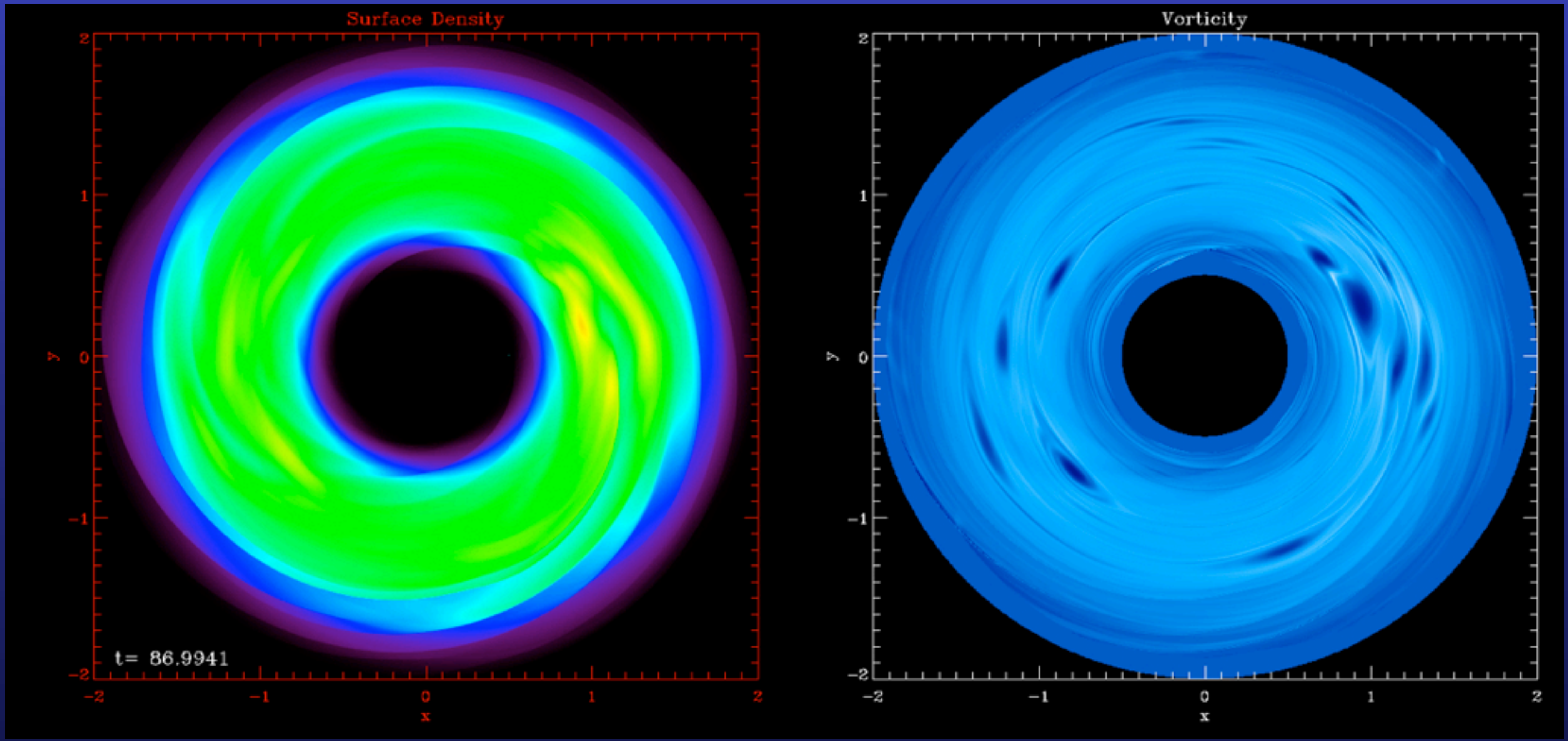
Les Houches, Feb. 7th, 2013

Disk Weather: Waves and Instabilities in Circumstellar Disks



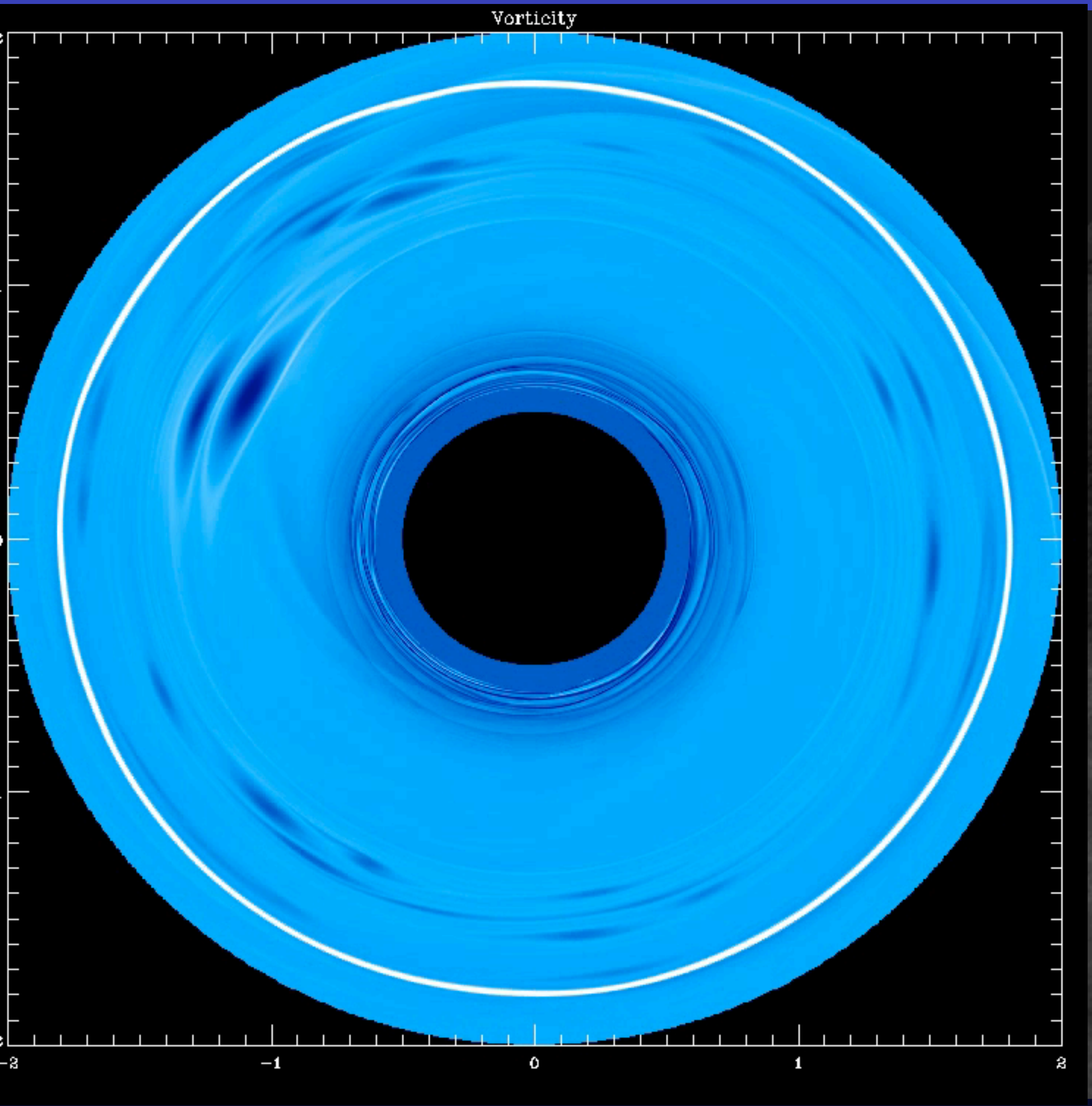
Hubert Klahr,

Max-Planck-Institut für Astronomie, Heidelberg

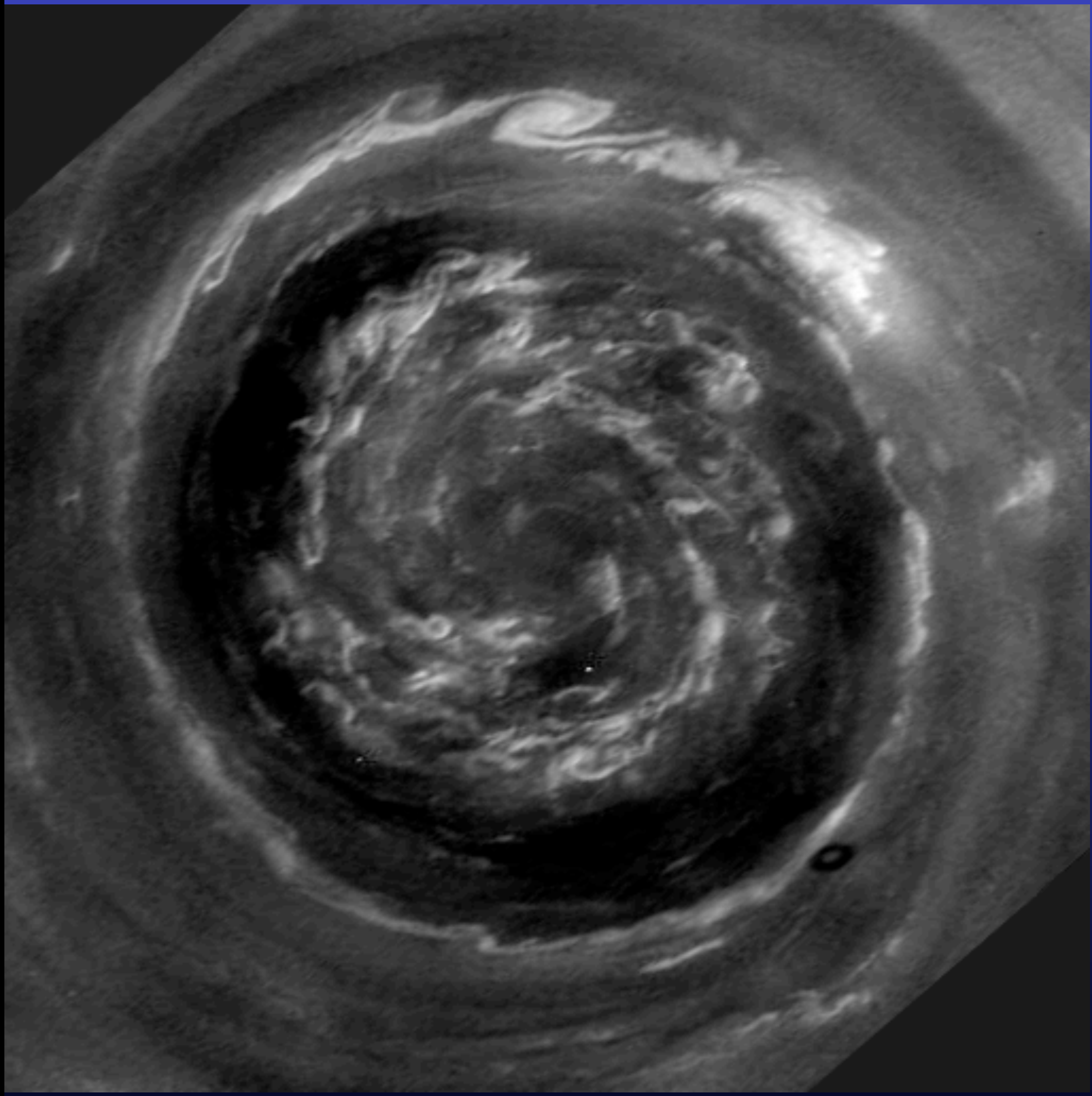
Natalie Raettig, Moritz Beutel, Karsten Dittrich (MPIA), Alex Hubbard(AMNH), Wlad Lyra (JPL), Peter Bodenheimer (UCSC), Helen Morrison (ITA)

Planetesimal Formation and MHD: Anders Johansen (Lund), Mario FLock (Paris), Rainer Spurzem (NAOC/ARI), Mario Trieloff (HD), Til Birnstiel, Barbara Ercolano (USM), Kees Dullemond (ITA), Chris Ormel (Berkley), Neal Turner (JPL), Doug Lin (KIAA, UCSC)

2 x Weather pattern:
Astrophysical and Geophysical flow



Proto PLANETARY disk



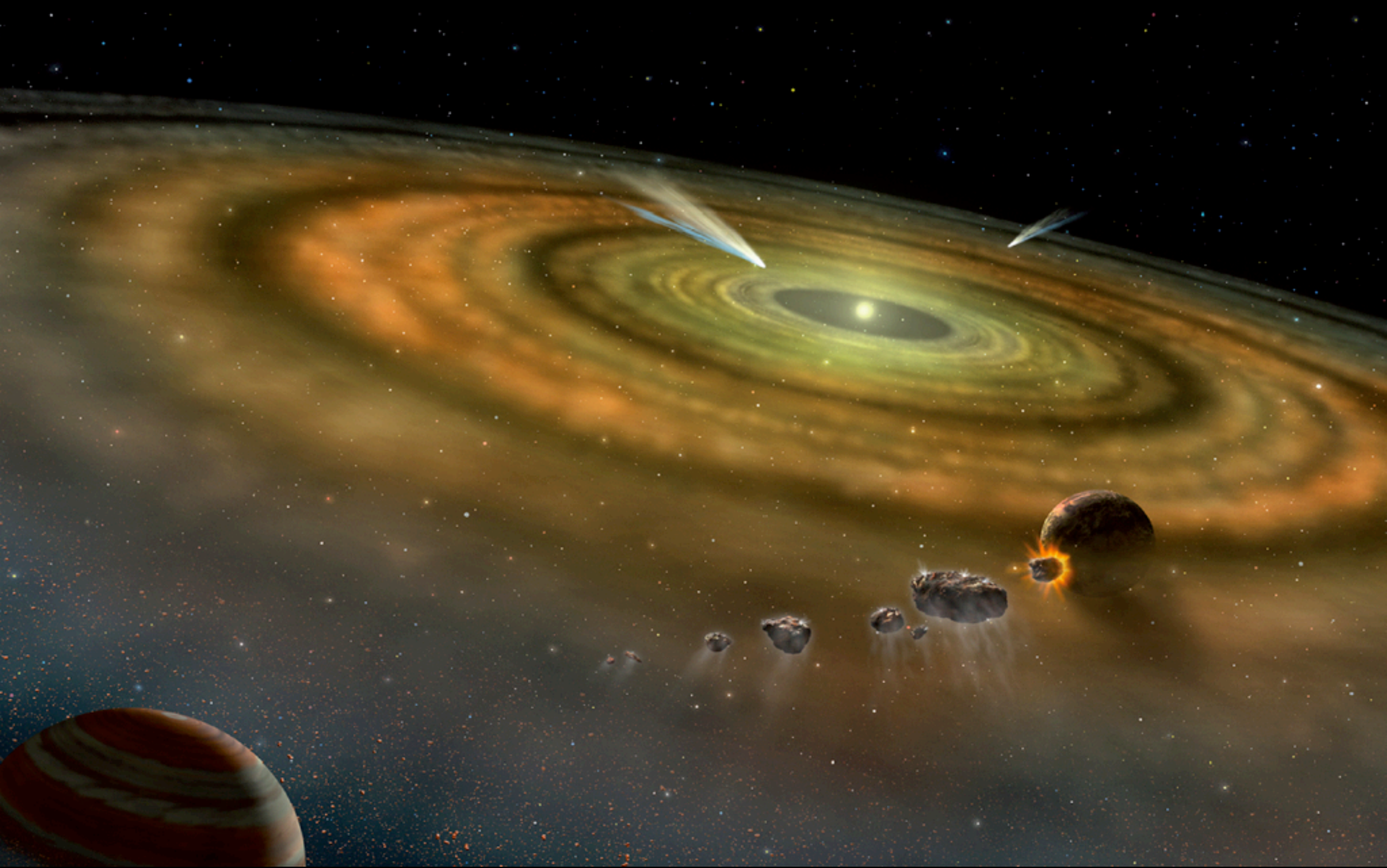
PLANETARY atmosphere

Outline:

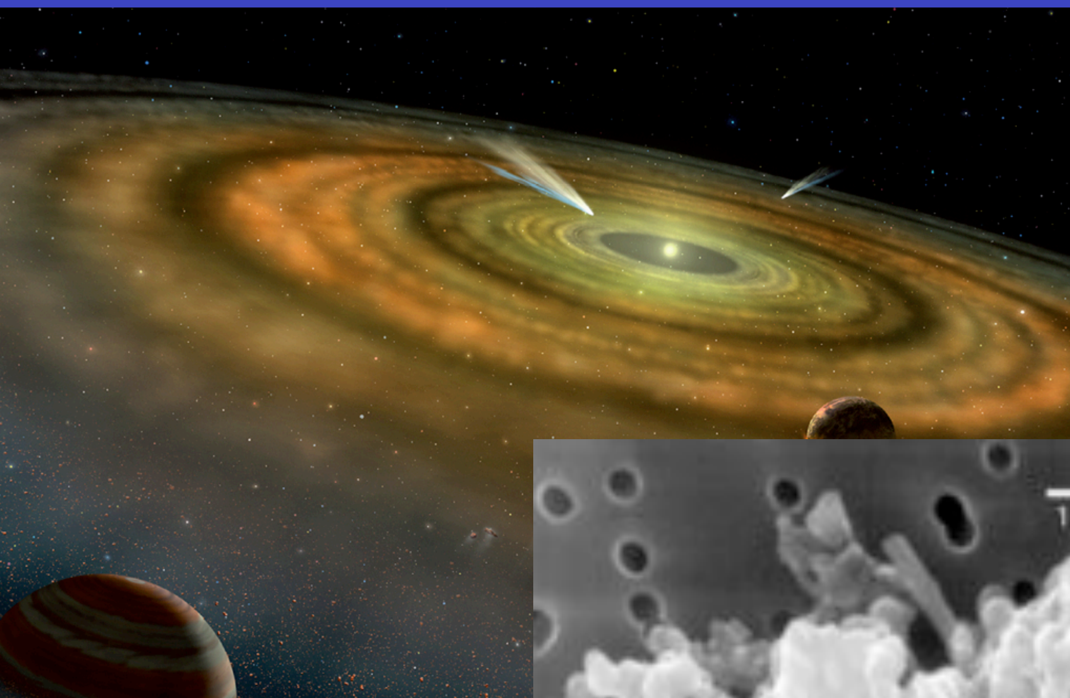
The role of Turbulence in Planet Formation

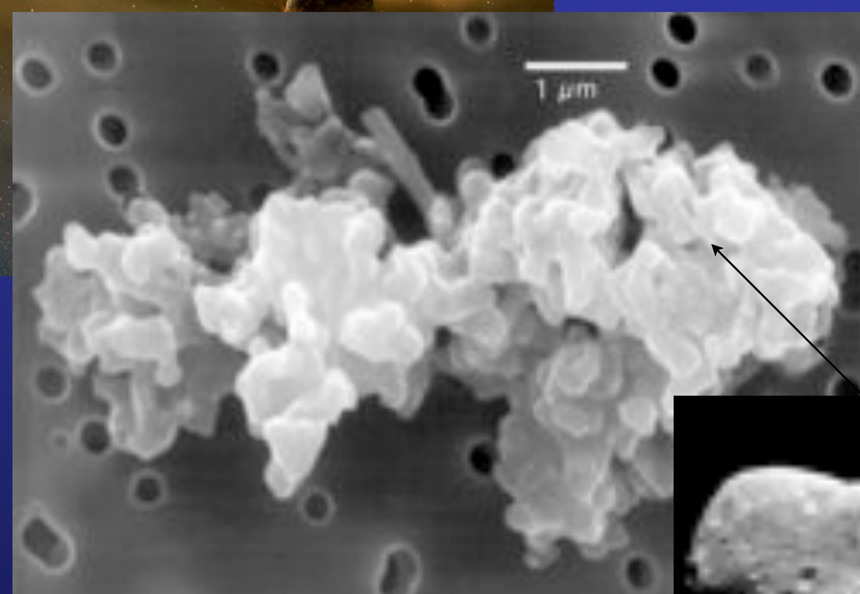
- Motivation - Planet Formation
- The rainfall of Planetesimal precursors and turbulence
- MHD turbulence
- Planetesimal formation via Gravoturbulence
- Convective Overstability => Vortices
- Goldreich-Schubert-Fricke
- Summary, Conclusions

“Birth places of Planets:” Gas and dust disks around young stars



Planet Formation





Surface sticking

Gravity bound

time

Gravoturbulent Planetesimal Formation from Gravel concentrated in Vortices and Zonal Flows

particles move inward
= up the pressure gradient

$$\partial_t v_g = -\frac{1}{\rho}\nabla p + \text{forces}$$

$$\partial_t v_d = -\frac{v_d - v_g}{\tau_f} + \text{forces}$$

$$v_d = v_g + \tau_f \frac{1}{\rho}\nabla p$$

Klahr & Lin 2000

Laminar disk: No growth beyond 10cm!

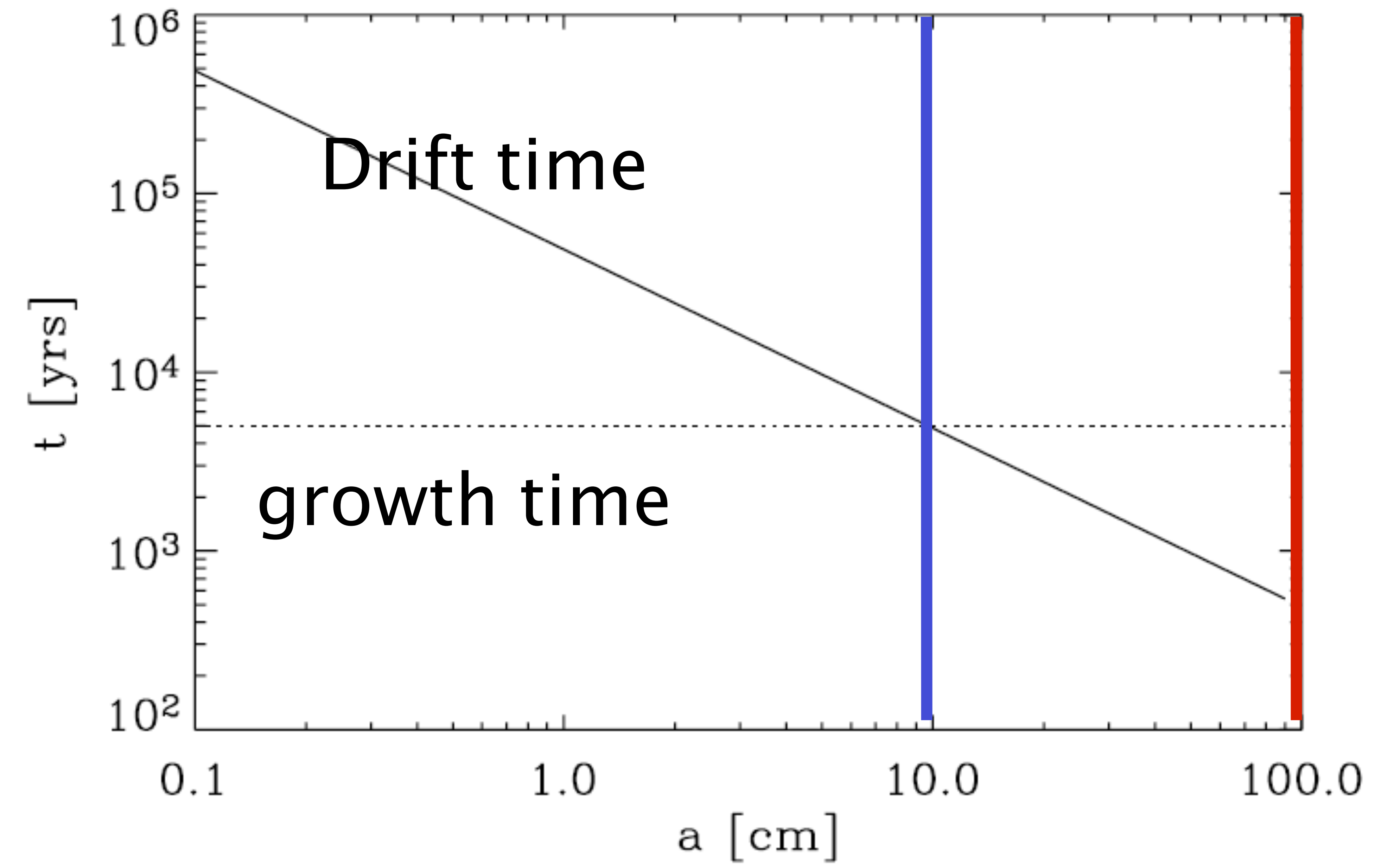
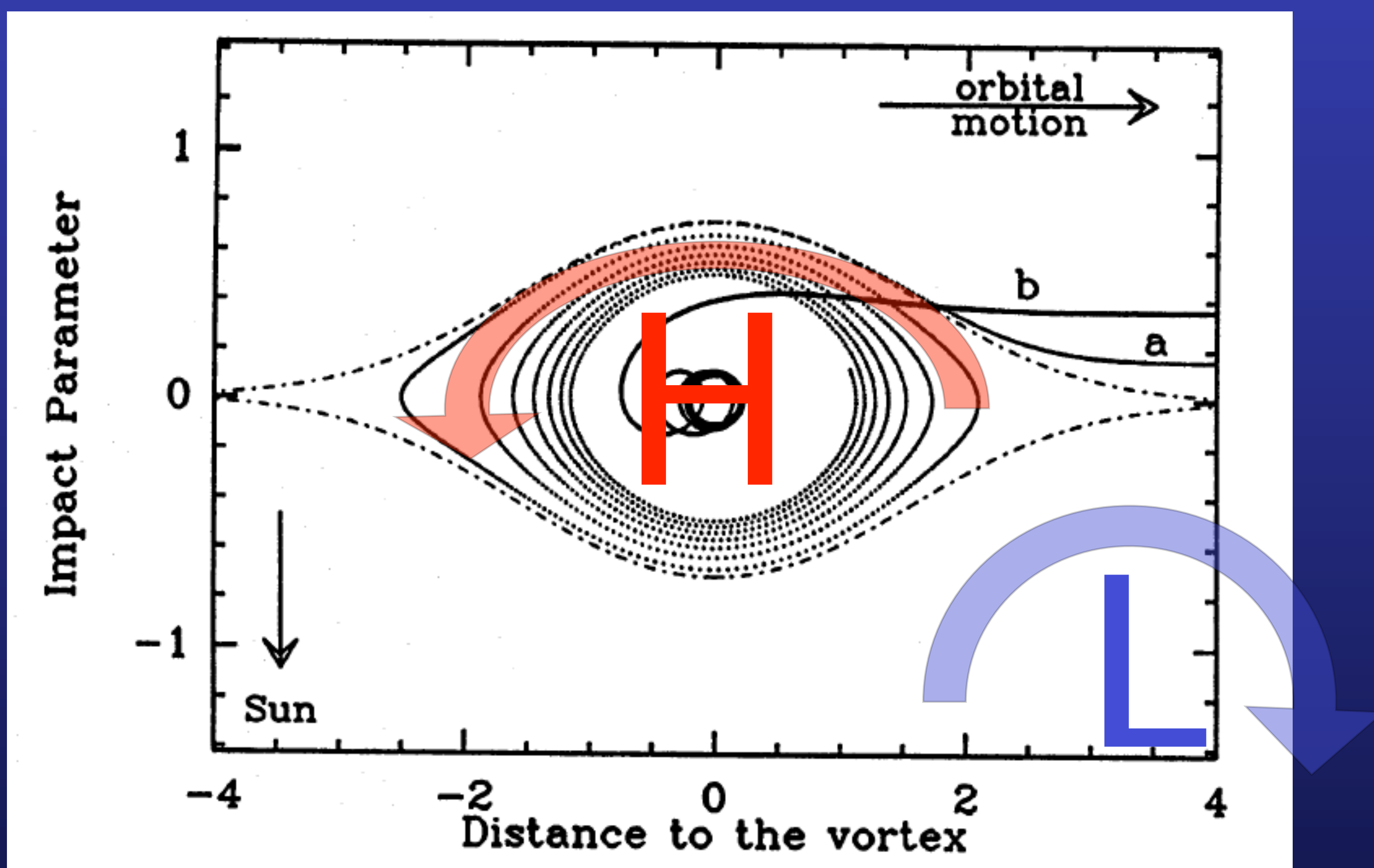


FIG. 1.—Comparison between drift time (*solid line*) and growth time (*dotted line*) for solids as a function of size. The values are calculated using the equations from this paper for a location of 7.5 AU in a minimum mass solar nebula.

Klahr and Bodenheimer 2006

Particle response in rotating (DISK) frame:
Geostophic flow: balance of pressure and Coriolis forces



VORTICES:

Barge & Sommeria 1995

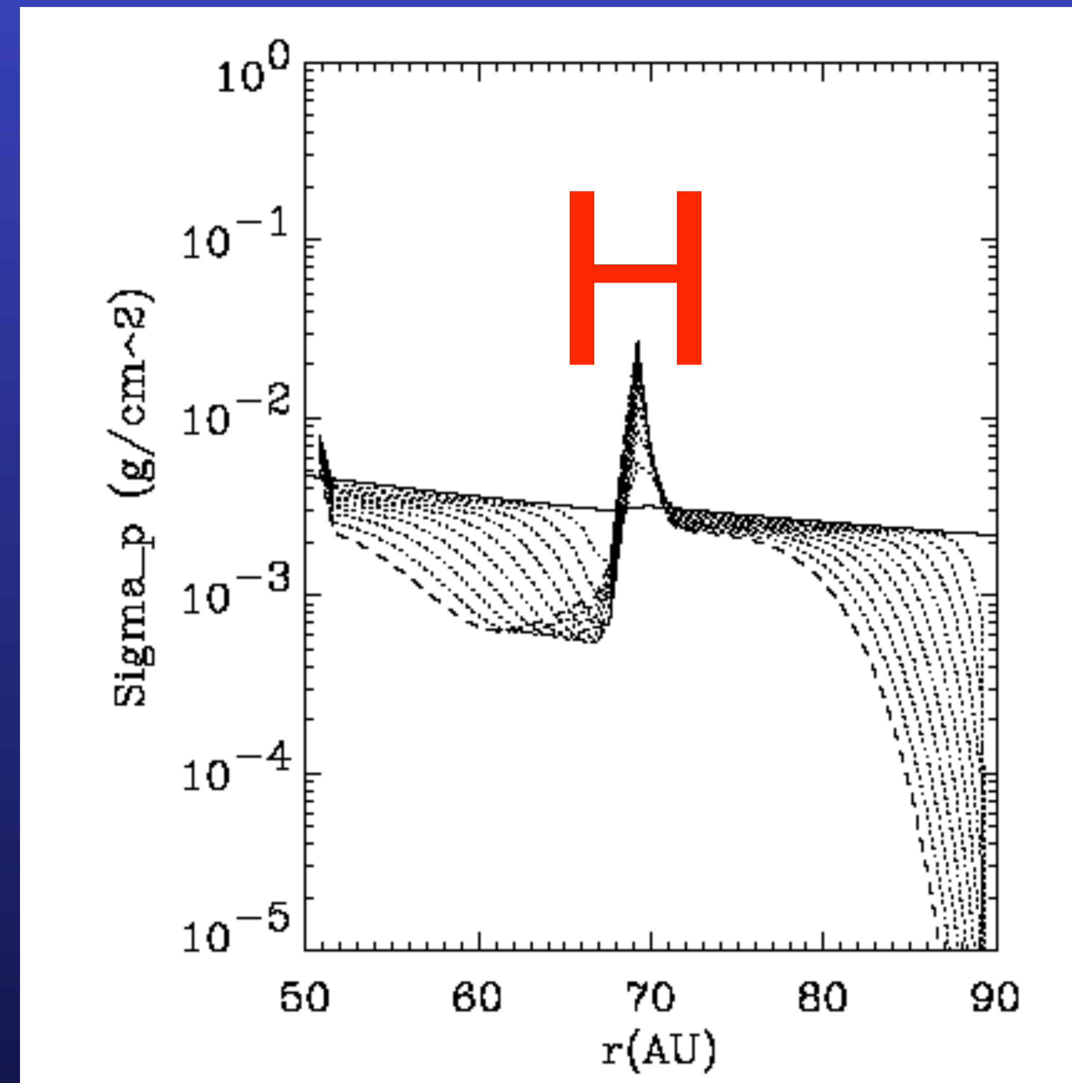


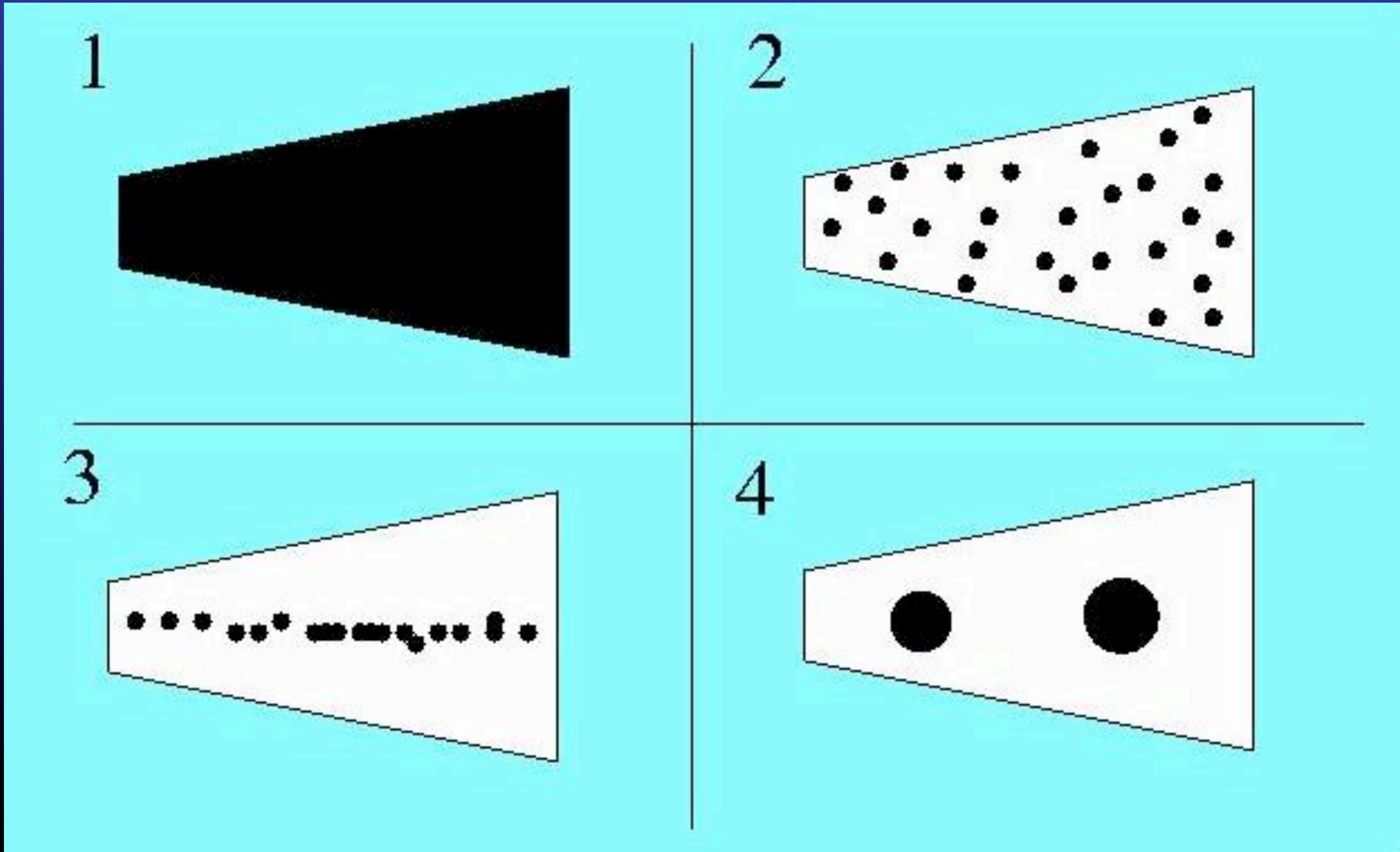
FIG. 7.—Model A: evolution of the 1 m size particle surface density distribution for the model in Fig. 2. The solid line gives the initial distribution. The following lines are snapshots every 10^5 yr.

ZONAL FLOWS:

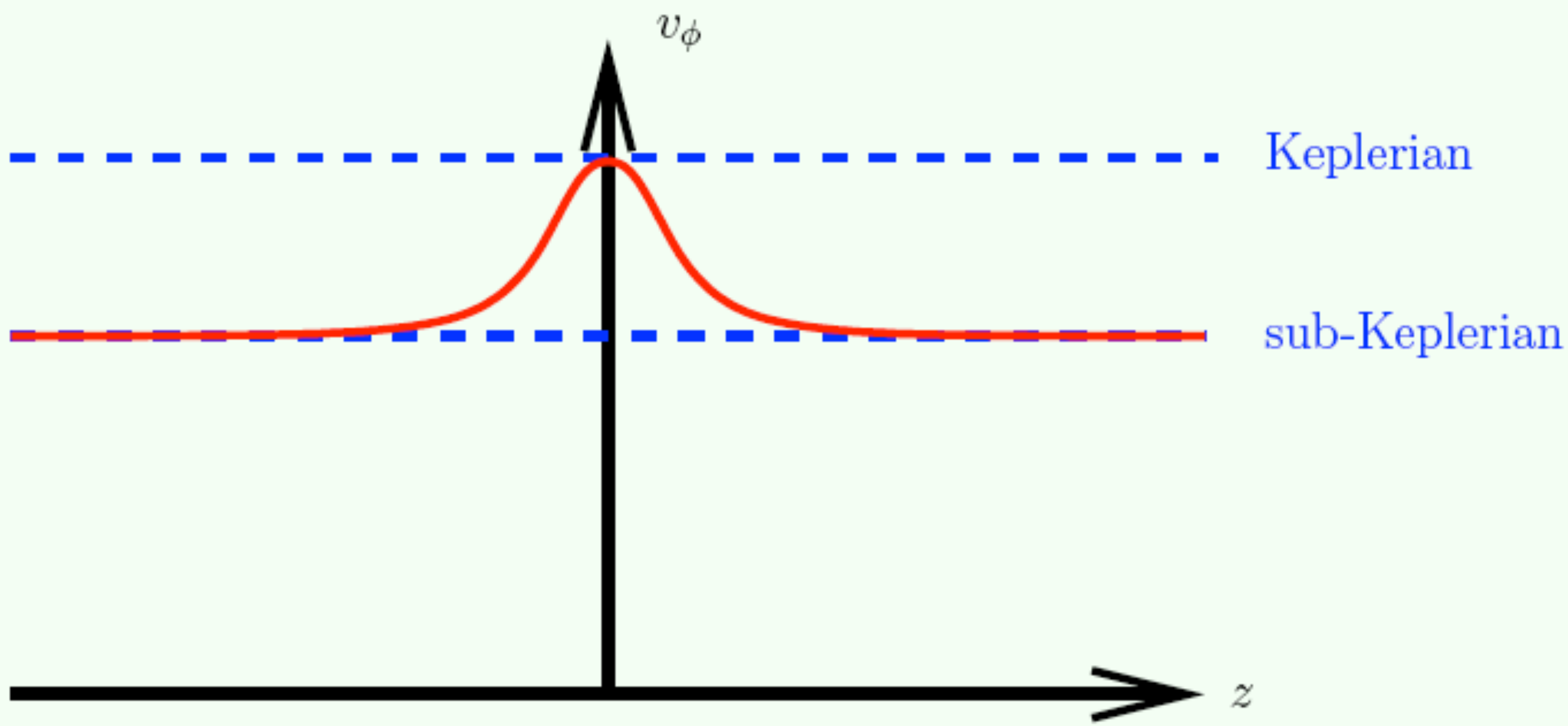
Radial Pressure maxima

Whipple 1964; Klahr & Lin 2000

What if there is no global turbulence?
=>Sedimentation to the midplane.
Gravitational instability in the dust midplane layer?
(Safronov 1969, Goldreich & Ward 1973)



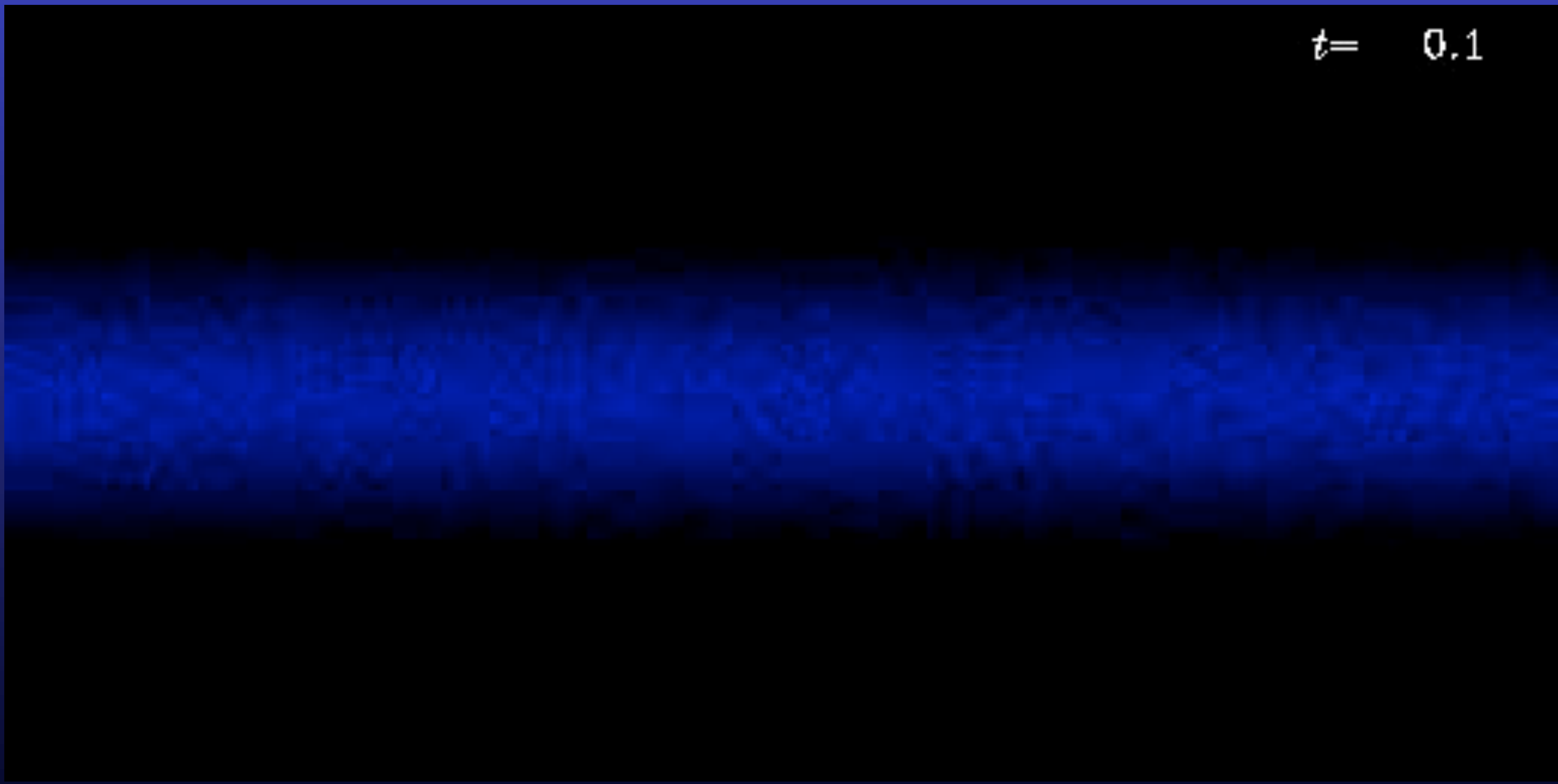
Kelvin-Helmholtz instability



- Gas forced to move sub-Keplerian away from the mid-plane (by the global pressure gradient) and Keplerian in the mid-plane (by the dust)
- Vertical shear is unstable to Kelvin-Helmholtz instability
- Subsequent turbulence lifts up the dust layer and reduces the dust density in the mid-plane

10 cm sized boulders:

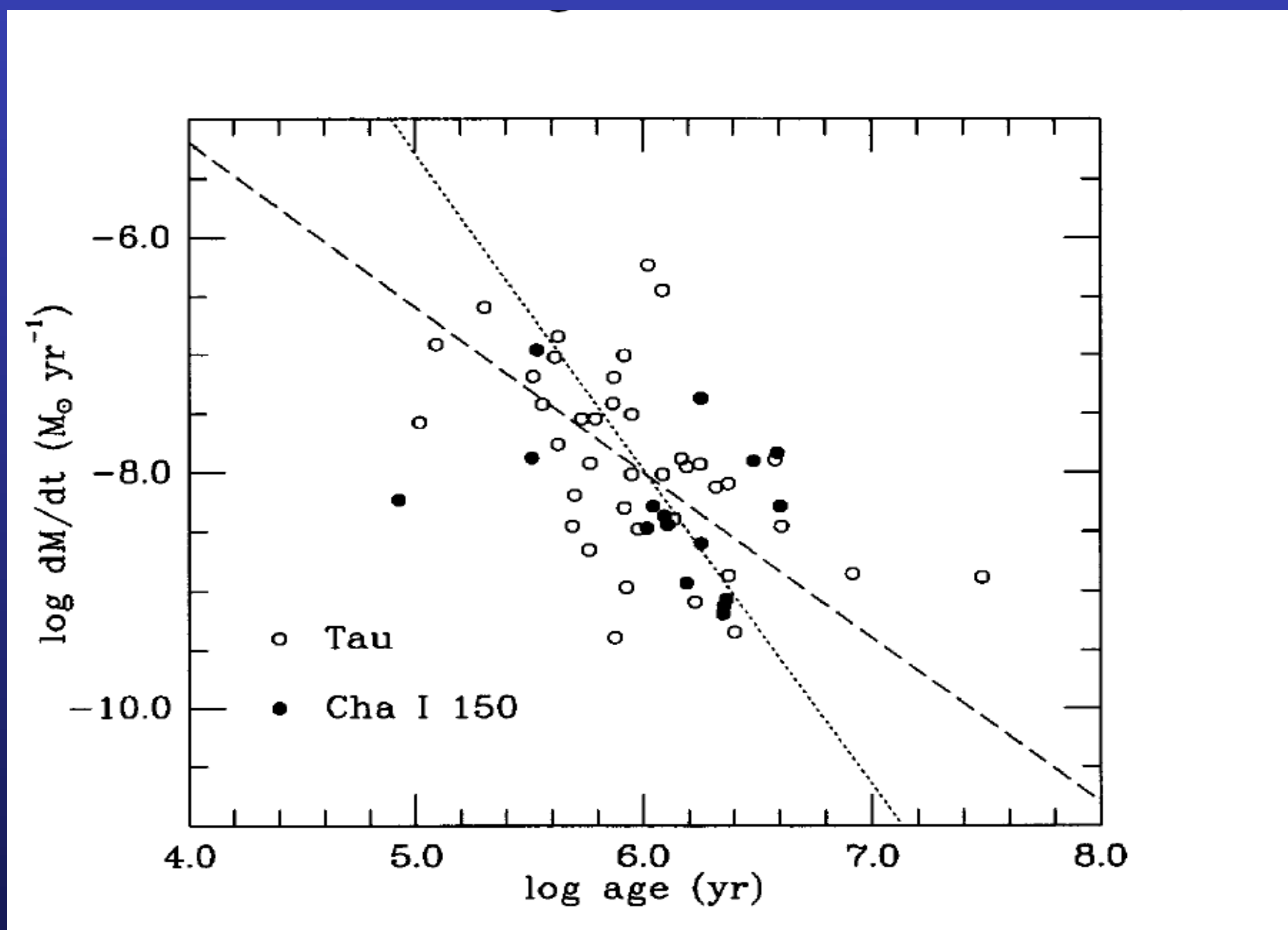
Vertical



horizontal

Johansen, Henning & Klahr 2006

Accretion Energy in rotating systems =>
Turbulent transport of angular momentum



Hartmann et al. 1998, 2006

alpha = 0.01

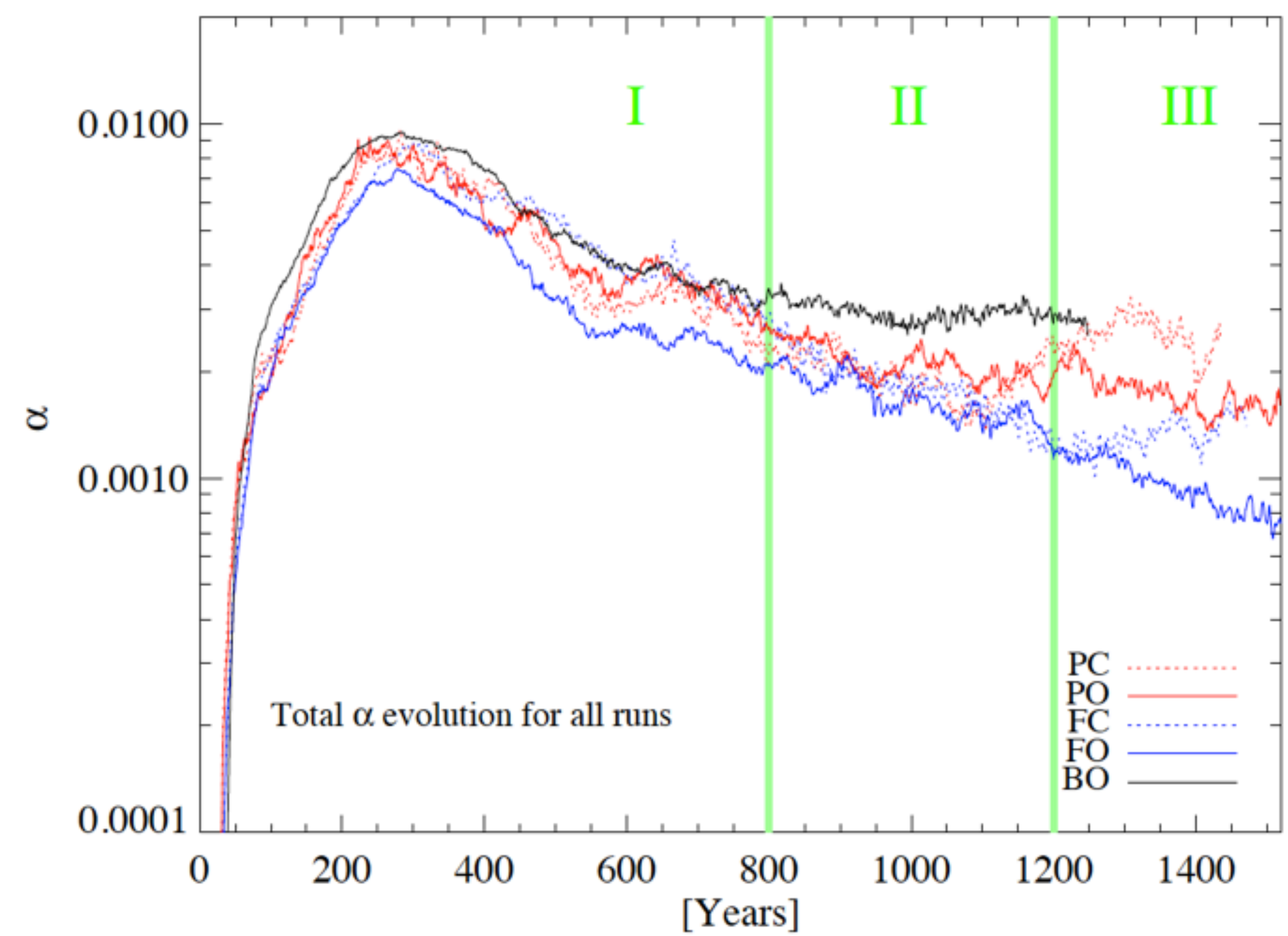
WHY DO T TAURI DISKS ACCRETE?

Turbulence in Disks: Candidates

- Self Gravity until mass too low
- Non-linear Shear Instability
- Magneto-Hydro turbulence
- Rossby-Wave Instability (Kelvin-Helmholtz in disks) => Heloise Meheut
- Convective Overstability => Vortices ("subcritical baroclinic instability")
- Goldreich-Schubert-Fricke
- Critical layer ("Zombie Vortices") => talk to Phil Marcus

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

Pluto Code: HLLD Upwind CT, piecewise linear reconstruction, Runge Kutta 2nd order



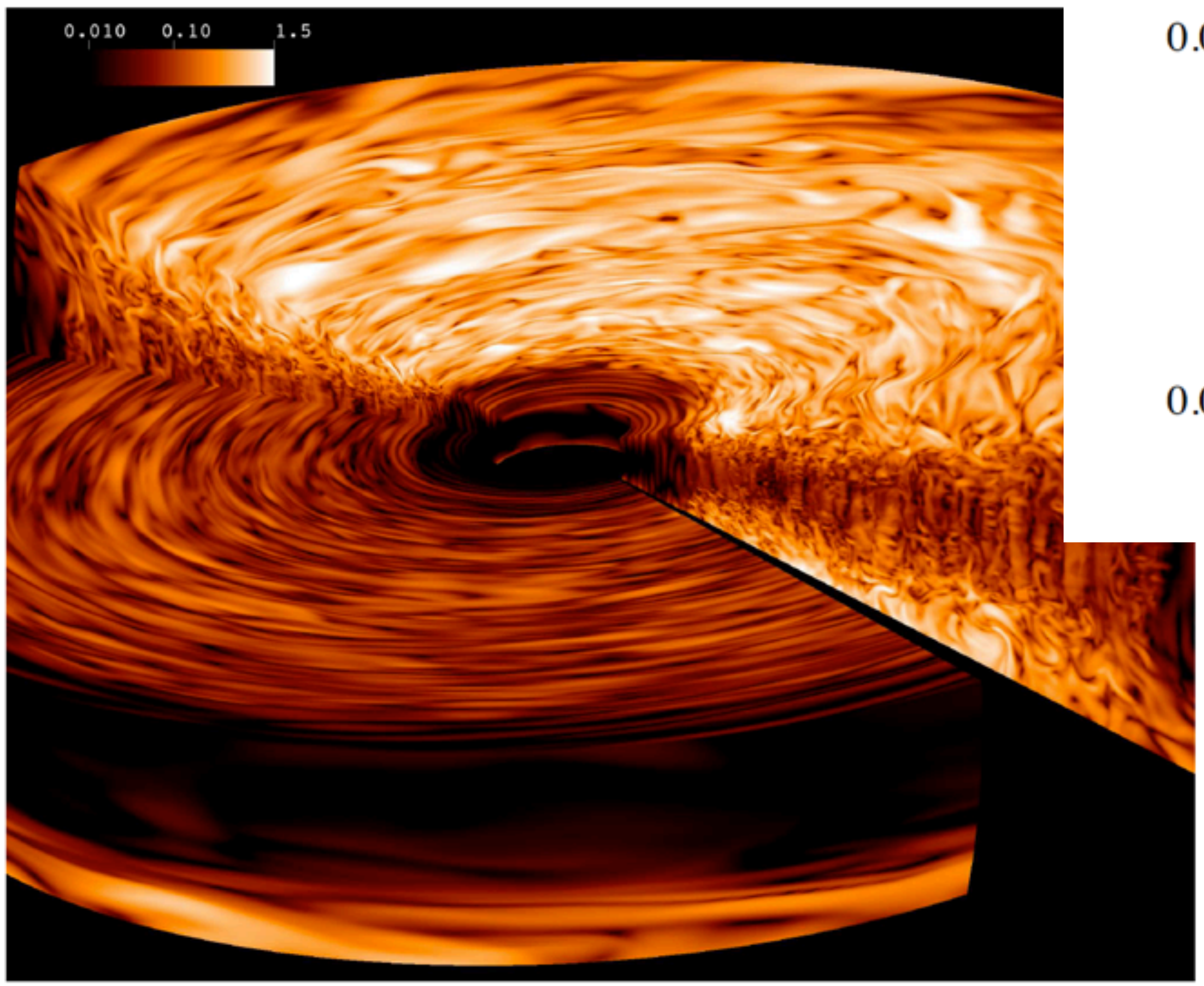


Fig. 5.— 3D contour plot of turbulent rms velocity at 750 inner orbits for model BO.

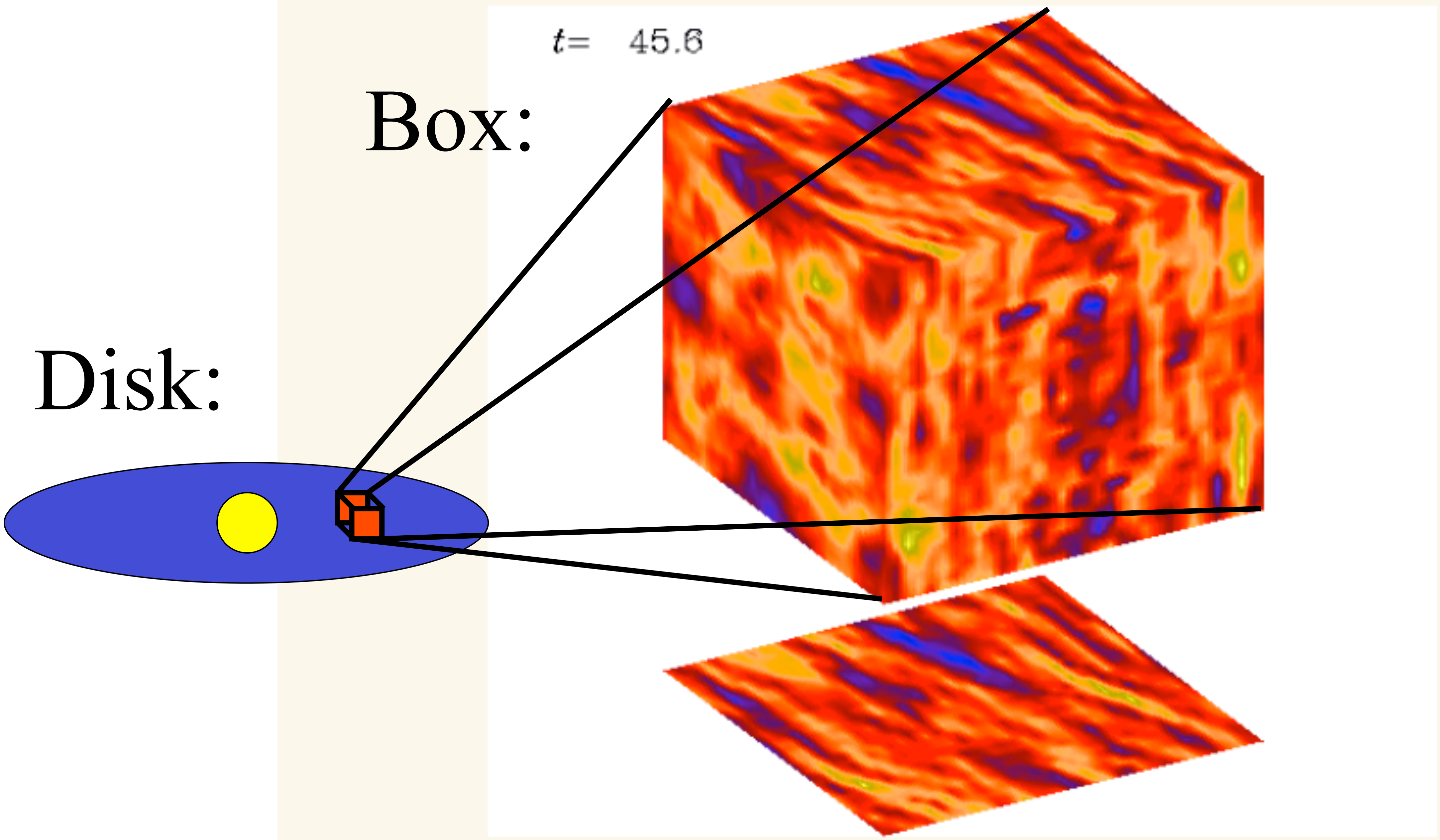
384x192x768

Flock, Dzyurkevich, Klahr, Turner, Henning, 2011

Global 360 stratified!
At 20 grid cells per H!
1.8 Million CPU hours

MRI turbulence

…because it is a reliable source for turbulence.



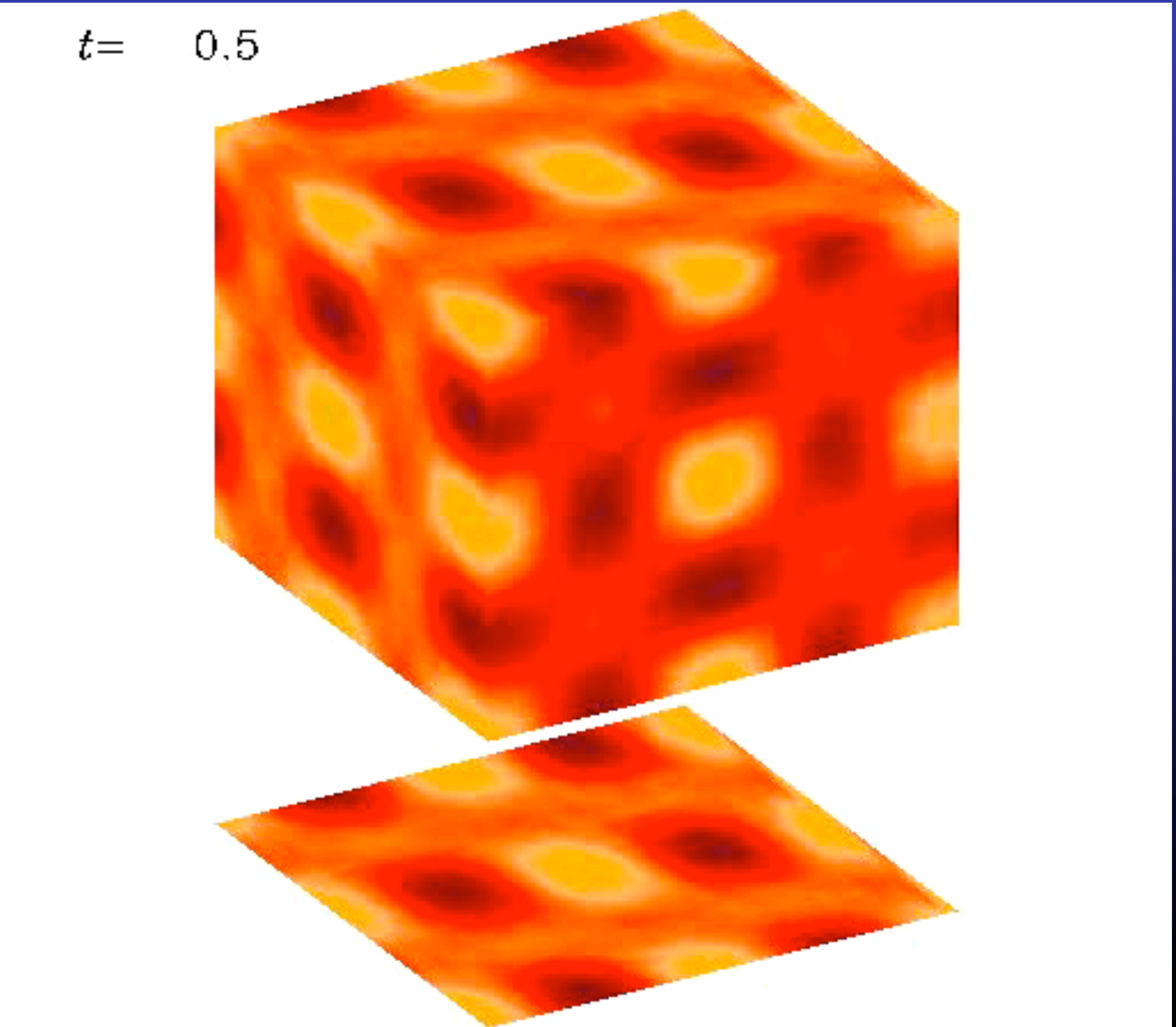
Code: The Pencil-Code [MHD code, finite differences, 6th order in space, 3rd order in time, Brandenburg (2003)]

Development of MHD Turbulence

From initial perturbation to saturation of the turbulence

Colors: gas density
yellow = high
blue = low

Standard magneto rotational instability simulation ala Balbus and Hawley

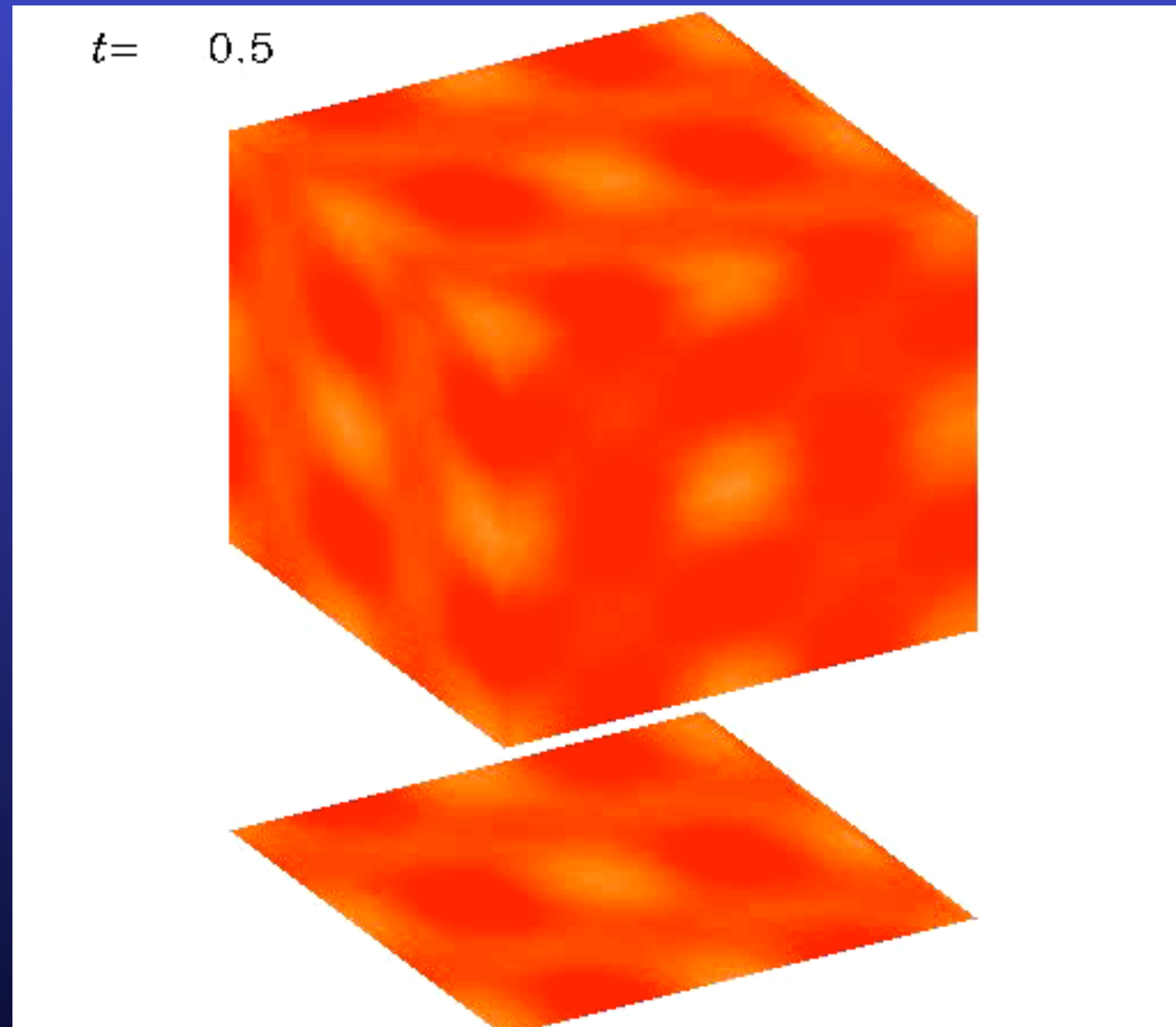


Dust Sedimentation

A vertical force field drives sedimentation.

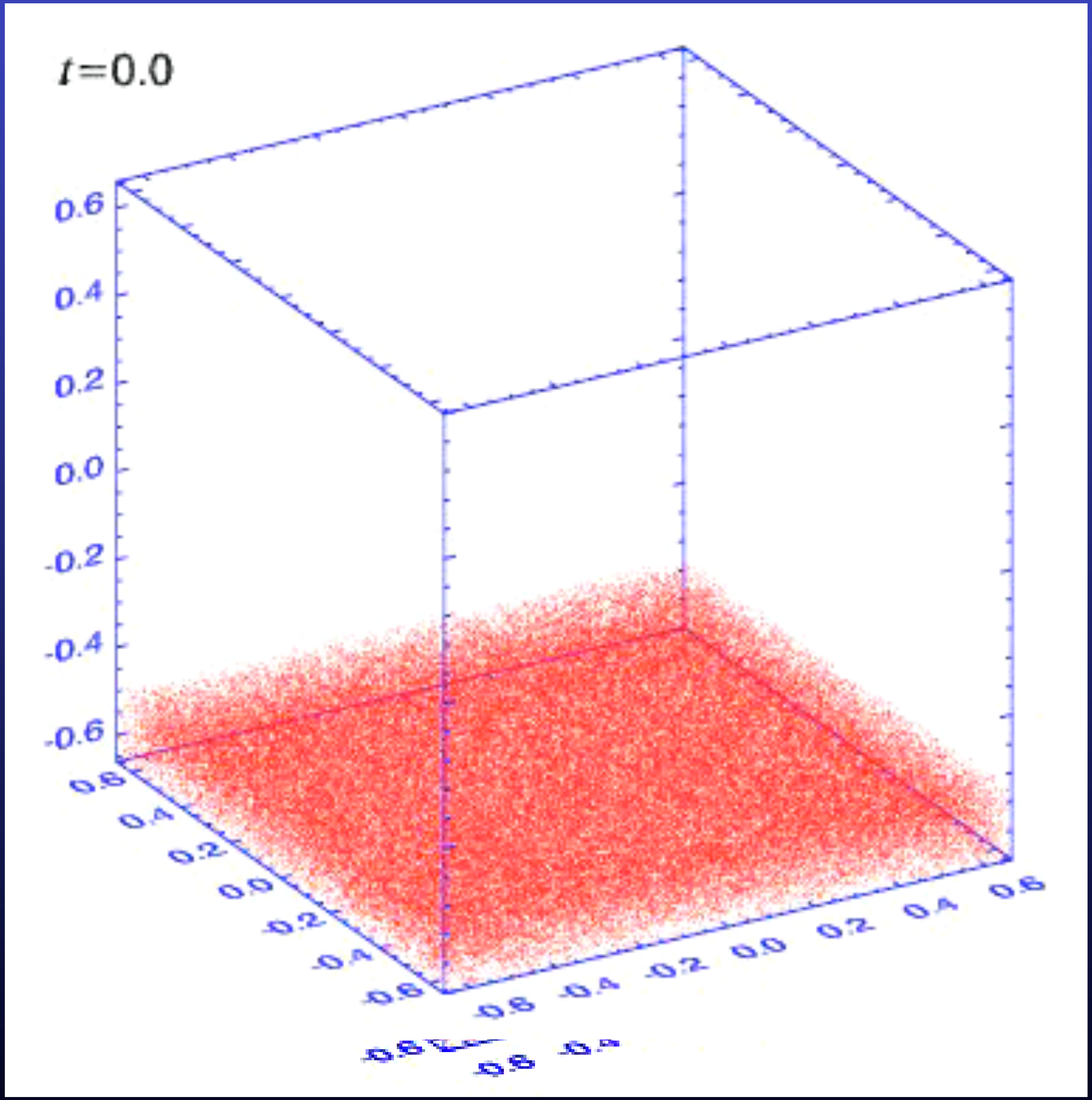
Dust number density:
yellow = high density
blue = low density

Easy to measure amplitude
=> diffusivity



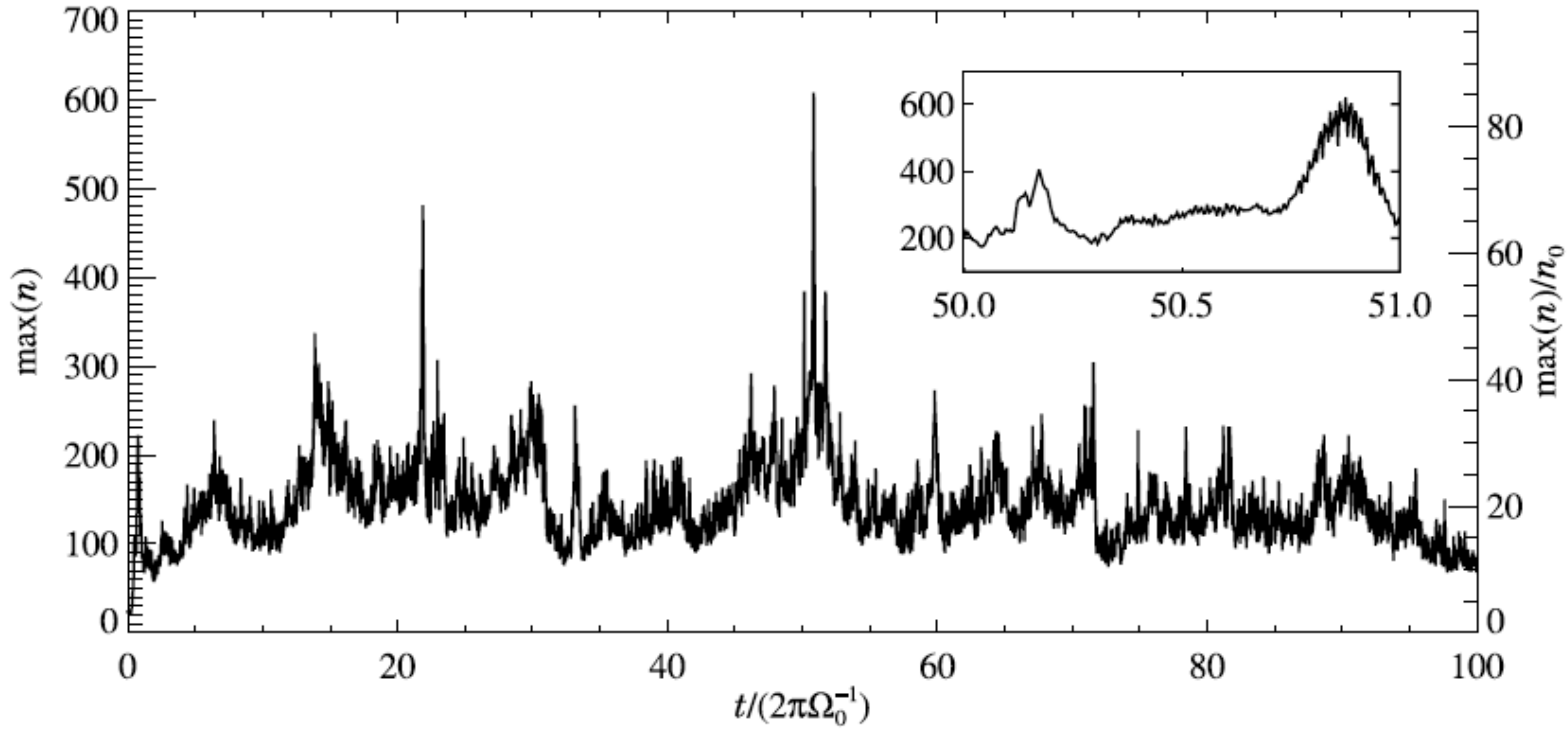
$$\text{Amplitude}=\frac{\tau_f g_0}{k_z D_t}$$

2,000,000 boulders of 1m size



Johansen, Klahr and Henning, 2006

1m boulders



=> Gravoturbulent formation of planetesimals:
Johansen, Klahr and Henning, 2006
See Poster by Karsten Dittrich!

MHD plus self-gravity for the dust, including particle feed back on the gas: Pencil Code

gas

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u} + u_y^{(0)}\frac{\partial \boldsymbol{u}}{\partial y} = 2\Omega u_y \hat{\boldsymbol{x}} - \frac{1}{2}\Omega u_x \hat{\boldsymbol{y}} - \boldsymbol{\nabla}\Phi + \frac{1}{\rho}\boldsymbol{J}\times\boldsymbol{B} - \frac{1}{\rho}c_{\mathrm{s}}^2\boldsymbol{\nabla}\rho - \frac{\rho_{\mathrm{d}}/\rho}{\tau_{\mathrm{f}}}(\boldsymbol{u}-\boldsymbol{w}) + \boldsymbol{f}_\nu(\boldsymbol{u},\rho)\,,$$

$$\frac{\partial \rho}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\rho + u_y^{(0)}\frac{\partial \rho}{\partial y} = -\rho\boldsymbol{\nabla}\cdot\boldsymbol{u} + f_{\mathrm{D}}(\rho)\,,$$

$$\frac{\partial \boldsymbol{A}}{\partial t} + u_y^{(0)}\frac{\partial \boldsymbol{A}}{\partial y} = \frac{3}{2}\Omega A_y \hat{\boldsymbol{x}} + \boldsymbol{u}\times\boldsymbol{B} + \boldsymbol{f}_\eta(\boldsymbol{A})\,,$$

$$\nabla^2\Phi = 4\pi G(\rho + \rho_{\mathrm{d}})\,.$$

dust

$$\frac{\partial \boldsymbol{v}^{(i)}}{\partial t} = 2\Omega v_y^{(i)}\hat{\boldsymbol{x}} - \frac{1}{2}\Omega v_x^{(i)}\hat{\boldsymbol{y}} - \Omega^2 z - \boldsymbol{\nabla}\Phi(\boldsymbol{x}^{(i)}) - \frac{1}{\tau_{\mathrm{f}}}[\boldsymbol{v}^{(i)} - \boldsymbol{u}(\boldsymbol{x}^{(i)})]\,,$$

$$\frac{\partial \boldsymbol{x}^{(i)}}{\partial t} = \boldsymbol{v}^{(i)} + u_y^{(0)}\hat{\boldsymbol{y}}\,.$$

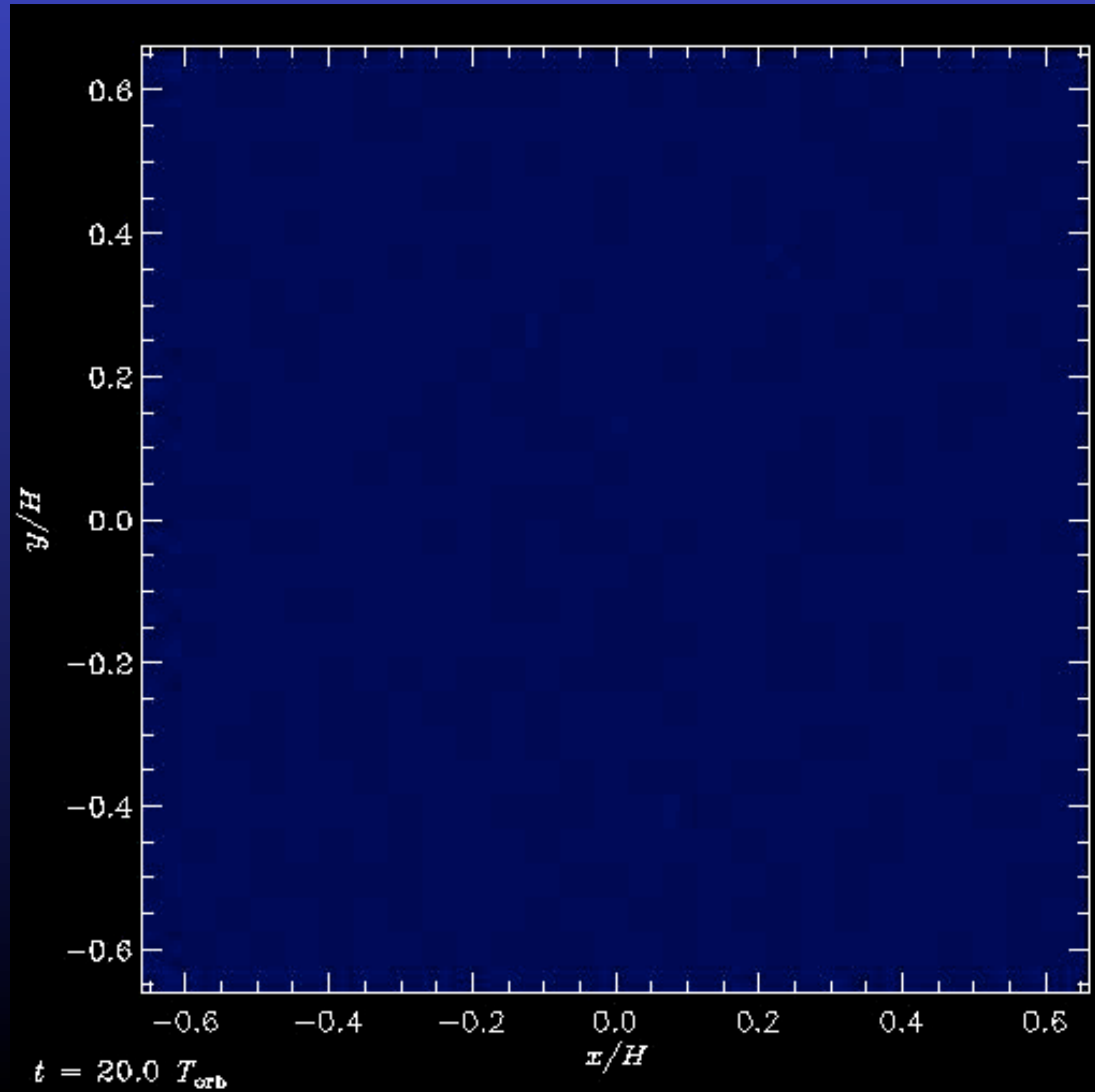
Poisson equation solved via FFT in parallel mode: up to 256^3 cells

Gravoturbulent formation of planetesimals - Concentration in Zonal Flows:

Formation Of Planetesimals From pressure trapped / gravitational Bound heaps of gravel - here magnetic turbulence:

Johansen, Klahr & Henning 2011. Vortices: Raettig, Klahr & Lyra

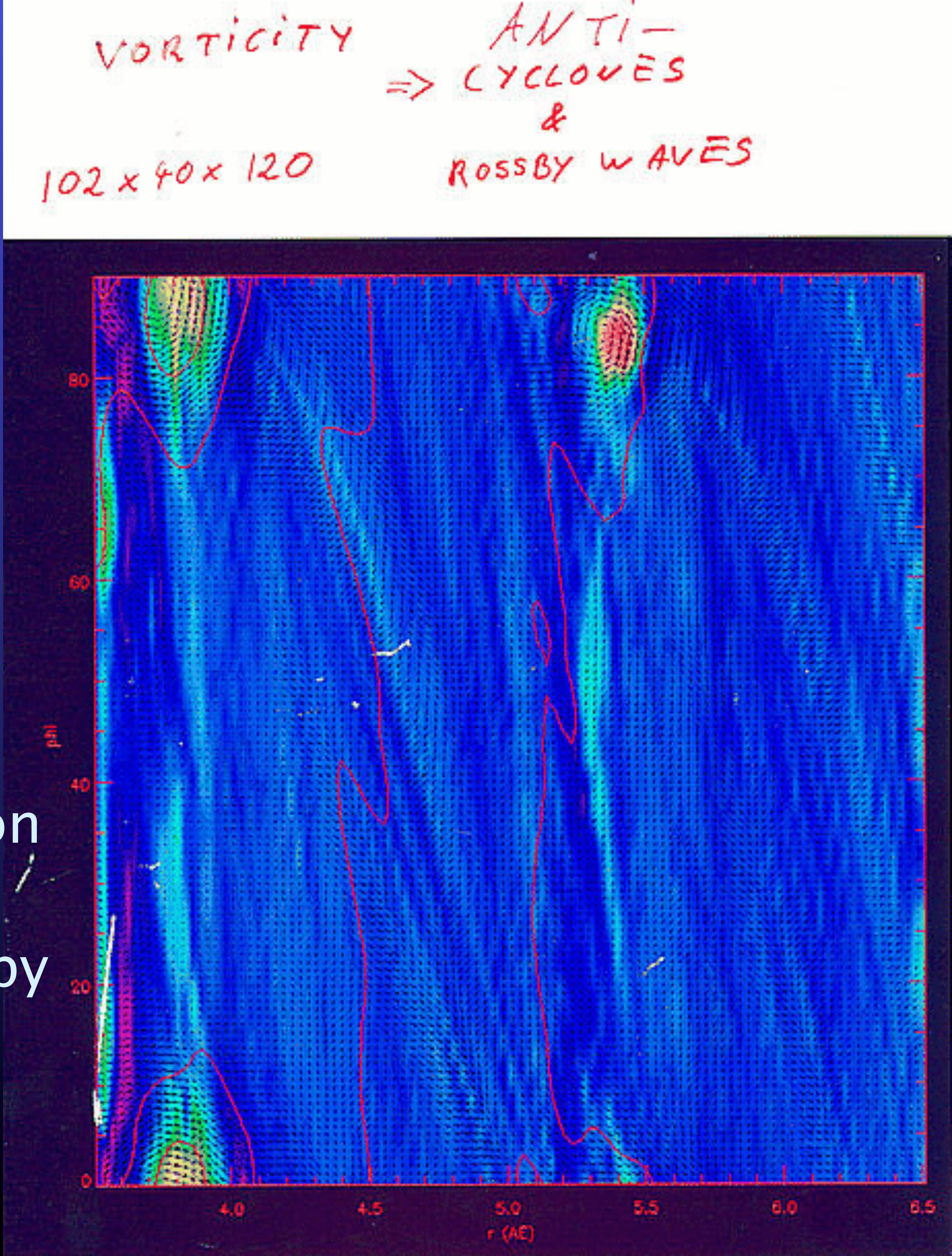
512 ^2 simulation
64 Mio particles
Entire project used 15 Mio. CPU hours.



14 years back…
…before I was doing this with MHD we tried Thermal Convection for turbulence

My very first vortices:
The historic Simulation:
About 1999
Large Scale
3D - Simulation
90 degree
3.5 - 6.5 AU
102 X 40 X 120 cells
=> Vortices

3D Global Disk Simulation
flux limited Diffusion
temperatur maintained by
artifical (viscous)heating



The Astrophysical Journal, 582:869–892, 2003 January 10

TURBULENCE IN ACCRETION DISKS: VORTICITY GENERATION AND ANGULAR MOMENTUM TRANSPORT VIA THE GLOBAL BAROCLINIC INSTABILITY

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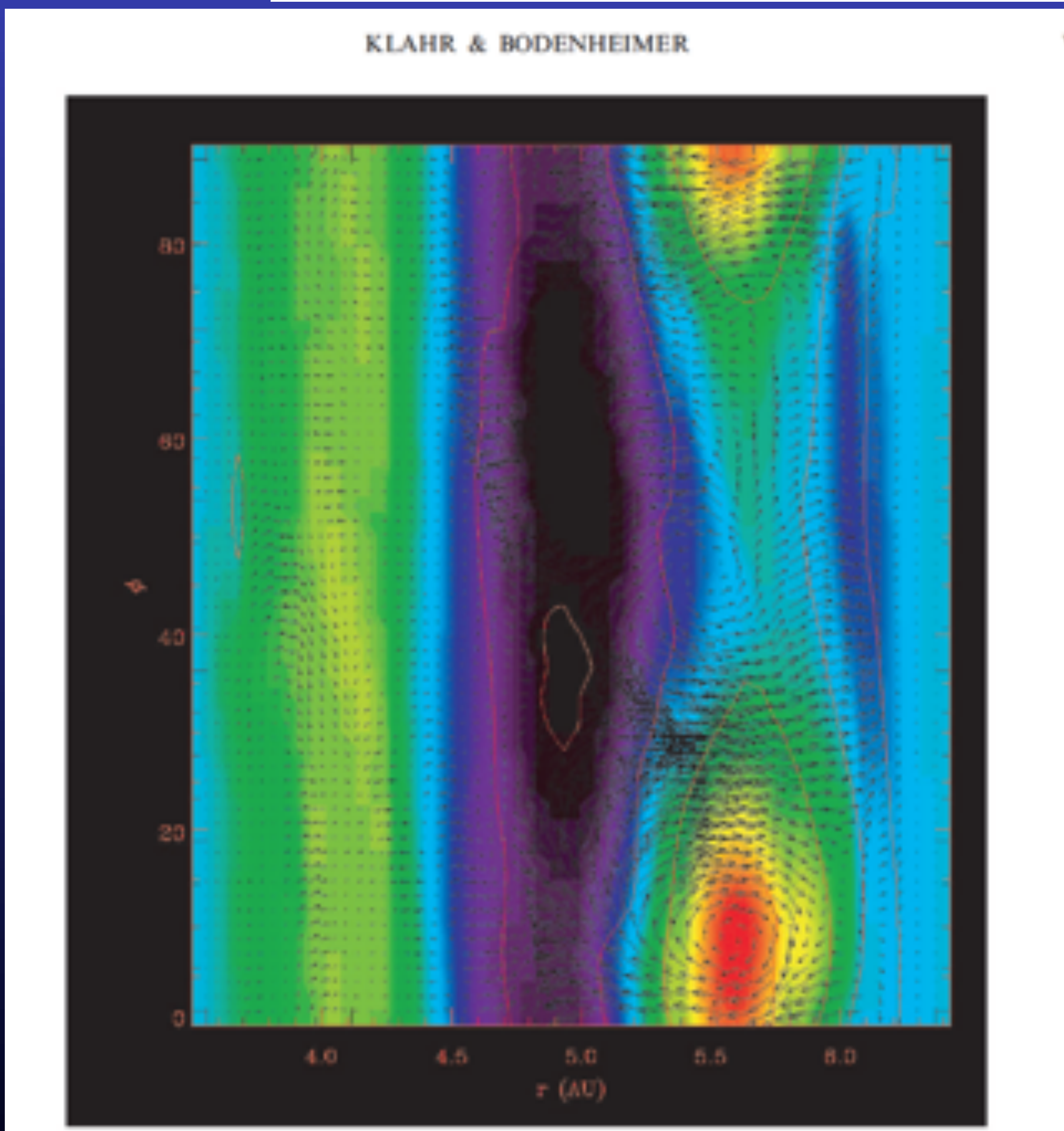
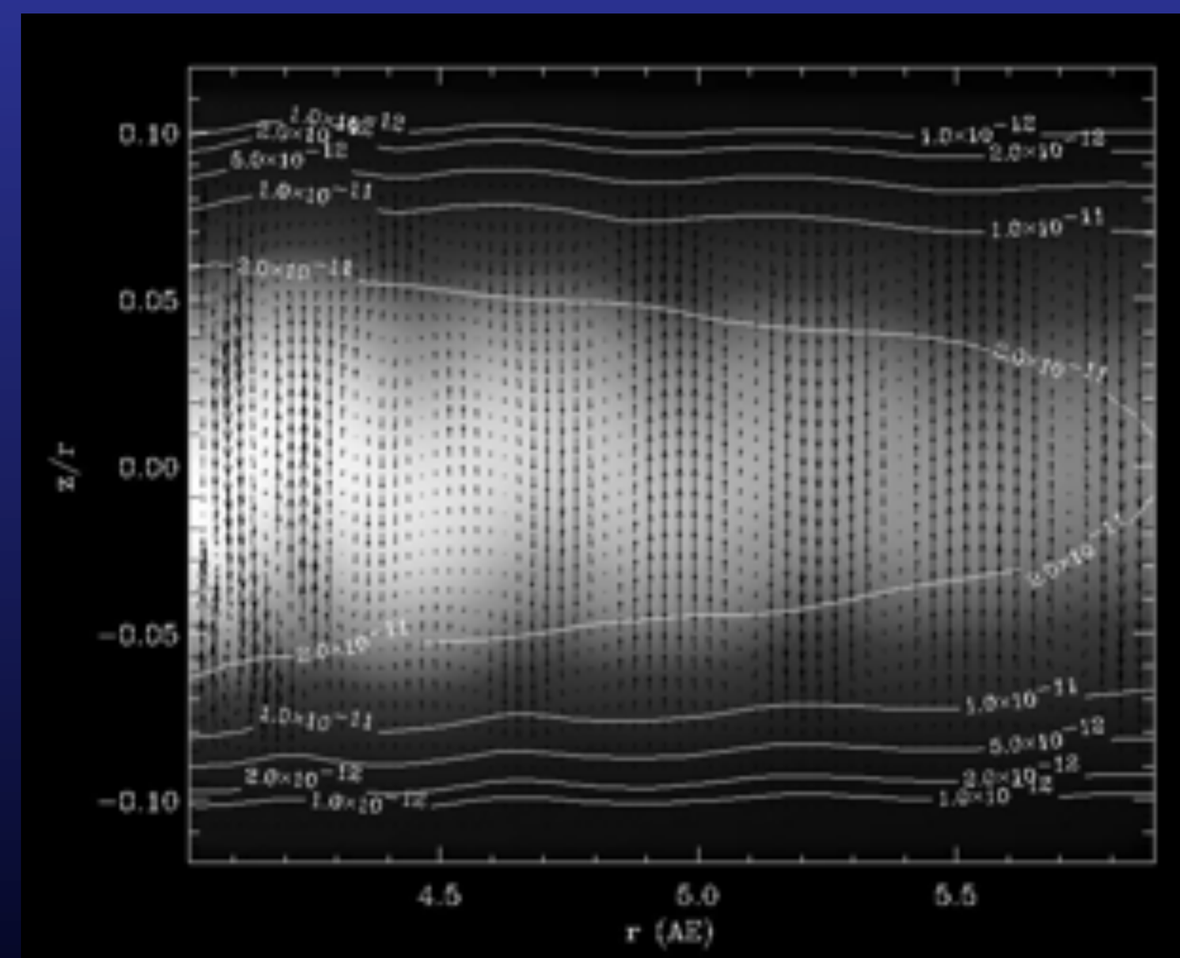
Received 2000 June 7; accepted 2002 September 17



3D - Radiation Hydro of Convection in Disks. Klahr, Henning & Kley 1999



Klahr & Bodenheimer 2003

Radial Entropy Gradient leads to vortices somehow…

Klahr 2004: not a linear instability

Because:

$$Ri^{-} = -\frac{2}{3\gamma}\left(\frac{H}{R}\right)^2 \beta_p \beta_s$$

$$-0.001 > Ri > -0.01$$

Then a lot of discussion started…

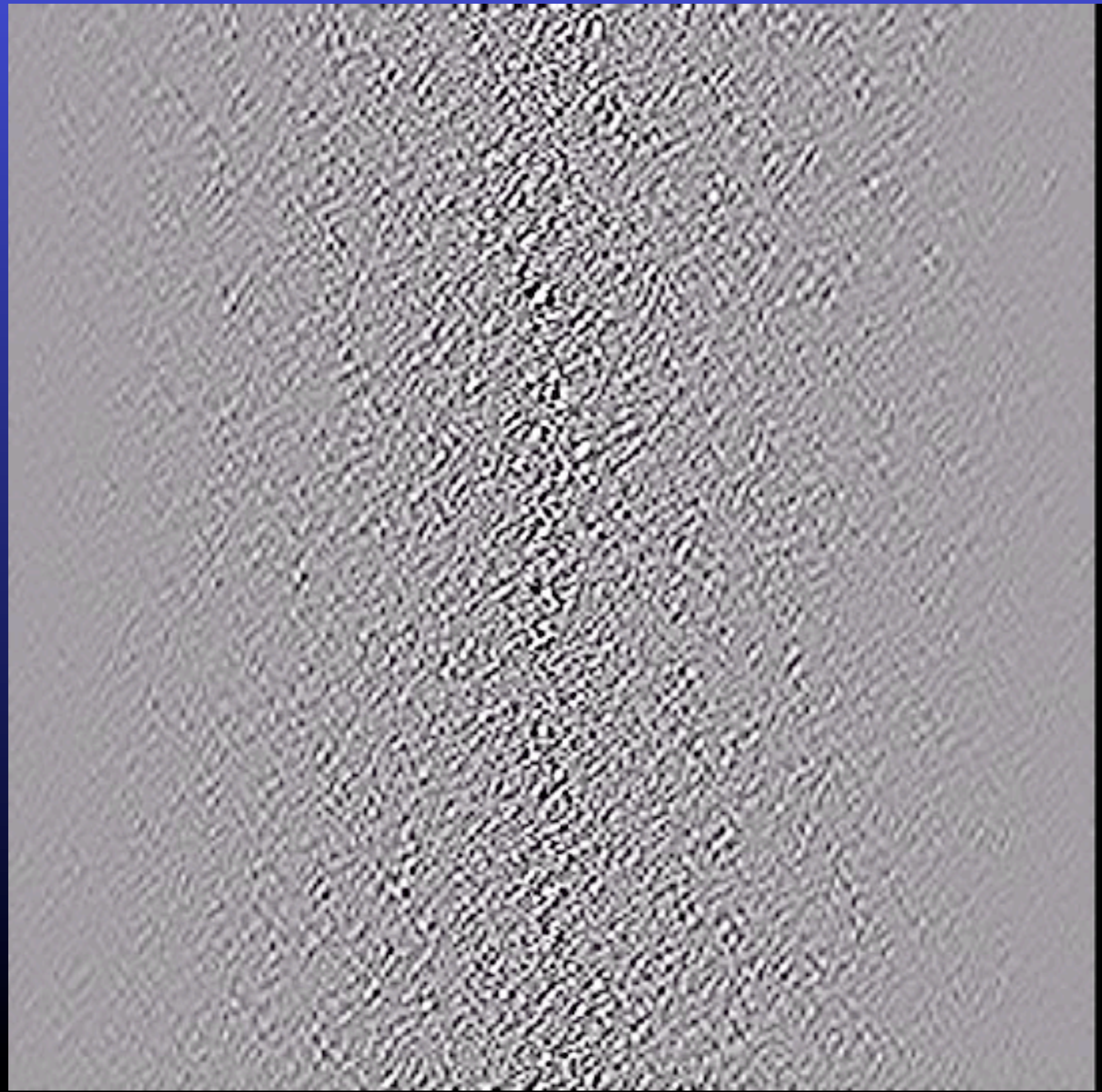
…but 4 years later:

Petersen, Stewart and Julien 2007:

“Works with the right amount of thermal relaxation!”

Vorticity

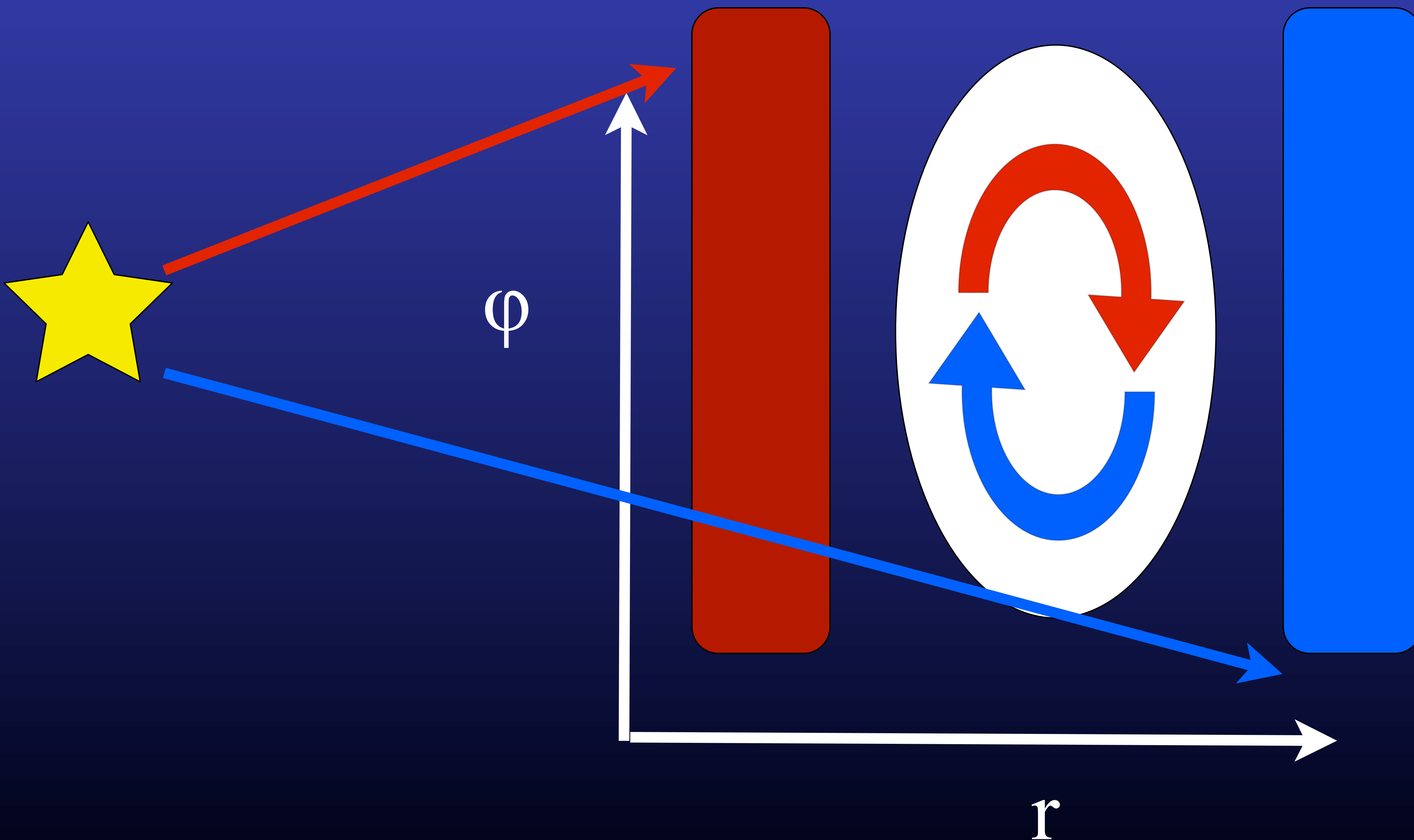
Vorticity: Pencil Code: Lyra and Klahr 2011; β = 2; N = 256; τ_c = 1



Lesur and Palaloizou 2010:"Subcritical Baroclinic Instability"

Like Convection Cells:

quasi Boussinesq



Convective Overstability!

2D - vertically integrated disk

(Klahr and Hubbard)

Stability under the influence of thermal relaxation

$$\partial_t u_R + u_R \partial_R u_R + \frac{u_\phi}{R} \partial_\phi u_R - \frac{u_\phi^2}{R} = -\frac{1}{\rho} \partial_R p + g_R$$

$$\partial_t u_\phi + u_R \partial_R u_\phi + \frac{u_\phi}{R} \partial_\phi u_\phi + \frac{u_\phi u_R}{R} = -\frac{1}{R\rho} \partial_\phi p$$

Incompressible Ansatz:

Constant Pressure Structure

$$\partial_t S + u_R \partial_R S + u_\phi \partial_\phi S = -\frac{S - S_0}{\tau}$$

2D - vertically integrated disk

(Klahr and Hubbard)

Stability under the influence of thermal relaxation

Linearized and WKB:

$$(\omega_m^2 - \kappa_R^2)(\omega_m + \frac{i}{\tau}) - \omega_m N_R^2 = 0$$

$\tau = 0$ => $\omega_m^2 = \kappa_R^2$ Rayleigh Criterion

$\tau = \infty$ => $\omega_m^2 = \kappa_R^2 + N_R^2$ Solberg-Hoiland

2D - vertically integrated disk

(Klahr and Hubbard)

Stability under the influence of thermal relaxation

$$(\omega_m^2 - \kappa_R^2)(\omega_m + \frac{i}{\tau}) - \omega_m N_R^2 = 0$$

$$\omega_m = \omega + i\Gamma$$

$$\Gamma = \frac{1}{2} \frac{-\tau N_R^2}{1 + \tau^2 \left(\kappa_R^2 + N_R^2\right)}$$

2D - vertically integrated disk

(Klahr and Hubbard)

Stability under the influence of thermal relaxation

$$\Gamma = \frac{1}{2}\frac{-\tau N_R^2}{1+\tau^2\left(\kappa_R^2+N_R^2\right)}$$

$$\Gamma = \frac{1}{2}\frac{-\frac{l^2}{\mu}N_R^2}{1+\left(\frac{l^2}{\mu}\right)^2\left(\kappa_R^2+N_R^2\right)} - \frac{\nu}{l^2}$$

2010 Similar to Lesur and Papaloizou 2010 for finite size vortices

$$\gamma \sim \frac{(-N^2)\sigma^2}{\mu}\phi_\omega(S\sigma^2/\mu) - \frac{\nu}{\sigma^2}.$$

2D - vertically integrated disk

(Klahr and Hubbard)

Stability under the influence of thermal relaxation

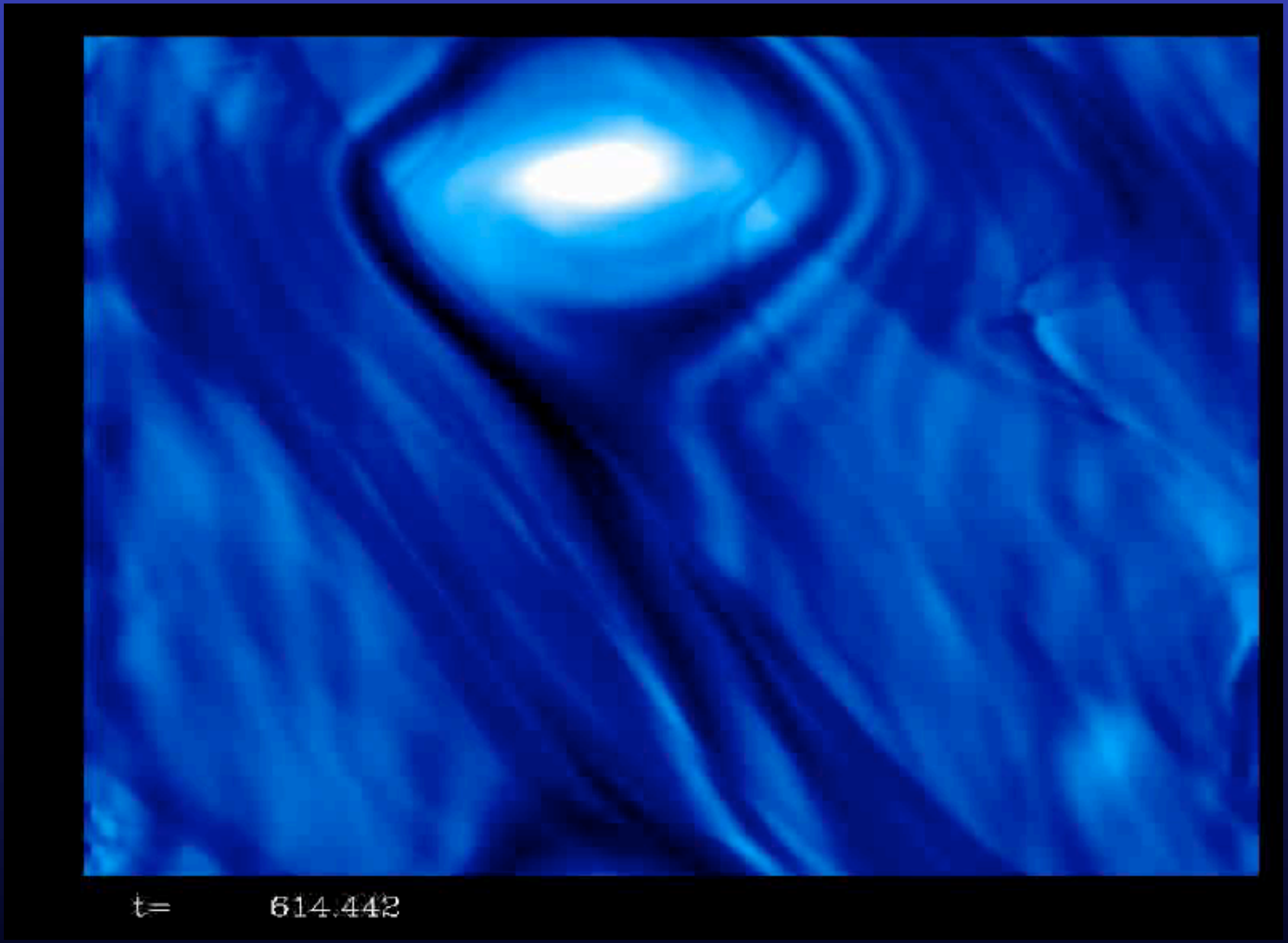
$$\tau\Omega << 1 \quad => \quad \frac{-N_R^2 l^4}{\nu\mu} > 2$$

Lesur and Papaloizou 2010: Rayleigh Number!

$$\tau\Omega = 1 \quad => \quad \Gamma = -\frac{1}{4} Ri\Omega - \frac{\nu}{l^2}$$

$$\frac{1}{4} RiRe \left(\frac{l}{H}\right)^2 \Omega > 1$$

Vorticity

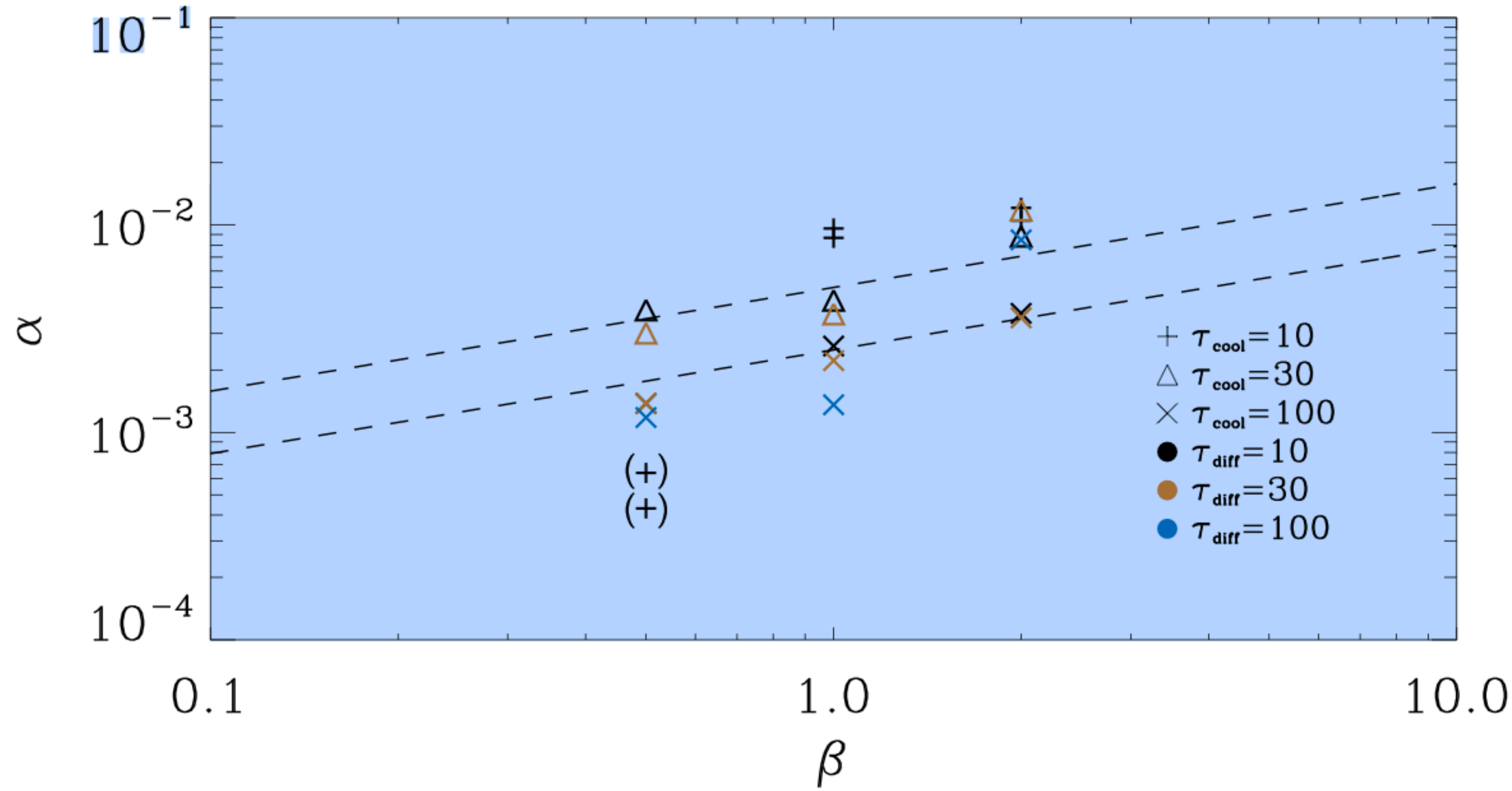


Density:

zimuthal

radial

Strength of alpha (local)
Raettig, Klahr and Lyra 2013



Growth rates

$$\Gamma = -\tau N_R^2 = -\frac{a^2}{D} N_R^2$$

see also Lesur and Papaloizou 2011

THE ASTROPHYSICAL JOURNAL, 723:1241–1254, 2010 November 10 doi:10.1088/0004-637X/723/2/1241

PROTOPLANETARY DISK STRUCTURES IN OPHIUCHUS. II. EXTENSION TO FAINTER SOURCES

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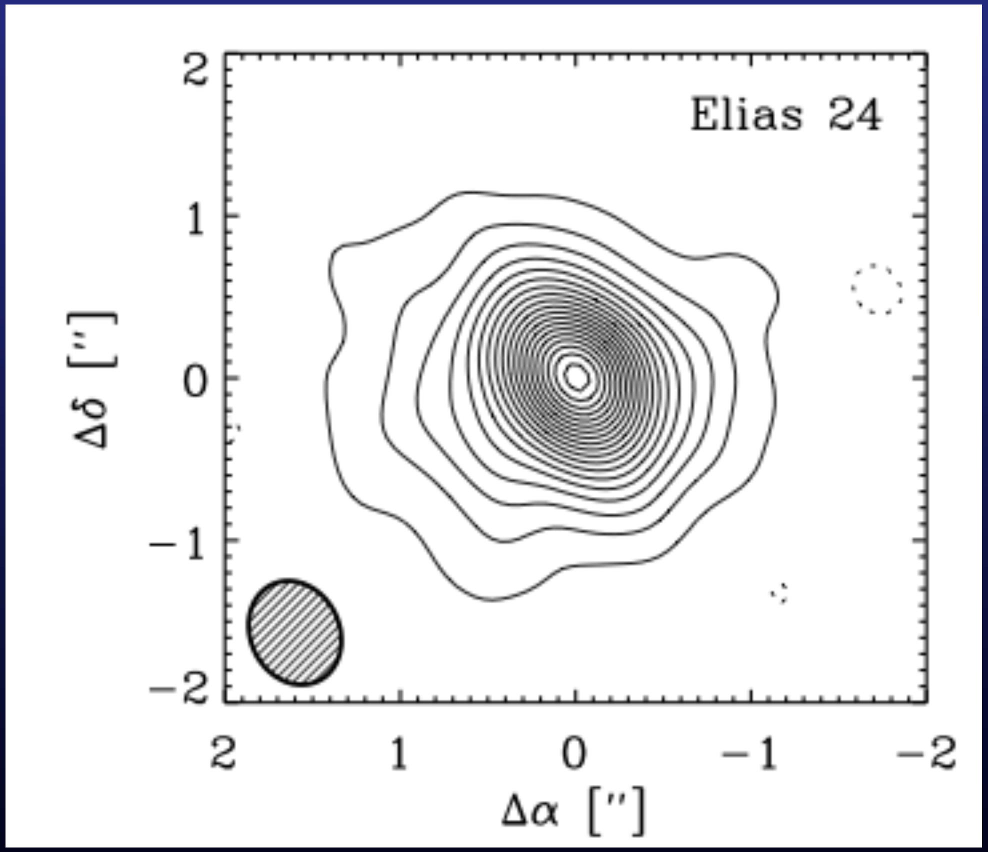
Received 2010 June 10; accepted 2010 September 9; published 2010 October 20

ABSTRACT

We present new results from a significant extension of our previous high angular resolution ($0\farcs3 \approx 40$ AU) submillimeter array survey of the 340 GHz (880 μm) thermal continuum emission from dusty circumstellar disks in the ~1 Myr old Ophiuchus star-forming region. An expanded sample is constructed to probe disk



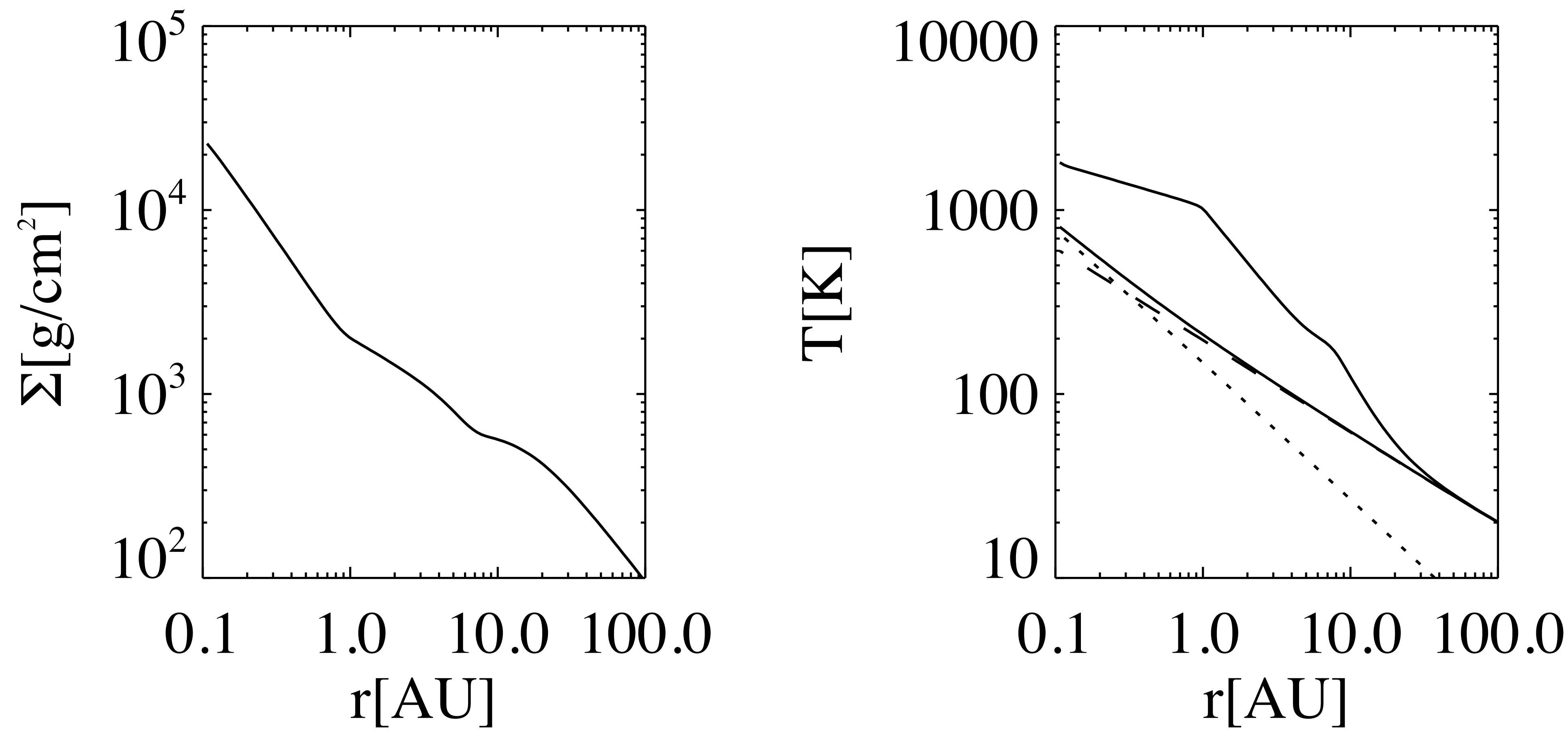
$$q = -\frac{d\log\Sigma}{d\log R} = 0.9 \pm 0.2$$

plus accretion rate:

$$p = -\frac{d\log T}{d\log R} = 1.5 - q = 0.6 \pm 0.2.$$

Klahr & Raettig in prep.
Using data from Sean Andrews: Accretion disks in Ophiuchus.

alpha = 0.001; Mdot = 1E-7 Msol/yr; Plus irradiation: Tstar = 4300; Rstar = 2 Rsol



Radial surfacedensity gradient:

$$q = -\frac{d\log\Sigma}{d\log R} = 0.9 \pm 0.2$$

+

Radial temperature gradient:

$$p = -\frac{d\log T}{d\log R} = 1.5 - q = 0.6 \pm 0.2.$$

=

Radial pressure gradient:

$$\beta_P = -\frac{d\log P}{d\log R} = 1.5$$

&

Radial entropy gradient:

$$\beta_K = -\frac{d\log K}{d\log R} = 1.5 - \gamma q = 0.28 \pm 0.27$$

As a consequence:

1.: Radially buoyancy:

$$N_R^2 = -\frac{1}{\gamma}\left(\frac{H}{R}\right)^2 \beta_K \beta_P \Omega^2,$$

2.: vertical shear
/thermal wind:

$$\Omega(R,Z) \quad = \quad \Omega_K\left[(p+q)\left(\frac{H}{R}\right)^2 + (1+q) - \frac{qR}{\sqrt{R^2+Z^2}}\right]^{1/2}$$

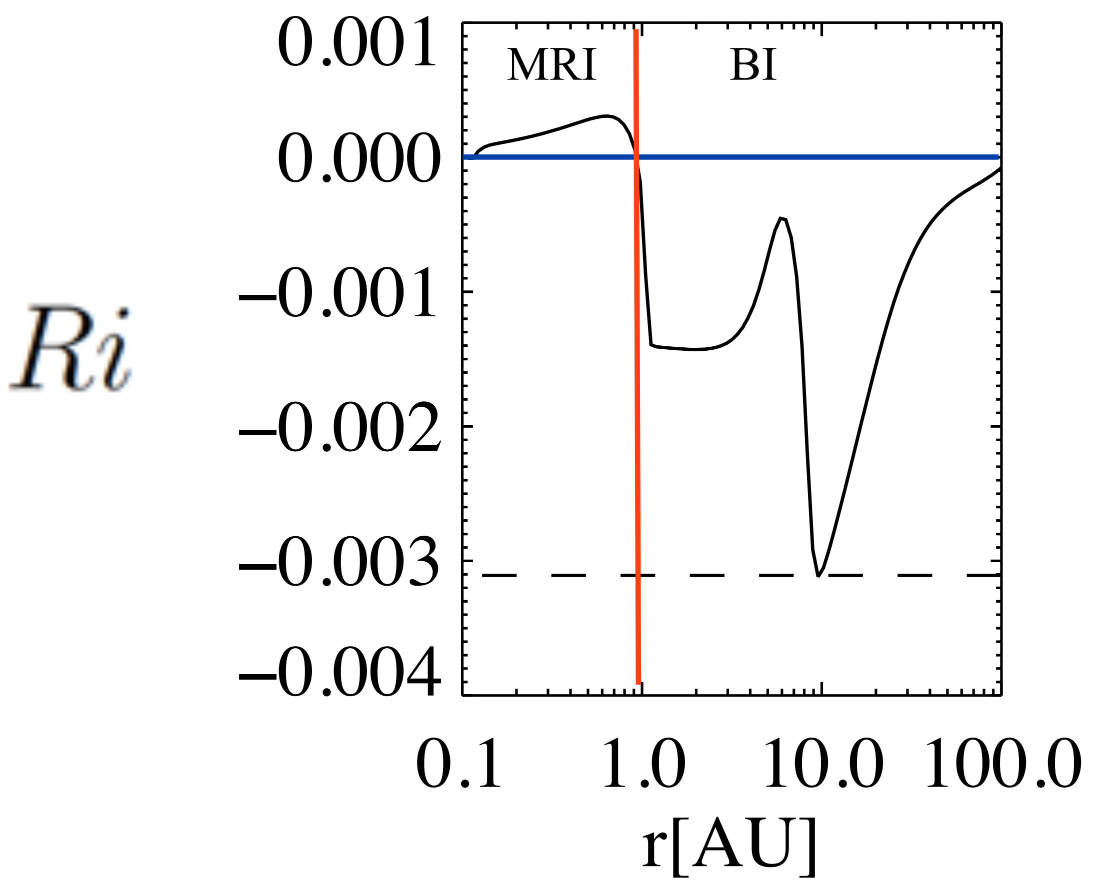
Richardson number & thermal diffusion time

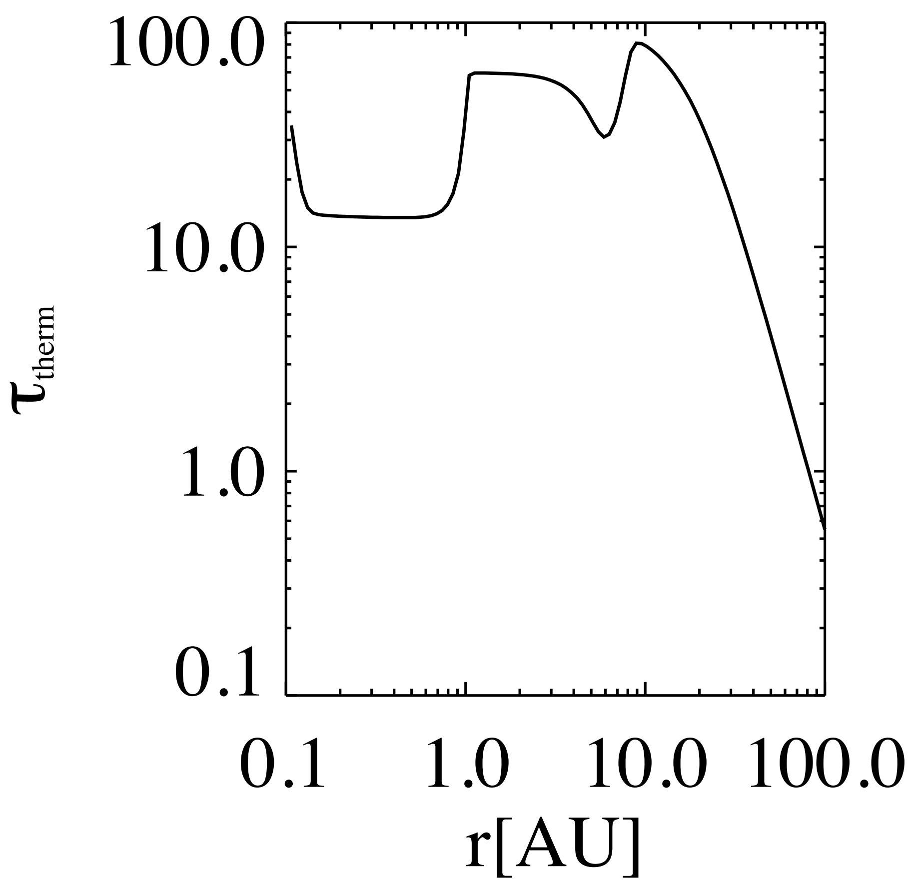
$$N^2 = -\frac{1}{\gamma}\left(\frac{H}{R}\right)^2 \beta_s\beta_p\Omega^2$$

$$Ri = -\frac{2}{3\gamma}\left(\frac{H}{R}\right)^2 \beta_p\beta_s$$

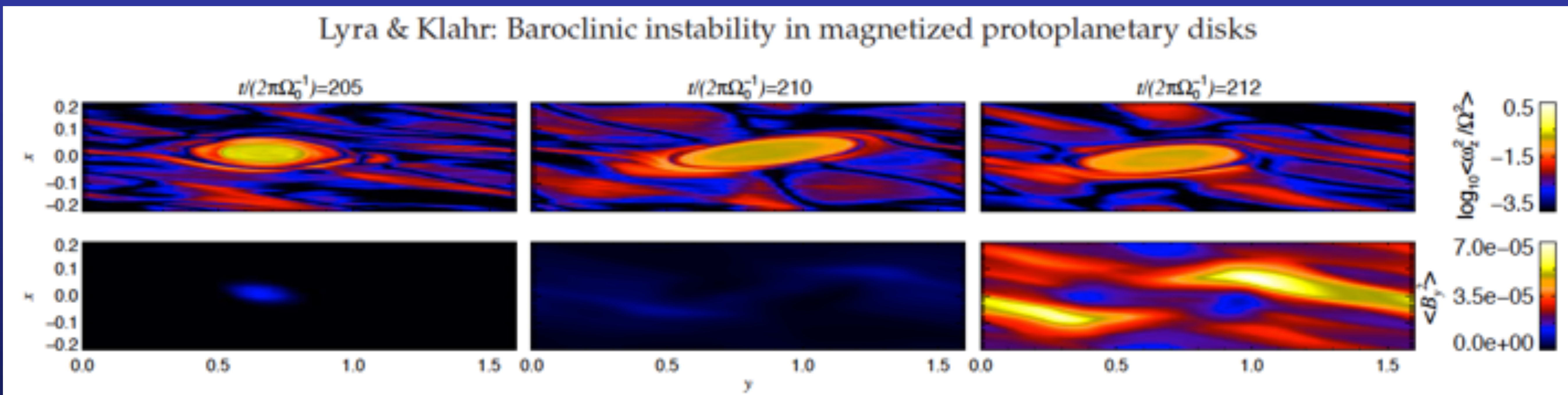
$$D = \frac{\lambda c 4 a_R T^3}{\rho(\kappa+\sigma)},$$

$$\tau_{therm} = H^2 / \frac{D}{\rho c_v}$$



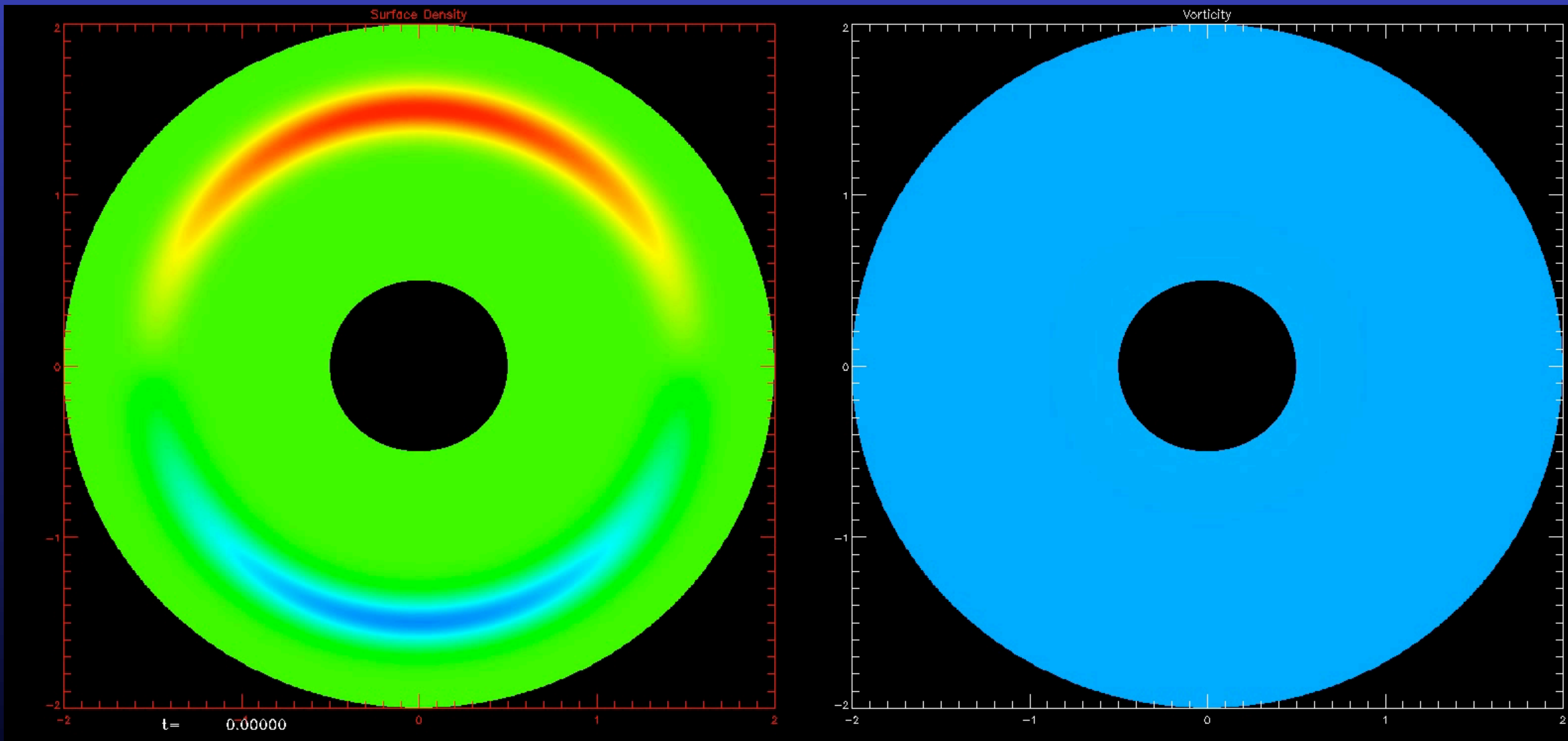


Lyra and Klahr 2011

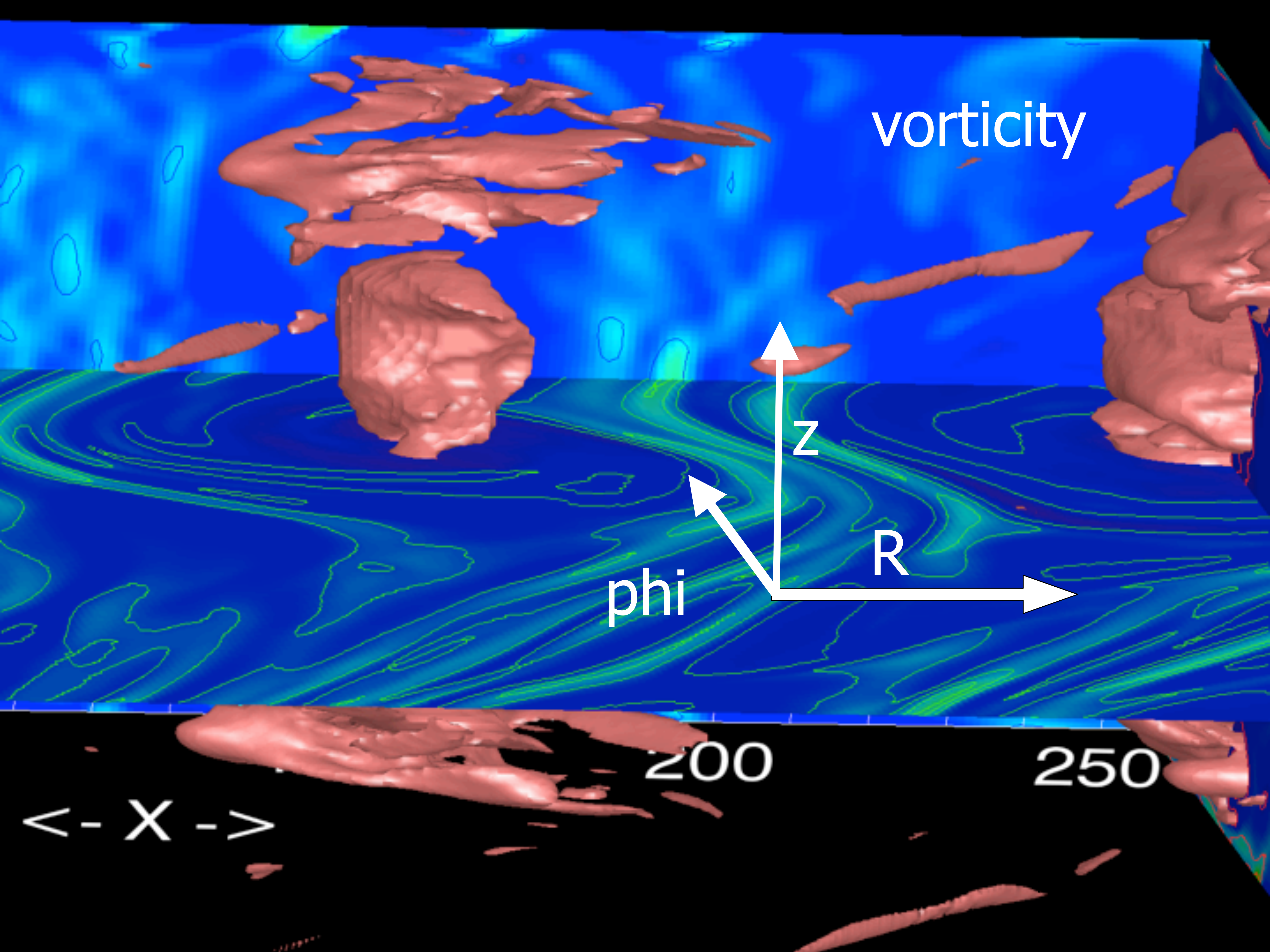


- BI can be the MIDWIFE for MRI... ;)

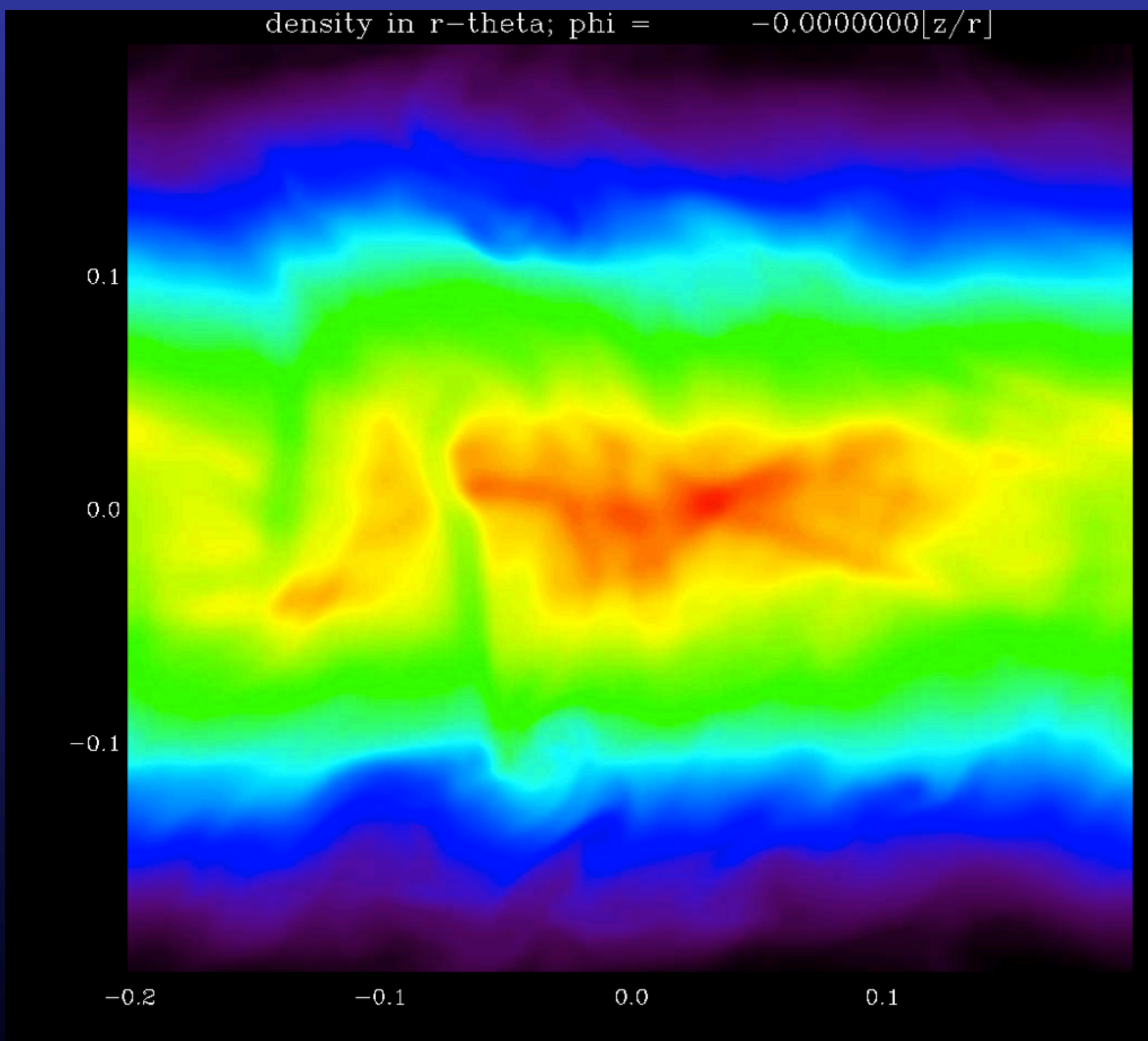
Pluto Code: 1024^2; WENO3-RK3; HLLE; FARGO
How to get a critical Vortex?
Here entropy pert. + Klahr 2004!

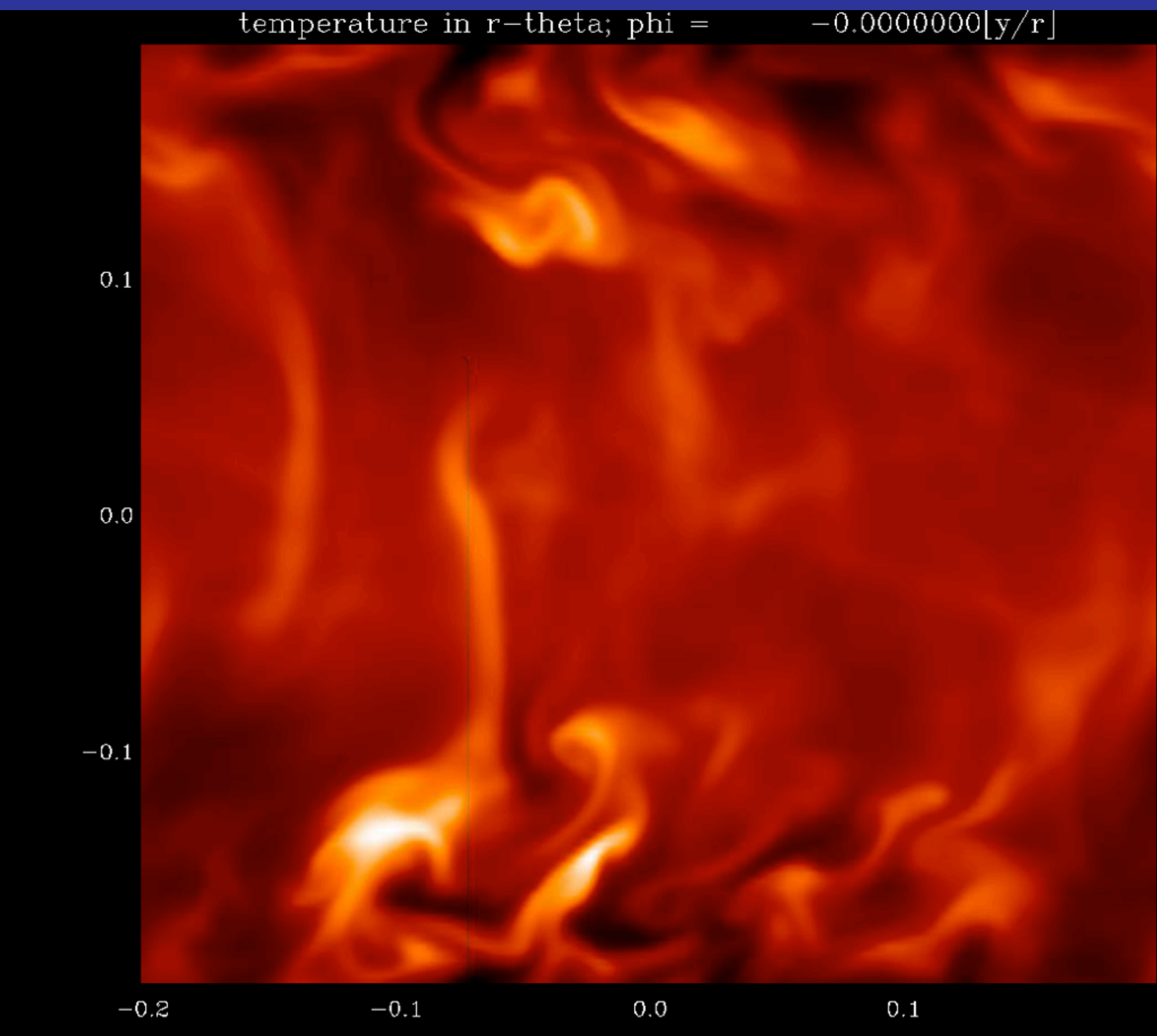


vortices migrate inward, but are recreated by waves from other vortices.


vorticity
z
phi
R
200
250
<- X ->

2D Local (radial - vertical), Including thermal wind / vertical shear! How Come?

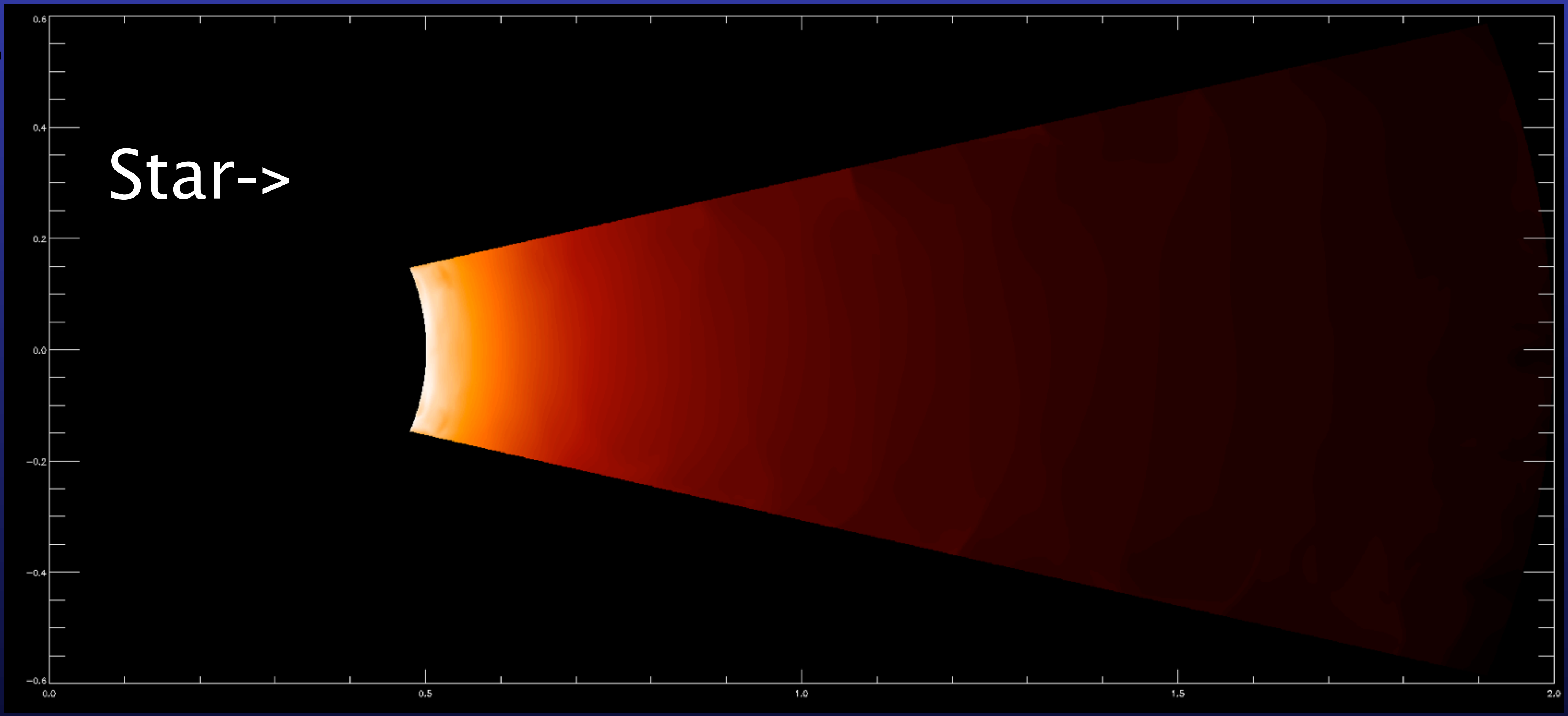




density

temperature pert.

2D axissymetric Pluto Simulation: Temperature due to irradiation from star and thermal relaxation tau = 0.1 (also works for flux limited diffusion in irradiated disks)

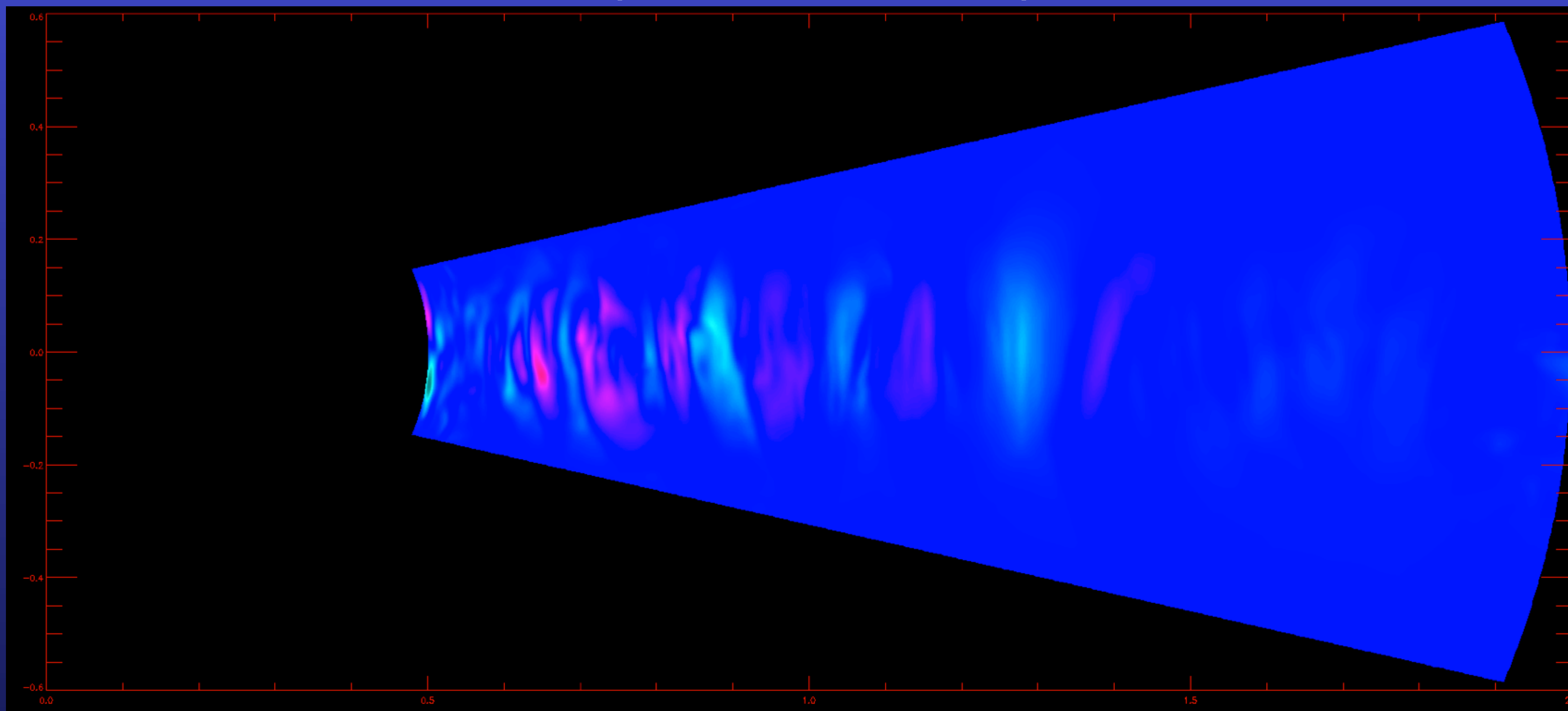


Thermal wind:

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

See Nelson, Gressel & Umurhan astro-ph

2D axissymetric Pluto Simulation:
Overstability due to thermal wind leads to convection like motion:
Symmetric Instability



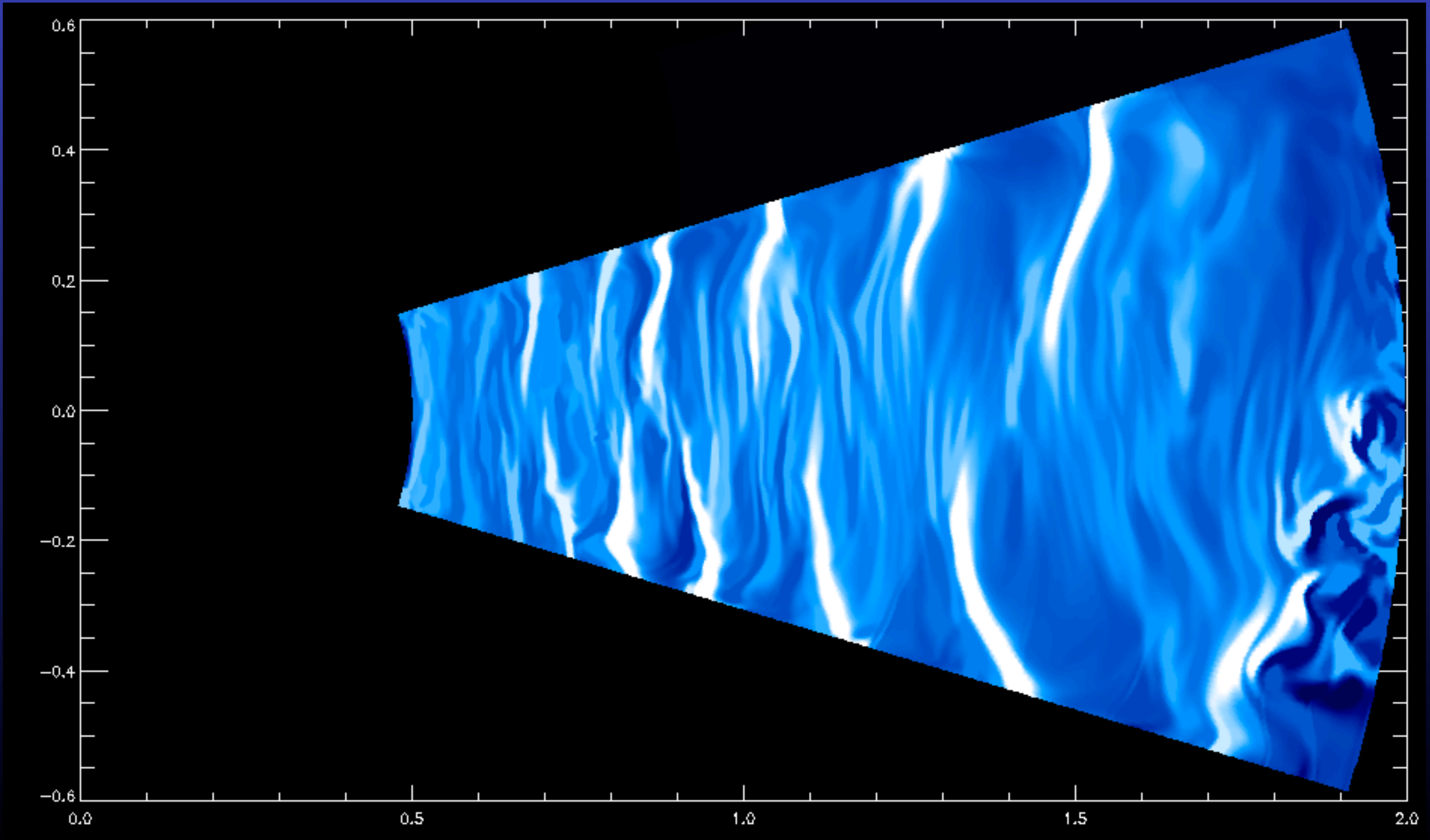
Modification of Solberg-Hoiland Criterion, including thermal relaxation:
In collaboration with Alexander Hubbard
Or instantanous cooling: Goldreich & Schubert 1967 - Fricke 1968 Instability

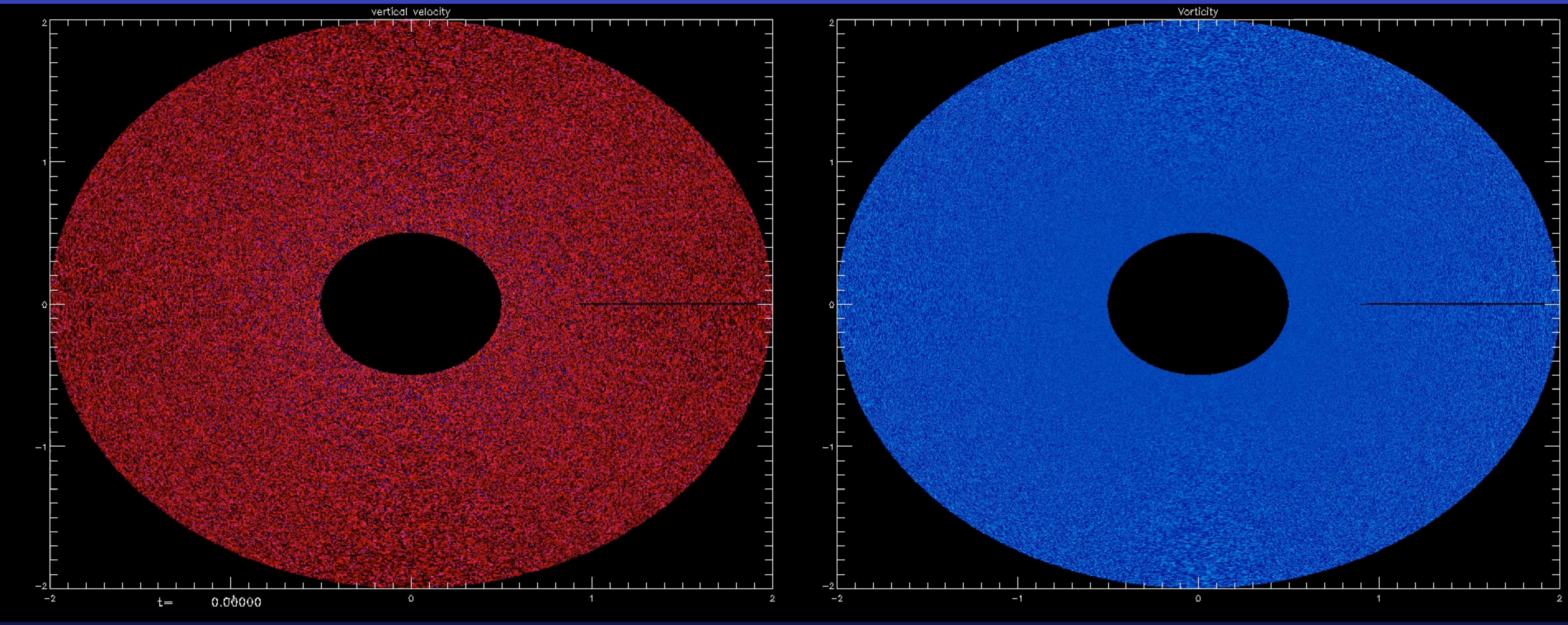
Linear and nonlinear evolution of the vertical shear instability in accretion discs

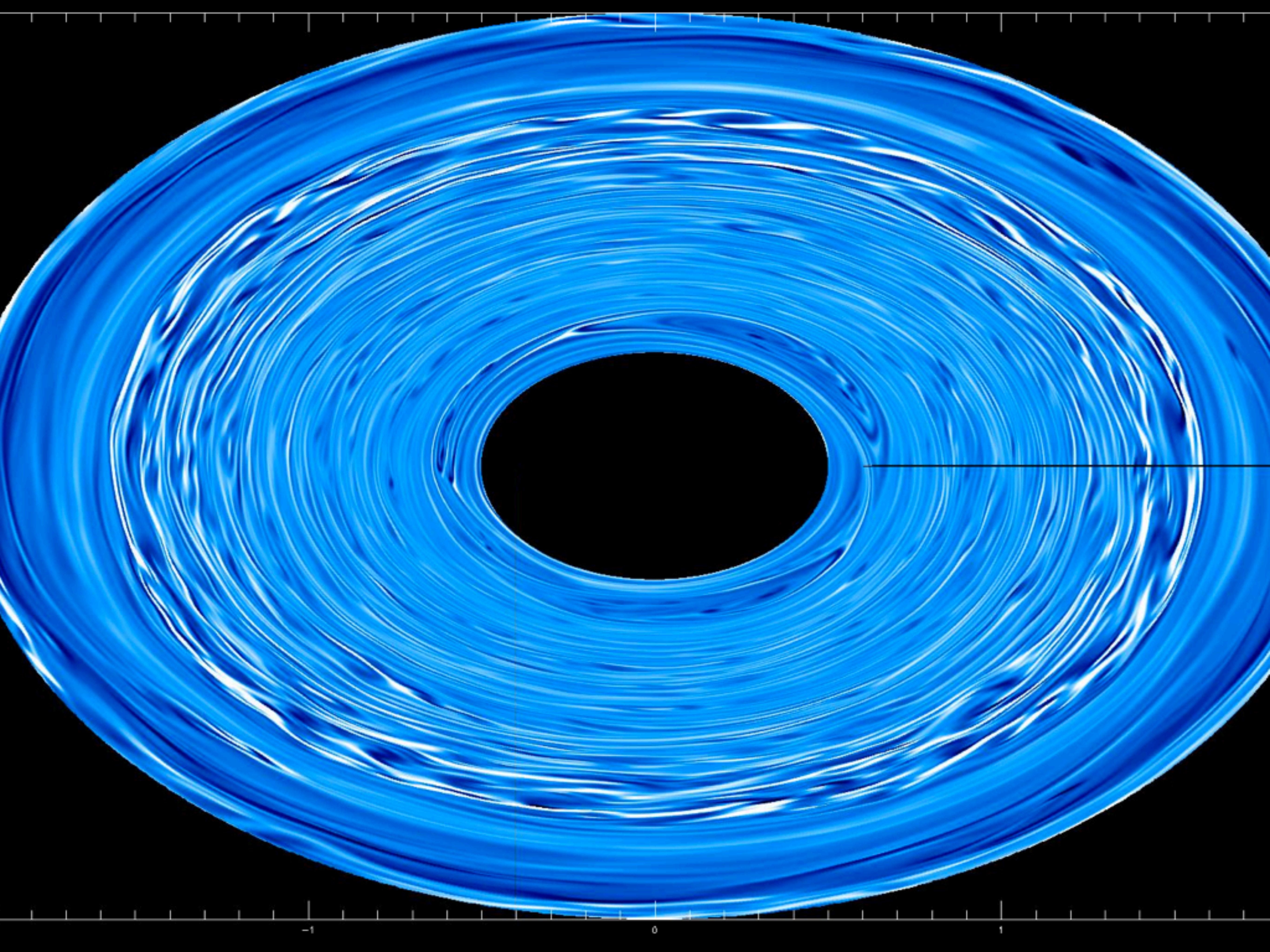
Richard P. Nelson[1★], Oliver Gressel[1,2★] and Orkan M. Umurhan[1,3★]
[1] *Astronomy Unit, Queen Mary University of London, Mile End Road, London E1 4NS*
[2] *NORDITA, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, 106 91 Stockholm, Sweden*
[3] *School of Natural Sciences, University of California, Merced, 5200 North Lake Rd, Merced, CA 95343, USA*

$$\frac{\partial j^2}{\partial R} - \frac{k_R}{k_Z}\frac{\partial j^2}{\partial Z} < 0.$$

2D axissymetric Pluto Simulation: vertical component of vorticity perturbations



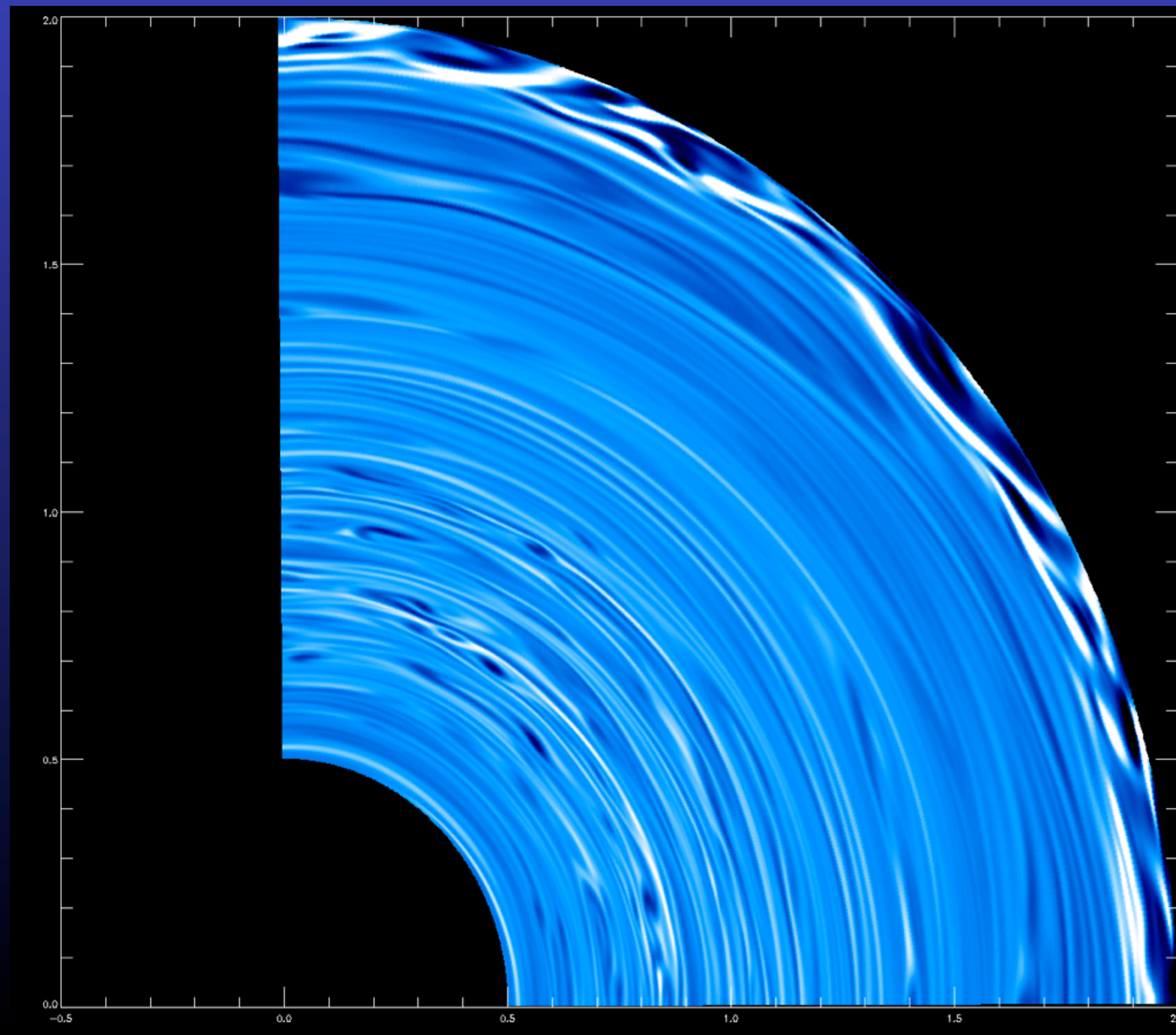

vertical velocity
Vorticity
t= 0.00000
2
1
0
−1
−2


-1
0
1

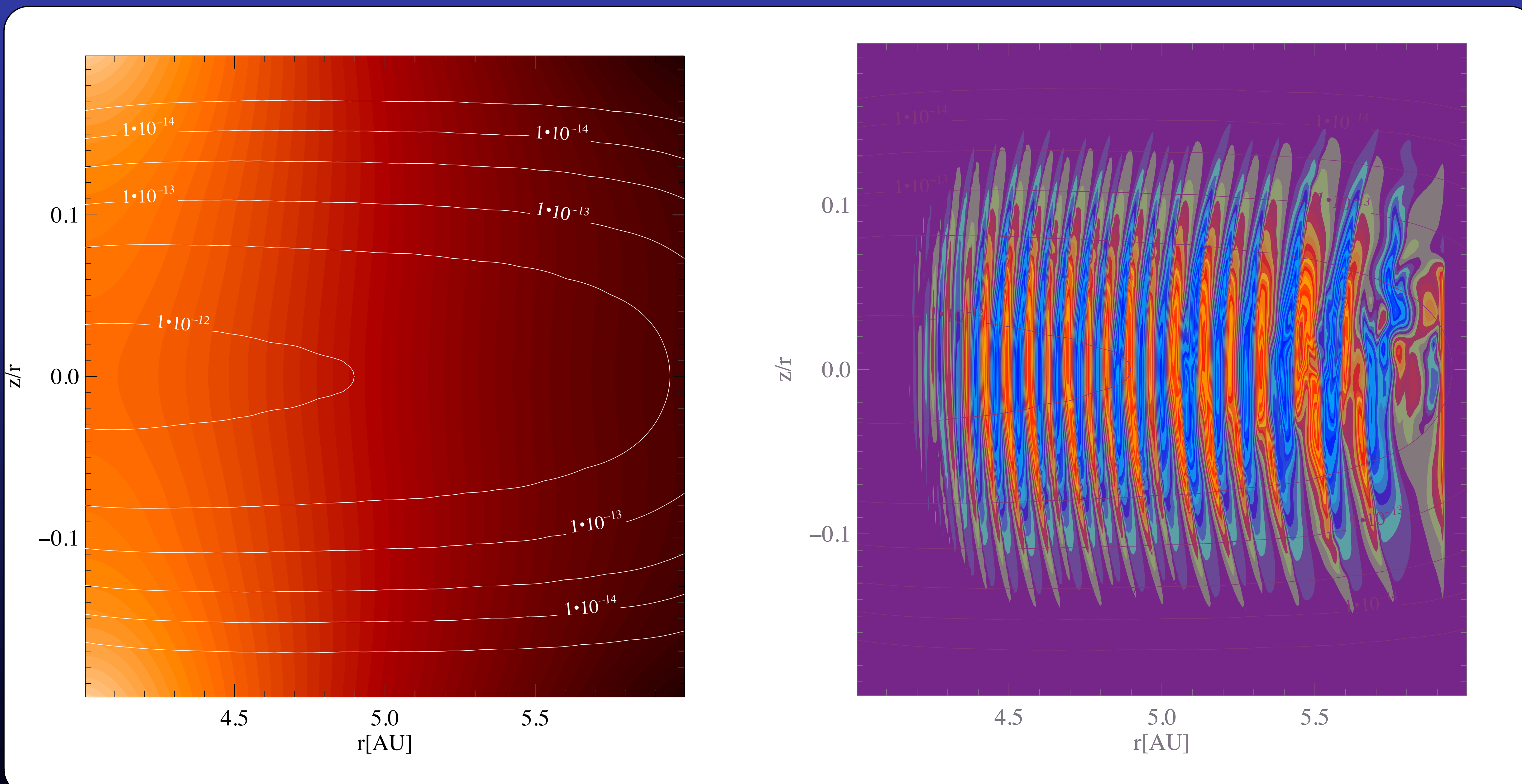
Full 3D Pluto Simulation: Spontanous Formation of Vortices from tiny perturabtions

=> Baroclinic Disks Form Vortices abundantly and further amplify them further!

Mission accomplished.



2D / 3D - Radiation Hydro of Irrdiated disks in Disks with dust opacities and realistic parameters!



Vertical Buoyancy Frequency:

$$\omega^2 = -\frac{1}{\rho_0 \gamma C_v} \partial_z p_0 \partial_z S_0 = N_z^2$$

Including thermal relaxation

$$\omega = -\frac{i}{2\tau} \pm i\sqrt{\frac{1}{4\tau^2} - N_z^2},$$

For short cooling no internal waves!

$4\tau^2 N_z^2 < 1$	Goldreich Schubert Fricke
$4\tau^2 N_z^2 >> 1$	Internal Waves / Crititical Layer
$\tau\Omega \approx 1$	Convective Overstability

Space-Filling Lattices of 3D Vortices Created by the Self-Replication of Critical Layers in Linearly Stable, Shearing, Stratified, Rotating Flows

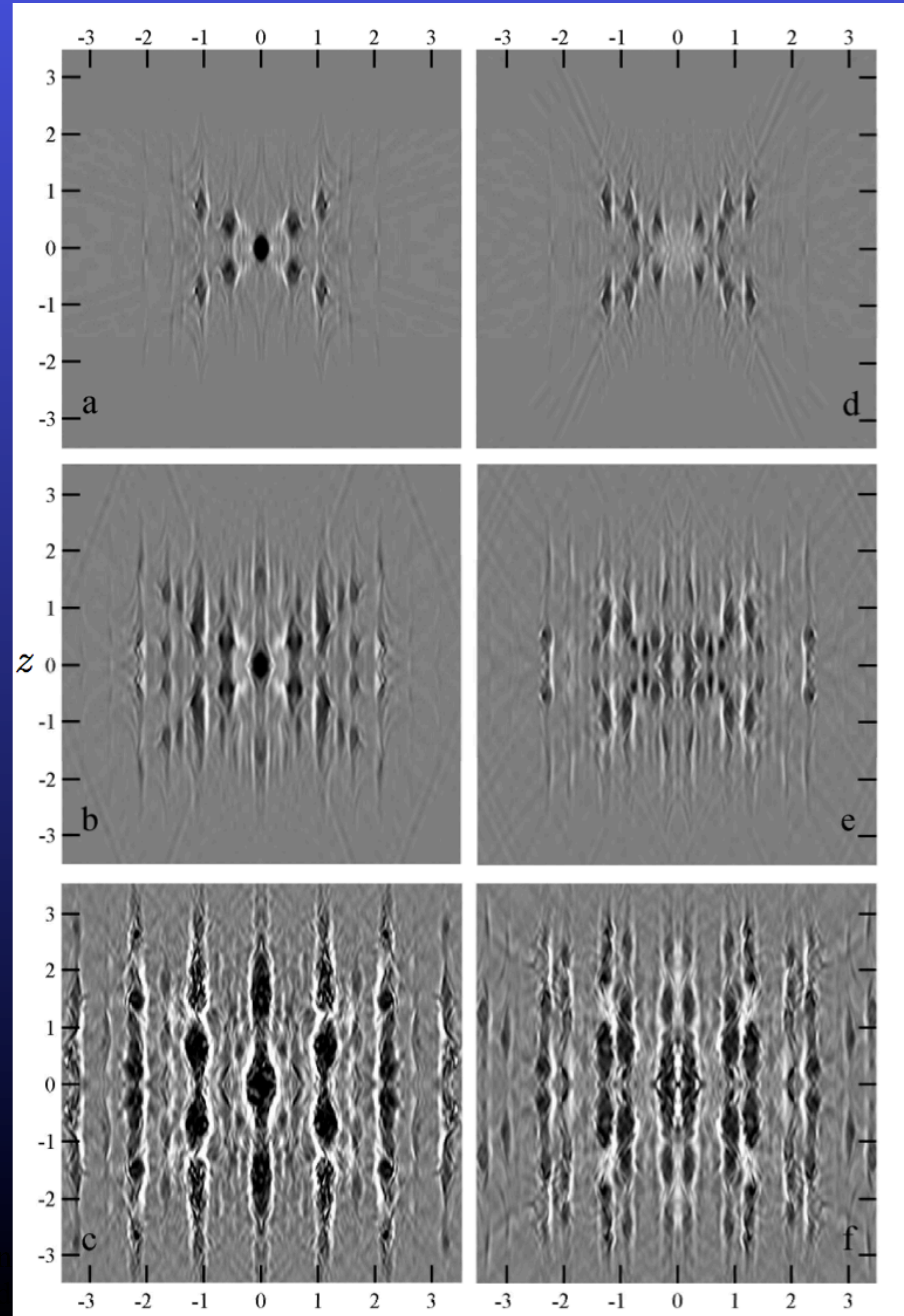
Philip S. Marcus, Suyang Pei, Chung-Hsiang Jiang, and Pedram Hassanzadeh
Department of Mechanical Engineering,
University of California, Berkeley, California, 94720, USA

(Dated: September 29, 2012)

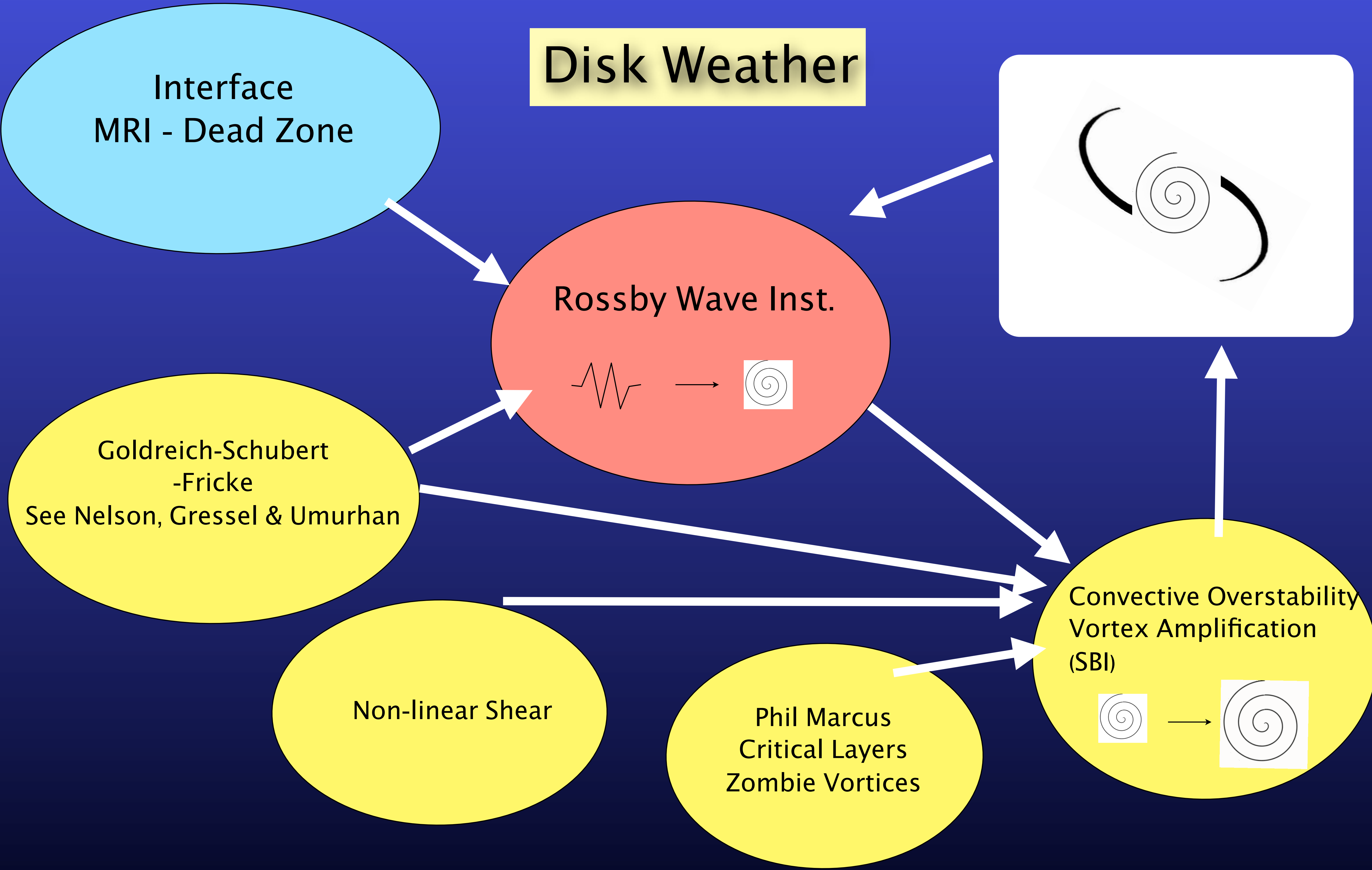
~~$4\tau^2 N_z^2 < 1$~~

$$4\tau^2 N_z^2 > 1$$

$$\tau\Omega \approx 1$$

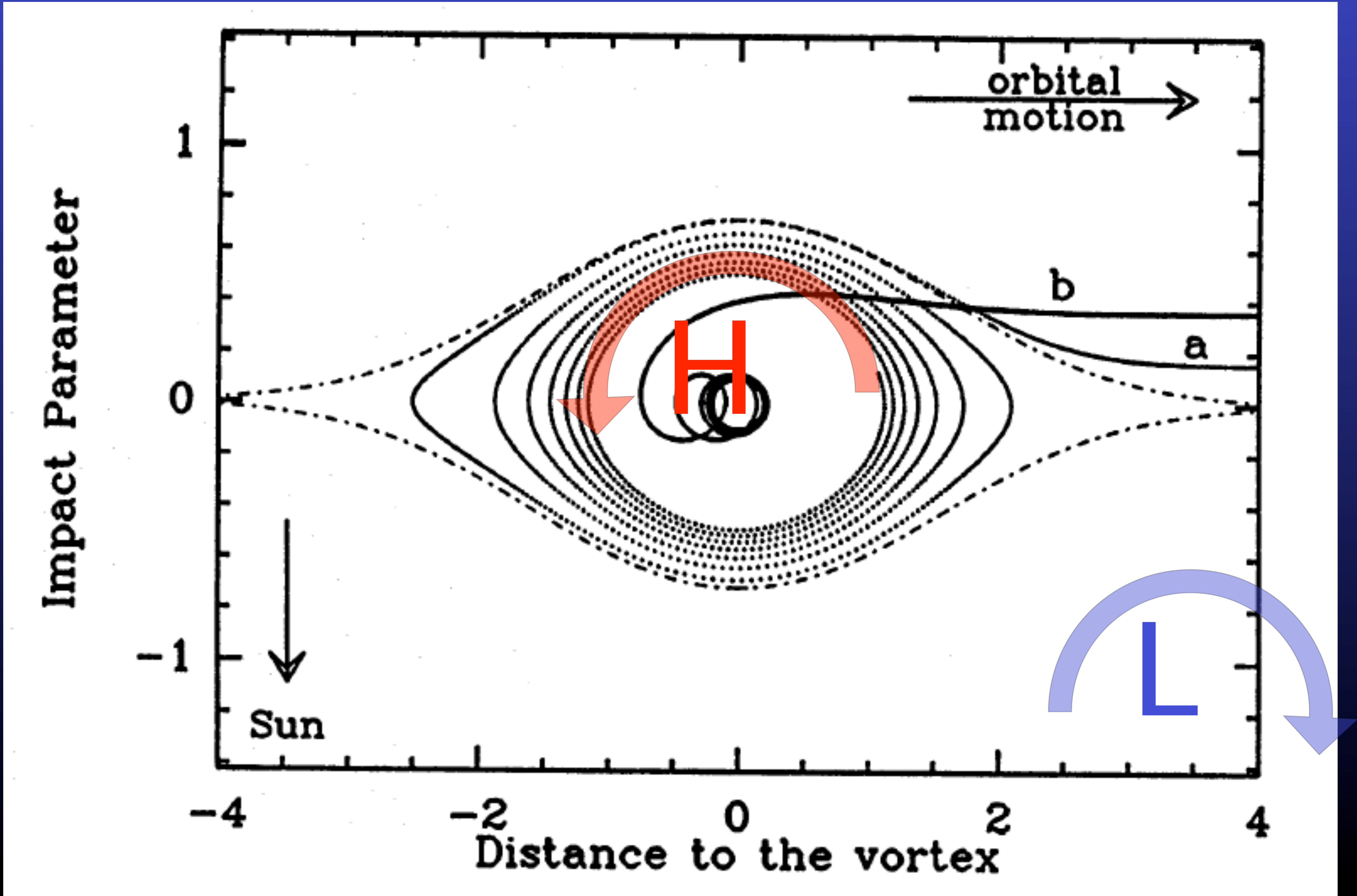


Disk Weather

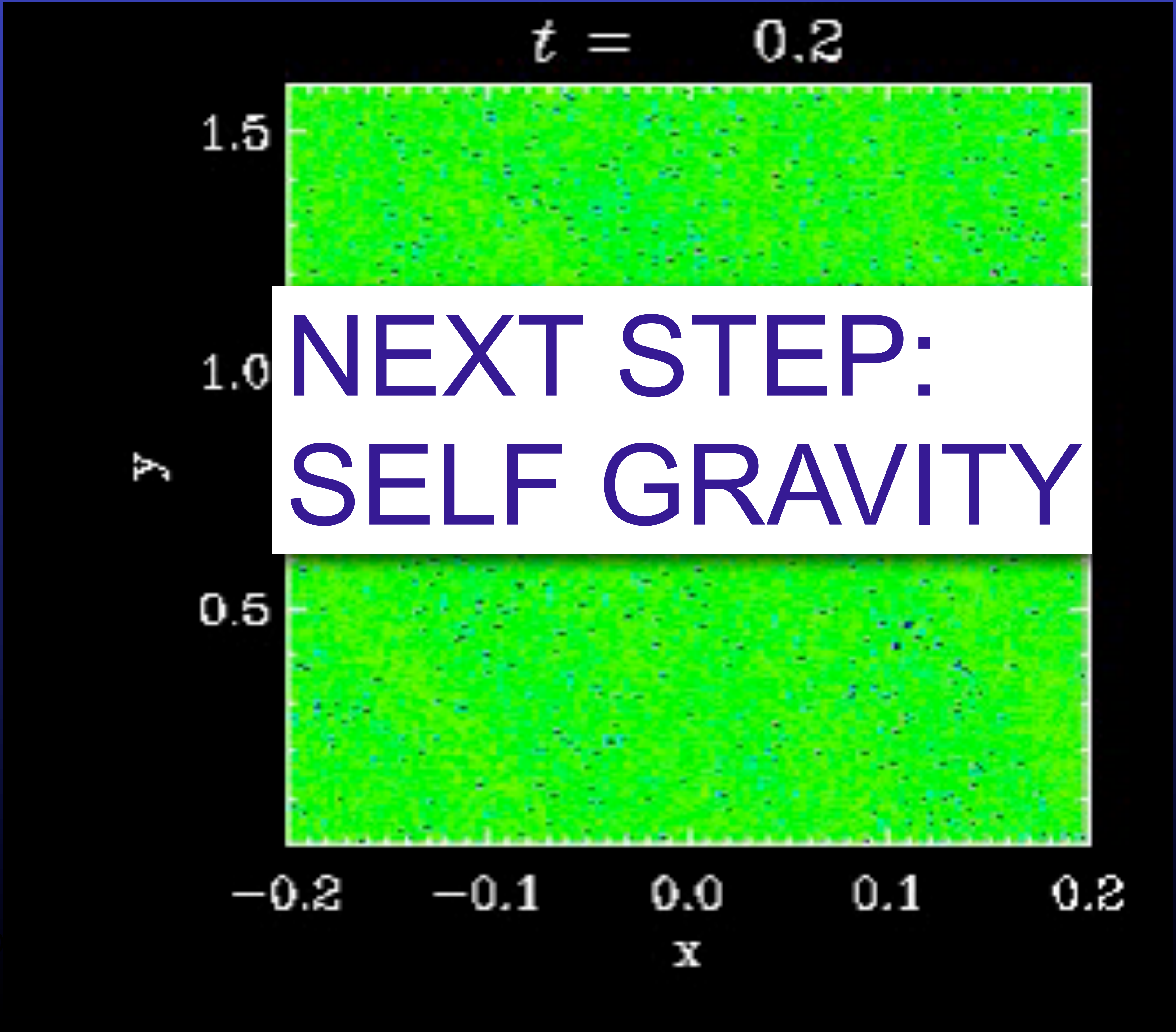


Radial Buoyancy : dS/dr < 0 & dP/dr <0 plus: thermal relaxation -> thermal wind dVphi/dz < 0

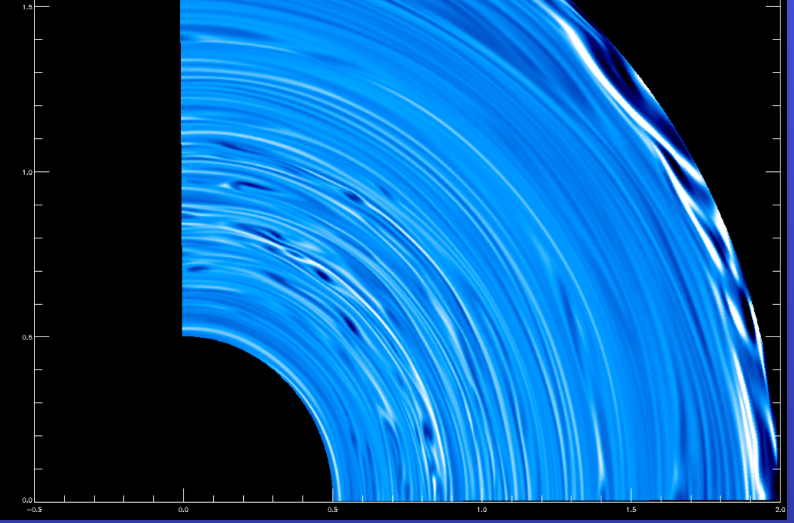
Small particles in pressure maxima e.g. a vortex e.g. Vortex is in balance between Coriolis forces and pressure = same for Zonal flow. Barge & Sommeria 1995



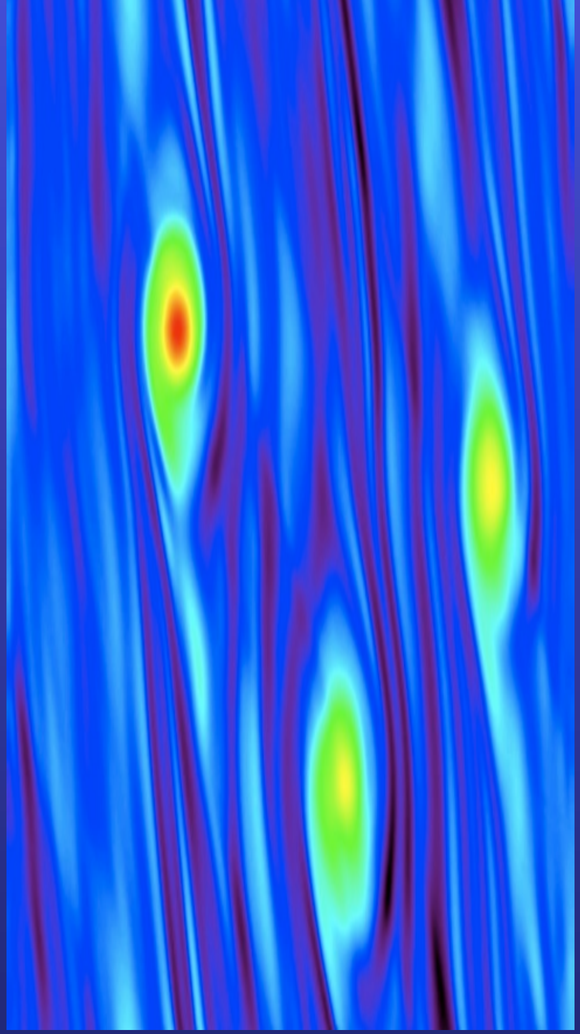
St = 0.05 particles (few millimeter) (white = x 1000) Natalie Raettig



NEXT STEP:
SELF GRAVITY



Conclusions:



- Disk turbulence can be magnetic in nature, but in resistive regions the thermal structure of the disk creates a thermal wind and eventually vortices.
- Irradiated disks are widely radial buoyant and thus Vortices are continuously created.
- Vortices can concentrate even St = 0.05 dust at initial abundance of eps = 1E-4 to the streaming instability and planetesimal formation.