# Evolution of circumstellar disks and planet formation

**Wladimir (Wlad) Lyra**

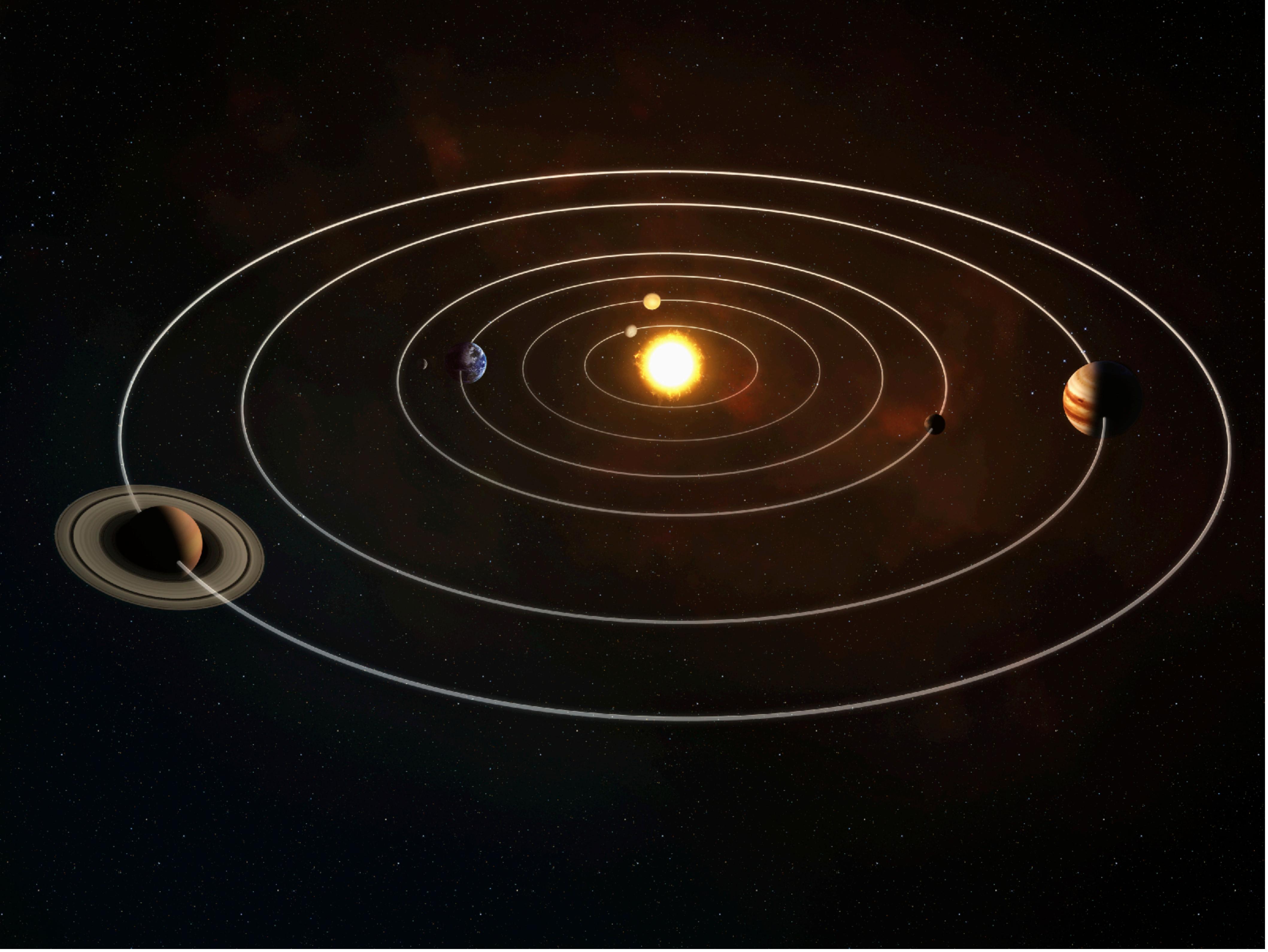
California State University Northridge (CSUN)

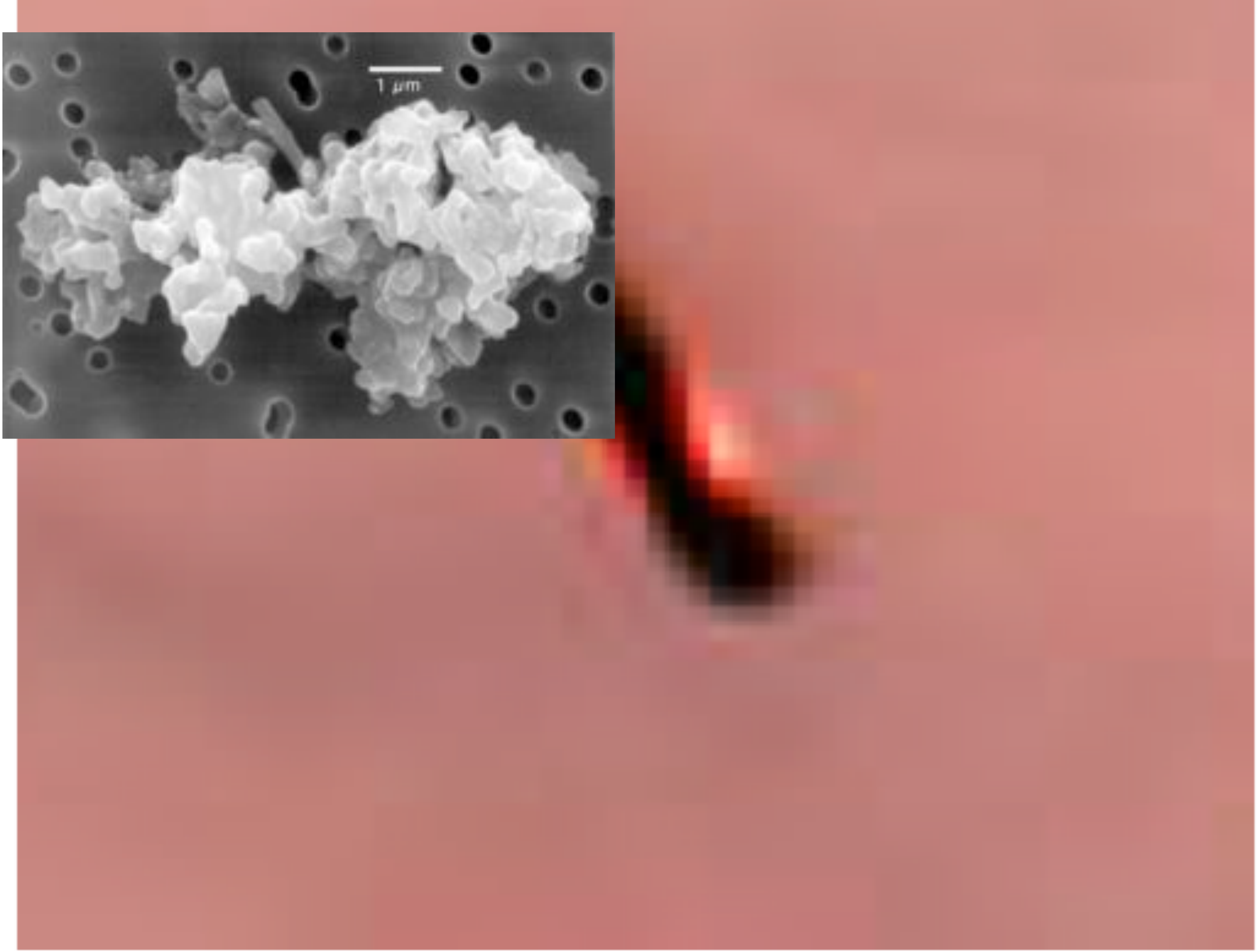
Jet Propulsion Laboratory (JPL)

Collaborators

Aaron Boley (Vancouver), Axel Brandenburg (Stockholm), Kees Dullemond (Heidelberg), Mario Flock (JPL), Anders Johansen (Lund), Tobias Heinemann (Copenhagen), Hubert Klahr (Heidelberg), Min-Kai Lin (ASU), Mordecai-Mark Mac Low (AMNH), Colin McNally (Copenhagen), Satoshi Okuzumi (JPL), Nikolai Piskunov (Uppsala), Natalie Raettig (Heidelberg), Alex Richert (PSU), Neal Turner (JPL), Nienke van der Marel (U Hawaii), Andras Zsom (MIT).

Caltech, Apr 19th, 2016




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

Mass: $10^{-3} - 10^{-1}$ $M_{sun}$

Dust-to-gas ratio ~0.01

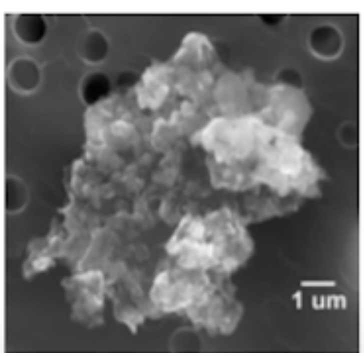
# Planet Formation

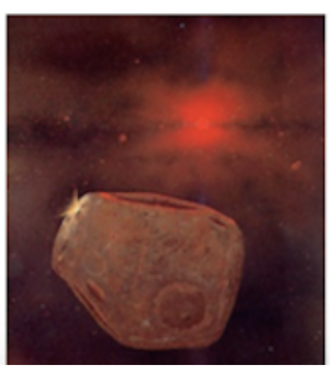
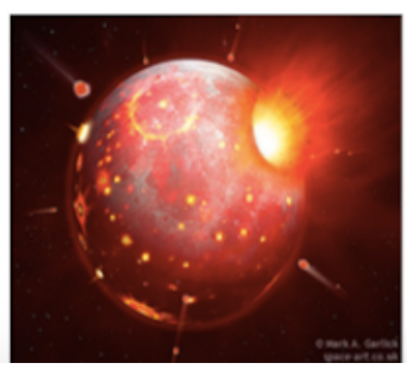
**Planetesimal Hypothesis (Safronov 1969)**

From dust to peebles
$\mu$m -> 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

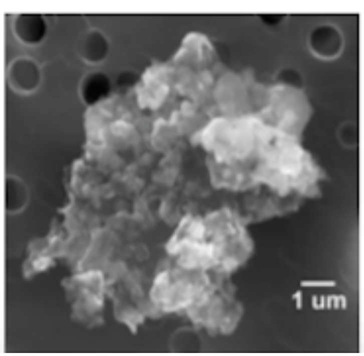
**Planetesimal Hypothesis (Safronov 1969)**

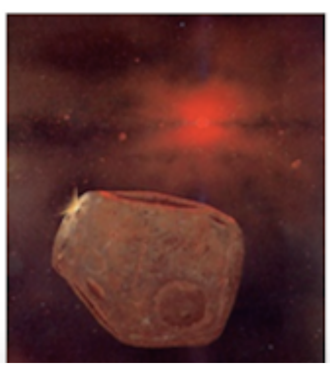
From dust to peebles
μm -> cm : hit-and-stick by van der Walls

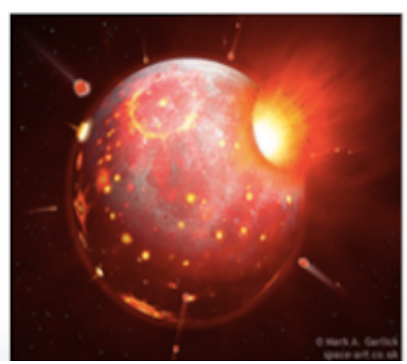
From pebbles to planetesimals
*Here be dragons….*

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

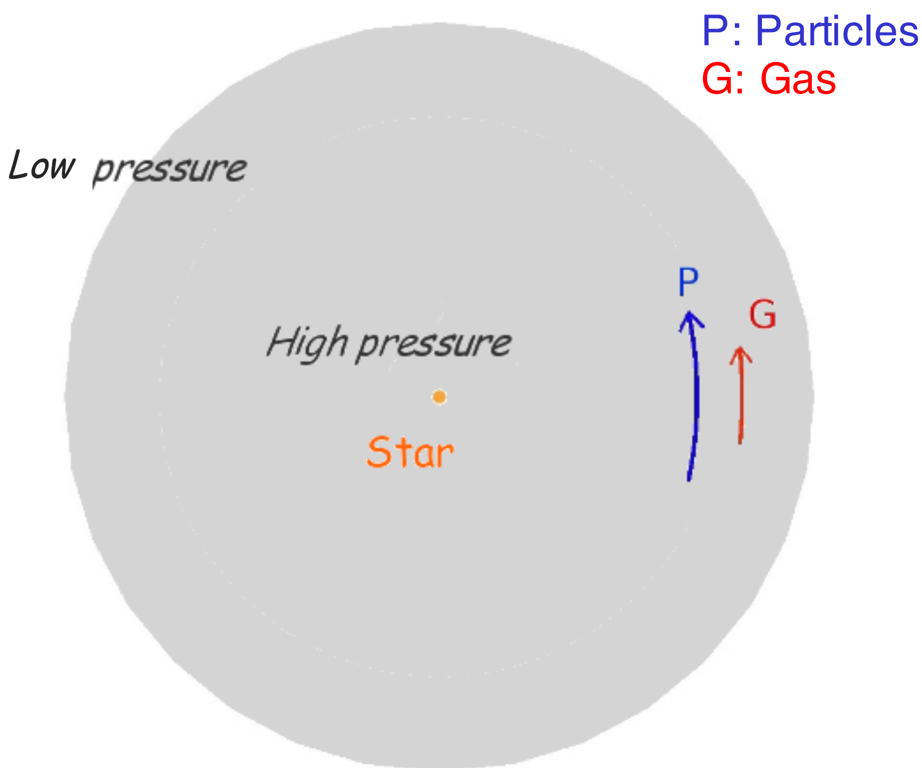
From planetary embryos to planets
Rocky planets: binary collisions
Gas giants: Attract gaseous envelope



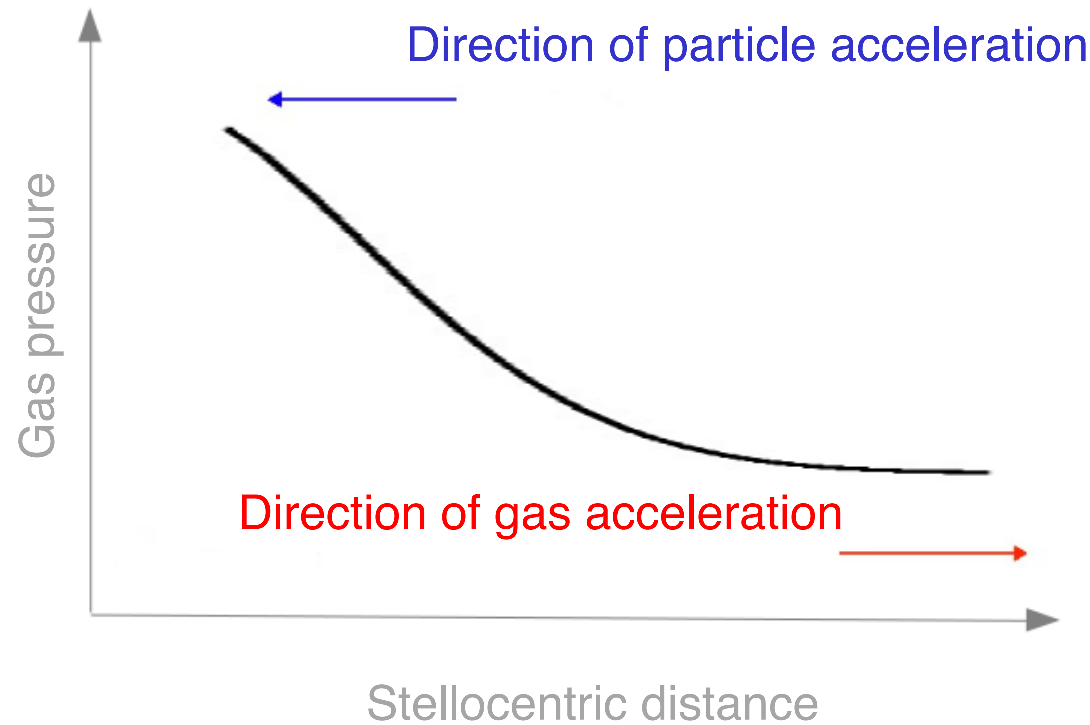





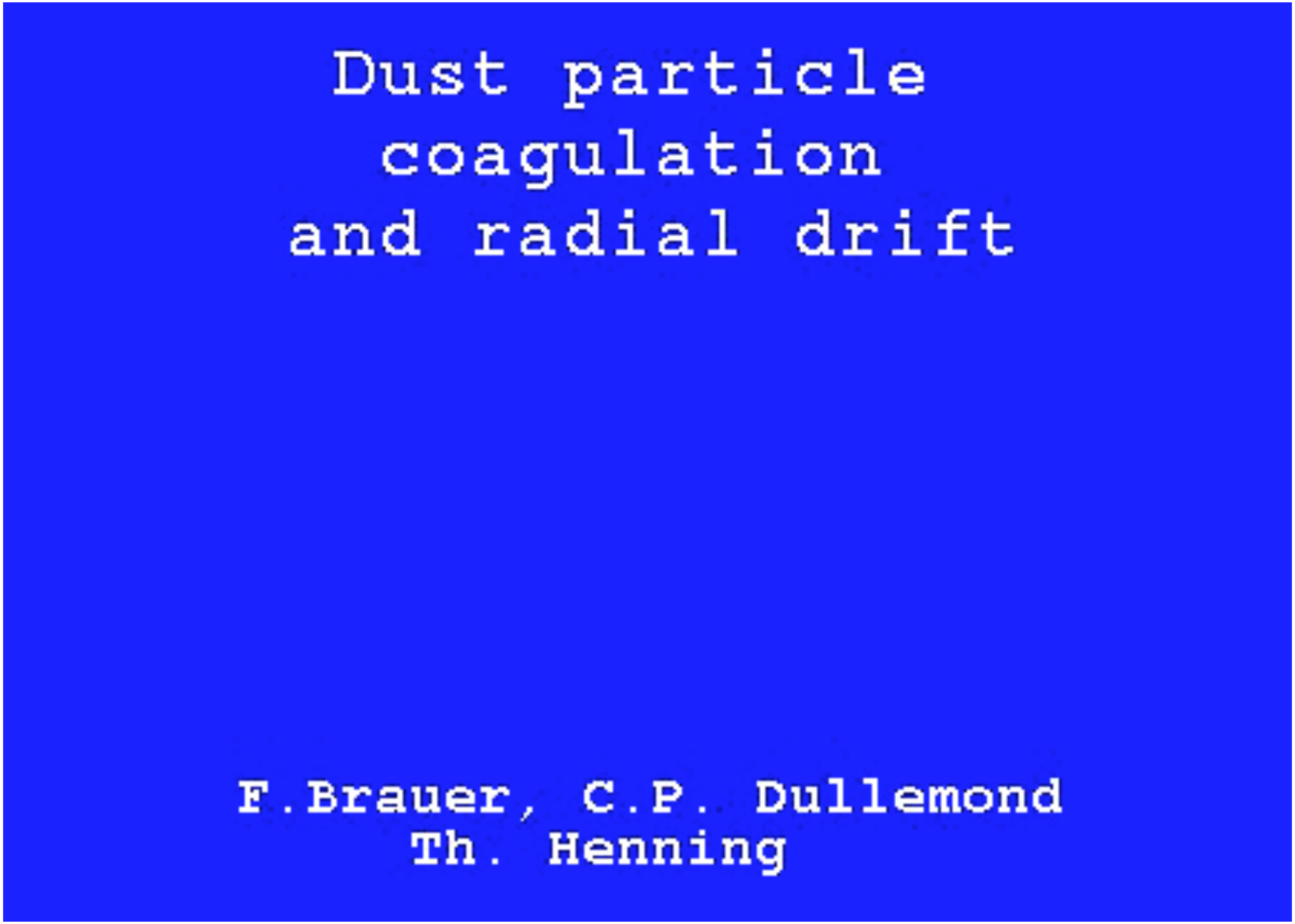
# Particle drift




Adapted from Whipple (1972)



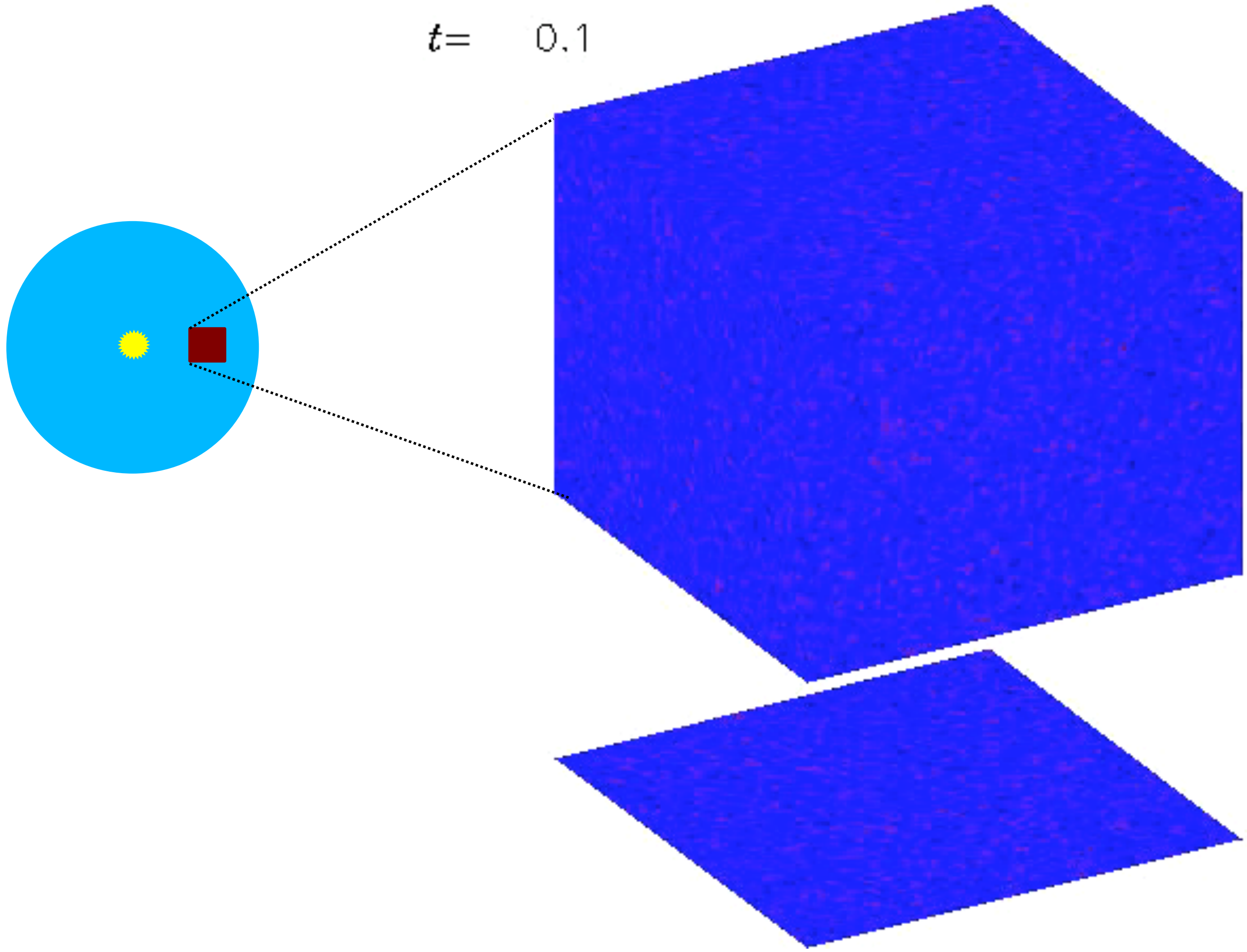
## Particle coagulation and drift




Brauer et al. (2008)

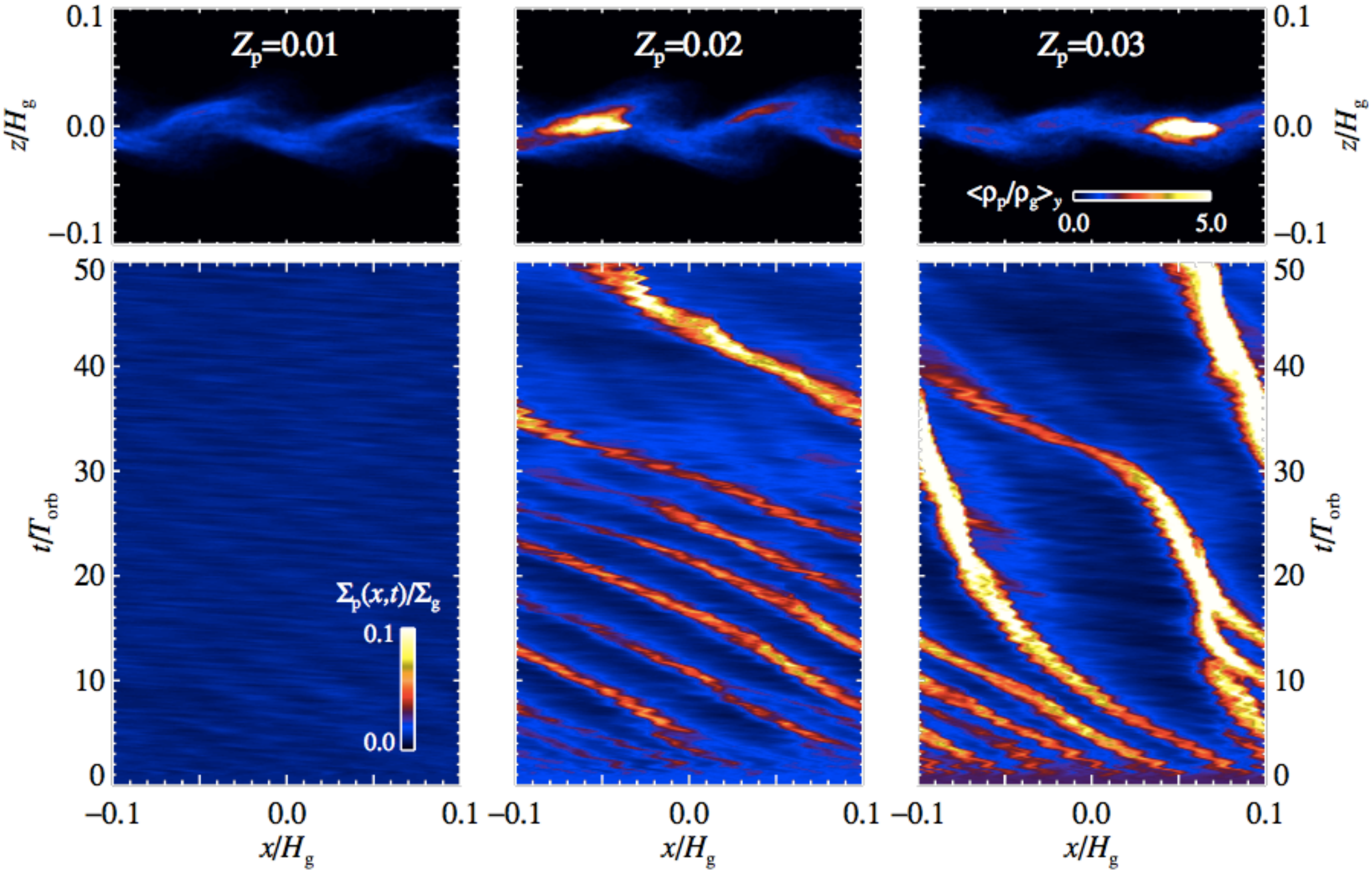
# Streaming Instability

The particle drift is linearly unstable




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

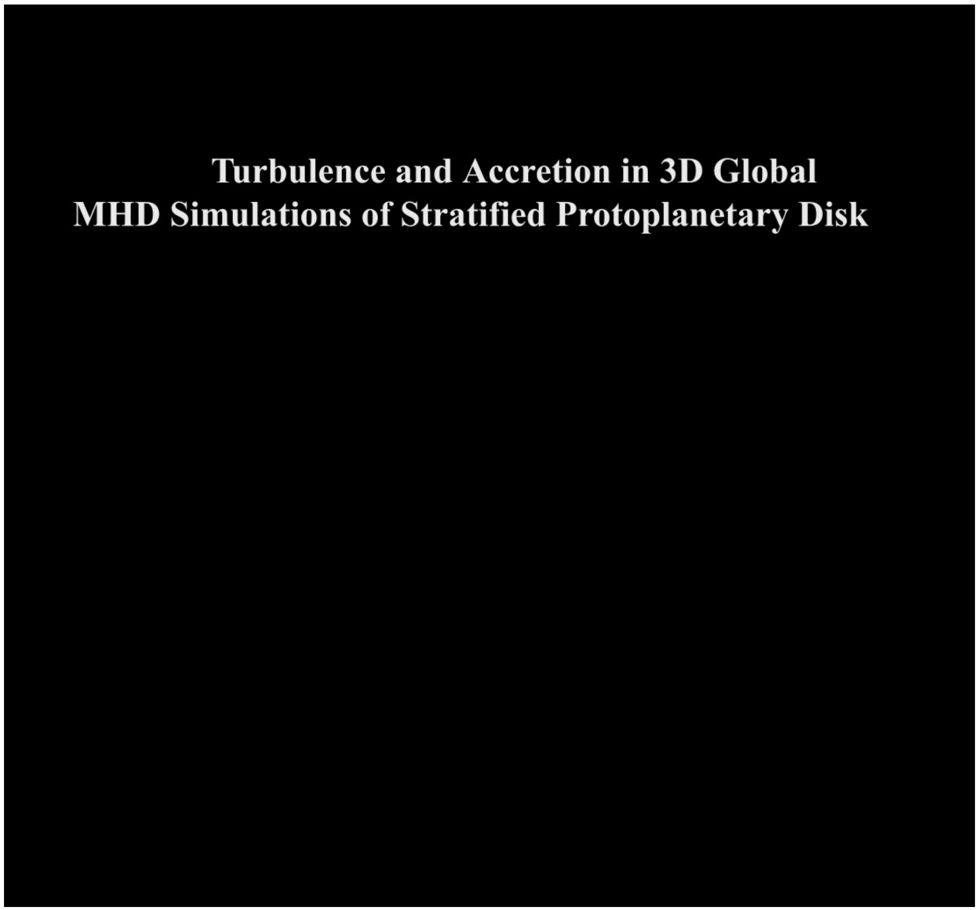
# Streaming Instability does not "work" for solar metallicity




Johansen et al. (2011)

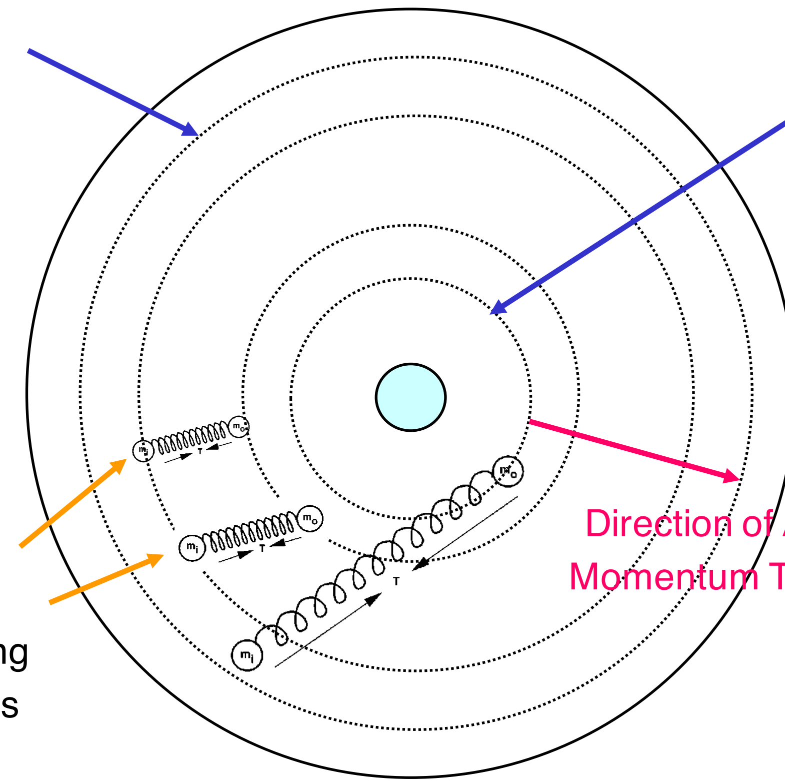
# Magneto-Rotational Instability

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



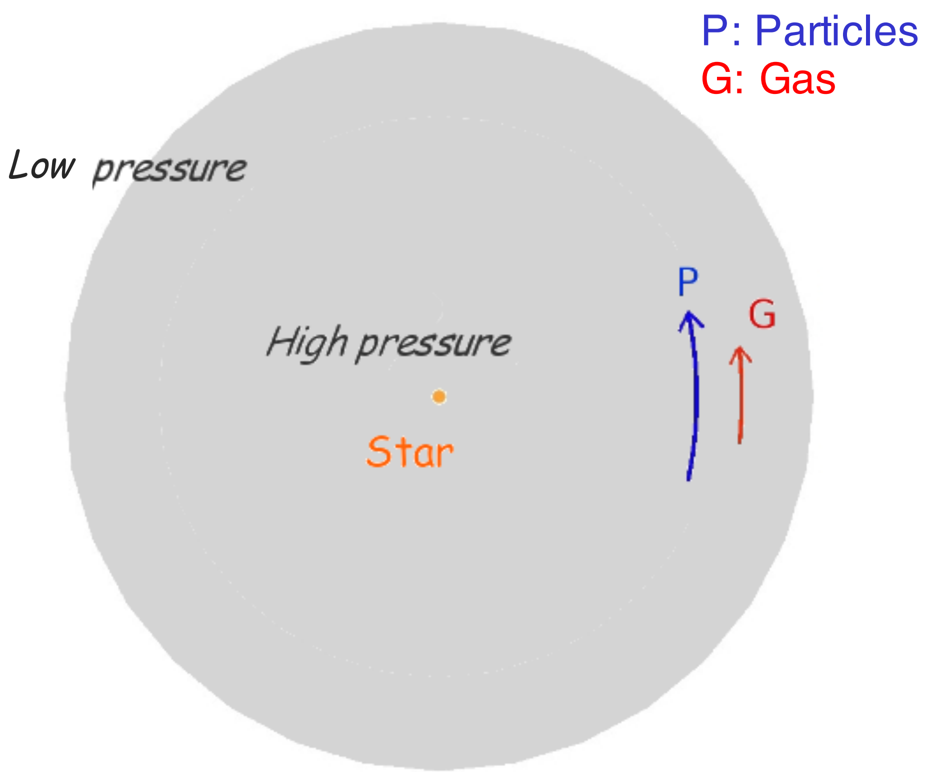

Flock et al. (2011)

MRI sketch

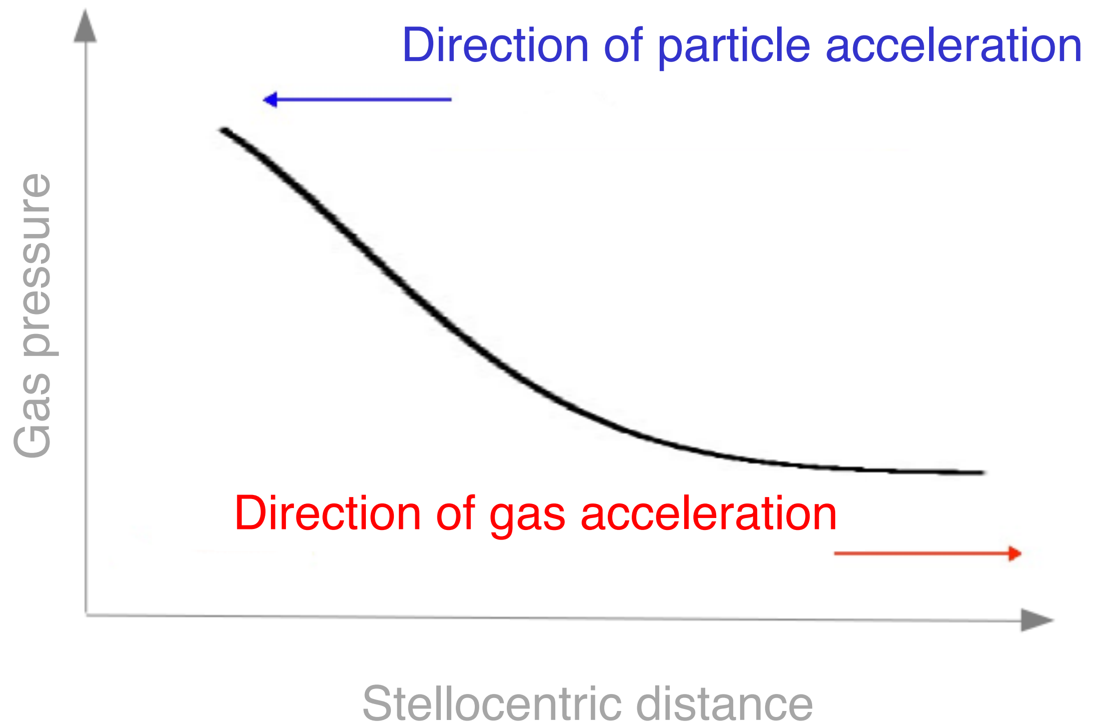



Unstable if angular velocity
decreases outward

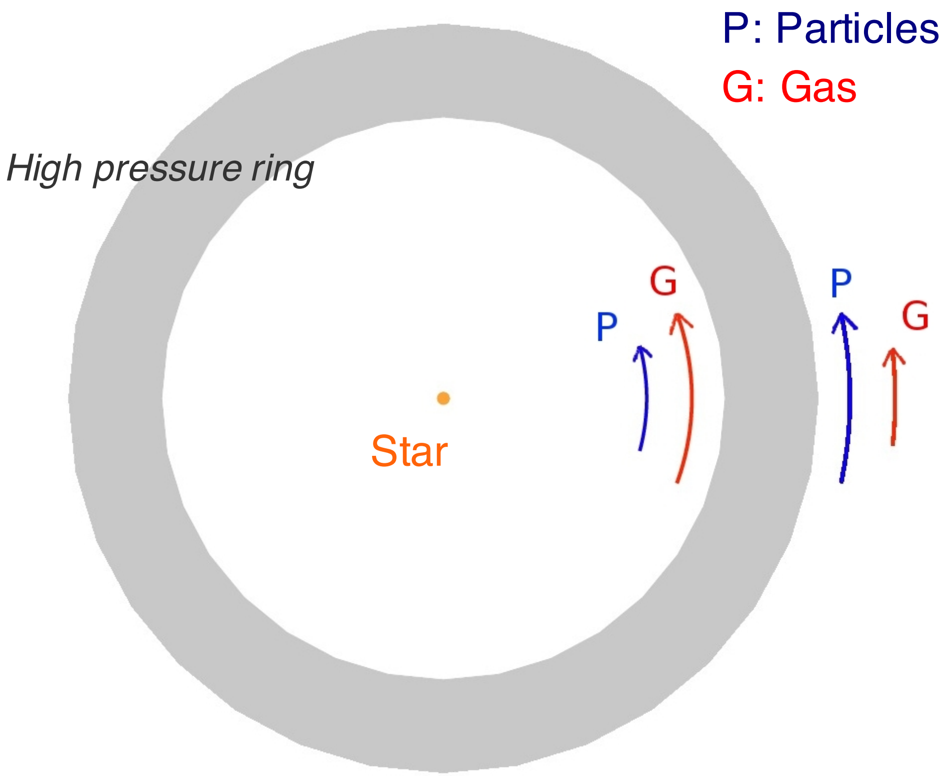
# Particle drift



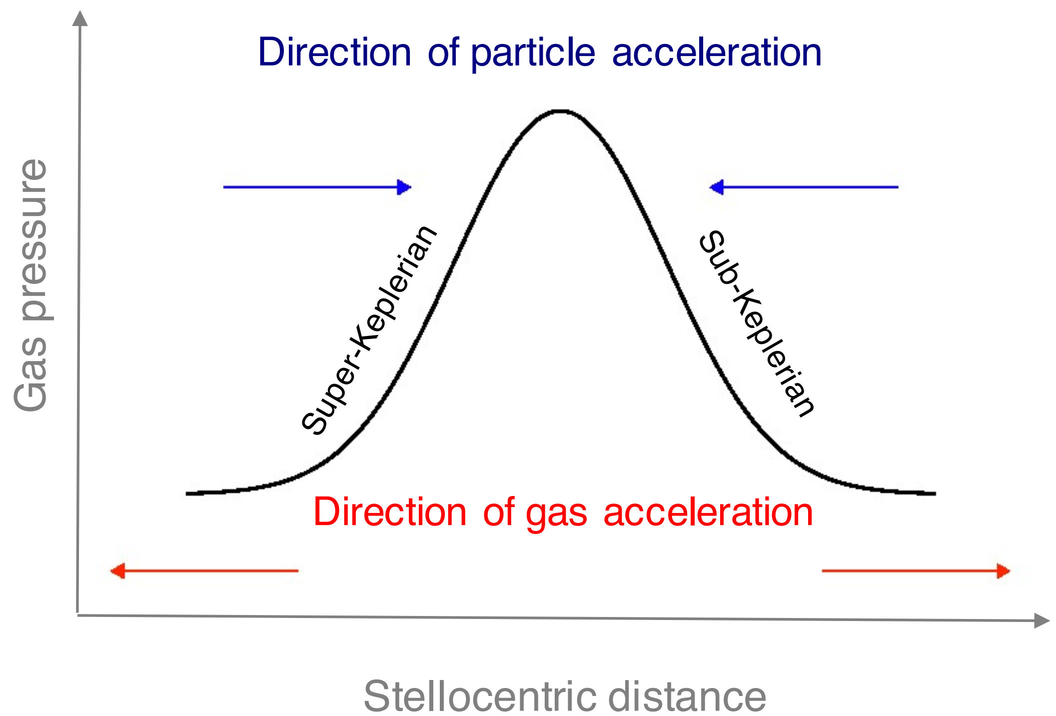

Adapted from Whipple (1972)



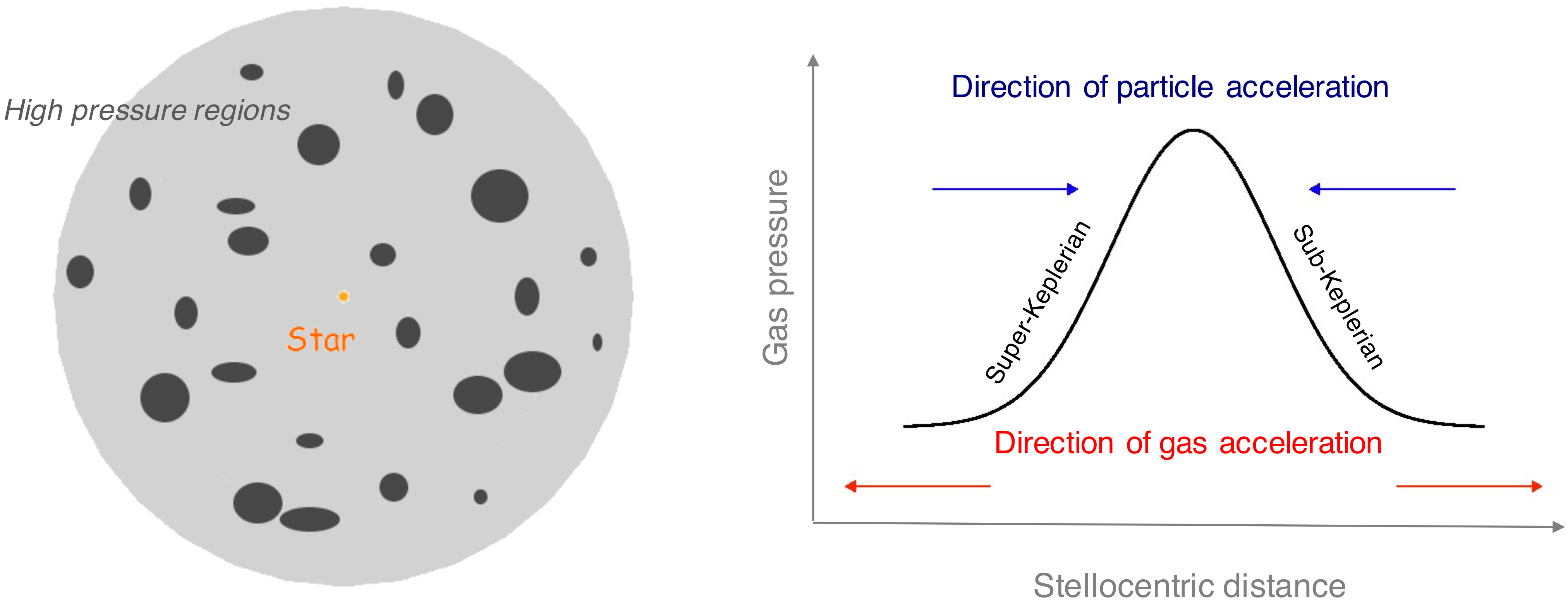
# Pressure Trap



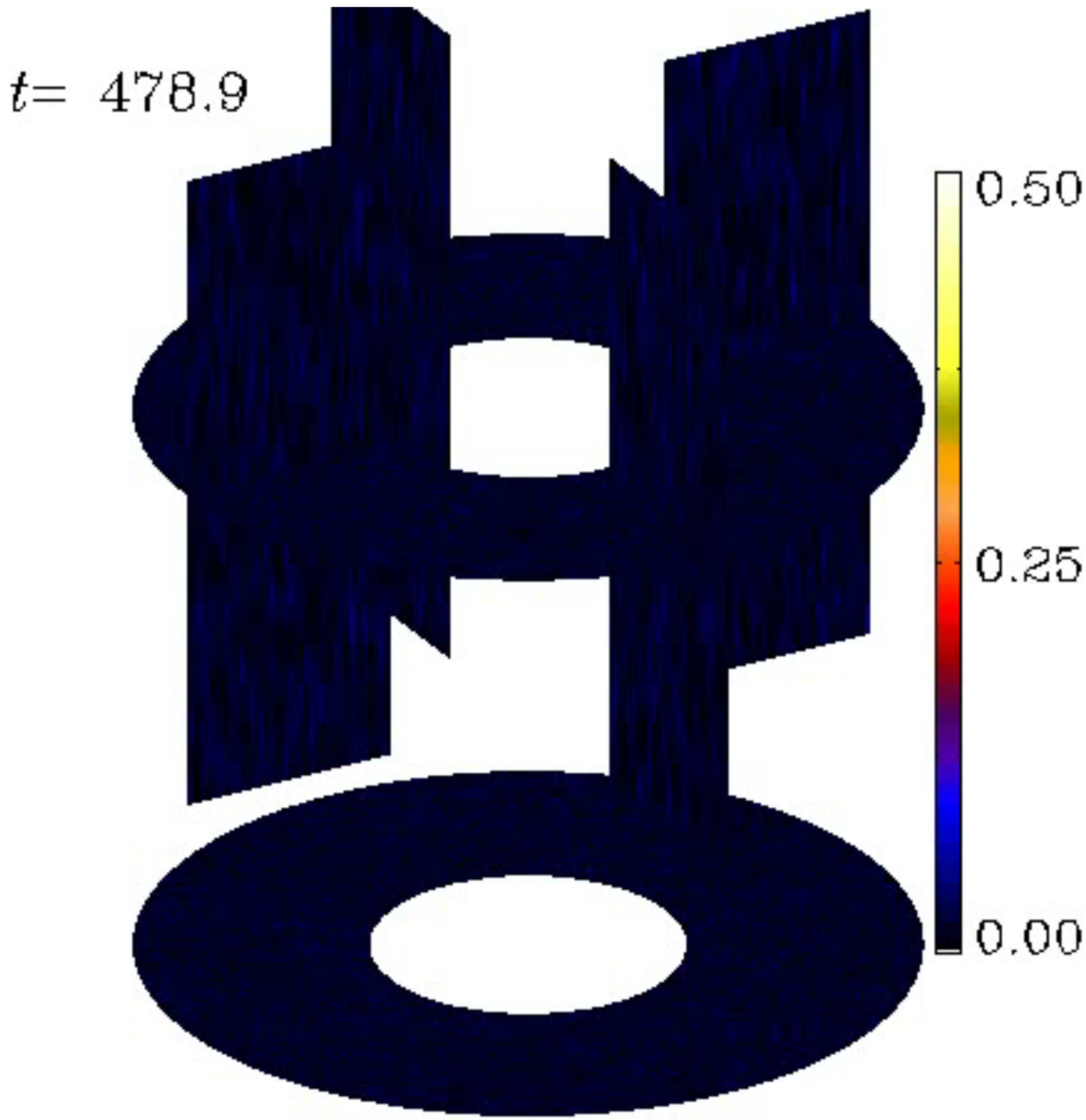

Adapted from Whipple (1972)



# Pressure Trap

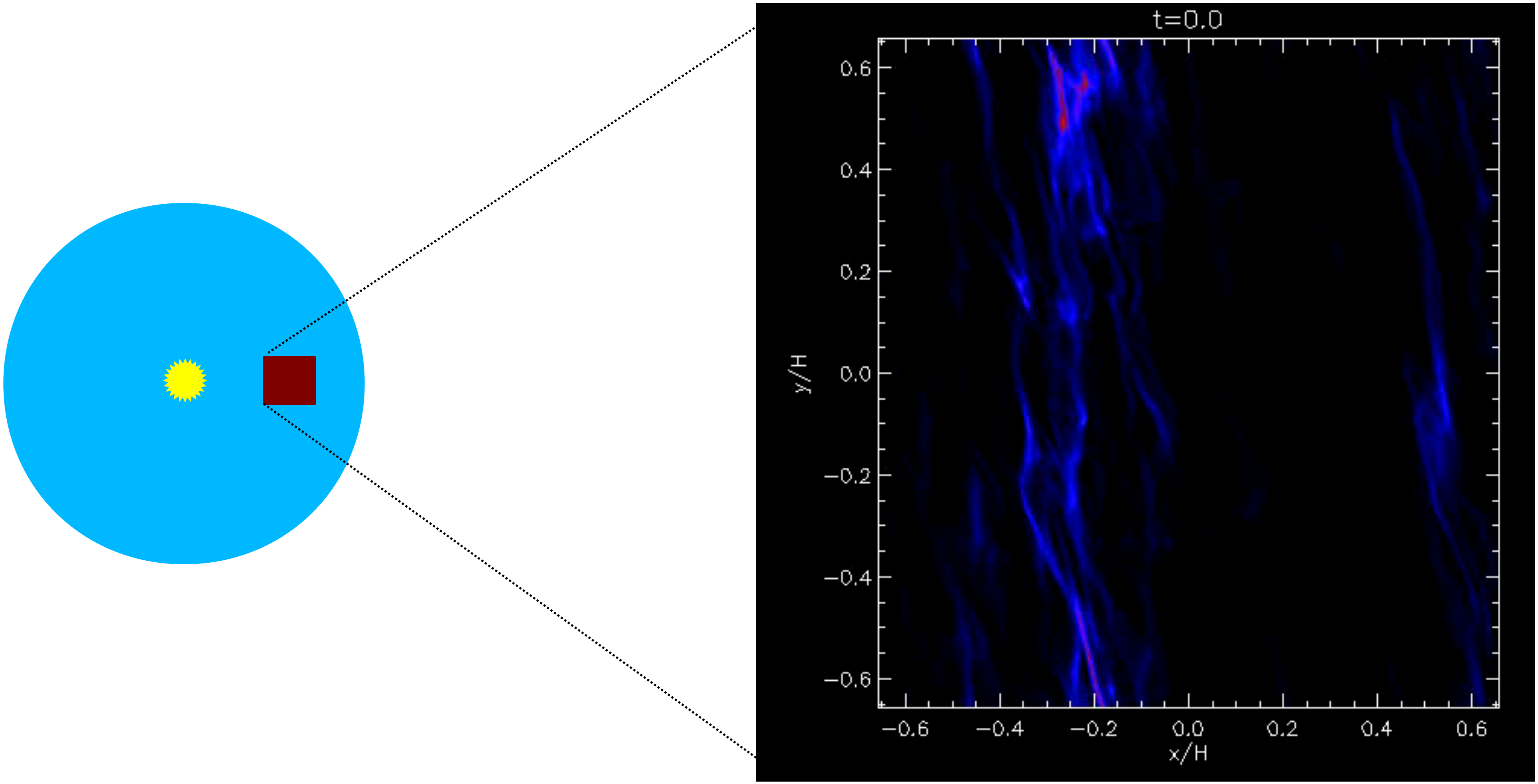


# Turbulence concentrates solids mechanically in pressure maxima



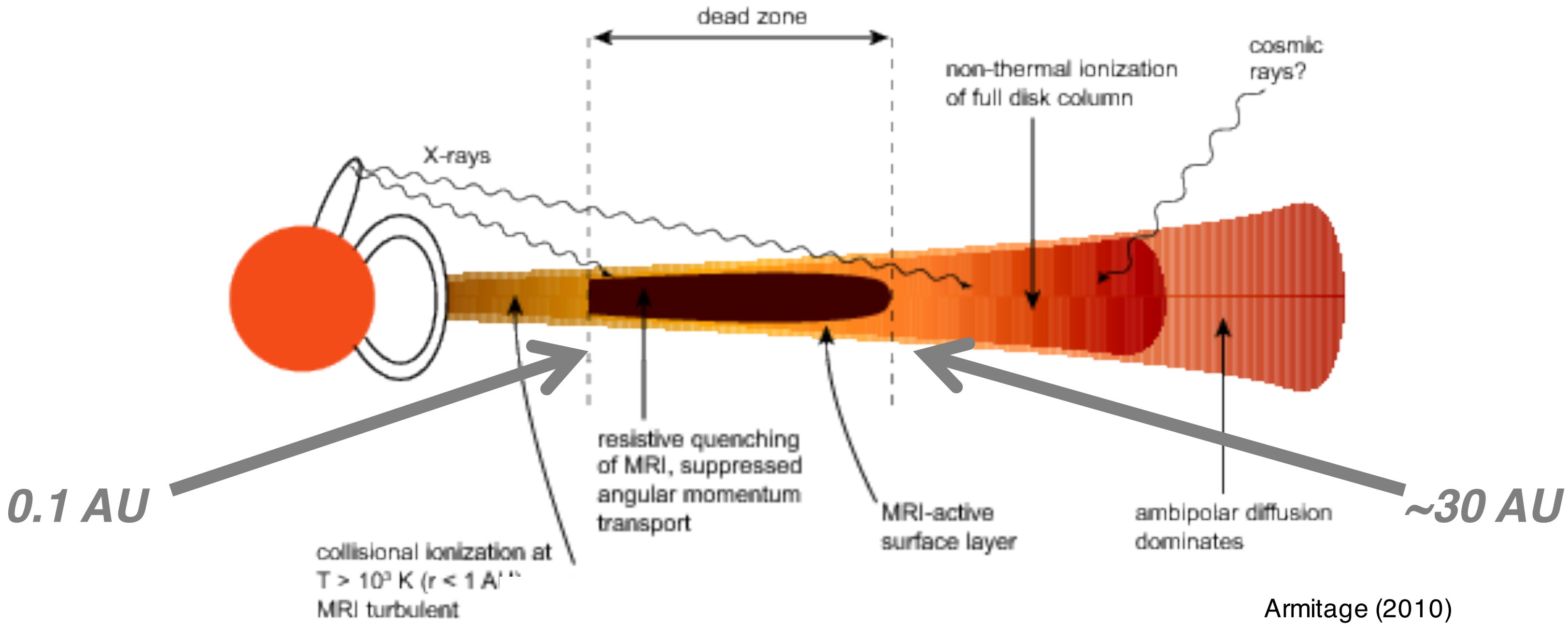

Lyra et al. (2008a)

# Gravitational collapse into planetesimals




Johansen et al. (2007)

# Dead zones are robust features of protoplanetary disks

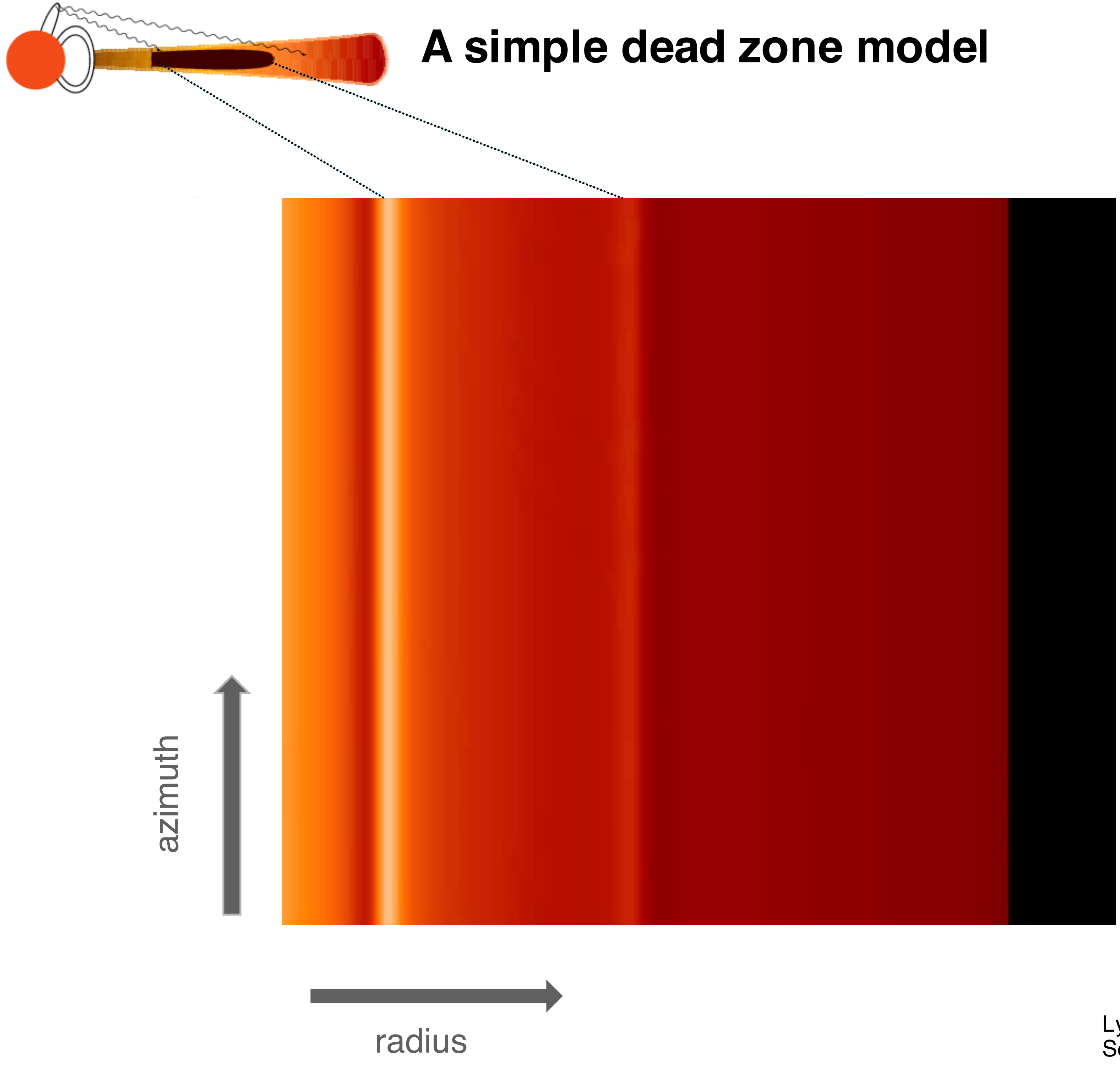



Armitage (2010)

Disks are cold and thus poorly ionized
(Blaes & Balbus 1994, Gammie 1996)

There should be a **magnetized, active zone**,
and a **non-magnetized, dead zone**.

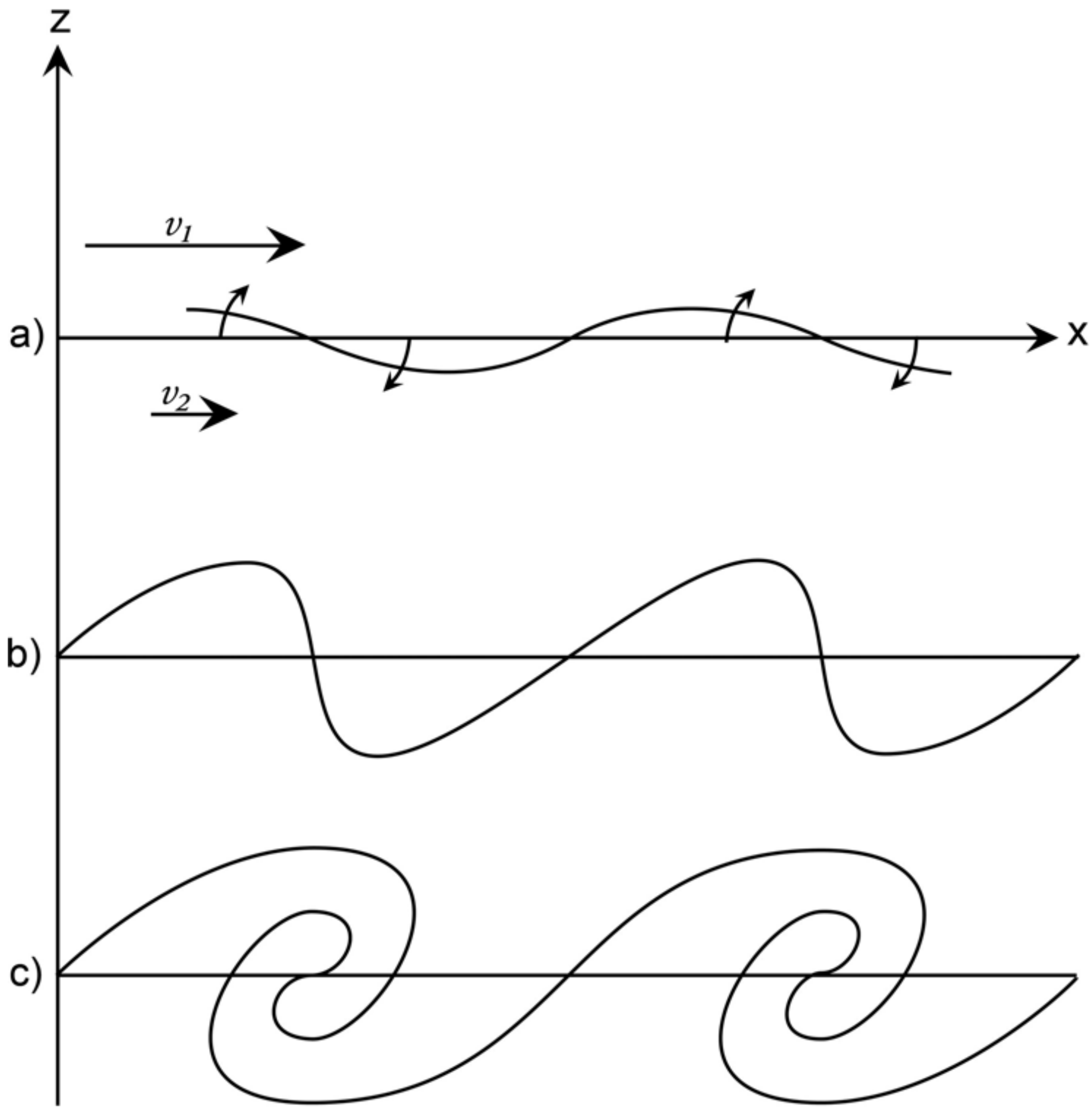
# A simple dead zone model



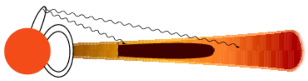

Lyra et al. (2008b, 2009a);
See also Varniere & Tagger (2006)

# Rossby wave instability

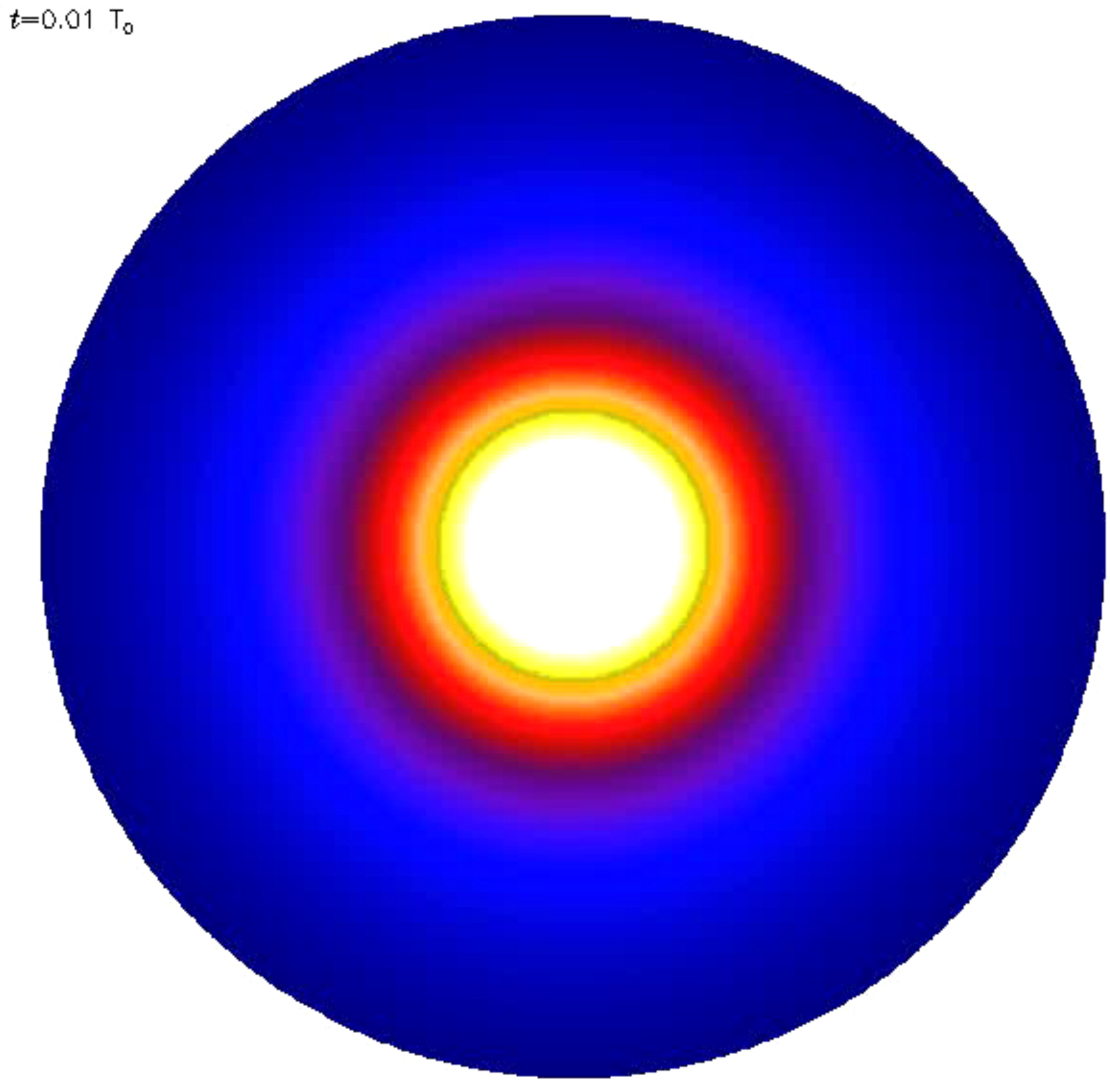
(or… Kelvin-Helmholtz in differentially rotating disks)







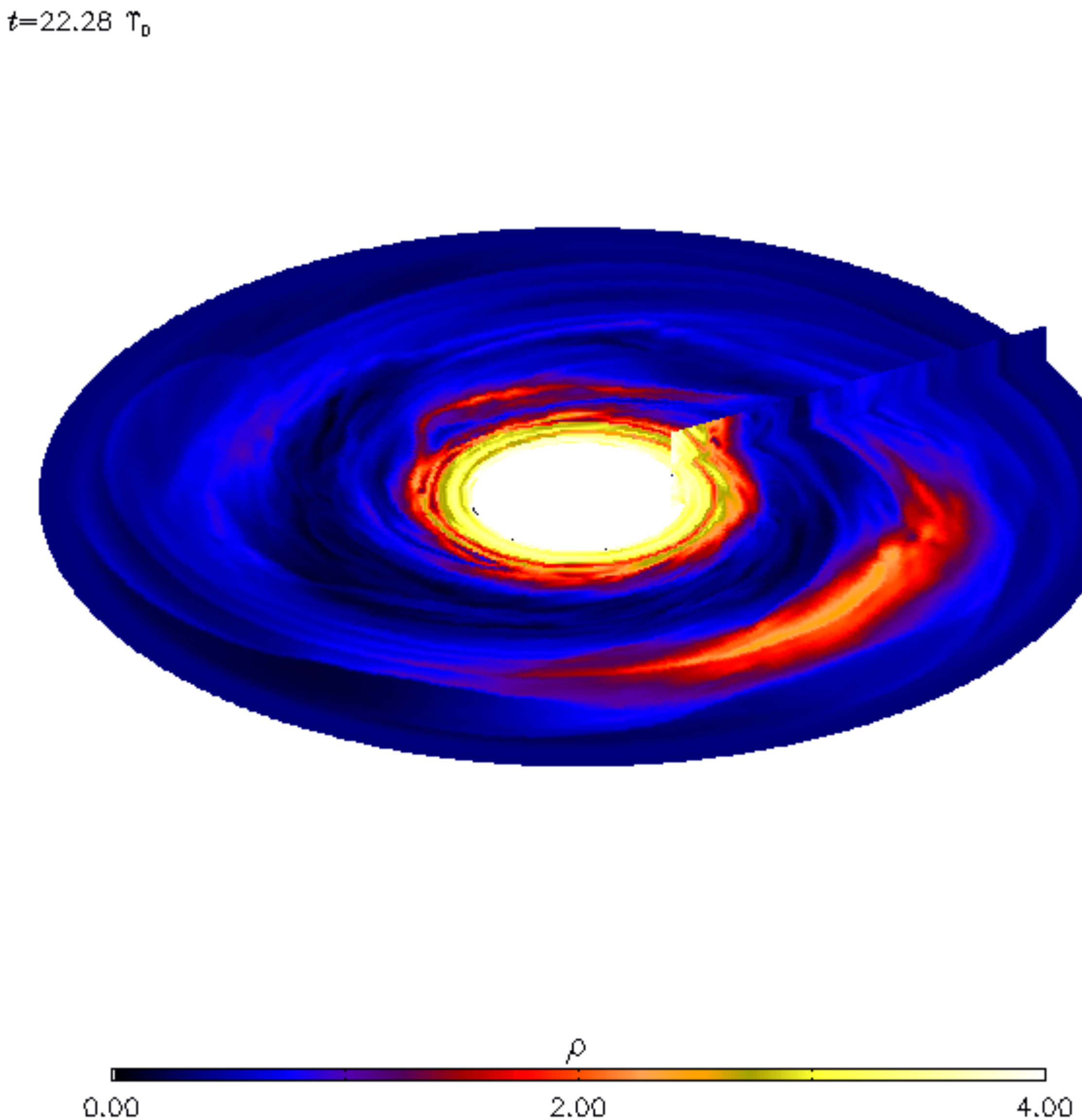
# Inner (0.1 AU) active/dead zone boundary

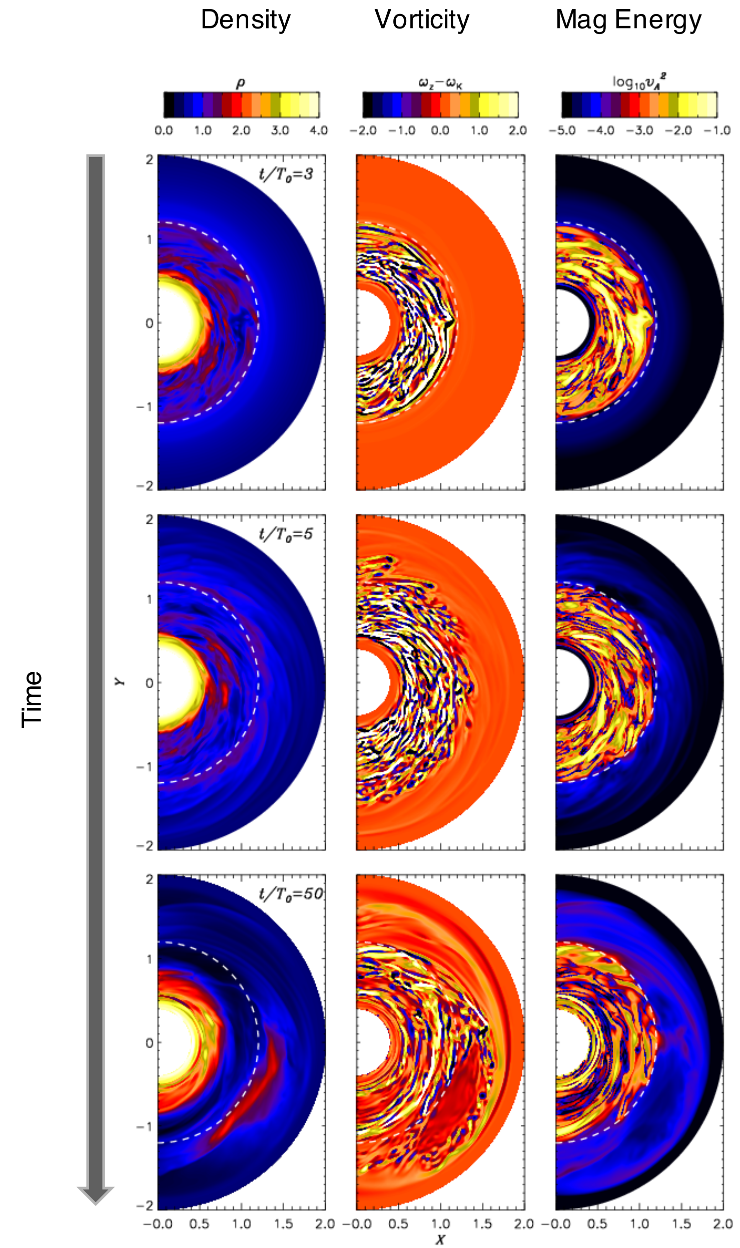



Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

# Inner (0.1 AU) active/dead zone boundary



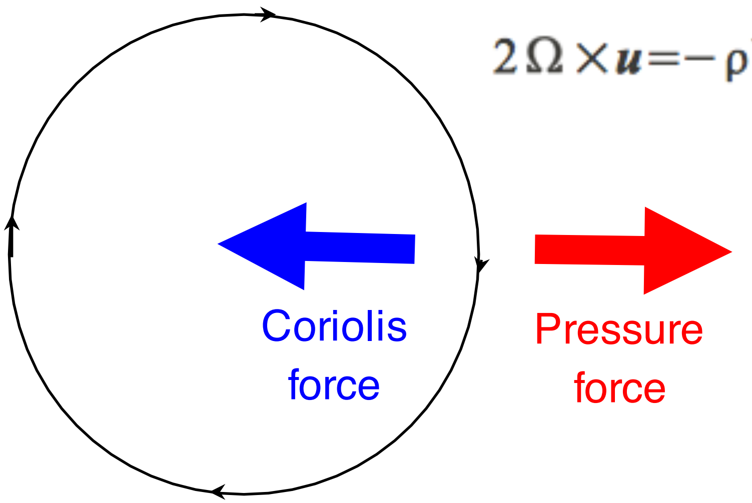

Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

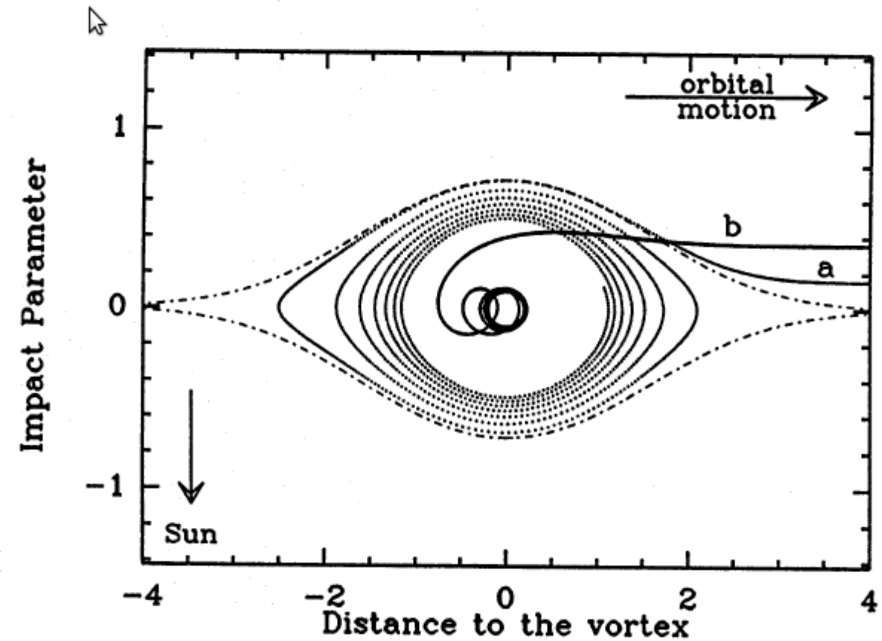
# The Tea-Leaf effect

Geostrophic balance:

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




Vortex streamline




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, Adams & Watkins 1996, Tanga et al. 1996)

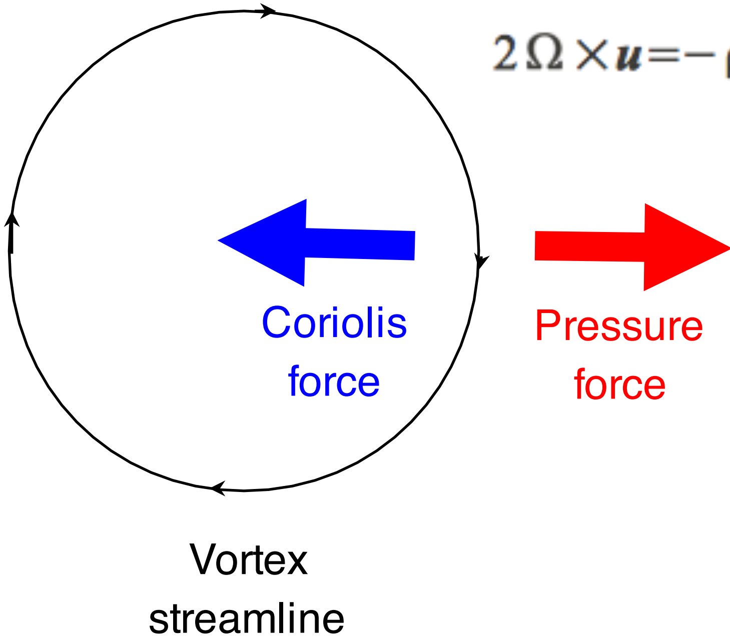
Speed up planet formation enormously

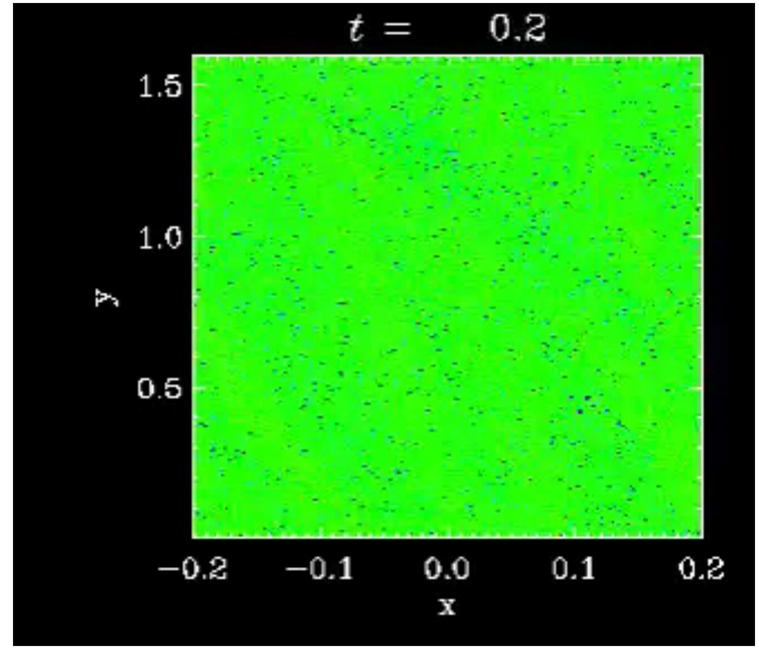
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

# The Tea-Leaf effect

Geostrophic balance:

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




Raettig, Lyra & Klahr (2012)

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

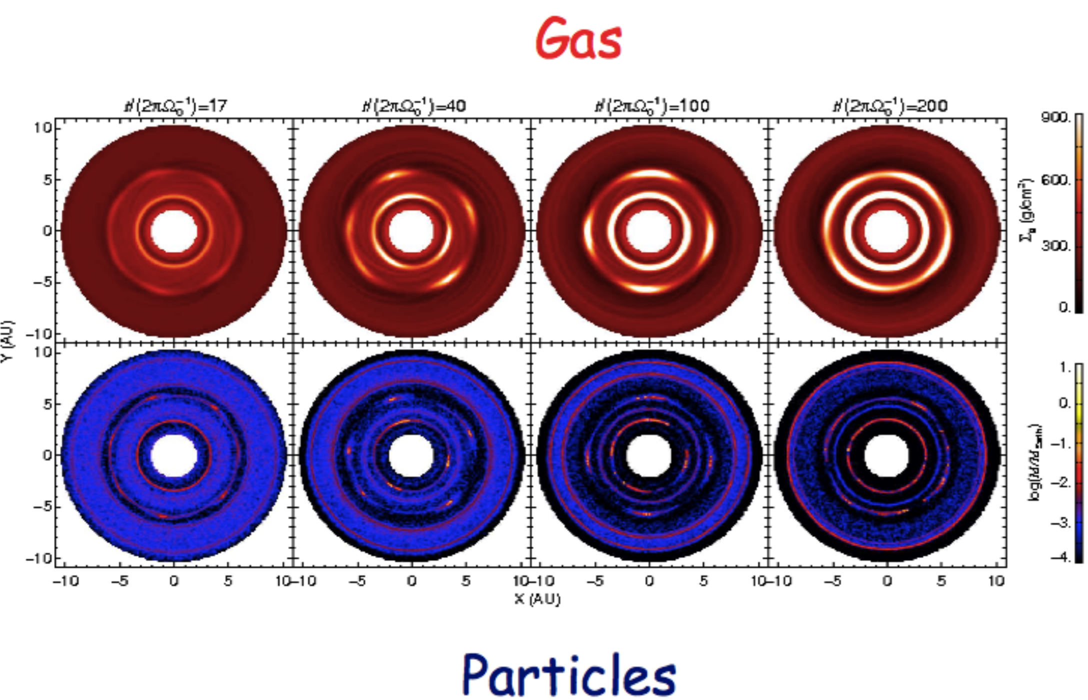
Aid to planet formation

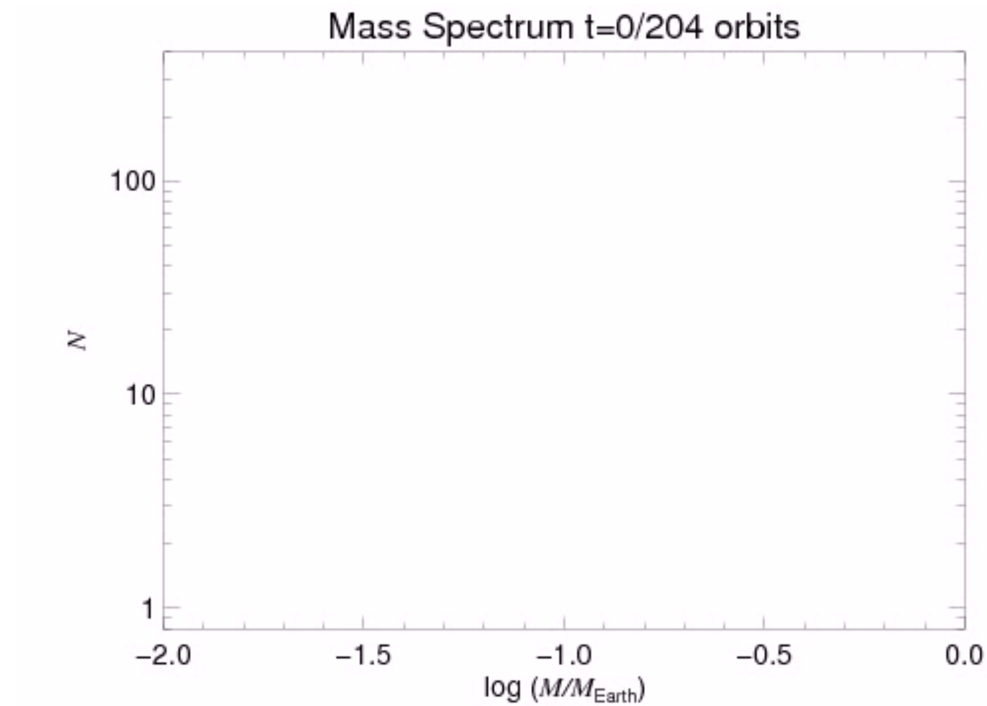
(Barge & Sommeria 1995, Adams & Watkins 1996, Tanga et al. 1996)

Speed up planet formation enormously

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

# Vortices and Planet Formation

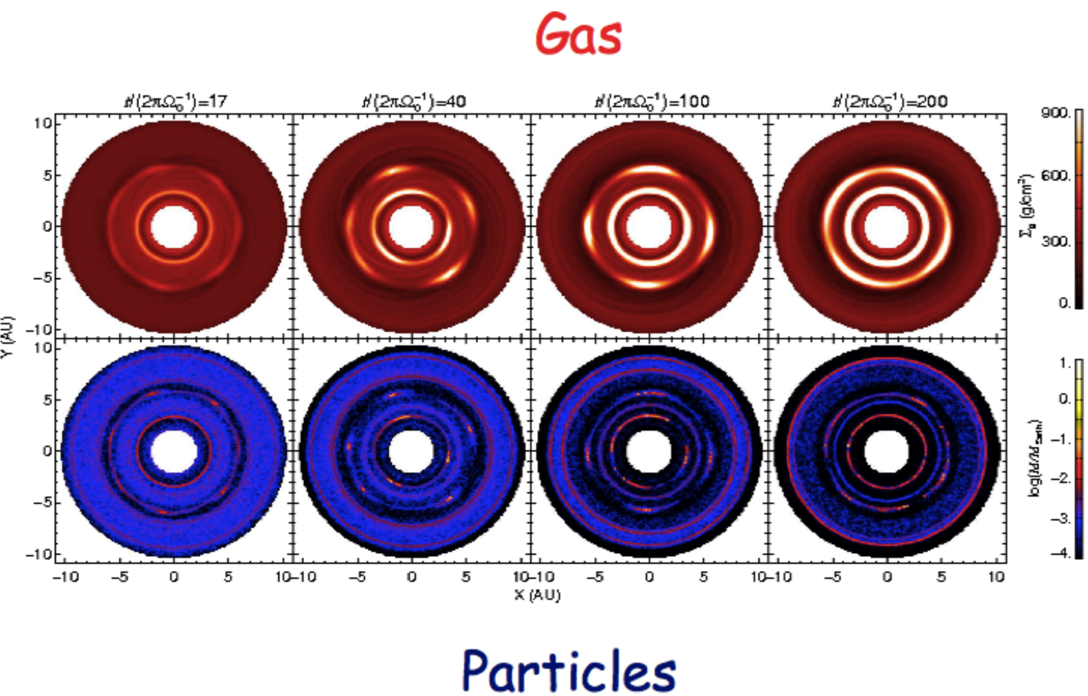


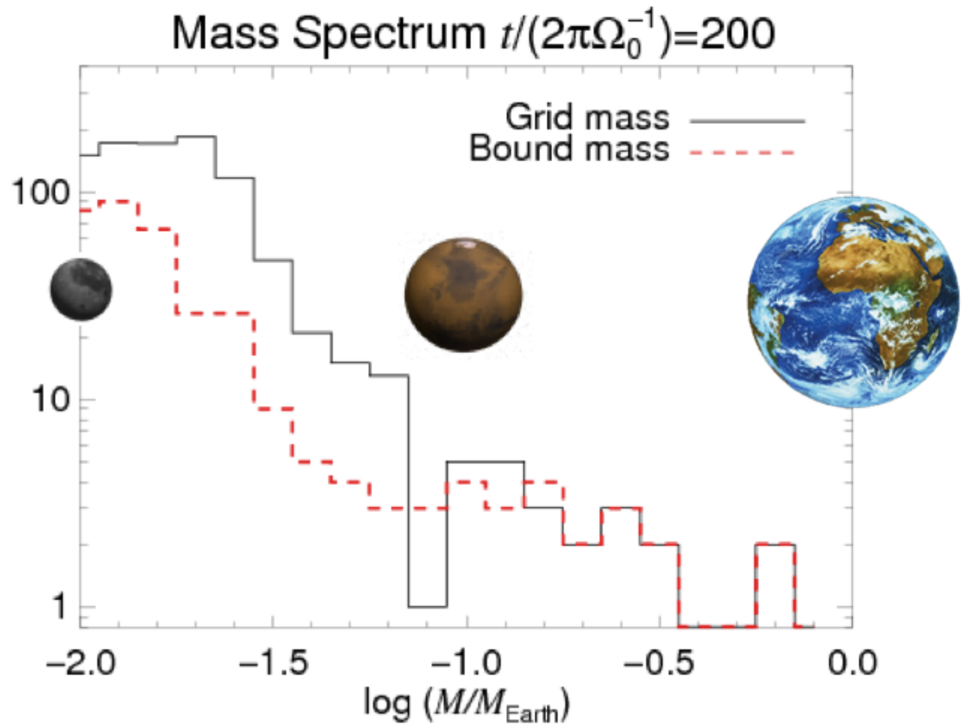




Collapse into Mars mass objects

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

# Vortices and Planet Formation

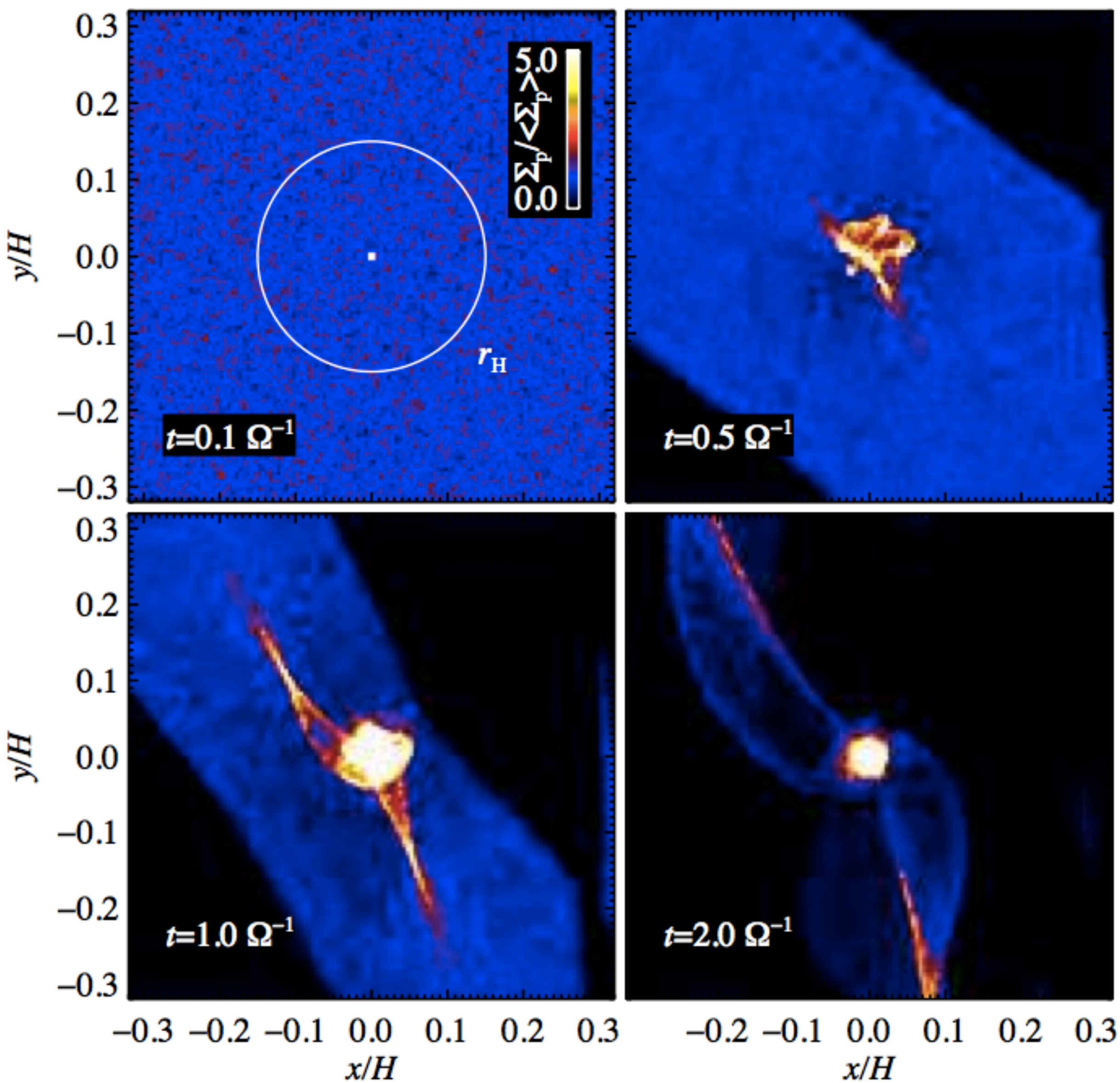



Collapse into Mars mass objects

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

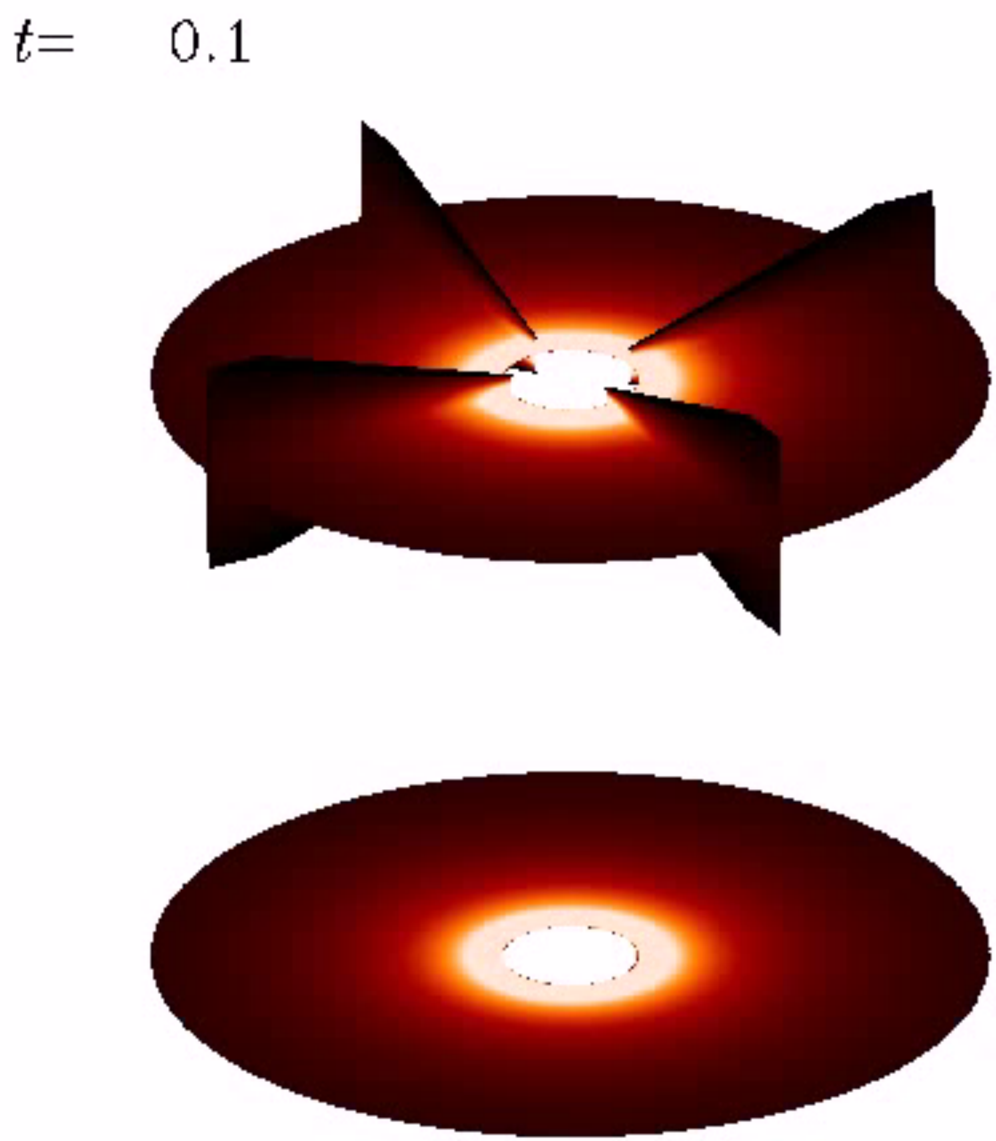
# Gas drag makes the motion dissipative.
# Enhances accretional radius.



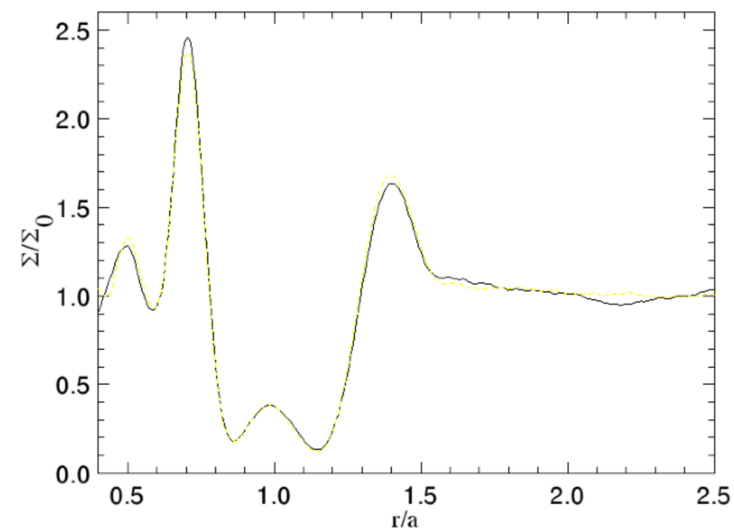

Lambrechts & Johansen (2012)

# Planetary gap RWI

(de Val-Borro et al. 2006, 2007)




Lyra (2009)

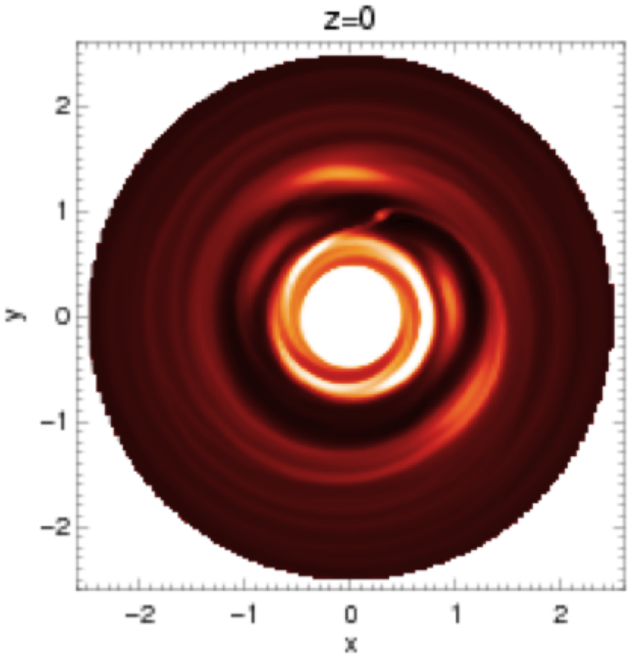


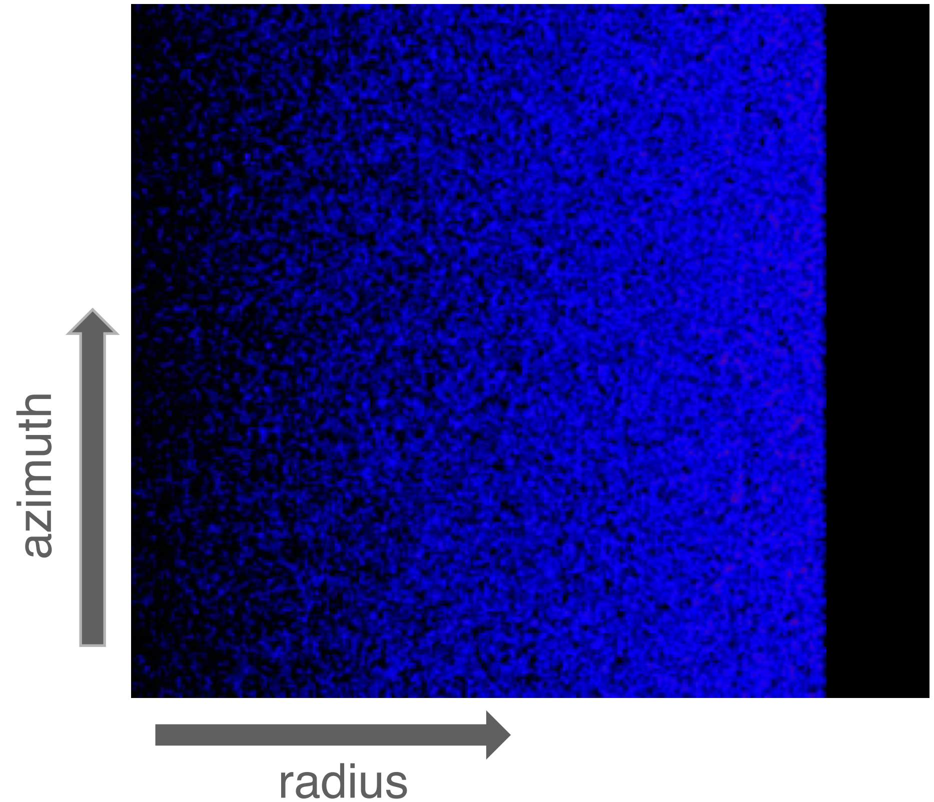

Planet tides carve gap

Gap walls are unstable to Kelvin-Helmholtz instability

# Planetary gap RWI

Lyra et al. (2009b),
see also de Val-Borro et al. (2007)



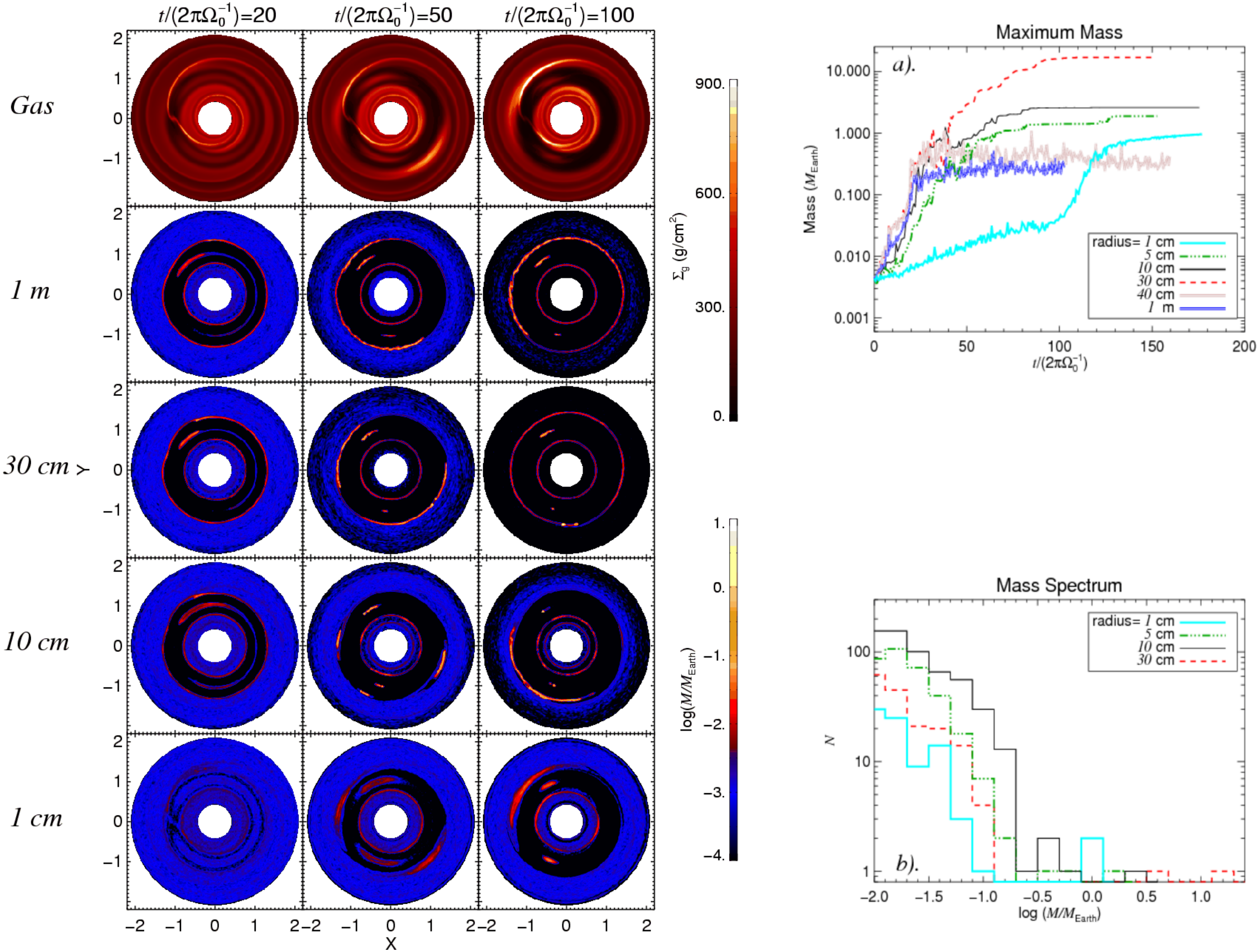




Burst of formation in gap vortices

Plus Trojan planets in Lagrangian clouds

Lyra et al. (2009)

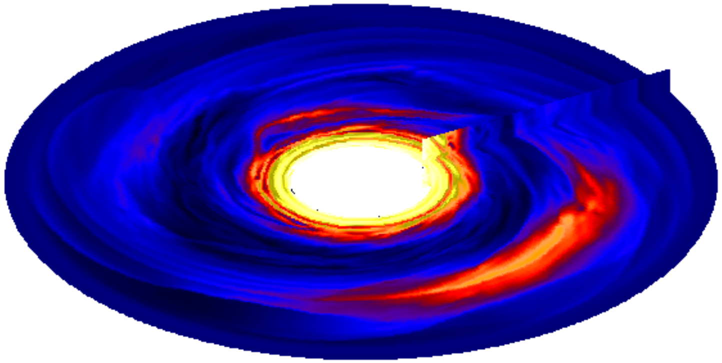
# Planetary gap RWI + secondary burst




Lyra et al. (2009)

# Sustaining vortices in disks

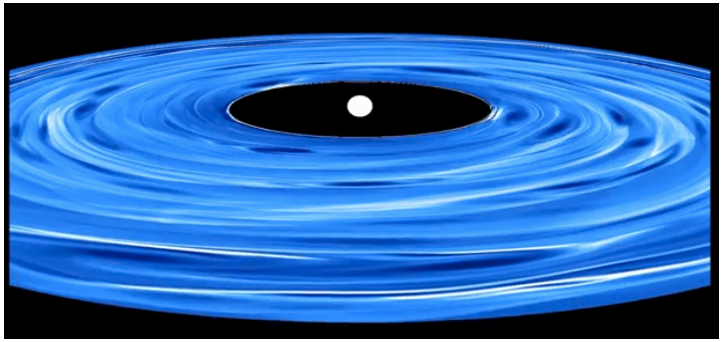
## Rossby wave instability



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)

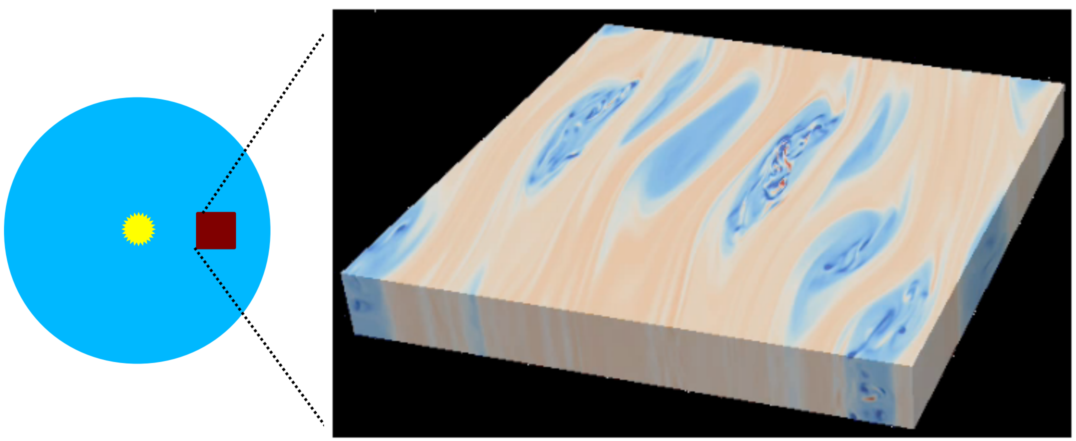
## Convective Overstability



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)

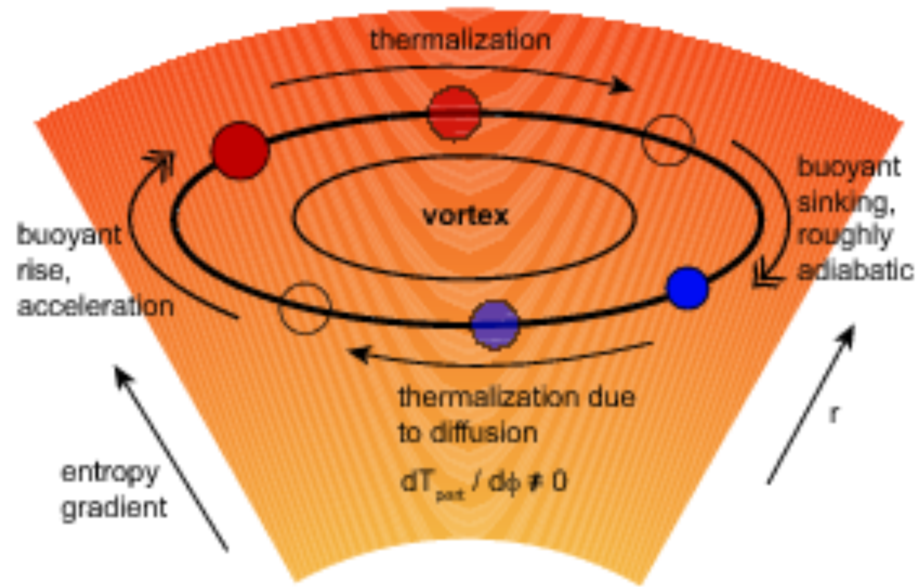
Powered by:
Buyoancy, thermal diffusion
(baroclinic source term)

# Convective Overstability (nee Baroclinic Instability)



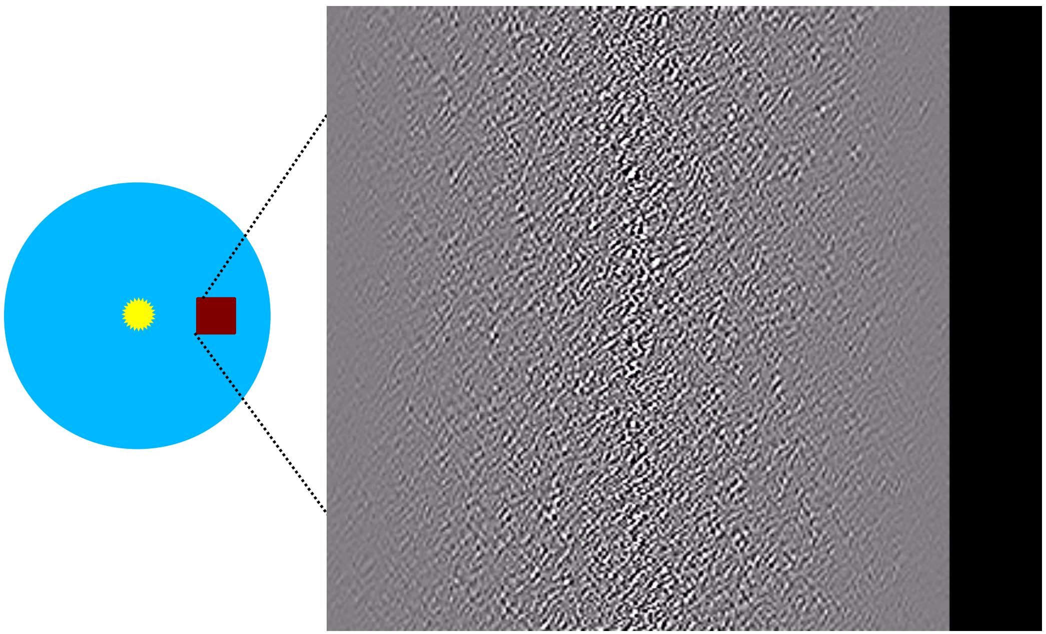
Lesur & Papaloizou (2010)

## Sketch of the Convective Overstability



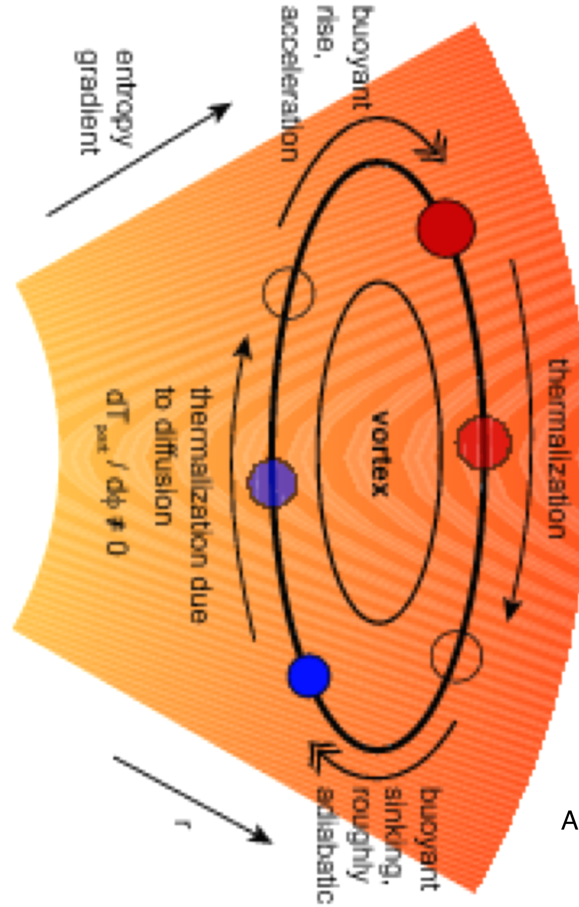

Armitage (2010)

# Convective Overstability



Lyra & Klahr (2011)

Sketch of the
Convective Overstability

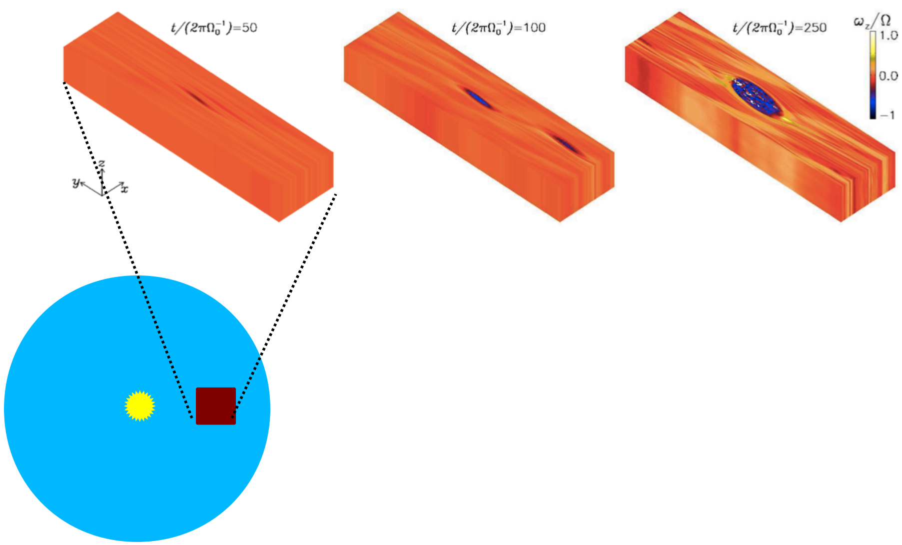



Armitage (2010)

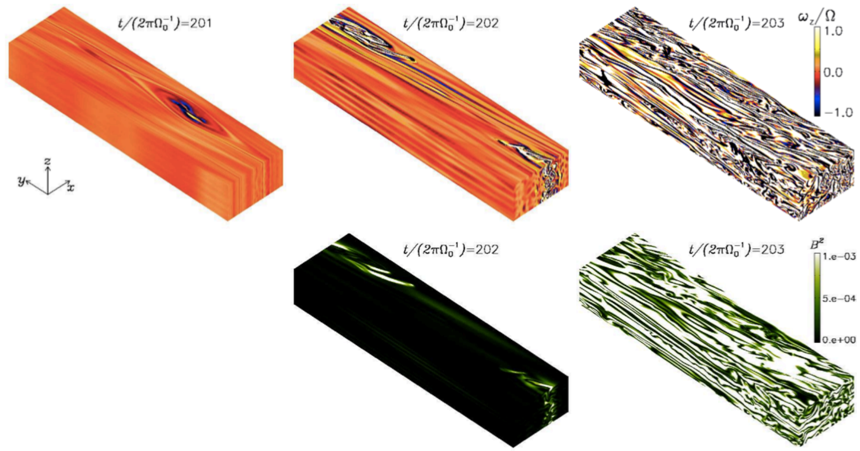
# Vortices and MHD

What happens when the disk is magnetized?

Hydro



MHD

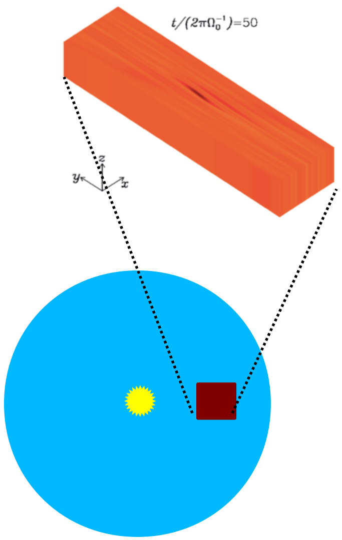


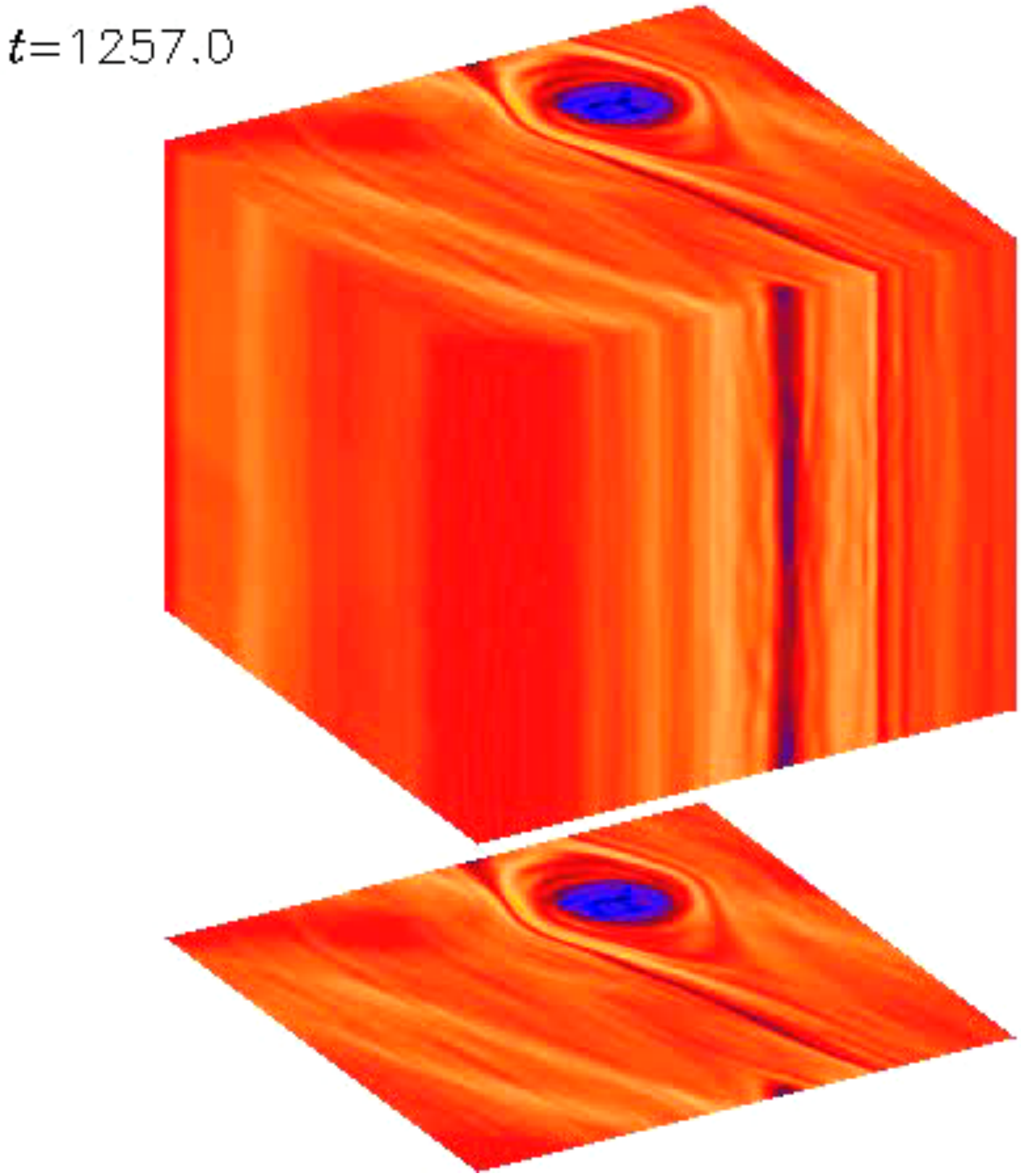
Vorticity

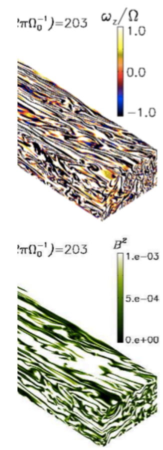
Mag. Energy

Lyra & Klahr (2011)

# Vortices and layered accretion



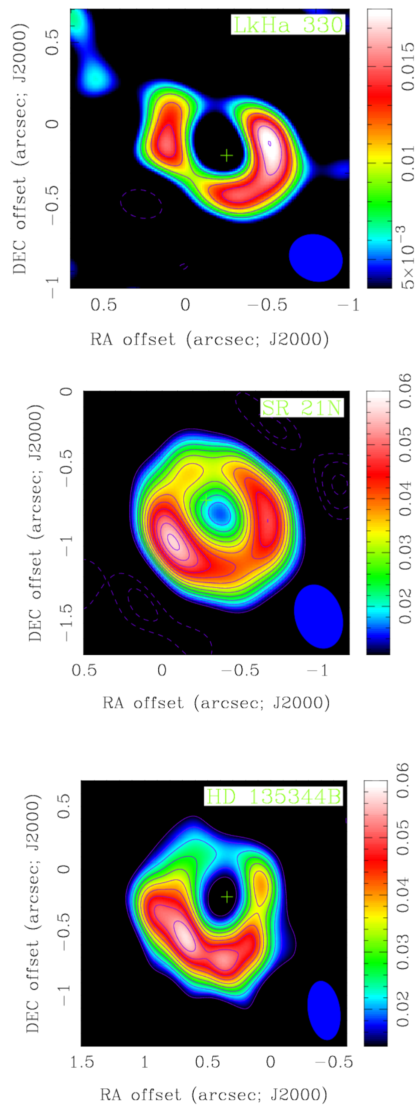

Vorticity

Mag. Energy

# Observational evidence in protoplanetary disks (Exonebulae)

## Observations

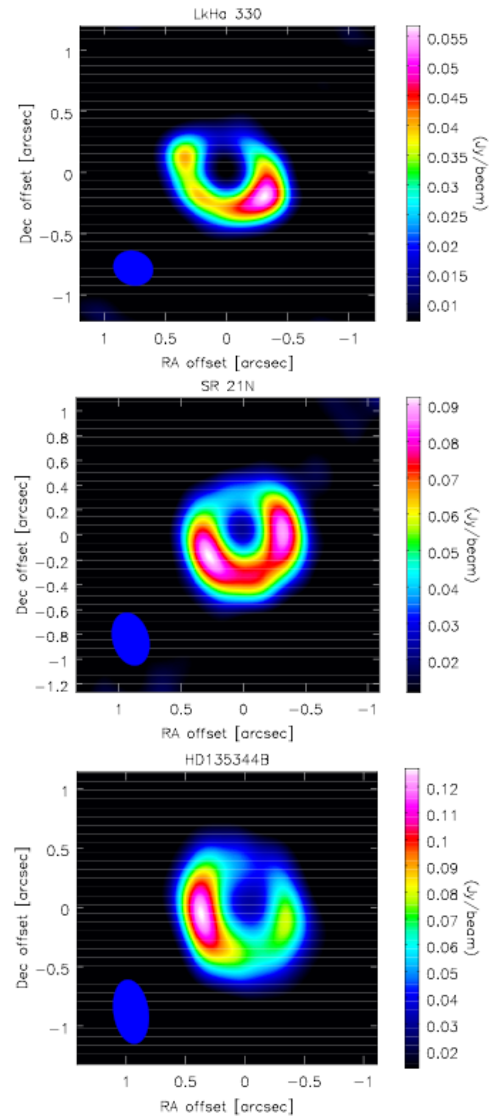
Brown et al. (2009)




## Models

Simulated observations

Regaly et al. (2012)



# Oph IRS 48

## A Major Asymmetric Dust Trap in a Transition Disk

Nienke van der Marel,[1*] Ewine F. van Dishoeck,[1,2] Simon Bruderer,[2] Til Birnstiel,[3] Paola Pinilla,[4] Cornelis P. Dullemond,[4] Tim A. van Kempen,[1,5] Markus Schmalzl,[1] Joanna M. Brown,[3] Gregory J. Herczeg,[6] Geoffrey S. Mathews,[1] Vincent Geers[7]

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

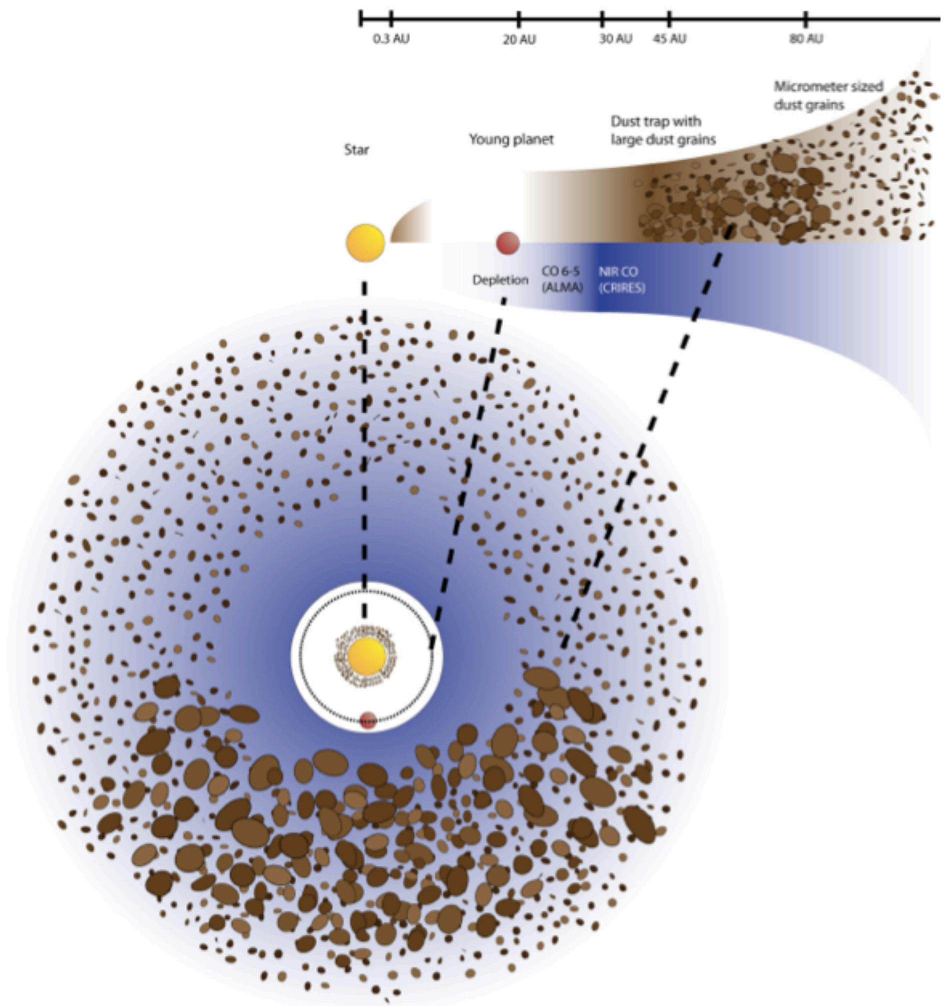
iencemag.org SCIENCE VOL 340 7 JUNE 2013 1199



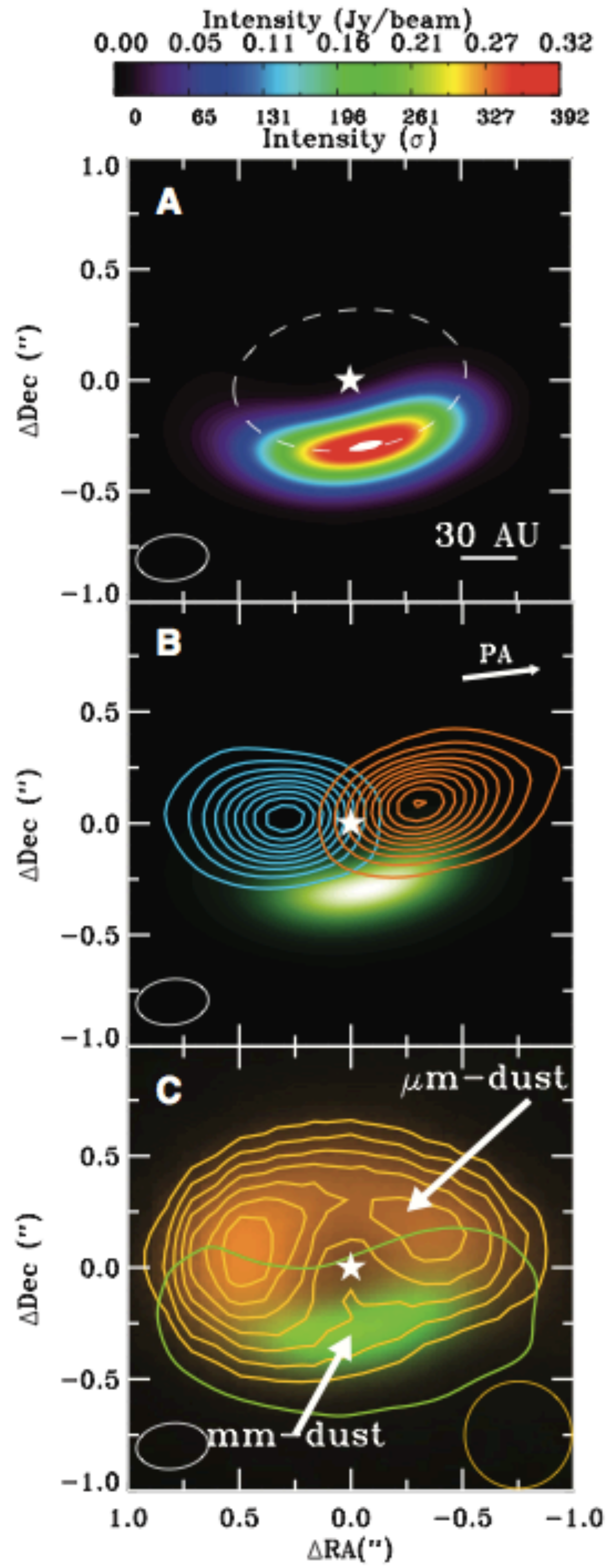
van der Marel et al. 2013

A possible huge vortex observed with ALMA

# *The Oph IRS 48 "dust trap"*




van der Marel et al. (2013)

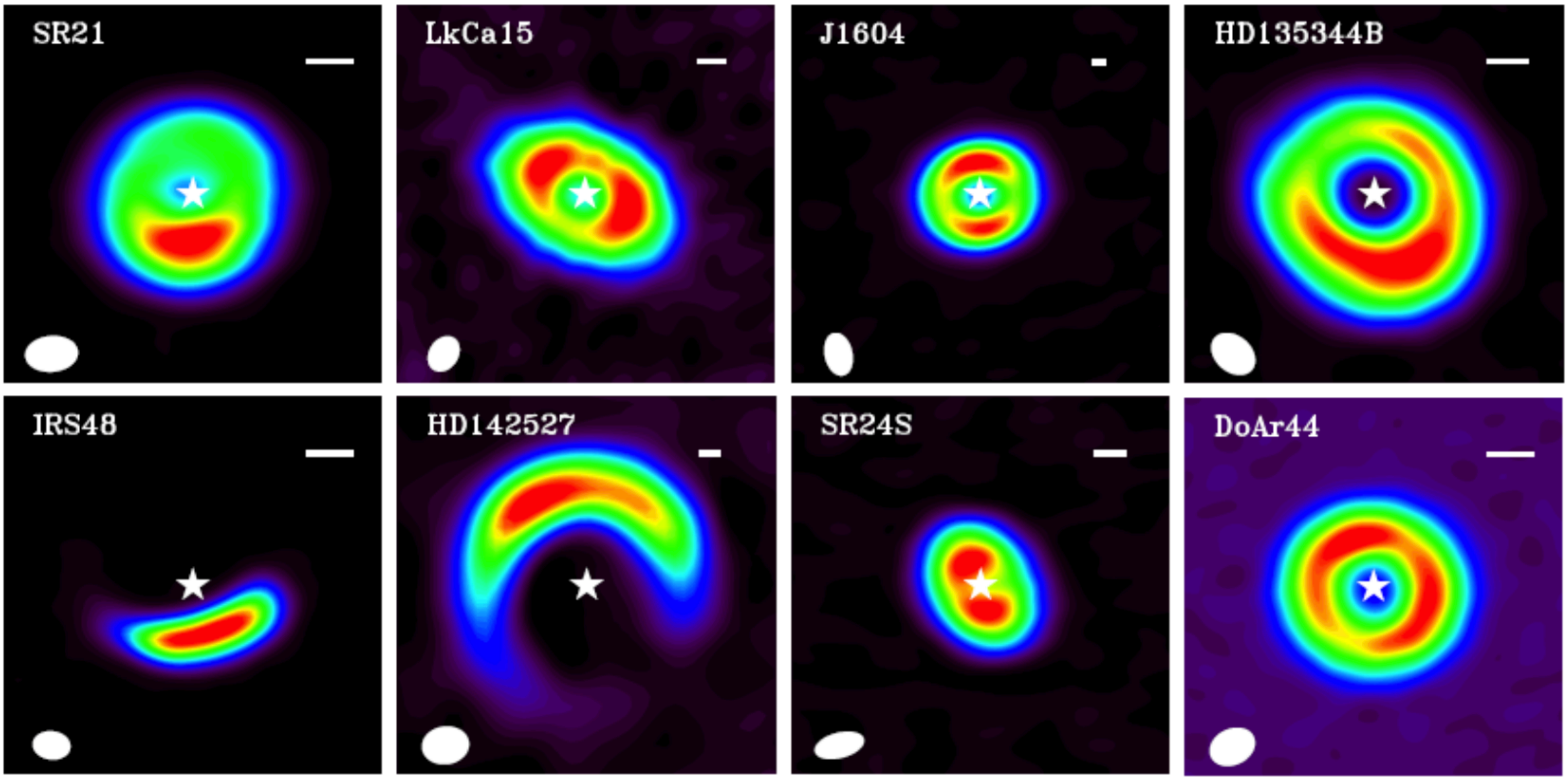



asymmetric
mm dust
at 63 AU

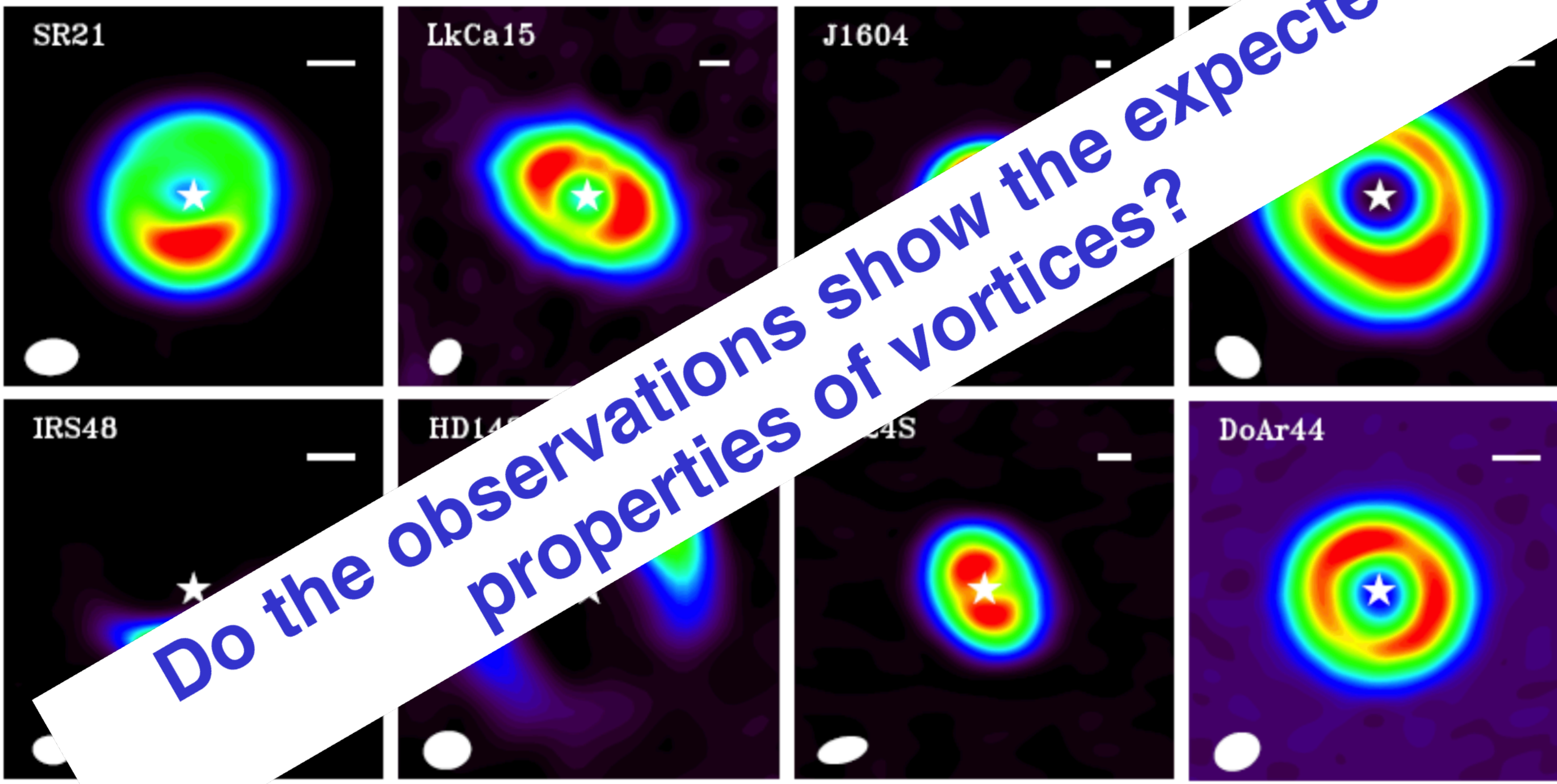
Gas detection:
Keplerian rotation

Micron-sized
dust follows gas

## “Asymmetries” everywhere

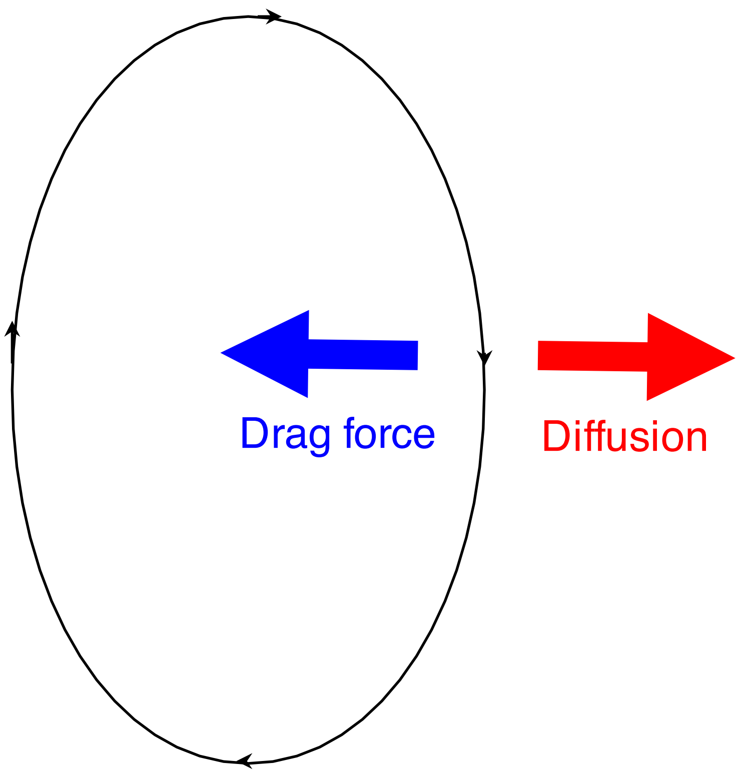


# “Asymmetries” everywhere




## Do the observations show the expected properties of vortices?

# Drag-Diffusion Equilibrium

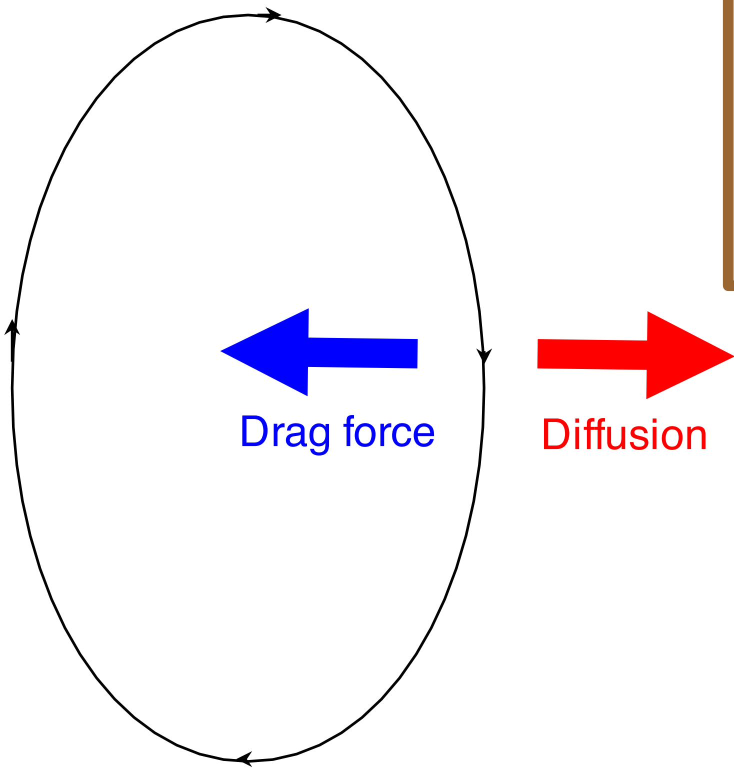



Trapped particle

Dust continuity equation

$$\frac{\partial \rho_d}{\partial t} = \underbrace{-(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d}_{\text{advection}} \underbrace{- \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v}}_{\text{compression}} + \underbrace{D\nabla^2 \rho_d}_{\text{diffusion}},$$

# Drag-Diffusion Equilibrium




Trapped particle

Steady-state solution

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

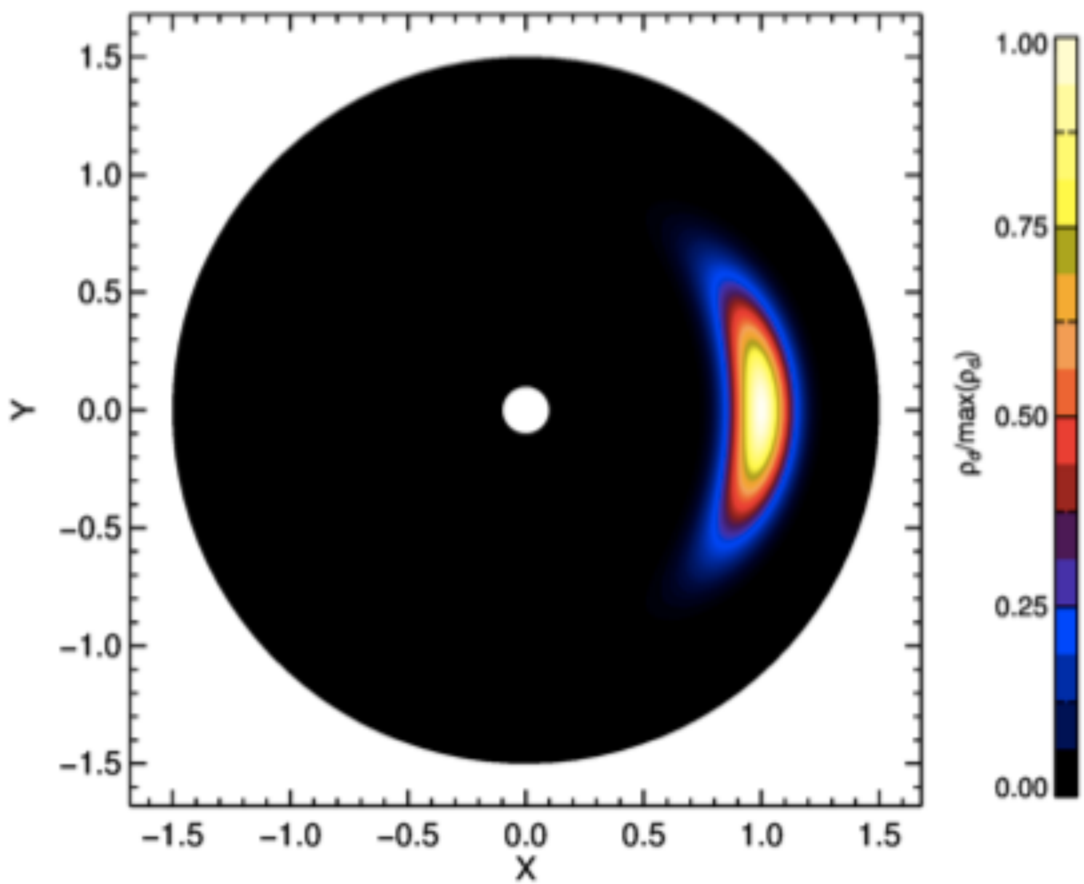
Lyra & Lin (2013)

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

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

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

# Analytical solution for dust trapping




Solution for

*H/r=0.1* *χ=4* *S=1*

**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)
$\chi$ = vortex aspect ratio
$\delta$ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function

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)
$\chi$ = vortex aspect ratio
$\delta$ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function
$\varepsilon$ = 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 $M_{Earth}$***

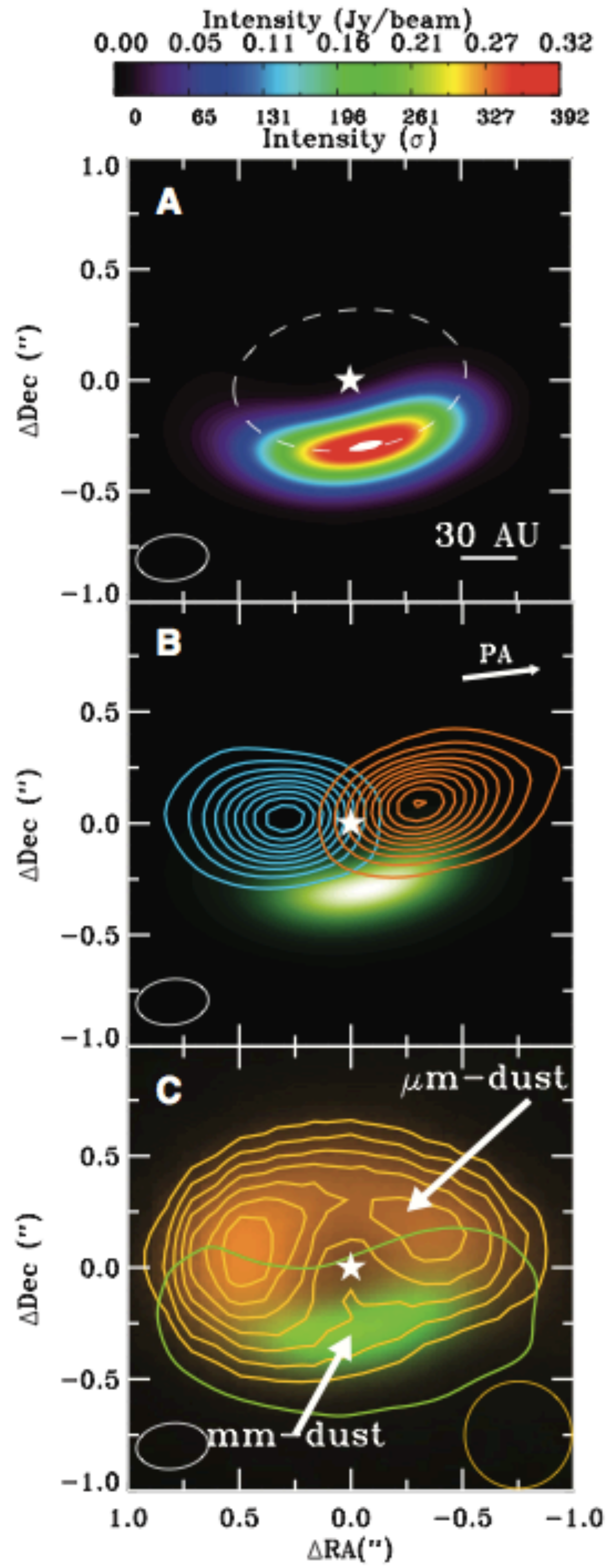
Derived parameters

S=4.8

Stokes number, St=0.008

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

***Trapped mass: 11 $M_{Earth}$***



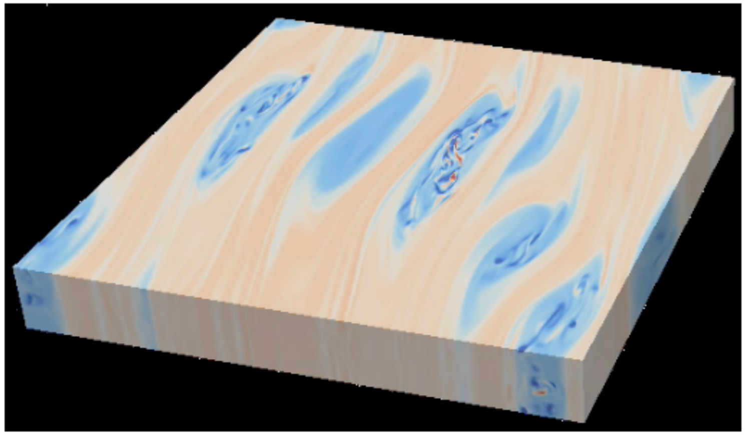

Lyra & Lin (2013)

asymmetric mm dust at 63 AU

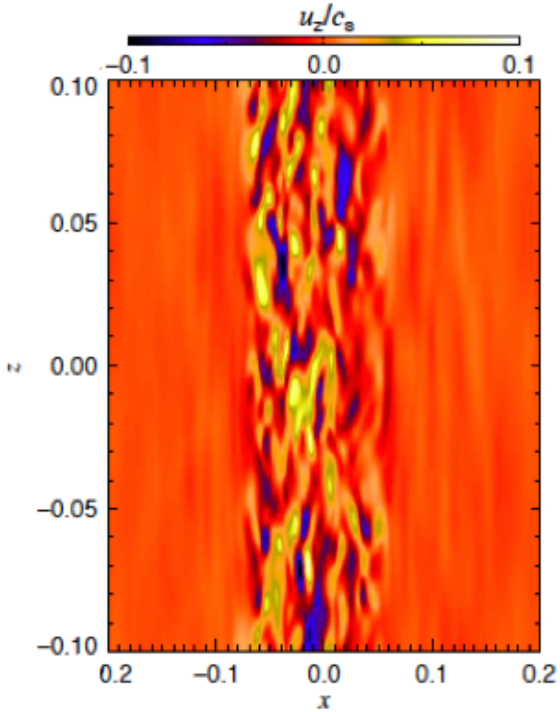
Gas detection: Keplerian rotation

Micron-sized dust follows gas

# Turbulence in vortex cores



Lesur & Papaloizou (2010)

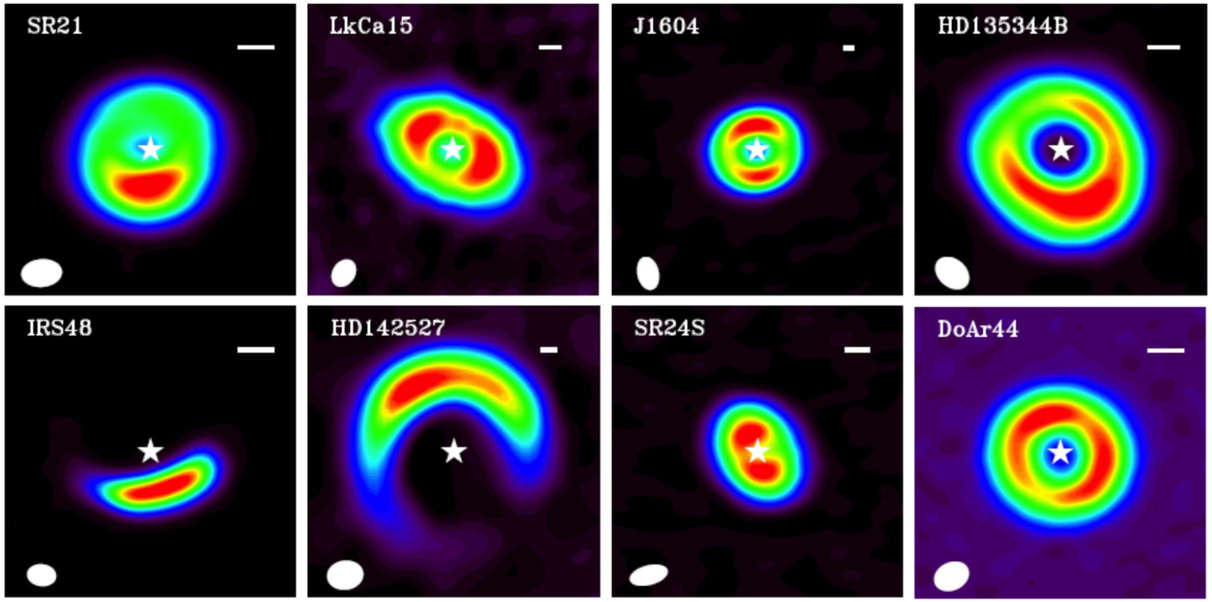


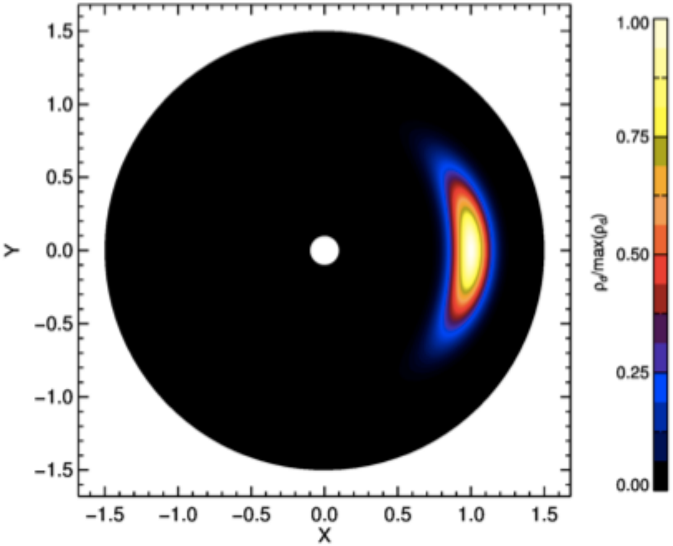

Lyra & Klahr (2011)

Turbulence in vortex cores:

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

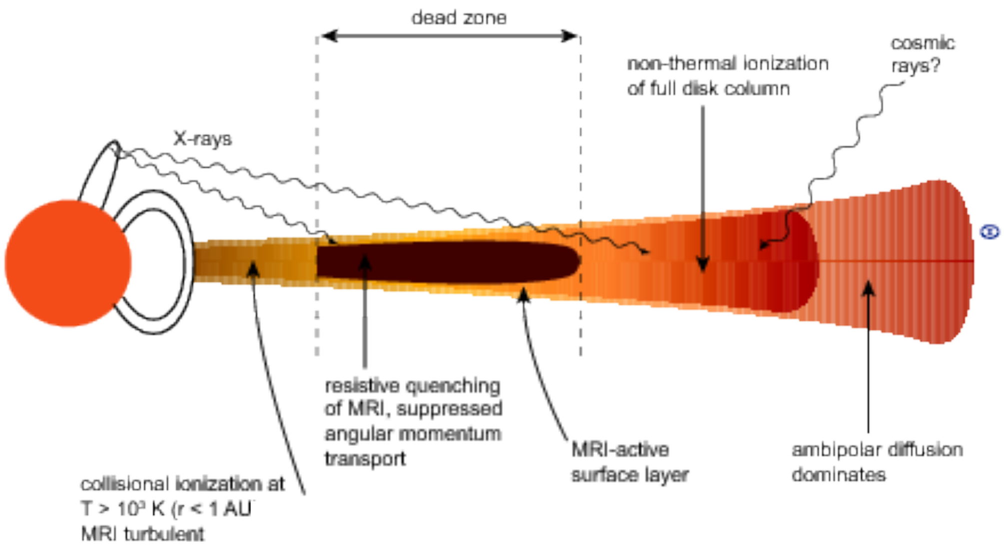
# Observed asymmetries consistent with vortices…



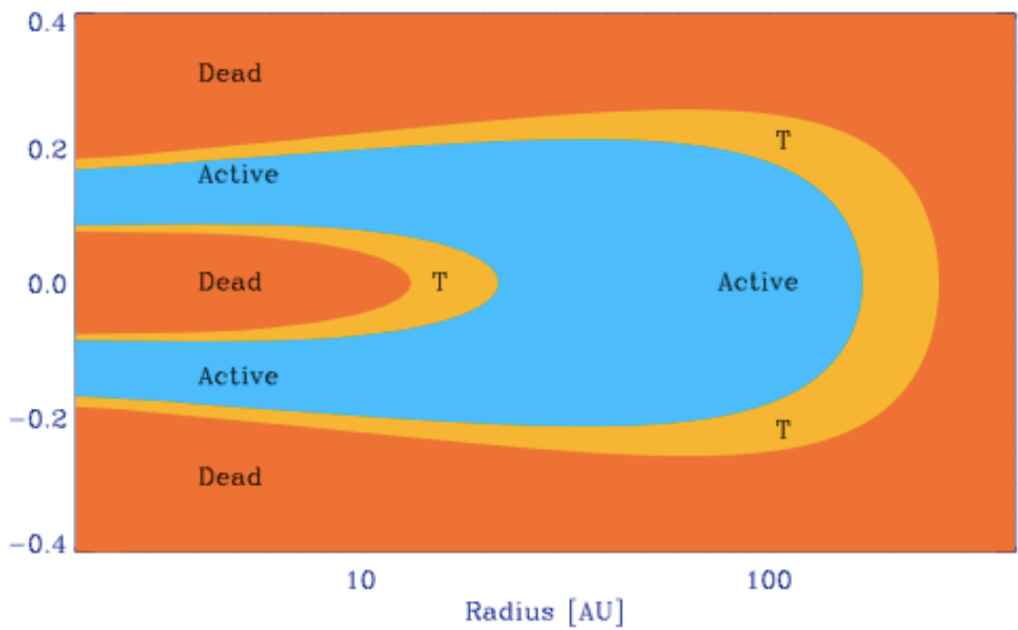




But origin still elusive…

# Outer Dead/Active zone transition RWI




Armitage (2010)



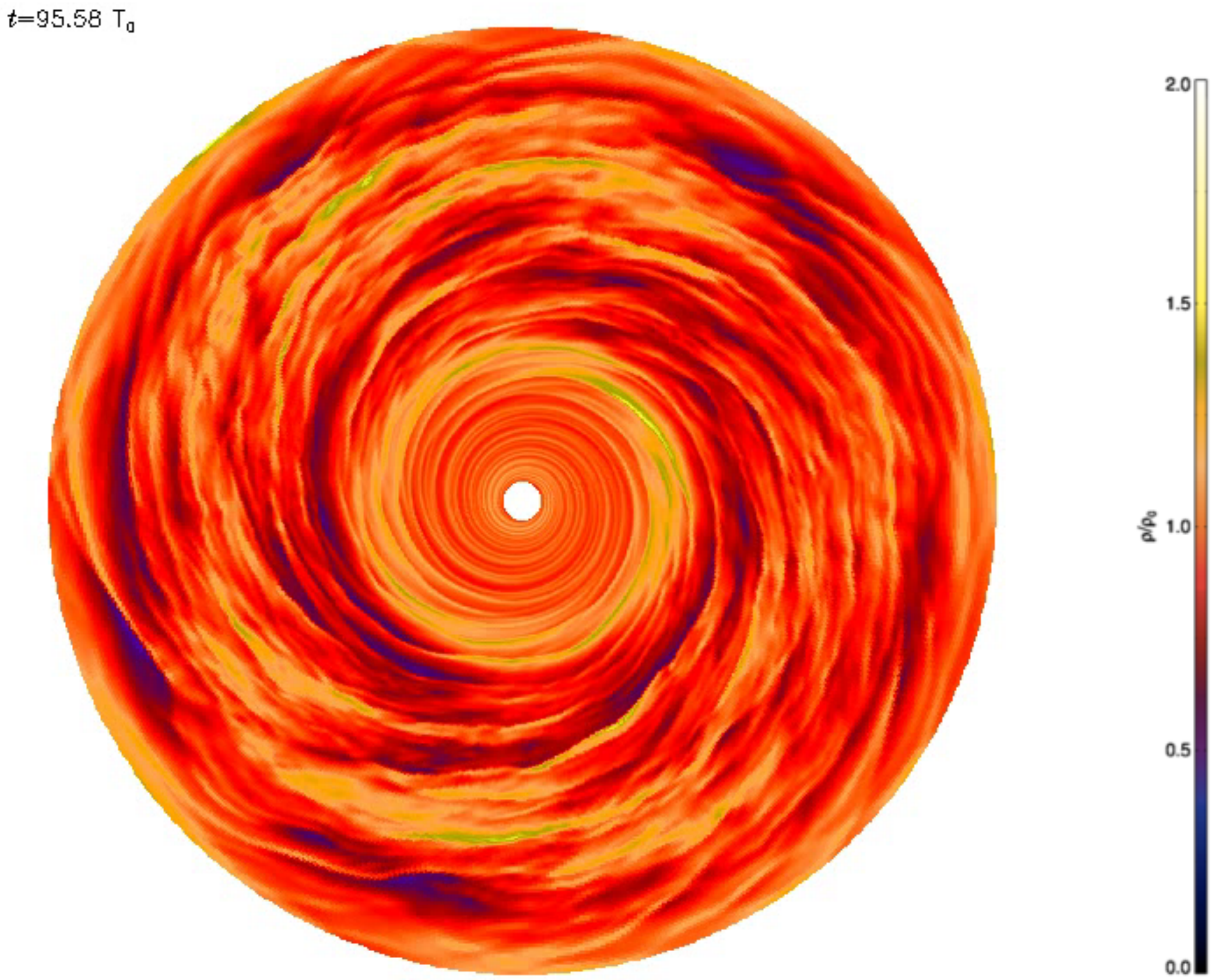

Dzyurkevitch et al (2013)

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

**TOO SMOOTH**

to generate an KH-unstable bump.

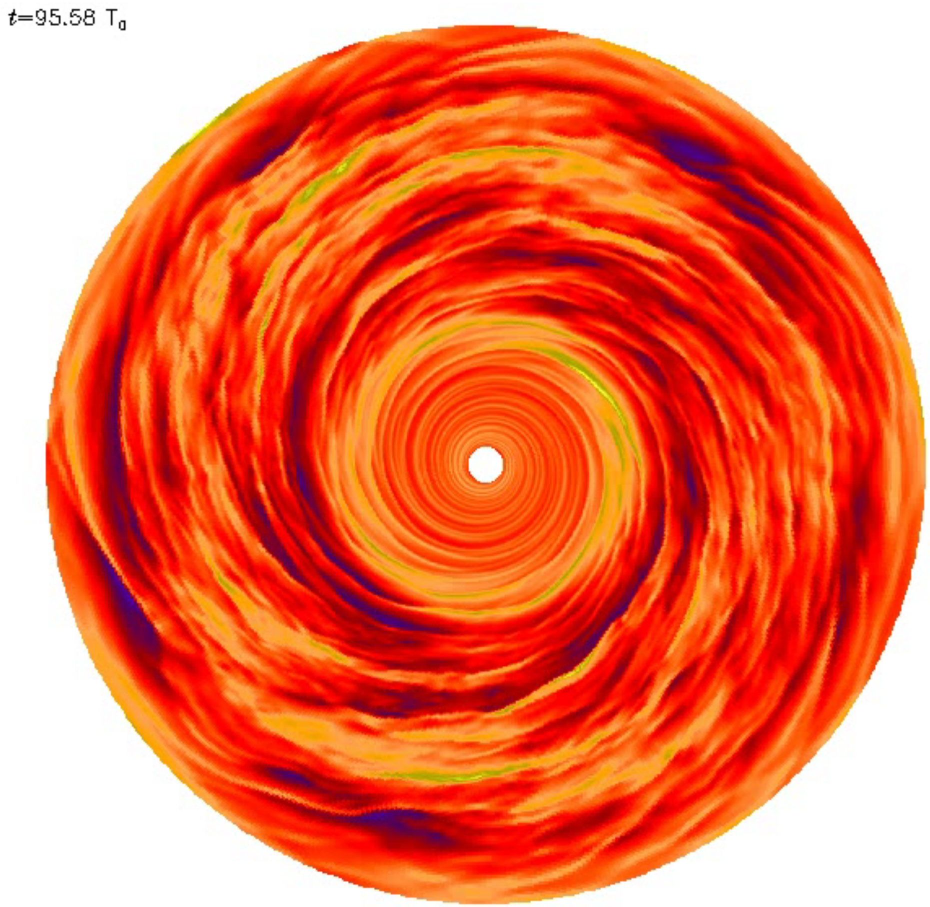
# Outer Dead/Active zone transition: 3D MHD

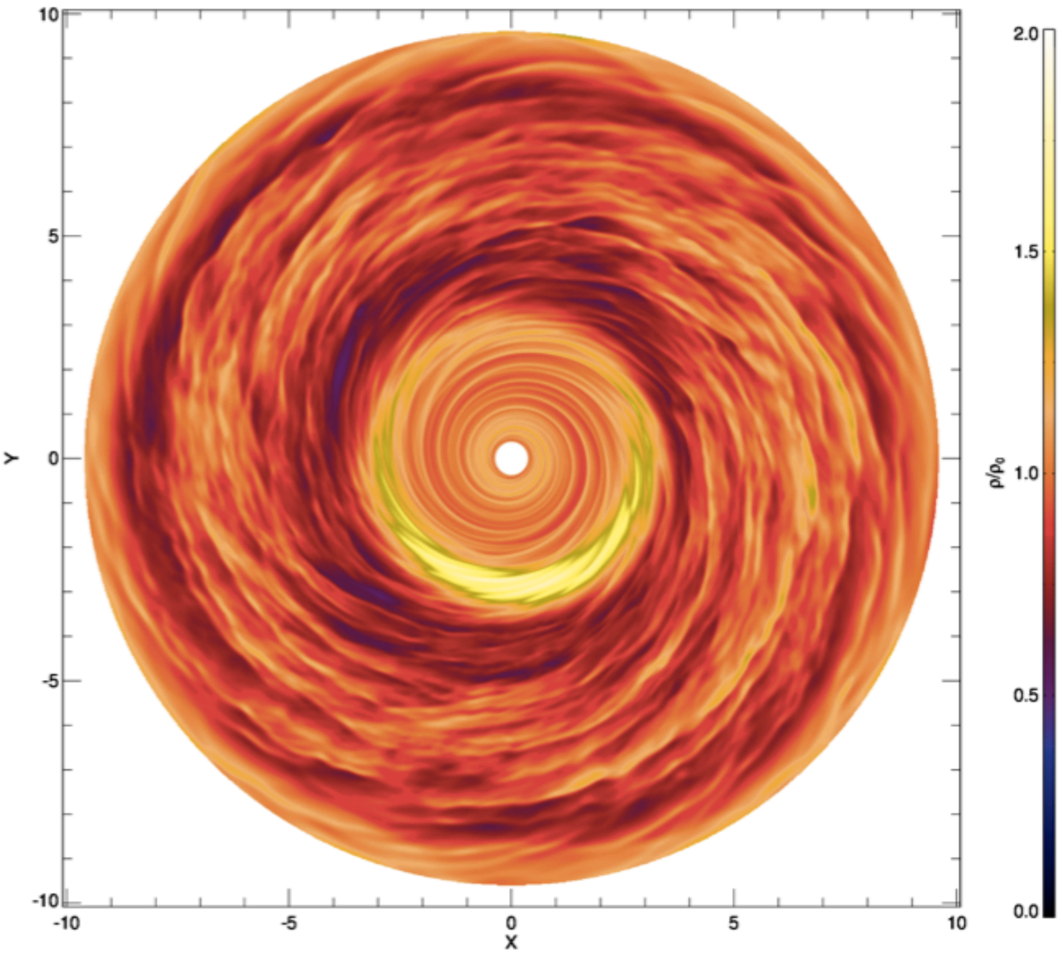



Resistive inner disk + magnetized outer disk

Lyra et al (2015)

# Outer Dead/Active zone transition KHI

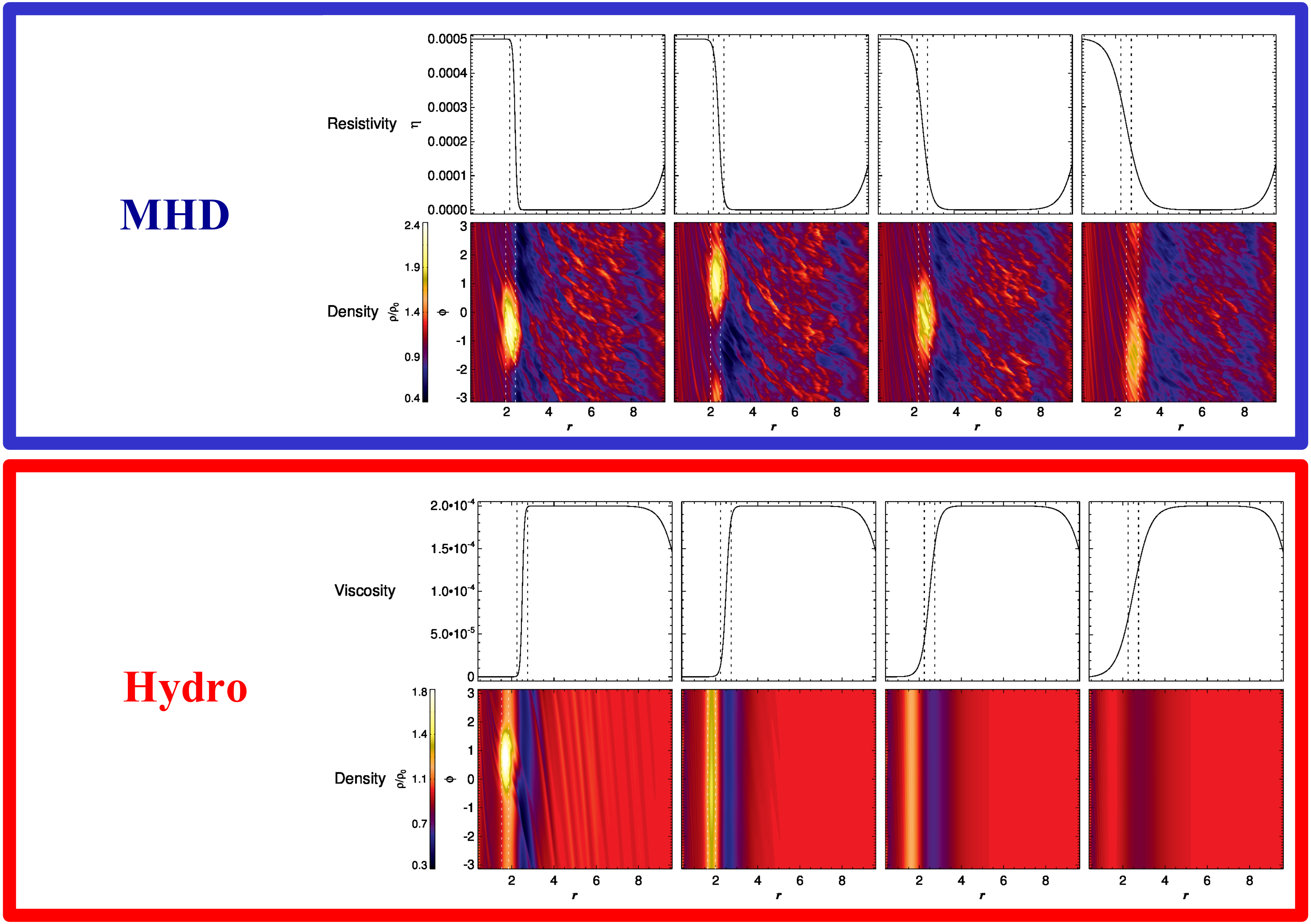



Resistive inner disk + magnetized outer disk

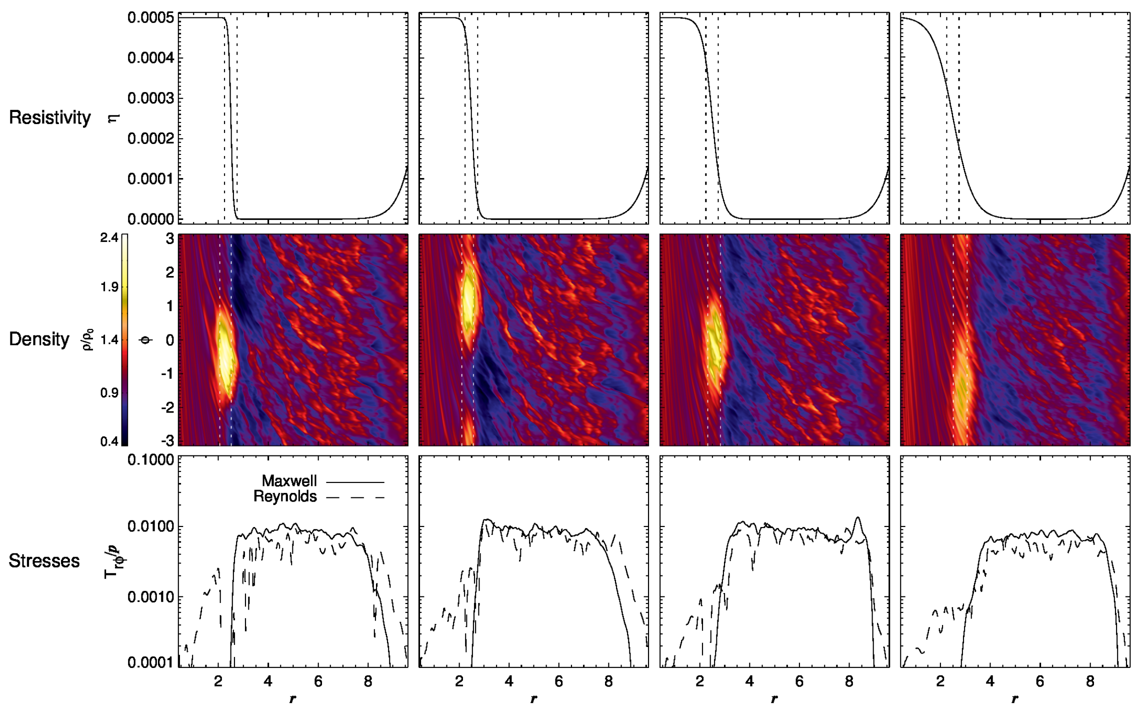
Lyra, Turner, & McNally (2015)

# Outer Dead/Active zone transition RWI




Lyra, Turner, & McNally (2015)

# Outer Dead/Active zone transition RWI




Lyra, Turner, & McNally (2015)

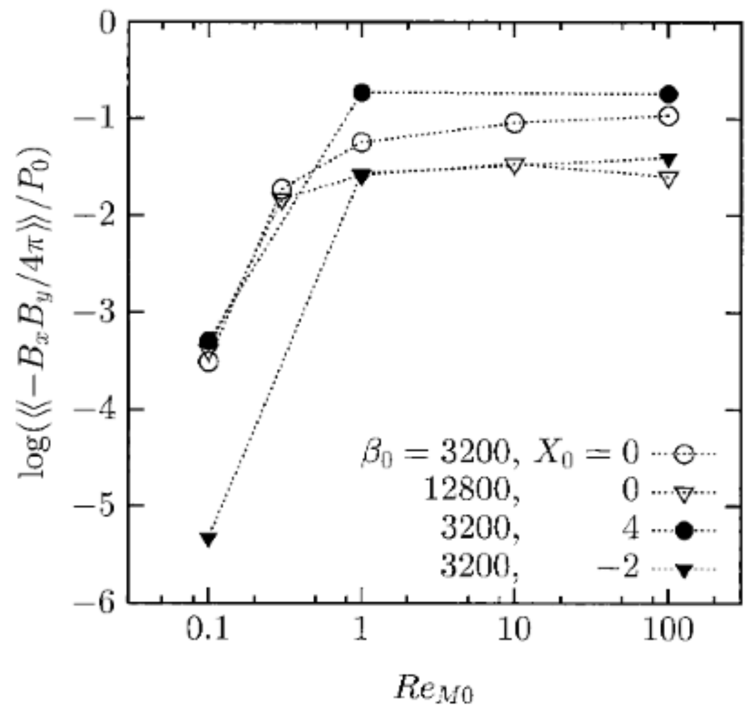
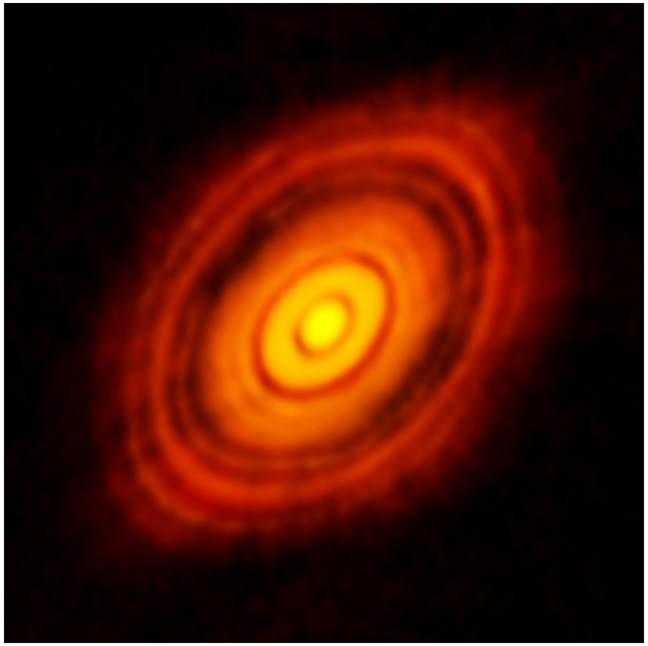


FIG. 9.—Saturation level of the Maxwell stress as a function of the magnetic Reynolds number $Re_{M0}$. Open circles and triangles denote the models without Hall term ($X_0 = 0$) for $\beta_0 = 3200$ and 12,800, respectively. The models including the Hall term are shown by filled circles ($X_0 = 4$) and triangles ($X_0 = -2$).

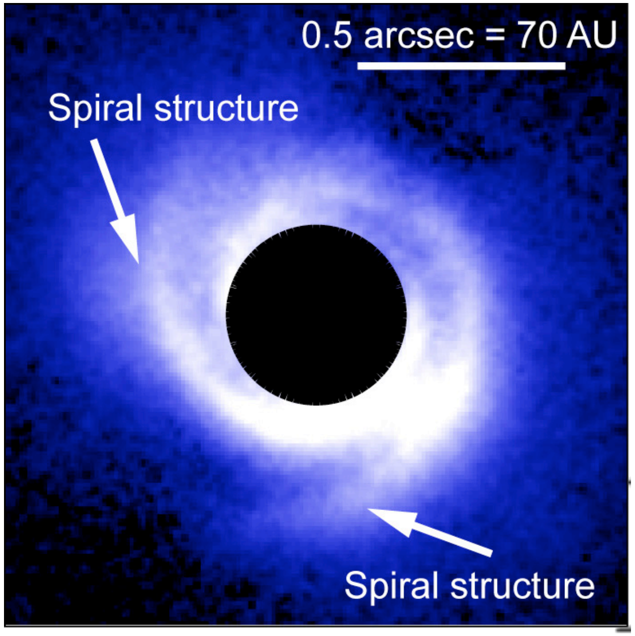
Sano and Stone (2002)

# Observational evidence: gaps, spirals, and vortices

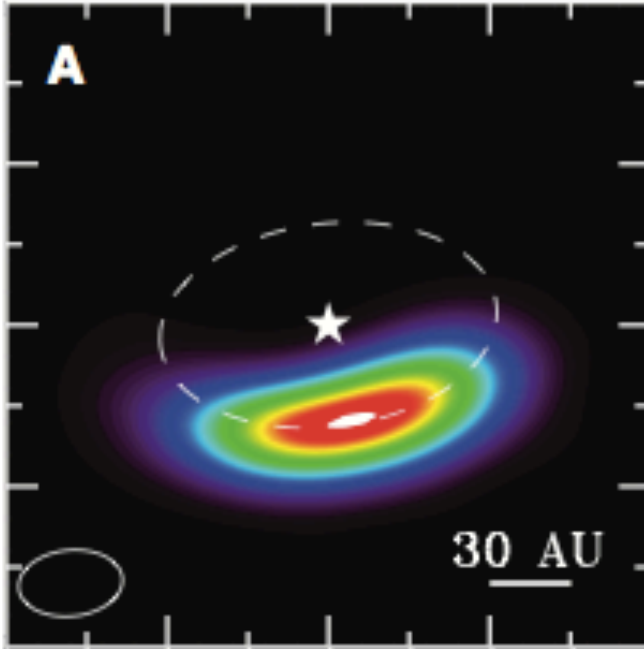
HL Tau



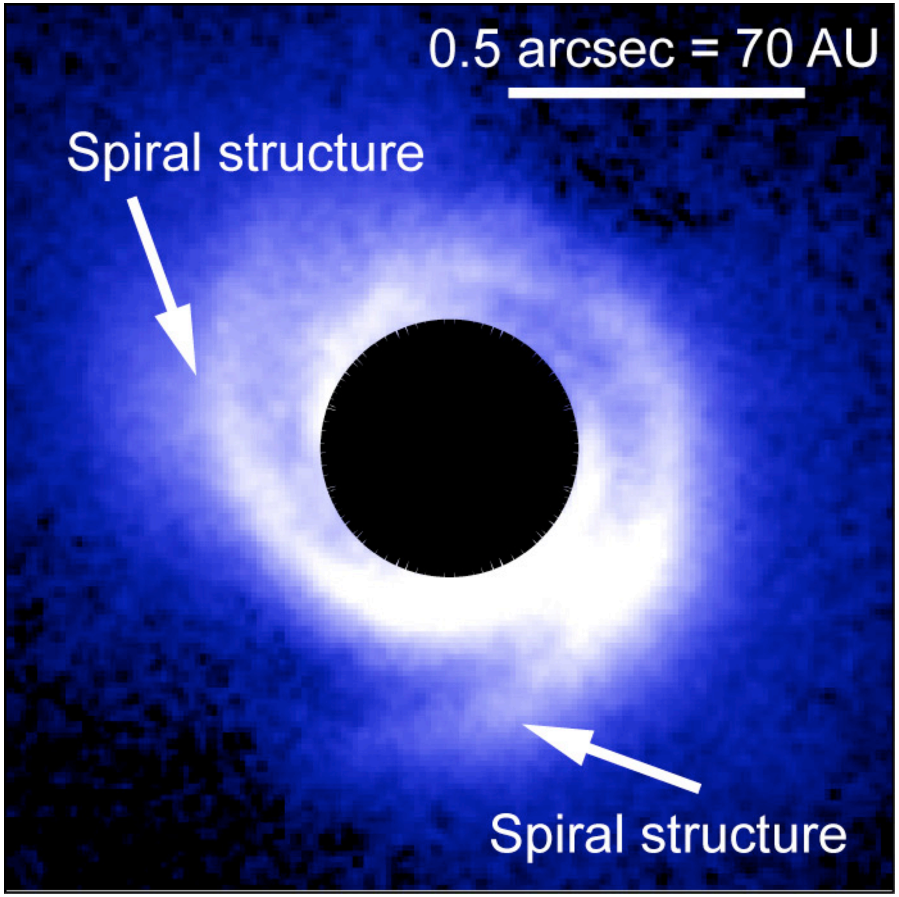
SAO 206462



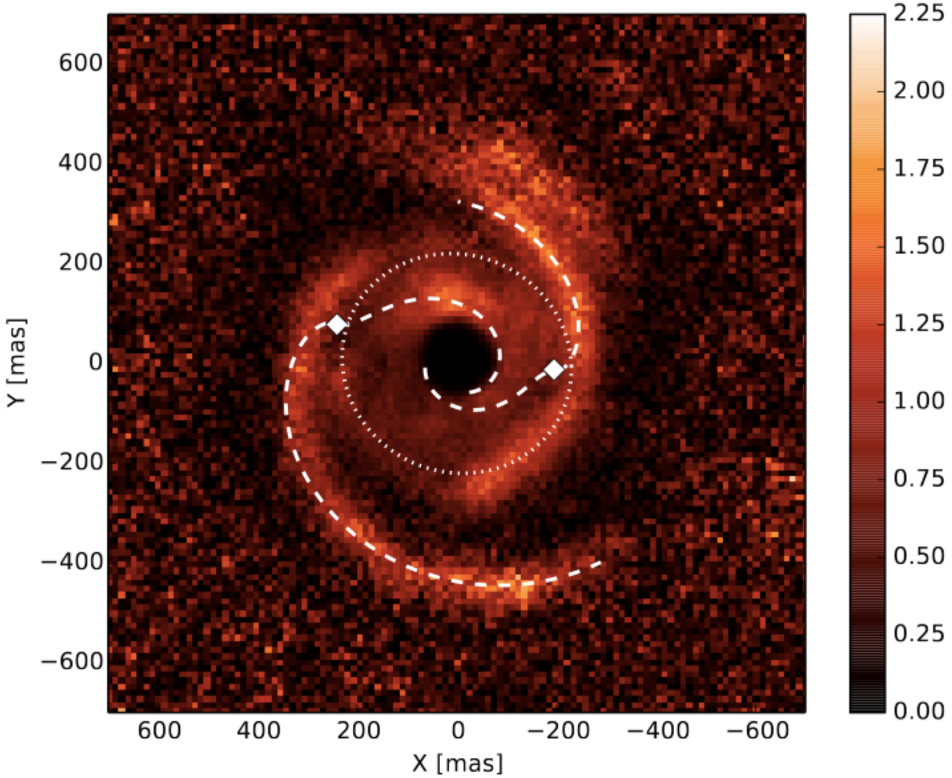

Oph IRS 48



# Observational evidence: Spirals



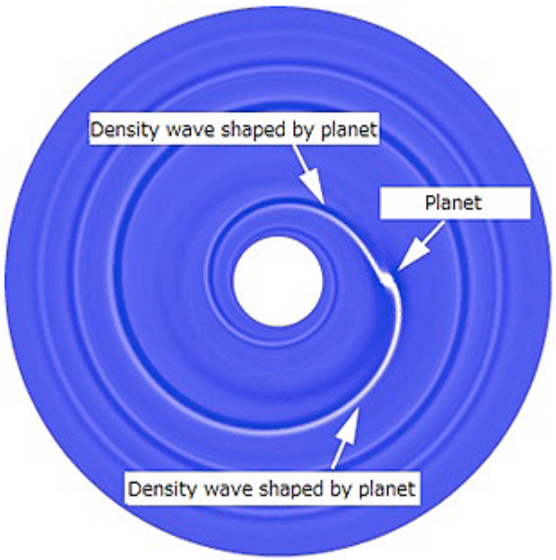

Muto et al. (2012)




Benisty et al. (2015)

# Spiral arm fitting leads to problems

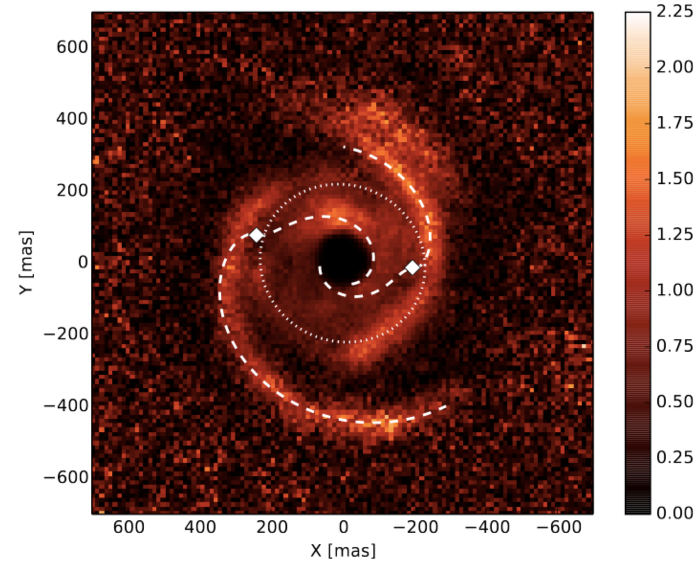
## Analytical spiral fit




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

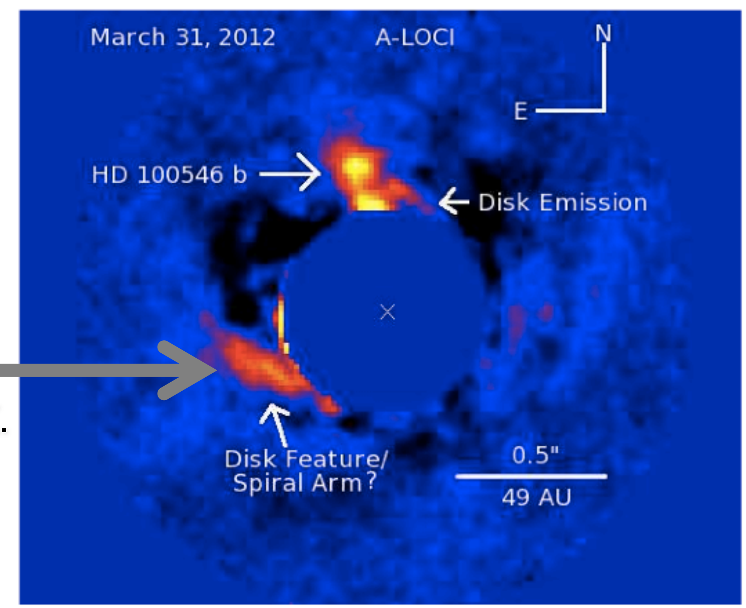
Rafikov (2002)
Muto et al. (2012)

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



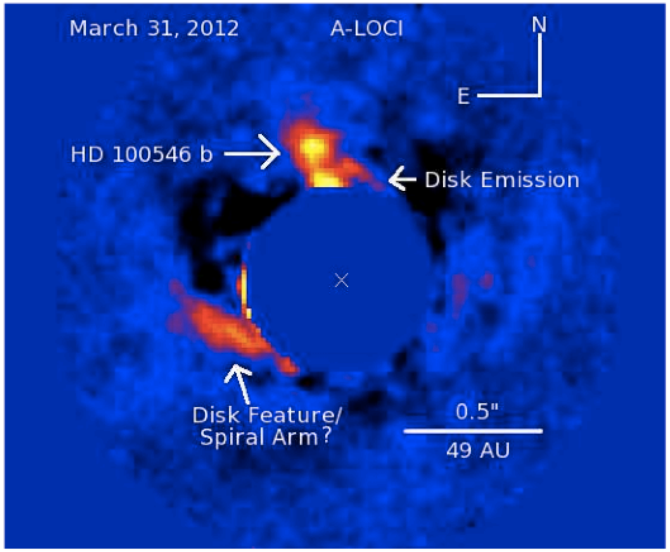

Benisty et al. (2015)

Spiral has little polarization. Must be thermal emission at ~450K.

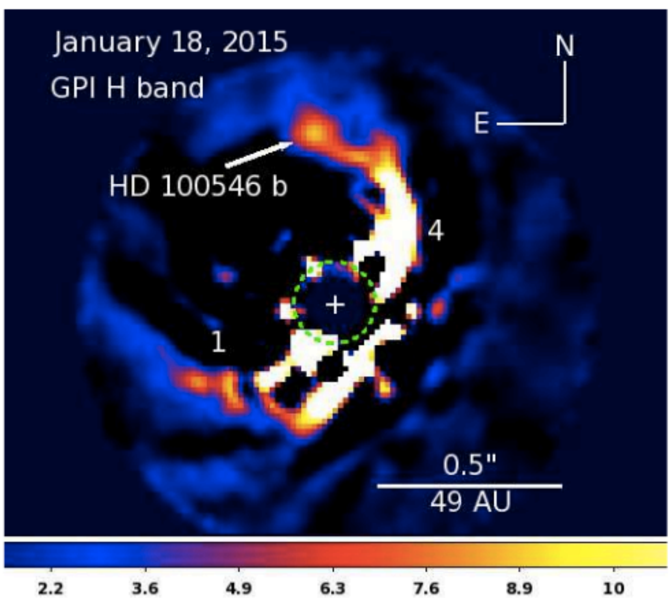



Currie et al. (2014)

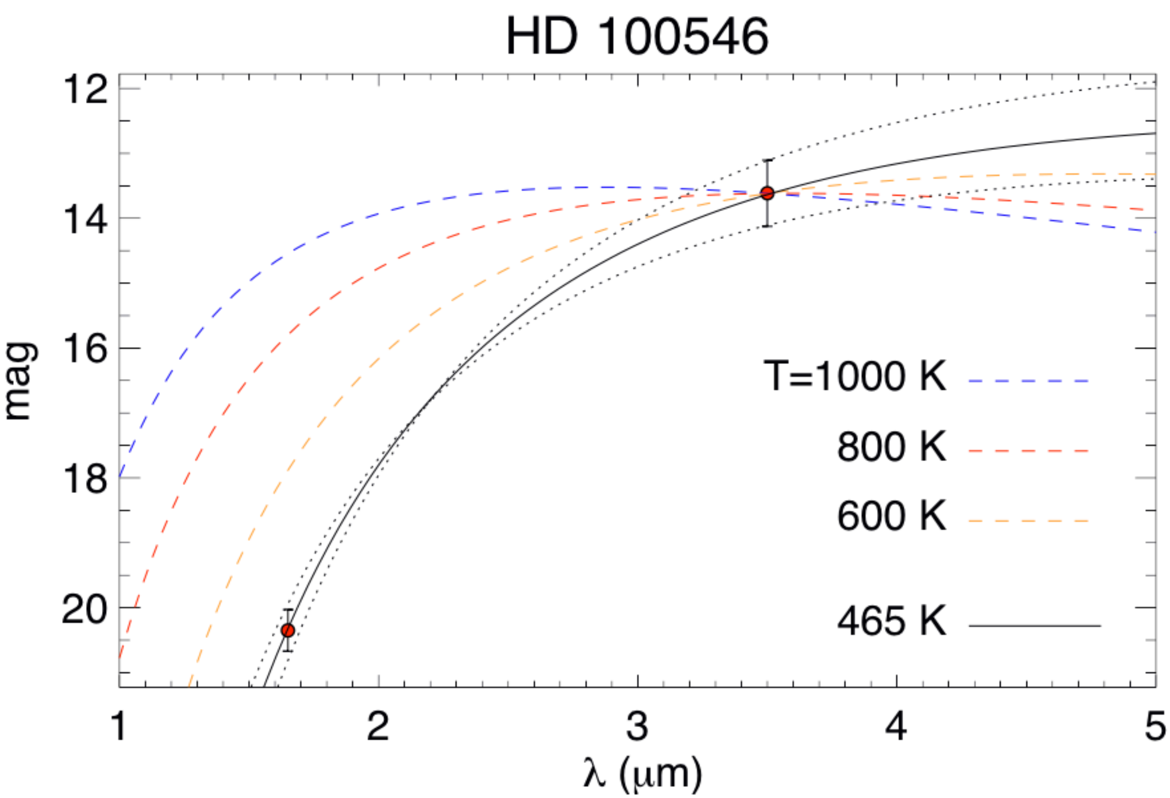
# HD 100546




Currie et al. (2014) – L band

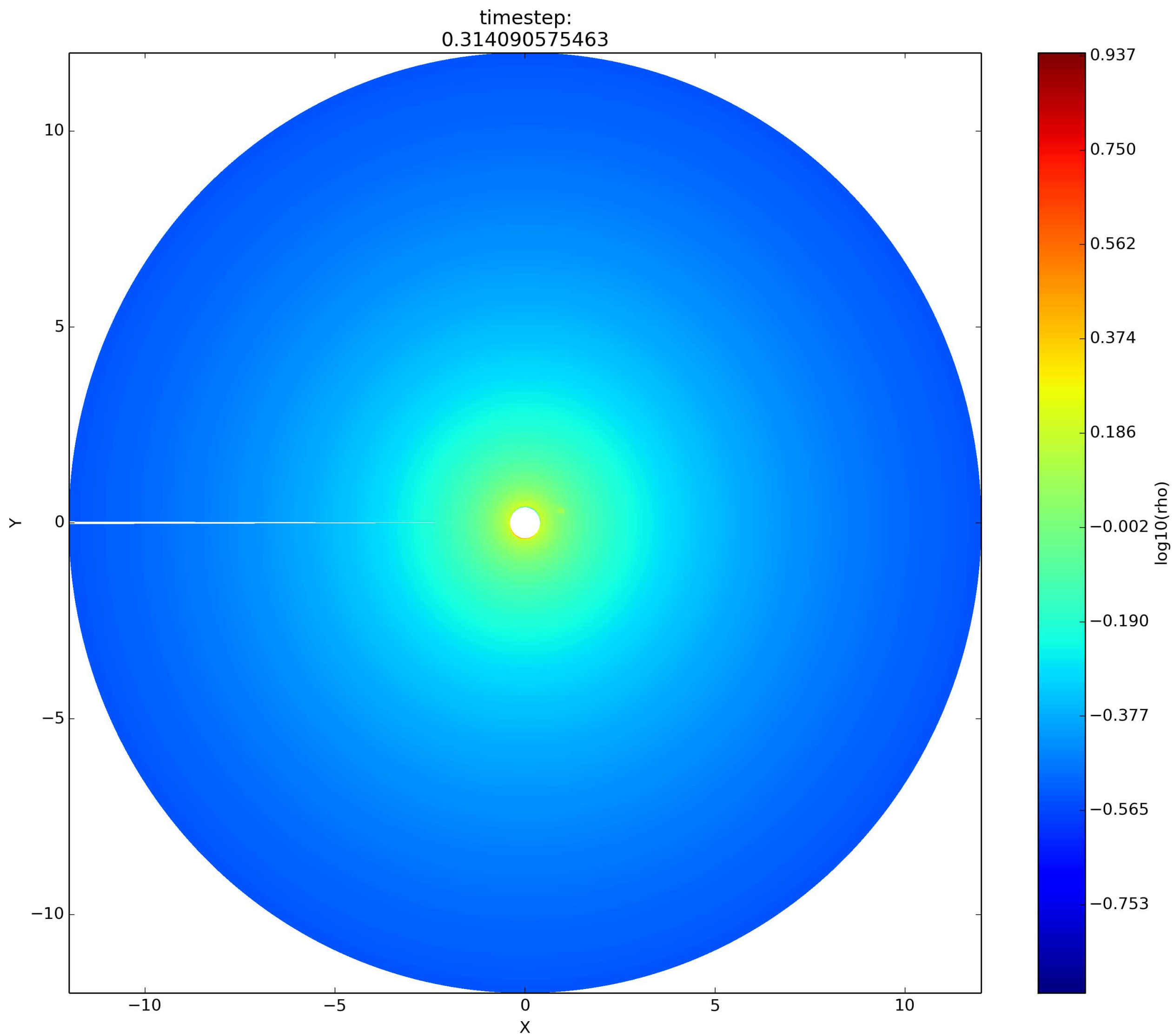



Currie et al. (2015) – H band



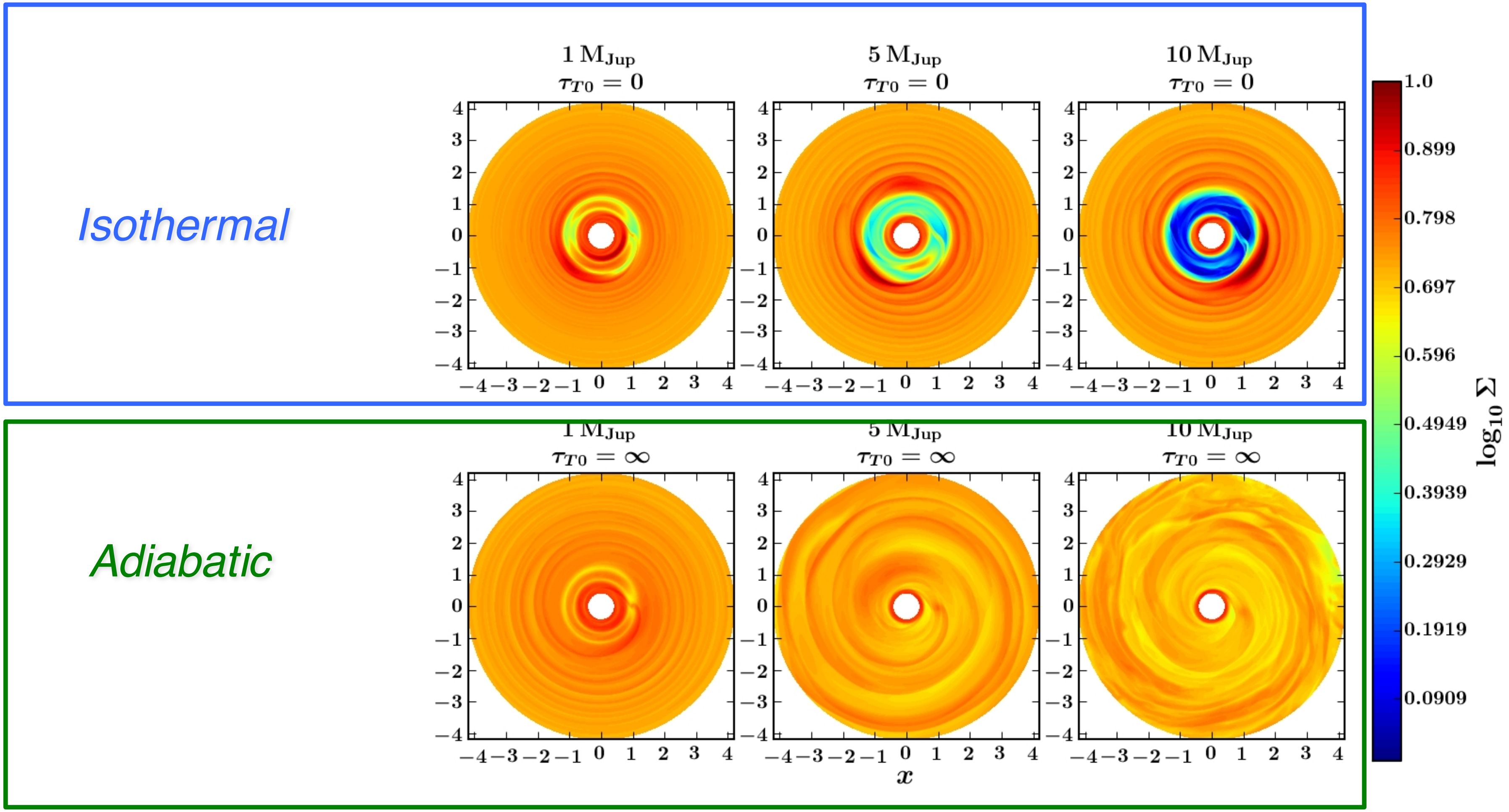

Lyra et al. (2016)

# Spiral wake of high-mass planets in non-isothermal disks



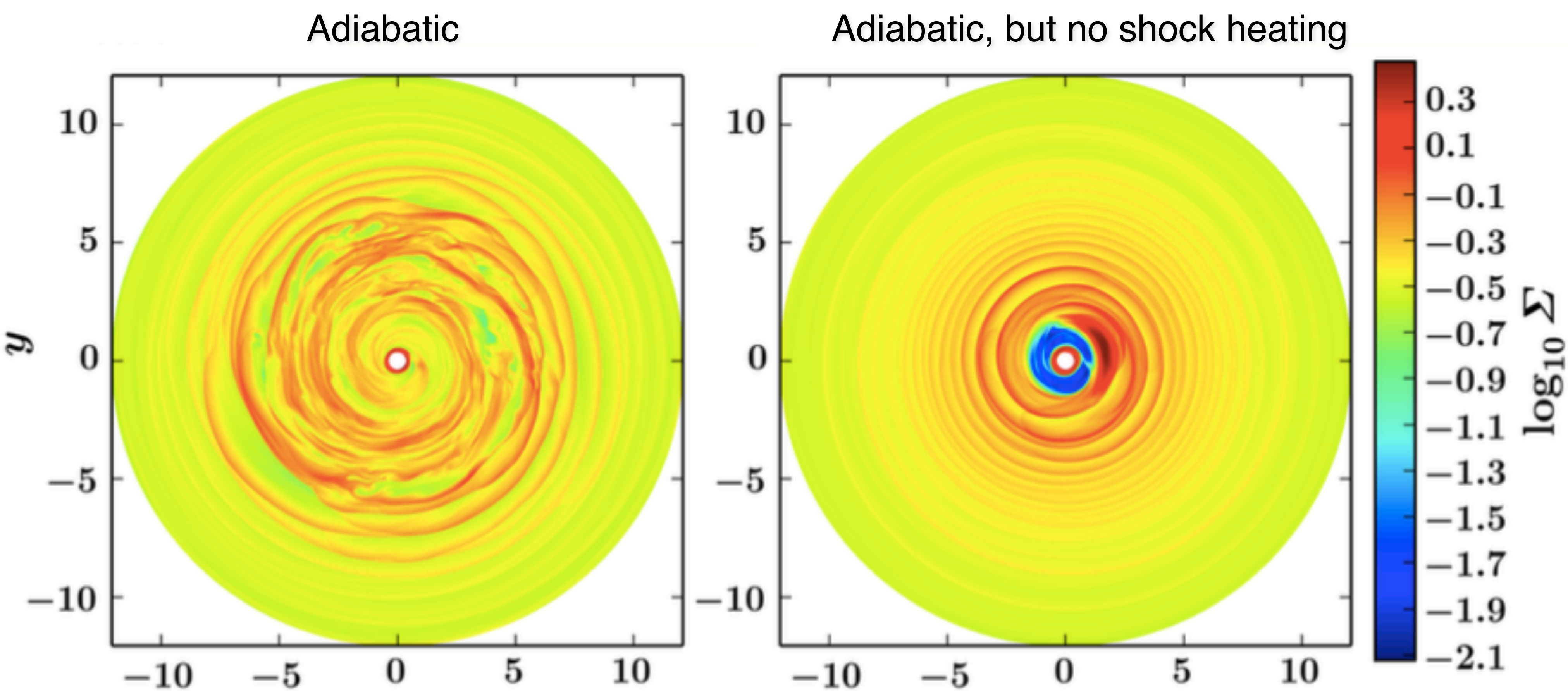

Richert et al. (2015)

# Shows up for high-mass planets in adiabatic disks



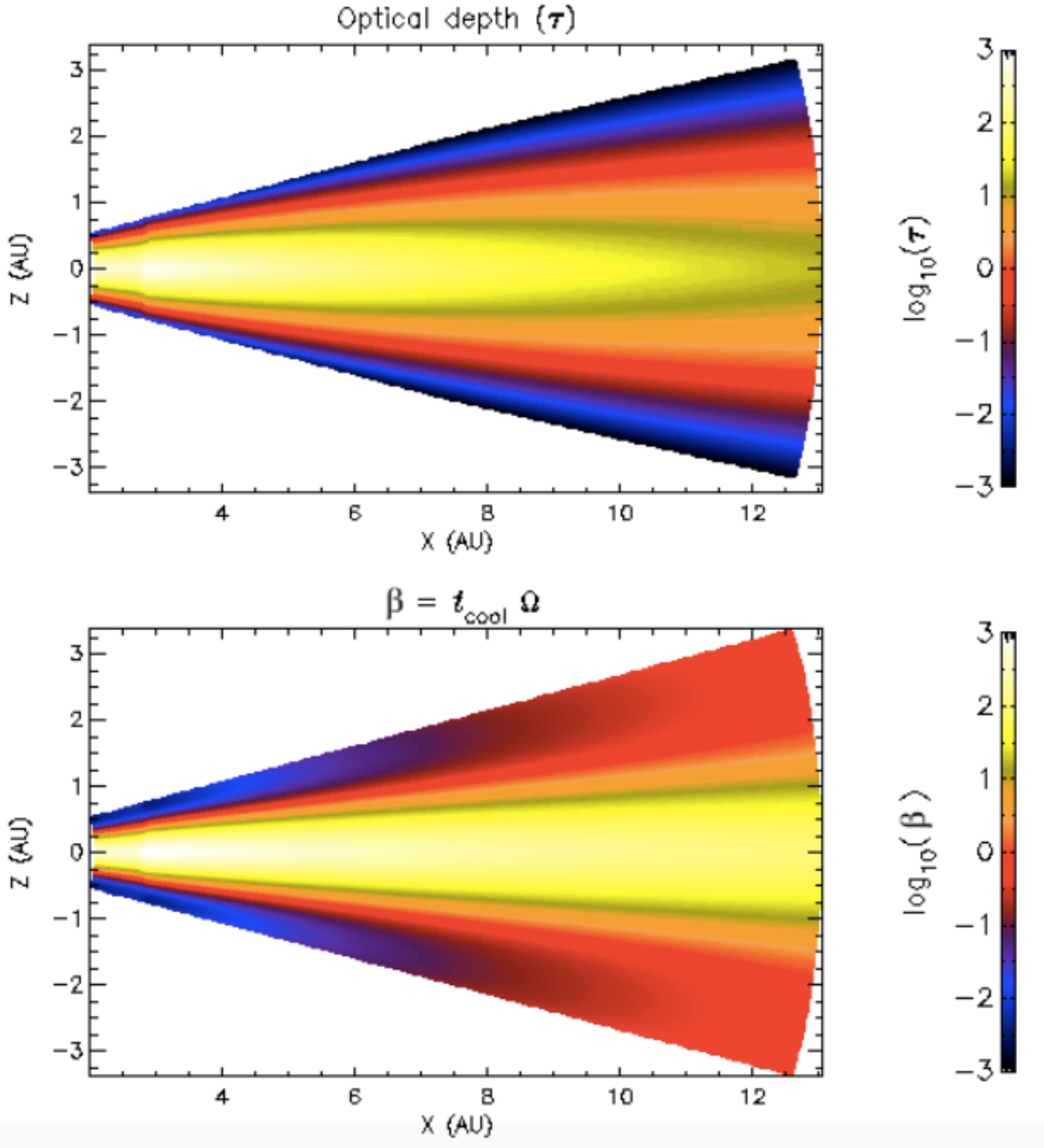

Richert et al. (2015)

# The energy source: shock heating!




Richert et al. (2015)

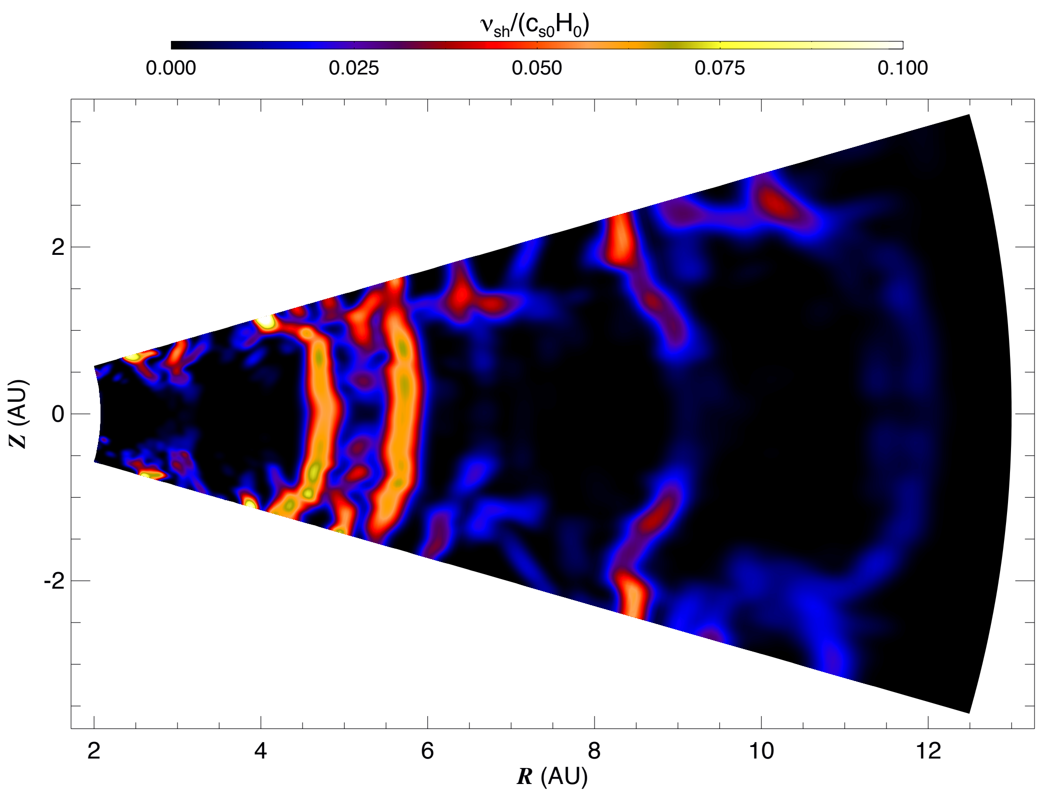
# Radiation Hydro: Dynamical cooling times



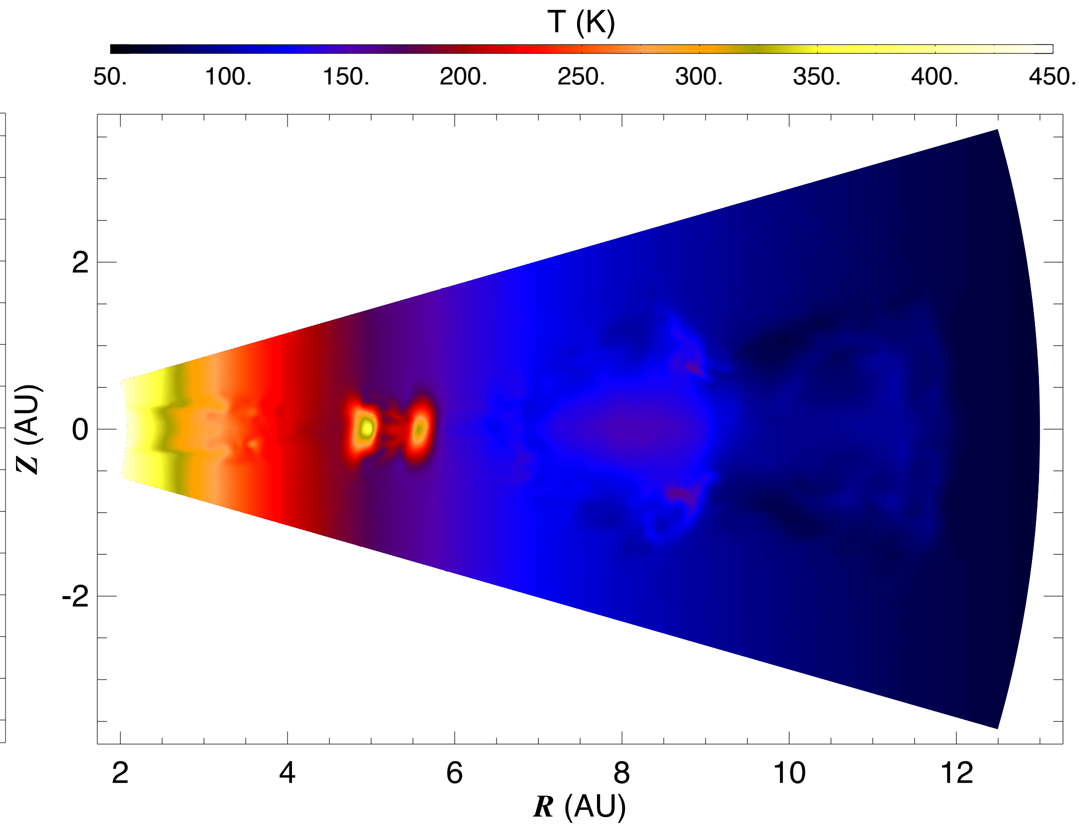

Lyra et al. (2016)

# Shock bores

## Velocity convergence

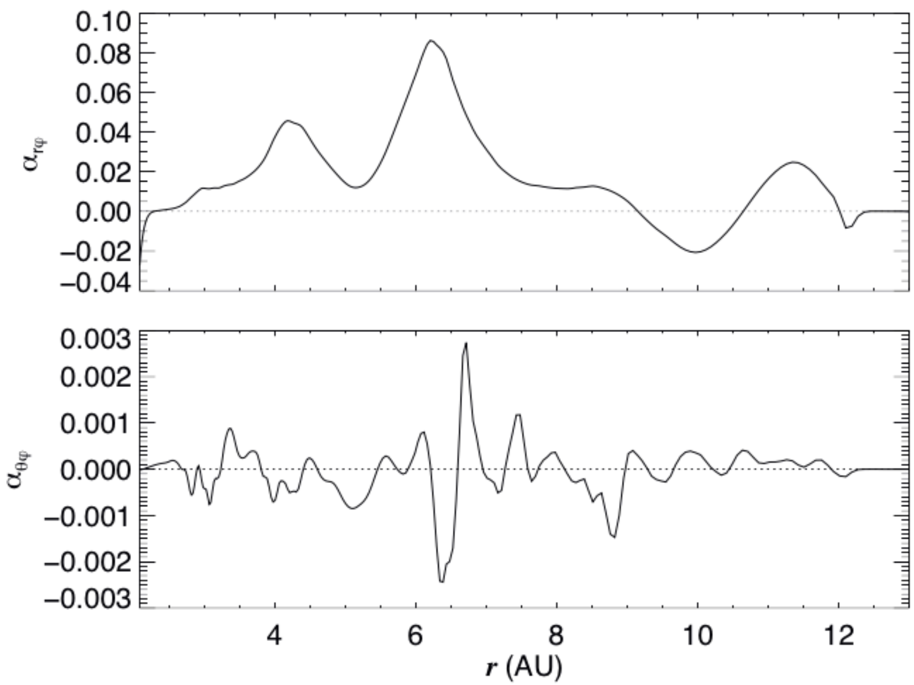


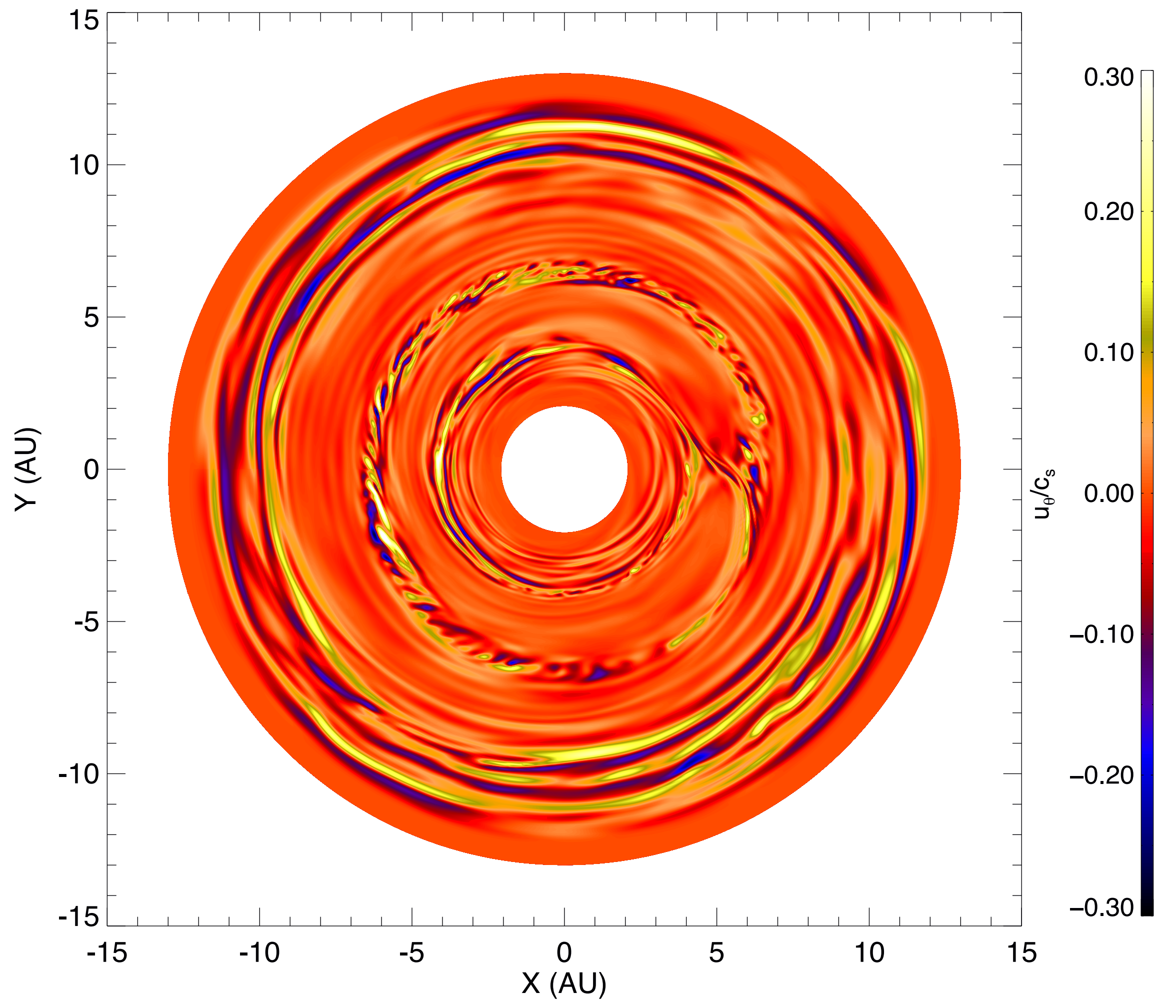

## Temperature




Lyra et al. (2016), see also Boley & Durisen (2006)

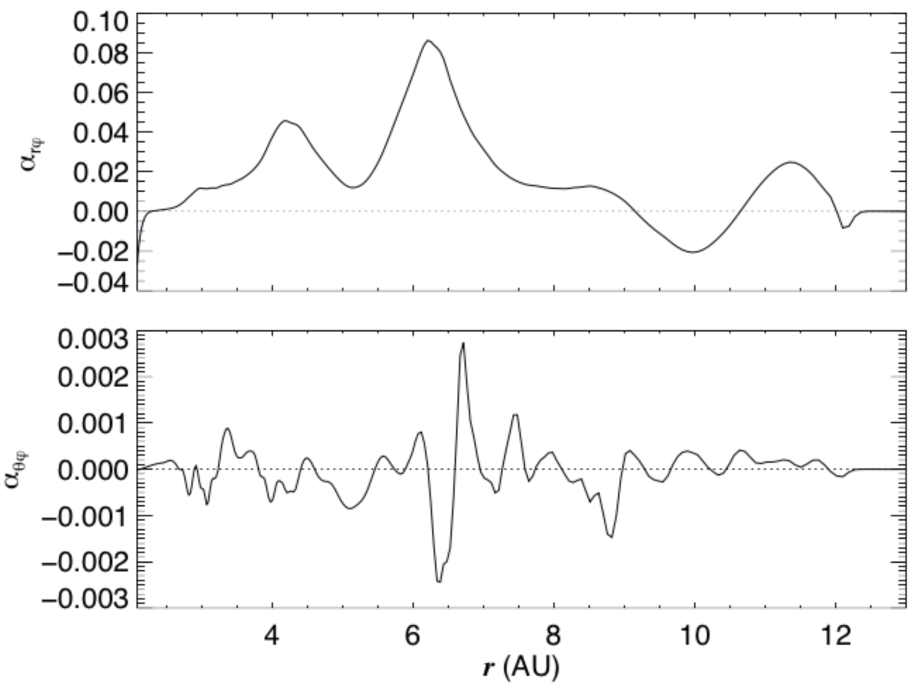
# Turbulent surf

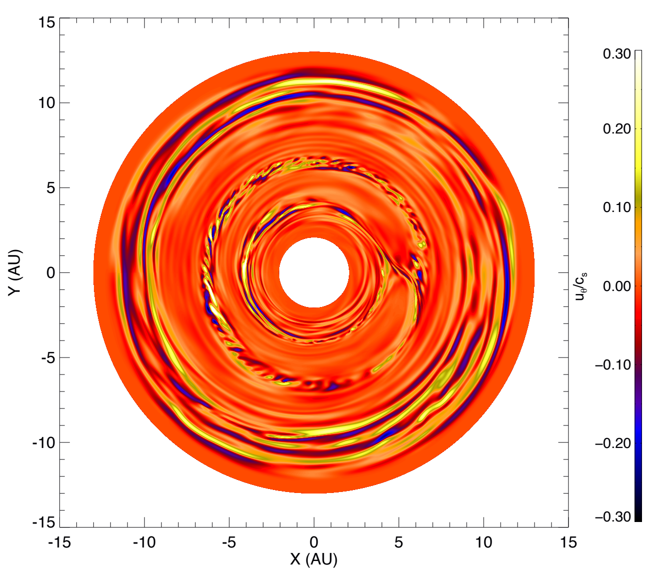


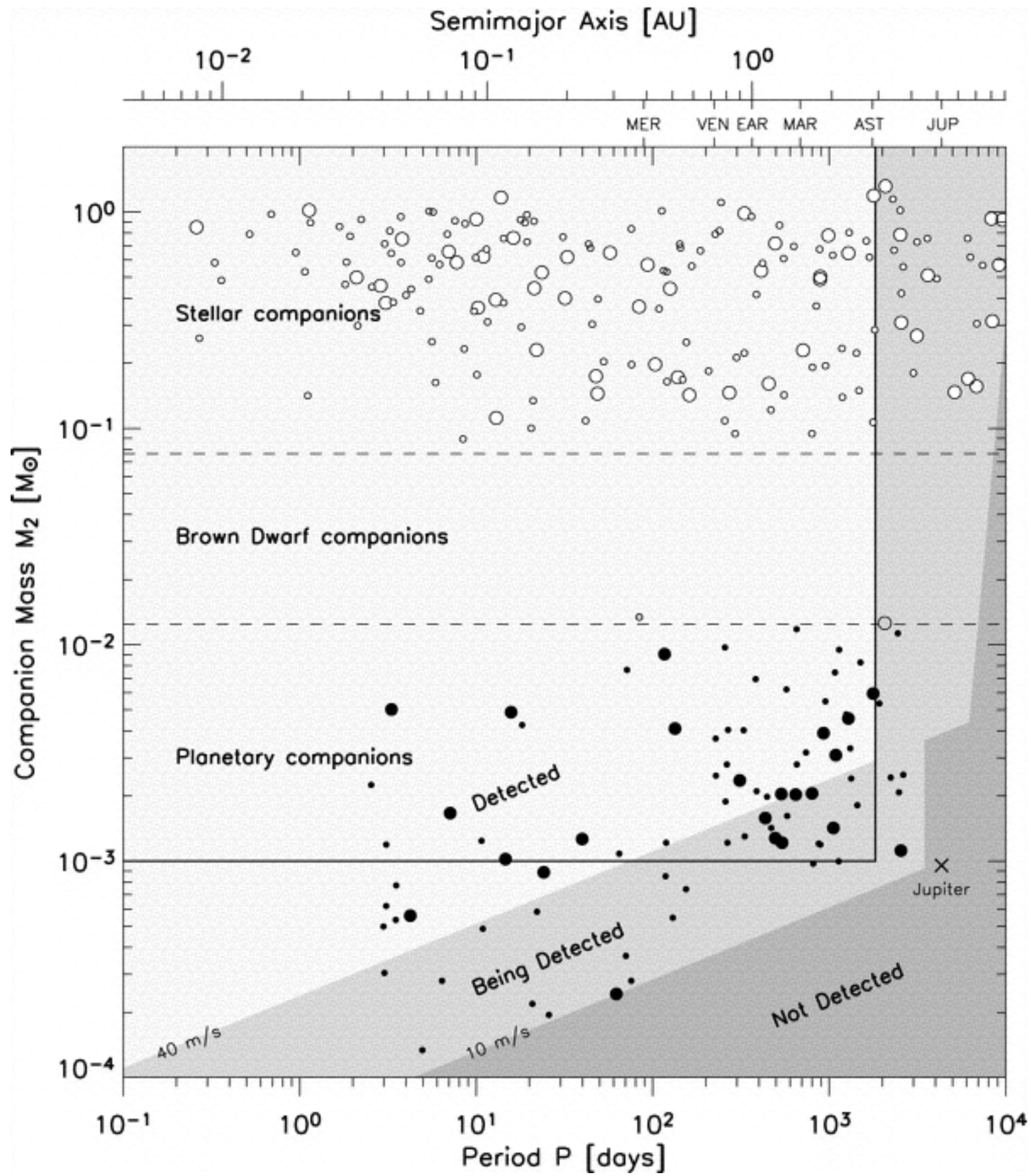




Lyra et al. (2016)

# Possible explanation for the brown dwarf desert?



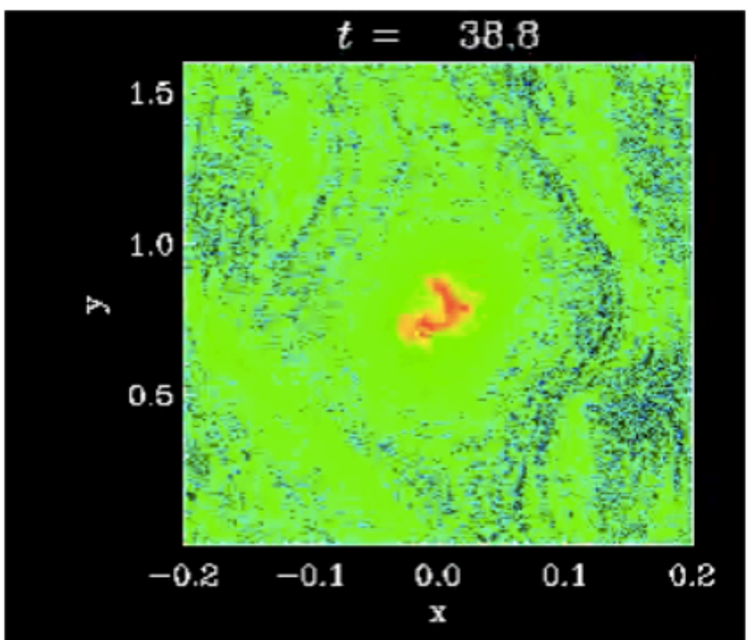



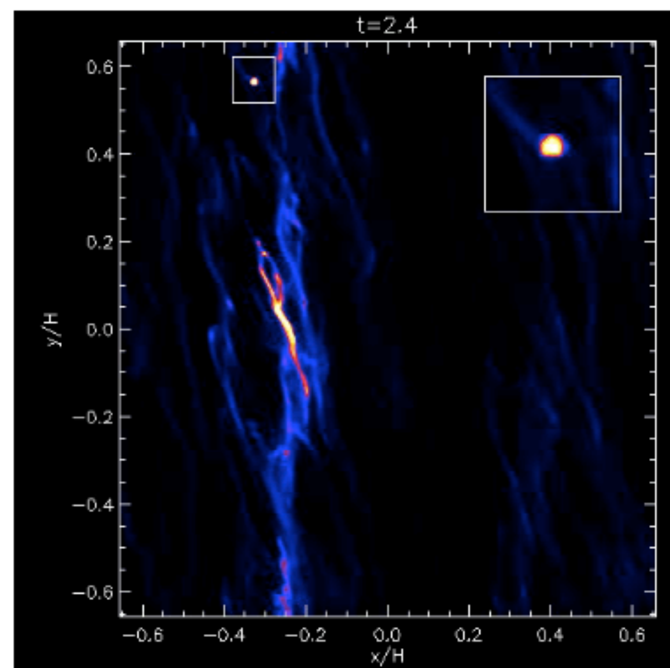



# Conclusions

- 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

of our model predictions!!

- 

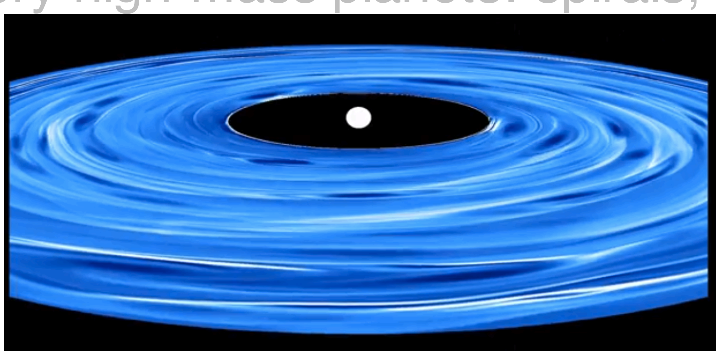


- t?)

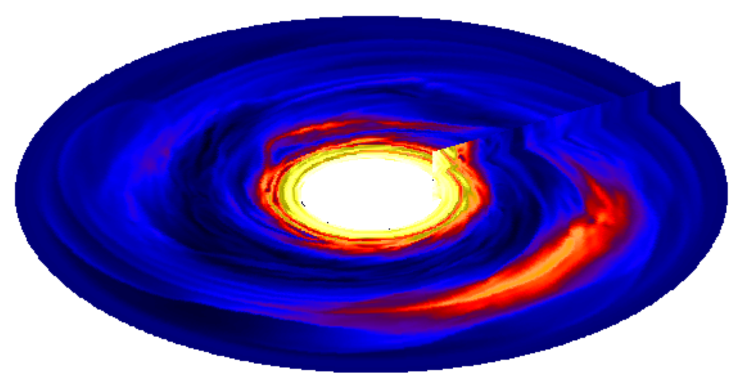
# Conclusions

- 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
- Several candidates: RWI/COI/Planets
- Very high-mass planets: spirals, turbulent sur ... ser?)

Baroclinic instability

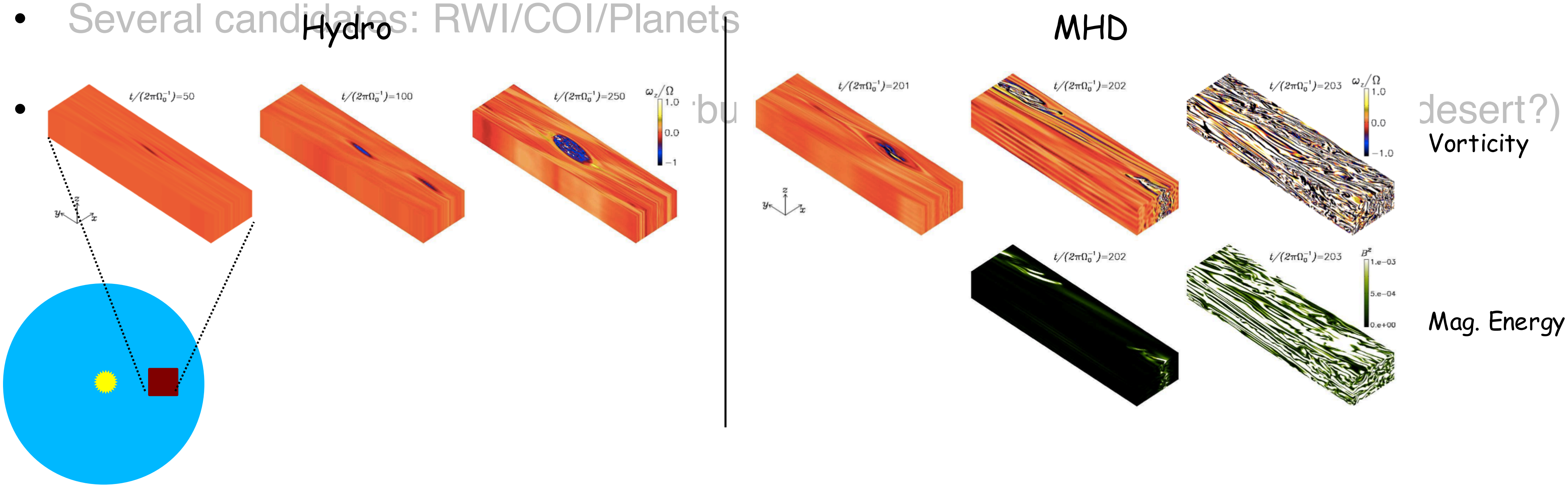


Rossby wave instability



# Conclusions

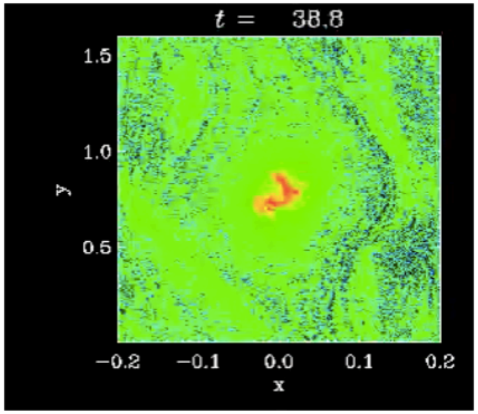
- Two modes of planet formation: Streaming Instability and Vortices
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortices do not survive magnetization
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains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

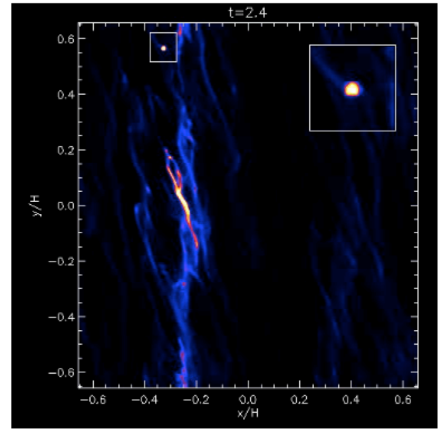



Lyra & Klahr (2011)

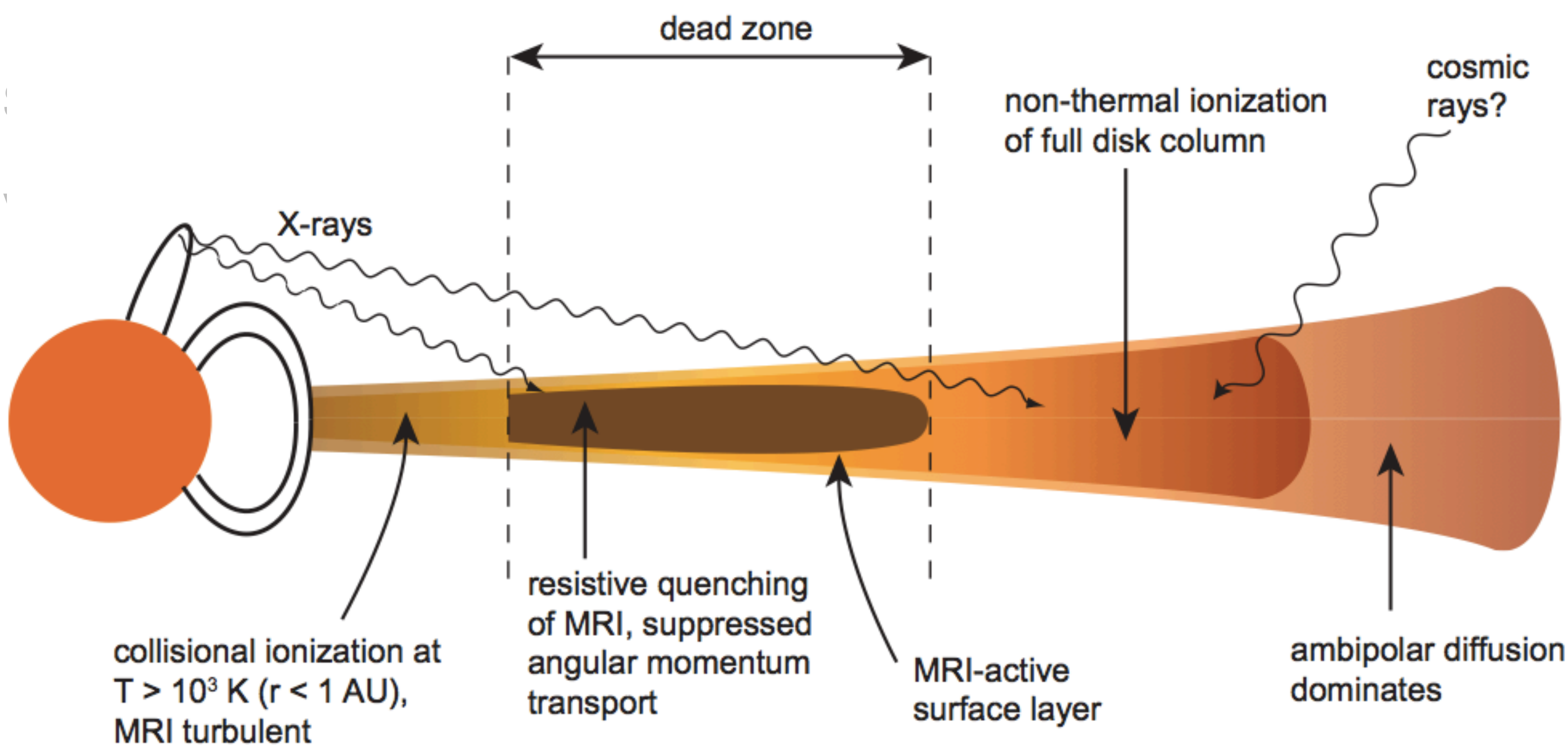
# Conclusions

- Two mod ... ces
- Two sust ... tive Overstability
- Vortices (




- Vortex-assisted and streaming instability are complementary
- ... s
- 
- ... 3D desert?)

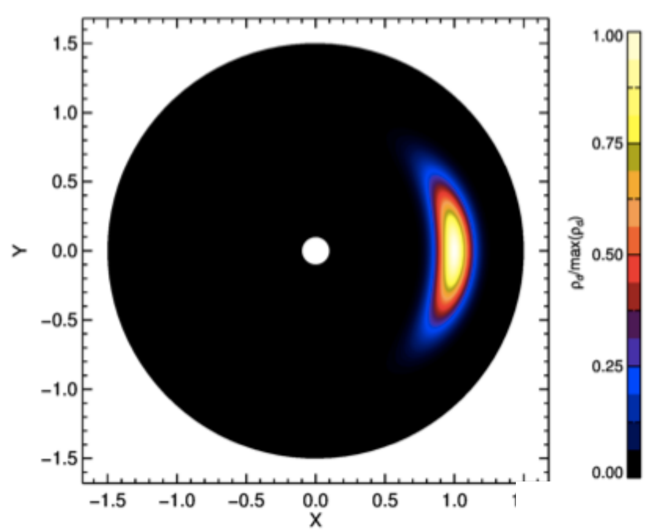


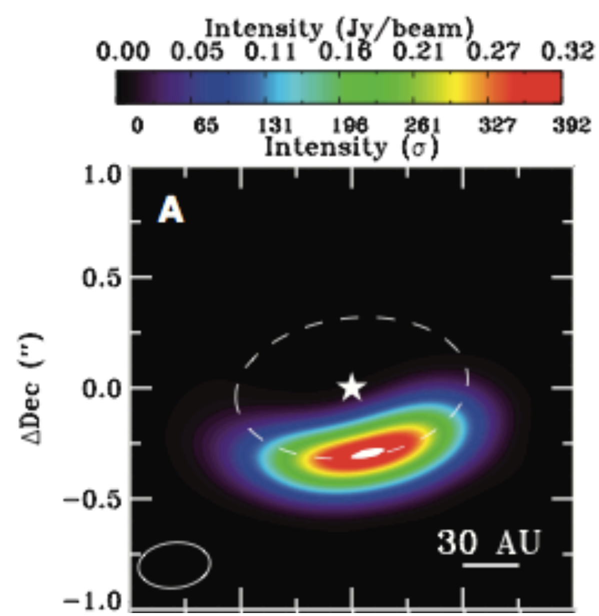
# Conclusions

- 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?)

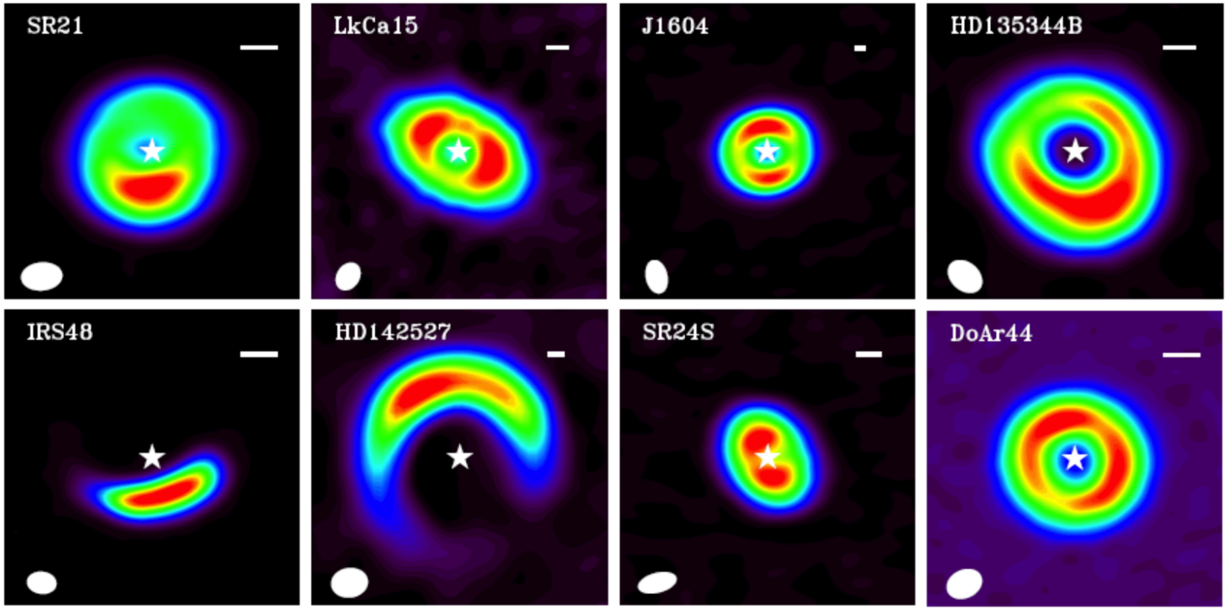
$$\rho_d(a,z) = \varepsilon\rho_0\,(S+1)^{3/2}\exp\left\{-\frac{[a^2 f^2(\chi)+z^2]}{2H^2}(S+1)\right\}$$

Lyra & Lin (2013)



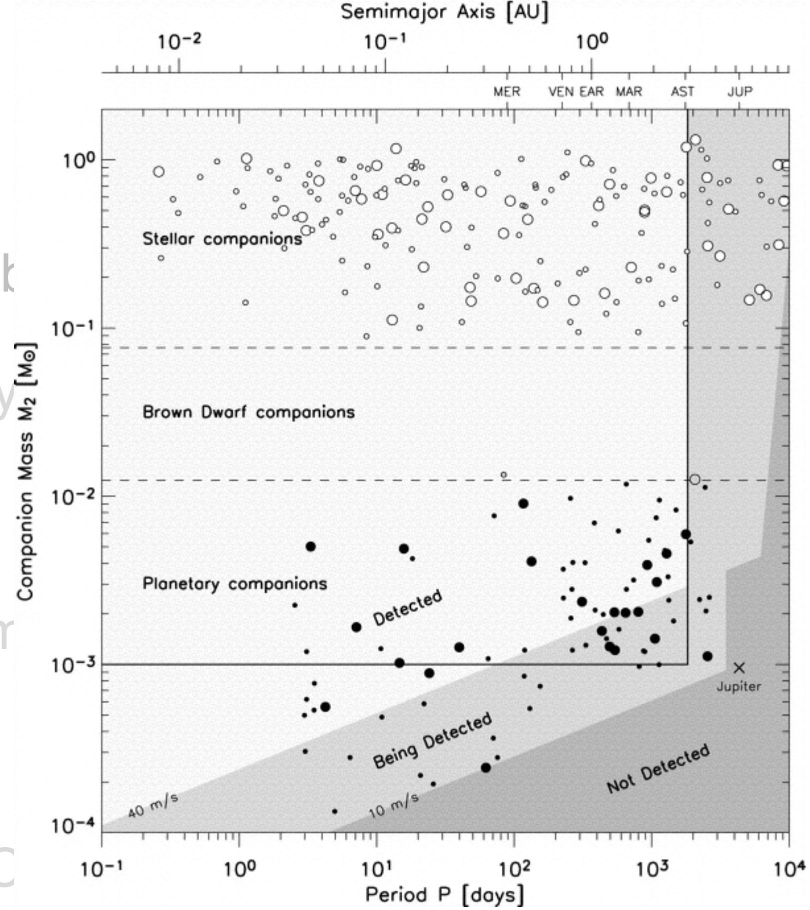



# Conclusions




- Two modes … es
- Two sustena… e Overstability
- Vortices do
- Vortex-assis
- Vortex-trapp … servations
- 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 Instal
- Two sustenance modes: Rossby Wave Instability
- Vortices do not survive magnetization
- Vortex-assisted and streaming instability are com
- Vortex-trapped dust in drag-diffusion equilibrium
- Several possible culprits for asymmetries: RWI/C
- Very high-mass planets: spirals, turbulent surf and high accretion rates (BD desert?)