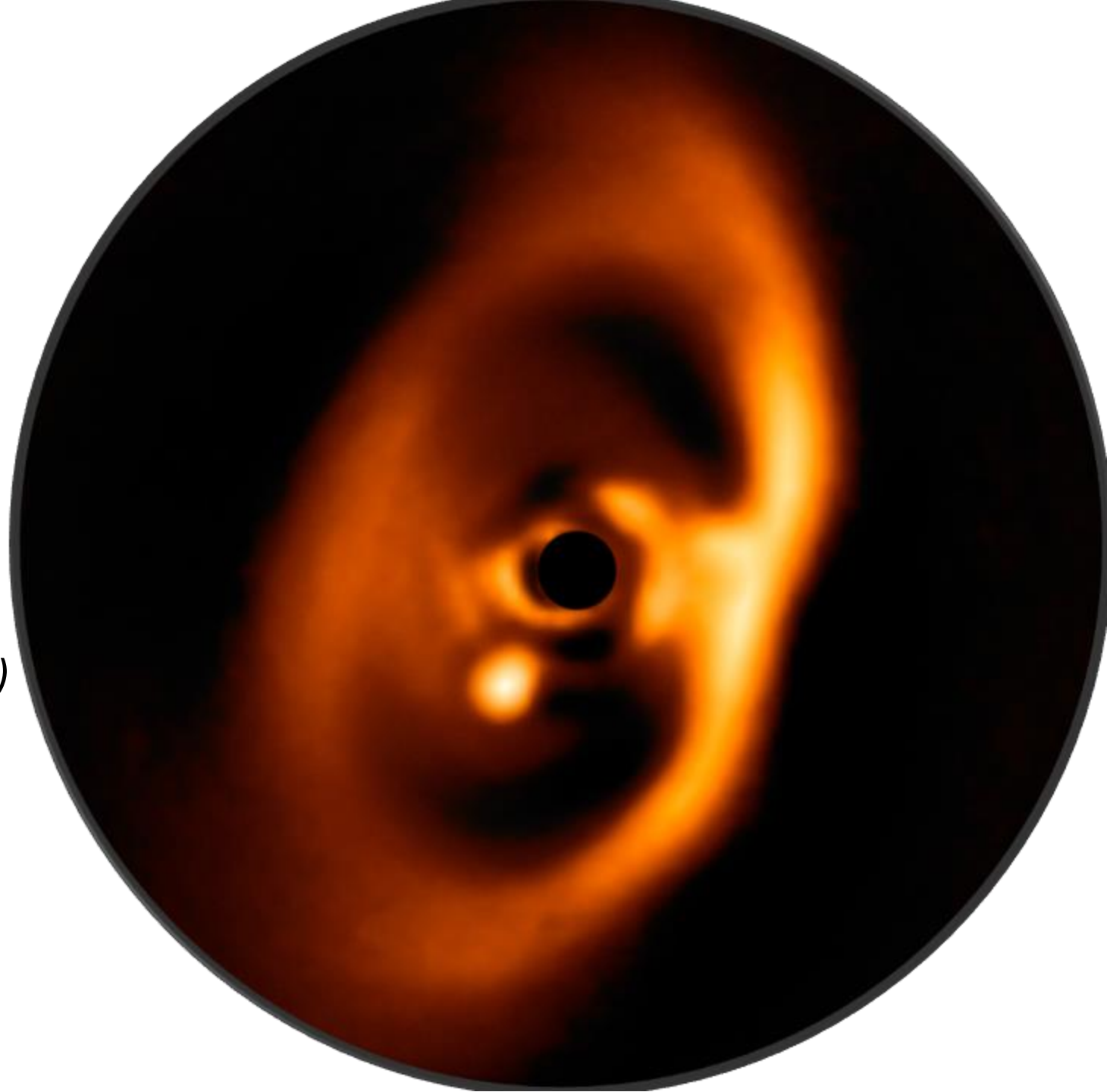


Differentiating **Hot/Cold-Start** for the PDS 70 Planets with New **Dynamical Masses**

*Presenter: David Trevascus
(Max Planck Institute for Astronomy)*

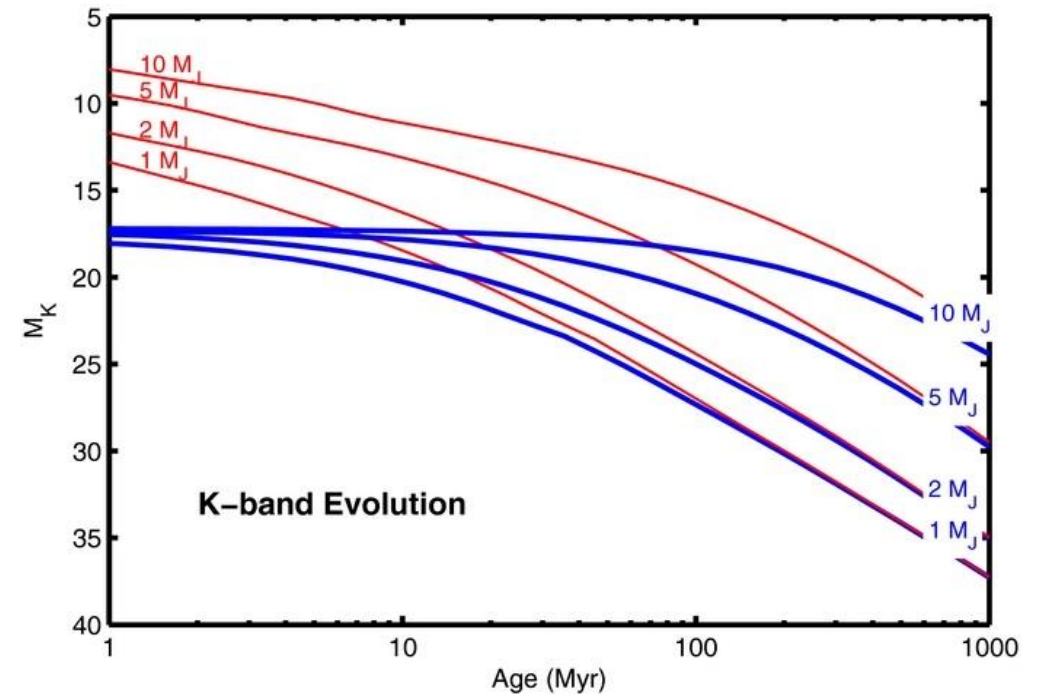


Image: Müller et al. (2018)



Hot vs Cold Start Formation

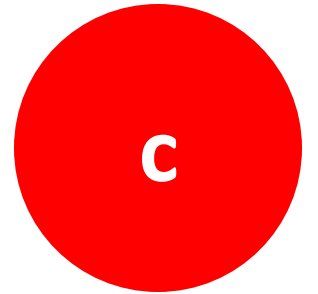
- Gas accretes onto planets and loses heat through shocks/radiation
- **Hot-start**: Gas retains energy, planet is brighter
- **Cold-start**: Gas radiates away energy, planet is dimmer
- **This impacts how many planets are visible via direct imaging**



Spiegel & Burrows (2012)

PDS 70

- Young (5.4 ± 1.0 Myr) system with protoplanetary disk
- 2 confirmed directly-imaged (giant) planets



How do we differentiate between hot/cold-start?

We need:

PDS 70

Age

5.4 ± 1.0 Myr (Müller+ 2018)

Luminosity

$\sim 10^{-4} L_{\text{Sun}}$ (Wang+ 2020)

Mass

Poorly constrained!

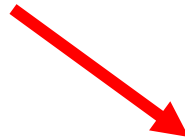
Previously: Wang+ (2021)

$$M_b < 10 M_{\text{Jup}}$$

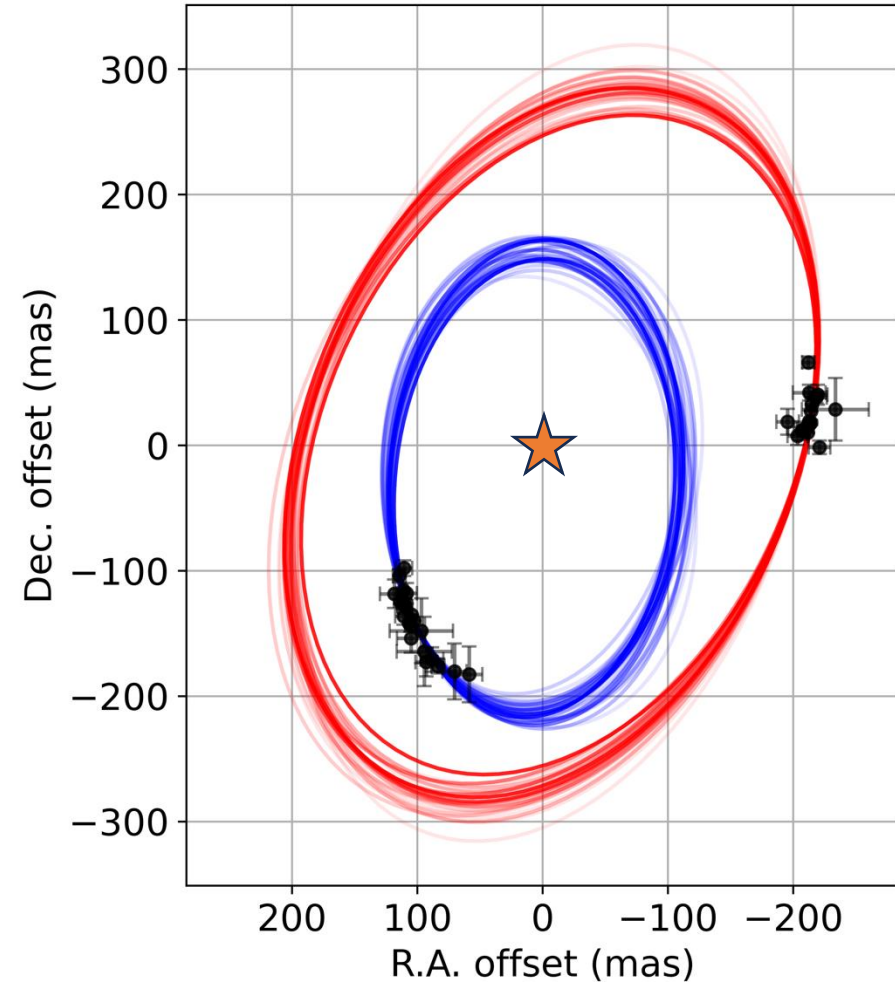
$$M_c < ?$$

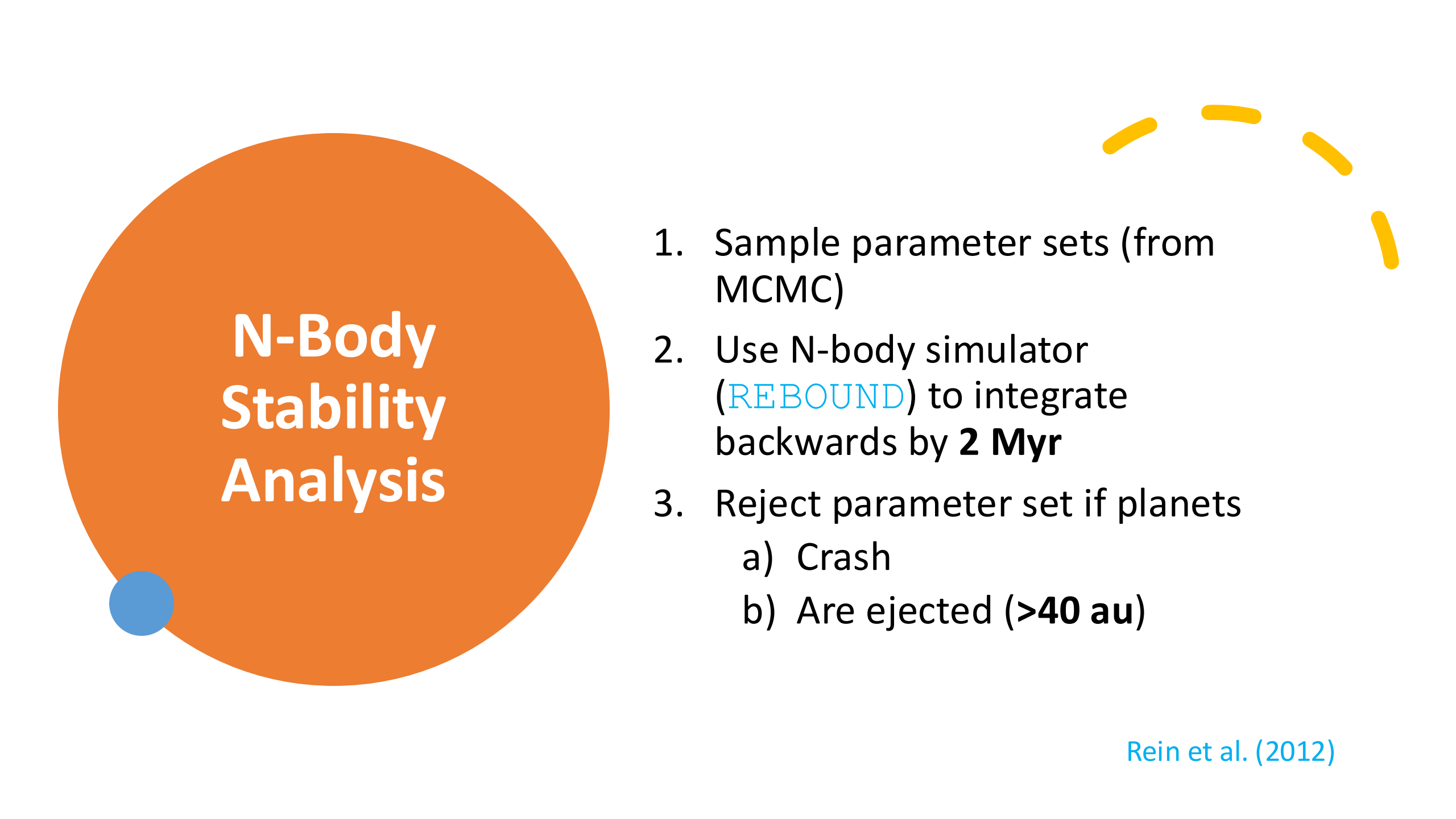
Astrometry to Dynamical Masses

~0.5 mas resolution!



- New astrometry from VLTI/GRAVITY
- Fit orbit parameters using MCMC with `orbitize`
 - Fits **dynamical masses** by modelling planet-star interactions

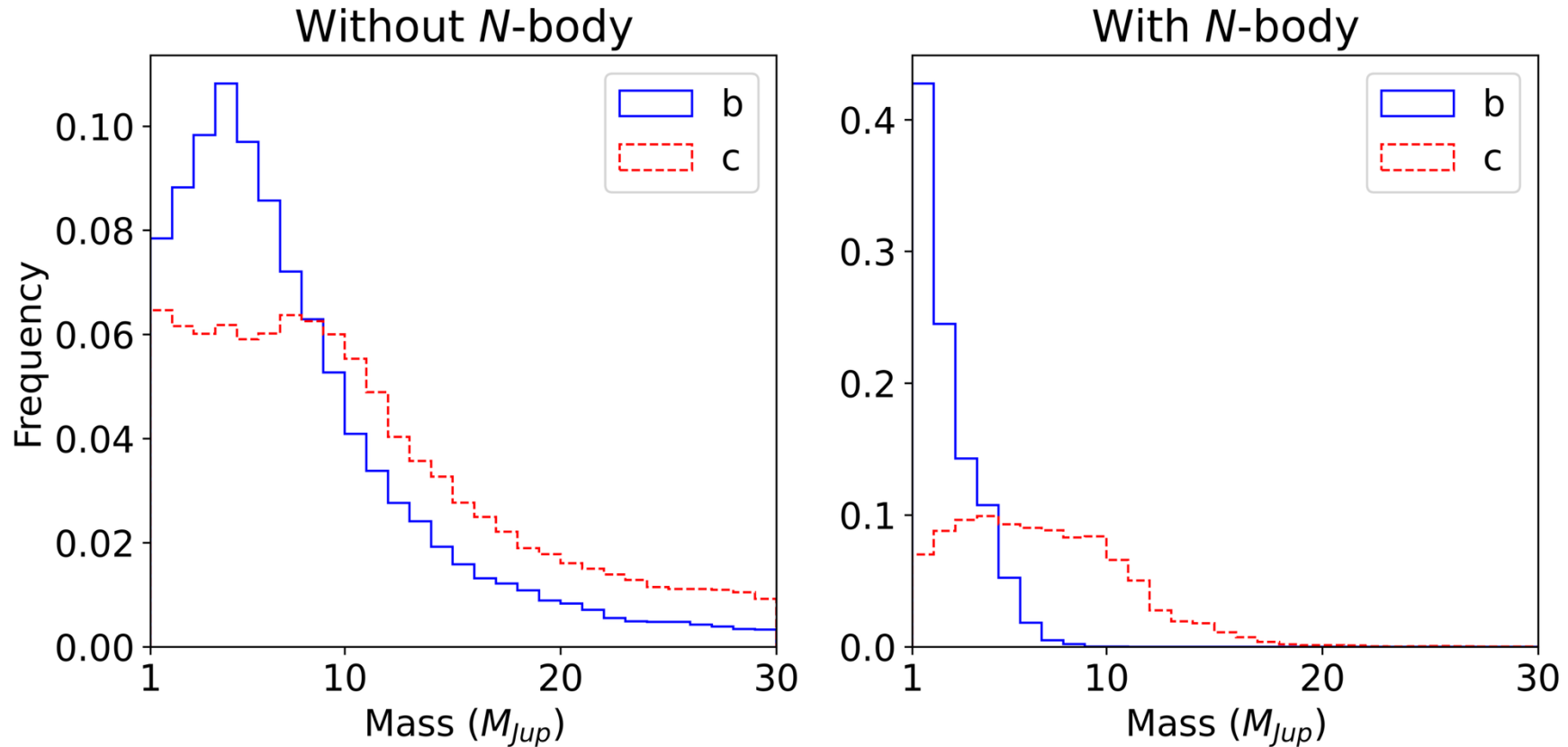




N-Body Stability Analysis

1. Sample parameter sets (from MCMC)
2. Use N-body simulator ([REBOUND](#)) to integrate backwards by **2 Myr**
3. Reject parameter set if planets
 - a) Crash
 - b) Are ejected (**>40 au**)

New Upper Mass Limits for PDS 70 *b* & *c*



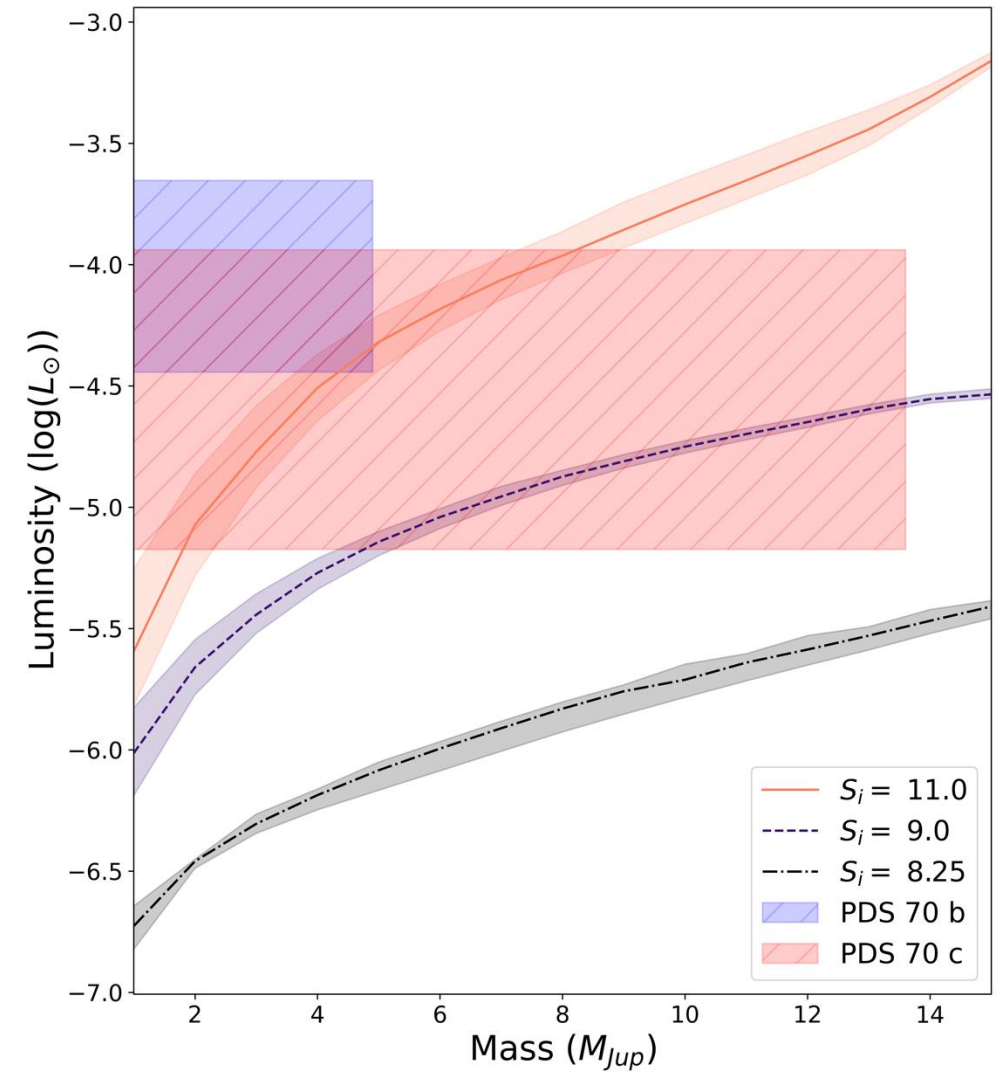
95% Confidence Upper Mass Limits:

$$M_b < 4.9 M_{Jup}$$

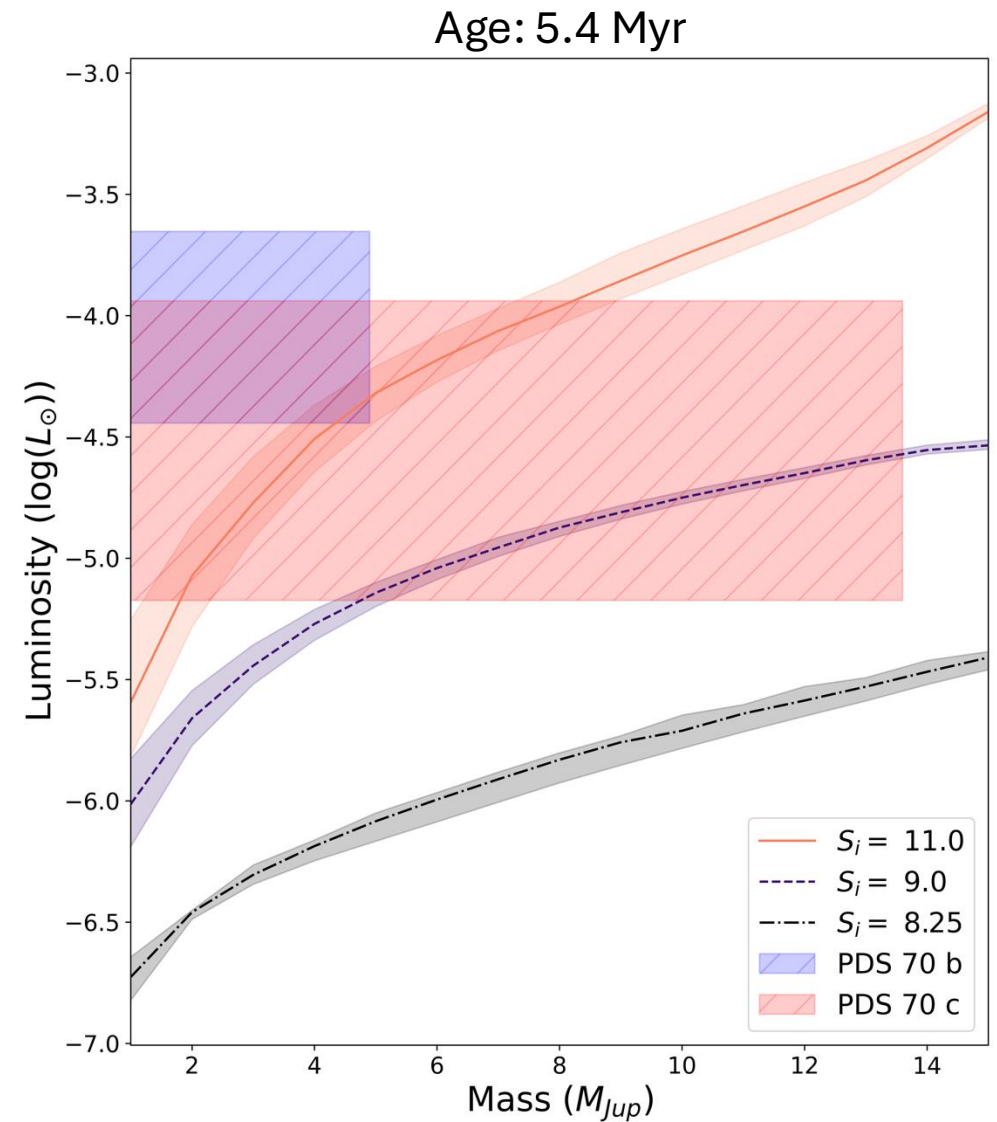
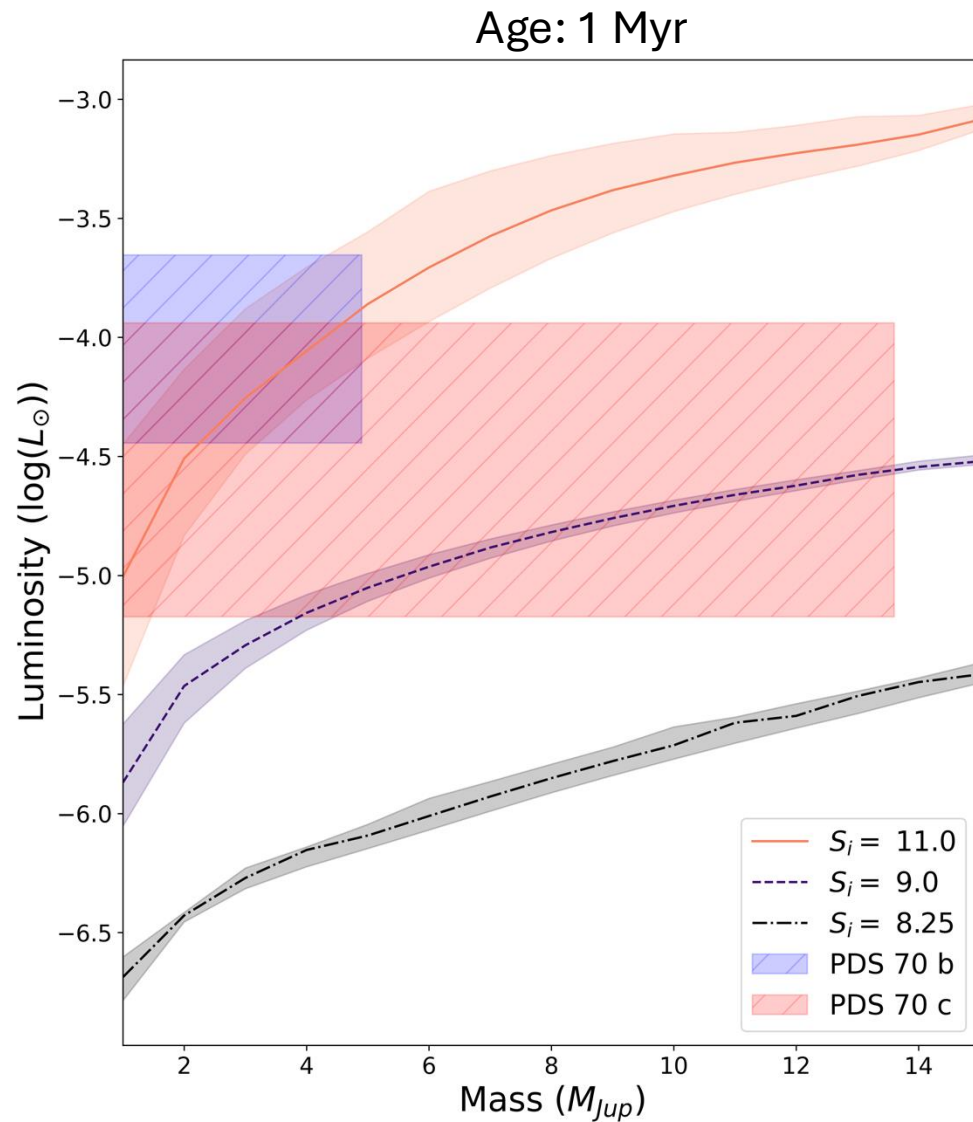
$$M_c < 13.6 M_{Jup}$$

PDS 70 *b* & *c* are Hot/Warm-start!

We compare mass and luminosity to models from Spiegel & Burrows (2012) at the age of PDS 70 (5.4 ± 1.0 Myr).



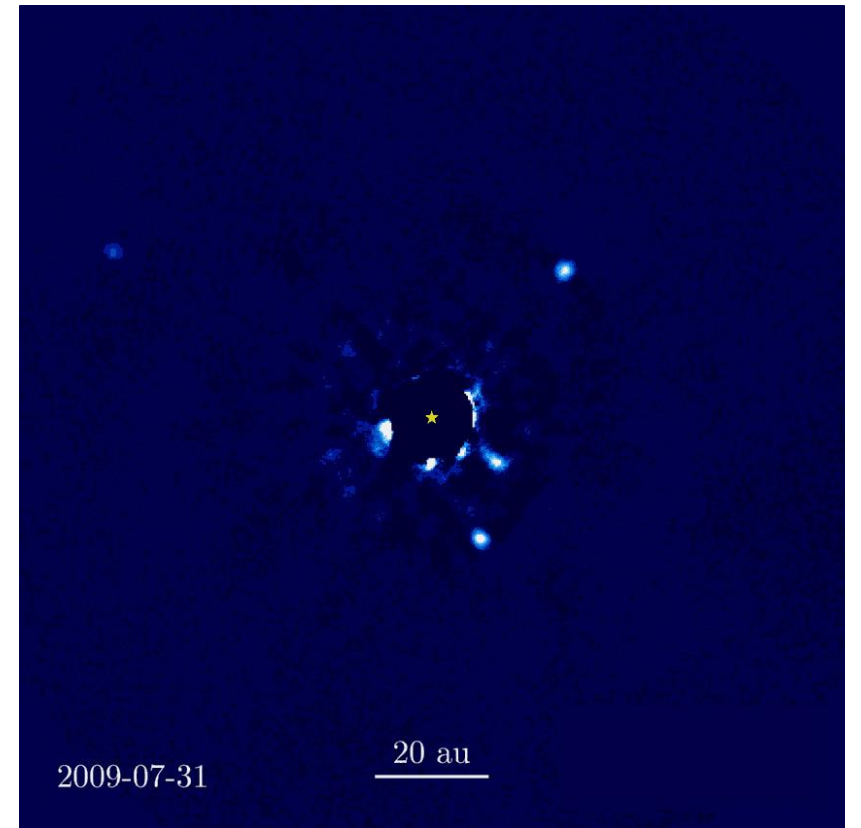
What if the planets are younger than the star?



Are hot-start planets normal?

Most directly imaged planets are hot/warm-start:

- HR 8799 planets (Marleau & Cumming, 2014)
- Beta Pic b (Marleau & Cumming, 2014)
- Beta Pic c (Brandt et al, 2021)



*HR 8799 Planets
Image: Jason Wang, Christian Marois*

New VLTI/GRAVITY+ Observations!

- New astrometry for PDS 70 *b* and *c*
- GRAVITY observations (2019-25) :
 - PDS 70 *b*: 5 epochs
 - PDS 70 *c*: 13 epochs

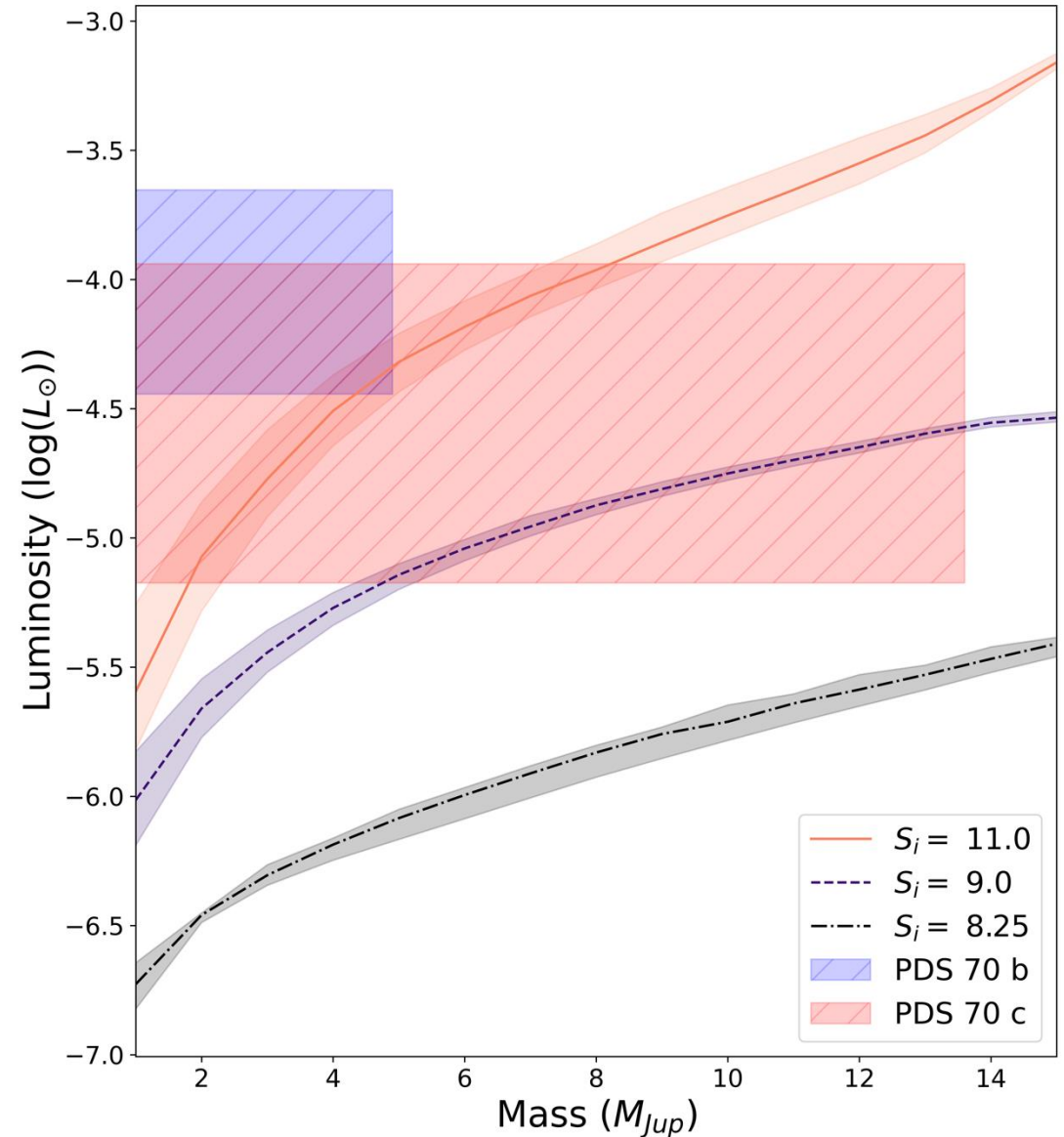


Take-Home Messages

- According to N-body stability analysis:
 - $M_b < 4.9 M_{Jup}$
 - $M_c < 13.6 M_{Jup}$
- PDS 70 b and c are both inconsistent with cold-start models



Scan the QR code for the full paper!



Orbit Fitting with PDS 70 d

