Evolution of Circumstellar Disks and Planet Formation

Wladimir Lyra

California State University

Jet Propulsion Laboratory

Collaborators

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ASIAA, July 19th, 2017

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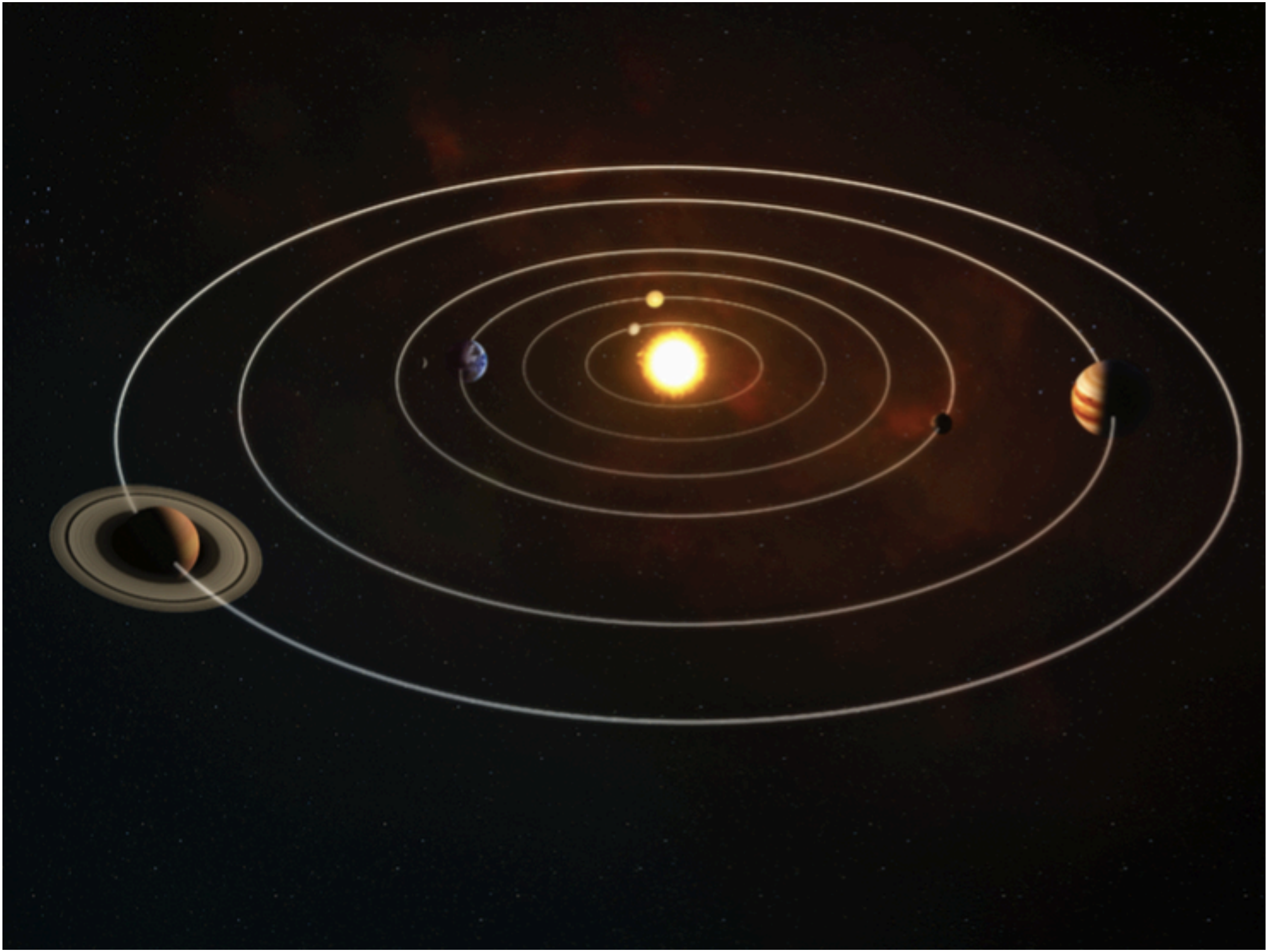
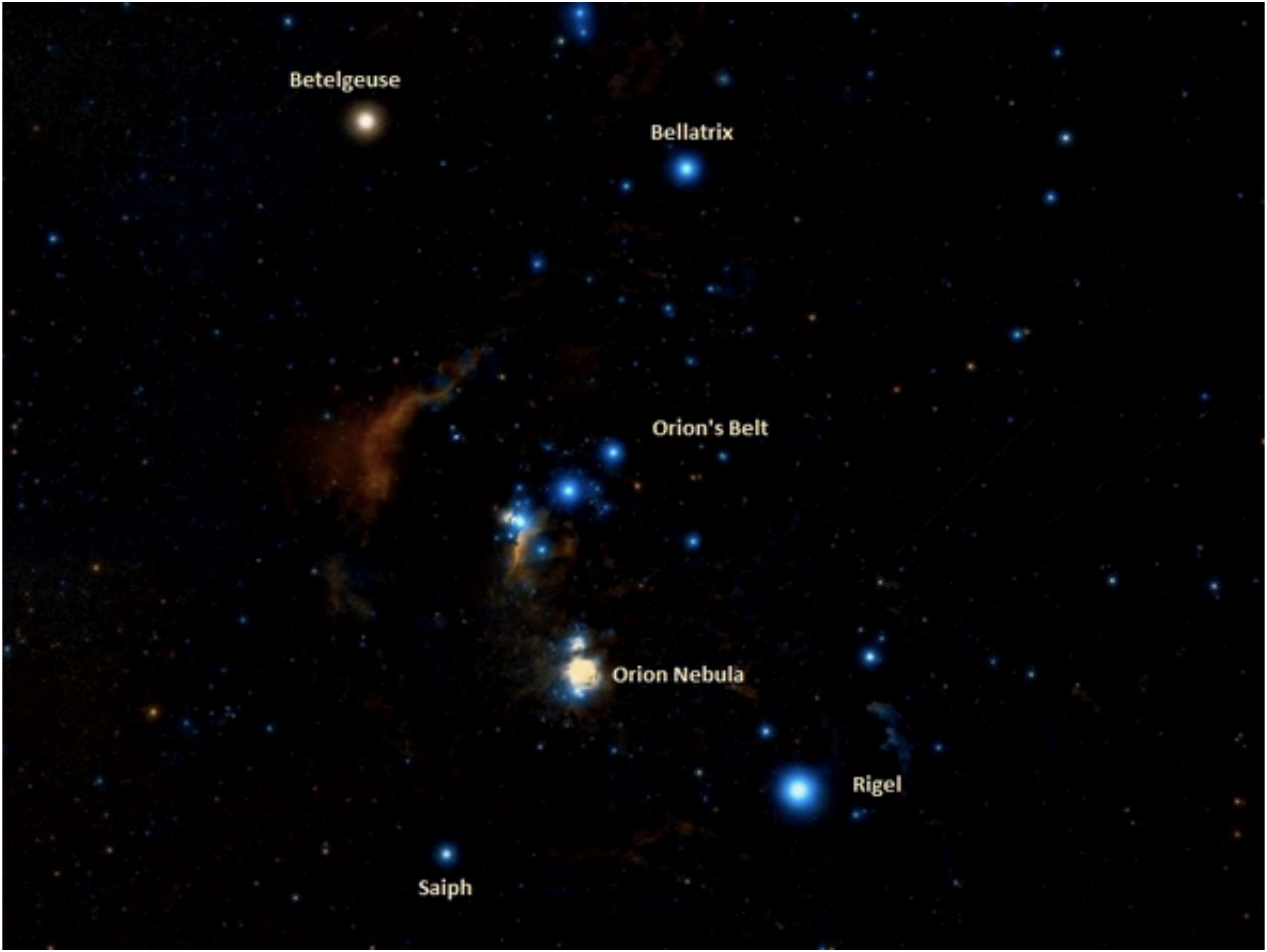
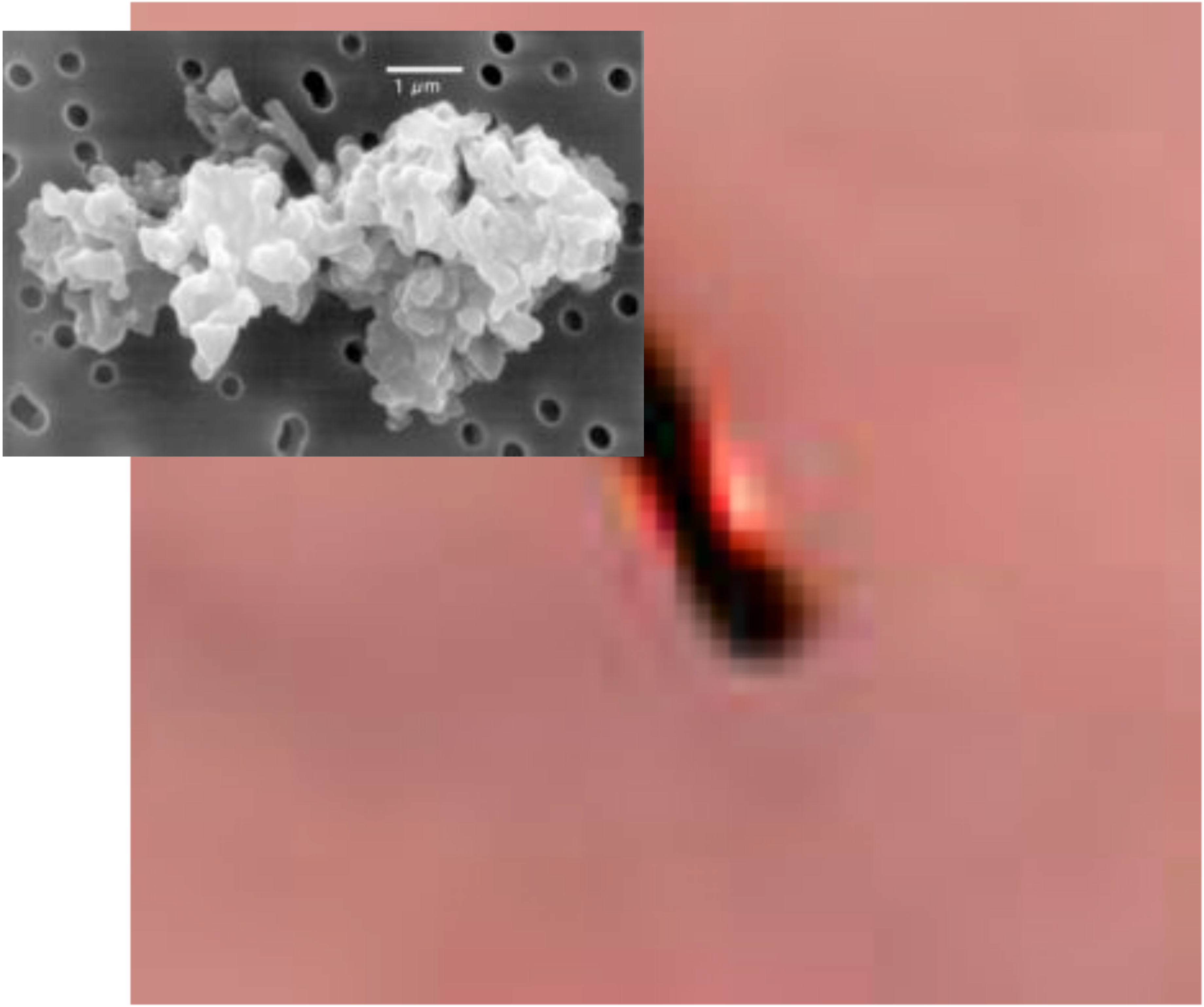
Outline

- Observational constraints
- The need for turbulence
    - "Streaming" Instability
    - Vortex trapping
- The importance of ionization: "active" and "dead" zones
    - Vortices in the "dead" zone
- The view of ALMA
- Observability




Betelgeuse
Bellatrix
Orion's Belt
Orion Nebula
Rigel
Saiph


1 µm

Protoplanetary Disks

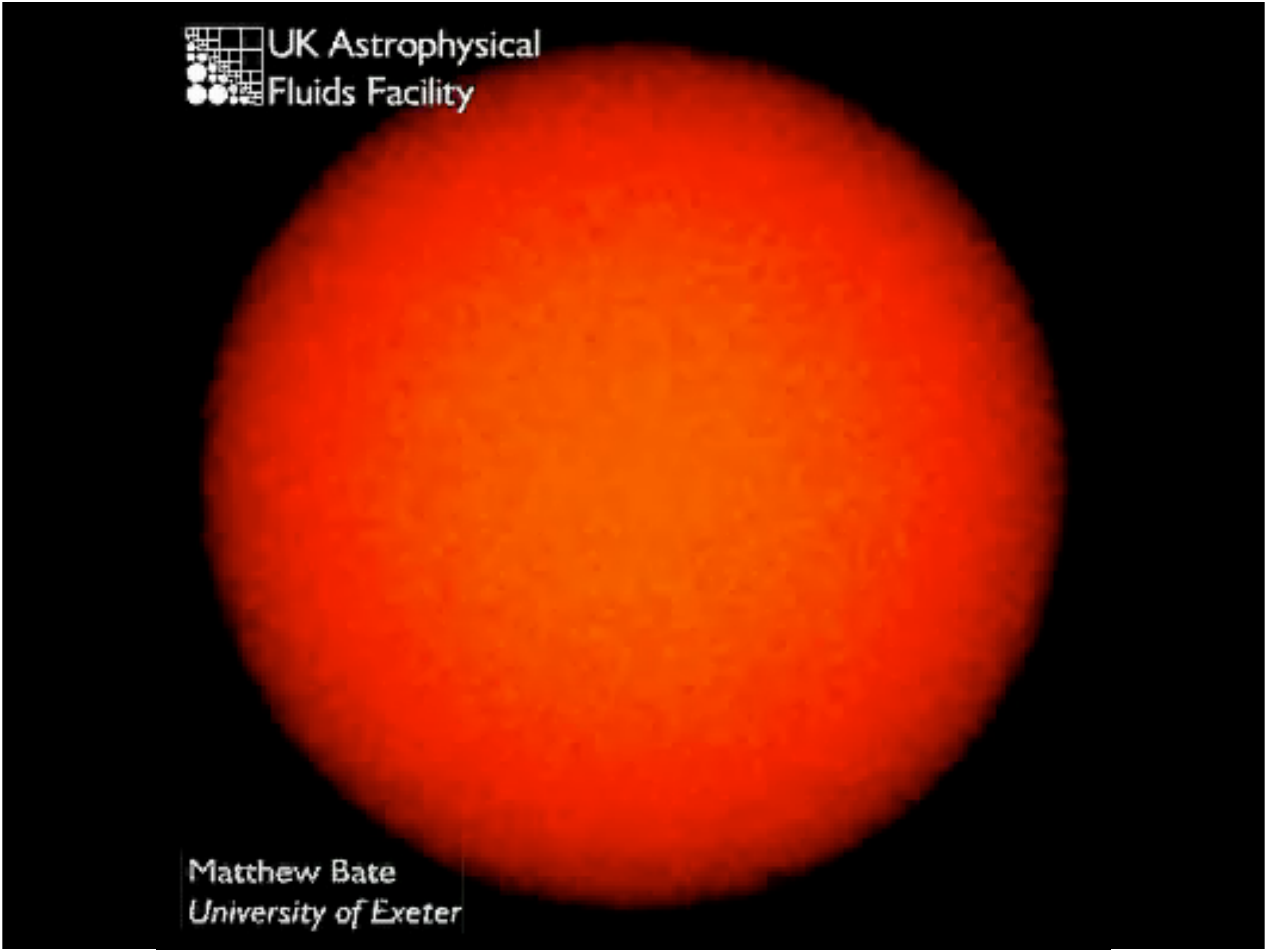
PP disk fact sheet

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

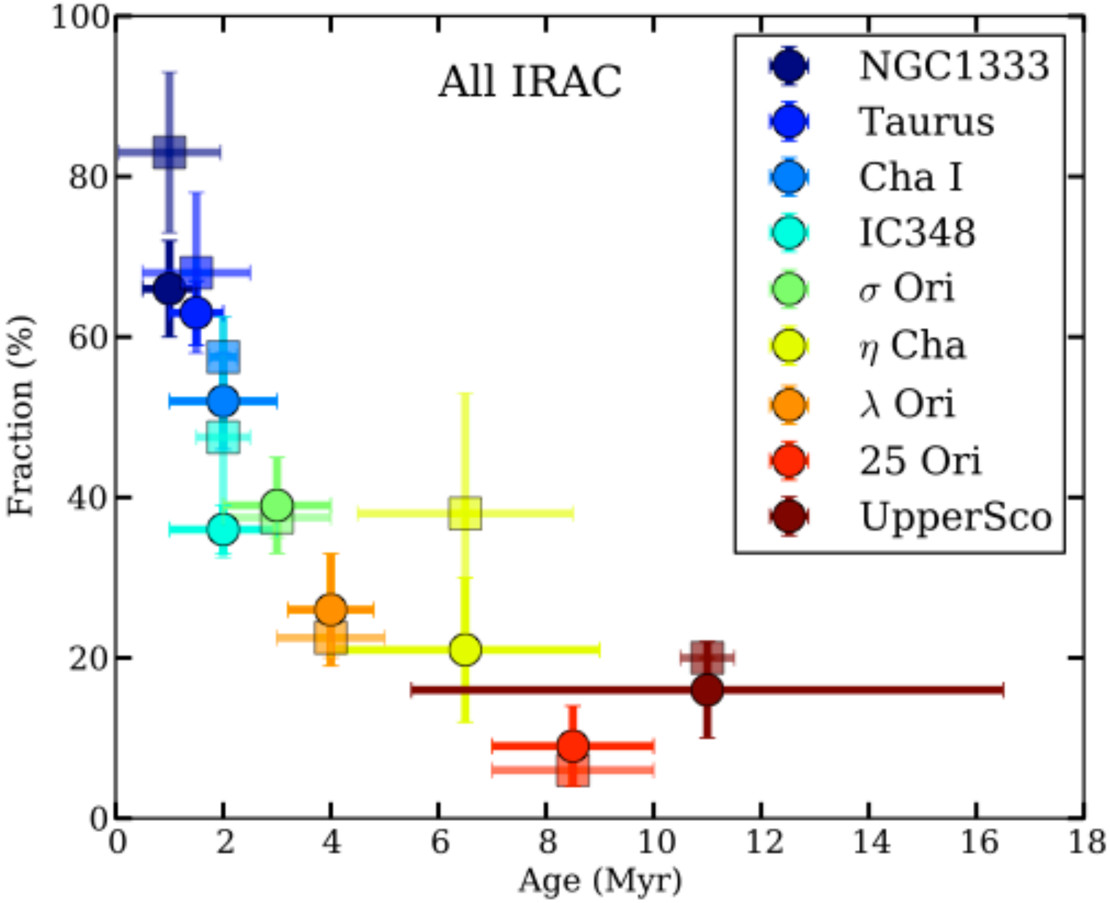
Temperature: 10-1000 K

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

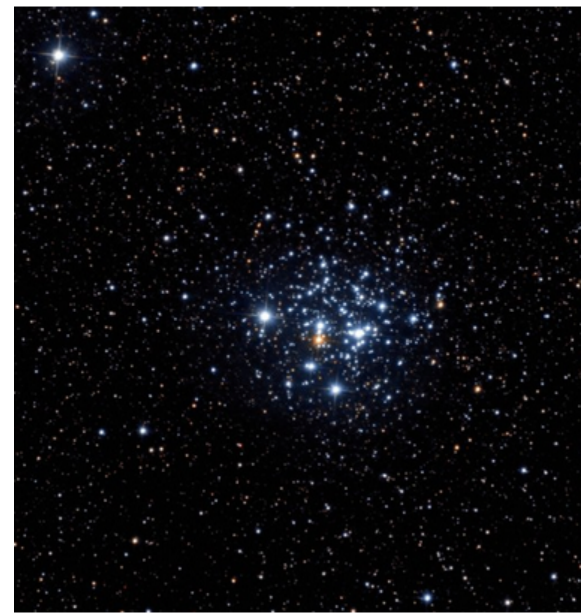
Mass: $10^{-3} - 10^{-1}$ M_{sun}
(1 M_{sun} = 2×10^{33} g)


UK Astrophysical
Fluids Facility
Matthew Bate
University of Exeter

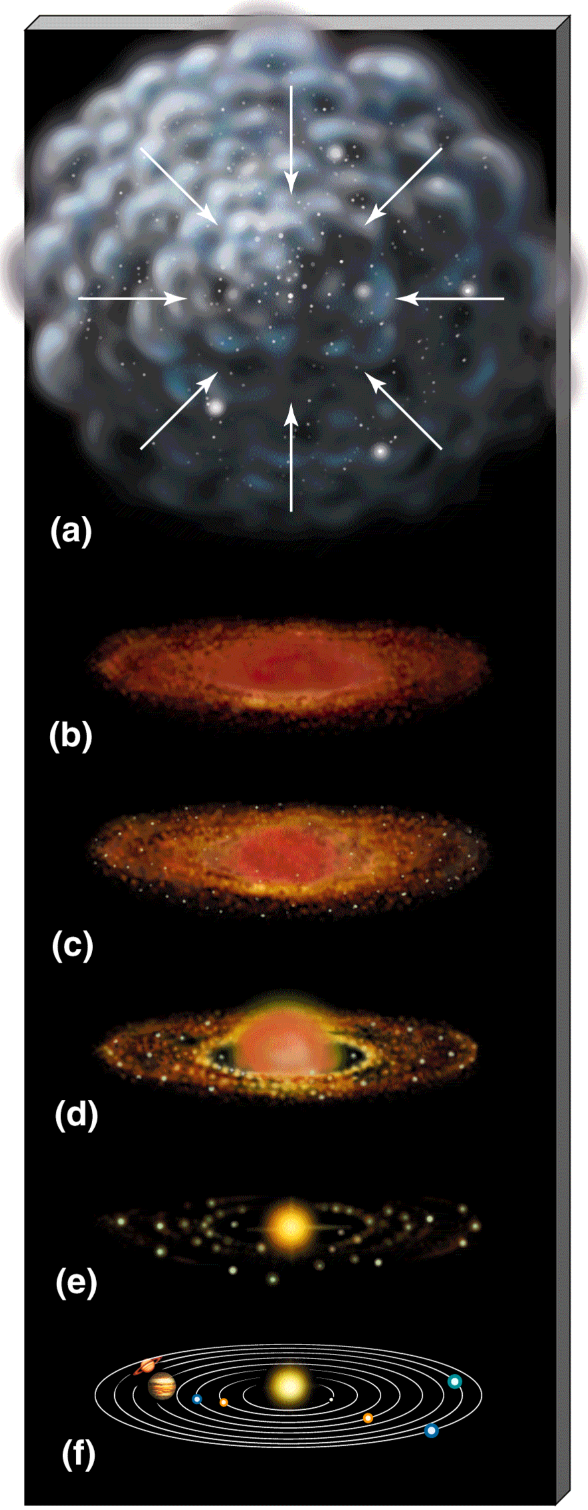
Disk lifetime



(Ribas et al. 2014)



Disks dissipate within ~10Myr



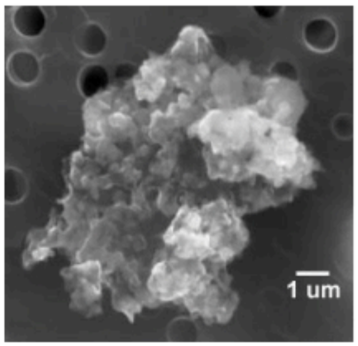
Disk Evolution

Gas-rich phase (< 10 Myr)
Primordial Disks

Gas-poor phase (>10 Myr)
Debris Disks

Planet Formation

"Planets form in disks of gas and dust"



A miracle happens

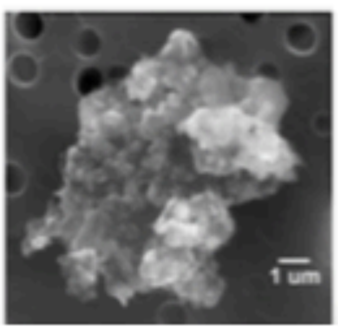
Planet Formation

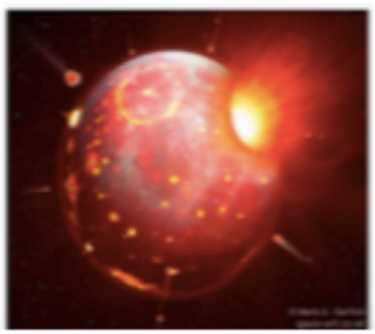
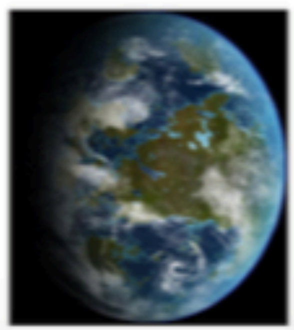
Planetesimal Hypothesis (Safronov 1969)

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
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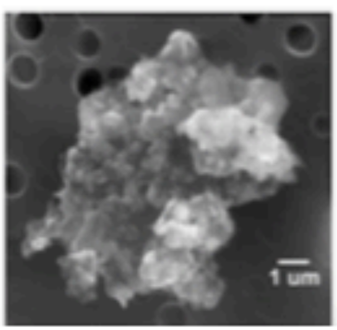
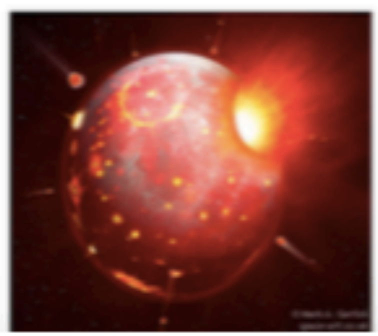
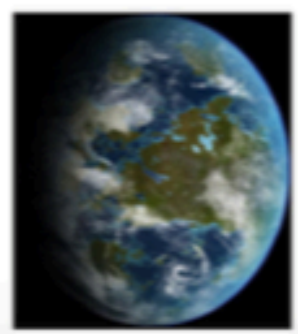
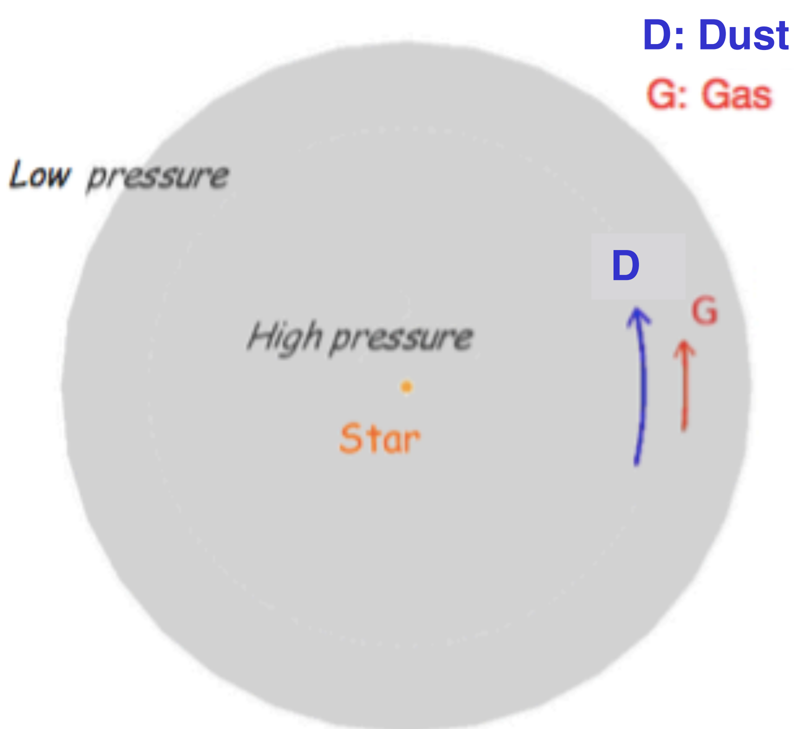


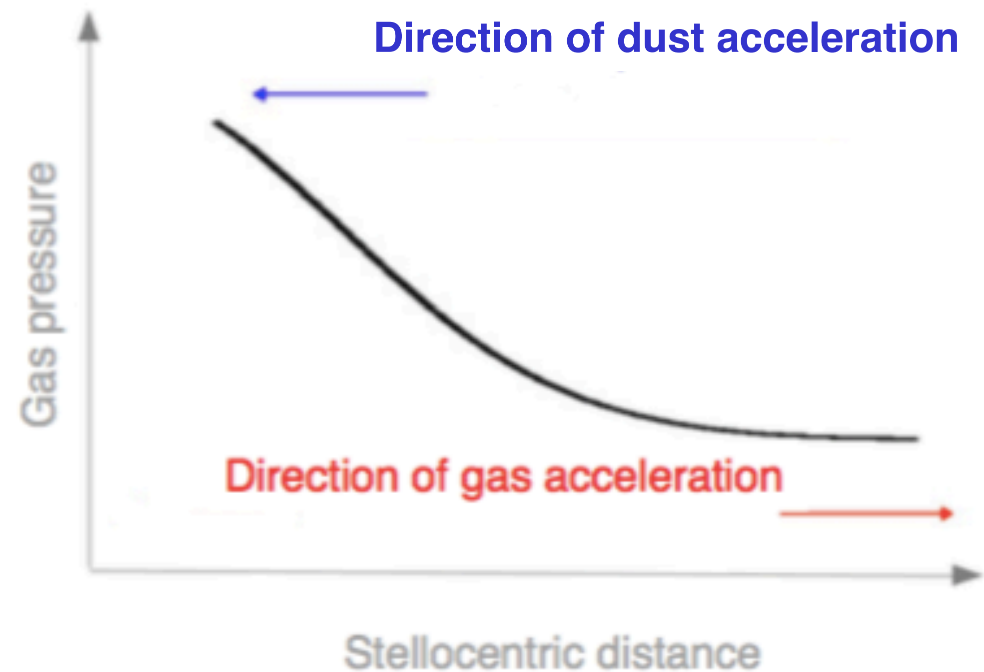




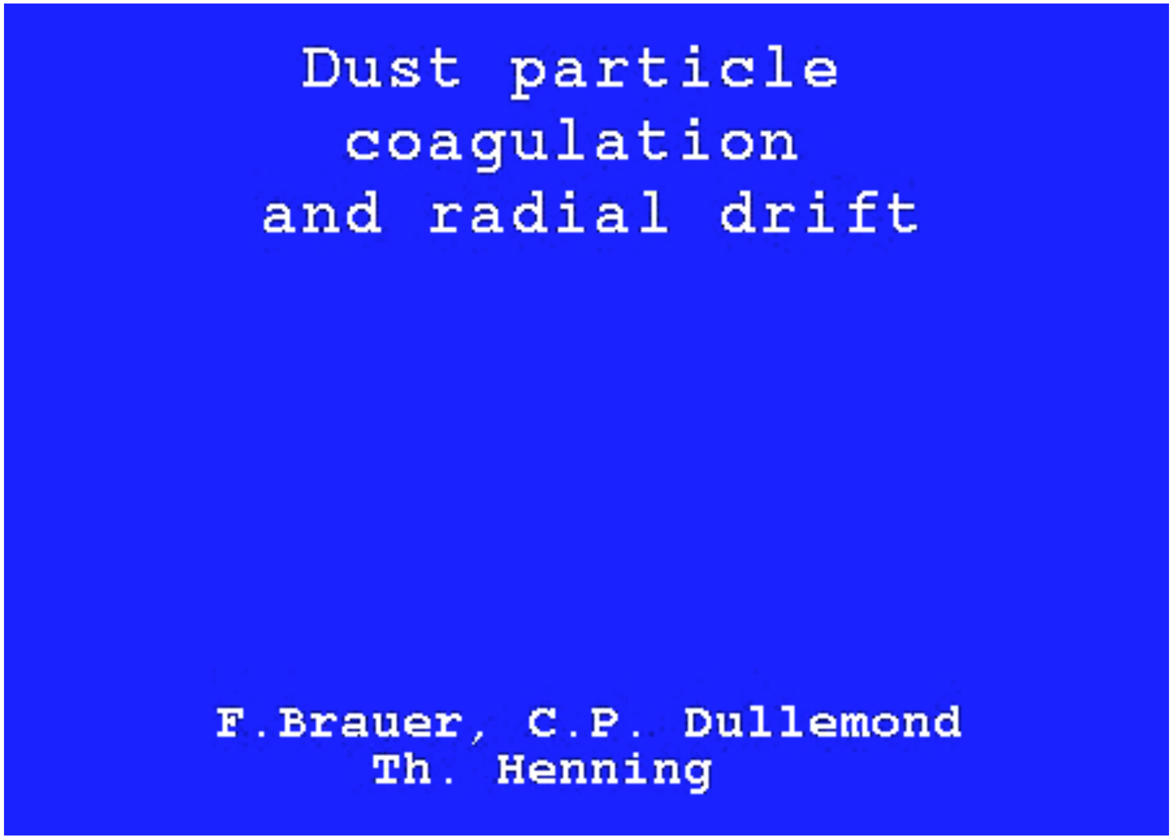
Dust Drift



Adapted from Whipple (1972)



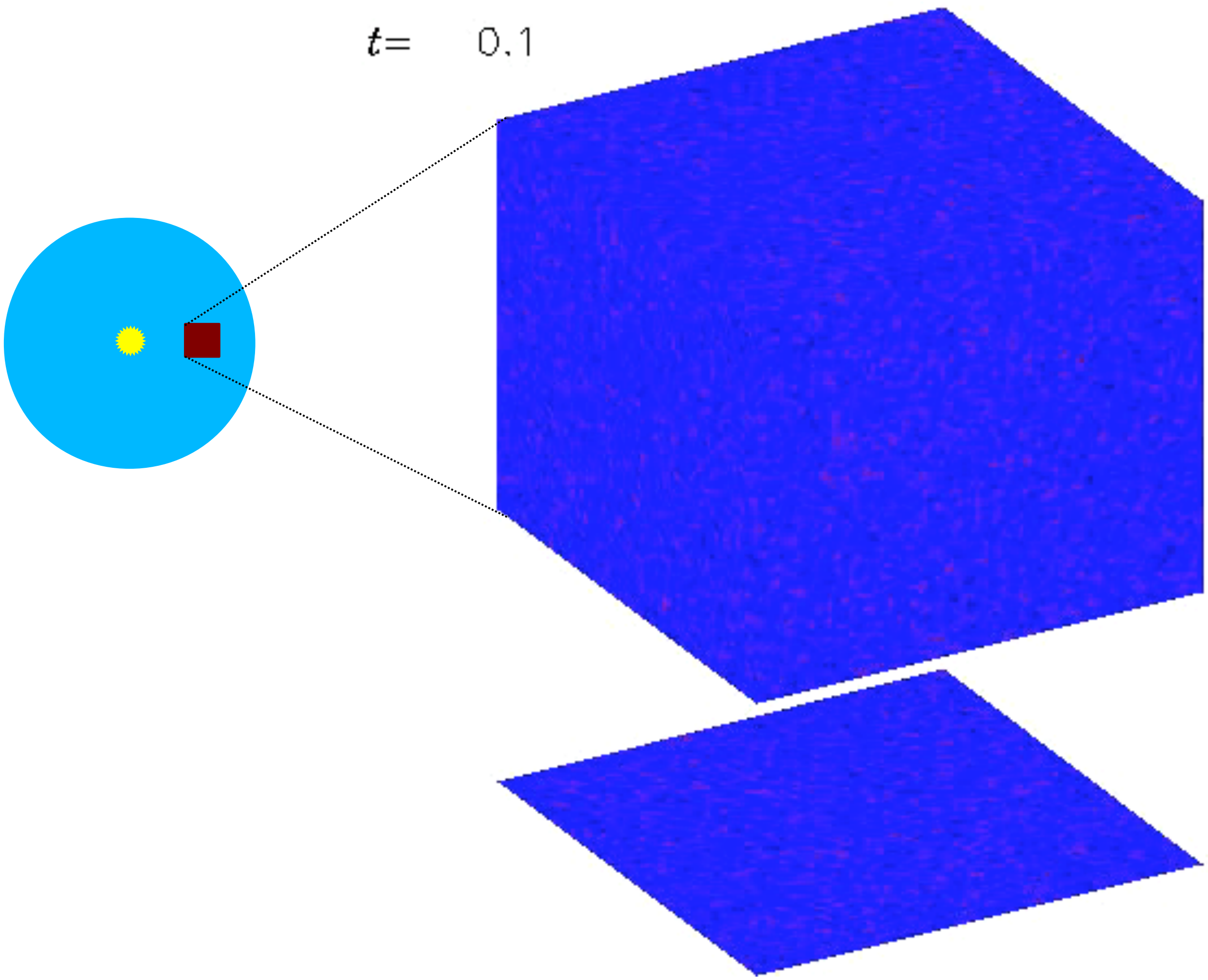
Dust Coagulation and drift



Brauer et al. (2008)

Streaming Instability

The dust drift is hydrodynamically unstable



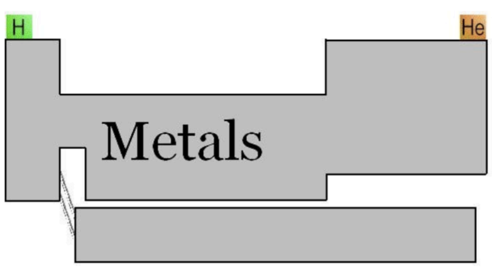
Youdin & Goodman (2005), Johansen & Youdin (2007), Youdin & Johansen (2007)

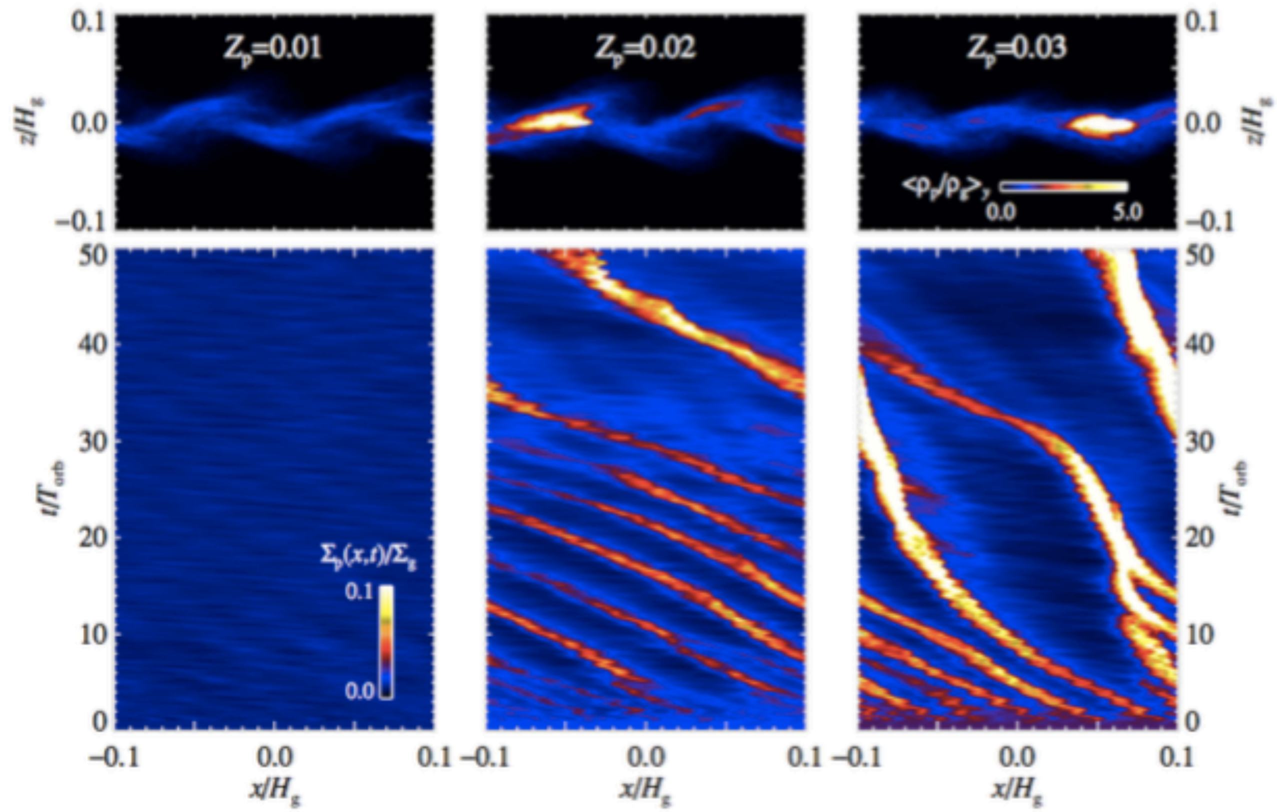
Streaming Instability does not "work" for solar composition

Solar composition:

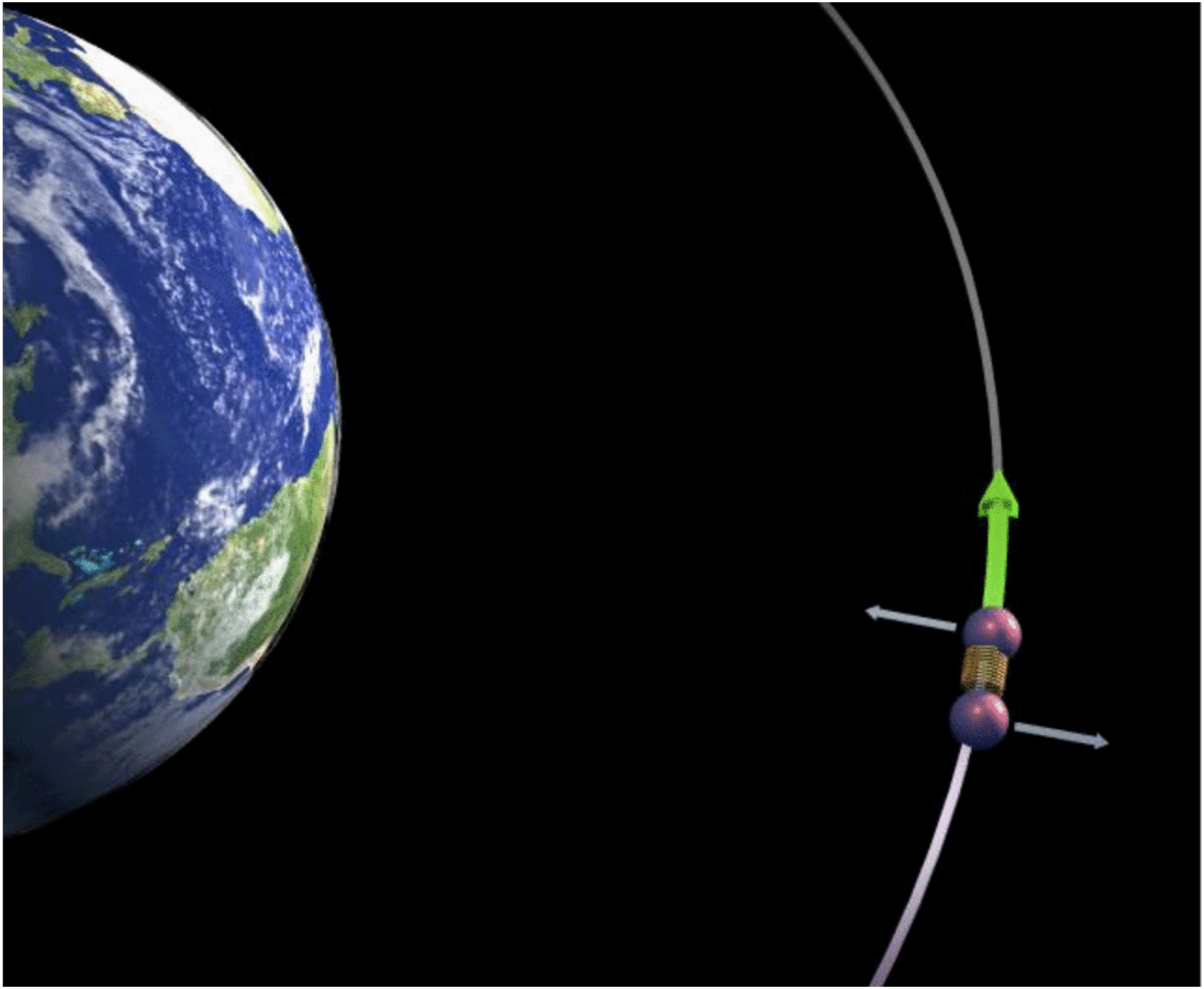
H (X) ~ 0.74
He (Y) ~ 0.25
Metals (Z) ~ 0.01

The Astronomer's Periodic Table:



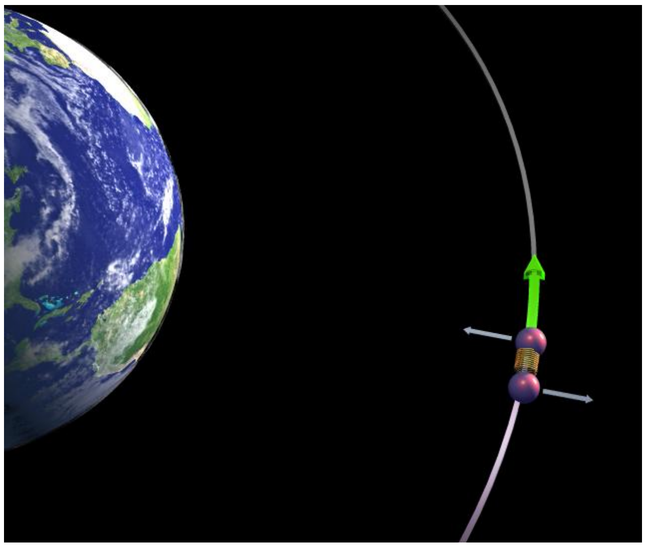


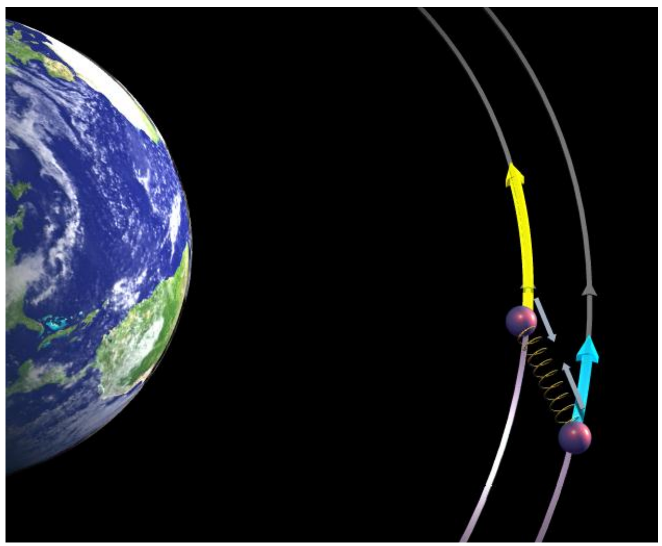
Johansen et al. (2011)

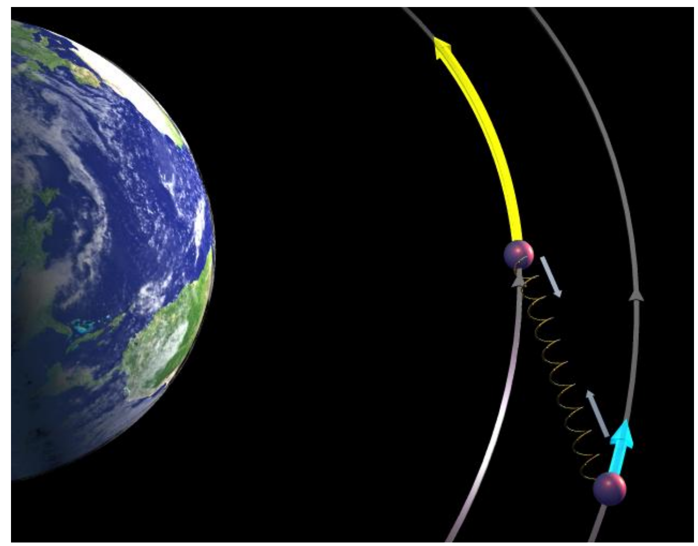


Stretching builds up tension

Tension resists shear

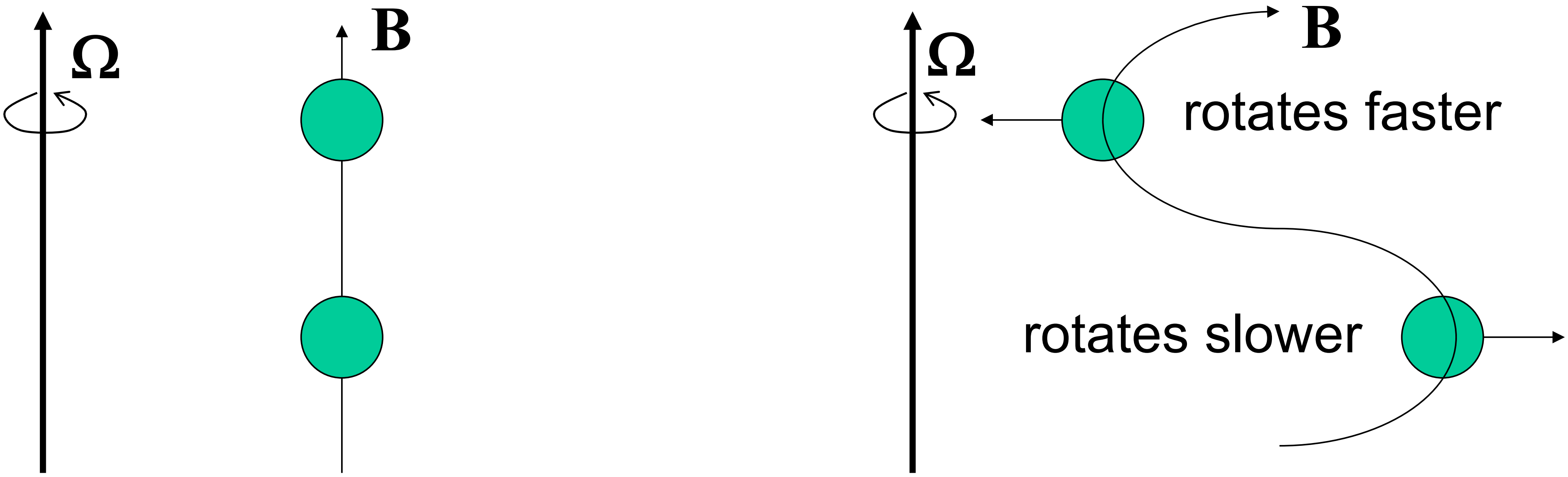






Beads exchange angular momentum

Magnetorotational Instability (MRI)



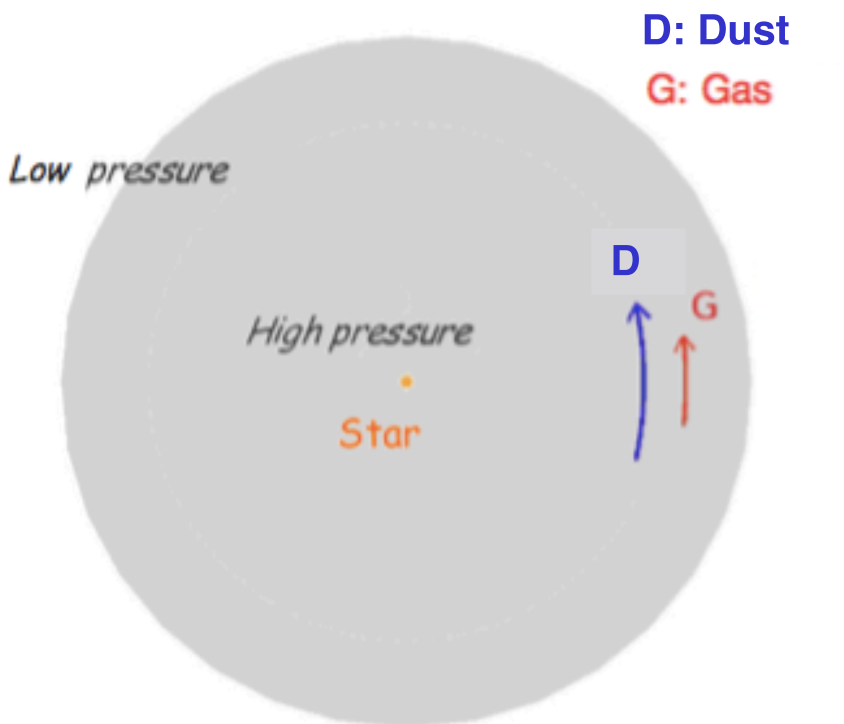
Magnetic fields

in a conducting rotating plasma behave

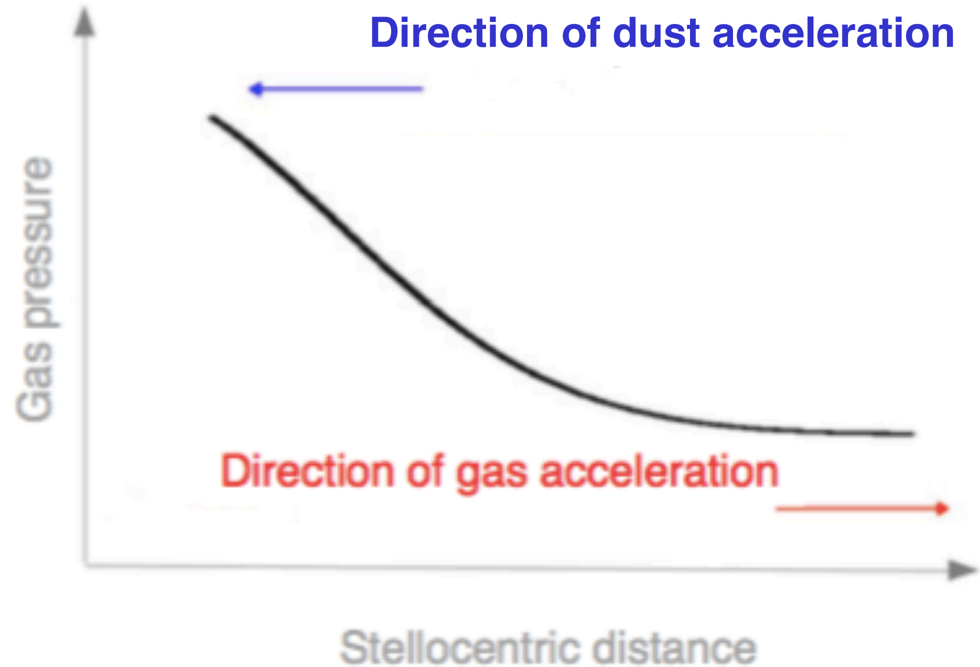
EXACTLY like ***springs***!

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

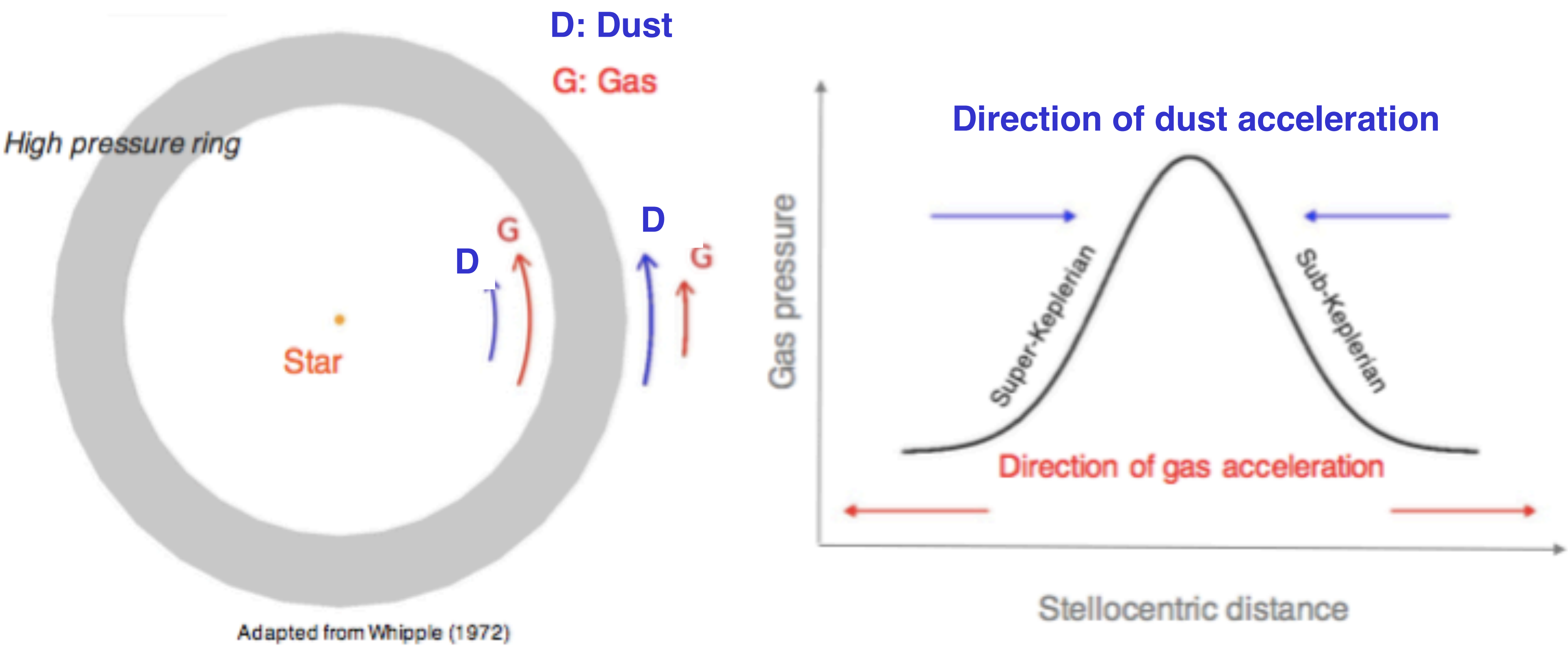
Dust Drift



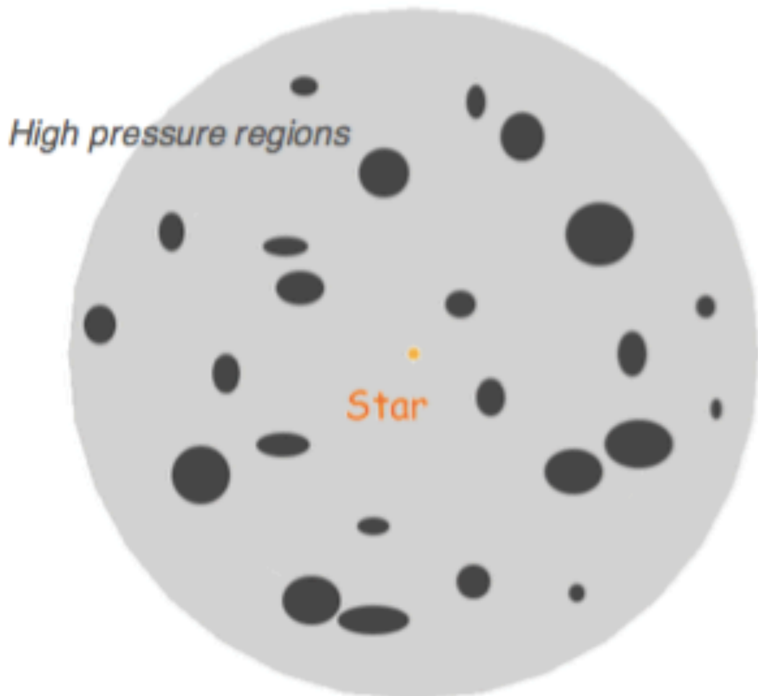
Adapted from Whipple (1972)

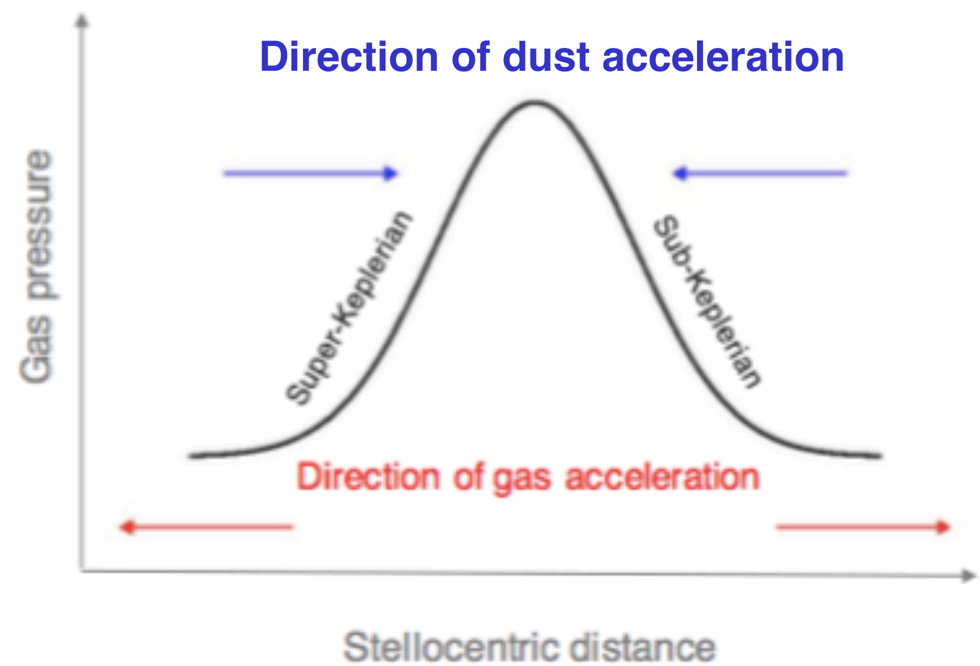


Pressure Trap

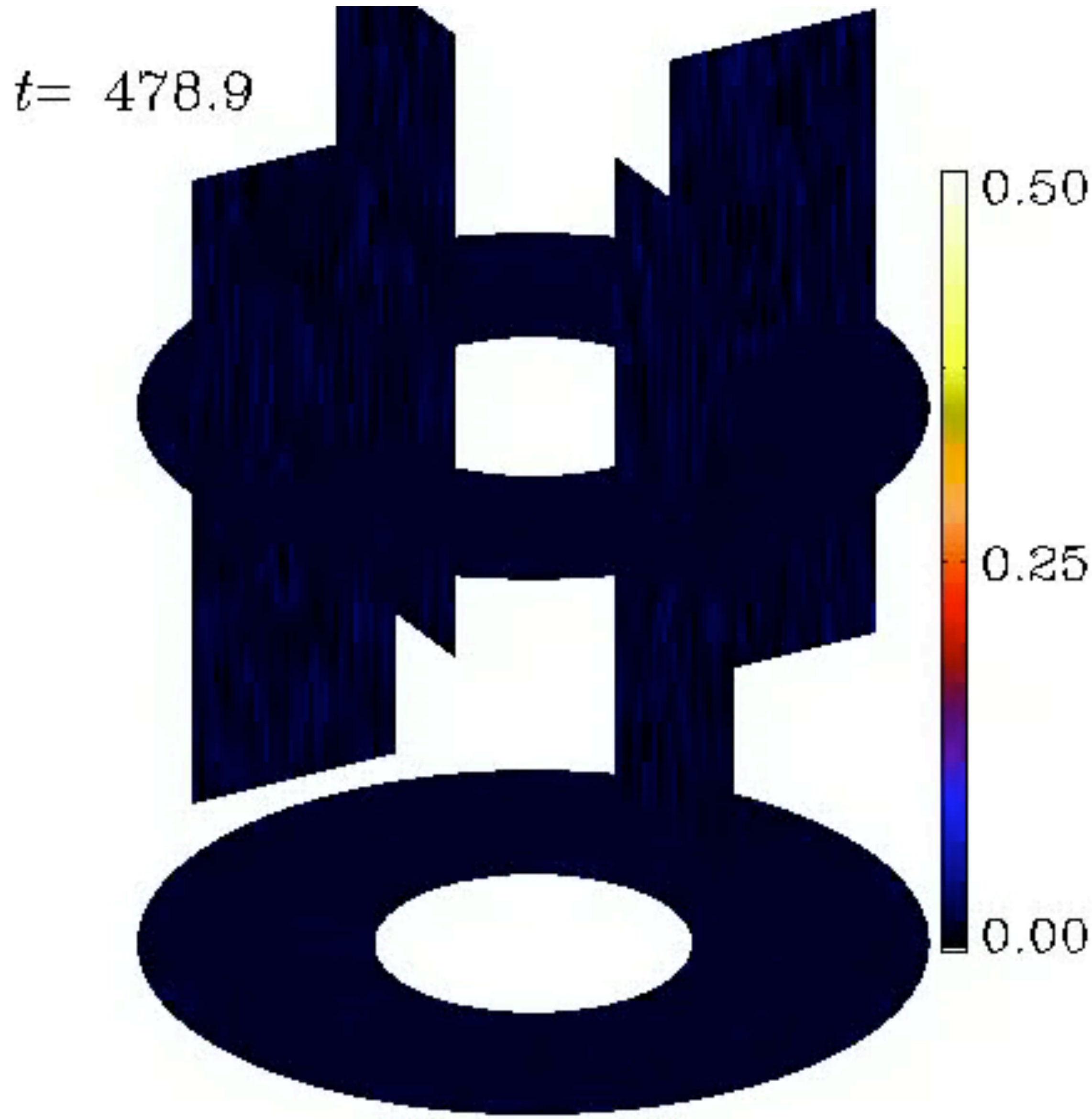


Pressure Trap



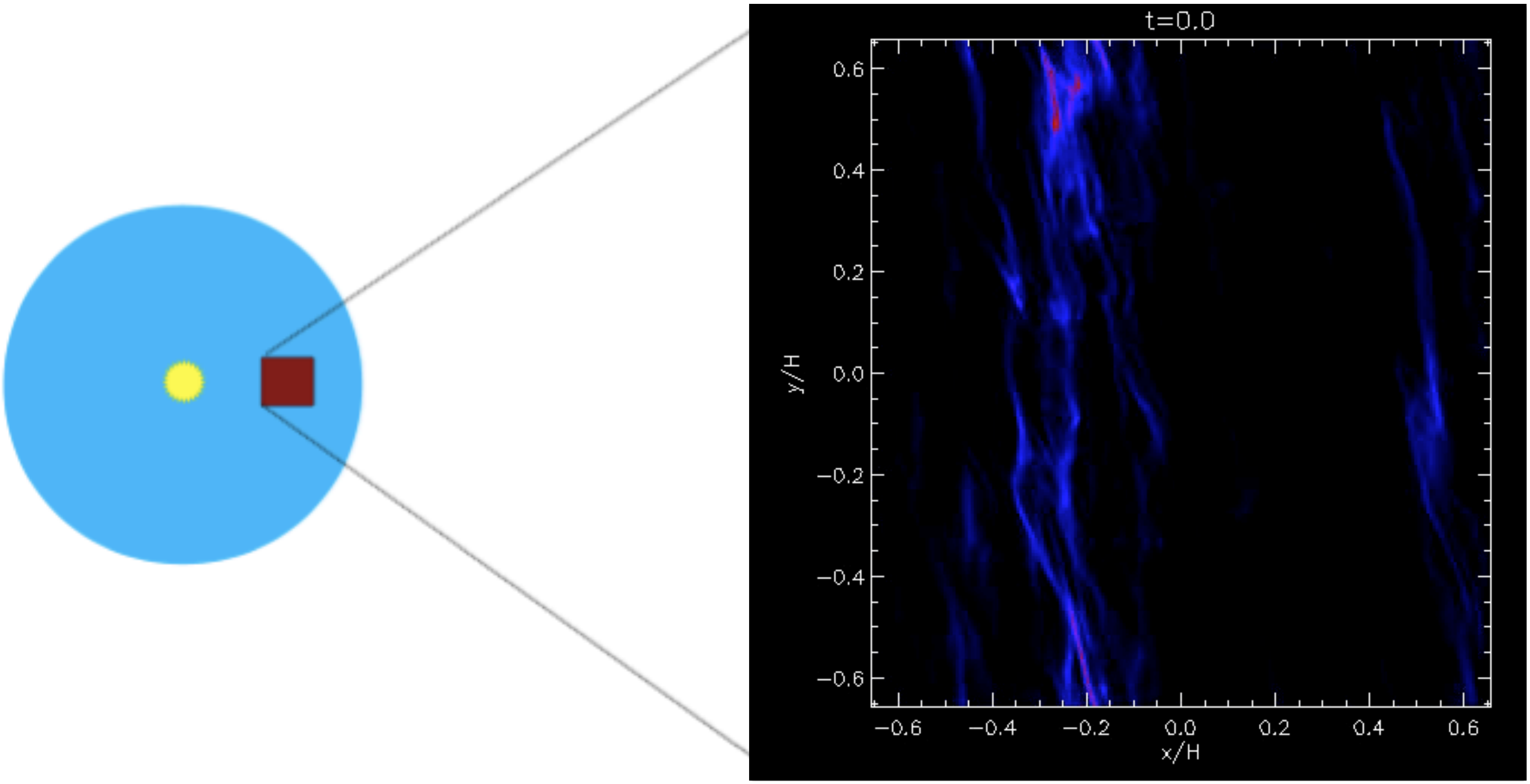


Turbulence concentrates solids mechanically in pressure maxima



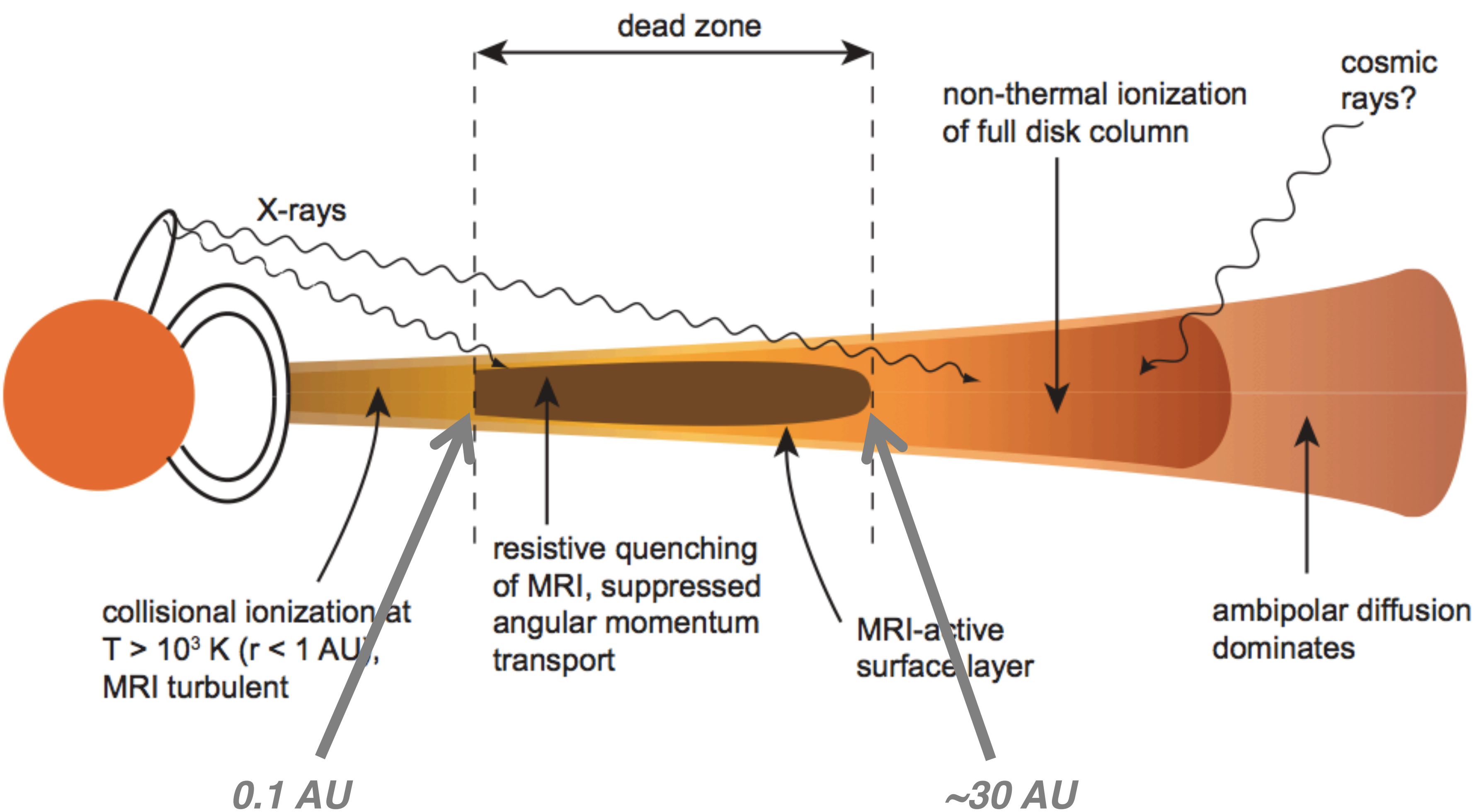
Lyra et al. (2008a)

Gravitational collapse into planetesimals



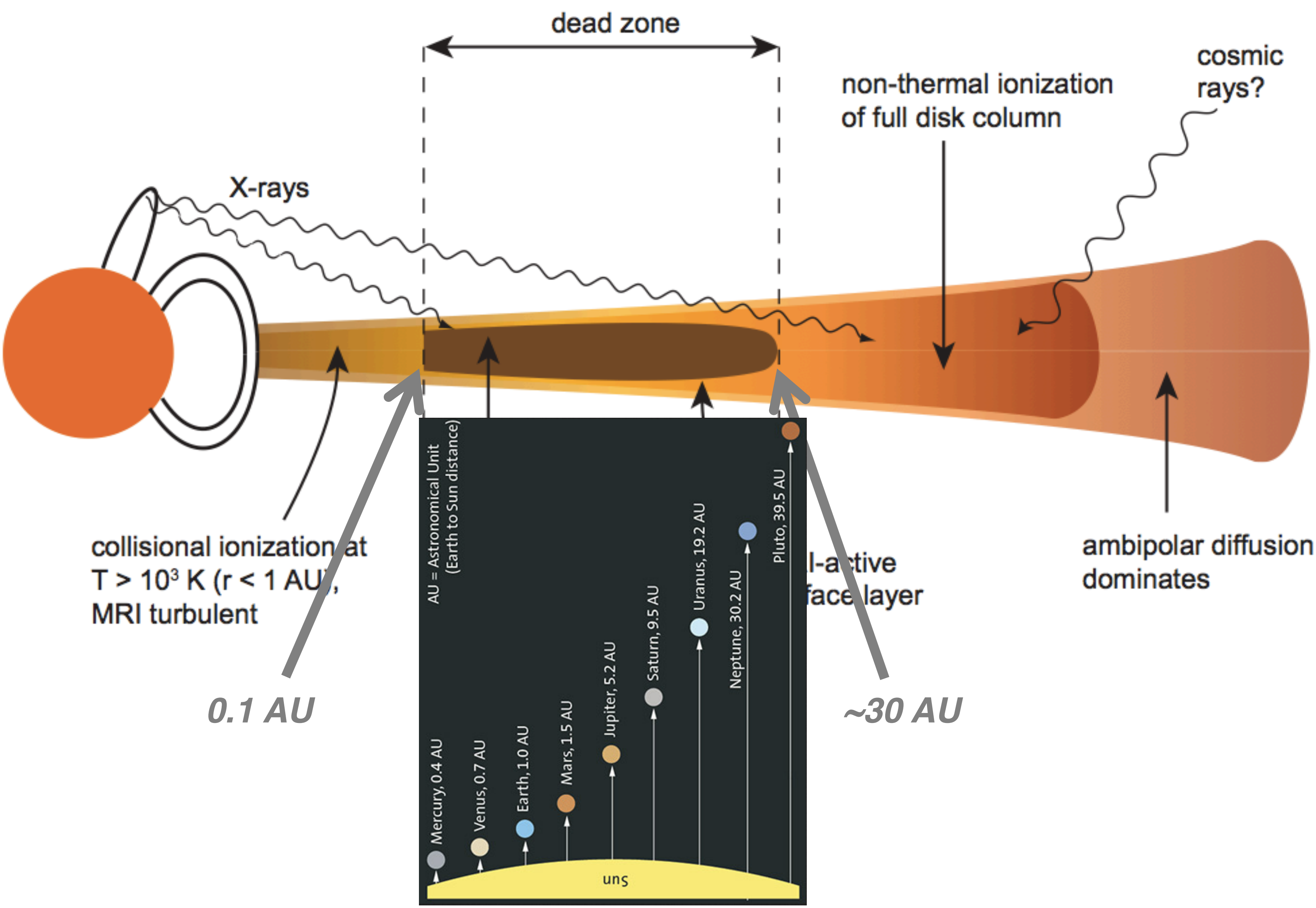
Johansen et al. (2007)

Dead zones

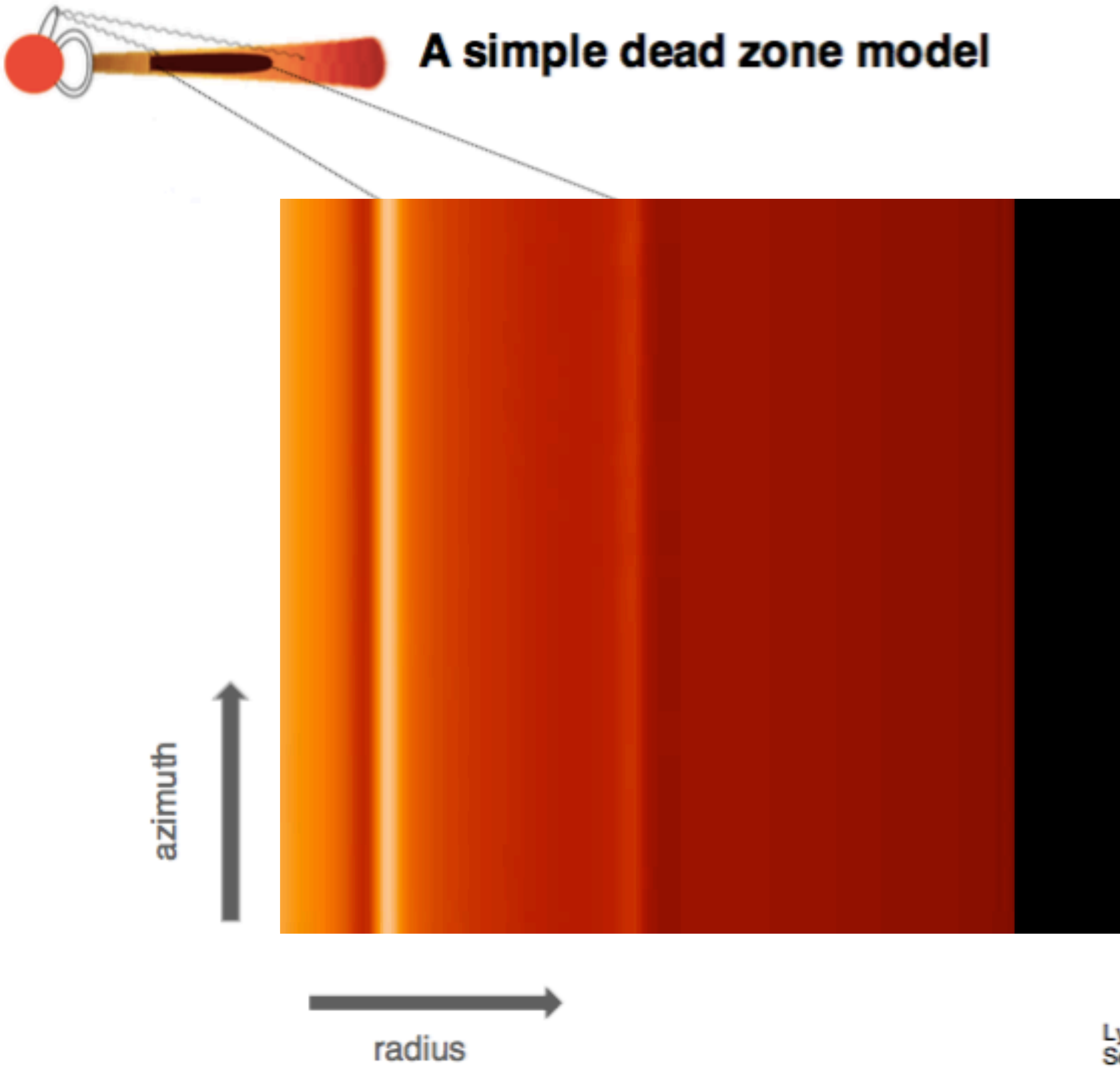


There should be a **magnetized, active zone** and a **non-magnetic, dead zone**

Dead zones

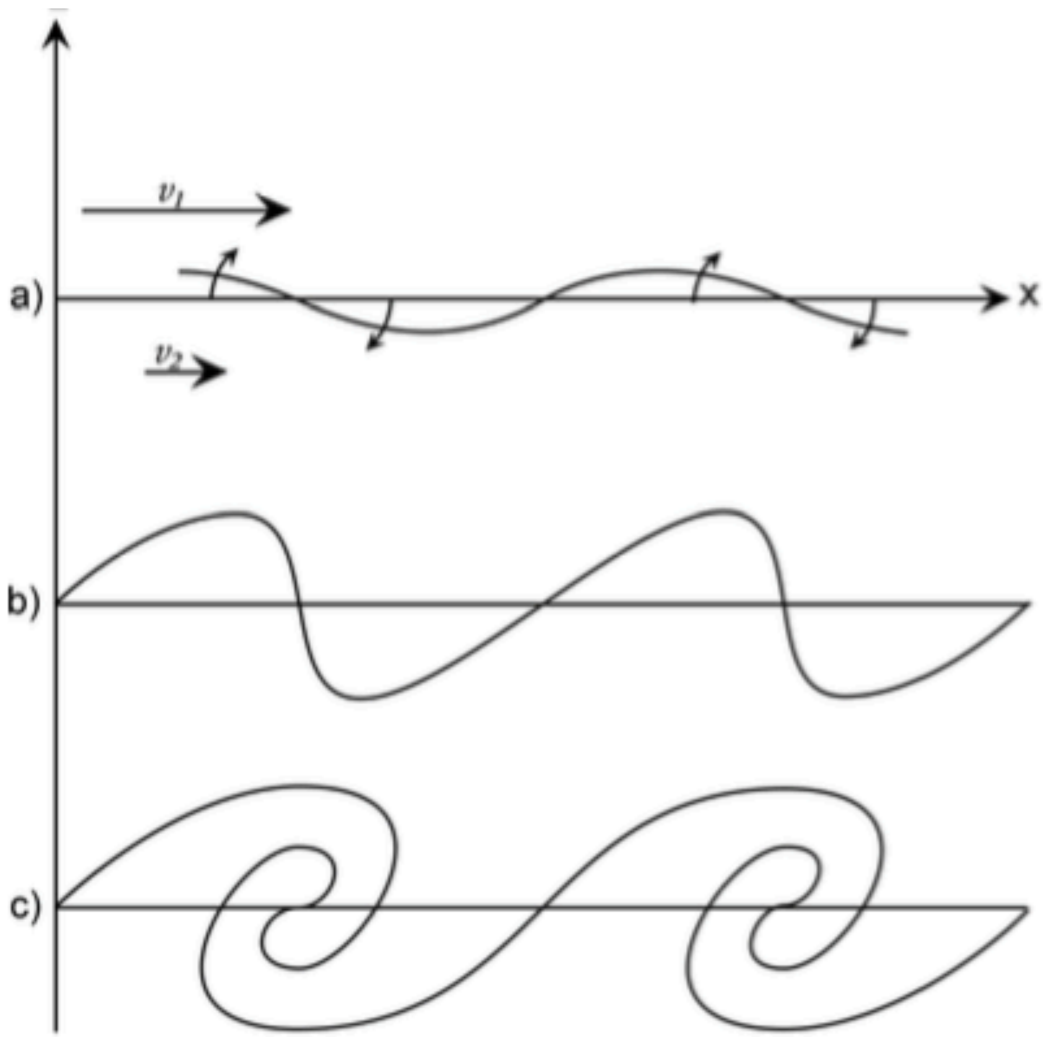

dead zone
X-rays
non-thermal ionization
of full disk column
cosmic
rays?
collisional ionization at
T > 10³ K (r < 1 AU),
MRI turbulent
l-active
face layer
ambipolar diffusion
dominates
0.1 AU
~30 AU
AU = Astronomical Unit
(Earth to Sun distance)
Mercury, 0.4 AU
Venus, 0.7 AU
Earth, 1.0 AU
Mars, 1.5 AU
Jupiter, 5.2 AU
Saturn, 9.5 AU
Uranus, 19.2 AU
Neptune, 30.2 AU
Pluto, 39.5 AU
Sun

A simple dead zone model



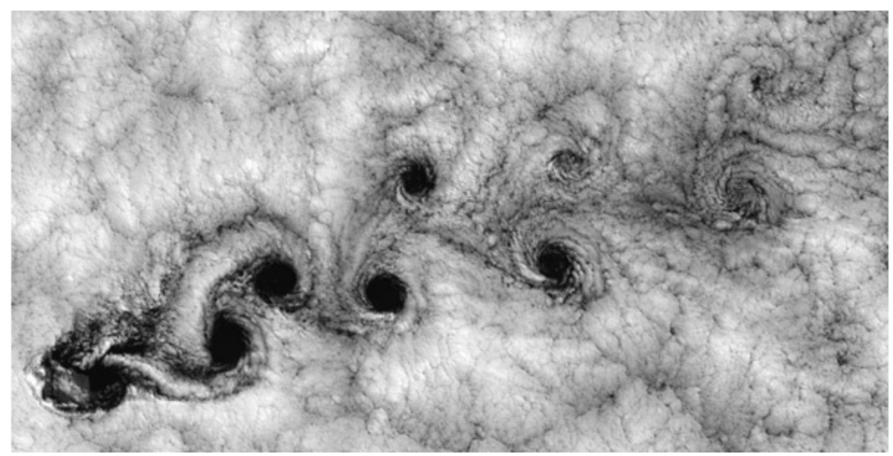
Lyra et al. (2008b, 2009a);
See also Varniere & Tagger (2006)

Rossby wave instability
(Kelvin-Helmholtz Instability in rotating disks)

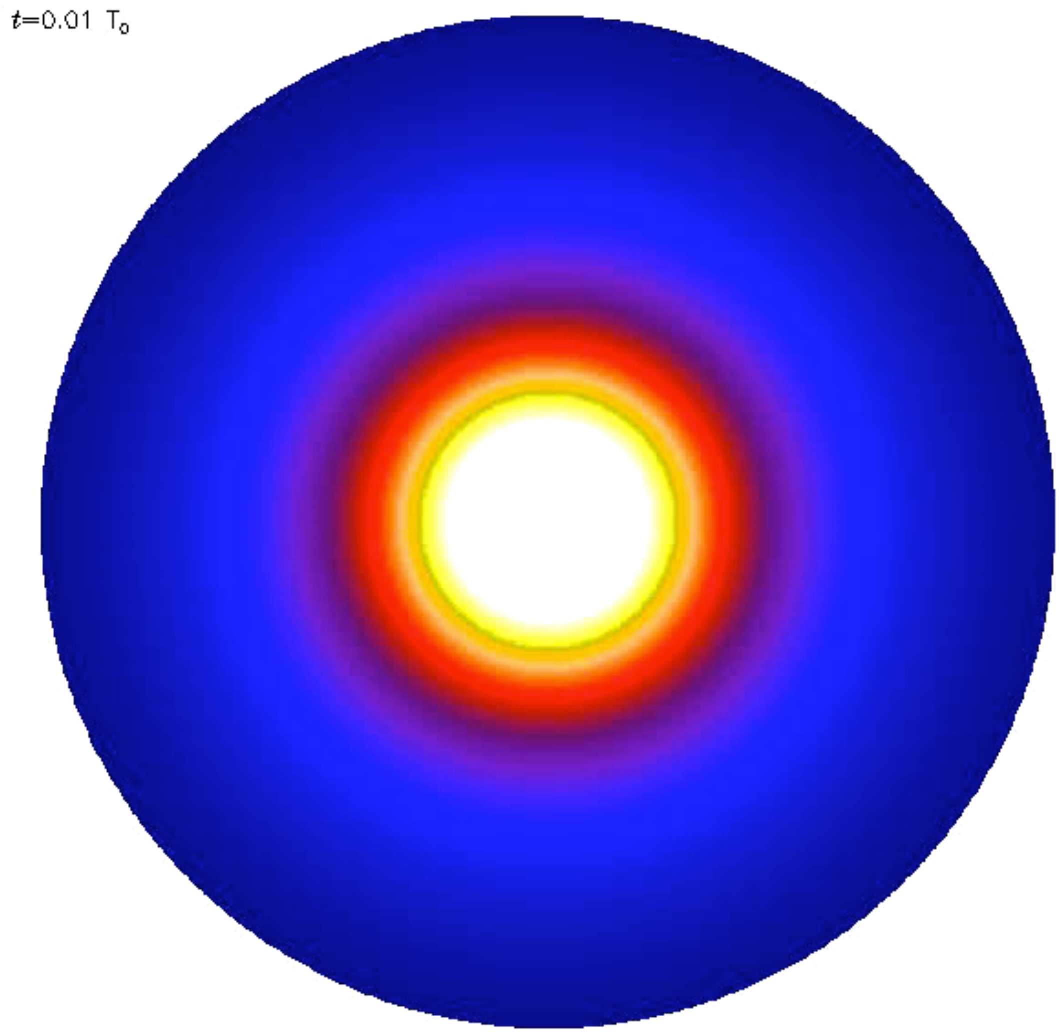


Vortices – an ubiquitous fluid mechanics phenomenon

Von Kármán *vortex street*



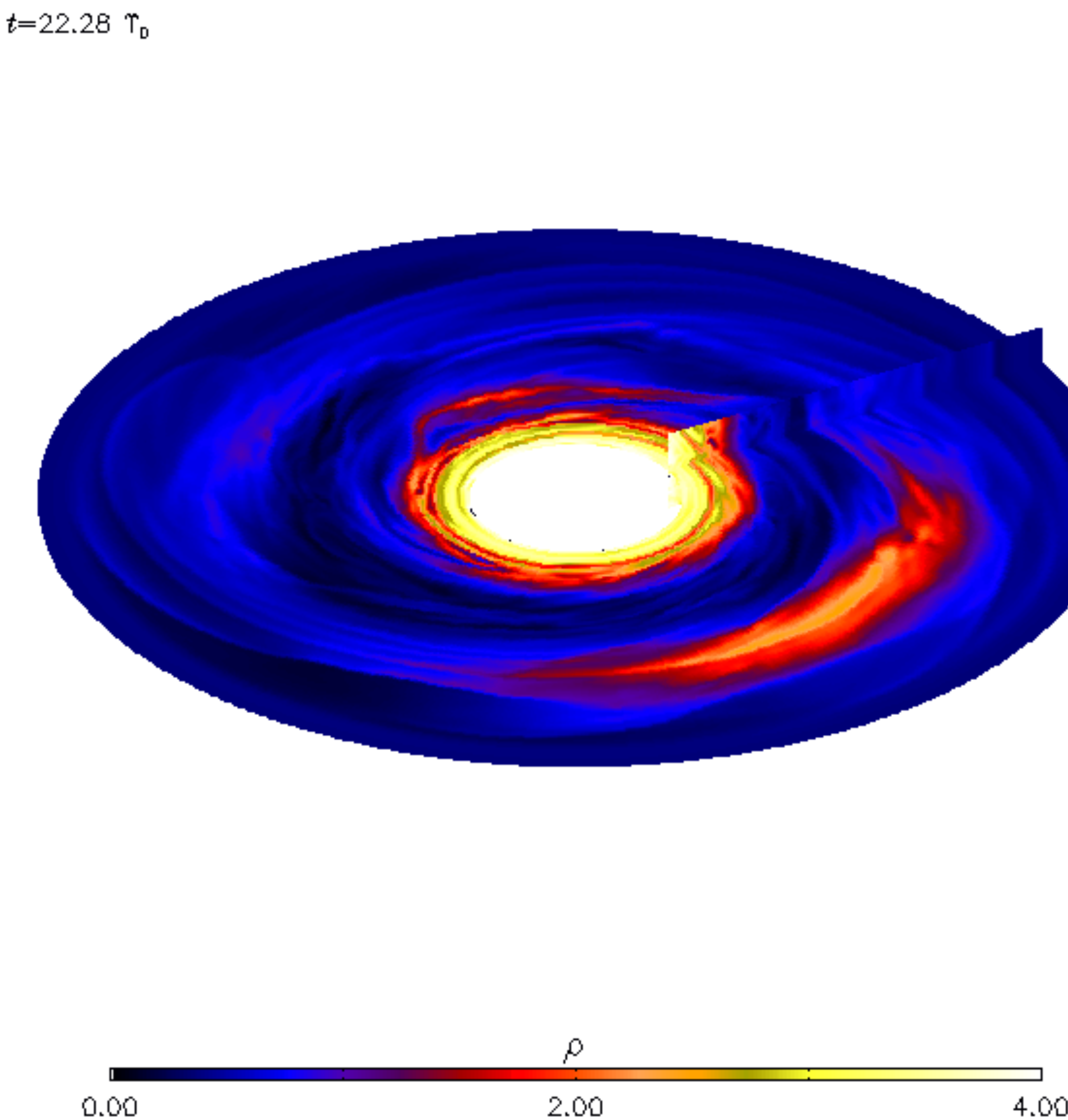
Inner (0.1 AU) active/dead zone boundary

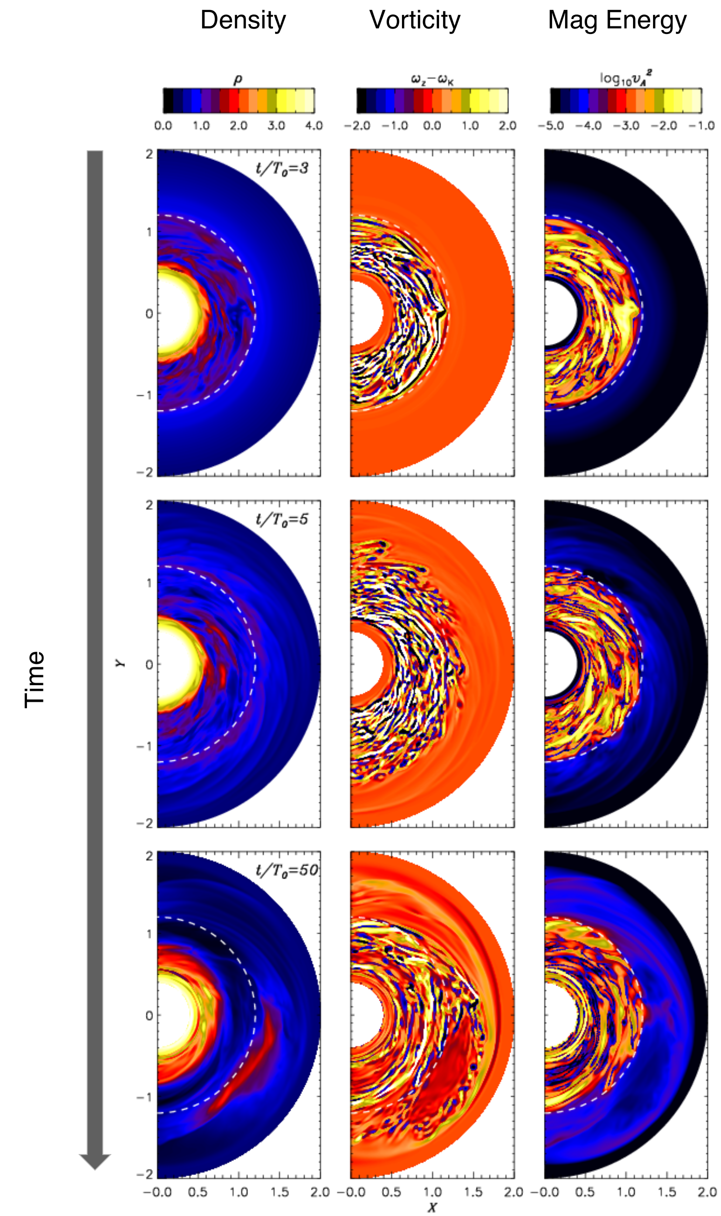


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Inner (0.1AU) active/dead zone boundary

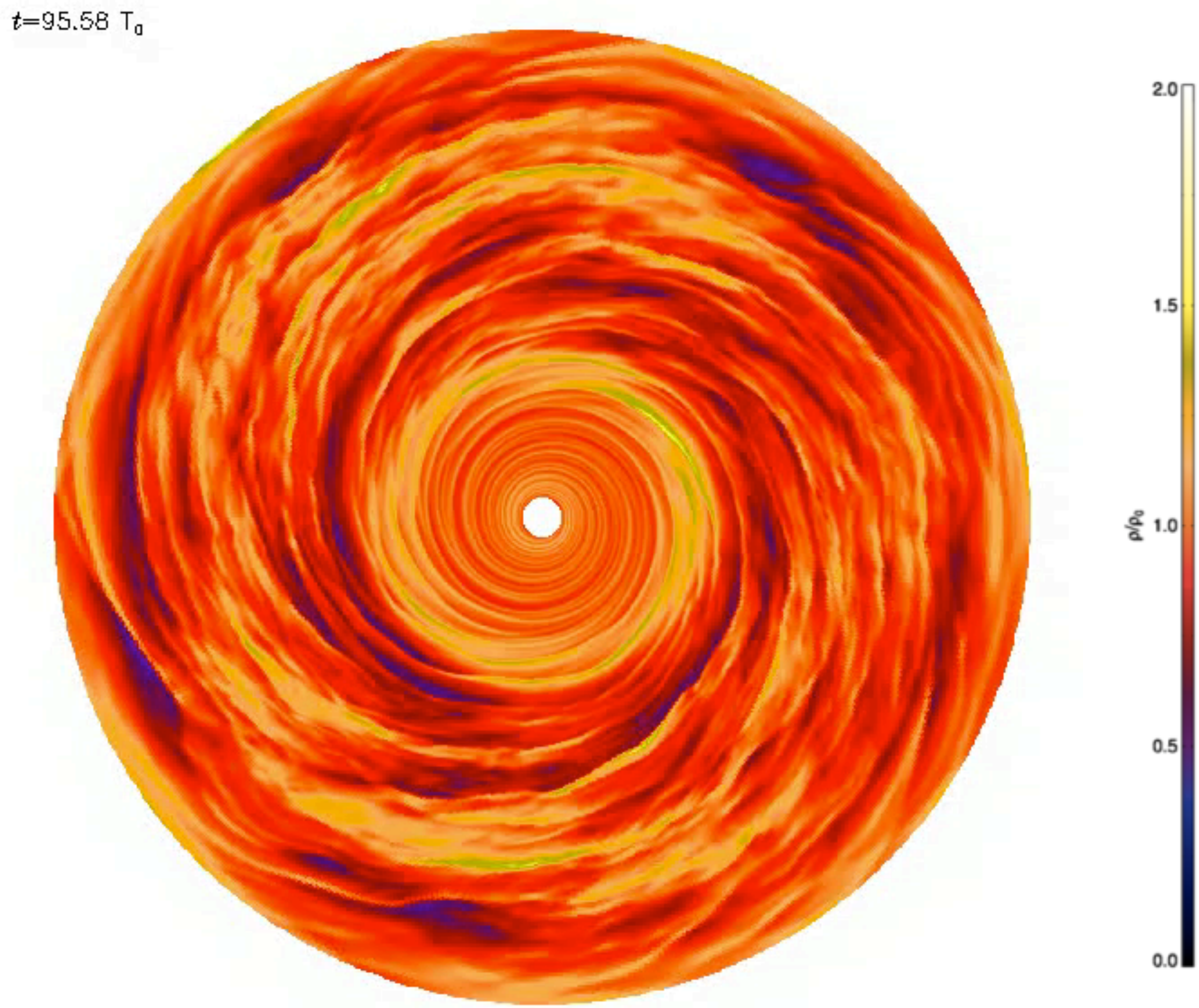




Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

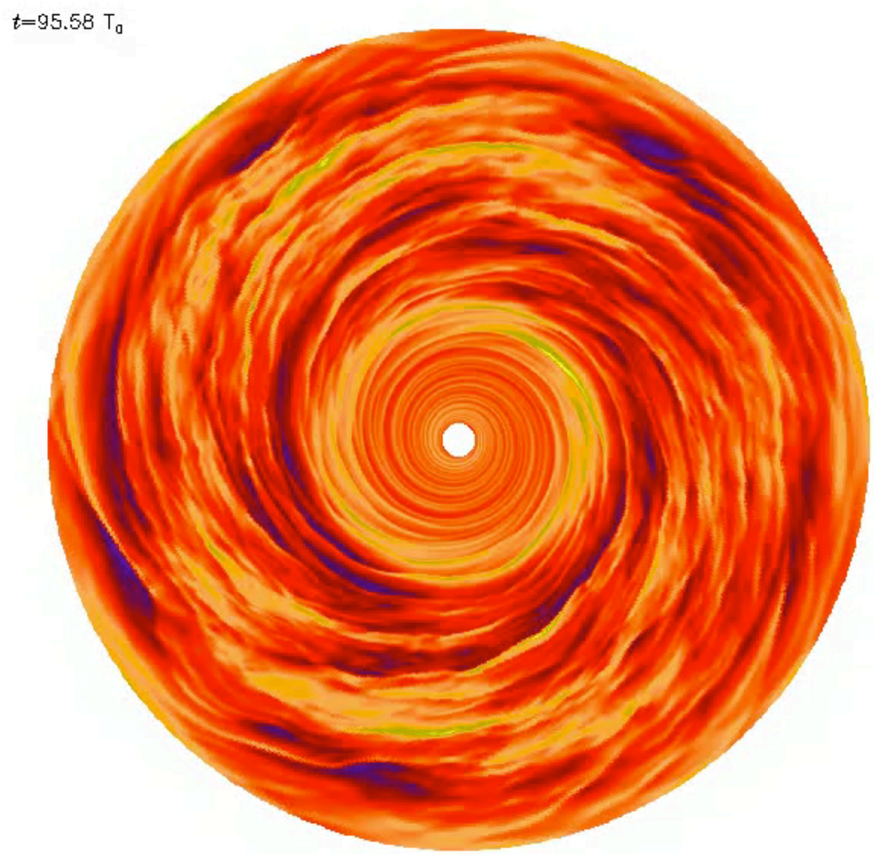
Outer Dead/Active zone transition

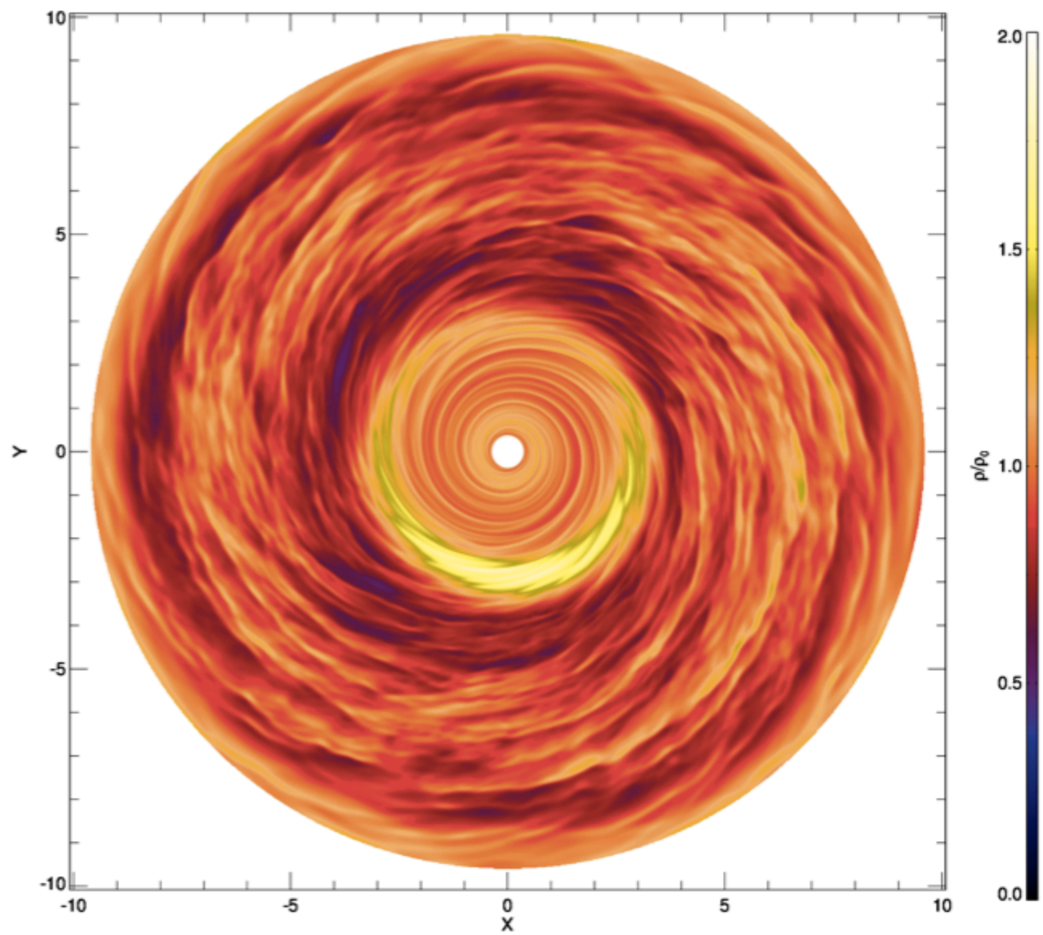


Resistive inner disk + magnetized outer disk

Lyra et al (2015)

Outer Dead/Active zone transition KHI

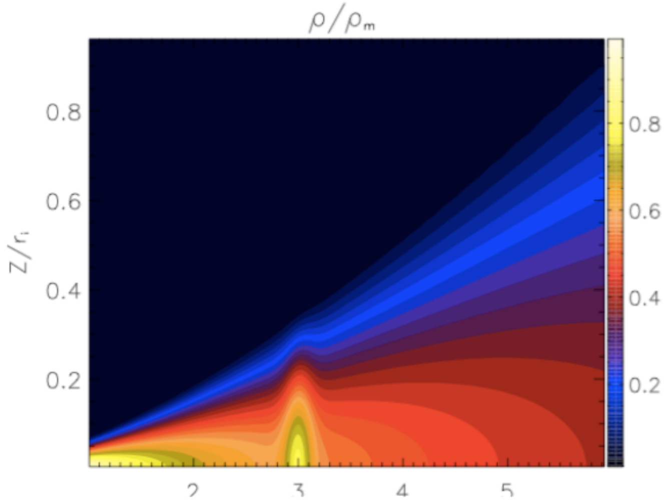




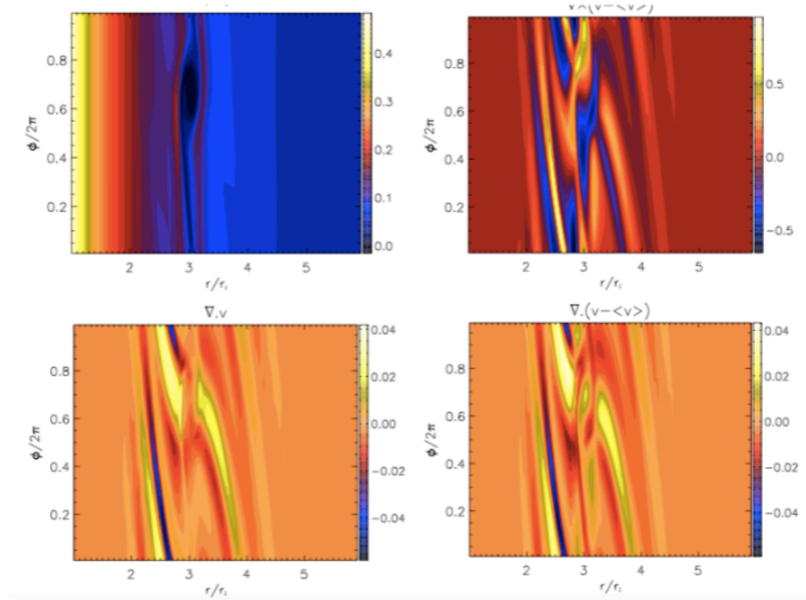
Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)

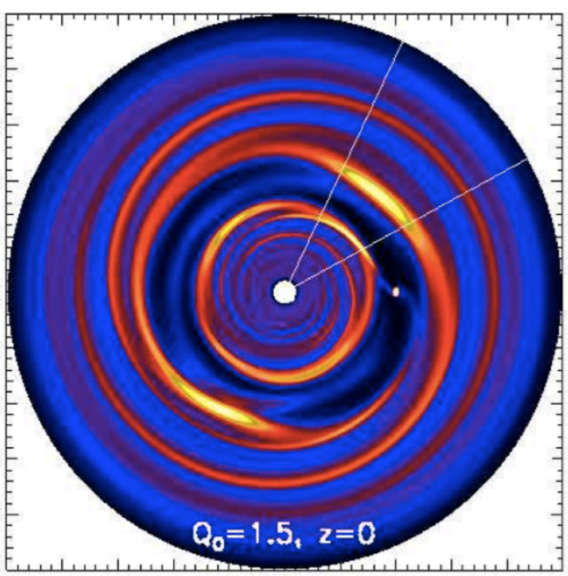
3D strat RWI



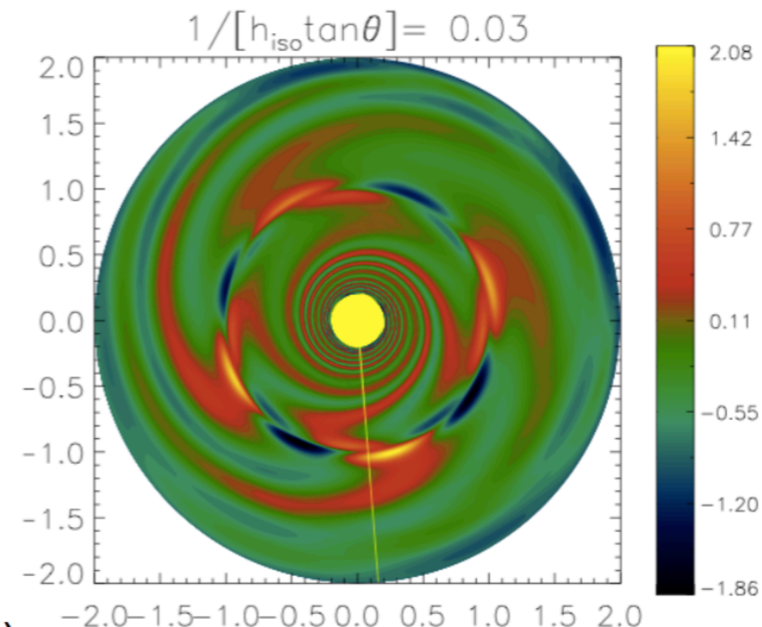
Meheut et al. (2010, 2012abc, 2013)



3D strat RWI self-gravity



3D strat RWI polytropic

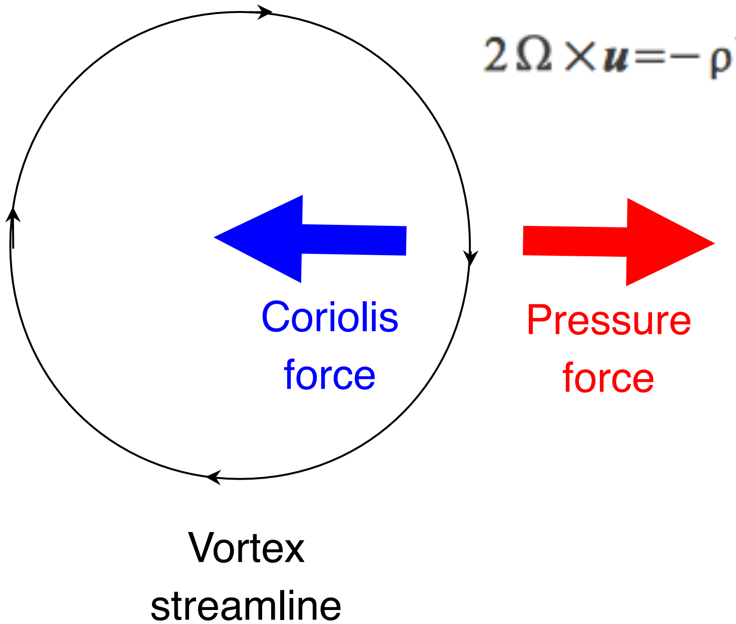


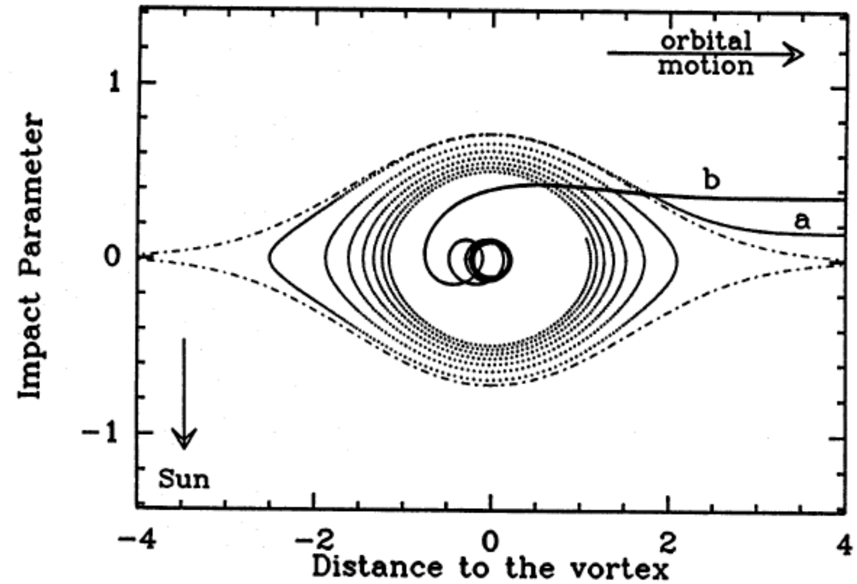
Lin (2012ab, 2013, 2014)

The Tea-Leaf effect

Geostrophic balance:

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





Barge & Sommeria (1995)

Grains 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)

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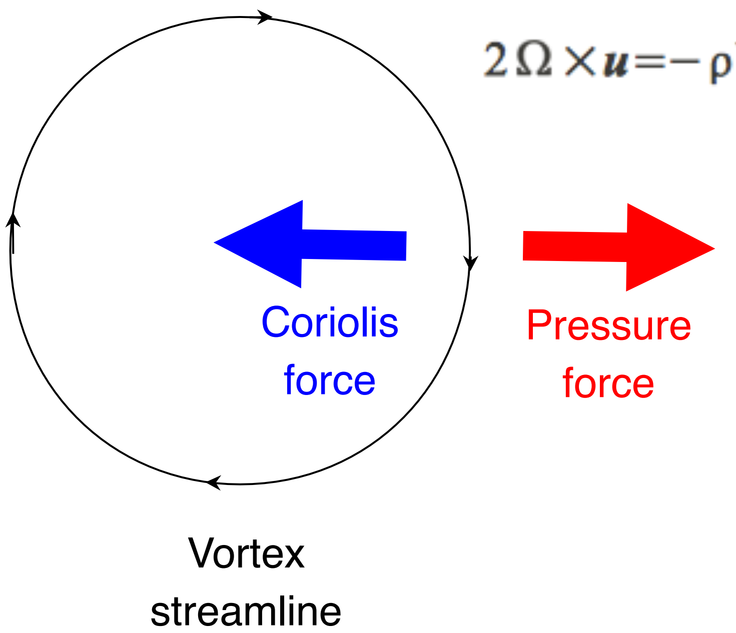

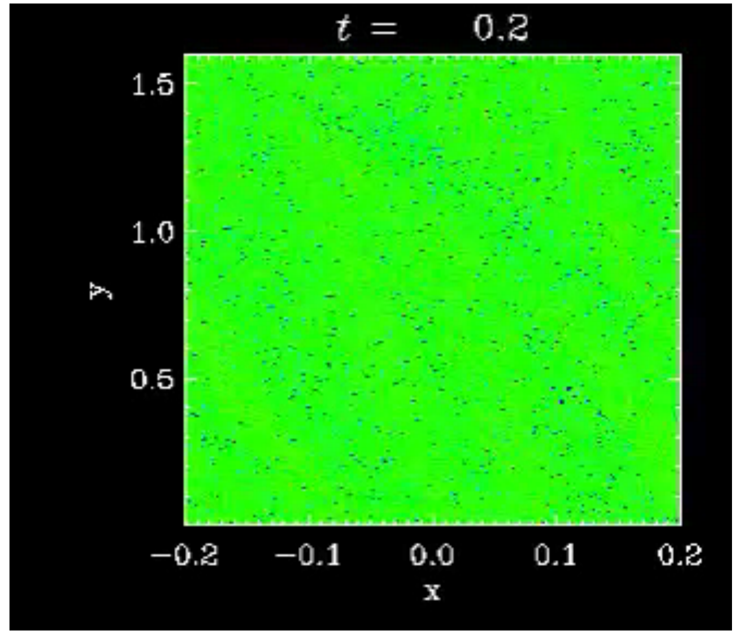

Raettig, Lyra, & Klahr (2013)

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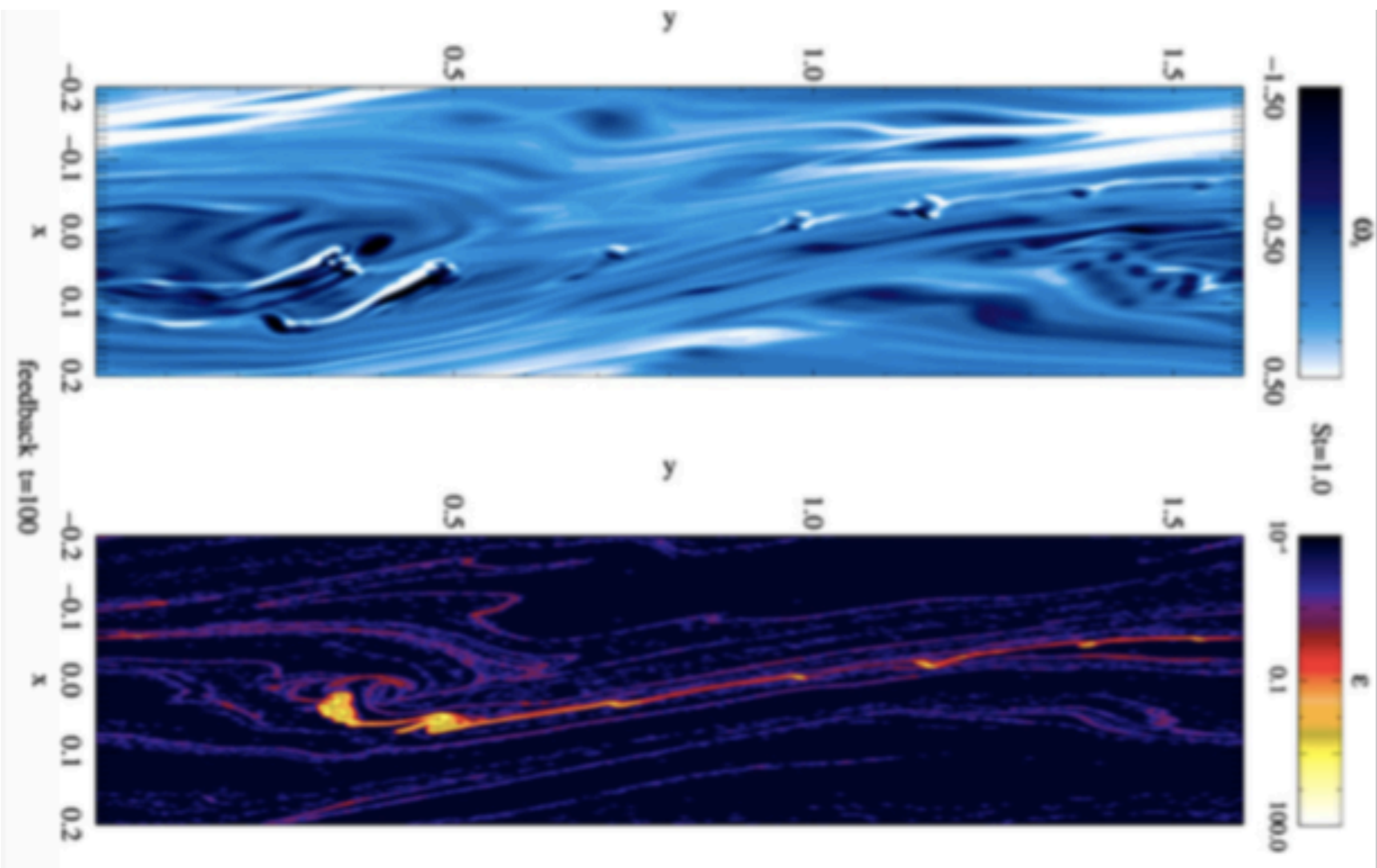
Clumping

Easily reaches dust-to-gas ratio > 1
even for solar (and sub-solar) metallicities.

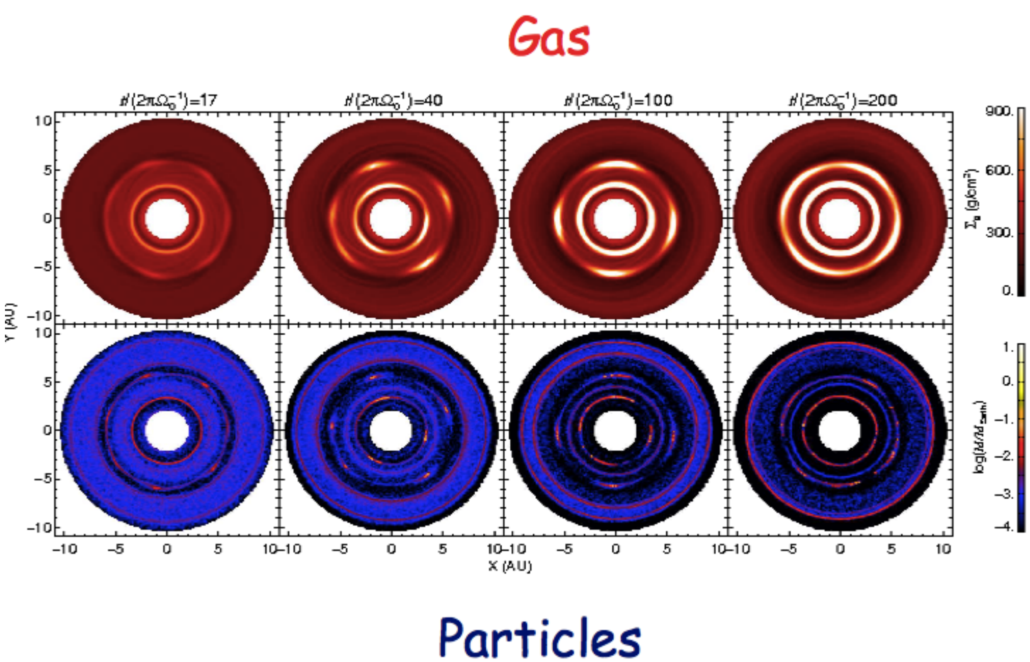


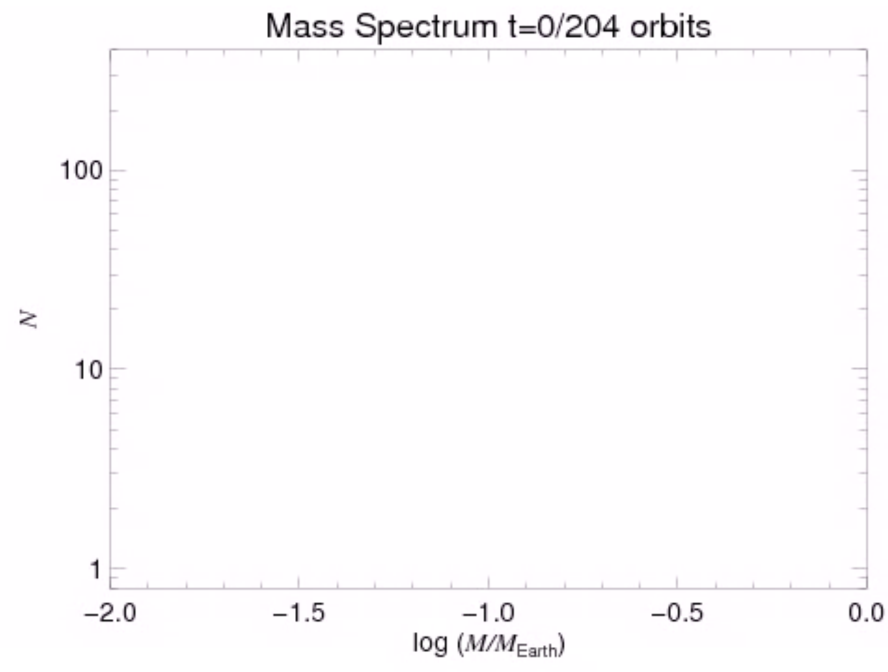
Gas vorticity

grains-to-gas ratio

Raettig et al. (2015)

Vortices and Planet Formation

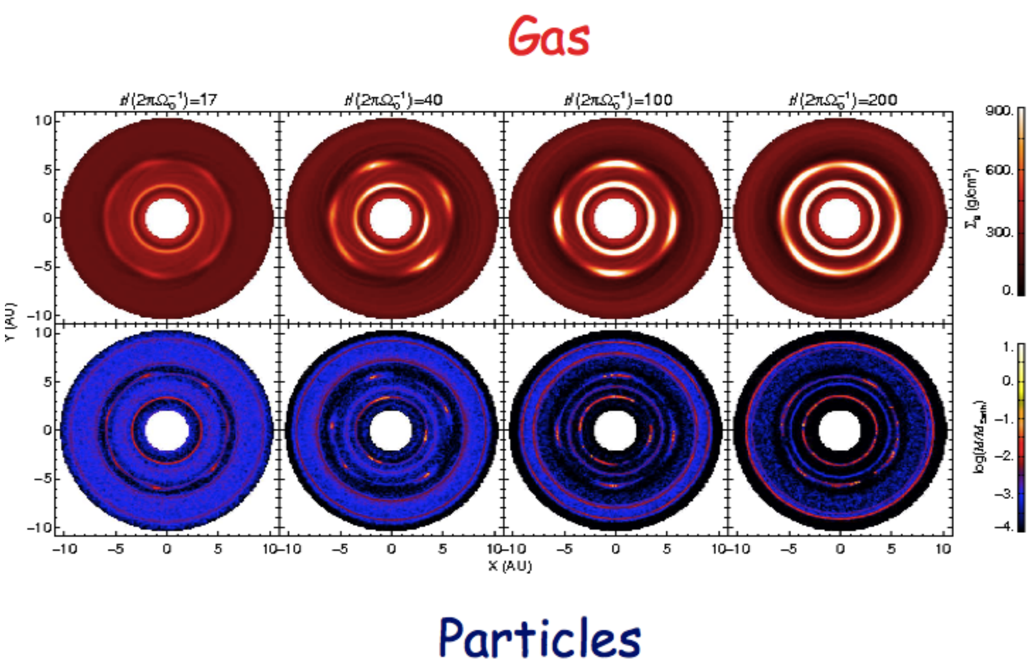


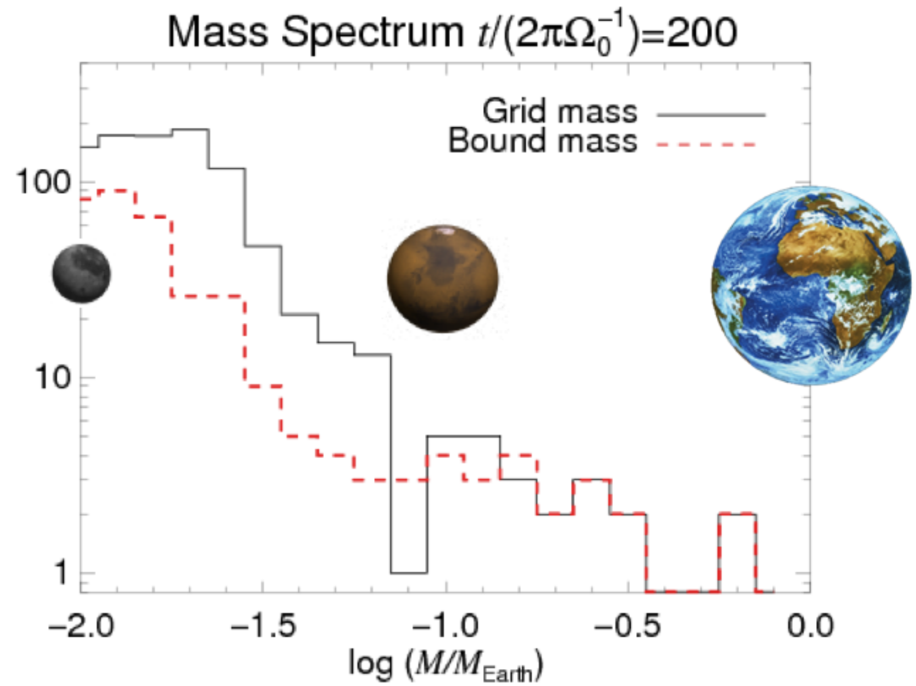


Collapse into Mars mass objects

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

Vortices and Planet Formation

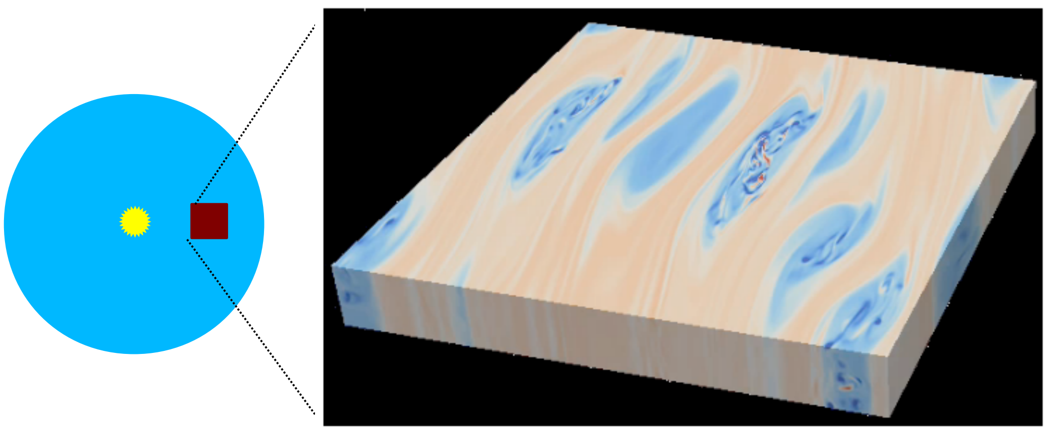




Collapse into Mars mass objects

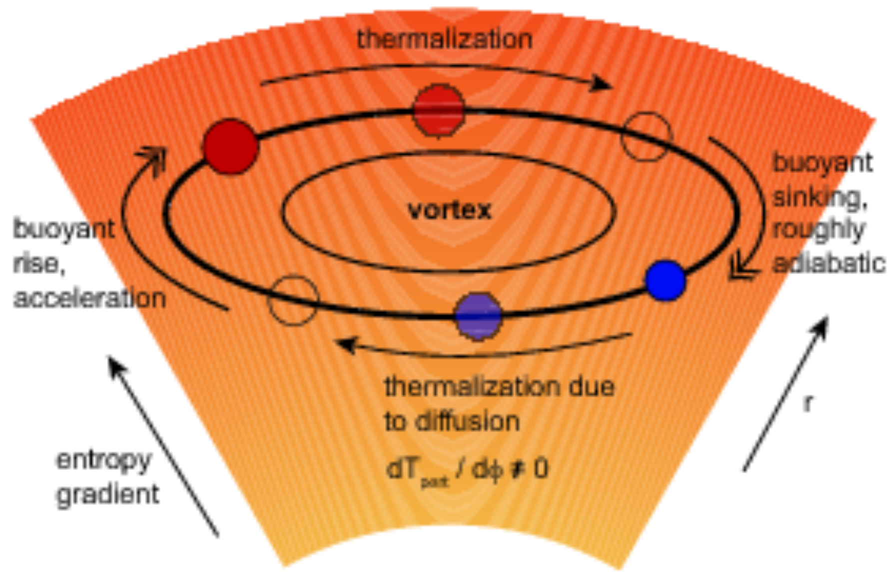
(Lyra et al. 2008b, 2009a,
Lambrechts & Johansen 2012)

Convection



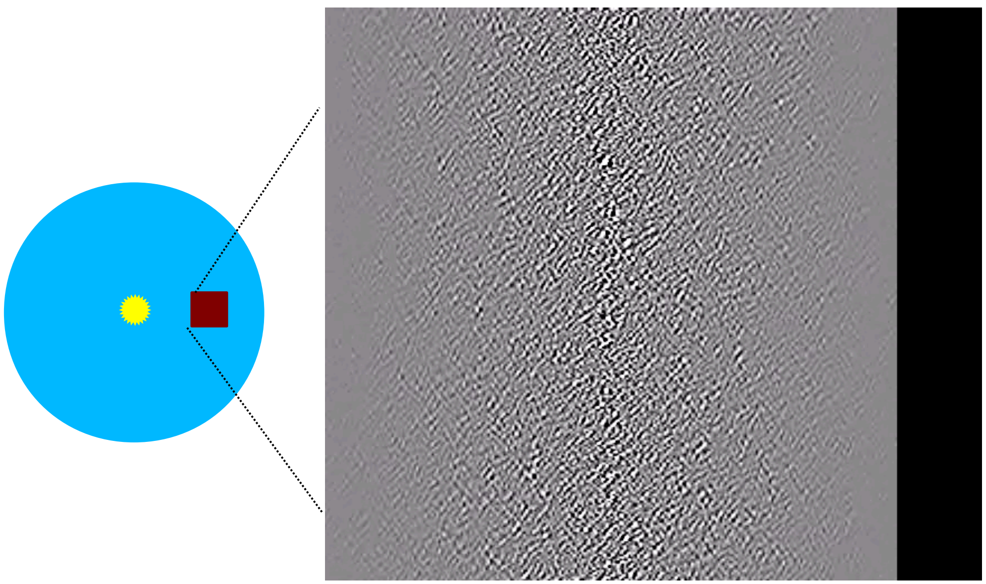
Lesur & Papaloizou (2010)

Sketch of Convection

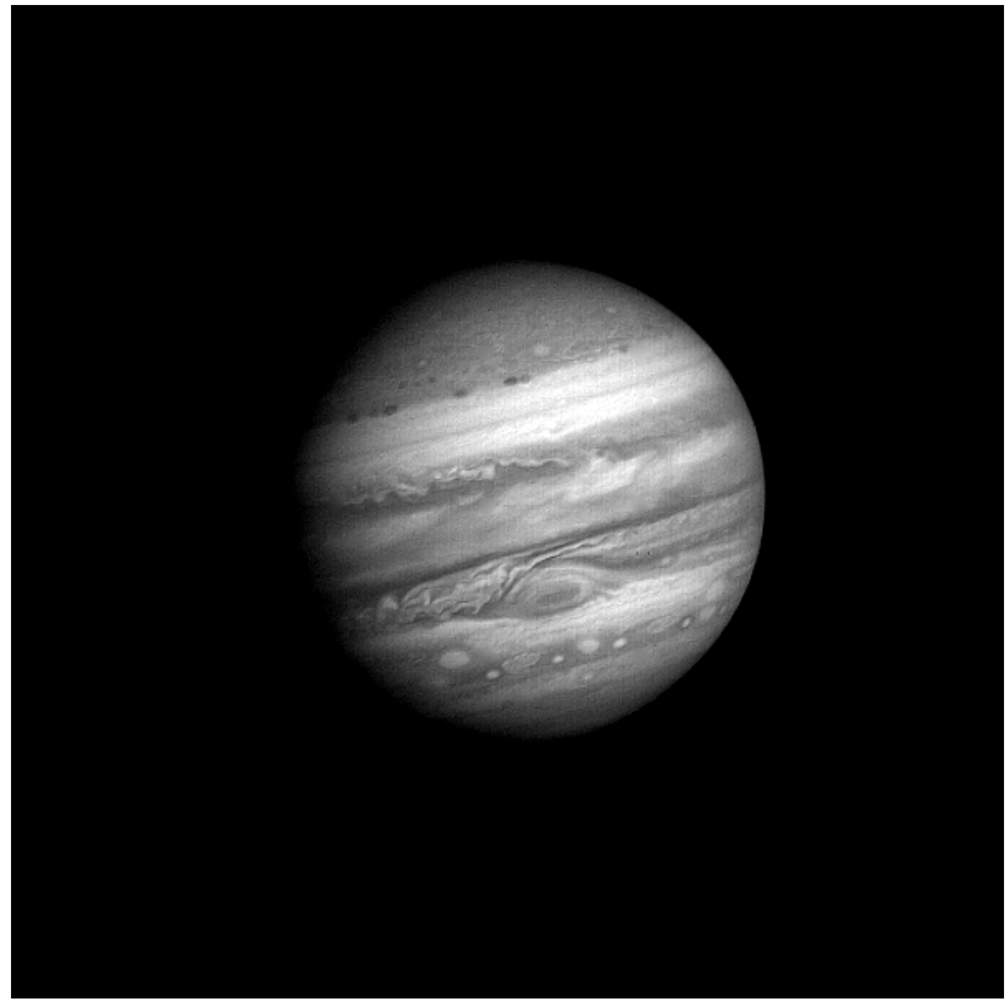


Armitage (2010)

Vortices in the dead zone



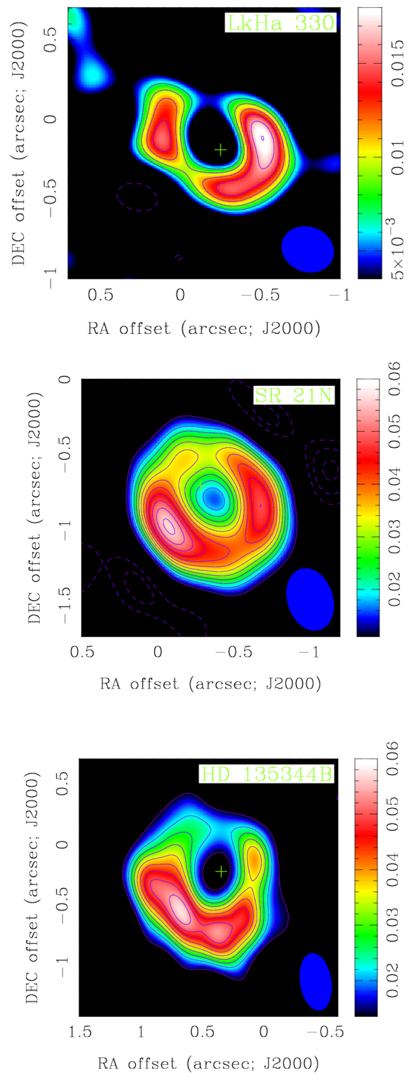
Lyra & Klahr (2011)

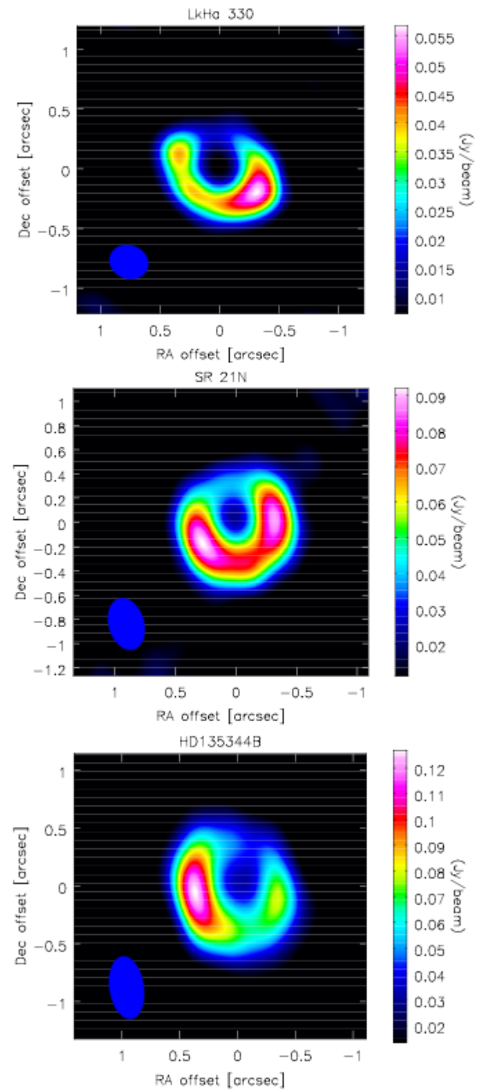


A possible detection of vortices in disks?

Observations

Brown et al. (2009)





Models

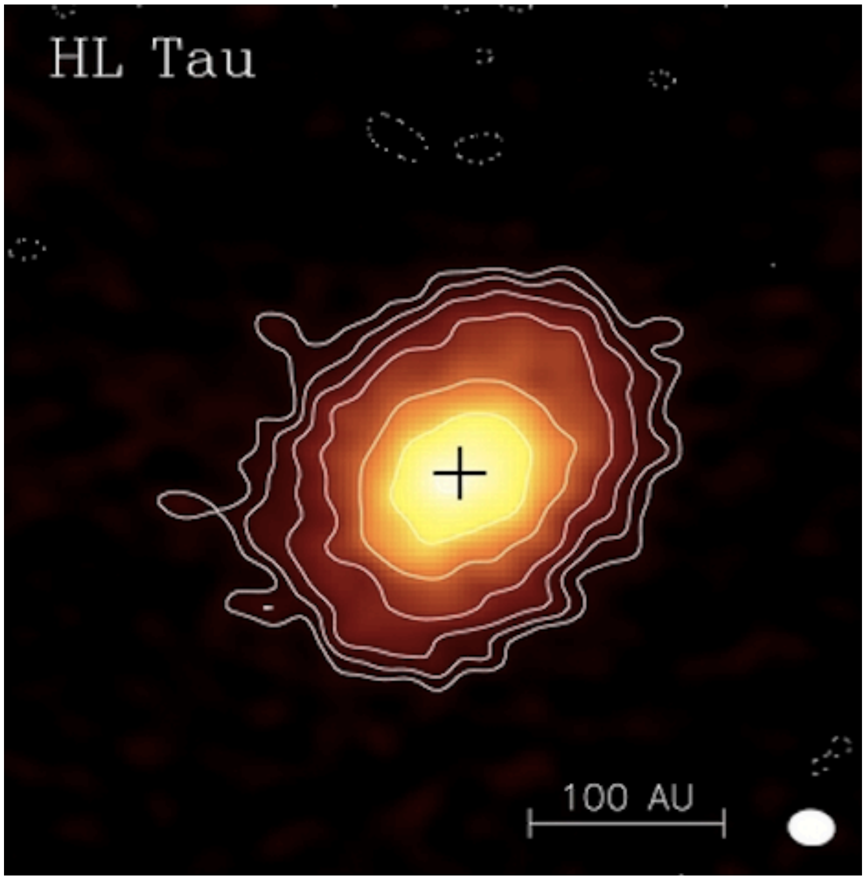
Simulated observations of Rossby vortices

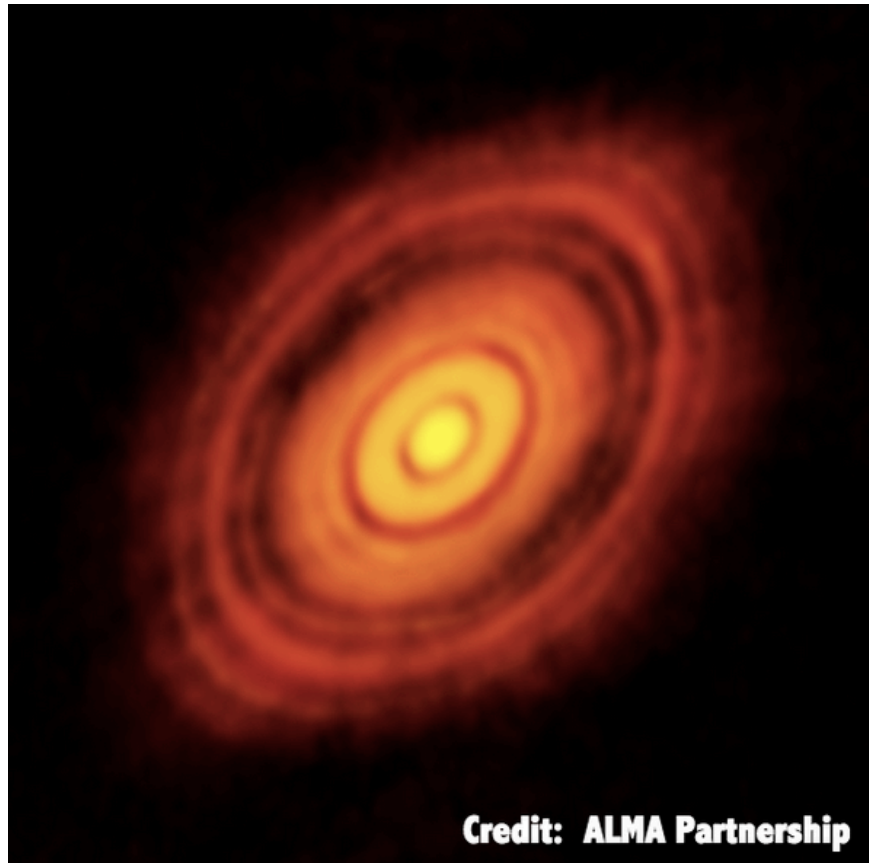
Regaly, Sándor et al. (2012)

The Atacama Large Millimeter Array (ALMA)

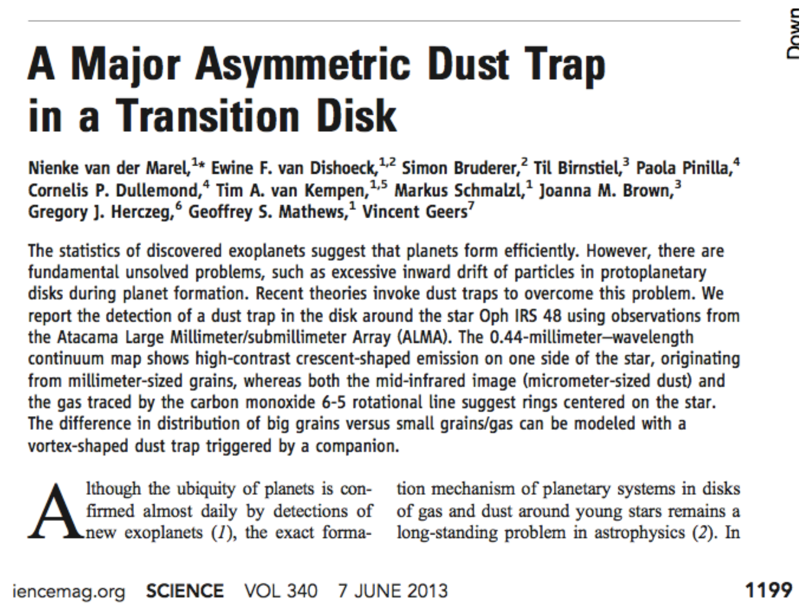
Before ALMA

ALMA





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]

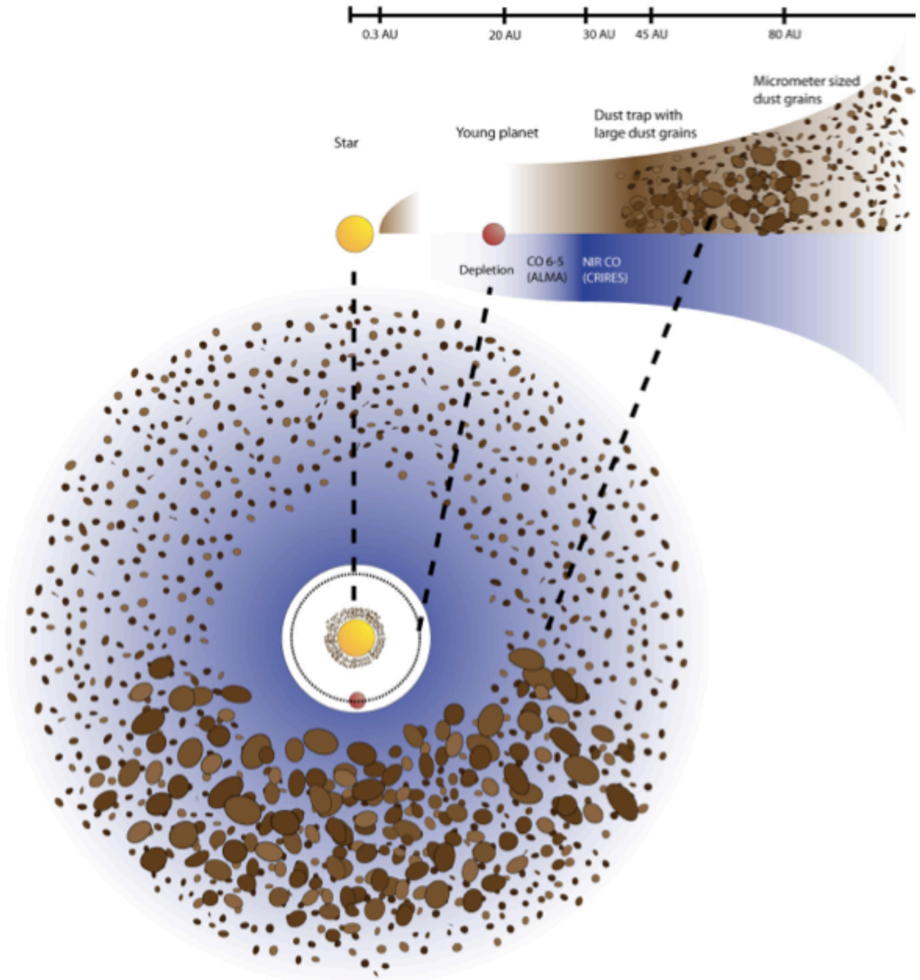
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection 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

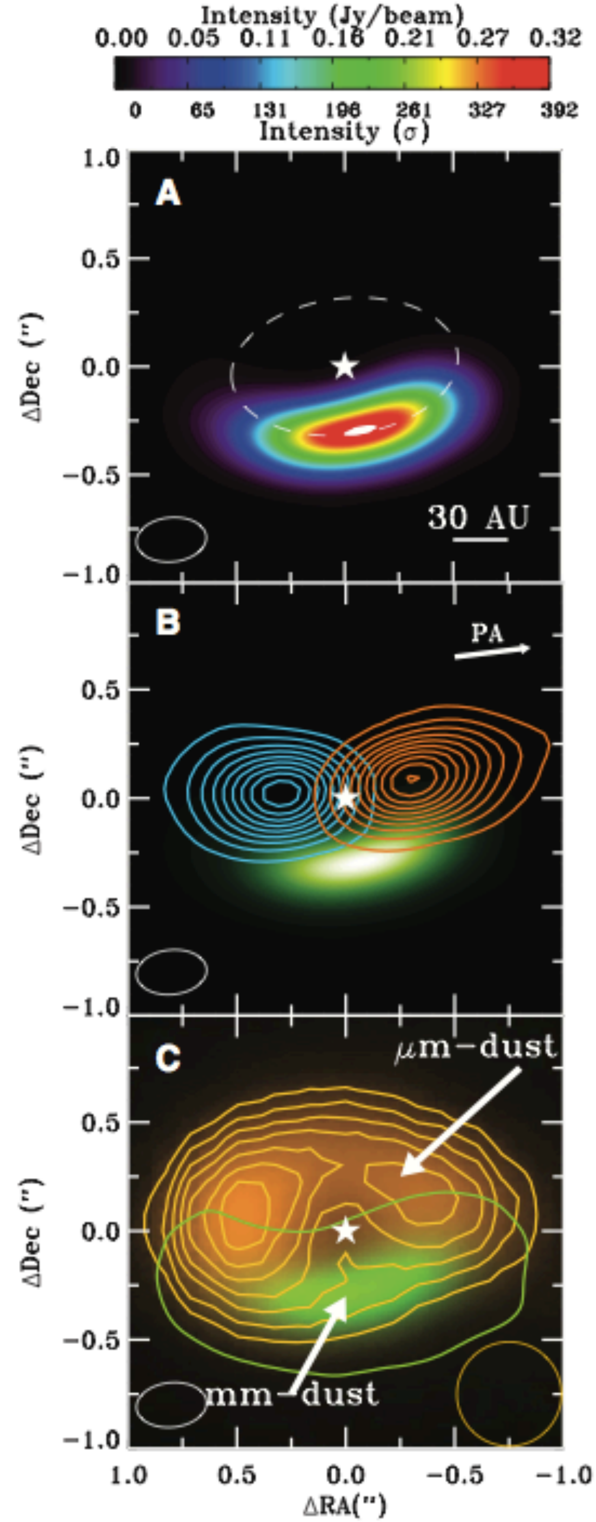
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 “dust trap”



van der Marel et al. (2013)

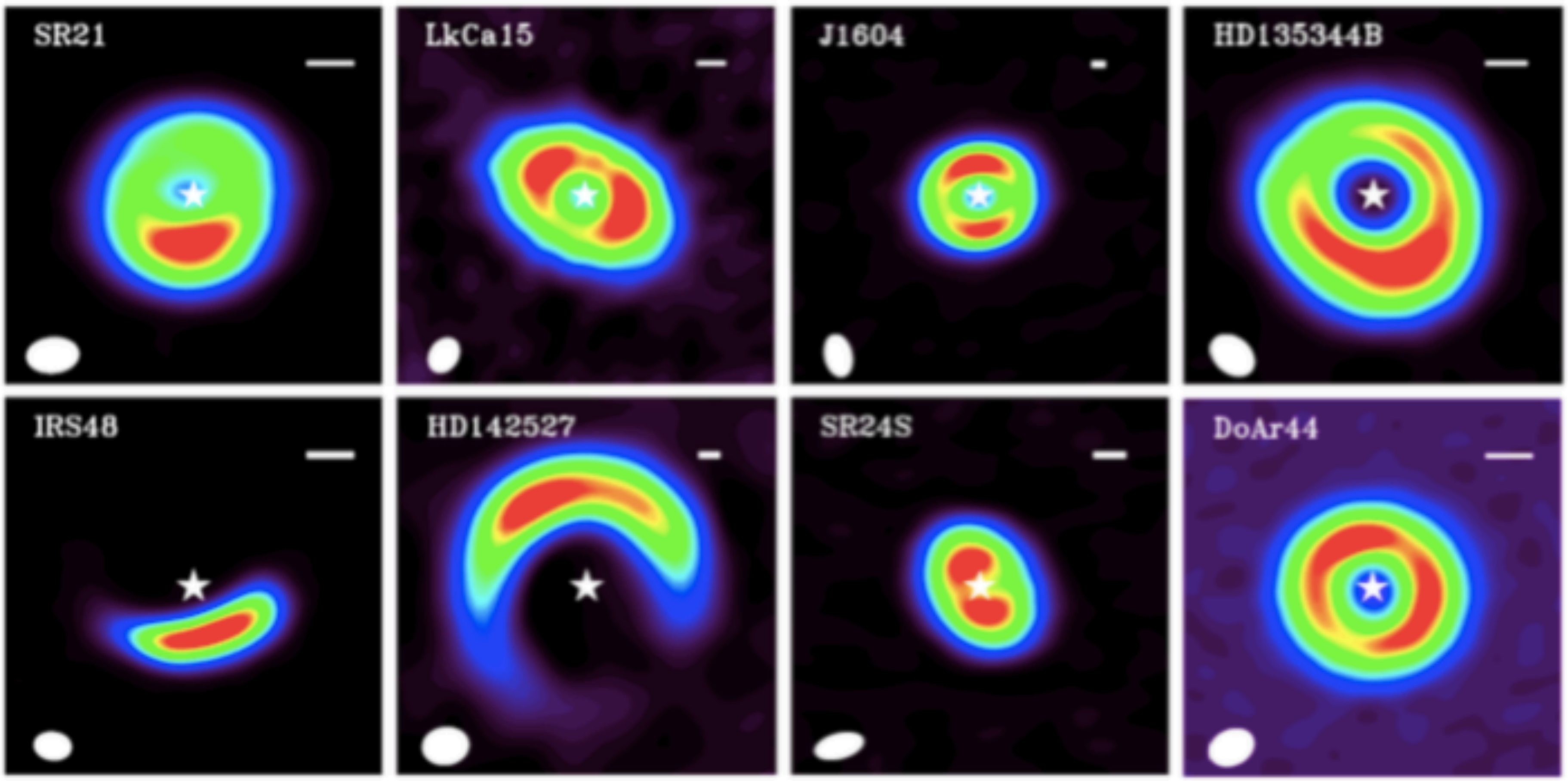


asymmetric mm dust at 63 AU

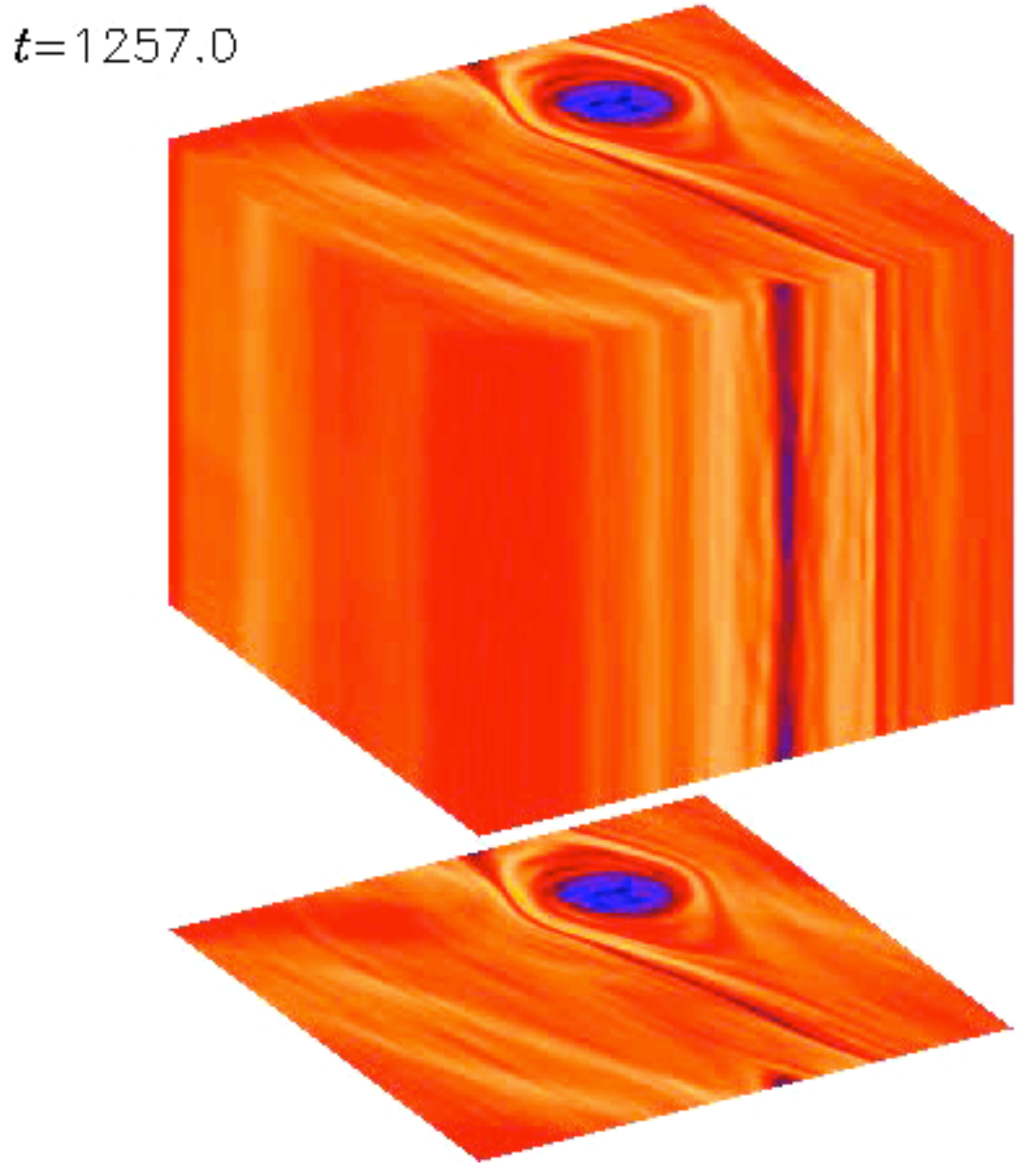
Gas detection: Keplerian rotation

Micron-sized dust follows gas

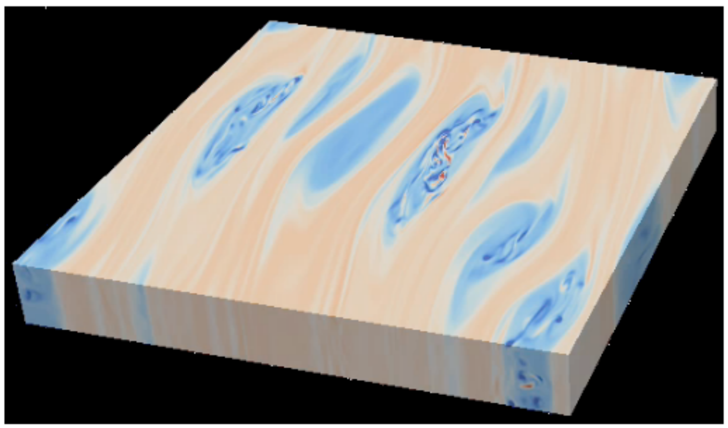
Vortices everywhere!



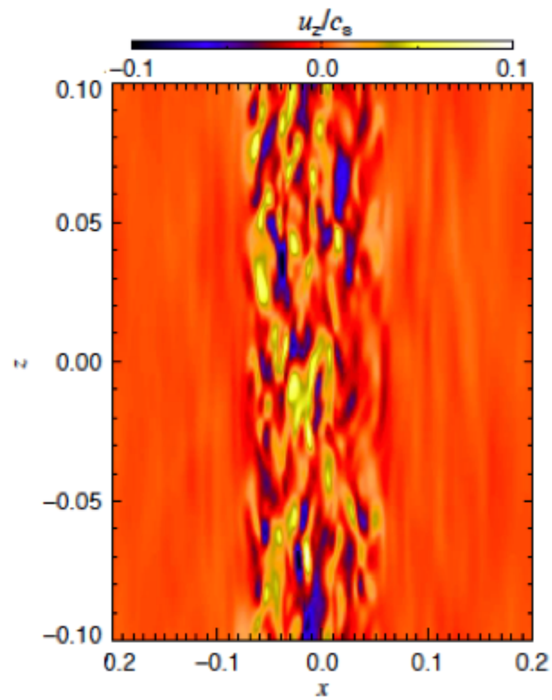
Turbulence in vortex cores



Turbulence in vortex cores



Lesur & Papaloizou (2010)

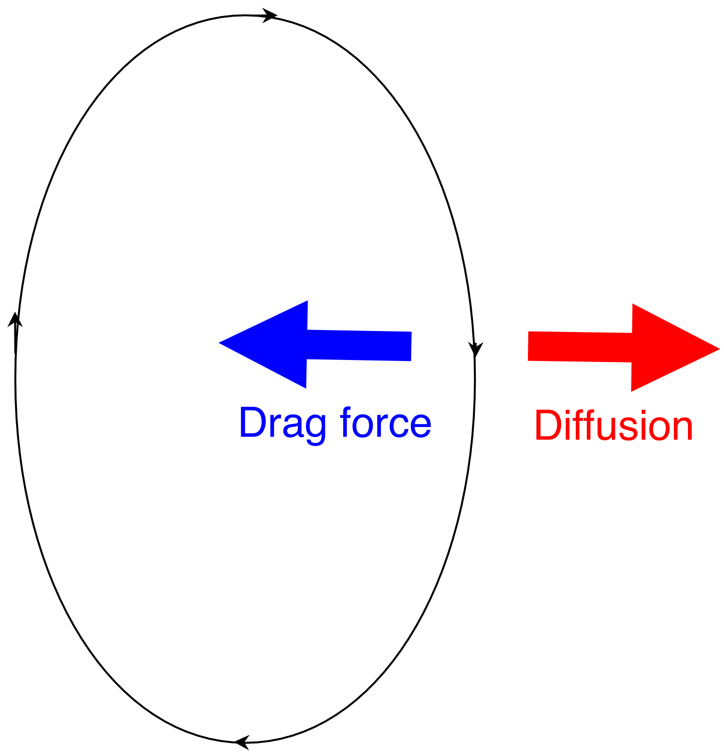


Lyra & Klahr (2011)

Turbulence in vortex cores:

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

Drag-Diffusion Equilibrium

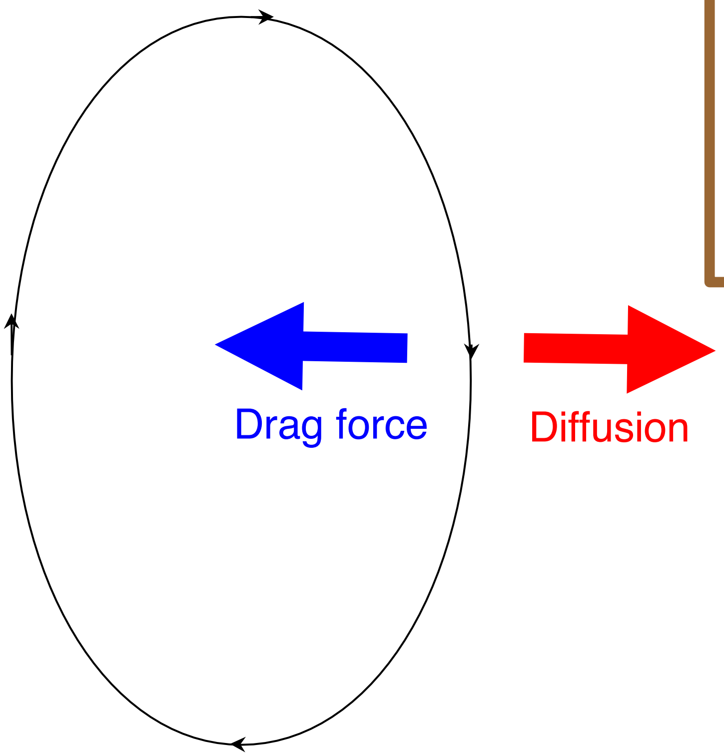


Trapped particle

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

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

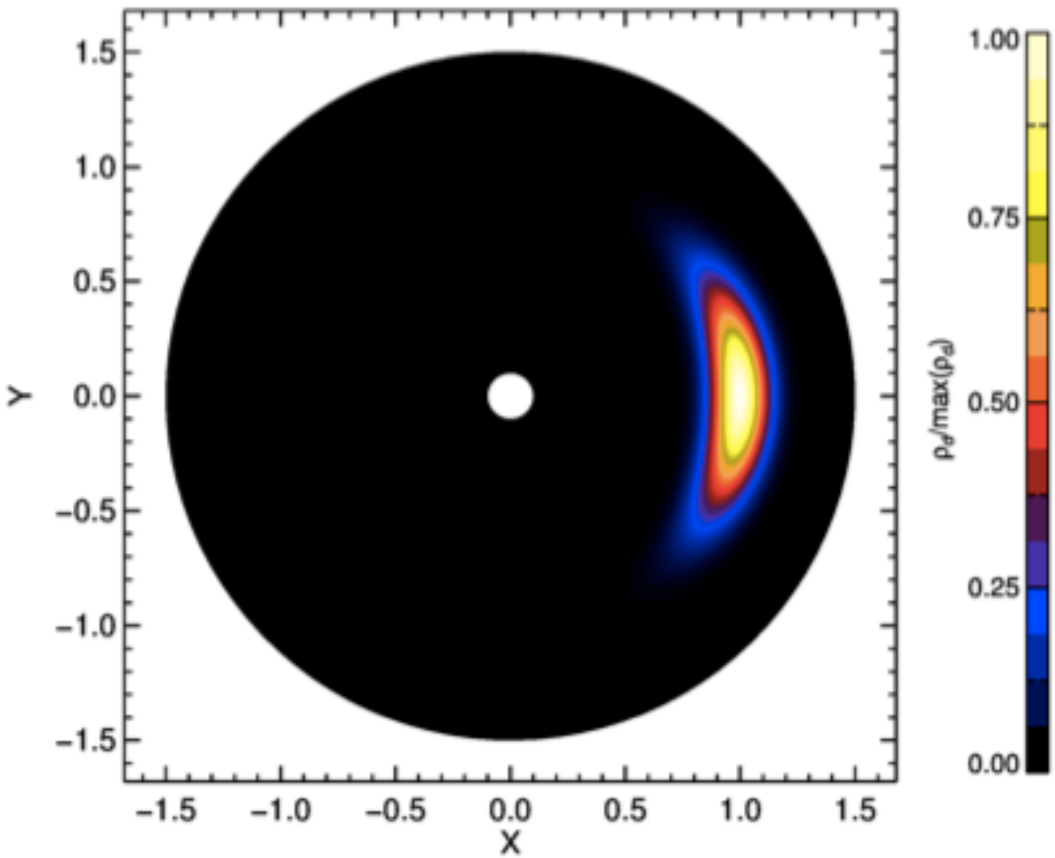
Lyra & Lin (2013)

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

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

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 in drag-diffusion equilibrium



Solution for

H/r=0.1 χ=4 *S*=1

Solution

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

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

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

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

a = distance to vortex center
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (grain 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)
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}

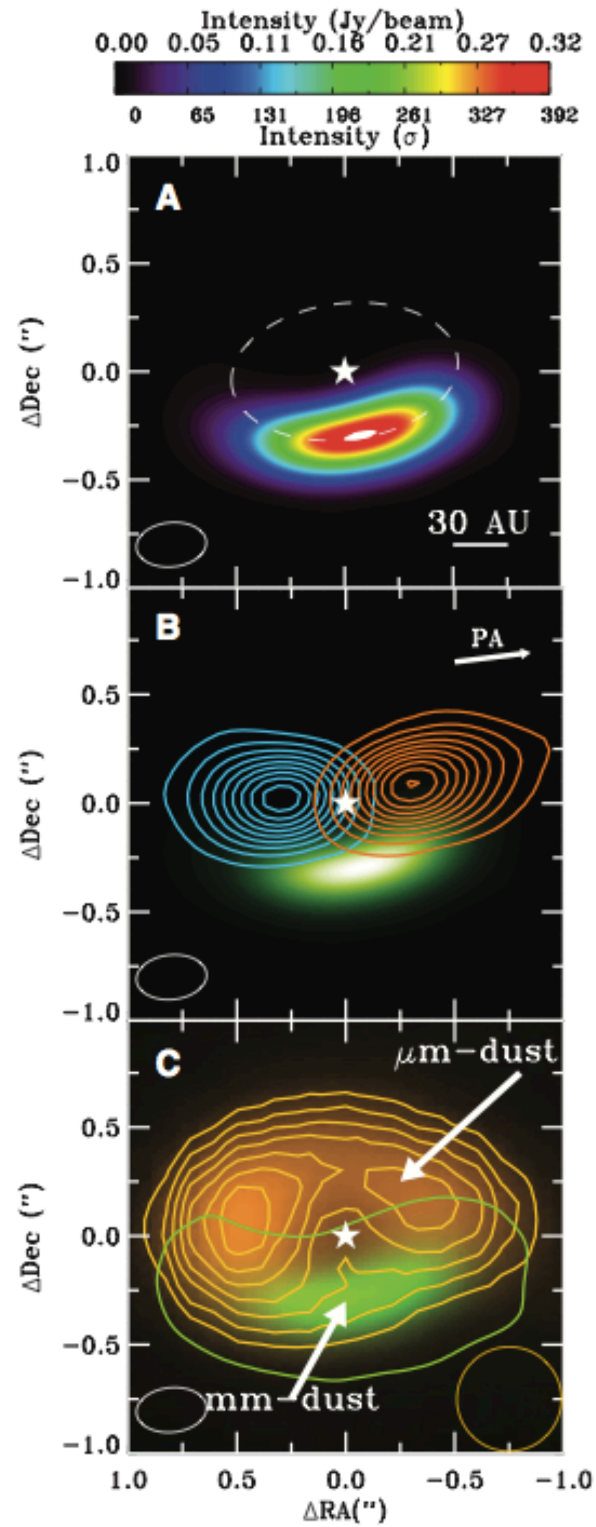
Derived parameters

S=4.8

St=0.008 $\delta = 0.005$

$v_{rms} = 4\%\ c_s$

Trapped mass: 11 M_{Earth}



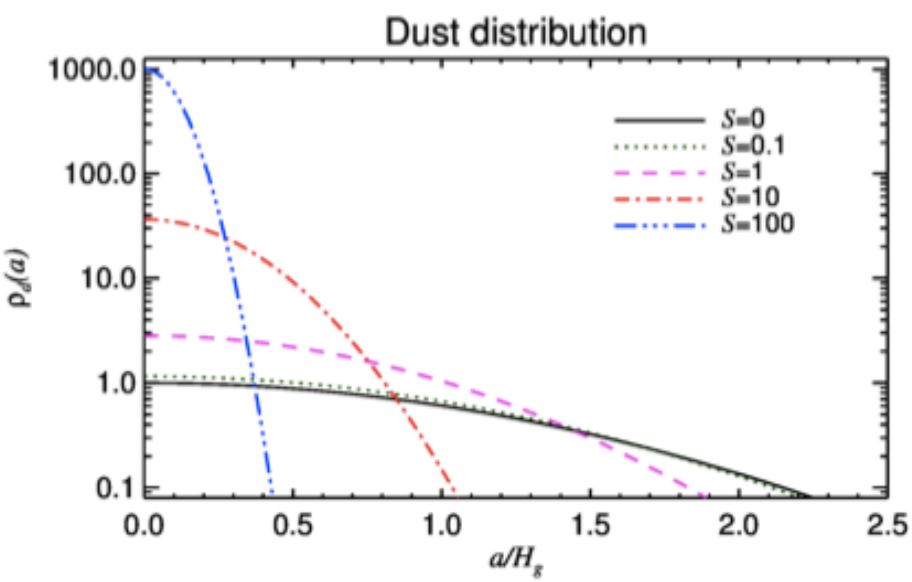
Lyra & Lin (2013)

asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

Micron-sized dust follows gas

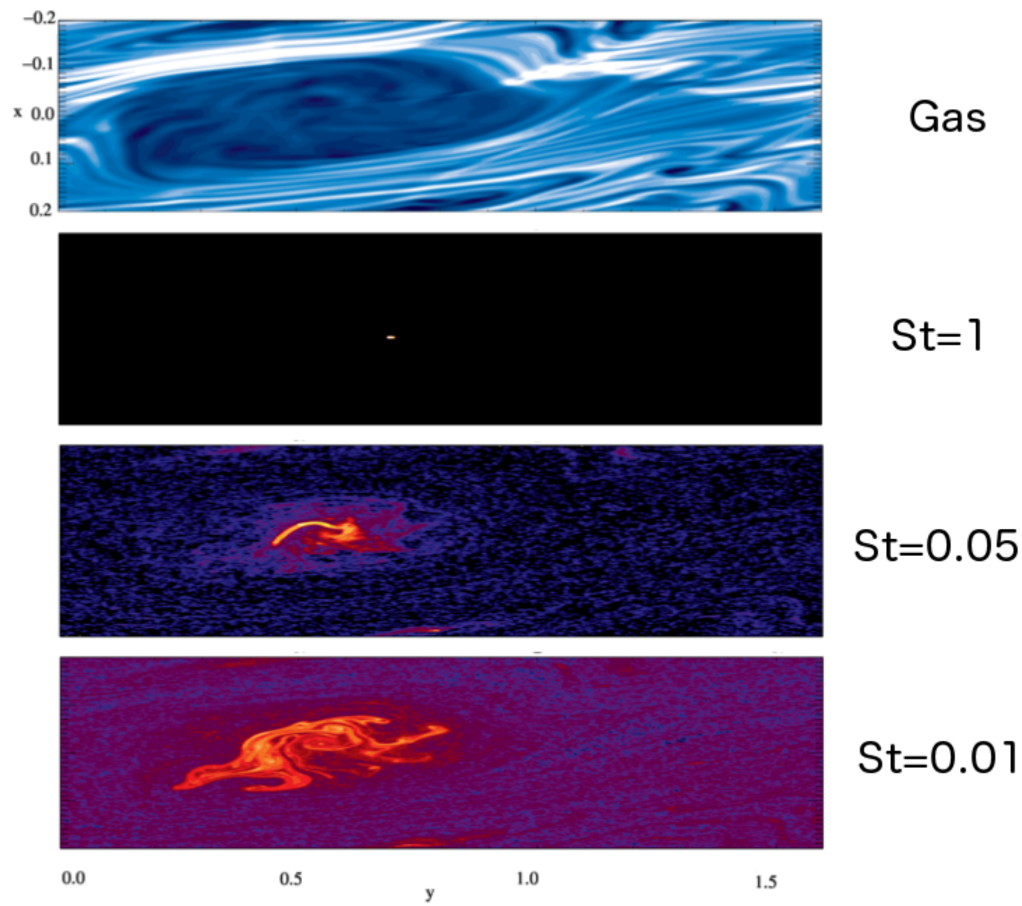
Analytical vs Numerical



$$S = \mathrm{St}/\delta$$

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

Lyra & Lin (2013)



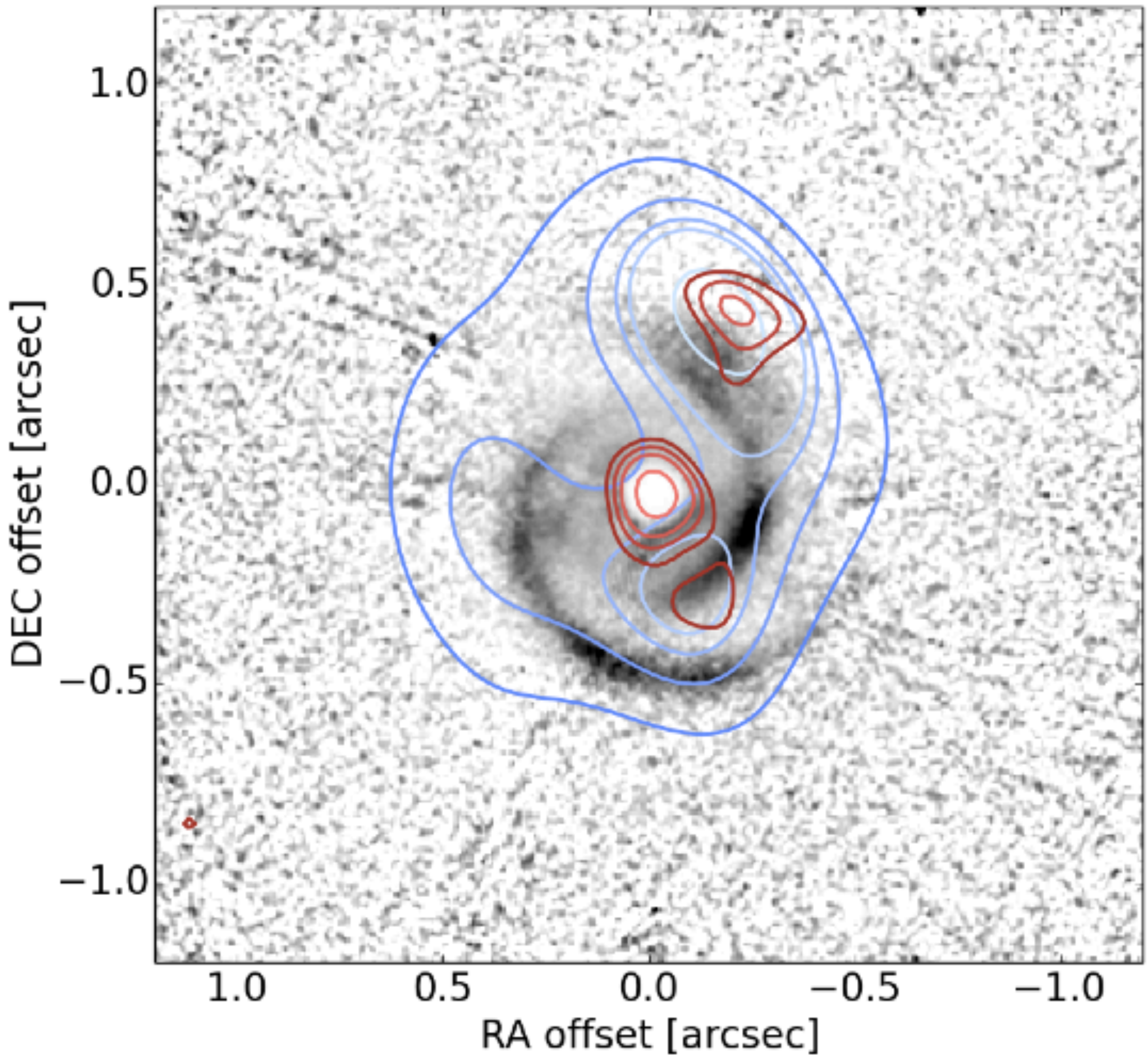
Raettig et al (2015)

SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

ALMA (~ mm)

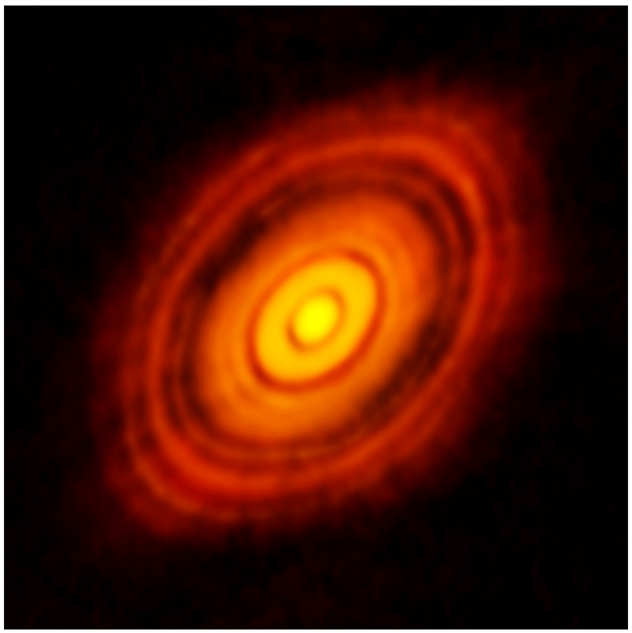
VLA (cm-m)



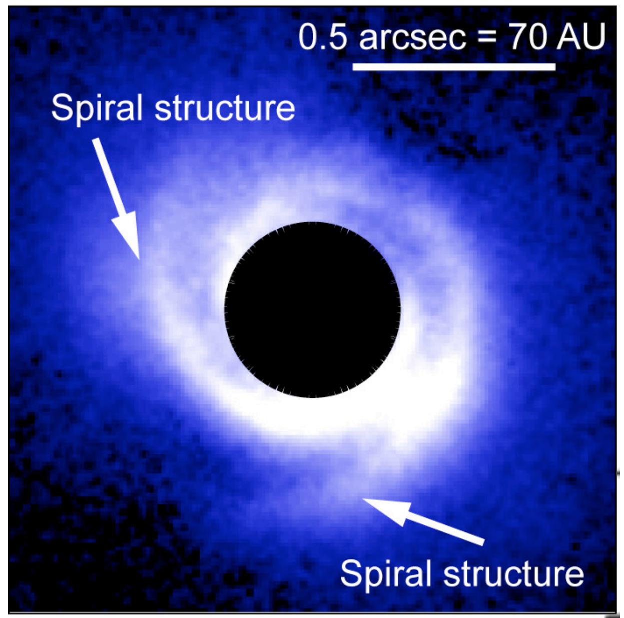
Marino et al. (2015)

Observational evidence: gaps, spirals, and vortices

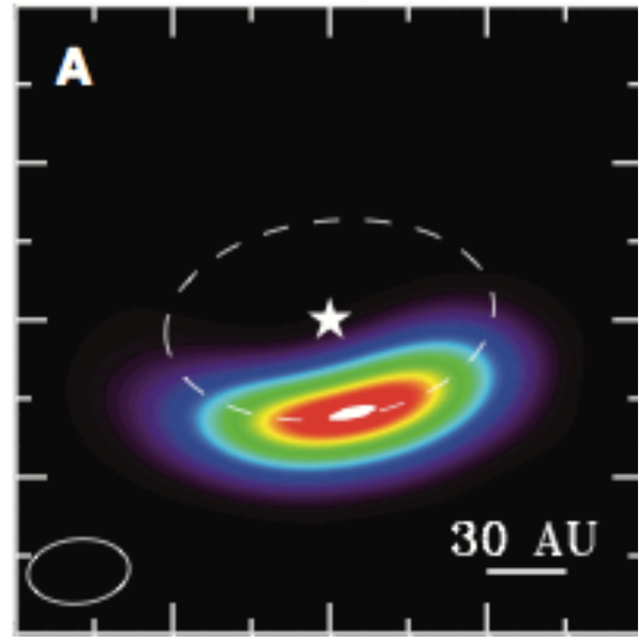
HL Tau



SAO 206462

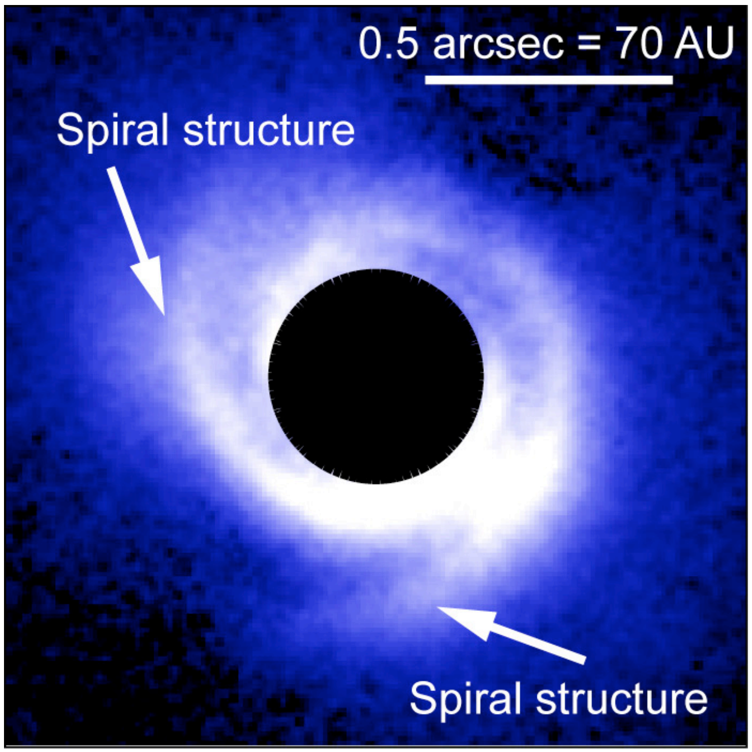


Oph IRS 48



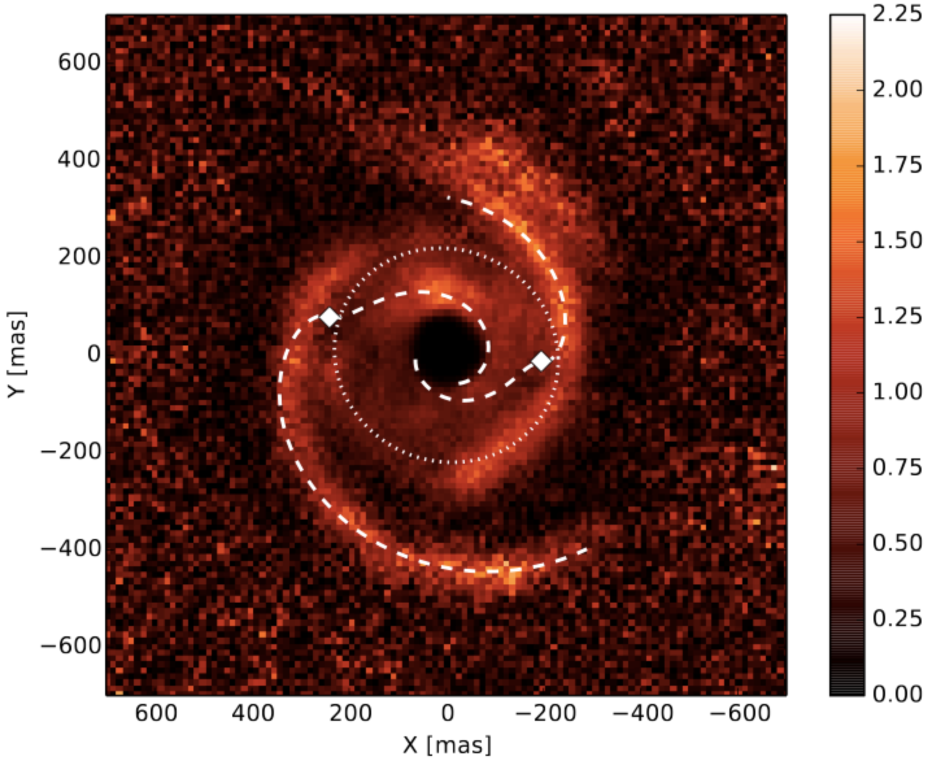
Observational Evidence: Spirals

SAO 206462



Muto et al. (2012)

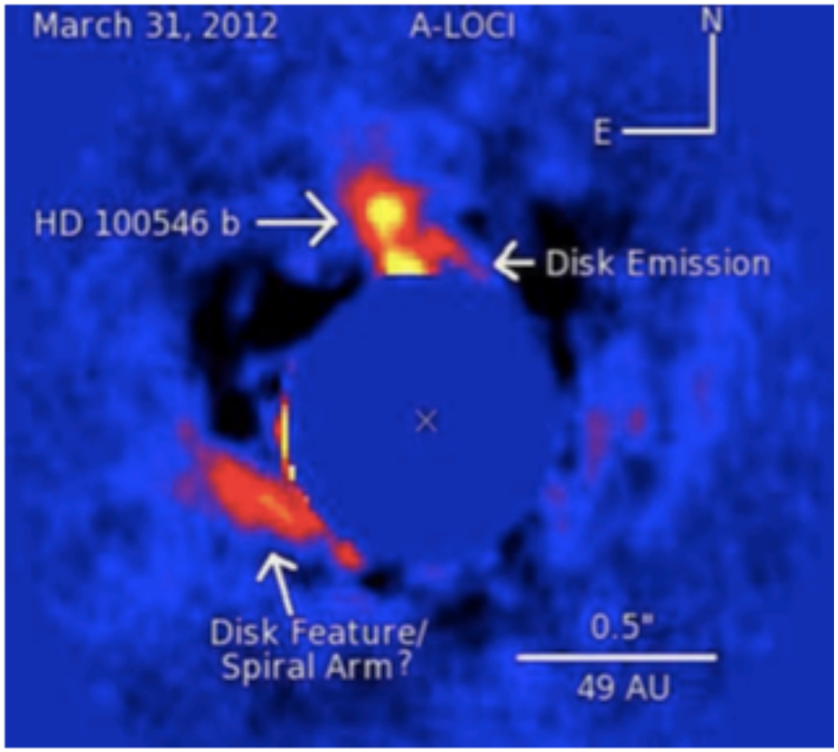
MWC 748



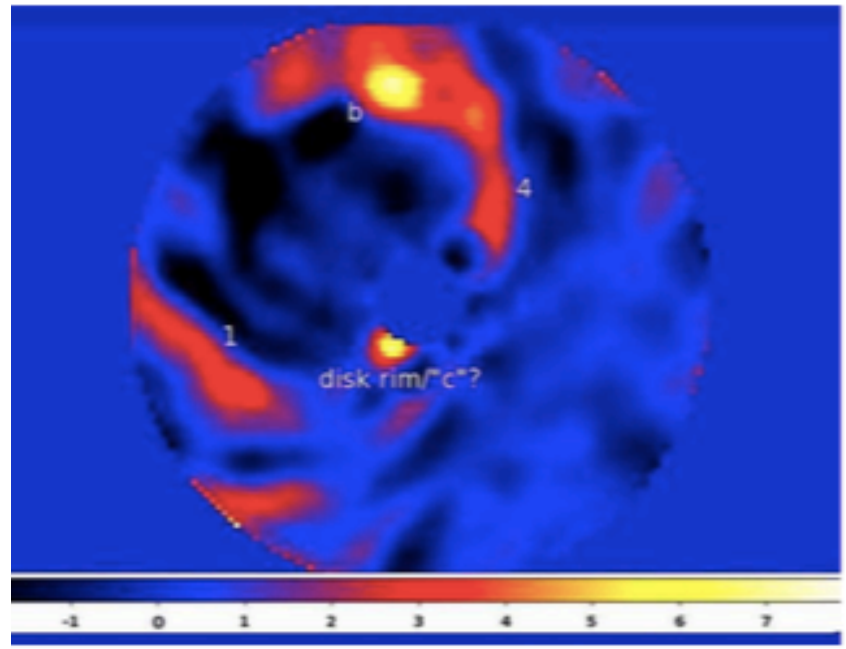
Benisty et al. (2015)

The strange case of HD 100546

L band (~3.5 μm)

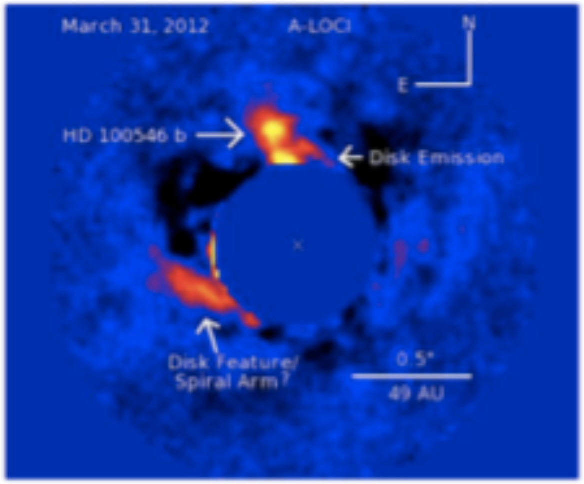


H band (~1.6 μm)

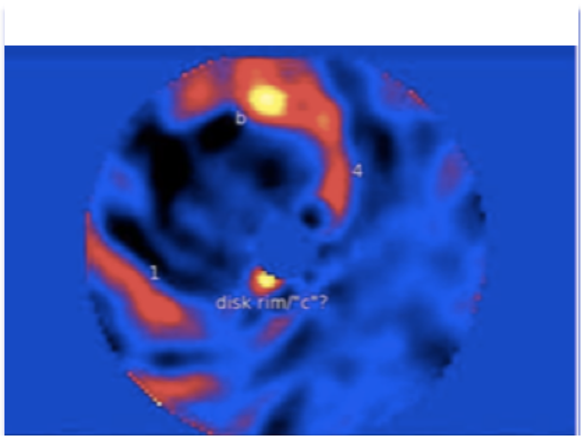


Currie et al. (2014), Currie et al. (2015)

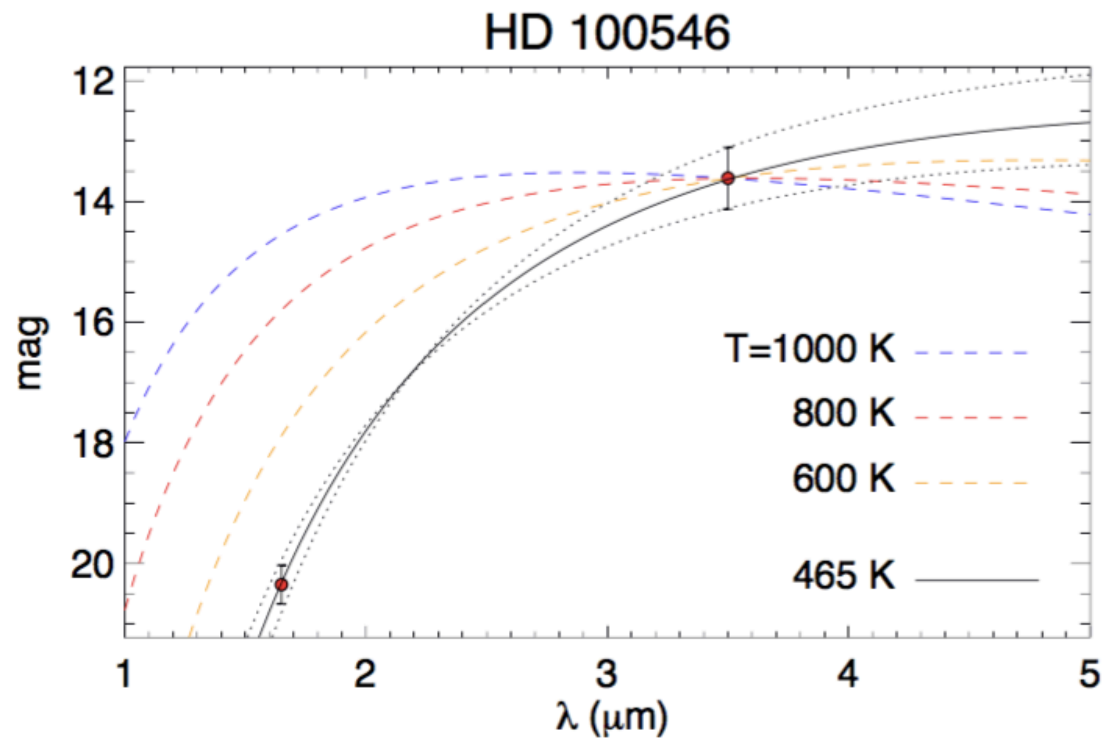
Pinning down the temperature



L band

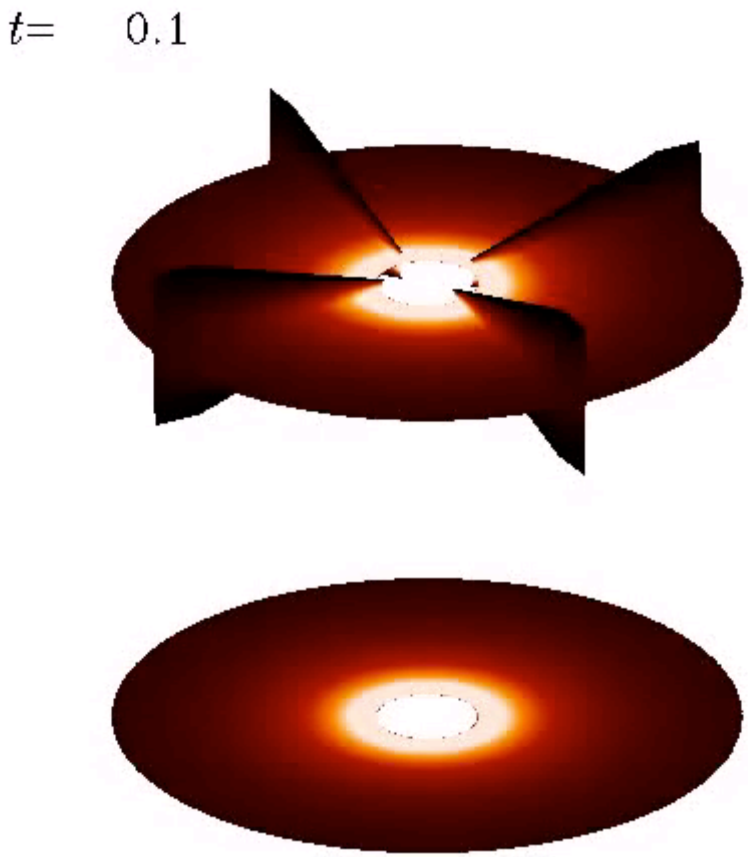


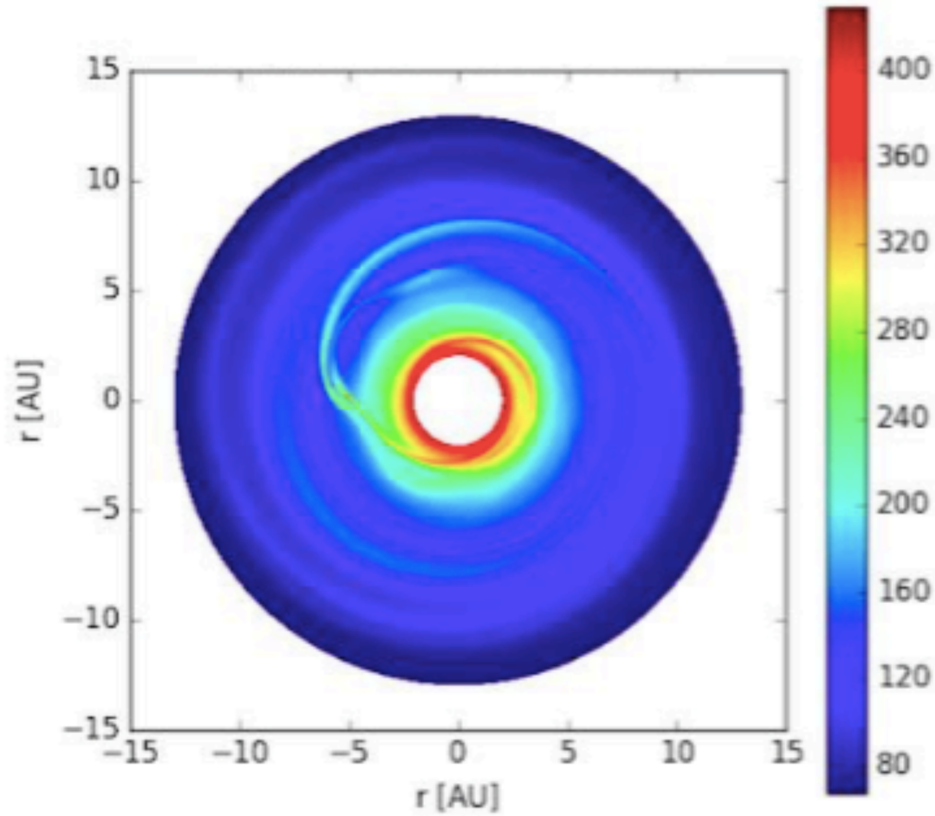
H band



Lyra et al. (2016)

Supersonic Wakes of High Mass Planets

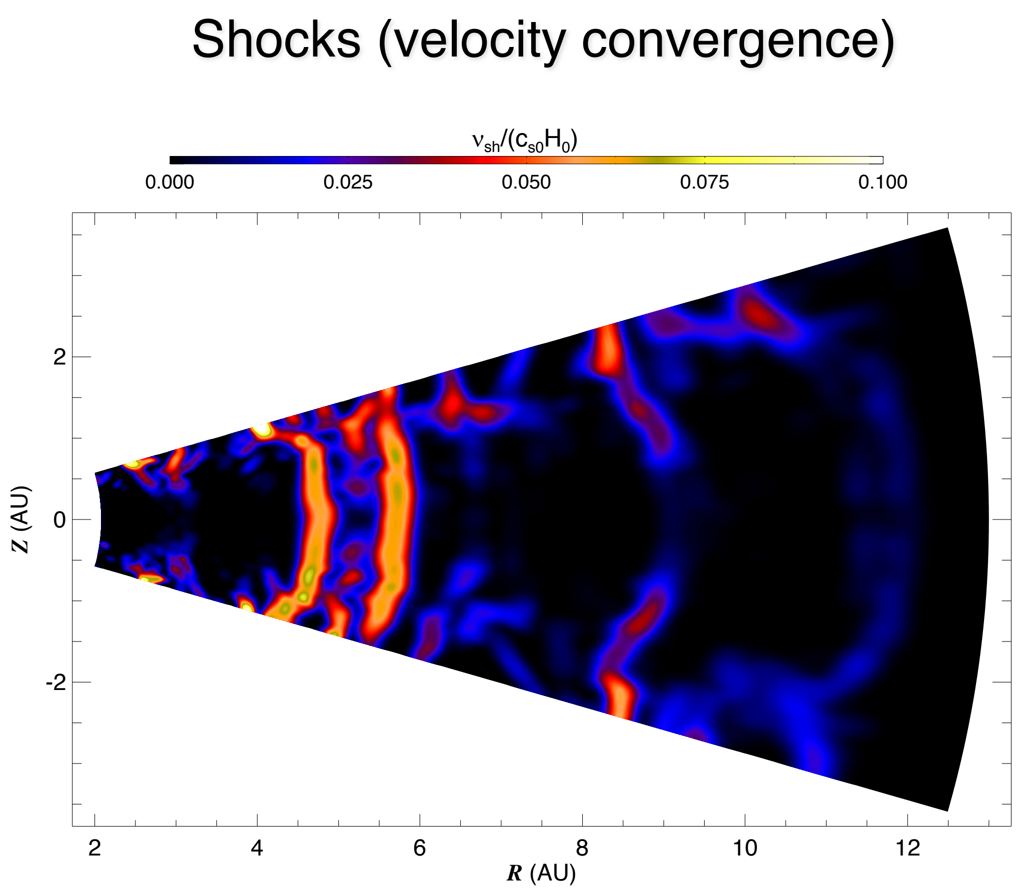


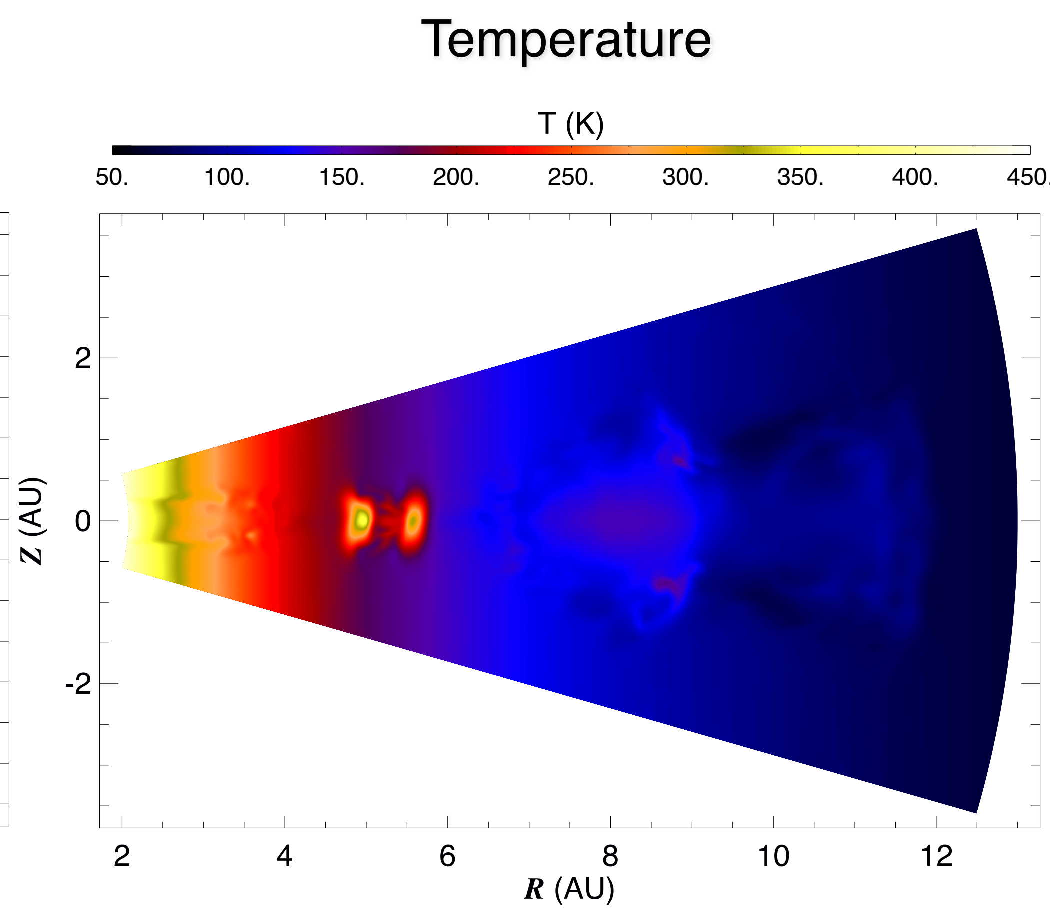


Temperature - 5M$_J$

Lyra et al. (2016)

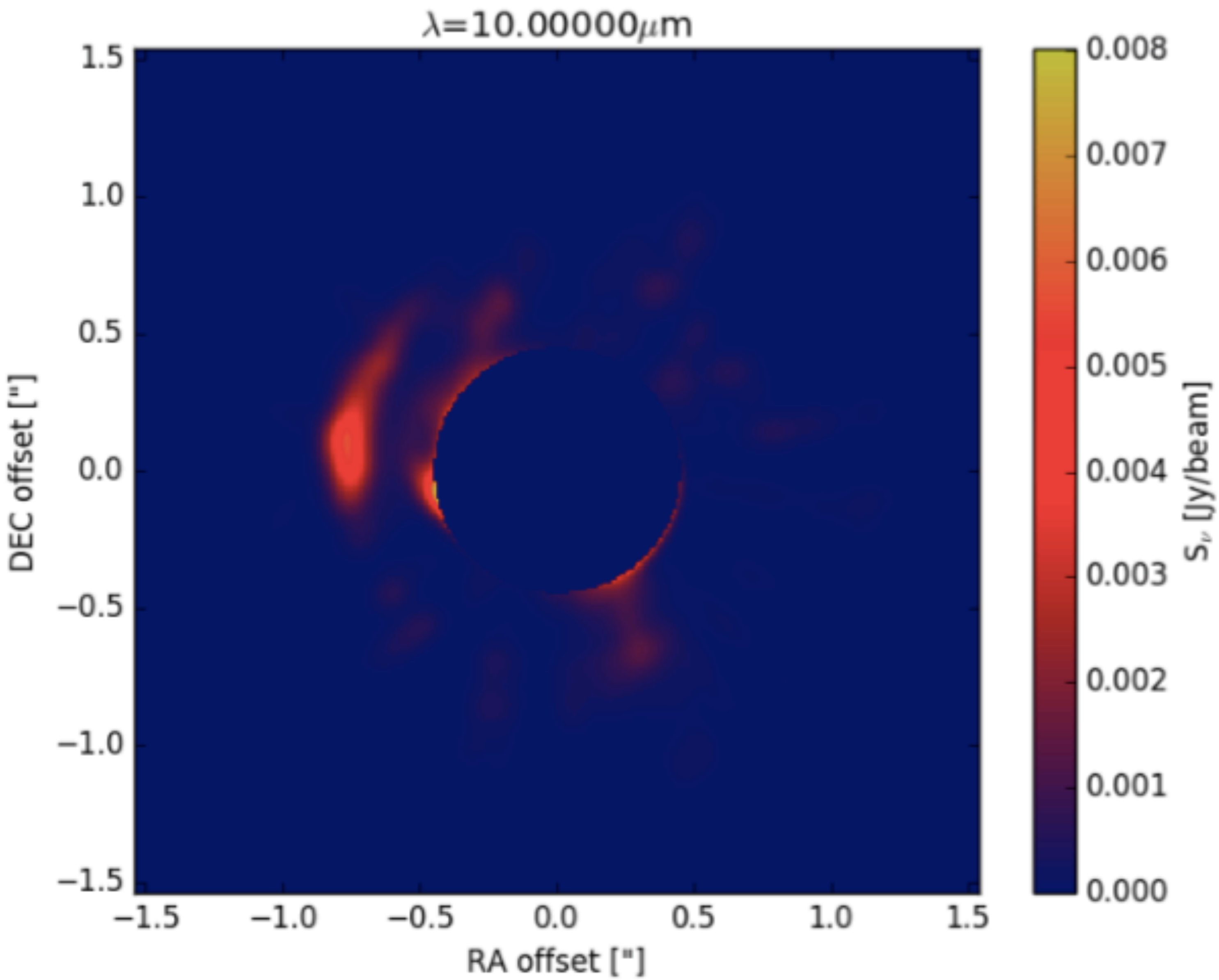
Shock bores





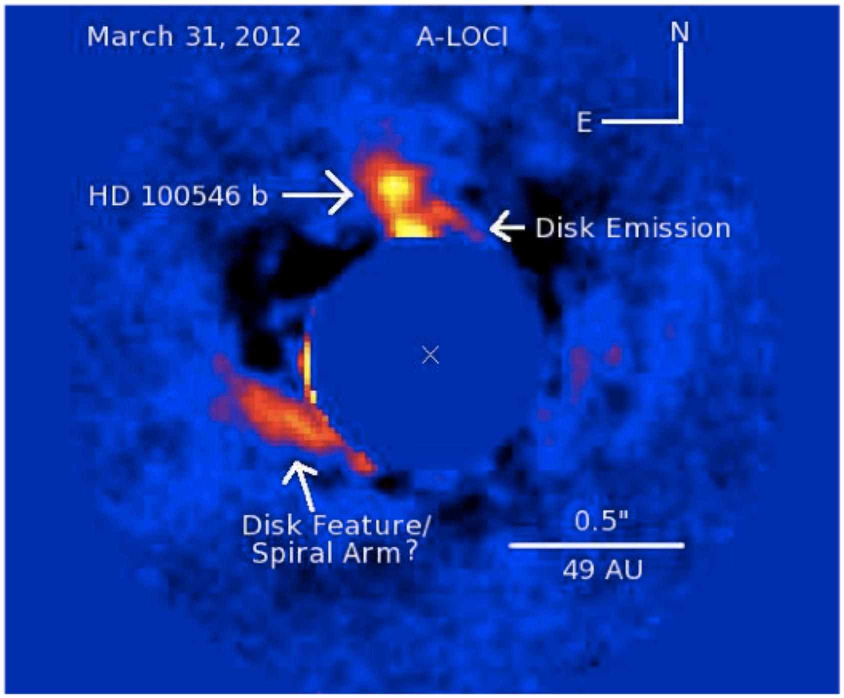
Lyra et al. (2016)

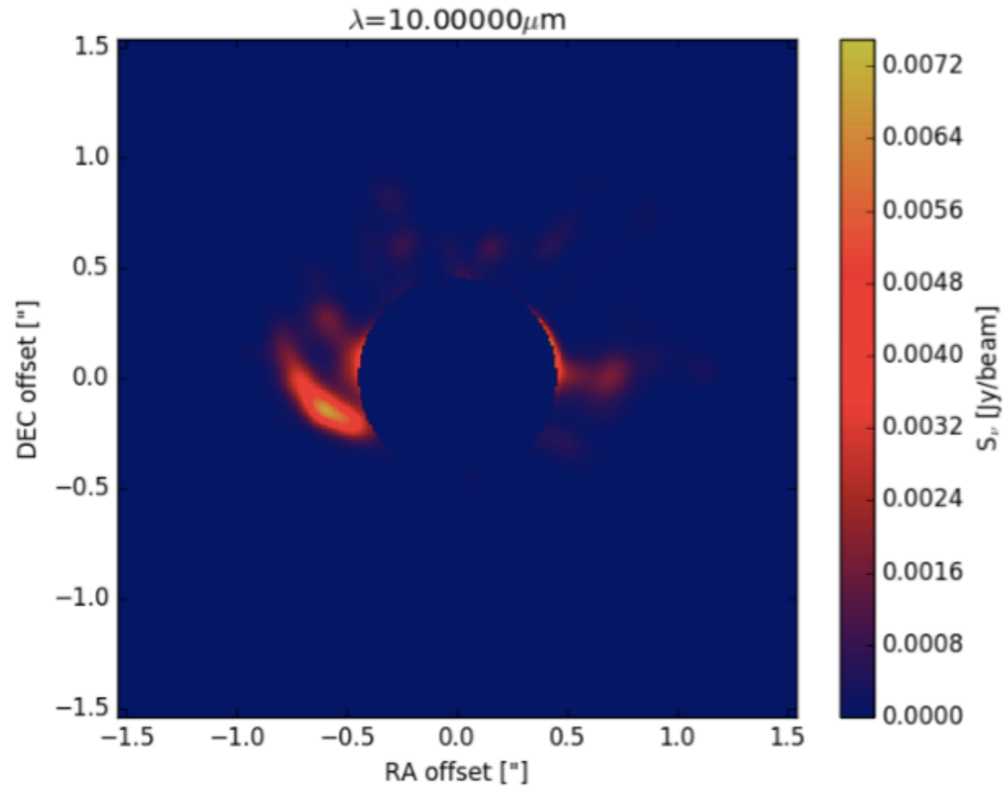
Synthetic image



Hord et al. (2017)

Observation vs Synthetic Image

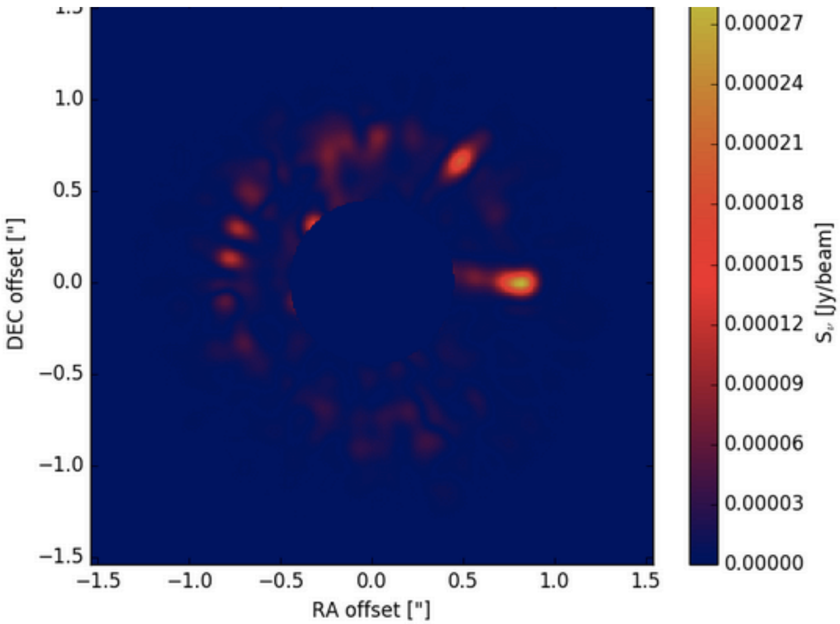




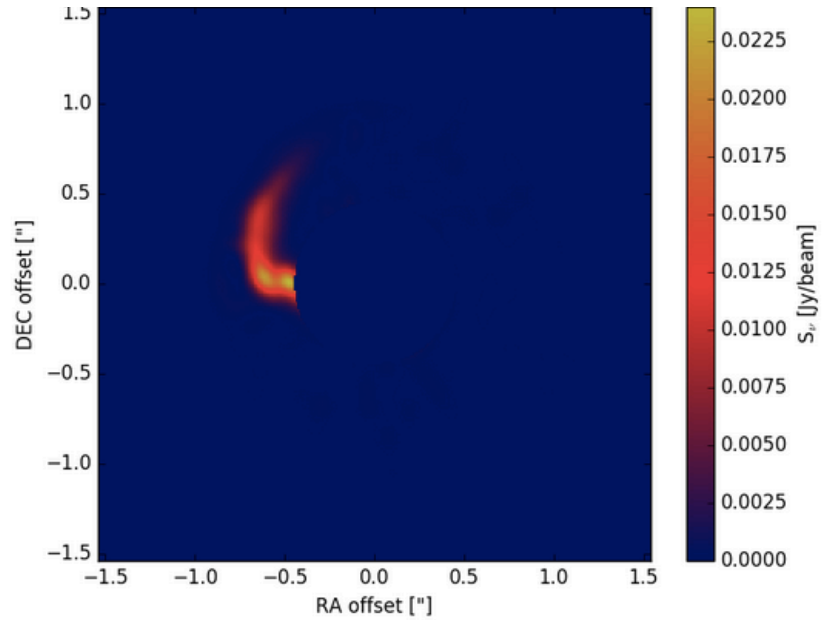
Hord et al. (2017)

Effect of shocks alone

1 μm

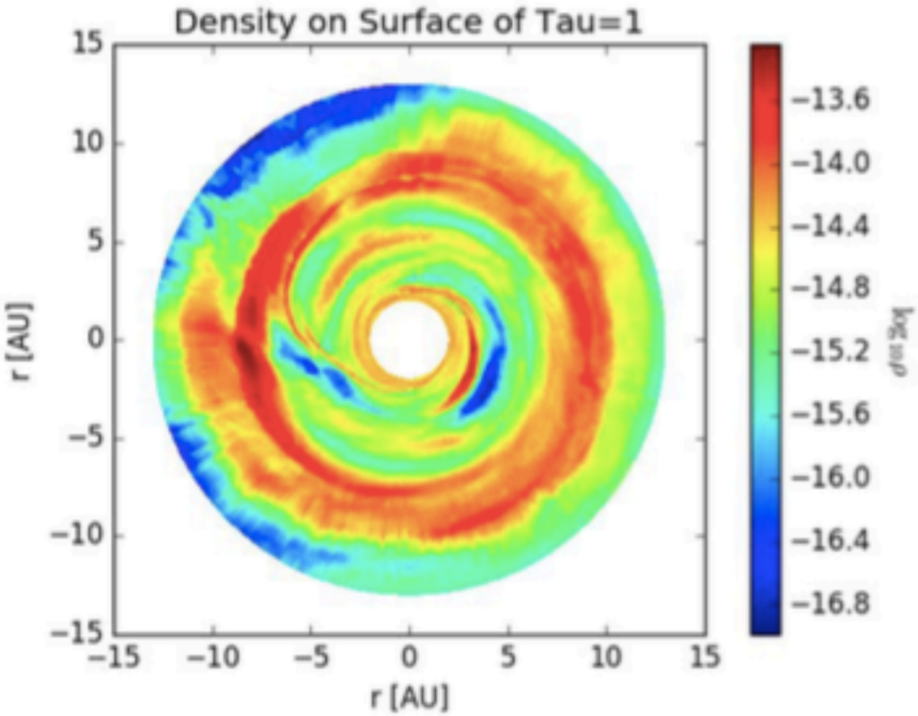


10 μm

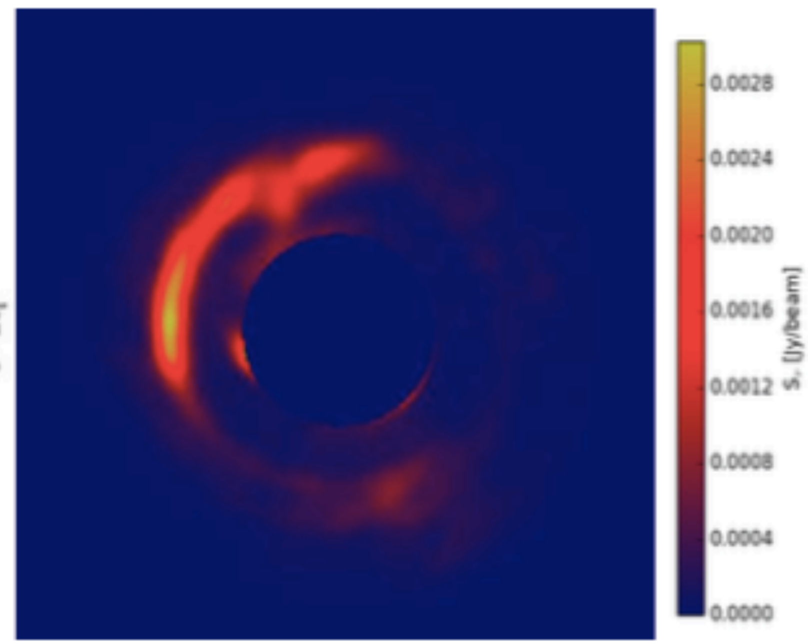


Hord et al. (2017)

Scattering in Image



Light scattered off **gap outer edge**

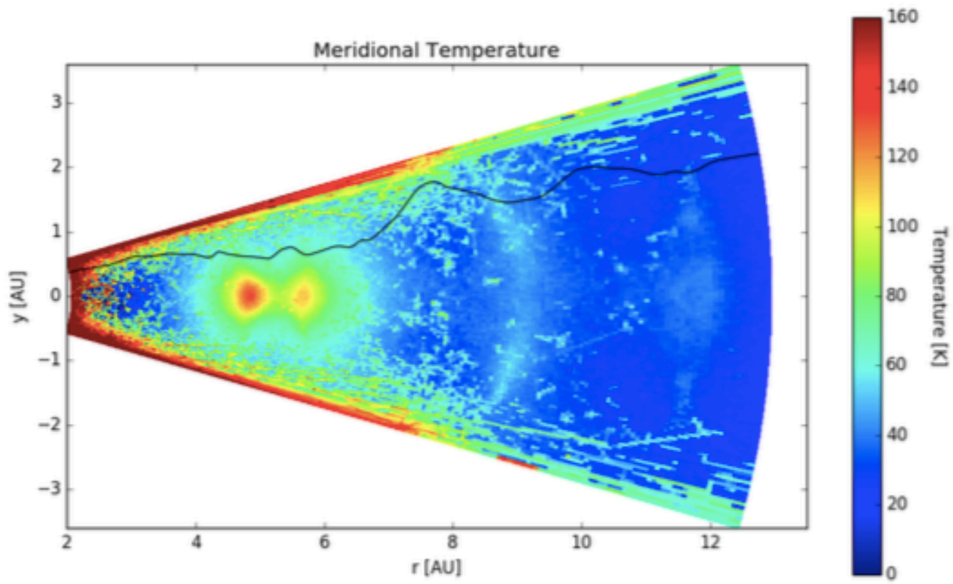


"Bird's eye view" synthetic image

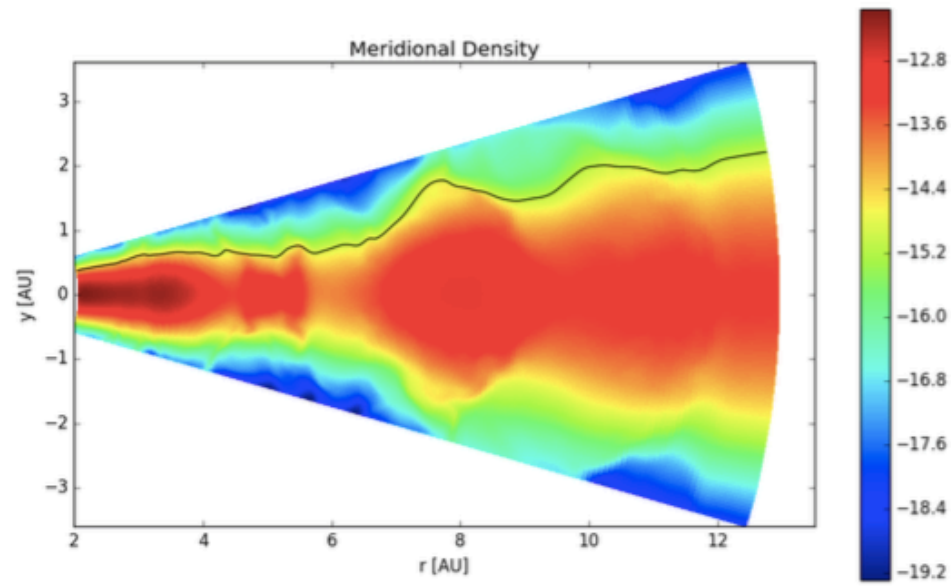
Hord et al. (2017)

A puffed-up outer gap

Temperature



Density

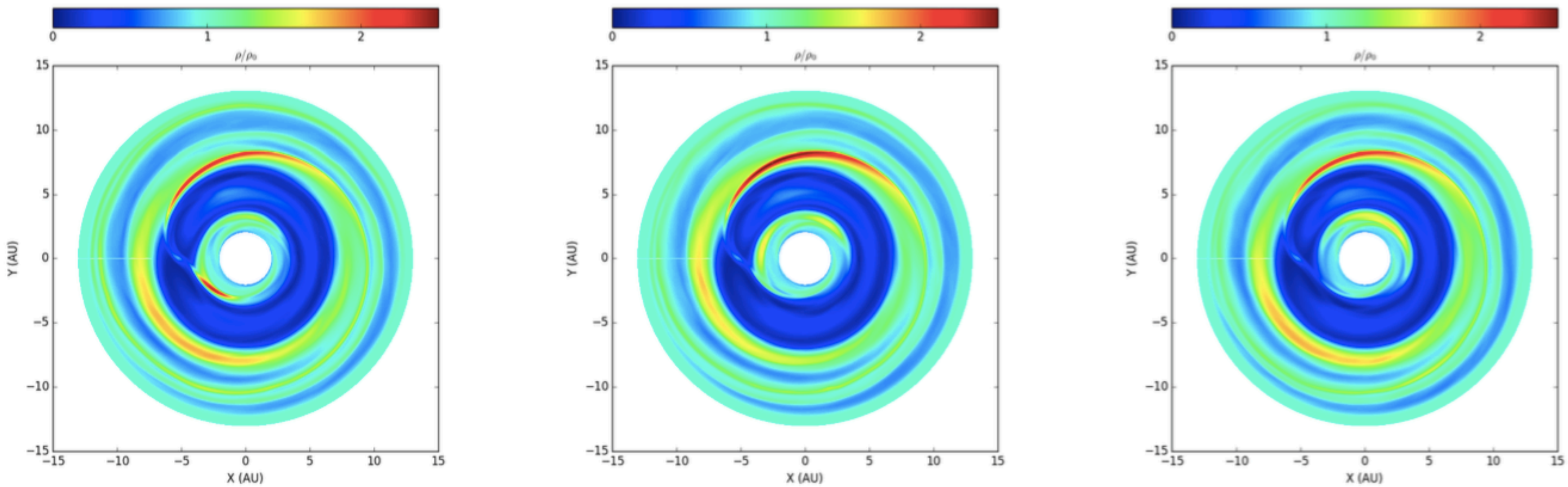


Hord et al. (2017)

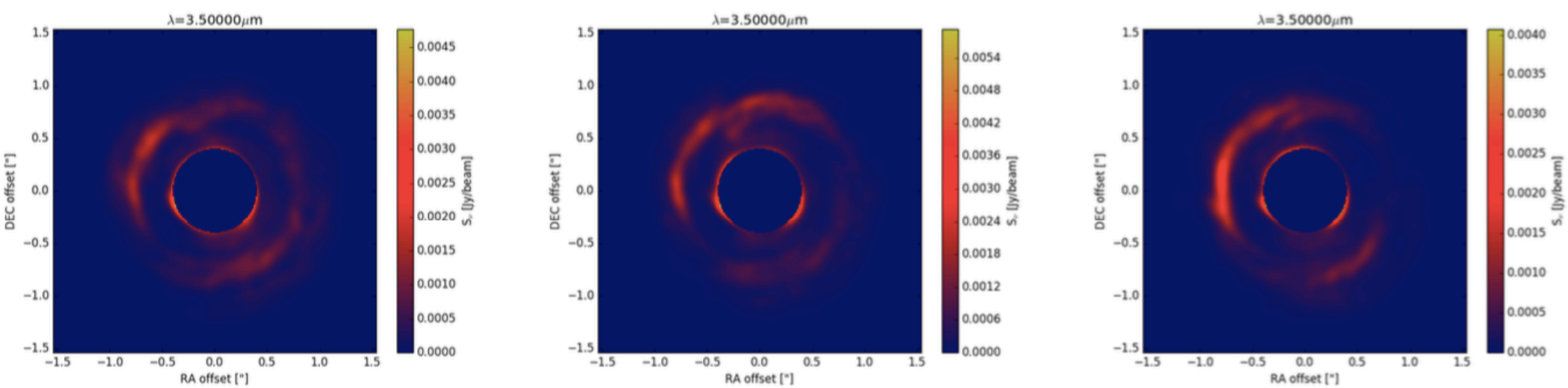
Dense hotter outer ring

T = 39 orbits | T = 40 orbits | T = 41 orbits

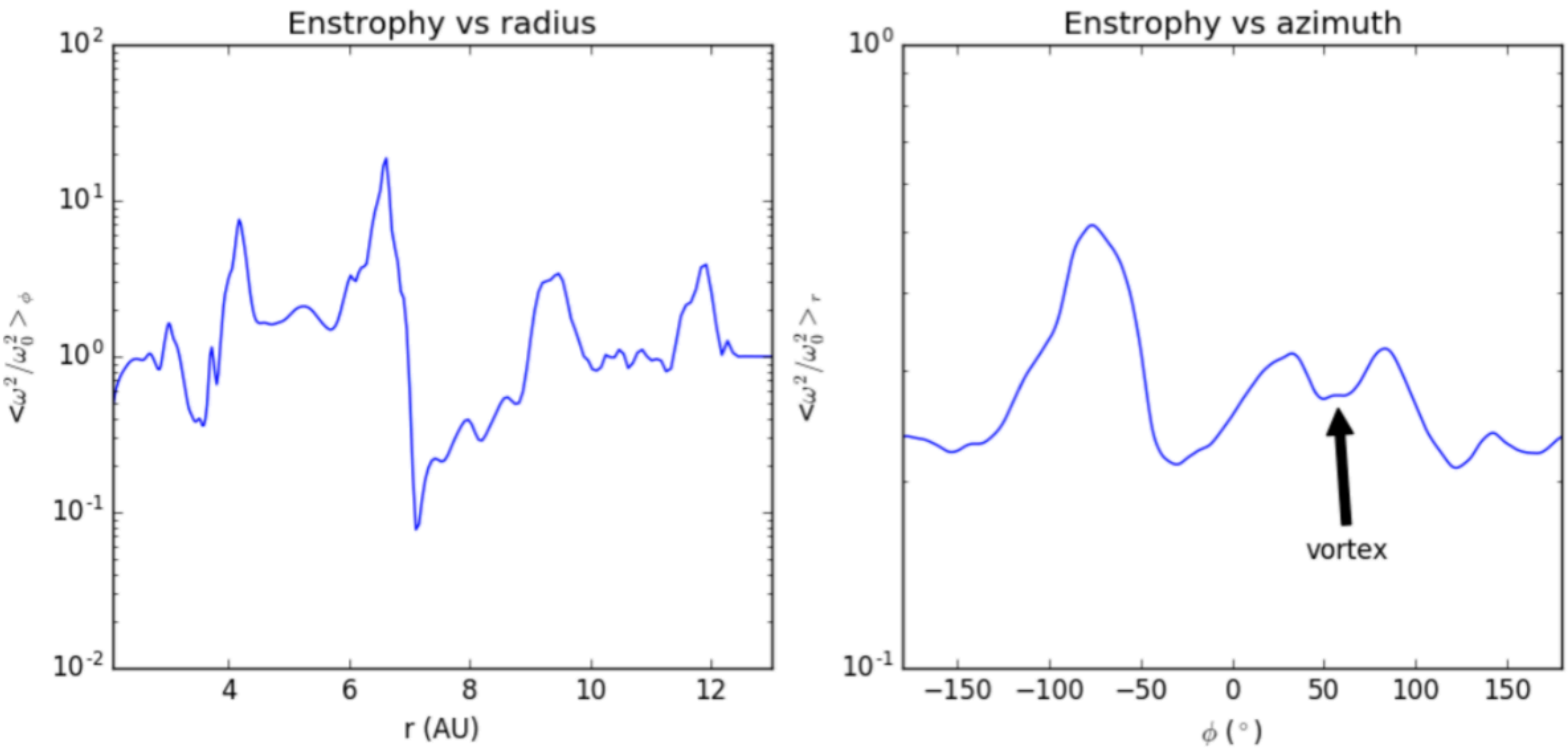
Density



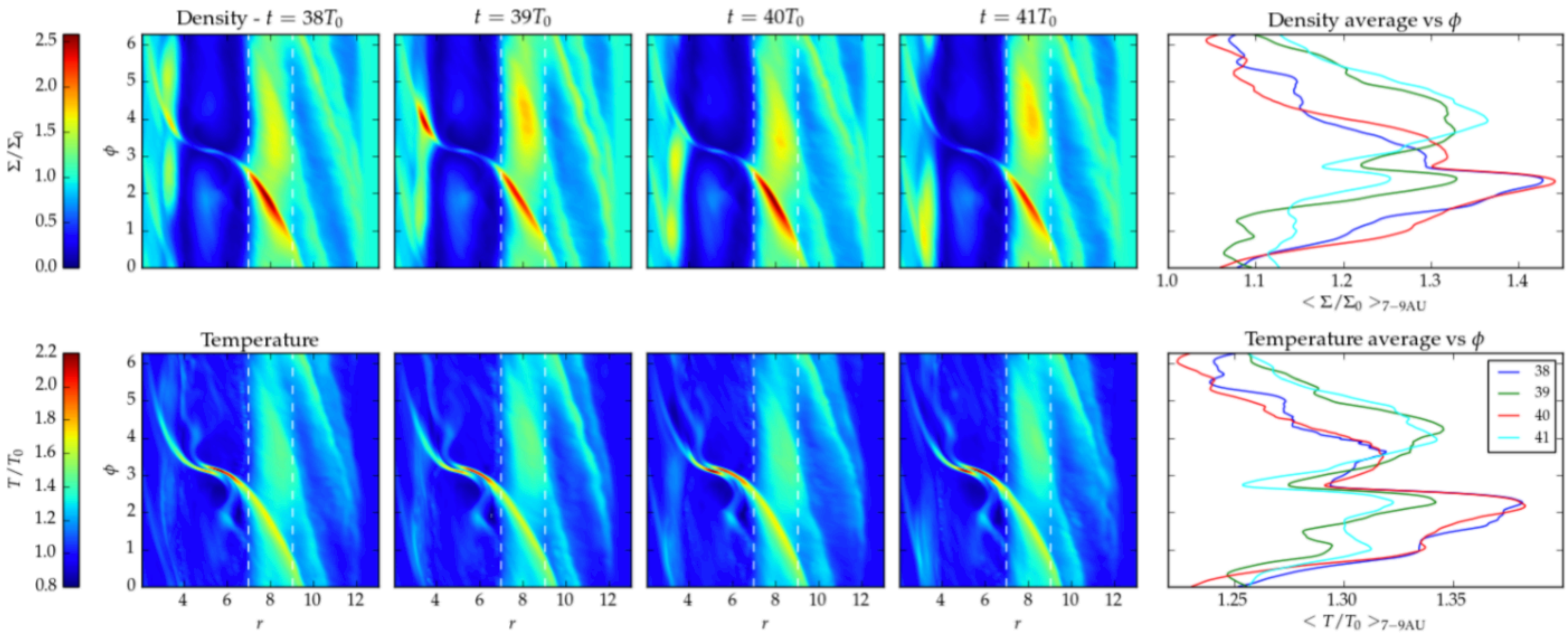
Intensity



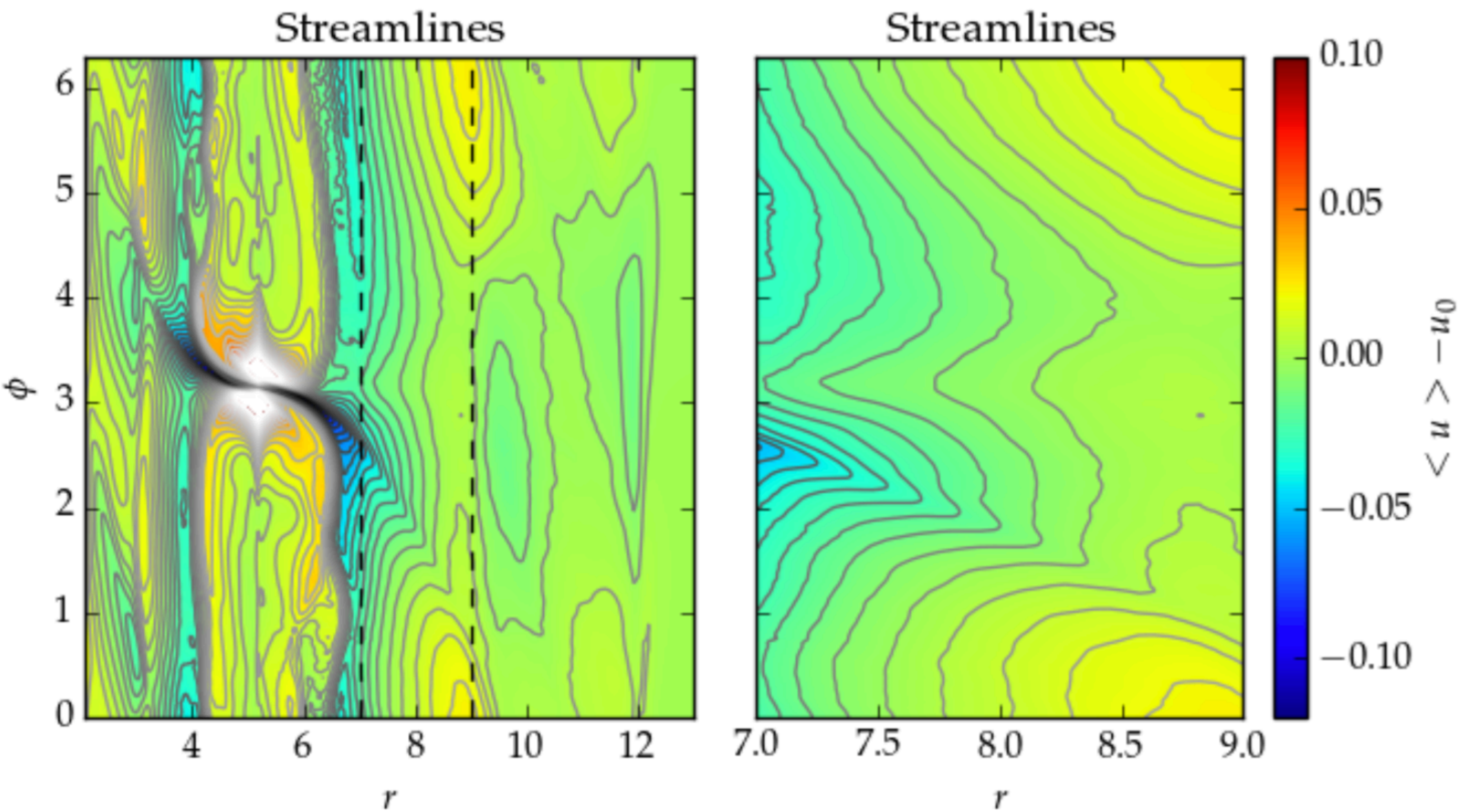
Vorticity depression



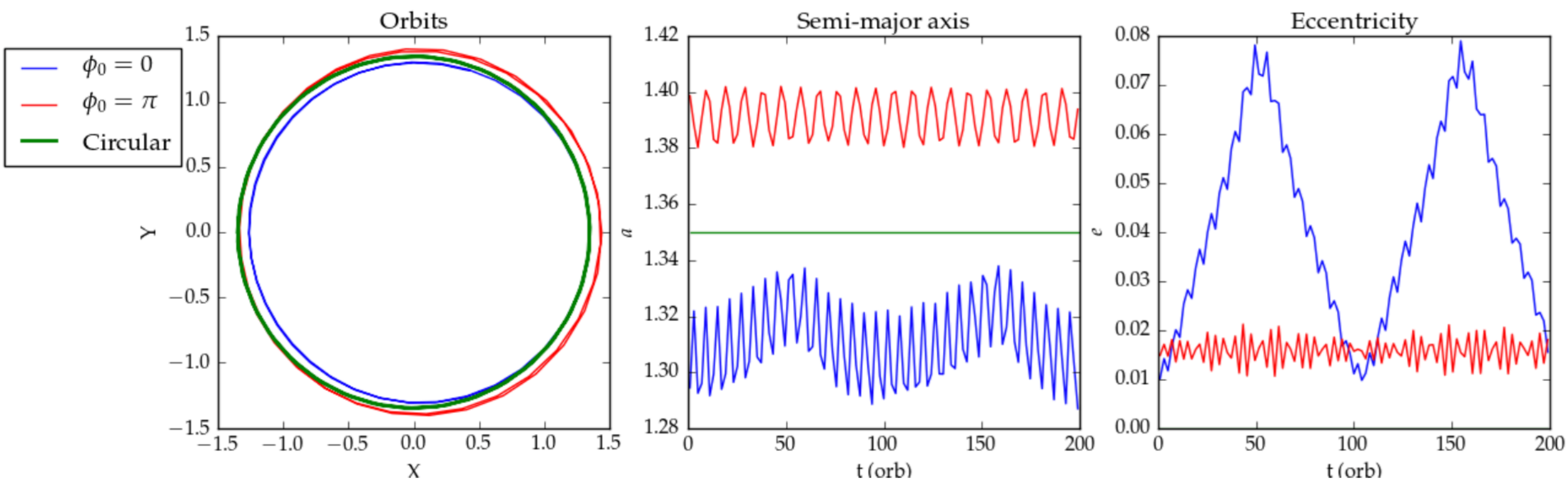
Stationary "vortex"



Eccentricity

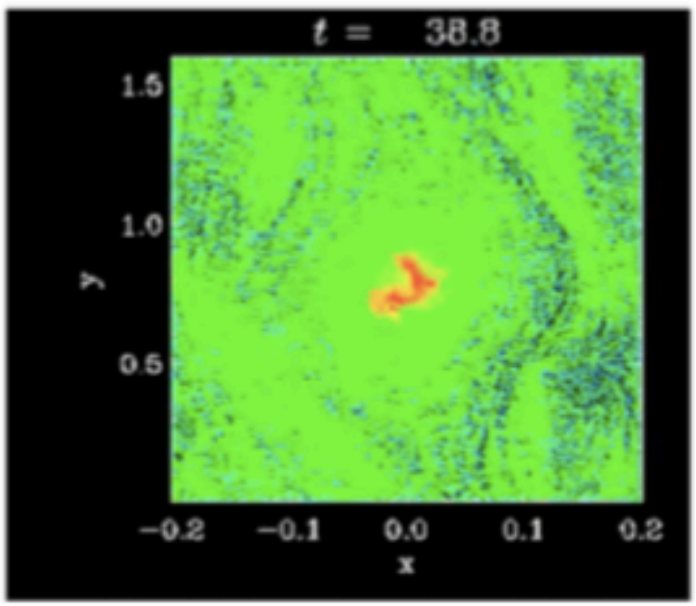


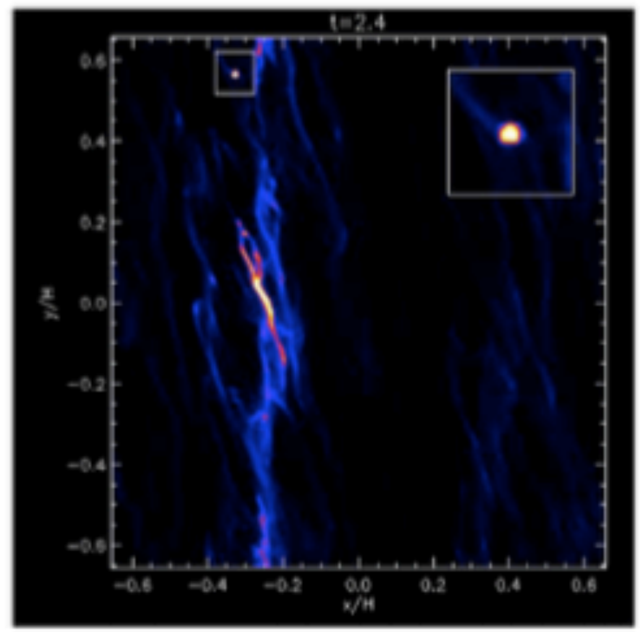
Eccentricity



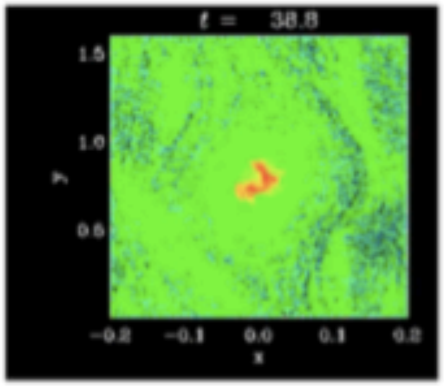
Conclusions

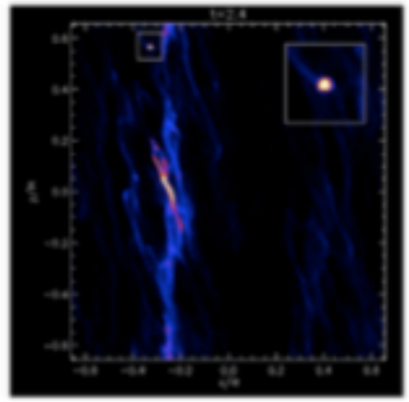
- Two modes of planet formation: Streaming Instability and Vortices
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortices do not survive magnetization
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains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



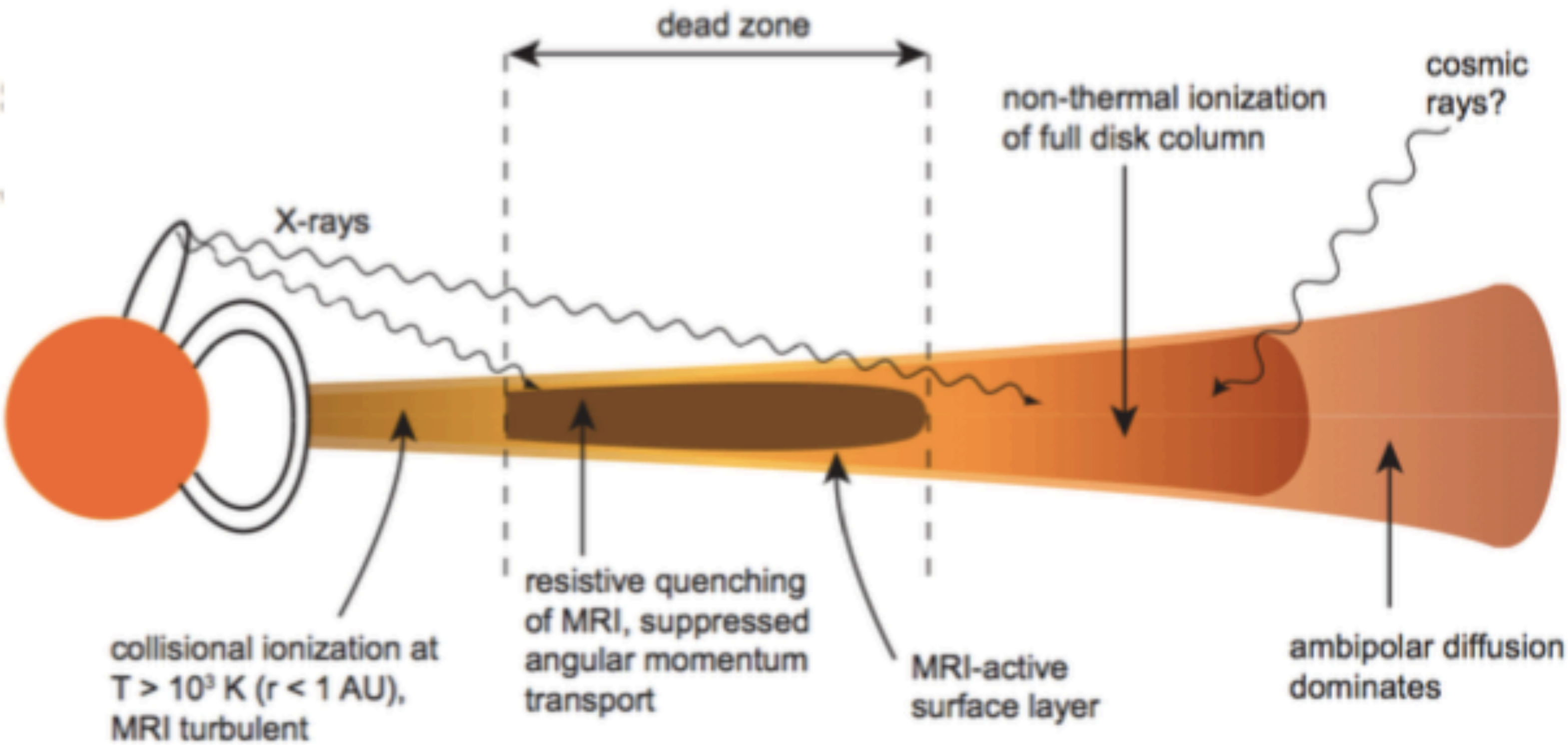


Conclusions





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

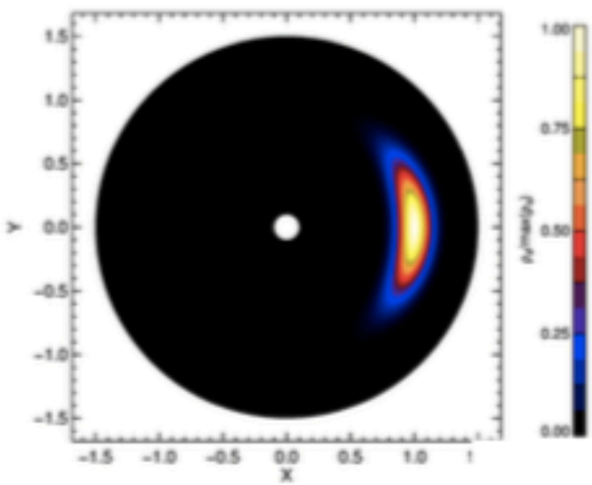


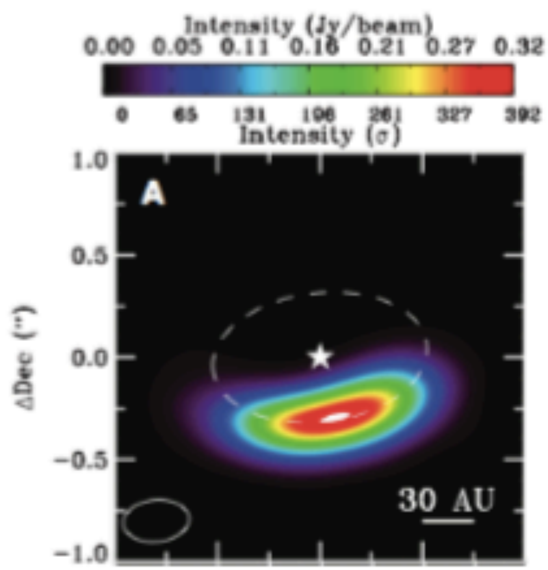
Conclusions

- 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?)

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

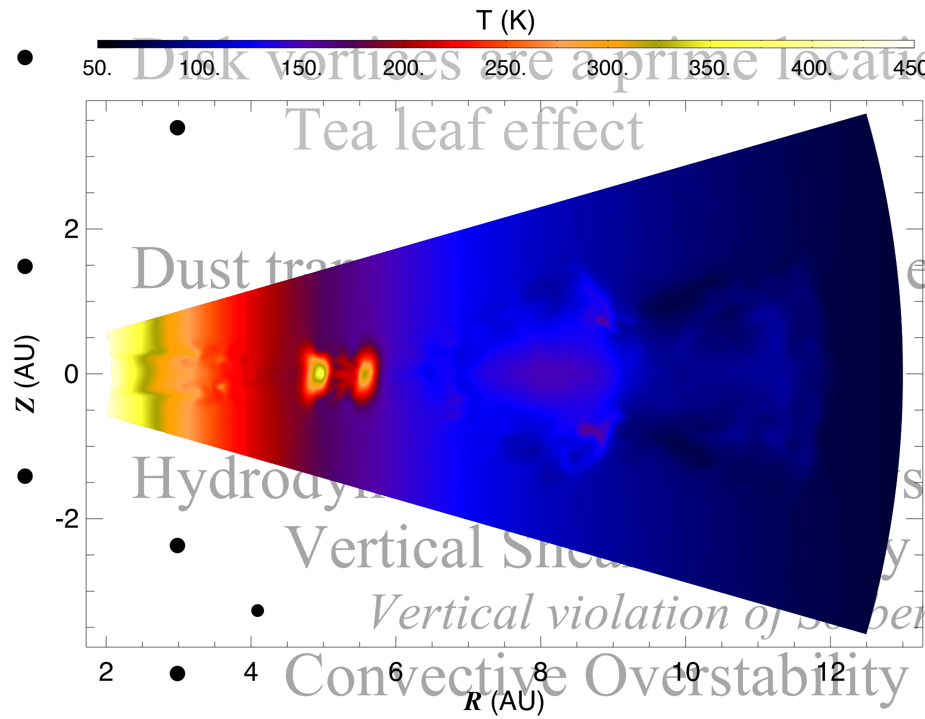
Lyra & Lin (2013)

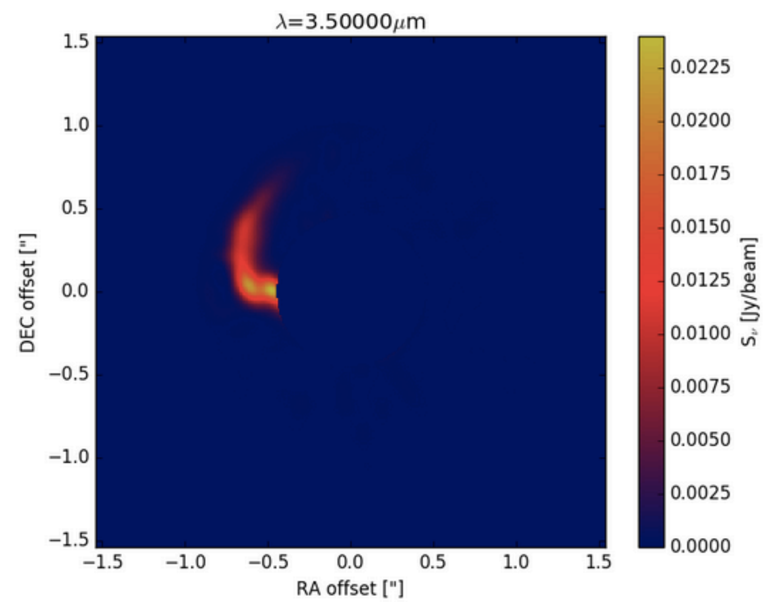




Conclusions

- Disk vortices are a prime location for planet formation
  - Tea leaf effect
- Dust tra... equilibr...
- Hydrody... s planet
  - Vertical She... y
    - *Vertical violation of S... berg-Hoilc*
  - Convective Overstability
    - *Amplification of epicyclic motion by buoyancy*
  - Zombie Vortex Instability
    - *Resonance between epicyclic and buyoancy frequency*





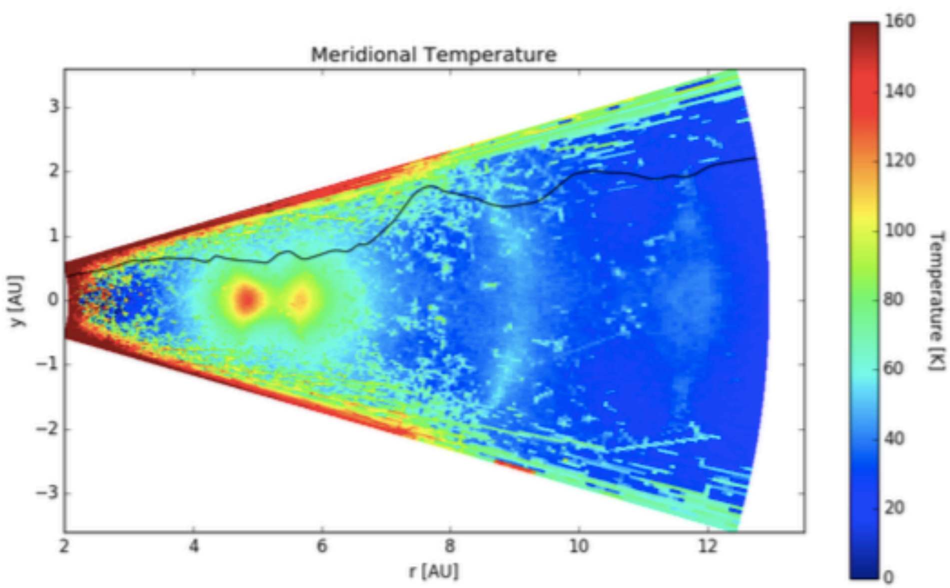
- Hot lobes next to high mass planets at high resolution

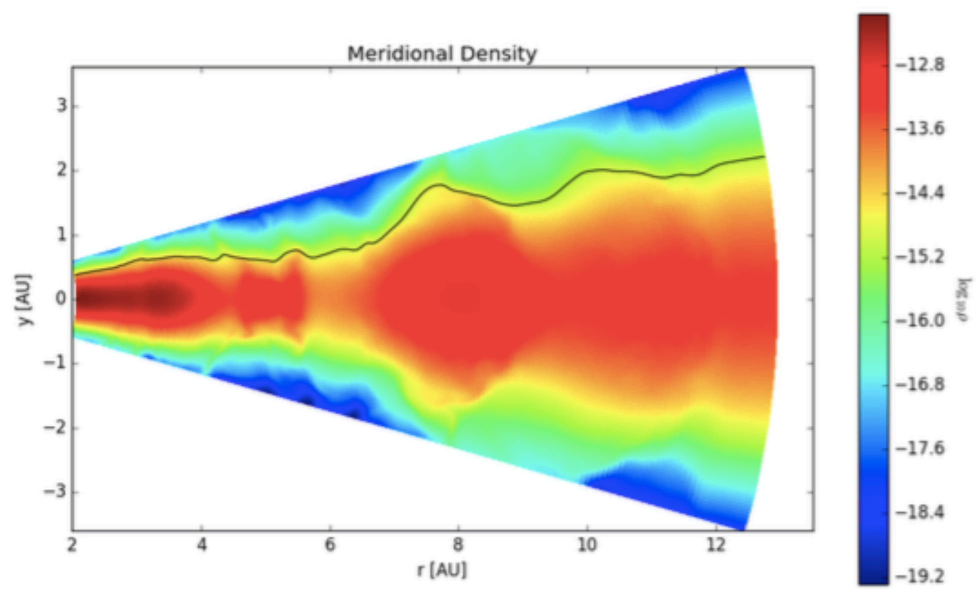
- Planets puff up their outer gap edges – visible in scattered light

Conclusions

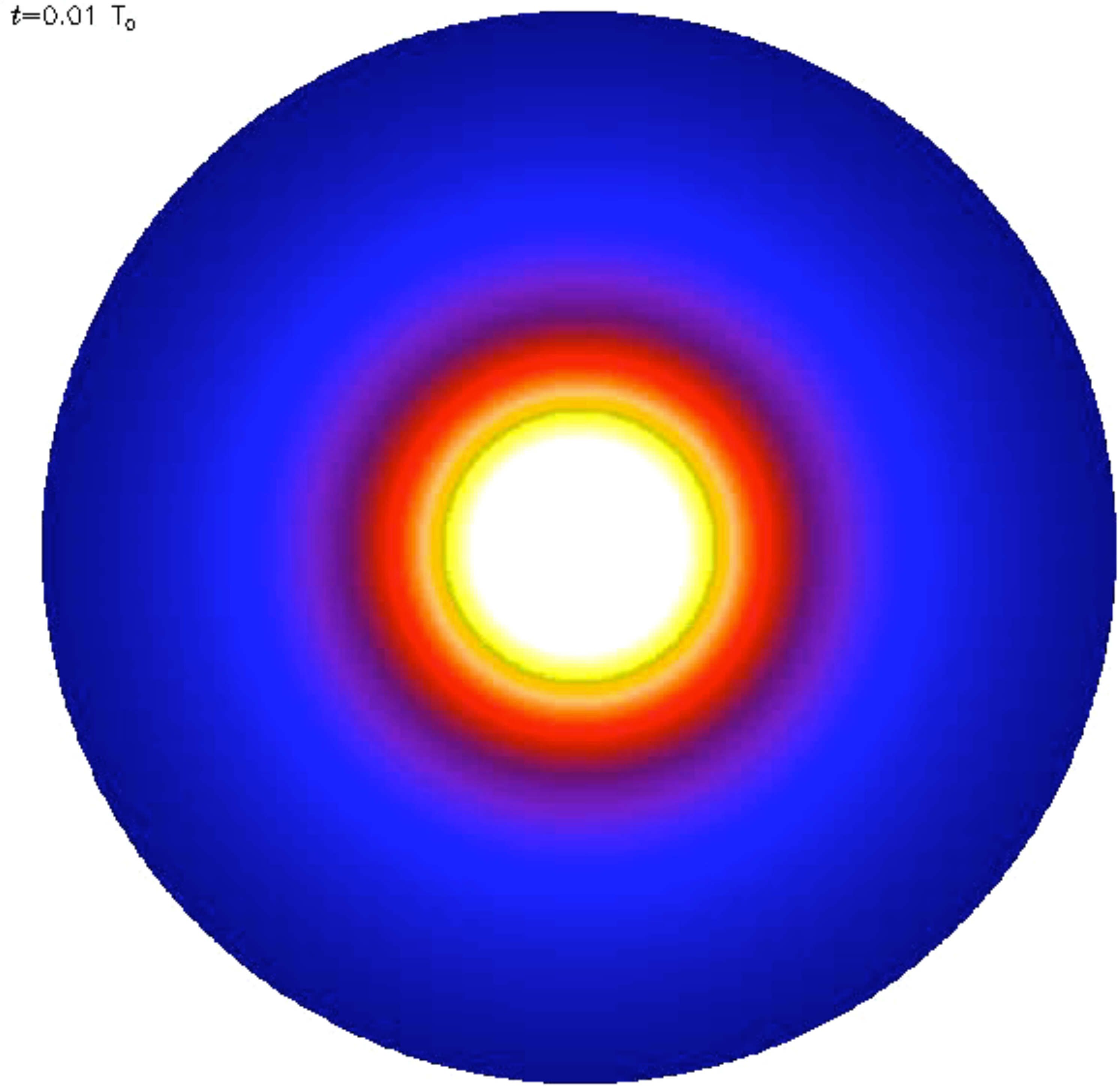
- Disk vortices are a prime location for planet formation
  - Tea leaf effect

- Dust trapped in drag-diffusion equilibrium explains the observations



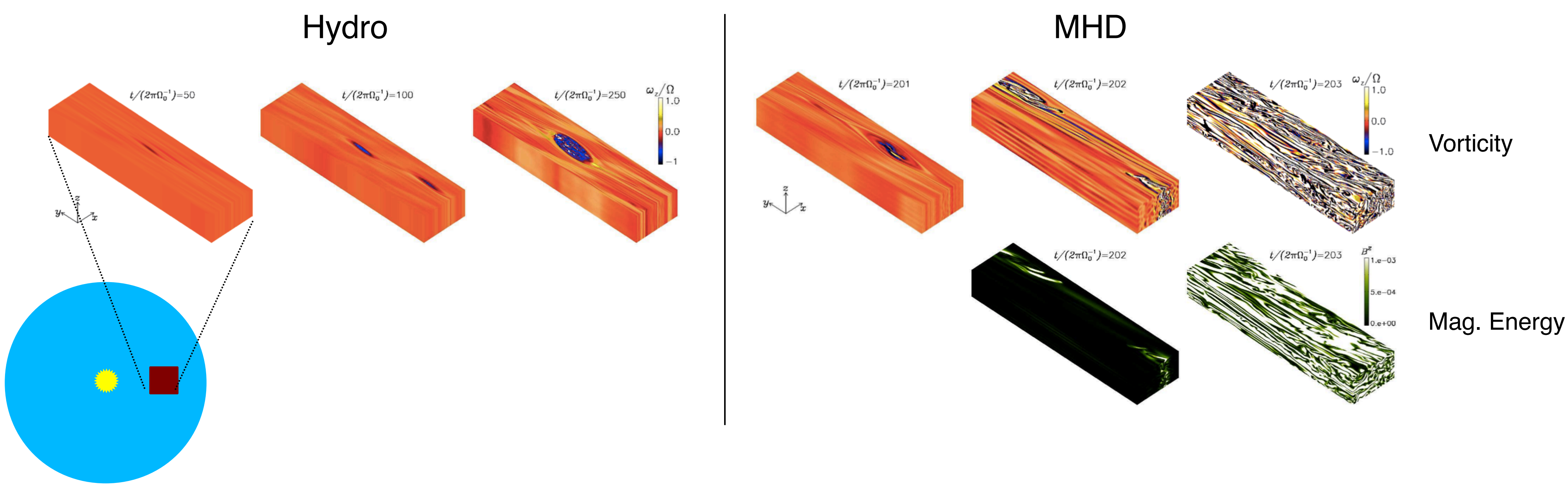


- Planets puff up their outer gap edges – visible in scattered light


t=0.01 T₀

Vortices and MHD

What happens when the disk is magnetized?



Lyra & Klahr (2011)