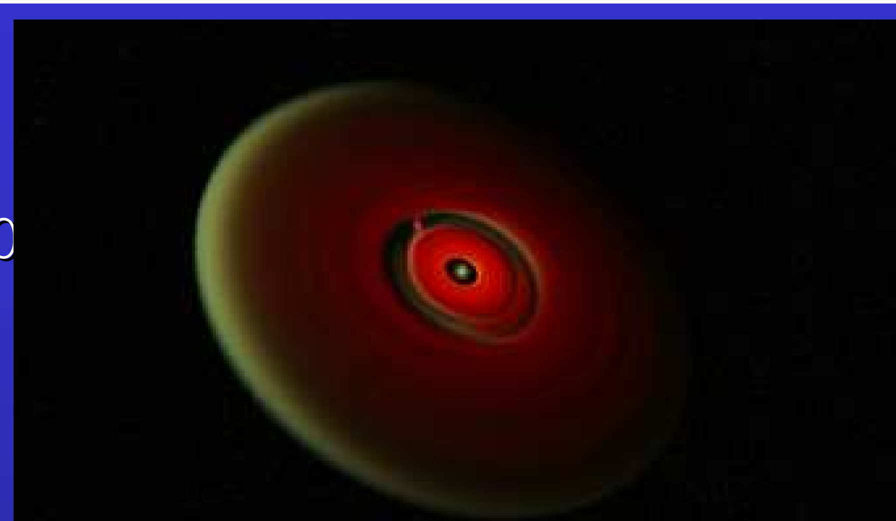
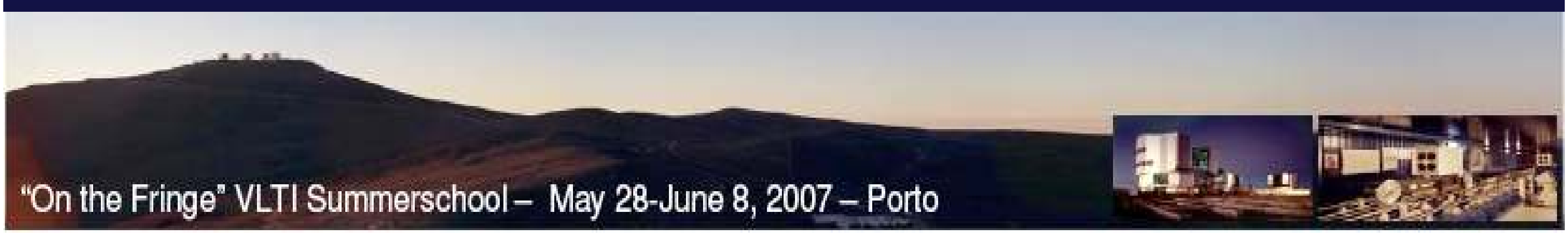
Porto,
June. 6th 200



"From disks to planetesimals II - Disk-planet interaction"

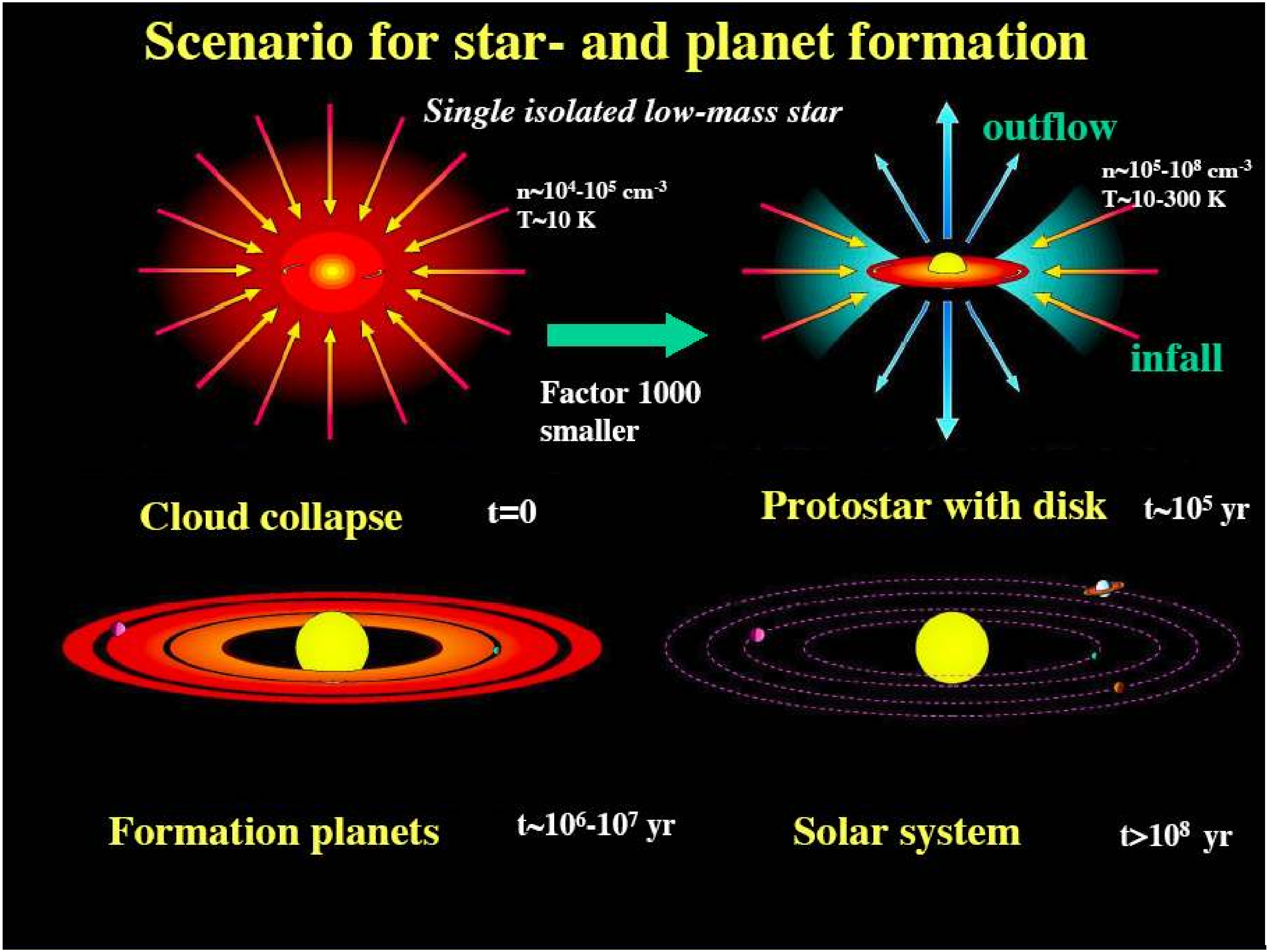
Hubert Klahr,

Max-Planck-Institut für Astronomie, Heidelberg



"from boulders via planetesimals to planetary systems"

1. dusty storms: dust transport in turbulent protoplanetary disks
2. gravoturbulent planetesimal formation: particle concentration in turbulence and N-body simulations
3. core accretion - gas capture: Pollacks model
4. nascent planets: observability of planet disk interaction and migration of young planets
5. system formation: population synthesis



Scenario for star- and planet formation
Single isolated low-mass star
$n \sim 10^4$-10^5 cm^{-3}
T~10 K
outflow
$n \sim 10^5$-10^8 cm^{-3}
T~10-300 K
infall
Factor 1000
smaller
Cloud collapse
t=0
Protostar with disk
$t \sim 10^5$ yr
Formation planets
$t \sim 10^6$-10^7 yr
Solar system
$t > 10^8$ yr

protoplanetary storms:

turbulence in the solar nebula

- Why do we need dust traps?
- Convection
- Dust trapping mechanisms

Planetesimal Formation- Coagulation and Sedimentation Collissions & sticking OR self gravity

What is the influence of turbulence?

1. Preventing sedimentation by stirring things up. -> Observation
2. Radial diffusive transport of grains. -> Observation (crystalline)
3. Generating concentrations of boulders.

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Klahr and Bodenheimer 2006

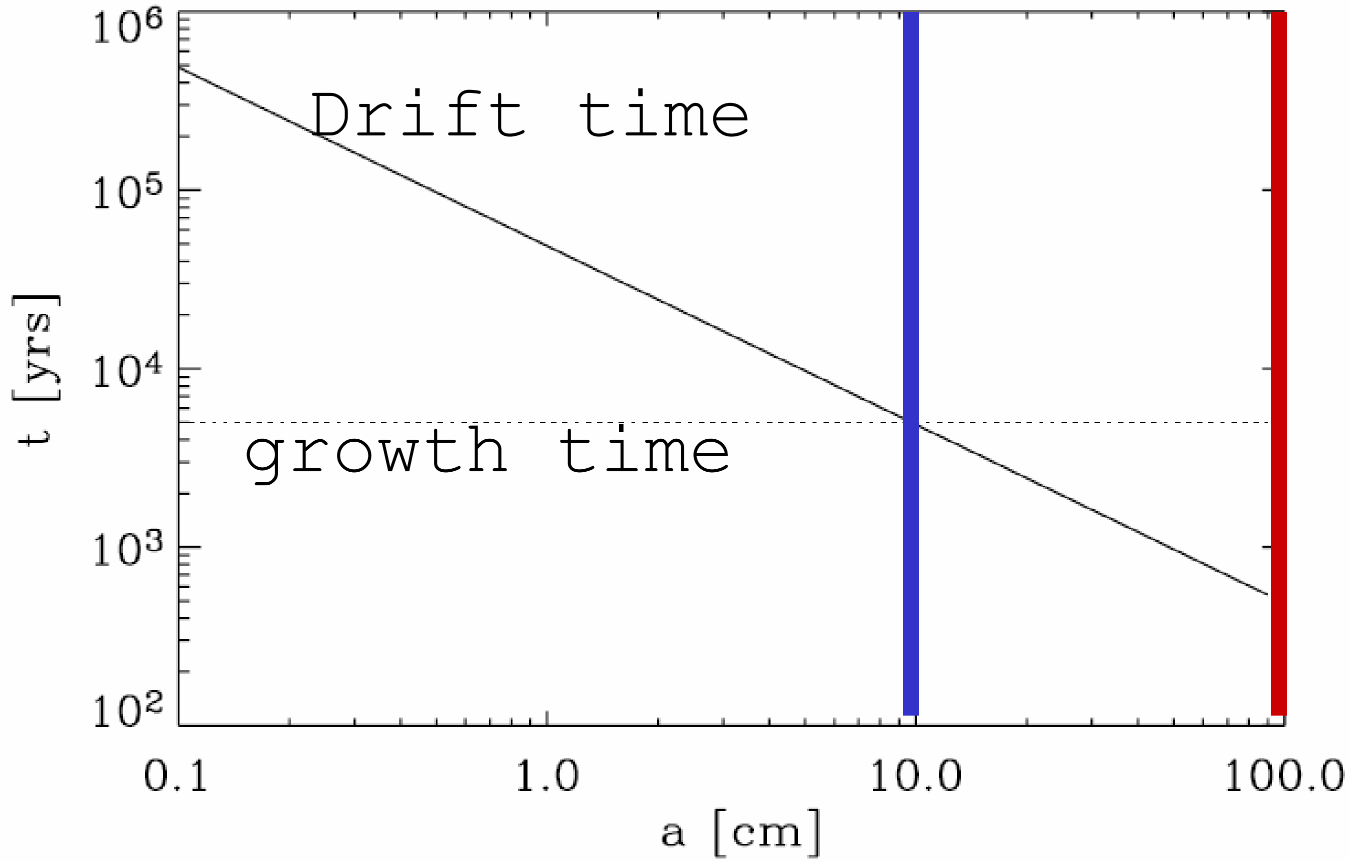


FIG. 1.—Comparison between drift time (*solid line*) and growth time (*dotted line*) for solids as a function of size. The values are calculated using the equations from this paper for a location of 7.5 AU in a minimum mass solar nebula.

particles drift 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

Klahr and Bodenheimer 2006

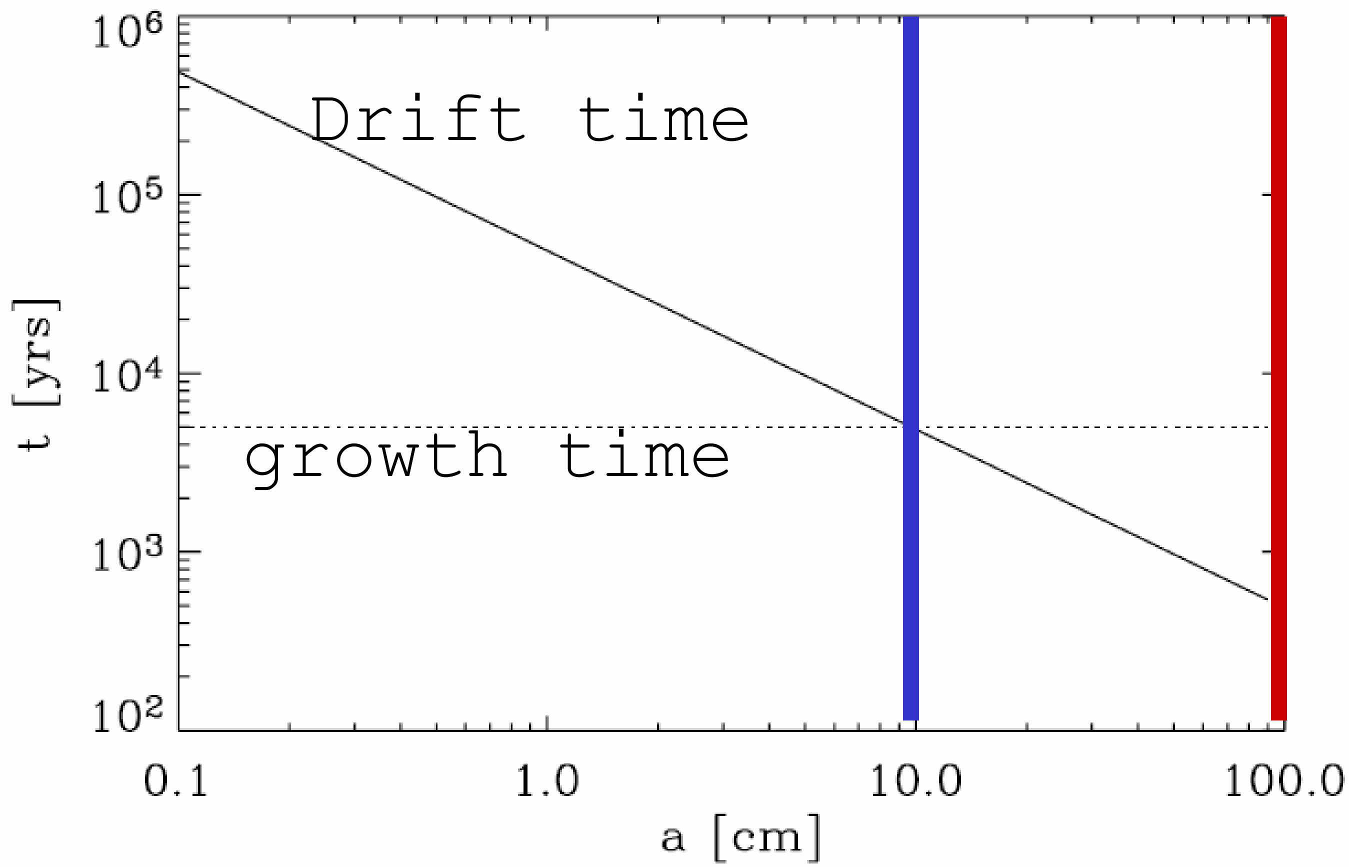


FIG. 1.—Comparison between drift time (*solid line*) and growth time (*dotted line*) for solids as a function of size. The values are calculated using the equations from this paper for a location of 7.5 AU in a minimum mass solar nebula.

PHYSICS OF THE PRIMITIVE SOLAR ACCRETION DISK

A. G. W. CAMERON
Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory, Cambridge, Mass., U.S.A.

(Received 18 October, 1977)

Besides meridional currents and infall: thermal convection

Still another driving force could arise from thermally-driven convection. This would require that superadiabatic temperature gradients exist within the gas in a region where there is a significant gas pressure gradient. It is argued below that the temperature gradient in the vertical direction in the disk will be strongly subadiabatic. The results of the study indicate that the temperature gradient along the midplane of the disk is approximately isentropic, except in the region where the midplane temperatures exceed about 2000 K. This region is strongly superadiabatic and may give rise to an extensive region of thermally-driven convection at the midplane.

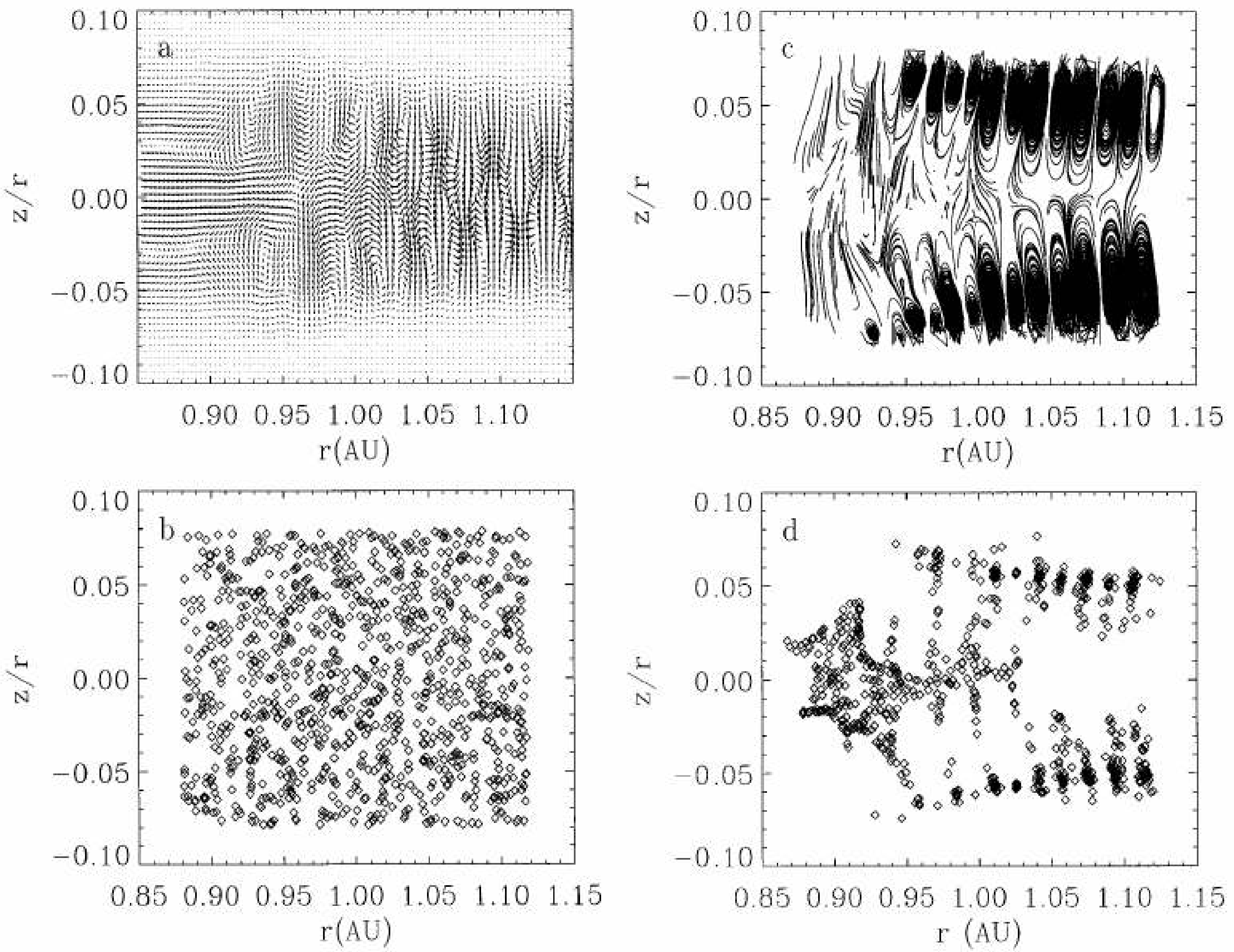
The Moon and the Planets 18 (1978) 5–40.

Radiation Hydro of PP Disks

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Klahr, Kley and Henning 1999

Klahr and Bodenheimer 2003



Klahr & Henning 1

Particle response to the gas flow 1:

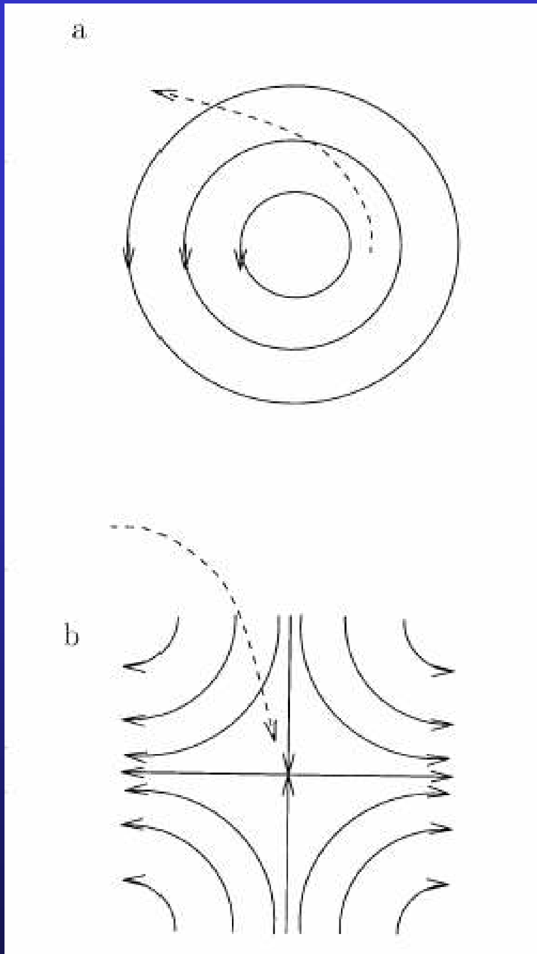
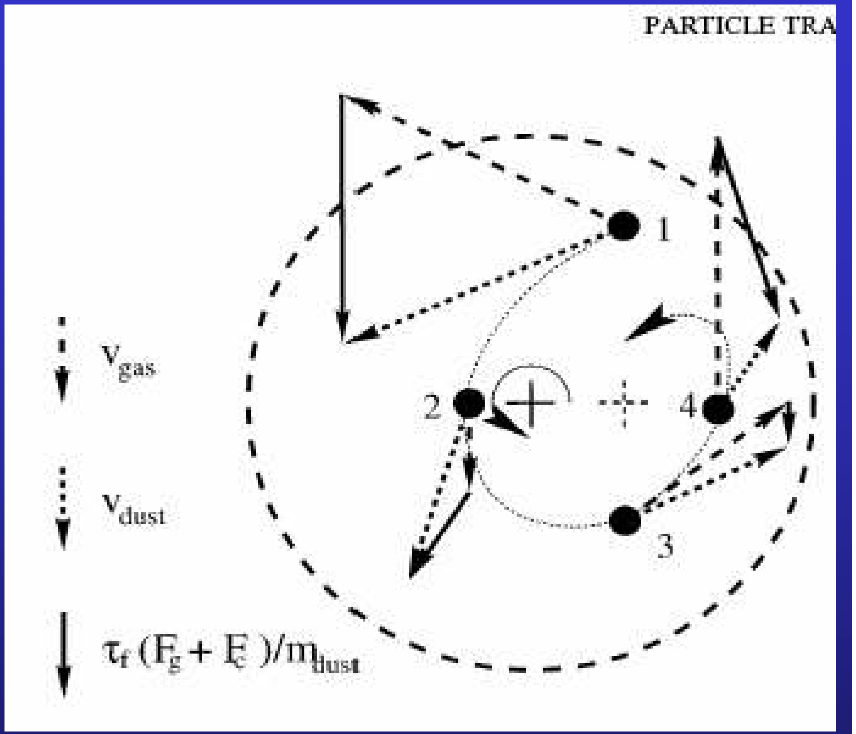


FIG. 1. Under laboratory-observed conditions particles (a) spiral out of the vortices (eddy), but (b) collect in convergence zones (strain fields).

Lab condition,

Cuzzi et al.

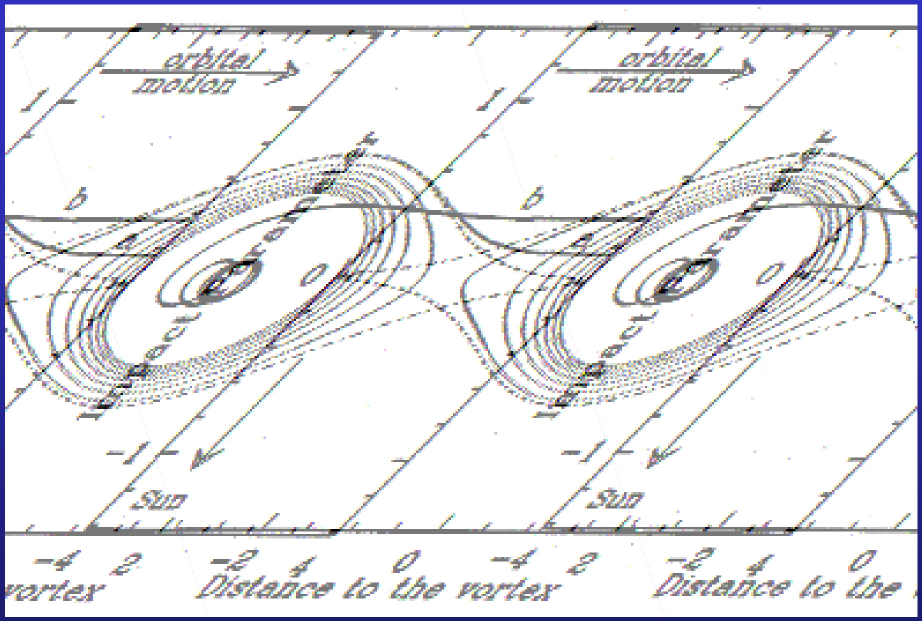


Vortex in the r-z plane:

Aka convection cell particle concentration.

Klahr & Henning 1997

Particle response to the gas flow 2:



Vortices:

Barge & Sommeria 1995

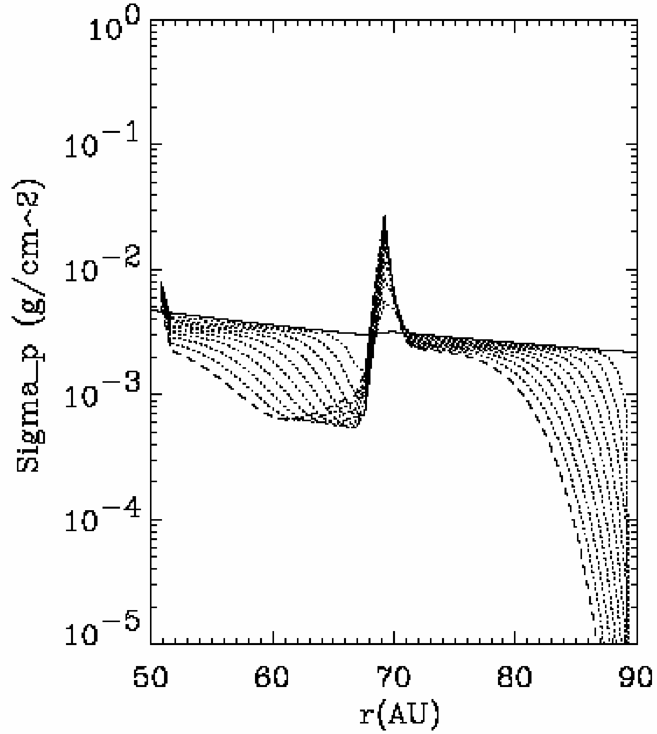
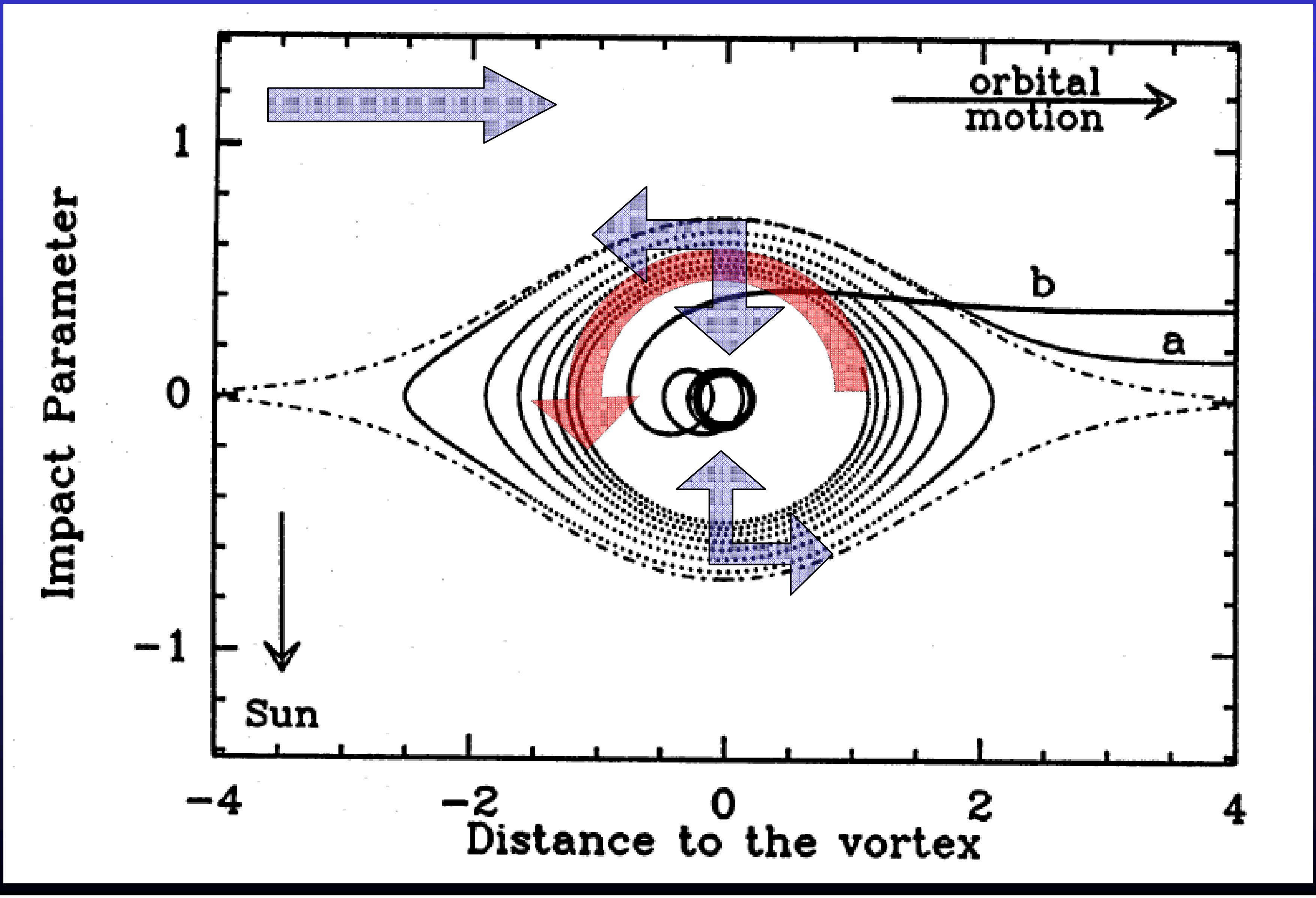


FIG. 7.—Model A: evolution of the 1 m size particle surface density distribution for the model in Fig. 2. The solid line gives the initial distribution. The following lines are snapshots every 10^5 yr.

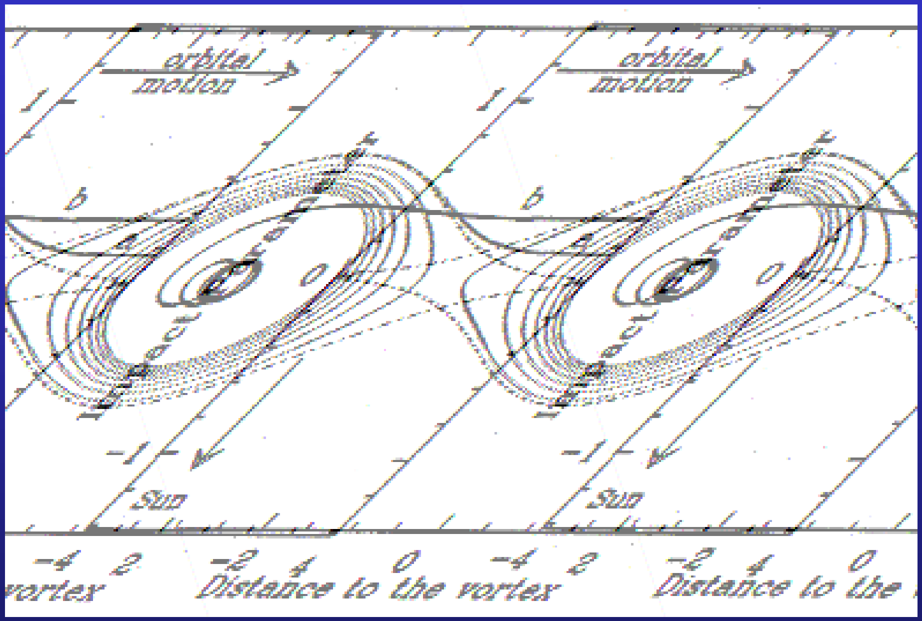
Pressure maxima:

Klahr & Lin 2000

Large particles in vortex:



Particle response to the gas flow 2:



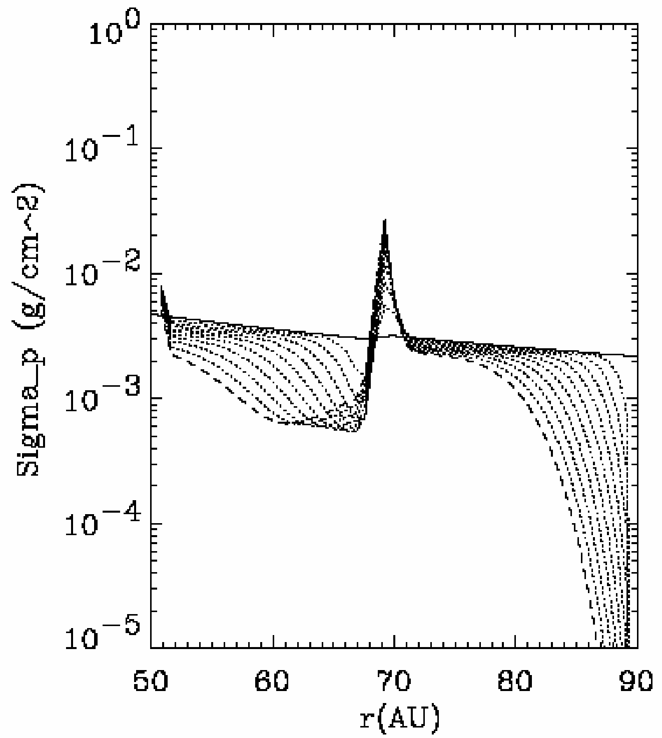


FIG. 7.—Model A: evolution of the 1 m size particle surface density distribution for the model in Fig. 2. The solid line gives the initial distribution. The following lines are snapshots every 10^5 yr.

Vortices:

Barge & Sommeria 1995

Pressure maxima:

Klahr & Lin 2000

Small particles in pressure maxima

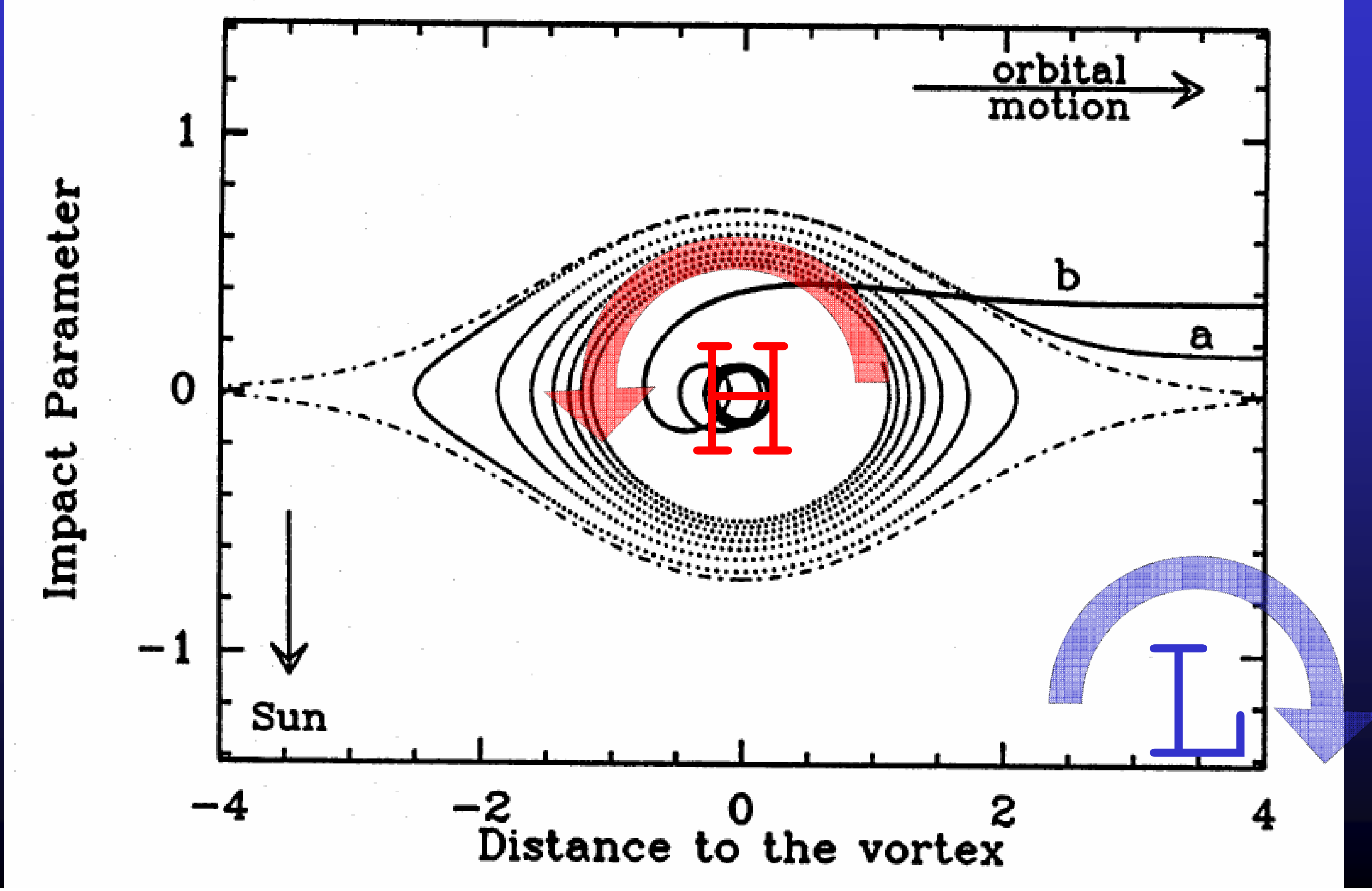
$$
\begin{aligned}
\partial_t v_g &= -\frac{1}{\rho}\nabla p + \mathrm{forces} \\
\partial_t v_d &= -\frac{v_d - v_g}{\tau_f} + \mathrm{forces}
\end{aligned}
$$

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

:

Klahr & Lin 2000

Small particles in pressure maxima e.g. a vortex



No self sustained convection possible

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

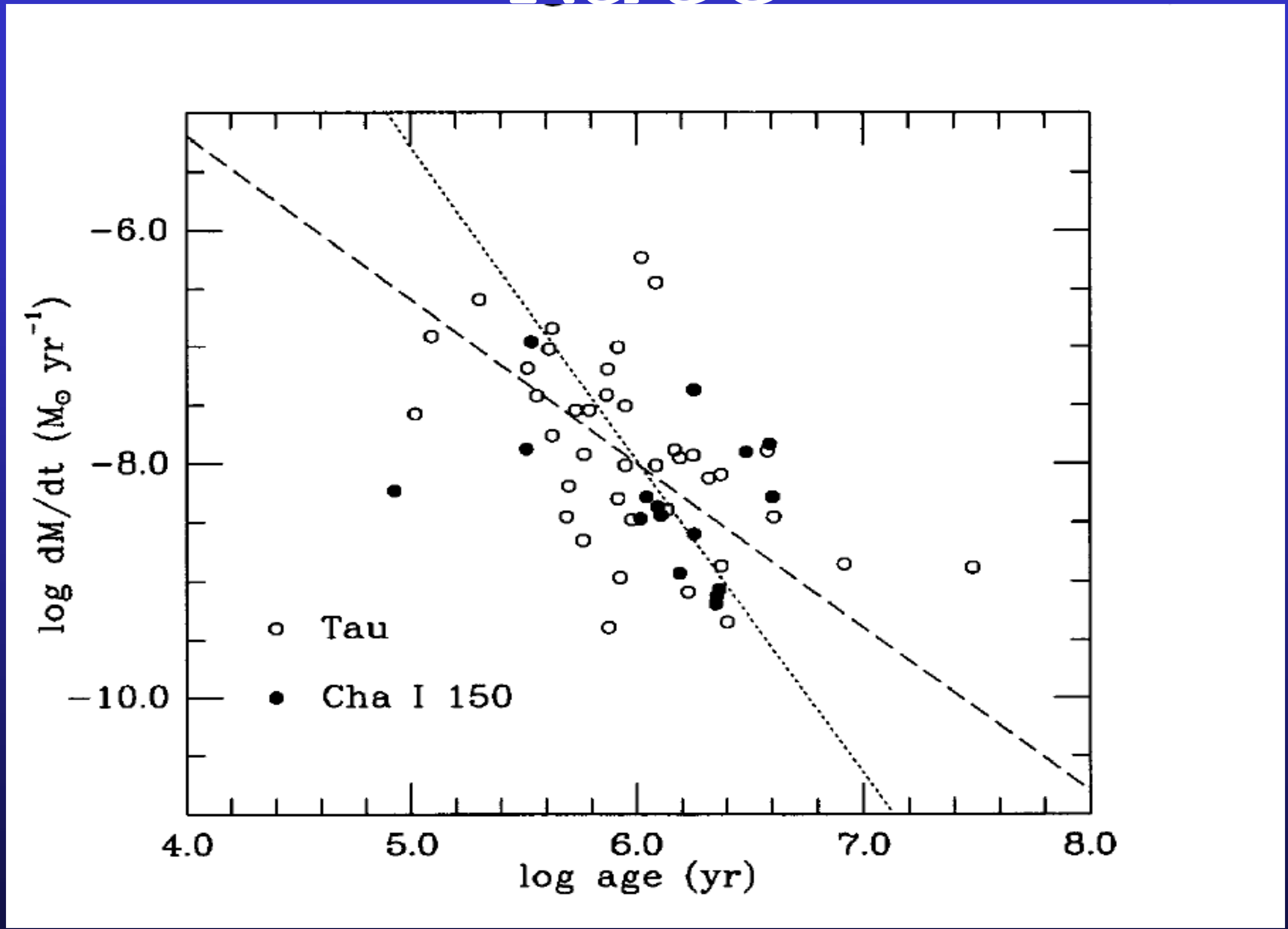
Klahr and Bodenheimer 2003; Klahr 2004;
Johnson & Gammie 2005; ...

magnetic storms:

turbulence in a protoplanetary disk

- Turbulence as a prerequisite for transport of dust
- 2D Simulations of active and dead zones

Age versus Accretion Rate



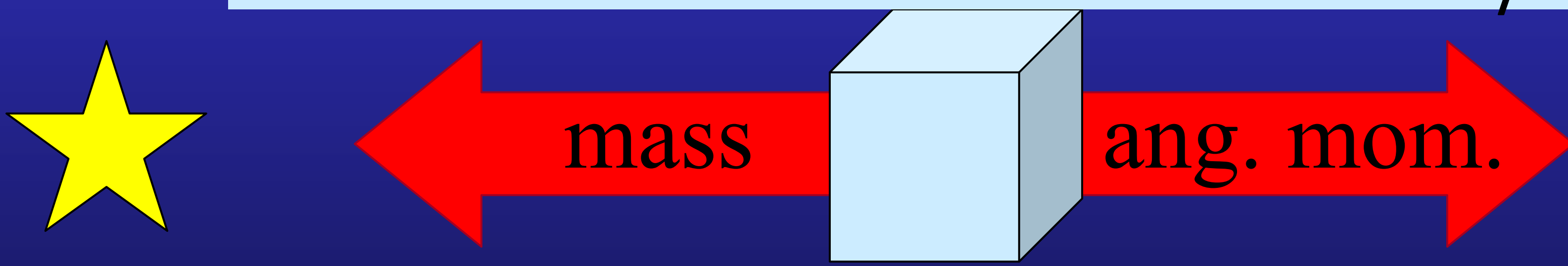
Hartmann et al. 1998, 2006

alpha = 0.01

WHY DO T TAURI DISKS ACCRETE?

Accretion in a rotating system is only possible if matter looses its angular momentum!

viscous stress tensor: $\boldsymbol{T_{r\,\phi}}$



Viscosity could do this,
but molecular viscosity is far too low.
Thus one invokes turbulent viscosity!

Possibilities for Turbulence and angular momentum transport:

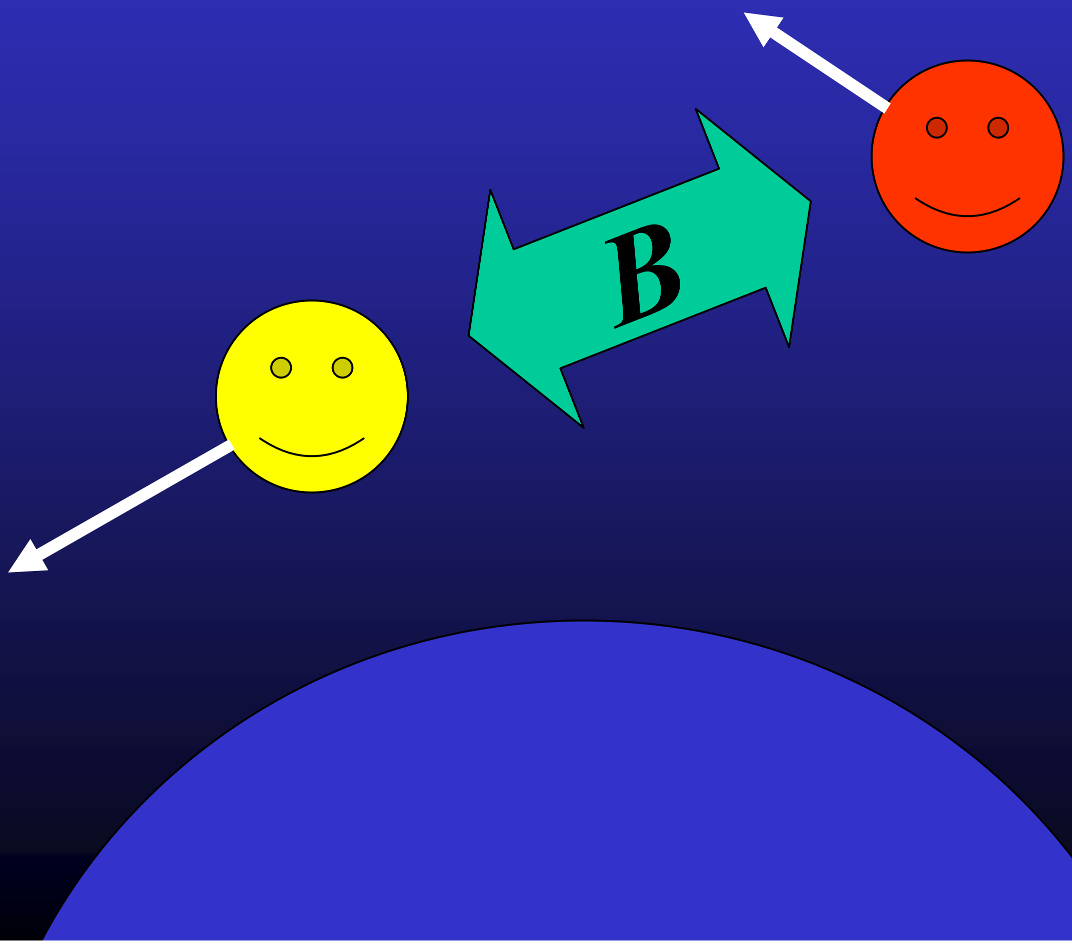
1. Non-Linear Shear Instability:	Richard et al. 2003	?
2. Self Gravity:	Toomre 1964	(+)
3. Thermal Convection:	Ryu & Goodman 1992	-
4. Magneto (Rotational) Instability:	Balbus & Hawley 1992	(+)
5. Baroclinic Instabilities:	Klahr & Bodenheimer 2003	(+)

Dependent on time and location within the disk, i.e. ionization state and temperature structure, one has most likely a mix of 2,4 and 5!

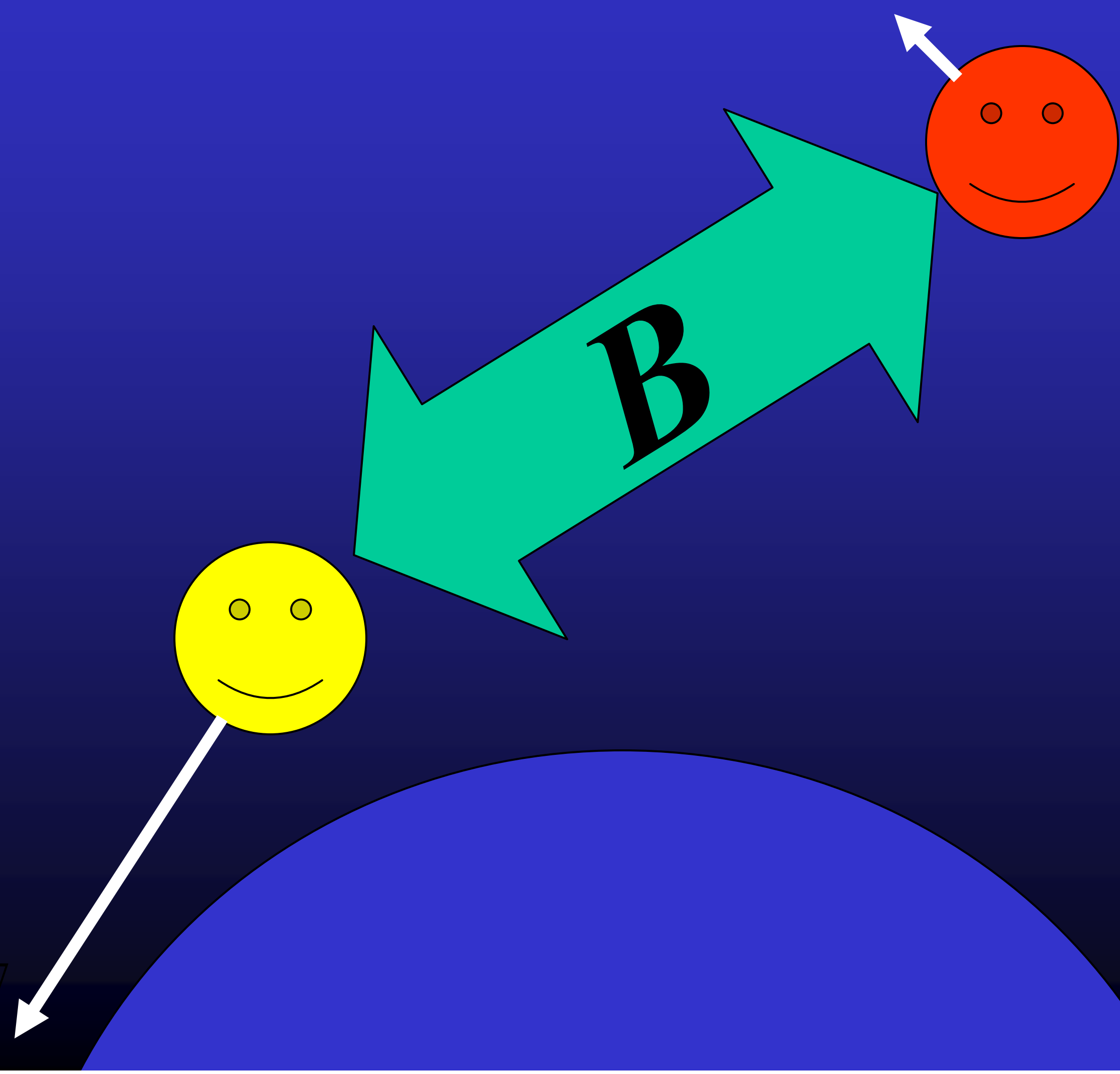
Ionized accretion disk around a black hole!
Simulation by John Hawley:

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

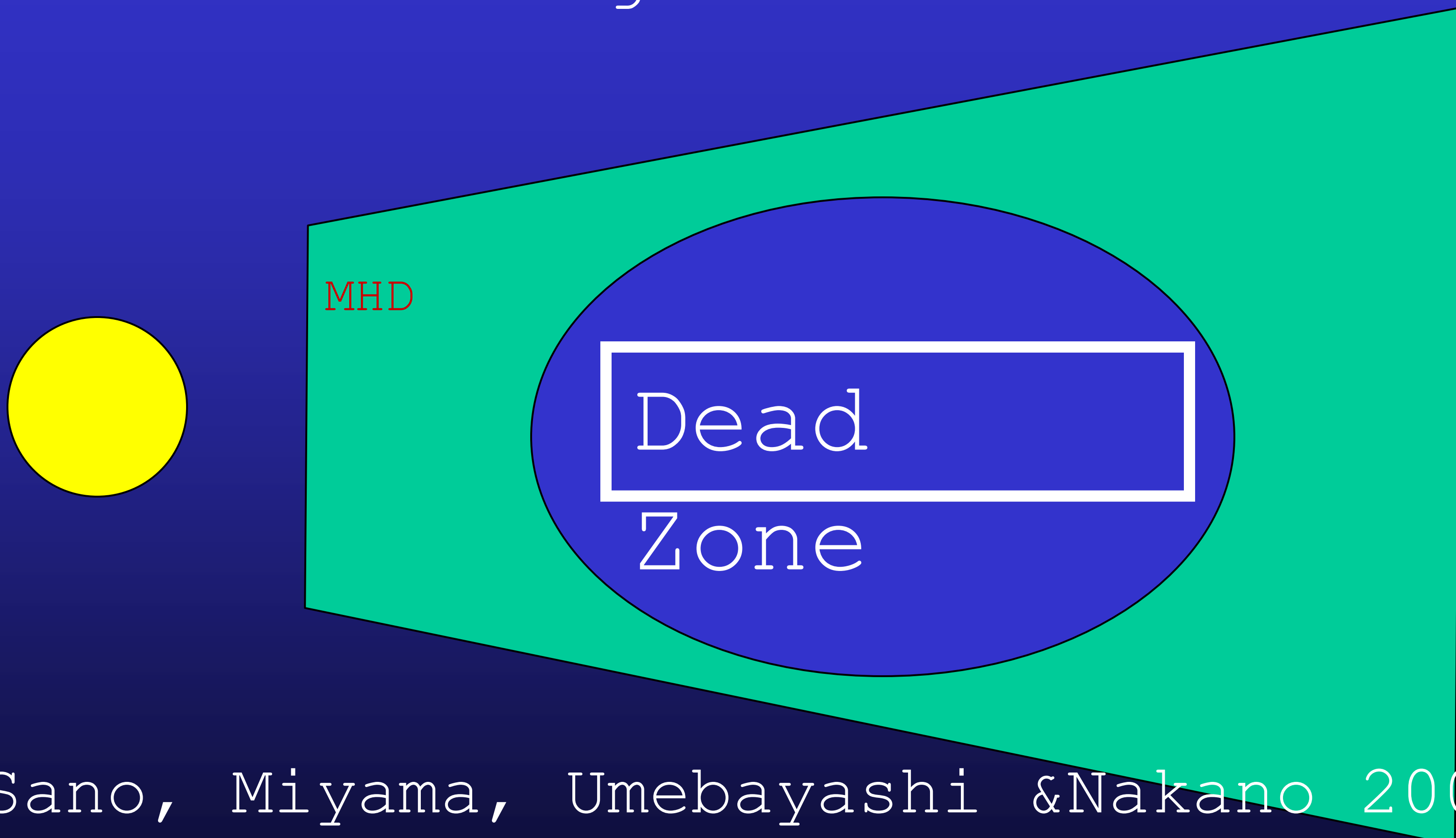
MRI: a.k.a - Rockets in an earth orbit accelerate when they break!



MRI: a.k.a - Rockets in an earth orbit accelerate when they break!



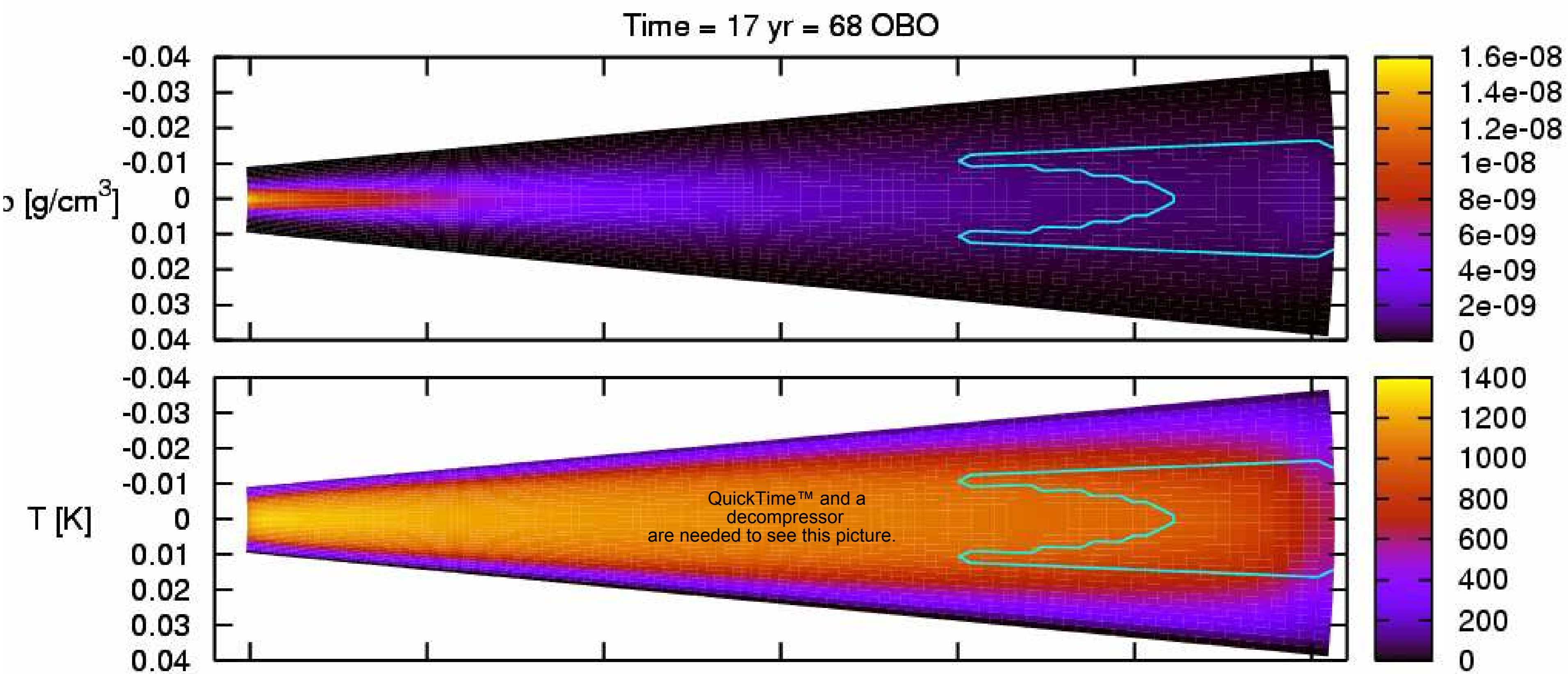
At least part of a proto planetary disk may not be ionized enough for MRI to work!



Sano, Miyama, Umebayashi &Nakano 2000
Fromang, Terquem, & Balbus 2002
Semenov, Wiebe, & Henning 2004

2D axisymmetric simulation of active/dead zone interaction.

Wünsch, Gawryszczak, Klahr & Rozyczka, 2006



Conclusion...

Sometimes it is stormy...

...sometimes the sun shines.

Direct observations of the turbulent state of a disk as function of space and time is difficult...

...so lets now investigate what are the effects IF the disk is turbulent.

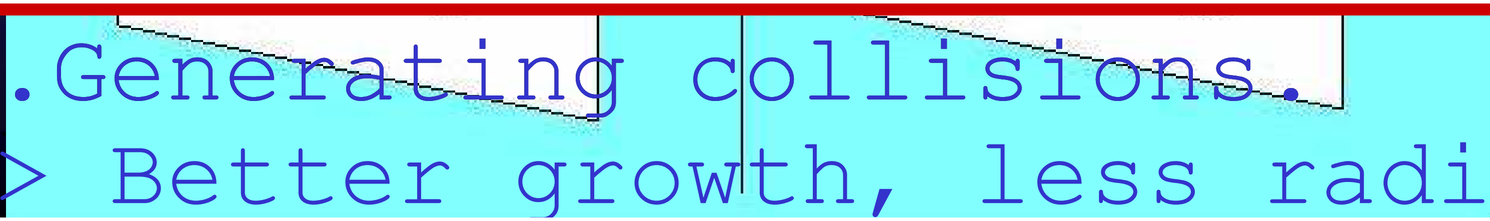
dusty storms: diffusion in a turbulent protoplanetary disk

- 3D Simulations of MHD turbulence
- Diffusion of smallest solids by turbulence
- Dependence on vertical B-field

Motivation: Planetesimal Formation- Coagulation and Sedimentation

What is the influence of turbulence?

1. Preventing sedimentation by stirring things up.
2. Radial diffusive transport of grains.
3. Local concentration of boulders.
4. Generating collisions.



12

=> Better growth, less radial

Dust Diffusion in Protoplanetary Discs by Magnetorotational Turbulence

Anders Johansen[1] and Hubert Klahr

johansen@mpia.de

Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

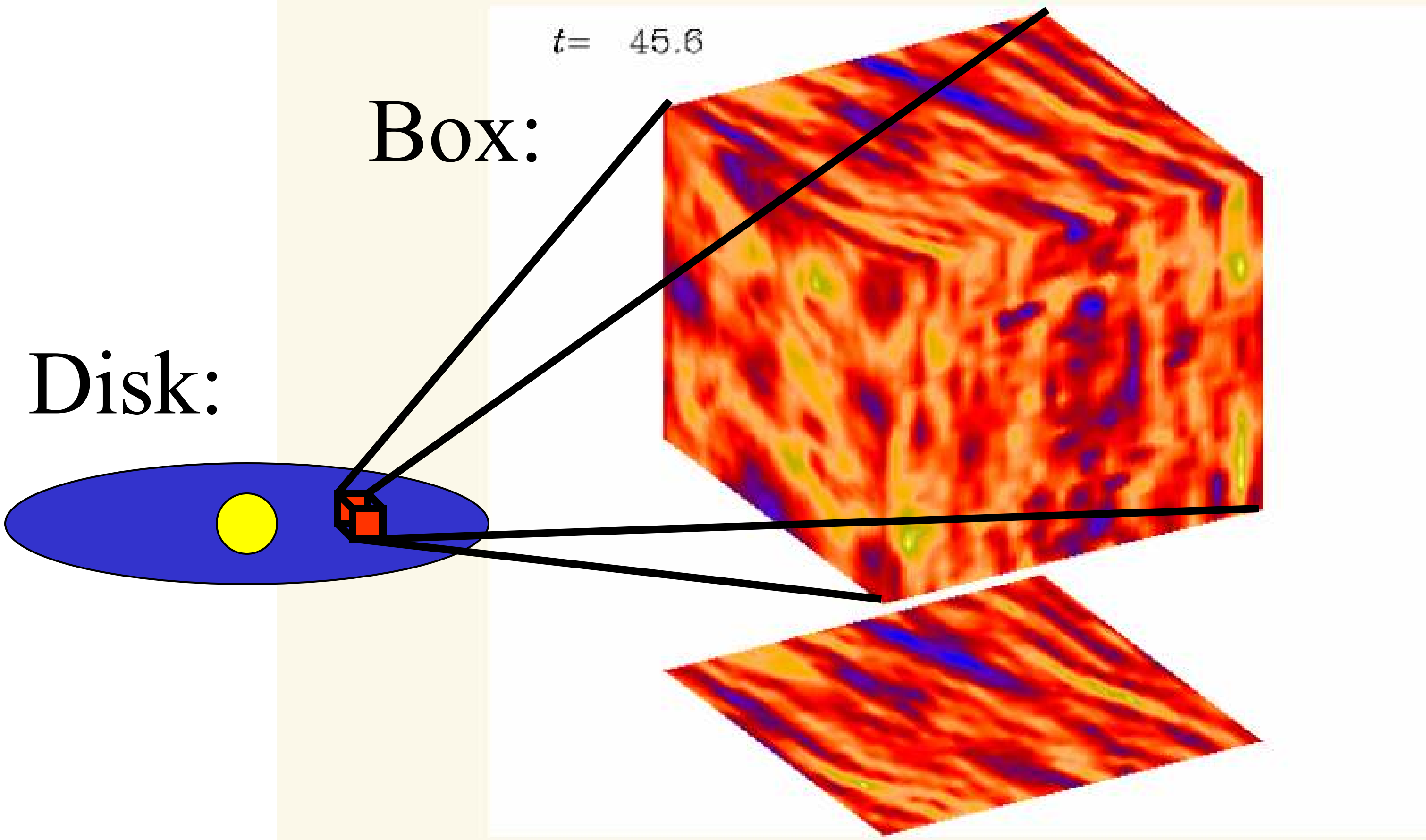
Johansen & Klahr 2005

SMALL GRAINS e.g. 0.1 $\mu \leq a \leq$ 1cm @ 5AU.

Small means a friction time smaller than the orbital period

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

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Diffusion of Dust in MHD Turbulence.

Dust is treated as a fluid without pressure, which couples to the gas motion via friction.

No additional forces e.g. gravity.

Colors: dust density
yellow = high
blue = low

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Drawback:

Diffusion of dust vs. settling.

Dust is treated as a fluid without pressure, which couples to the gas motion via friction and feels an additional force field.

The forces are only for the measurement of diffusivity.

Benefit: precise measurement of diffusivity

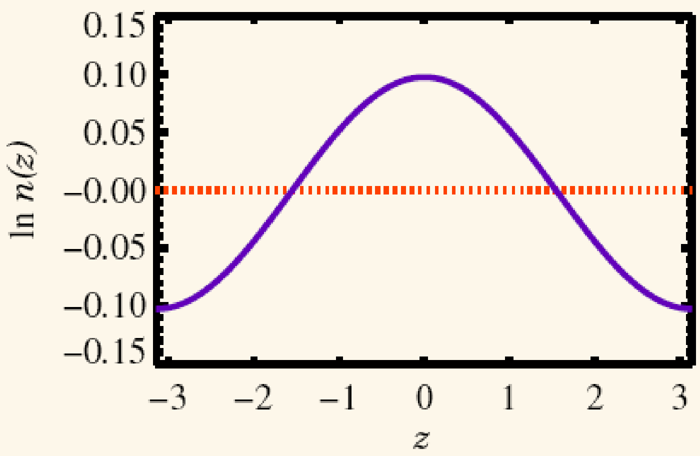
Diffusion equilibrium

External force field drives diffusive equilibrium.

$$g_z = -g_0 \sin(k_z z)$$

Expected equilibrium

$$\ln n(z) = \ln n_0 + \frac{\tau_\mathrm{f} g_0}{k_z D_\mathrm{t}} \cos(k_z z)$$



Amplitude$=\frac{\tau_\mathrm{f} g_0}{k_z D_\mathrm{t}}$

Dust Sedimentation

A vertical force field drives sedimentation.

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

Easy to measure amplitude

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

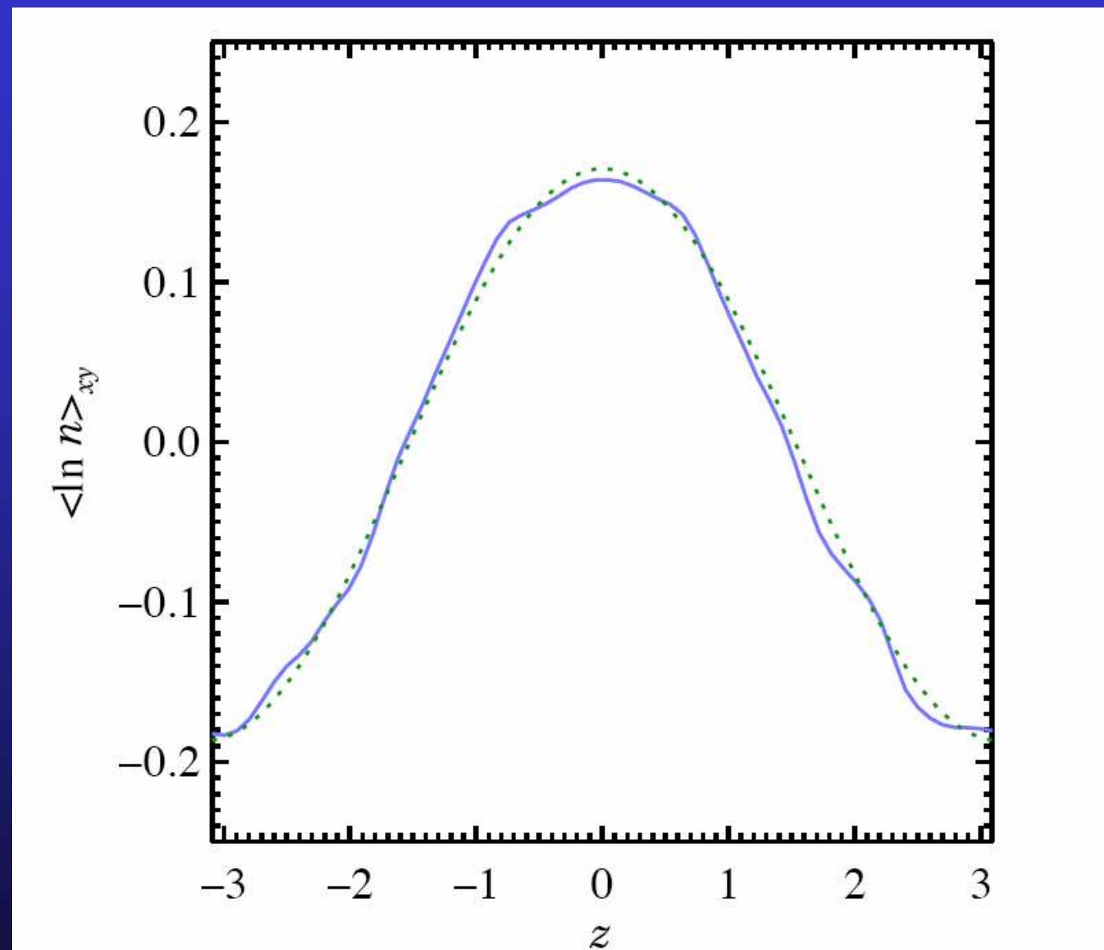
$$\text{Amplitude} = \frac{\tau_{\mathrm{f}}\, g_0}{k_z\, D_{\mathrm{t}}}$$

Dust Sedimentation

A vertical force field drives sedimentation.

Radial and azimuthal average profile

Easy to measure amplitude with good statistics:
⇒Diffusivity



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

Schmidt number:

$$\mathrm{Sc} = \frac{\nu_t}{D_t}.$$

Anisotropic Diffusion!

Run	$\alpha_{\mathrm{t}}/10^{-3}$	$\alpha_{\mathrm{t}}^{(\mathrm{mag})}/10^{-3}$	$D_z^{(\mathrm{t})}/10^{-3}$	$D_x^{(\mathrm{t})}/10^{-3}$	Sc_z	Sc_x
64a_z,x	0.33 ± 0.08	1.47 ± 0.29	1.16 ± 0.12	2.07 ± 0.26	1.55	0.87
64b_z,x	0.33 ± 0.08	1.47 ± 0.29	1.16 ± 0.12	2.07 ± 0.26	1.55	0.87
64c_z,x	0.33 ± 0.08	1.47 ± 0.29	1.12 ± 0.14	2.12 ± 0.75	1.61	0.85
128a_z,x	0.18 ± 0.04	0.83 ± 0.18	0.77 ± 0.12	1.24 ± 0.17	1.31	0.81
128c_z,x	0.18 ± 0.04	0.83 ± 0.18	0.79 ± 0.13	1.27 ± 0.30	1.28	0.80

1. Vertical Diffusion is roughly half as strong as radial Diffusion!
2. Radial Diffusion > Viscosity > Vertical Diffusion
3. Radial Diffusion is more then 7 times stronger than Reynolds Stresses

More recent work:

- **Carballido etal. 2005 find a Schmidt number of 10, but they have vertical net B-field.**
- **Neal Turner also finds Schmidt numbers of unity for vertical diffusion of passive scalars.**
- **Fromang and Papaloizou 2005 are somehow in-between… ;)**

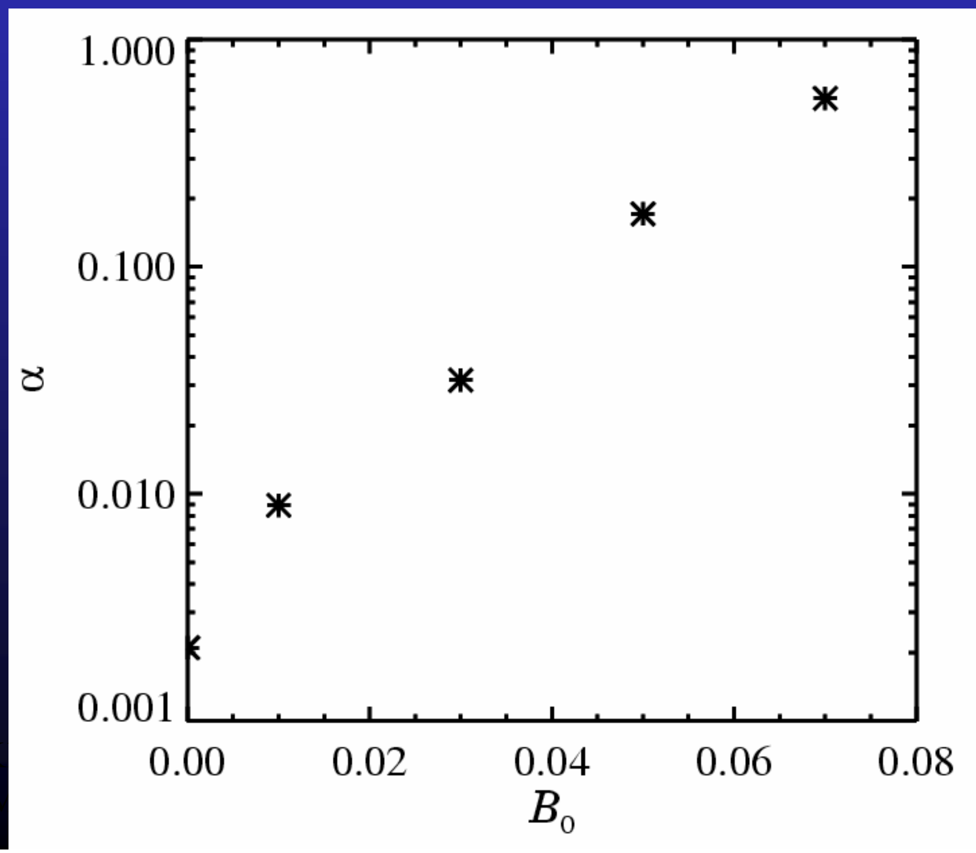
Striking difference?
Assumption on vertical net B-field and thus stronger

Turbulent diffusion in protoplanetary discs: The effect of an imposed magnetic field

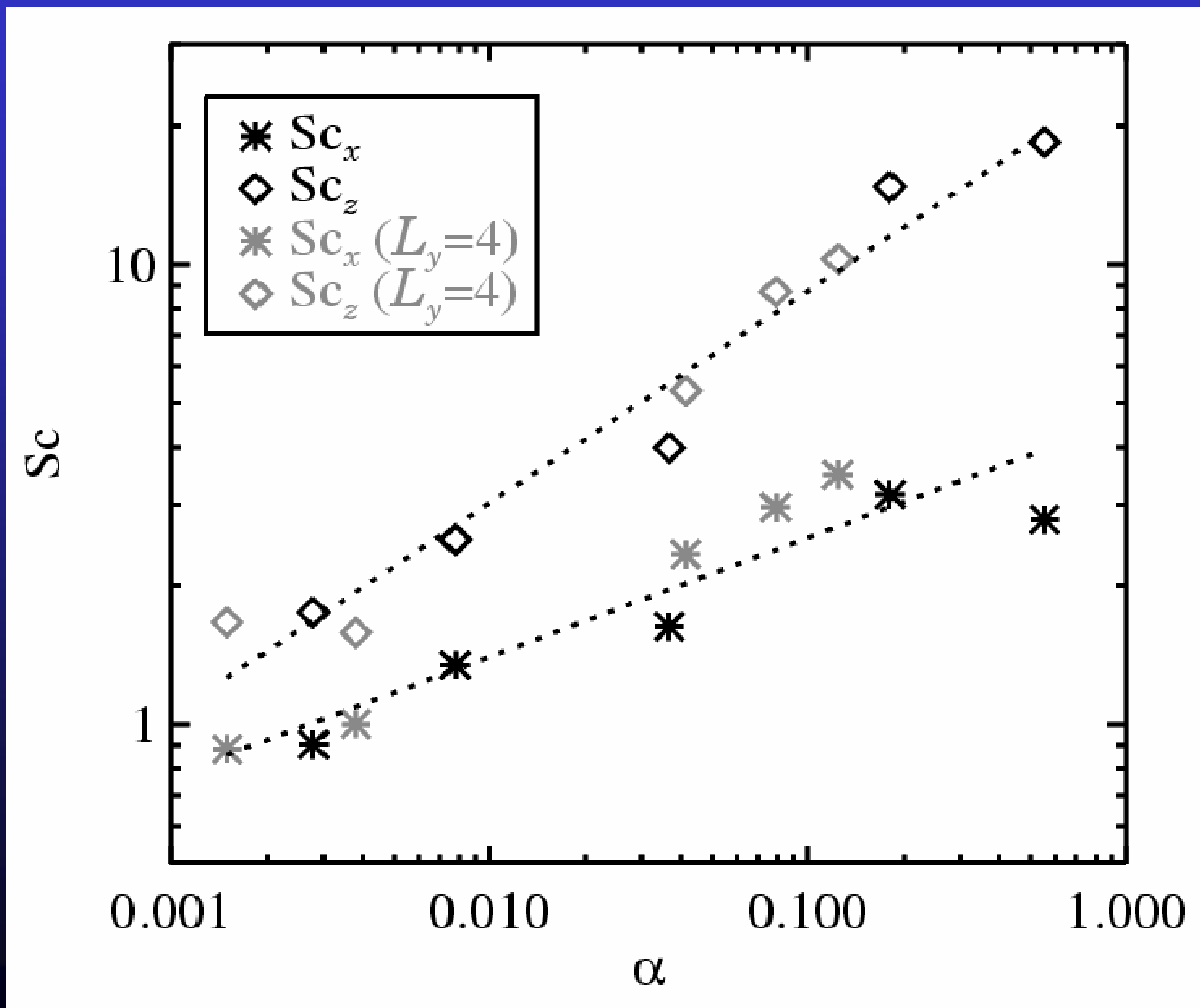
A. Johansen[1], H. Klahr[1] and A.J. Mee[2]
[1]Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[2]School of Mathematics and Statistics, University of Newcastle upon Tyne, NE1 7RU, UK

2006, MNRAS-L

- Strength of MRI depends on boundary conditions, e.g. B_z
- But diffusion is less increased than alpha!



diffusion is not proportional to alpha!



Limits of the Diffusion Picture: Turbulence does also:

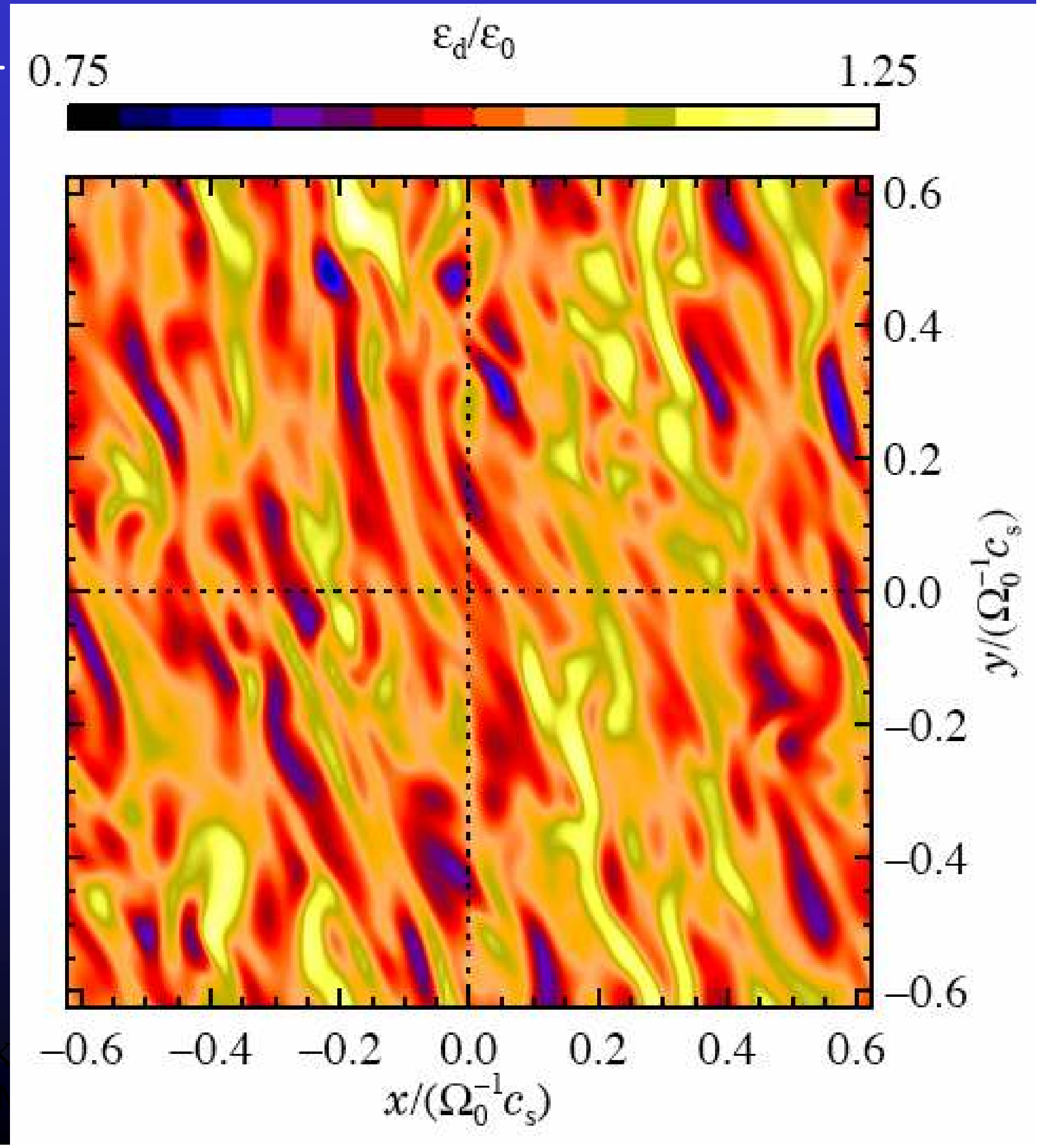
- Size Segregation
- Local concentration of intermediate sized solids

Johanson and Klahr 2005

Concentration of cm sized grains in anti-cyclonic eddies in th

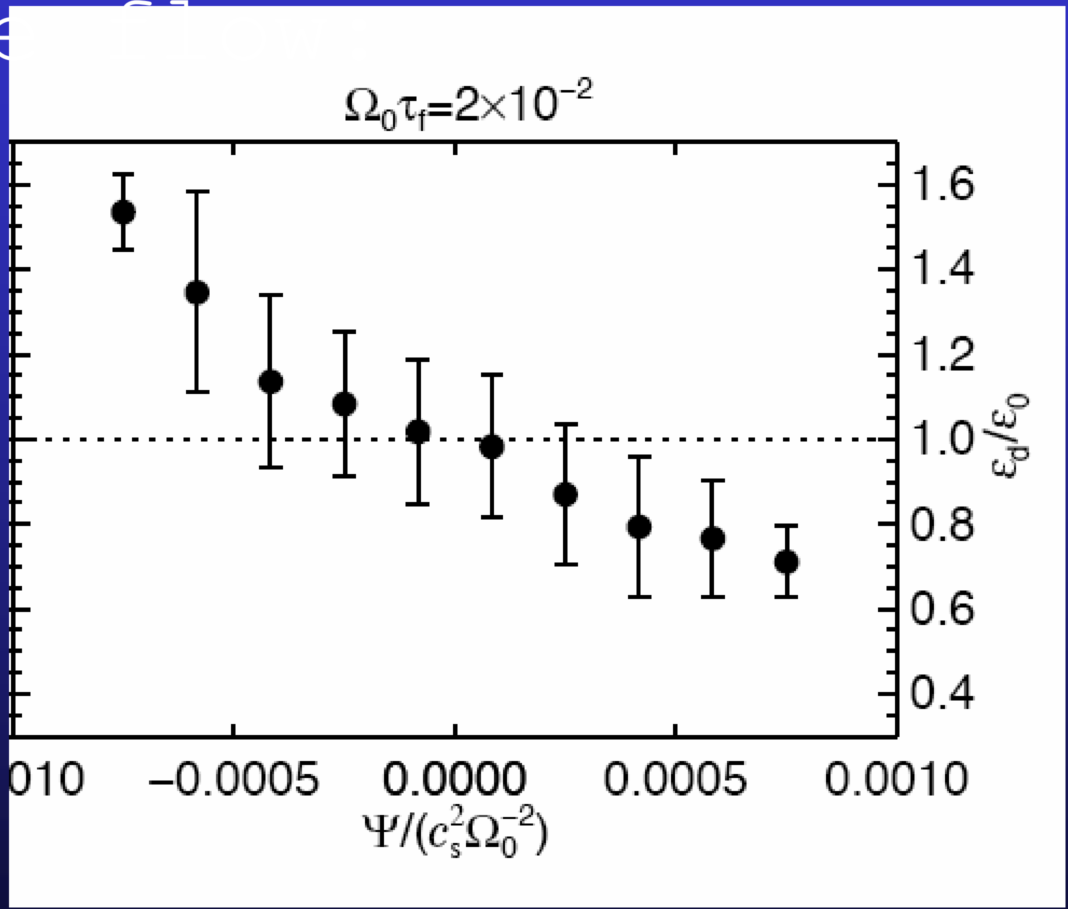
Blue = low number density (-25%)

Red = higher number density (+25%)



Concentration of cm sized grains in anti-cyclonic eddies in the flow

Correlation between density and vortex test function Ψ. Negative values of Ψ indicate anti-cyclonic motion and positive values cyclonic motion.



Compare this to Barge and Sommeria

THE ASTROPHYSICAL JOURNAL, 639:432–440, 2006 March 1

FORMATION OF GIANT PLANETS BY CONCURRENT ACCRETION OF SOLIDS AND GAS INSIDE AN ANTICYCLONIC VORTEX

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AND

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Received 2003 December 19; accepted 2005 October 18

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 5 September 2005 (MN LaTeX style file v2.2)

On the accumulation of solid bodies in global turbulent protoplanetary disc models

Sébastien Fromang[1]* & Richard P. Nelson
[1] *Astronomy Unit, Queen Mary, University of London, Mile End Road, London E1 4NS*

Fromang and Nelson 2005 dust in global MHD turbulence:

Mon. Not. R. Astron. Soc. 000, 000–000 (0000) Printed 5 September 2005 (MN LaTeX style file v2.2)

On the accumulation of solid bodies in global turbulent protoplanetary disc models

Sébastien Fromang[1]* & Richard P. Nelson
[1] Astronomy Unit, Queen Mary, University of London, Mile End Road, London E1 4NS

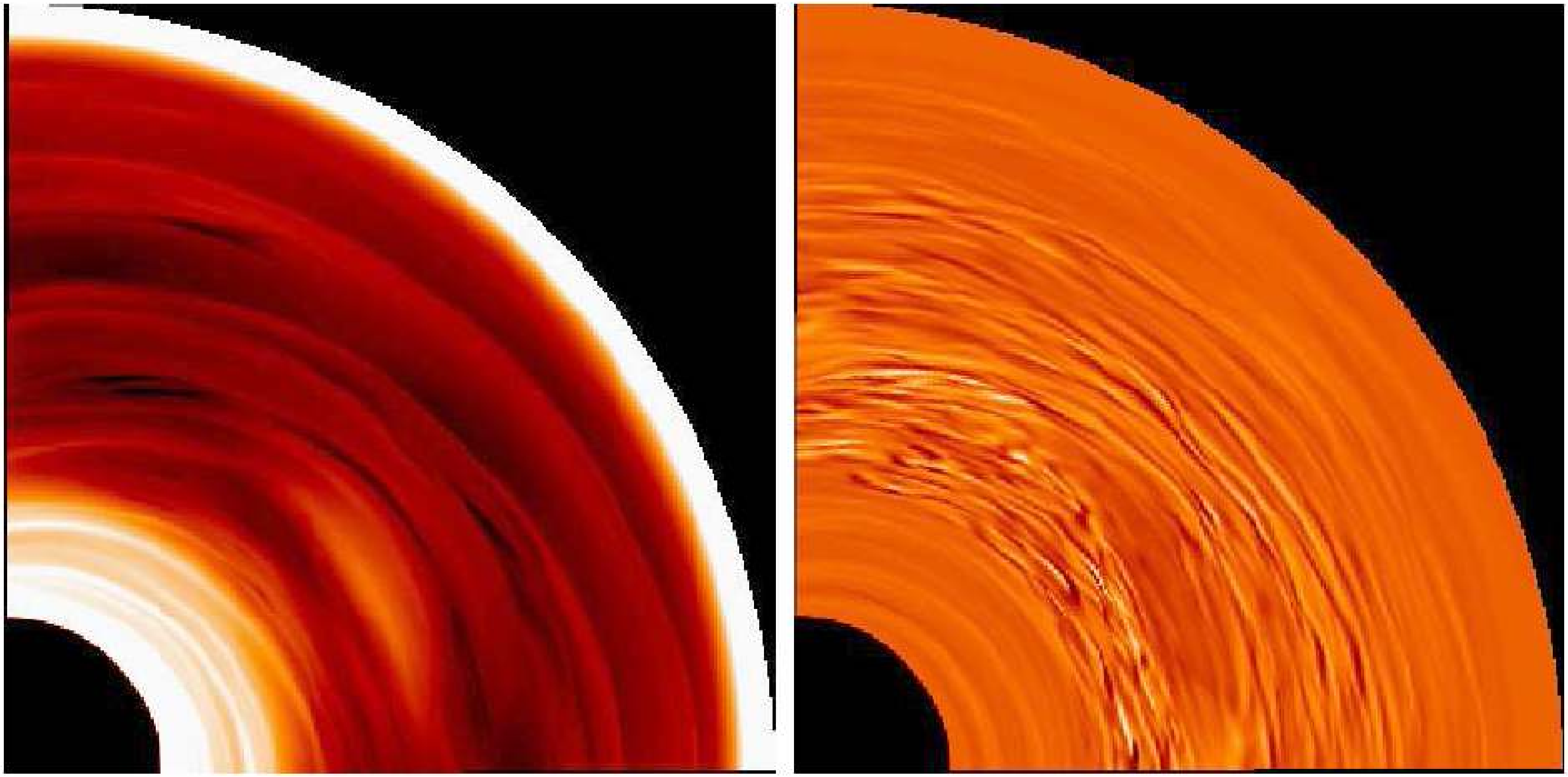

Figure 1. Logarithm of the density in the disc (*left panel*) and vorticity in the local rotating frame (*right panel*). Both quanti-

gravoturbulent planetesimal formation:

1. particle concentration in magneto rotational turbulence
2. N-body simulations of the gravitational collapse of the cloud of boulders

Particle-Gas Dynamics and Primary Accretion

Jeffrey N. Cuzzi; Ames Research Center
Stuart J. Weidenschilling; Planetary Science Institute

4.4 Getting to planetesimals: triggered gravitational instability?

A chapter for "Meteorites and the Early Solar System - II"; January 17, 2005

THE ASTROPHYSICAL JOURNAL, 636:1121–1134, 2006 January 10

GRAVOTURBULENT FORMATION OF PLANETESIMALS

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Received 2005 April 28; accepted 2005 September 14

Johansen, Klahr and Henning 2006

This work considers boulders e.g. a ≈ 1m @ 5AU.
This means a friction time
of about one sixth of an orbital period: ≈2 yrs!

In this size regime objects climb up any pressure gradient: the global disk gradient, as well as any local pressure perturbation.
Remember: cyclonic vortices are low pressure regions and high pressure regions are anti-cyclonic vortices.

gas

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} + u_y^{(0)}\frac{\partial \boldsymbol{u}}{\partial y} = \boldsymbol{f}(\boldsymbol{u}) - c_s^2\nabla\ln\rho + \frac{1}{\rho}\boldsymbol{J}\times\boldsymbol{B} + \boldsymbol{f}_\nu(\boldsymbol{u},\rho),$$

$$\frac{\partial \boldsymbol{A}}{\partial t} + u_y^{(0)}\frac{\partial \boldsymbol{A}}{\partial y} = \boldsymbol{u}\times\boldsymbol{B} + \frac{3}{2}\Omega_0 A_y\hat{\boldsymbol{x}} + \boldsymbol{f}_\eta(\boldsymbol{A}),$$

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

dust

$$\frac{\partial \boldsymbol{v}_i}{\partial t} = \boldsymbol{f}(\boldsymbol{v}_i) - \frac{1}{\tau_f}(\boldsymbol{v}_i - \boldsymbol{u}) + c_s\Omega_0\beta\hat{\boldsymbol{x}},$$

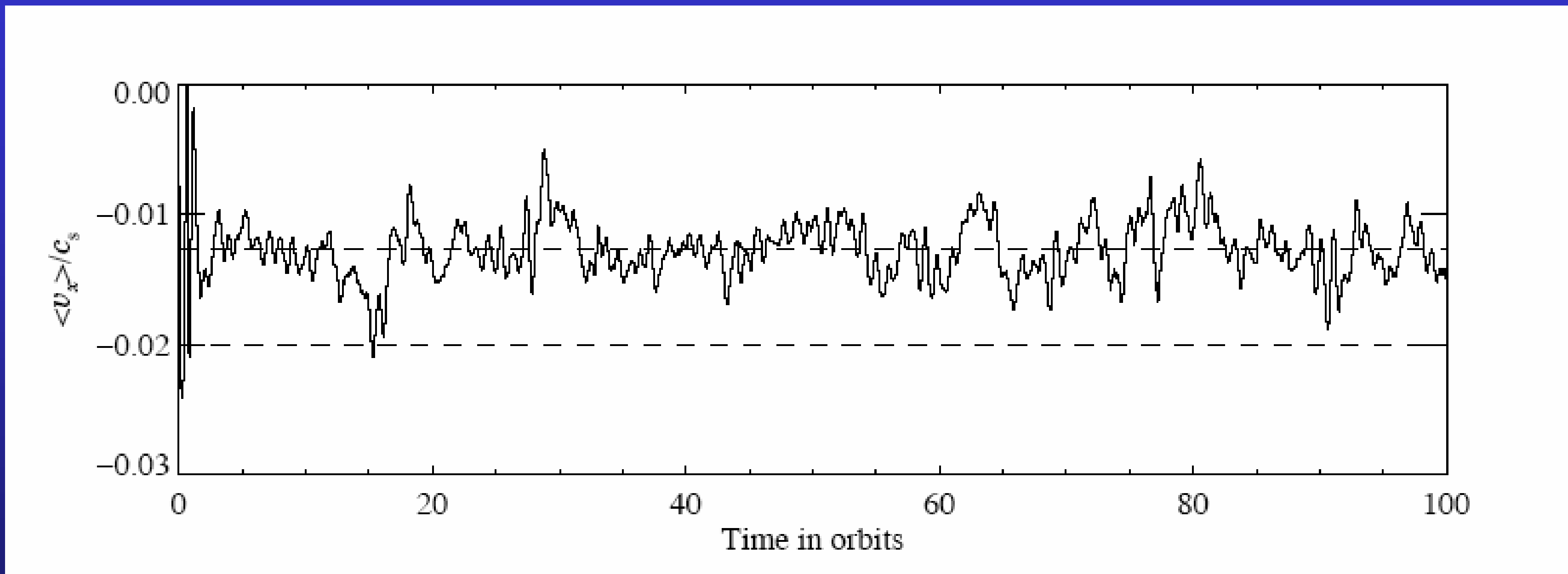
$$\frac{\partial \boldsymbol{x}_i}{\partial t} = \boldsymbol{v}_i + u_y^{(0)}\hat{\boldsymbol{y}}.$$

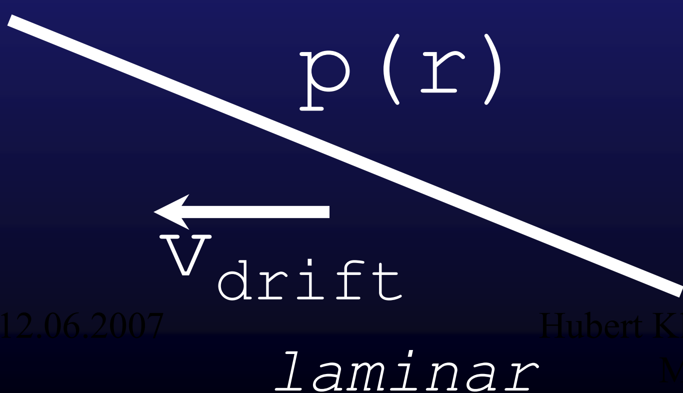
2,000,000 boulders of 1m size

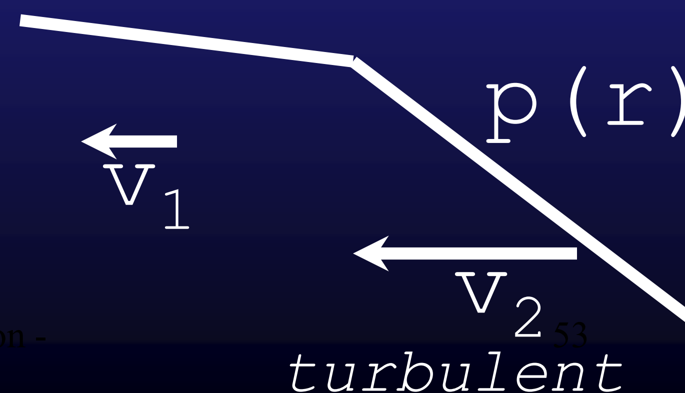
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Johansen, Klahr and Henning, 20

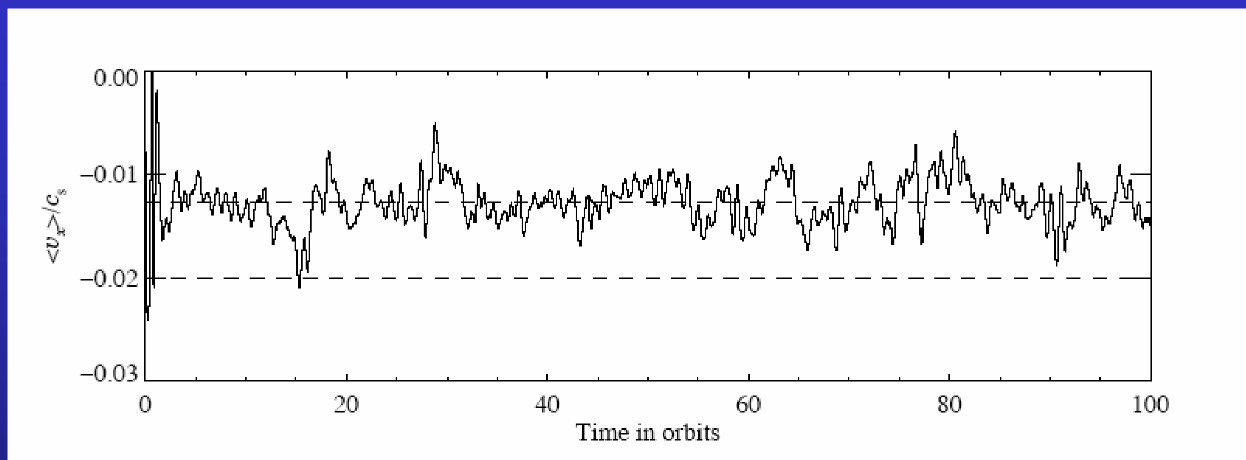
Turbulence slows down radial drift!







Turbulence slows down radial drift!



$$t = 2s/v_{mean} = s/(v_0 + dv) + s/(v_0$$

$$v_{mean}/v_0 = 1 - (dv/v_0)^2$$

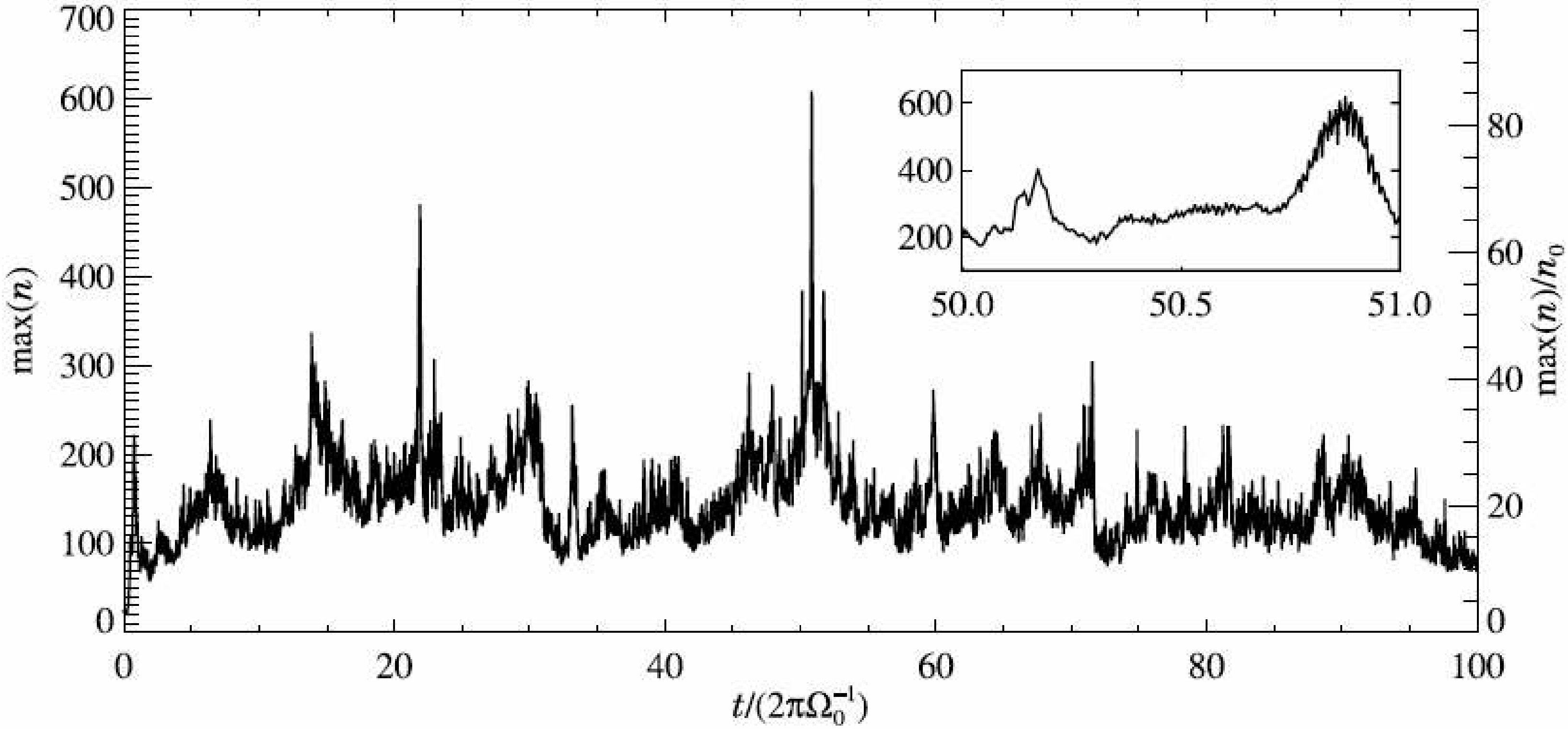
Johansen, Klahr and Henning 200

2,000,000 boulders of 1m size

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Johansen, Klahr and Henning, 20

1m boulders



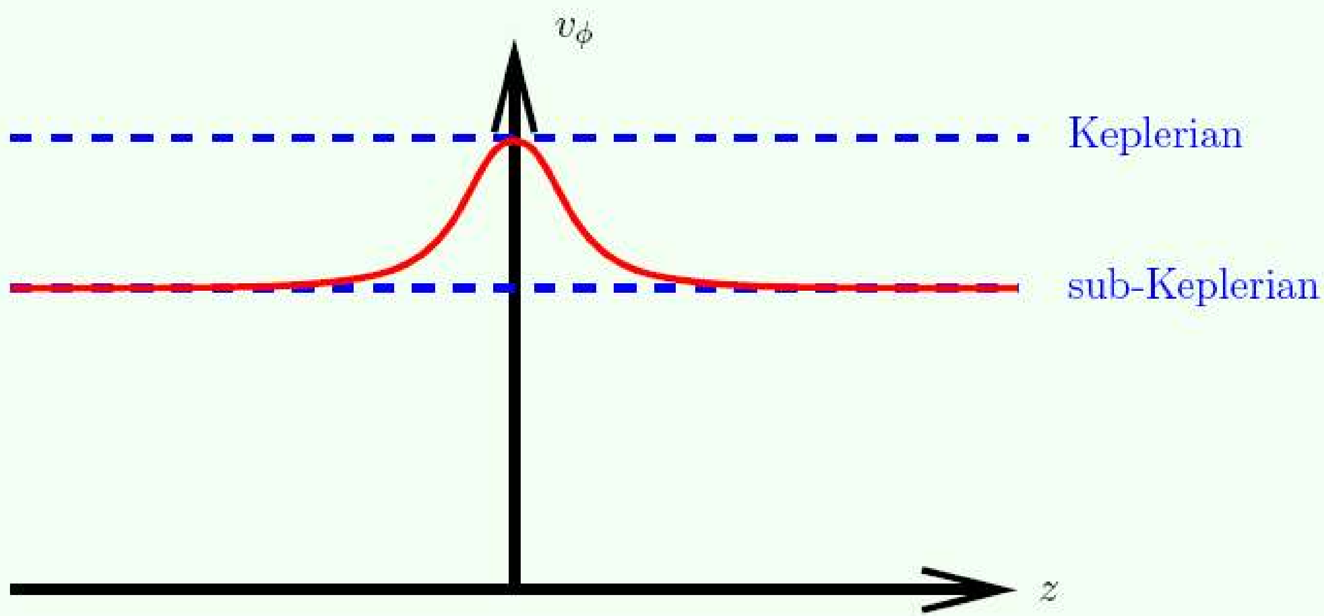
700
600
500
400
300
200
100
0
max(n)
0
20
40
60
80
100
$t/(2\pi\Omega_0^{-1})$
80
60
40
20
0
max(n)/n_0
600
400
200
50.0
50.5
51.0

Motivation: Planetesimal Formation- Coagulation and Sedimentation

What if there is no turbulence?

1. Fast radial drift (loss) of boulders
2. How to overcome the 1m barrier?
3. Possibly a Streaming and/or Kelvin-Helmholtz instability for the boulders

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:

v
e
r
t
i
c
a
l

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

h o r i z o n t
a l

Johansen, Henning & Klahr

Huge overdensities for 1m objects

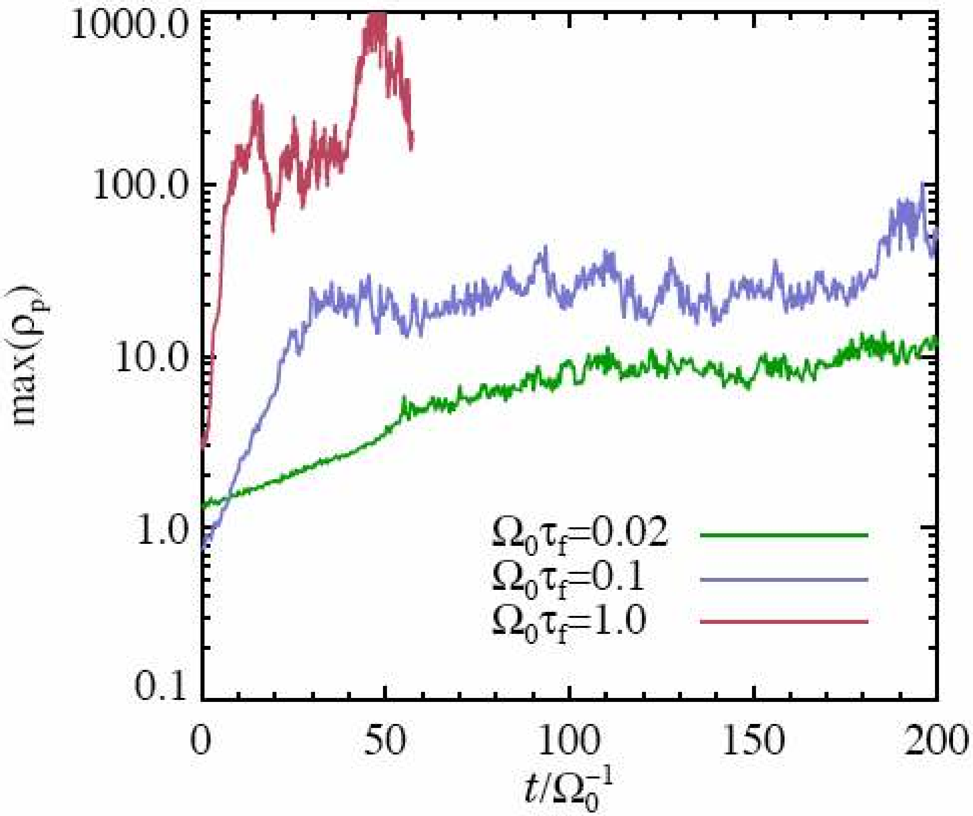
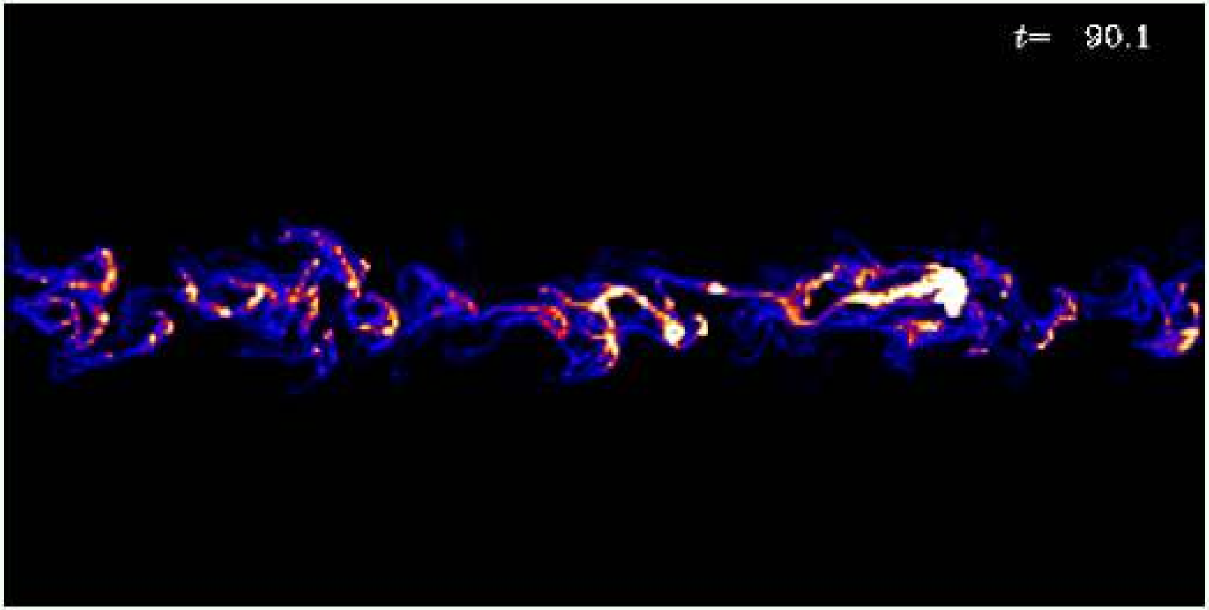


Fig. 9.— Maximum dust density, in units if the gas mid-plane density

Streaming instability

Youdin & Goodman (2005) :
"Streaming Instabilities in Protoplanetary Disks"



The secret behind the instability:

$$
\begin{aligned}
w_r &= w_r(\epsilon) \\
w_\phi &= w_\phi(\epsilon)
\end{aligned}
$$

Dust velocity depends only on dust-to-gas ratio ϵ
(Nakagawa, Sekiya, & Hayashi 1986).

Streaming instability for radial drift:

vertical

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

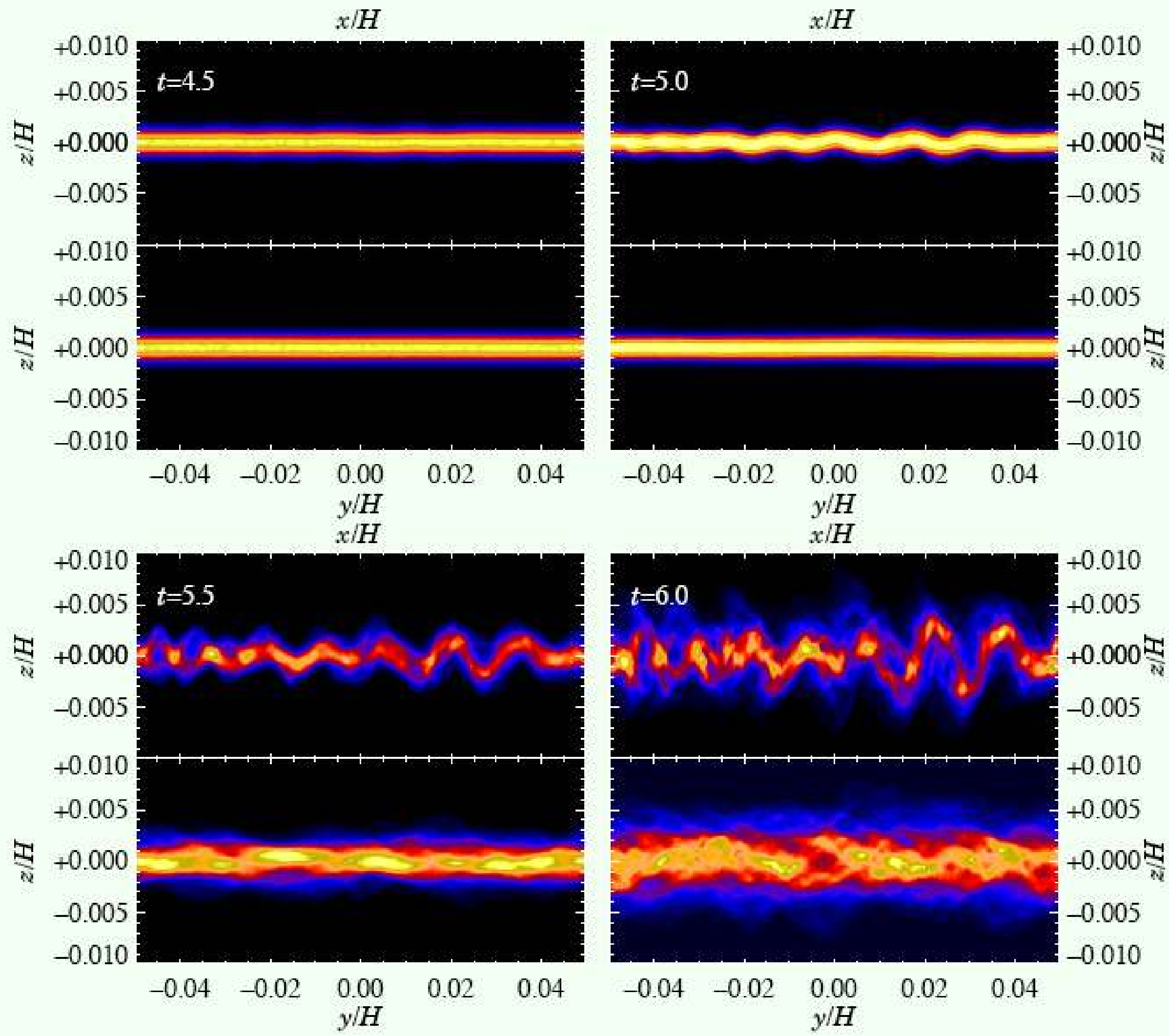
radial

This is what *laminar* radial drift actually looks like!

KHI in 3D for 1m bodies:

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Radial KHI



The Kelvin-Helmholtz instability sets in in the radial direction first, at least for $\Omega_0\tau_{\rm f} = 1.0$.

Conclusions from first part:

1. **Turbulence is not uniform in space and time**
2. **Transient concentration of solids in anti-cyclonic vortices**
    1. **--> *gravitationally unstable?***
    2. ***Influence on coagulation?***
3. **Turbulence slows down the radial drift**
4. **Anisotropic diffusion radial:vertical (2:1) in MHD turbulence**
5. **Nevertheless, Schmidt Number of**

MRI plus self-gravity for the dust, including particle feed back on the gas: collaboration with Mac

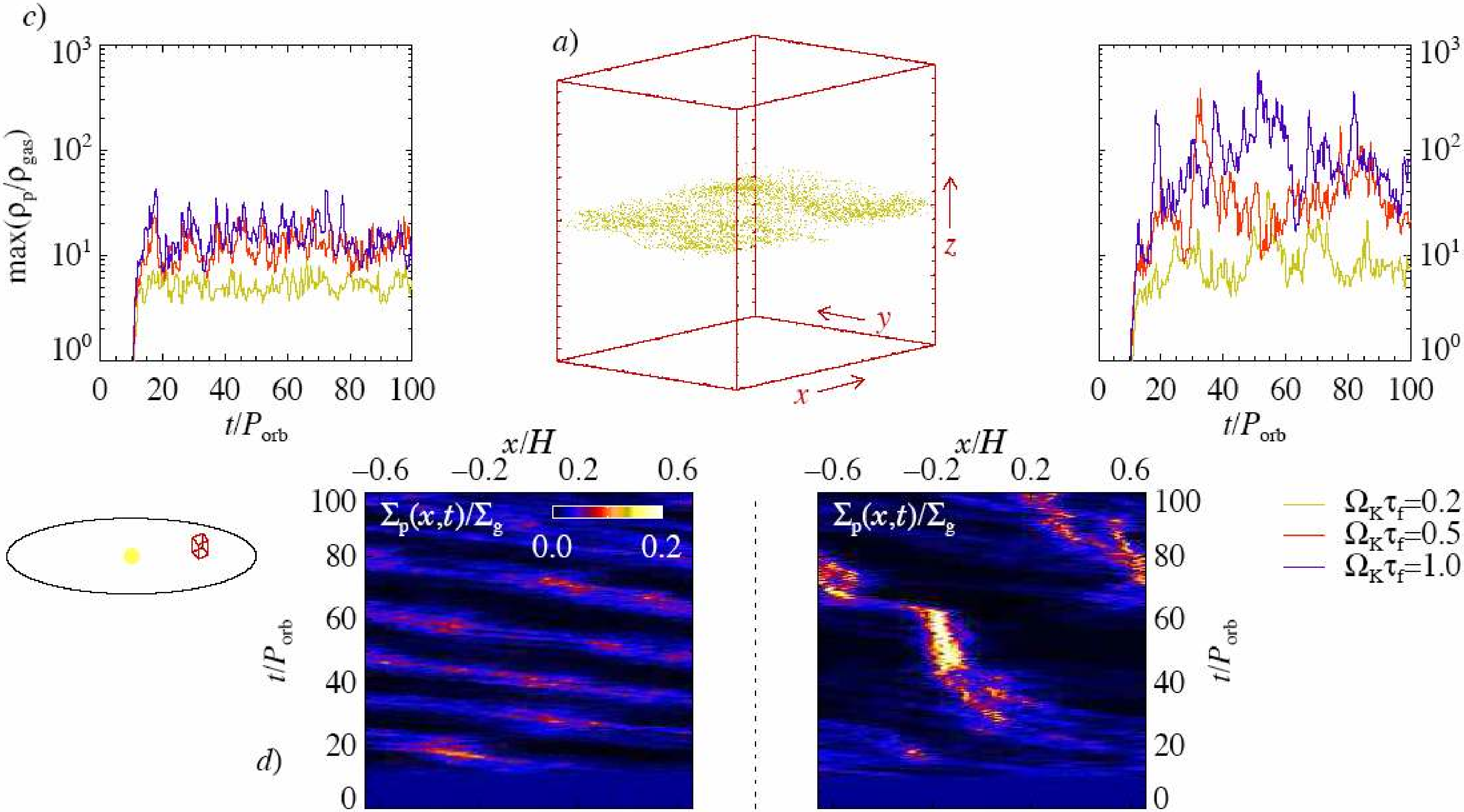
Pia 256 + 8 Opteron processor cluster bought with a grand from the MPG.

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

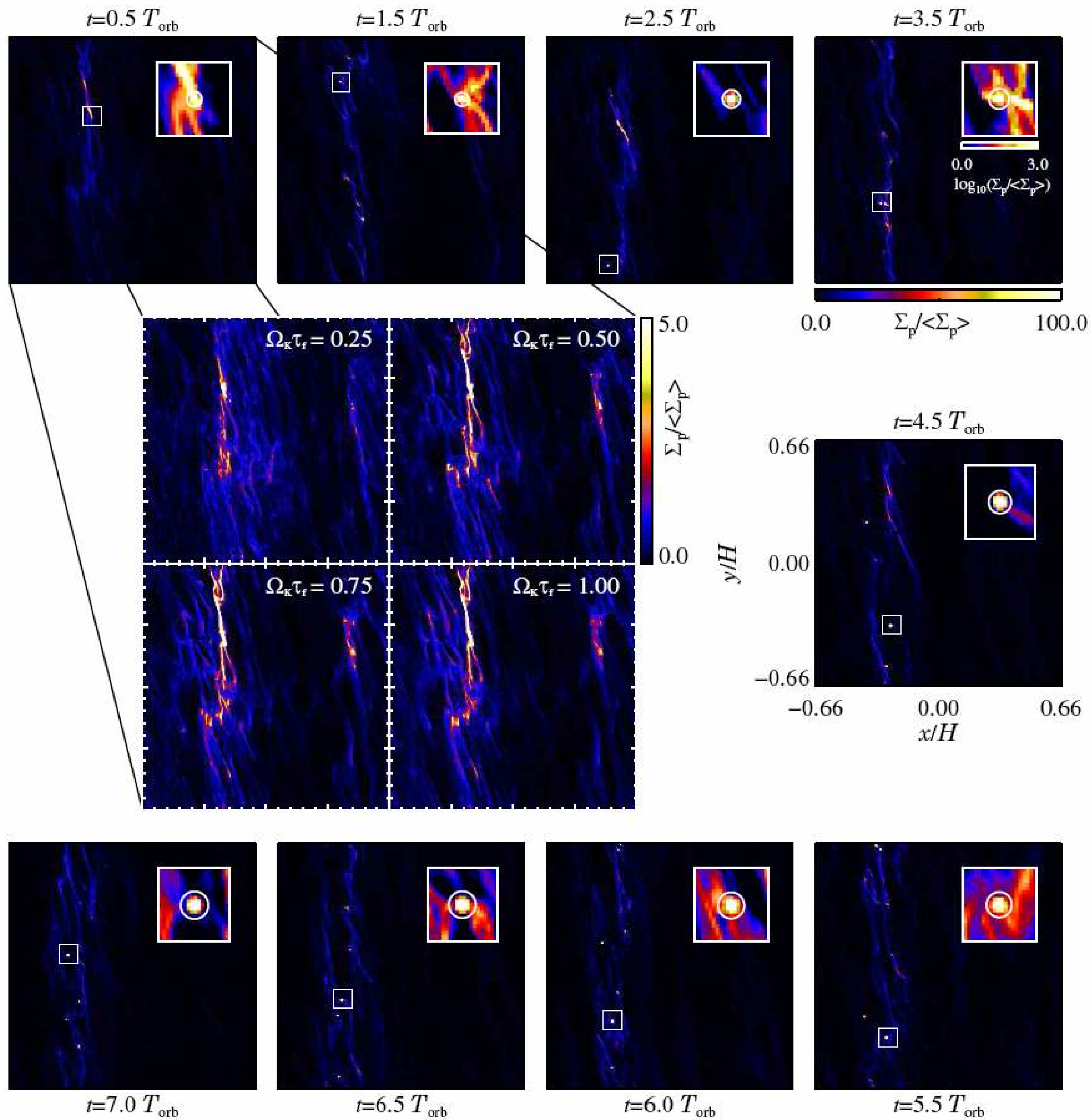
MRI plus self-gravity for the dust, including particle feed back on the gas: together with MacLow & Oichi AMNH

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

The effect of back reaction

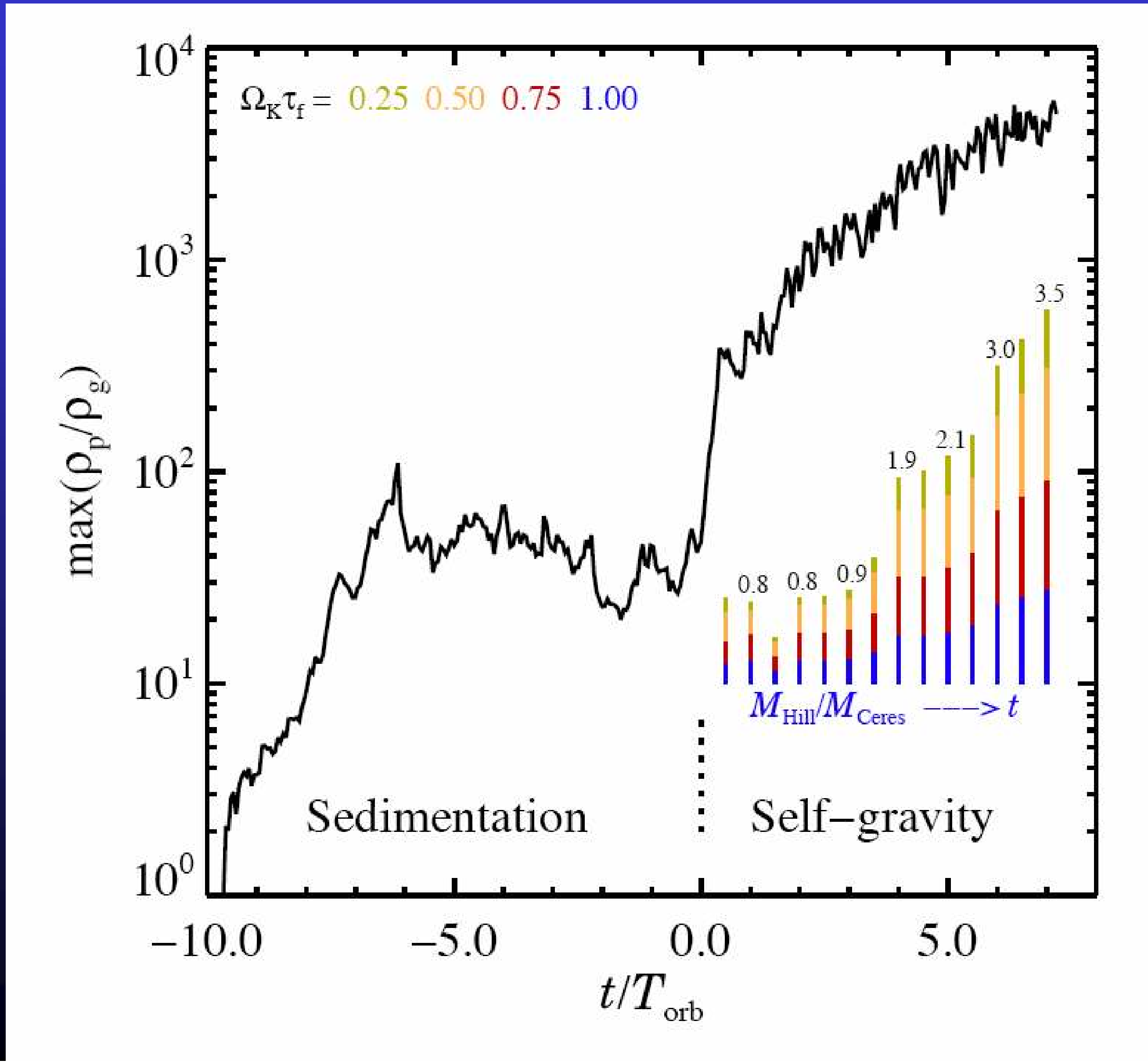


QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.



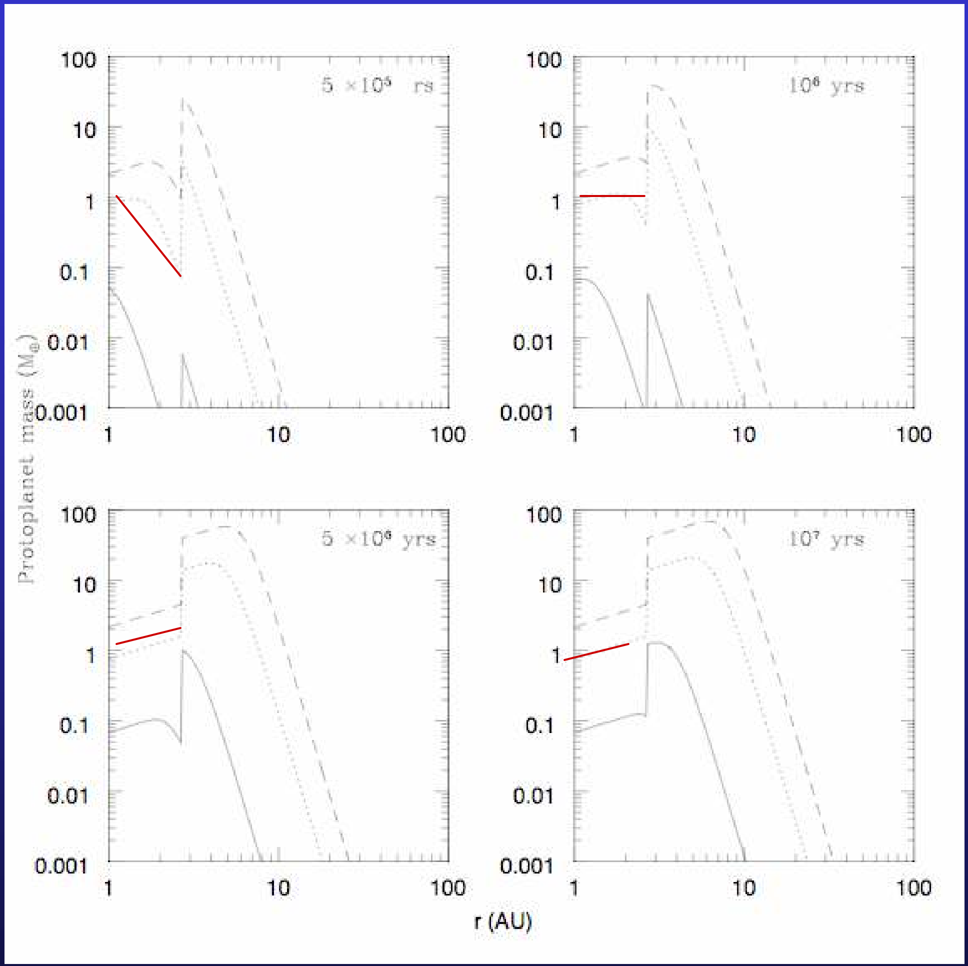
t=0.5 T_orb
t=1.5 T_orb
t=2.5 T_orb
t=3.5 T_orb
0.0
3.0
log10(Σp/<Σp>)
0.0
Σp/<Σp>
100.0
ΩKτf = 0.25
ΩKτf = 0.50
ΩKτf = 0.75
ΩKτf = 1.00
5.0
Σp/<Σp>
0.0
t=4.5 T_orb
0.66
0.00
−0.66
y/H
−0.66
0.00
0.66
x/H
t=7.0 T_orb
t=6.5 T_orb
t=6.0 T_orb
t=5.5 T_orb

Growth of Planetary Core?



Core size as function of time and

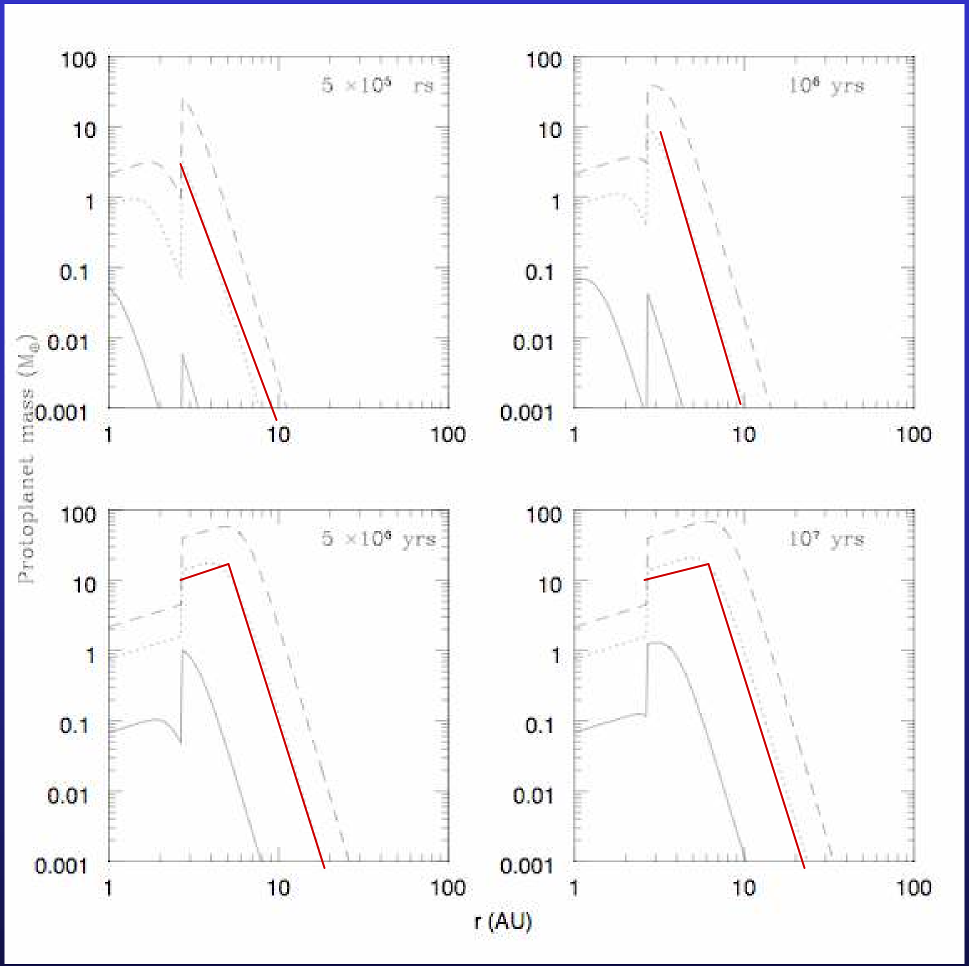
Inner disk fast growth due to frequent collisions - yet low truncation mass due to proximity of the star (Hill radius)



Thommes & Duncan 200

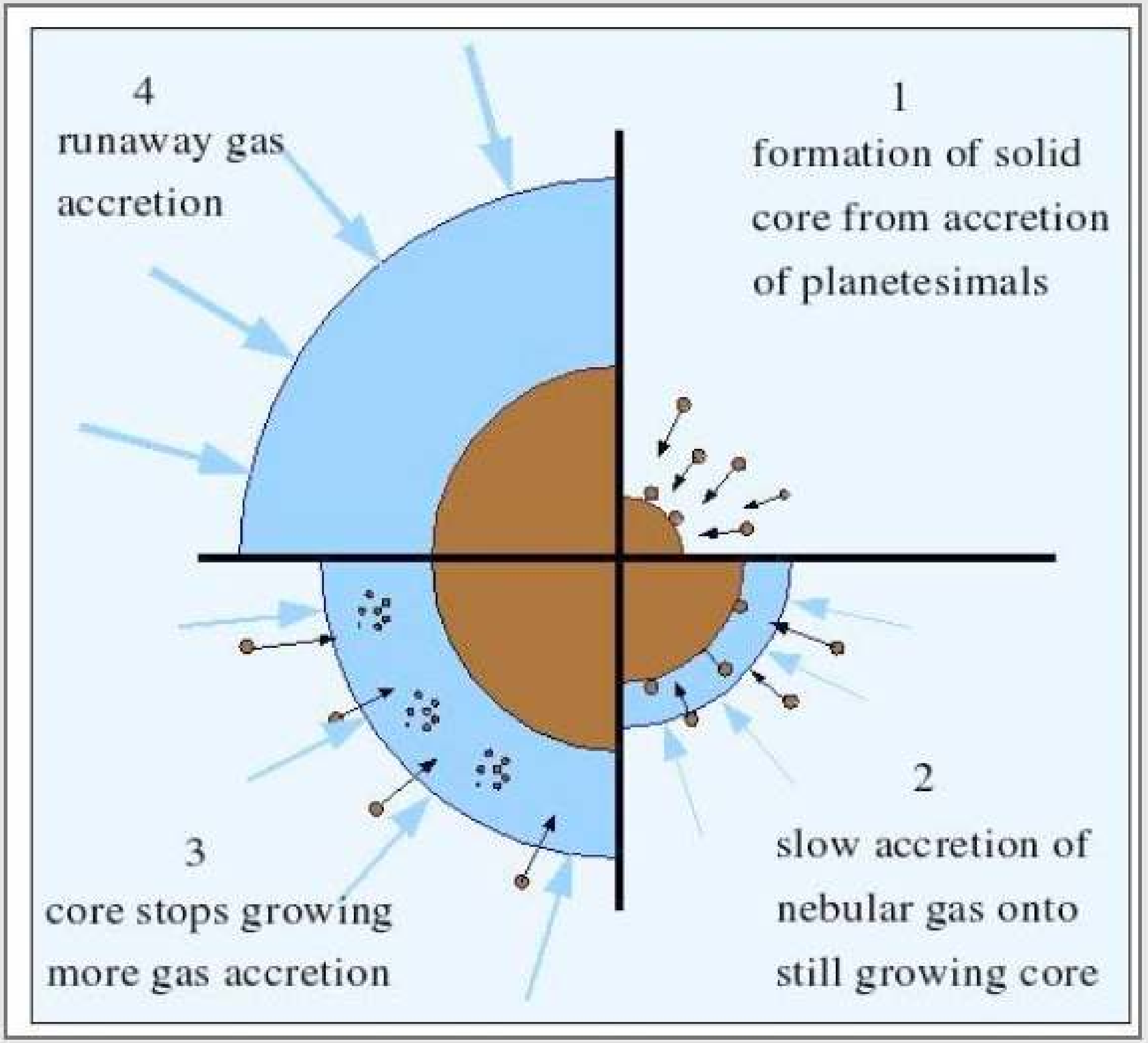
Core size as function of time and

Outer disk slow growth due to rare collisions - yet high truncation mass due to distance from the star (Hill radius)



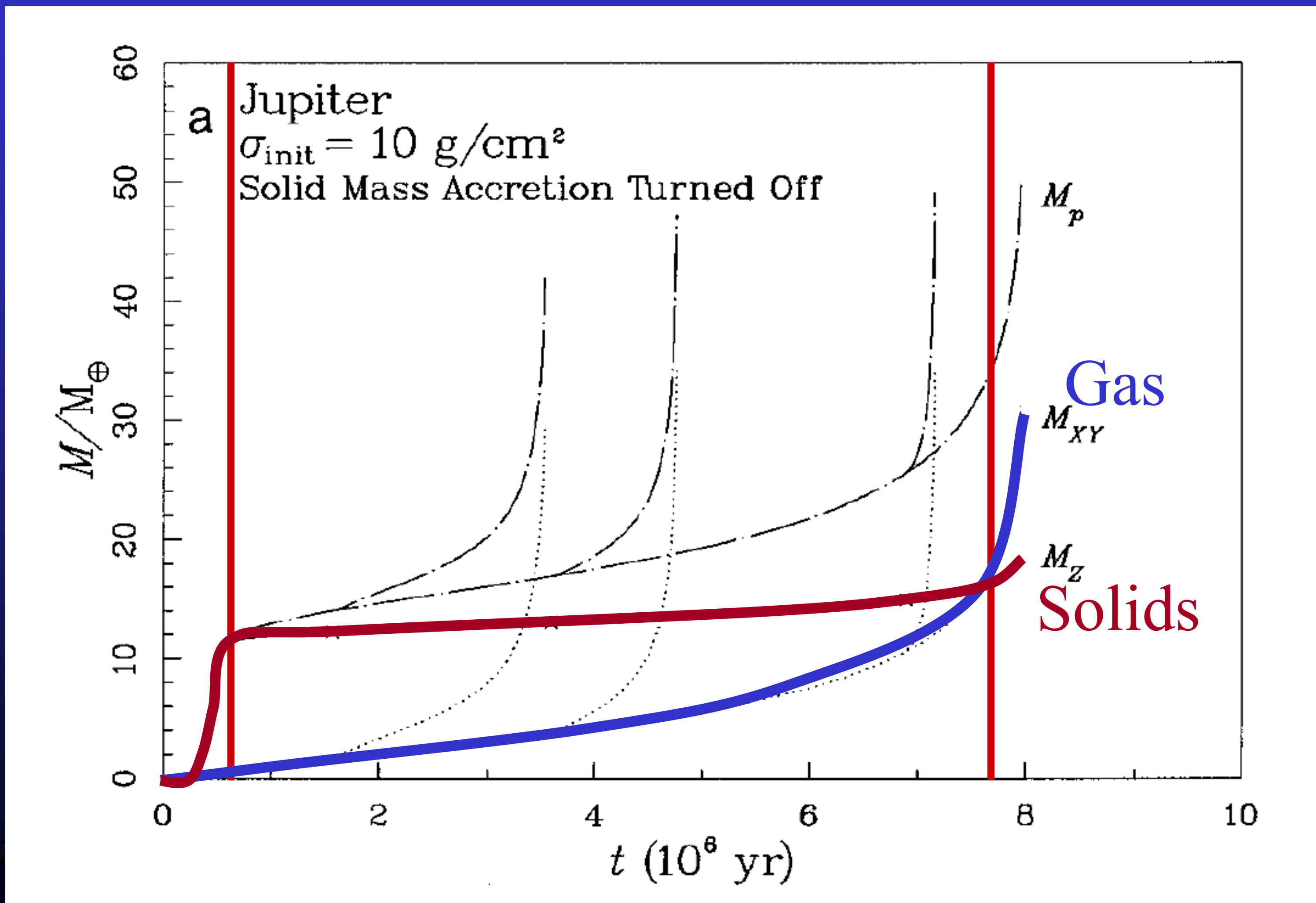
Thommes & Duncan 200

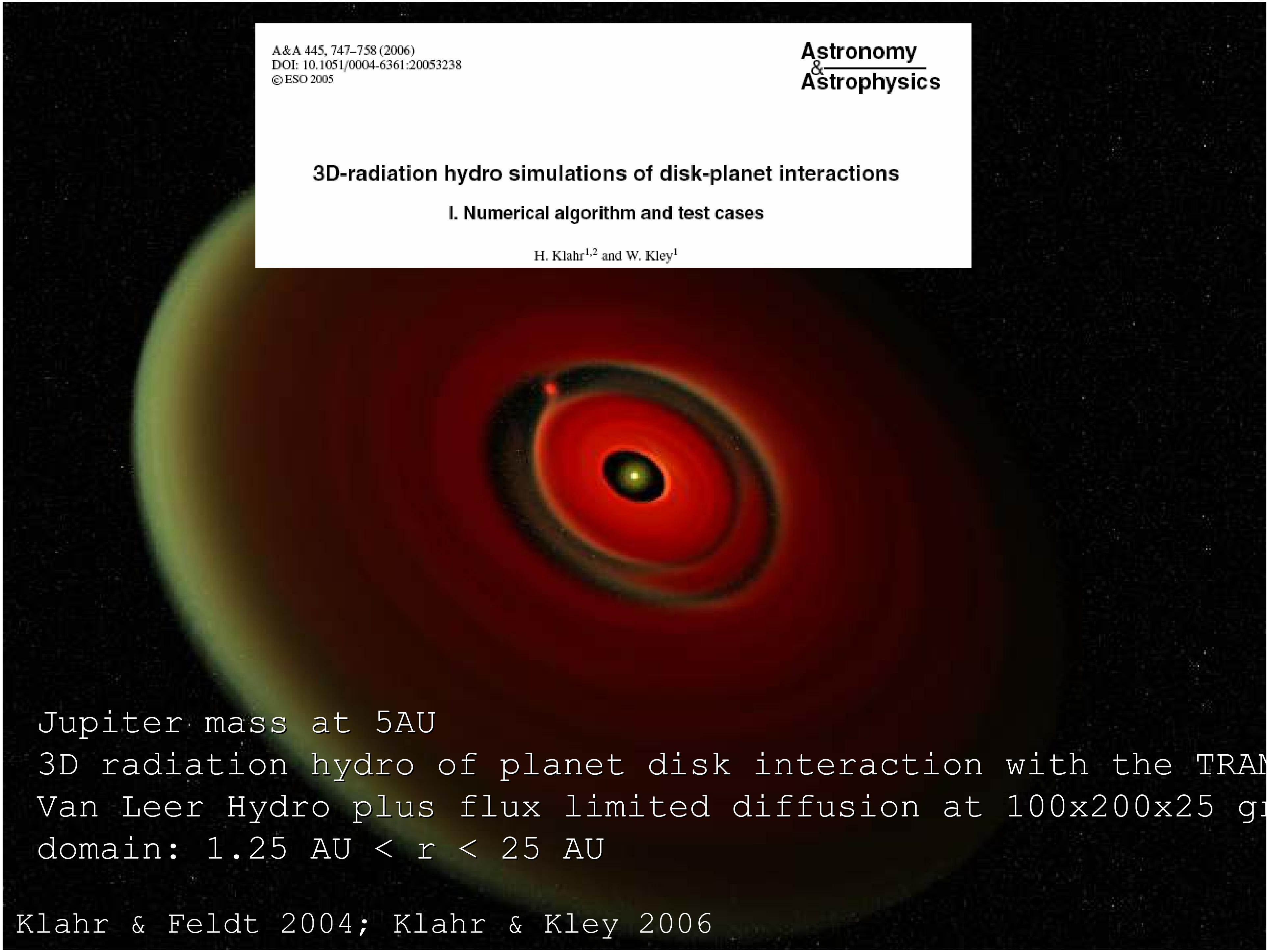
Giant planet formation: core accretion model



Core Accretion (Pollack et al. 1996)

Usually takes too long!

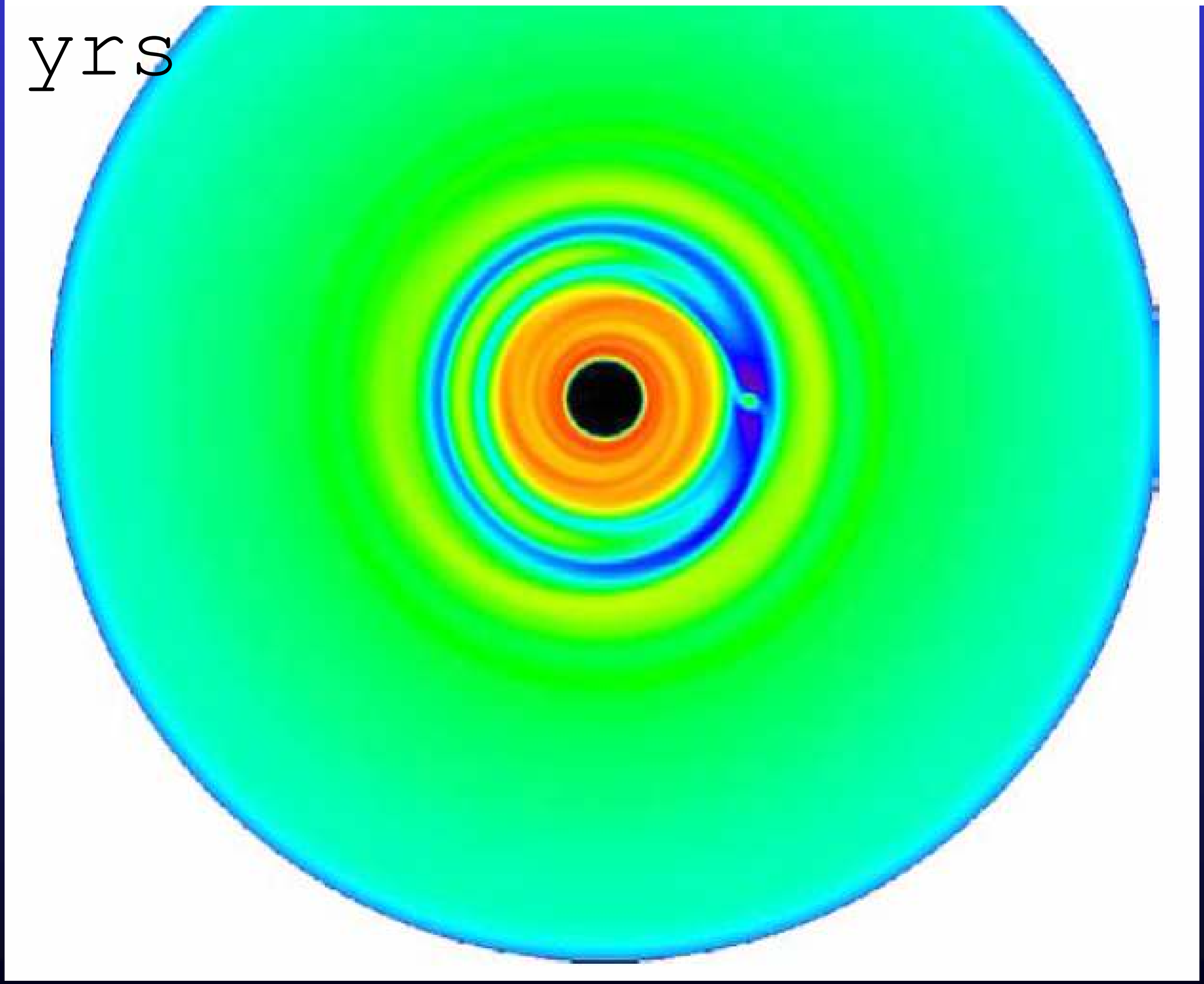



A&A 445, 747–758 (2006)
DOI: 10.1051/0004-6361:20053238
© ESO 2005
Astronomy & Astrophysics
3D-radiation hydro simulations of disk-planet interactions
I. Numerical algorithm and test cases
H. Klahr[1,2] and W. Kley[1]
Jupiter mass at 5AU
3D radiation hydro of planet disk interaction with the TRA
Van Leer Hydro plus flux limited diffusion at 100x200x25 g
domain: 1.25 AU < r < 25 AU
Klahr & Feldt 2004; Klahr & Kley 2006

[redacted]

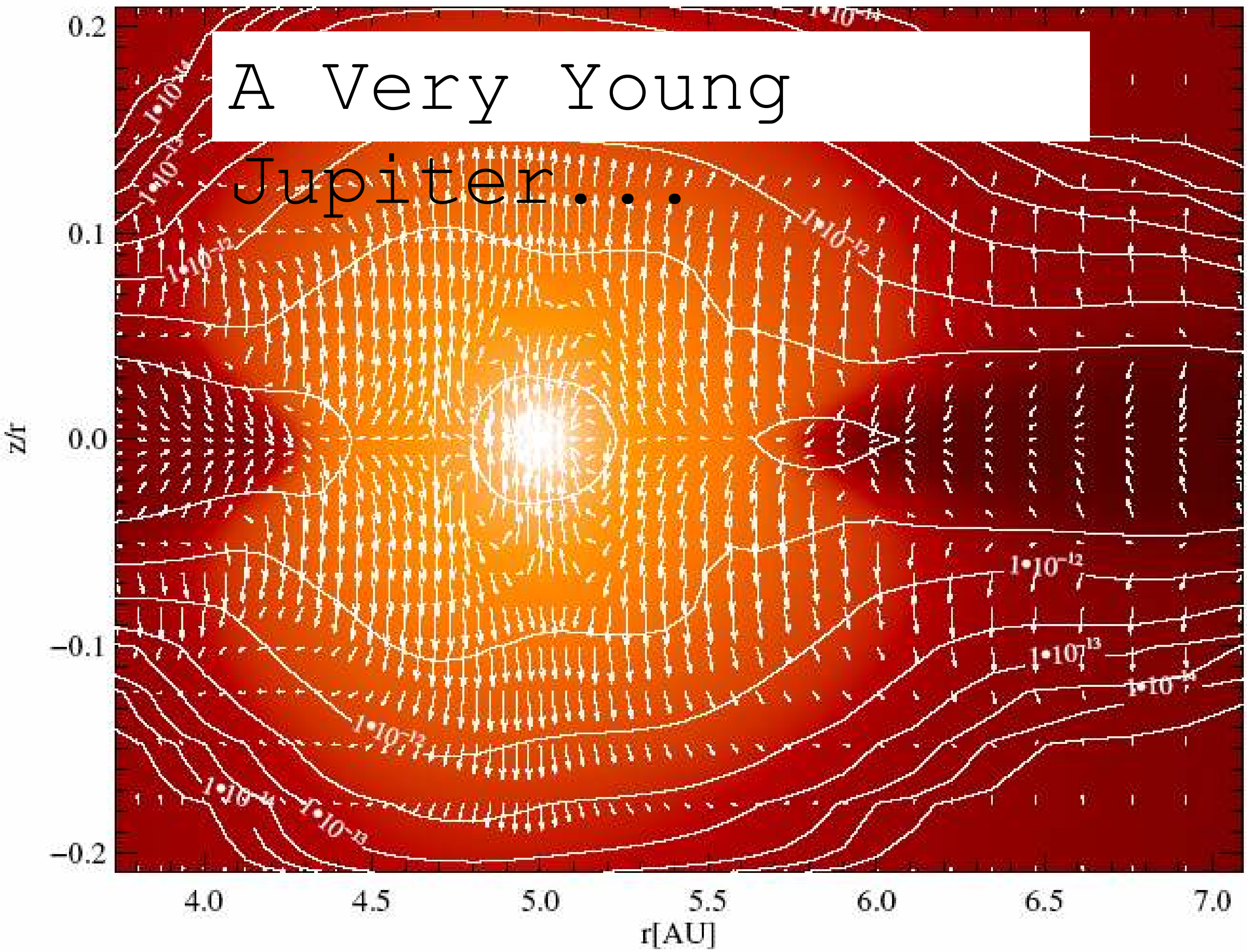
Surface Density

A Young Jupiter: >1000 yrs

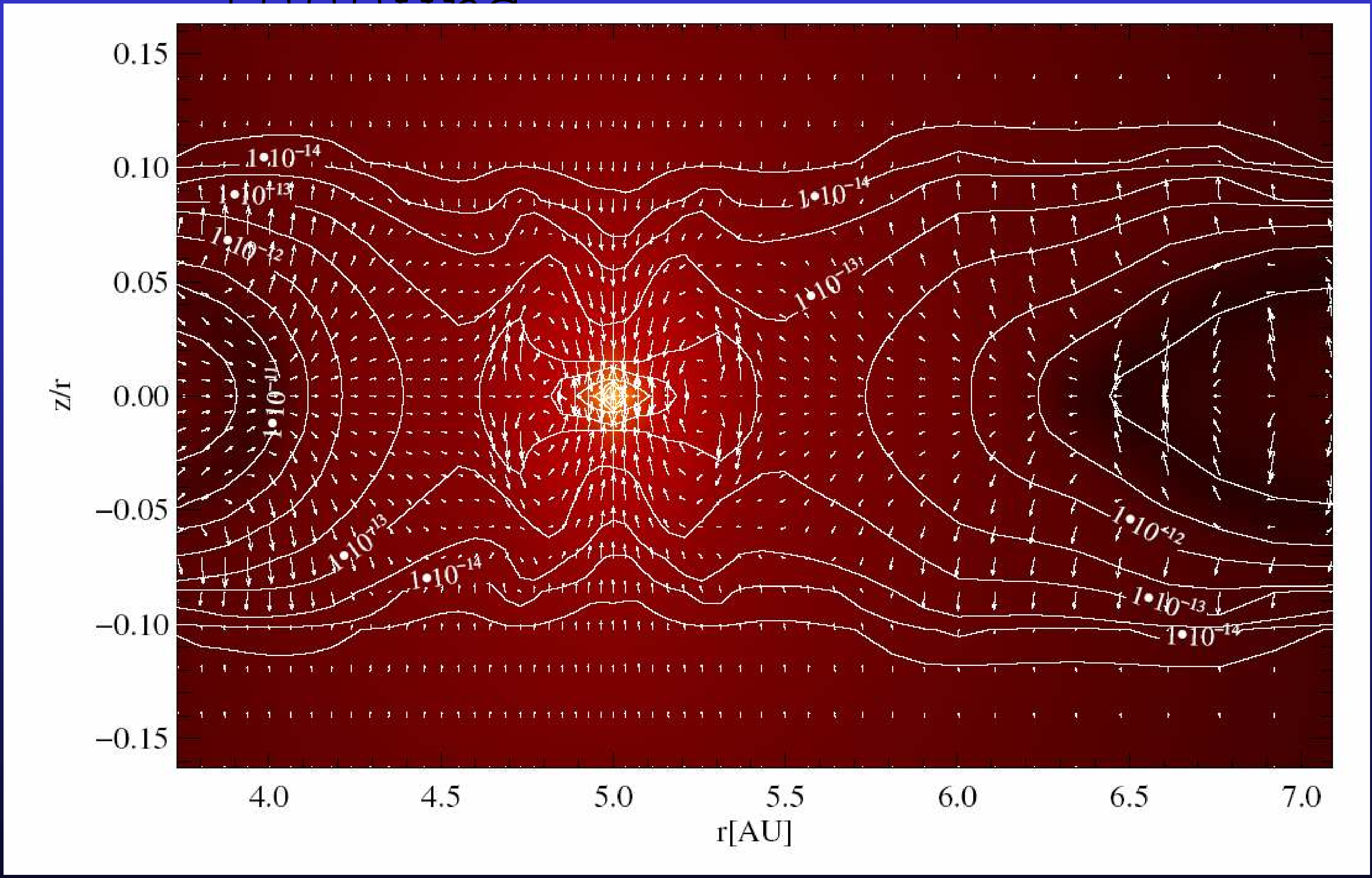


A Very Young Jupiter...

H. Klahr and W. Kley: Temperature, velocity and density contours.

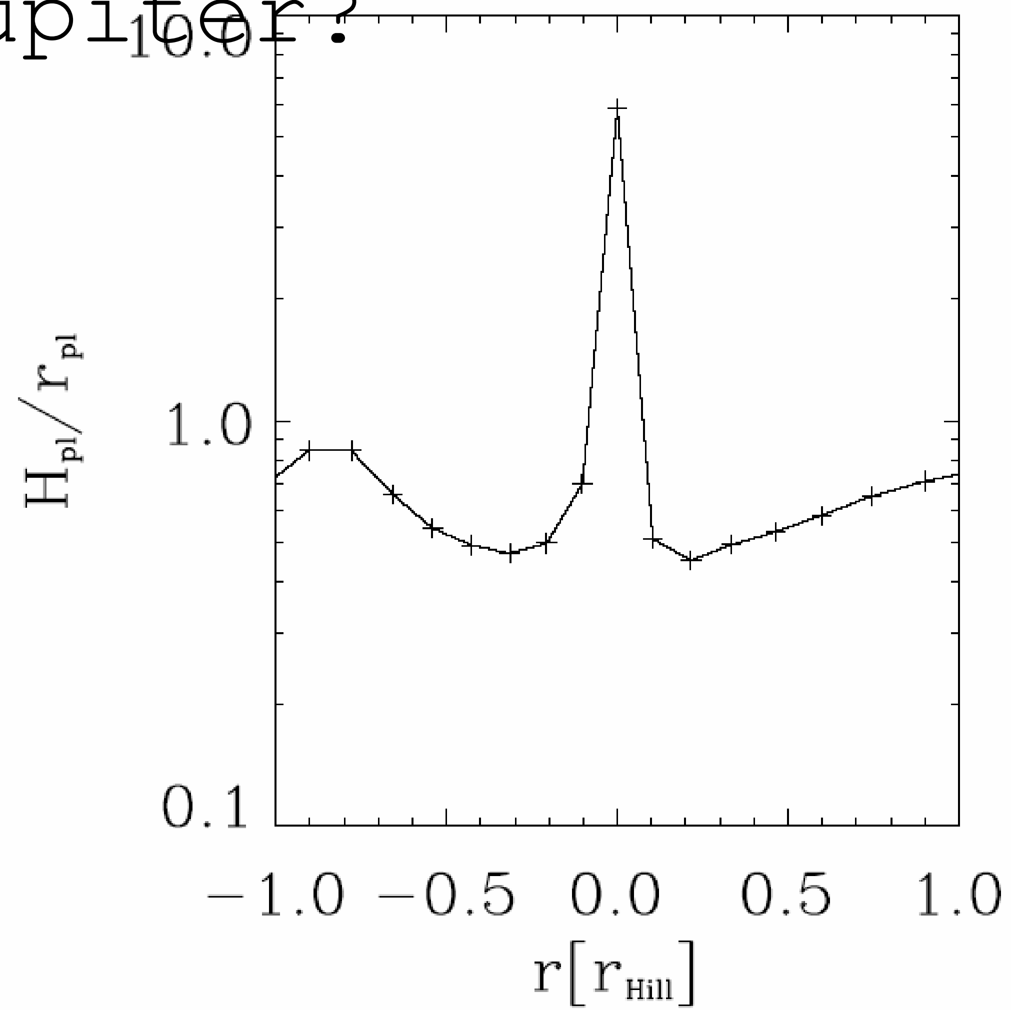


A Young Jupiter... > 1000yrs



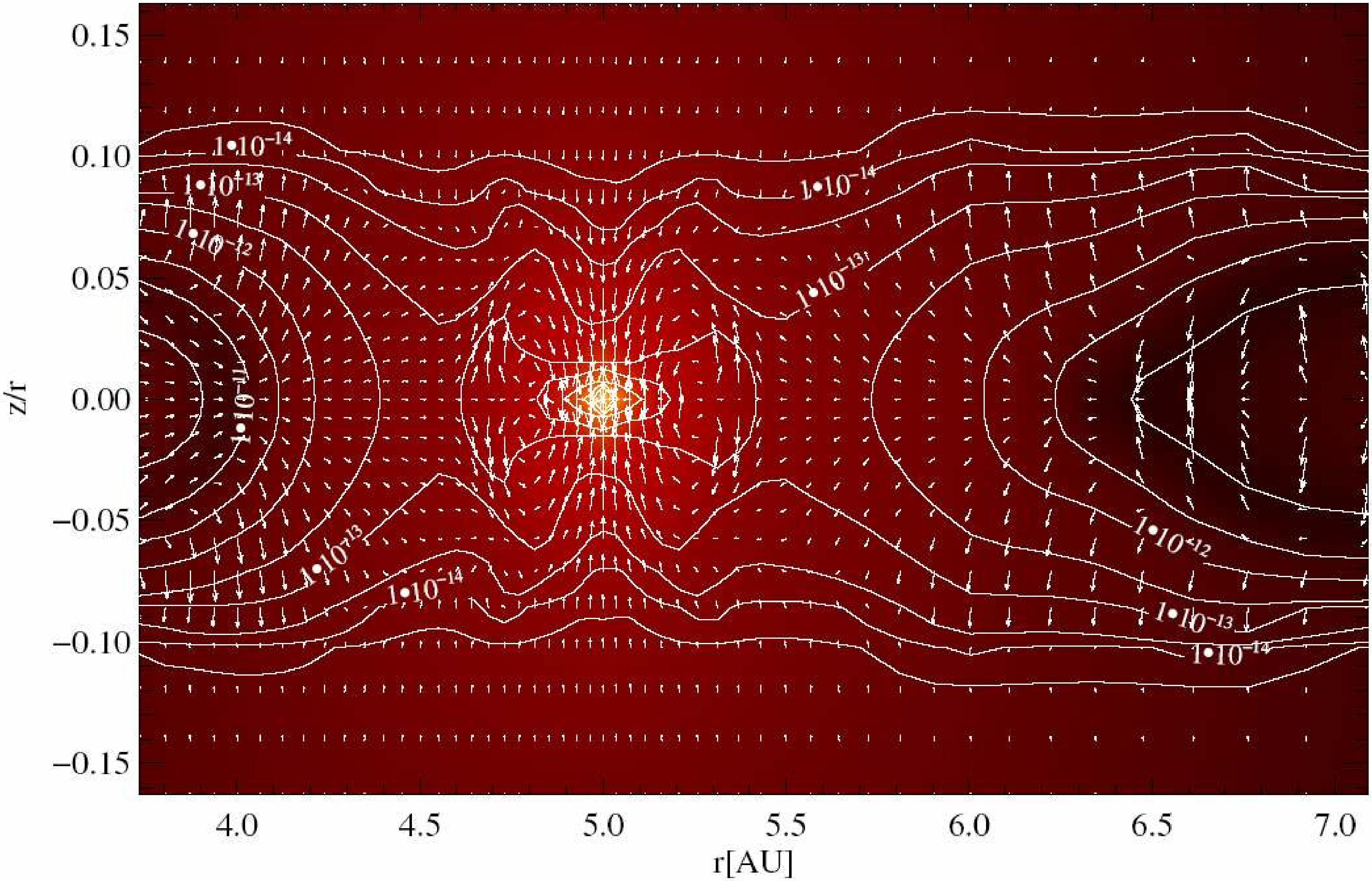
Temperature, velocity and density

Disk or Donut around Jupiter?

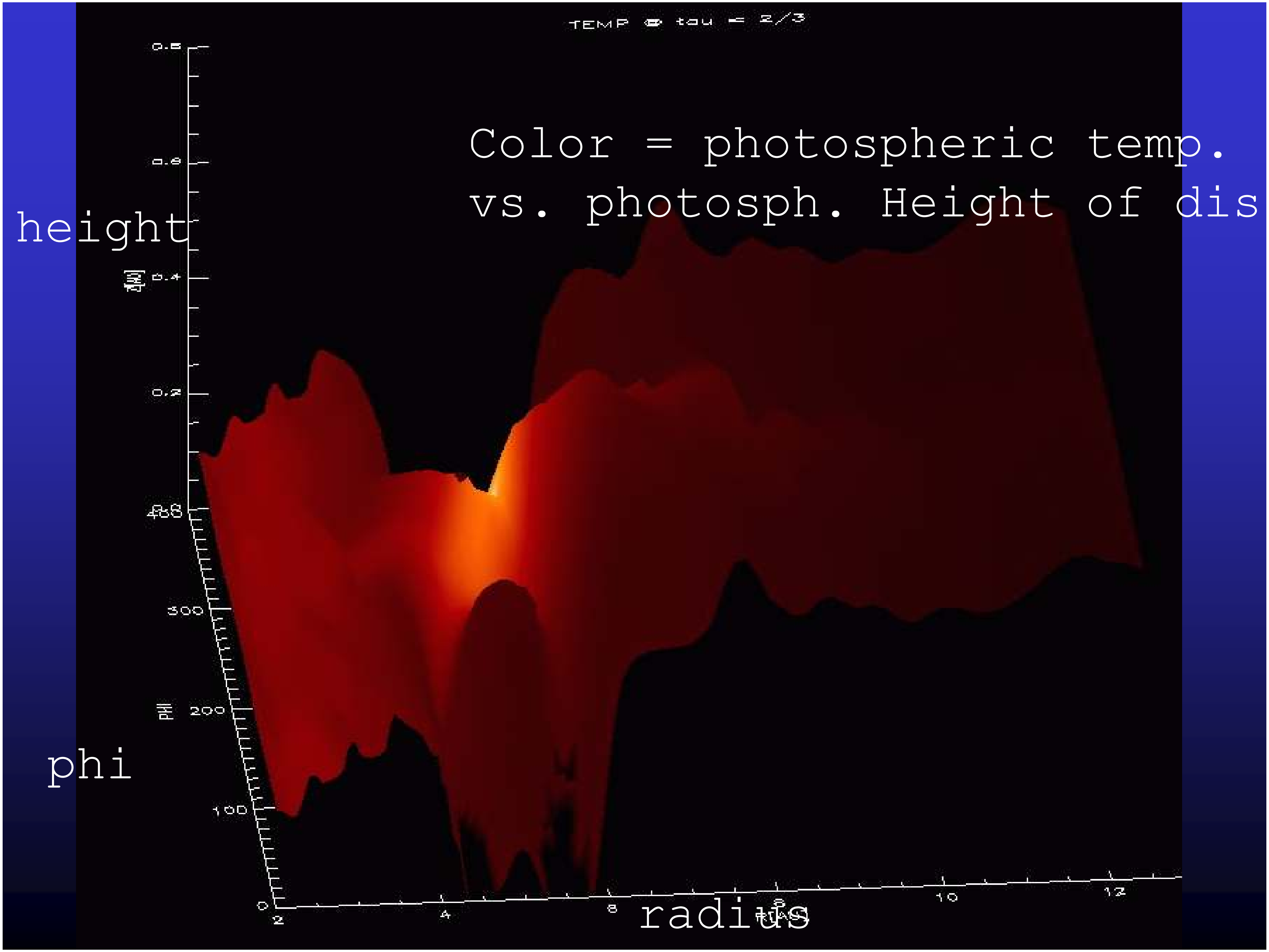


Pressure scale height in “Blob” over the Roche lobe.

A Young Jupiter... > 1000yrs



Temperature, velocity and density


Color = photospheric temp.
vs. photosph. Height of dis
height
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radius
PHI
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0.4
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200
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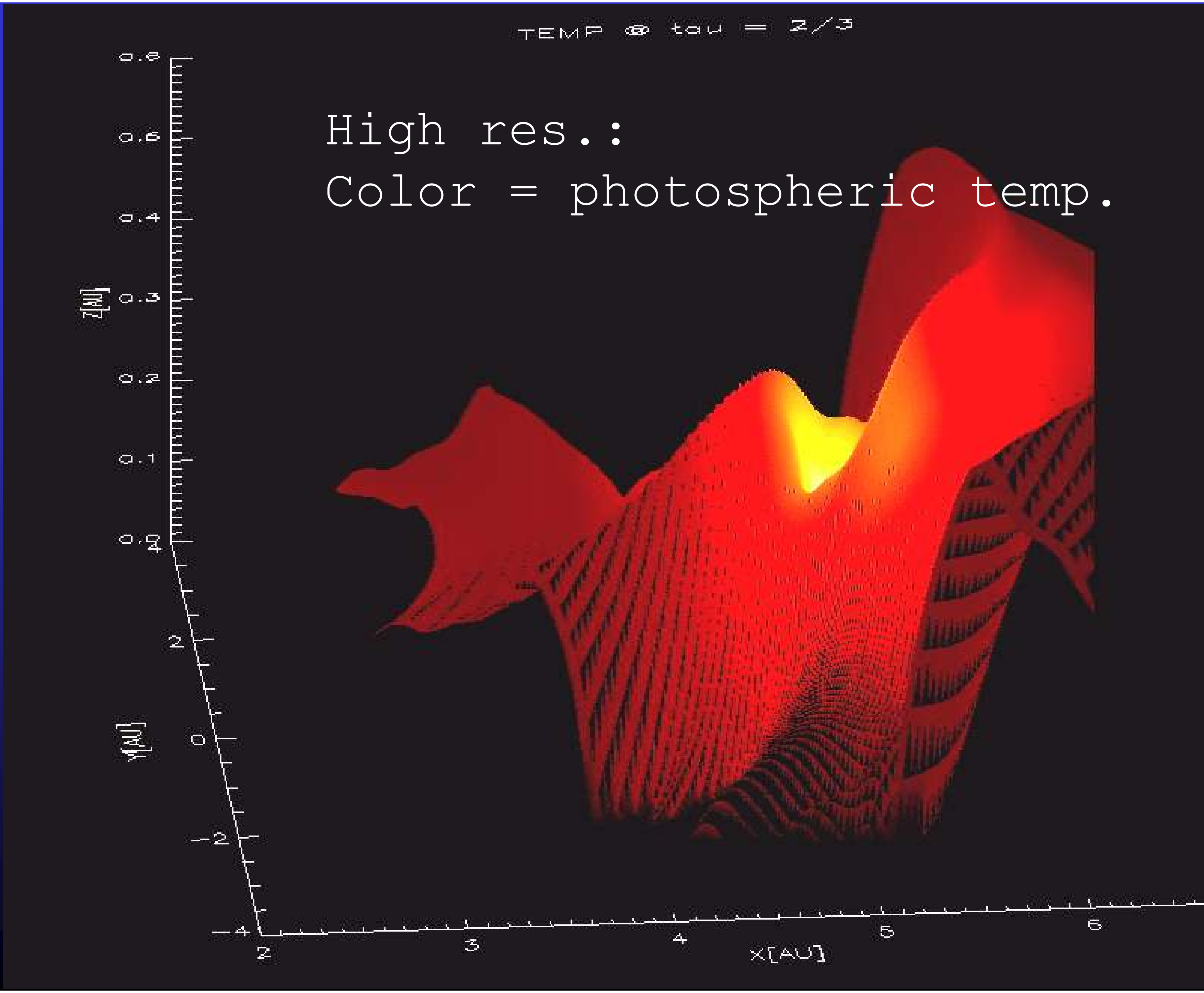
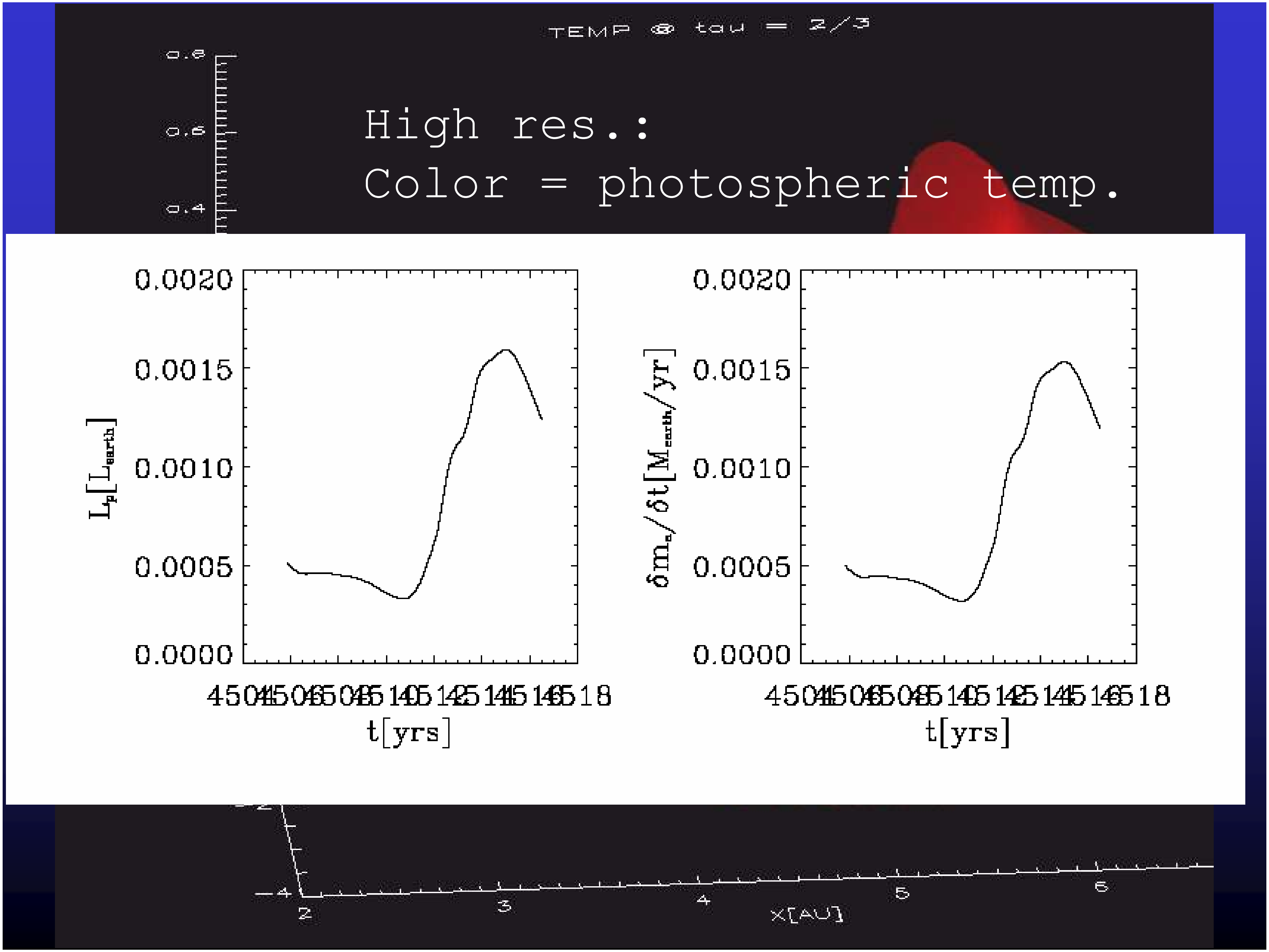
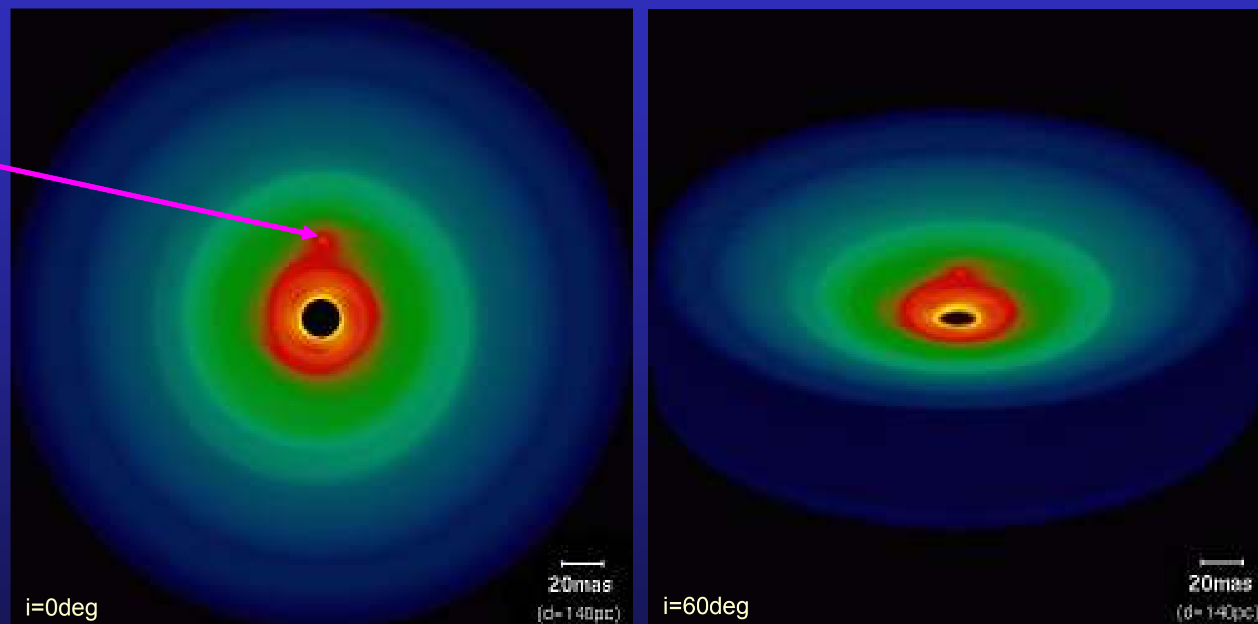
2
4
8
10
12


TEMP @ tau = 2/3
High res.:
Color = photospheric temp.
Z[AU]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Y[AU]
4
2
0
-2
-4
X[AU]
2
3
4
5
6


TEMP @ tau = 2/3
0.8
0.6
0.4
High res.:
Color = photospheric temp.
0.0020
0.0015
0.0010
0.0005
0.0000
$L_p[L_{earth}]$
t[yrs]
0.0020
0.0015
0.0010
0.0005
0.0000
$\delta m_c/\delta t[M_{earth}/yr]$
t[yrs]
-2
-4
2
3
4
5
6
X[AU]

Imaging in the Mid-infrared (~10micron)

Hot Accretion Region around the Planet



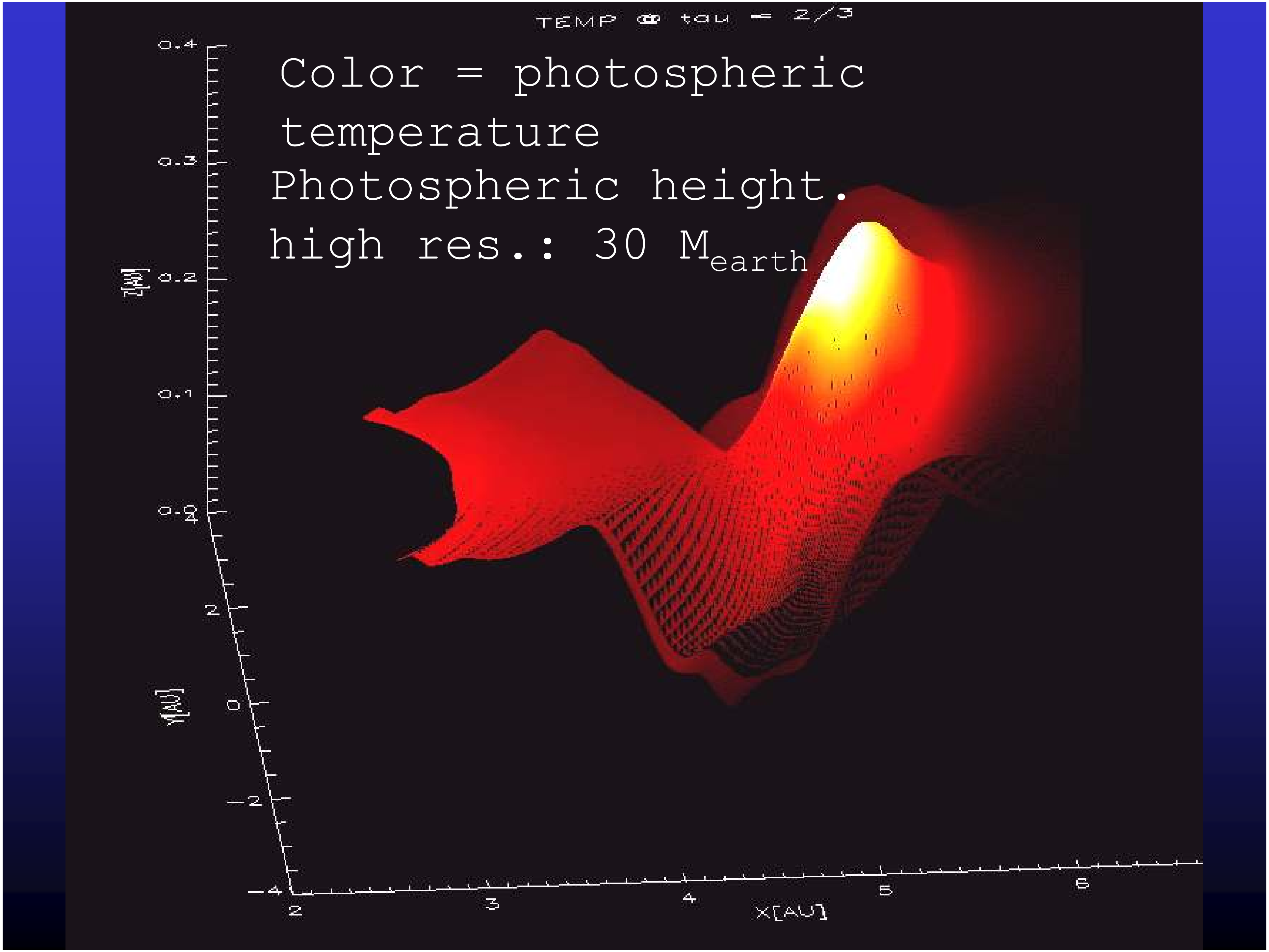
10mm surface brightness profile of a T Tauri disk with an embedded planet (inner 40AUx40AU, distance: 140pc)

[Wolf & Klahr 2005]

Science Case Study for T-OWL:

Thermal Infrared Camera for OWL (Lenzen et al. 2005)

Justification of the Observability in the Mid-IR for nearby objects (d<100pc)

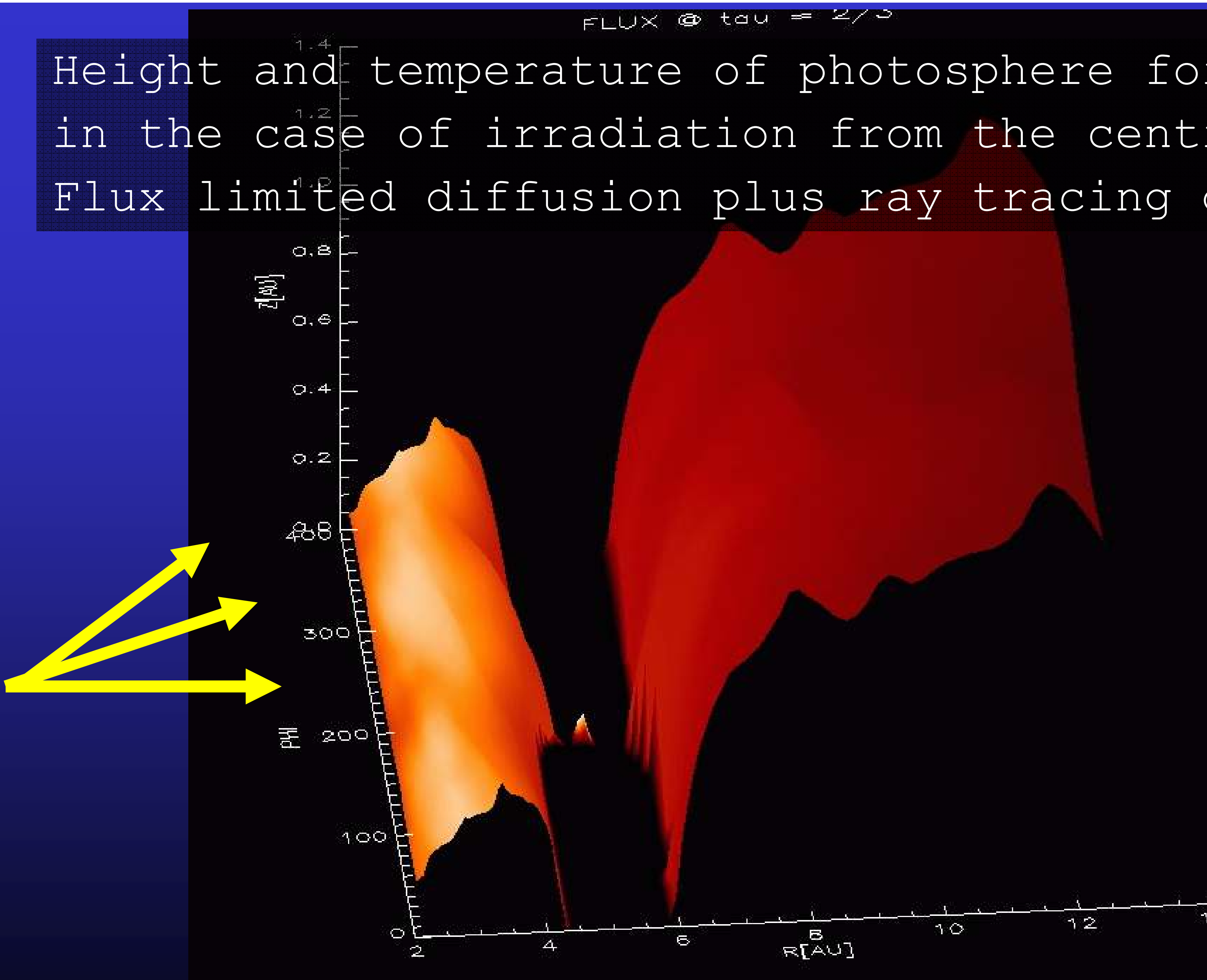

TEMP @ tau = 2/3
Color = photospheric temperature
Photospheric height.
high res.: 30 M$_{earth}$
0.4
0.3
0.2
0.1
0.0
Z[AU]
4
2
0
−2
−4
Y[AU]
2
3
4
5
6
X[AU]

Hydro + flux limited Diffusion + ray t

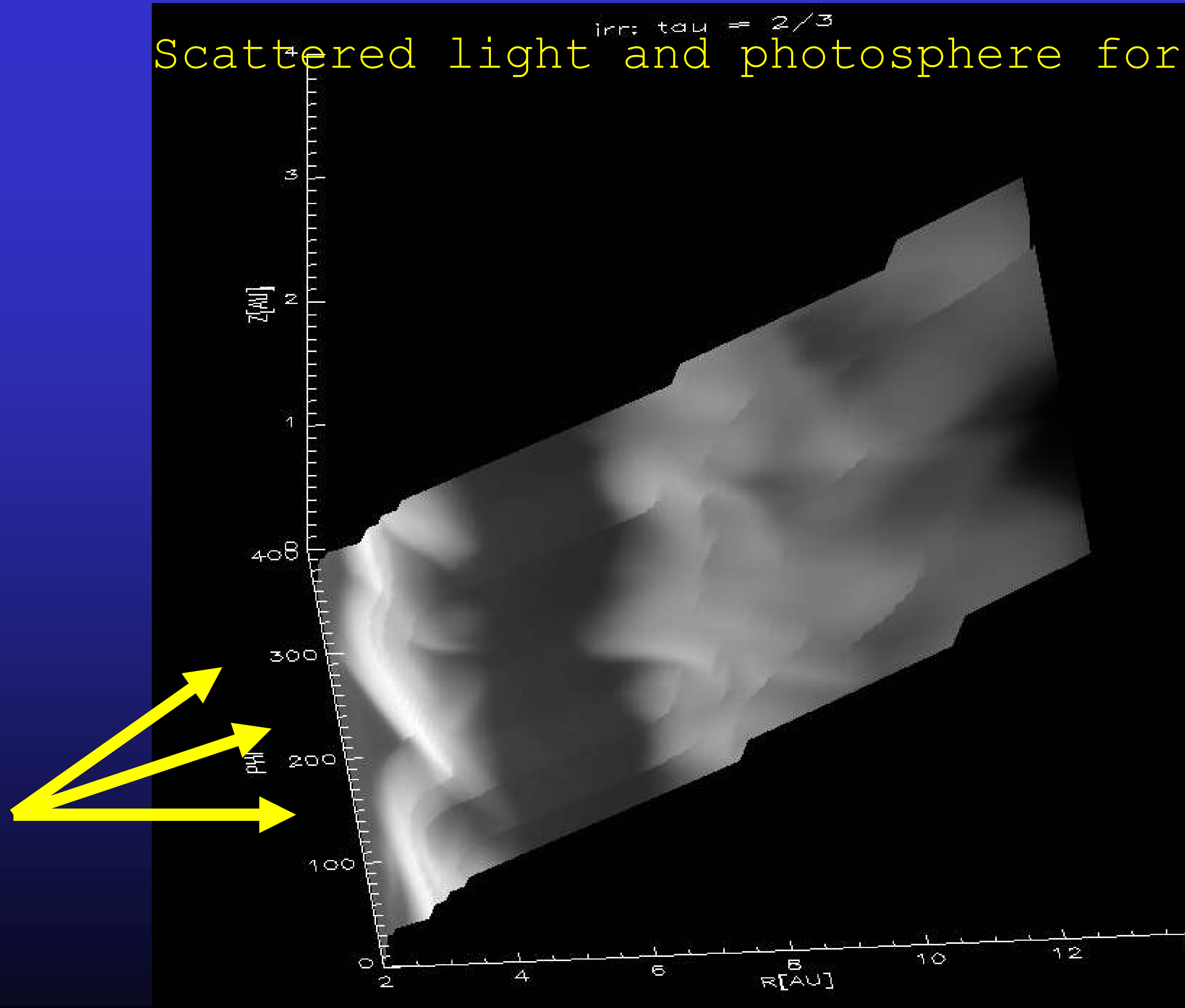
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Inner Rim: with Kees Dullemond

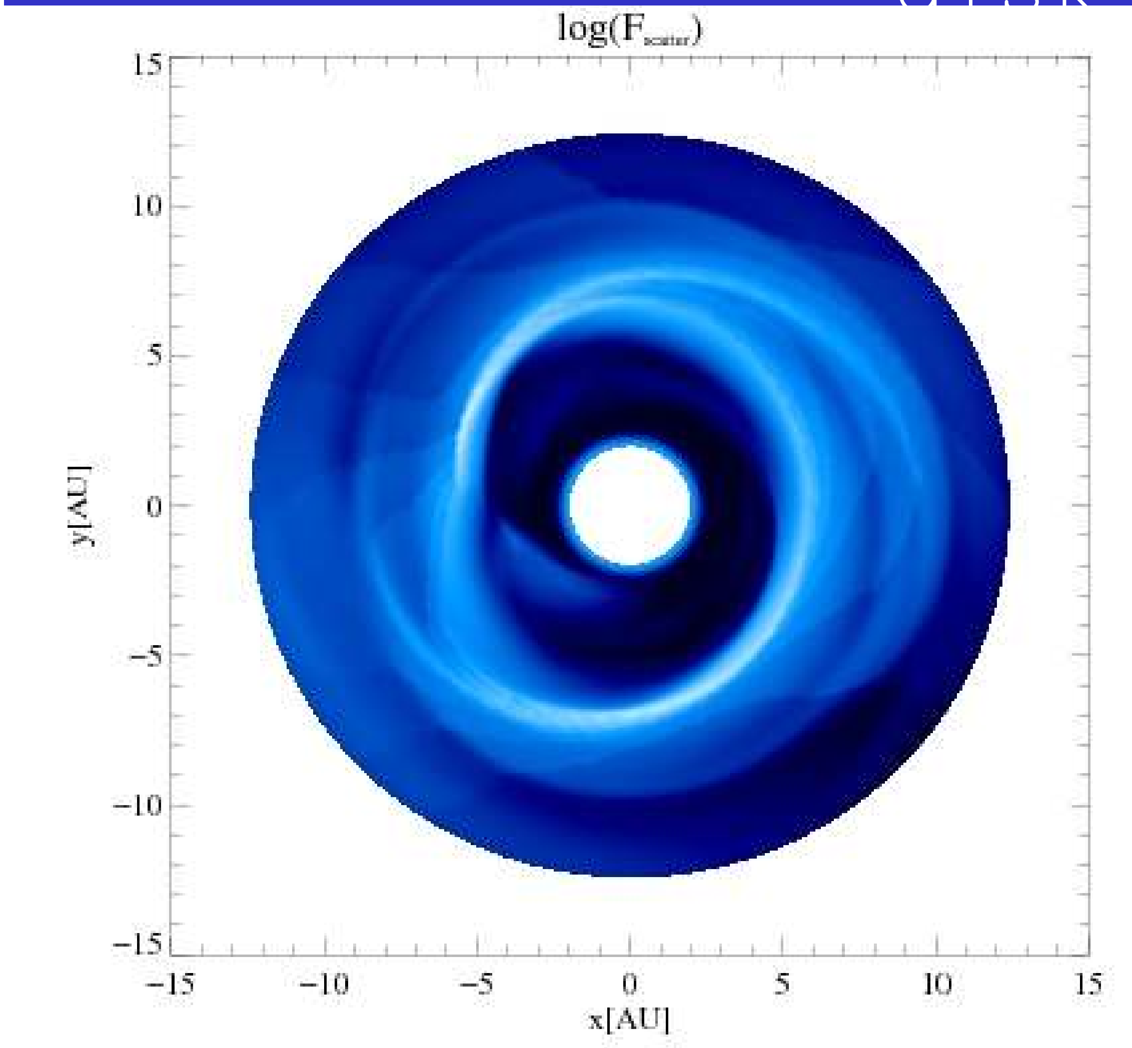
Height and temperature of photosphere for disk e
in the case of irradiation from the central obje
Flux limited diffusion plus ray tracing during t

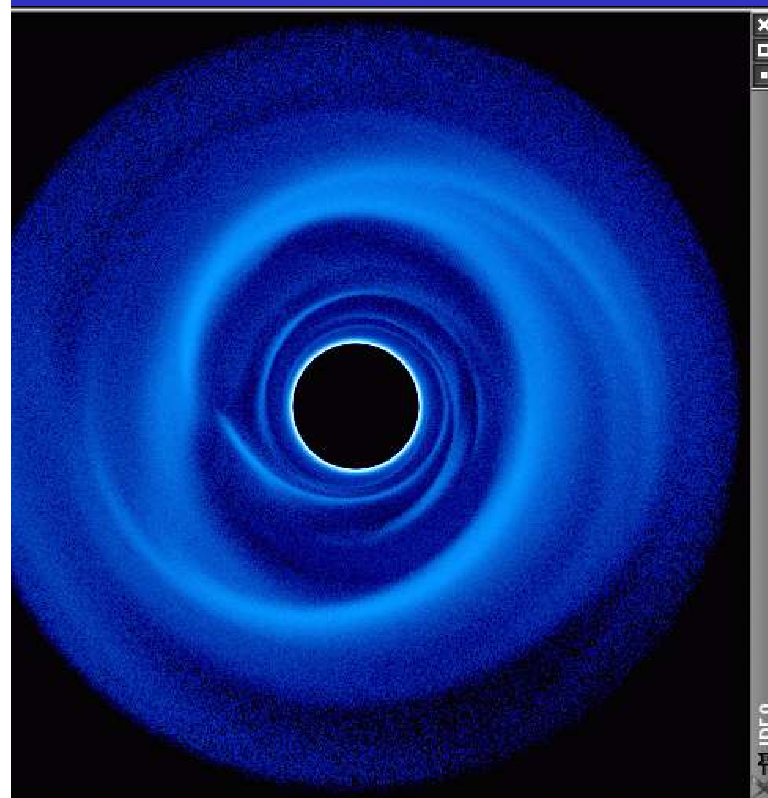


Scattered light and photosphere for irradi



Test of Radiation transport: scattered light/role of inner disk

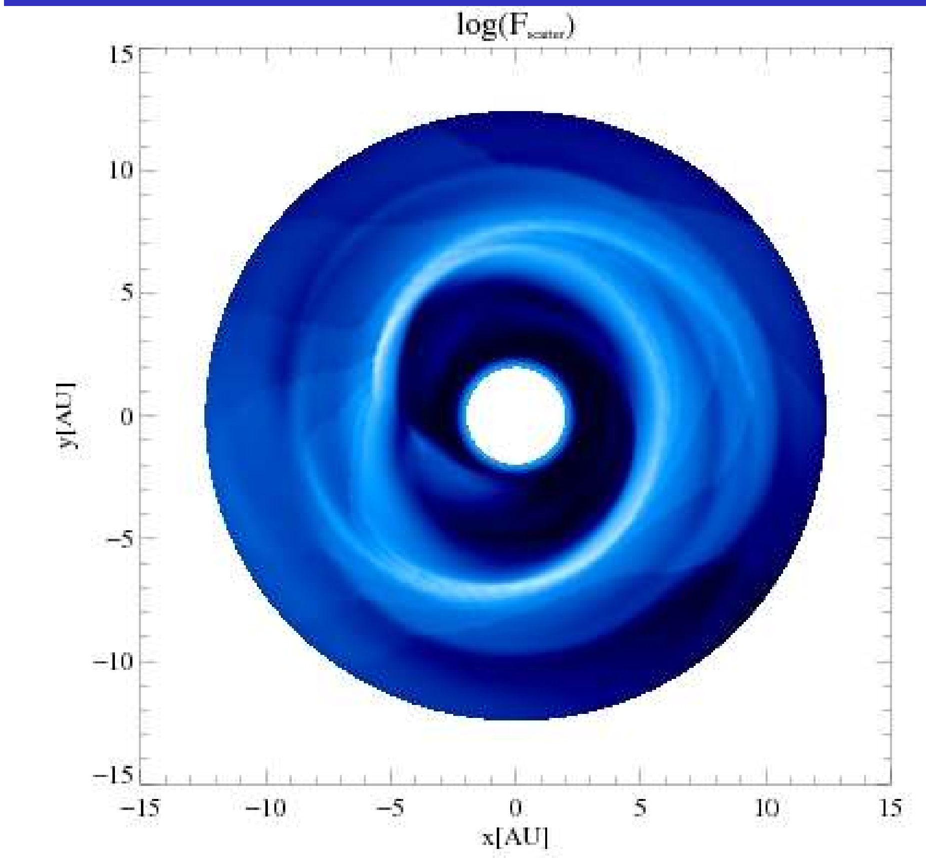


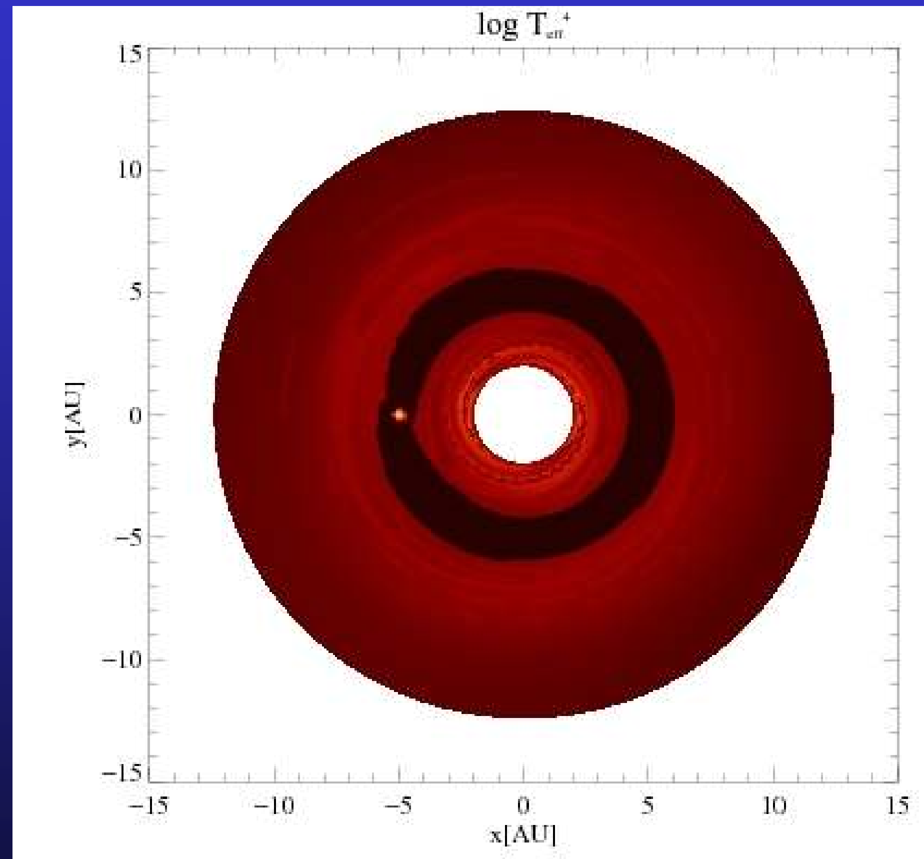


TRAMP (Radiation-Hydro)

MC3D (S. Wolf)

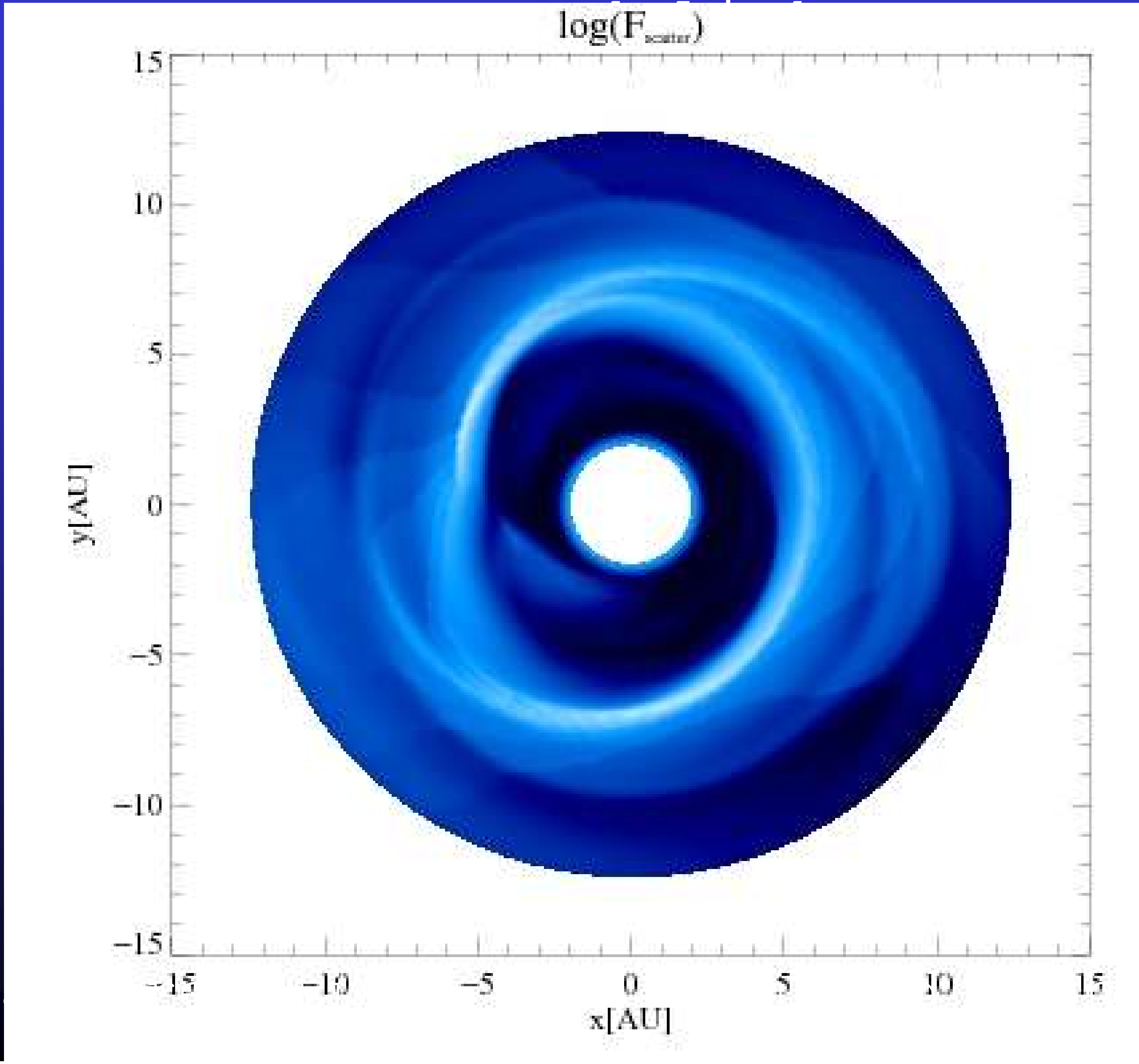
Test of Radiation transport: scattered light





scattered light　　　　emitted light

Test of Radiation transport:



SC

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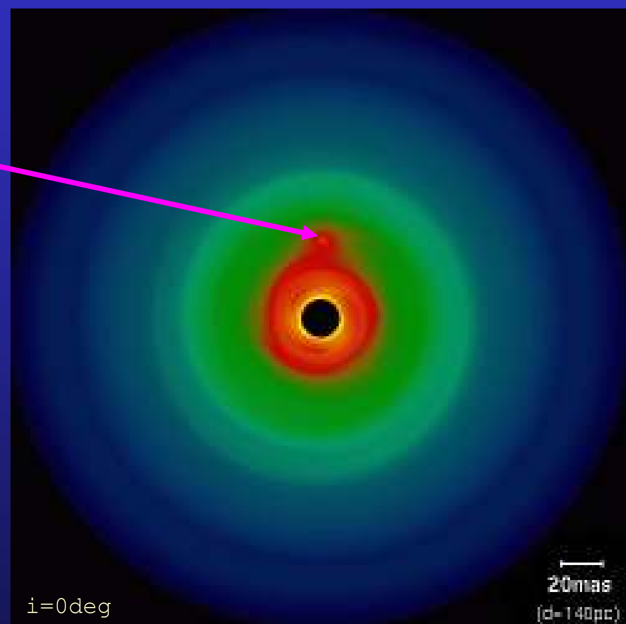

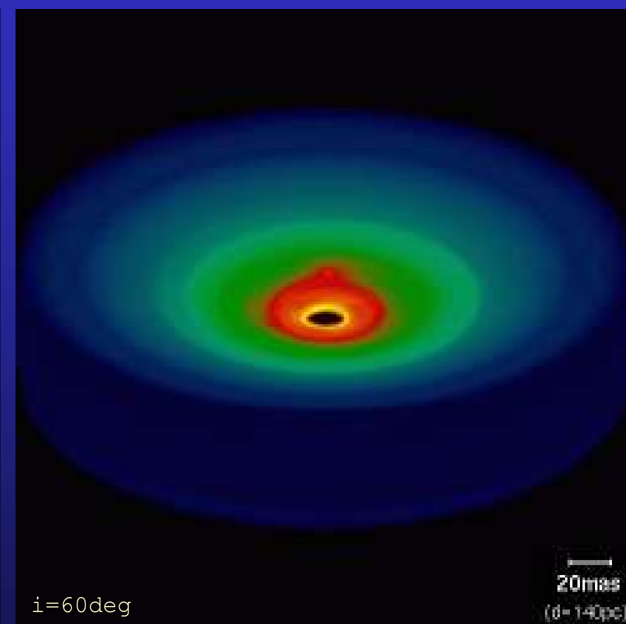

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Science Case Study for T-OWL:

Thermal Infrared Camera for OWL (Lenzen et al. 2005)

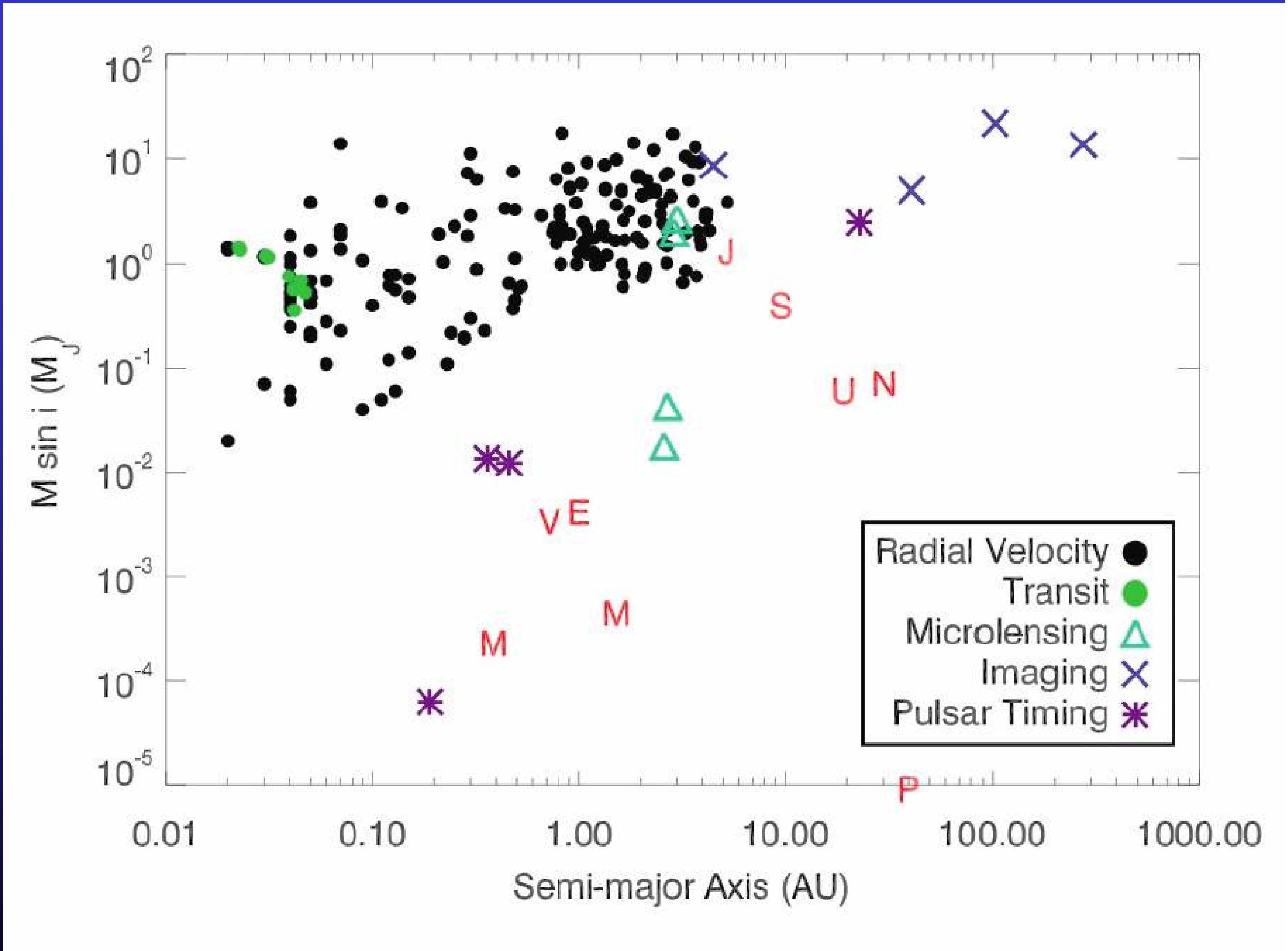
Justification of the Observability in the Mid-IR for nearby objects (d<100pc)

The Solar System

Planet sizes are to scale. Separations are not.

Characterizing extrasolar planets: very different from solar system planets, yet solar system planets are their local analogues

Known Planets:



Courtesy by Jeremy Richardson May 2006
Based on data compiled by J. Schneider

Types of migration

- Type I: low mass planets
- Type II: high mass planets
- Type III: medium mass planet but massive disk

See **Papaloizou** et al. PPV

arXiv:astro-ph/0603196 v1 8 Mar 2006

Type I & II migration:

- Planet's gravity generates spiral patterns in the disk gas
- These spirals exert torque on planet because they are not rot. symmetric:
  - Inner spiral wave put ang. mom. on planet
  - Outer spiral wave takes ang. mom. from planet
- Outer spiral dominates: inward migration

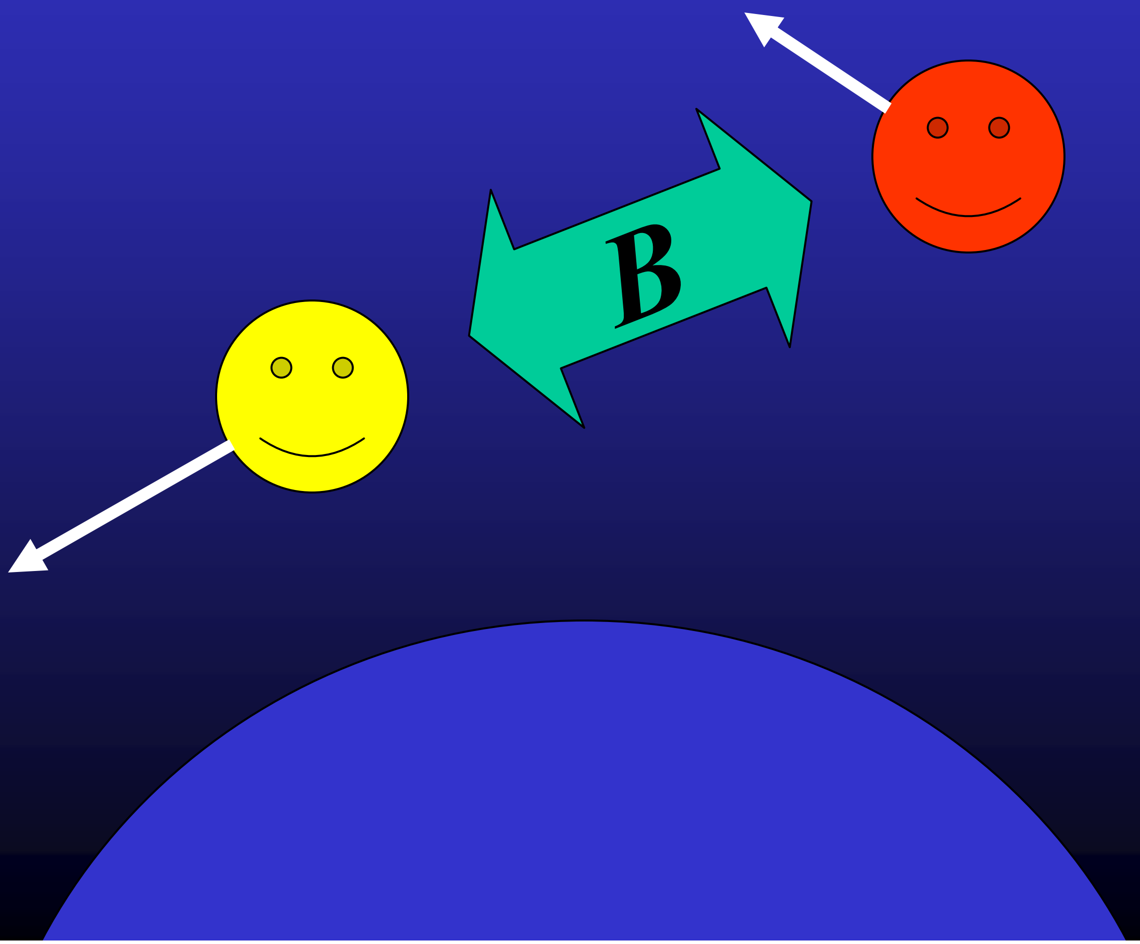
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

+

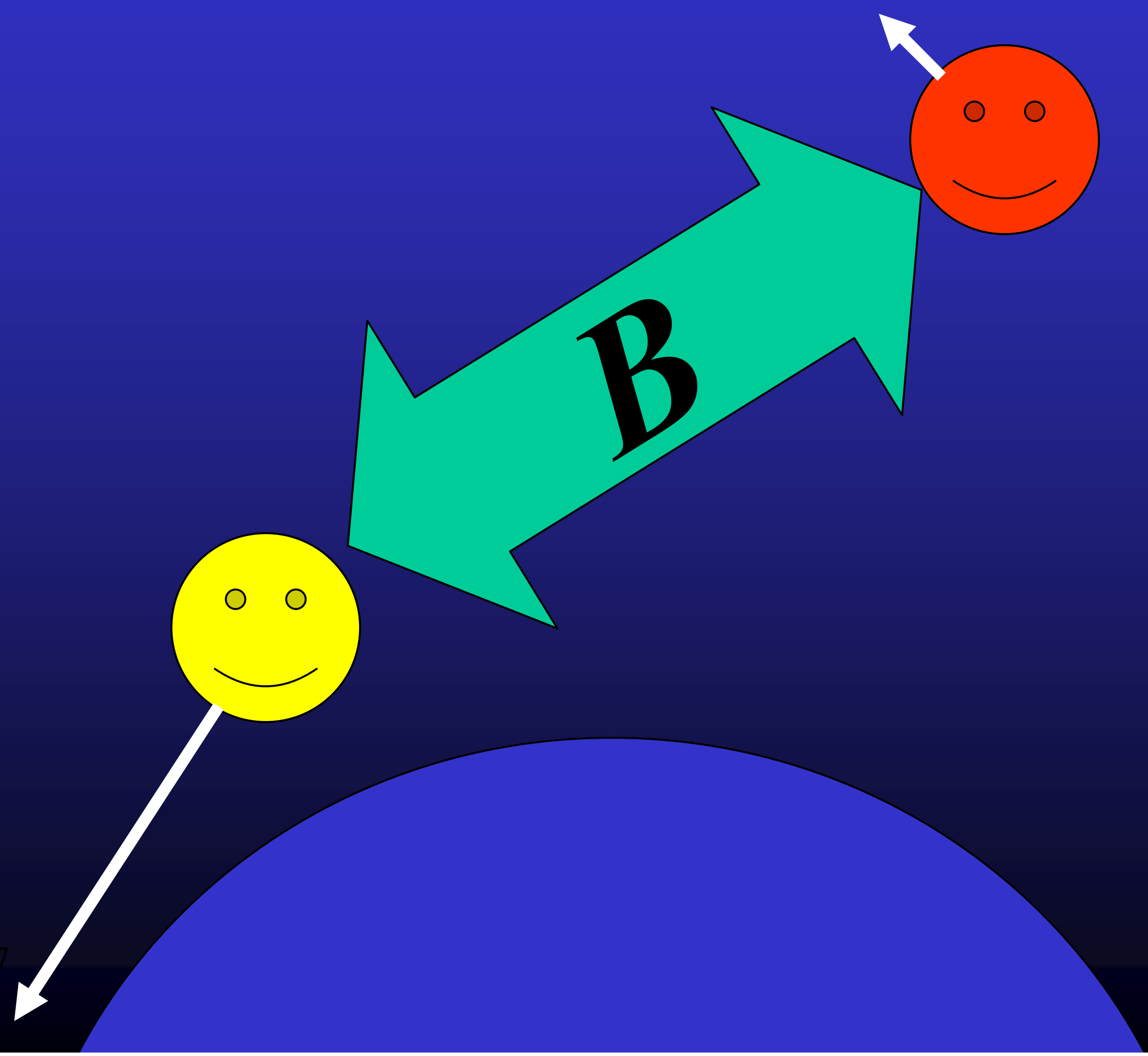
−

by Frederic Masset

MRI: a.k.a - Rockets in an earth orbit accelerate when they break!

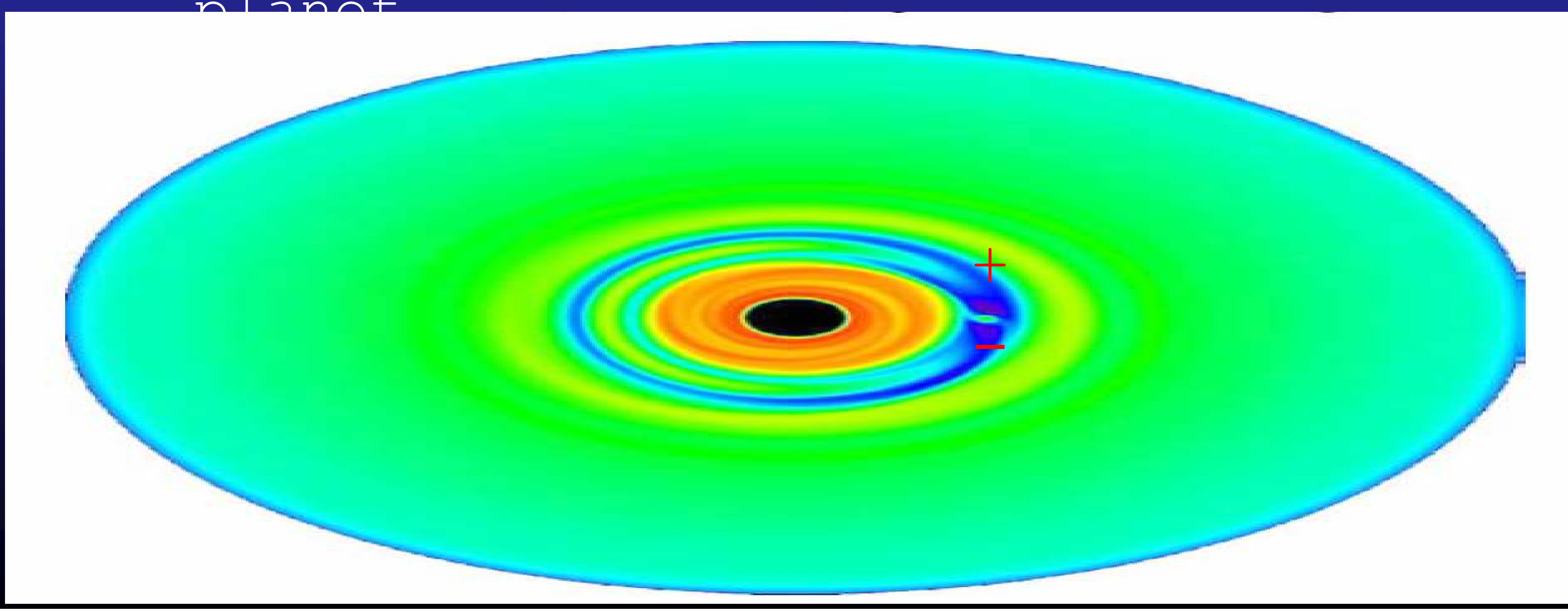


MRI: a.k.a - Rockets in an earth orbit accelerate when they break!

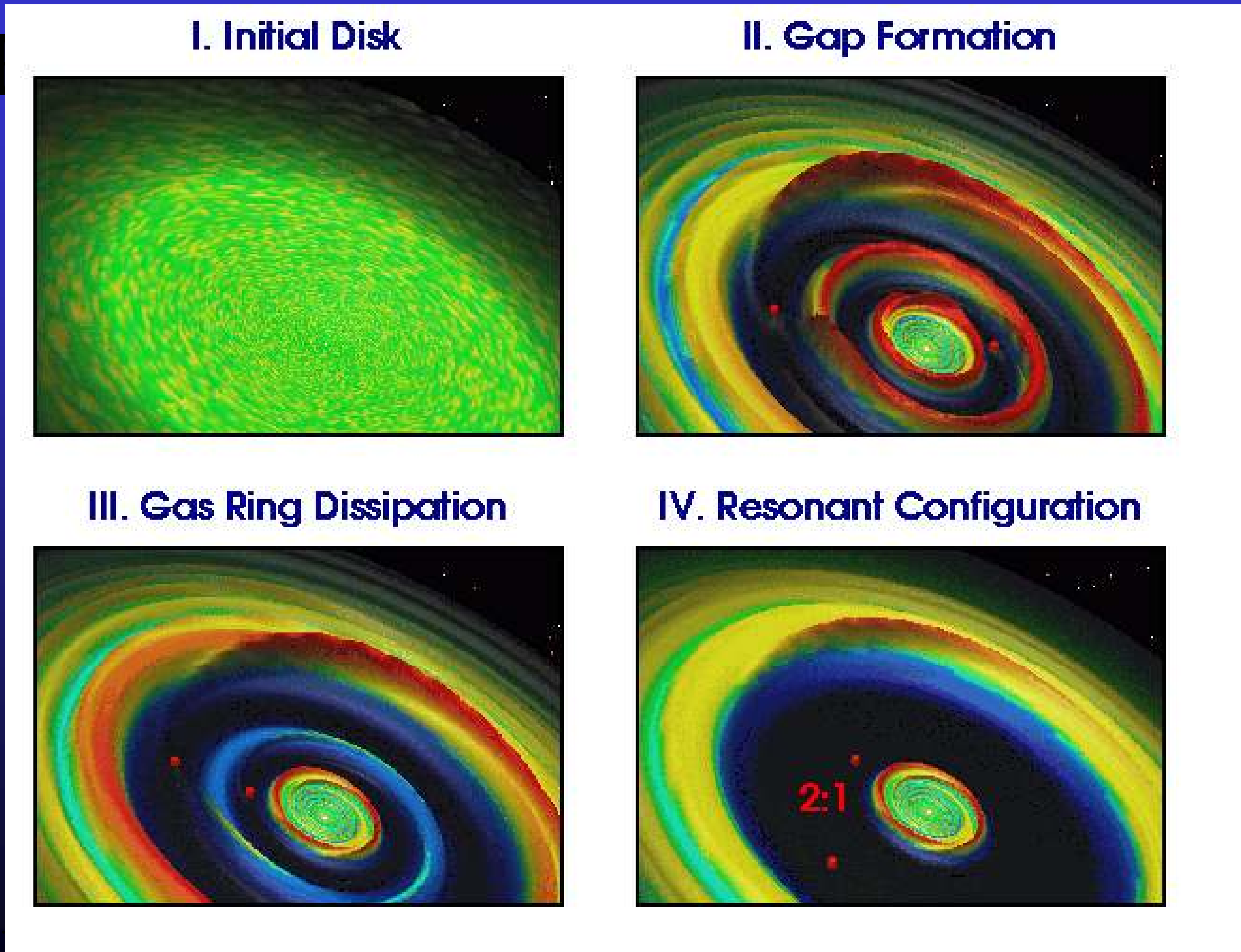


Type III migration:

- Lot of mass at the corotation radius
- The gas on the horseshoe orbit also pulls on the planet:
  - : + region puts ang. mom. on planet
  - : − region takes ang. mom. from planet

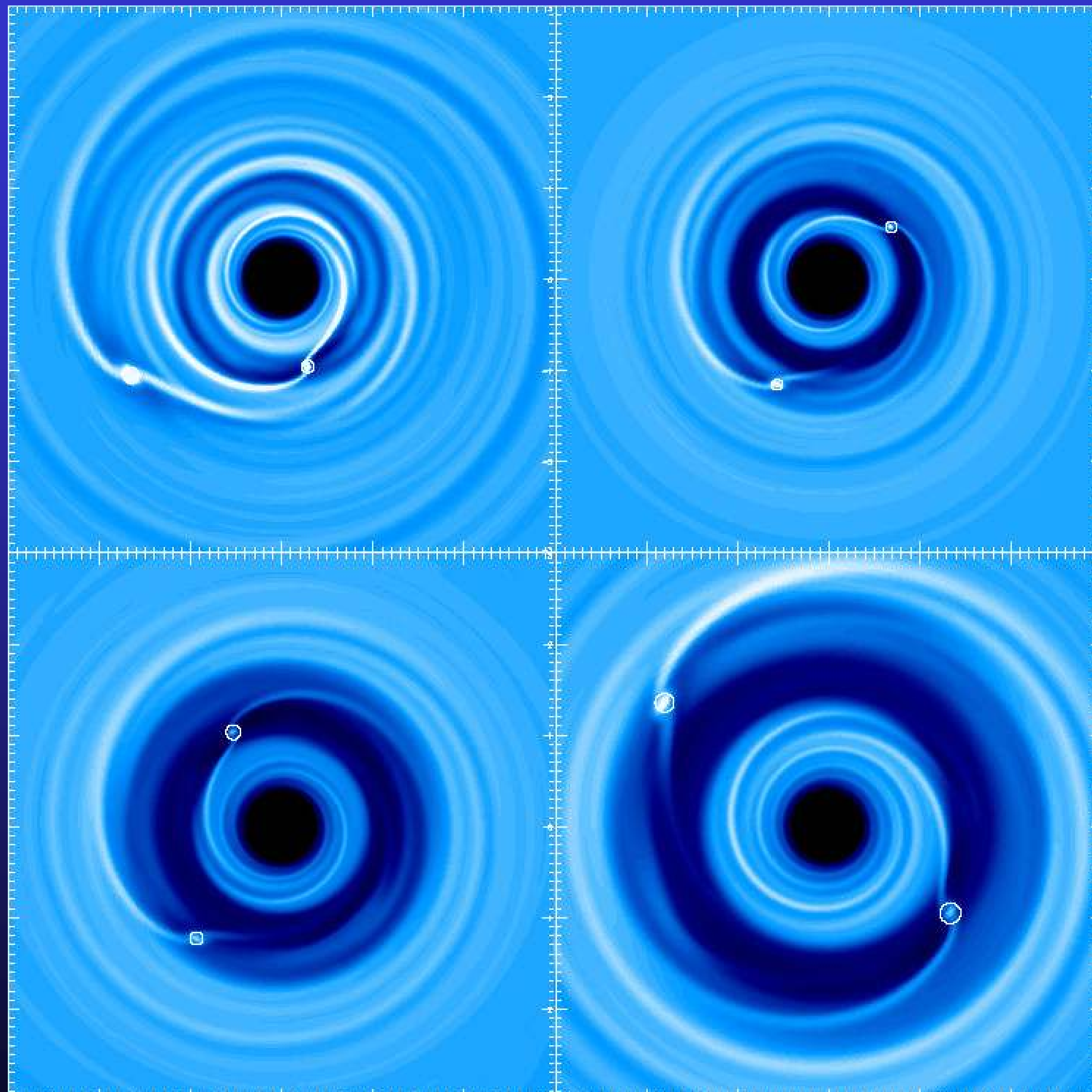


set


I. Initial Disk
II. Gap Formation
III. Gas Ring Dissipation
IV. Resonant Configuration
2:1

G. Bryden

Resonance trapping



Masset & Snellgrove

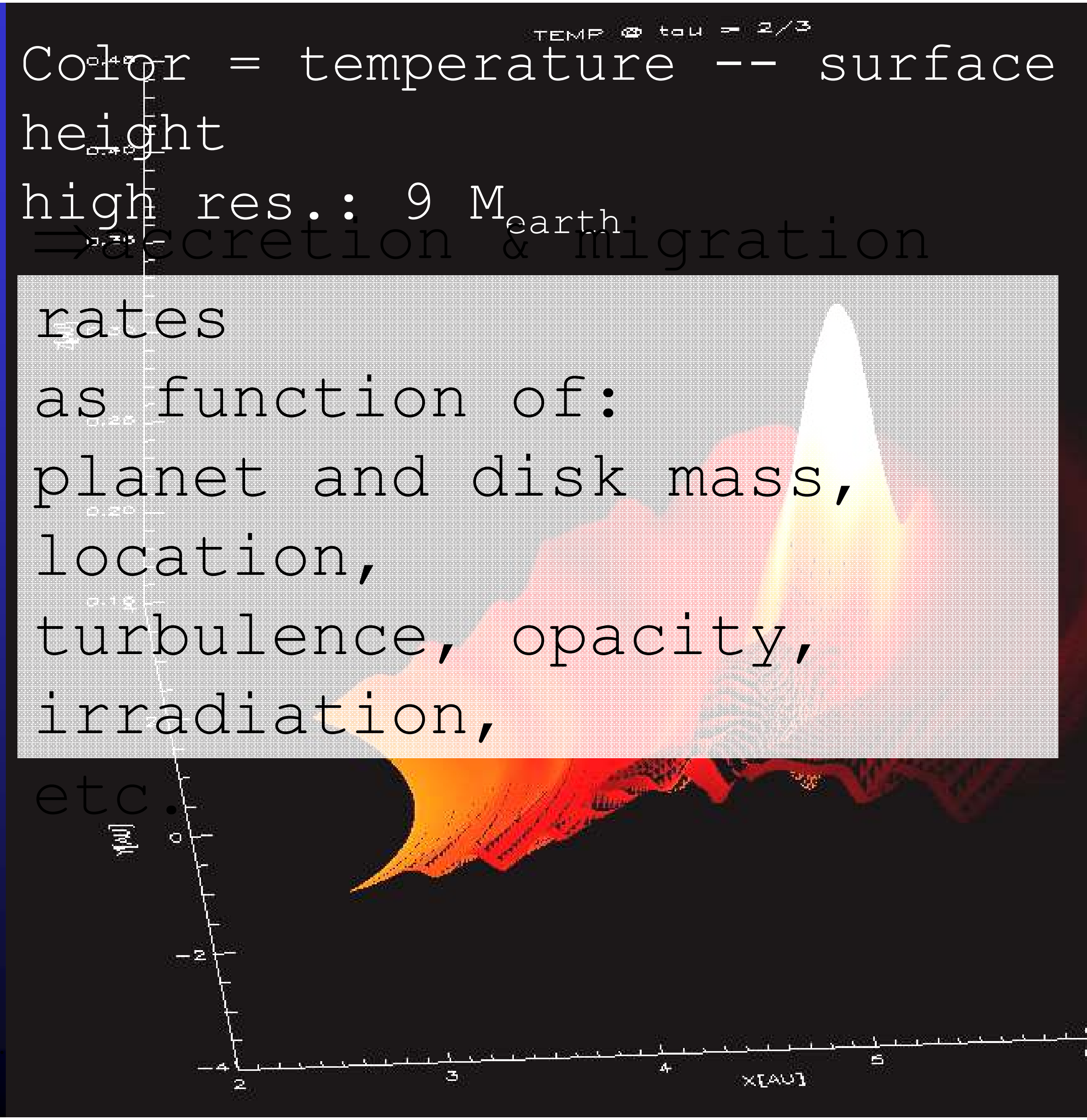
Color = temperature -- surface = height

high res.: 9 M_{earth}

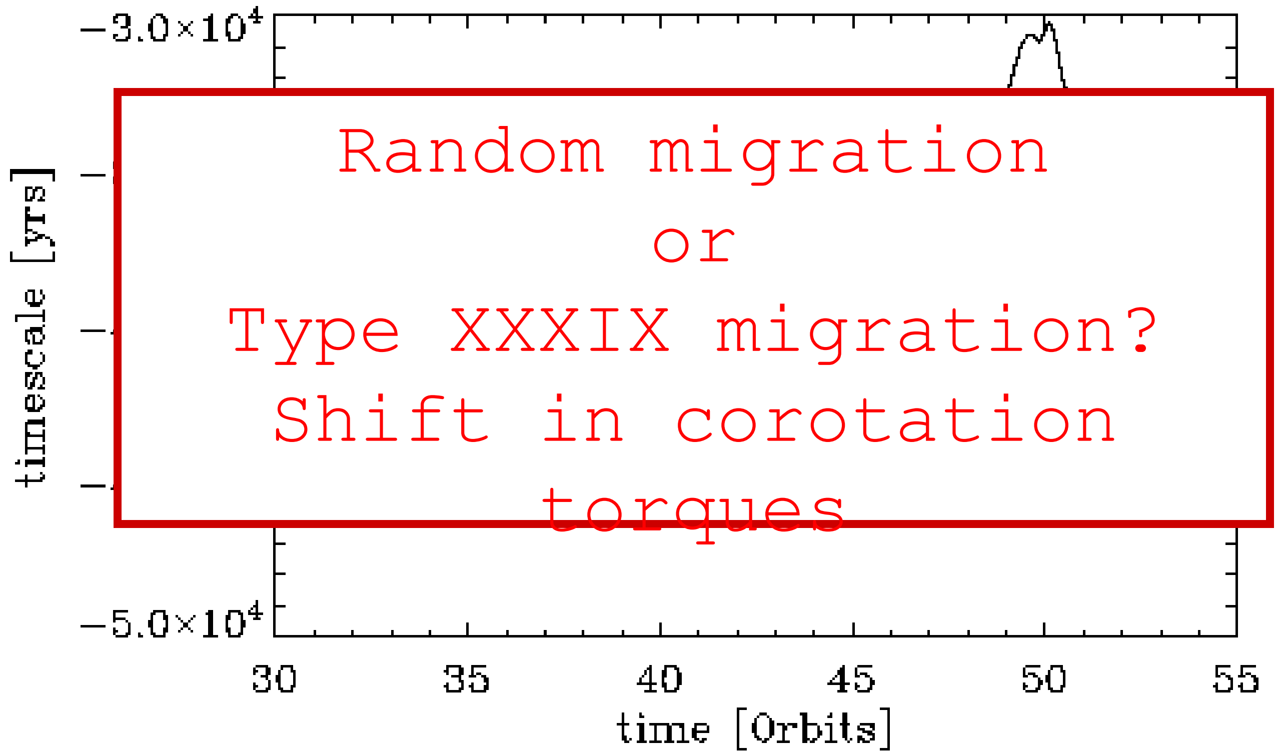
⇒ accretion & migration rates

as function of:

planet and disk mass, location, turbulence, opacity, irradiation, etc.



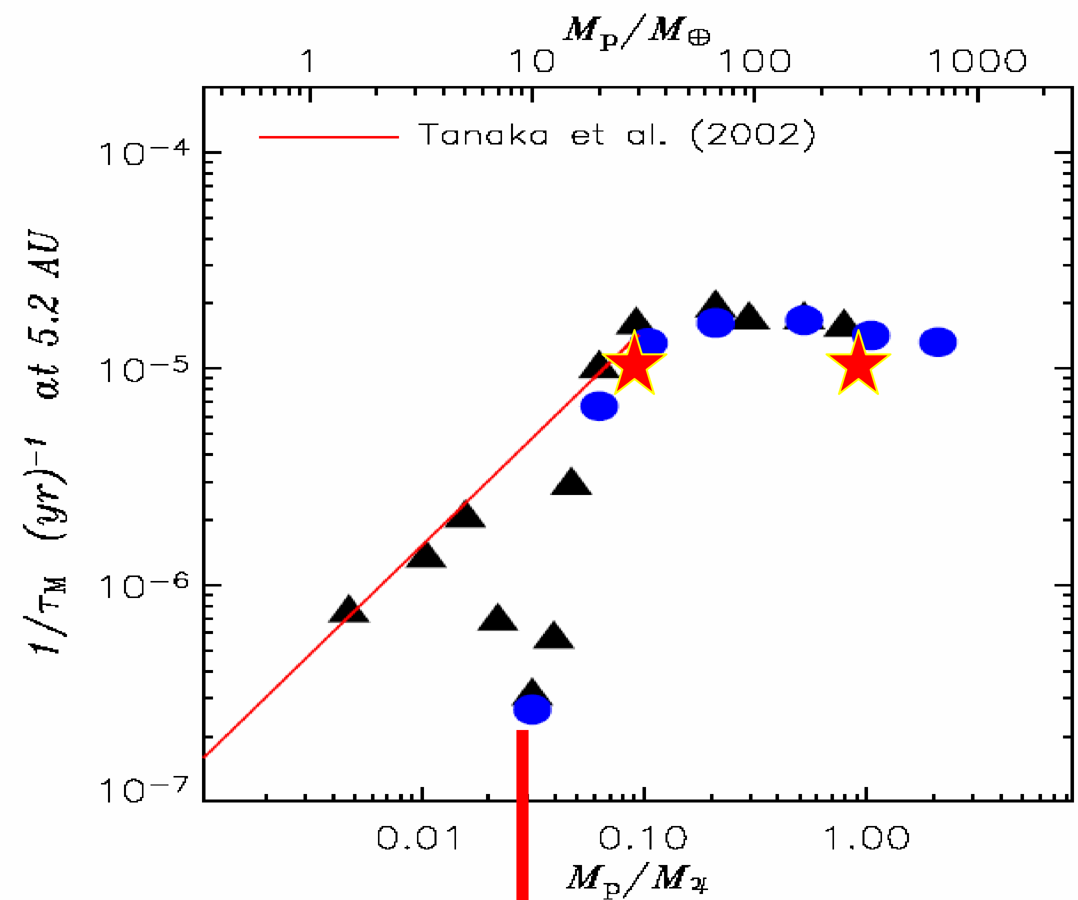
Torques for a 9 M_{Earth} planet:



Random migration
or
Type XXXIX migration?
Shift in corotation torques

Negative = outward drift!

no accretion

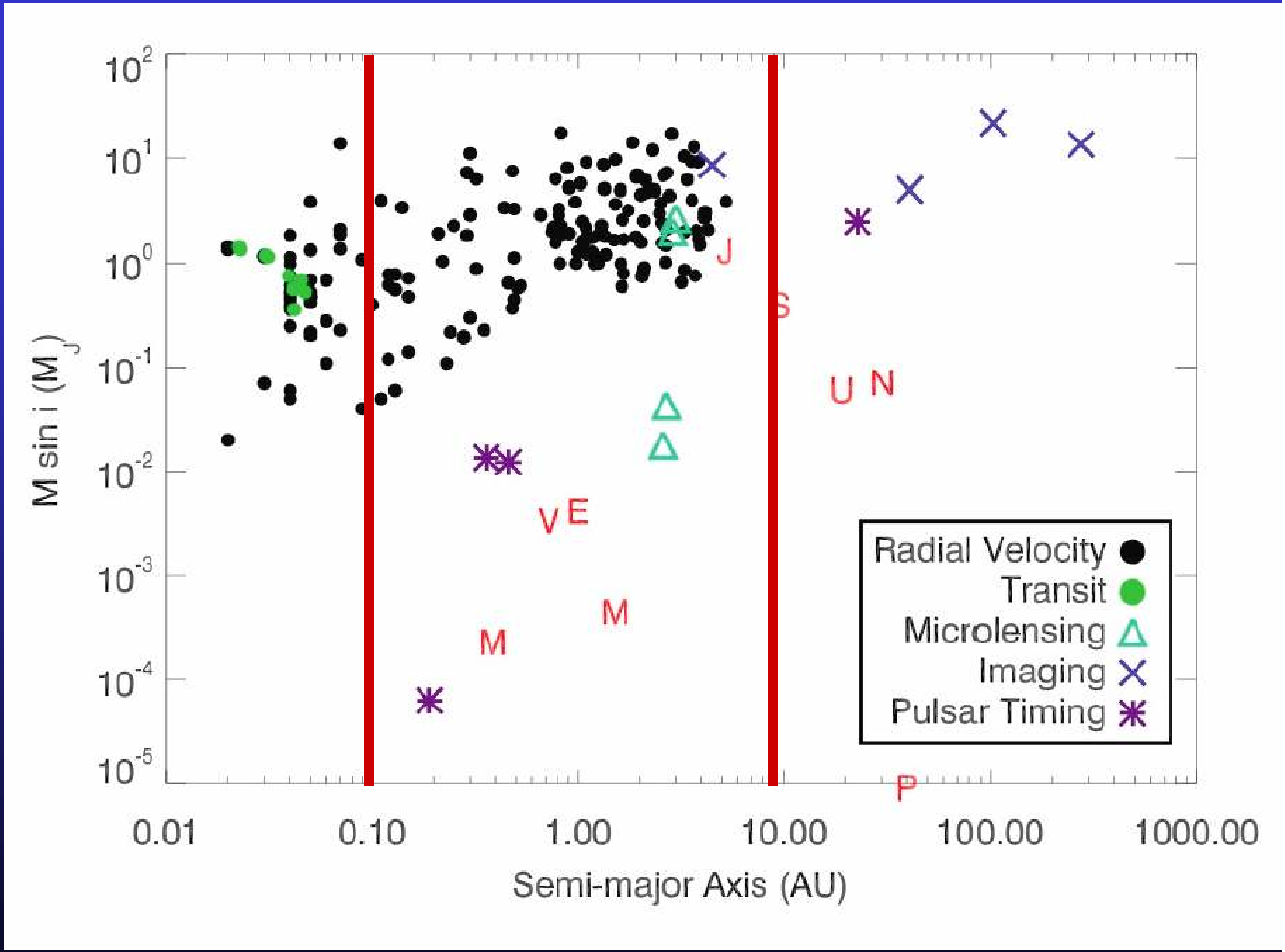


after D'Angelo, ★ Henning & Kley
2003b

outward drift: -10^{-4}/yr

plus new results by: Klahr, Bryden & Kley

Known Planets:



Courtesy by Jeremy Richardson May 2006
Based on data compiled by J. Schneider

Conclusions:

migration depends on disk evolution. ;)

MHD/dead-zone/Irradiation/Evaporation/coagulation/drift/multiple Planets/etc.

...thats why comparisons to upcoming instruments/observations are so important! (VLTI, LBT, ALMA, ELT etc.)

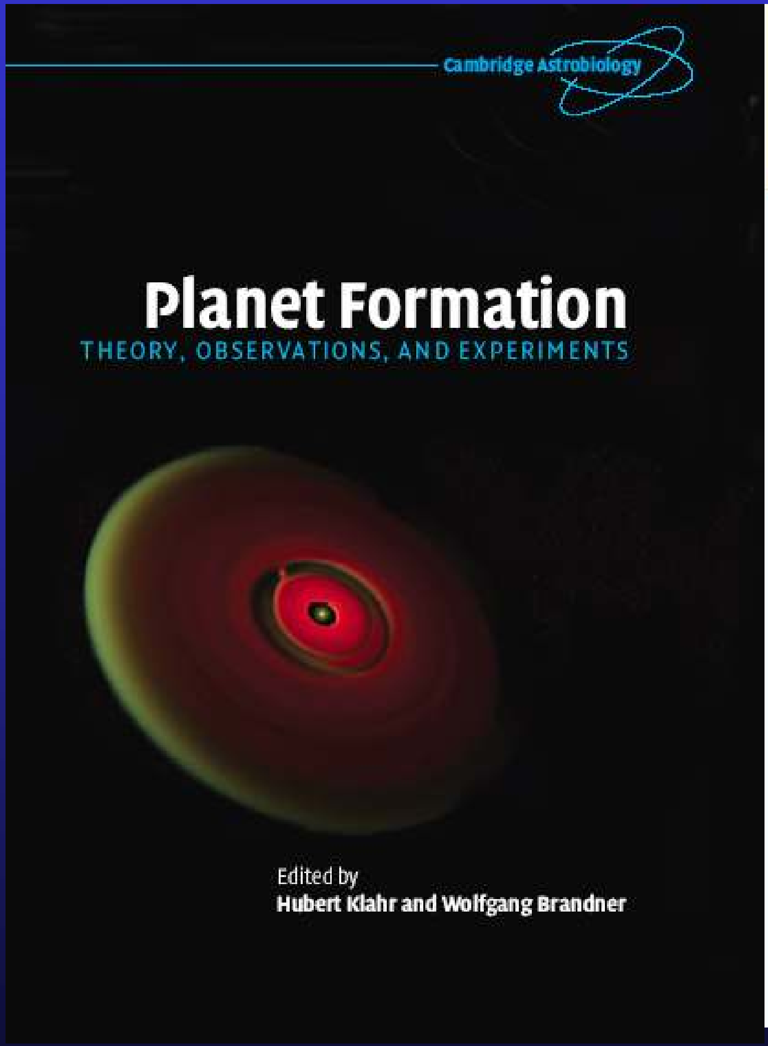
Embedded Planets will be our

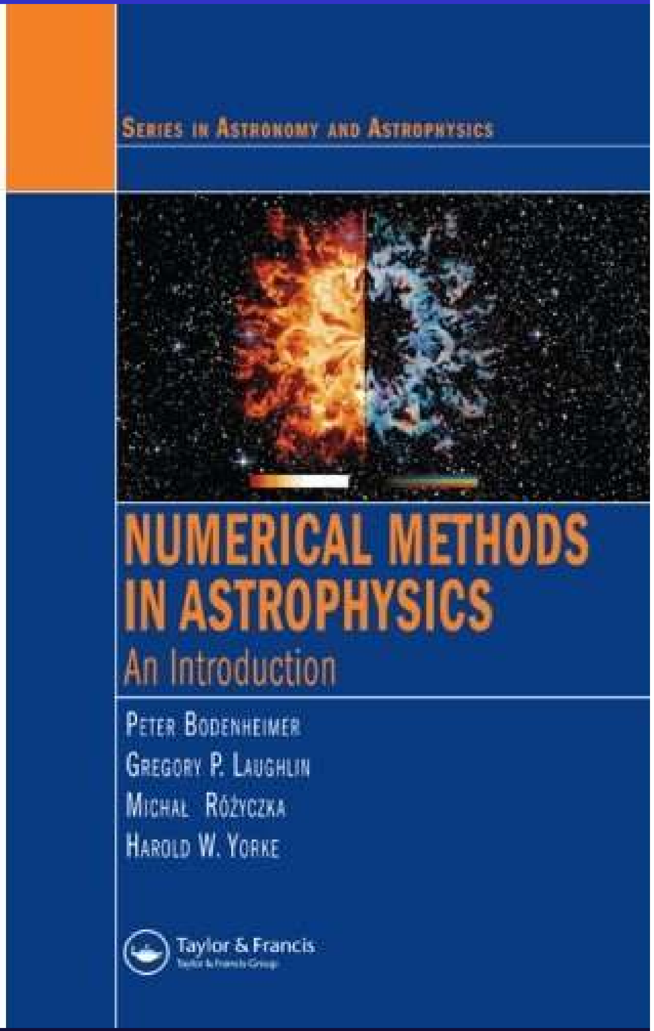
"THE FUTURE"

1. Preparation of the detection of nascent planets in disks (9-100 Mearth):
   Simulations for ALMA etc.
   => Validation of core accretion scenario
2. Measurements of accretion rates for planets in disks: Linc-Nirvana, ELT, FIRM, ...
   Deducing migration rates
   => Improving of our numerical models
3. Input for population Synthesis of Exo-Planets: Disk evolution, Dust (Planetesimal) distribution, planet migration and accretion,
   -> Pan-Planets

   => Predictions for Kepler and other future observations of planets?

Further reading...





...let your supervisors org