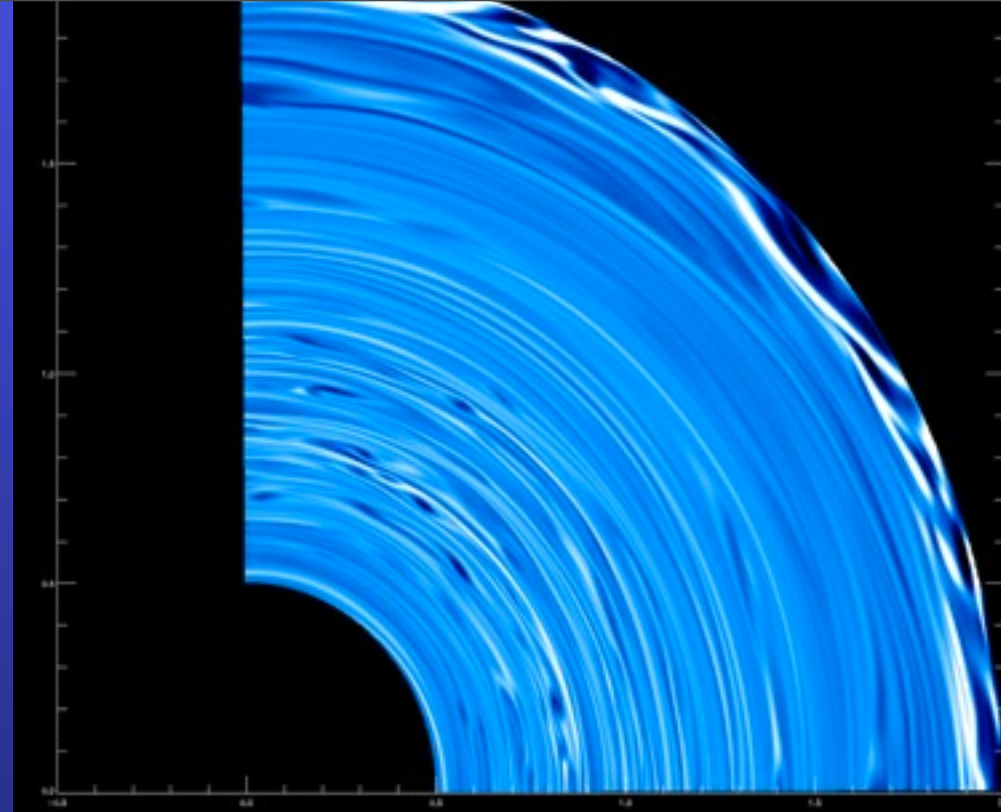
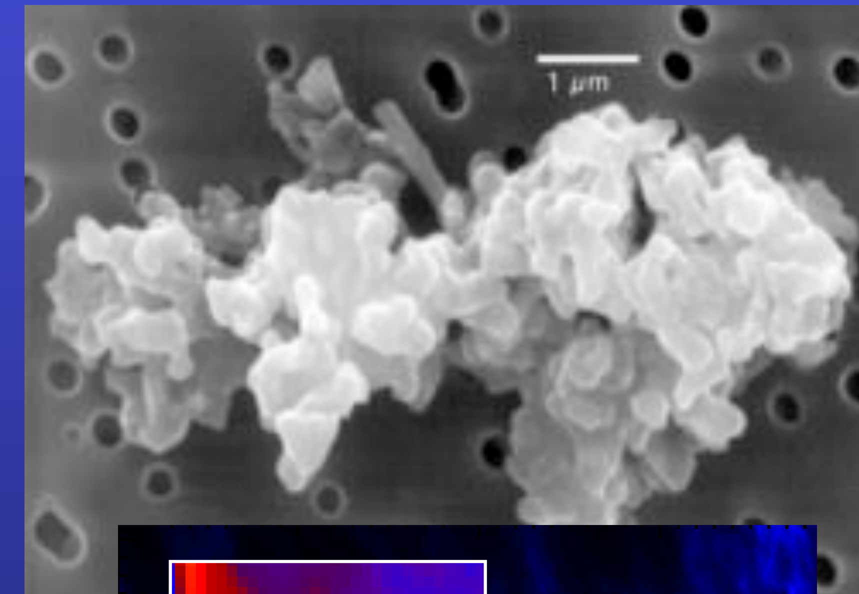
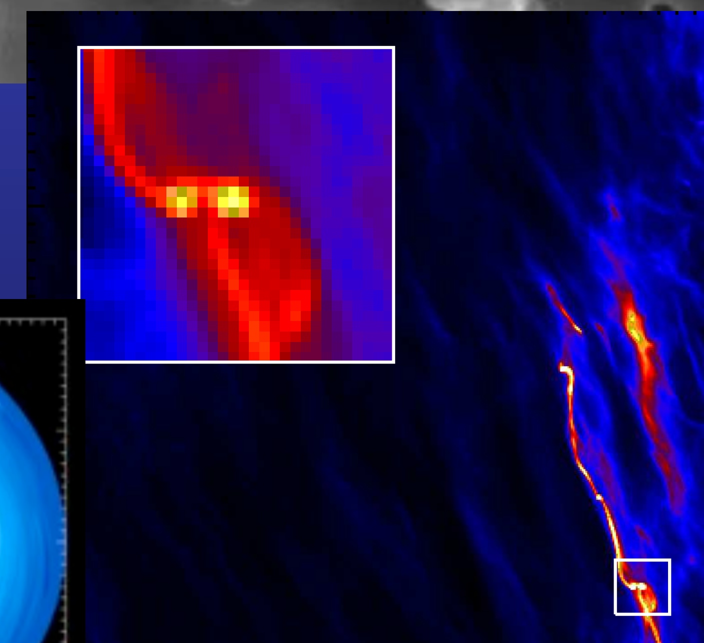
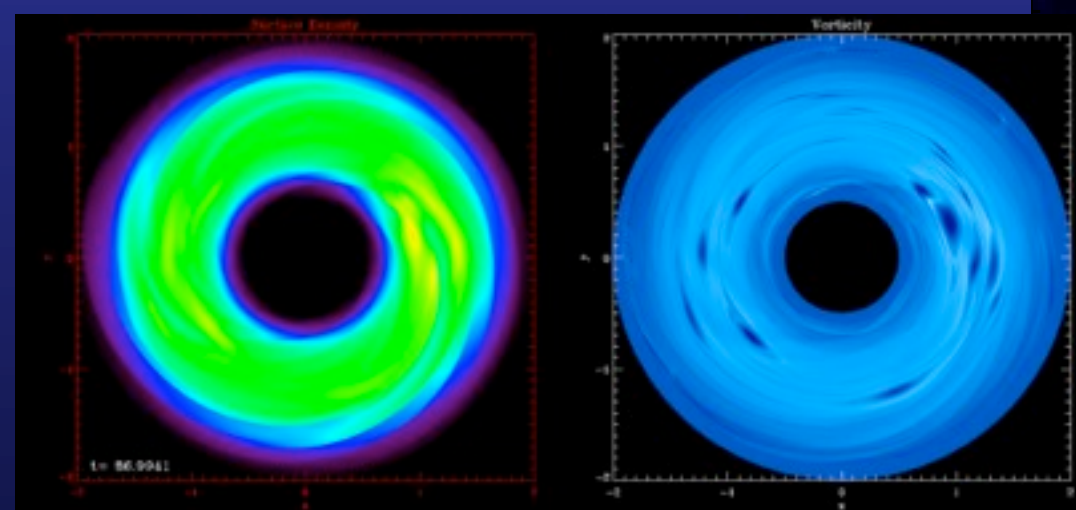
Marseille, Sep. 18th, 2012







Disk Weather: Baroclinic Instability and Vortex Amplification



Hubert Klahr,

Max-Planck-Institut für Astronomie, Heidelberg

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

Planetesimal Formation: 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) Anders Johansen (Lund)

Outline:

Disk Weather: Baroclinic Instability and Vortex Amplification - From physical conditions in disks to 3D global radiation hydro simulations

- Current state of MHD turbulence and Gravoturbulent Planetesimal formation
- Turbulence and vortices in Baroclinic disks: Disk Weather
- Linear Axisymmetric Instability
- Dust capturing in 3D vortices
- Summary, Conclusions

Turbulence in a non rotating frame:

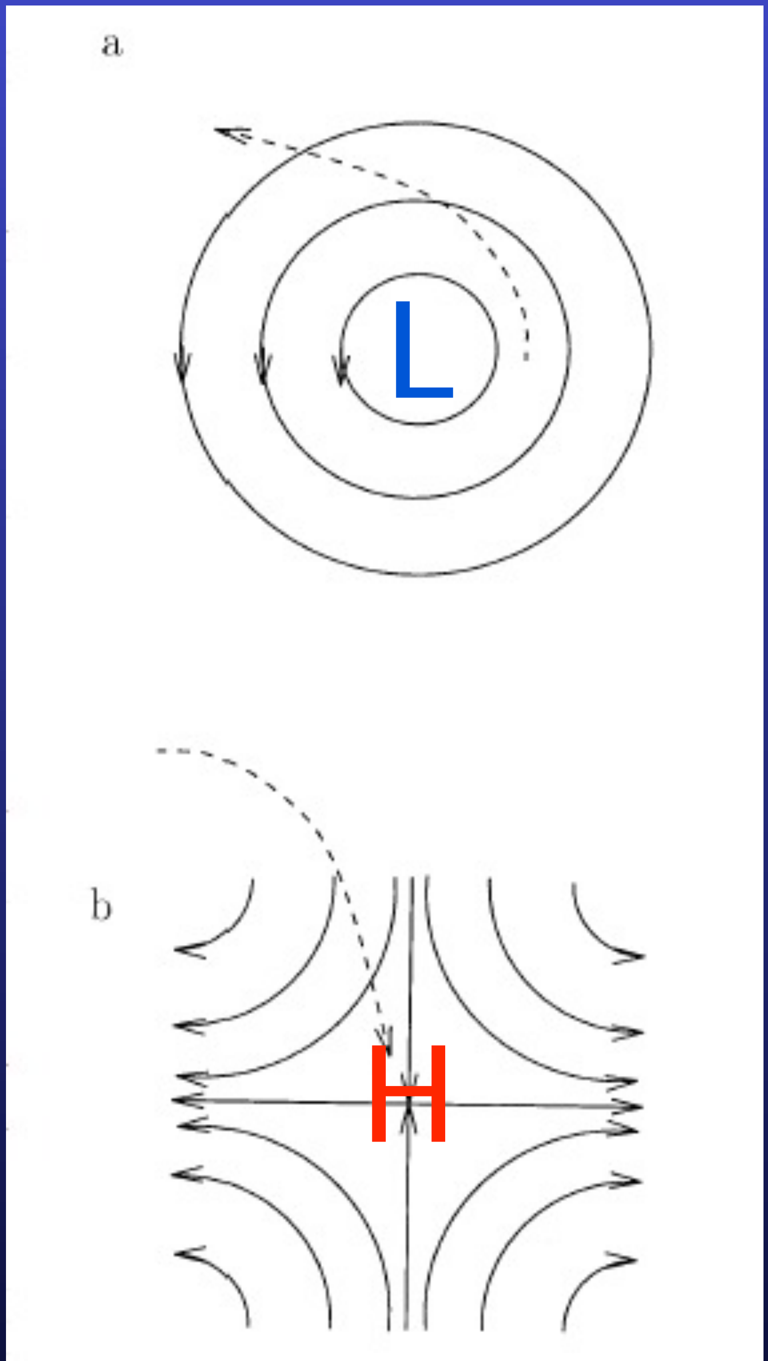


FIG. 1. Under laboratory-observed conditions particles (a) spiral out of the vortices (eddy), but (b) collect in convergence zones (strain fields).

Cuzzi et al.

Laboratory Conditions

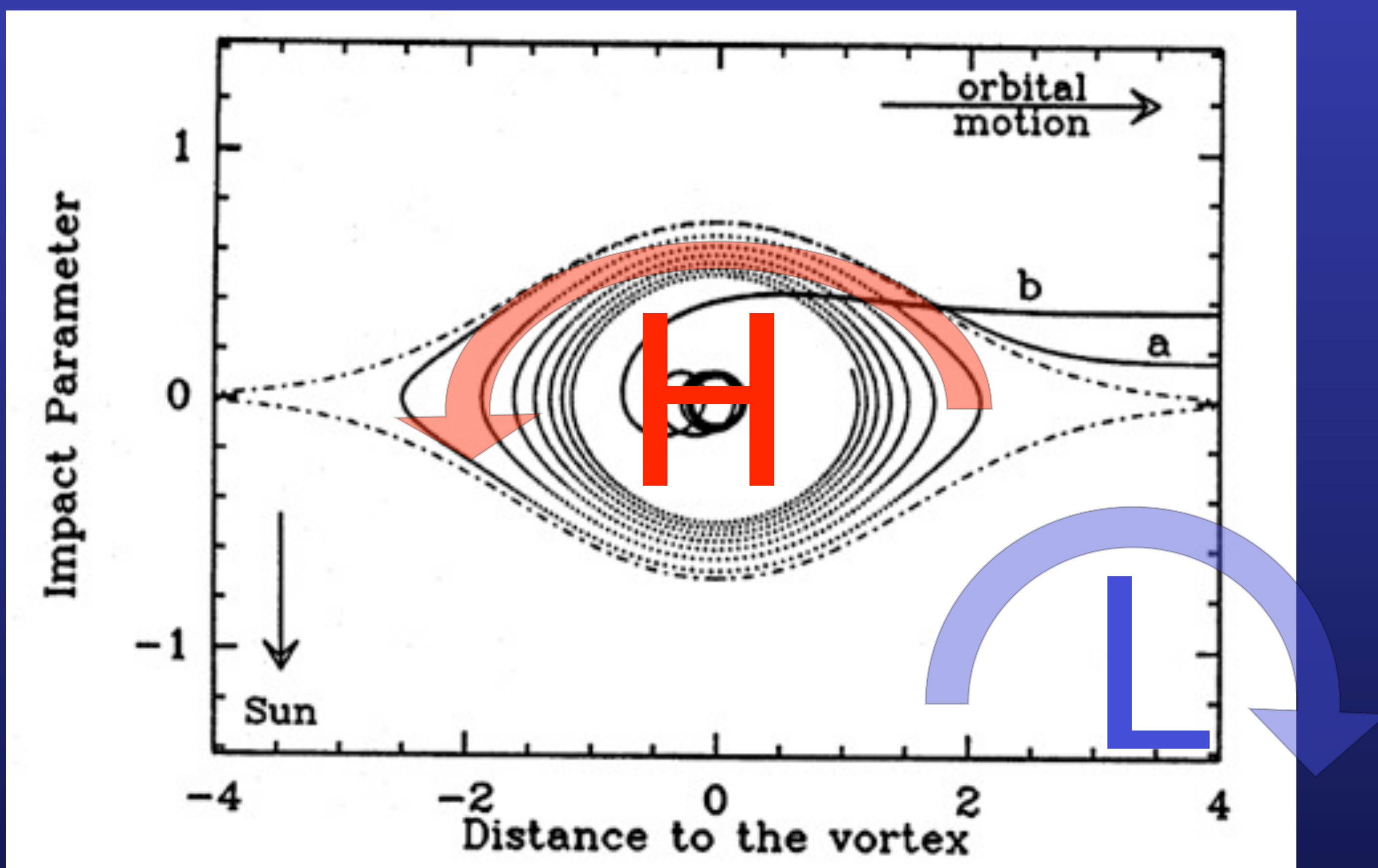
Dust collects between vortices (high pressure)

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

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

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

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



VORTICES:

Barge & Sommeria 1995

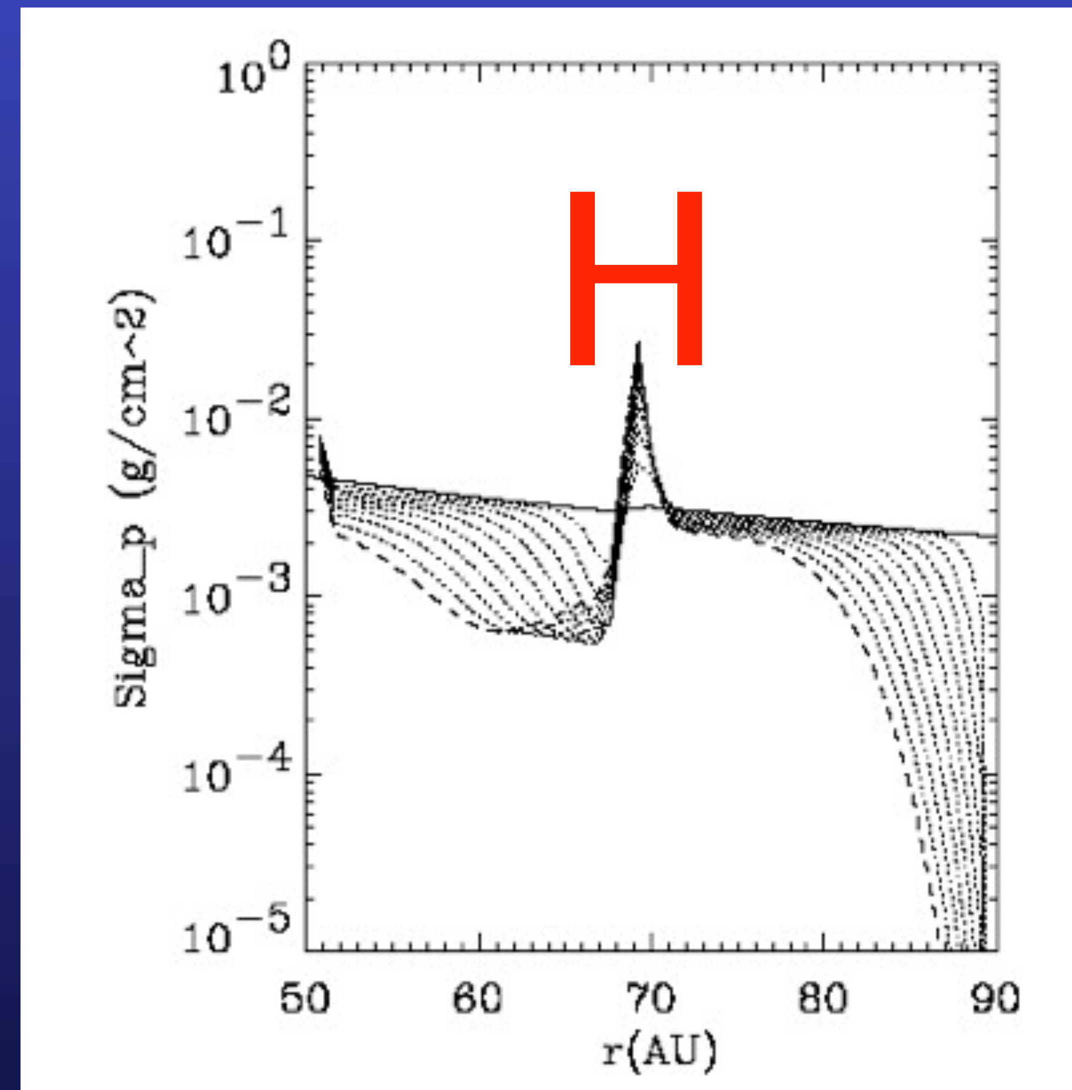


FIG. 7.—Model A: evolution of the 1 m size particle surface density distribution for the model in Fig. 2. The solid line gives the initial distribution. The following lines are snapshots every 10^5 yr.

ZONAL FLOWS:

Radial Pressure maxima

Klahr & Lin 2000

From dust/gas eq. 1 => Streaming Instability -> dust densities larger than local Roche density, e.g. Planetesimals can form.

V
e
r
t
i
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a
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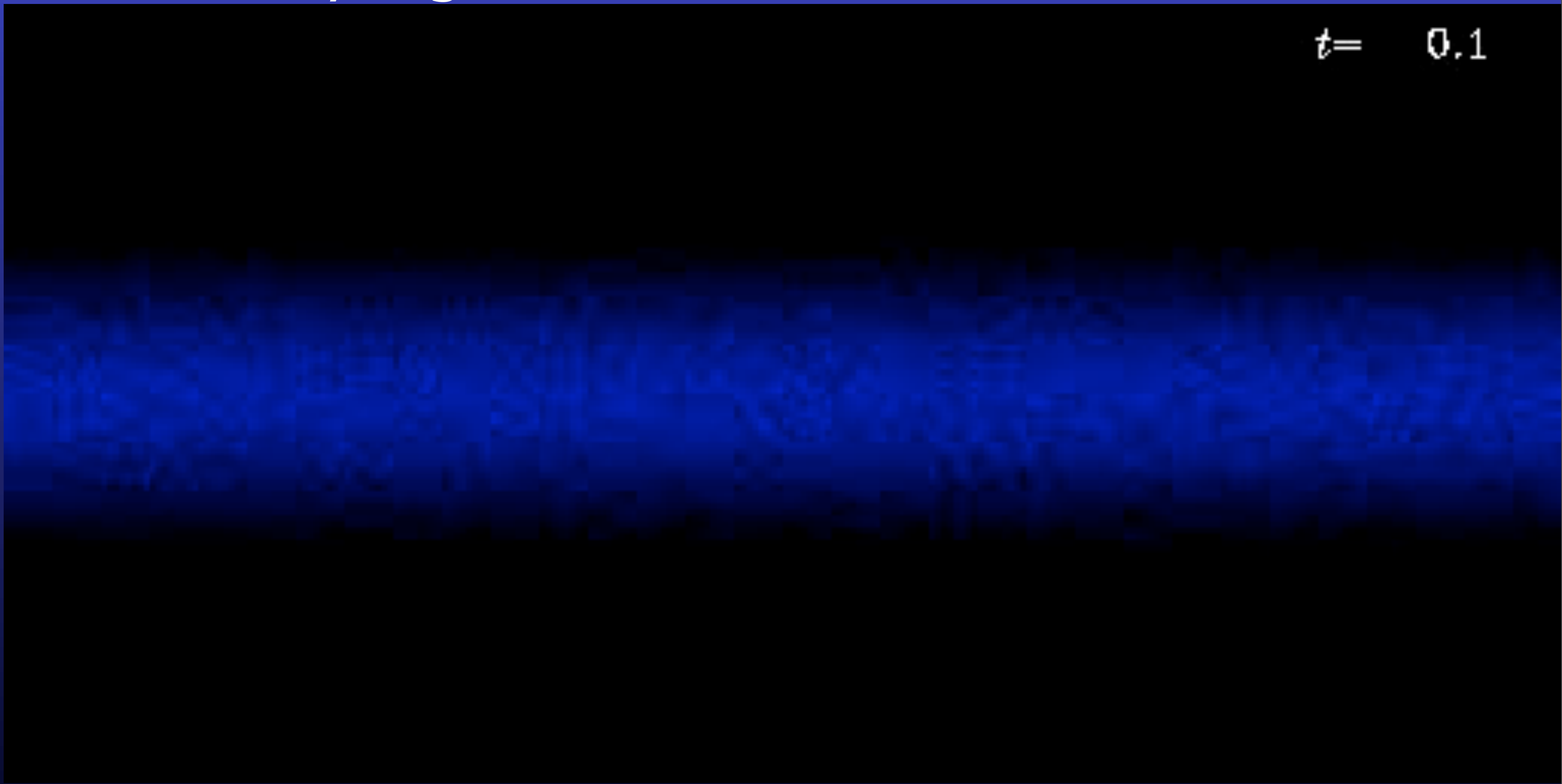
h o r i z o n t a l

Johansen, Henning & Klahr 2006

From dust/gas eq. 1 => Streaming Instability -> dust densities larger than local Roche density, e.g. Planetesimals can form.

V e r t i c a l

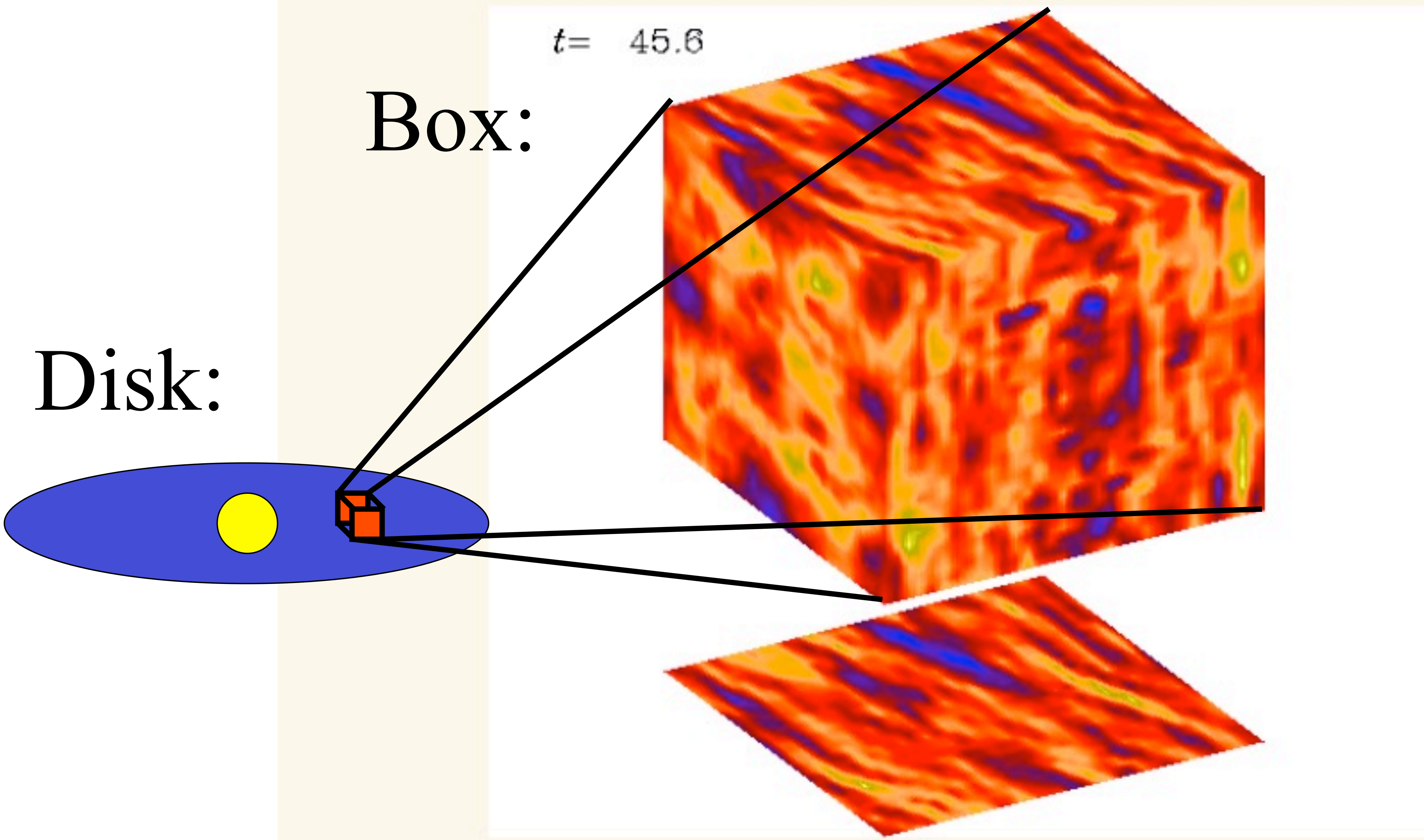


h o r i z o n t a l

Johansen, Henning & Klahr 2006

MRI turbulence

…because it is a reliable source for turbulence.

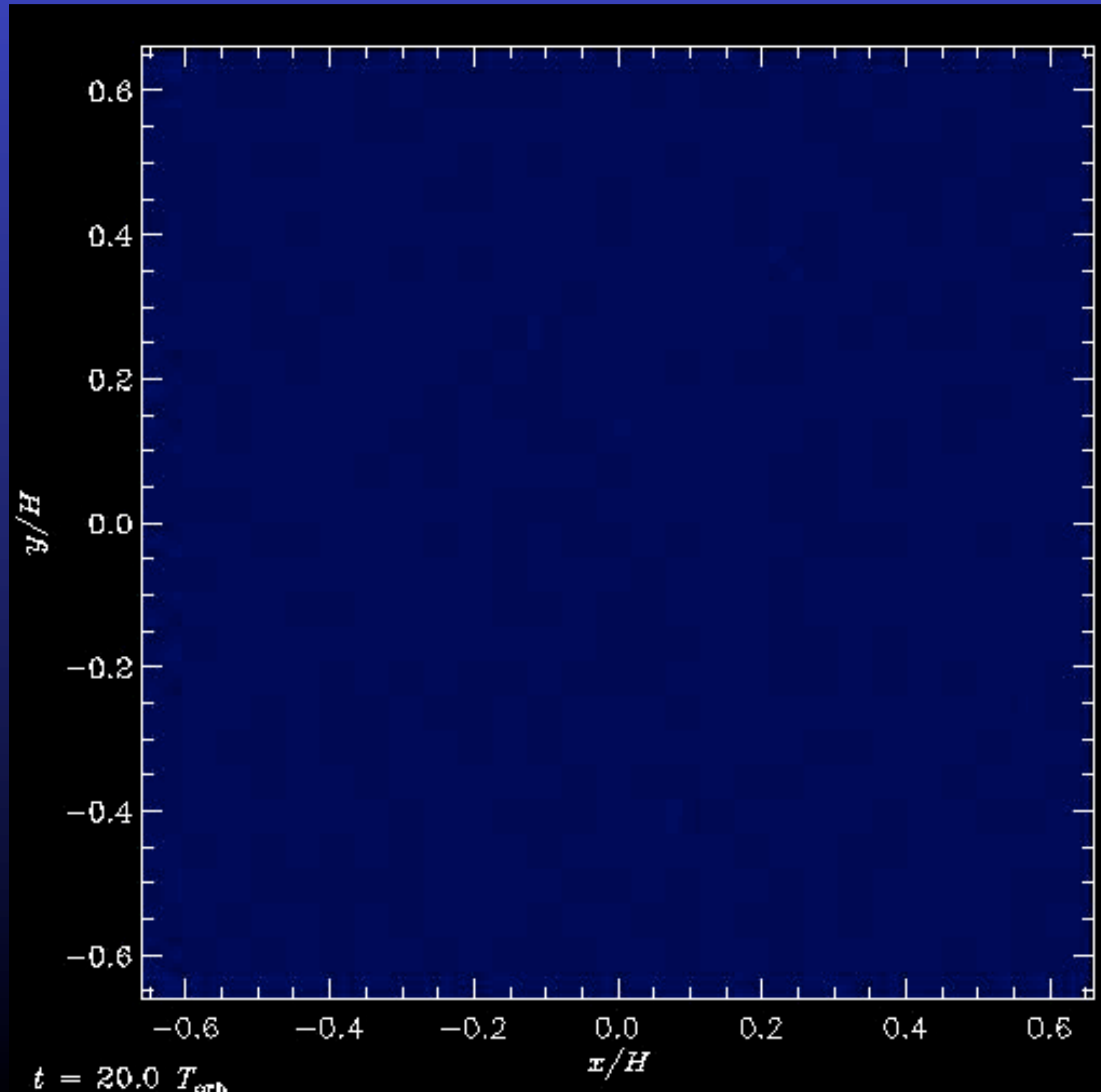


Code: The Pencil-Code [MHD code, finite differences, 6th order in space, 3rd order in time, Brandenburg (2003)]

Concentration in Zonal Flows:

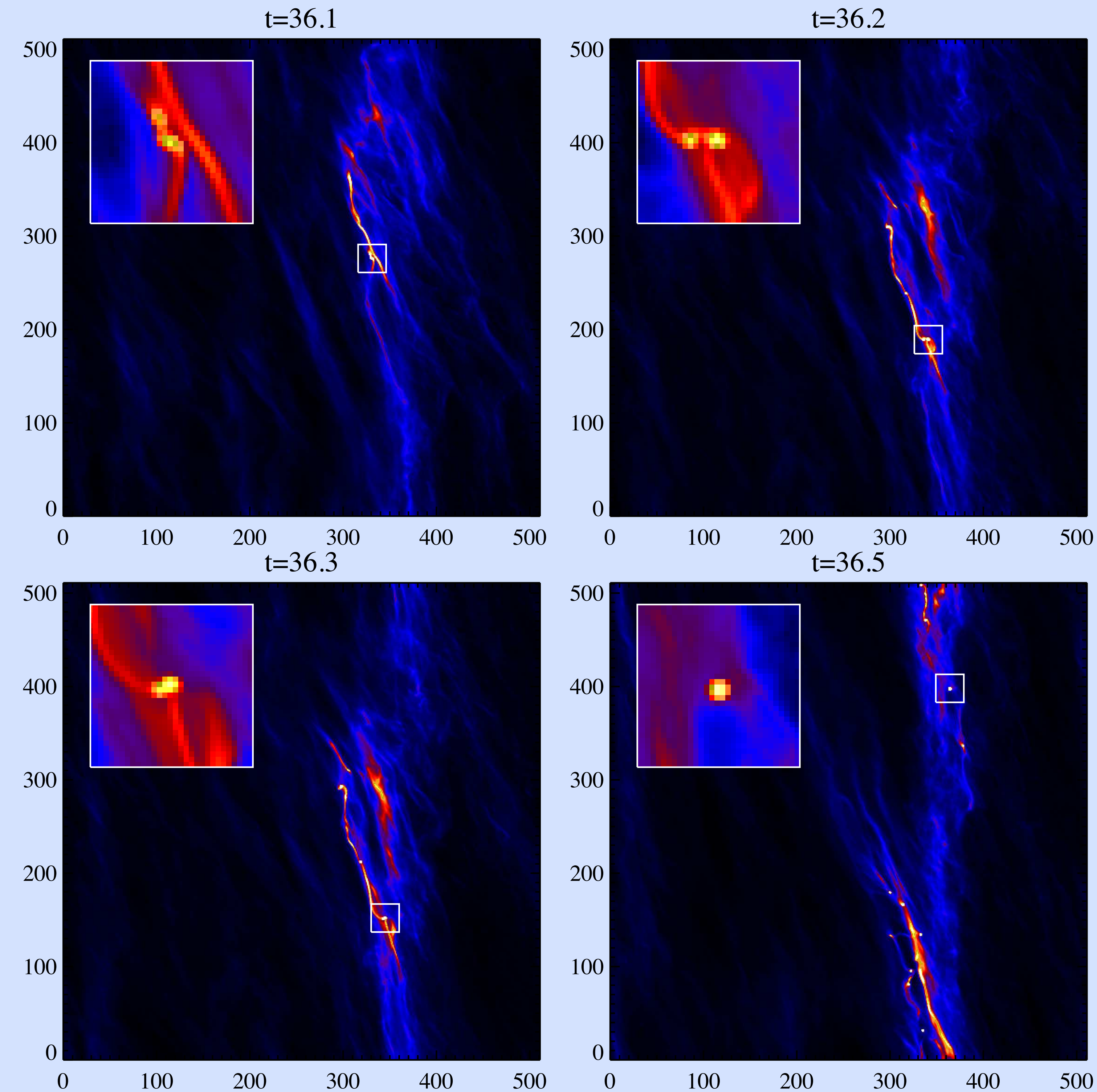
Formation Of Planetesimals From pressure trapped / gravitational Bound heaps of gravel - here magnetic turbulence: Johansen, Klahr & Henning 2011. Next: Raettig & Lyra

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



12/13/2009

At 512^3 and the usual set up: As before mass of planetesimals depends on the available mass.



new: Intermediate Formation of Binaries; Johansen, Klahr & Henning (2011)

Not the process but numerical resolution limit the smallest possible planetesimals. Johansen, Klahr & Henning 2011

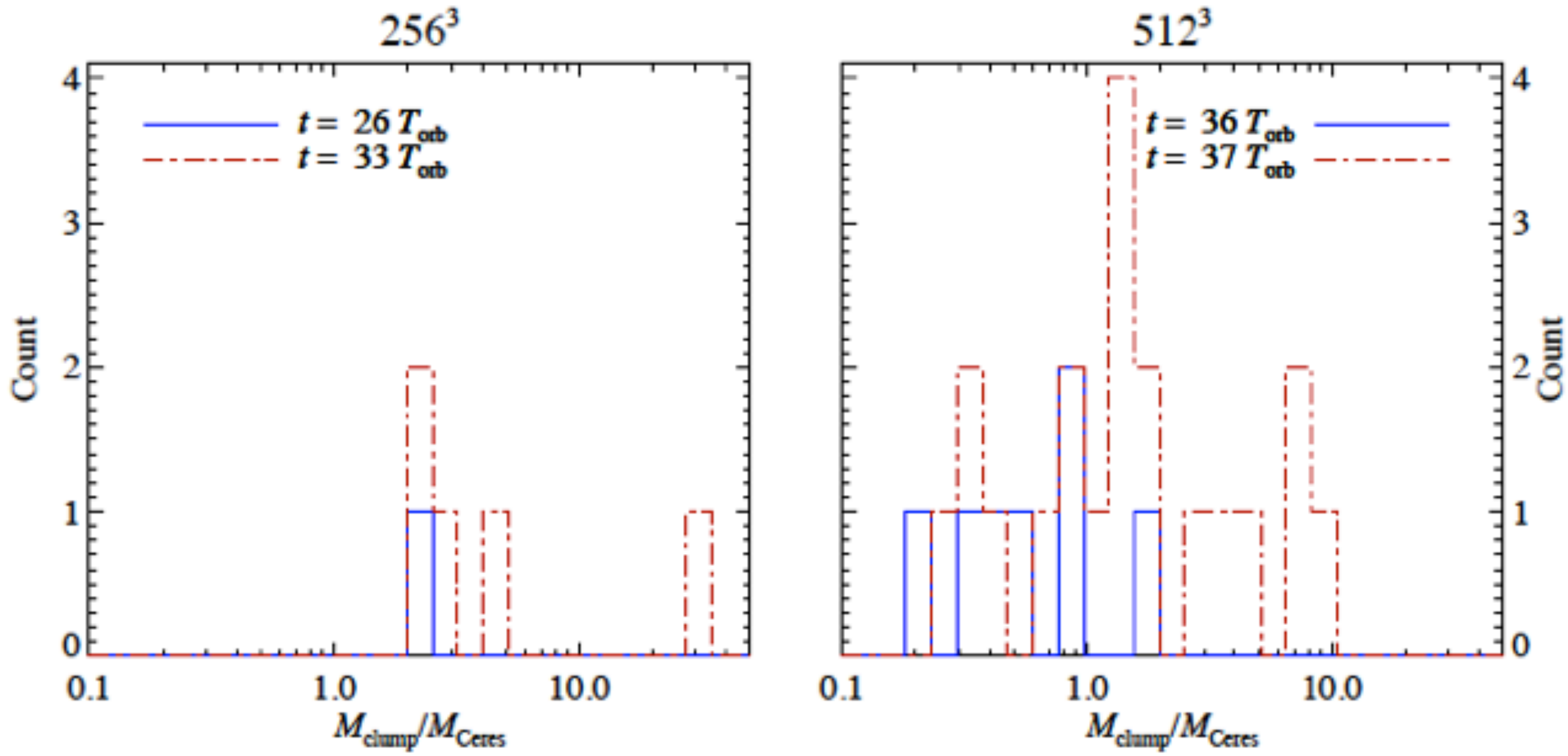


Fig. 10. Histogram of clump masses after first production of bound clumps and at the end of the simulation. At moderate resolution (left panel) only a single clump condenses out initially, but seven orbits later there are five clumps, including the 30+ M_{Ceres} object formed by merging. At high resolution (right panel) the initial planetesimal burst leads to the formation of many sub-Ceres-mass clumps. The most massive clump is similar to what forms initially in the moderate-resolution run.

To predict an initial mass distribution of Planetesimals one needs A: the proper size distribution of precursors and B: the likely hood for concentrations as a function of particle size.

Larger Boxes = better concentration
Dittrich, Klahr & Johansen submitted

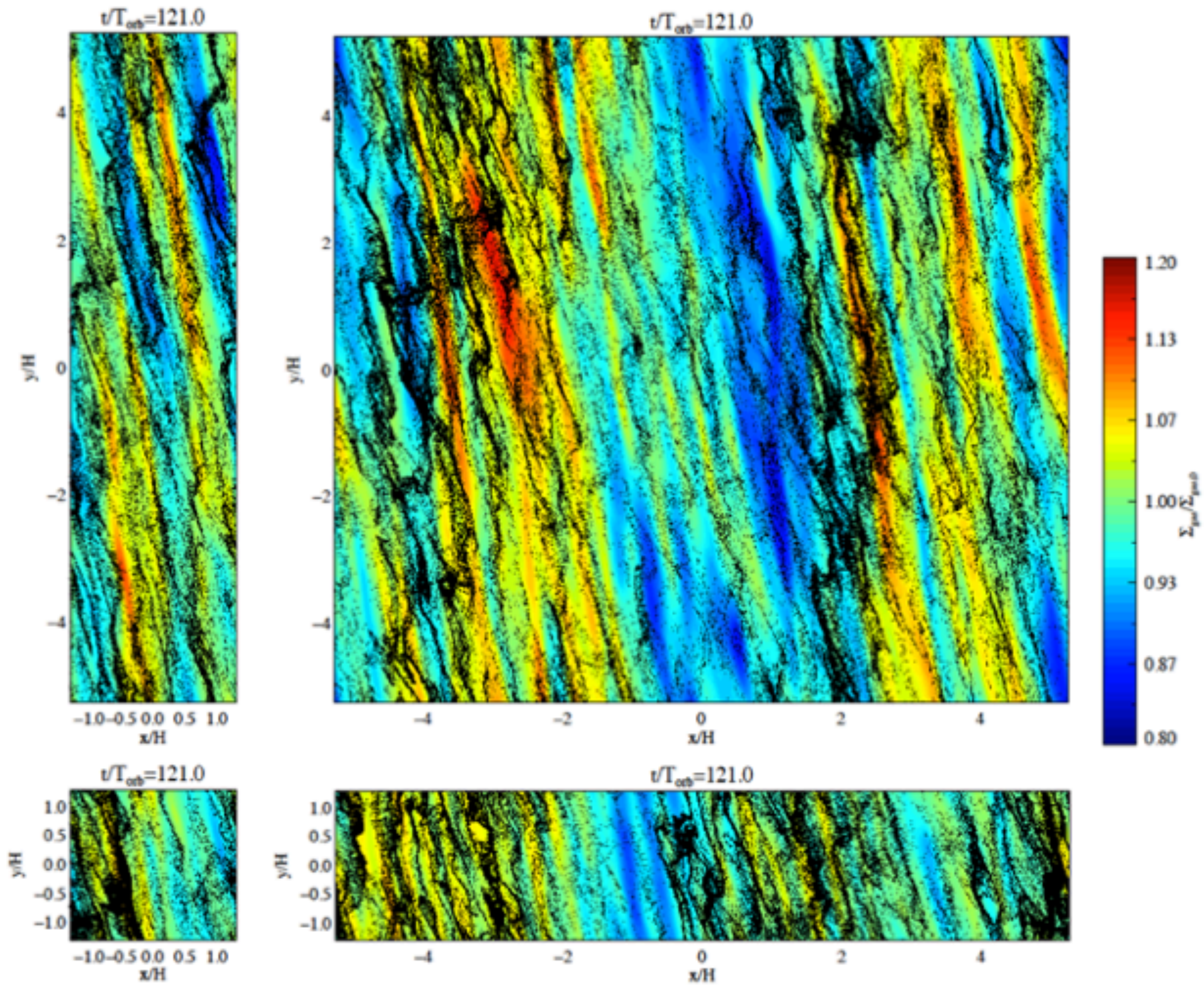
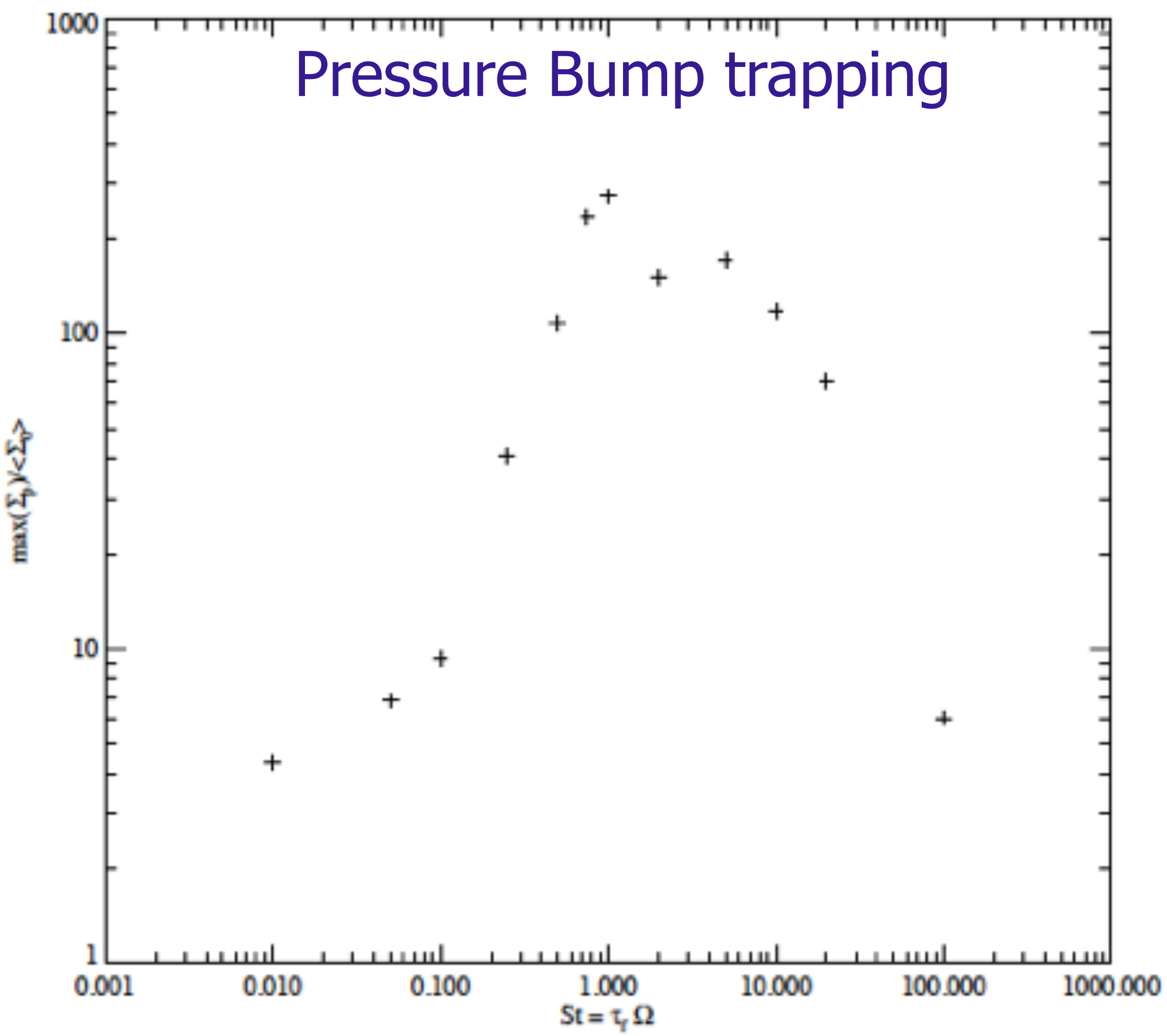
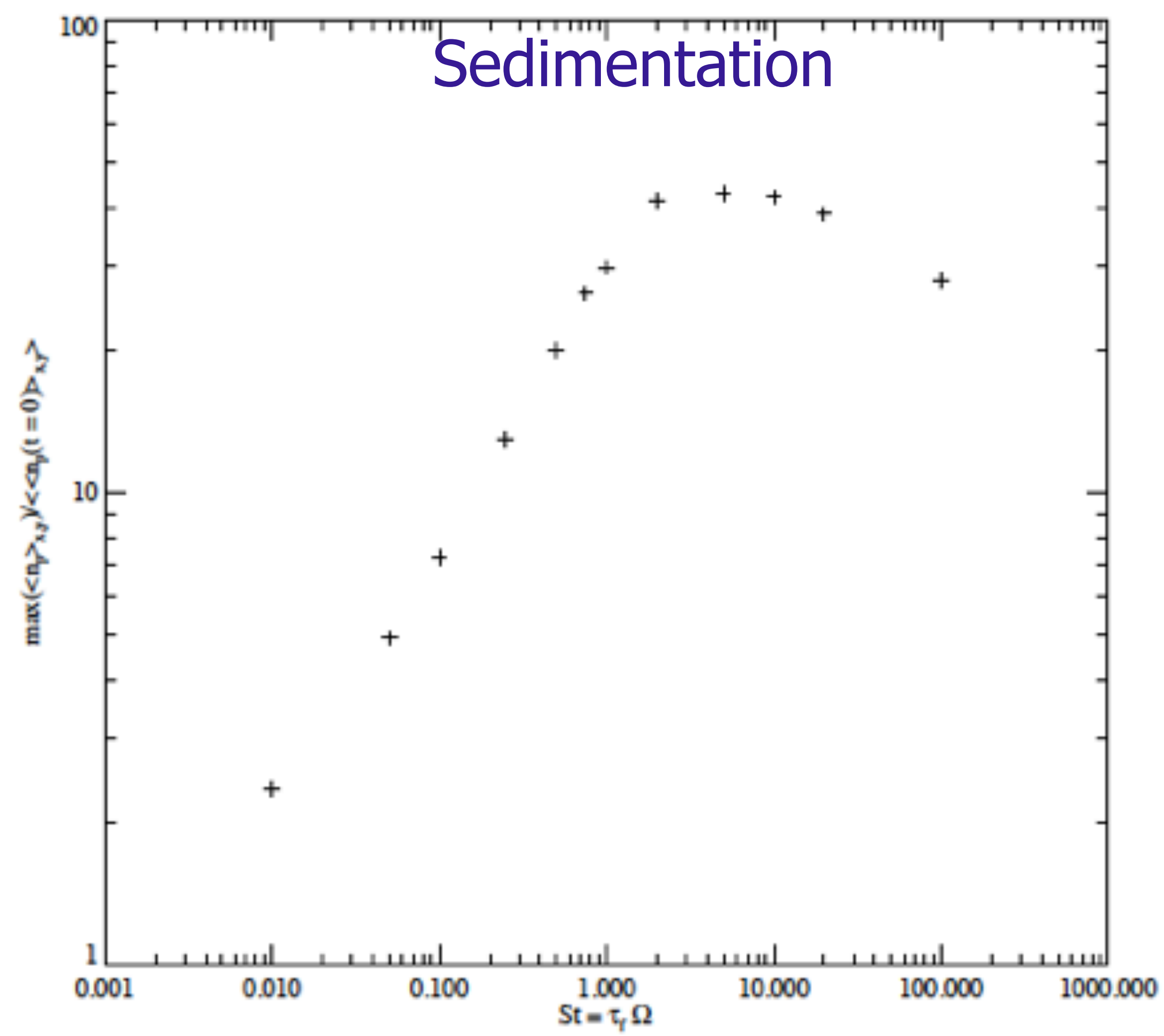


Figure 4. A collage of 4 surface gas density plots of the simulations *y-XL*, *XL*, *M*, and *x-XL* (from the upper left to the lower right panel respectively), each at the end of the simulation. The color bar at the right-hand side is valid for all 4 panels. This collage shows that over-densities are most pronounced in the biggest box. The azimuthally extended box shows regions of similar high density as simulation *XL*. However, the structure seems to be thinner for simulation *y-XL*. The black dots represent the position of every 20th particle, integrated in vertical direction.

Larger Boxes = better concentration
Even for much smaller particles!
Even St = 0.1 can ignite streaming inst.
and grav.-turb. planetesimal formation

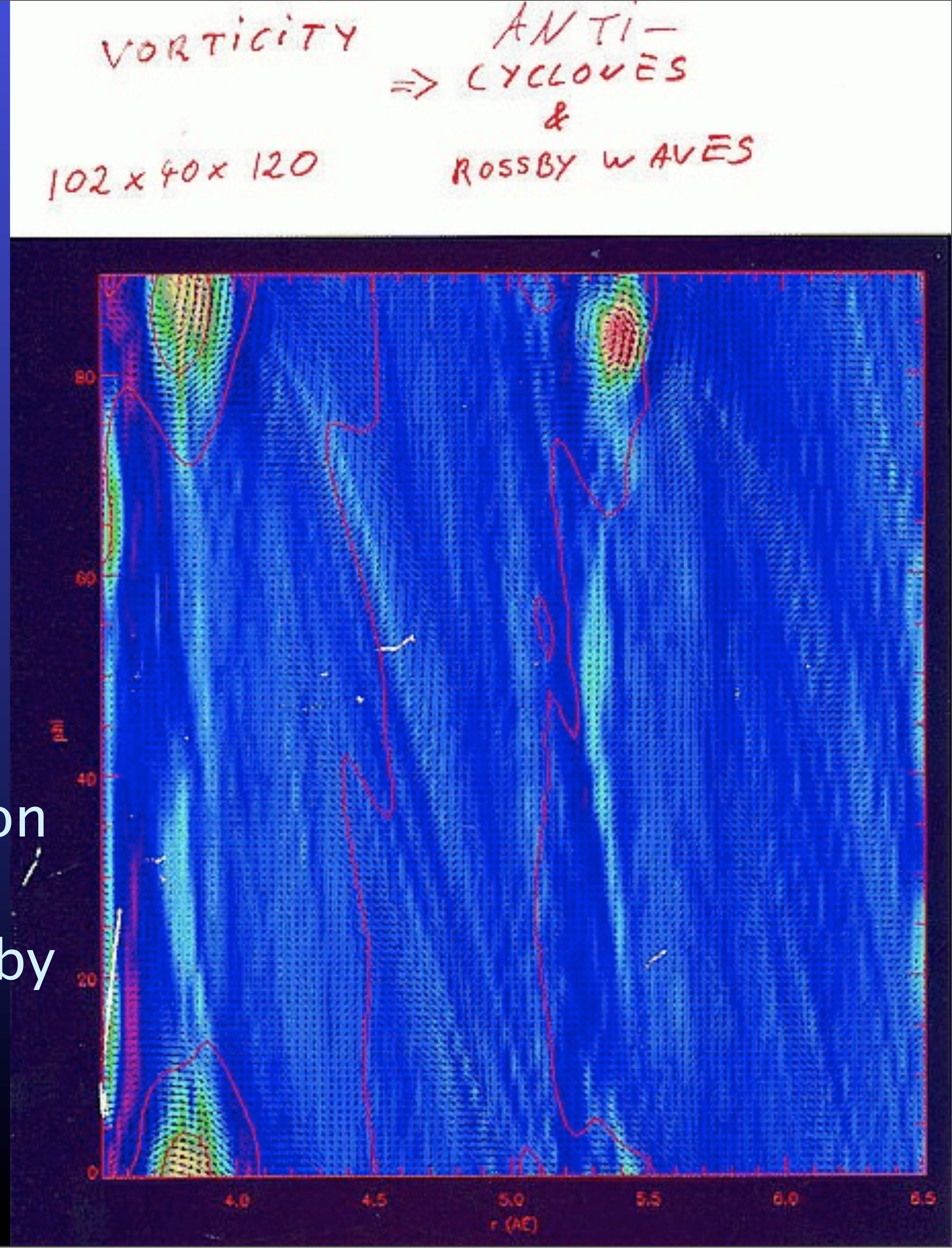




14 years back...
...before I was doing this with MHD we tried Thermal Convection because my advisors said so... ;)

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 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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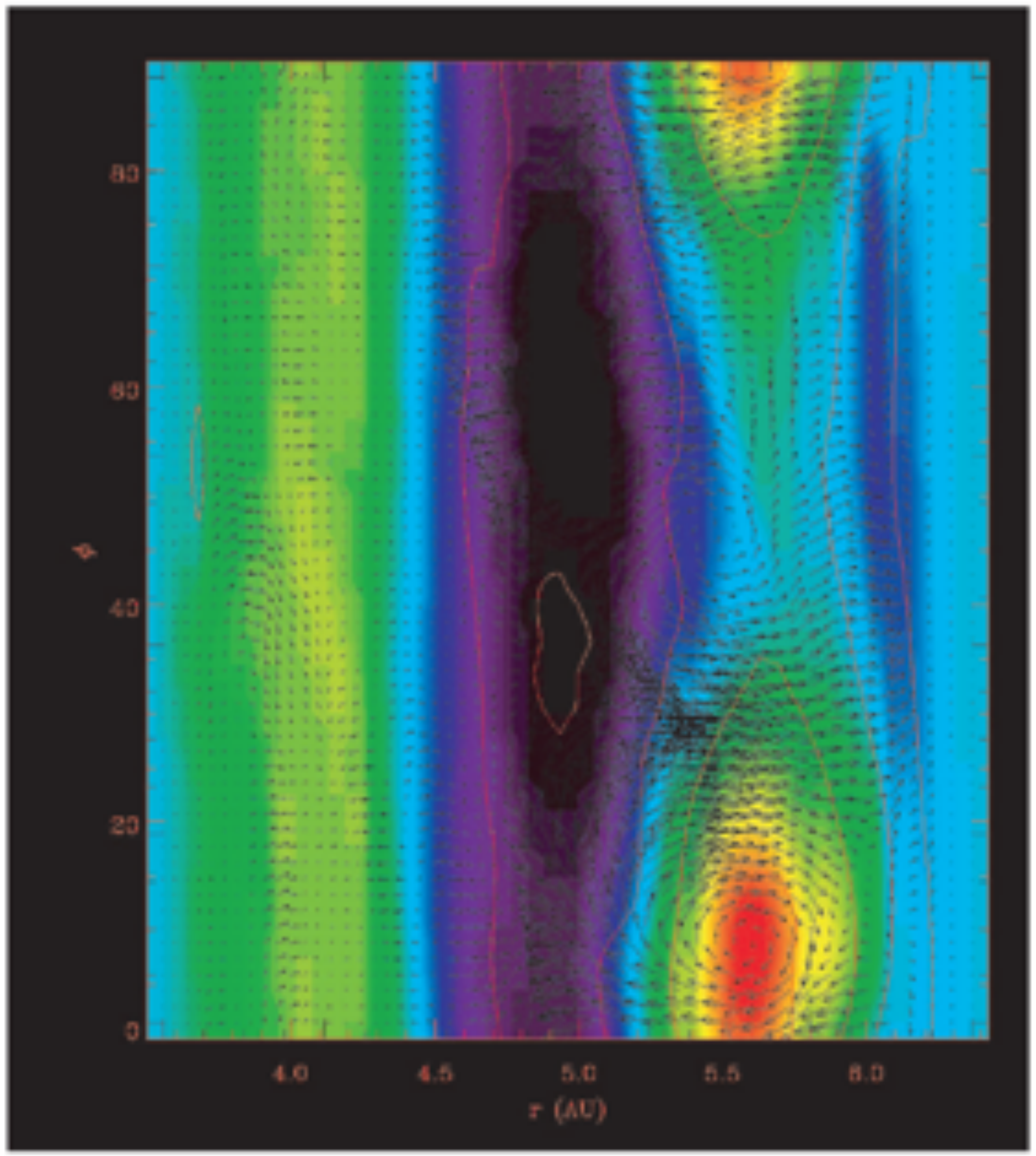
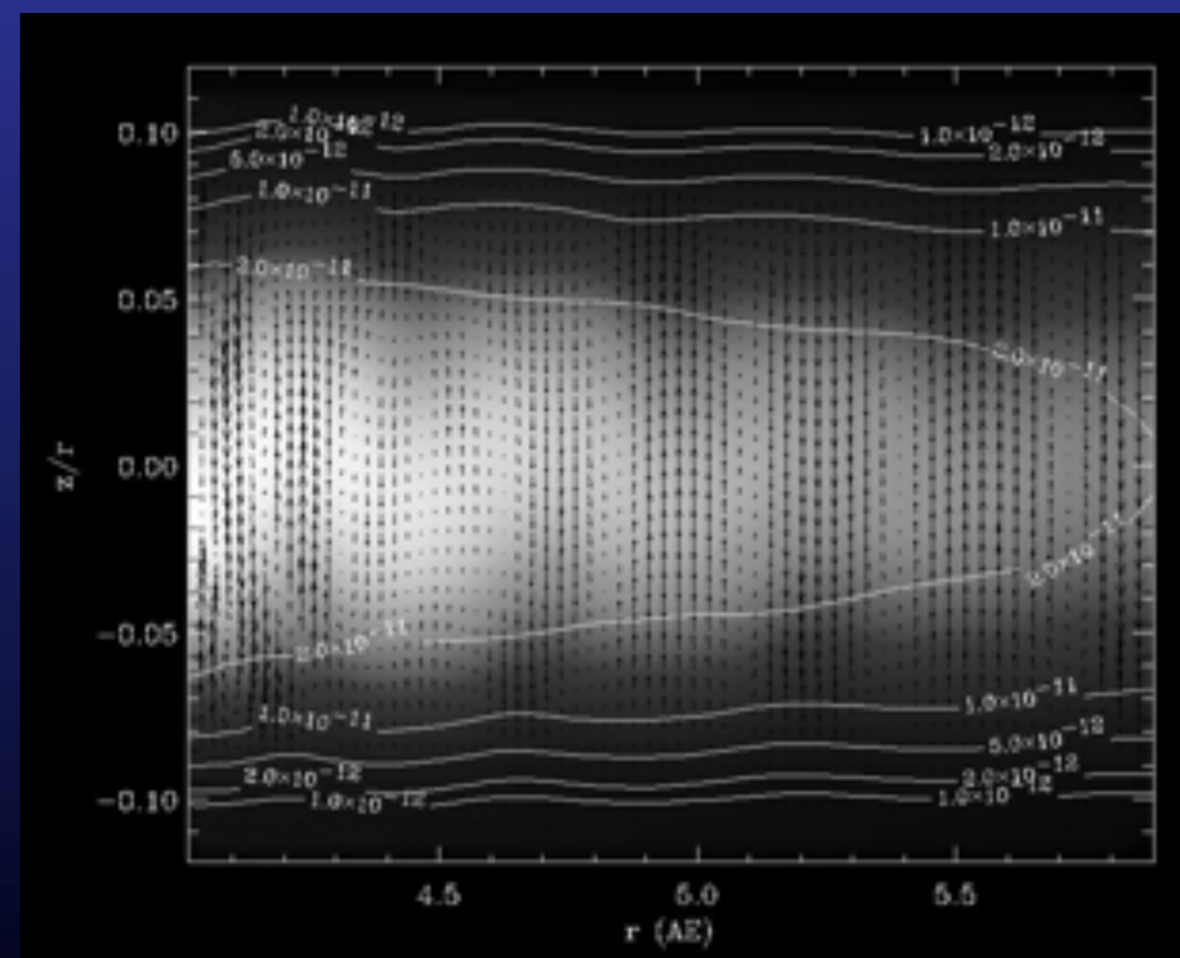
Received 2000 June 7; accepted 2002 September 17

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





Klahr & Bodenheimer 2003

Radial Entropy Gradient leads to vortices somehow... Klahr 2004?

Then a lot of discussion started...

...but 4 years later:

Petersen et al. 2007

Yeah!

Now with thermal relaxation

Simulations are robust!

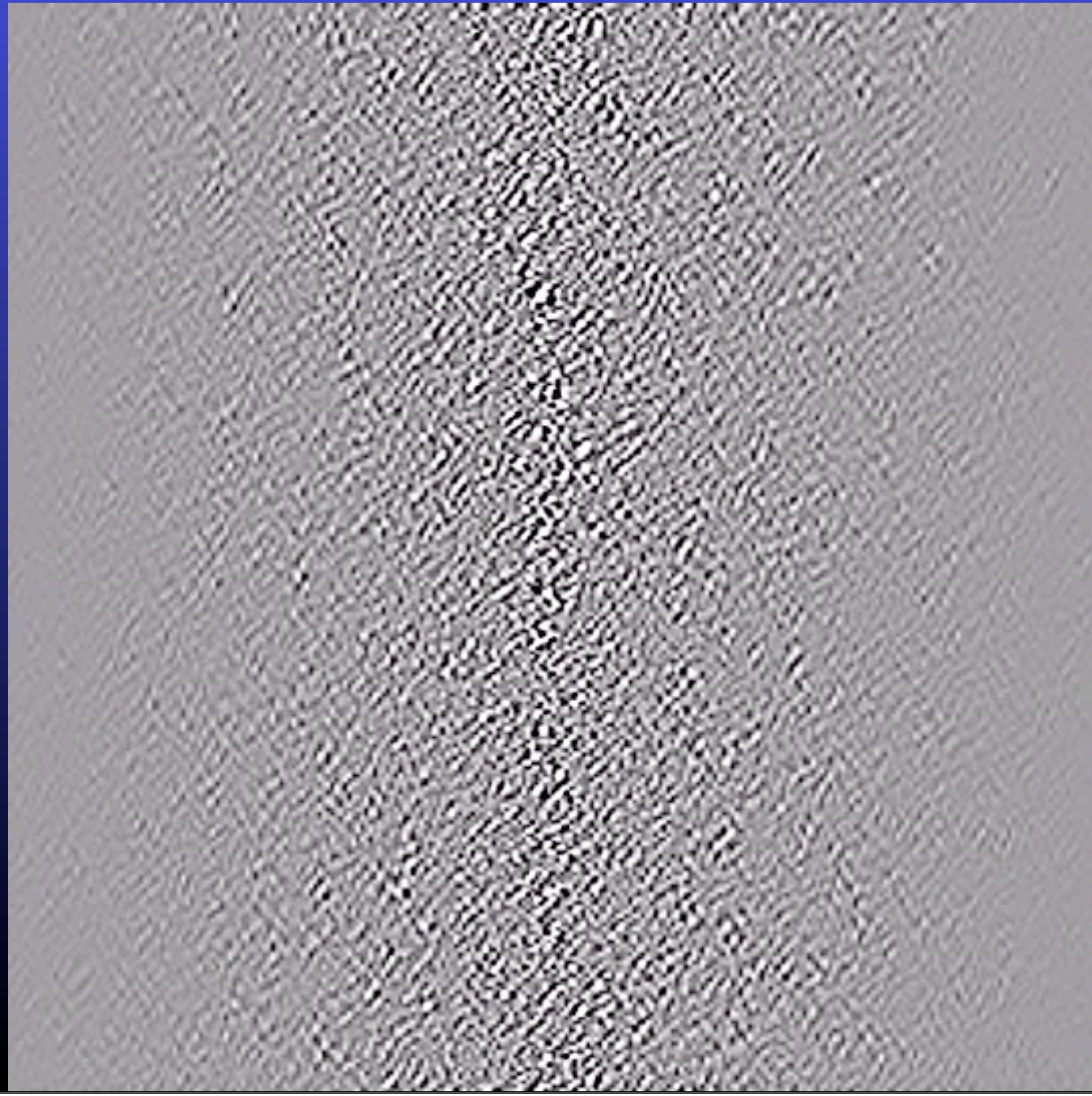
Vorticity

Vorticity: Pencil Code: Lyra and Klahr 2011; $\beta = 2$; $N = 256$; $\tau_c = 1$

radial

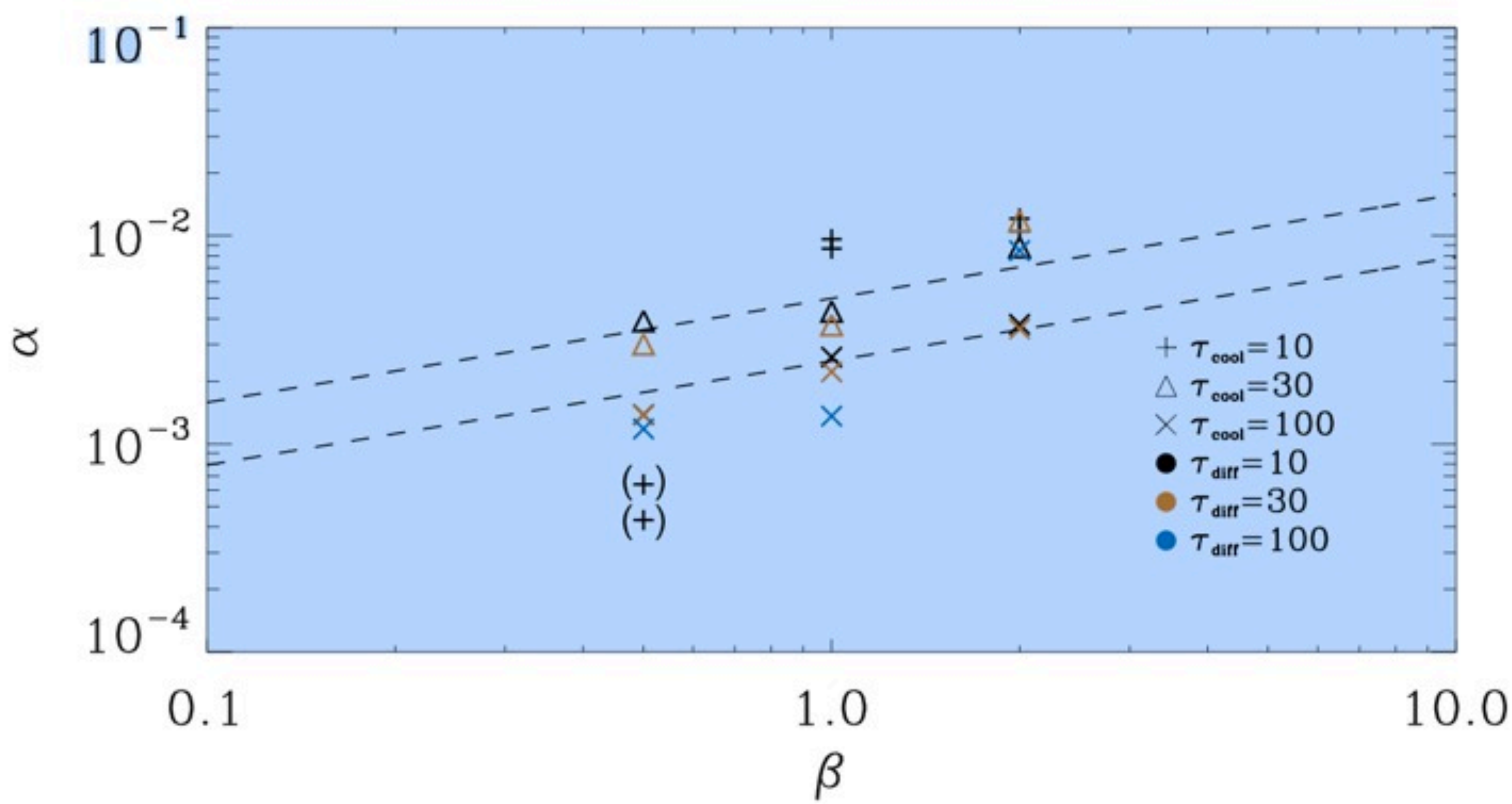
Vorticity

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



12/13/2009

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



Growth rates

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

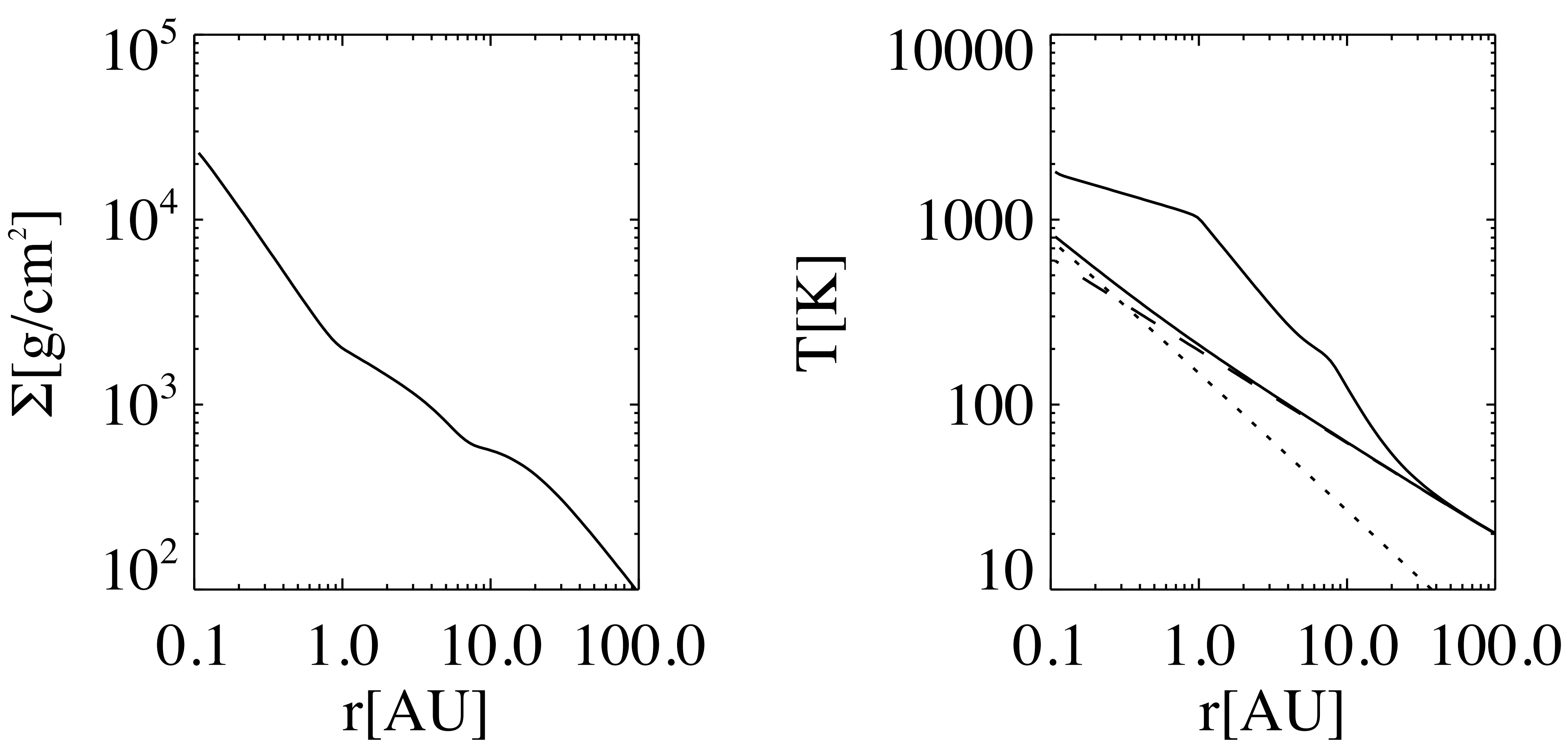
see also John's talk

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



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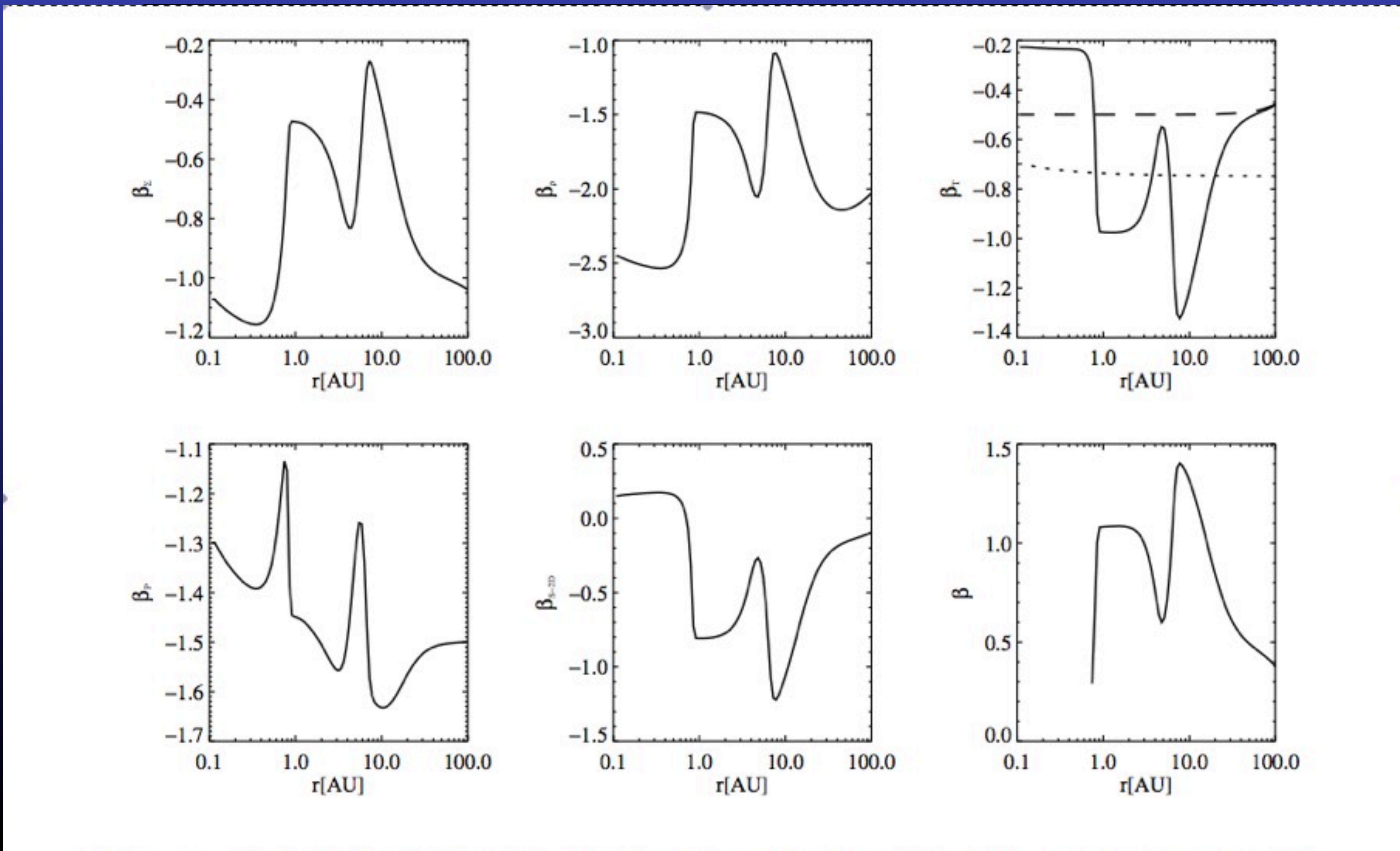


Richardson number & thermal diffusion time

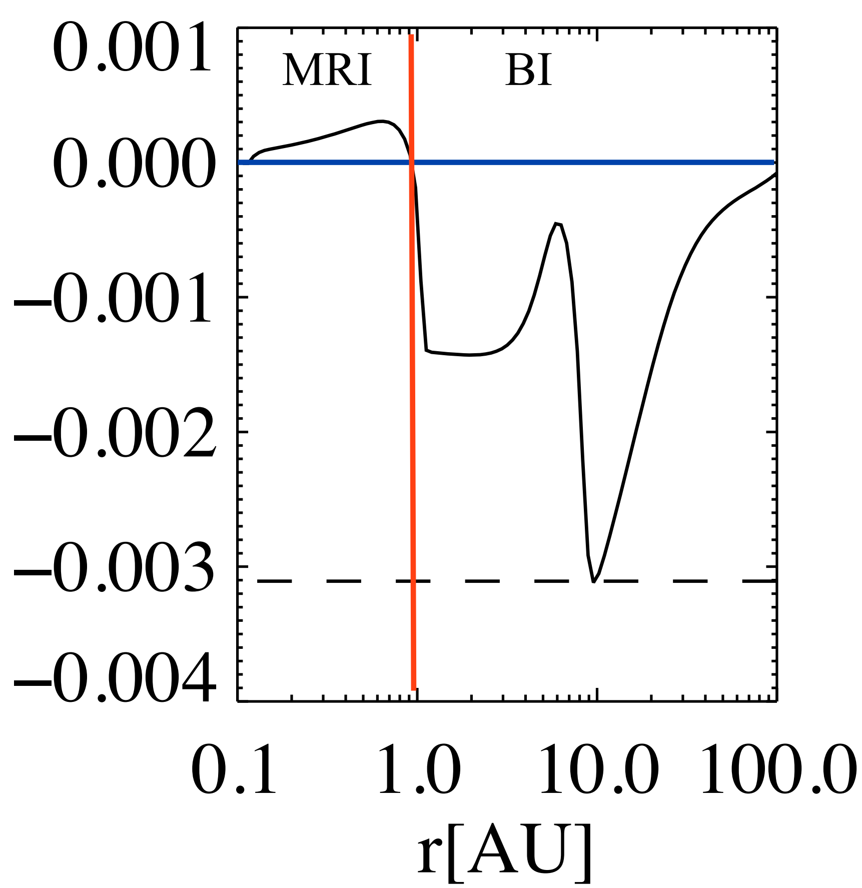
$$N^2 = -\frac{1}{\gamma}\left(\frac{H}{R}\right)^2 \beta_s \beta_p \Omega^2$$

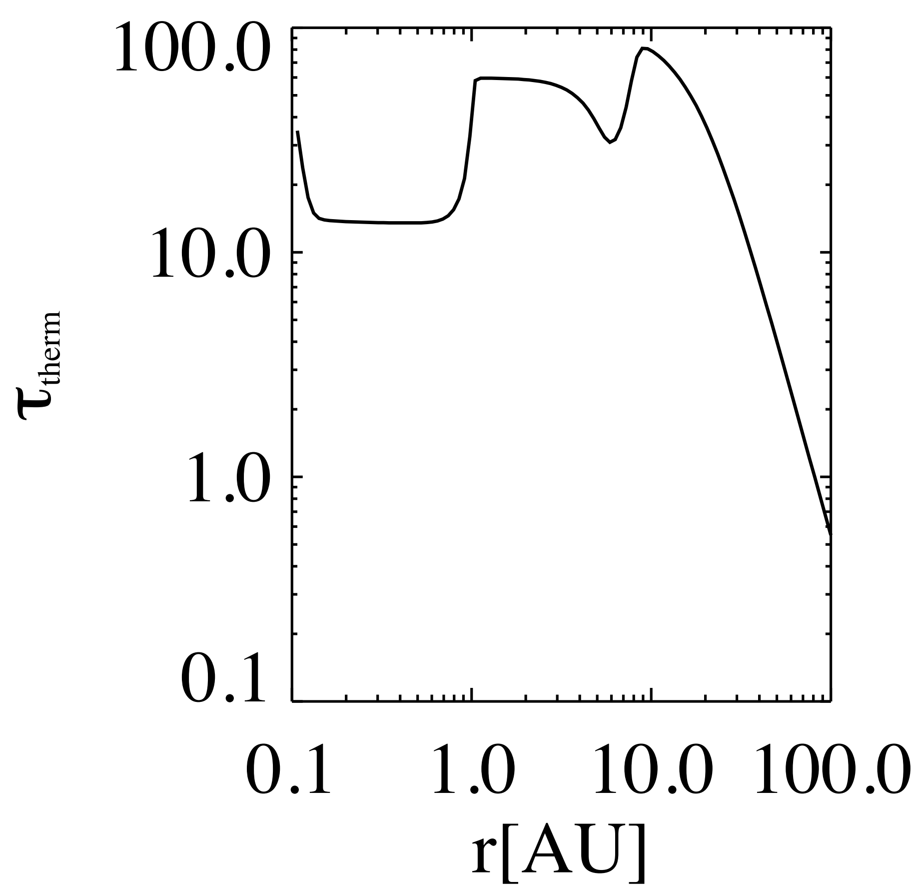
$$Ri = -\frac{2}{3\gamma}\left(\frac{H}{R}\right)^2 \beta_p \beta_s$$

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

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

Ri





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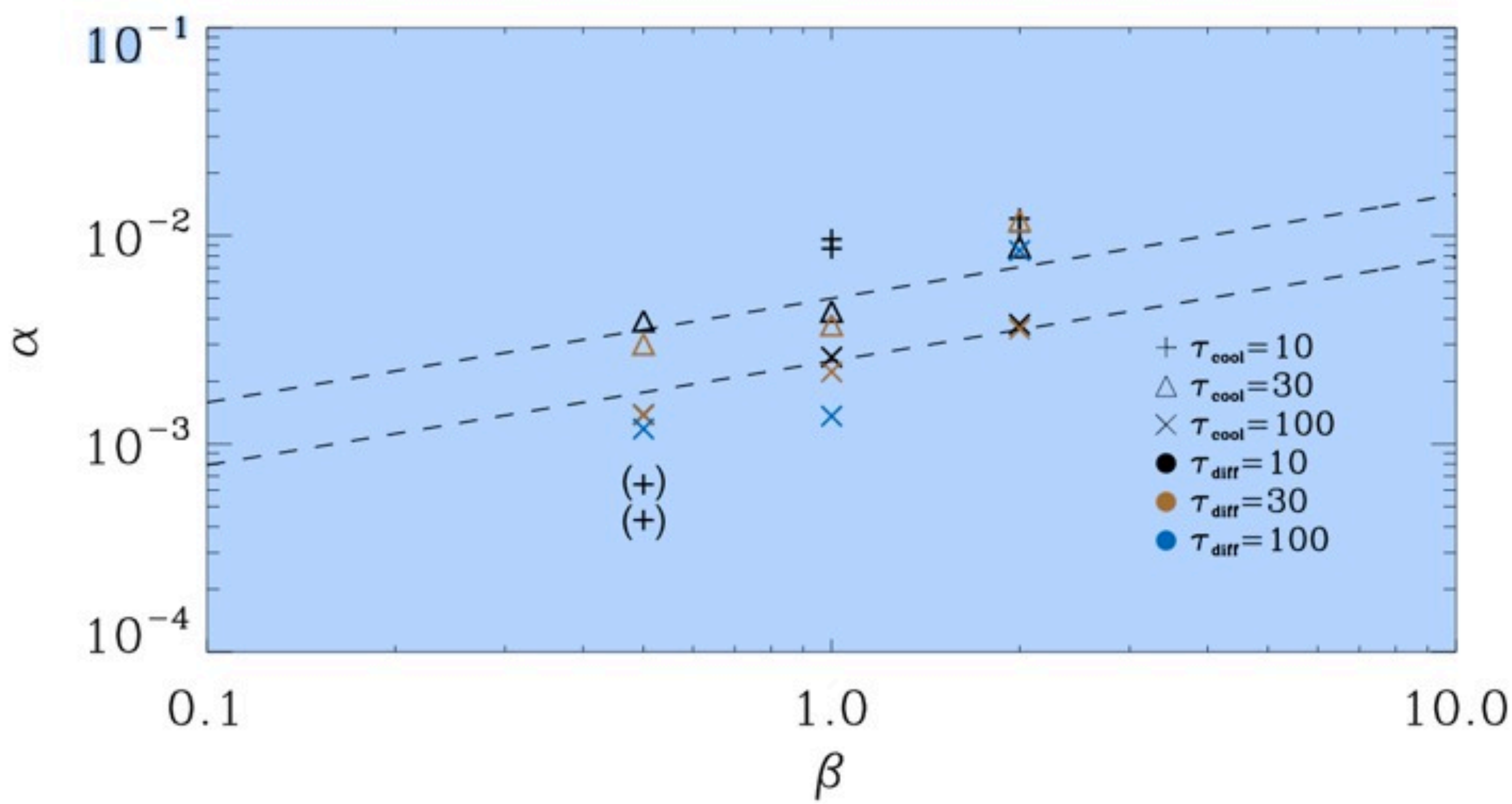

Growth rates

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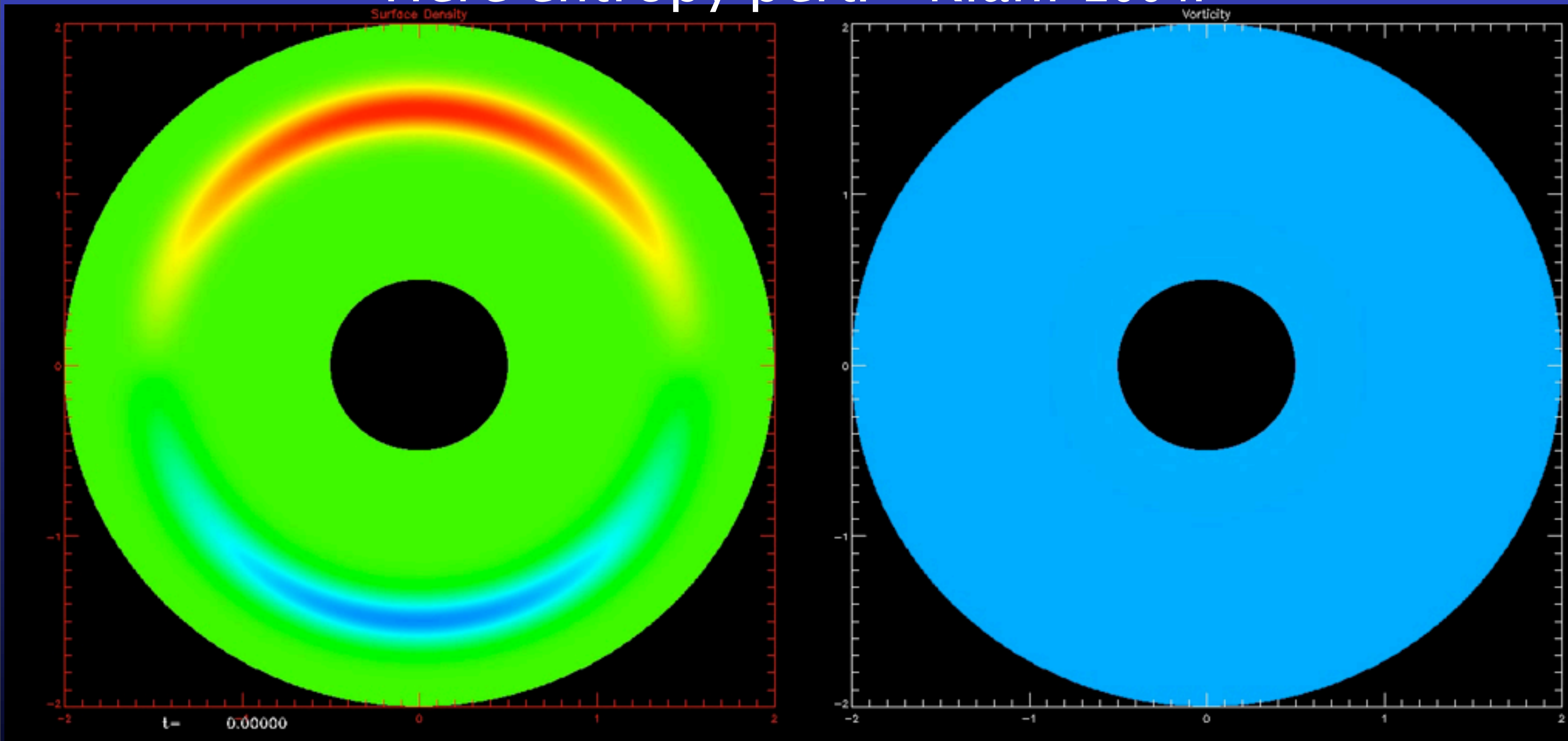
Pluto Code: 1024^2; WENO3-RK3; HLLE; FARGO
How to get a critical Vortex?
Here entropy pert. + Klahr 2004!



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

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

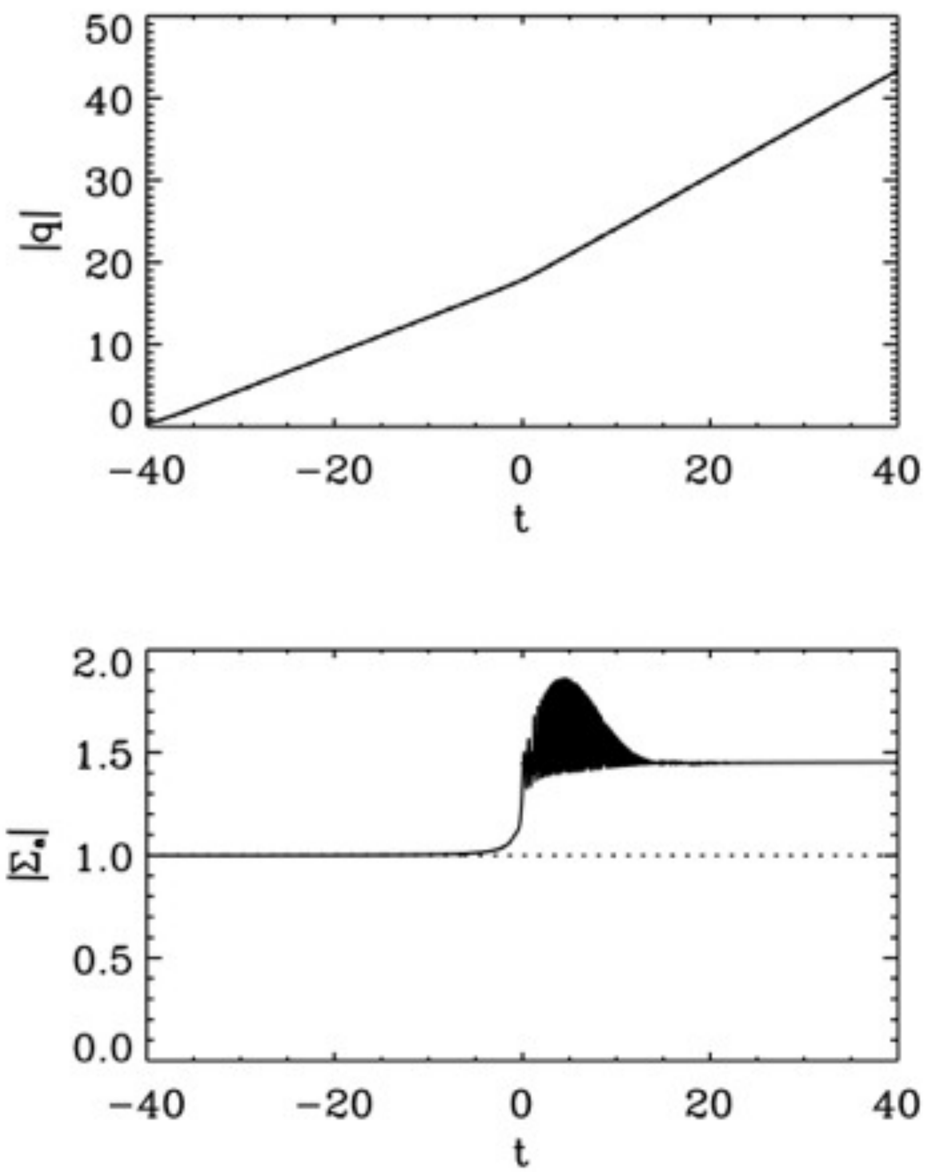


FIG. 8.—Evolution of the perturbations in a Keplerian disk for case C ($\beta = 1$ and zero initial vorticity). The amplitudes of surface density Σ_a and potential vorticity q are plotted.

Pluto Code: 1024^2; WENO3-RK3; HLLE; FARGO

Non linear stage of Klahr 2004

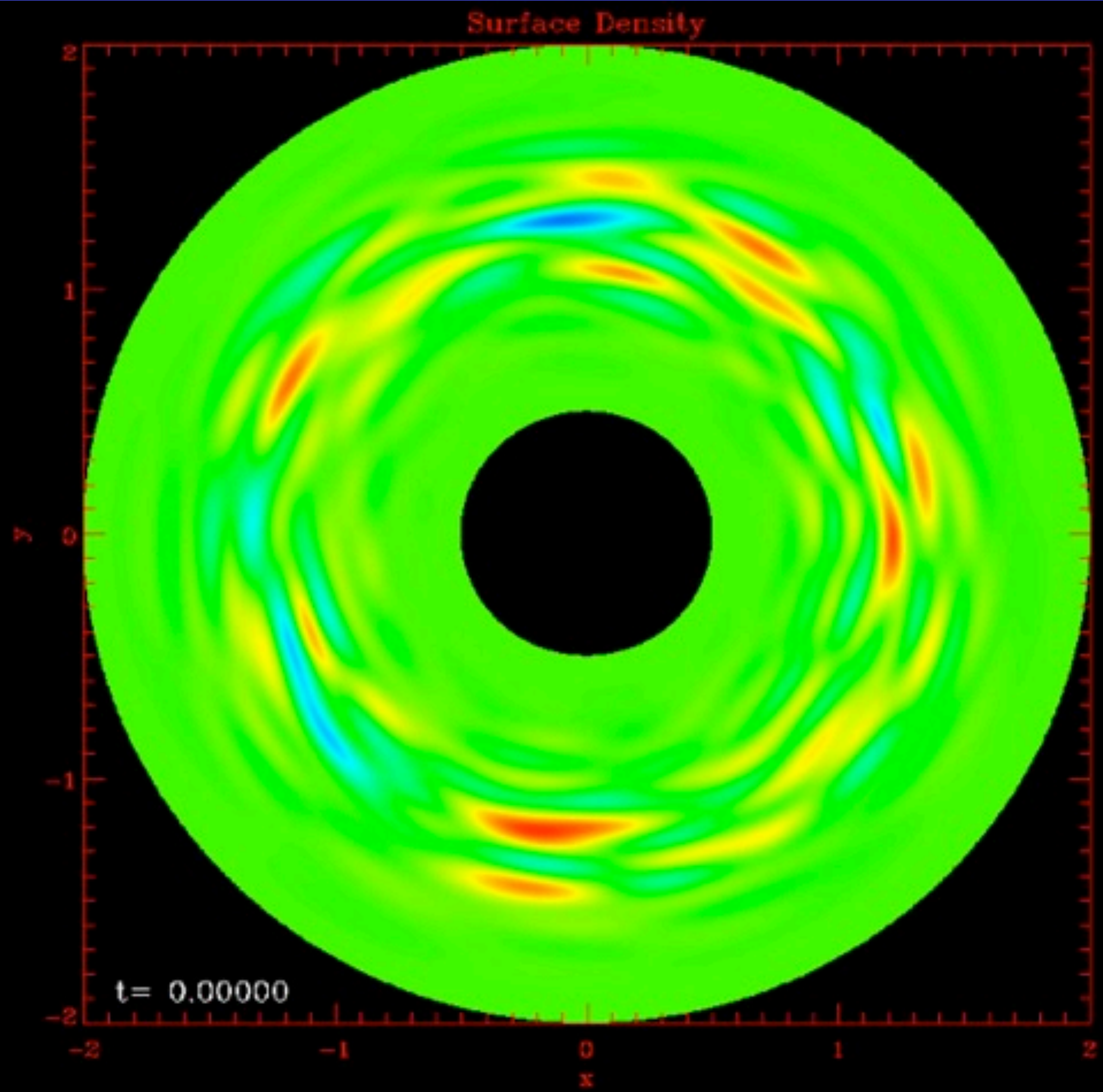
1.) entropy perturbation

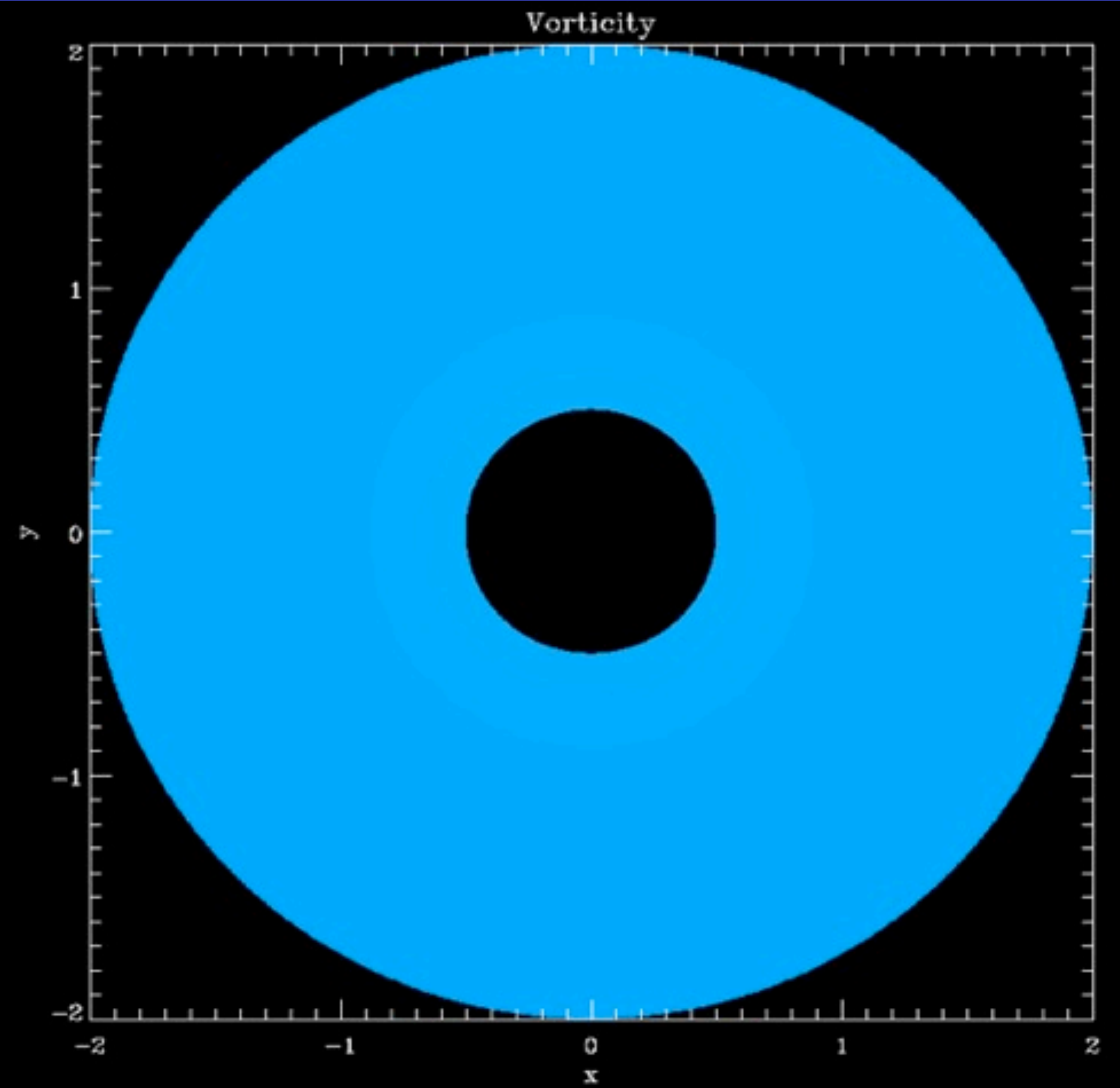
2.) tightly wrapped growing perturbation of vorticity

3.) Papaloizou Pringle - RWI Instability

4.) SBI - Vortex Amplification

5.) Spirals - GOTO 2.)





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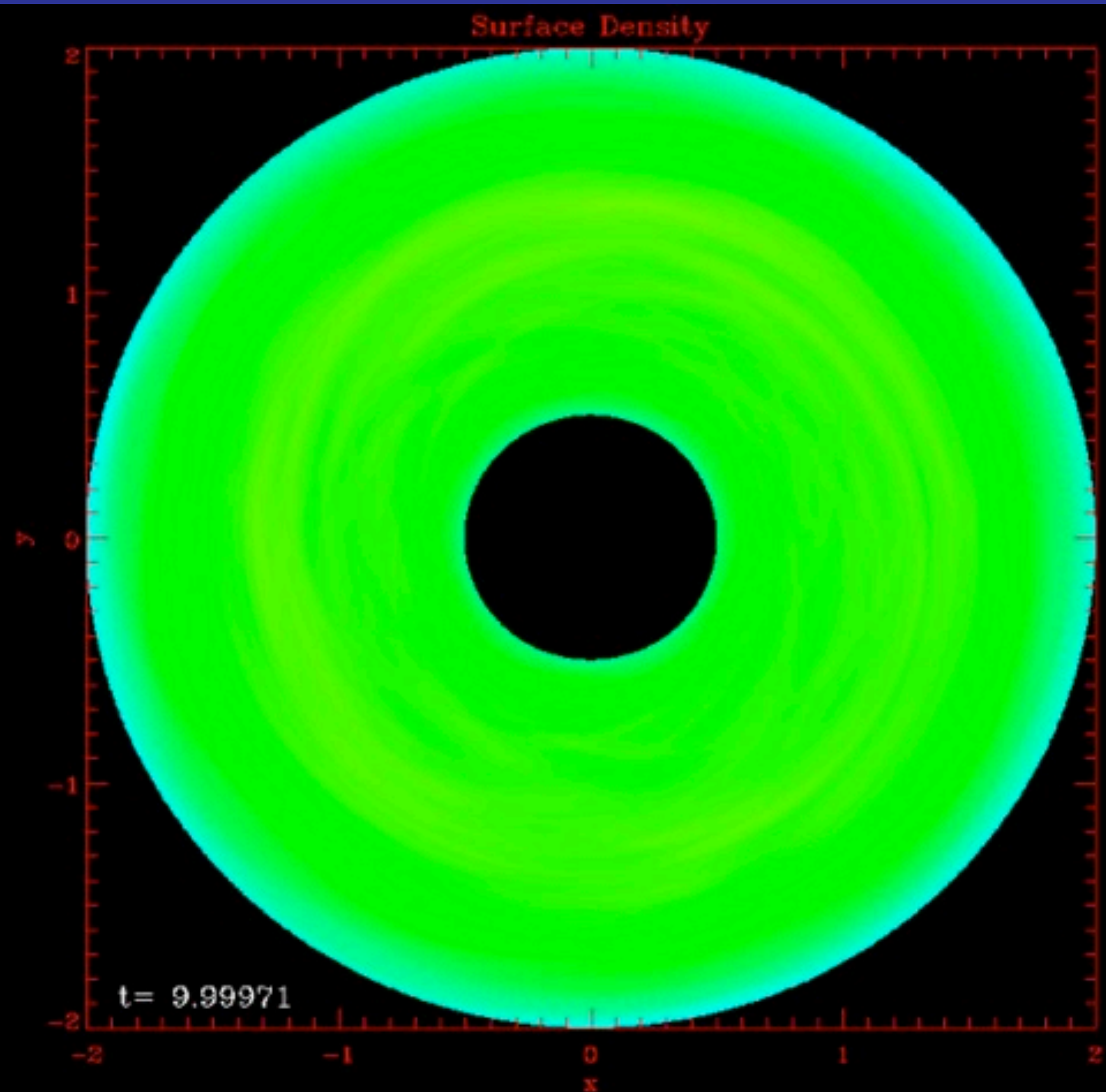

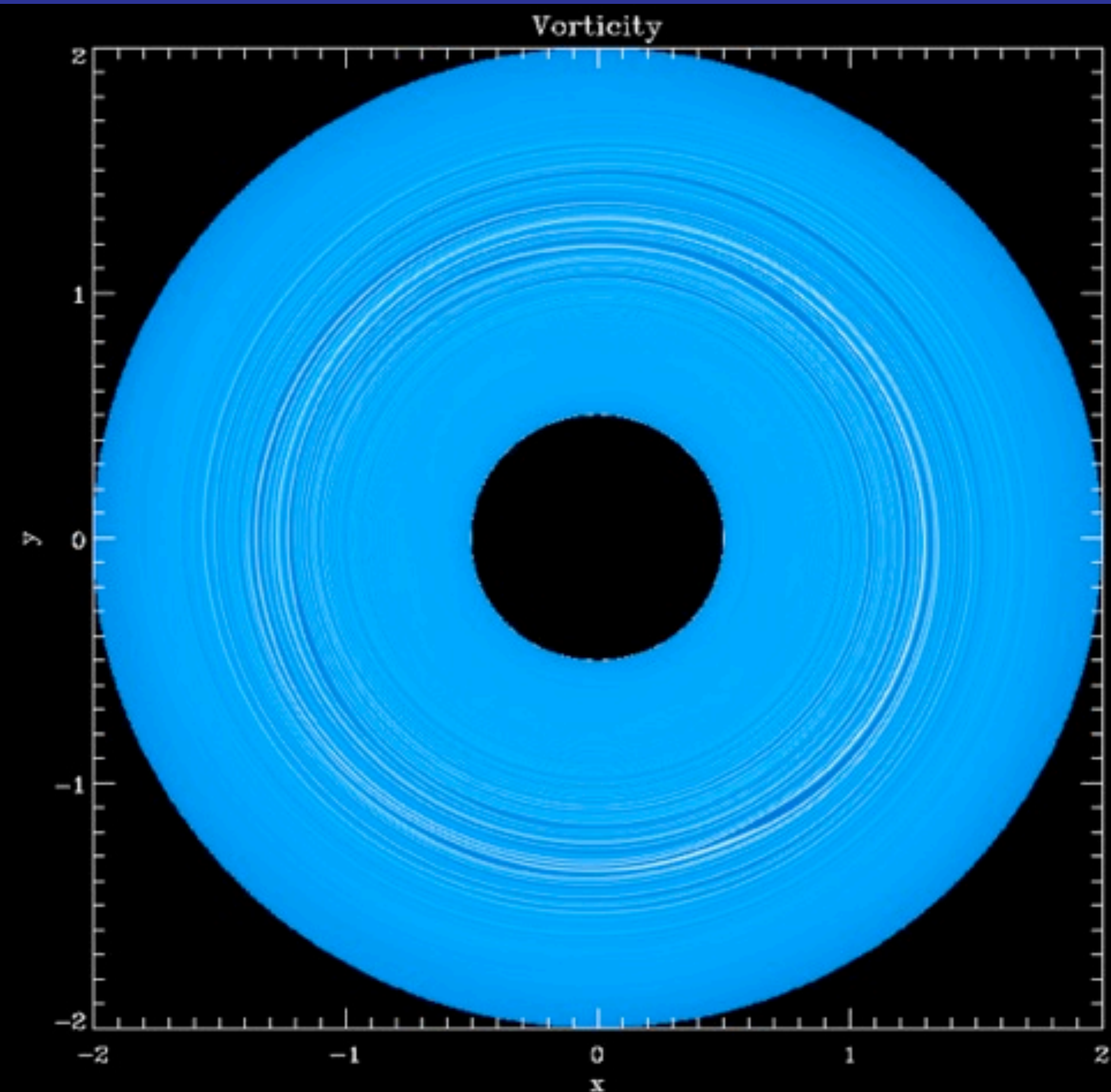

Pluto Code: 1024^2; WENO3-RK3; HLLE; FARGO

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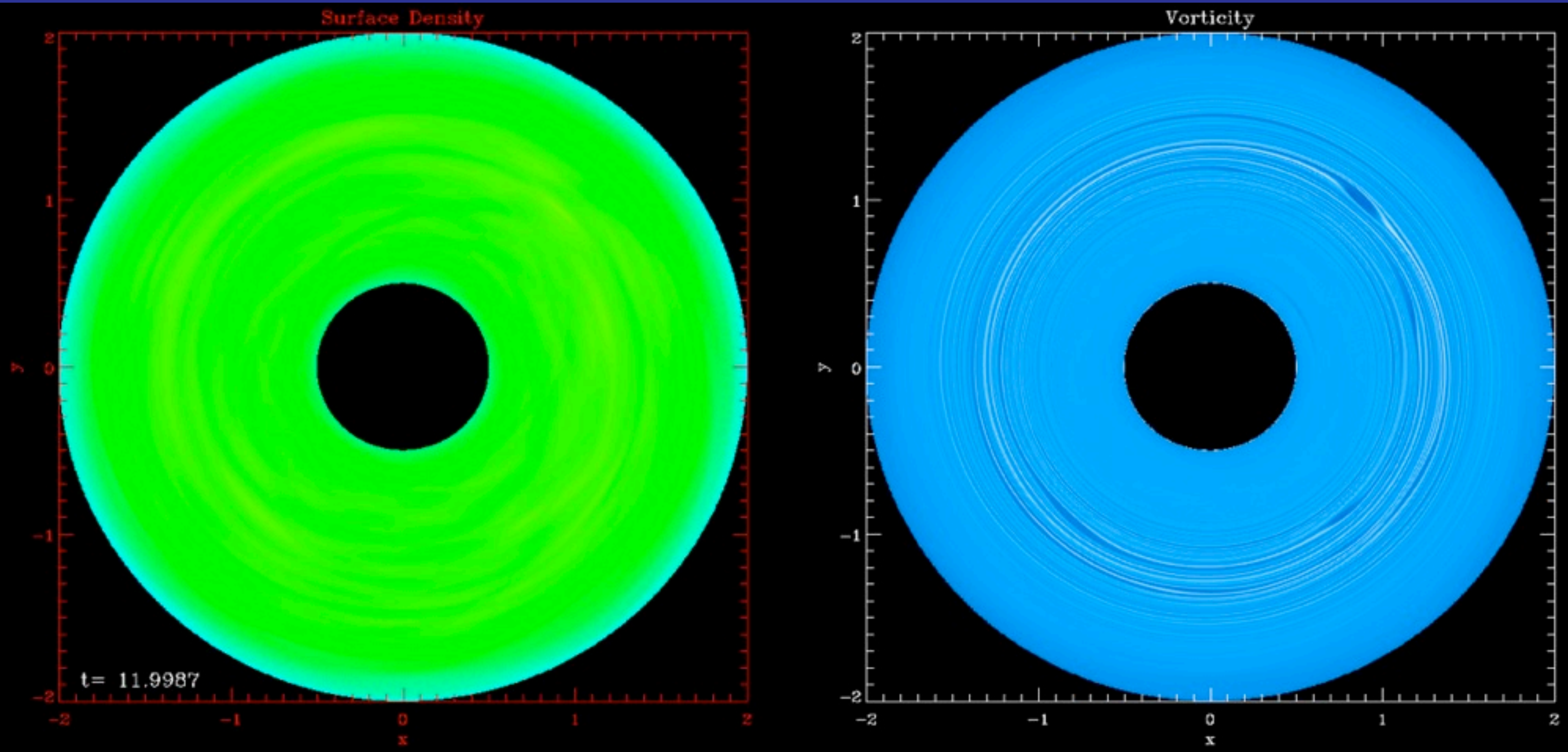

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Non linear stage of Klahr 2004

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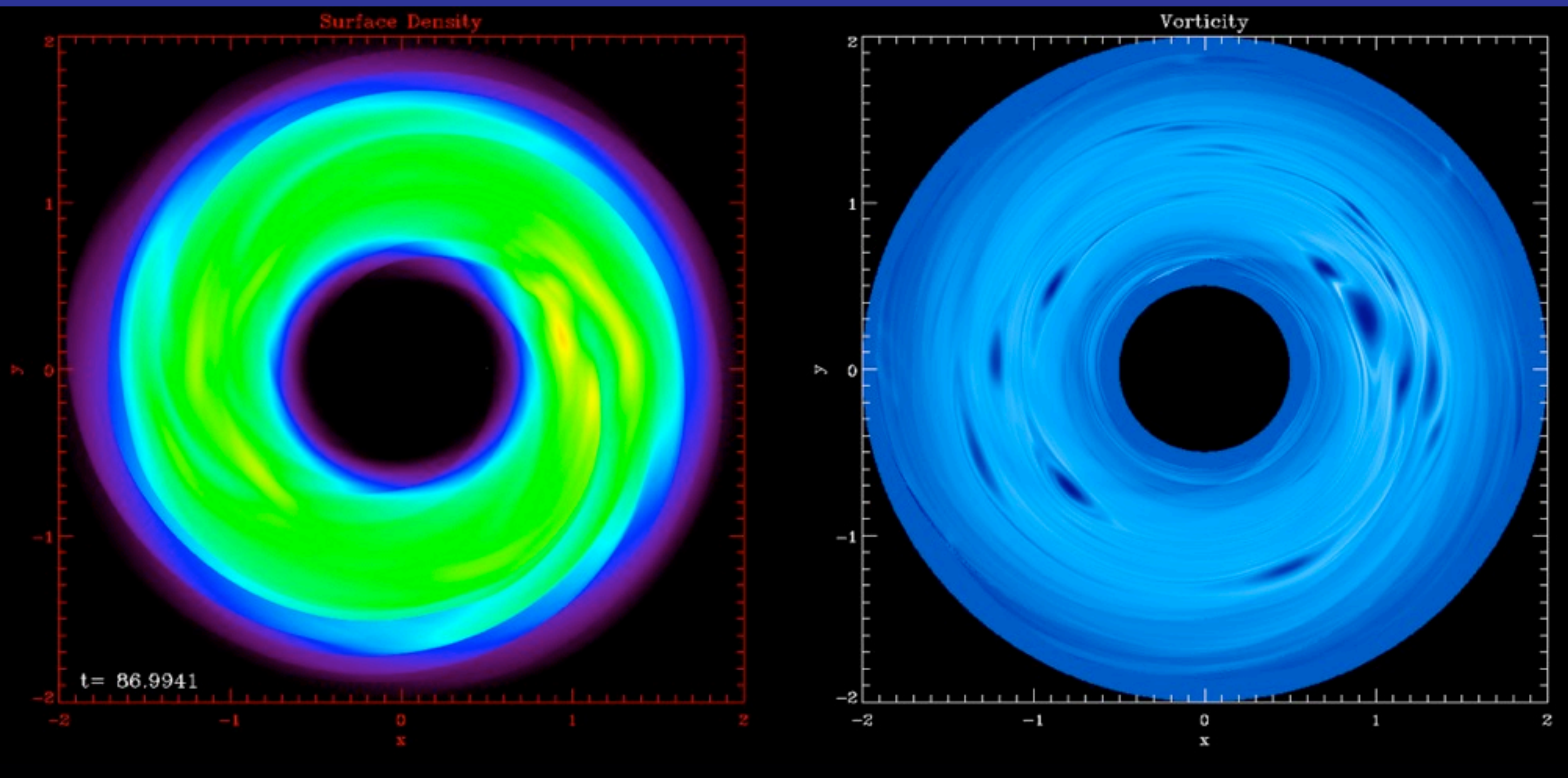
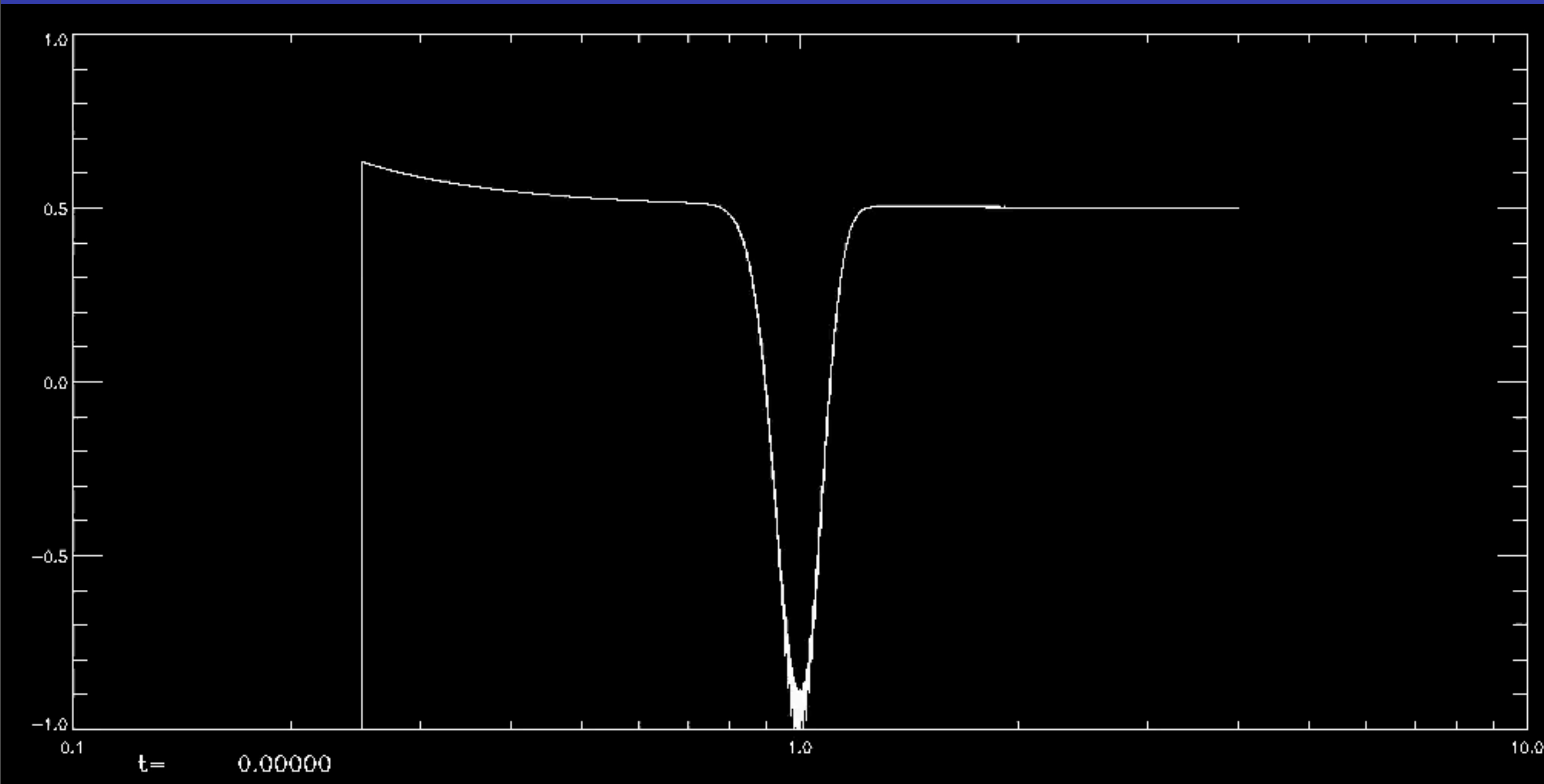
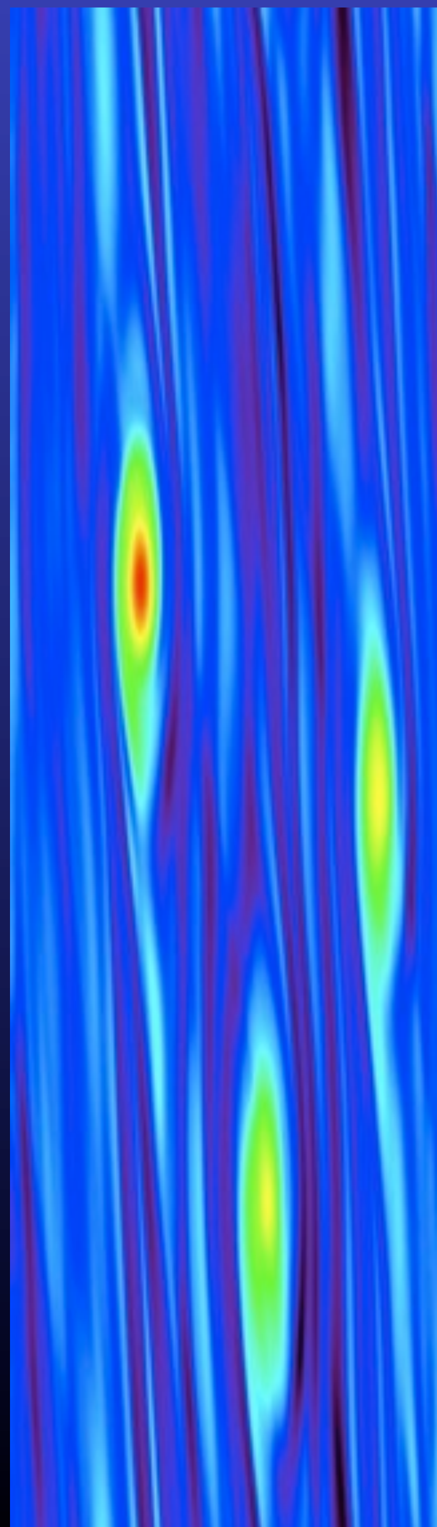


Vortex Migration: Local minimum of vorticity:

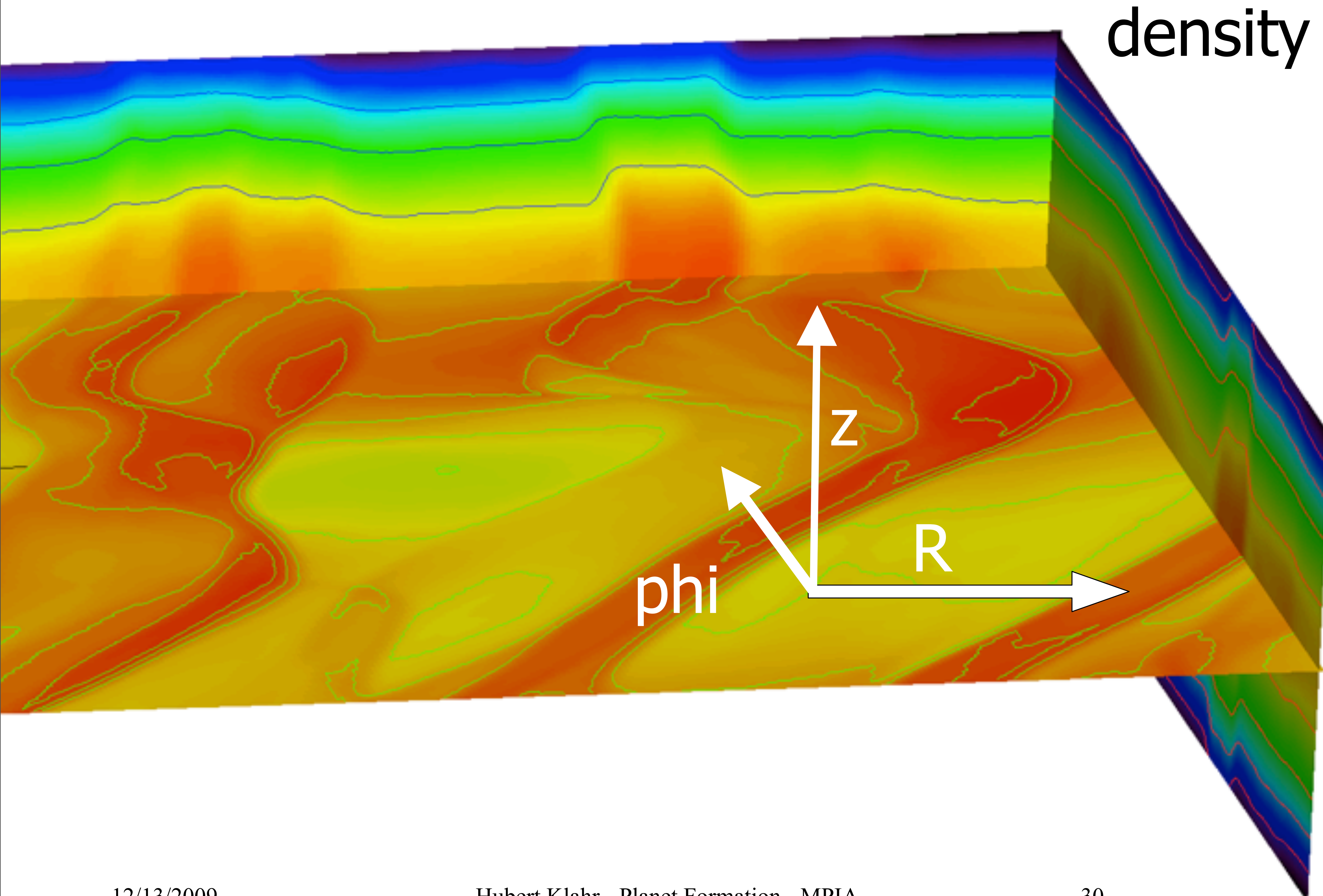


- Parameter: 3D; 256^2x128 LX = 4H;
- LY = 16H; LZ = 4H; β = 2; t_{cool} = 1; H/R = 0.1

azimuthal



Radial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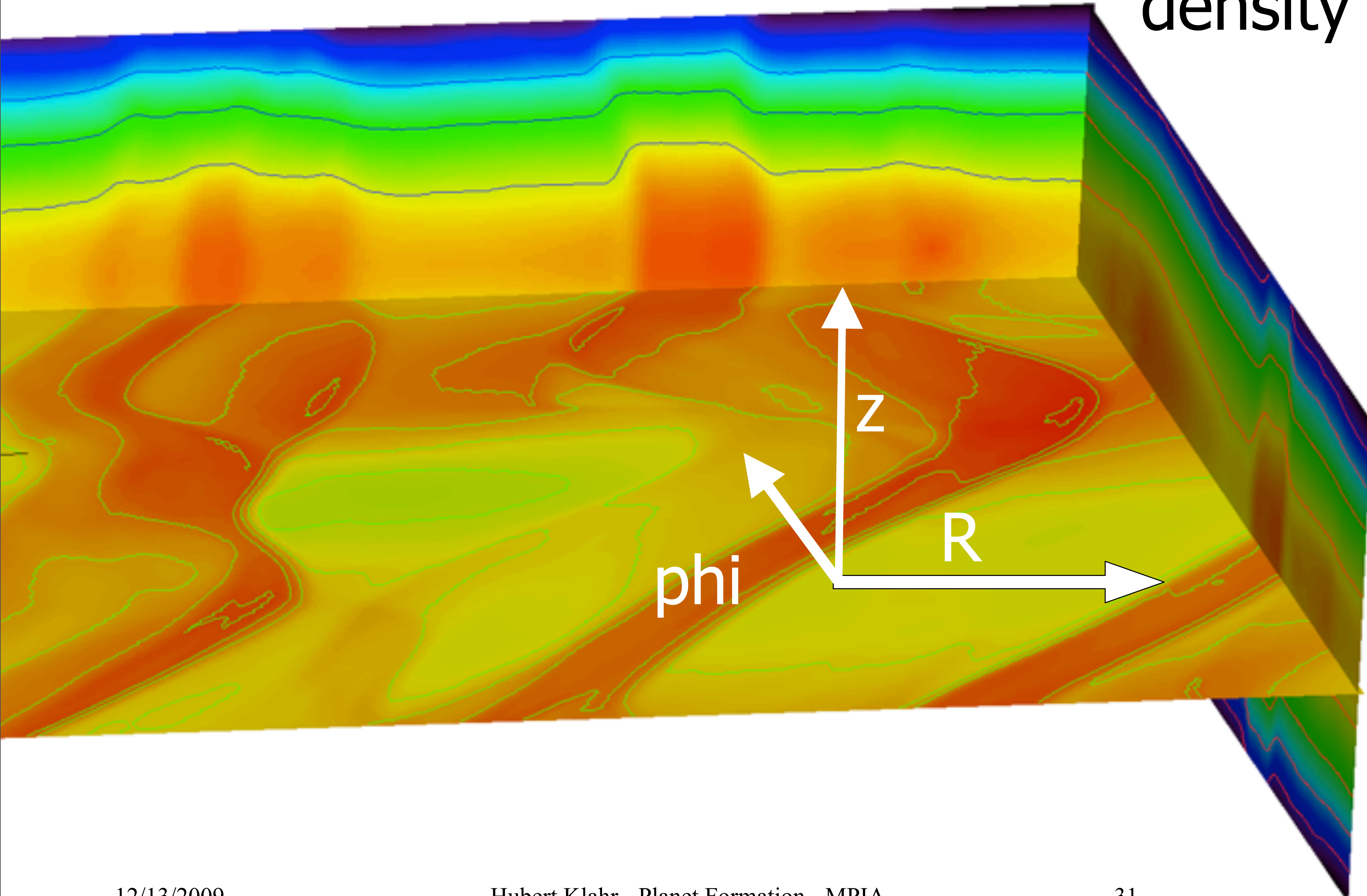
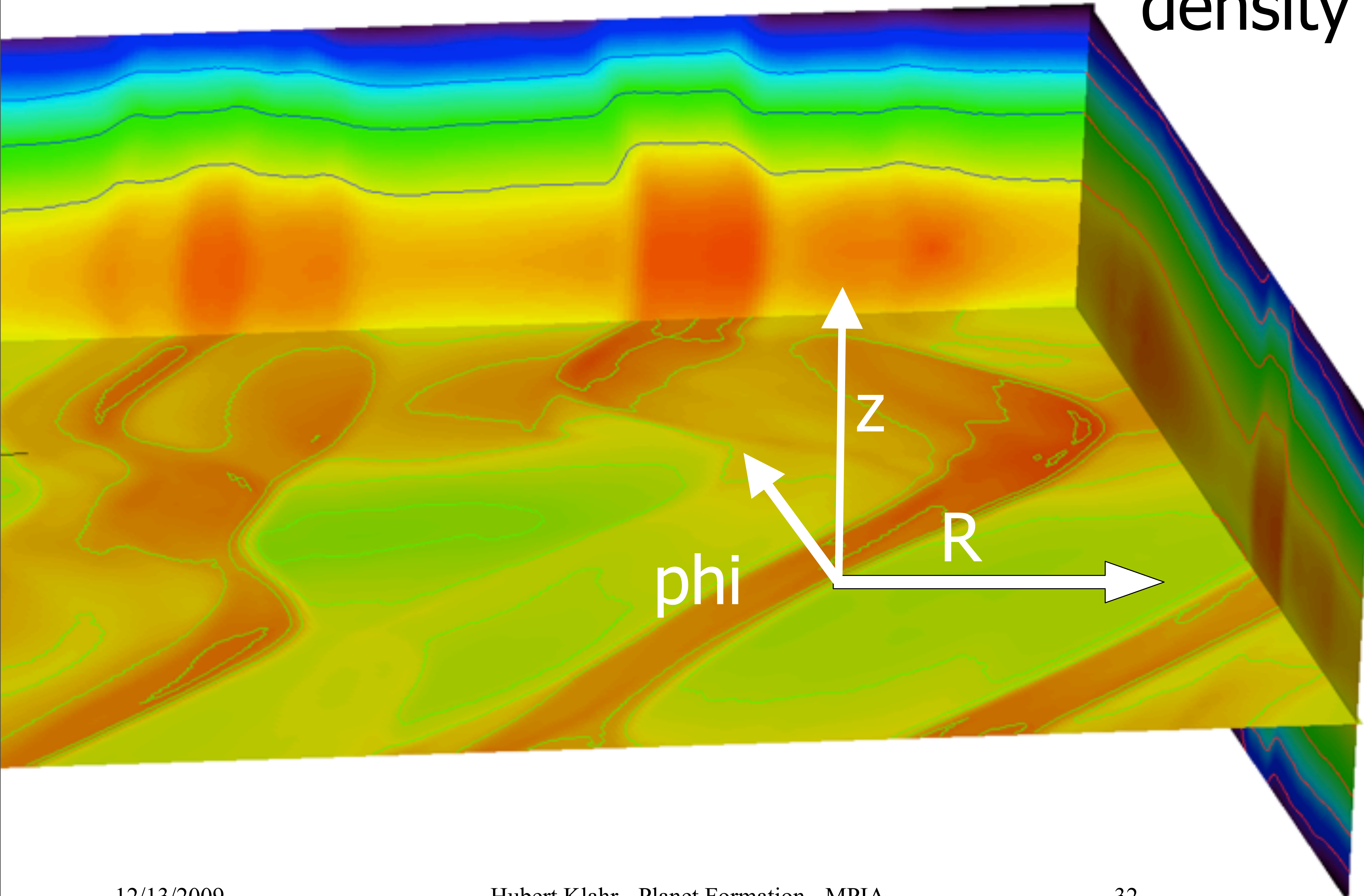
density

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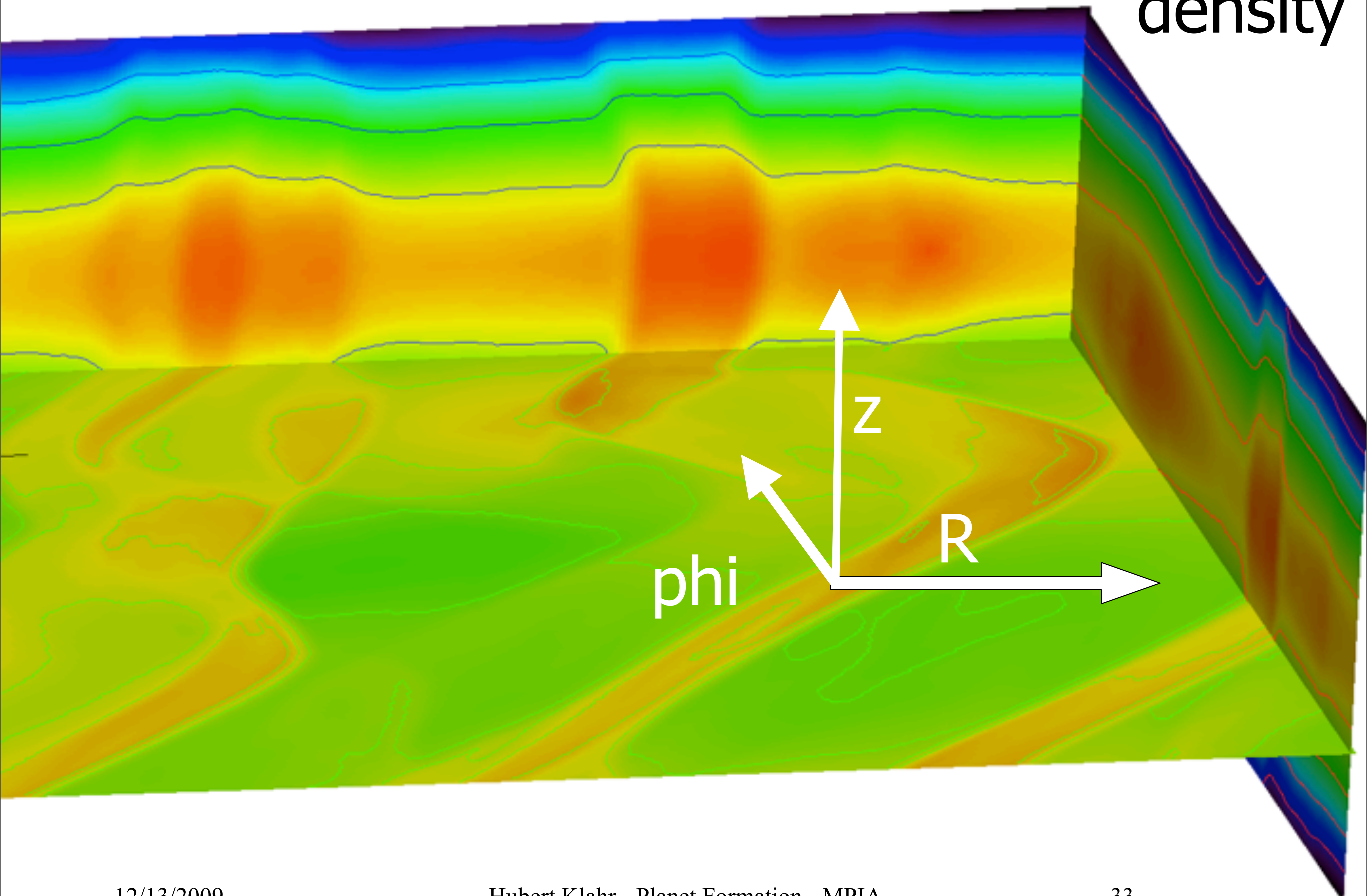
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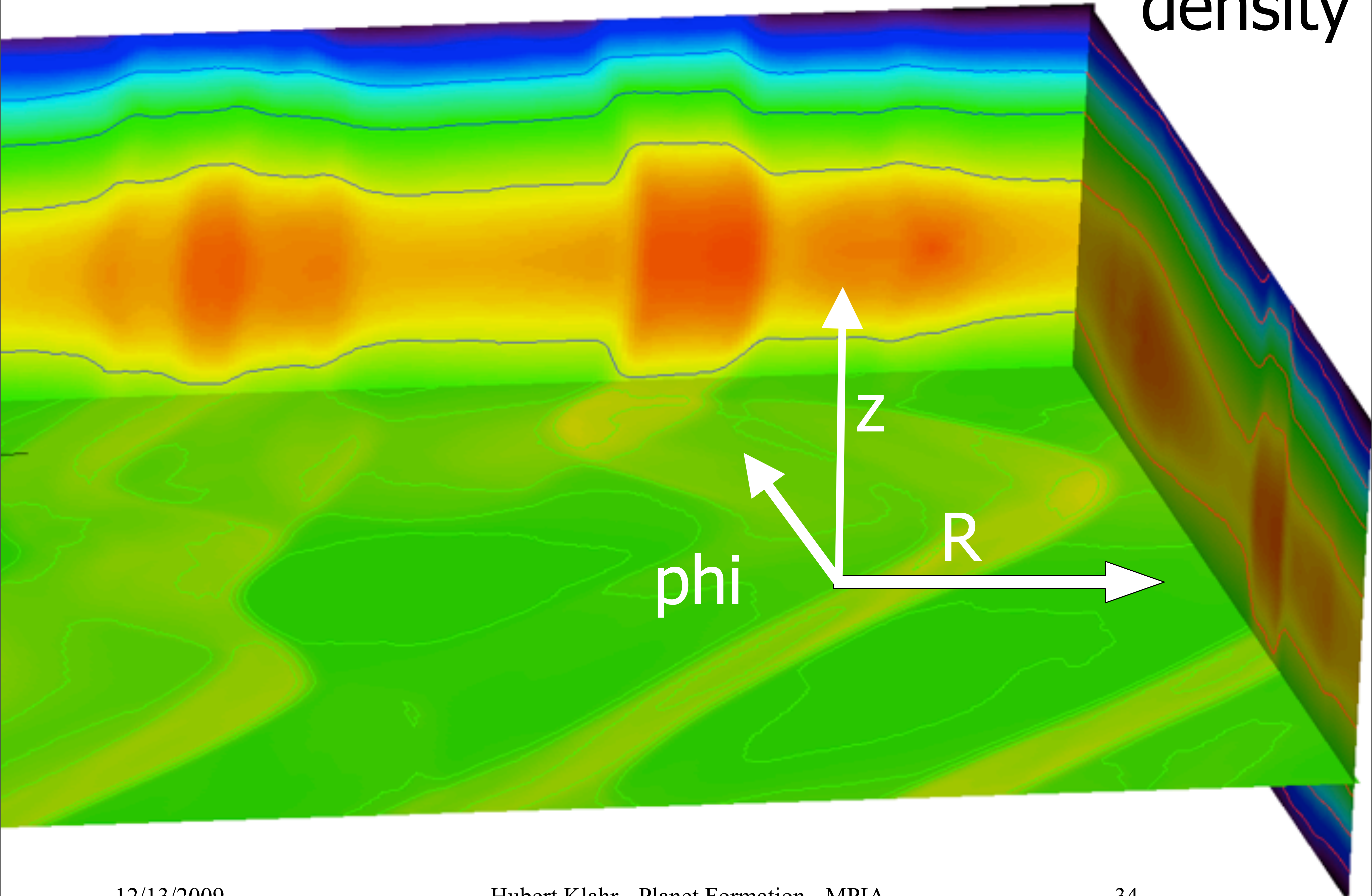
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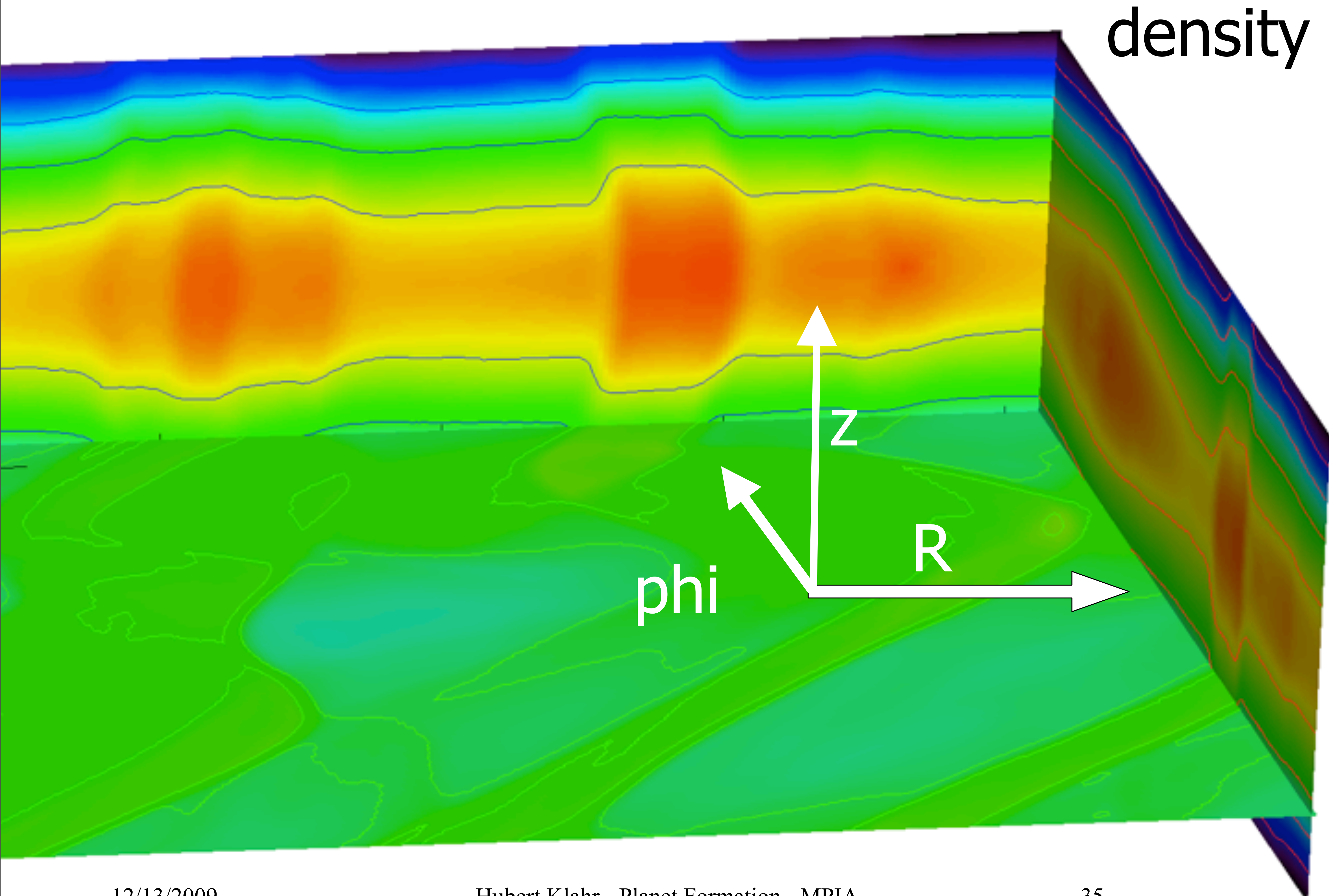
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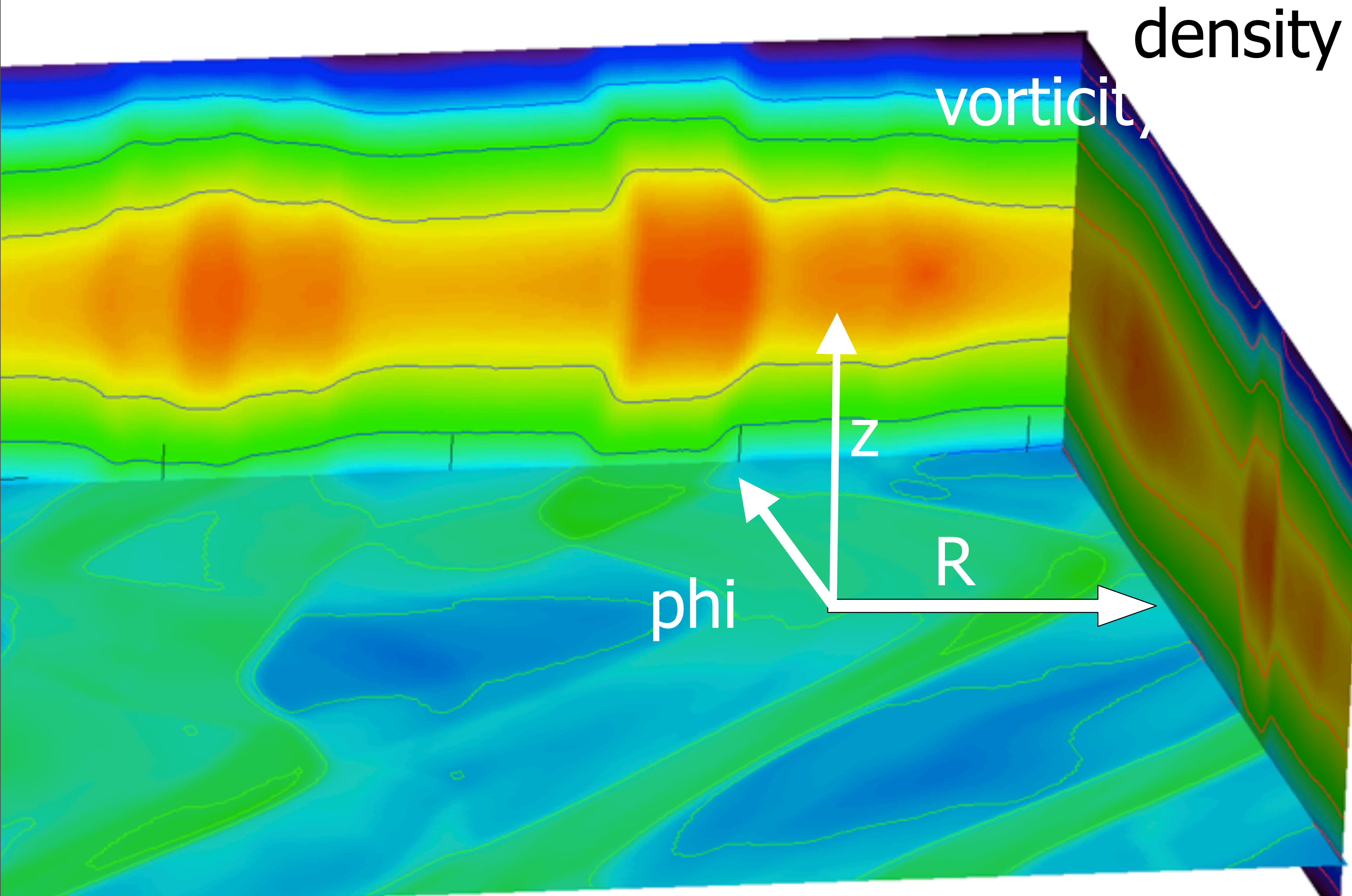
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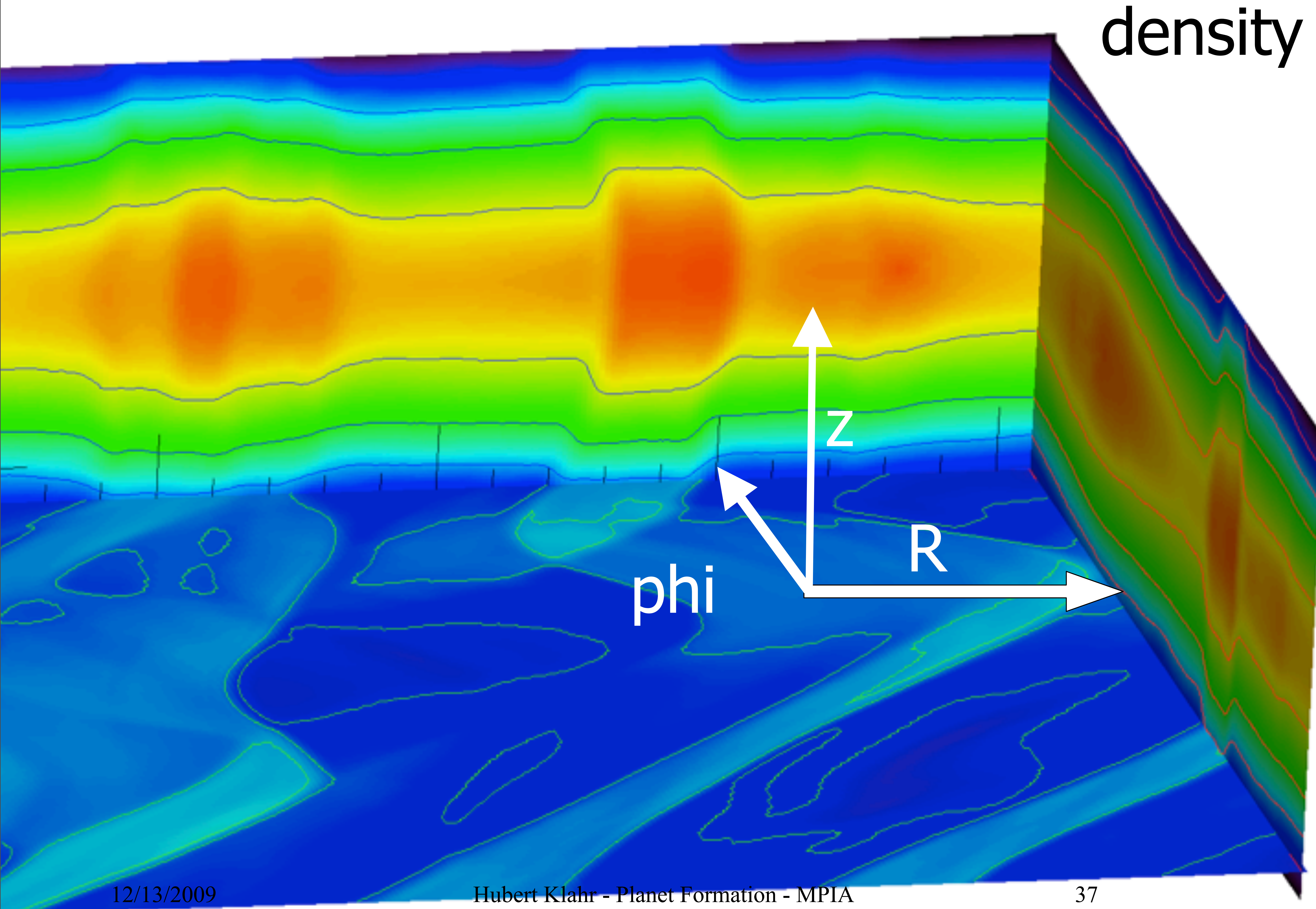
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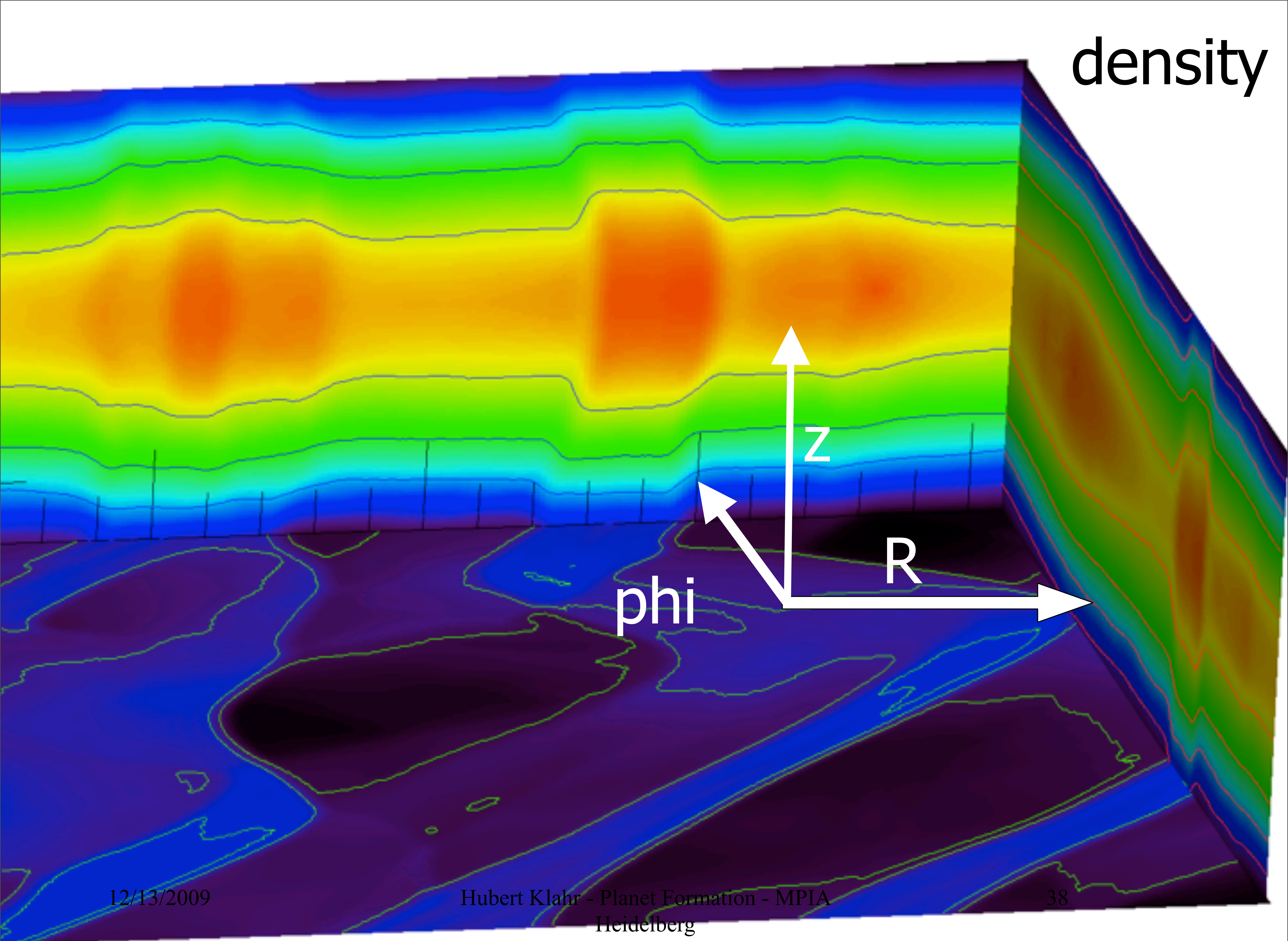
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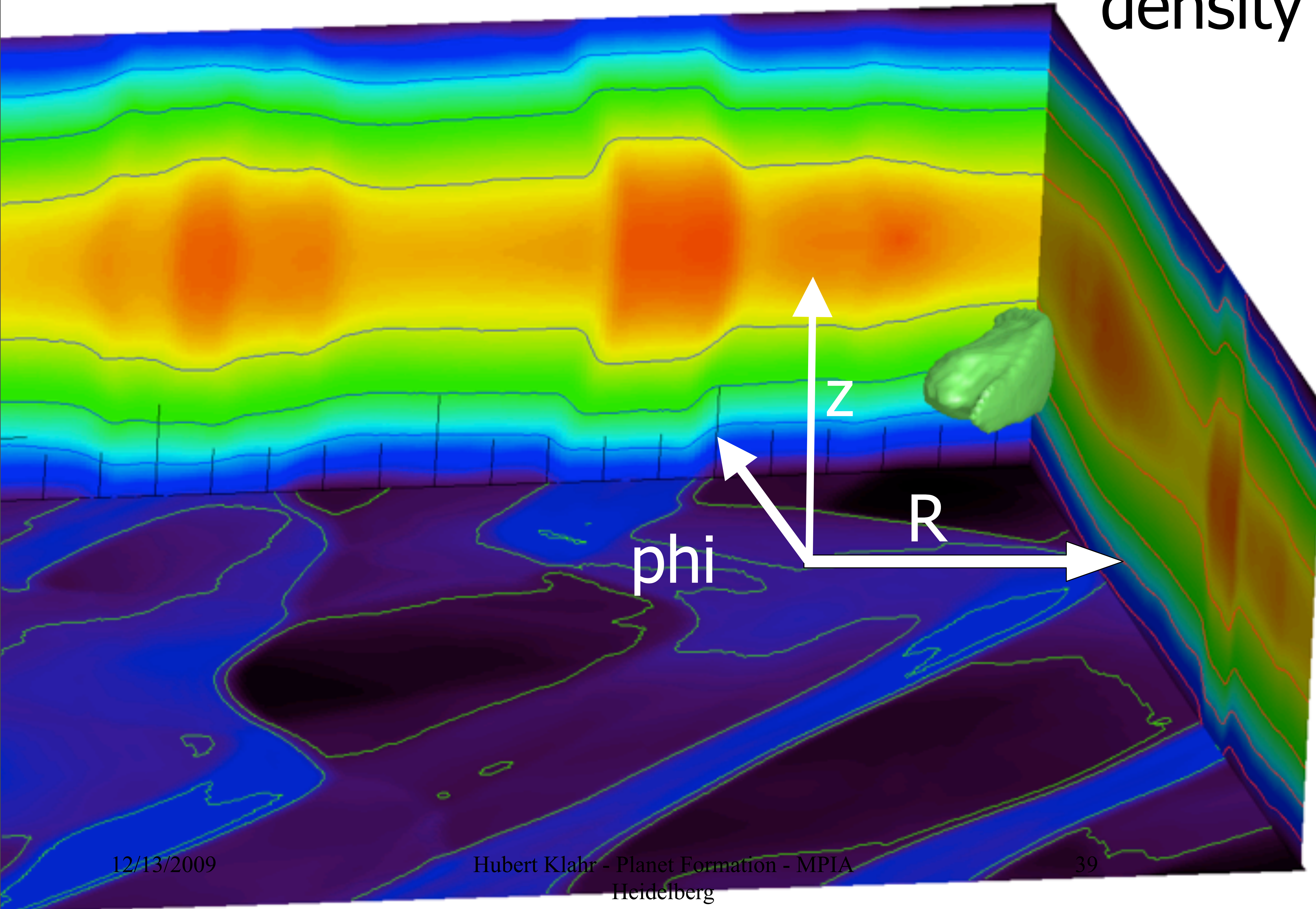
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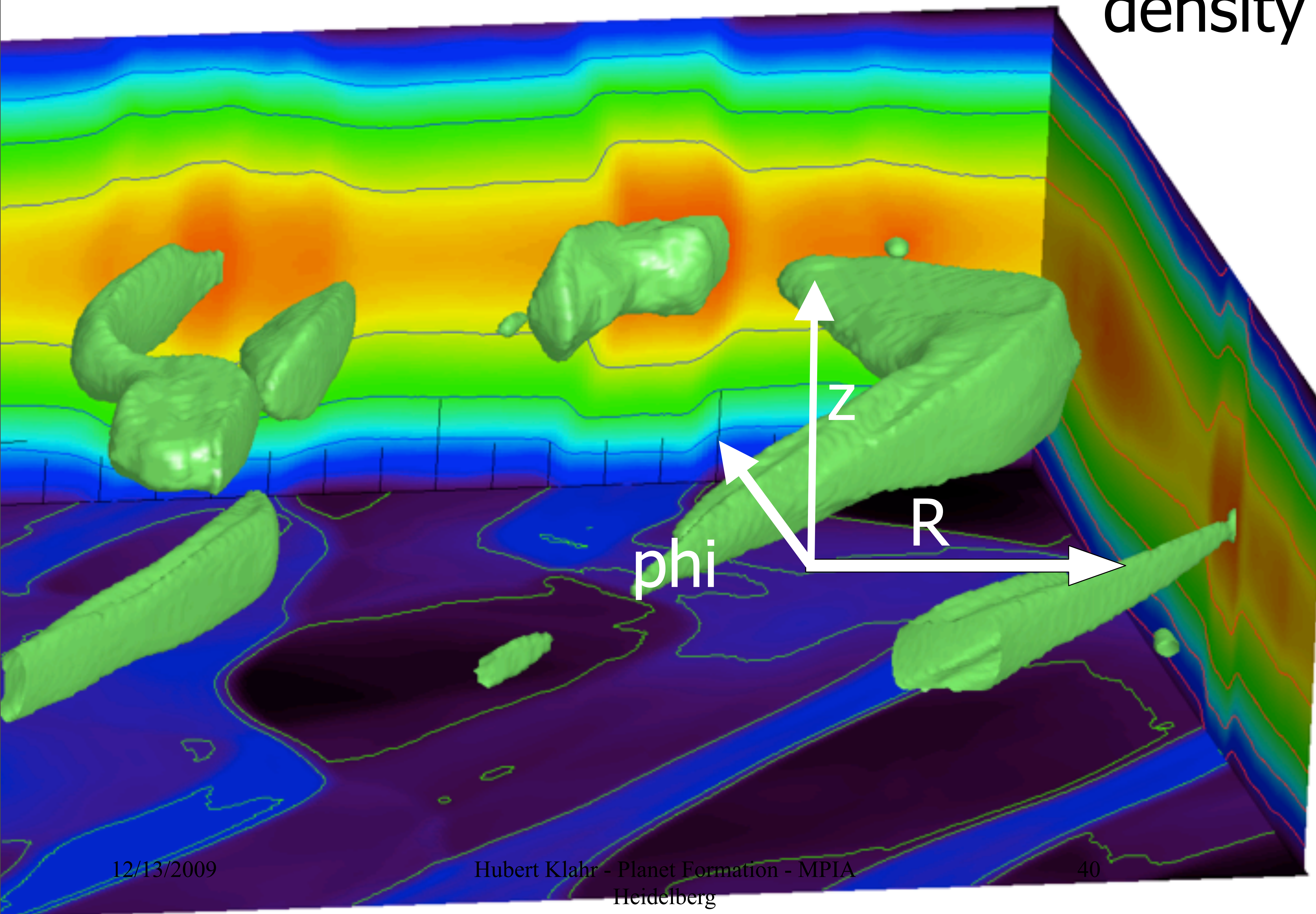

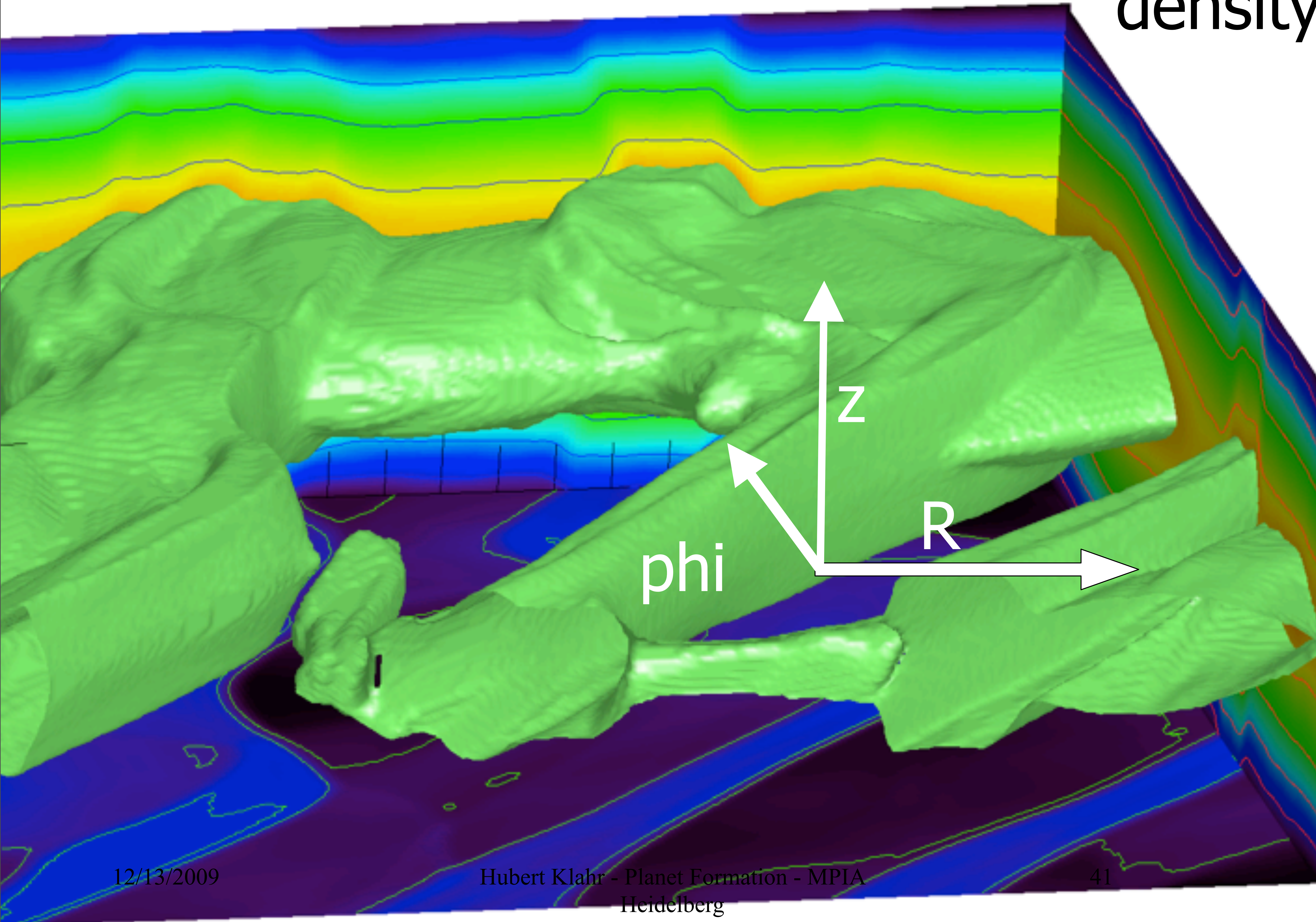
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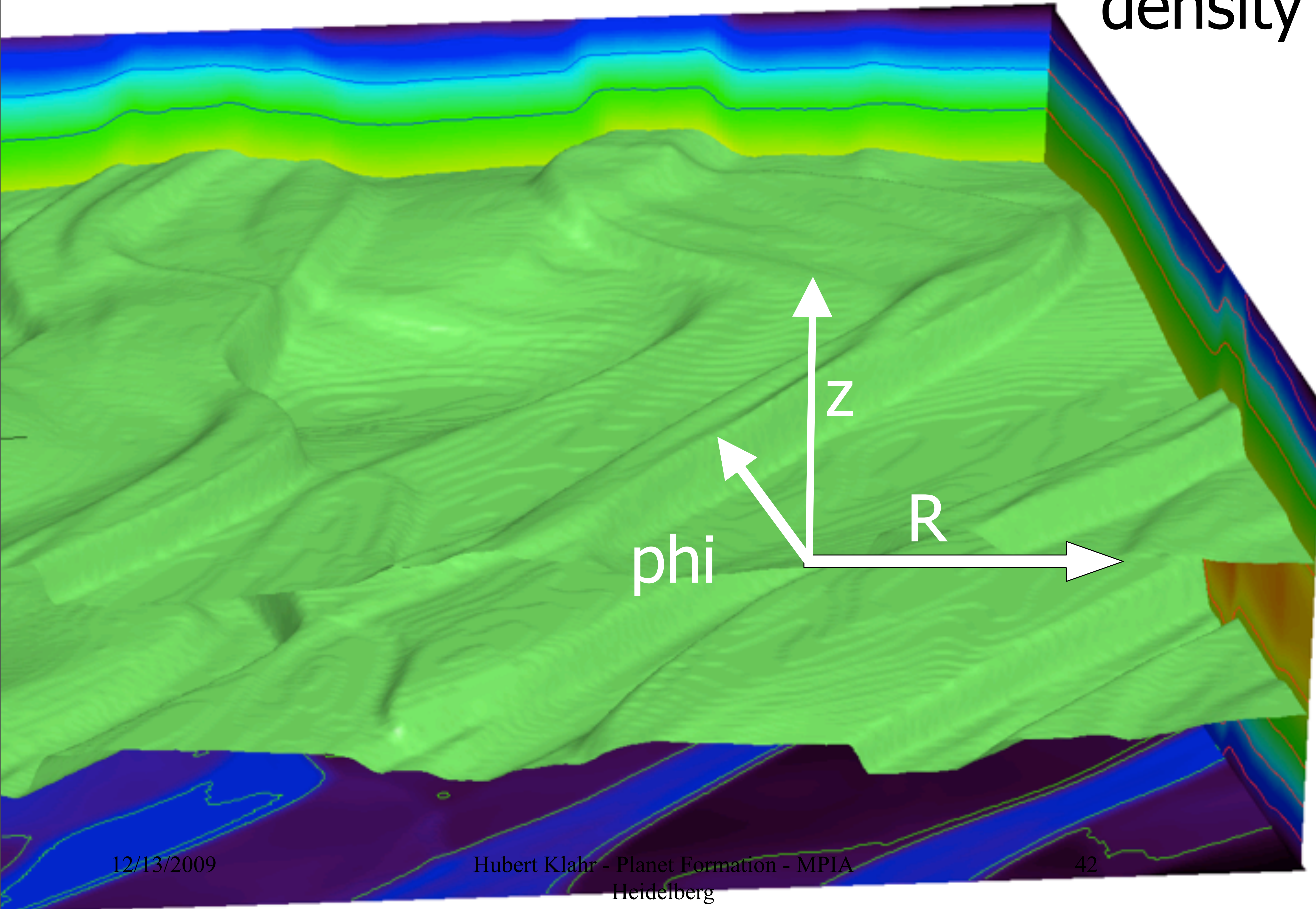
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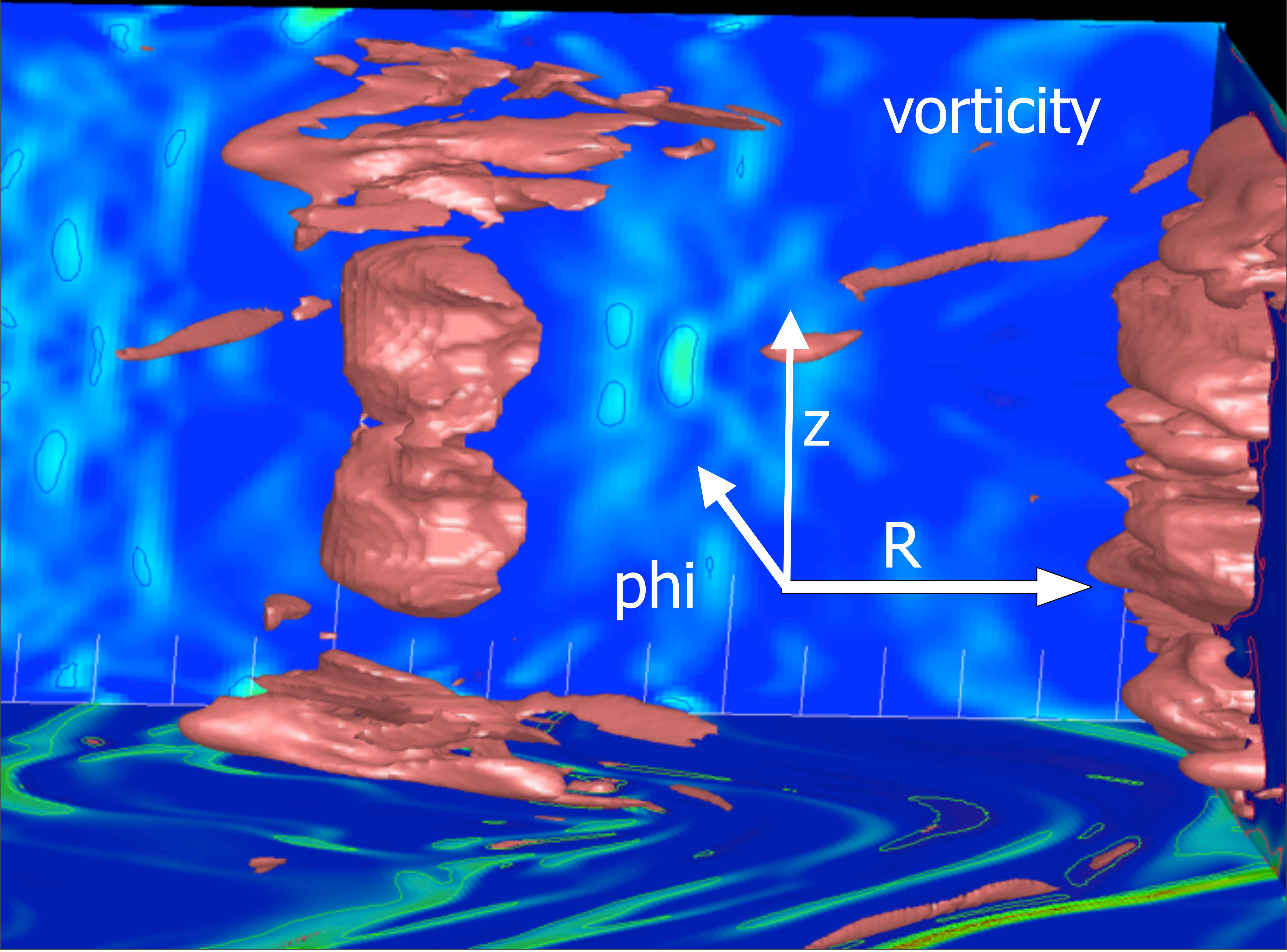
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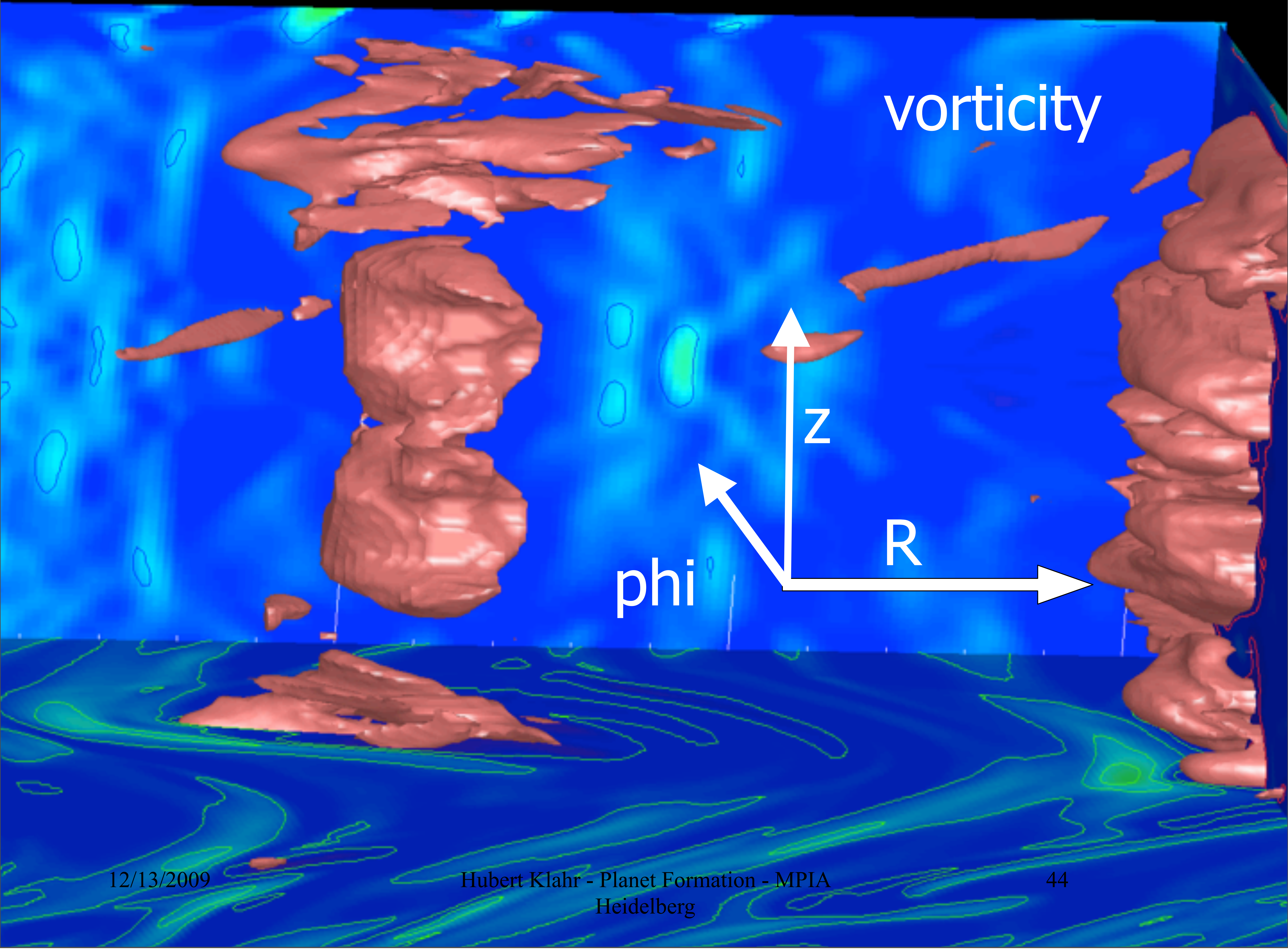
vorticity
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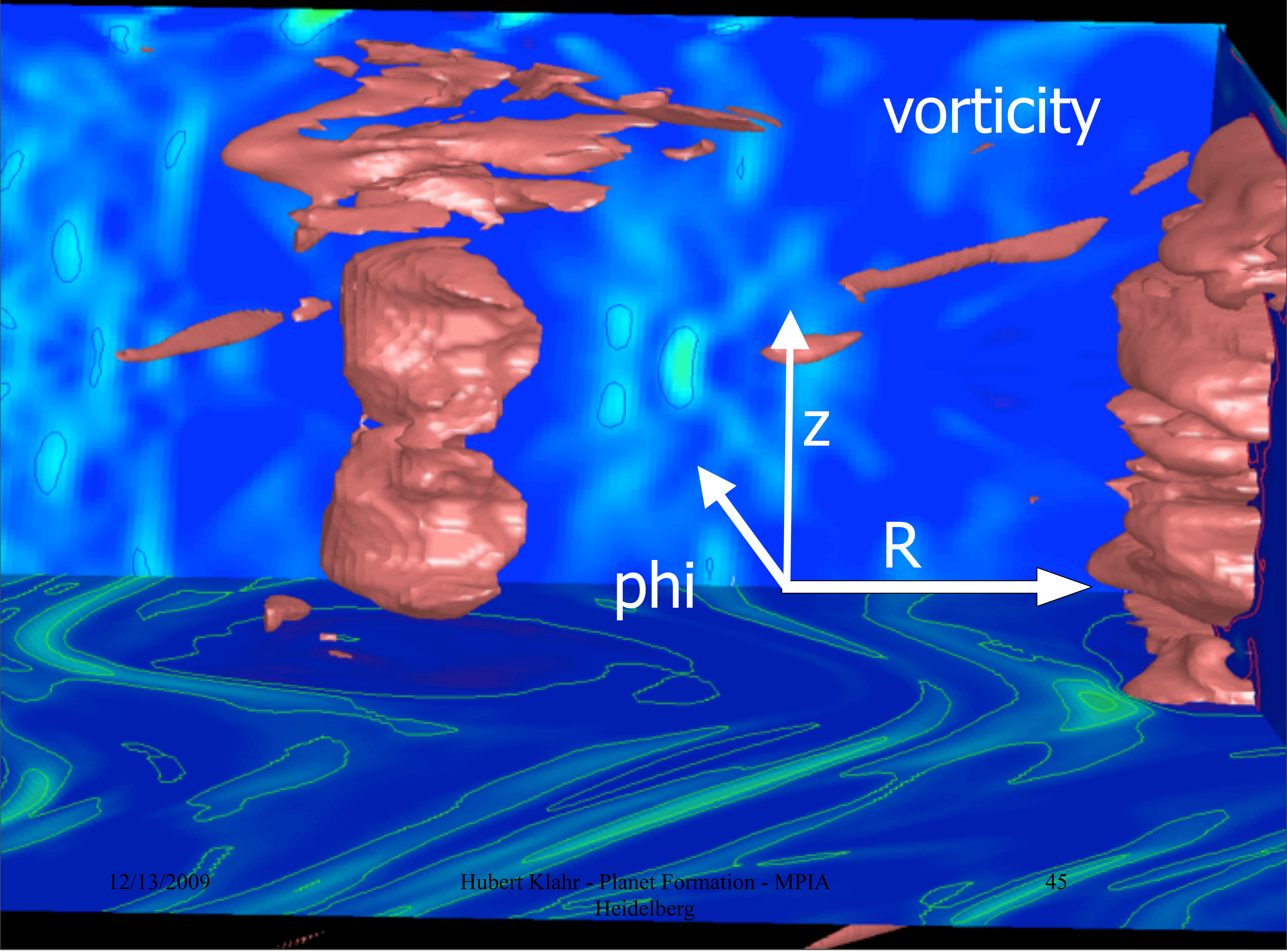
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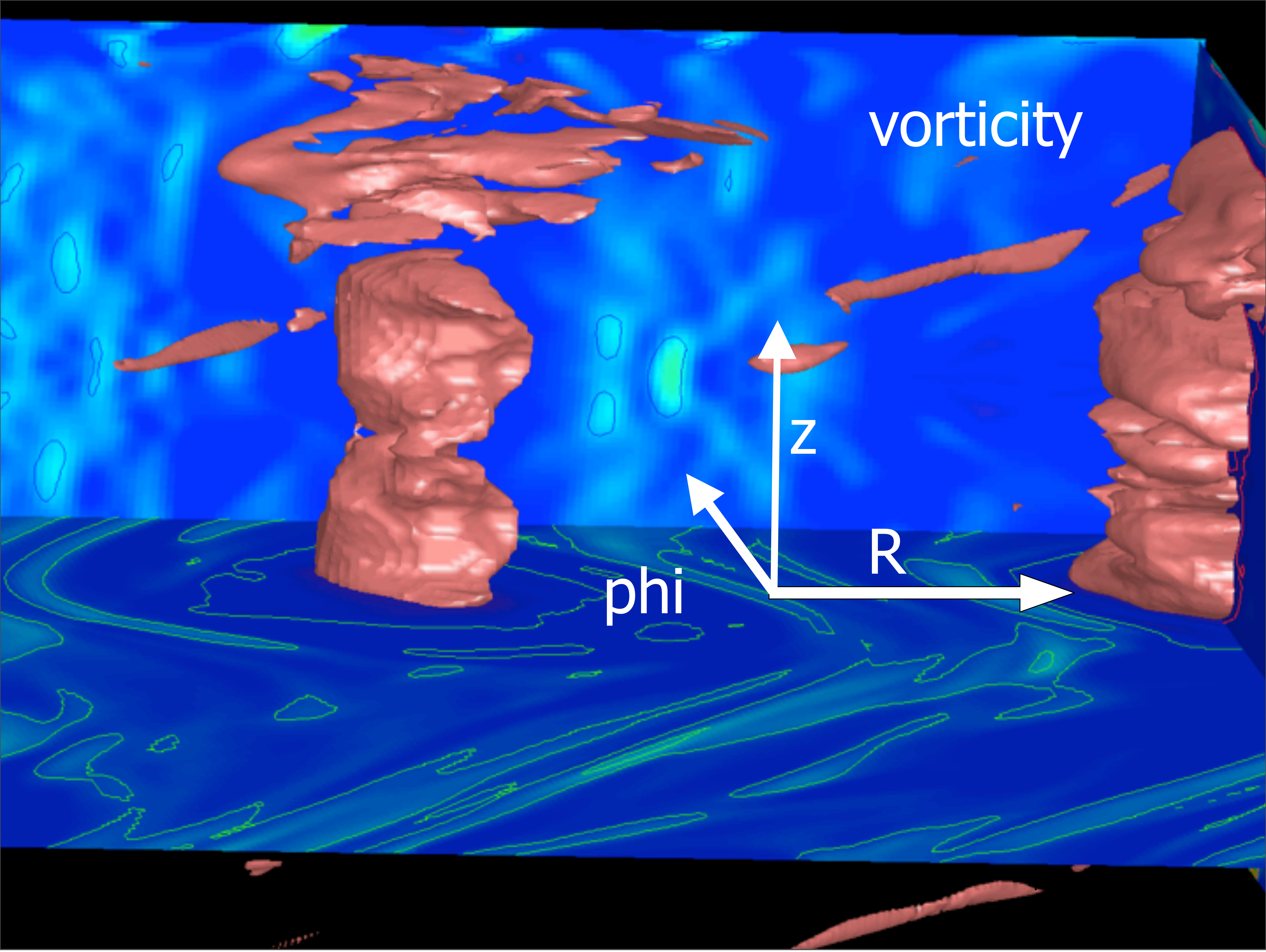
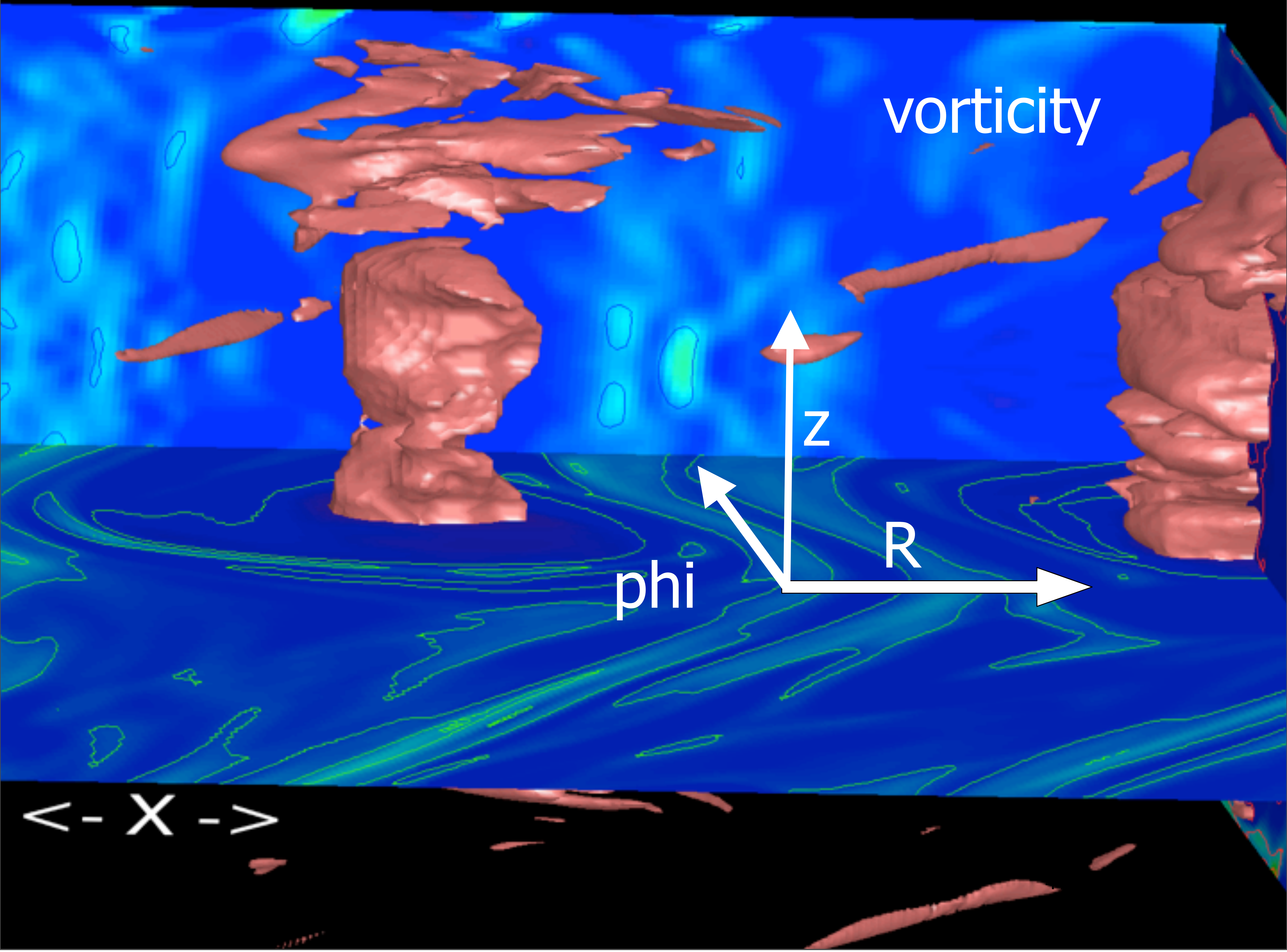
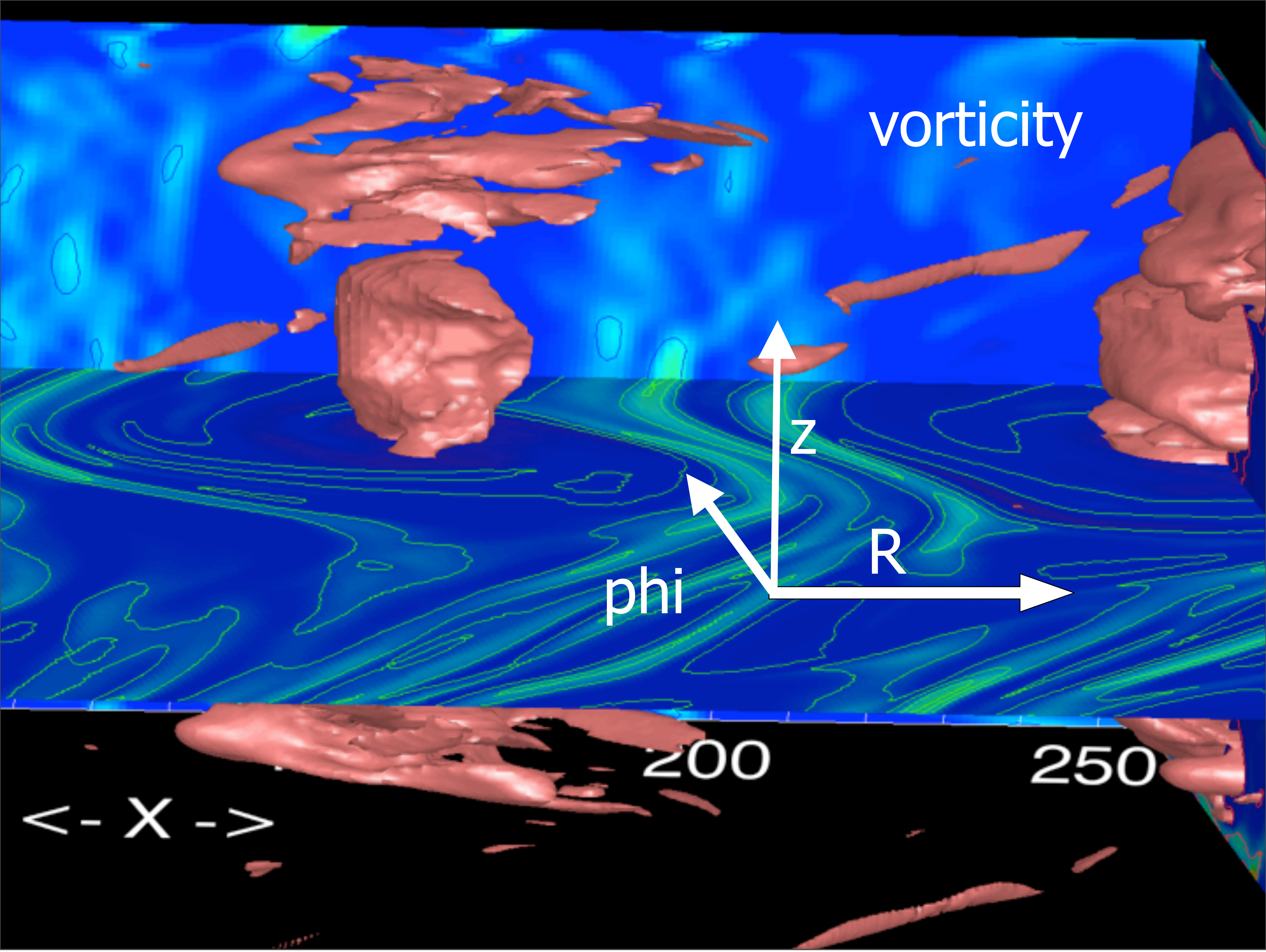
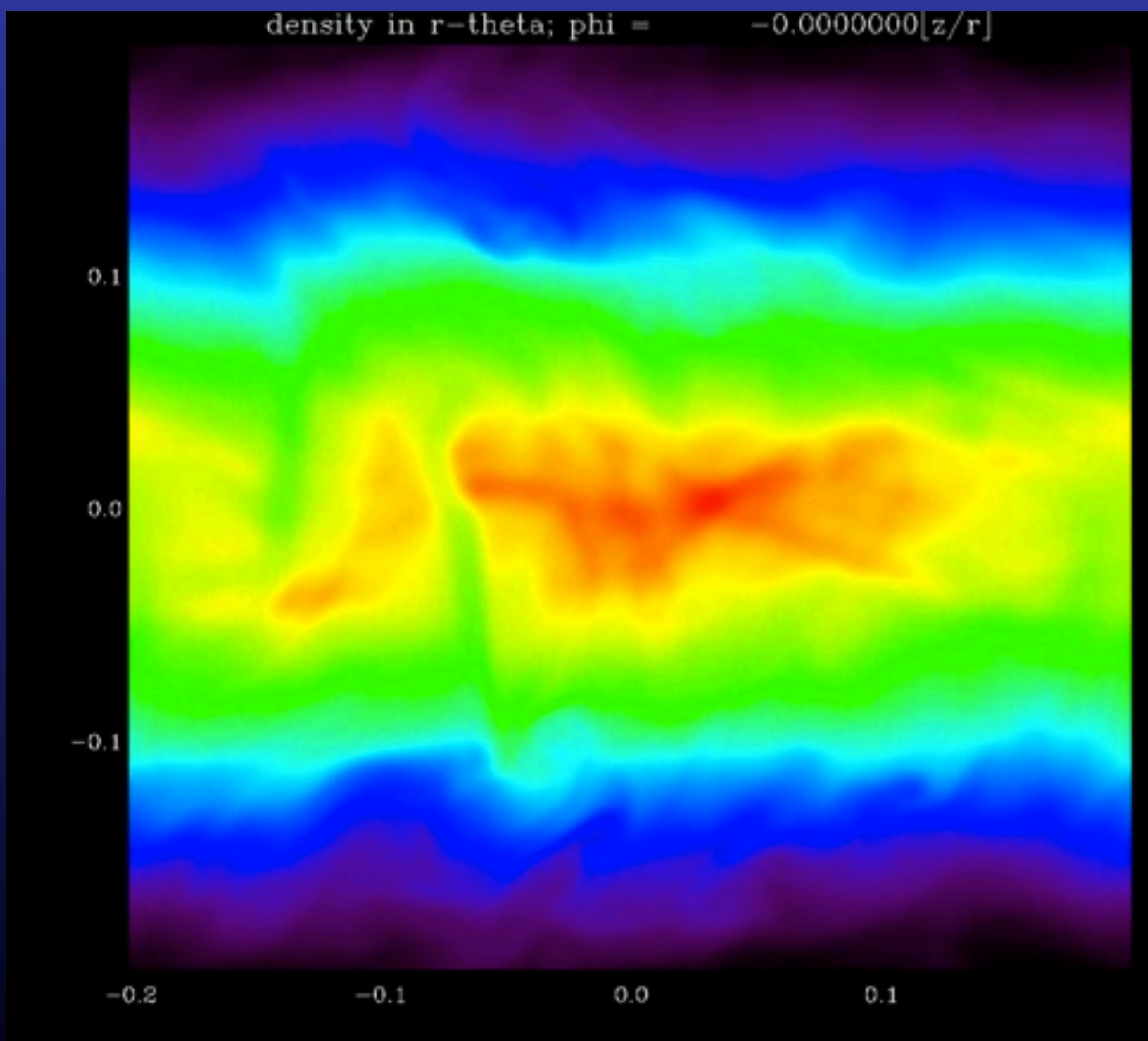
phi
R


vorticity
z
R
phi

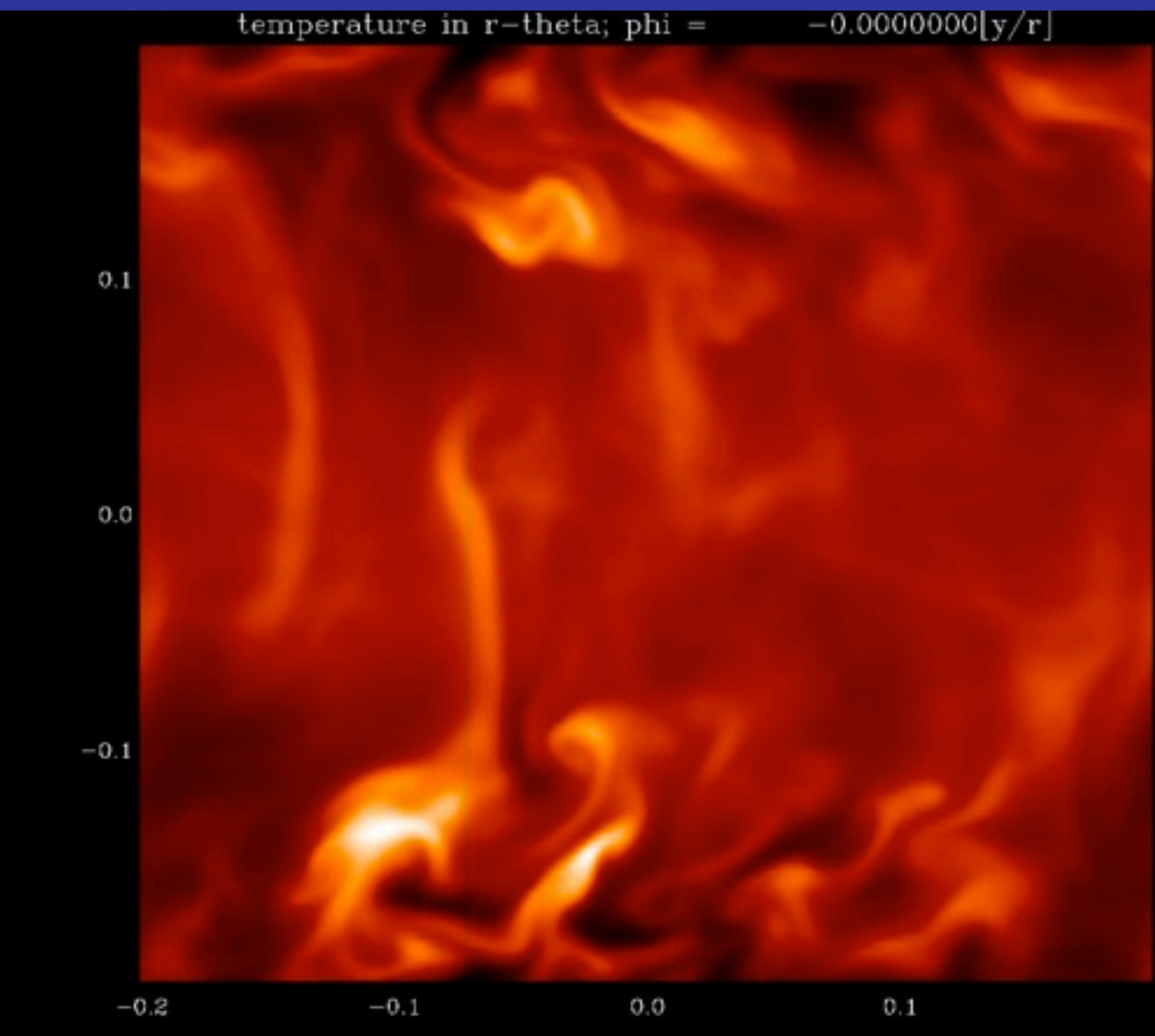

vorticity
z
phi
R
<- X ->


vorticity
z
phi
R
200
250
<- X ->

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

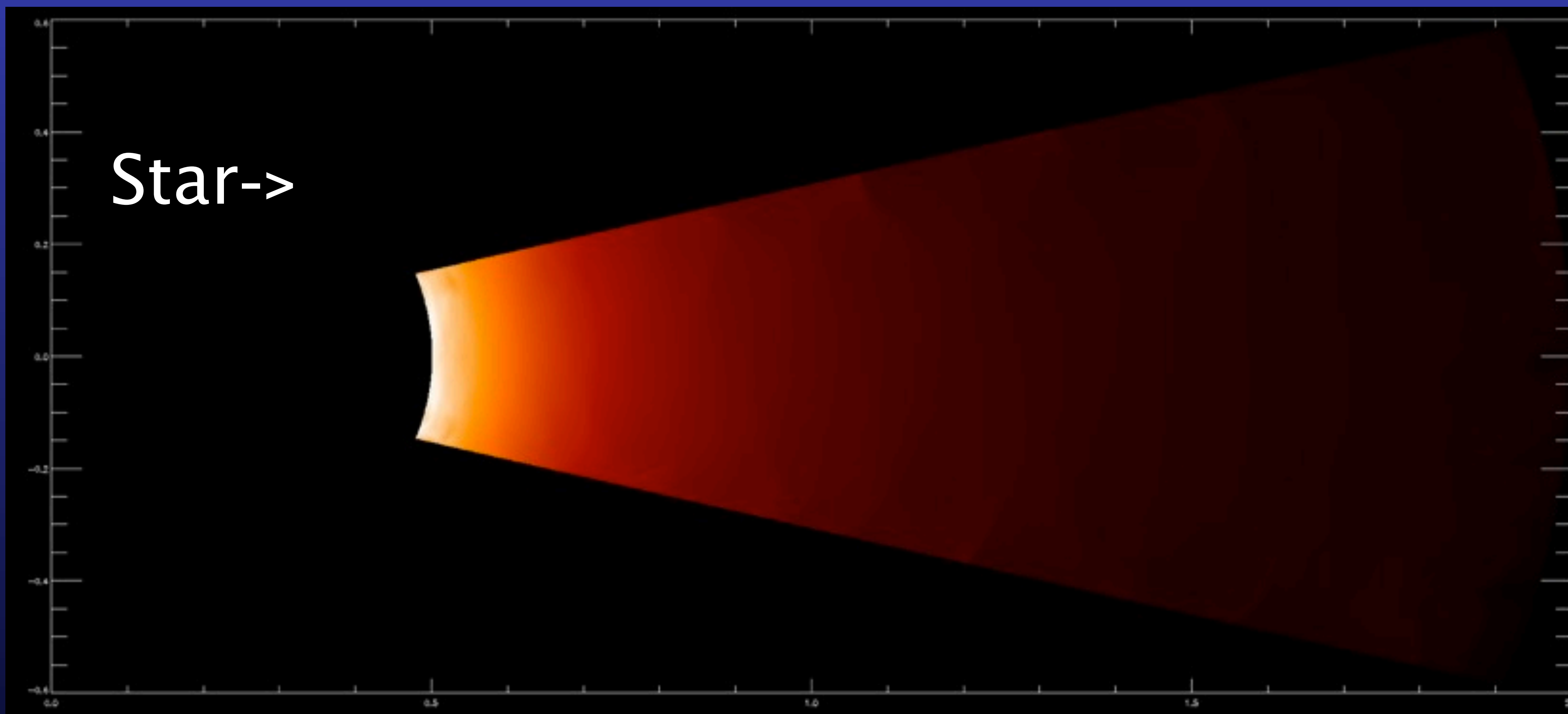


density



temperature pert.

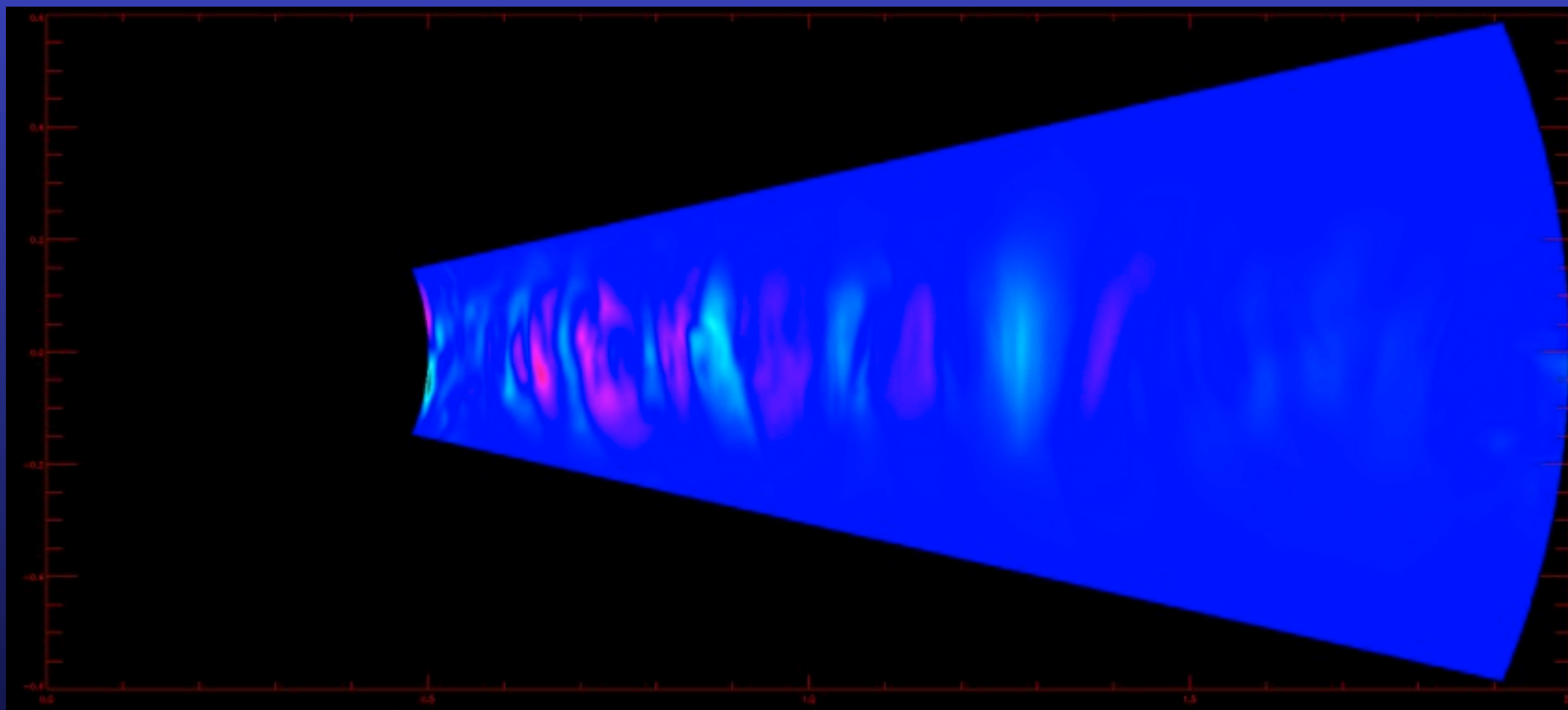
2D axissymetric Pluto Simulation: Temperature due to irradiation from star and thermal relaxation tau = 0.1 (also works for flux limited diffusion in irradiated disks)



Thermal wind:

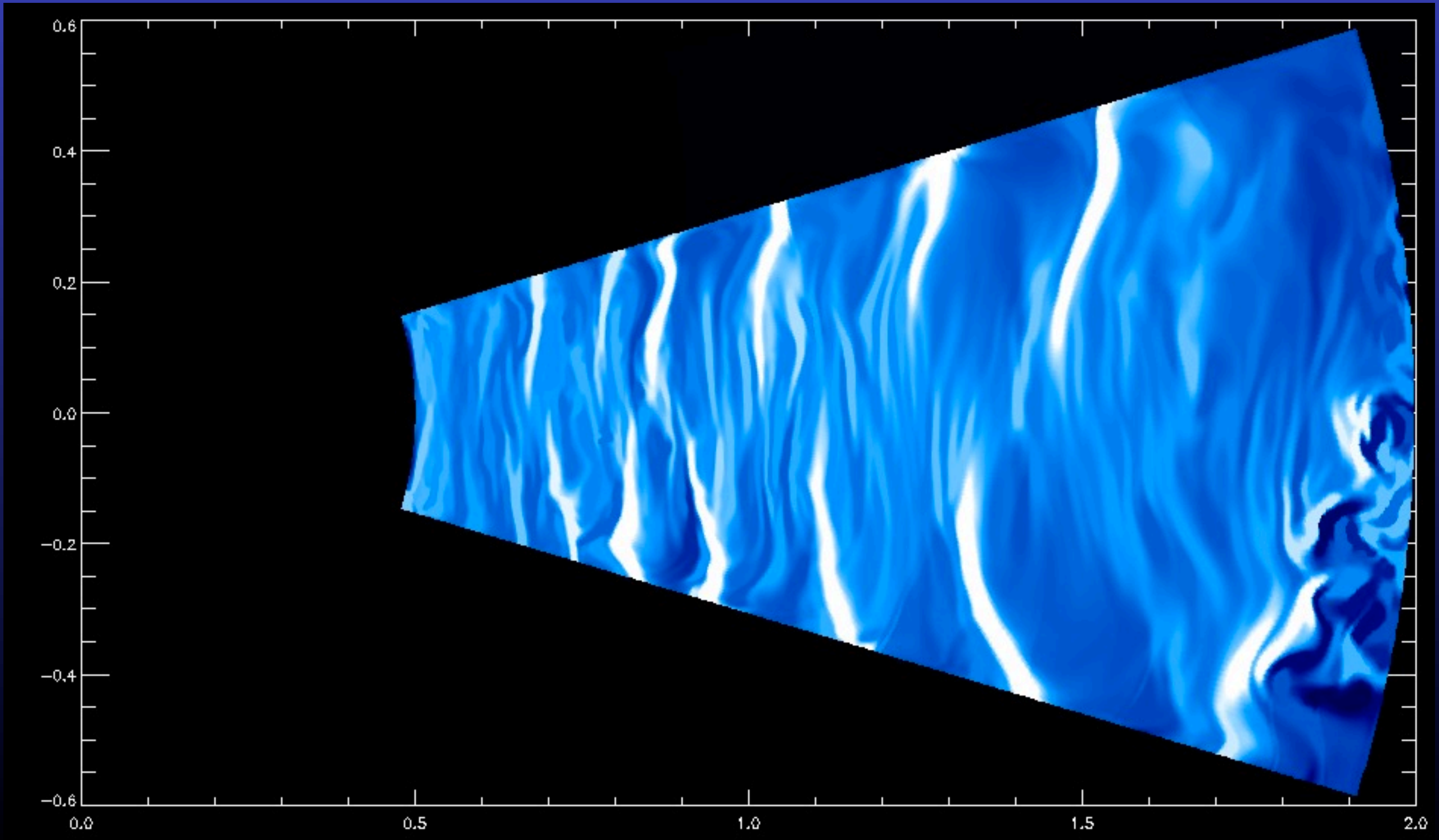
$$\Omega_K \left[1 + \frac{1}{2} \left(\frac{H}{R} \right)^2 \left(p + q + \frac{q}{2} \frac{Z^2}{H^2} \right) \right]$$

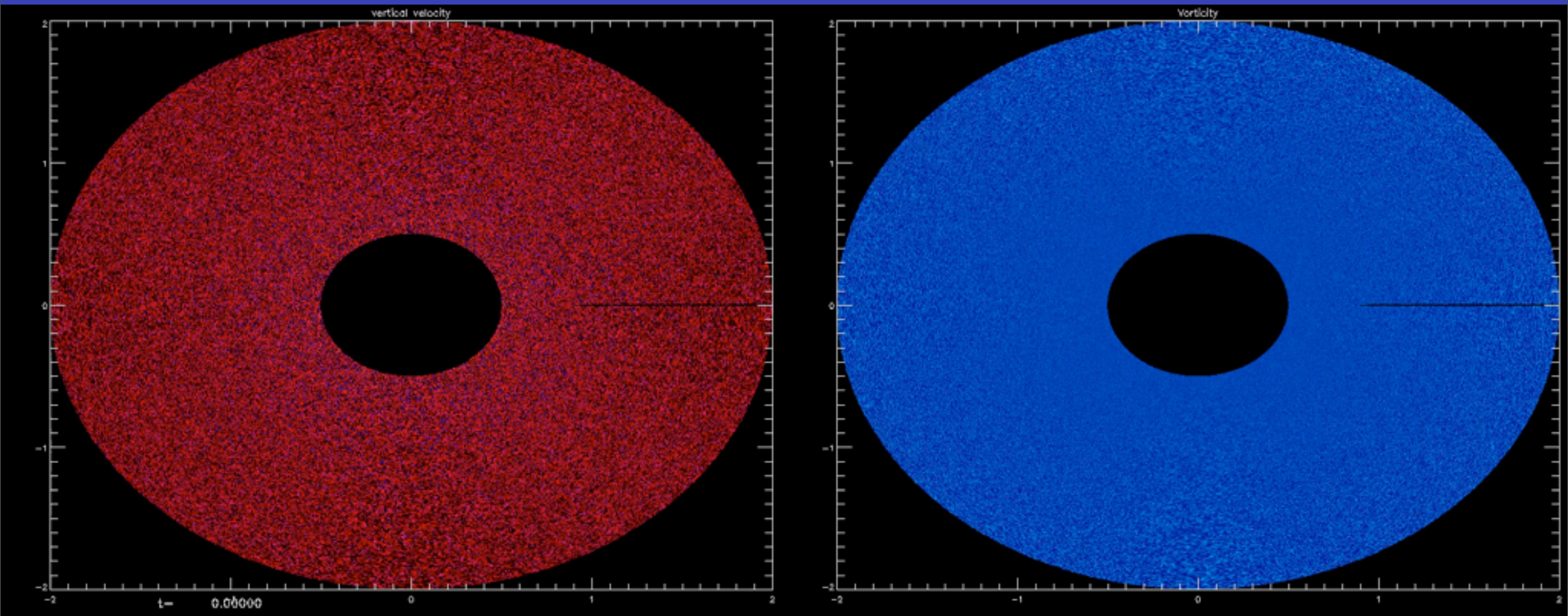
2D axissymetric Pluto Simulation: Overstability due to thermal wind leads to convection like motion: Symmetric Instability

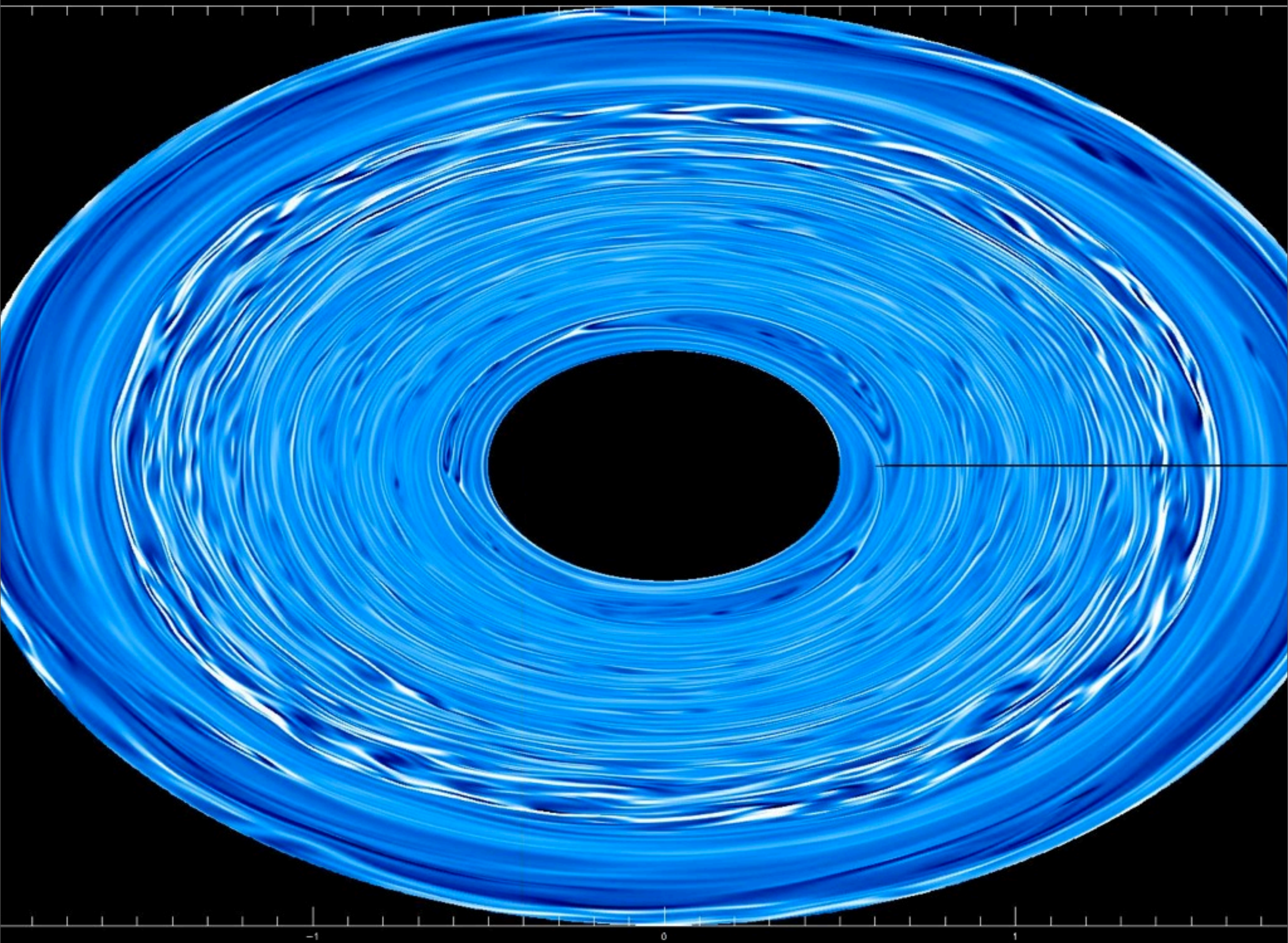


Modification of Solberg-Hoiland Criterion, including thermal relaxation:
In collaboration with Alexander Hubbard

2D axissymetric Pluto Simulation: Resulting vorticity perturbations



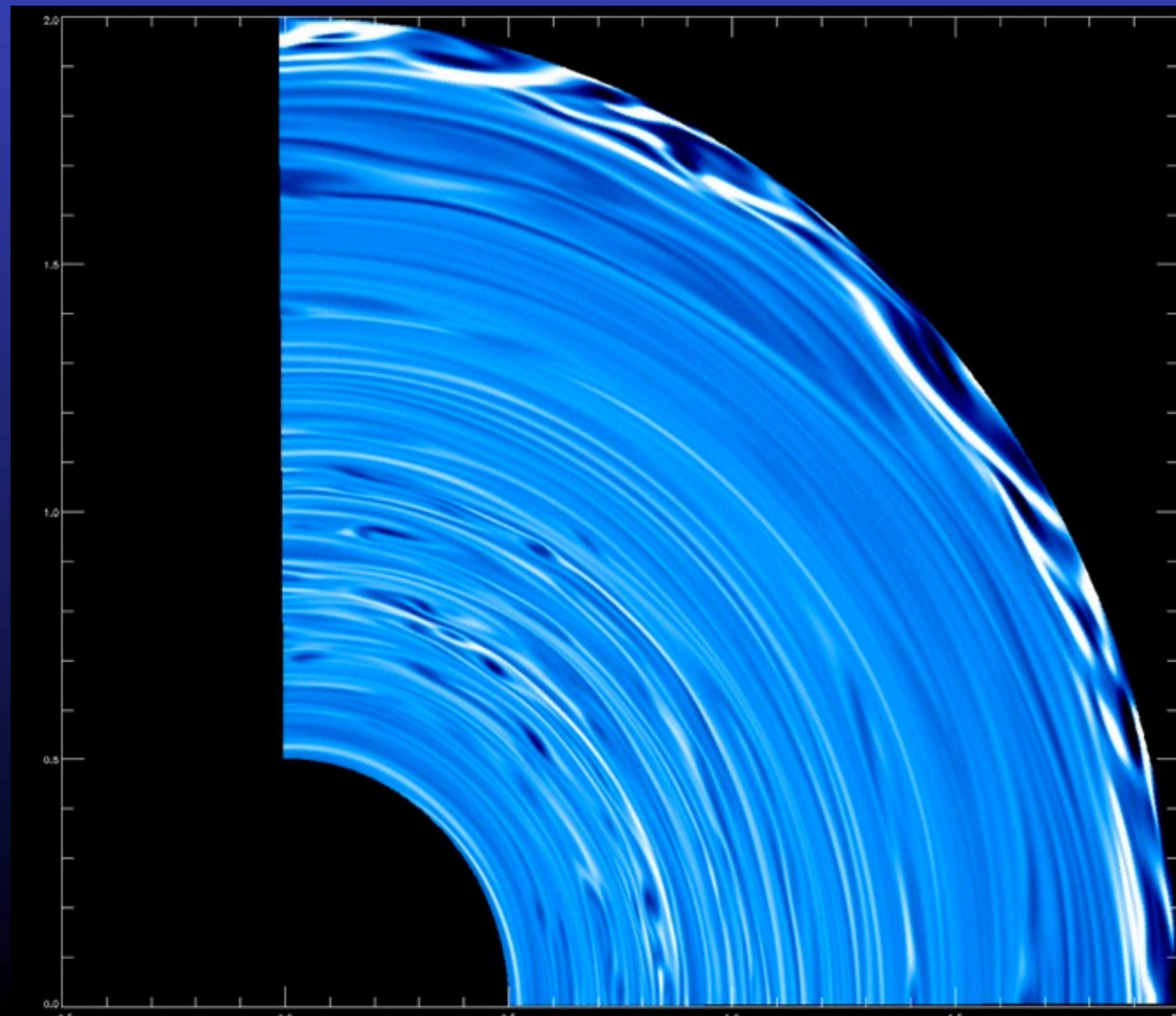

vertical velocity
Vorticity
t= 0.00000


-1
0
1

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

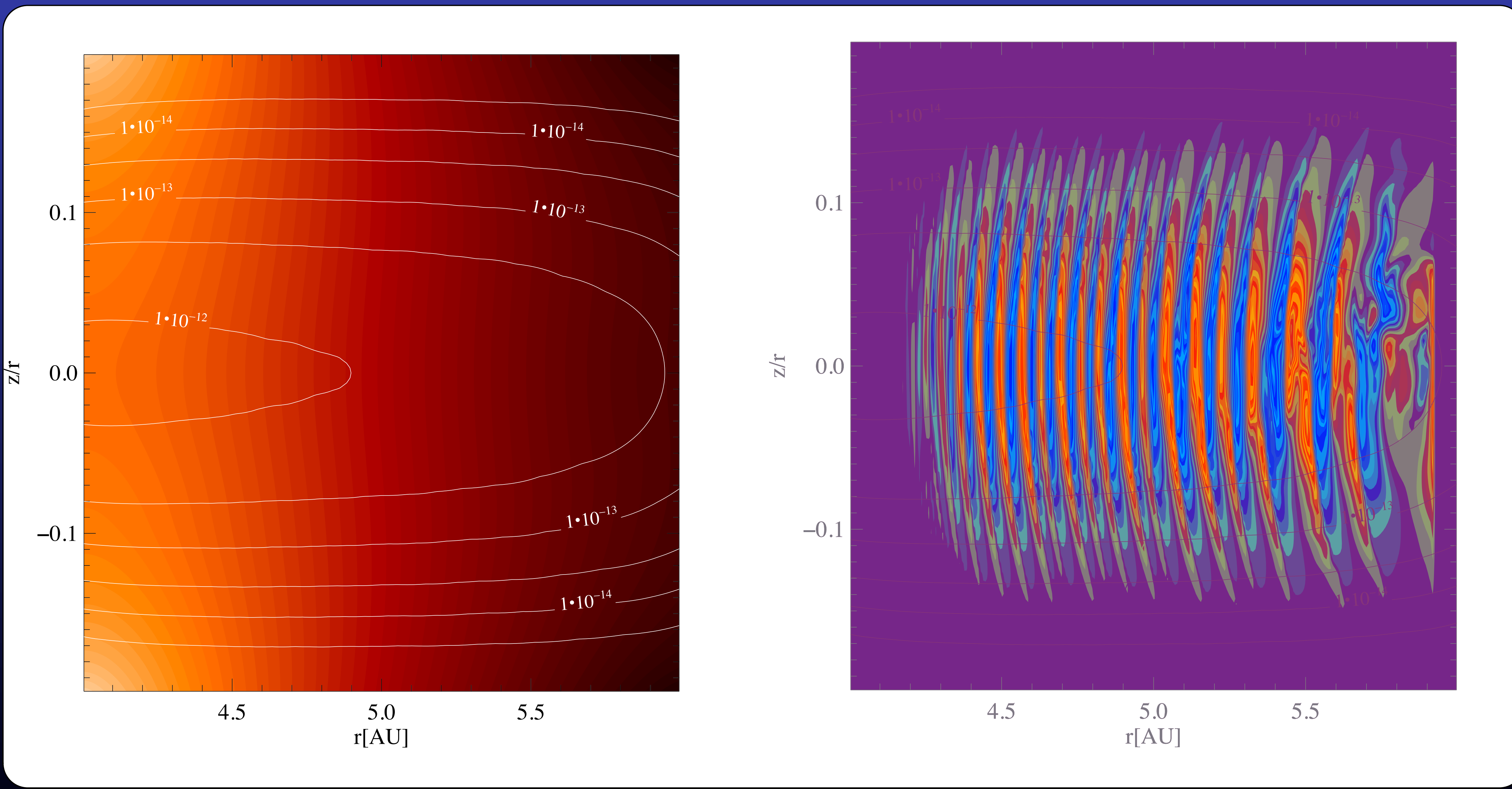
=> Baroclinic Disks Form Vortices abundantly and further amplify them further!

Mission accomplished.



12/13/2009

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



Disk Weather

Interface
MRI - Dead Zone

Papaloizou-Pringle
Rossby Wave Inst.

linear
axisymmetric
Vertical Shear Inst.:
Solberg-Hoiland
See Nelson, Gressel & Umurhan

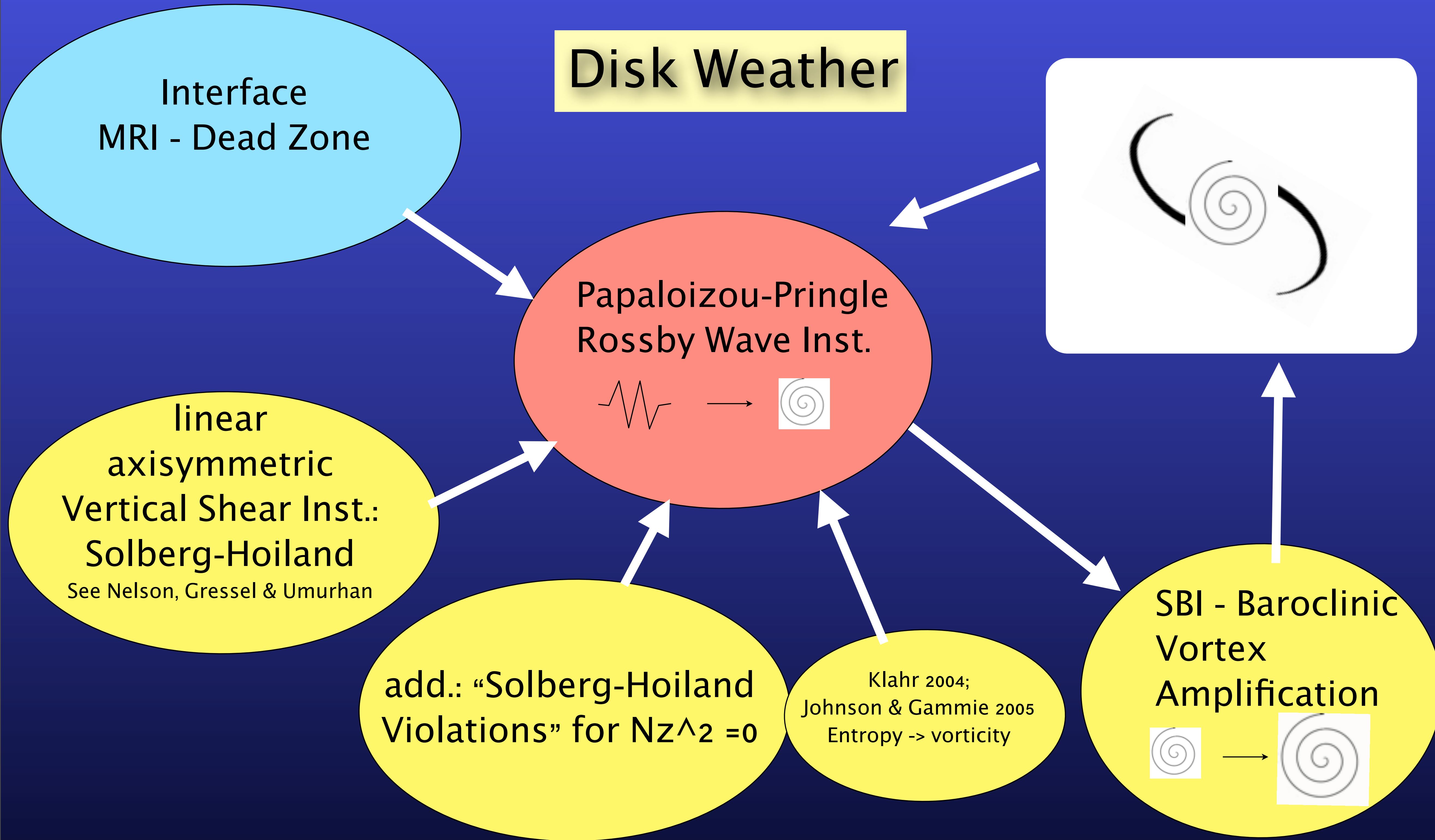
add.: “Solberg-Hoiland
Violations” for Nz^2 =0

Klahr 2004;
Johnson & Gammie 2005
Entropy -> vorticity

SBI - Baroclinic
Vortex
Amplification

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

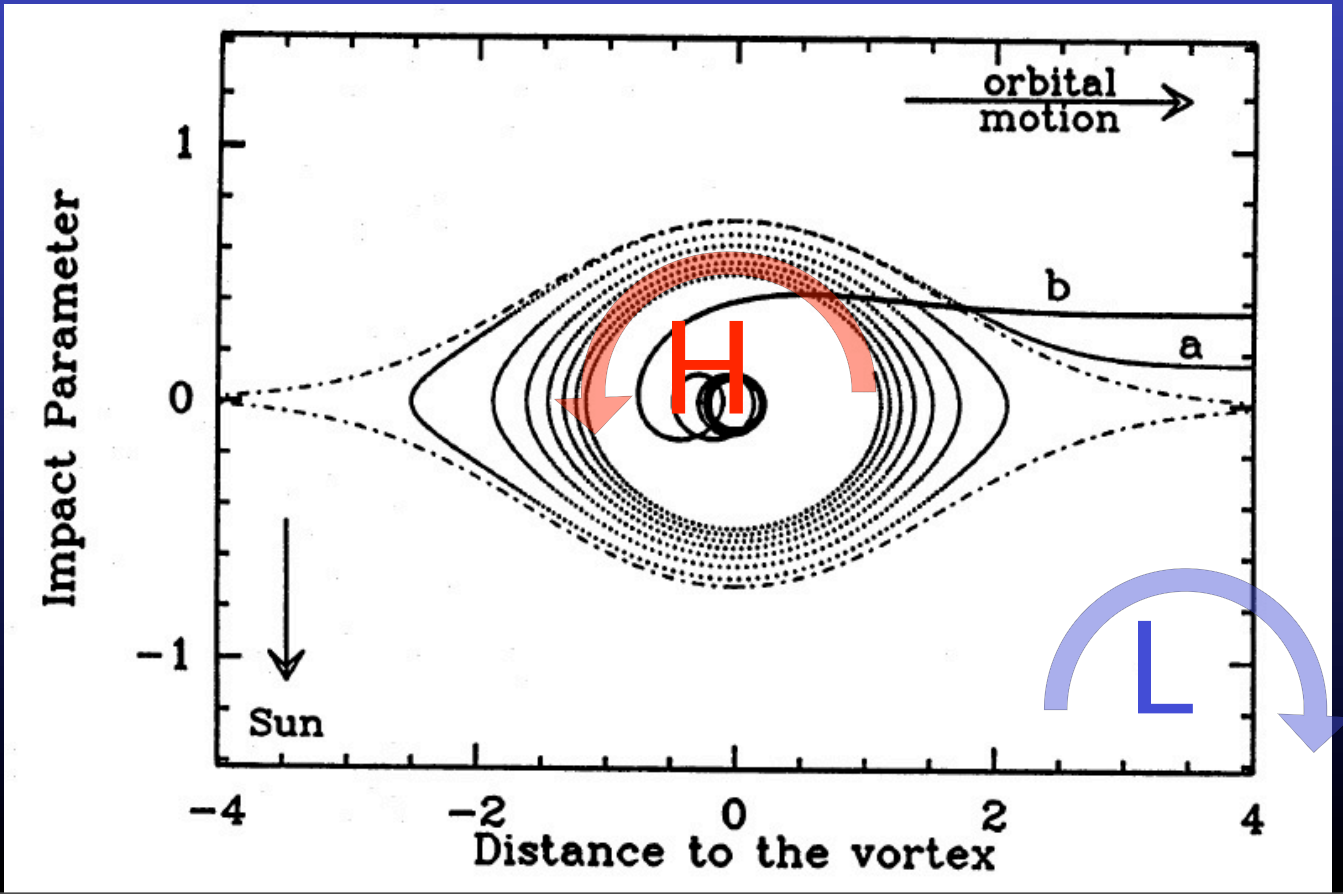
Disk Weather



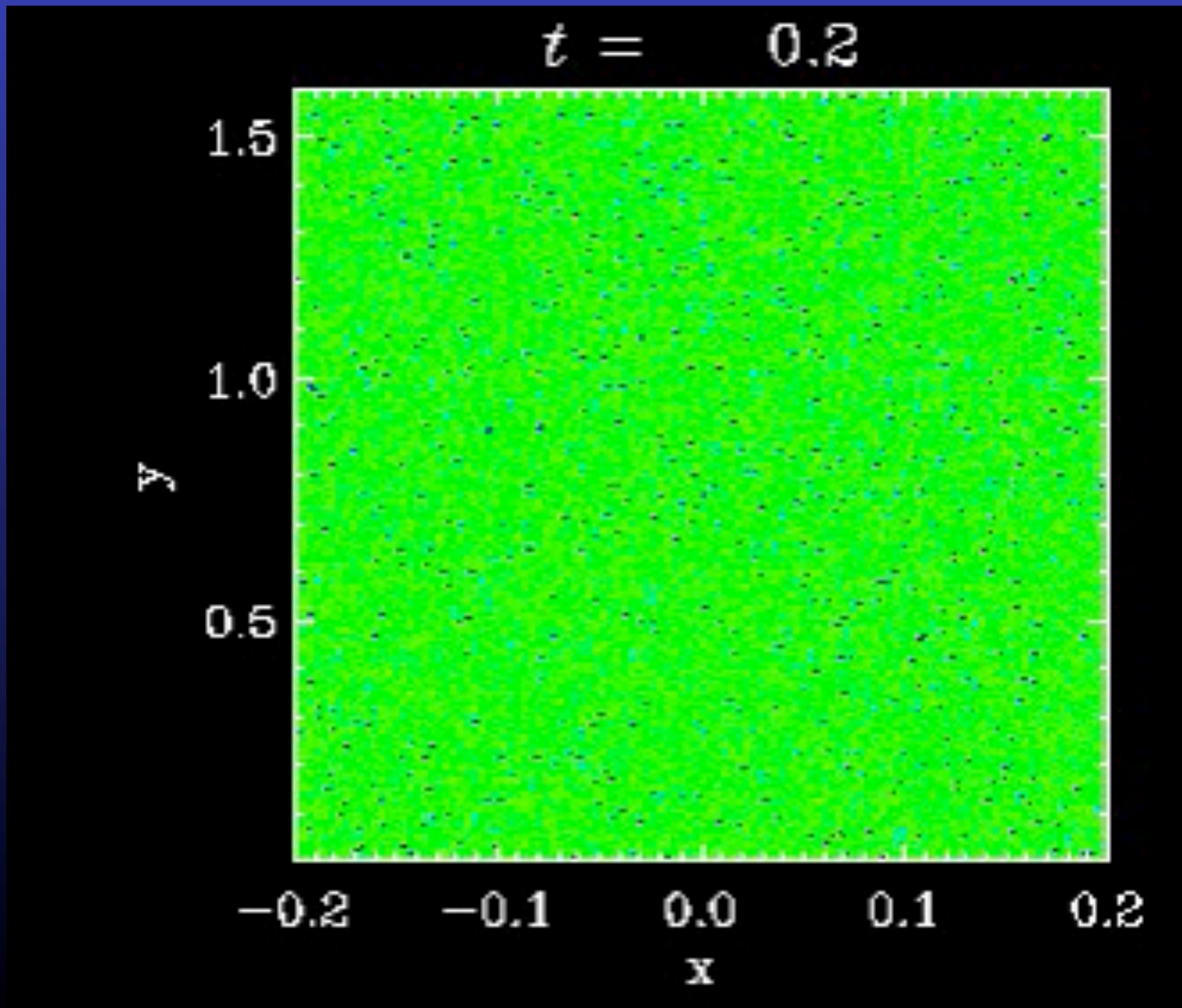
Radial Buoyancy : dS/dr < 0 & dP/dr <0

-> thermal wind dVphi/dz < 0 plus: thermal relaxation

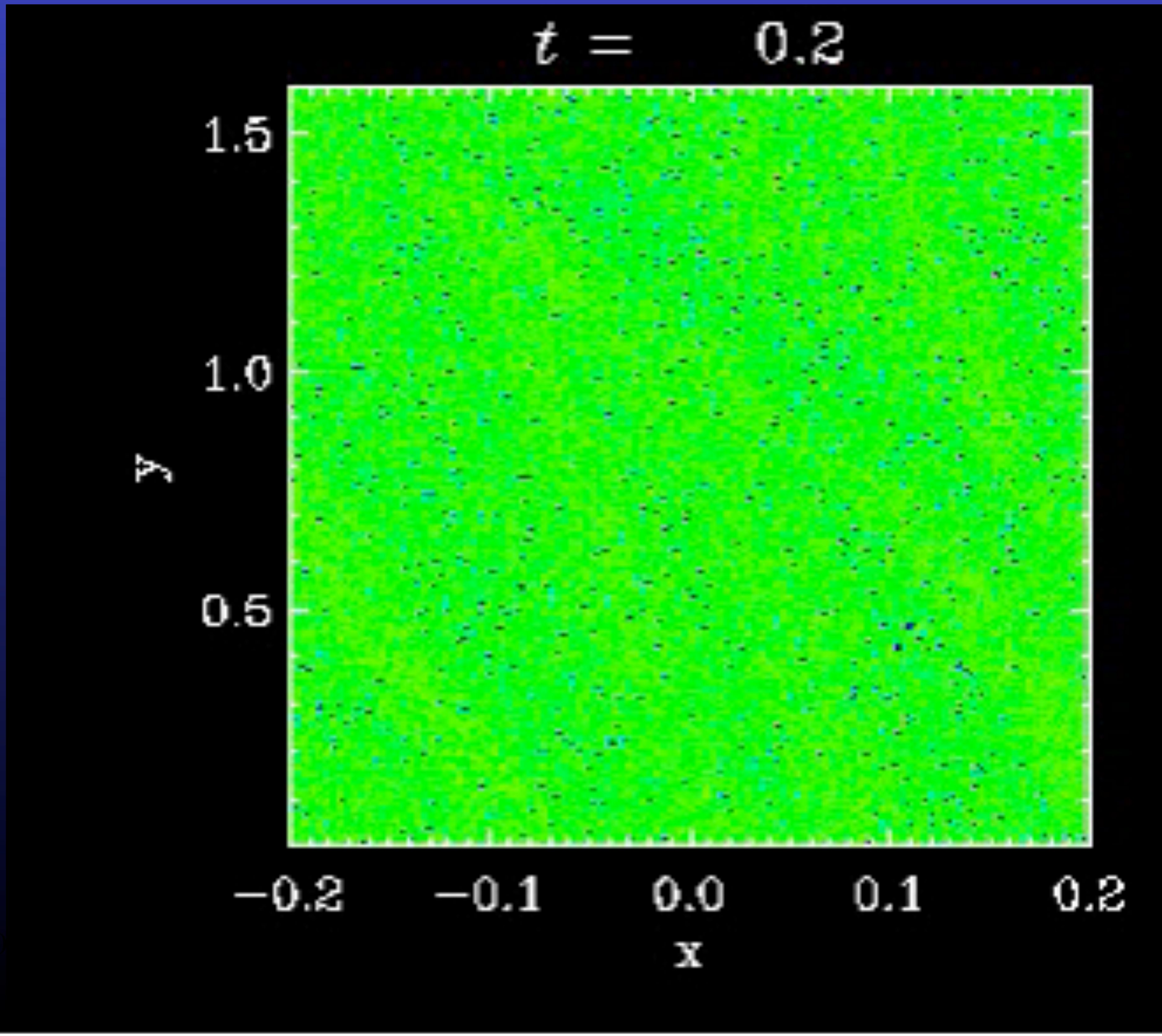
Small particles in pressure maxima e.g. a vortex e.g. Vortex is in balance between Coriolis forces and pressure = same for Zonal flow. Barge & Sommeria 1995



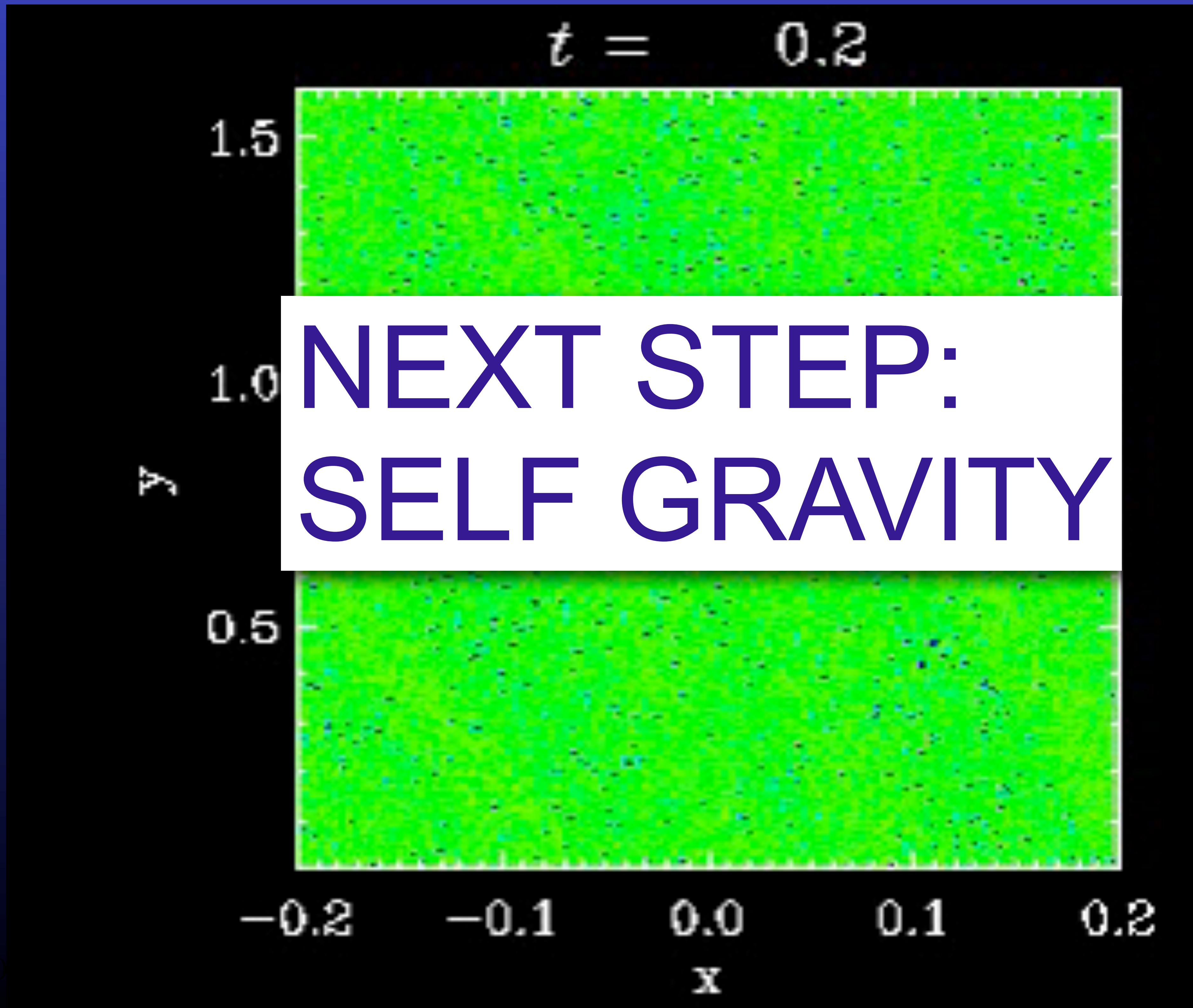
2D: St = 1 particles (20cm) (white = x 1000) Natalie Raettig



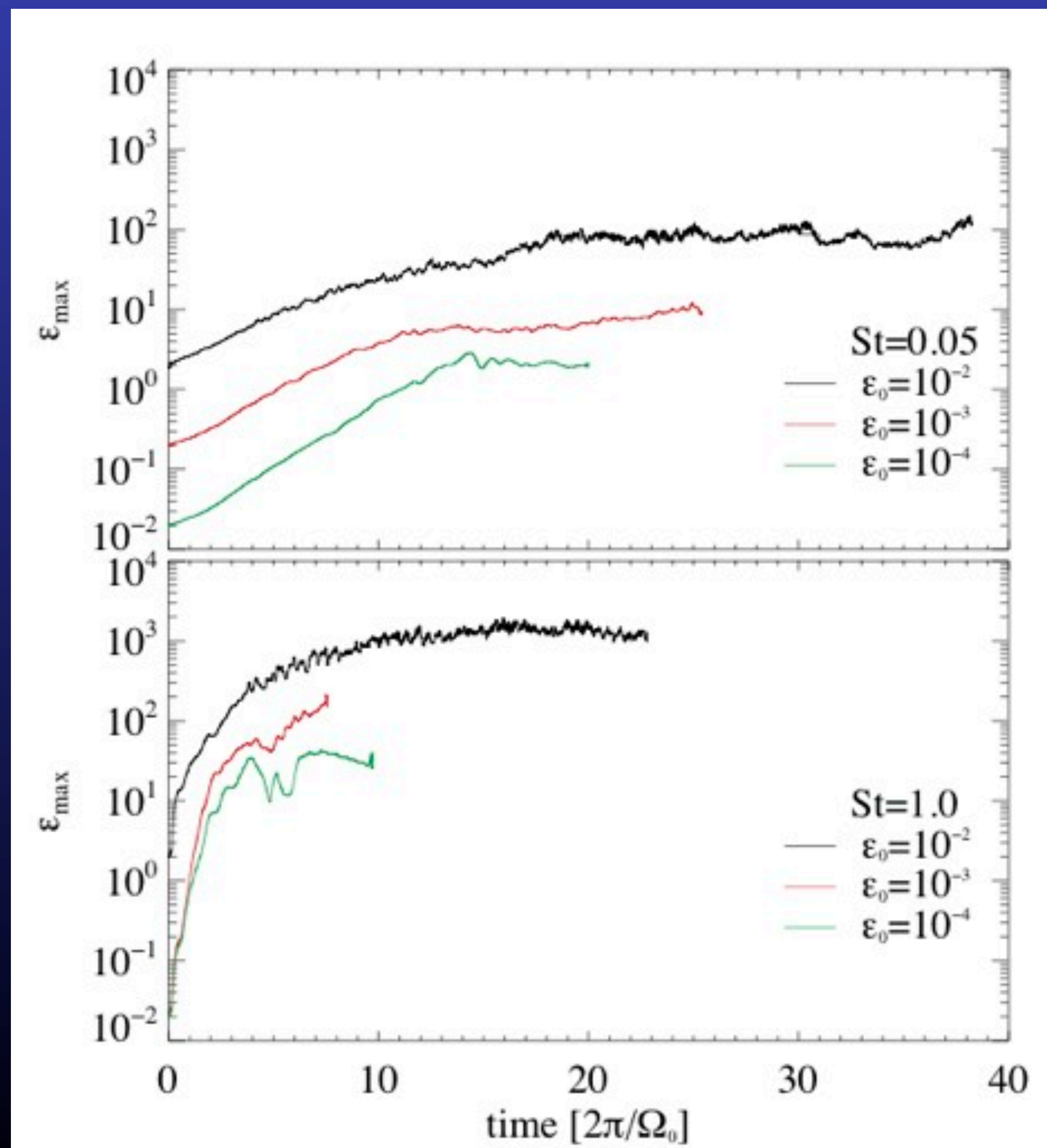
St = 0.05 particles (few millimeter) (white = x 1000) Natalie Raettig

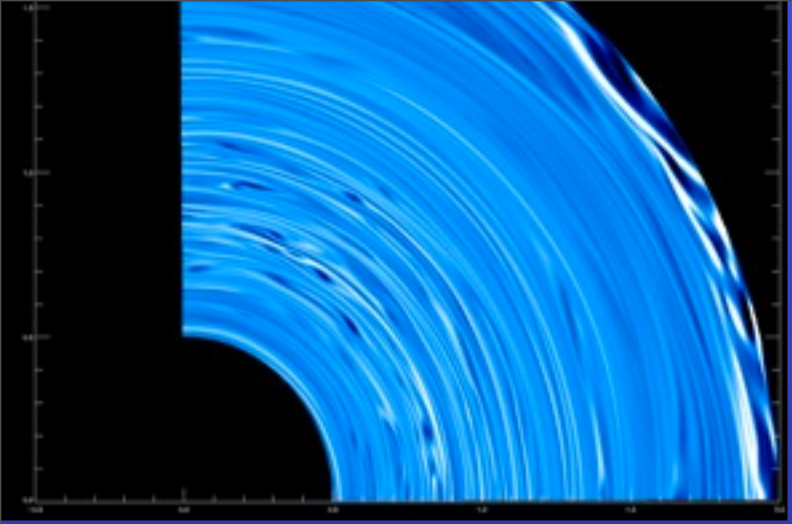


St = 0.05 particles (few millimeter) (white = x 1000) Natalie Raettig

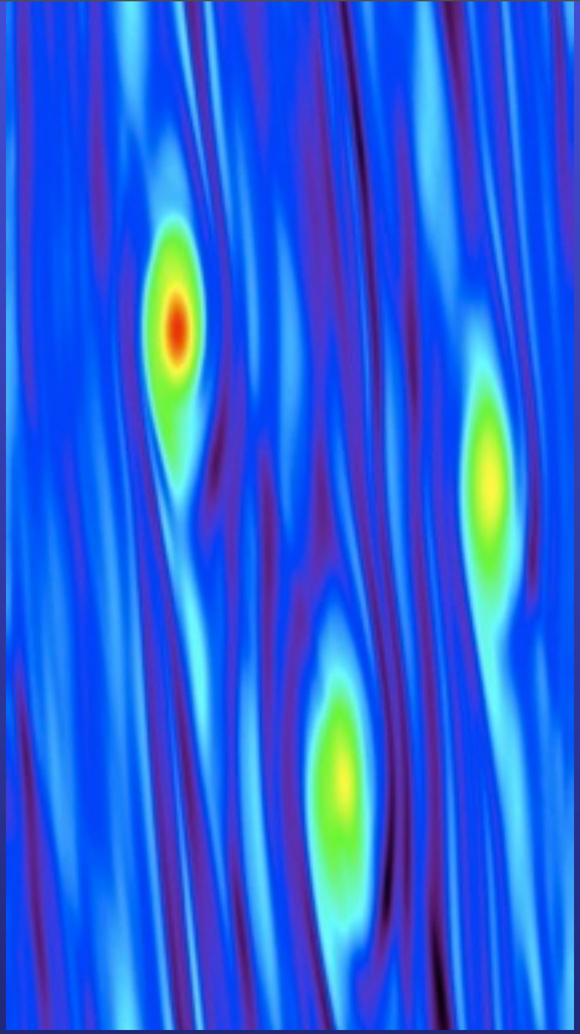


Dust Concentration in 3D Vortices: Raettig and Klahr, in prep





Conclusions:



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