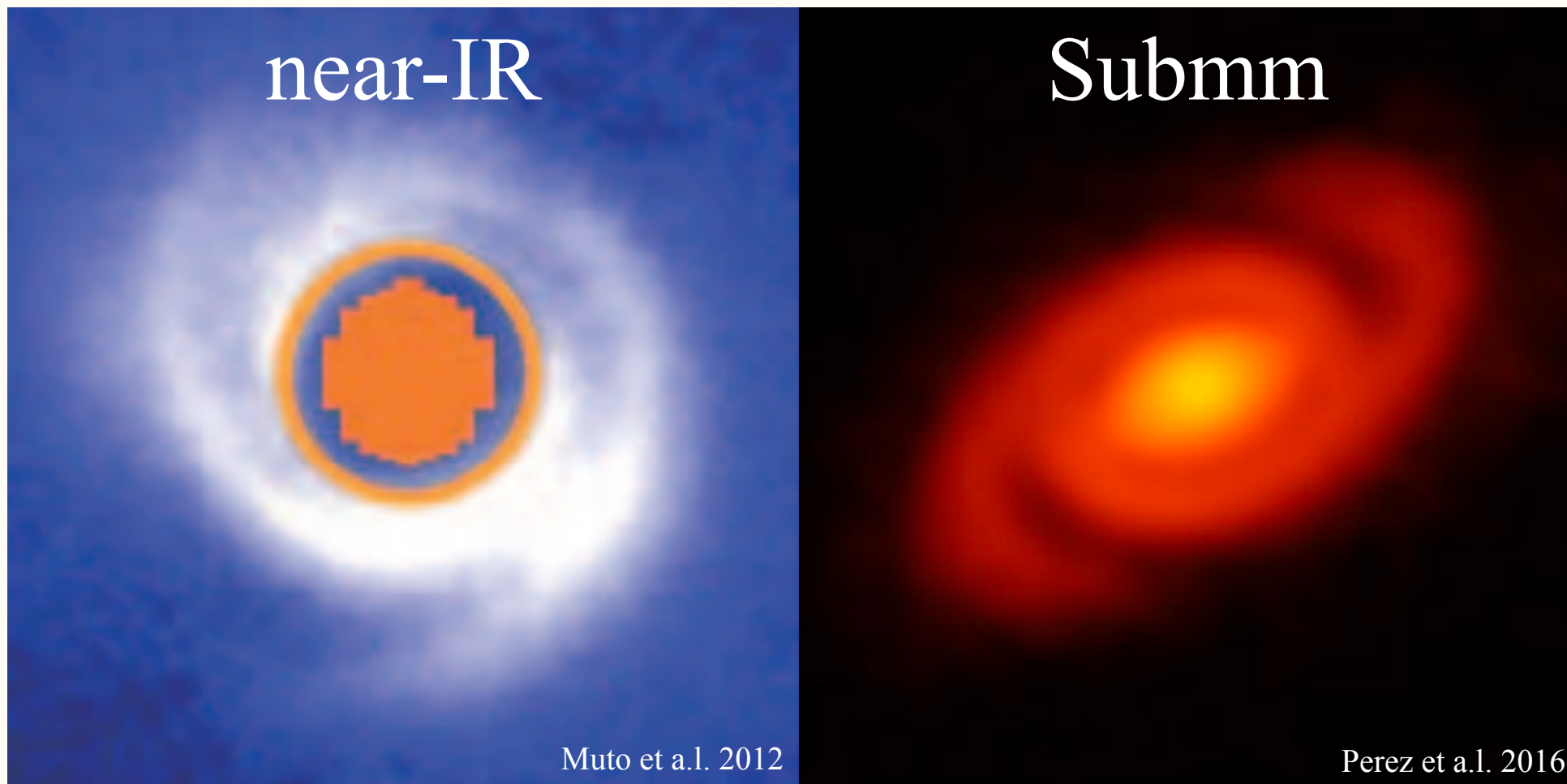


Protoplanetary disks

Zhaohuan Zhu
University of Nevada, Las Vegas



NGC 2264

Rosette
Nebula

L1622

H α

Barnard
Loop

CO

L1641

YSO

$\Delta\delta$ [deg]

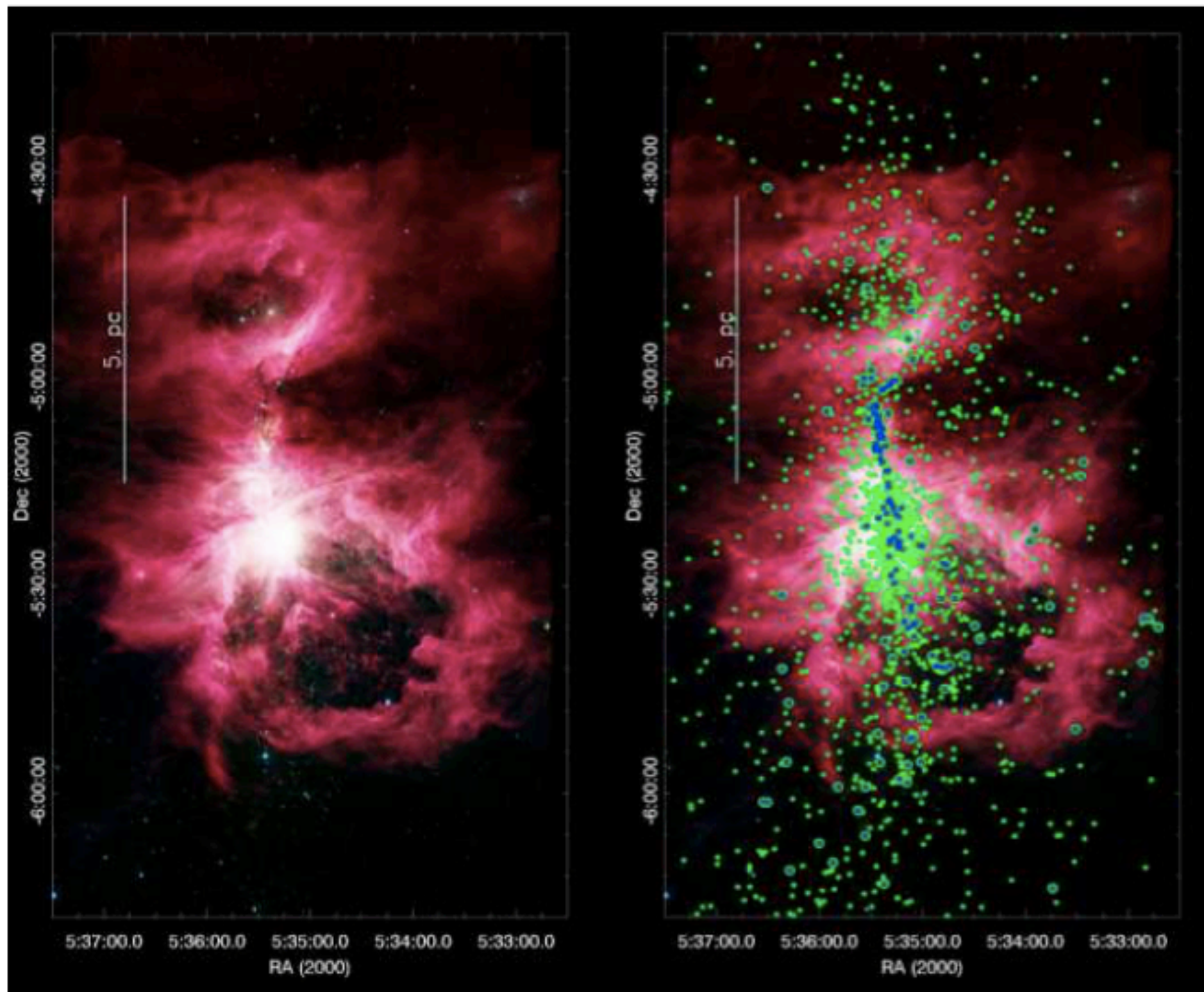
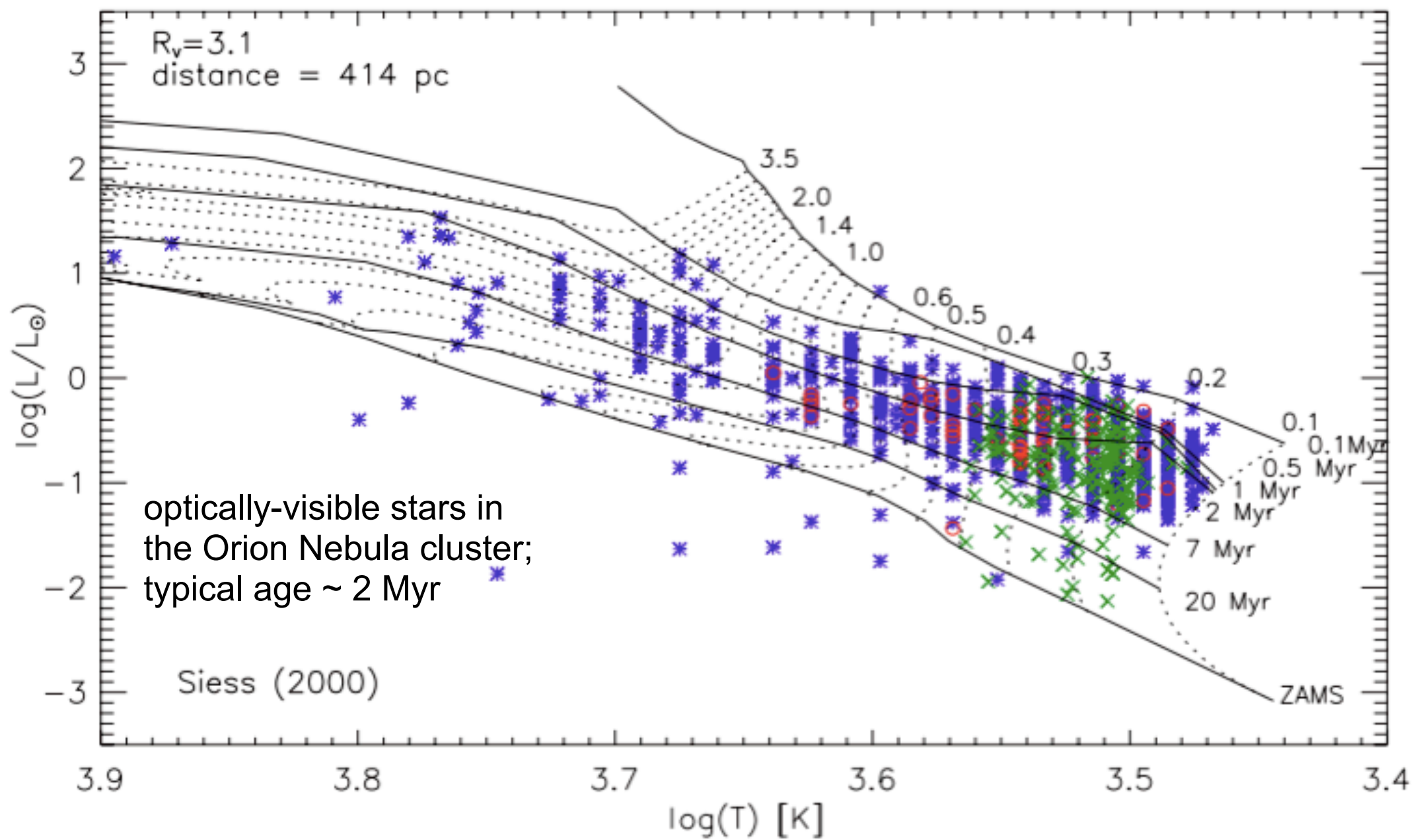


Fig. 8.— Left: Image of warm dust emission in the neighborhood of the Orion Nebula Cluster taken with the Spitzer Space Telescope. Right: same background, with positions of infrared-excess young stars; ringed circles denote protostars. Courtesy of Tom Megeath.

OPTICAL PHOTOMETRY OF THE ONC. II.



Protostellar and protoplanetary disk study

YSO Classes (Lada & Wilking 1984)

From SED slope between 1-20 μm

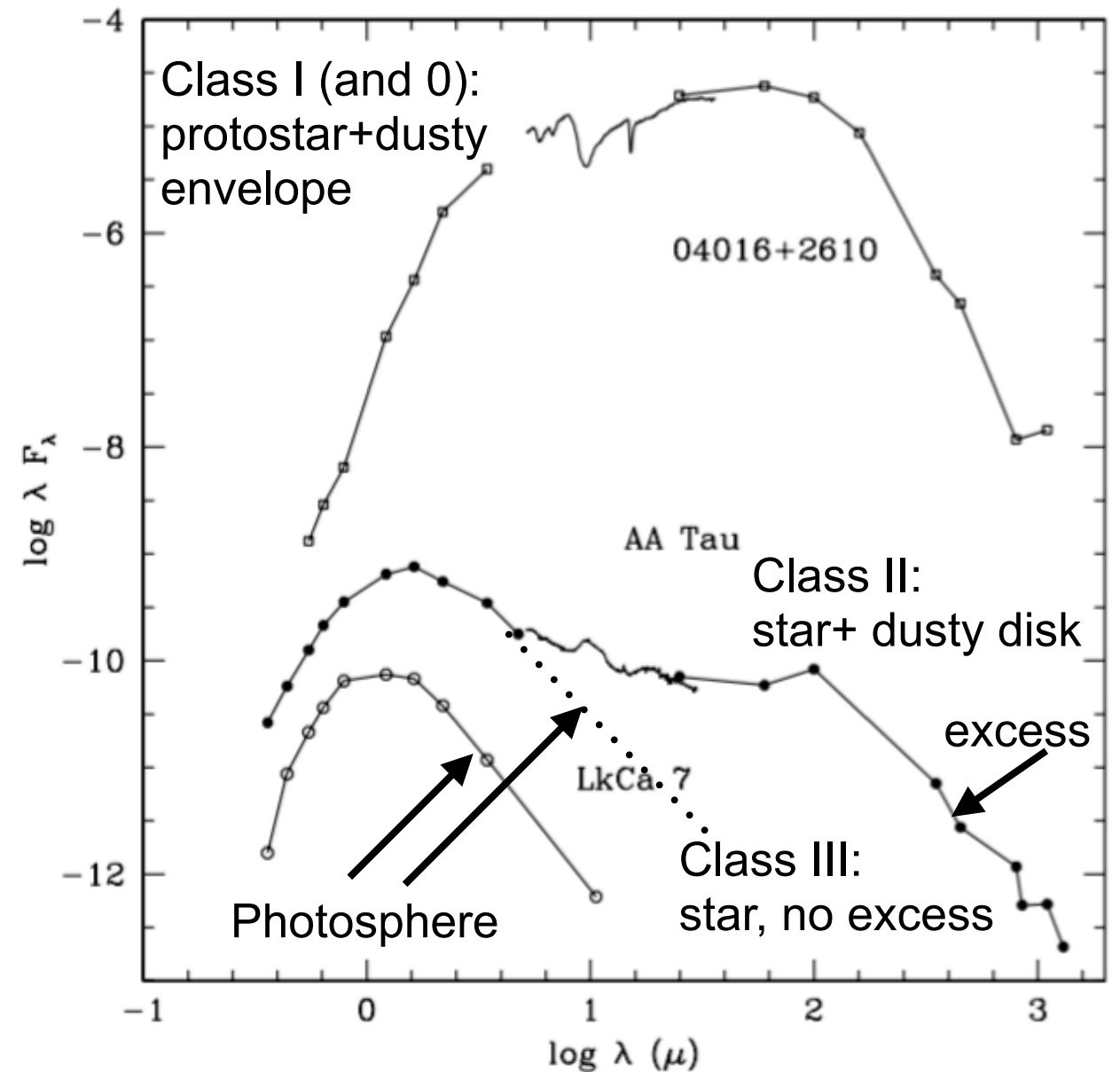
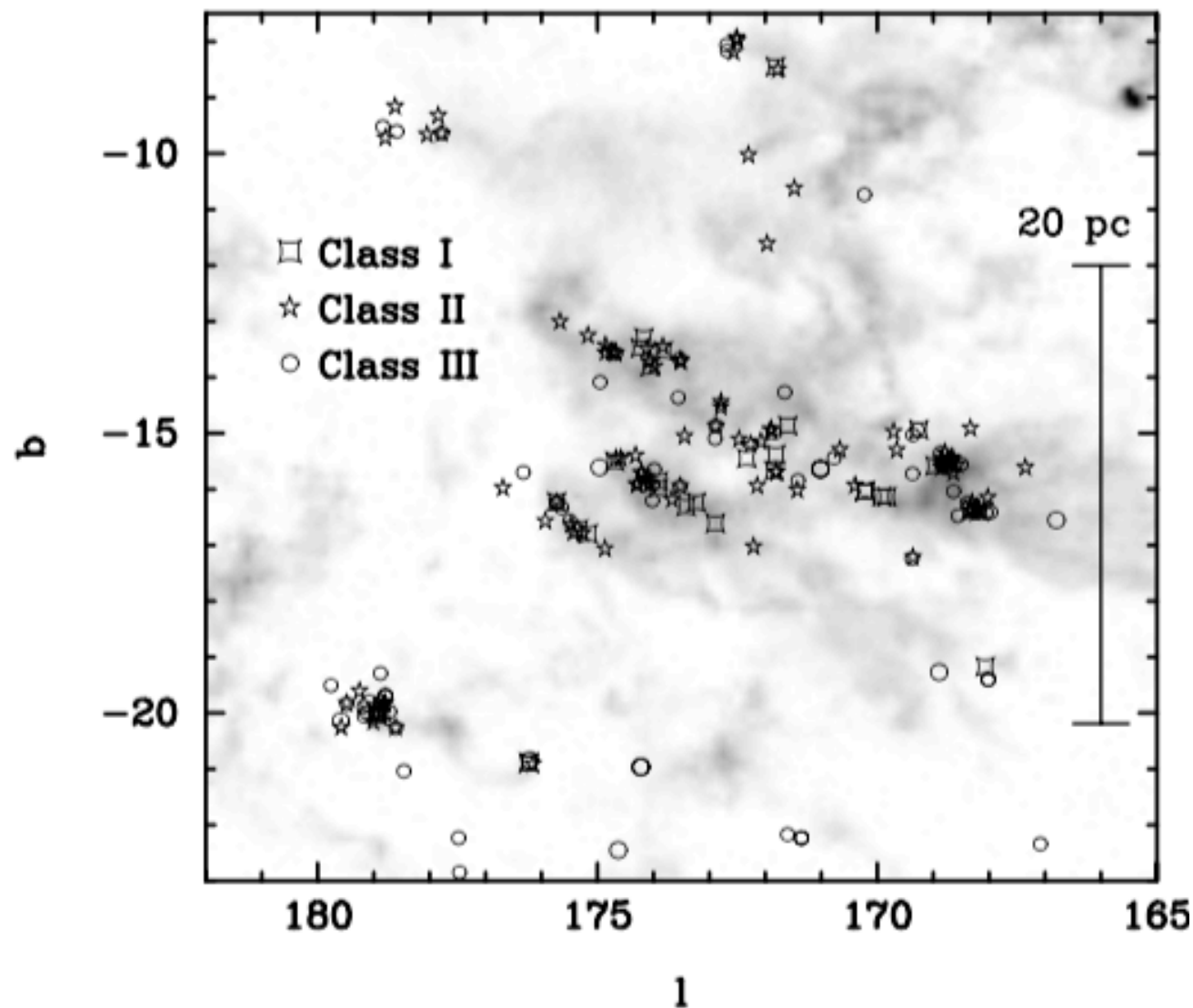
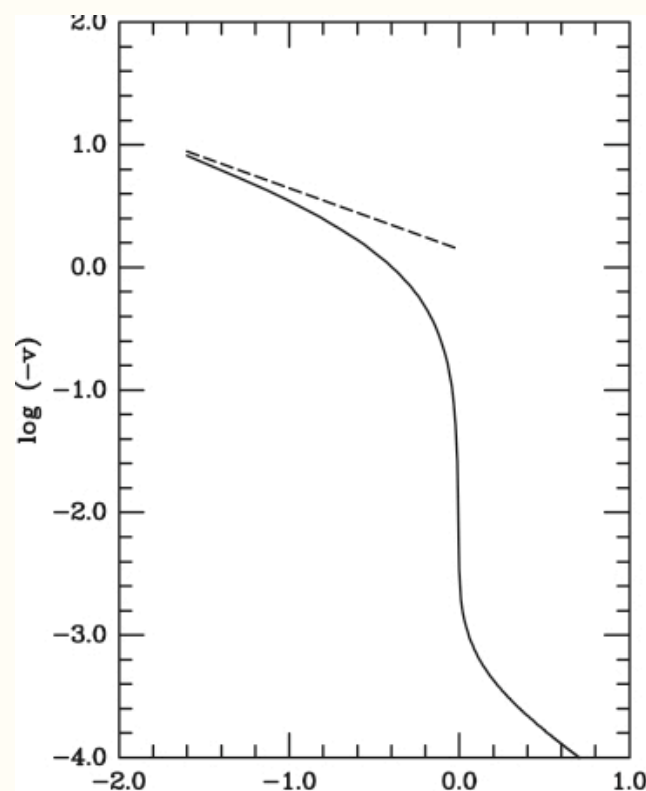
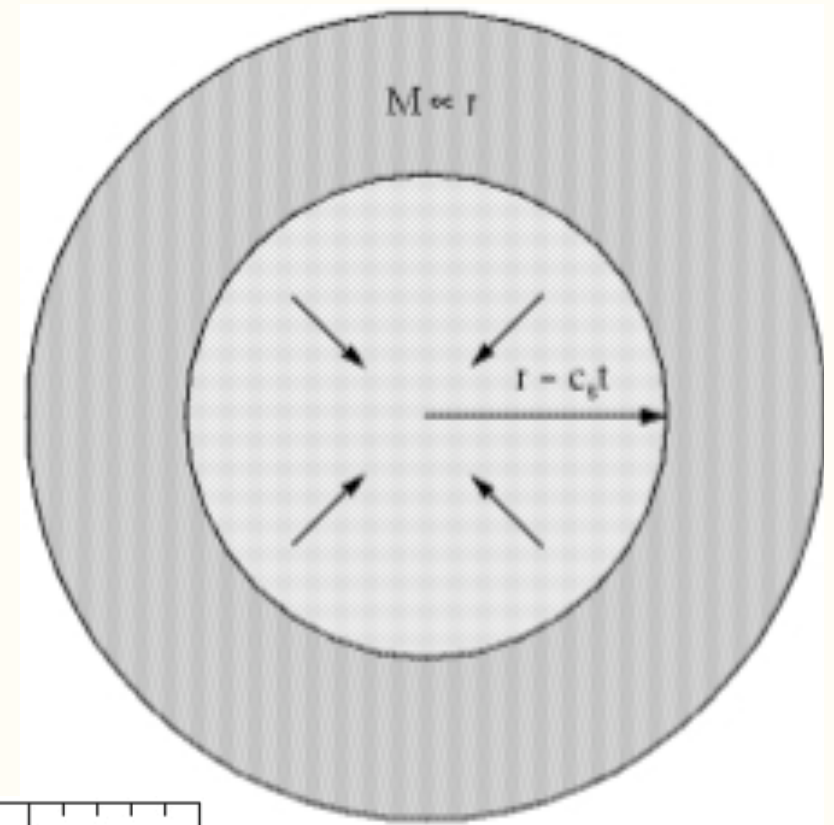


Fig. 1.1. The Taurus-Auriga molecular cloud complex. Gray-scale shows in ^{12}CO emission, taken from Megeath, Dame, & Thaddeus (2001). The 1 of known young stars (ages ~ 1 Myr) have been superimposed. The pre-main-sequence stars (Class II and III) are generally clustered near regions of high gas column density; the likely protostars (Class I) are found only in high density regions (e.g., Onishi *et al.* 1998).

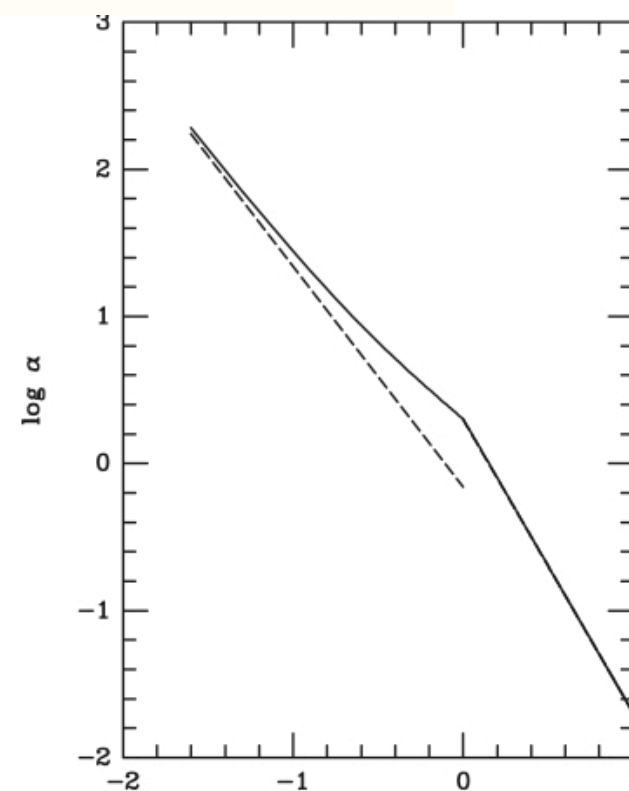
A simple collapse model (singular isothermal sphere $\rho \sim r^{-2}$)

To illustrate basic ideas of protostellar formation, consider the simple “inside-out” collapse starting from a singular isothermal sphere (Shu 1977).

Inner regions collapse first because shortest $t_{\text{ff}} \propto \rho^{-1/2}$; because spherical, outer regions don't know about inner collapse until reduction in pressure as stuff falls in



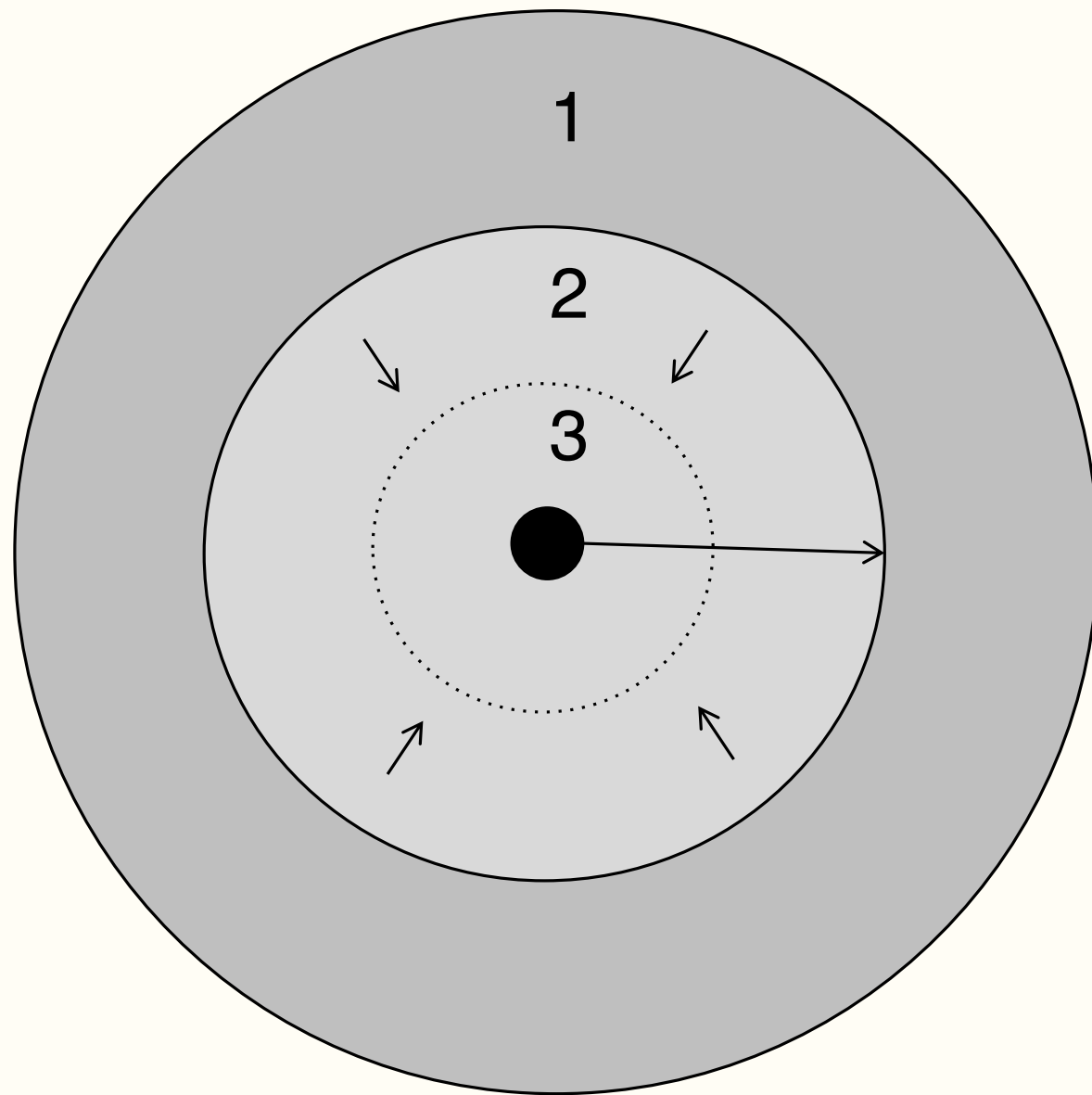
normalized velocity



density

$$x = r/c_s t$$

A simple collapse model (singular isothermal sphere $\rho \sim r^{-2}$)



1: undisturbed SIS, $\rho \propto r^{-2}$, $v=0$

2: infall region

$r_2 = c_{st}$, $\rho \propto r^{-3/2}$, $v \propto r^{-1/2}$

3: region from which the mass in the “central star” (+small disk) originated;
 $r_3 \approx 1/2 r_2$;

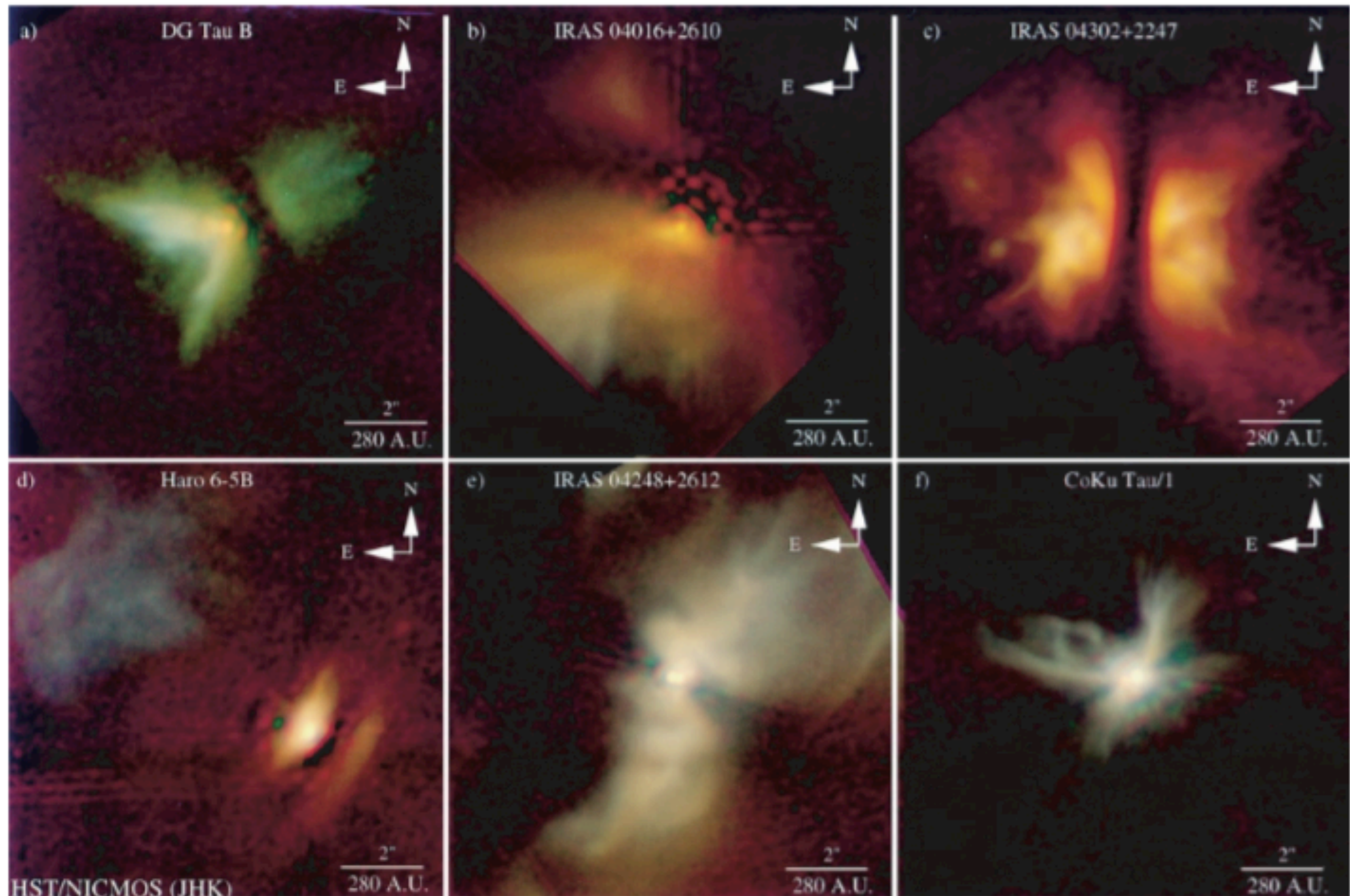
M goes as r

therefore

$M(\text{central star})$

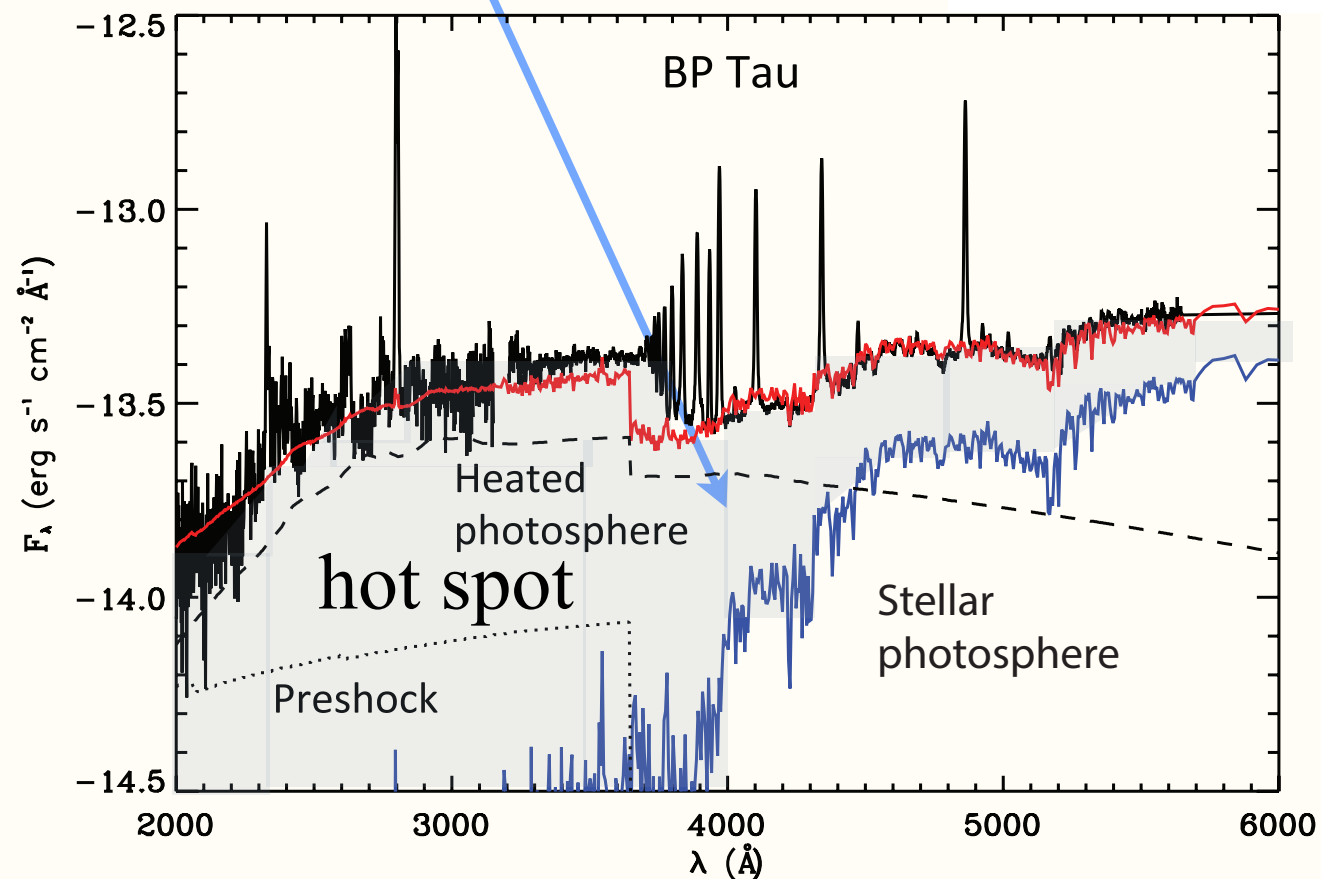
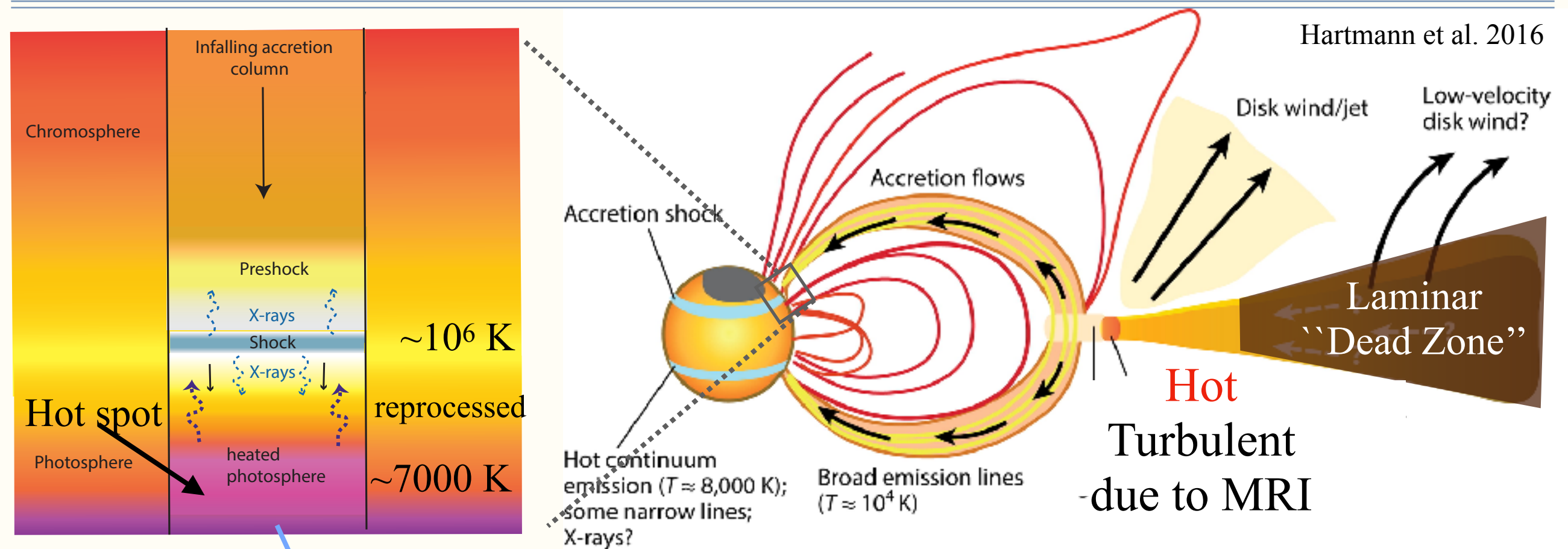
$\approx 1/2 M(r_2)$

With rotation -> disk formation



Padgett+ 99: envelope cavities seen in IR scattered light

Inner disks: accretion



Accretion indicator $L \sim \frac{GM_* \dot{M}}{R_*} \Rightarrow \dot{M}$

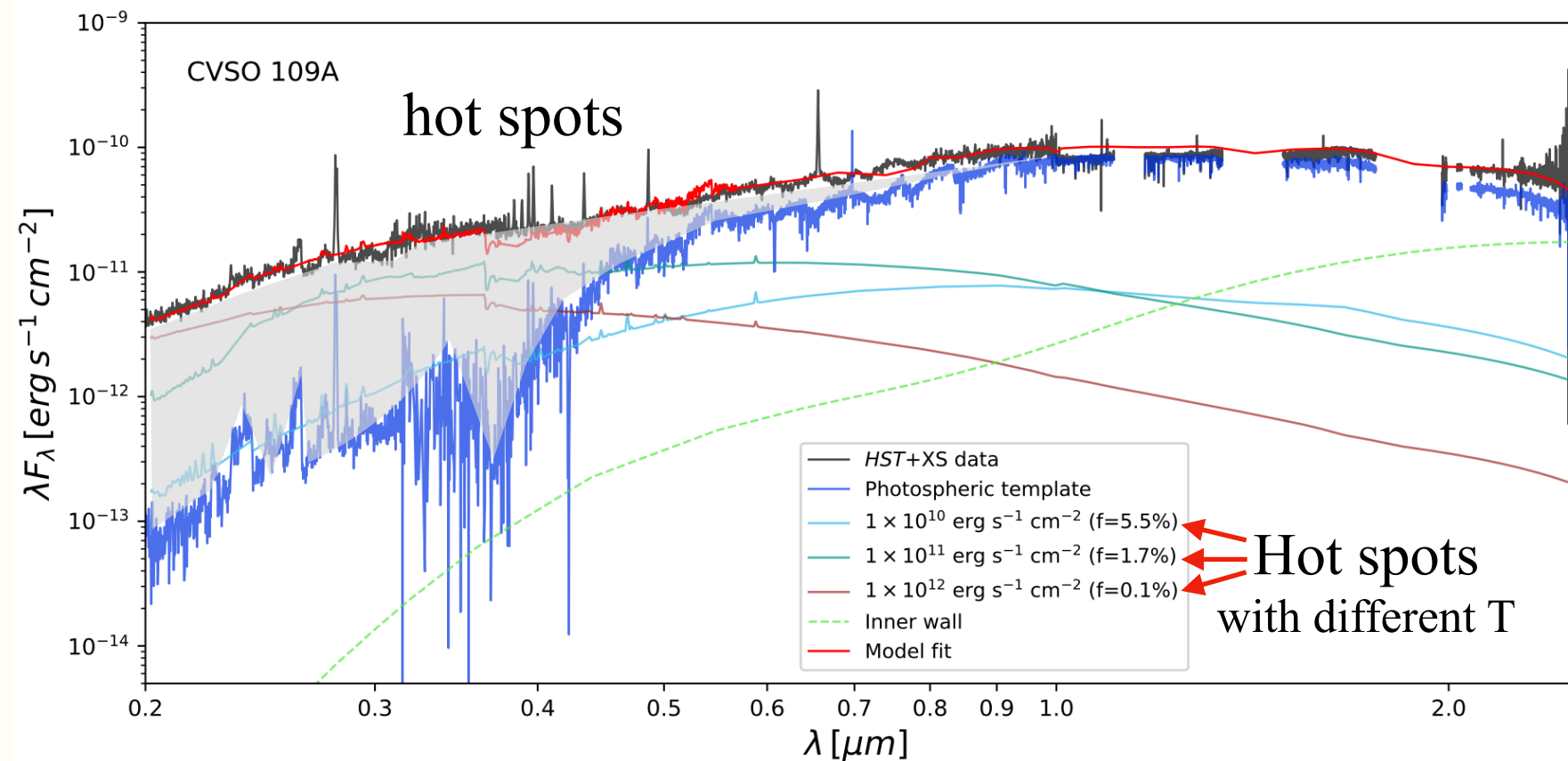
Excess UV affects outer disks:

- Photoevaporation
- Molecular dissociation/chemistry (JWST)

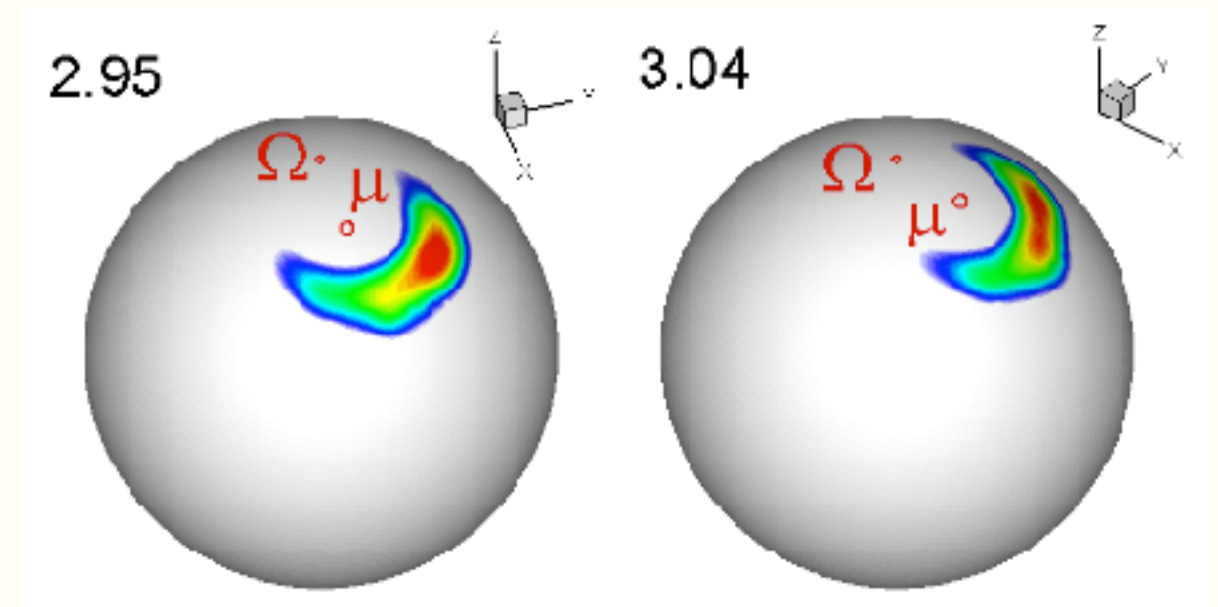
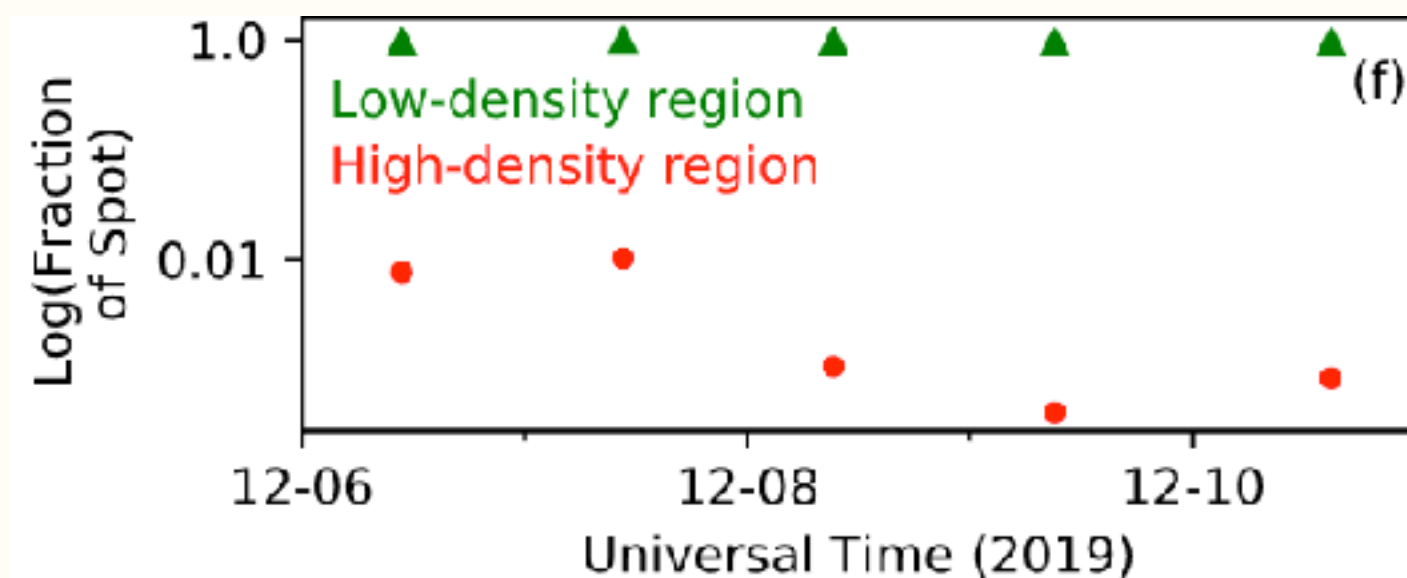
Inner disks dynamics and observations:



Roman-Duval et al. 2020
Manara et al. 2021



Espaillat et al. 2022
Wendeborn et al. 2024ab



Espaillat et al. 2021

Outer disks: extreme AO and ALMA

Ground-based 10m telescope with extreme AO



(Subaru SEEDS, Gemini GPI, VLT Sphere)

$$\text{Resolution: } \frac{\lambda}{D} = \frac{1 \mu m}{10 m} = 0.02''$$

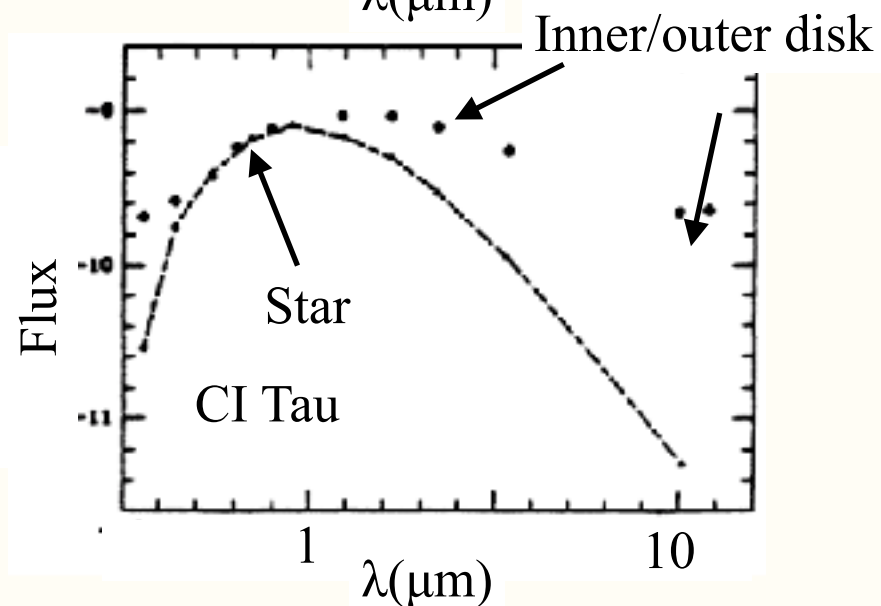
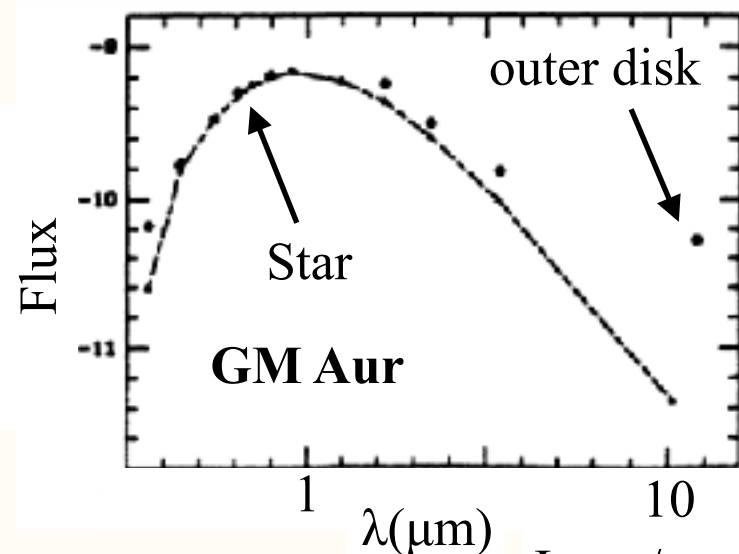
Radio interferometer (ALMA, VLA) $\frac{\lambda}{D} = \frac{1 mm}{16 km} = 0.013''$



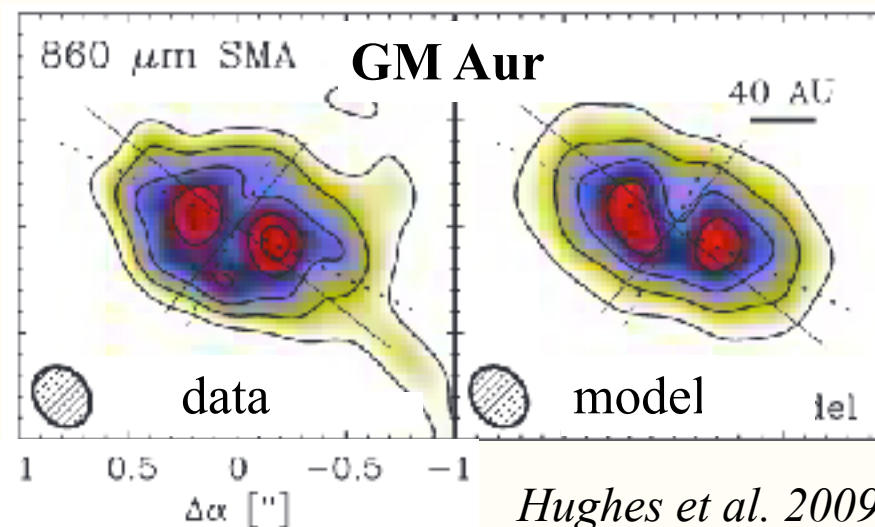
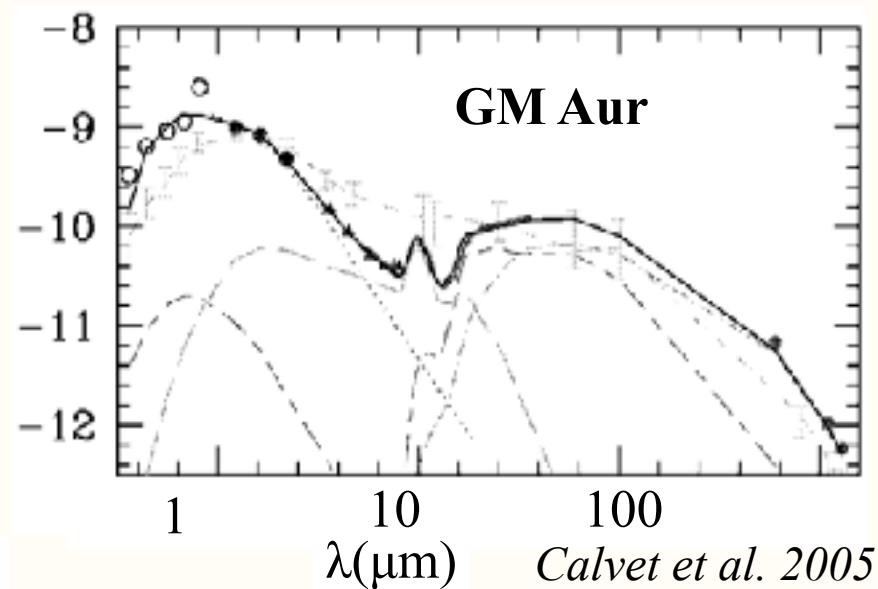
3 AU resolution
Planet forming zone

Protoplanetary disk observations: early days

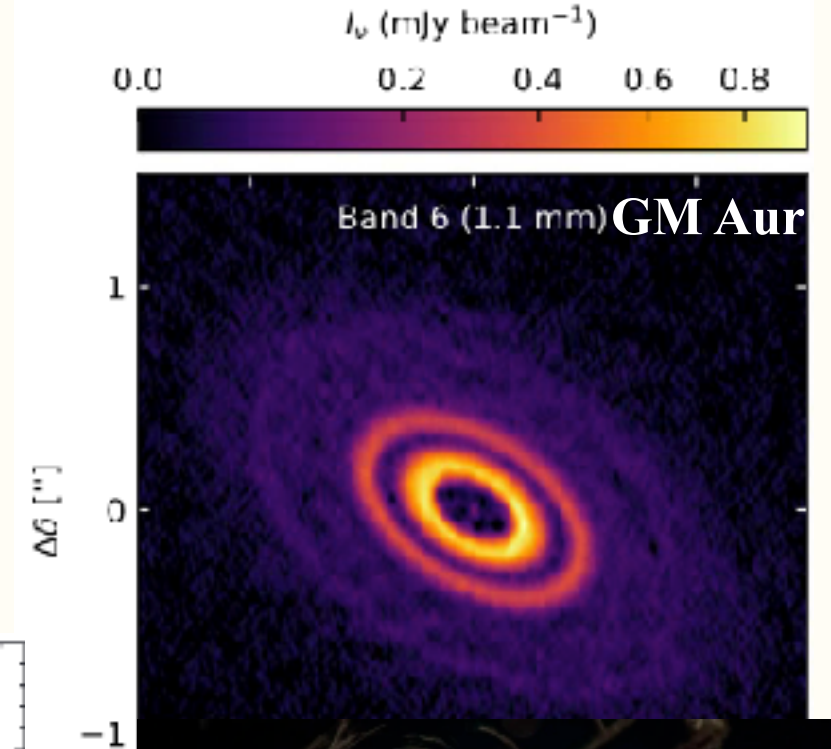
YSO SED (*IRAS*)



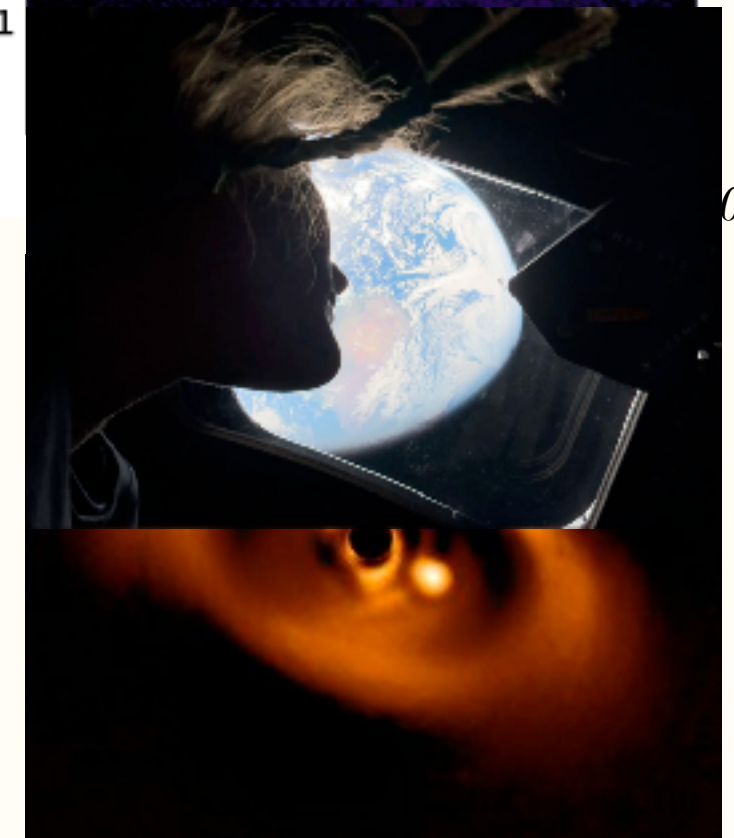
Transitional Disks (*Spitzer*, *SMA*)



Ground 10m, ALMA



020



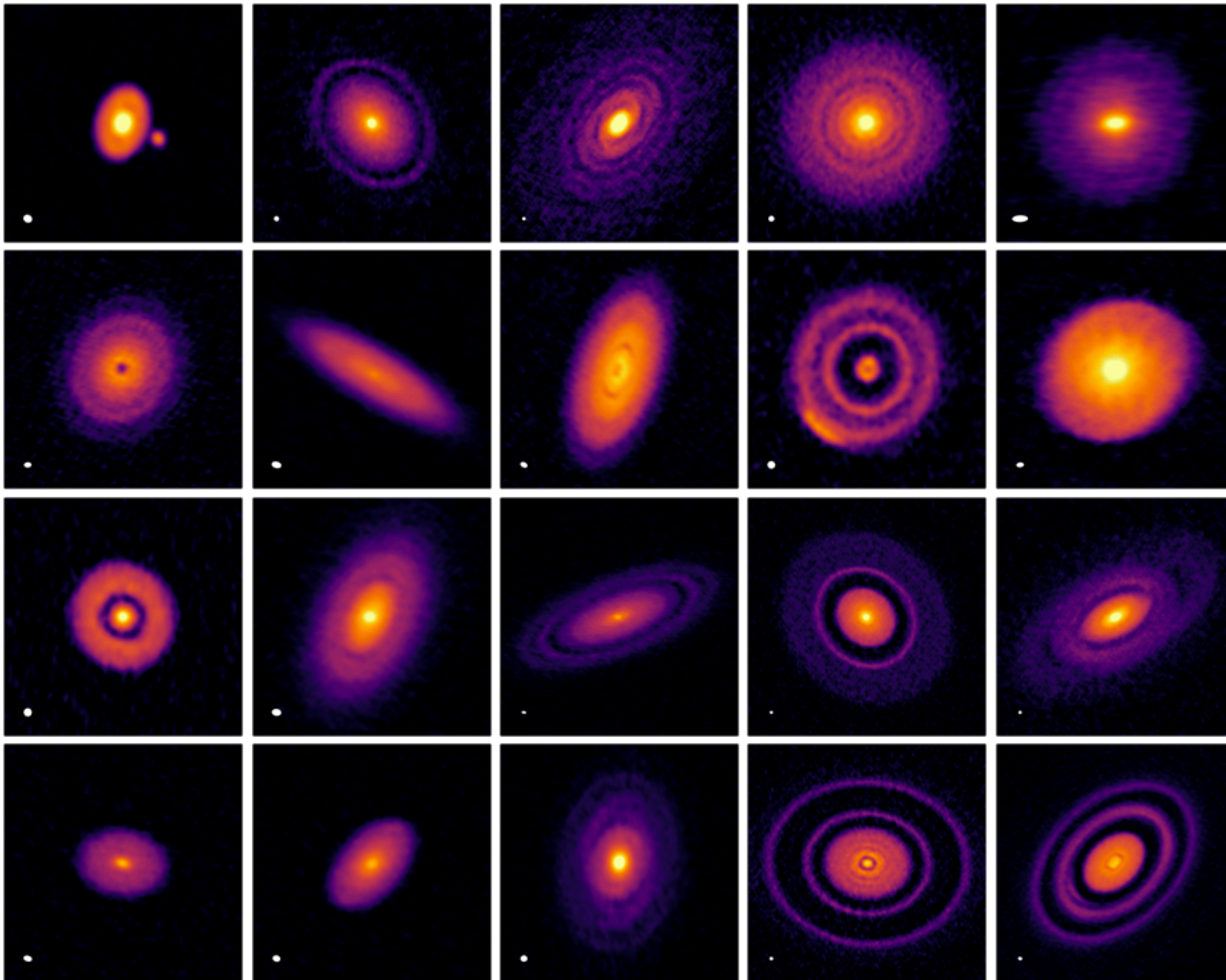
Keppler et al. 2018

K. Strom, S. Strom, Edwards, Cabrit, Skrutskie 1989

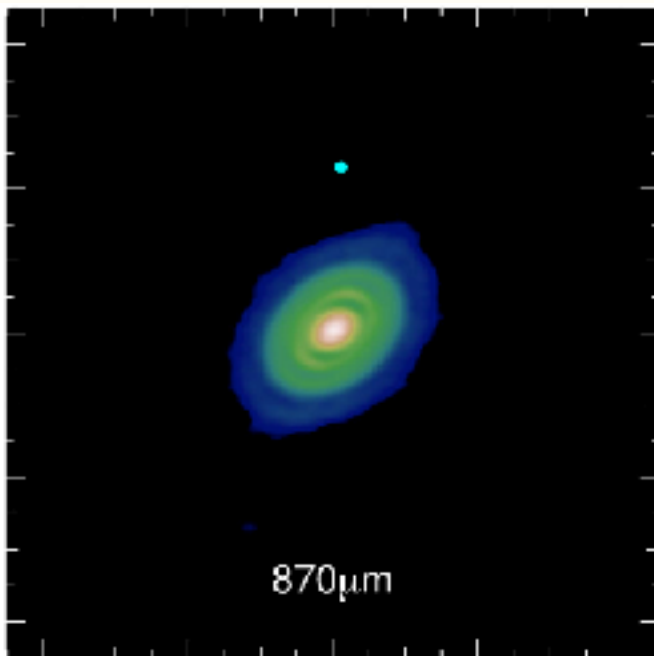
“...disks whose inner regions ($r < 0.1$ AU) are relatively devoid of distributed matter, ... Such inner holes may be indicative of the first stages of planet building as distributed dust is assembled into larger bodies.”

Protoplanetary disk observations:

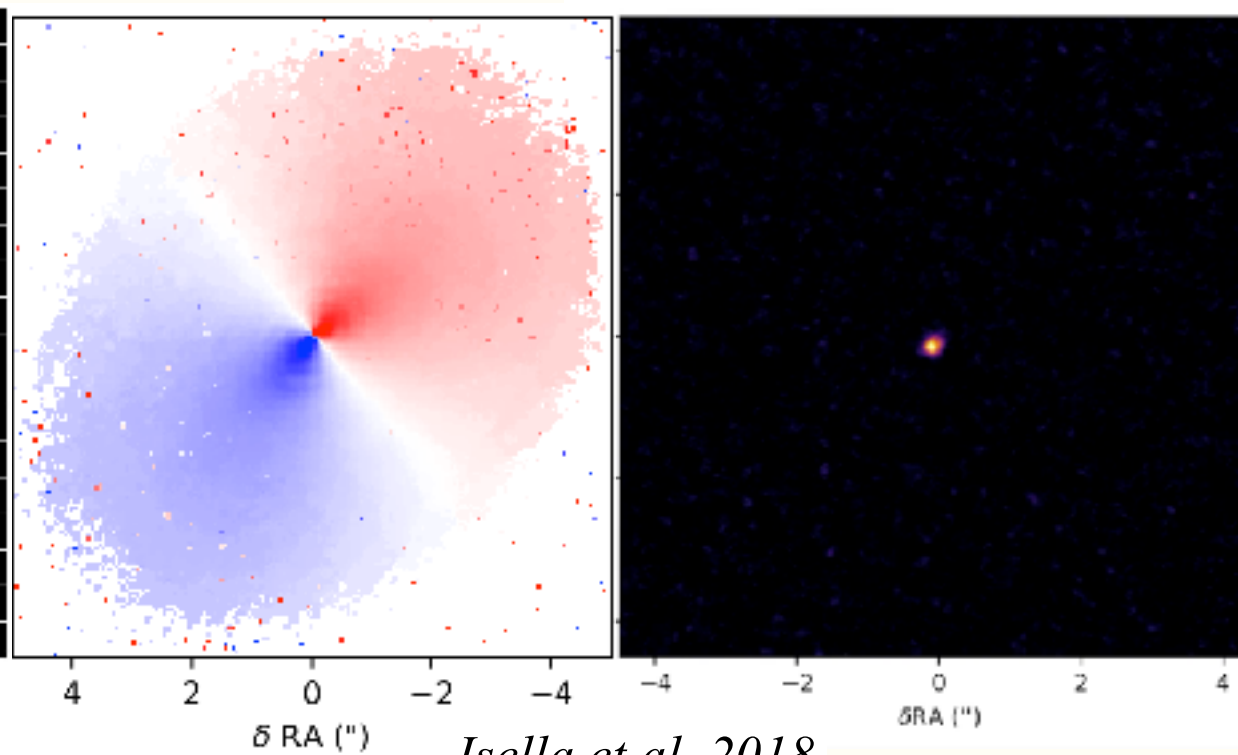
Dust continuum observations: disks are not smooth (density structure)



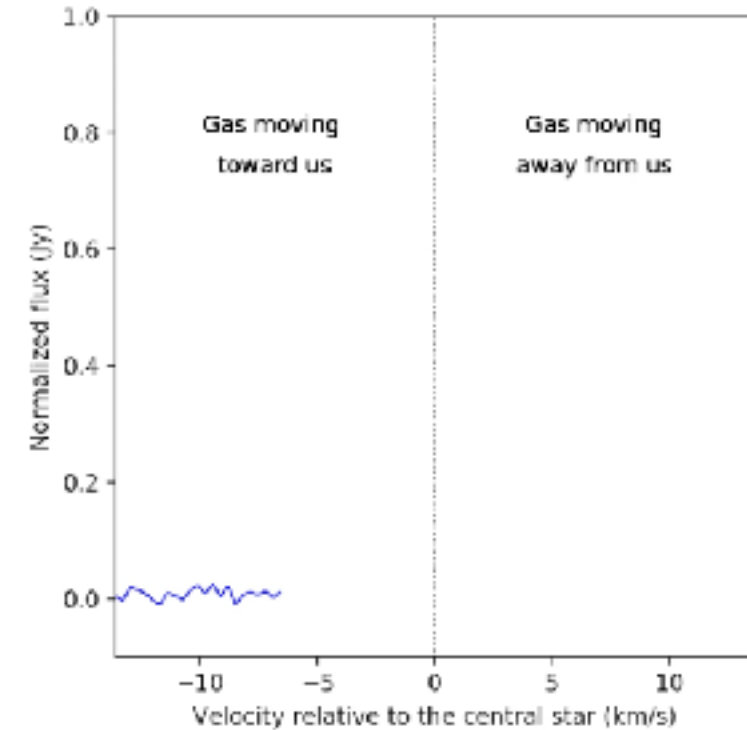
Protoplanetary disk observations: 3-D view



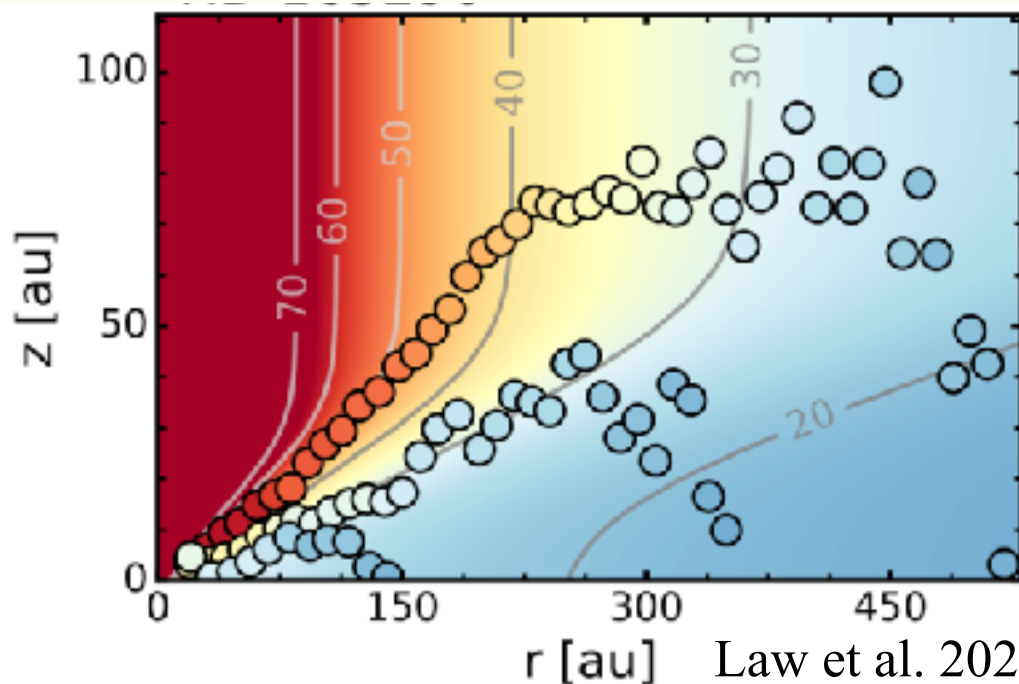
Pinte et al. 2018



Isella et al. 2018

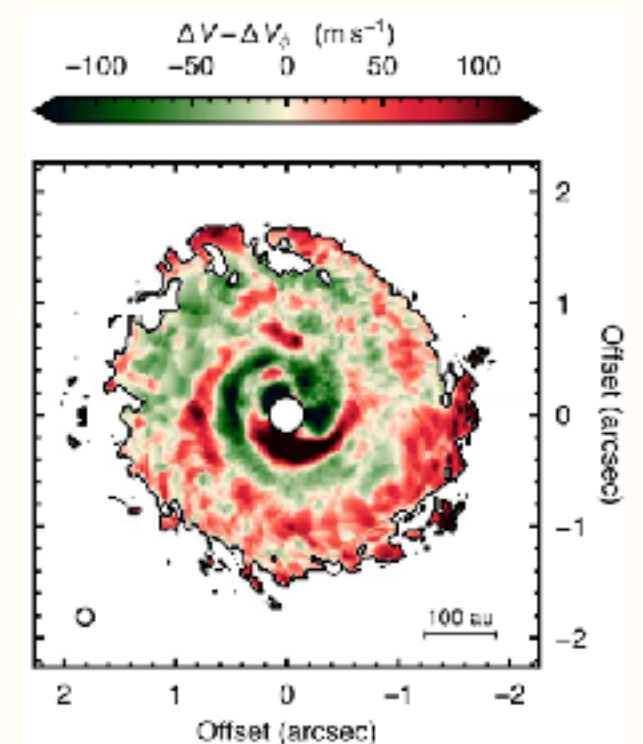


- disks have vertical stratification (Temperature)



Law et al. 2021 (MAPS IV)

- Kinematics (velocity)



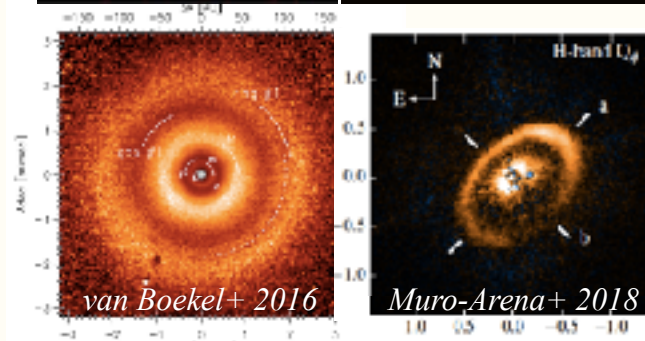
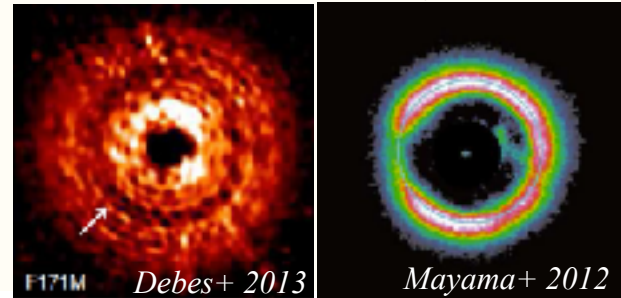
Teague et al. 2025 (exoALMA)

Outer disks: disk substructures

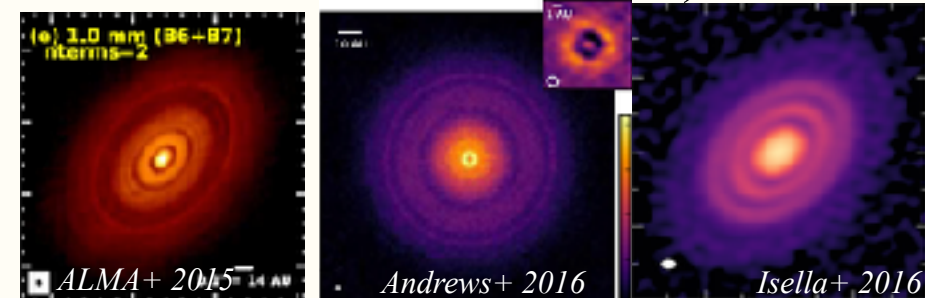
Axisymmetric

Rings/gaps

Optical/Near-IR(μm dust)

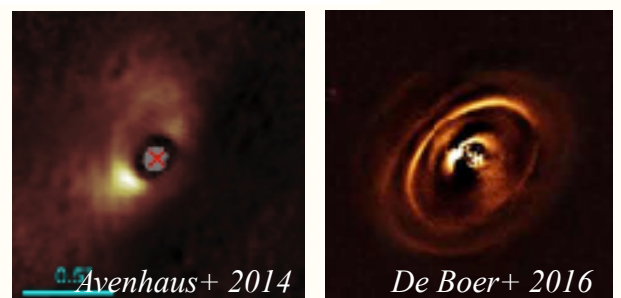


Radio (mm dust)

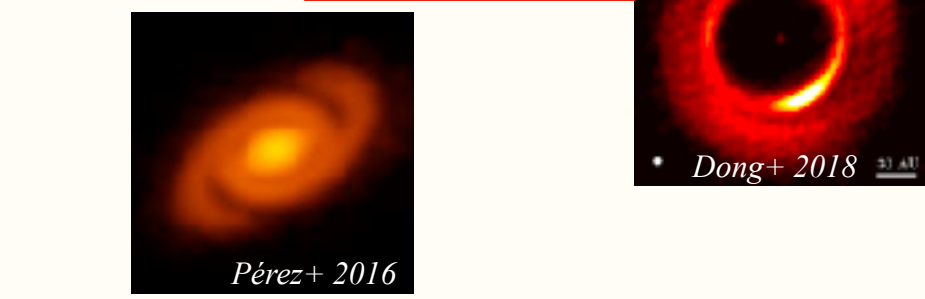
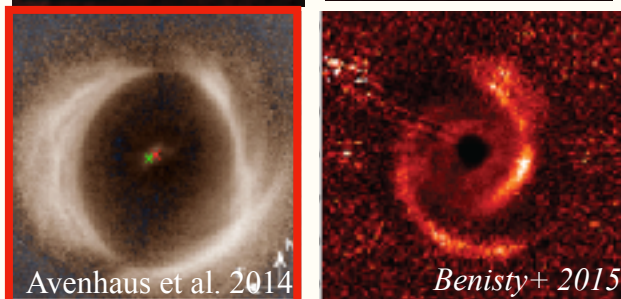


nonaxisymmetric

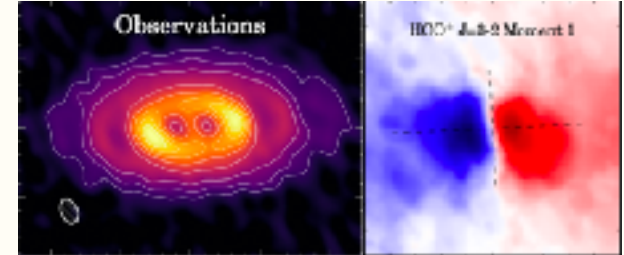
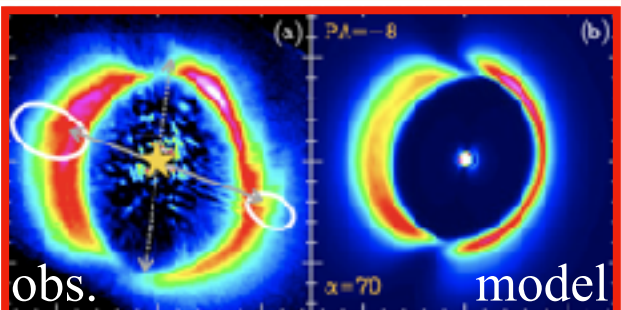
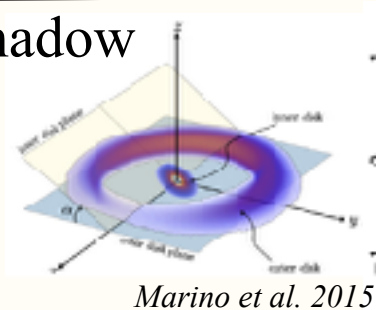
Crescents



Spirals

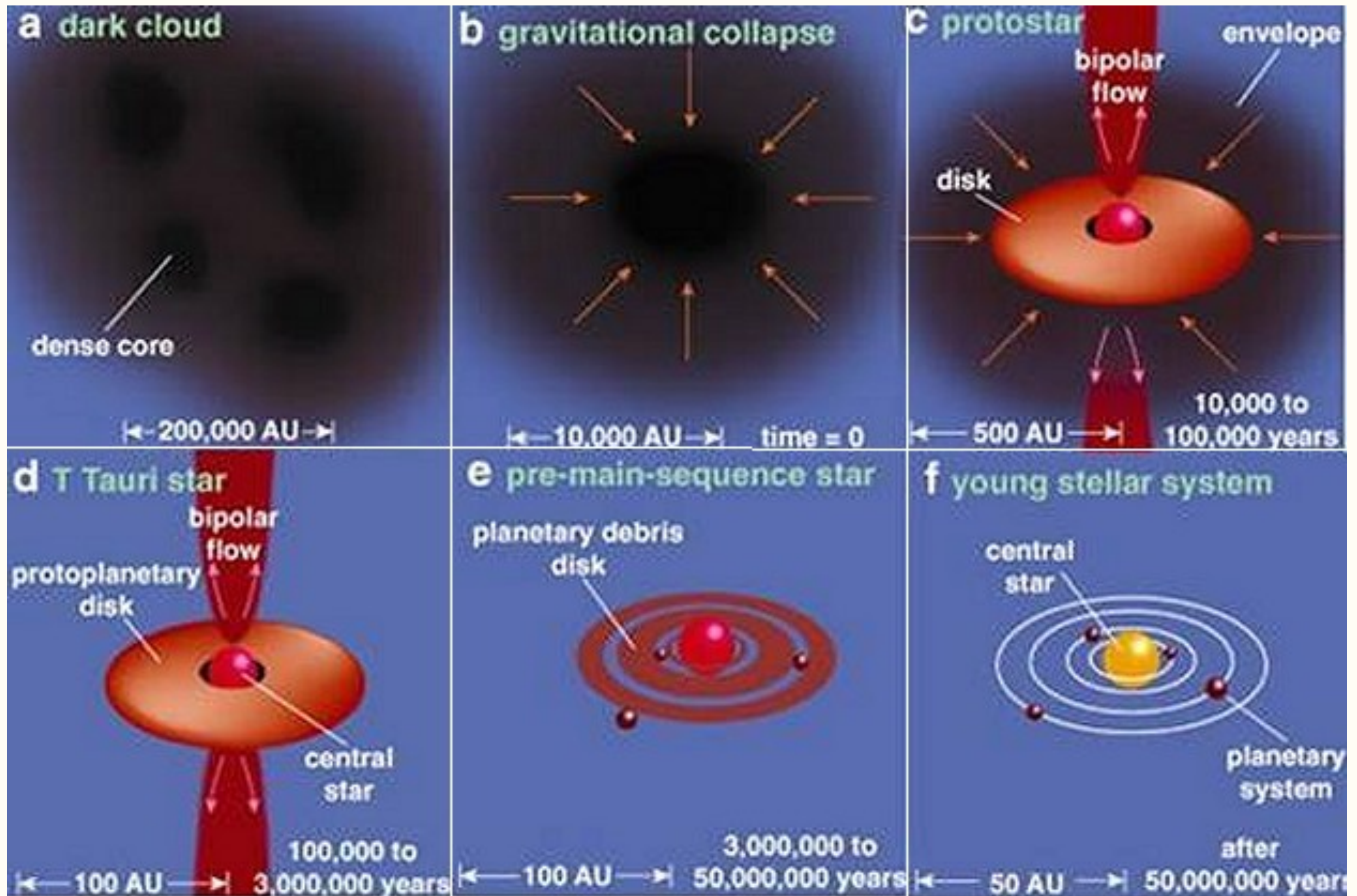


Disk Shadow



Loomis et al. 2017

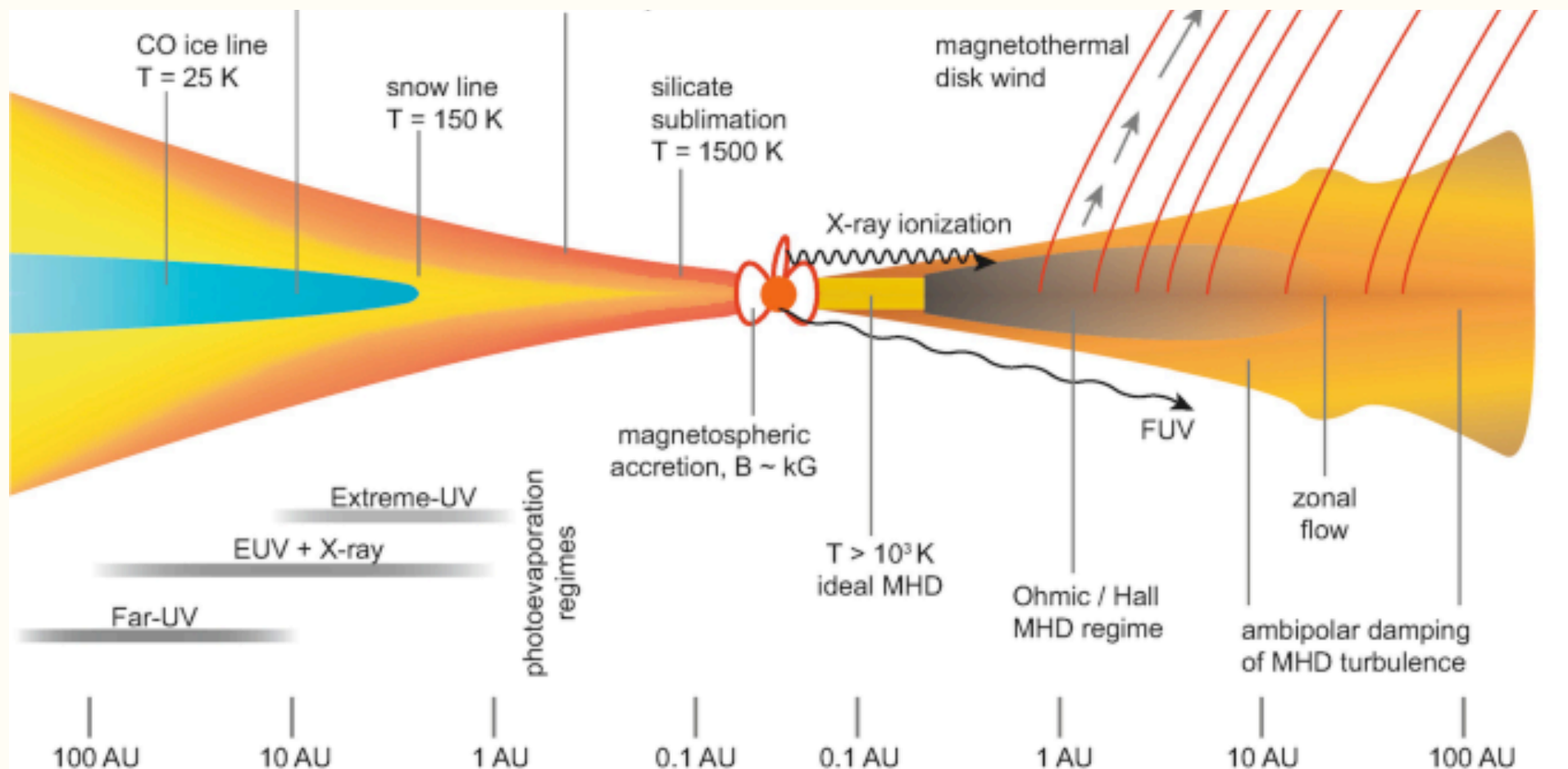
Star/Planet Formation



Protoplanetary disk and planet formation theory:

First-principle simulations are needed:

- self-consistent generated turbulence (HD, MHD, RMHD)
- Ionization and non-ideal MHD
- Chemistry (molecules)
- Dust growth and dust-gas dynamics
- Planetesimal formation
- Gas accretion onto planets



Armitage 2018
Turner et al. 2014
Lesur et al. 2023

Outline

- Accretion
- Inner disk simulations
- Outer disk simulations

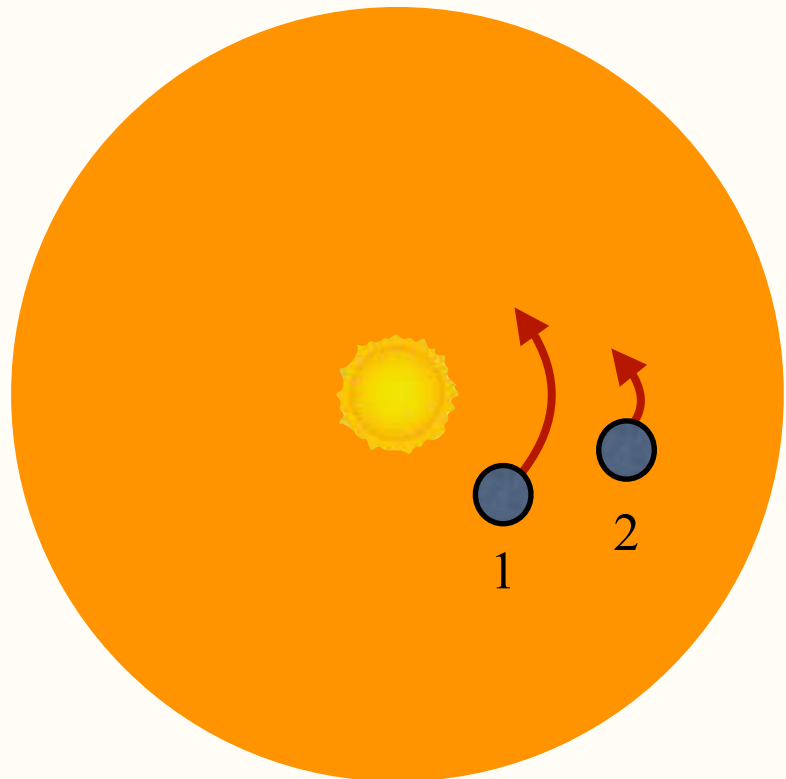
Disk Accretion: basic arguments

If there is no connection between different disk annuli, each annulus will rotate at the Keplerian velocity

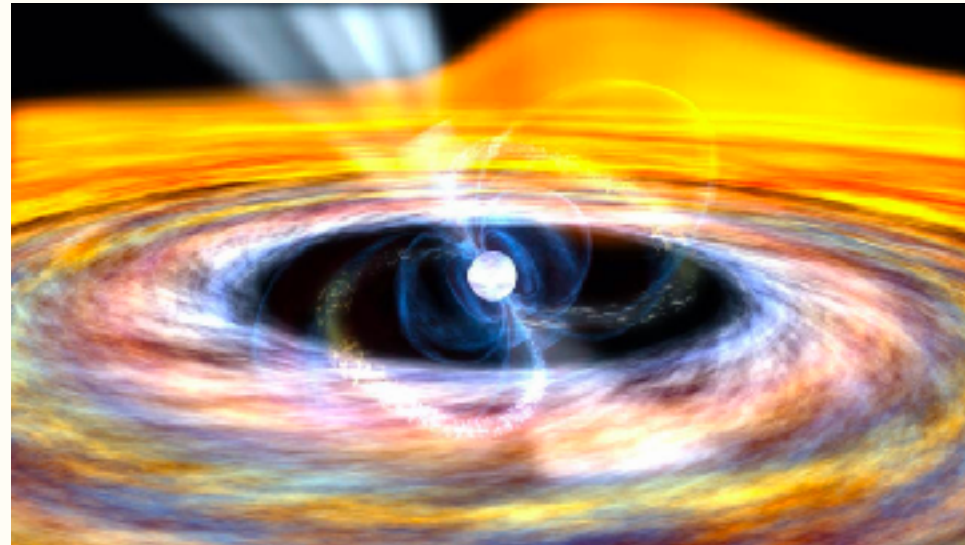
$$\sqrt{\frac{GM_*}{R}}$$

Although with a large shear, in a rotating system with $L=r*v=r^2\Omega$,

$$\frac{dL^2}{dr} < 0 \quad \text{for instability} \quad (\text{Rayleigh's criterion})$$



$\Omega \sim r^{-3/2}$ or $L \sim r^{1/2}$, so it is stable



Proof: two volume elements 1 and 2 (incompressible) with angular momentum L_1 and L_2

so the total kinetic energy is

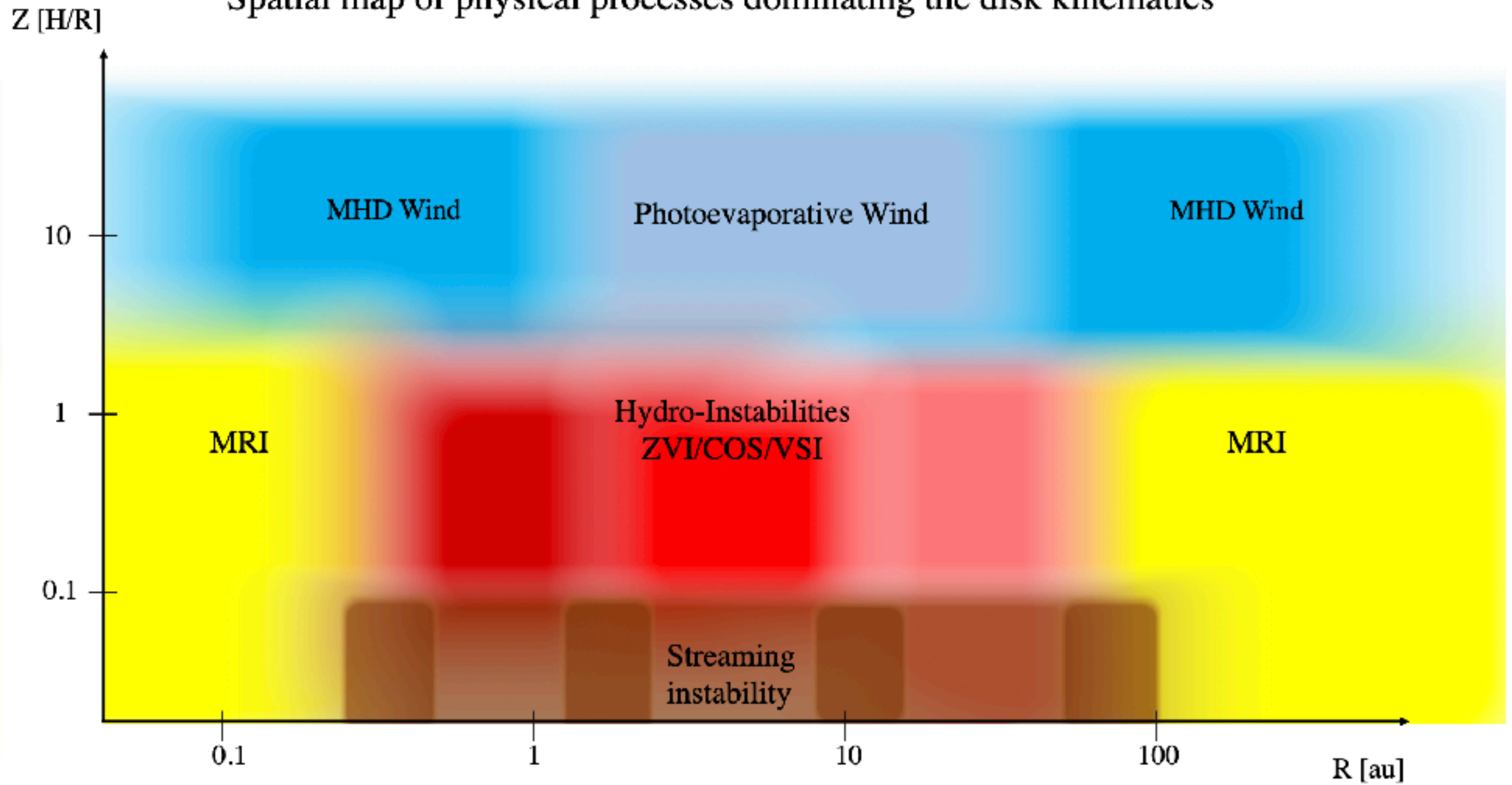
$$\frac{1}{2}\rho v^2 = \frac{1}{2} \frac{\rho L^2}{r^2} \quad E = \frac{1}{2} \left(\frac{\rho L_1^2}{r_1^2} + \frac{\rho L_2^2}{r_2^2} \right)$$

Now elements 1 and 2 are switched while conserving angular momentum

$$E_{\text{new}} = \frac{1}{2} \left(\frac{\rho L_1^2}{r_2^2} + \frac{\rho L_2^2}{r_1^2} \right)$$

Unstable: E_{new} has to be smaller only if $L_1 > L_2$

Spatial map of physical processes dominating the disk kinematics



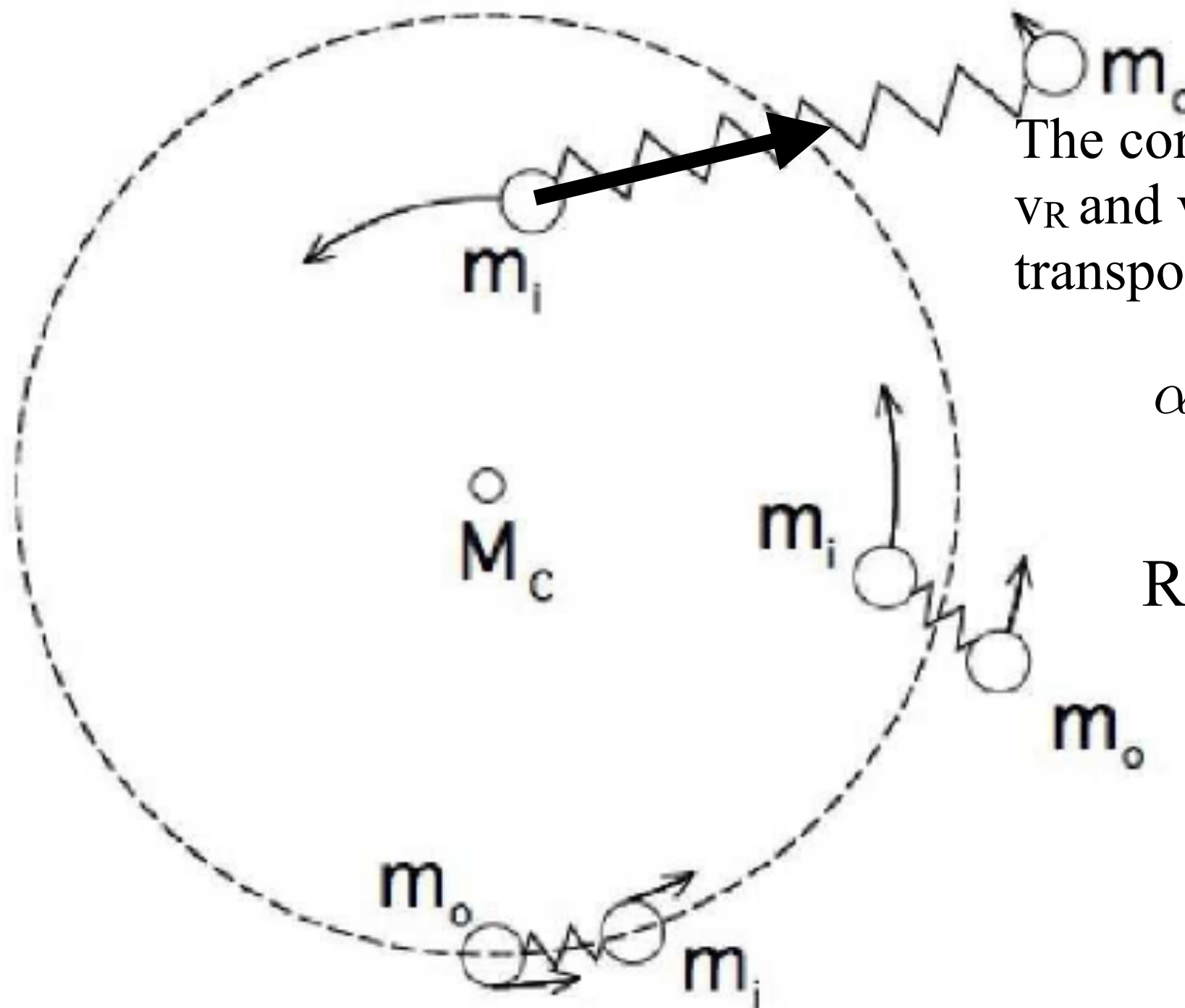
Lecture notes: Non-ideal MHD

Need something to make the disk unstable: B

Magnetic Fields:

MRI: Balbus & Hawley 1991

Ideal MHD: magnetic fields are frozen with ionized gas (spring)



The correlation between B_R and B_ϕ or v_R and v_ϕ leads to angular momentum transport

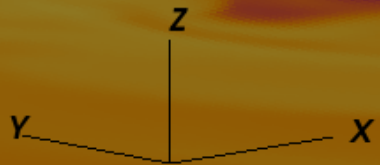
$$\alpha = \frac{\rho \delta v_R \delta v_\phi}{P} - \frac{B_R B_\phi}{4\pi P}$$

Reynolds stress Maxwell stress

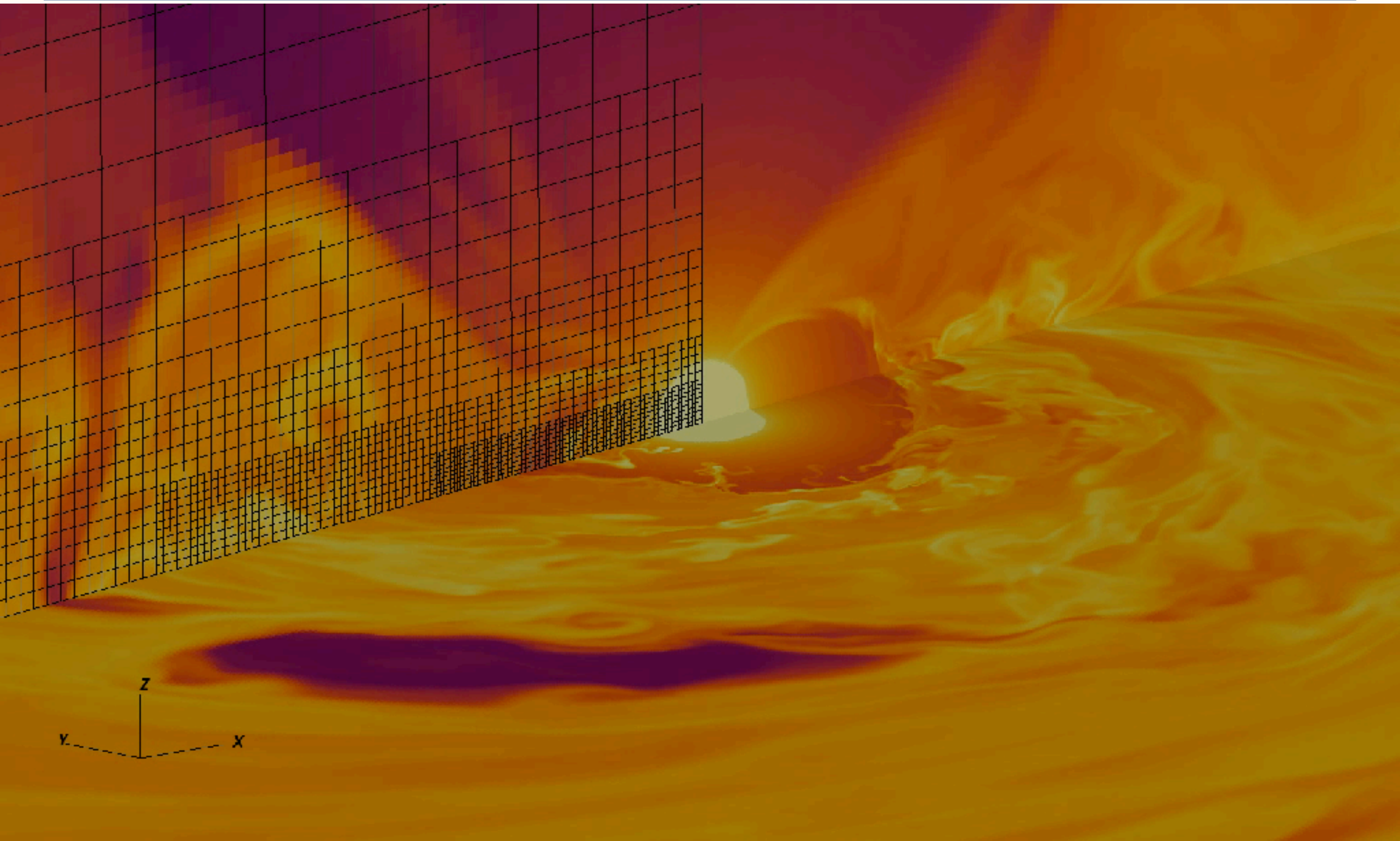
Runaway effect (instability)
leads to turbulence

3-D global ideal MHD simulation

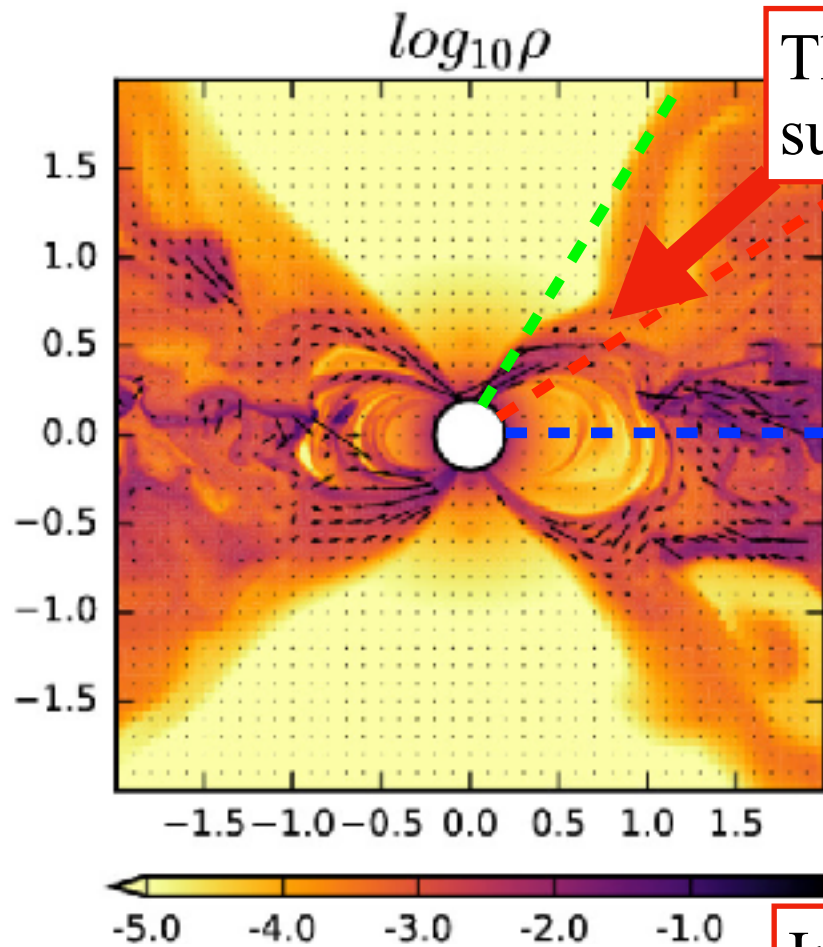
- Cartesian grid with 7 level mesh-refinement
- Include a non-rotating star
- Dipole fields
- $2157 T_{\text{in}}$



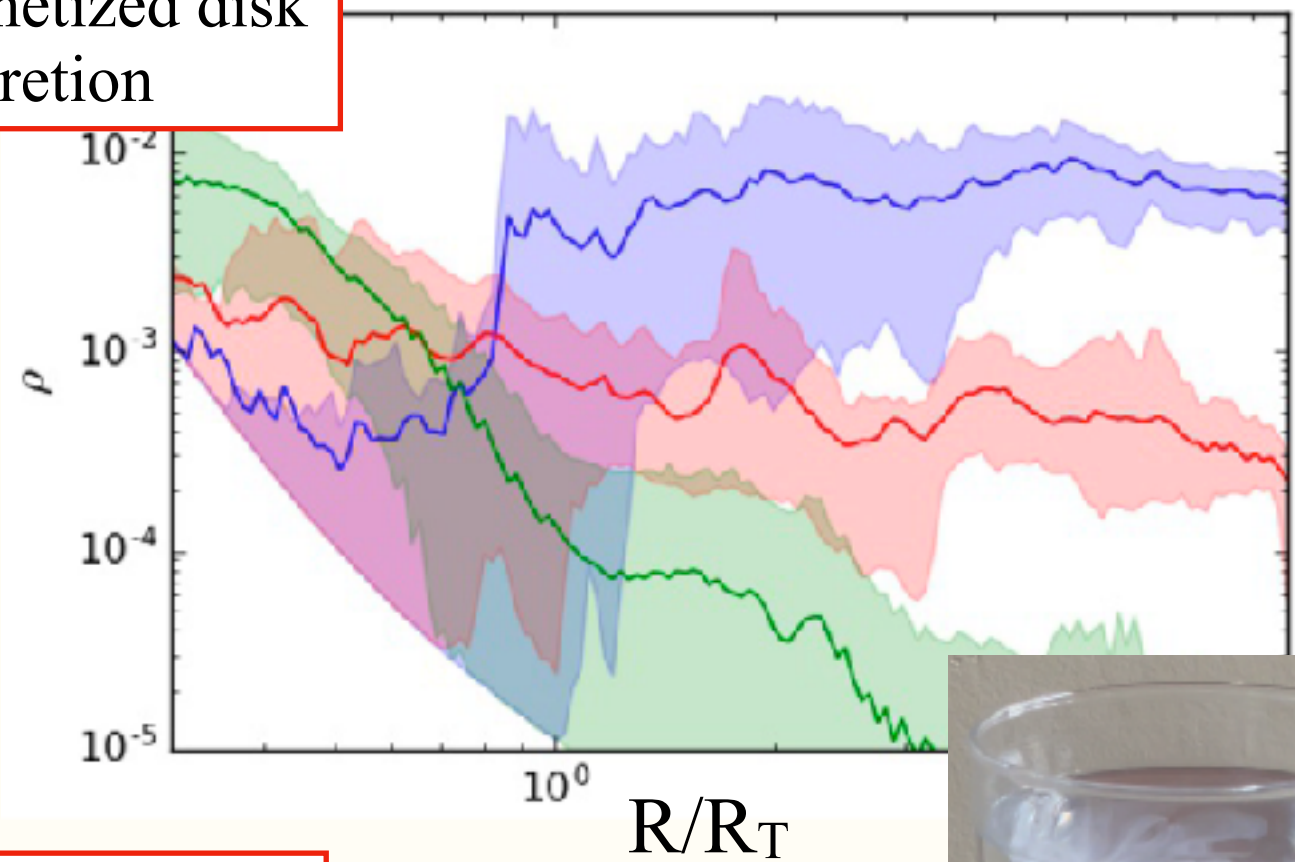
3-D global ideal MHD simulation



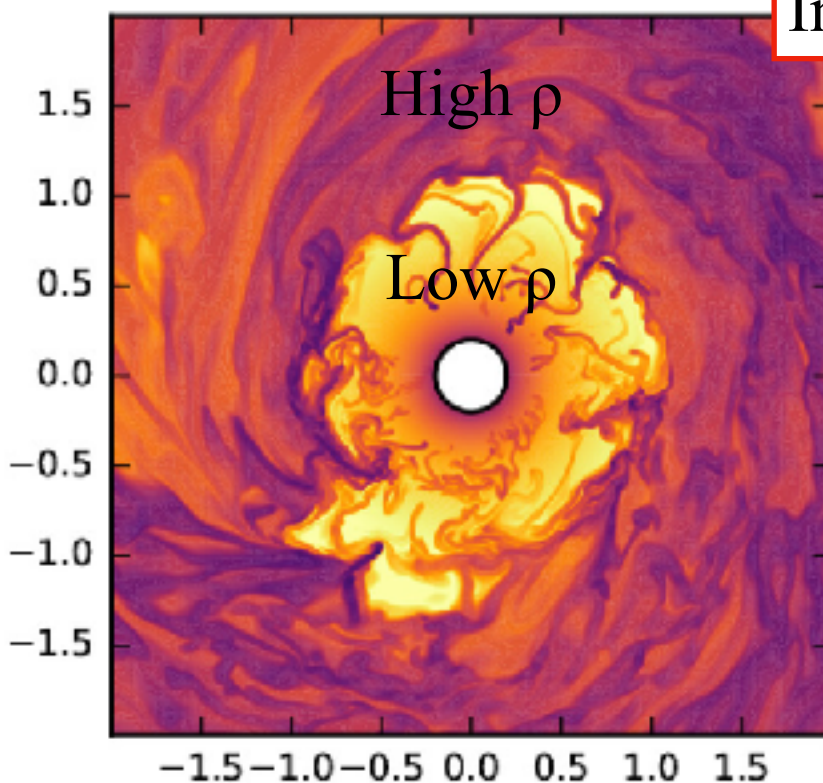
Polar and equator accretion



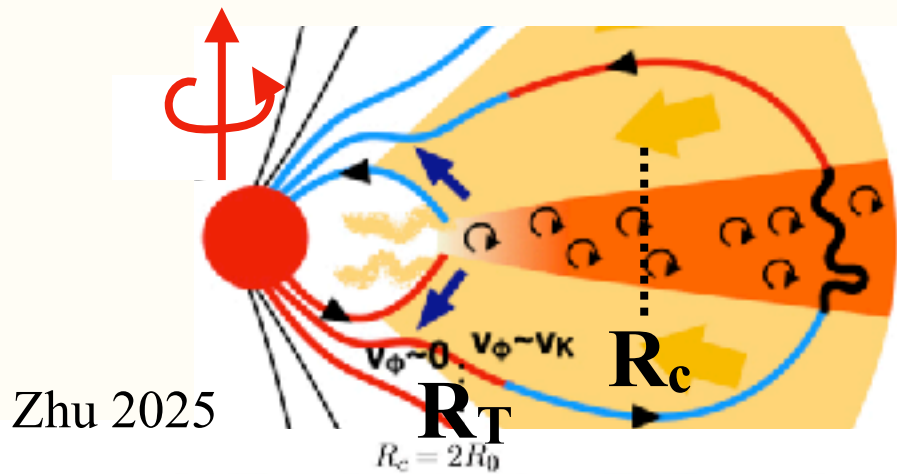
Thick magnetized disk
surface accretion



Interchange Instability

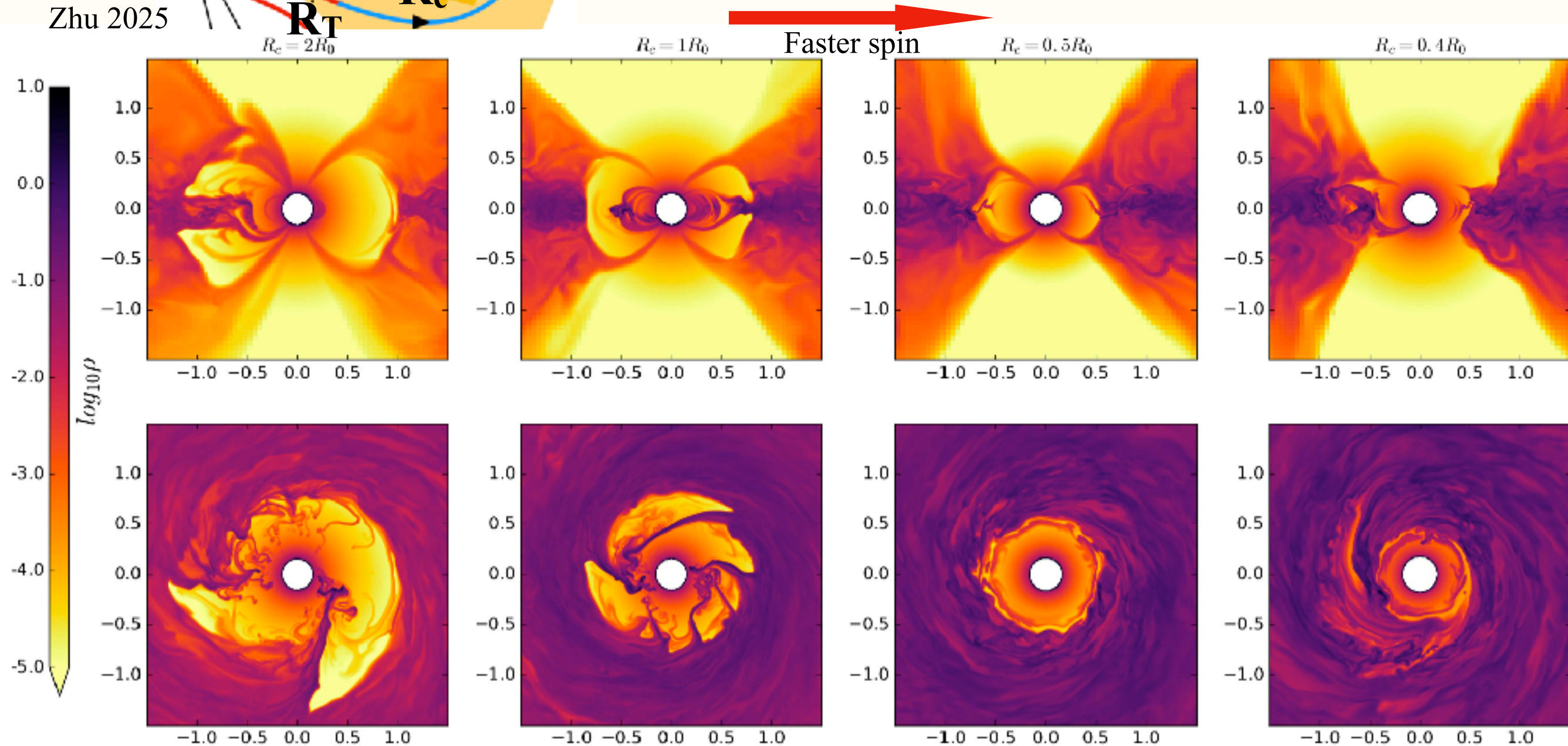


The effects of stellar spin: Suppress filaments



Corotation radius: R_c $\Omega_* = \Omega_K$

$$\alpha \sim R_T / R$$



Non-ideal MHD effects

But, in outer protoplanetary disks, the disk is not sufficiently ionized
Thermal ionization only works at the inner disk (<0.3 au, $T > 1000$ K),
X-ray/cosmic rays only work at the disk surface.

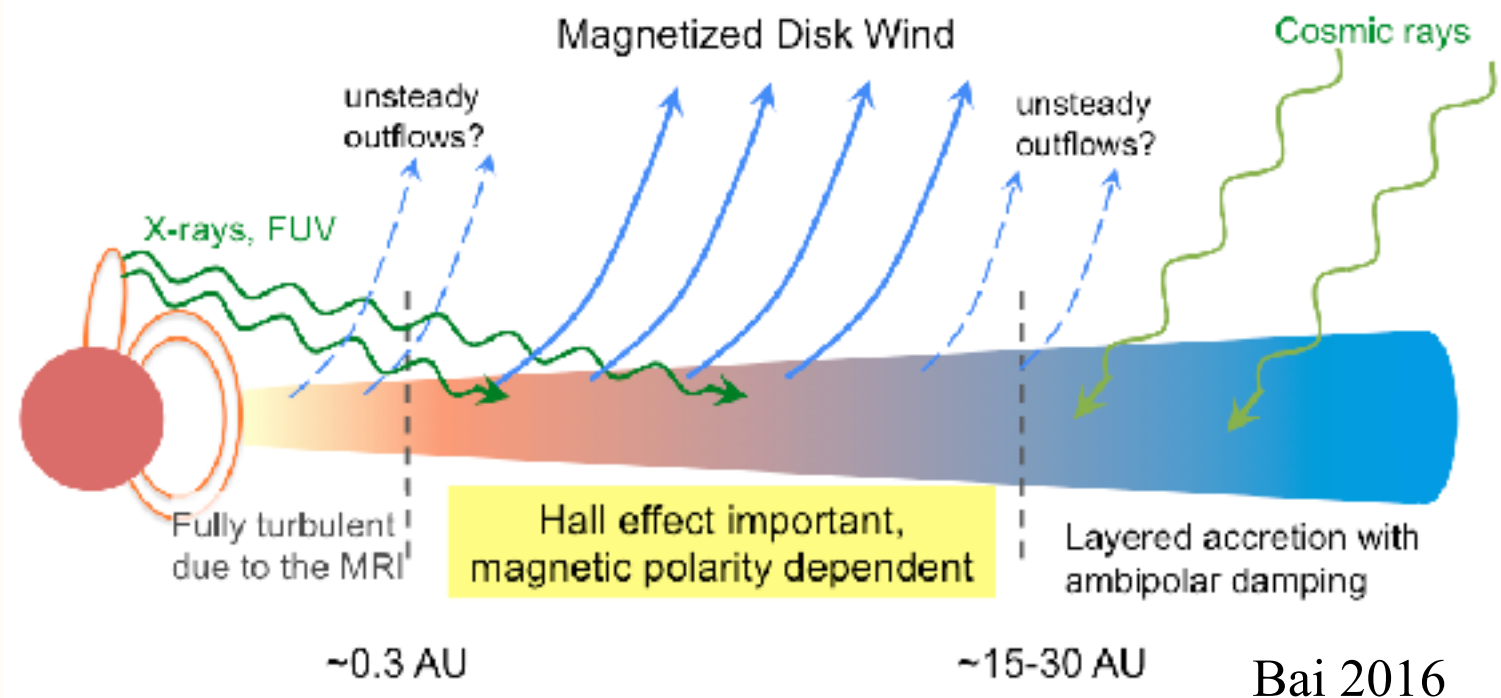
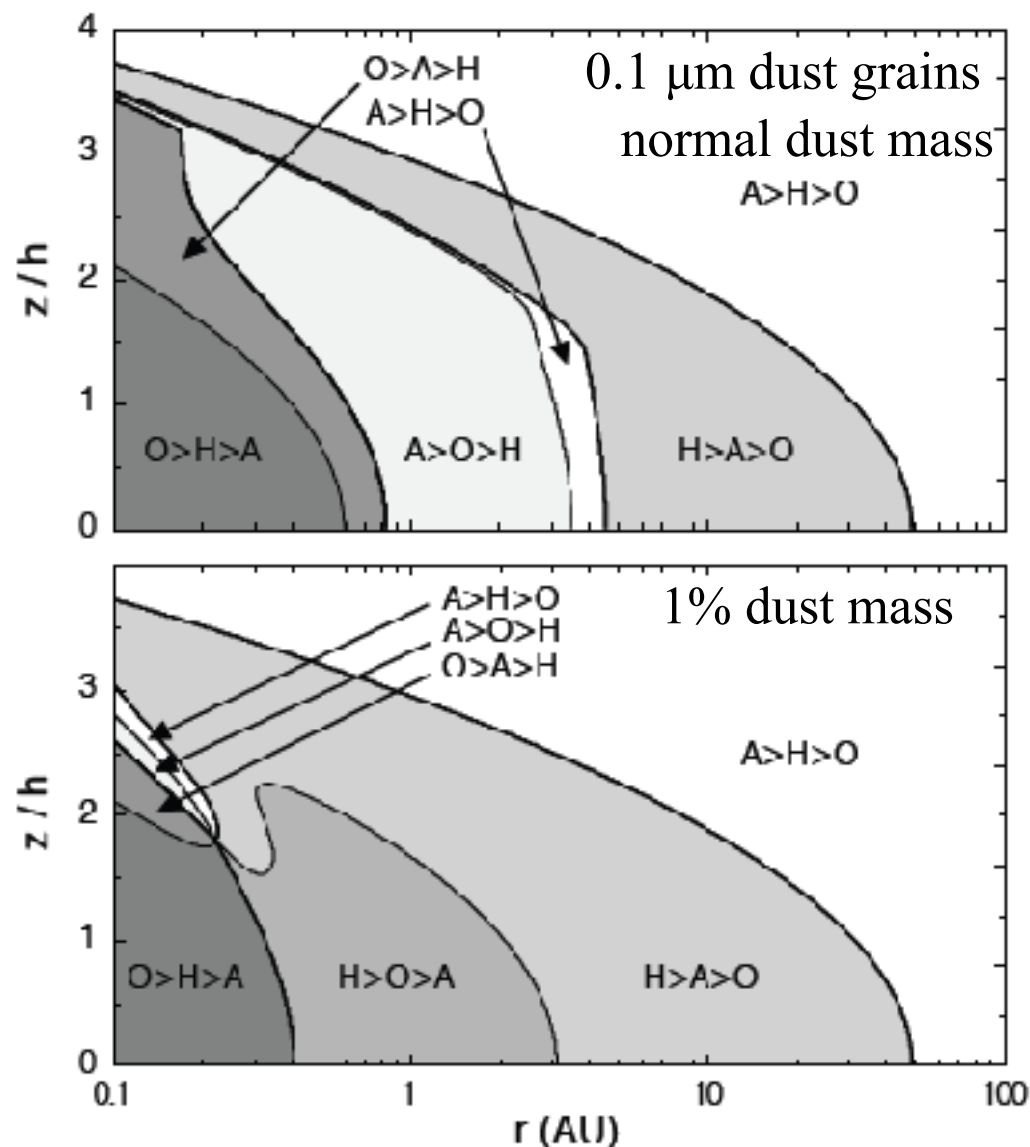
Non-ideal MHD effects:

Ohmic dissipation - collisions between electrons and neutrals

Ambipolar diffusion - collisions between ions and neutrals

Hall effect - by velocity difference between electrons and ions (B and L aligned or anti-aligned)

(Gammie 1996, Turner et al. 2007, Bai & Goodman 2009)



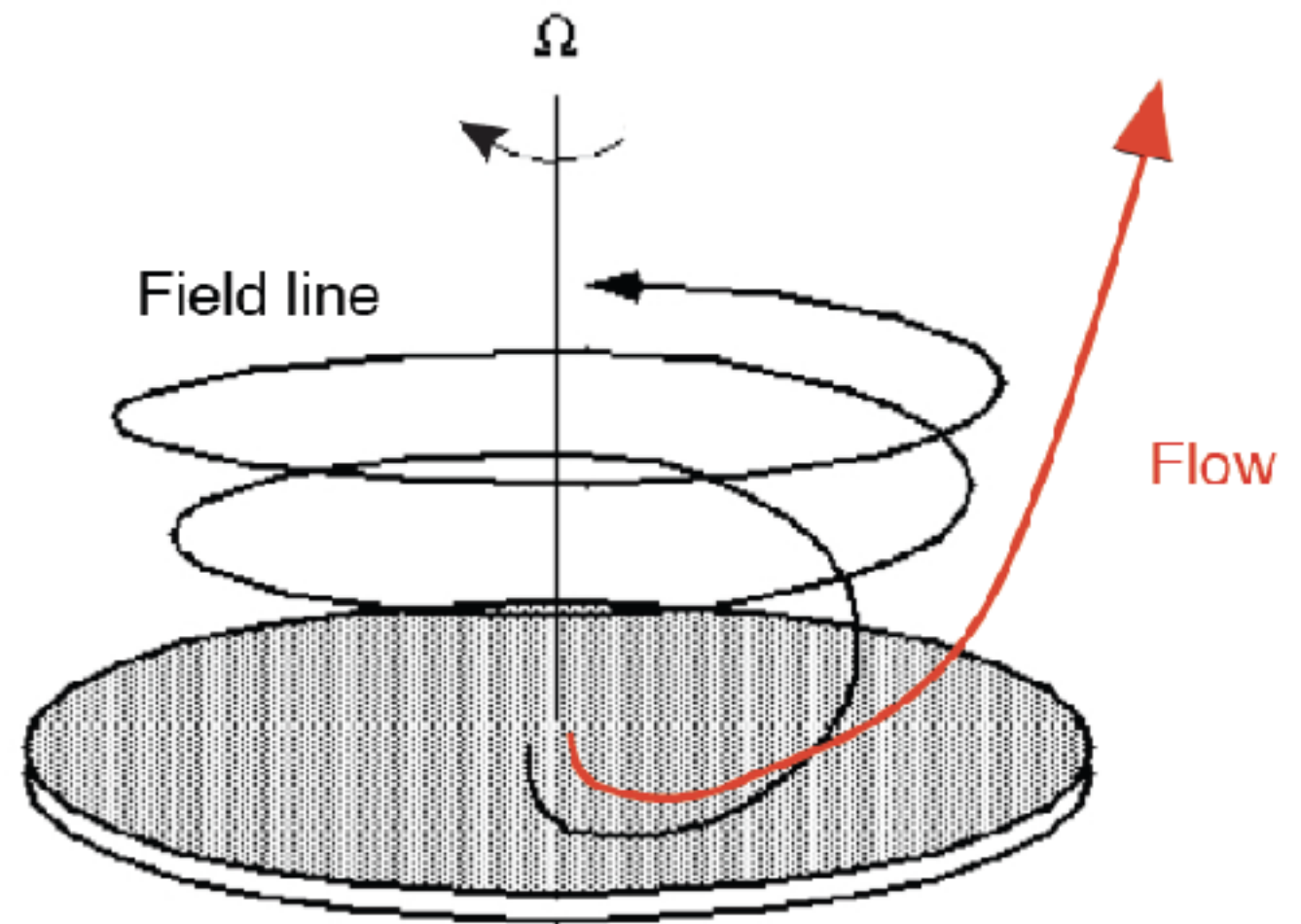
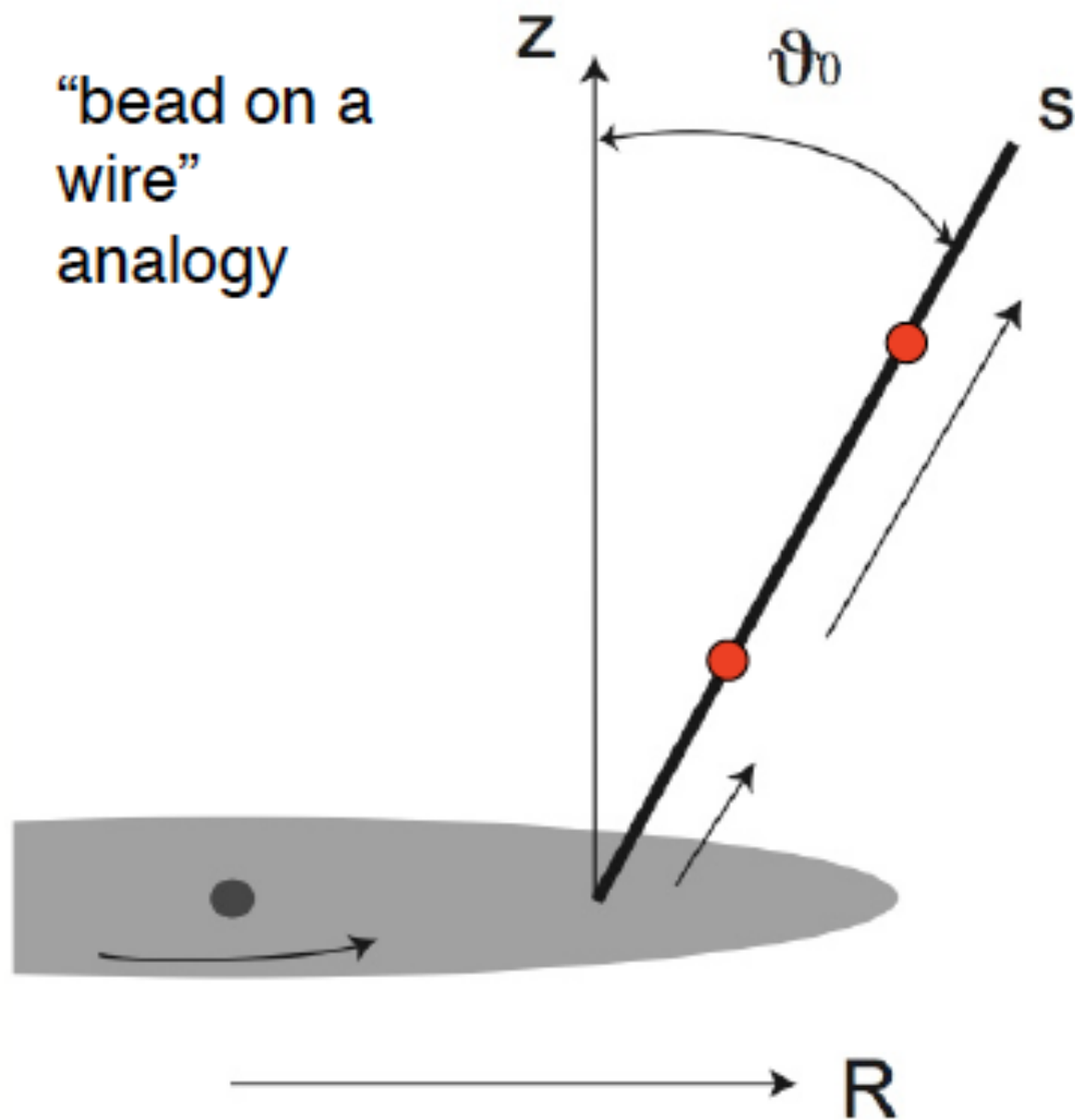
Turner et al. 2014

Require disk wind for angular momentum transport

Magnetized disk Wind (Blandford & Payne 1982) (require net vertical magnetic fields)

$$\theta > 30^\circ$$

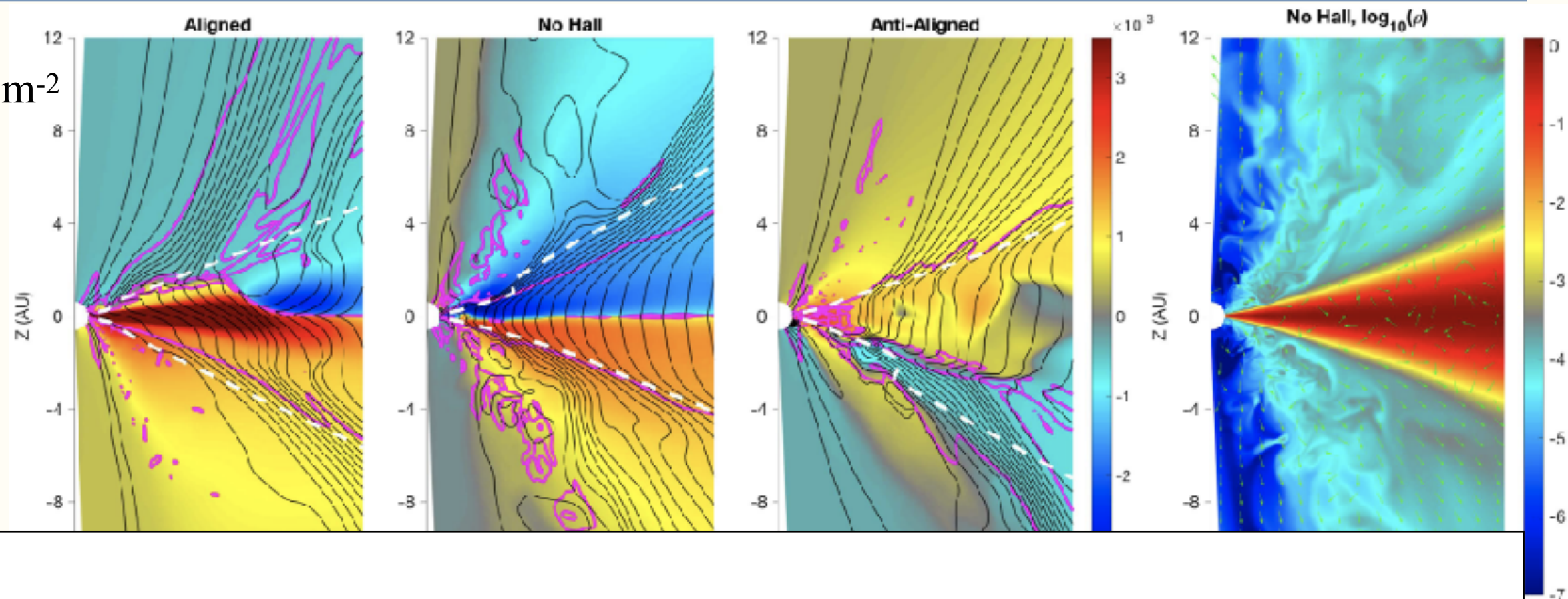
“bead on a wire” analogy



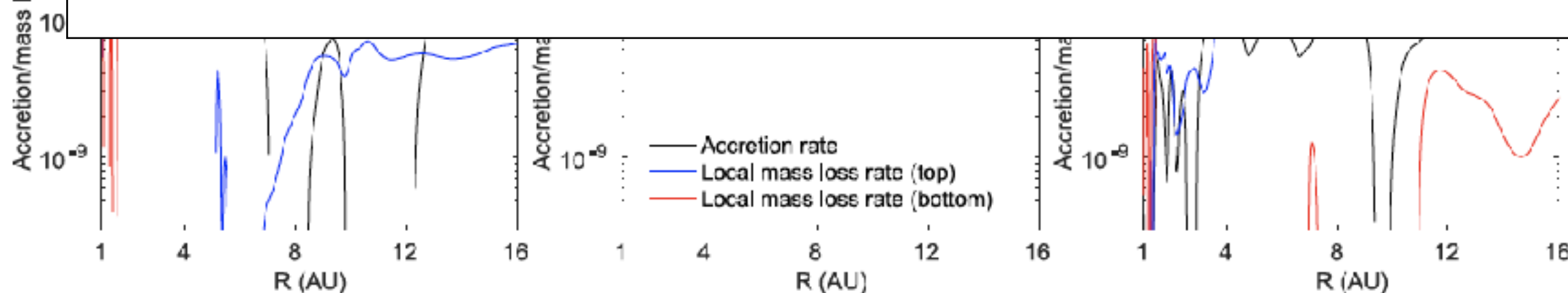
Non-ideal MHD effects

$$\beta=10^5$$

$$\text{FUV } 0.3 \text{ g cm}^{-2}$$



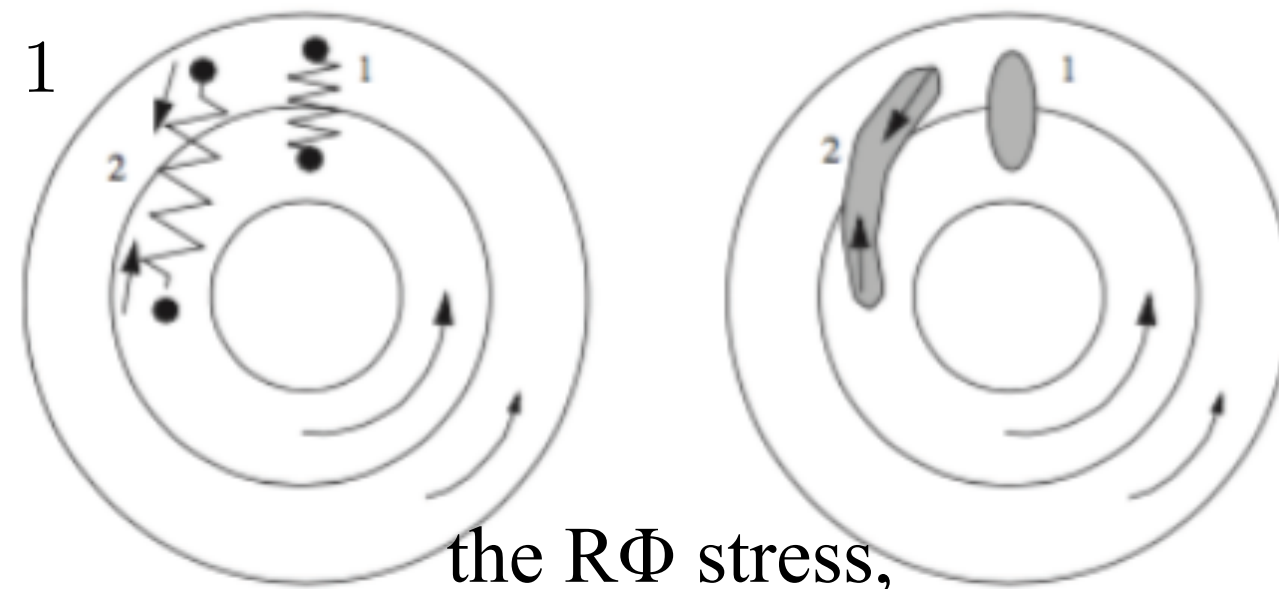
MRI can drive accretion but coupled with chemistry and non-ideal MHD effects



Very outer disks at early stages: Self-gravity

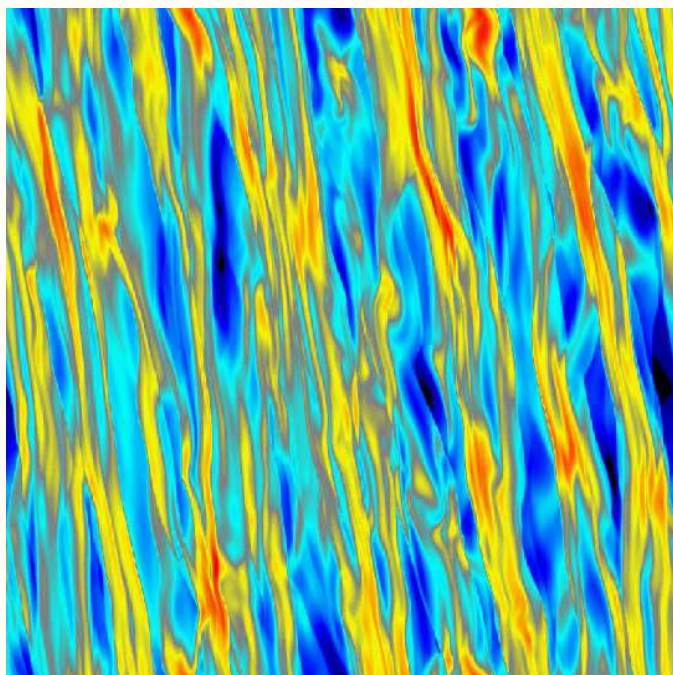


$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} \sim 1$$

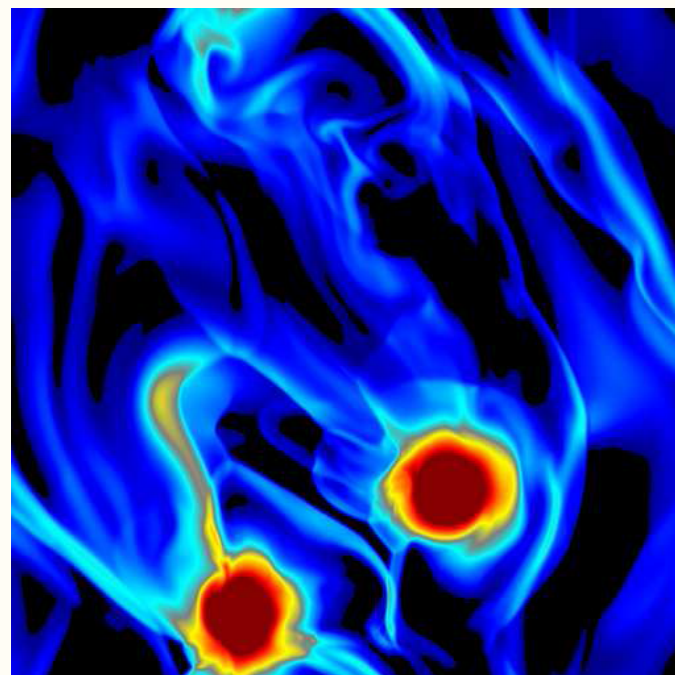


the $R\Phi$ stress,
angular momentum transport

GI is a thermal self-regulating instability



$t_{\text{cool}} \Omega = 50$



$t_{\text{cool}} \Omega = 2$

High Q , no GI, no heating



Cools down, Q decreases

If Q too small, GI strong



Heat up, Q increase ($Q \sim 1$)

Too fast cooling
leads to fragment

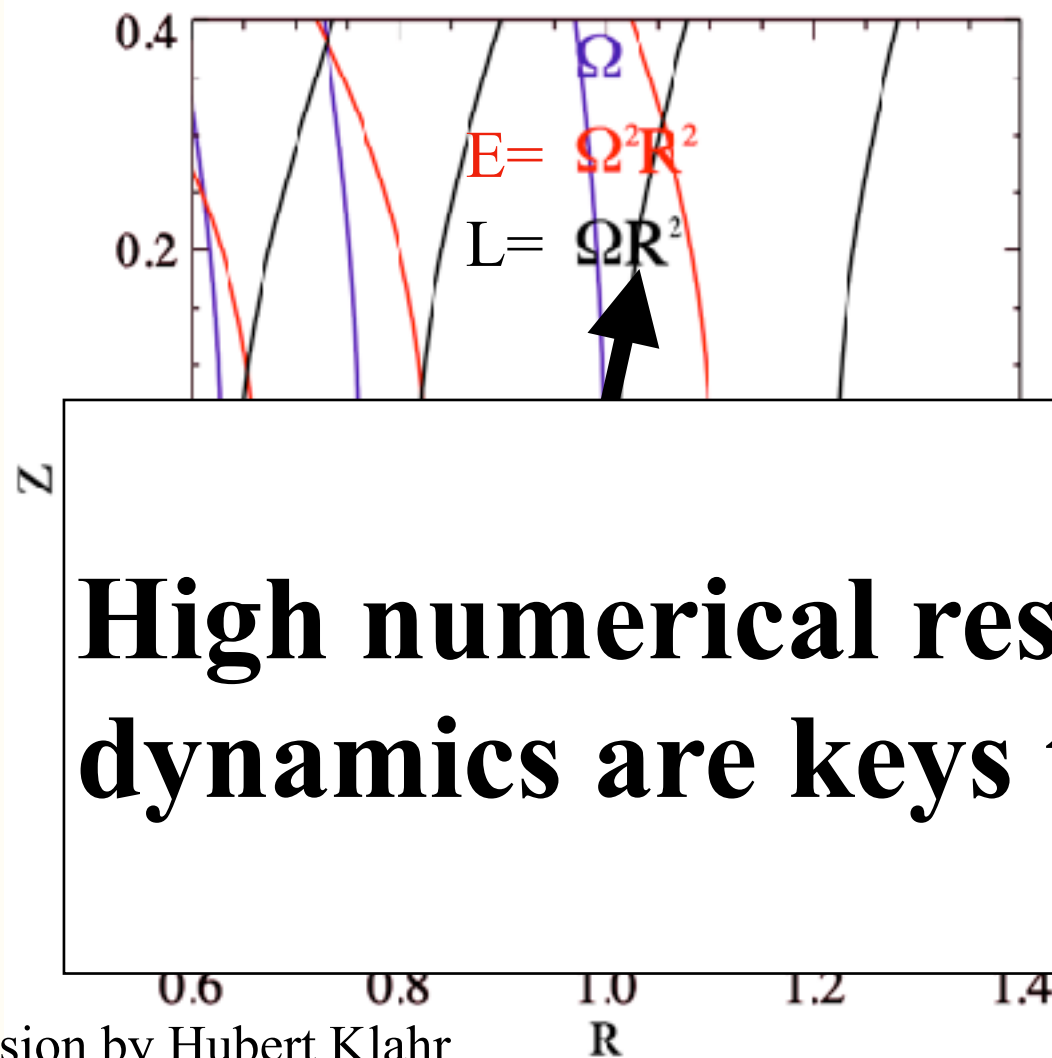
Gammie 2001

Instabilities due to thermal effects

Vertical Shear Instability

Nelson et al. 2013, Lin&Youdin 2015, Umurhan et al. 2016

Contours of constant Rotation and angular Momentum
and kinetic Energy



High numerical resolution and the thermal dynamics are keys to these hydro instability

PROCS-RIVERA et al. 2020

Permission by Hubert Klahr

Convective Overstability

Klahr 2013, Petersen et al. 2007, Lesur & Papaloizou 2010, Lyra & Klahr 2011

Zombie Vortex Instability (non-linear instability)

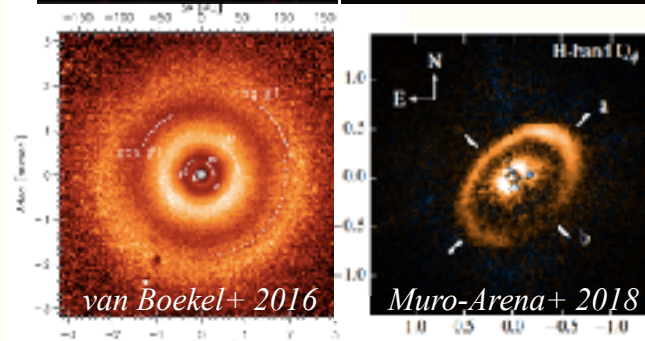
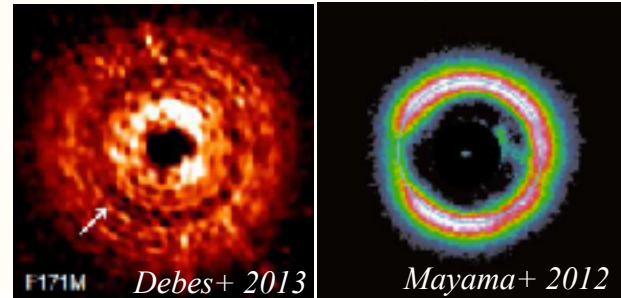
Marcus et al. 2012, 2015, 2016, Lesur & Latter 2016

Outer disks: disk substructures

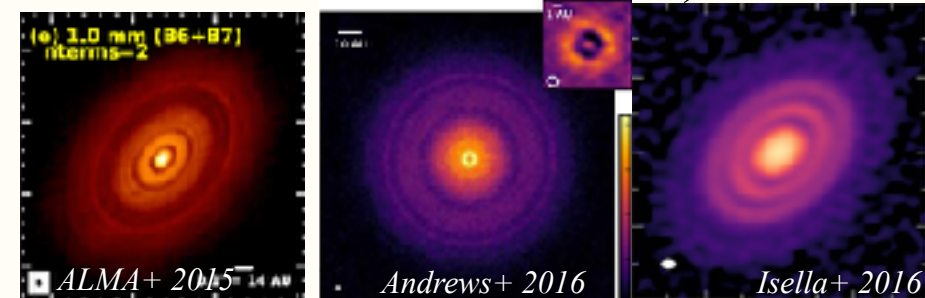
Axisymmetric

Rings/gaps

Optical/Near-IR(μm dust)

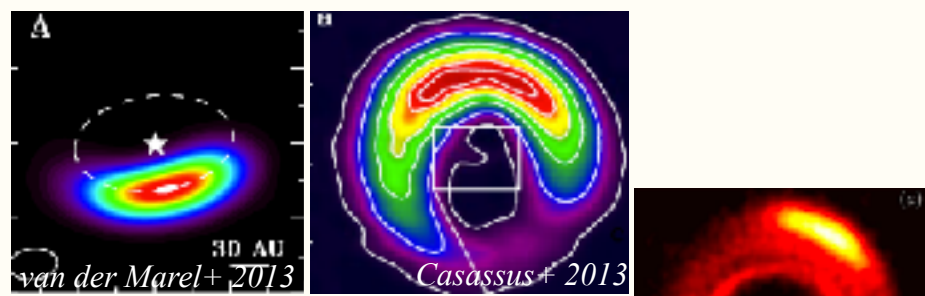
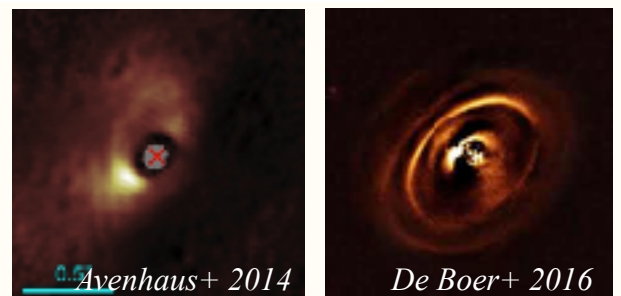


Radio (mm dust)

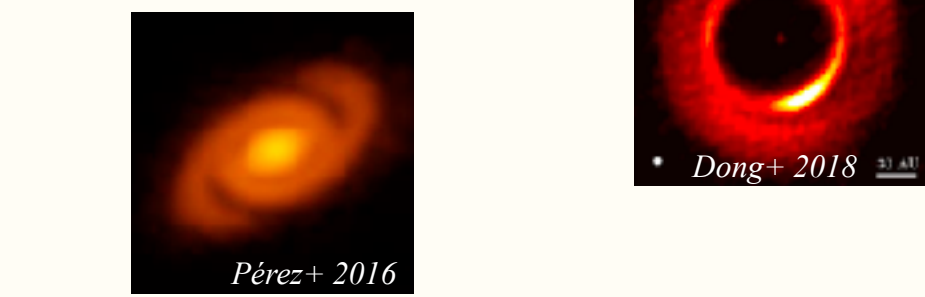
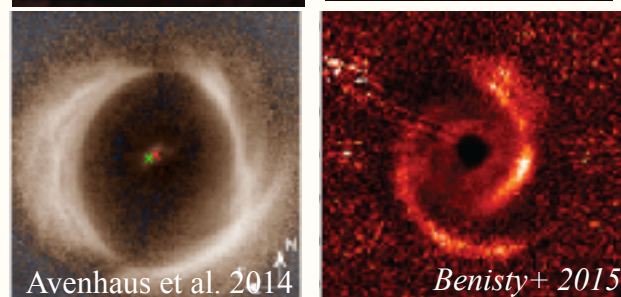


nonaxisymmetric

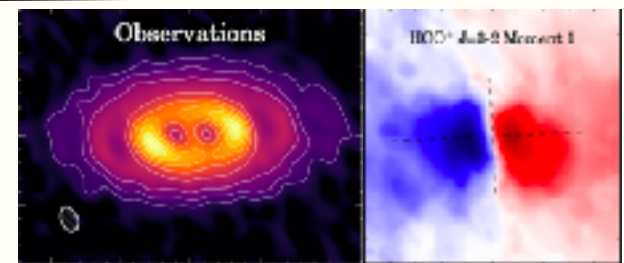
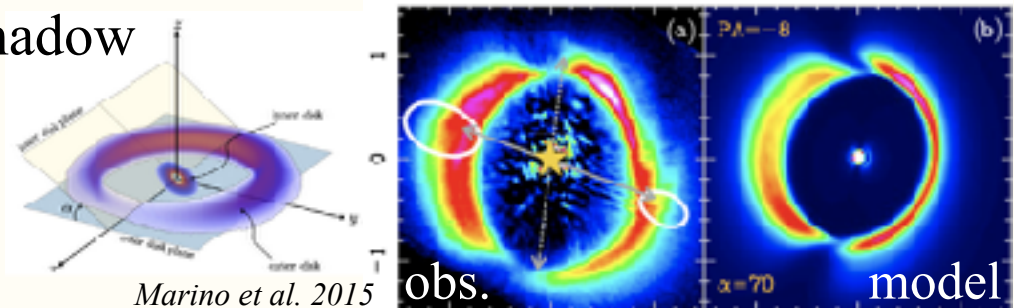
Crescents



Spirals



Disk Shadow

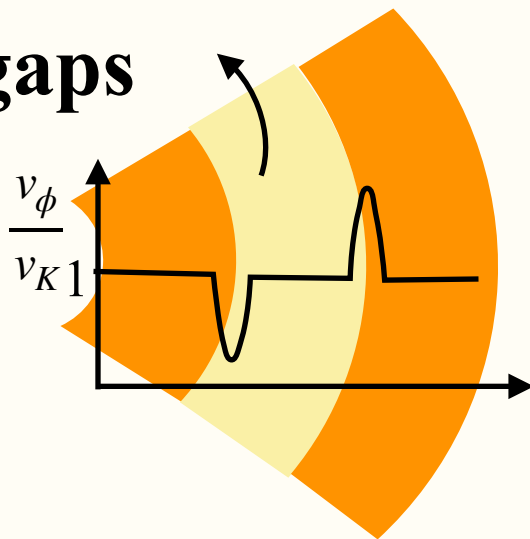


Loomis et al. 2017

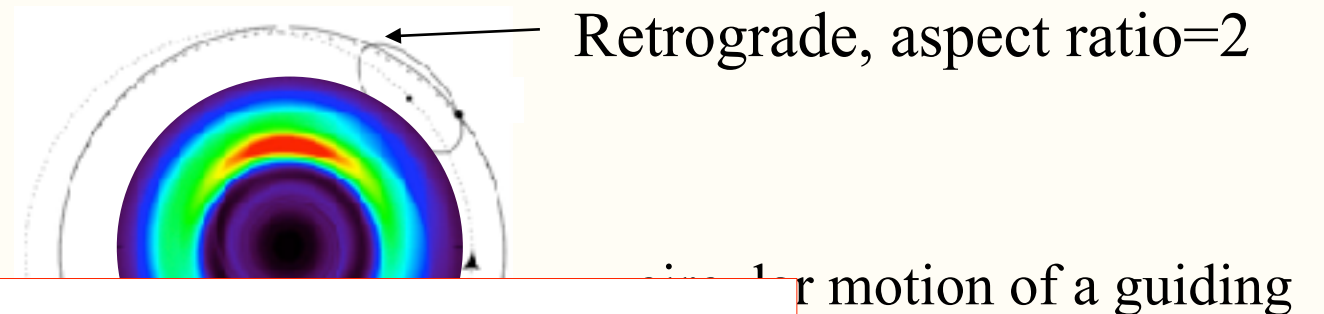
Why gaps/crescents/spirals in Protoplanetary

Basic properties of a **rotating** disk

Rings/gaps

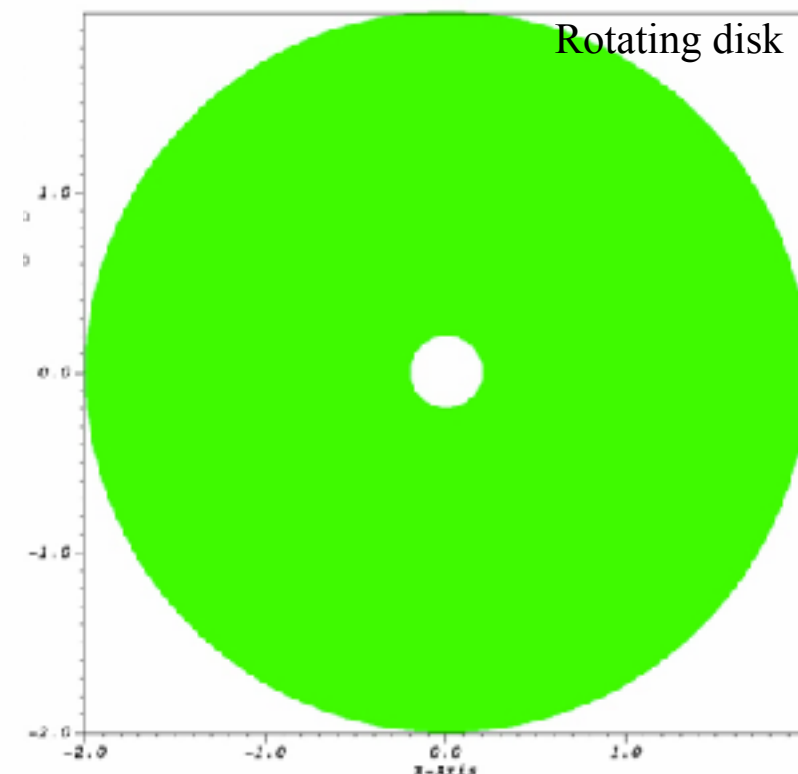
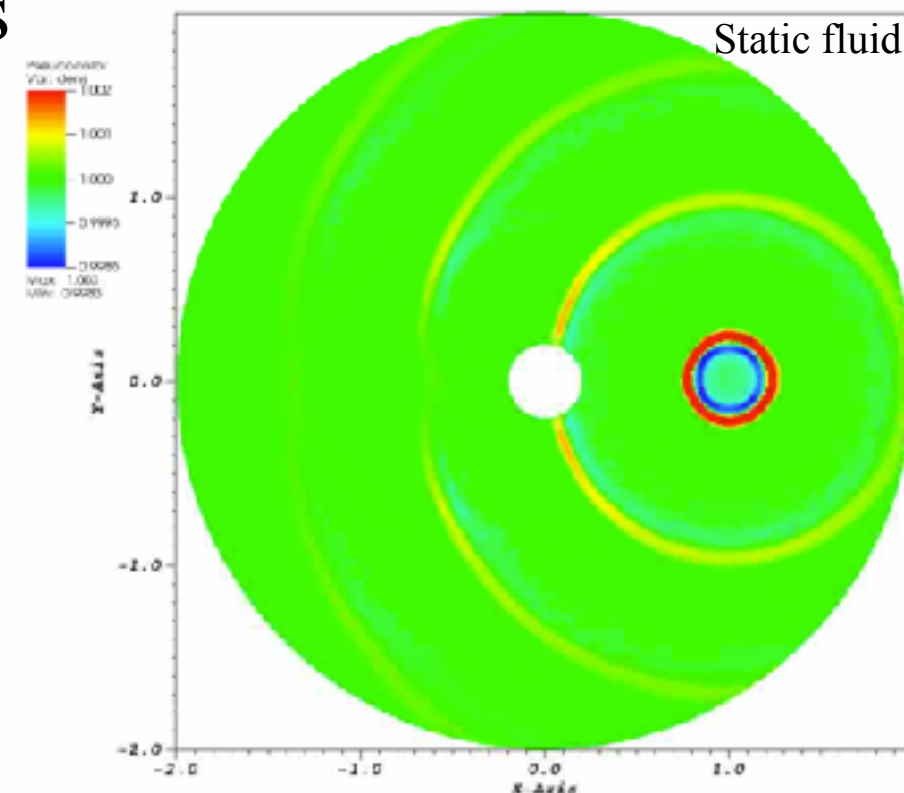


Vortex: epicyclic motion



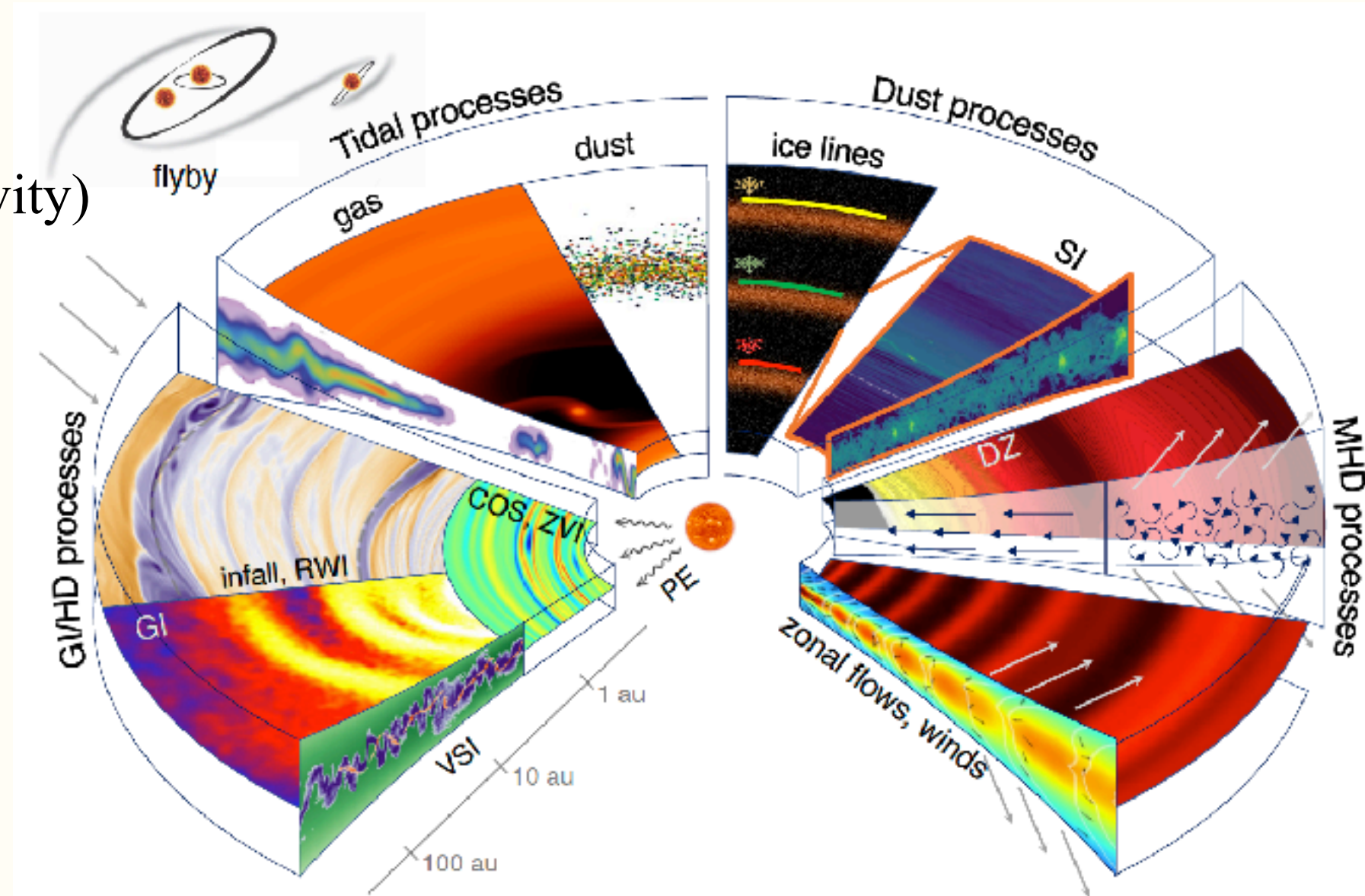
What drives these features?

Spirals: waves



Processes responsible for substructures

- Hydrodynamics
- MHD (B)
- Self-gravity (gravity)
- Perturber (external gravity)
- Dust (multi-fluids)



Hydrodynamics

- Vertical Shear Instability (VSI)

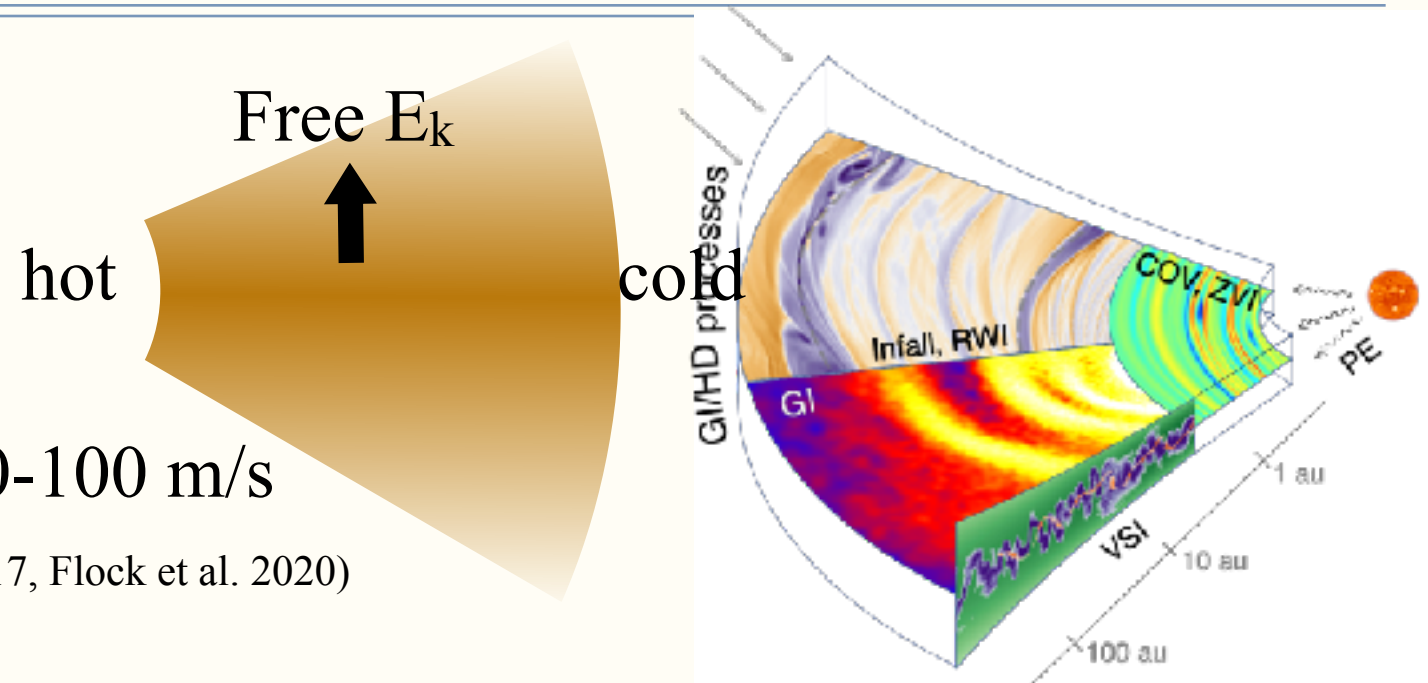
(Nelson et al. 2013, Lin&Youdin 2015, Umurhan et al. 2016, Flock et al. 2017, 2020, Barraza-

Fast cooling, >10 au

Narrow (rings) corrugation mode: 10-100 m/s

Strong vertical dust stirring (Stoll et al. 2017, Flock et al. 2020)

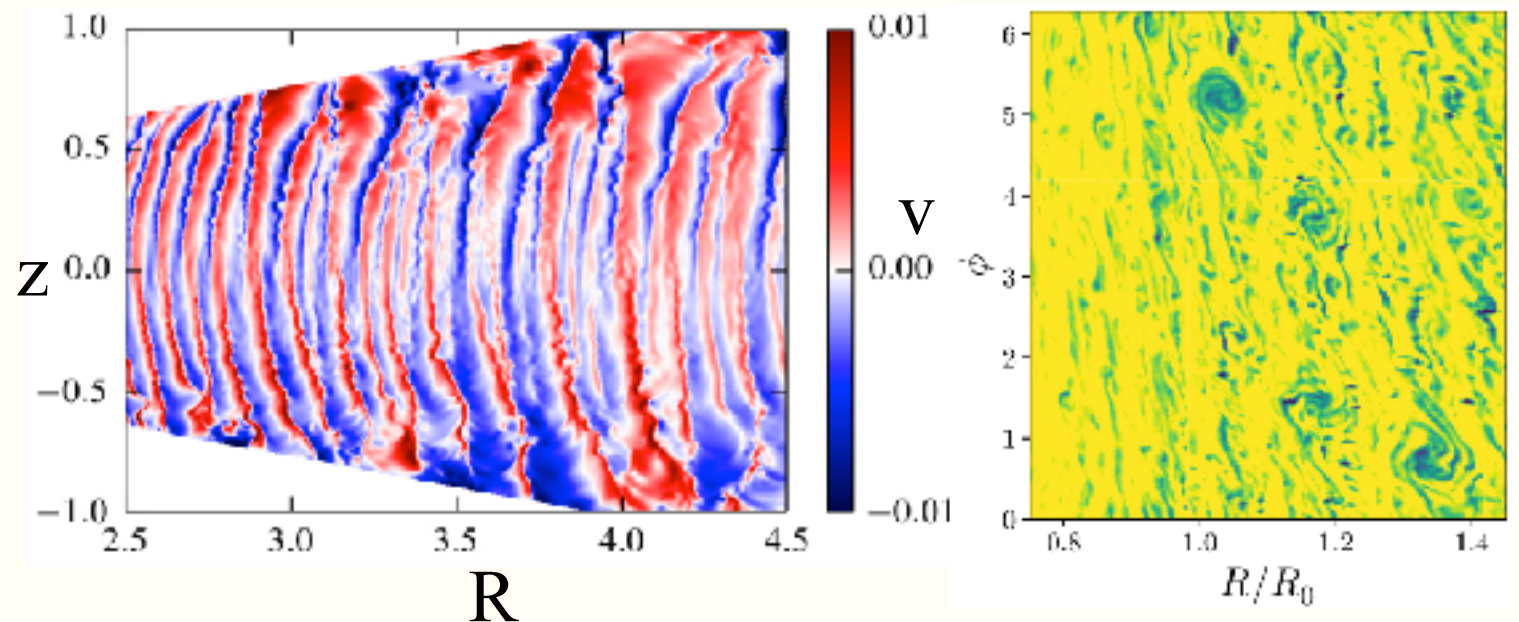
Vortices in 3-D



More instabilities at the inner disk
(<10 au, vortices):

Klahr 2013, Petersen et al. 2007, Lesur & Papaloizou 2010, Lyra & Klahr 2011

Marcus et al. 2012, 2015, 2016, Lesur & Latter 2016



(Stoll & Kley 2014)

(Manger et al. 2020)

Hydrodynamics

- Rossby Wave Instability (main feature **vortices**)

(Lovelace et al. 1999)

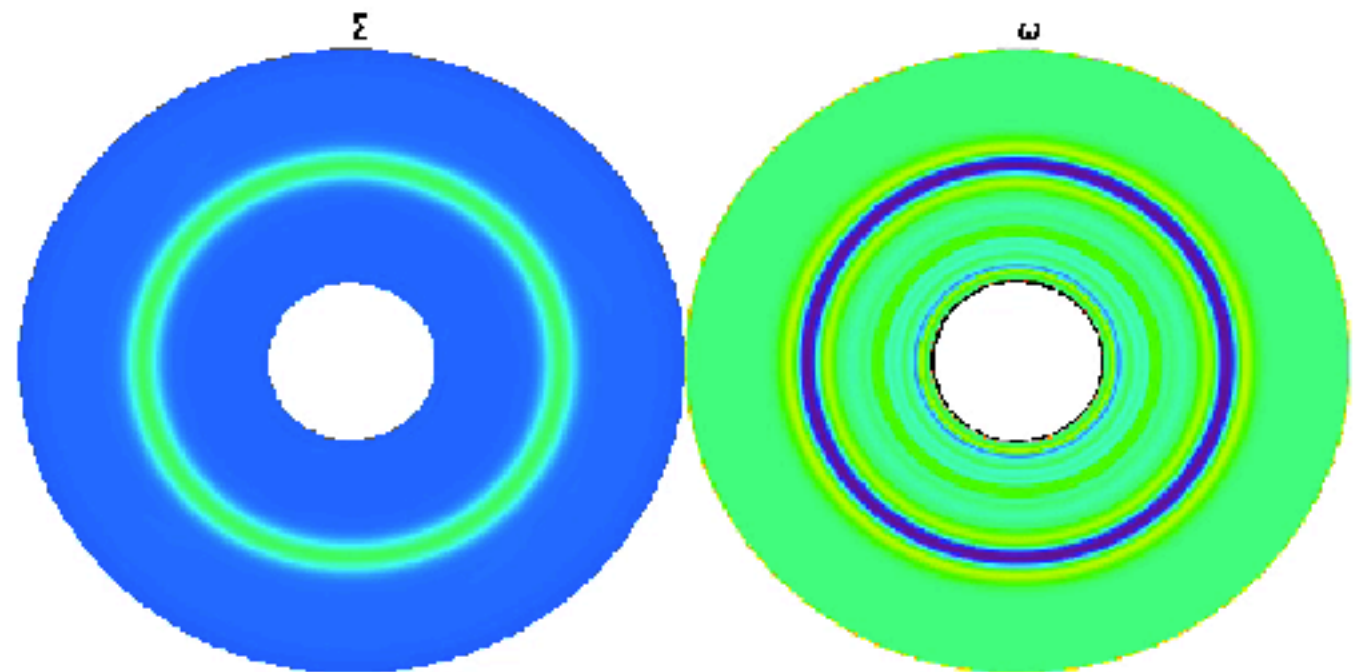
Sharp gaseous density ring (strong “shear” in the rotational velocity)

(1) at the edge of planet-induced gaps

(de Val-Borro et al. 2007, Lyra et al. 2009, Fu et al. 2014, Lin et al. 2014, Bae et al. 2016)

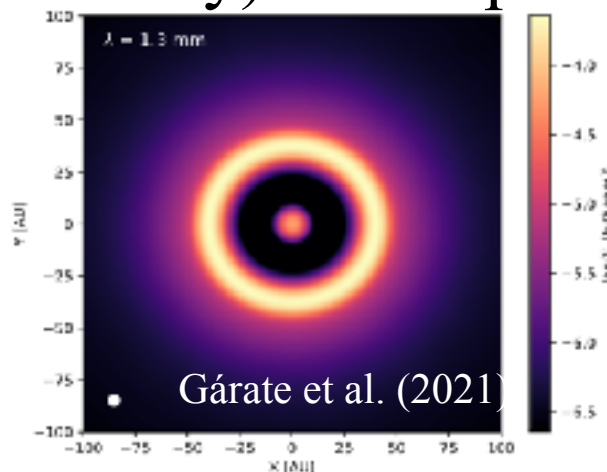
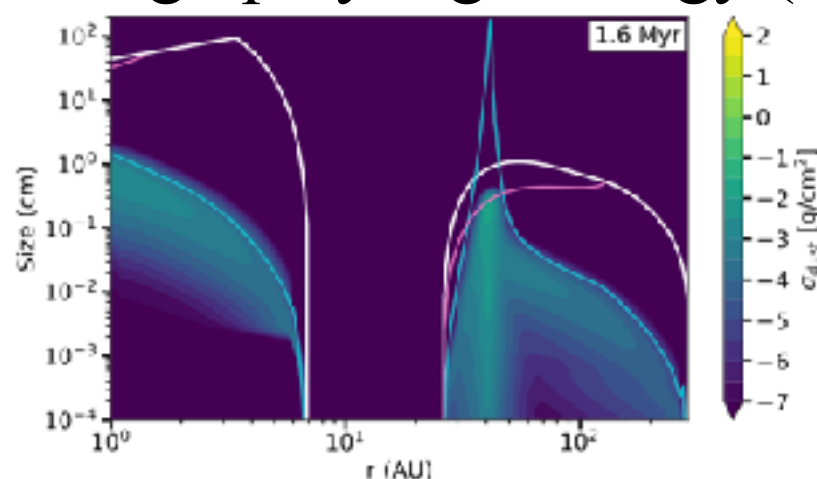
(2) at the infall location

(Bae et al. 2015, Kuznetsova et al. 2022)



- Photoevaporation (cavity):

heating up by high-energy (UV/X-ray) stellar photons ($\sim$ au and beyond)



(Ercolano et al. 2008, Owen et al. 2010, Alexander et al. 2014 PPVI, Picogna et al. 2019, Pascucci PPVII)

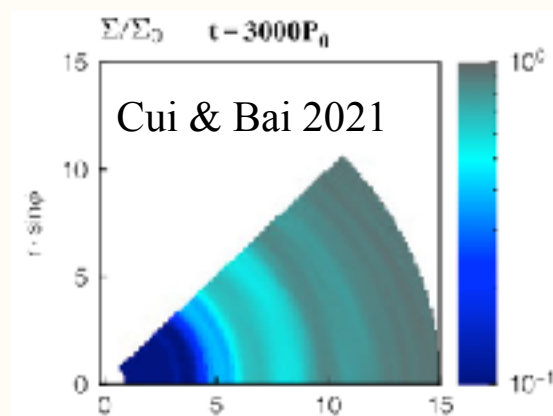
Magneto-hydrodynamics

B field can destabilize the disk (MRI). Non-ideal MHD effects are important.

- **Zonal flows** (B self-organization, **rings**)

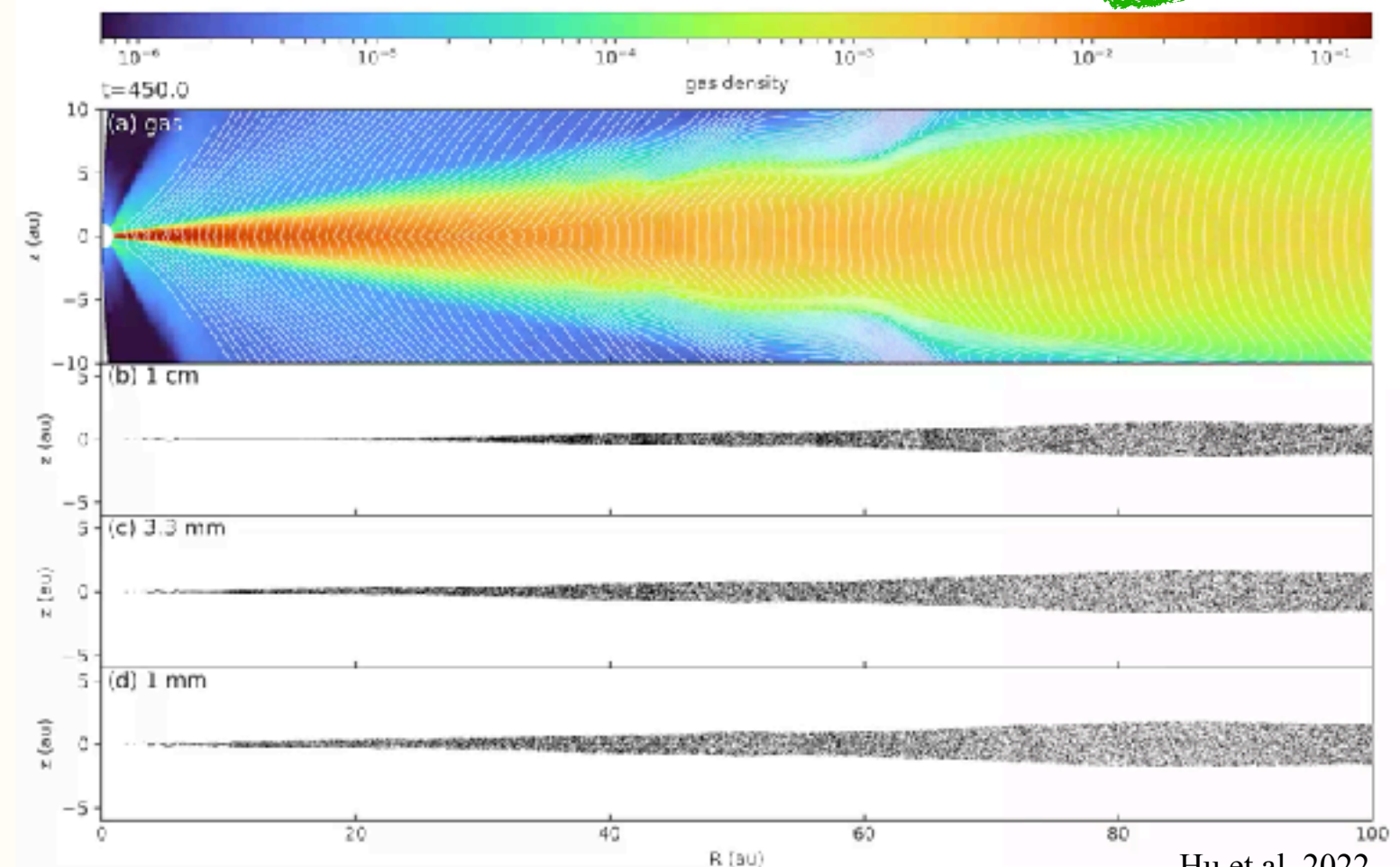
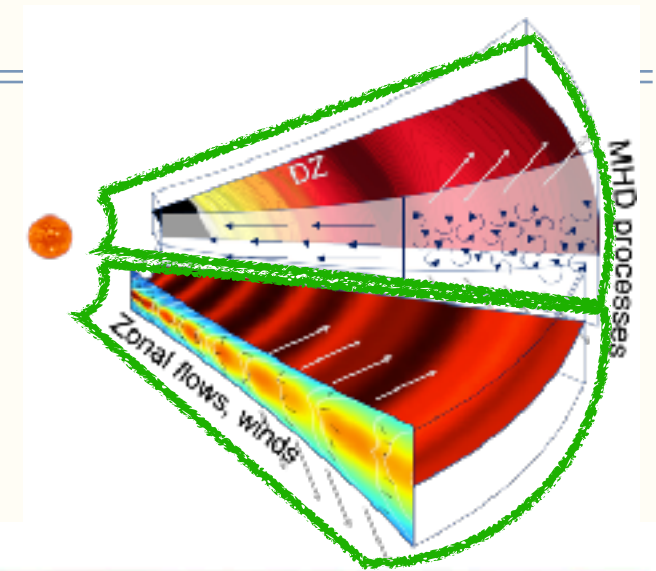
Kunz & Lesur 2013; Béthune et al. 2016; Krapp et al. 2018, Bai & Stone 2014; Simon & Armitage 2014; Béthune et al. 2017; Riols & Lesur 2018; Suriano et al. 2018, 2019; Cui & Bai 2021; Suzuki et al. 2016; Takahashi & Muto 2018

No spirals and vortices



- **Mass pile-up at the transition between two MRI regimes (rings, vortices)**

(Varniere & Tagger 2006, Inaba & Barge 2006, Lyra et al. 2008, Meheut et al. 2010, Dzyurkevich et al. 2010, 2013; Lyra & Mac Low 2012, Lyra et al. 2015; Flock et al. 2015, 2017; Ruge et al. 2016, Miranda et al. 2017, Pierens & Lin 2018)



Hu et al. 2022

Self-gravity

- Gravitational Instability

Massive, early system, easier for the outer disk

Main feature: **spirals**

$M_d \nearrow$, the pitch angle $\nearrow$ (10° - 20°),

no. of spiral $\searrow$ ($10 \Rightarrow 2$ when $q \sim 0.2$)

Pattern speed is local Ω within the GI disk

Trapping particles at all sizes

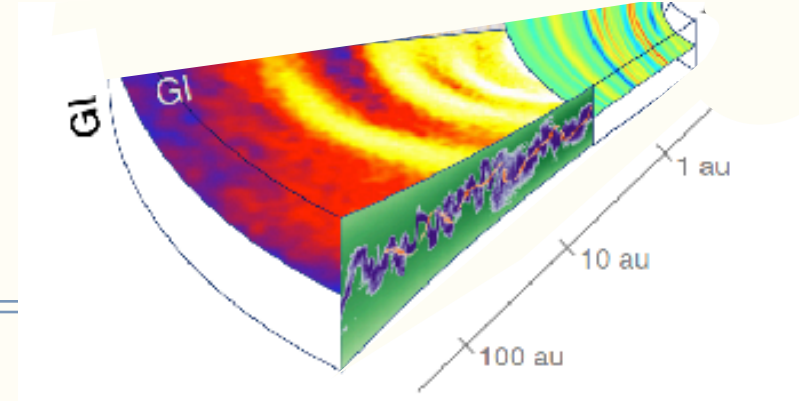
(Rice et al. 2006, Gibbons et al. 2014, Baehr & Zhu 2021)

Observable by ALMA dust continuum

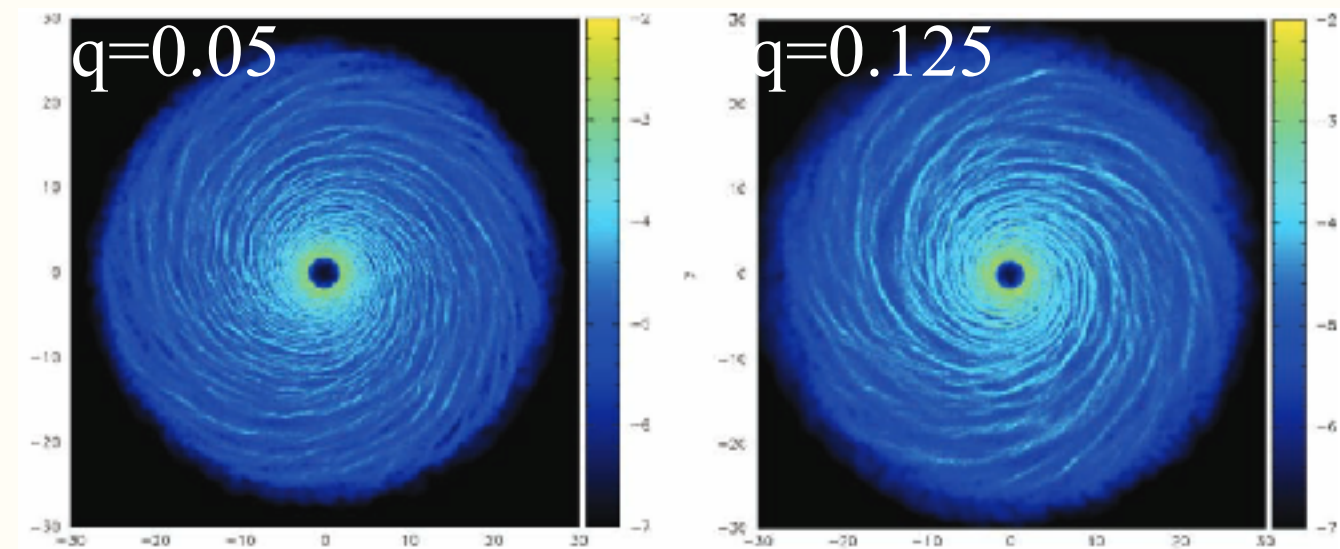
(Cossins et al. 2010, , Forgan et al. 2018, Hall et al. 2018)

Spiral velocity perturbation $\sim 20\%$ C_s (horizontal plane)

kinematics (Shi & Chiang 2014, Hall et al. 2020)



$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} \gtrsim 1$$



(Cossins et al. 2009, , Forgan et al. 2011, 2018, Hall et al. 2018, 2019,

Perturber - Planets

- Particle trapping by spirals is inefficient.

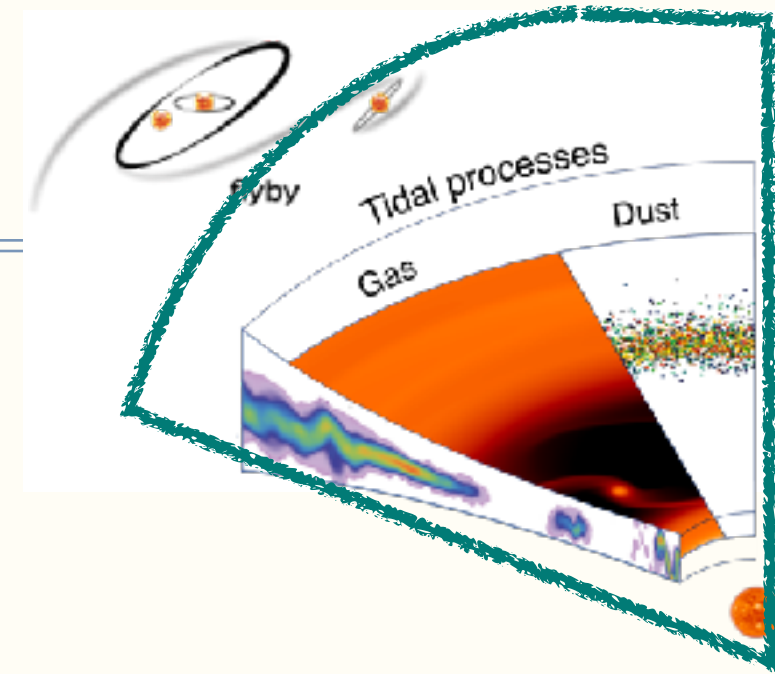
(Isella & Turner 2018, Sturm et al. 2020, Speedie et al. 2022)

- Thermal dynamics and 3-D effects are important for spirals

(Miranda&Rafikov 2020, Zhang&Zhu 2020, Juhász&Rosotti 2018, Bae et al. 2021, Bi et al. 2021, Binkert et al. 2021, Zhu 2018, Nealon et al. 2018)

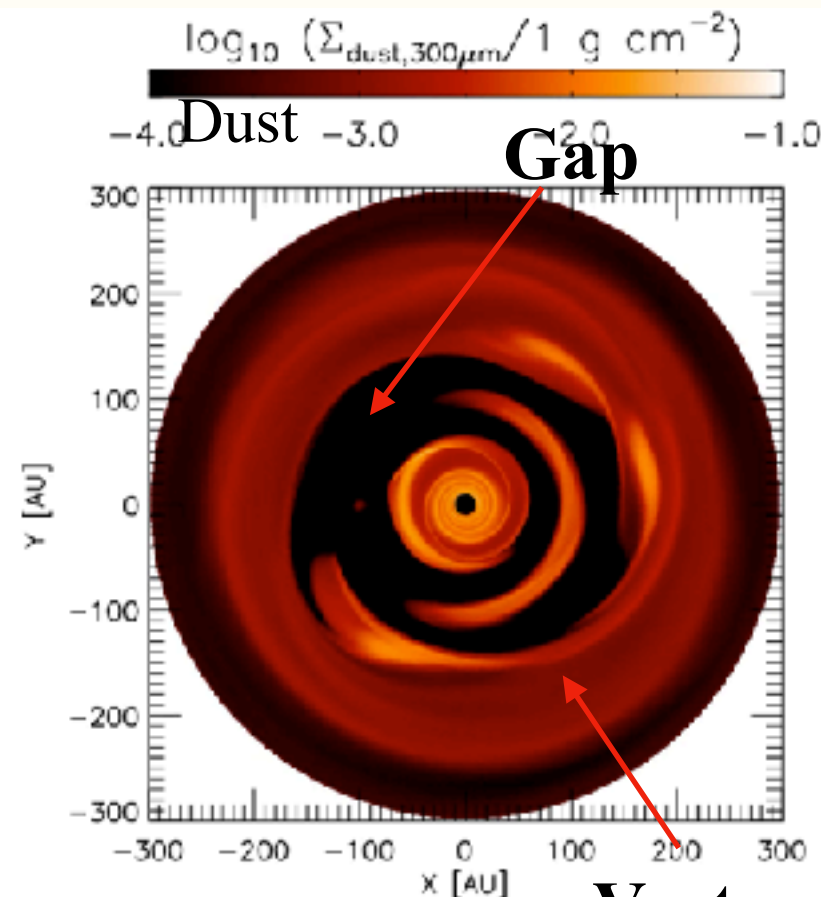
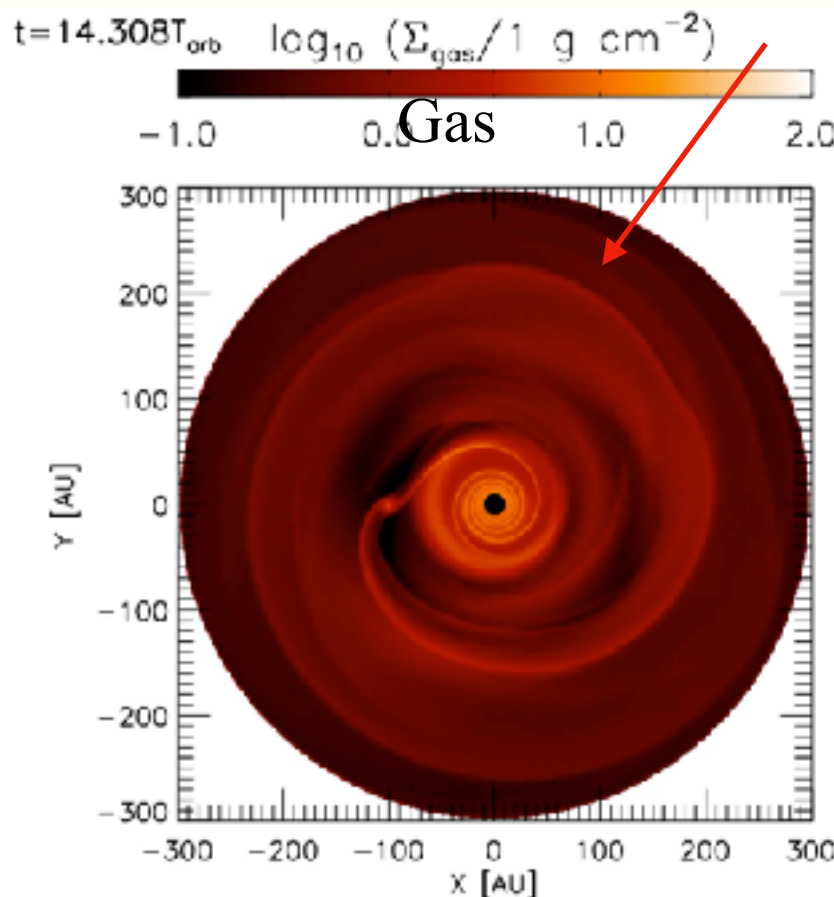
- No. of rings and vortices depends on planet treatment (migration, growth)

(Meru et al. 2019, Kanagawa et al. 2020, Hammer et al. 2017)

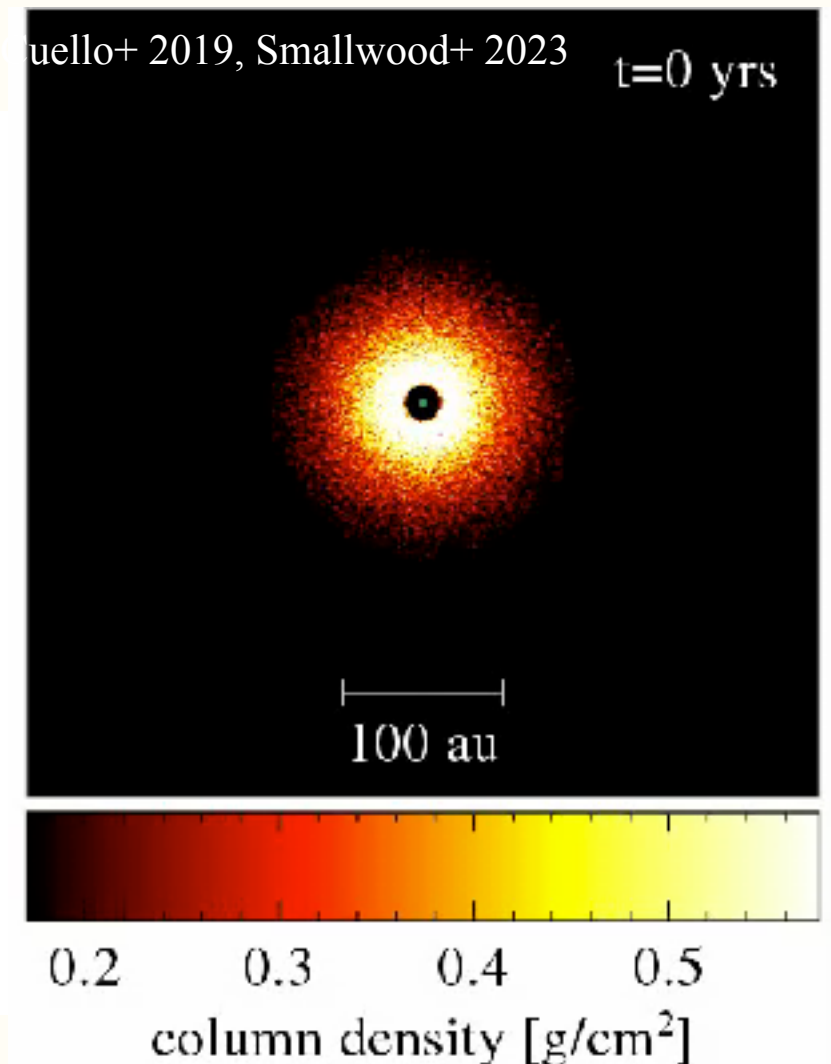


-Fly-by (transient spirals)

Spiral



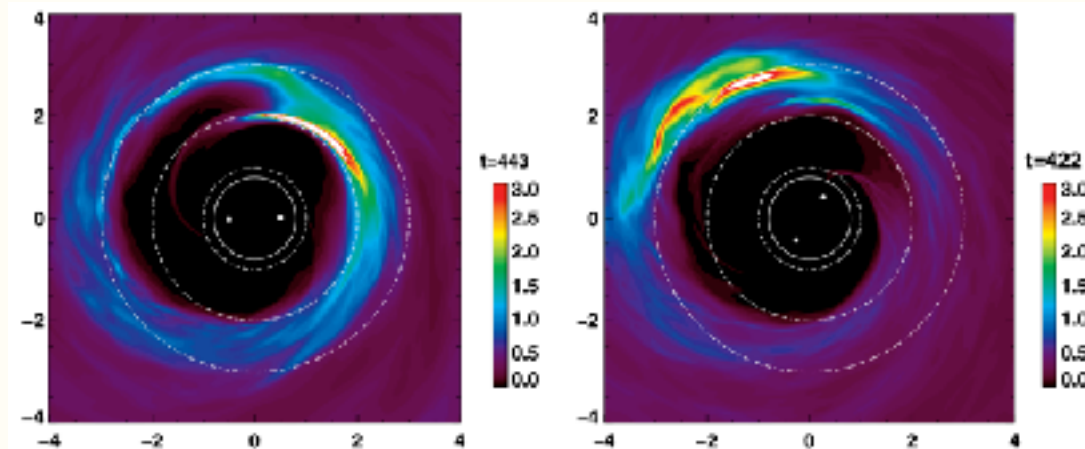
Vortex



Perturber - circumbinary disks

Coplanar

Spirals, cavity, lump



MRI simulation, $\alpha \sim 0.1$

Shi et al. 2012, Miranda et al. 2017, Ragusa et al. 2017

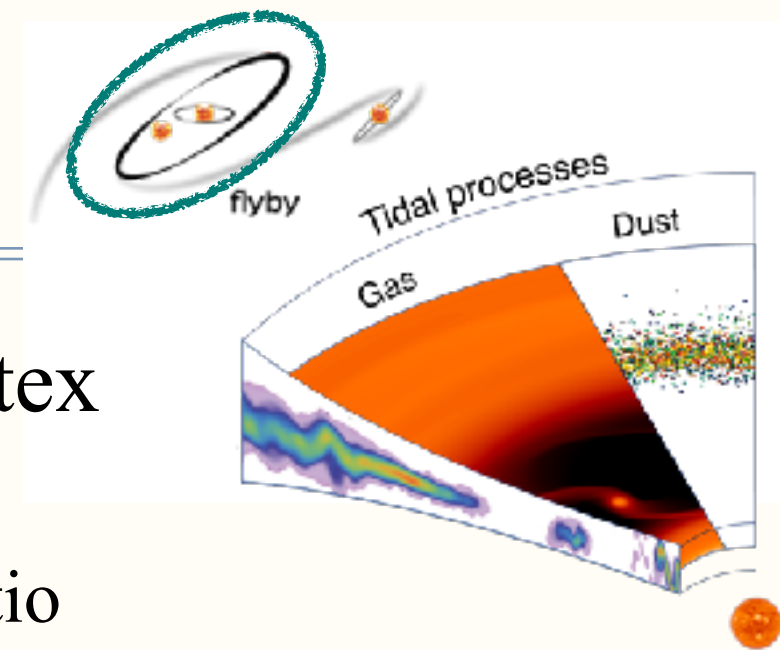
Lump vs Vortex

Similarities:

- large aspect ratio
- Rotate at local Ω , trap particles

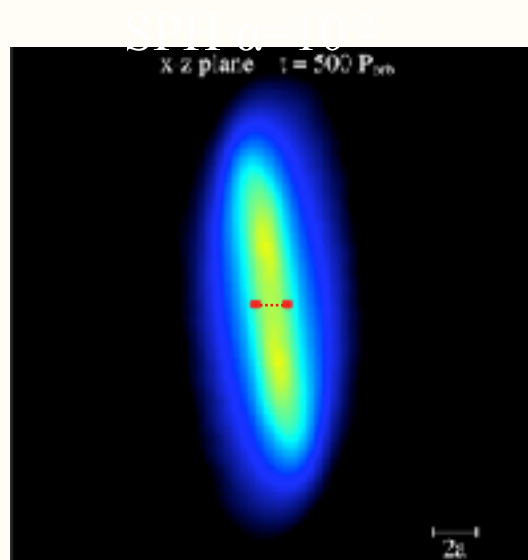
Differences:

- dynamic, due to spiral disk interaction
- no vorticity minimum



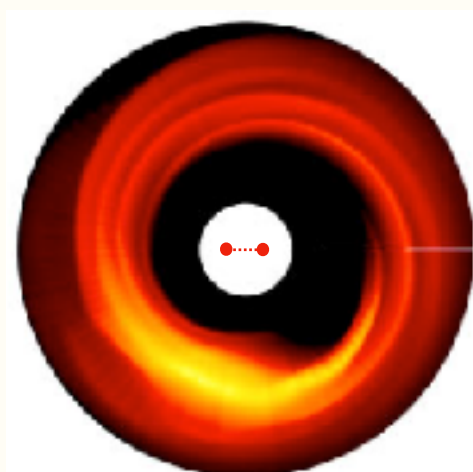
Polar

Spirals, cavity, vortex

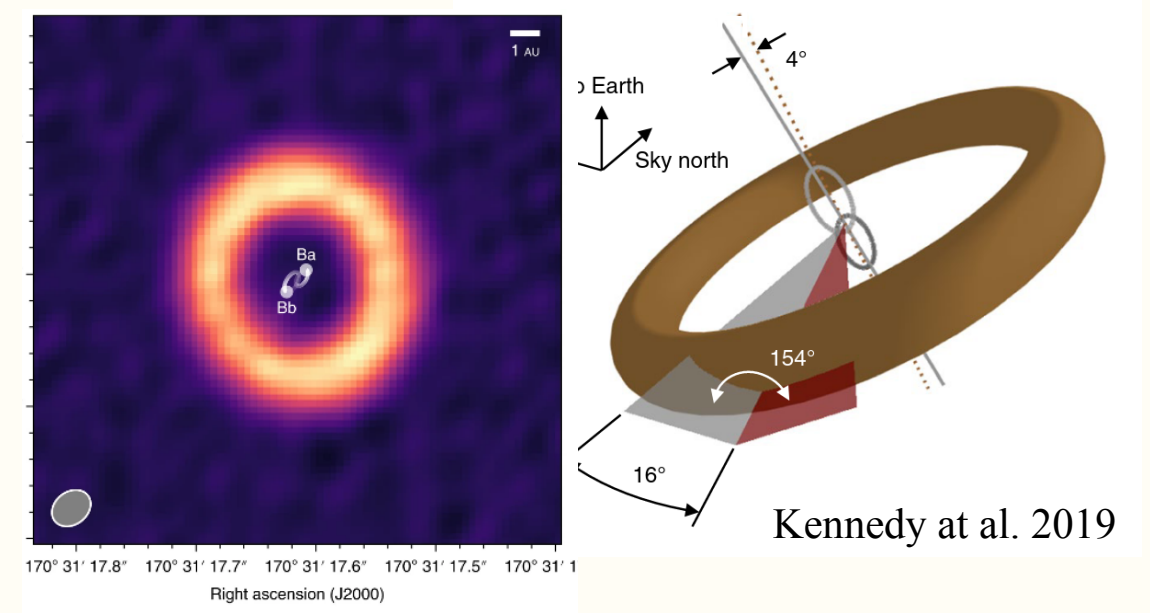


Aly et al. 2015, Martin&Lubow 2017

Grid Simu. $\alpha=10^{-5}$



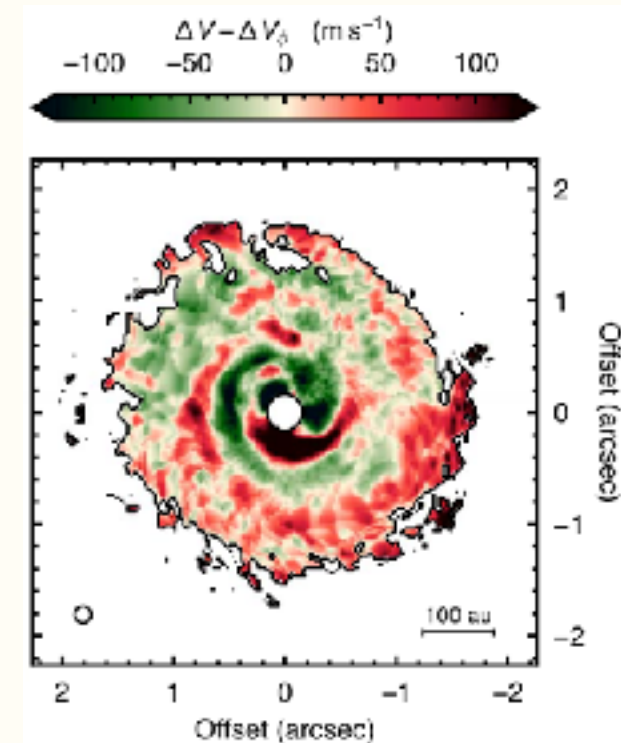
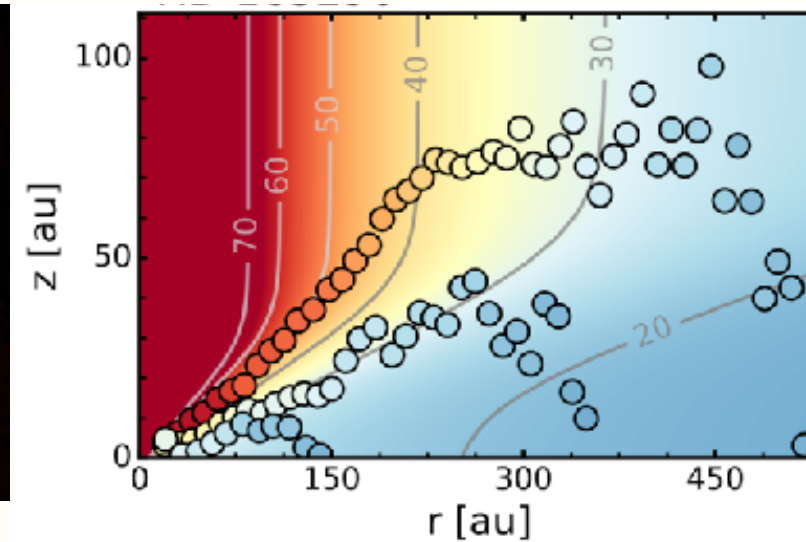
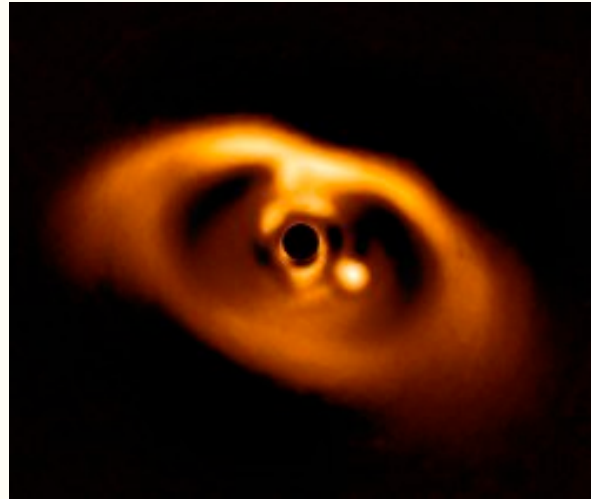
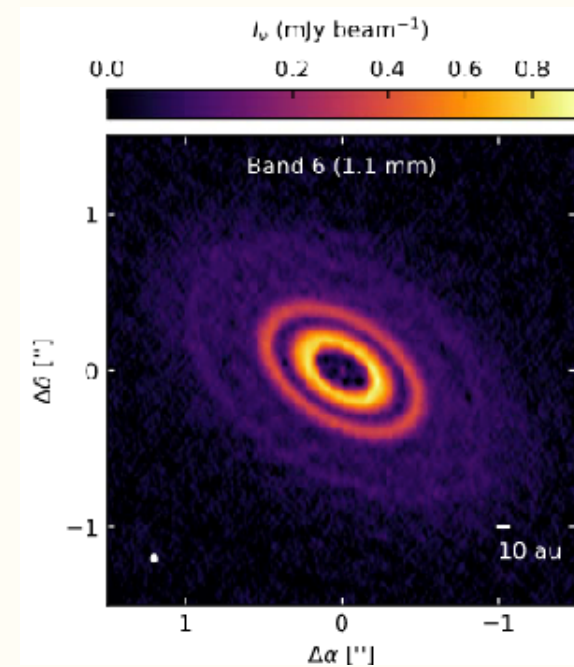
Rabago et al. 2023



Kennedy et al. 2019

Protoplanetary disk studies

- Observations reveal so many details



- Rich theoretical processes
 - self-consistent generated turbulence (HD, MHD, RMHD)
 - Ionization and non-ideal MHD
 - Chemistry (molecules)
 - Dust growth and dust-gas dynamics (Jake's talk)
 - Planetesimal and planet formation (Jake's talk)
 - Gas accretion onto planets (Jake's talk)



Visualization Studio
California Academy of Sciences

Simulations by Chao-Chin Yang & Zhaohuan Zhu
Rendered by California Academy of Sciences
“Big Astronomy” <https://www.youtube.com/watch?v=qV5nkCLutH8>

Potential projects

- HD: a hydrostatic disk (Nelson et al 2013)
- HD+self-gravity: Code comparison project (Baehr)
- MHD: implementing Hall
- Tomorrow: companion-disk interaction, immersed solid boundary