Radiation Hydrodynamic Simulation of the Formation of Circumplanetary Disks

Yuri Fujii (IAR, Nagoya University)

Oliver Gressel (AIP), Kengo Tomida (Osaka U.), Udo Ziegler (AIP)

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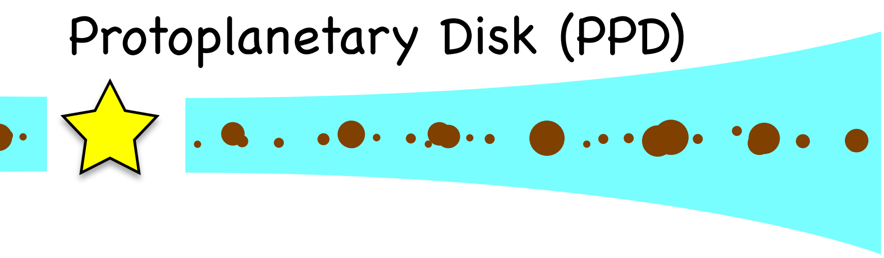
Career Development Project for Researchers of Allied Universities

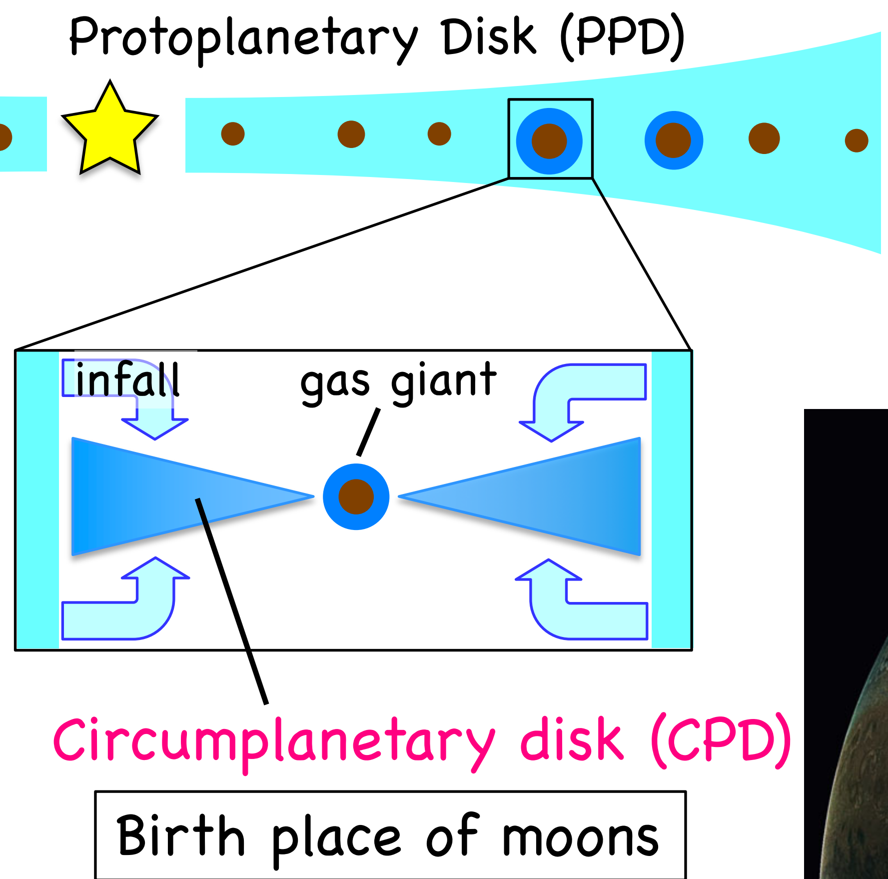
INSTITUTE FOR ADVANCED RESEARCH NAGOYA UNIVERSITY SINCE 2002

Planet Formation in PPD



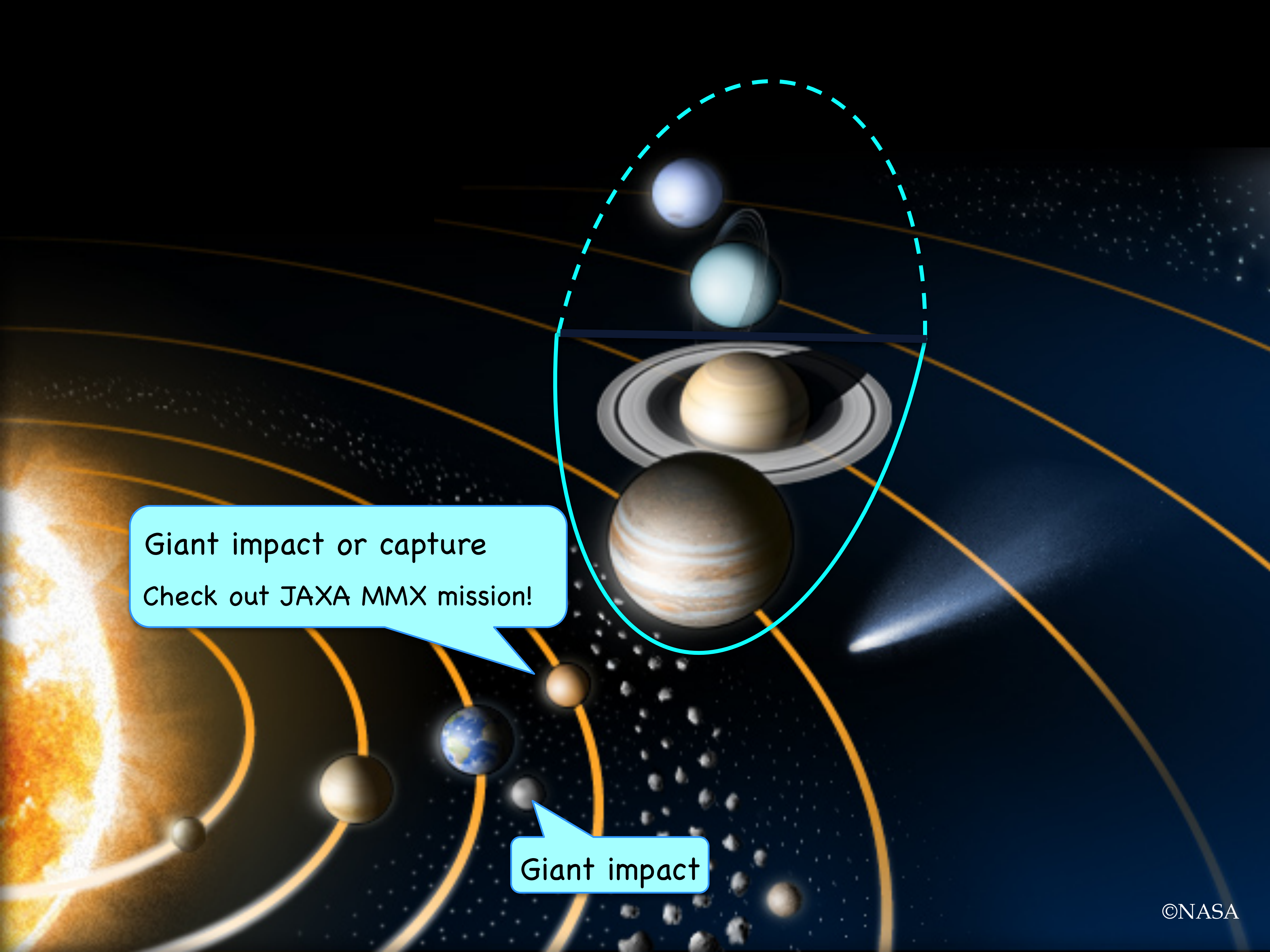
Planetesimal formation

Planet Formation in PPD

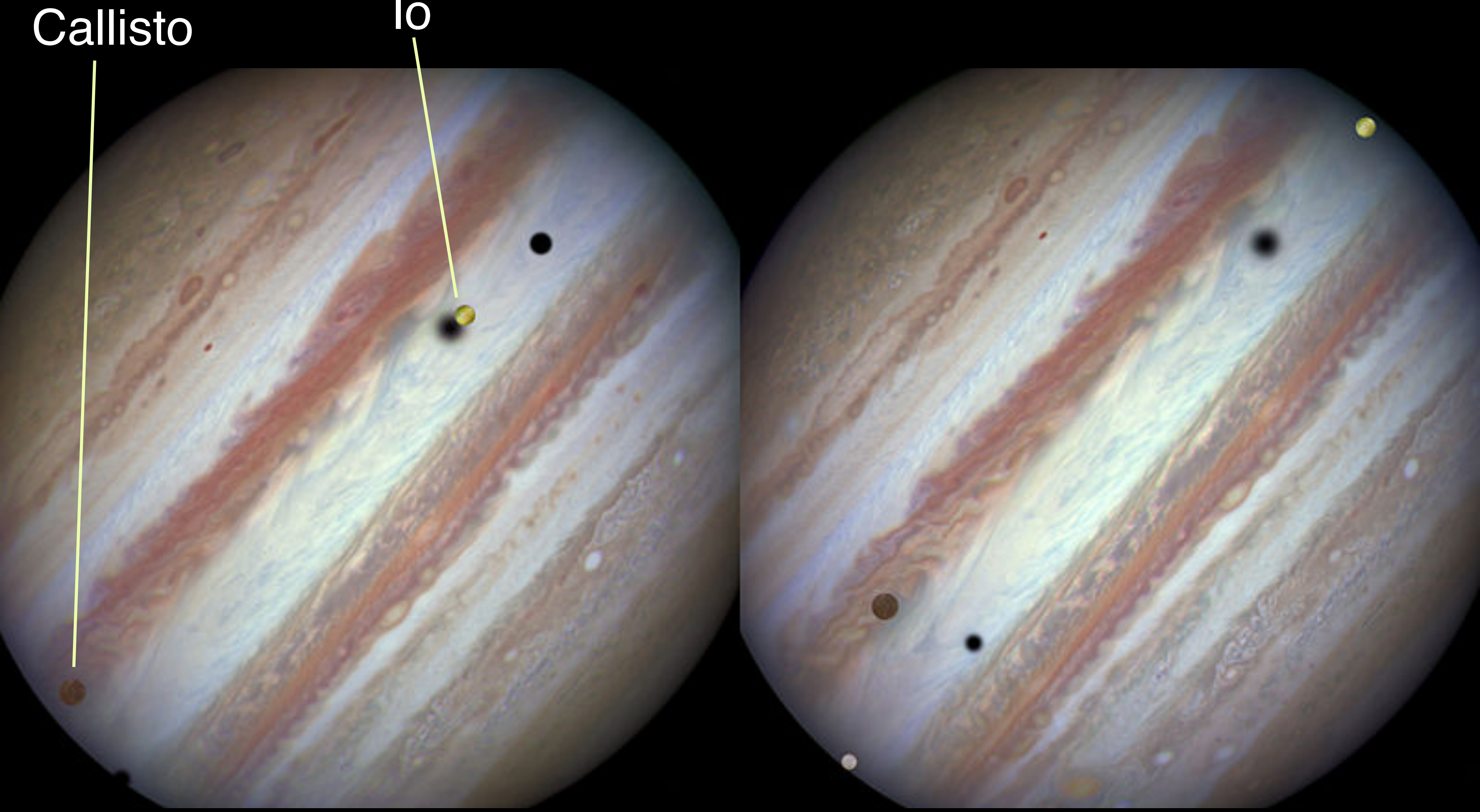


Gas accretion

= Formation of gas giants

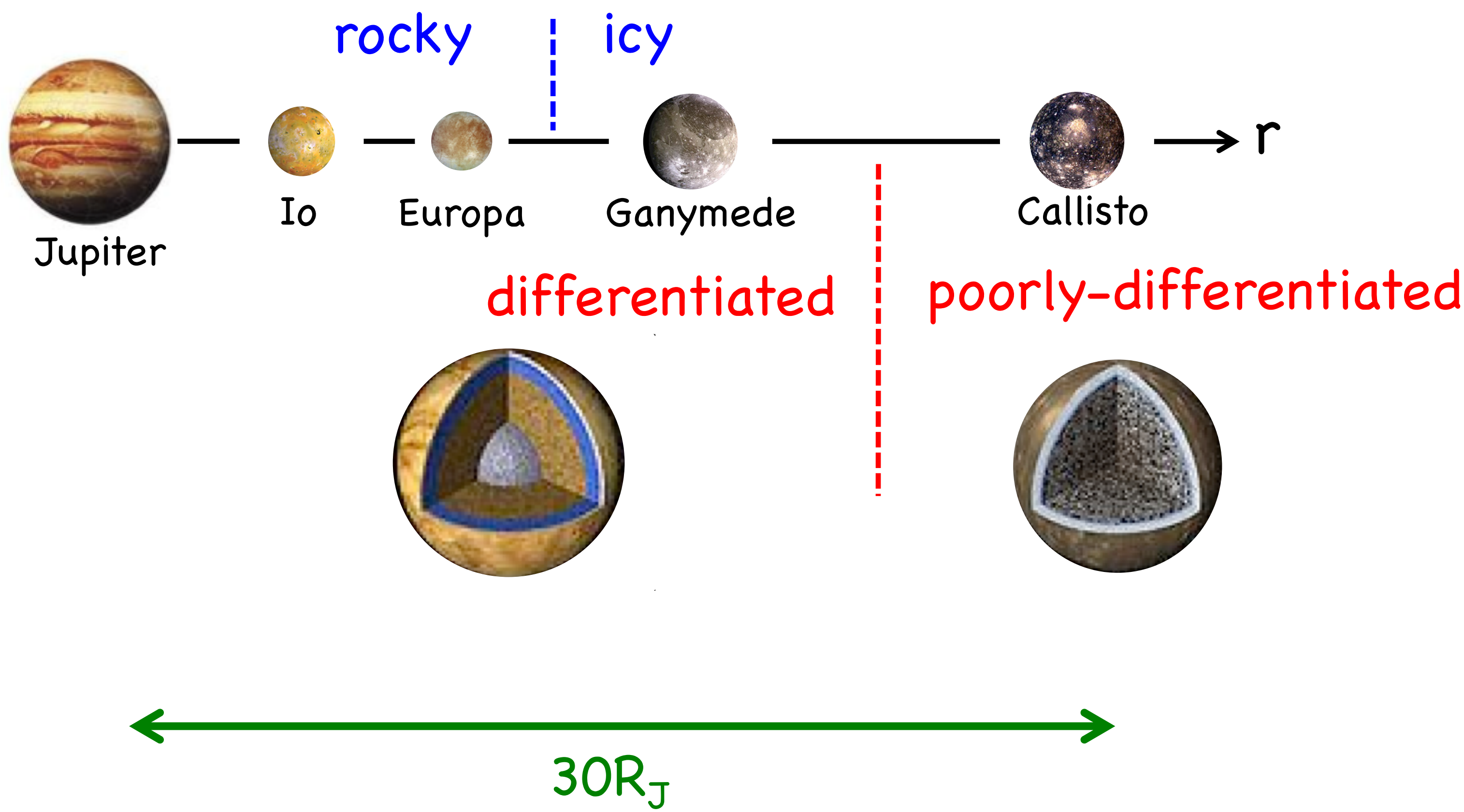


Giant impact or capture
Check out JAXA MMX mission!
Giant impact
©NASA



Triple transit of Jupiter by Europa, Callisto and Io
(24 January 2015, Hubble telescope)

Galilean Moons



cf. 1 AU = 215 R_{sun}

Image from NASA/JPL

Satellite Formation

- In circumplanetary disks (CPD)
  - Minimum mass sub-nebula models

    e.g. Lunine & Stevenson (1982), Lissauer & Stewart (1993)
  - Solid enhanced minimum mass model

    Mosqueira & Estrada (2003ab), Miguel & Ida (2016)
  - Gas-starved disk model

    Canup & Ward (2002, 2006), Sasaki+ (2010), Ogihara+ (2012)
  - Others (based on simulations)

    Fujii+ (2014, 2017), Shibaike+ (2017), Cilibrasi+ (2018)

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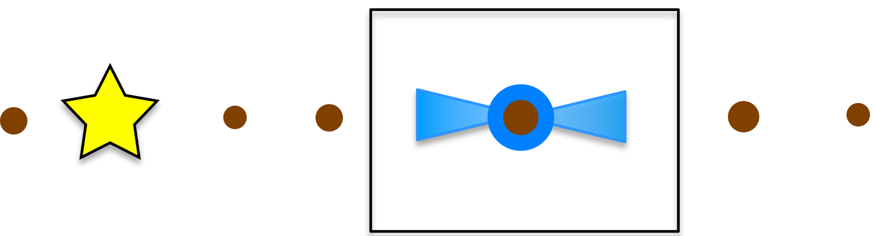
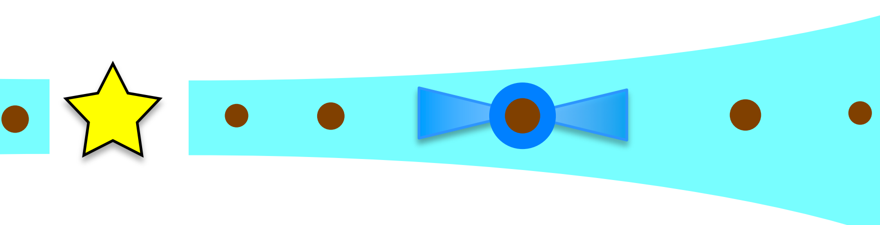


isolated system
(learn controlling parameters)

  - Gas-starved disk model
  - Others (based on simulations)



embedded in PPD
(learn environments)

Satellite Formation

- In circumplanetary disks (CPD)
  - Minimum mass sub-nebula models

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  - Others (based on simulations)

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- From tidally spreading solid disks

  Crida & Charnoz (2012), Hyodo+ (2016)

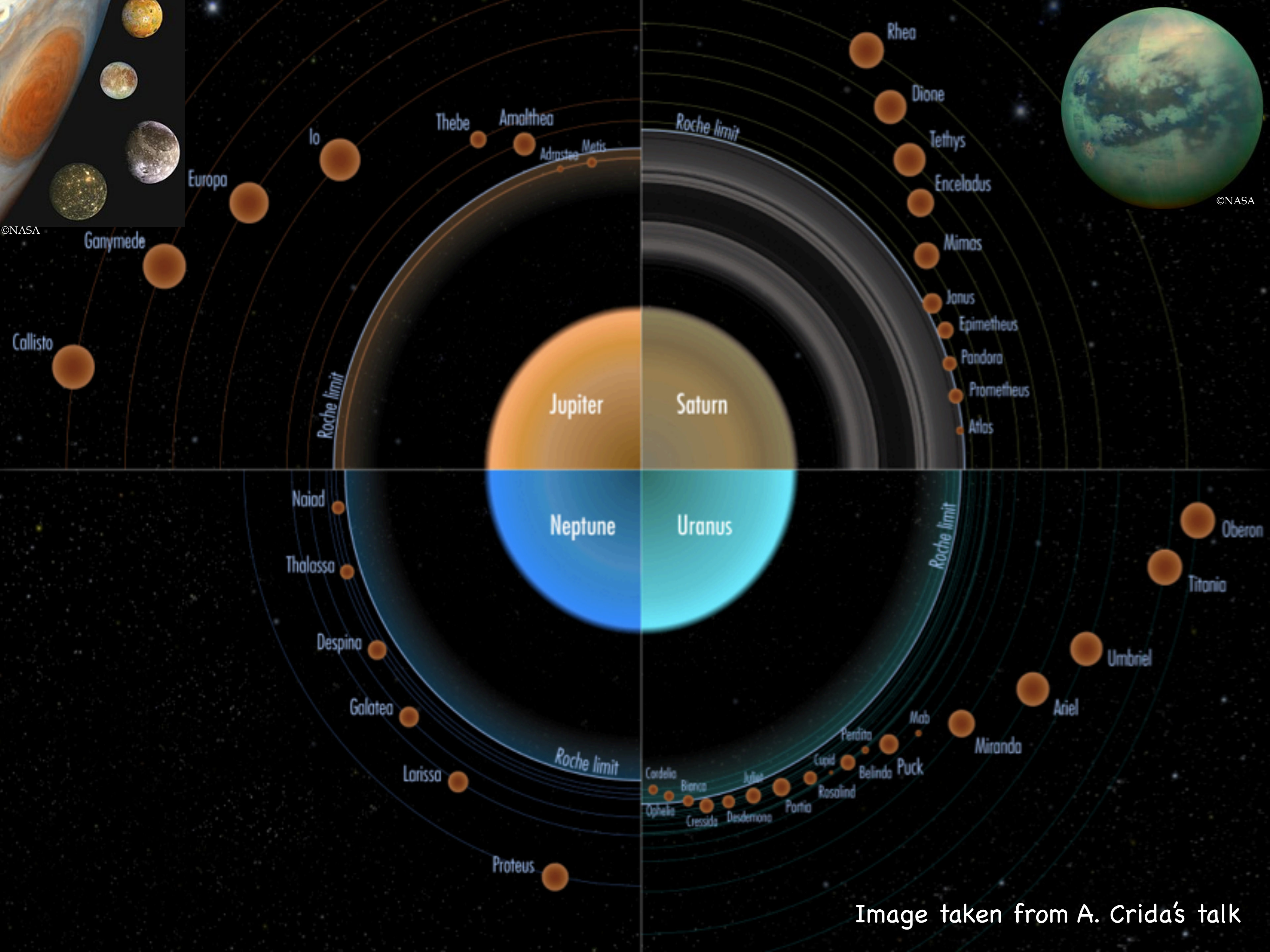
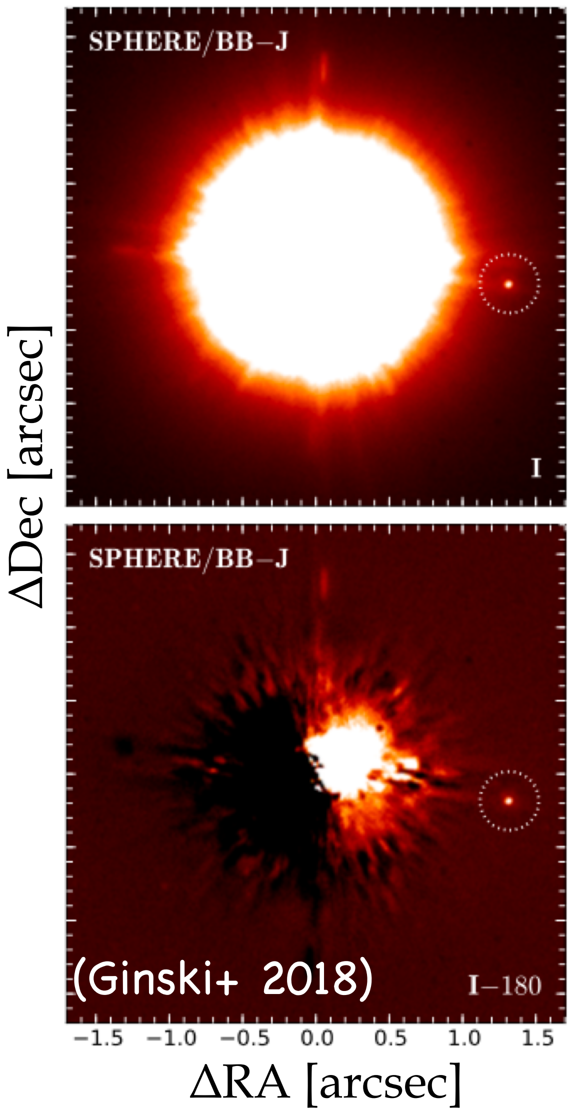


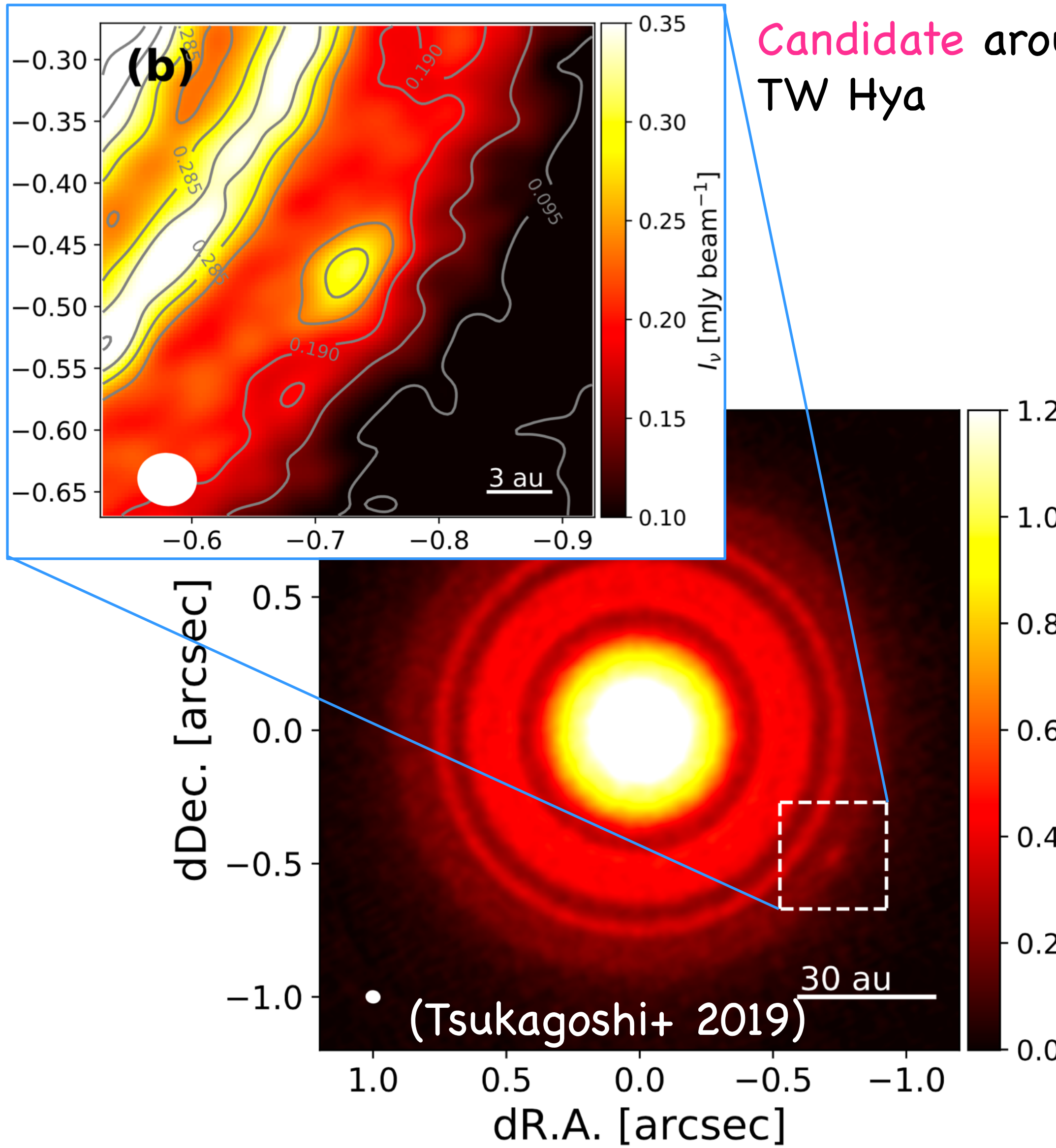
Image taken from A. Crida's talk

What does CPD look like?

Candidate around CS Cha

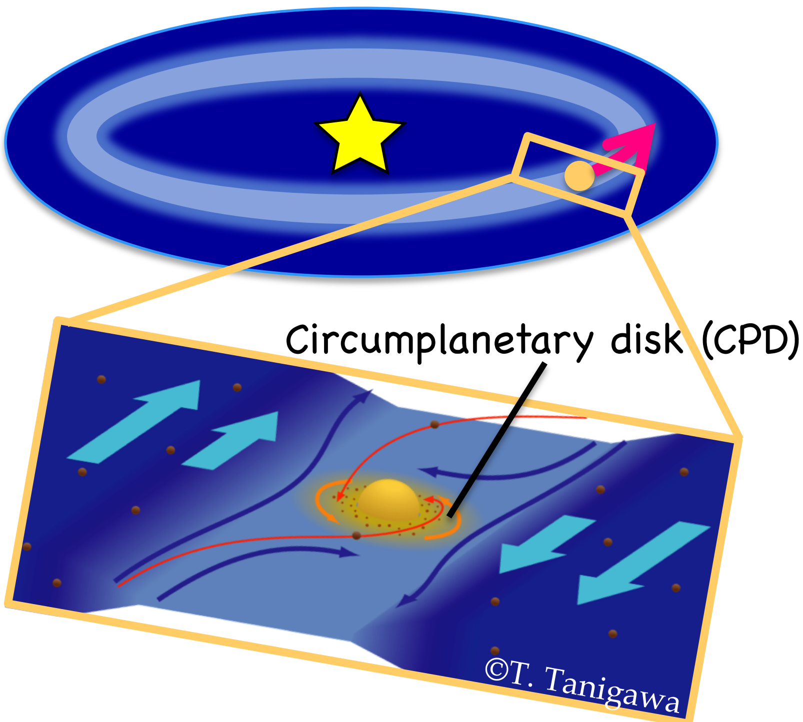


Candidate around TW Hya



Detailed Analysis of Flow onto CPD

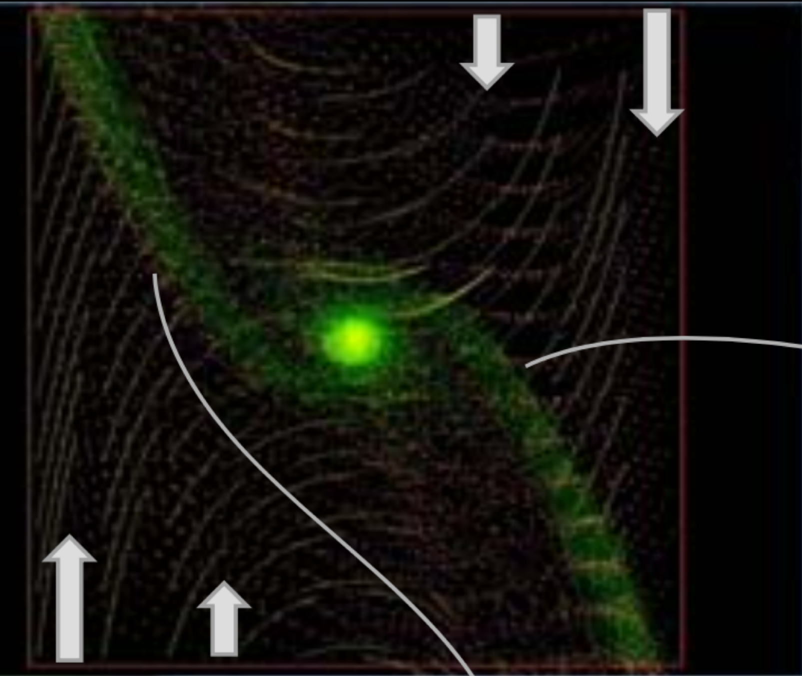
Tanigawa, Ohtsuki & Machida (2012)

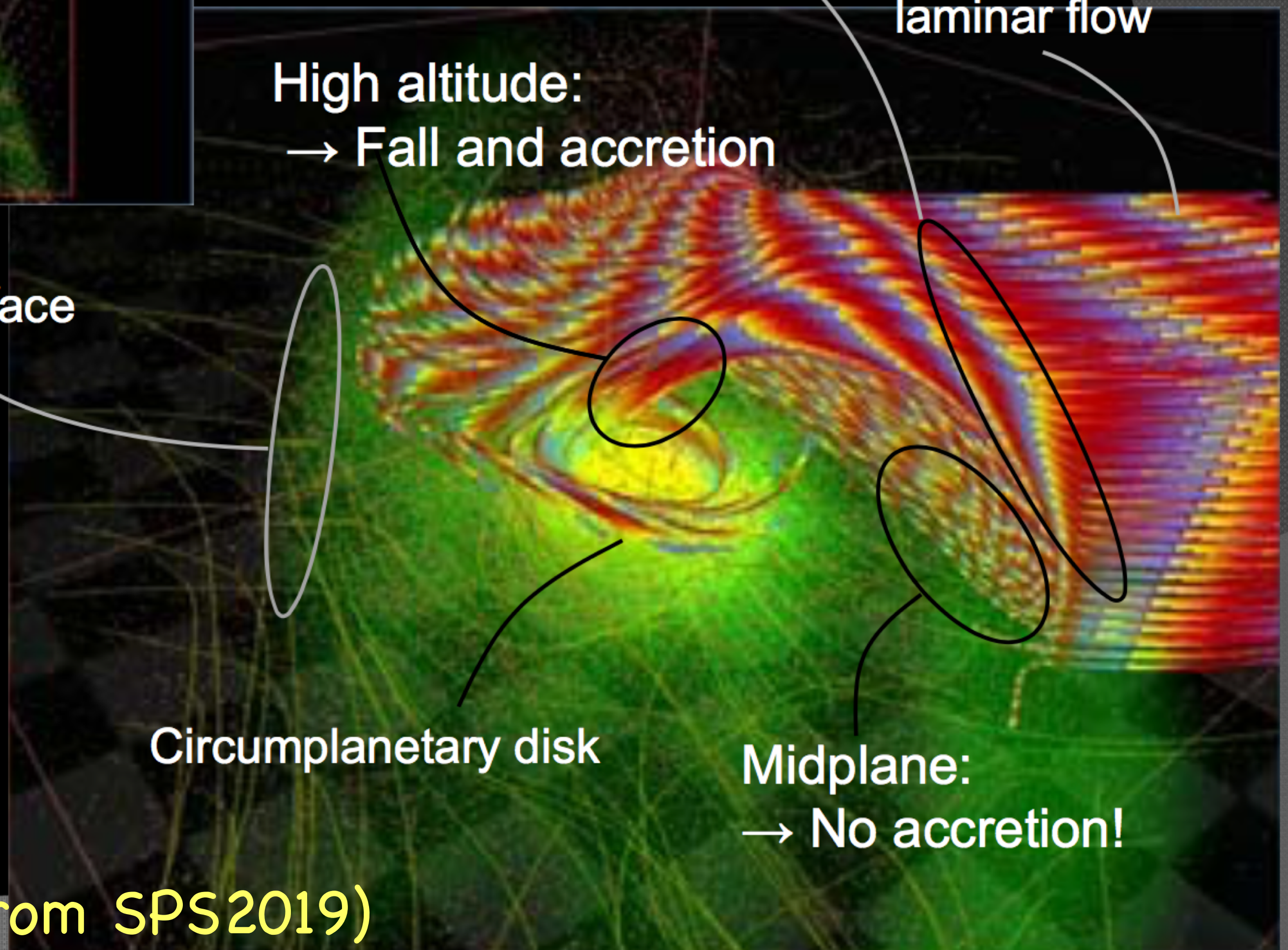


- Local (shearing box) simulation
- 11 layers of nested grids
  finest grid ~ $1/4R_J$
  smoothing length ~ $0.0007r_H$
- Isothermal
- Inviscid
- $0.4M_J$ at 5.2AU

Poloidal inflow
No inflow from midplane

HD simulation of Tanigawa+ (2012)





Visualized by T, Takeda
(Vasa Entertainment & NAOJ

T. Tanigawa's slides from SPS2019)

RHD Simulations (Szulagyi 2017)

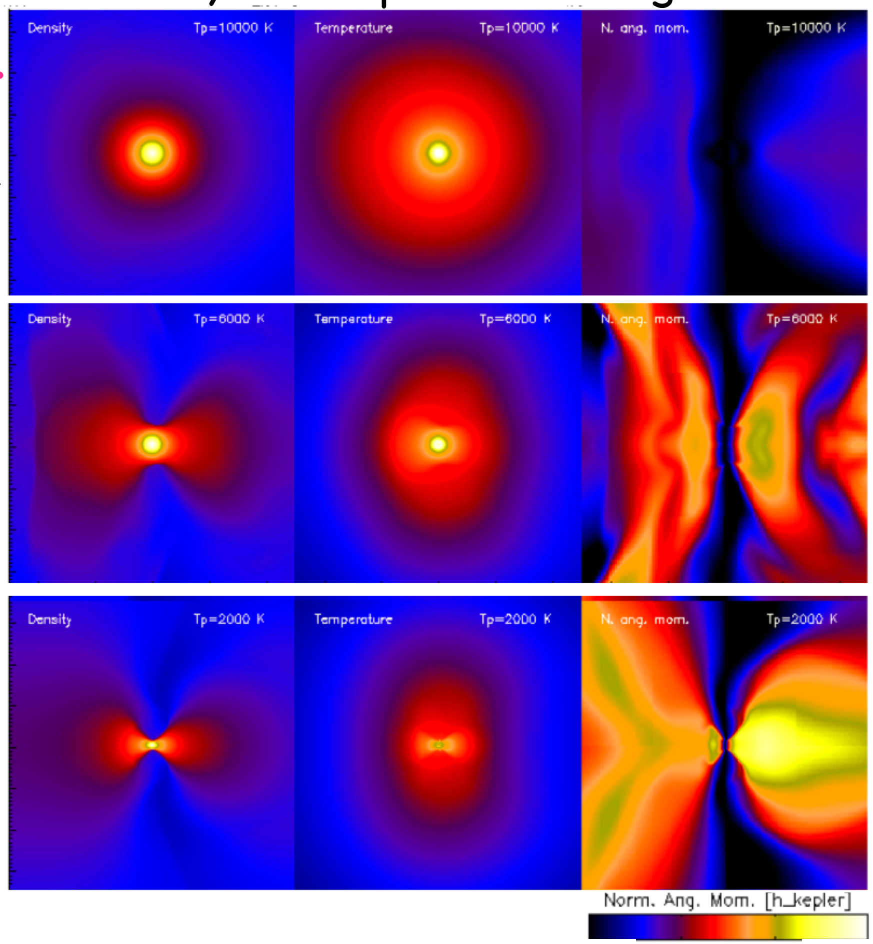
Density Temperature Ang. moment.

Planet temp.

Tp=10000K

Tp=6000K

Tp=2000K



zero Kepler

Finest grid ~ $0.8R_J$

Smoothing length ~ $5R_J$ ~ $0.01r_H$

$\gamma = 1.43$

Bell & Lin opacity

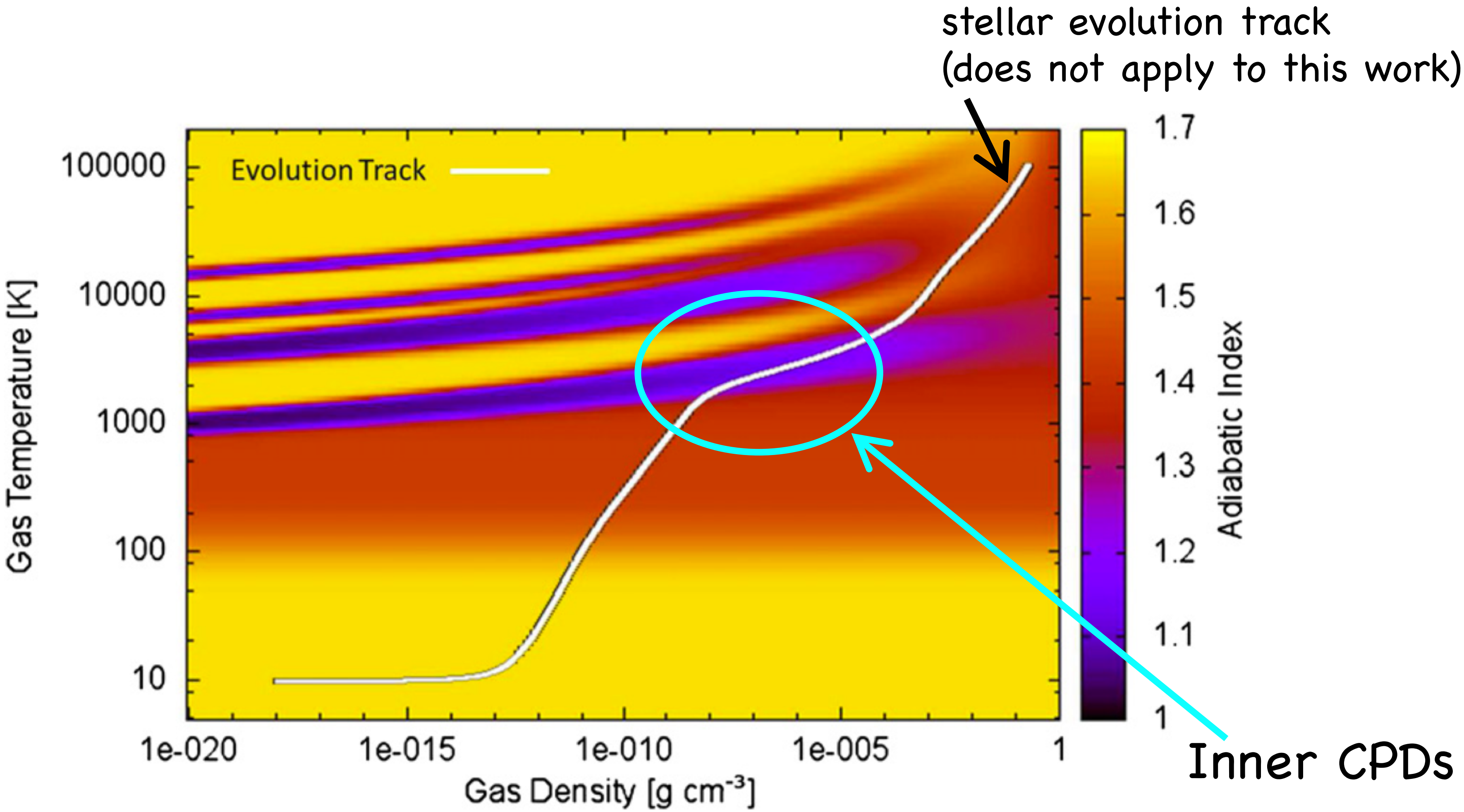
Viscosity: α~0.004

$1M_J$ planet @5.2AU

Need to wait until planet cools down

Without fixed planetary temperature: T_{max}~13,000K (Szulagyi+ 2016)

Realistic EOS



Tomida+ (2013)

Need Magnetic Fields?

Cosmic rays, X-rays, and radionuclides don't give sufficient ionization for magnetorotational instability (MRI) to be well-developed in satellite-forming region.

Fujii+ (2011, 2014), Turner+ (2014), Keith & Wardle (2014)

However,

- outer radii can sustain MRI
- thermal ionization can trigger MRI at inner radii (when $T \gtrsim 2500$)

Keith & Wardle (2014), Fujii+ (2017)

Gressel+ (2013)

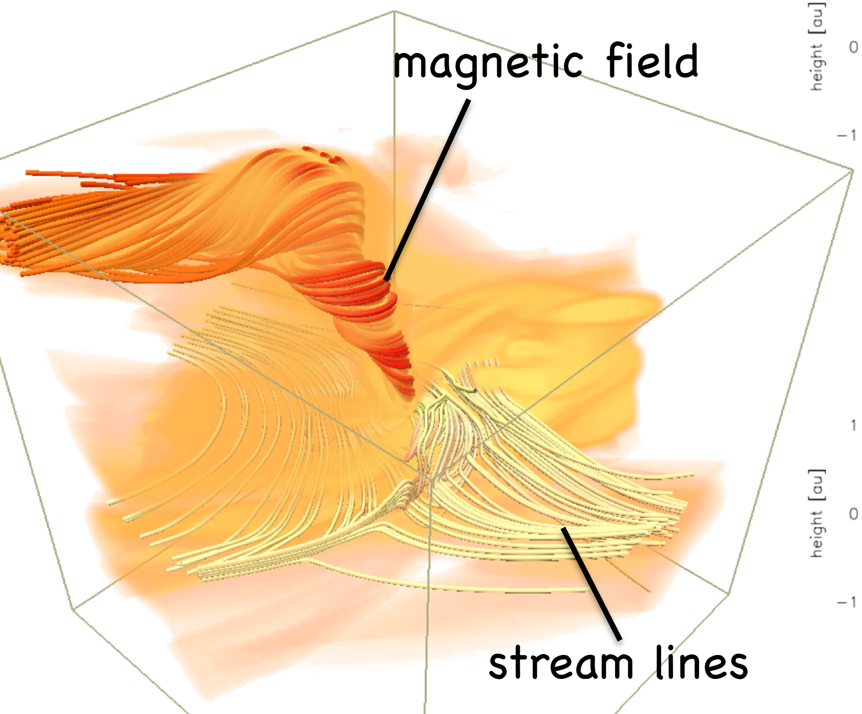
Global

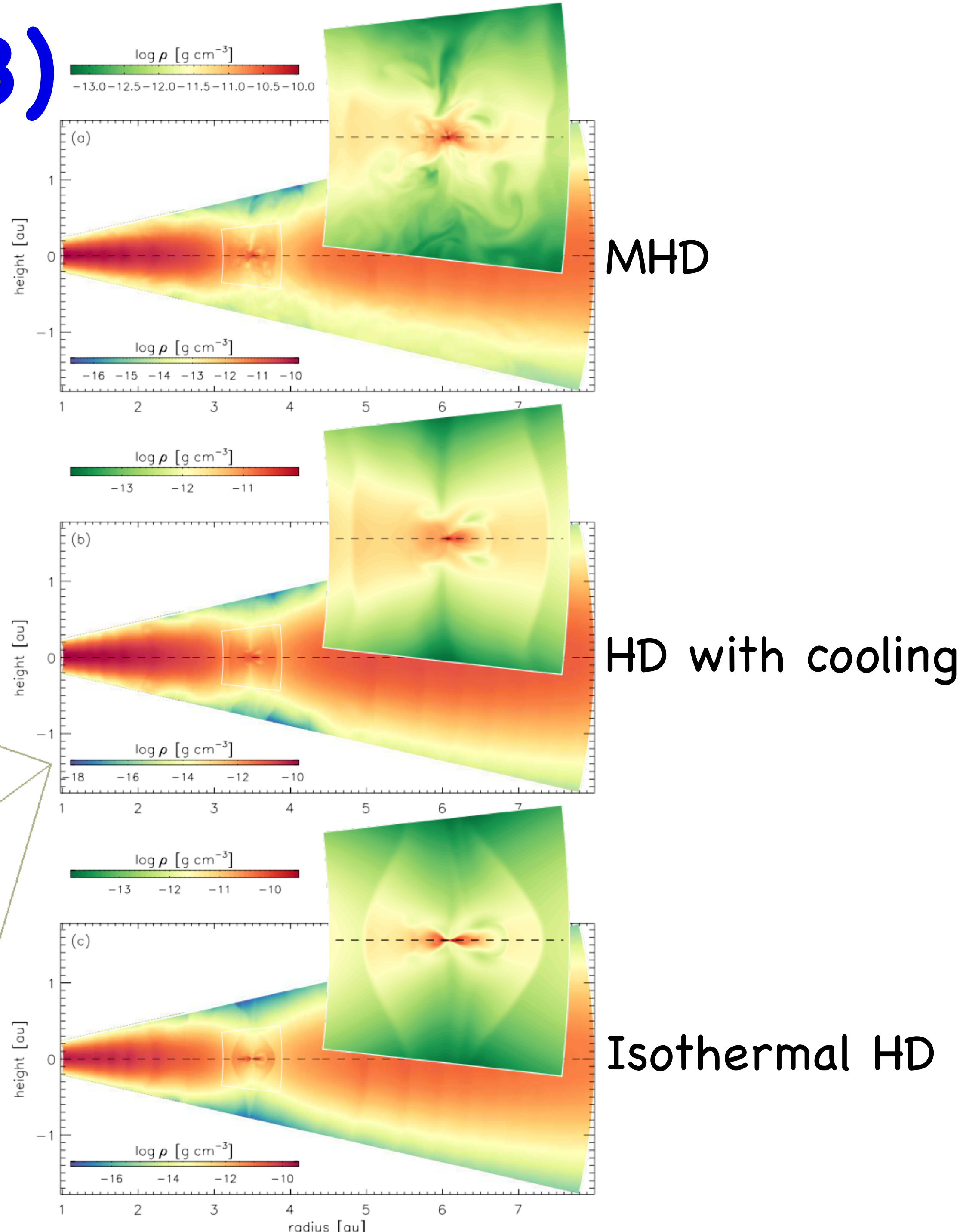
Viscous (MRI)

3-levels of AMR

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

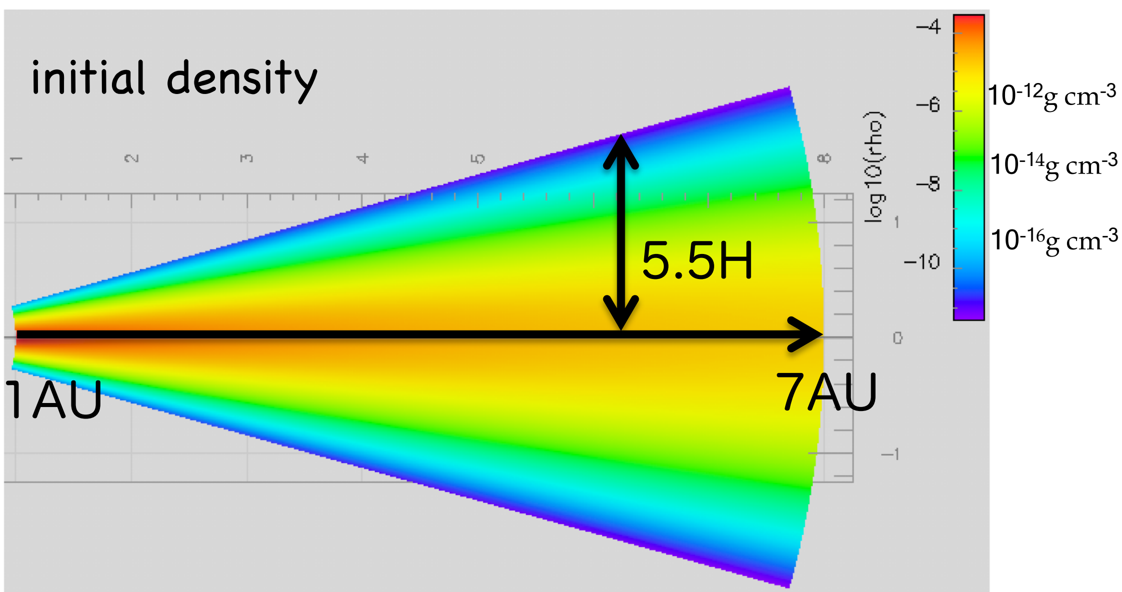
(~Calisto's semi-major axis)

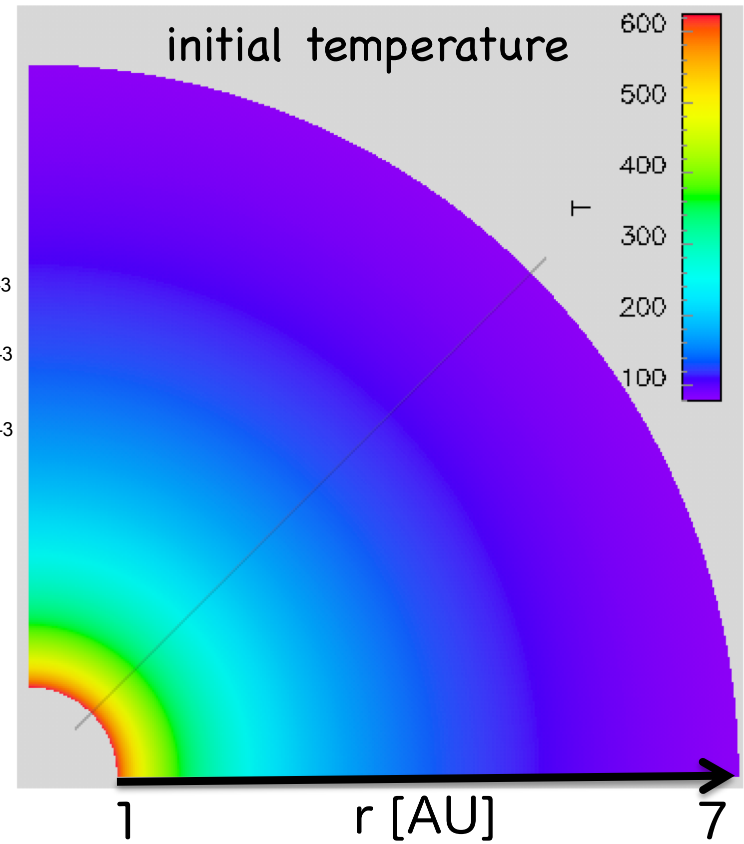




Radiation HD Simulations

- Code: NIRVANA3.5 (Ziegler 2004&2011, modified by Oliver Gressel)
- Adopted realistic EOS table by Tomida+ (2013, 2015), $\alpha=10^{-4}$
- Opacity: Semenov (2003), Helling+ (2000)
- planet: 1 Jupiter mass, orbit=3.5AU
- disk model, domain size:





- resolution: $N_r \times N_\theta \times N_\varphi$ = 160x80x128 (base) + 3-5 levels of SMR

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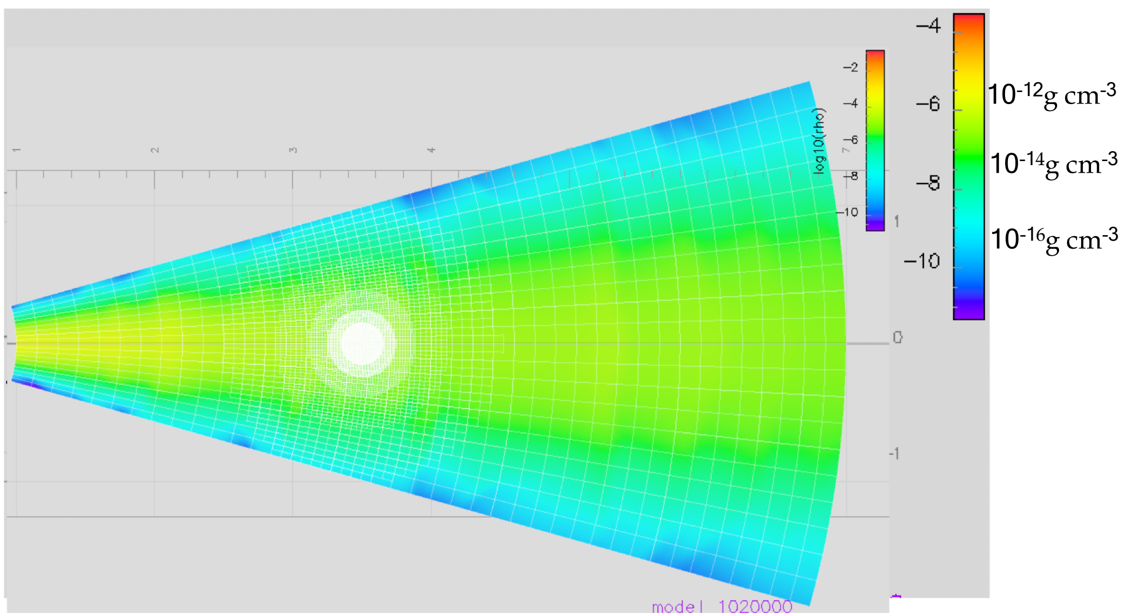

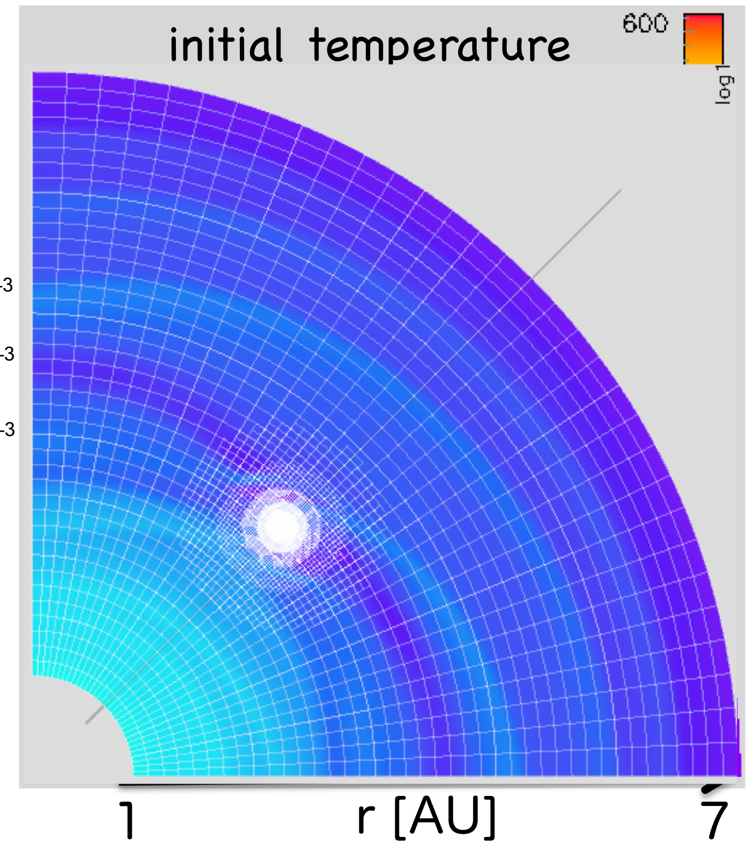

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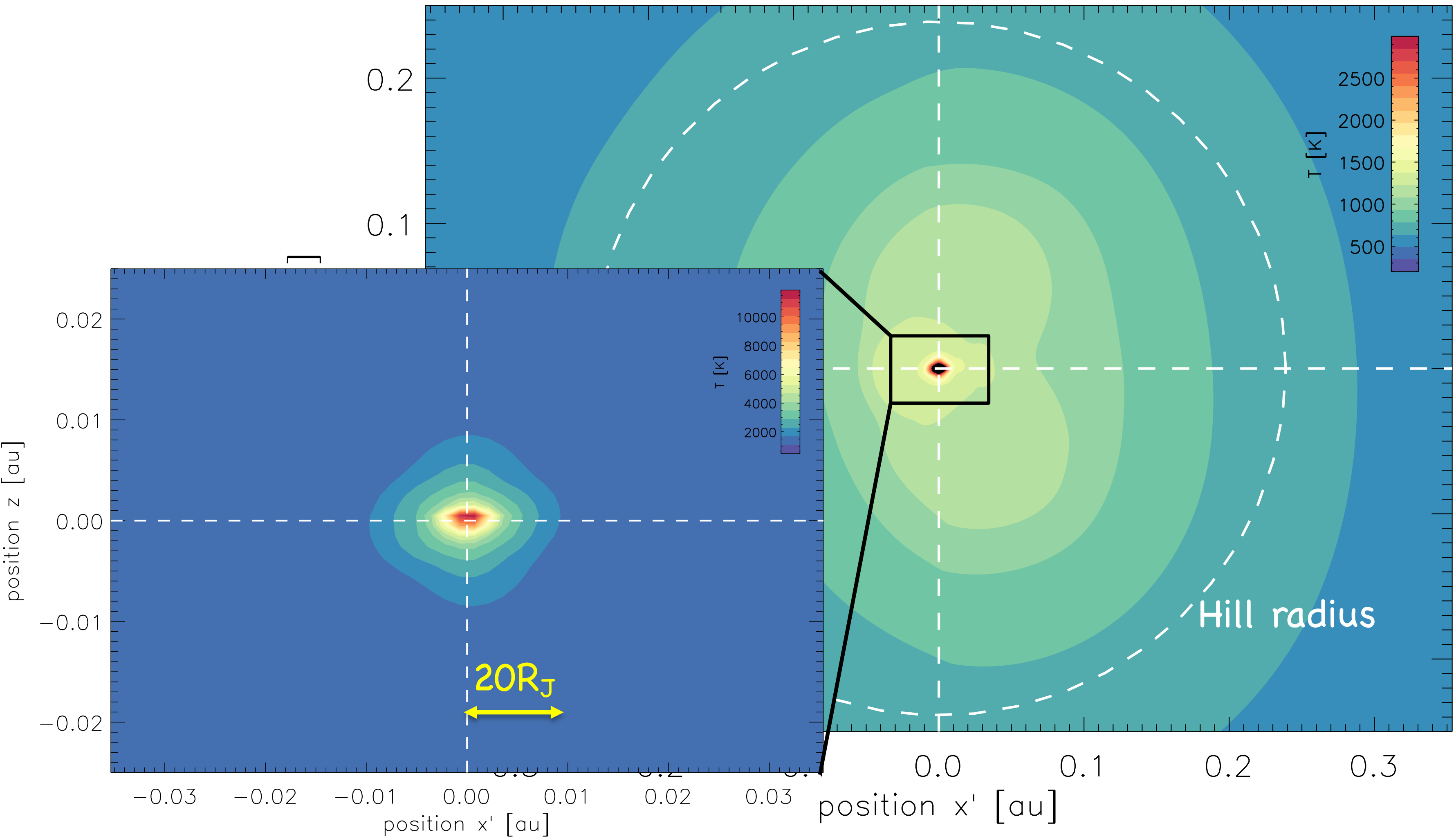
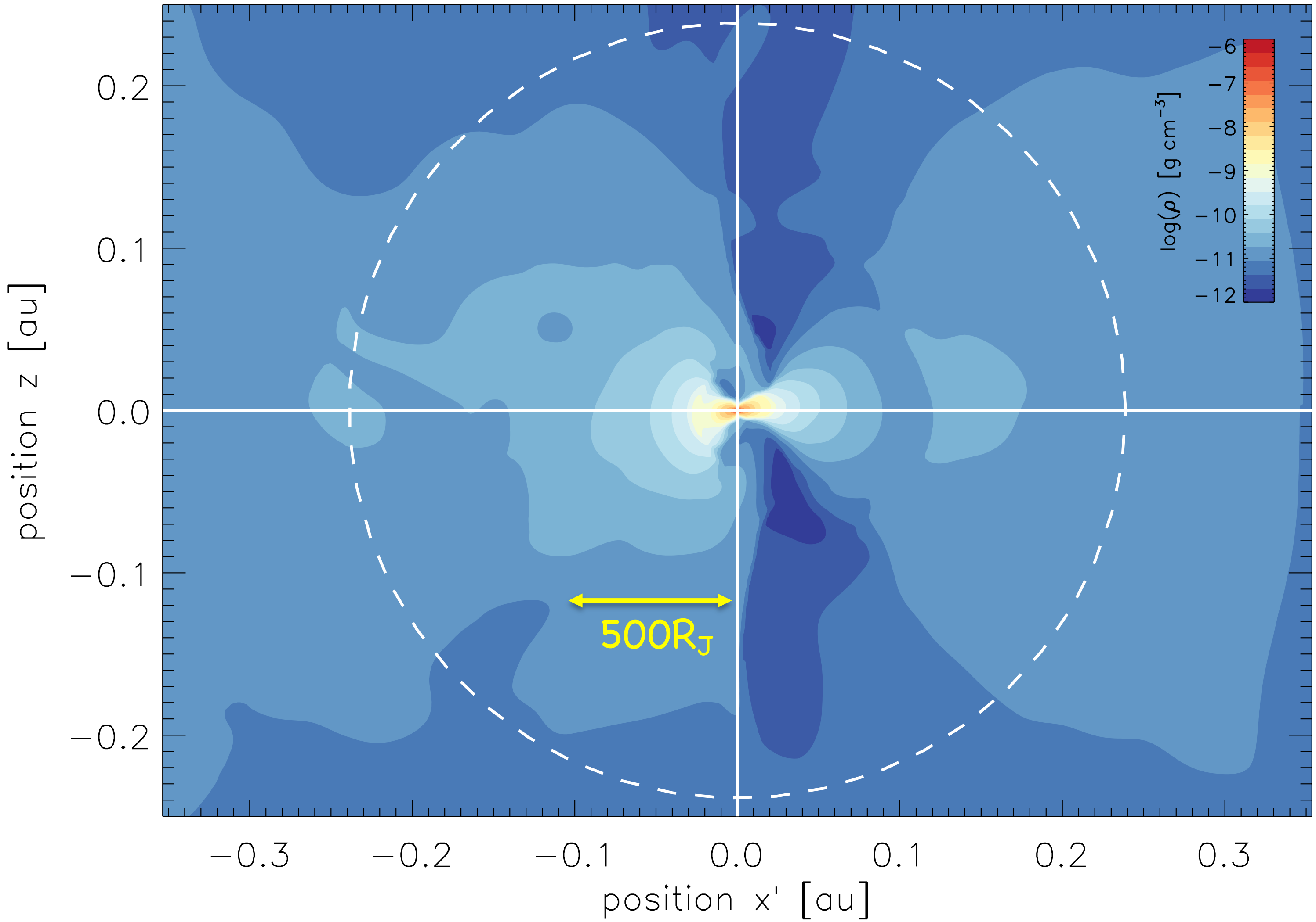
Vertical Temperature Distribution

5 levels of refinement (finest grid width: $\sim 2R_J$)

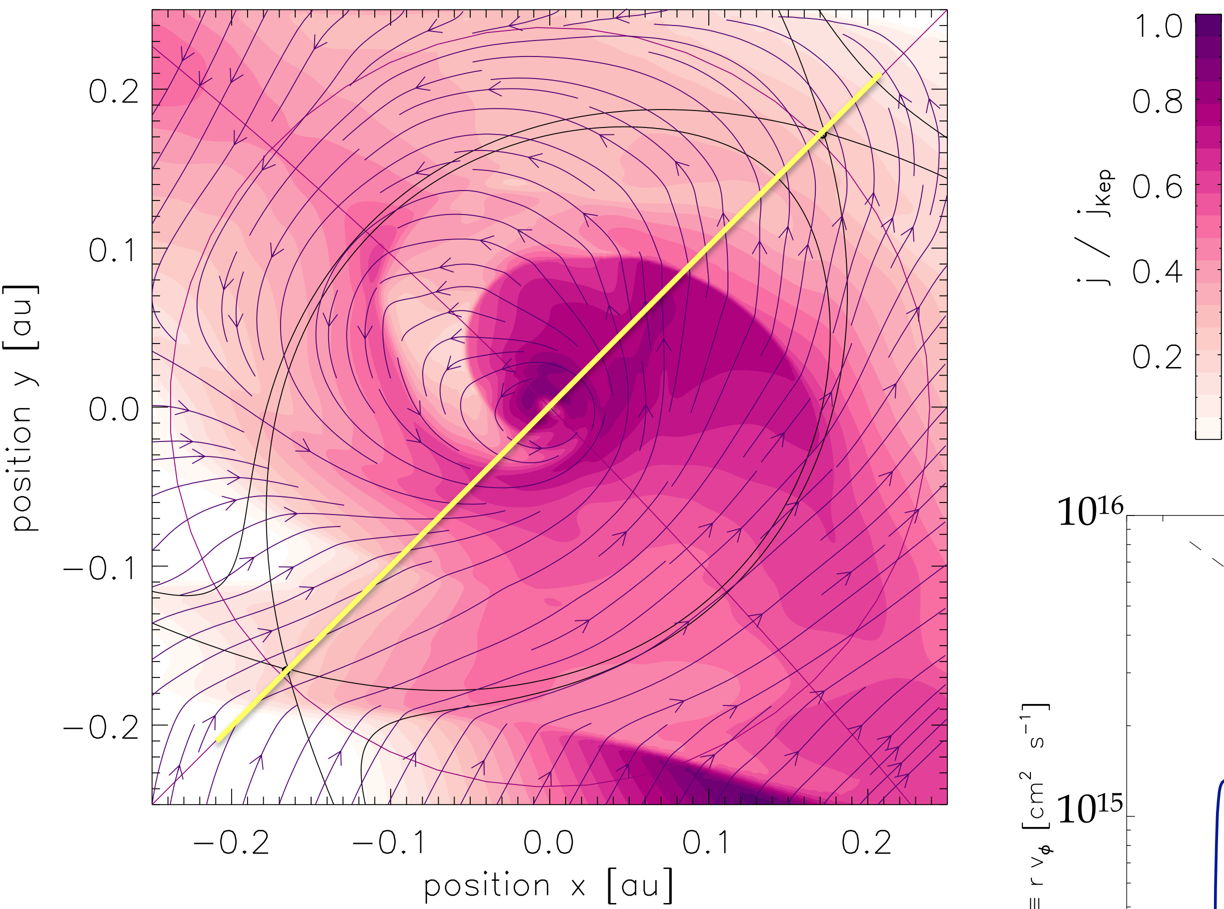


Vertical Density Distribution

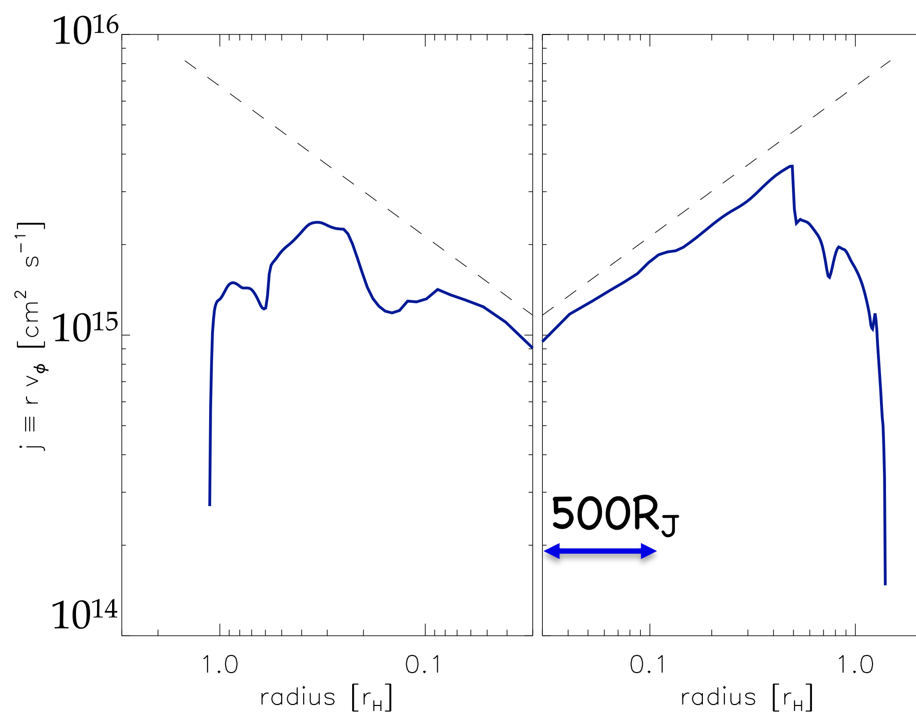
5 levels of refinement (finest grid width: ~$2R_J$)



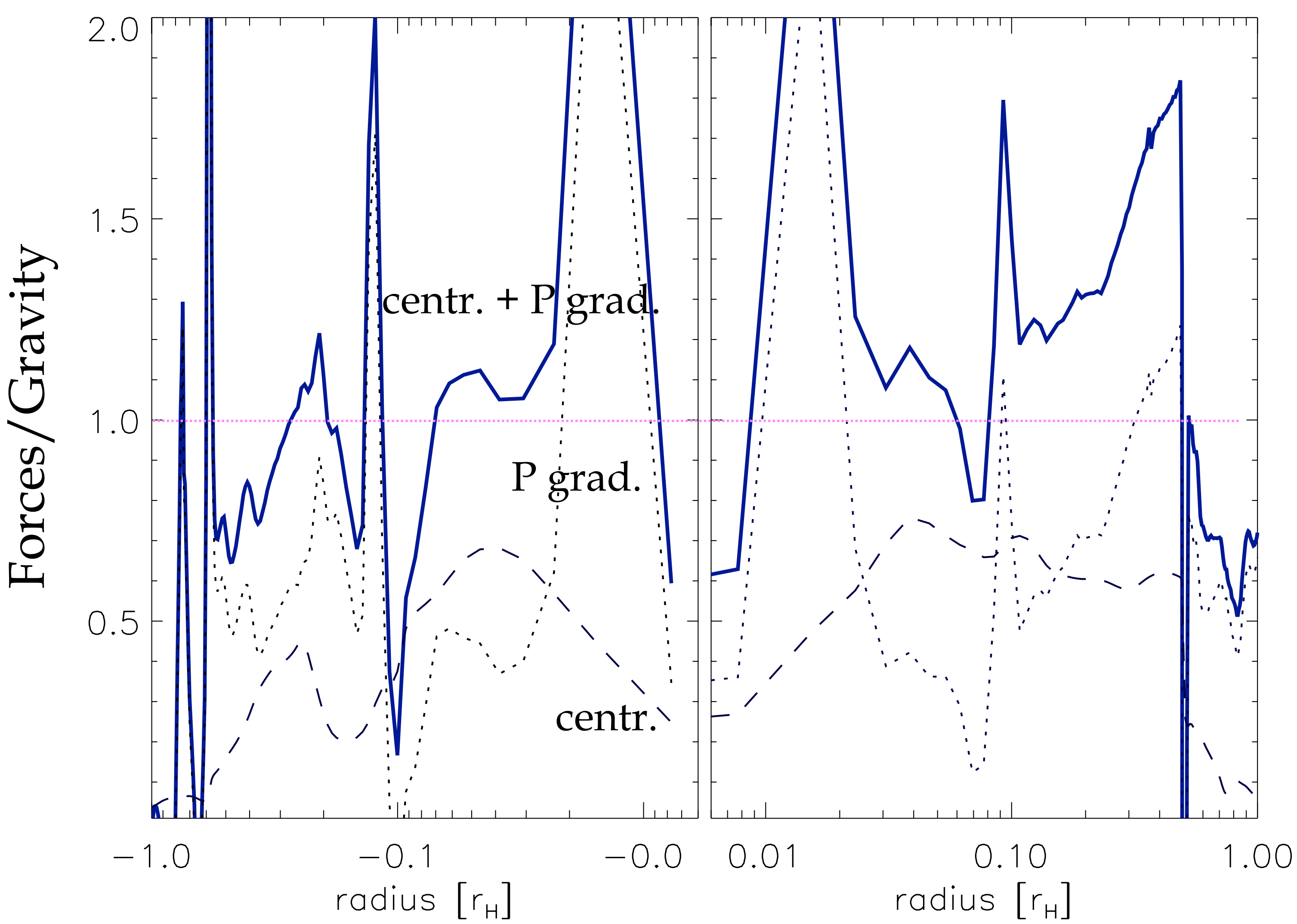
Specific Angular Momentum



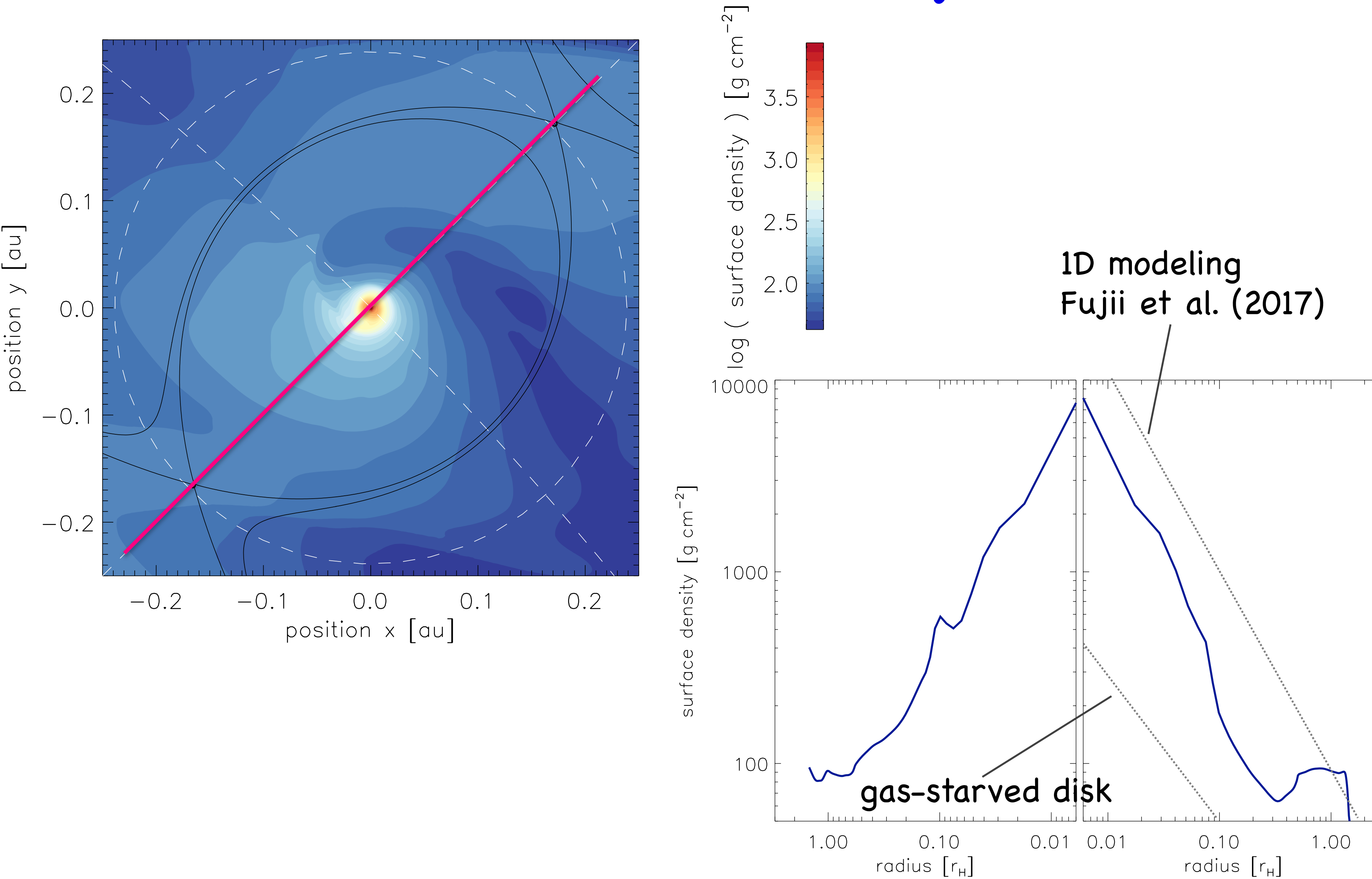
midplane



Balance of Forces



Surface Density

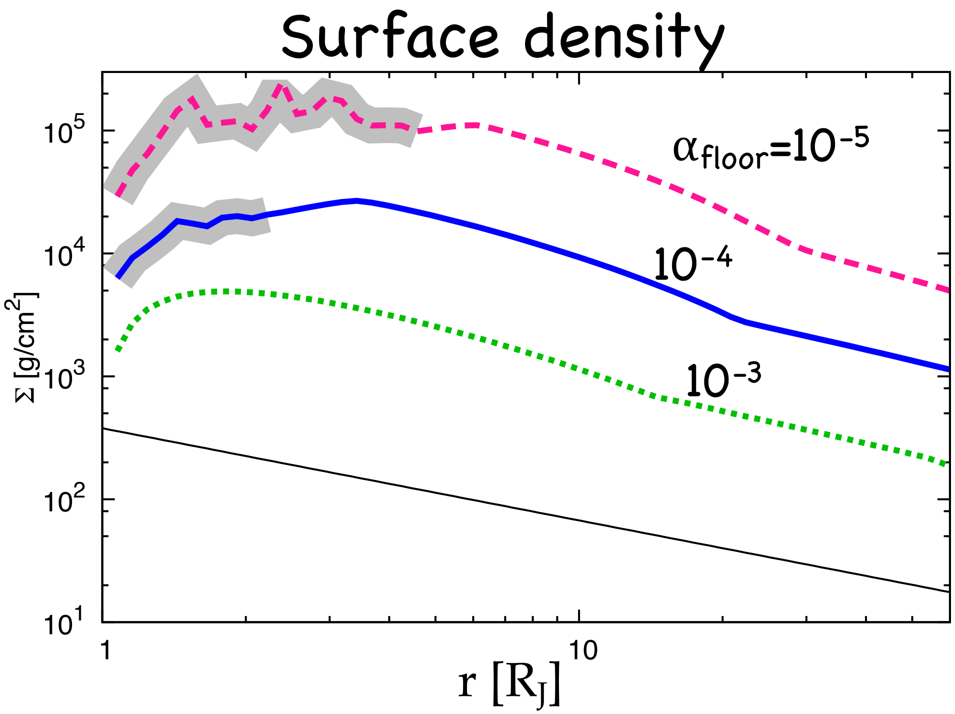


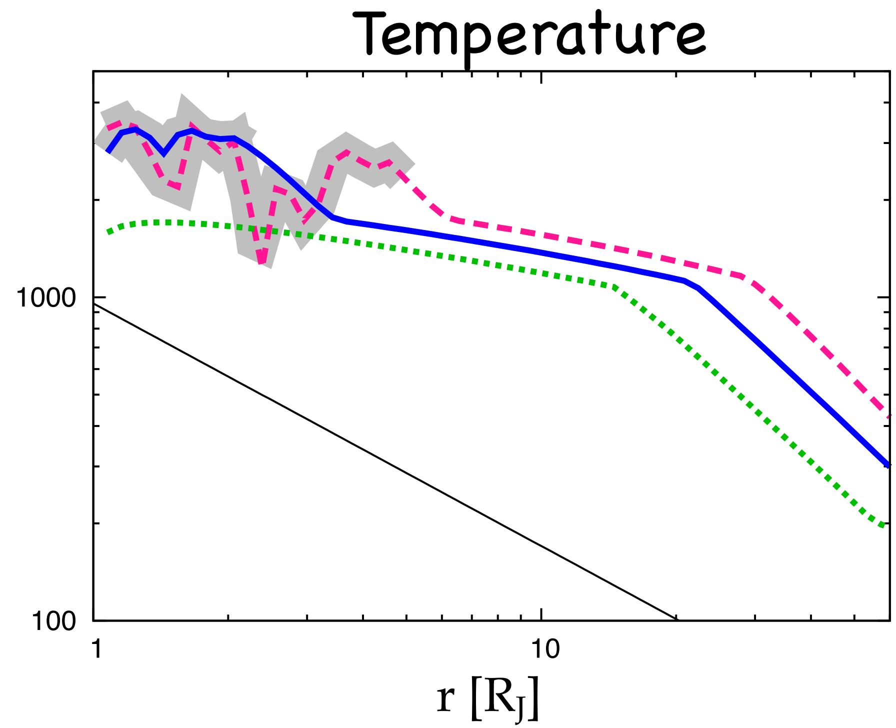
Summary

- We performed global RHD simulations of formation of circumplanetary disks
- We adopted tabulated EOS by Tomida+ (2013, 2015) so that we can calculate temperature accurately
- Although it is not thin Keplerian, we observed CPD forming in our simulations from early stage
  -> start satellite formation before solid depletes?
- What's important? Mass? Temperature? Complicated?
- Will thermal ionization change the results?
  ➔ MHD simulations are needed

MRI Regulates Temperature?

1D model of CPDs by Fujii+ (2017)





T ≳ 2500

➔ Thermal ionization triggers MRI

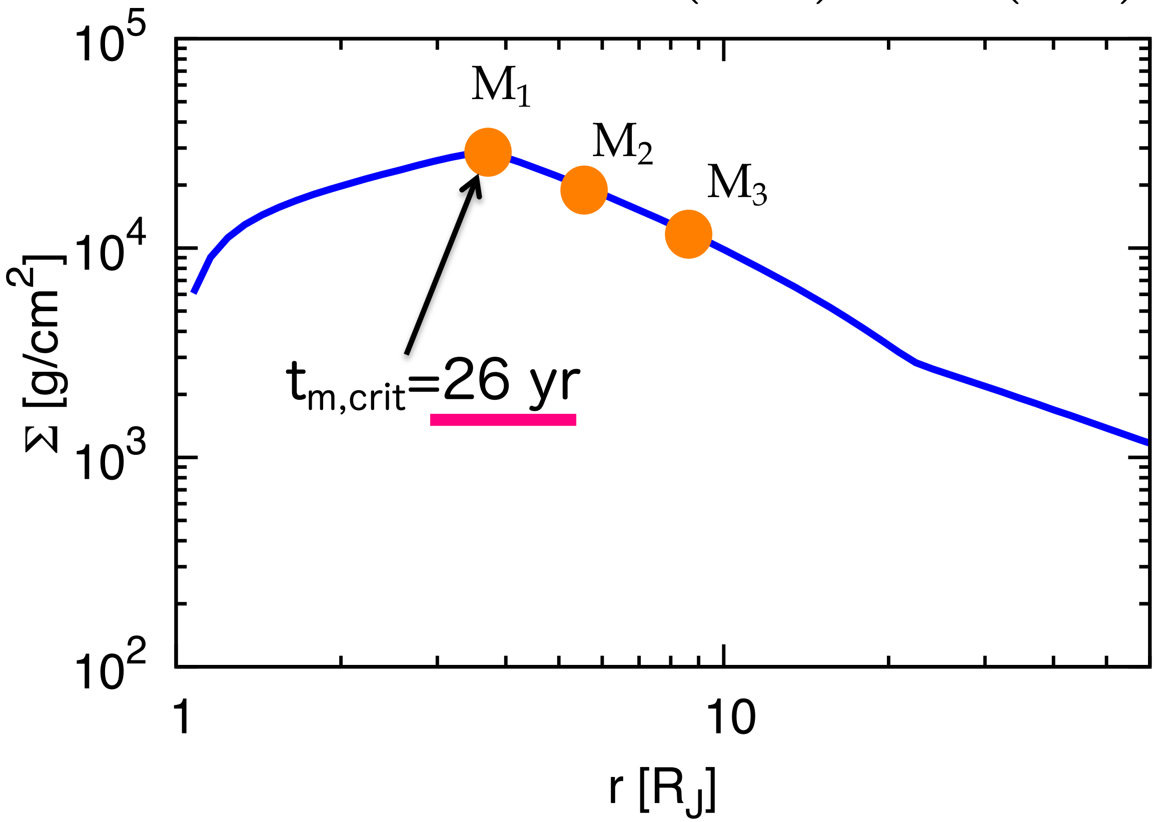
➔ Accretion rate increases

Bell & Lin opacity
No compression heating

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)



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