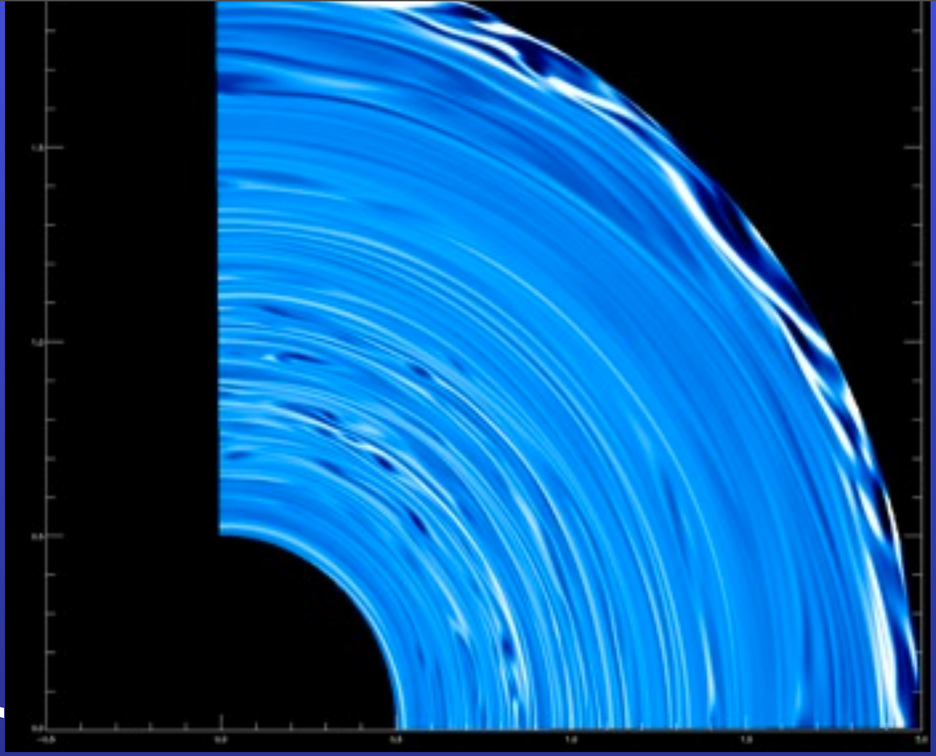
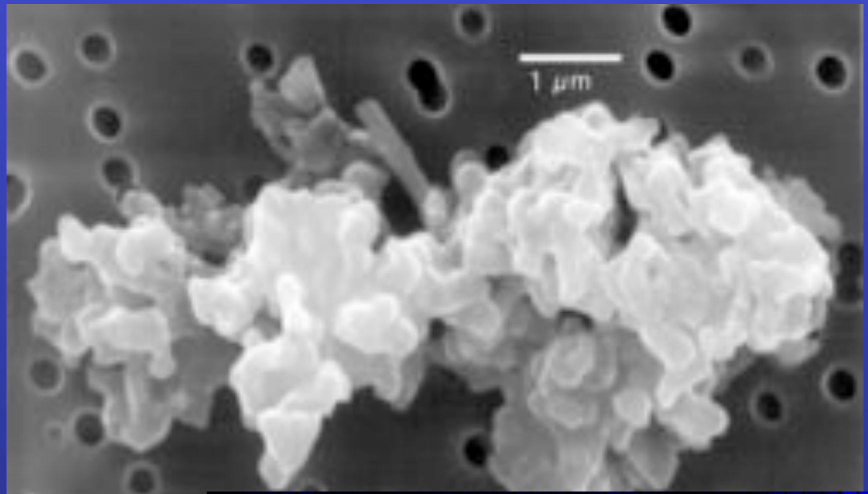
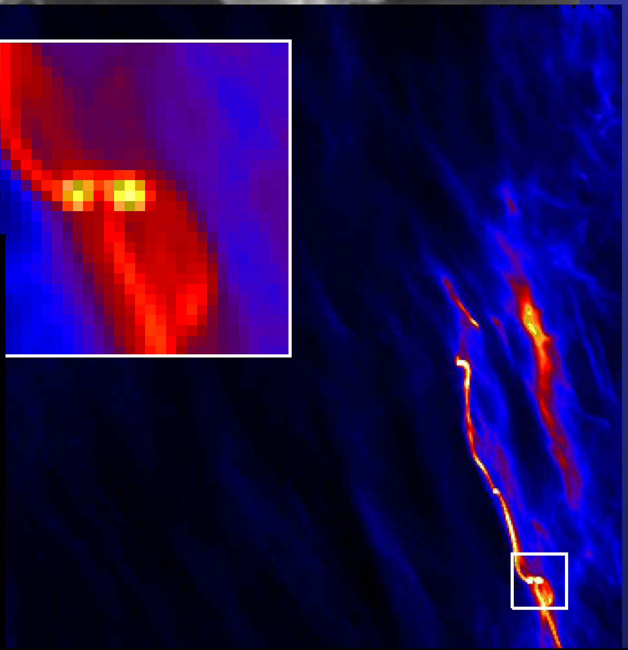
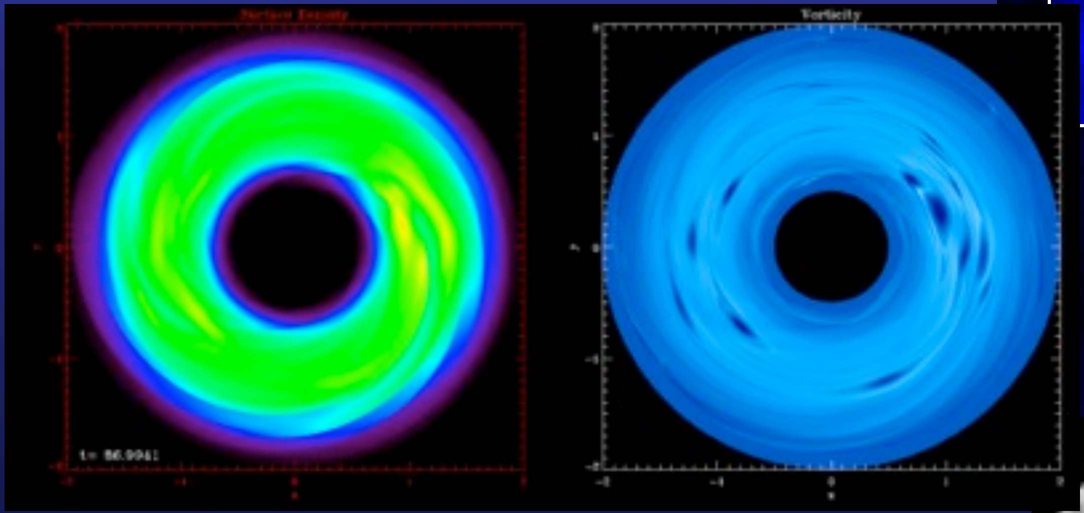
München, Sep. 5th, 2012







The Role of Turbulence in Planetesimal Formation



Hubert Klahr,

Max-Planck-Institut für Astronomie, Heidelberg

Natalie Raettig, Helen Morrison, Karsten Dittrich, Mario Flock, Natalia Dzyurkevich, Karsten Dittrich, Ana Uribe(MPIA), Rainer Spurzem (NAOC/ARI), Mario Trieloff (HD), Til Birnstiel, Barbara Ercolano (USM), Kees Dullemond (ITA), Chris Ormel (Berkley), Neal Turner (JPL), Wlad Lyra (AMNH), Peter Bodenheimer (UCSC), Doug Lin (KIAA, UCSC) Anders Johansen (Lund), Andrew Youdin (CfA), Jeffrey S. Oishi (Berkley), Mordecai-Mark Mac Low (AMNH)

Outline:

The role of Turbulence in Planet Formation

- Capturing Dust in Pressure maxima e.g. Zonal flows and vortices
- MHD turbulence and Gravoturbulent Planetesimal formation -> Karsten Dittrich
- Turbulence and vortices in Baroclinic disks: Disk Weather
- Modified Symmetric Instability
- Dust capturing in 3D vortices
- Summary, Conclusions

Turbulence in a non rotating frame:

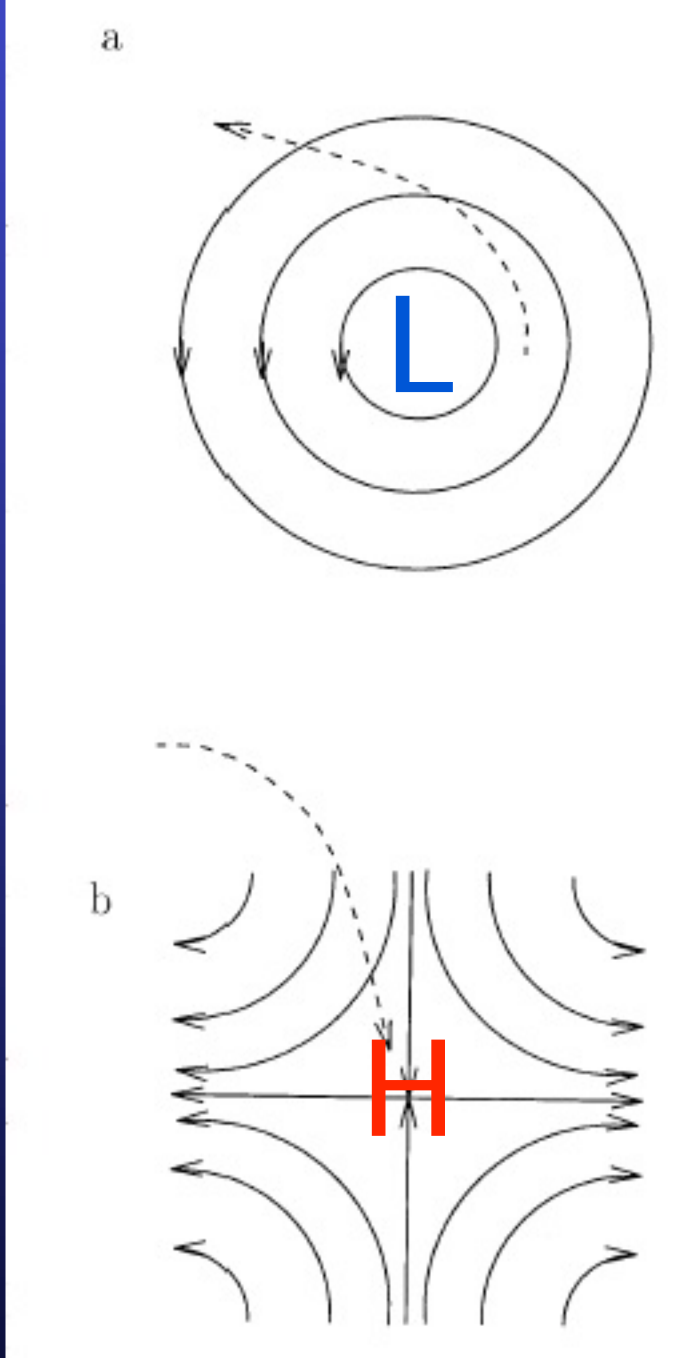


FIG. 1. Under laboratory-observed conditions particles (a) spiral out of the vortices (eddy), but (b) collect in convergence zones (strain fields).

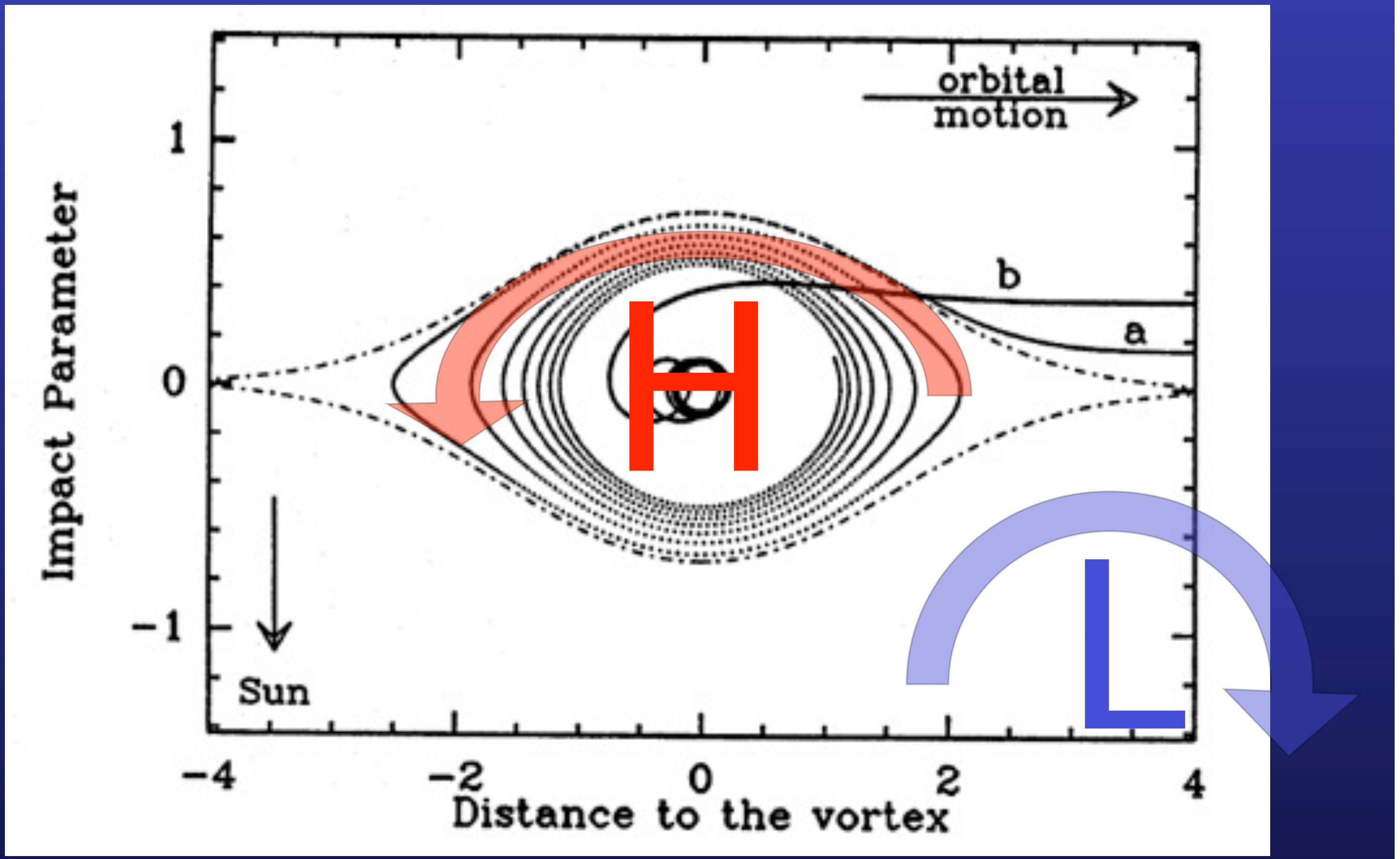
Cuzzi et al.

Laboratory Conditions

Dust collects between vortices (high pressure)

$$\begin{aligned} \partial_t v_g &= -\frac{1}{\rho}\nabla p + \text{forces} \\ \partial_t v_d &= -\frac{v_d - v_g}{\tau_f} + \text{forces} \\ v_d &= v_g + \tau_f \frac{1}{\rho}\nabla p \end{aligned}$$

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



VORTICES:

Barge & Sommeria 1995

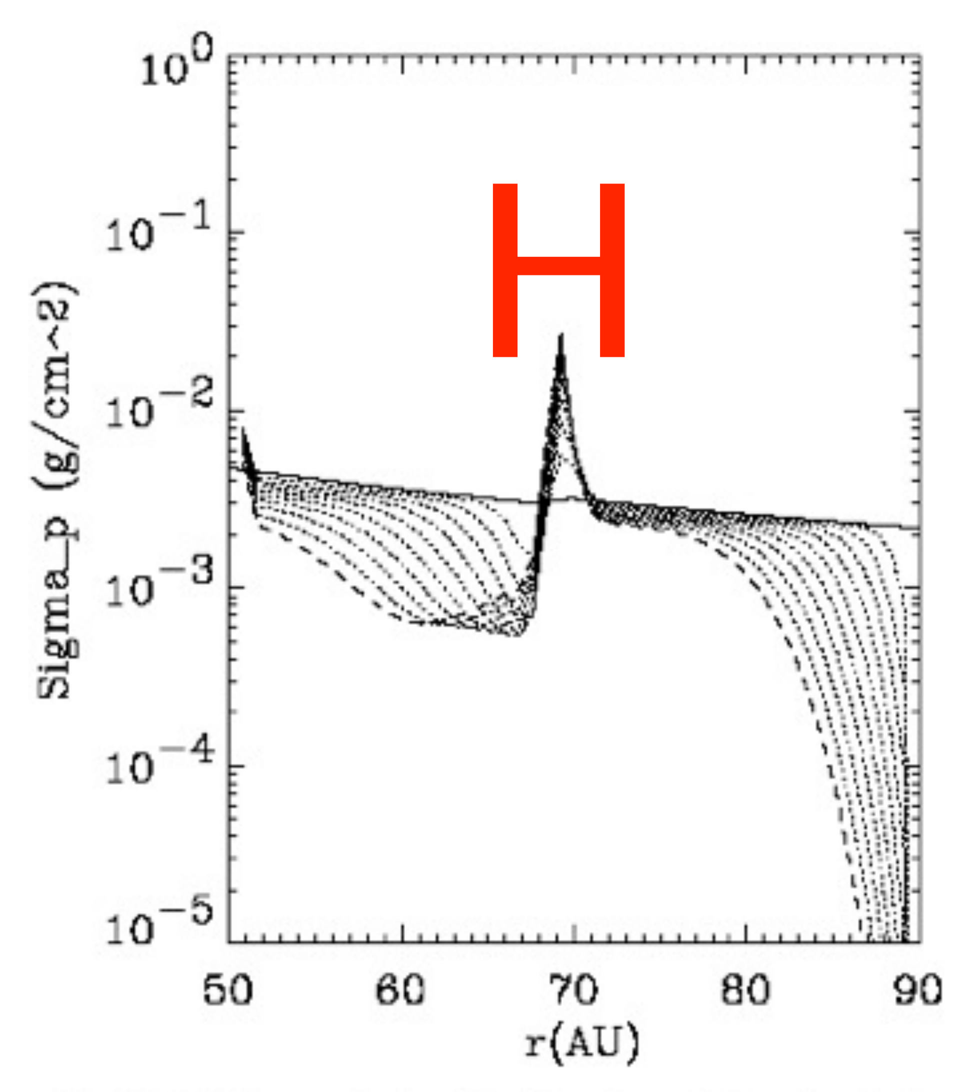


FIG. 7.—Model A: evolution of the 1 m size particle surface density distribution for the model in Fig. 2. The solid line gives the initial distribution. The following lines are snapshots every 10^5 yr.

ZONAL FLOWS:

Radial Pressure maxima

Klahr & Lin 2000

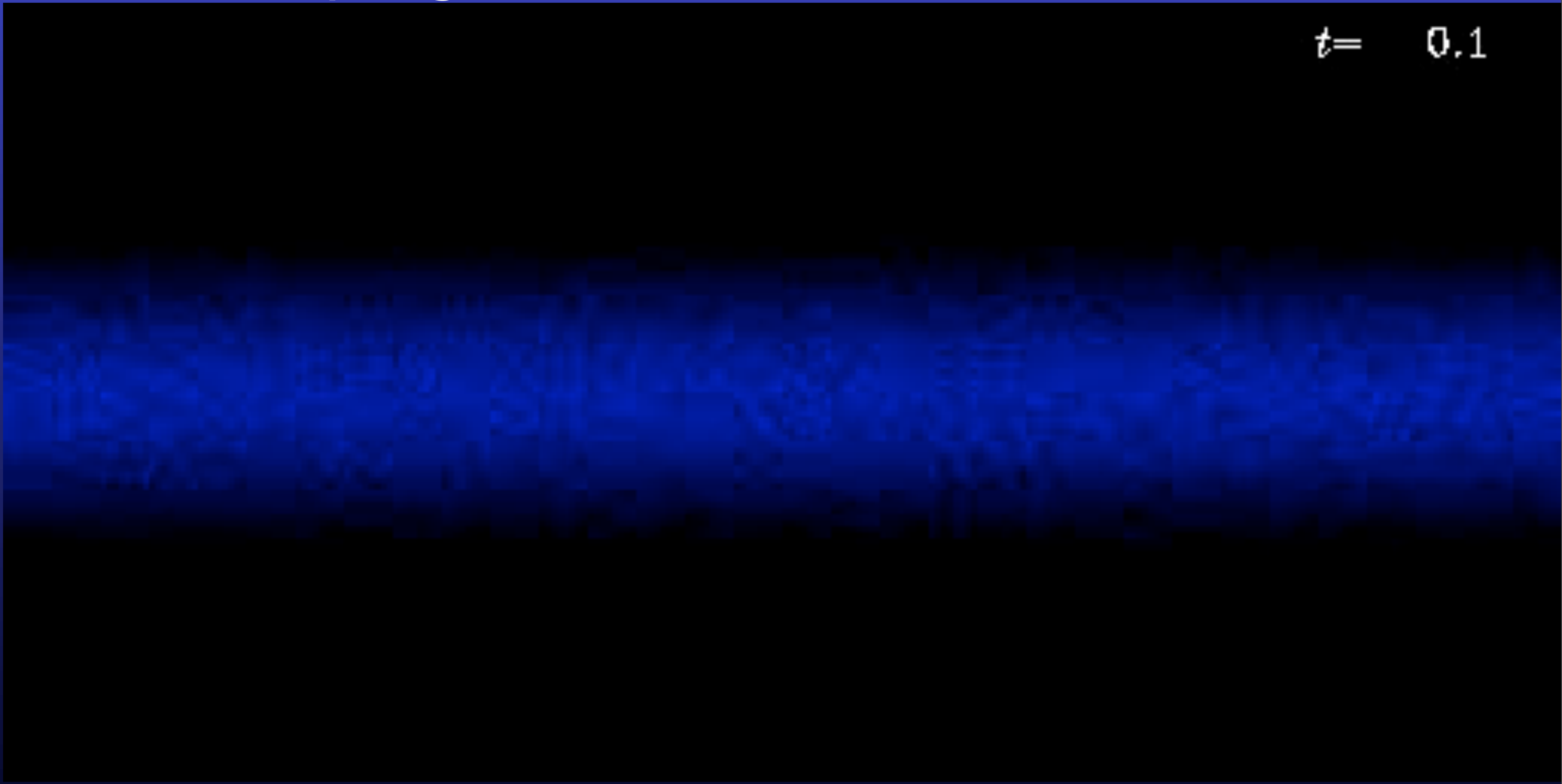
From dust/gas eq. 1 => Streaming Instability -> dust densities larger than local Roche density, e.g. Planetesimals can form.

Vertical

horizontal

Johansen, Henning & Klahr 2006

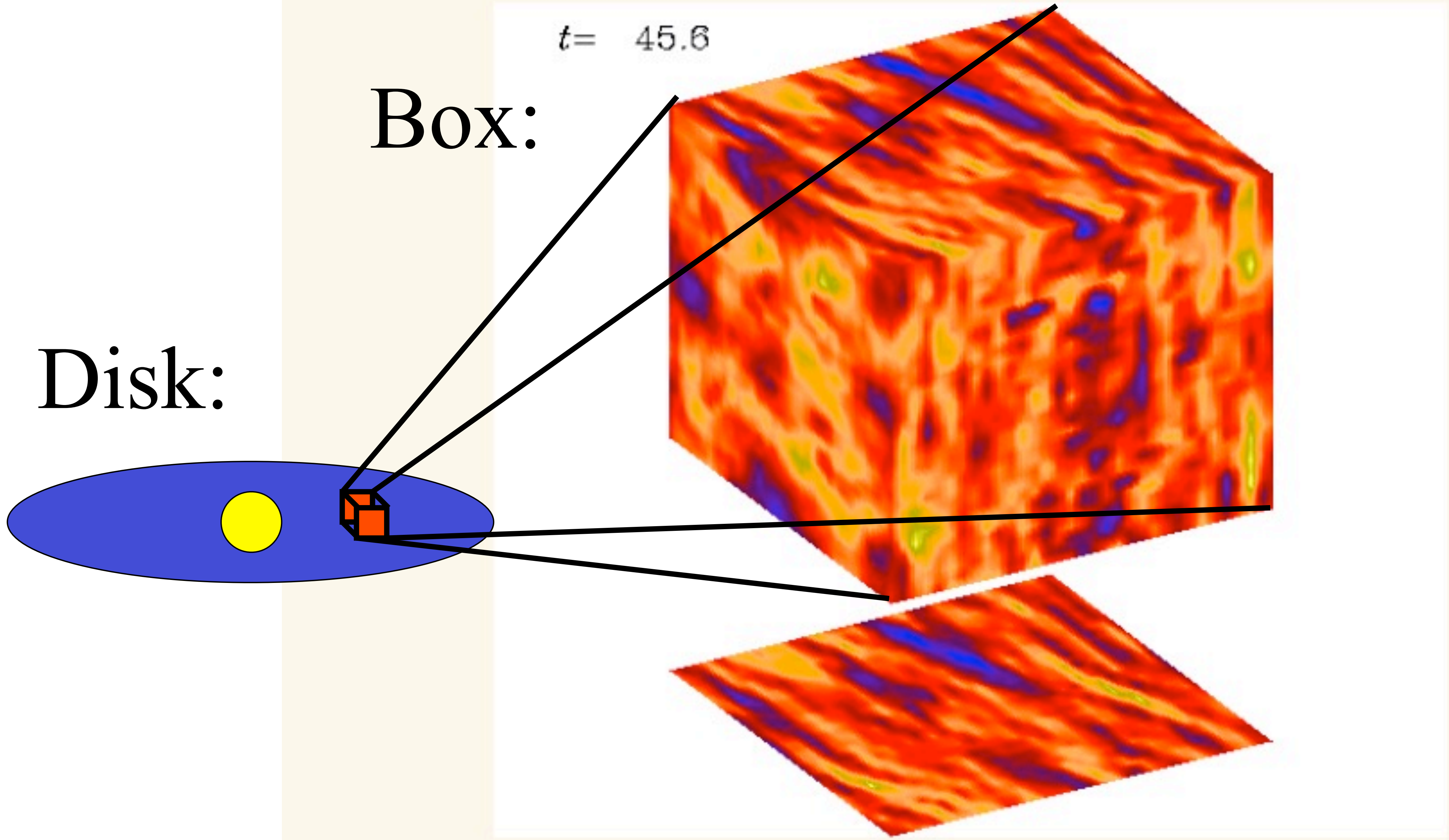
From dust/gas eq. 1 => Streaming Instability -> dust densities larger than local Roche density, e.g. Planetesimals can form.



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)]

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

$$\begin{aligned}
\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u} + u_y^{(0)}\frac{\partial \boldsymbol{u}}{\partial y} &= 2\Omega u_y \hat{\boldsymbol{x}} - \frac{1}{2}\Omega u_x \hat{\boldsymbol{y}} - \boldsymbol{\nabla}\Phi + \frac{1}{\rho}\boldsymbol{J}\times\boldsymbol{B} \\
&\quad - \frac{1}{\rho}c_{\rm s}^2\boldsymbol{\nabla}\rho - \frac{\rho_{\rm d}/\rho}{\tau_{\rm f}}(\boldsymbol{u}-\boldsymbol{w}) + \boldsymbol{f}_\nu(\boldsymbol{u},\rho)\,, \\
\frac{\partial \rho}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\rho + u_y^{(0)}\frac{\partial \rho}{\partial y} &= -\rho\boldsymbol{\nabla}\cdot\boldsymbol{u} + f_{\rm D}(\rho)\,, \\
\frac{\partial \boldsymbol{A}}{\partial t} + u_y^{(0)}\frac{\partial \boldsymbol{A}}{\partial y} &= \frac{3}{2}\Omega A_y \hat{\boldsymbol{x}} + \boldsymbol{u}\times\boldsymbol{B} + \boldsymbol{f}_\eta(\boldsymbol{A})\,, \\
\nabla^2\Phi &= 4\pi G(\rho + \rho_{\rm d})\,.
\end{aligned}$$

gas

$$\begin{aligned}
\frac{\partial \boldsymbol{v}^{(i)}}{\partial t} &= 2\Omega v_y^{(i)}\hat{\boldsymbol{x}} - \frac{1}{2}\Omega v_x^{(i)}\hat{\boldsymbol{y}} - \Omega^2 z - \boldsymbol{\nabla}\Phi(\boldsymbol{x}^{(i)}) - \frac{1}{\tau_{\rm f}}[\boldsymbol{v}^{(i)} - \boldsymbol{u}(\boldsymbol{x}^{(i)})]\,, \\
\frac{\partial \boldsymbol{x}^{(i)}}{\partial t} &= \boldsymbol{v}^{(i)} + u_y^{(0)}\hat{\boldsymbol{y}}\,.
\end{aligned}$$

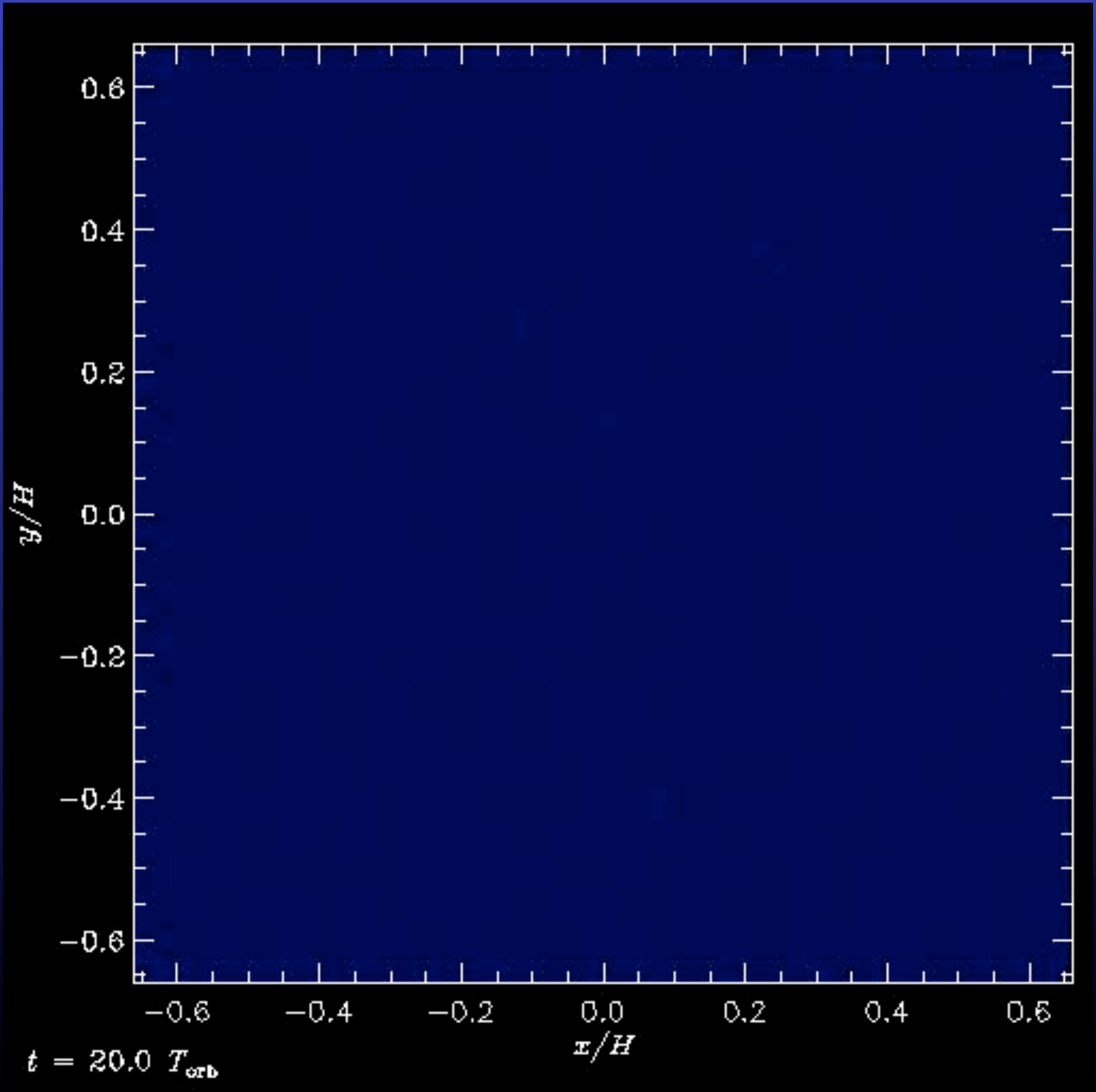
dust

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

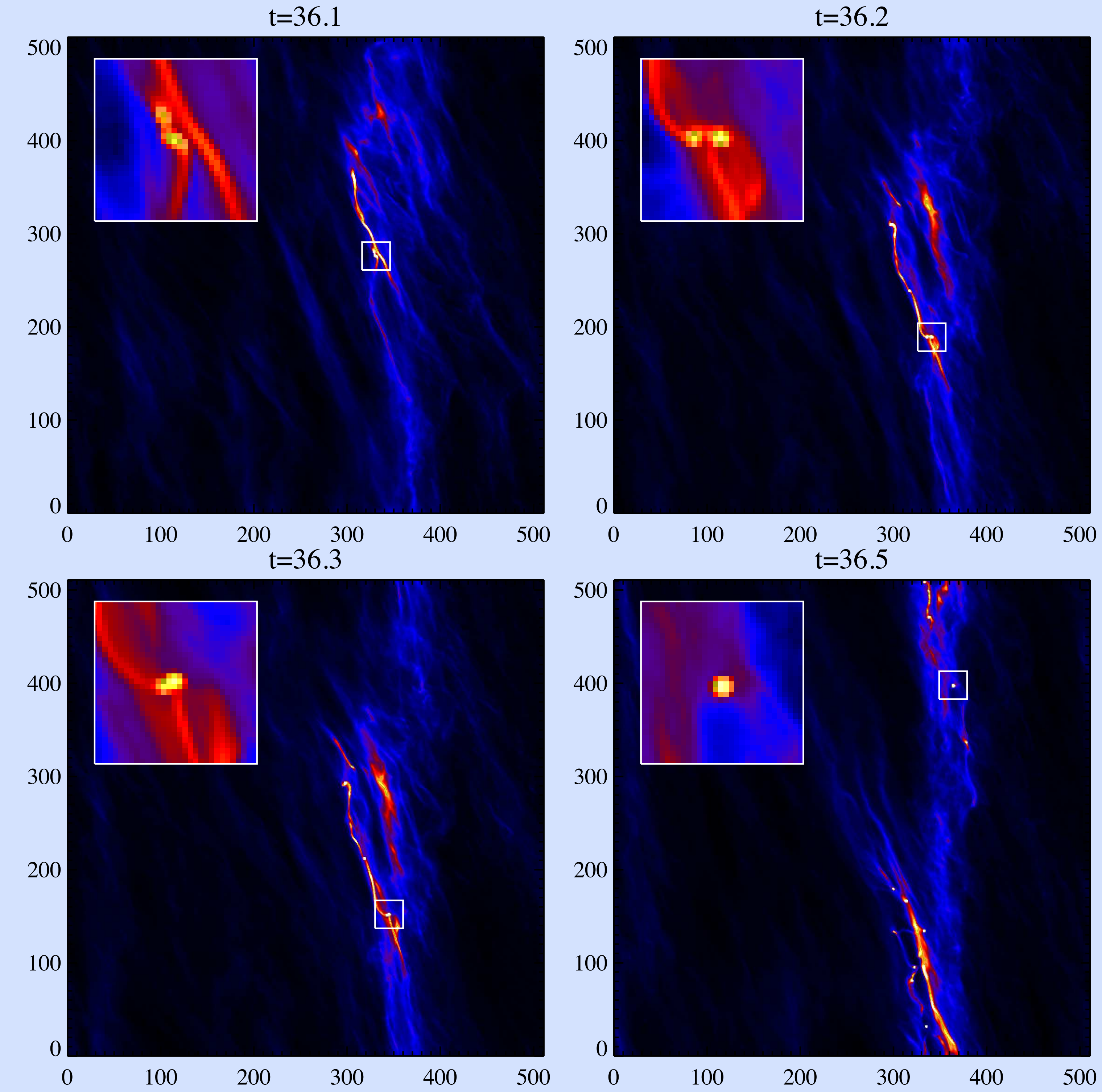
Concentration in Zonal Flows:

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.



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

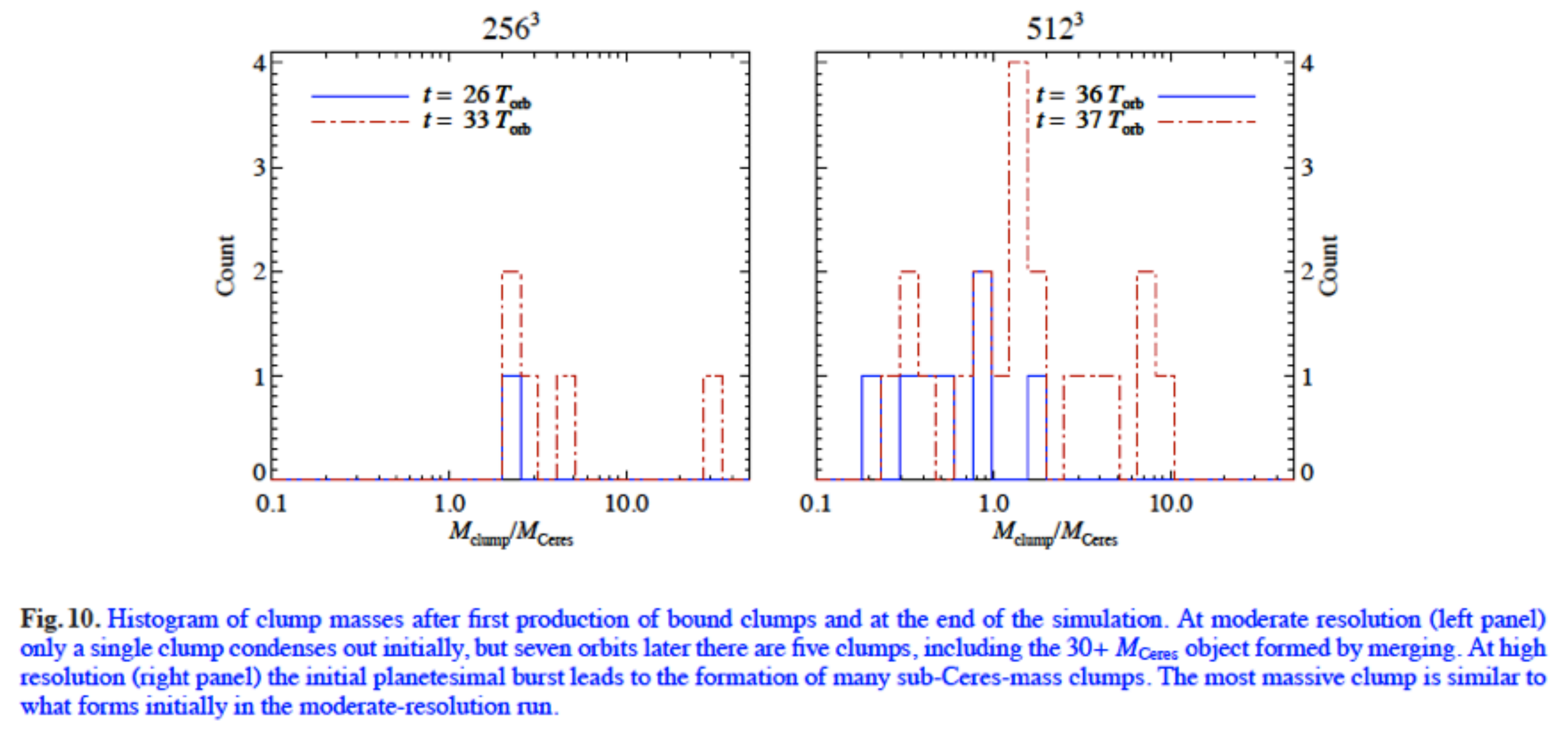
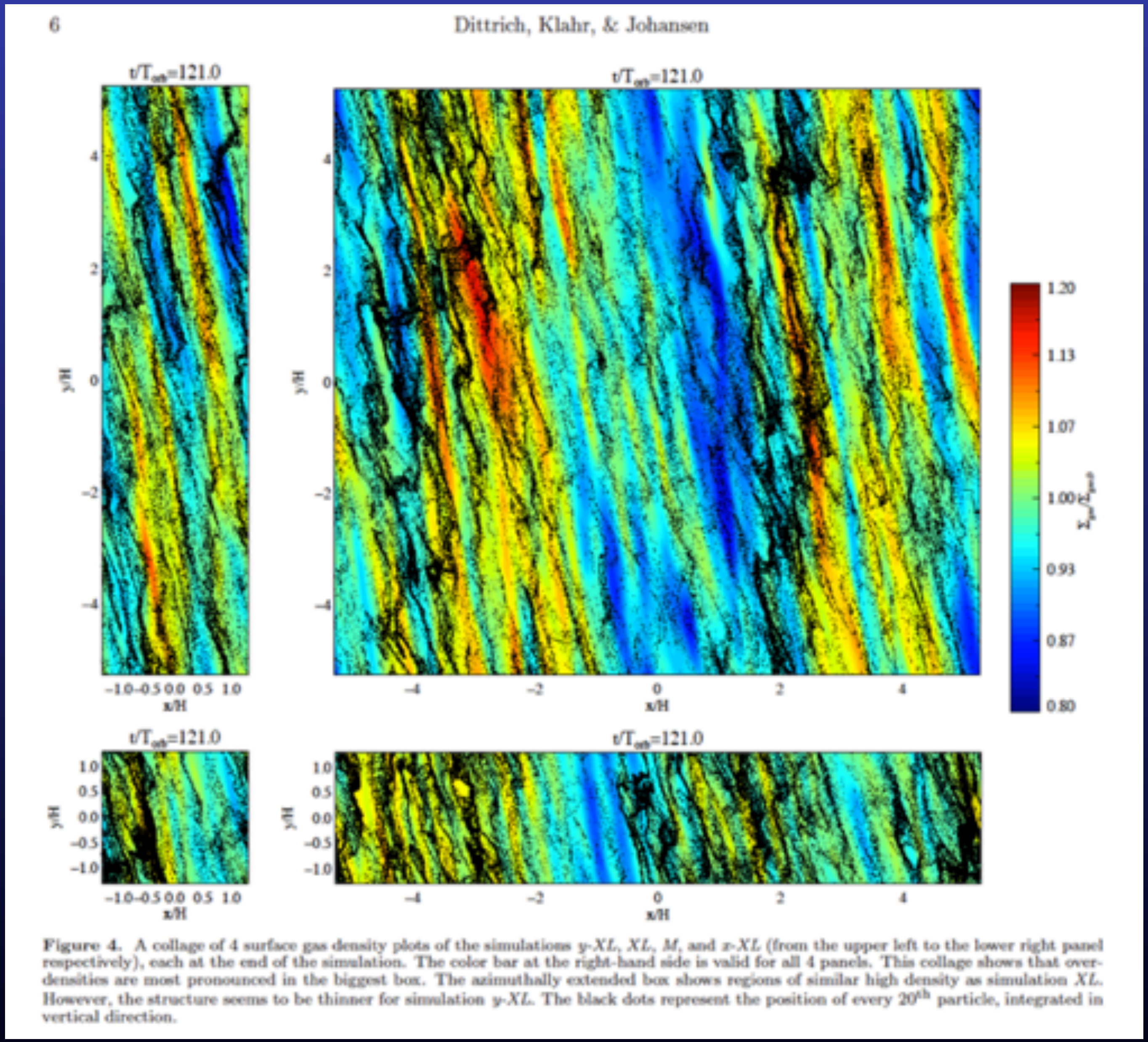


Fig. 10. Histogram of clump masses after first production of bound clumps and at the end of the simulation. At moderate resolution (left panel) only a single clump condenses out initially, but seven orbits later there are five clumps, including the 30+ $M_{\rm Ceres}$ object formed by merging. At high 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

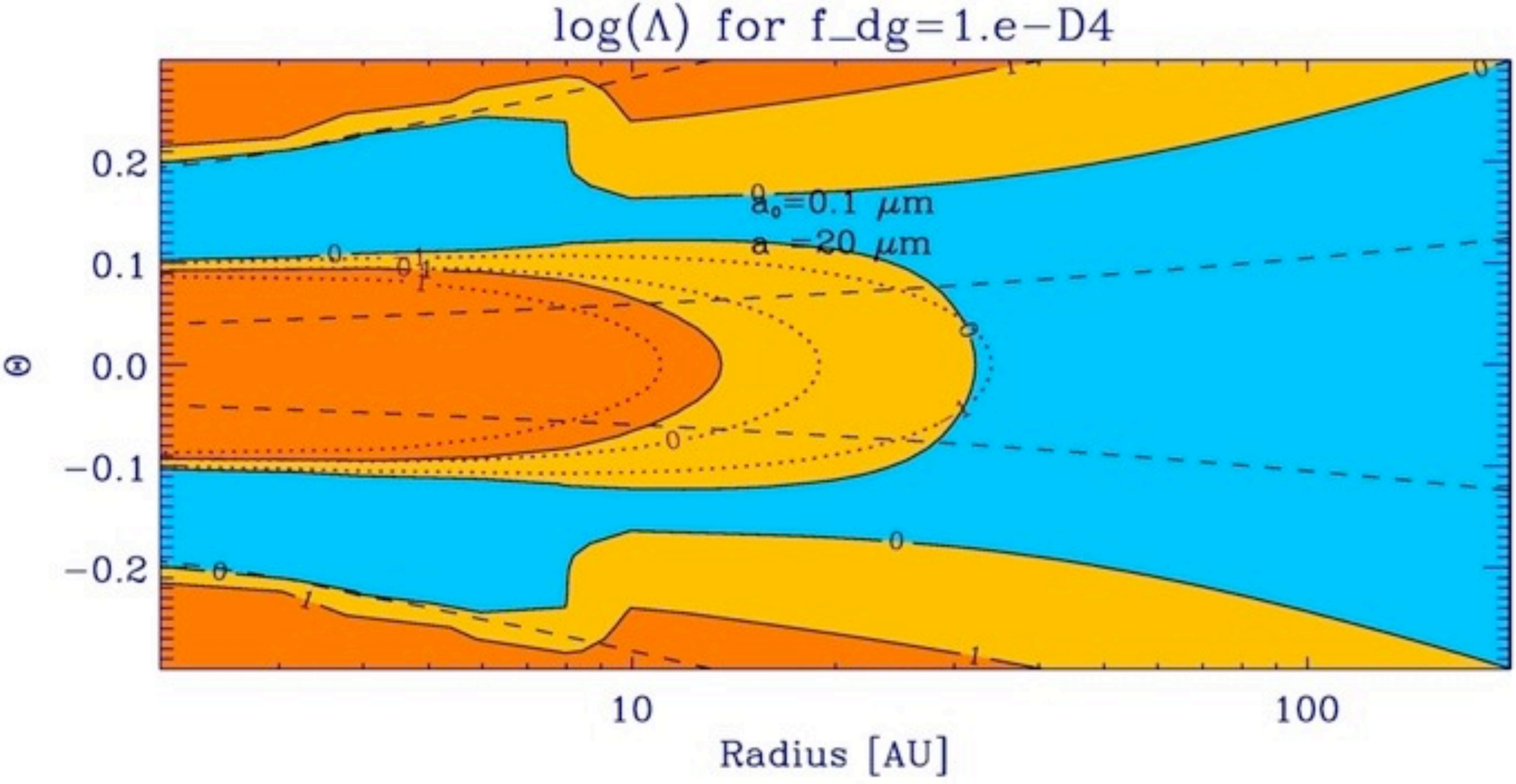
See Talk by Karsten Dittrich



6 Dittrich, Klahr, & Johansen

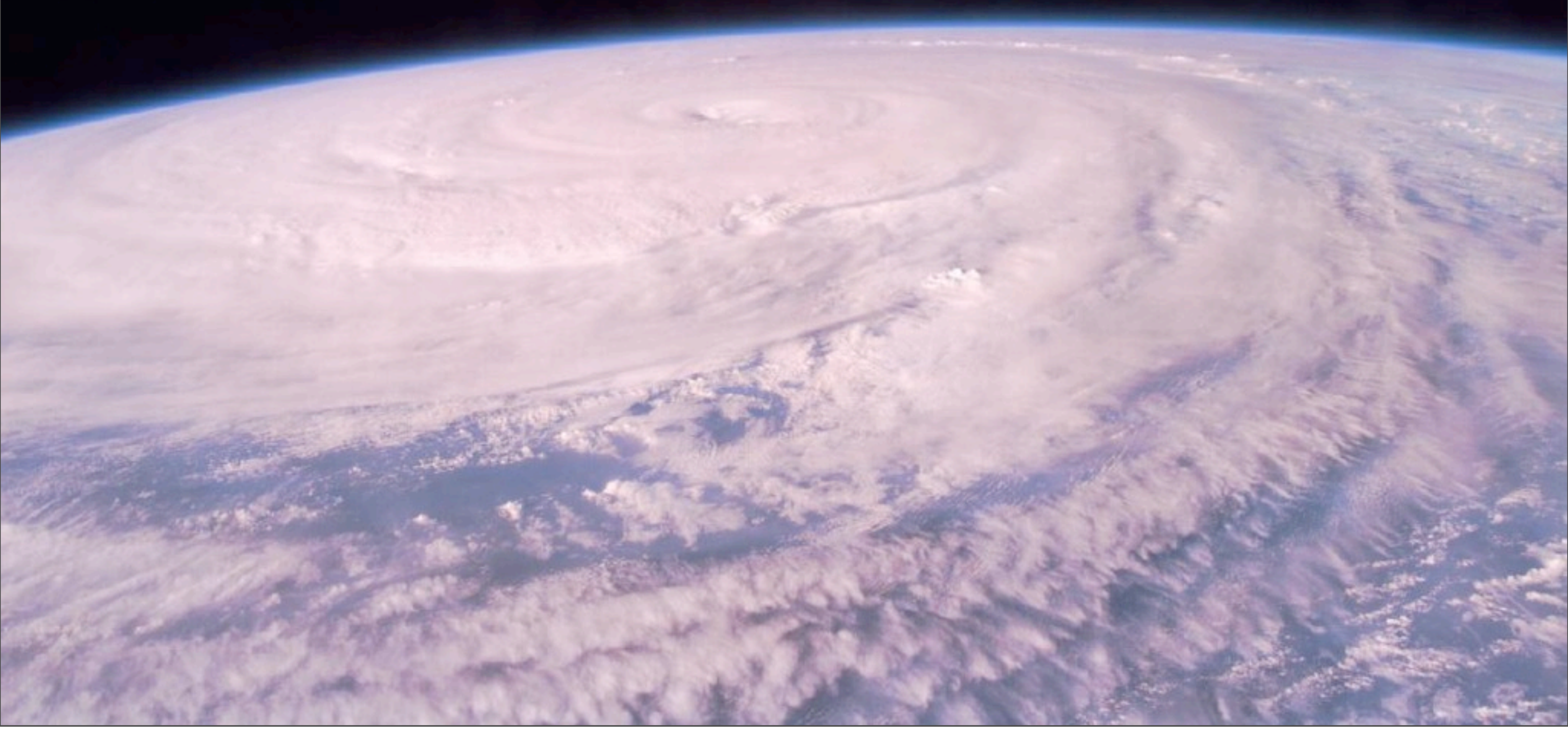
Figure 4. A collage of 4 surface gas density plots of the simulations *y-XL*, *XL*, *M*, and *x-XL* (from the upper left to the lower right panel respectively), each at the end of the simulation. The color bar at the right-hand side is valid for all 4 panels. This collage shows that over-densities are 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.

Natalia Dziurkevich (in prep.) see her POSTER!
Active (Blue) and Dead (Yellow/Orange) Zones

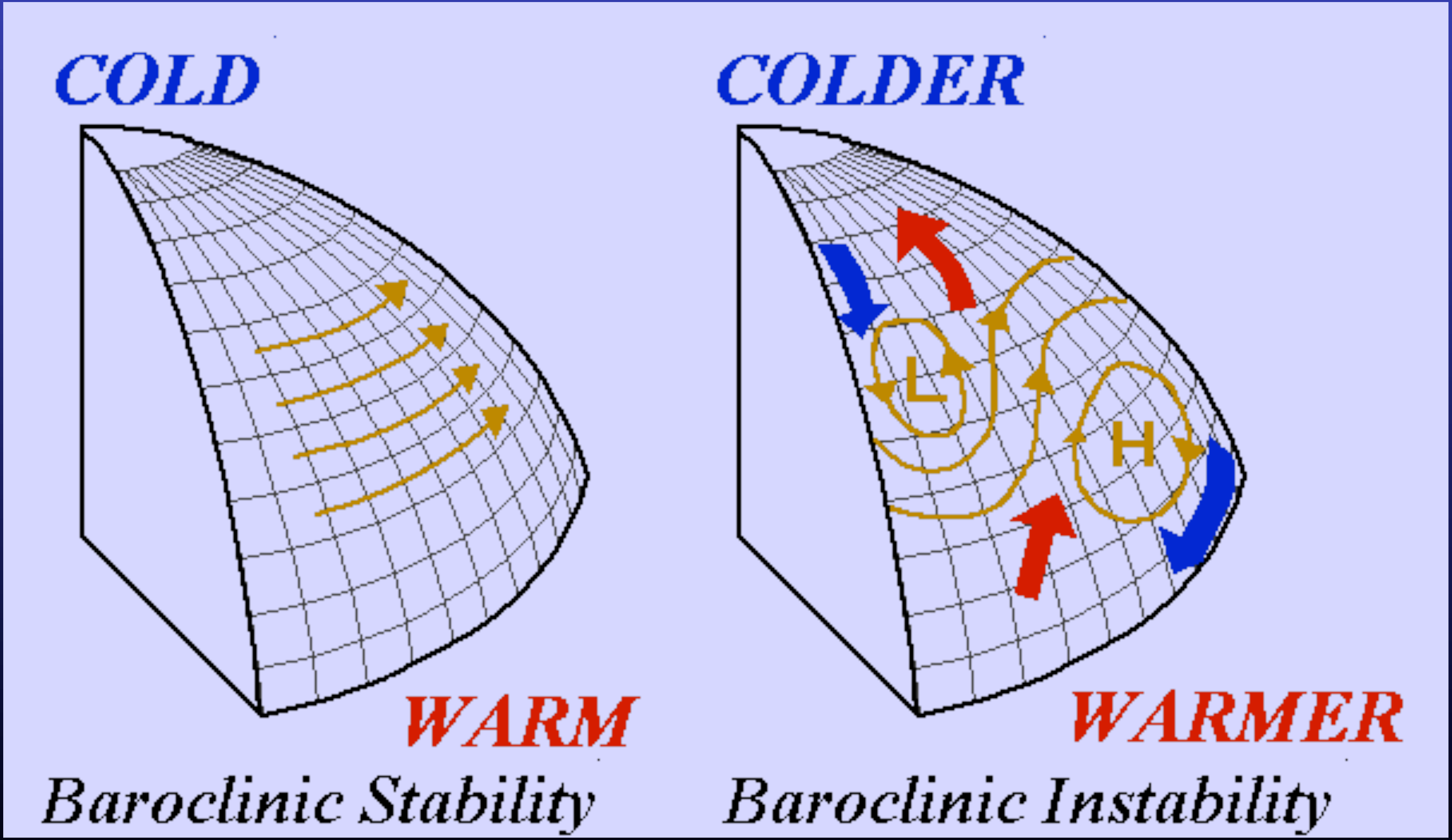


=> Planetesimals are needed in the Dead Zone.

Baroclinic Effects on Earth: Formation of Hurricanes



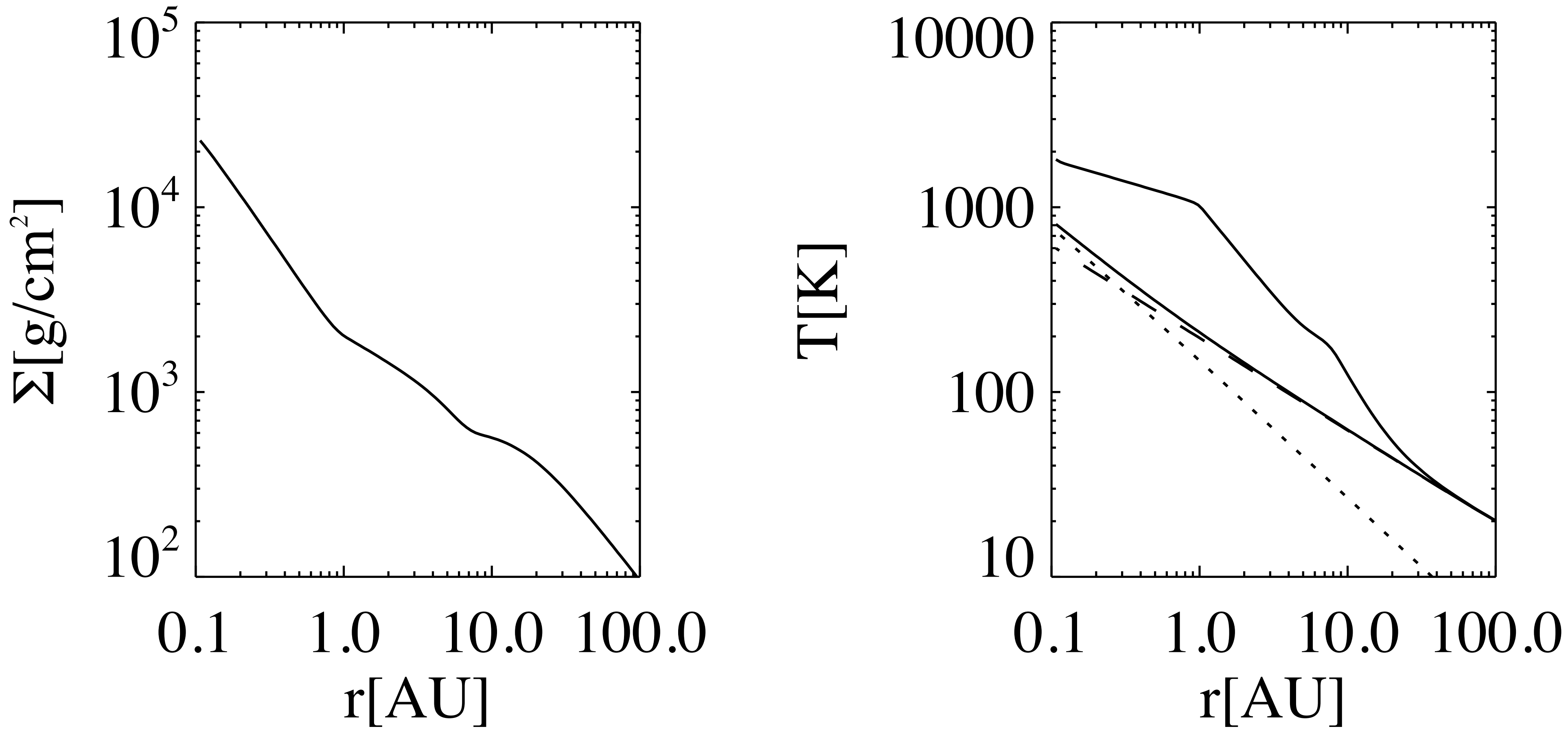
Geophysical Baroclinic Instability



Klahr & Raettig in prep.
Using data from Sean Andrews

alpha = 0.001; Mdot = 1E-7 Msol/yr;

Plus irradiation: Tstar = 4300; Rstar = 2 Rsol



12/13/

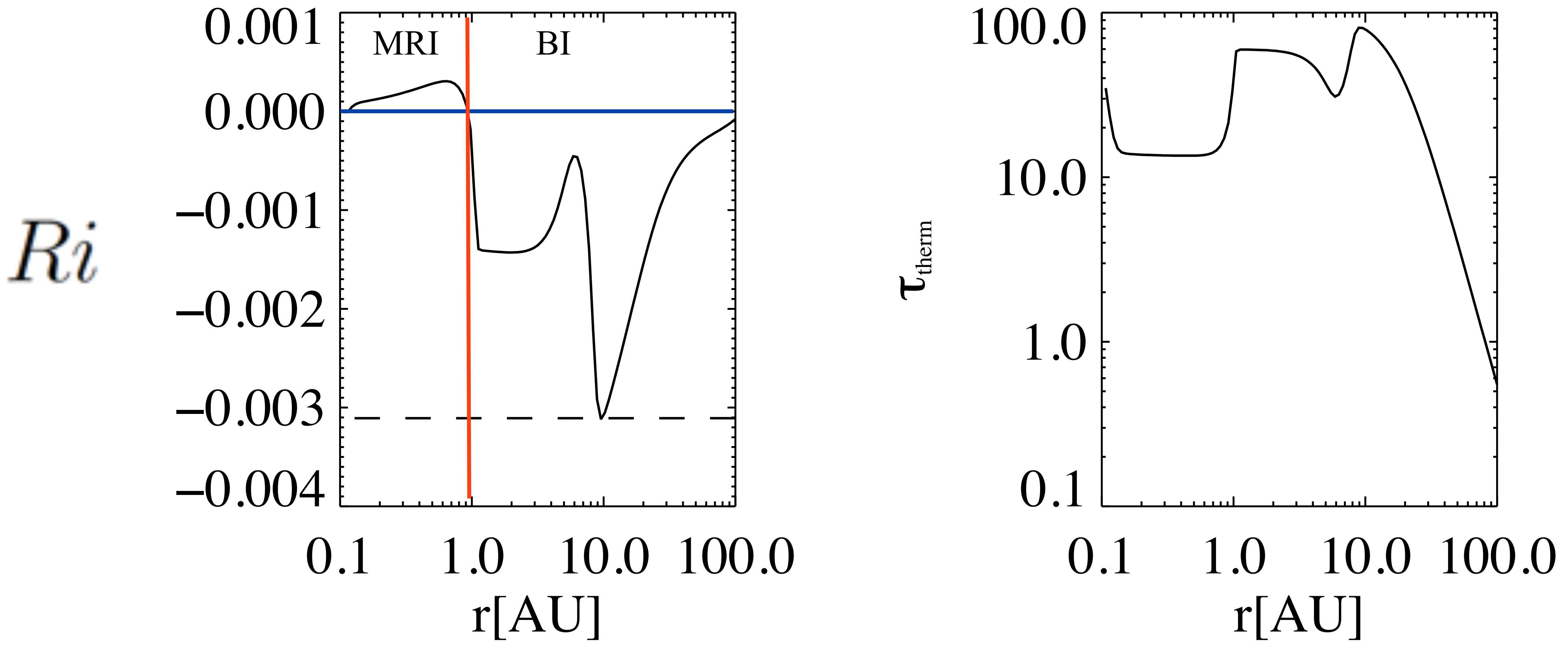
Richardson number & Thermal diffusion time

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

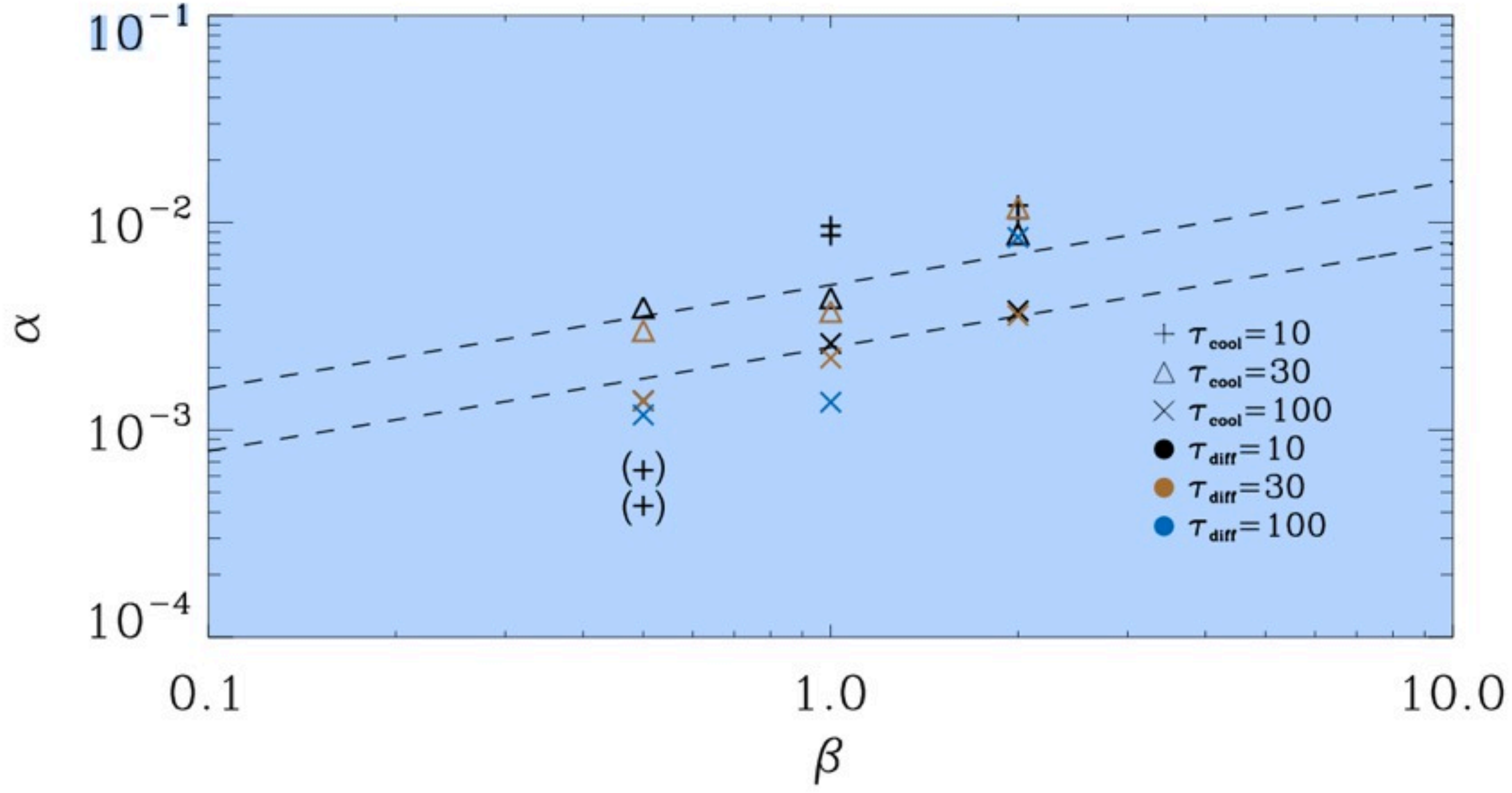
$$Ri \;\; = -\frac{2}{3\gamma}\left(\frac{H}{R}\right)^2 \beta_p \beta_s$$

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

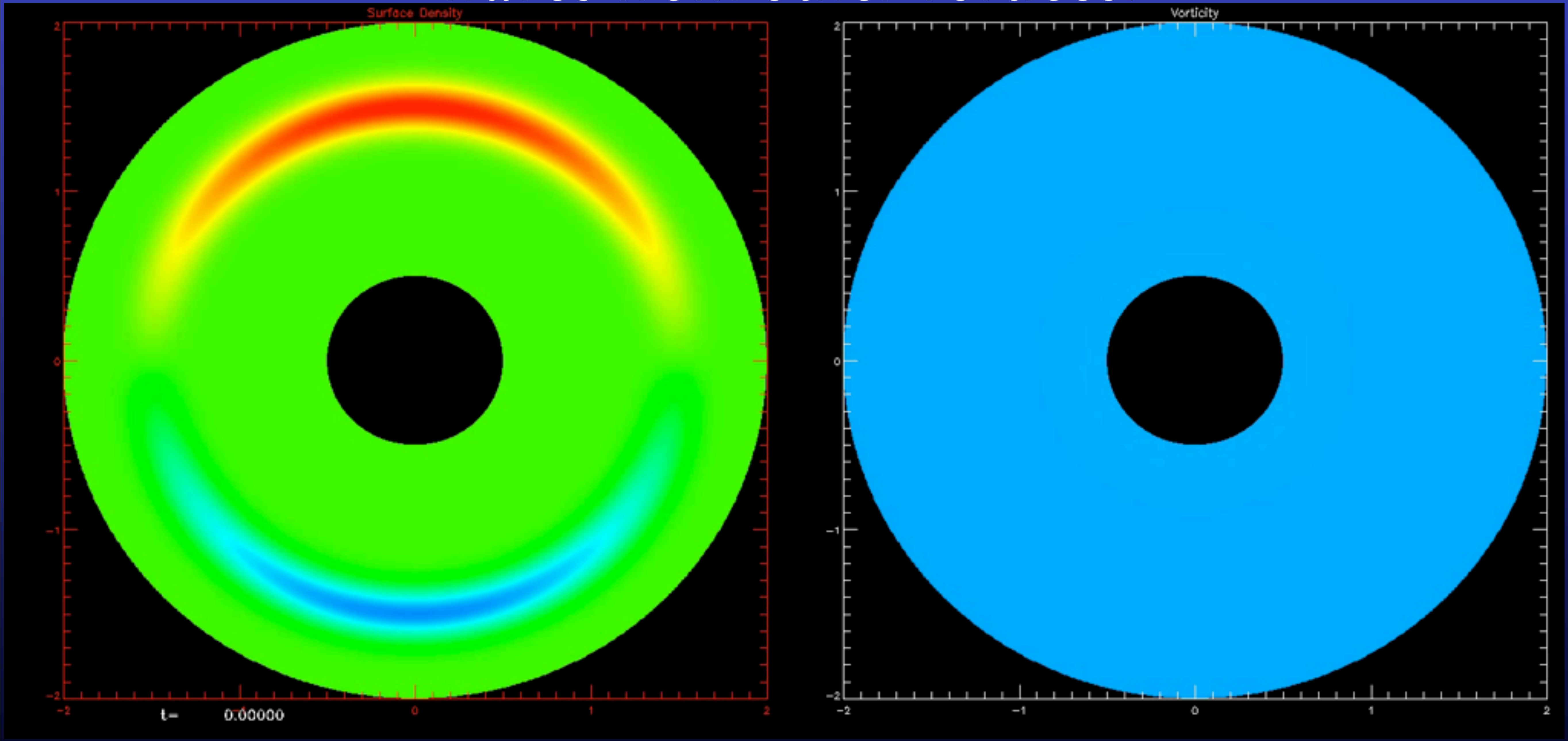
$$\tau_{therm} = H^2 / \frac{D}{\rho c_v}$$



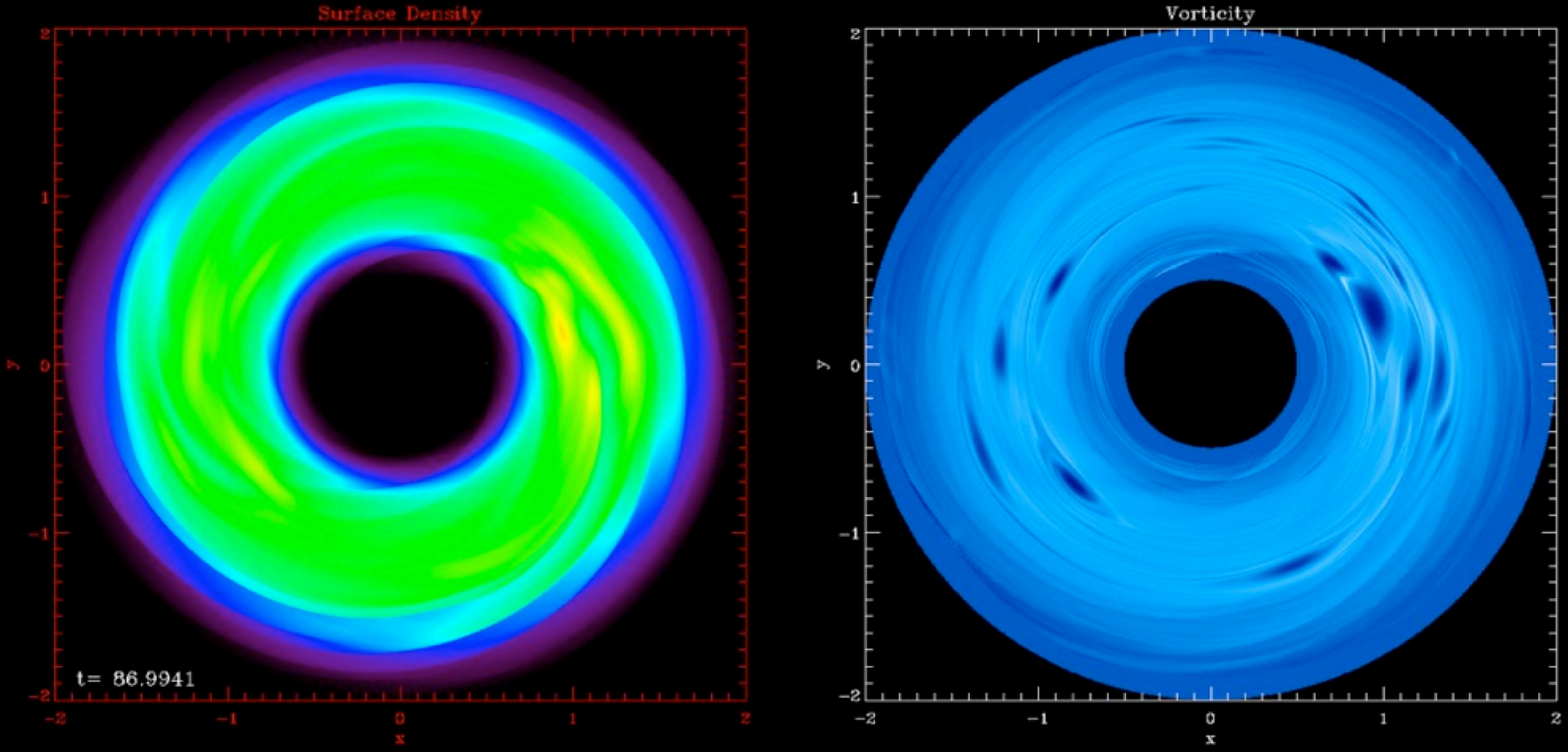
Strength of alpha?
Raettig, Klahr and Lyra, submitted



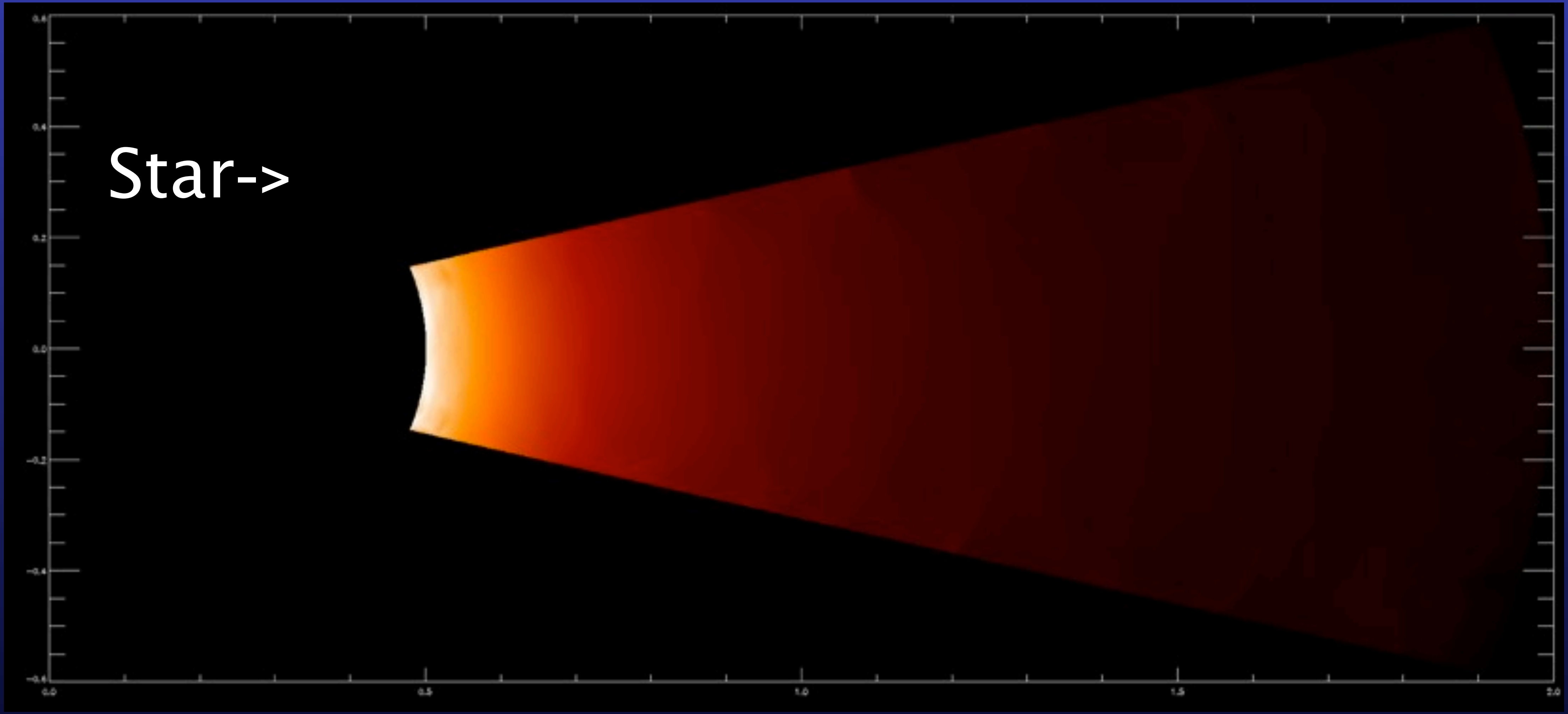
Pluto Code: 1024^2; WENO3-RK3; HLLE; FARGO vortices migrate inward, but are recreated by waves from other vortices.



Pluto Code: 1024^2; WENO3-RK3; HLLE; FARGO
Spirals spawn new vortices further out, many cycles of vortices!



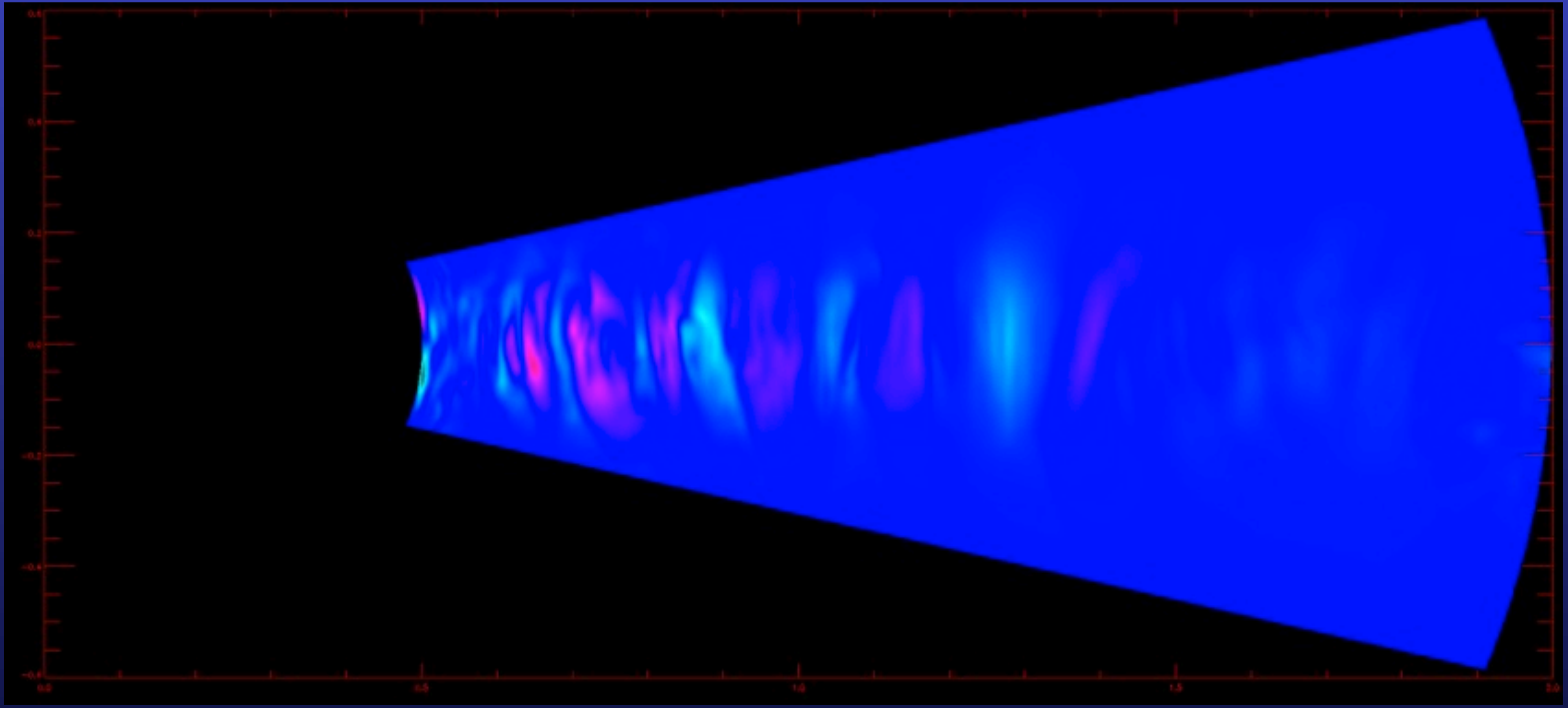
2D axissymetric Pluto Simulation: Temperature due to irradiation from star and thermal relaxation tau = 0.1 (also works for flux limited diffusion in irradiated disks)



Thermal wind:

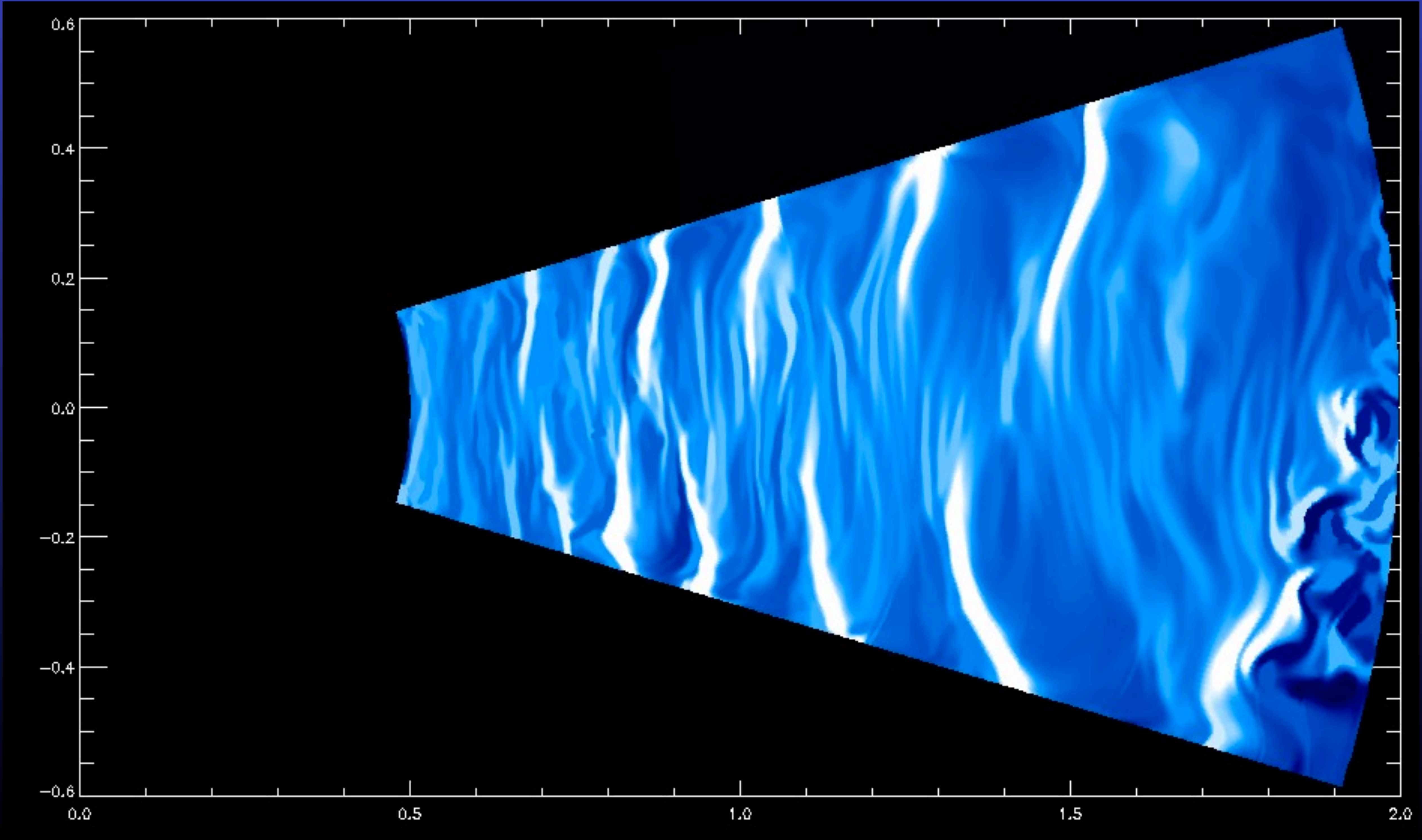
$$\Omega_K \left[1 + \frac{1}{2} \left(\frac{H}{R} \right)^2 \left(p + q + \frac{q}{2} \frac{Z^2}{H^2} \right) \right]$$

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

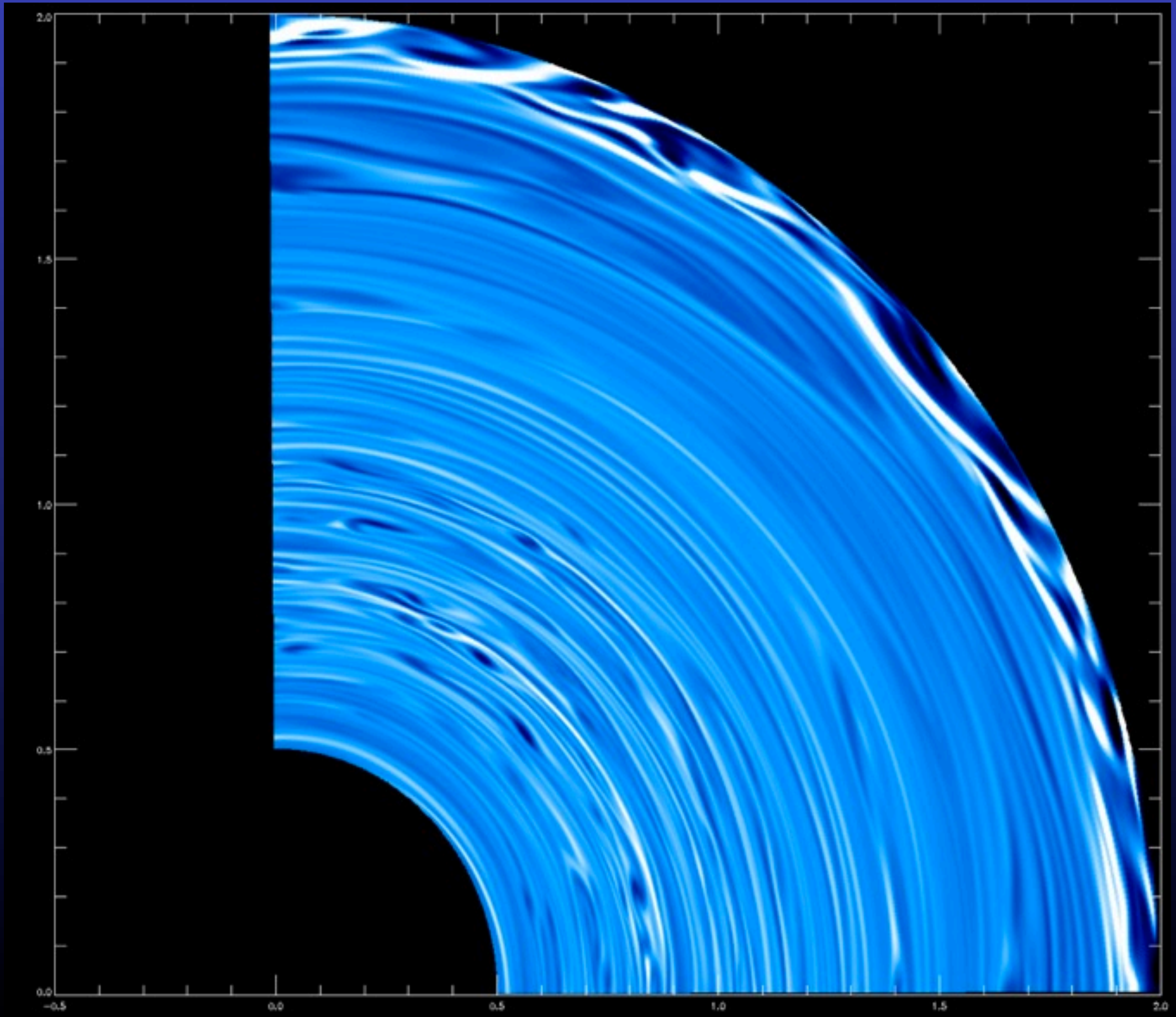


Modification of Solberg-Hoiland Criterion, including thermal relaxation:
In collaboration with Alexander Hubbard

2D axissymetric Pluto Simulation: Resulting vorticity perturbations

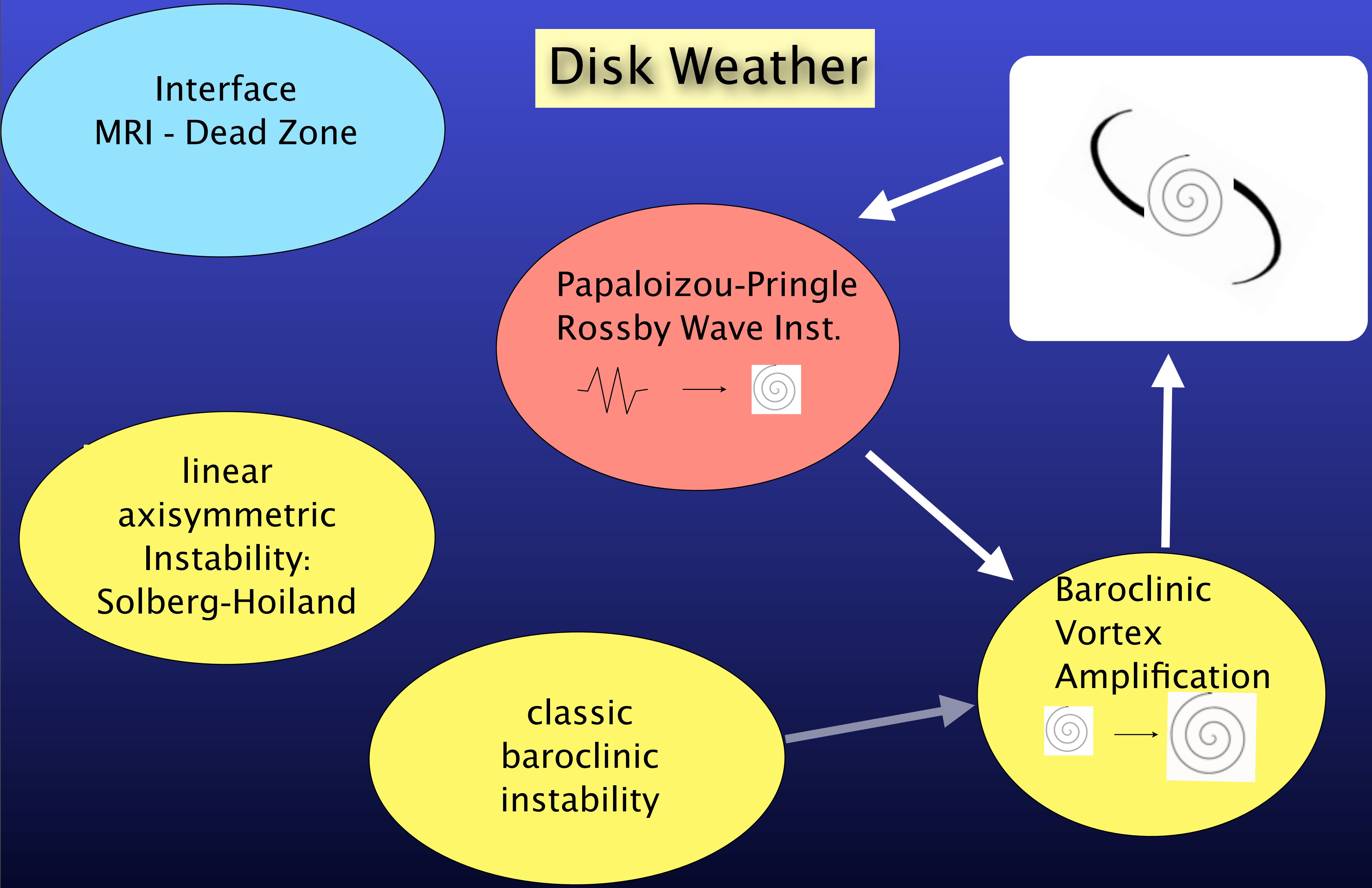


Full 3D Pluto Simulation: Spontanous Formation of Vortices from tiny perturabtions



12/13/2009

Disk Weather



Interface
MRI - Dead Zone

Papaloizou-Pringle
Rossby Wave Inst.

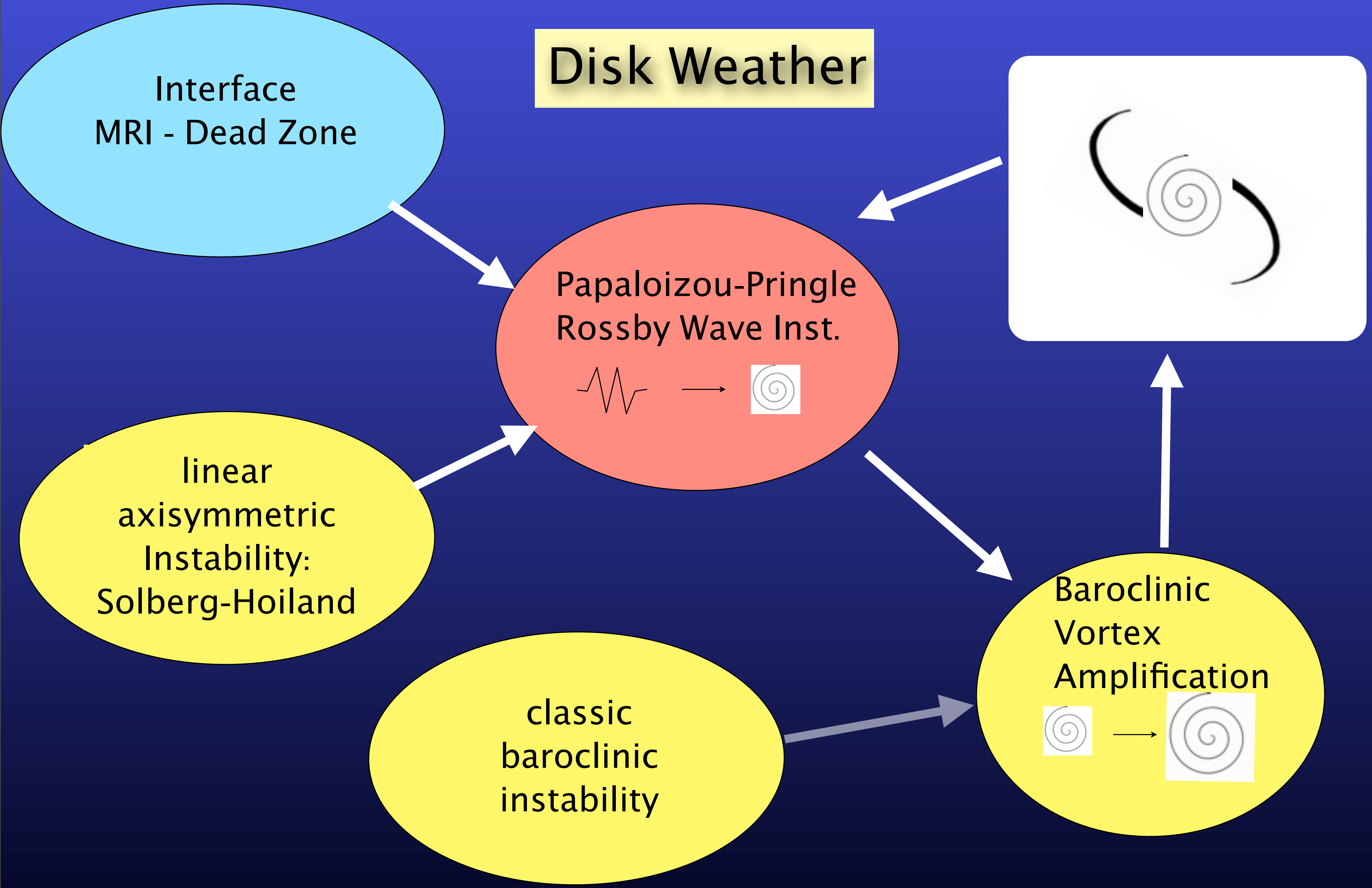
linear
axisymmetric
Instability:
Solberg-Hoiland

classic
baroclinic
instability

Baroclinic
Vortex
Amplification

Radial Buoyancy : $dS/dr < 0$ & $dP/dr<0$
-> thermal wind $dV_{phi}/dz < 0$ plus: thermal relaxation

Disk Weather



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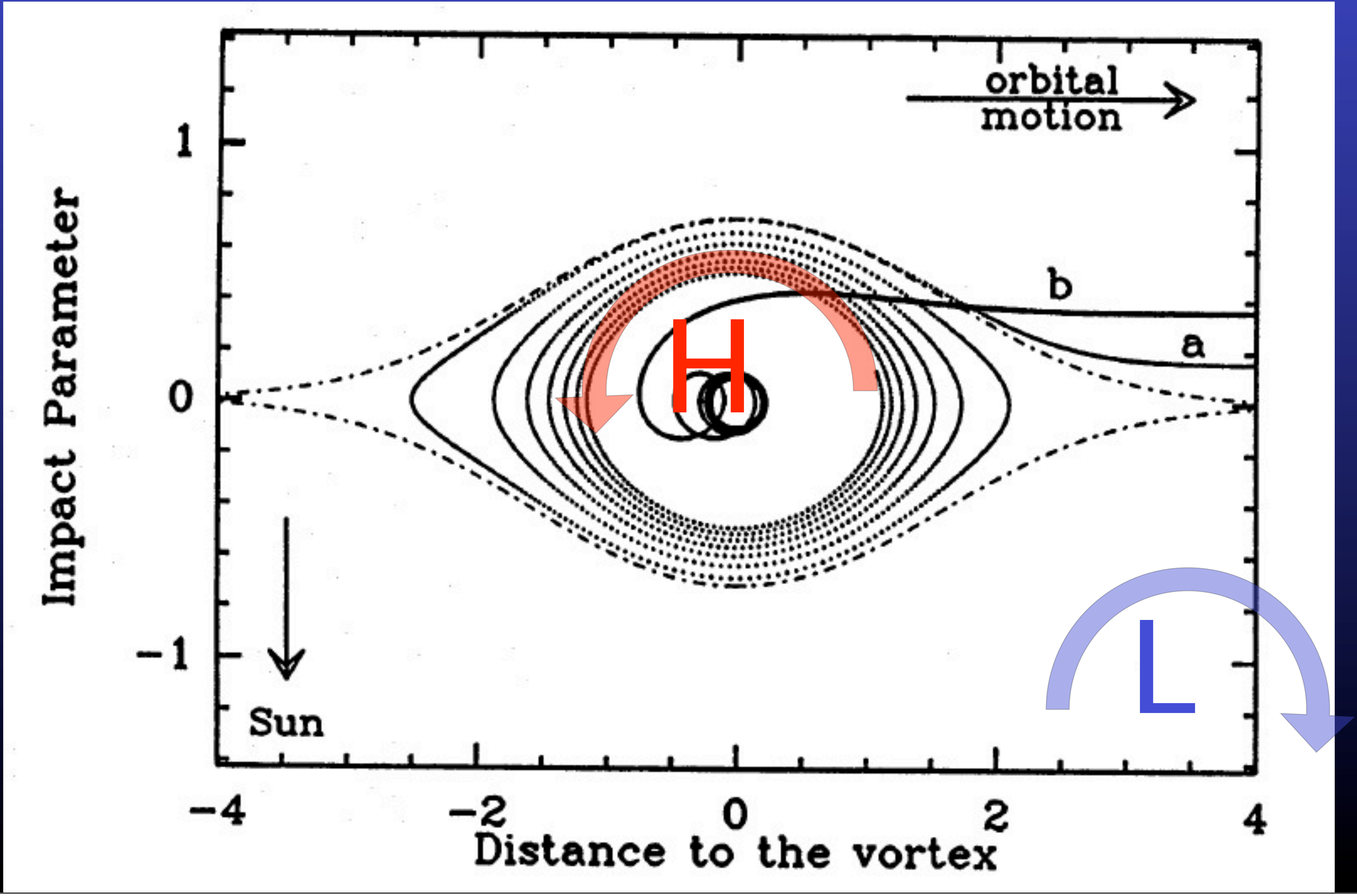
instability

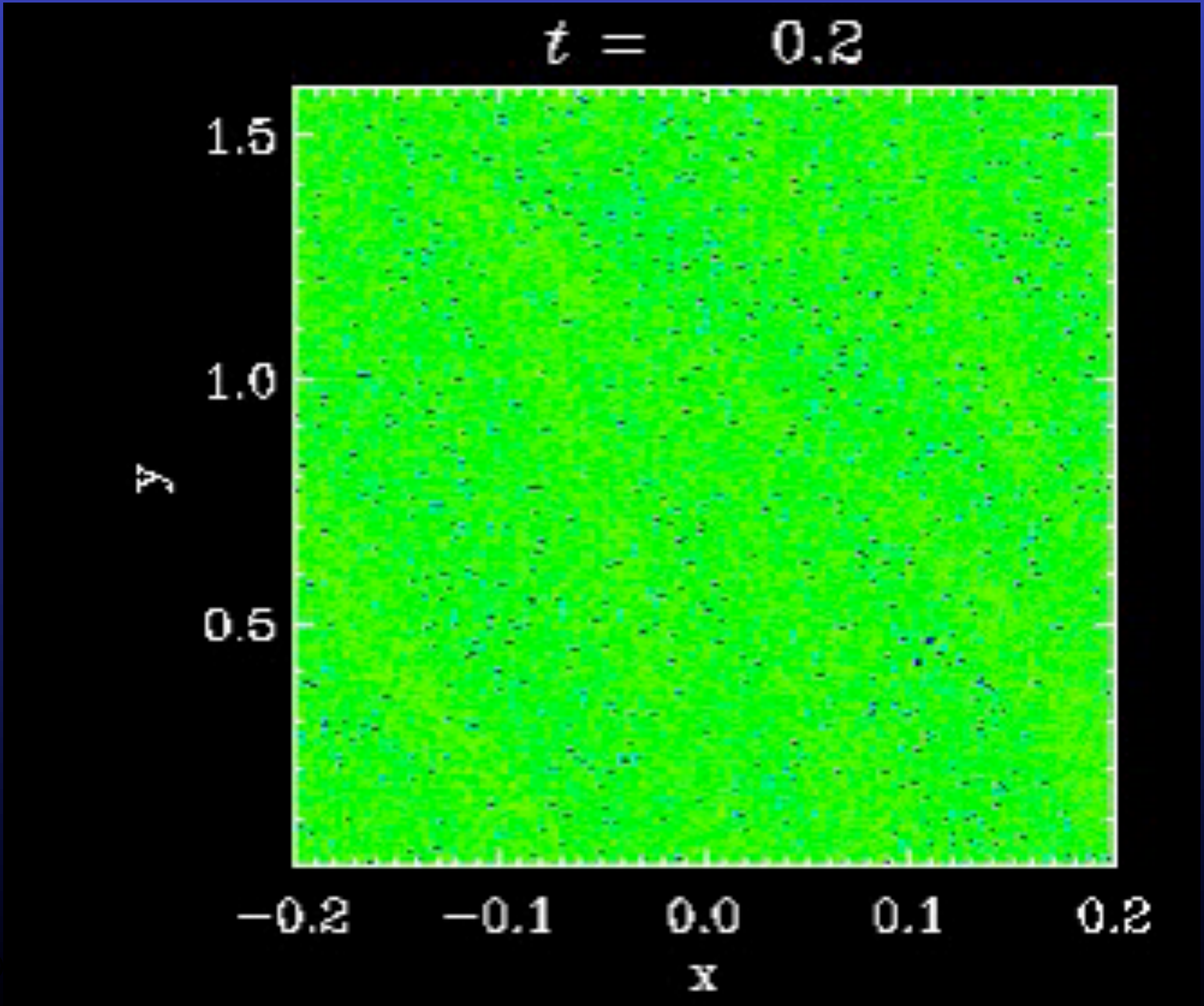
Baroclinic
Vortex
Amplification

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.



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



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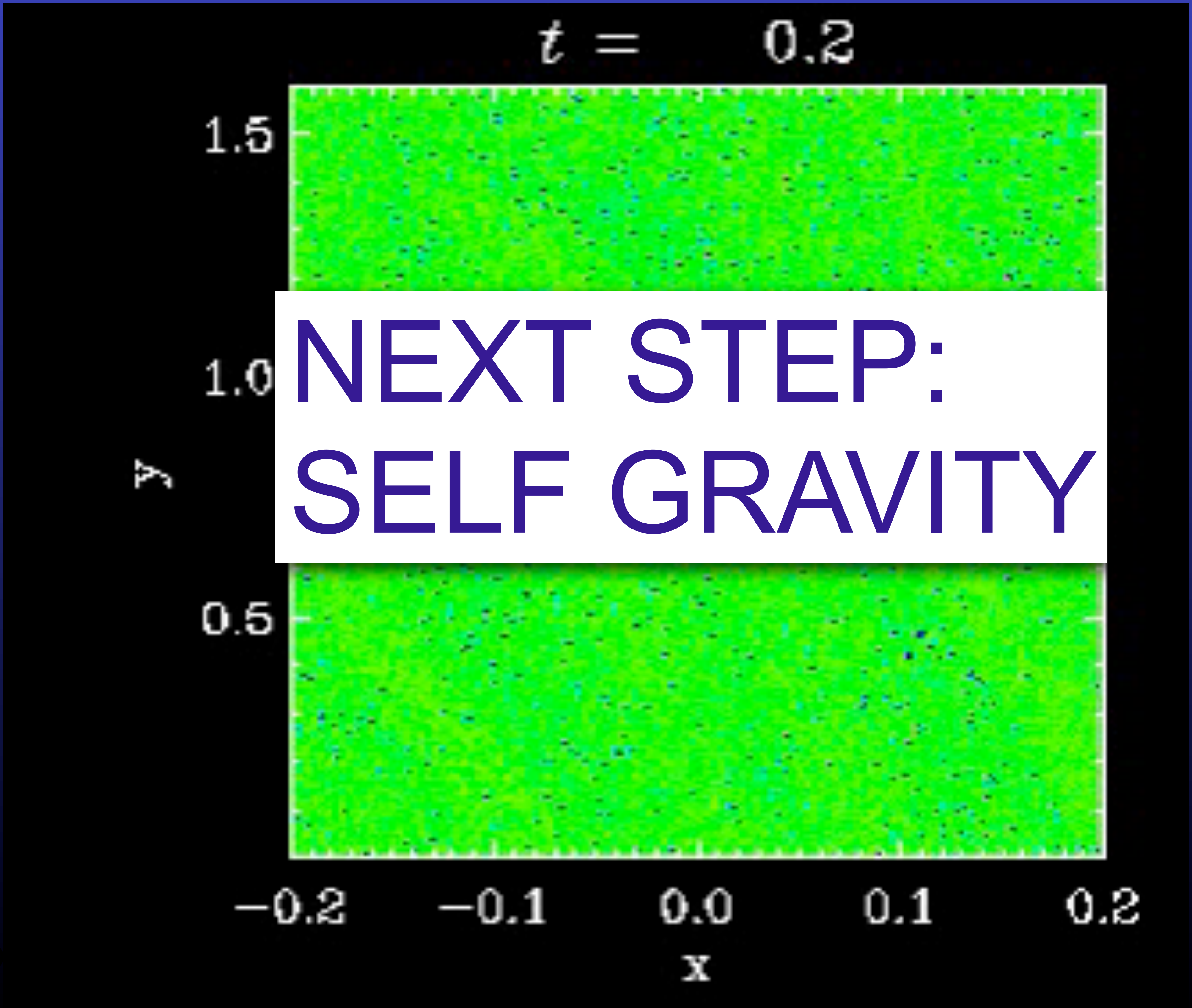
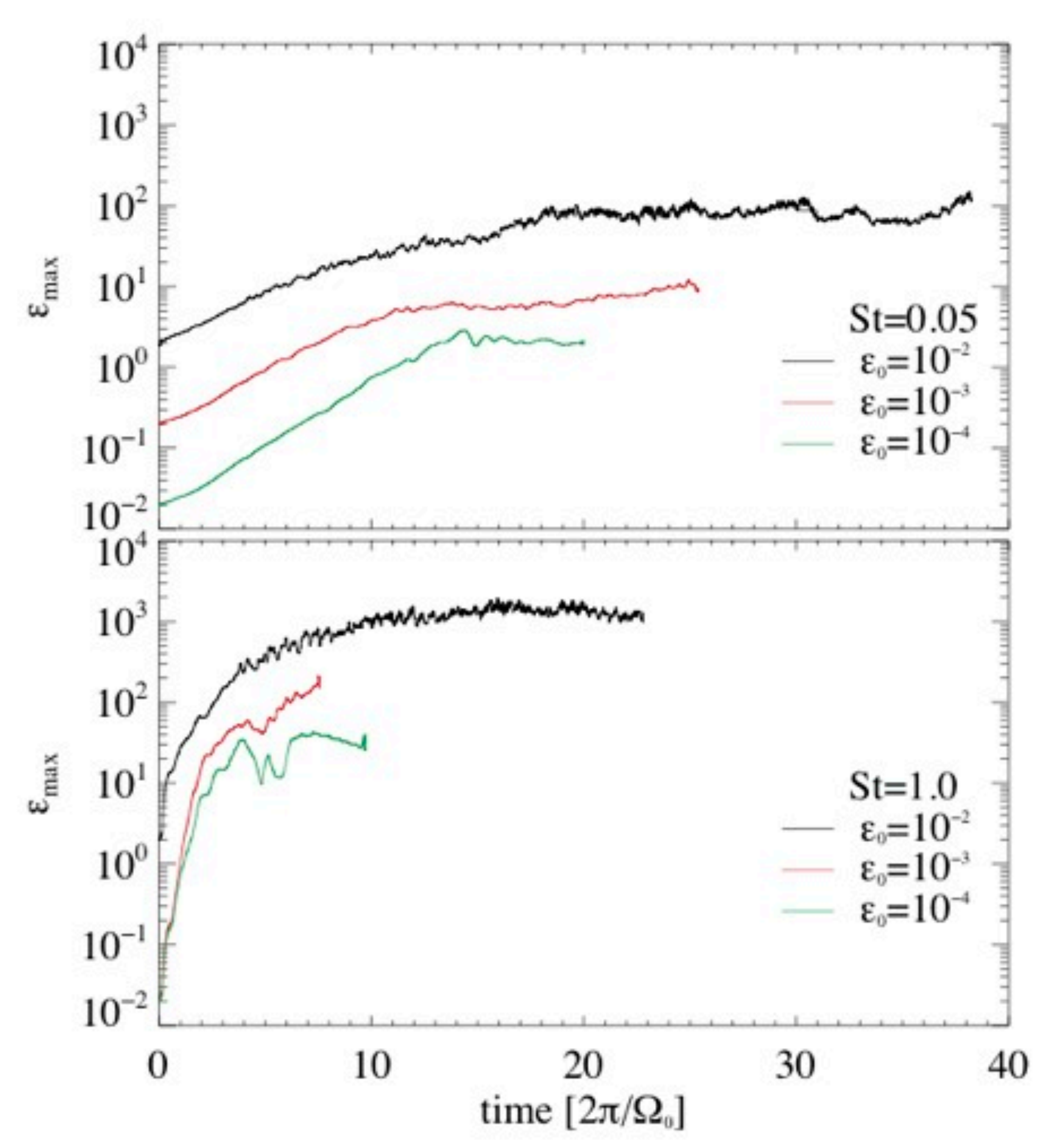
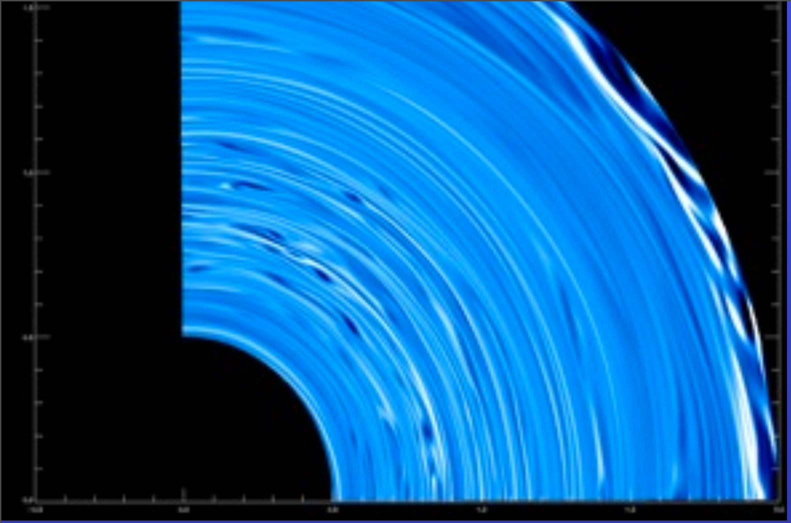


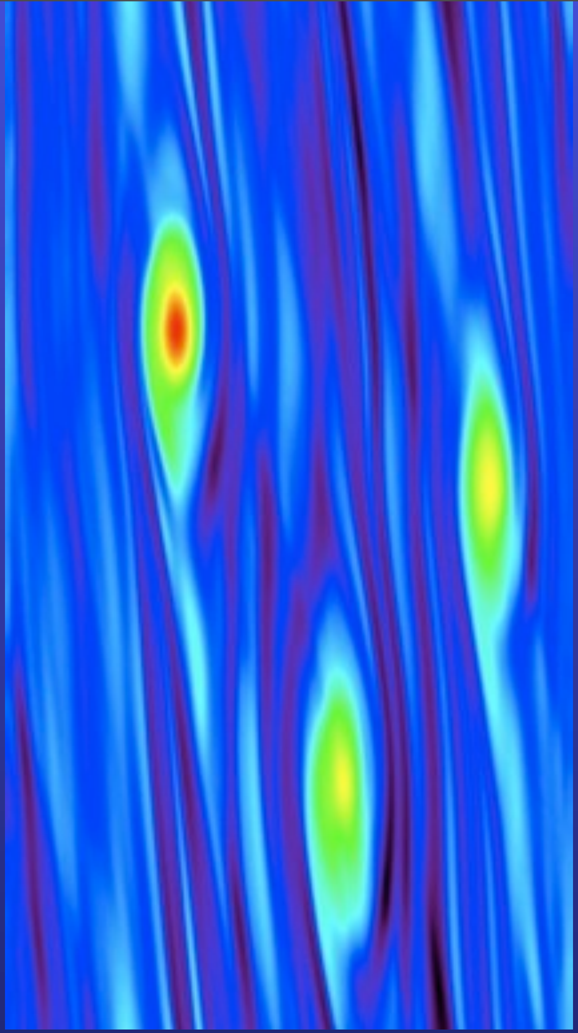
NEXT STEP:
SELF GRAVITY

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.
- Any turbulence with gravity can form rapidly planetesimals over a broad range of sizes
- Vortices can concentrate St = 0.05 dust at initial abundance of eps = 1E-4 to the streaming instability and planetesimal formation.