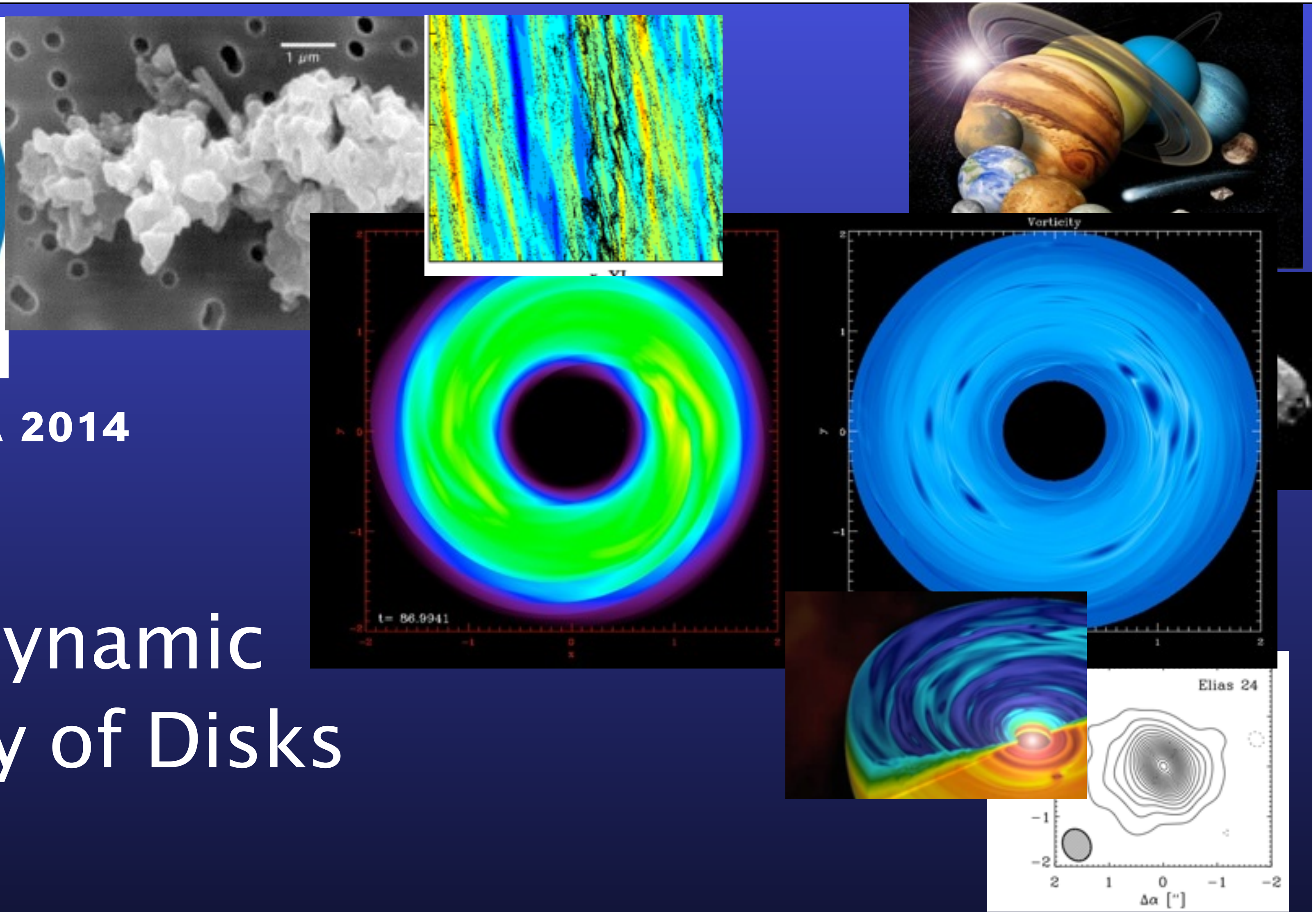
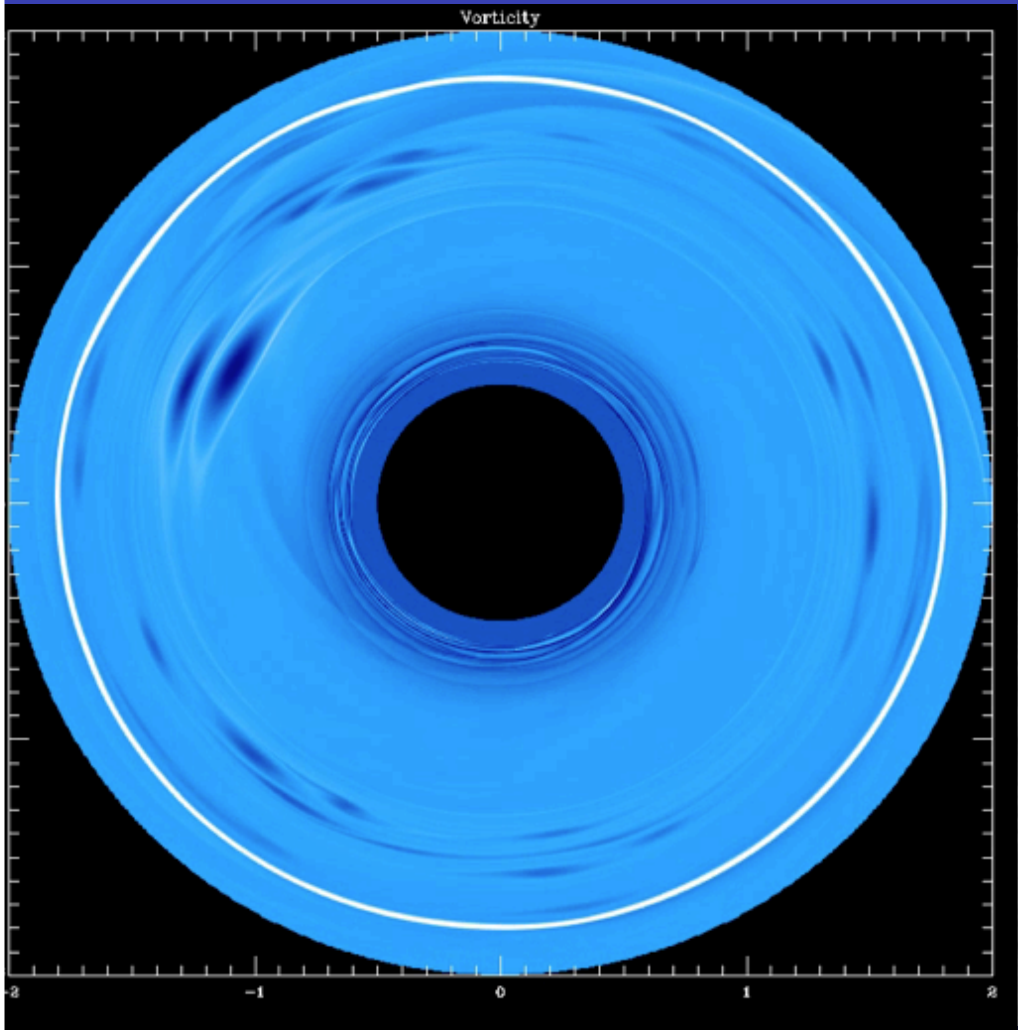


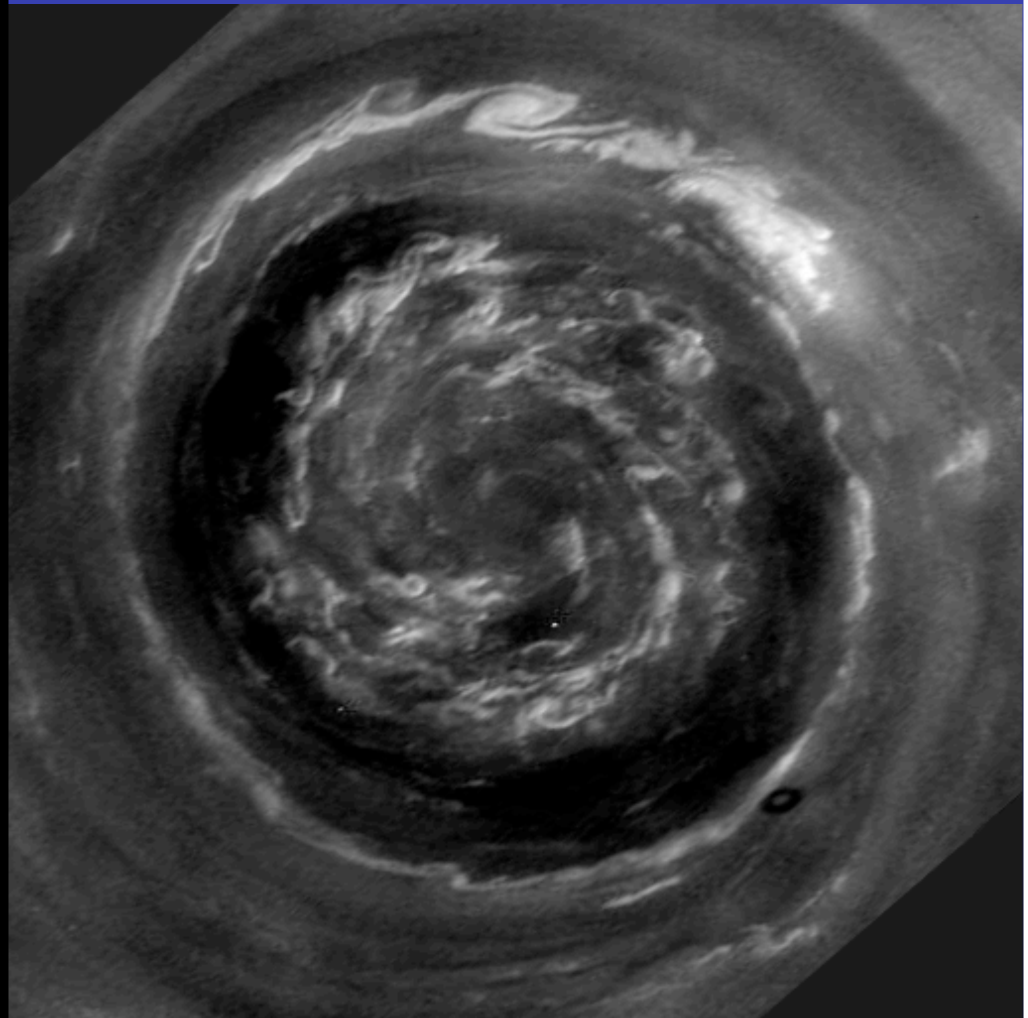
IPAM / UCLA 2014

Hydrodynamic Stability of Disks

Hubert Klahr, Alex Hubbard, Lingsong Ge, Wlad Lyra, Richard Nelson

2 x Weather pattern:
Astrophysical and Geophysical flow

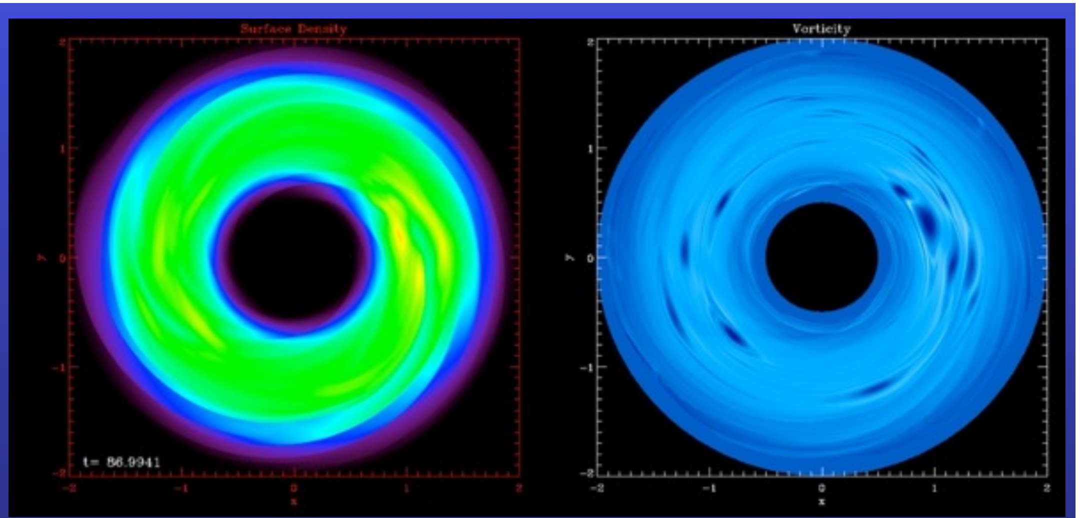




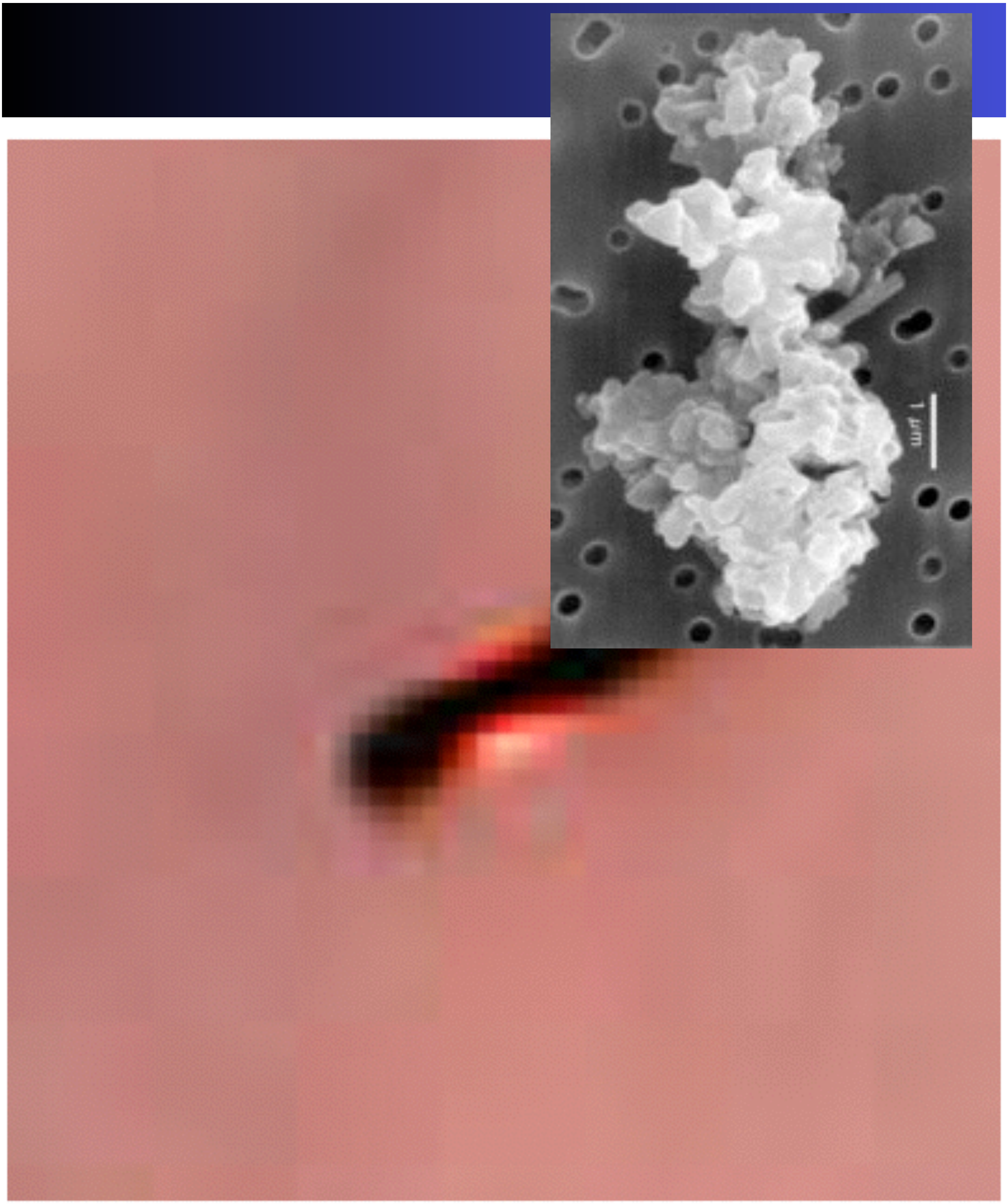
Proto PLANETARY disk:
generation of Vortices

PLANETARY atmosphere:
Saturns polar vortex

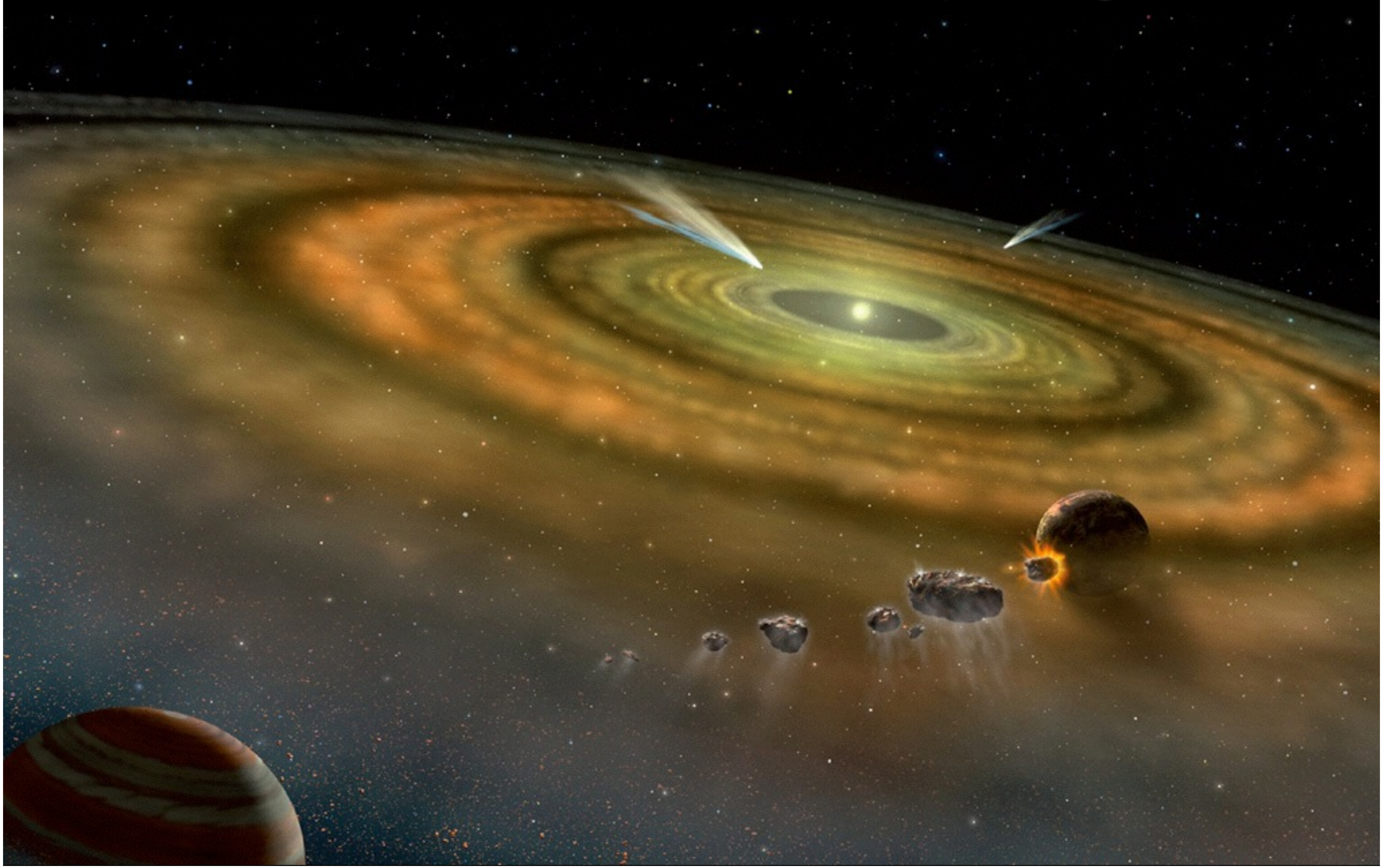
Outline:

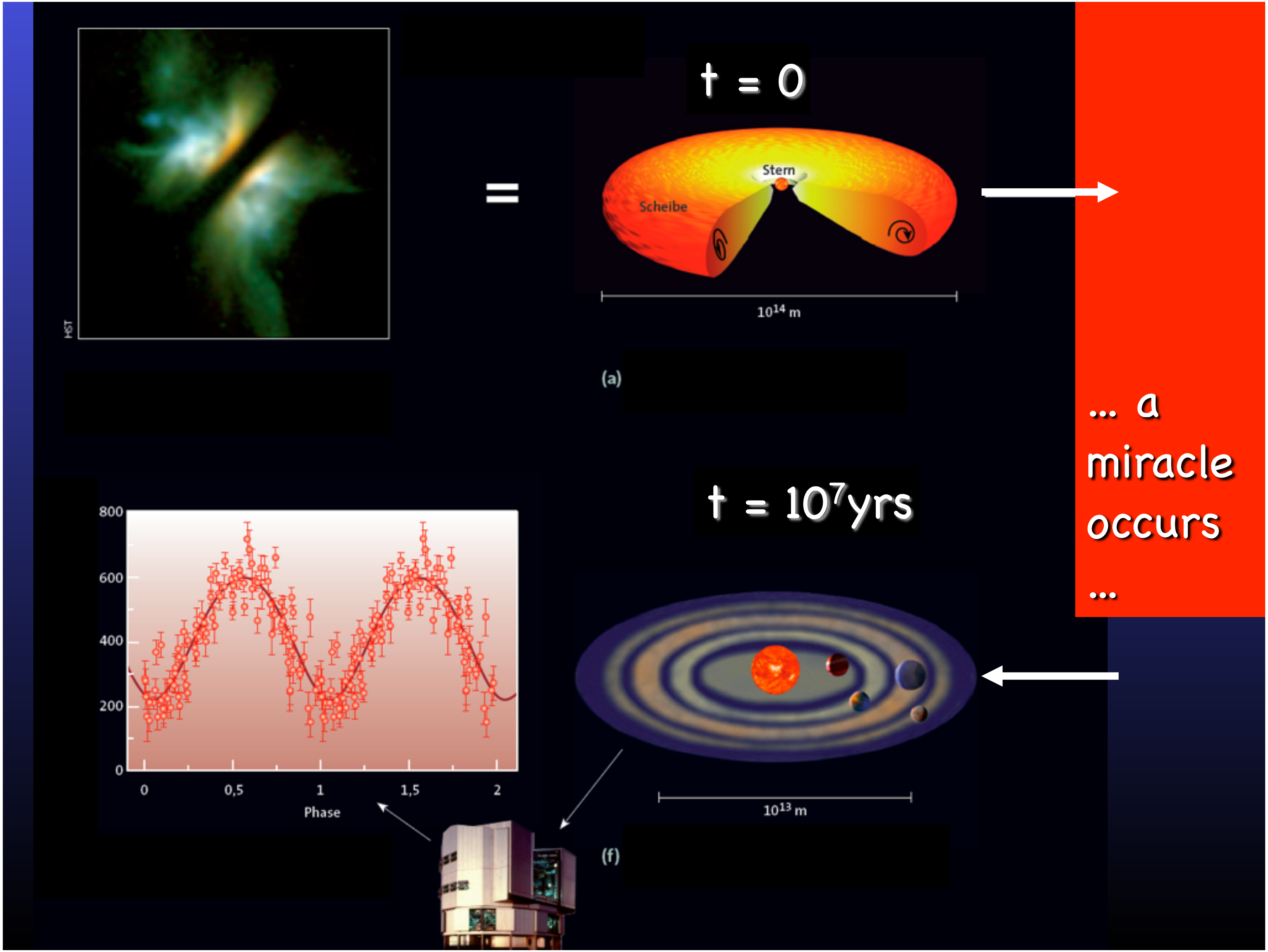


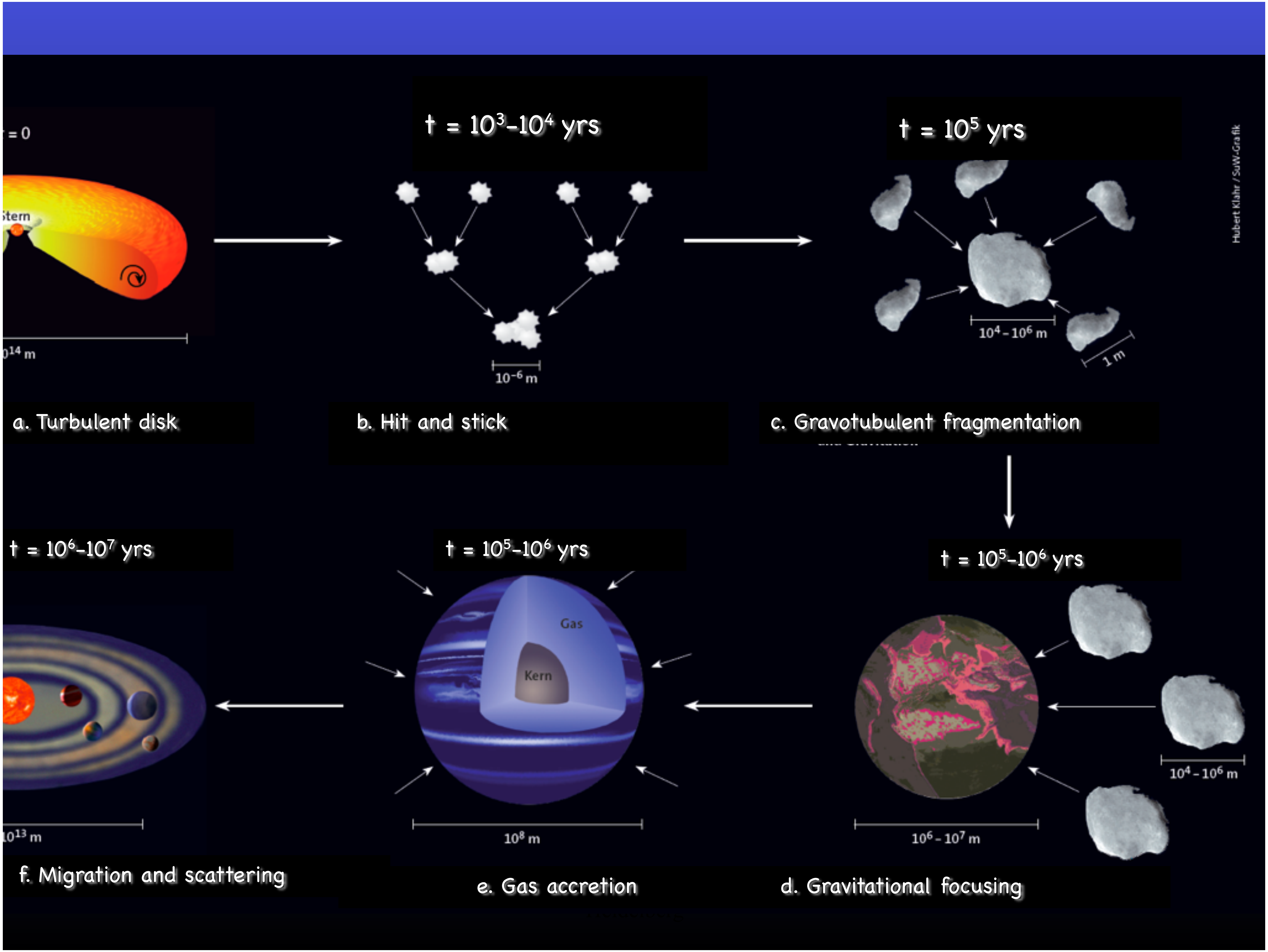
- Planet Formation
- *Global "Baroclinic" Instability*
- *Subcritical "Baroclinic" Instability*
- Goldreich-Schubert-Fricke Inst.
- Convective Overstability
- Linear theory and non-linear Simulations


1 μm

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

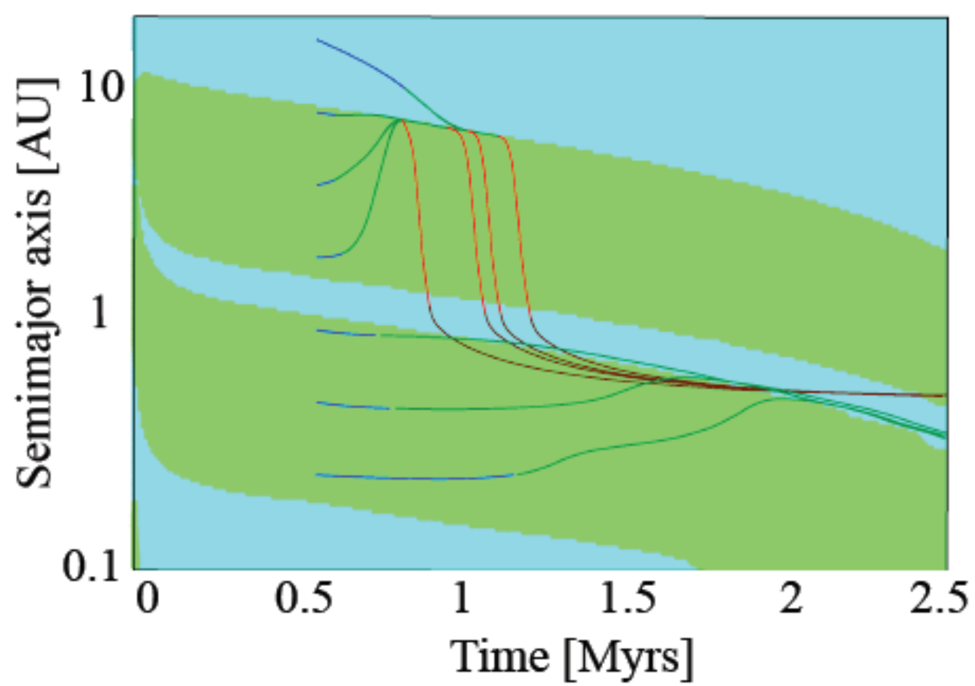



HST
=
t = 0
Stern
Scheibe
10^14 m
(a)
... a
miracle
occurs
...
t = 10^7yrs
800
600
400
200
0
0
0,5
1
1,5
2
Phase
10^13 m
(f)



t = 0
Stern
10^{14} m
t = 10^3–10^4 yrs
10^{-6} m
t = 10^5 yrs
10^4 – 10^6 m
1 m
Hubert Klahr / SuW-Grafik
a. Turbulent disk
b. Hit and stick
c. Gravotubulent fragmentation
t = 10^6–10^7 yrs
t = 10^5–10^6 yrs
Gas
Kern
t = 10^5–10^6 yrs
10^4 – 10^6 m
10^{13} m
10^8 m
10^6 – 10^7 m
f. Migration and scattering
e. Gas accretion
d. Gravitational focusing

Synthetic Populations…



…and to test the individual modeling steps of planet formation by comp. To observations.

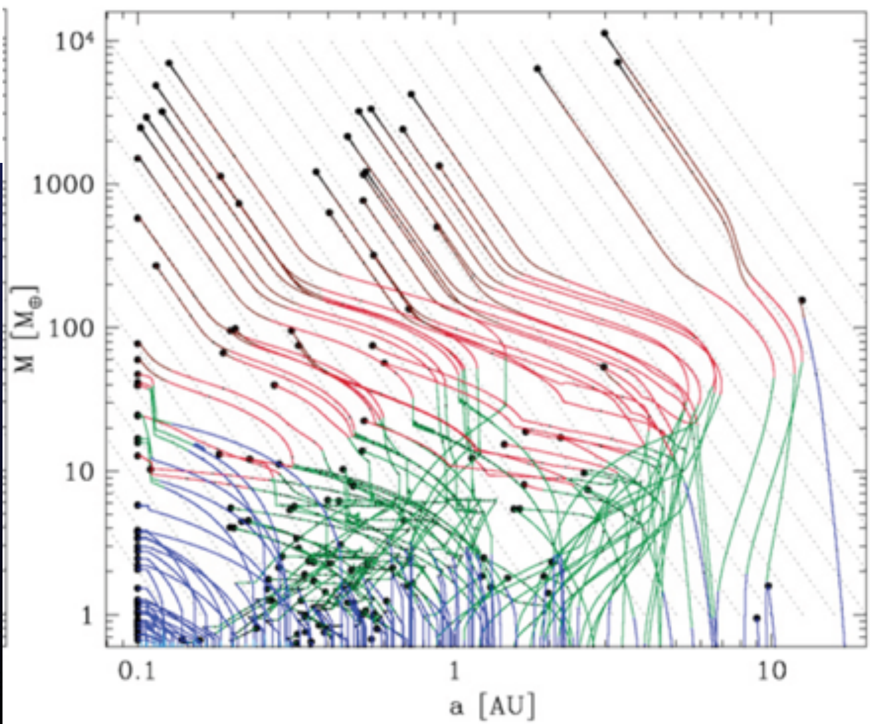
Application of recent results on the orbital migration of low mass planets in planetary population synthesis

C. Mordasini[1], K.-M. Dittkrist[1], Y. Alibert[2], H. Klahr[1], W. Benz[2] and T. Henning[1]

[1]Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany
email: mordasini@mpia.de

[2]Physikalisches Institut, Sidlerstrasse 5, CH-3012 Bern, Switzerland

…to explore the importance of metallicity, stellar mass, etc…

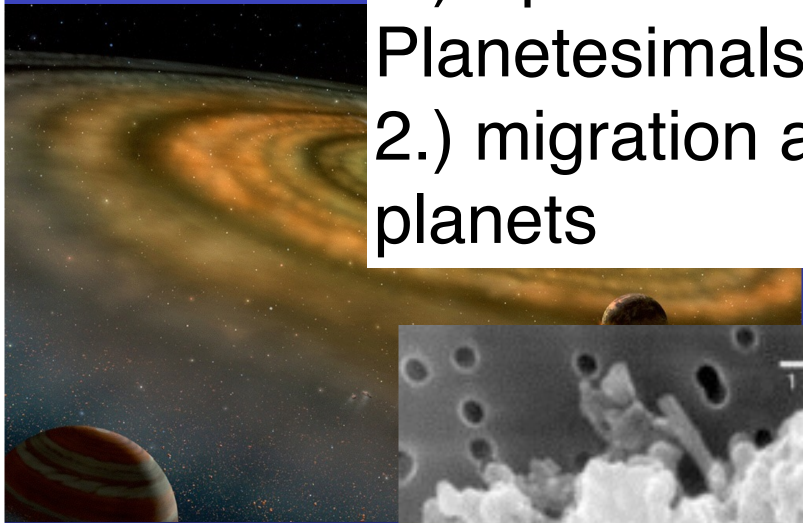


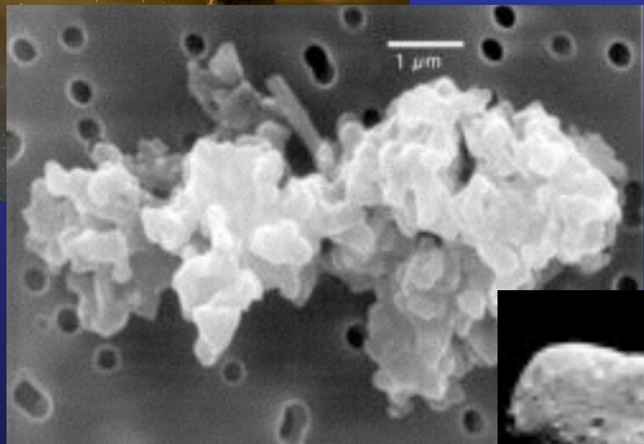
Our Input for Pop. Synthesis:

1.) Spatial and Size Distribution of Planetesimals

2.) migration and accretion rates of planets

time



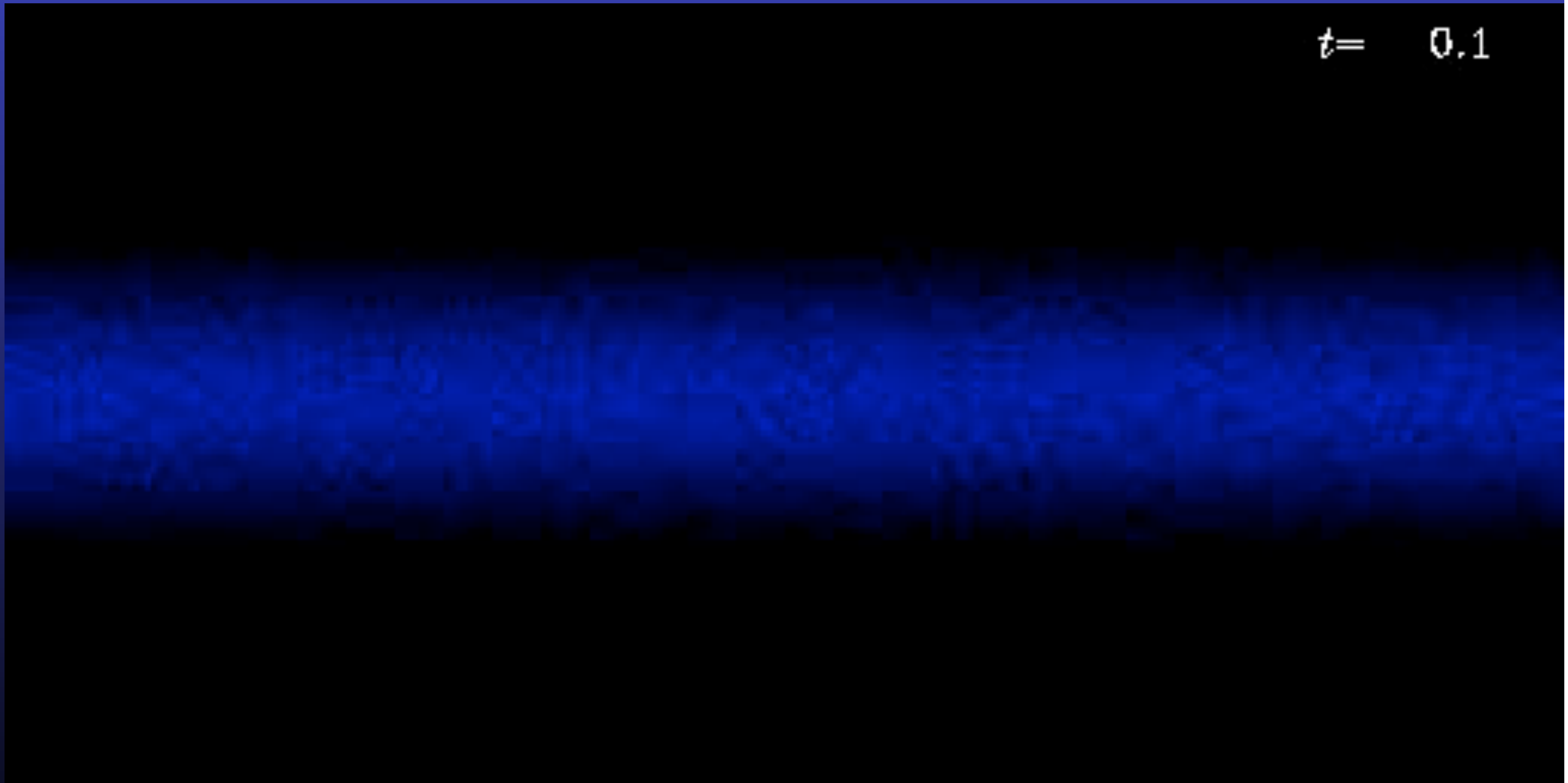


Surface sticking

Gravity bound

Gravoturbulent Planetesimal Formation from Gravel concentrated in Vortices and Zonal Flows

10 cm sized boulders:

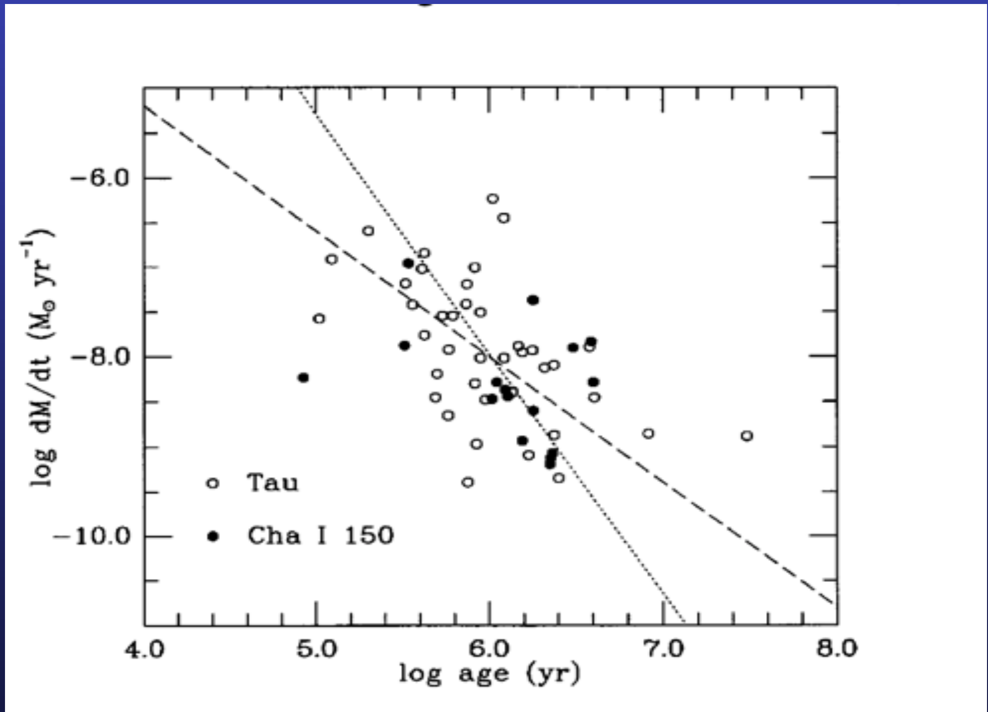


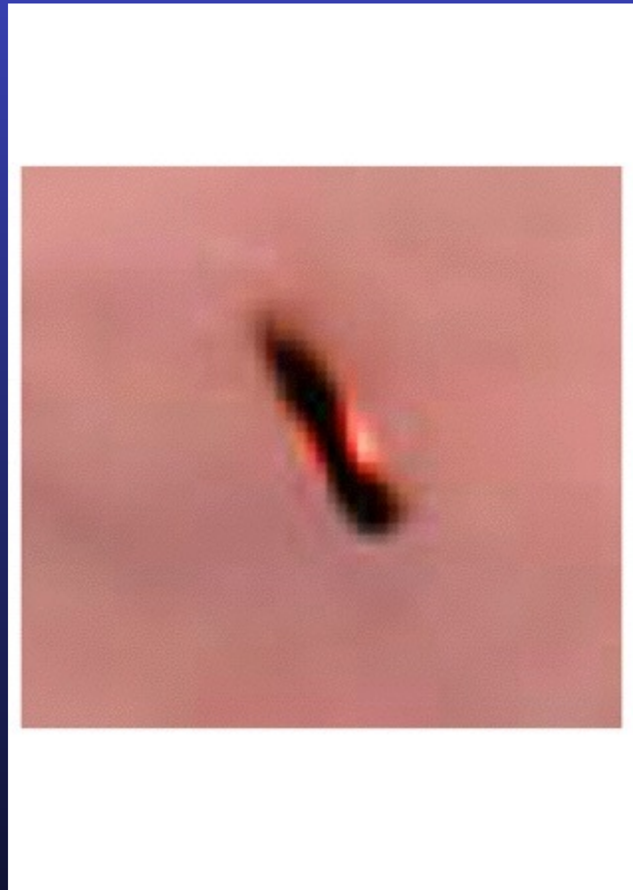
Vertical

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?

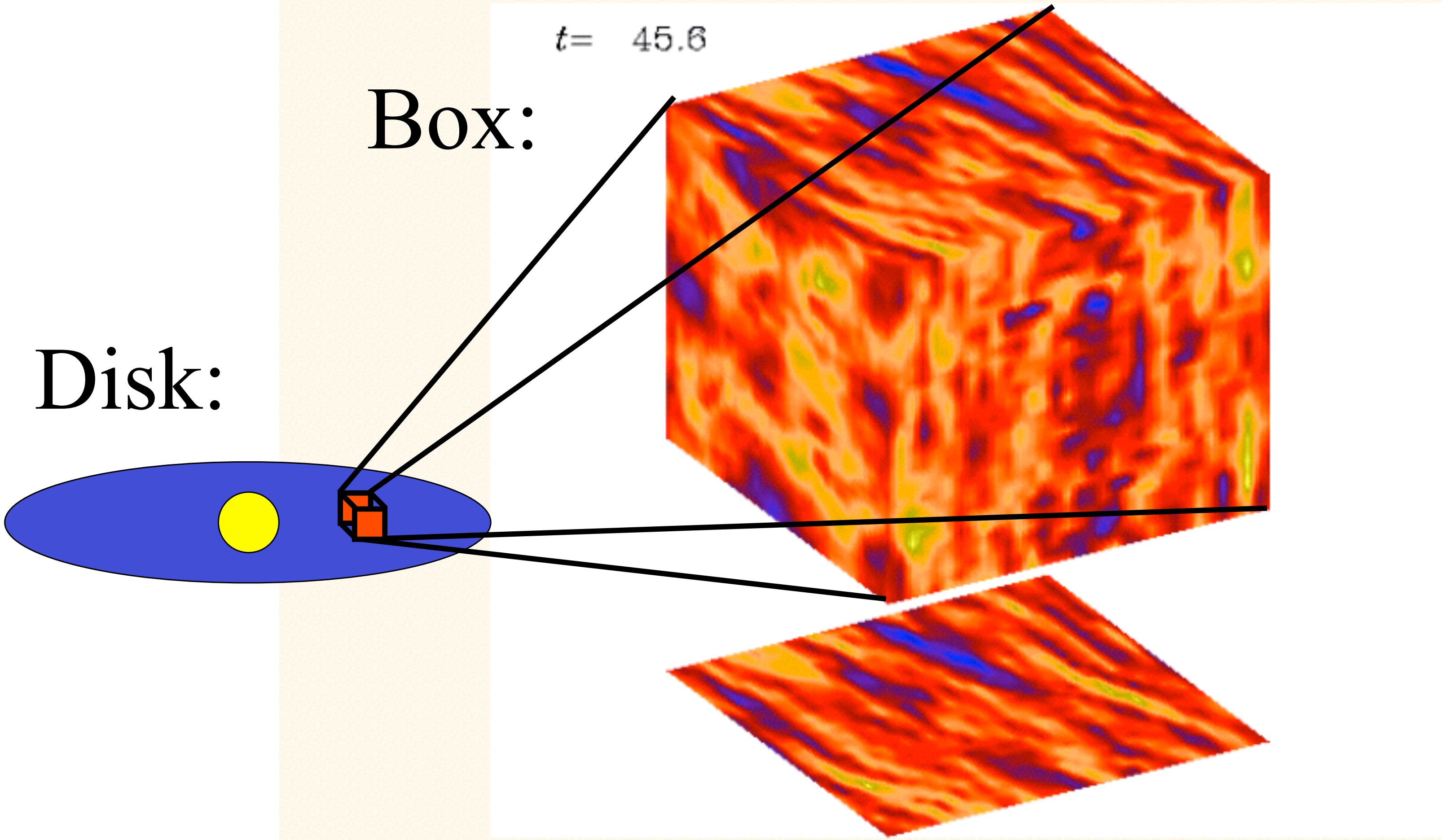
Turbulence in Disks: Candidates

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

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

MRI turbulence

…because it is a reliable source for turbulence.

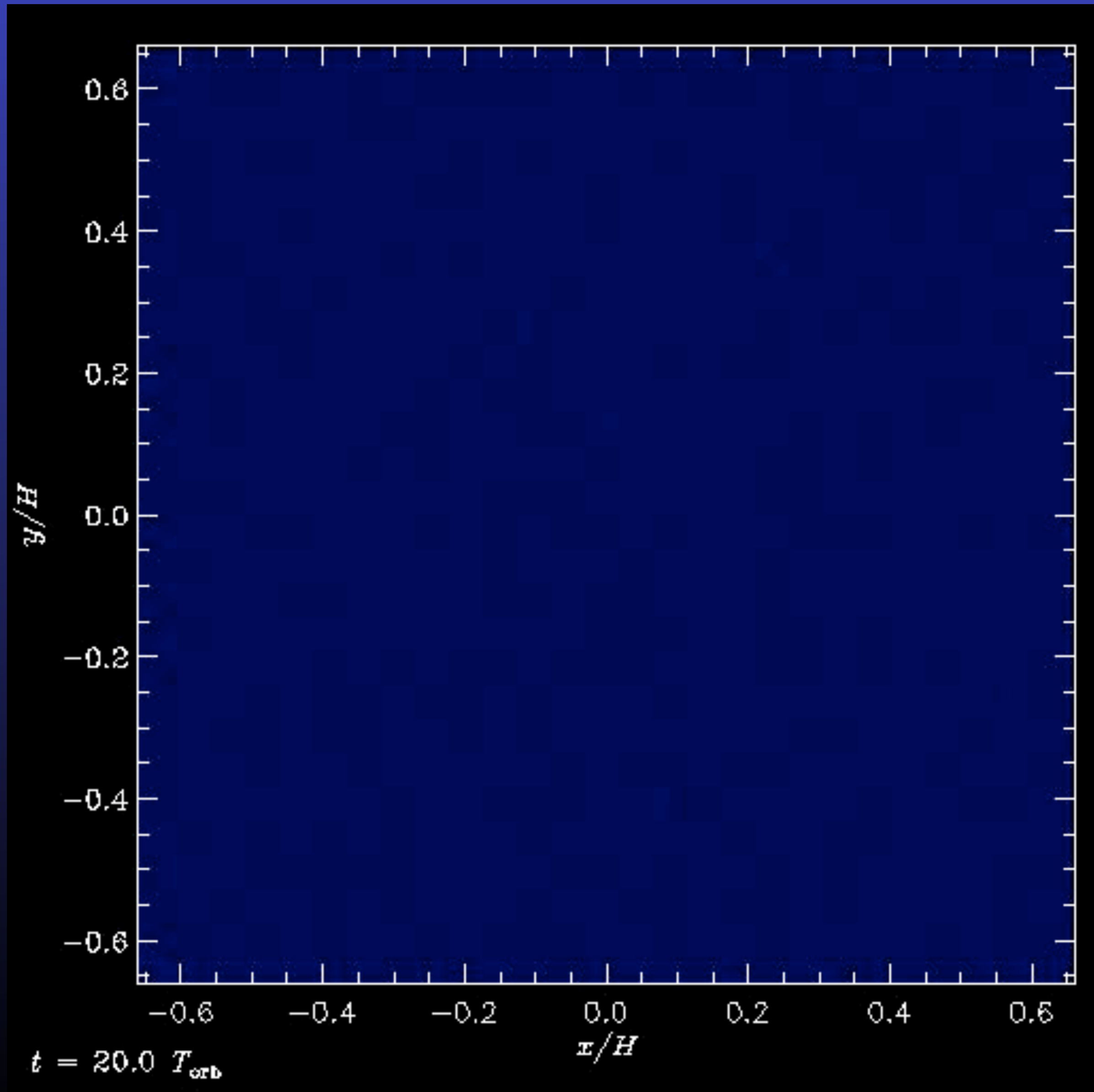


Code: The Pencil-Code [MHD code, finite differences, 6th order in space, 3rd order in time, Brandenburg (2003)]

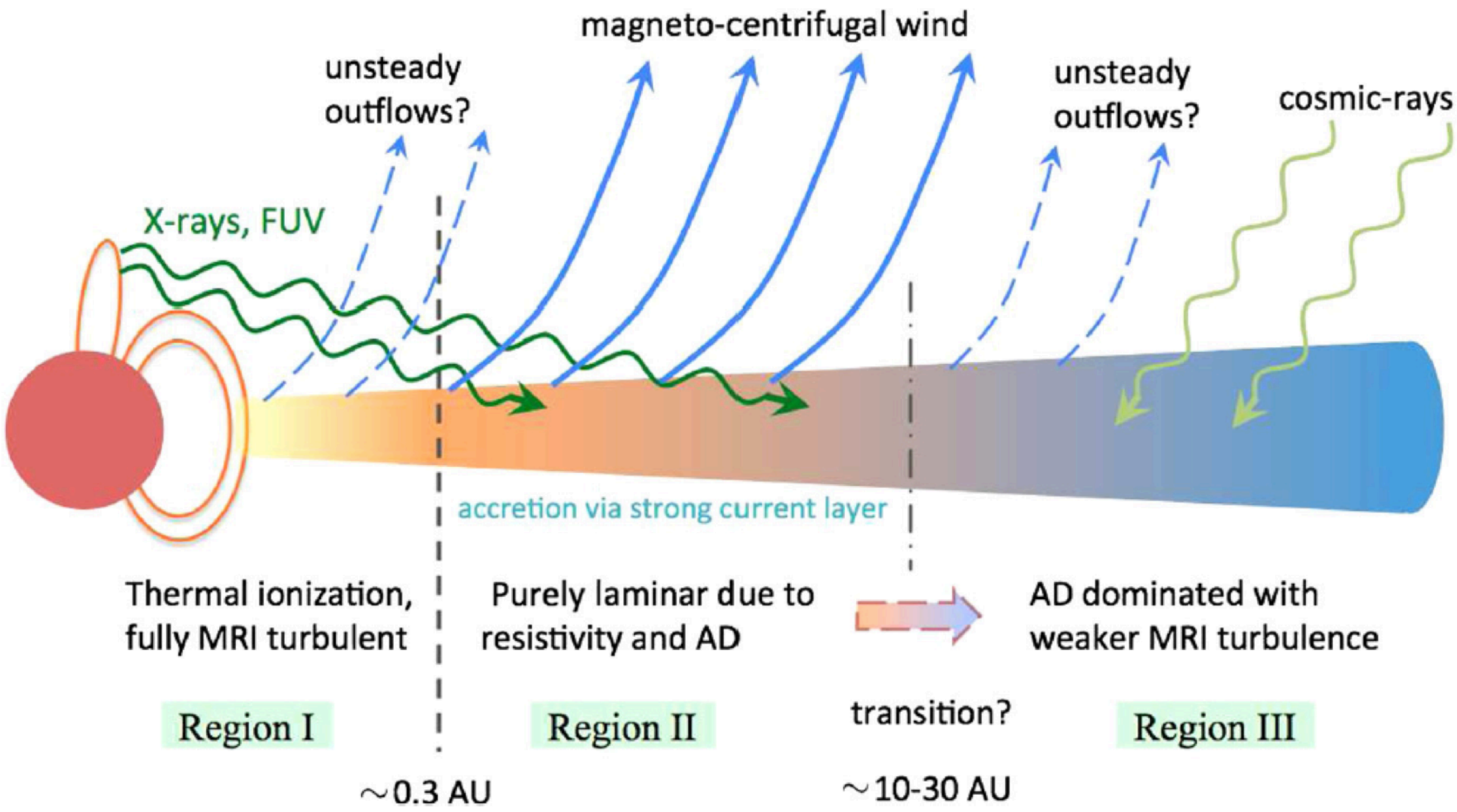
Gravoturbulent formation of Planetesimals - Concentration of dust in Zonal Flows in MRI turbulence:

1. Johansen & Klahr 2005,
2. Johansen, Klahr & Henning 2006,
3. Johansen, Klahr & Mee 2006,
4. Johansen et al. 2007,
5. Flock et al . 2010,
6. Dzyurkevich 2011,
7. Flock et al . 2011a, 2011b,
8. Uribe et al . 2011,
9. Johansen, Klahr & Henning 2011,
10. Flock et al. 2012a, 2012b,
11. Dittrich et al . 2013, …

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



revised schematics of protostellar disc



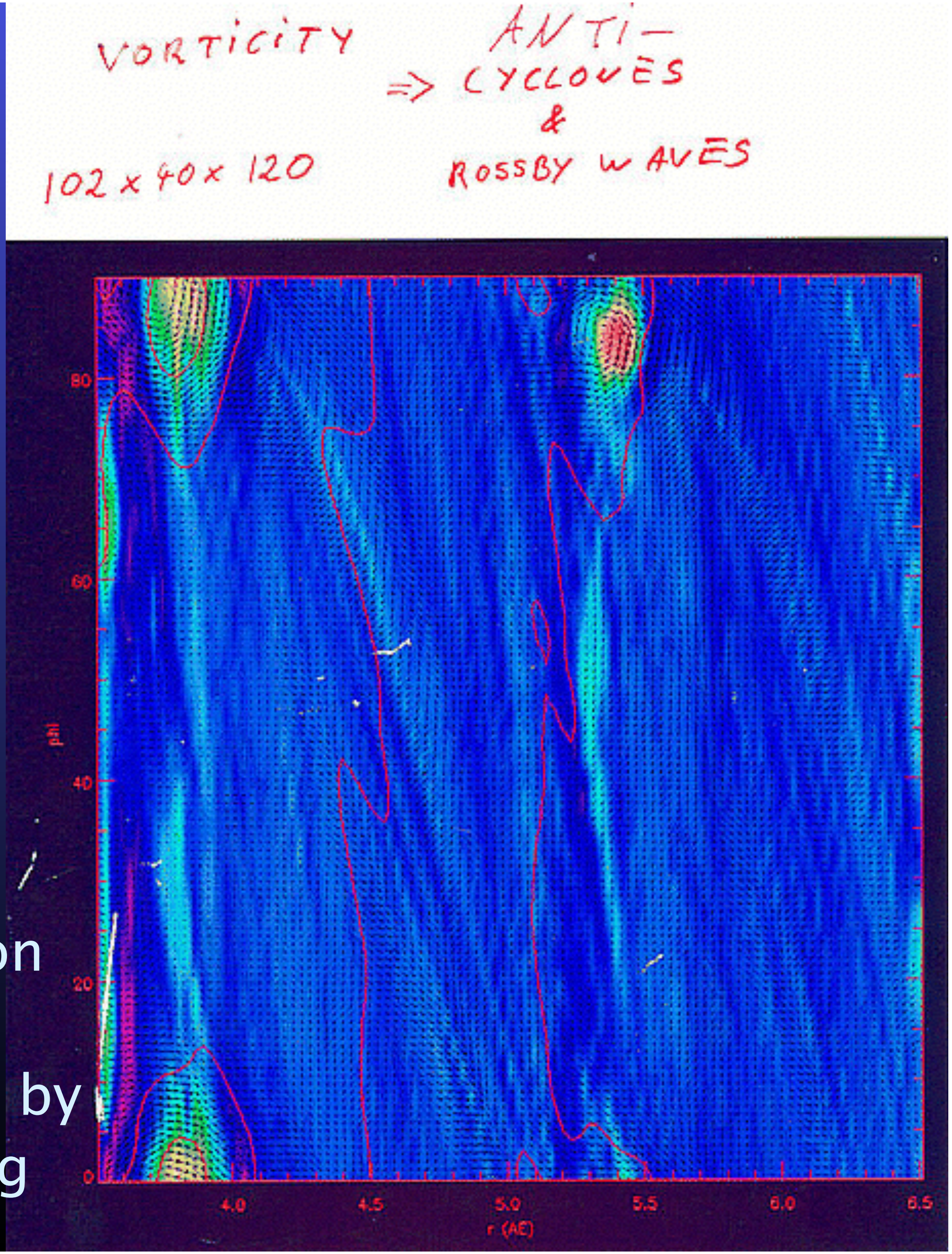
Bai & Stone (2013), Simon et al. (2013), Bai (2013), Kunz & Lesur (2013), Lesur, Fromang & Kunz (2014)

Used with kind permission by Oliver Gressel.

Simulations of thermal convection in disks:
1999 with
Peter Bodenheimer

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
temperature maintained by
artificial (viscous) heating



Klahr & Bodenheimer 2003

Radial Entropy Gradient leads to vortices somehow…

Klahr 2004, Johnson & Gammie 2005, etc. :

not a linear instability

Because:

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

$$-0.001 > Ri > -0.01$$

Then a lot of discussion started…

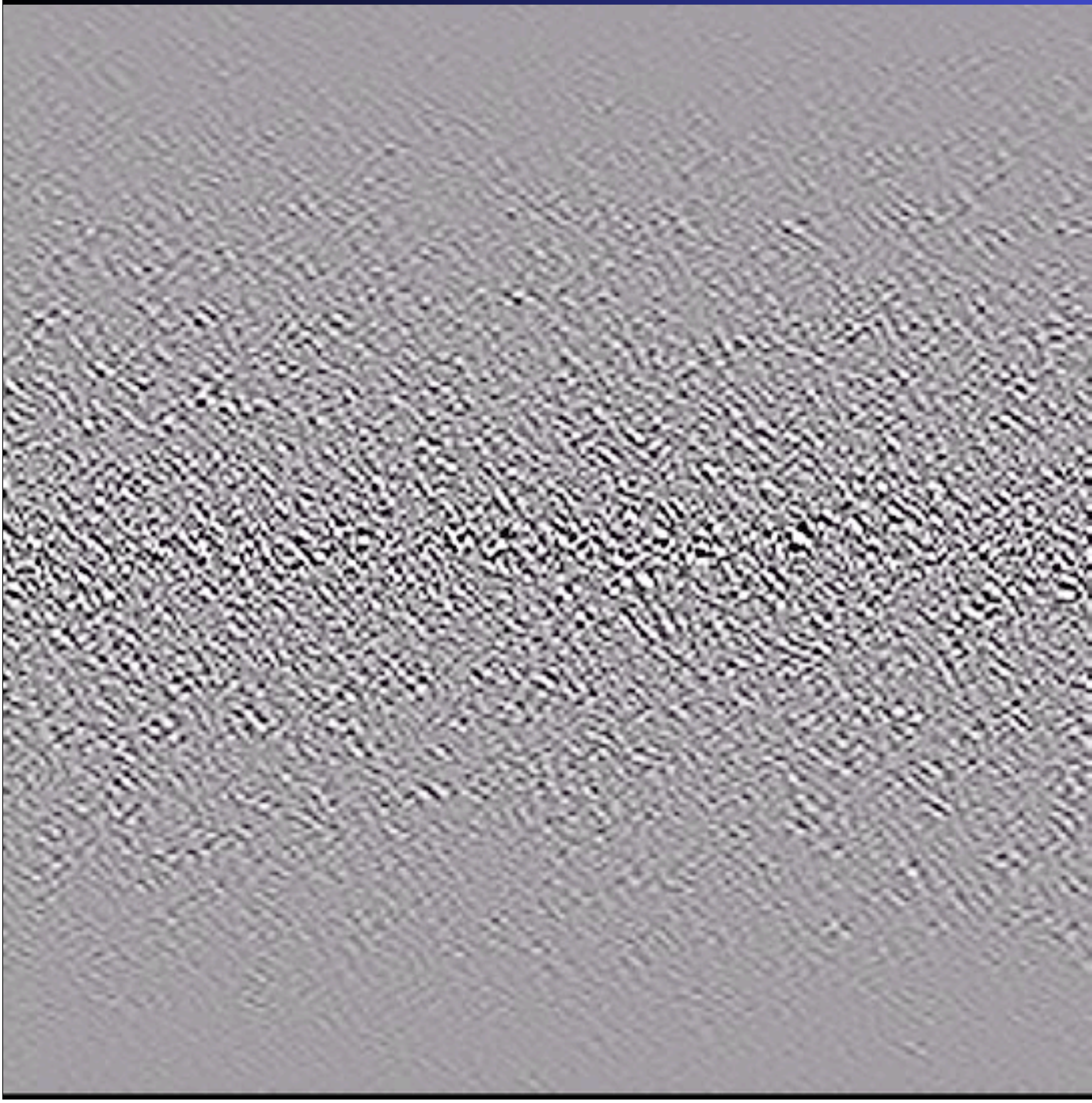
…but 4 years later:

Petersen, Stewart and Julien 2007:

“Works with the right amount of thermal relaxation!”

12/13/2009

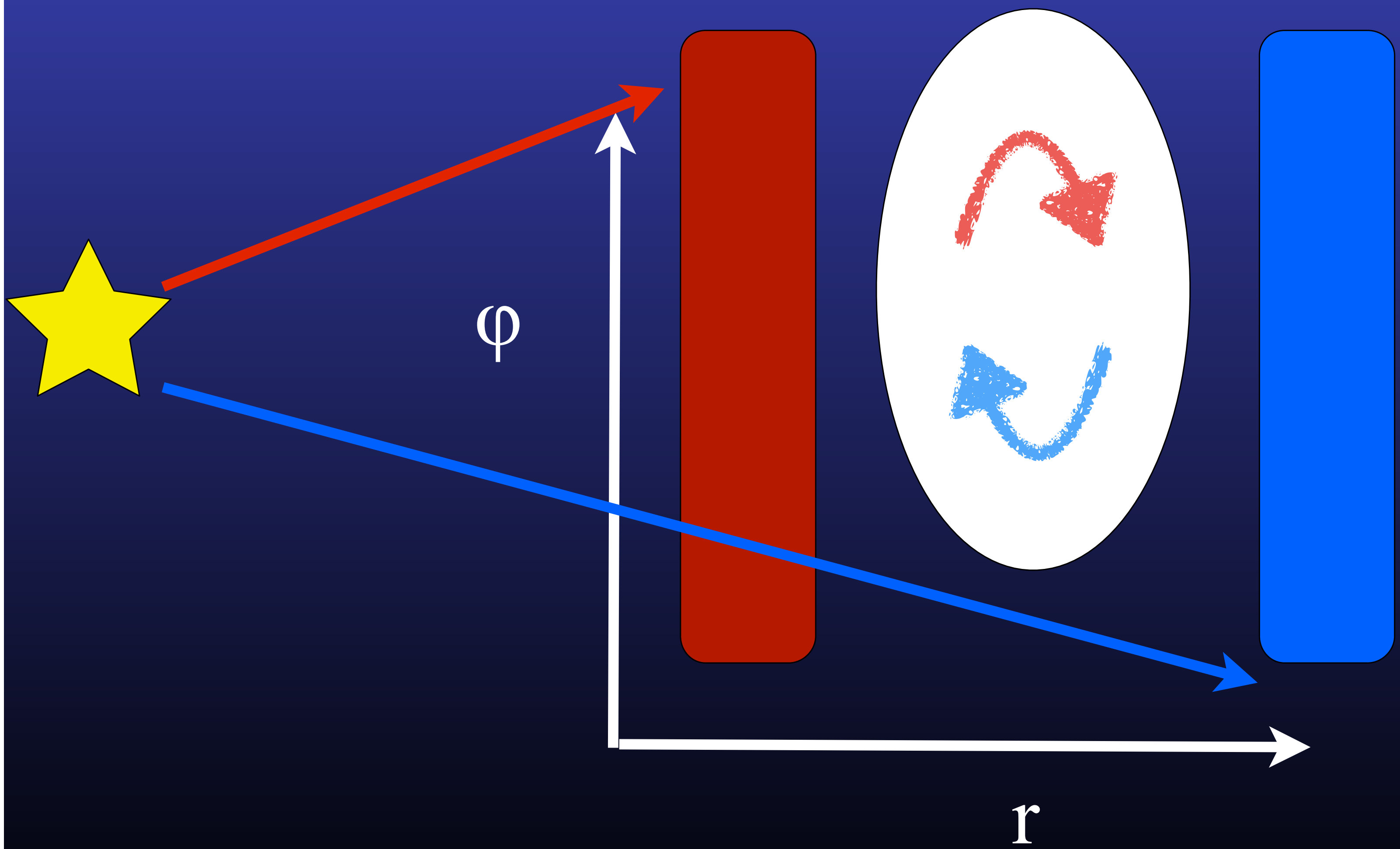
Vorticity: Pencil Code: Lyra and Klahr 2011; β = 2; N = 256; τ_c = 1



Vorticity

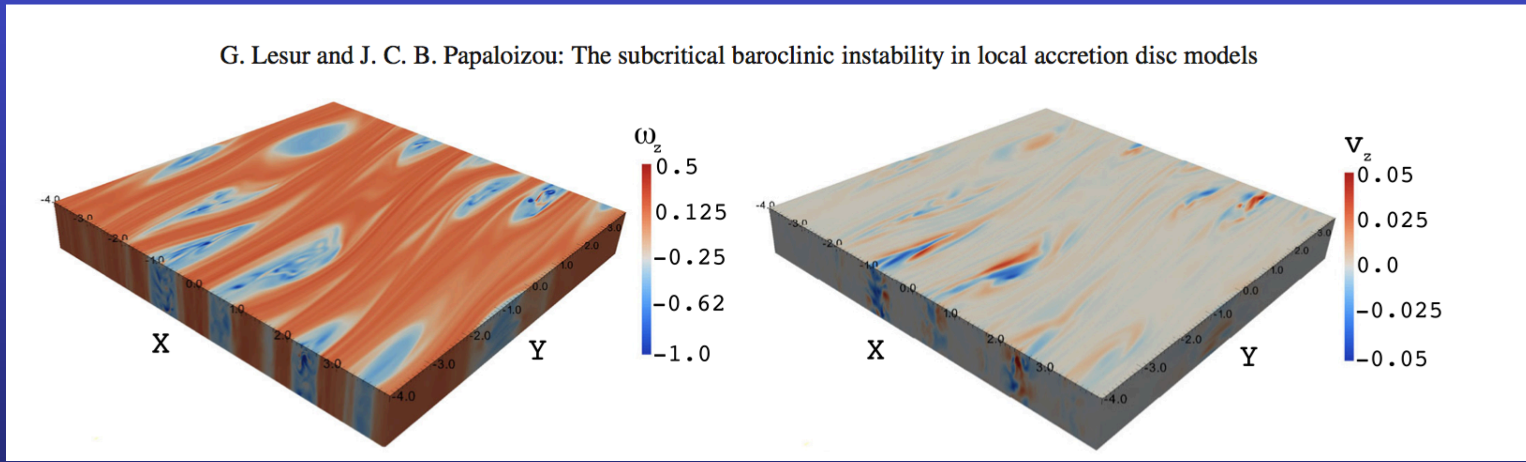
Lesur and Palaloizou 2010: "Subcritical Baroclinic Instability"

In plane Convection Cells:

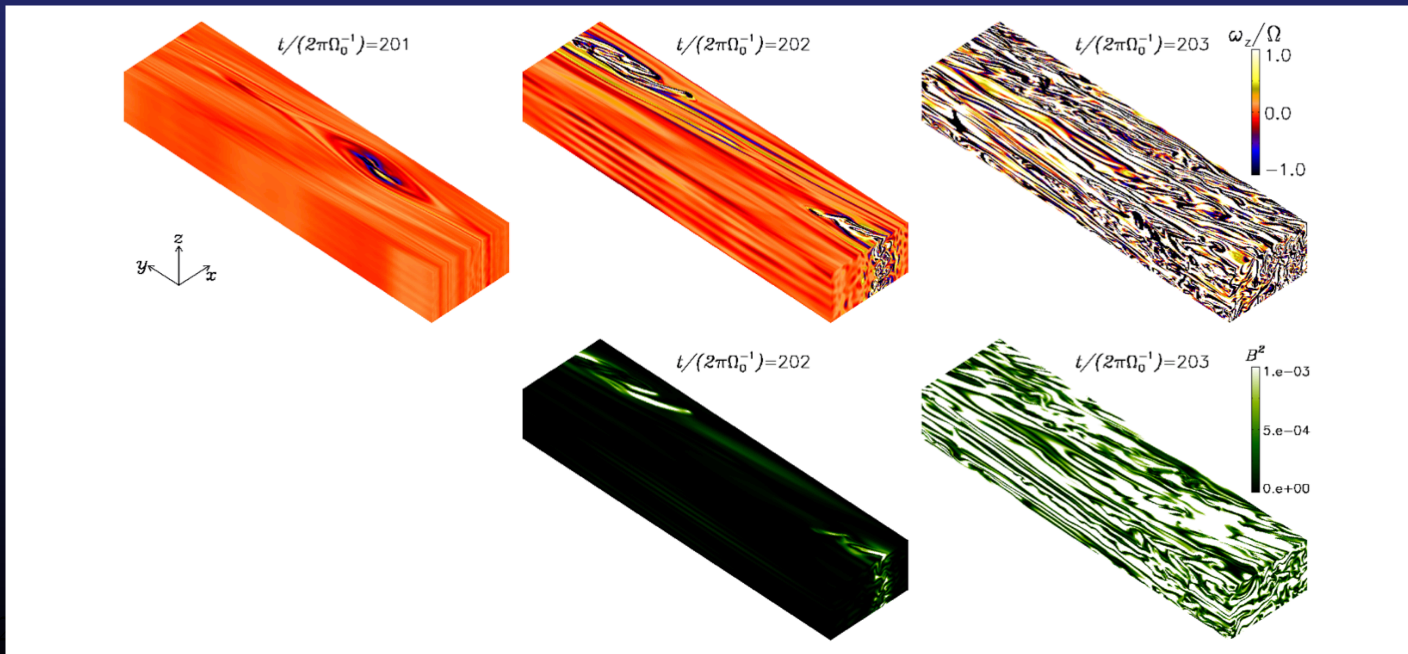


Convective Overstability!

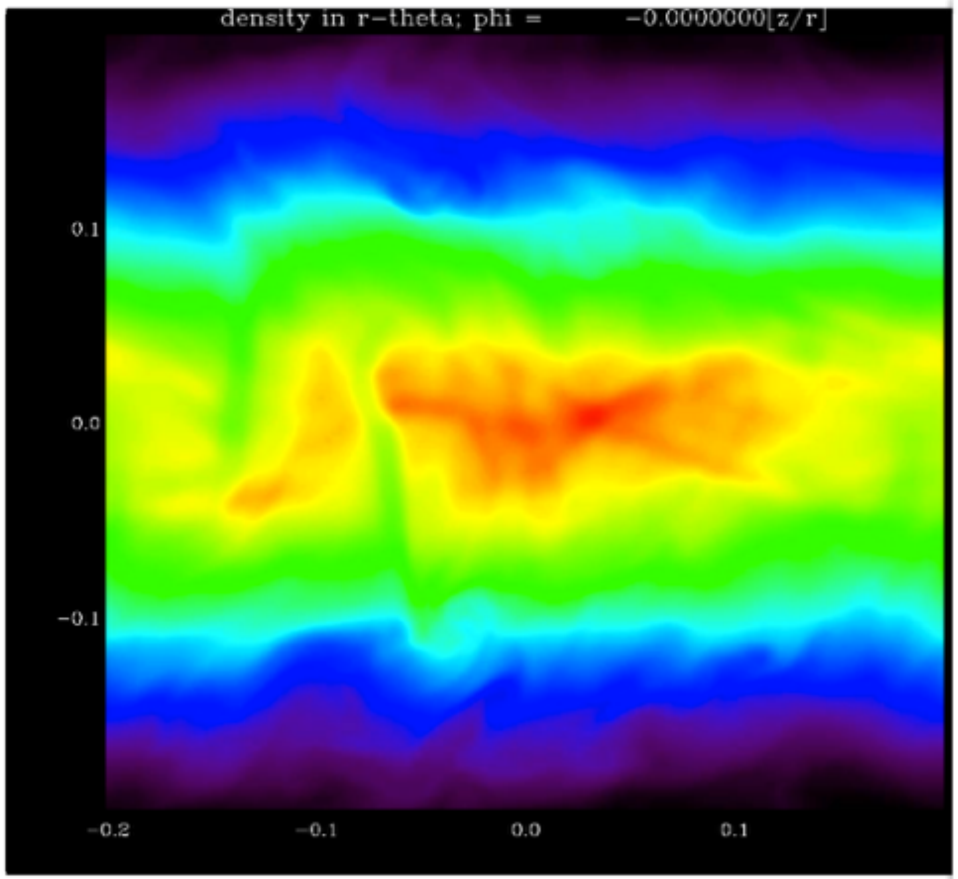
Lesur and Palaloizou 2010: 3D Unstratified Boussinesq



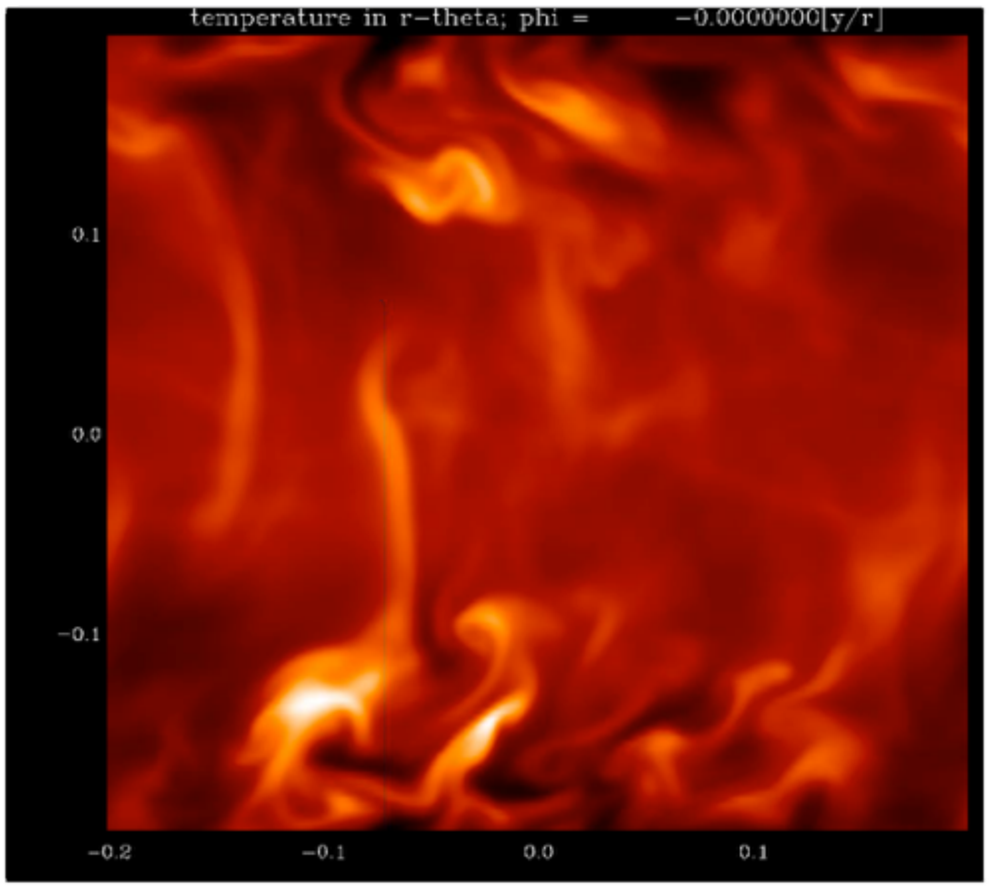
Lyra and Klahr 2011: 3D Unstratified Compressible + MHD



2.5D Local (radial - vertical), Including thermal wind / vertical shear: turbulen! How come?

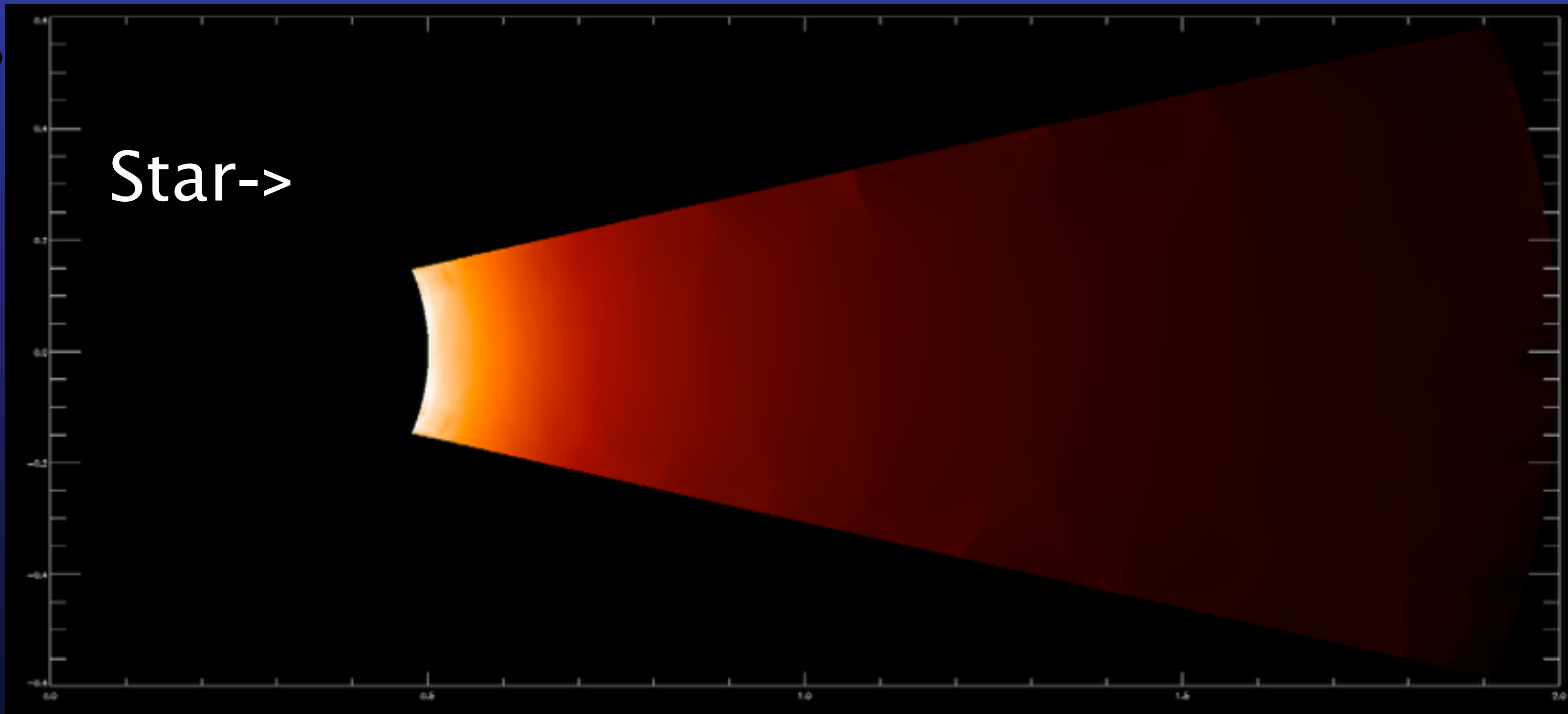


density



temperature pert.

2D axissymetric Pluto Simulation: Temperature due to irradiation from star and thermal relaxation tau = 0 (also works for flux limited diffusion in irradiated disks)

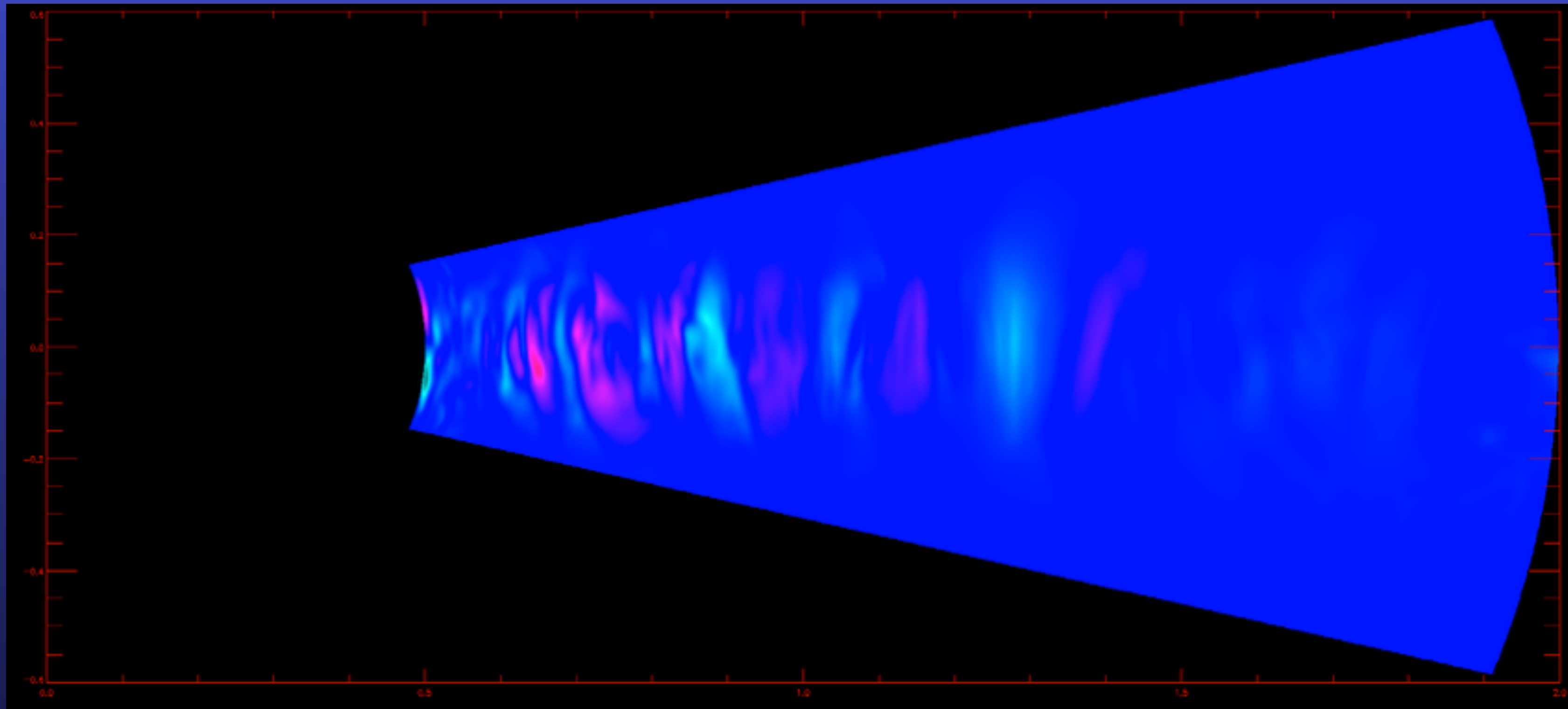


Thermal wind:

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

See Nelson, Gressel & Umurhan 2013

2D axissymetric Pluto Simulation:



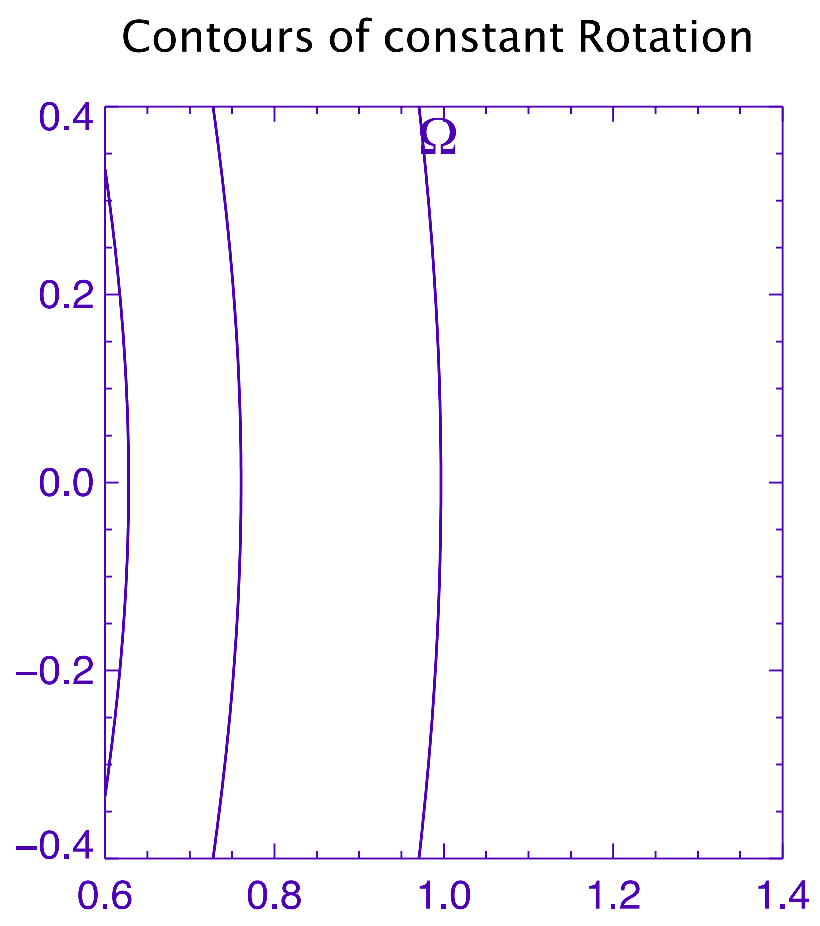
Modification of Solberg-Hoiland Criterion, including thermal relaxation:
In collaboration with Alexander Hubbard
Or instantanous cooling: Goldreich & Schubert 1967 - Fricke 1968 Instability

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

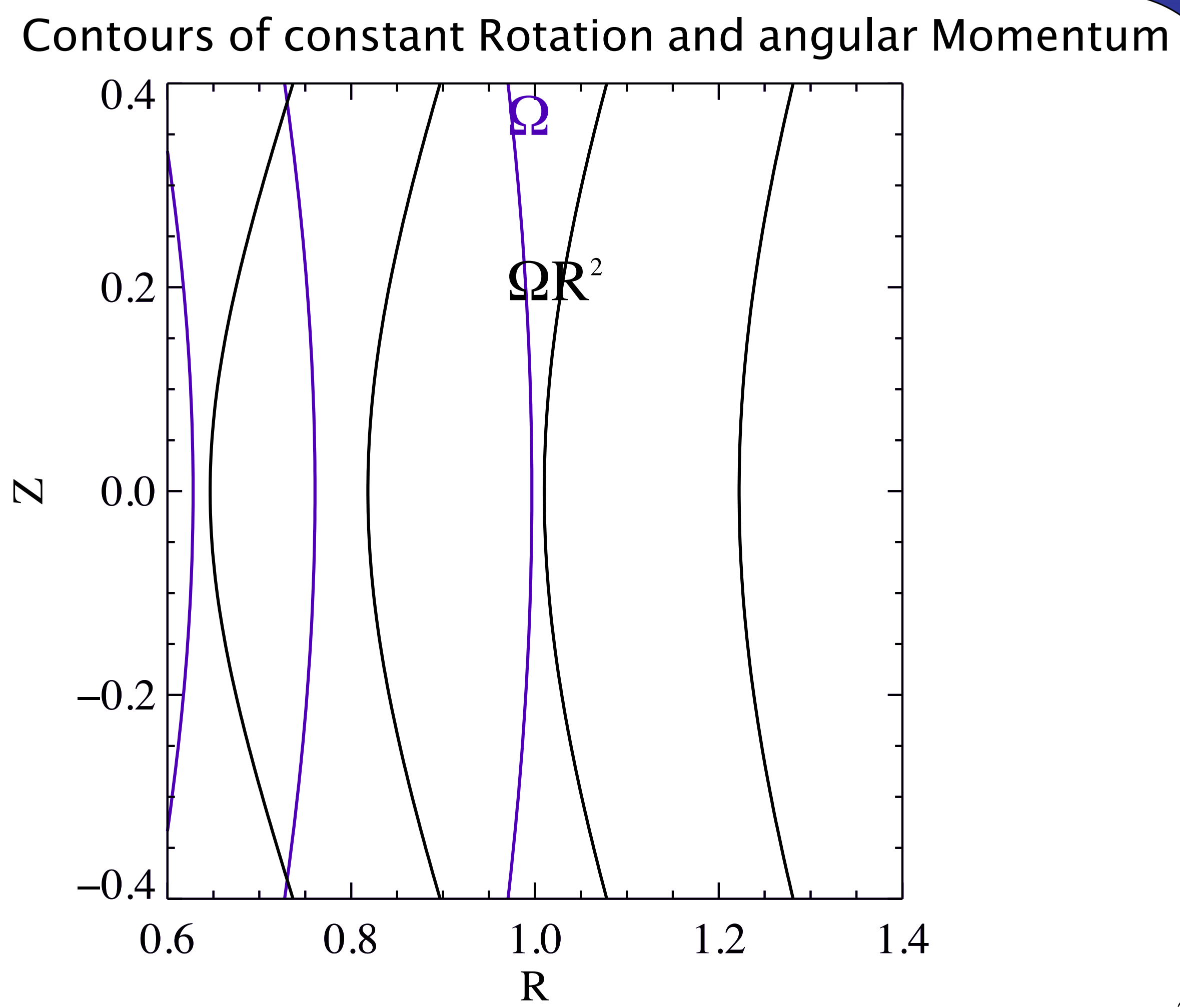
Richard P. Nelson[1]*, Oliver Gressel[1,2]* and Orkan M. Umurhan[1,3]*
[1] Astronomy Unit, Queen Mary University of London, Mile End Road, London E1 4NS
[2] NORDITA, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, 106 91 Stockholm, Sweden
[3] School of Natural Sciences,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

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

Disk with radial temp. profile: $T \sim R^{-q}$ with $q = 1$

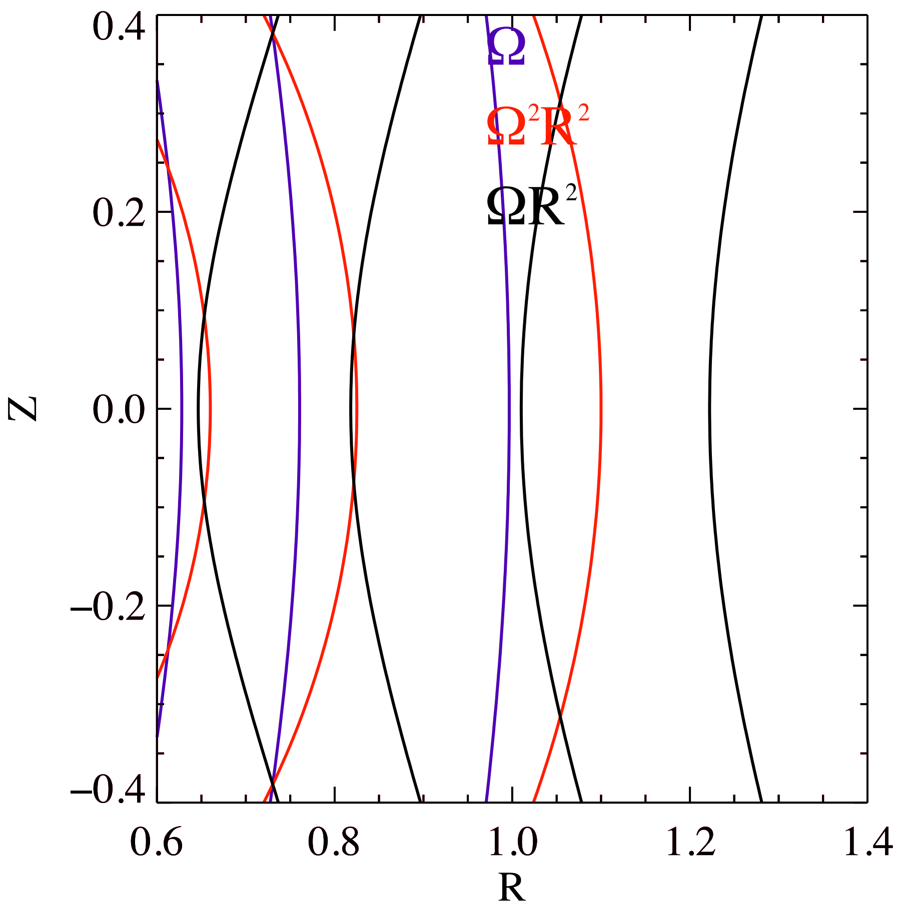


Disk with radial temp. profile: $T \sim R^{-q}$ with $q = 1$



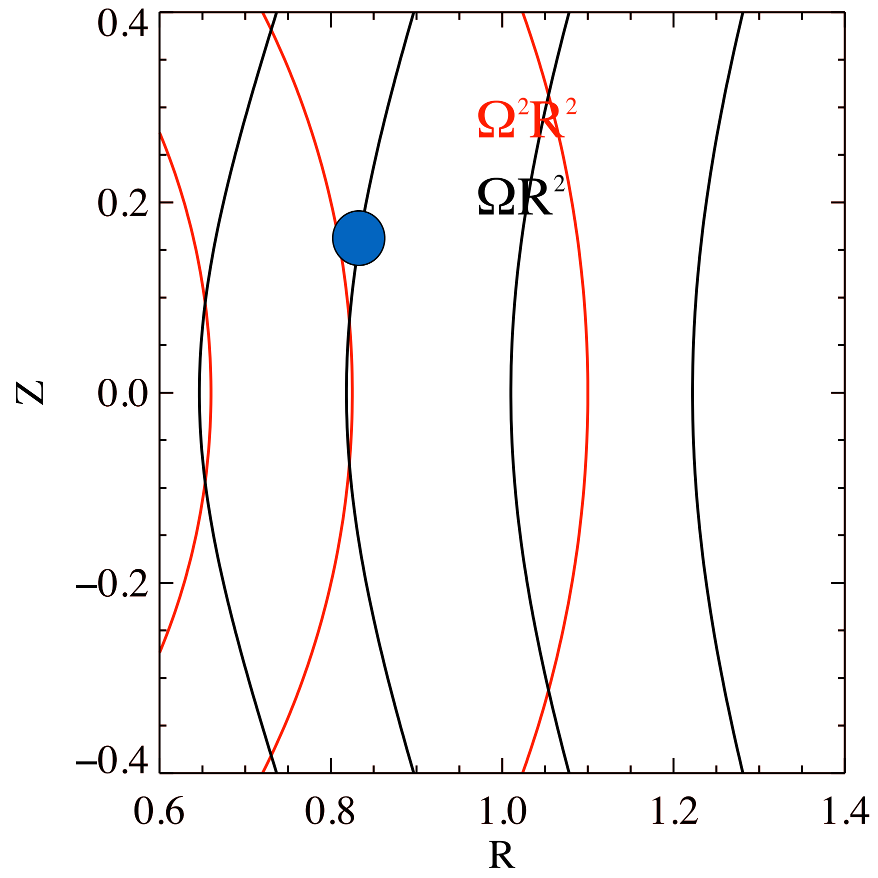
Disk with radial temp. profile: $T \sim R^{-q}$ with $q = 1$

Contours of constant Rotation and angular Momentum and kinetic Energy

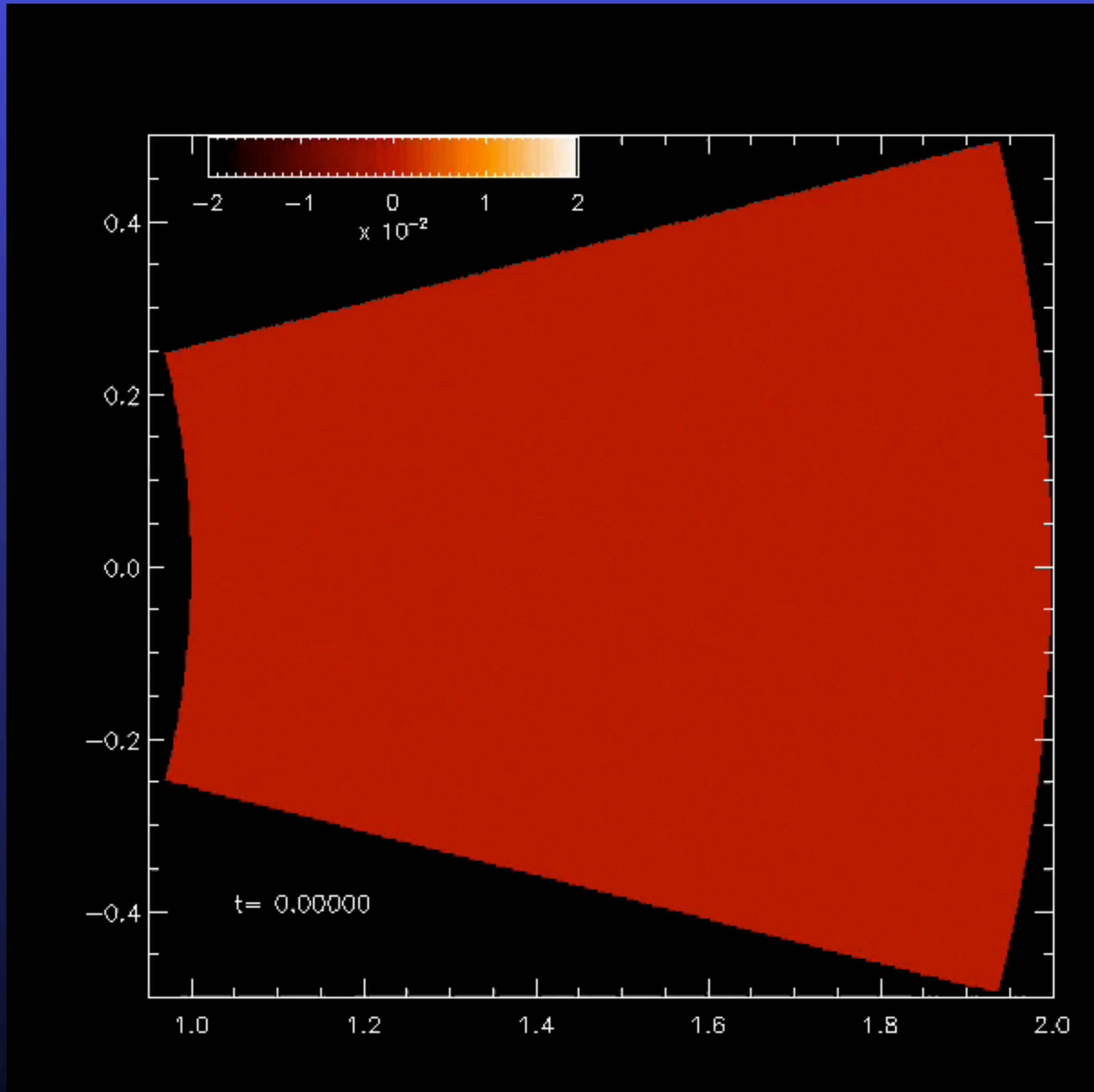


Disk with radial temp. profile: $T \sim R^{-q}$ with q = 1

Contours of constant Rotation and angular Momentum and kinetic Energy



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



Movie by Richard Nelson

Is VSI / GSF already at stage 3?

We assume the grains are well mixed with the gas by either turbulent motion generated by convection, or effects like meridional circulation or Goldreich–Schubert–Fricke instabilities in radiative regions (Goldreich & Schubert 1967; Fricke 1968).

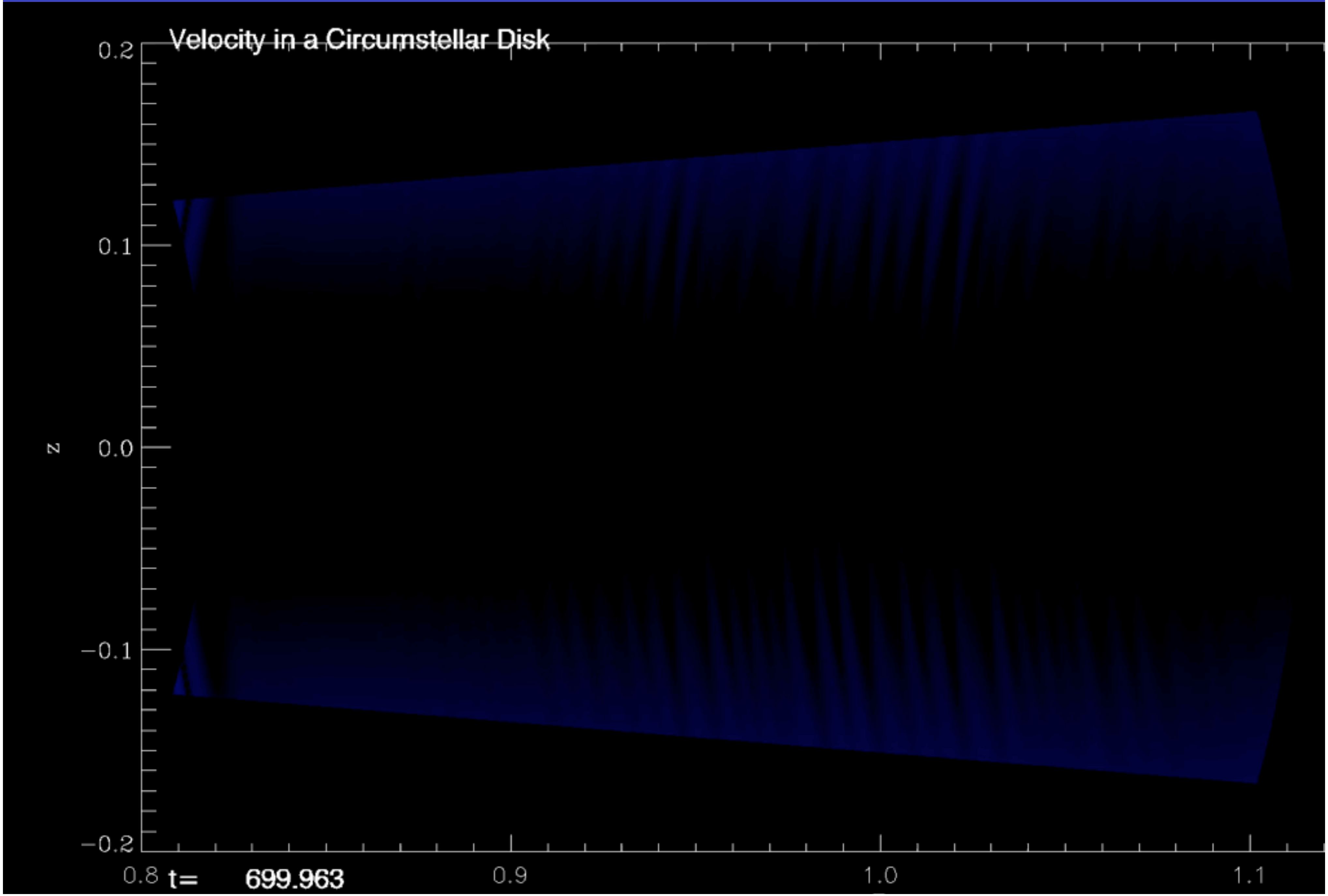
Mon. Not. R. astr. Soc. (1980) **191**, 37–48

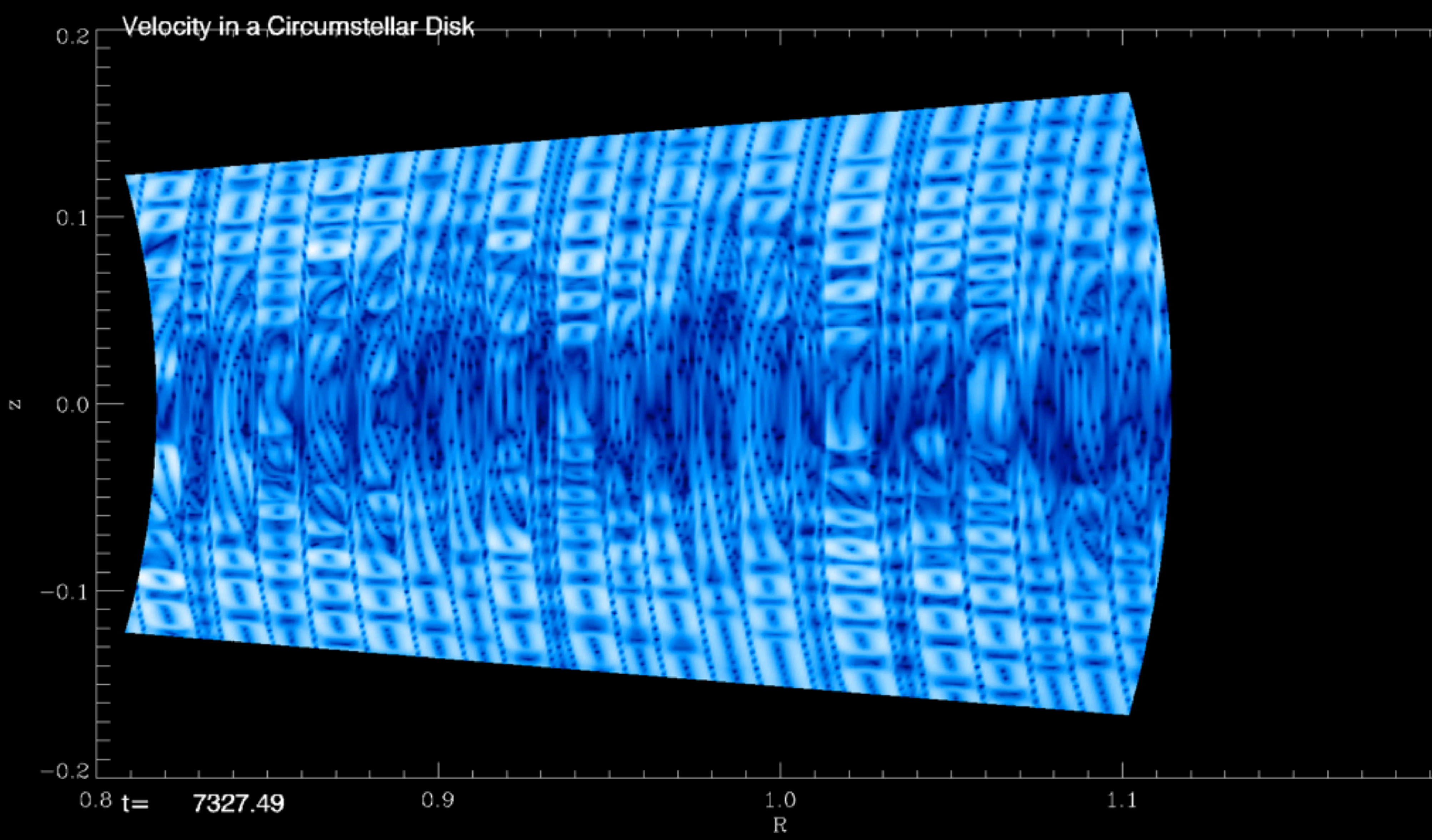
On the structure and evolution of the primordial solar nebula

D. N. C. Lin and J. Papaloizou *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA and Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA*

Received 1979 July 30; in original form 1979 April 20

G.S.F. also for $\Omega\tau \approx 10$?




Velocity in a Circumstellar Disk
0.2
0.1
0.0
−0.1
−0.2
z
0.8
0.9
1.0
1.1
R
t= 7327.49

Stability of vertically unstratified disk

(Klahr and Hubbard 2014)

Stability under the influence of thermal relaxation

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

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

2010Similar to Lesur and Papaloizou 2010 for finite size vortices

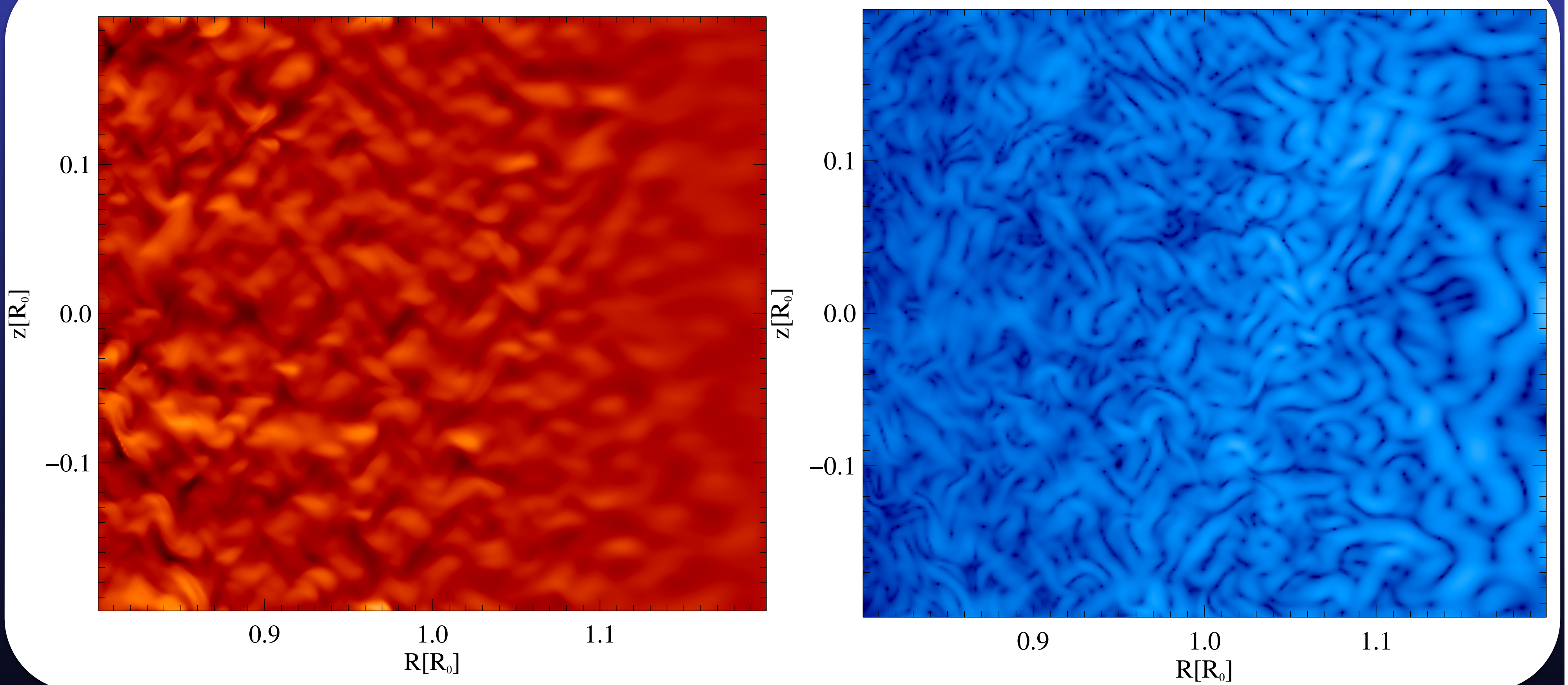
$$\gamma \sim \frac{(-N^2)\sigma^2}{\mu}\phi_\omega(S\sigma^2/\mu) - \frac{\nu}{\sigma^2}.$$

Convective Overstability in radially stratified accretion disks under thermal relaxation

Hubert Klahr[1] & Alexander Hubbard[2]

klahr@mpia.de

ApJ in press



Convective Overstability in radially stratified accretion disks under thermal relaxation

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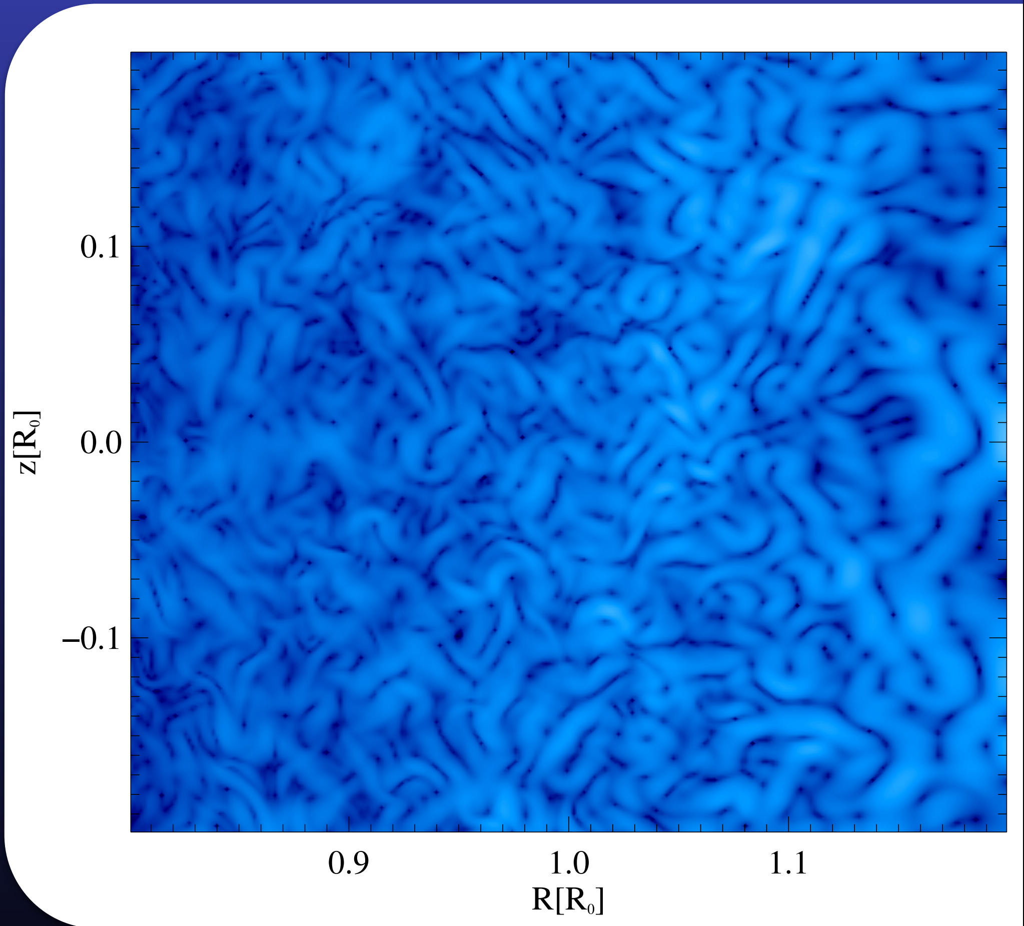
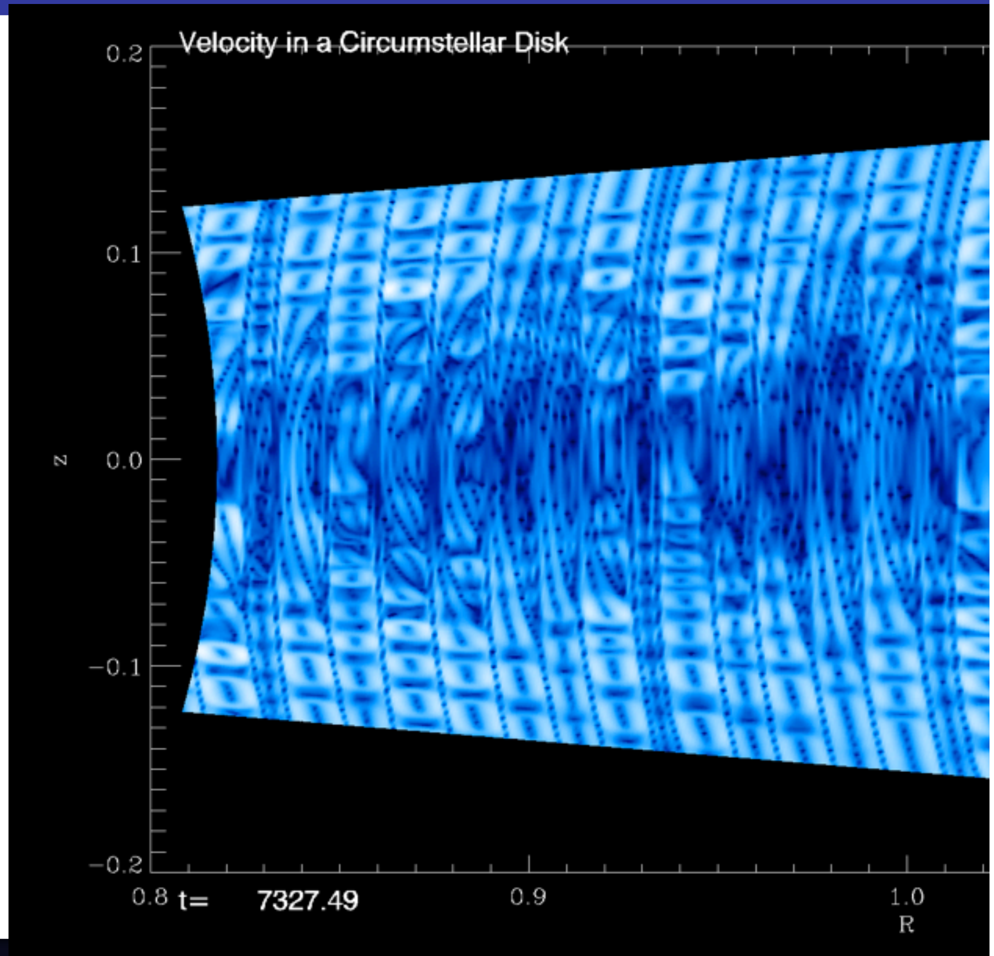


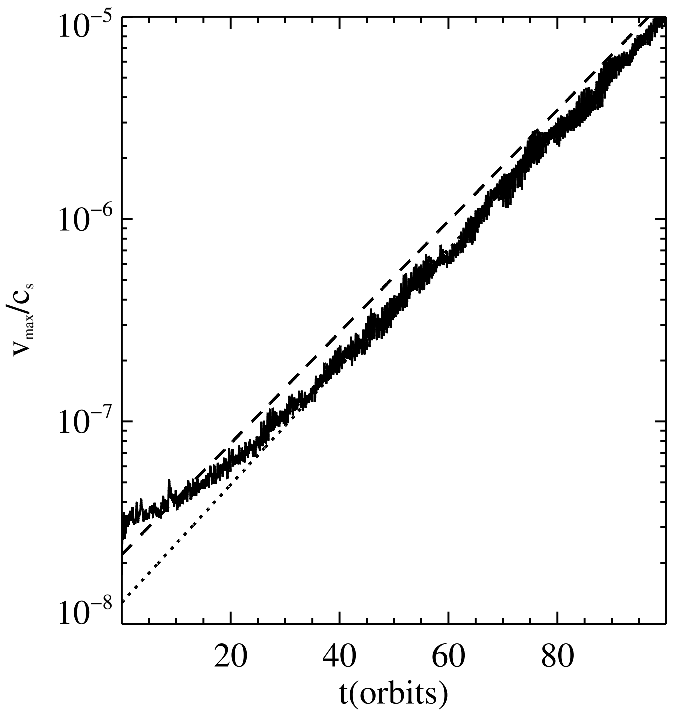


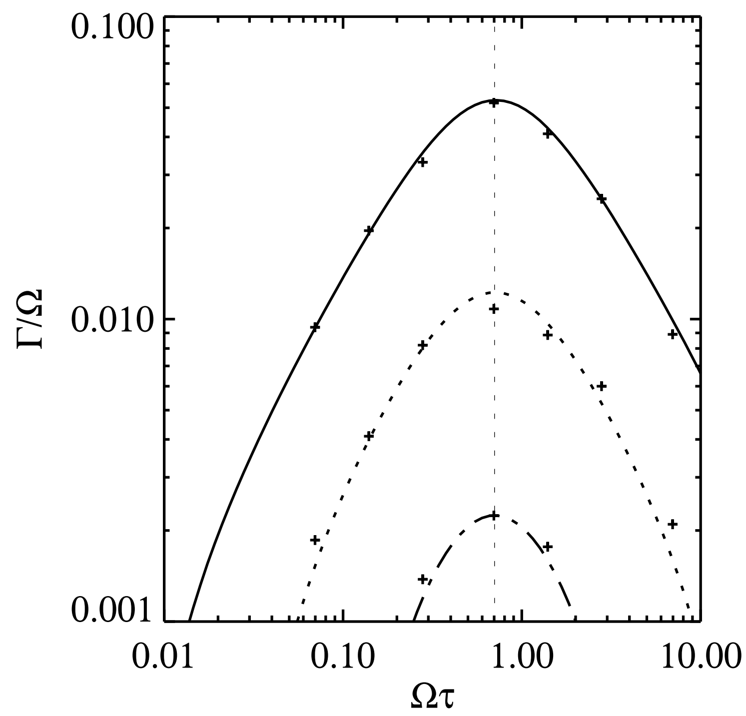
Unstratified

Stratified

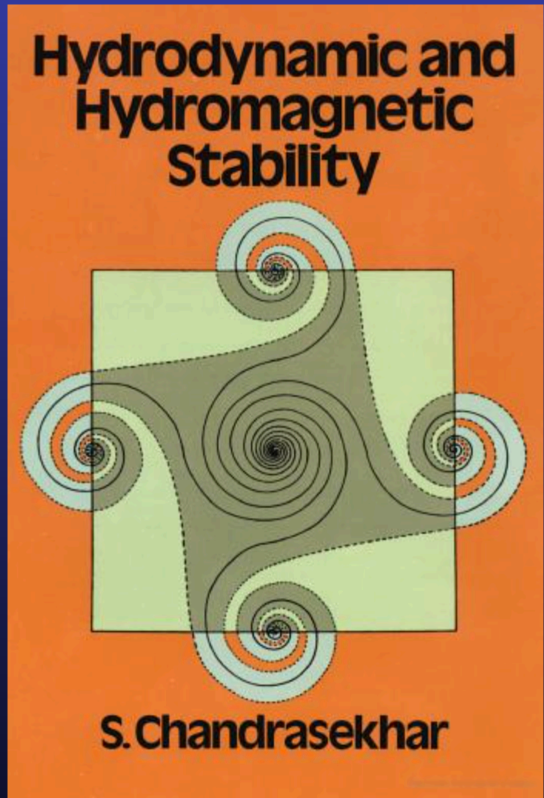
Analytic and Numerical results:

Klahr and Hubbard 2014





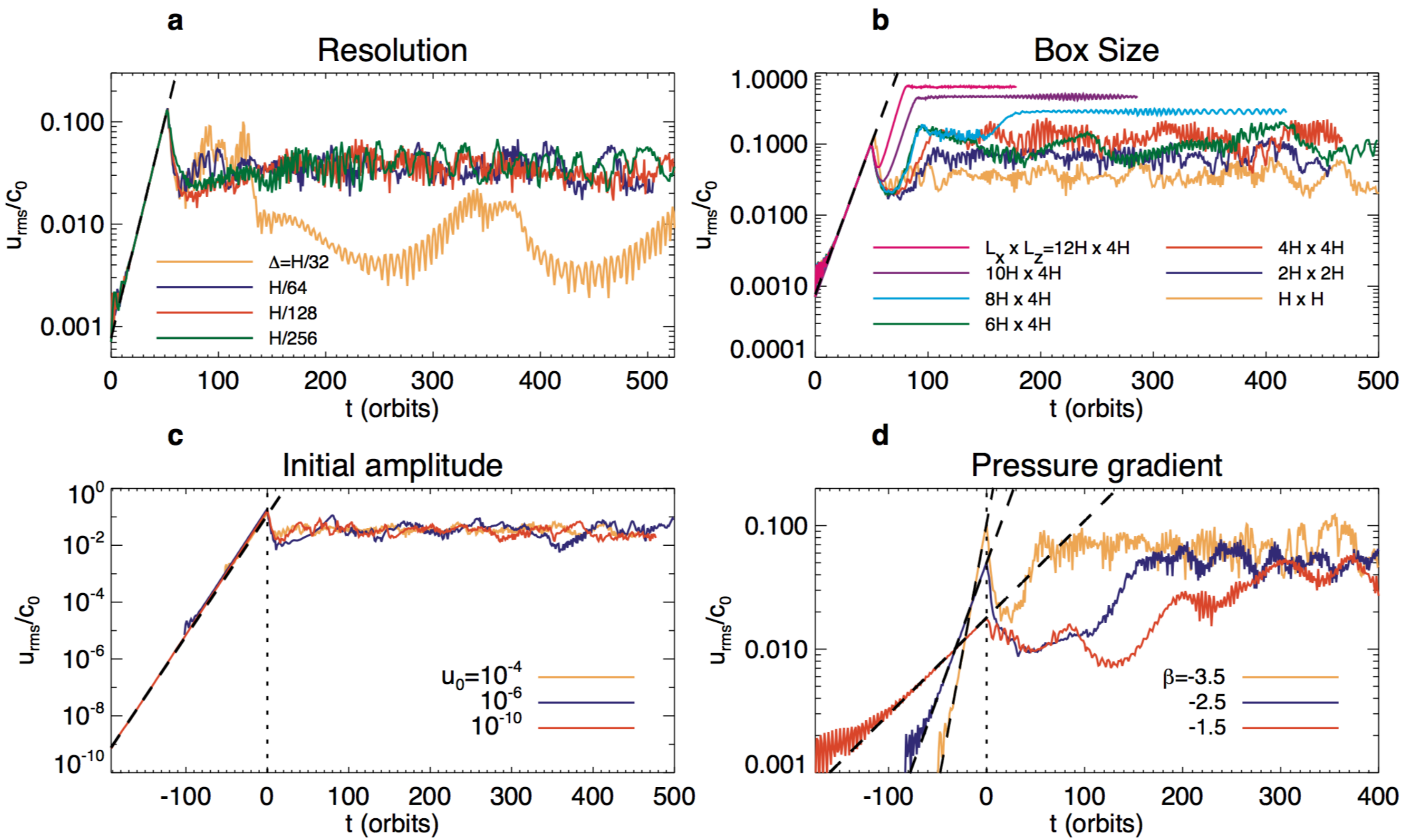
This guy knew it, but only investigated the $\hat{g}$ parallel $\boldsymbol{\Omega}$ case.



"…the other angles will be similar to the MHD case…"

CONVECTIVE OVERSTABILITY IN ACCRETION DISKS
3D LINEAR ANALYSIS AND NONLINEAR SATURATION

WLADIMIR LYRA[1,2,3] ApJ 2014



CONVECTIVE OVERSTABILITY IN ACCRETION DISKS
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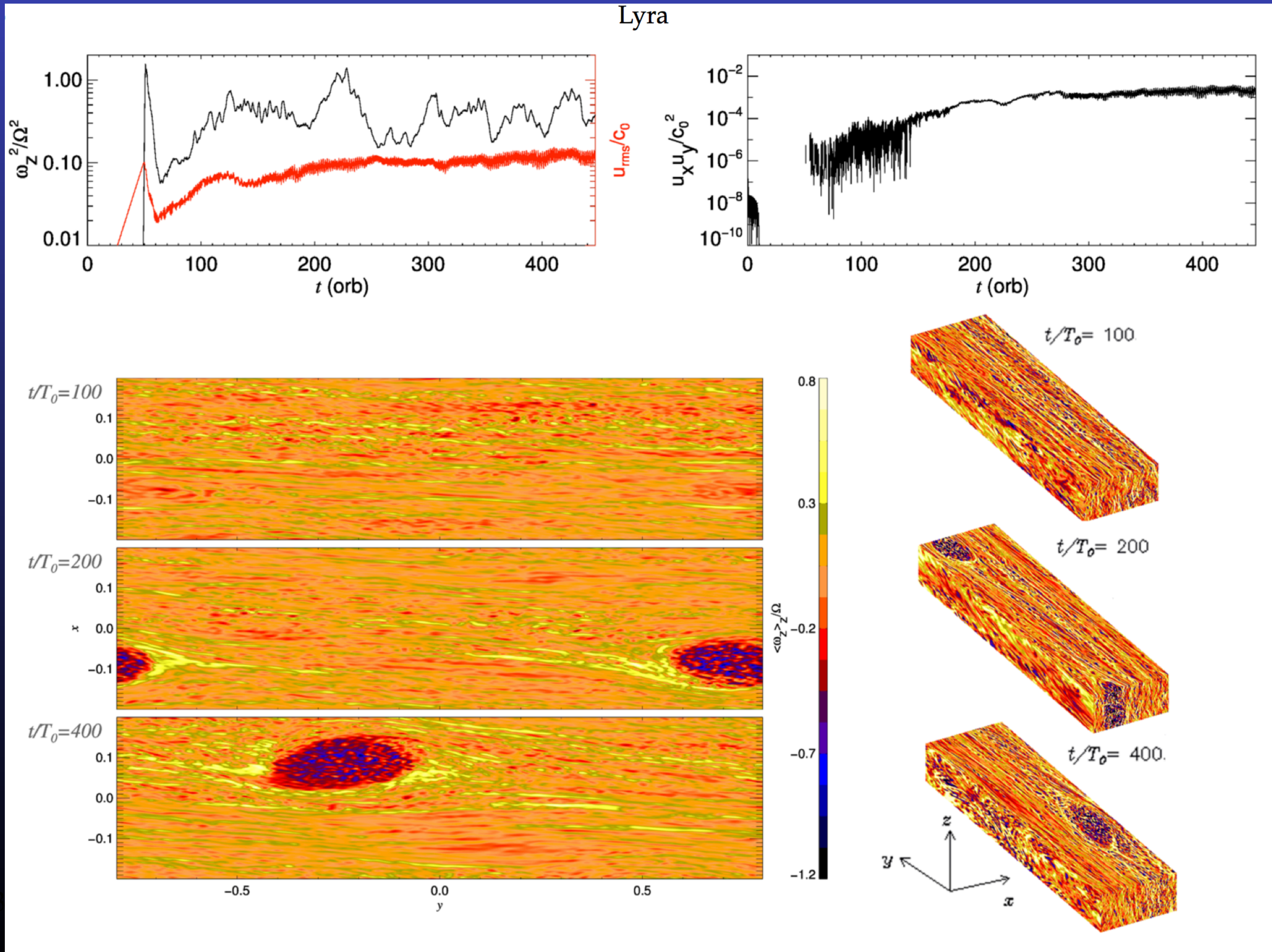
WLADIMIR LYRA[1,2,3] ApJ 2014



Stability in vertically and radially stratified accretion disks under thermal relaxation

Hubert Klahr[1] Lingsong Ge[1] & Alexander Hubbard [2]

$$\partial_t \rho + \frac{1}{R}\partial_R R \rho u_R + \frac{1}{R}\partial_\phi \rho u_\phi + \partial_z \rho u_z = 0.$$

$$\partial_t S + u_R \partial_R S + \frac{u_\phi}{R}\partial_\phi S + u_z \partial_z S = -\frac{c_v}{T_0}\frac{T - T_0}{\tau}.$$

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

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

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

WKB Ansatz: $m \ll k_{R,z}$

plain waves $\exp[i(k_r R + k_z z + m\phi - \omega t)]$.

$$-i(\omega - m\Omega)u_R - 2\Omega u_\phi + ik_R \frac{p_1}{\rho_0} - \frac{\rho_1}{\rho_0^2}\partial_R p_0 = 0$$

$$-i(\omega - m\Omega)u_\phi + \frac{1}{R}\partial_R(R^2\Omega)u_R + R\partial_z(\Omega)u_z = 0$$

$$-i(\omega - m\Omega)u_z + ik_z \frac{p_1}{\rho_0} - \frac{\rho_1}{\rho_0^2}\partial_z p_0 = 0$$

$$-i(\omega - m\Omega)\frac{\rho_1}{\rho_0} + \partial_R \log \rho_0 u_R + \partial_z \log \rho_0 u_z + ik_R u_R + ik_z u_z = 0$$

and

$$\left(-i(\omega - m\Omega) + \frac{1}{\tau}\right)\frac{p_1}{p_0} - \left(-i(\omega - m\Omega) + \frac{1}{\gamma\tau}\right)\gamma\frac{\rho_1}{\rho_0} + u_R\frac{1}{c_v}\partial_R S_0 + u_z\frac{1}{c_v}\partial_z S_0 = 0$$

A&A 391, 781–787 (2002)
DOI: 10.1051/0004-6361:20020853

Astronomy & Astrophysics

Hydrodynamic stability in accretion disks under the combined influence of shear and density stratification

G. Rüdiger[1], R. Arlt[1], and D. Shalybkov[1,2]

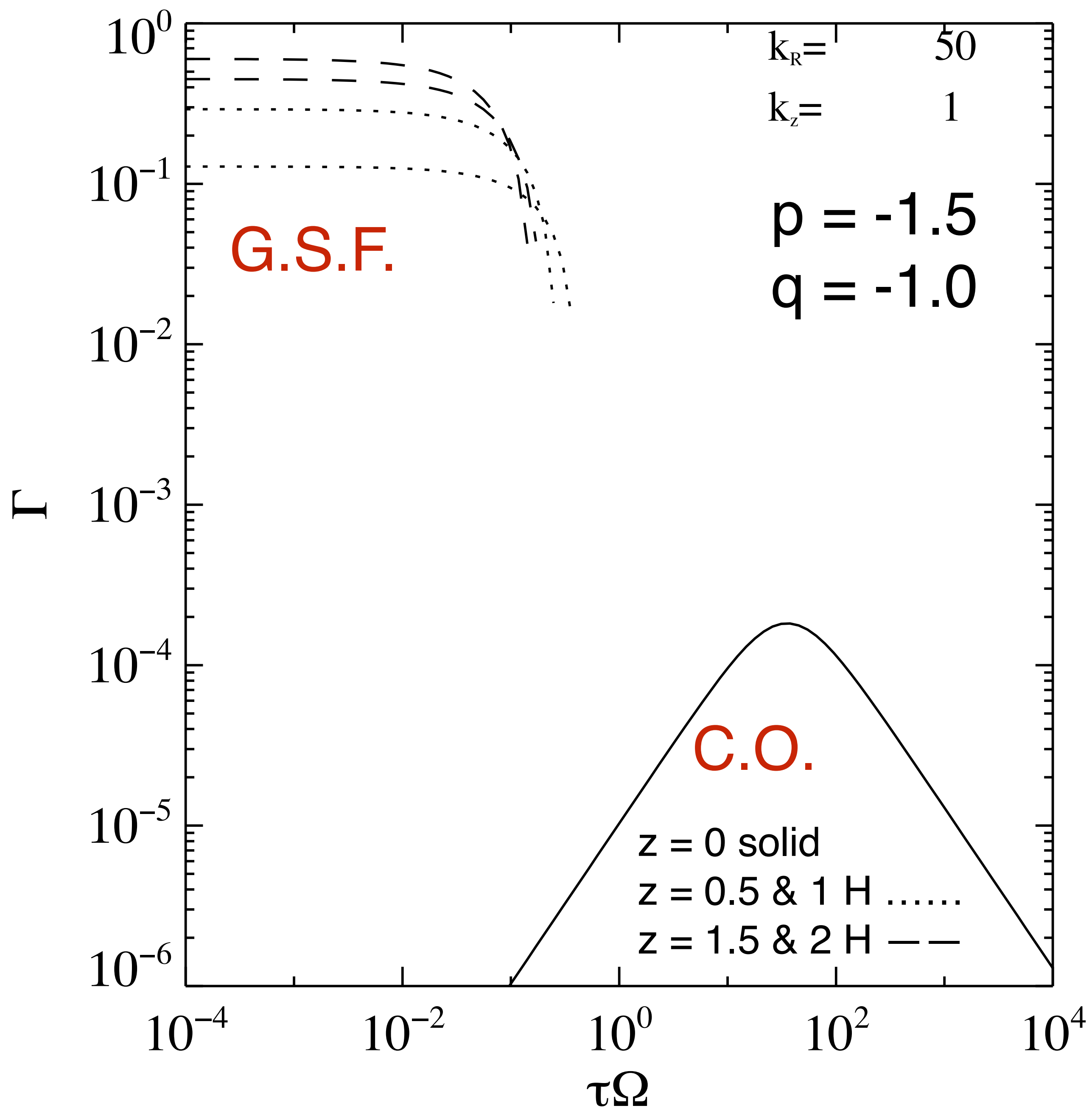
$$\omega_m^5 + \frac{i}{\tau}\omega_m^4 - A\omega_m^3 + B\frac{i}{\tau}\omega_m^2 + C\omega_m + \frac{i}{\tau}D = 0$$

$$A = k^2c_s^2 + \frac{1}{\rho_0^2}\frac{\partial p_0}{\partial R}\frac{\partial \rho_0}{\partial R} + \frac{1}{\rho_0^2}\frac{\partial p_0}{\partial z}\frac{\partial \rho_0}{\partial z} + \kappa_R^2$$

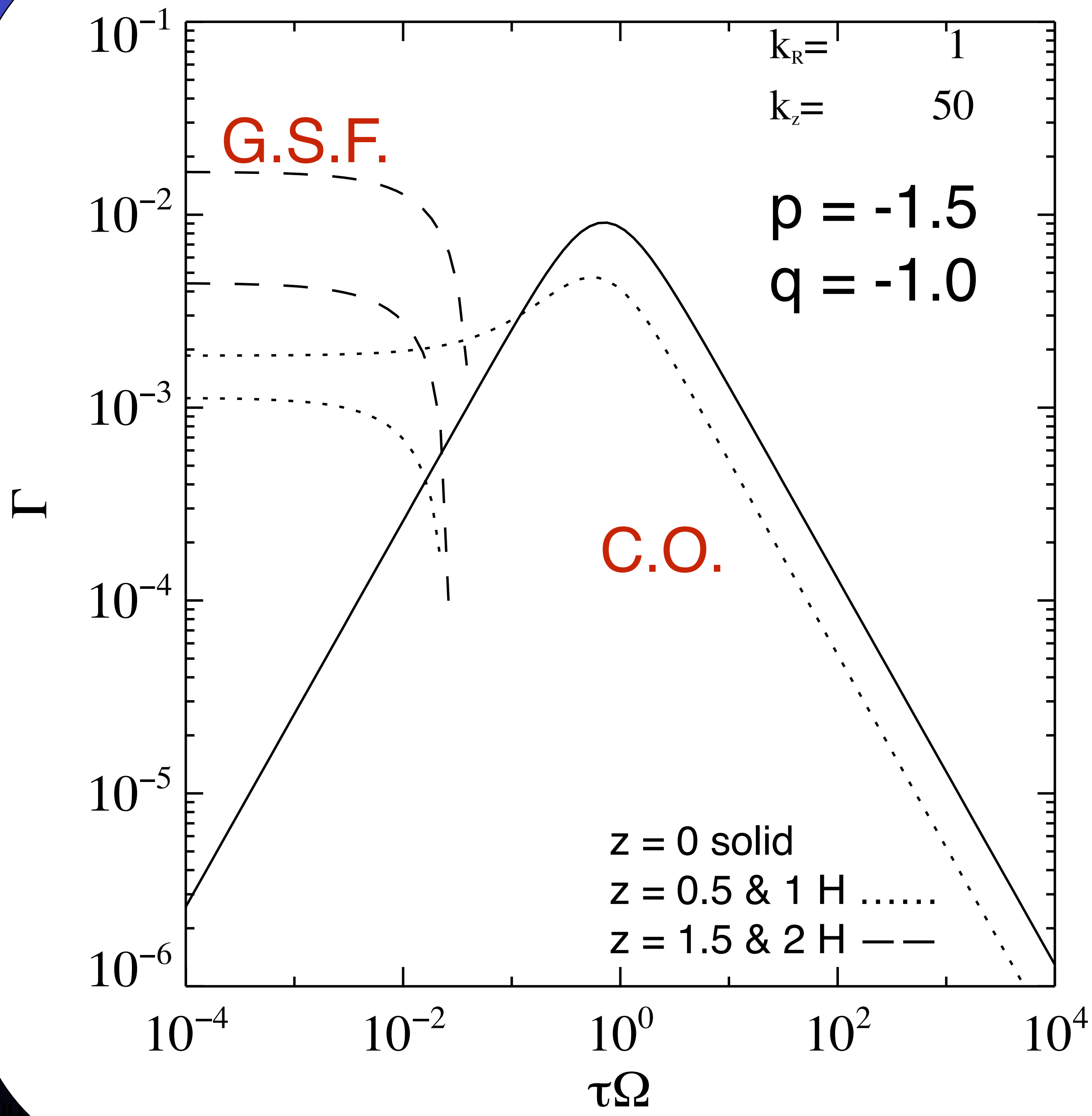
$$\begin{aligned} B =& - i\left(\frac{k_z}{\rho_0}\frac{\partial p_0}{\partial z} + \frac{k_R}{\rho_0}\frac{\partial p_0}{\partial R} - \frac{k_z c_s^2}{\rho_0\gamma}\frac{\partial \rho_0}{\partial z} - \frac{k_R c_s^2}{\rho_0\gamma}\frac{\partial \rho_0}{\partial R}\right) \\ & - \left(\frac{k^2c_s^2}{\gamma} + \frac{1}{\rho_0^2}\frac{\partial p_0}{\partial R}\frac{\partial \rho_0}{\partial R} + \frac{1}{\rho_0^2}\frac{\partial p_0}{\partial z}\frac{\partial \rho_0}{\partial z} + \kappa_R^2\right) \end{aligned}$$

$$\begin{aligned} C =& \left(\frac{k_R}{\rho_0}\frac{\partial p_0}{\partial z} - \frac{k_z}{\rho_0}\frac{\partial p_0}{\partial R}\right)\left[\frac{k_R c_s^2}{c_v\gamma}\frac{\partial S_0}{\partial z} - \frac{k_z c_s^2}{c_v\gamma}\frac{\partial S_0}{\partial R} + \frac{i}{\rho_0^2}\left(\frac{\partial p_0}{\partial z}\frac{\partial \rho_0}{\partial R} - \frac{\partial p_0}{\partial R}\frac{\partial \rho_0}{\partial z}\right)\right] \\ & + \kappa_R^2\left(k_z^2c_s^2 + \frac{1}{\rho_0^2}\frac{\partial \rho_0}{\partial z}\frac{\partial p_0}{\partial z}\right) - \kappa_z^2\left[k_R k_z c_s^2 + \frac{1}{\rho_0^2}\frac{\partial \rho_0}{\partial z}\frac{\partial p_0}{\partial z} + i\left(\frac{k_R}{\rho_0}\frac{\partial p_0}{\partial z} - \frac{k_z}{\rho_0}\frac{\partial p_0}{\partial R}\right)\right] \end{aligned}$$

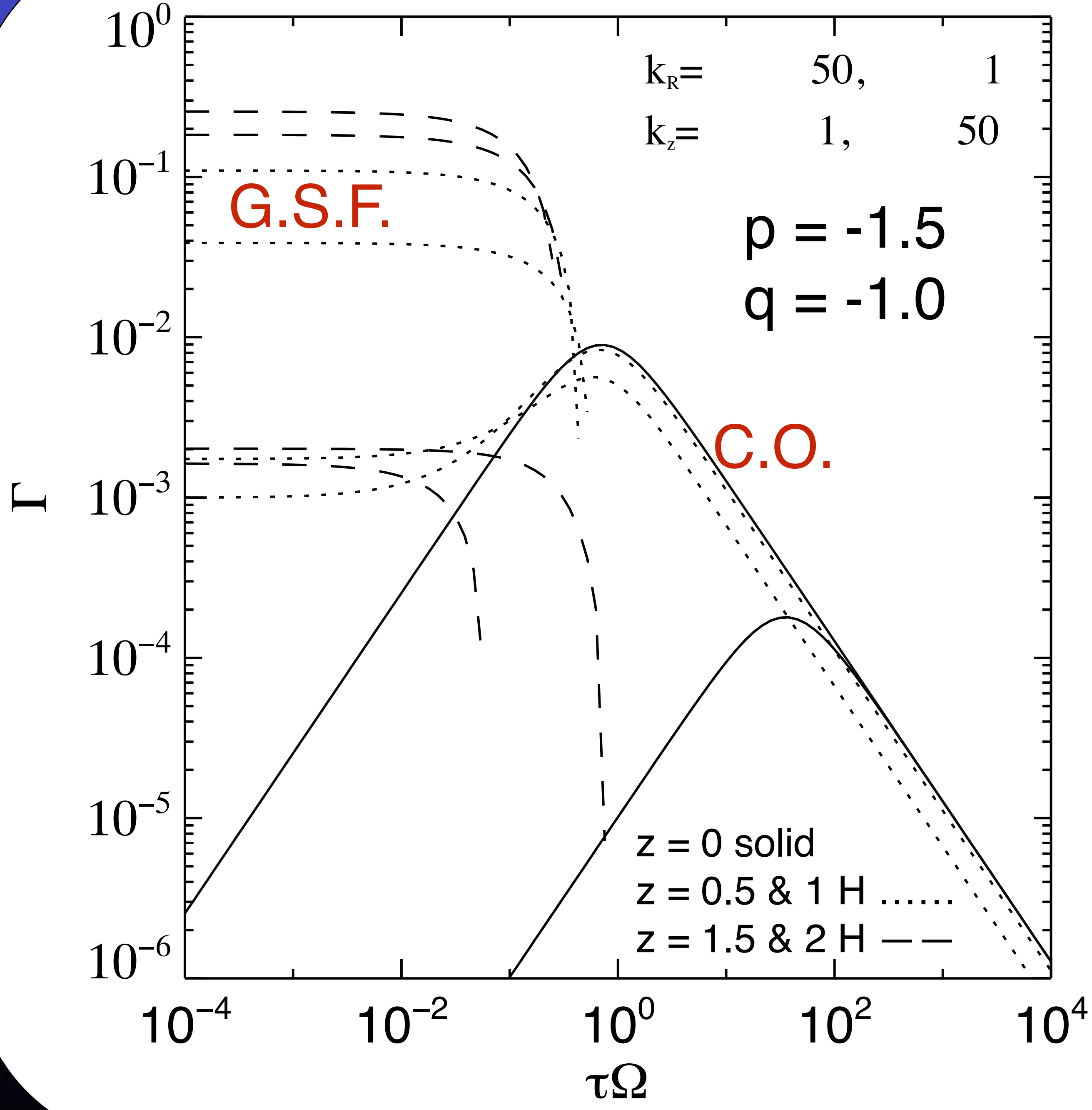
$$\begin{aligned} D =& \kappa_R^2\left[\frac{c_s^2k_z^2}{\gamma} + \frac{1}{\rho_0^2}\frac{\partial \rho_0}{\partial z}\frac{\partial p_0}{\partial z} - i\frac{k_z c_s^2}{\rho_0\gamma}\frac{\partial \rho_0}{\partial z} + i\frac{k_z}{\rho_0}\frac{\partial p_0}{\partial z}\right] \\ & + \kappa_z^2\left[\frac{c_s^2k_z k_R}{\gamma} + \frac{1}{\rho_0^2}\frac{\partial \rho_0}{\partial R}\frac{\partial p_0}{\partial z} - i\frac{k_z c_s^2}{\rho_0\gamma}\frac{\partial \rho_0}{\partial R} + i\frac{k_R}{\rho_0}\frac{\partial p_0}{\partial z}\right] \end{aligned}$$



Γ
10^0
10^−1
10^−2
10^−3
10^−4
10^−5
10^−6
10^−4
10^−2
10^0
10^2
10^4
τΩ
k_R= 50
k_z= 1
p = -1.5
q = -1.0
G.S.F.
C.O.
z = 0 solid
z = 0.5 & 1 H ......
z = 1.5 & 2 H — —



G.S.F.
C.O.
k_R= 1
k_z= 50
p = -1.5
q = -1.0
z = 0 solid
z = 0.5 & 1 H ......
z = 1.5 & 2 H — —
Γ
τΩ



k_R= 50, 1
k_z= 1, 50
G.S.F.
p = -1.5
q = -1.0
C.O.
Γ
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
z = 0 solid
z = 0.5 & 1 H ......
z = 1.5 & 2 H — —
10^{-4}
10^{-2}
10^0
10^2
10^4
τΩ

$$\omega_m^5 + \frac{i}{\tau}\omega_m^4 - A\omega_m^3 + B\frac{i}{\tau}\omega_m^2 + C\omega_m + \frac{i}{\tau}D = 0$$

$$A = k^2c_s^2 + \frac{1}{\rho_0^2}\frac{\partial p_0}{\partial R}\frac{\partial \rho_0}{\partial R} + \frac{1}{\rho_0^2}\frac{\partial p_0}{\partial z}\frac{\partial \rho_0}{\partial z} + \kappa_R^2$$

$$\begin{aligned} B =& -i\left(\frac{k_z}{\rho_0}\frac{\partial p_0}{\partial z} + \frac{k_R}{\rho_0}\frac{\partial p_0}{\partial R} - \frac{k_z c_s^2}{\rho_0\gamma}\frac{\partial \rho_0}{\partial z} - \frac{k_R c_s^2}{\rho_0\gamma}\frac{\partial \rho_0}{\partial R}\right) \\ & - \left(\frac{k^2c_s^2}{\gamma} + \frac{1}{\rho_0^2}\frac{\partial p_0}{\partial R}\frac{\partial \rho_0}{\partial R} + \frac{1}{\rho_0^2}\frac{\partial p_0}{\partial z}\frac{\partial \rho_0}{\partial z} + \kappa_R^2\right) \end{aligned}$$

$$\begin{aligned} C =& \left(\frac{k_R}{\rho_0}\frac{\partial p_0}{\partial z} - \frac{k_z}{\rho_0}\frac{\partial p_0}{\partial R}\right)\left[\frac{k_R c_s^2}{c_v\gamma}\frac{\partial S_0}{\partial z} - \frac{k_z c_s^2}{c_v\gamma}\frac{\partial S_0}{\partial R} + \frac{i}{\rho_0^2}\left(\frac{\partial p_0}{\partial z}\frac{\partial \rho_0}{\partial R} - \frac{\partial p_0}{\partial R}\frac{\partial \rho_0}{\partial z}\right)\right] \\ & + \kappa_R^2\left(k_z^2c_s^2 + \frac{1}{\rho_0^2}\frac{\partial \rho_0}{\partial z}\frac{\partial p_0}{\partial z}\right) - \kappa_z^2\left[k_R k_z c_s^2 + \frac{1}{\rho_0^2}\frac{\partial \rho_0}{\partial z}\frac{\partial p_0}{\partial z} + i\left(\frac{k_R}{\rho_0}\frac{\partial p_0}{\partial z} - \frac{k_z}{\rho_0}\frac{\partial p_0}{\partial R}\right)\right] \end{aligned}$$

$$\begin{aligned} D =& \kappa_R^2\left[\frac{c_s^2k_z^2}{\gamma} + \frac{1}{\rho_0^2}\frac{\partial \rho_0}{\partial z}\frac{\partial p_0}{\partial z} - i\frac{k_z c_s^2}{\rho_0\gamma}\frac{\partial \rho_0}{\partial z} + i\frac{k_z}{\rho_0}\frac{\partial p_0}{\partial z}\right] \\ & + \kappa_z^2\left[\frac{c_s^2k_z k_R}{\gamma} + \frac{1}{\rho_0^2}\frac{\partial \rho_0}{\partial R}\frac{\partial p_0}{\partial z} - i\frac{k_z c_s^2}{\rho_0\gamma}\frac{\partial \rho_0}{\partial R} + i\frac{k_R}{\rho_0}\frac{\partial p_0}{\partial z}\right] \end{aligned}$$

Incompressible limit: cs -> inf.

$$A'\omega_m^3 - B'\frac{1}{\tau}\omega_m^2 - C'\omega_m - \frac{1}{\tau}D' = 0$$

If $k_R \gg k_z$

$$\omega_m^2 = \frac{k_z^2}{k_R^2}(\kappa_R^2 - \frac{k_R}{k_z}\kappa_z^2)$$

G.S.F. or V.S. instability

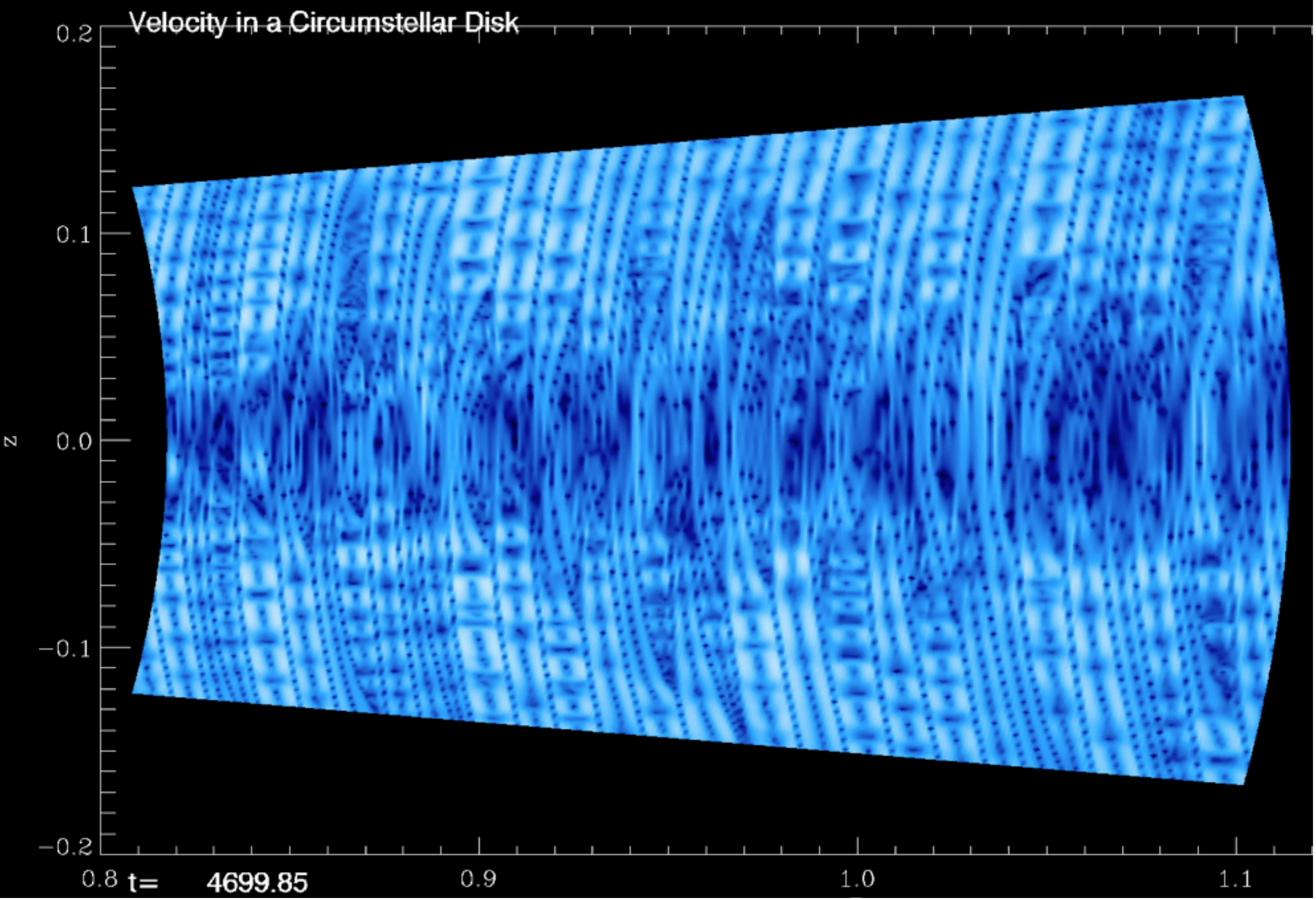
If $k_R \ll k_z$

$$\omega_m^3 + \frac{i}{\gamma\tau}\omega_m^2 - (N_R^2 + \kappa_R^2)\omega_m - \frac{i\kappa_R^2}{\gamma\tau} = 0$$

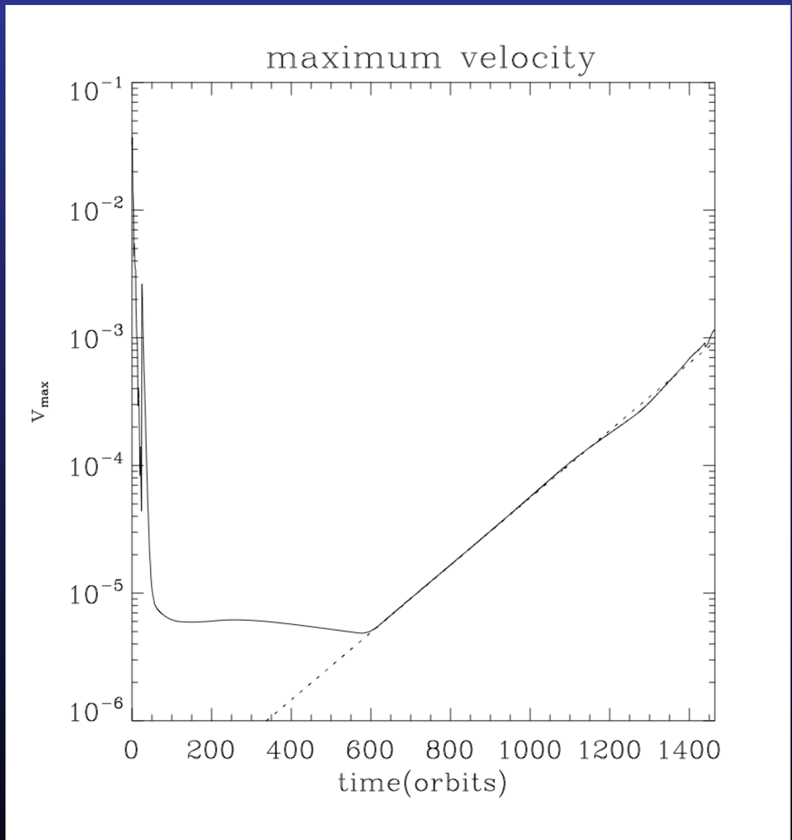
Convective Overstability

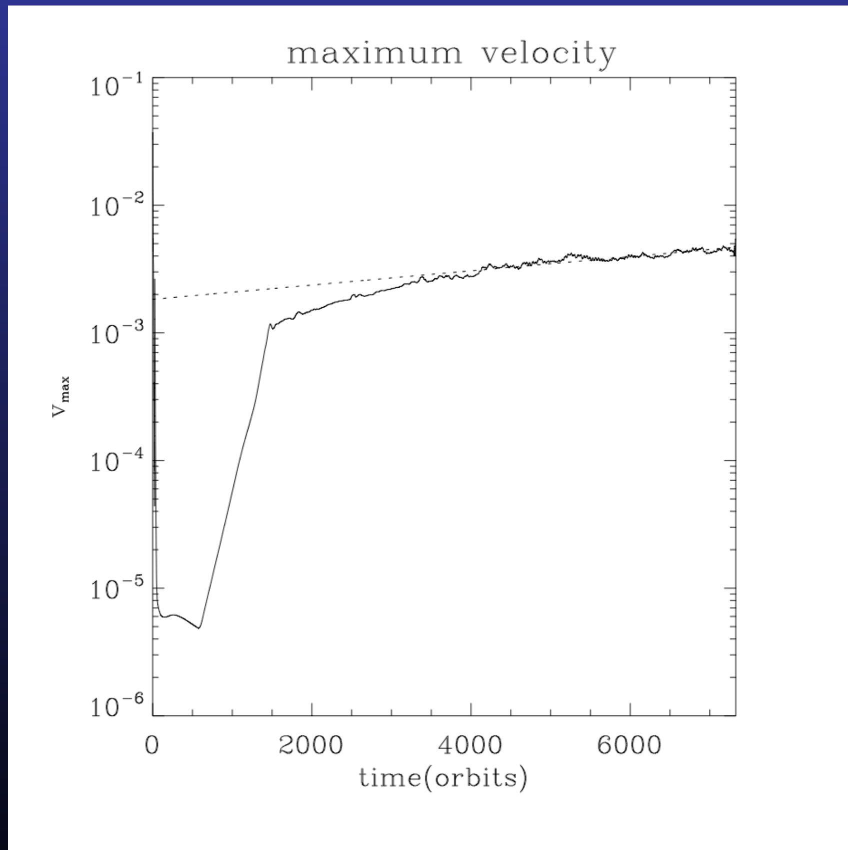
$$\Gamma = \frac{1}{2}\frac{-\tau N_R^2}{1 + \tau^2\left(\kappa_R^2 + N_R^2\right)}$$

C.O. $\Omega\tau = 10$; $p = -0.66$; $q = 1$; $H/R = 0.1$

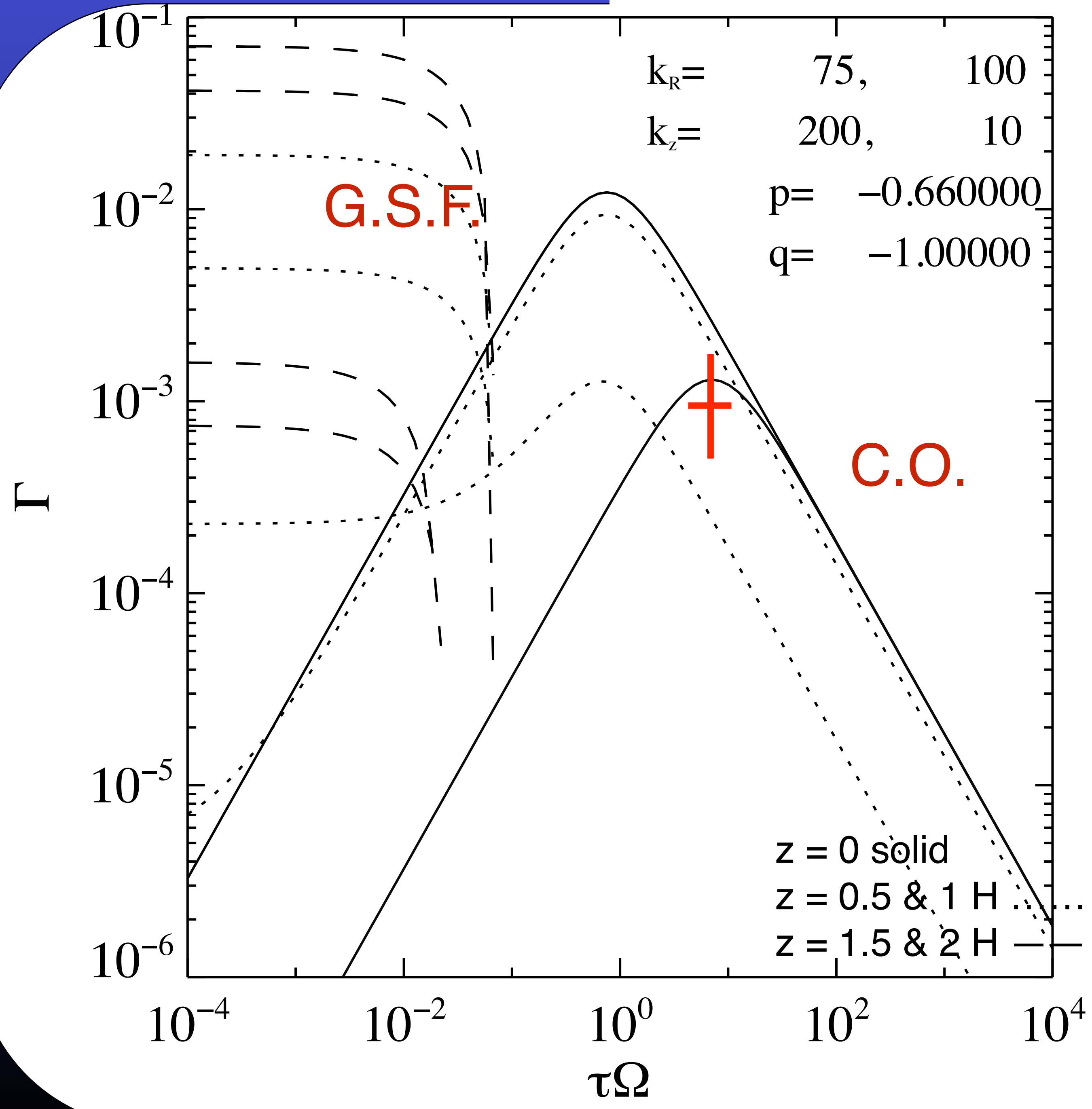


Evolution of largest velocity in simulation domain:





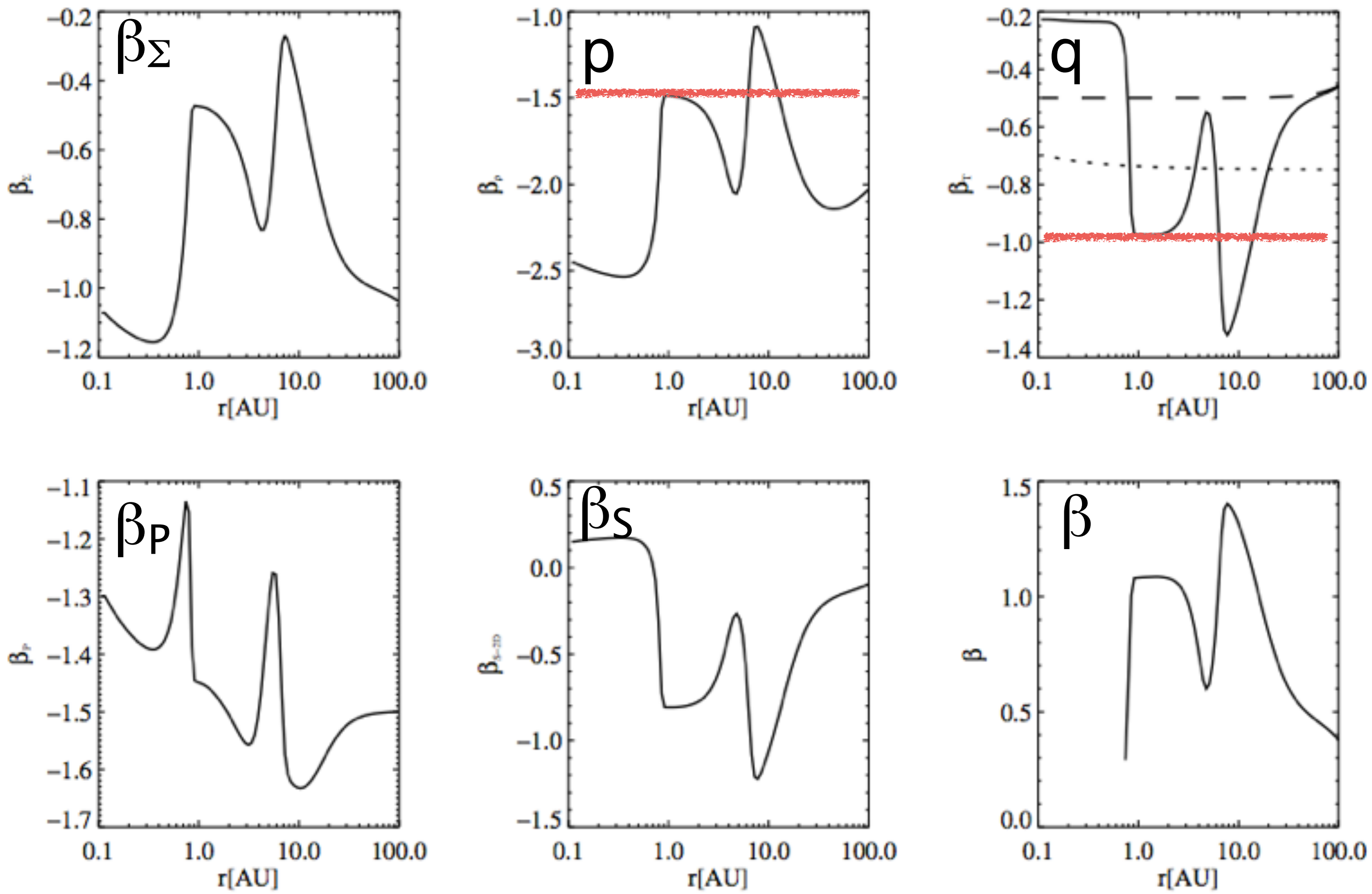
Numerical Result vs. linear theory



Radial Stratification of acc. disks: Modeling observational data from Sean Andrews

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

Plus irradiation: Tstar = 4300; Rstar = 2 Rsol



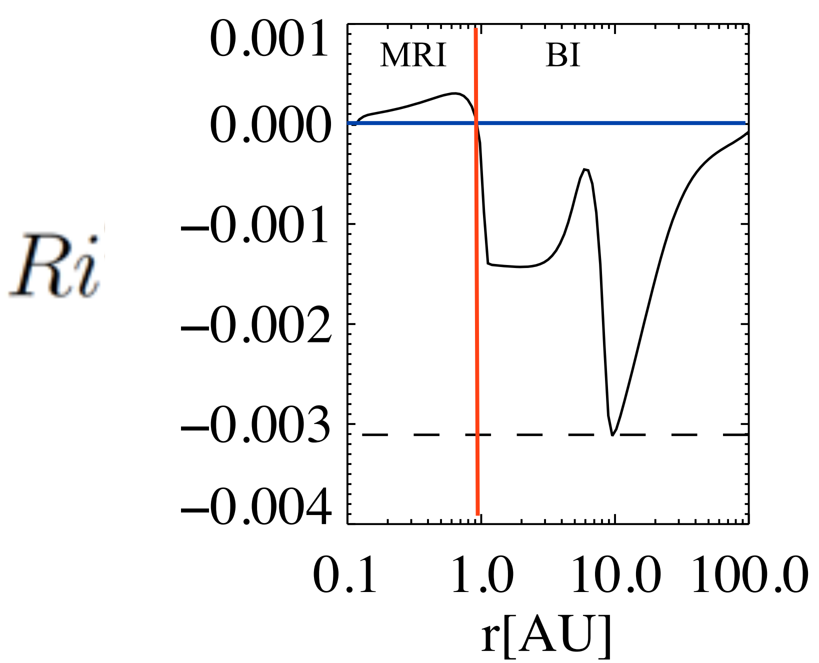
Richardson number & thermal diffusion time

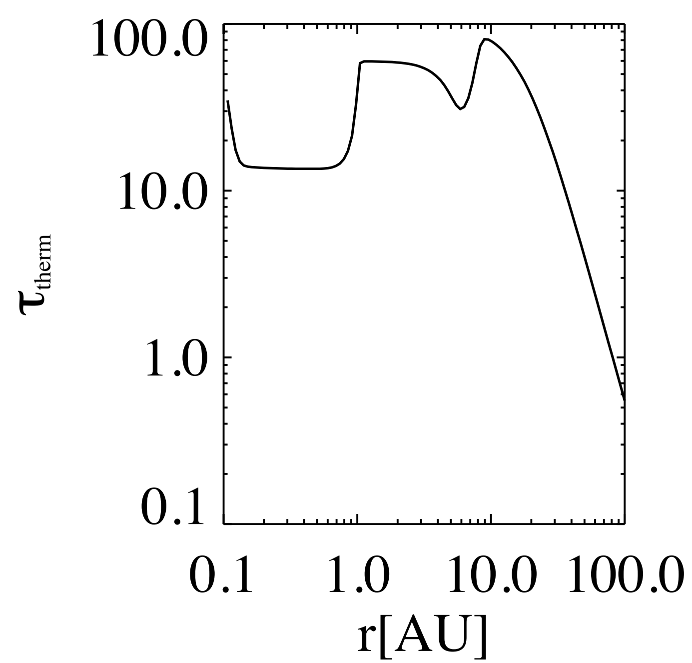
$$N^2 = -\frac{1}{\gamma}\left(\frac{H}{R}\right)^2 \beta_s\beta_p\Omega^2$$

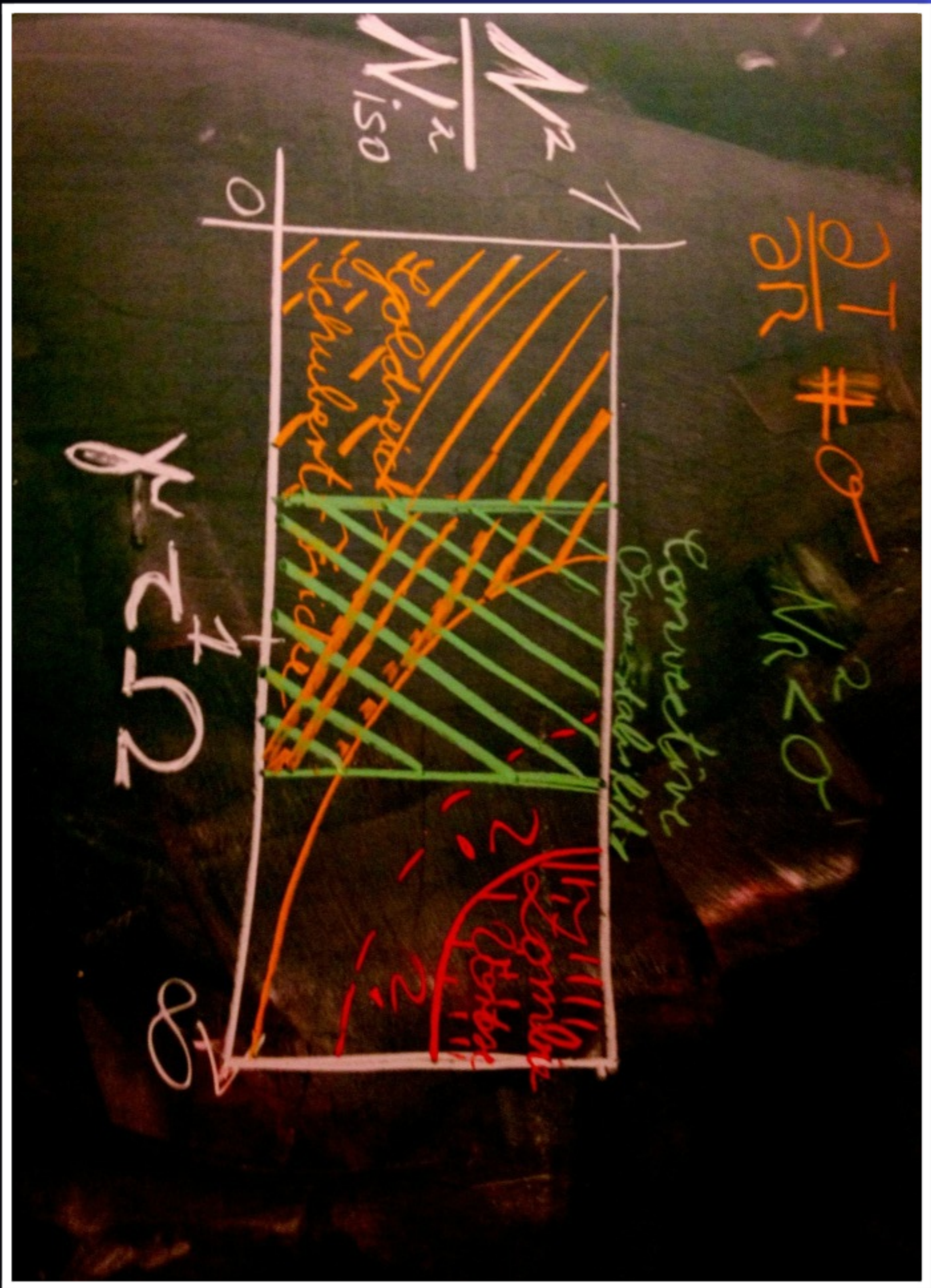
$$Ri = -\frac{2}{3\gamma}\left(\frac{H}{R}\right)^2 \beta_p\beta_s$$

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

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







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

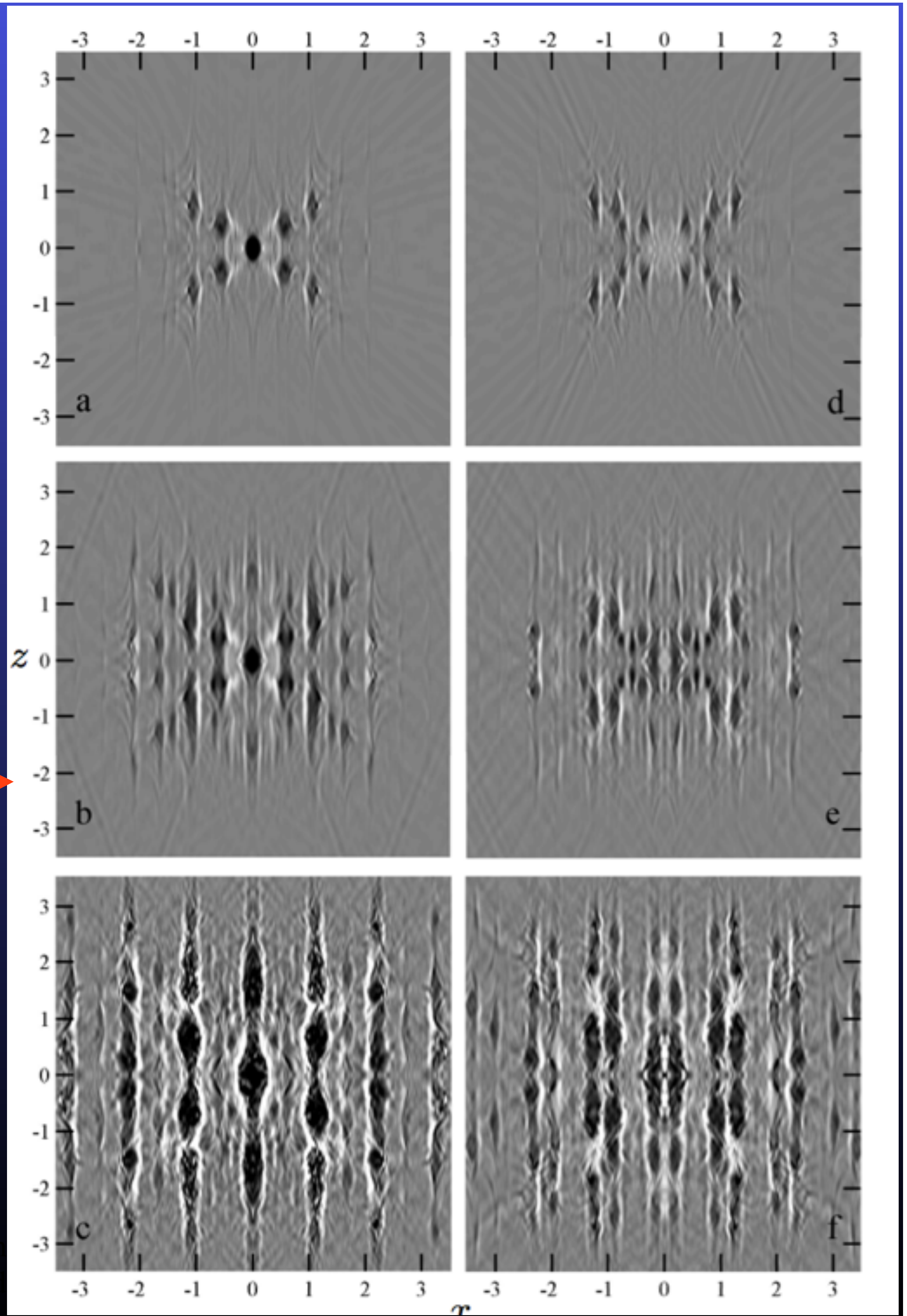
Philip S. Marcus, Suyang Pei, Chung-Hsiang Jiang, and Pedram Hassanzadeh
Department of Mechanical Engineering,
University of California, Berkeley, California, 94720, USA

(Dated: September 29, 2012)

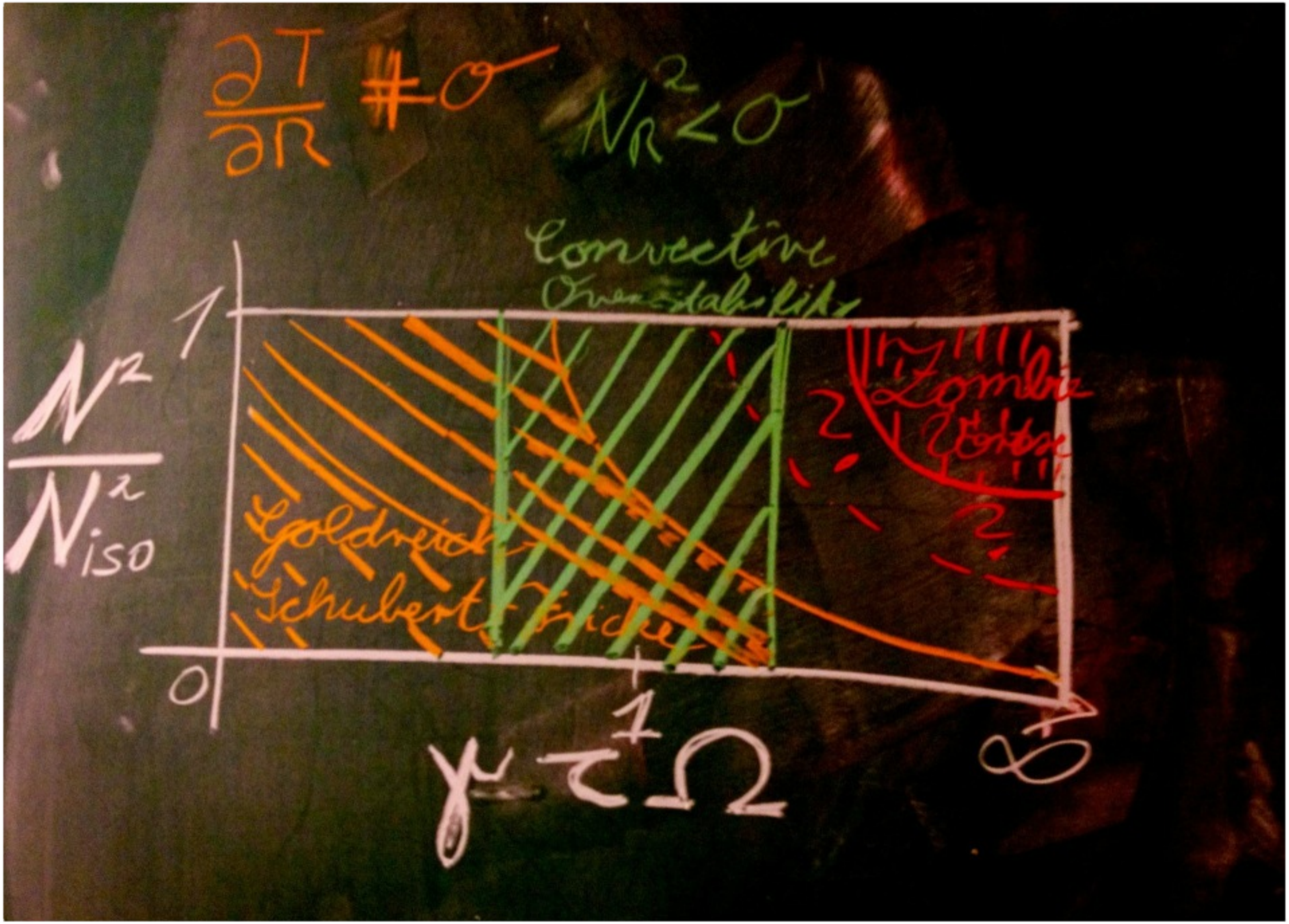
~~$4\tau^2 N_z^2 < 1$~~

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

~~$\tau\Omega \approx 1$~~

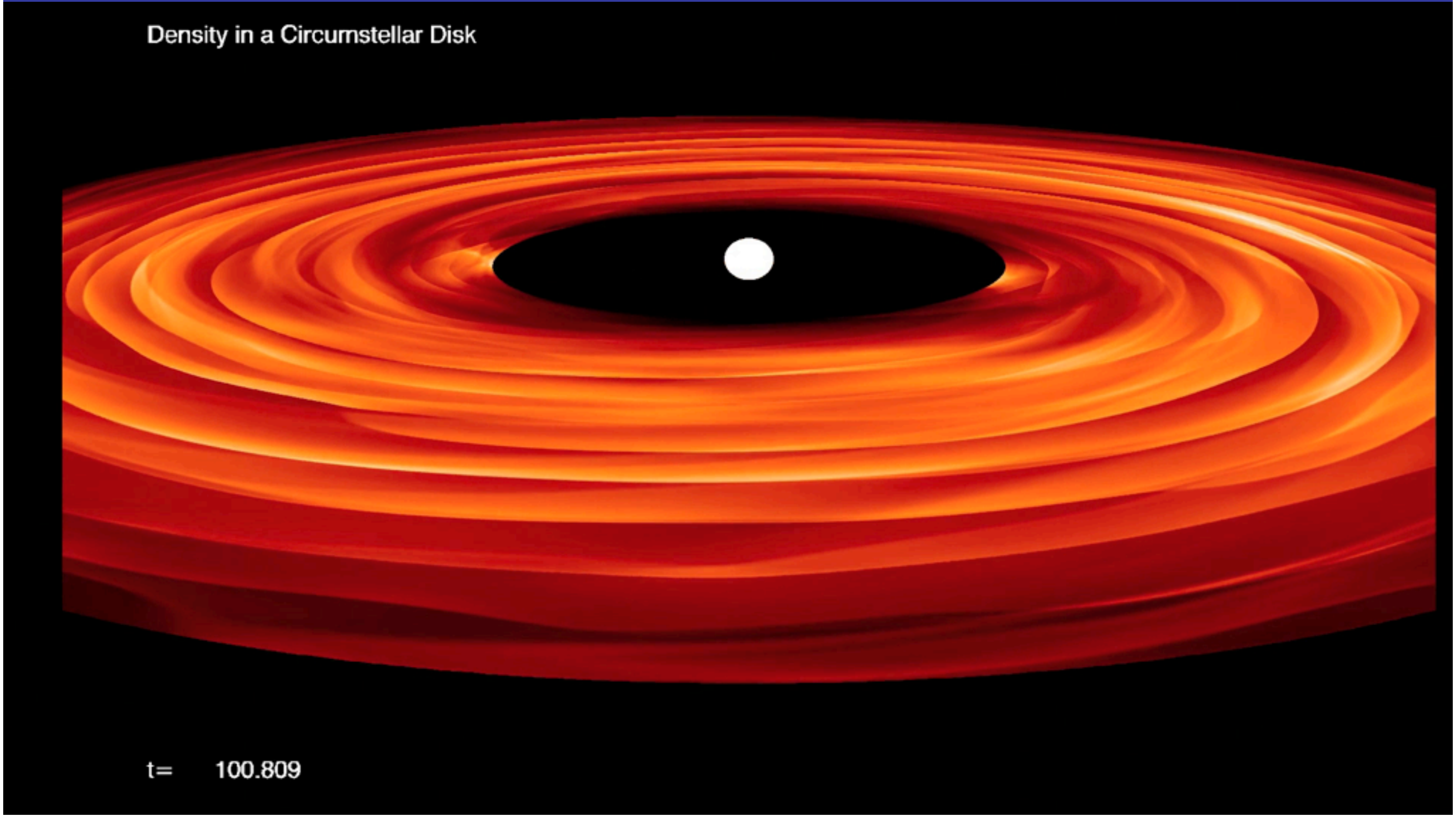


Pedram Hassanzadeh, and Daniel Lecoanet


∂T/∂R ≠ 0
N_R^2 < 0
Convective
Overstability
N^2 / N^2_iso
1
0
Goldreich-
Schubert-Fricke
Zombie
1
∞
γ^μ τ Ω

Convective Overstability: Klahr and Hubbard 2014:
For given radial pressure and entropy gradient:

$$\omega_m^4 \left(1+\frac{i}{\gamma\tau\omega}\right) - \omega_m^2 \left[\kappa_R^2 \left(1+\frac{i}{\gamma\tau\omega}\right) + N_R^2 + N_z^2\right] + \Omega^2 z \left(\kappa_r^2 \frac{1}{\gamma C_v}\partial_z S_0 - \kappa_z^2 \frac{1}{\gamma C_v}\partial_R S_0\right) = 0$$

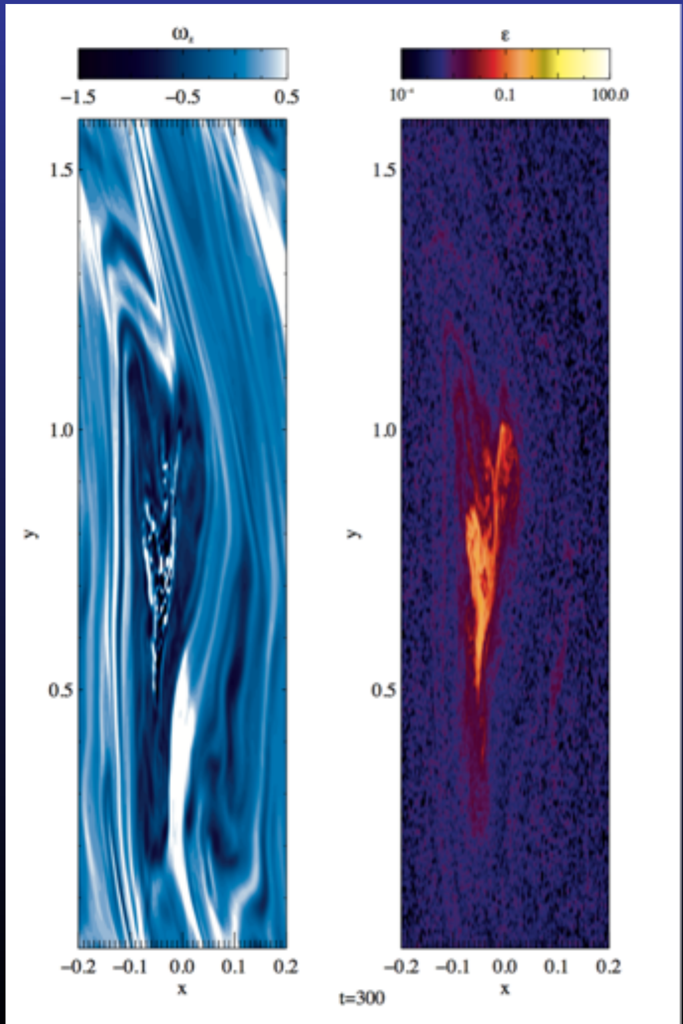


Basic Picture 2: Starving Mode...

Huge Concentration in traps: 100-10000

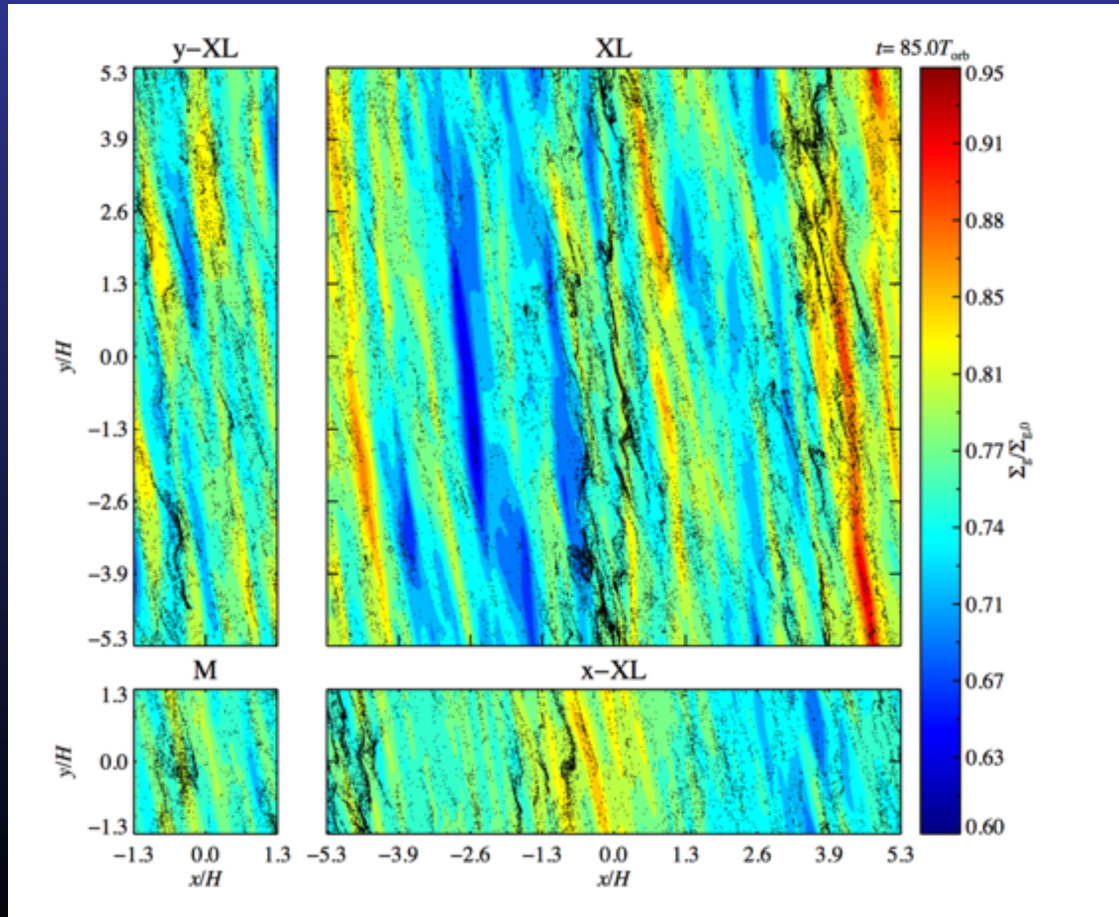
Vortices: 1-10 AU

Raettig 2012



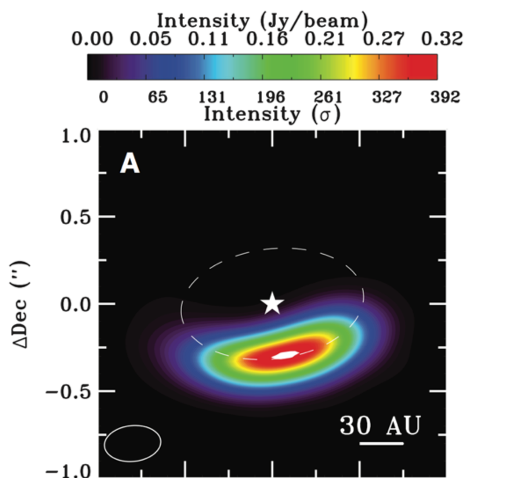
Zonal Flows: > 10 AU

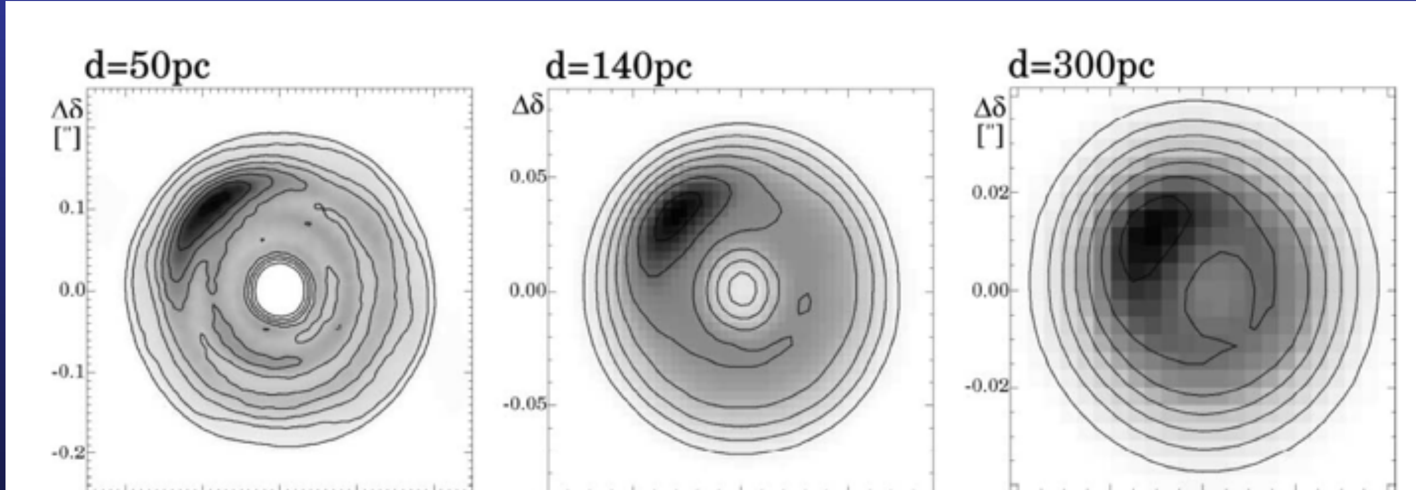
Dittrich et al. 2013



A Major Asymmetric Dust Trap in a Transition Disk

Nienke van der Marel,[1*] Ewine F. van Dishoeck,[1,2] Simon Bruderer,[2] Til Birnstiel,[3] Paola Pinilla,[4] Cornelis P. Dullemond,[4] Tim A. van Kempen,[1,5] Markus Schmalzl,[1] Joanna M. Brown,[3] Gregory J. Herczeg,[6] Geoffrey S. Mathews,[1] Vincent Geers[7]





The Astrophysical Journal, 578:L79–L82, 2002 October 10

LARGE-SCALE VORTICES IN PROTOPLANETARY DISKS: ON THE OBSERVABILITY OF POSSIBLE EARLY STAGES OF PLANET FORMATION

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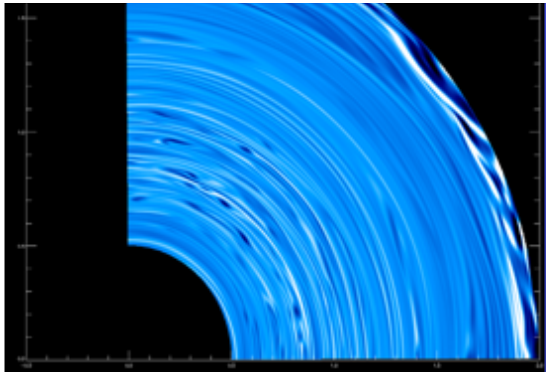
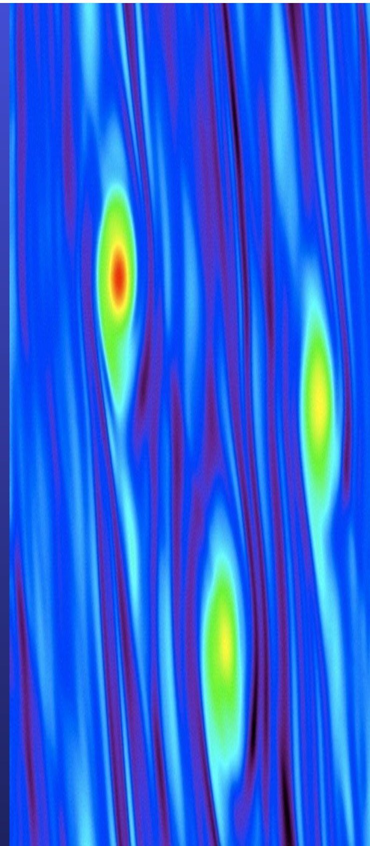


Conclusions

GSF: Nelson, Umurhan & Gressel et al . 2013
CO: Klahr & Hubbard 2014, Lyra 2014



- 2 new / rediscovered instabilities that should occur in sufficiently MHD dead zones.
- 3D Properties and fate of vortices?
- 3D full radiation hydro runs… revisiting: Klahr & Bodenheimer 2003