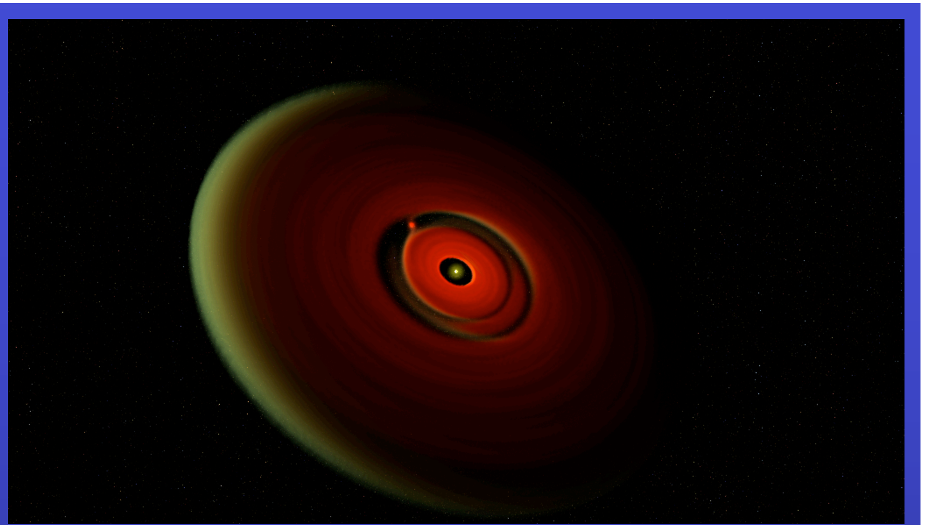
Bonn, MPIfR
April. 17th 2008



"The Cradle of Life": Proto Planets and Circumstellar Disks:

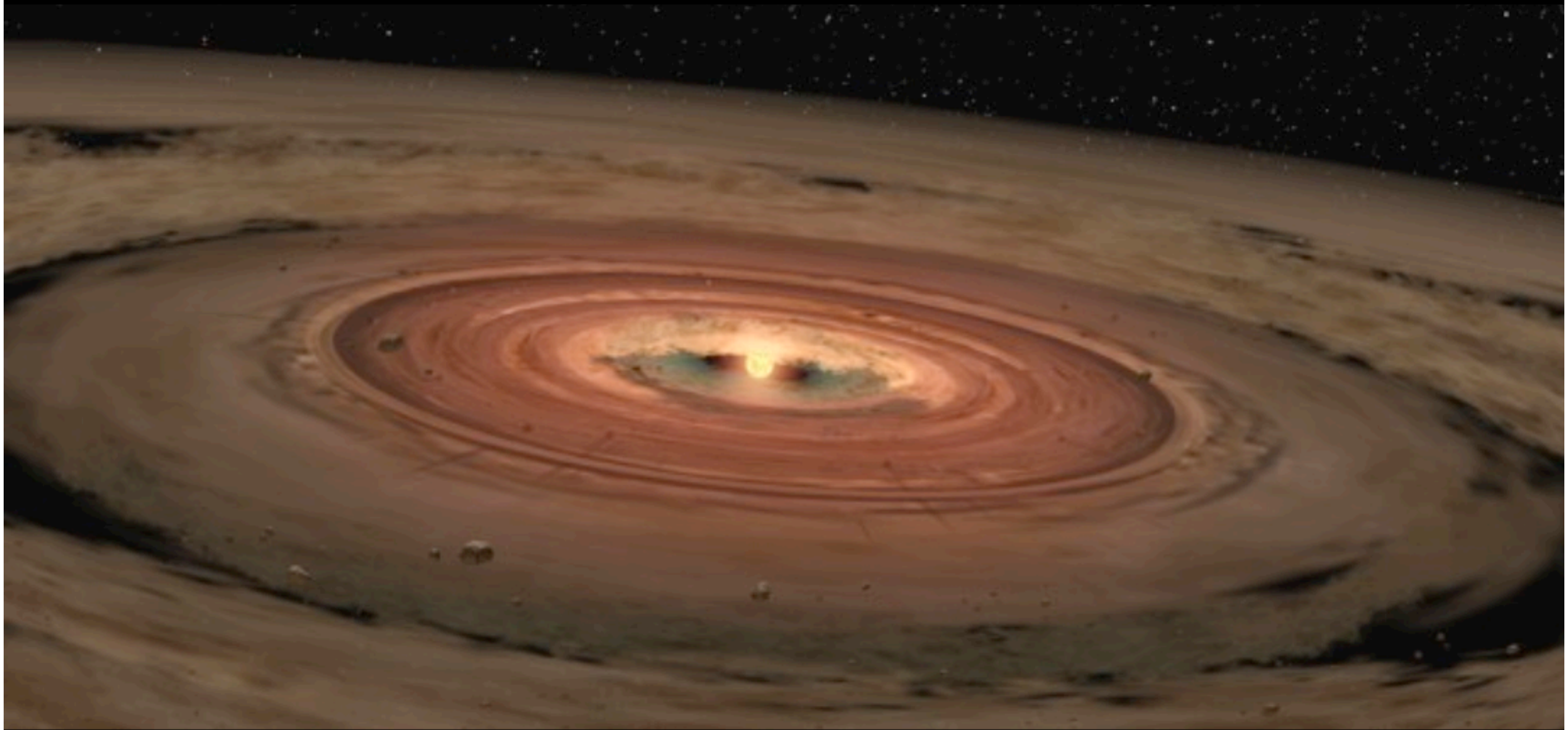
Hubert Klahr,

Max-Planck-Institut für Astronomie, Heidelberg

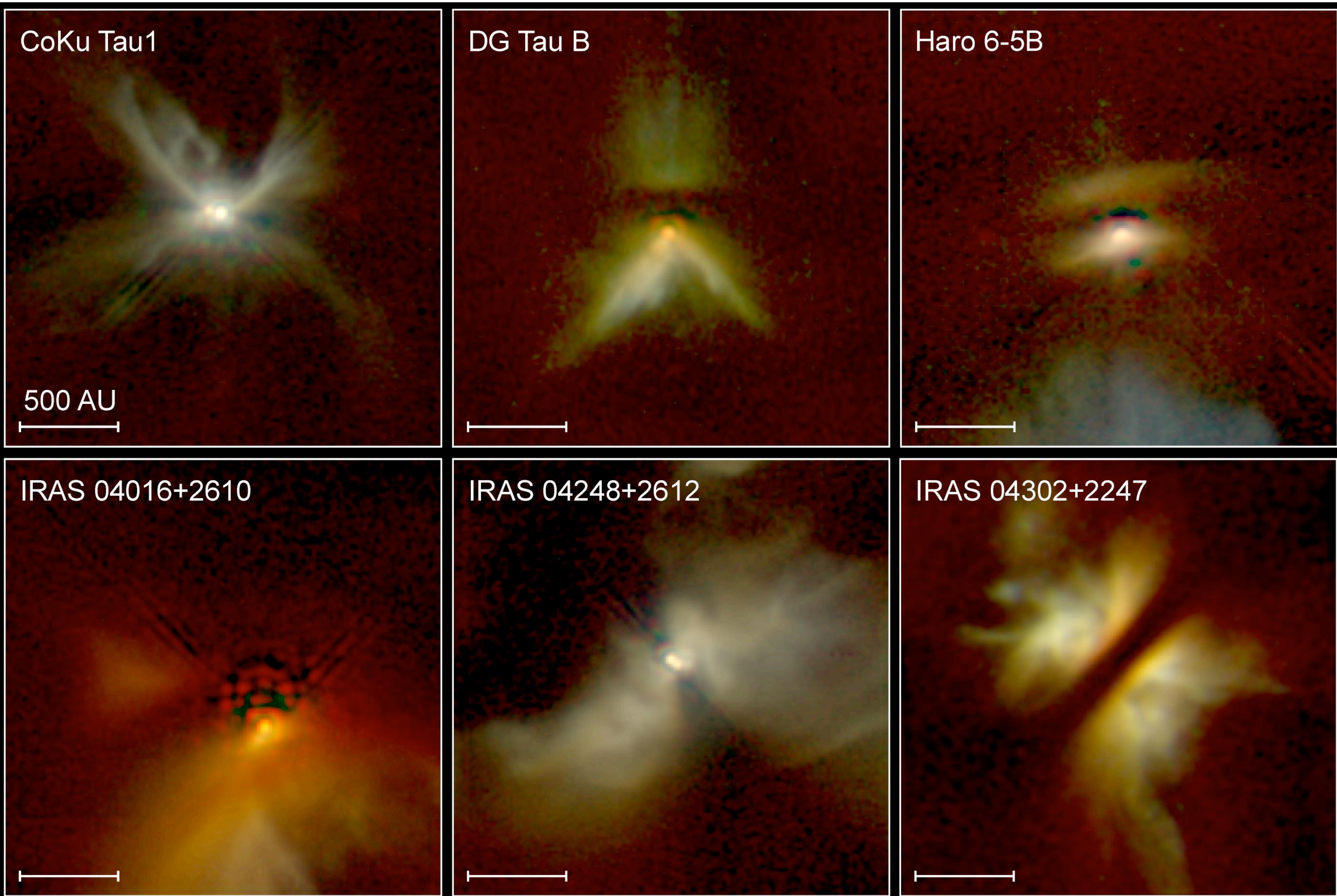
"planet formation theory and observational tests e.g. via SKA"

1. Theoretical background: solar system vs. Exo-Planets
2. planetesimal formation: growth of dust to planetary building bricks in turbulent accretion disks
3. core accretion - gas capture: Concept
4. nascent planets: observability of planet disk interaction and migration of young planets
5. system formation: population synthesis

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



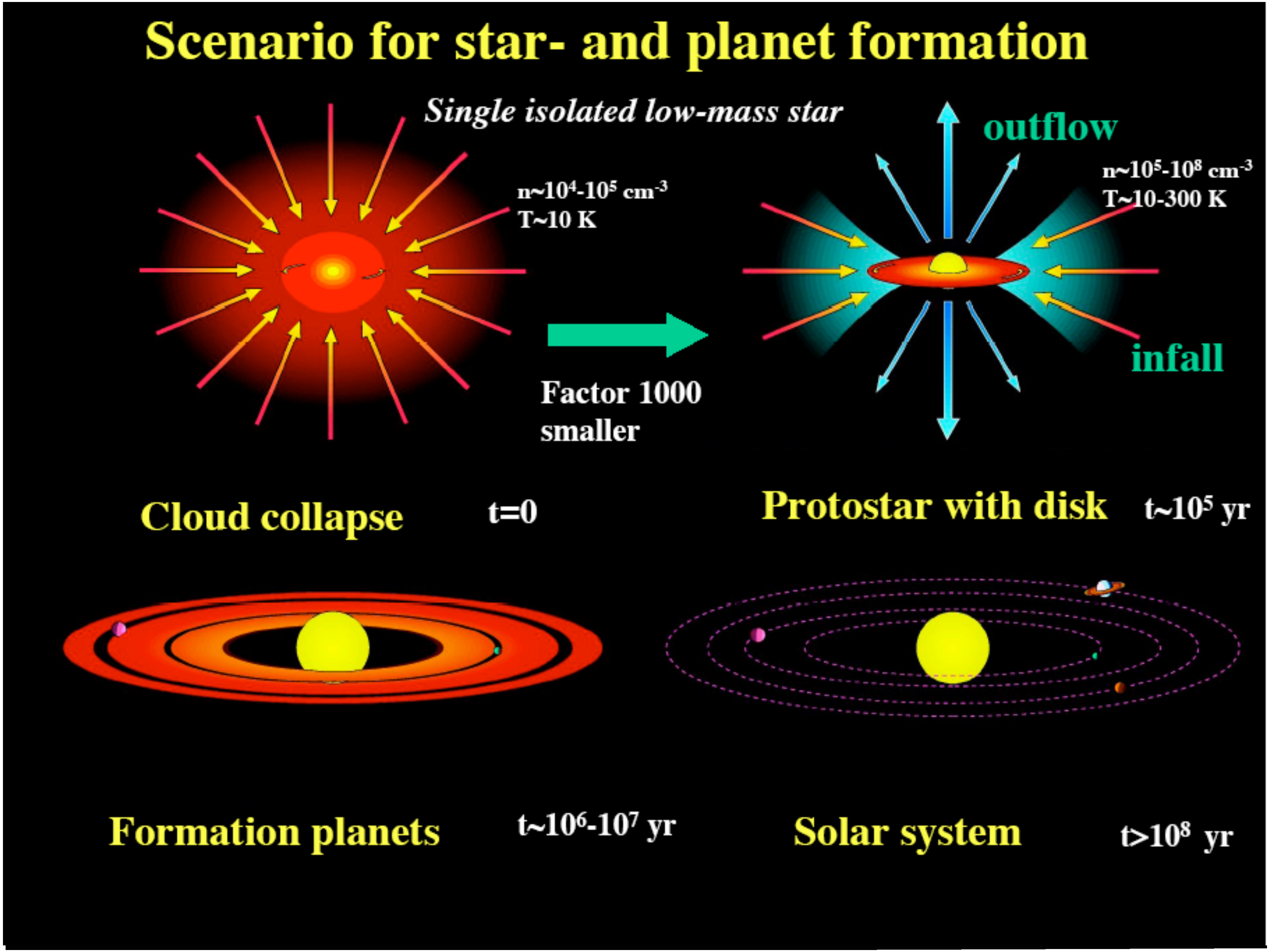
C.P. Dullemond

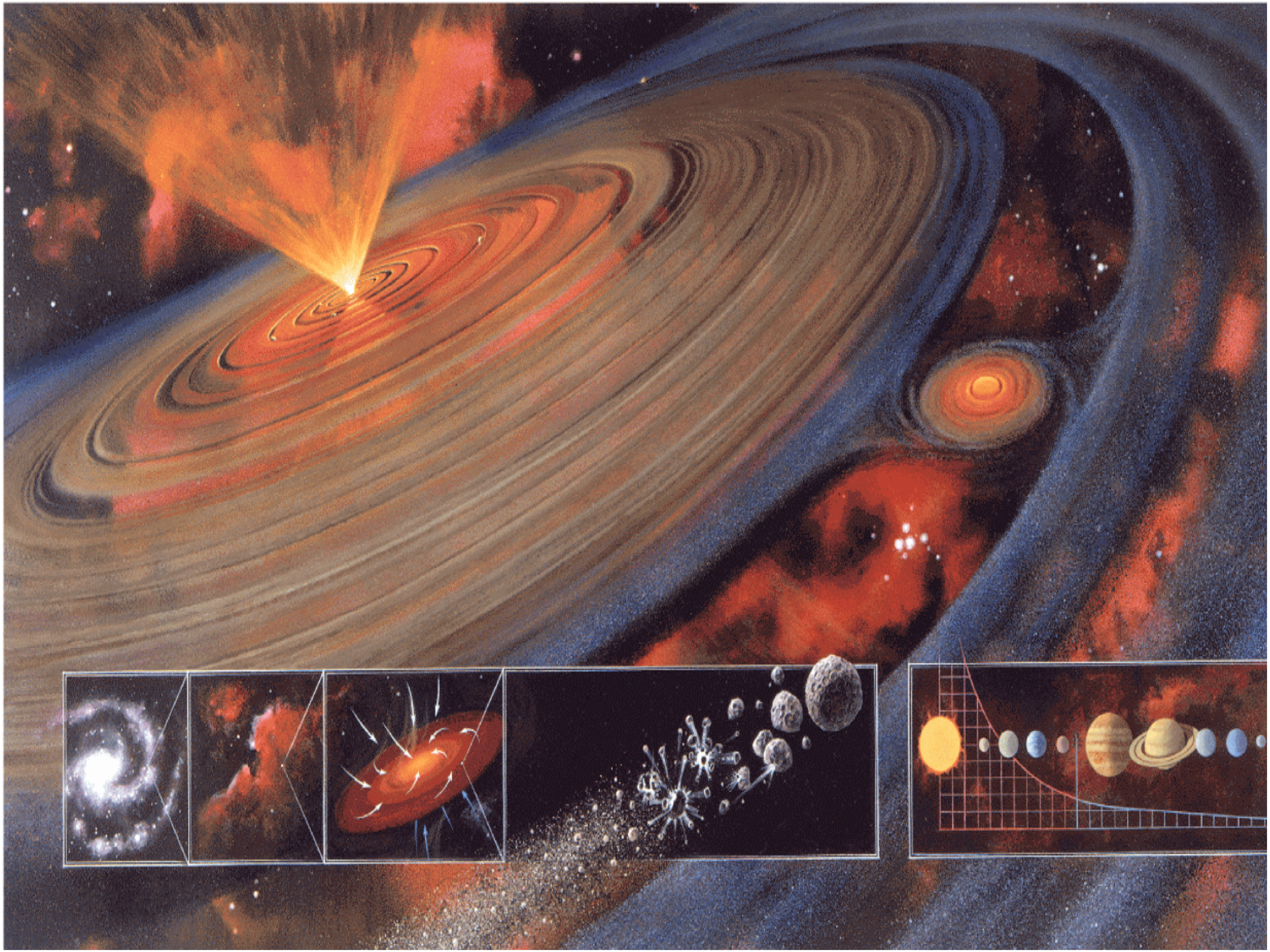


Young Stellar Disks in Infrared

Hubble Space Telescope • NICMOS

PRC99-05a • STScI OPO • D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA


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

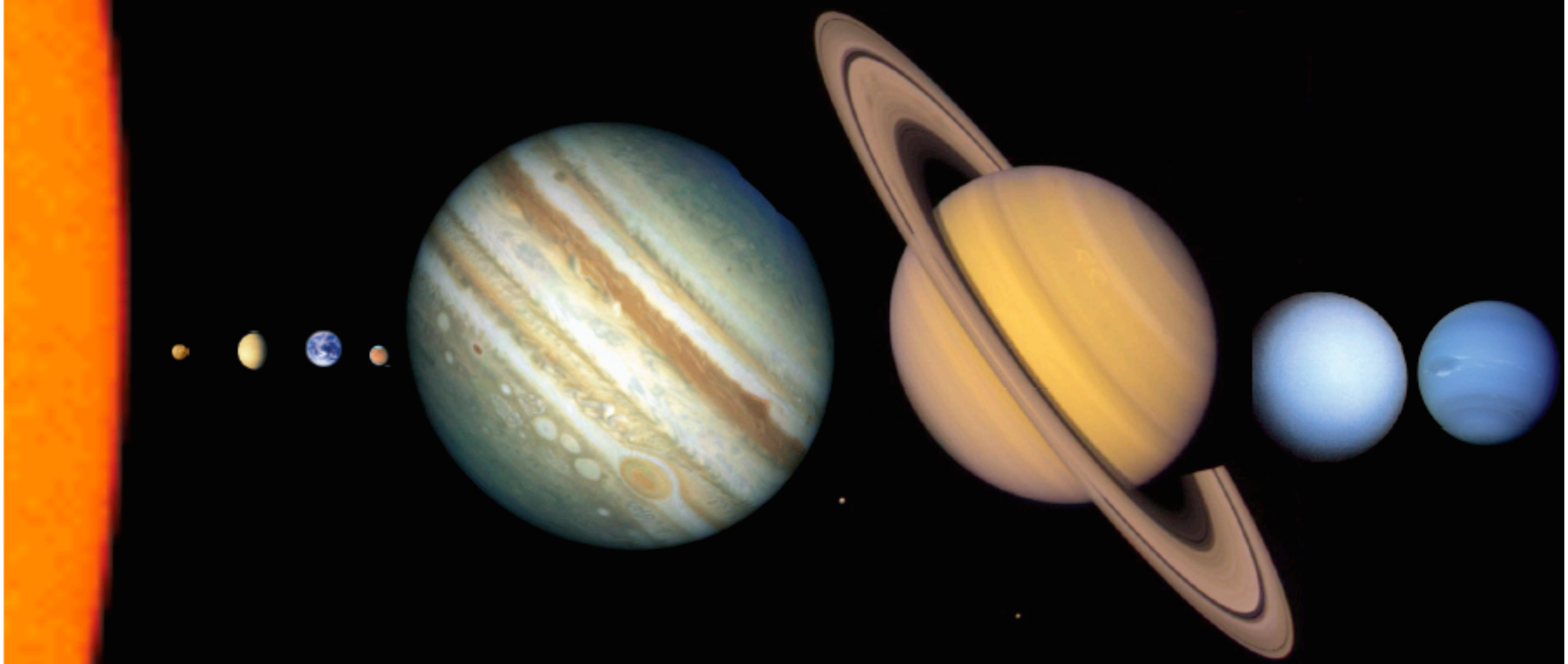


"Planet Formation Processes on the Computer"

1. turbulence in circumstellar disks:
   dust distribution in turbulent protoplanetary disks (project in the new German Science Foundation interdisciplinary research collaboration "Planetesimal Formation")
   => Observational signatures (ALMA, SKA, etc.)
2. gravoturbulent planetesimal formation:
   particle concentration in magneto rotational turbulence plus N-body simulations => Riddle of Planetesimal Formation
3. hot blobs around nascent planets
   observability of planet disk interaction and migration of young planets (ALMA, SKA, VLT-I, LBT, ELT, etc.) => Constraining Planet Formation Theory I
4. Planetary system statistics
   population synthesis and (Corot, Kepler, PAN-PLANETS, etc.) => Constraining Planet Formation Theory II

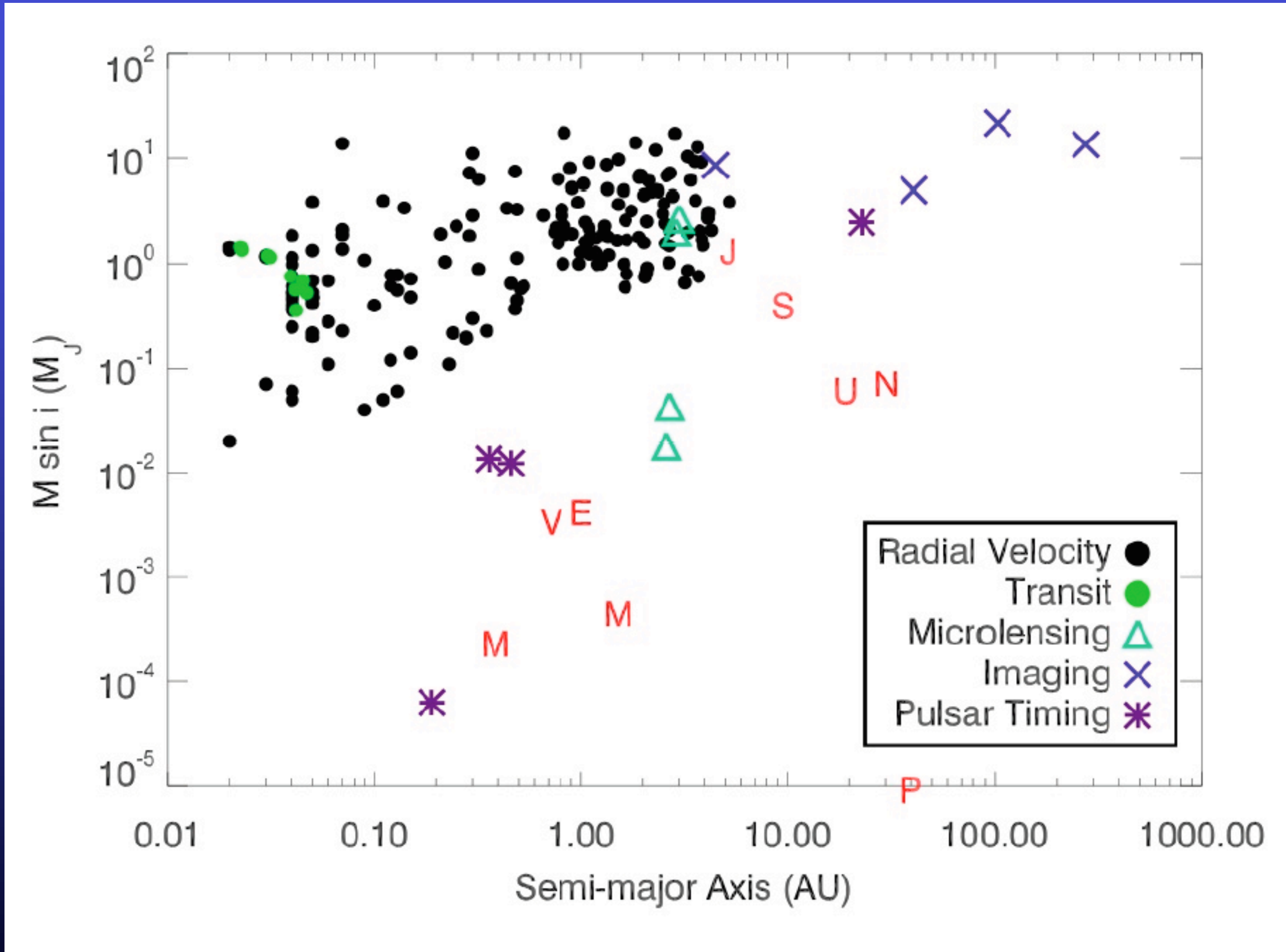
The Solar System

Planet sizes are to scale. Separations are not.



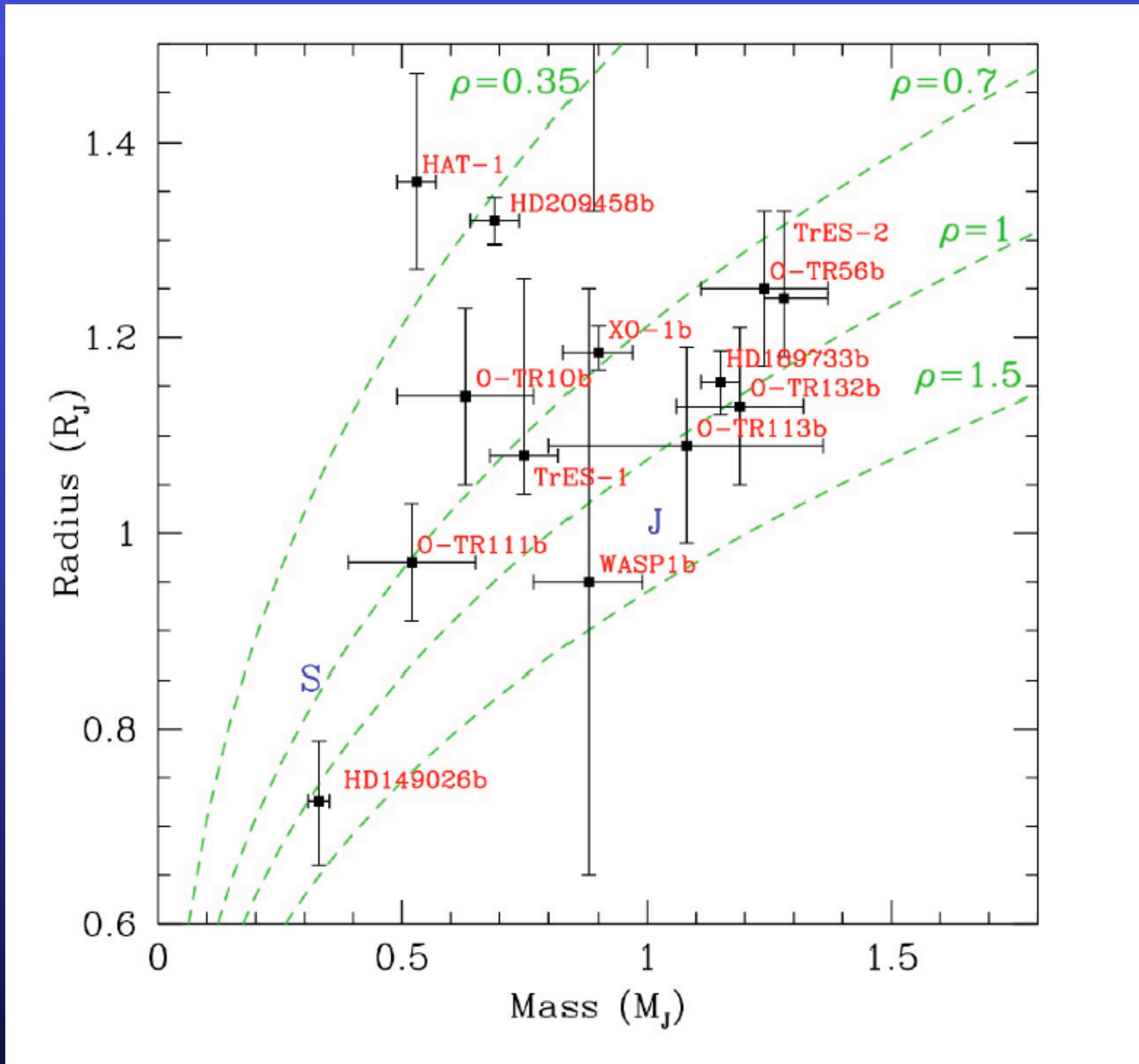
Characterizing extrasolar planets: very different from solar system planets, yet solar system planets are their local analogues

Known Planets:



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

Transiting Planets: mass + radius

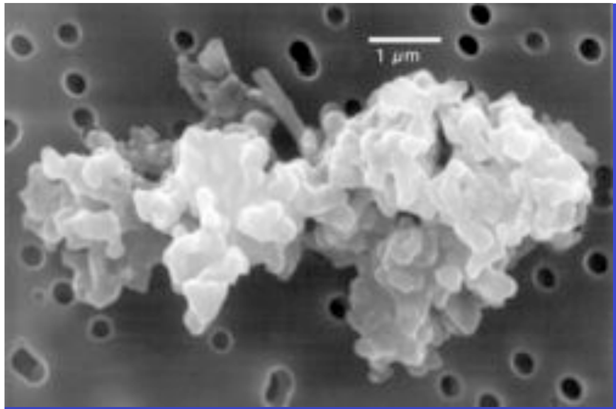


New field: “Physics and Chemistry of Extrasolar Planets”

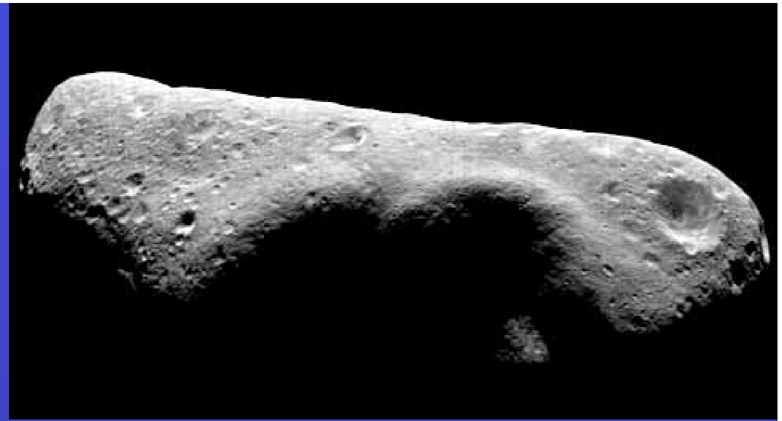
"Master Plan for theory of planet formation"

1. Thepry input for population Synthesis of Exo-Planets: Disk evolution, Dust (Planetesimal) distribution, planet migration and accretion, -> Kepler, Pan-Planets (PAN-STARRS)

   => "Physics and Chemistry of Exo-Planets"
2. Detection of nascent planets in disks (10-100 Mearth): Simulations for ALMA, SKA etc.
   => Validation of core accretion scenario (=> 1.)
3. Measurements of accretion rates for planets in disks: Linc-Nirvana, ELT, FIRM...
   Deducing migration rates
   => Improving of our numerical models (=> 1.)

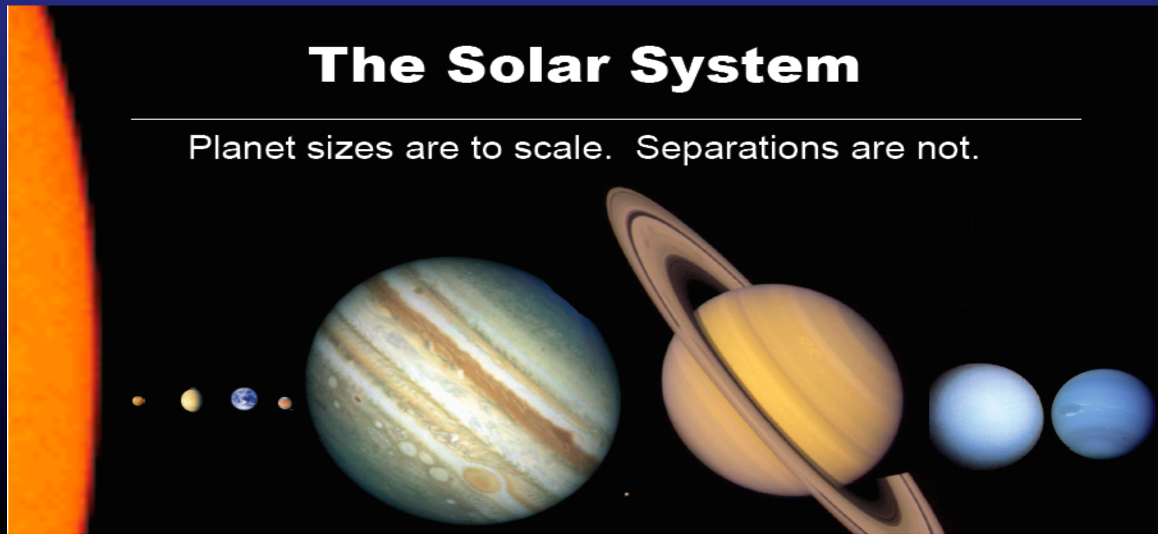


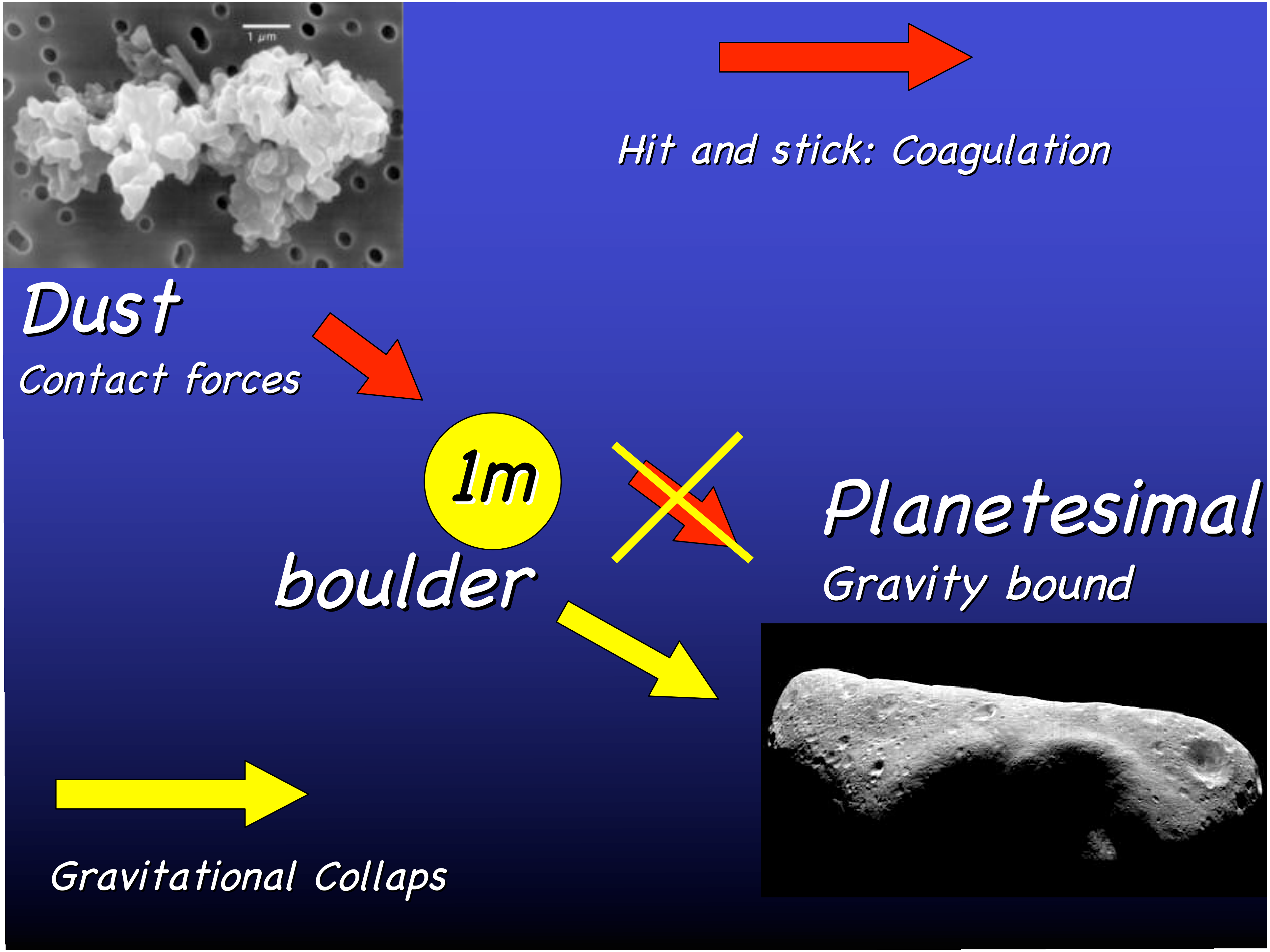
dust



planetesimal

planets




1 μm
Hit and stick: Coagulation
Dust
Contact forces
1m
boulder
Planetesimal
Gravity bound
Gravitational Collaps

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. Local concentration of boulders.
4. Generating collisions. -> Observation of debris

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

No growth beyond m!

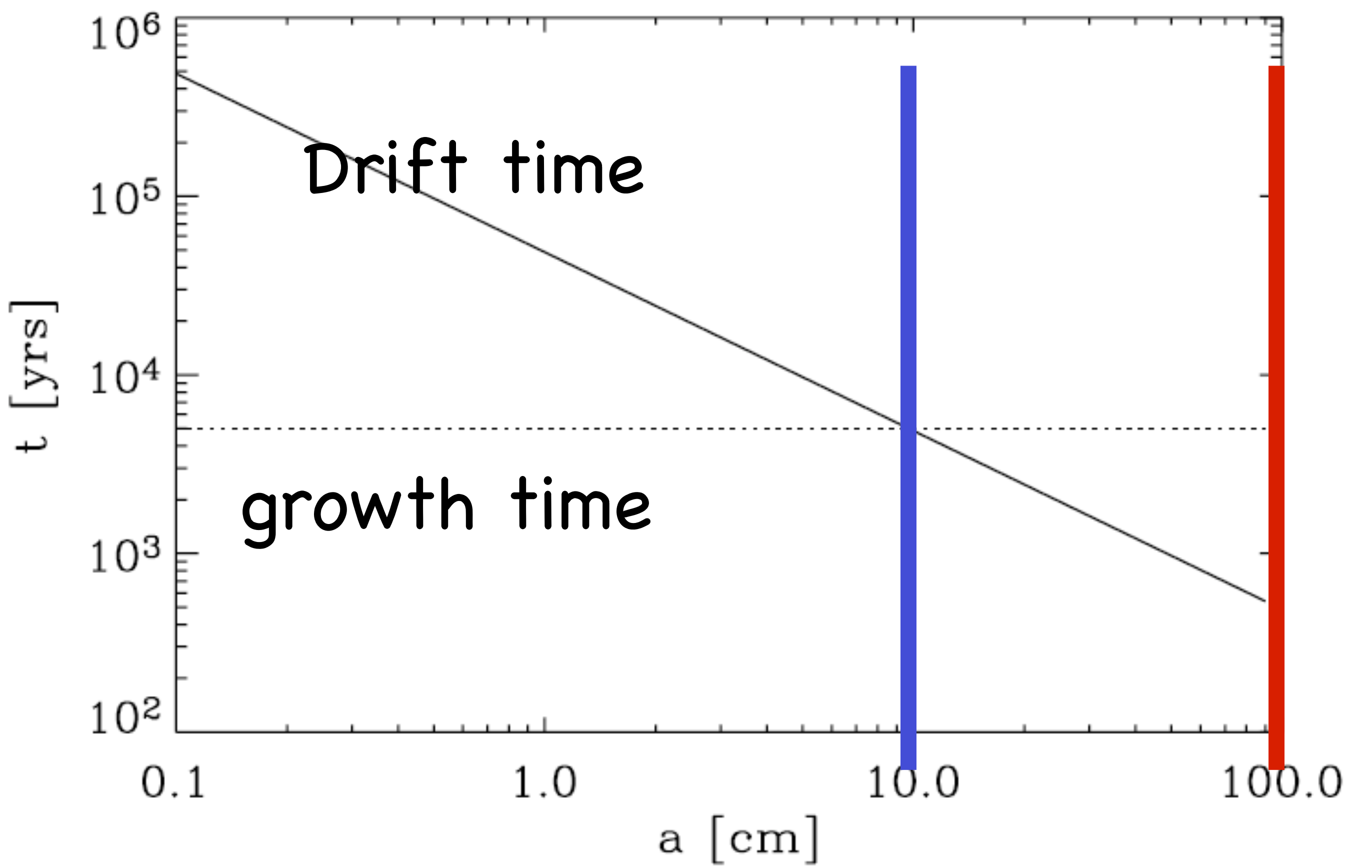


FIG. 1.—Comparison between drift time (*solid line*) and growth time (*dotted line*) for solids as a function of size. The values are calculated using the equations from this paper for a location of 7.5 AU in a minimum mass solar nebula.

Klahr and Bodenheimer 2006

Particle response to the gas flow 1:

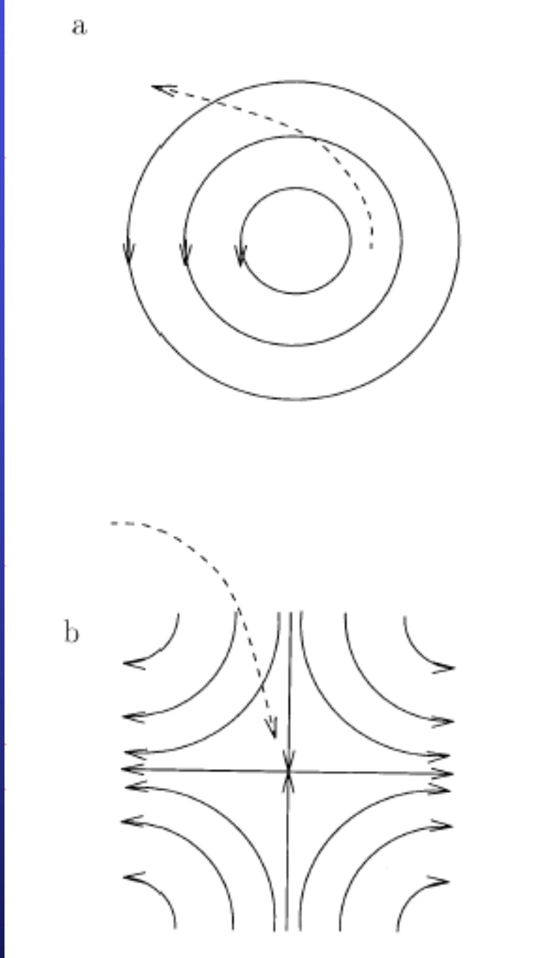
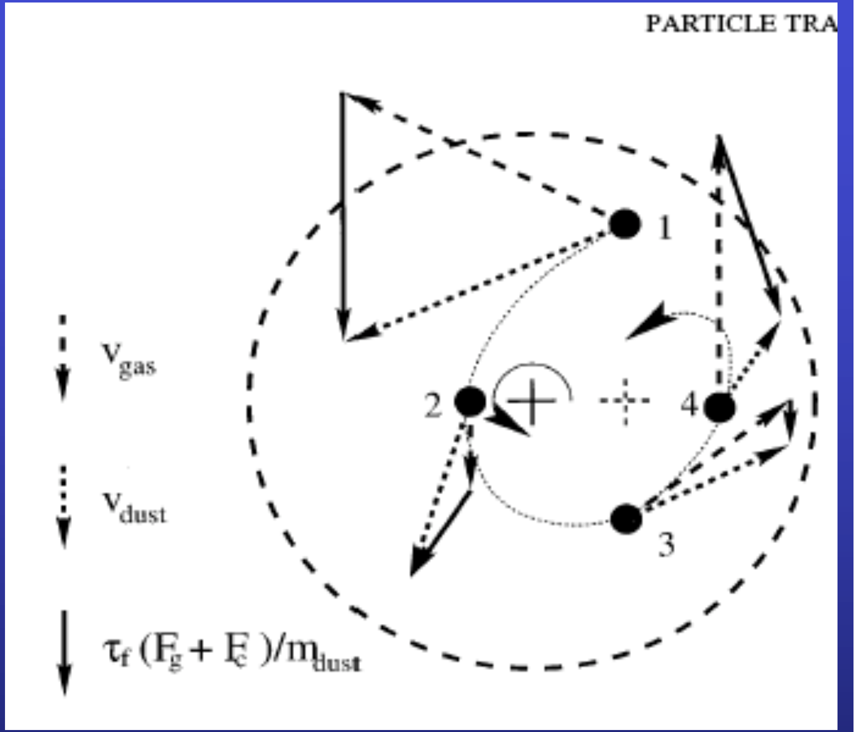


FIG. 1. Under laboratory-observed conditions particles (a) spiral out of the vortices (eddy), but (b) collect in convergence zones (strain fields).

Lab condition,
Cuzzi et al.



Vortex in the r-z plane:
Aka convection cell
particle concentration.
Klahr & Henning 1997

Small particles in pressure maxima

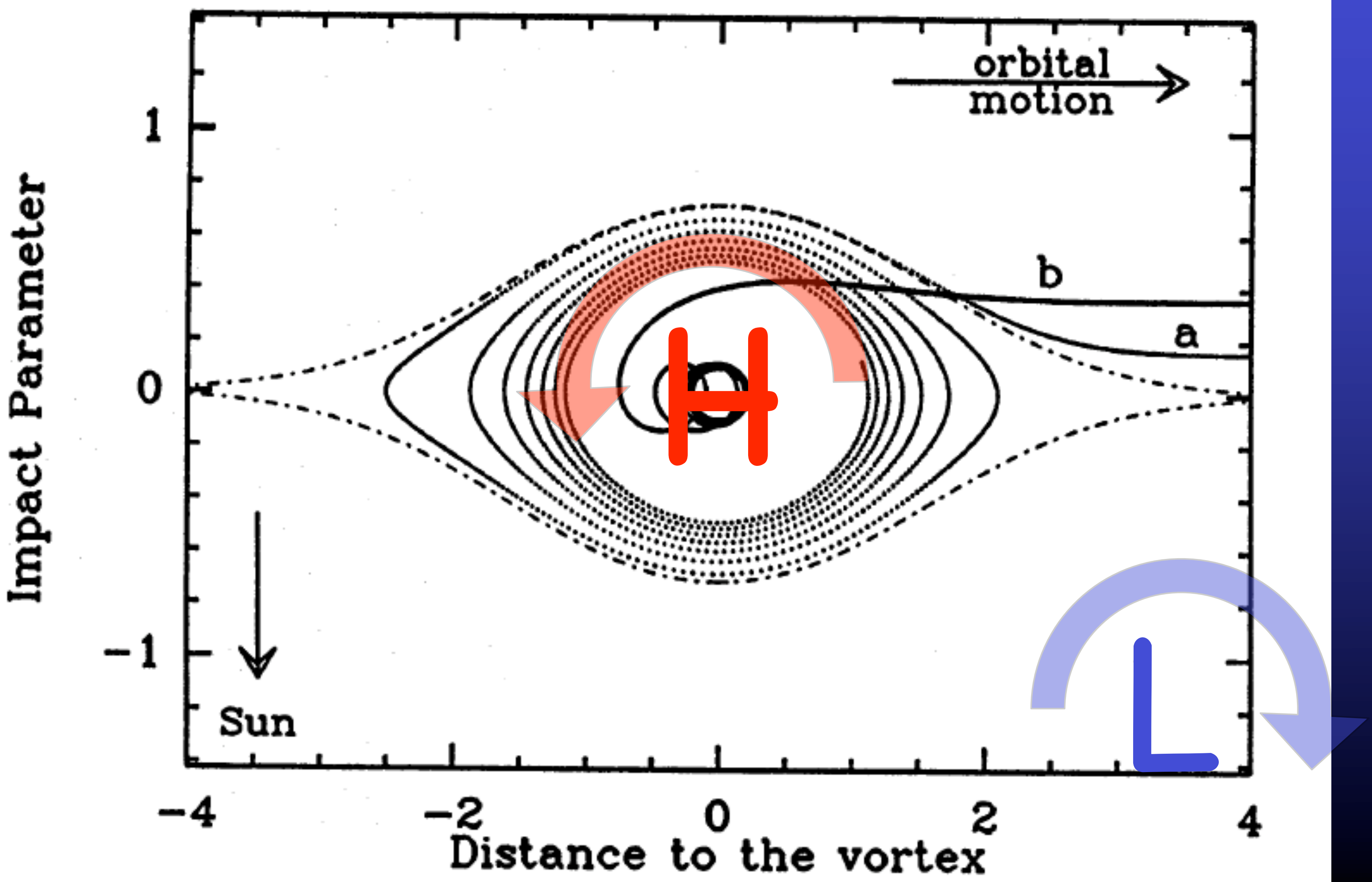
$$\partial_t v_g = -\frac{1}{\rho}\nabla p + \text{forces}$$

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

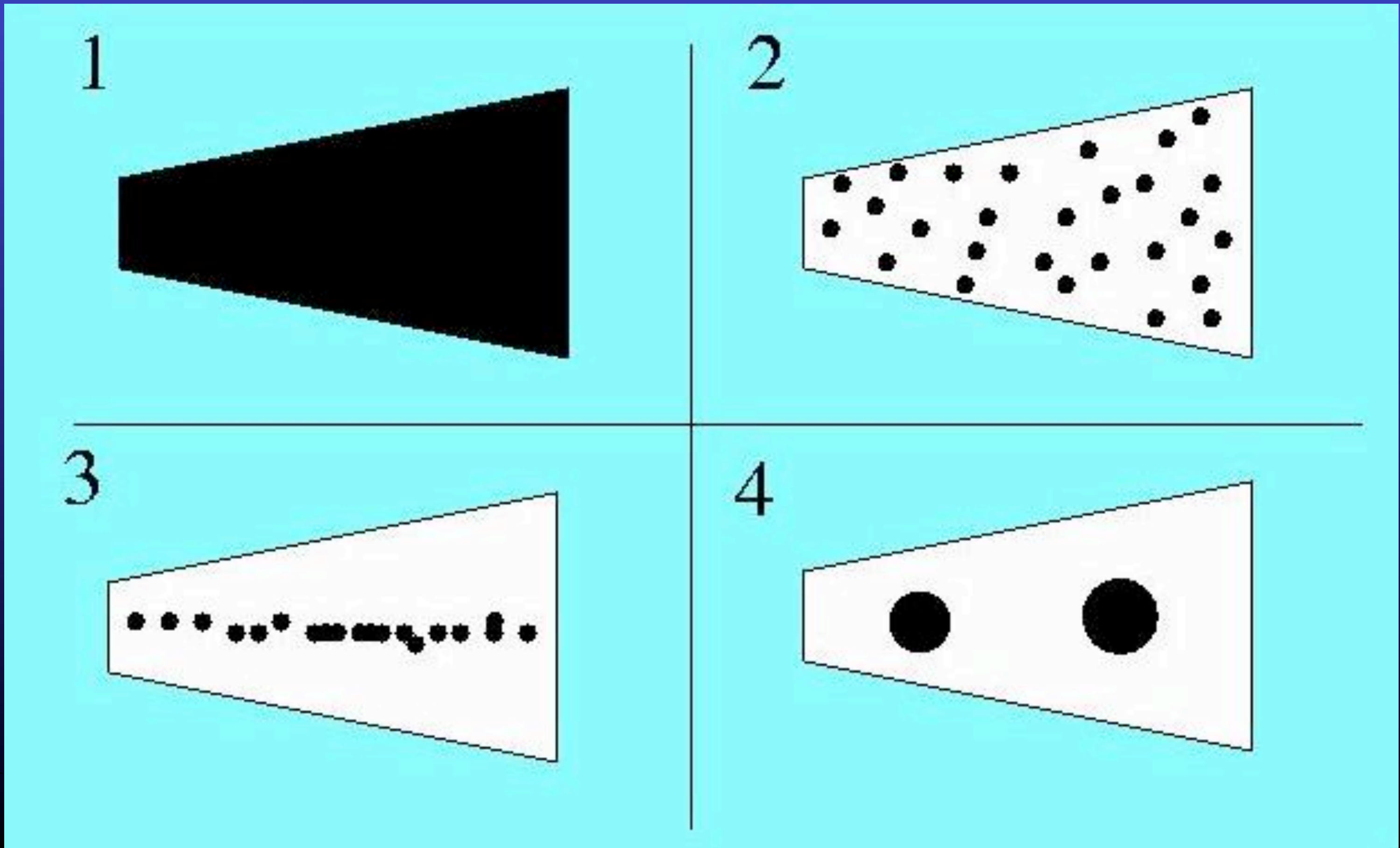
$$v_d = v_g + \tau_f \frac{1}{\rho}\nabla p$$

Klahr & Lin 2000

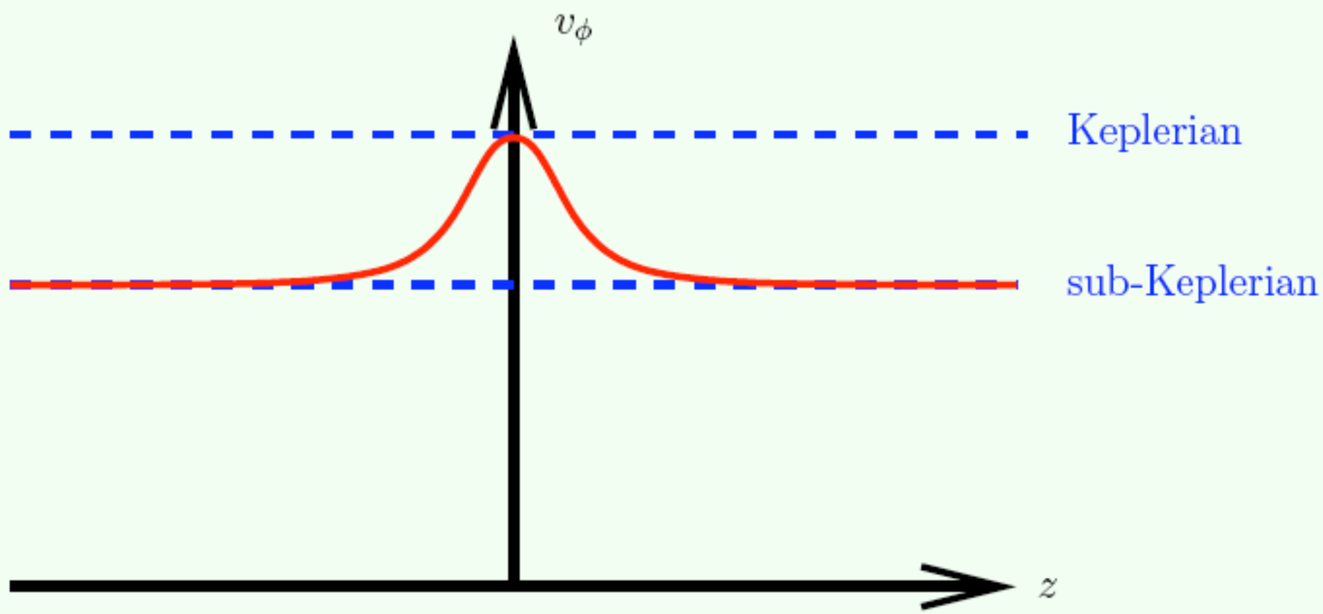
Small particles in pressure maxima e.g. a vortex



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

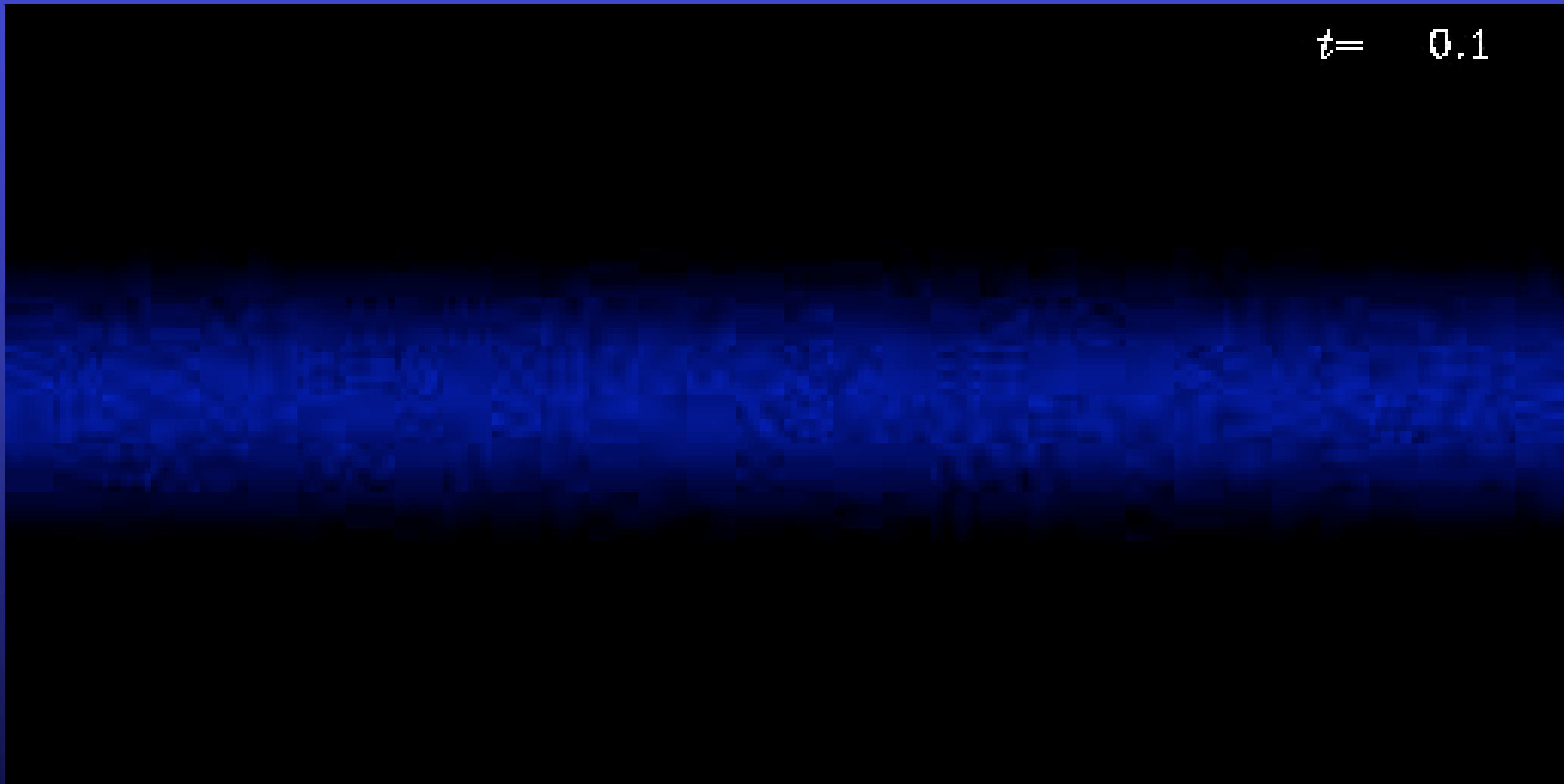


Kelvin-Helmholtz instability



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

10 cm sized boulders:



vertical

horizontal

Johansen, Henning & Klahr 2006

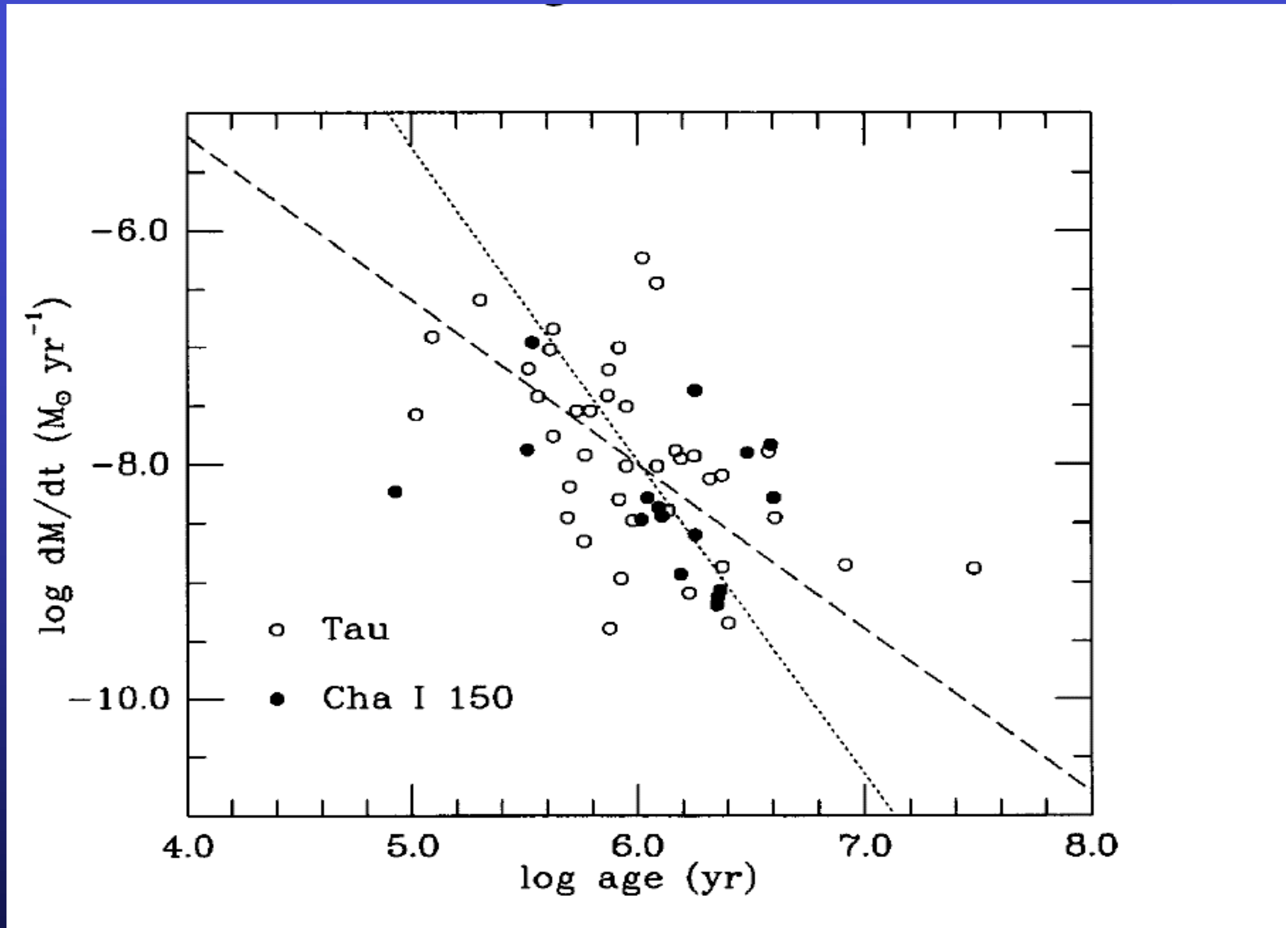
Conditions for planetesimal formation:

	non-turbulent	turbulent
Coagulation	Stu Weidenschilling	Weidenschilling, Dullemond & Dominik 2005, See also Brauer
Gravitational Collapse	Safronov 1969, Goldreich & Ward 1973	Johansen, Klahr & Henning 2006, Johansen etal. 2007

Apparent Problems in planetesimal formation:

	non-turbulent	turbulent
Coagulation	Radial drift, too fast	Bouncing and Collisional destruction
Gravitational Collapse	No thin midplane layer, because of Kelvin-Helmholtz turbulence ->	No thin midplane (vertical diffusion) BUT: Locally very high densities!

Age versus Accretion Rate



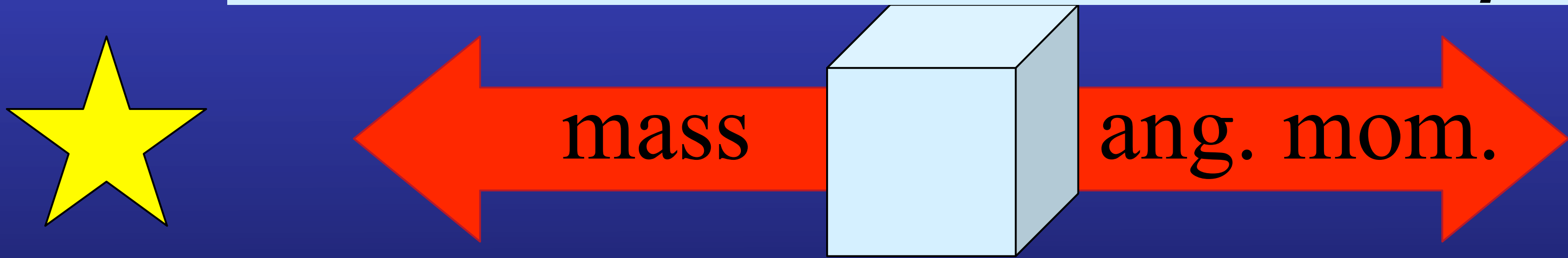
Hartmann et al. 1998, 2006

alpha = 0.01

WHY DO T TAURI DISKS ACCRETE?

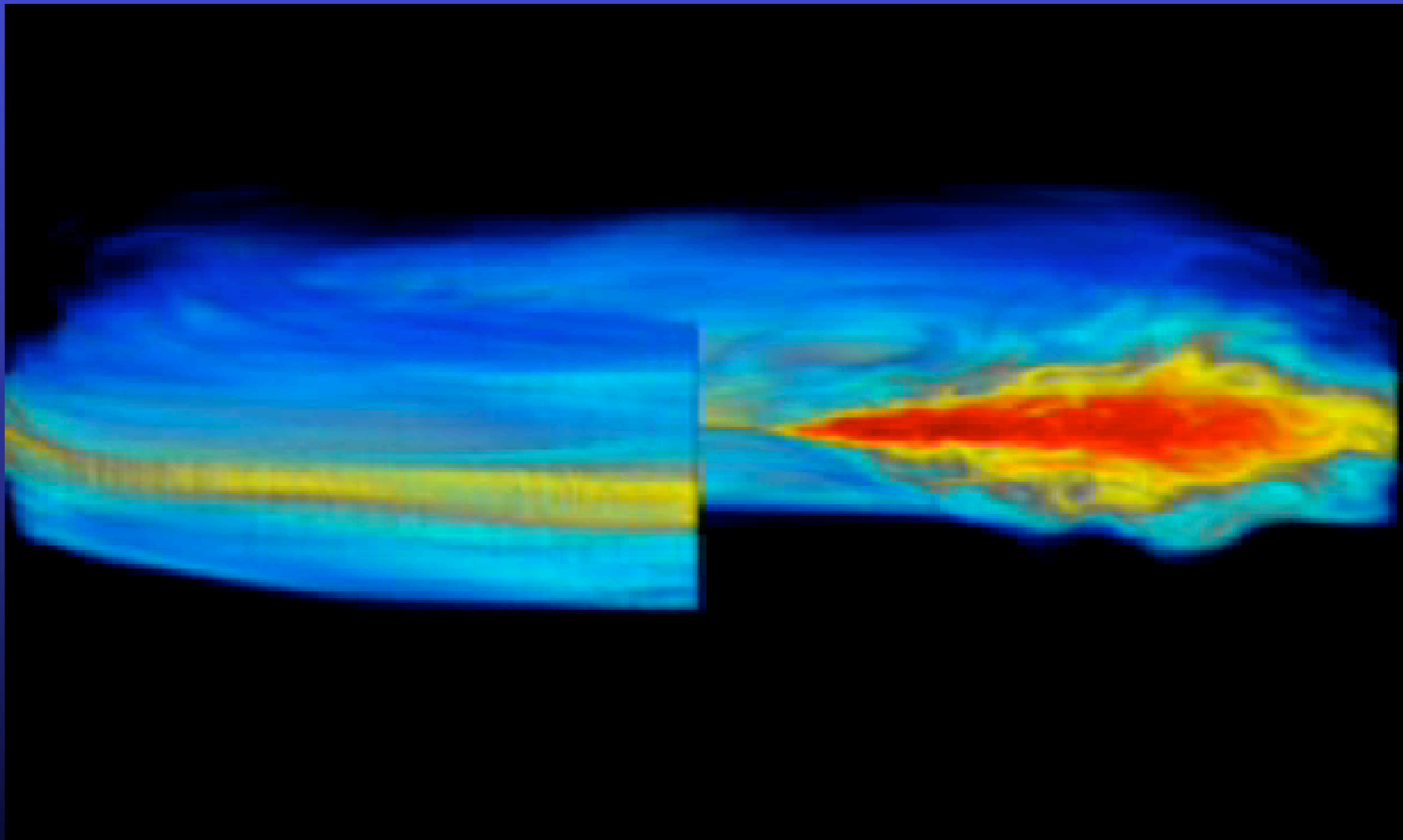
Accretion in a rotating system is only possible if matter looses its angular momentum!

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



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

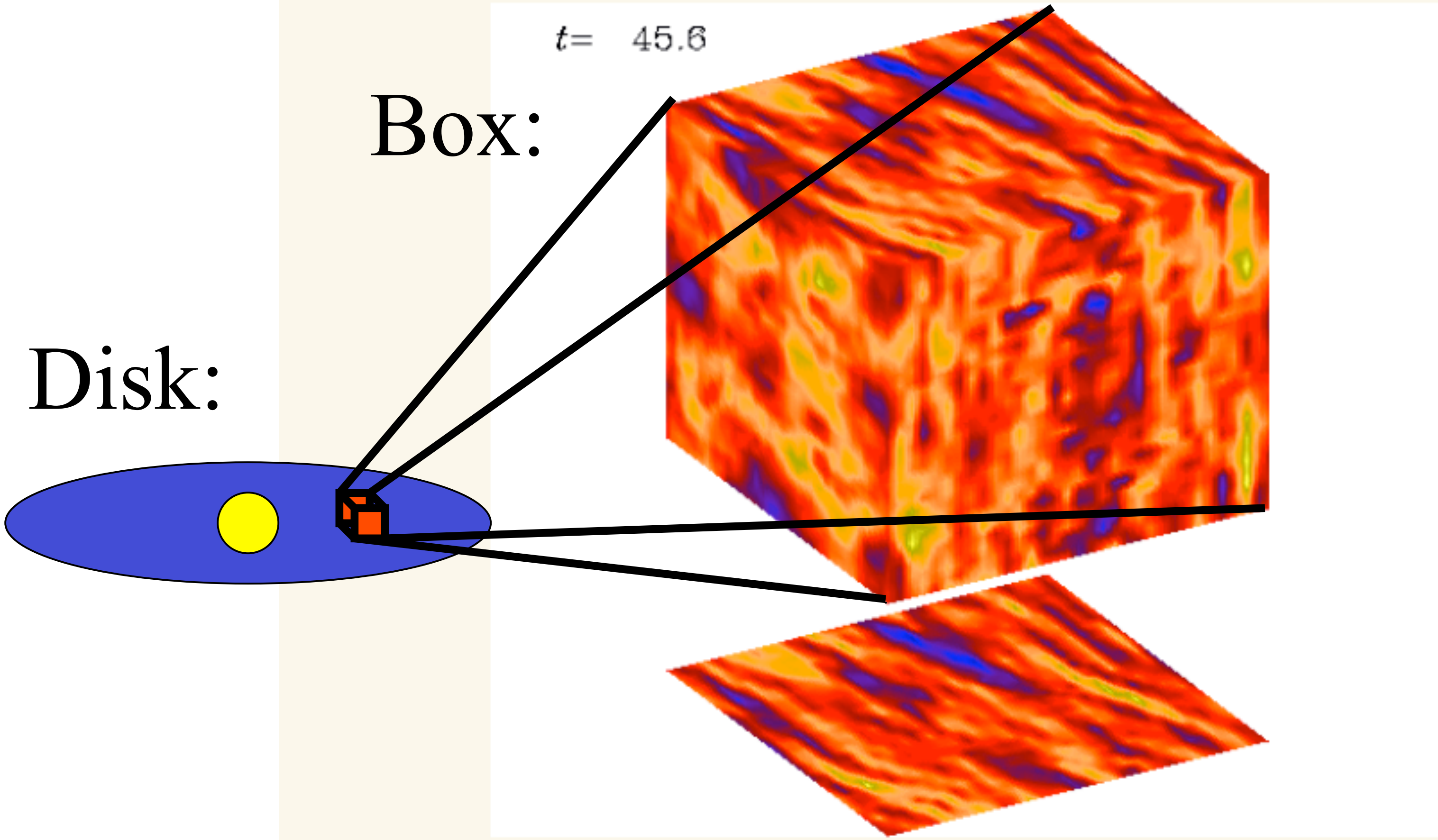
Magneto Rotational Instability (MRI) drives turbulence in accretion disks



Simulation by John Hawley:

MRI turbulence

…because it is a reliable source for turbulence.



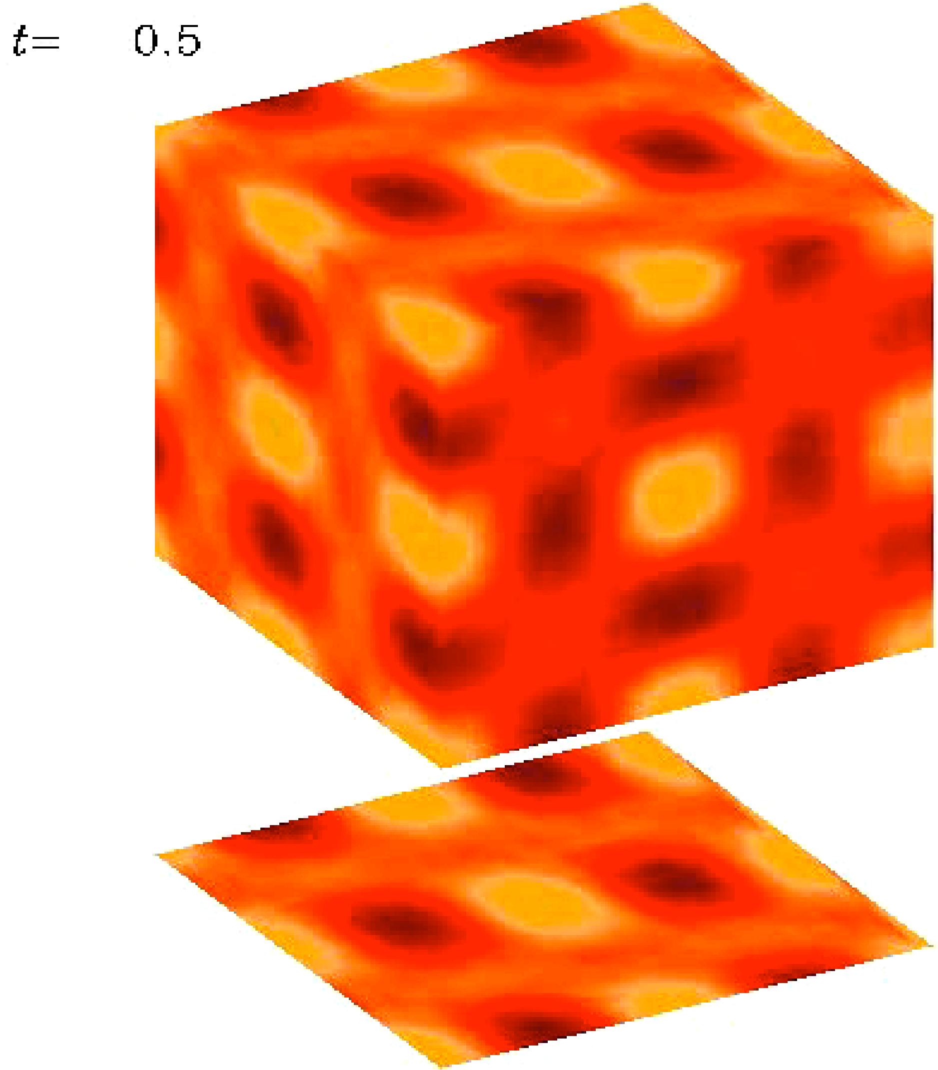
Code: The Pencil-Code [MHD code, finite differences, 6th order in space, 3rd order in time, Brandenburg (2003)]

Development of MHD Turbulence

From initial perturbation to saturation of the turbulence

Colors: gas density
yellow = high
blue = low

Standard magneto rotational instability simulation ala Balbus and Hawley



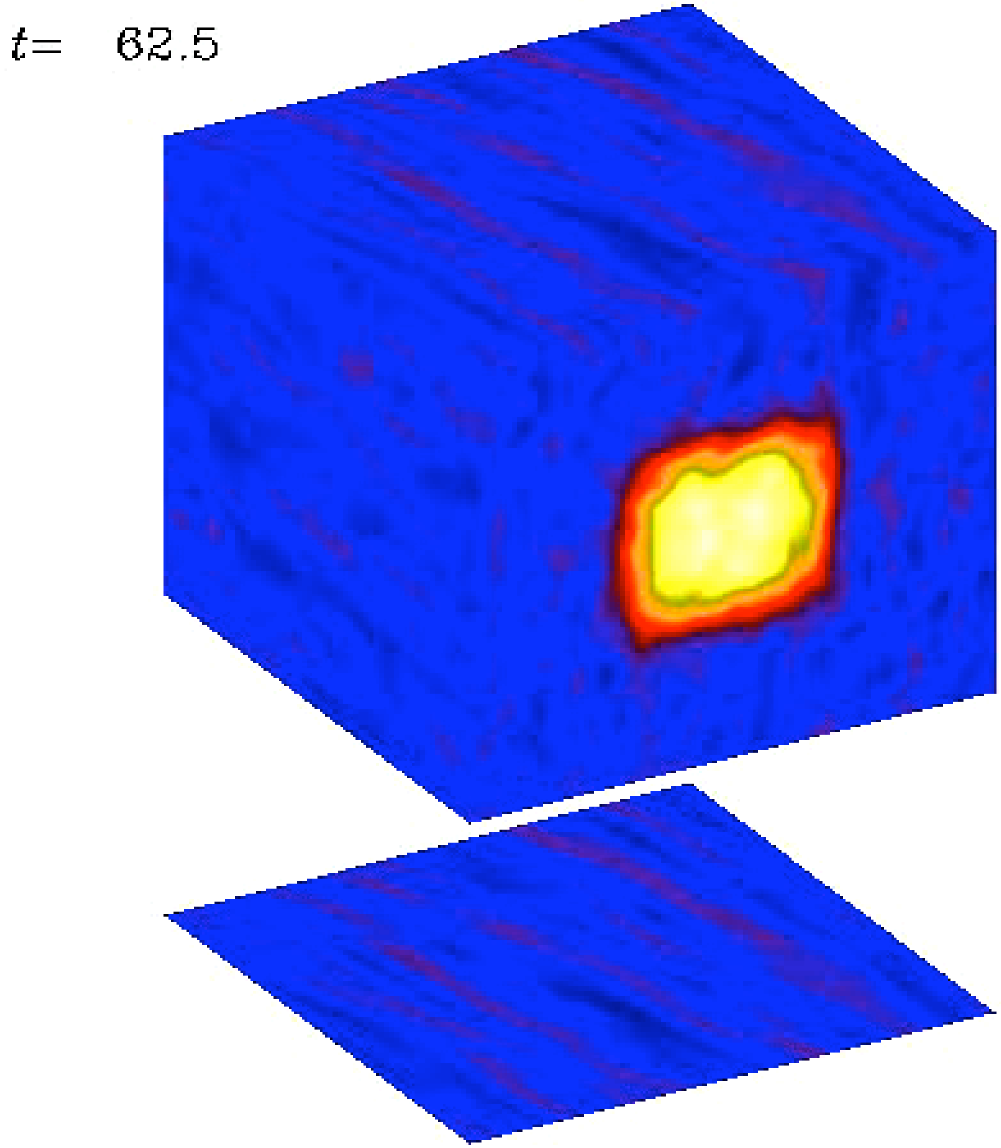
Diffusion of Dust in MHD Turbulence.

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

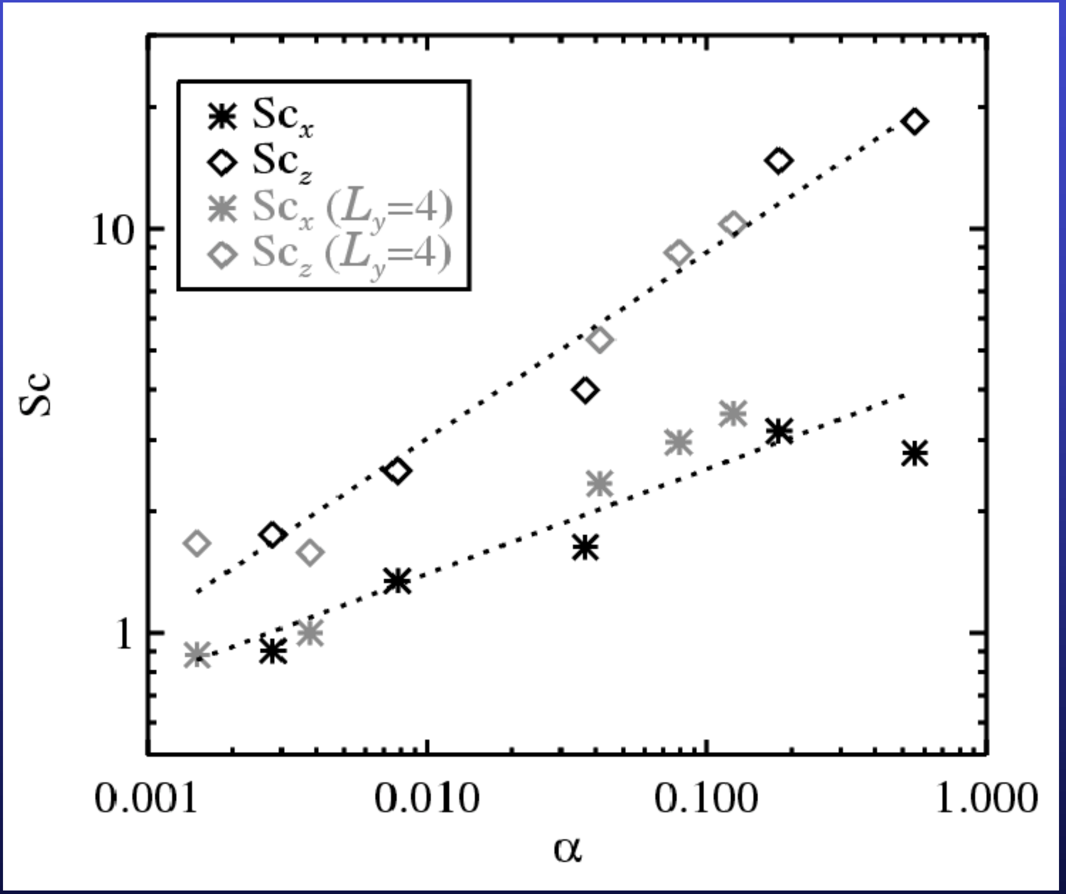
No additional forces e.g. gravity.

Colors: dust density
yellow = high
blue = low

Drawback: difficult to measure diffusivity



Diffusion is not proportional to turbulent strength! What about concentration?



Johansen, Klahr & Mee 2006

Limits of the Diffusion Picture:
Turbulence does also:

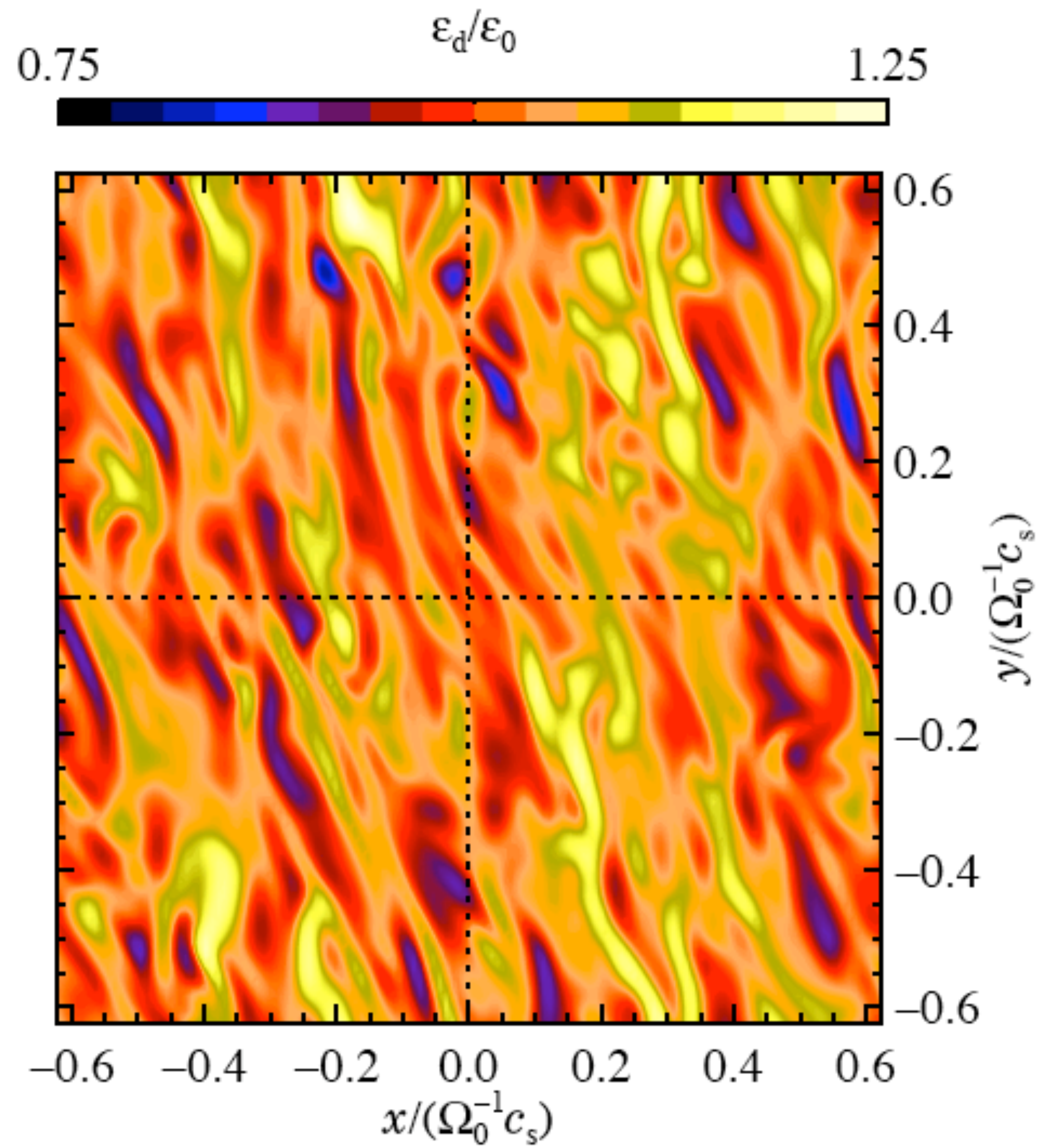
- Size Segregation
- Local concentration of intermediate sized solids
- Subsonic turbulence in the gas yet supersonic turbulence among the particles

Johanson and Klahr 2005

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

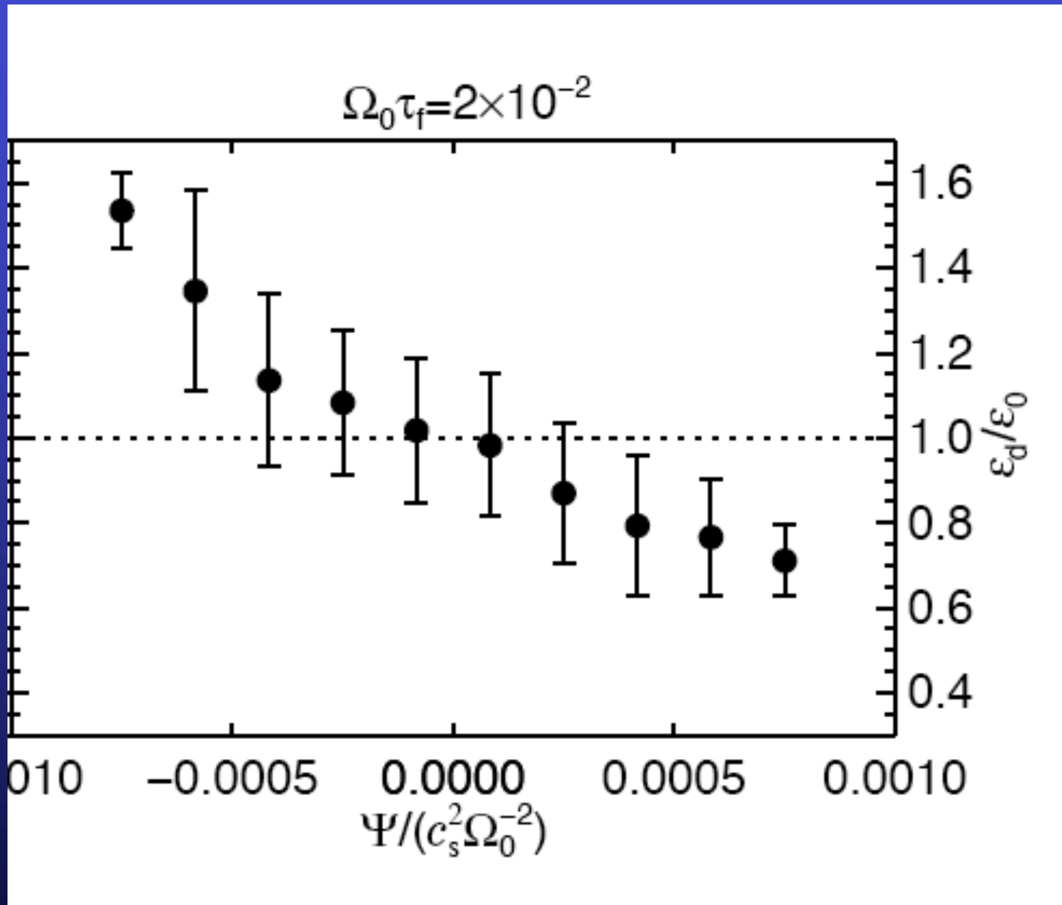
Blue = low number density (-25%)

Red = higher number density (+25%)



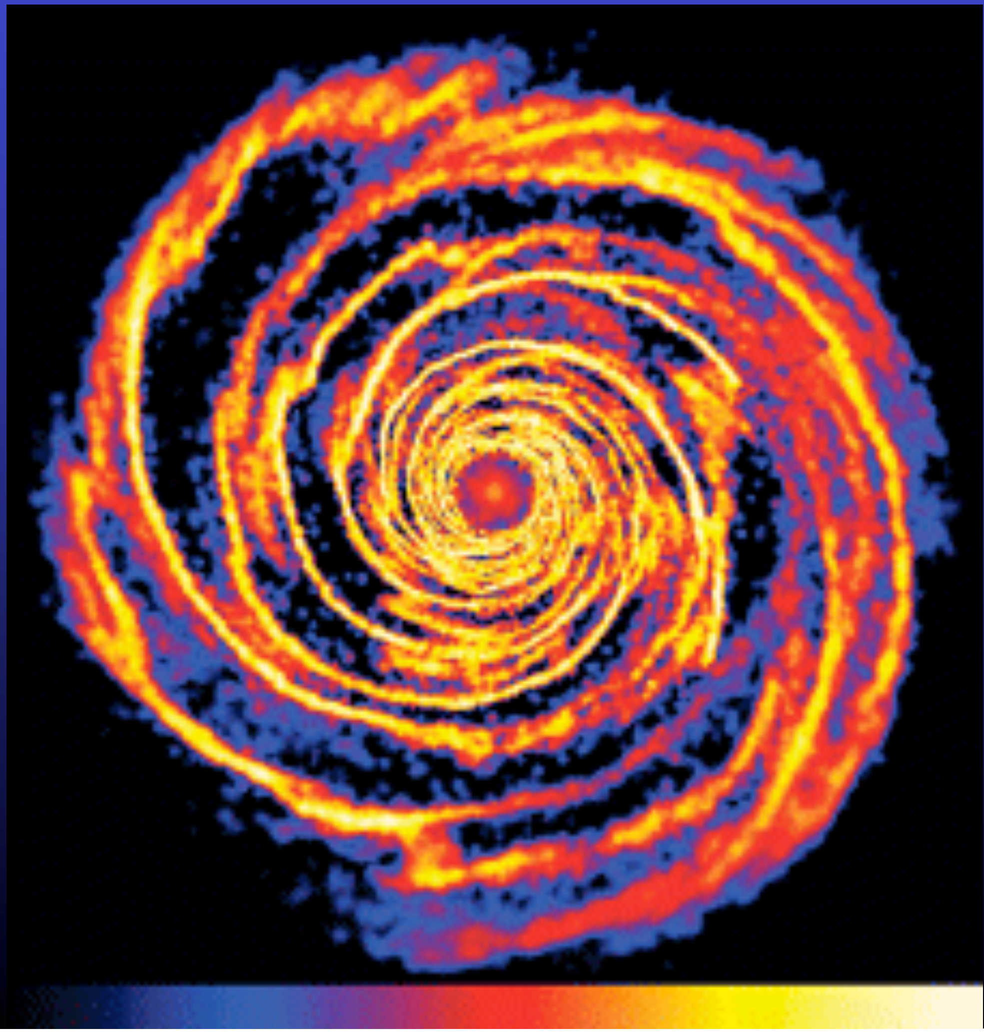
Concentration of cm sized grains in anti-cyclonic eddies in the flow:

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

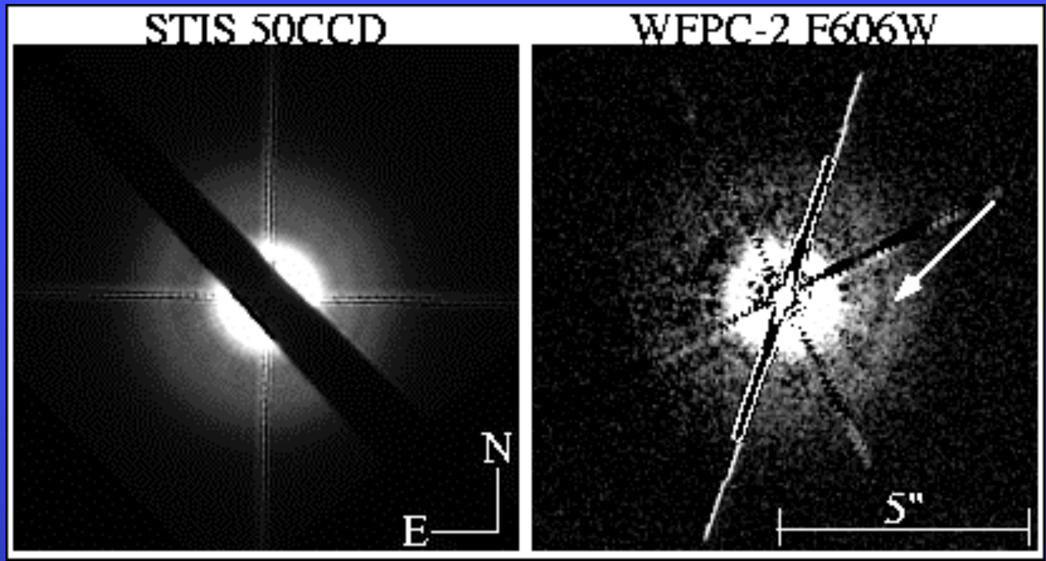


Compare this to Barge and Sommeria 1995

Global dust distribution in a self gravitating disk: Rice etal. 2006

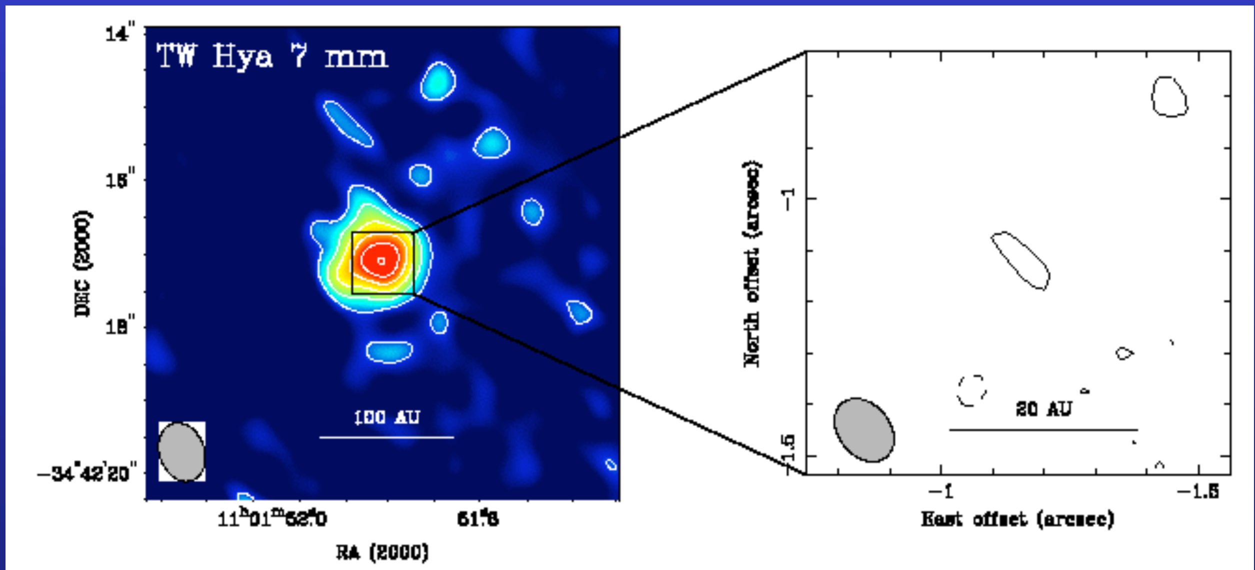


State-of-the-Art Disk Imaging



TW Hya: @ 56 pc

Hubble Space Telescope
optical scattered light
(Schneider et al. 2001)



VLA
7mm dust emission
(Wilner et al. 2000)

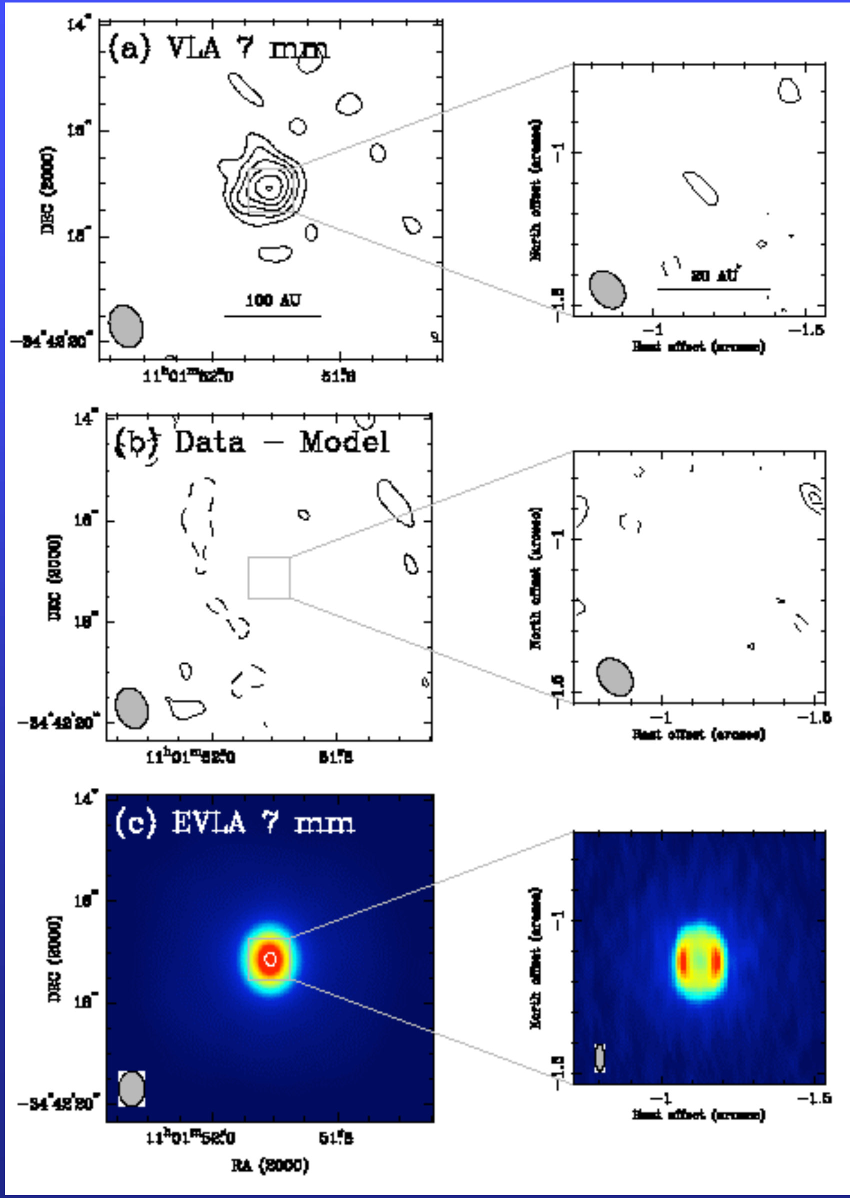
Courtesy David Wilner

TW Hya: an eVLA Simulation

- physical model of irradiated accretion disk adapted from Calvet et al. (2002) ApJ, 568, 1008

- VLA + Pie Town configuration, 7 mm

- eVLA + PT could image 4 AU radius hole (if it exists)



Courtesy David Wilner

Next Generation High Resolution Imaging

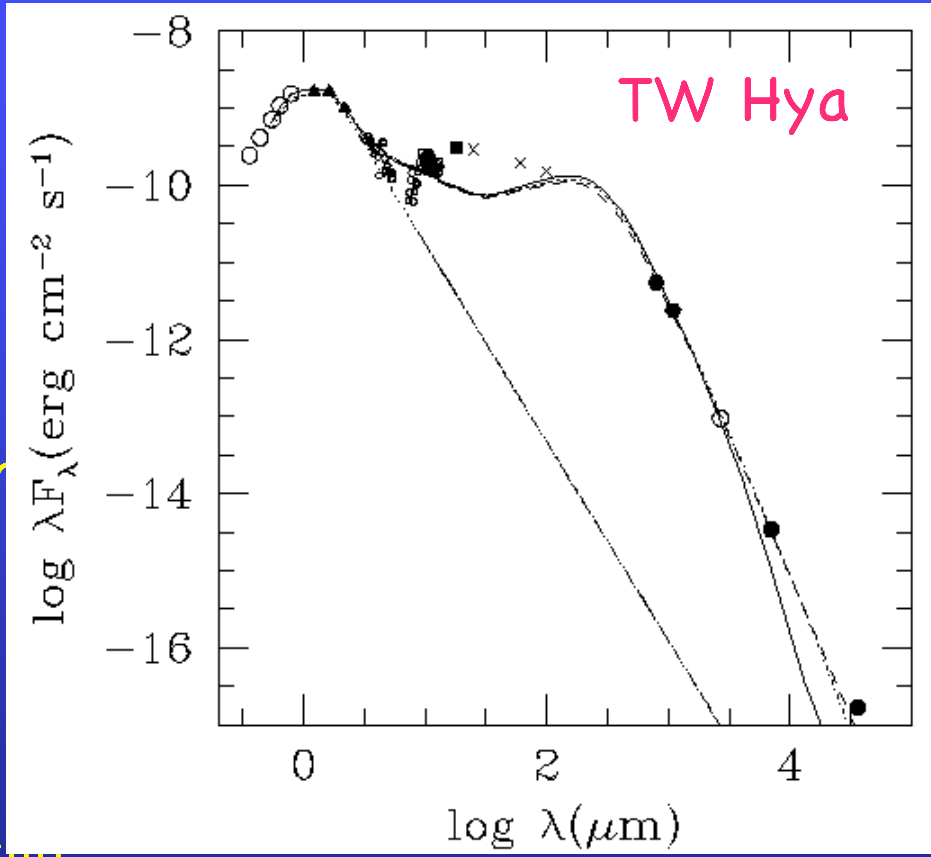
TMT: scattered light
θ ~ 13 mas x (1.6 mm/30 m)
(and infrared spectroscopy that probes inner disks indirectly)

ALMA: dust emission
θ ~ 13 mas x (345 GHz/18 km)
(molecular lines at lower resolution

long λ's (cm): dust emission
=> low dust opacity
=> penetrate inner disks

SKA: θ ~ 1 mas x (24 GHz/2500 km)
for rms ~ 10 K at θ ~ 1 mas, need rms ~ 20 nJy

EVLAII: θ ~ 7 mas x (24 GHz/360 km)



Courtesy David Wilner

Cradle of Life & SKA specs.

- Terrestrial Planet formation within 1AU
  planets (gas giants) found within this radius
  - several resolution elements to cover 1AU @ 140pc

1 mas => 0.14 AU @ 140pc

- High frequency - compromise between rapidly increasing flux, increasing opacity (& resolution)

~ 20-30 GHz

- Imaging dust of 50-300 K.

Continuum brightness sensitivity ~ 10K

For θ ~ 1 mas (2500 km @ 24 GHz), rms ~ 10 nJy gives 10K

Courtesy David Wilner

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

GRAVOTURBULENT FORMATION OF PLANETESIMALS

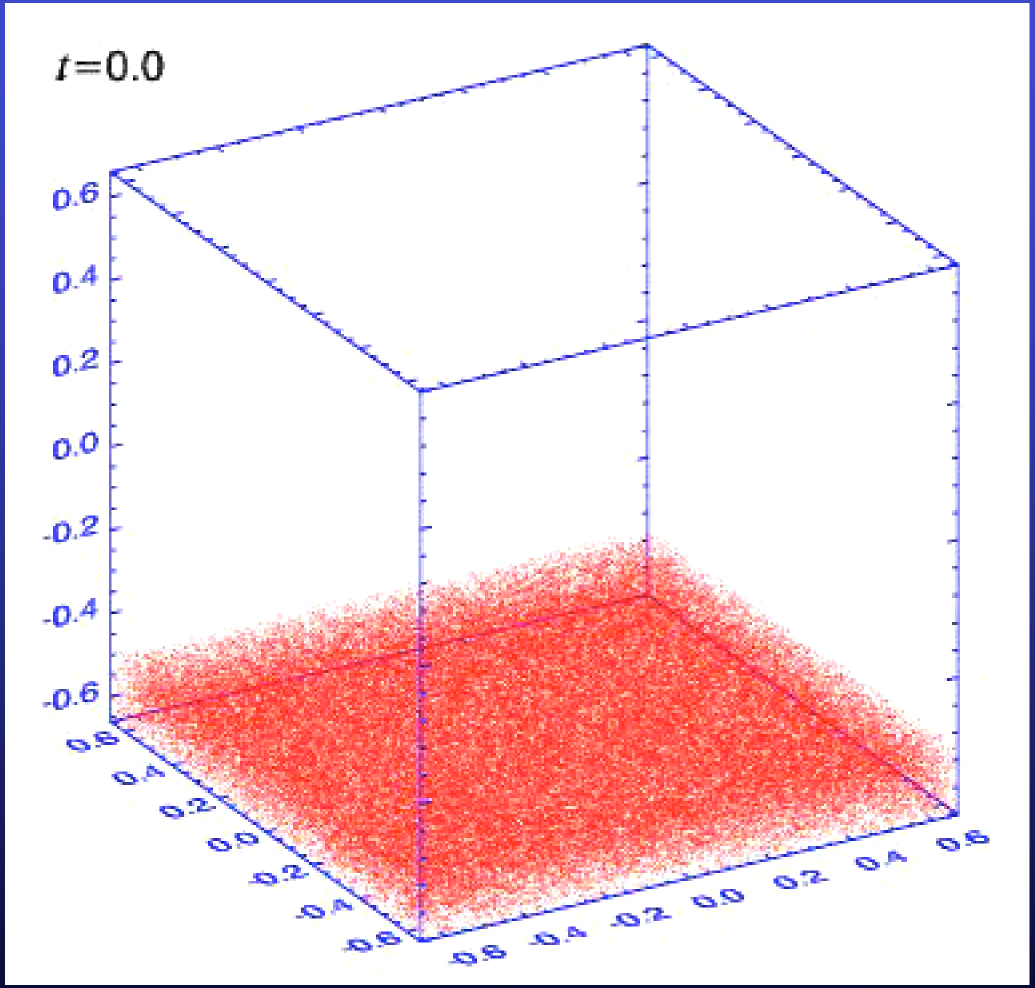
A. JOHANSEN, H. KLAHR, AND TH. HENNING
Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
Received 2005 April 28; accepted 2005 September 14

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!

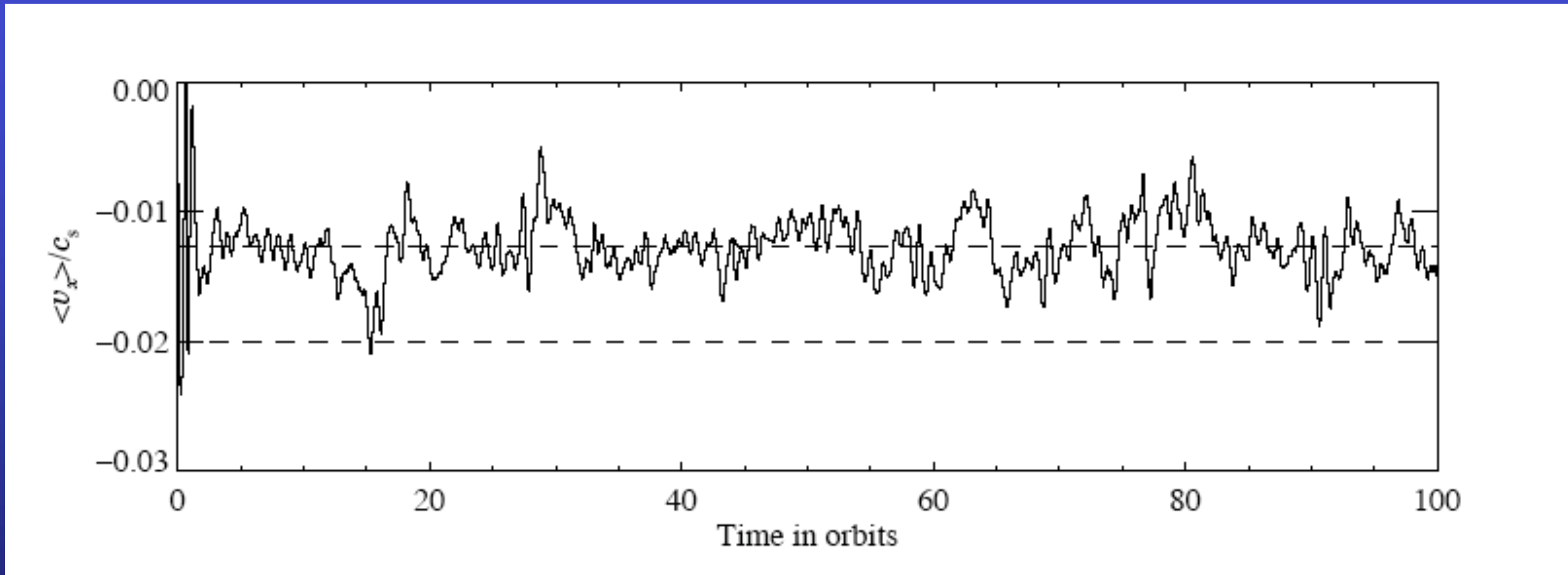
In this size regime objects climb up any pressure gradient: the global disk gradient, as well as any local pressure perturbation. Remember: cyclonic vortices are low pressure regions and high pressure regions are anti-cyclonic vortices.

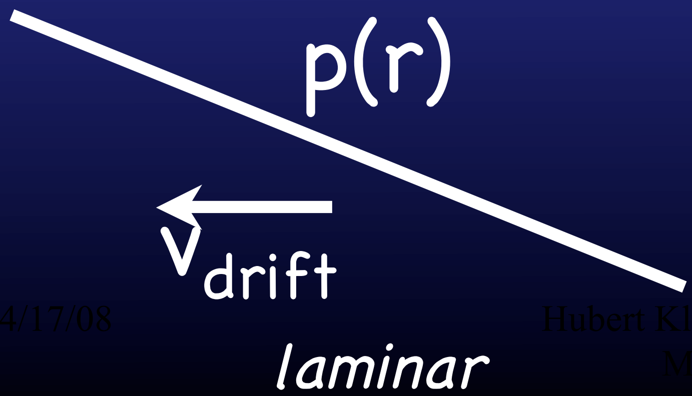
2,000,000 boulders of 1m size

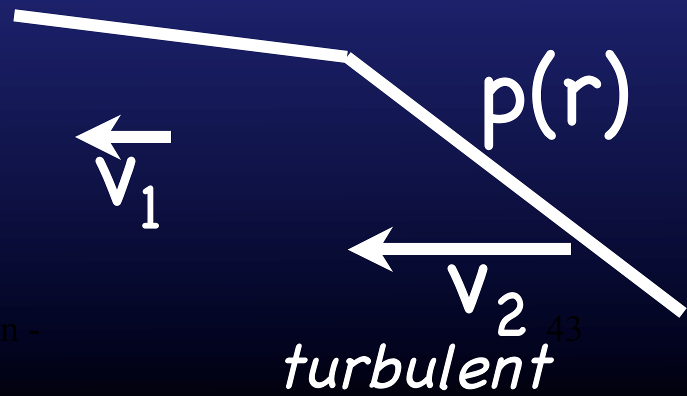


Johansen, Klahr and Henning, 2006

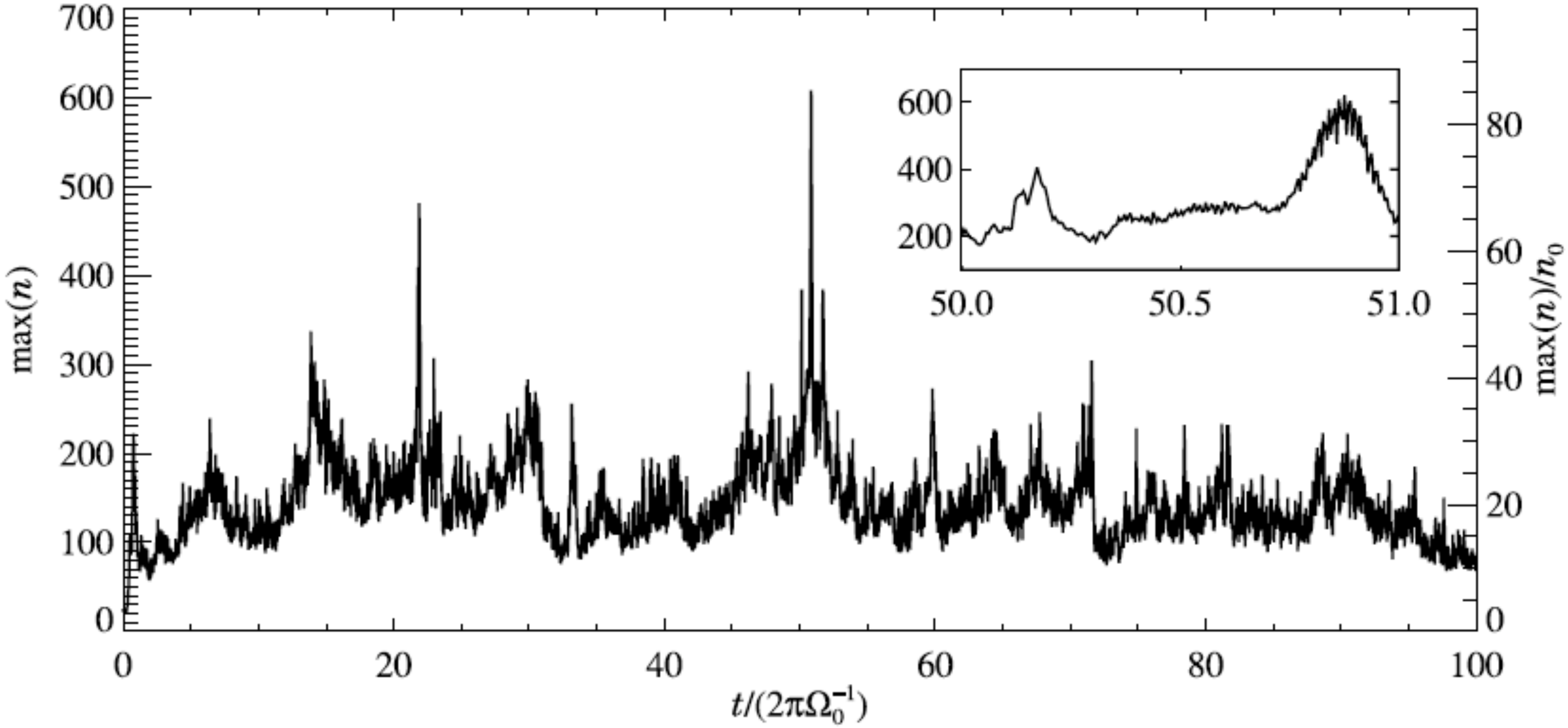
Turbulence slows down radial drift!



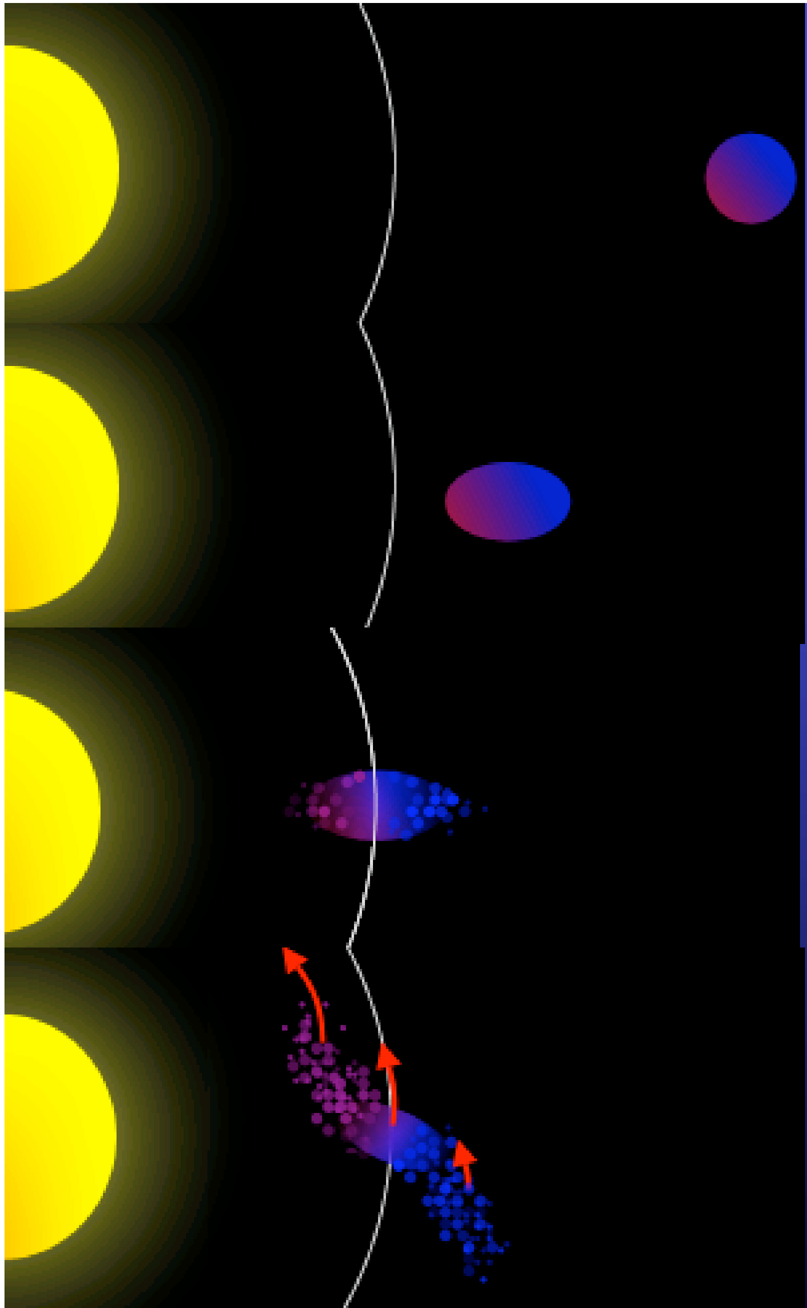




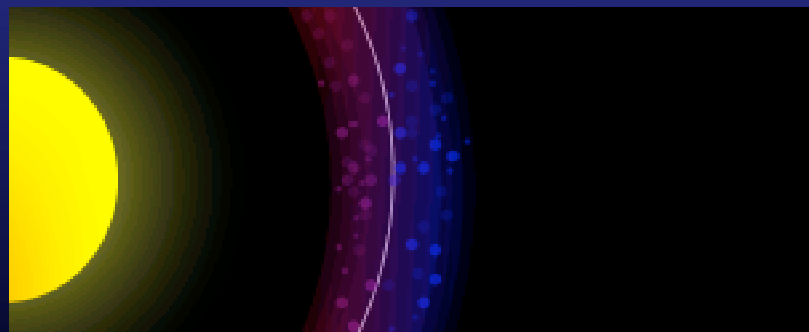
1m boulders

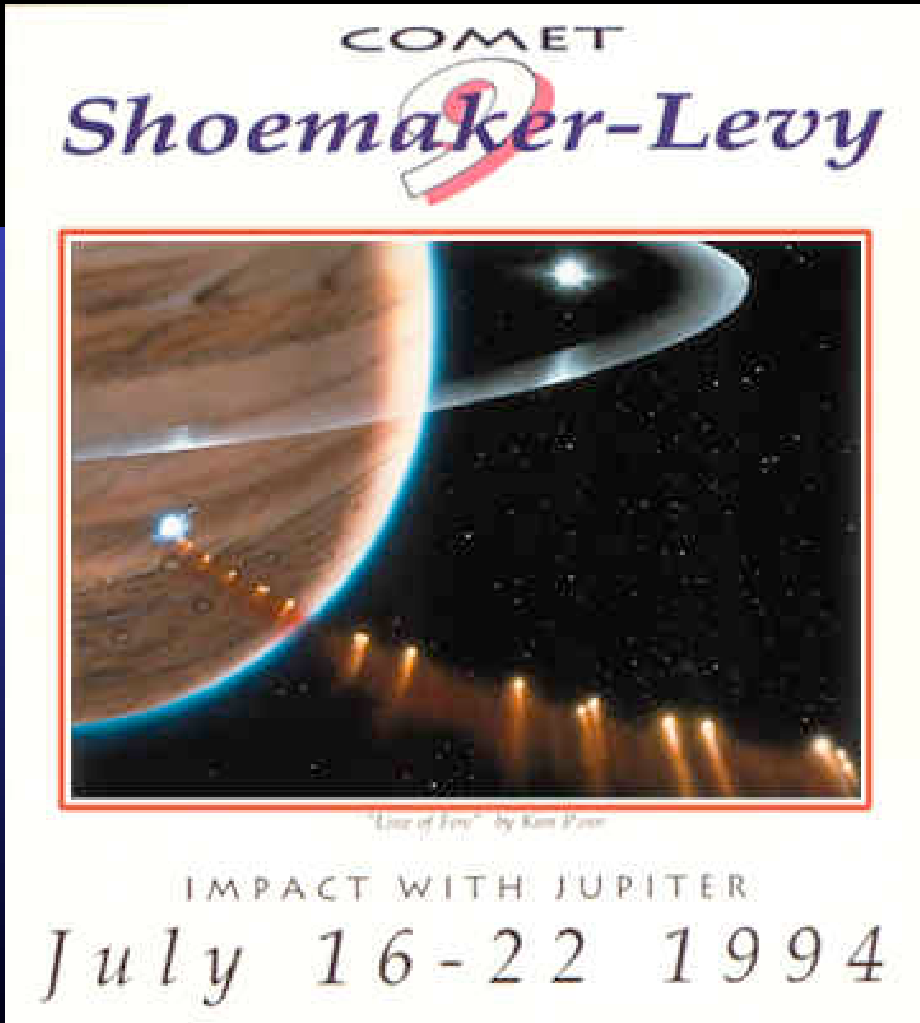


max(n)
max(n)/n_0
$t/(2\pi\Omega_0^{-1})$
0
100
200
300
400
500
600
700
0
20
40
60
80
100
50.0
50.5
51.0



Inside the Roche Lobe objects get destroyed by tidal forces





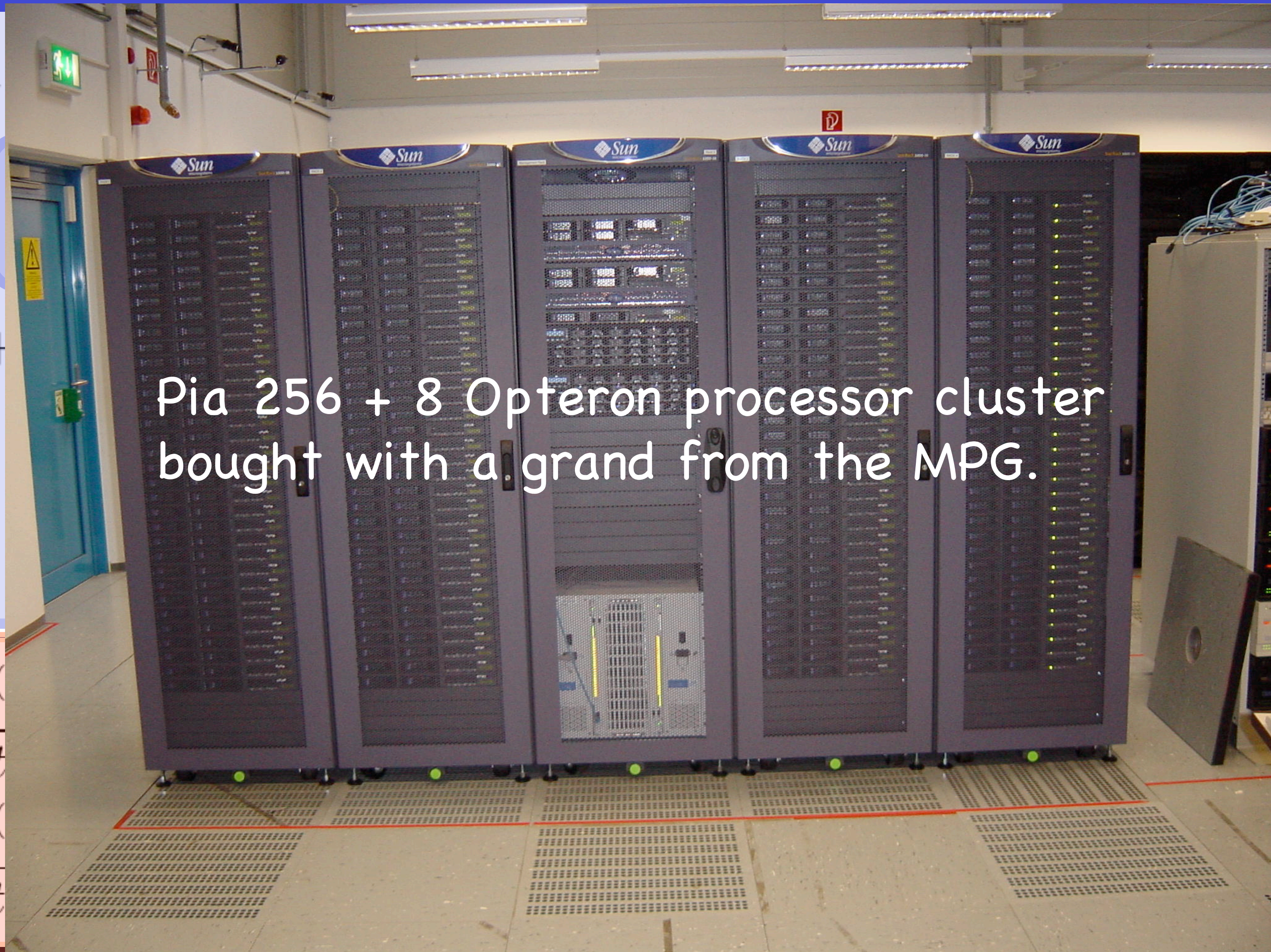
If density too low:

$$\rho_{object} < \rho_{Roche} = 3\frac{M}{\frac{4}{3}\pi R^3}$$

If a particle heap fits in ist own Roche lobe, than ist gravitationally bound.
Density has to be large enough.

white = Roche-Lobe
brown = Planetsimal/Asteroid/Comet

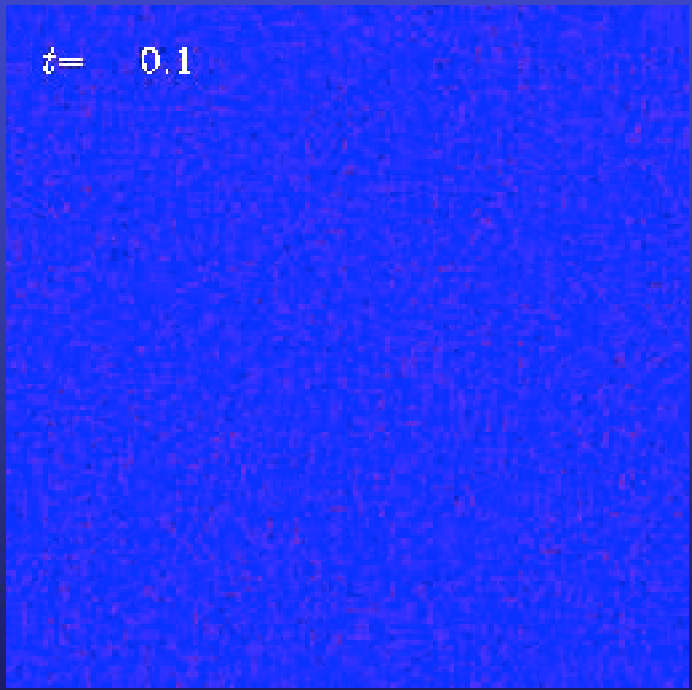
MRI plus self-gravity for the dust, including particle feed back on the gas: collaboration with Mac Low & Oichi AMNH



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

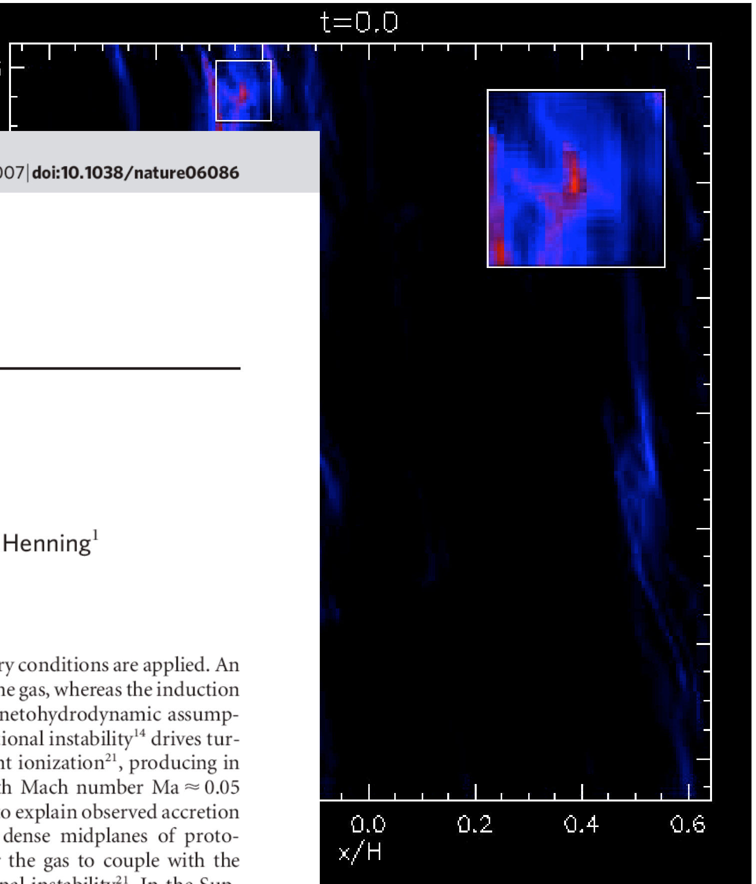
Streaming instability for radial drift: Johansen and Youdin 2007

v e r t i c a l



r a d i a l

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



nature | Vol 448 | 30 August 2007 | **doi:10.1038/nature06086**

LETTERS

Rapid planetesimal formation in turbulent circumstellar disks

Anders Johansen[1], Jeffrey S. Oishi[2,3], Mordecai-Mark Mac Low[1,2], Hubert Klahr[1], Thomas Henning[1] & Andrew Youdin[4]

During the initial stages of planet formation in circumstellar gas disks, dust grains collide and build up larger and larger bodies[1]. How this process continues from metre-sized boulders to kilometre-scale planetesimals is a major unsolved problem[2]: boulders are expected to stick together poorly[3], and to spiral into the protostar in a few hundred orbits owing to a 'headwind' from the slower rotating gas[4]. Gravitational collapse of the solid component has been suggested to overcome this barrier[1,5,6]. But even low levels of turbulence will inhibit sedimentation of solids to a sufficiently dense midplane layer[2,7], and turbulence must be present to explain observed gas accretion in protostellar disks[8]. Here we report that boulders can undergo efficient gravitational collapse in locally overdense regions in the midplane of the disk. The boulders concentrate initially in transient high pressure regions in the turbulent gas[9], and these concentrations are augmented a further order of magnitude by a streaming instability[10–12] driven by the relative flow of gas and solids. We find that gravitationally bound clusters form with masses comparable to dwarf planets and containing a distribution of boulder sizes. Gravitational collapse happens much faster than radial drift, offering a possible path to planetesimal formation in accreting circumstellar disks.

star at a fixed distance. Periodic boundary conditions are applied. An isothermal equation of state is used for the gas, whereas the induction equation is solved under the ideal magnetohydrodynamic assumption of high conductivity. Magnetorotational instability[14] drives turbulence in keplerian disks with sufficient ionization[21], producing in our unstratified models turbulence with Mach number $\mathrm{Ma} \approx 0.05$ and viscosity $\alpha \approx 10^{-3}$, a realistic value to explain observed accretion rates[8]. The ionization fraction in the dense midplanes of protoplanetary disks may be insufficient for the gas to couple with the magnetic field to drive magnetorotational instability[21]. In the Supplementary Information we therefore describe unmagnetized models as well.

Solid objects orbit the protostar with keplerian velocity v_K in the absence of gas drag. A radial pressure gradient partly supports the gas, however, so it orbits at sub-keplerian velocity v_g, with $\Delta v \equiv v_g - v_K < 0$. As a result, large (approximately metre-sized) solid objects are exposed to a strong headwind that causes them to drift radially inwards[4] with a maximum drift velocity Δv. They also 'feel' gas drag as they fall towards the disk midplane in the effective gravity field of the star. A sedimentary midplane layer forms, with a width determined by a balance between settling and turbulent

10

P

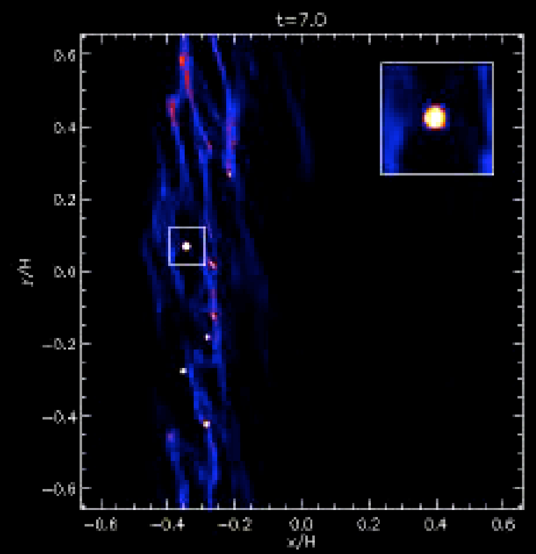
Mag

plus

2 we

Klahr & Bodenheimer 2006
Johansen, Klahr & Henning 2006
Johansen, Oishi, Mac Low, Klahr, Henning & Youdin 2007, nature

Johansen, Oichi, MacLow, Klahr, Henning & Youdin, 2007, nature

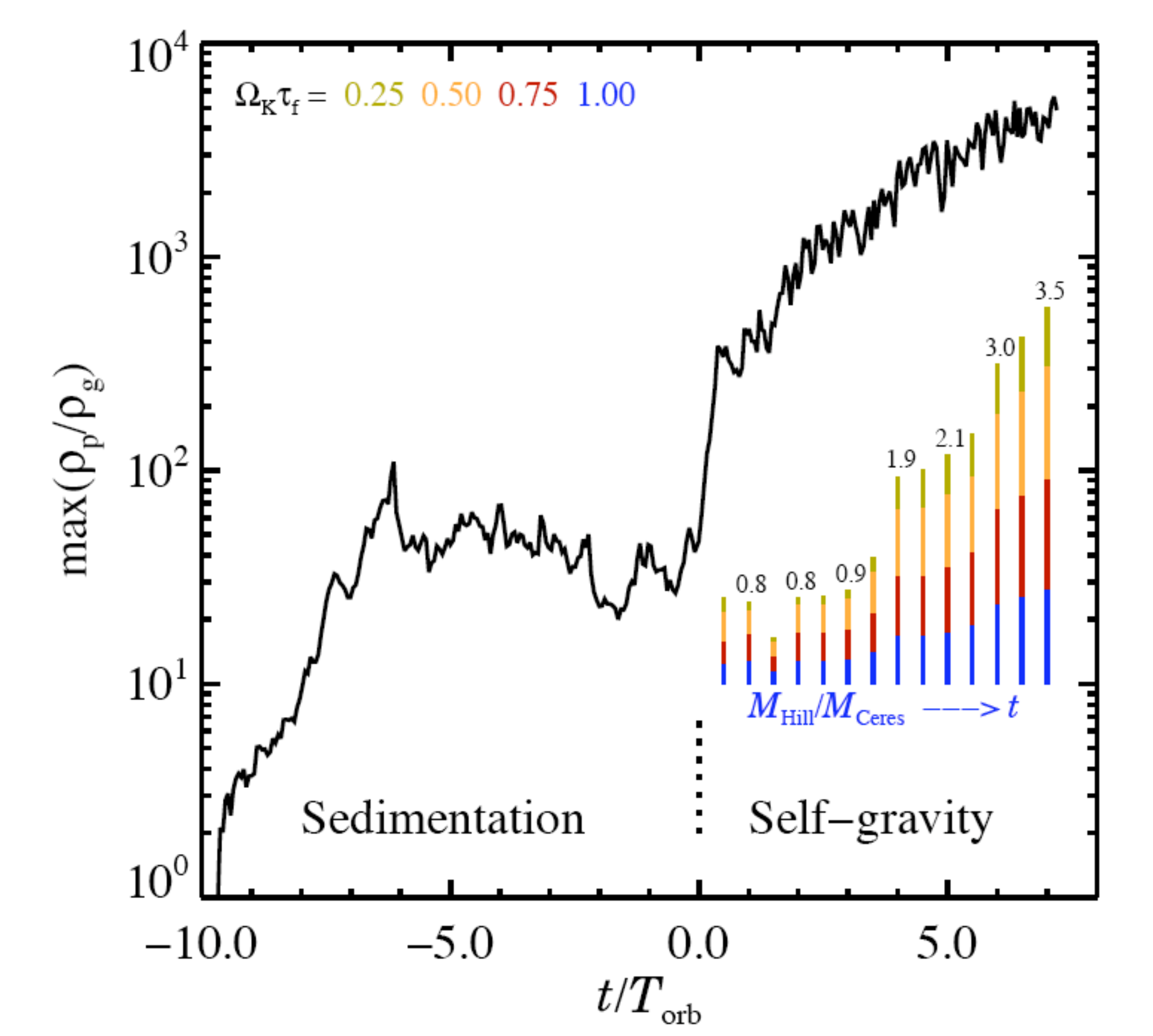


Rapid planetesimal formation
in turbulent circumstellar discs
Nature, vol. 448, p. 1022-1025

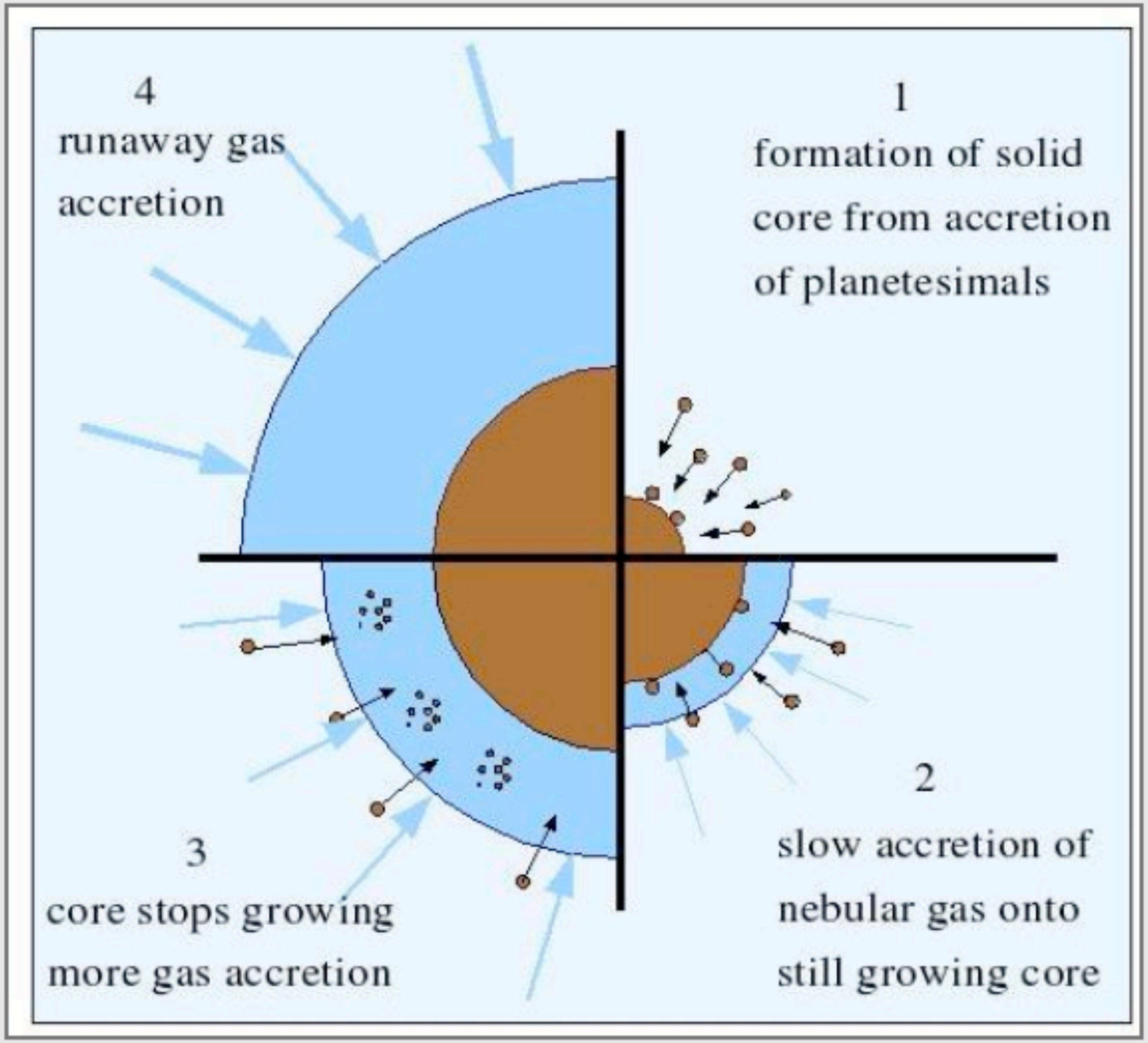
A. Johansen[1], J. Oishi[2], M.-M. Mac Low[2,1], H. Klahr[1], Th. Henning[1], A. Youdin[3]
[1]Max-Planck-Institut für Astronomie, Heidelberg
[2]American Museum of Natural History, New York
[3]CITA, University of Toronto, Canada

http://www.mpia.de/homes/johansen/research_en.php

Growth of Planetary Core?

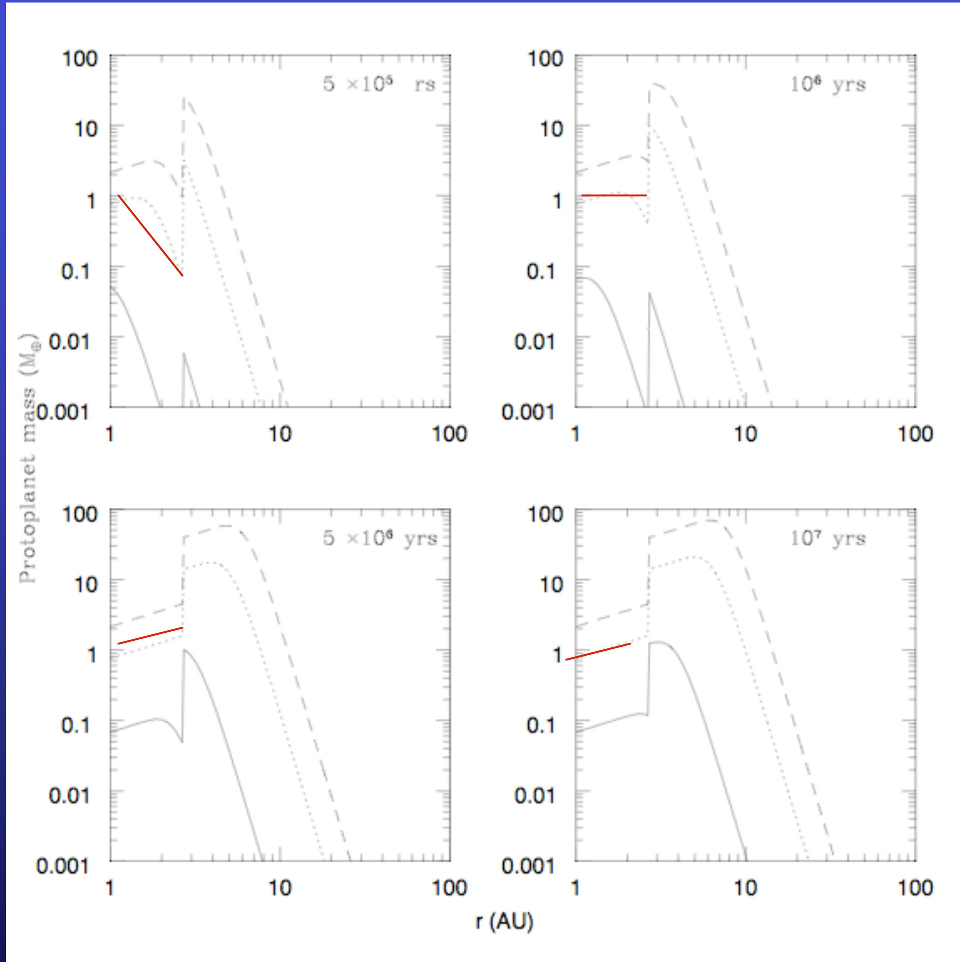


Giant planet formation: core accretion model



Core size as function of time and distance

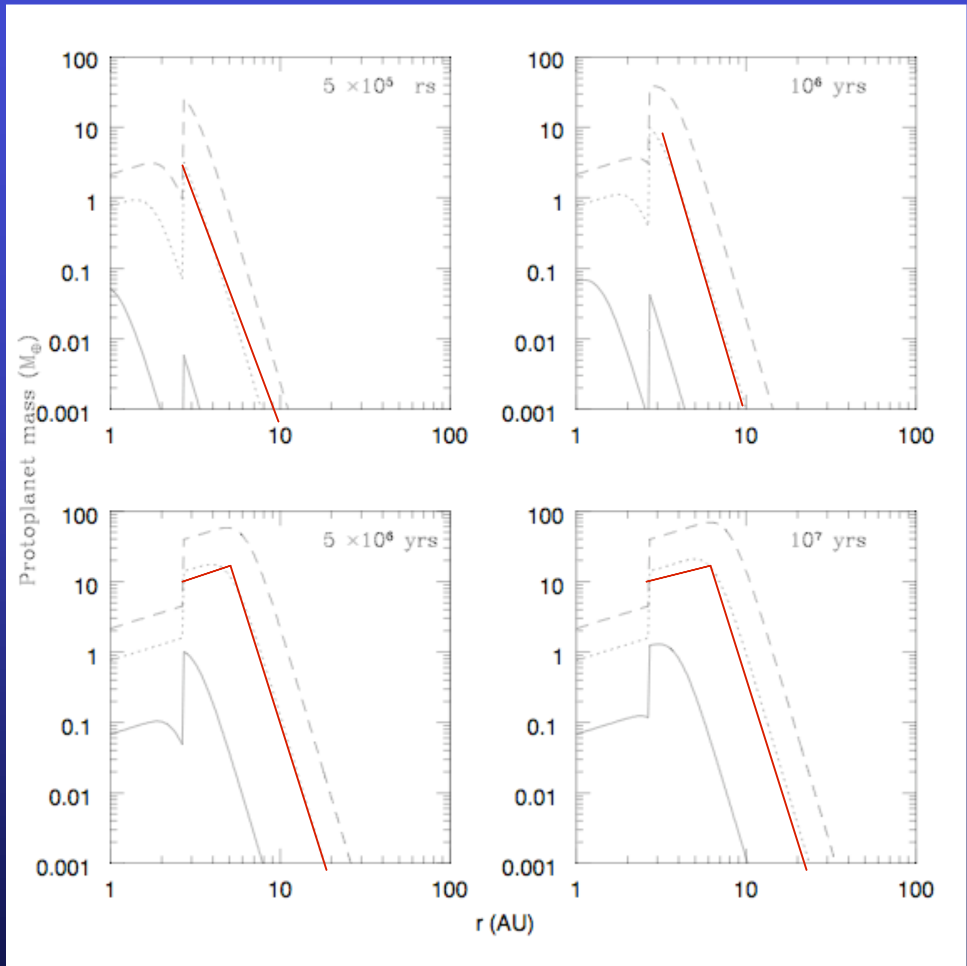
Inner disk fast growth due to frequent collisions - yet low truncation mass due to proximity of the star (Hill radius)



Thommes & Duncan 2006

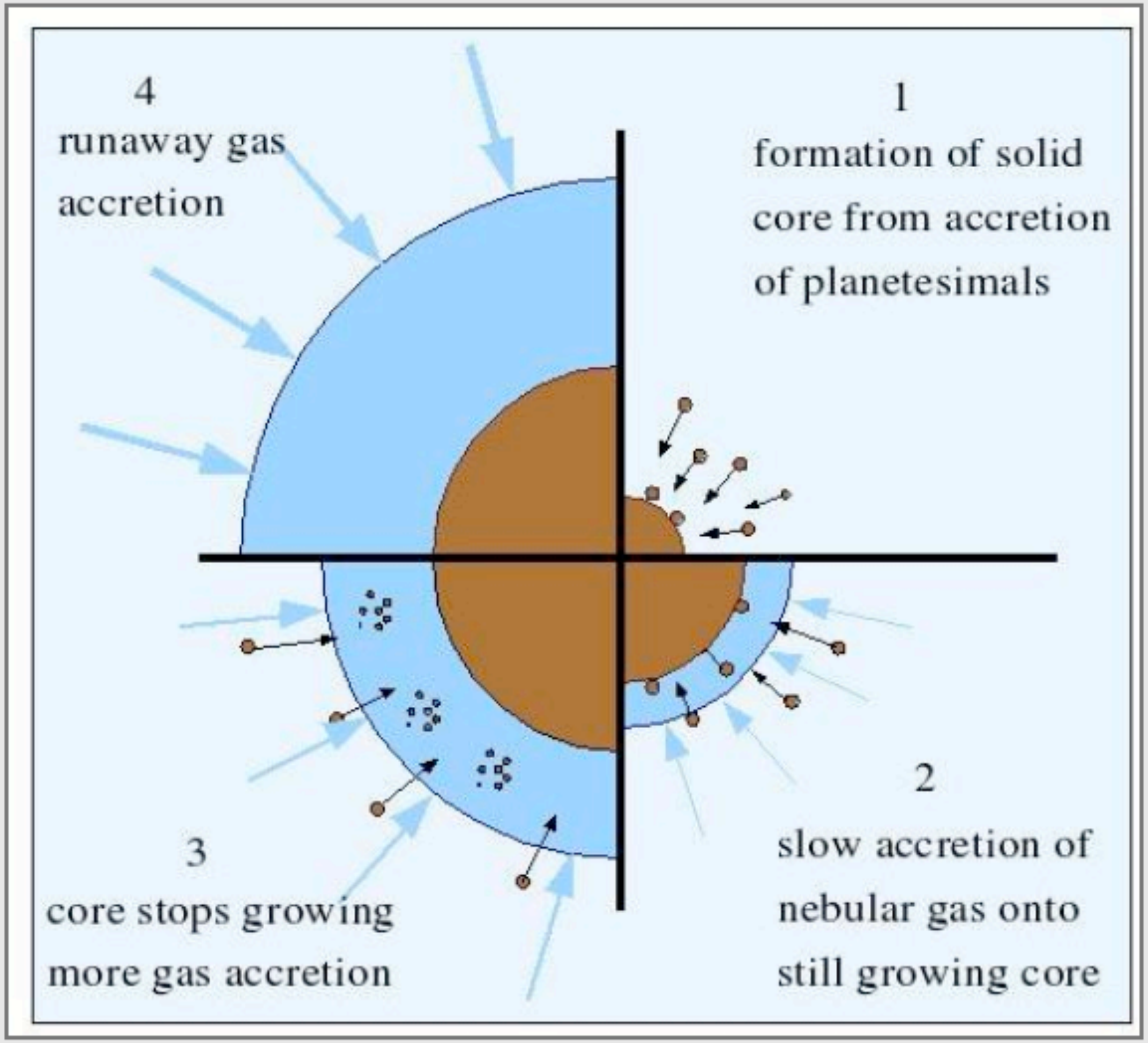
Core size as function of time and distance

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



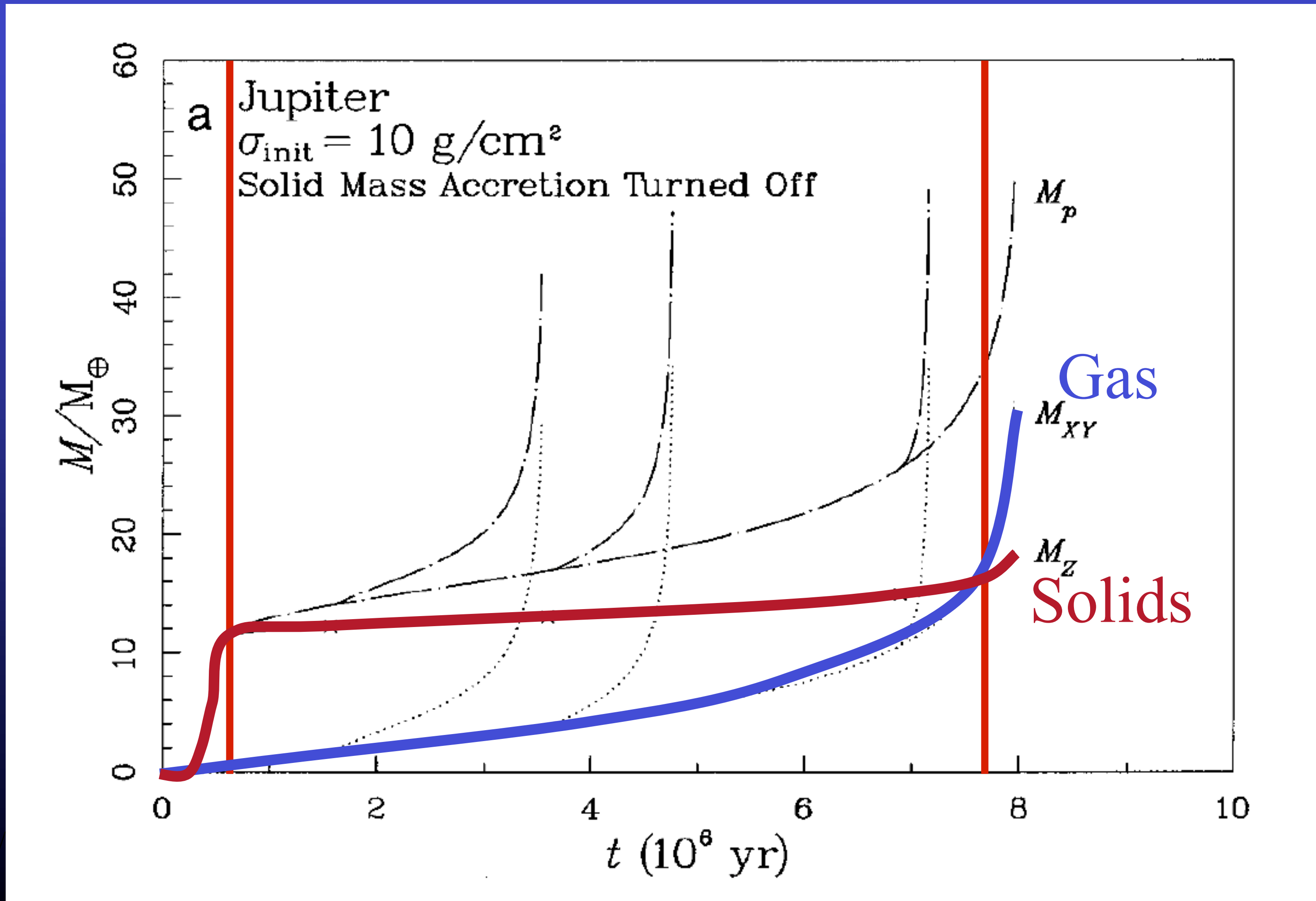
Thommes & Duncan 2006

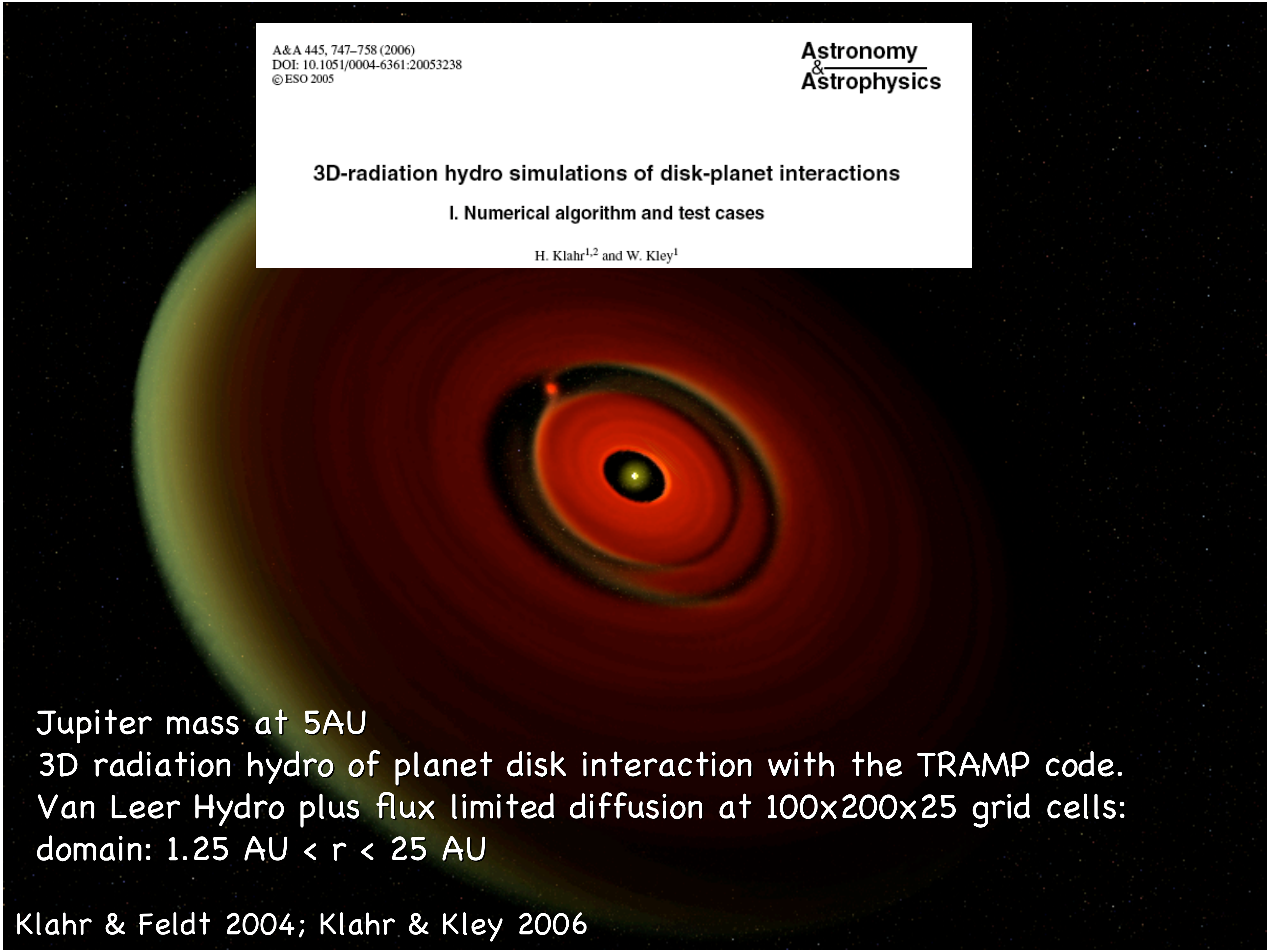
Giant planet formation: core accretion model



Core Accretion (Pollack et al. 1996)

Usually takes too long!



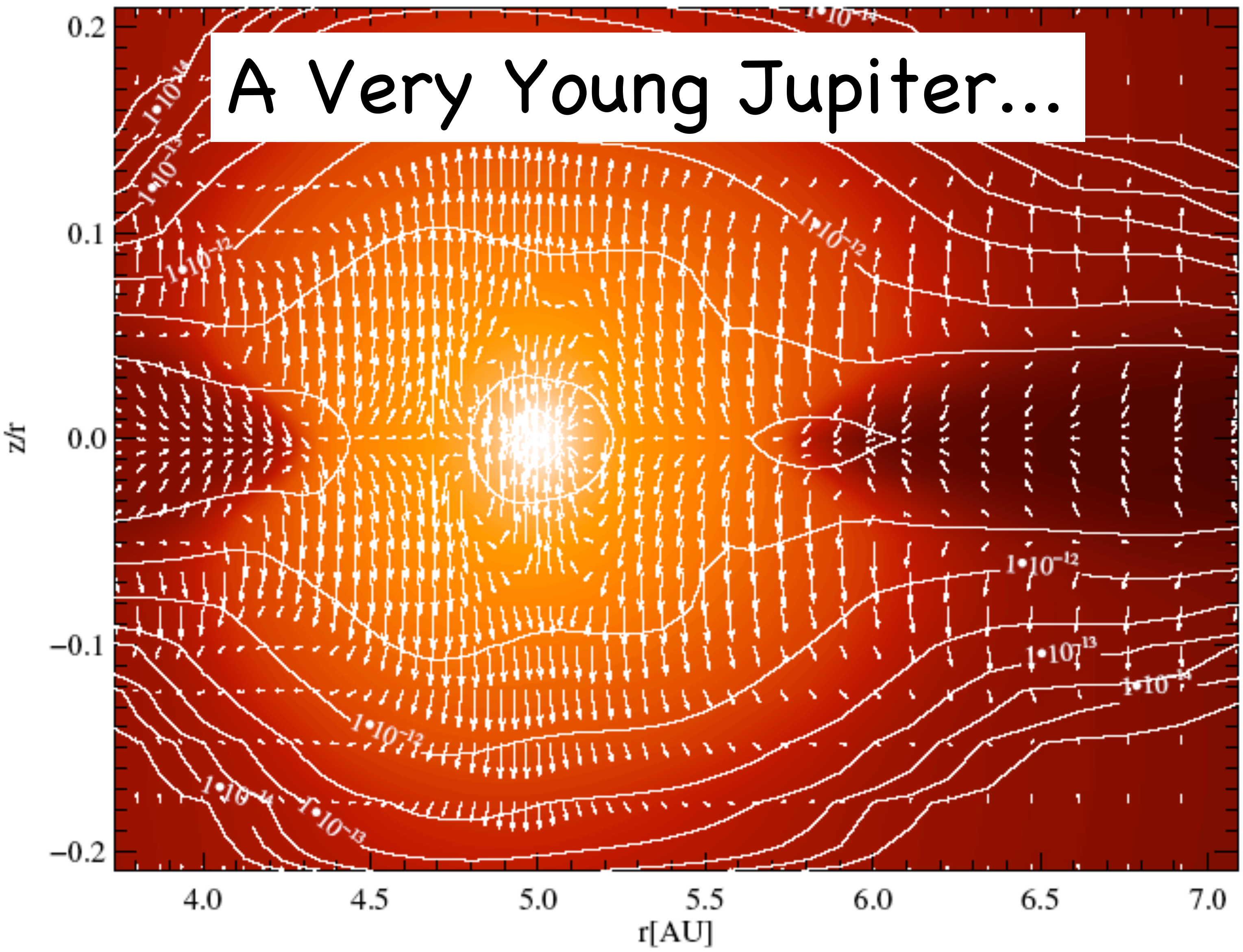

A&A 445, 747–758 (2006)
DOI: 10.1051/0004-6361:20053238
© ESO 2005
Astronomy & Astrophysics
3D-radiation hydro simulations of disk-planet interactions
I. Numerical algorithm and test cases
H. Klahr[1,2] and W. Kley[1]
Jupiter mass at 5AU
3D radiation hydro of planet disk interaction with the TRAMP code.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

3D-Radiation Hydro Simulation of Planet-Disk Interaction

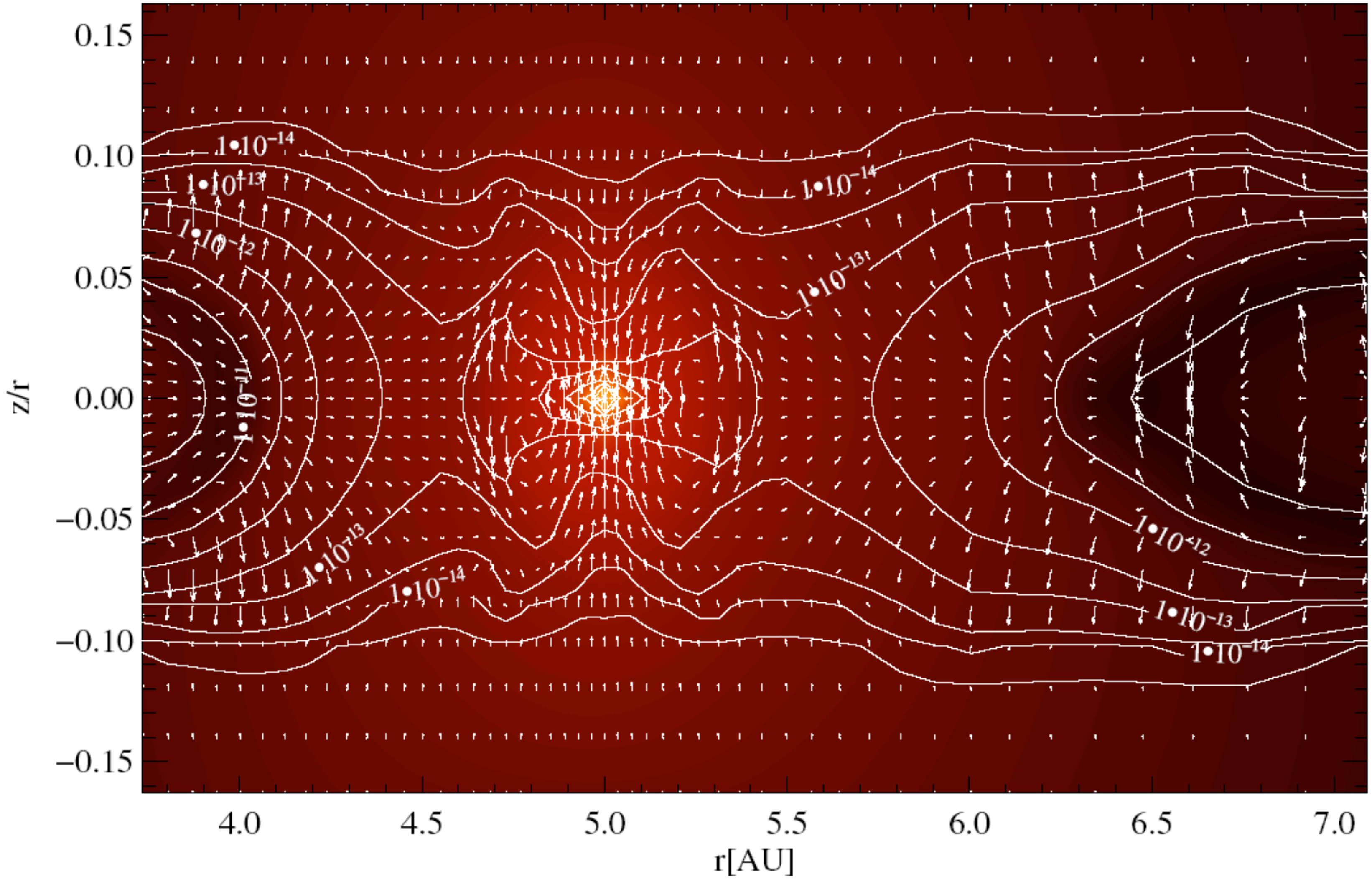
"A Jupiter mass planet opens a gap in a solar nebula. The gas around the planet is heated by the accretion of mass onto the planetary surface."

Simulation by Hubert Klahr, MPIA and Wilhelm Kley, Uni Tübingen
Animation by Markus Feldt, Hubert Klahr & Anders Johansen
Max-Planck-Institut für Astronomie, Heidelberg

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

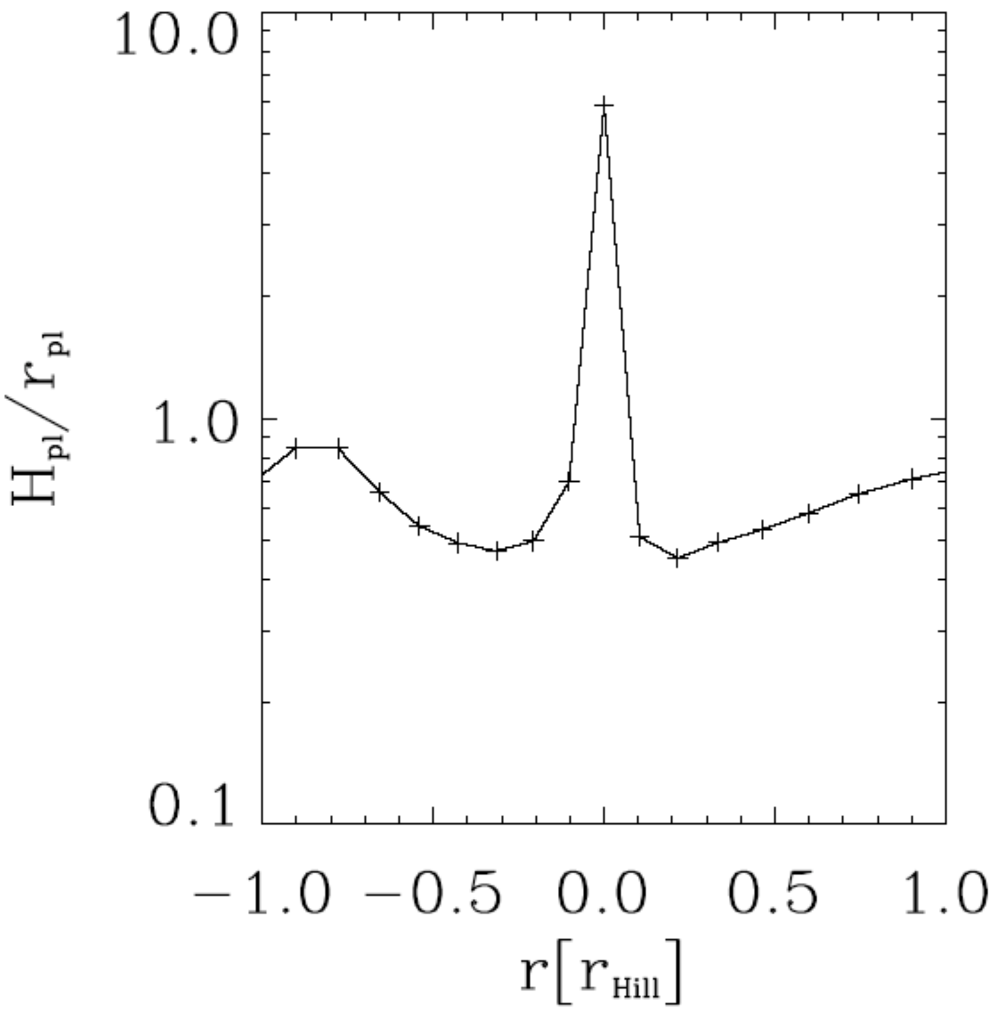


A Young Jupiter... > 1000yrs



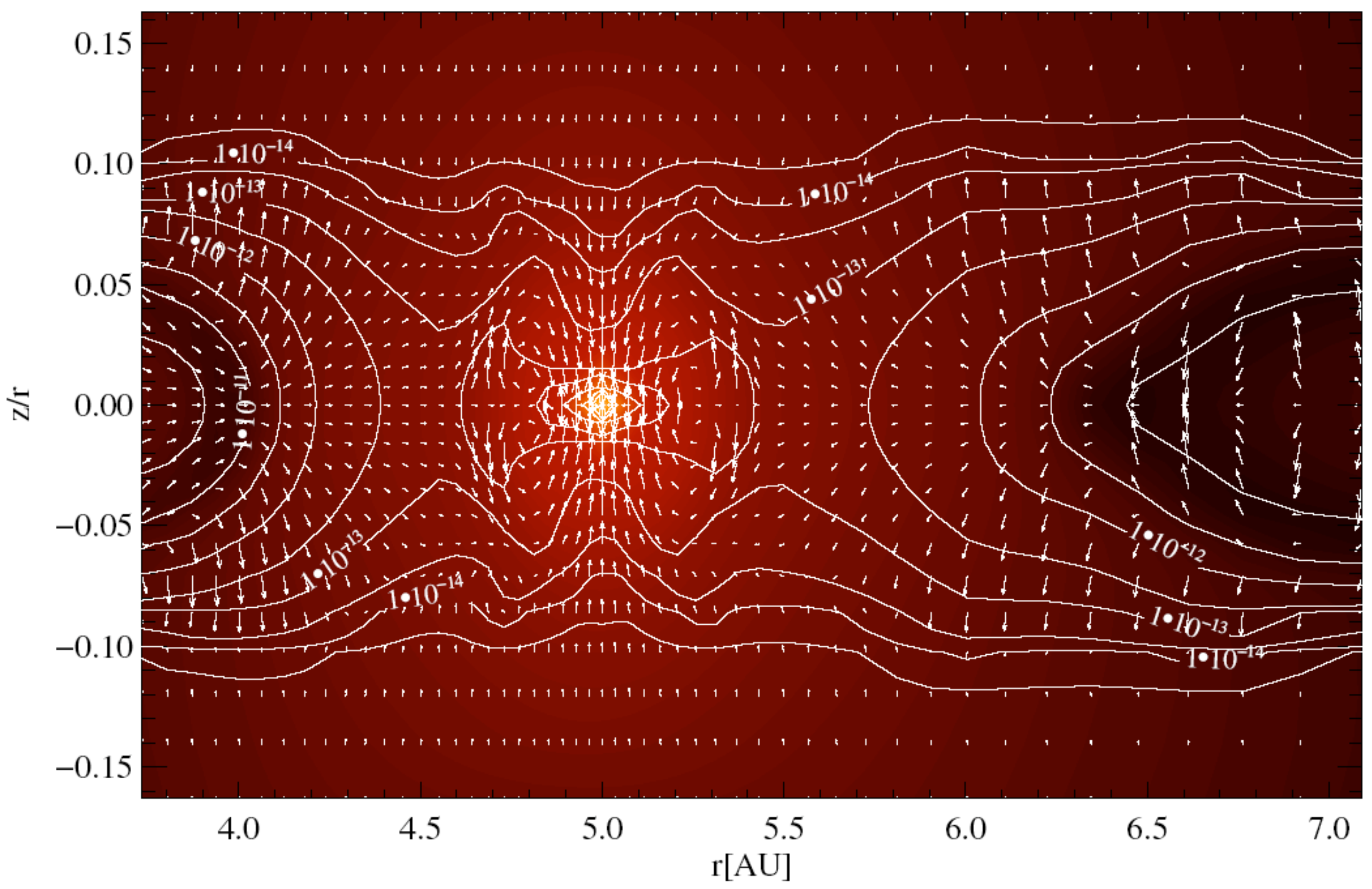
Temperature, velocity and density contours.

Disk or Donut around Jupiter?



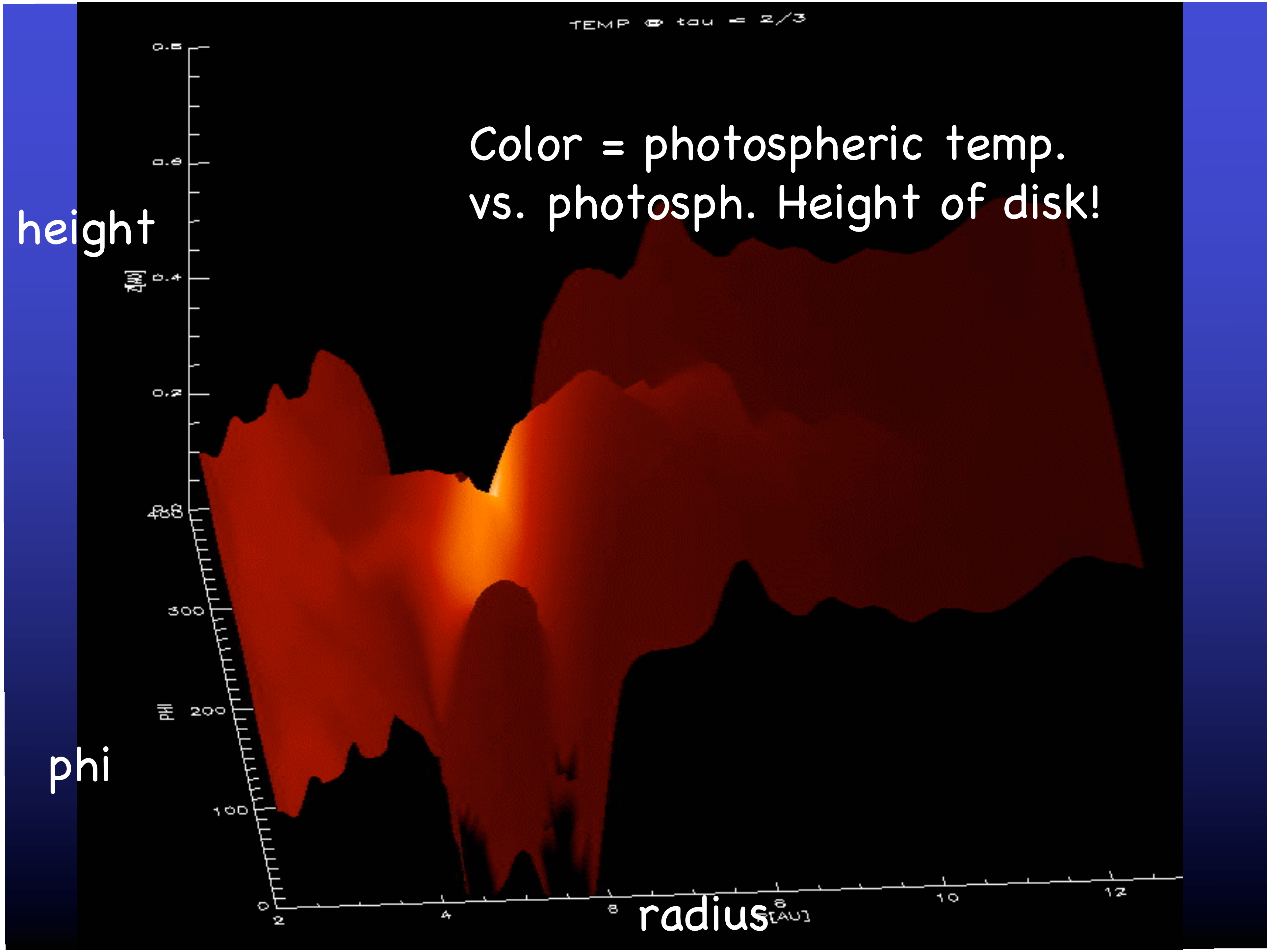
Pressure scale height in "Blob" over the Roche lobe.

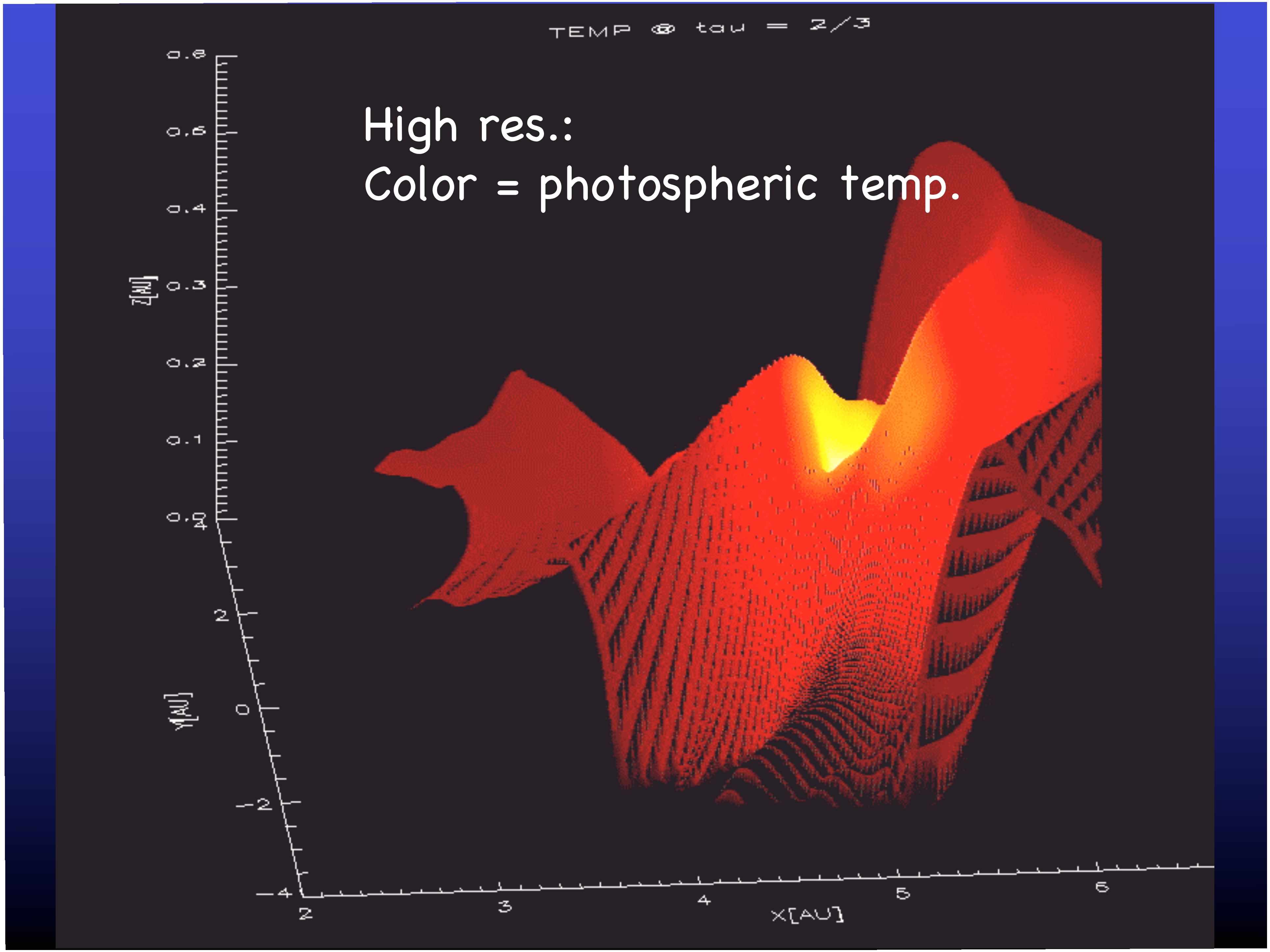
A Young Jupiter... > 1000yrs



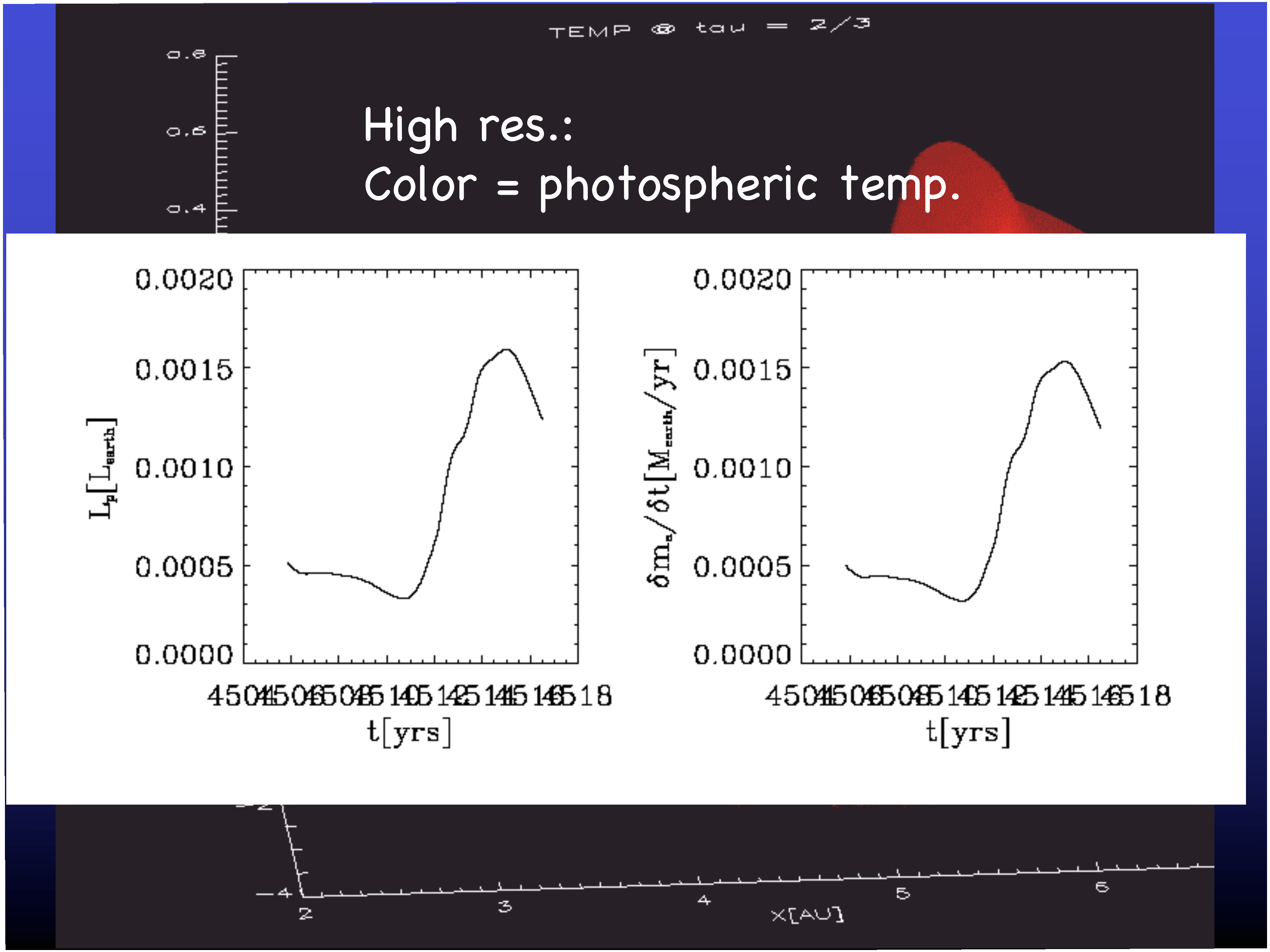
Temperature, velocity and density contours.

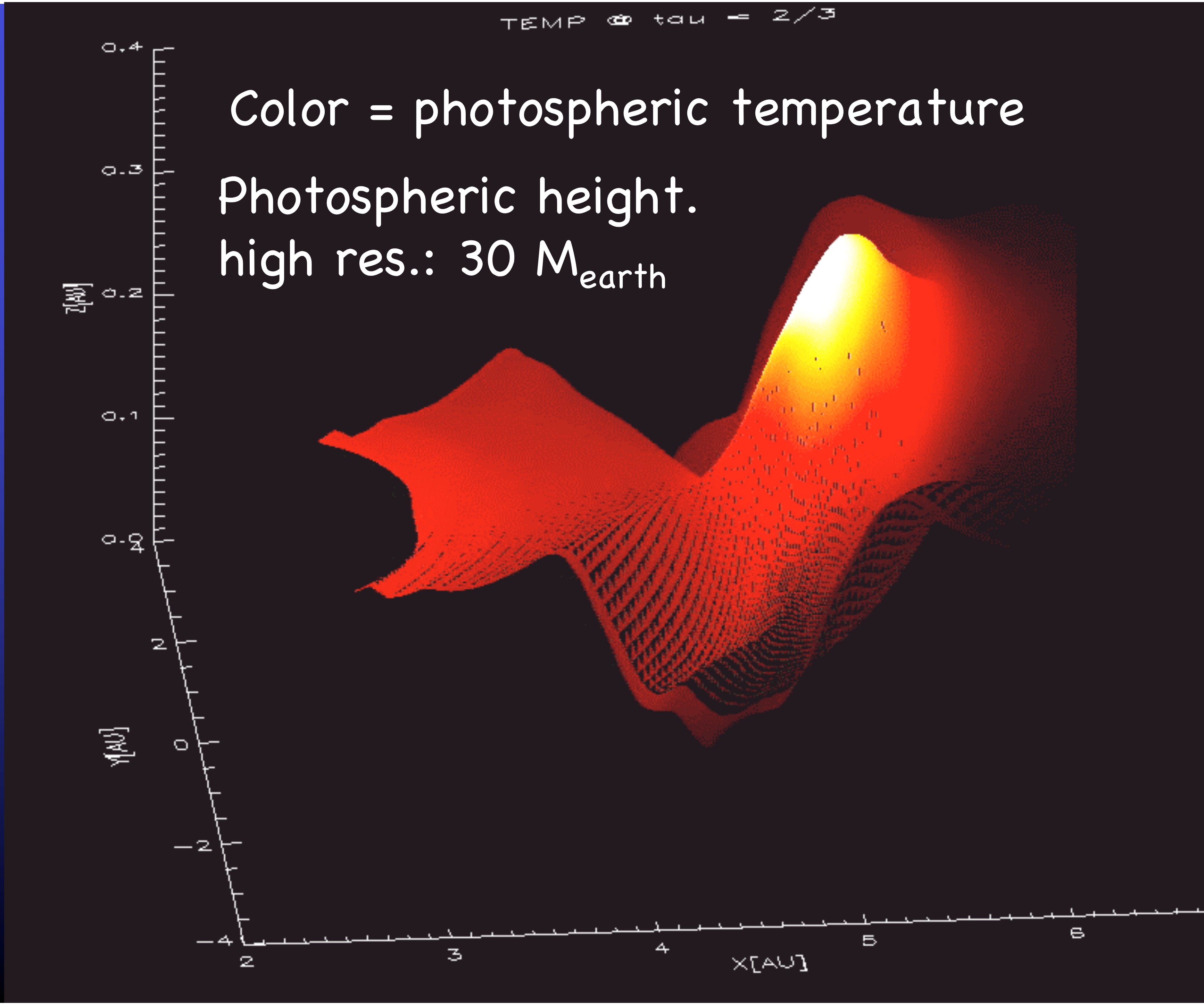
Color = photospheric temp.
vs. photosph. Height of disk!




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

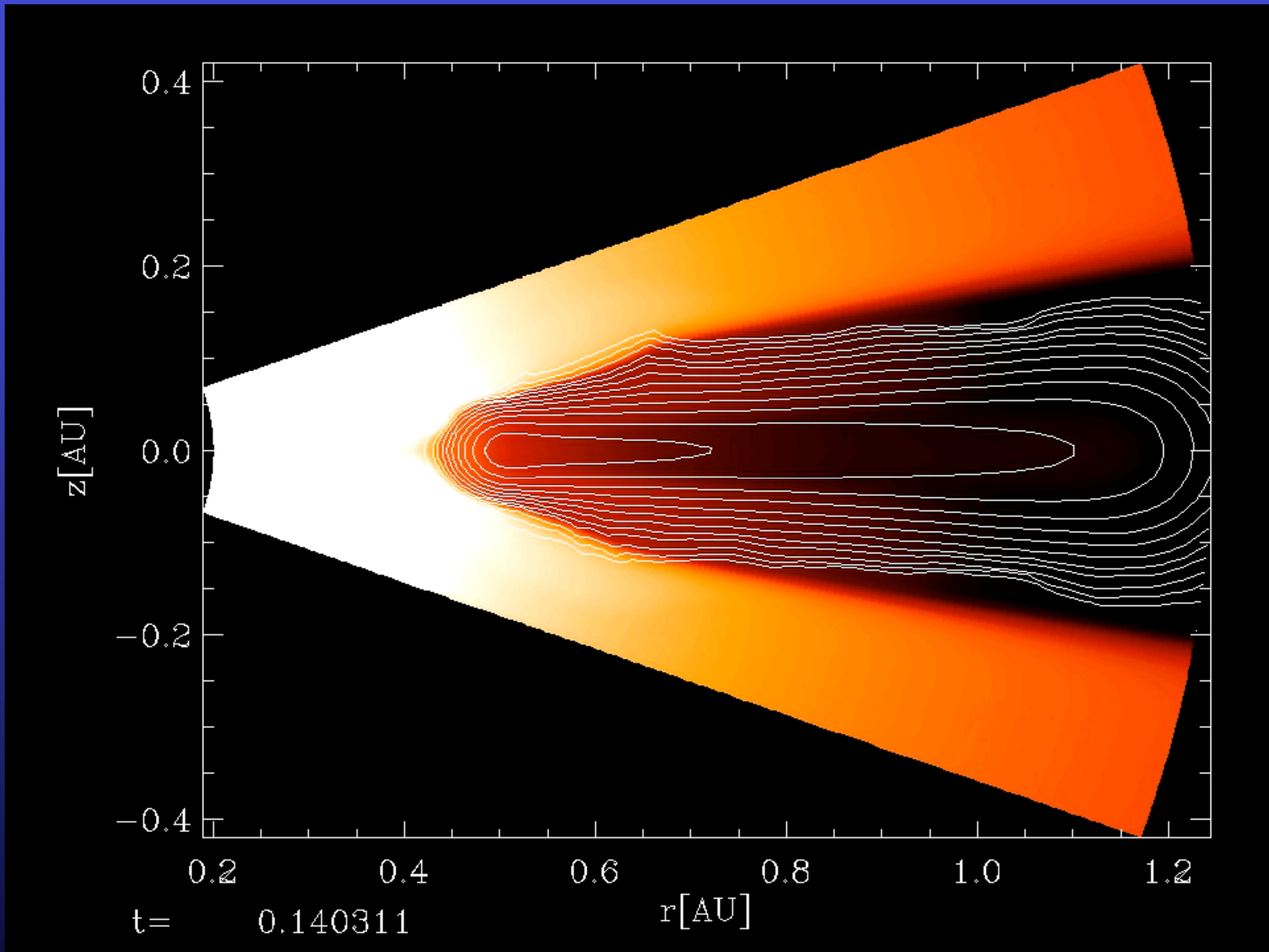
High res.:
Color = photospheric temp.





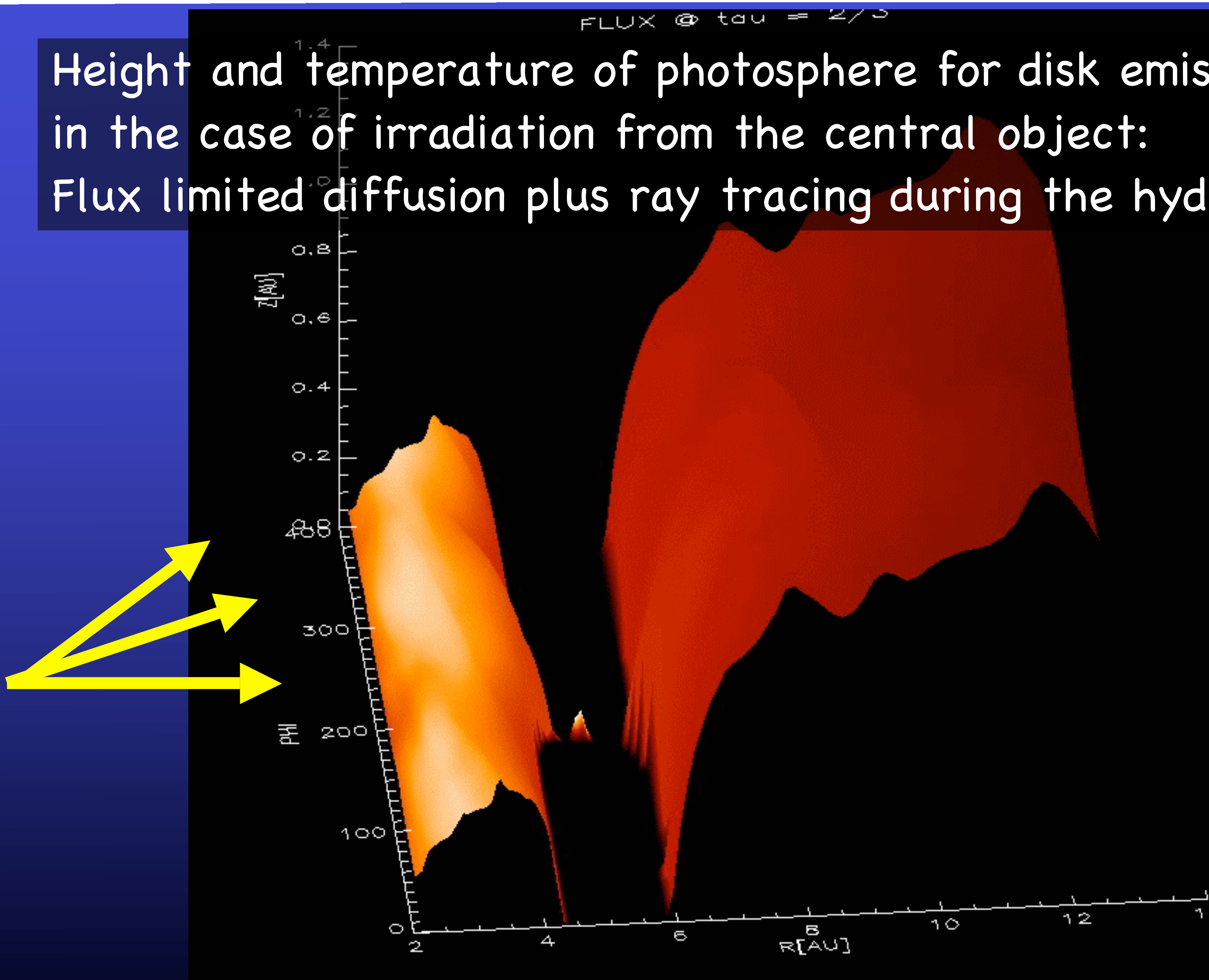
TEMP @ tau = 2/3
Color = photospheric temperature
Photospheric height.
high res.: 30 M_{earth}
Z[AU]
0.4
0.3
0.2
0.1
0.0
Y[AU]
4
2
0
−2
−4
X[AU]
2
3
4
5
6

Hydro + flux limited Diffusion + ray tracing

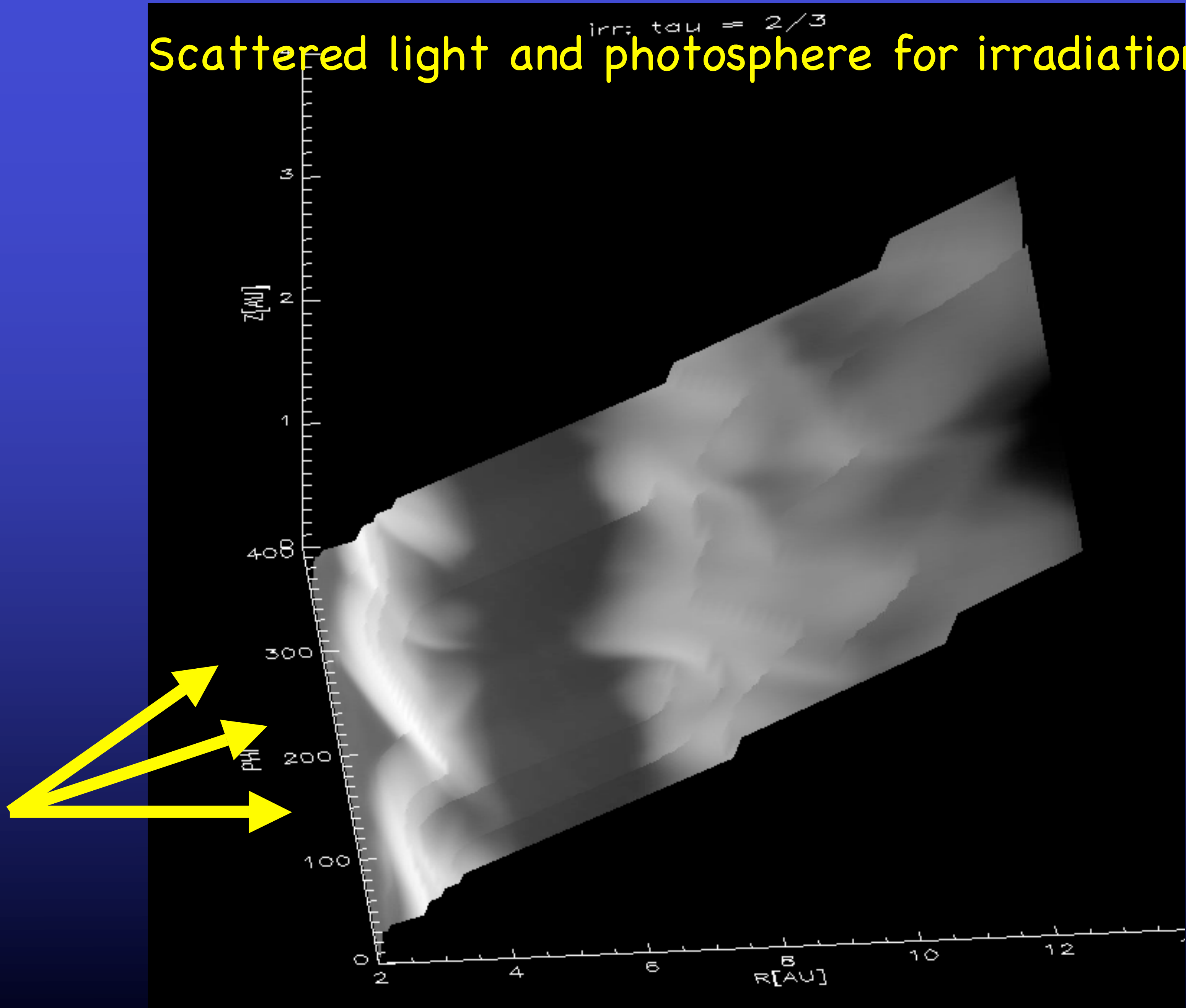


Inner Rim: with Kees Dullemond

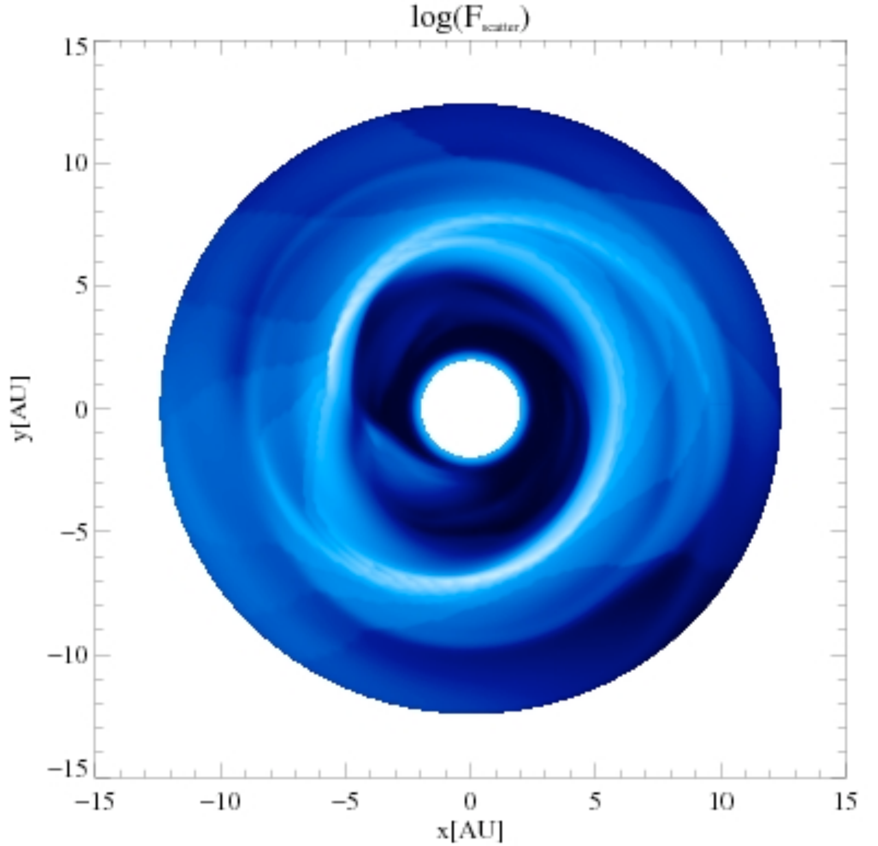
Height and temperature of photosphere for disk emission in the case of irradiation from the central object:
Flux limited diffusion plus ray tracing during the hydro run!

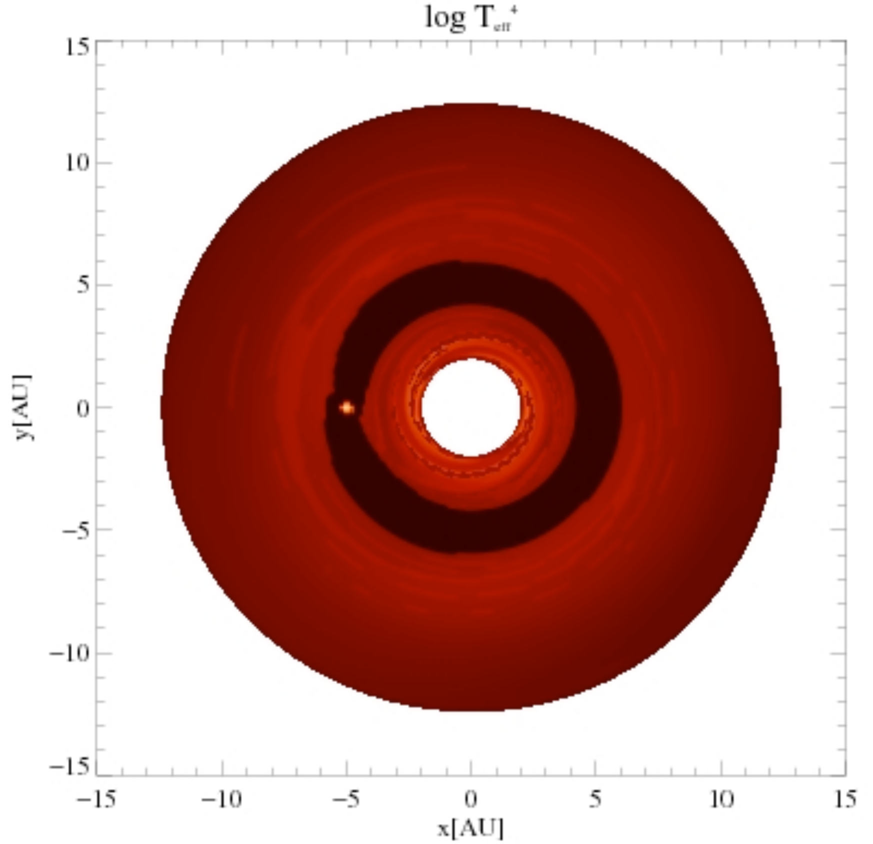


Scattered light and photosphere for irradiation:



1 Jup @ 5AU





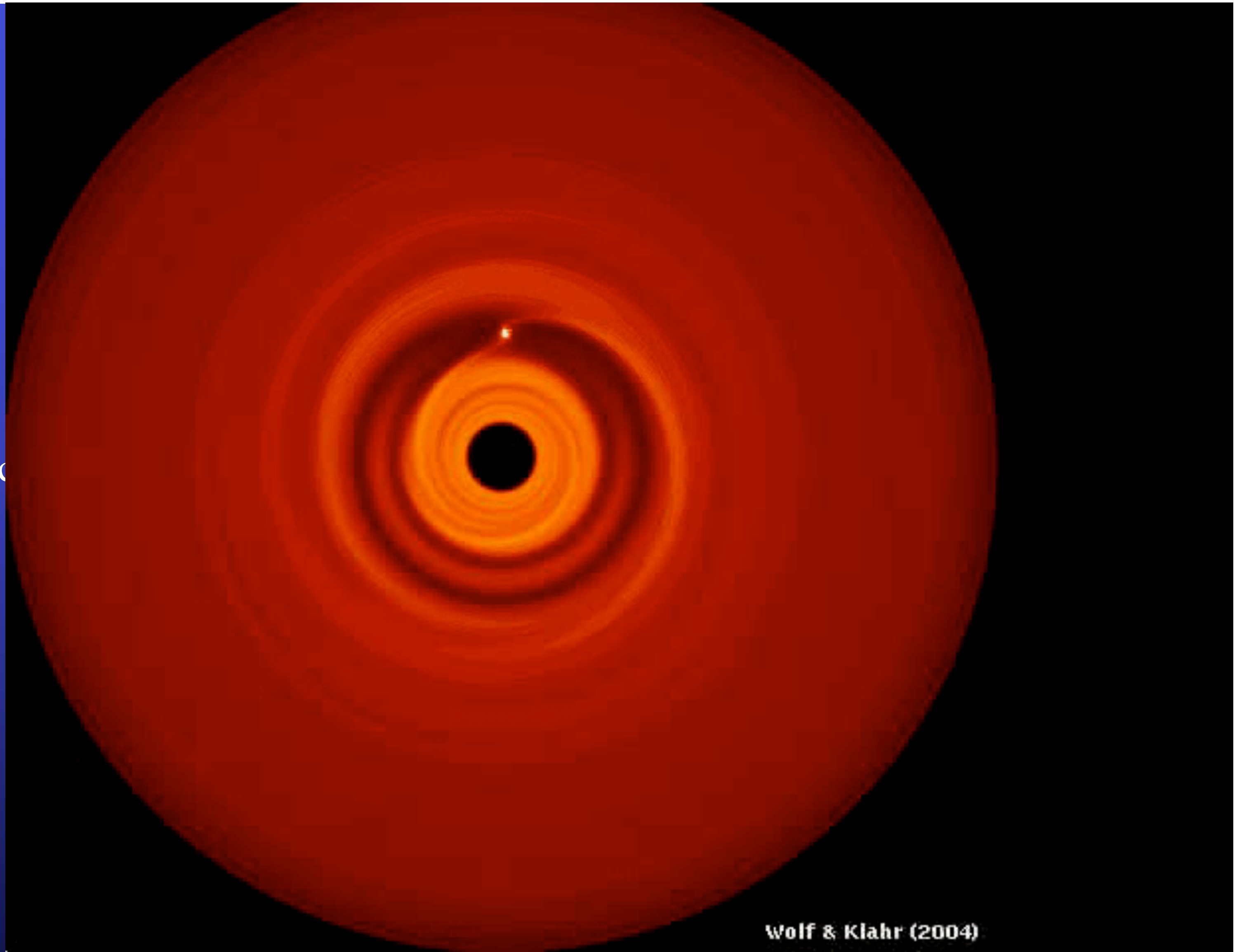
scattered light

emitted light

Reemitted light.
Simulation with
MC3D
by S. Wolf.

TRAMP =
Temperature
MC3D = Appearanc

Nice signatures,
but resolution
problems!
What camera?

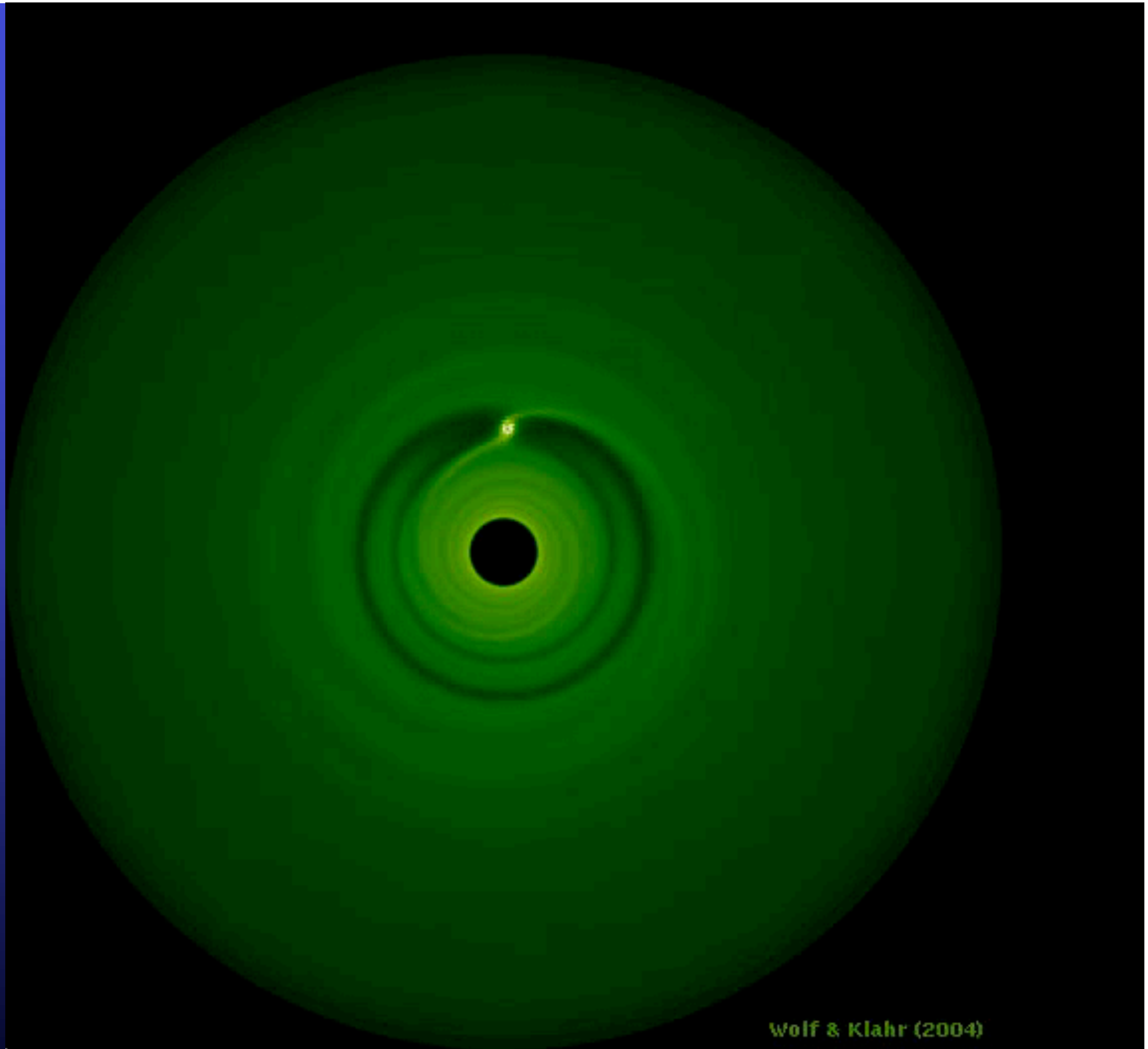


Wolf and Klahr

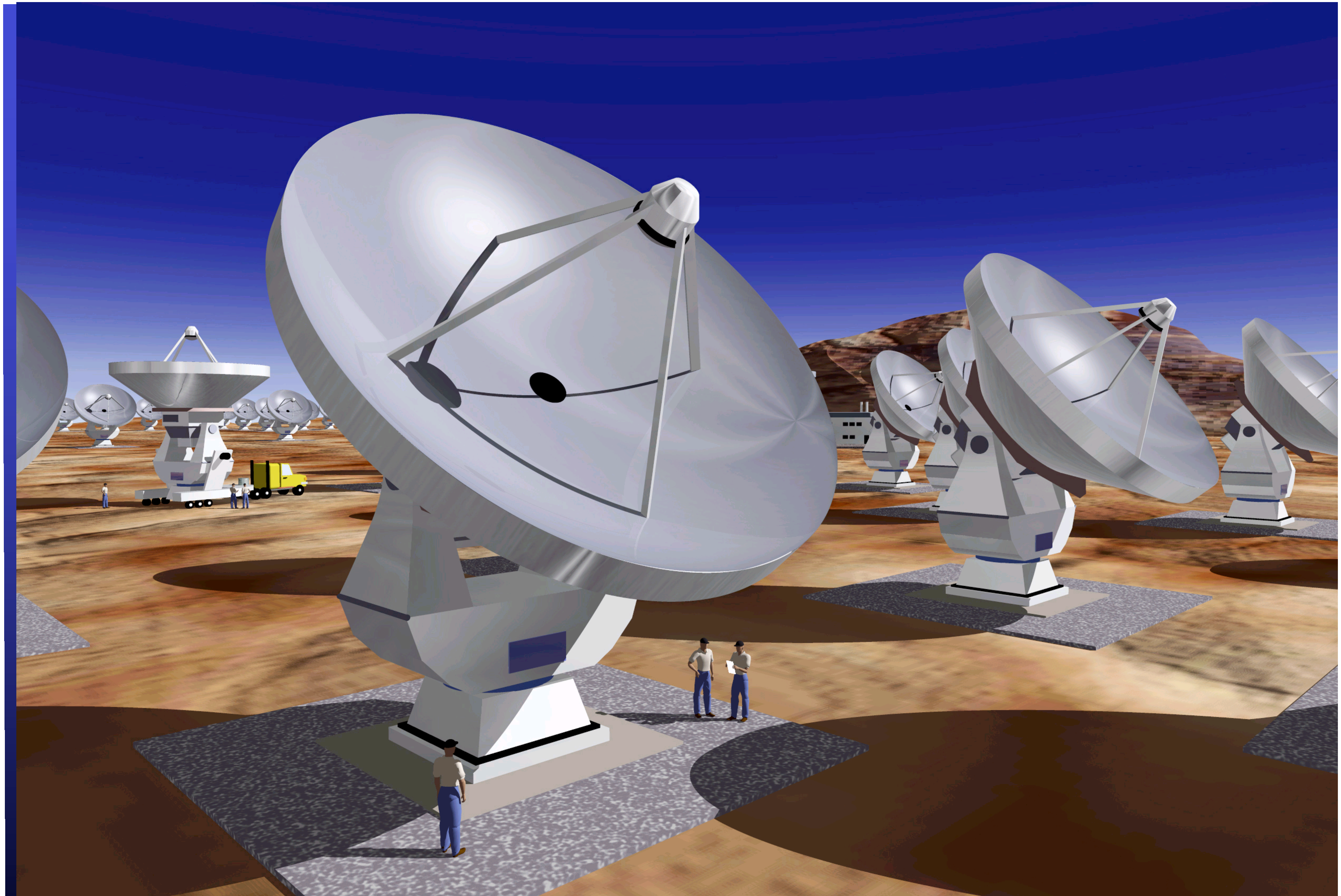
Jupiter @ 5AU: 1300μ

Nice signatures:
and the perfect
bate for ALMA!

What you see is
not the planet
but its dusty
warm envelope.

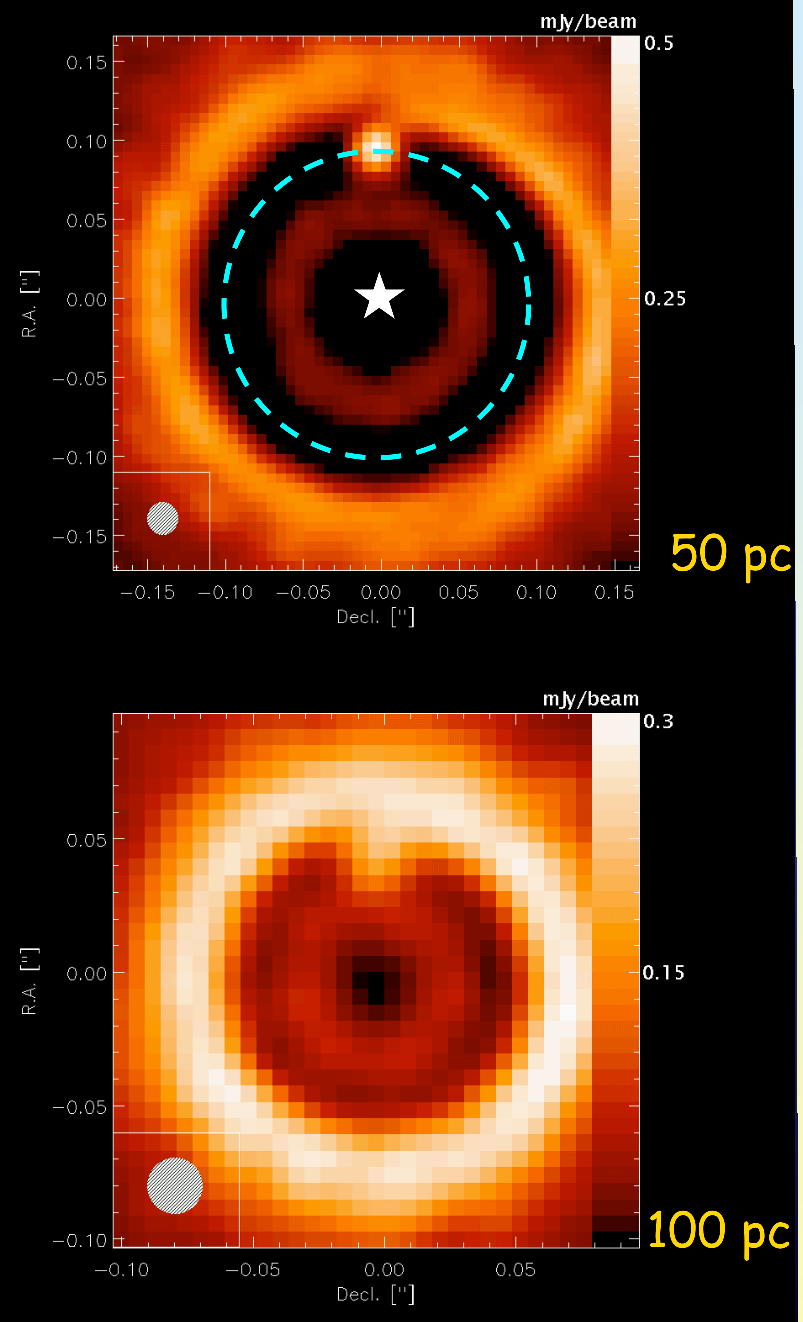


Jupiter @ 5AU: 330μ



Artist's Impression of ALMA
(Atacama Large Millimetre Array)

ESO PR Photo 24a/99 (8 June 1999)



Wolf & D'Angelo (2005)

Close-up view: Planetary region

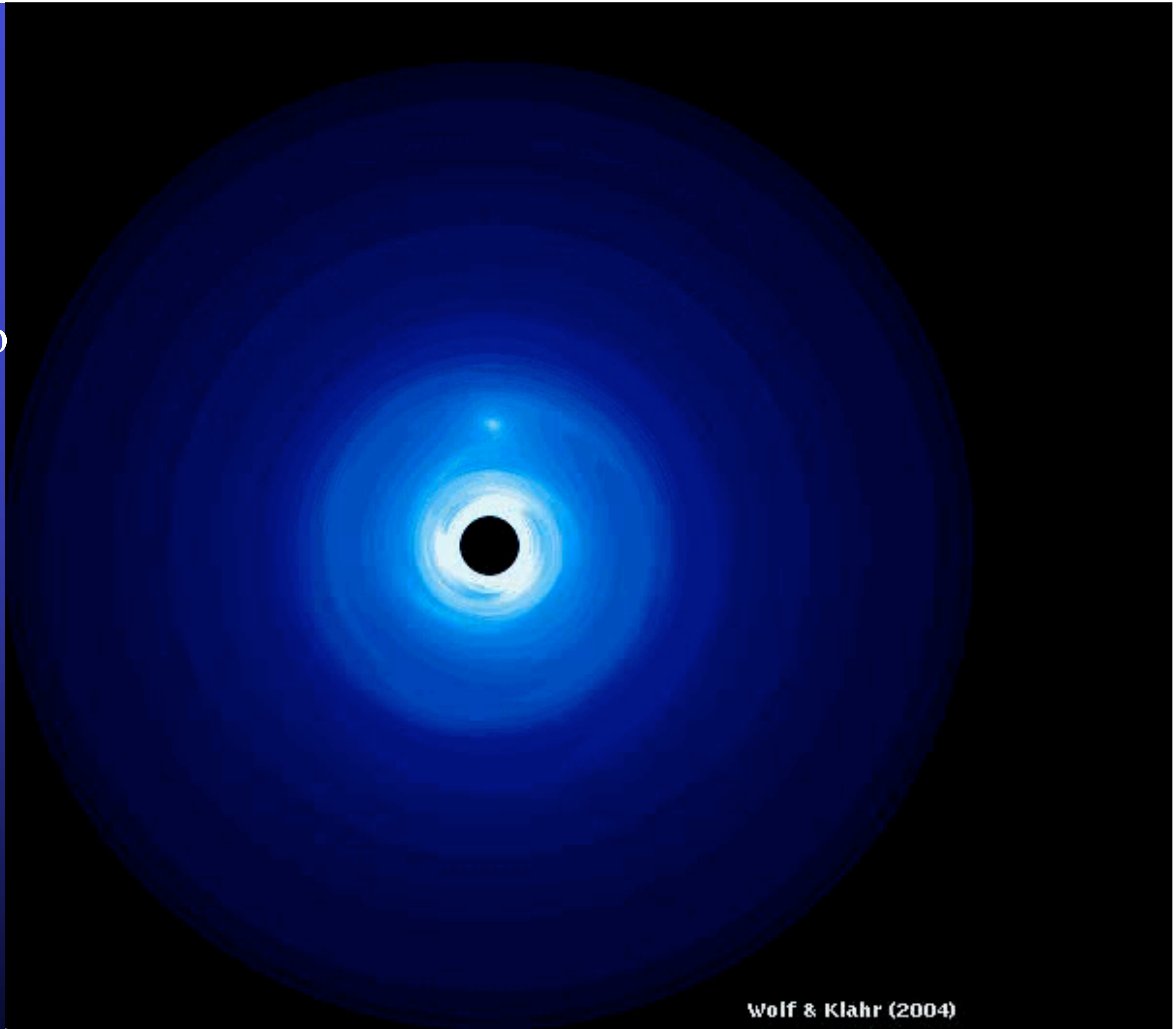
1. The resolution of the images to be obtained with ALMA will allow detection of the warm dust in the vicinity of the planet only if the object is at a **distance of not more than about 100 pc**.
   For larger distances, the contrast between the planetary region and the adjacent disk in all of the considered planet/star/disk configurations will be too low to be detectable.

2. Even at a distance of 50 pc, a sufficient resolution to allow a study of the circumplanetary region can be obtained only for those **configurations with the planet on a Jupiter-like orbit** but not when it is as close as 1 AU to the central star.

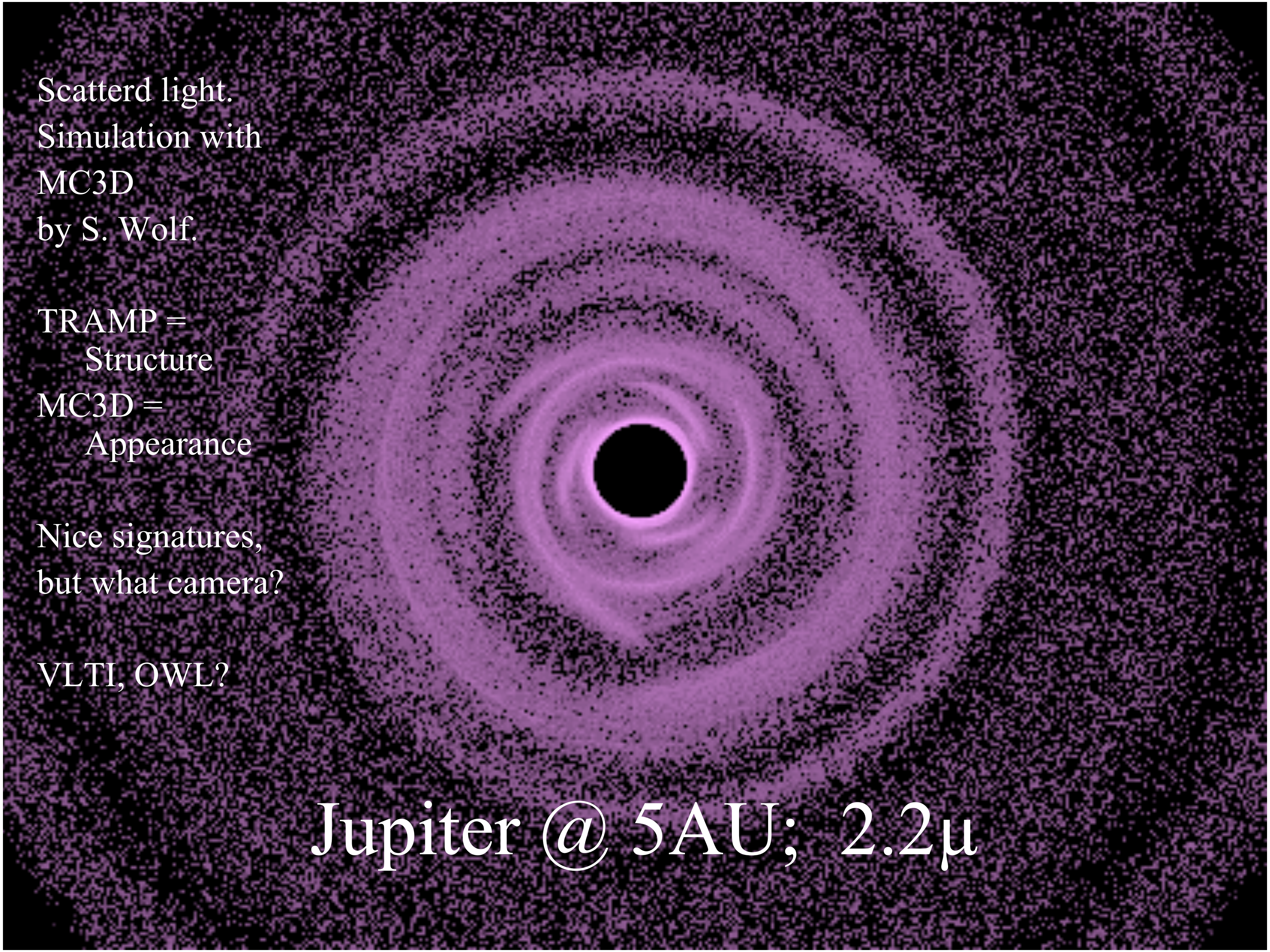
3. The observation of the emission from the dust in the vicinity of the planet will be possible only in the case of the **most massive, young circumstellar disks** we analyzed.

Weaker signatures!

Less chances to Observe.

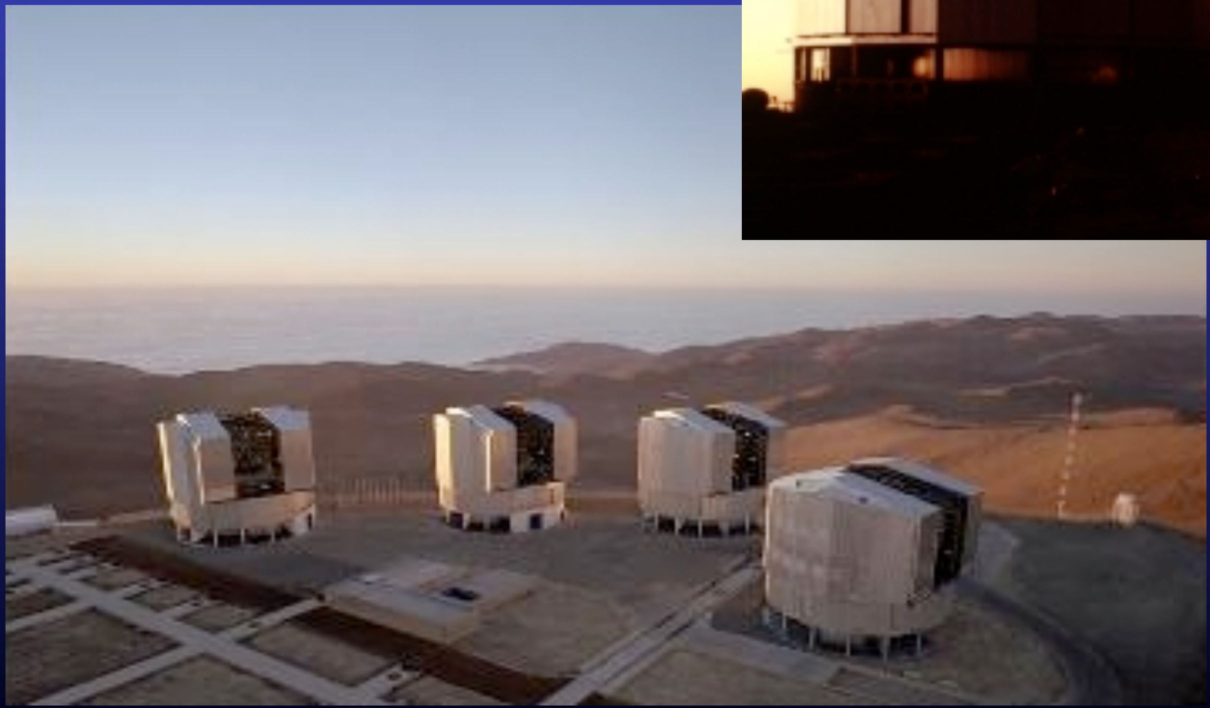


Jupiter @ 5AU: 10μ

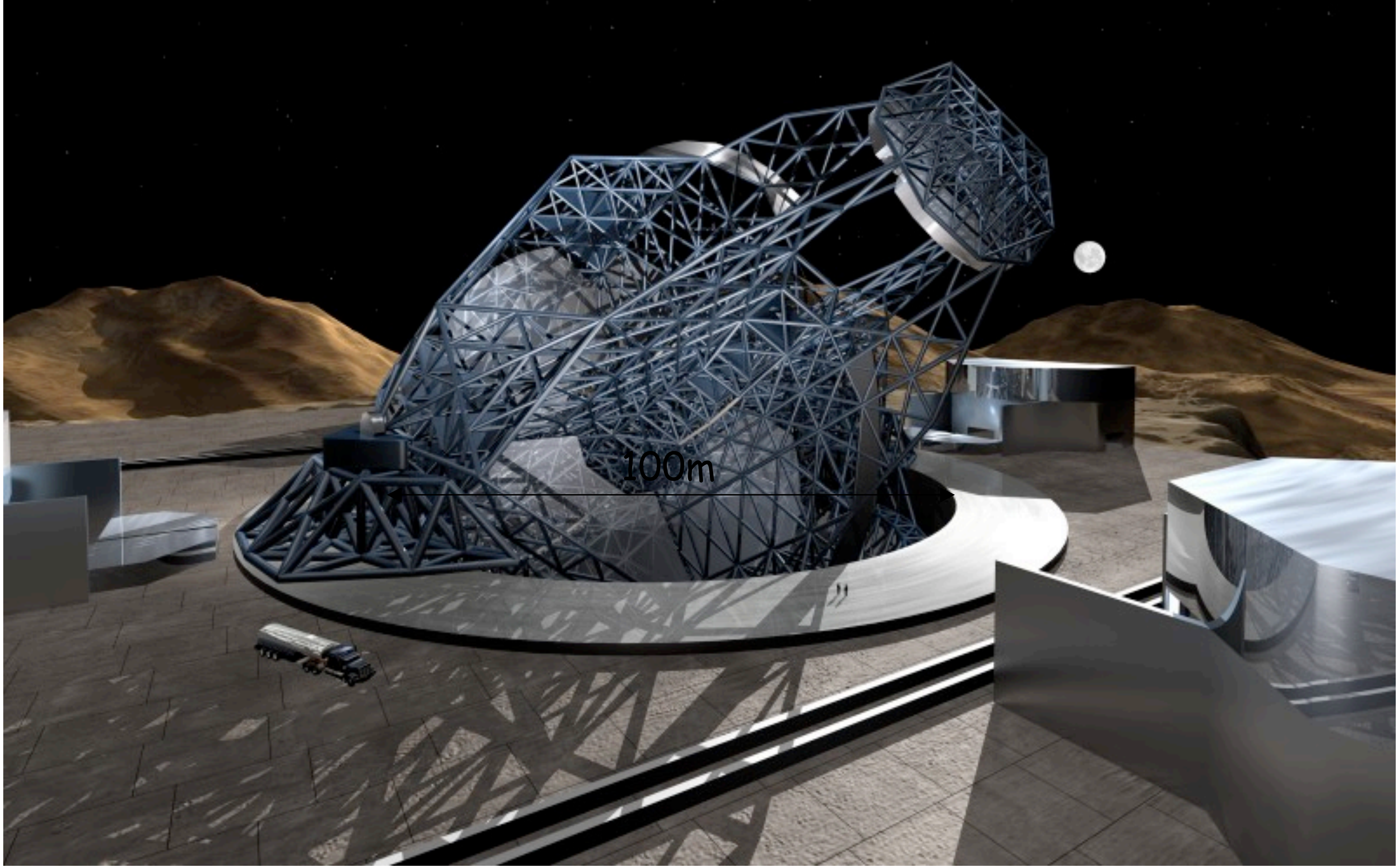

Scatterd light.
Simulation with
MC3D
by S. Wolf.
TRAMP =
Structure
MC3D =
Appearance
Nice signatures,
but what camera?
VLTI, OWL?
Jupiter @ 5AU; 2.2μ

Current Telescopes:

VLTI

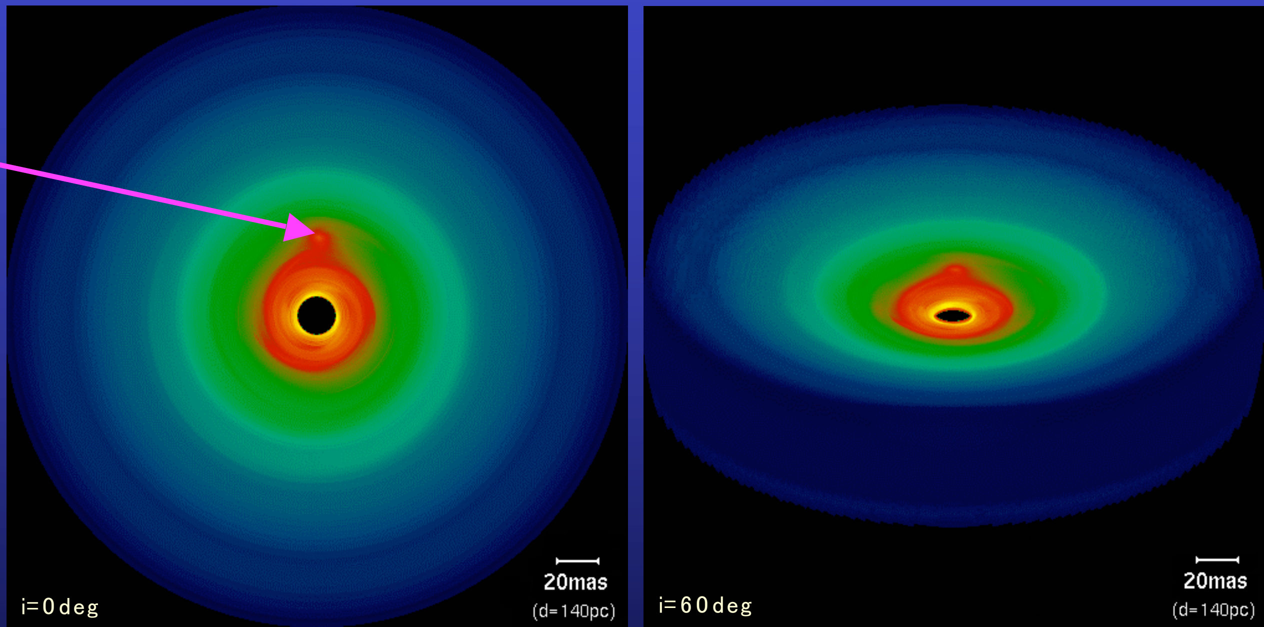


Far Future: OWL: OverWhelmingly Large Telescope
More realistic a 42m ELT.



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)

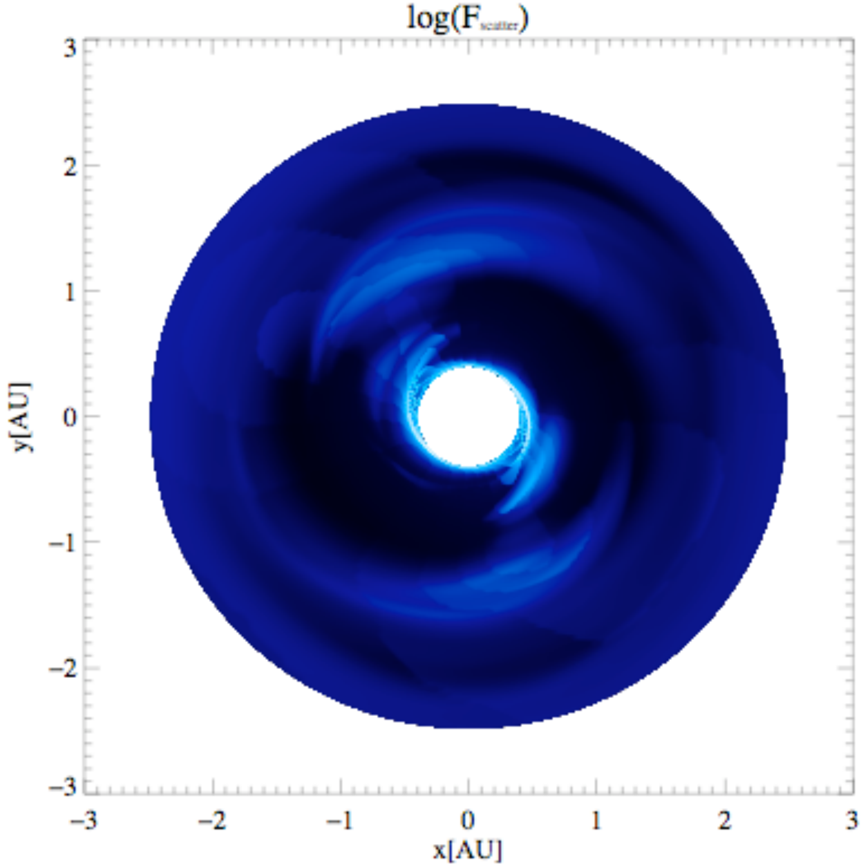
[Wolf & Klahr 2005]

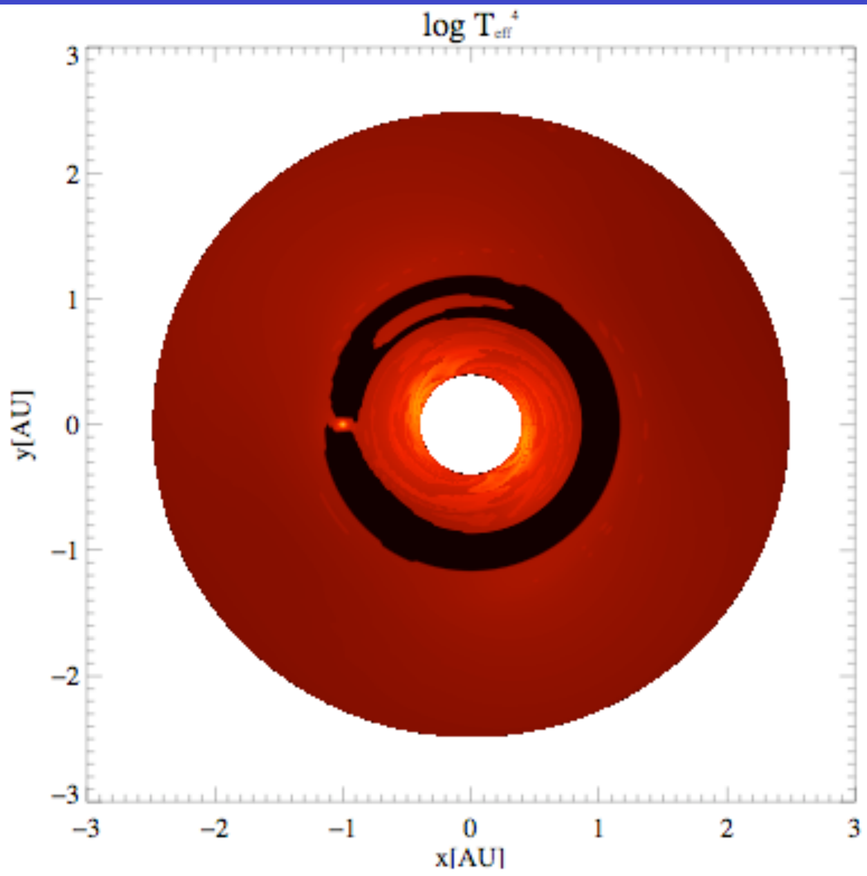
Science Case Study for T-OWL:

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

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

1 Jup @ 1AU

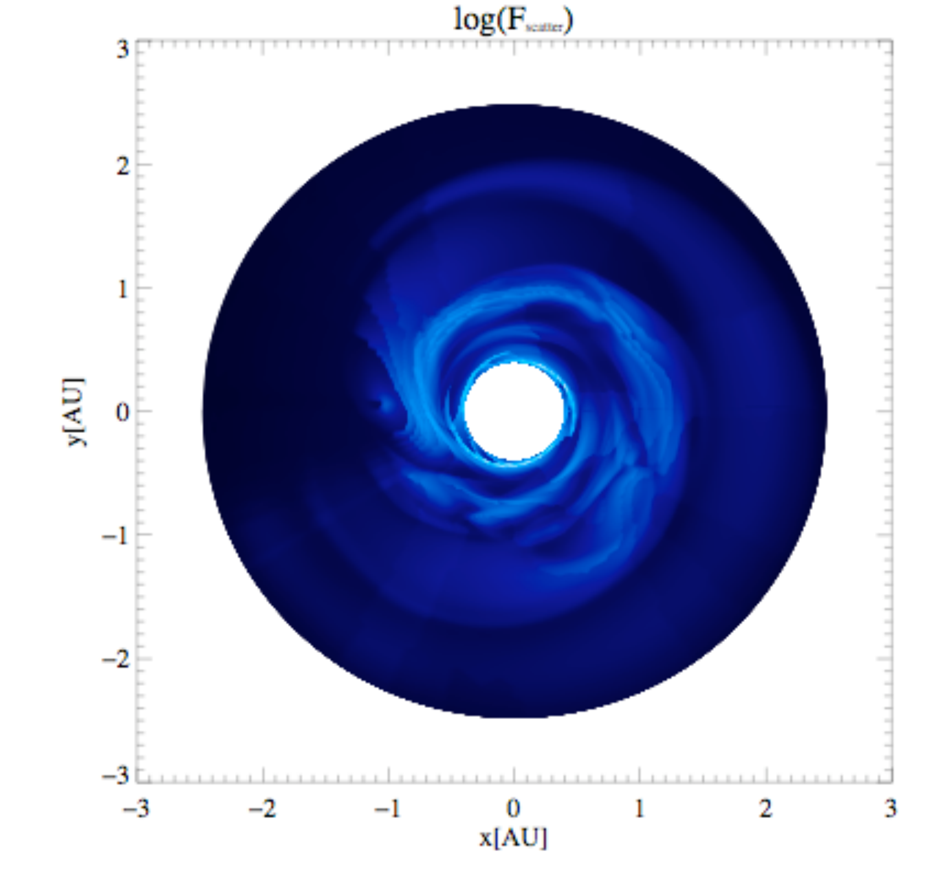


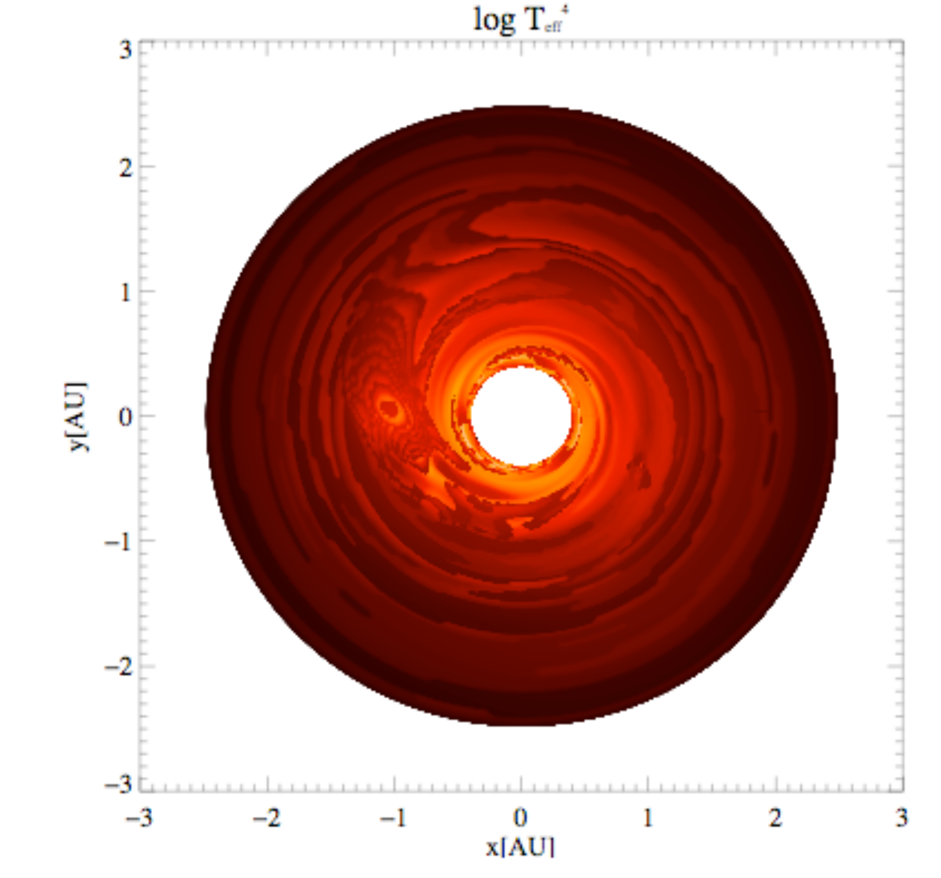


scattered light

emitted light

0.2 Jup @ 1AU

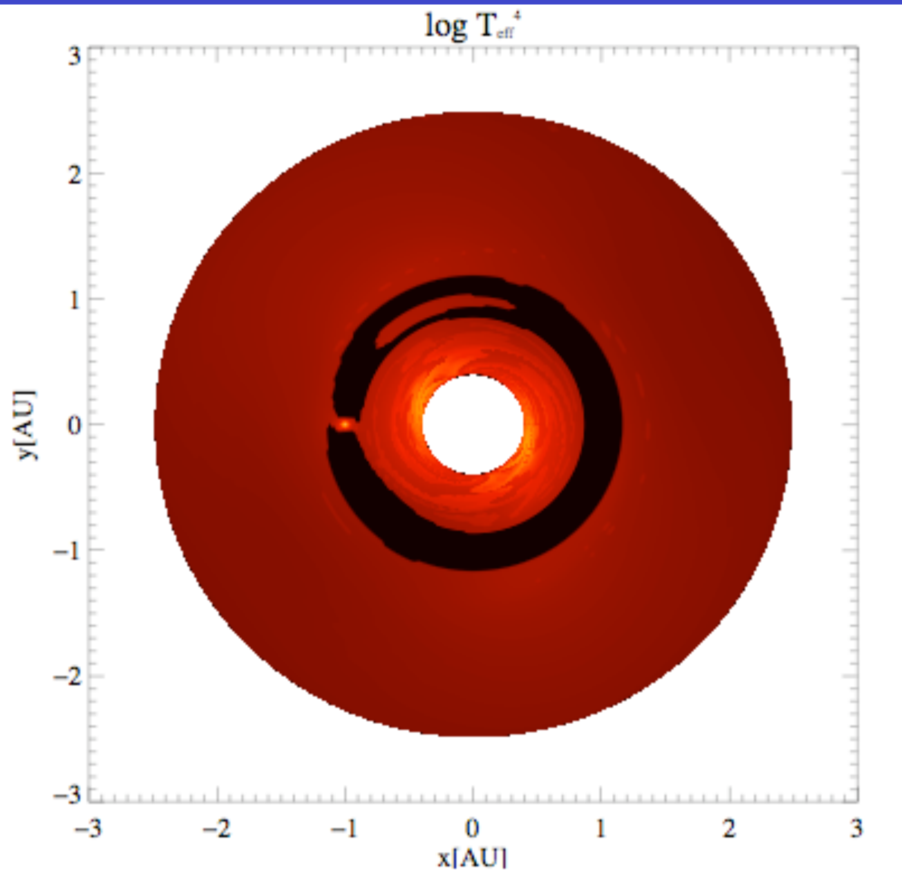


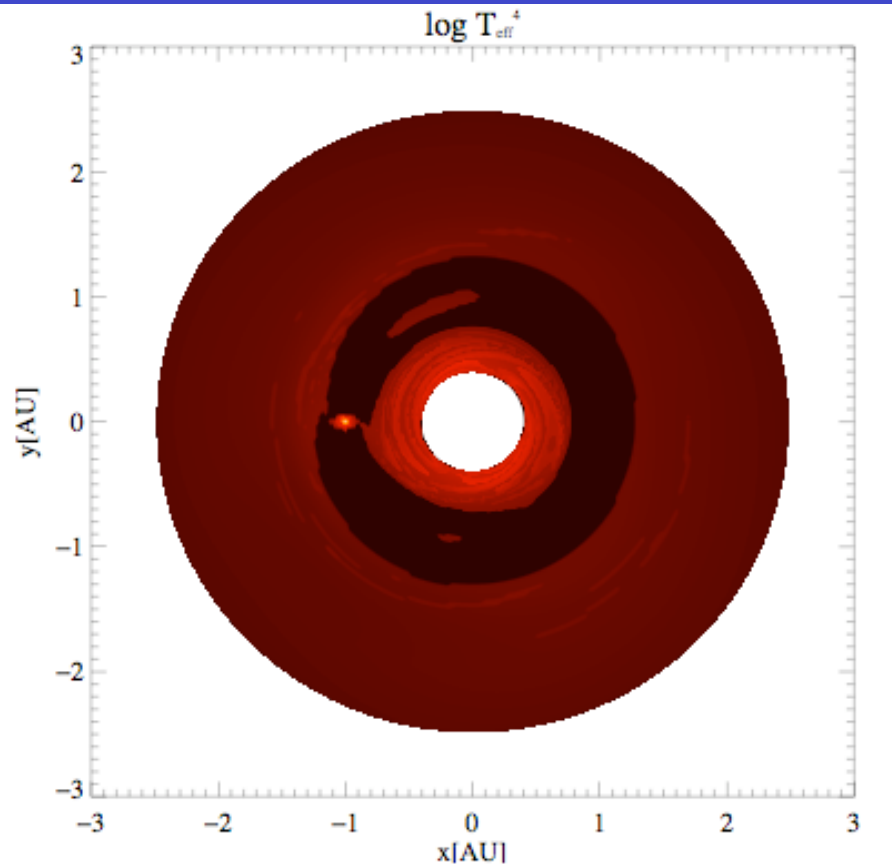


scattered light

emitted light

1 Jup & 5 Jup @ 1AU

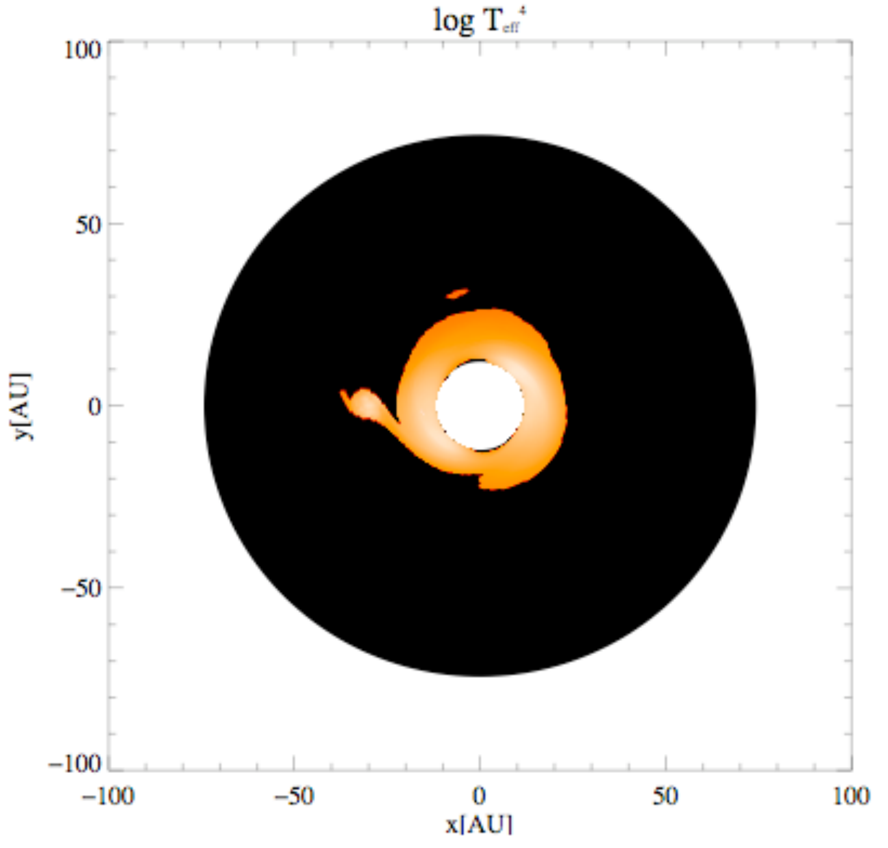


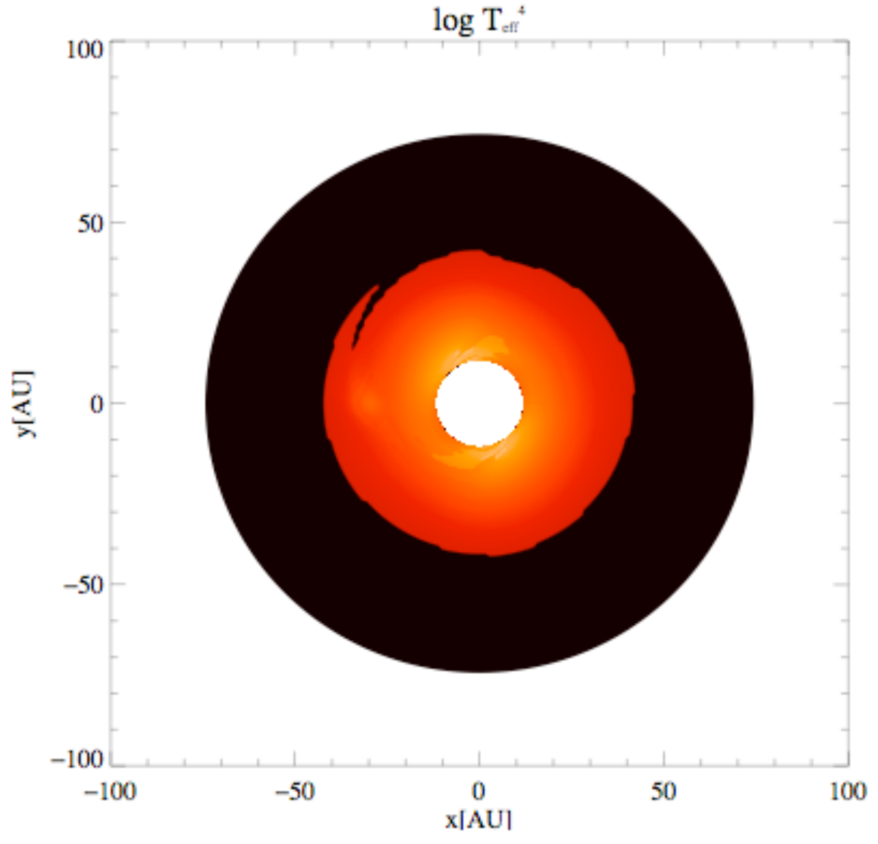


emitted light

emitted light

5 Jup @ 30AU & 0.2 Jup @ 30AU

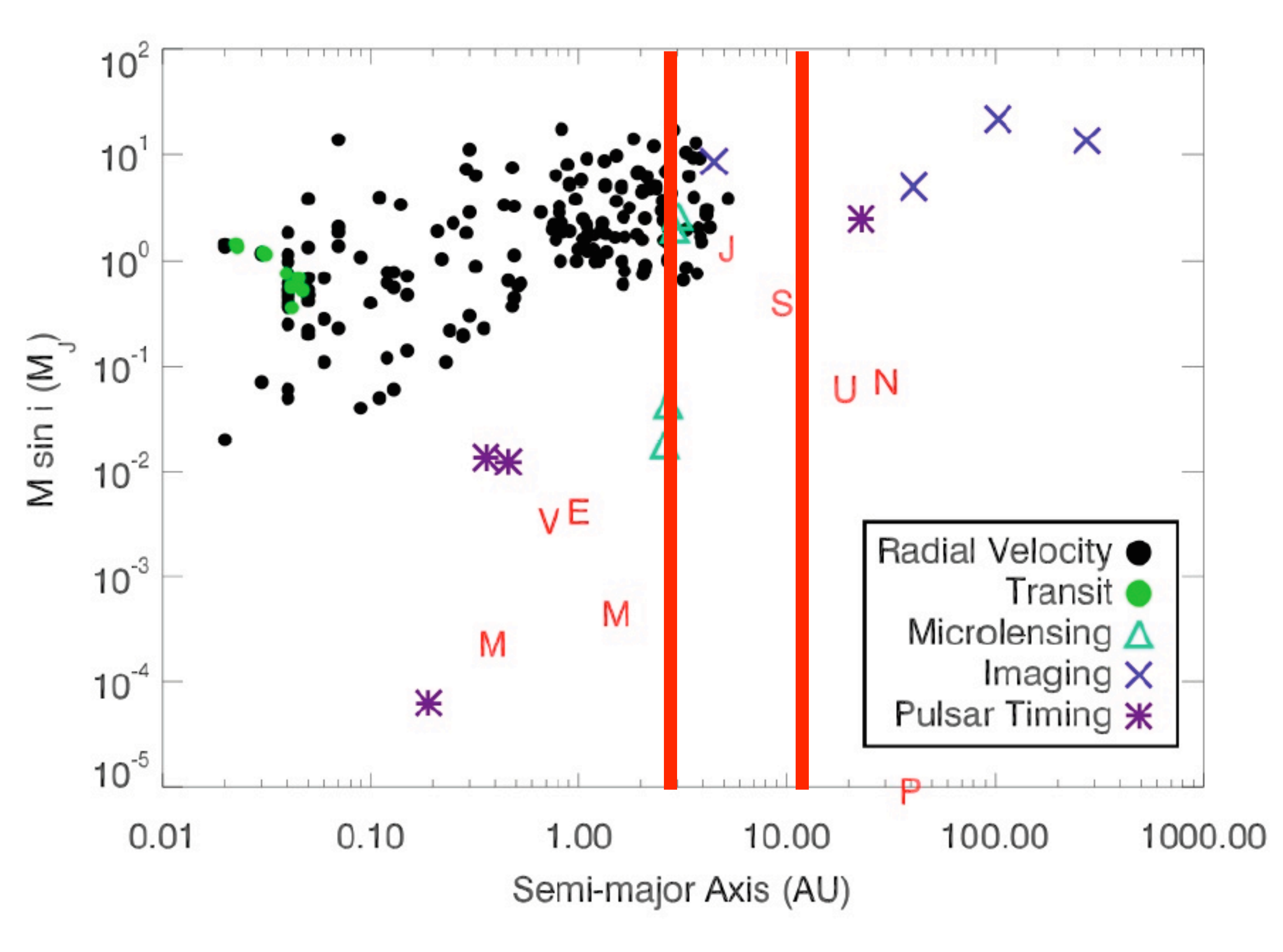




emitted light

emitted light

Known Planets:



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

Types of migration

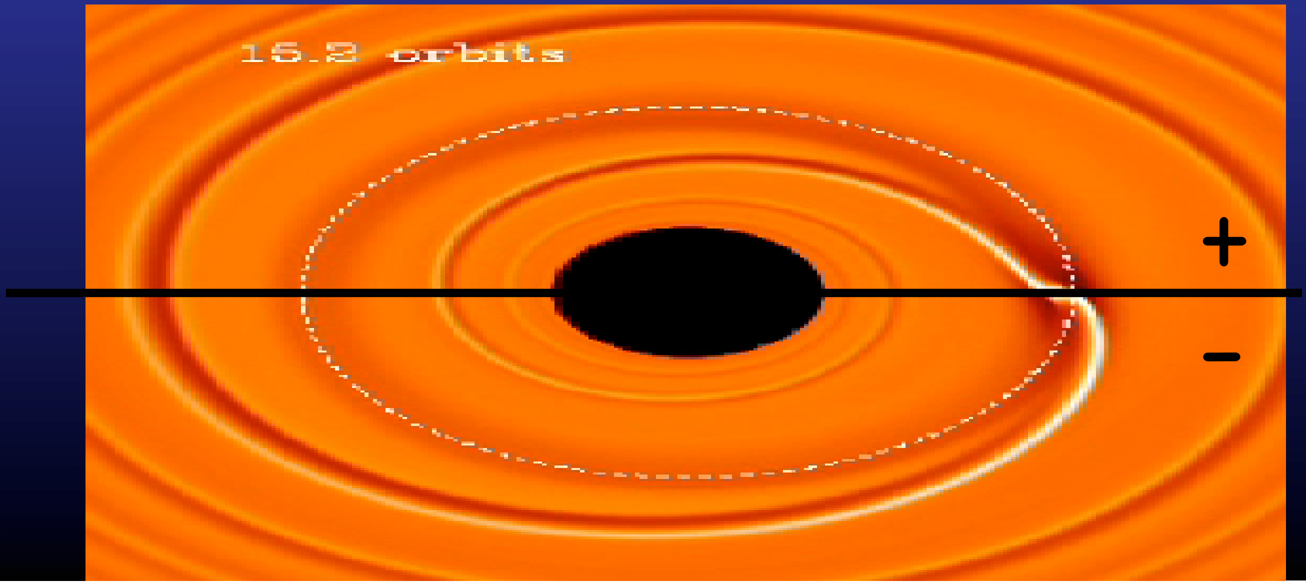
- Type I: low mass planets
- Type II: high mass planets
- Type III: medium mass planet but massive disk

See **Papaloizou** et al. PPV

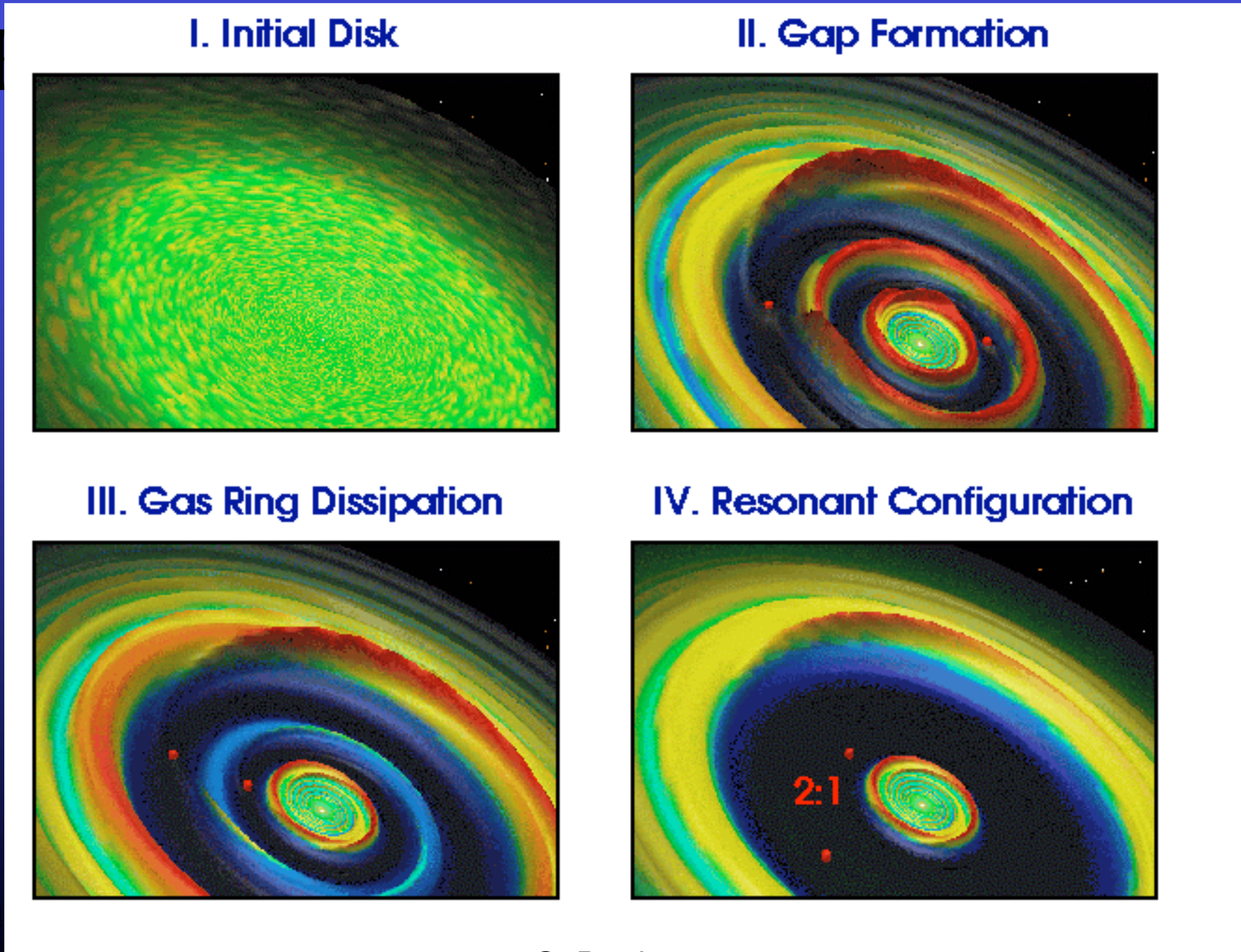
arXiv:astro-ph/0603196 v1 8 Mar 2006

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



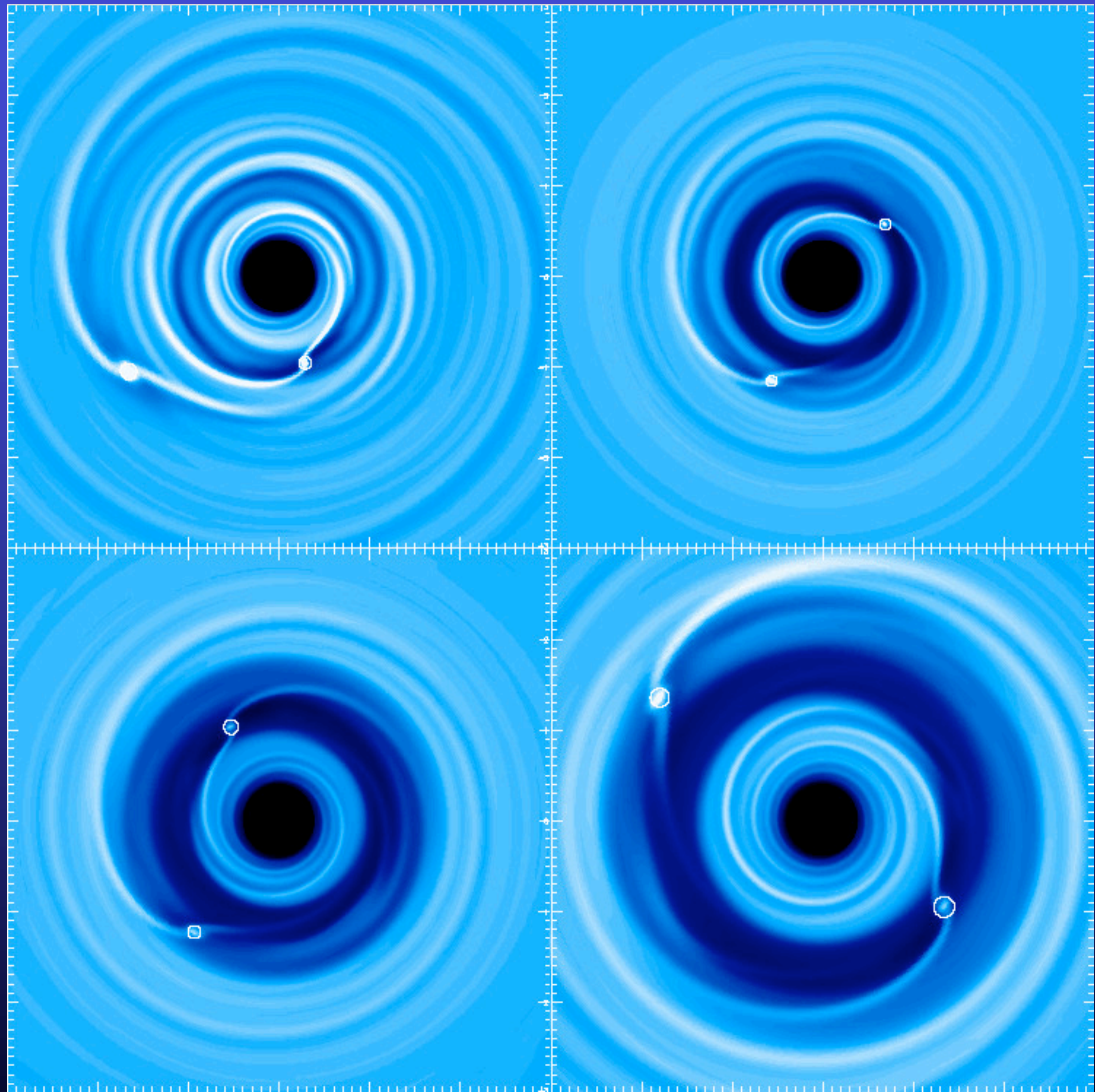
by Frederic Masset



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

G. Bryden

Resonance trapping

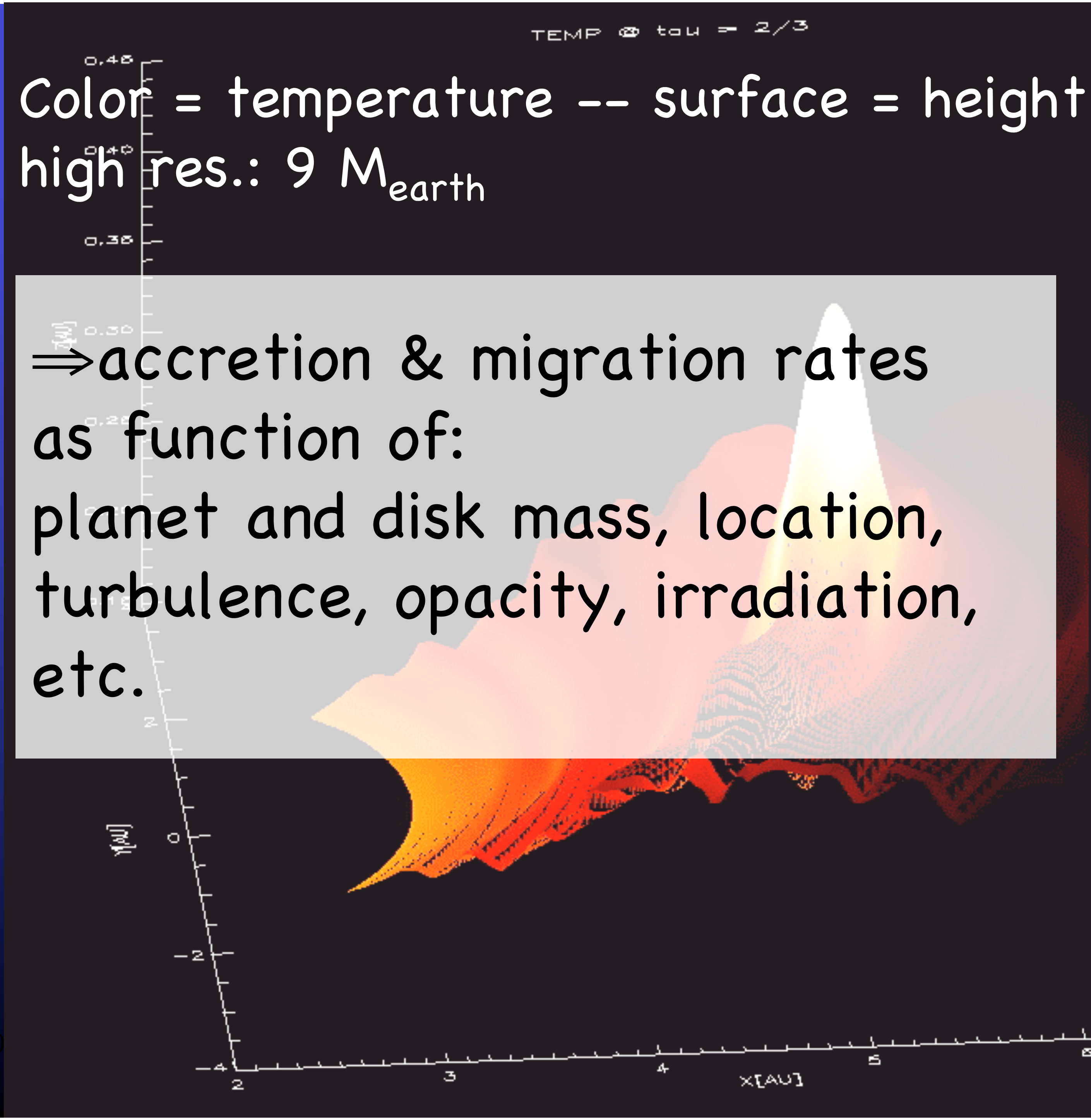


Masset & Snellgrove

Color = temperature -- surface = height

high res.: 9 M_{earth}

⇒accretion & migration rates as function of:
planet and disk mass, location, turbulence, opacity, irradiation, etc.



"Master Plan"

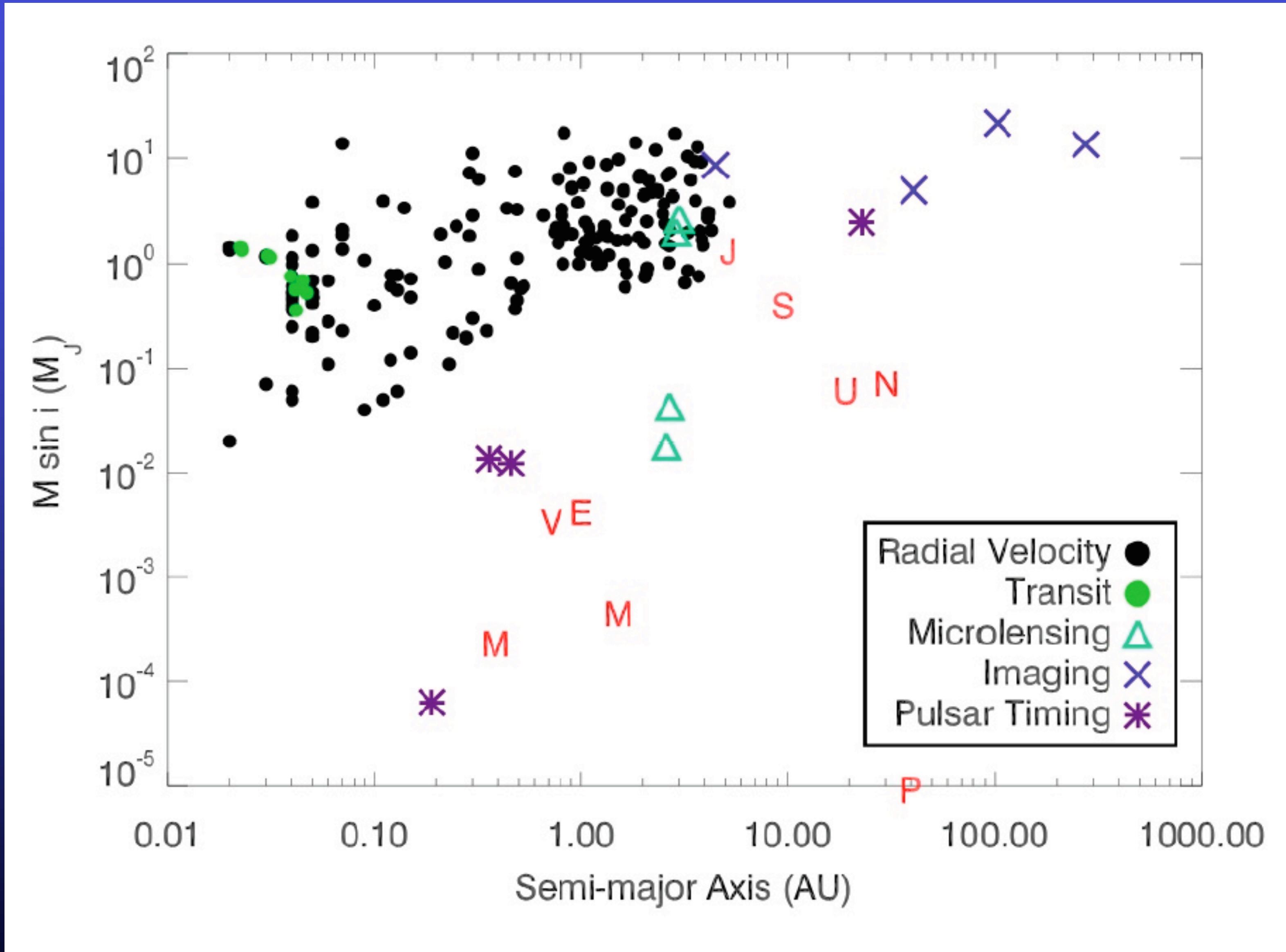
1. Input for population Synthesis of Exo-Planets: Disk evolution, Dust (Planetesimal) distribution, planet migration and accretion, -> Pan-Planets (PAN-STARRS)

   => Future EU-Network "Physics and Chemistry of Exo-Planets"

2. Detection of nascent planets in disks (10-100 Mearth): Simulations for ALMA, SKA etc.
   => Validation of core accretion scenario (=> 1.)

3. Measurements of accretion rates for planets in disks: Linc-Nirvana, ELT, FIRM, ...
   Deducing migration rates
   => Improving of our numerical models (=> 1.)

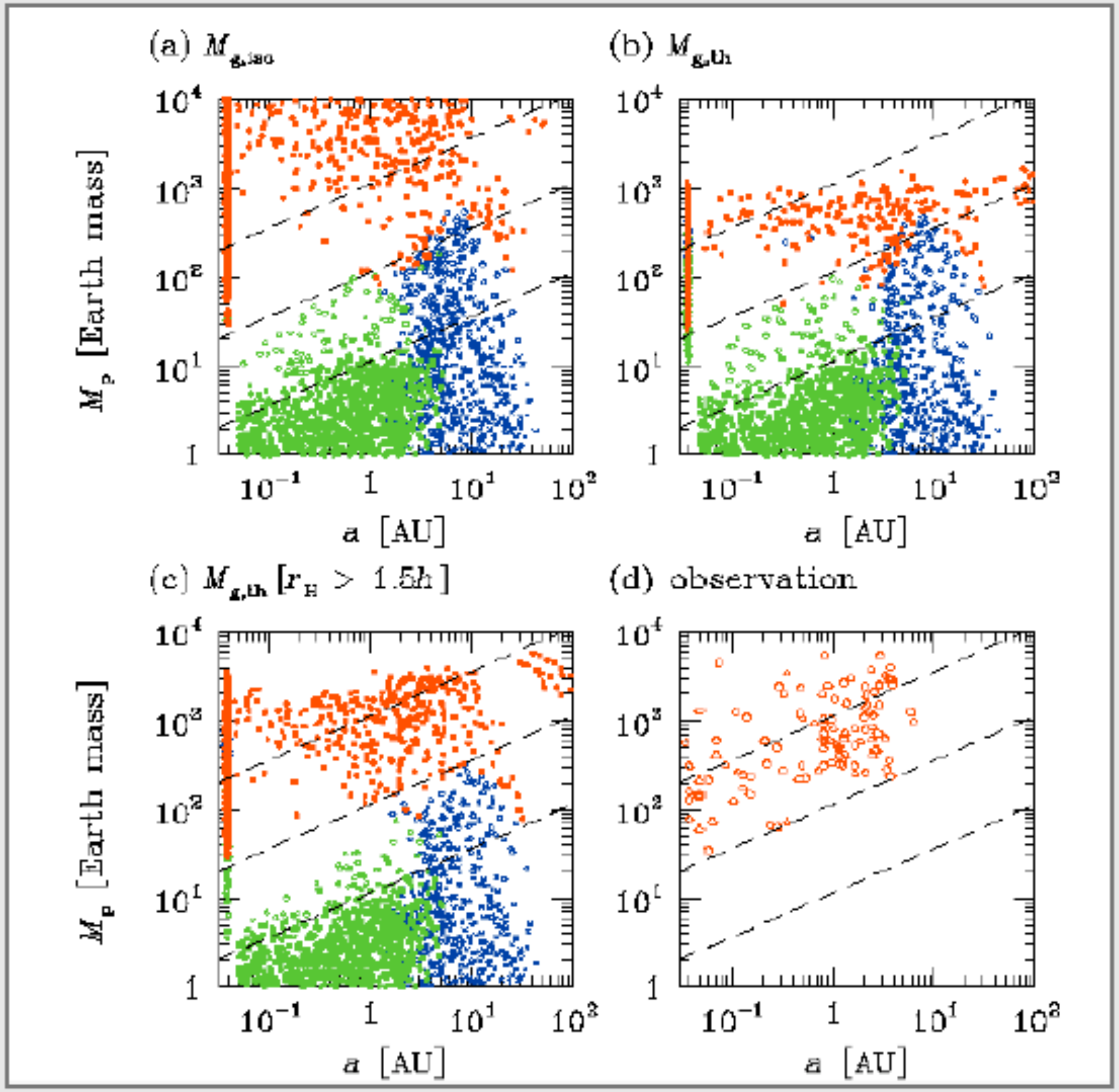
Known Planets:

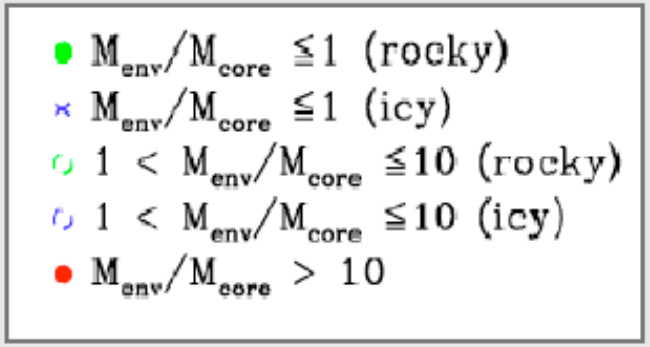


Courtesy by Jeremy Richardson May 2006
Based on data compiled by J. Schneider

Monte Carlo studies

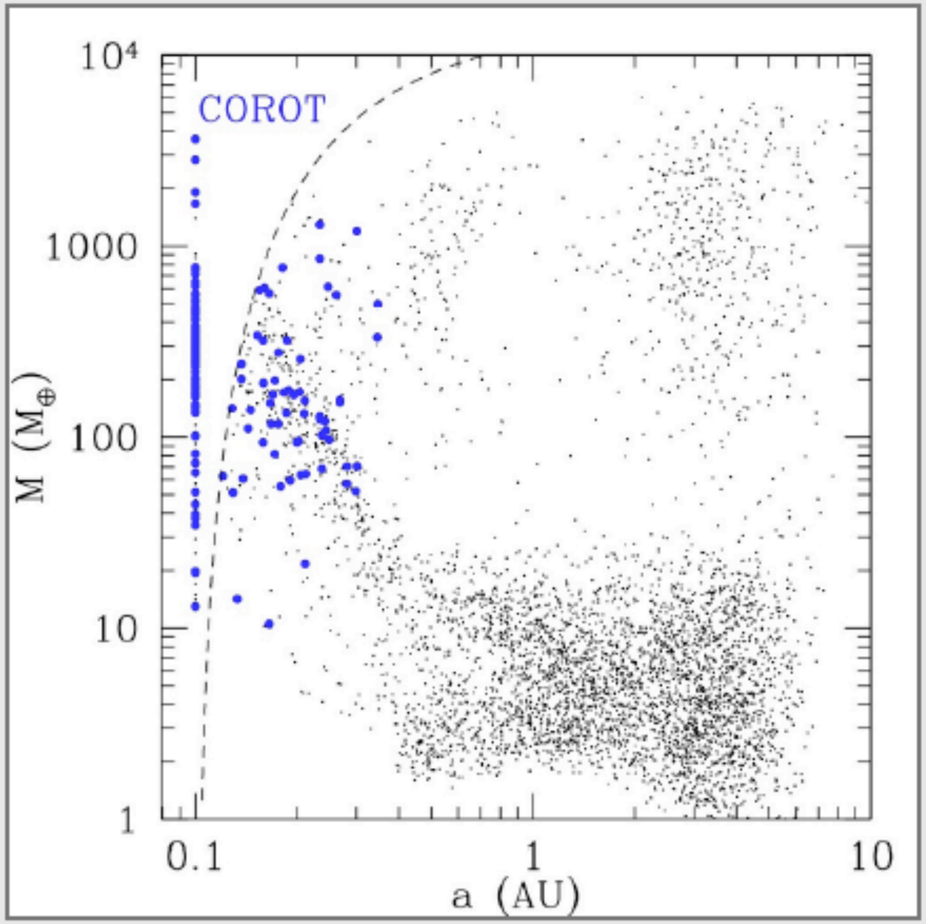
Ida & Lin (2004a, 2004b, 2005)

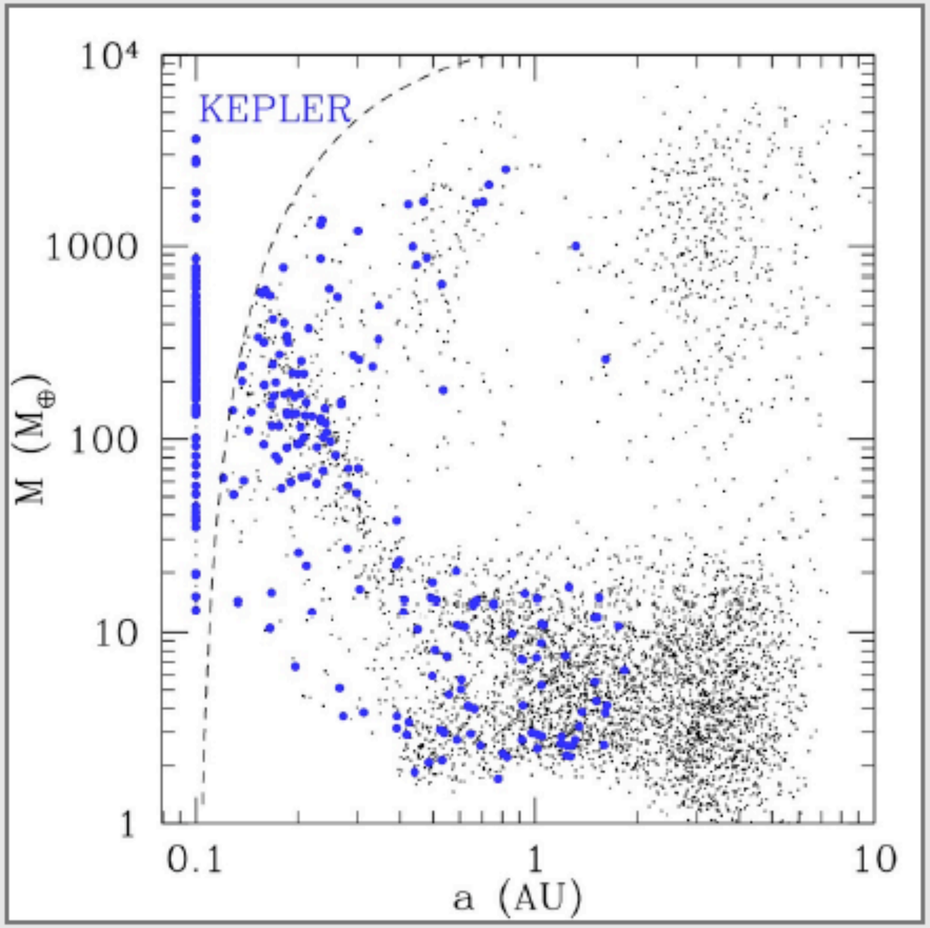




- *planet desert*
- *separation of types in a/m*
- *Fe/H correlation*

Detectable planet by COROT and KEPLER



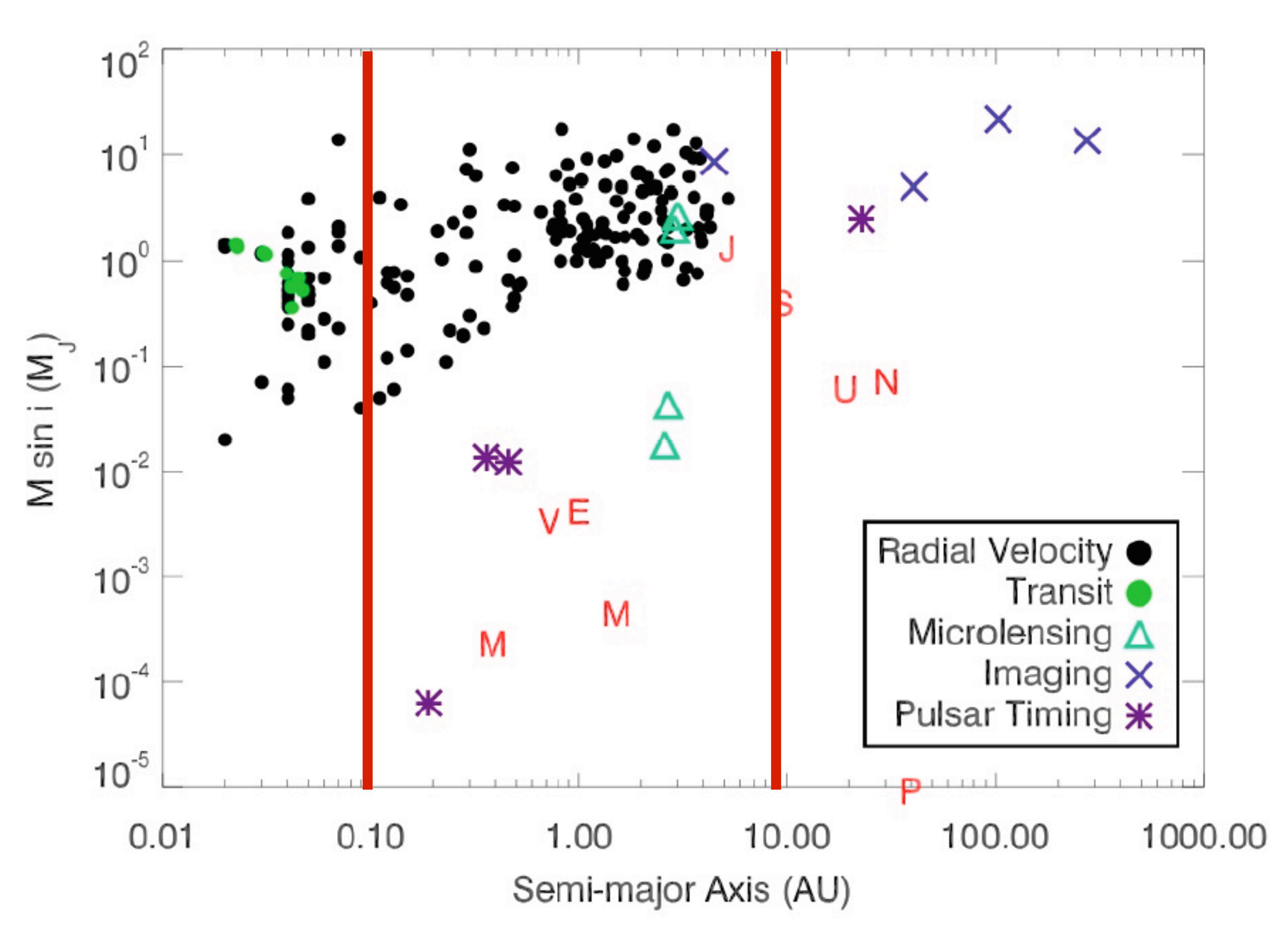


KEPLER will be able to detect the existence of planetary desert due essentially to longer survey length

Alibert & Benz:

No close in P., no multiple systems, no U&N

Known Planets:

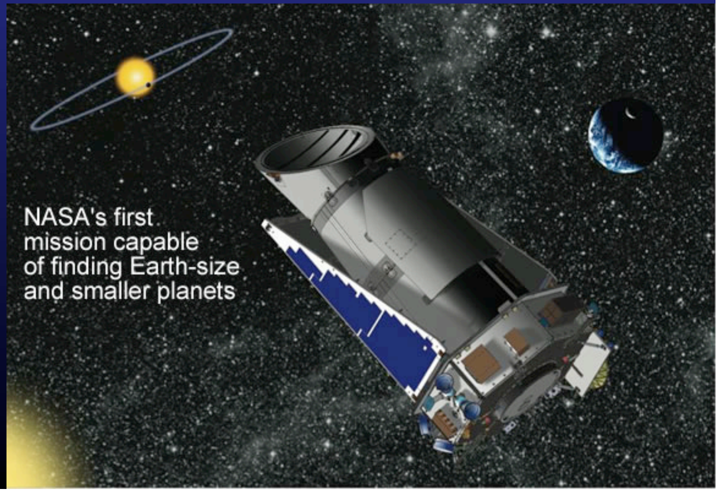


Courtesy by Jeremy Richardson May 2006
Based on data compiled by J. Schneider

"THE FUTURE"

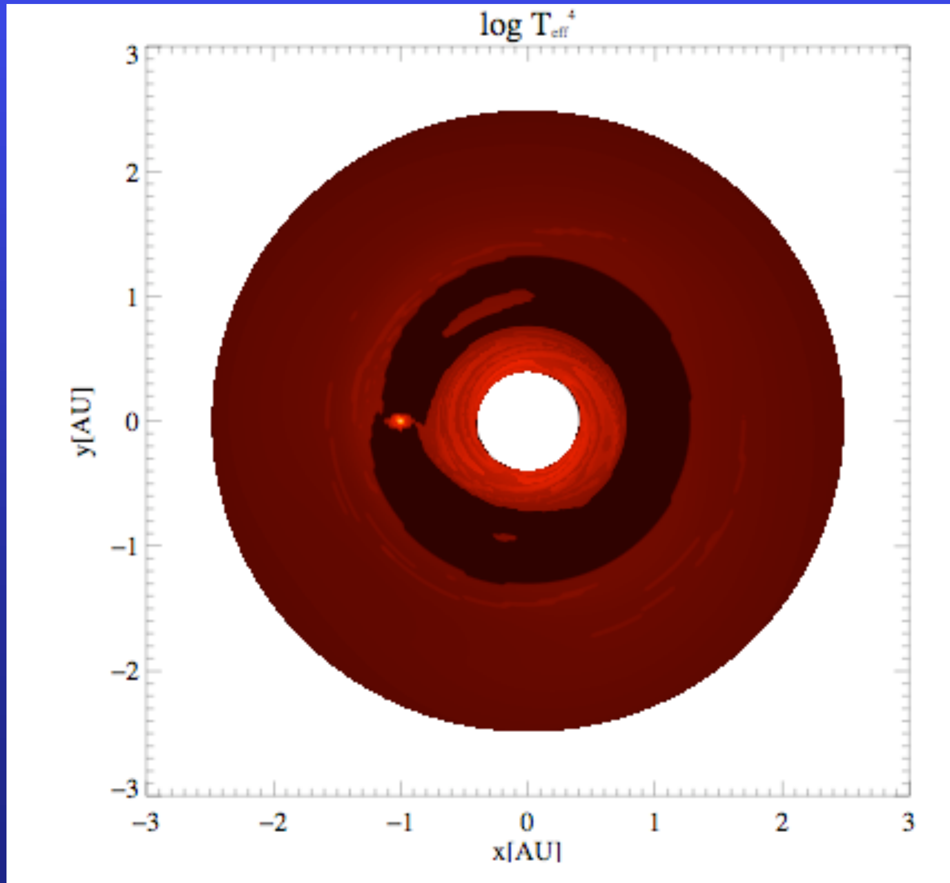
1. Preparation of the detection of nascent planets in disks (9-100 Mearth):
   Simulations for ALMA, SKA etc.
   => Validation of core accretion scenario
2. Measurements of accretion rates for planets in disks: Linc-Nirvana, ELT, FIRM, ALMA, SKA...
   Deducing migration rates
   => Improving of our theoretic understanding
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, fine-tuning of planet formation theory.



SKA could play Unique Role in Disk Studies

- If capable at > 20 GHz, SKA will have best resolution/sensitivity for imaging thermal emission.
- For direct detection of structure in disks induced by planets, sub-AU resolution is key. (synergy with other facilities)
- High angular resolution probes terrestrial planet region and enables following evolution over orbital timescales.
- Short centimeter wavelengths are critical for tracking grain growth from sub-micron interstellar size particles to “pebbles”.



Further reading...