Evolution of Circumstellar Disks and Planet Formation

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Collaborators

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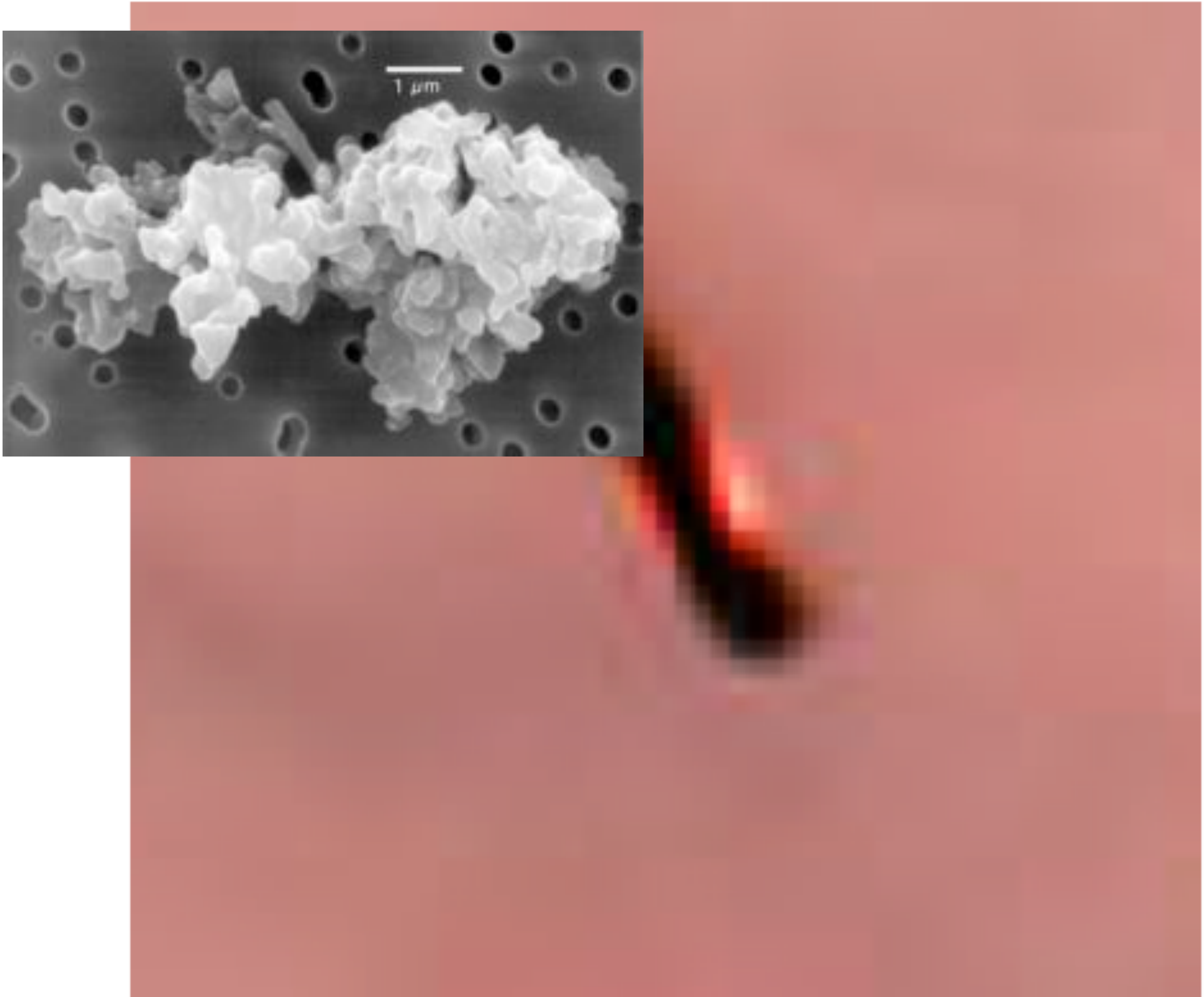
University of California Santa Cruz, Nov 14th, 2016

Outline

- Observational constraints
- Planet Formation
    - The need for turbulence
        - Active and dead zones
        - Magneto-rotational instability
        - Convective Overstability
- Active/dead boundary
    - Rossby wave instability
- Vortex-trapping mode of planet formation
- Spiral features in circumstellar disks


1 µm

Protoplanetary Disks

PP disk fact sheet

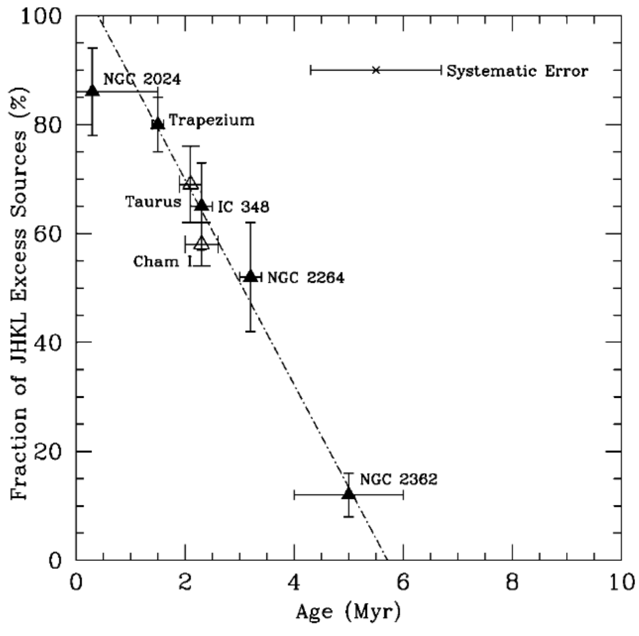
Density: $10^{13} - 10^{15}$ cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

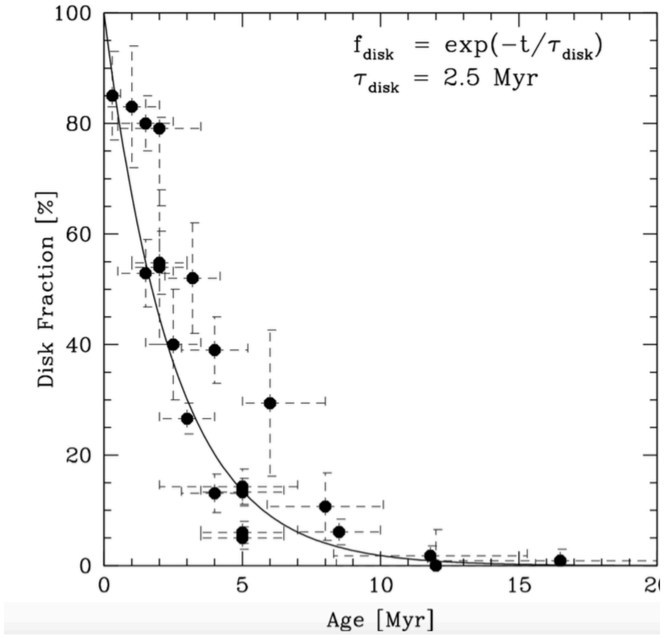
Scale: 0.1-100AU
(1 AU = 1.49×10^{13} cm)

Mass: $10^{-3} - 10^{-1}$ M_{sun}
($1\ M_{sun} = 2 \times 10^{33}$ g)

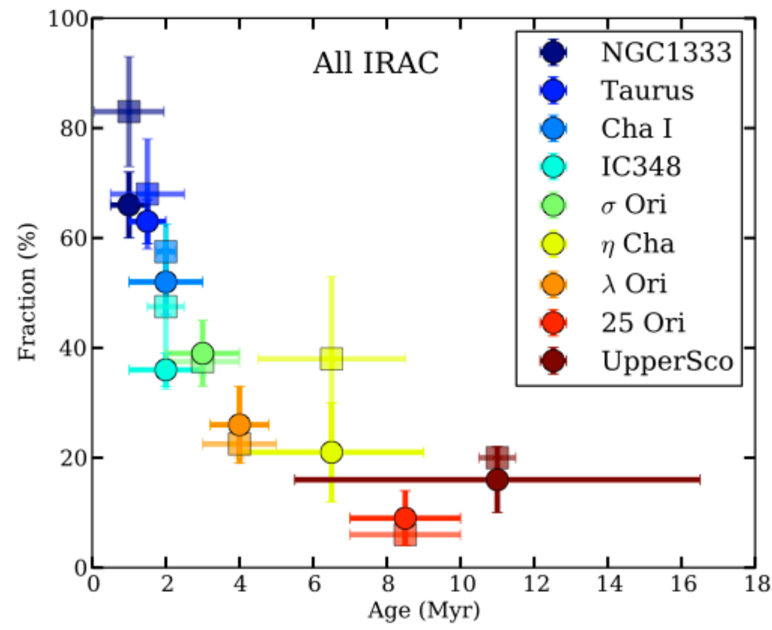
Disk lifetime



(Haisch et al. 2001)

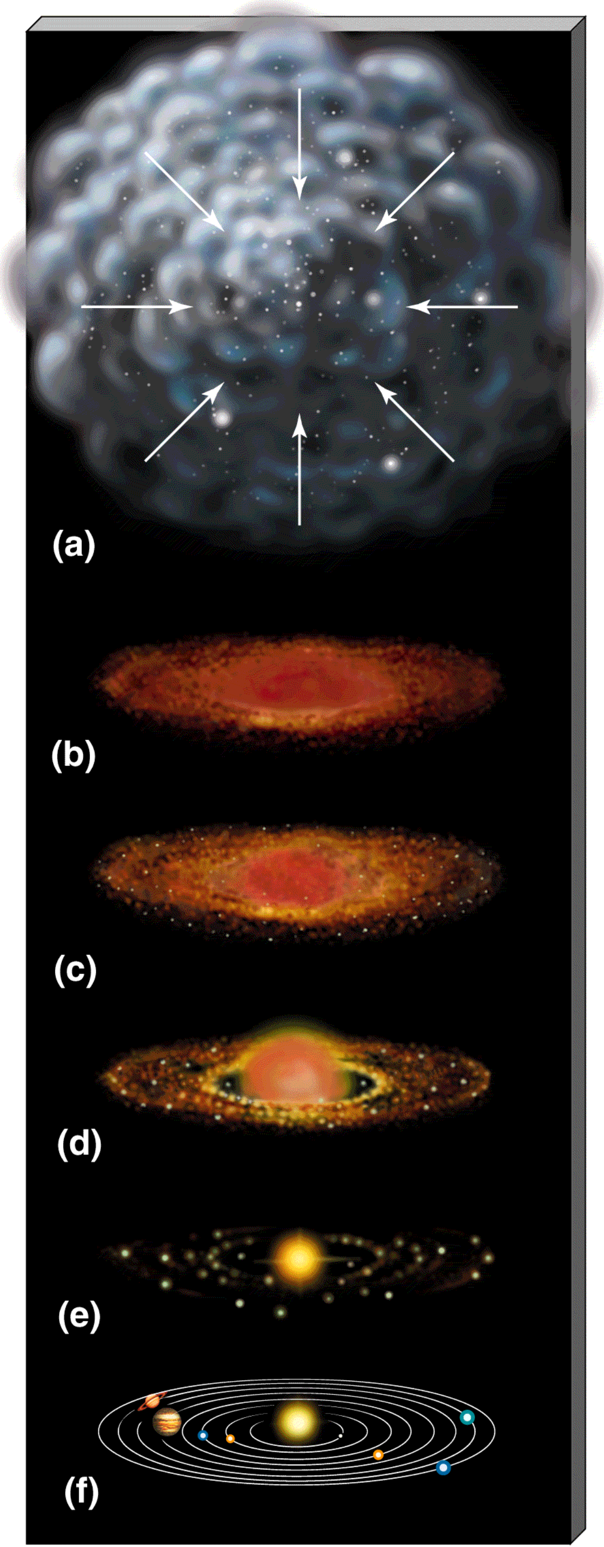


(Mamajek et al. 2009)



(Ribas et al. 2014)

Disks dissipate with an e-folding time of 2.5 Myr



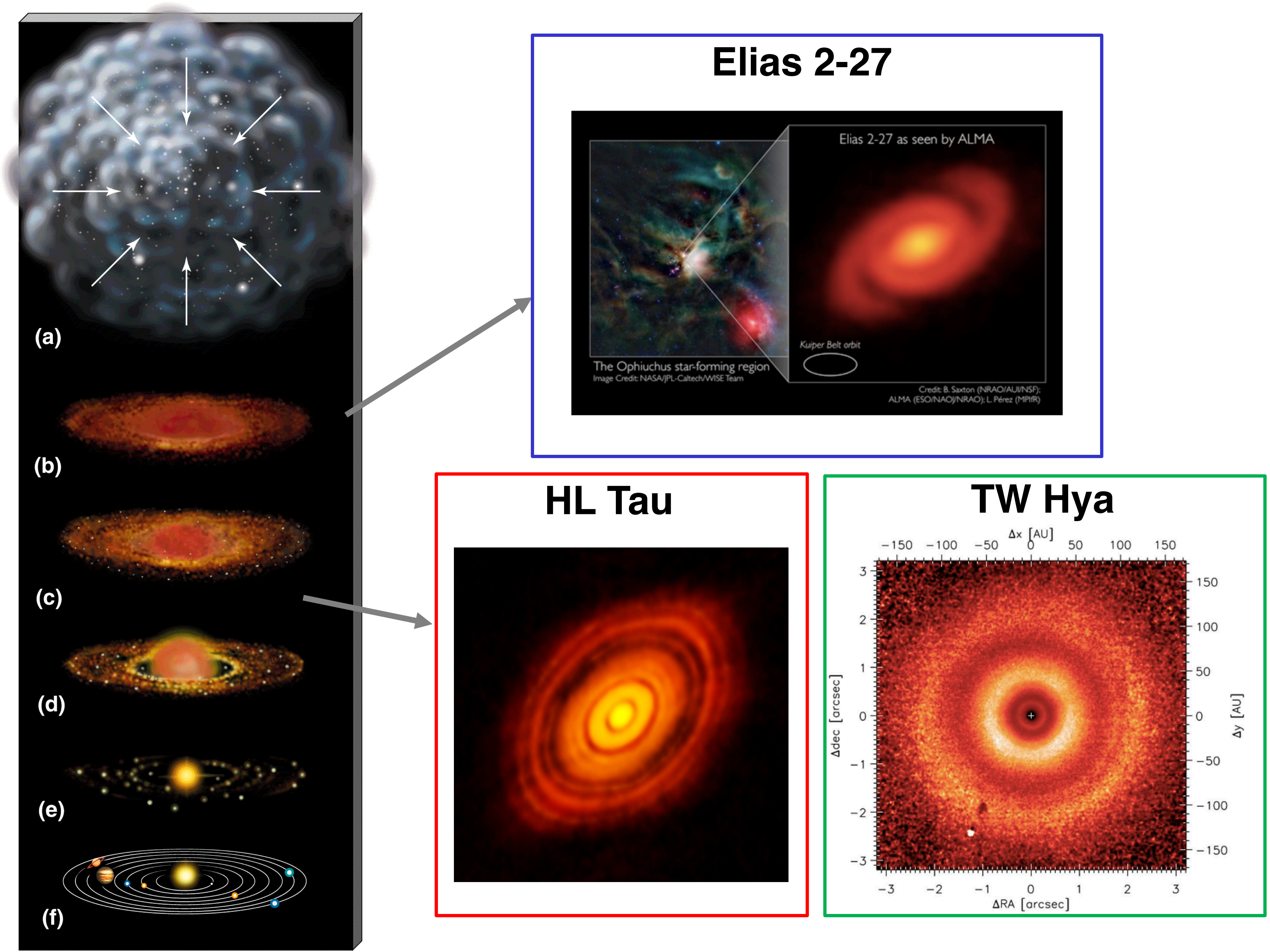
Planet Formation

Gas-rich phase (< 10 Myr)

Primordial Disks

Gas-poor phase (>10 Myr)

Debris Disks



(a)
(b)
(c)
(d)
(e)
(f)
Elias 2-27
Elias 2-27 as seen by ALMA
Kuiper Belt orbit
The Ophiuchus star-forming region
Image Credit: NASA/JPL-Caltech/WISE Team
Credit: B. Saxton (NRAO/AUI/NSF);
ALMA (ESO/NAOJ/NRAO); L. Pérez (MPIfR)
HL Tau
TW Hya
Δx [AU]
ΔRA [arcsec]
Δdec [arcsec]
Δy [AU]

Planet Formation

Planetesimal Hypothesis (Safronov 1969)

From dust to peebles

μm -> cm : hit-and-stick by van der Walls

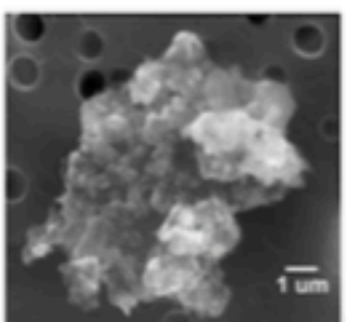
From planetesimals to planetary embryos

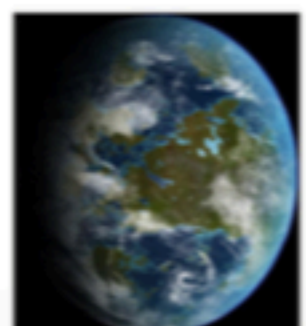
km -> 1000 km : Gravity

From planetary embryos to planets

Rocky planets: binary collisions

Gas giants: Attract gaseous envelope





Planet Formation

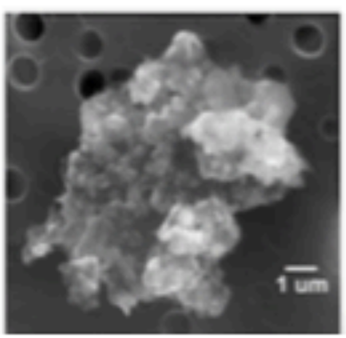
Planetesimal Hypothesis (Safronov 1969)

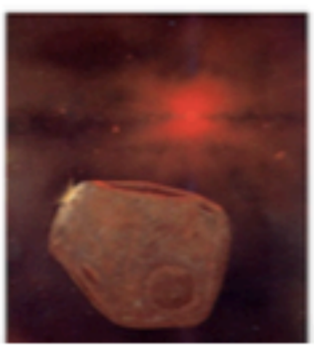
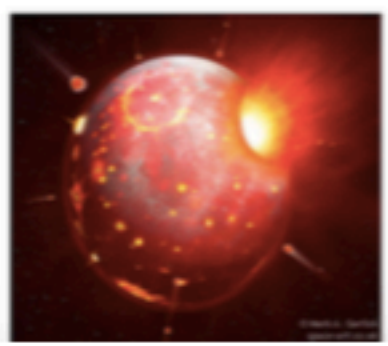
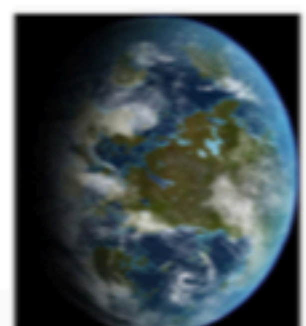
From dust to peebles
μm -> cm : hit-and-stick by van der Walls

From pebbles to planetesimals
Here be dragons....

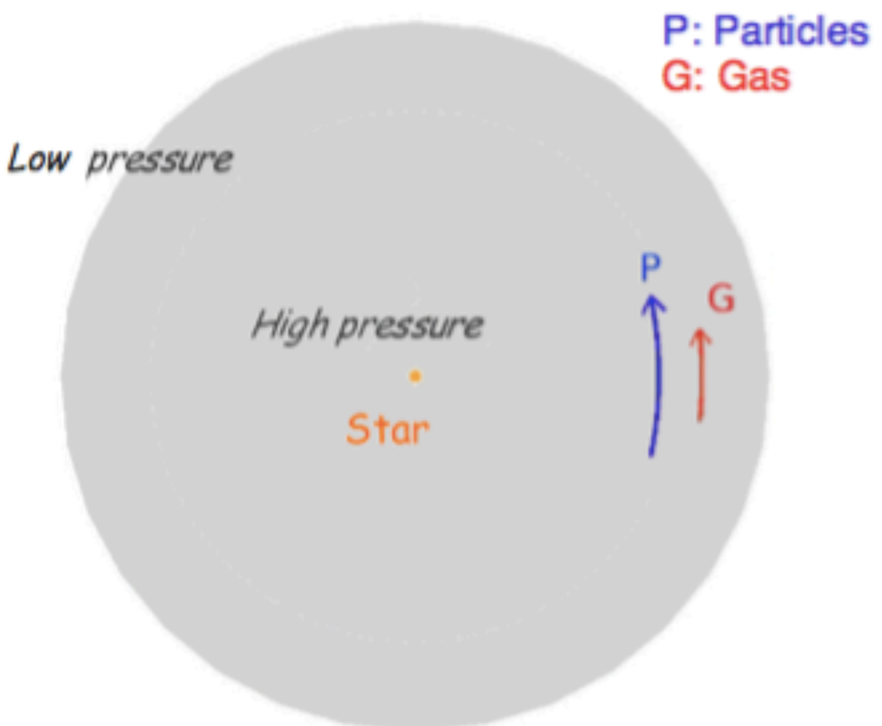
From planetesimals to planetary embryos
km -> 1000 km : Gravity

From planetary embryos to planets
Rocky planets: binary collisions
Gas giants: Attract gaseous envelope

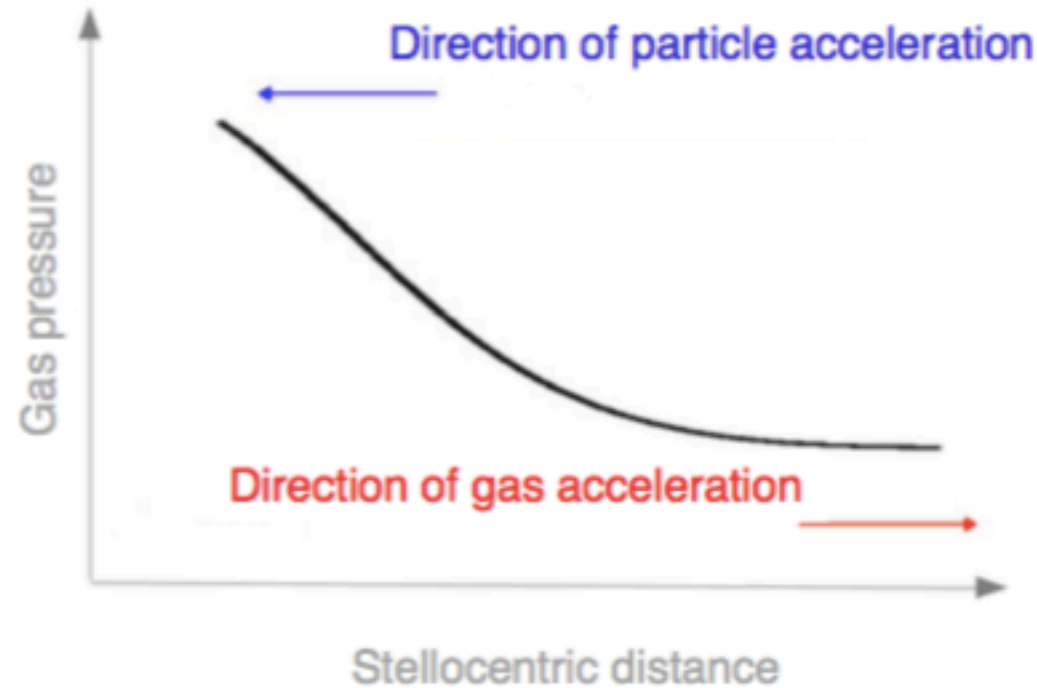



Particle drift



Adapted from Whipple (1972)



Particle Coagulation and drift

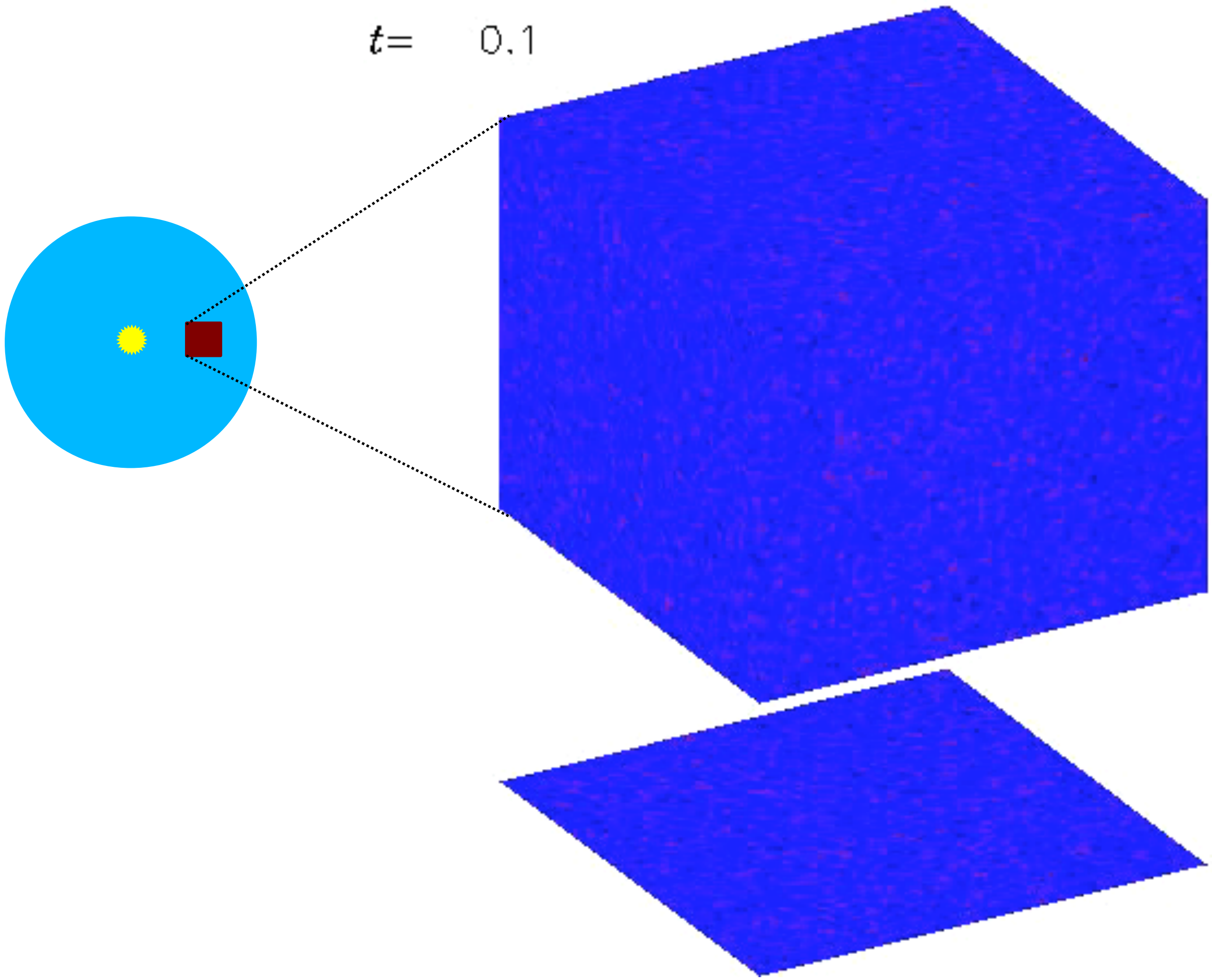
Dust particle
coagulation
and radial drift

F.Brauer, C.P. Dullemond
Th. Henning

Brauer et al. (2008)

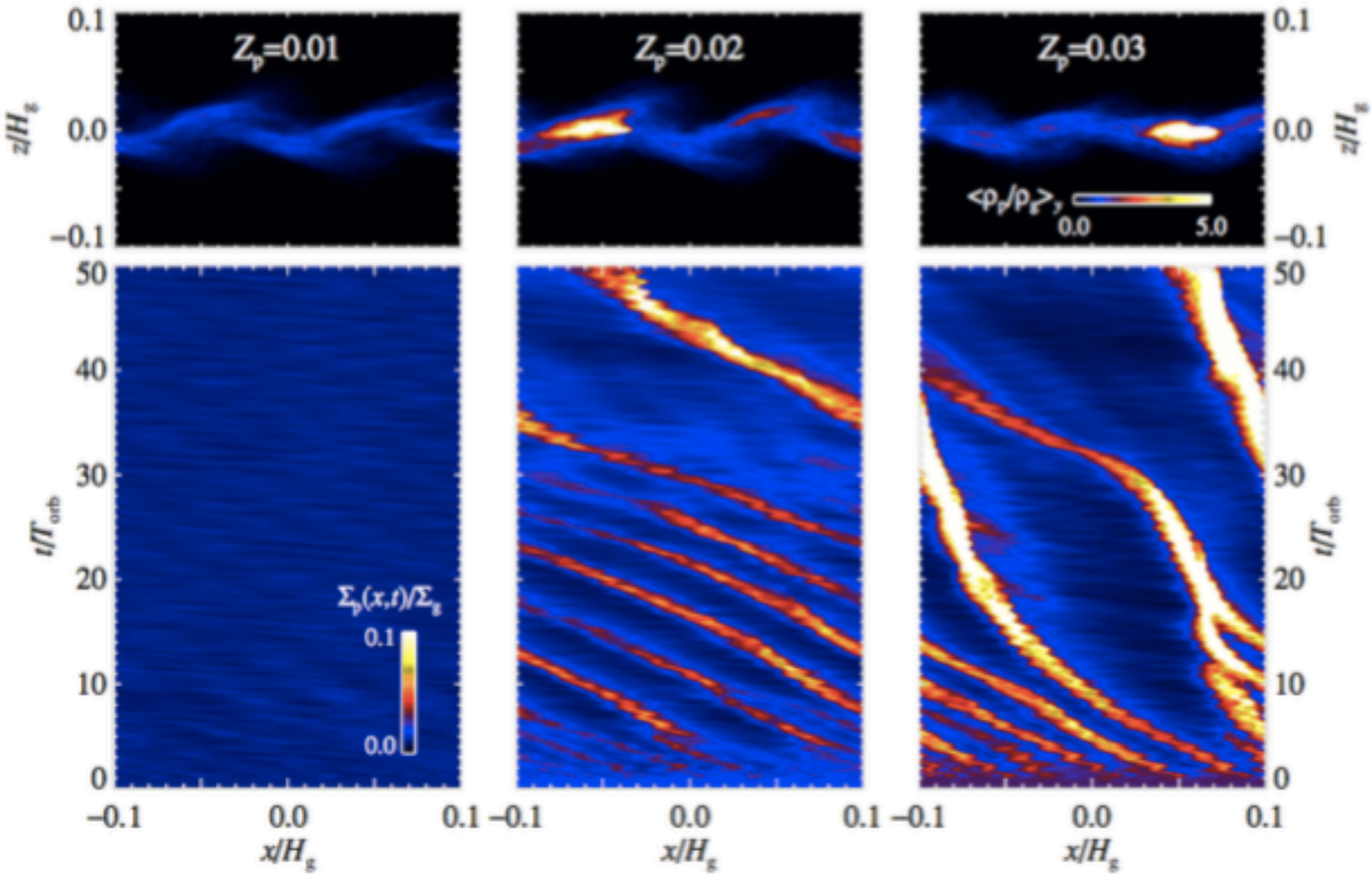
Streaming Instability

The particle drift is linearly unstable



Youdin & Goodman (2005), Johansen & Youdin (2007), Youdin & Johansen (2007)

Streaming Instability does not "work" for solar metallicity

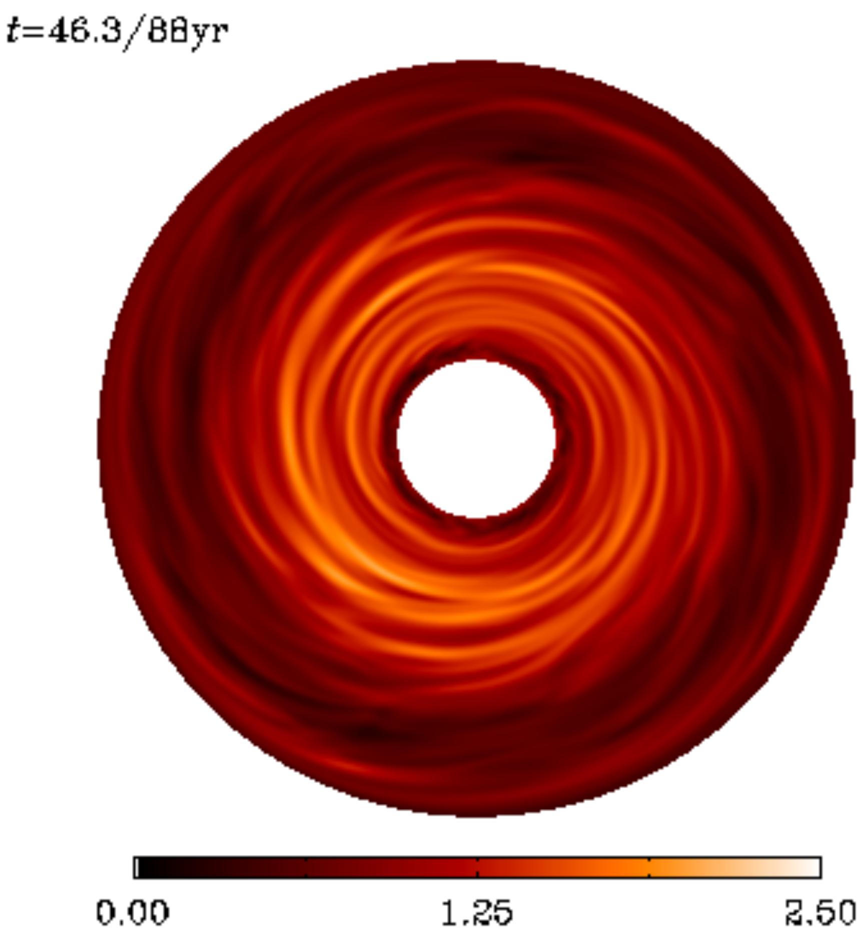


Johansen et al. (2011)

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

Magneto-Rotational Instability

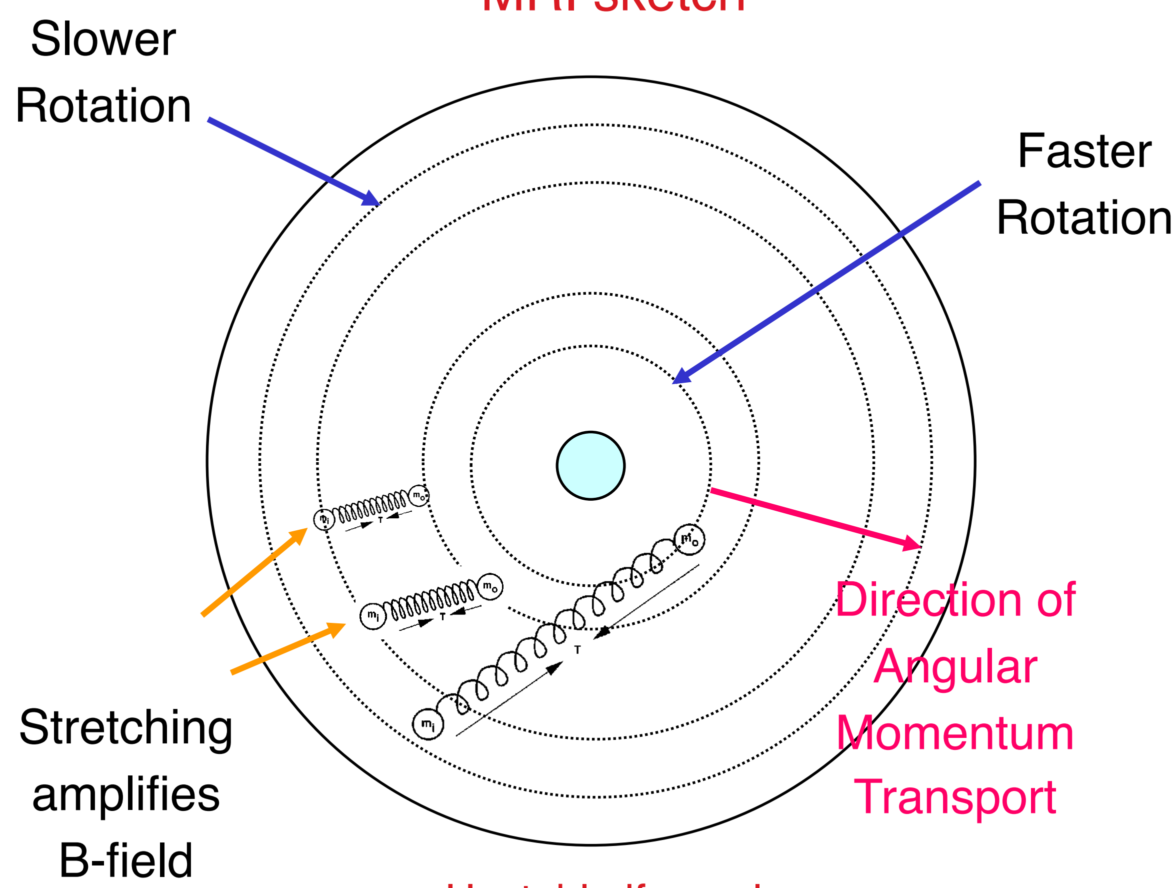
Turbulence in disks is enabled by the Magneto-Rotational Instability (Balbus & Hawley, 1991)



Magnetized disk

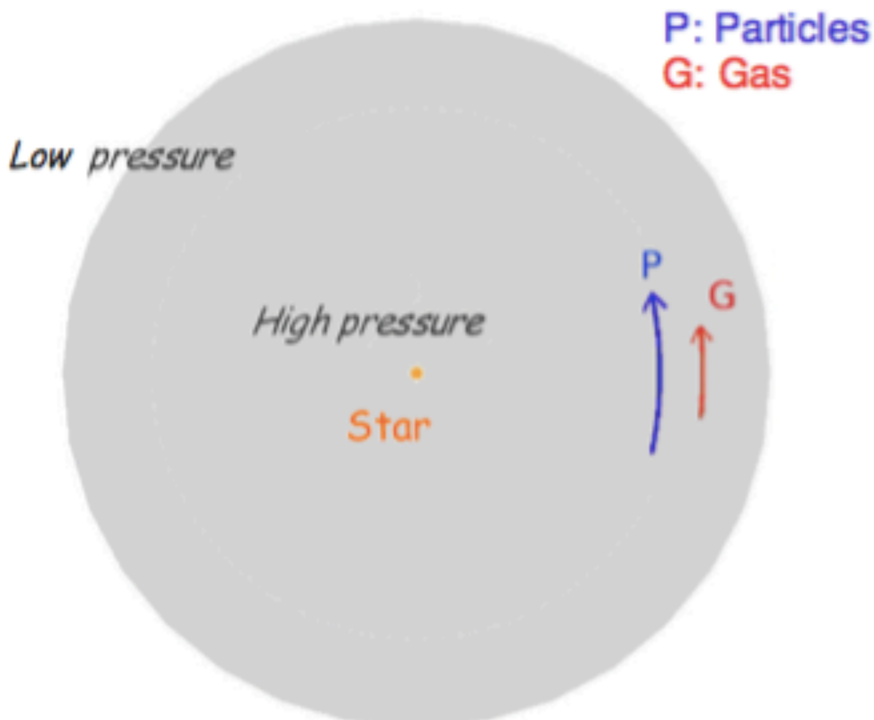
Lyra et al. (2008a)

MRI sketch

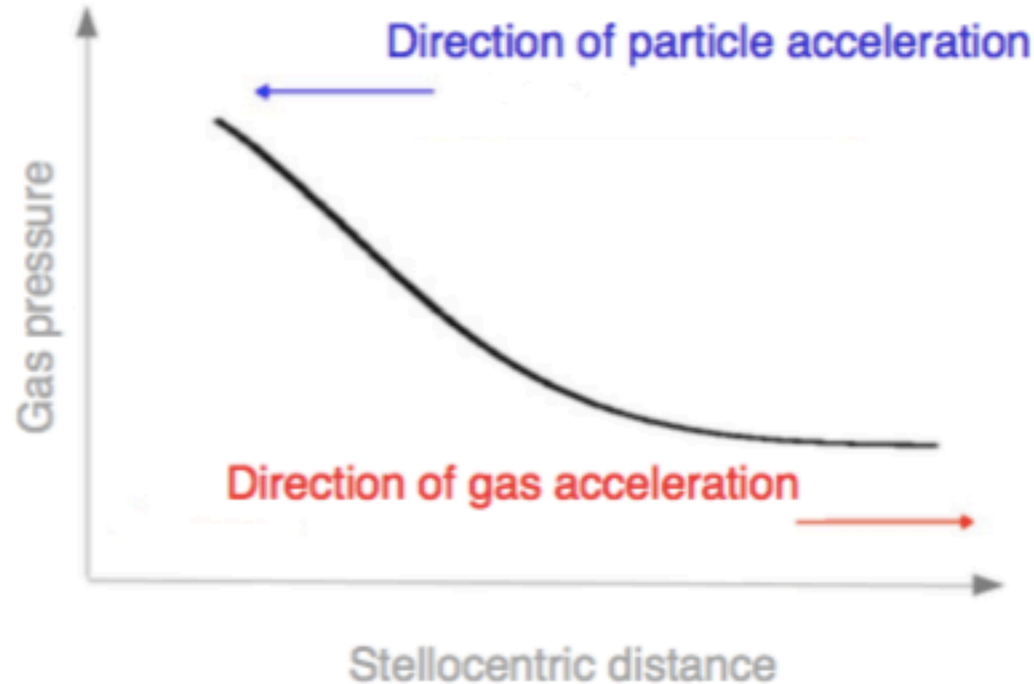


Unstable if angular velocity decreases outward

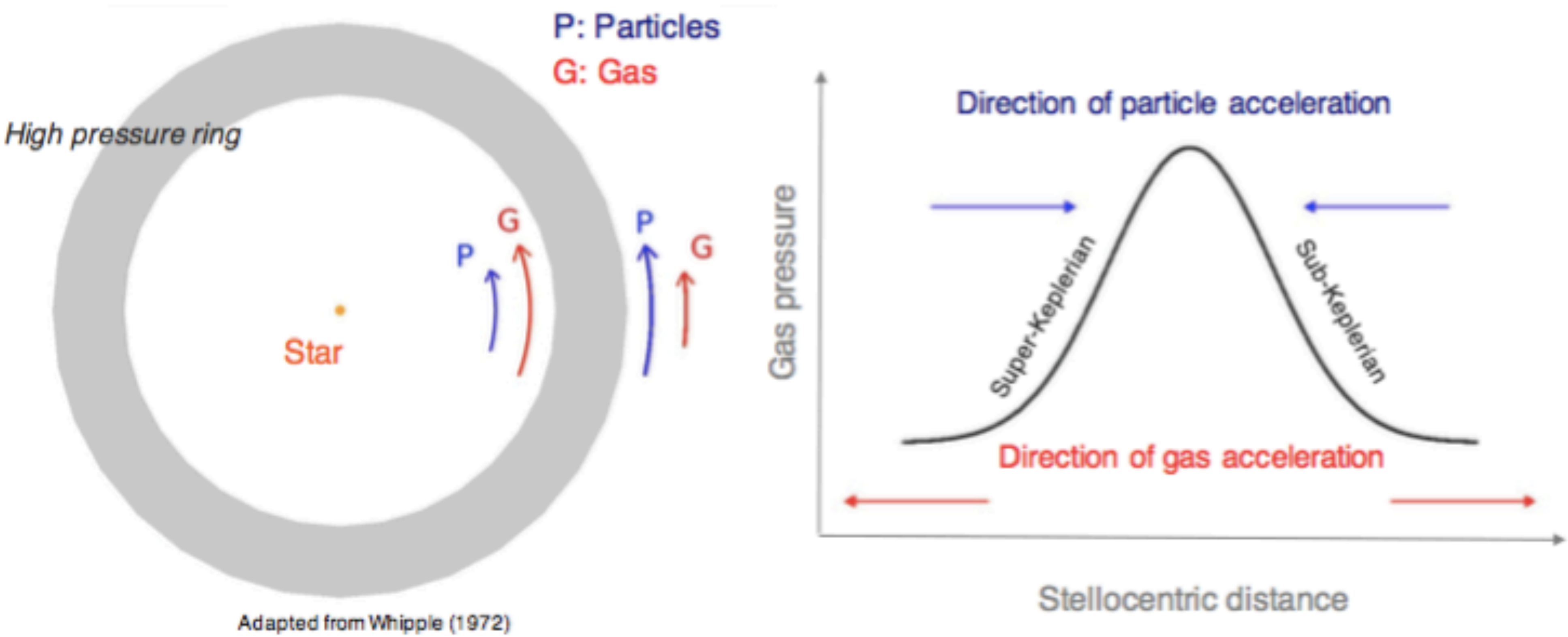
Particle drift



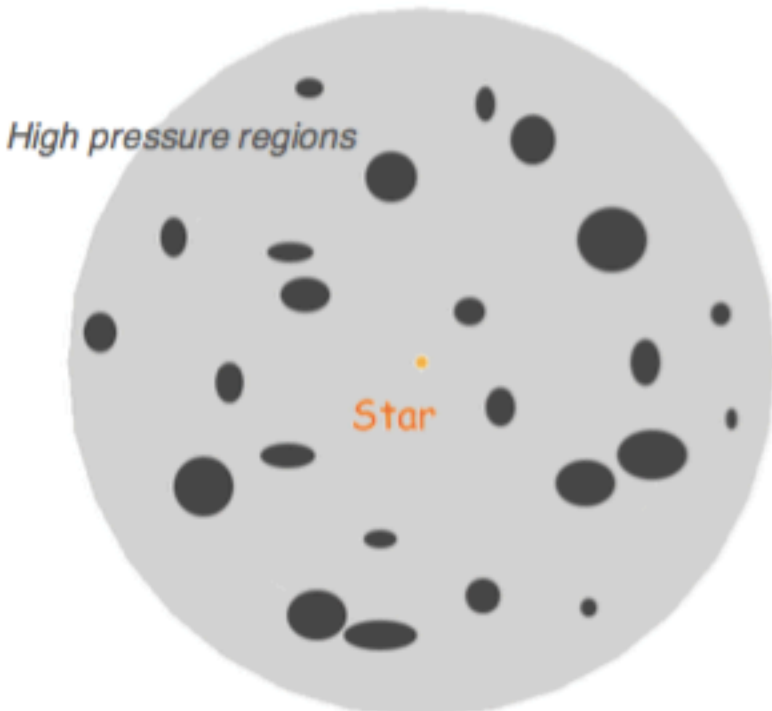
Adapted from Whipple (1972)

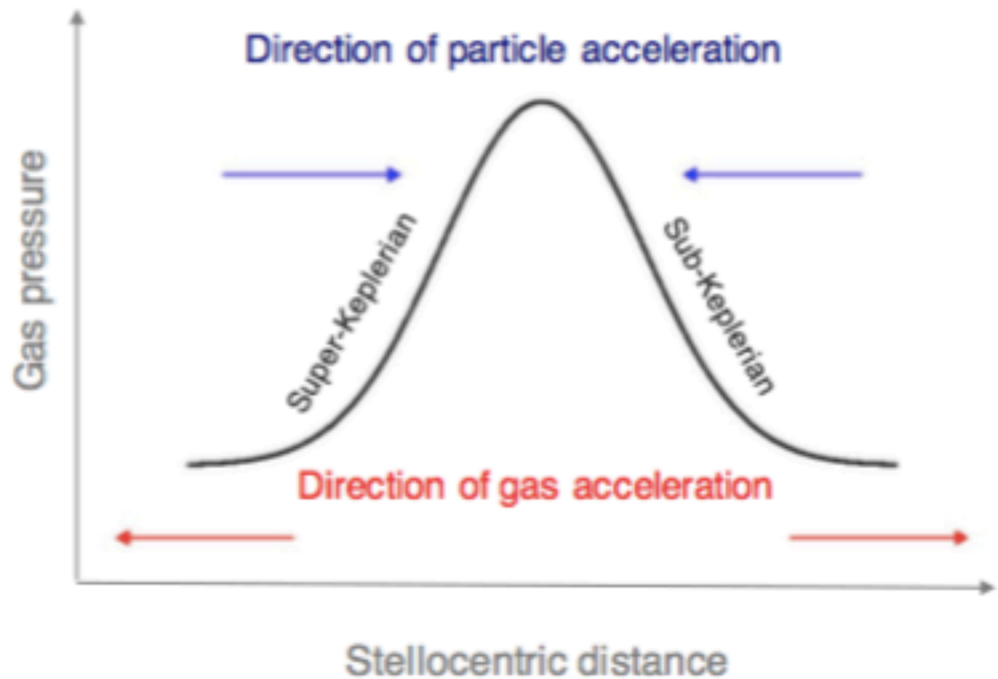


Pressure Trap

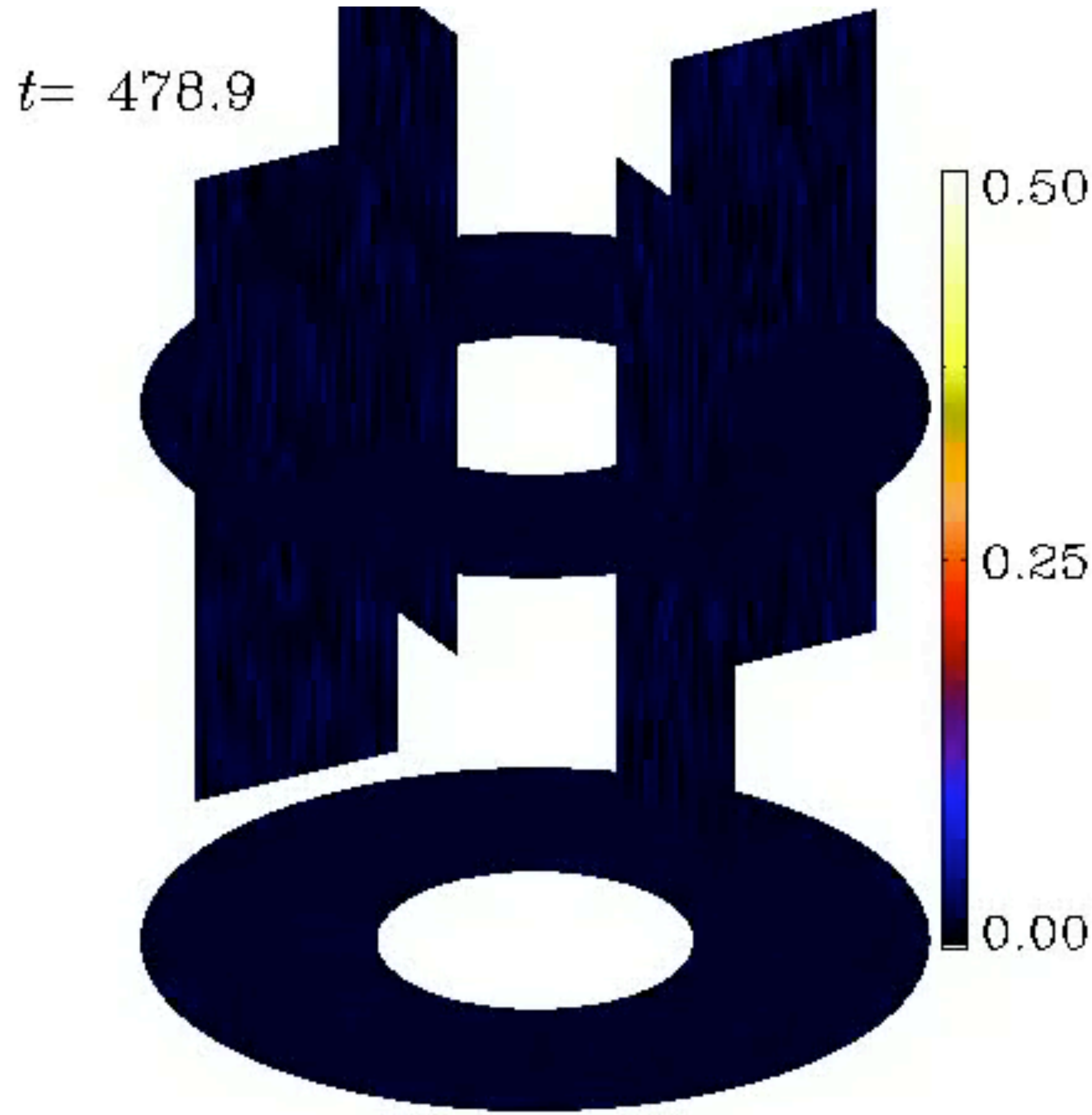


Pressure Trap



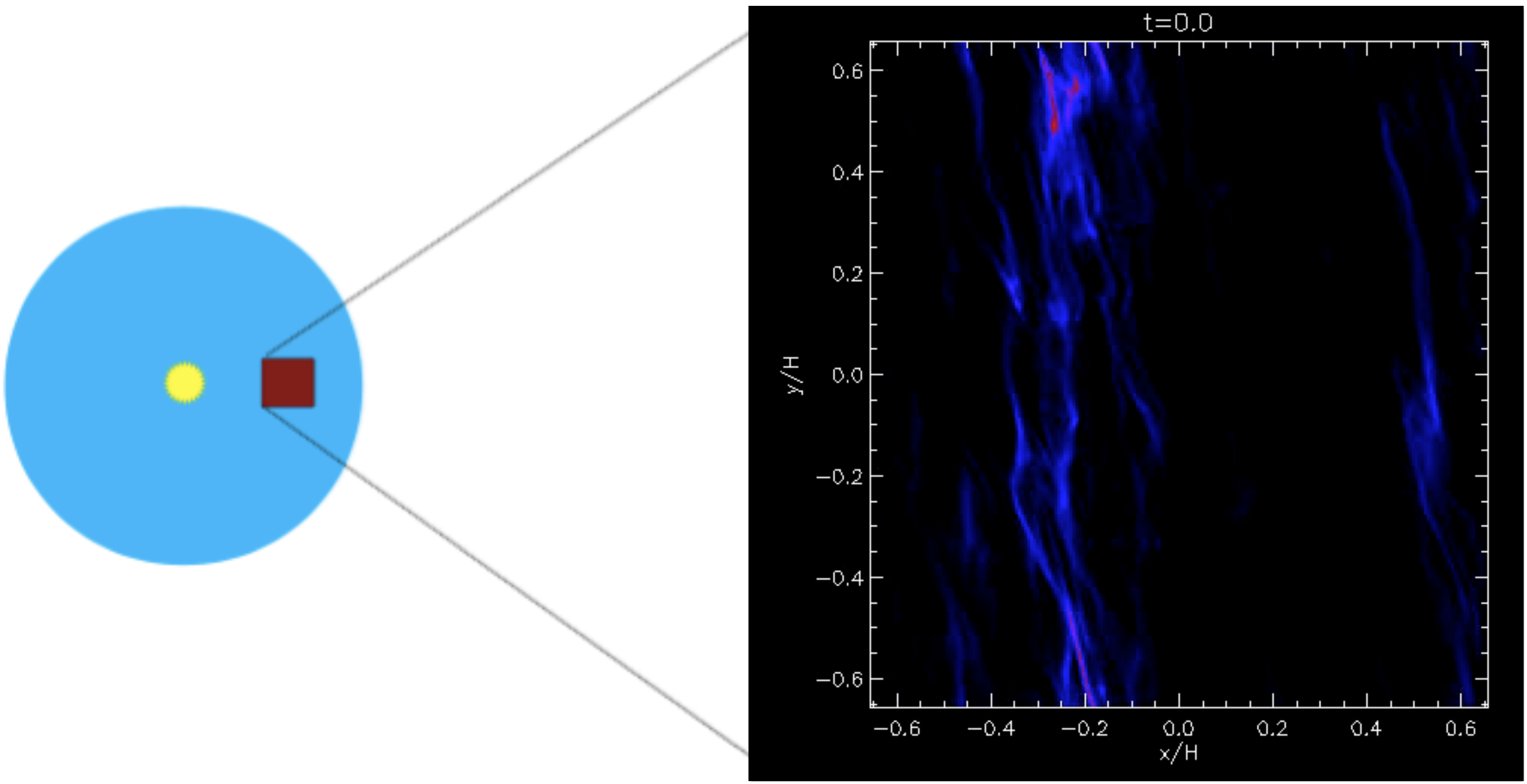


Turbulence concentrates solids mechanically in pressure maxima



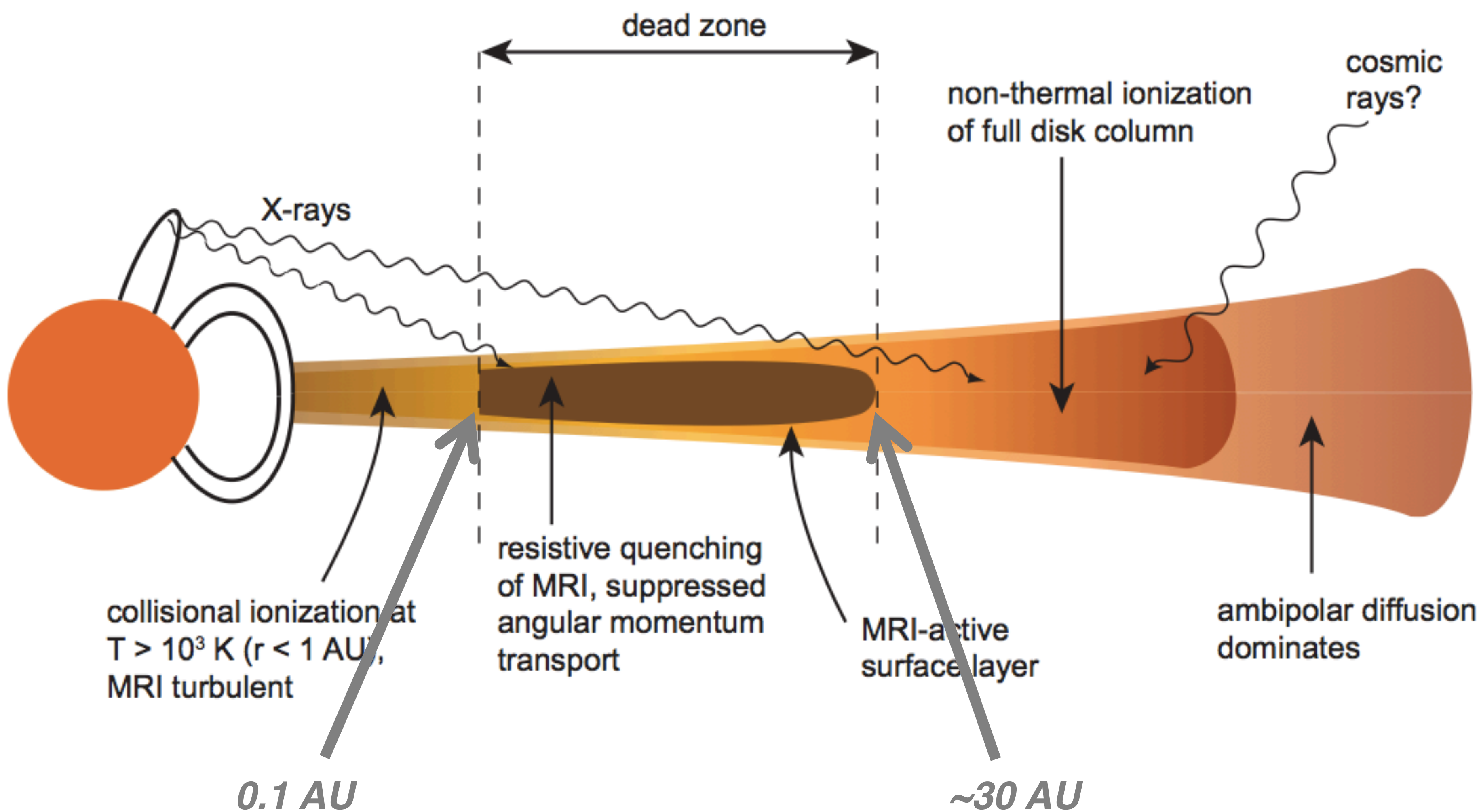
Lyra et al. (2008a)

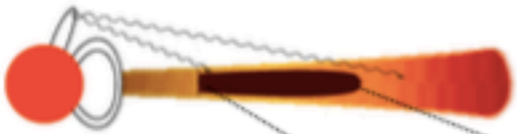
Gravitational collapse into planetesimals



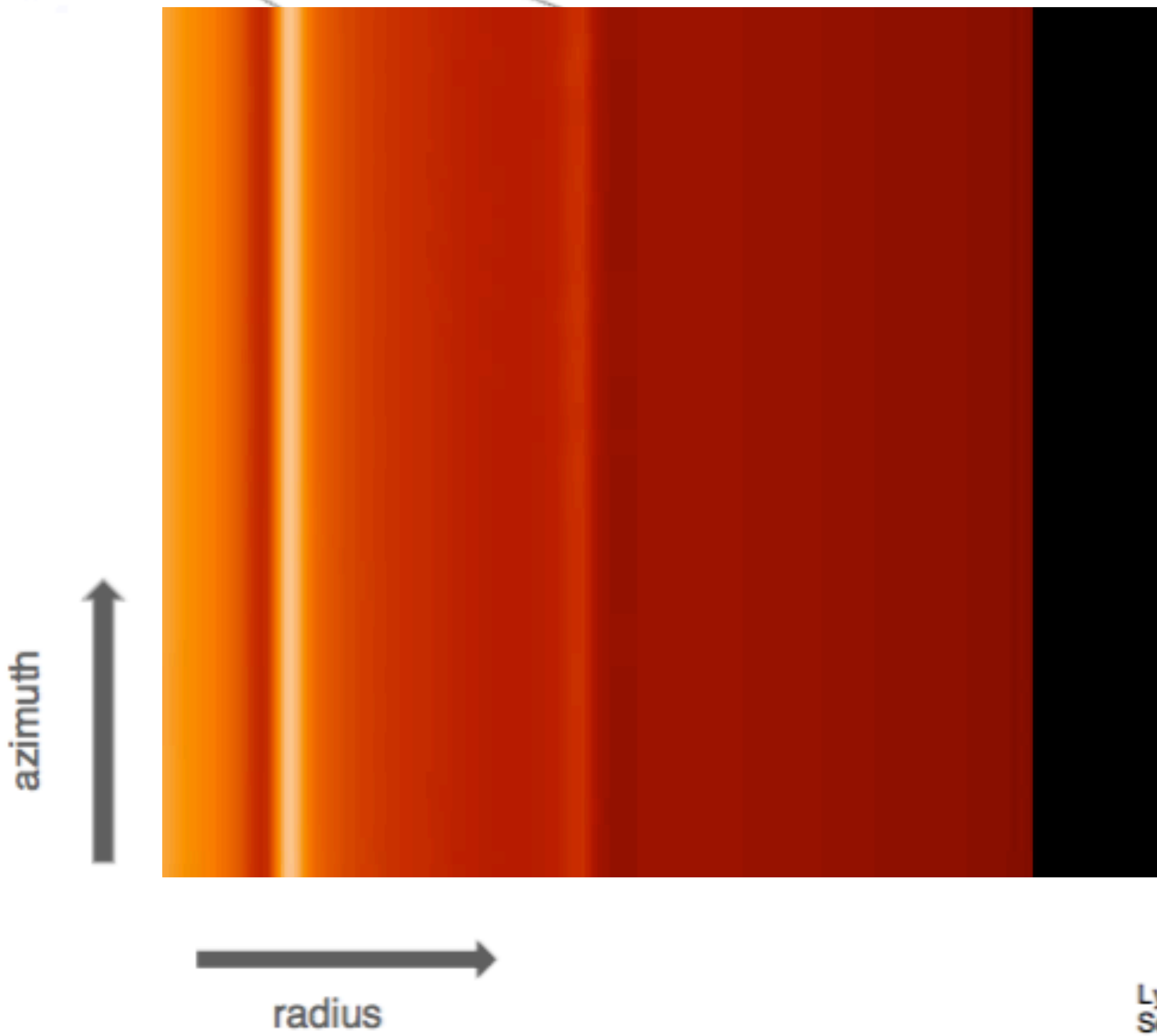
Johansen et al. (2007)

Dead zones


dead zone
non-thermal ionization
of full disk column
cosmic
rays?
X-rays
collisional ionization at
T > 10³ K (r < 1 AU),
MRI turbulent
resistive quenching
of MRI, suppressed
angular momentum
transport
MRI-active
surface layer
ambipolar diffusion
dominates
0.1 AU
~30 AU



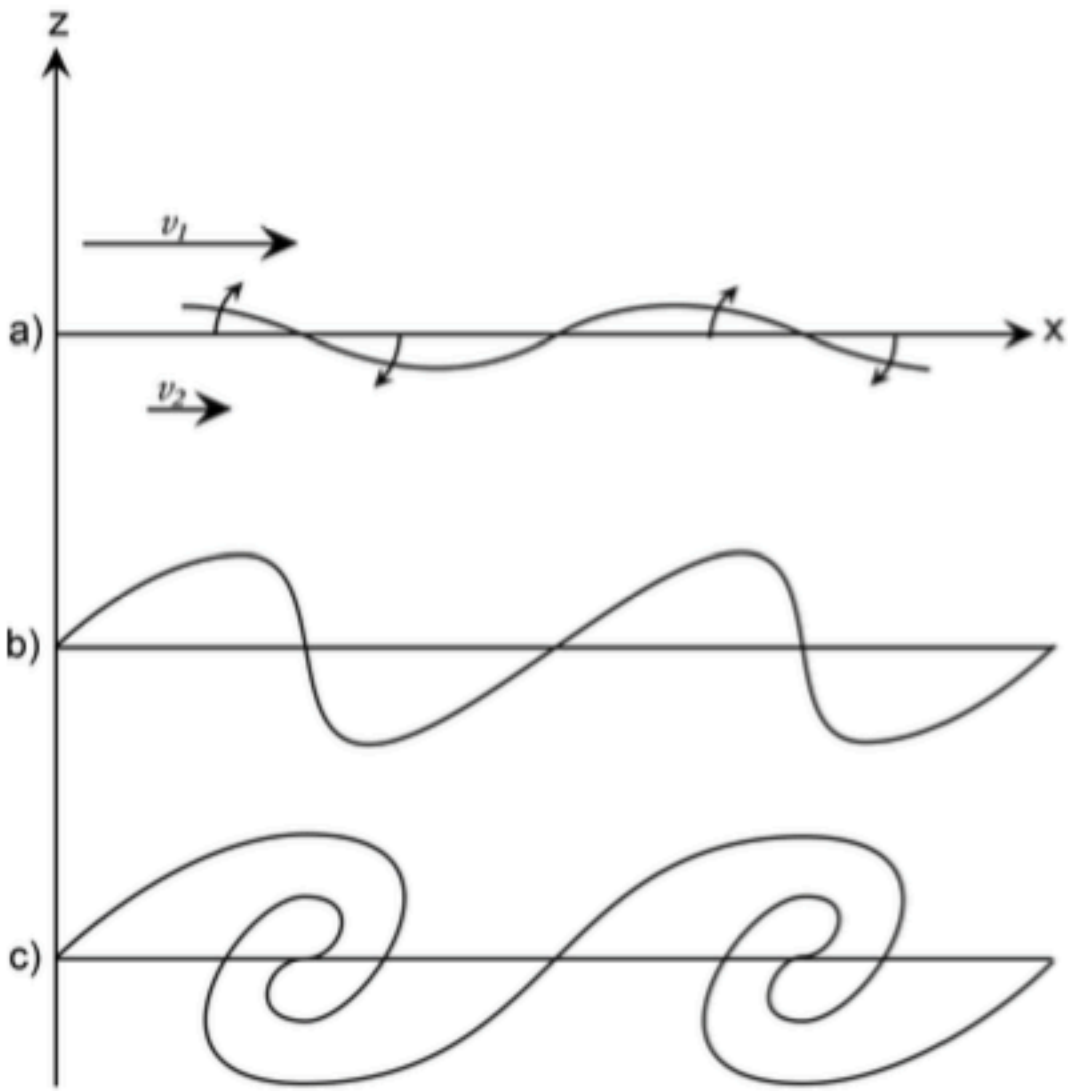
A simple dead zone model



Lyra et al. (2008b, 2009a);
See also Varniere & Tagger (2006)

Rossby wave instability

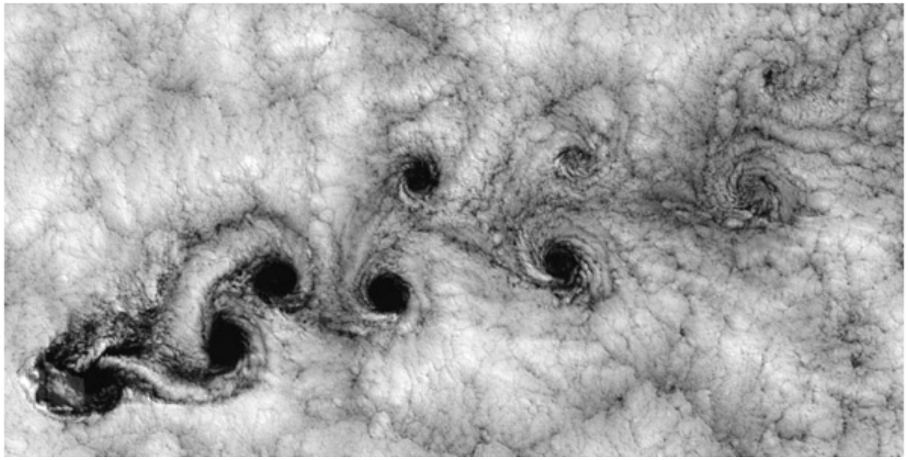
(or… Kelvin-Helmholtz in differentially rotating disks)



Vortices – an ubiquitous fluid mechanics phenomenon



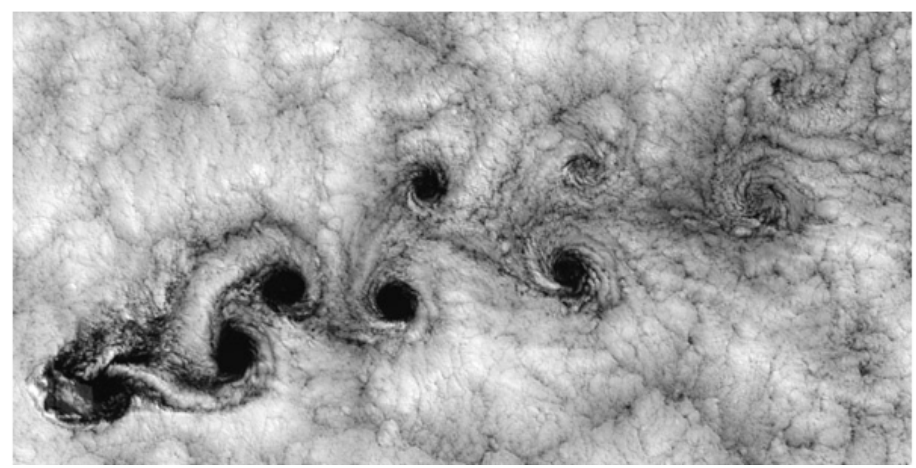




Vortices – an ubiquitous fluid mechanics phenomenon

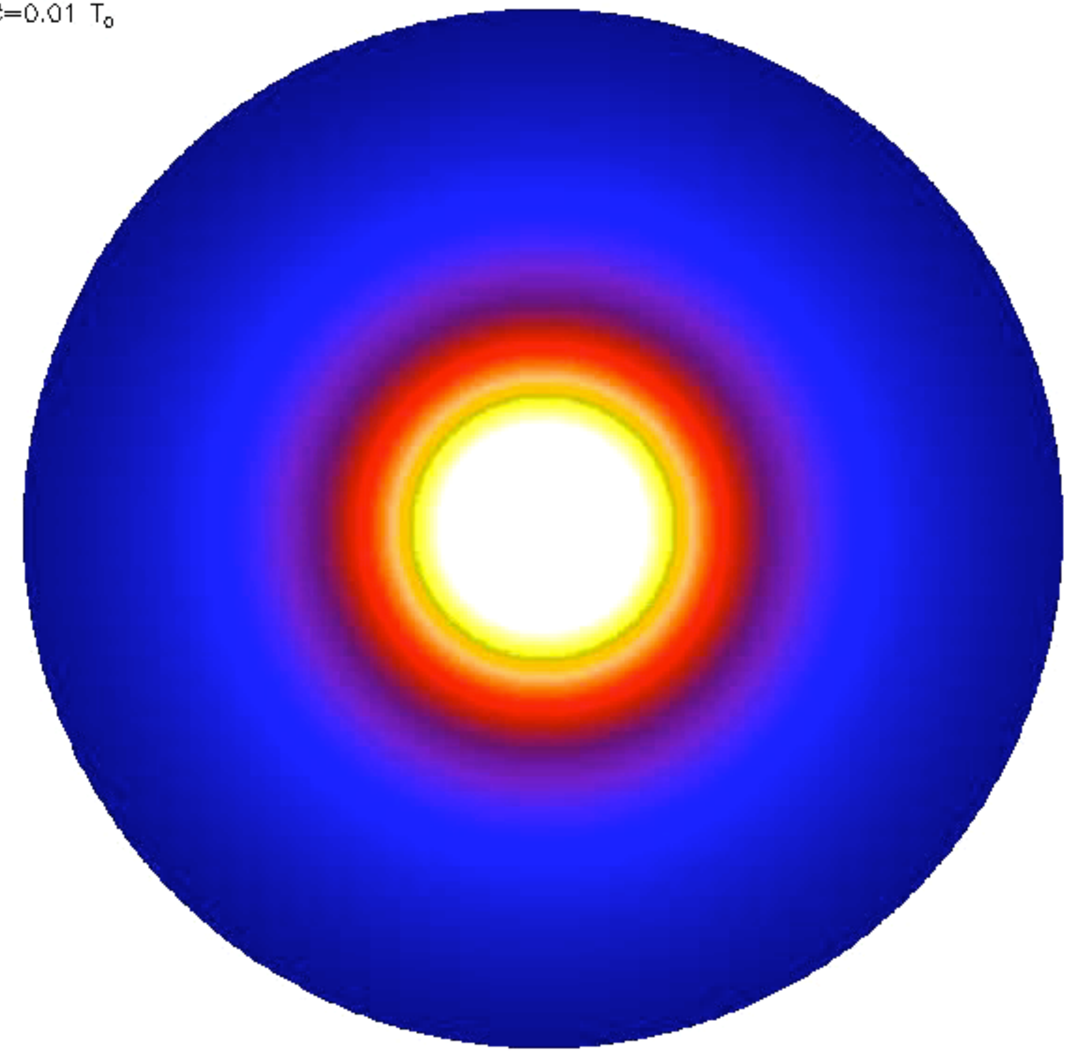


Von Kármán *vortex street*

Inner (0.1 AU) active/dead zone boundary

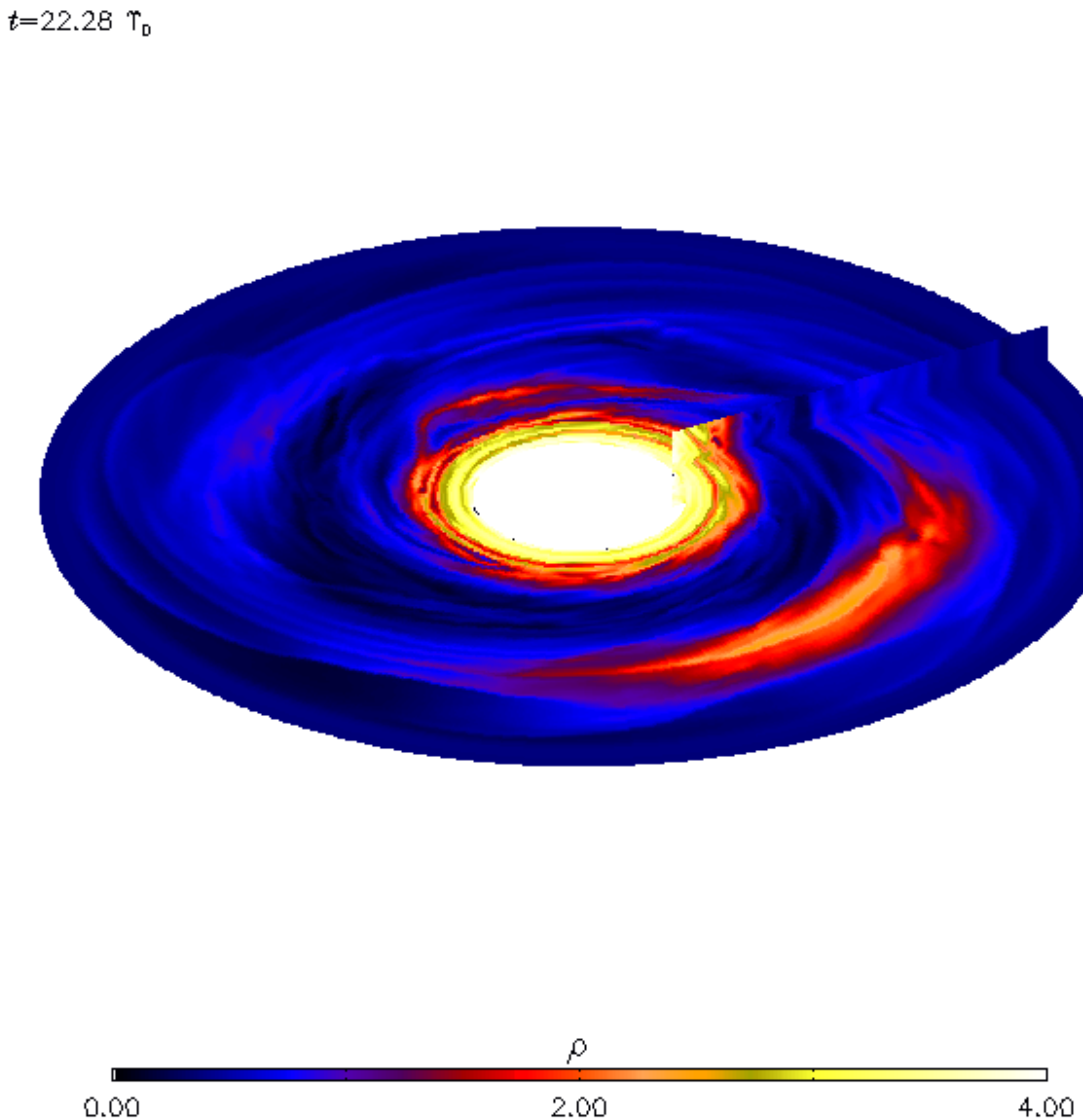
t=0.01 T_0

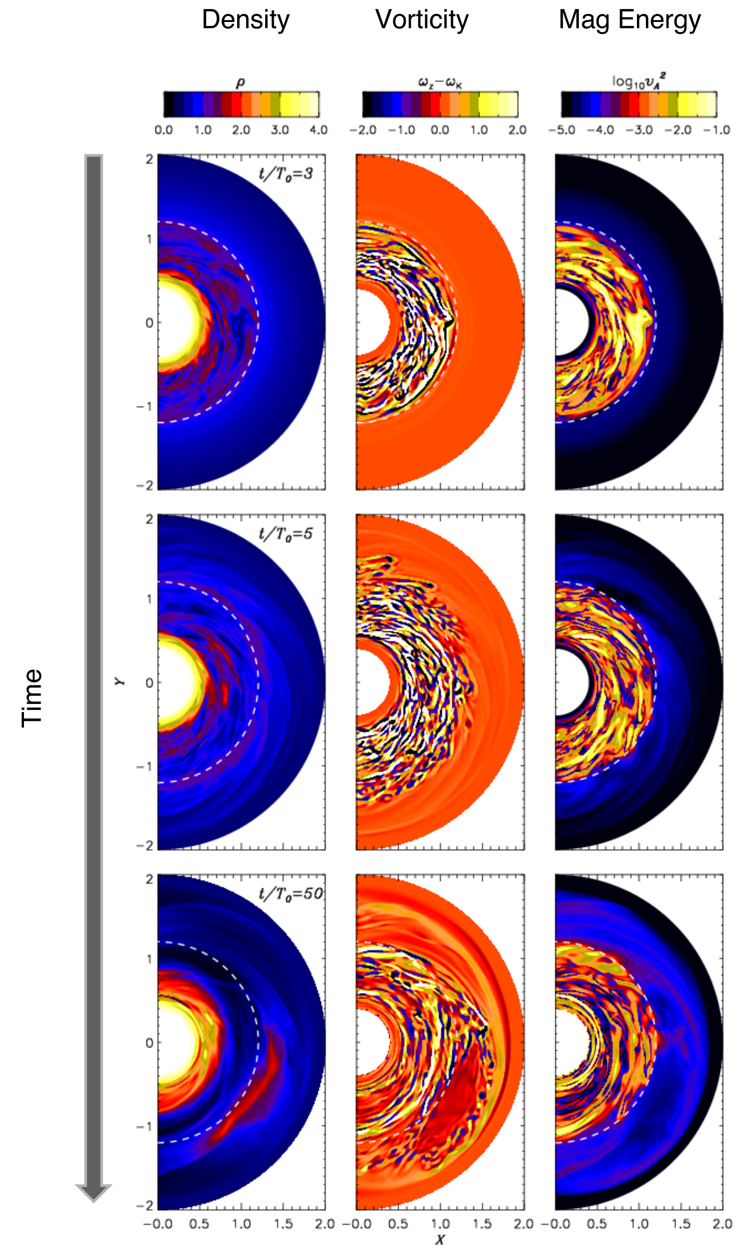


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Inner (0.1AU) active/dead zone boundary





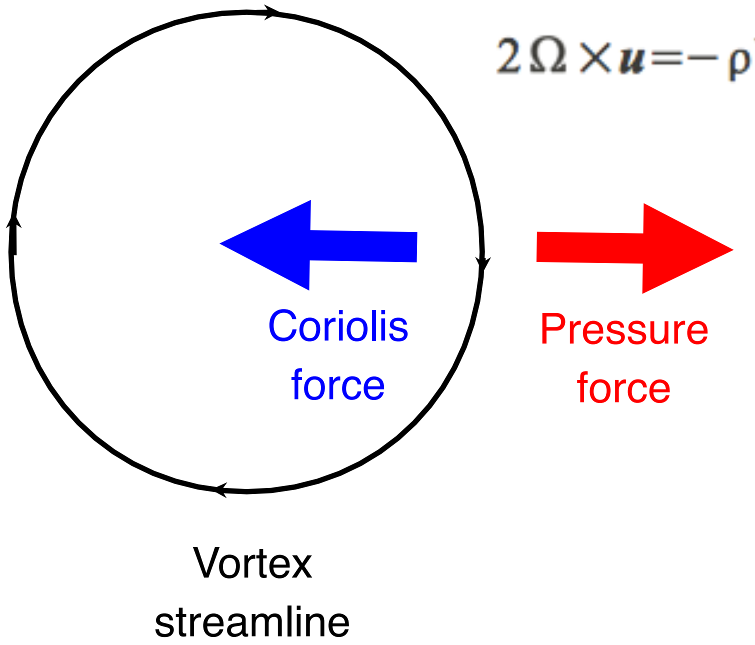
Magnetized inner disk + resistive outer disk

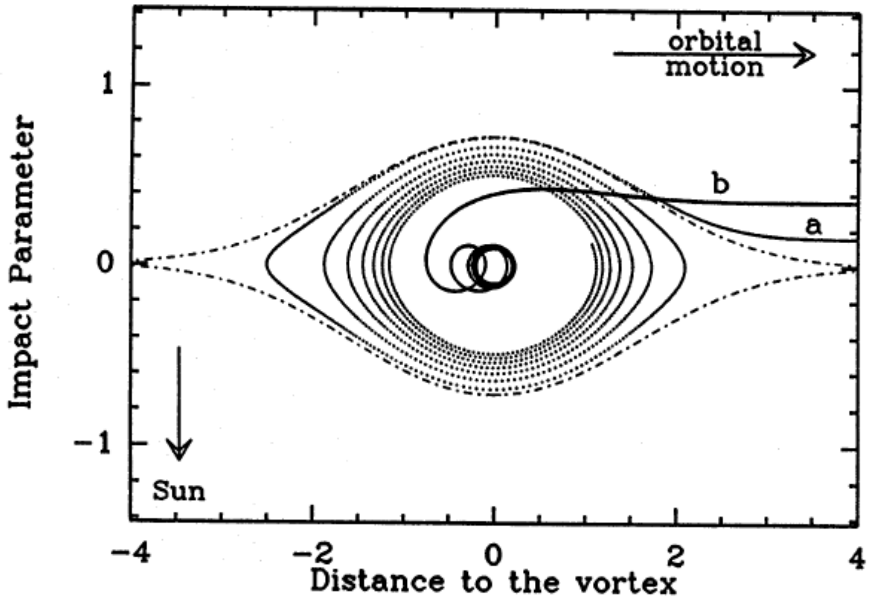
Lyra & Mac Low (2012)

The Tea-Leaf effect

Geostrophic balance:

$$2\Omega \times \boldsymbol{u} = -\rho^{-1}\nabla p$$





Barge & Sommeria (1995)

Particles do not feel the pressure gradient.
They sink towards the center, where they accumulate.

Aid to planet formation

(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

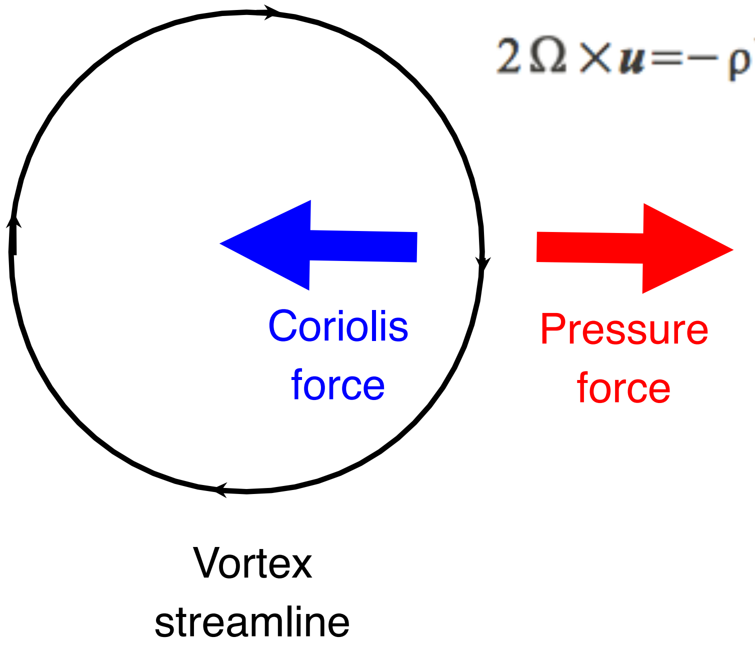
Speed up planet formation enormously

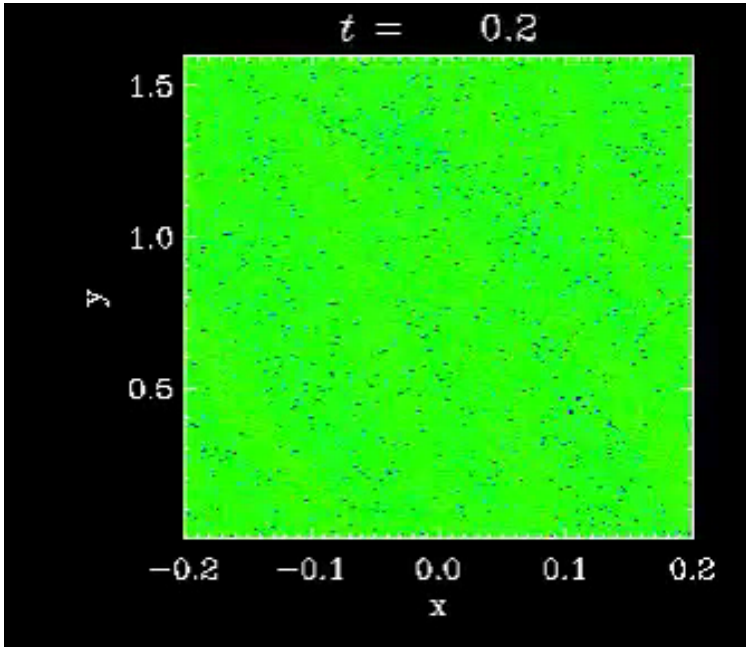
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

The Tea-Leaf effect

Geostrophic balance:

$$2\Omega \times \boldsymbol{u} = -\rho^{-1} \nabla p$$





Raettig, Lyra, & Klahr (2013)

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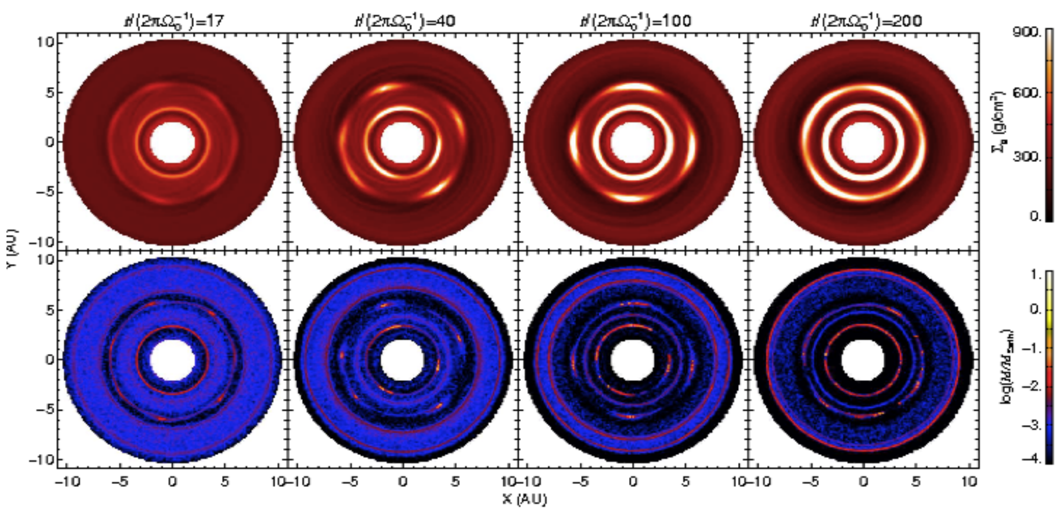
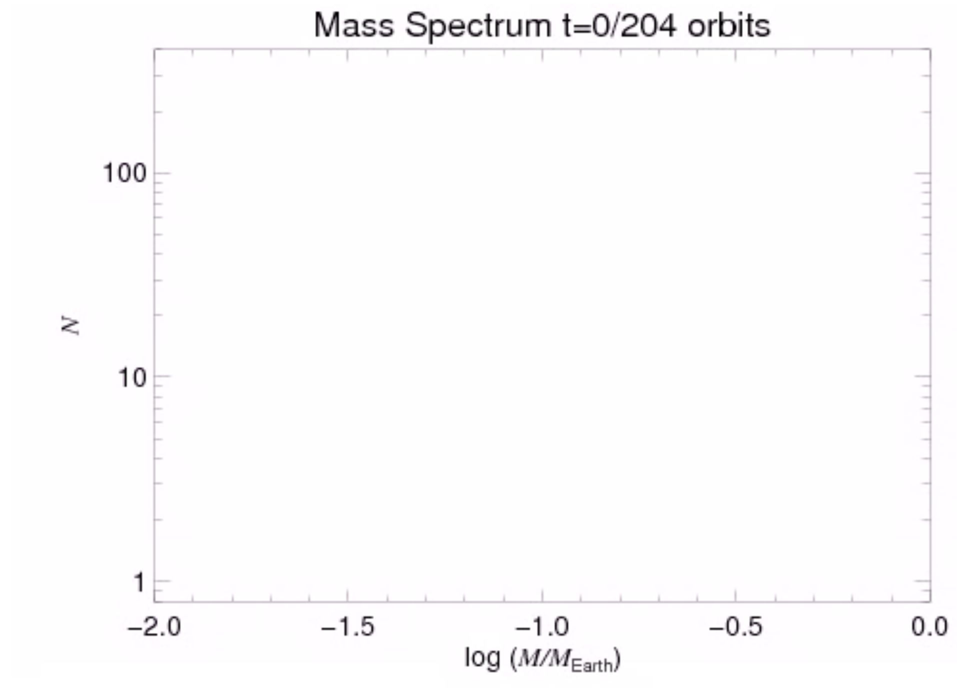
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

Vortices and Planet Formation

Gas



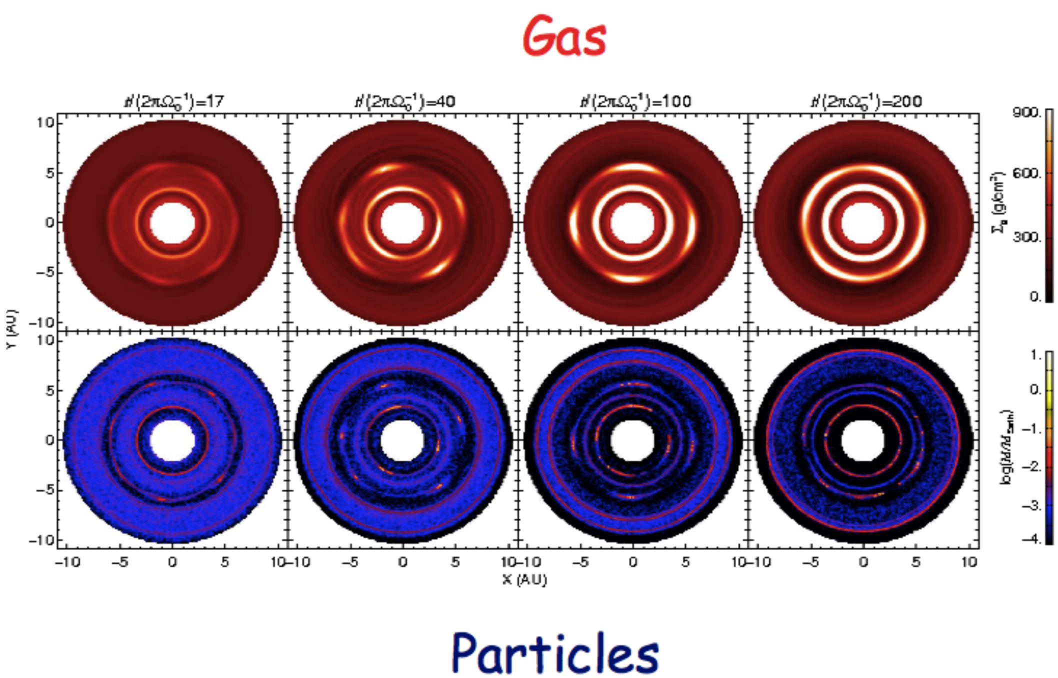
Particles

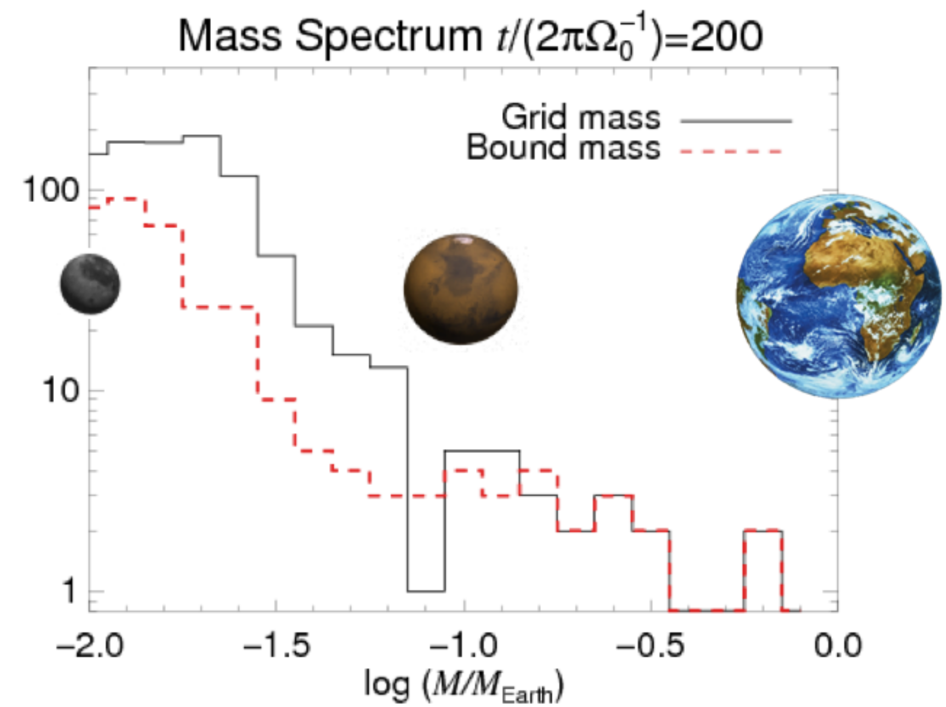


Collapse into Mars mass objects

(Lyra et al. 2008b, 2009a,
Lambrechts & Johansen 2012)

Vortices and Planet Formation

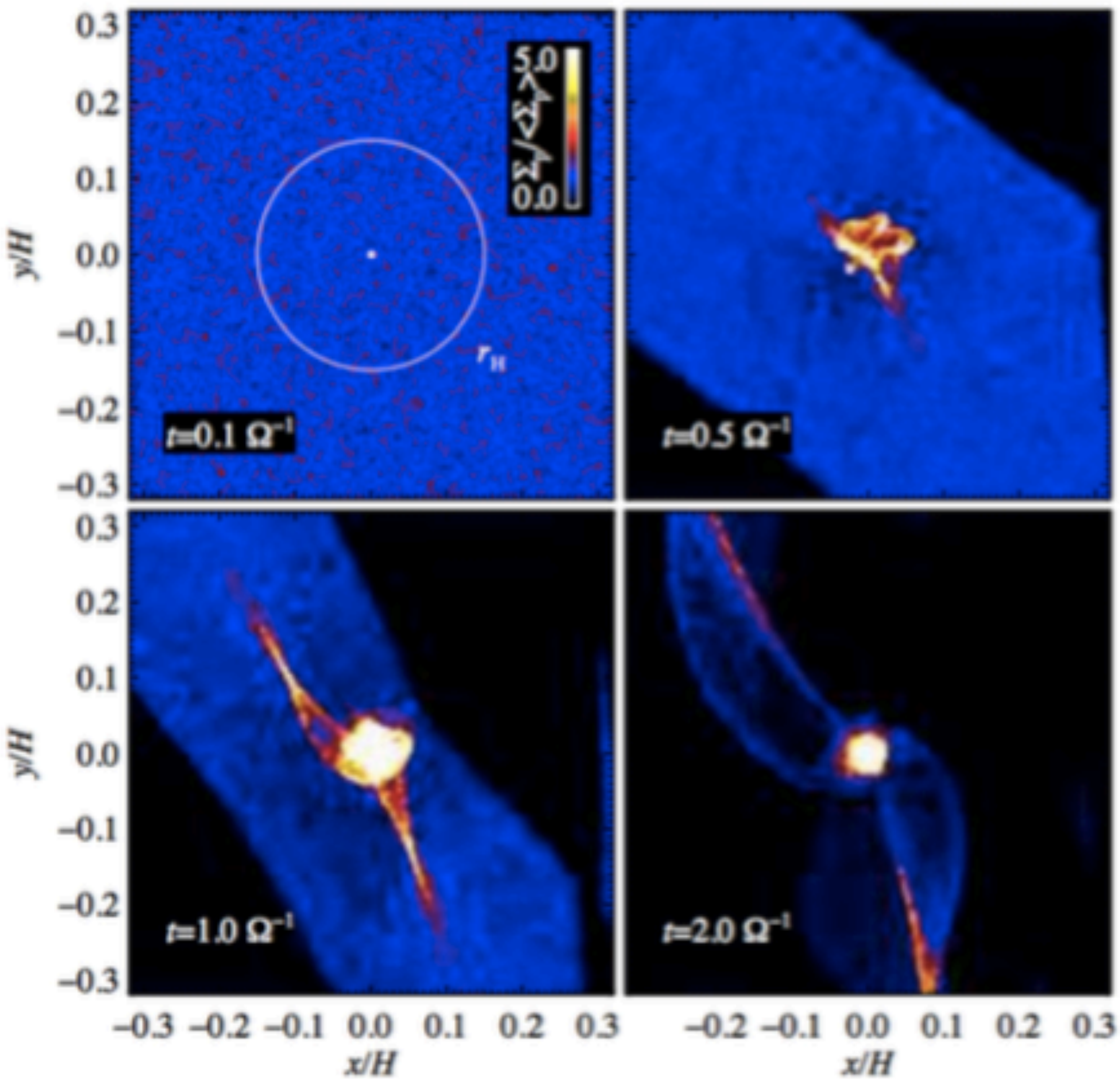




Collapse into Mars mass objects

(Lyra et al. 2008b, 2009a,
Lambrechts & Johansen 2012)

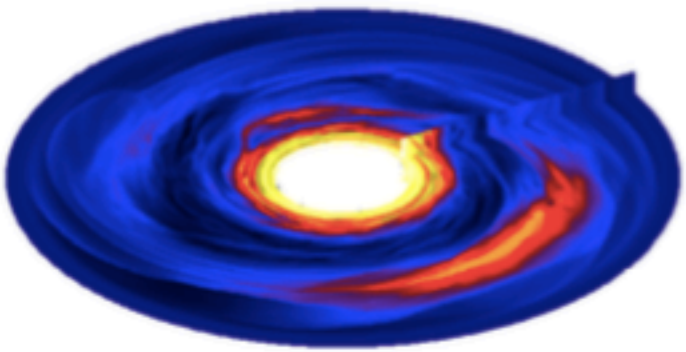
Gas drag makes the motion dissipative.
Enhances accretional radius.



Lambrechts & Johansen (2012)

Sustaining vortices in disks

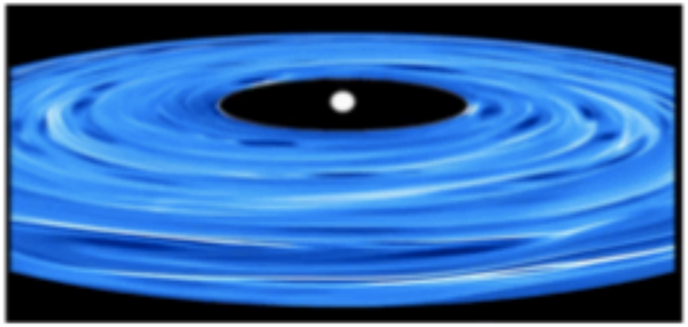
Rossby wave instability



Lovelace & Hohlfeld (1978), Toomre (1981), Papaloizou & Pringle (1984, 1985), Hawley et al. (1987), Lovelace et al. (1999), Li et al. (2000,2011), Tagger (2001), Varniere & Tagger (2006), de Val-Borro et al. (2007), Lyra et al. (2008b,2009ab), Mehuet et al. (2010, 2012abc), Lin & Papaloizou (2011ab, 2012), Lyra & Mac Low (2012), Regaly et al. (2012, 2013), Lin (2012ab, 2013), Ataiee et al. (2013, 2014), Lyra et al. (2014)

Powered by:
Modification of shear profile
(external vorticity reservoir)

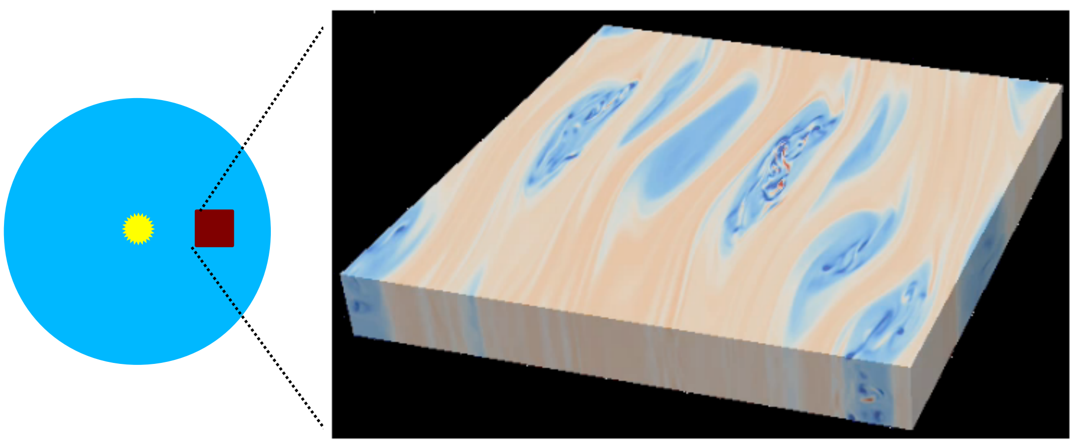
Convective Overstability



Klahr & Bodenheimer (2003), Klahr (2004), Johnson & Gammie (2005), Petersen et al. (2007ab), Lesur & Papaloizou (2010), Lyra & Klahr (2011), Raettig et al. (2013) Klahr & Hubbard (2014), Lyra (2014), Latter (2015)

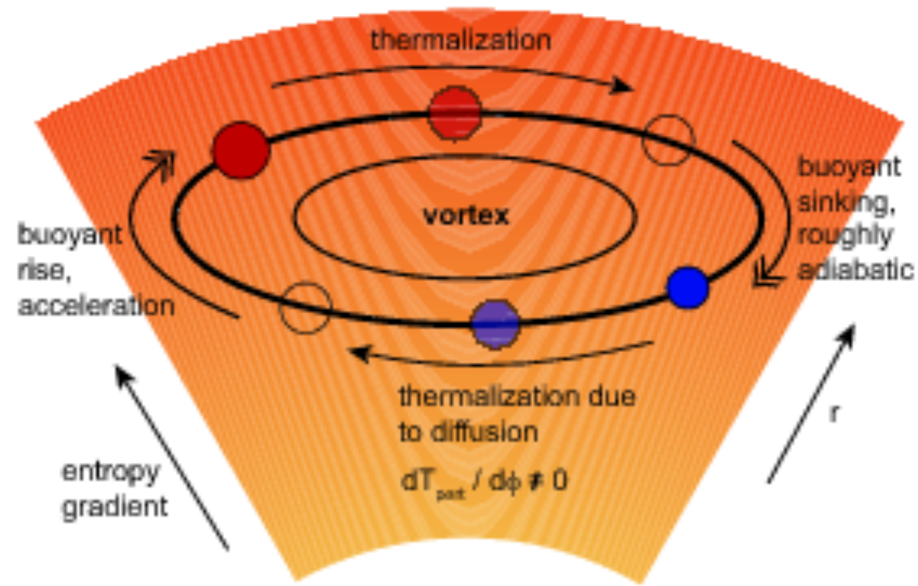
Powered by:
Buyoancy, thermal diffusion
(baroclinic source term)

Convective Overstability (née Baroclinic Instability)



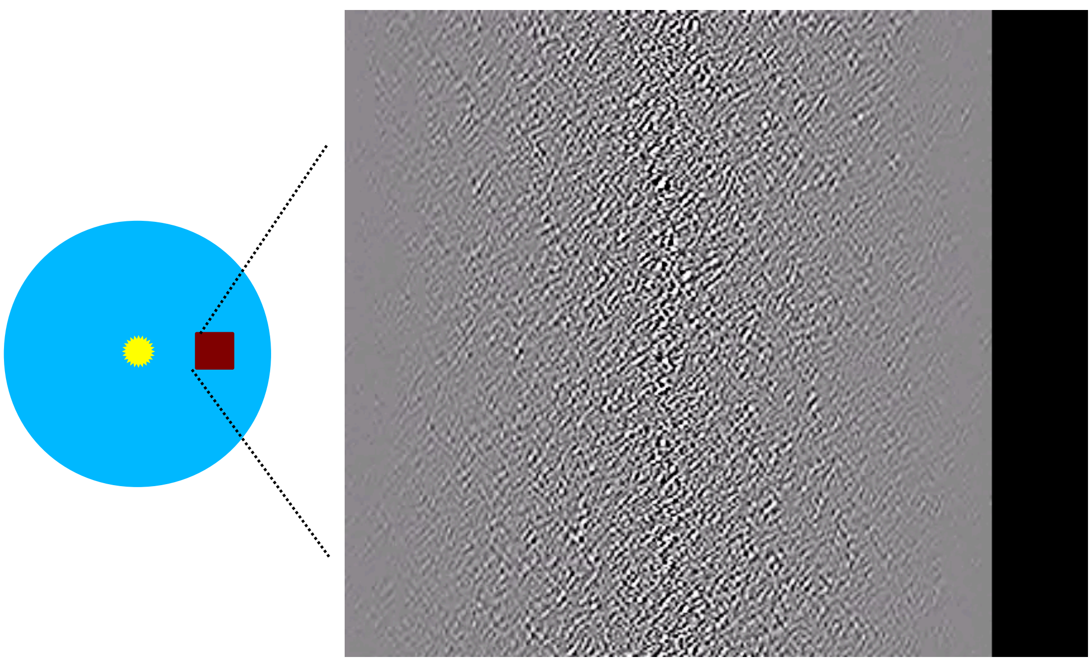
Lesur & Papaloizou (2010)

Sketch of the Convective Overstability



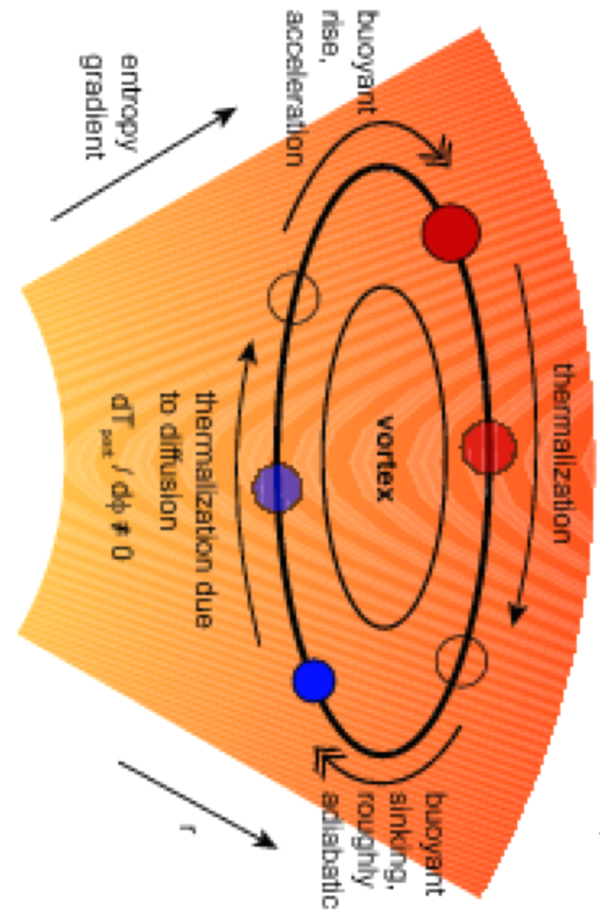
Armitage (2010)

Convective Overstability



Lyra & Klahr (2011)

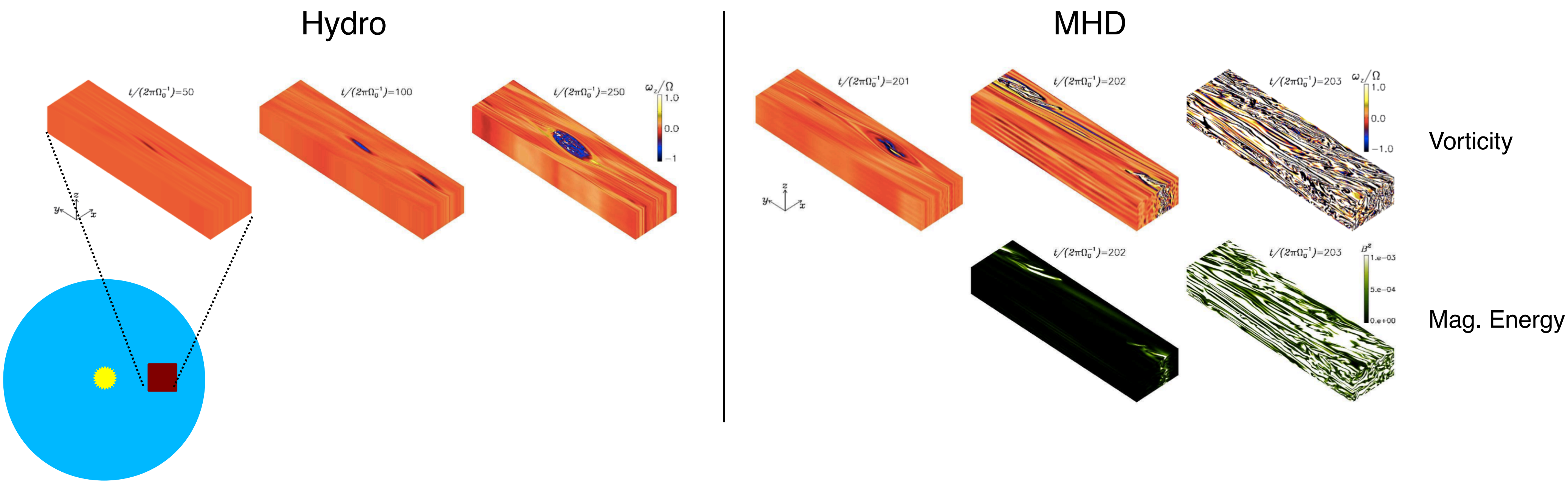
Sketch of the
Convective Overstability



Armitage (2010

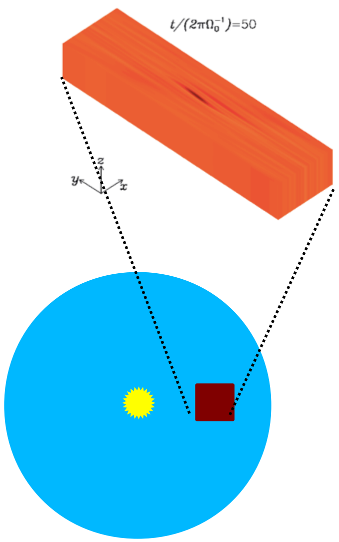
Vortices and MHD

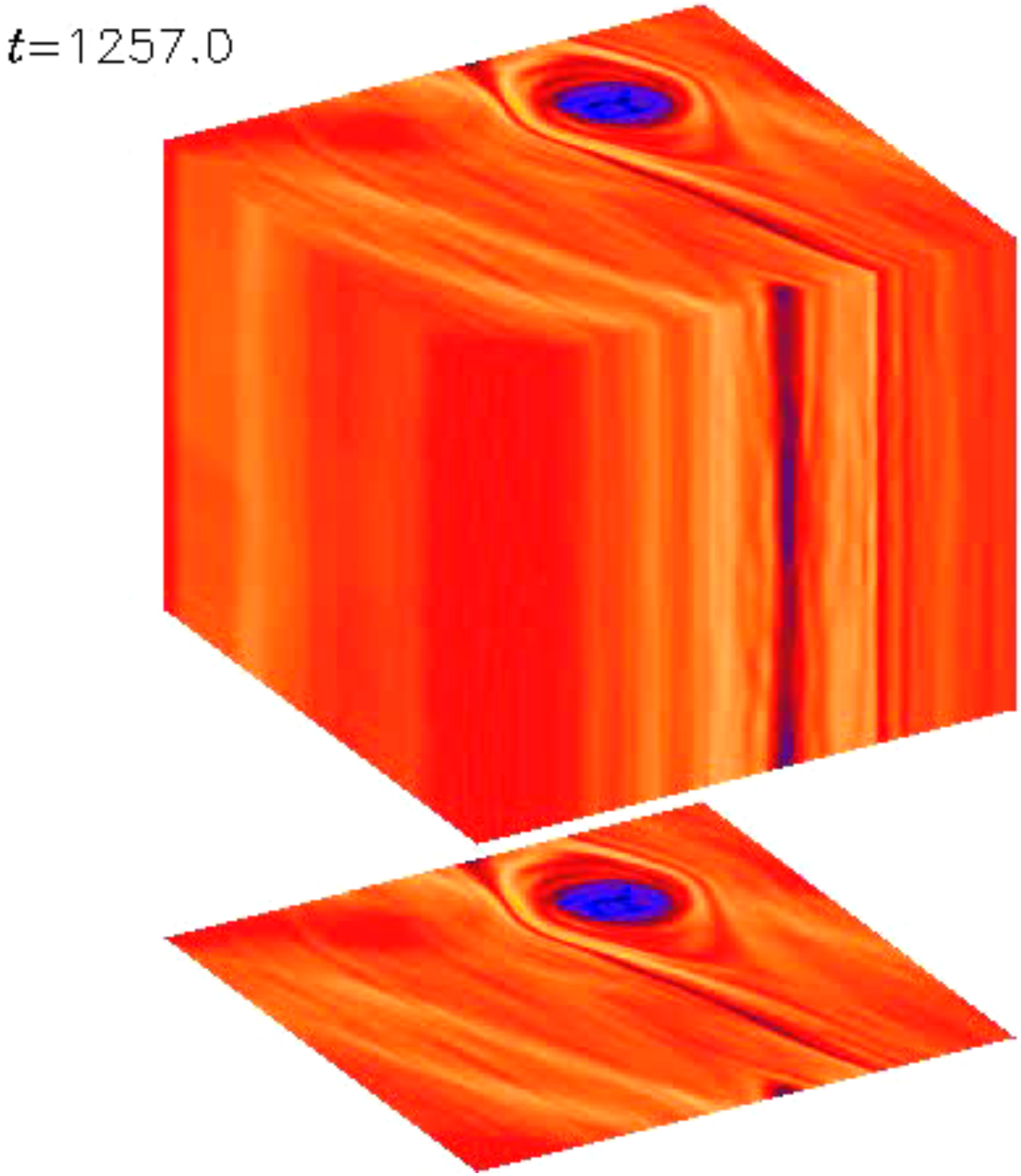
What happens when the disk is magnetized?

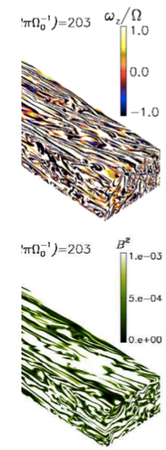


Lyra & Klahr (2011)

Vortices and MHD







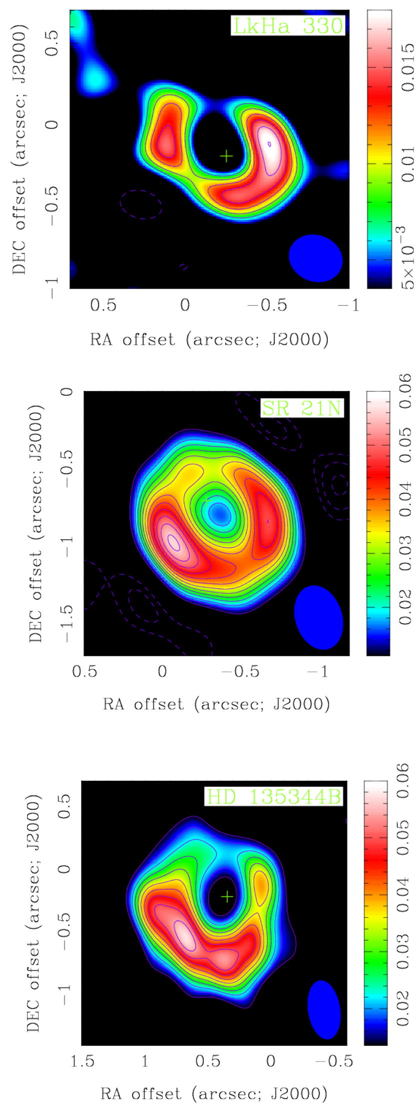
Vorticity

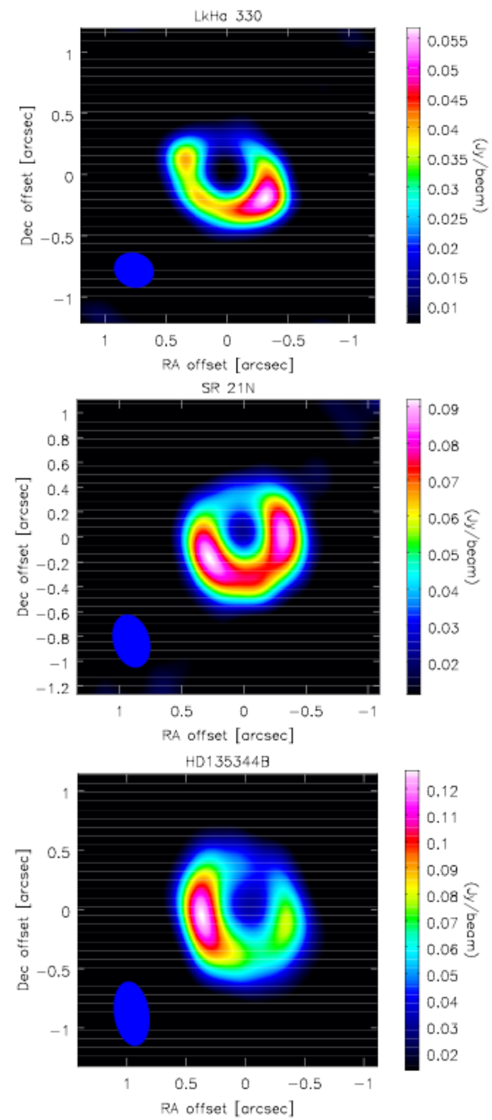
Mag. Energy

Observational evidence in protoplanetary disks (Exonebulae)

Observations

Brown et al. (2009)





Models

Simulated observations

Regaly et al. (2012)

Oph IRS 48

A Major Asymmetric Dust Trap in a Transition Disk

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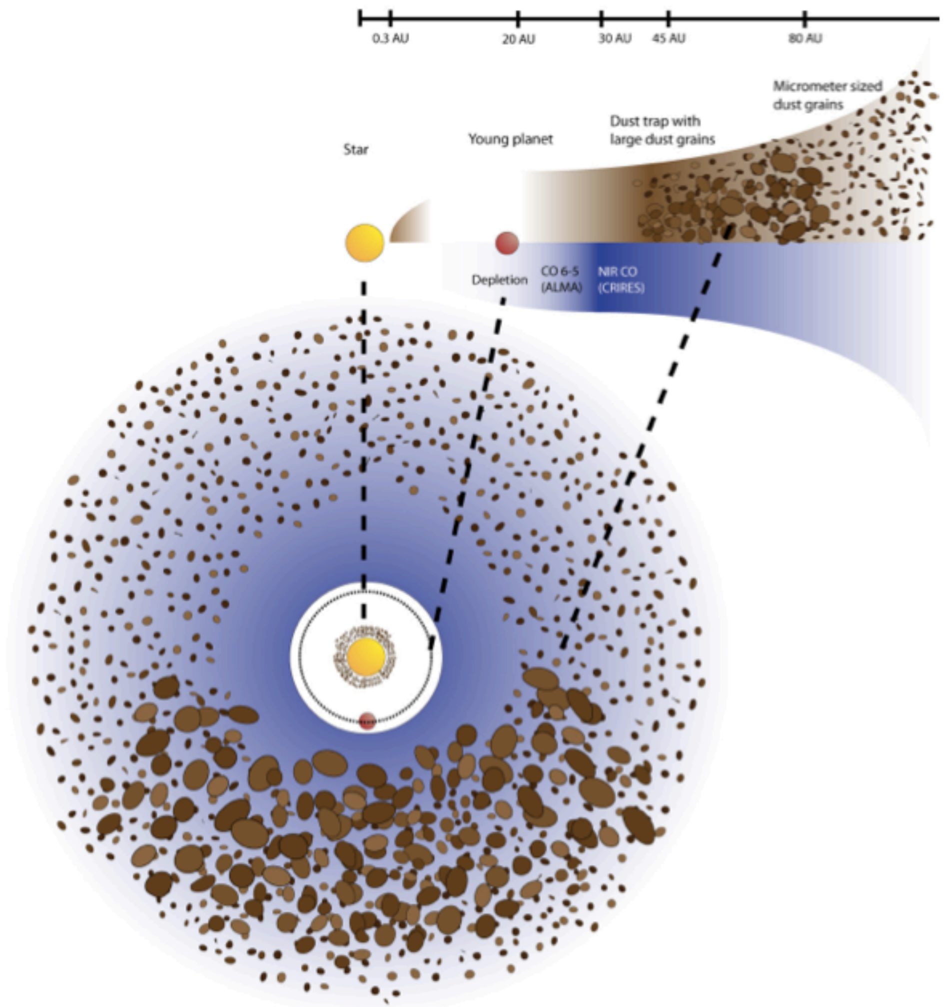
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection of a dust trap in the disk around the star Oph IRS 48 using observations from the Atacama Large Millimeter/submillimeter Array (ALMA). The 0.44-millimeter–wavelength continuum map shows high-contrast crescent-shaped emission on one side of the star, originating from millimeter-sized grains, whereas both the mid-infrared image (micrometer-sized dust) and the gas traced by the carbon monoxide 6-5 rotational line suggest rings centered on the star. The difference in distribution of big grains versus small grains/gas can be modeled with a vortex-shaped dust trap triggered by a companion.

Although the ubiquity of planets is confirmed almost daily by detections of new exoplanets (*1*), the exact formation mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

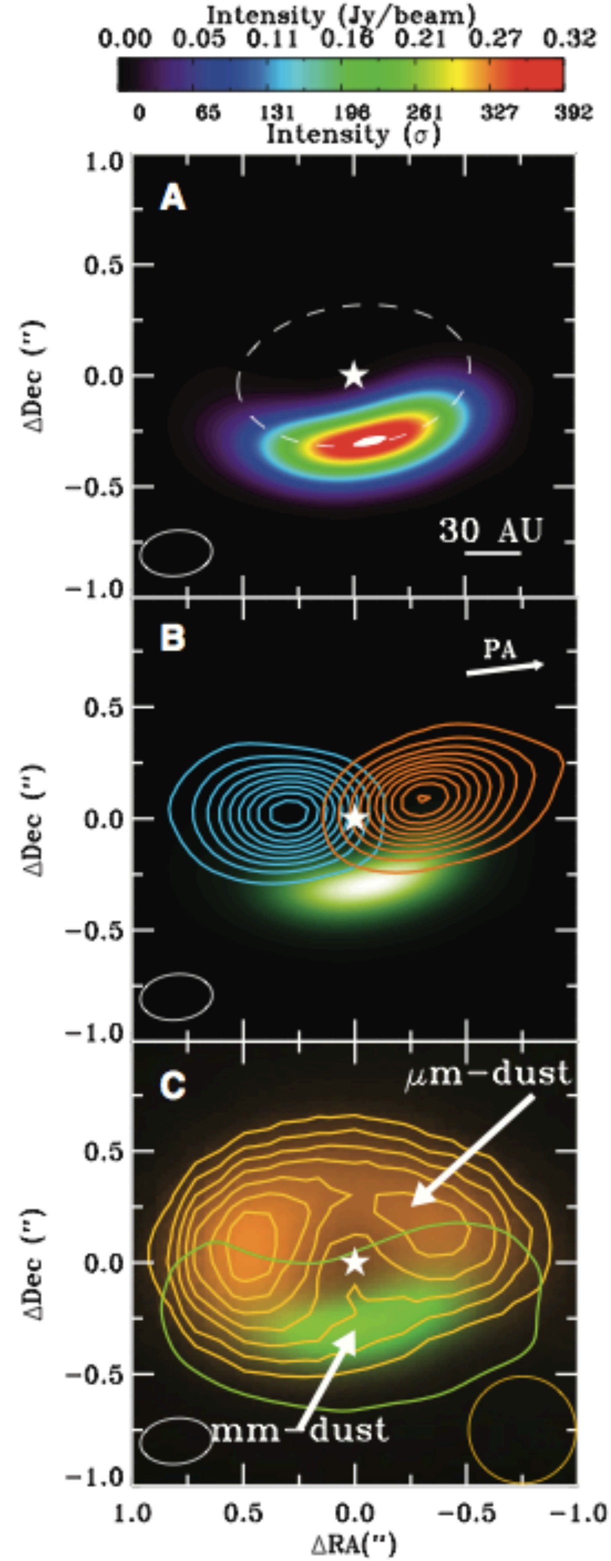
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

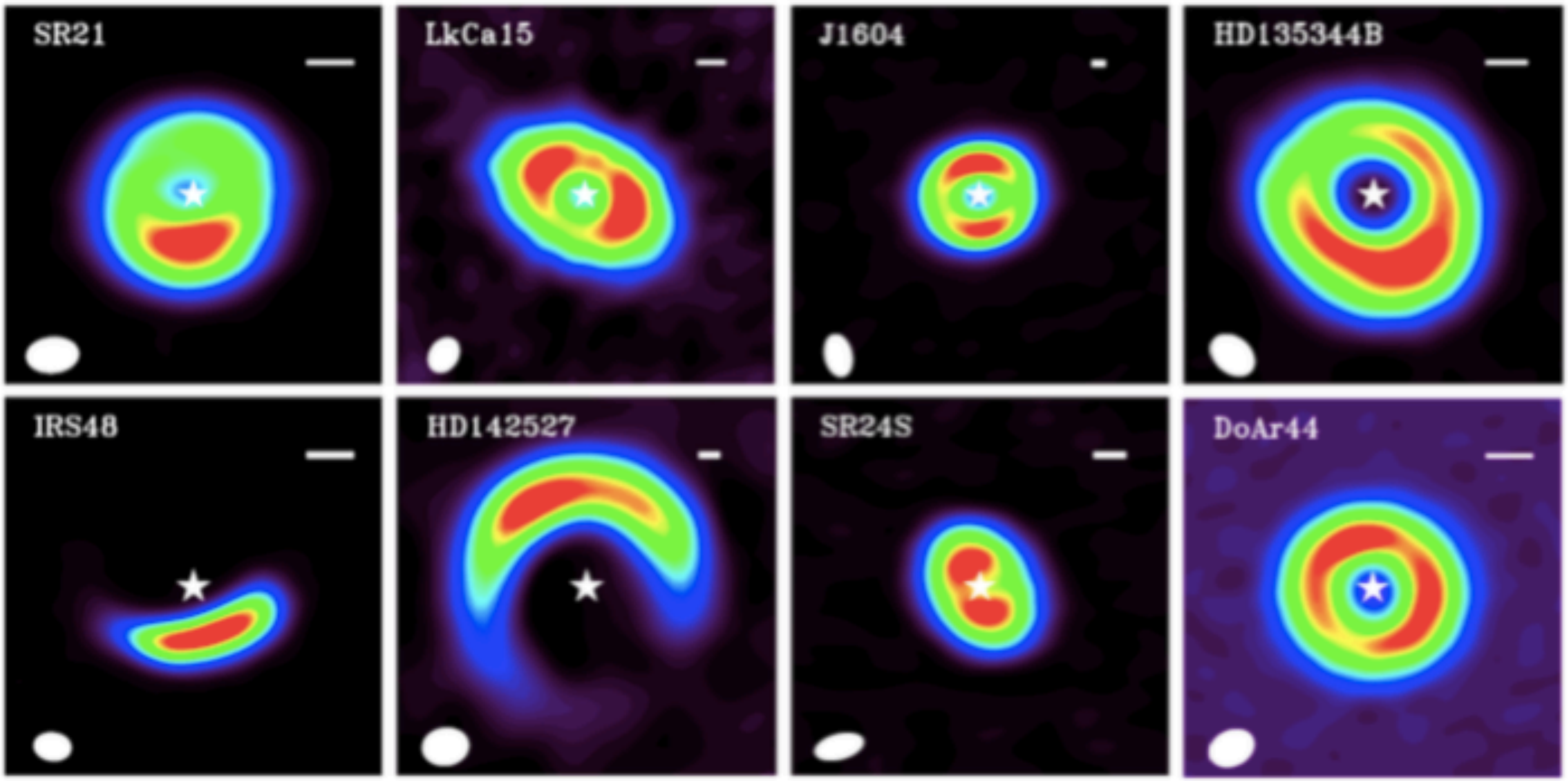


asymmetric mm dust at 63 AU

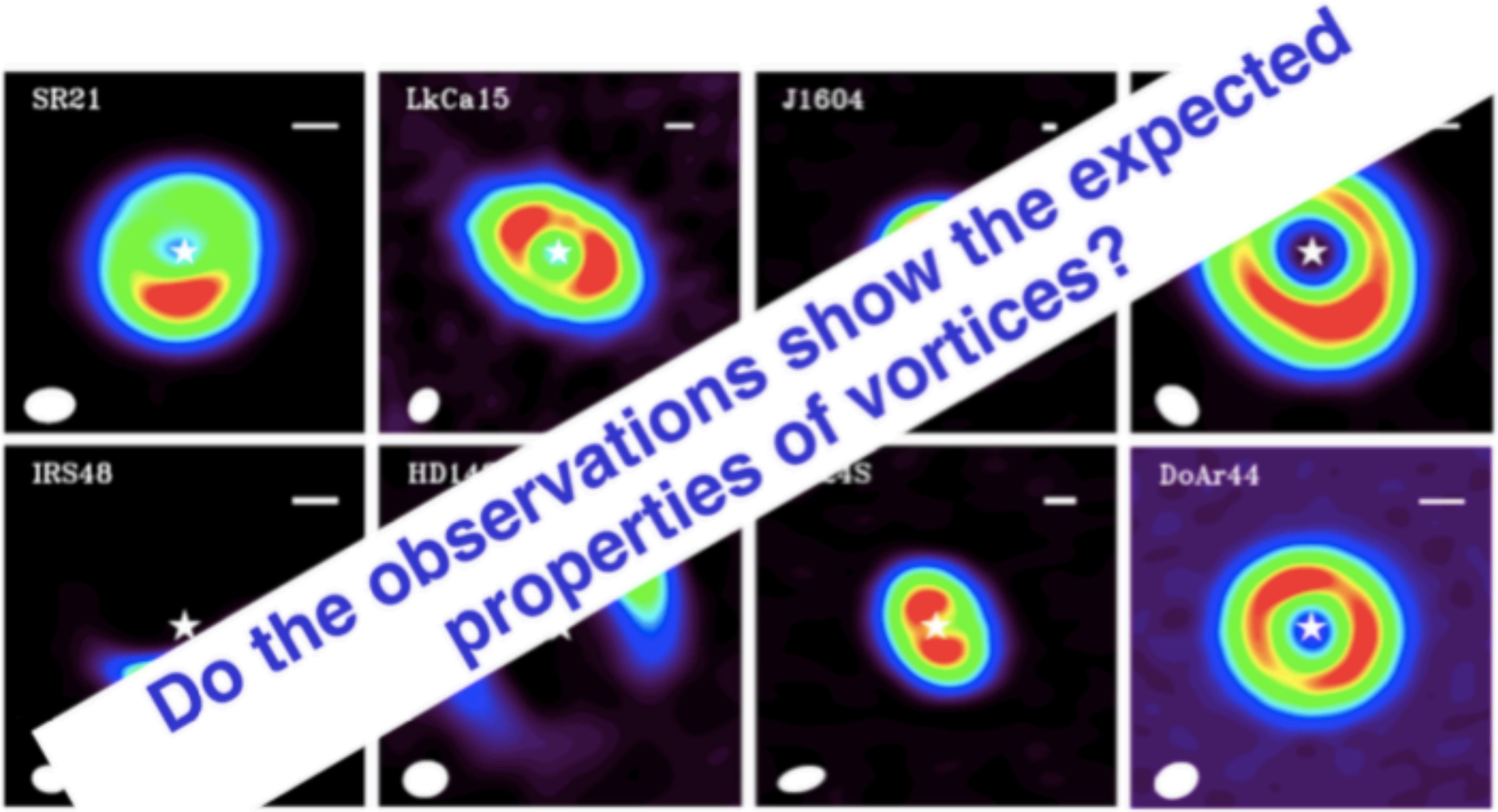
Gas detection: Keplerian rotation

Micron-sized dust follows gas

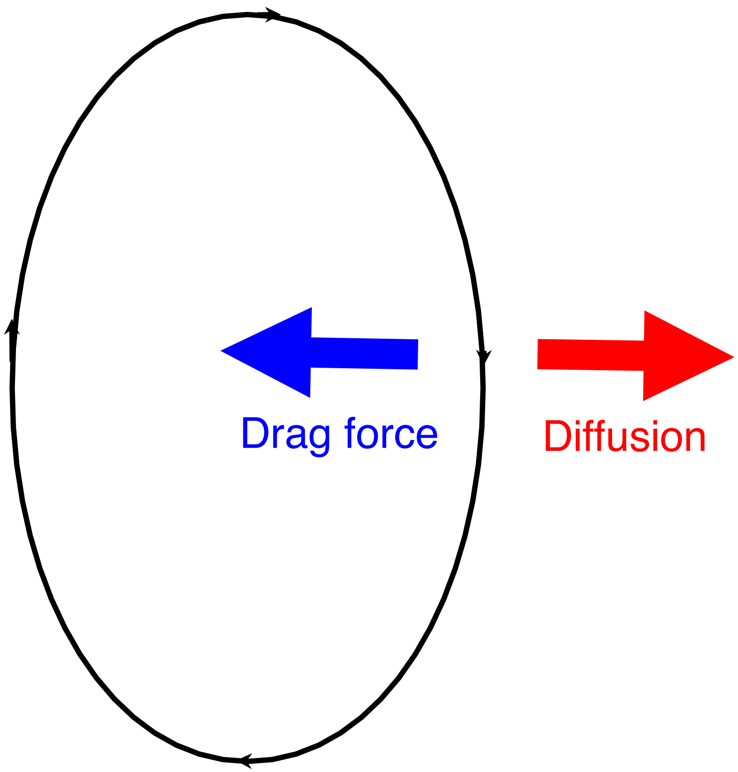
“Asymmetries” everywhere



“Asymmetries” everywhere



Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

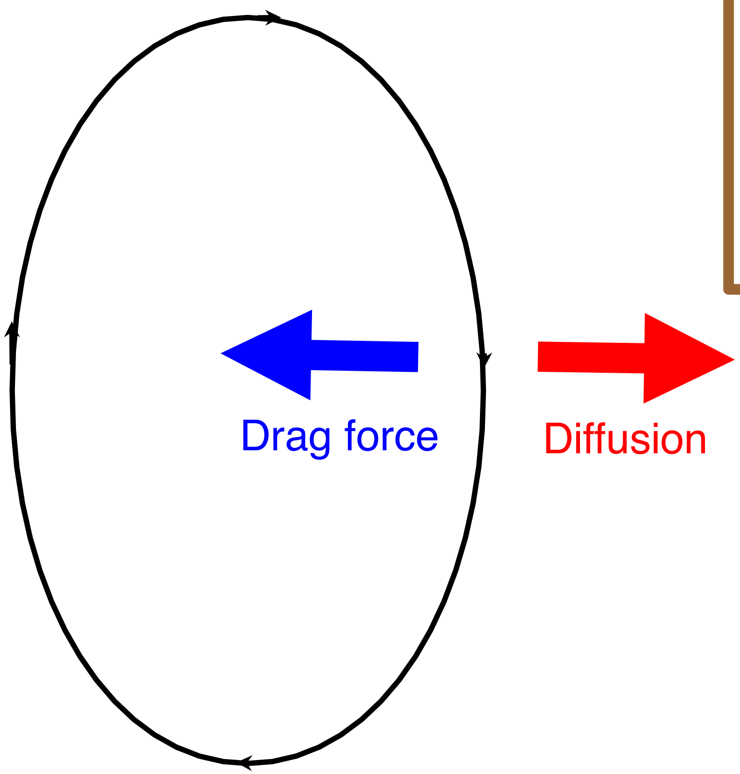
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v} + D\nabla^2 \rho_d,$$

advection

compression

diffusion

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

$$\rho_d(a,z) = \varepsilon \rho_0 (S+1)^{3/2} \exp\left\{ -\frac{[a^2 f^2(\chi) + z^2]}{2H^2}(S+1) \right\}$$

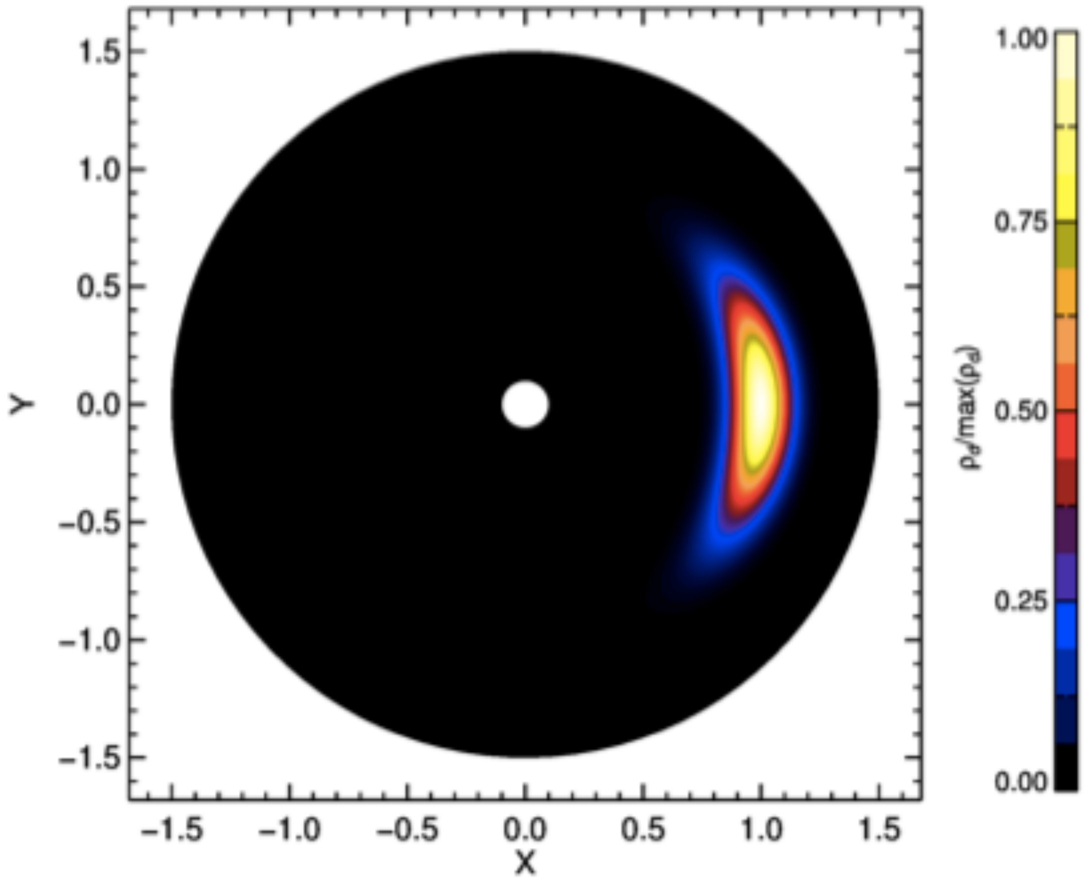
Lyra & Lin (2013)

$$S = \frac{St}{\delta}$$

$$\delta = v_{\rm rms}^2 / c_s^2,$$

- a = vortex semi-minor axis
- H = disk scale height (temperature)
- χ = vortex aspect ratio
- δ = diffusion parameter
- St = Stokes number (particle size)
- $f(\chi)$ = model-dependent scale function

Analytical solution for dust trapping



Solution

$$\rho_d(a) = \rho_{d\,\max} \exp\left(-\frac{a^2}{2H_V^2}\right),$$

$$H_V = \frac{H}{f(\chi)}\sqrt{\frac{1}{S+1}}$$

$$S = \frac{St}{\delta}$$

$$\delta = v_{\rm rms}^2 / c_s^2,$$

a = vortex semi-minor axis
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function

Solution for

$H/r=0.1$ $\chi=4$ $S=1$

Lyra & Lin (2013)

Derived quantities

$$\rho_d(a,z) = \varepsilon \rho_0 (S+1)^{3/2} \exp\left\{ -\frac{[a^2 f^2(\chi) + z^2]}{2H^2}(S+1) \right\}$$

Lyra & Lin (2013)

Gas distribution

$$\rho_g(a) = \rho_{g\,\max} \exp\left(-\frac{a^2}{2H_g^2}\right),$$

Maximum dust density

$$\rho_{d\,\max} = \varepsilon\, \rho_0\, (S+1)^{3/2}$$

Gas contrast

$$\frac{\rho_{g\,\max}}{\rho_{g\,\min}} = \exp\left[\frac{f^2(\chi)}{2\chi^2\omega_V^2}\right],$$

Dust contrast

$$\frac{\rho_{d\,\max}}{\rho_{d\,\min}} = \frac{\rho_{g\,\max}}{\rho_{g\,\min}} \exp(S),$$

Total trapped mass

$$\int \rho_d(a,z)dV = (2\pi)^{3/2}\, \varepsilon \rho_0\, \chi H H_g^2$$

Vortex size

$$a_s = H(\chi\omega_V)^{-1}$$

H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function
ε = dust-to-gas ratio

Applying the model to Oph IRS 48

Observed parameters

Aspect ratio: 3.1

Dust contrast: 130

Temperature: 60K

Trapped mass: 9 M_{Earth}

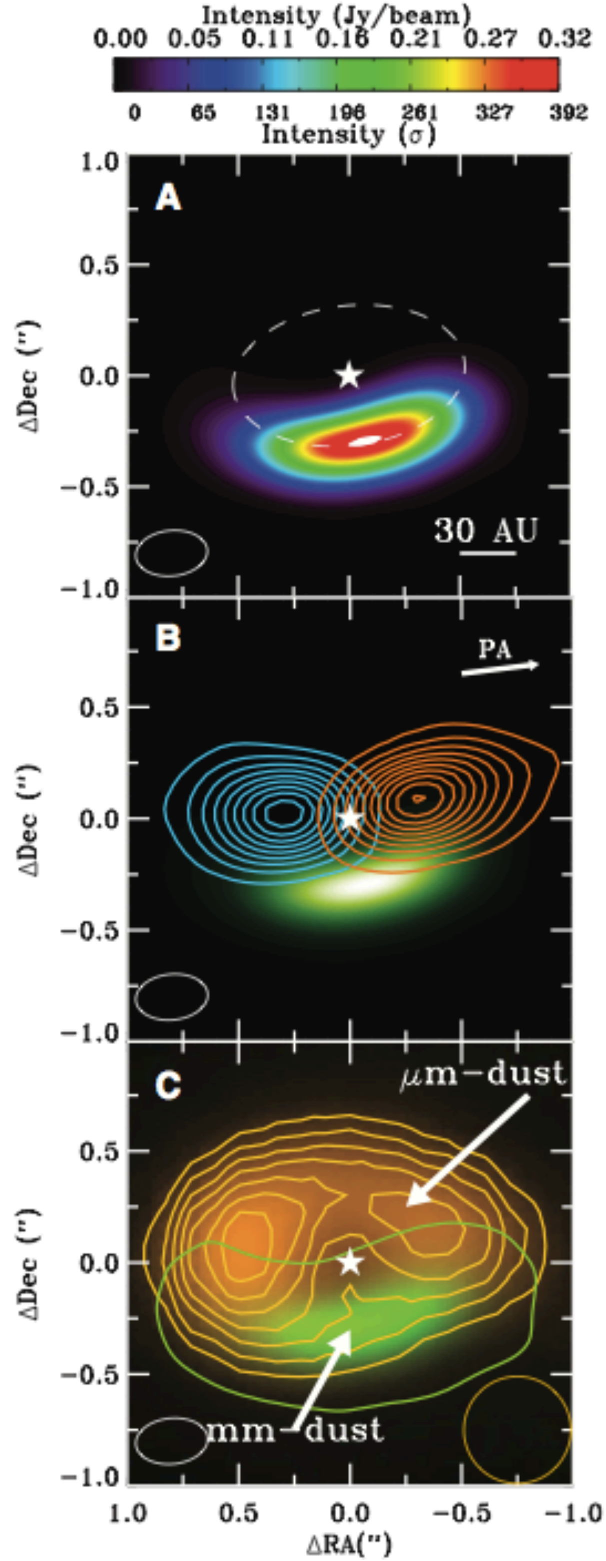
Derived parameters

S=4.8

Stokes number, St=0.008

$\delta = 0.005$, $v_{rms} = 4\% \, c_s$

Trapped mass: 11 M_{Earth}



asymmetric mm dust at 63 AU

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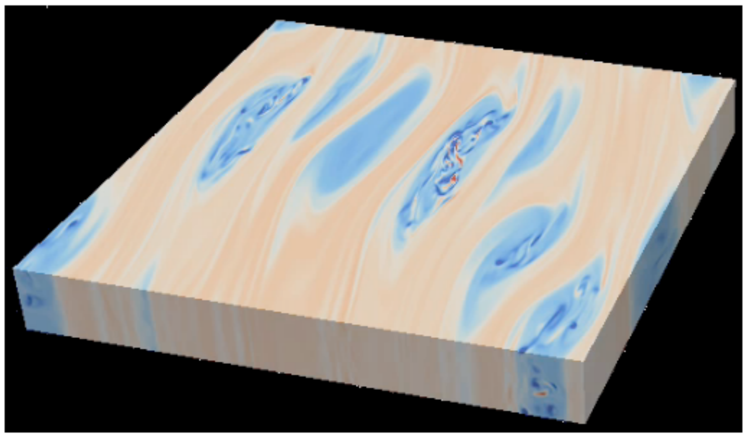
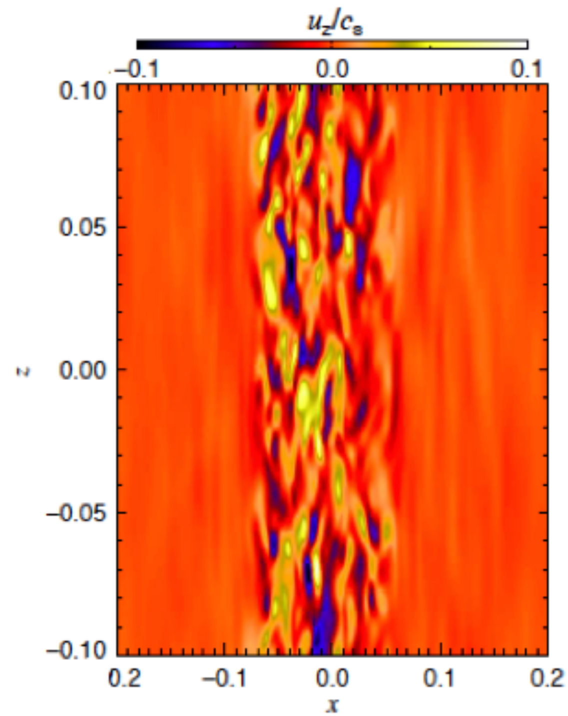
Lyra & Lin (2013)

Turbulence in vortex cores



Lesur & Papaloizou (2010)

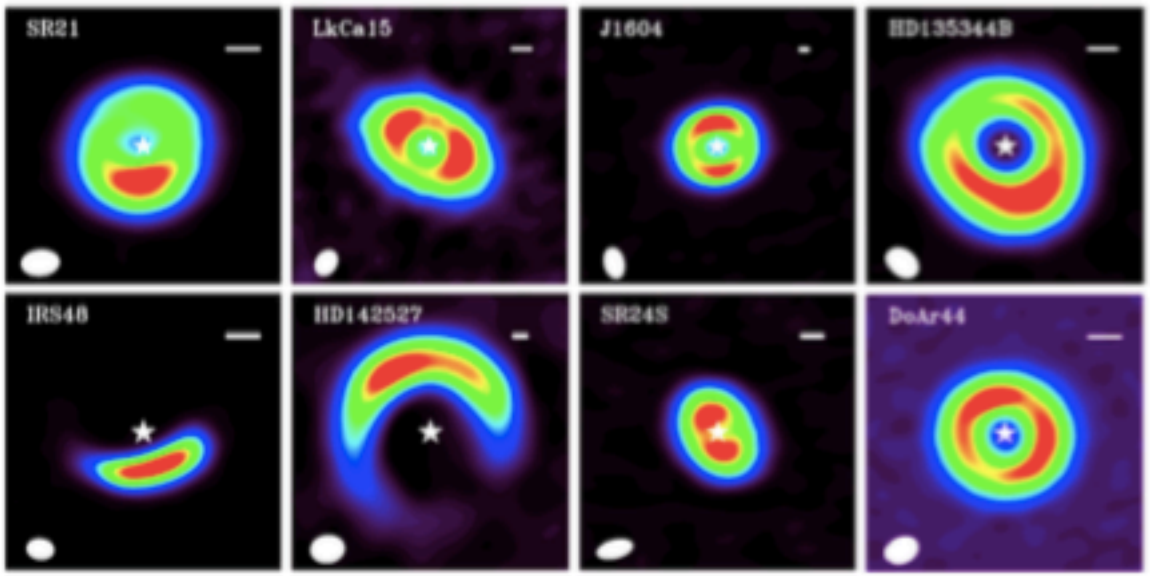


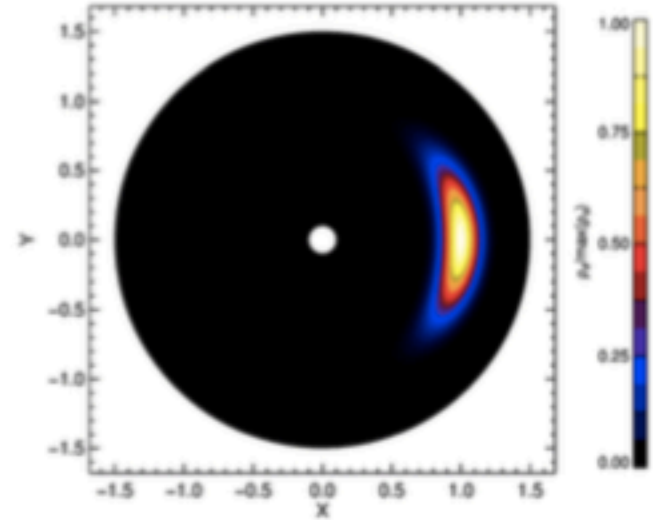
Lyra & Klahr (2011)

Turbulence in vortex cores:

max at ~10% of sound speed
rms at ~3% of sound speed

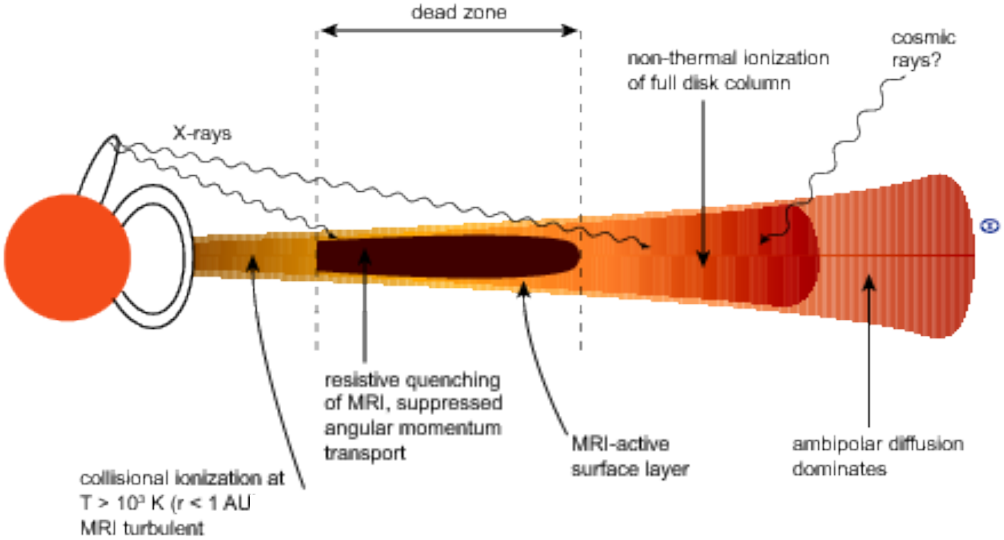
Observed asymmetries consistent with vortices...



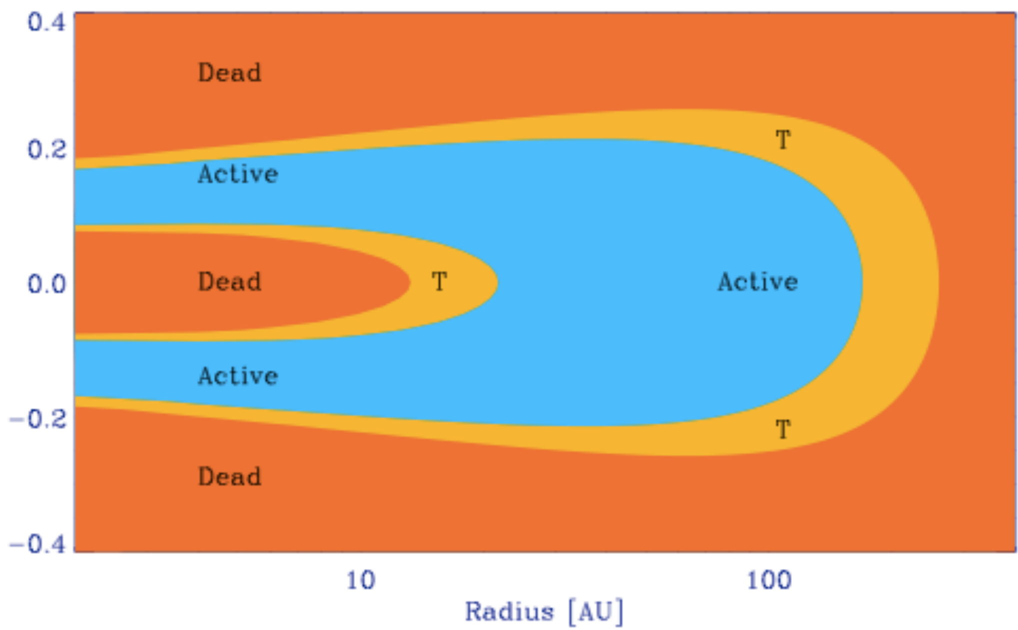


But origin still elusive...

Outer Dead/Active zone transition KHI



Armitage (2010)



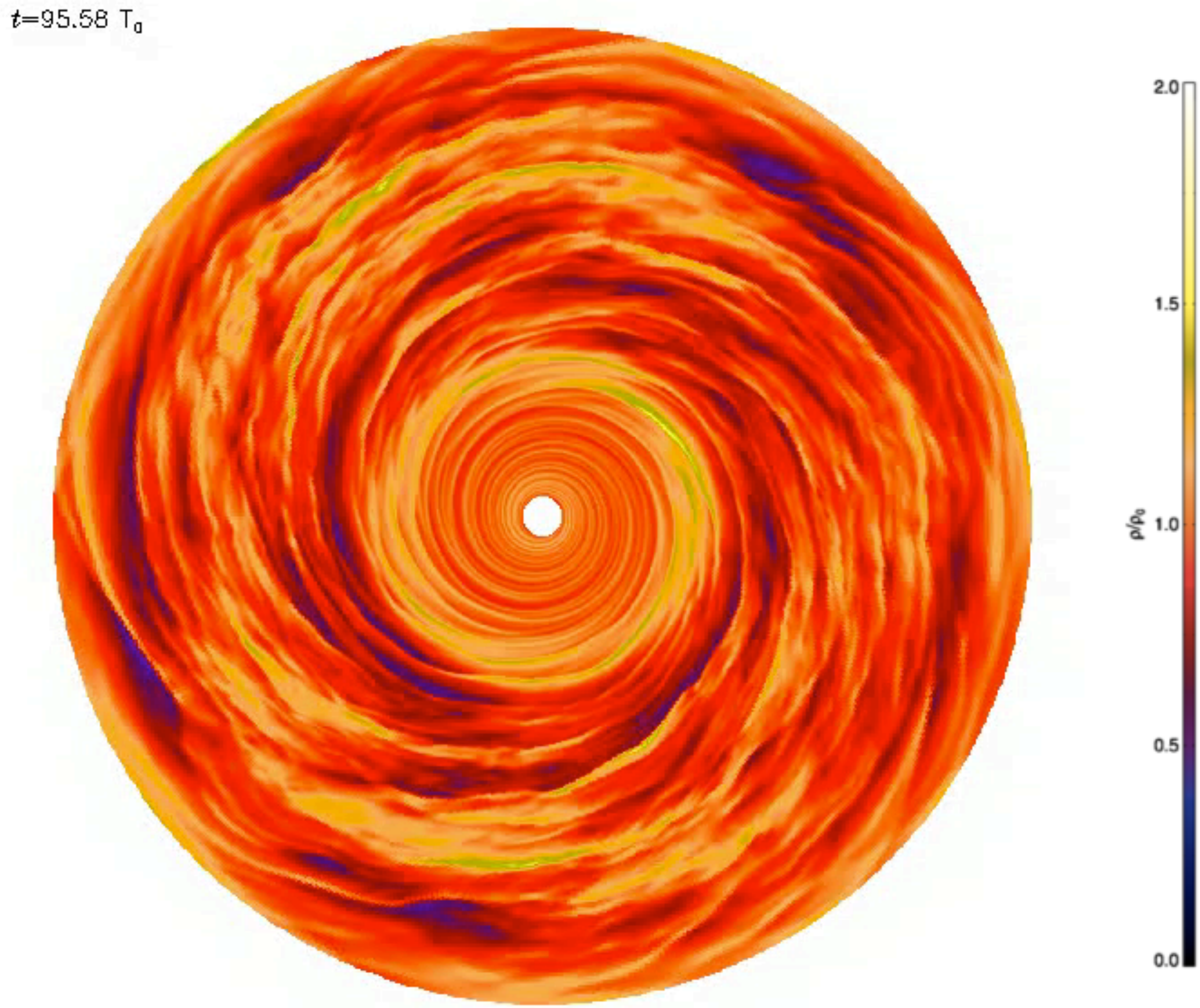
Dzyurkevitch et al (2013)

The **outer** dead zone transition in ionization supposed

TOO SMOOTH

to generate an KH-unstable bump.

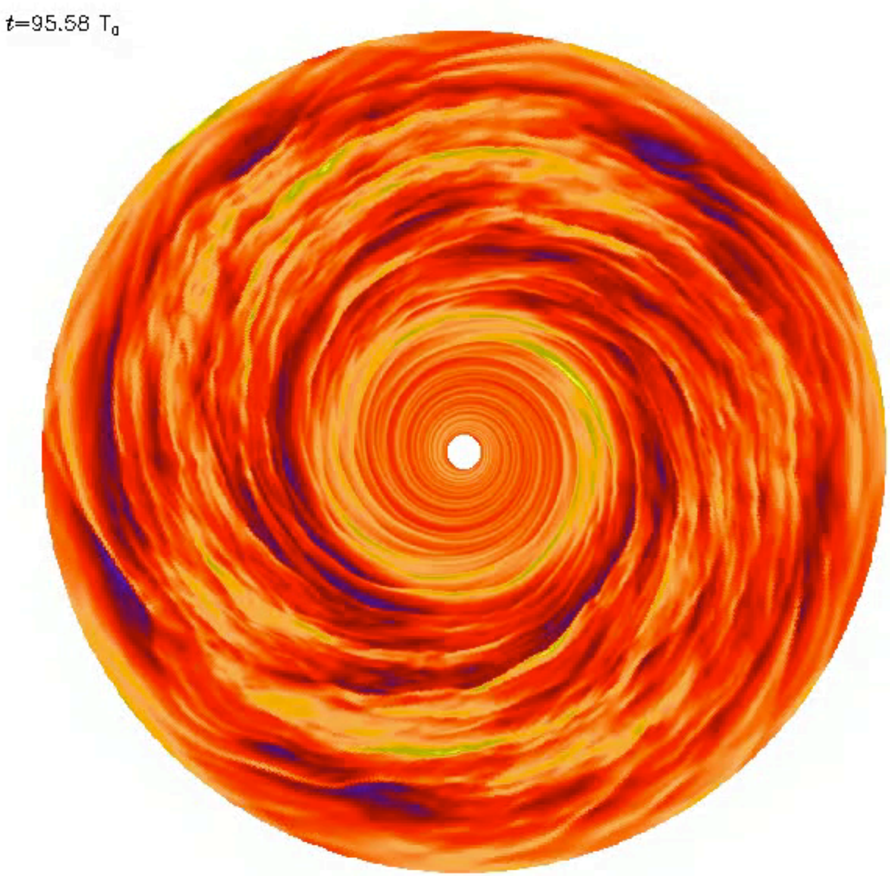
Outer Dead/Active zone transition: 3D MHD

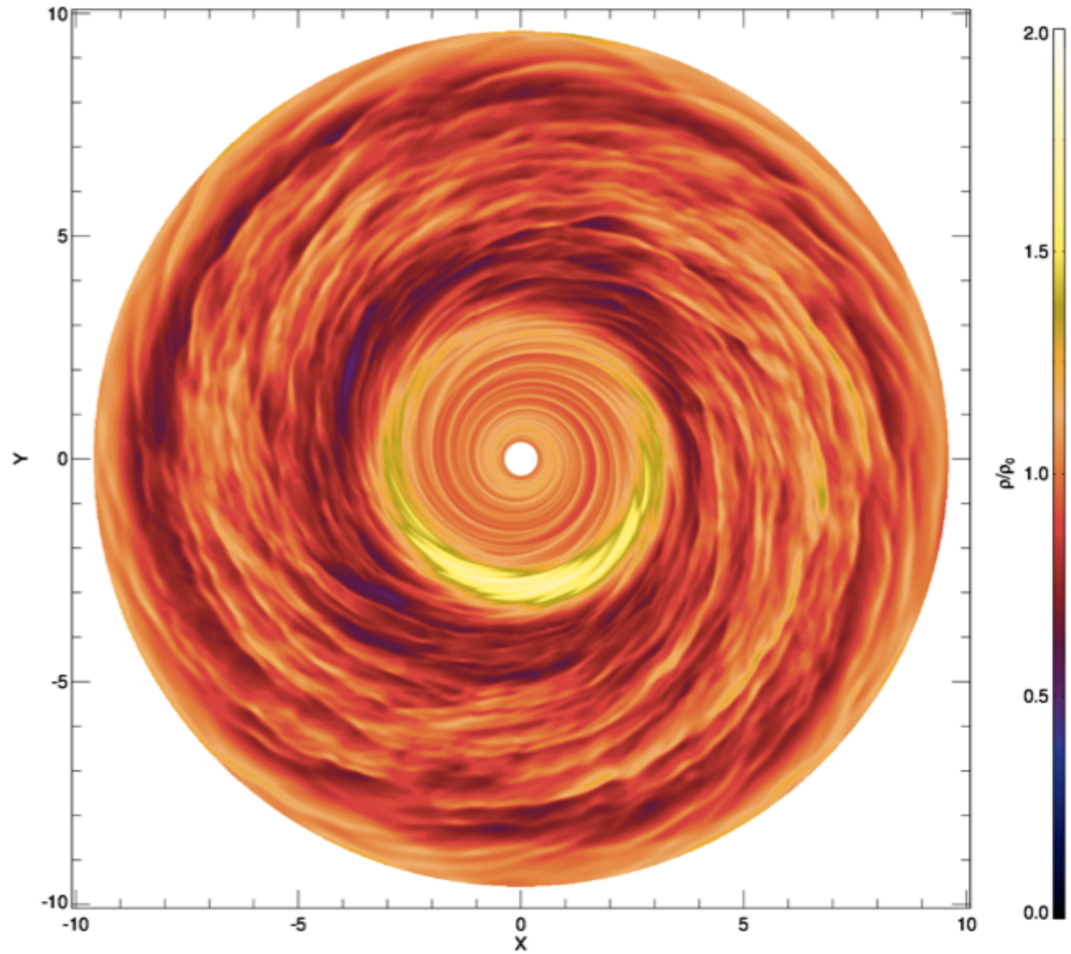


Resistive inner disk + magnetized outer disk

Lyra et al (2015)

Outer Dead/Active zone transition KHI

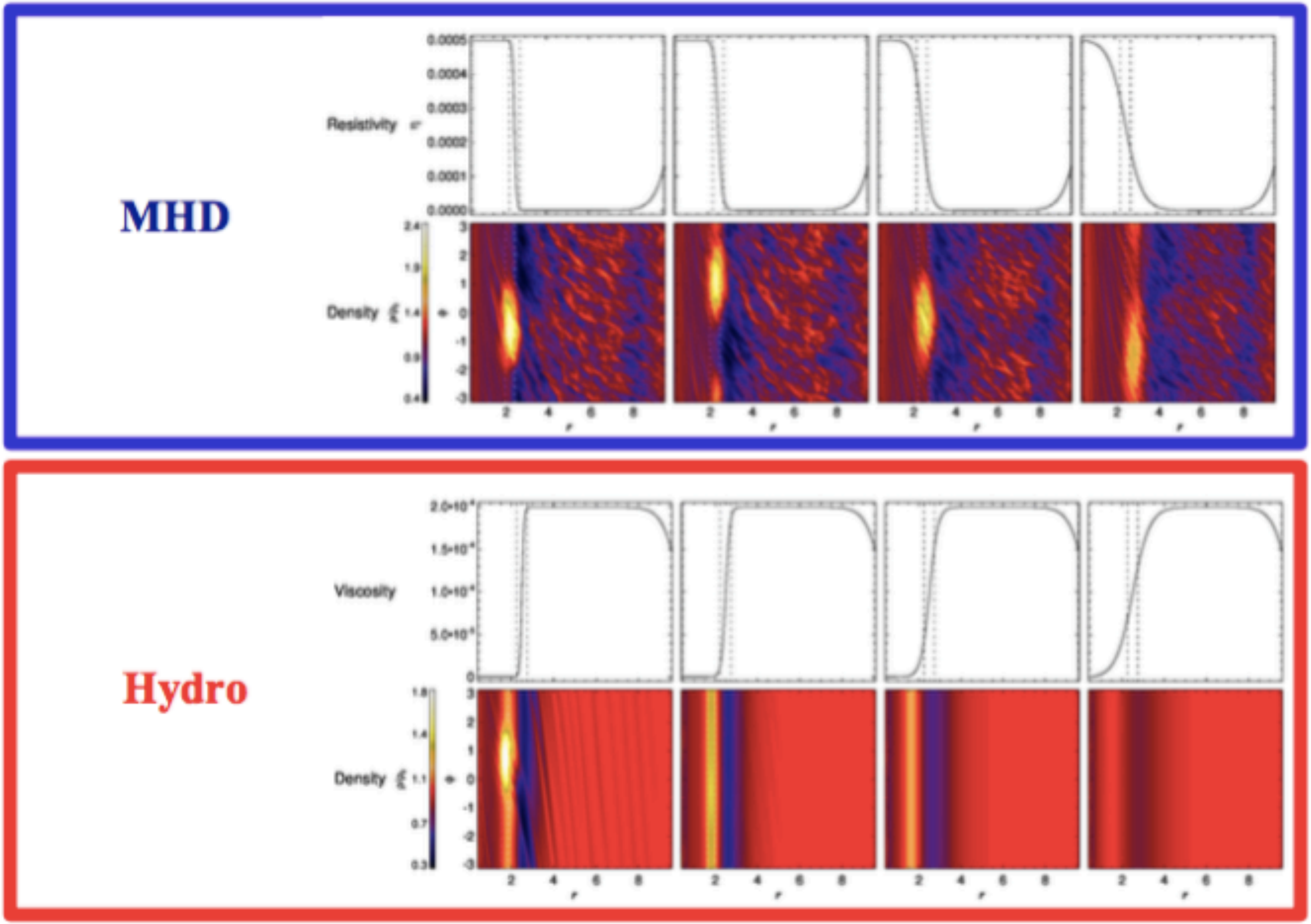




Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)

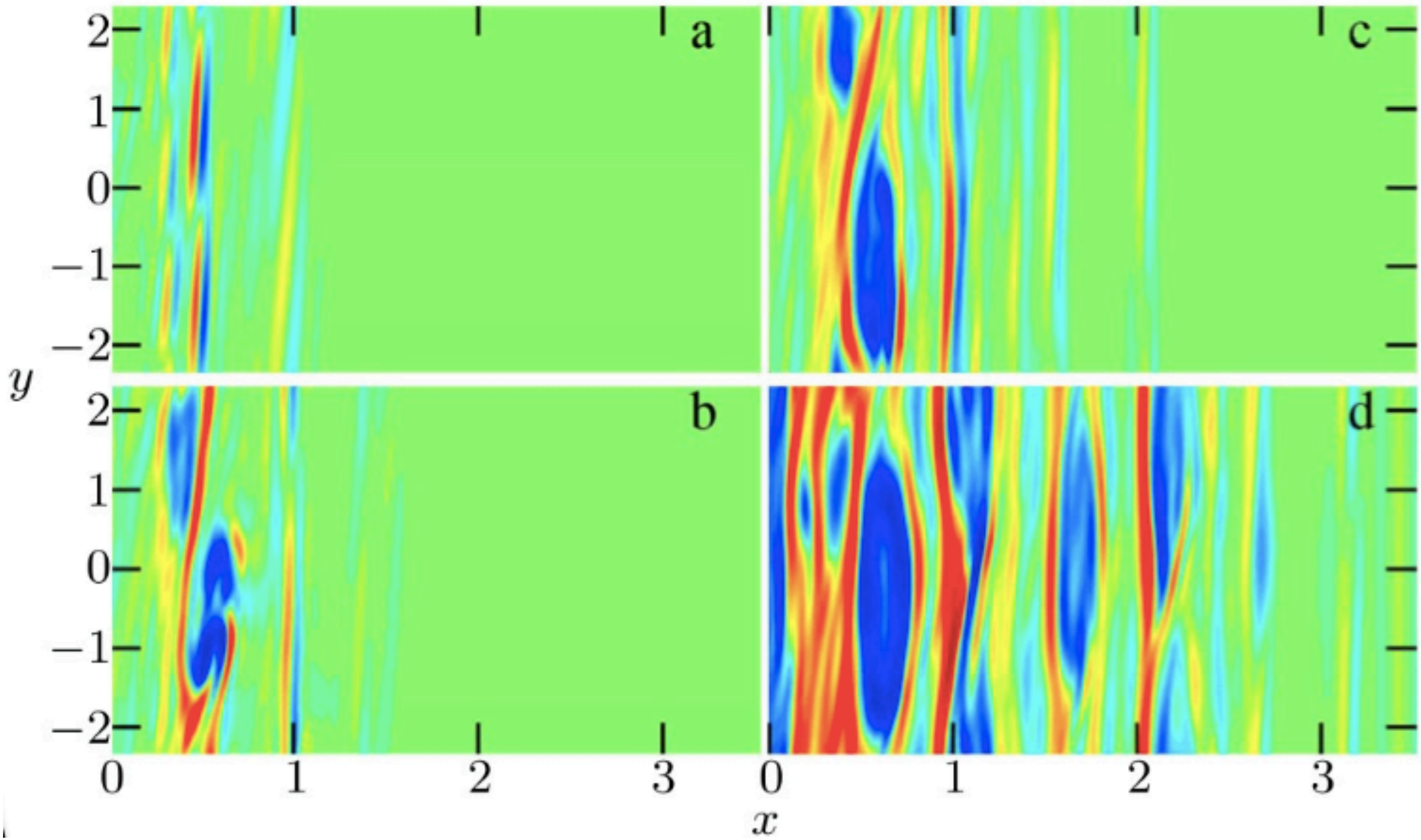
Outer Dead/Active zone transition RWI



Lyra, Turner, & McNally (2015)

Other Dead Zone Instabilities

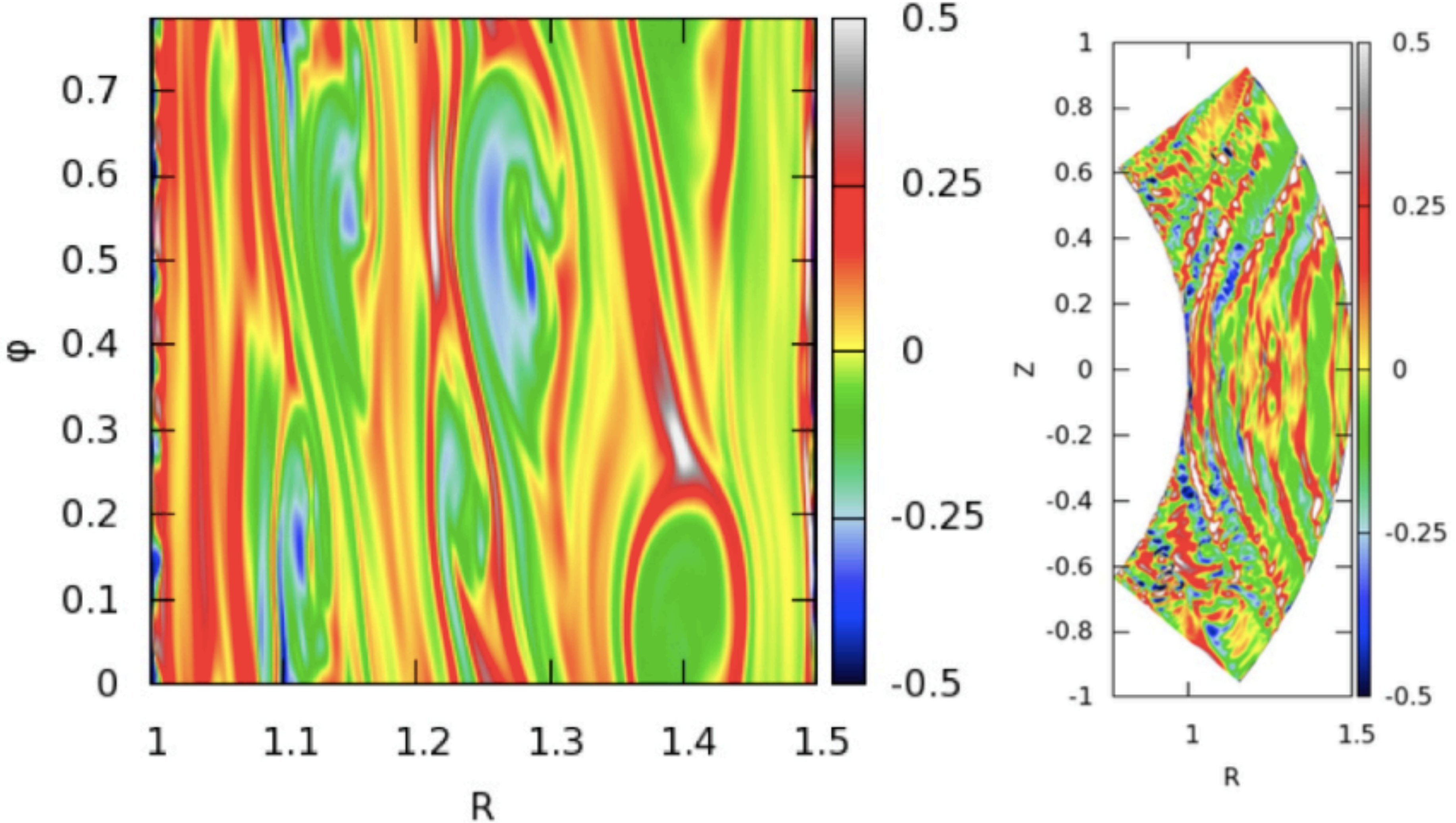
Zombie Vortex Instability



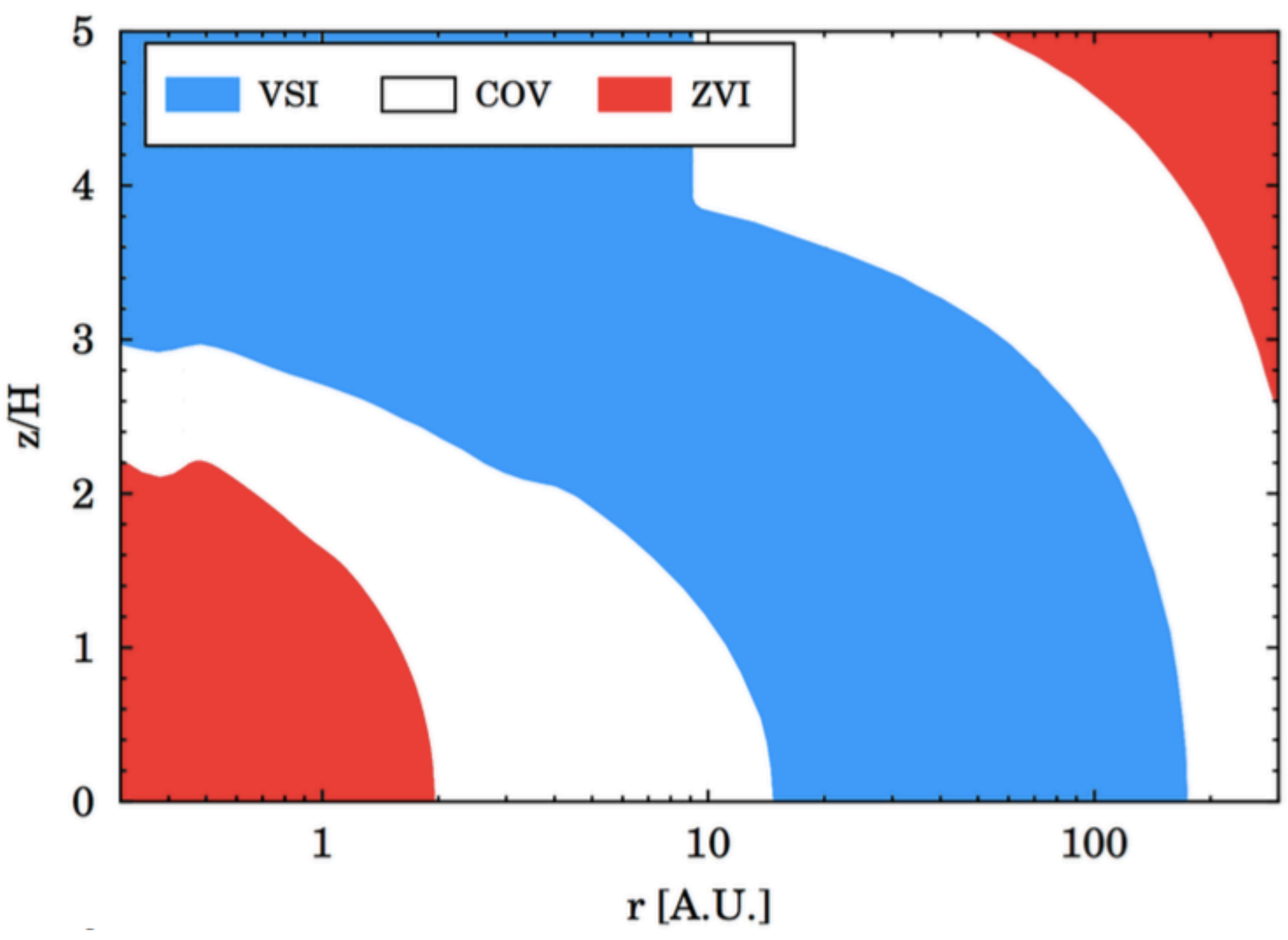
Marcus et al. (2015, 2016)

Other Dead Zone Instabilities

Vertical Shear Instability

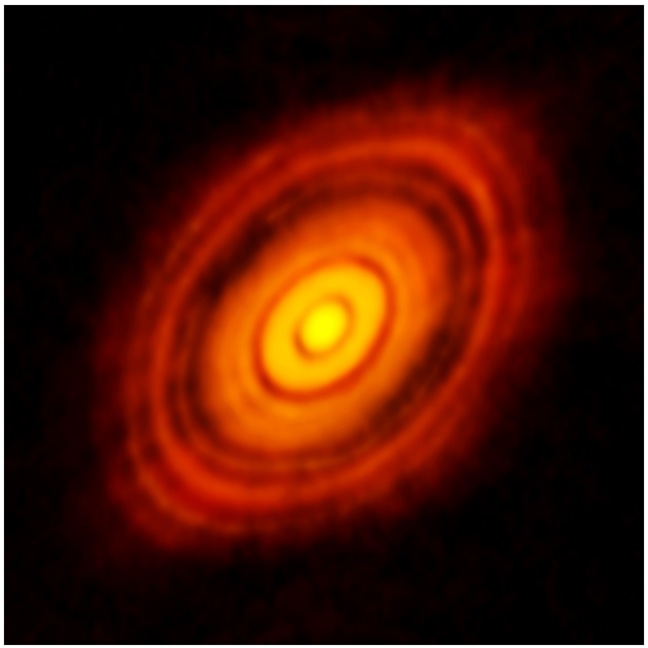


Nelson et al. (2013)

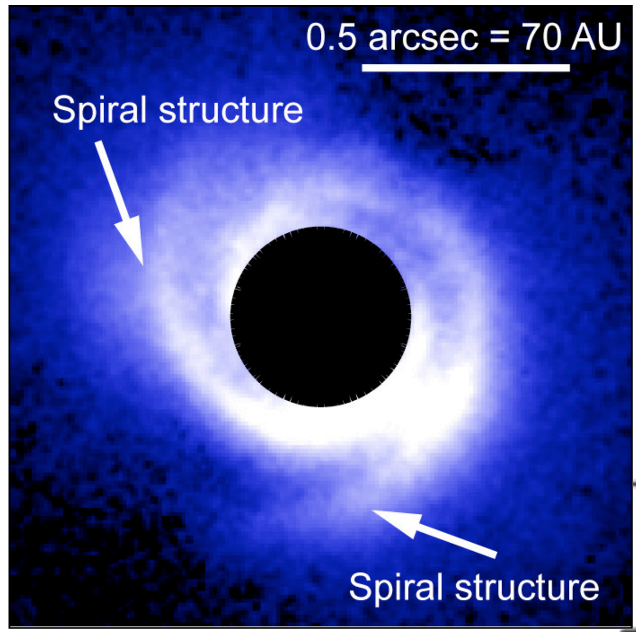

VSI
COV
ZVI
5
4
3
2
1
0
z/H
1
10
100
r [A.U.]

Observational evidence: gaps, spirals, and vortices

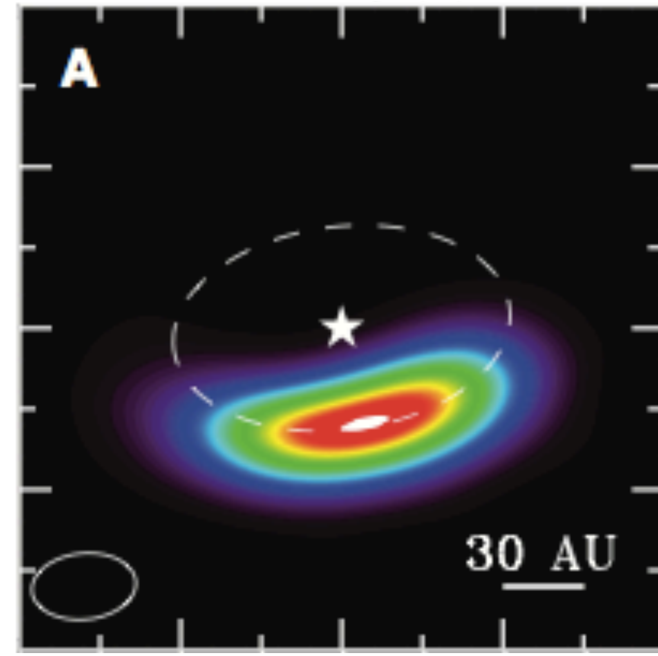
HL Tau



SAO 206462

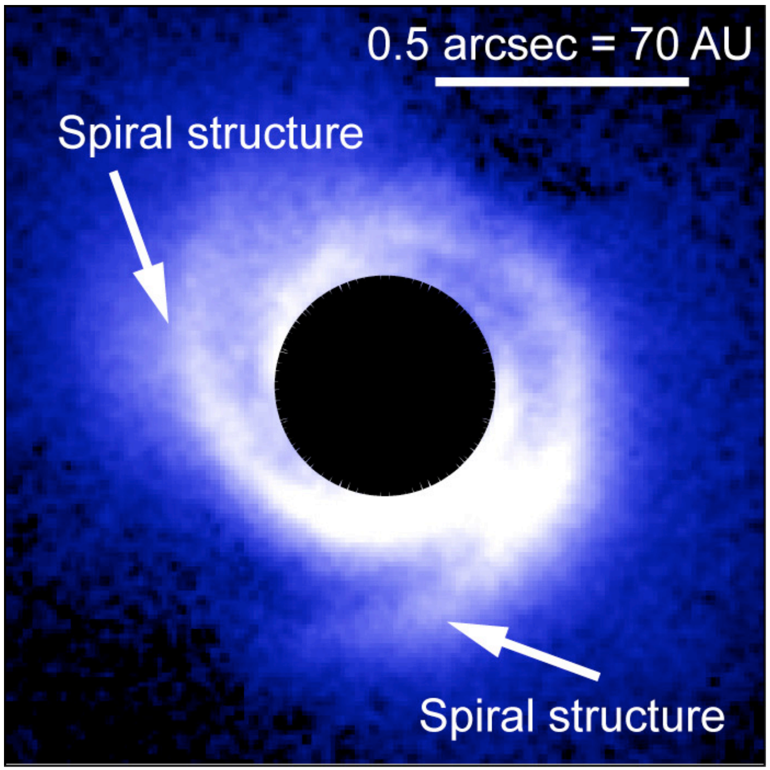


Oph IRS 48



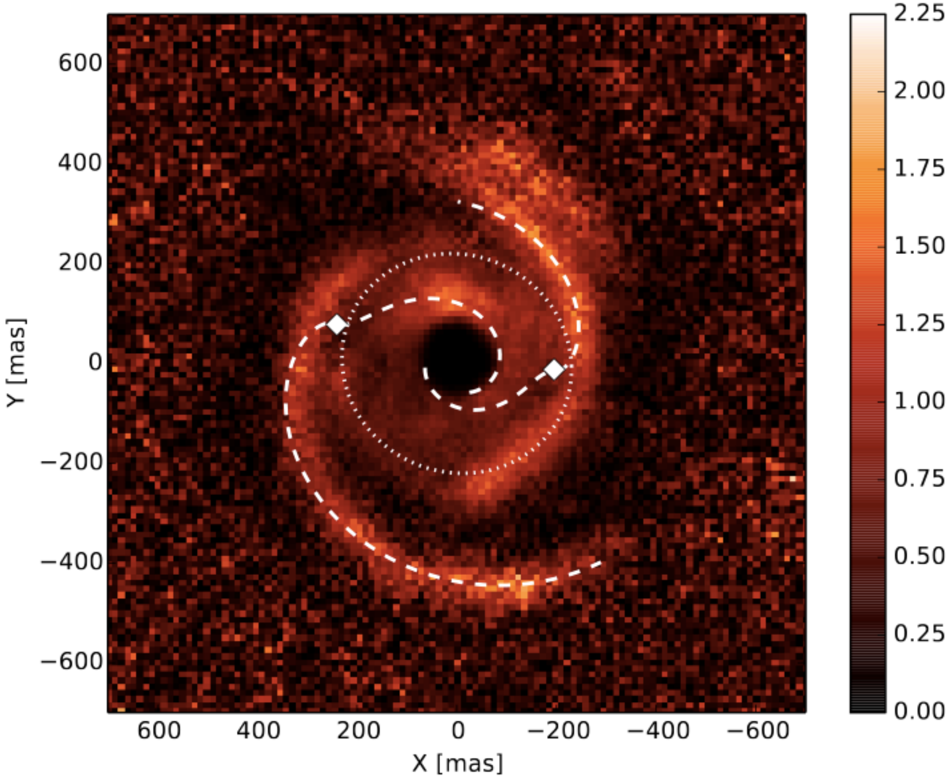
Observational evidence: Spirals

SAO 206462



Muto et al. (2012)

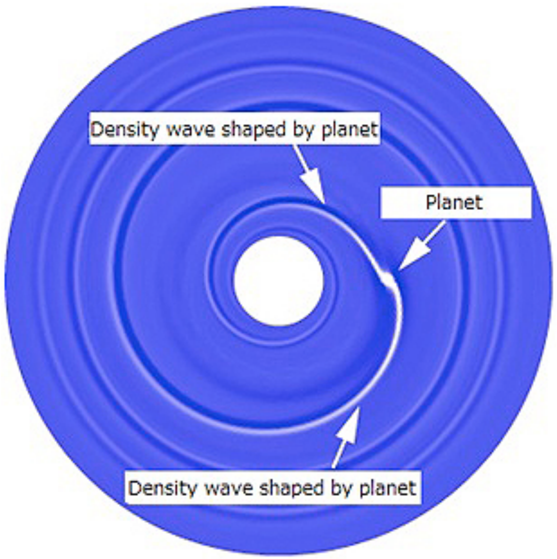
MWC 748



Benisty et al. (2015)

Spiral arm fitting leads to problems

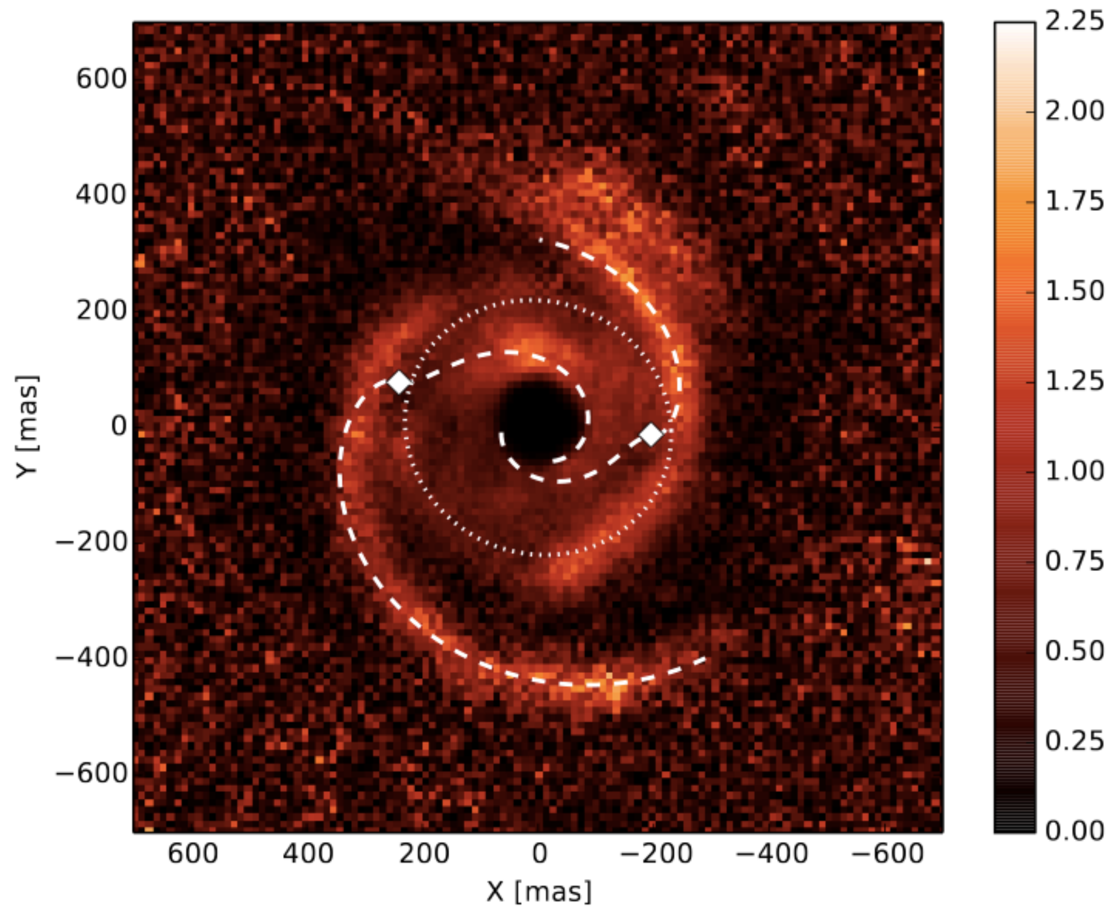
Analytical spiral fit



$$\theta(r) = \theta_c + \frac{\mathrm{sgn}(r - r_c)}{h_c} \times \left\{ \left(\frac{r}{r_c}\right)^{1+\beta} \left[\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta}\left(\frac{r}{r_c}\right)^{-\alpha}\right] - \left(\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta}\right)\right\},$$

Rafikov (2002)
Muto et al. (2012)

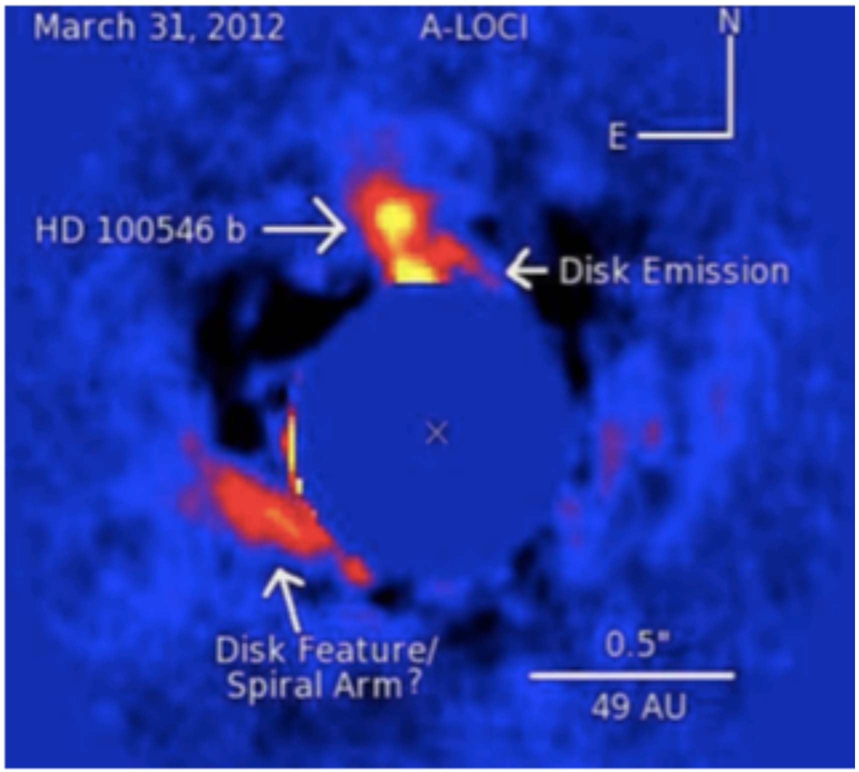
Spirals are **too wide**,
hotter (300K) than ambient gas (50K).



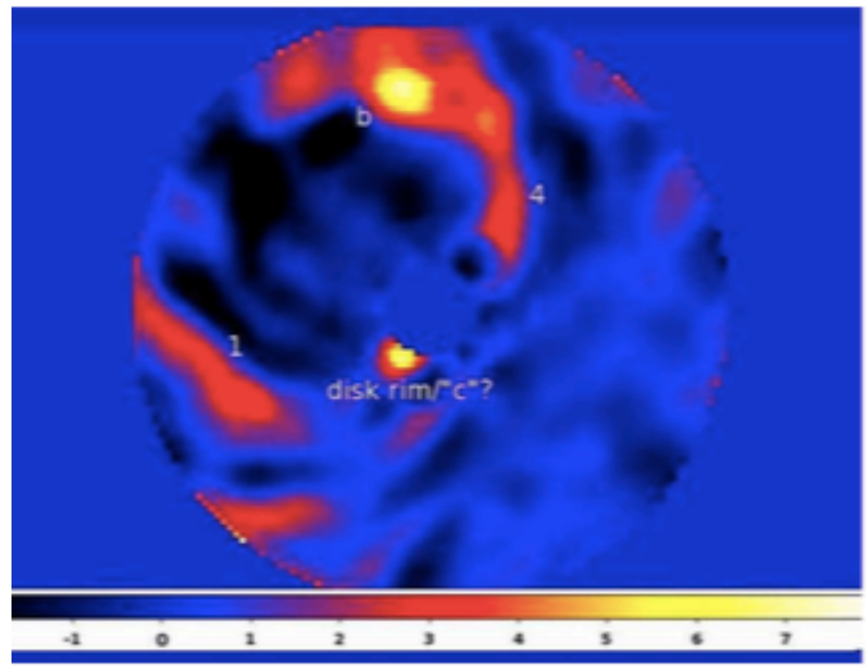
Benisty et al. (2015)

The strange case of thermal emission in HD 100546

L band (~3.5 μm)

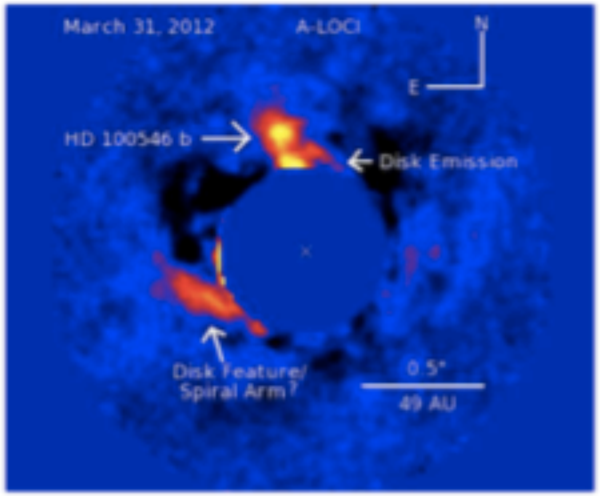


H band (~1.6 μm)

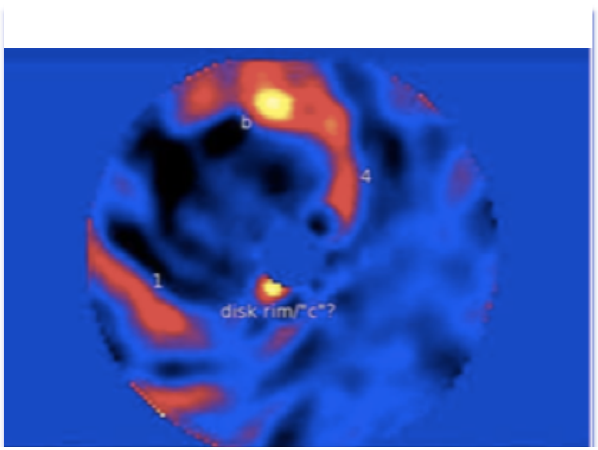


Currie et al. (2014), Currie et al. (2015)

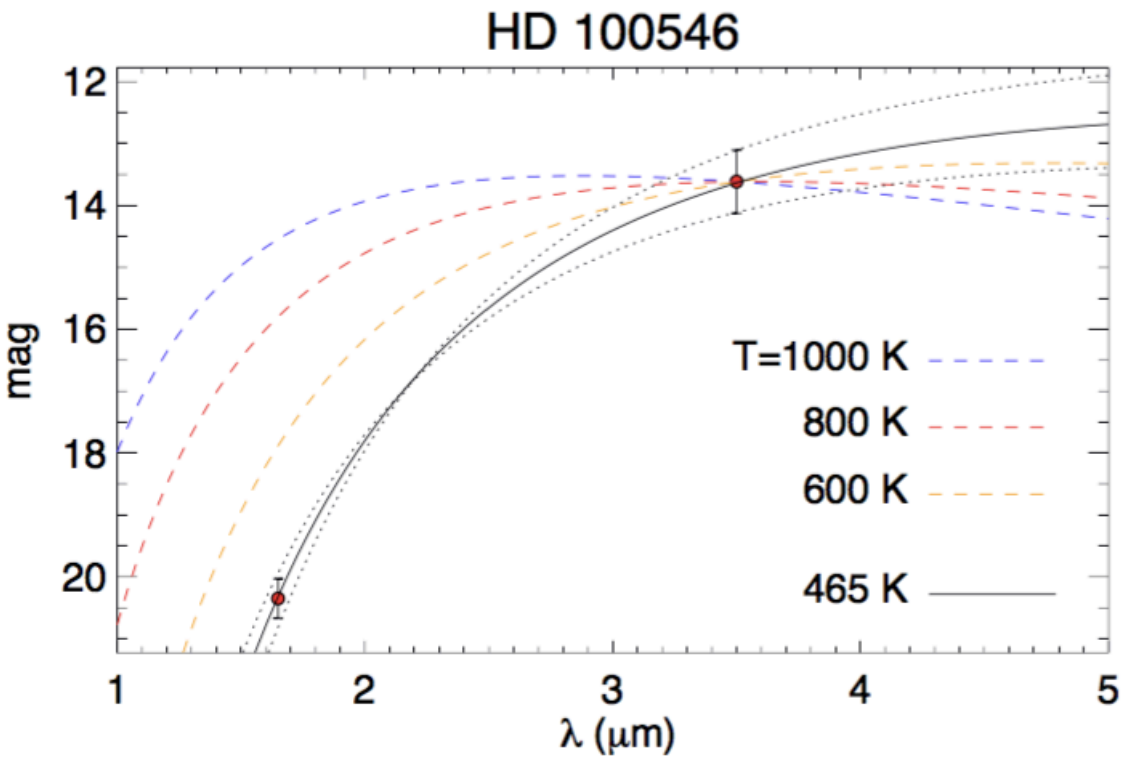
Pinning down the temperature



L band

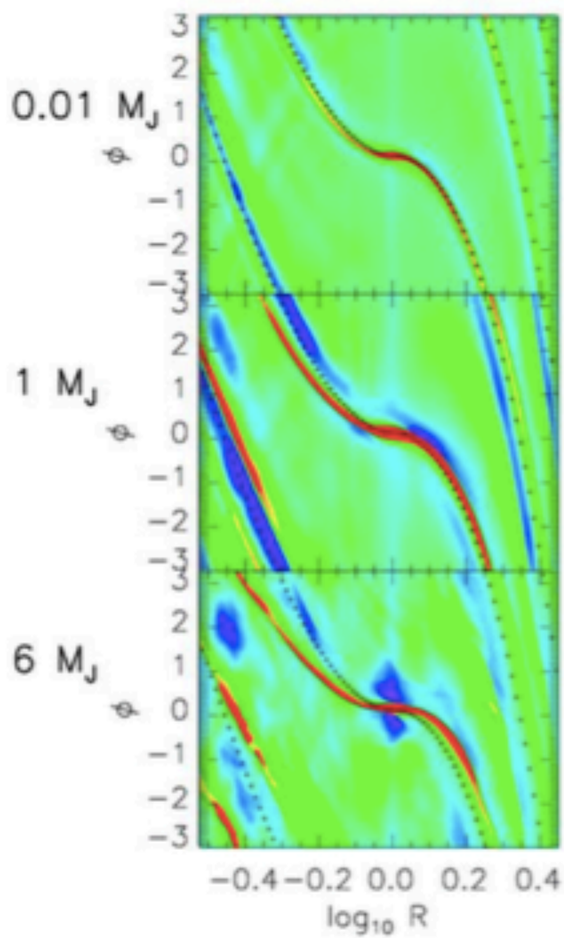


H band



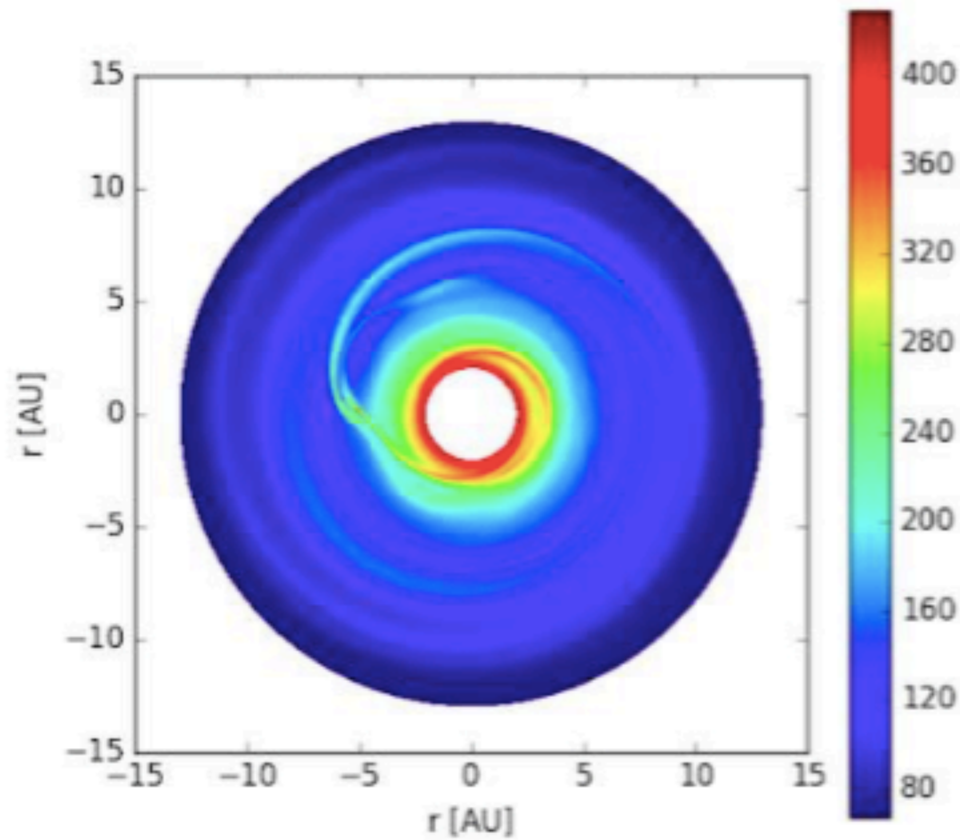
Lyra et al. (2016)

Supersonic Wakes of High Mass Planets



Density

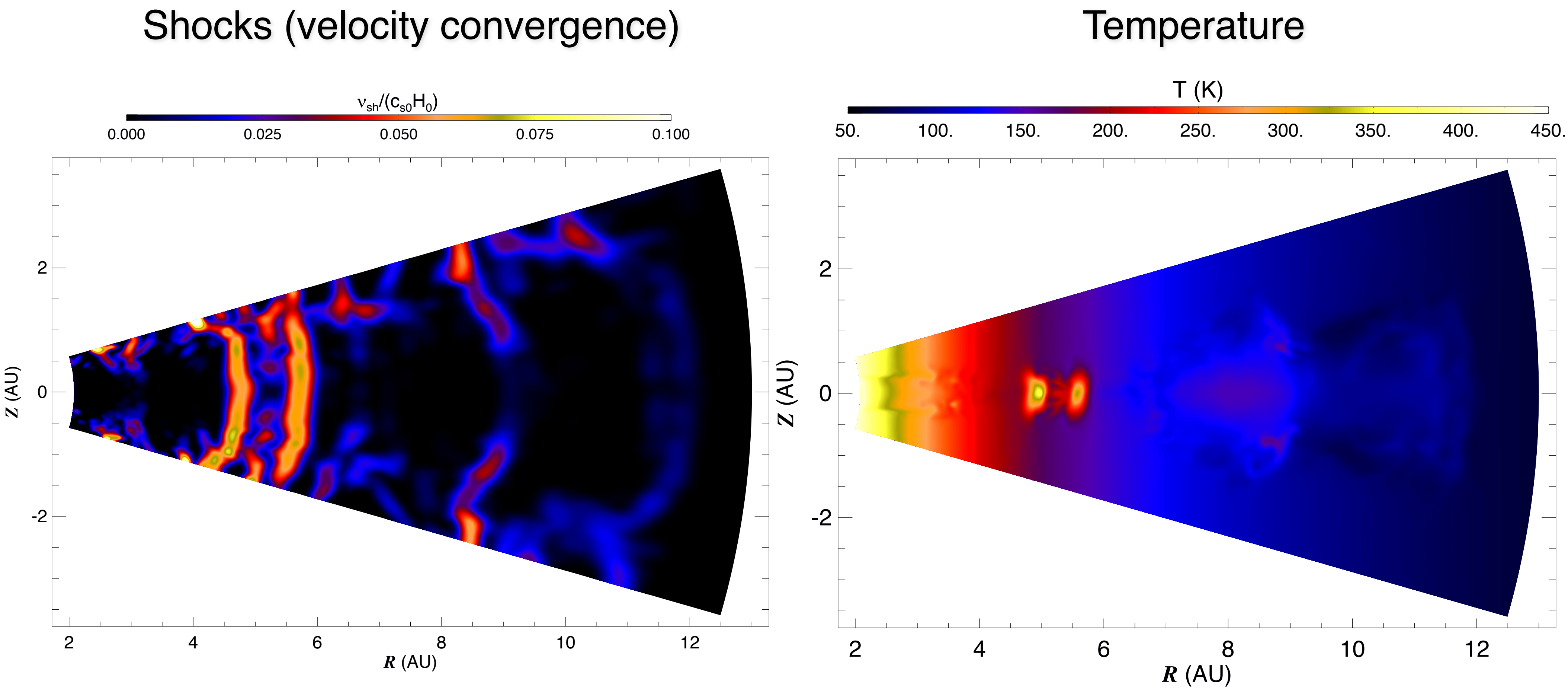
Zhu et al. (2015)



Temperature - **5M$_J$**

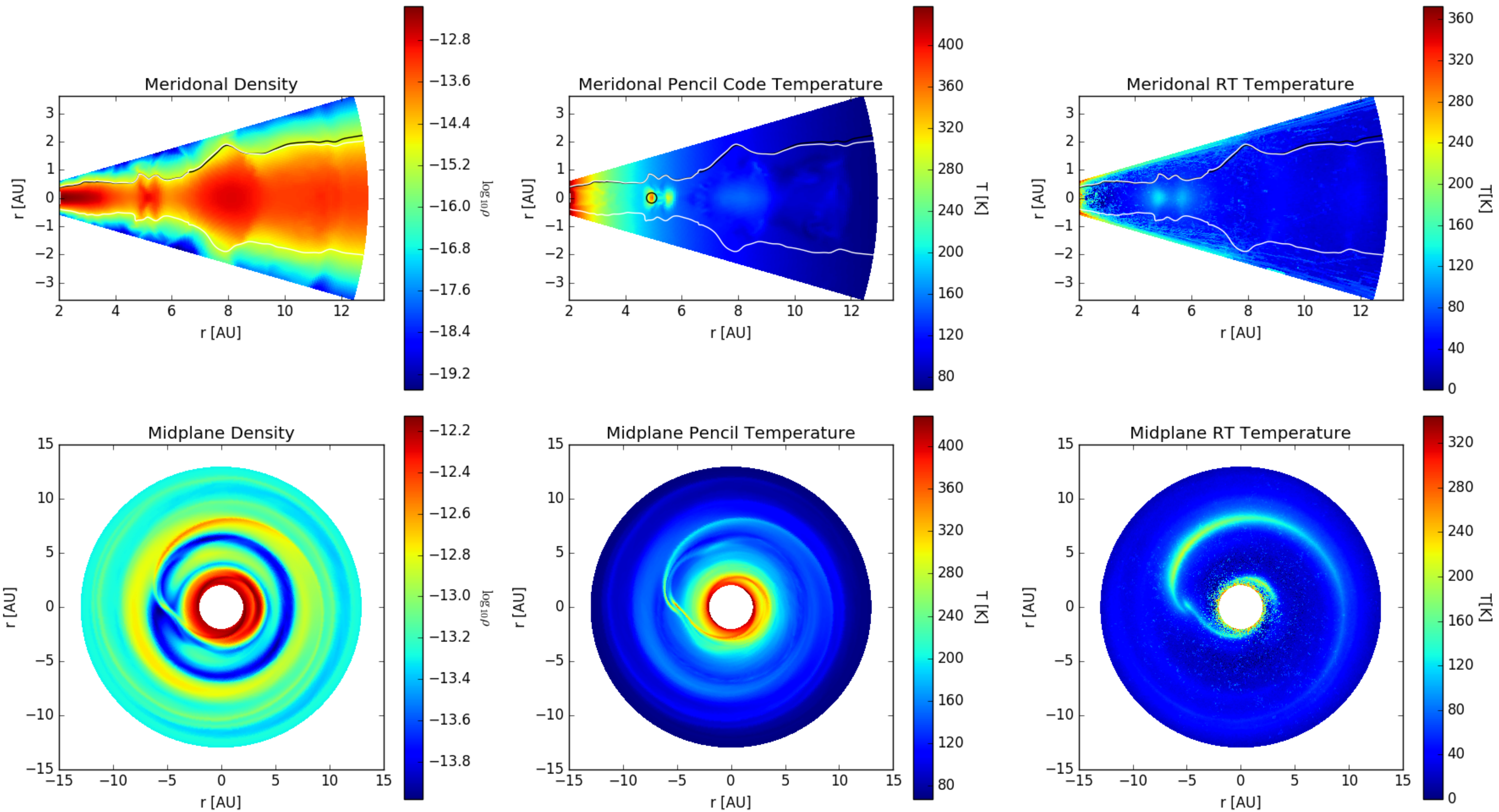
Lyra et al. (2016)

Shock bores



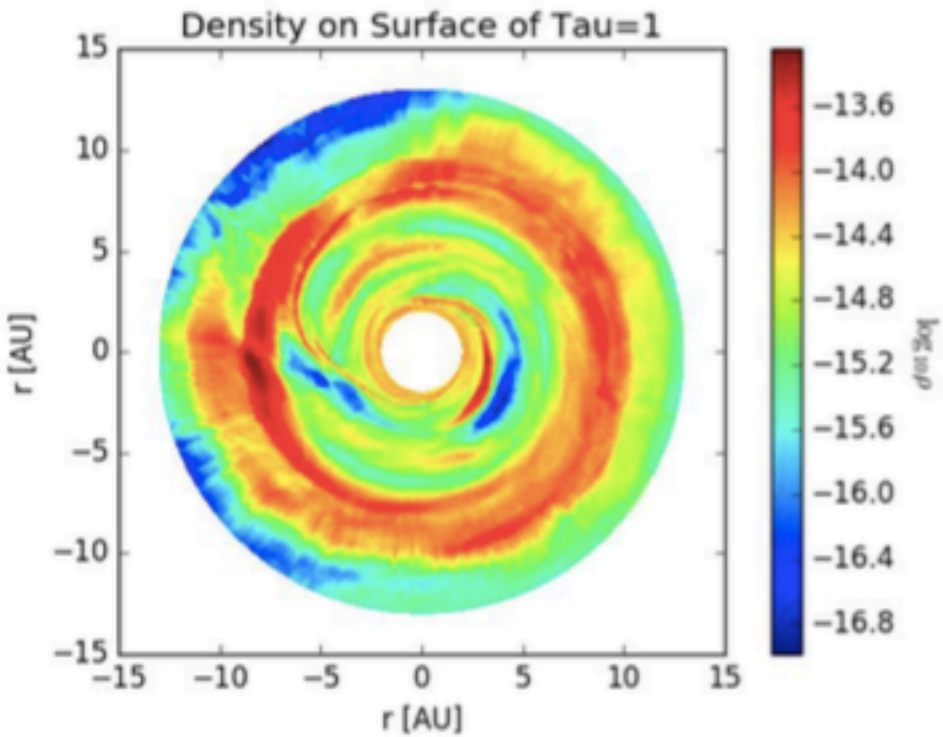
Lyra et al. (2016)

Radiative Transfer post-processing

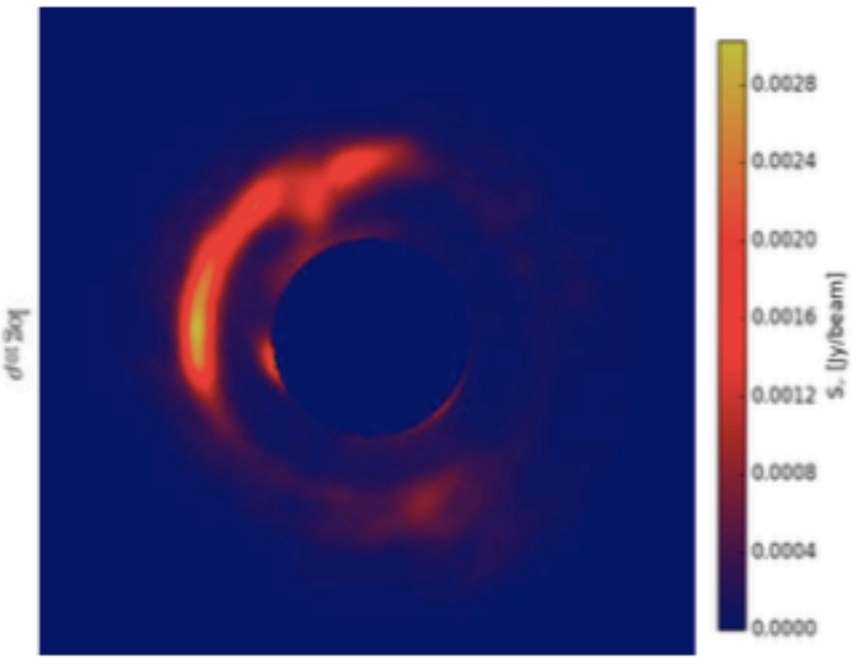


Hord et al. (2016, in prep)

Scattering in Image



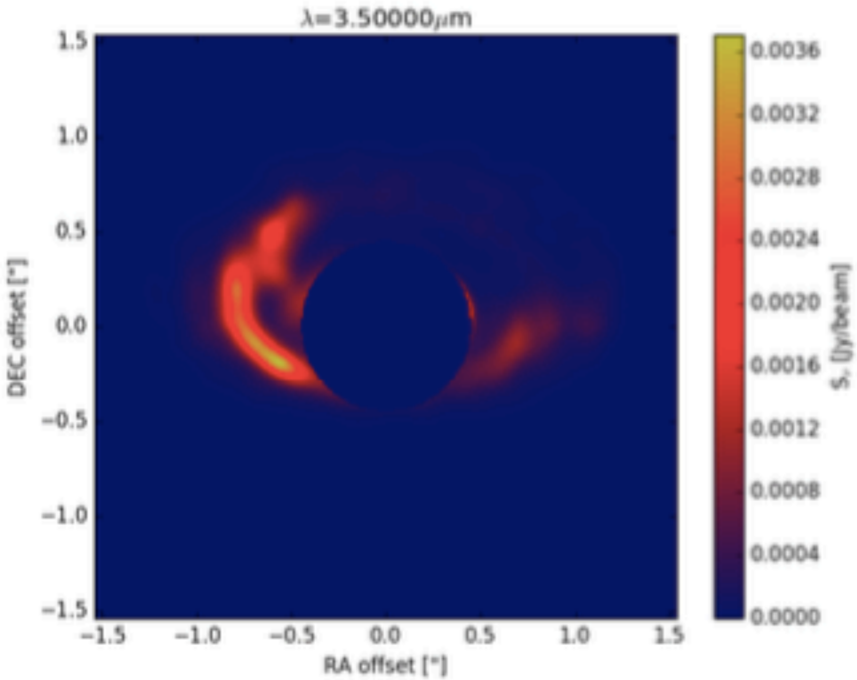
Light scattered off **gap outer edge**

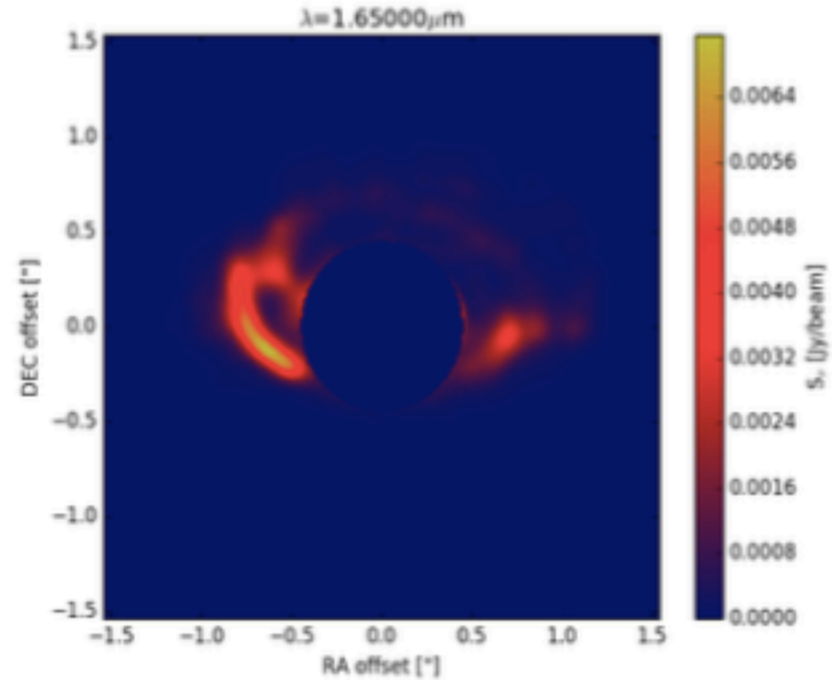


"Bird's eye view" synthetic image

Hord et al. (2016, in prep)

Synthetic Images





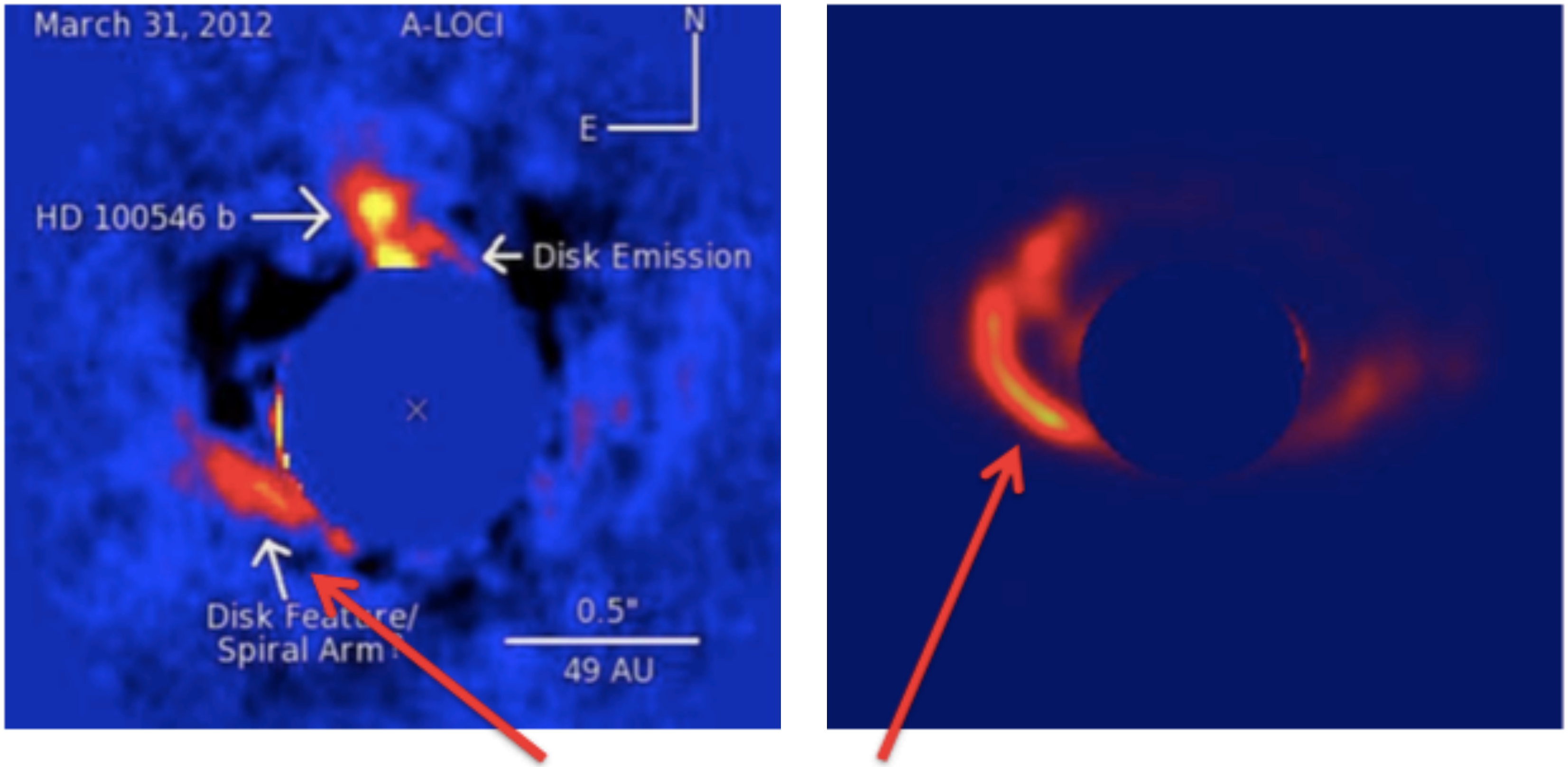
λ = 3.5 microns (**L' Band**) λ = 1.65 microns (**H Band**)

Made with 138 degree position angles and 50 degree inclination angles to match Currie et al. (2014) observations.

Disk scaled by factor of 10 to map T Tauri 5 AU to Herbig Ae 50 AU

Hord et al. (2016, in prep)

Comparison

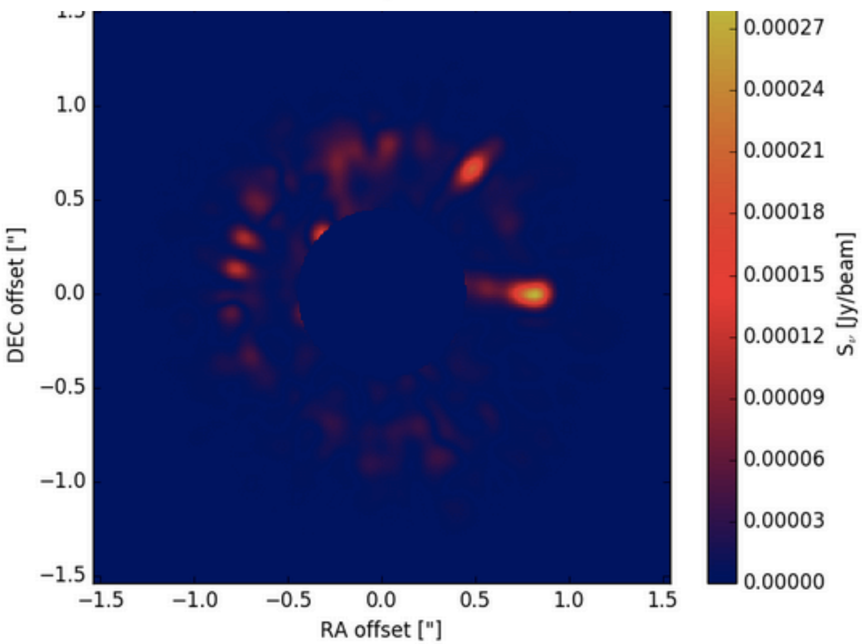


Matching general morphologies

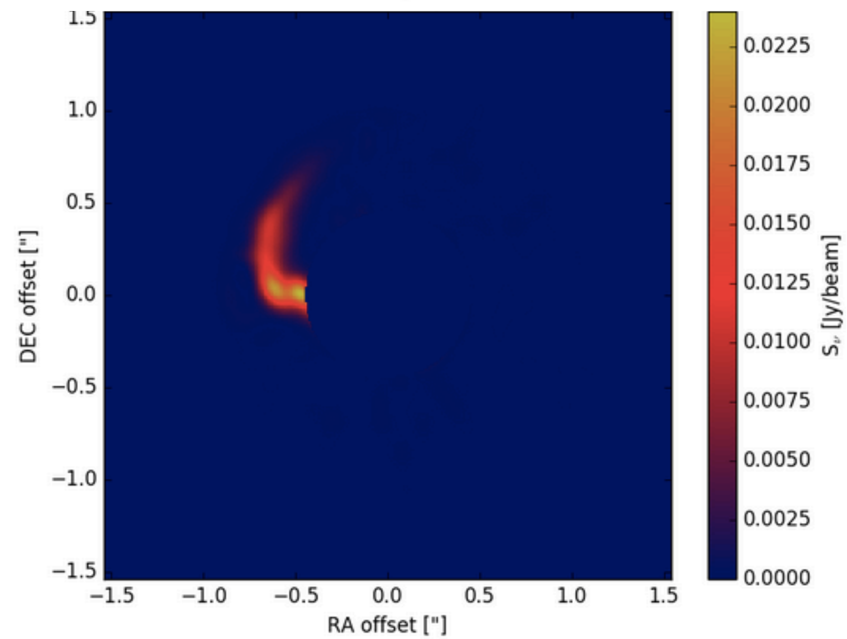
Hord et al. (2016, in prep)

Effect of shocks alone

1 μm

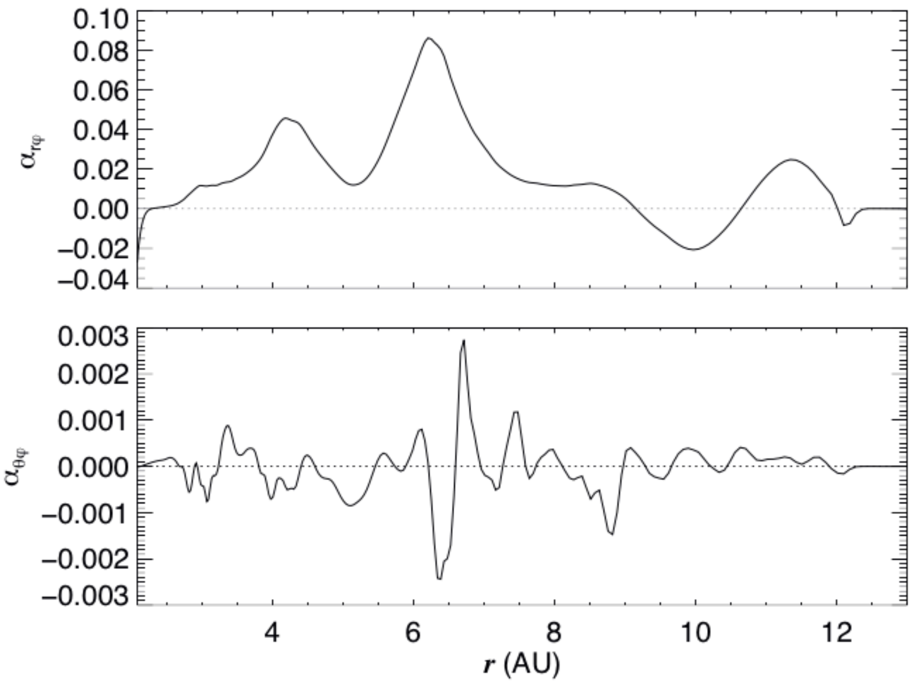


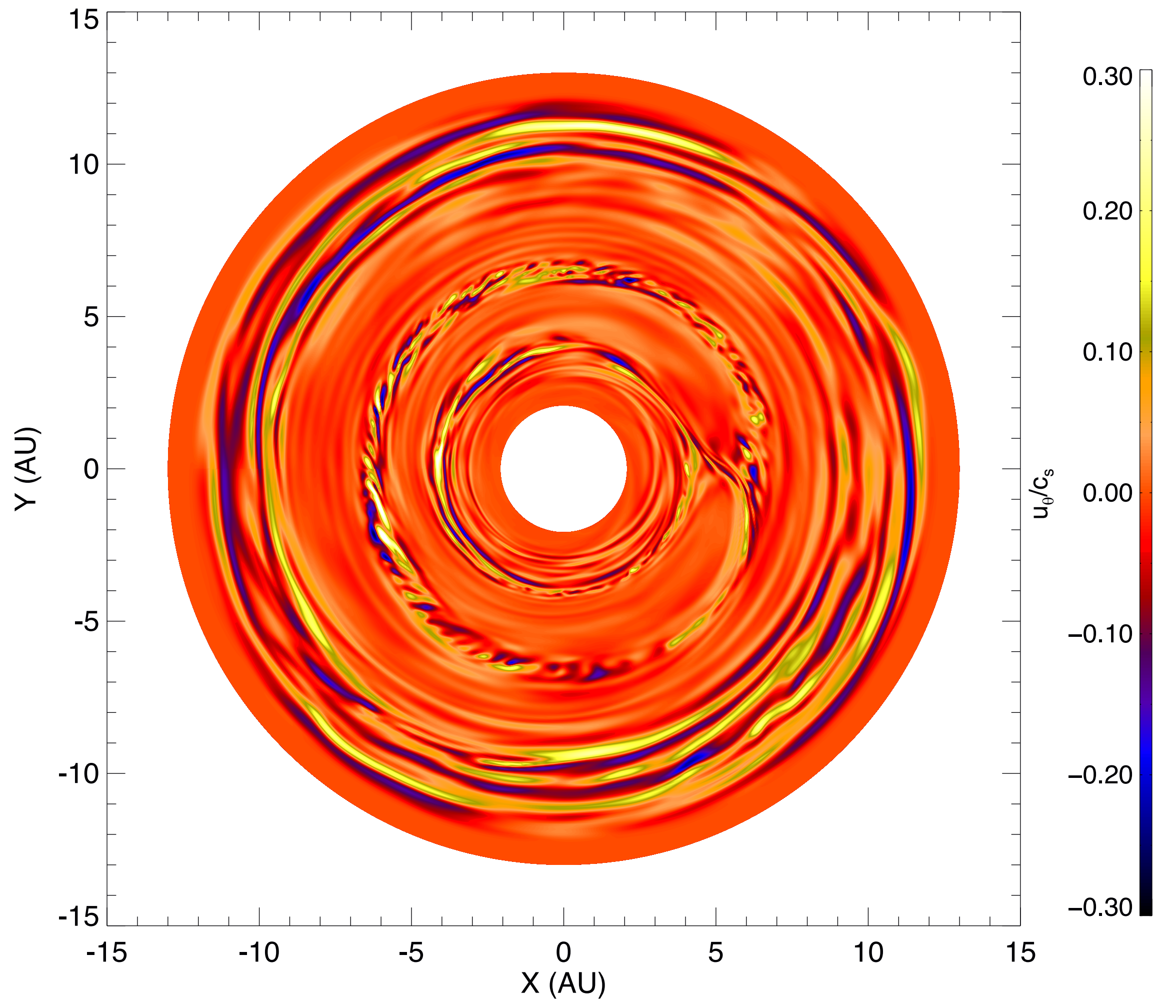
10 μm



Hord et al. (2016, in prep)

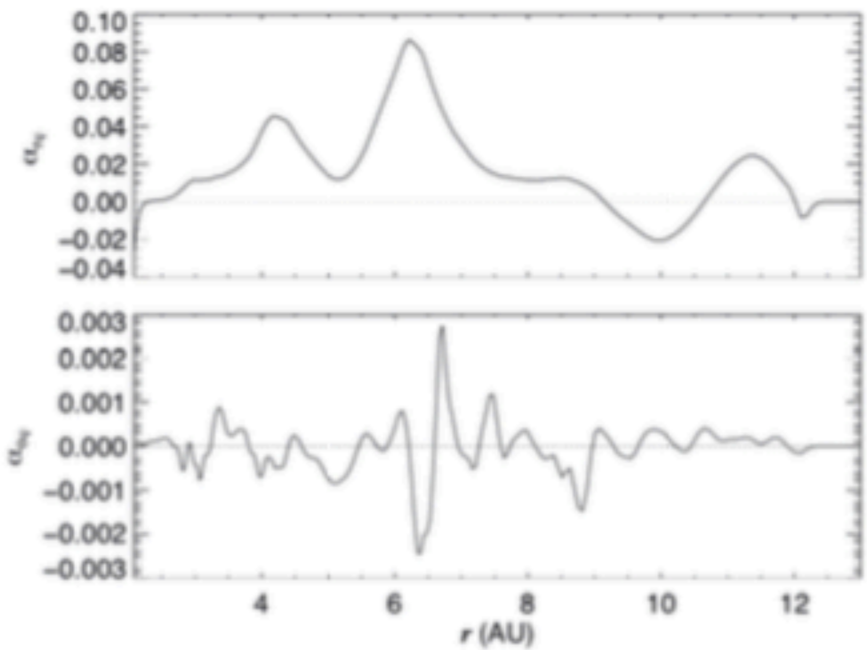
Prediction for spectroscopy: Turbulent surf

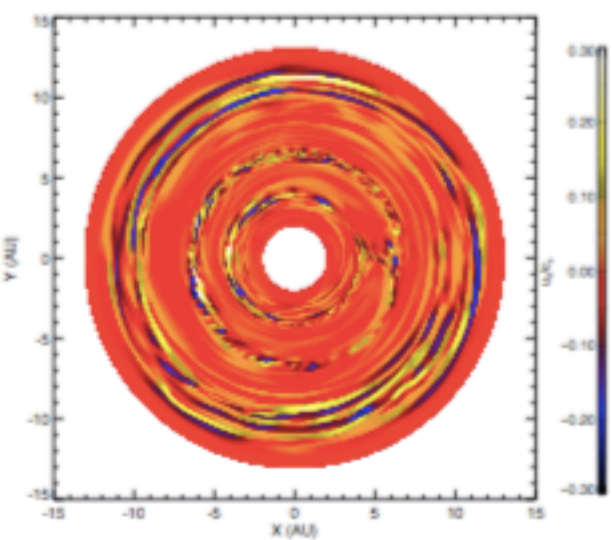


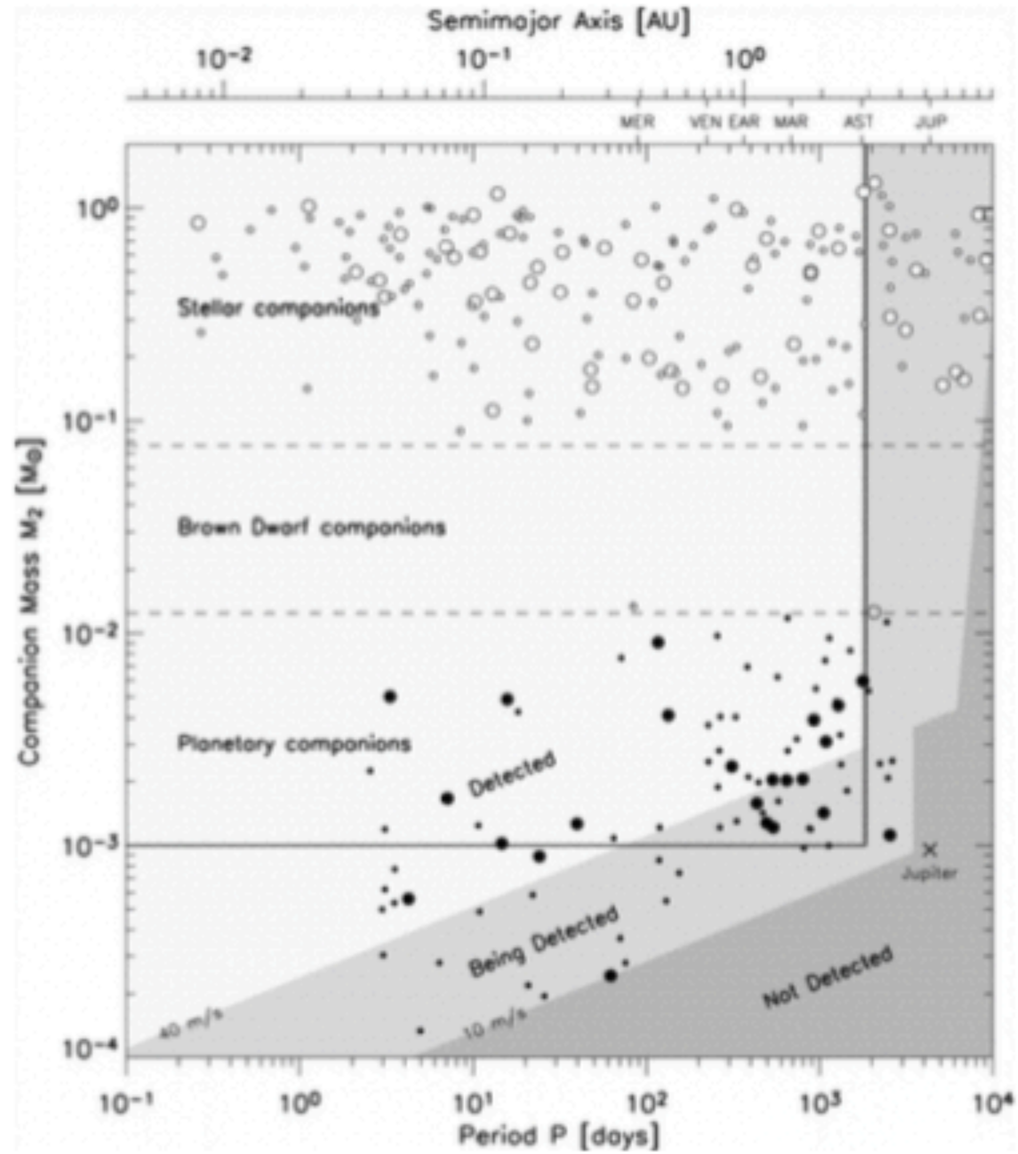


Lyra et al. (2016)

Possible explanation for the brown dwarf desert?

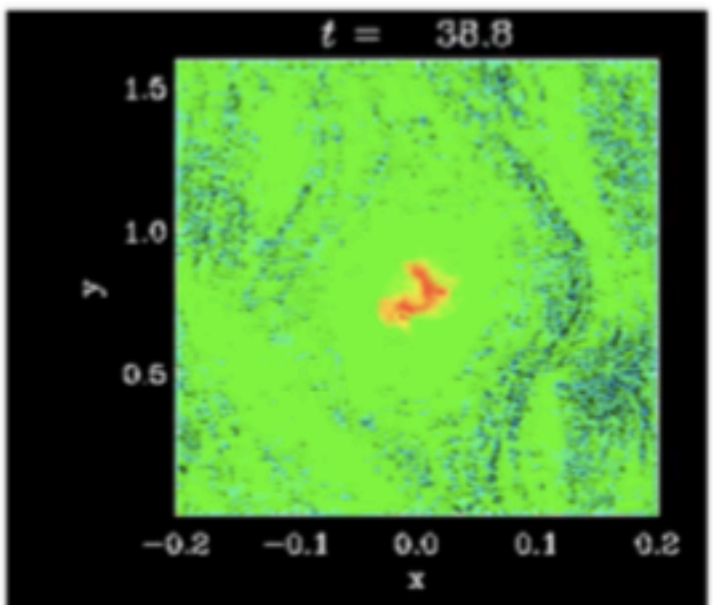


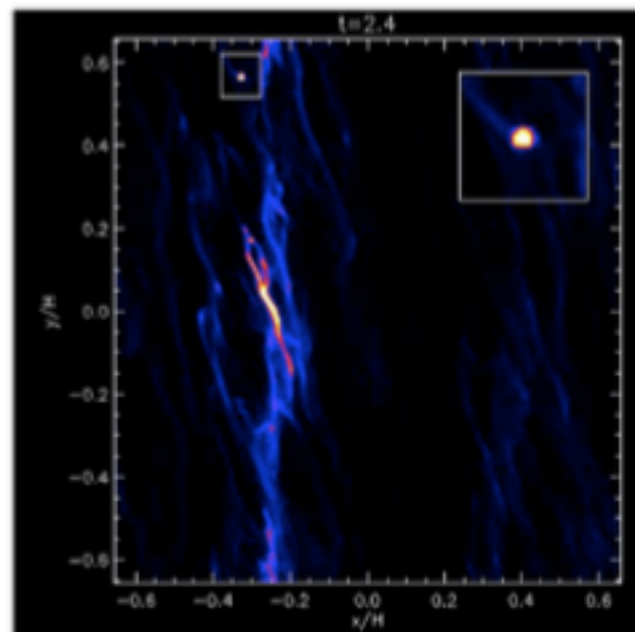




Conclusions

- Two modes of planet formation: Streaming Instability and Vortices
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortices do not survive magnetization
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- t?)





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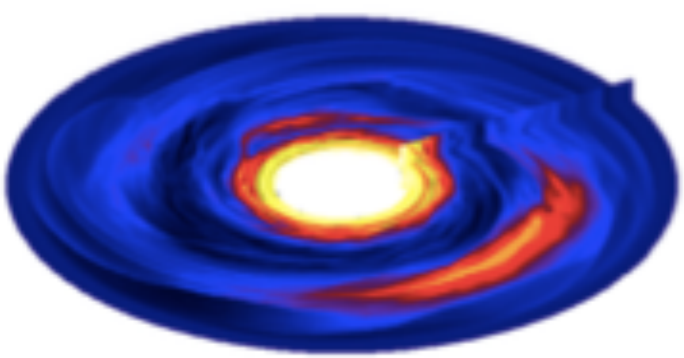
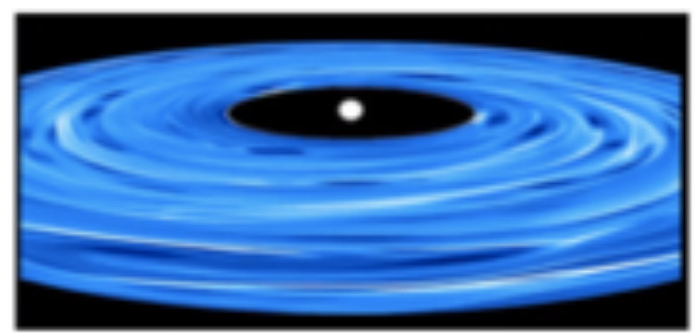
Rossby wave instability



Convective Overstability



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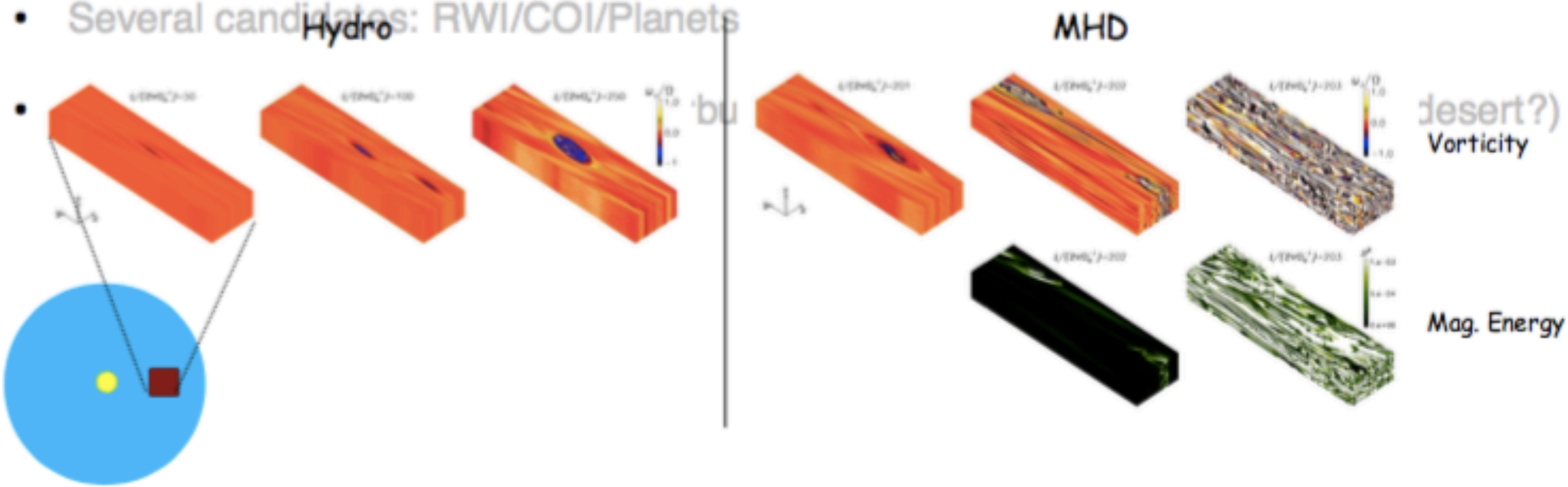
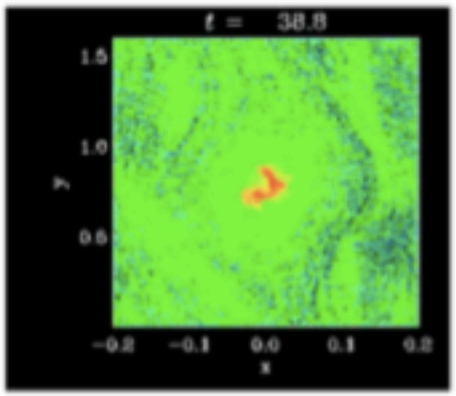
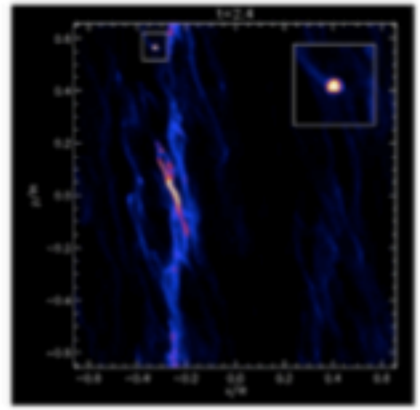
- Several candidates: RWI/COI/Planets
- bu desert?)



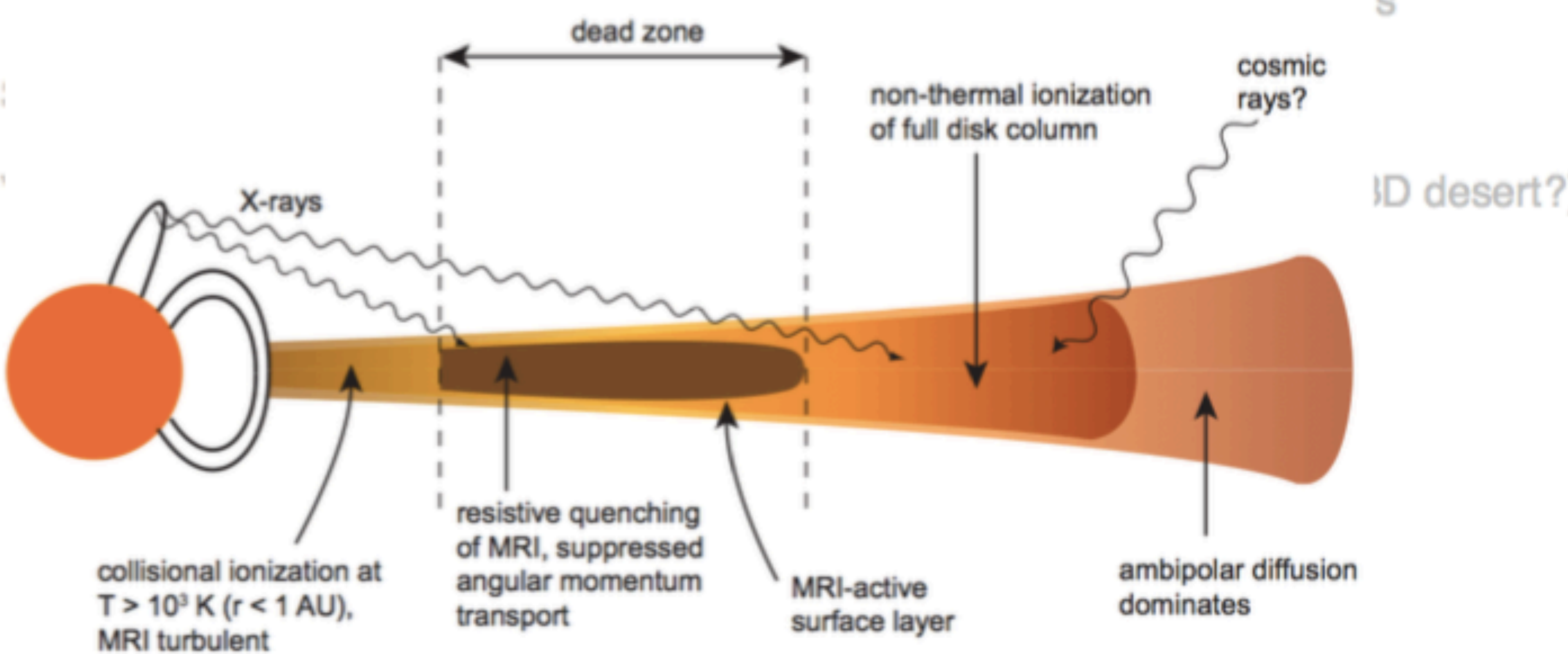
Lyra & Klahr (2011)

Conclusions





- Two mod ... ces
- Two sust ... ive Overstability
- Vortices (
- Vortex-assisted and streaming instability are complementary
- ... s
-
- ... 3D desert?)

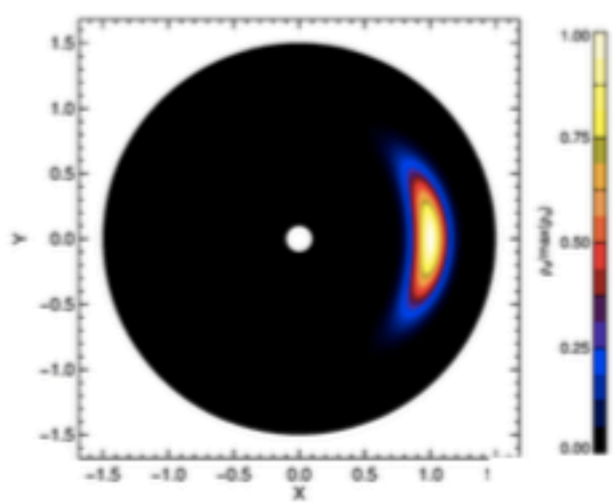


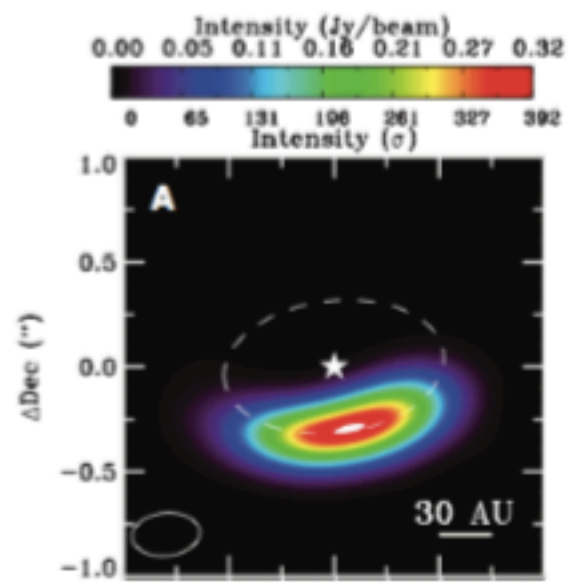
Conclusions

- Two modes of planet formation
- Two sustenance modes: Rossb
- Vortices do not survive magne
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Several candidates: RWI/COI/Planets
- Very hig es (BD desert?)

$$\rho_d(a,z) = \varepsilon \rho_0 (S+1)^{3/2} \exp\left\{-\frac{[a^2 f^2(\chi) + z^2]}{2H^2}(S+1)\right\}$$

Lyra & Lin (2013)





Conclusions

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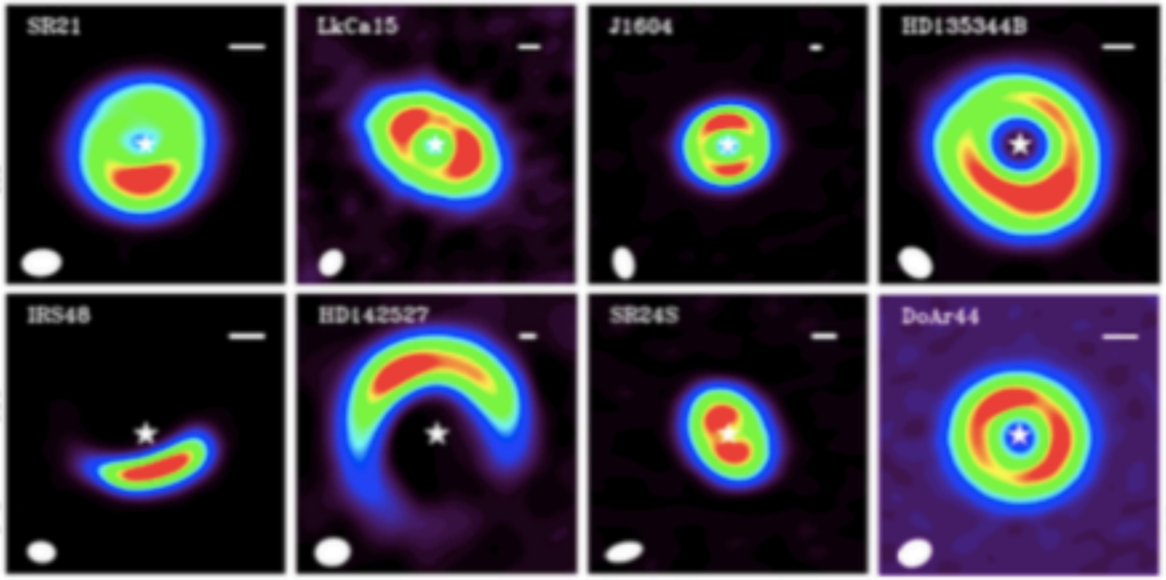

- Several possible culprits for asymmetries: RWI/COI/Planets
- Very high-mass planets: spirals, turbulent surf and high accretion rates (BD desert?)

Conclusions

- Two modes of planet formation: Streaming Instat
- Two sustenance modes: Rossby Wave Instability
- Vortices do not survive magnetization
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- Vortex-trapped dust in drag-diffusion equilibrium
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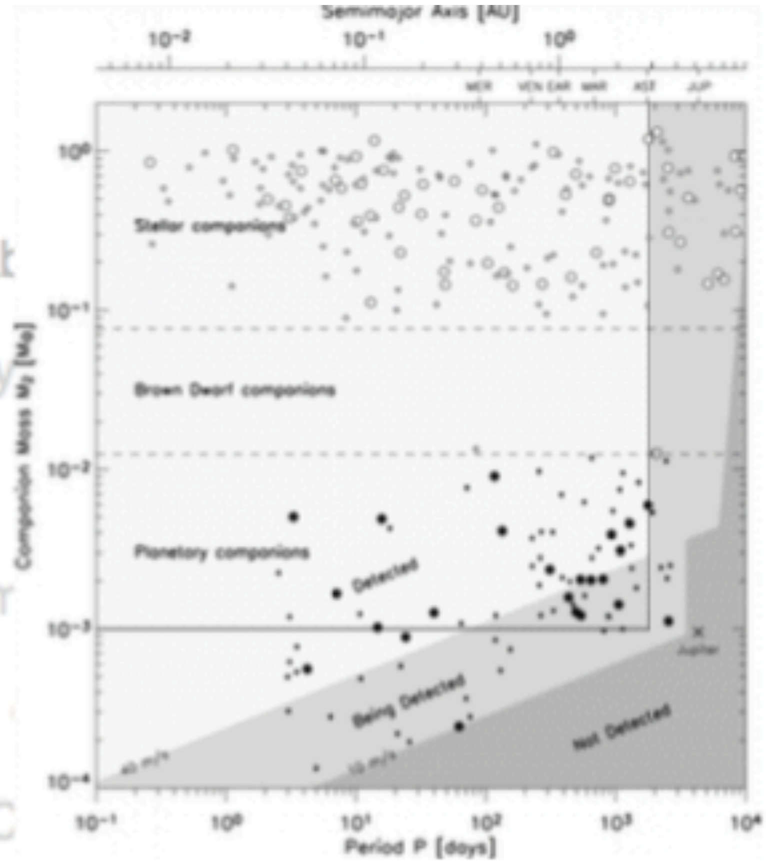
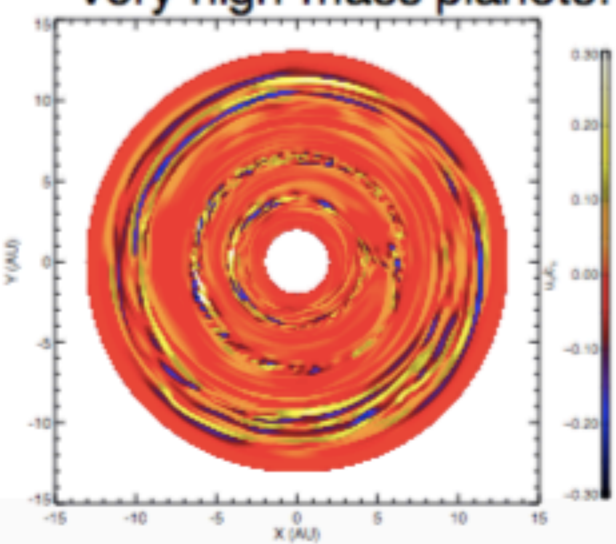


- Very high-mass planets: spirals, turbulent surf and high accretion rates (BD desert?)



Conclusions

- Predictions:
  - Hot lobes next to high mass planets at high resolution
  - High(er) turbulence around the orbit of a high-mass planet

- Shocks from high-mass planets (~> 5 Mjup) is a significant source of radiation in disks.
- Shocks due to high mass planets better fits to observed spirals.