Vortex theory meets observation:
Is ALMA seeing vortices in transitional disks?

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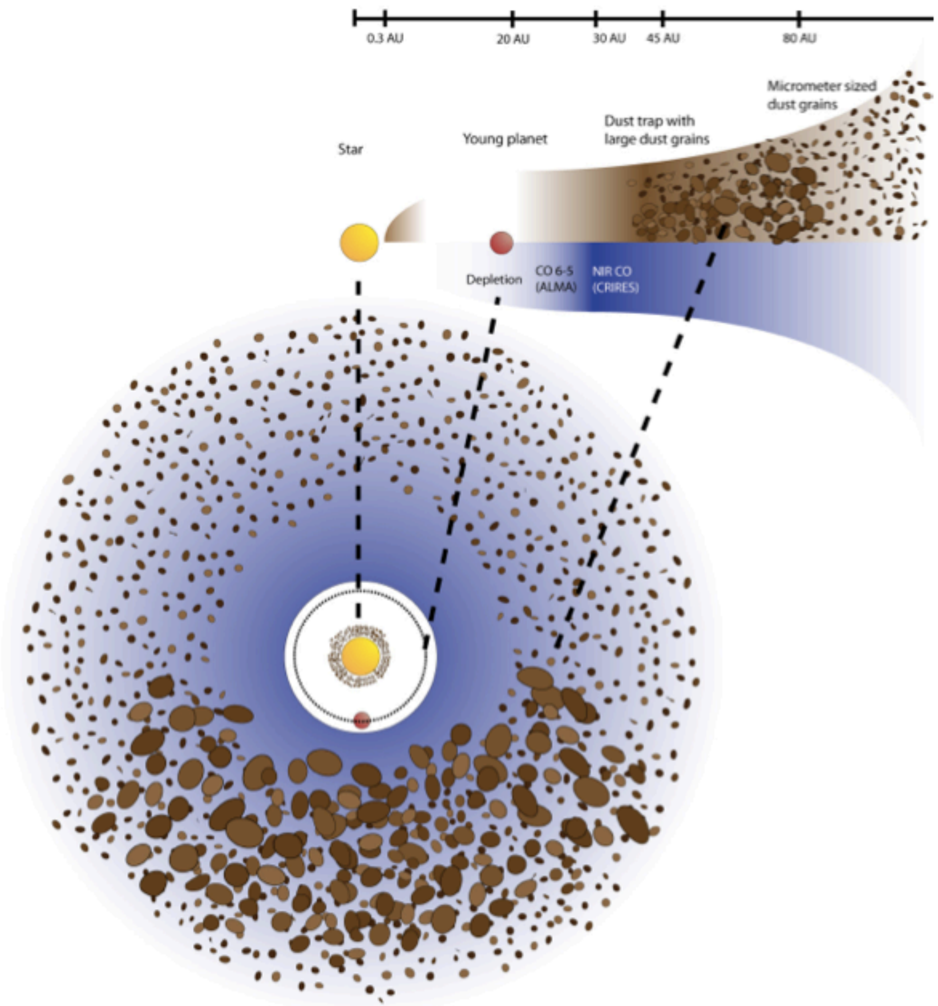
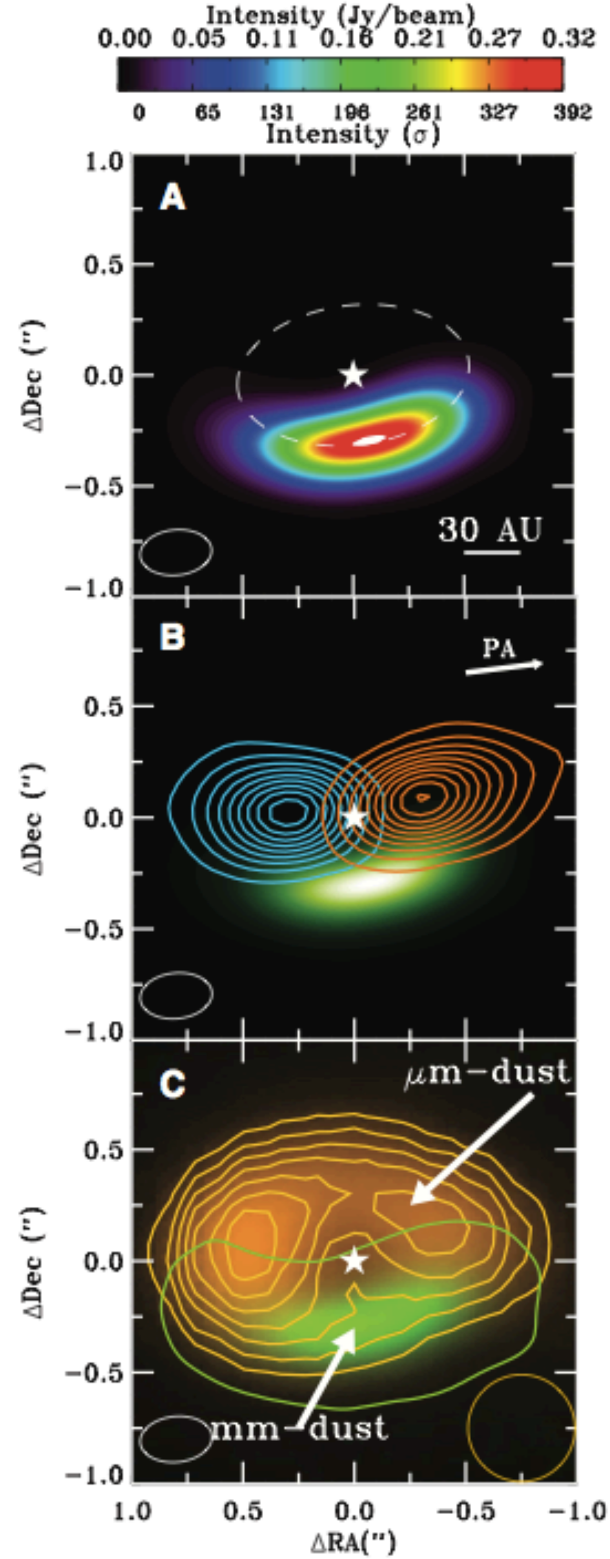
Natalie Raettig (MPIA), Neal Turner (Caltech-JPL)

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

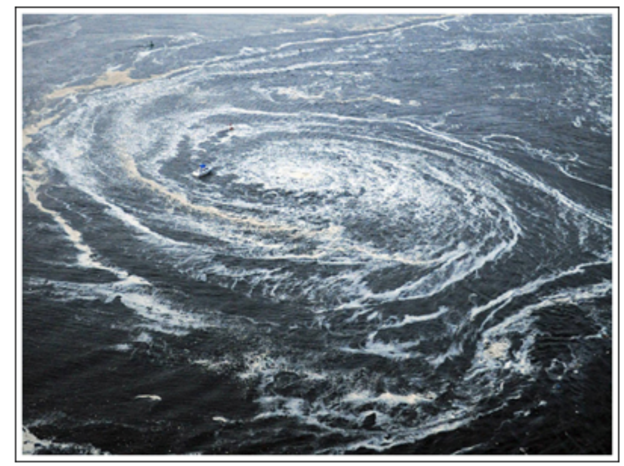


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

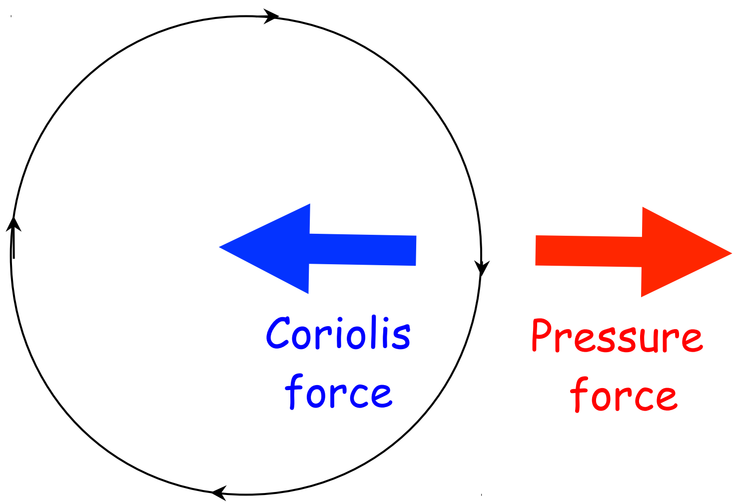
Micron-sized dust follows gas

Vortices – An ubiquitous fluid mechanics phenomenon



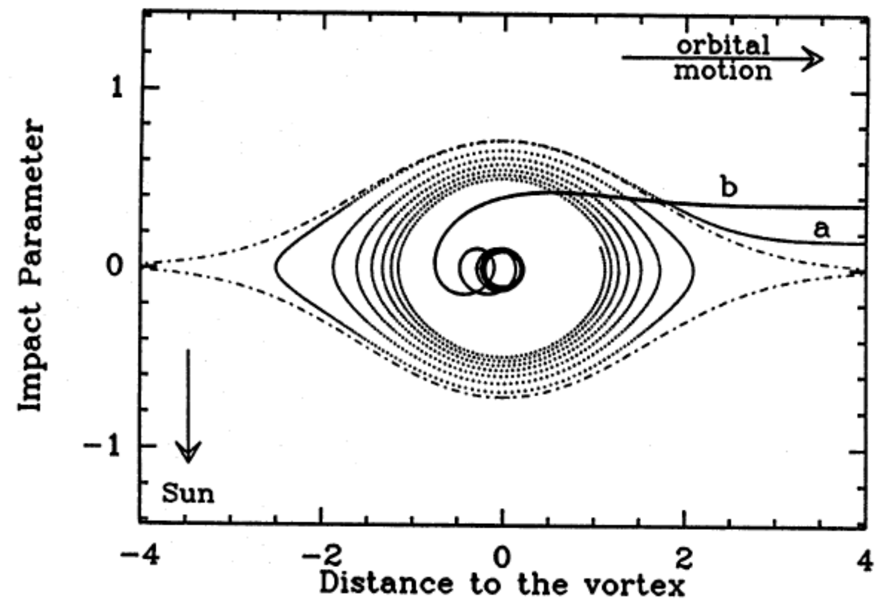
Dust trapping properties

Geostrophic balance:



Vortex streamline

Tea-leaf effect

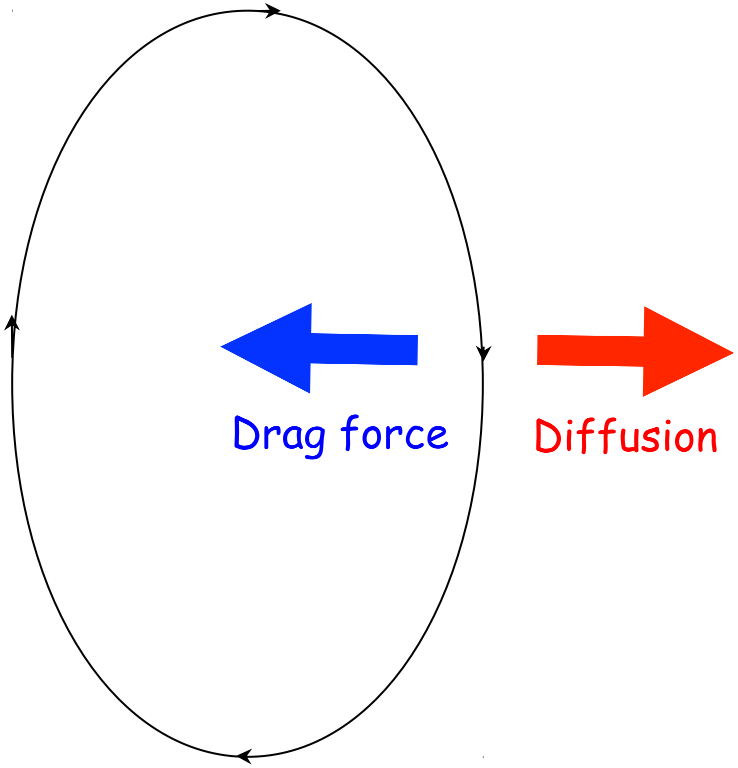


Barge & Sommeria (1995)

Dust does not feel the pressure gradient.
Particles sink to the center

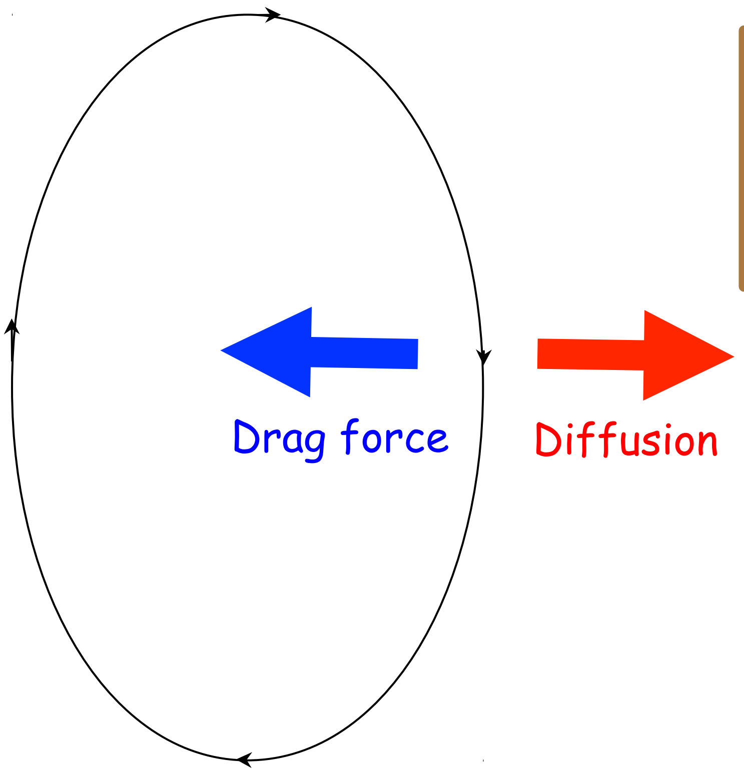
Also independently suggested by:
Tanga et al. 1996
Adams & Watkins 1996

Drag-Diffusion Equilibrium



Trapped particle

Drag-Diffusion Equilibrium



Trapped particle

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

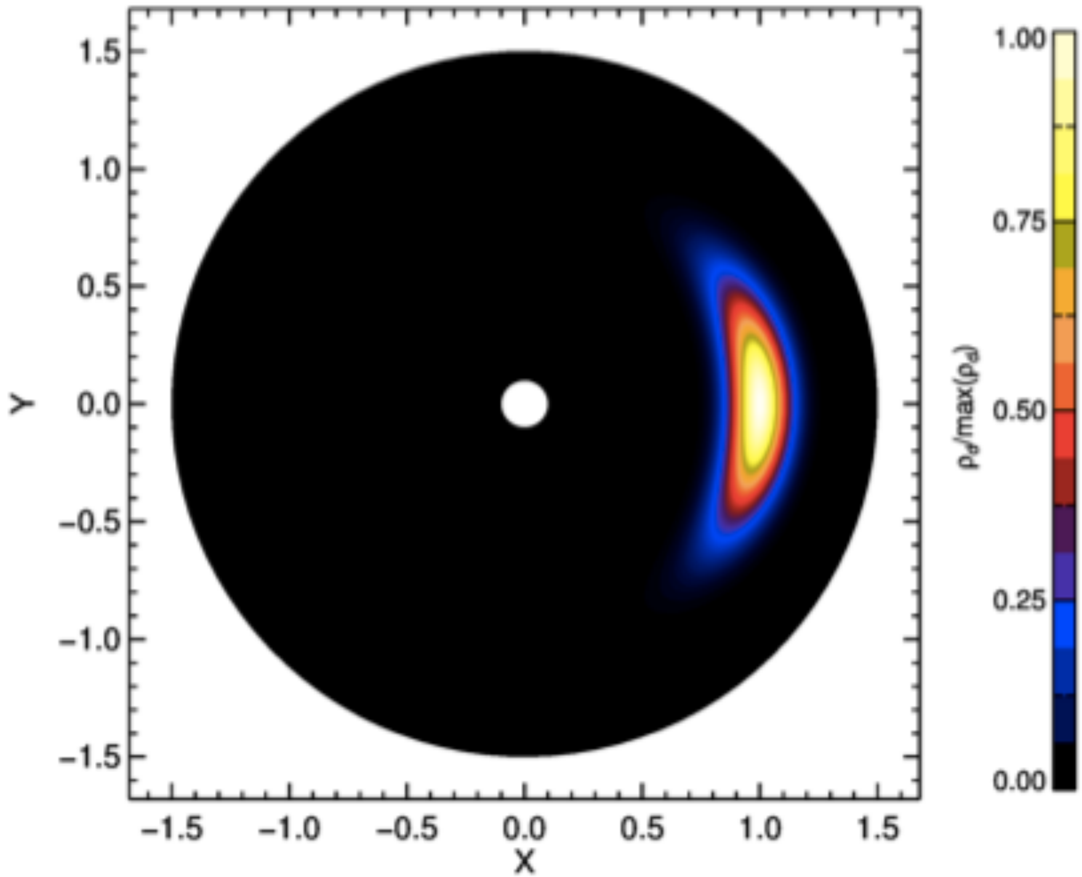
Lyra & Lin (2013)

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

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

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

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

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

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

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

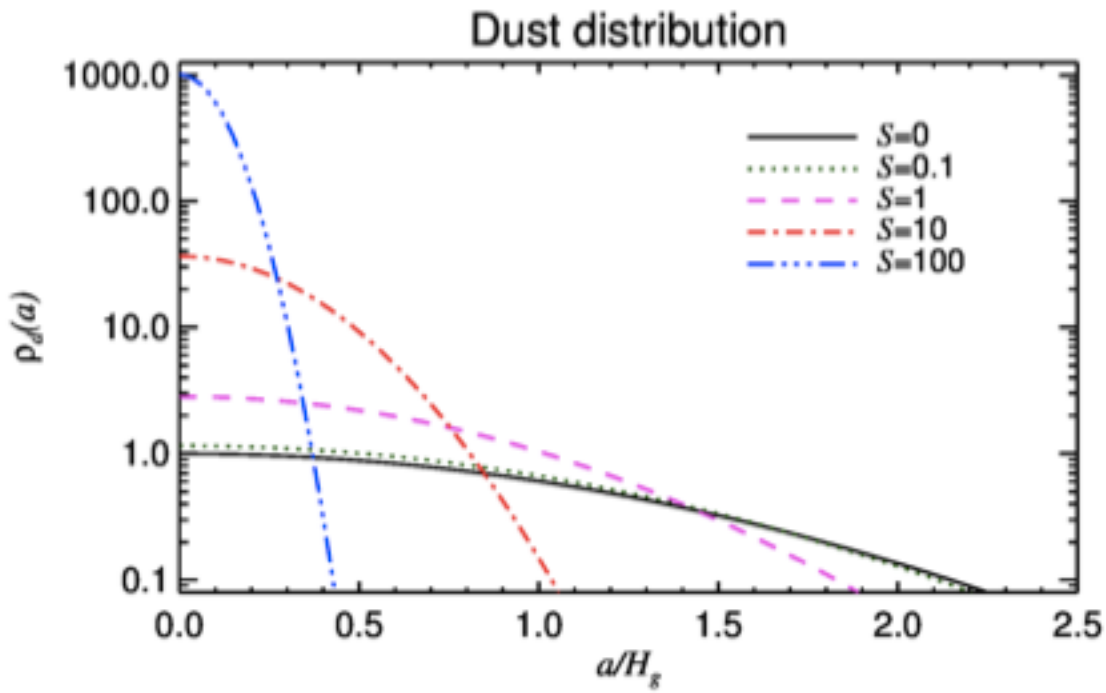
Solution for

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

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 solution for dust trapping

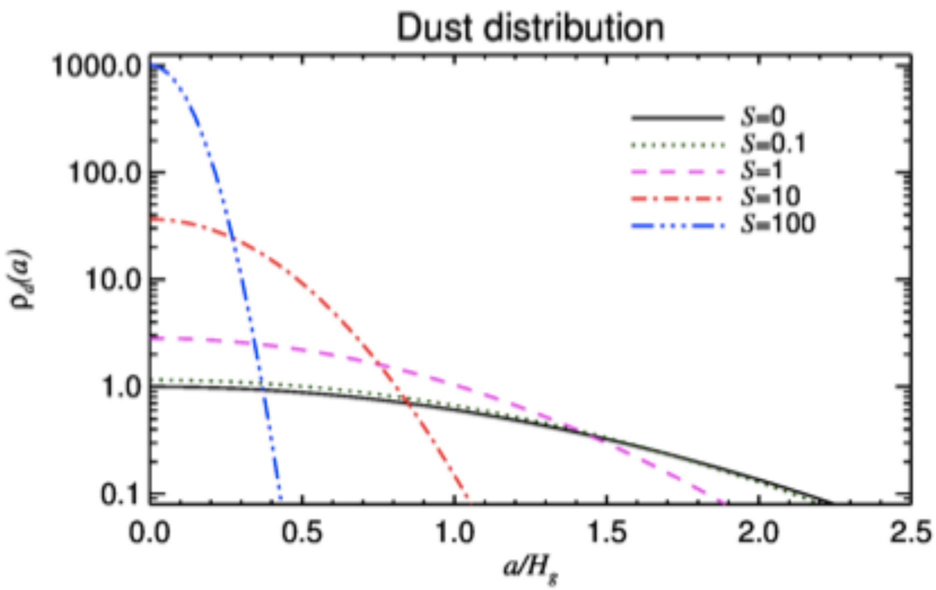


$$S = \frac{St}{\delta}$$

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

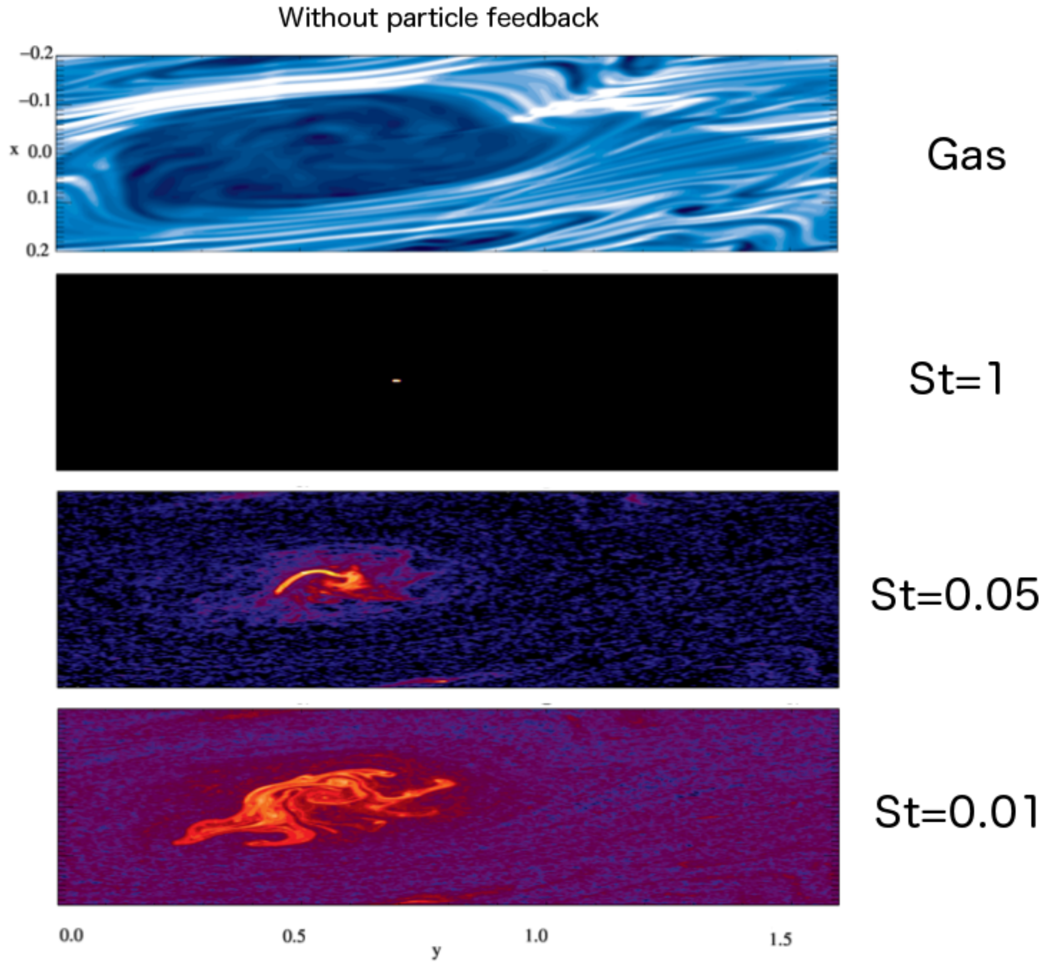
Lyra & Lin (2013)

Analytical vs Numerical



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

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



Derived quantities

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

Lyra & Lin (2013)

Gas distribution

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

Maximum dust density

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

Gas contrast

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

Dust contrast

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

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

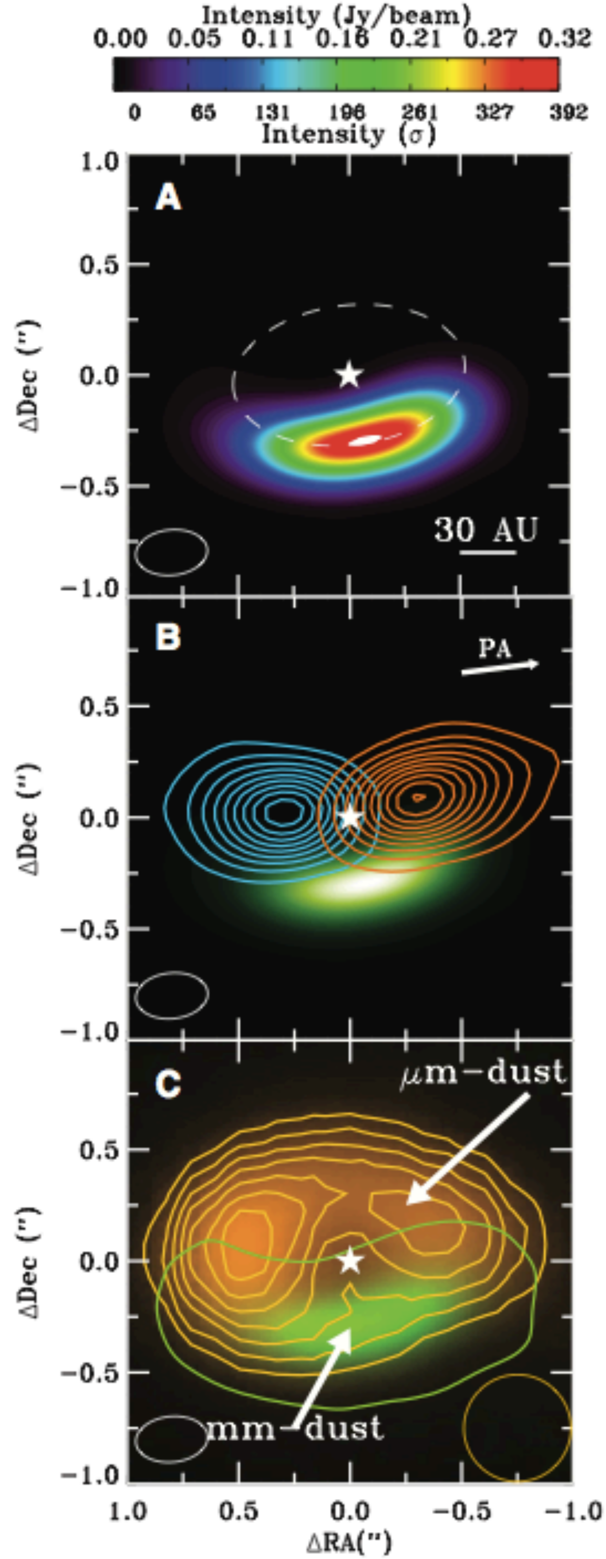
Derived parameters

S=4.8

Stokes number, St=0.008

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

Trapped mass: 11 M_{Earth}



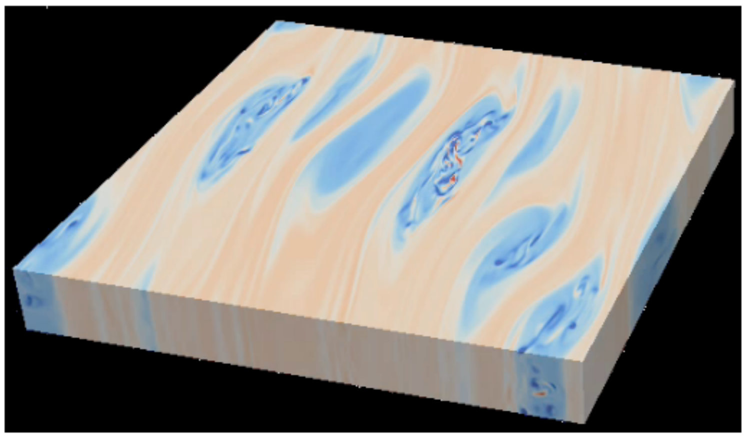
asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

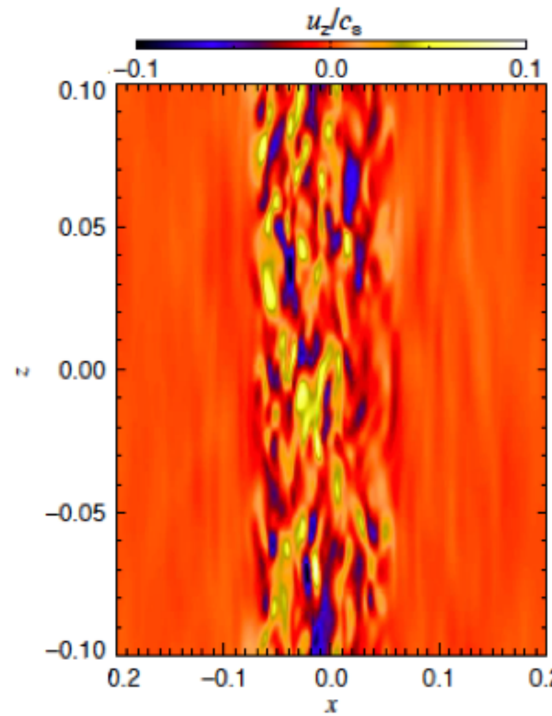
Micron-sized dust follows gas

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

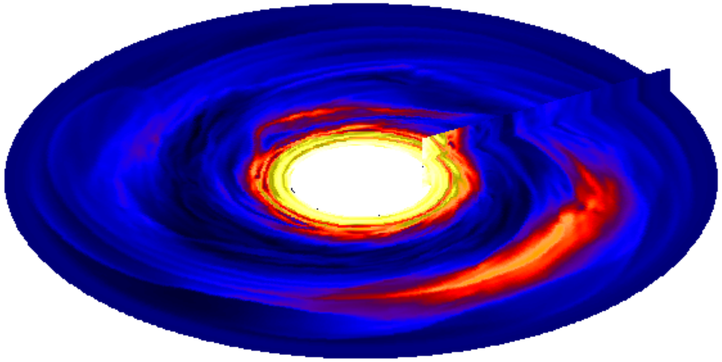
It seems to have the properties of vortices.

But… is it really a vortex?

Sustaining vortices in disks

Known mechanisms

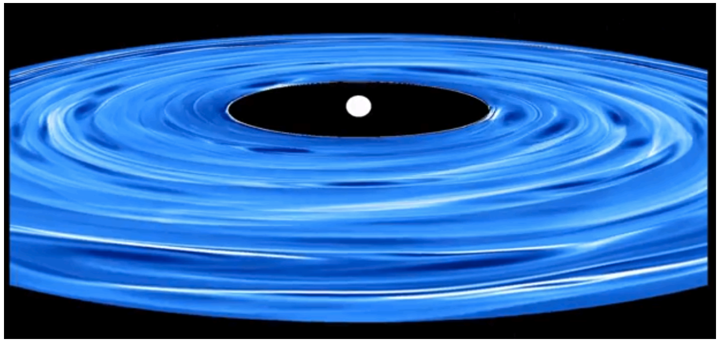
Rossby wave instability



Lovelace et al. (1999)
Lyra & Mac Low (2012)

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

Baroclinic instability



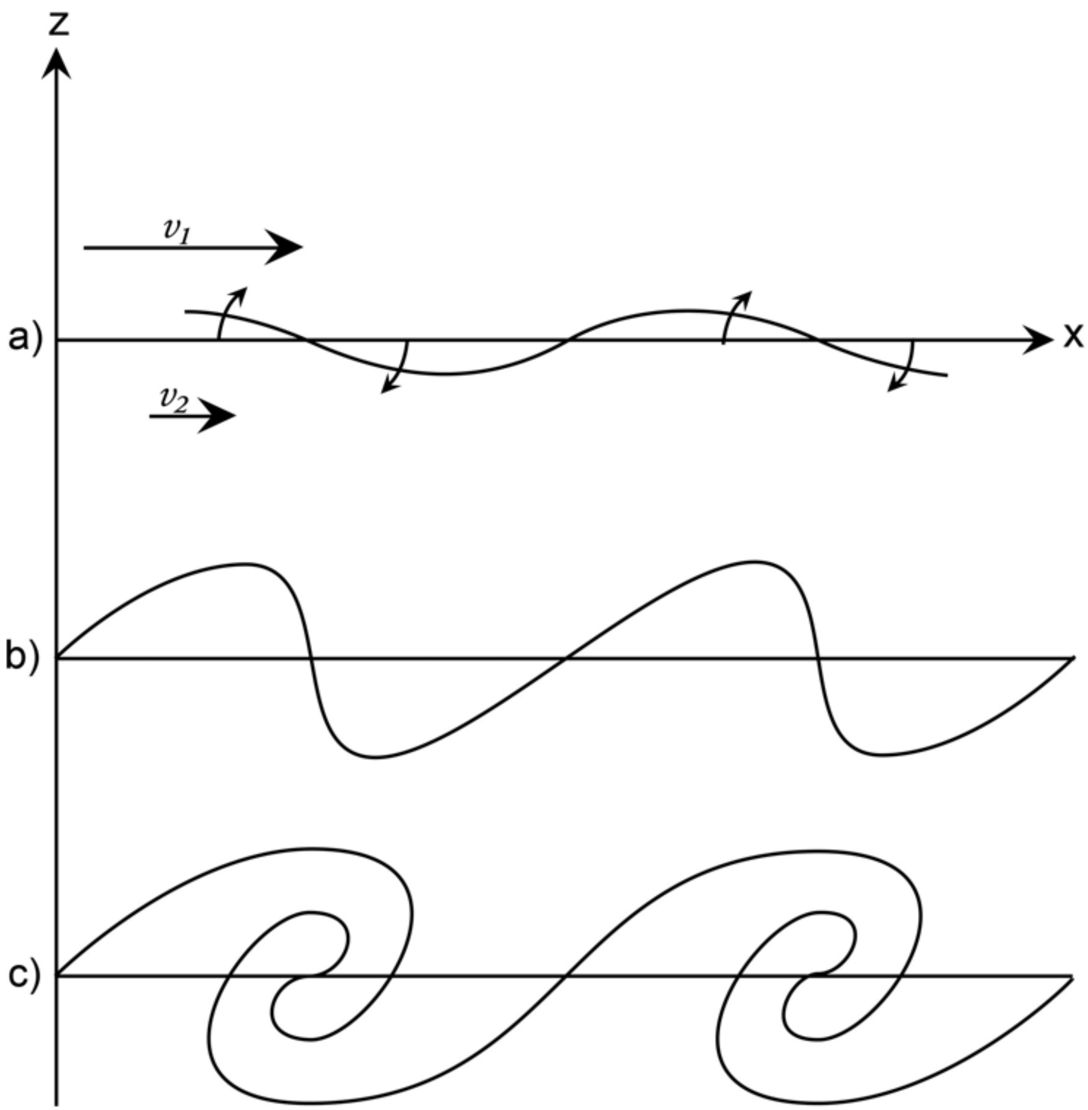
Klahr & Bodenheimer (2003)
Raettig et al. (2013)

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

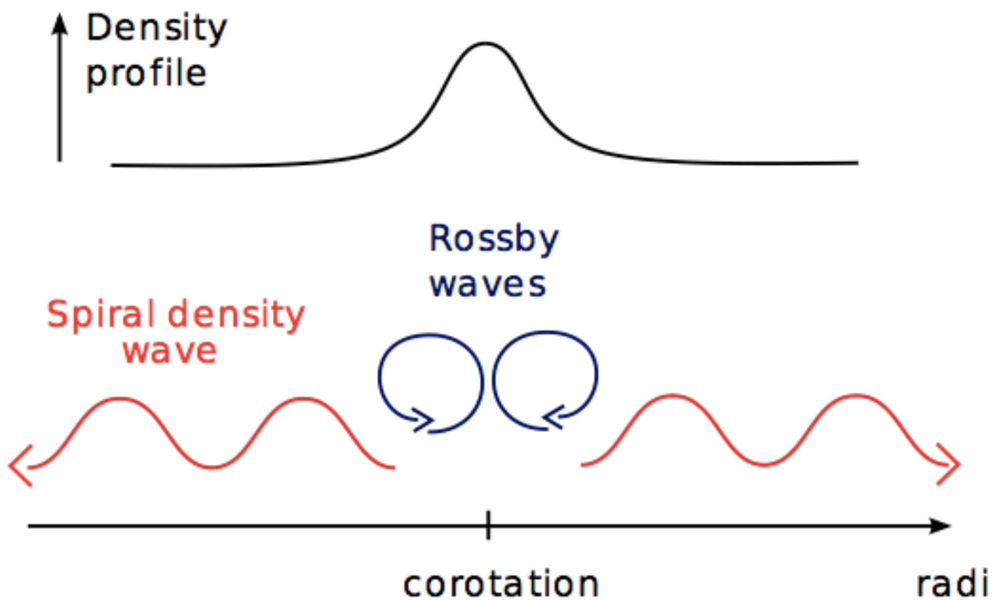
Sustaining vortices

Rossby Wave Instability

(or.... **Kelvin-Helmholtz** in rotating disks)



Rossby wave instability



Meheut et al (2010)

Needs a pressure bump.

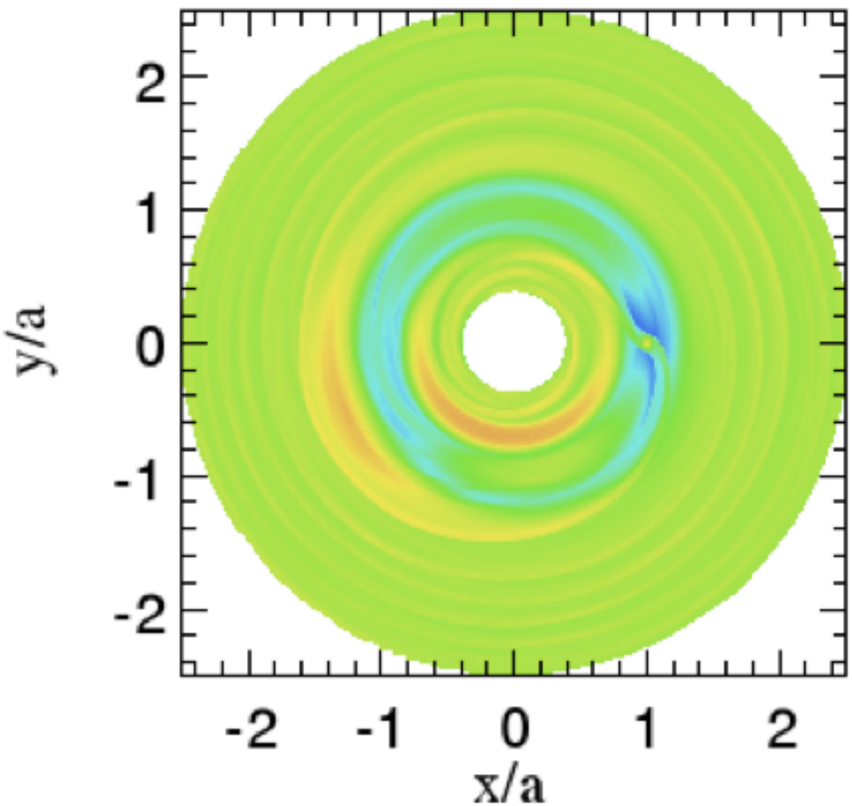
Rule of thumb:

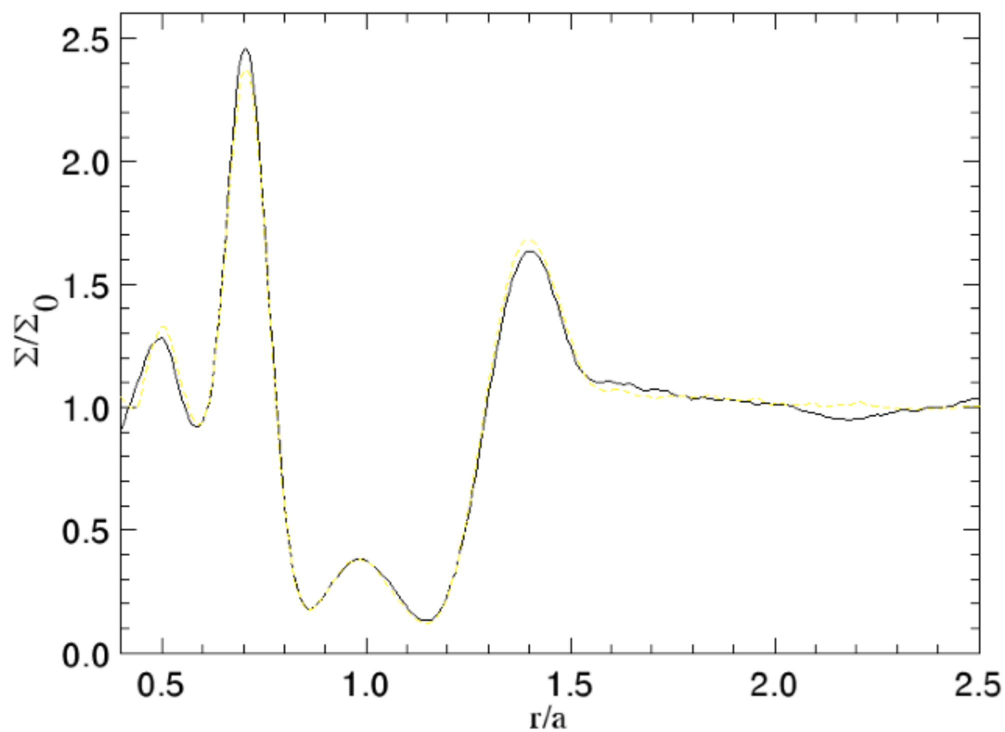
Modest **~30% local increase** yet SHARP **sharper than 2H.**

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

Planetary gap RWI

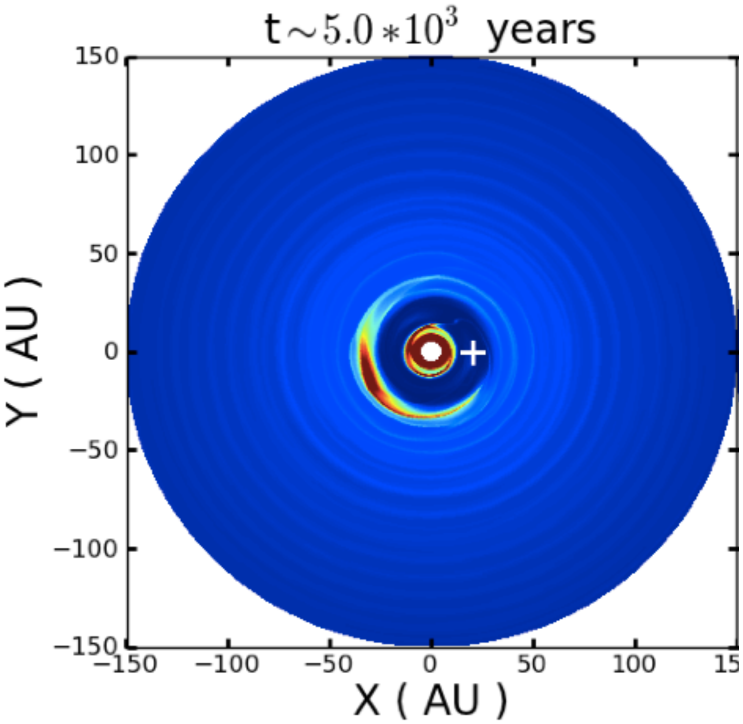
The gap walls are
sharp pressure transitions
and thus RWI-unstable.





de Val-Borro et al. (2007)

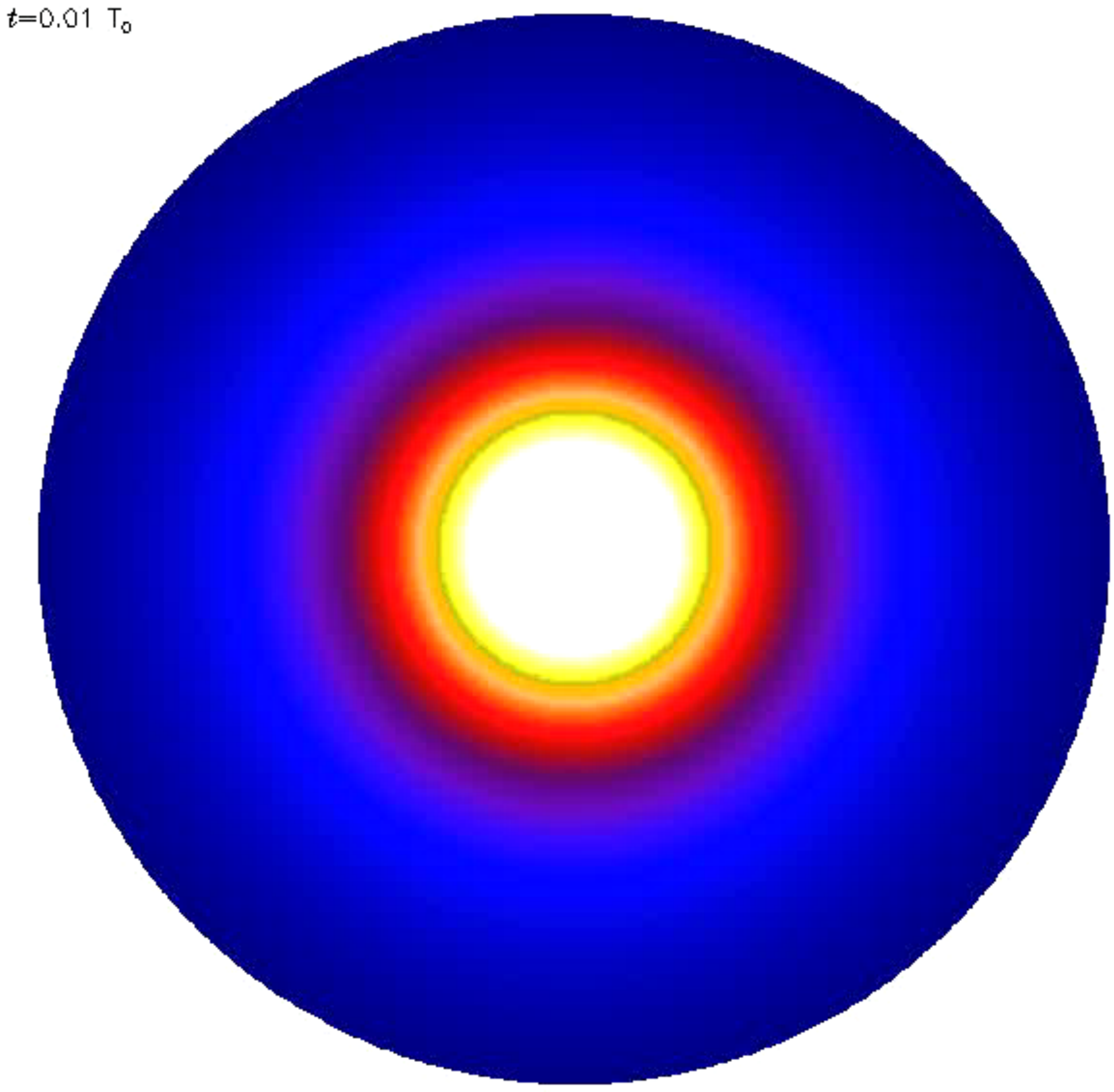
The dust trap is too far from the planet!



A gap in gas emission suggests a 10 MJ planet at **15-20 AU**.

The trap is centered at **63 AU**.

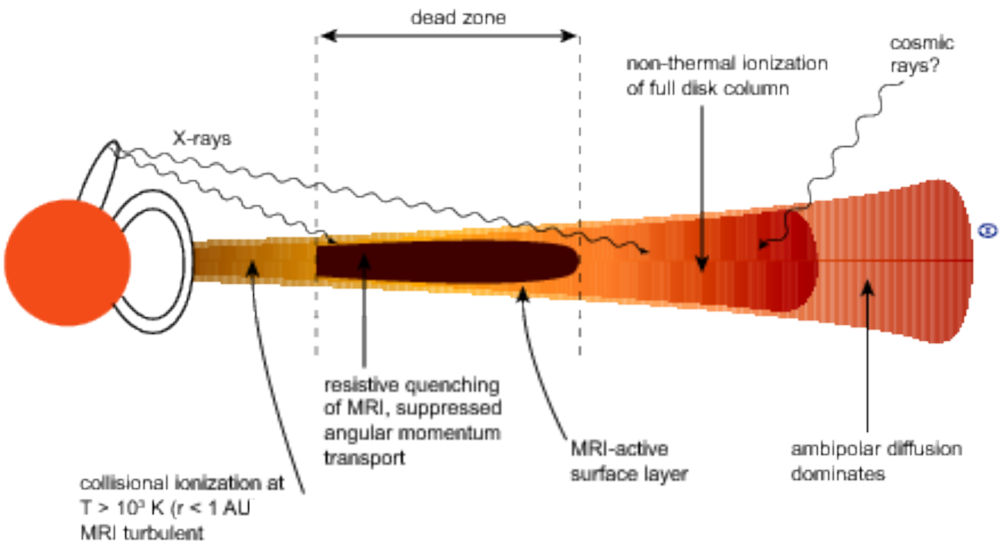
Dead zone edge RWI?



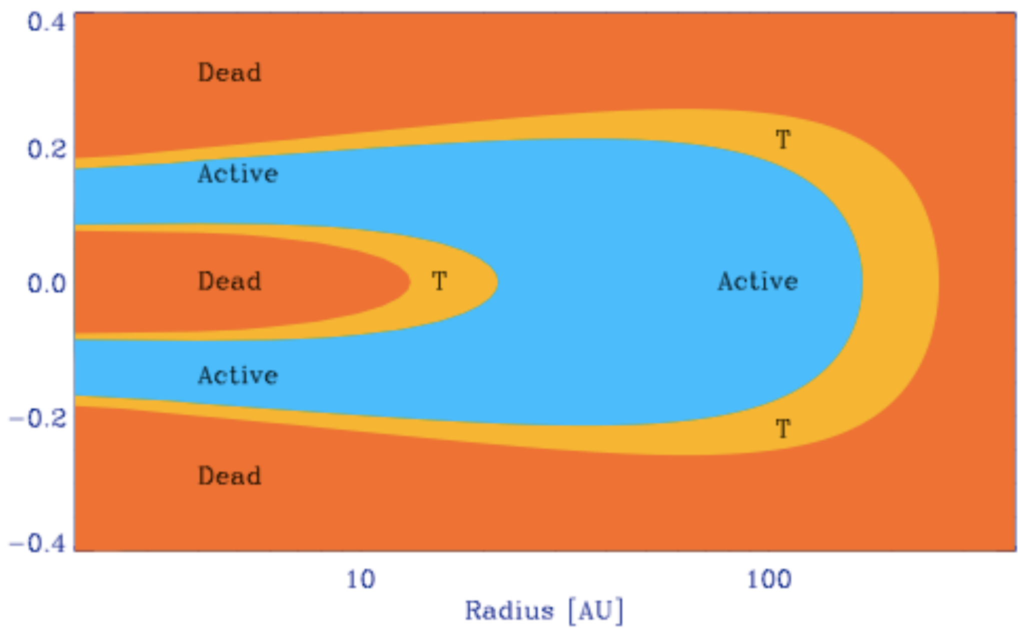
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Dead zone RWI fails!



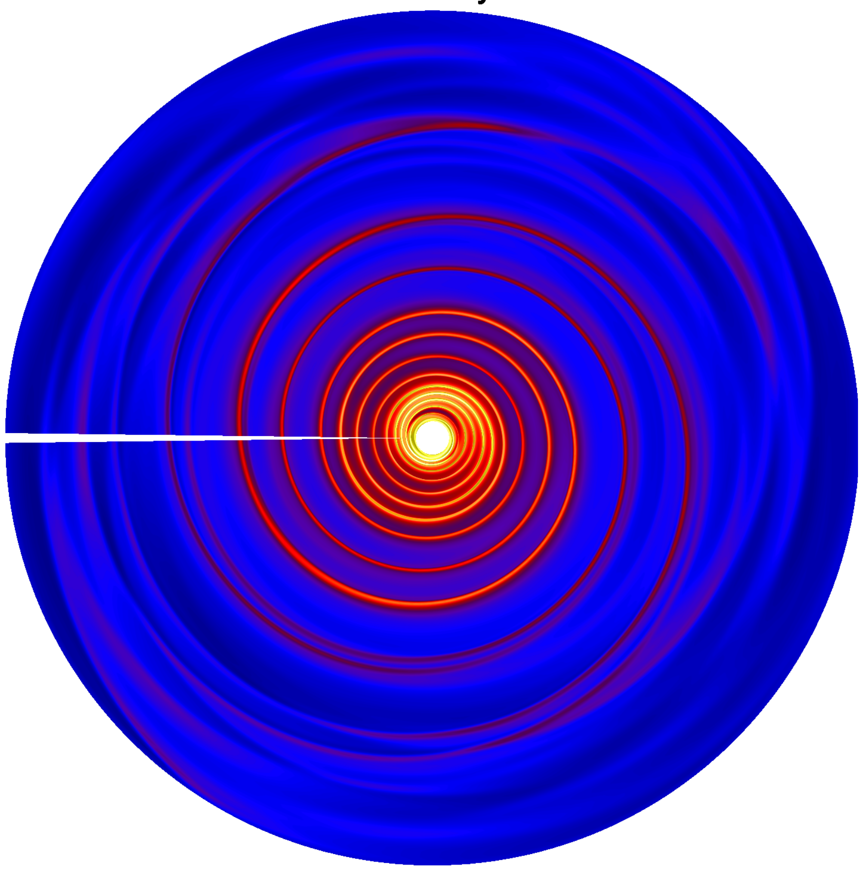
Armitage (2010)



Dzyurkevitch et al (2013)

The **outer** dead zone transition in ionization is
TOO SMOOTH
to generate an RWI-unstable bump.

Outer active zone/inner dead zone transition

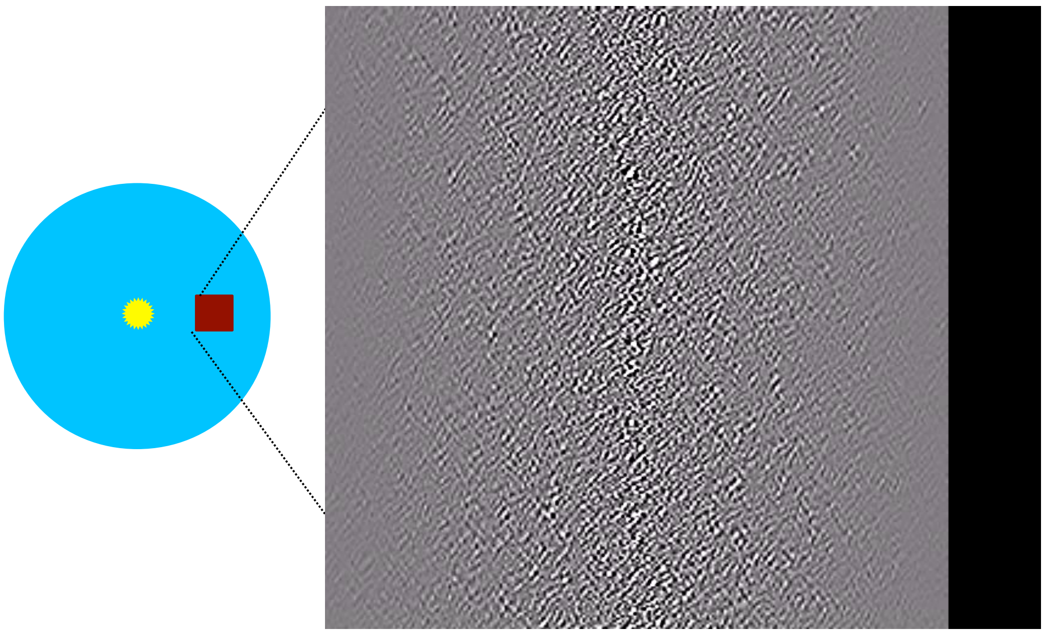


The **outer** active/dead zone transition is
TOO SMOOTH
to generate an RWI-unstable bump.

Waves from turbulent zone propagate into dead zone as **SPIRALS**.

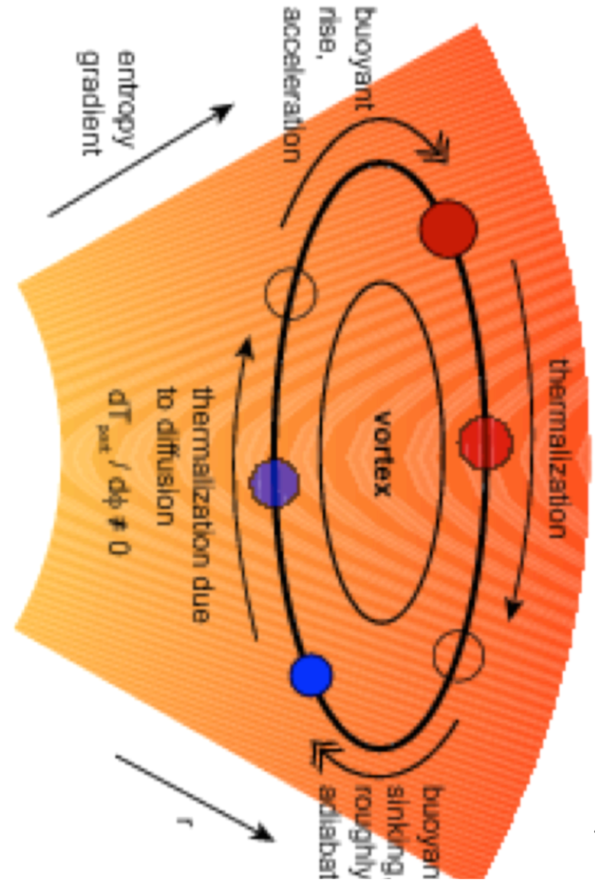
Baroclinic Instability - Excitation and self-sustenance of vortices

1. *Radial entropy gradient*
2. *Thermal diffusion*



Lyra & Klahr (2011)

Sketch of the
Baroclinic Instability



Armitage (2010

$$\frac{\partial \omega}{\partial t} = -(\boldsymbol{u}\cdot\nabla)\omega - \omega(\nabla\cdot\boldsymbol{u}) + (\omega\cdot\nabla)\boldsymbol{u} + \frac{1}{\rho^2}\nabla\rho\times\nabla p + \nu\nabla^2\omega$$

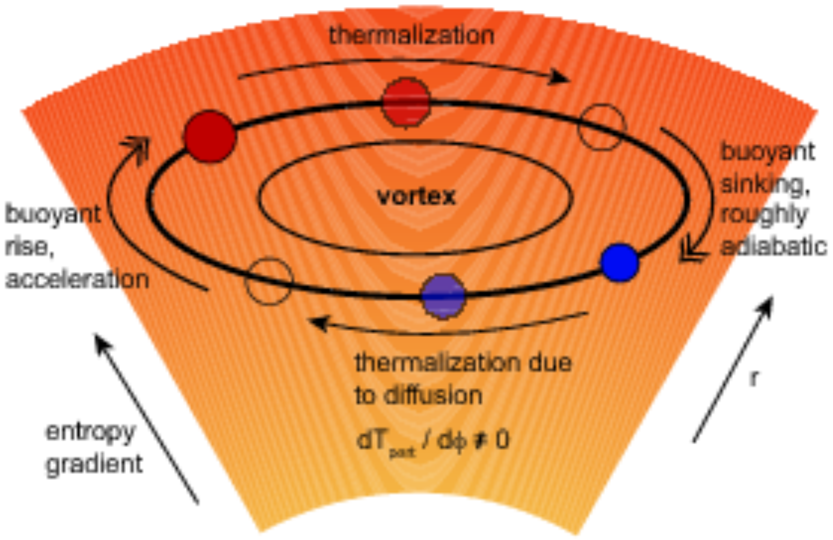
advection, compression, stretching, baroclinicity, dissipation

Baroclinic instability

1. Radial entropy gradient

2. Thermal diffusion

$$t_{\rm rad} = \frac{c_V \Sigma \tau_{\rm eff}}{6\sigma T^3}$$

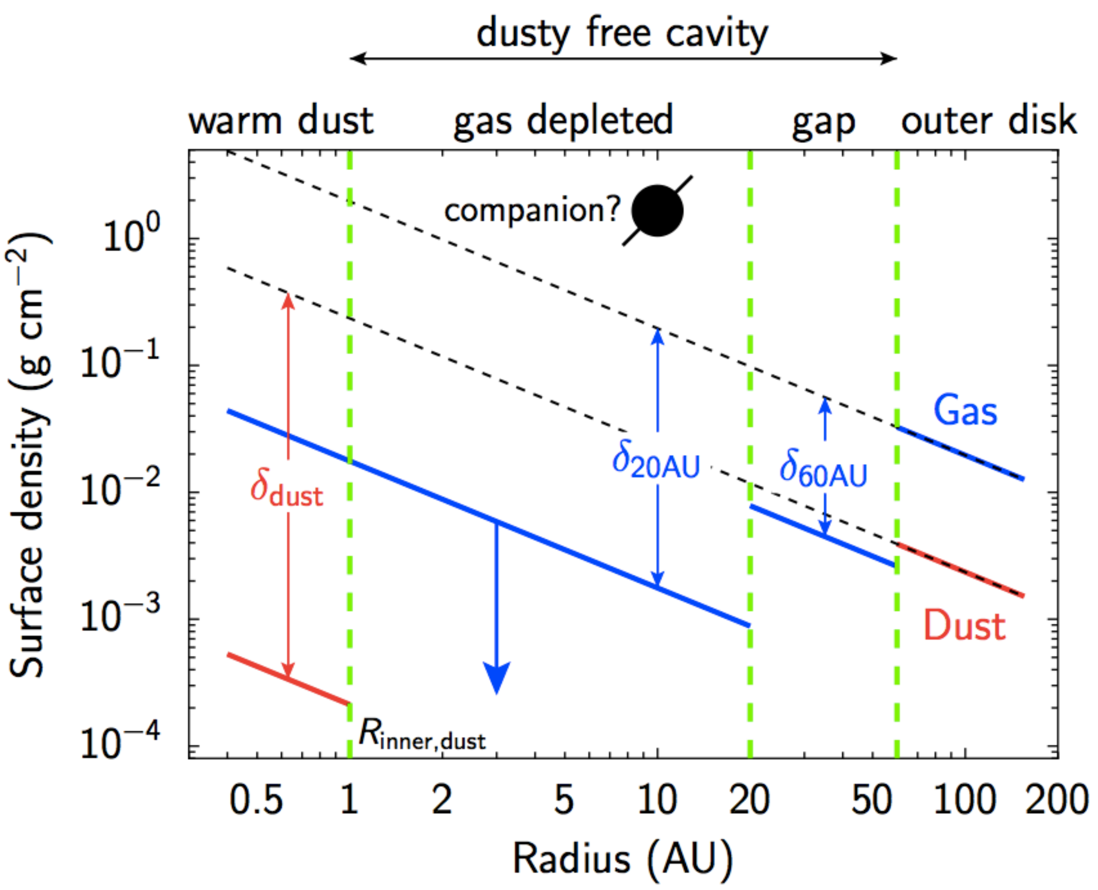


The thermal diffusion time for the gas in IRS Oph 48 is **0.1 orbits**.

Too close to isothermal for the baroclinic instability.

Addendum

The dust trap WAS too far from the planet!



New analysis (Bruderer et al. 2014)
better explains the system,
with a shallow gap at 60 AU,
consistent with a (~x) Neptune-mass planet.

Applying the model to Oph IRS 48

Observed parameters

Aspect ratio: 3.1

Dust contrast: 130

Temperature: 60K

Trapped mass: 9 M_{Earth}

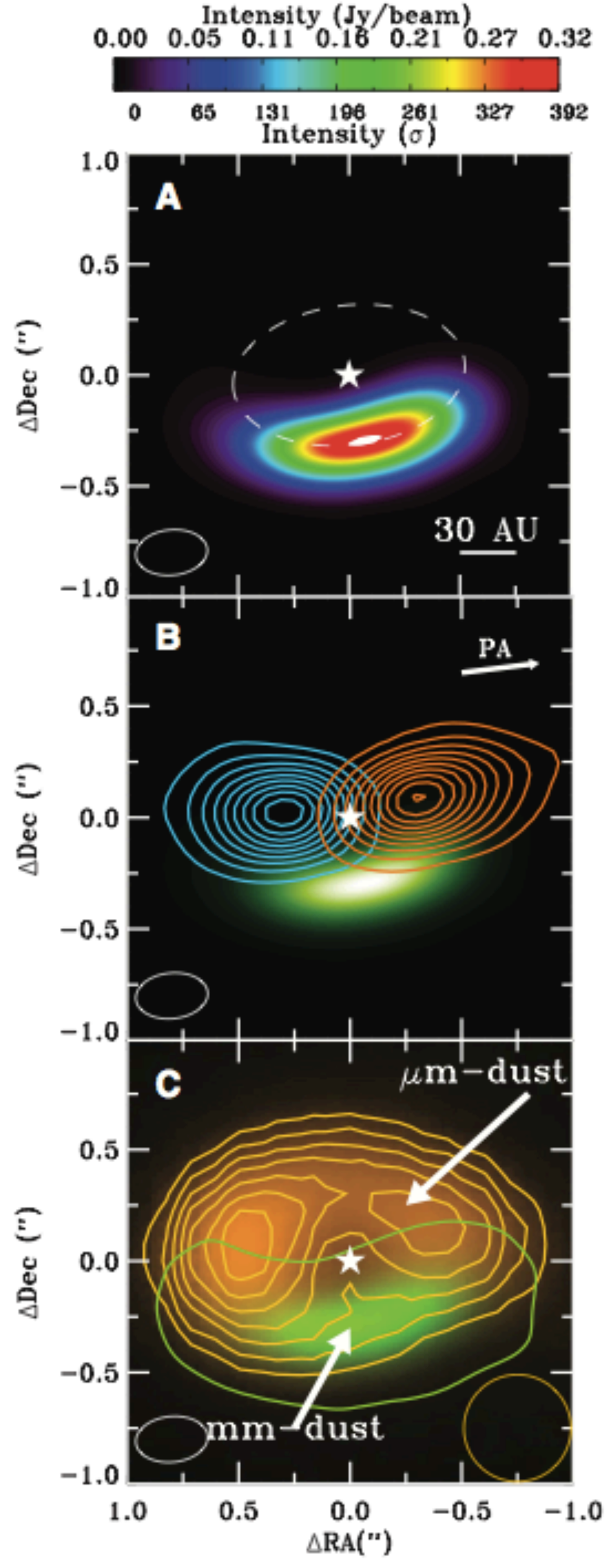
Derived parameters

S=4.8

Stokes number, St=1.5

$\delta = 0.26$, v_{rms} = 50% c_s

Trapped mass: 1 M_{Earth}



asymmetric mm dust at 63 AU

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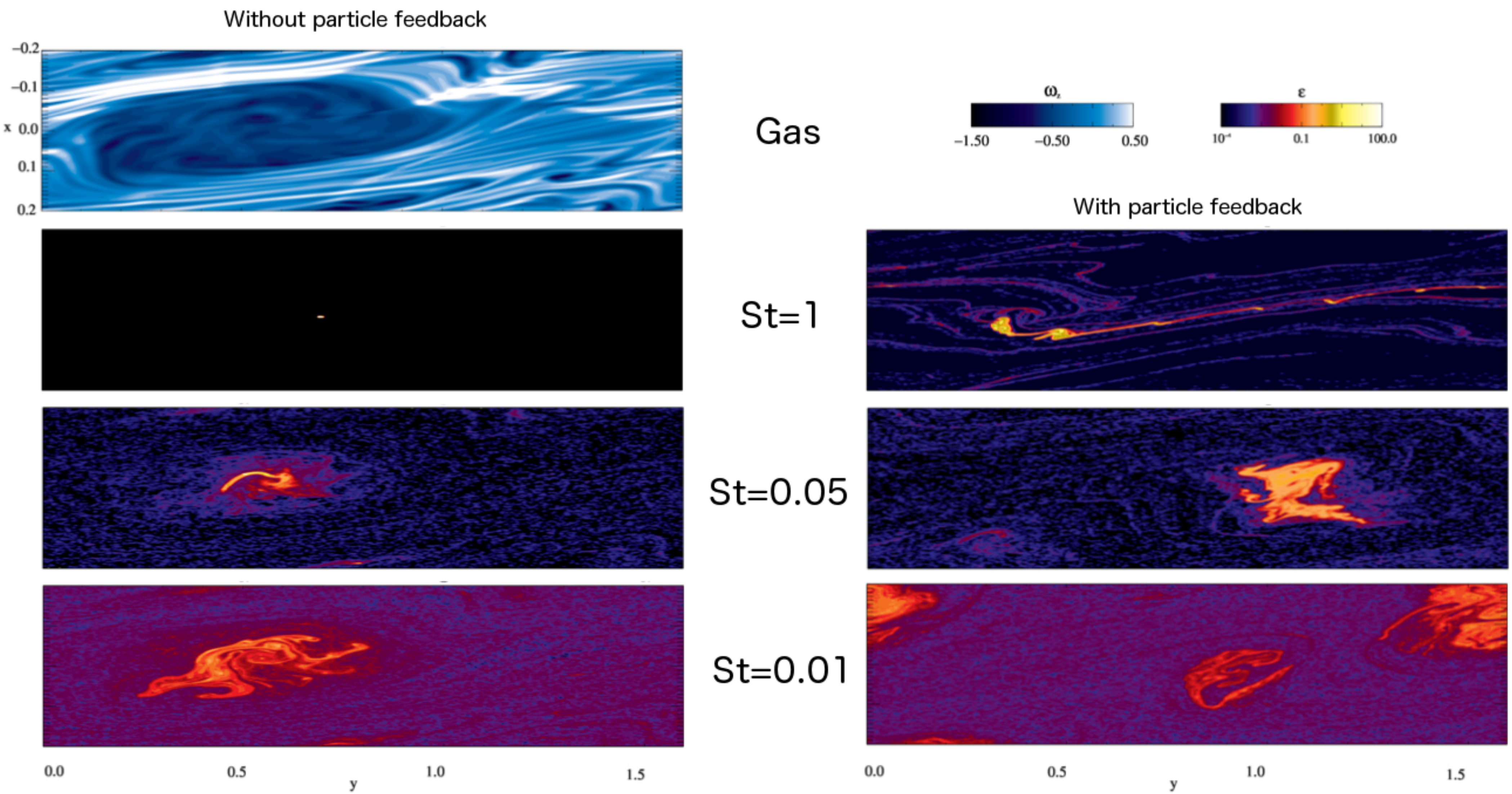
Lyra & Lin (2013)

Drag force backreaction



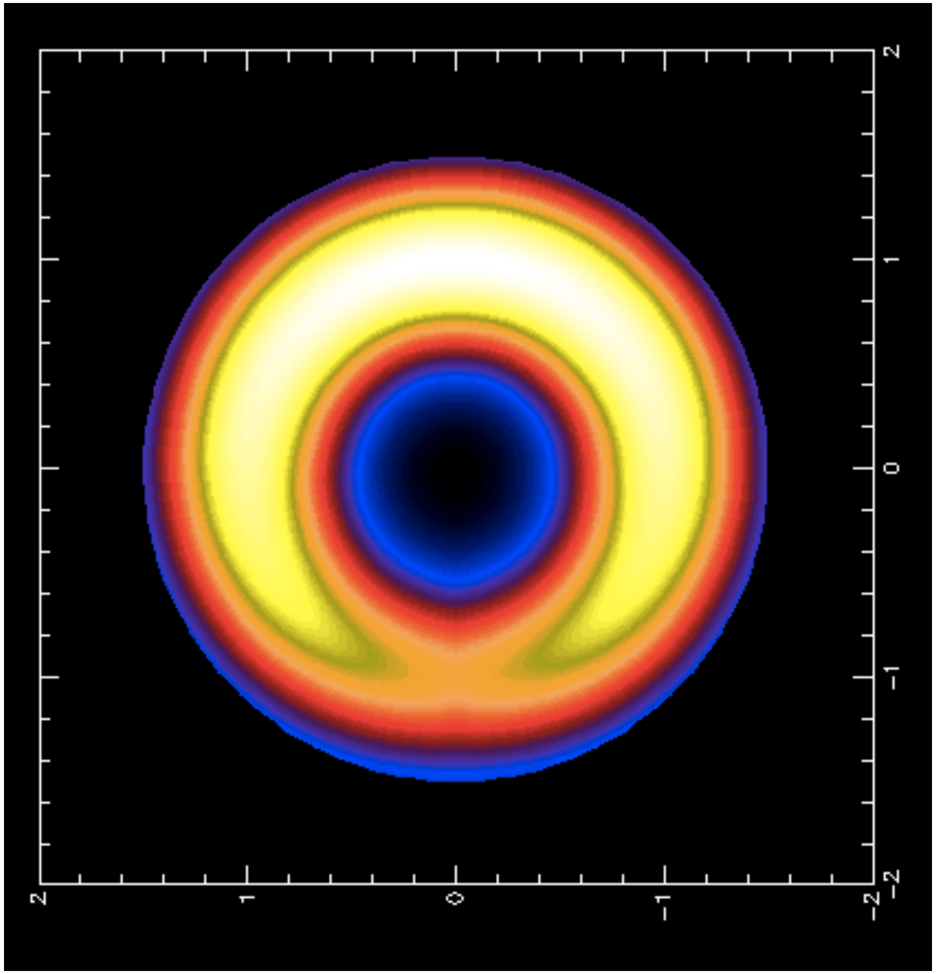
HD 142527

Observed parameters

Aspect ratio: 10

Dust contrast: 3

Temperature: 25K



Derived parameters

S=3.5

Stokes number, St=0.004

$\delta = 0.001$, $v_{rms} = 4\%\ c_s$

Conclusions

We derived an analytical solution for vortex trapping (Lyra & Lin 2013).

Planetary gap RWI by a few x Neptune mass-planet at 60AU is feasible.

The revised gas density (Bruderer et al. 2014) makes it harder to interpret the dust trap of Oph IRS 48 as a drag-diffusion equilibrium phenomenon.

Maybe drag force backreaction (?).