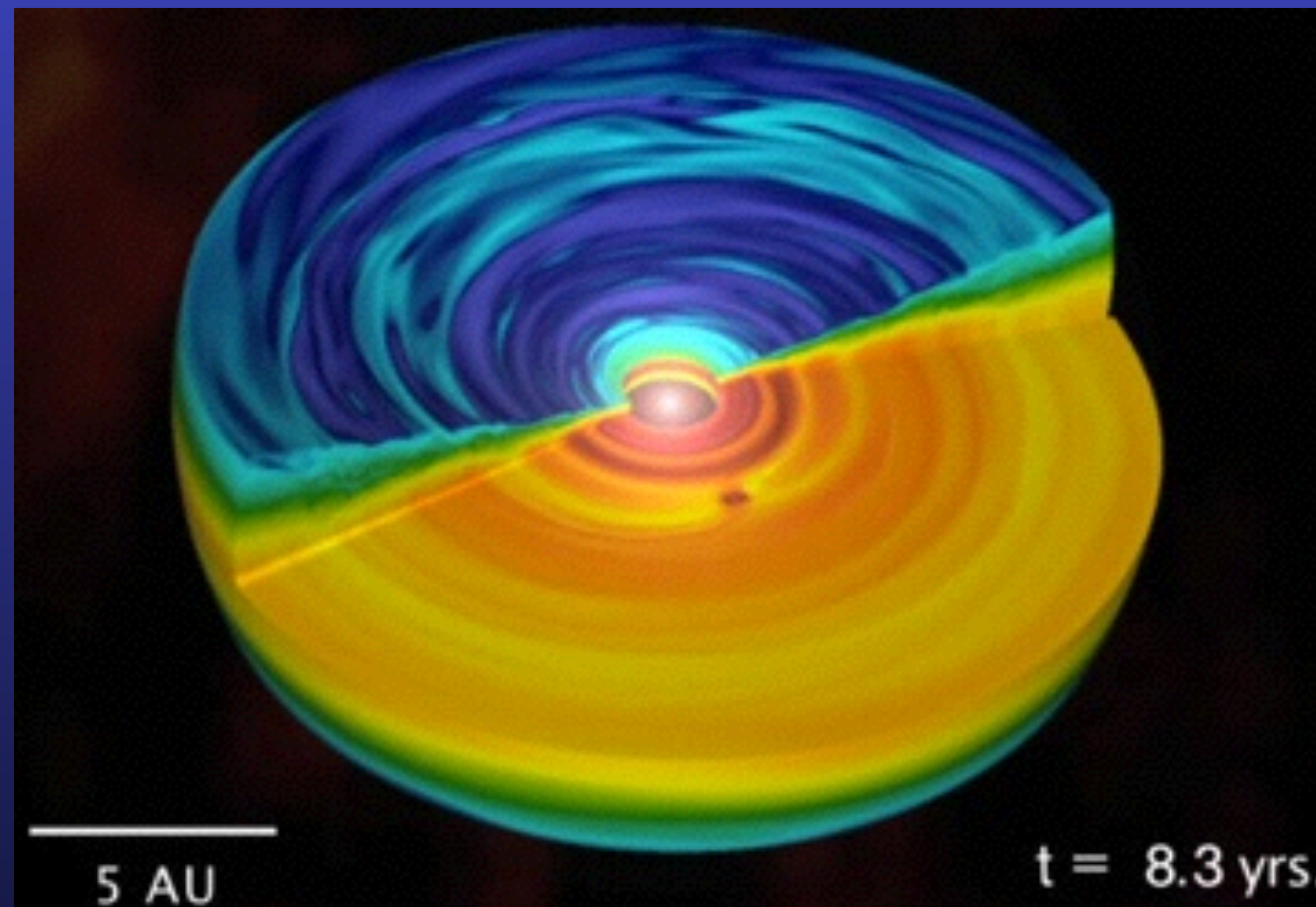
Kiel, Sep, 9th

Planet - Disk - Interaction



Hubert Klahr,

Max-Planck-Institut für Astronomie, Heidelberg

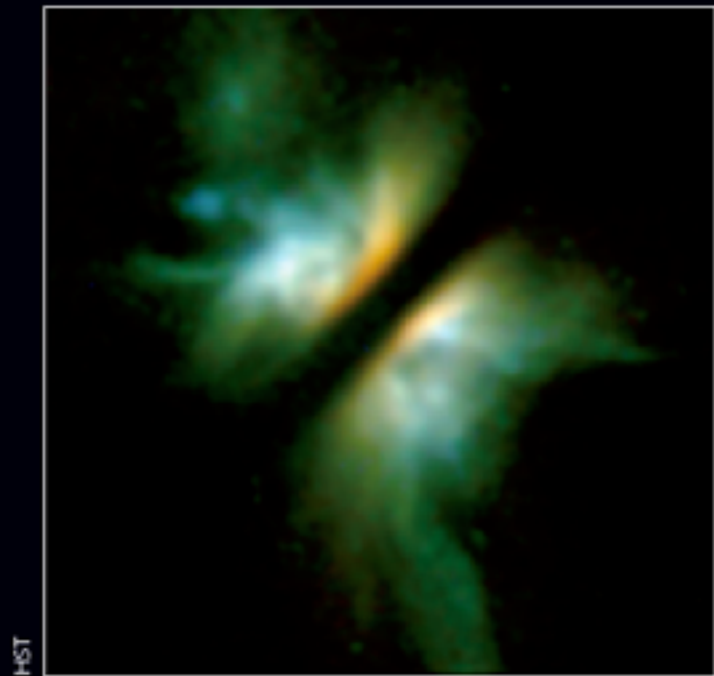
Aiara Lobo Gomes, Kai-Martin Dittkrist, Christoph Mordasini, Mario Flock (Saclay), Ana Uribe (Chicago), Willy Kley (Tübingen), Bertram Bitsch (Lund)

add. material: O. Gressel, G. Lesur, M. Kunz, A. Crida

Outline:

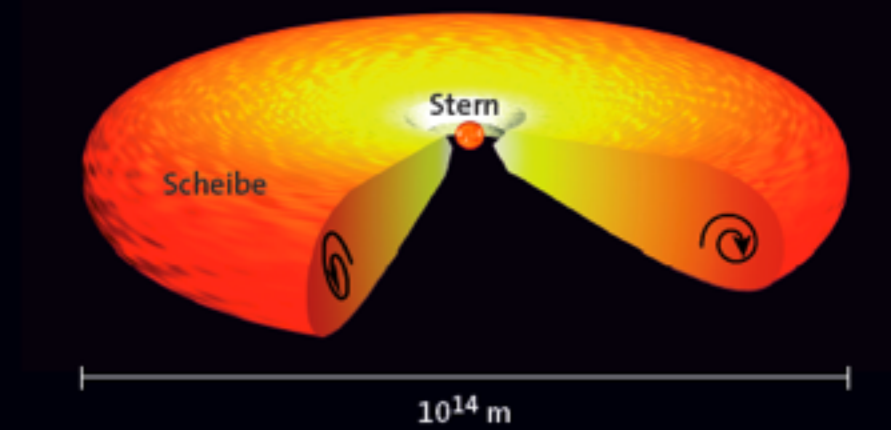
"Migration and Gas Accretion"

- Motivation - Planet Formation / Evolution on the mass/distance diagram
- Migration of planets type 1, 2, …
- Role of turbulence (viscosity)
  - status of magnetic instabilities
  - status of non-magnetic instabilities
- Role of radiation transport (thermal relaxation time)
- Summary / Outlook



=

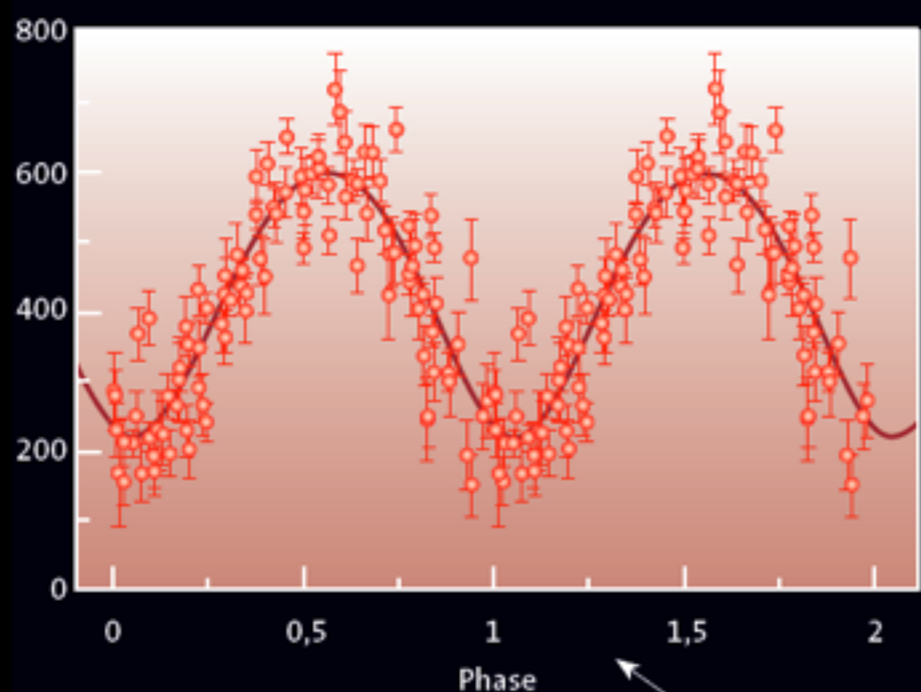
t = 0

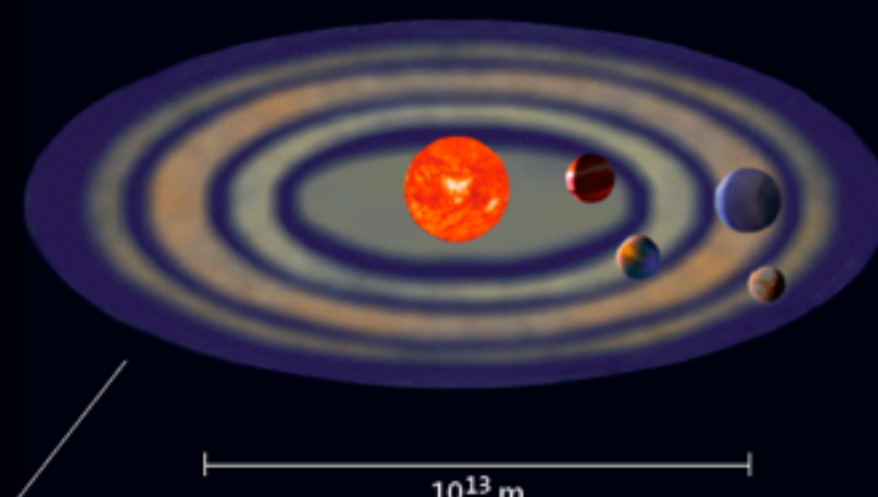


(a) [redacted]

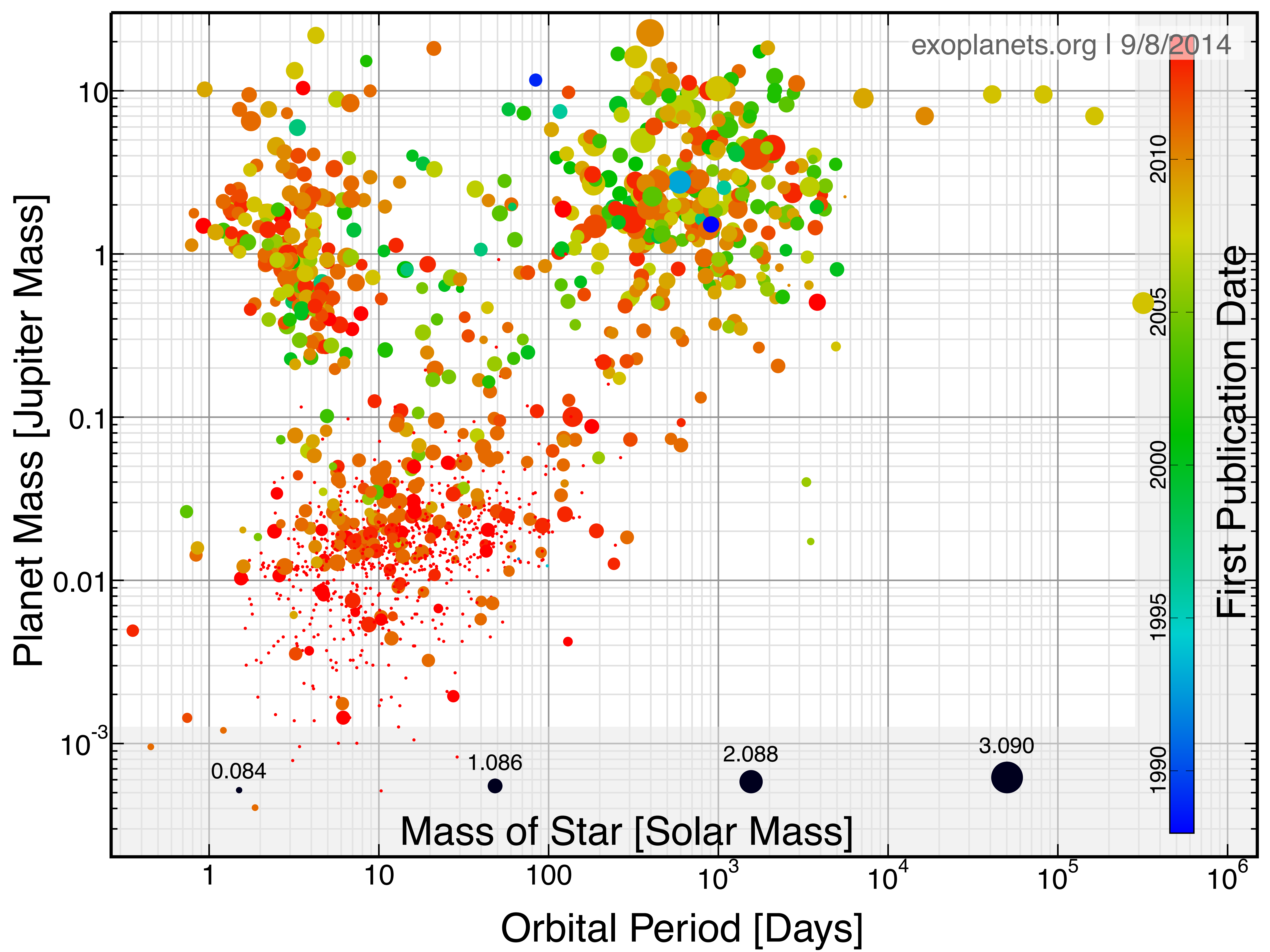
... a miracle occurs ...

t = 10^7 ihre



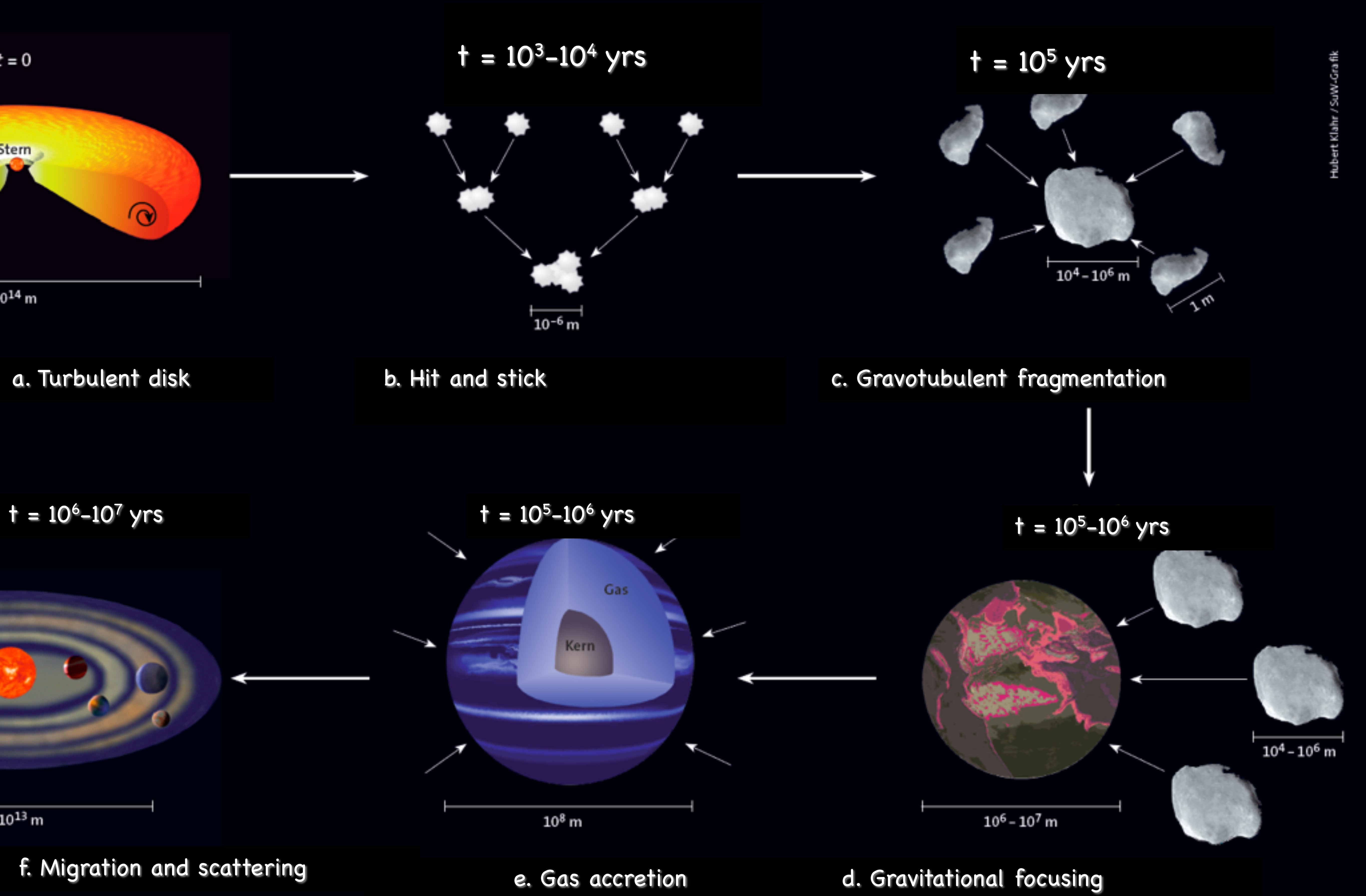


(f) [redacted]

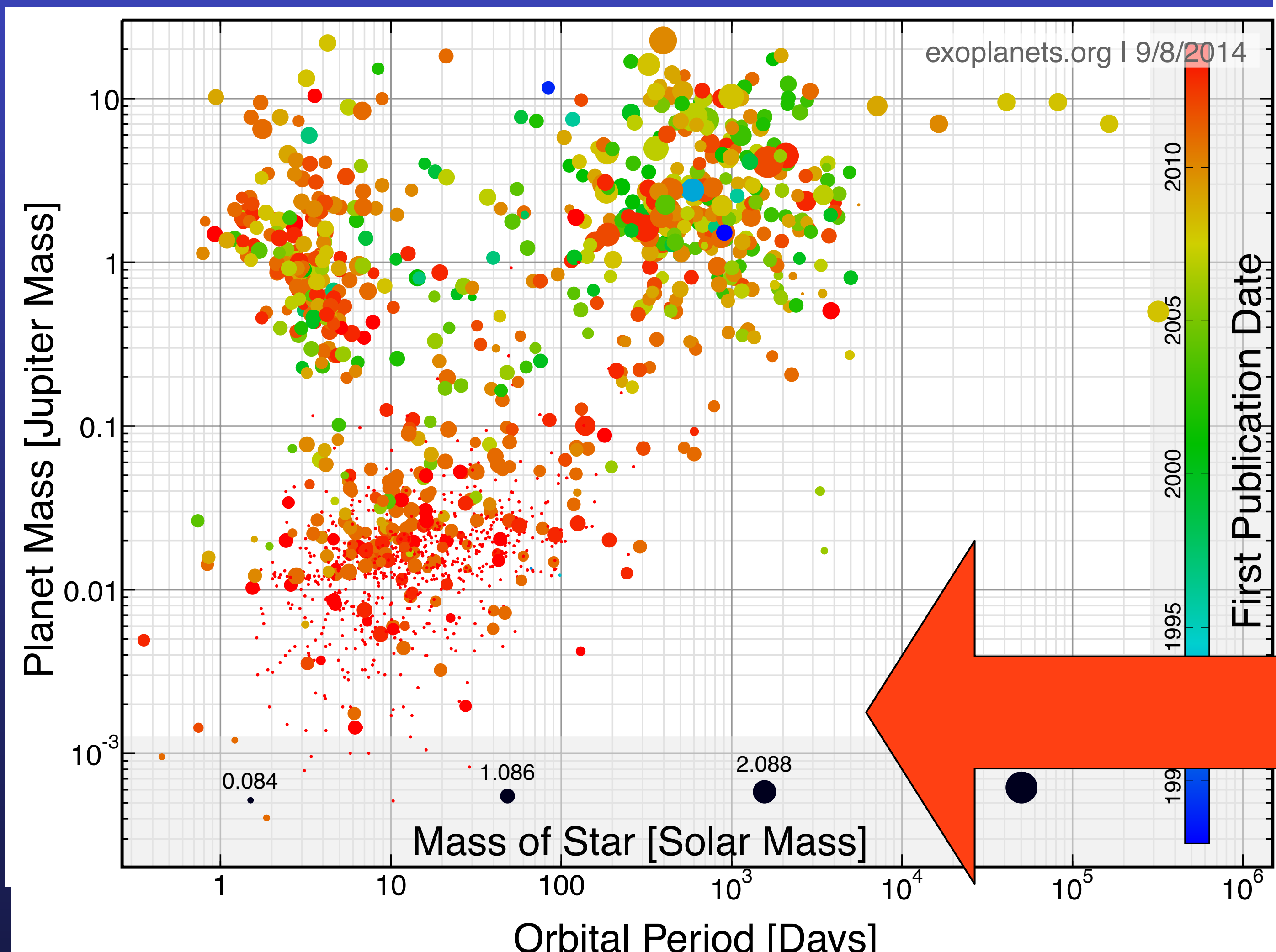


exoplanets.org | 9/8/2014
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
0.084
1.086
2.088
3.090
Mass of Star [Solar Mass]
1
10
100
10^3
10^4
10^5
10^6
Orbital Period [Days]
First Publication Date
2010
2005
2000
1995
1990

The planetary construction plant.



Synthetic Populations…



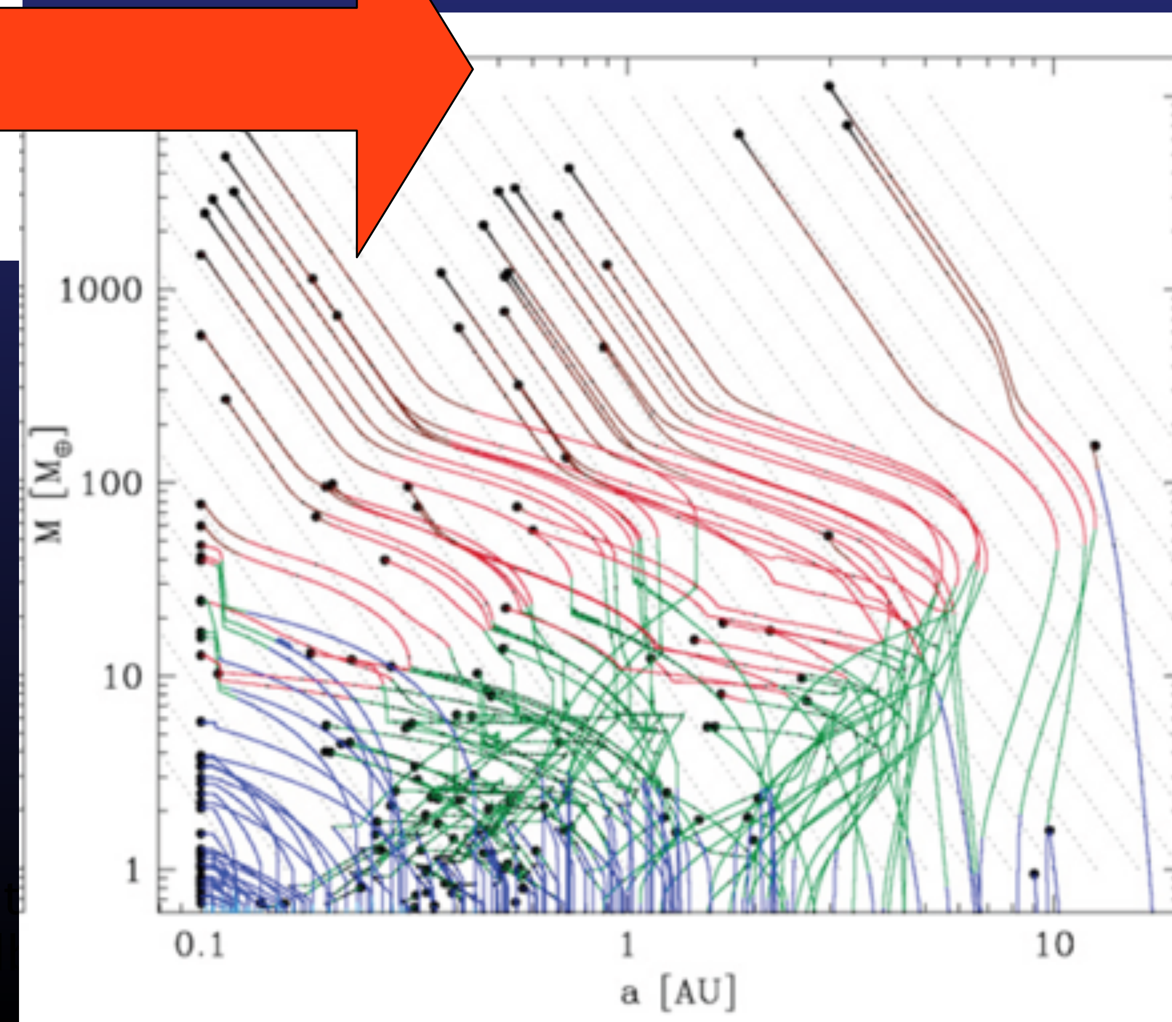
Application of recent results on the orbital migration of low mass planets in planetary population synthesis

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…



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

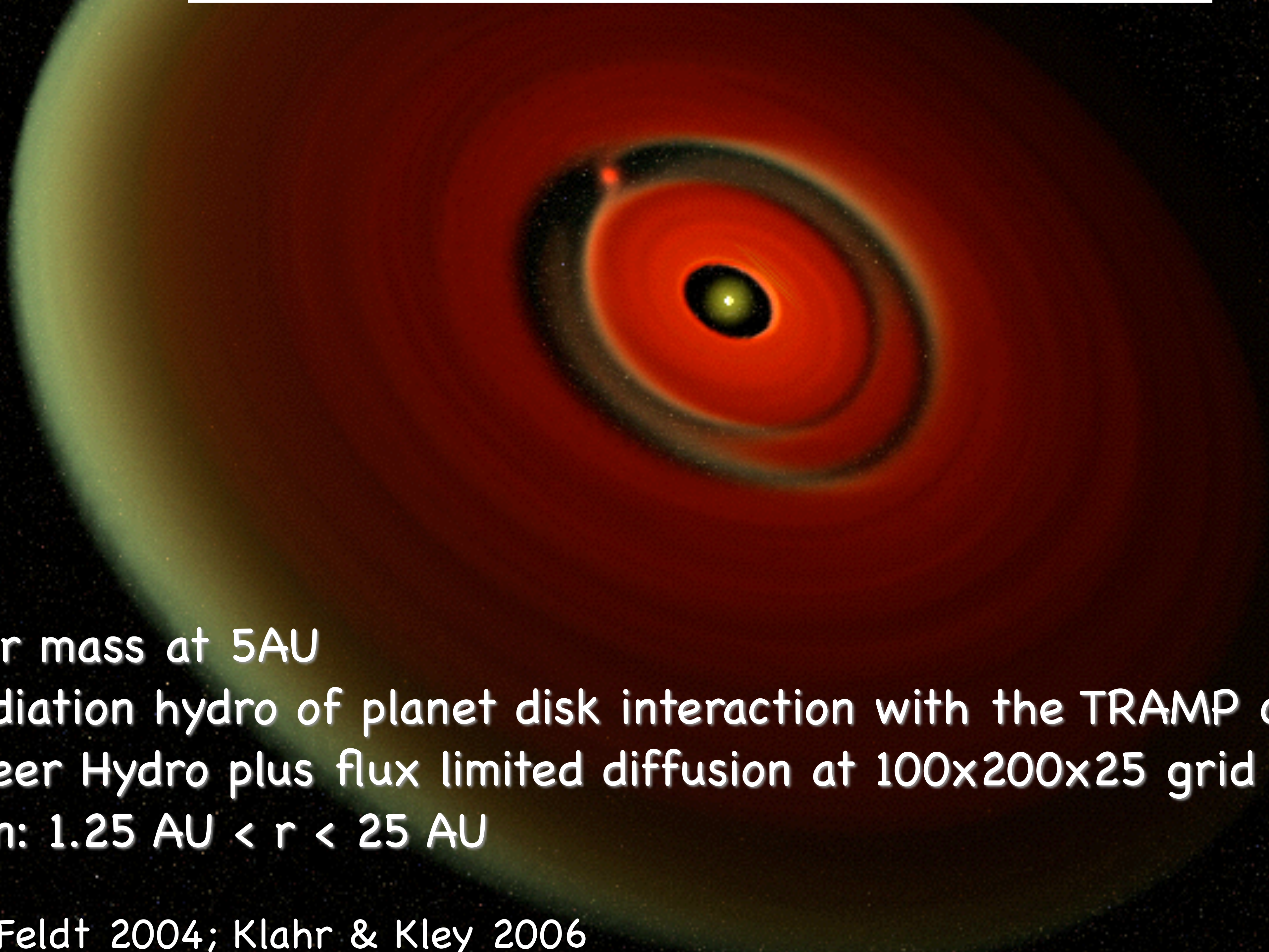
A&A 445, 747–758 (2006)
DOI: 10.1051/0004-6361:20053238

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

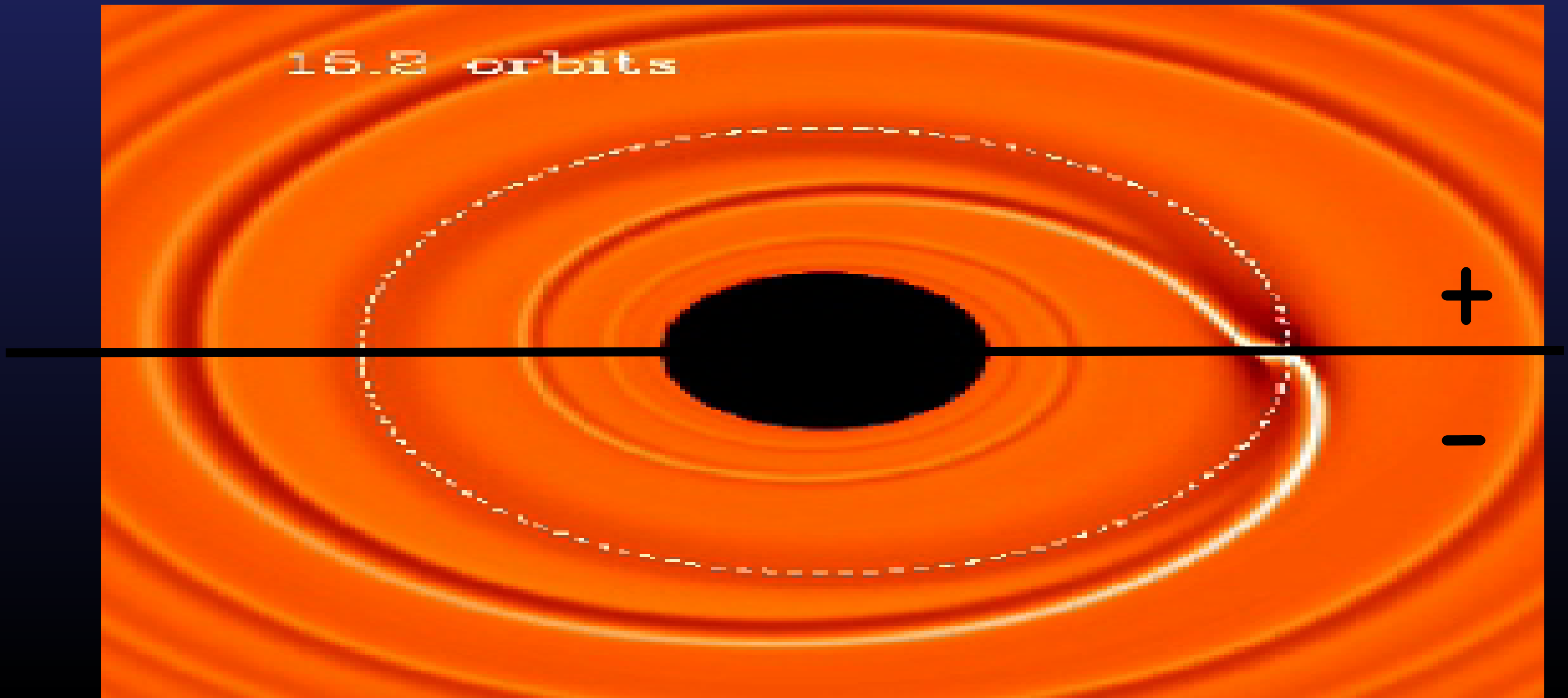
Types of migration

- Type I: low mass planets: no gap
- Type II: high mass planets: gap
- Type III: medium mass planet but massive disk

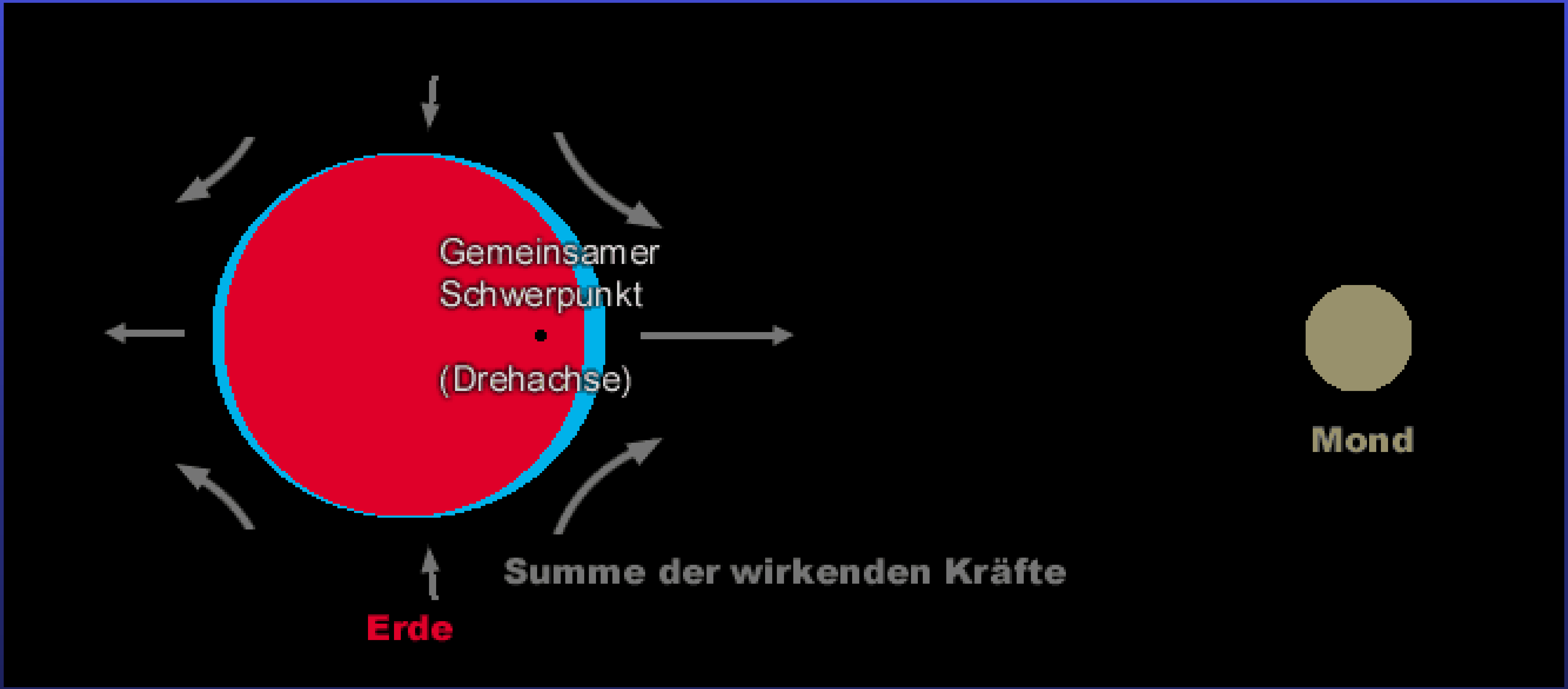
See **Baruteau** et al. PPVI

Type I migration:

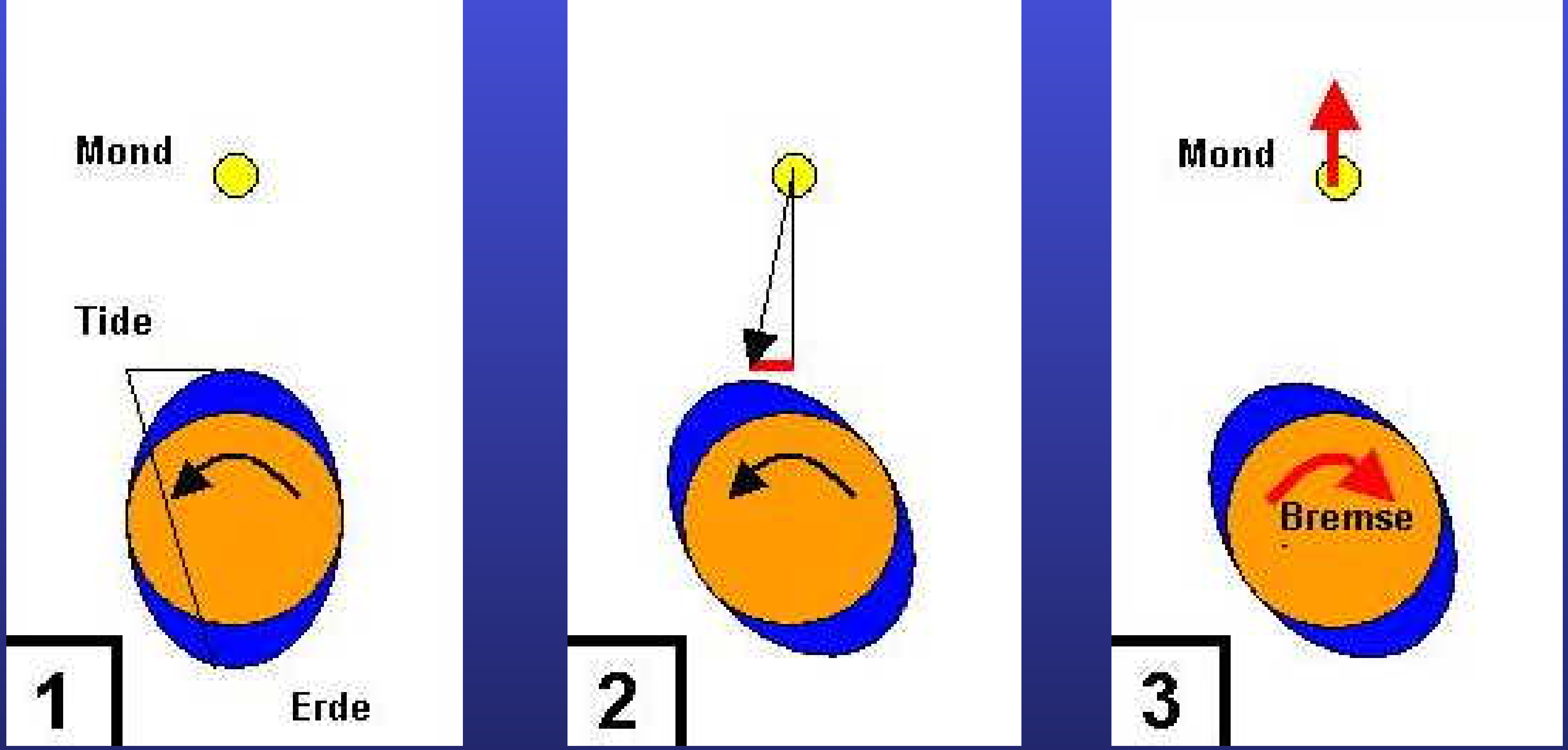
- Planet's gravity generates spiral patterns in the disk gas
- These spirals exert torque on planet because they are not rot. symmetric:
  - Inner spiral wave put ang. mom. on planet
  - Outer spiral wave takes ang. mom. from planet
- Outer spiral dominates: inward migration



by Frederic Masset

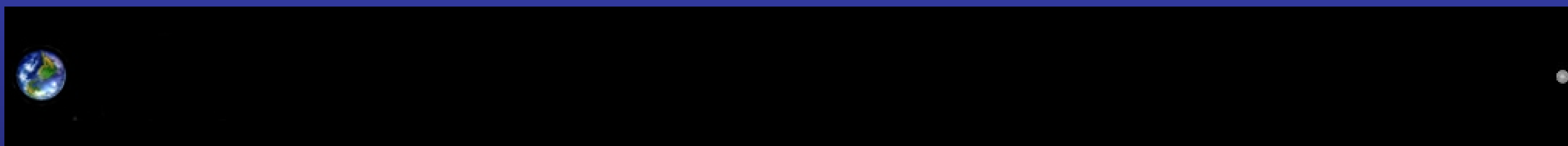


iBasic Picture: Tides in the earth moon system.



- Angular momentum transport from earth spin to moon orbit!
- Outward migration of the moon!
- The role of viscosity of the earth!

Moon is moving away...



- Today: 384.400 km
- 4527 Million Years ago: 60.000 km

TYPE I MIGRATION

The torque scales with $\Gamma_0 = (q/h)^2 \Sigma_p r_p^4 \Omega_p^2$ (Lin & Papaloizou 1980, Goldreich & Tremaine 1979)

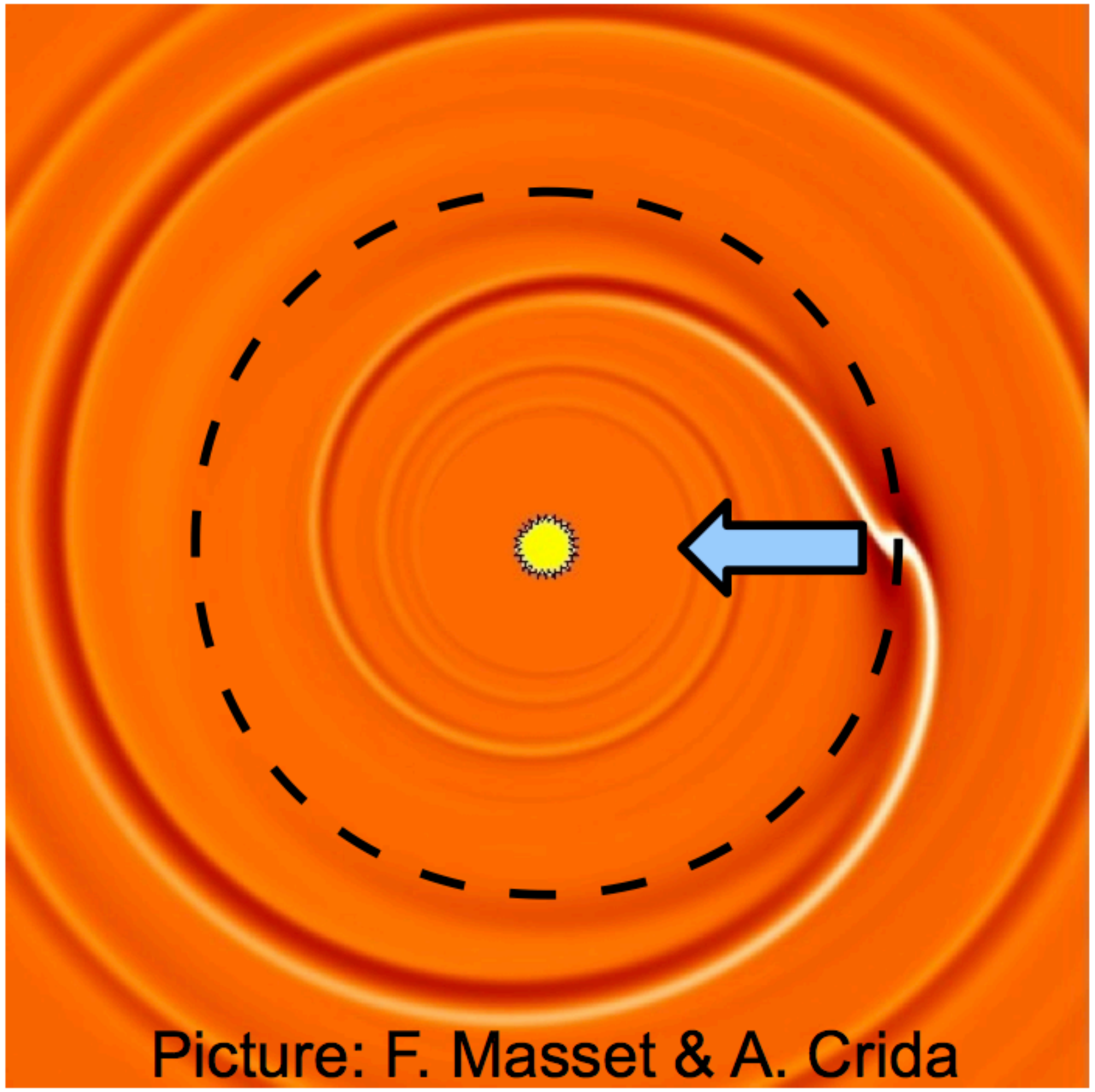
The torque due to the wave is, in a 2D adiabatic disc :

$$\gamma\Gamma_L / \Gamma_0 = -2.5 - 1.7\beta_T + 0.1\alpha_\Sigma$$

where γ = adiabatic index,

$\Sigma \sim r^{-\alpha_\Sigma}$, $T \sim r^{-\beta_T}$.

(Paardekooper et al. 2010)



In general, $0.5<\alpha_\Sigma<1.5$ and $\beta_T \approx 1$

→ negative torque, fast inward migration.

Slide by A. Crida

TYPE I MIGRATION

$$\gamma\Gamma_c / \Gamma_0 = 1.1\ (3/2 - \alpha_\Sigma) + 7.9\ \xi/\gamma$$

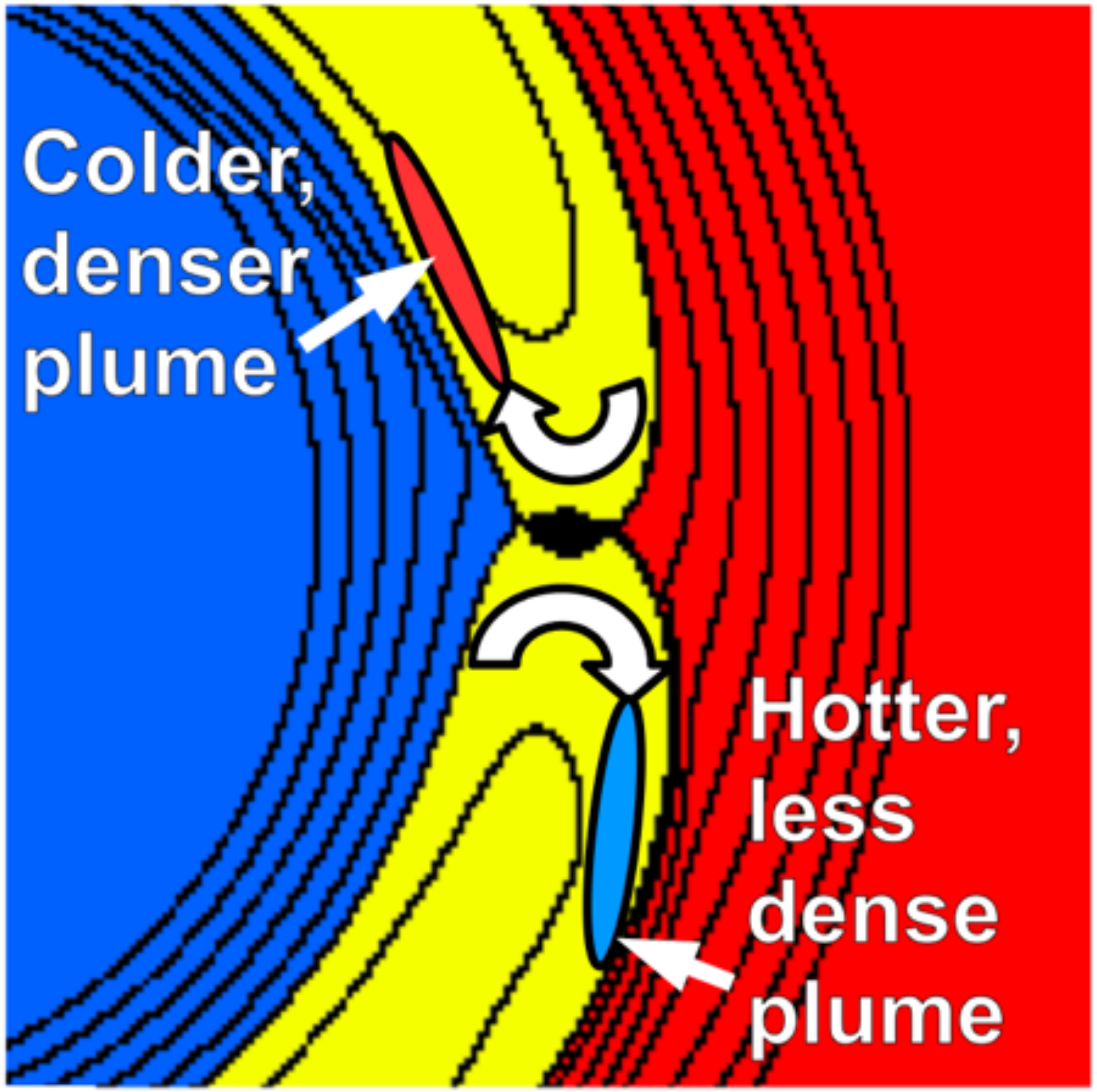
$$\xi = \beta_T - (\gamma-1)\alpha_\Sigma$$

(Paardekooper et al. 2010)

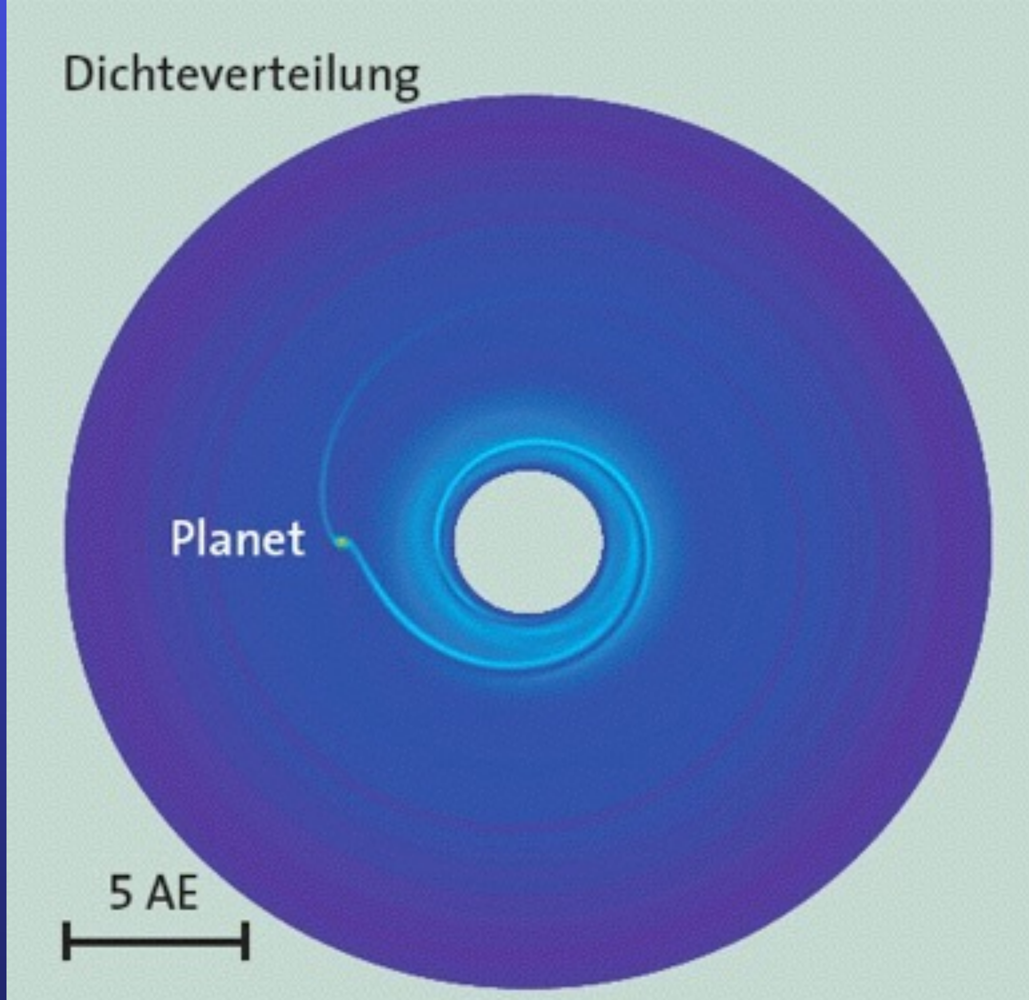
1st term : barotropic part
(e.g.: Ward 1991, Masset 2001, Paardekooper & Papaloizou 2009)

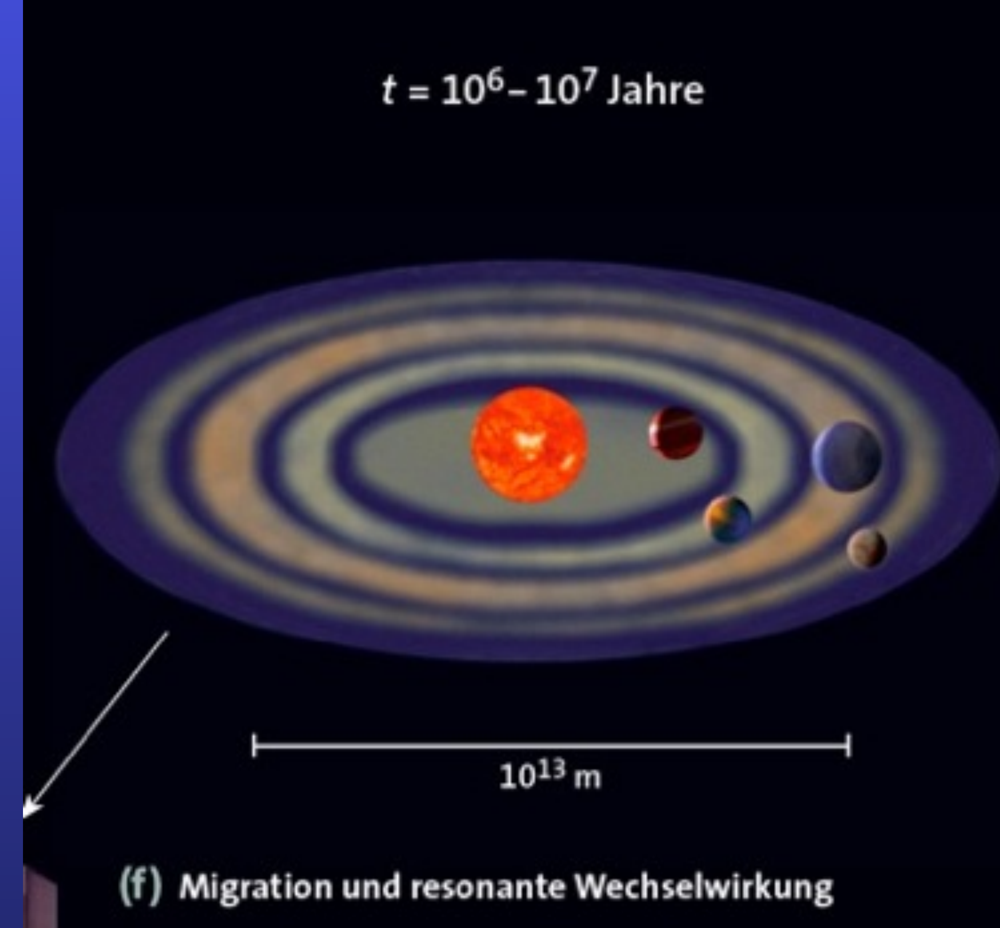
2nd term : thermal part, due to the advection of the entropy :
ξ = - dlog(entropy) / dlog(r)

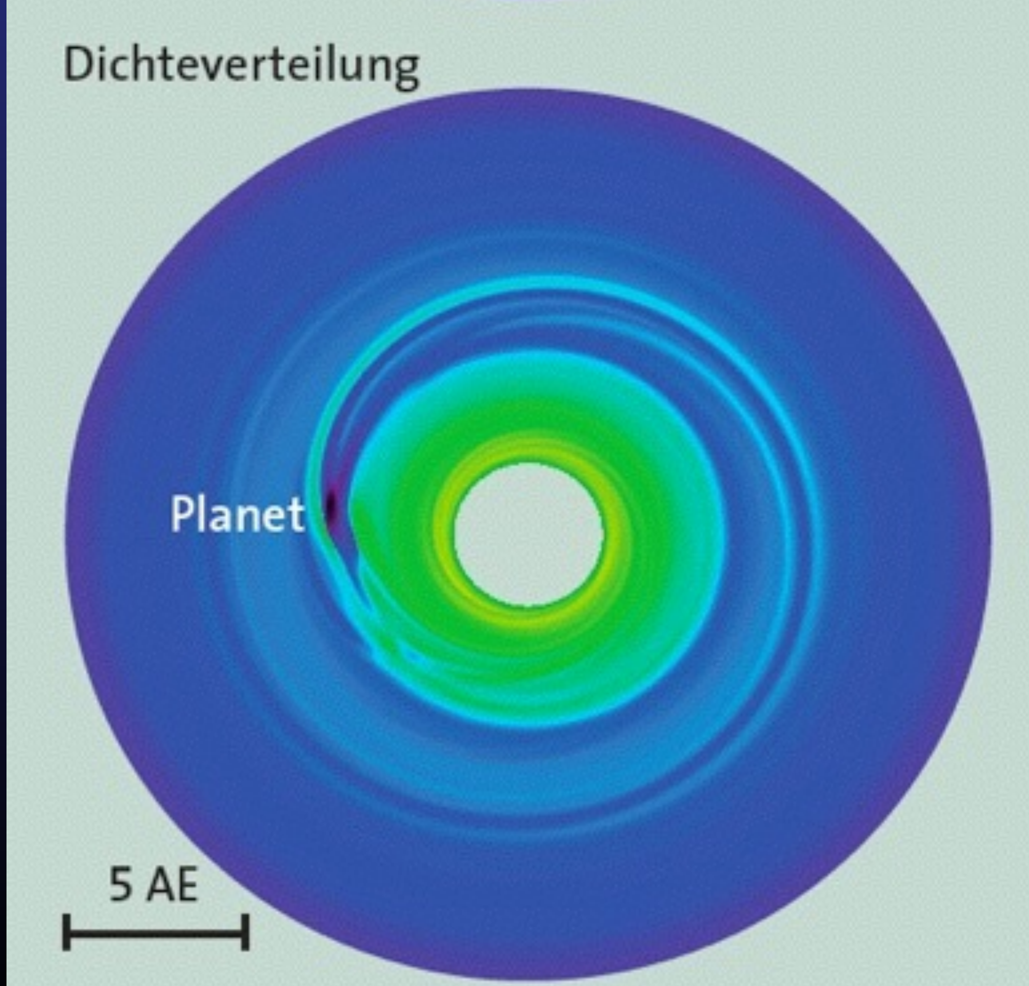
(Paardekooper & Mellema 2008, Baruteau & Masset 2008)

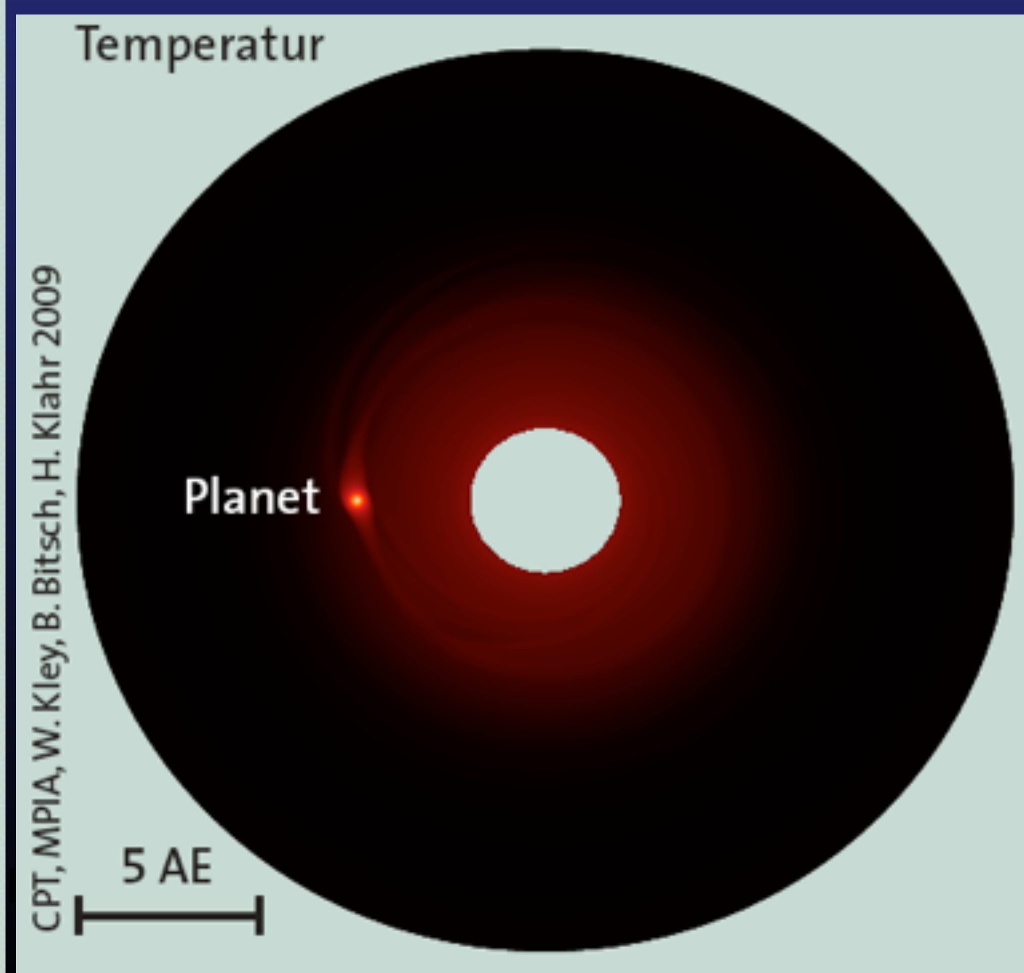


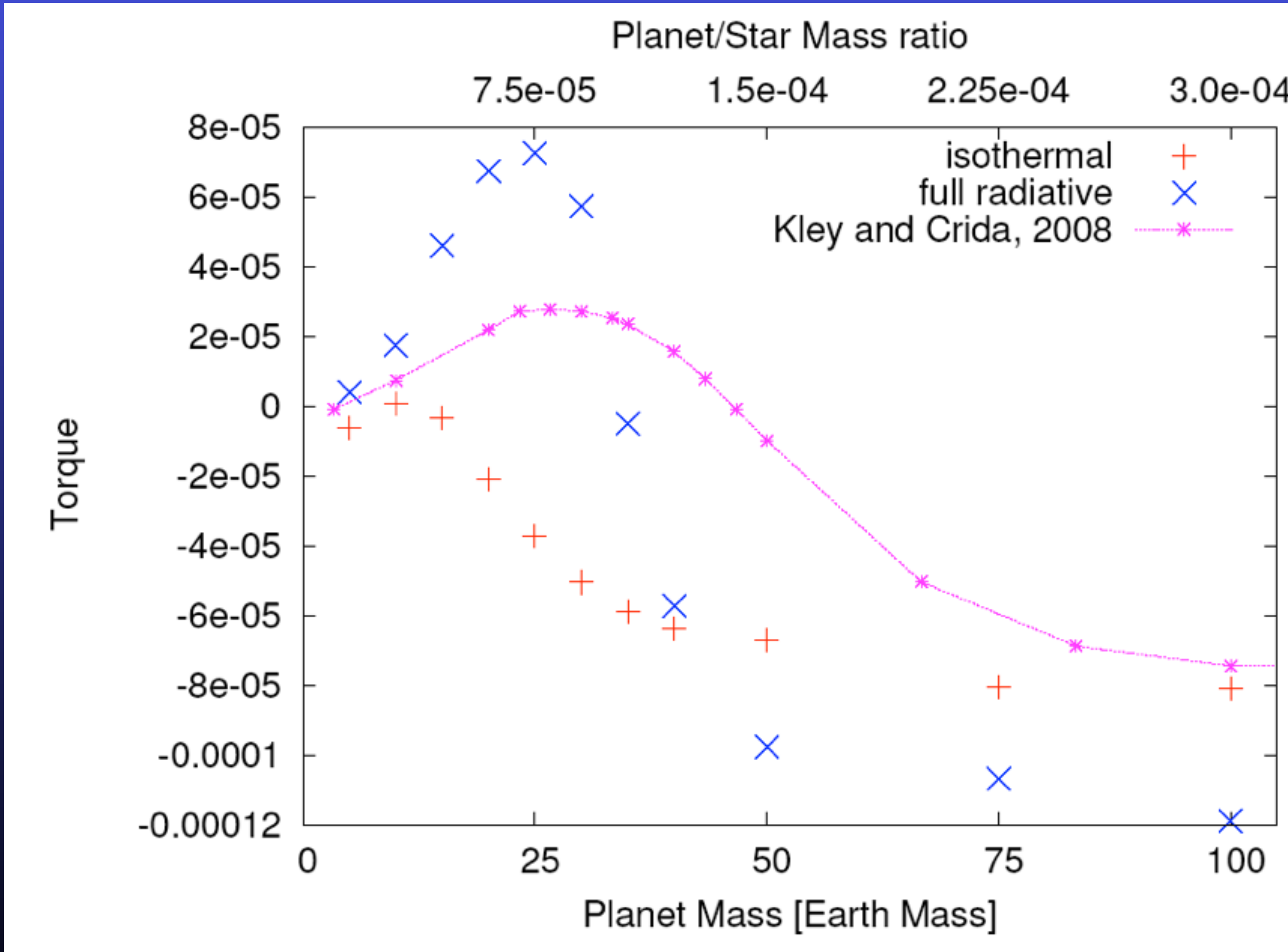
Slide by A. Crida


Dichteverteilung
Planet
5 AE


$t = 10^6 - 10^7$ Jahre
10^{13} m
(f) Migration und resonante Wechselwirkung


Dichteverteilung
Planet
5 AE


Temperatur
Planet
5 AE
CPT, MPIA, W. Kley, B. Bitsch, H. Klahr 2009



Kley, Bitsch and Klahr, 2009, etc....

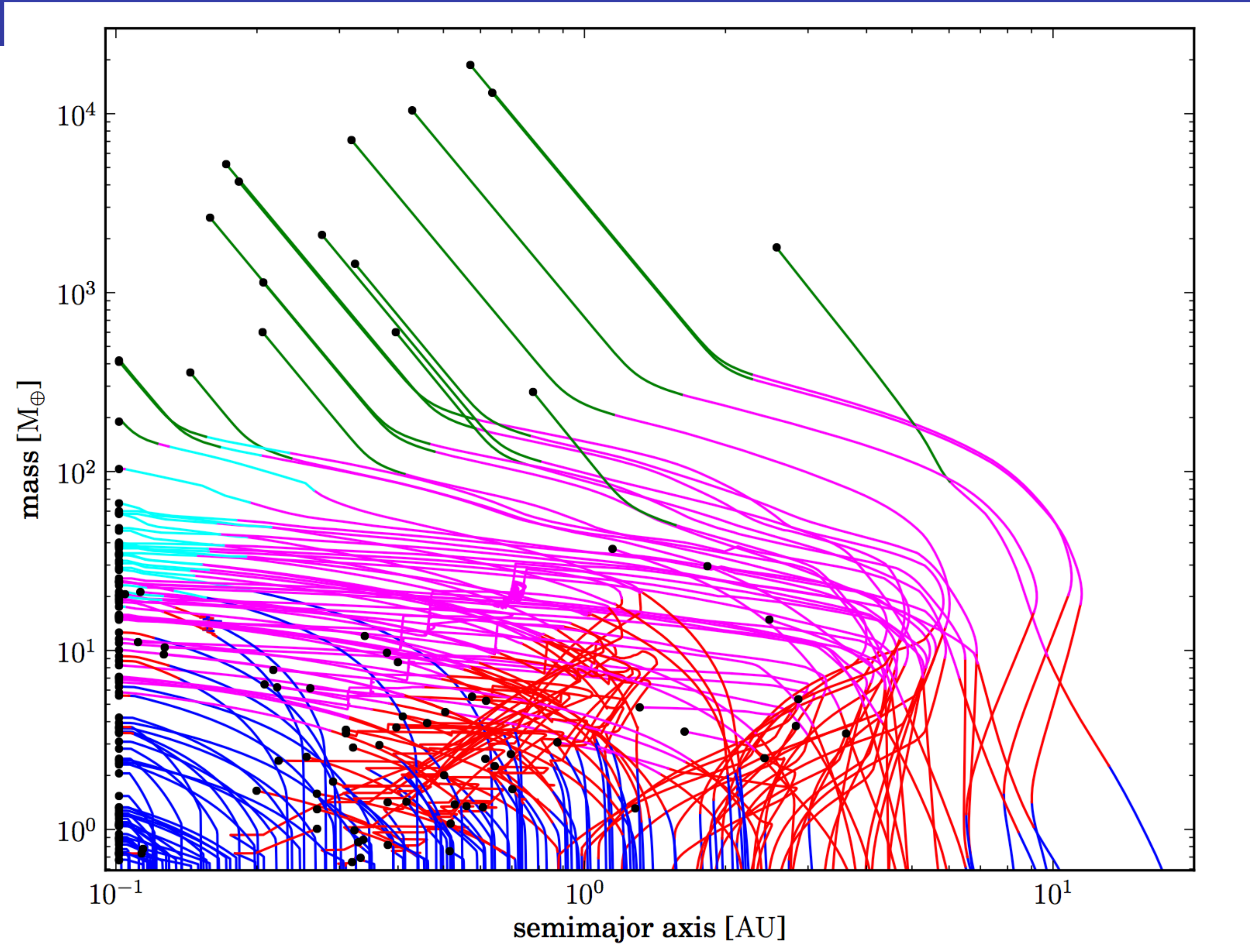
Impacts of planet migration models on planetary populations

Effects of saturation, cooling and stellar irradiation

K.-M. Dittkrist[1], C. Mordasini[1]*, H. Klahr[1], Y. Alibert[2,3], and T. Henning[1]

[1] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[2] Physikalisches Institut, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
[3] Institut UTINAM, CNRS-UMR 6213, Observatoire de Besançon, BP 1615, 25010 Besançon Cedex, France

Received July 2013 / Accepted 16.02.2014



Better solution than fudge factor in migration rate!

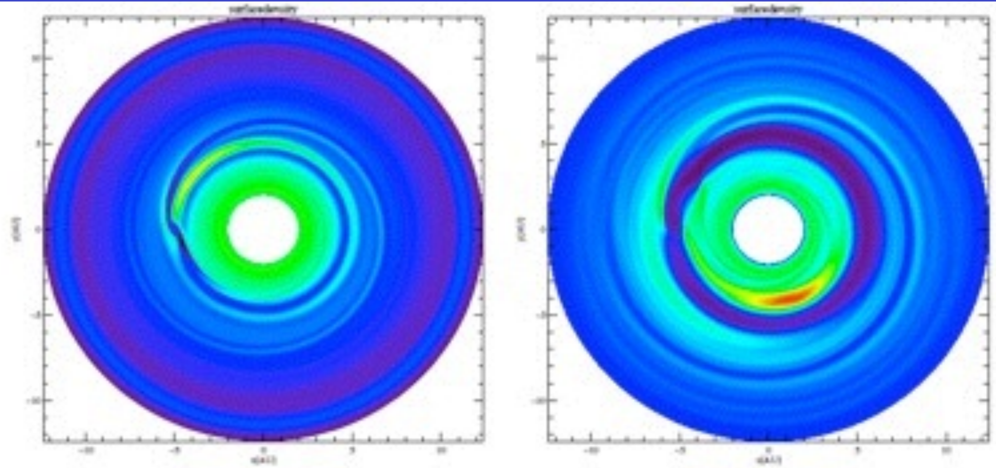


Fig. 1.— Surface density distribution - left: $10M_{\oplus}$ and $\kappa = 0.1\kappa_0$; right: $100M_{\oplus}$ and $\kappa = 100\kappa_0$

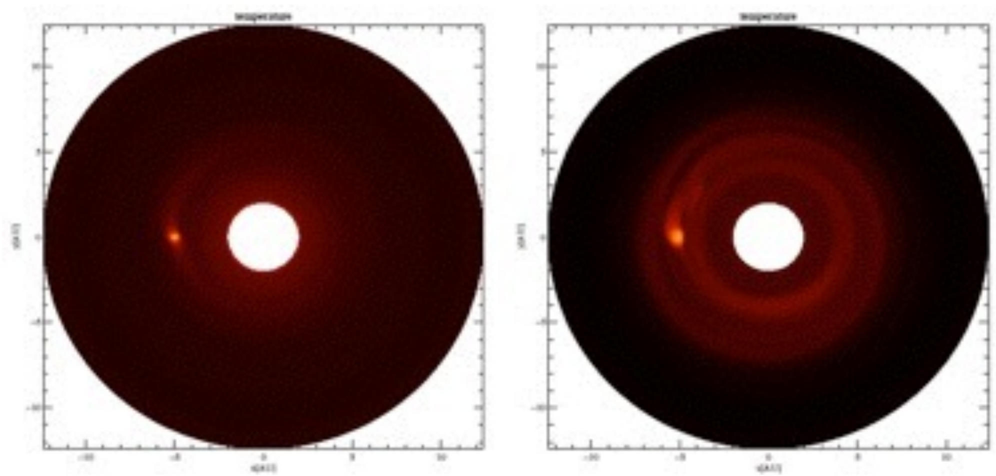
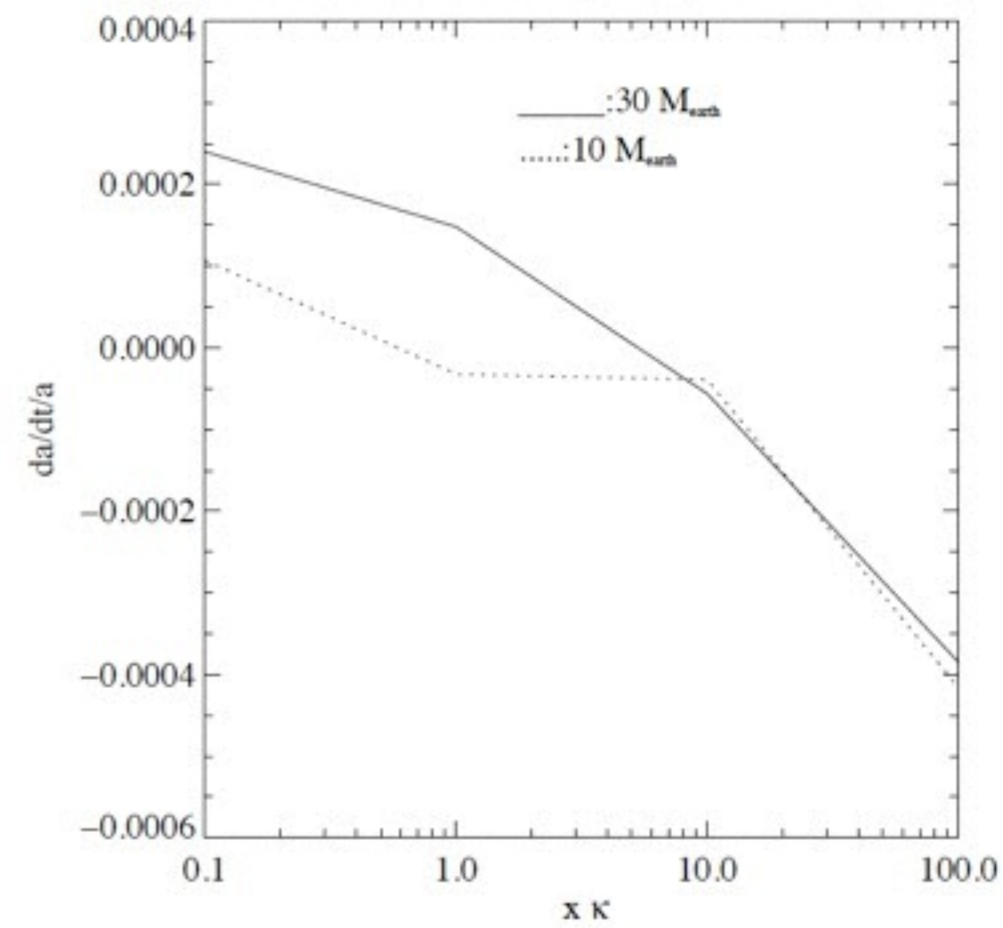
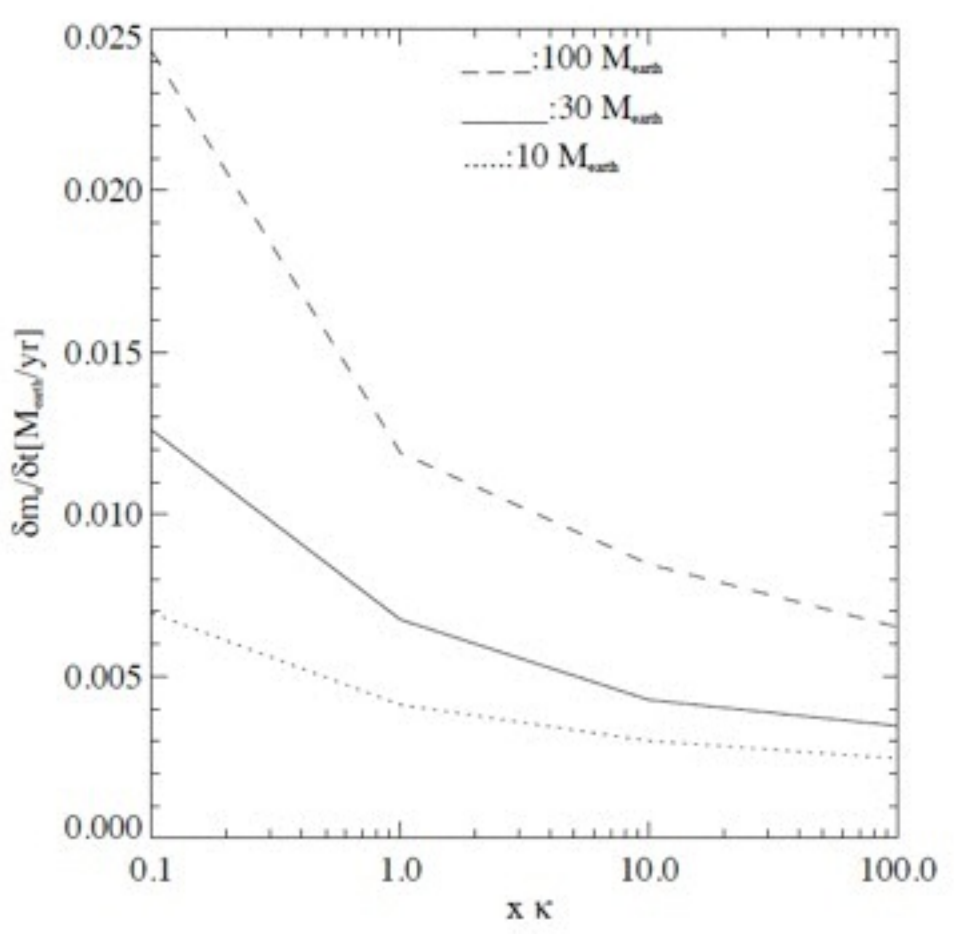


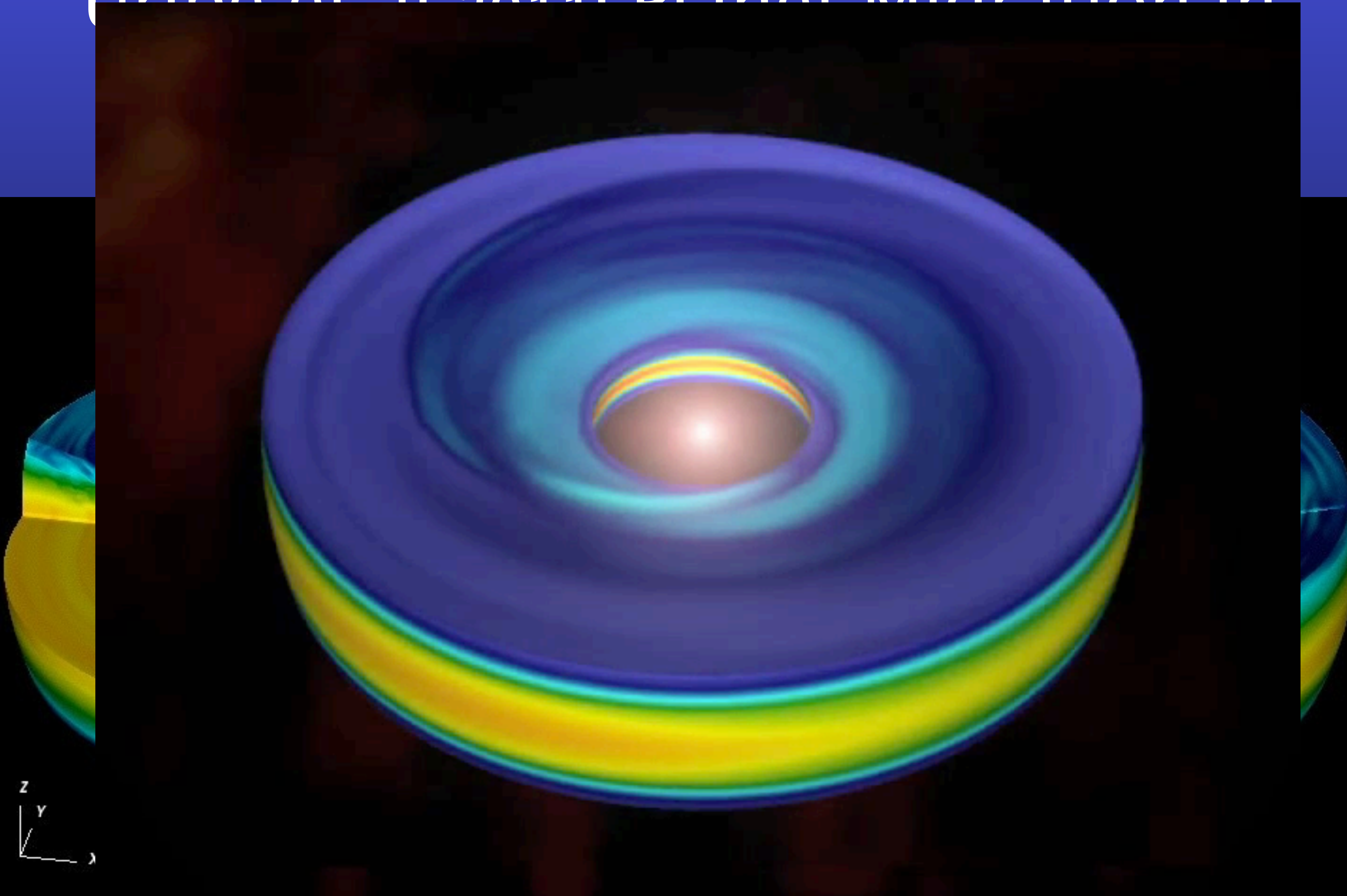
Fig. 2.— Tempertature distribution - left: $10M_{\oplus}$ and $\kappa = 0.1\kappa_0$; right: $100M_{\oplus}$ and $\kappa = 100\kappa_0$





Torques and Gas accretion depend on dust size / abundance! Klahr and Lin in prep.

Uribe et al 2011: Planet Migration in



Uribe et al 2011: Planet Migration in 3D
Global MHD runs... Outward migration even for isothermal cases:
Reason - Local positive pressure gradient.

4. 3D MHD SIMULATIONS OF PLANET MIGRATION IN TURBULENT STRATIFIED DISKS

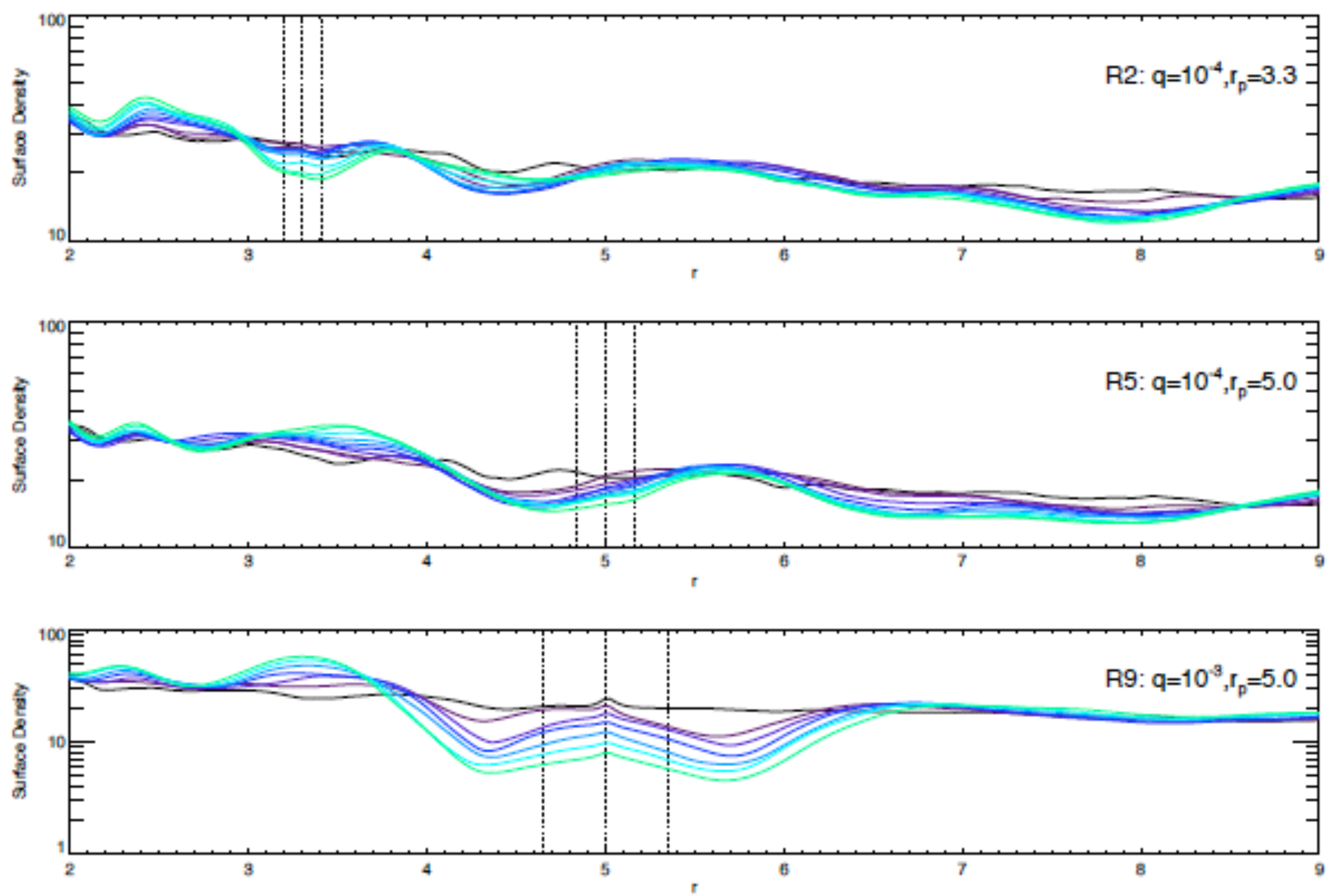
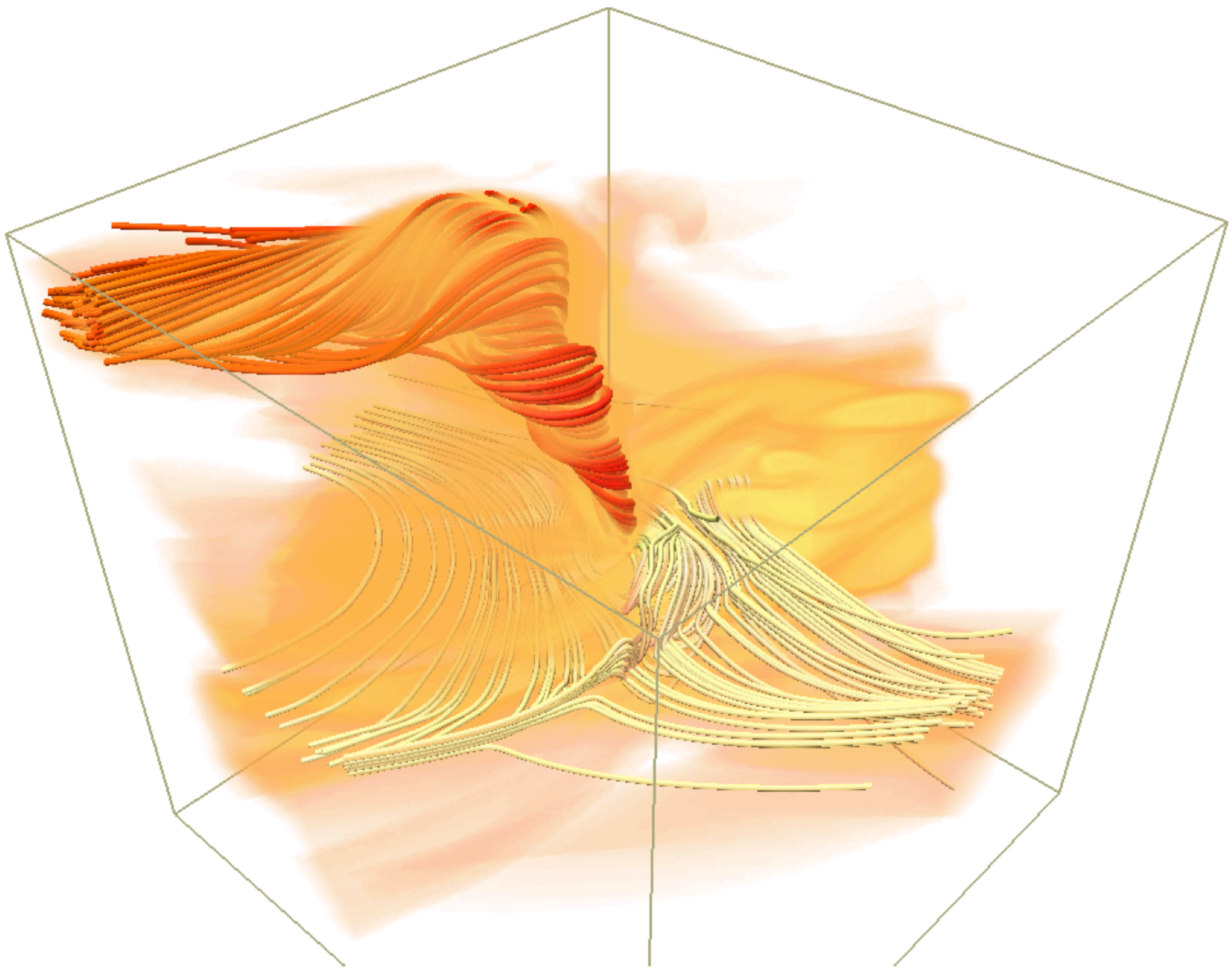


Figure 4.12: Surface density at different times in the simulation. Top, middle and bottom plot show the surface density for runs R2, R5 and R9 respectively. The vertical lines shows the position of the planet and the extent of the Hill radius.

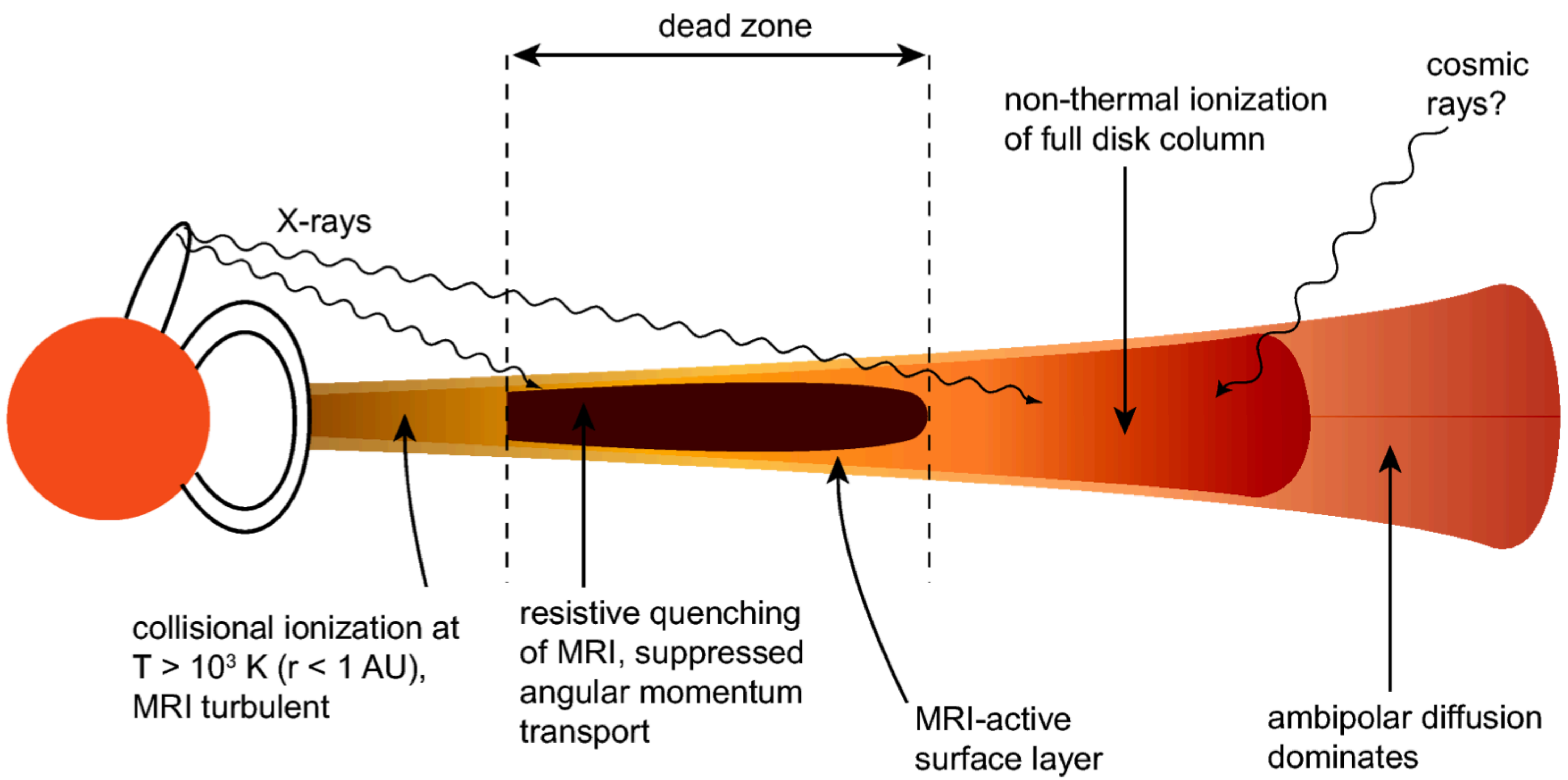
circum-jovian jet



- Gressel et al. (2013), predicted by Quillen & Trilling (1998) and Fendt (2003), also cf. Machida et al. (2006)

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

schematics of protostellar disc



Armitage (2011)

play

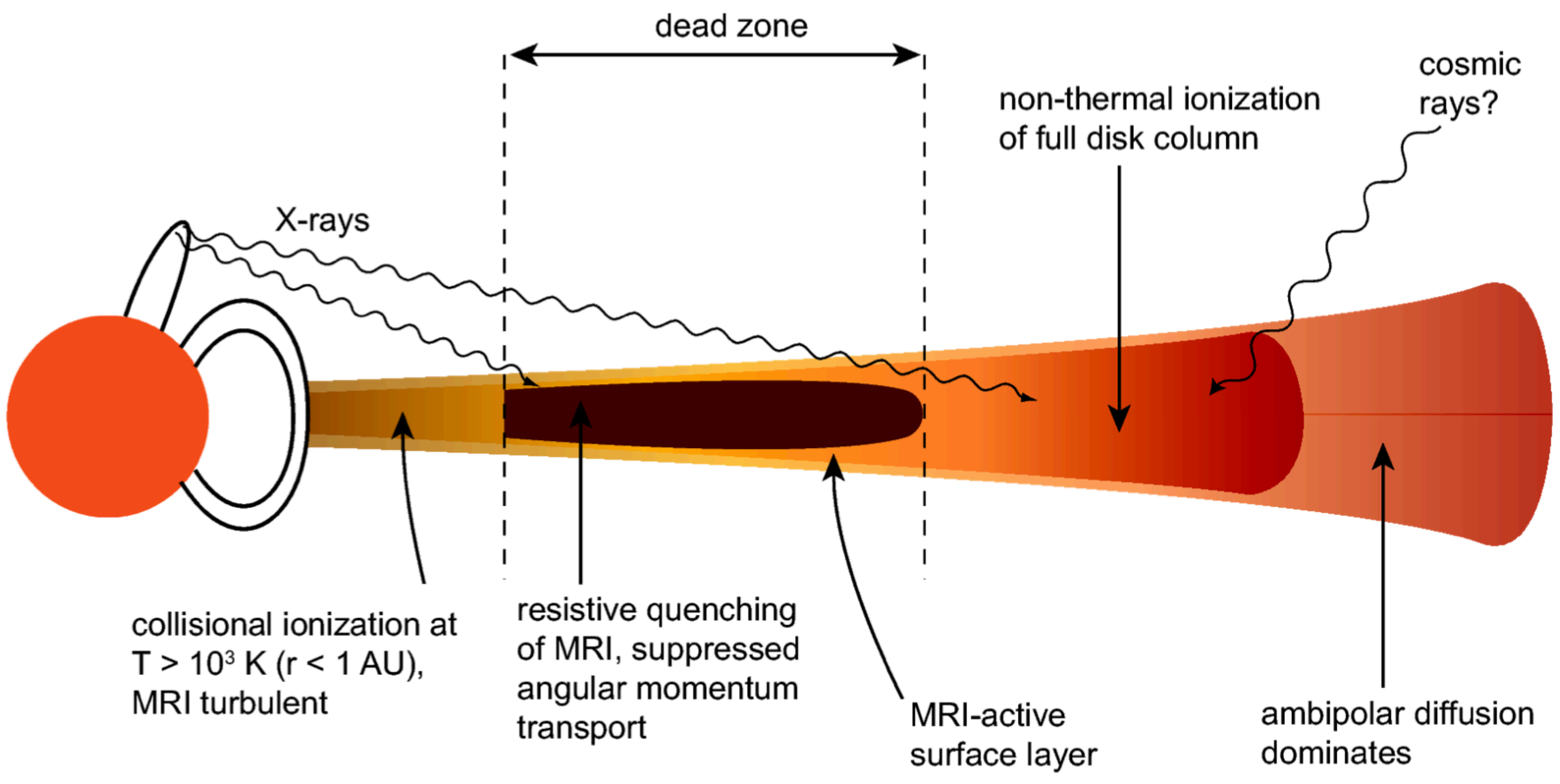
From ideal to non-ideal MHD

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{v}_{\rm f} \times \boldsymbol{B})$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times \Big[\boldsymbol{v}_{\rm n} \times \boldsymbol{B} + \underbrace{(\boldsymbol{v}_{\rm f} - \boldsymbol{v}_{\rm e}) \times \boldsymbol{B}}_{-\frac{4\pi\eta}{c}\boldsymbol{J}}\Big]$$

Ohmic dissipation

schematics of protostellar disc



Armitage (2011)

play

From ideal to non-ideal MHD

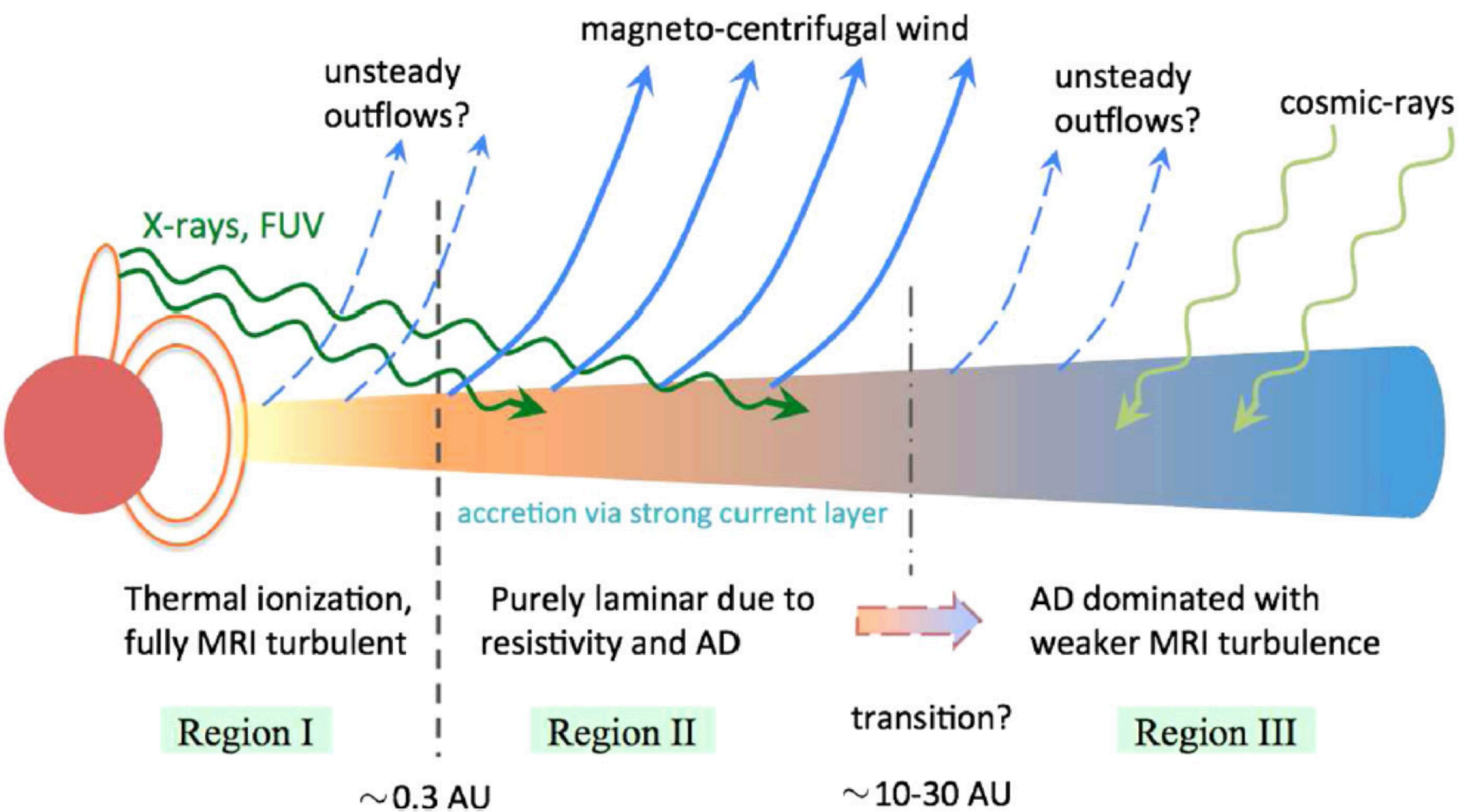
$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{v}_\mathrm{f} \times \boldsymbol{B})$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times \left[\boldsymbol{v}_\mathrm{n} \times \boldsymbol{B} + \underbrace{(\boldsymbol{v}_\mathrm{i} - \boldsymbol{v}_\mathrm{n})}_{\dfrac{\boldsymbol{J} \times \boldsymbol{B}}{c\rho\tau_\mathrm{ni}^{-1}}} \times \boldsymbol{B} + \underbrace{(\boldsymbol{v}_\mathrm{f} - \boldsymbol{v}_\mathrm{e})}_{-\dfrac{4\pi\eta}{c}\boldsymbol{J}} \times \boldsymbol{B}\right]$$

ambipolar diffusion

Ohmic dissipation

revised schematics of protostellar disc



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

Thanatology in Protoplanetary Discs

The combined influence of Ohmic, Hall, and ambipolar diffusion on dead zones

Geoffroy Lesur[1,2], Matthew W. Kunz[3]⋆, and Sébastien Fromang[4]

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e-mail: geoffroy.lesur@ujf-grenoble.fr
[2] CNRS, IPAG, F-38000 Grenoble, France
[3] Department of Astrophysical Sciences, 4 Ivy Lane, Peyton Hall, Princeton University, Princeton, NJ 08544, U. S. A.
[4] Laboratoire AIM, CEA/DSM–CNRS–Université Paris 7, Irfu/Service d'Astrophysique, CEA-Saclay, 91191 Gif-sur-Yvette, France

Accepted 8 Apr 2014.

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{v}_{\rm f} \times \boldsymbol{B})$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times \Big[\boldsymbol{v}_{\rm n} \times \boldsymbol{B} + \underbrace{(\boldsymbol{v}_{\rm i} - \boldsymbol{v}_{\rm n})}_{\frac{\boldsymbol{J} \times \boldsymbol{B}}{c\rho\tau_{\rm ni}^{-1}}} \times \boldsymbol{B} + \underbrace{(\boldsymbol{v}_{\rm e} - \boldsymbol{v}_{\rm i})}_{-\frac{\boldsymbol{J}}{e n_{\rm e}}} \times \boldsymbol{B} + \underbrace{(\boldsymbol{v}_{\rm f} - \boldsymbol{v}_{\rm e})}_{-\frac{4\pi\eta}{c}\boldsymbol{J}} \times \boldsymbol{B} \Big]$$

ambipolar diffusion | Hall effect | Ohmic dissipation

Thanatology in Protoplanetary Discs

The combined influence of Ohmic, Hall, and ambipolar diffusion on dead zones

Geoffroy Lesur[1,2], Matthew W. Kunz[3]★, and Sébastien Fromang[4]

[1] Univ. Grenoble Alpes, IPAG, F-38000 Grenoble, France
e-mail: geoffroy.lesur@ujf-grenoble.fr
[2] CNRS, IPAG, F-38000 Grenoble, France
[3] Department of Astrophysical Sciences, 4 Ivy Lane, Peyton Hall, Princeton University, Princeton, NJ 08544, U. S. A.
[4] Laboratoire AIM, CEA/DSM–CNRS–Université Paris 7, Irfu/Service d'Astrophysique, CEA-Saclay, 91191 Gif-sur-Yvette, France

Accepted 8 Apr 2014.

α – Maxwell Stress

Ohmic:

Ohmic +Ambipola

Ohmic + Ambipola + Hall:

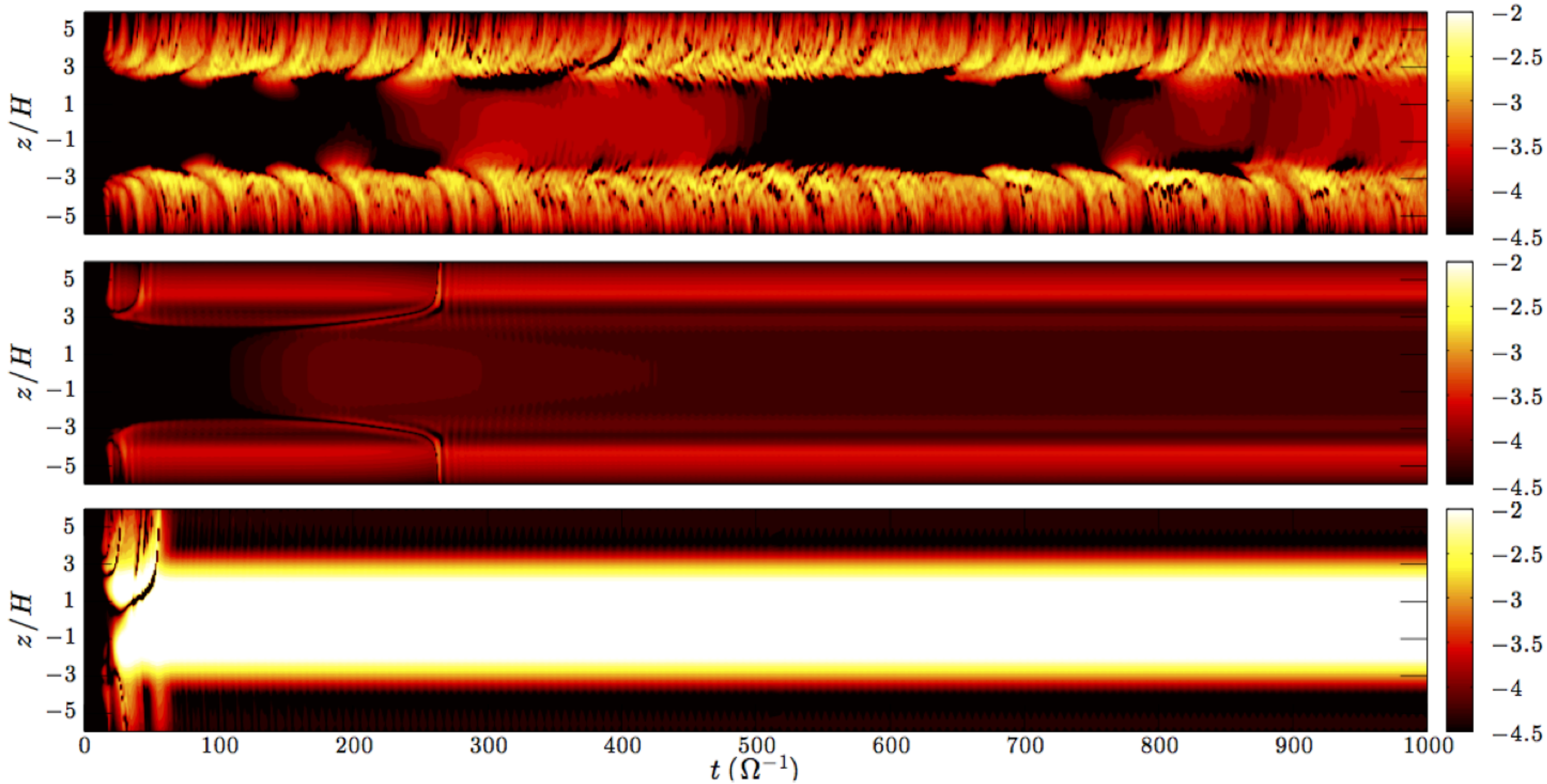


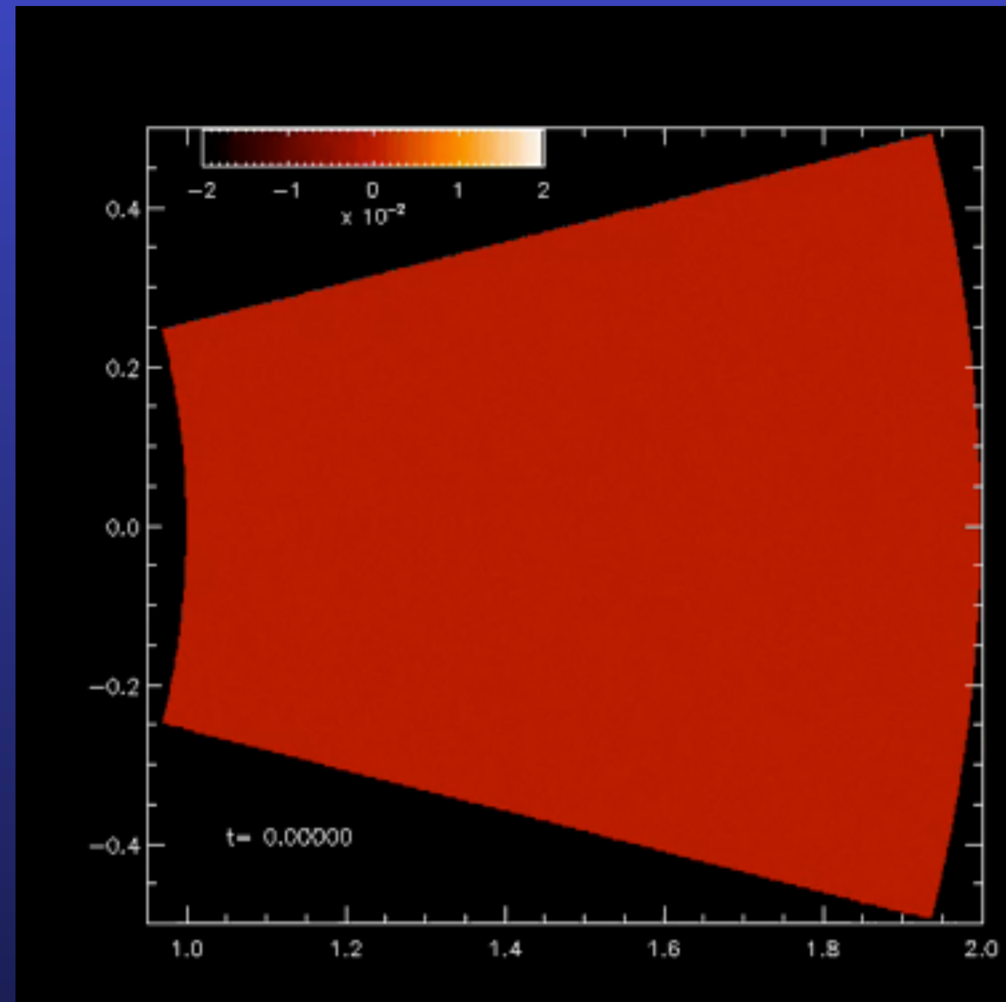
Fig. 9. Space-time evolution of the logarithm of the horizontally-averaged magnetic stress, $\log\langle M_{xy}\rangle$, in the Ohmic (1-O-5; top), Ohmic-ambipolar (1-OA-5; middle), and Ohmic-ambipolar-Hall (1-OHA-5; bottom) runs.

Effects on Planet Migration? Role of Zonal flows?

Three new Hydro Instabilities:

- Vertical Shear / Goldreich-Schubert-Fricke instability (Nelson, Gressel & Umurhan 2013)
- Critical Layer Instability/Zombie Vortices (Marcus et al 2013)
- Convective Overstability (Klahr and Hubbard 2014, Lyra 2014)

2D axissymetric Disk vertically isothermal yet radial temp. gradient:



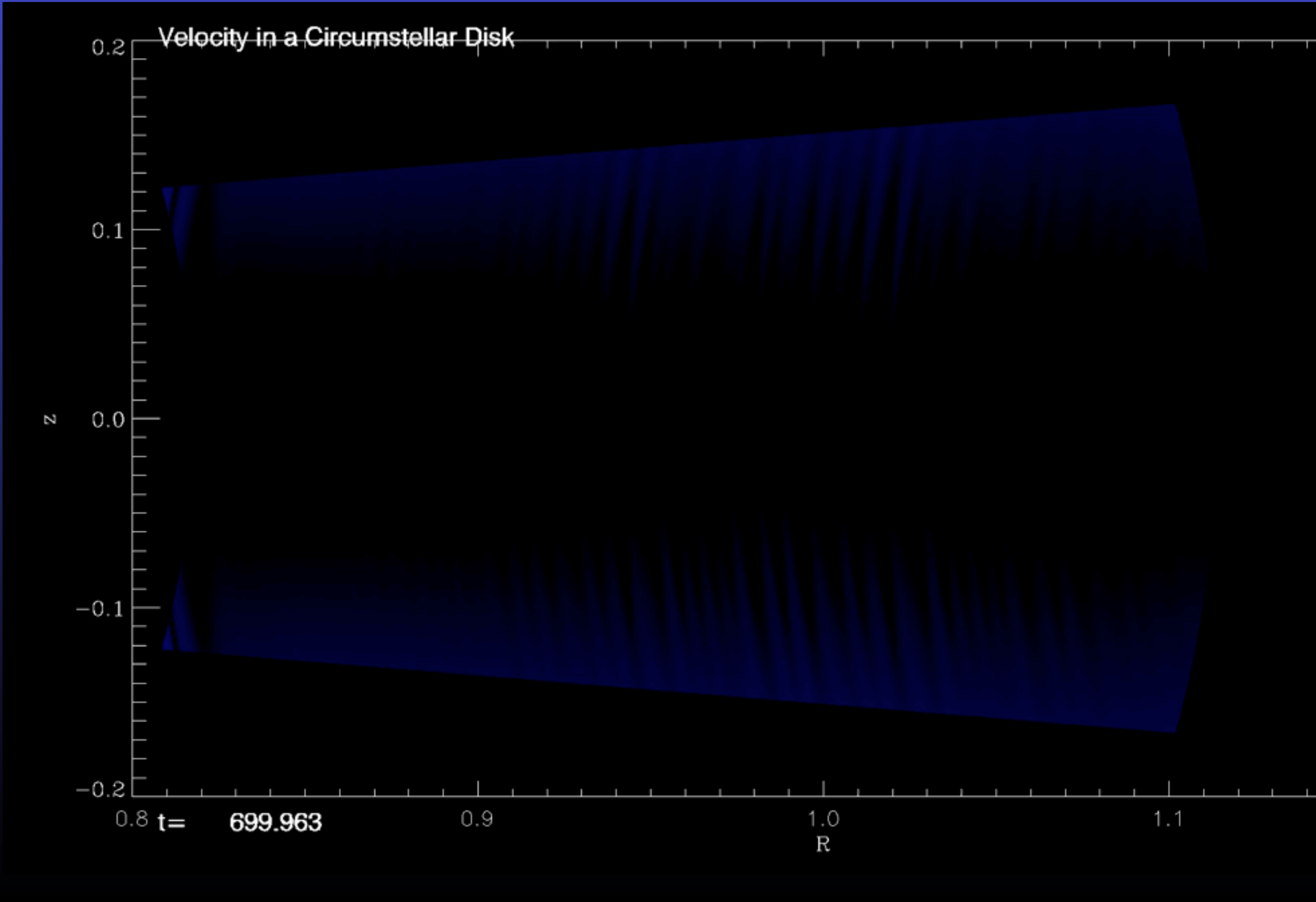
Modification of Solberg-Hoiland Criterion, including thermal relaxation:
In collaboration with Alexander Hubbard
Or instantanous cooling: Goldreich & Schubert 1967 - Fricke 1968 Instability

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

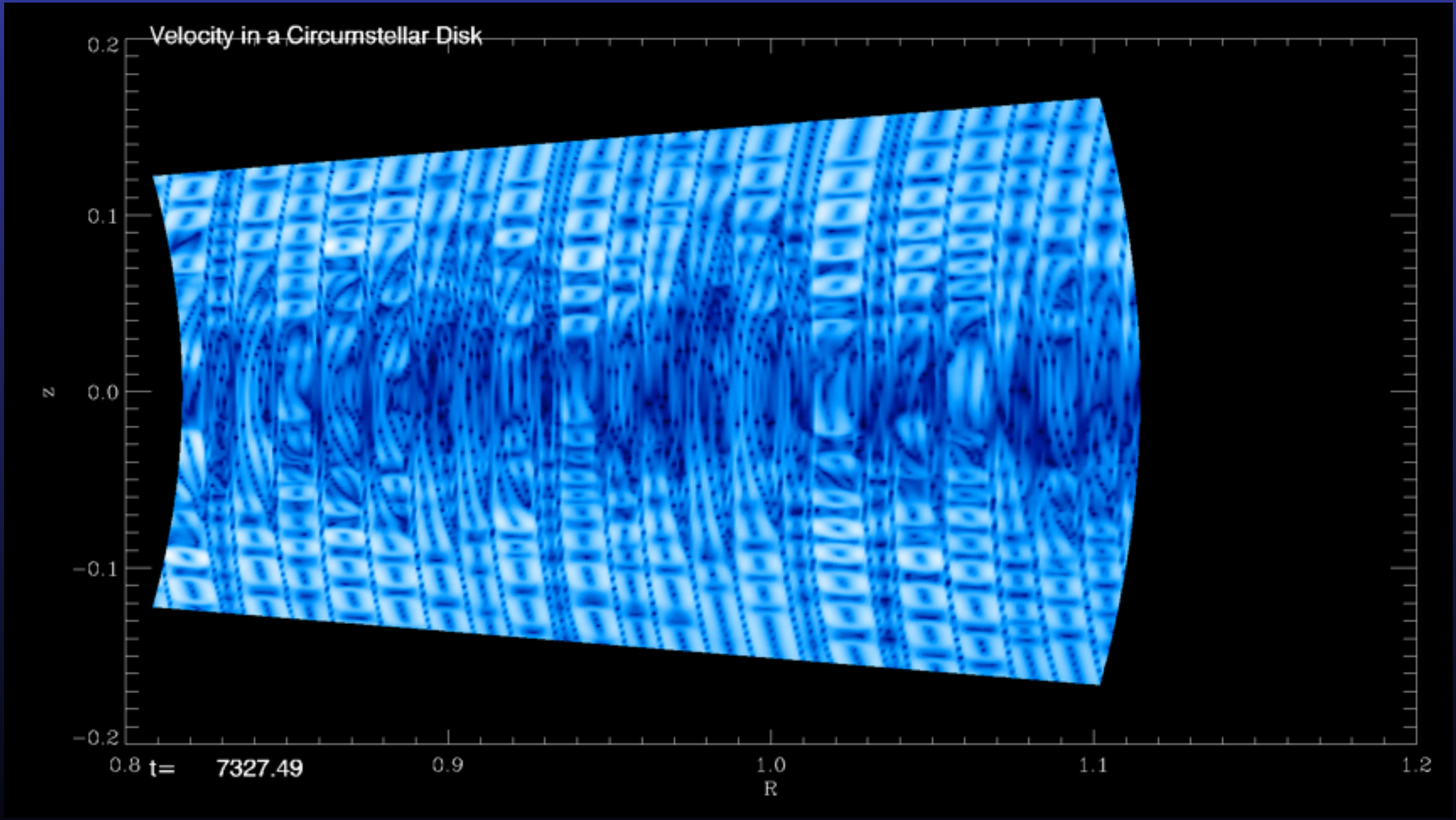
Richard P. Nelson[1]★, Oliver Gressel[1,2]★ and Orkan M. Umurhan[1,3]★
[1] *Astronomy Unit, Queen Mary University of London, Mile End Road, London E1 4NS*
[2] *NORDITA, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, 106 91 Stockholm, Sweden*
[3] *School of Natural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

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

Convective Overstability for $\Omega\tau \approx 10$
Klahr and Hubbard 2014



Convective Overstability for $\Omega\tau \approx 10$
Klahr and Hubbard 2014



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

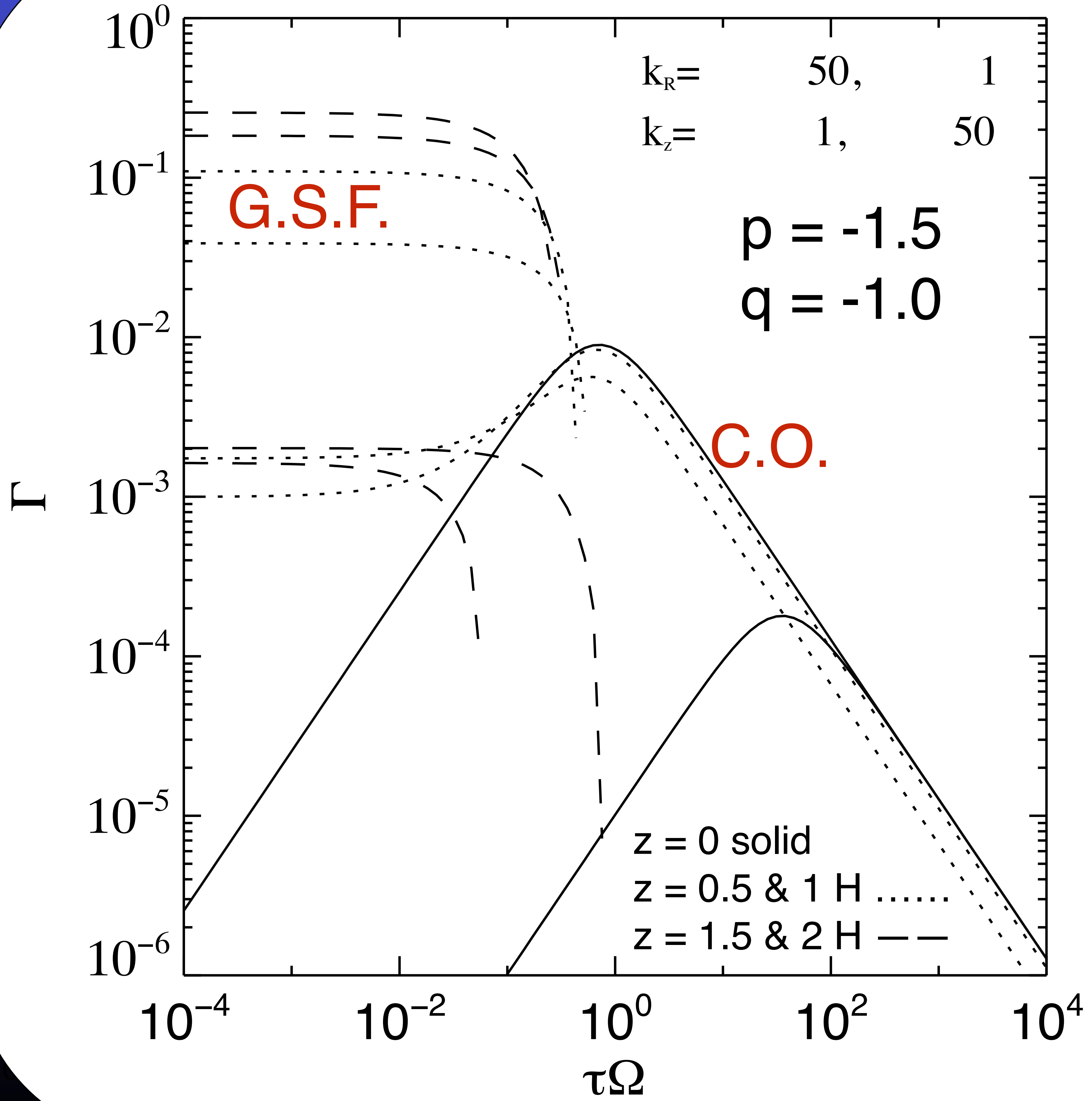
$$A = k^2 c_s^2 + \frac{1}{\rho_0^2}\frac{\partial p_0}{\partial R}\frac{\partial \rho_0}{\partial R} + \frac{1}{\rho_0^2}\frac{\partial p_0}{\partial z}\frac{\partial \rho_0}{\partial z} + \kappa_R^2$$

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

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

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

Klahr and Hubbard 2014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k_z= 1, 50
G.S.F.
p = -1.5
q = -1.0
C.O.
z = 0 solid
z = 0.5 & 1 H ......
z = 1.5 & 2 H — —
Γ
τΩ
10^0
10^{-1}
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10^{-4}
10^{-5}
10^{-6}
10^{-4}
10^{-2}
10^0
10^2
10^4

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,

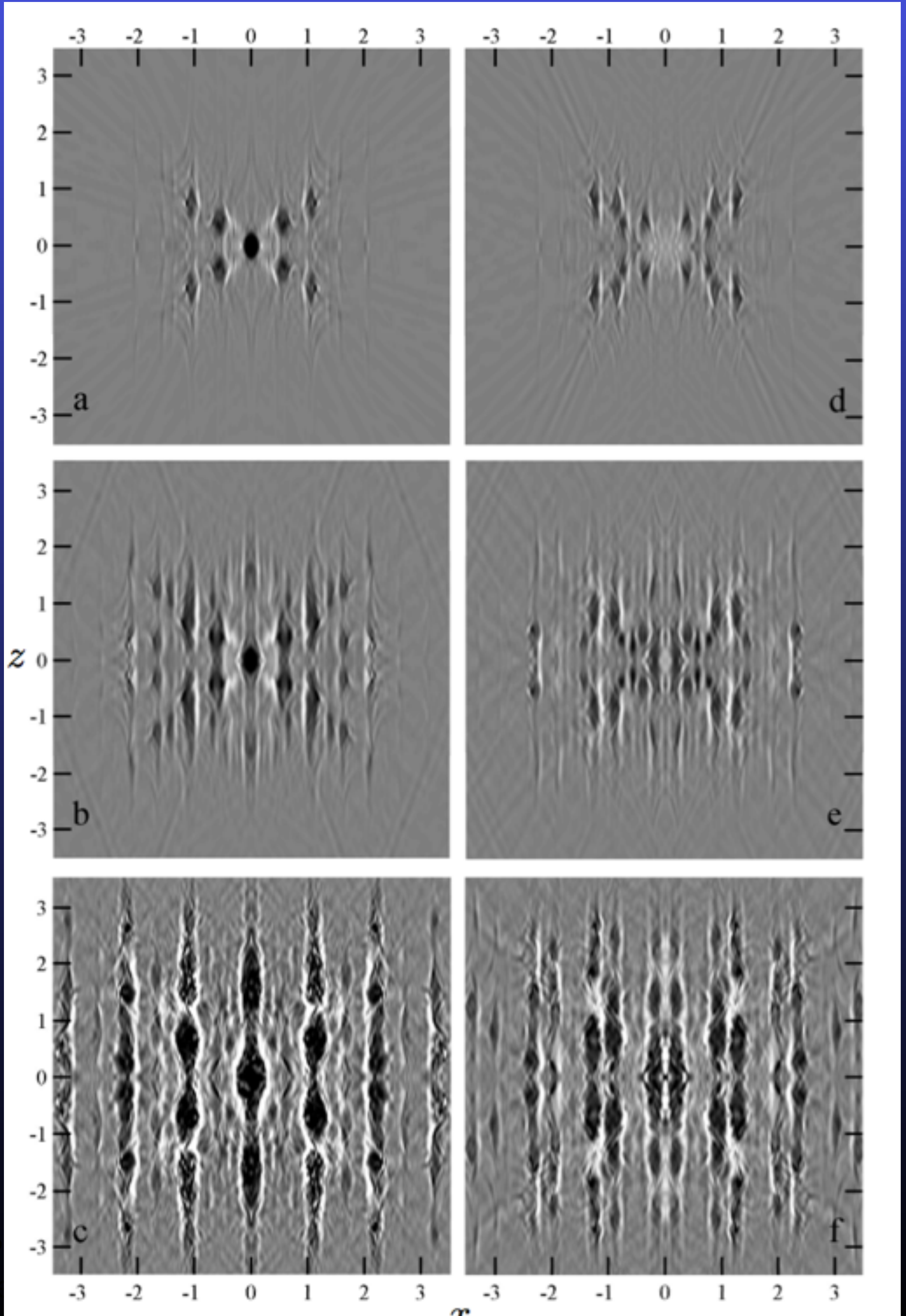
University of California, Berkeley, California, 94720, USA

(Dated: September 29, 2012)

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

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

$$\tau\Omega \approx 1$$



Three new Hydro Instabilities:

- Vertical Shear / Goldreich-Schubert-Fricke instability (Nelson, Gressel & Umurhan 2013)
- Critical Layer Instability/Zombie Vortices (Marcus et al 2013)
- Convective Overstability (Subcritical Baroclinic Instability) (Klahr and Hubbard 2014, Lyra 2014)

What is their interaction with non-ideal MHD?

What is their effect on Planet migration?

Migration models are only as good as

LETTER

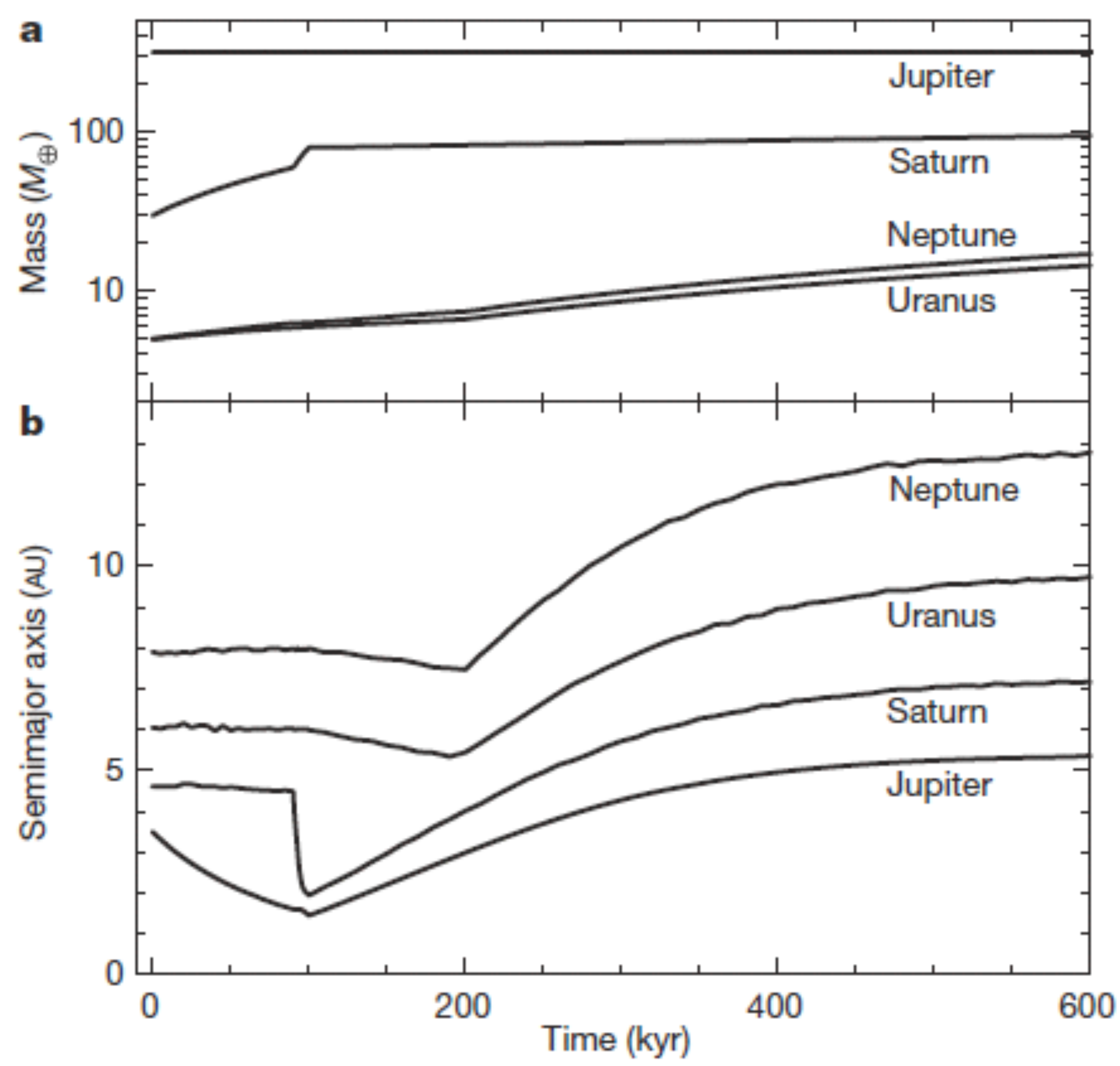
doi:10.1038/nature10201

A low mass for Mars from Jupiter's early gas-driven migration

Kevin J. Walsh[1,2], Alessandro Morbidelli[1], Sean N. Raymond[3,4], David P. O'Brien[5] & Avi M. Mandell[6]

Auch Jupiter und Saturn könnten gewandert sein!

Erst rein, dann wieder raus… ;)



A low mass for Mars from Jupiter’s early gas-driven migration

- **Kevin J. Walsh**, **Alessandro Morbidelli**, **Sean N. Raymond**, **David P. O'Brien** & **Avi M. Mandell**

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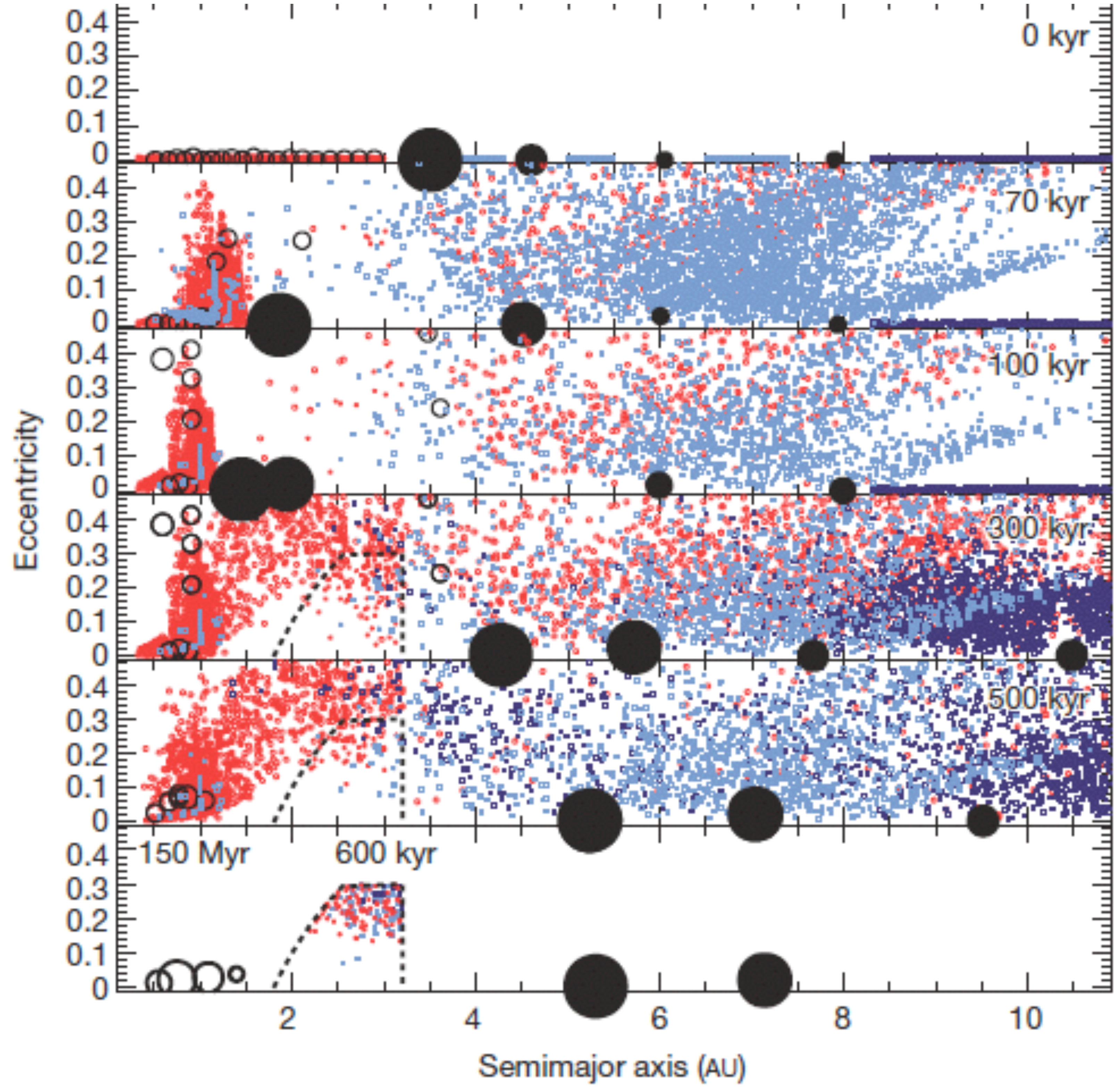
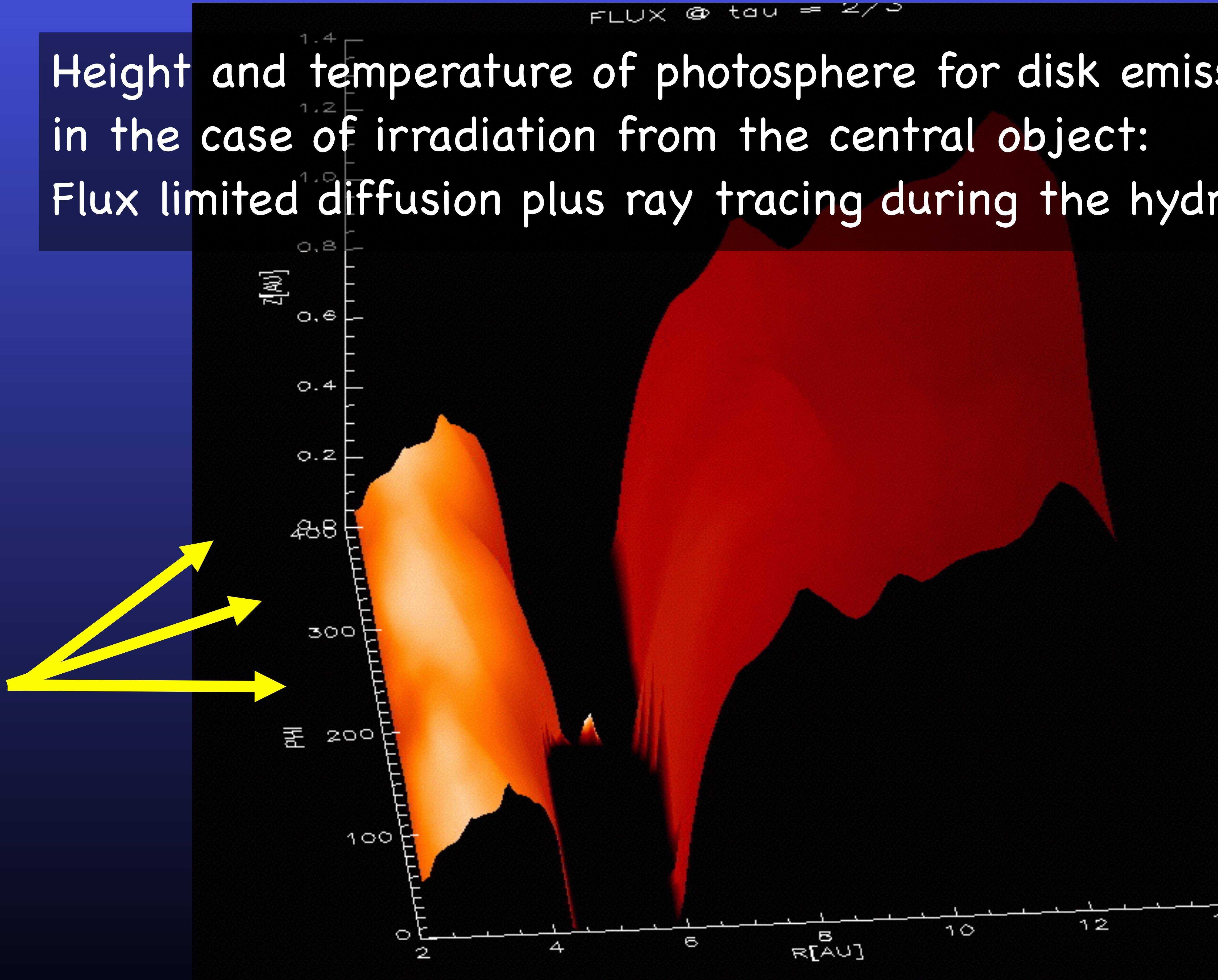
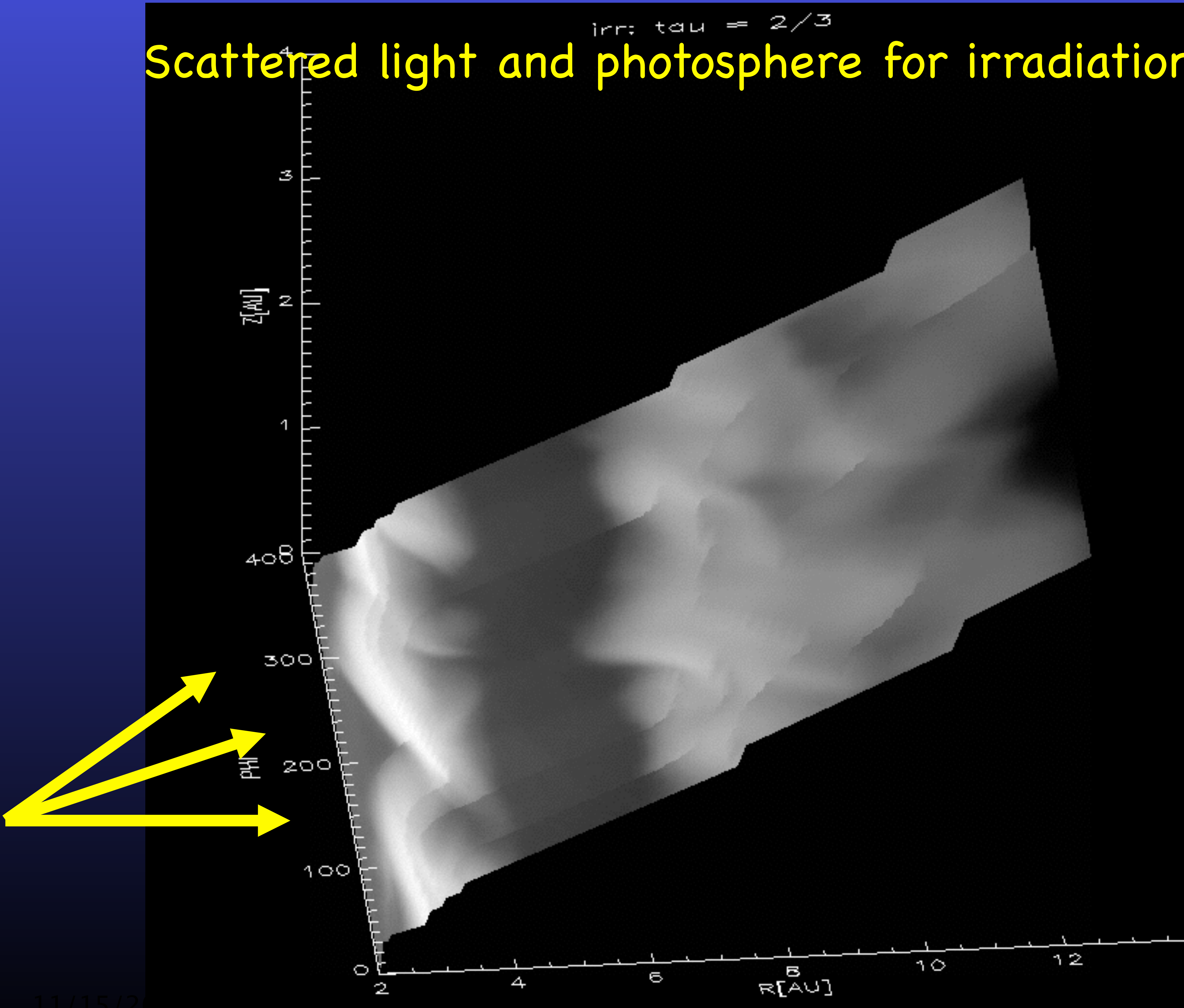
Geburstshilfe für die terresttrischen Planeten:



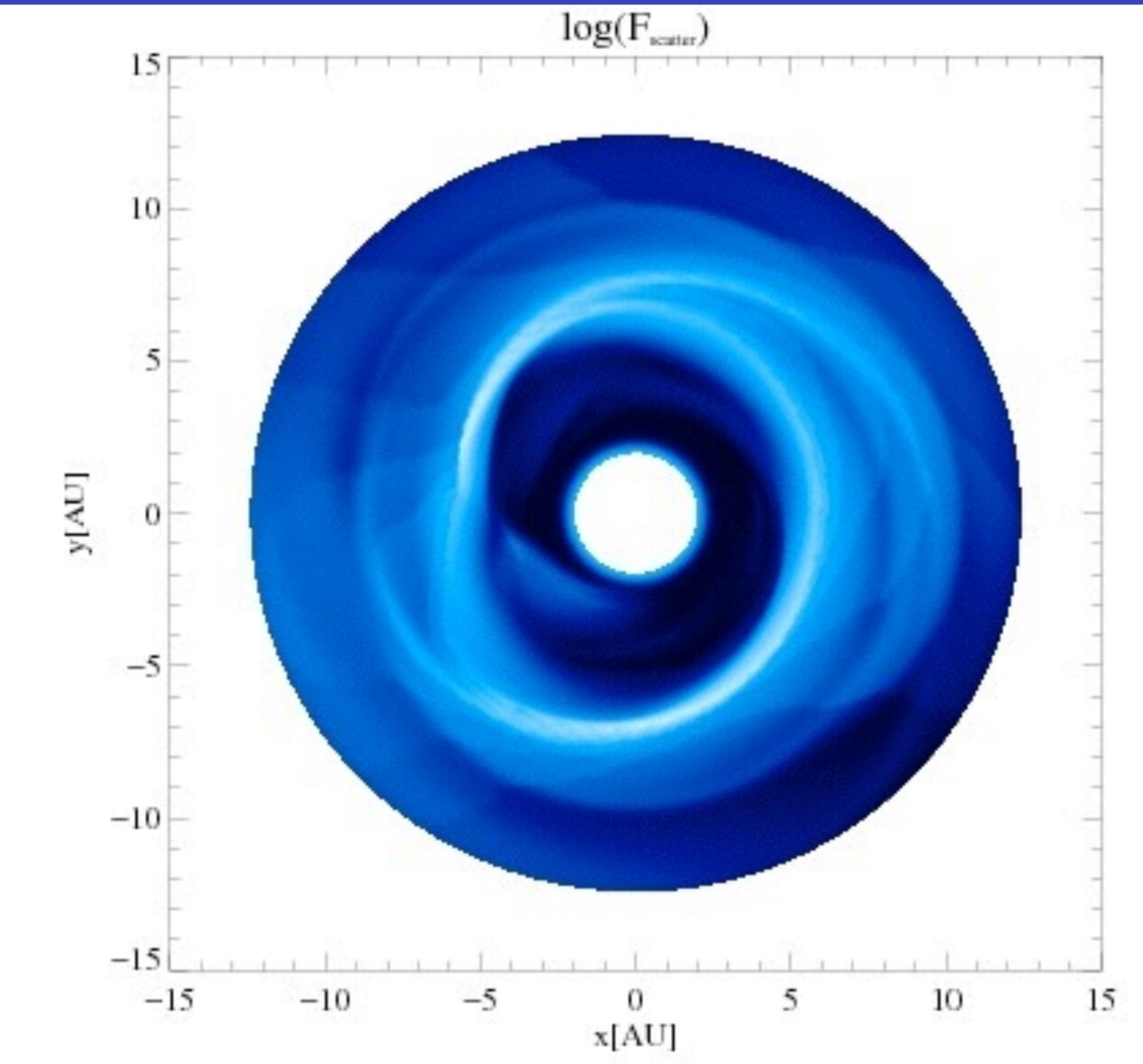
Height and temperature of photosphere for disk emission in the case of irradiation from the central object:
Flux limited diffusion plus ray tracing during the hydro run!



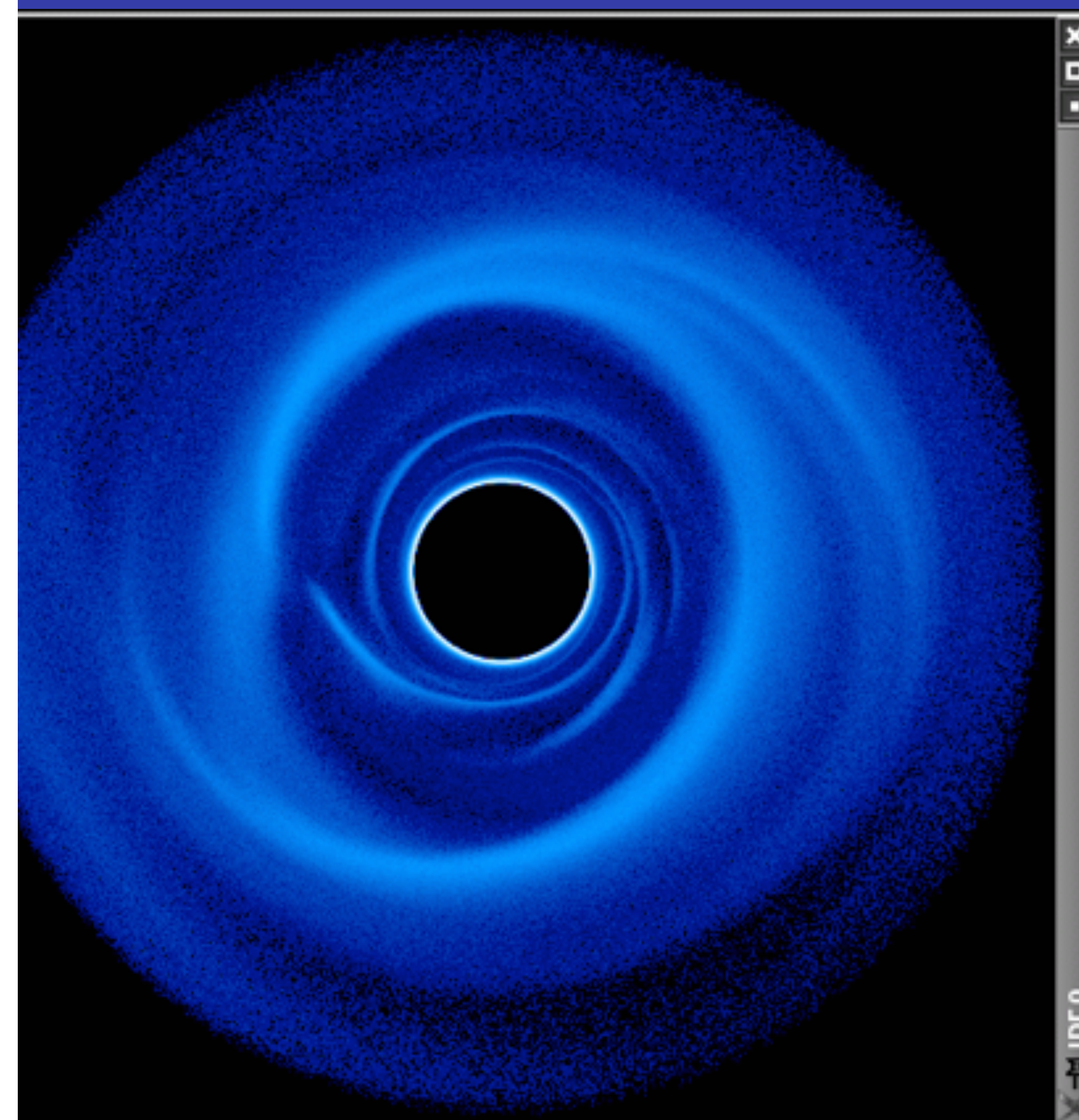
Scattered light and photosphere for irradiation:



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

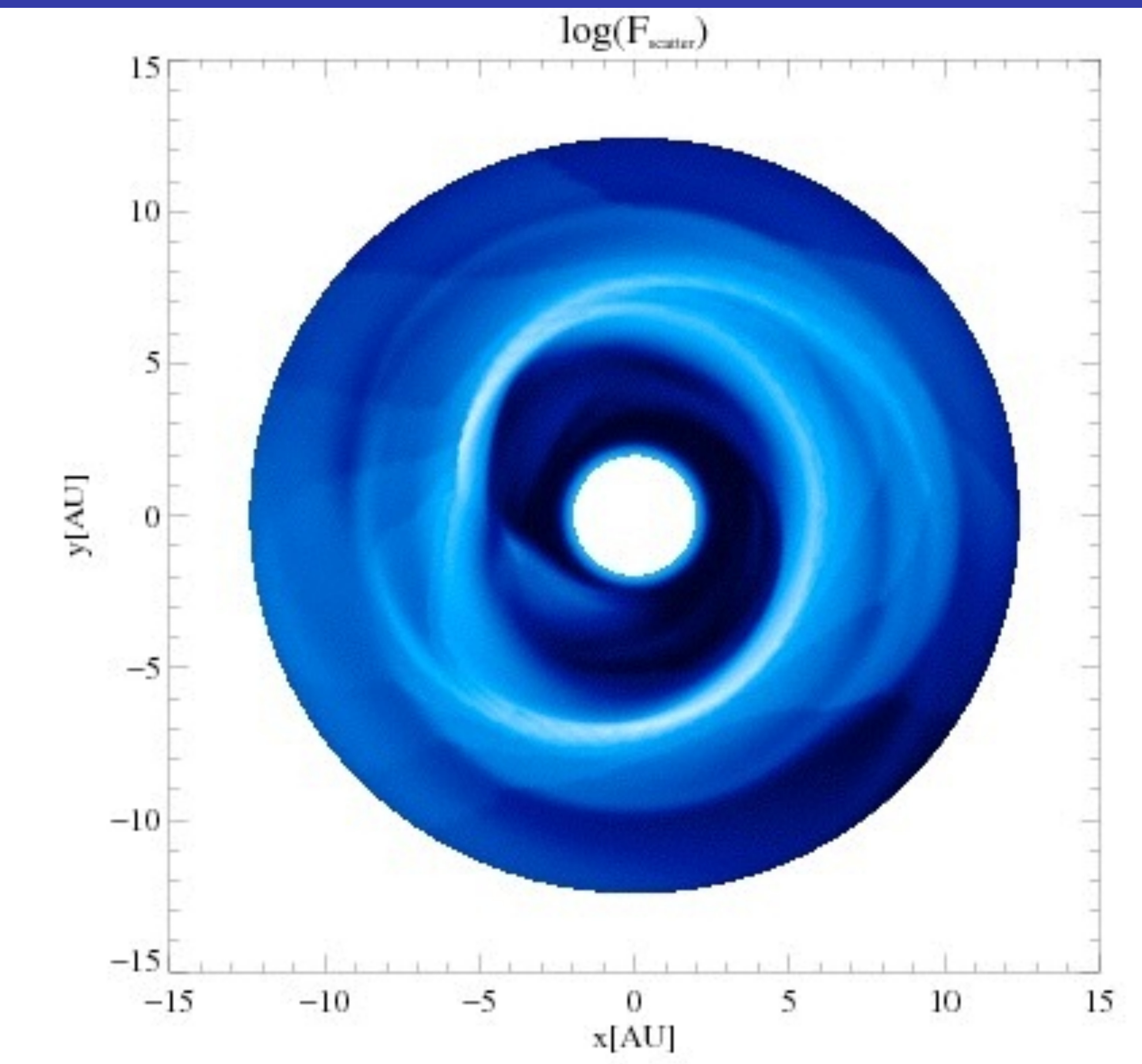


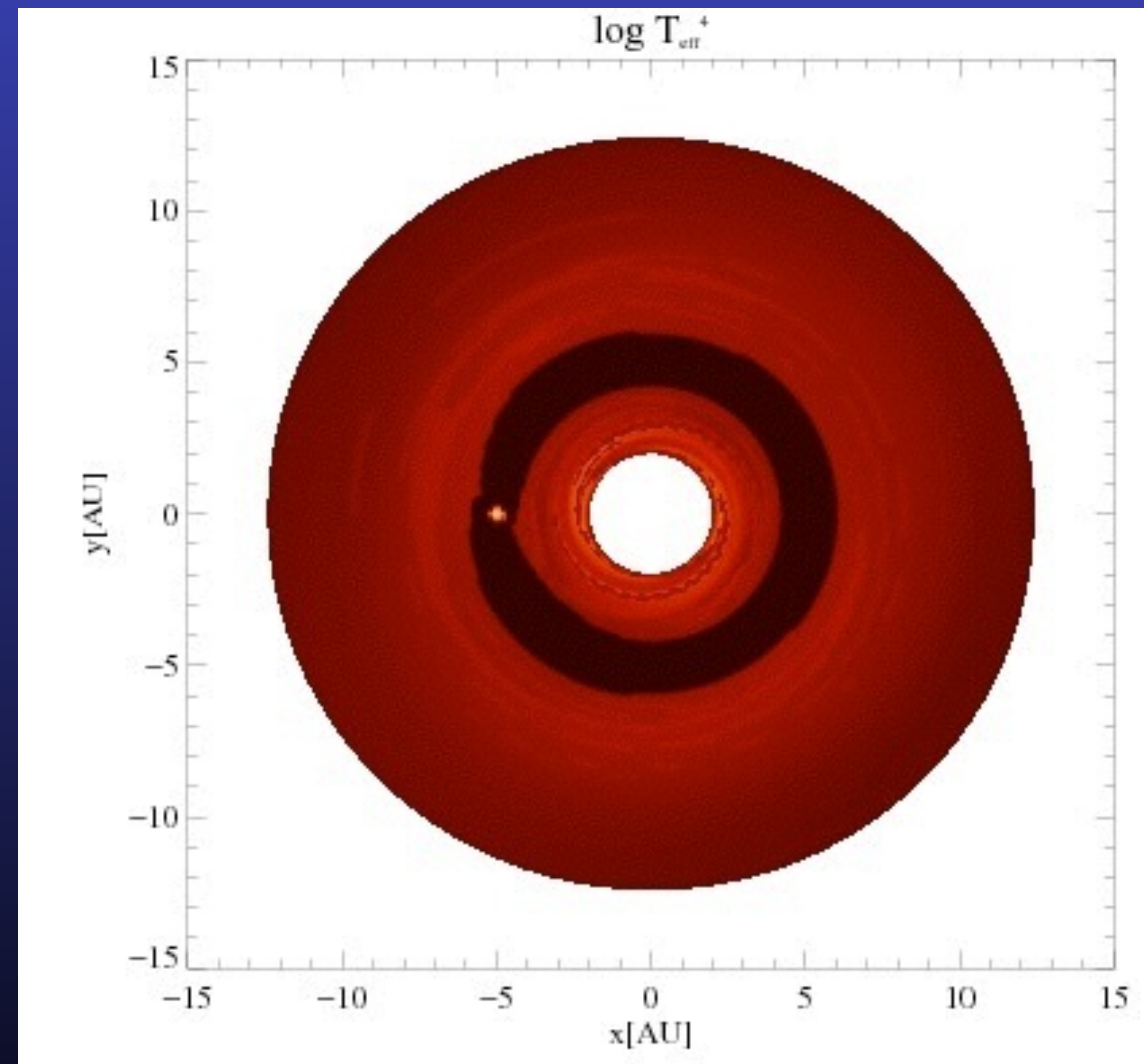
TRAMP (Radiation- Hydro)



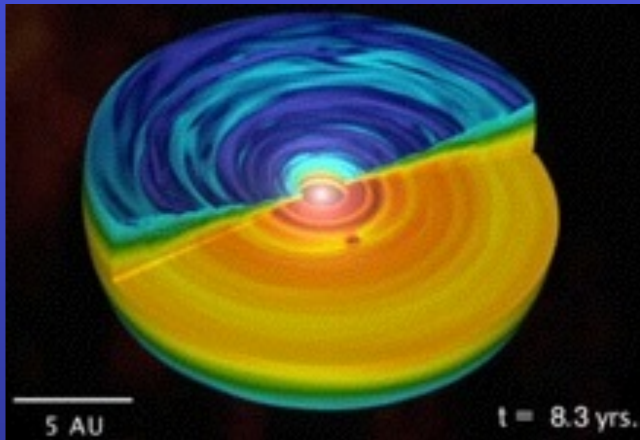
MC3D (S. Wolf)

Test of Radiation transport: scattered light

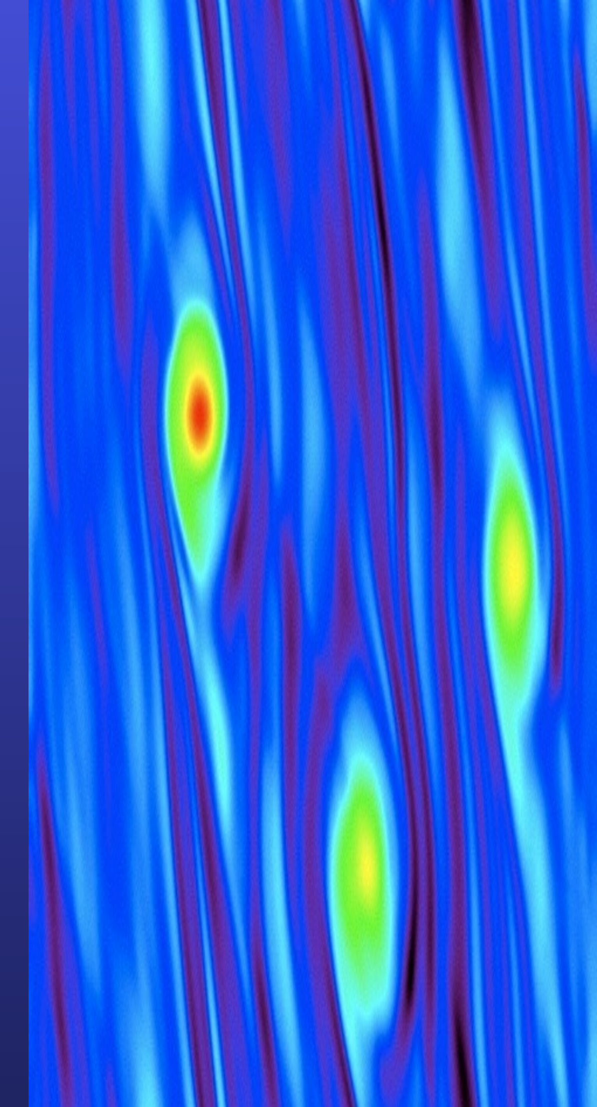




scattered light   emitted light



Conclusions:



- Quantitative Details of Planet-Disk interaction can be tested by comparing Population Synthesis vs. Observed planetary populations.
- Many details of migration are understood, but the turbulent state and pressure profile of disks is unclear.
- Planet migration and gas accretion in turbulent disks still contain many addressable questions.