周惑星円盤の形成に関する輻射流体力学シミュレーション

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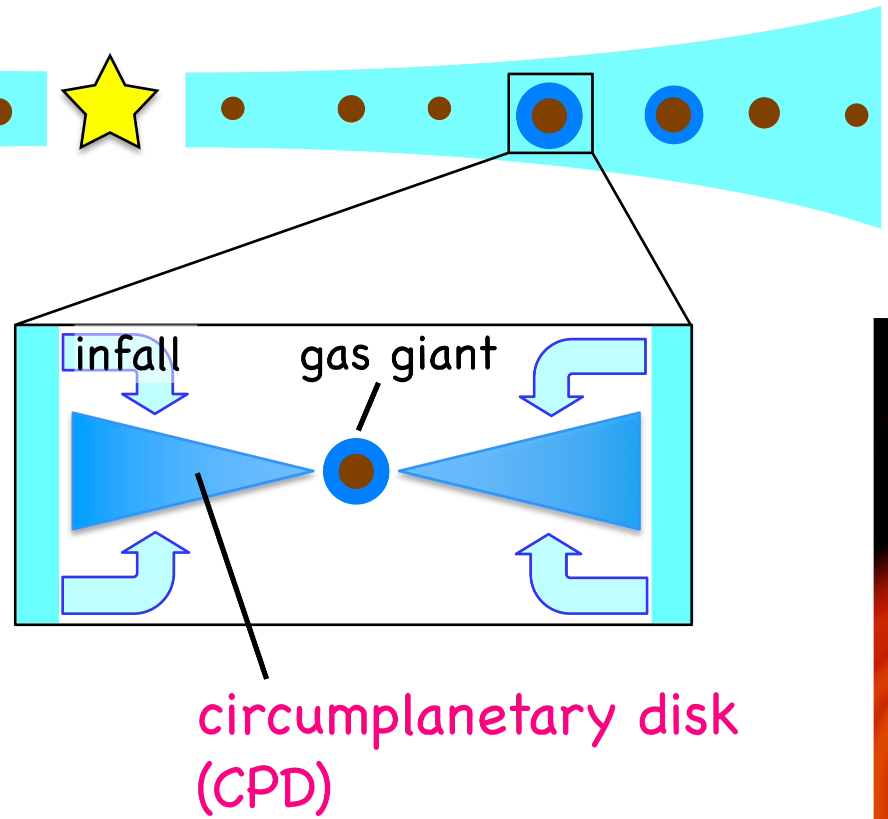
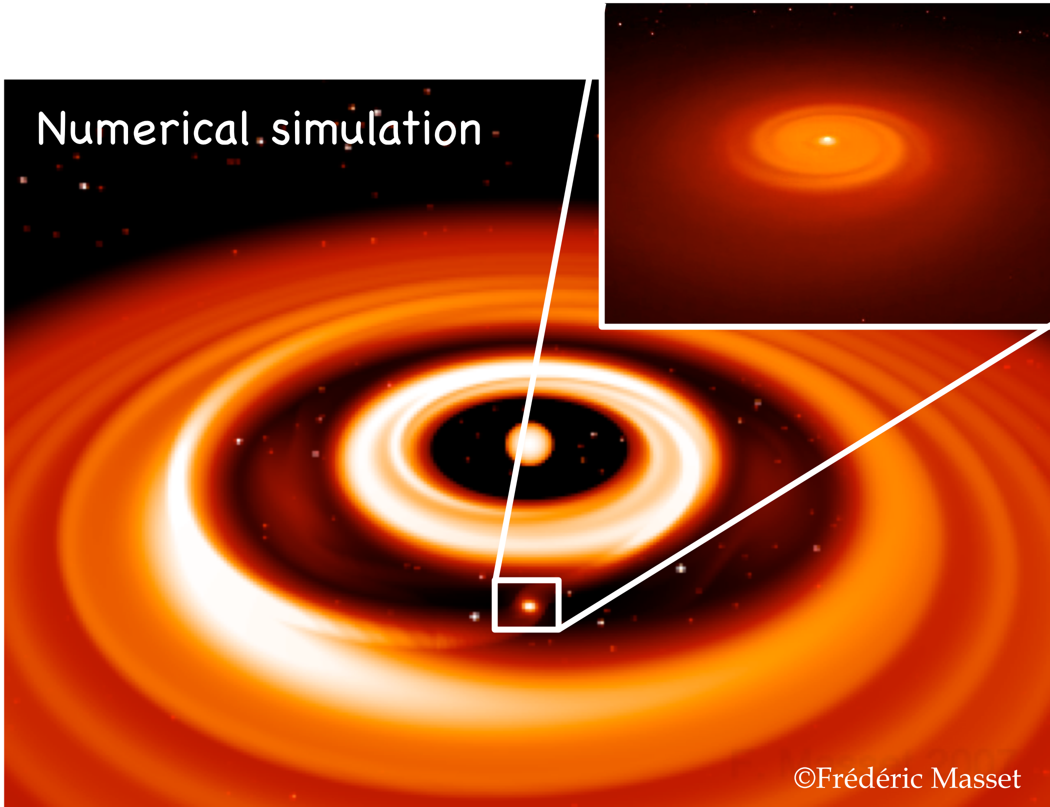
INSTITUTE FOR ADVANCED RESEARCH
NAGOYA UNIVERSITY
SINCE 2002

Formation of Circumplanetary Disk





CPD Models & Moon Formation

- Minimum mass sub-nebula models
  - hold whole material to form moons

e.g. Lunine & Stevenson (1982), Lissauer & Stewart (1993)

- Solid enhanced minimum mass model
  - gas component reduced, laminar

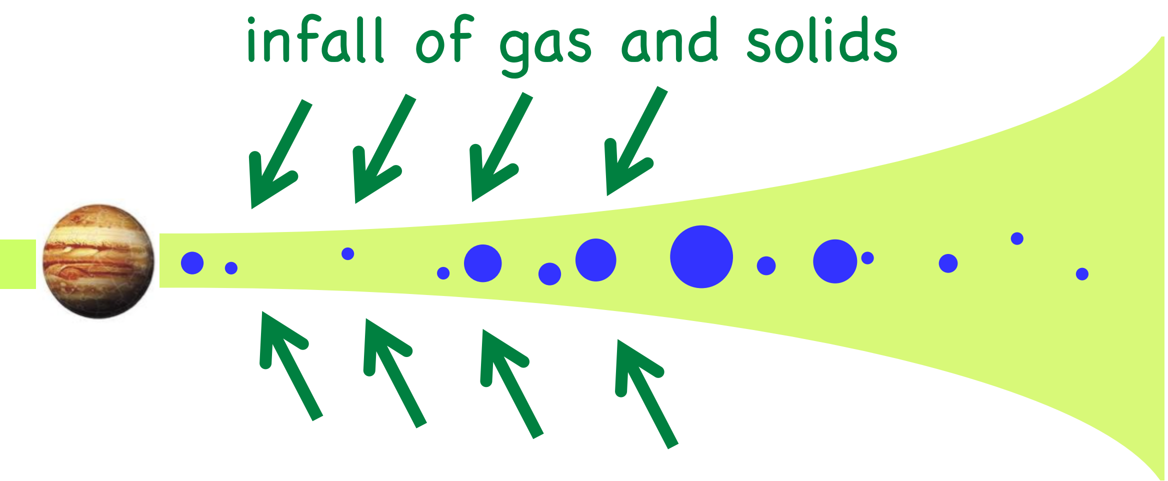
Mosqueira & Estrada (2003ab)

- Gas-starved disk model
  - actively supplied viscously evolving disk

Canup & Ward (2002, 2006), Sasaki+ (2010)

Moon Formation in Gas-starved Disk

Canup & Ward (2002, 2006)



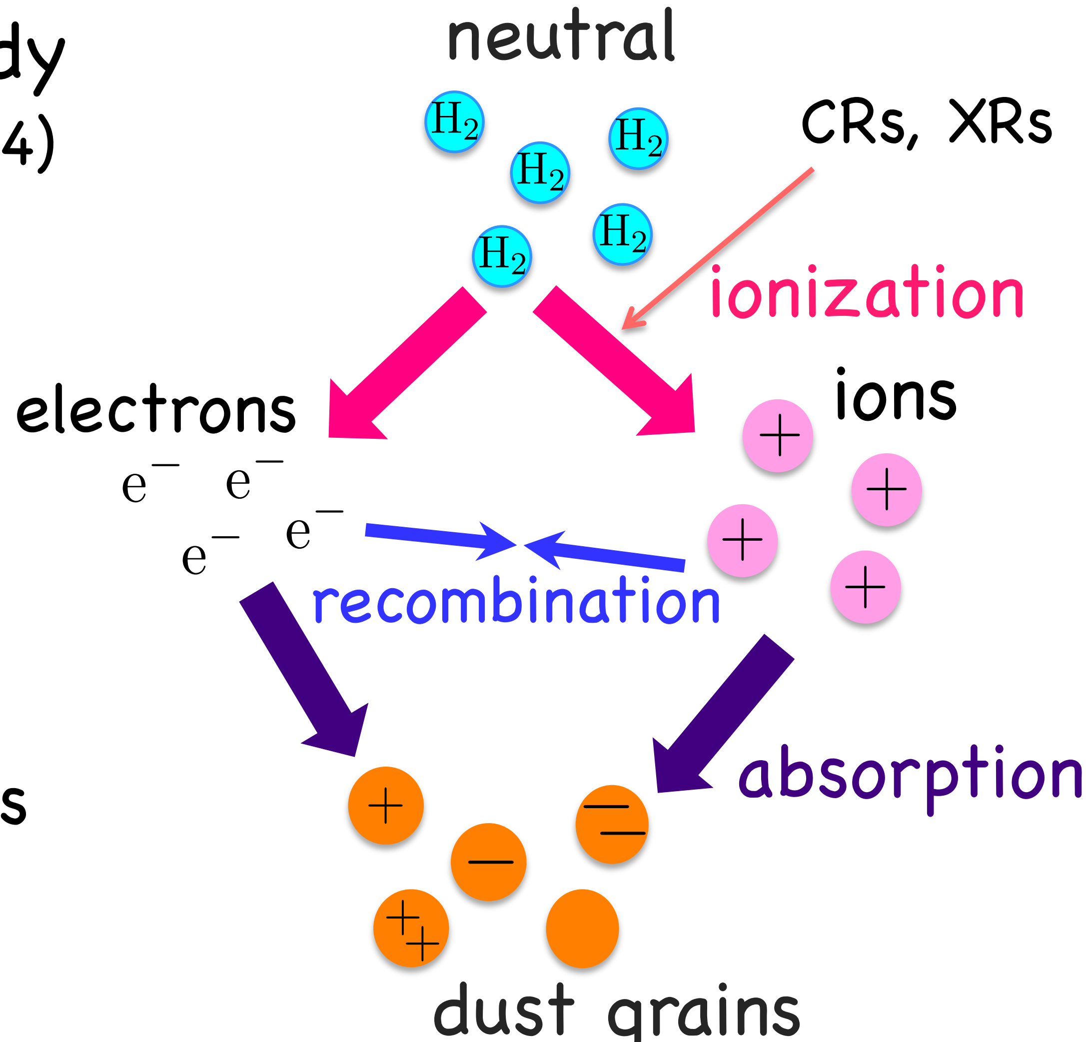
- continuous mass infall from PPD
- turbulent viscosity keeps disk less massive

What is origin?

Can CPDs Sustain MRI?

Our previous study
(Fujii et al. 2011, 2014)

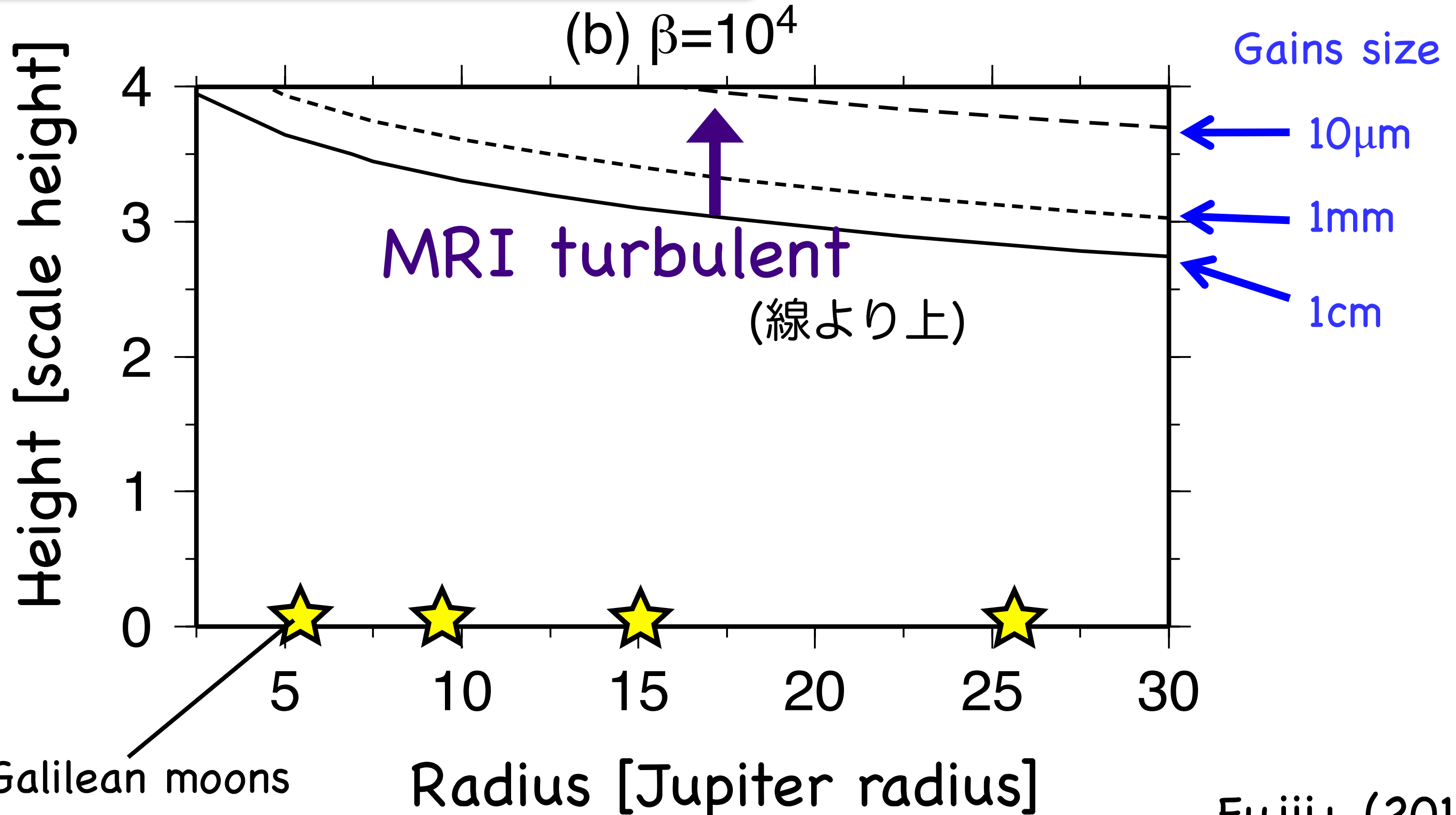
Ionization sources
- cosmic rays
- scattered X-rays
- Radionuclides



Feasibility of MRI in Gas-starved Disk Model

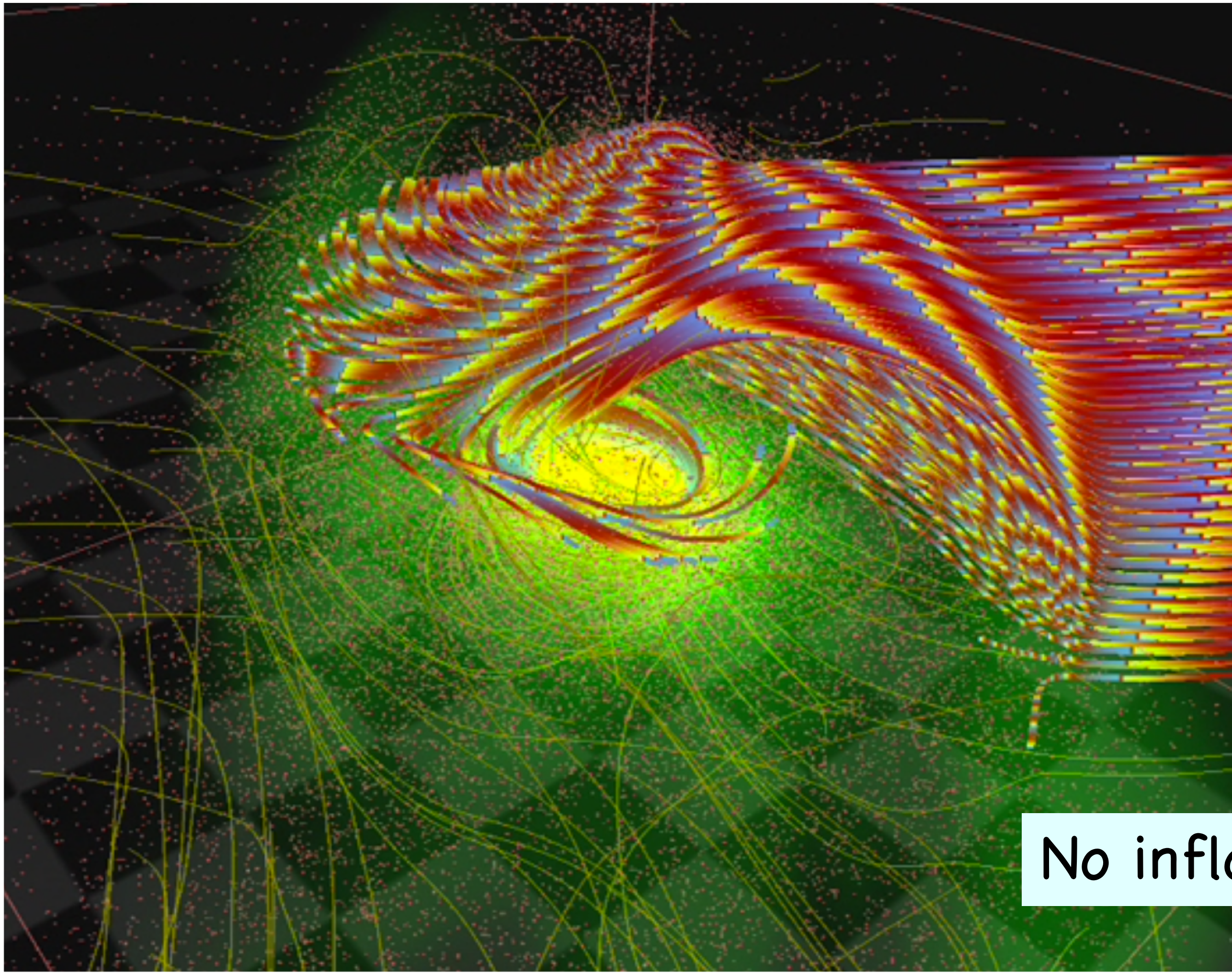
期待される粘性値は達成できない

dust-to-gas mass ratio = 10^{-2}



Fujii+ (2011)

Simulations of CPD Formation



Tanigawa et al. (2012, Visualization: T. Takeda)

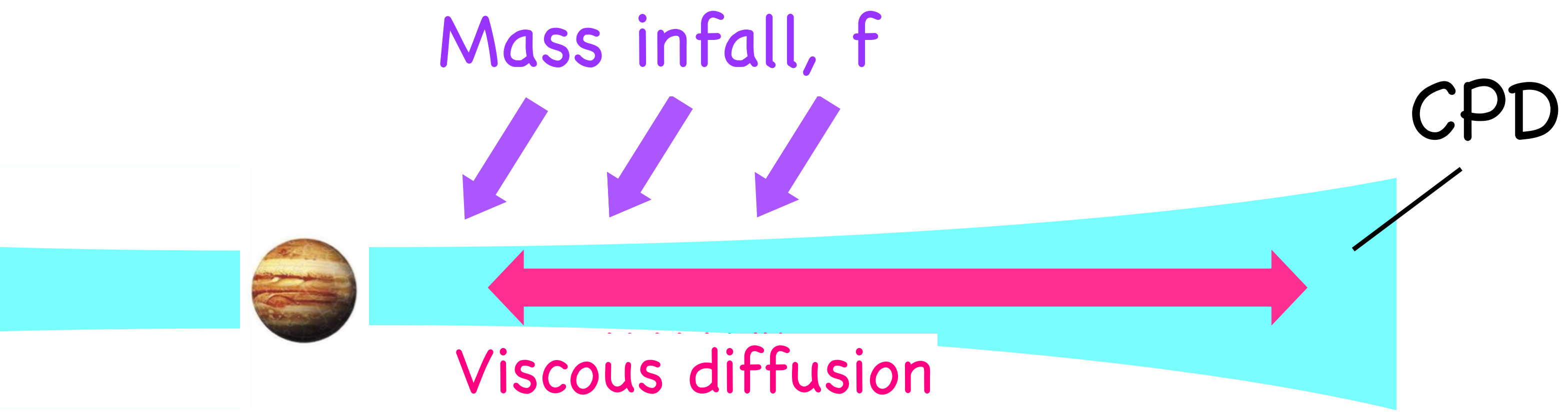
Isothermal
Inviscid

Local simulation
11-levels of SMR

$r_{smooth}=r_{sink} \sim 0.4R_J$
$(0.07\%$ of $r_H)$

No inflow from midplane

CPD Models Based on Tanigawa+ (2012)



Diffusion equation with additional term of infall

$$\frac{\partial \Sigma}{\partial t} = \underline{\frac{1}{r}\frac{\partial}{\partial r}\left(3r^{\frac{1}{2}}\frac{\partial}{\partial r}\left(r^{\frac{1}{2}}\nu\Sigma\right)\right)} + \underline{f}$$

r : radius
Σ: surface density
c_s: sound speed
H: scale height

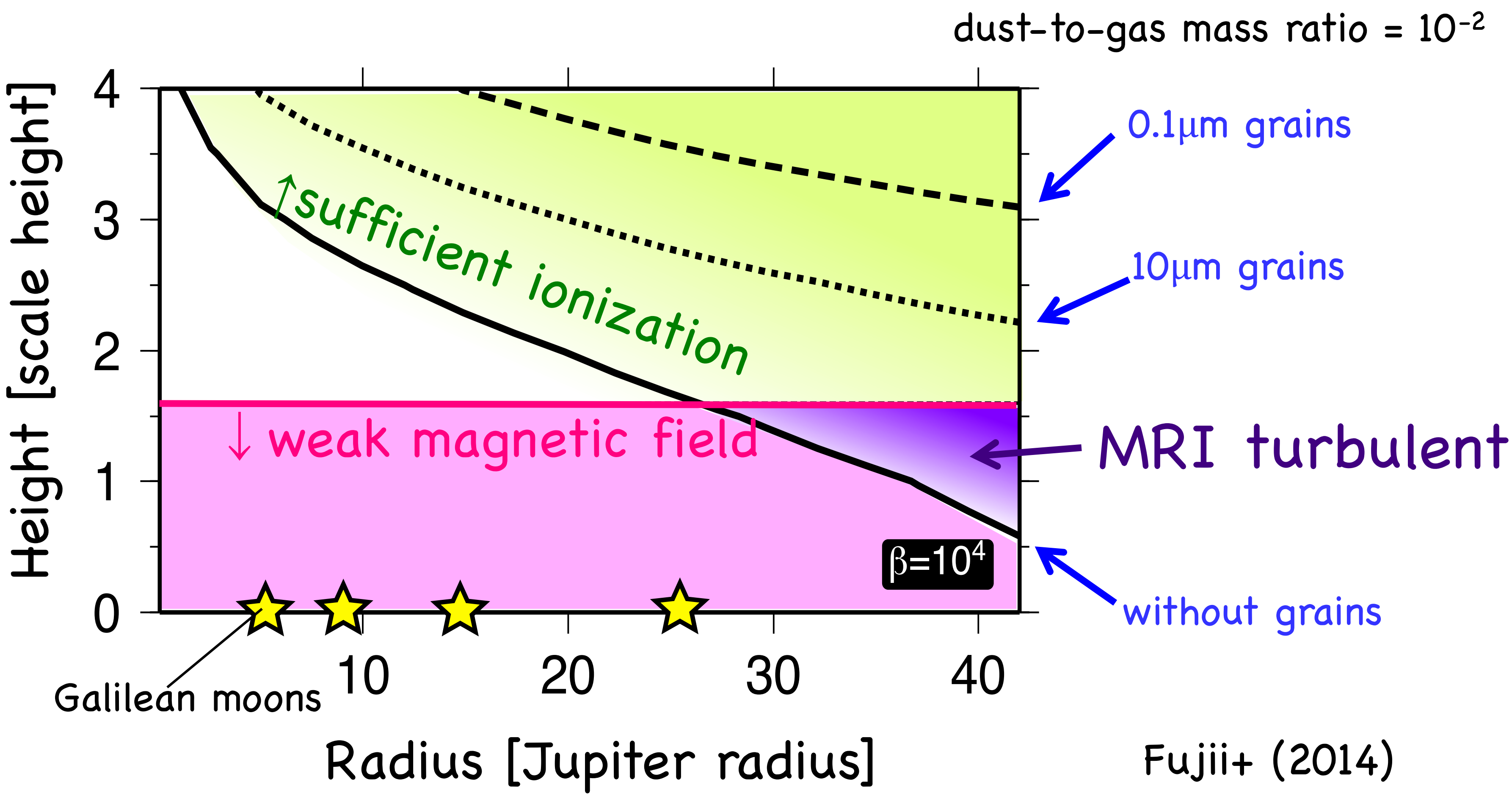
$\nu=\alpha c_s H$:
viscous coefficient
α: viscous parameter

$$f = 1.3\times 10^{-3}\epsilon\left(\frac{\Sigma_{\rm p}}{143\ {\rm g\ cm^{-2}}}\right)\left(\frac{r}{R_{\rm J}}\right)^{-1}\ {\rm g\ cm^{-2}\ s^{-1}}$$

(Tanigawa+ 2012)

↑ reduction factor (これは単純なモデル, Fujii+ 2014, 2017)

Feasibility of MRI in CPD Models Based on Tanigawa et at. (2012)

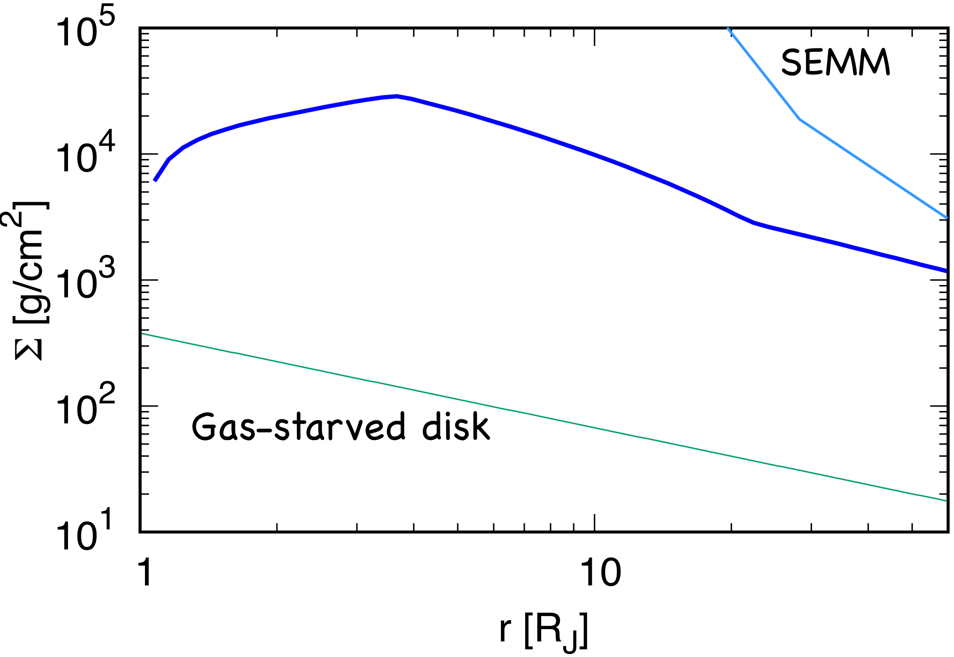


Turbulence cannot develop in moon forming region

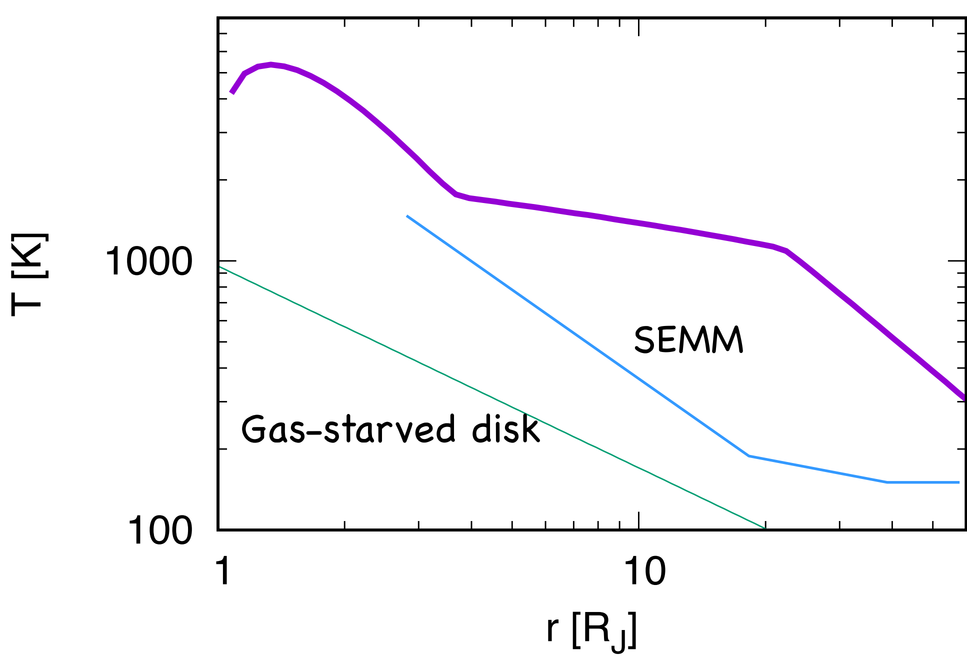
Moon Formation in Weakly Accreting Disks

Disk structure with $\begin{cases} \alpha_{floor}=10^{-4} \\ \varepsilon=10^{-2} \text{ (with gap in PPD)} \end{cases}$

Surface density



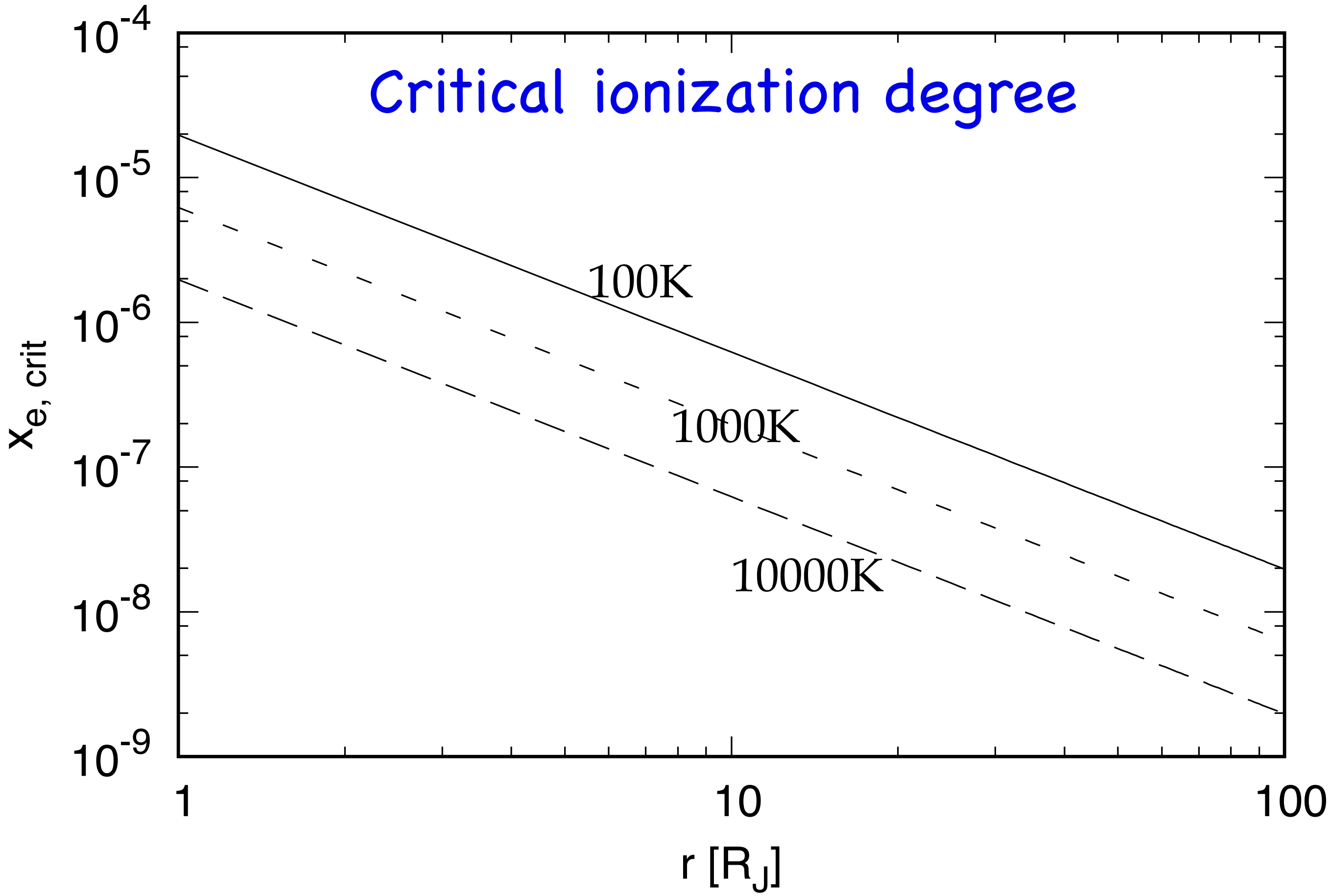
Temperature



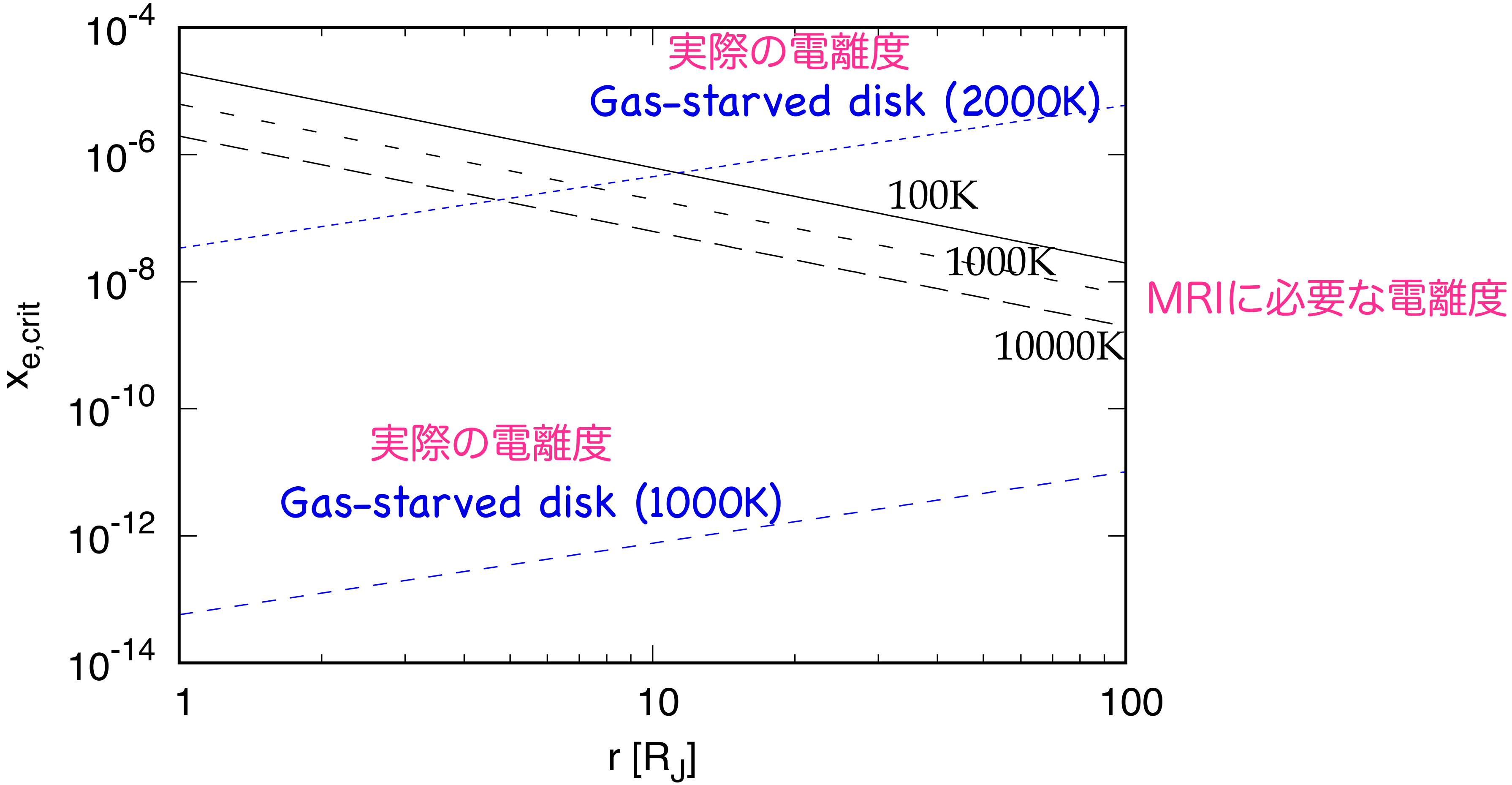
Thermal Ionization in CPD?

Saha equation for K, Na, Mg, & H

Typical assumption: if T > 1000K ⇒ MRI active



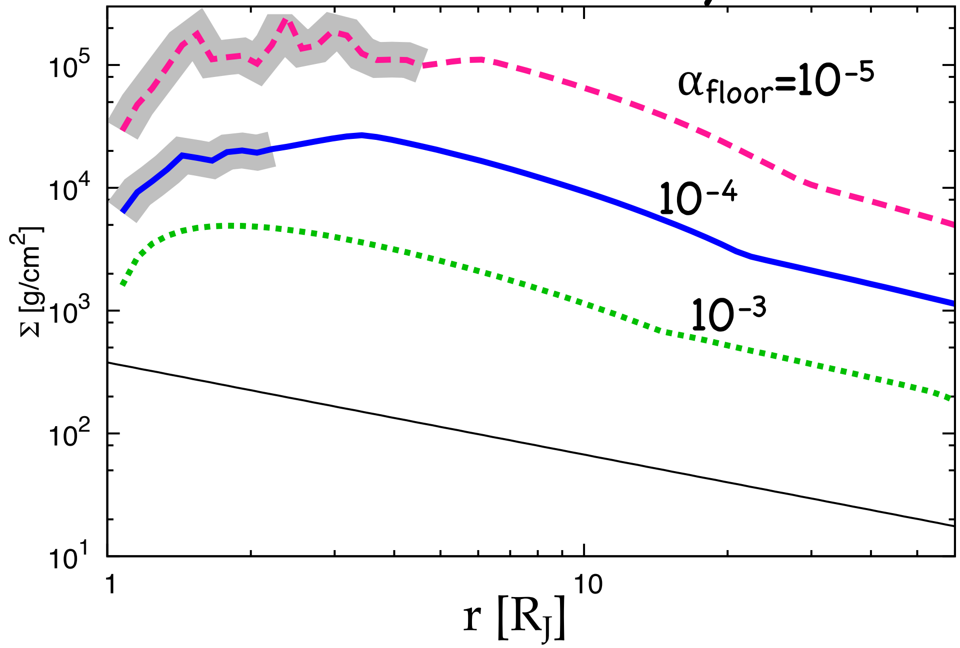
T=1000K is not Enough in CPD



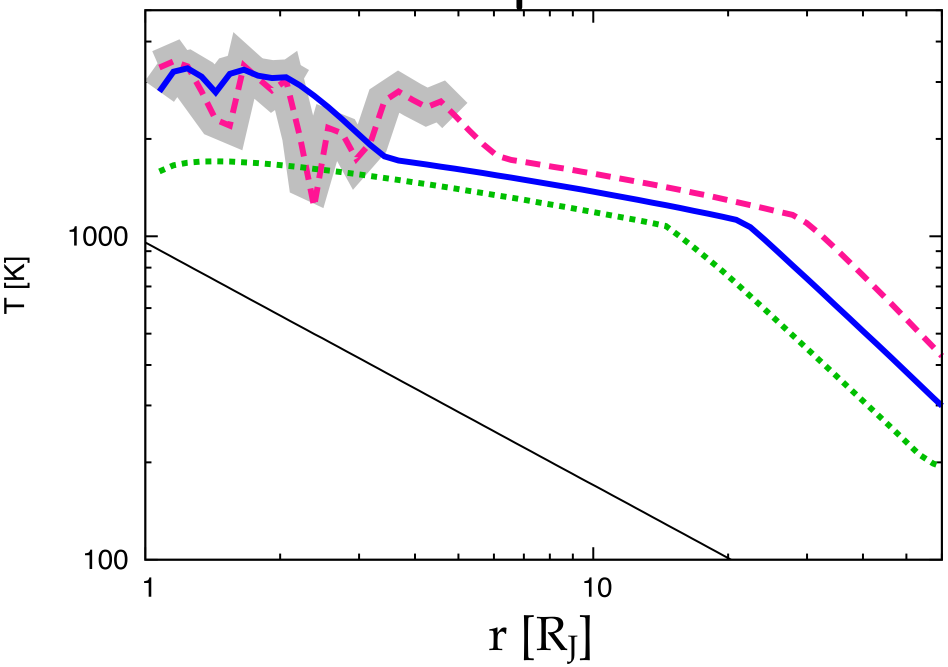
MRI Regulates Temperature?

1D model of CPDs by Fujii+ (2017)

Surface density



Temperature



T $\gtrsim$ 2500

➔ Thermal ionization triggers MRI

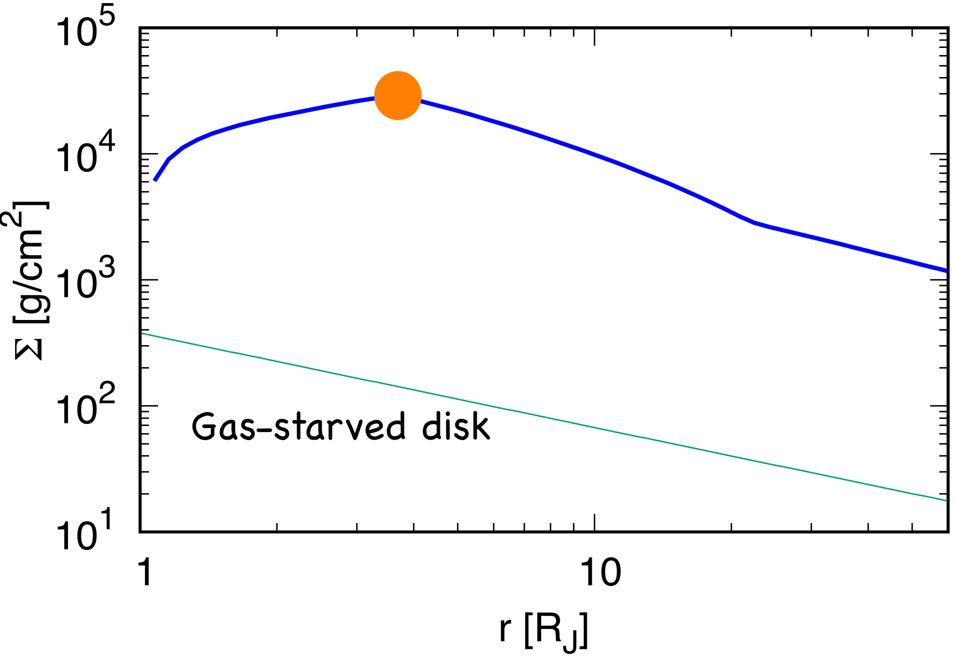
➔ Accretion rate increases

Bell & Lin opacity
No compression heating

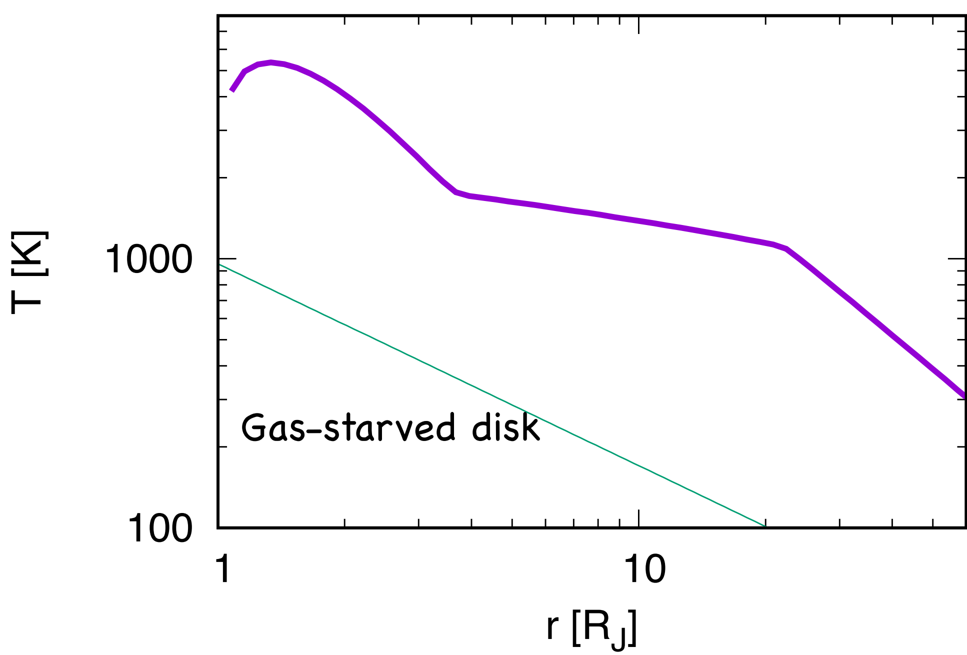
Can Moon Stop Migrating?

α_{floor}=10^{-4}
ε=10^{-2} (with gap in PPD)

Surface density



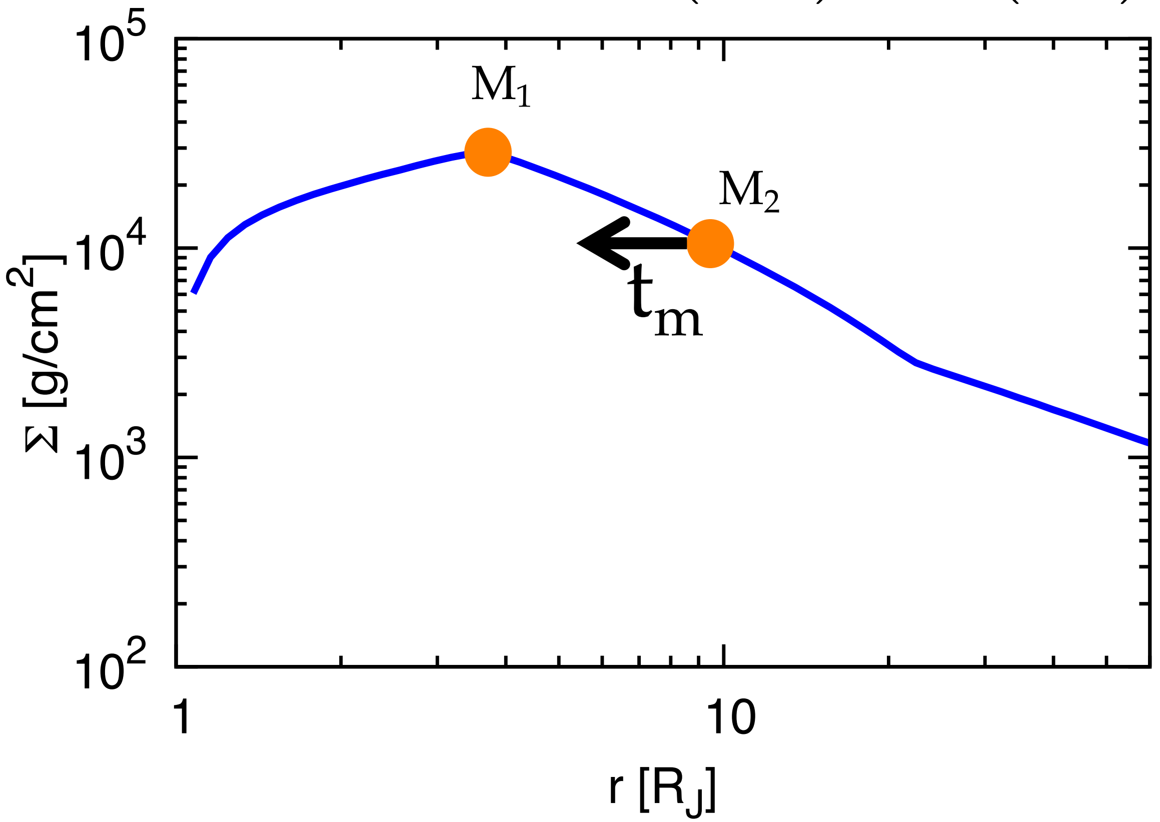
Temperature



Capture of Moons in Resonance

$t_m > t_{m,\mathrm{crit}} \Rightarrow$ captured

$$t_{m,\mathrm{crit}} = 2.5 \times 10^4 \left(\frac{M_\mathrm{s}}{M_\mathrm{Io}}\right)^{-4/3} \left(\frac{M_p}{M_\mathrm{J}}\right)^{4/3} T_K$$ (Ogihara & Kobayashi 2013)



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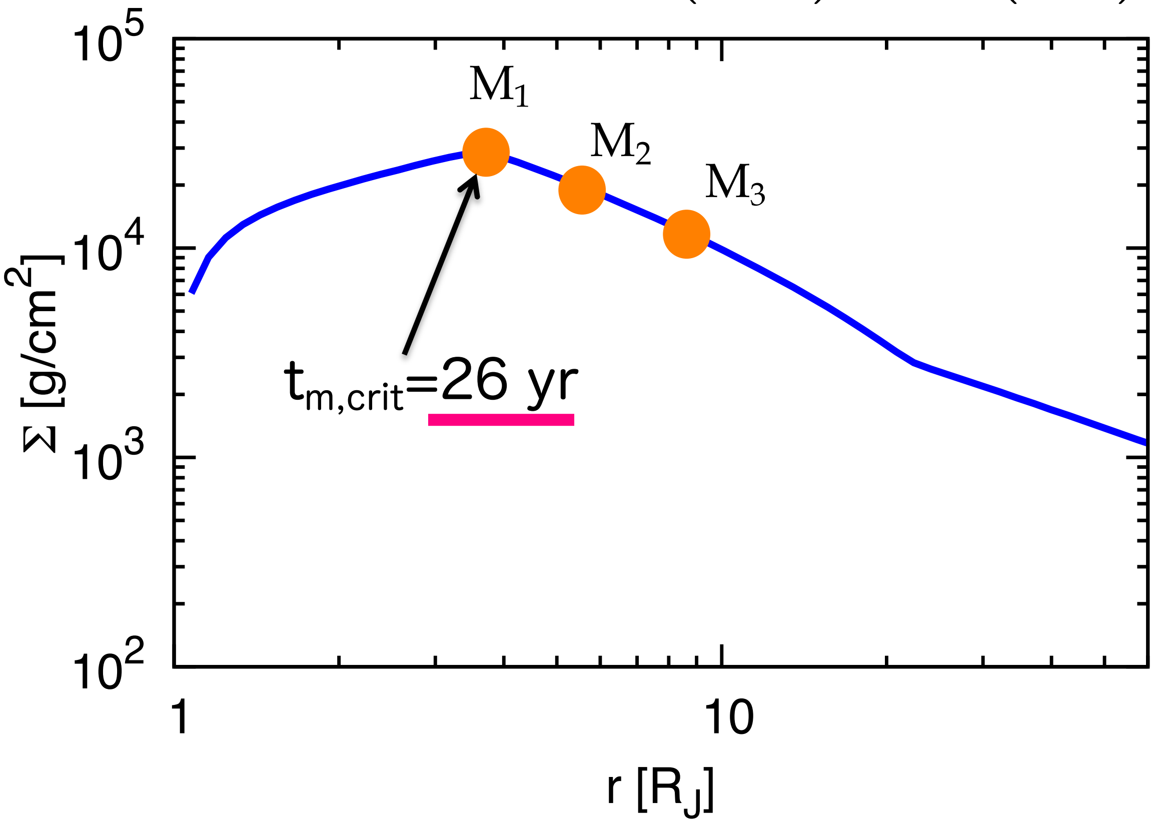


2:1 resonance with M_1(@3.5R_J)
$\Rightarrow$ M_2 @5.6R_J

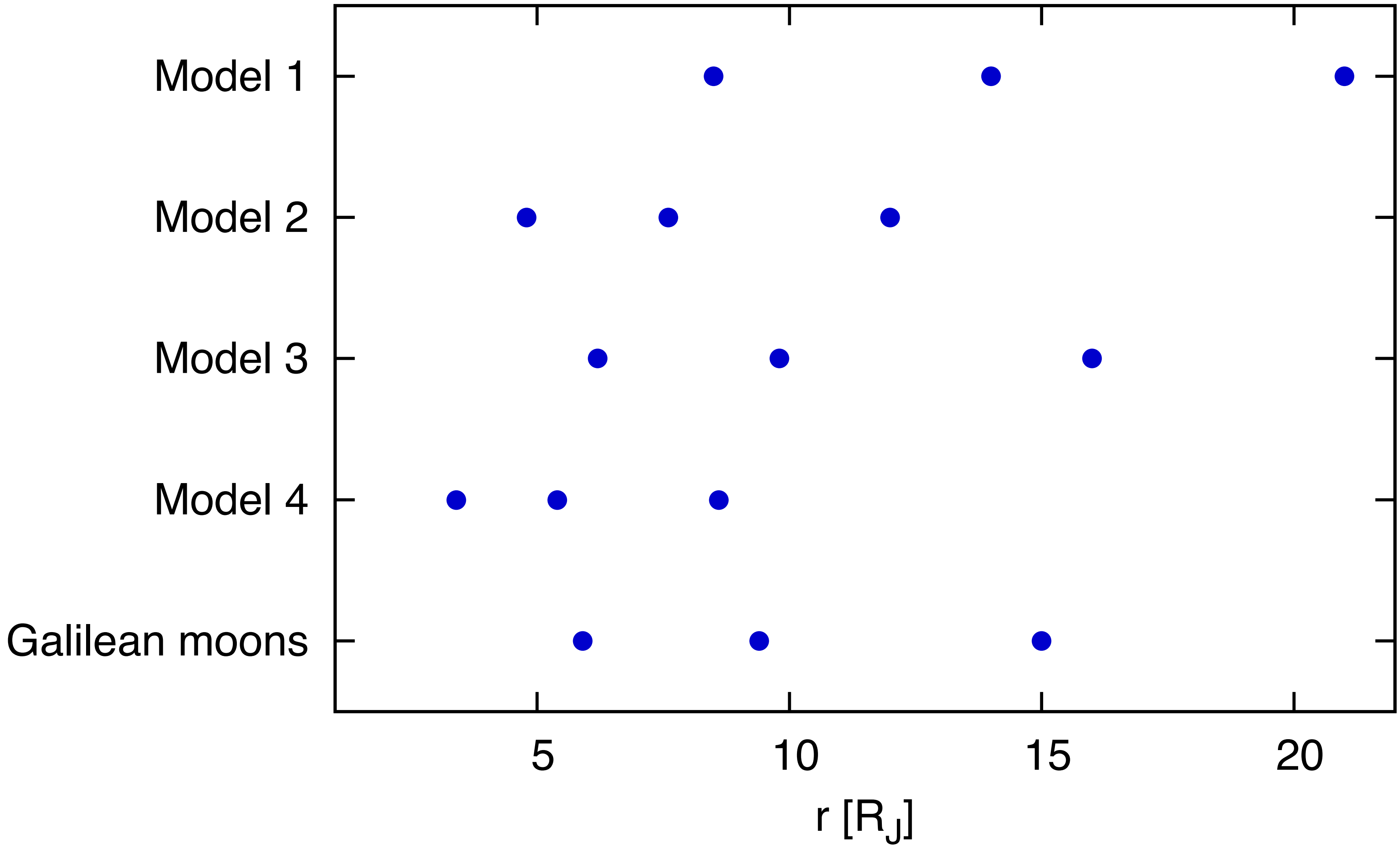
$t_m(5.6R_J)$=2400 yr > $t_{m,\mathrm{crit}}$
$\Rightarrow$ captured

M_3 can be also captured @8.8R_J

$M_1:M_2:M_3=4:2:1$

Orbits of Systems

Fujii+ (2017)



ガリレオ衛星のようなものは一旦は作れそう (Fujii+2017)

それが生き残れるかは円盤の進化次第

周惑星円盤の長時間進化が知りたい

その前に、、、

磁場の影響や温度進化も考慮すると周惑星円盤の形成の様子も異ってくるかもしれない

磁場ありの計算

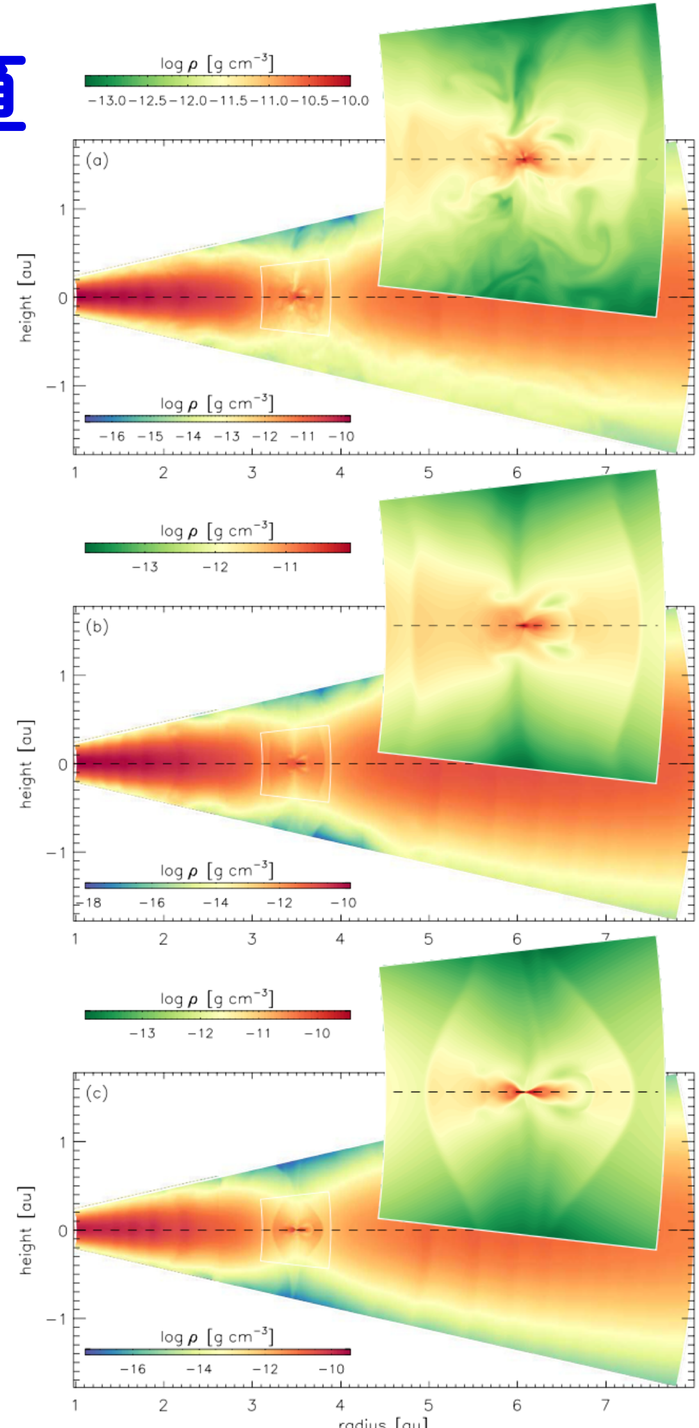
Gressel et al. (2013)

Global
Viscous (MRI)

3-levels of AMR

$r_{smooth}= r_{sink}$: 5% of r_H

(~Calisto's semi-major axis)



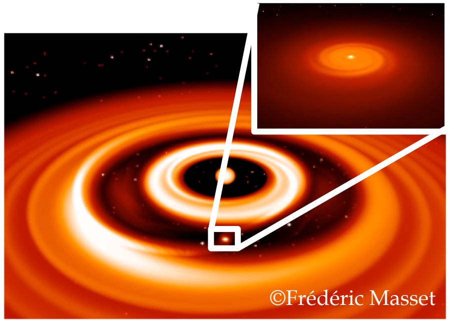
MHD

HD with cooling

Isothermal HD

Extremely High Temperature

3D-RHD simulation by Szulagyi+ (2016)



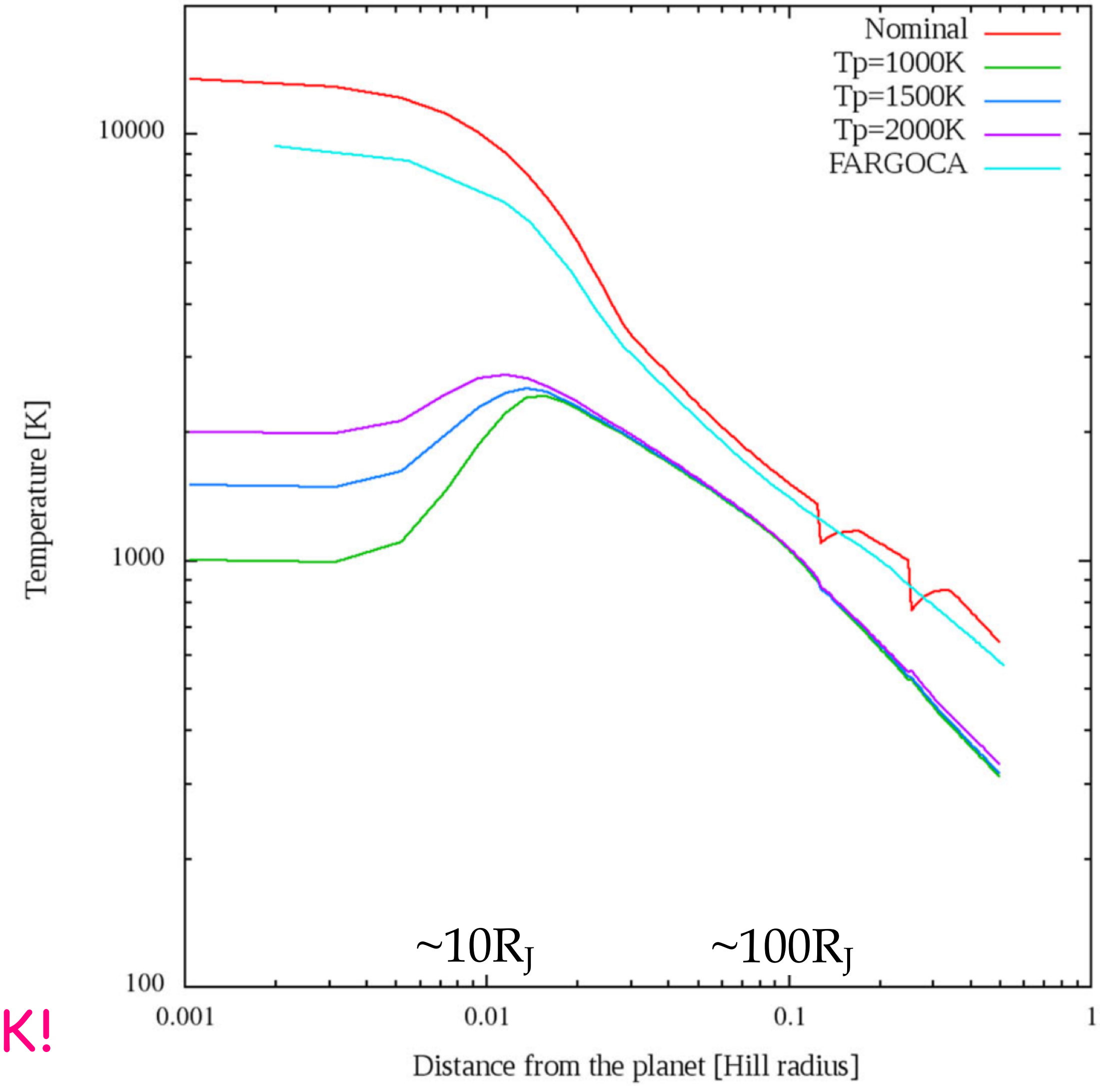
$1M_J$ planet at 5.2AU

Adiabatic EOS γ=1.43

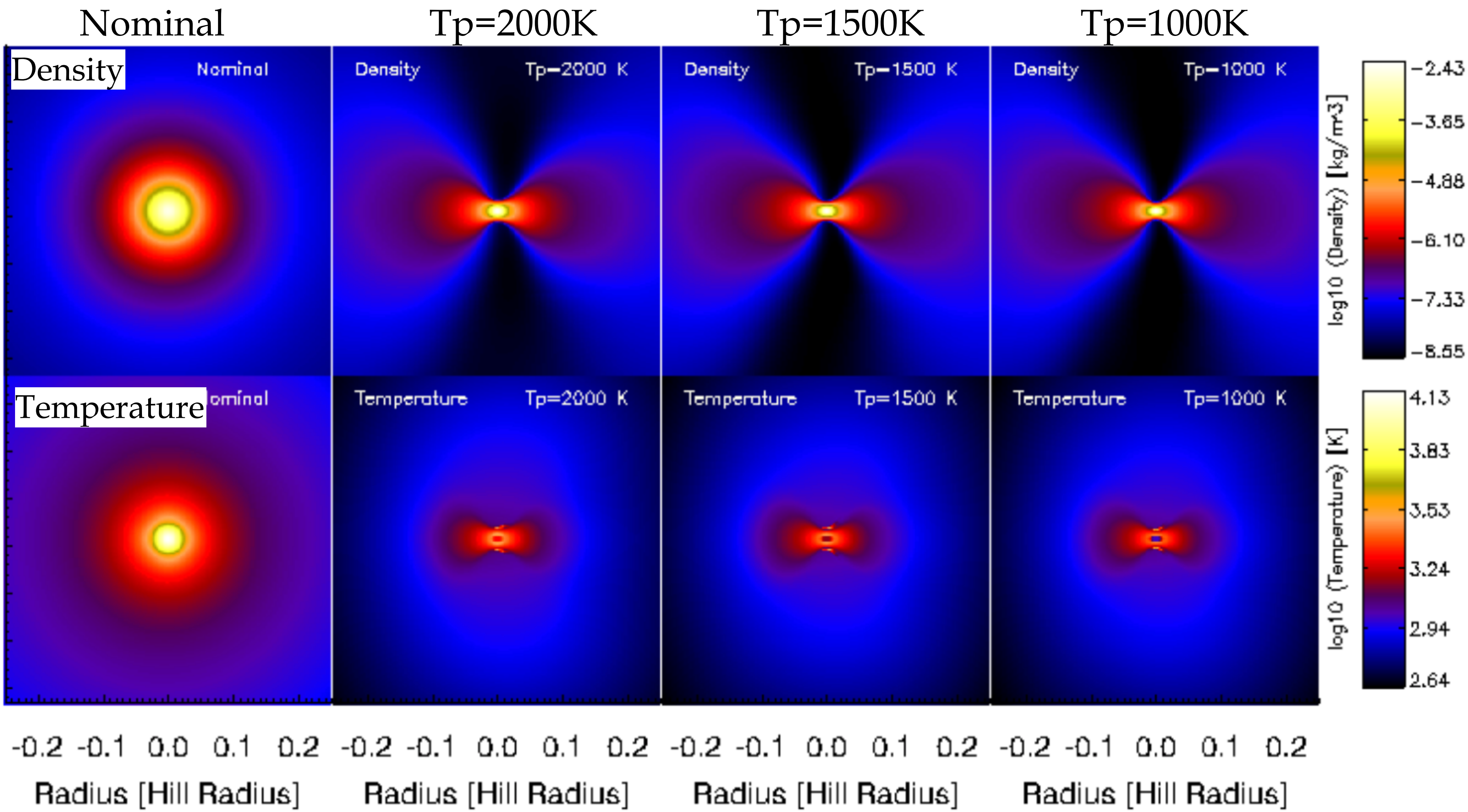
Bell & Lin opacity

Viscosity: α~0.004

Max temperature: 13000K!

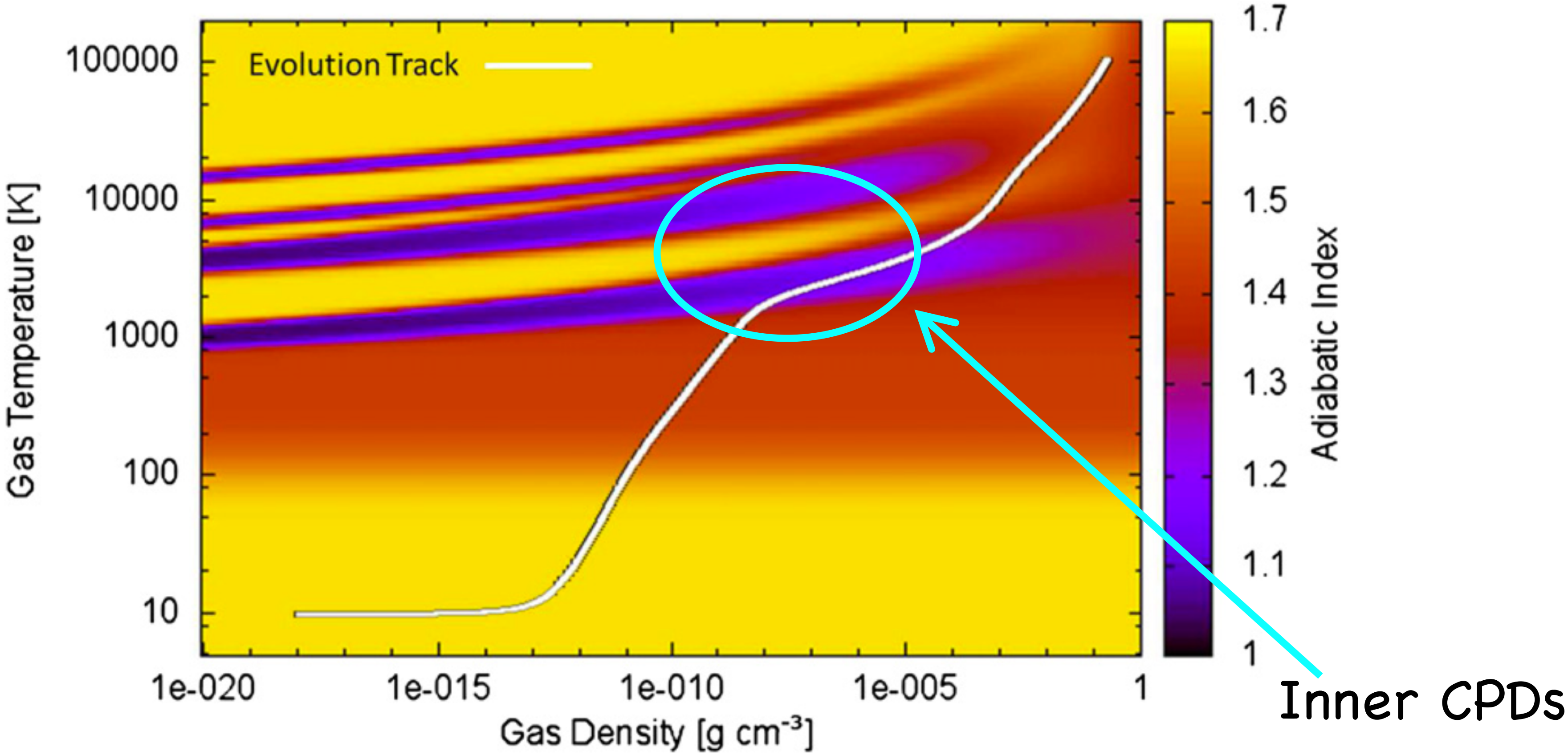


Envelope? Disk?



Szulagyi+ (2016)

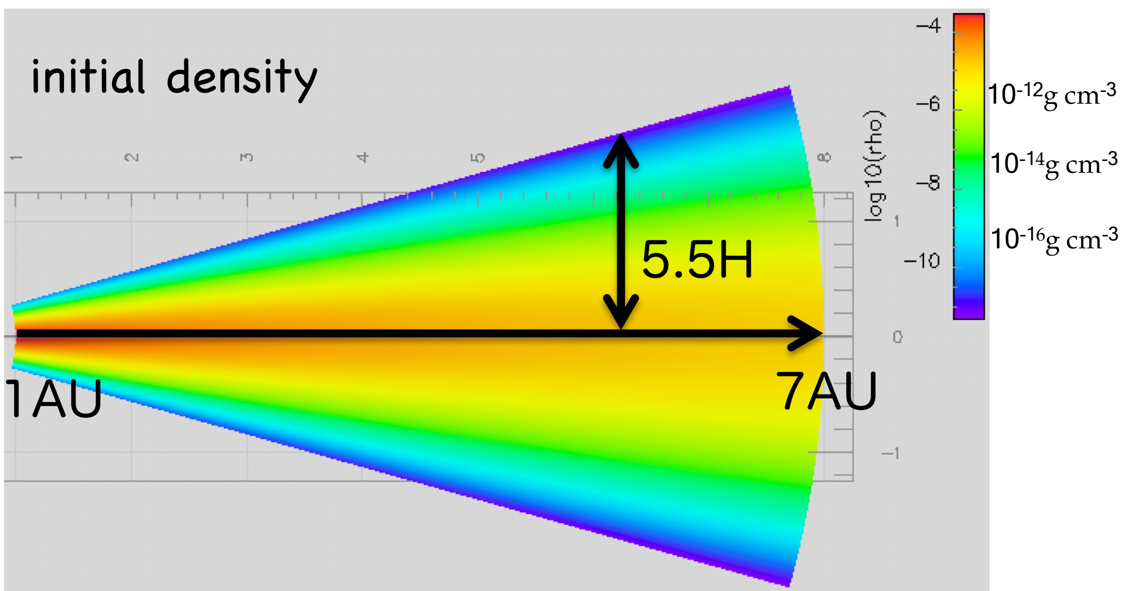
Realistic EOS

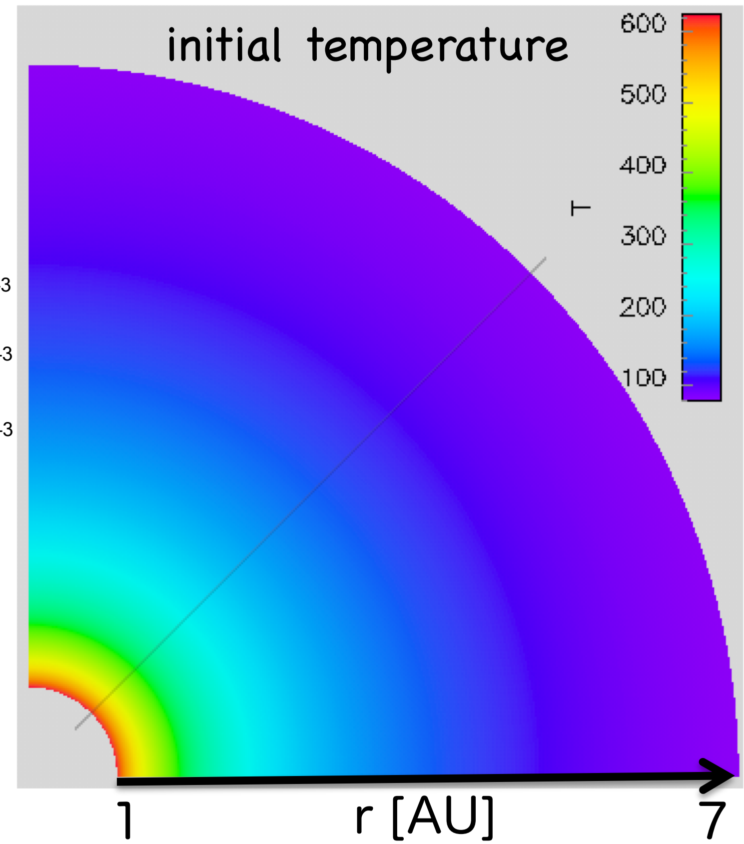


Tomida+ (2013)

Radiation HD Simulations

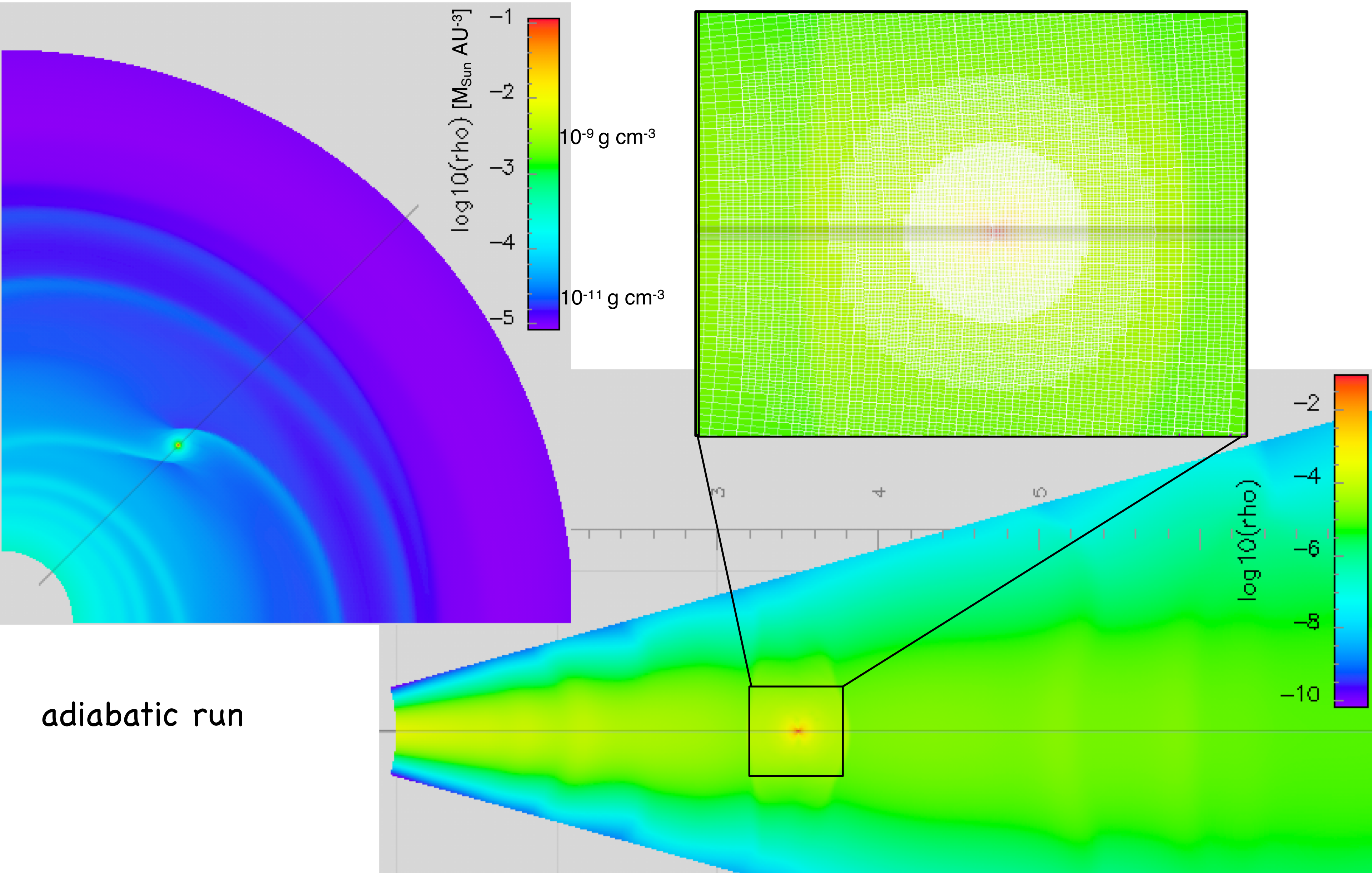
- code: NIRVANA3.5 (Ziegler 2004&2011, modified by Oliver Gressel)
- Adopted realistic EOS table by Tomida+ (2013, 2015), $\alpha=10^{-4}$
- planet: 1 Jupiter mass, orbit=3.5AU
- disk model, domain size:





- resolution: $N_r \times N_\theta \times N_\varphi$ = 160x80x128 (base) + 5 levels of AMR

Snapshot: Density Distribution



adiabatic run