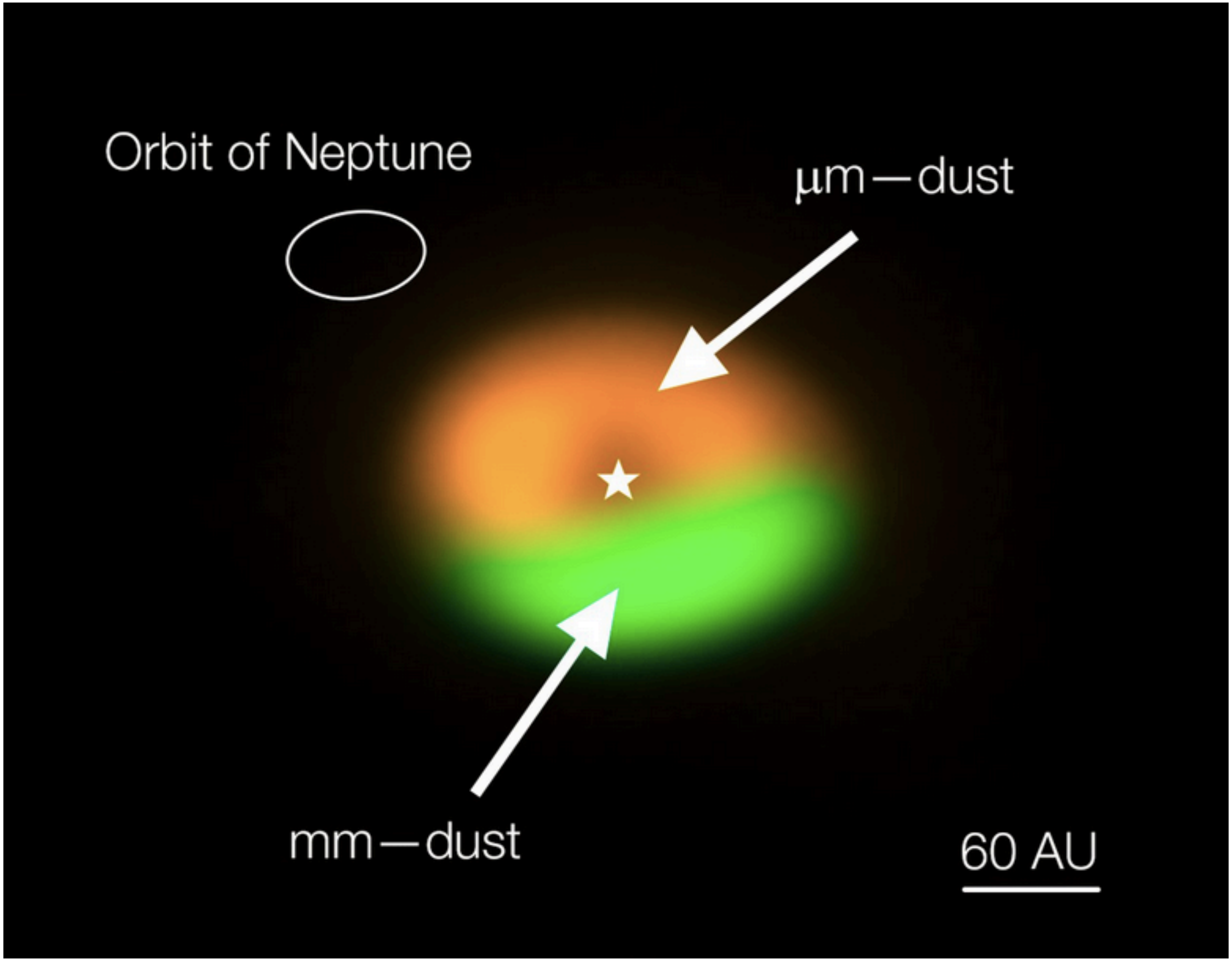
Connecting the Solar Nebula to Extrasolar Nebulae

Observing comet formation sites in circumstellar disks.

Wladimir Lyra
Jet Propulsion Laboratory
California State University

Sofia, June 21st, 2017

Oph IRS 48



Oph IRS 48

eso1325 — Science Release

ALMA Discovers Comet Factory

New observations of a "dust trap" around a young star solve long-standing planet formation mystery

6 June 2013

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

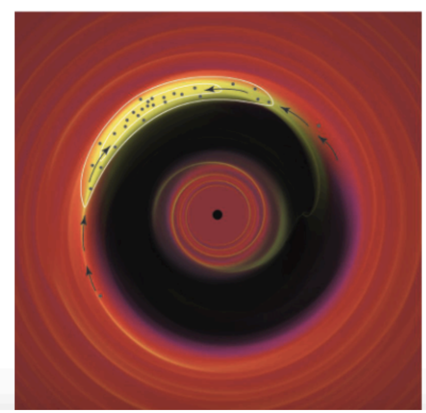
ASTRONOMY

A Trap for Planet Formation

The detection of a pocket of trapped particles may provide a hint to understanding the mechanism of planet formation.

Philip J. Armitage[1,2]

The raw material for forming planets is micrometer to millimeter-sized particles of dust that orbit along with gas in protoplanetary disks around young low-mass stars. These disks are known to be common and to persist for several million years (*1*). The Kepler mission (*2*) showed that mature planetary systems are also common. What is not known, however, is the full sequence of steps that allows the dust within protoplanetary disks to grow into planets. On page 1199 of this issue, van der Marel *et al.* (*3*) report observations from the Atacama Large Millimeter/submillimeter Array (ALMA) that hint at how the most problematic step may be surmounted—millimeter-sized par-

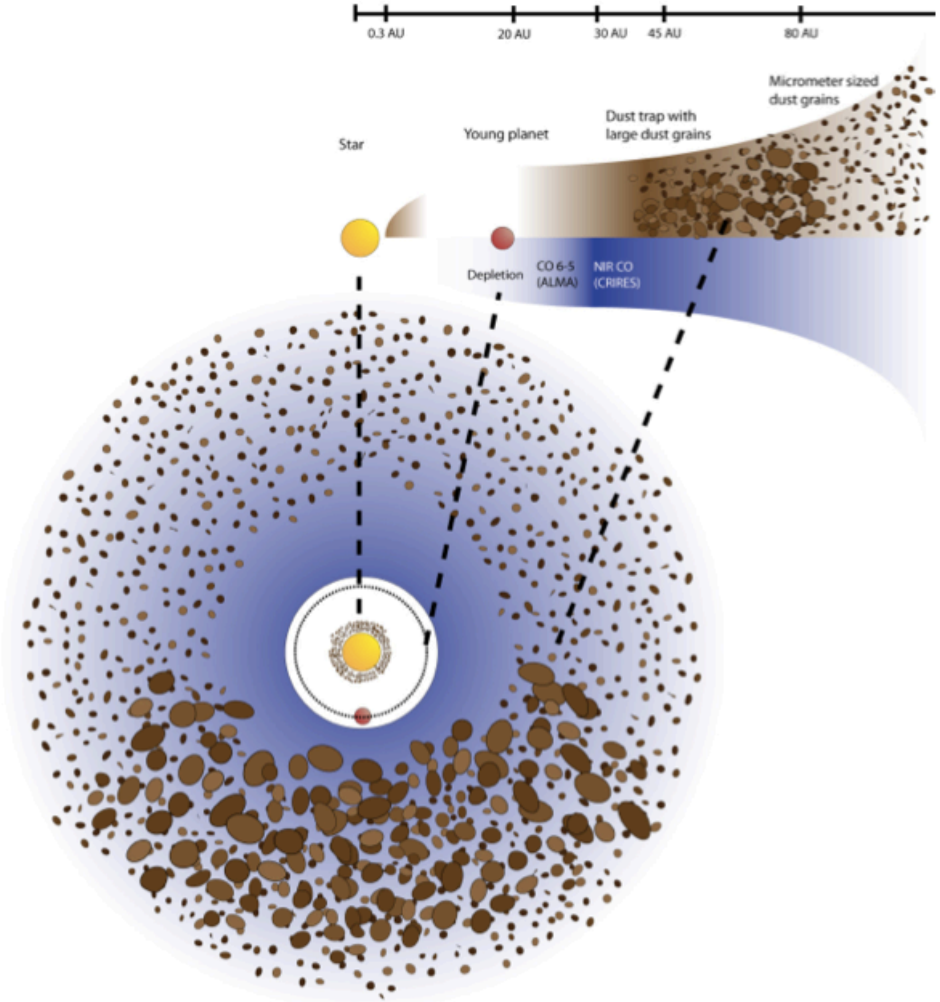


From dust to planet. Illustration of the proposed mechanism that creates a dust trap in the disk of IRS 48. A massive planet (plus symbol) creates an annular gap in the gas disk, whose surface density is shown as a color map. A high-pressure vortex (contours) forms at the gap edge, collecting and trapping millimeter-sized dust particles that would otherwise spiral rapidly inward through the disk.

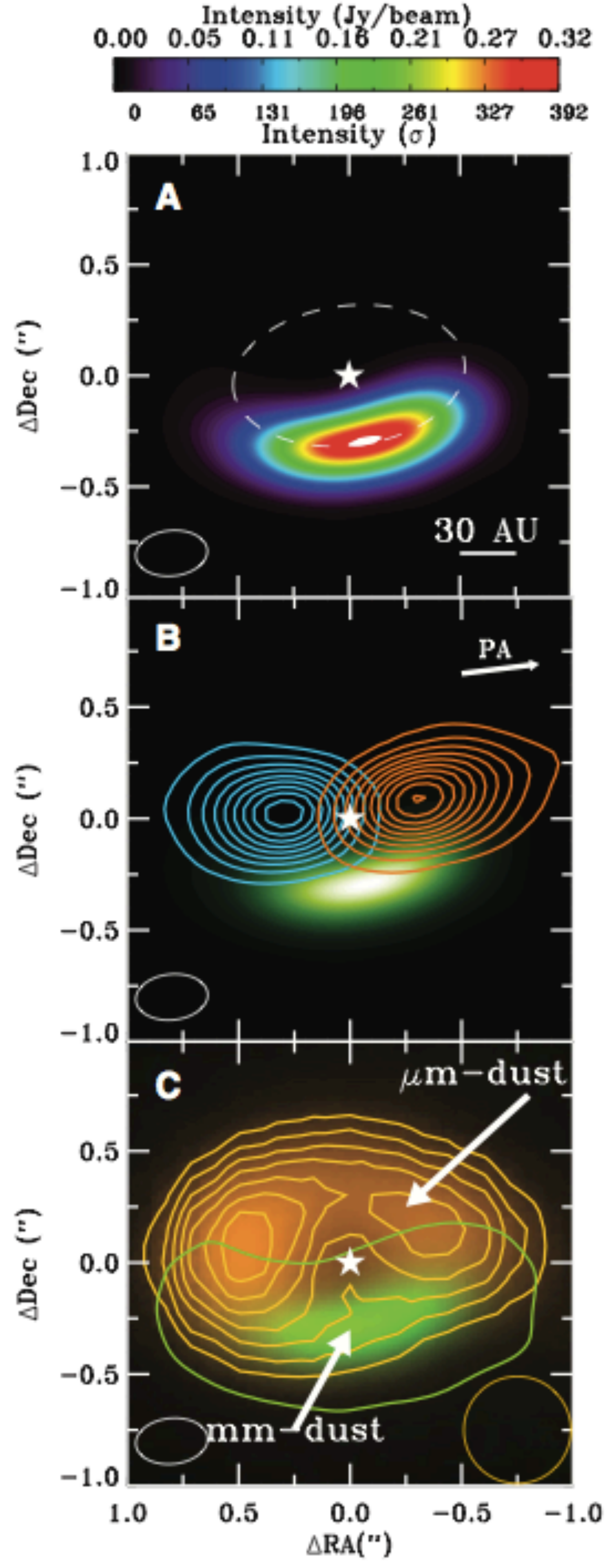
metric distribution. The emission from smaller dust particles, measured separately at infrared wavelengths, is also distributed uniformly around the orbit (*11*). These observations are consistent with theoretical expectations for a dust trap, in which a modest peak in gas pressure is able to strongly concentrate the millimeter-sized solid particles that

van der Marel et al. 2013

The Oph IRS 48 “dust trap”



van der Marel et al. (2013)

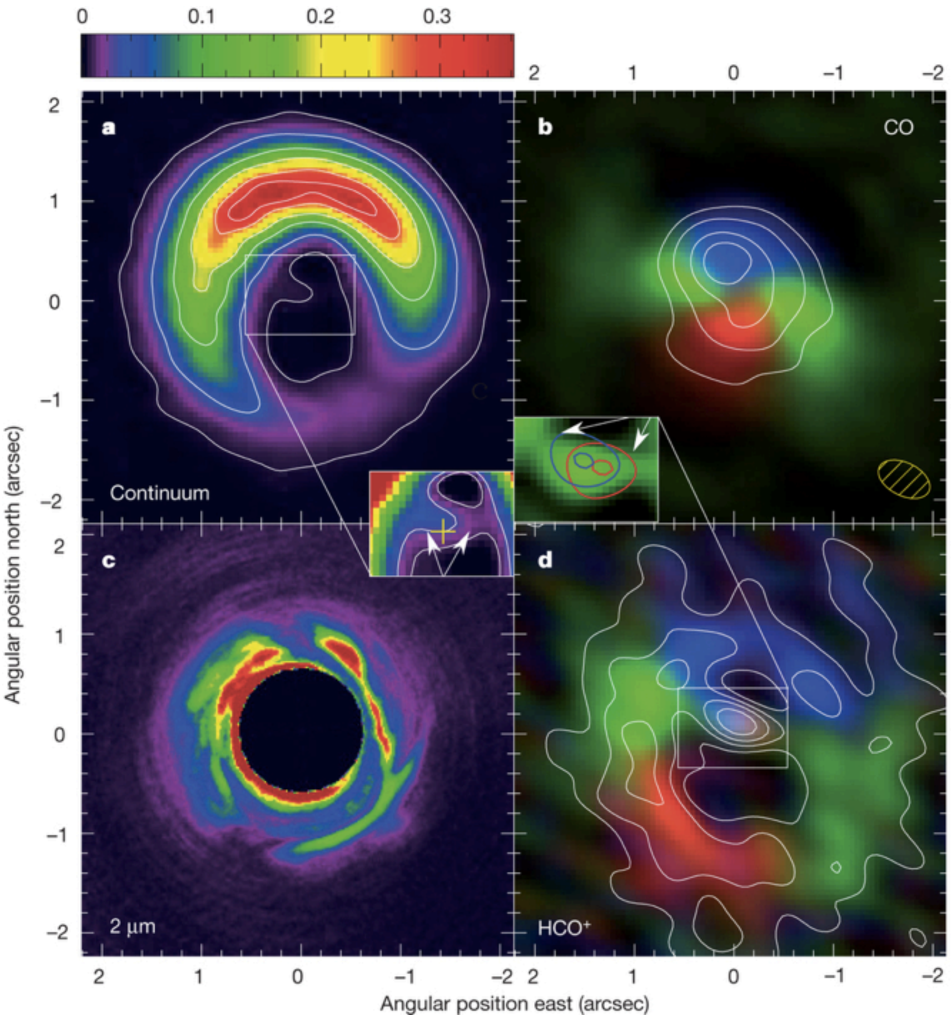


asymmetric mm dust at 63 AU

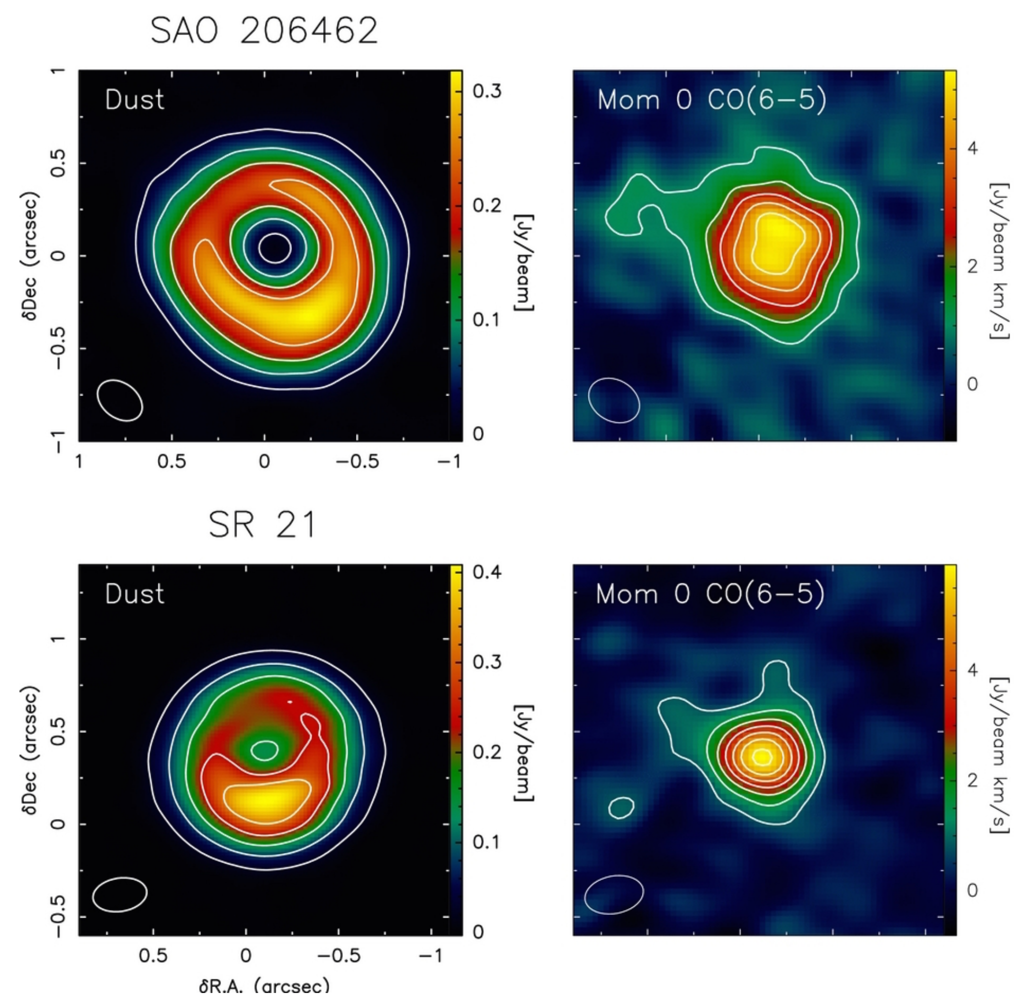
Gas detection: Keplerian rotation

Micron-sized dust follows gas

Other “asymmetries”

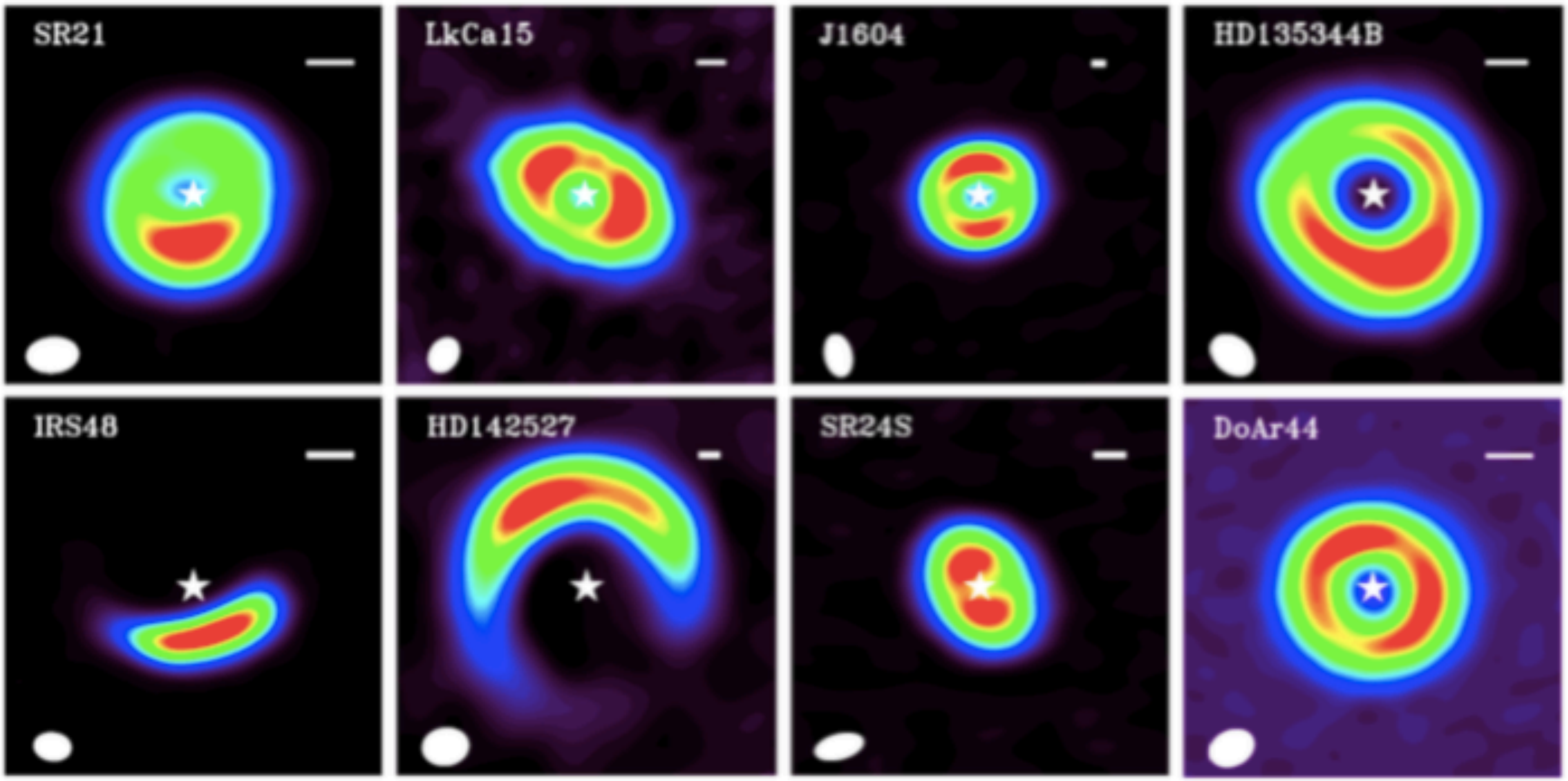


Casassus et al. (2013)



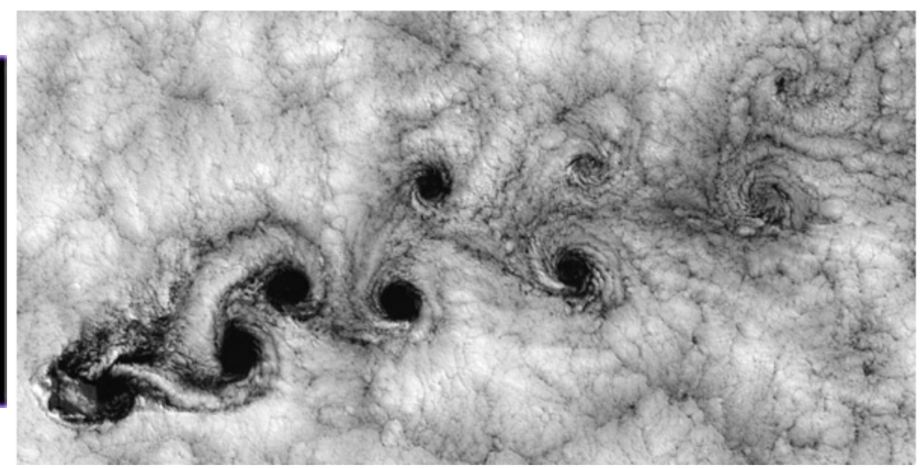
Perez et al. (2014)

“Asymmetries” everywhere



Vortices – an ubiquitous fluid mechanics phenomenon

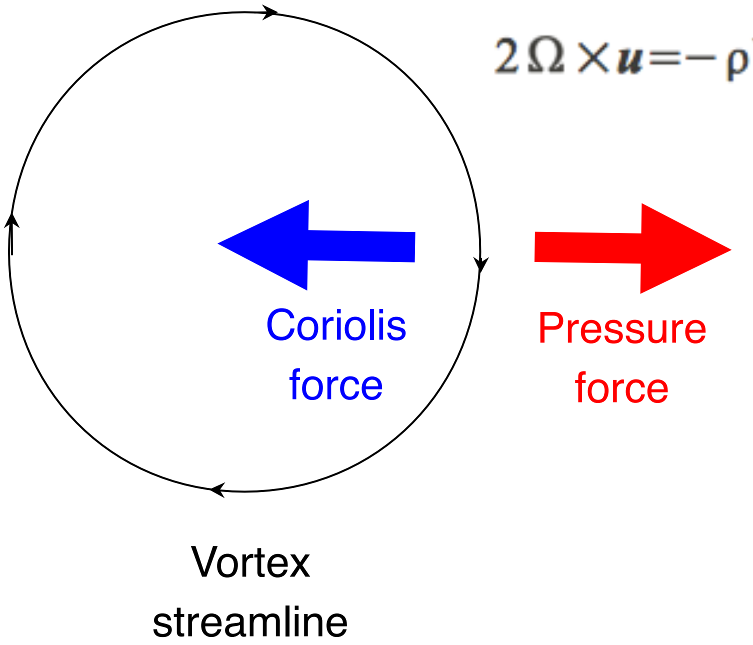
Von Kármán *vortex street*

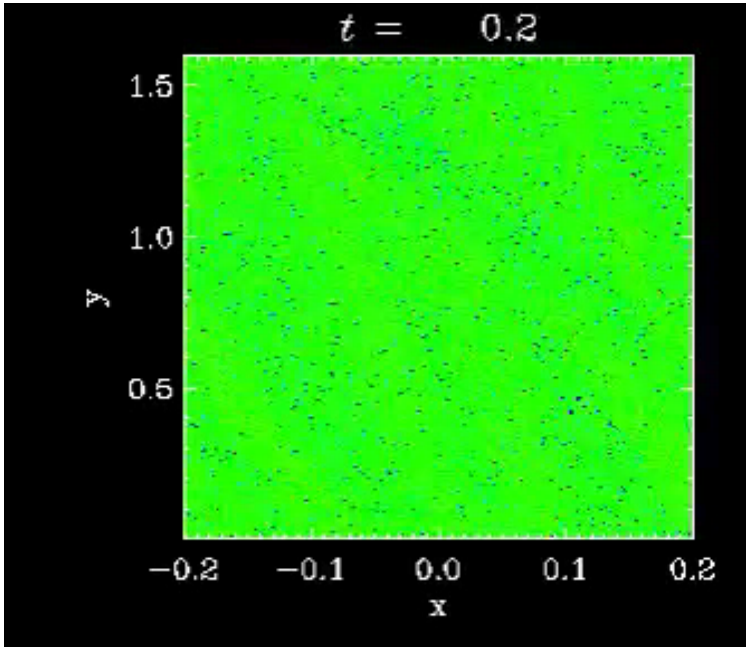


The Tea-Leaf effect

Geostrophic balance:

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





Raettig, Lyra, & Klahr (2013)

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

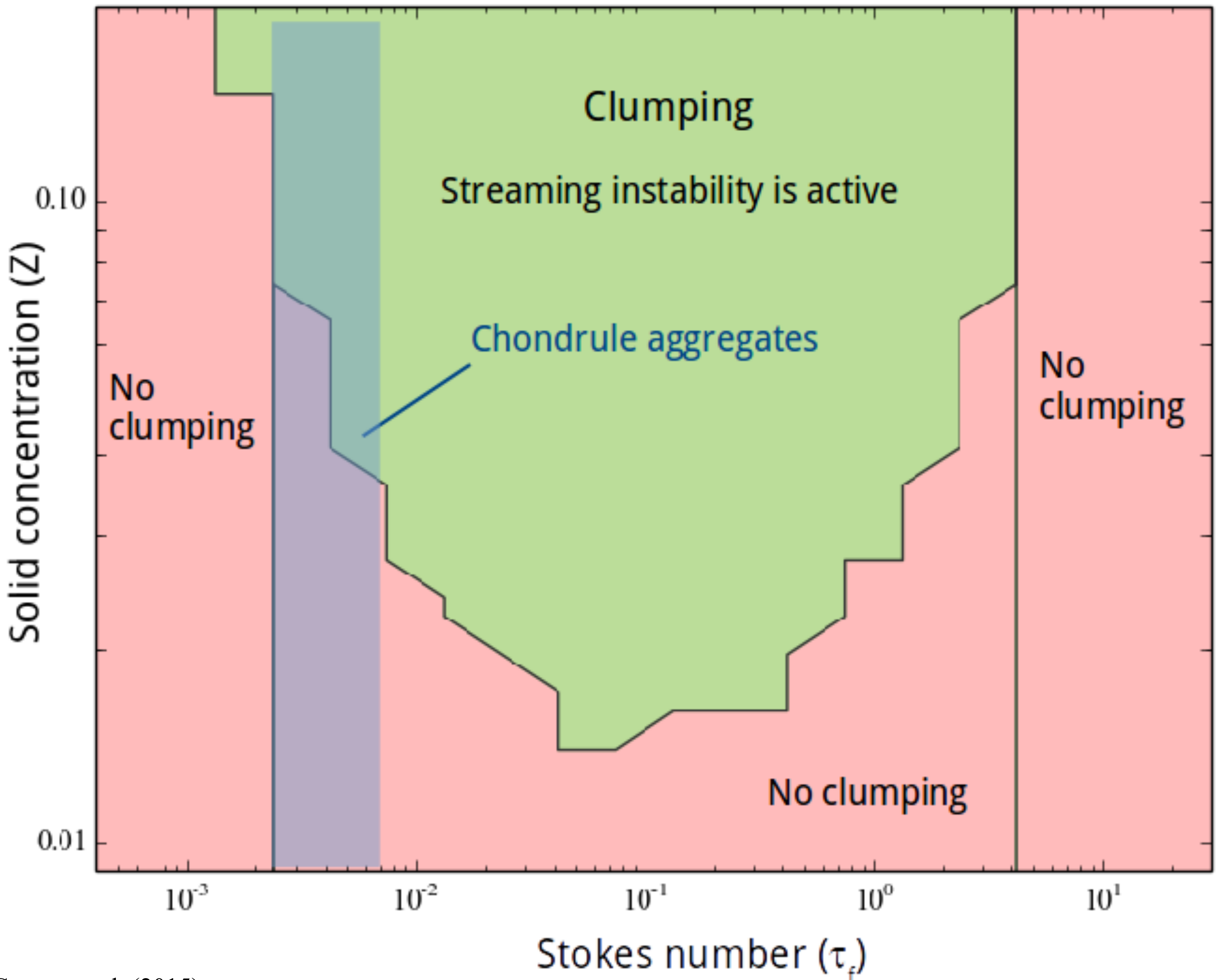
Aid to planet formation

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

Speed up planet formation enormously

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

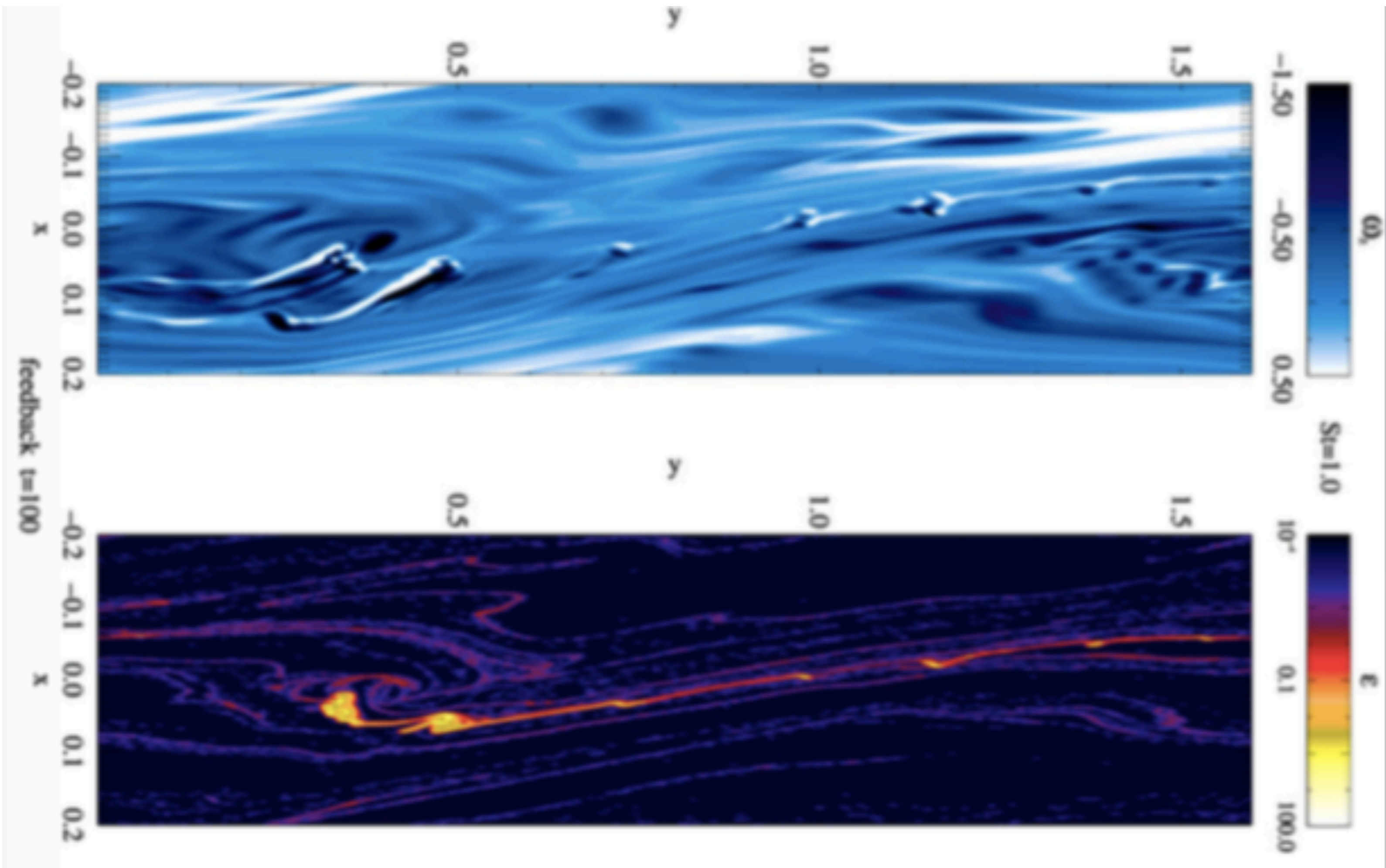
Streaming Instability does not "work" for solar metallicity



Carrera et al. (2015)

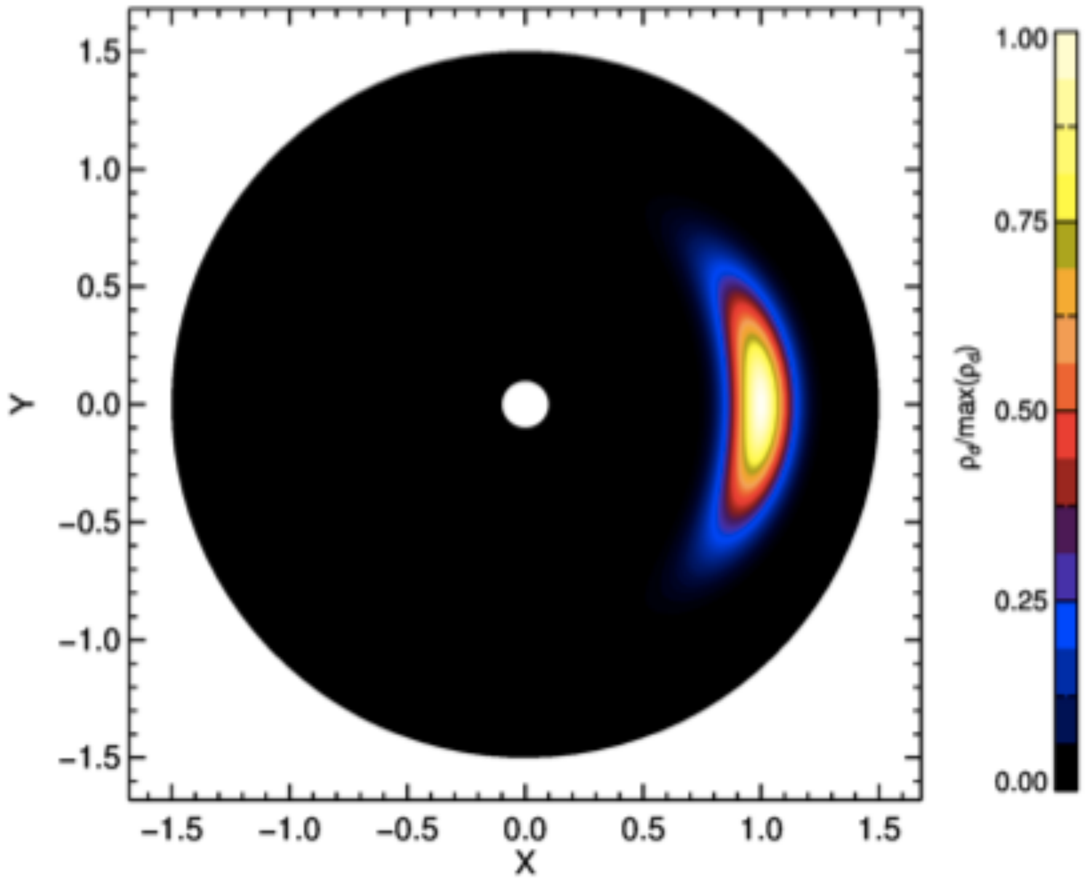
Clumping

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



Raettig et al. (2015)

Drag-Diffusion Steady State



Solution

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

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

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

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

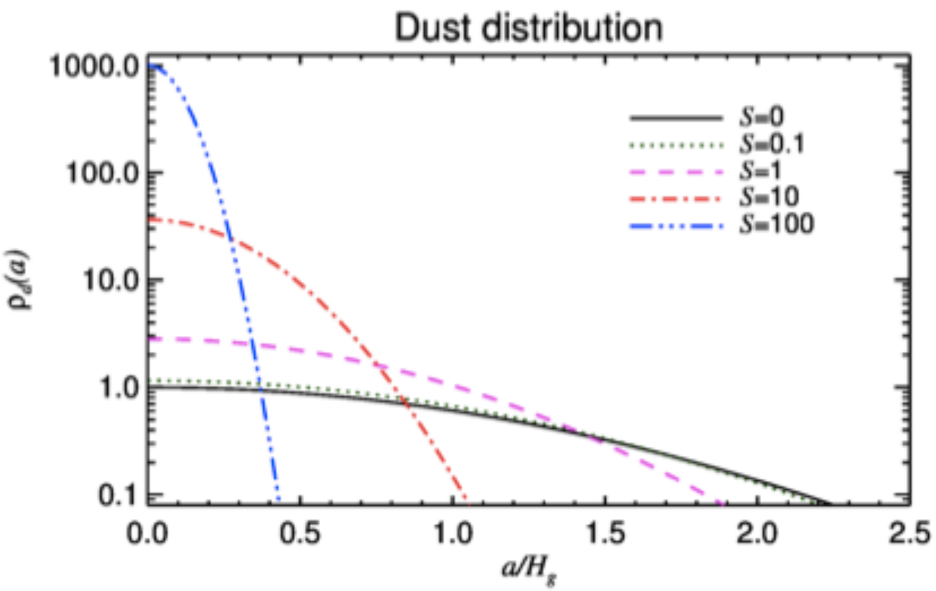
Solution for

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

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

Lyra & Lin (2013)

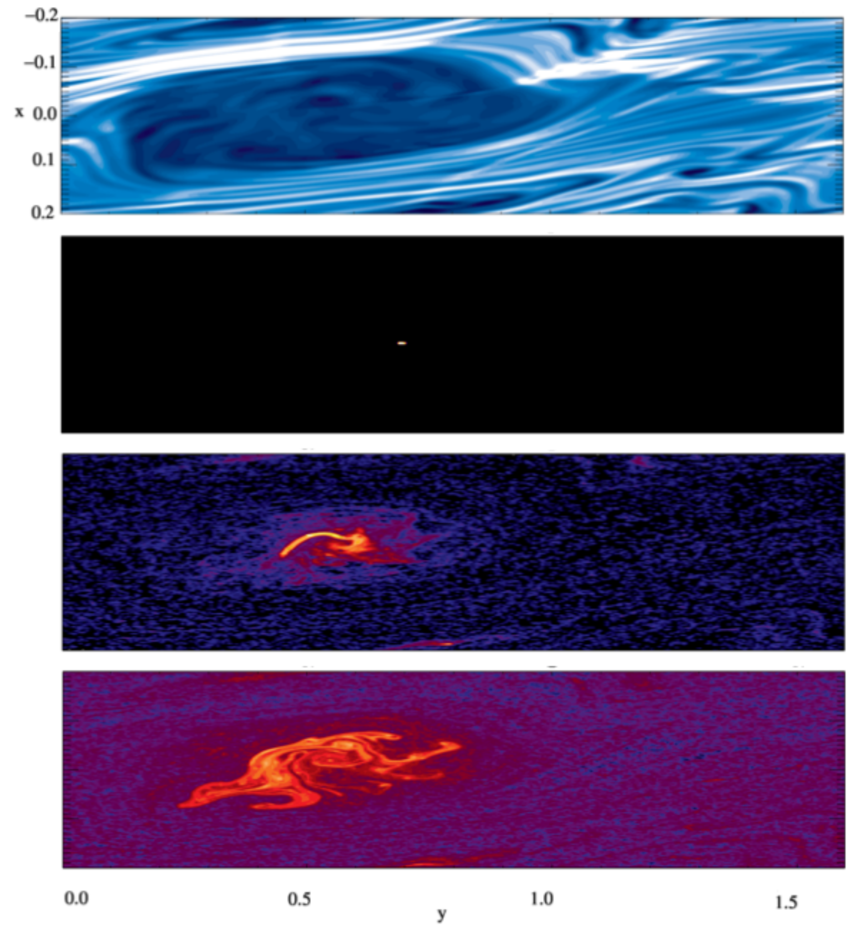
Analytical vs Numerical



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

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

Lyra & Lin (2013)



Gas

St=1

St=0.05

St=0.01

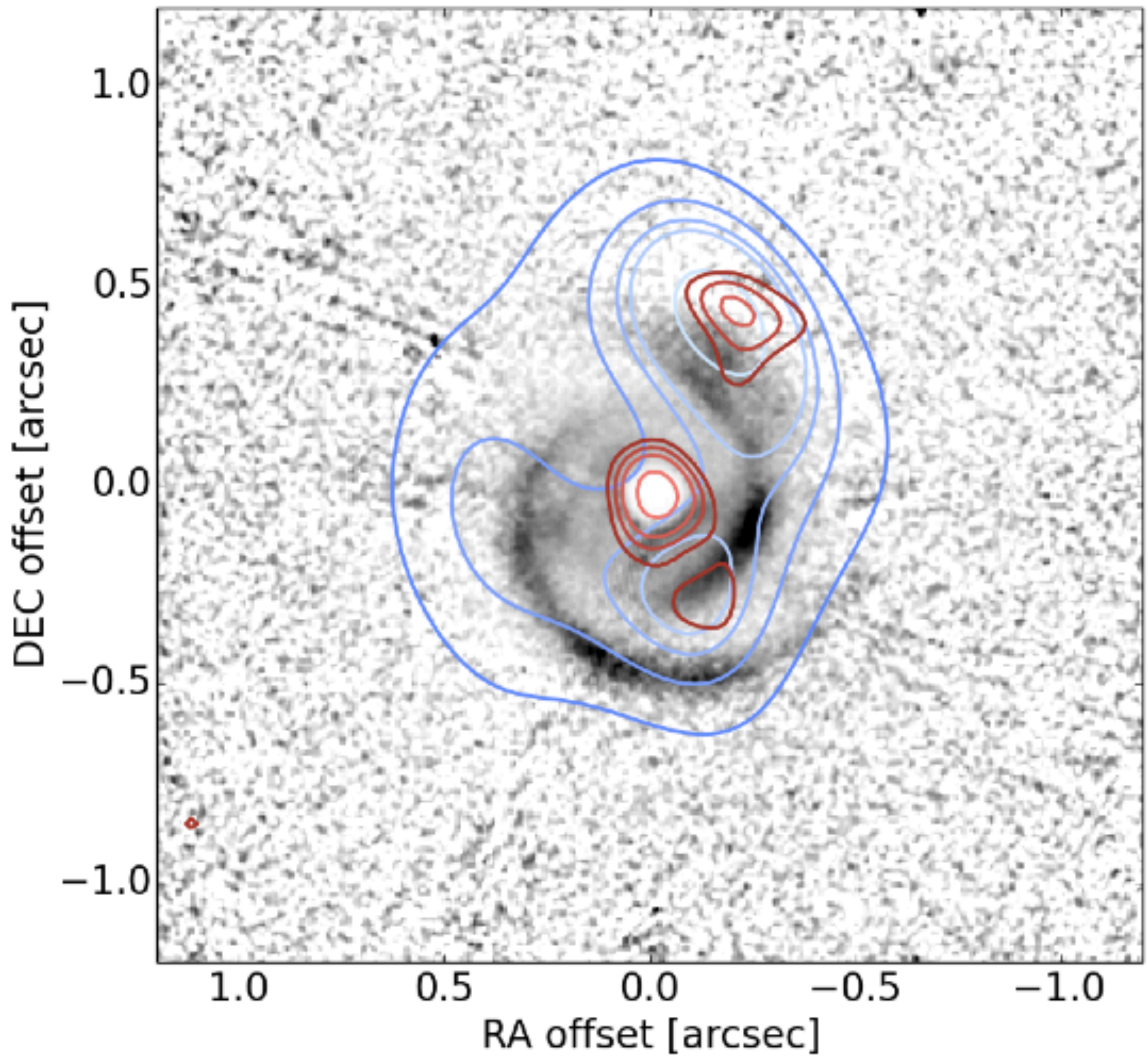
Raettig et al (2015)

SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

ALMA (~ mm)

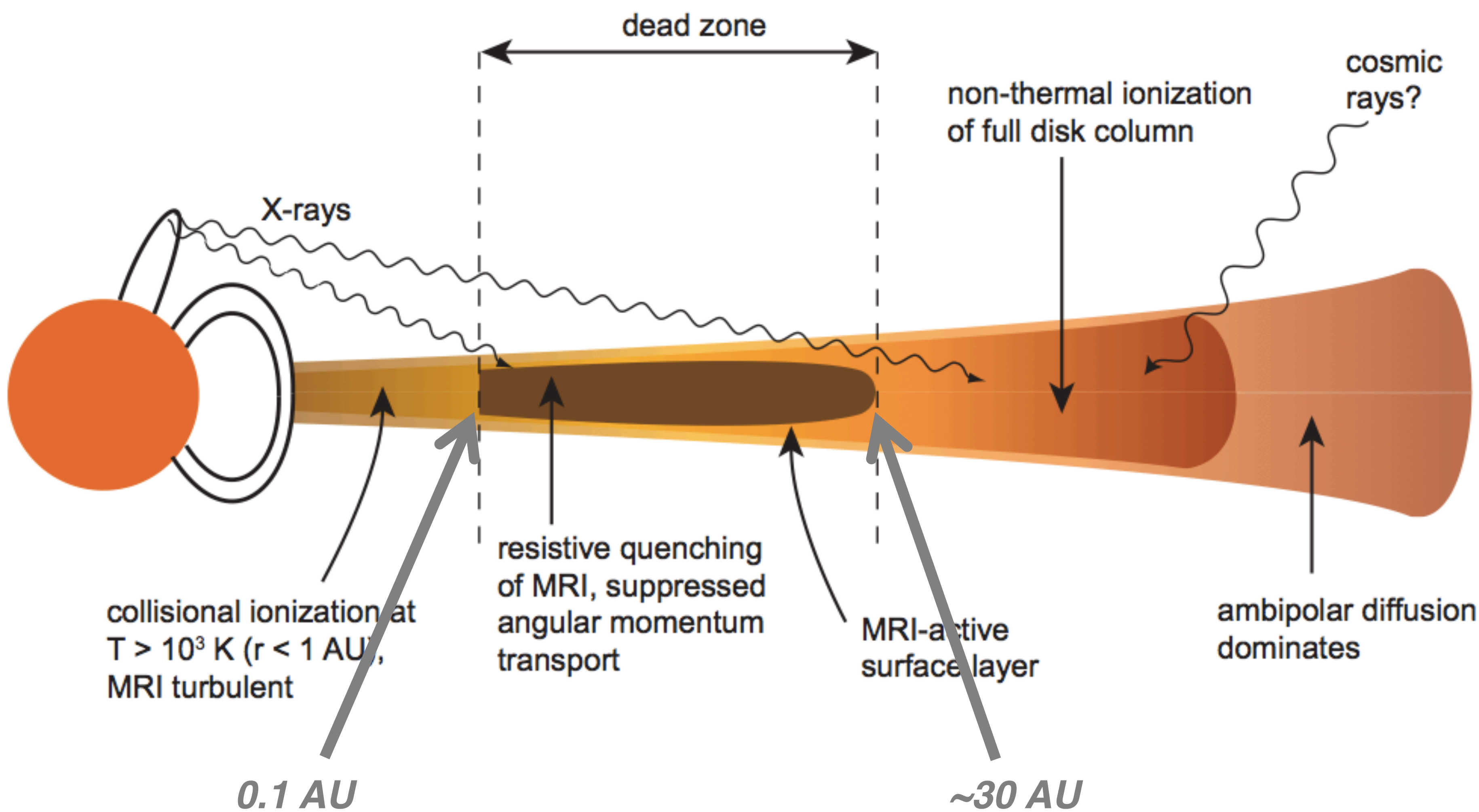
VLA (cm-m)



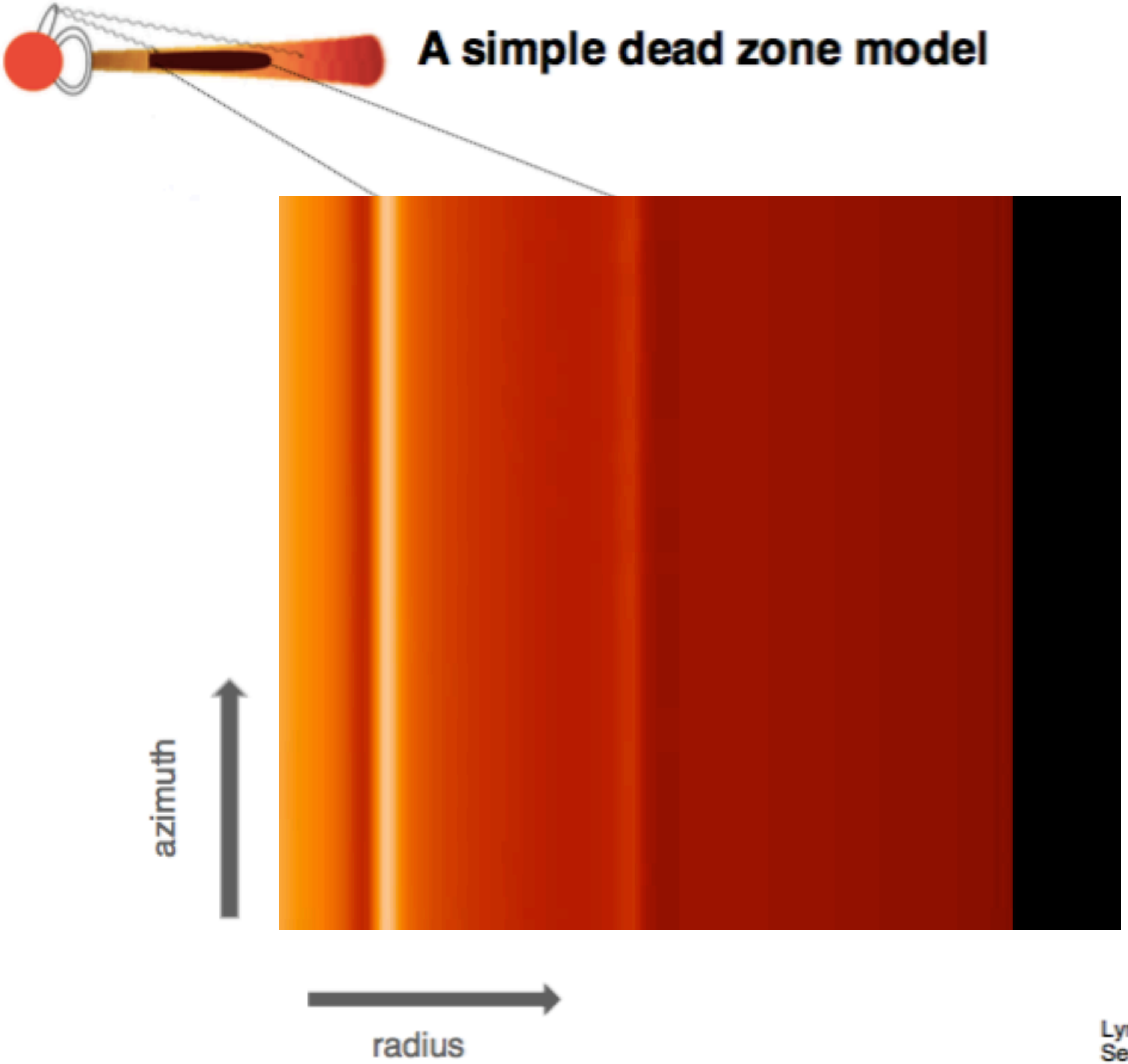
Marino et al. (2015)

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

Dead zones

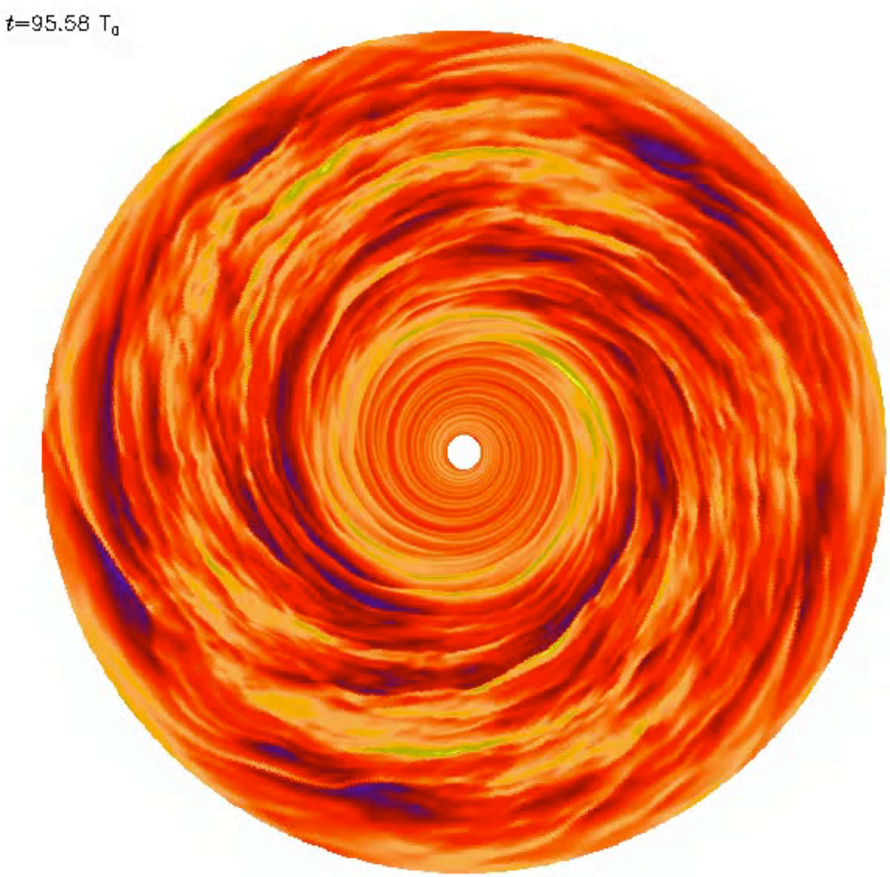

dead zone
non-thermal ionization of full disk column
cosmic rays?
X-rays
collisional ionization at T > 10³ K (r < 1 AU), MRI turbulent
resistive quenching of MRI, suppressed angular momentum transport
MRI-active surface layer
ambipolar diffusion dominates
0.1 AU
~30 AU

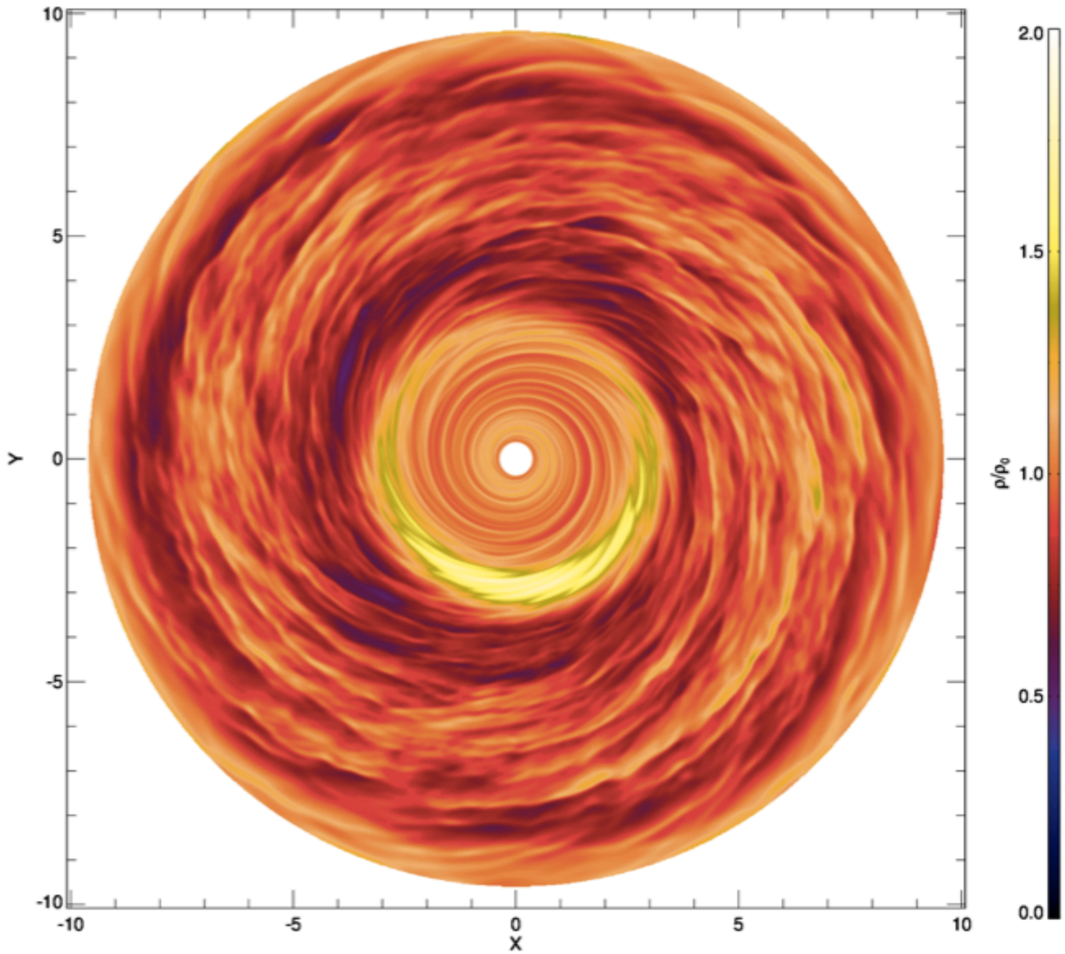
A simple dead zone model



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

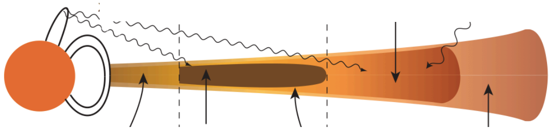
Outer Dead/Active zone transition





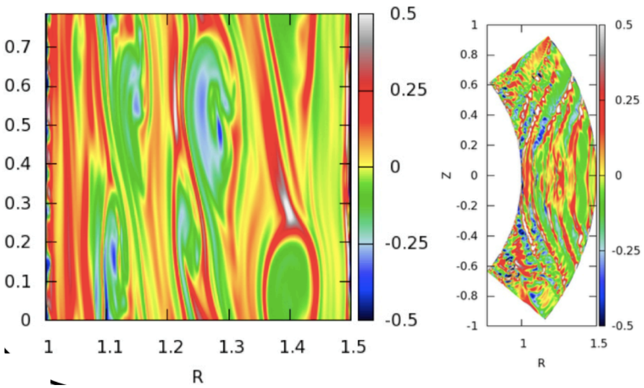
Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)



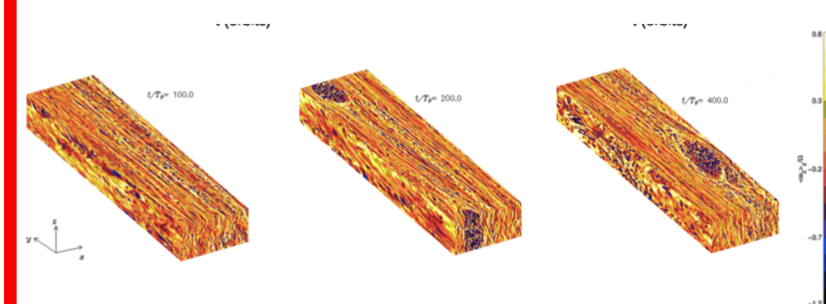
The MRI is dead
Long live the *Thermal Instabilities*

Vertical Shear Instability



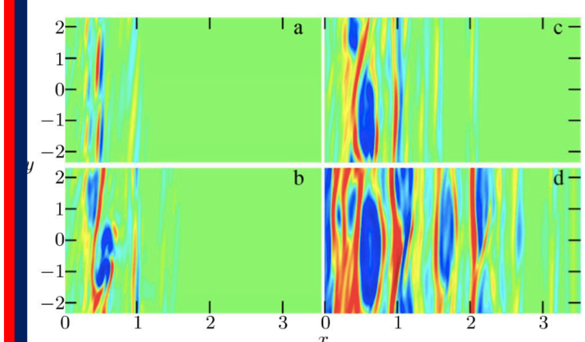
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



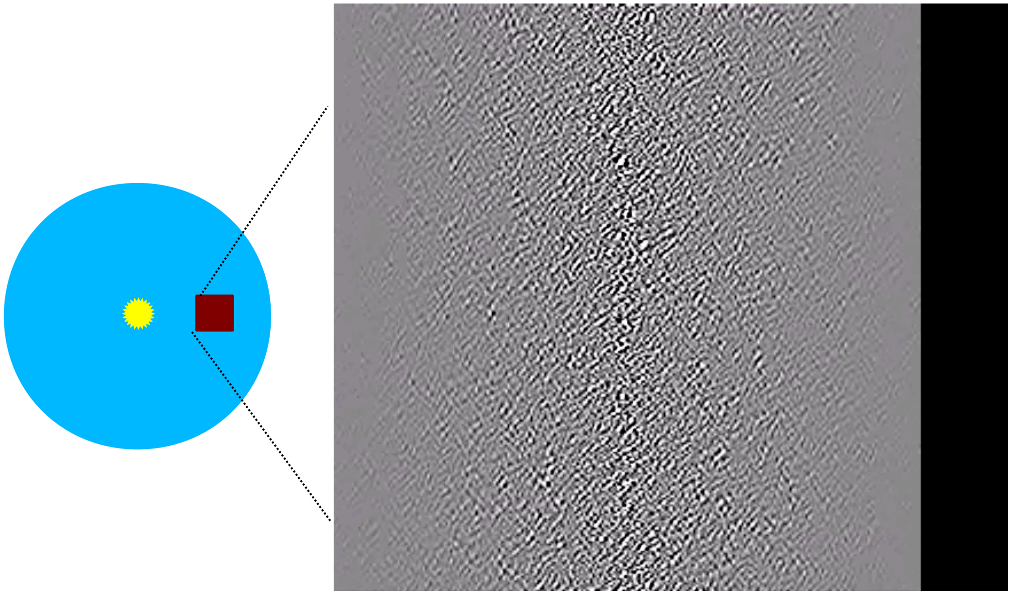
Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

Zombie Vortex Instability



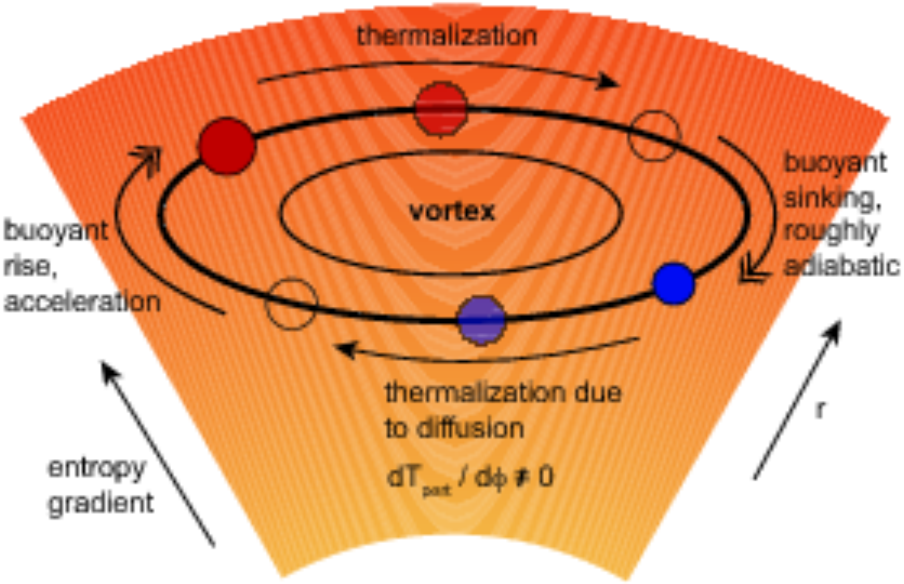
Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

Convective Overstability (née “Subcritic Baroclinic Instability”)



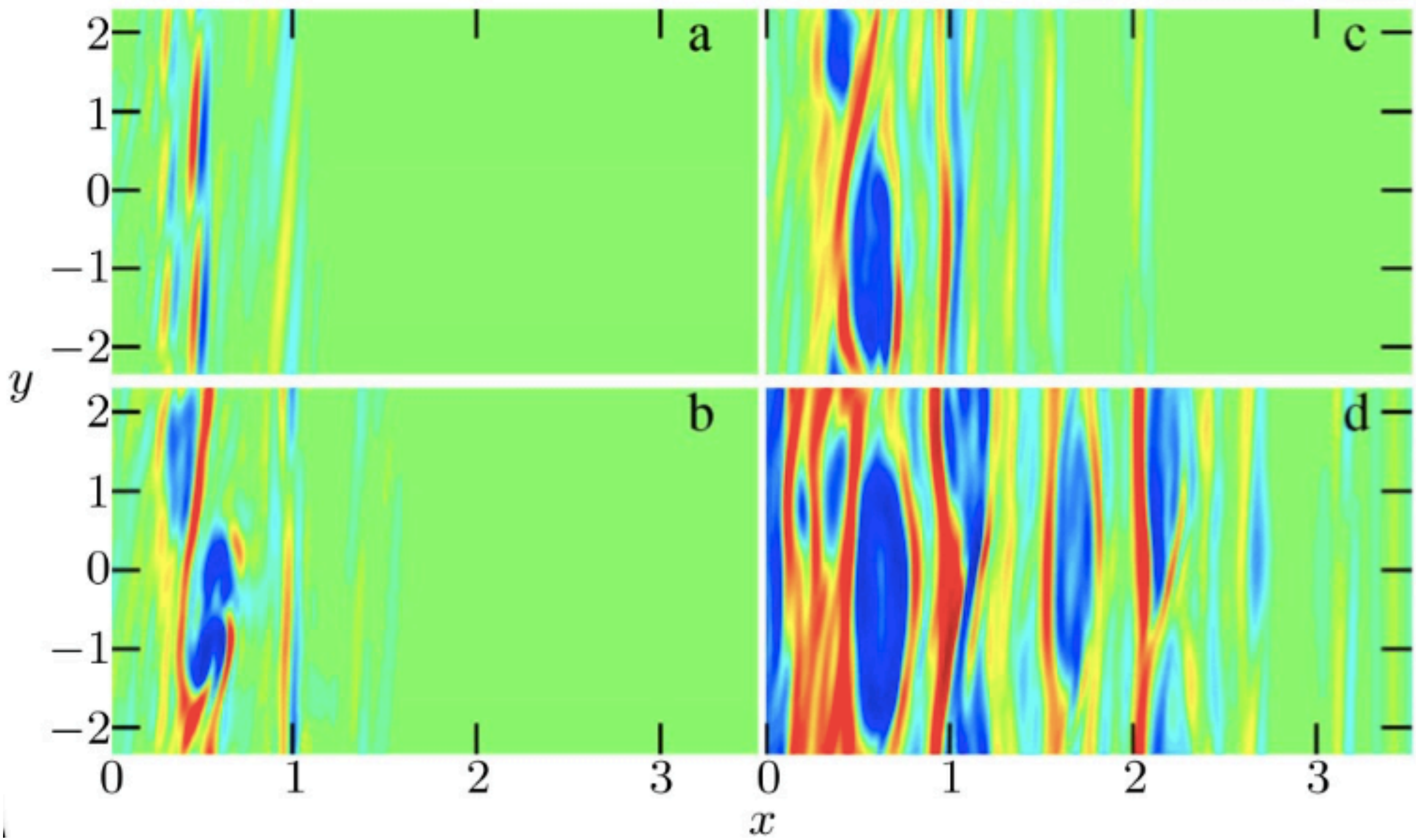
Lyra & Klahr (2011)

Sketch of the
Subcritic Baroclinic Instability



Armitage (2010)

Zombie Vortex Instability



Cascade of baroclinic critical layers

Marcus et al. (2015, 2016)

Vertical shear instability

$$\rho_{\rm mid} = \rho_0 \left(\frac{R}{R_0}\right)^p ,$$

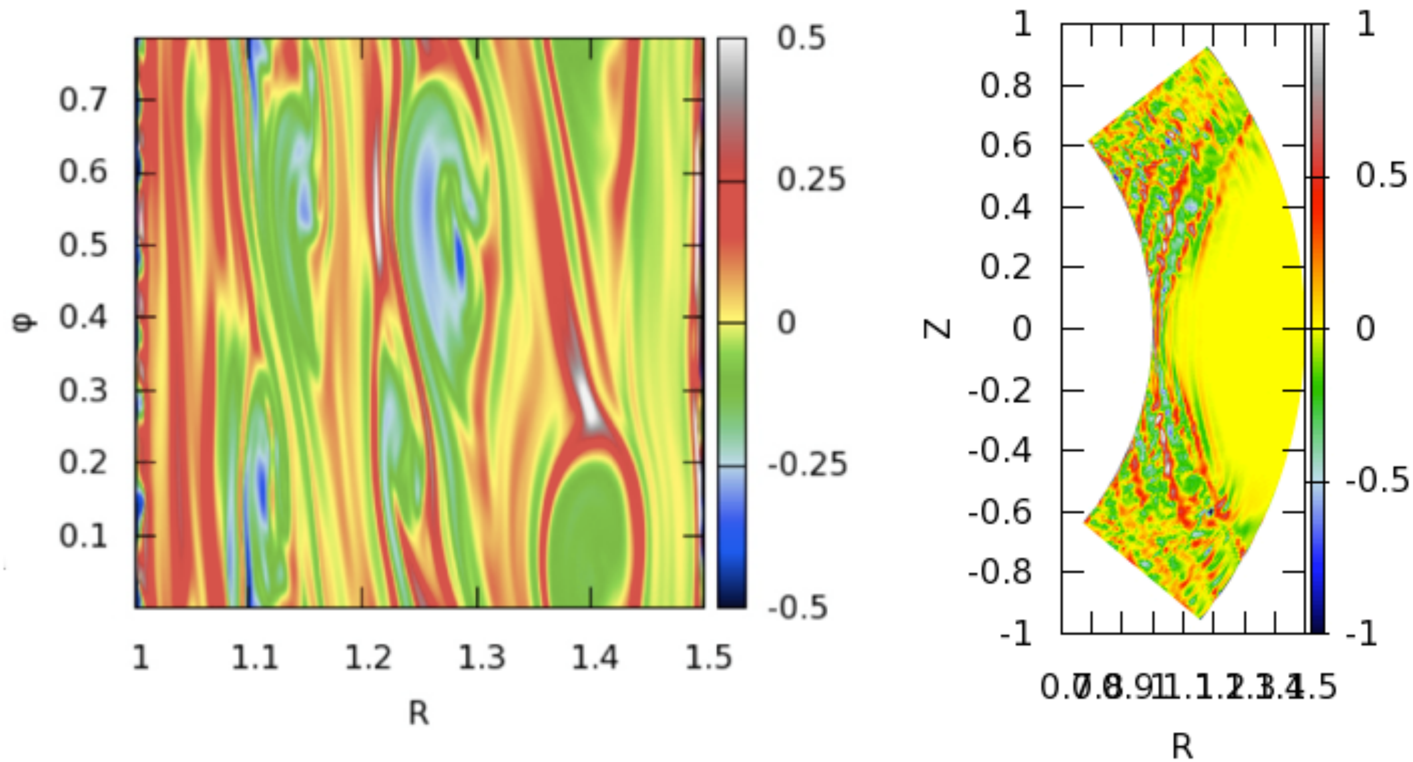
$$c_s^2 = c_0^2 \left(\frac{R}{R_0}\right)^q ,$$

$$\Omega = \Omega_K \left[1 + \frac{1}{2}\left(\frac{H}{R}\right)^2 \left(p + q + \frac{q}{2}\frac{Z^2}{H^2}\right)\right]$$

$d\Omega / dz \neq 0 \; ; \; \kappa_z^2 < 0$ => Rayleigh unstable

Solberg-Hoiland stability criterion

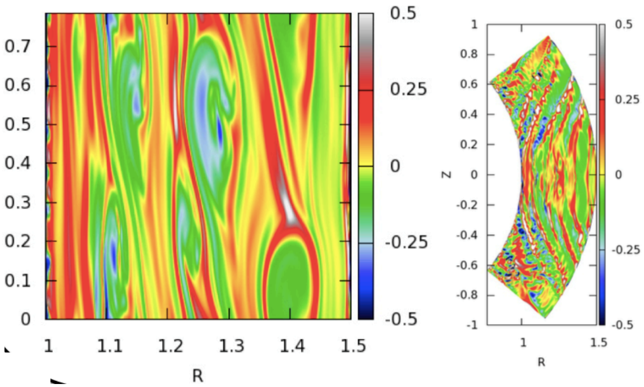
$\kappa^2 + N^2 > 0$



Nelson et al. (2013)

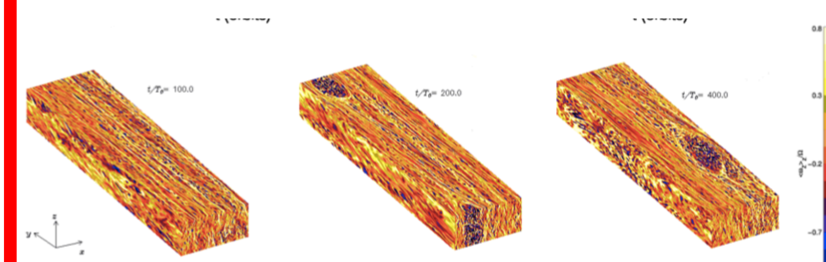
Thermal Instabilities

Vertical Shear Instability



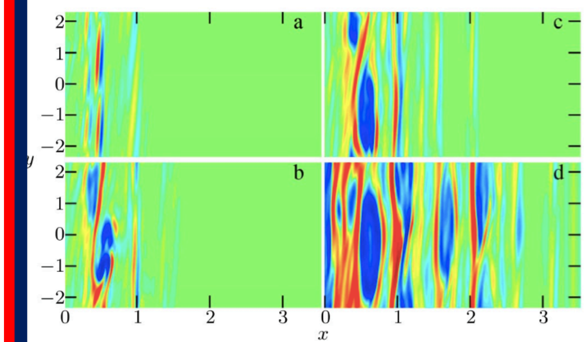
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

Zombie Vortex Instability



Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

$\Omega\tau << 1$
($\kappa < 1$ cm^2/g)

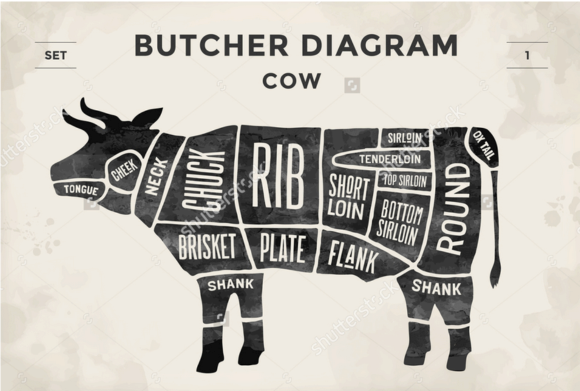
$\Omega\tau \sim 1$
($\kappa \sim 1$–50 cm^2/g)

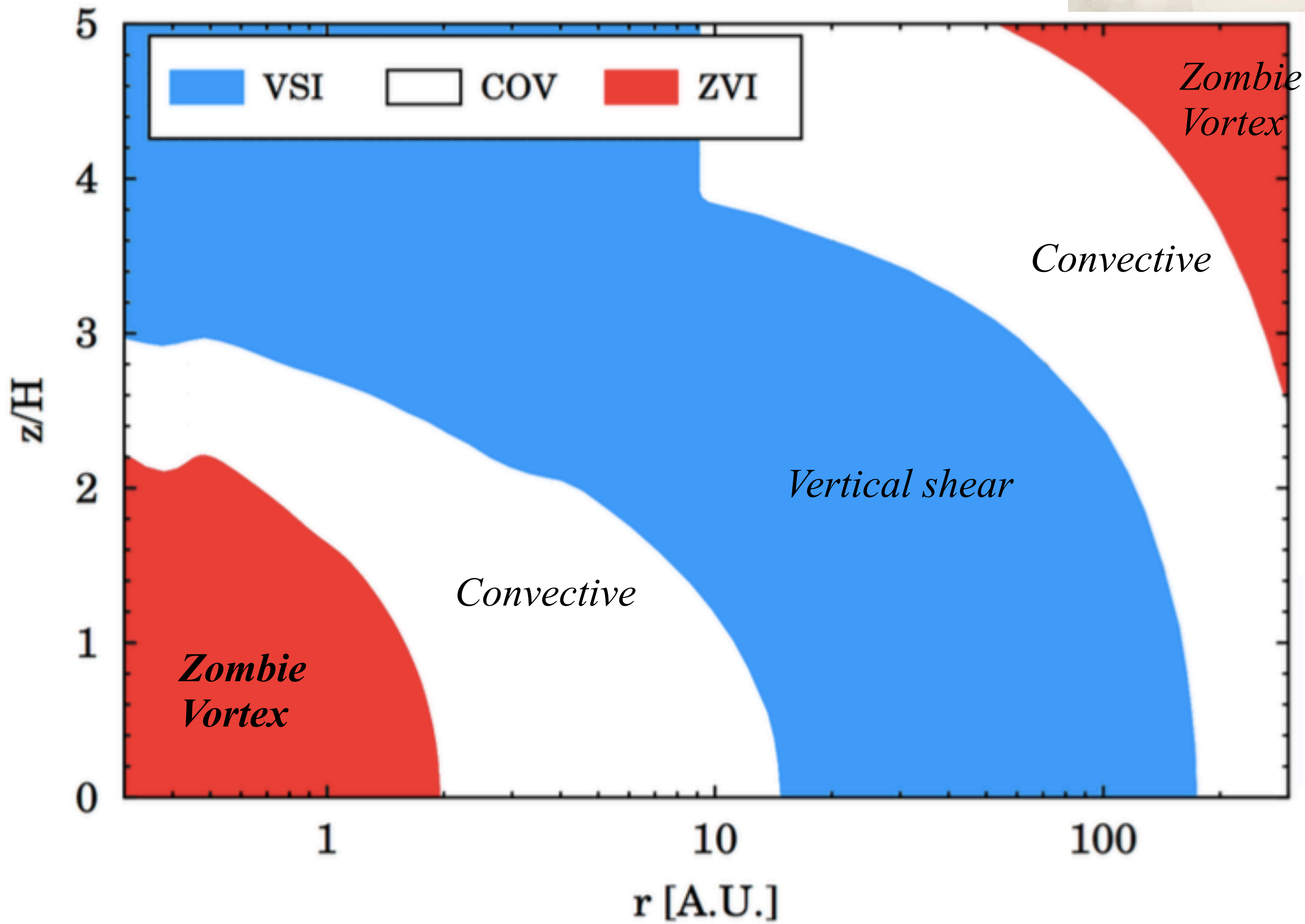
$\Omega\tau >> 1$
($\kappa > 50$ cm^2/g)

Opacity

Synthesis

A "butcher diagram" for hydro instabilities.





Malygin et al. 2017
Umurhan & Lyra 2017 (review)

Conclusions

- Disk vortices are a prime location for planet formation
  - Tea leaf effect: strong clumping
  - Works for solar metallicity

- Dust trapped in drag-diffusion equilibrium explains the observations

- Possible origin: Thermal instabilities in MRI-dead zone
  - Vertical Shear Instability
    - *Vertical violation of Solberg-Hoiland criterion*
  - Convective Overstability
    - *Amplification of epicyclic motion by buoyancy*
  - Zombie Vortex Instability
    - *Resonance between epicyclic and buyoancy frequency*