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

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ExoGRAVITY

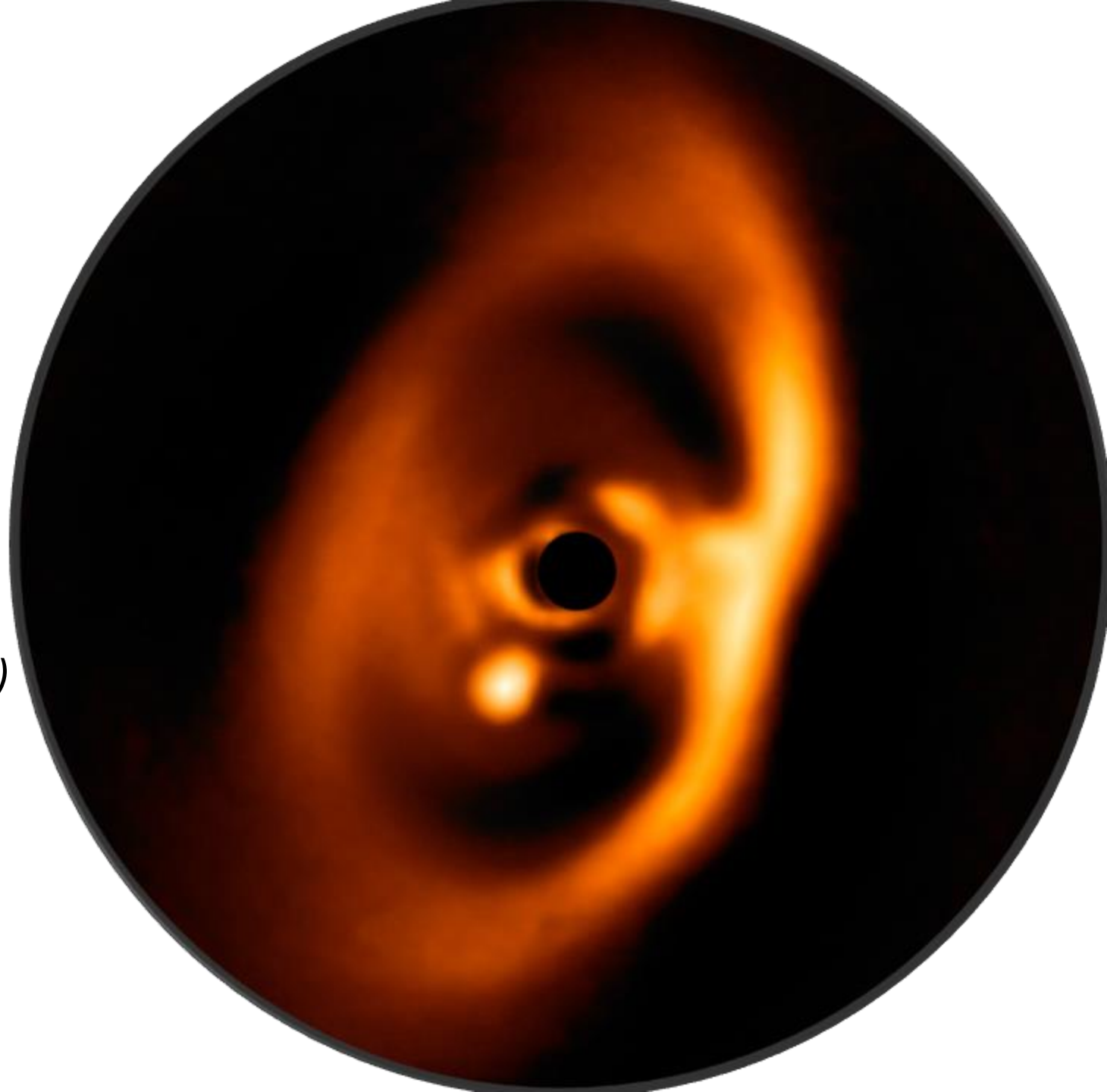
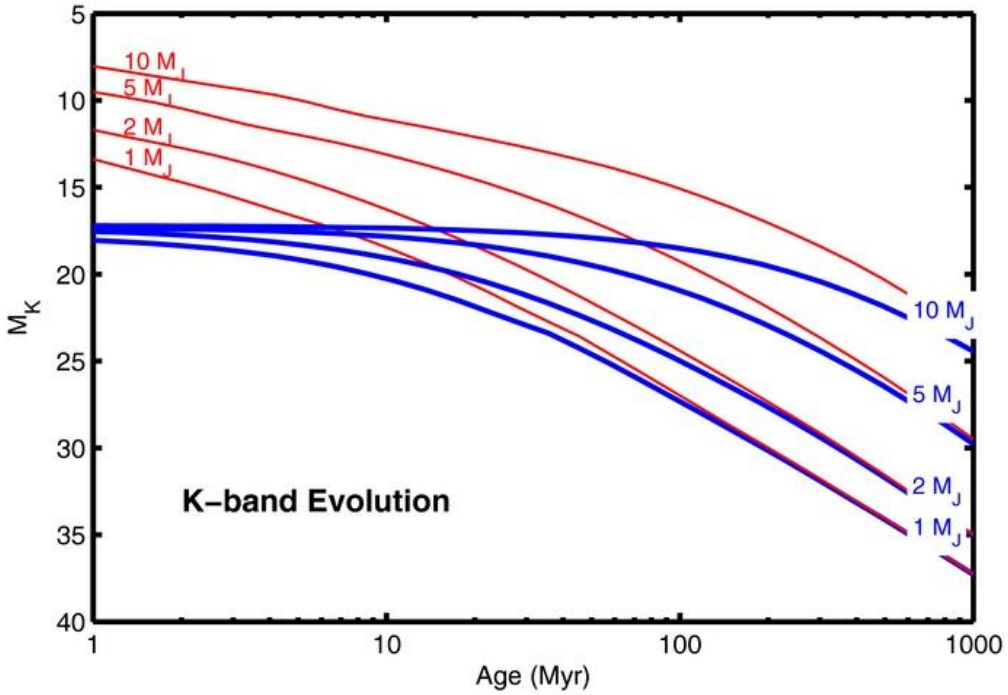


*Image: Müller et al. (2018)*

# 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 | ~$10^{-4}$ $L_{Sun}$ (Wang+ 2020) |
| *Mass* | ***Poorly constrained!*** |

**Previously: Wang+ (2021)**

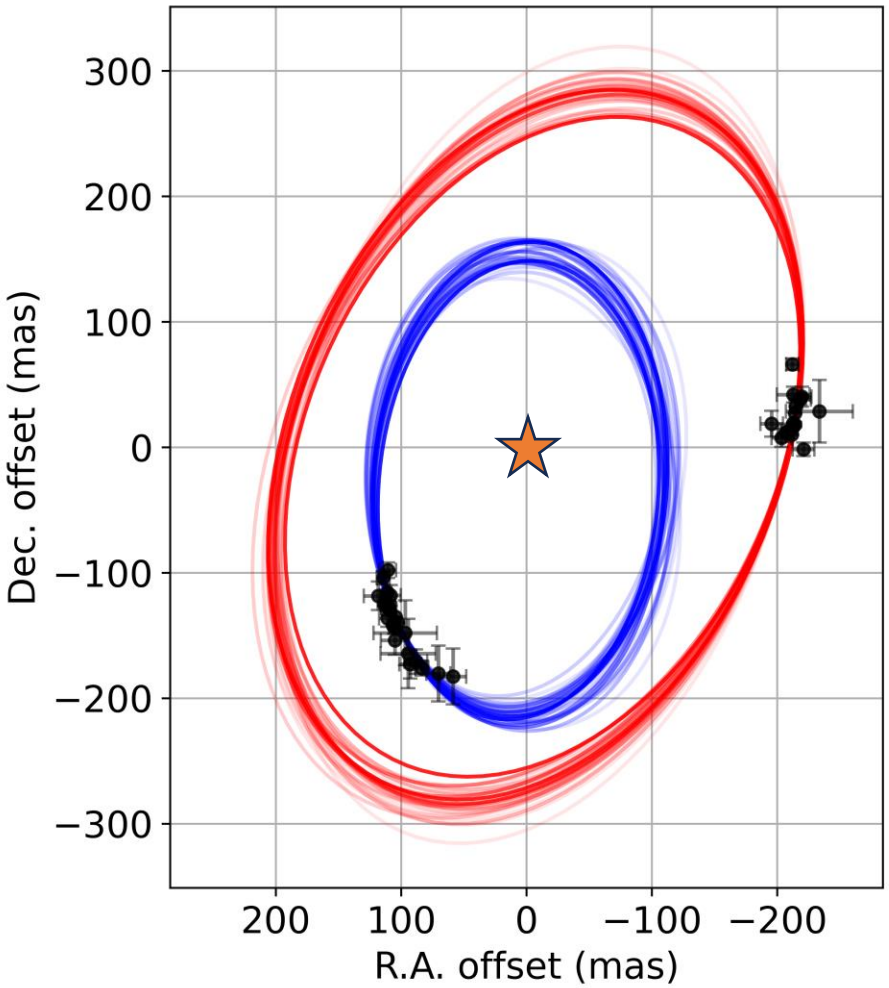
$\mathbf{M_b} < 10\ M_{Jup}$

$\mathbf{M_c} < ?$

# Astrometry to Dynamical Masses

**~0.5 mas resolution!**

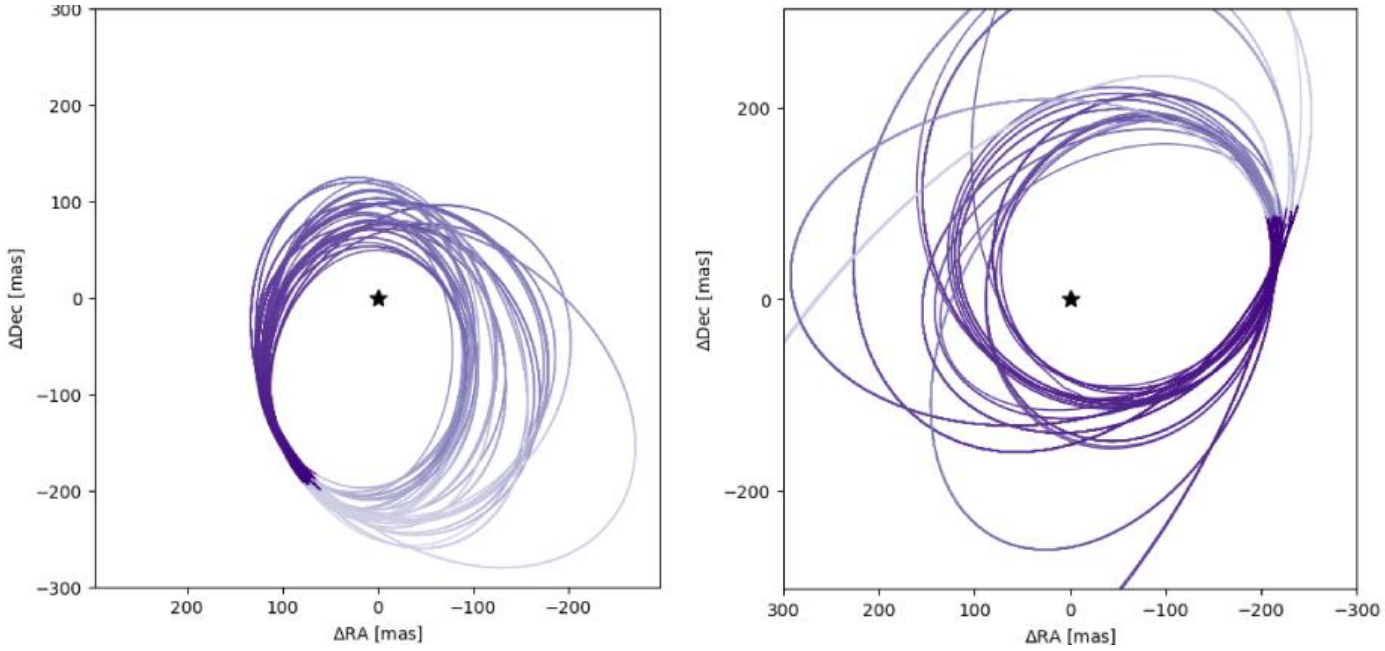
- New astrometry from VLTI/GRAVITY
- Fit orbit parameters using MCMC with `orbitize`
  - Fits **dynamical masses** by modelling planet-star interactions

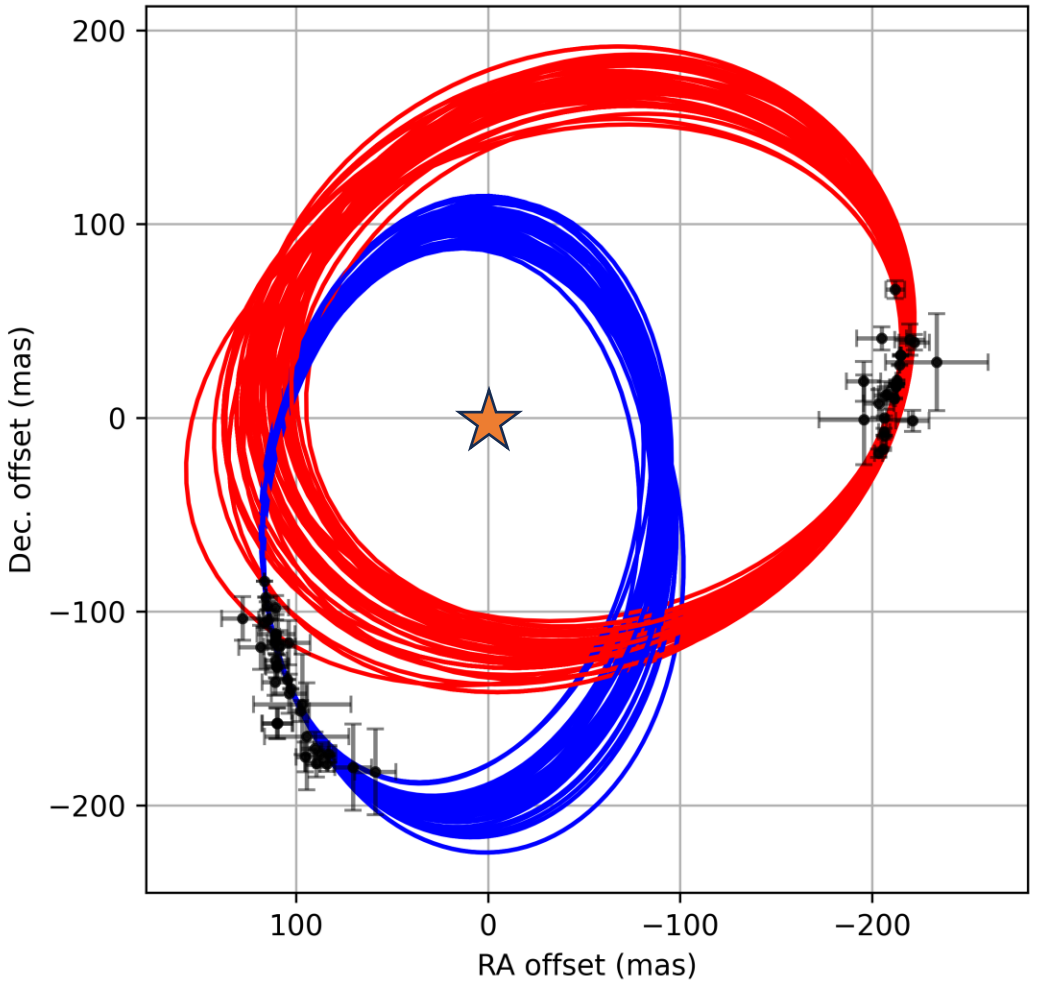



Blunt et al. (2019)

# Fitting Orbits for Long Period Planets

- ~100 yr periods vs 10 yr observations
- Need to enforce non-crossing orbits!




Wahhaj+ (2024)

# 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**)

Rein et al. (2012)

# Fitting Orbits for Long Period Planets

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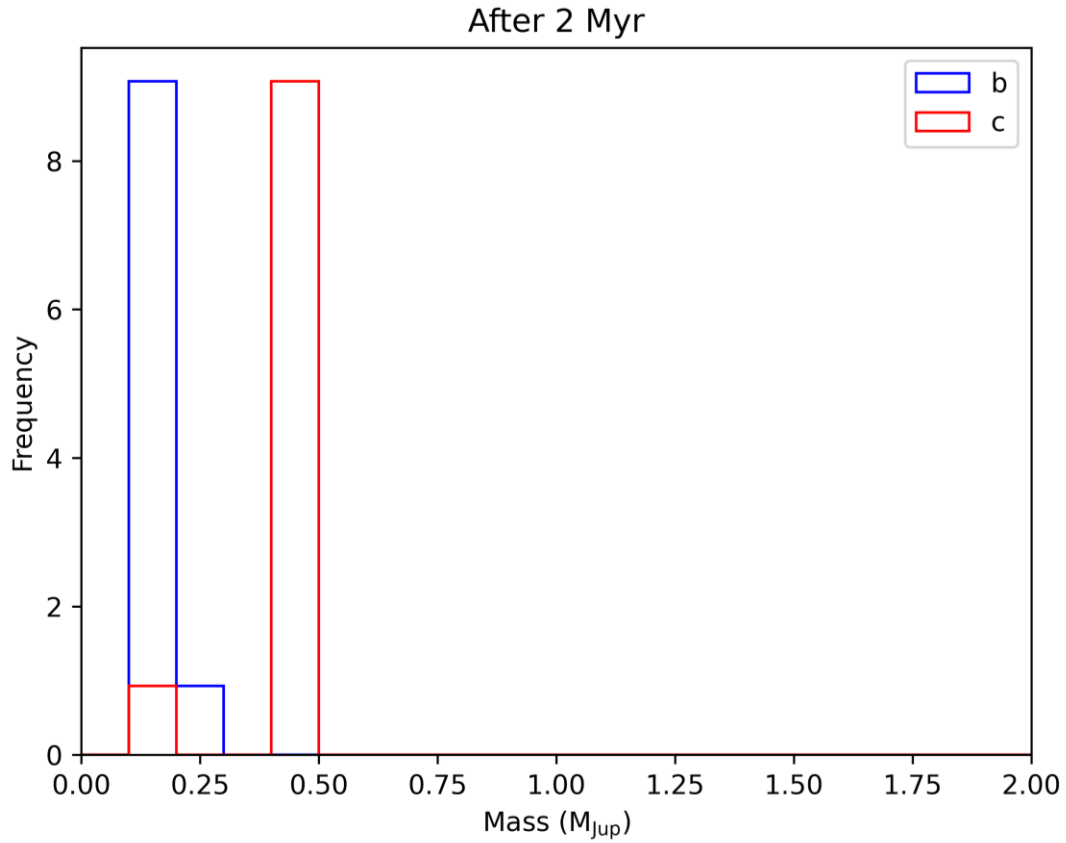
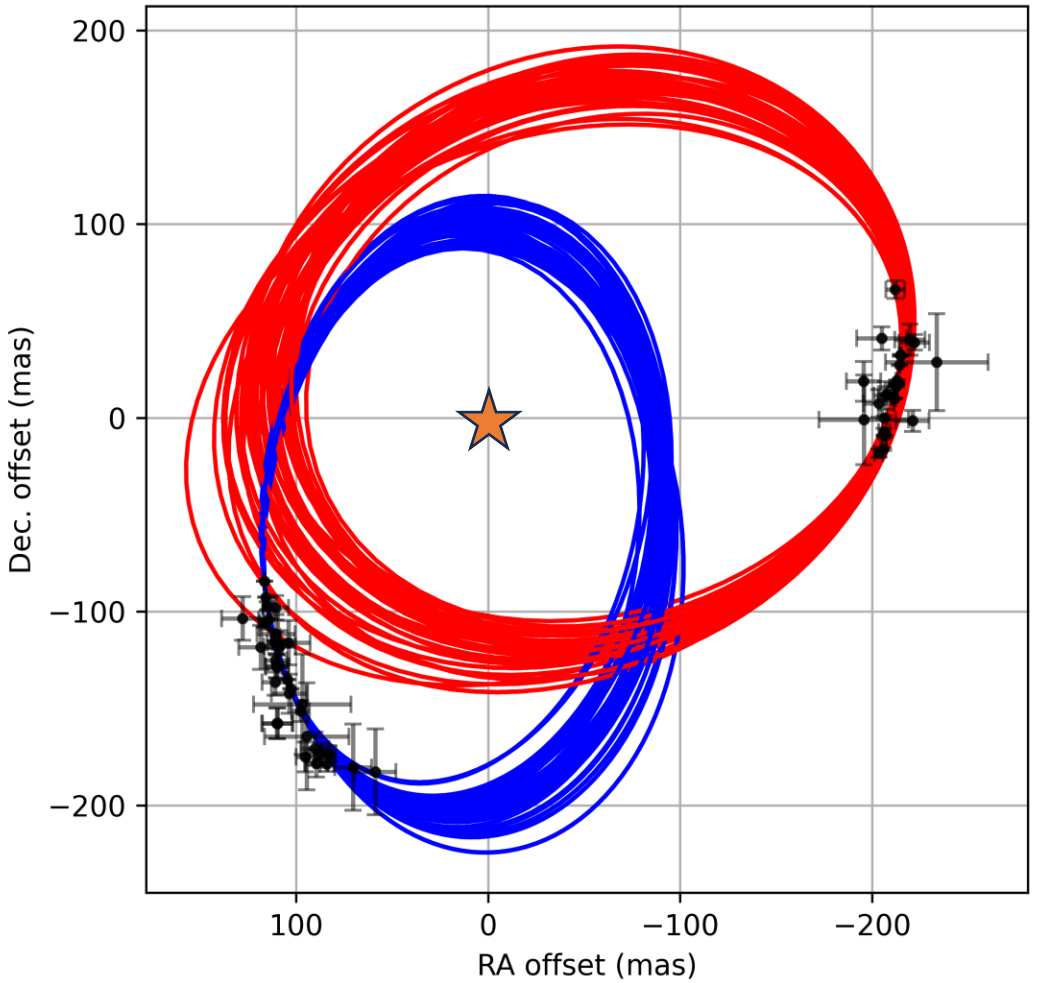
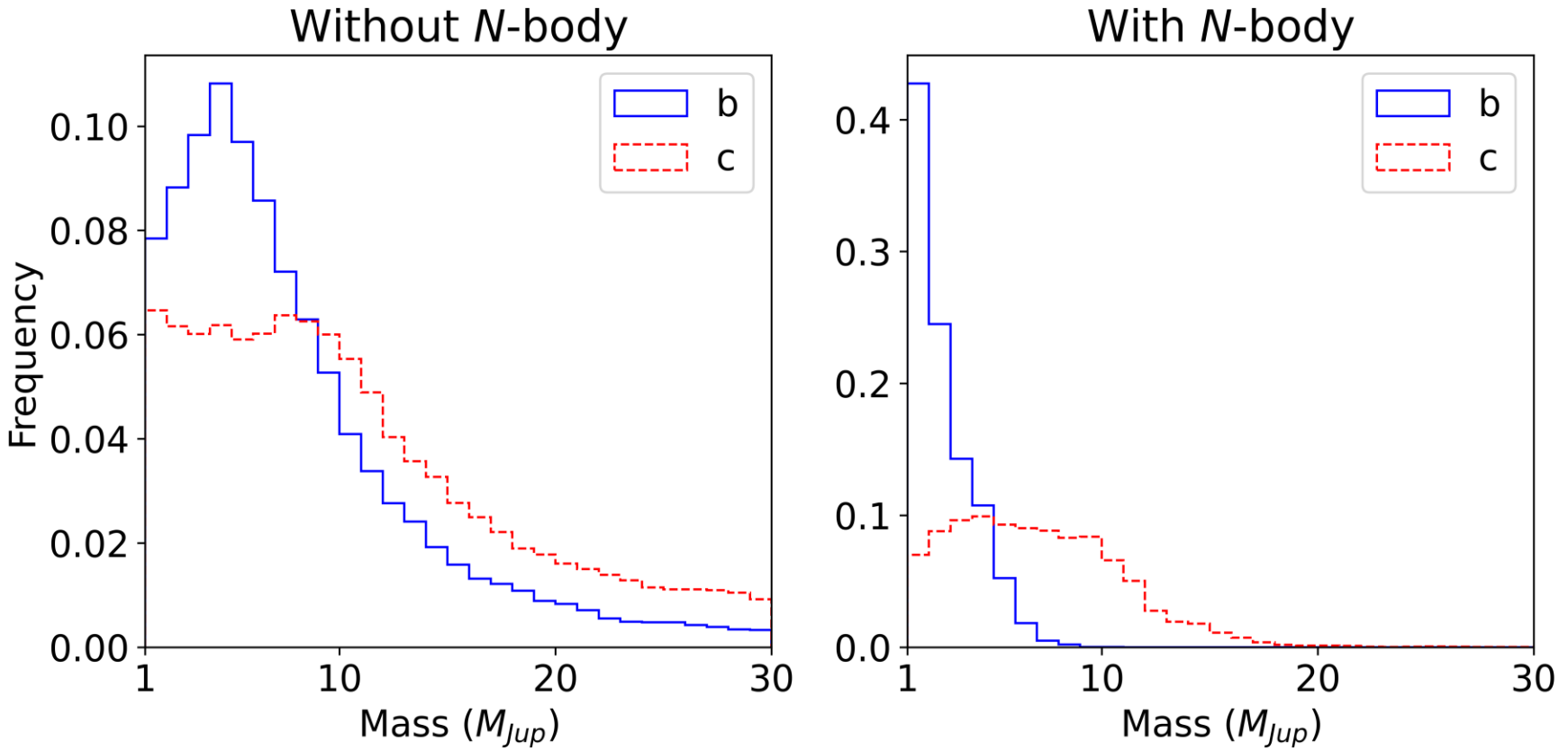


# New Upper Mass Limits for PDS 70 *b* & *c*

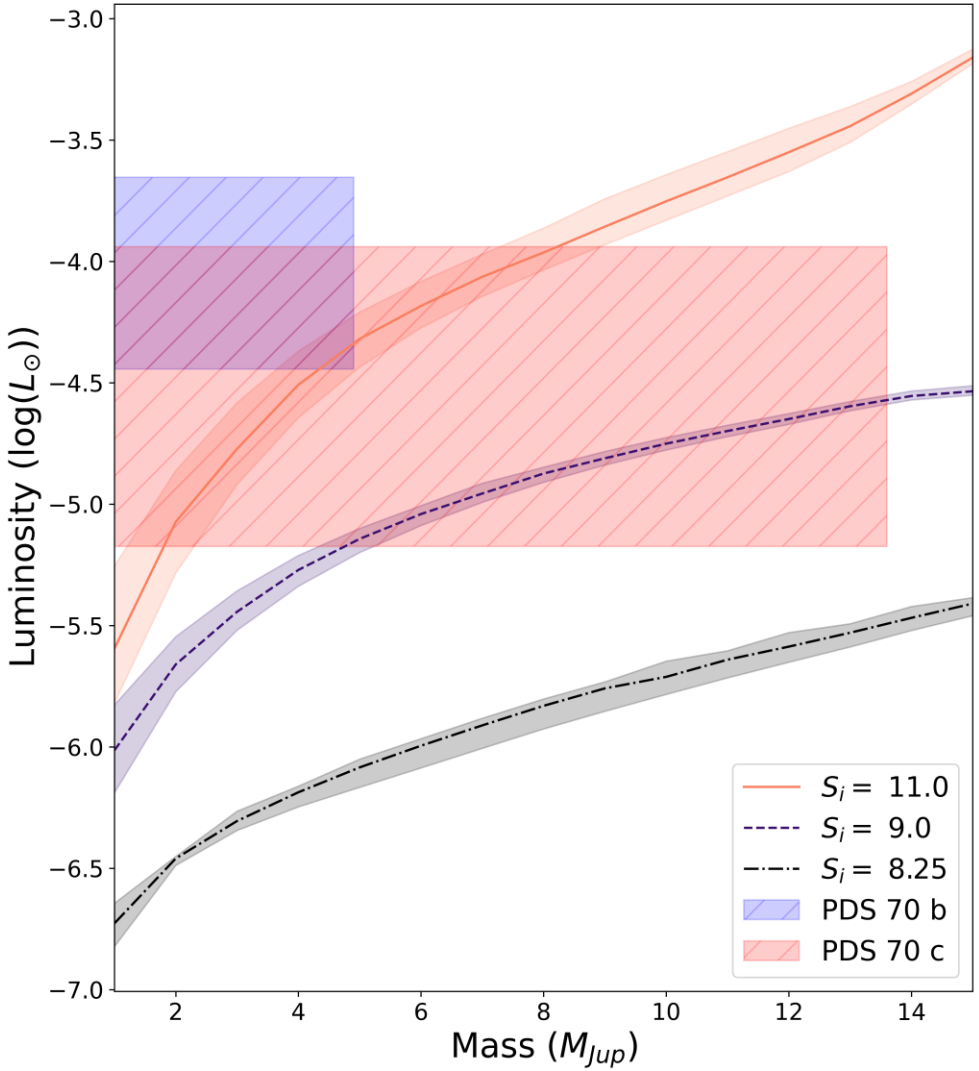



**95% Confidence Upper Mass Limits:**

$\mathbf{M_b} < 4.9\ M_{Jup}$ $\mathbf{M_c} < 13.6\ M_{Jup}$

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

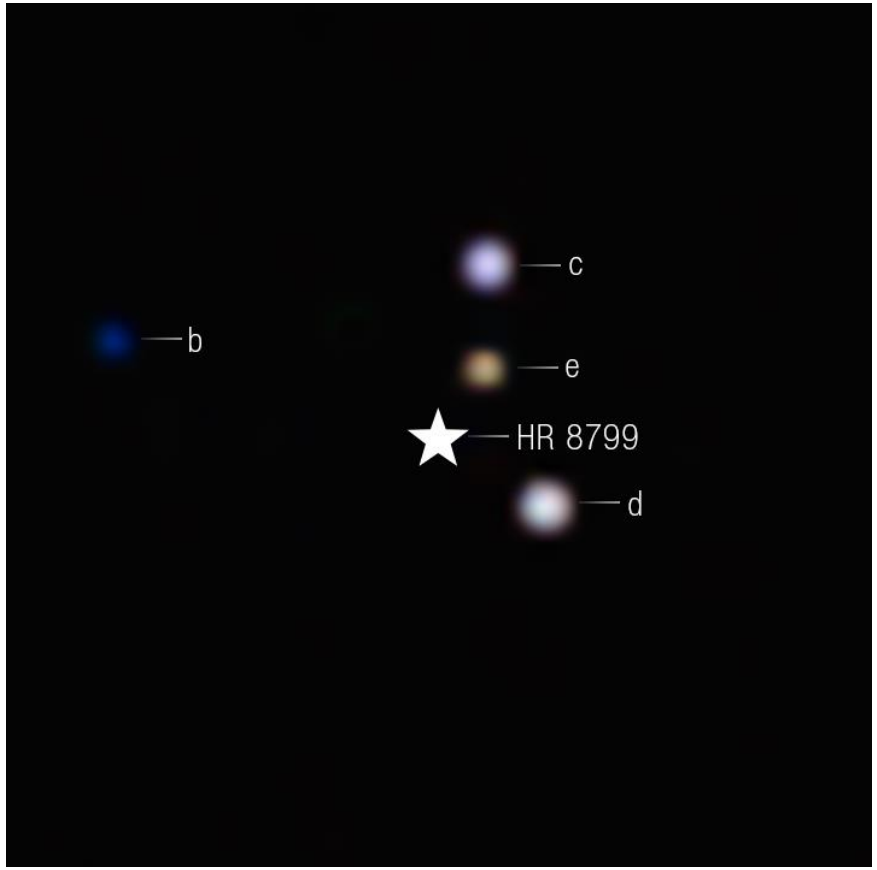
We compare mass and luminosity to models from Spiegel & Burrows (2012) at the age of PDS 70 (5.4 ± 1.0 Myr).

# 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)

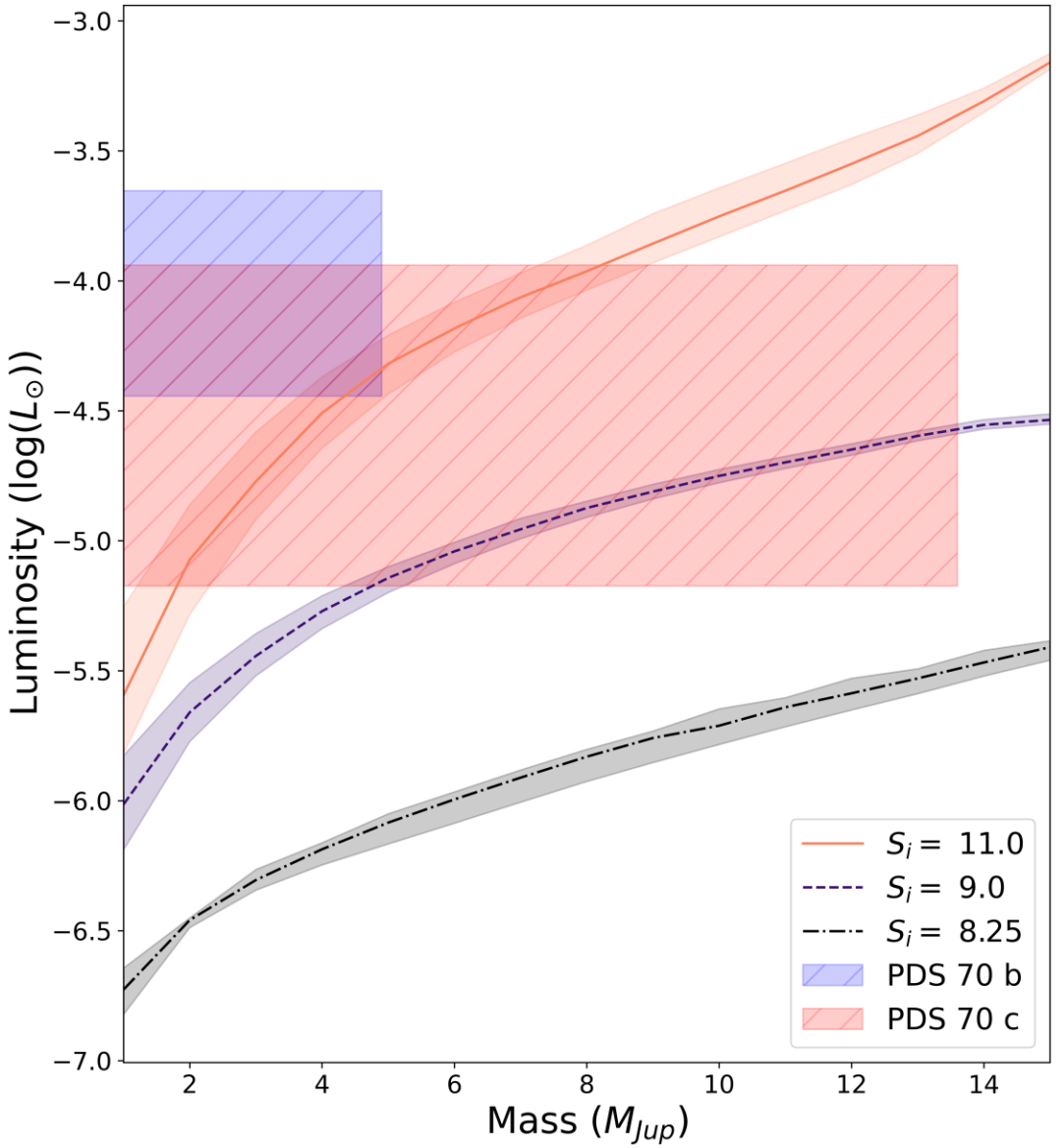



*HR 8799 Planets*
*Image: W. Balmer, L. Pueyo, M. Perrin*

# Take-Home Messages

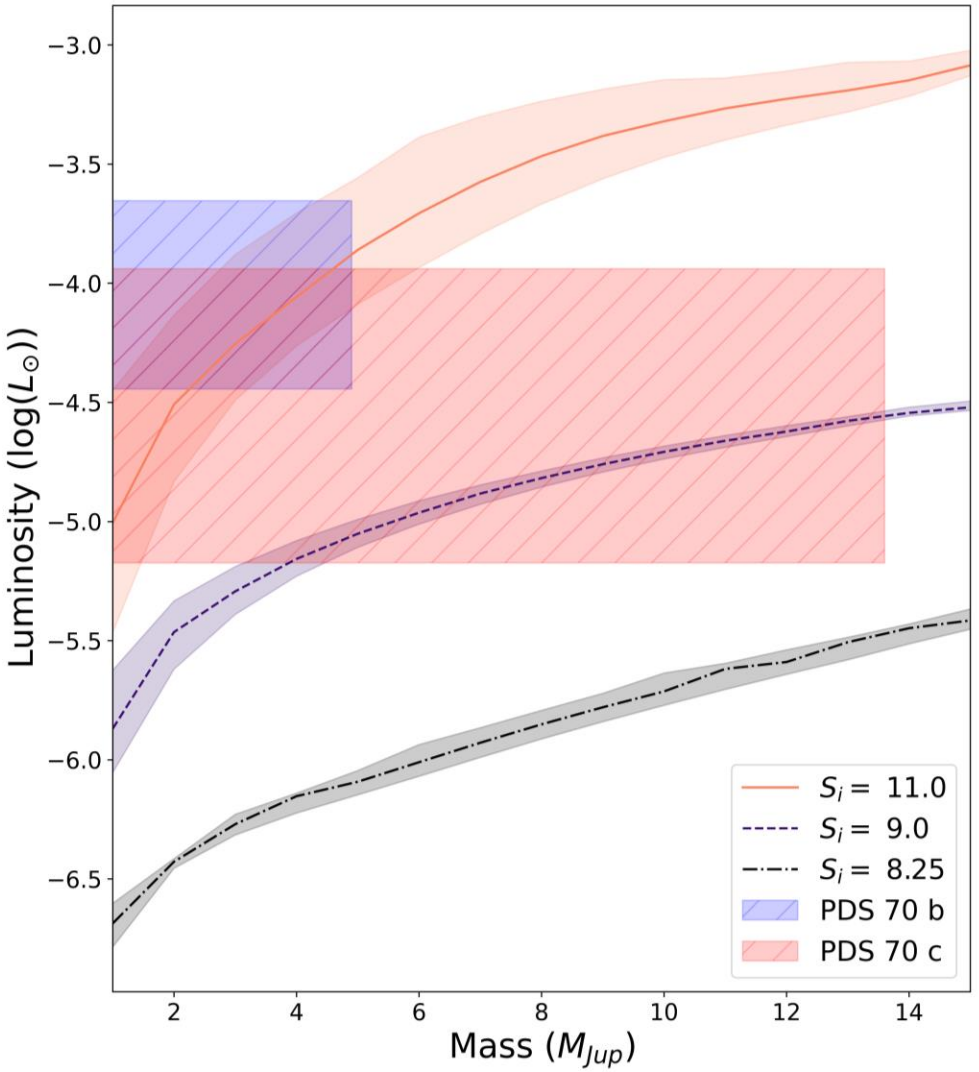
- According to N-body stability analysis:
  - $M_b < 4.9\ M_{Jup}$
  - $M_c < 13.6\ M_{Jup}$
- PDS 70 b and c are both inconsistent with cold-start models

Scan the QR code for the full paper!

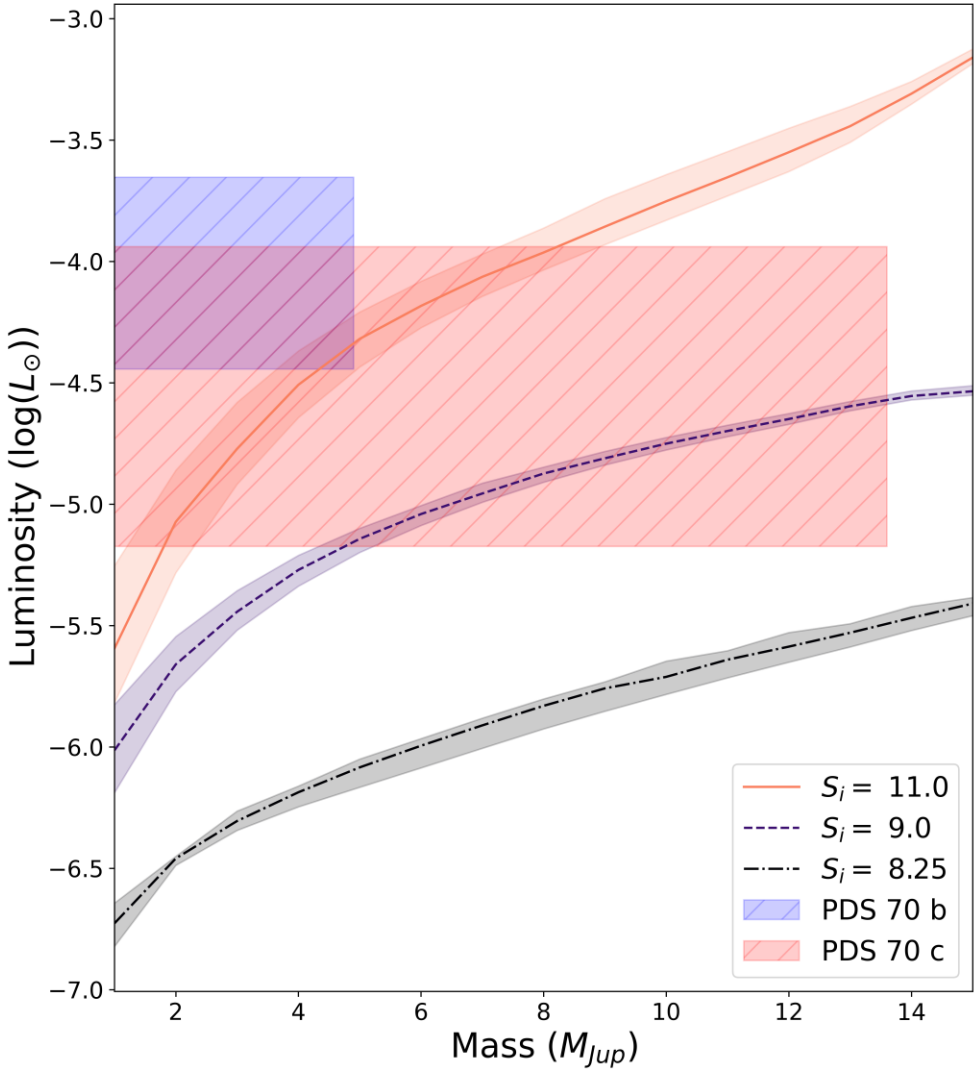


# What if the planets are younger than the star?

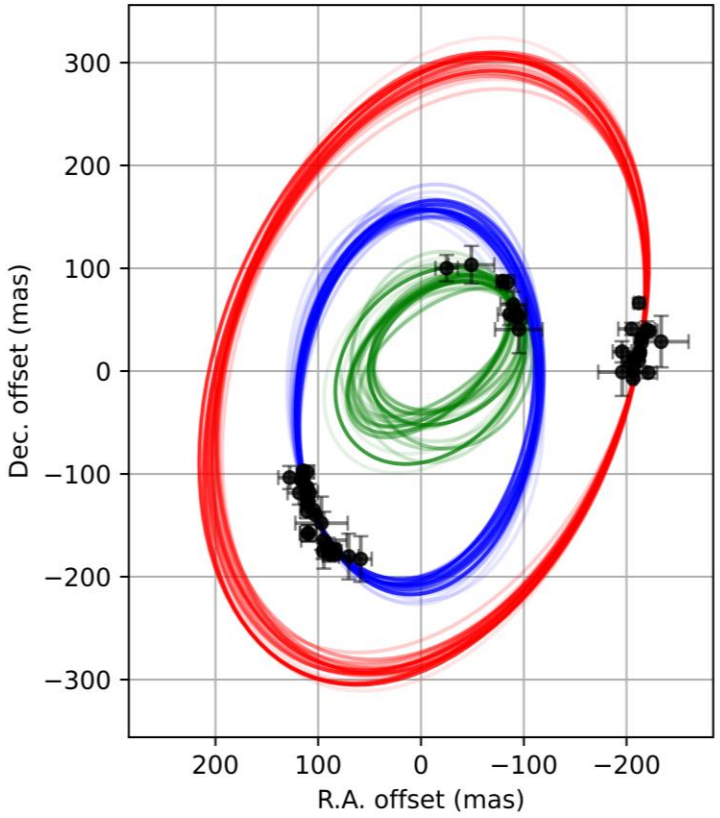
Age: 1 Myr

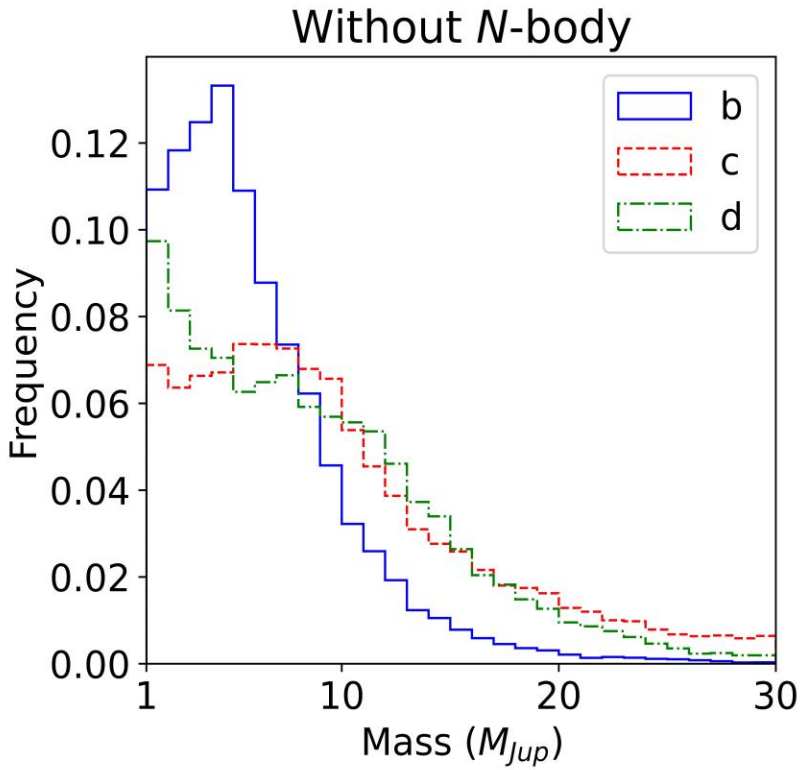


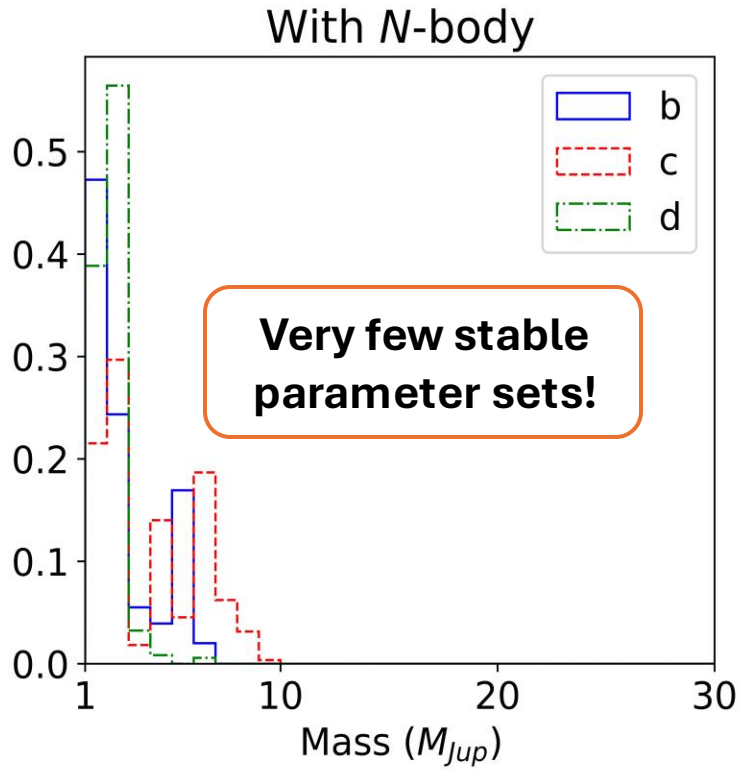

Age: 5.4 Myr



# Orbit Fitting with PDS 70 d




**Very few stable parameter sets!**