How shocks driven by high-mass planets can explain the spirals seen in transition disks

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Shocks driven by high-mass planets

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ON SHOCKS DRIVEN BY HIGH-MASS PLANETS IN RADIATIVELY INEFFICIENT DISKS. I. TWO-DIMENSIONAL GLOBAL DISK SIMULATIONS

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ABSTRACT

Recent observations of gaps and non-axisymmetric features in the dust distributions of transition disks have been interpreted as evidence of embedded massive protoplanets. However, comparing the predictions of planet–disk interaction models to the observed features has shown far from perfect agreement. This may be due to the strong approximations used for the predictions. For example, spiral arm fitting typically uses results that are based on low-mass planets in an isothermal gas. In this work, we describe two-dimensional, global, hydrodynamical simulations of disks with embedded protoplanets, with and without the assumption of local isothermality, for a range of planet-to-star mass ratios 1–10 M_J for a 1 $M_\odot$ star. We use the Pencil Code in polar coordinates for our models. We find that the inner and outer spiral wakes of massive protoplanets ($M \gtrsim 5\,M_J$) produce significant shock heating that can trigger buoyant instabilities. These drive sustained turbulence throughout the disk when they occur. The strength of this effect depends strongly on the mass of the planet and the thermal relaxation timescale; for a 10 M_J planet embedded in a thin, purely adiabatic disk, the spirals, gaps, and vortices typically associated with planet–disk interactions are disrupted. We find that the effect is only weakly dependent on the initial radial temperature profile. The spirals that form in disks heated by the effects we have described may fit the spiral structures observed in transition disks better than the spirals predicted by linear isothermal theory.

Key words: hydrodynamics – planet–disk interactions – planets and satellites: formation – protoplanetary disks – shock waves – turbulence

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ON SHOCKS DRIVEN BY HIGH-MASS PLANETS IN RADIATIVELY INEFFICIENT DISKS. II. THREE-DIMENSIONAL GLOBAL DISK SIMULATIONS.

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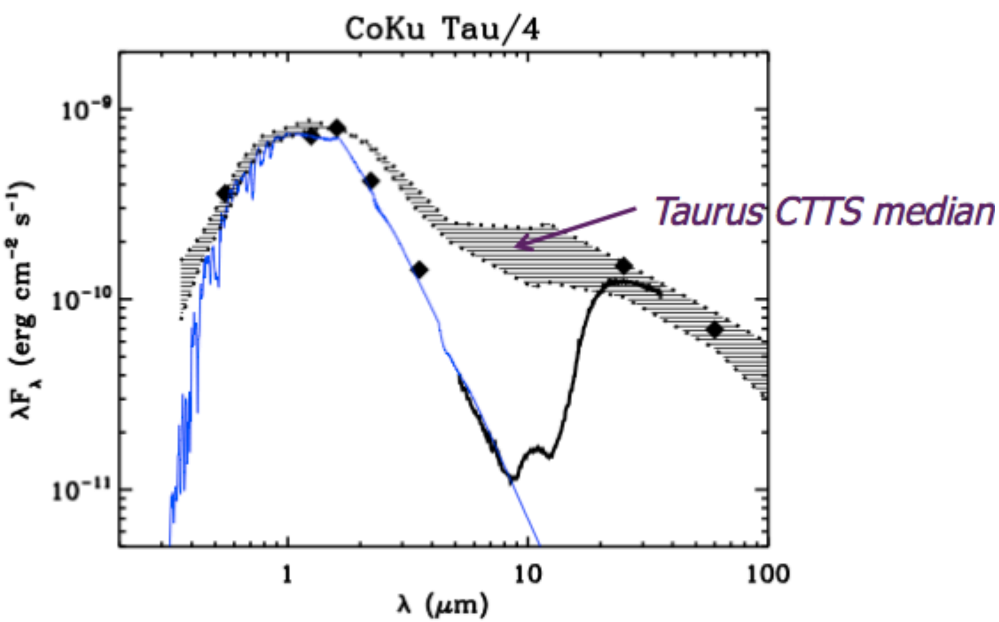
Draft version

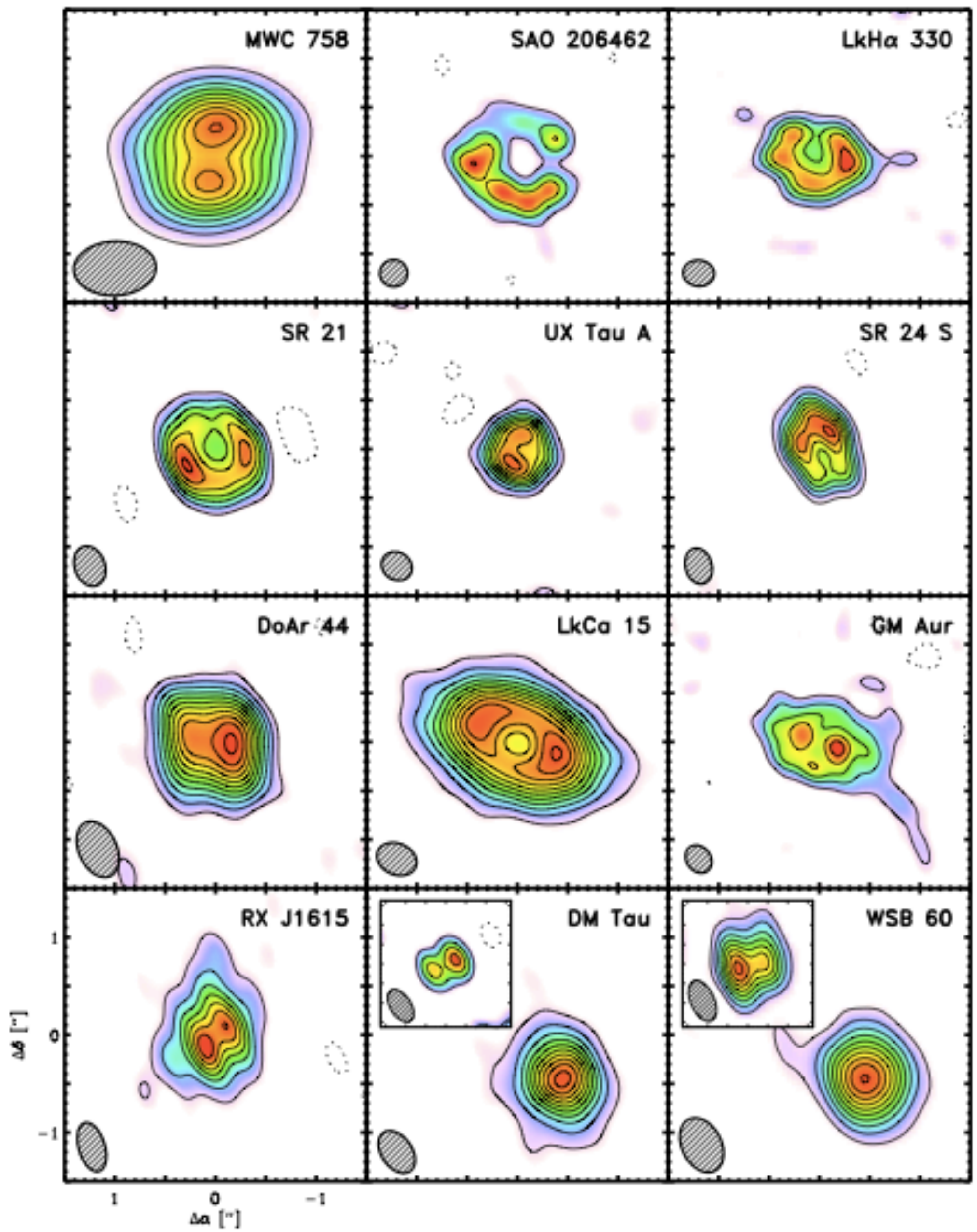
ABSTRACT

Recent high-resolution, near-infrared images of protoplanetary disks have shown that these disks often present spiral features. Spiral arms are among the structures predicted decades ago by numerical simulations of disk-planet interaction and thus it is tempting to suspect that planetary perturbers are responsible for the observed signatures. However, such interpretation is not free of problems. The spirals are found to have large pitch angles, and in at least one case the spiral feature appears effectively unpolarized, which implies thermal emission at roughly 1000 K. We have recently shown in two-dimensional models that shock dissipation in the supersonic wake of high-mass planets can lead to significant heating if the disk is sufficiently adiabatic. In this paper we extend this analysis to three dimensions in thermodynamically evolving disks. We use the Pencil Code in spherical coordinates for our models, with a prescription for thermal cooling based on the optical depth of the local vertical gas column. We use a $5M_J$ planet, and show that shocks in the Lindblad lobes around the planet heat the gas to substantially higher temperatures than the ambient disk gas at that radius. The gas is accelerated vertically away from the midplane by the shocks to form shock bores, and the gas falling back toward the midplane breaks up into a turbulent surf near the Lindblad resonances. This turbulence, although localized, has high α values, reaching 0.05 in the inner Lindblad resonance, and 0.1 in the outer one. We also find evidence that the disk regions heated up by the planetary shocks eventually becomes superadiabatic, generating convection far from the planet's orbit.

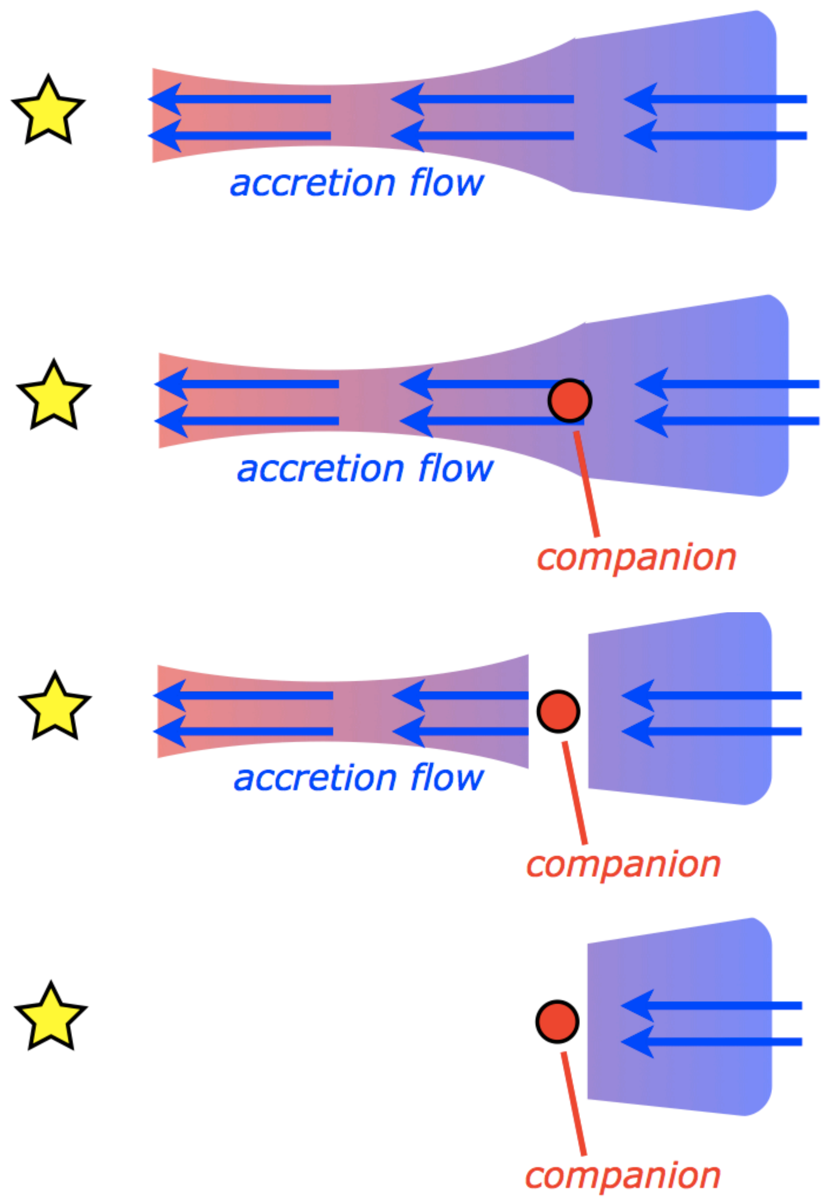
Subject headings: hydrodynamics — planet-disk interactions — planets and satellites: formation — protoplanetary disks — shock waves — turbulence

Transition Disks: Disks with missing hot dust.

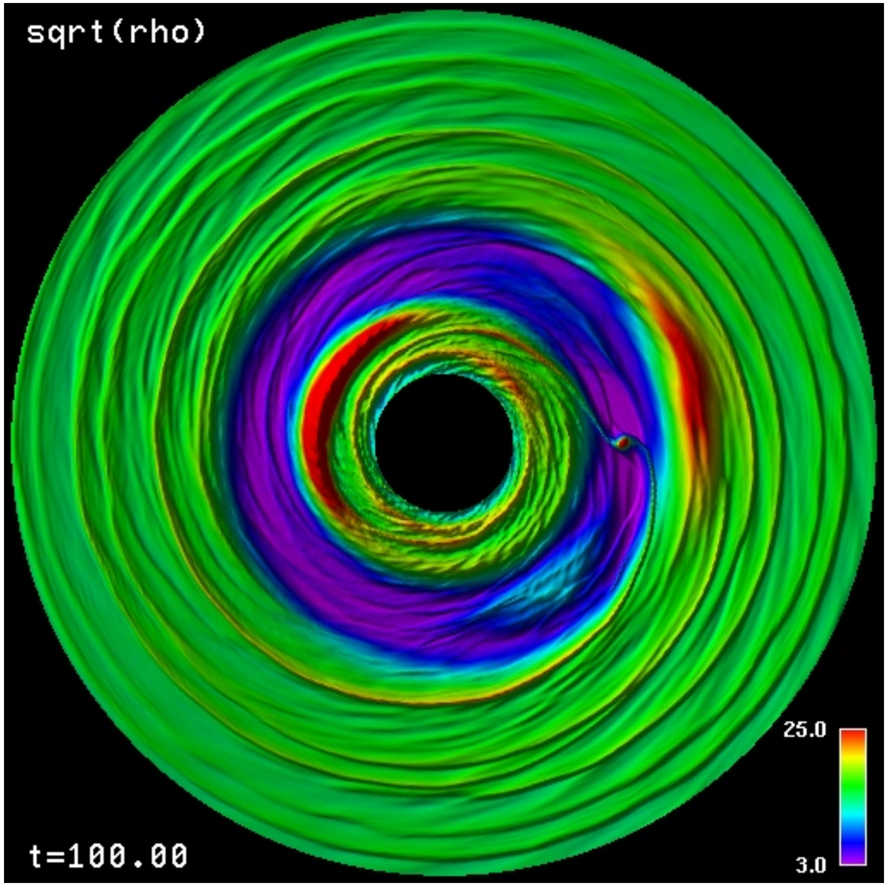


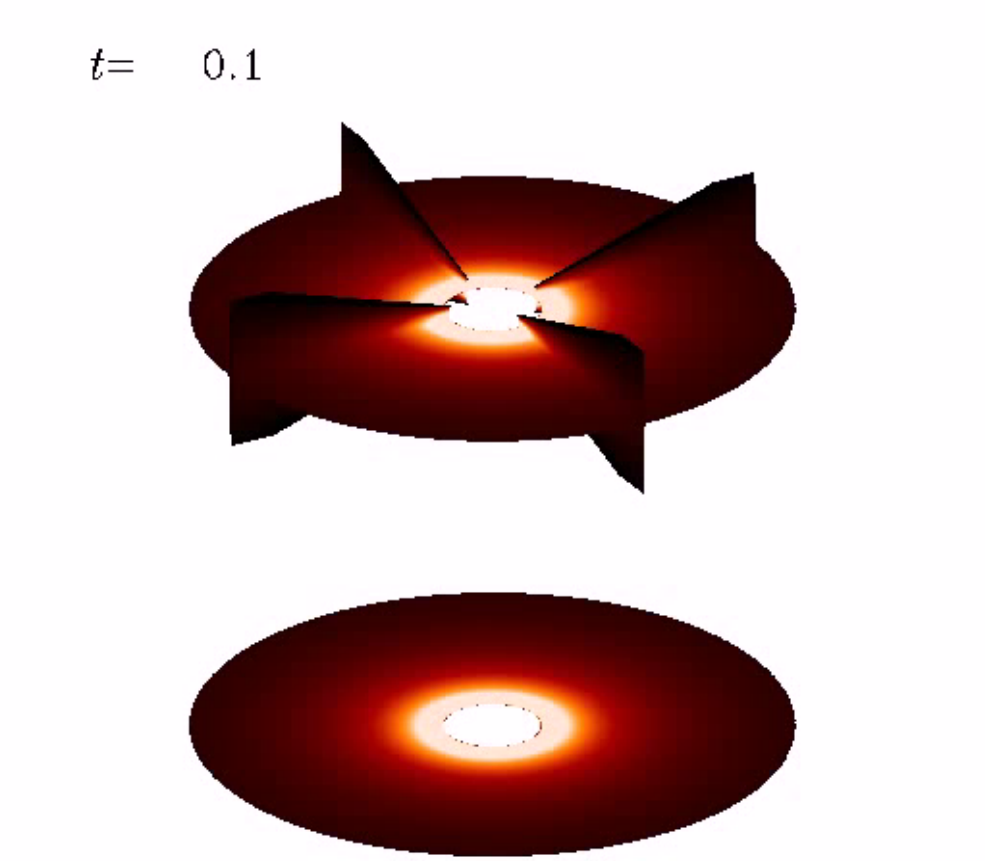


Planetary companion



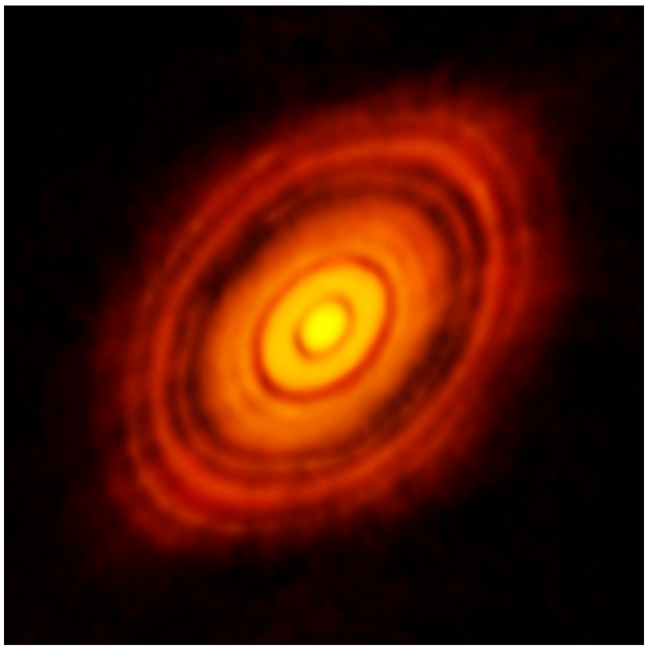
Planet-disk interaction: gaps, spirals, and vortices.



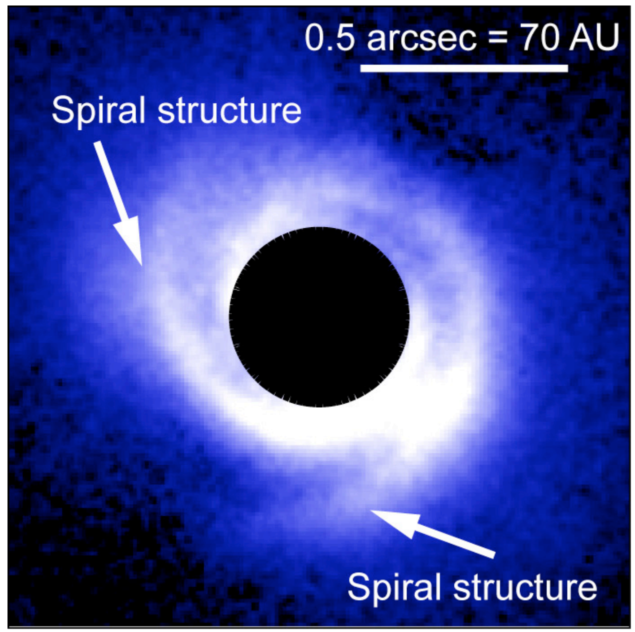


Lyra (2009)

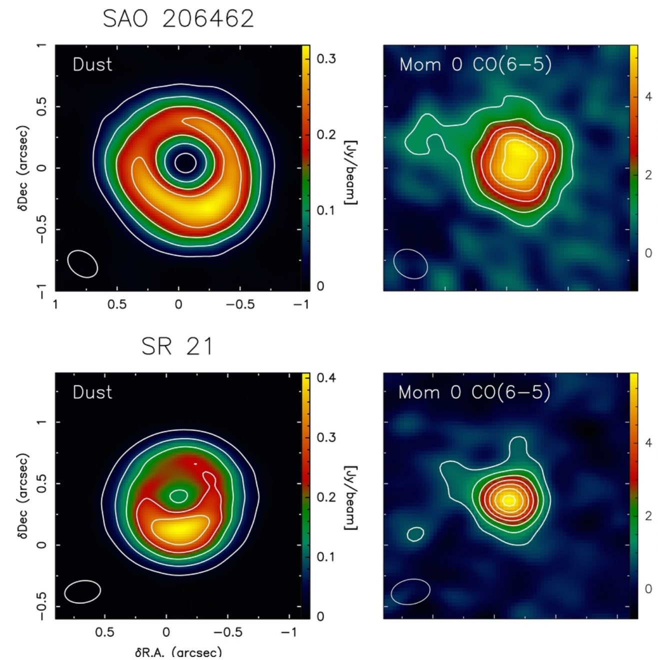
Observational evidence: gaps, spirals, and vortices



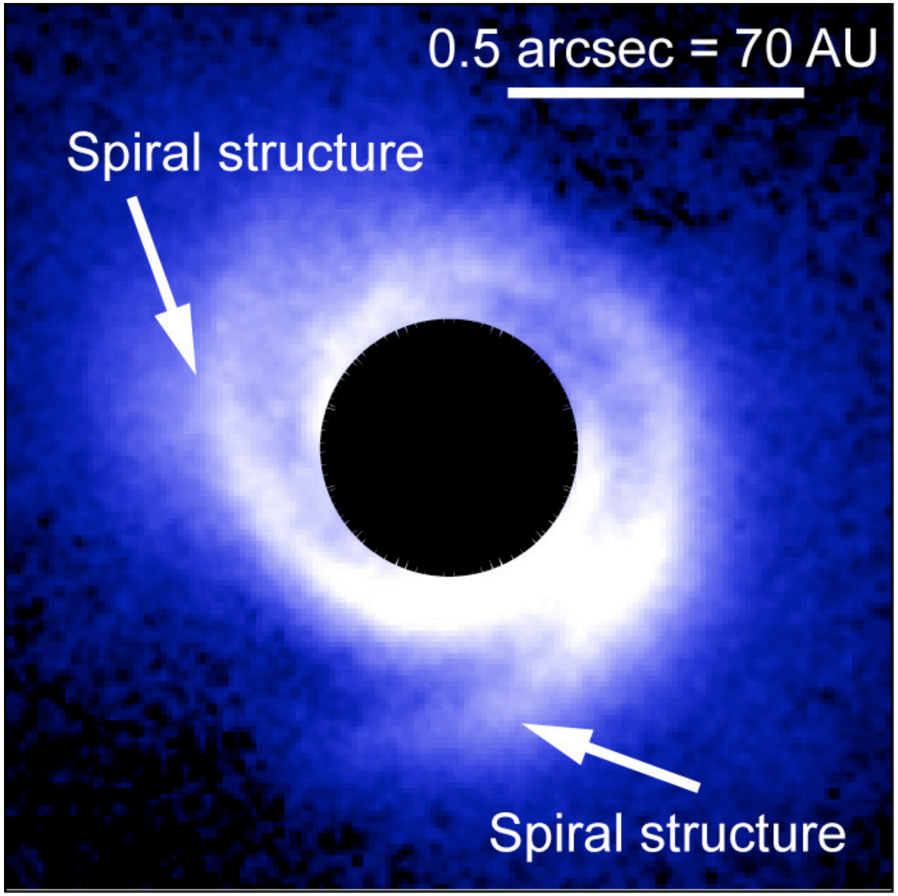
The ALMA Partnership et al. (2015)



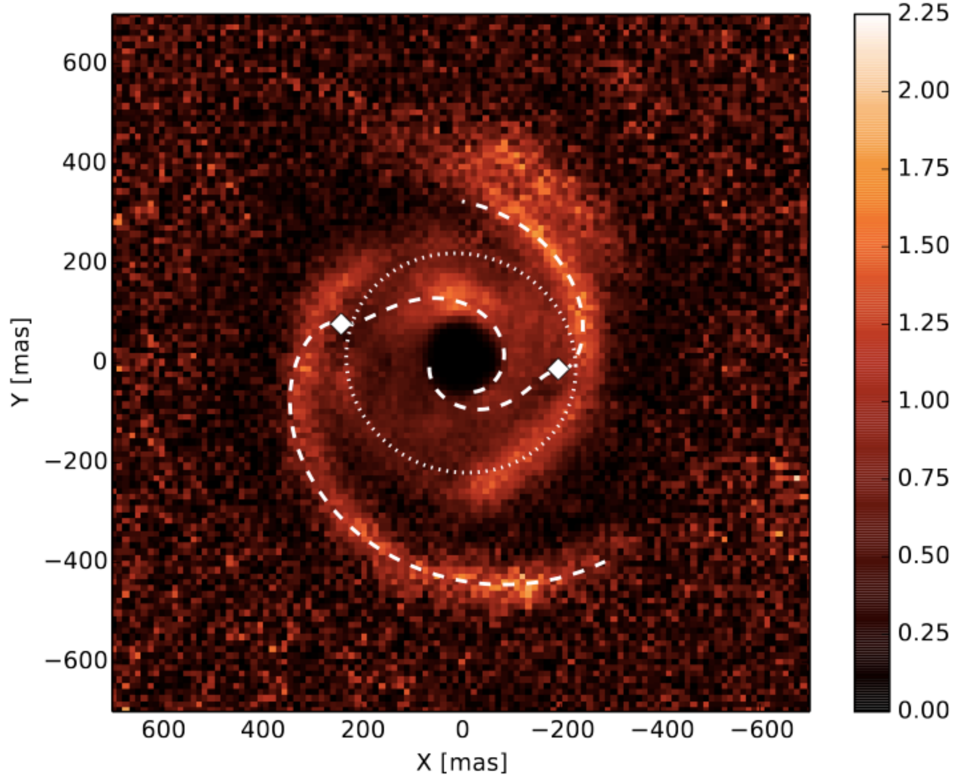
Muto et al. (2012)



Observational evidence: Spirals



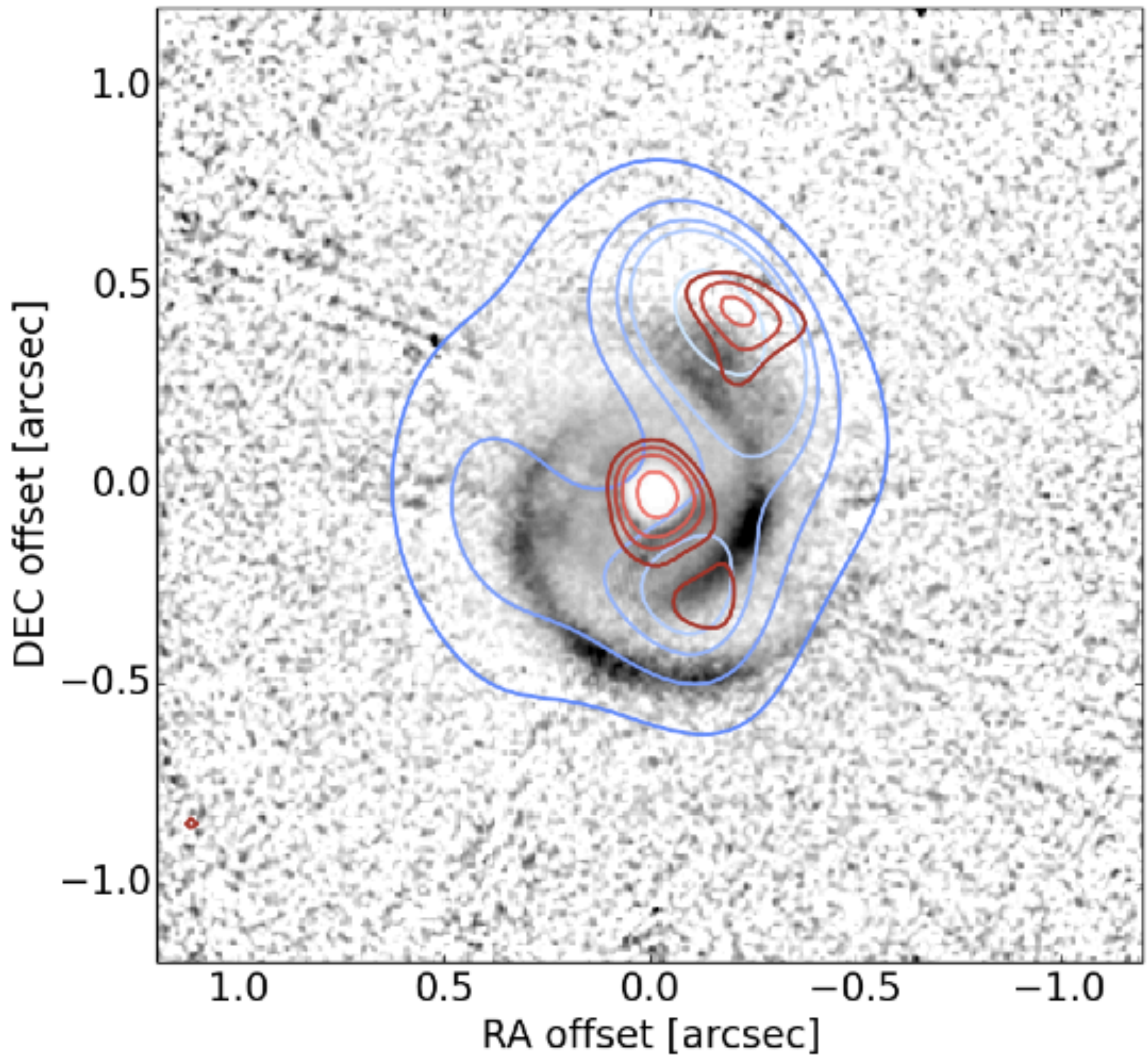
Muto et al. (2012)



Benisty et al. (2015)

SPHERE-ALMA-VLA overlay of MWC 758

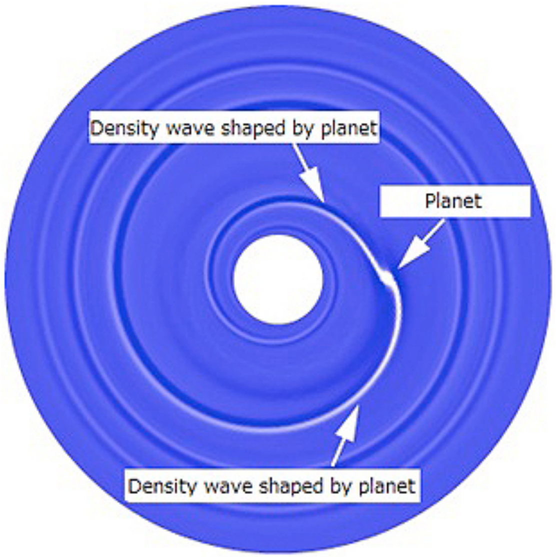
SPHERE
ALMA
VLA



Marino et al., (2015)

Spiral arm fitting leads to problems

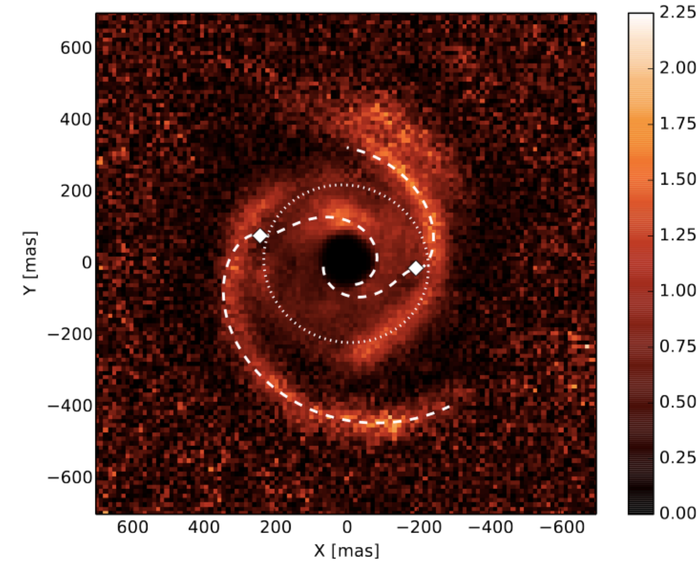
Analytical spiral fit



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

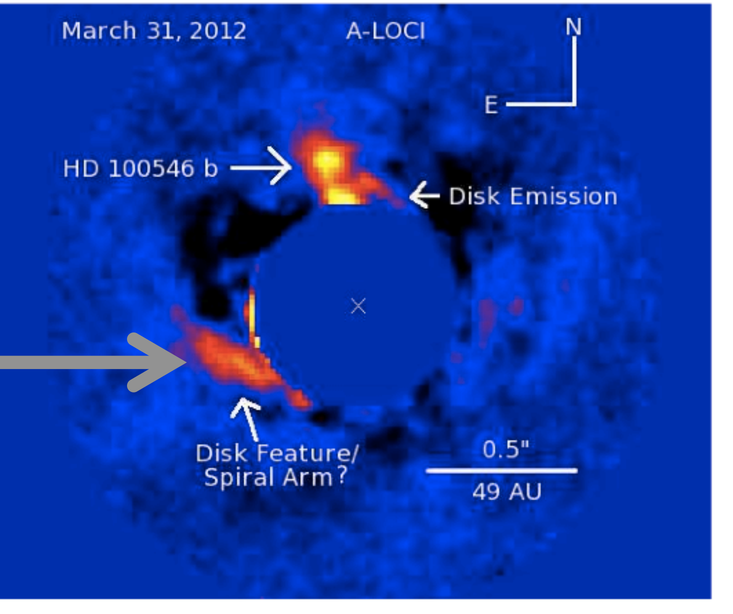
Rafikov (2002)
Muto et al. (2012)

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



Benisty et al. (2015)

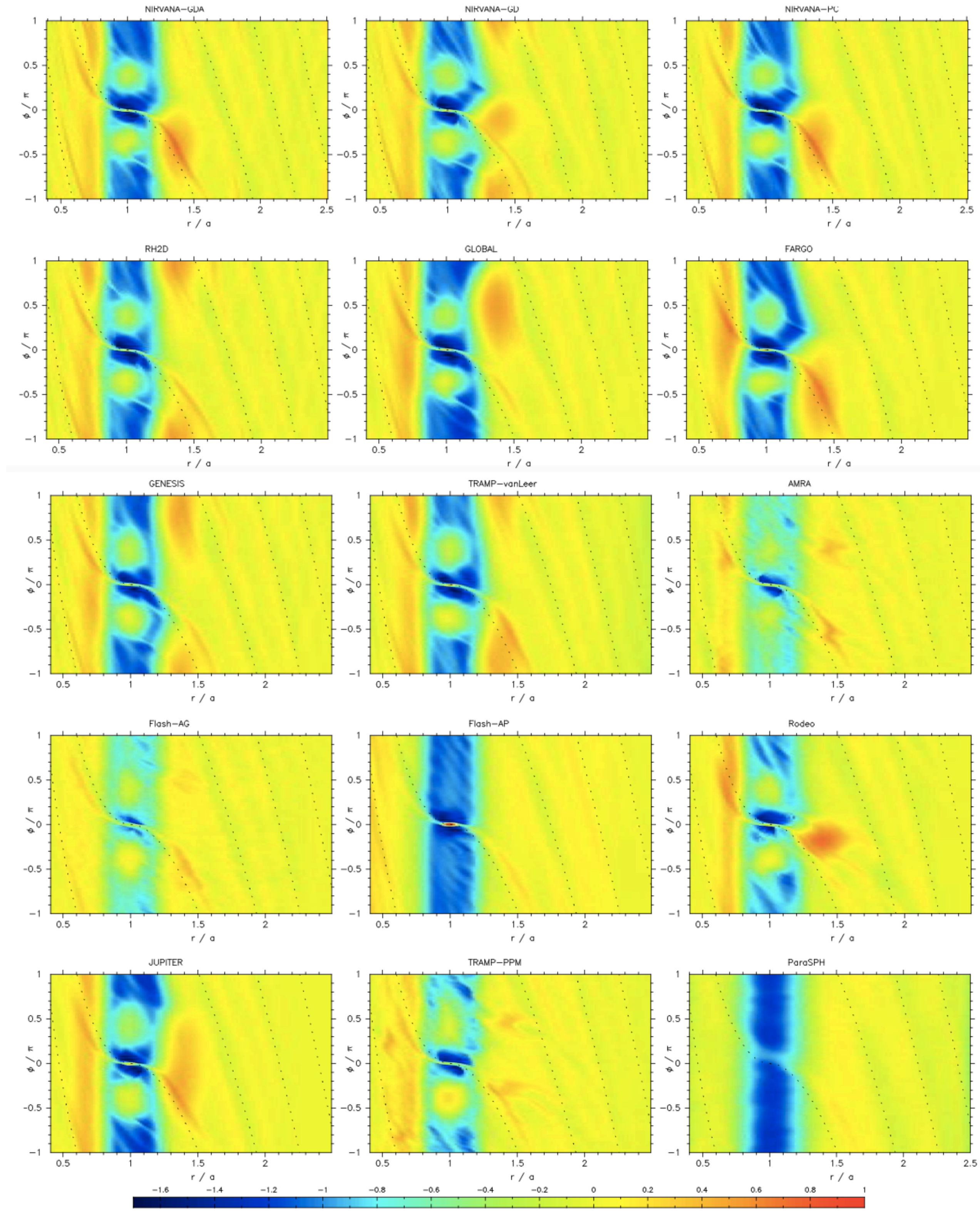
Spiral has little polarization. Must be thermal emission at 1000K.



Currie et al. (2014)

The code comparison project of 2006 (de Val-Borro et al. 2006)

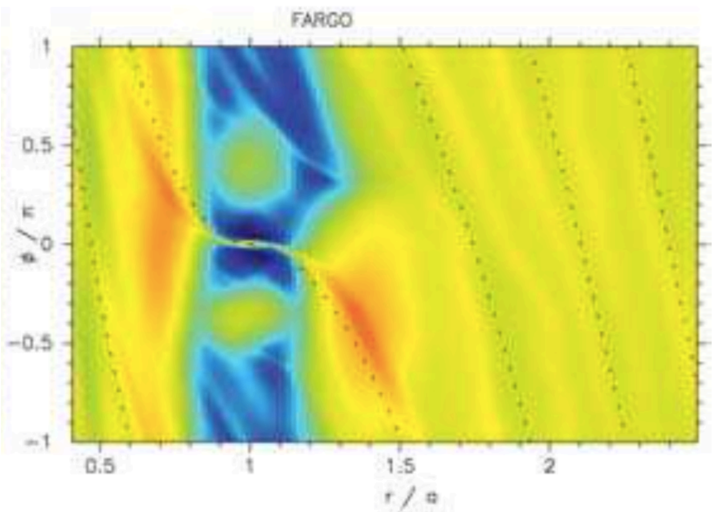
Problem of choice:
2D ‘vanilla’ planet-disk interaction.



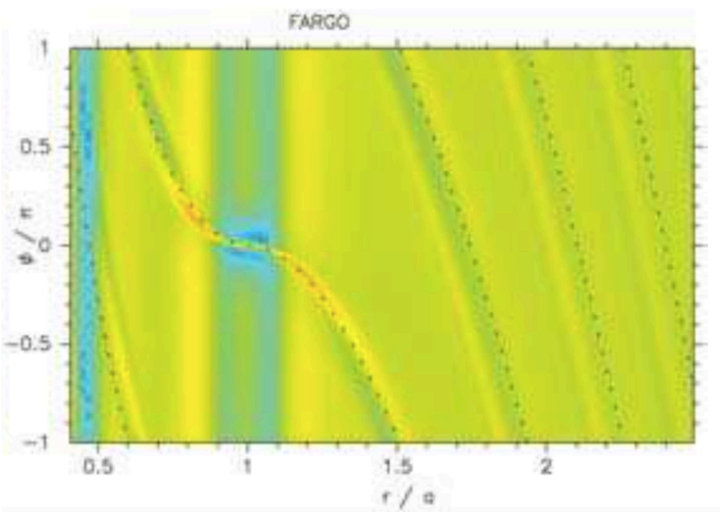
The “hot spiral problem” has never been a problem

Wakes of high-mass planets are not sonic, but *supersonic*.

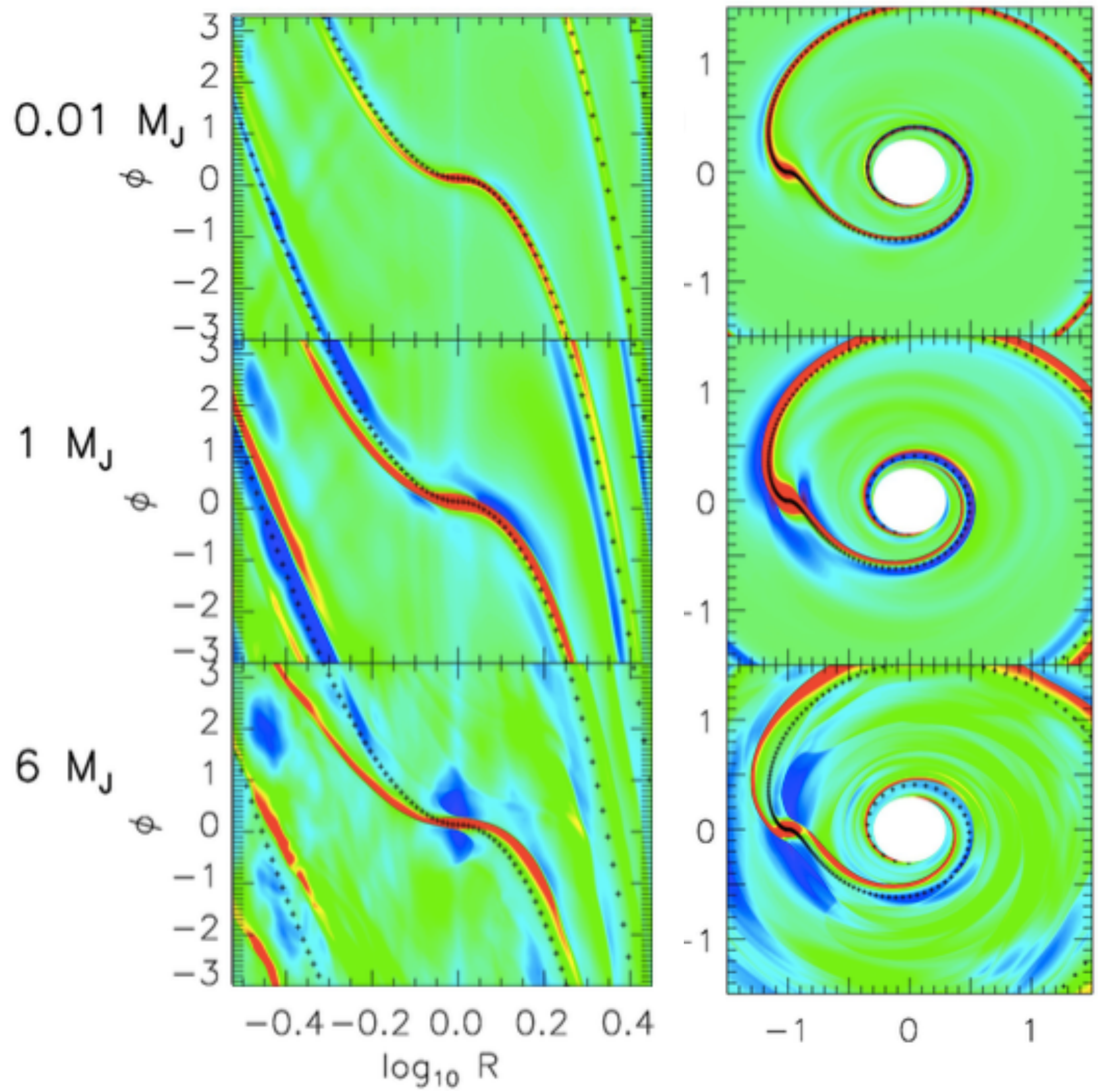
Jupiter-mass (non-linear)



Neptune-mass (linear)

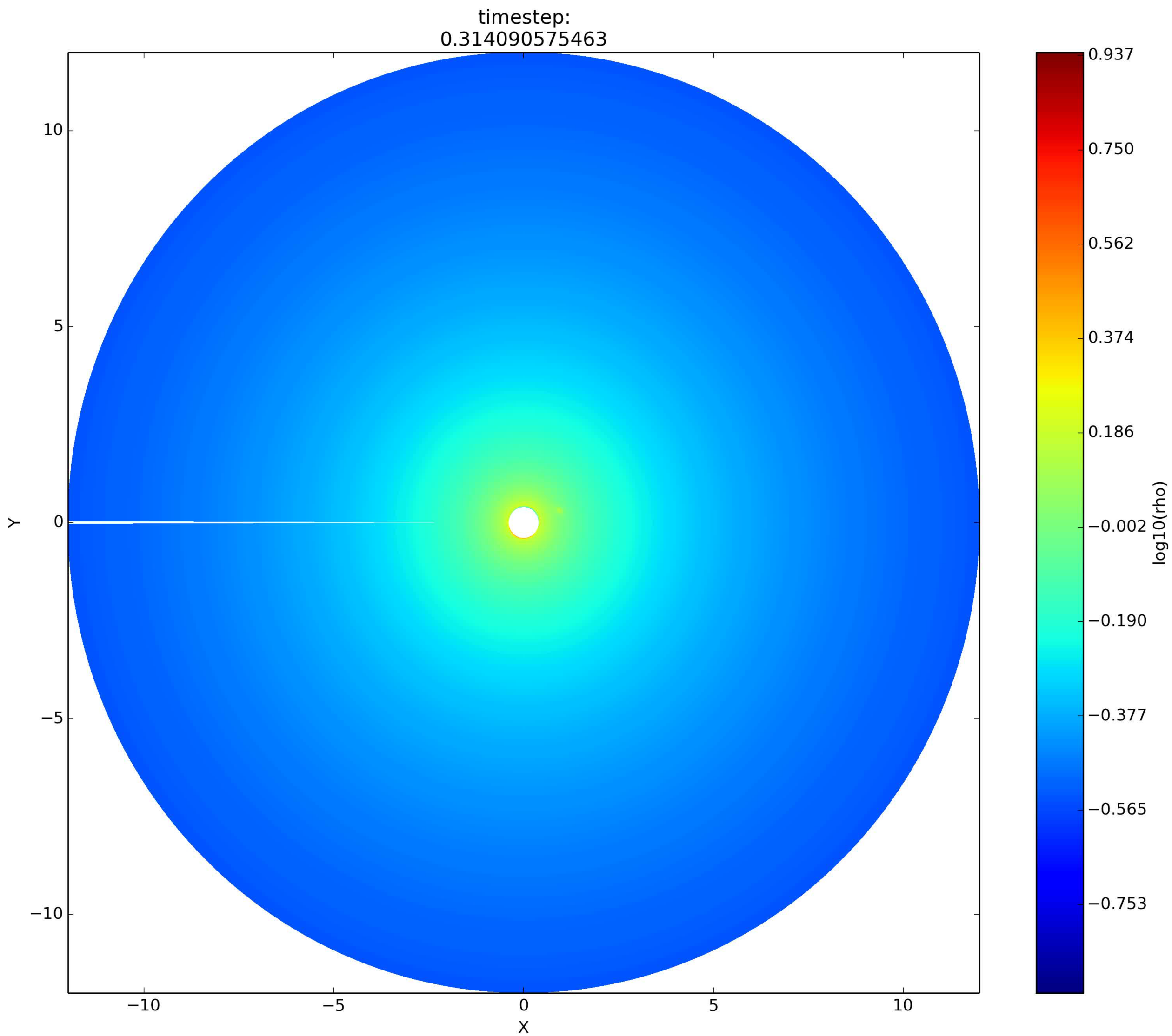


de Val-Borro al. (2006)



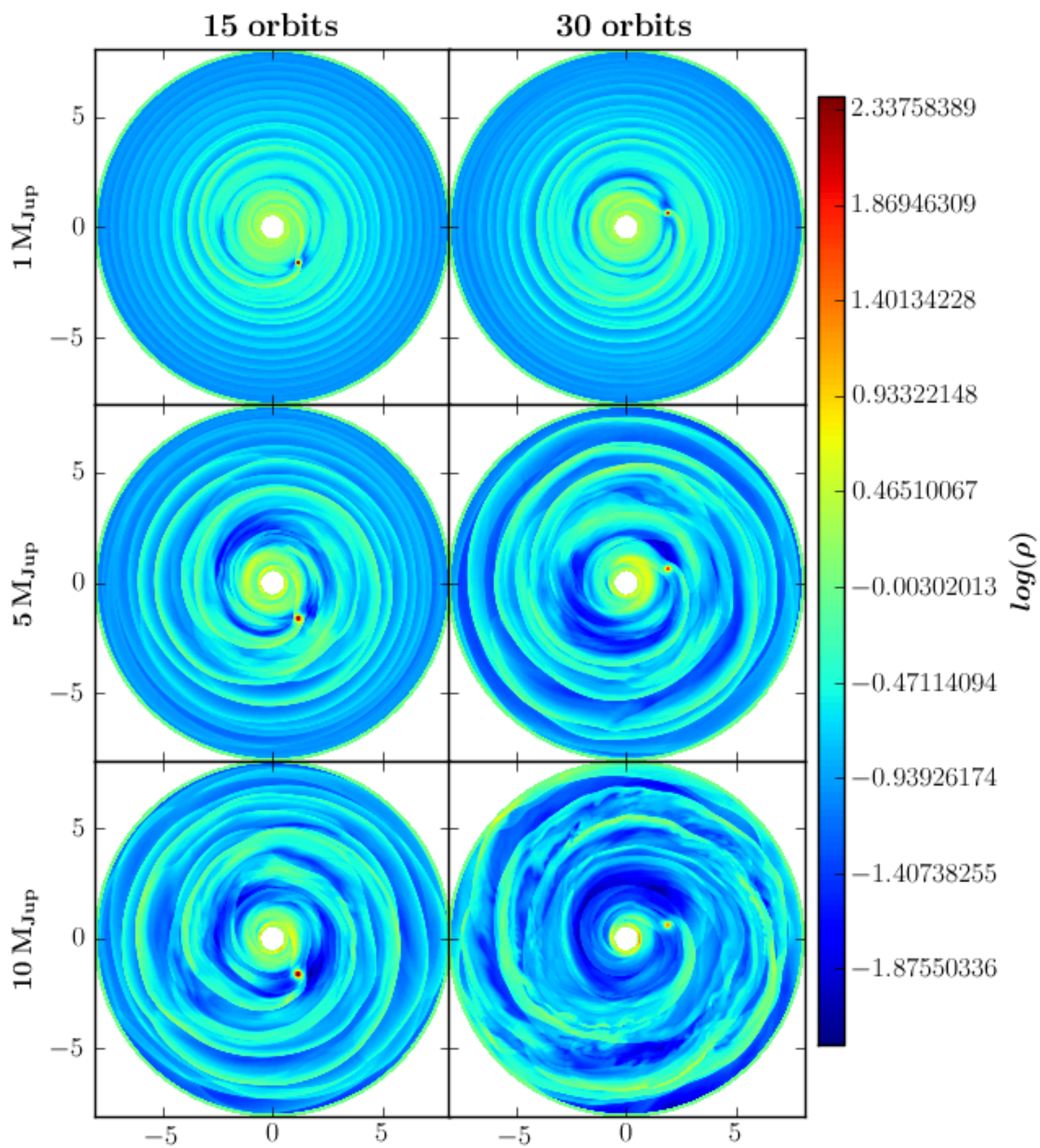
Zhu et al. (2015)

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

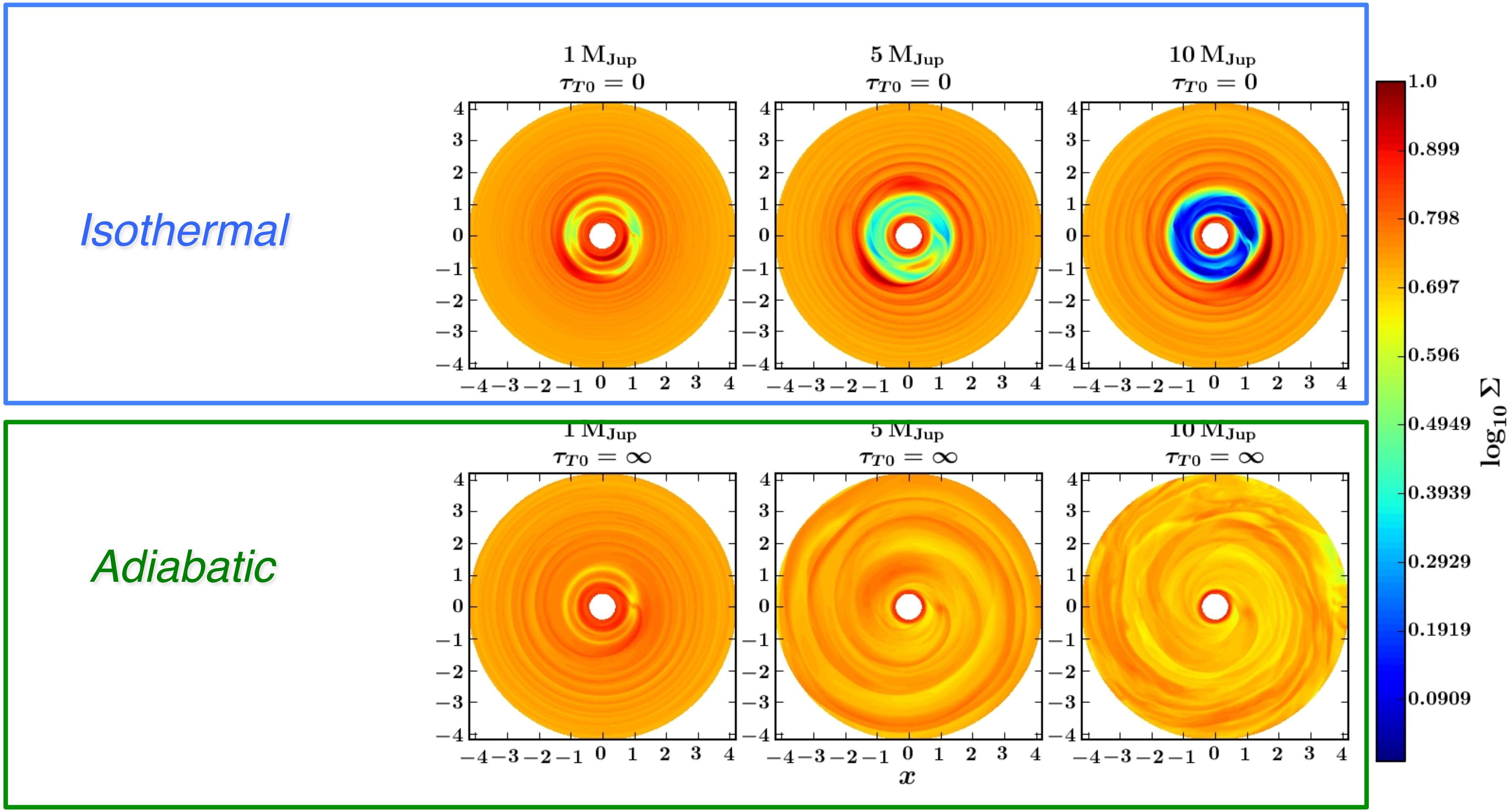


Richert et al. (2015)

Some crazy turbulence showing up at high planet mass….

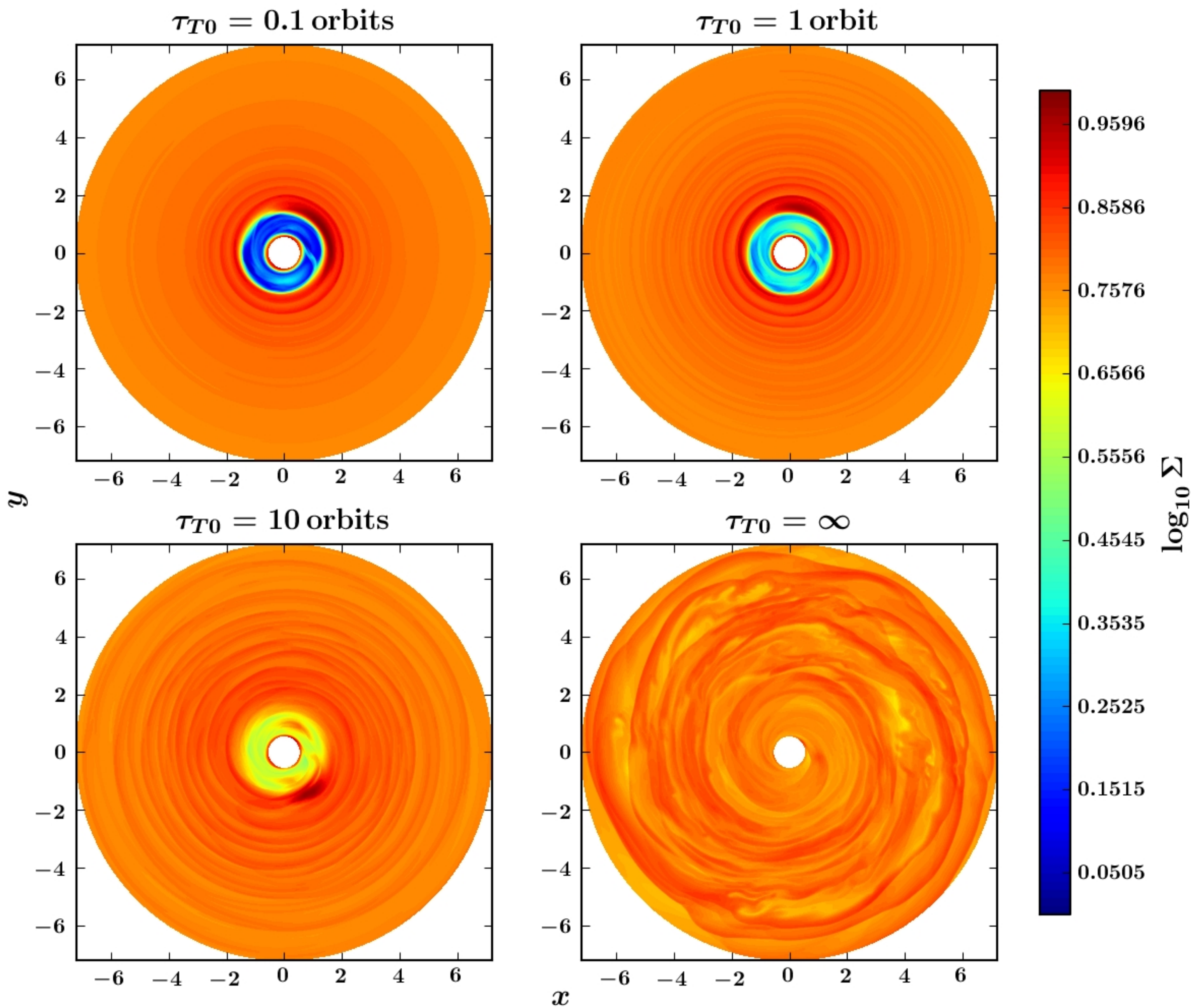


Shows up for high-mass planets in adiabatic disks

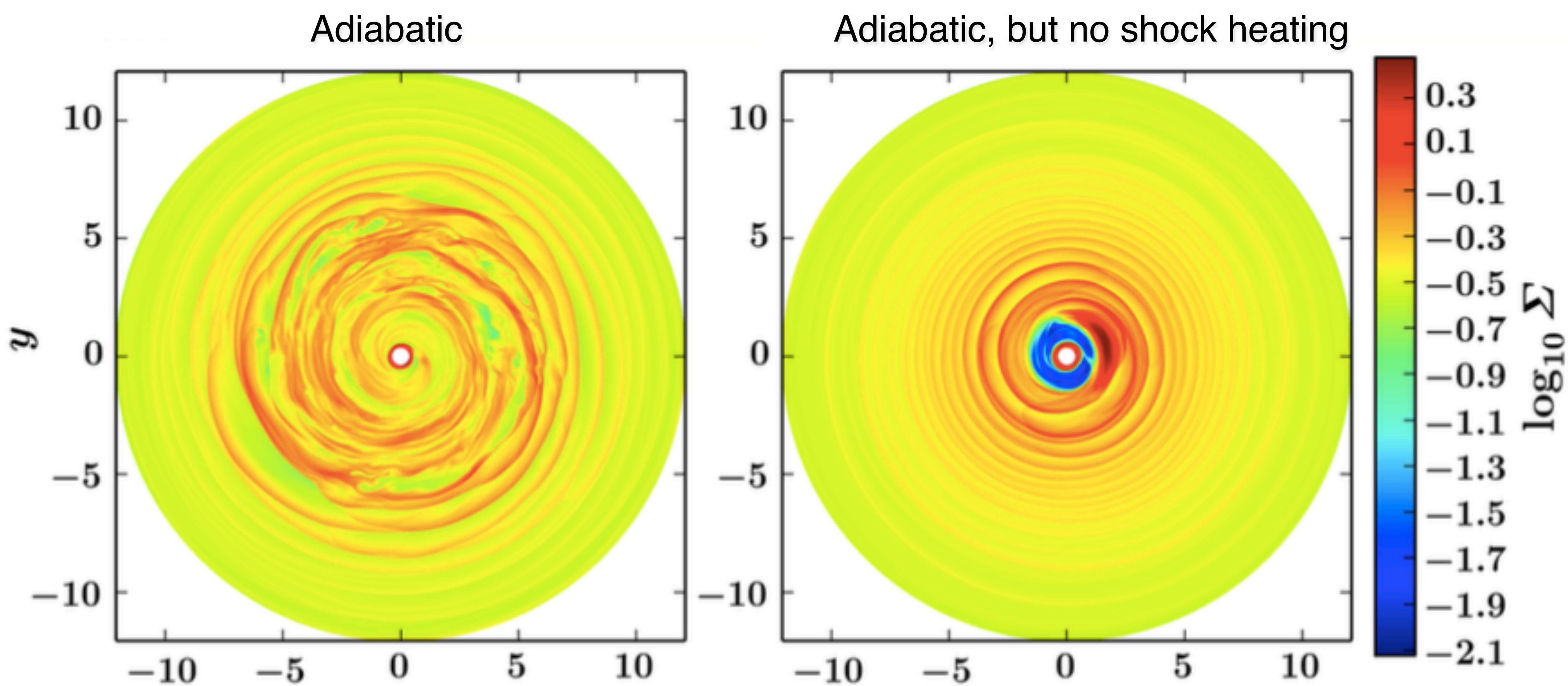


Richert et al. (2015)

Shows up for long cooling times….

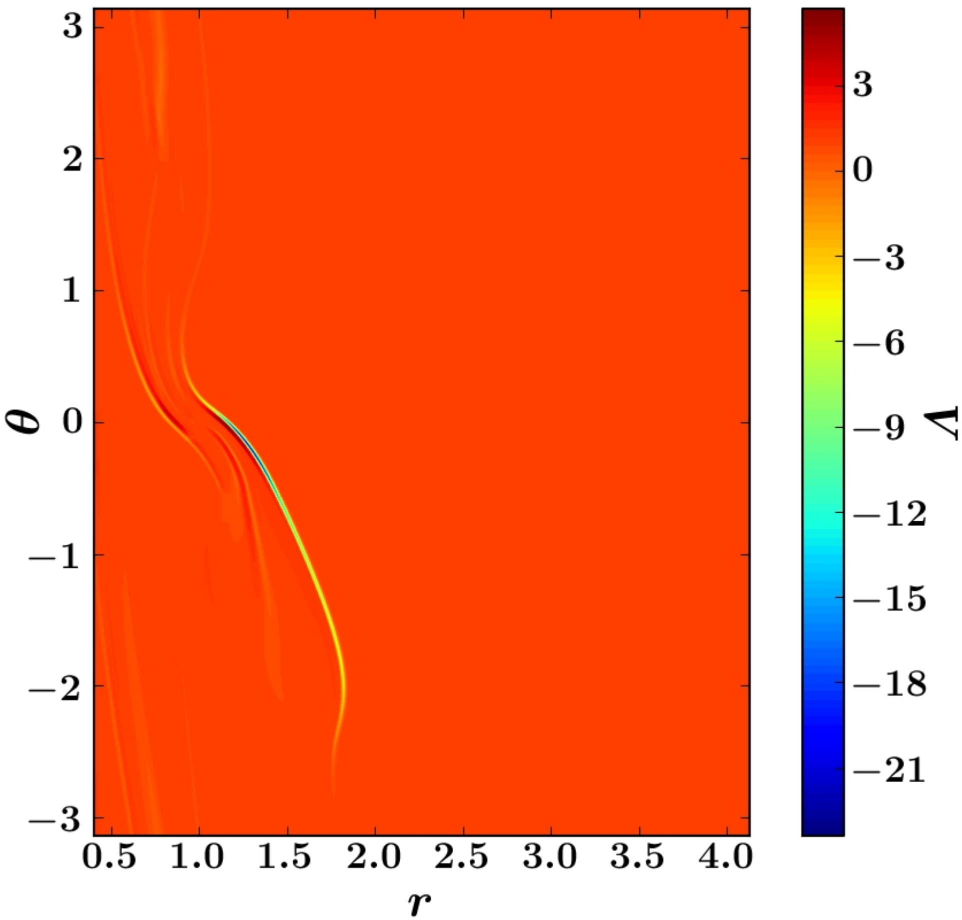


The energy source: shock heating!

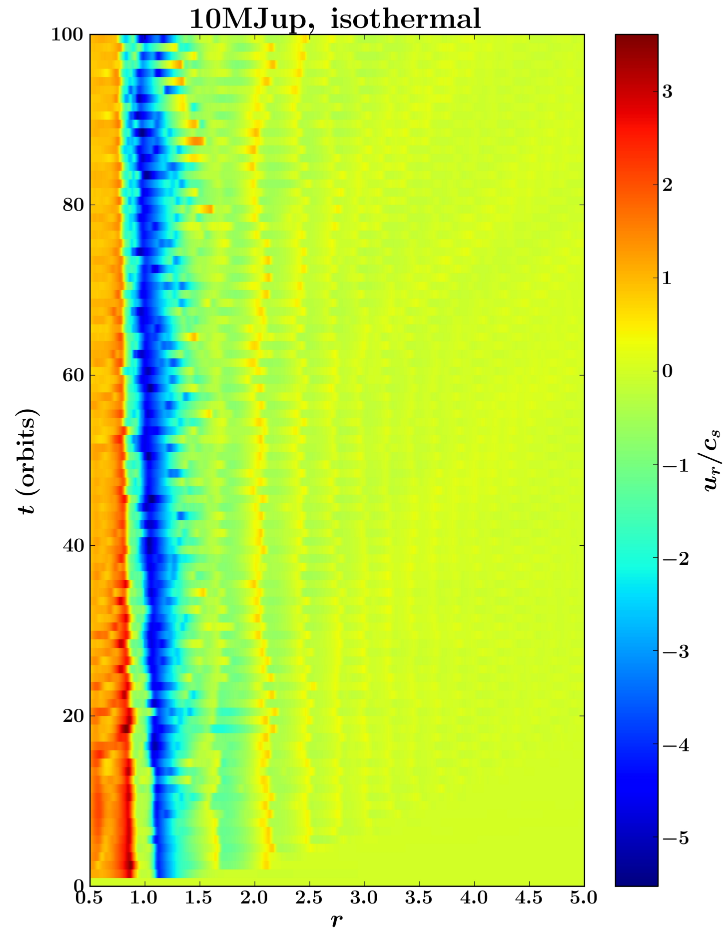


Richert et al. (2015)

The spiral is buoyantly unstable



The spiral has Ma >~ 1



Richert et al. (2015)

Radiative transfer approximation

$$T\frac{\mathrm{D}s}{\mathrm{D}t} = -c_V\frac{(T - T_{\mathrm{ref}})}{t_{\mathrm{cool}}} + \Gamma_{\mathrm{sh}},$$

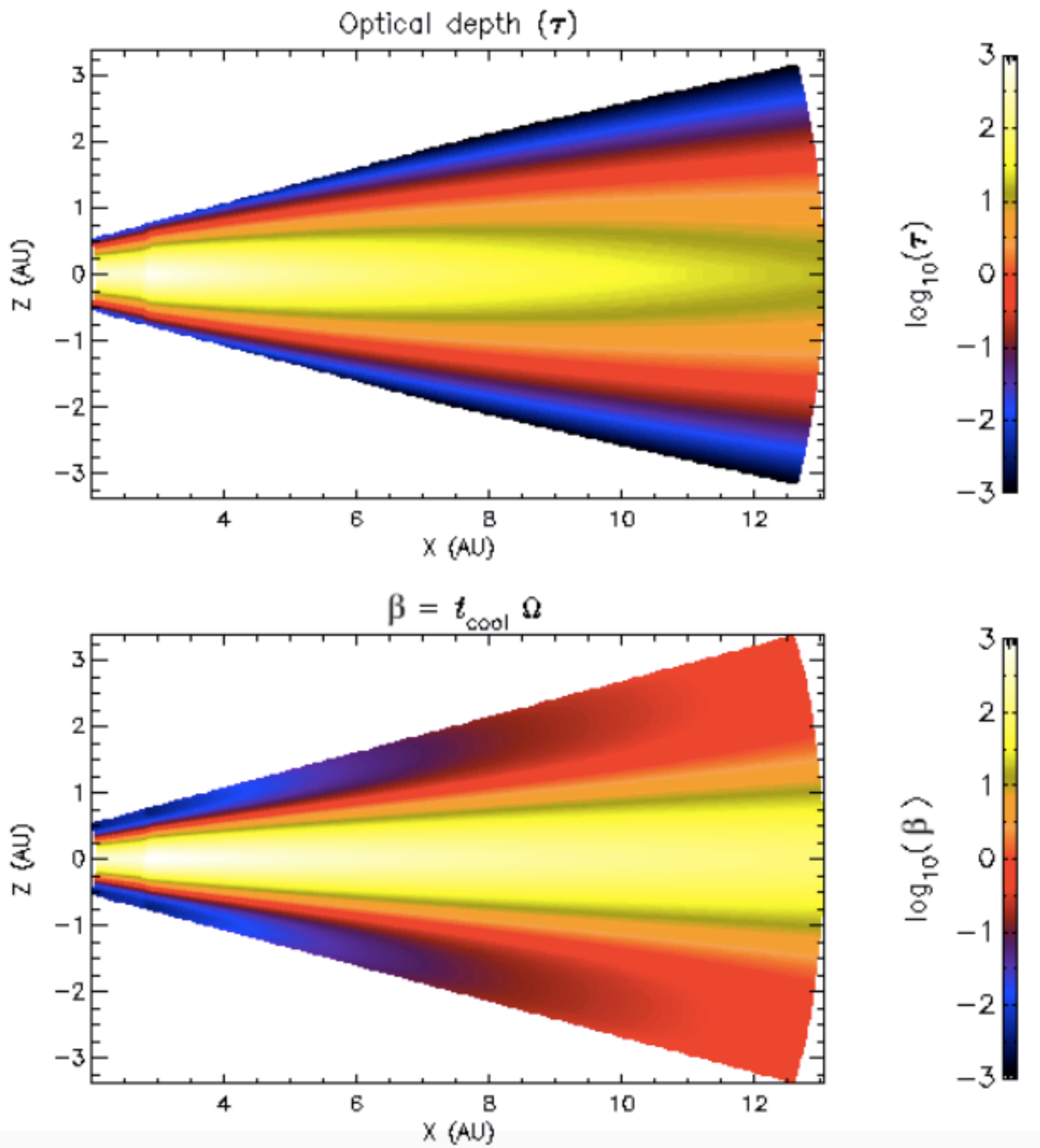
$$t_{\mathrm{rad}} = E/\dot{E}$$

$$\dot{E} = \boldsymbol{\nabla}\cdot\boldsymbol{F}$$

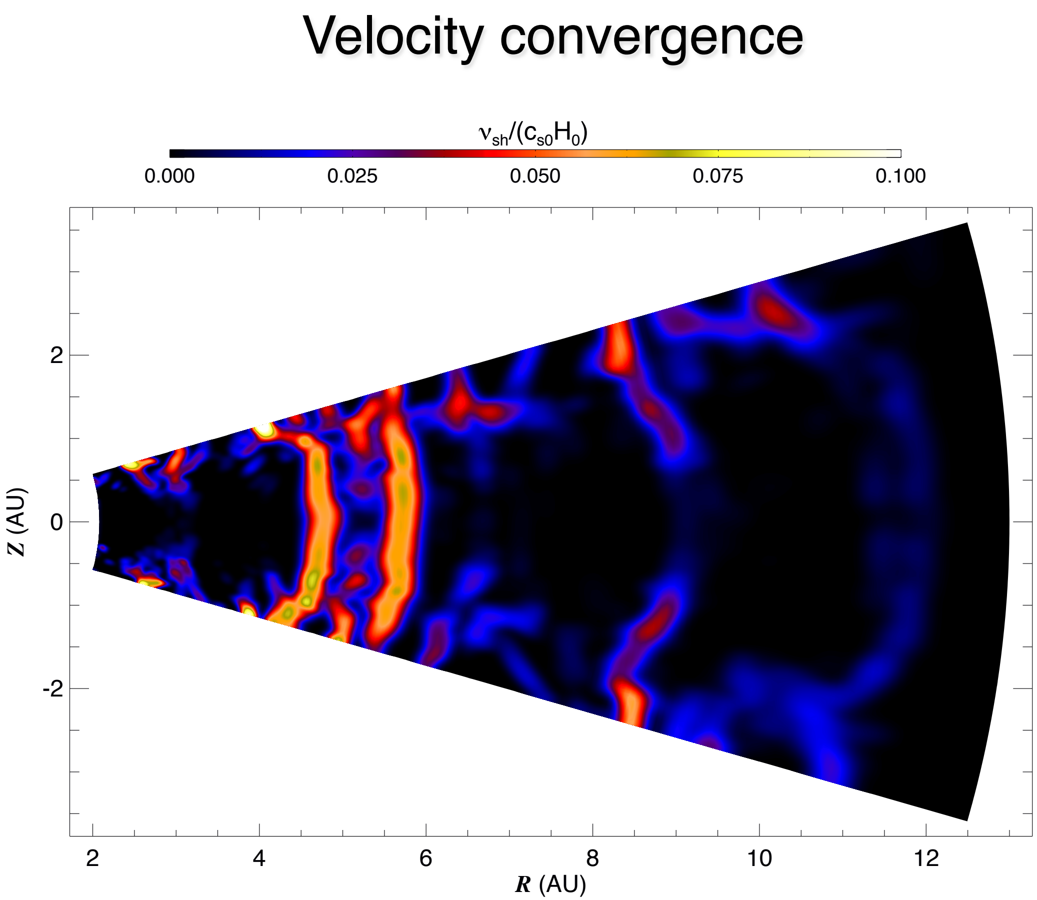
$$t_{\mathrm{cool}} \equiv \frac{\int E dV}{\int F\hat{\boldsymbol{n}}\cdot d\boldsymbol{A}}.$$

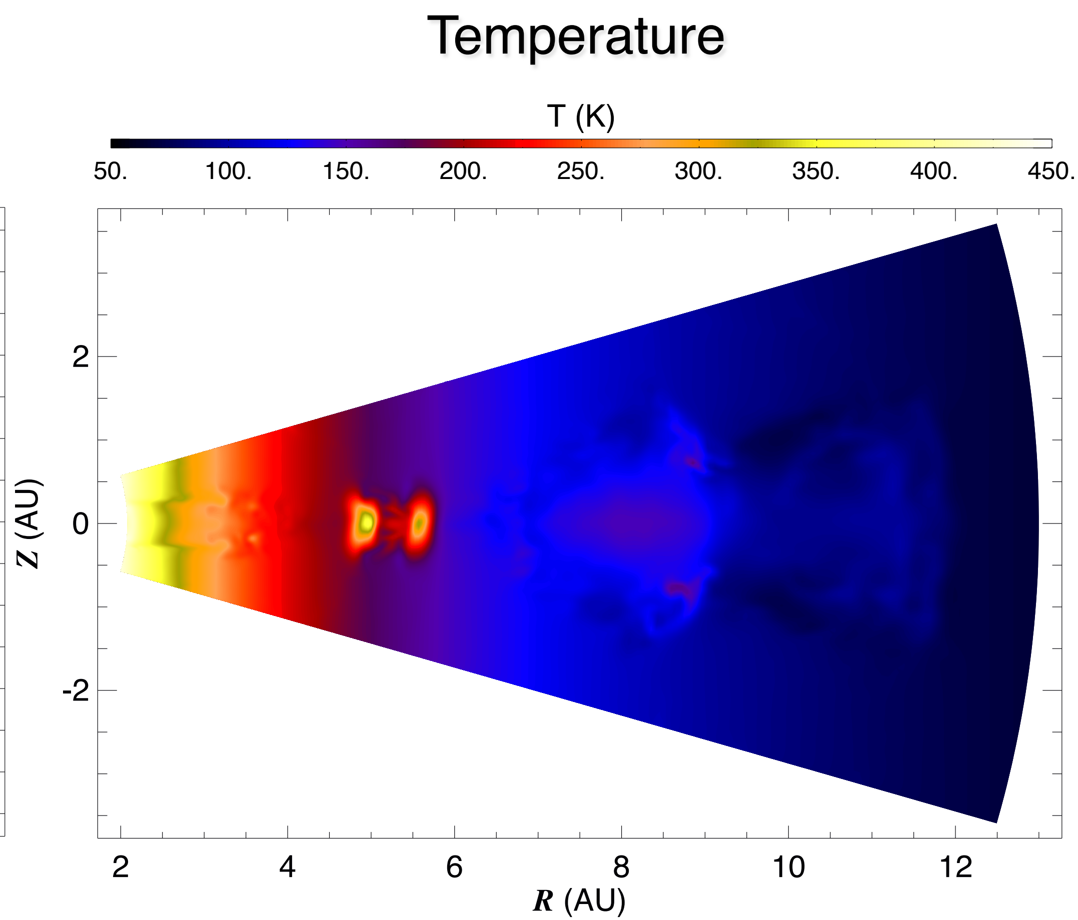
$$t_{\mathrm{cool}} = \frac{c_V\rho H\tau_{\mathrm{eff}}}{3\sigma T^3}.$$

$$\tau_{\mathrm{eff}} = \frac{3\tau}{8} + \frac{\sqrt{3}}{4} + \frac{1}{4\tau}.$$



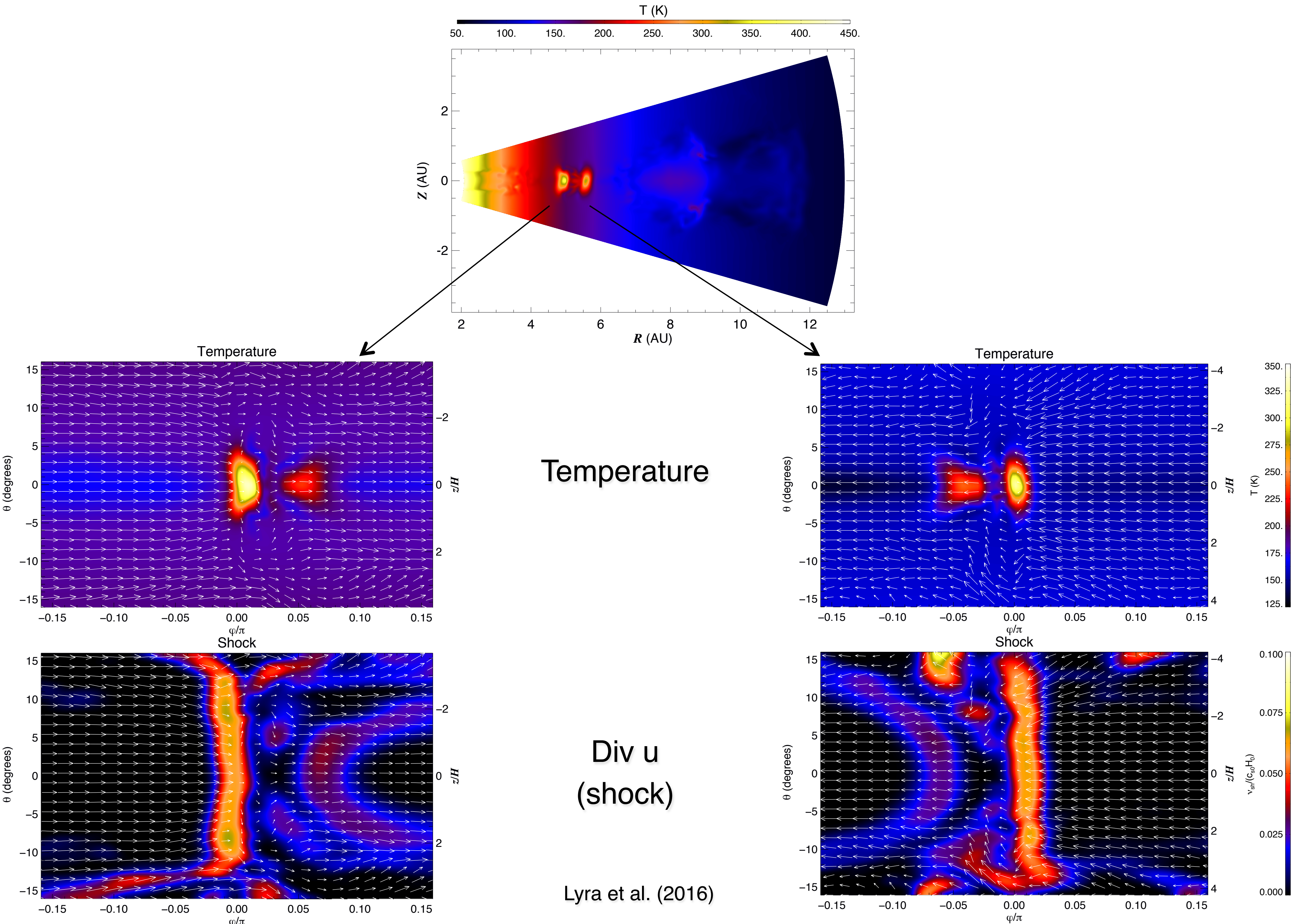
Shock bores





Lyra et al. (2016)

3D shocks: bores and breaking waves

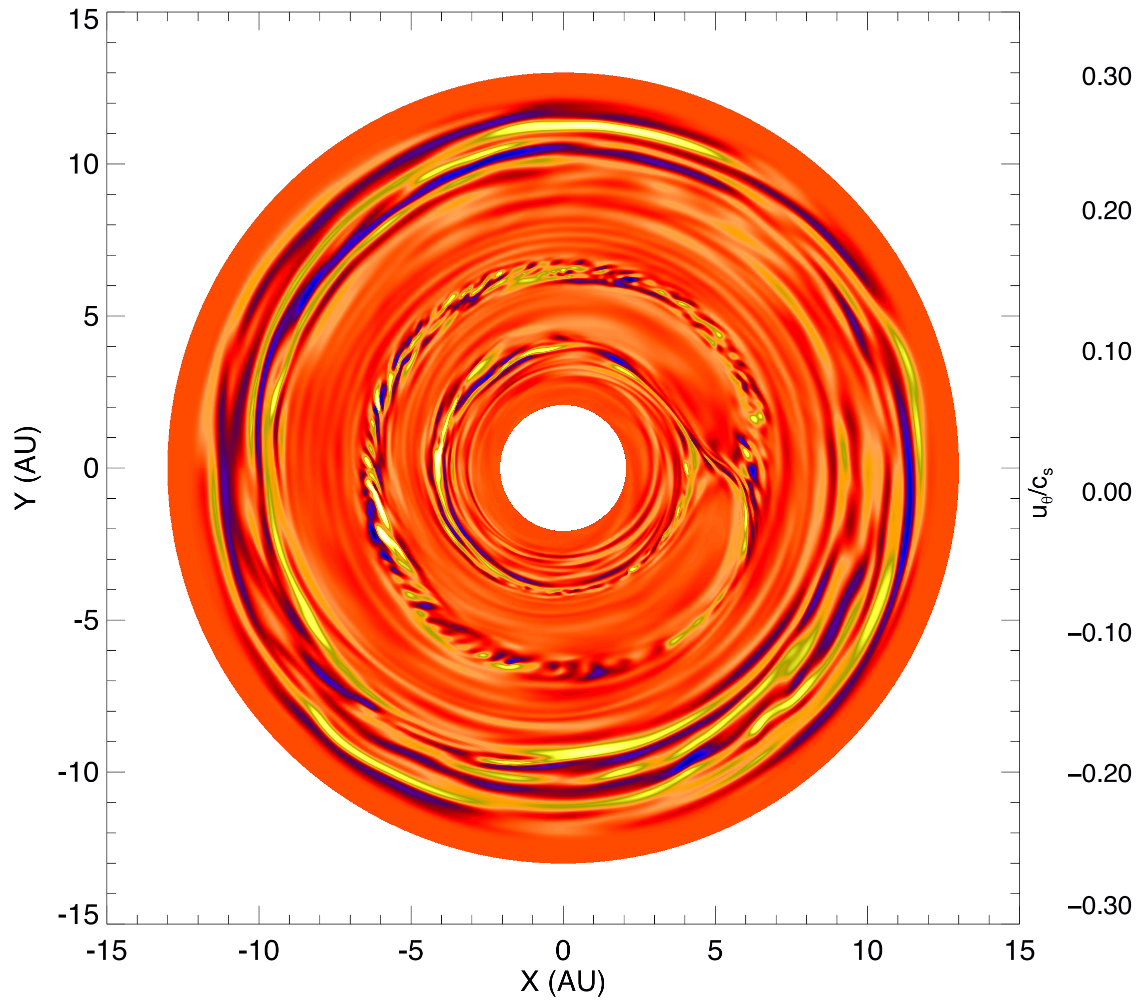


Temperature

Div u
(shock)

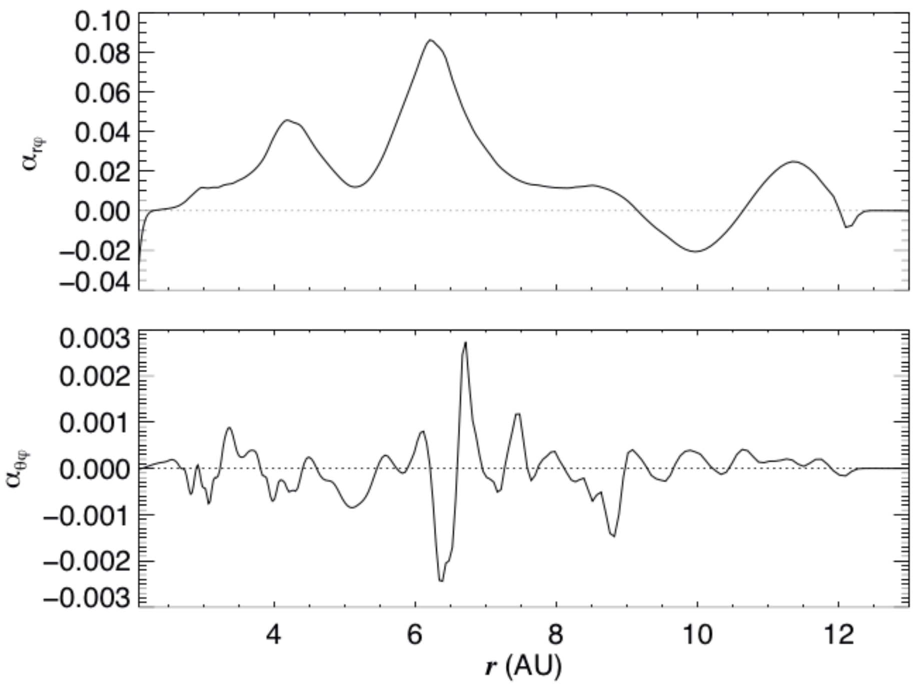
Lyra et al. (2016)

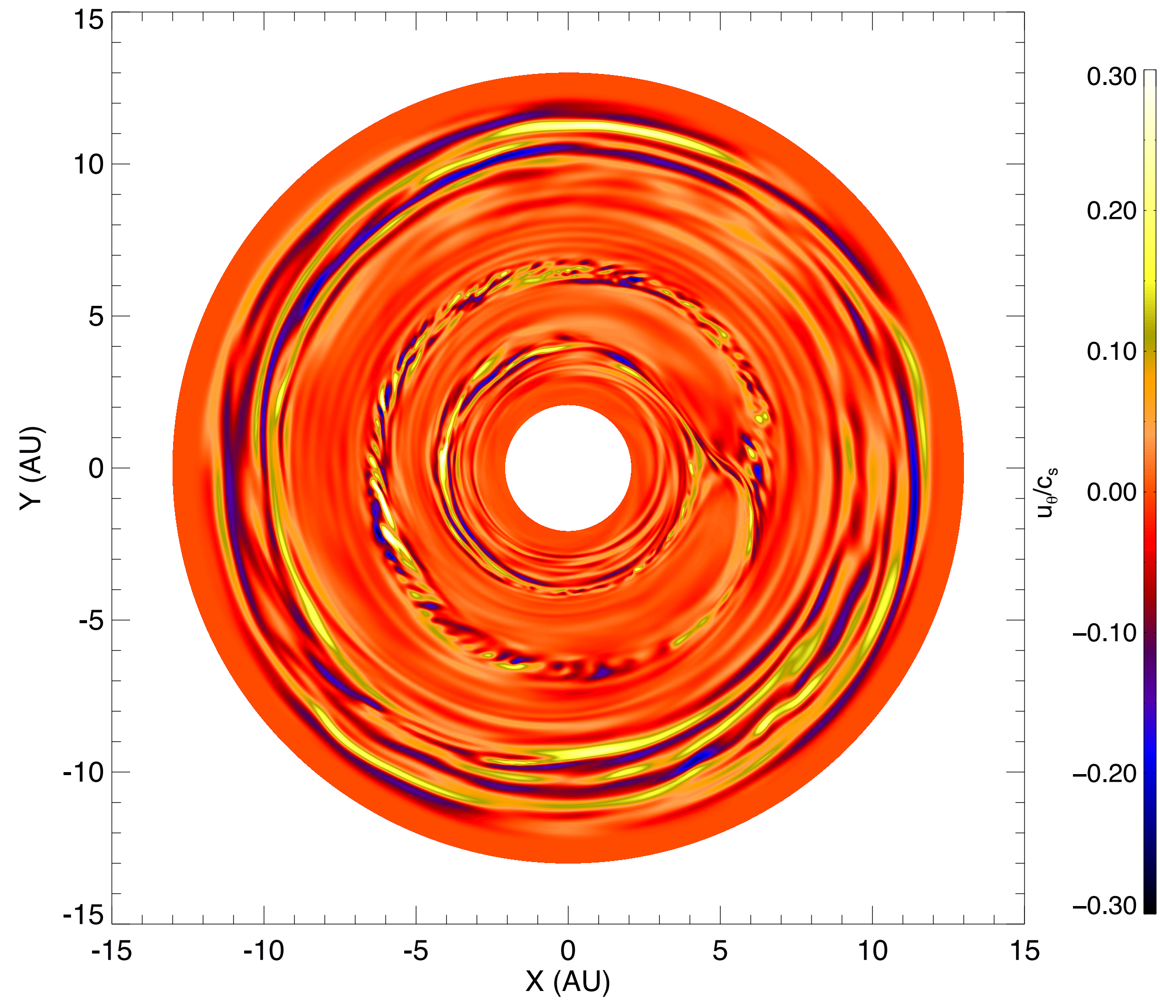
Turbulent surf



Lyra et al. (2016)

Turbulent surf





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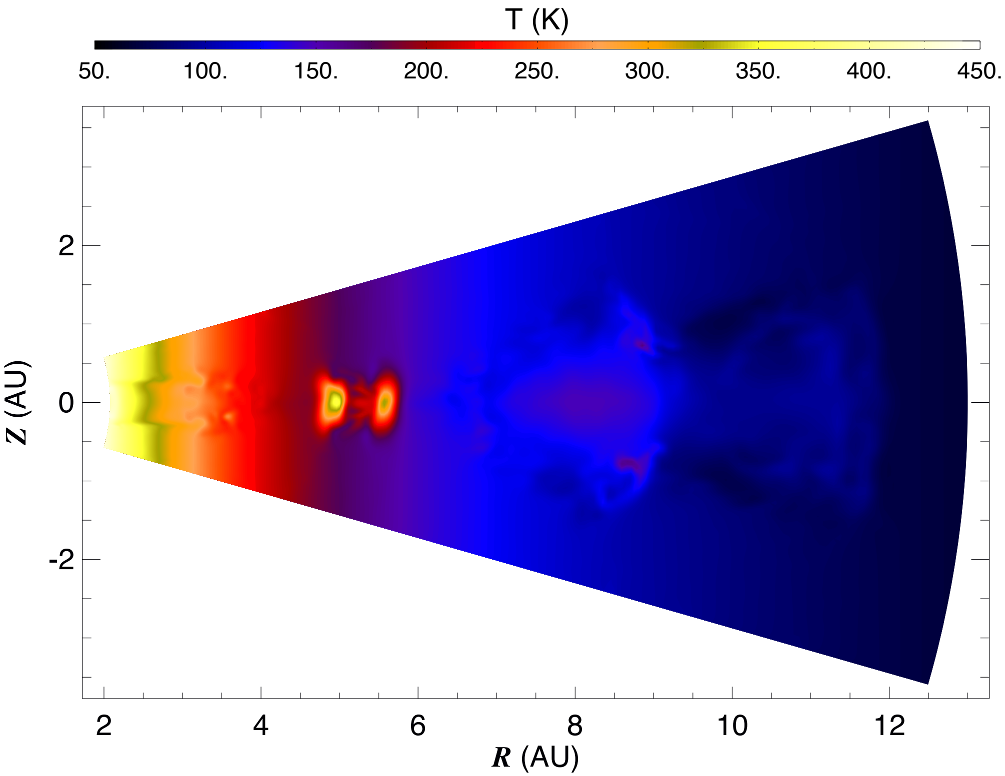
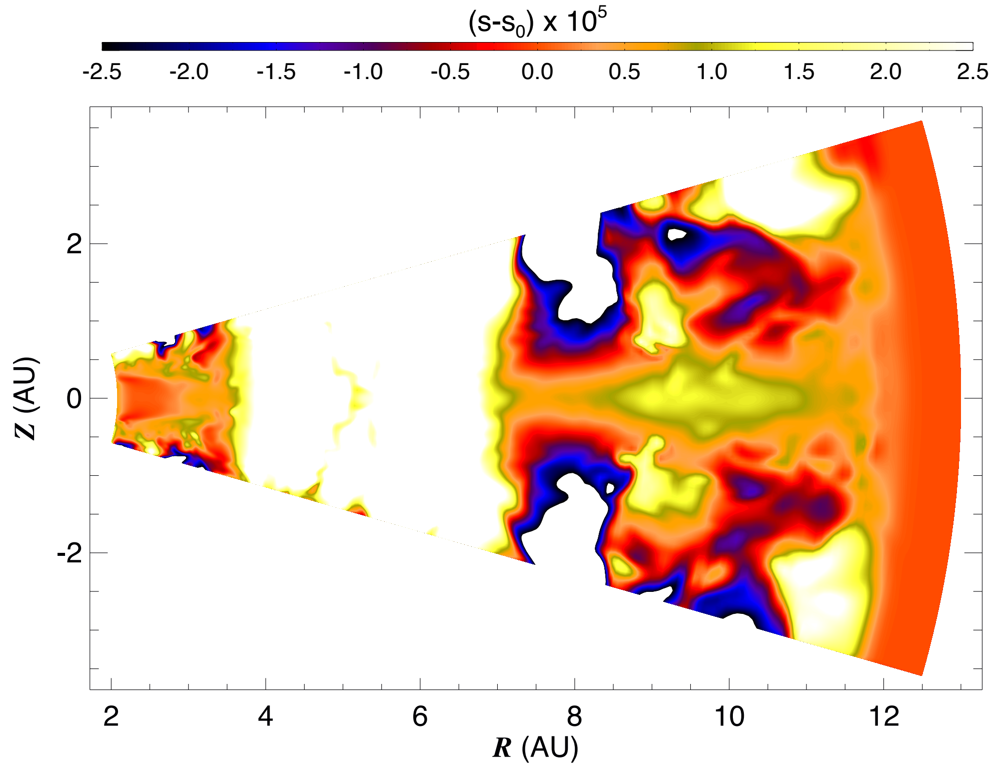
Convection

Temperature

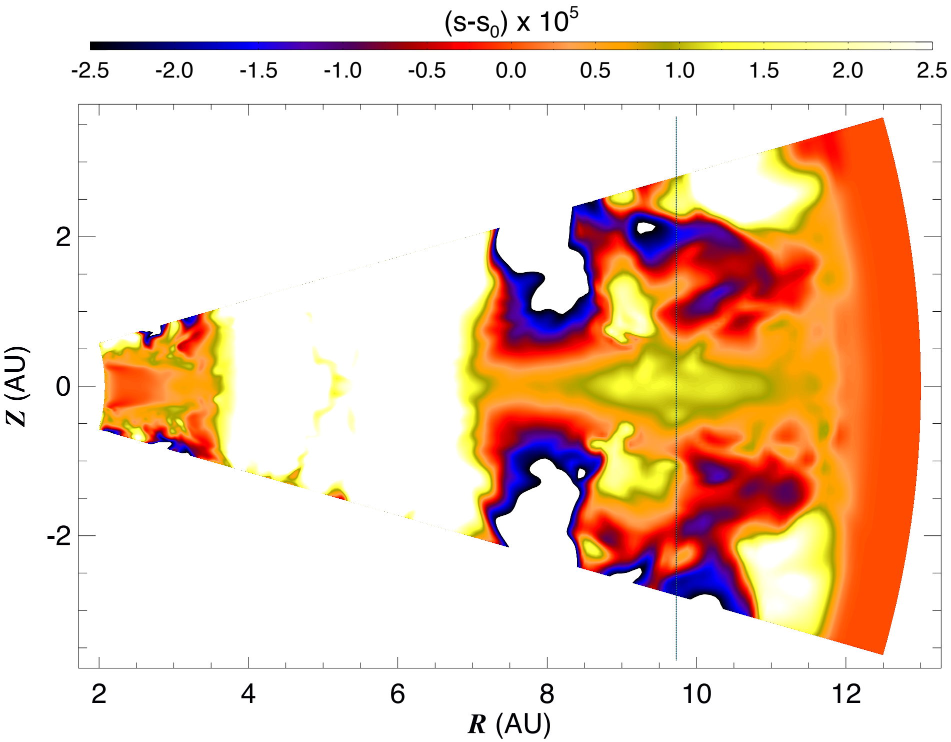


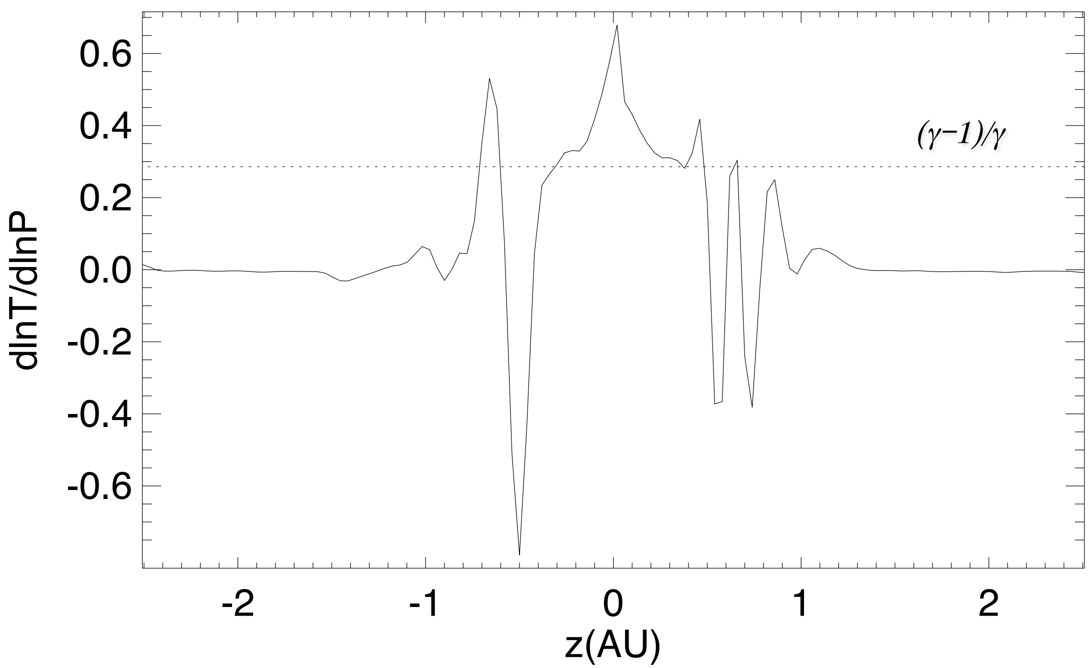
Entropy



Lyra et al. (2016)

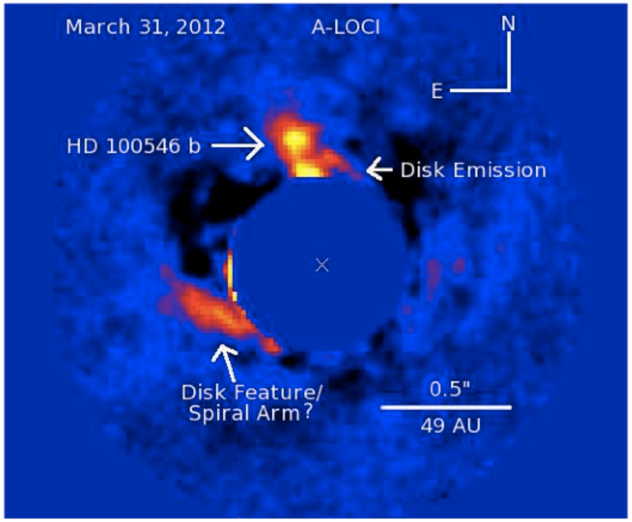
Convection



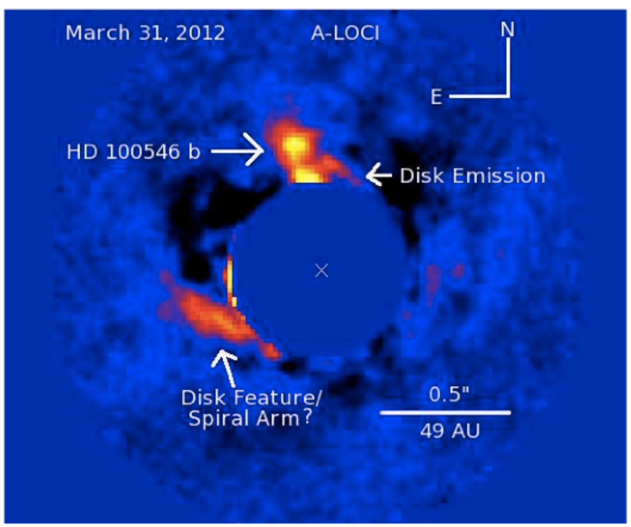


Lyra et al. (2016)

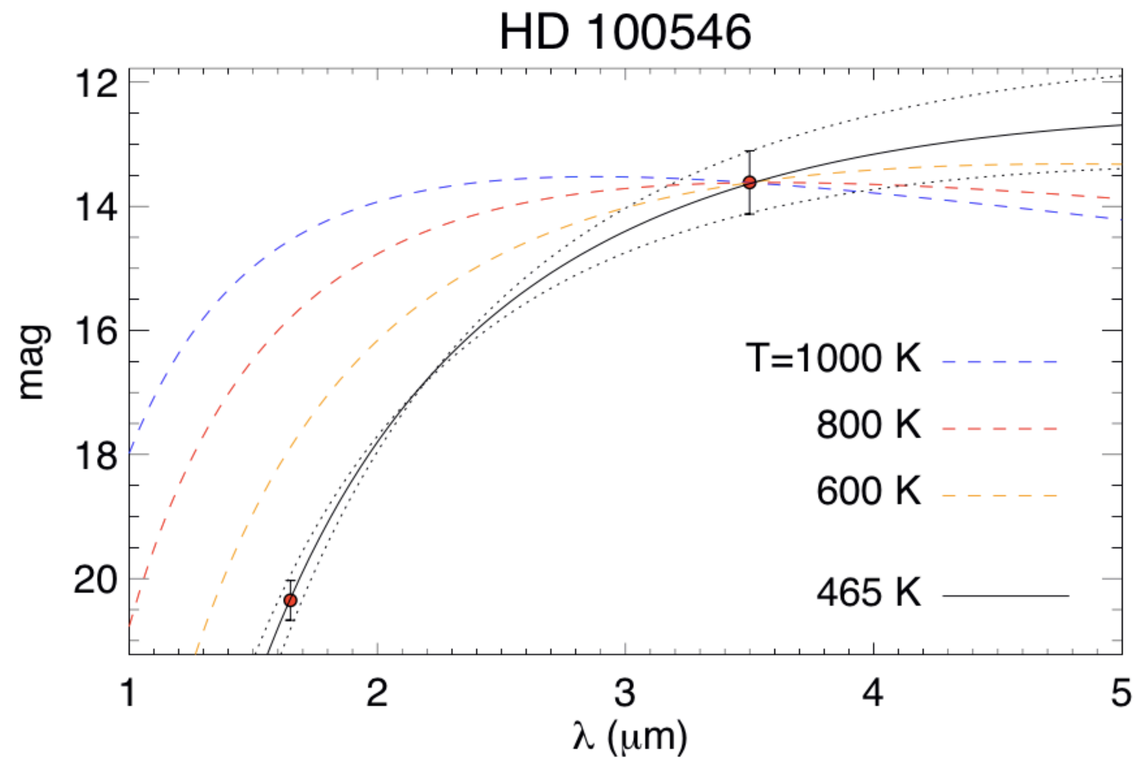
Pinning down the temperature



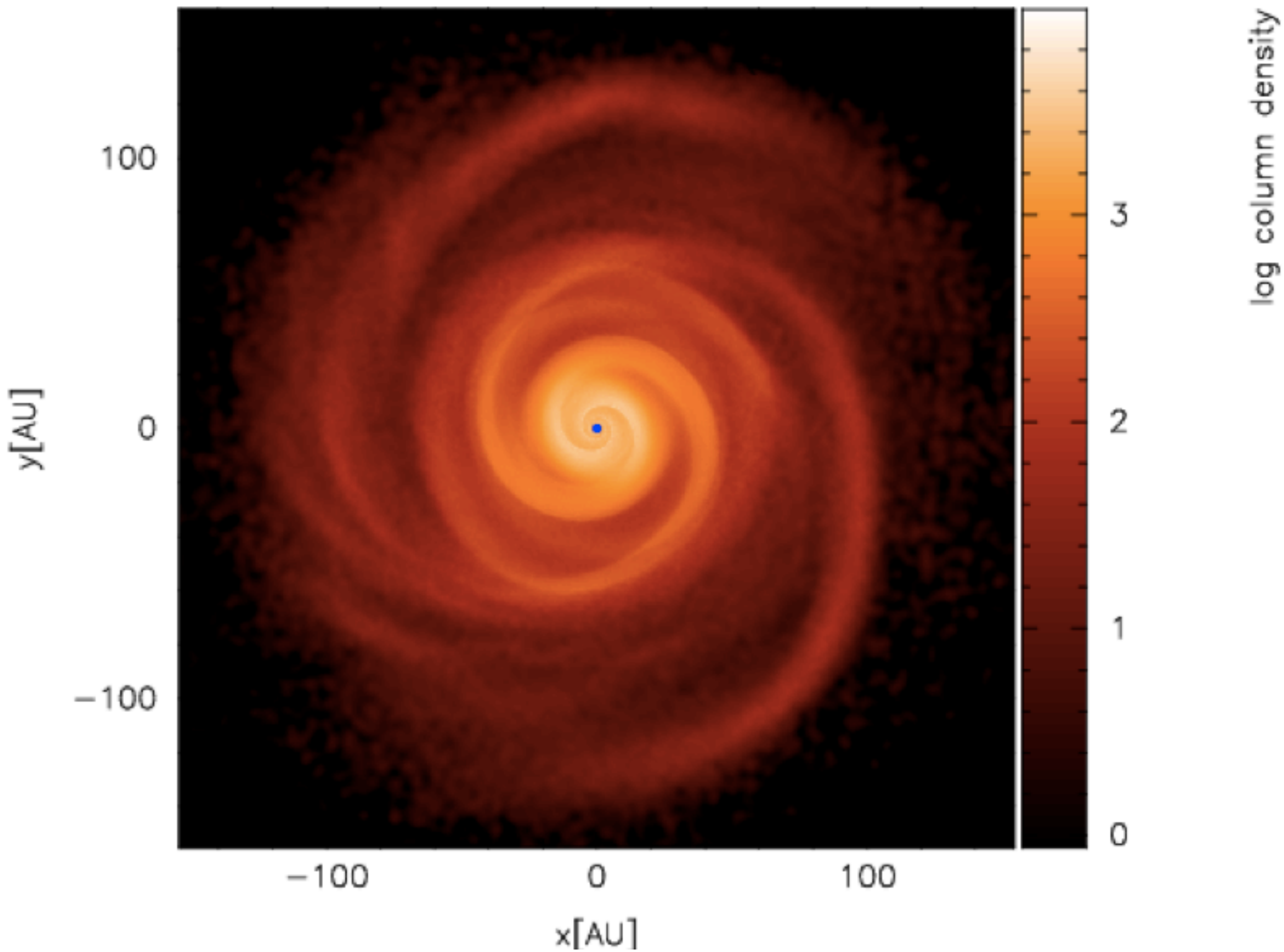
L band



H band

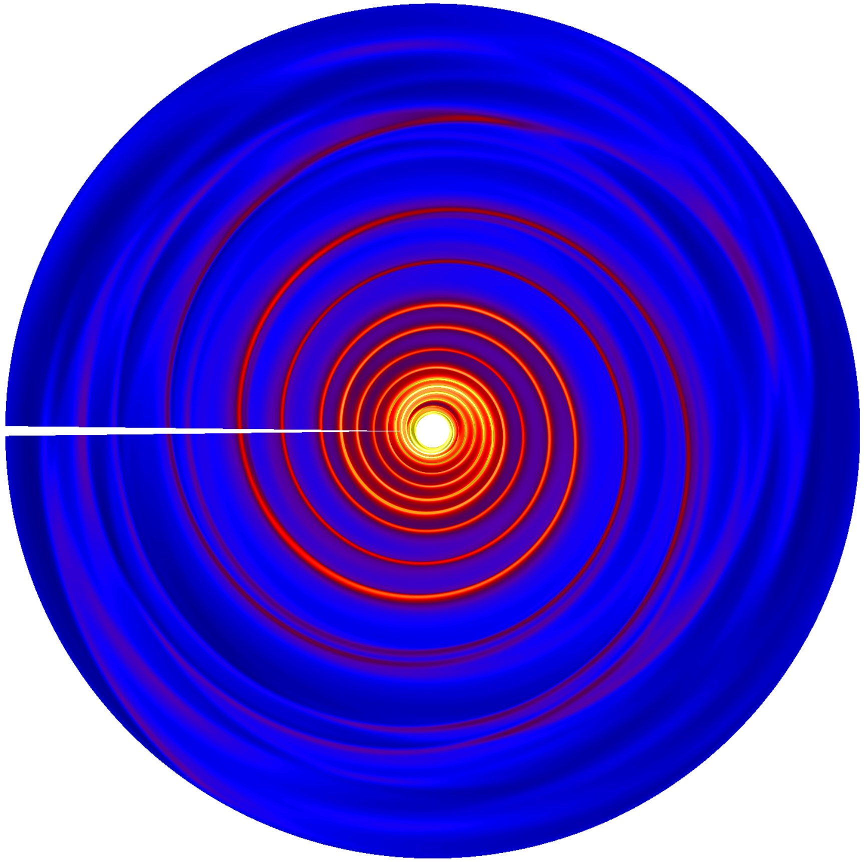


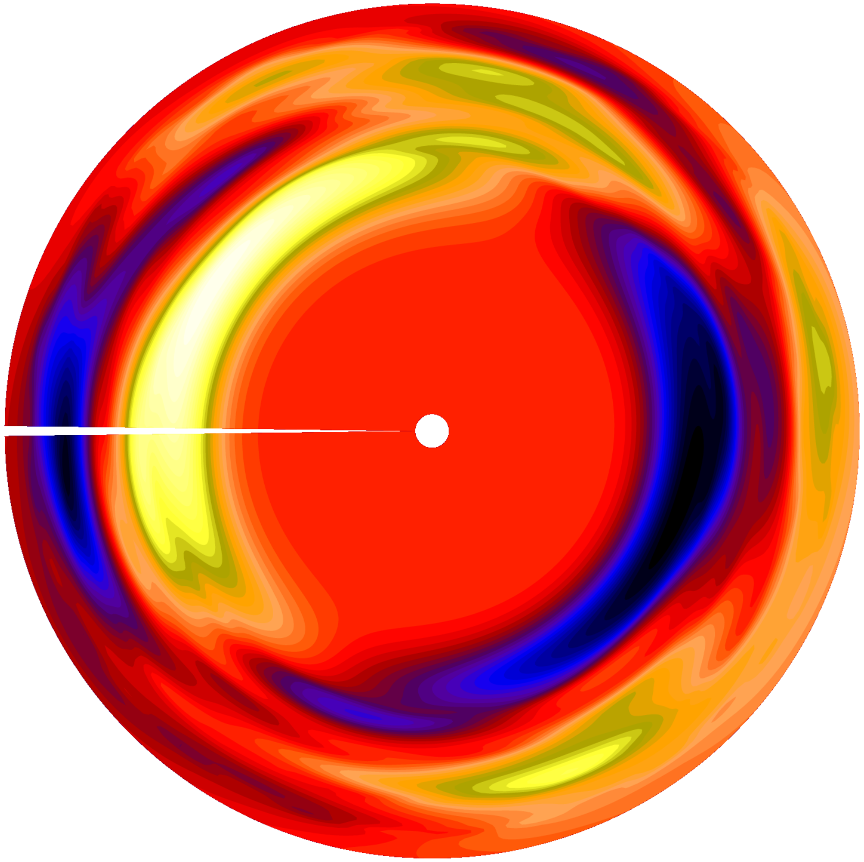
Alternate spiral formation



See Pohl et al. (2015)

Outer Dead/Active zone transition: Spirals without planets

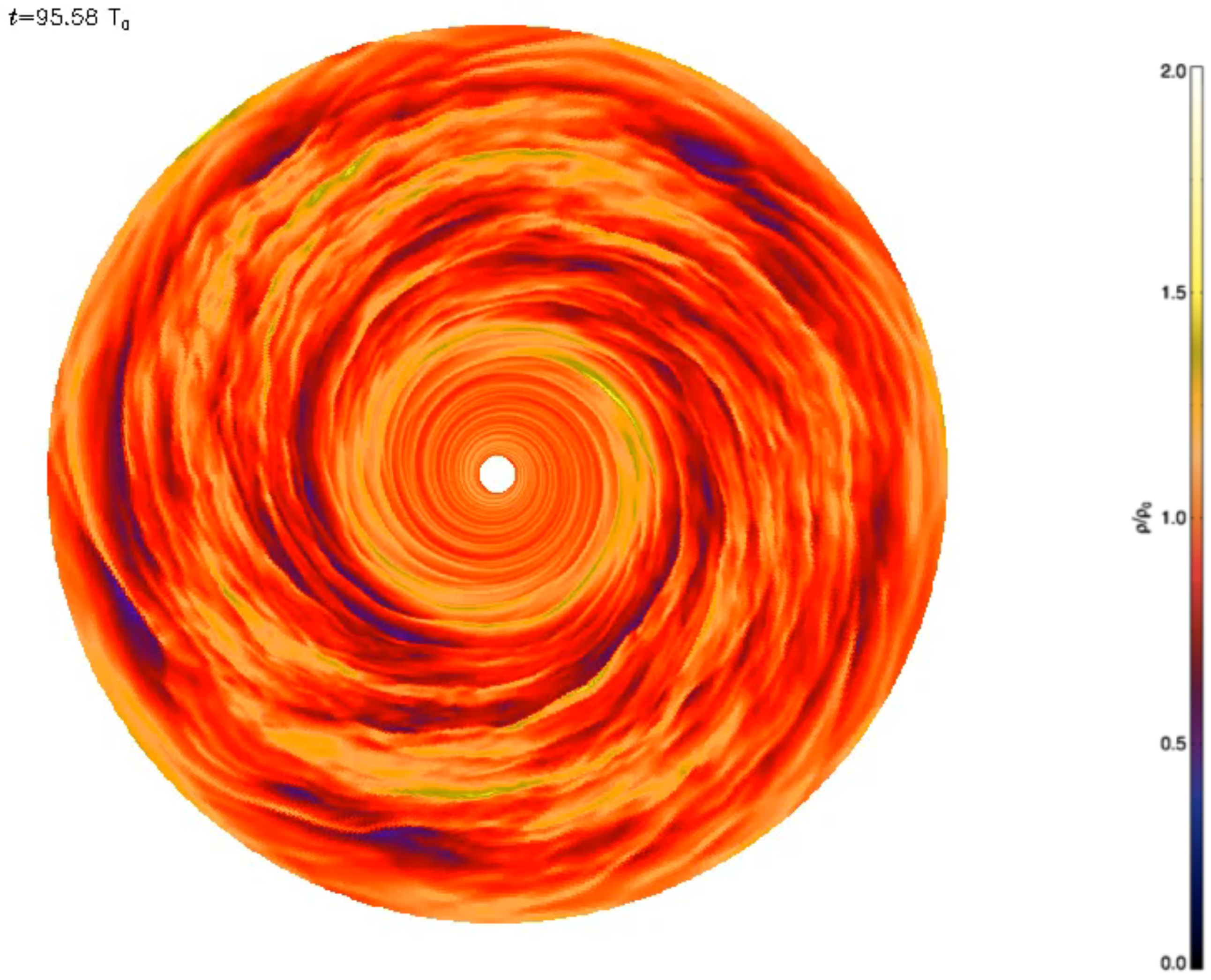




Waves launched at the active zone propagate into the dead zone as a coherent spiral.

Lyra et al (2015)

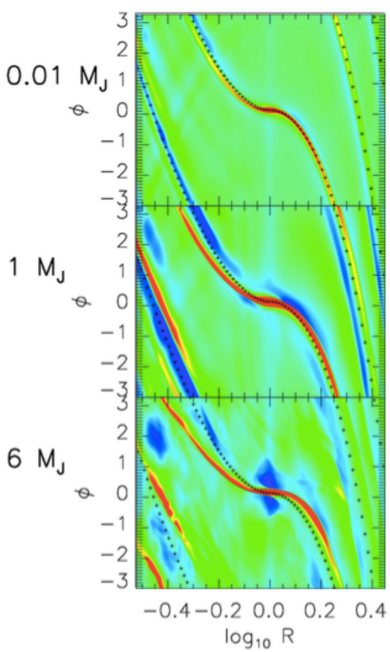
Spirals without planets

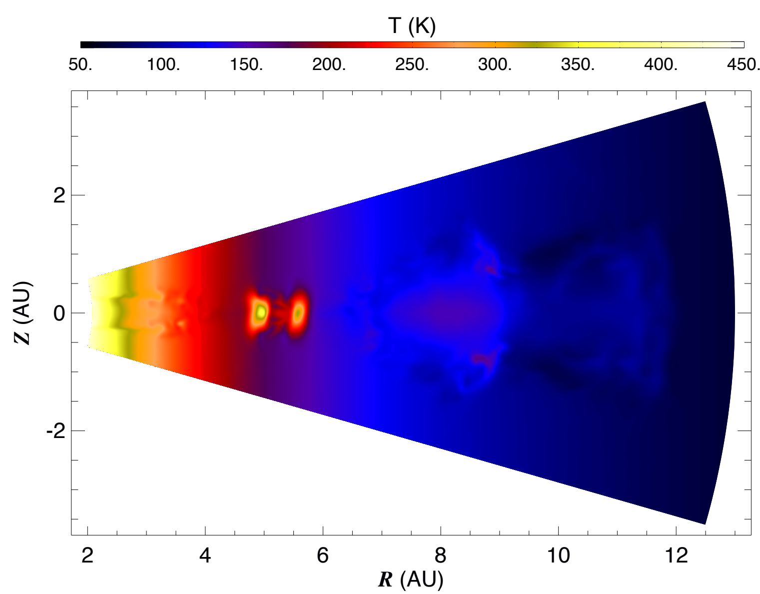


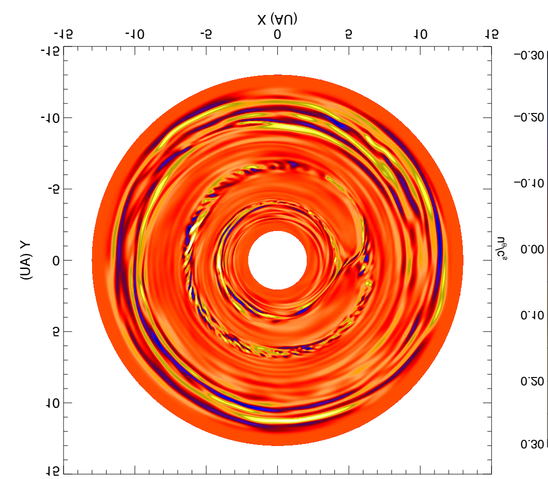
Lyra et al (2015)

Summary and Conclusions

- Shocks due to high mass planets yield good fits to observed spirals.
- In addition to **supersonic pitch angles**, we predict:
    - **high-temperature lobes** and **turbulent surf** near the planet
    - **convection** far from the planet's orbit
- Waves propagating into non-turbulent regions will be shaped into spirals (***careful before you shout "Planet!"***)







To do list

- Post-processing radiative transfer to yield observables *(τ = 1* surface)
- Planet at several distances to check if the same degree of heating is expected in the outer disk.