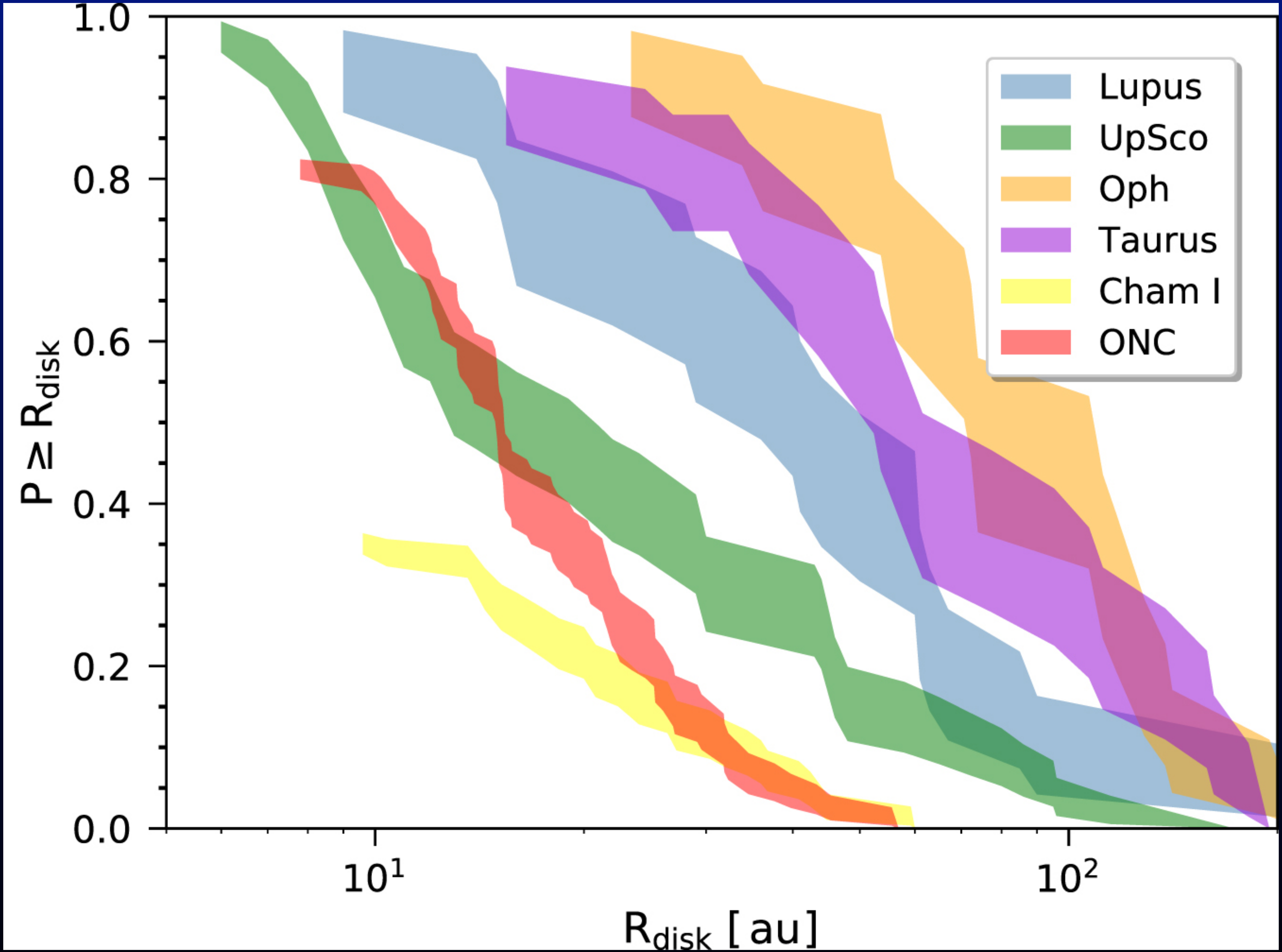
Sicilia-Aguilar et al. (2006)

Accretion rates



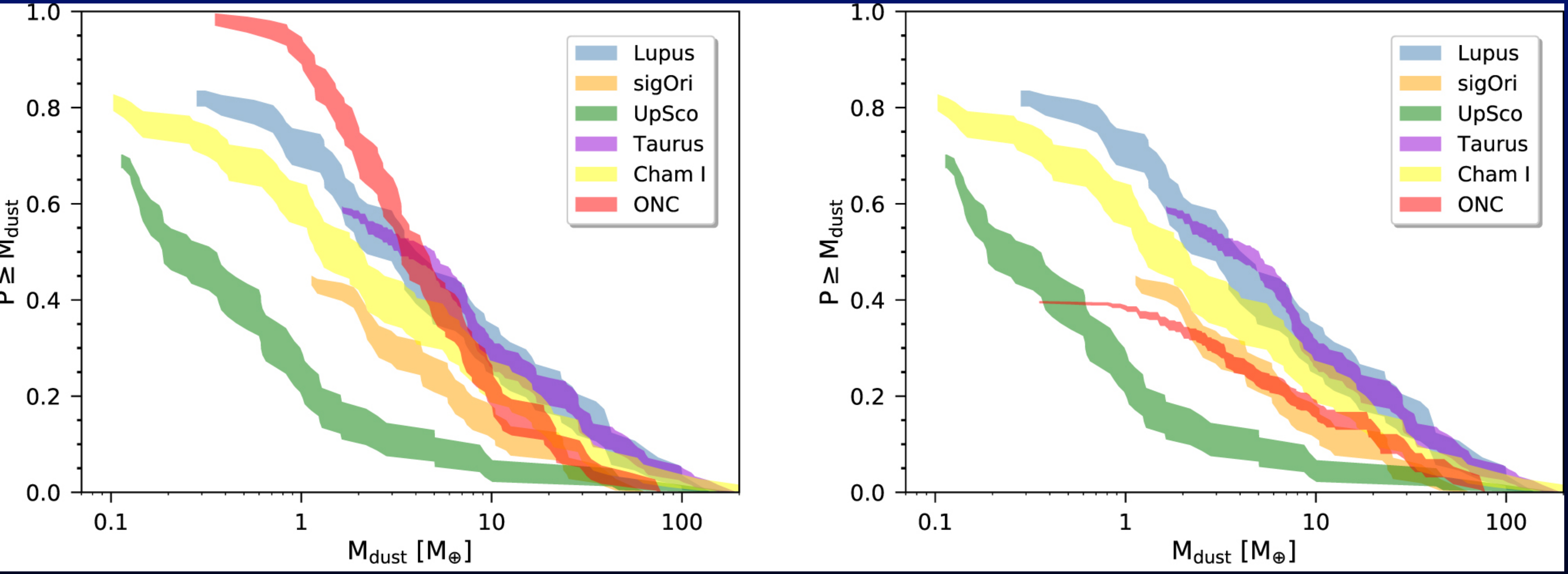
Muzerolle et al. (2000)

Disc sizes



Data compilation from Eisner et al. (2018)

Disc masses



Data compilation from Eisner et al. (2018)

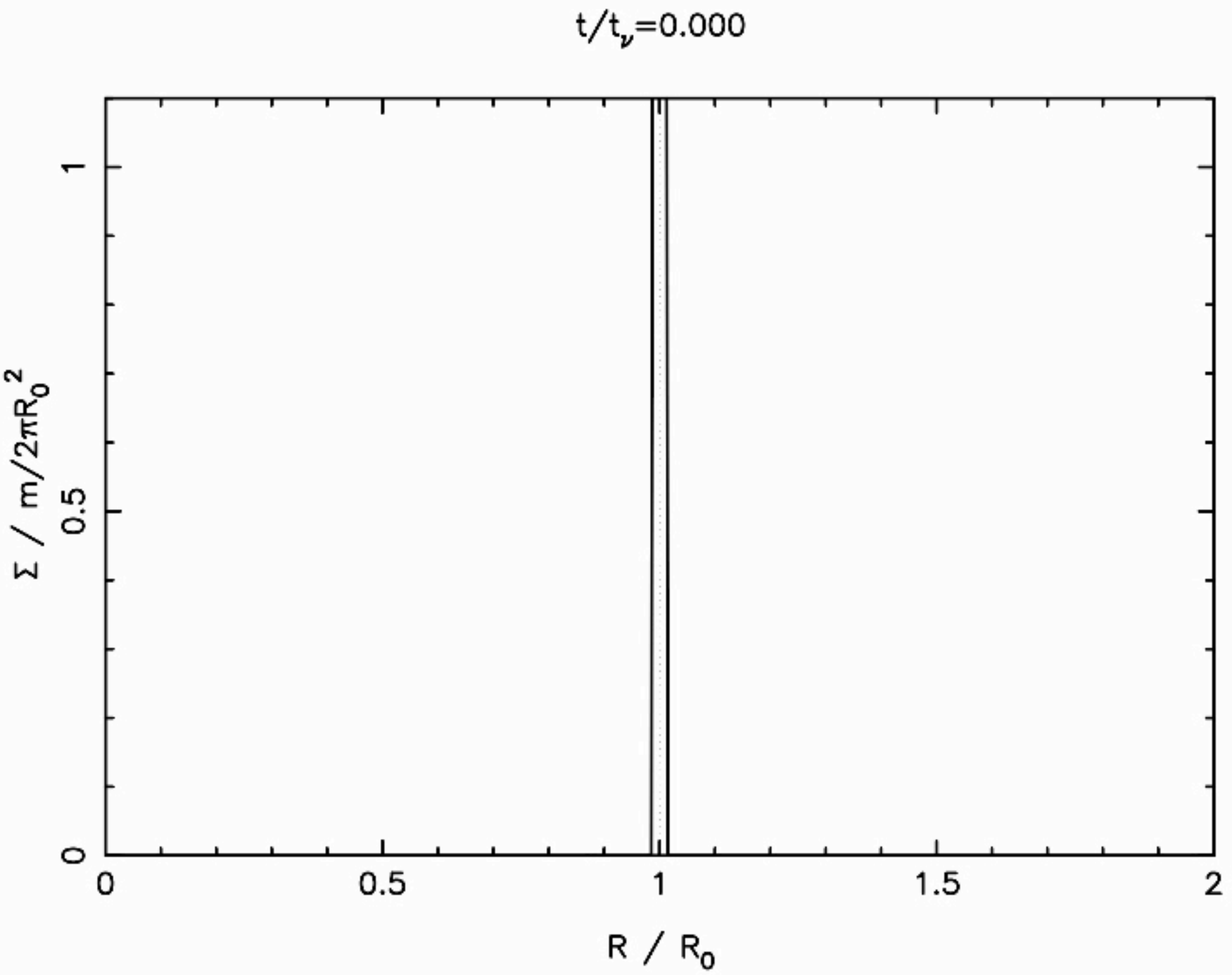
Observational Summary

- Discs are tens to hundreds of AU in size.
- Disc masses range from $>0.1M_\odot$ to $\lesssim 0.001M_\odot$.
- Accretion rates span $>10^{-7}M_\odot yr^{-1}$ to $\lesssim 10^{-10}M_\odot yr^{-1}$.
- Disc lifetimes are ~Myr (gas and dust tracers), with significant scatter.
- Cessation of (gas) accretion roughly simultaneous with (dust) disc clearing.

- Disc lifetimes set a limit on the time-scale for (giant) planet formation.
- Disc observations tell us the typical conditions for planet formation.

Viscous spreading ring

Pringle (1981)



Viscous disc similarity solution

Lynden-Bell & Pringle (1974)

$$\nu \propto R^{\gamma}$$

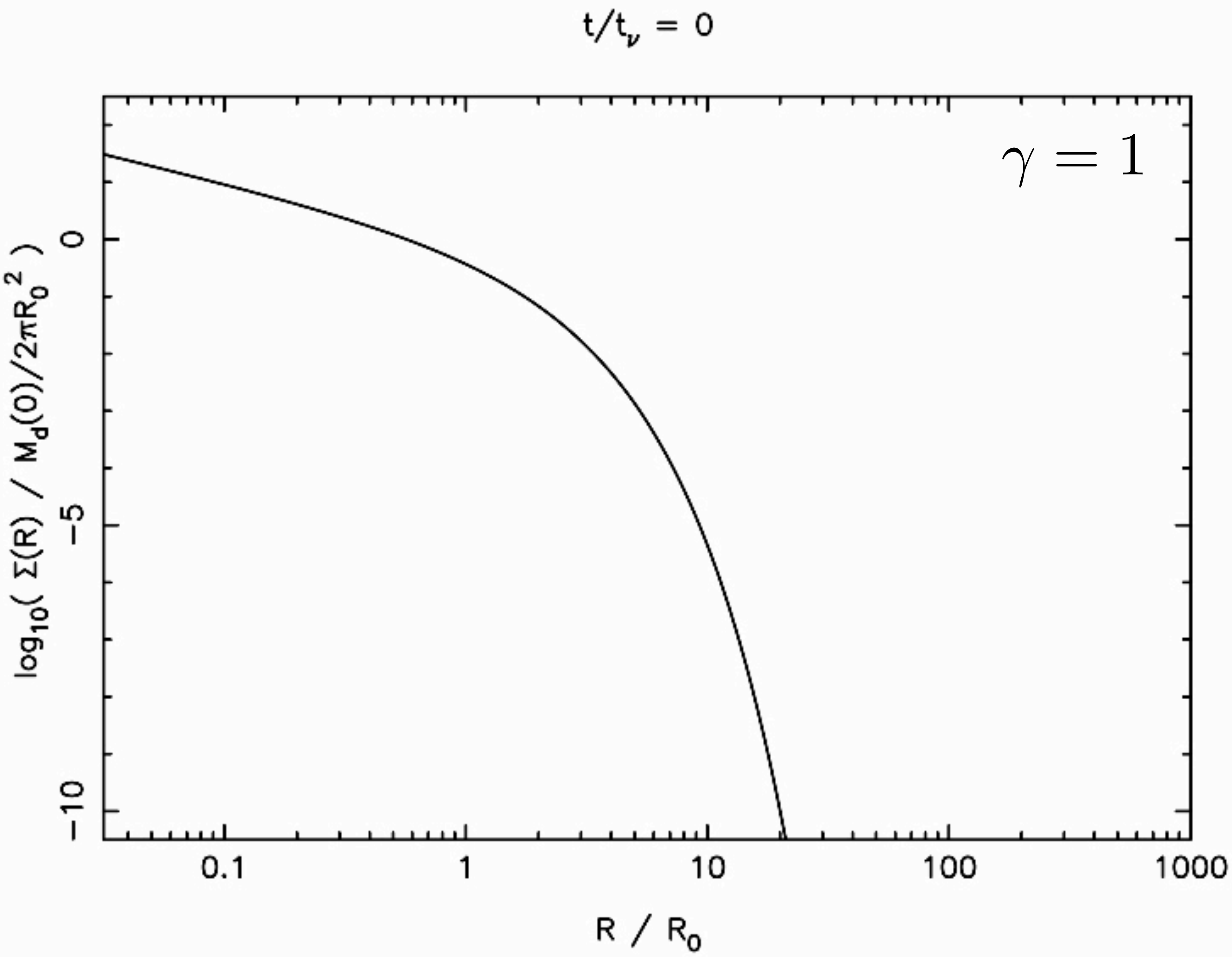
$$\Sigma(R,t) = \frac{M_d(0)(2-\gamma)}{2\pi R_0^2 r^{\gamma}} \tau^{\frac{-(5/2-\gamma)}{2-\gamma}} \exp\left(-\frac{r^{2-\gamma}}{\tau}\right)$$

$$r = R/R_0 \qquad \tau = t/t_{\nu} + 1 \qquad t_{\nu} = \frac{R_0^2}{3(2-\gamma)^2 \nu_0}$$

$$\dot{M}_{acc} = \frac{M_d(0)}{2(2-\gamma)t_{\nu}} \tau^{\frac{-(5/2-\gamma)}{2-\gamma}}$$

Viscous disc similarity solution

Lynden-Bell & Pringle (1974)



Disc stability criteria

- Purely hydrodynamic disc (Rayleigh). Unstable if:

$$\kappa^2 = \frac{2\Omega}{R}\frac{d}{dR}\left(R^2\Omega\right) < 0$$

- MHD disc. Unstable if:

$$(\mathbf{k}.\mathbf{u}_{\mathrm{A}})^2 + \frac{d\Omega^2}{d\ln R} < 0$$

- Alfvén velocity:

$$u_{\mathrm{A}} = \sqrt{B^2/4\pi\rho}$$

- In limit $B \to 0$ (weak B-field), unstable if:

$$\frac{d\Omega^2}{d\ln R} < 0$$

The magnetorotational instability

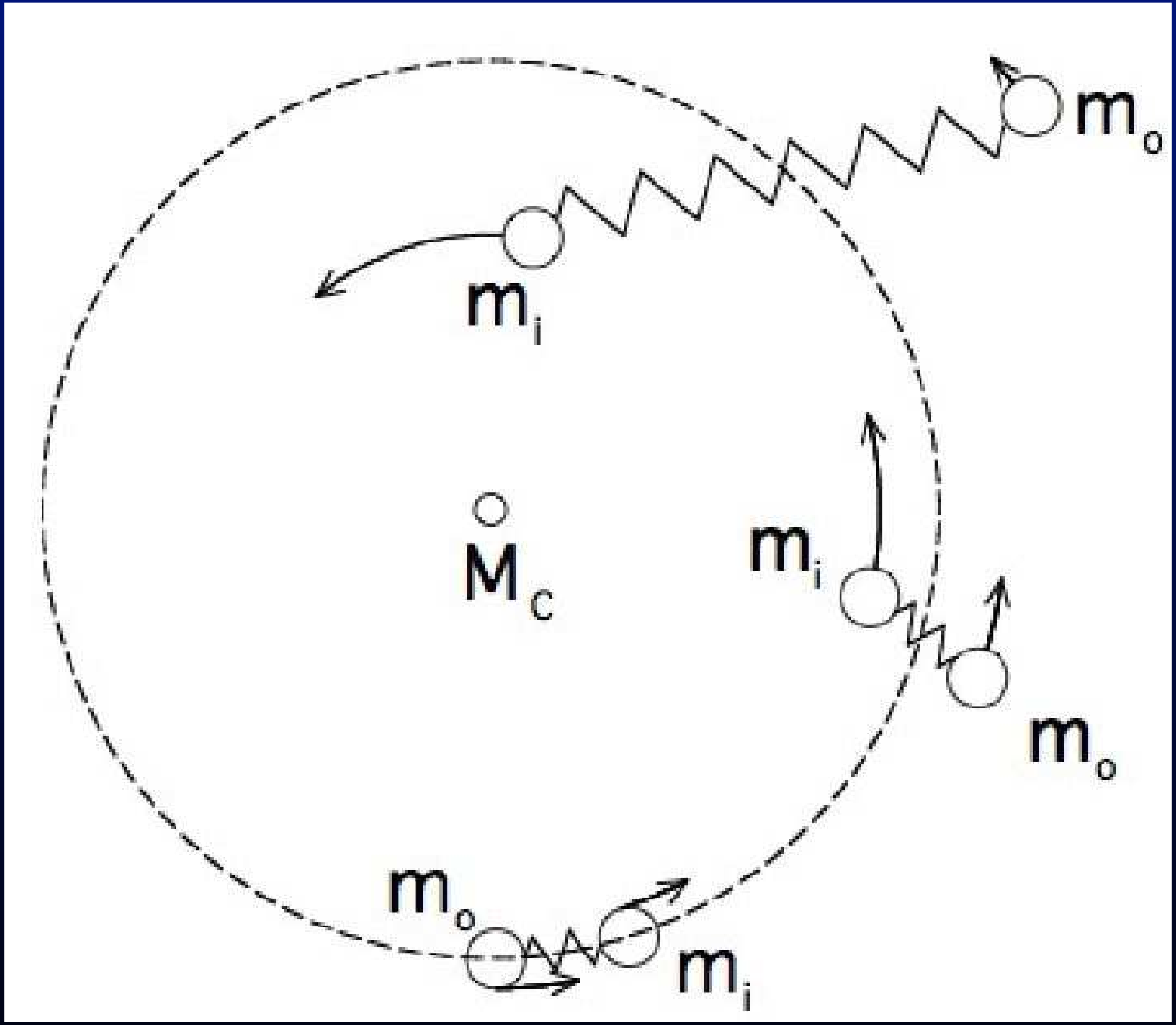
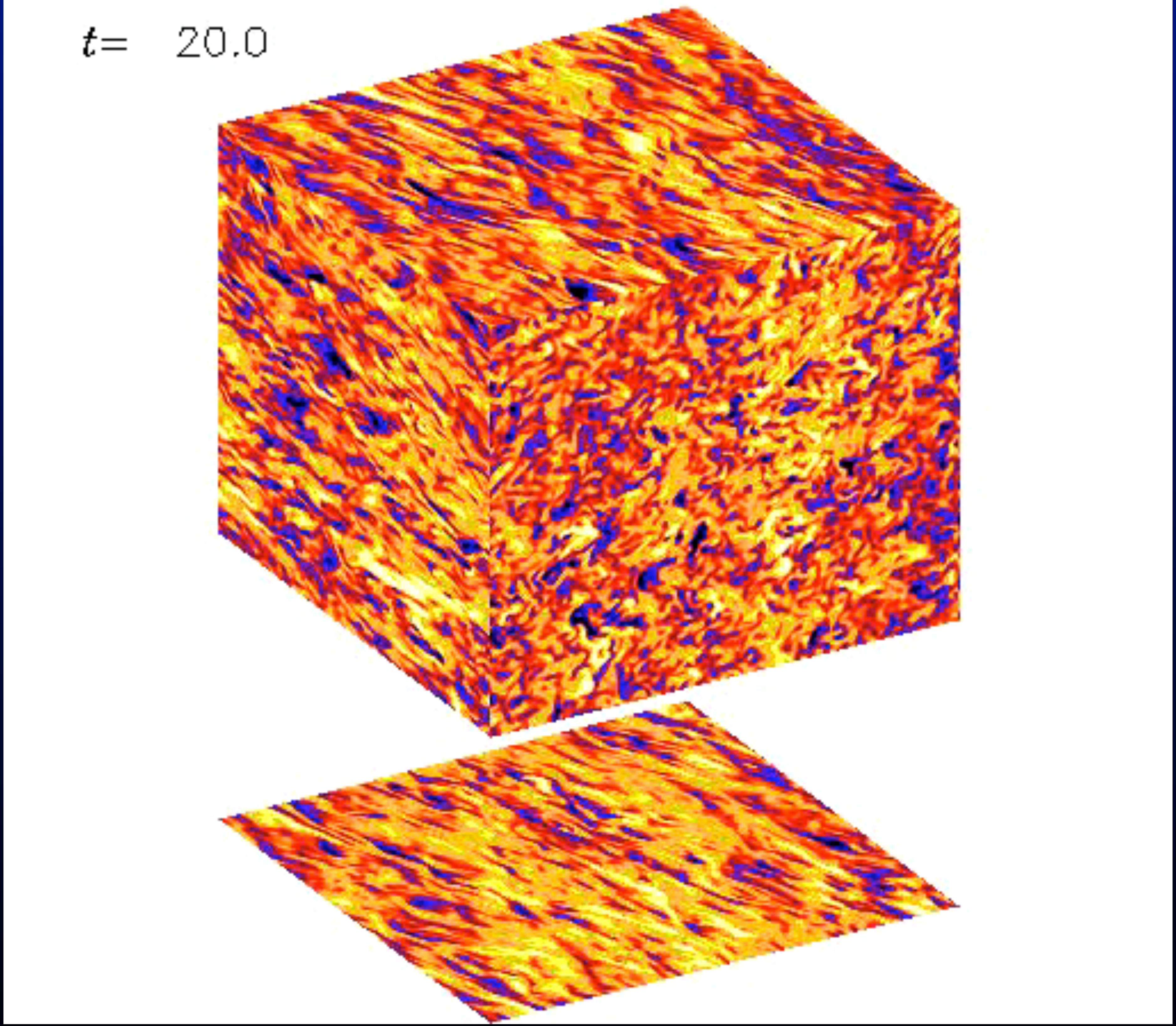


Figure from Balbus (2011)

Local simulations (ideal MHD)



Animation courtesy of Anders Johansen (Lund)

Global simulations (ideal MHD)

Accretion and Outflows in 3D Global MHD Simulations of Stratified Protoplanetary Disk

Mario Flock
Ringberg 2011

Animation from Flock et al. (2011)

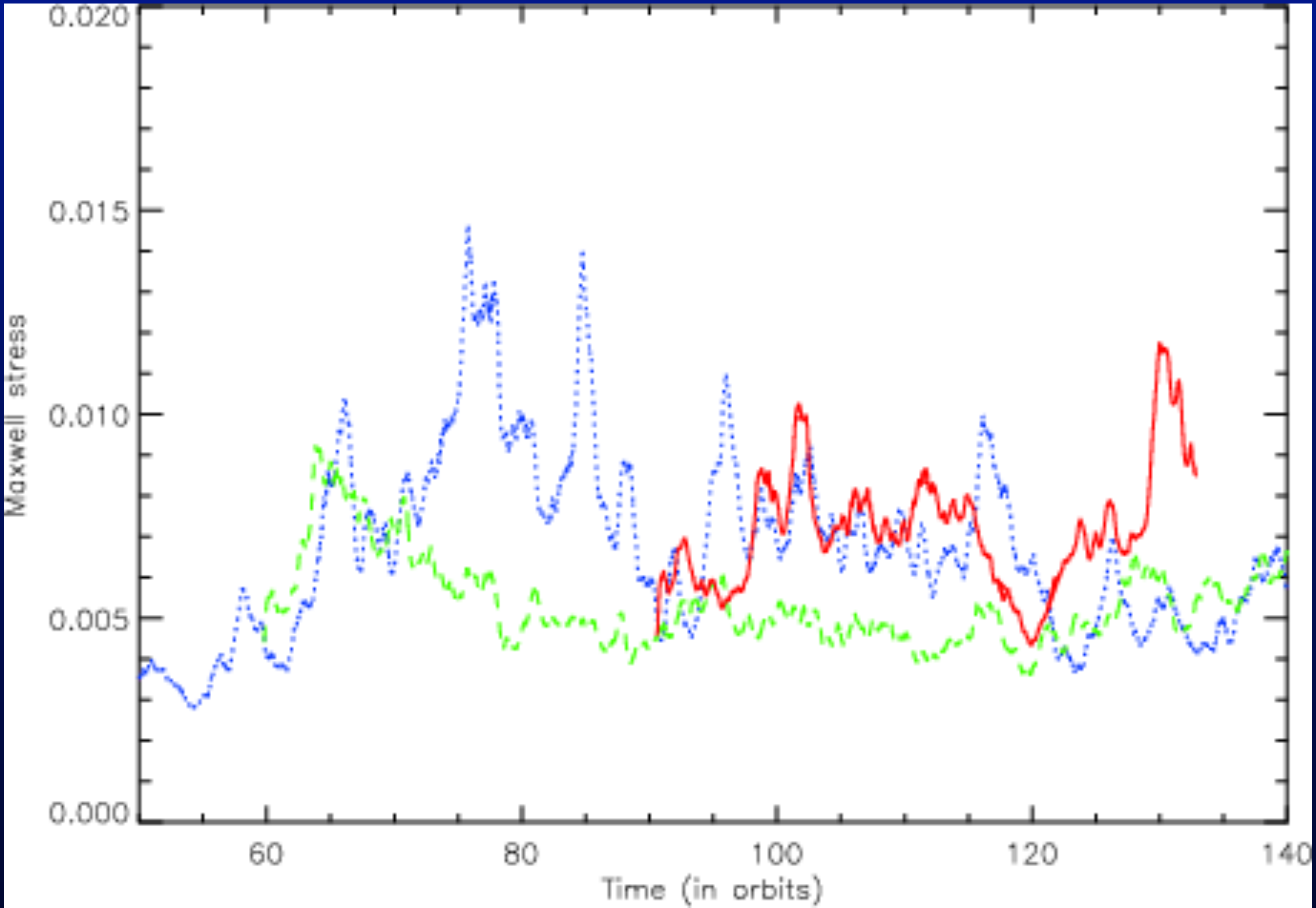


Figure from Fromang (2010)

Numerical simulations suggest that (ideal) MRI turbulence can drive angular momentum transport with an “effective alpha” value $\alpha \sim 0.01$.

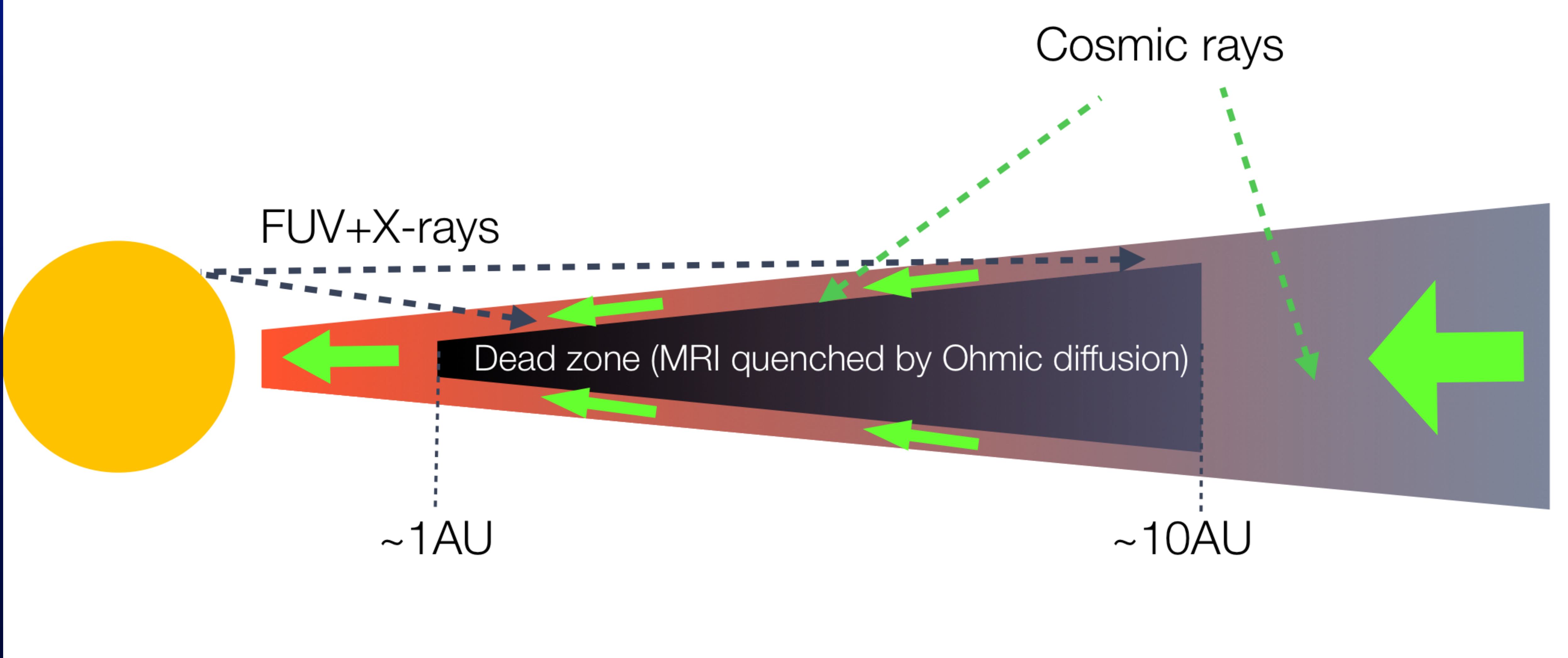


Figure from Geoffroy Lesur (PP6 talk), after Gammie (1996)

MRI requires that disc be partially ionized ($\sim 10^{-12}$). The midplane regions of protoplanetary discs may be "MRI dead", resulting in a layered disc structure.

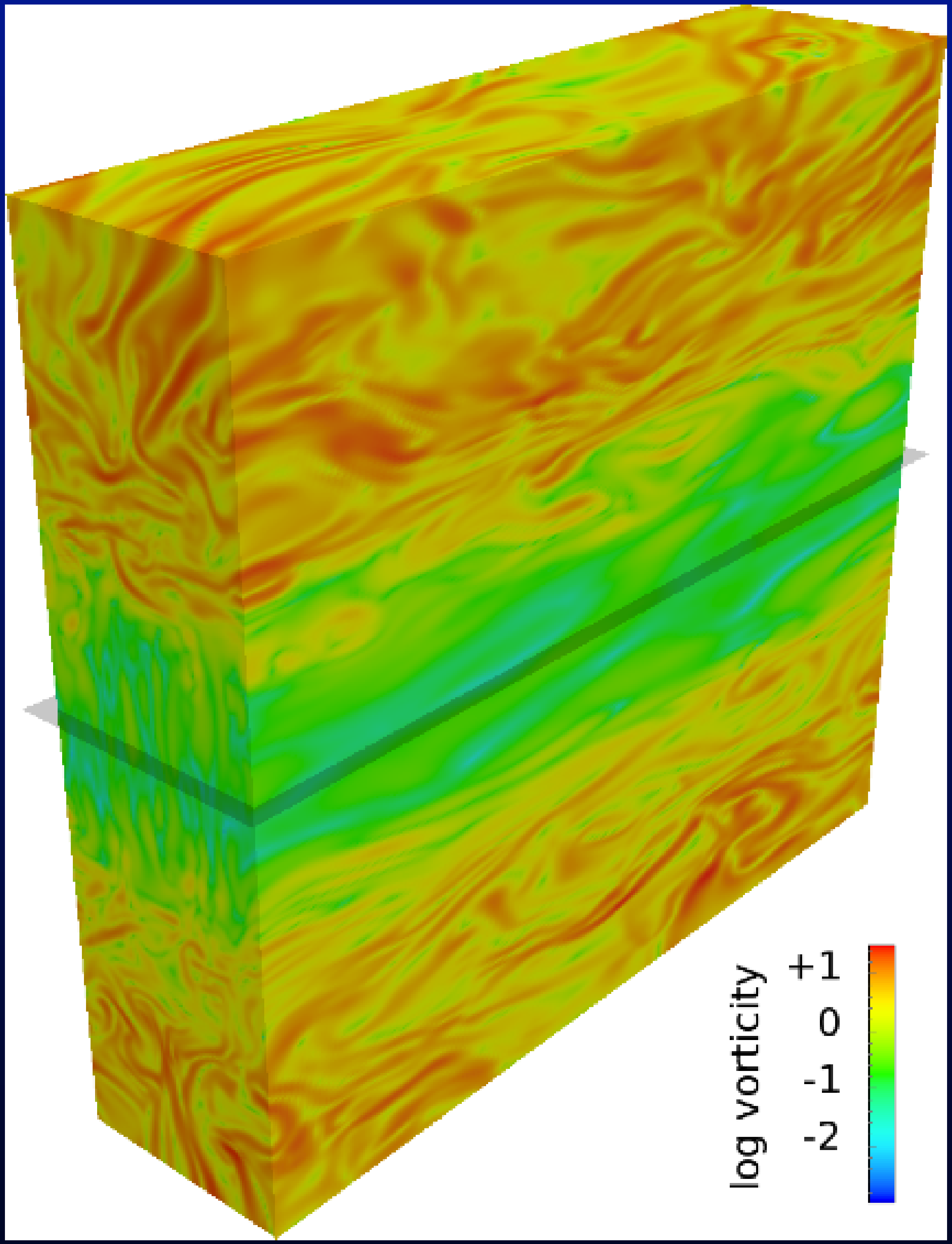


Figure from Gressel, Nelson & Turner (2011)

MRI requires that disc be partially ionized (~10^{-12}). The midplane regions of protoplanetary discs may be "MRI dead", resulting in a layered disc structure.

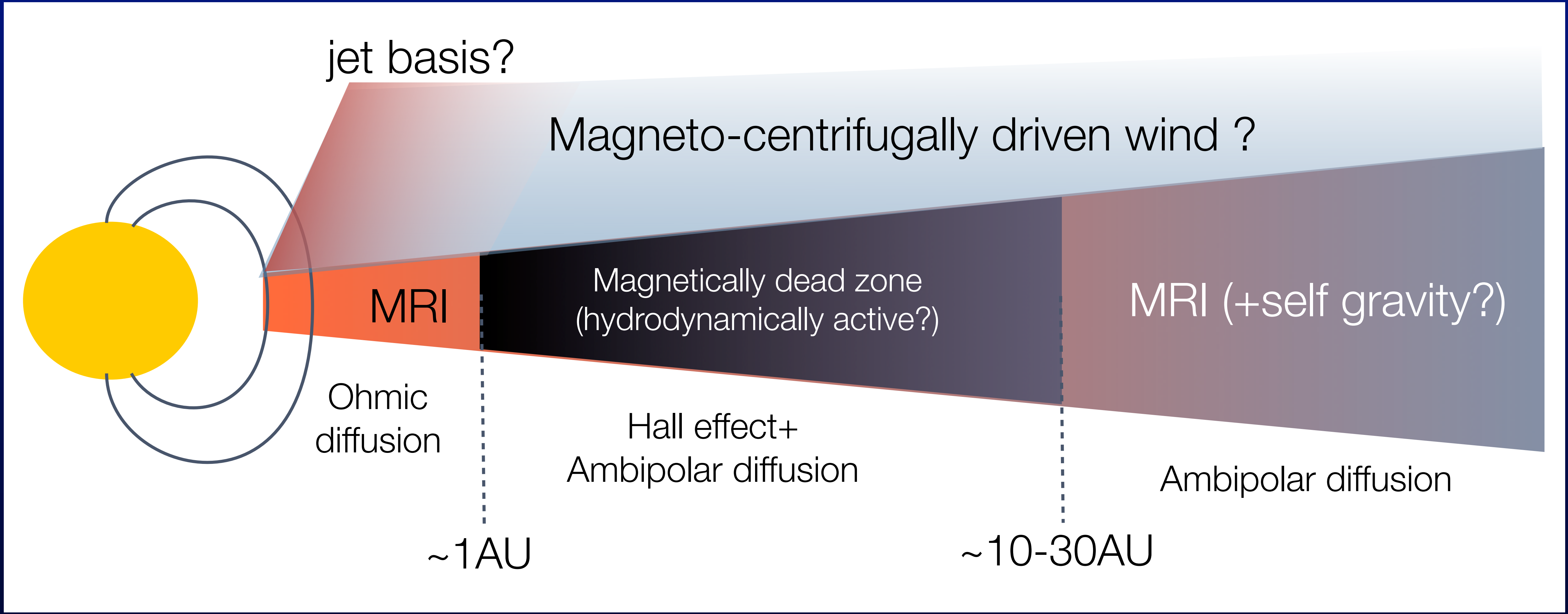
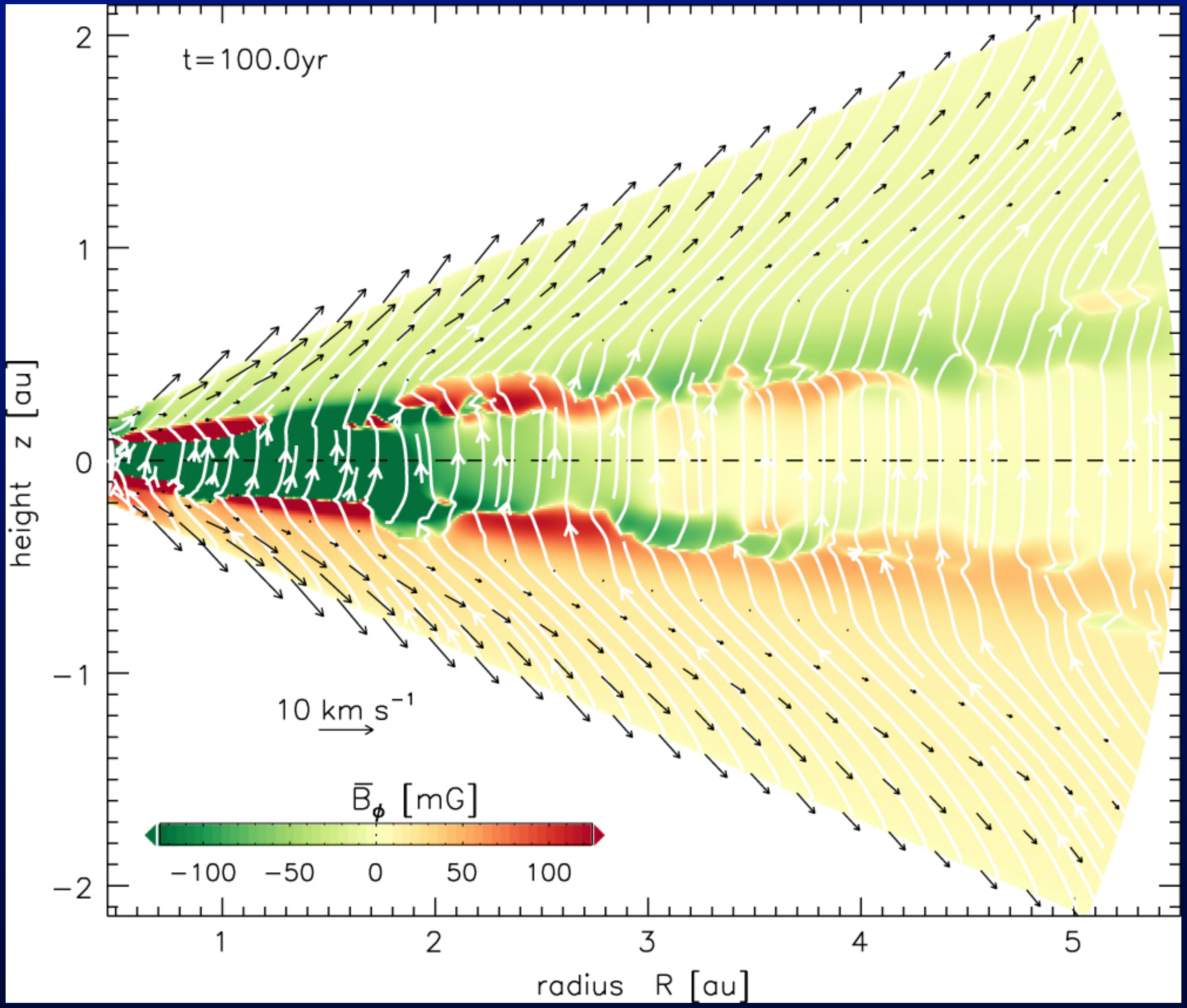
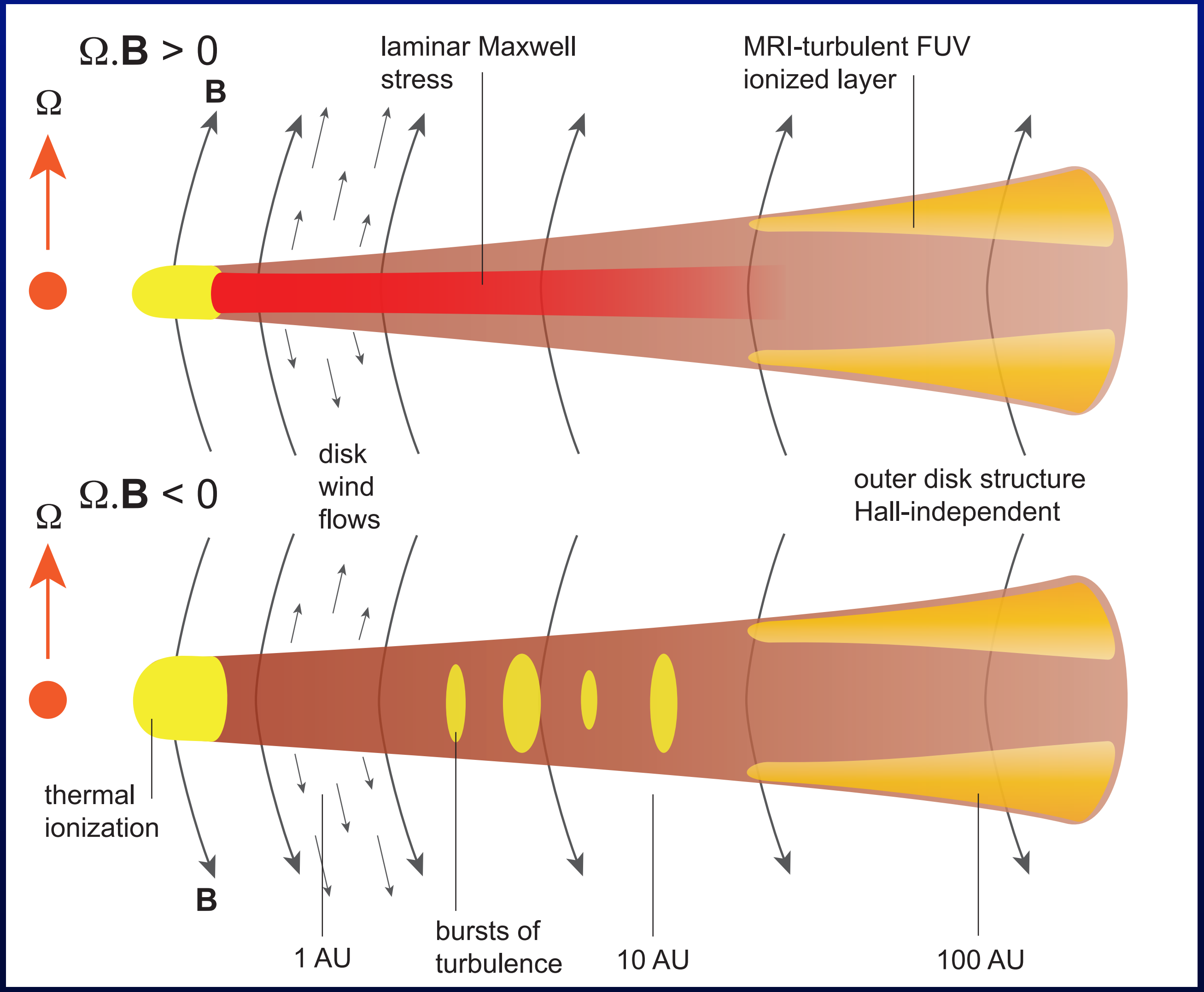


Figure courtesy of Geoffroy Lesur

In non-ideal MHD simulations, ambipolar diffusion + a vertical (poloidal) B-field always results in a magnetically-launched disc wind.

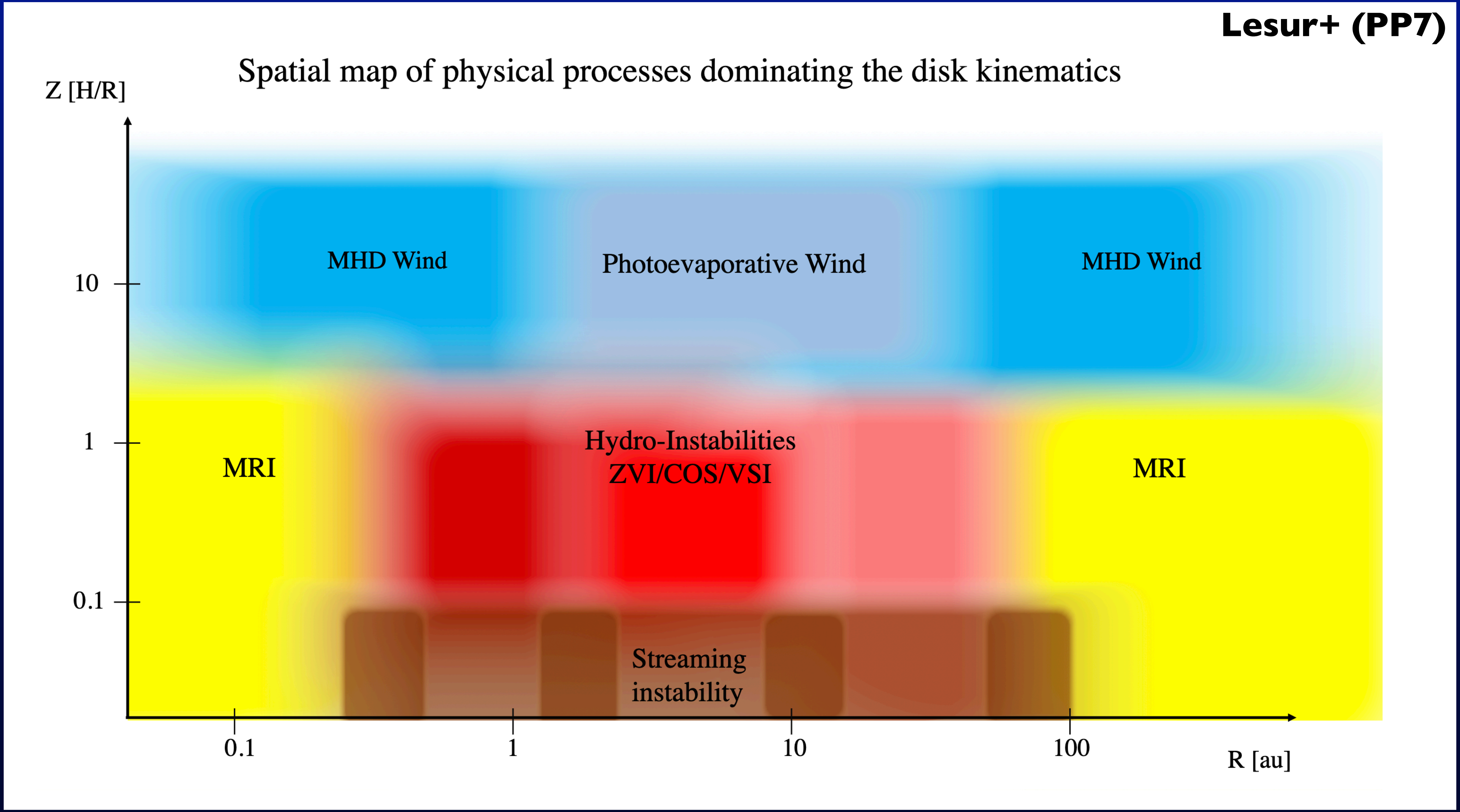


Gressel+ (2015)



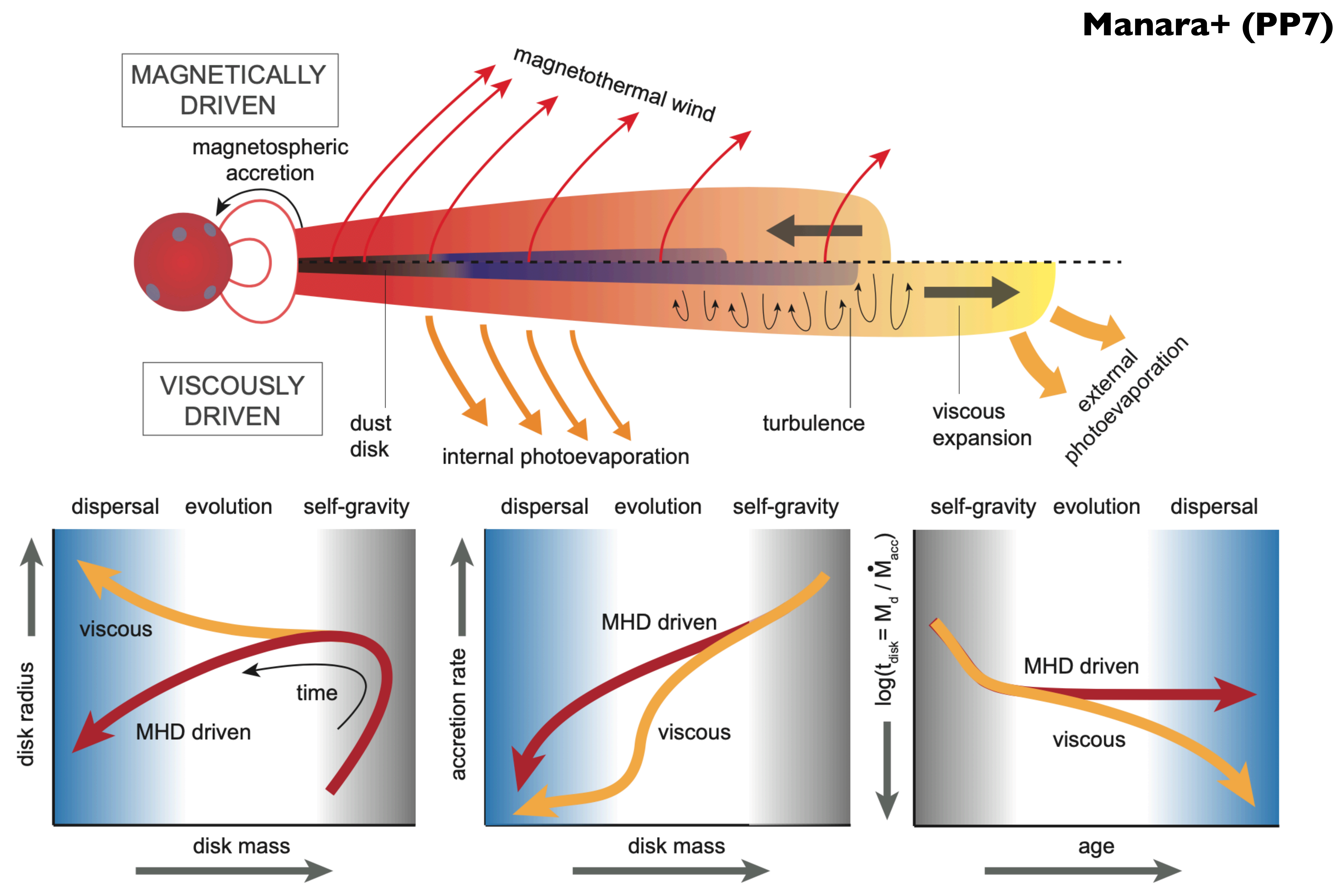
Simon+ (2015)

Many uncertainties remain, but broad picture is now largely agreed - "dead zones" always launch winds. Likely that mass-loss is a combination of MRI-wind + photoevaporation: "magneto-thermal wind" (Bai+ 2016).



Dominant transport processes vary with R and z, and probably also with time (as disc evolves).

[We'll discuss the streaming instability in Lecture 3.]



It's not clear whether turbulence or the wind torque is the dominant driver of disc accretion/evolution. Most likely both play a role…