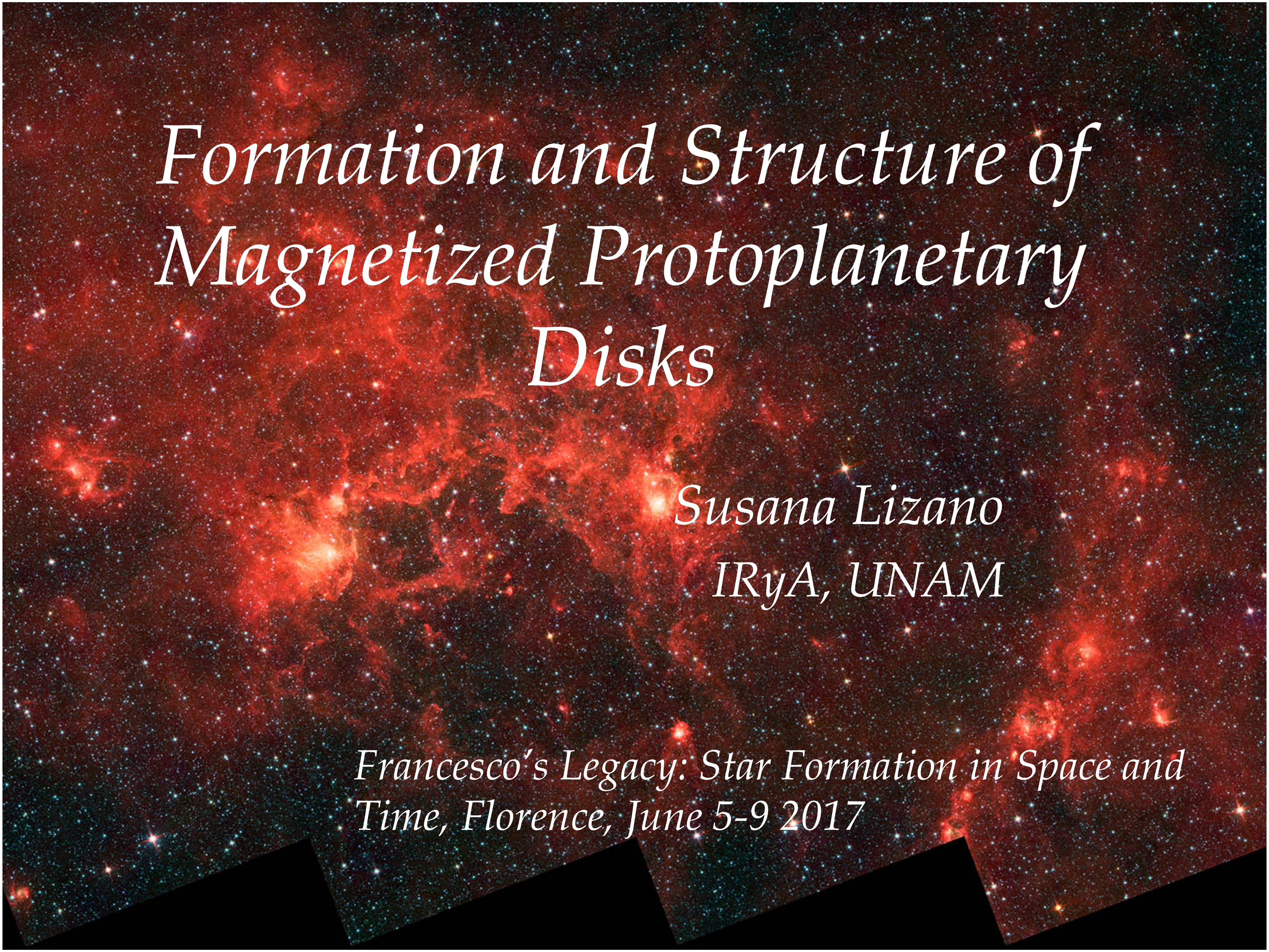

Formation and Structure of Magnetized Protoplanetary Disks

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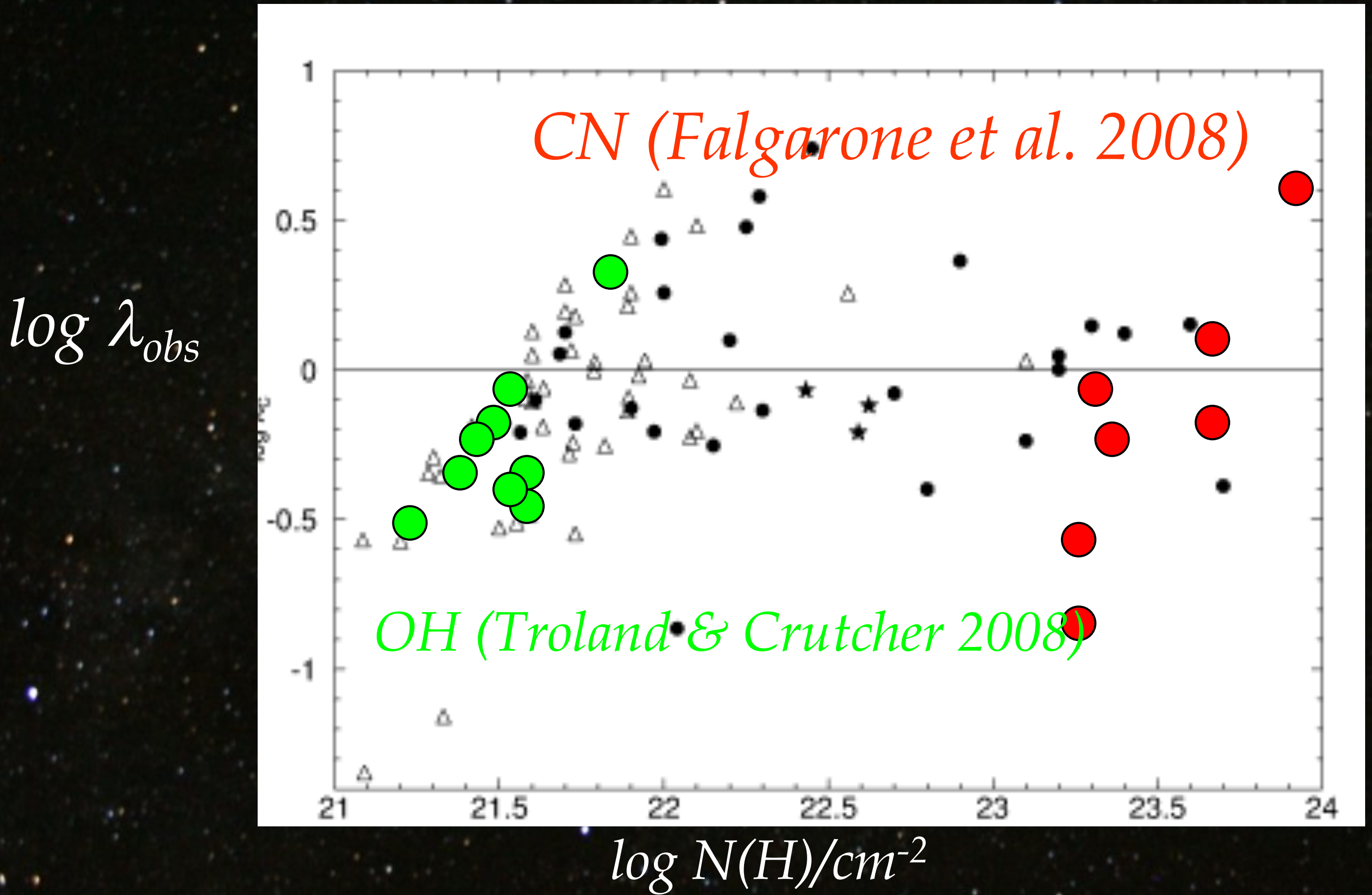
Francesco's Legacy: Star Formation in Space and Time, Florence, June 5-9 2017

The mass-to-magnetic flux ratio determines the relevance of magnetic support in cloud cores

$$\lambda = 2\pi G^{1/2} M/\Phi; \qquad \lambda > 1 \ \text{instability.}$$



After geometric corrections, λ_{core}~1-4

(Falgarone et al. 2008)

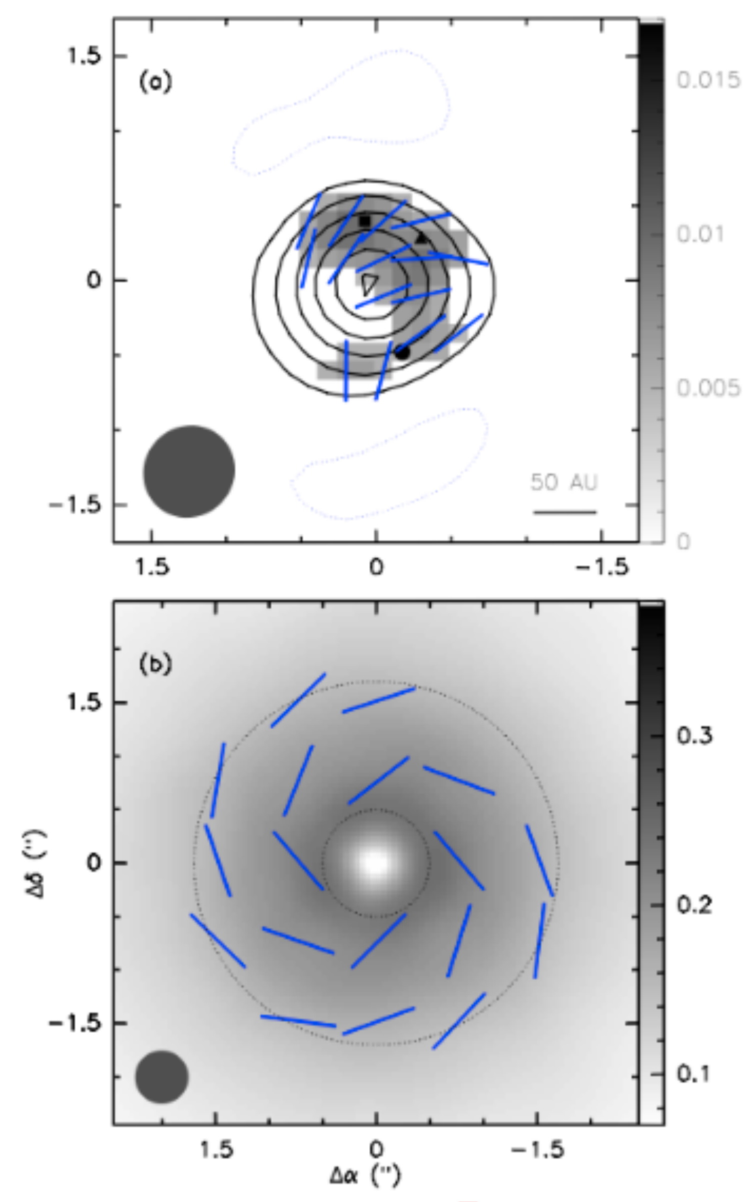
Zeeman splitting => $B_{l.o.s.}$ ~10 – 300 μG at n~3×10^{3} - 4×10^{5} cm^{-3}.

Polarized dust emission from circumstellar disks

SMA 878μm subarcsec observations of the disk of IRAS 16293 -2422B protostar find B_ϕ consistent with field line wrapping (Rao + 2014).

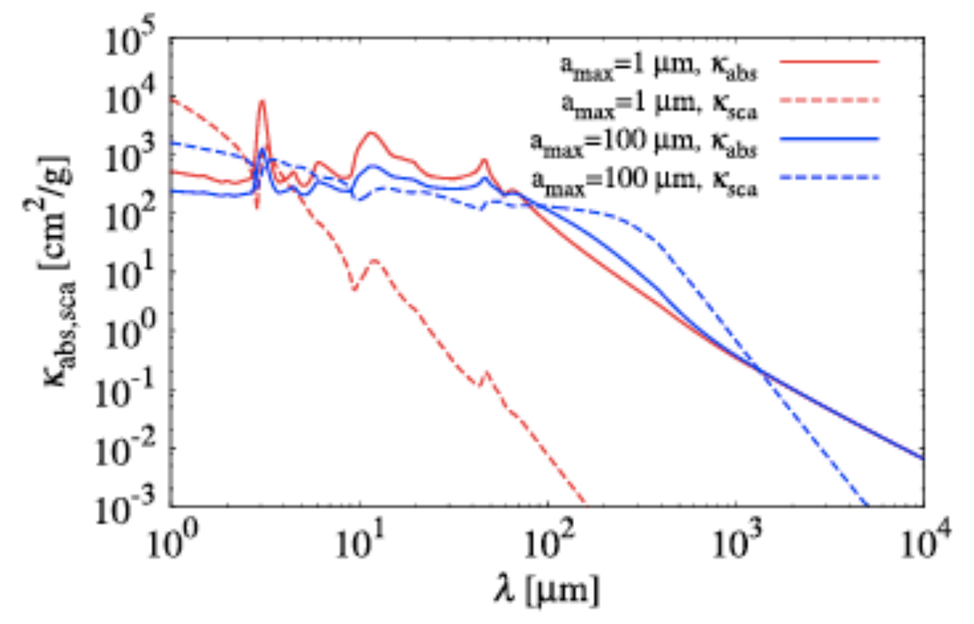
Also L1527 (Segura-Cox 2015).

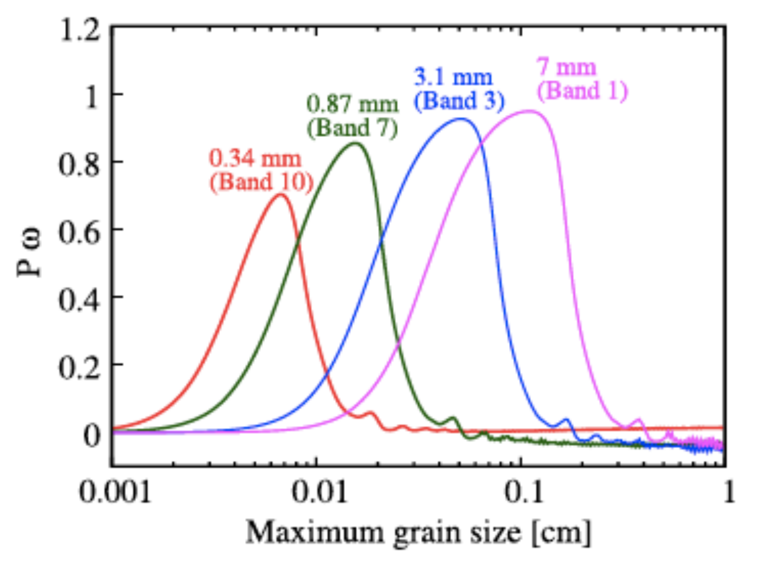
But scattered light can be important at mm (Katoaka +15).



140 pc

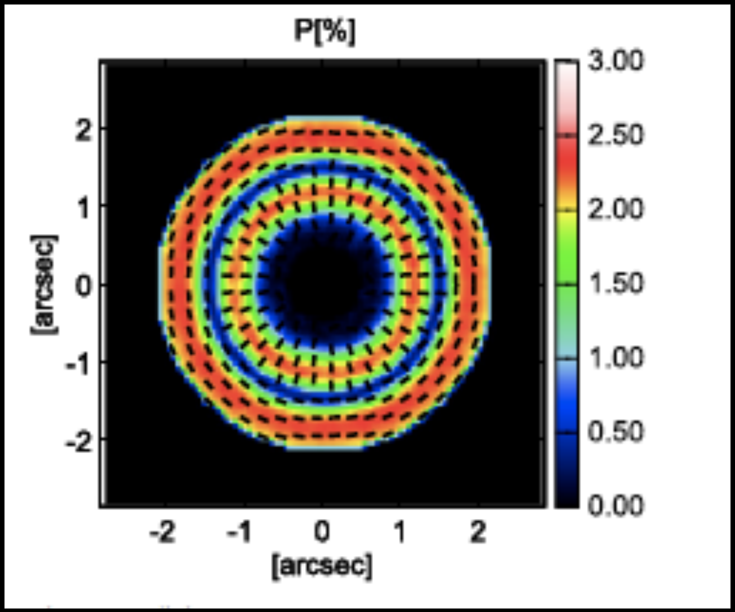
Aligned dust emission vs dust scattering



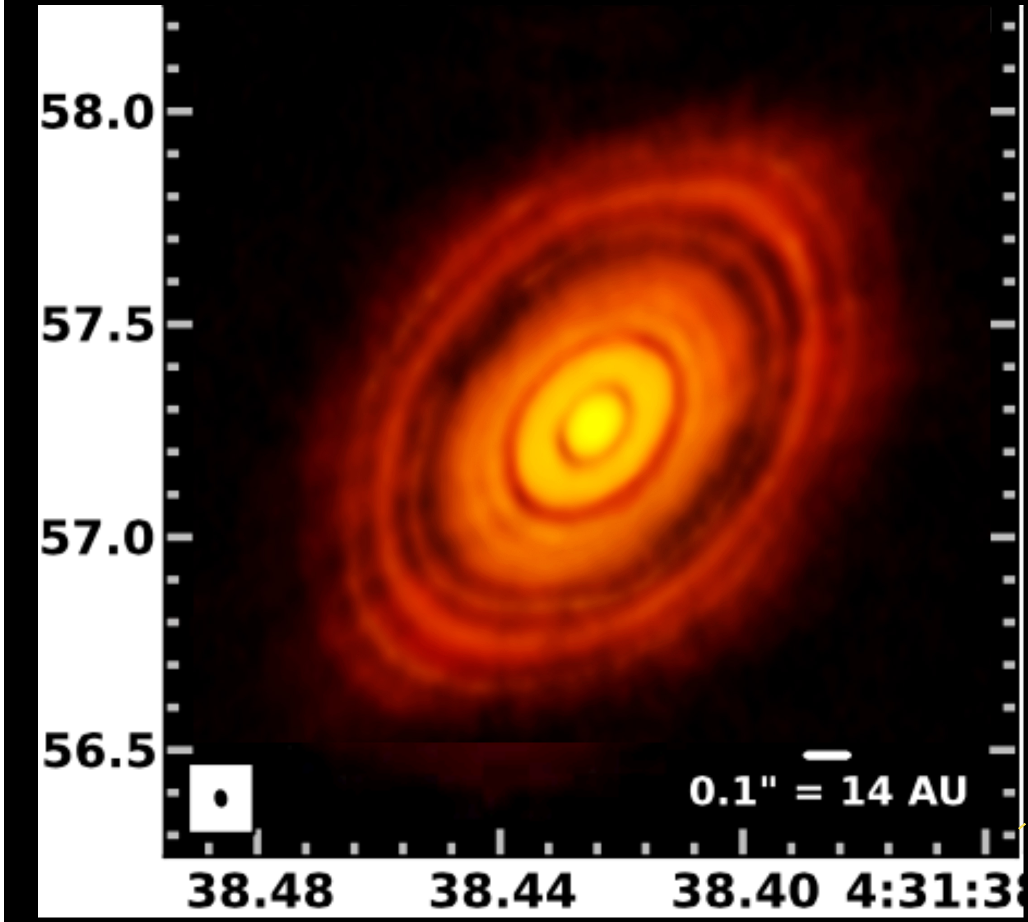


Katoaka + 2015; Yang + 2016

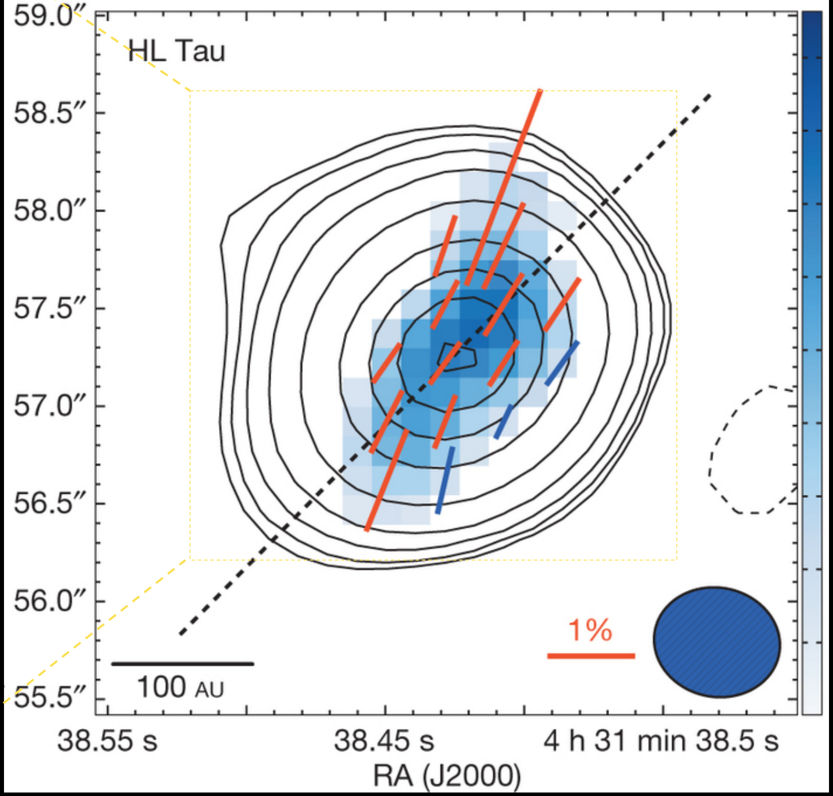
Polarized mm emission due to dust self-scattering



The HL Tau disk

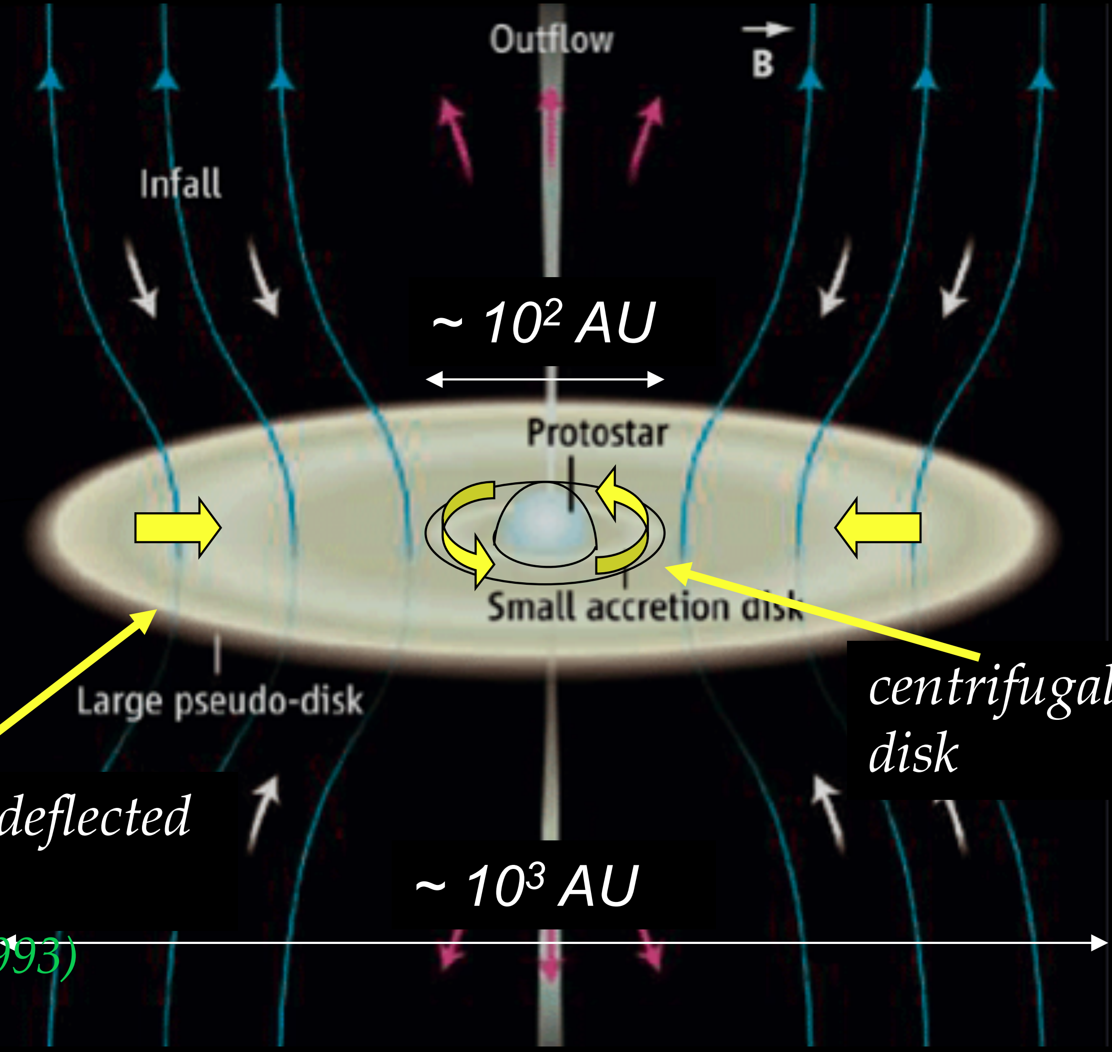


ALMA dust continuum at 1mm (Brogan et al. 2015).



CARMA dust continuum and polarization at 1.3mm (Stephens et al. 2015). But Yang +16.

Collapse of a rotating magnetized core: the naive expectation



~ 10^2 AU

~ 10^3 AU

centrifugally supported disk

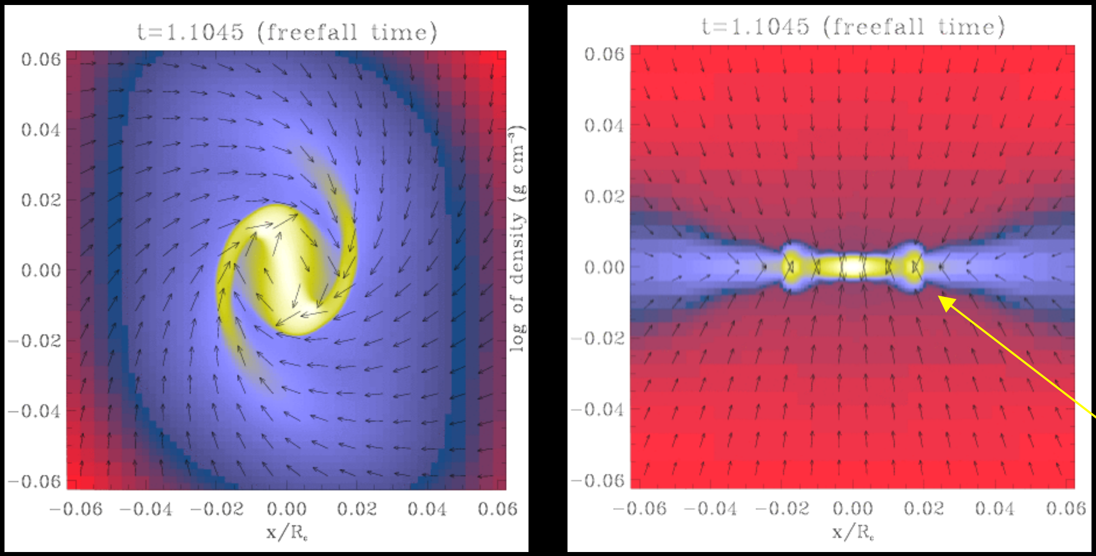
Magnetically deflected pseudo disk

Galli & Shu (1993)

from Crutcher (2006)

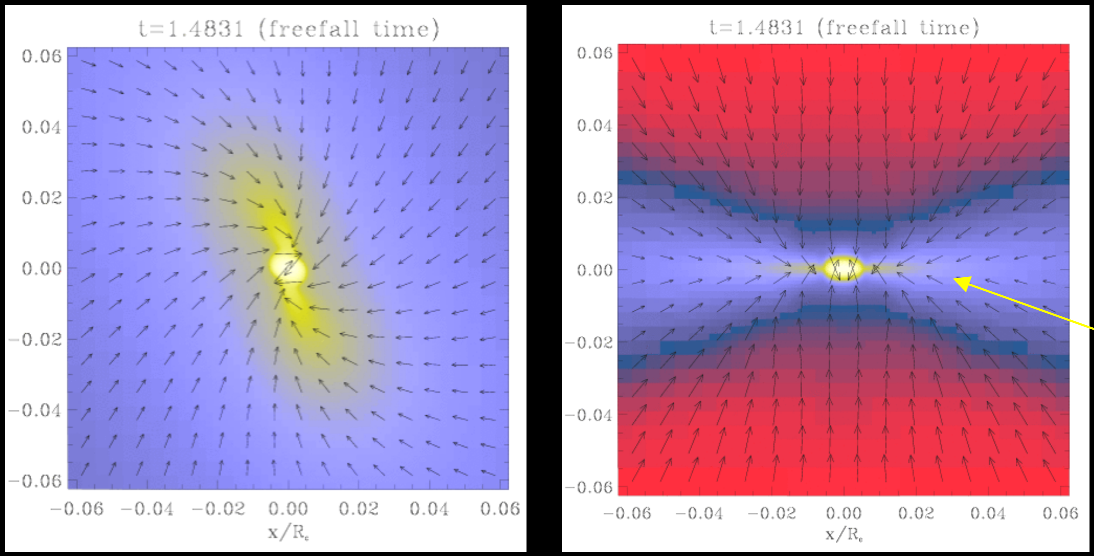
no B field ($\lambda = \infty$)

Fromang et al. (2006)



centrifugal disk

with B field ($\lambda = 2$)



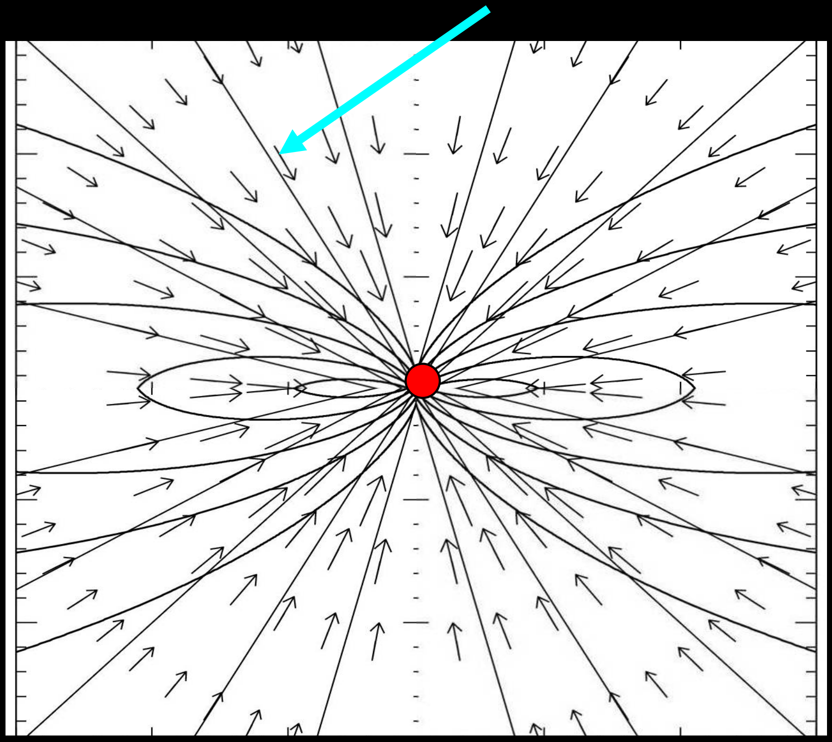
magnetic pseudo-disk (not supported centrifugally)

top view

side view

The explanation

In ideal MHD, during gravitational collapse, ***B*** *trapped in the central star acquires a split monopole configuration => catastrophic magnetic braking!*

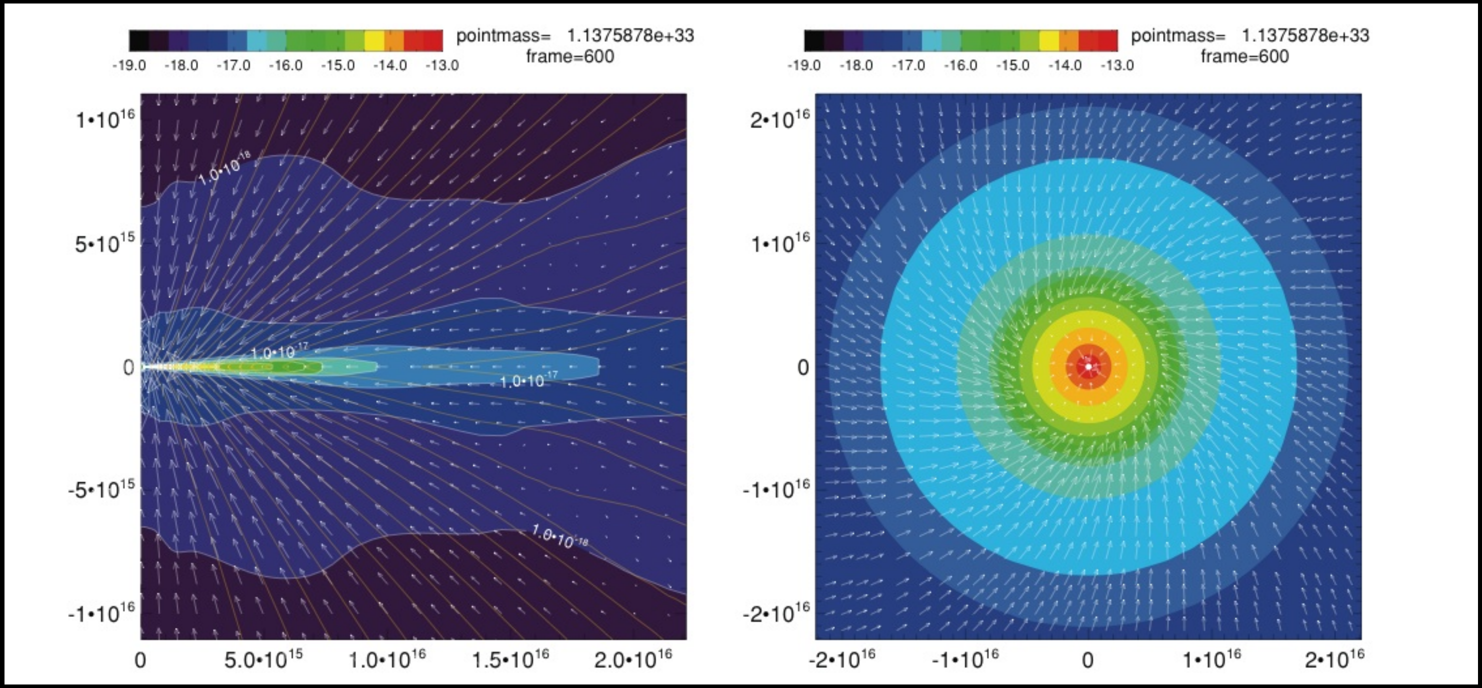


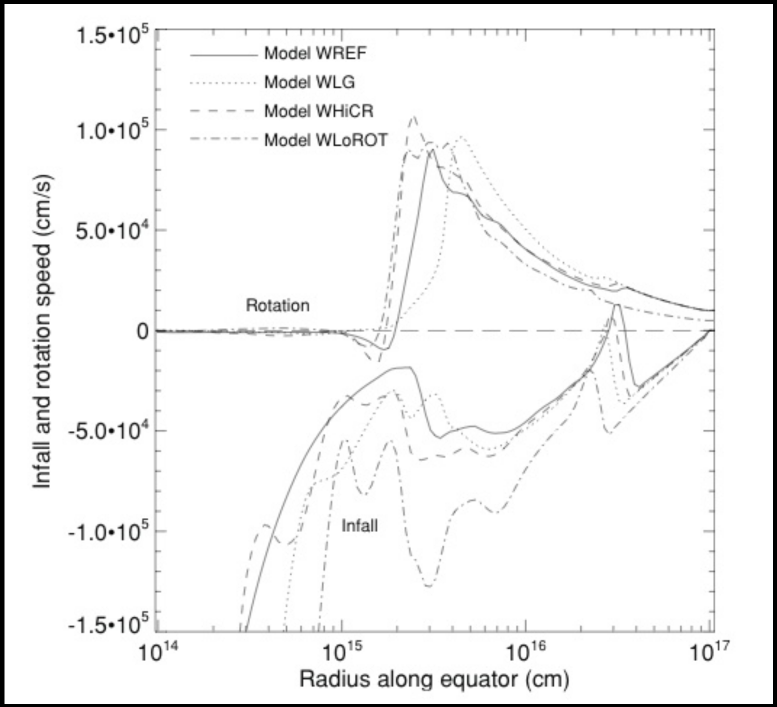
side view: pseudodisk

Galli et al. (2006)

$$B_r \sim a^3 t / (G^{1/2} r^2)$$

$$v_\varphi \sim -r^{1/2}$$





Gravitational collapse with ambipolar diffusion, Ohmic dissipation and Hall effect (e.g., Li et al. 2011.) Small disks can form R ~ 1AU (Tsukamoto et al. 2015) unless unstable cloud (Machida et al. 2016).

Alternative solutions:

- *Misalignement between B and Ω reduces braking torque (Hennebelle & Ciardi 2009; Joos + 2012; Krumholz +2013) → requires strong misalignement and low magnetization (e.g., Hull + 2014).*
- *The disk could grow when the envelope has been depleted and magnetic braking becomes inefficient (e.g., Machida+2011). But Tobin+12; Murillo+13;Codella+14*
- *Turbulence enhances the rate of field reconnection and diffusion (e.g., Seifried +2012, Santos-Lima+2012-13) → requires high levels of turbulence, caution with numerical diffusion.*
- *Removal of small grains increases AD (Zhao+2016).*
- *CRs cannot penetrate wrapped field lines (Galli+2016).*

Disk Formation

The disk will drag the magnetic field from the parent core that has $\lambda_{core} \sim 1–4$.

One expects ***B*** *dissipation* $\lambda_{disk} \approx$ 4-16? (*Shu+2007; Hennebelle & Fromang 2007*).

A protostar has $\lambda_* \approx 10^3$-10^4 , *thus, the magnetic field brought in during gravitational collapse remains in the disk, the mass accretes to the star.*

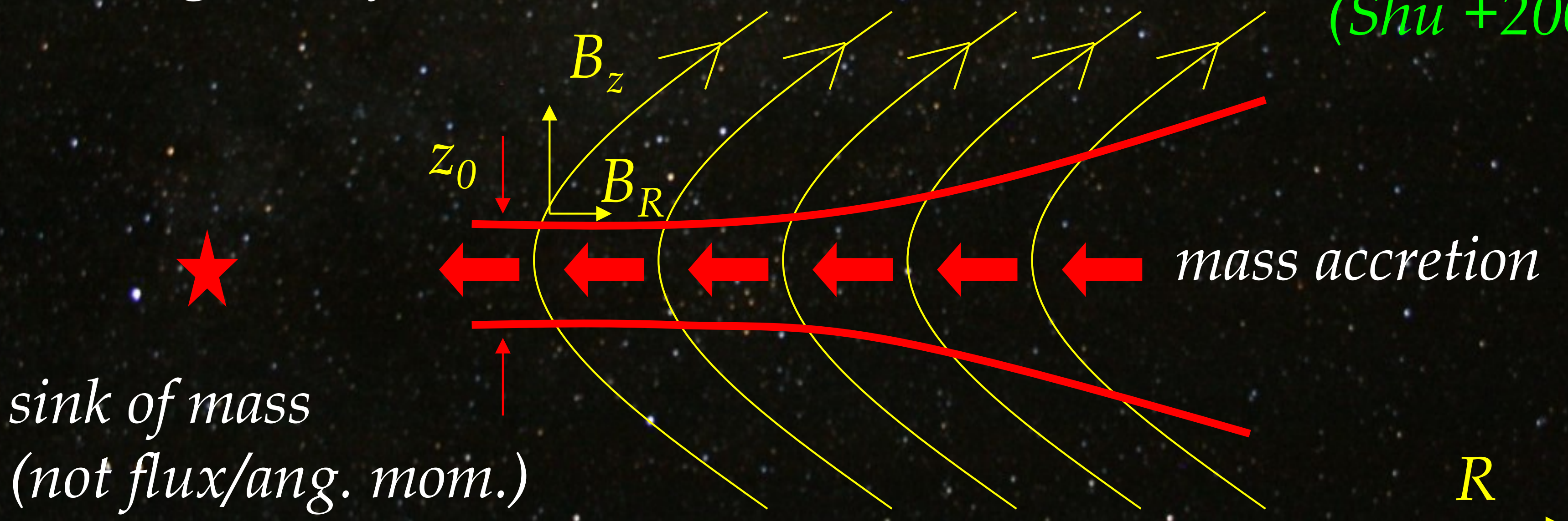
Magnetized accretion disks

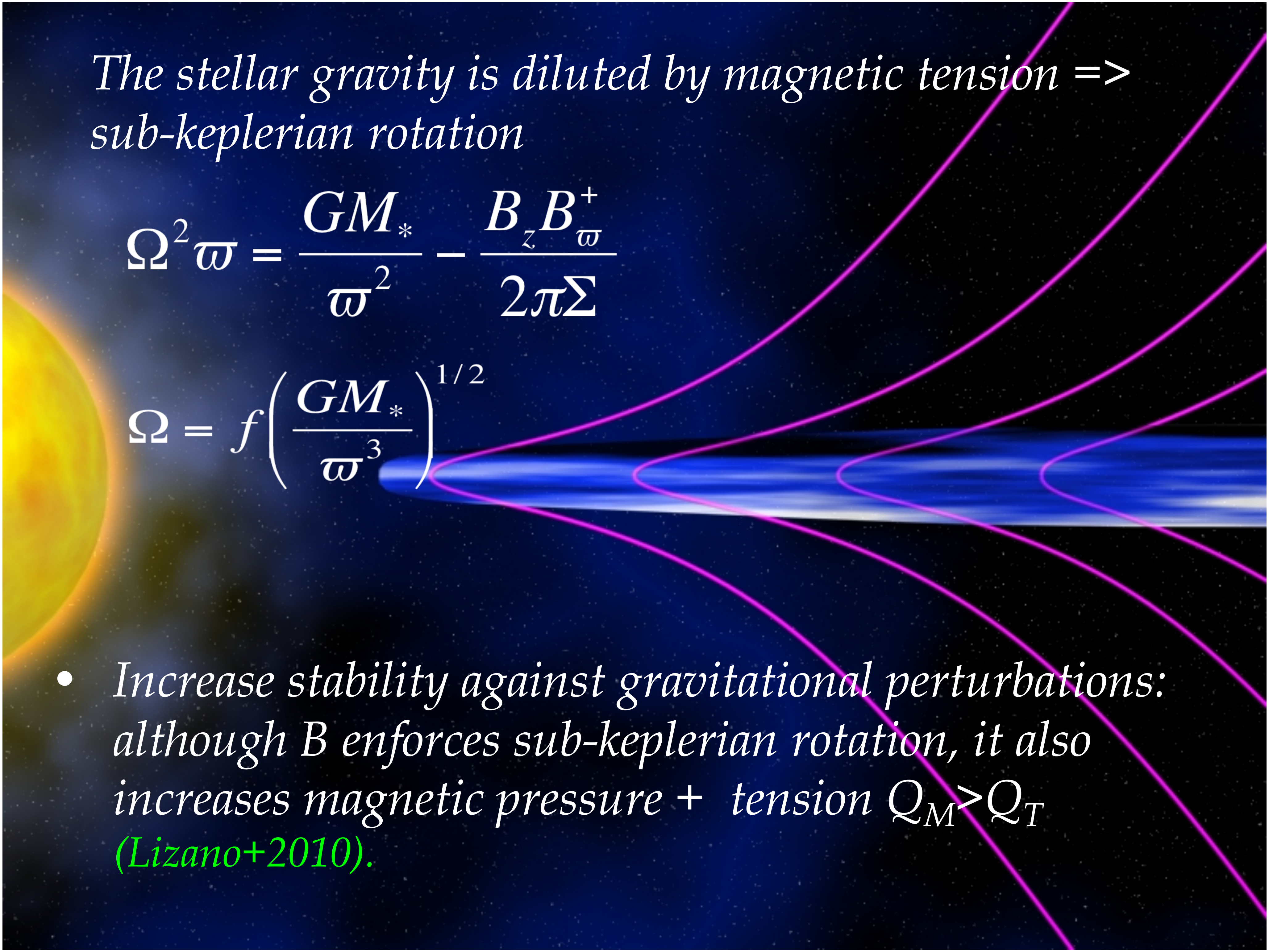
***B** modifies the structure and dynamics of accretion disks*

Disks subject to two diffusive processes:

- *Viscosity ν → allows matter to accrete (MRI)*
- *Resistivity η → allows matter to slip through the magnetic field lines*

(Shu +2007)





The stellar gravity is diluted by magnetic tension => sub-keplerian rotation

$$\Omega^2 \varpi = \frac{GM_*}{\varpi^2} - \frac{B_z B_\varpi^+}{2\pi\Sigma}$$

$$\Omega = f\left(\frac{GM_*}{\varpi^3}\right)^{1/2}$$

- *Increase stability against gravitational perturbations: although B enforces sub-keplerian rotation, it also increases magnetic pressure + tension* $Q_M > Q_T$ *(Lizano+2010).*

Vertical structure of magnetized accretion disks subject to irradiation + viscous and resistive heating.

Lizano, Tapia, Boehler, D'Alessio 2016

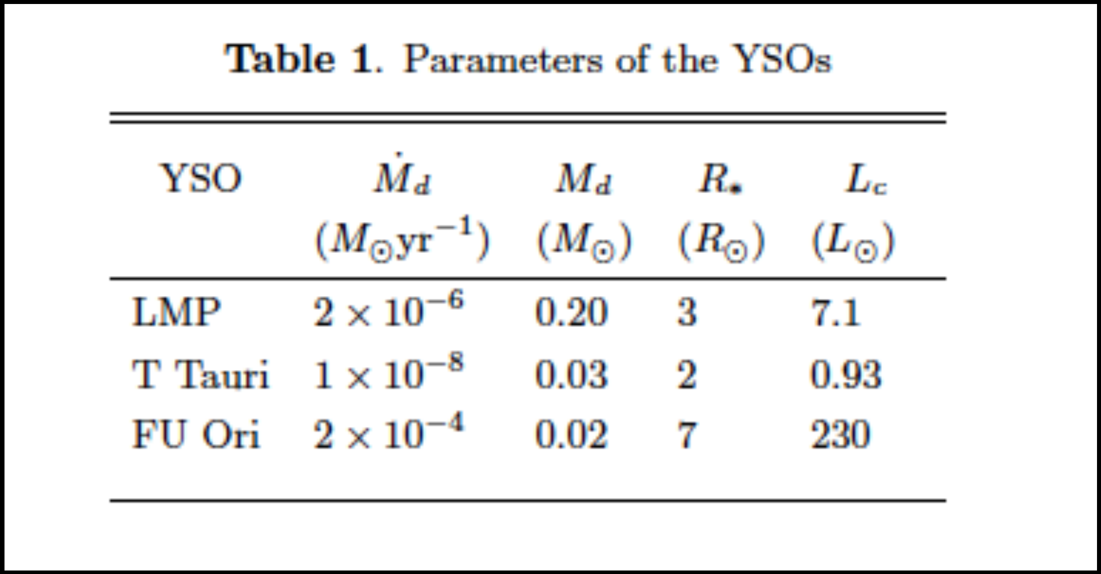


Table 1. Parameters of the YSOs

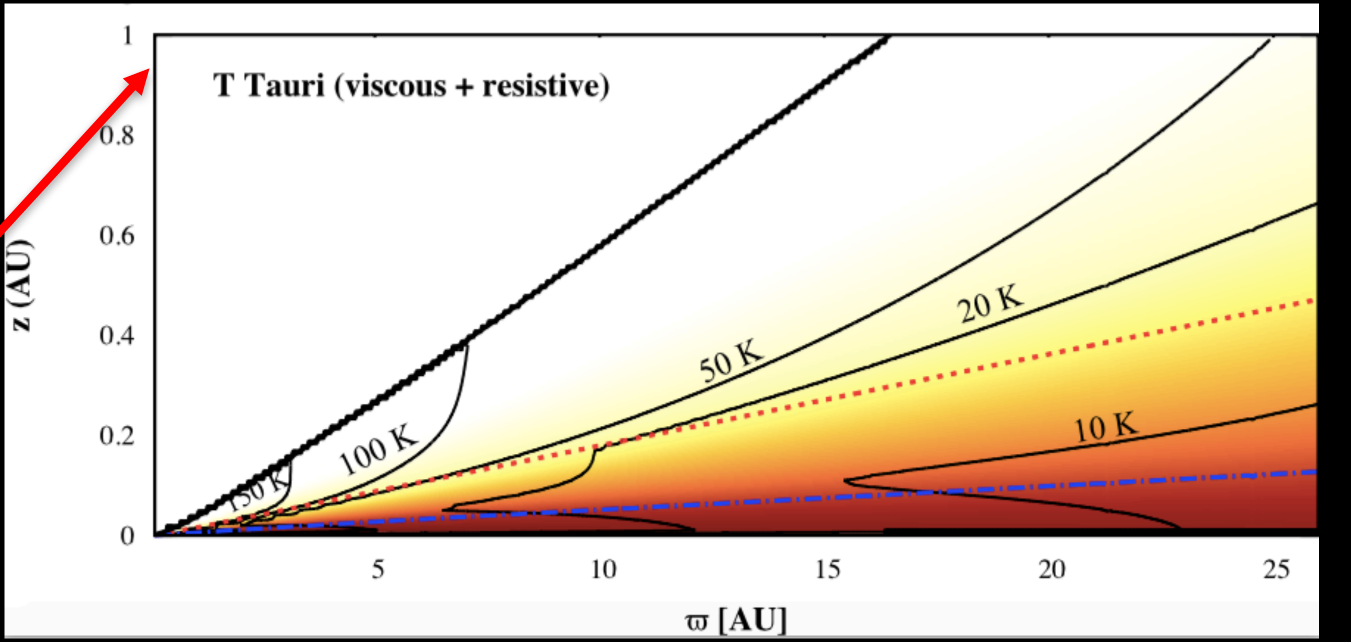
YSO	$\dot{M}_d$ ($M_\odot \mathrm{yr}^{-1}$)	M_d ($M_\odot$)	R_* ($R_\odot$)	L_c ($L_\odot$)
LMP	2×10^{-6}	0.20	3	7.1
T Tauri	1×10^{-8}	0.03	2	0.93
FU Ori	2×10^{-4}	0.02	7	230

Different heating mechanisms dominate the midplane

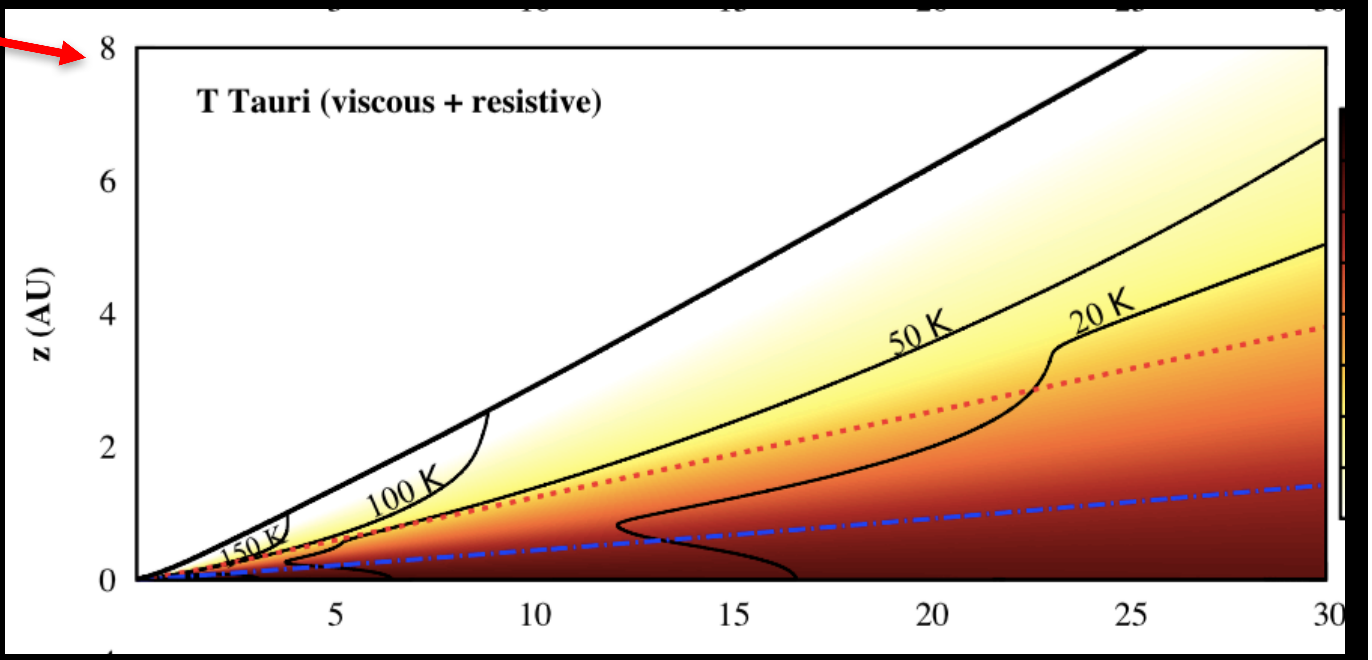
- *Low mass protostar disks ← viscous heating*
- *FU Ori disks ← resistive heating*
- *T Tauri disks ← stellar irradiation.*

Magnetic compression

T Tauri disk is highly compressed for $\lambda_{sys}=4$, *H/R ~ 0.01*



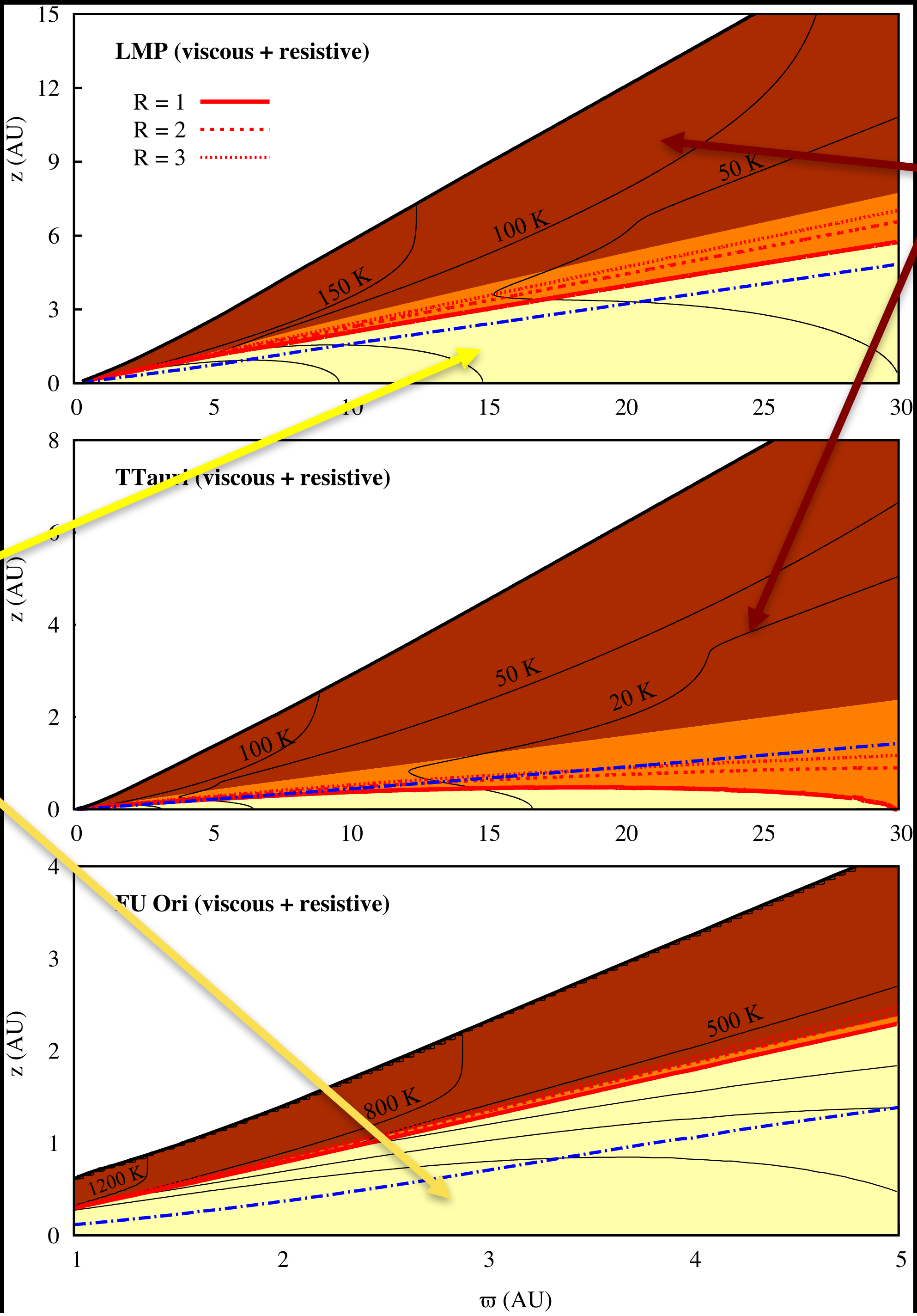
For $\lambda_{sys}=12$, *H/R ~ 0.1, similar to inferred values (e.g., Grafe et al. 2013).*



External heating vs internal heating

λ_{disk}= 12

Active regions:
viscous - resistve heating

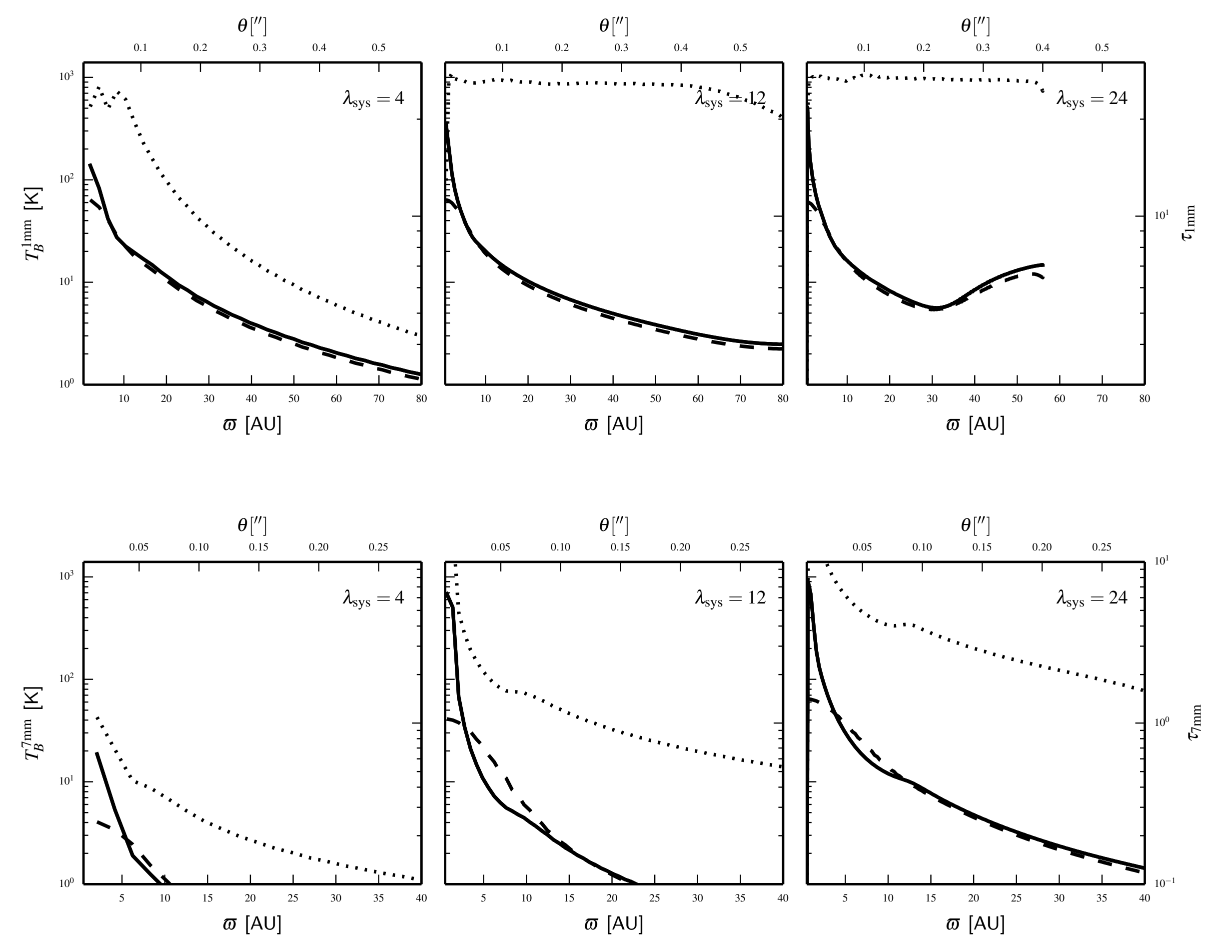


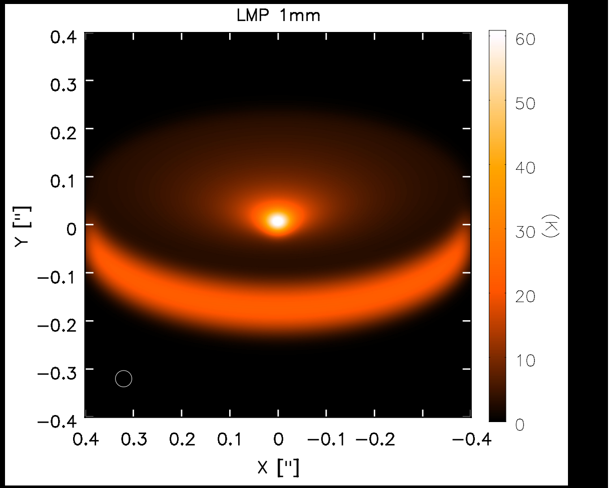
Hot atmosphere:
F_{irr} is absorbed

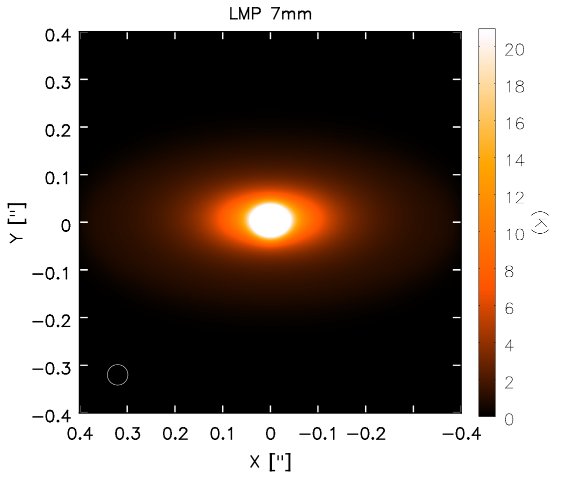
$R=(T_{rp}/T_{vr})^4$

LMP Disk (θ = 60^{o})

λ=24





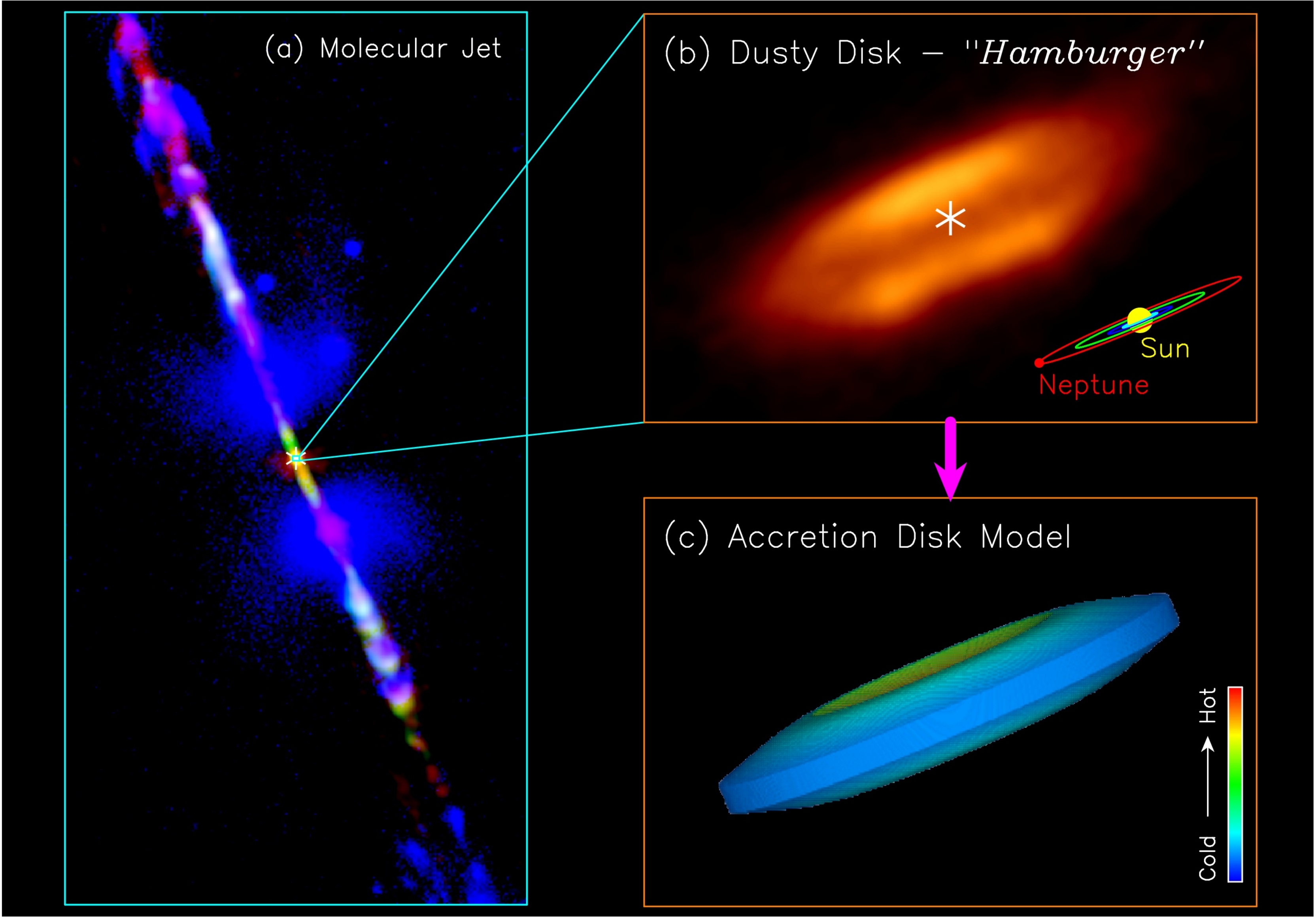


Tapia & Lizano 2017

Emission increases with λ_{sys}: the disks are hotter and denser

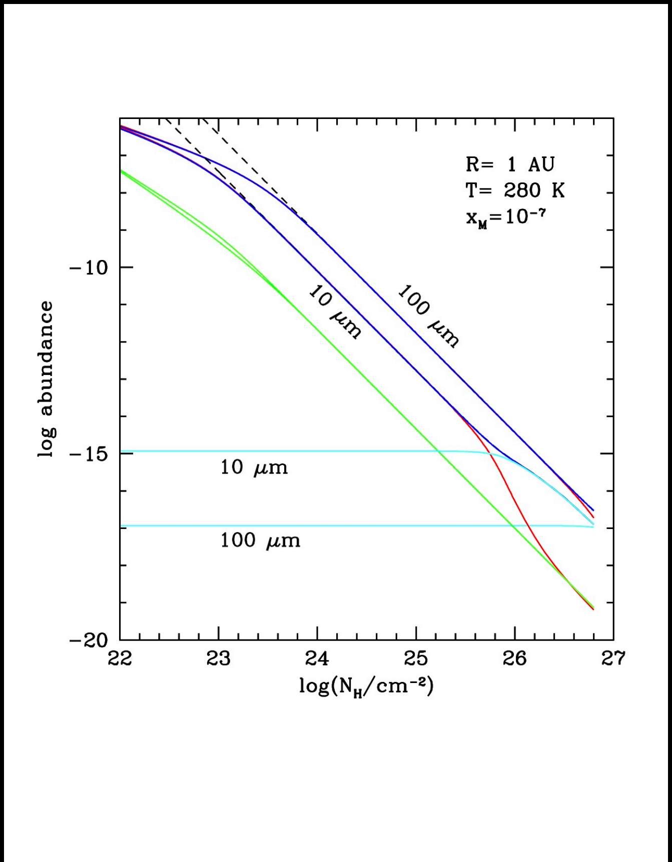
HH 212 Class 0 source in Orion with ALMA

Lee+2017



Disk ionization with X rays → B coupling and MRI (Glassgold +2017)

Ionization: x_e , x_{M}^{+} x_{m}^{+} , x_{d}^{+}

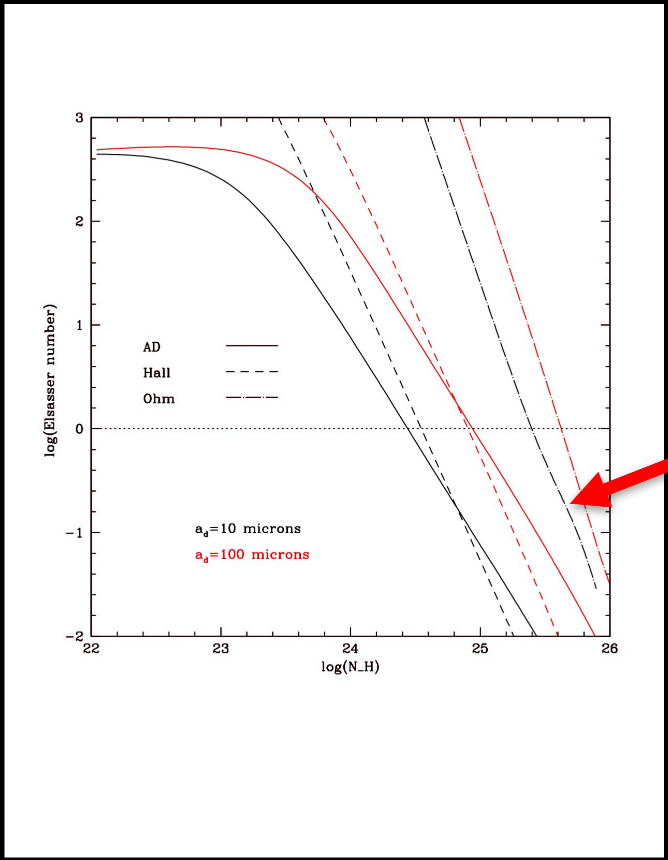


Umebayashi & Nakano 1980

Elsasser number = $v_A^2/\eta\ \Omega$

η_{Ohm} *→ B-plasma coupling*

η_{AD} *→ ions-neutrals coupling*



T Tauri disk λ=12

Dead zone

e.g., Flock + 2012

Summary

- *B fields observed in molecular clouds hinder the formation of centrifugally supported disks. Magnetic field dissipation, misalignment, envelope depletion, turbulence, proposed to avoid catastrophic braking and form rotationally supported protoplanetary disks.*
- *B fields modify the disk structure: sub-keplerian rotation and magnetic compression.*
- *Both diffusive processes in magnetized disks (ν, η) dissipate energy and heat the disks.*
- *The structure and emission of magnetized disks constrains λ_{disk}*
- *ALMA will be able to measure B, λ_{disk} and Ω and test these models.*

Thank you!