

Post Runaway

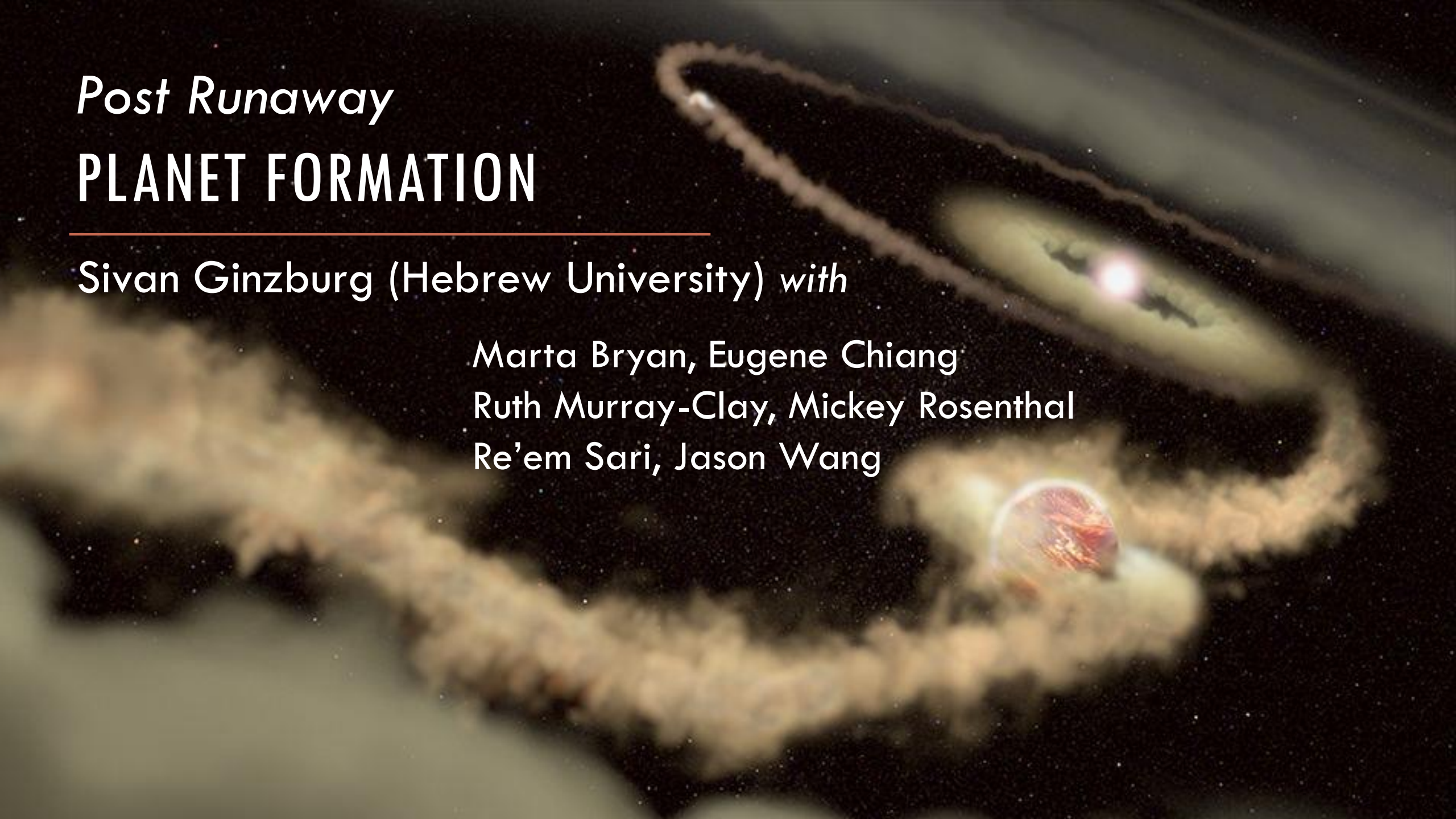
PLANET FORMATION

Sivan Ginzburg (Hebrew University) *with*

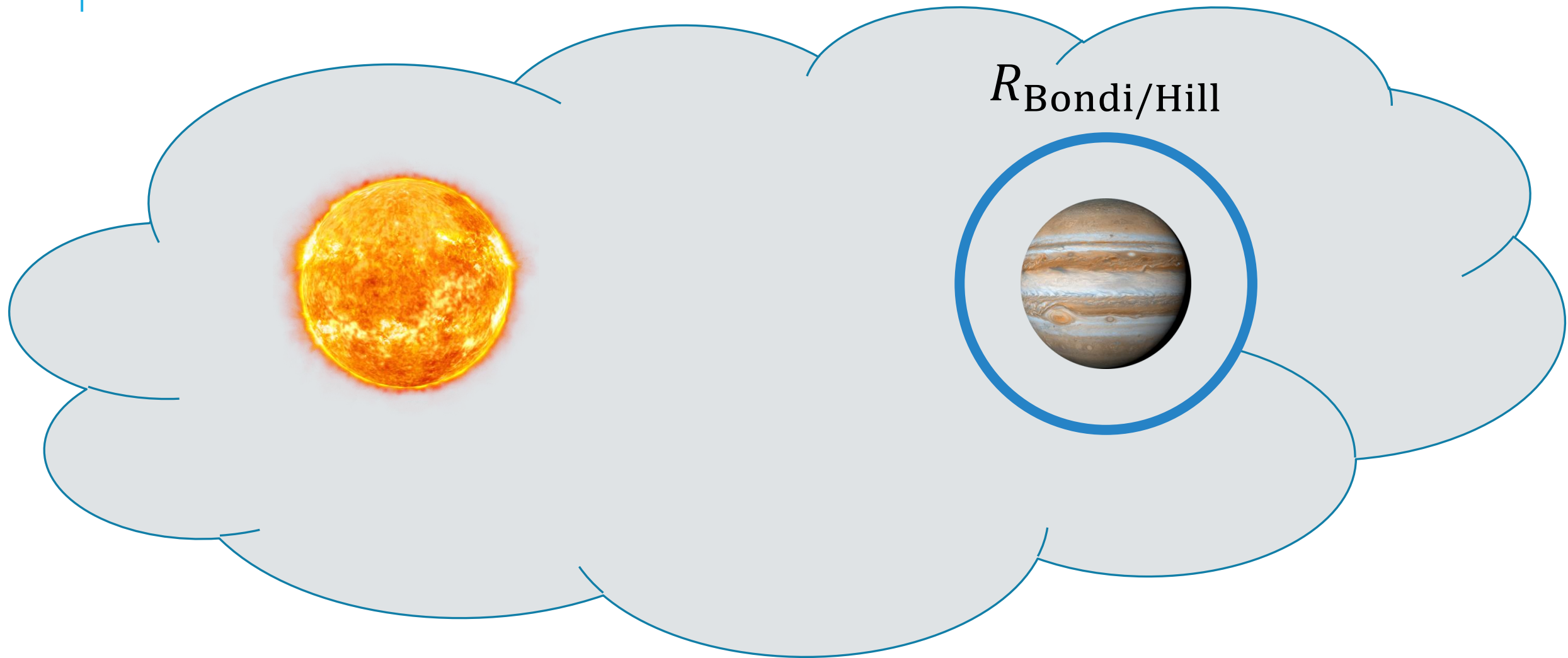
Marta Bryan, Eugene Chiang

Ruth Murray-Clay, Mickey Rosenthal

Re'em Sari, Jason Wang



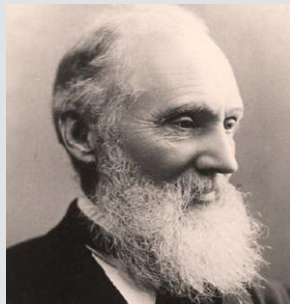
FORMATION IN A DISK



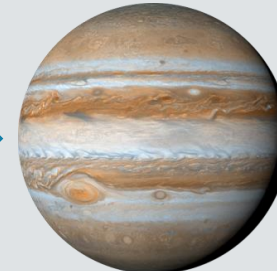
FORMATION IN A DISK



$$t_{\text{KH}} \sim \frac{GM^2}{RL}$$

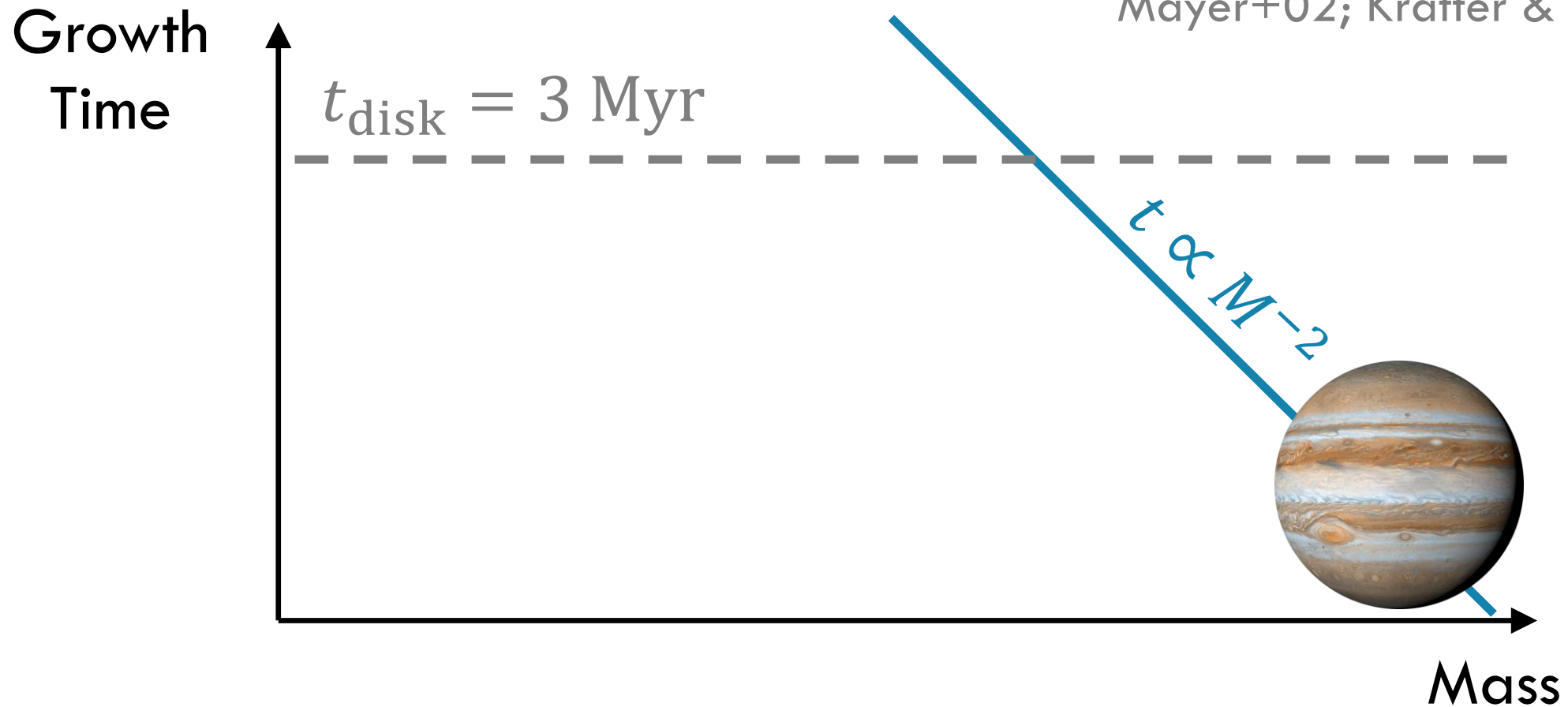


$R_{\text{Bondi/Hill}}$



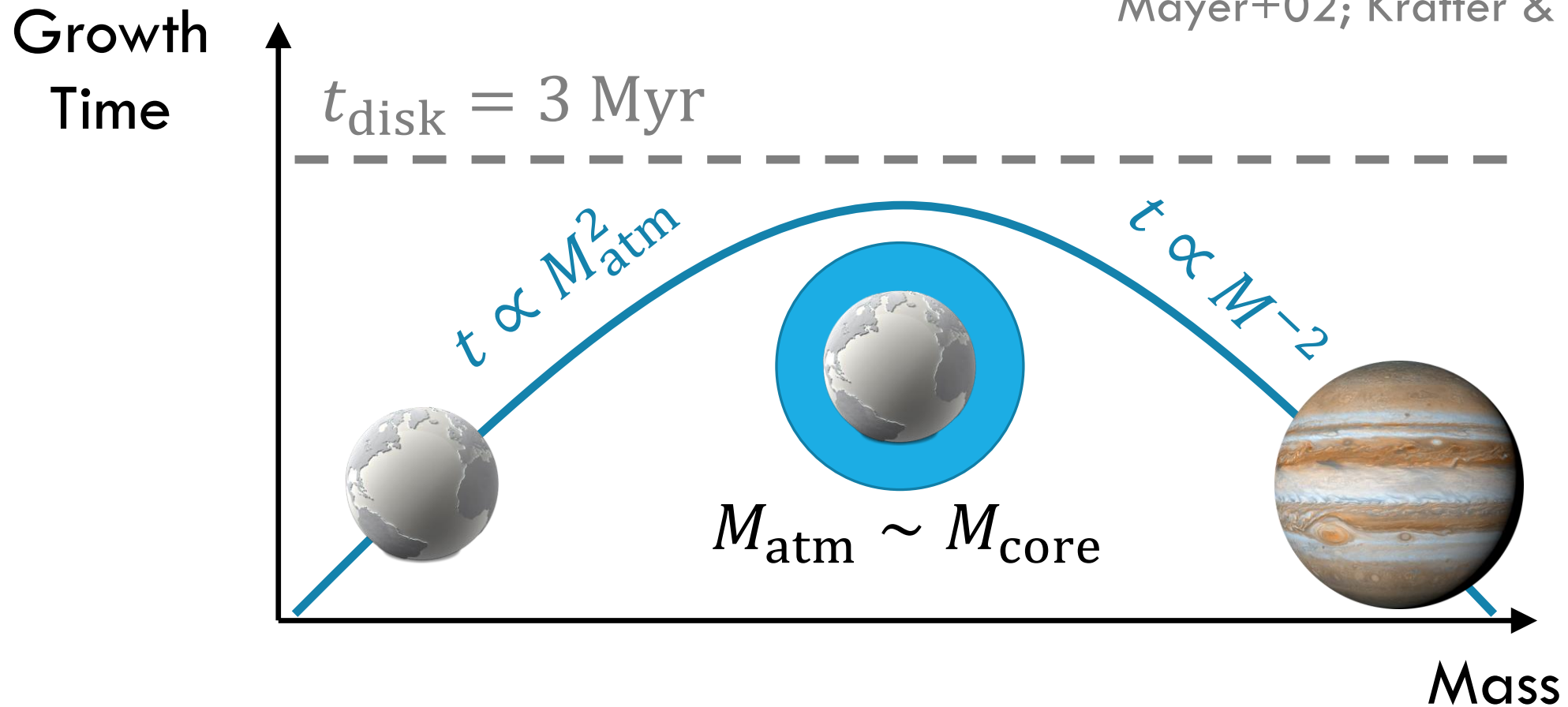
RUNAWAY GROWTH

Bodenheimer & Pollack 1986
Piso & Youdin 2014
Piso, Youdin, Murray-Clay 2015
Mayer+02; Kratter & Lodato 16



RUNAWAY GROWTH

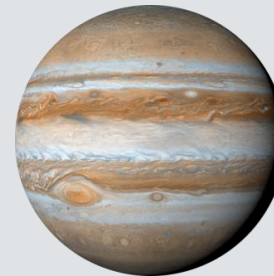
Bodenheimer & Pollack 1986
Piso & Youdin 2014
Piso, Youdin, Murray-Clay 2015
Mayer+02; Kratter & Lodato 16



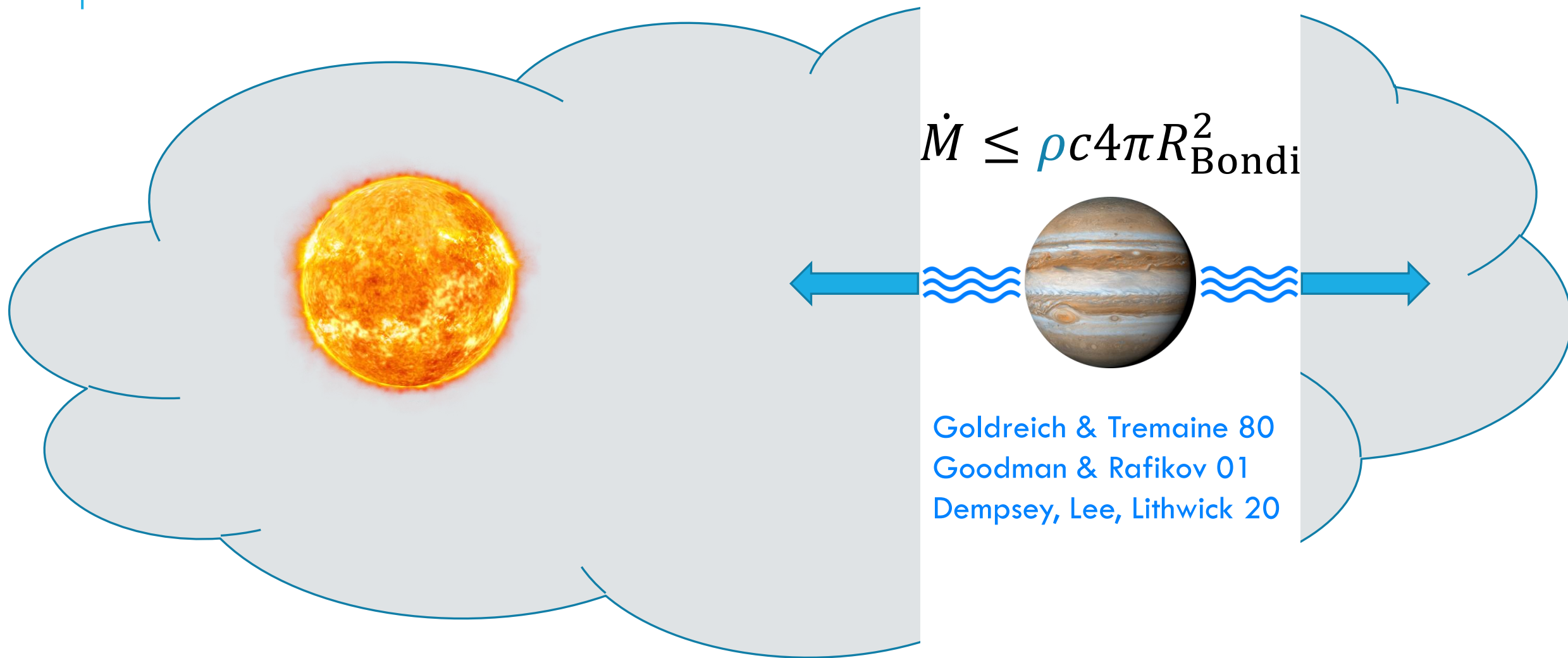
GAP OPENING



$$\dot{M} \leq \rho c 4\pi R_{\text{Bondi}}^2$$

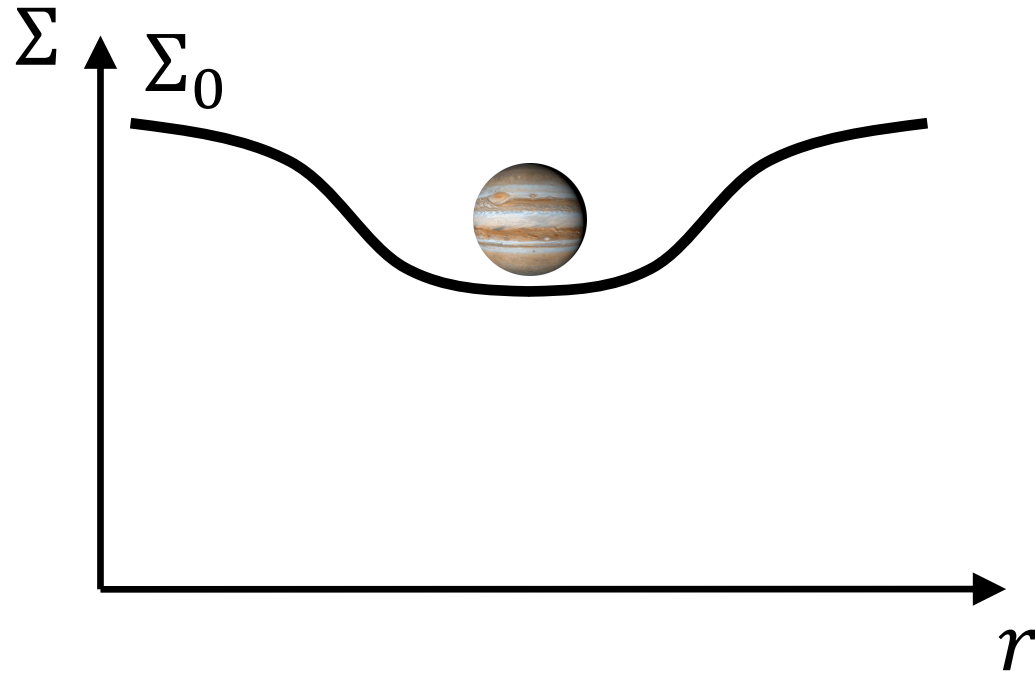


GAP OPENING



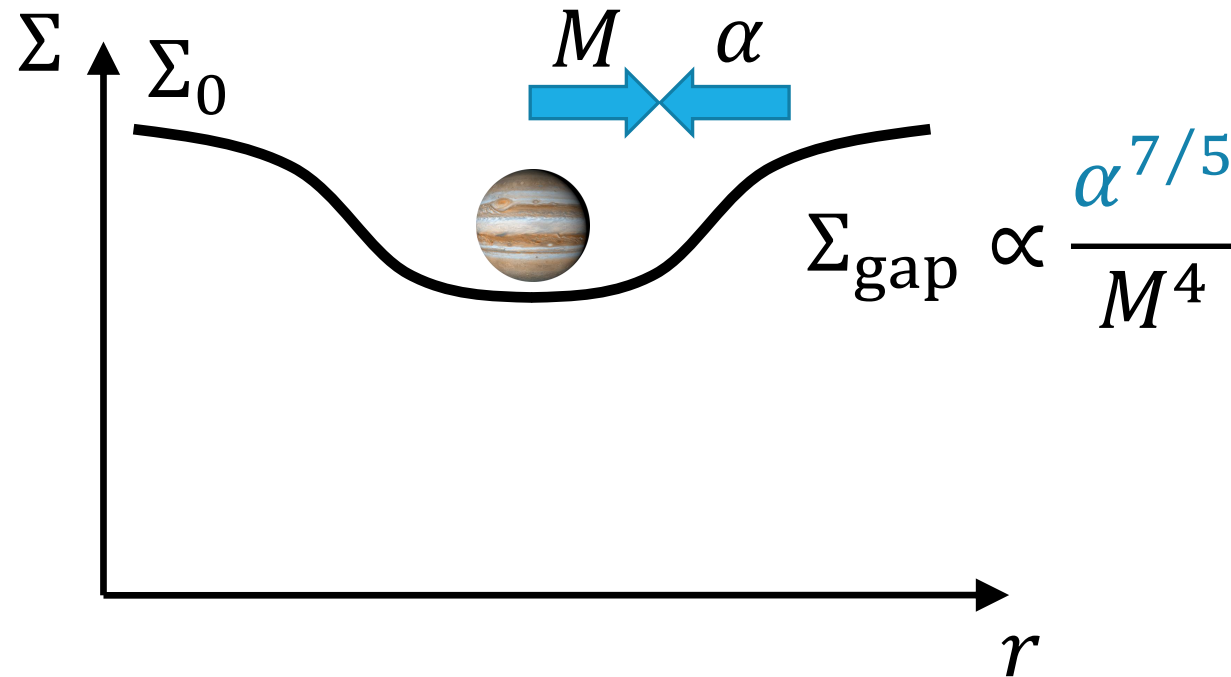
GAP DEPTH

Sari & Goldreich 04; Kratter, Murray-Clay, Youdin 10
Kocsis, Haiman, Loeb 12; D'Orazio, Haiman, MacFadyen 13
Duffell & MacFadyen 13; Fung, Shi, Chiang 14
Dipierro, ..., Lodato 15; Malik, ..., Mayer+ 15
Dempsey, Lee, Lithwick 20; Duffell 20



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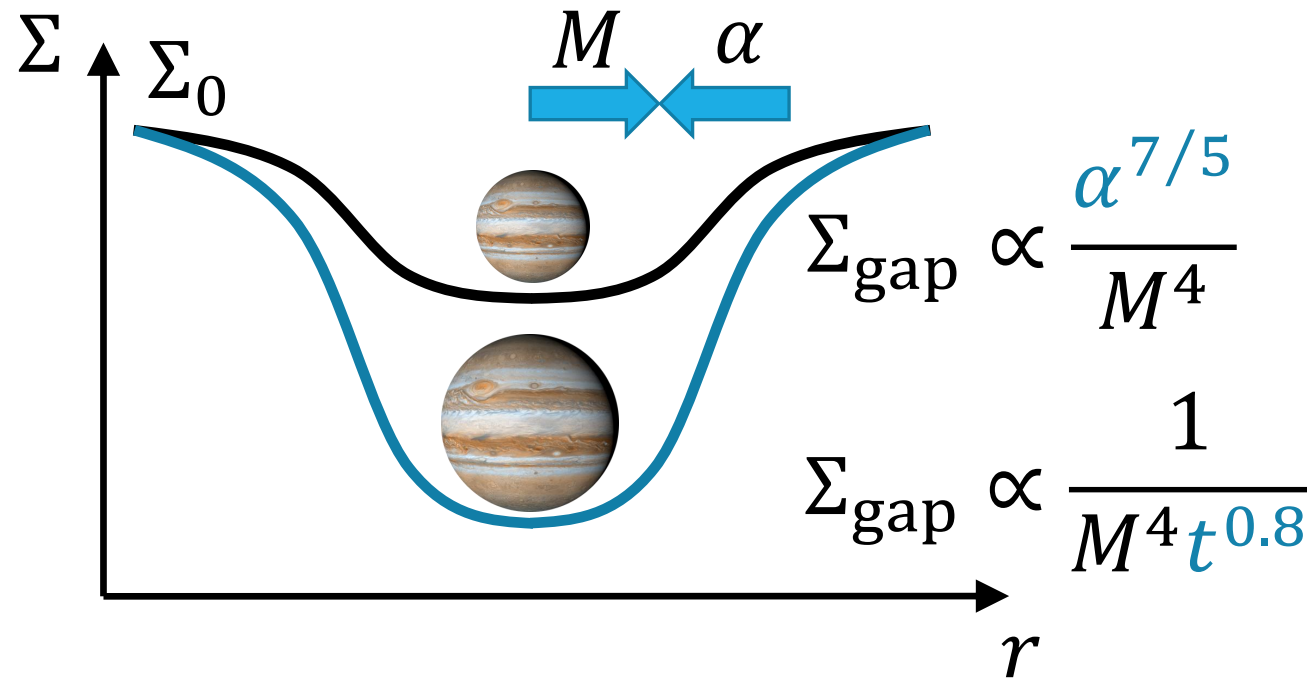


Equilibrium

Ginzburg & Sari 2018

GAP DEPTH

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Equilibrium

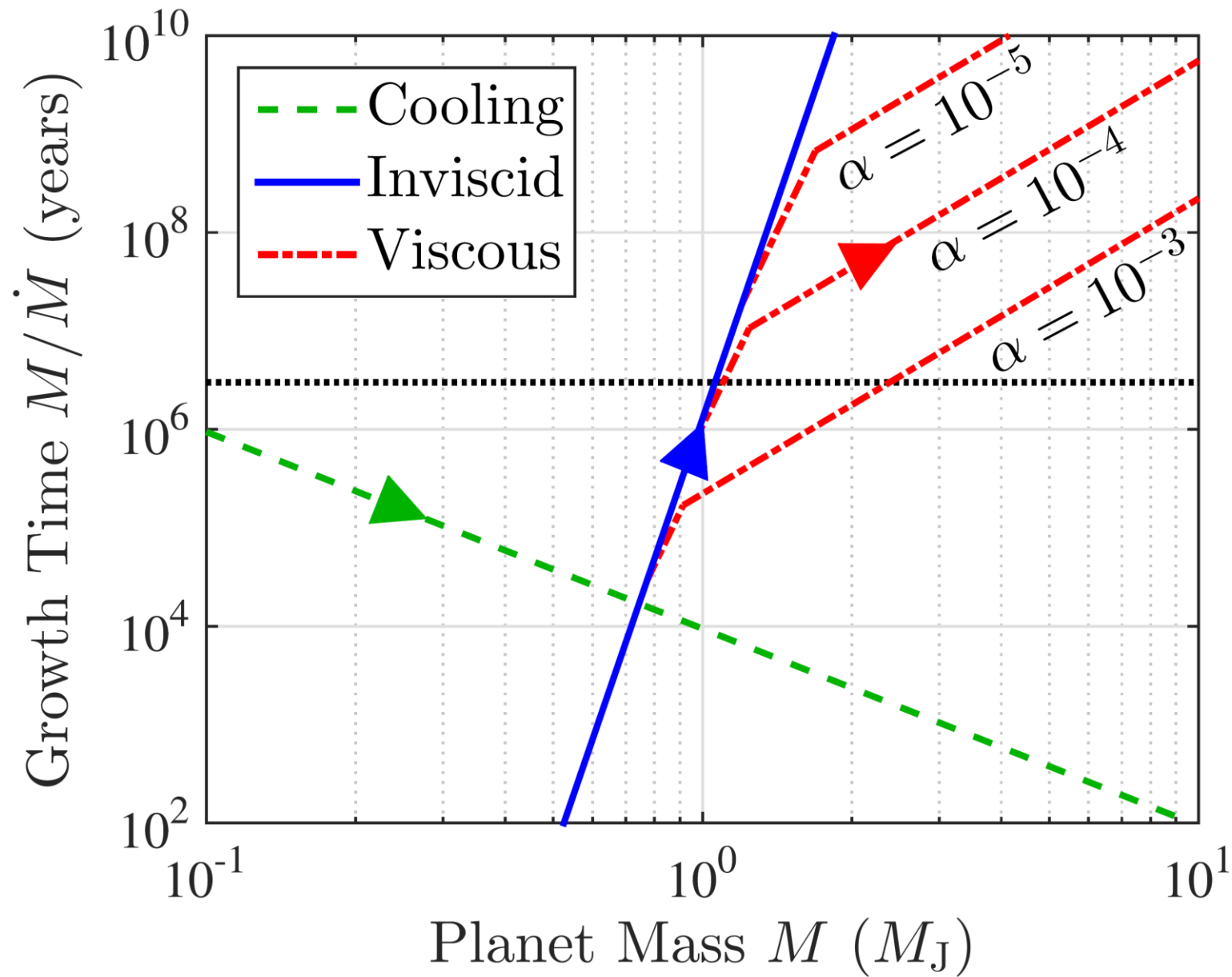
Ginzburg & Sari 2018

Time dependent

Ginzburg & Chiang 2019

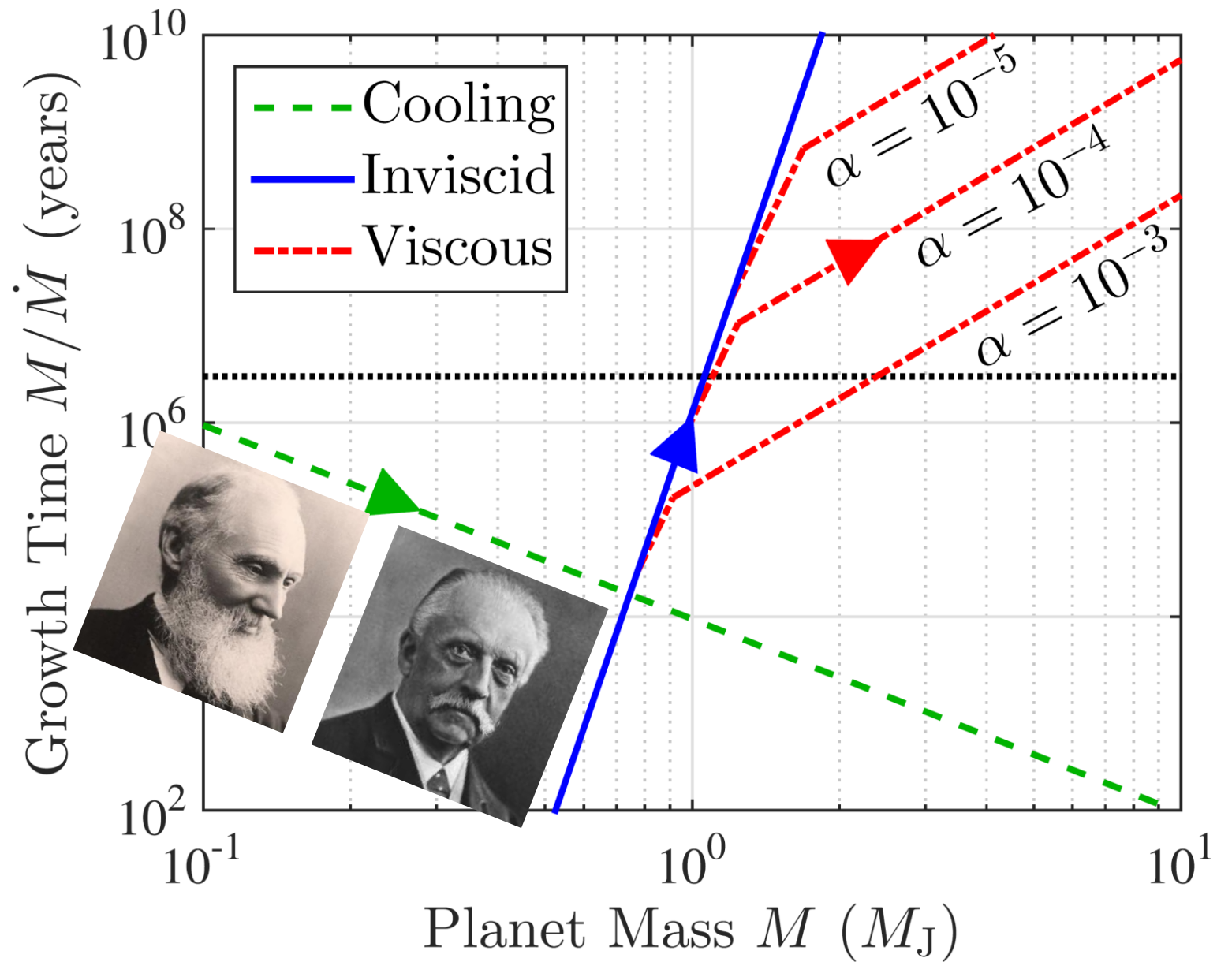
PLANET GROWTH

SG & Chiang 2019a



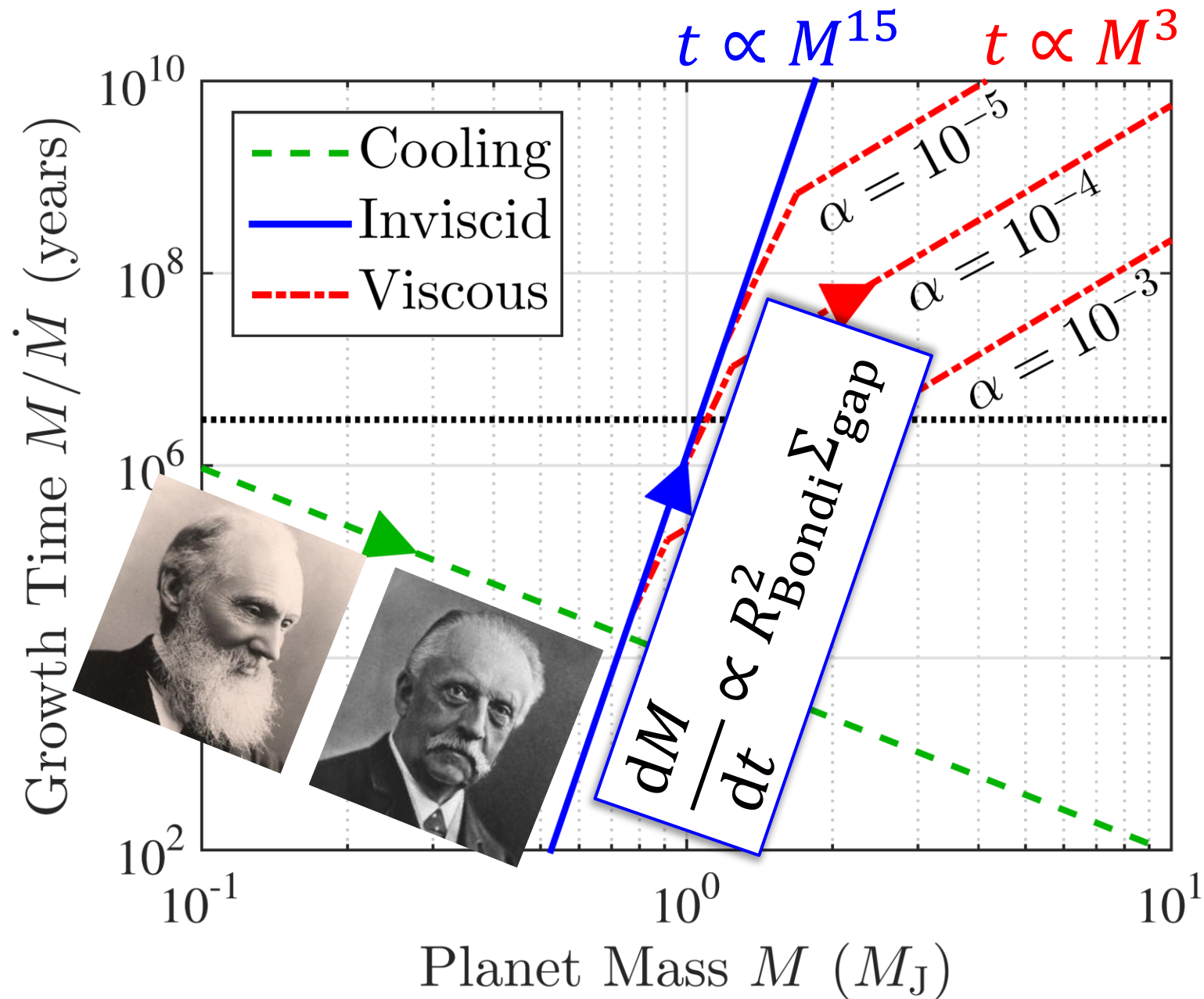
PLANET GROWTH

SG & Chiang 2019a



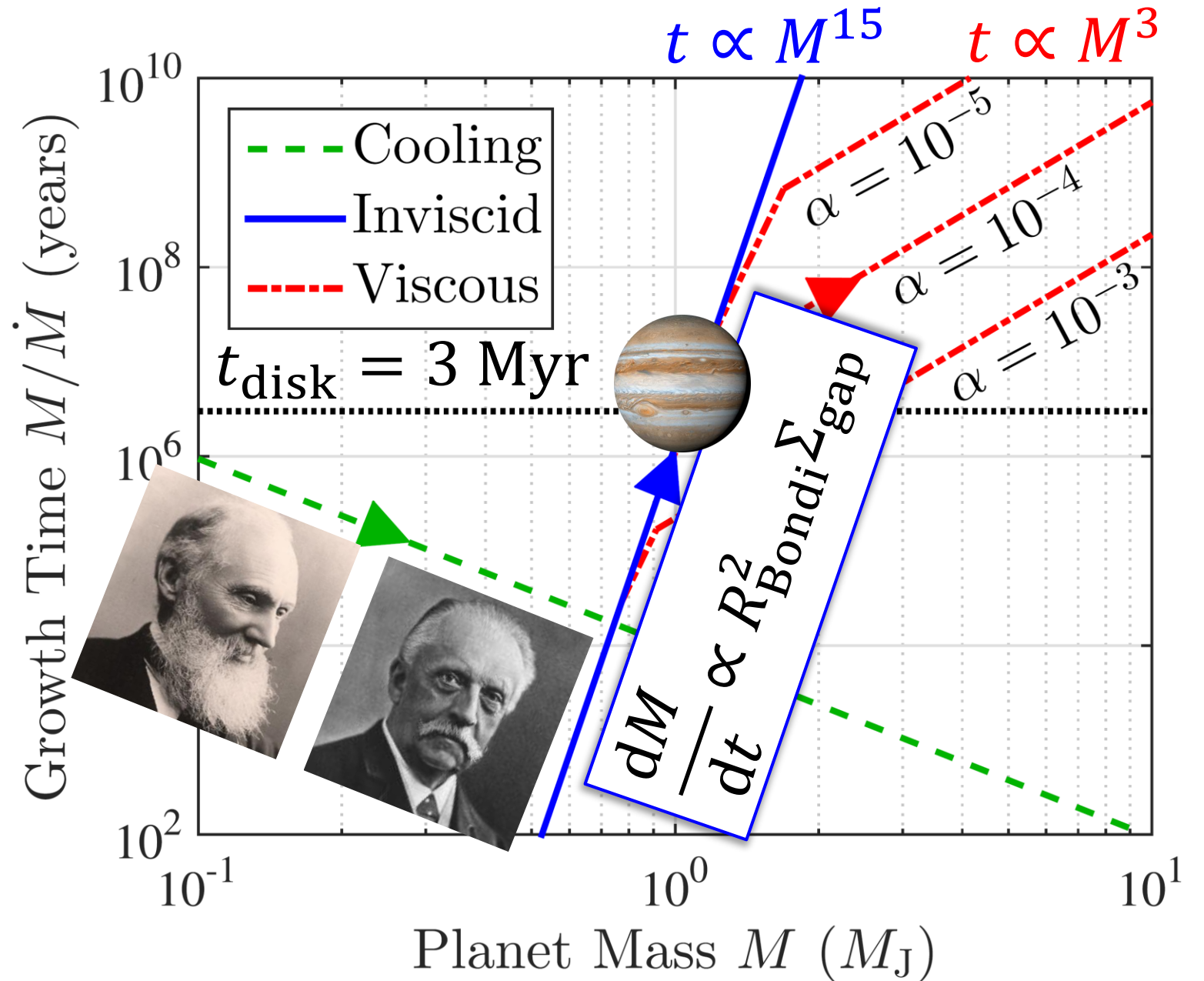
PLANET GROWTH

SG & Chiang 2019a



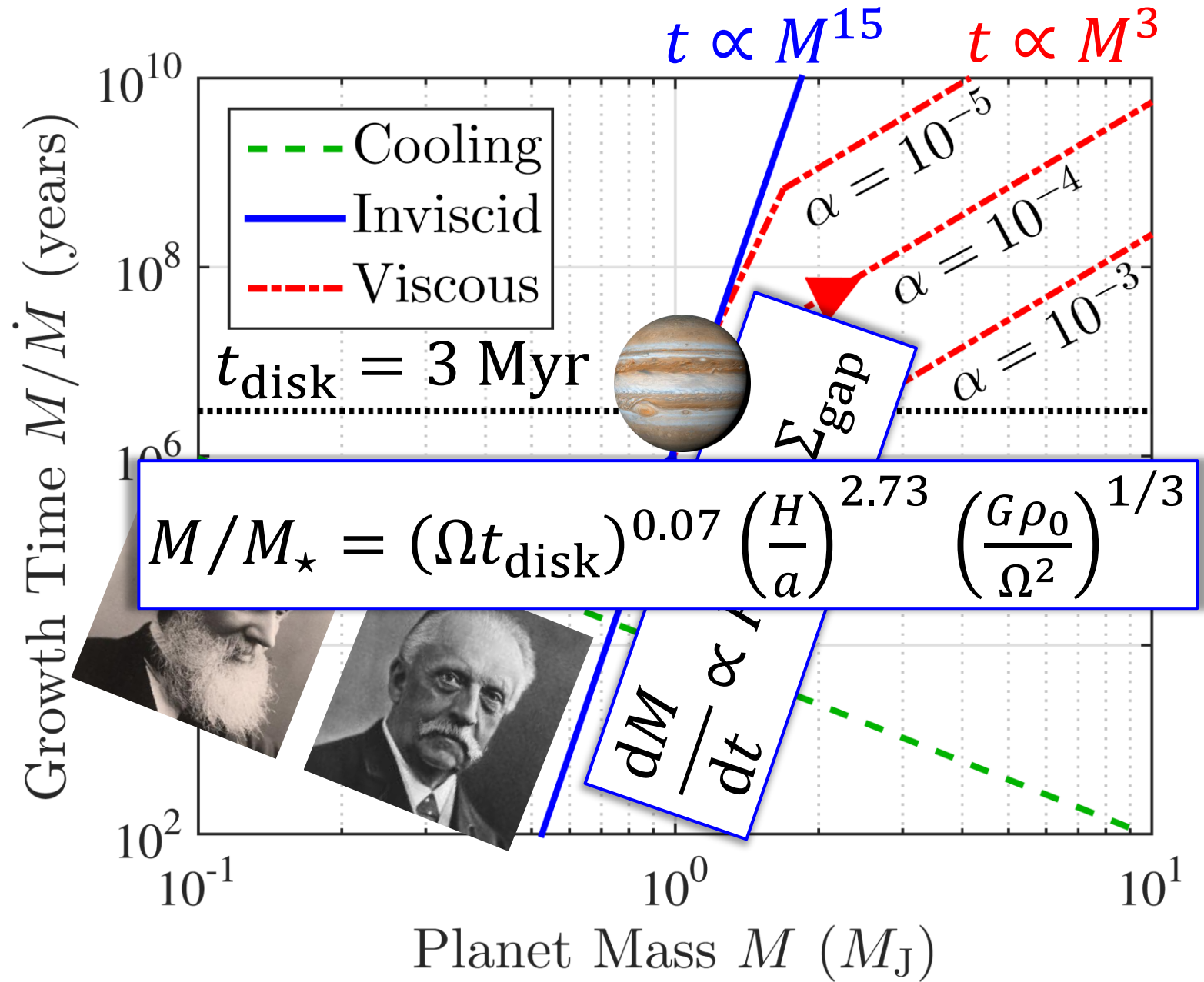
PLANET GROWTH

SG & Chiang 2019a

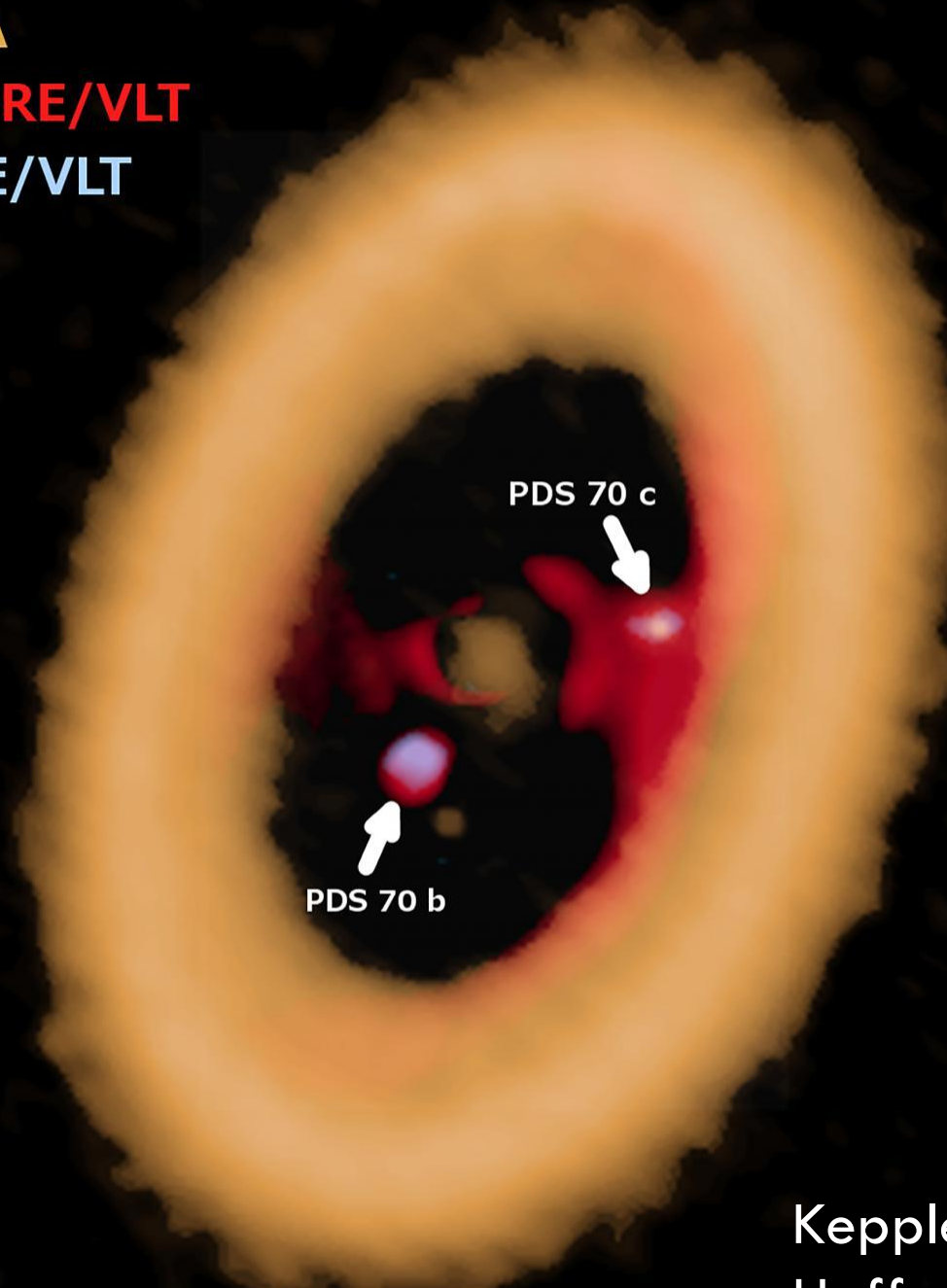


PLANET GROWTH

SG & Chiang 2019a



ALMA
SPHERE/VLT
MUSE/VLT



PDS 70 c

PDS 70 b

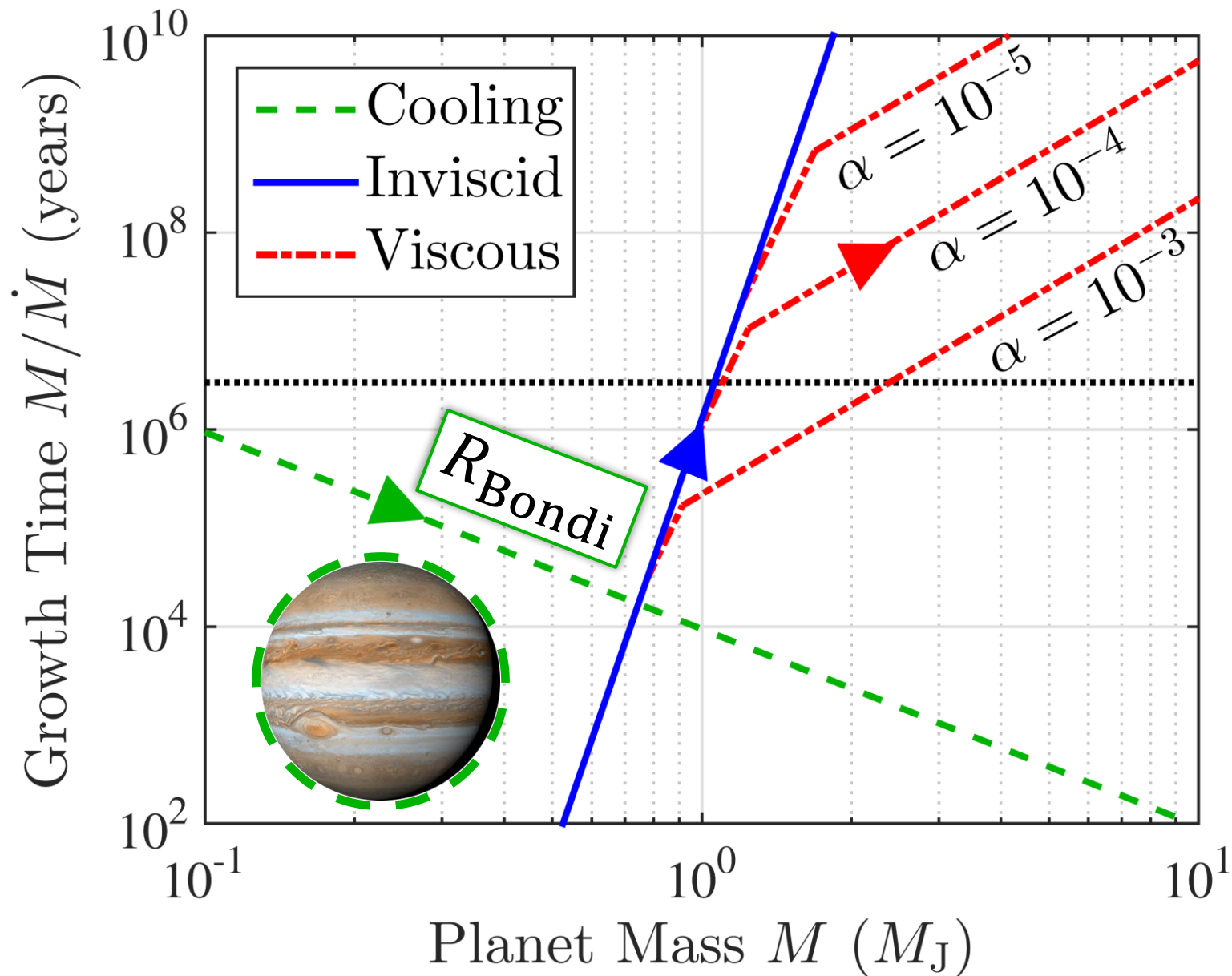
Keppler+ 2018
Haffert+ 2019

LUMINOSITY

- $L = \frac{GM\dot{M}}{R}$
- $10^3 R_{\text{Jup}} \rightarrow R_{\text{Jup}}$

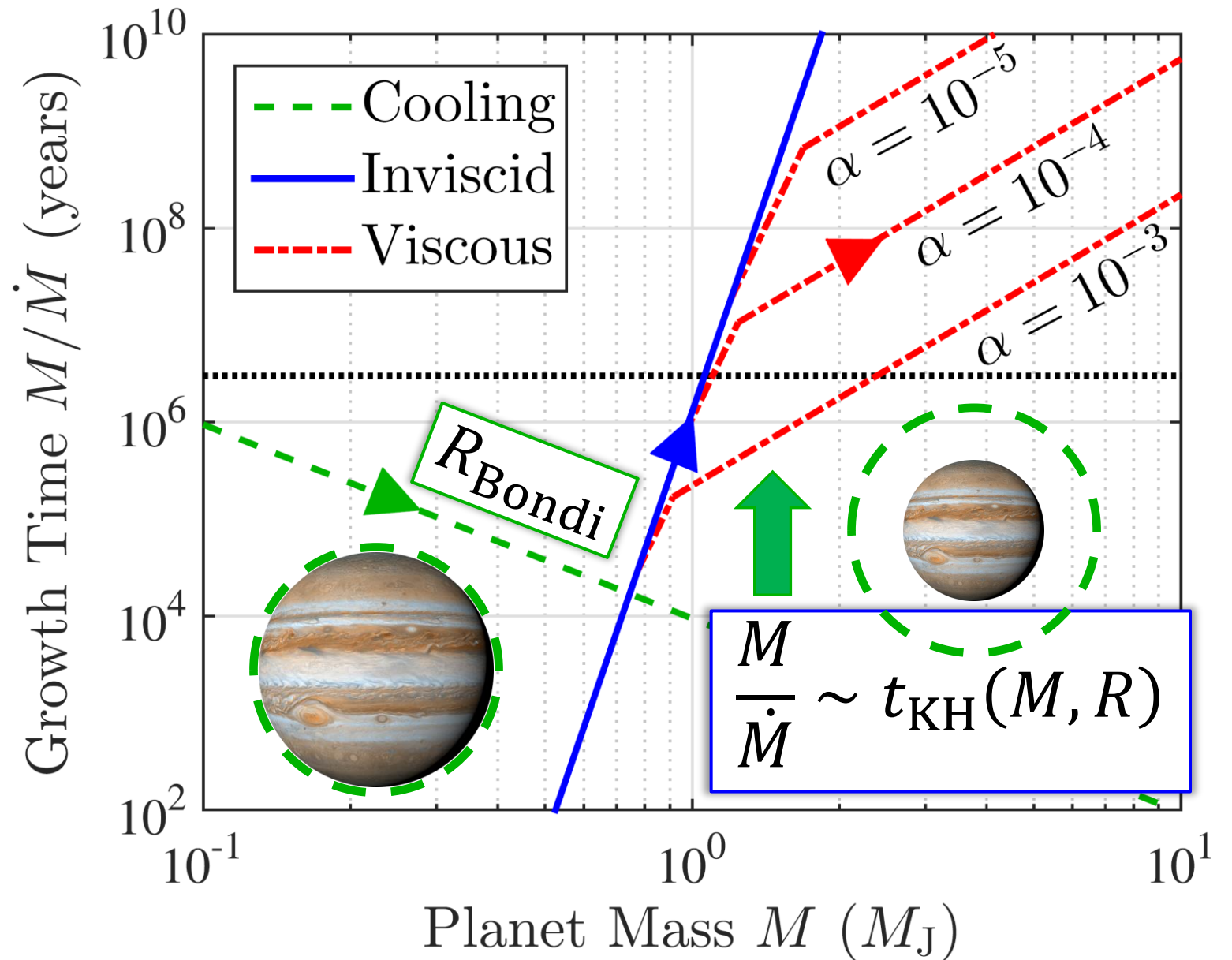
LUMINOSITY

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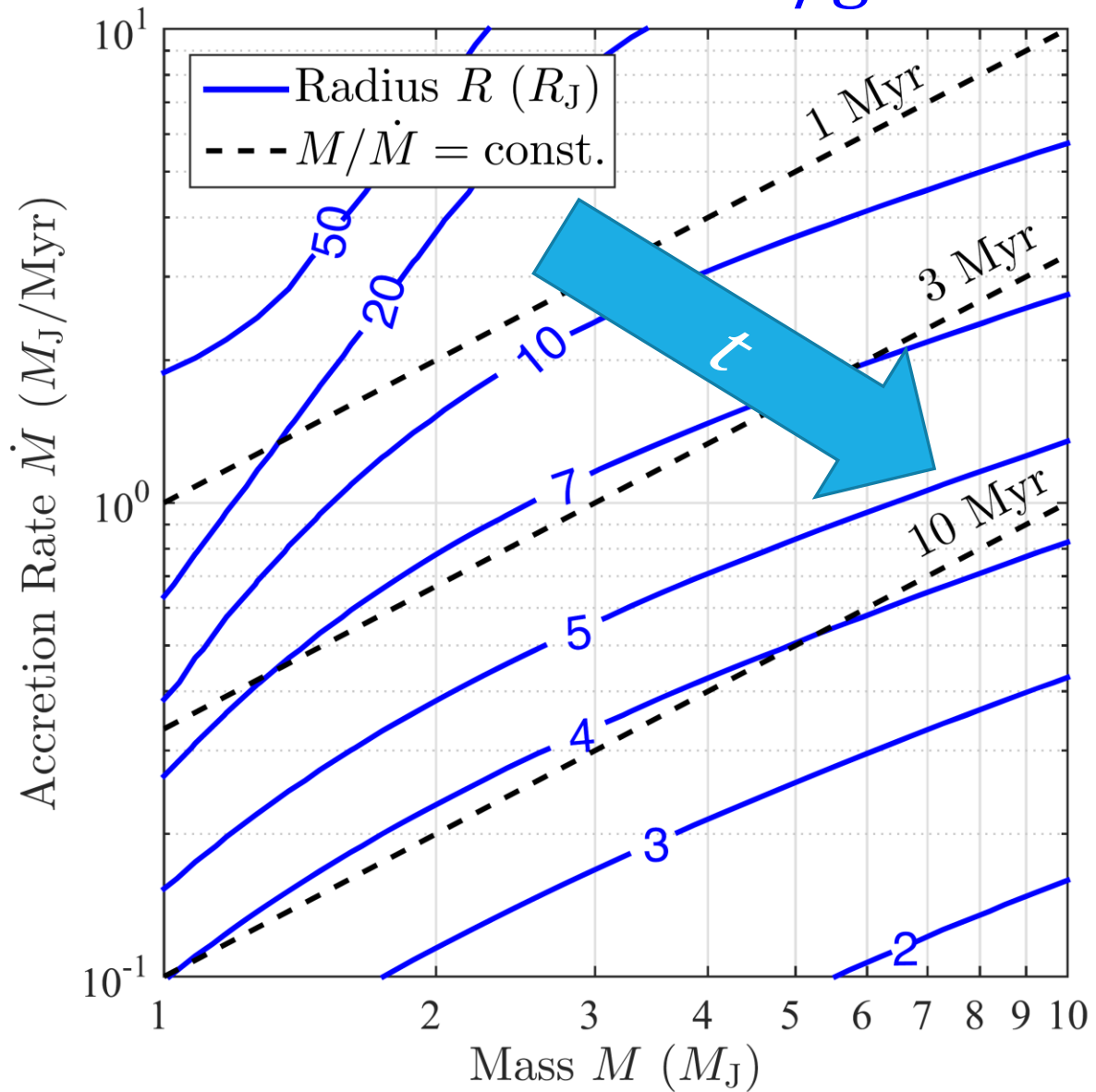


LUMINOSITY

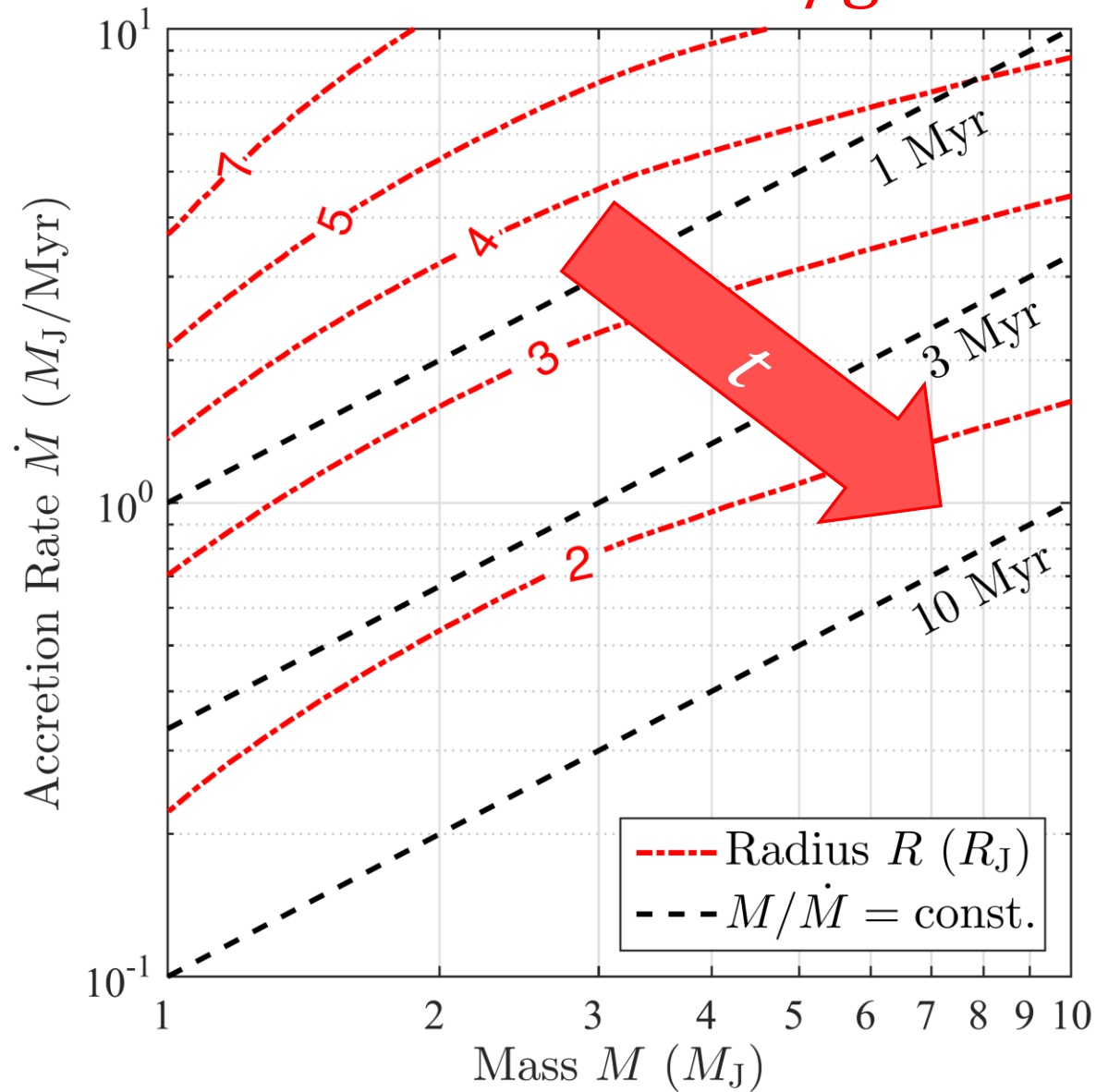
- $L = \frac{GM\dot{M}}{R}$
- $10^3 R_{\text{Jup}} \rightarrow R_{\text{Jup}}$



$\kappa = 10^{-1} \text{ cm}^2/\text{g}$

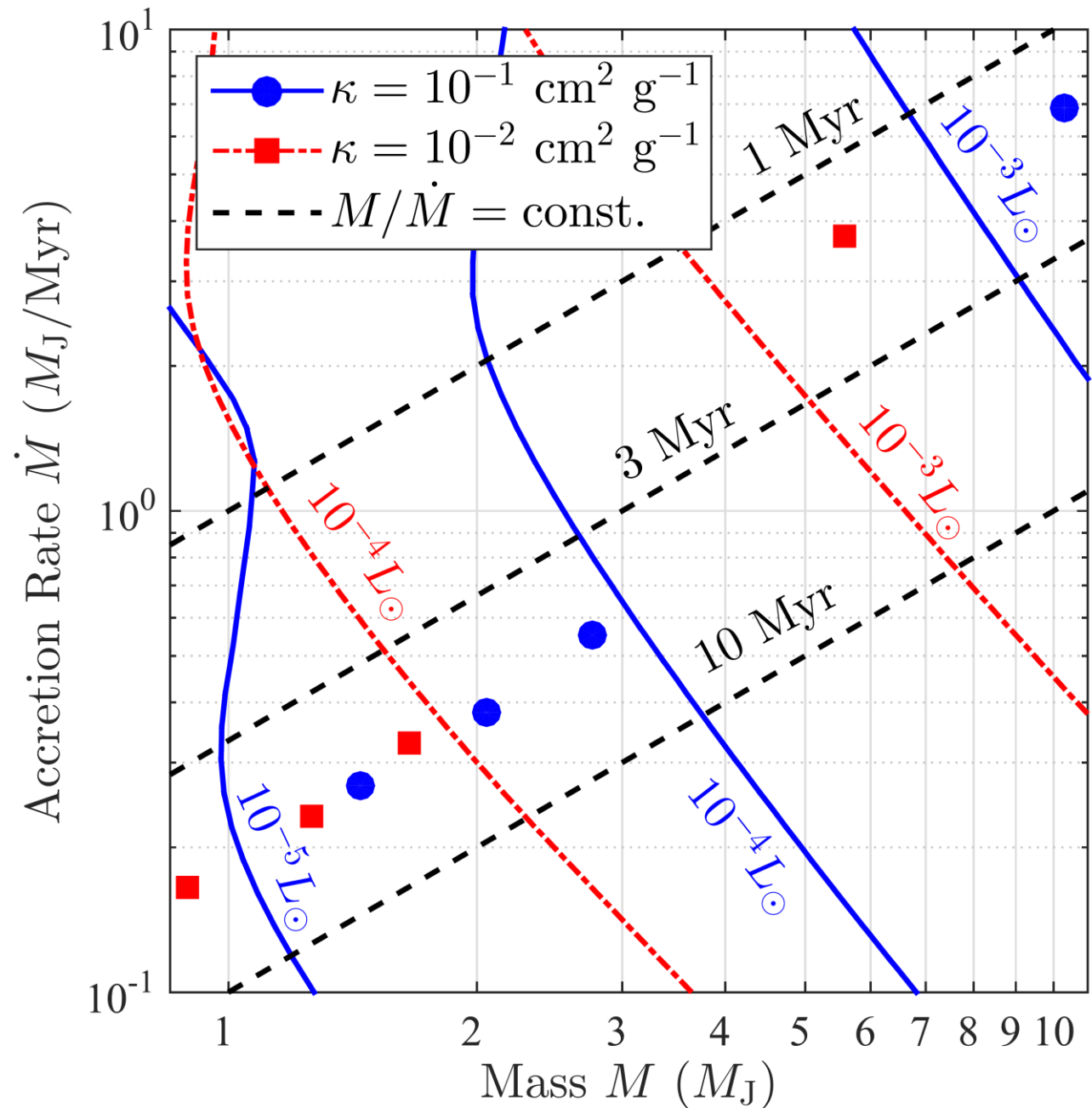


$\kappa = 10^{-2} \text{ cm}^2/\text{g}$



OBSERVATIONS

SG & Chiang 2019b
Wang, SG+ 2020

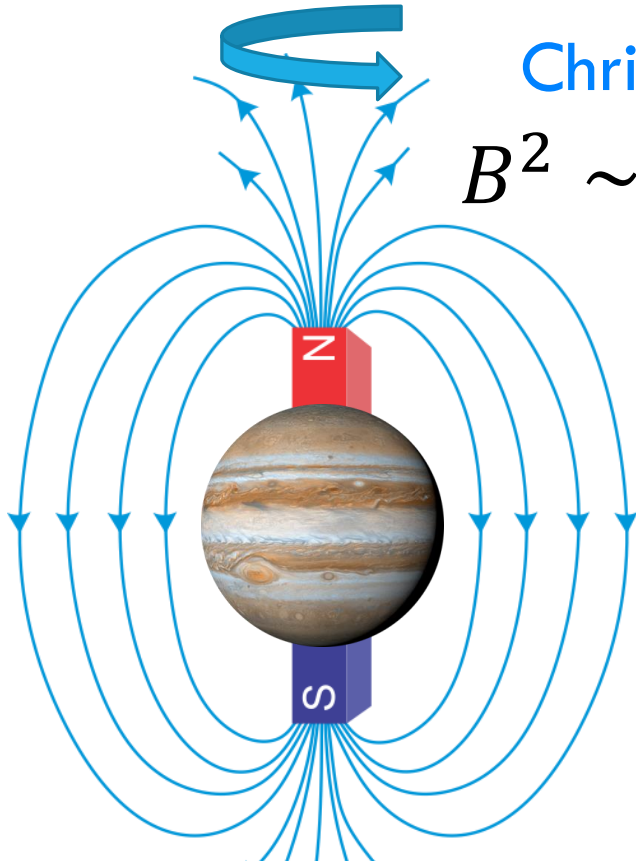


PLANETARY SPINS

$$\omega = 2\pi/P$$

Christensen+ 2009

$$B^2 \sim \rho v_{\text{conv}}^2 \propto L^{2/3}$$



PLANETARY SPINS

$$\omega = 2\pi/P$$

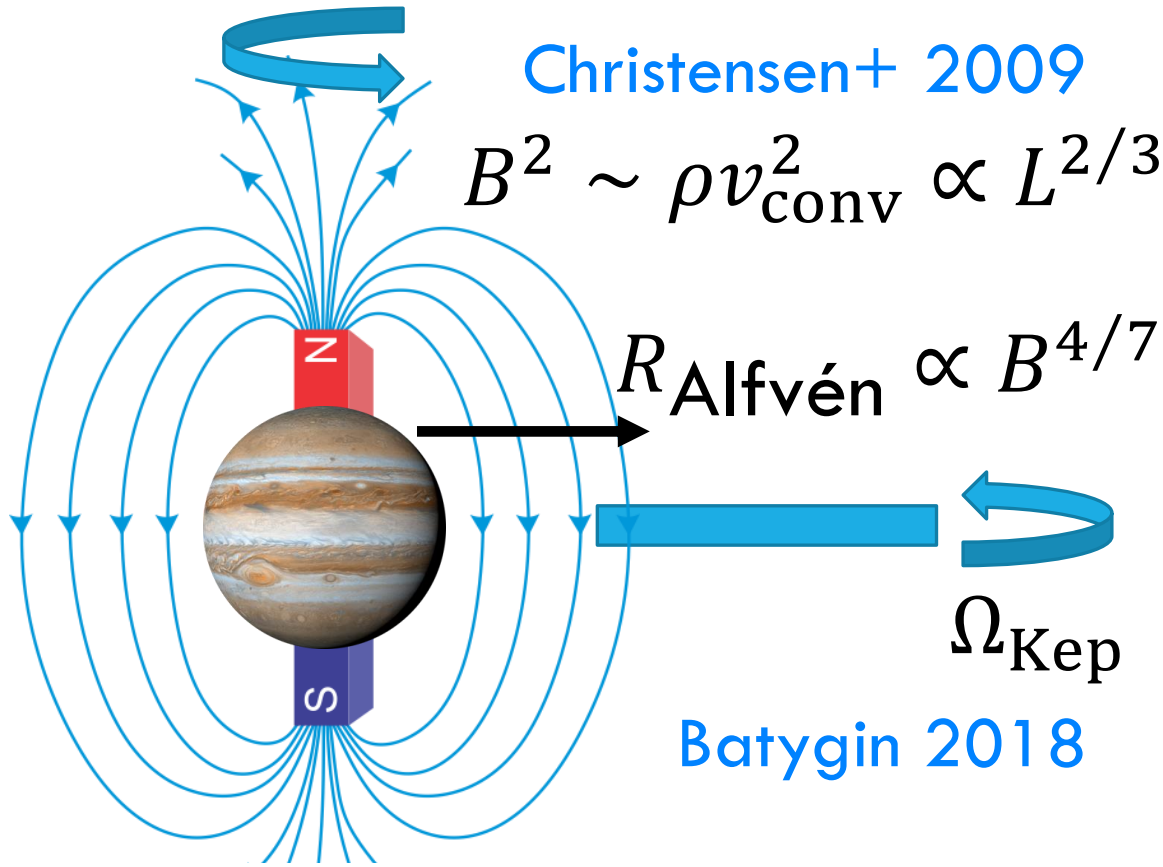
Christensen+ 2009

$$B^2 \sim \rho v_{\text{conv}}^2 \propto L^{2/3}$$

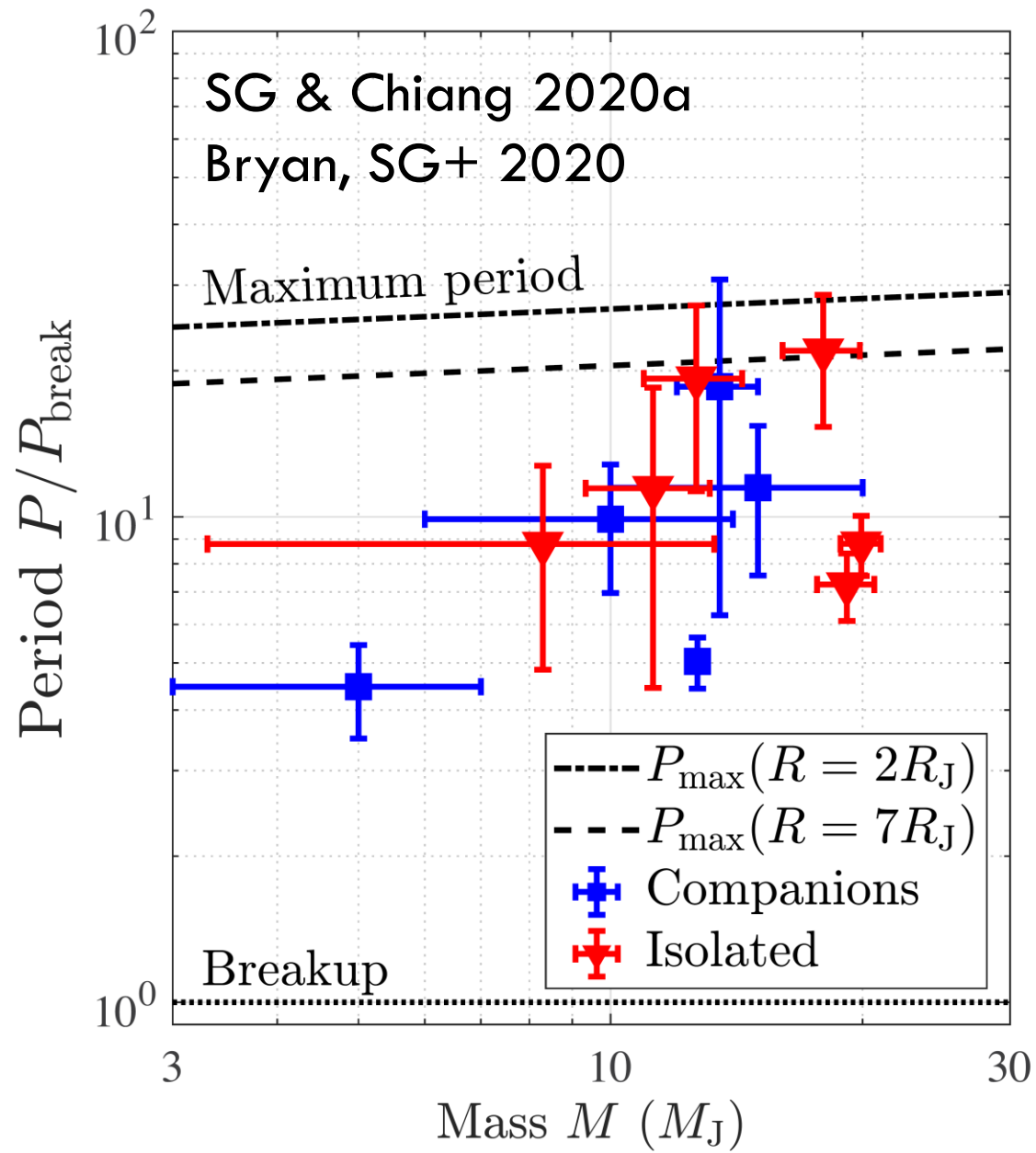
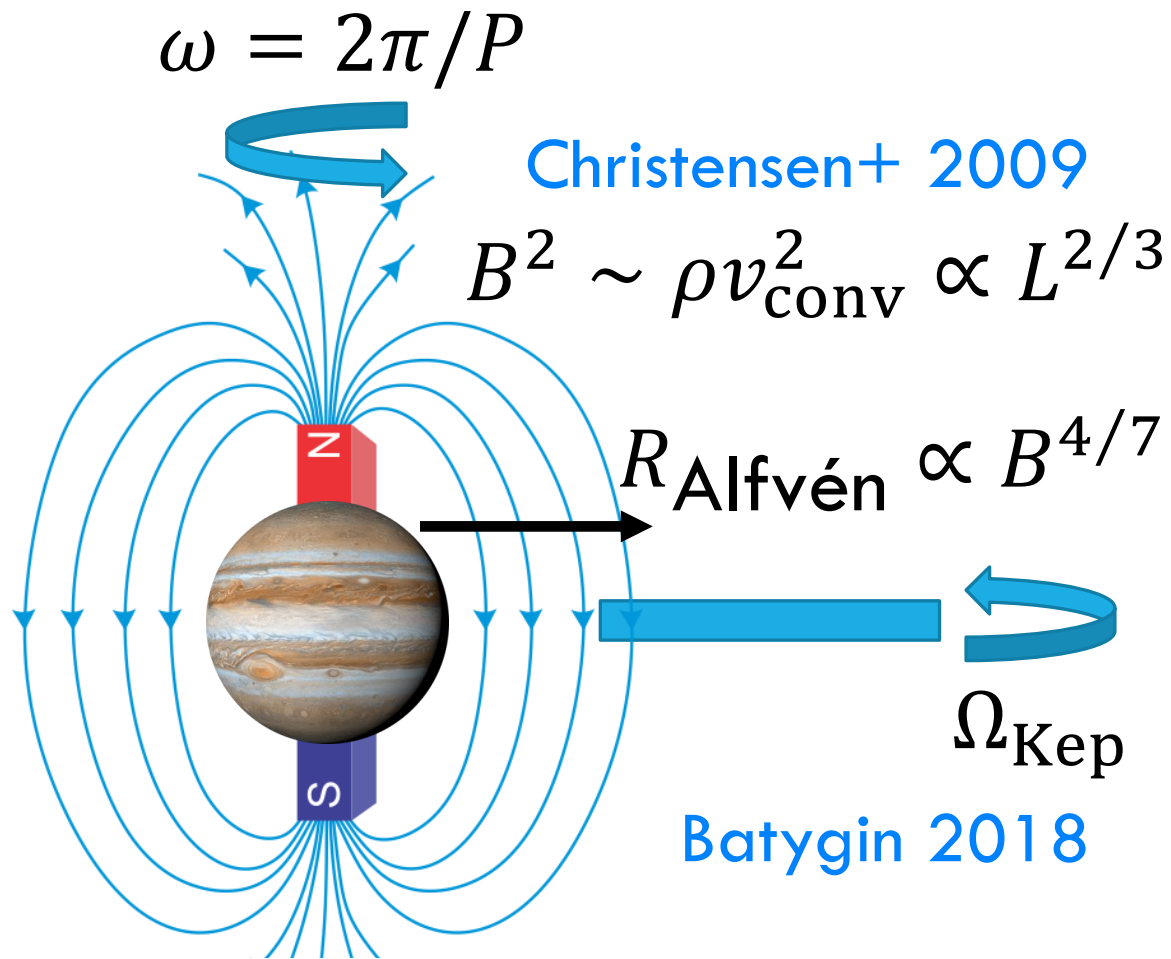
$$R_{\text{Alfvén}} \propto B^{4/7}$$

$$\Omega_{\text{Kep}}$$

Batygin 2018

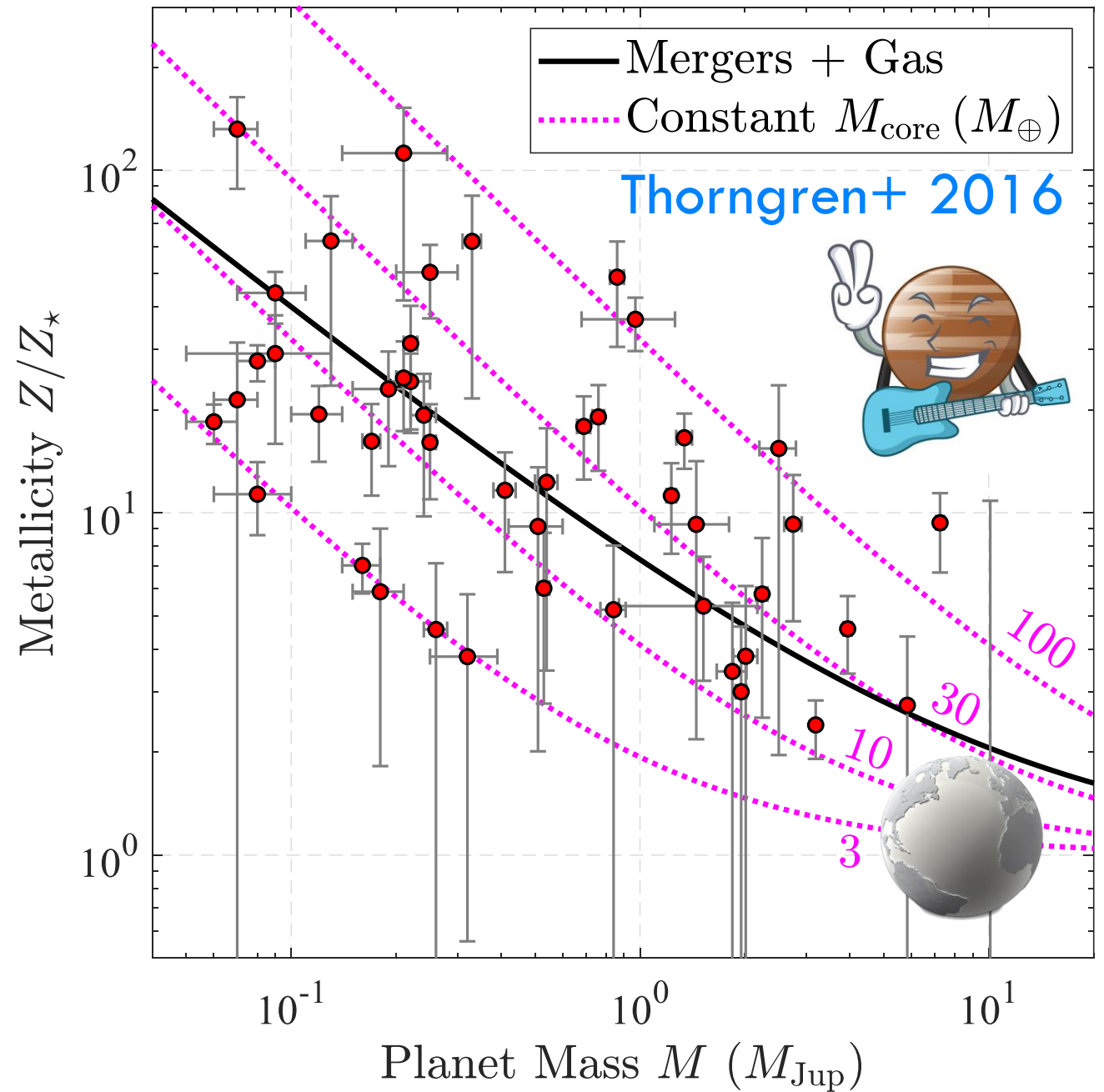


PLANETARY SPINS



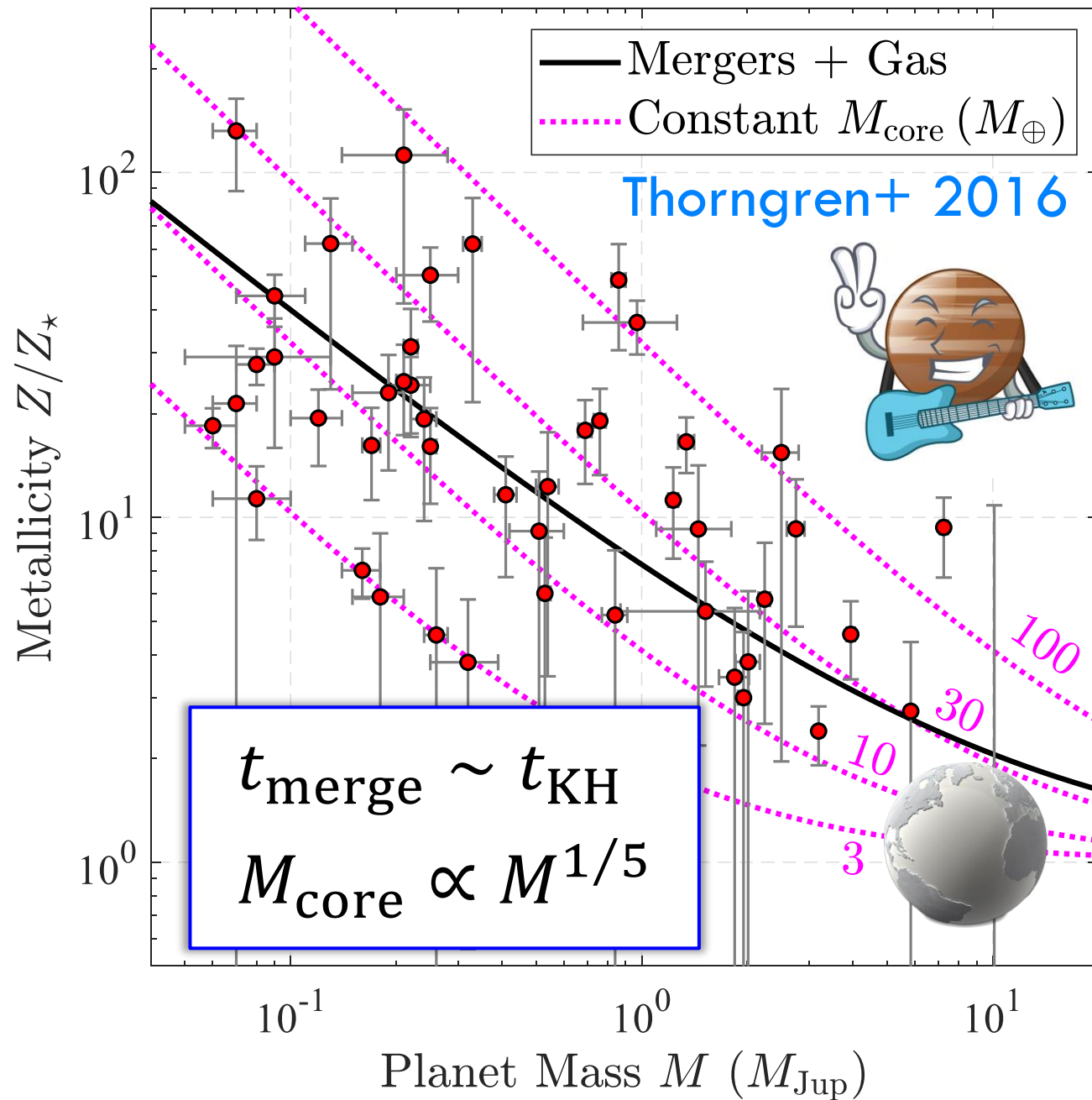
HEAVY METAL JUPITERS

SG & Chiang 2020b



HEAVY METAL JUPITERS

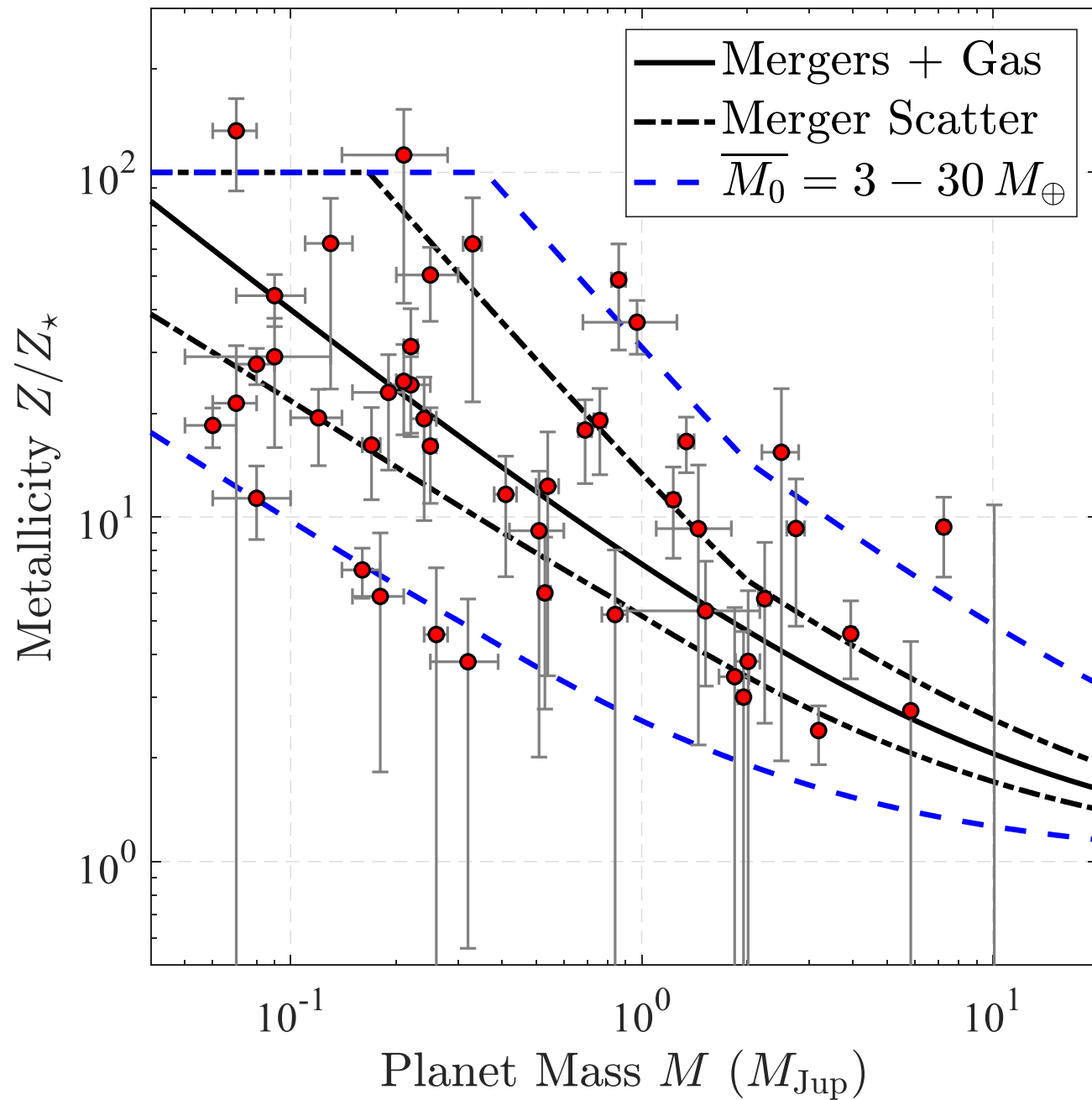
SG & Chiang 2020b



CHAOS → SCATTER



Rice+18
Hussain & Tamayo 20



Mass



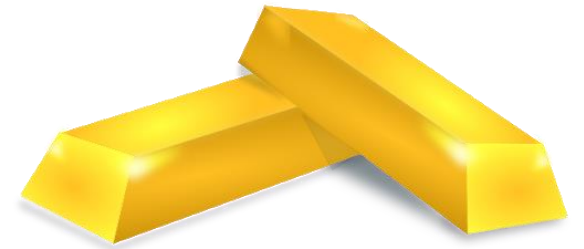
Luminosity



Spin

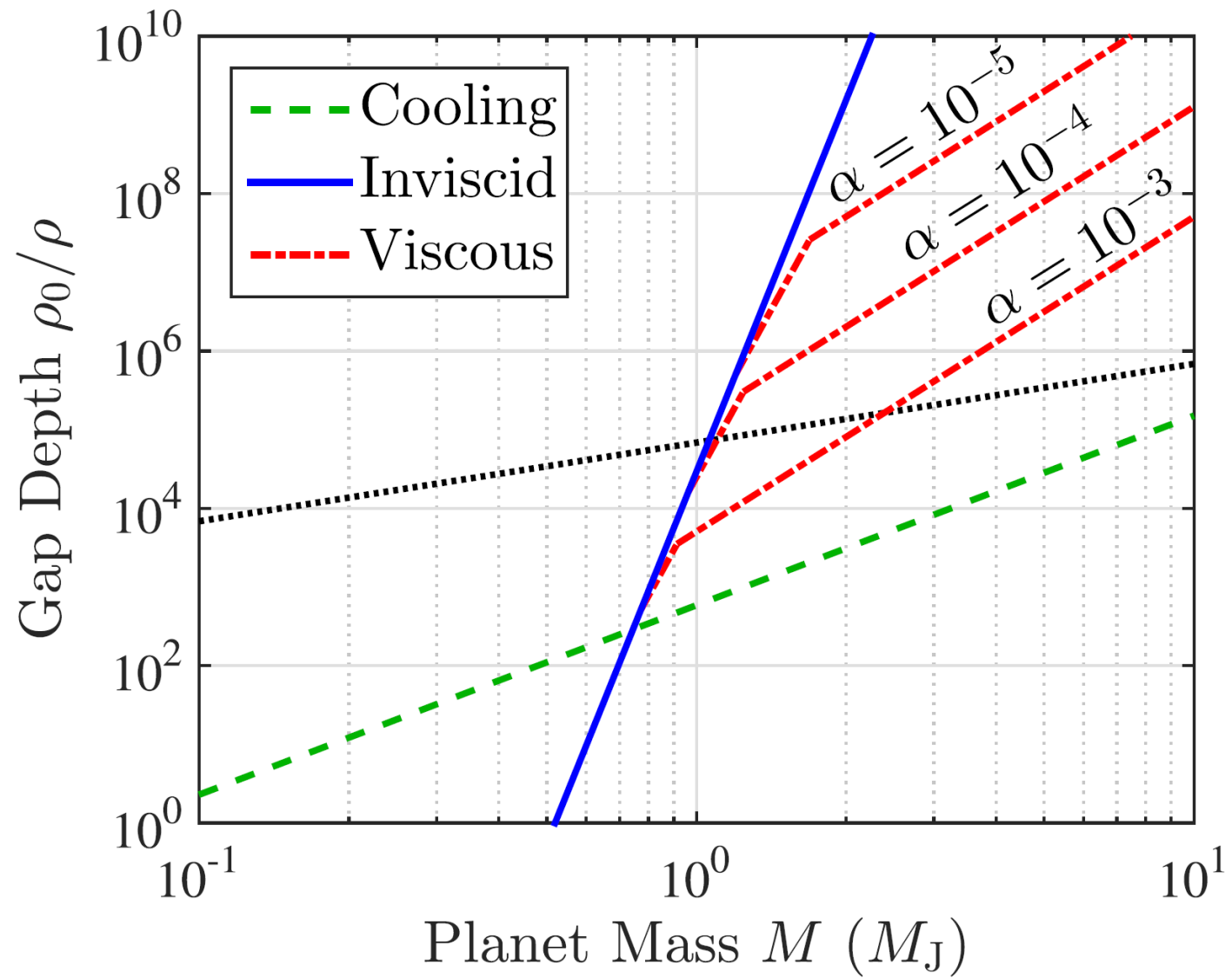


Metallicity



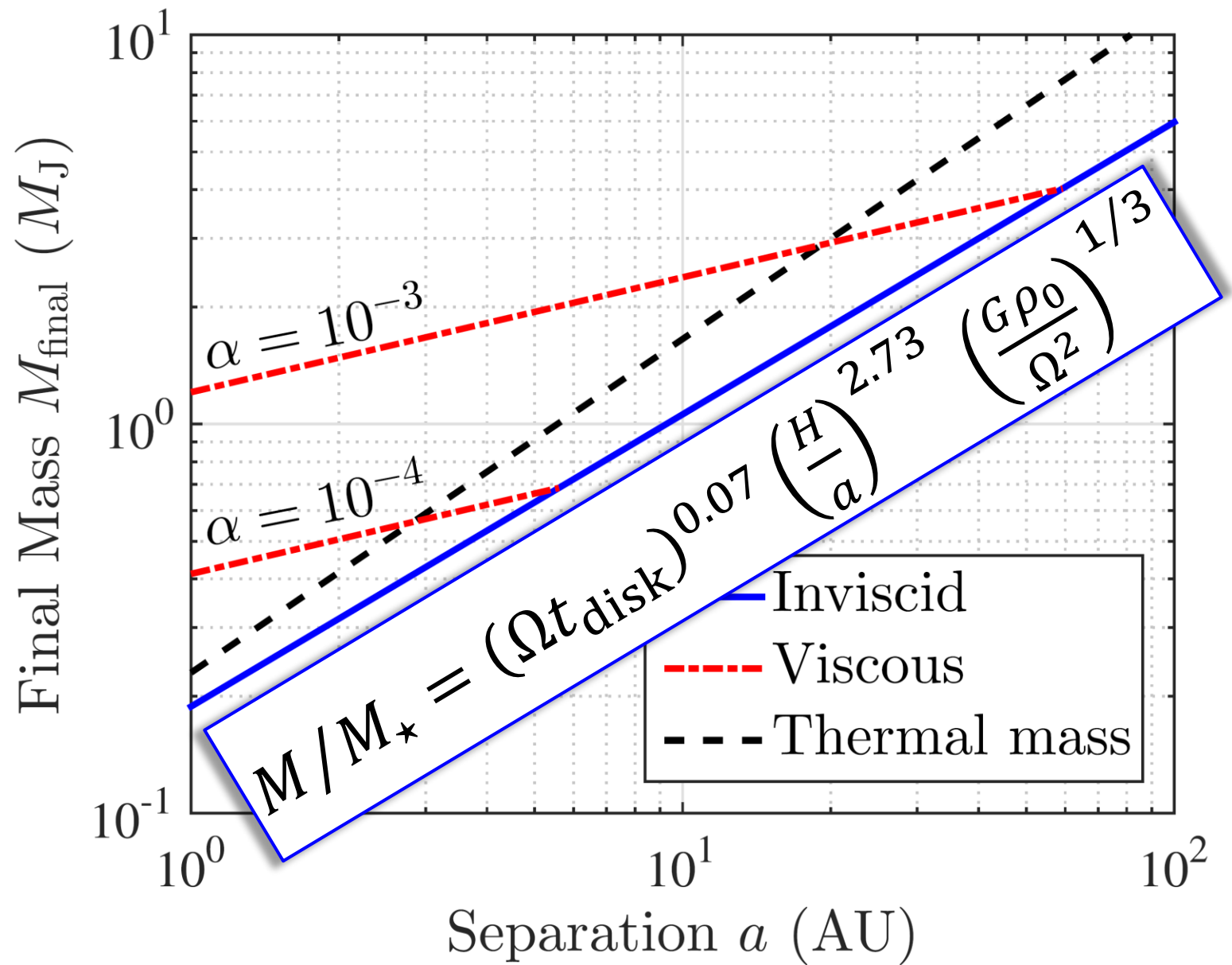
POST RUNAWAY PHASE

Thank you!



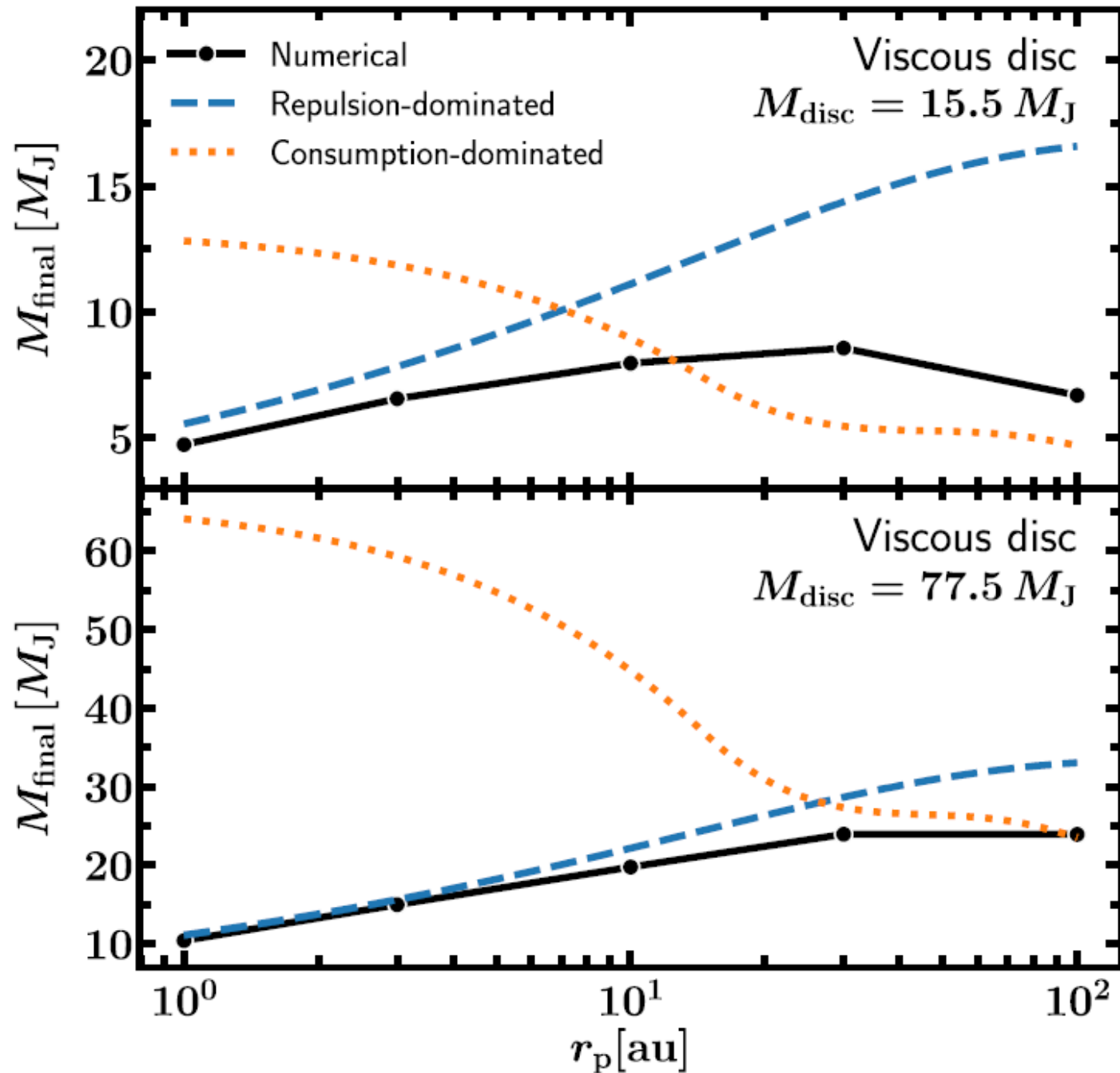
FINAL MASS

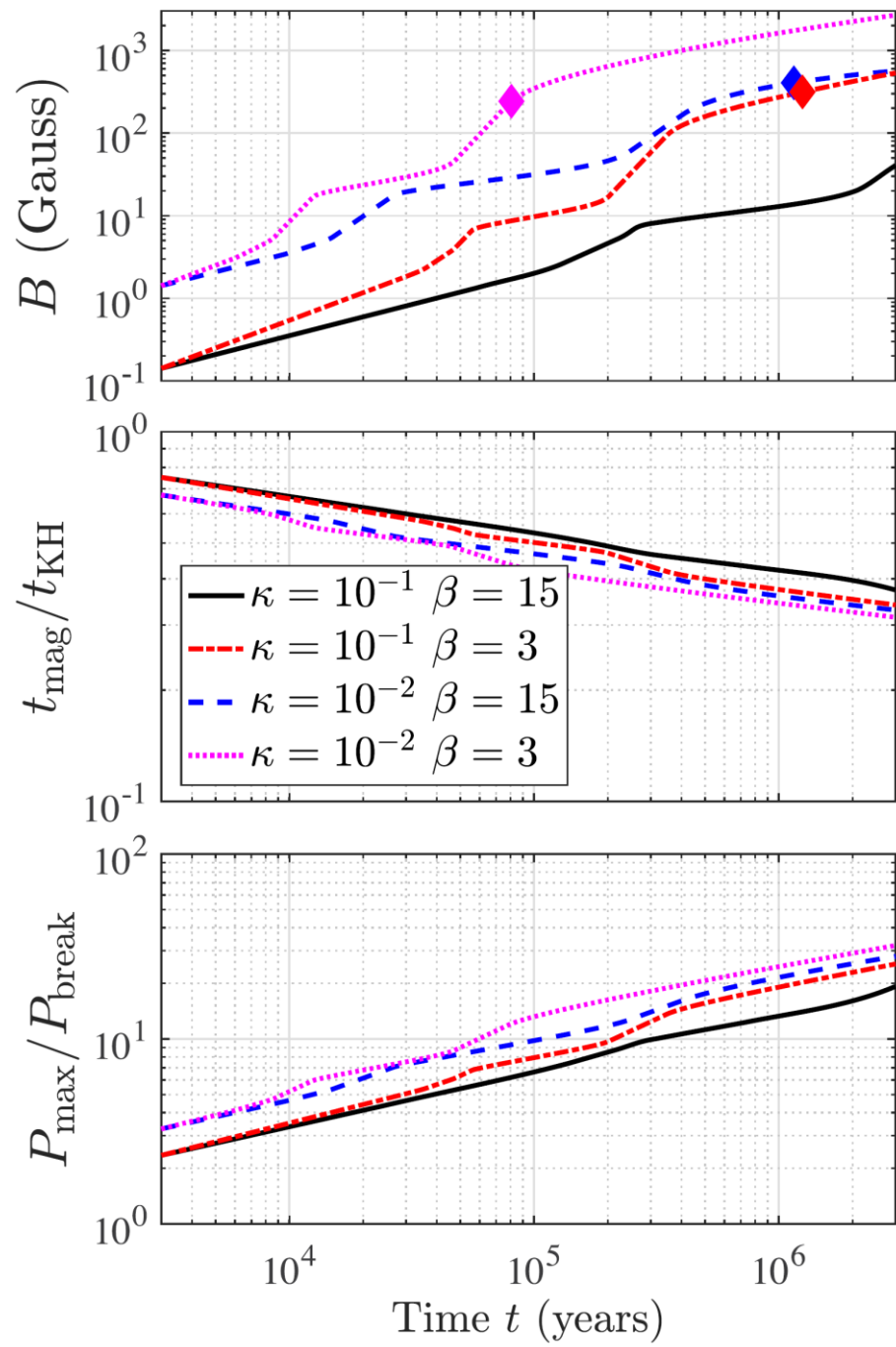
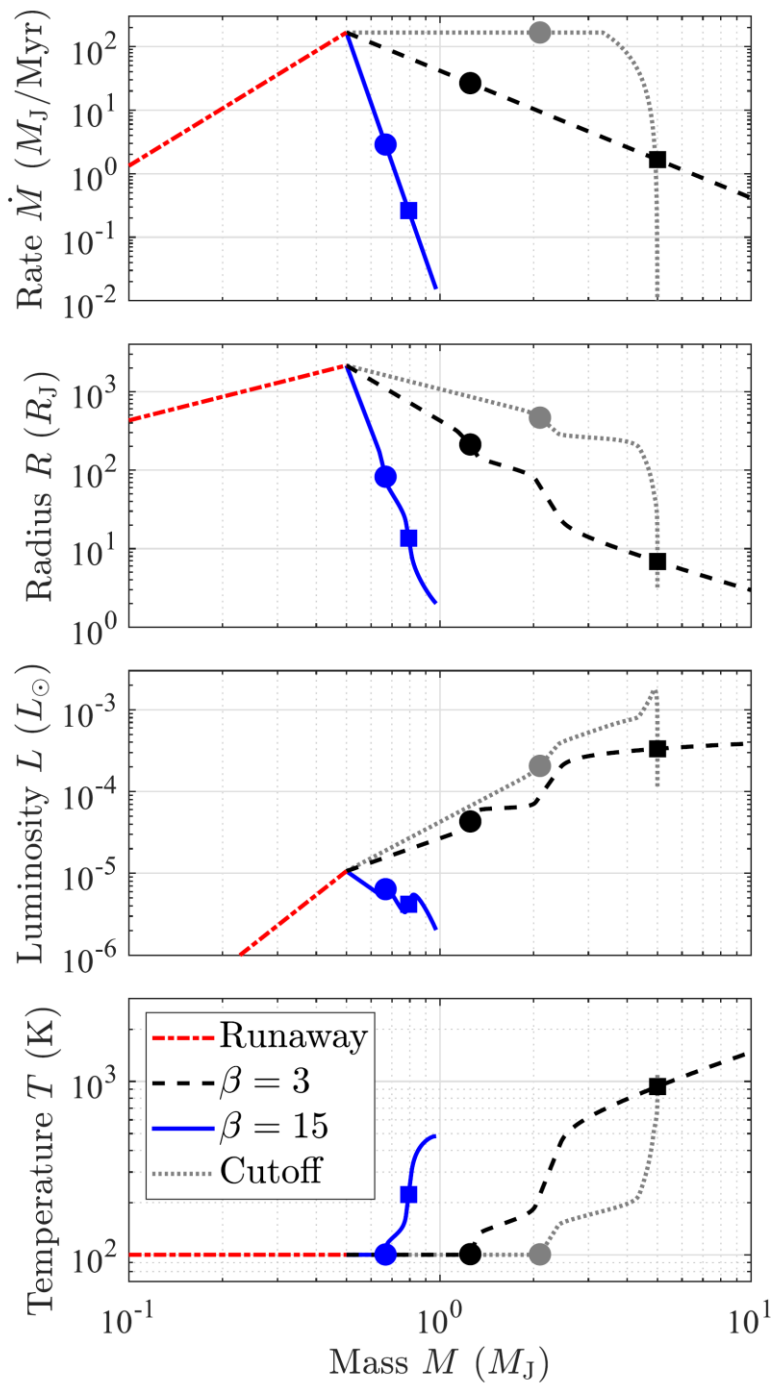
SG & Chiang 2019a

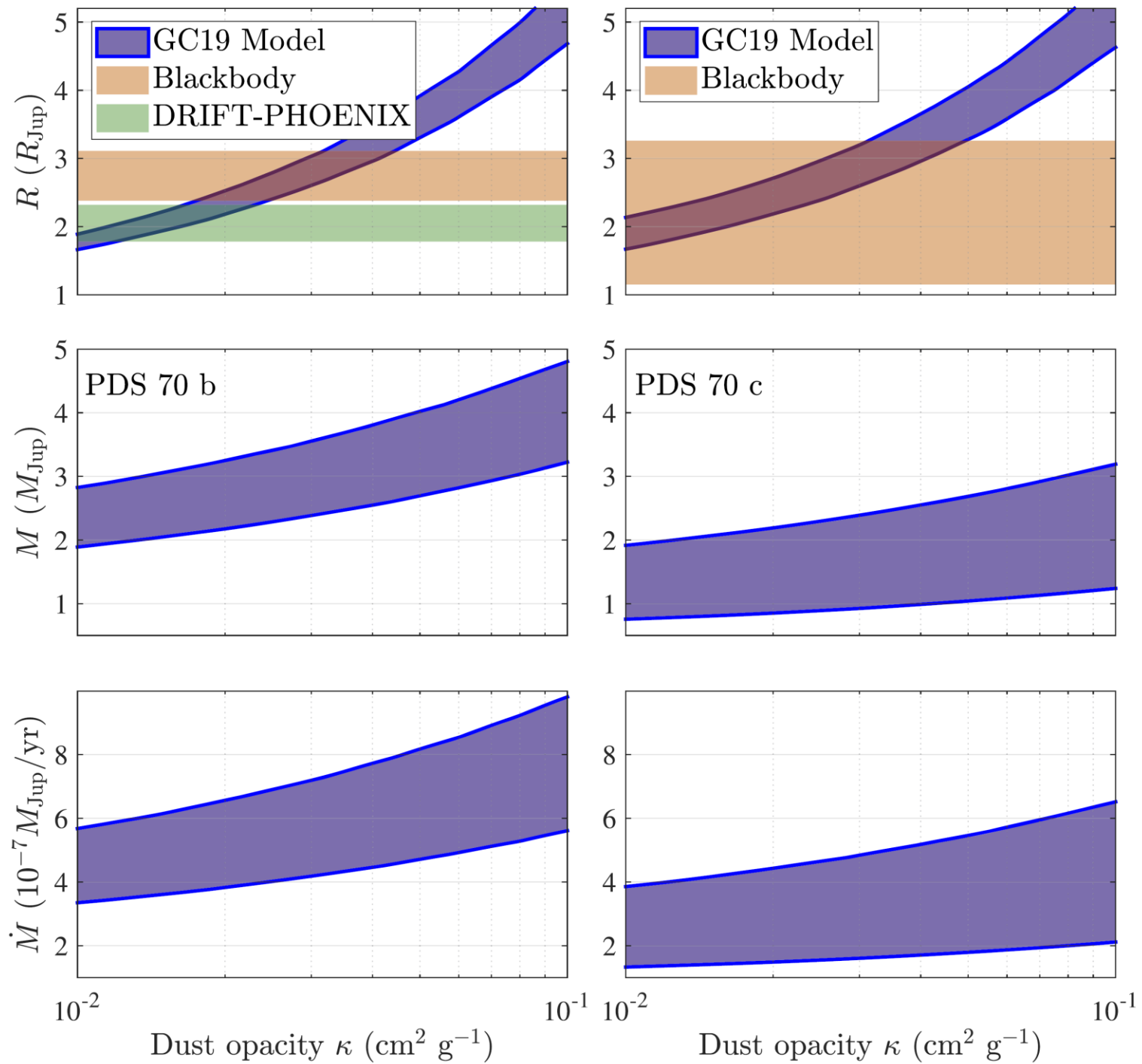


FINAL MASS

Rosenthal, Chiang,
SG, Murray-Clay
2020



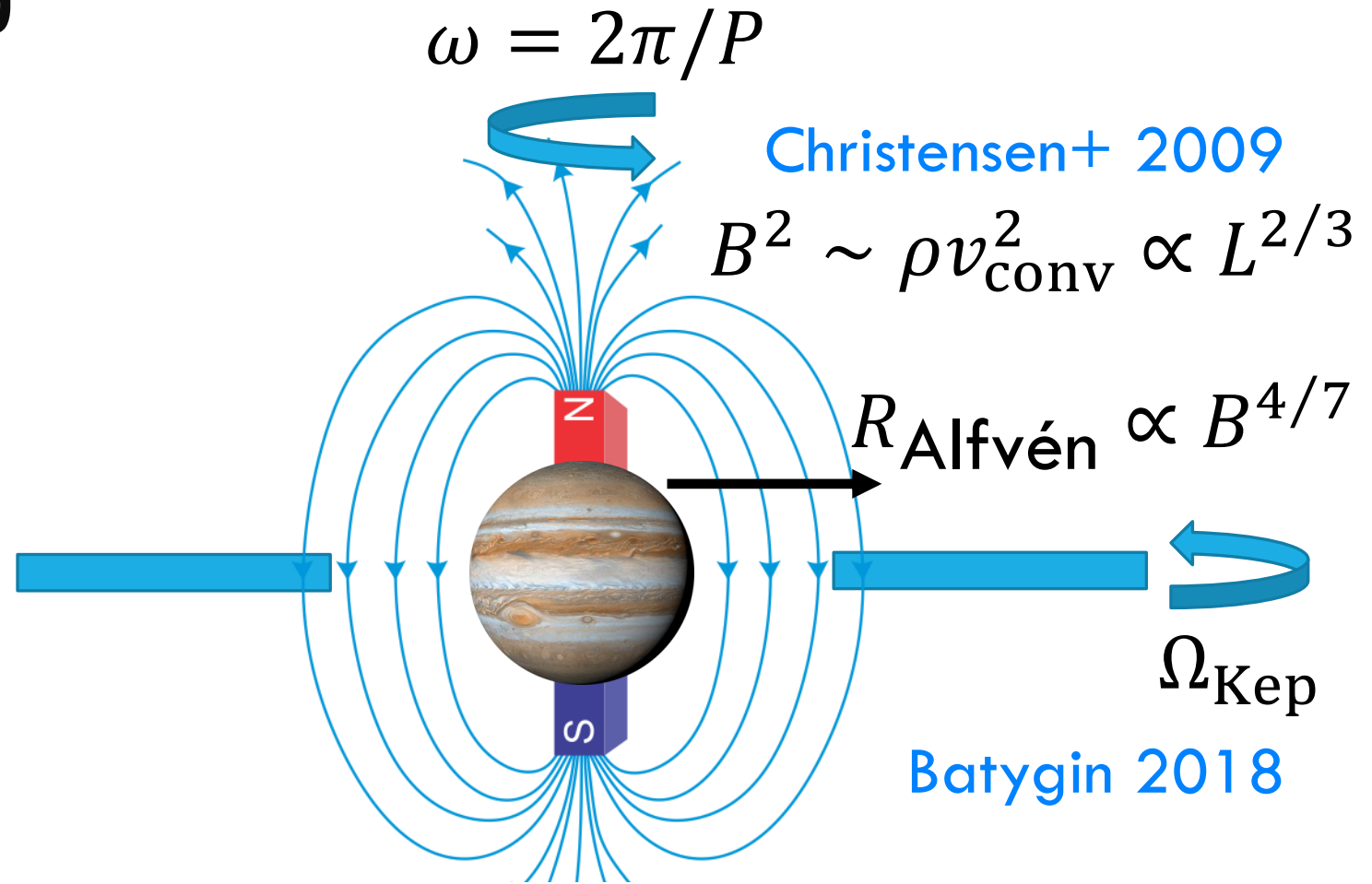




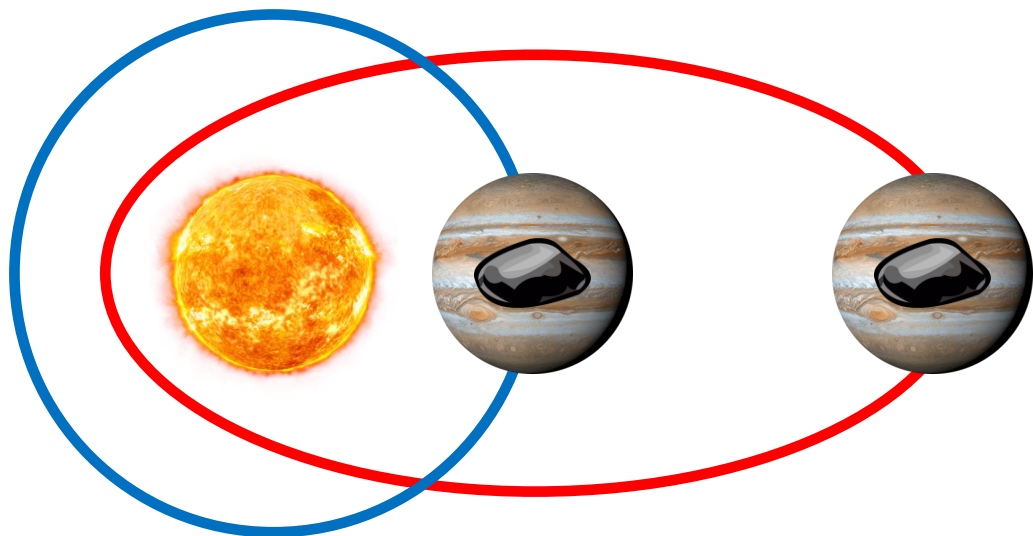
MAGNETIC BRAKING

- $$\frac{t_{\text{mag}}}{t_{\text{KH}}} \sim \left(\frac{P_{\text{break}}}{t_{\text{KH}}} \right)^{1/21}$$

- $$\frac{P_{\text{max}}}{P_{\text{break}}} \sim \left(\frac{t_{\text{KH}}}{P_{\text{break}}} \right)^{1/7}$$

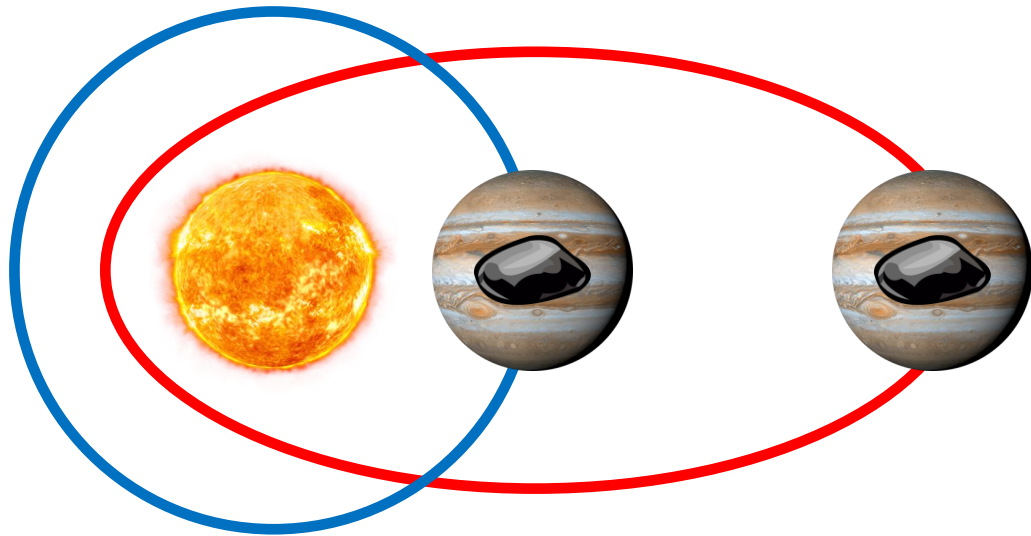


ECCENTRICITY DAMPING



$$t_{\text{damp}} \sim \Omega^{-1} \left(\frac{M_{\star}}{M} \right) \left(\frac{M_{\star}}{\Sigma_{\text{gas}} a^2} \right) h^4$$

ECCENTRICITY DAMPING



$$t_{\text{damp}} \sim \Omega^{-1} \left(\frac{M_{\star}}{M} \right) \left(\frac{M_{\star}}{\Sigma_{\text{gas}} a^2} \right) h^4$$

Just enough for a Jupiter:

$$\frac{\Sigma_{\text{gas}} a^2}{M_{\odot}} \gtrsim 10^{-3} \left(\frac{M_{\text{core}}^0}{10 M_{\oplus}} \right) \left(\frac{a}{10 \text{ AU}} \right)^{\frac{37}{14}}$$

Thorngren+ 2016

