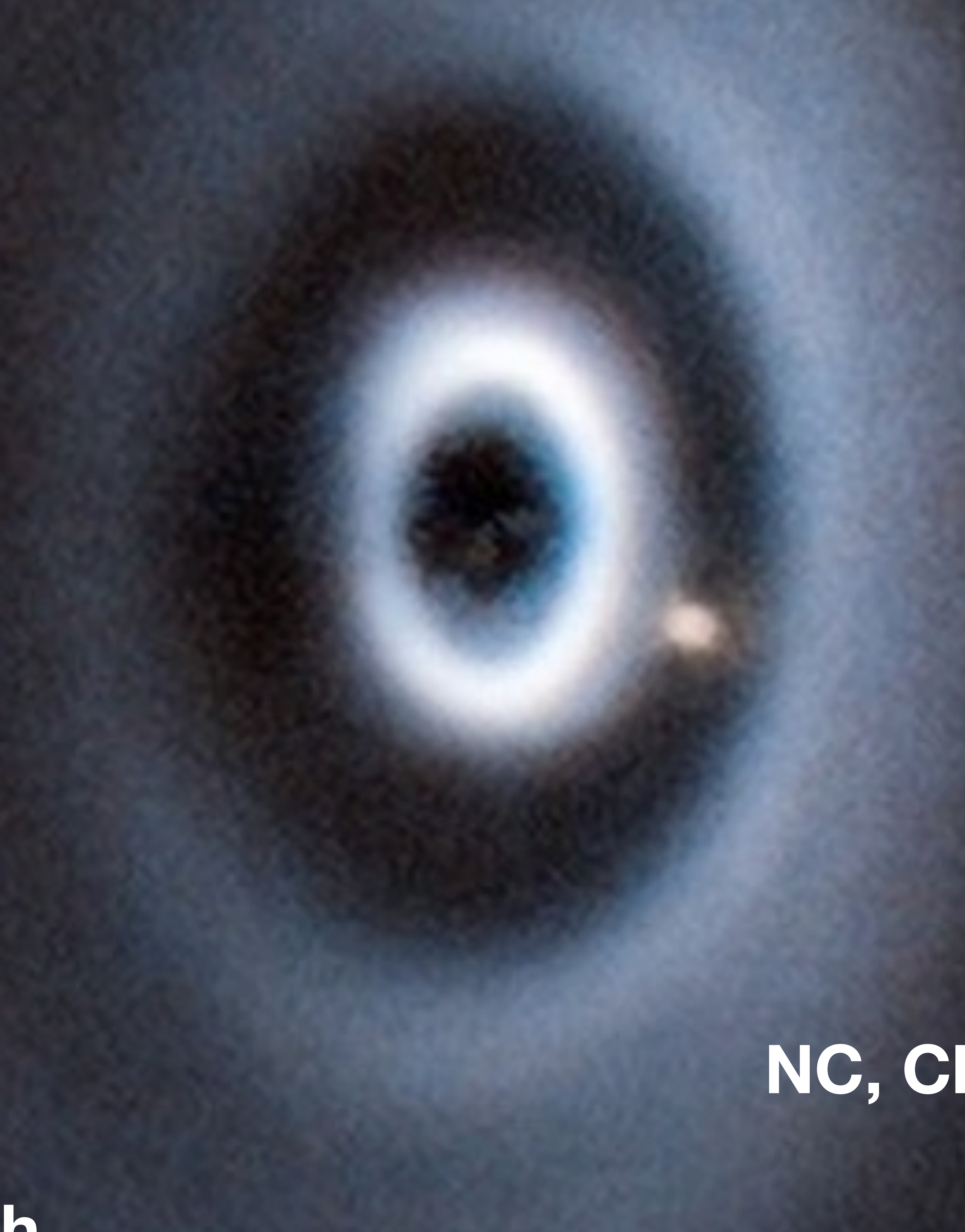
DIRECTLY IMAGING RUNAWAY ACCRETION

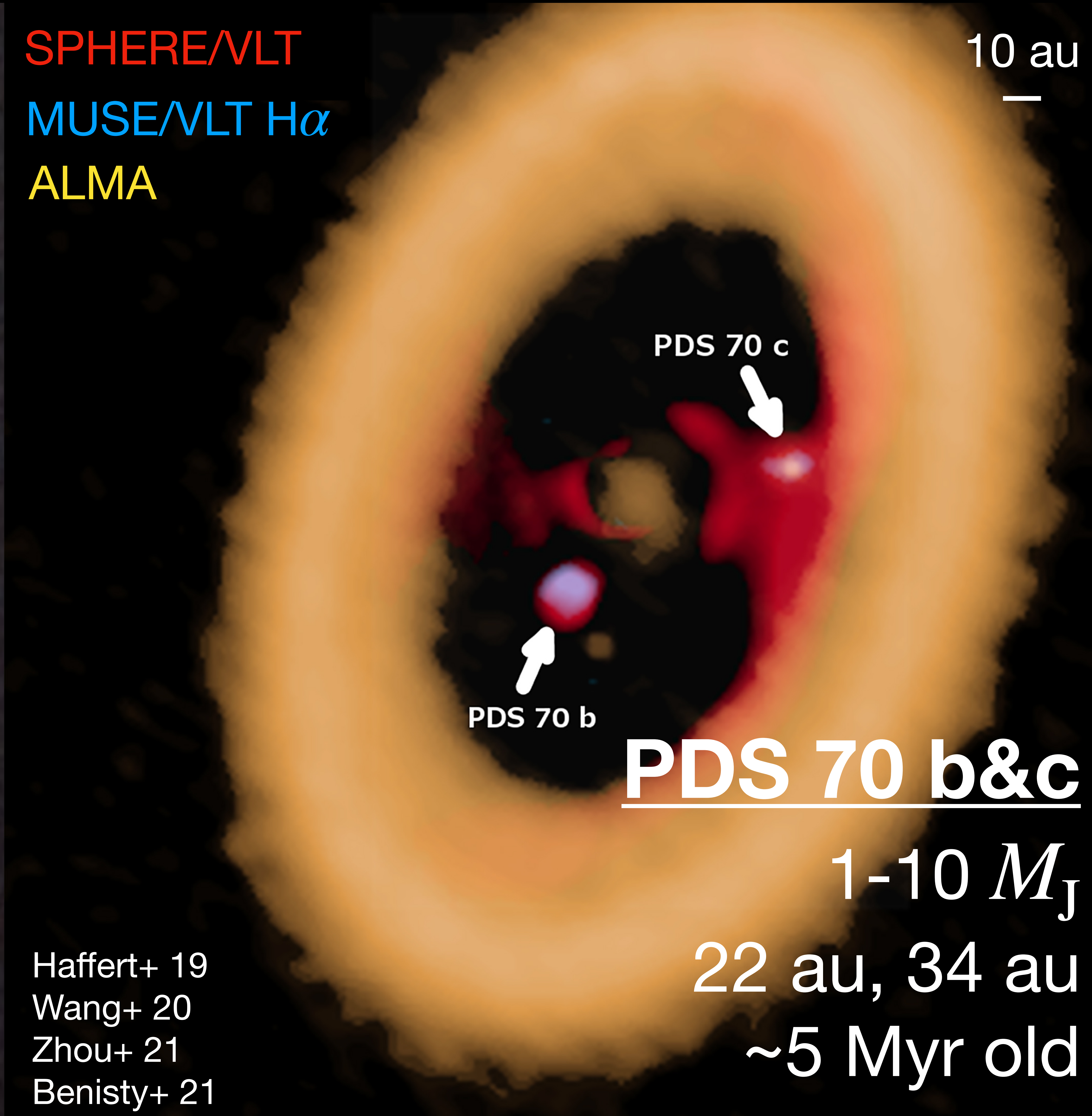


van Capelleveen+ 25, VLT/SPHERE

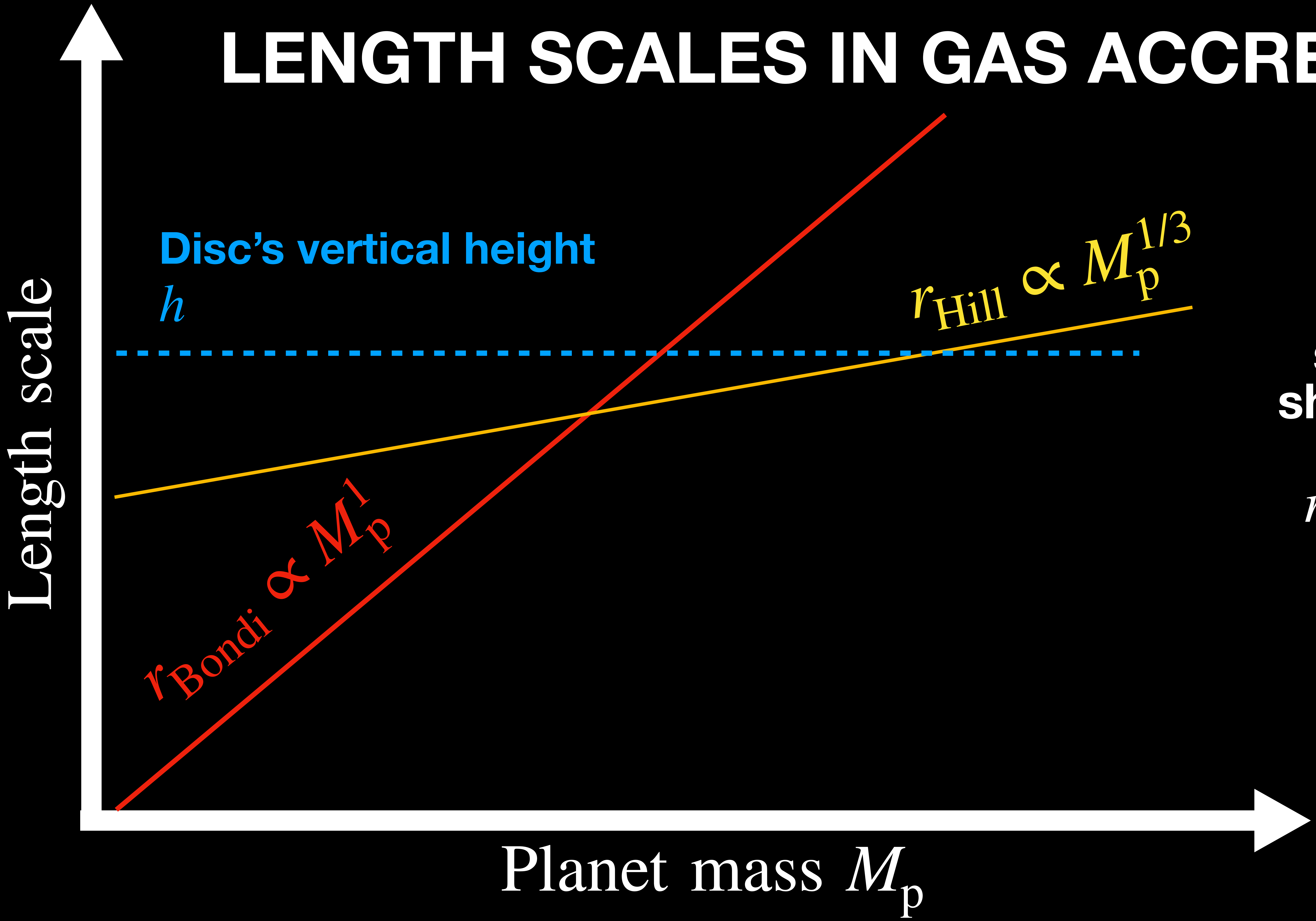
NC & Chiang 2022
NC, Chiang, Fung, & Zhu 2023
NC & Chiang 2025
NC & Gao in prep

Nick Choksi
51 Pegasi b fellow, Caltech

OBSERVED ACCRETING PLANETS



LENGTH SCALES IN GAS ACCRETION



Planet-disk simulations should resolve smallest of $r_{\rm Hill}$, $r_{\rm Bondi}$, h

NC, Chiang, Fung, & Zhu 23

3D GLOBAL PLANET-DISK SIMULATIONS

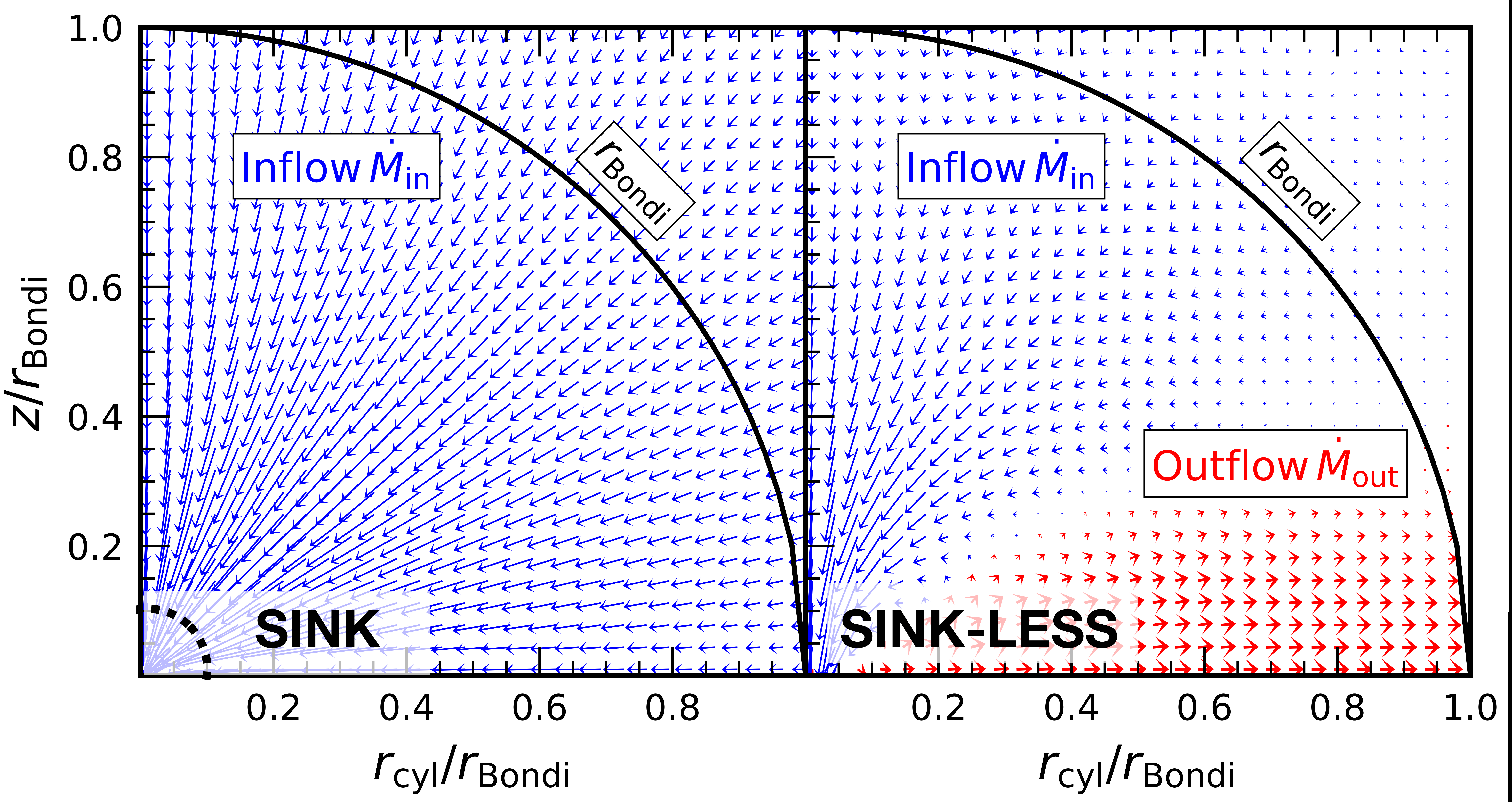
min(r_B, r_H, h) resolved with 64^3 cells

NC, Chiang, Fung, & Zhu 23

TOP-DOWN

VERTICAL SLICE

NC, Chiang, Fung, & Zhu 23



WHAT CAN WE ROBUSTLY MEASURE FROM HYDRO SIMS?

$\dot{M}_{\rm in}$ does not depend on boundary condition

"decretion disks" are artefacts of boundary Condition

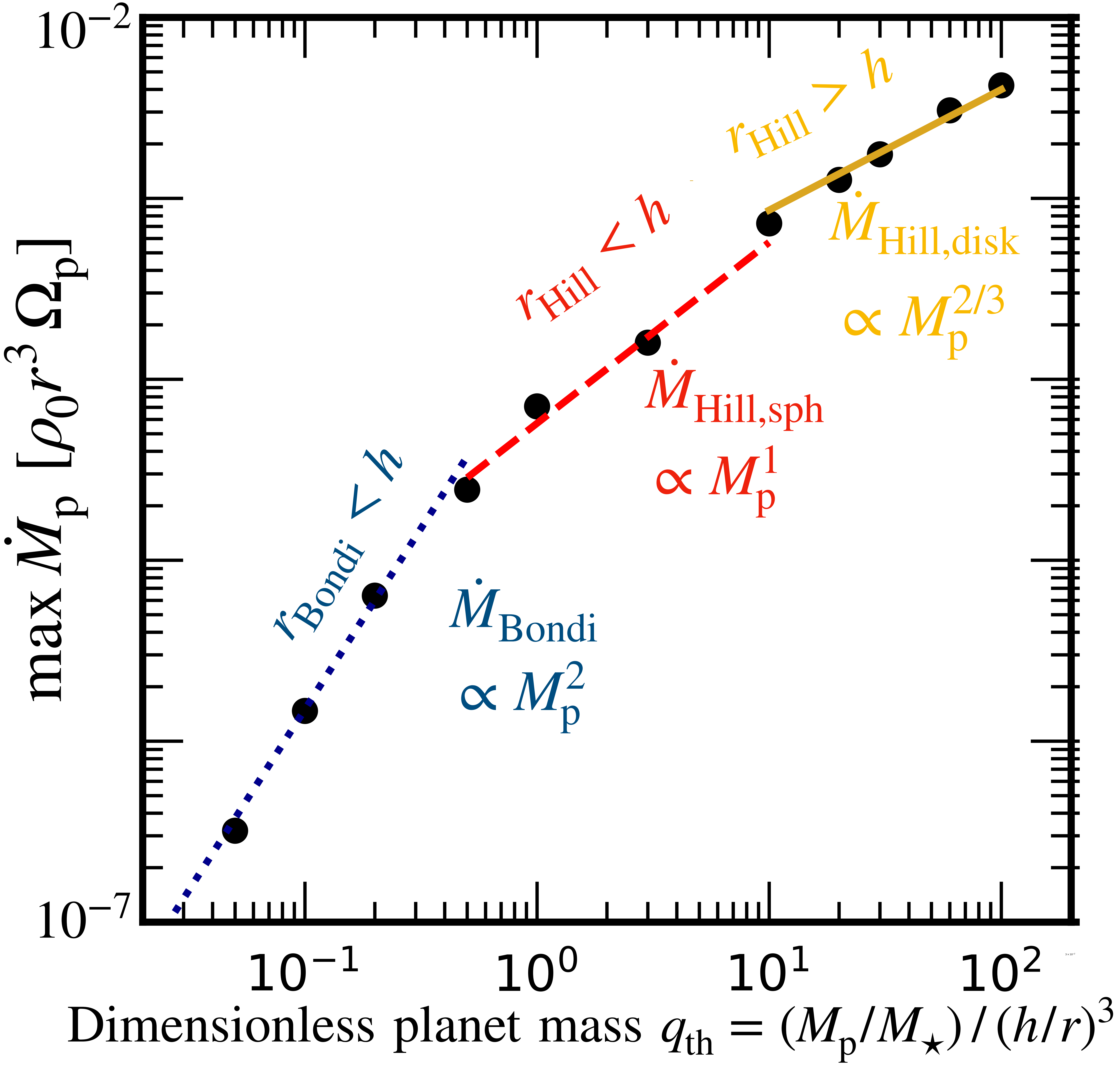
$$\dot{M}_{\rm net} = \dot{M}_{\rm in} - \cancel{\dot{M}_{\rm out}}$$

$$\dot{M}_{\rm net} = \dot{M}_{\rm in} - \dot{M}_{\rm out} \boxed{= 0}$$

NC, Chiang, Fung, & Zhu 23

NC, Chiang, Fung, & Zhu 23

Intermediate masses : $r_{\rm Hill} < h < r_{\rm Bondi}$
Most massive : $h < r_{\rm Hill} < r_{\rm Bondi}$
$r_{\rm Bondi}$
$r_{\rm Hill}$
$\rho(<h) \approx \rho_0$
$\hat{z}$
$\hat{r}$
Feeding area
$\sim r_{\rm Hill} h$
$\dot{M} \sim \rho_0 \times (3/2)\Omega r_{\rm Hill} \times r_{\rm Hill}^2 \propto M_{\rm p}^1$
$\dot{M} \sim \rho_0 \times (3/2)\Omega r_{\rm Hill} \times r_{\rm Hill} h \propto M_{\rm p}^{2/3}$
Scaled inflow $\dot{M}_{\rm in}$
scaled by
$M_{\rm p}^1 (h/a)^0$
10^1
10^0
$1M_{\rm J}, h/a = 0.07$
$125M_\oplus, 0.07$
$45M_\oplus, 0.07$
$15M_\oplus, 0.035$
0.2
$r/r_{\rm Hill}$
1
$M_{\rm p}^{2/3} (h/a)^1$
$9M_{\rm J}, h/a = 0.035$
$5M_{\rm J}, 0.035$
$3M_{\rm J}, 0.07$
$3M_{\rm J}, 0.035$
$1.5M_{\rm J}, 0.035$
$1M_{\rm J}, 0.035$
$150M_\oplus, 0.035$
NC, Chiang, Fung, & Zhu 23



THREE REGIMES OF RUNAWAY GAS ACCRETION

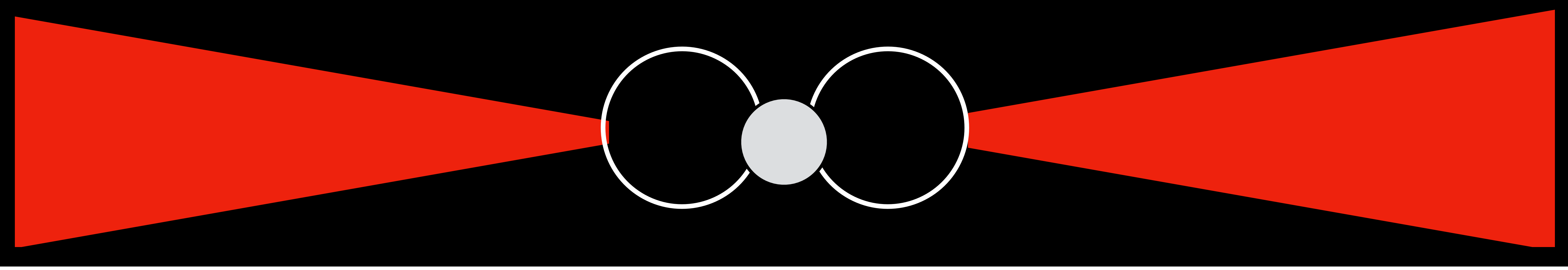
$$\dot{M}_{\rm Hill,disk} \sim r_{\rm Hill} h \times \frac{3}{2}\Omega r_{\rm Hill} \times \rho_0$$

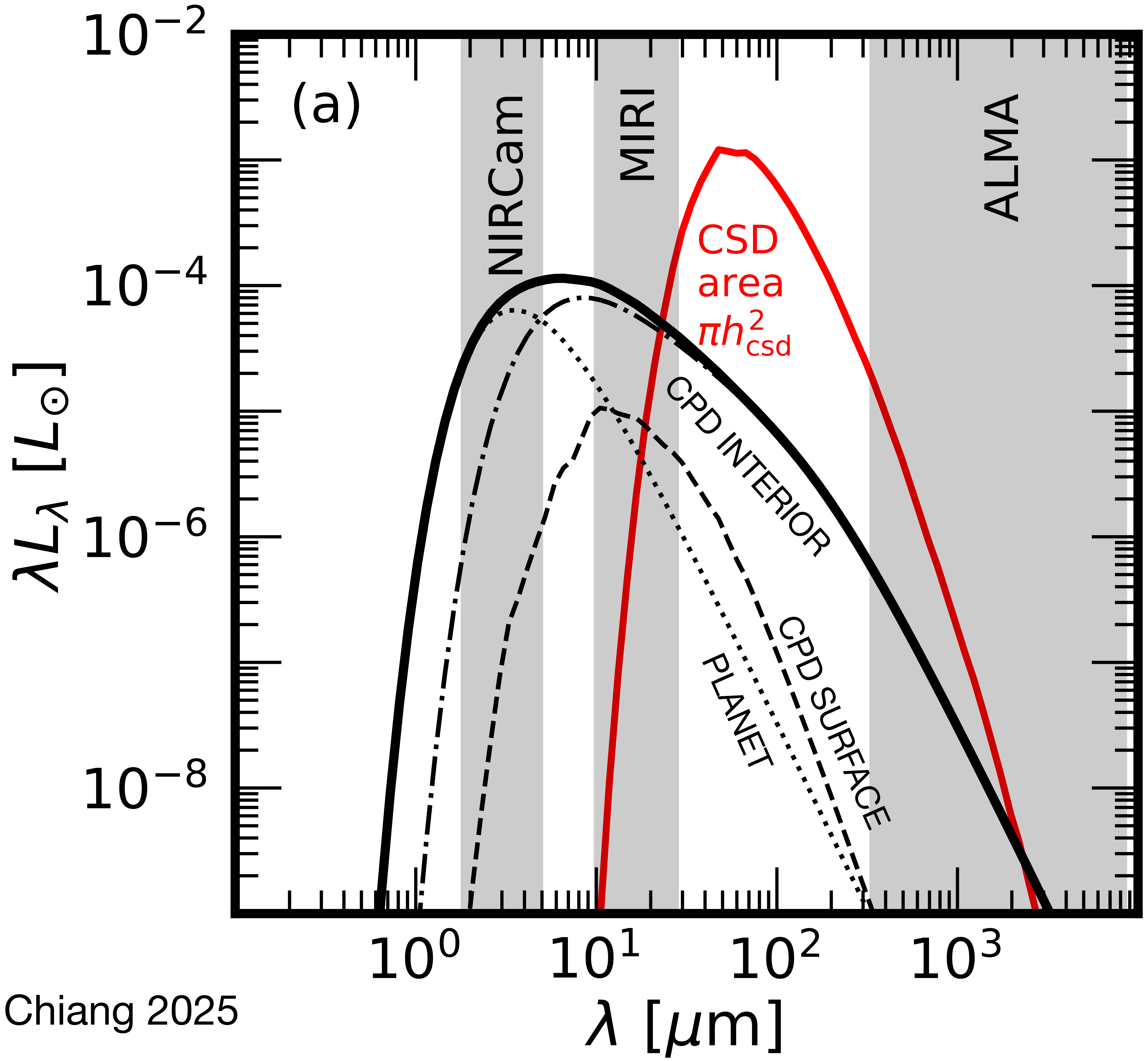
$$\dot{M}_{\rm Hill,sph} \sim r_{\rm Hill}^2 \times \frac{3}{2}\Omega r_{\rm Hill} \times \rho_0$$

$$\dot{M}_{\rm Bondi} \sim r_{\rm Bondi}^2 \times c_{\rm s} \times \rho_0$$

NC, Chiang, Fung, & Zhu 23

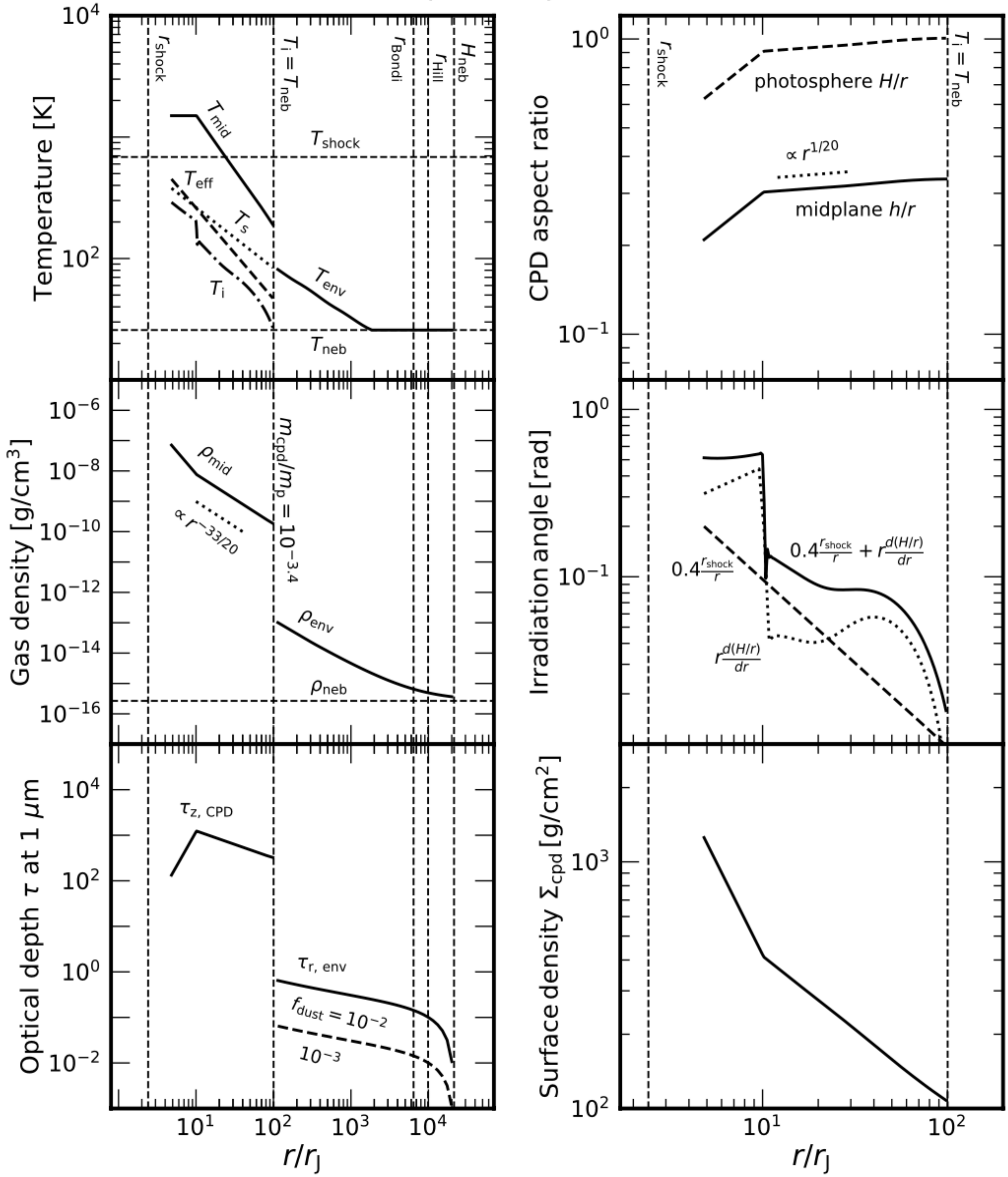
SEDs OF CIRCUMPLANETARY DISKS



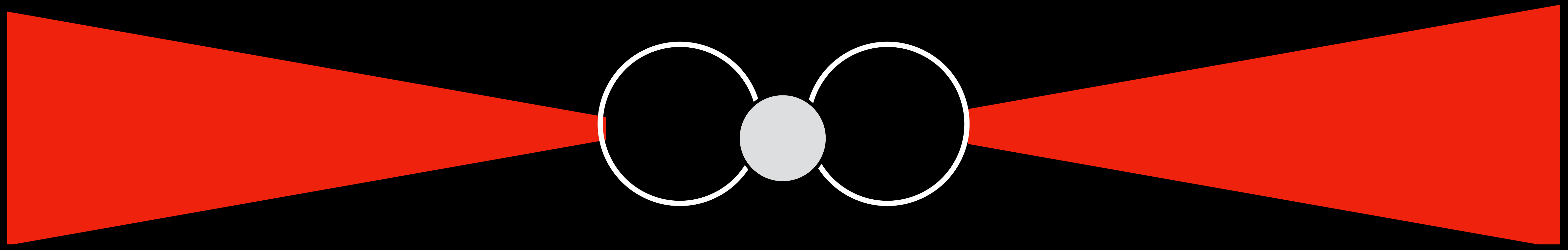


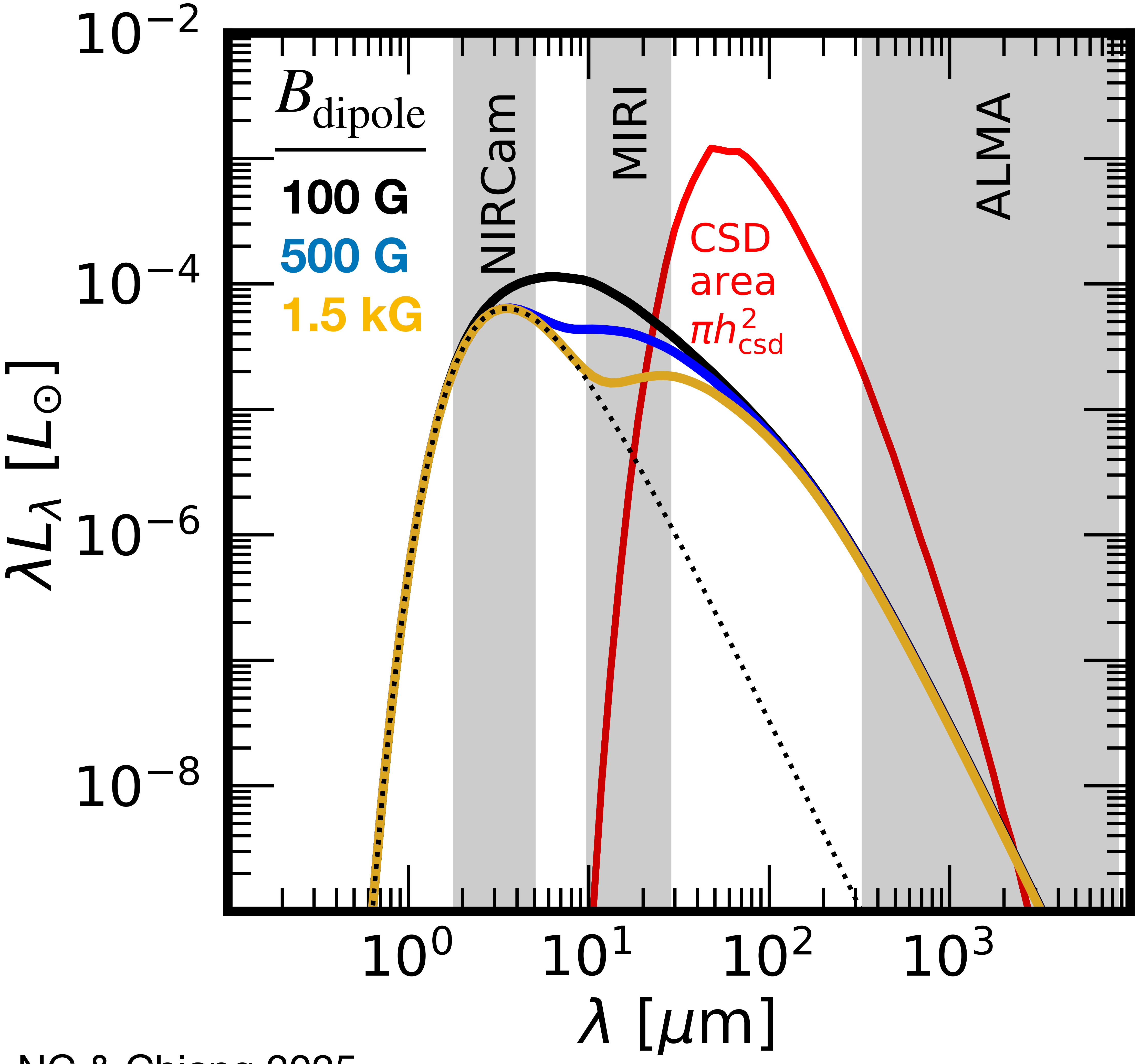
NC & Chiang 2025

CPDs heated by irradiation and dissipation

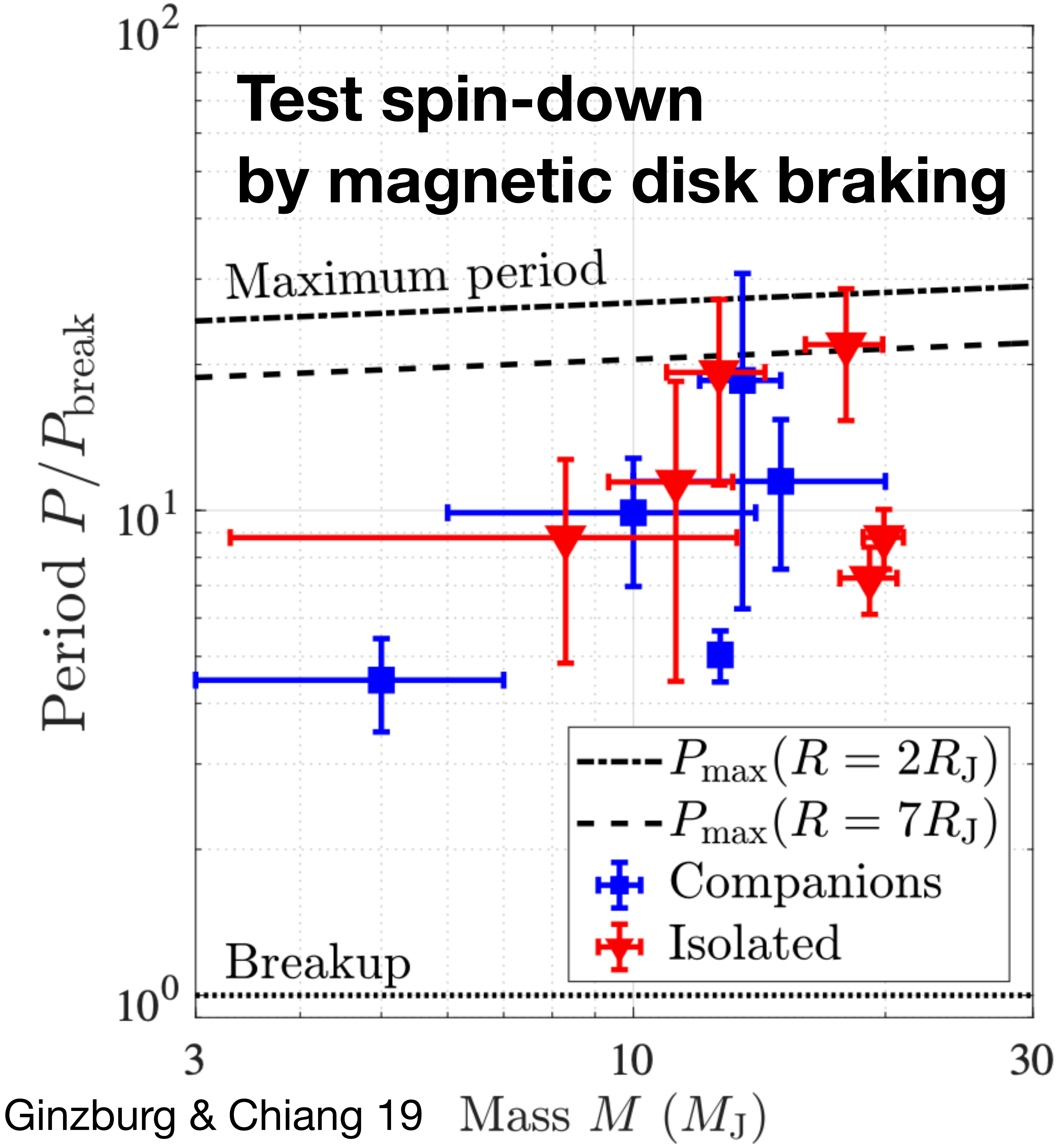


SEDs OF MAGNETICALLY TRUNCATED CPDs

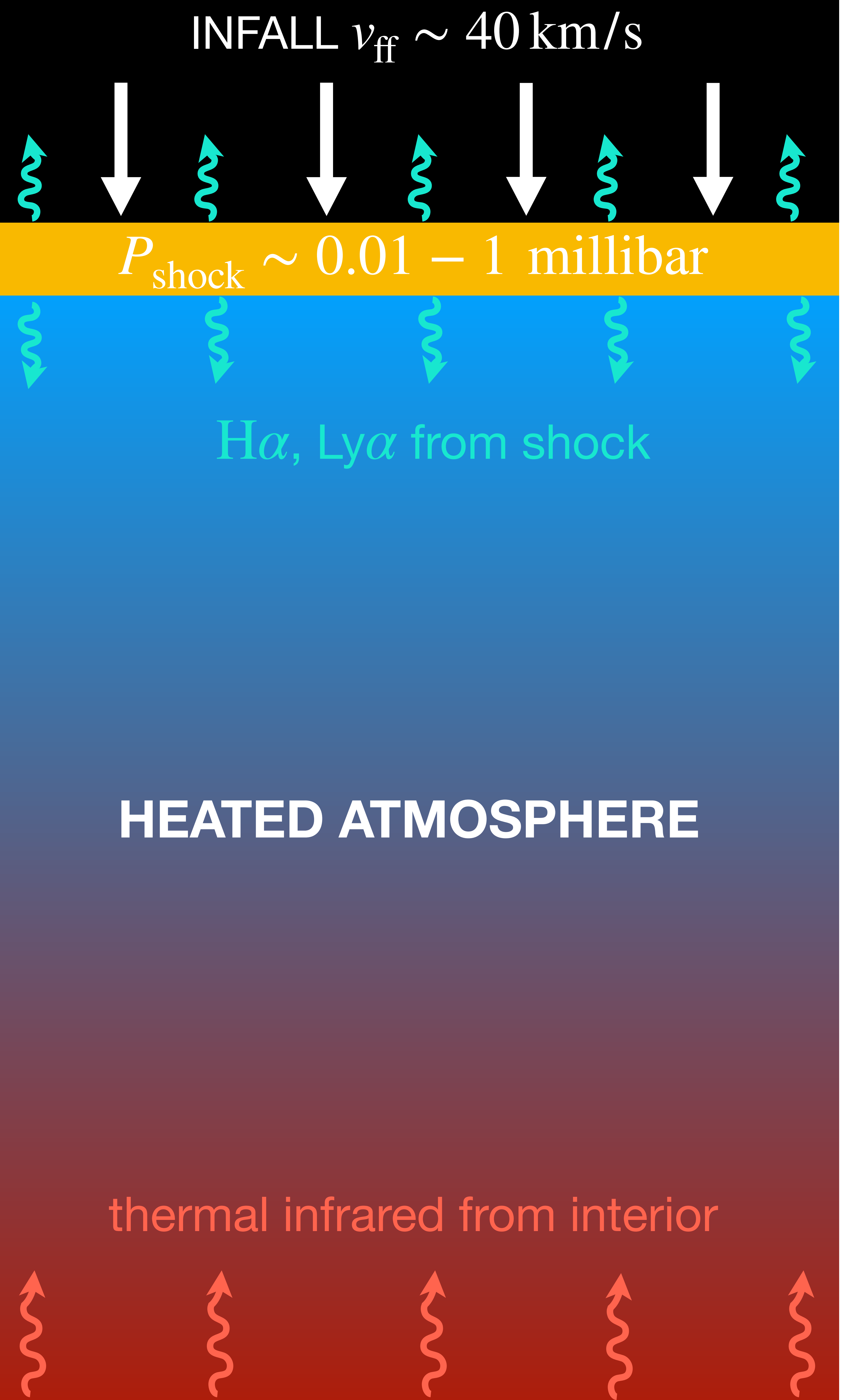




NC & Chiang 2025



Bryan+ 18
Batygin 18, Ginzburg & Chiang 19

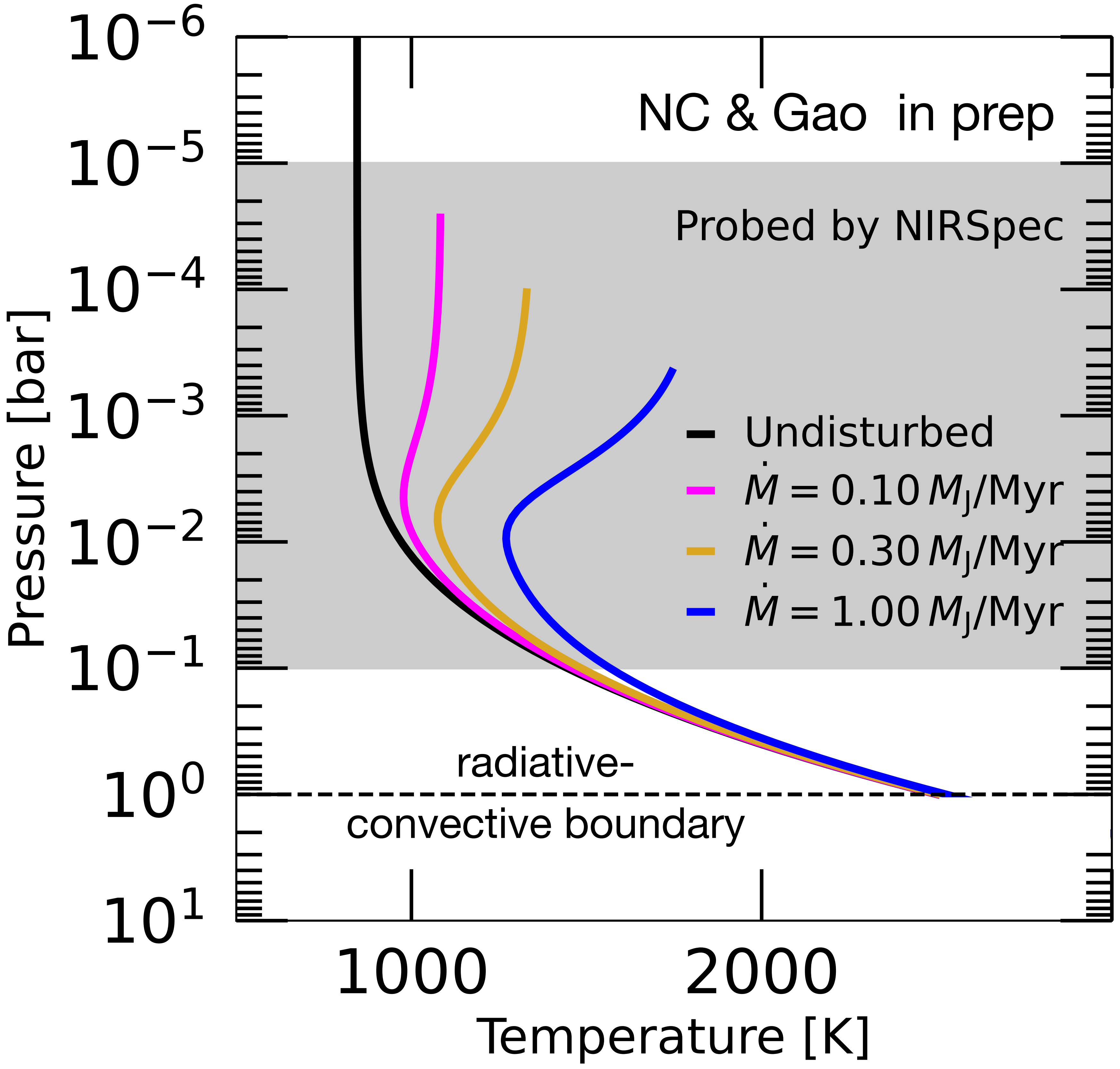


ACCRETIONALLY HEATED ATMOSPHERES

$$T^4_{\rm atm}(\tau) \approx \frac{3}{4} T^4_{\rm int}\left[\frac{2}{3} + \tau\right] + \frac{3}{4}\frac{GM\dot{M}}{4\pi R^3 f_{\rm fill}\sigma} q e^{-q\tau}$$

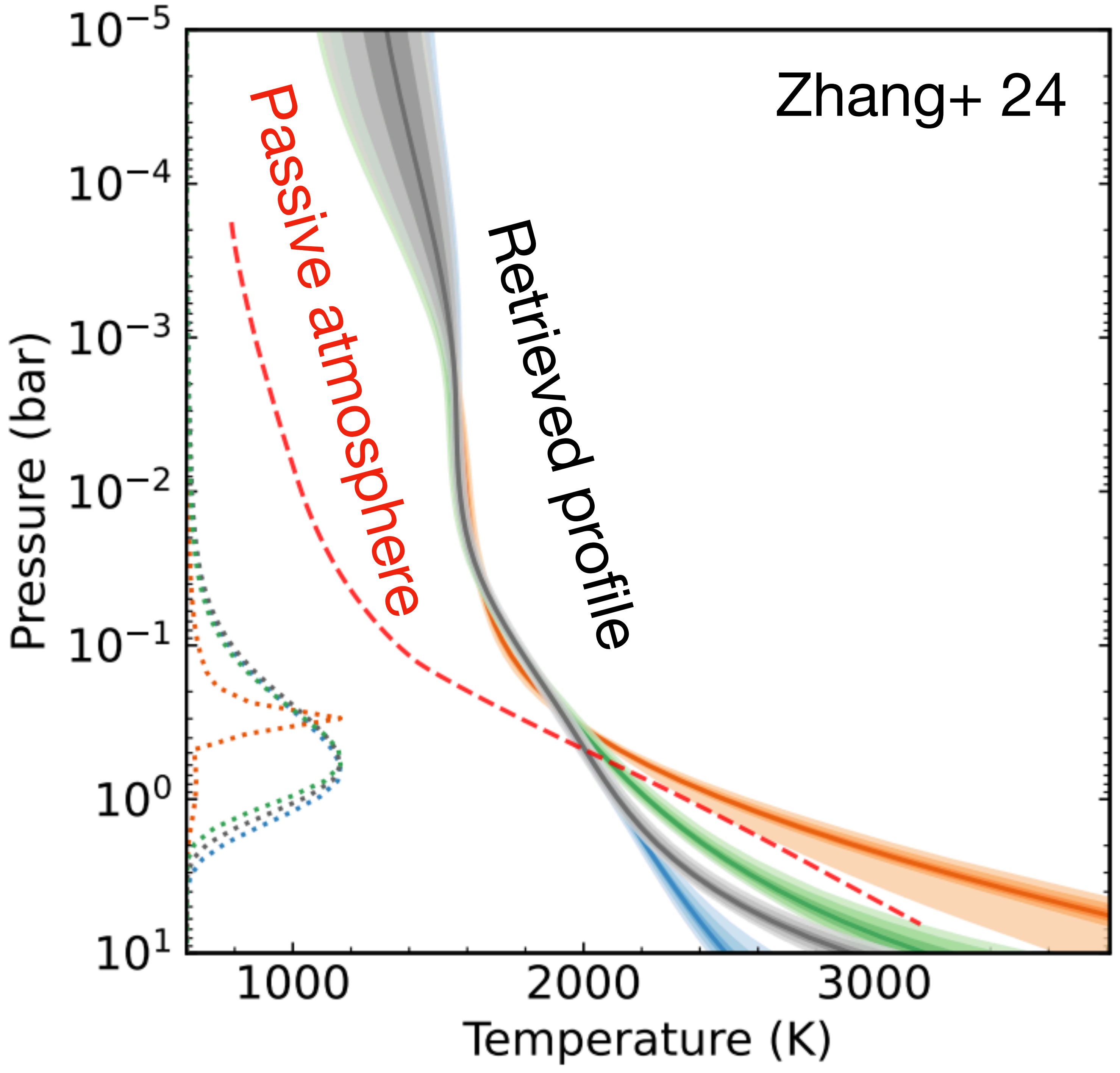
$$\frac{dP}{d\tau} = g/\kappa_{\rm IR} \qquad q \equiv \kappa_{\rm shock}/\kappa_{\rm IR}$$

e.g. Guillot 2010



Radiative transfer with radmc3d

The heated atmosphere of YSES 1b



SUPPLY-LIMITED ACCRETION IN PDS 70

Accretion rate from hydro

$$\max \dot{M}_\mathrm{p} \sim r_\mathrm{Hill} h \times (3/2)\Omega r_\mathrm{Hill} \times \rho_\mathrm{gas}$$

from ALMA

$$\sim 1\, M_\mathrm{J}/\mathrm{Myr}$$

$$\sim M_\mathrm{p}/t_\mathrm{age}$$

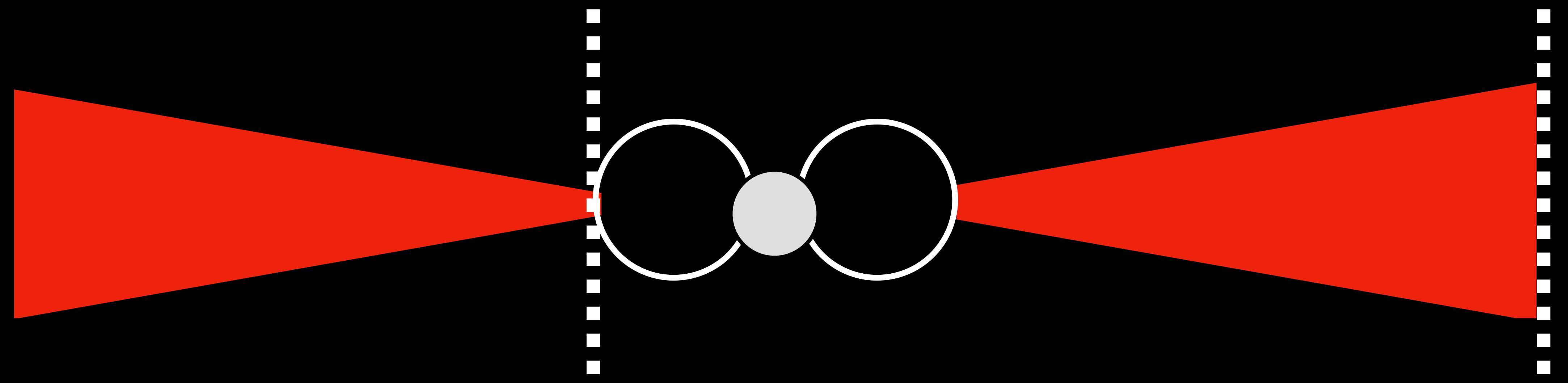
cf. 100x lower $\dot{M}_\mathrm{p}$ from Hα

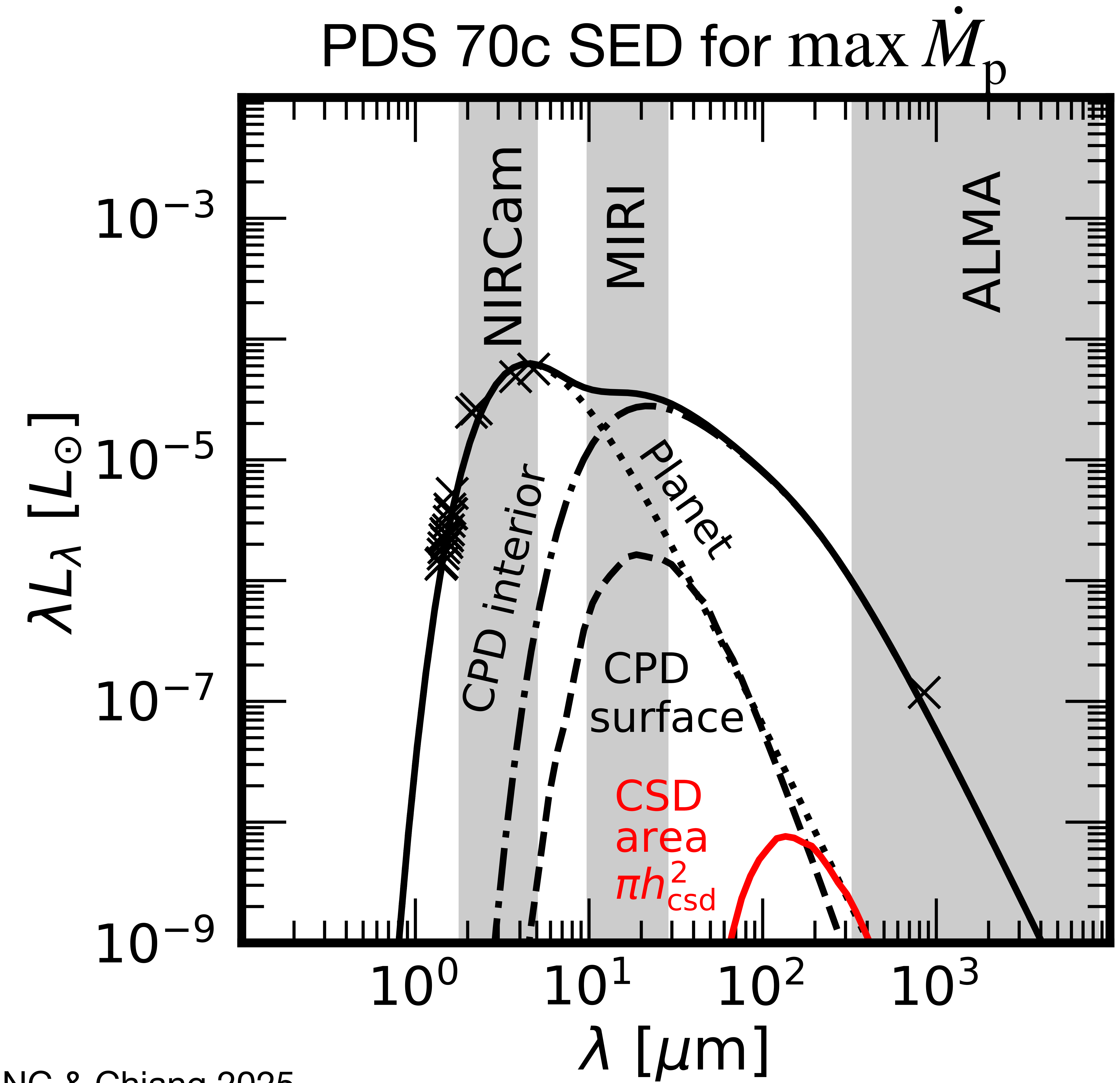
e.g. Haffert+ 19

Circumplanetary disk from SED

$$> 20 R_\mathrm{J}$$

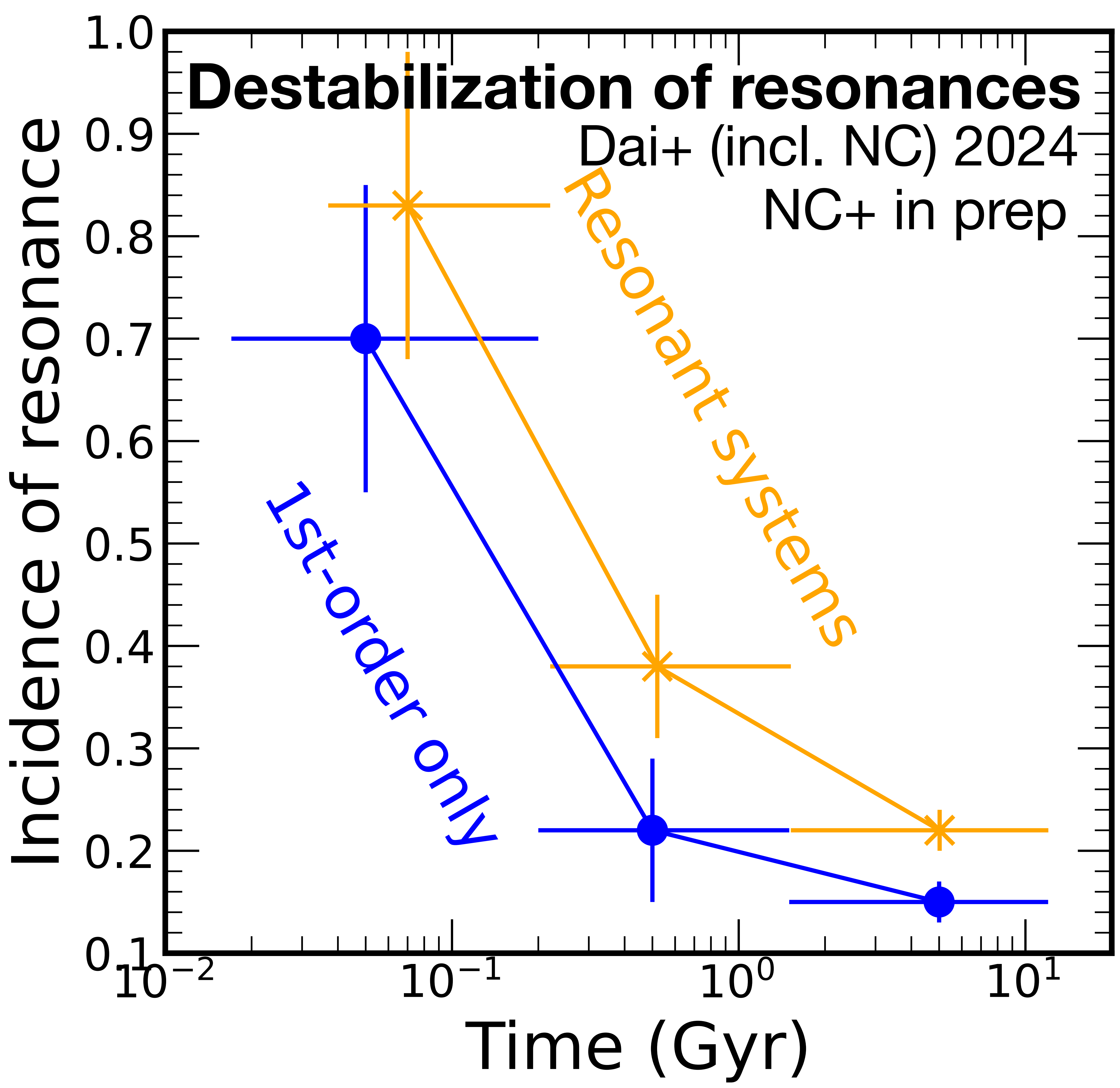
$$(B_\mathrm{dipole} > 200\,\mathrm{G}) \qquad \sim 0.1 R_\mathrm{Hill}$$

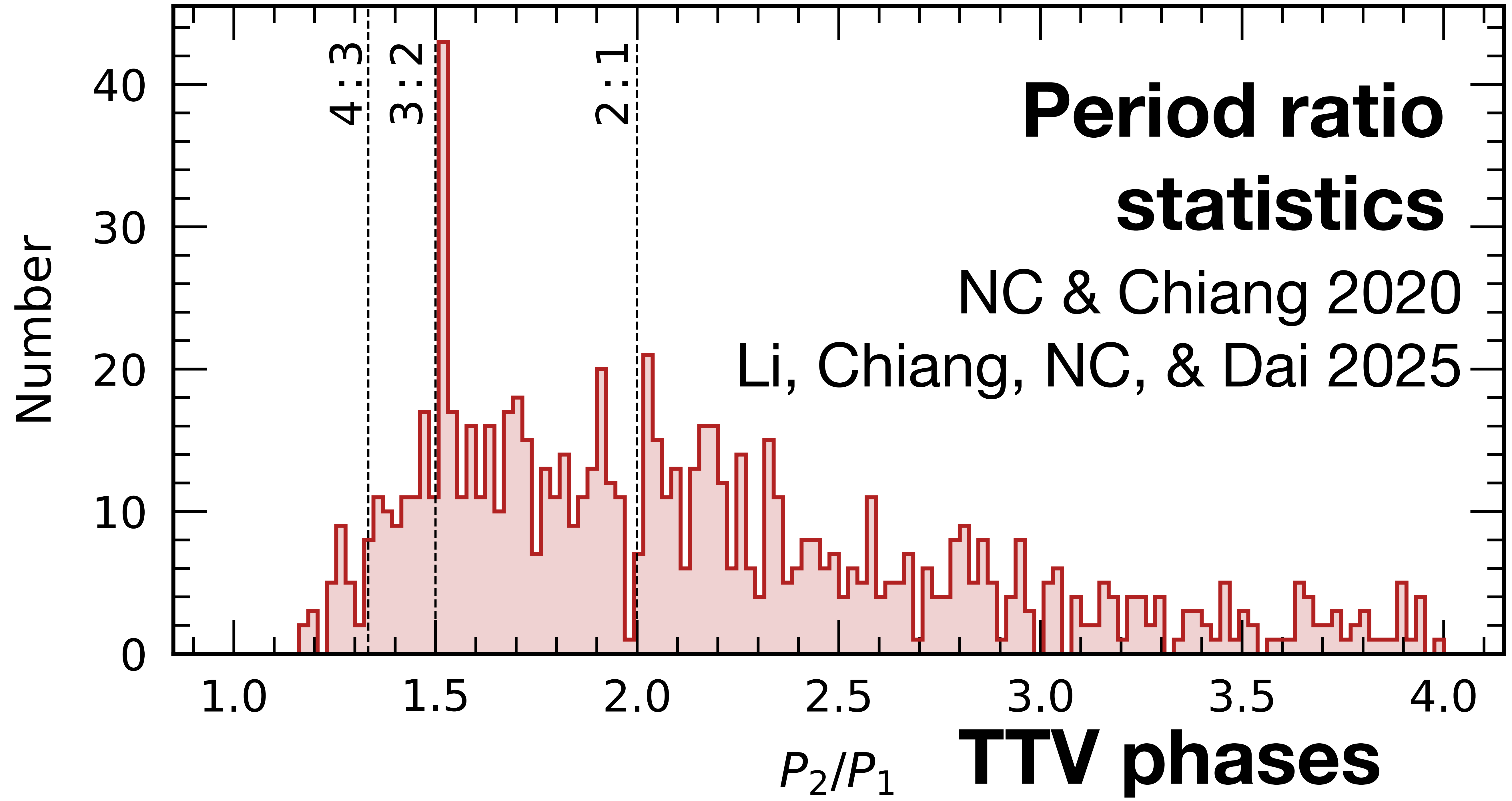




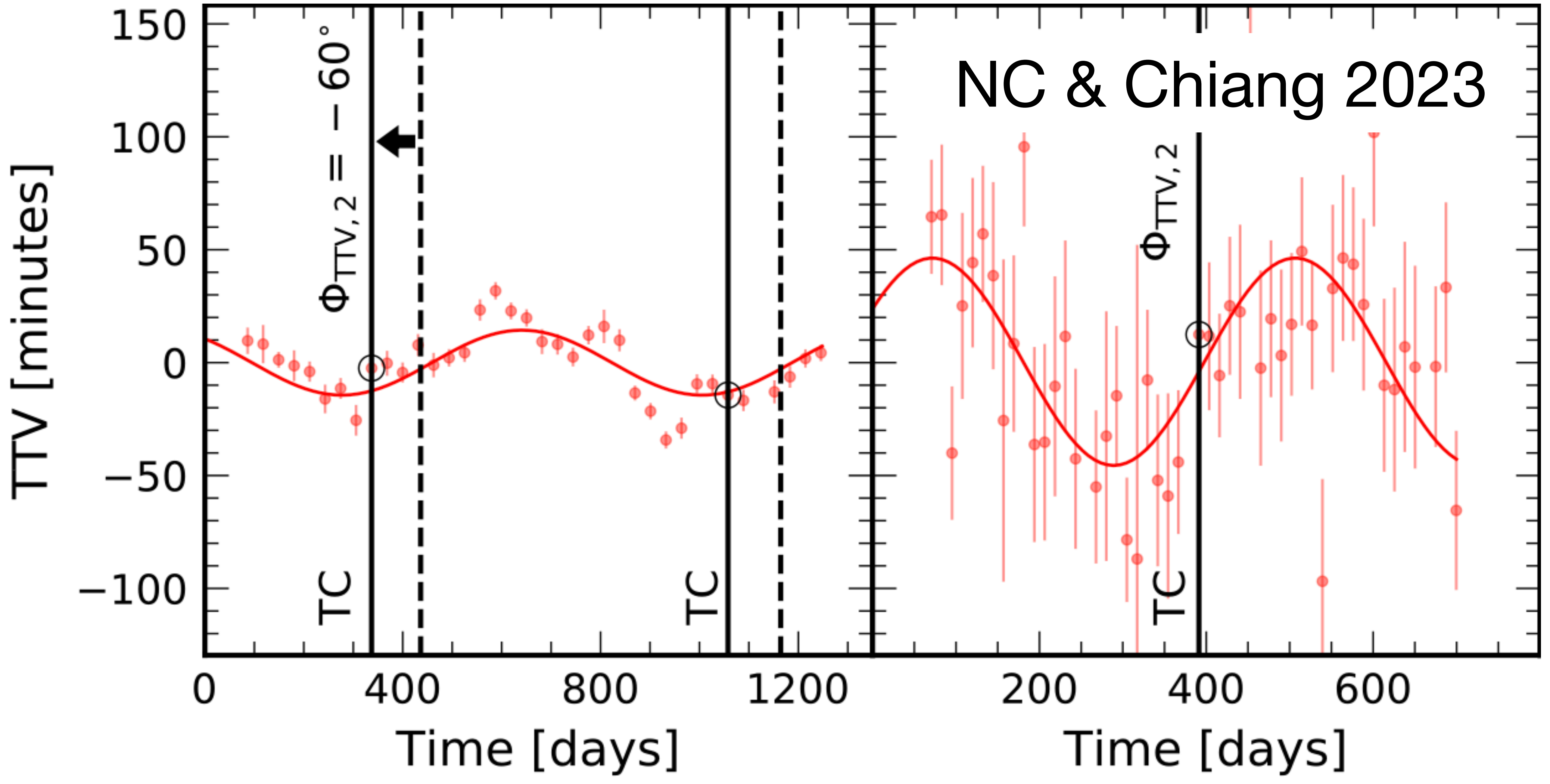
NC & Chiang 2025

RESONANCES AS SIGNPOSTS OF SUPER-EARTH ASSEMBLY



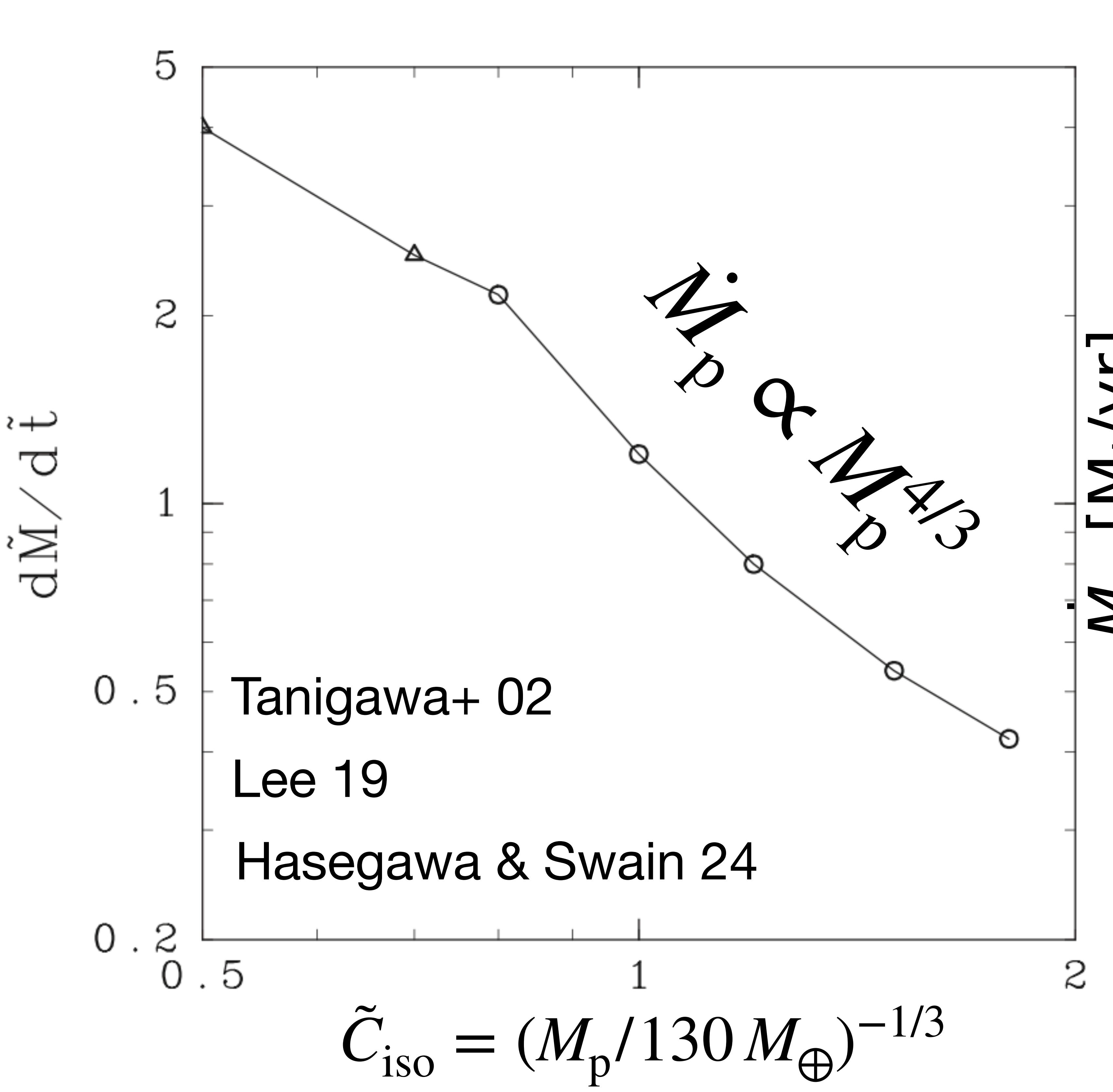


TTV phases

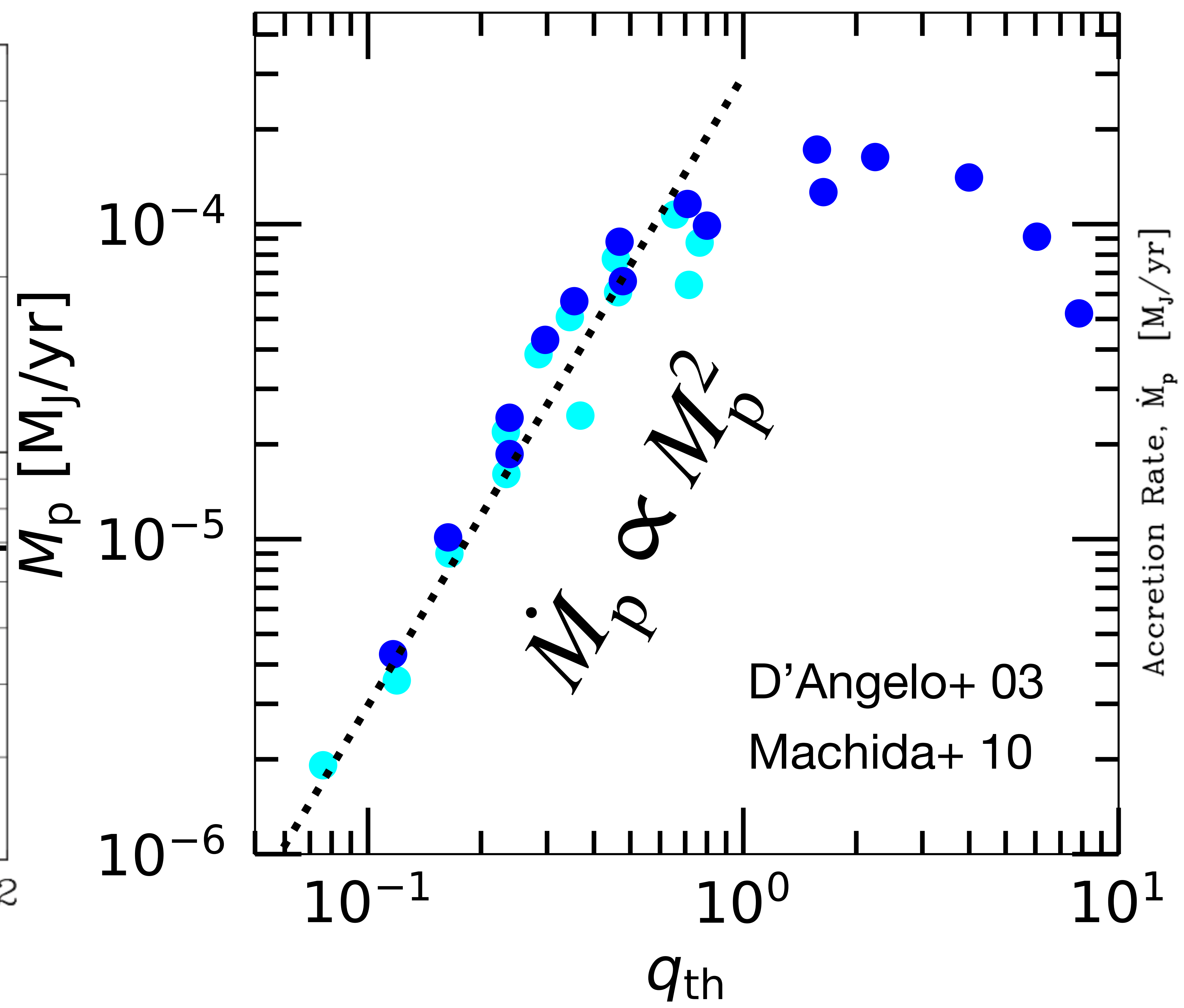


EXTRA SLIDES

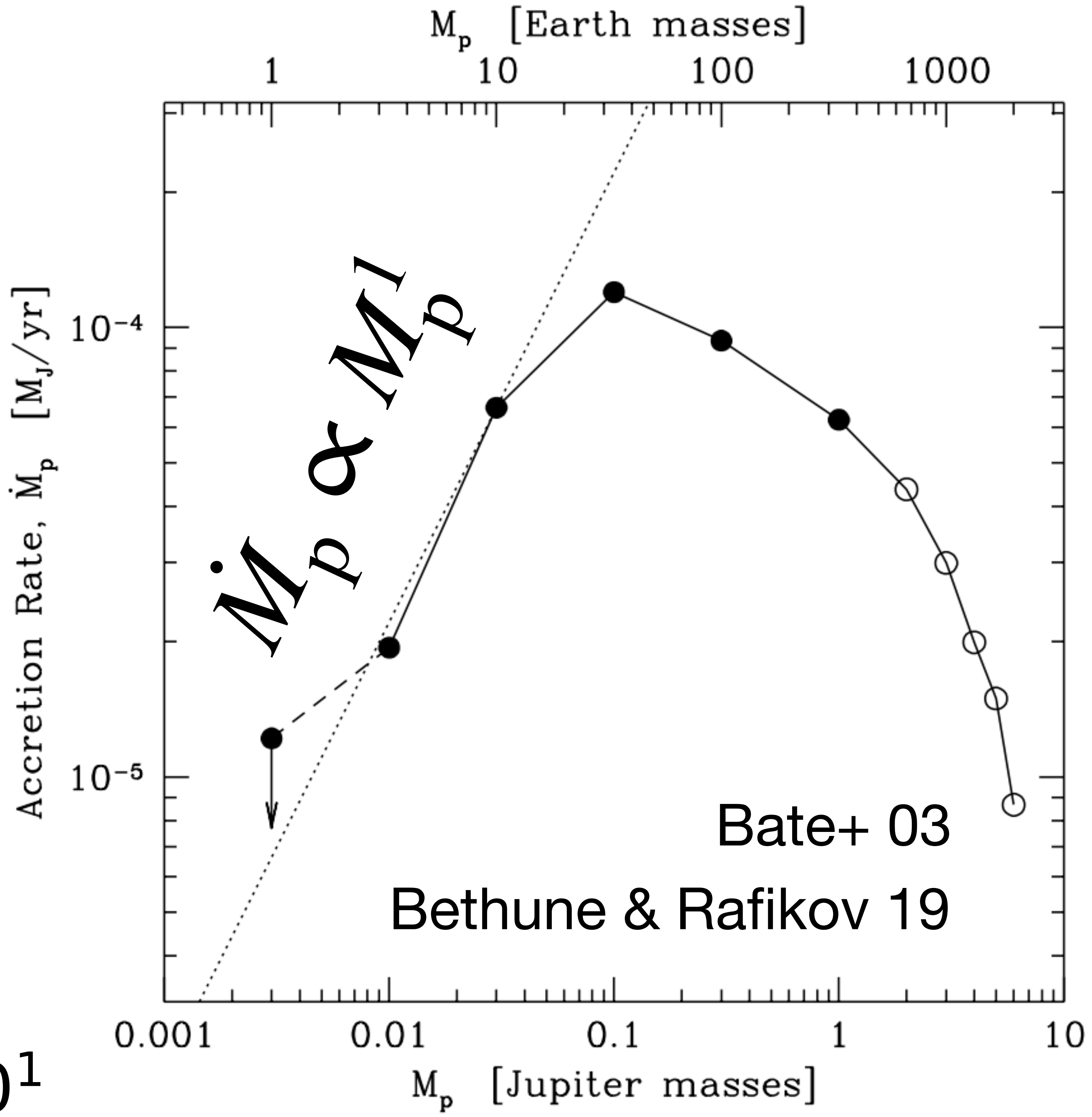
HOW FAST DO PLANETS ACCRETE GAS?



2D isothermal shearing box



3D isothermal global

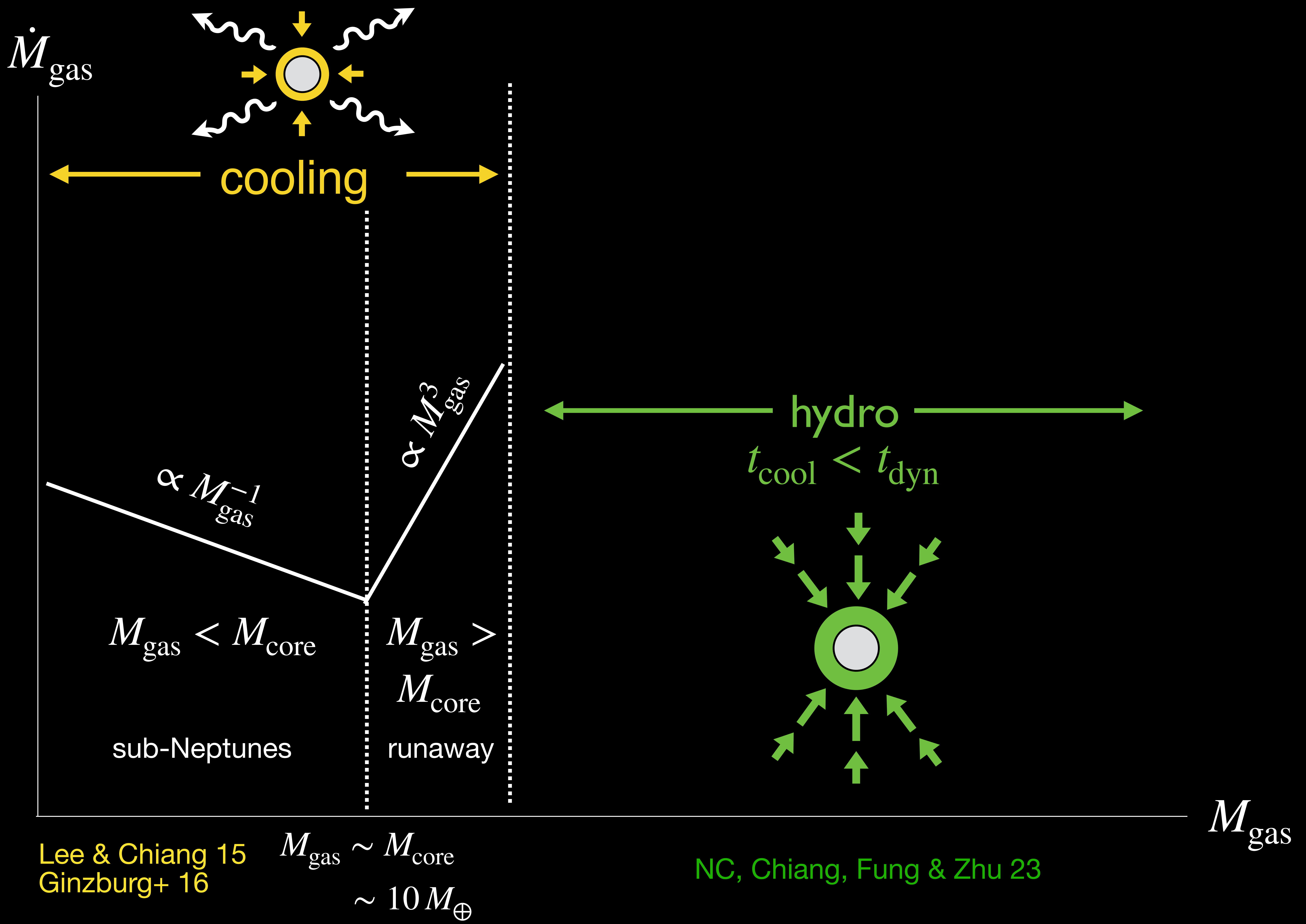


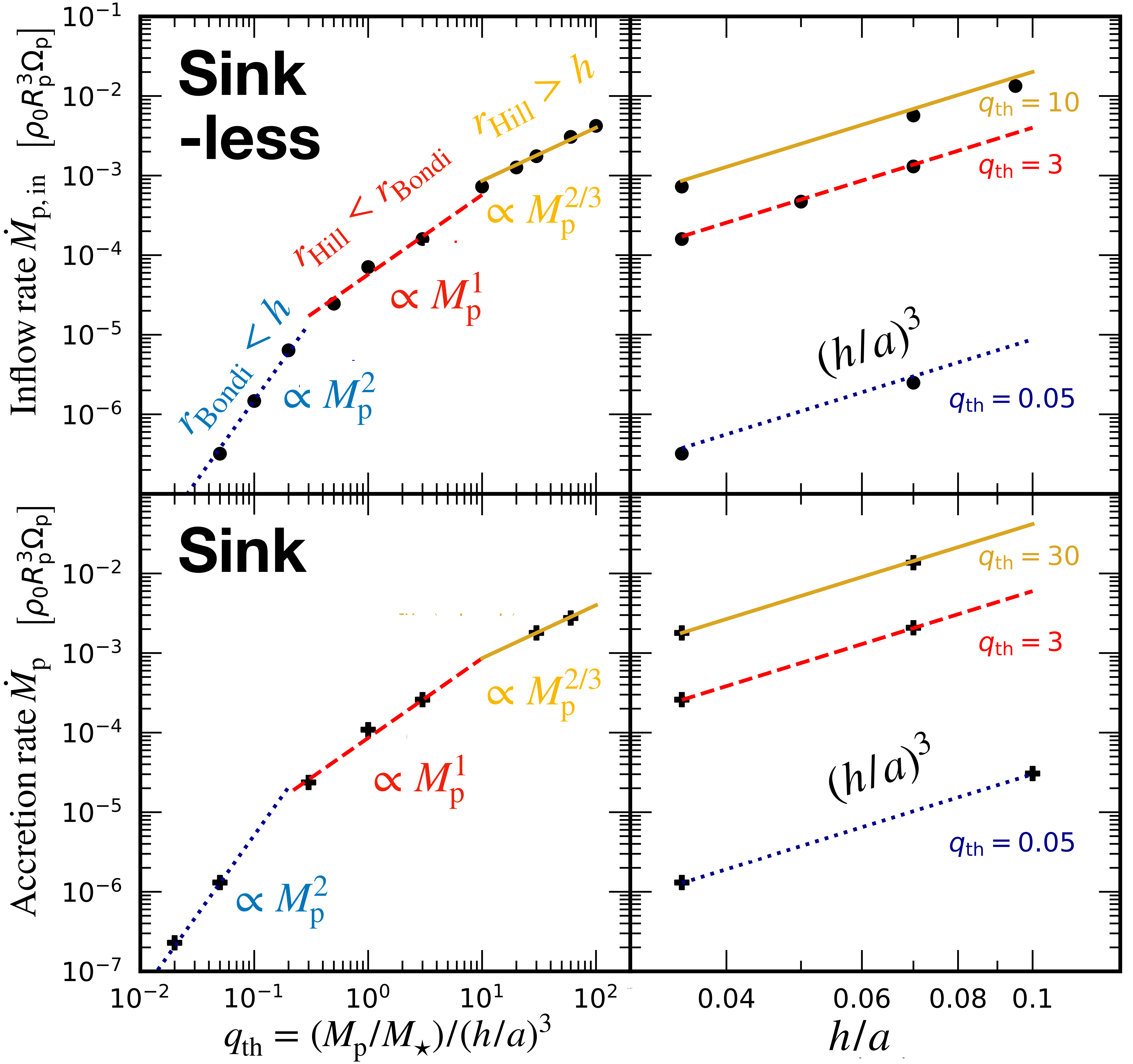
3D isothermal global

also $\dot{M}_p \propto M_p^{2/3}$

Zhu+ 12

HOW FAST DO PLANETS ACCRETE GAS?





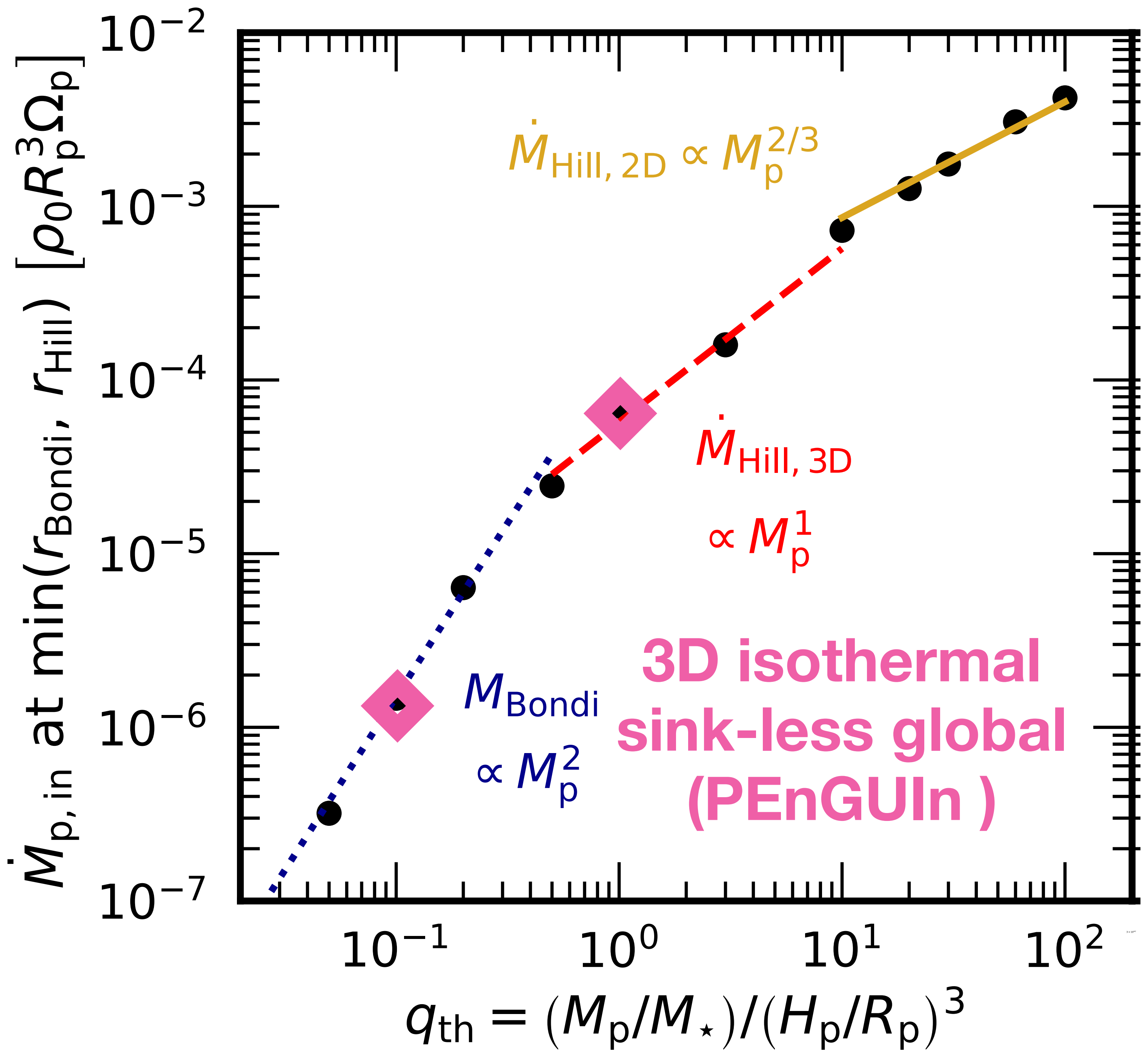
THE MAXIMUM ACCRETION RATE OF A PROTOPLANET

$$\dot{M}_{\rm Bondi} \sim r_{\rm Bondi}^2 \times c_{\rm s} \times \rho$$
$$\propto M_{\rm p}^2 \, (h/a)^{-3}$$

$$\dot{M}_{\rm Hill,3D} \sim r_{\rm Hill}^2 \times (3/2)\Omega r_{\rm Hill} \times \rho$$
$$\propto M_{\rm p}^1 \, (h/a)^0$$

$$\dot{M}_{\rm Hill,2D} \sim r_{\rm Hill} h \times (3/2)\Omega r_{\rm Hill} \times \rho$$
$$\propto M_{\rm p}^{2/3} \, (h/a)^1$$

NC+ 23



Scalings supported by other works

$$\dot{M}_{\mathrm{Bondi}} \propto M_{\mathrm{p}}^2$$

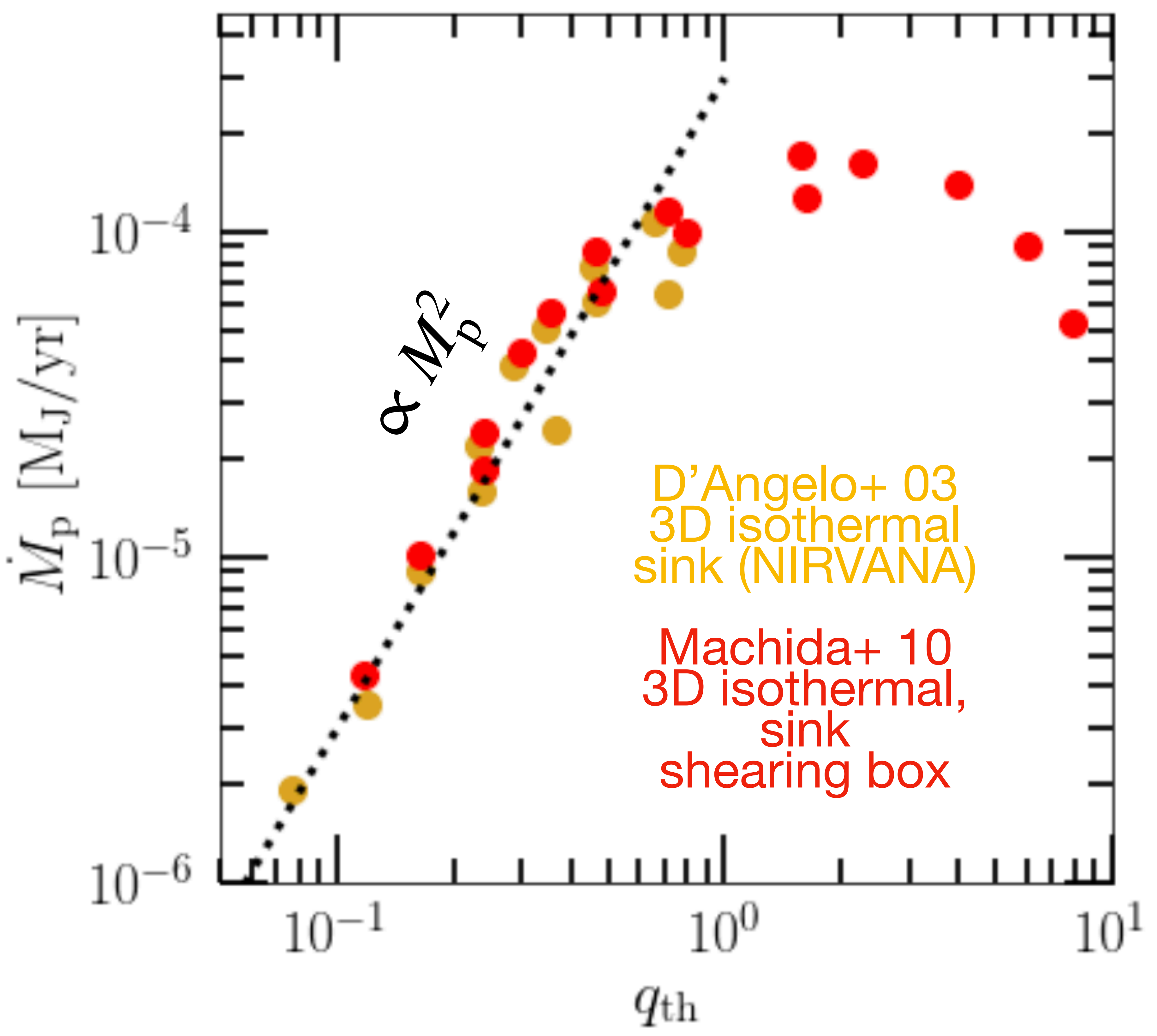
D'Angelo+ 03, Machida+ 10, Li+ 23

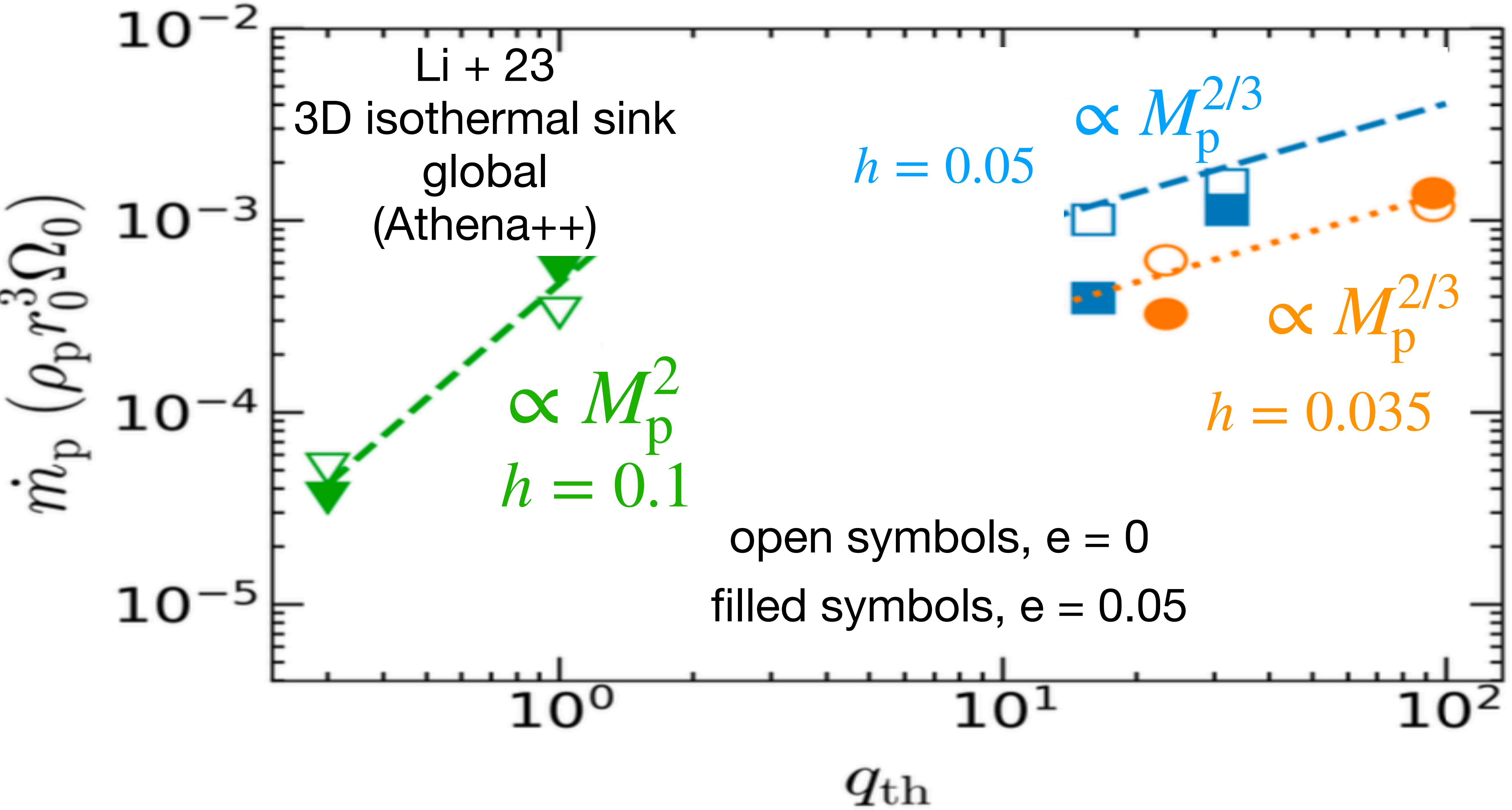
$$\dot{M}_{\mathrm{Hill}} \propto M_{\mathrm{p}}^1$$

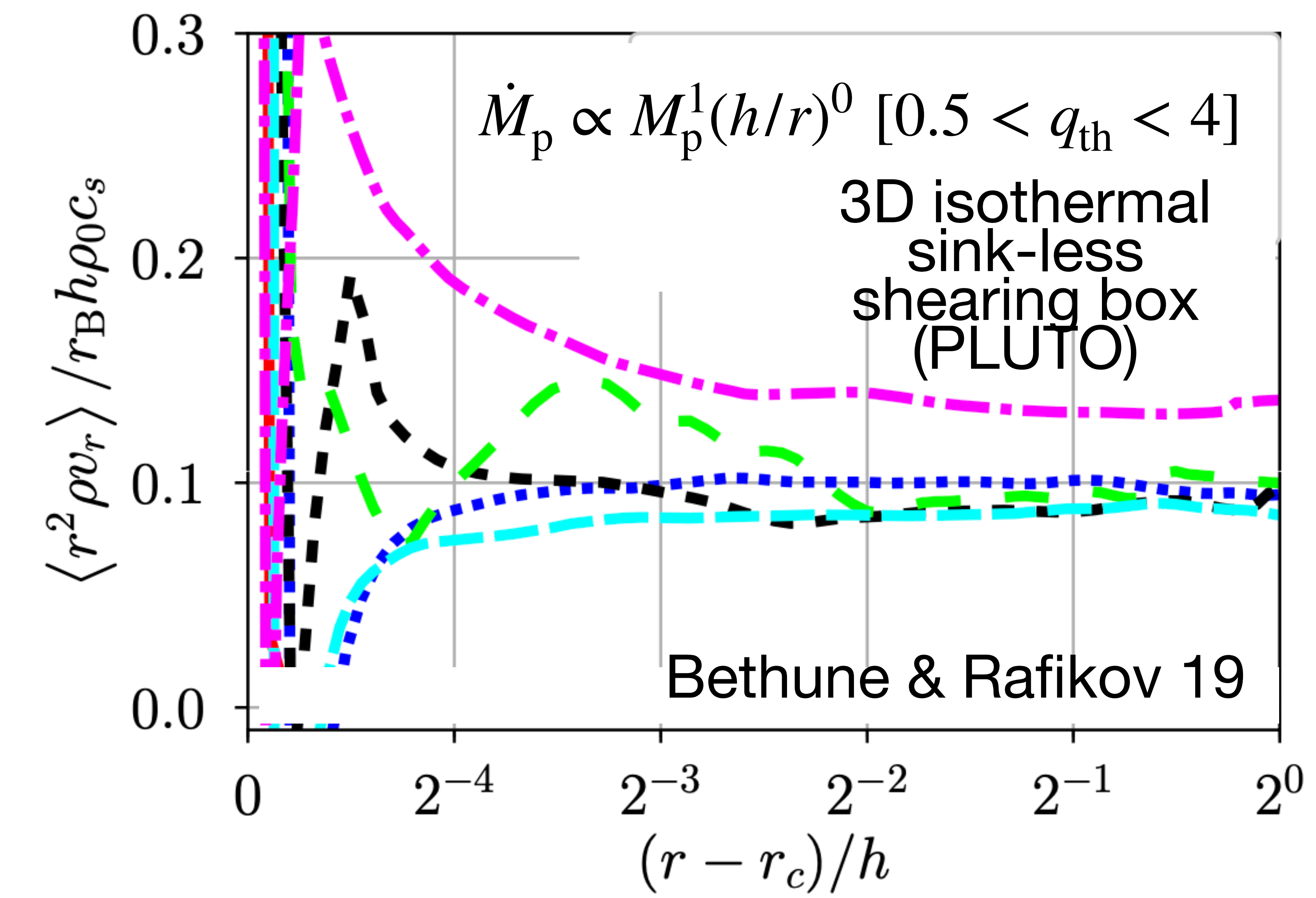
Bate+ 03, Bethúne & Rafikov+ 19

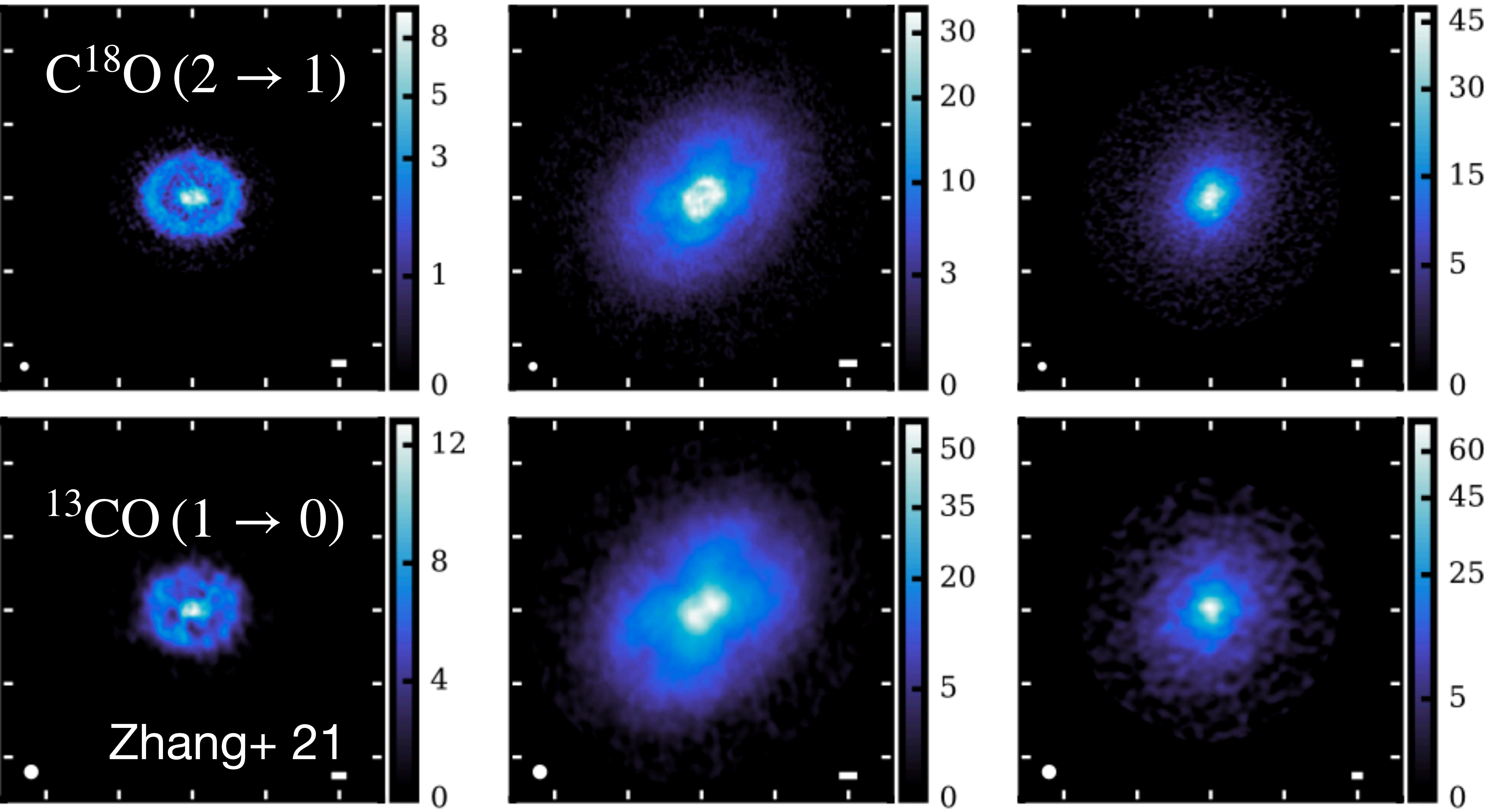
$$\dot{M}_{\mathrm{Hill,2D}} \propto M_{\mathrm{p}}^{2/3}$$

Zhu+ 12, Li+ 23



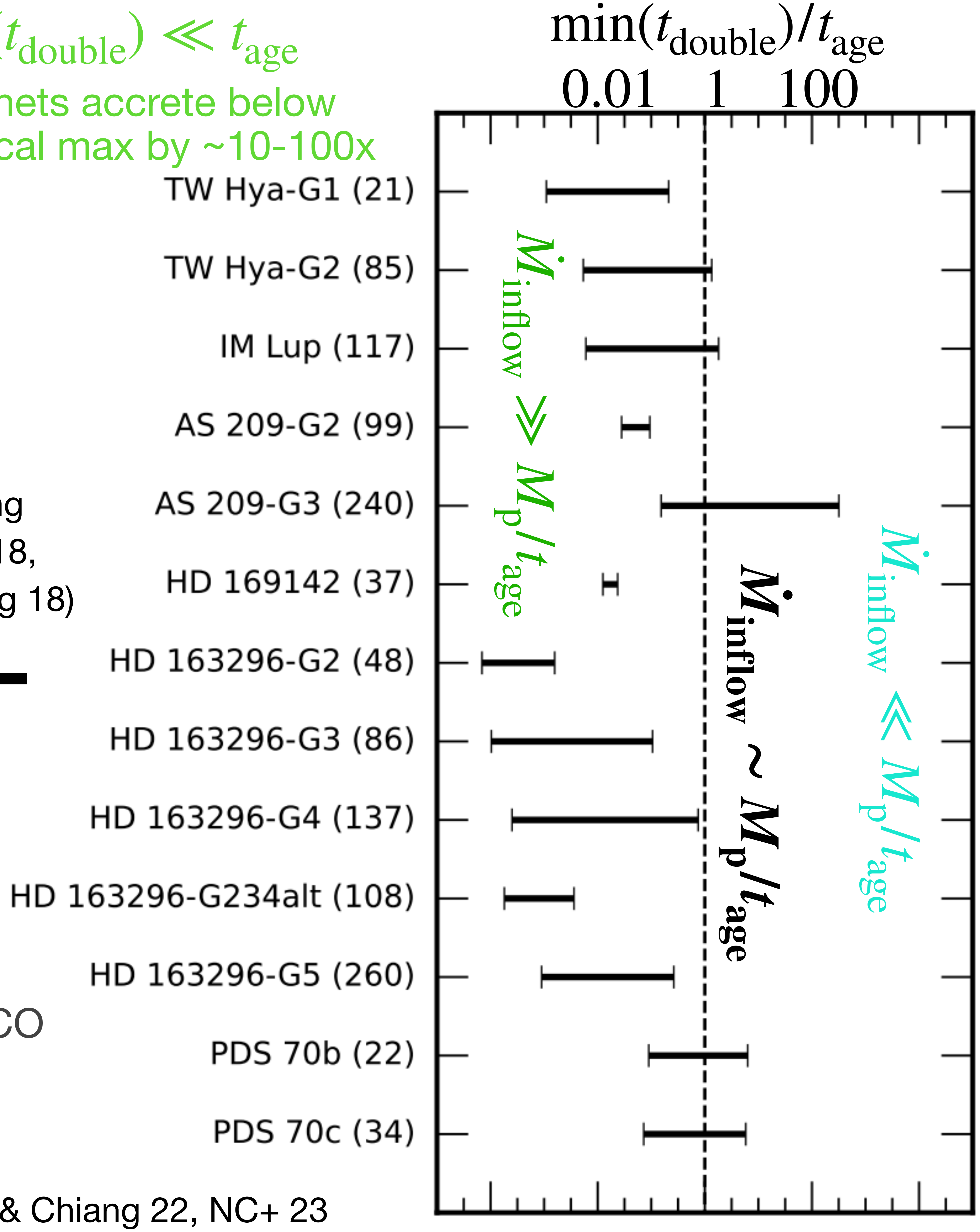






$\min(t_{\rm double}) \ll t_{\rm age}$

∴ planets accrete below theoretical max by ~10-100x



Use optically thin CO isotopologues to estimate gap depth

$$\Sigma_{H_2} = X_{\rm CO} N_{\rm CO}$$

$$N_{\rm CO} \sim X_{\rm iso} \frac{k_B}{\nu S d^2} \frac{Q}{g_J} e^{E_u/k_B T} I_\nu \Delta v$$

e.g. Mangum & Shirley 15

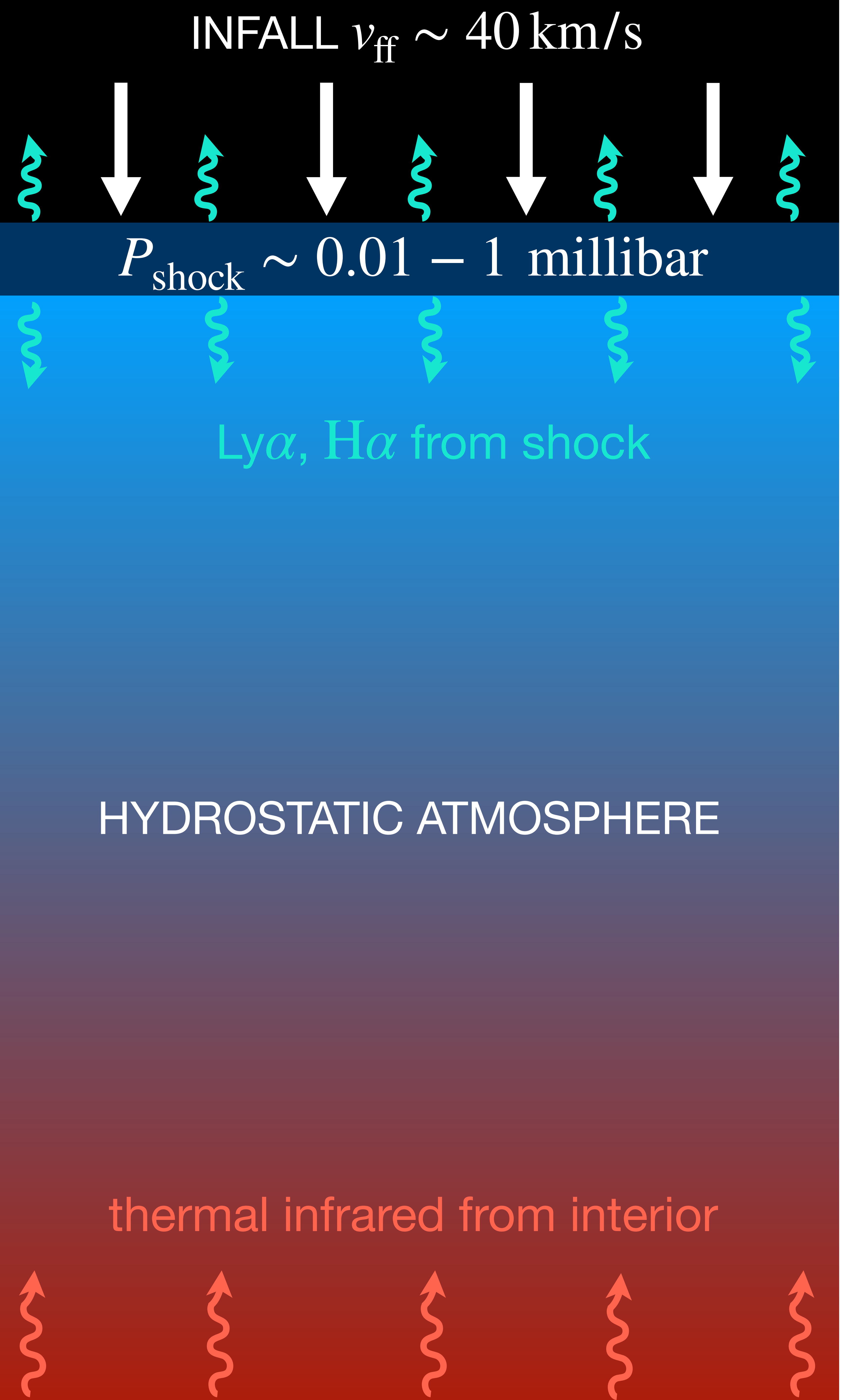
from gap-fitting (Zhang+ 18, Dong & Fung 18)

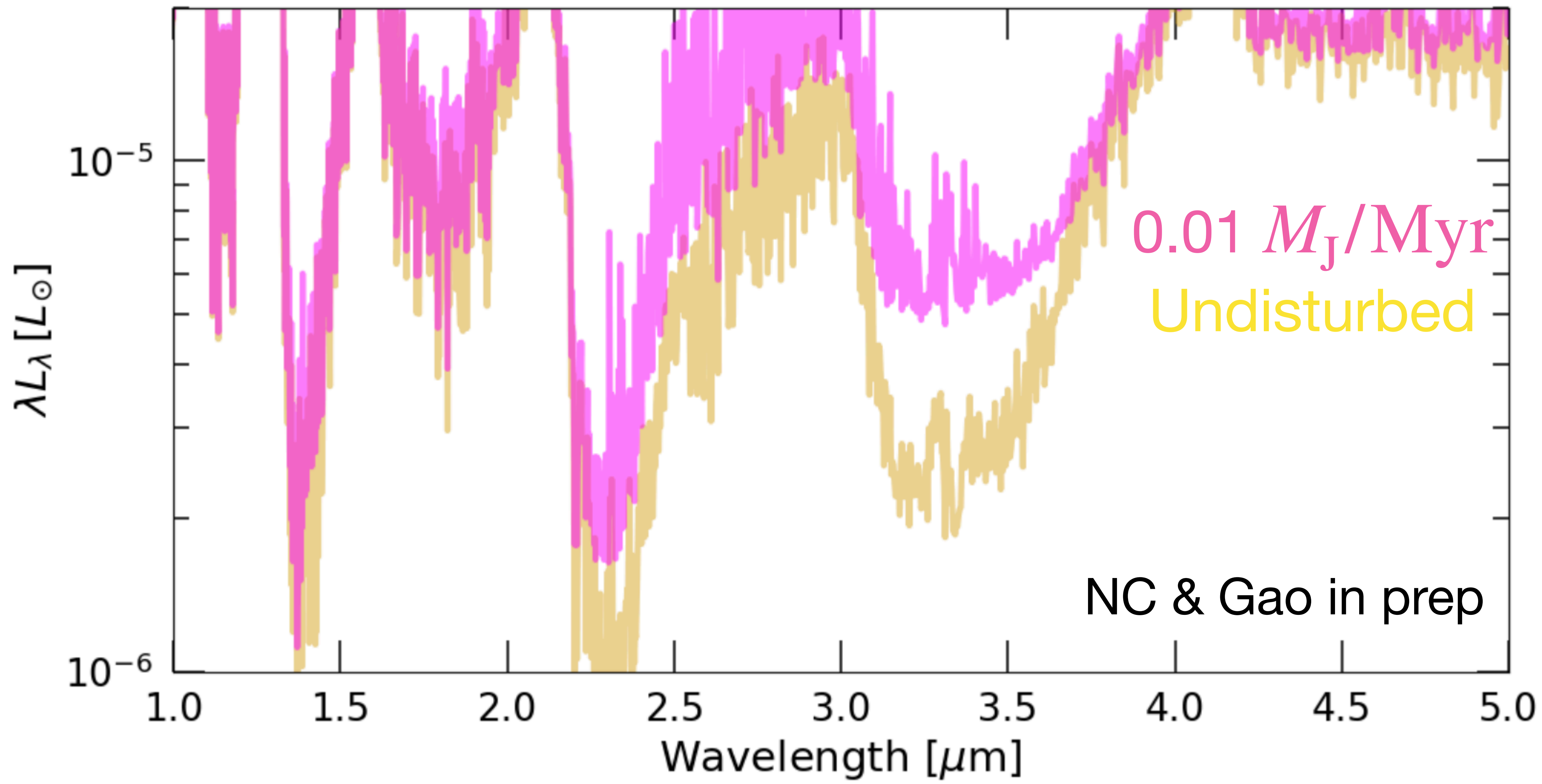
$$\min(t_{\rm double}) \equiv \frac{M_{\rm p}}{\dot{M}_{\rm inflow}}$$

new scalings + gap densities from CO

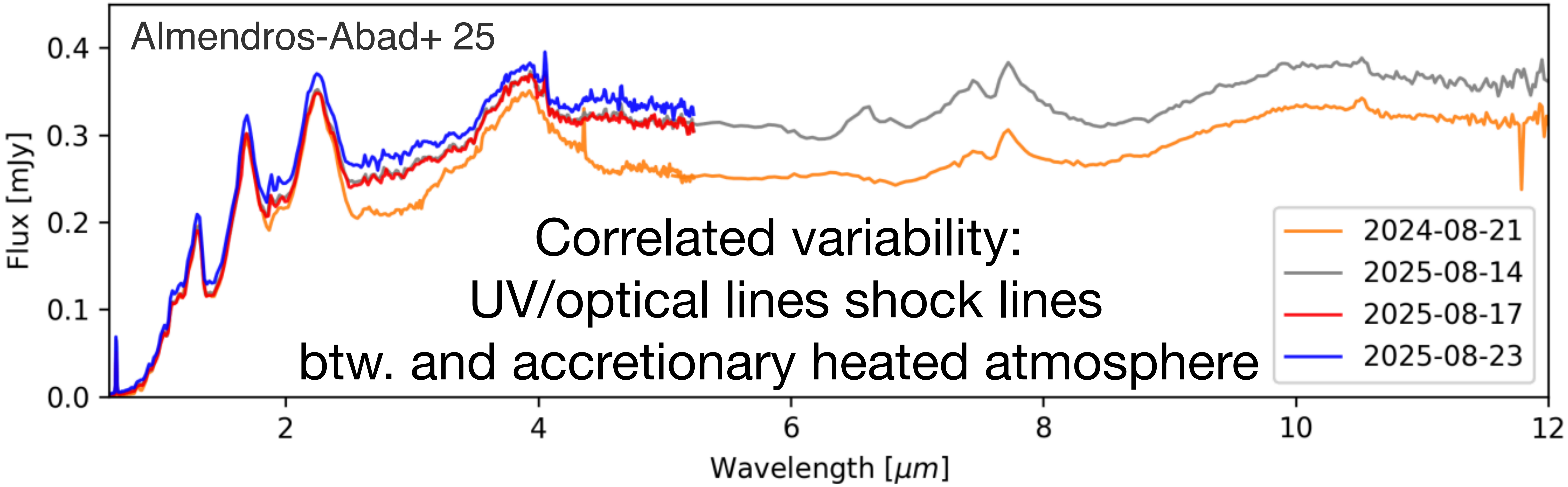
NC & Chiang 22, NC+ 23

ACCRETIONALLY HEATED ATMOSPHERES

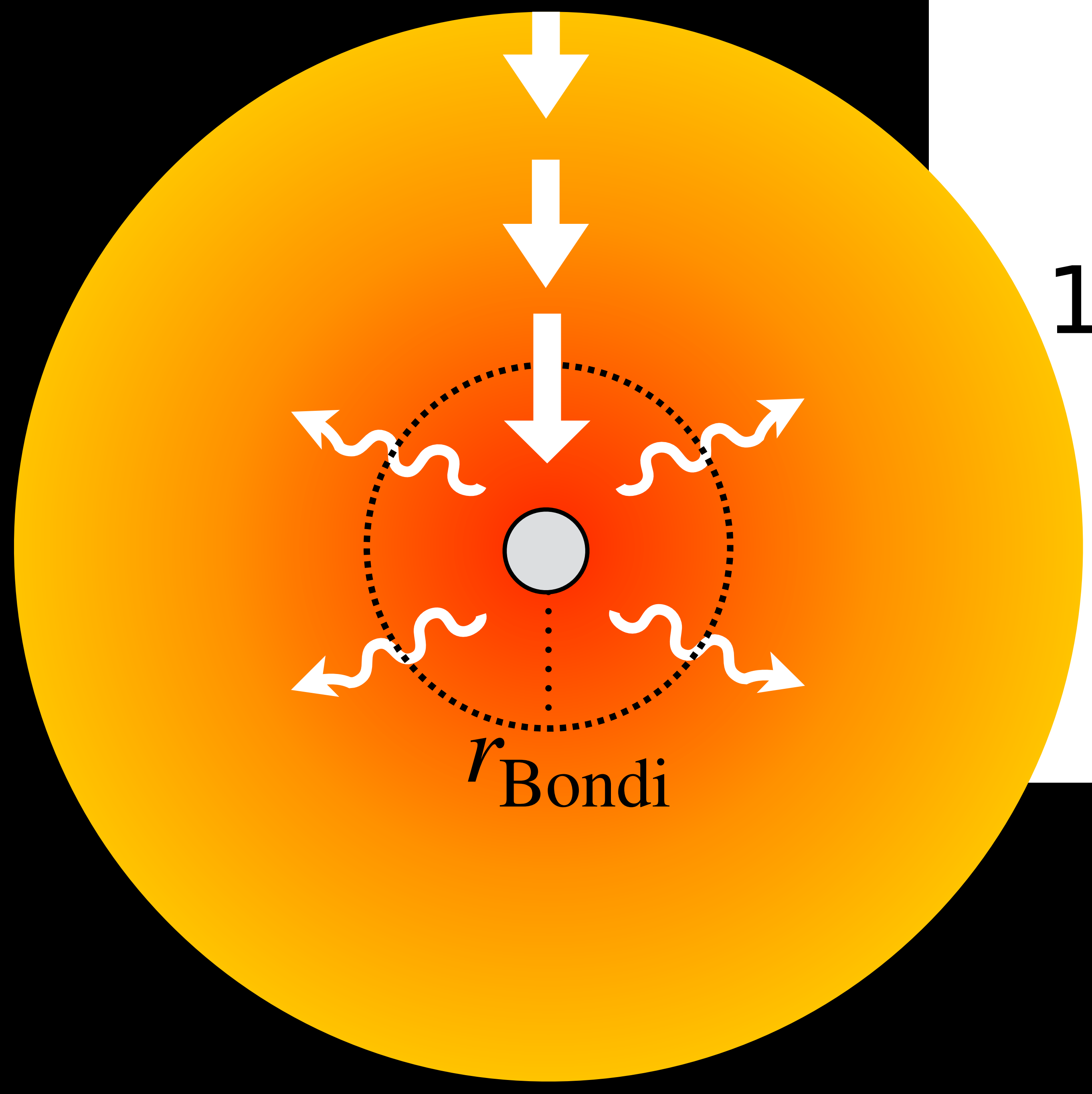




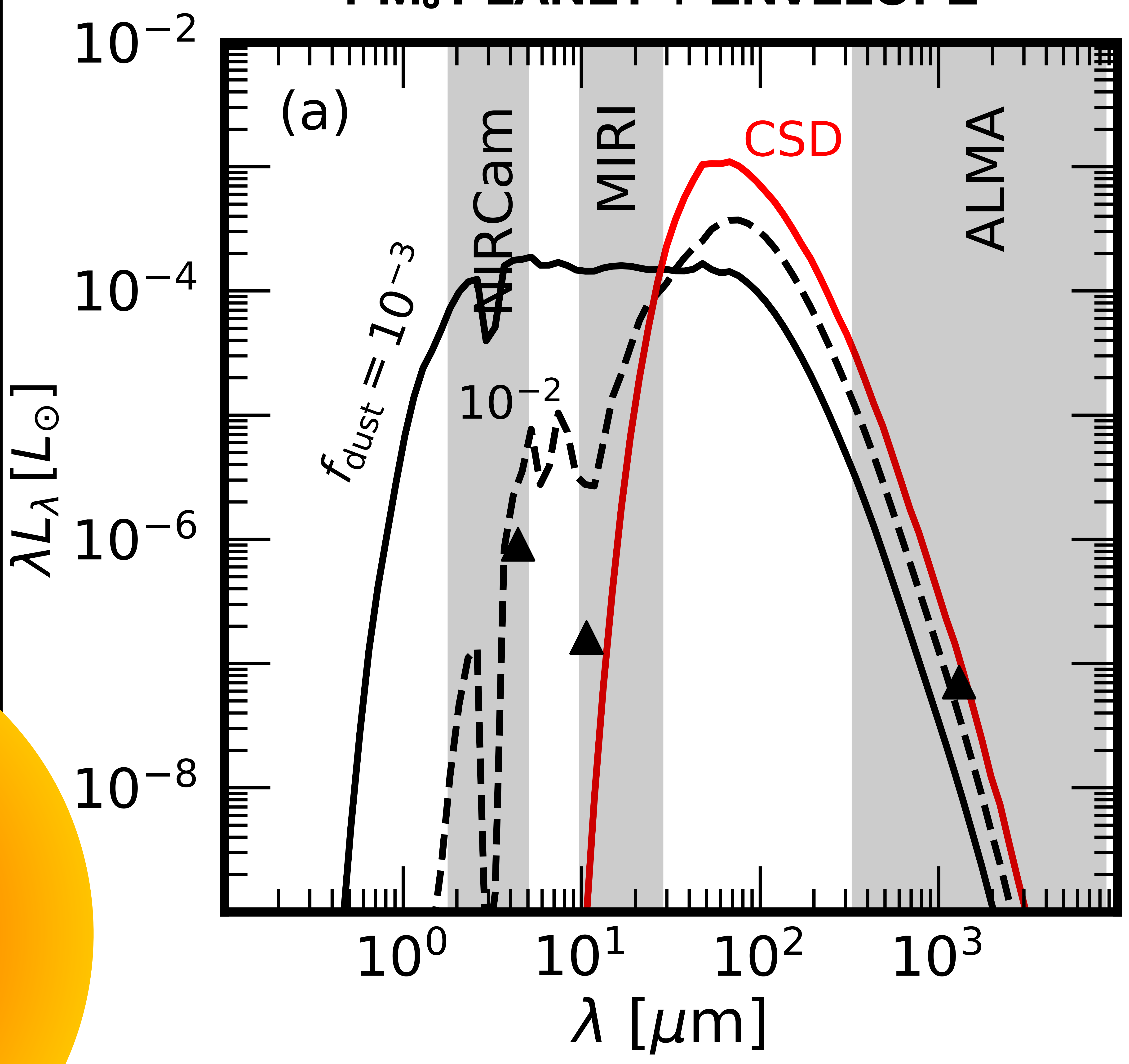
Elevated NIR continuum from an accreting brown dwarf

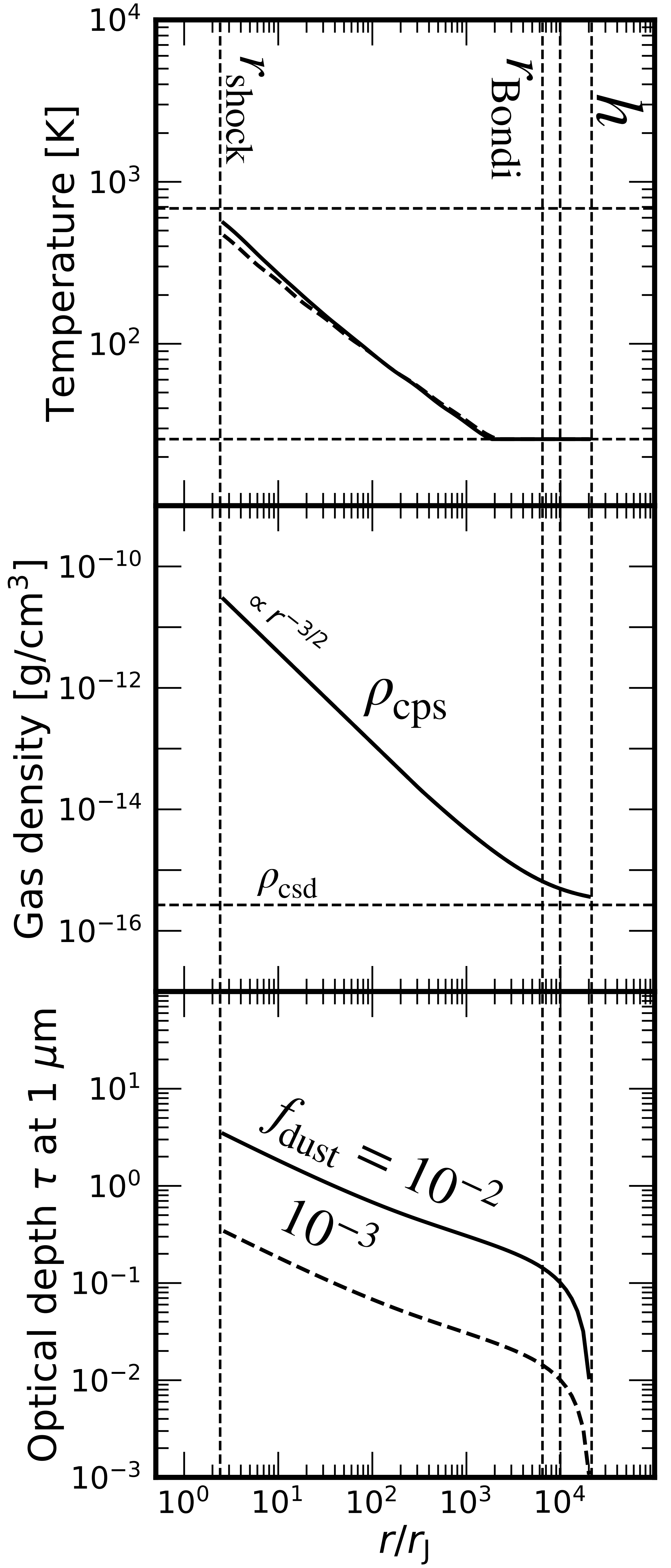


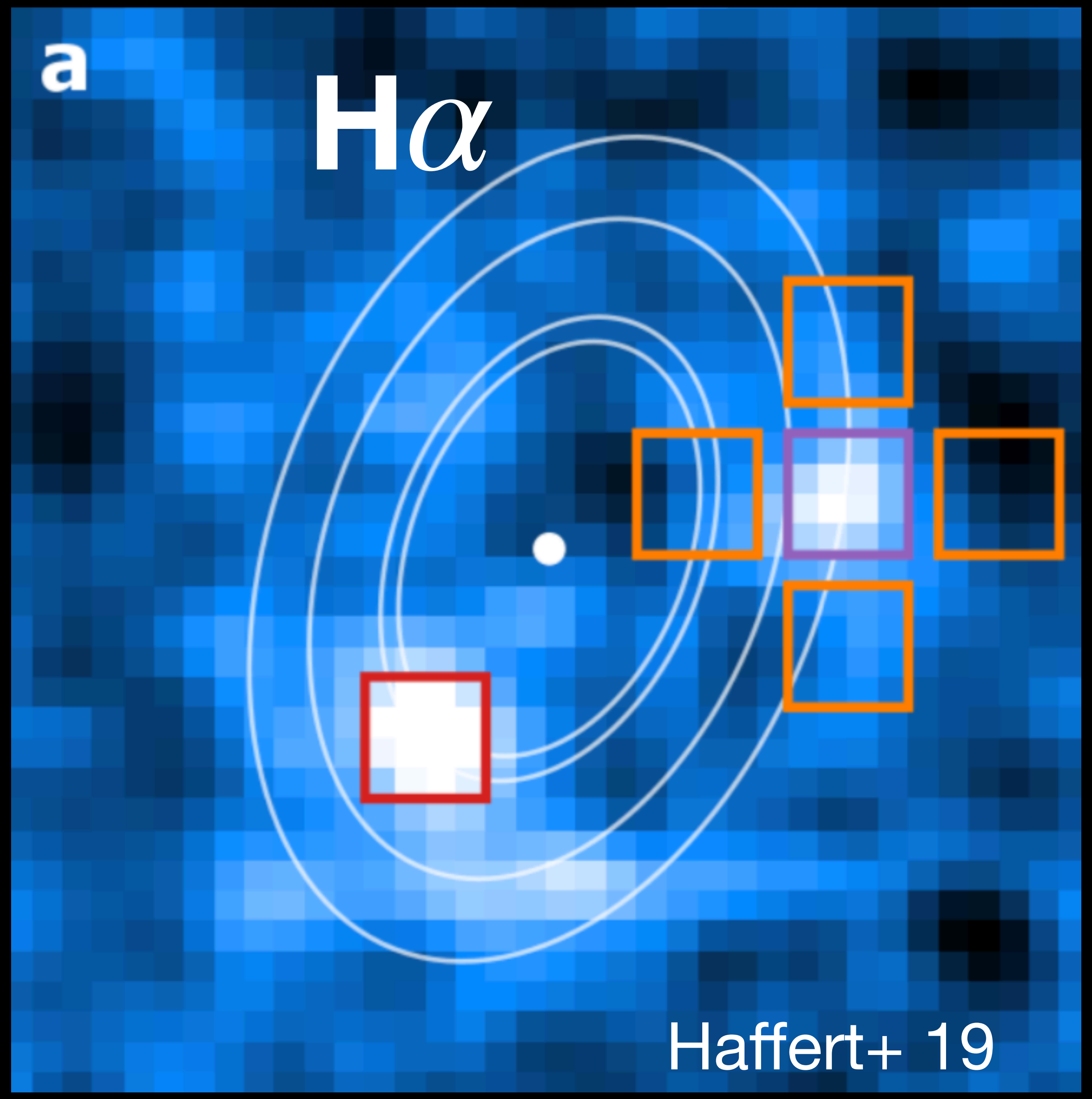
REPROCESSING BY DUSTY CIRCUM-PLANETARY ENVELOPES

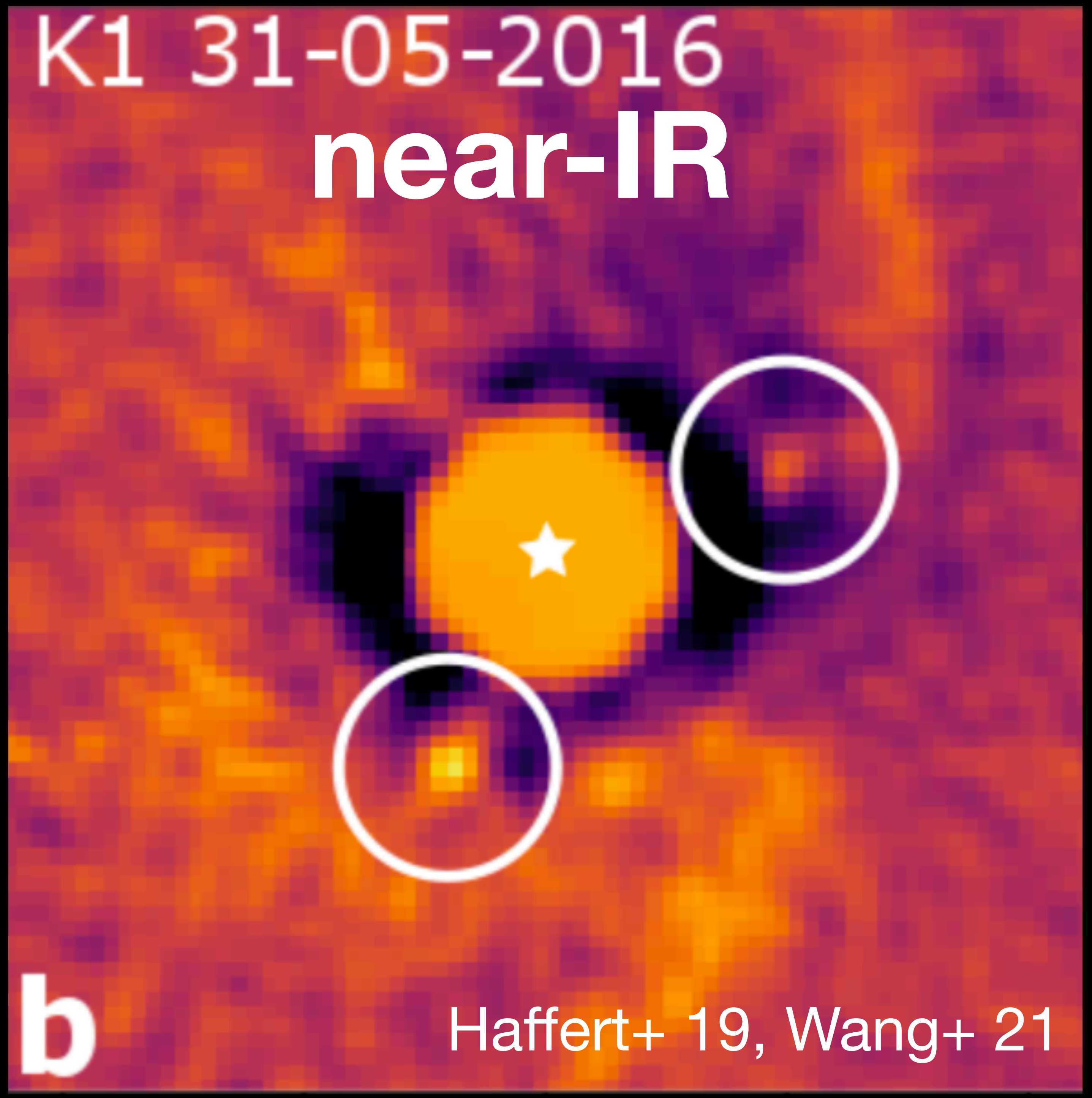


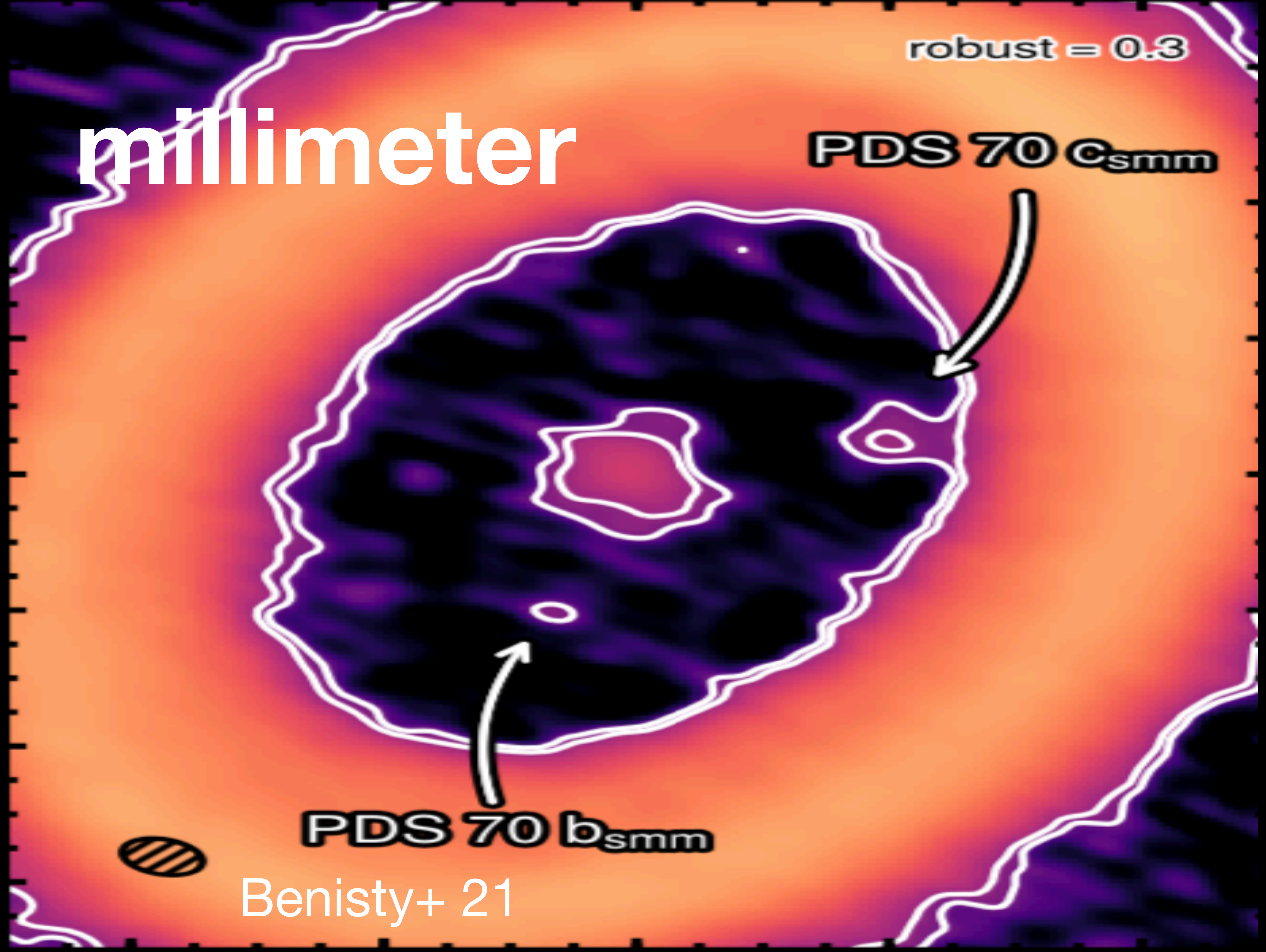
1 M_J PLANET + ENVELOPE











PDS 70 across the spectrum

two giant planets in a disk gap

$M_p \sim 1 - 10 M_J$

from cavity size, SED, and dynamical stability

Bae+ 19, Ginzburg & Chiang 19, Toci+ 20, Wang+ 21

(1) $\langle \dot{M}_p \rangle \sim 3M_J/5\,\text{Myr}$
$\sim 0.6\,M_J/\text{Myr}$

---

(2) $\max \dot{M}_p \sim r_{\text{Hill}} h \times (3/2)\Omega r_{\text{Hill}} \times \rho$
$\sim 1\,M_J/\text{Myr}$

---

(3) $\dot{M}_p \sim L_{\text{bol}} 4R_J/(G \times 3M_J)$
$\sim 1\,M_J/\text{Myr}$

NC & Chiang 22, NC+ 23