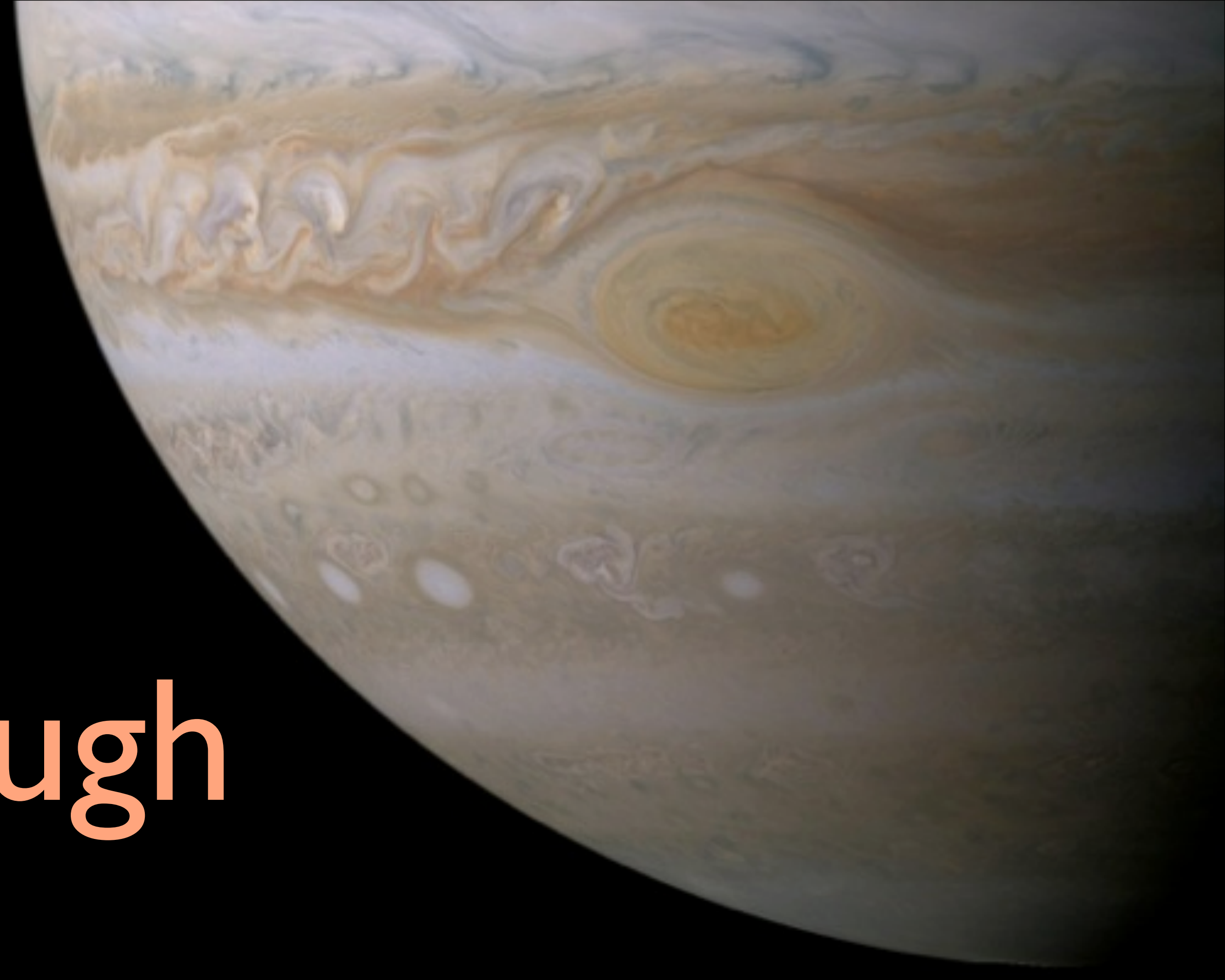


Accretion through giant planet circumplanetary disks

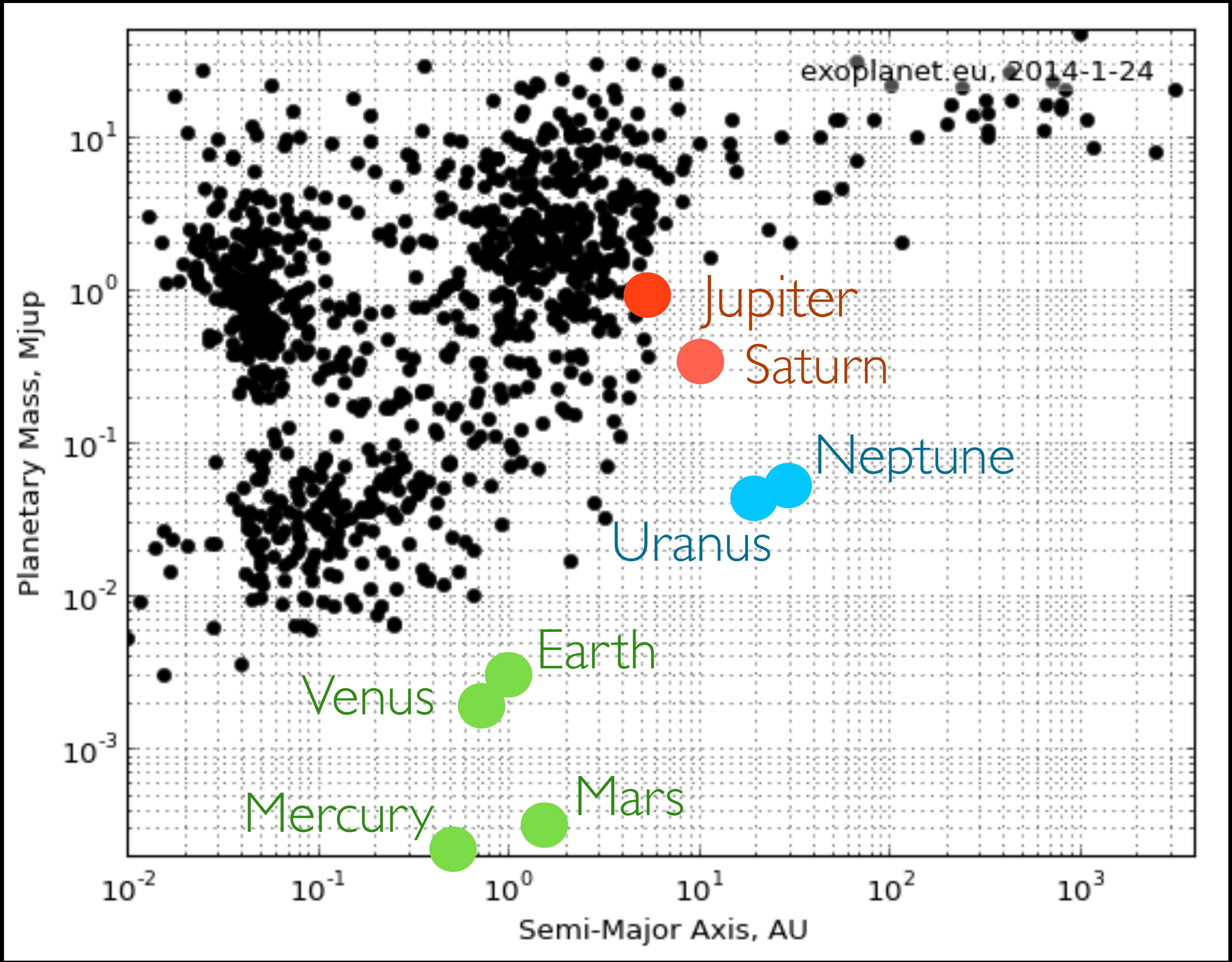
Sarah Keith

Macquarie University & JBCA

Email: sarah.l.keith@mq.edu.au

1074 planets
812 planetary systems

Exoplanets



source: exoplanet.eu

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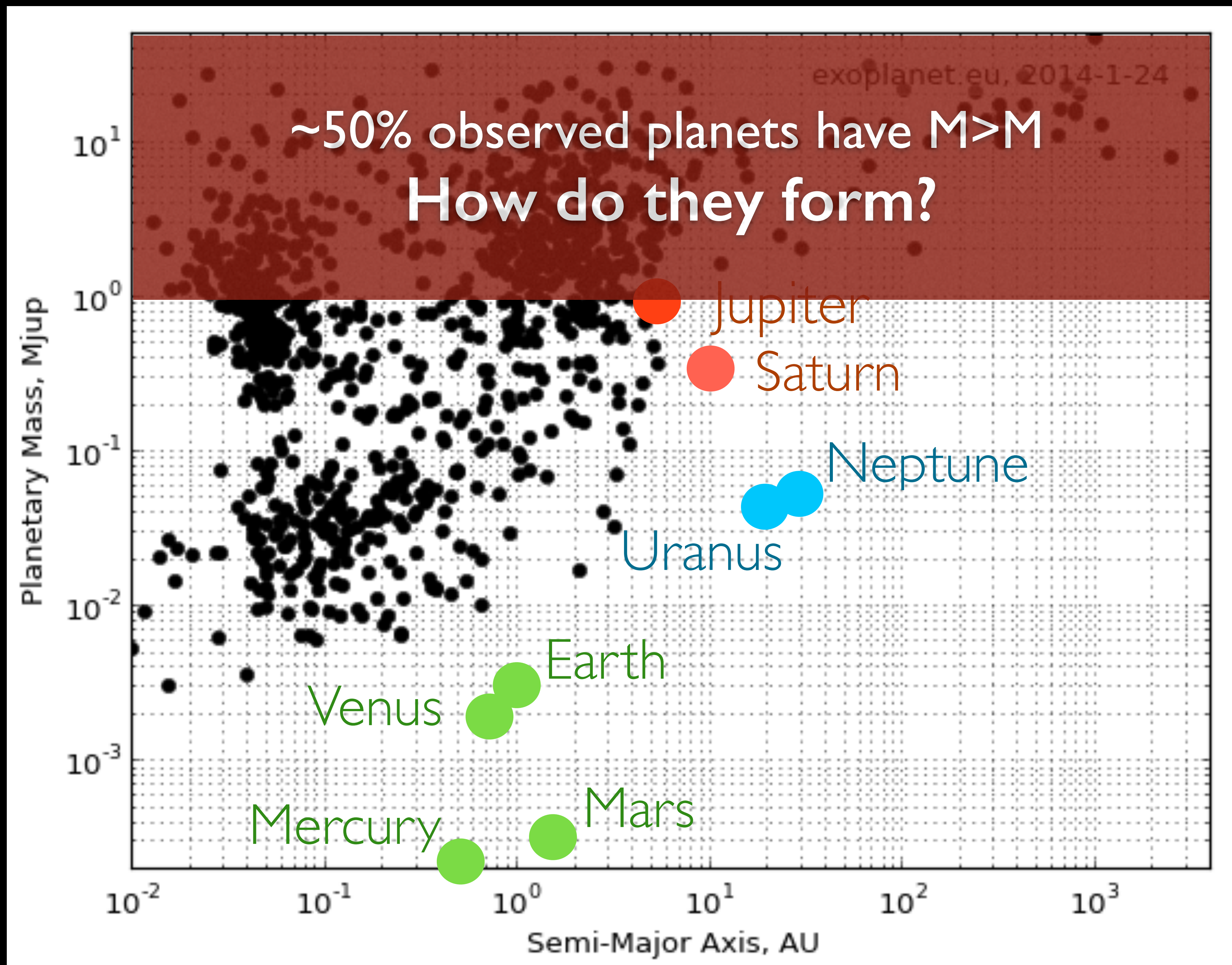
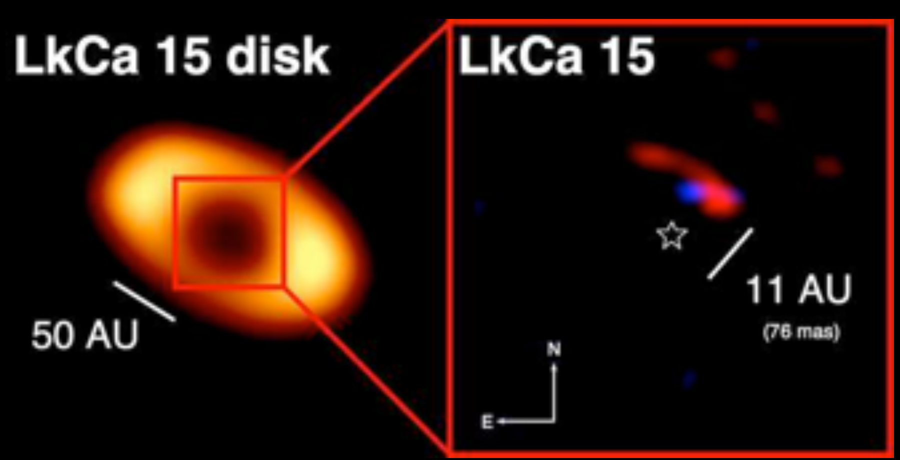


source: exoplanet.eu

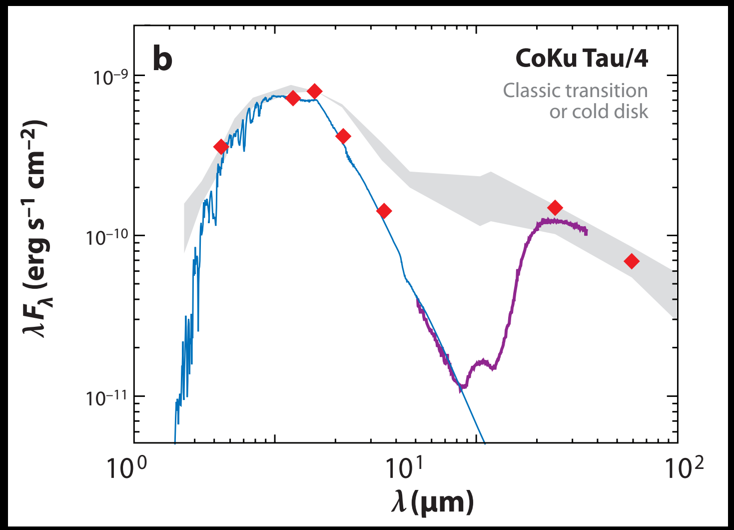
Constraints on planet formation

Review: Williams & Ceiza 2011

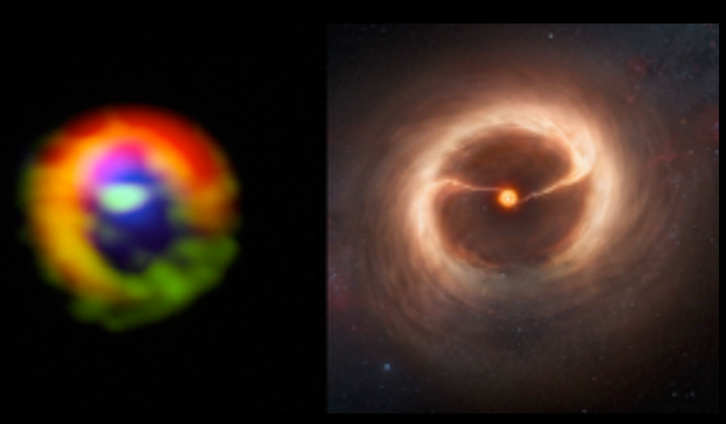
- Formation timescale from protoplanetary disk life-time (3x10^6 yrs)
- Spectra, direct imaging show planet gaps (& spiral arms)
- Protoplanetary disk temperature, density profiles
- Exoplanet semi-major axis & mass distribution



LkCa15b - Kraus+2011



Williams & Ceiza 2011


HD 142527 - Casassus+2013

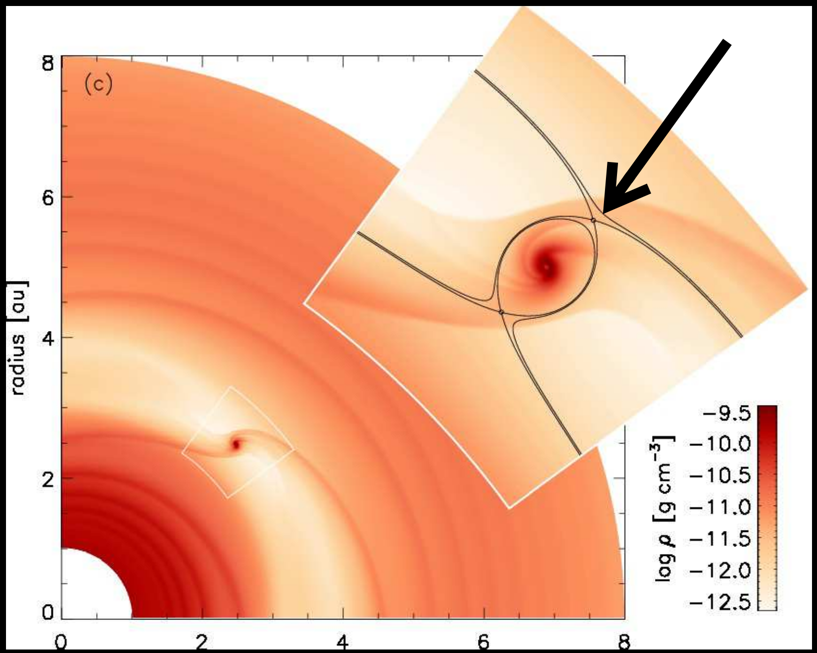
Giant planet formation

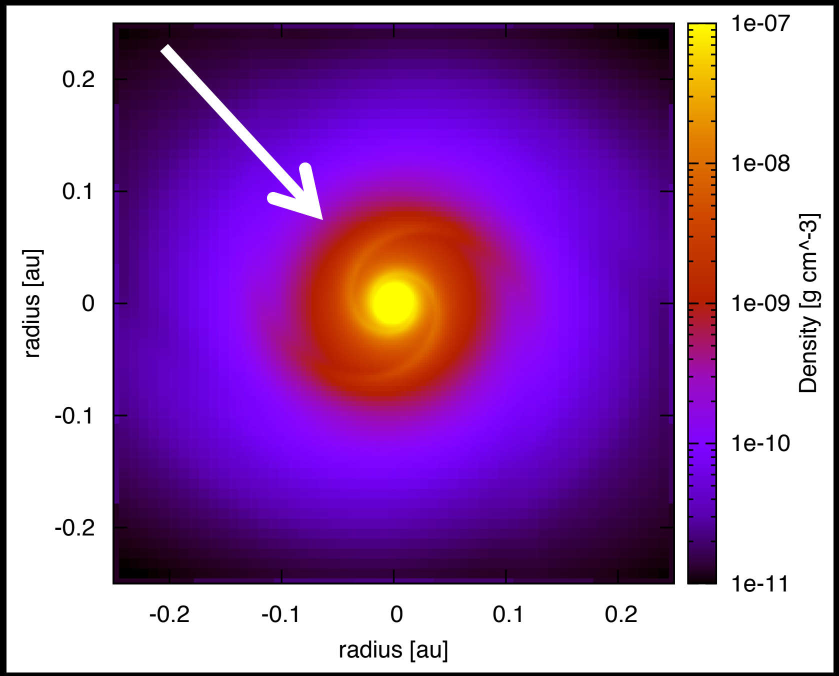
See review: Armitage 2010

- Planetary embryo forms via core accretion or direct collapse (>100au)
- Runaway gas accretion and envelope collapse
- Planet opens a gap (~au) in the disk.
- Formation of circumplanetary disk
- +Migration

Circumplanetary disk

Gressel+2013





Tanigawa+2012

Circumplanetary Disk

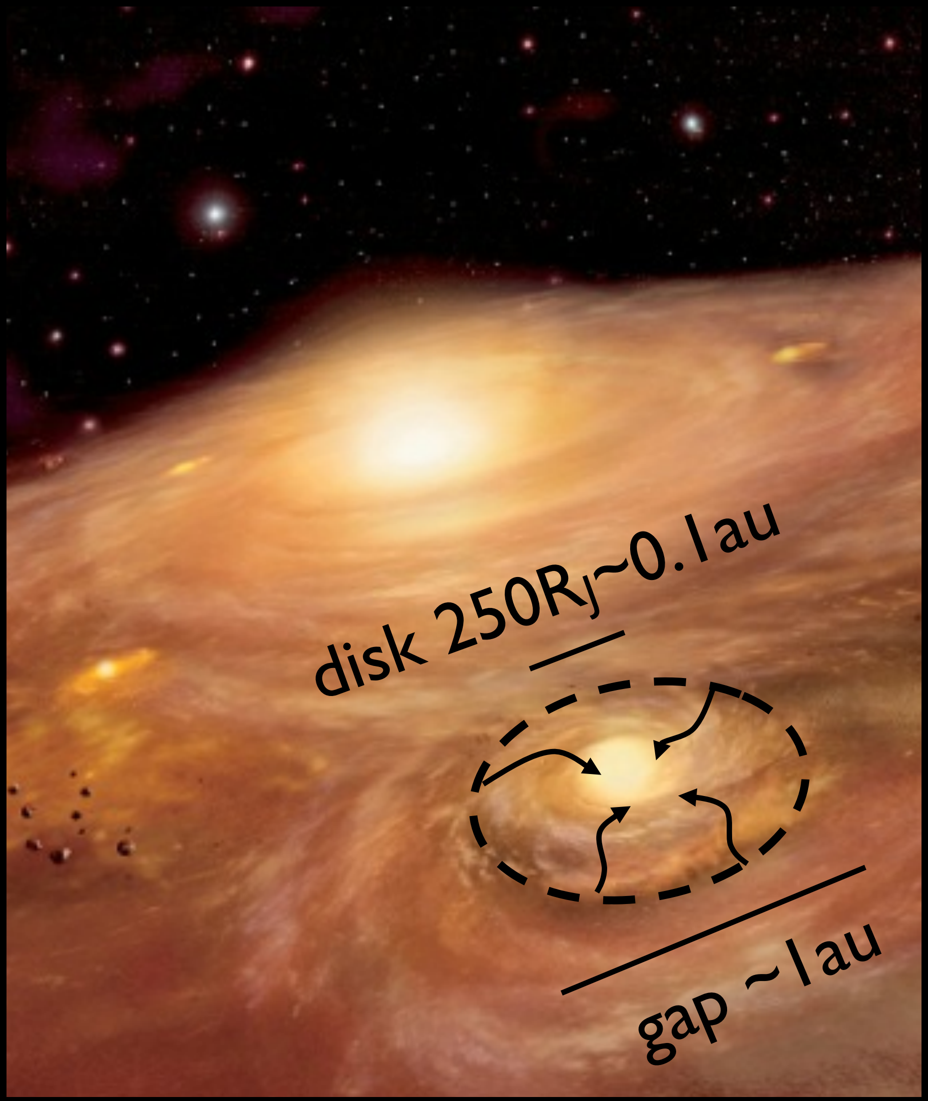
… an accretion disk around a forming giant planet

Dual purpose disk

- Initially the disk is hot delivering mass to the planet ($M \sim {}^2/_3 M_J$)

- Later the disk cools, the formation site for satellites

- Not yet observable, little studied



source: National Geographic

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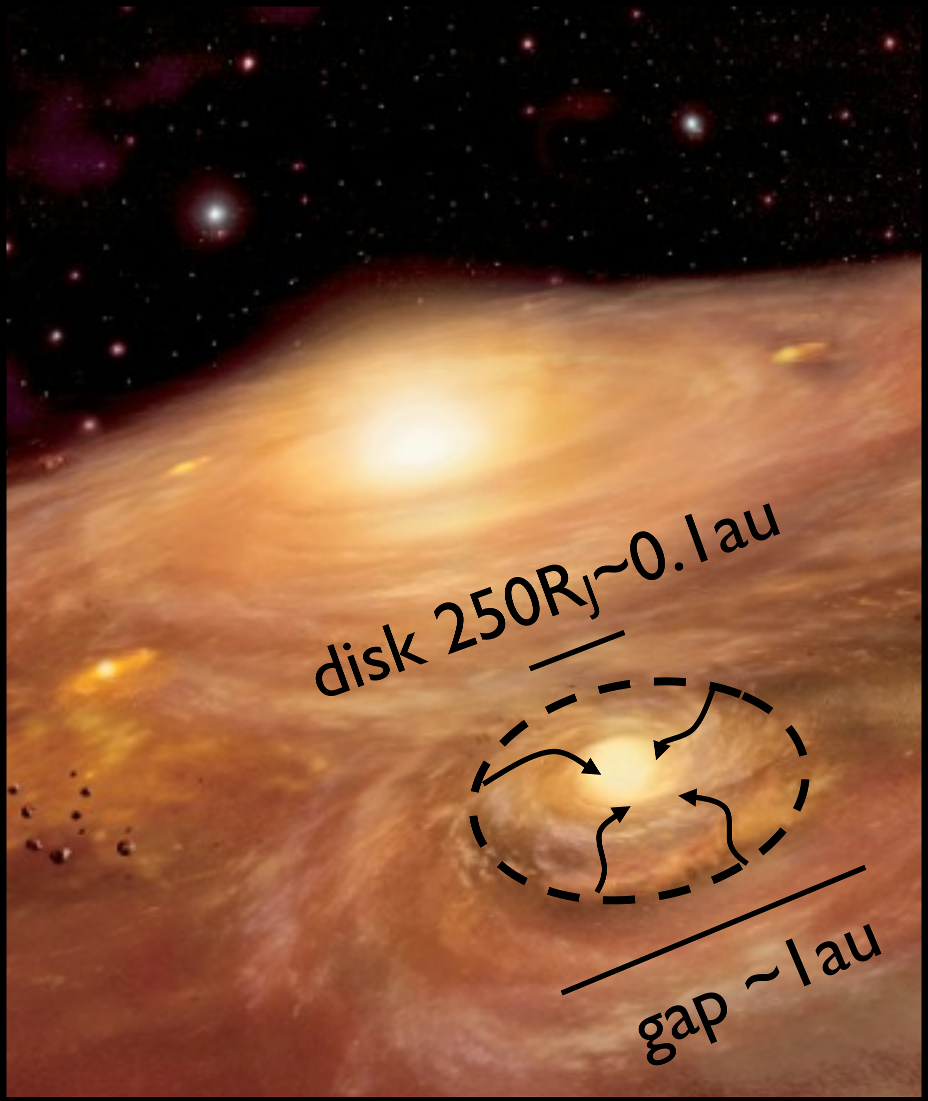

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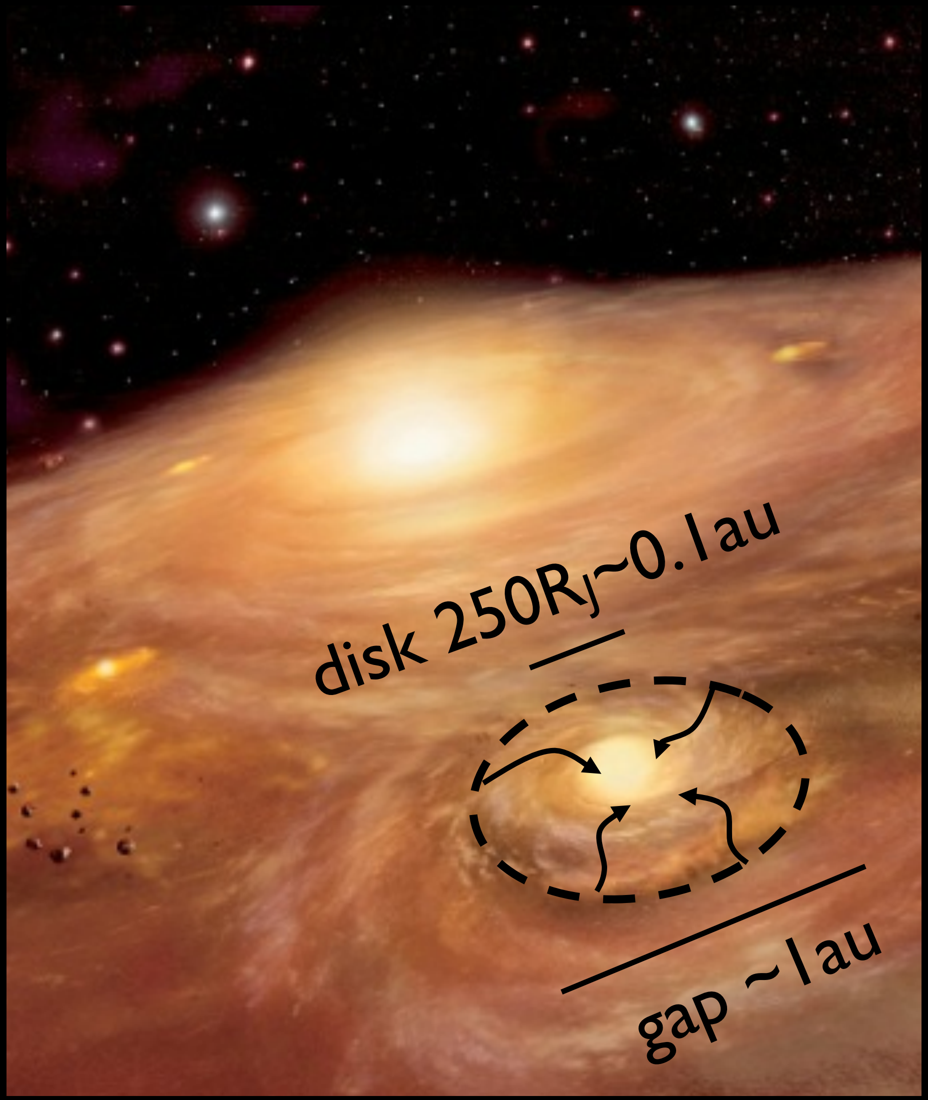
Circumplanetary Disk

… an accretion disk around a forming giant planet

- Accretion requires angular momentum loss
- An effective viscosity is needed for mass inflow
- Accretion mechanism could be hydromagnetic turbulence, large scale winds/jets or gravitational instability



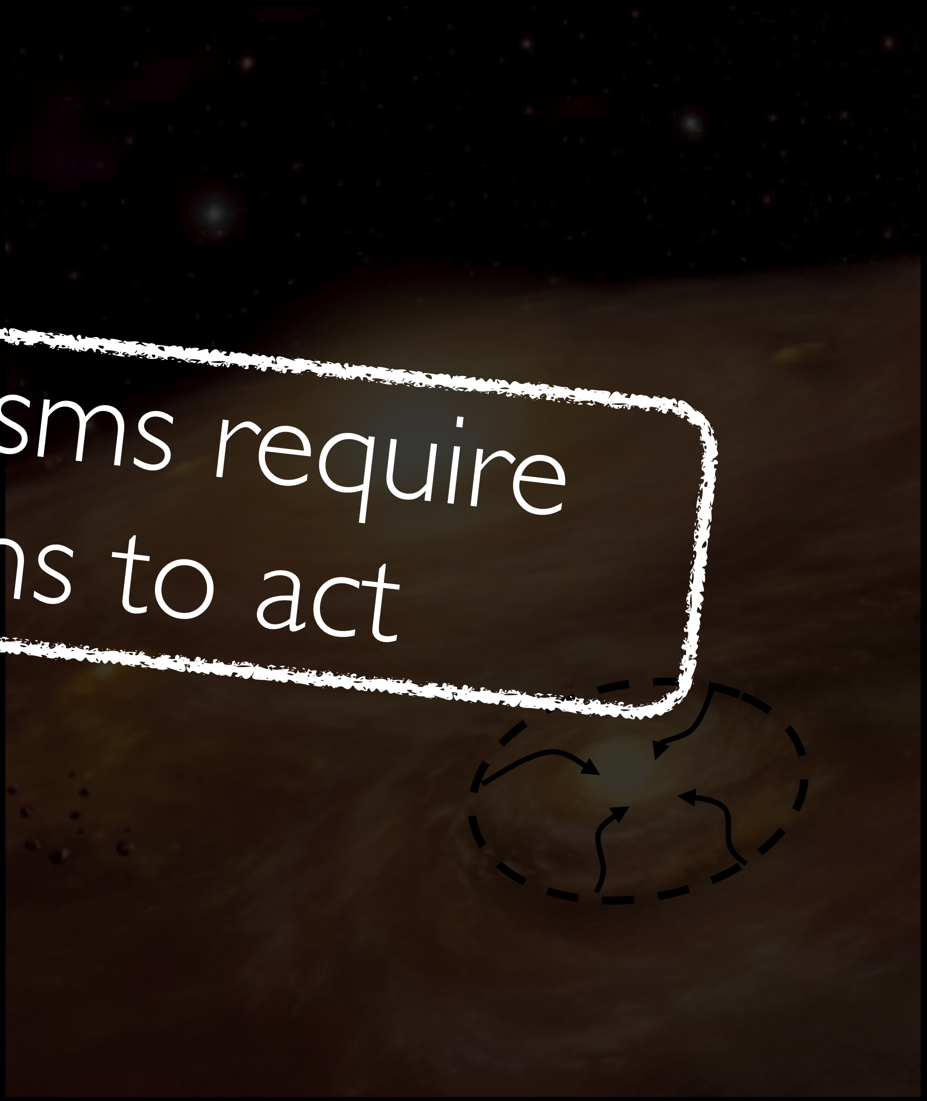
source: National Geographic

Circumplanetary Disk

… an accretion disk around a forming giant planet

- Accretion requires angular momentum loss
- An effective viscosity is needed for mass inflow
- Accretion mechanism could be hydromagnetic turbulence, large scale winds/jets or gravitational instability

But these mechanisms require special conditions to act

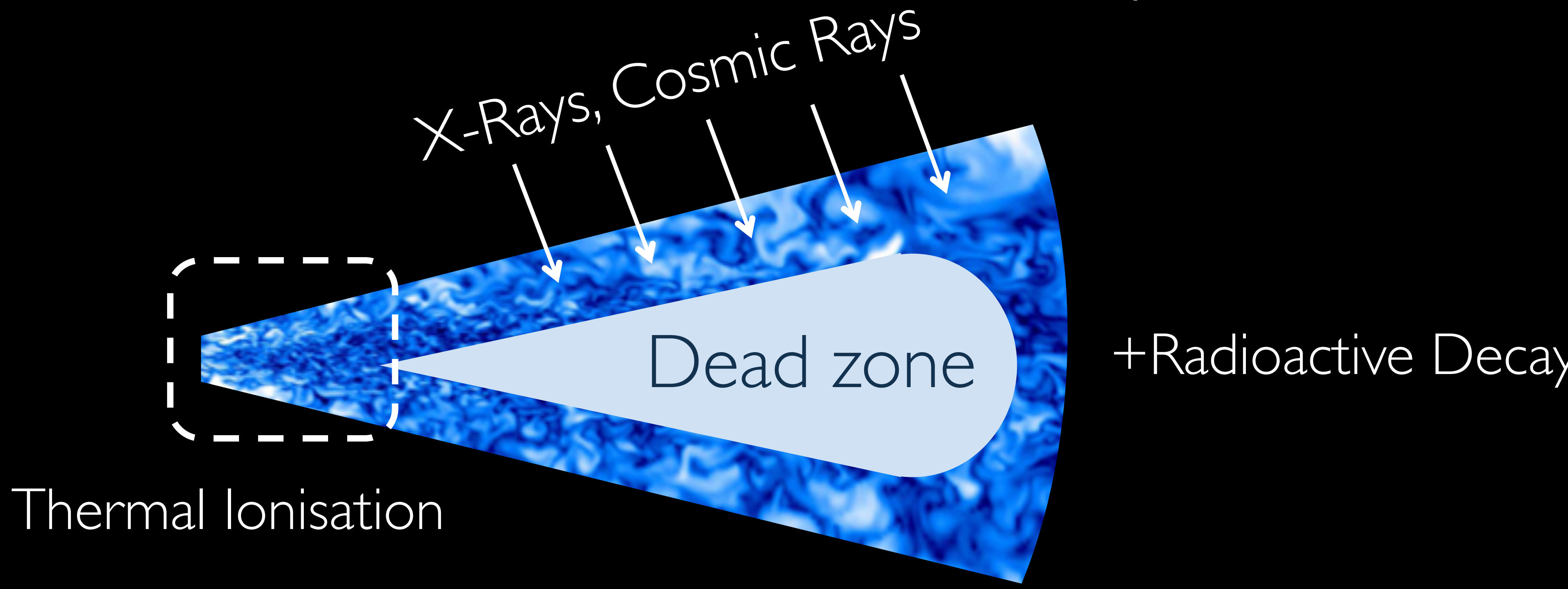


source: National Geographic

Accretion mechanism: Magnetic field

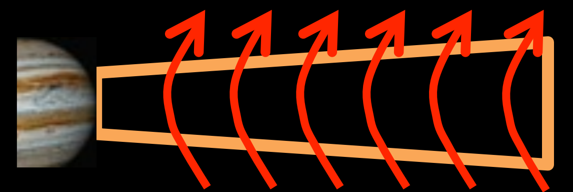
Active regions: Ionised; B field coupled; turbulent; accreting

Dead Zones: Low ionisation; B field decoupled; Not accreting



Small-scale field — Magnetorotational Instability (MRI)

...or large-scale fields — Magnetic braking, Centrifugal disk wind, Jet



Accretion mechanisms: Gravitoturbulence

Gammie 2001

Gravitationally unstable for massive disks

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} < Q_{\mathrm{crit}} \simeq 1$$

$$M_{\mathrm{disk}} \gtrsim \frac{H}{r} M_* \,, \quad \text{Toomre (1964)}$$

Cooling determines final state

$$\Omega t_{\mathrm{cool}} = \frac{\Sigma c_s^2 \Omega}{\sigma T_s^4} \quad \begin{matrix} <30 & \text{fragmentation} \\ >30 & \text{turbulence} \end{matrix}$$

Gammie 2001, Meru & Bate 2012

Aim

- Determine whether these mechanisms are effective in a circumplanetary disk (particularly for B-field).
- Develop a disk model self-consistently with the level of accretion from these mechanisms.
- Assess the viability of the resulting disk.

Disk model

Review: Pringle 1981

We adopt the standard 1D accretion disk model:

Keplerian	$\Omega = \sqrt{\frac{GM}{r^3}}$	Active Midplane	$\dot{M} = 2\pi\nu\Sigma$
Sound speed	$c_s = \sqrt{kT/m_n}$	Local heating	$T_s = \left(\frac{3\dot{M}\Omega^2}{8\pi\sigma}\right)^{\frac{1}{4}}$
Self Gravity	$Q = \frac{c_s\Omega}{\pi G\Sigma}$	Plane-parallel stellar atmosphere model	$\sigma T^4 = \frac{3}{8}\tau\sigma T_s^4$
Scale Height	$H = \frac{2Q}{1+\sqrt{1+4Q^2}}\frac{c_s}{\Omega}$	Optical depth	$\tau = \kappa\Sigma/2 \gg 1$
Average Density	$\rho = \frac{\Sigma}{2H}$	Turbulent viscosity	$\nu = \alpha c_s H.$

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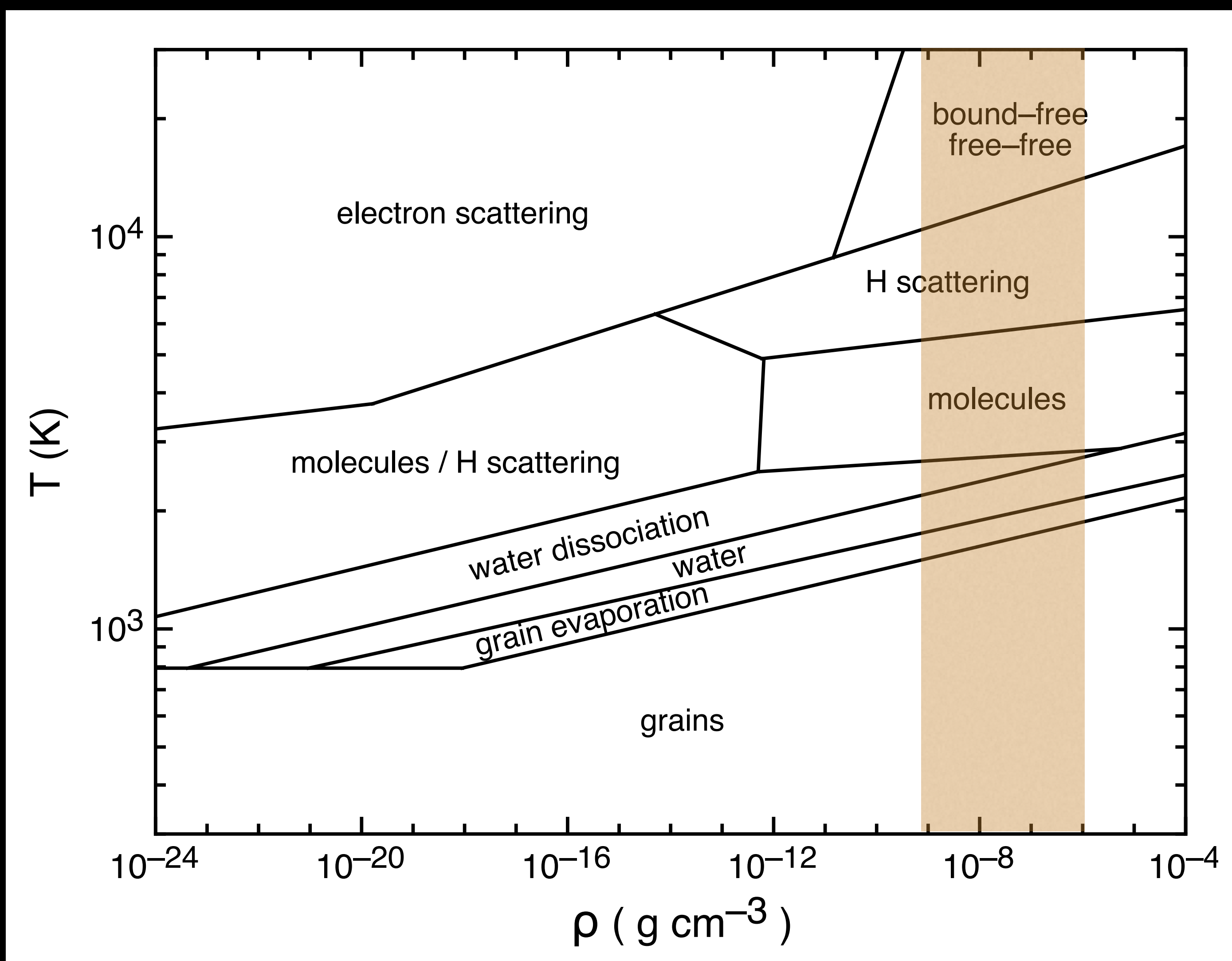
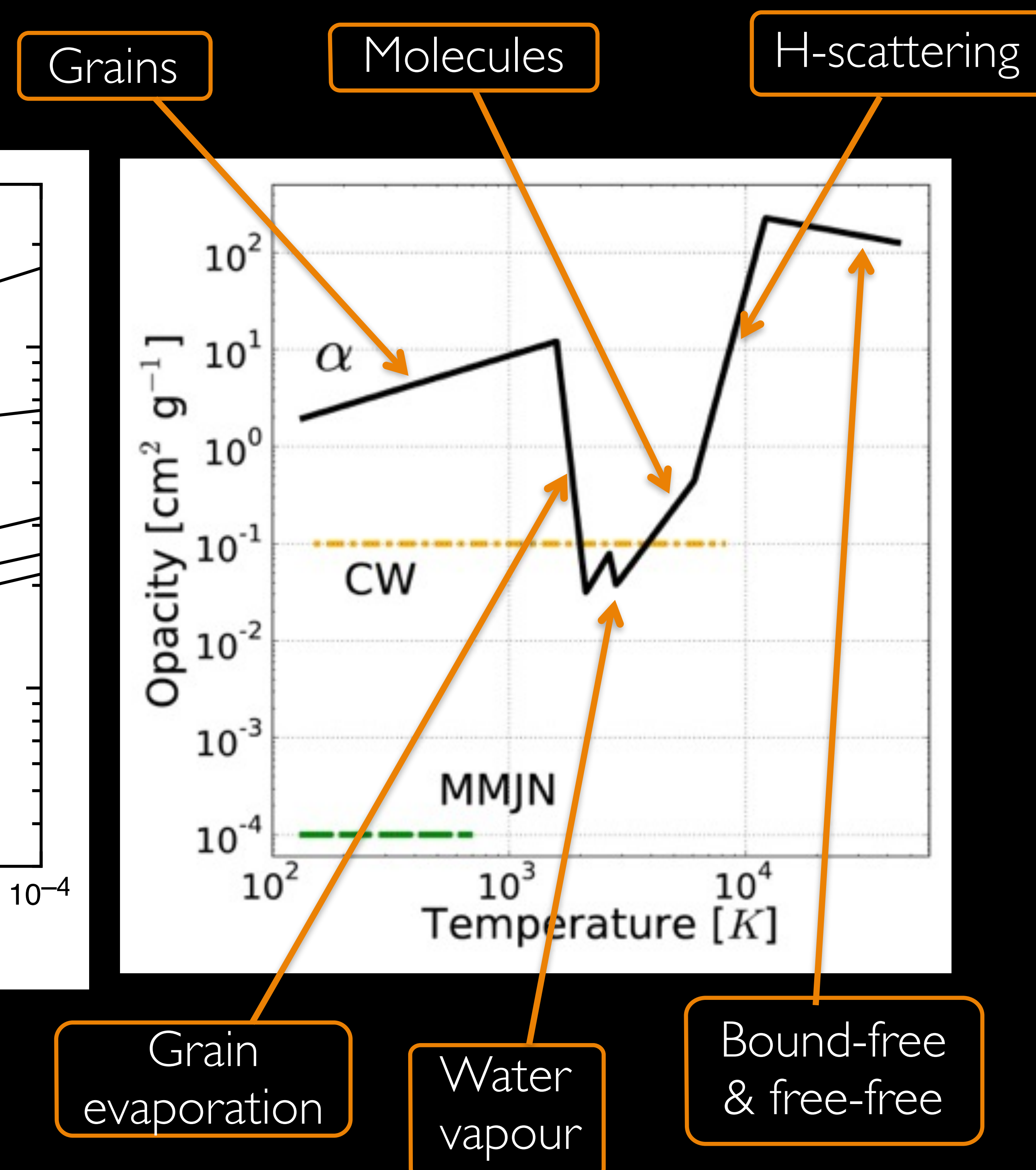
Opacity model



Zhu et al (2009) power-law fit



Alpha

… quantifies the strength of turbulent viscosity.

Viscosity in alpha model (Shakura & Sunyaev 1973)

$\nu = \alpha c_s H$

H → length scale

c_s → velocity scale

Observations and MRI simulations give $\alpha_{sat} \sim 0.001\text{-}0.1$ (King+2007)

In modelling α is typically taken to be uniform at the maximum value BUT this requires ideal MHD.

If Ohmic or Hall diffusivity, η, is important: (Sano & Stone 02)

$$\alpha = \begin{cases} \alpha_{\rm sat} v_a^2 / \left(\eta\Omega\right) & \text{for an MRI field,} \\ \alpha_{\rm sat} c_s^2 / \left(\eta\Omega\right) & \text{for a vertical field.} \end{cases}$$

Disk model

Equation to solve for the radial temperature profile with root-finding in each opacity regime

$$T^{\frac{3}{2}a-b+5} = \frac{9\kappa_i}{2^{2a+8}\sigma}\left(\frac{\mu m_p}{k}\right)^{\frac{3}{2}a+1} \alpha^{-(a+1)} \left(\frac{\dot{M}}{\pi}\right)^{a+2} \left(\frac{GM}{r^3}\right)^{a+\frac{3}{2}}$$

$$\alpha = \begin{cases} \alpha_{\rm sat} v_a^2/\left(\eta\Omega\right) & \text{for an MRI field,} \\ \alpha_{\rm sat} c_s^2/\left(\eta\Omega\right) & \text{for a vertical field.} \end{cases}$$

We calculate **α** self-consistently with the disk structure, according to the amount of diffusivity (**η**).

Ionisation

Cold, outer regions

Radioactive decay, cosmic rays, X-rays - rate equations

$$
\begin{aligned}
\frac{dn_i}{dt} &= \zeta n - k_{ei} n_i n_e - k_{ig} n_g n_i, \\
\frac{dn_e}{dt} &= \zeta n - k_{ei} n_i n_e - k_{eg} n_g n_e, \\
\frac{dZ_g}{dt} &= k_{ig} n_i - k_{eg} n_e, \\
0 &= n_i - n_e + Z_g n_g
\end{aligned}
$$

Hot, inner regions

>1000 K

Thermal - Saha Equation

$$\frac{n_e n_{i,j}}{n_j} = g_e \left(\frac{2\pi m_e k T}{h^3} \right)^{\frac{3}{2}} \exp\left(-\frac{\chi_j}{kT} \right)$$

$$Z_g = \psi\tau - \frac{1}{1 + \sqrt{\tau_0/\tau}}$$

Grains

+ Charge Neutrality

$$n_i - n_e + Z_g n_g = 0.$$

Ionisation

Cold, outer regions

Radioactive decay, cosmic rays, X-rays - rate equations

Ionisation energy, χ_j

Element	Atomic weight (amu)	Abundance	Ionisation potential (eV)
H	1.01	9.21×10^{-1}	13.60
He	4.00	7.84×10^{-2}	24.59
Na	22.98	1.60×10^{-6}	5.14
Mg	24.31	3.67×10^{-5}	7.65
K	39.10	9.87×10^{-8}	4.34

Treat ions as magnesium

Hot, inner regions

>1000 K

Thermal - Saha Equation

$$\frac{n_e n_{i,j}}{n_j} = g_e \left(\frac{2\pi m_e kT}{h^3}\right)^{\frac{3}{2}} \exp\left(-\frac{\chi_j}{kT}\right)$$

$$Z_g = \psi\tau - \frac{1}{1+\sqrt{\tau_0/\tau}}$$

+ Charge Neutrality

$$n_i - n_e + Z_g n_g = 0.$$

Not planet

Disk magnetic field

MRI field

MRI shearing box simulations

(Sano+2004)

$$\alpha \approx 0.5\beta^{-1} = 0.5\frac{B^2}{8\pi P}$$

$$B_{\rm MRI} = \left(\frac{\dot{M}\Omega^2}{c_s}\right)^{\frac{1}{2}} \sim 1\,\mathrm{G}$$

Vertical field

Minimum strength

(Wardle 2007)

$$B_{\rm V} = \sqrt{\frac{\dot{M}\Omega}{2r}} \sim 0.1\,\mathrm{G}$$

Determines and depends on inflow rate

c.f. present day surface field of Jupiter: 4.2 G, Inferred field in protoplanetary disk ~3mG-1G

Magnetic Diffusivity

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla(\mathbf{v} \times \mathbf{B}) - \nabla \times [\eta_O(\nabla \times \mathbf{B}) + \eta_H(\nabla \times \mathbf{B}) \times \hat{\mathbf{B}}] - \nabla \times [\eta_A(\nabla \times \mathbf{B})_\perp$$

Diffusivity	Density	Coupled to field? Electrons	Coupled to field? Ions	Typical range [cm^2/s]
Ohmic, η_O	High	✗	✗	10^{12}-10^{16}
Hall, η_H	Intermediate	✓	✗	10^{10}-10^{14}
Ambipolar, η_A	Low	✓	✓	10^{6} -10^{10}

Low diffusivity - well coupled

High diffusivity - poorly coupled

Magnetic Diffusivity

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Each diffusivity < coupling threshold:

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Hall, η_H	Intermediate	✓	✗	[illegible]
Ambipolar, η_A	Low	✓	✓	10^{6}-10^{10}

Threshold

$\eta < c_s^2/\Omega \sim h^2\Omega$: Vertical field

$\eta < v_a^2/\Omega \sim (2\sqrt{\alpha}h)^2\Omega$: MRI field

Low diffusivity - well coupled

High diffusivity - poorly coupled

Results - models

This work

- Simple constant-alpha model - α
- Self-consistent accretion with MRI field - MRI

for comparison

- Minimum mass Jovian Nebula from satellite system- MMJN

Three accretion modes

Saturated magnetic transport

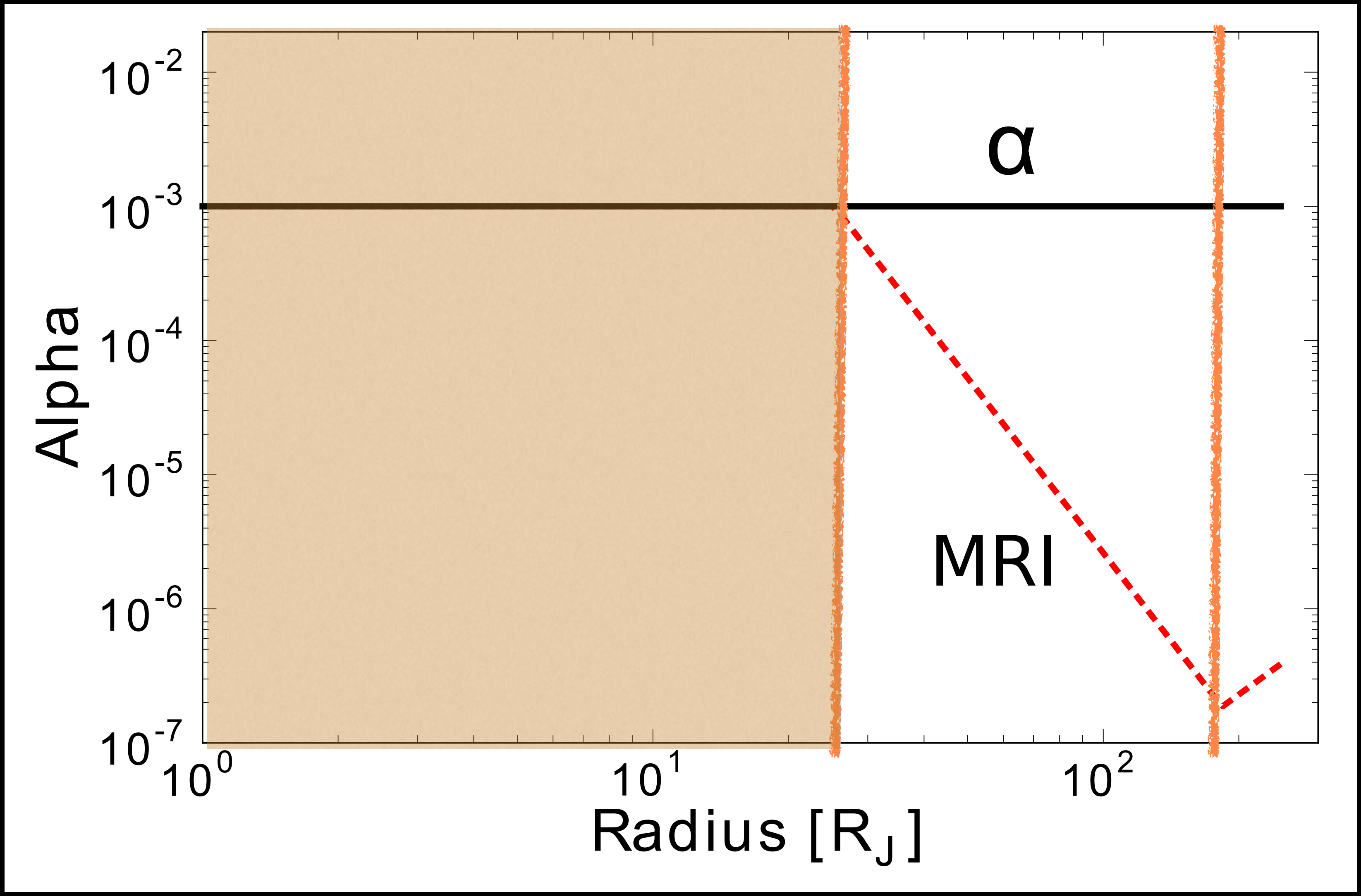
η small, Q>1

Inefficient magnetic transport

η large, Q>1

Gravitoturbulent transport (not magnetic)

η large, Q=1



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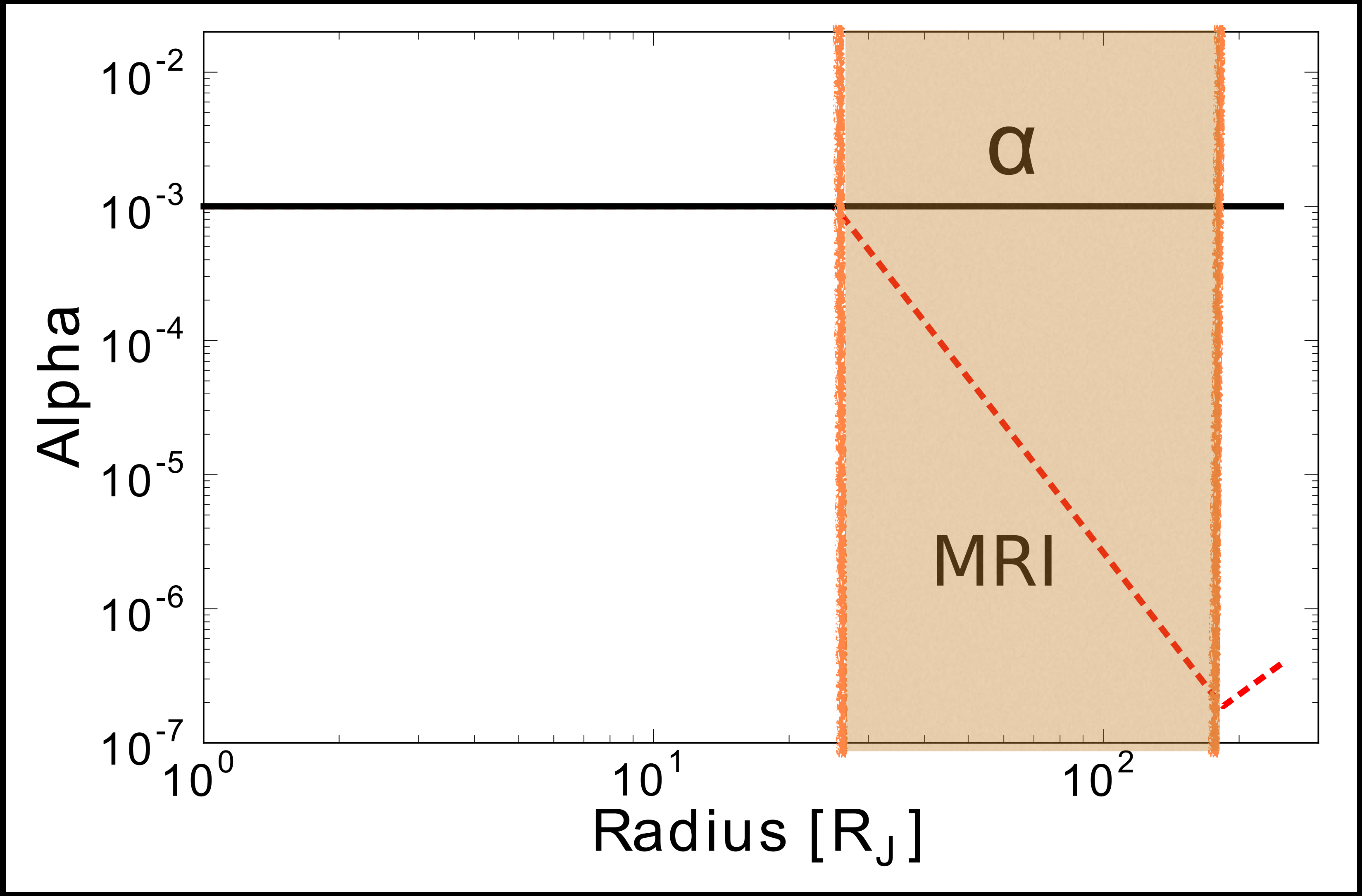

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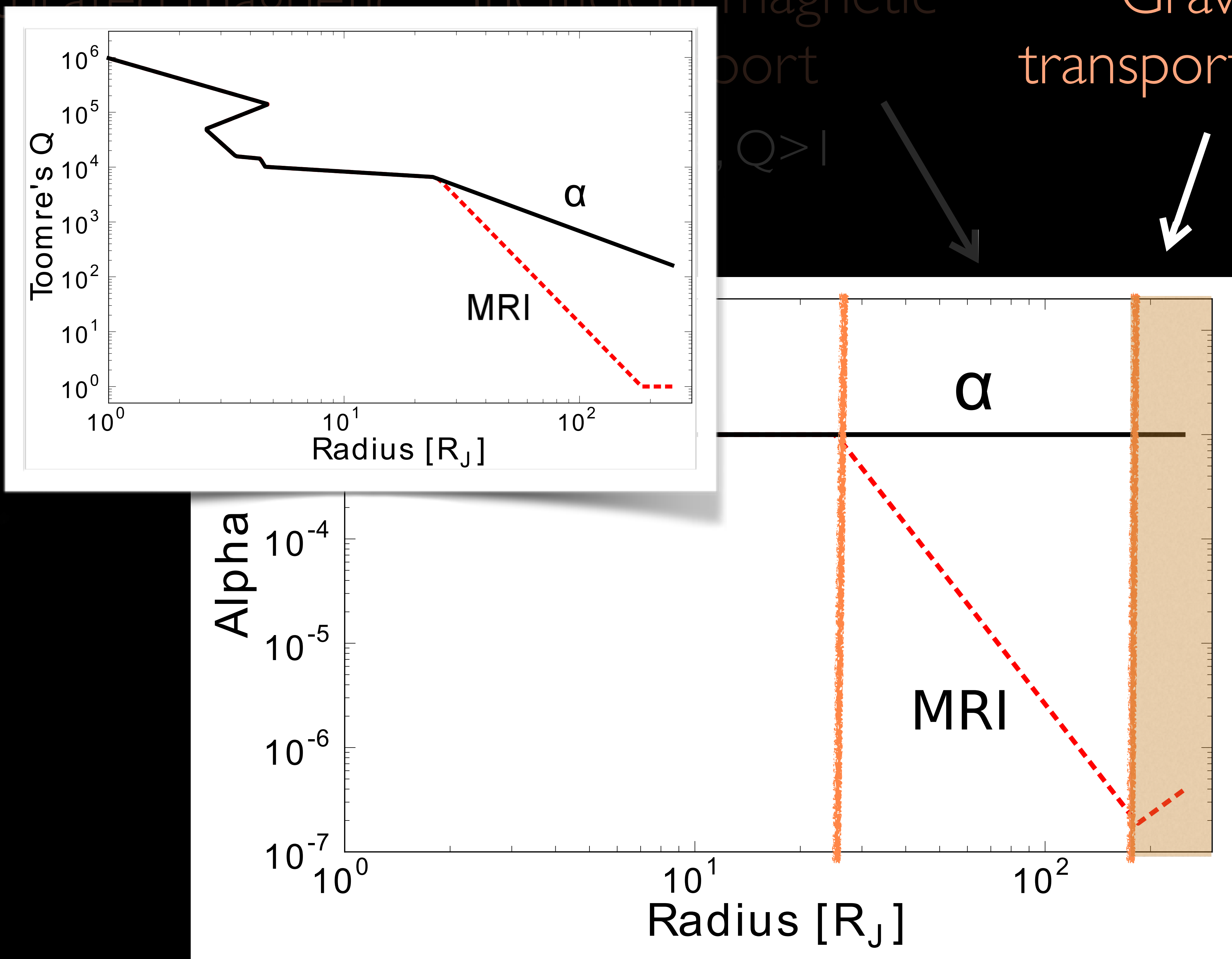
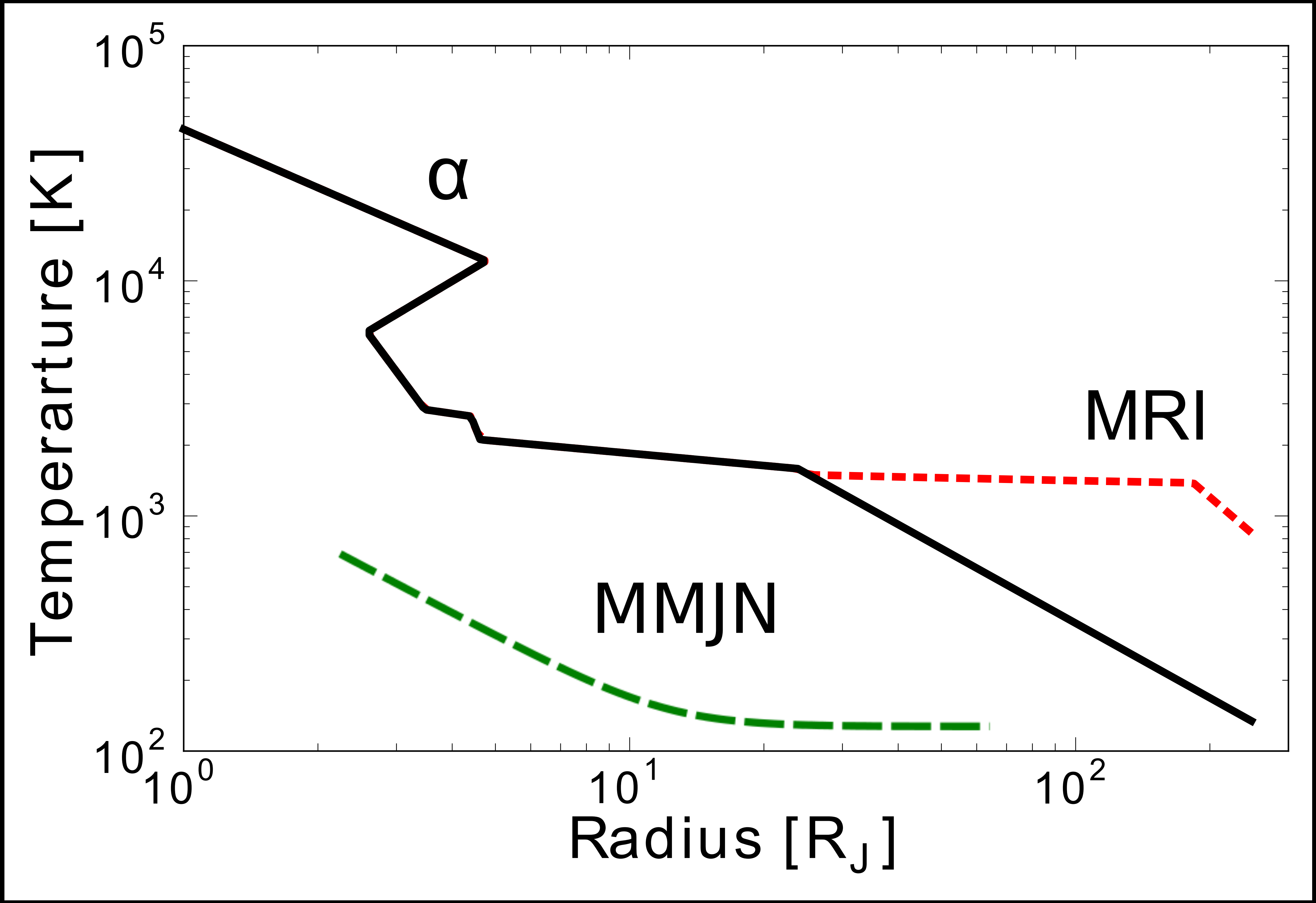


Temperature



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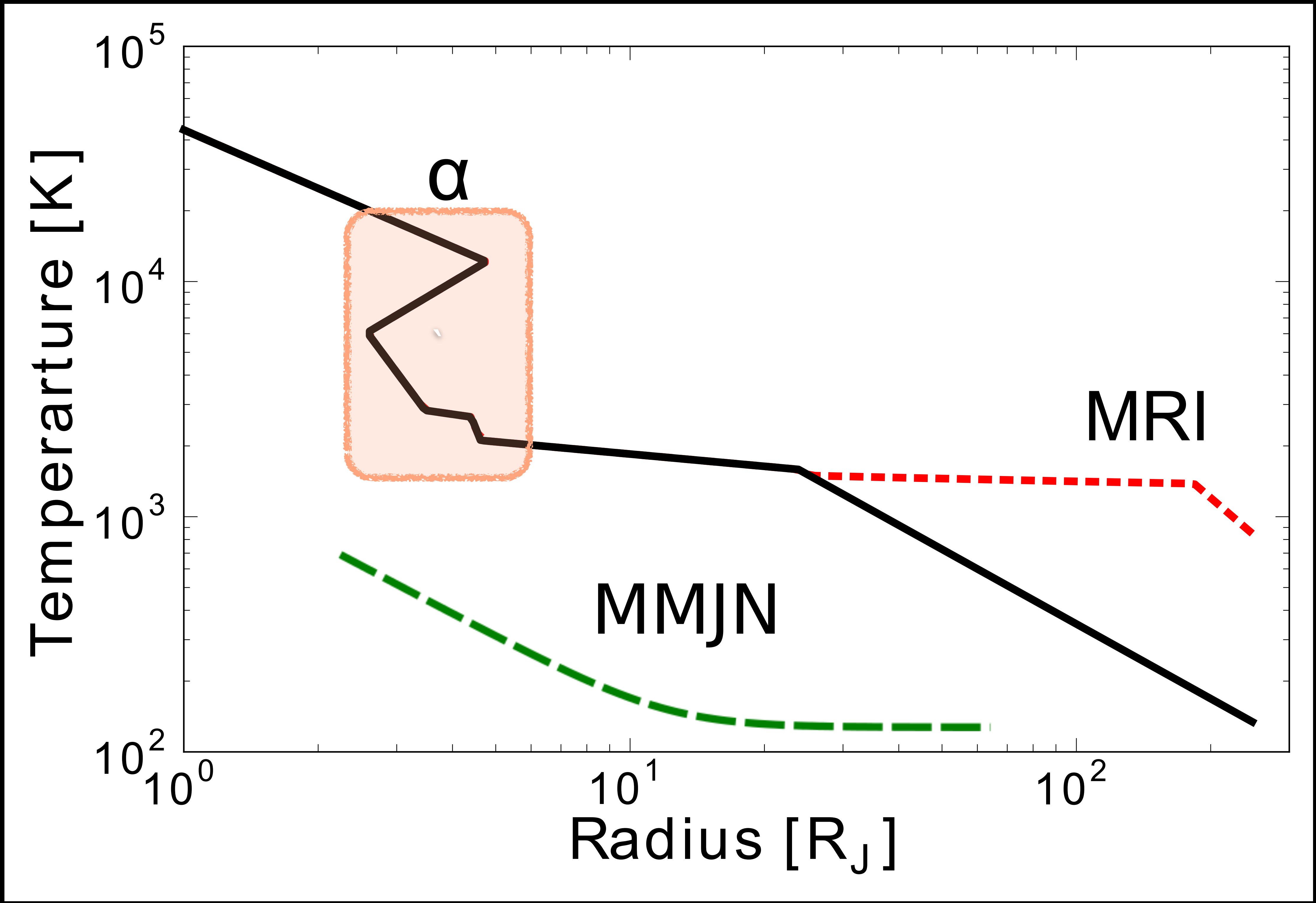
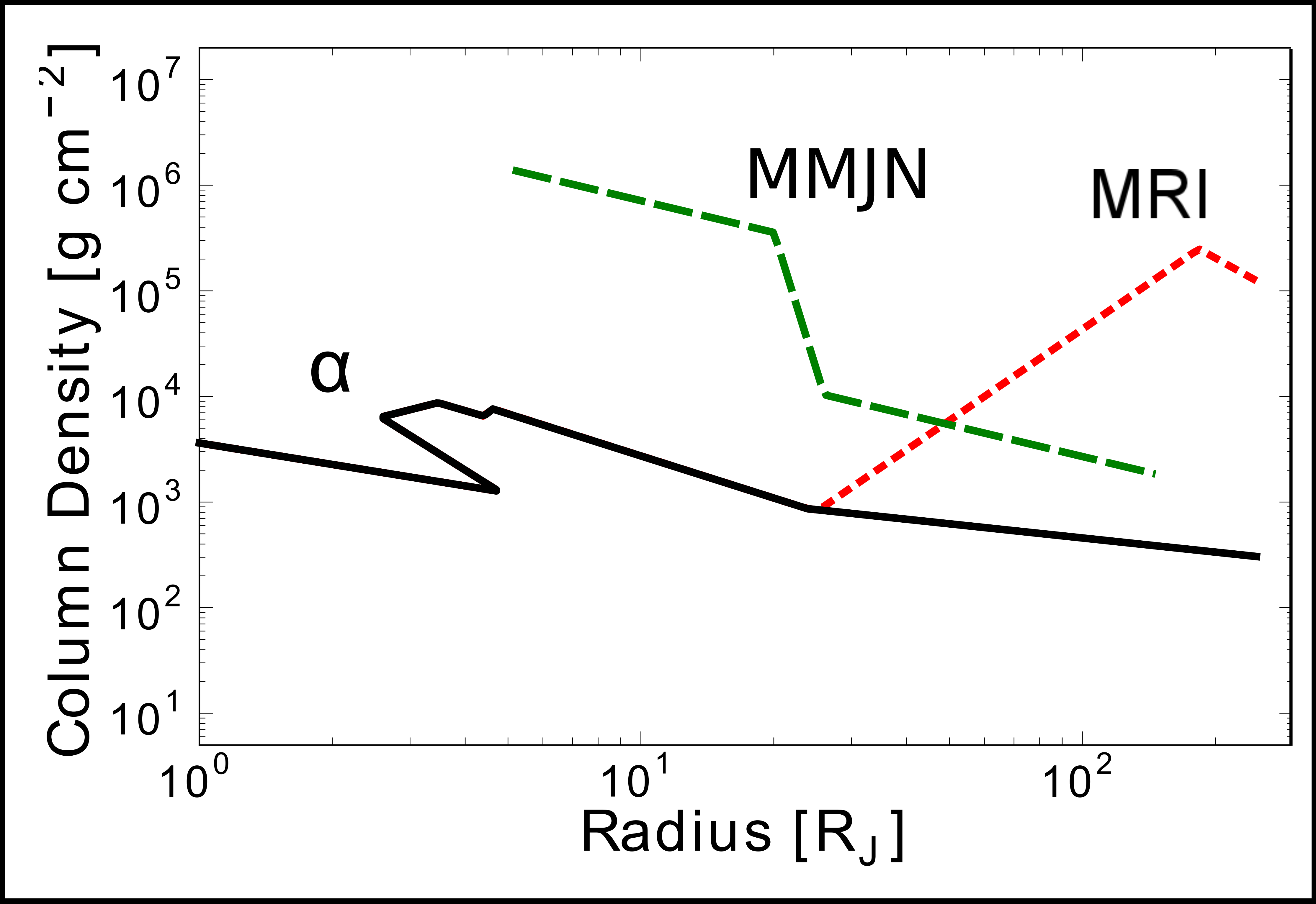
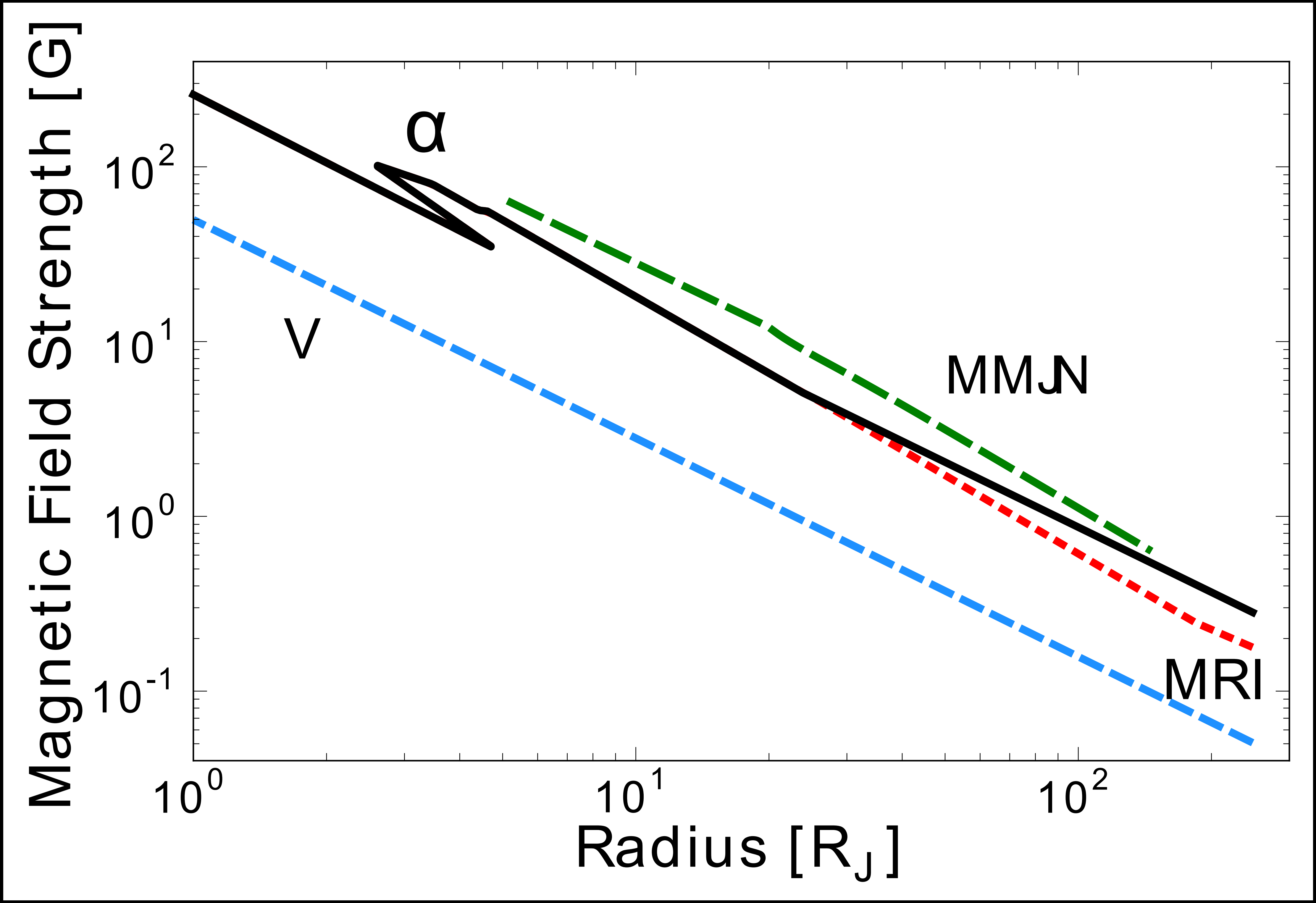


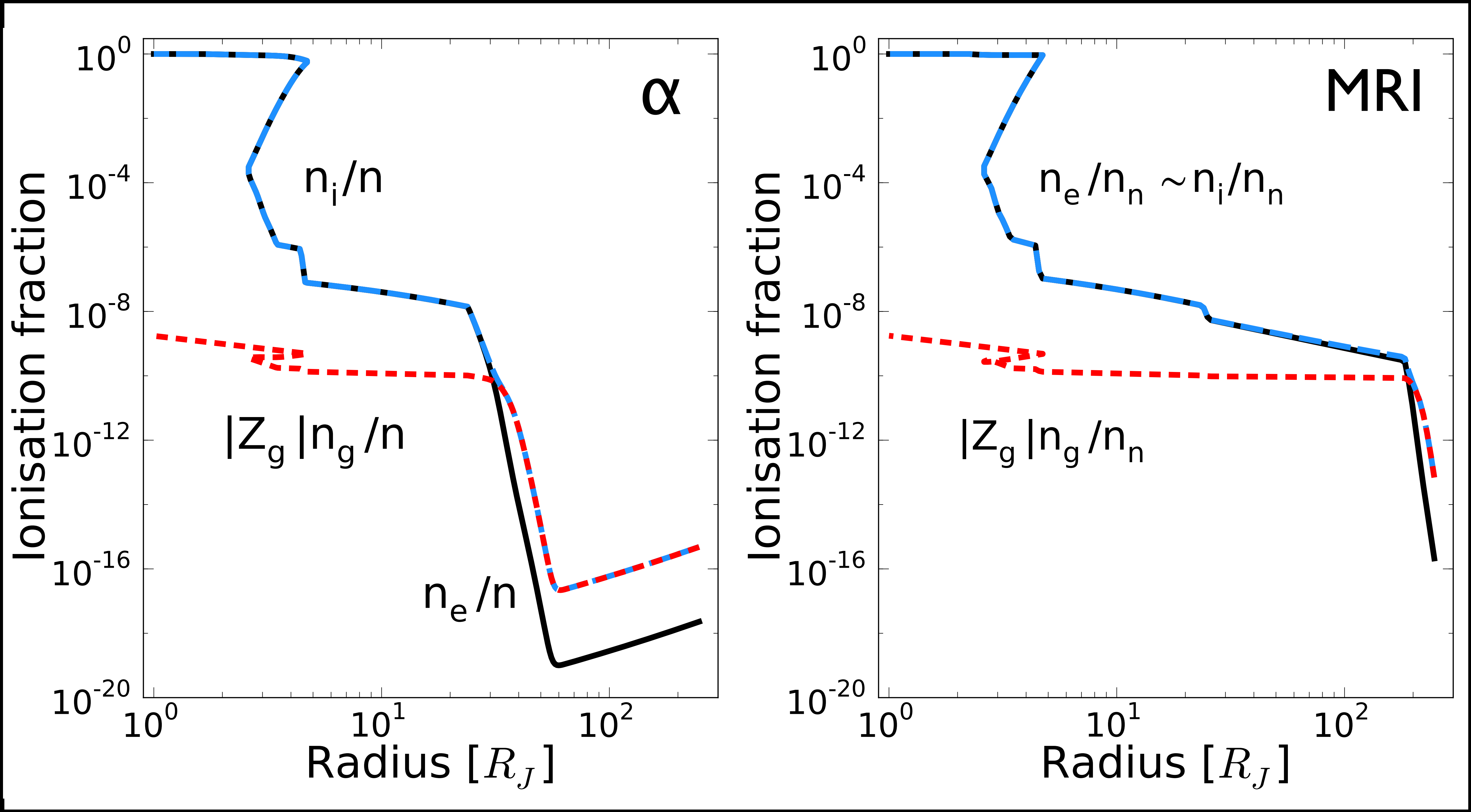
Column Density



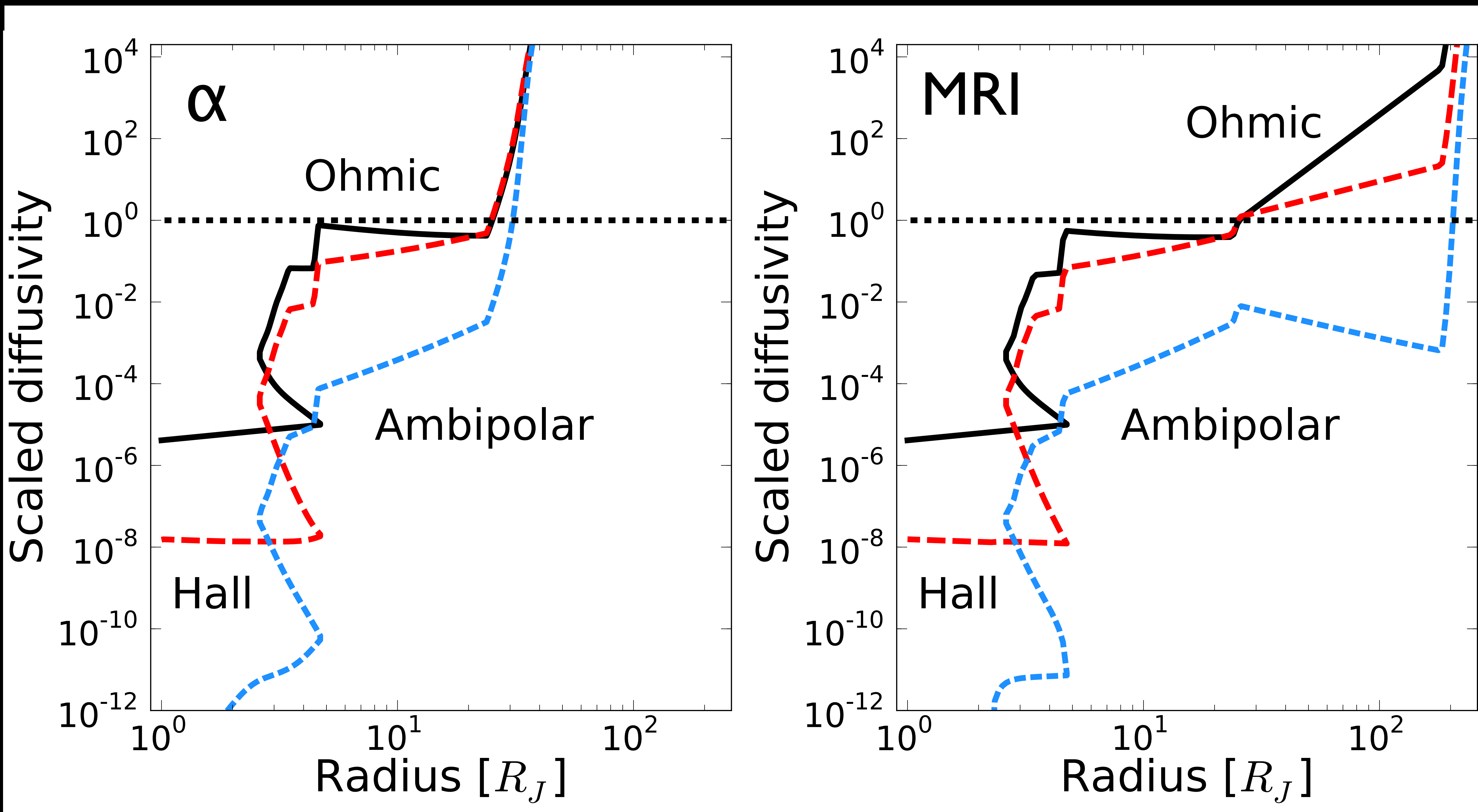
Magnetic Field



Ionisation fraction



Diffusivity



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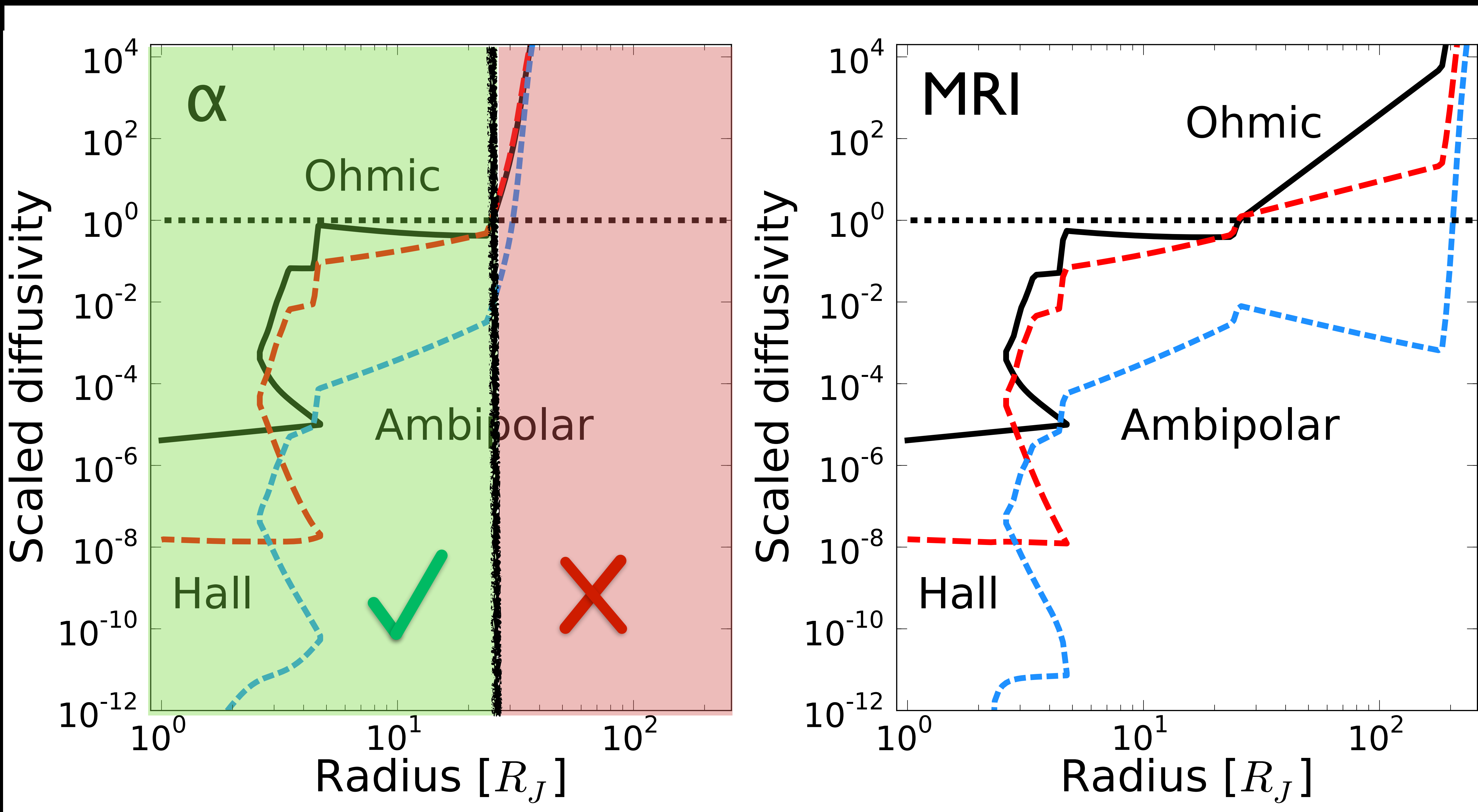

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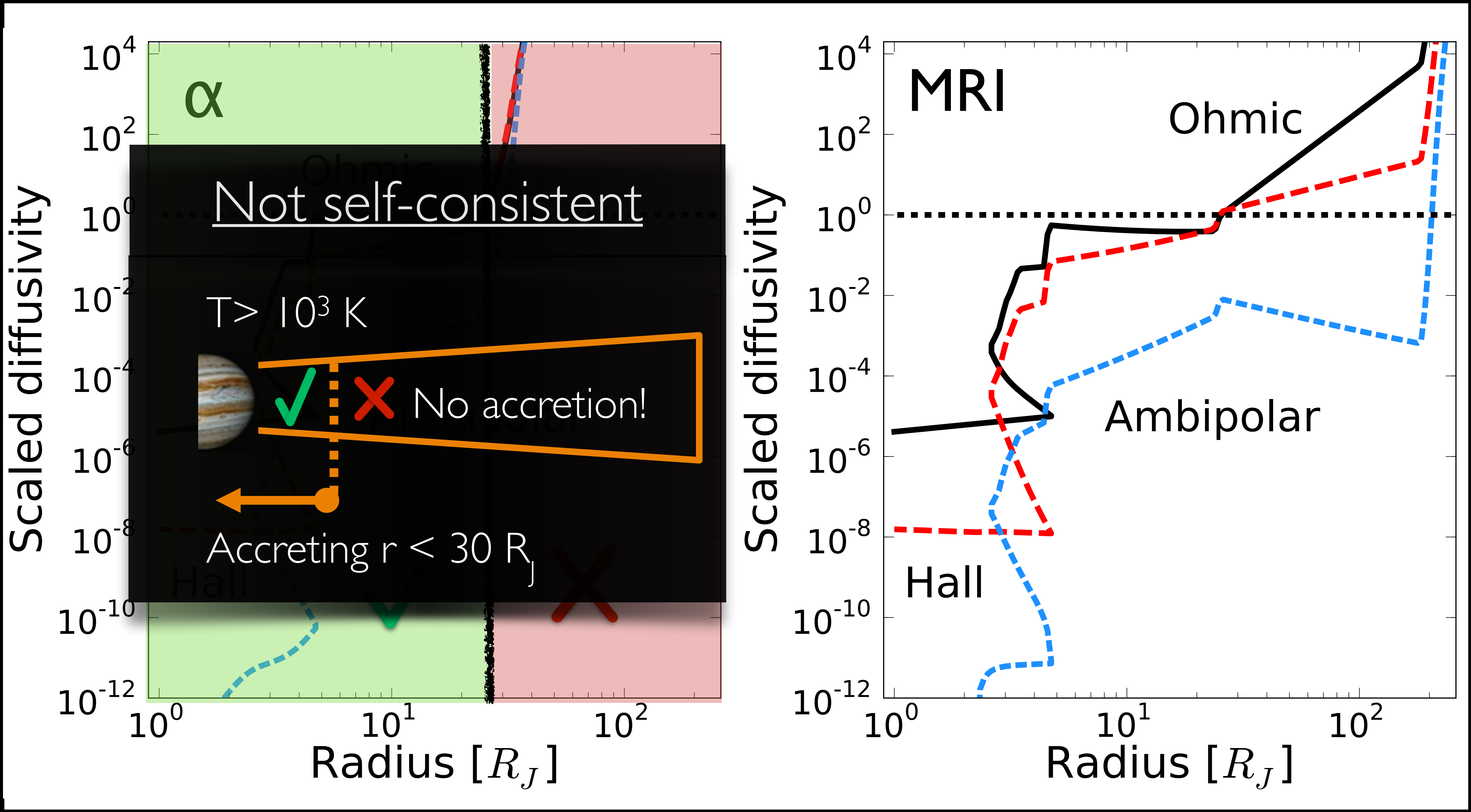
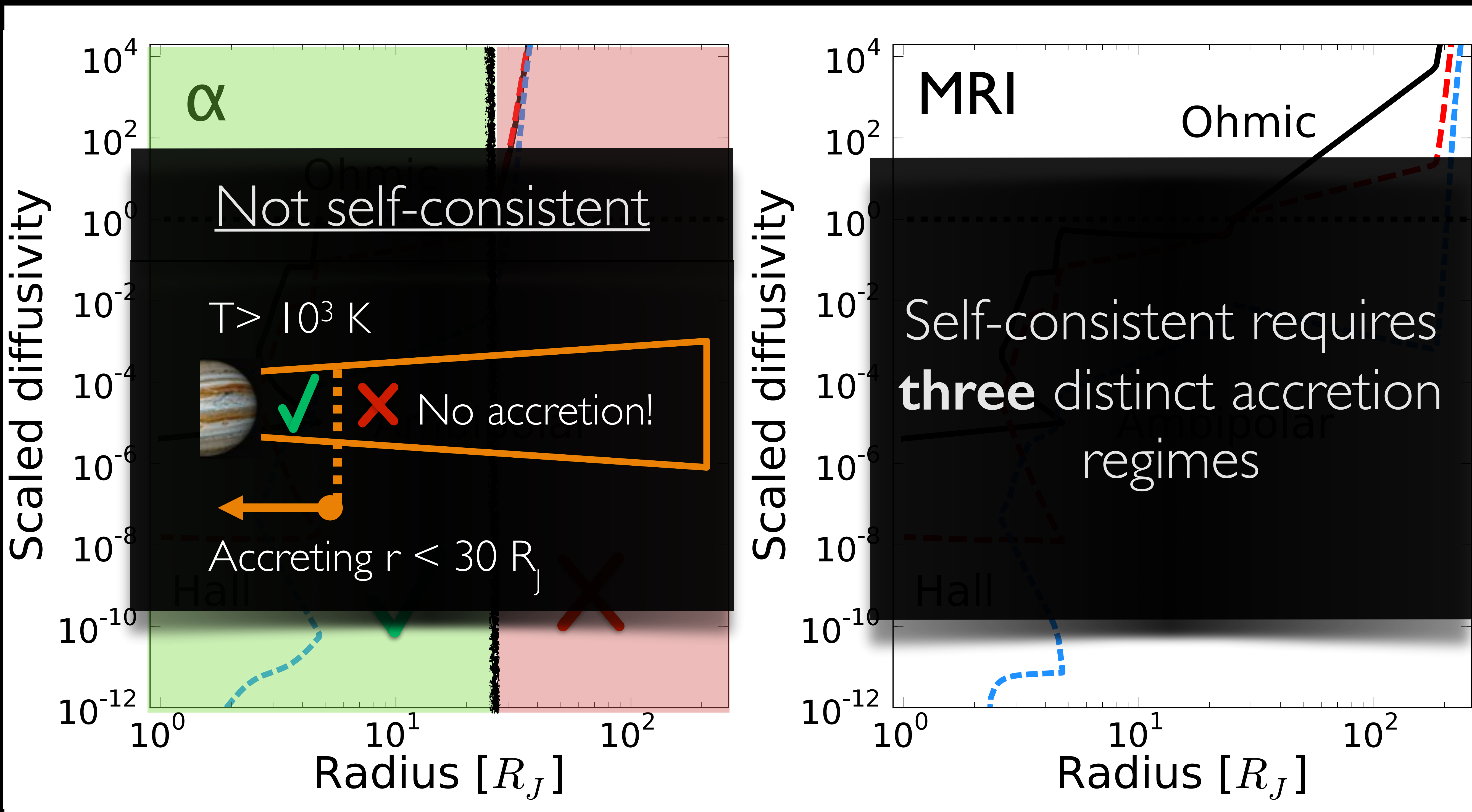


Diffusivity



Conclusion

- Magnetically driven accretion requires $T \sim 800K$ across 80% of disk, as thermal ionisation is key.
- Disk is massive with $M \sim 0.5M_J$
- Accretion occurs in three different modes - saturated, marginally coupled, and gravitoturbulence.
- Similar results for transport by a Vertical field
- First circumplanetary disk model to include transport with imperfect magnetic coupling.