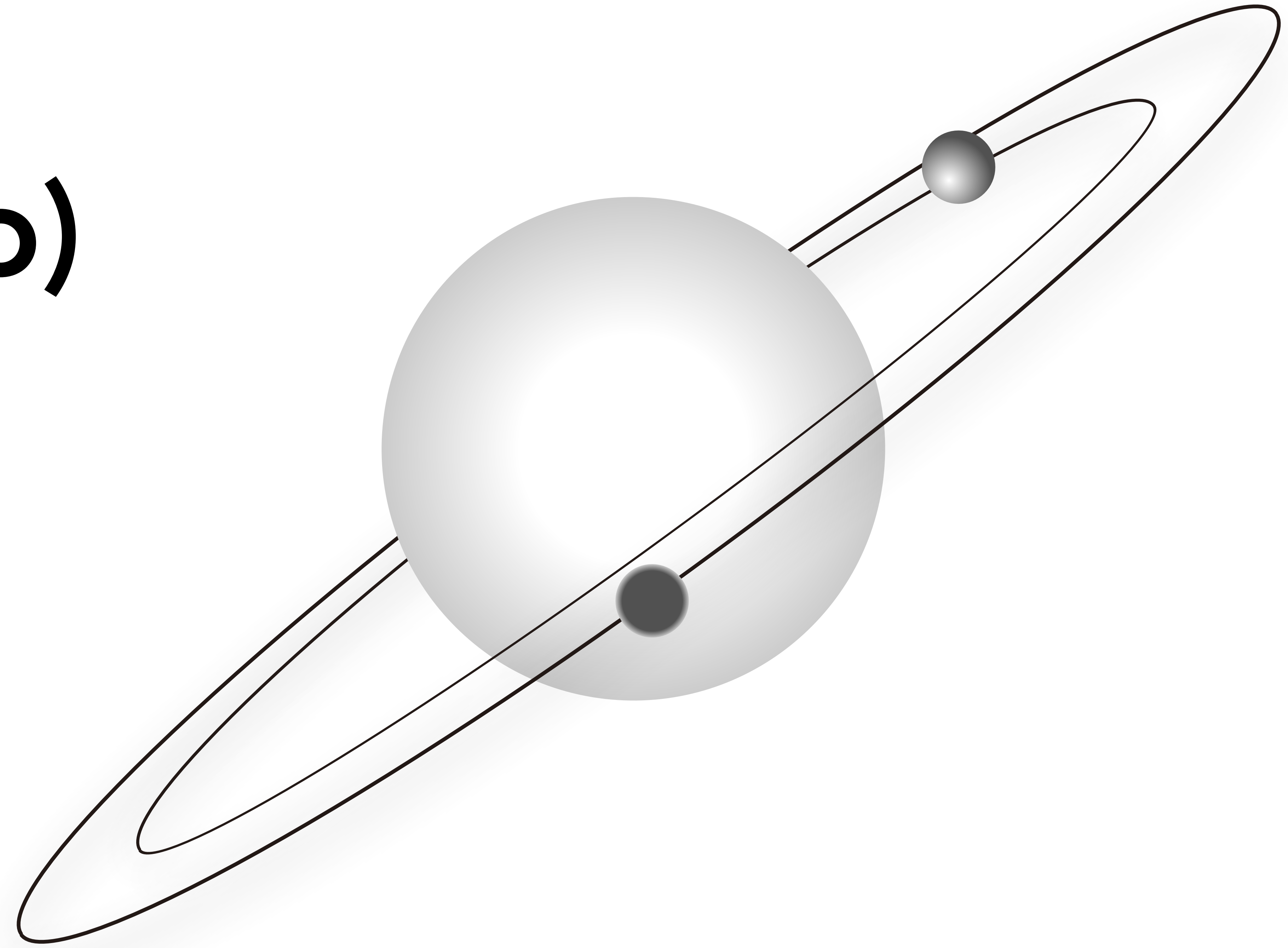
Subaru Telescope 20th Anniversary - Optical & Infrared Astronomy for the Next Decade -
19th Nov. 2019, The Big island of Hawaii, USA

Progress in and prospects for understanding of planet formation

Late Stage Accretion of Gas Giants

Masahiro IKOMA (Univ. Tokyo)

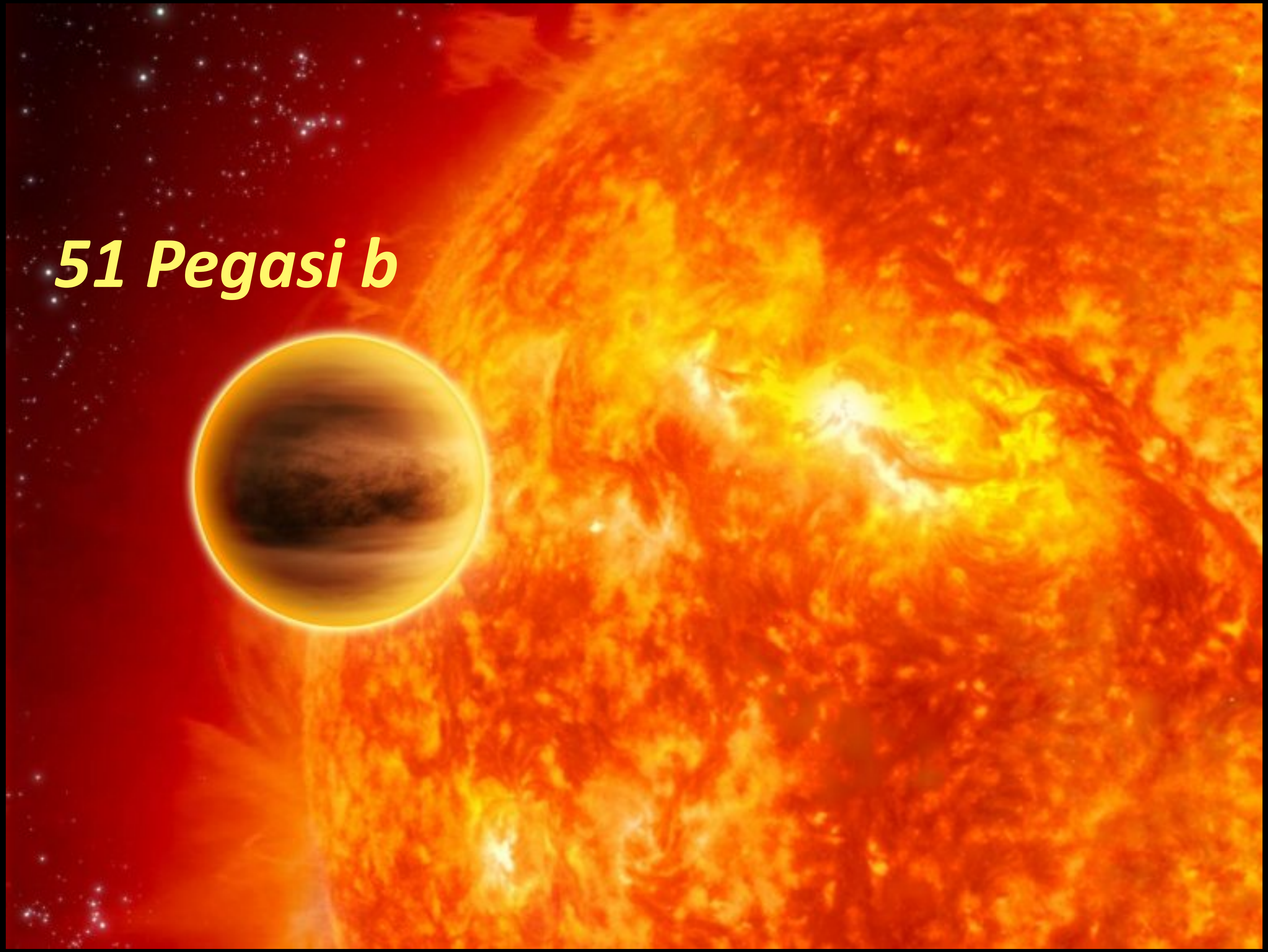


References: *Aoyama, Ikoma, & Tanigawa (2018, ApJ)*
Aoyama & Ikoma (2019, ApJL)
Shibata & Ikoma (2019, MNRAS)
Shibata, Helled, & Ikoma (2019, A&A)

1995

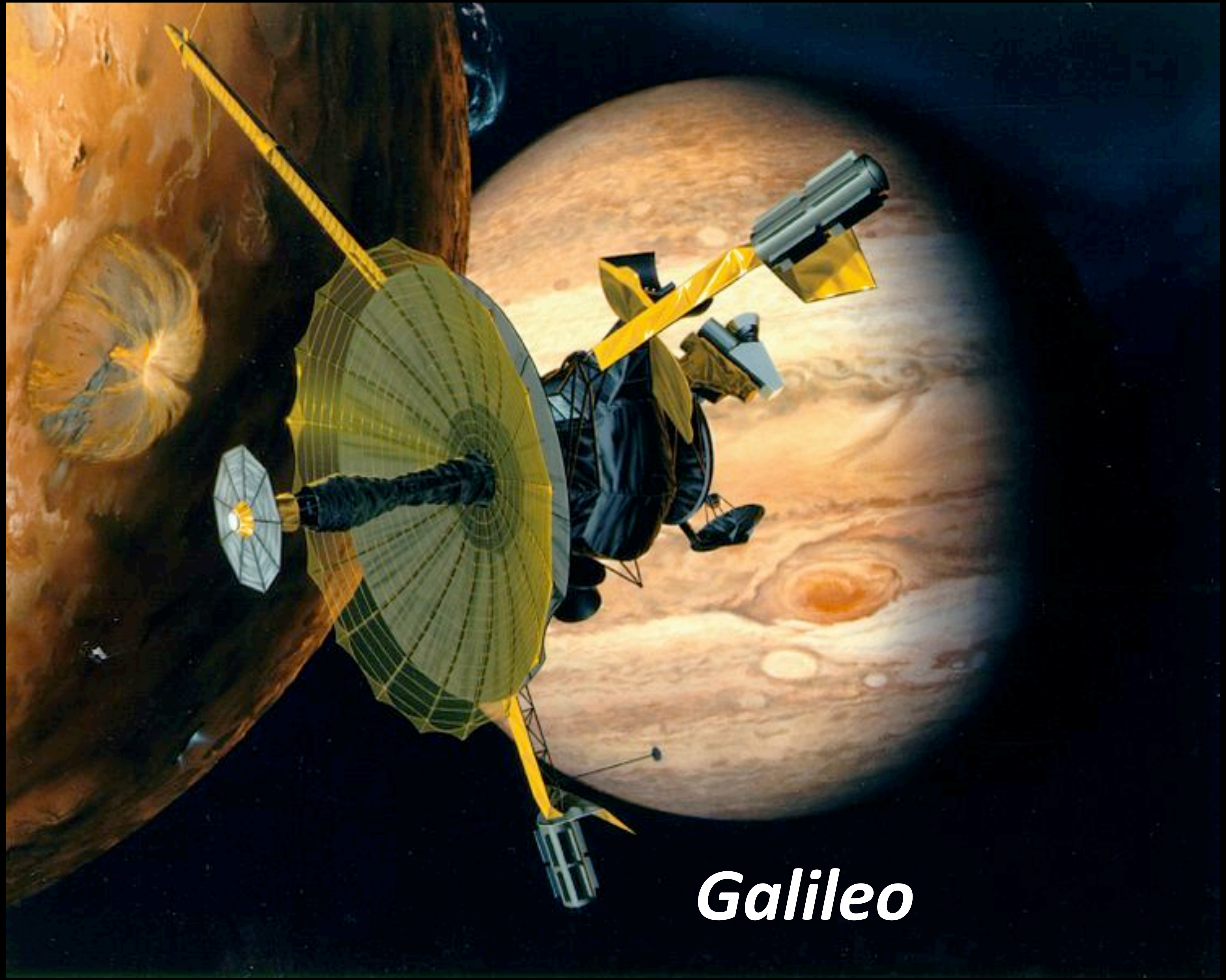
23 November (Mayor & Queloz 1995)

Discovery of Exoplanet



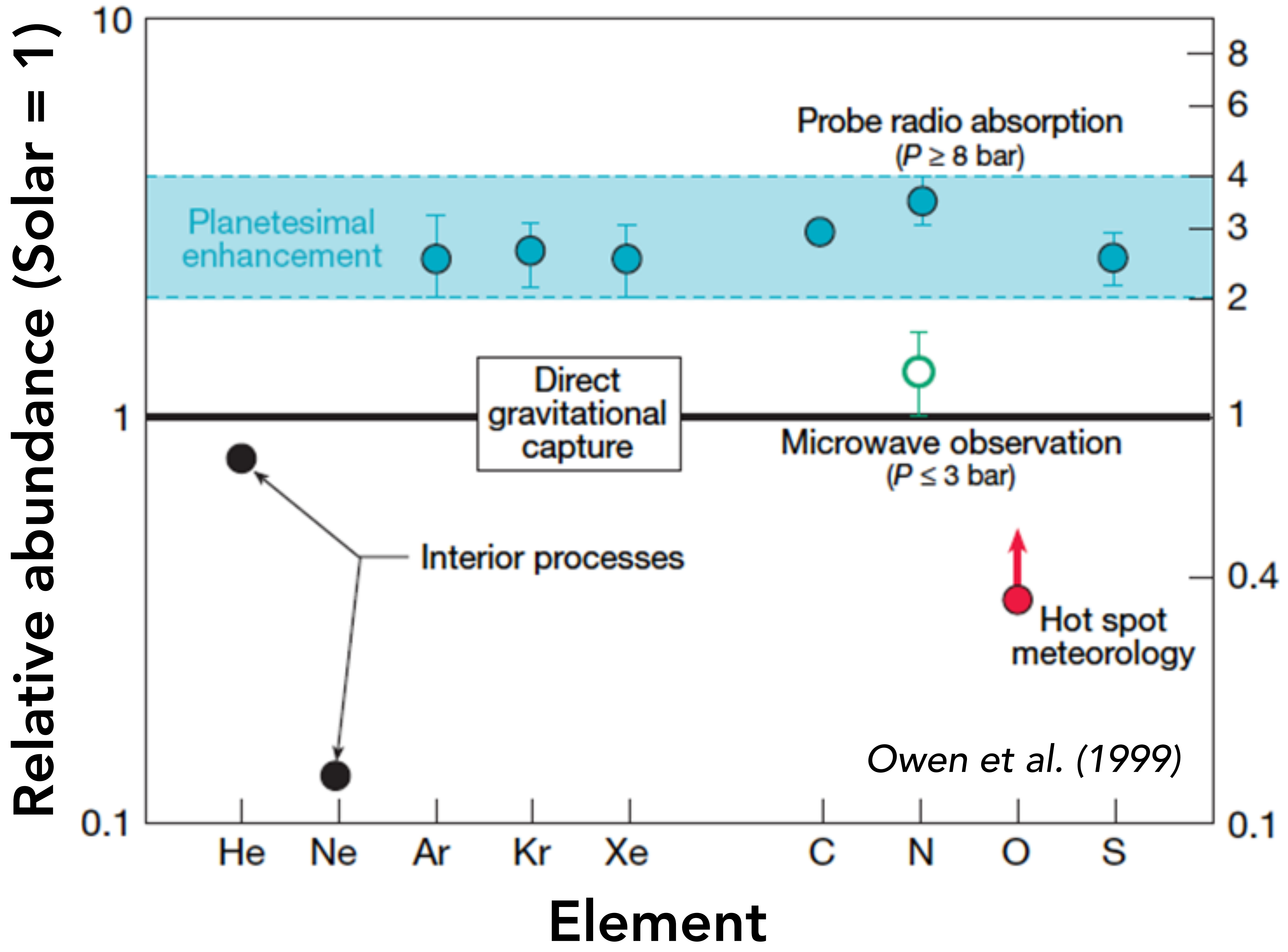
7 December

Probe Entry into Jupiter's Atmosphere



1995

In situ measurement of element abundances in Jupiter's atmosphere



Jupiter's atmosphere is **enriched with heavy elements** relative to the solar abundances, similarly to its interior.

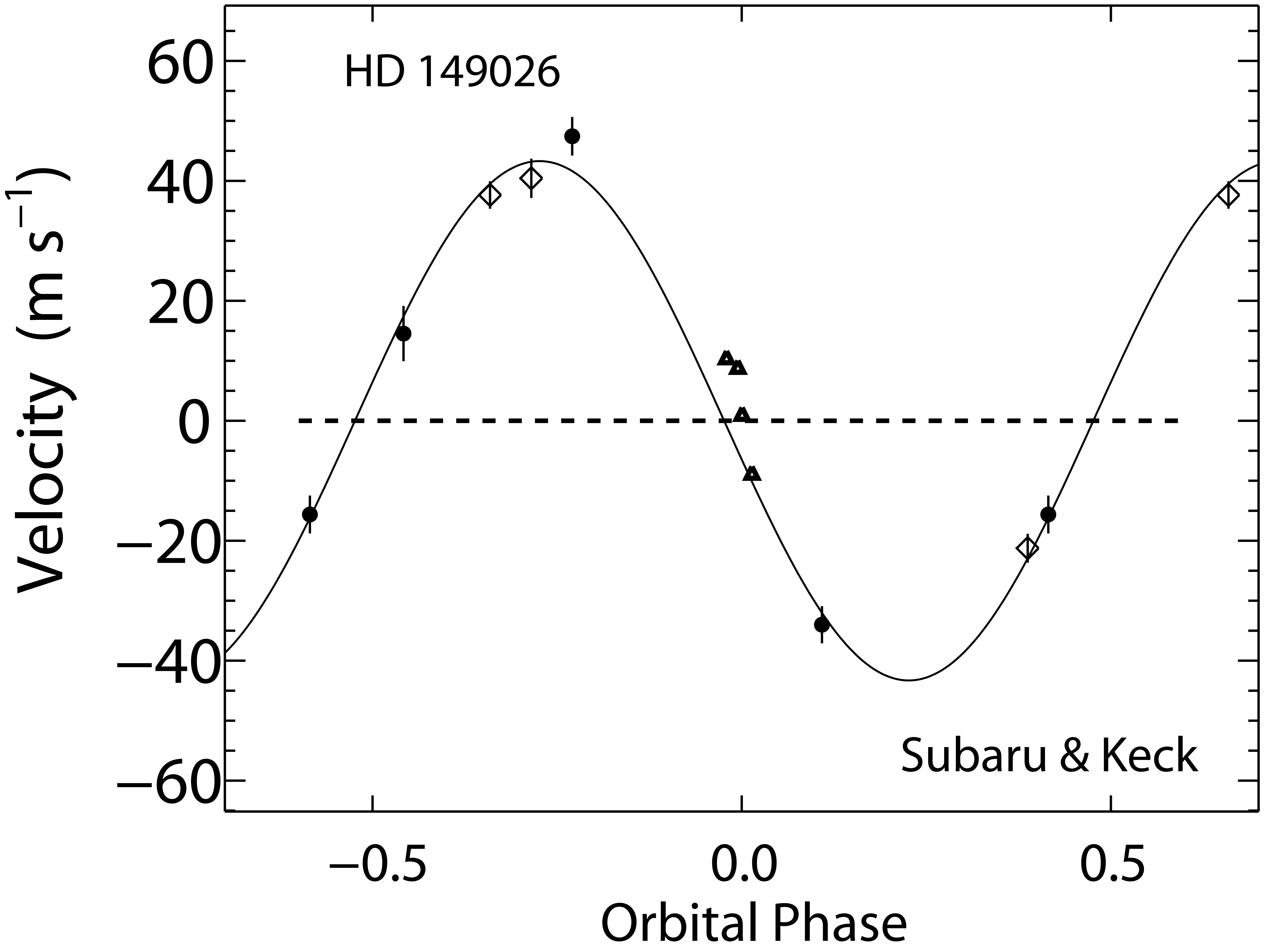
Oxygen and thus water was **missing**.

Did the probe happen to enter a dry region?

Was oxygen fixed in the core in the form of ice?

2005

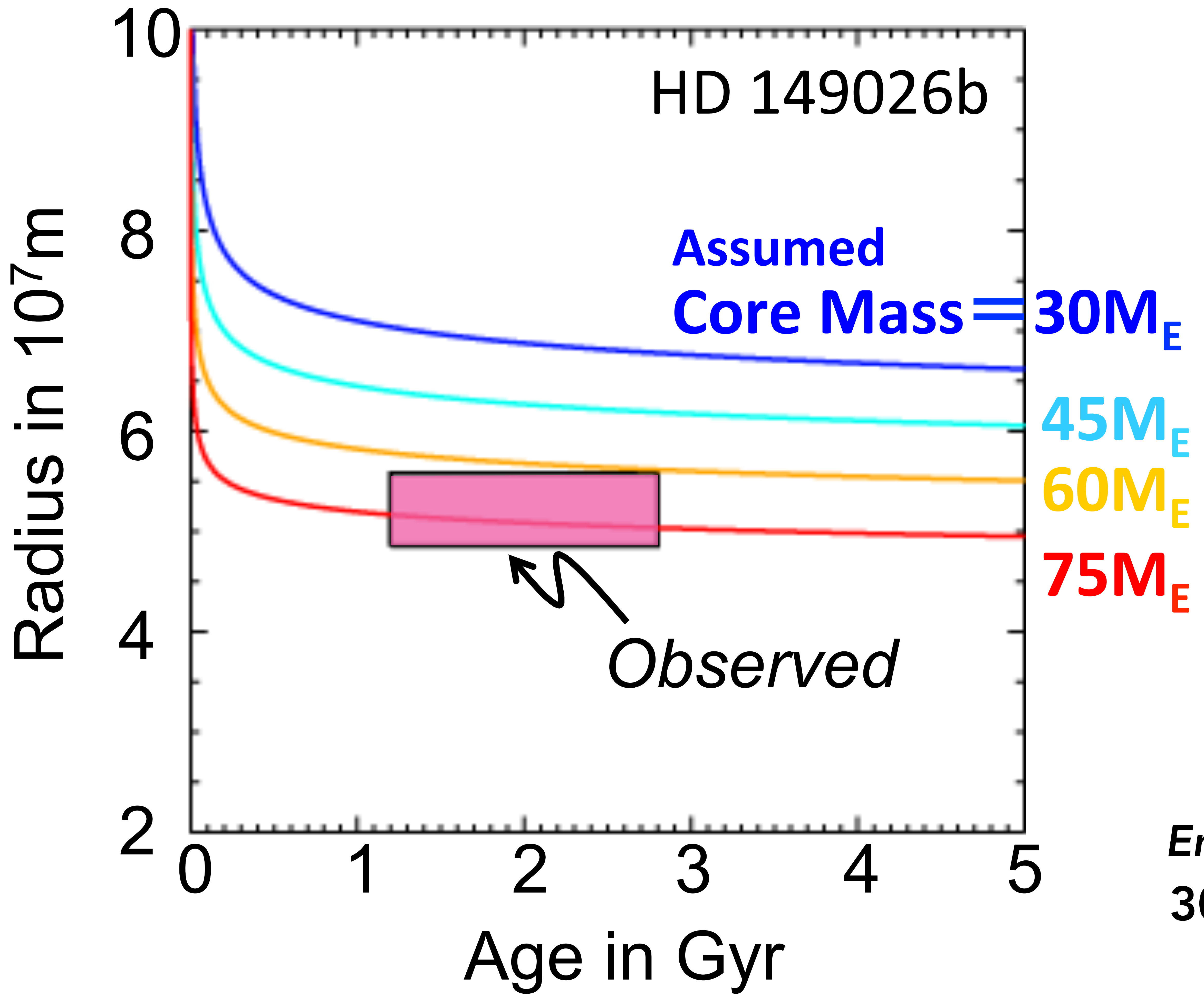
Detection of RV variation for HD149026 *with Subaru* (*Sato+ 2005*)



Mass = 0.36 Jupiter
Radius = 0.73 Jupiter
Semimajor axis = 0.042 AU

2005

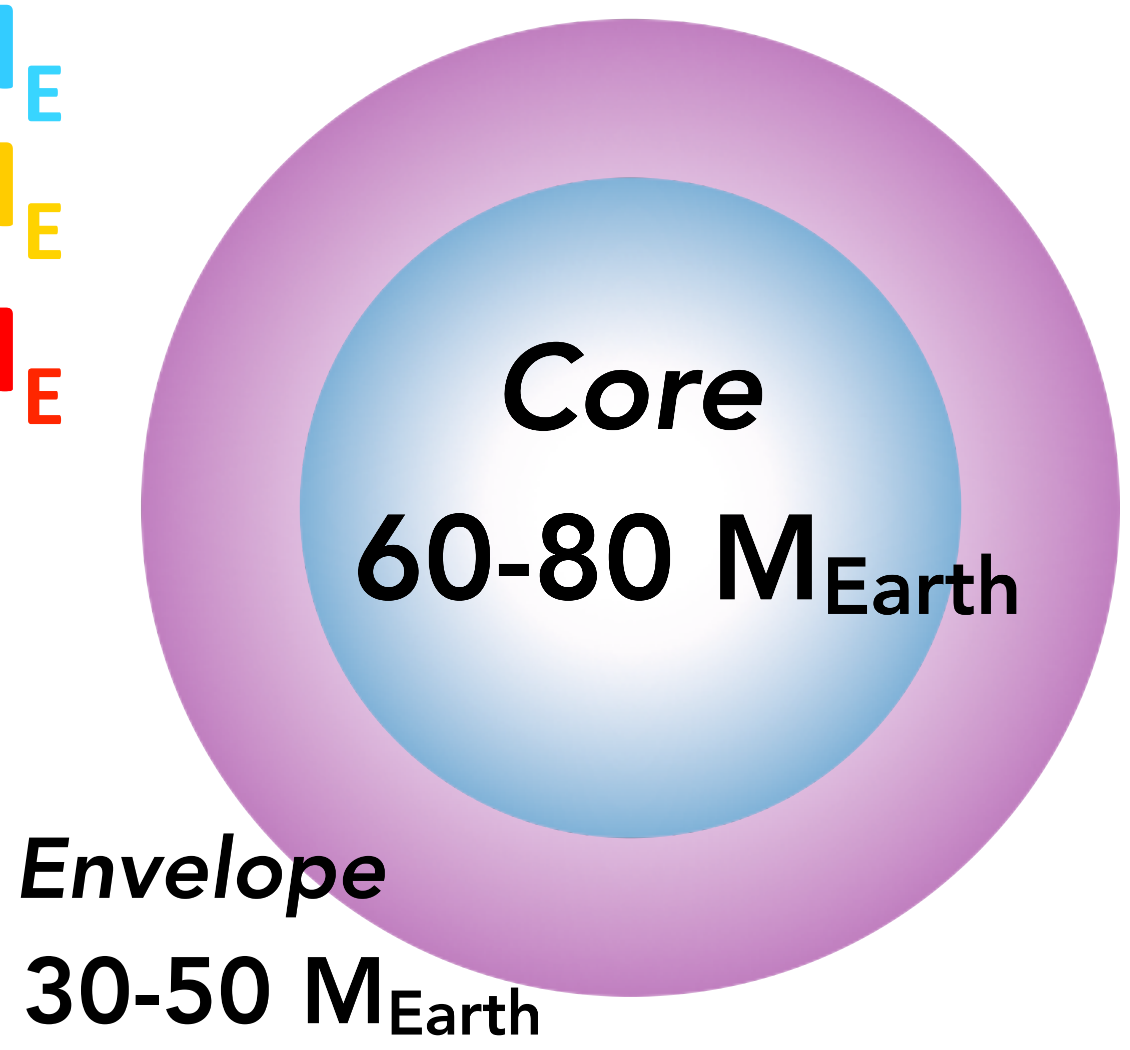
Detection of RV variation for HD149026 ***with Subaru*** (*Sato+ 2005*)



HD149026b

A **surprisingly dense** close-in gas giant

← *Thermal evolution models (Ikoma+ 2006)*



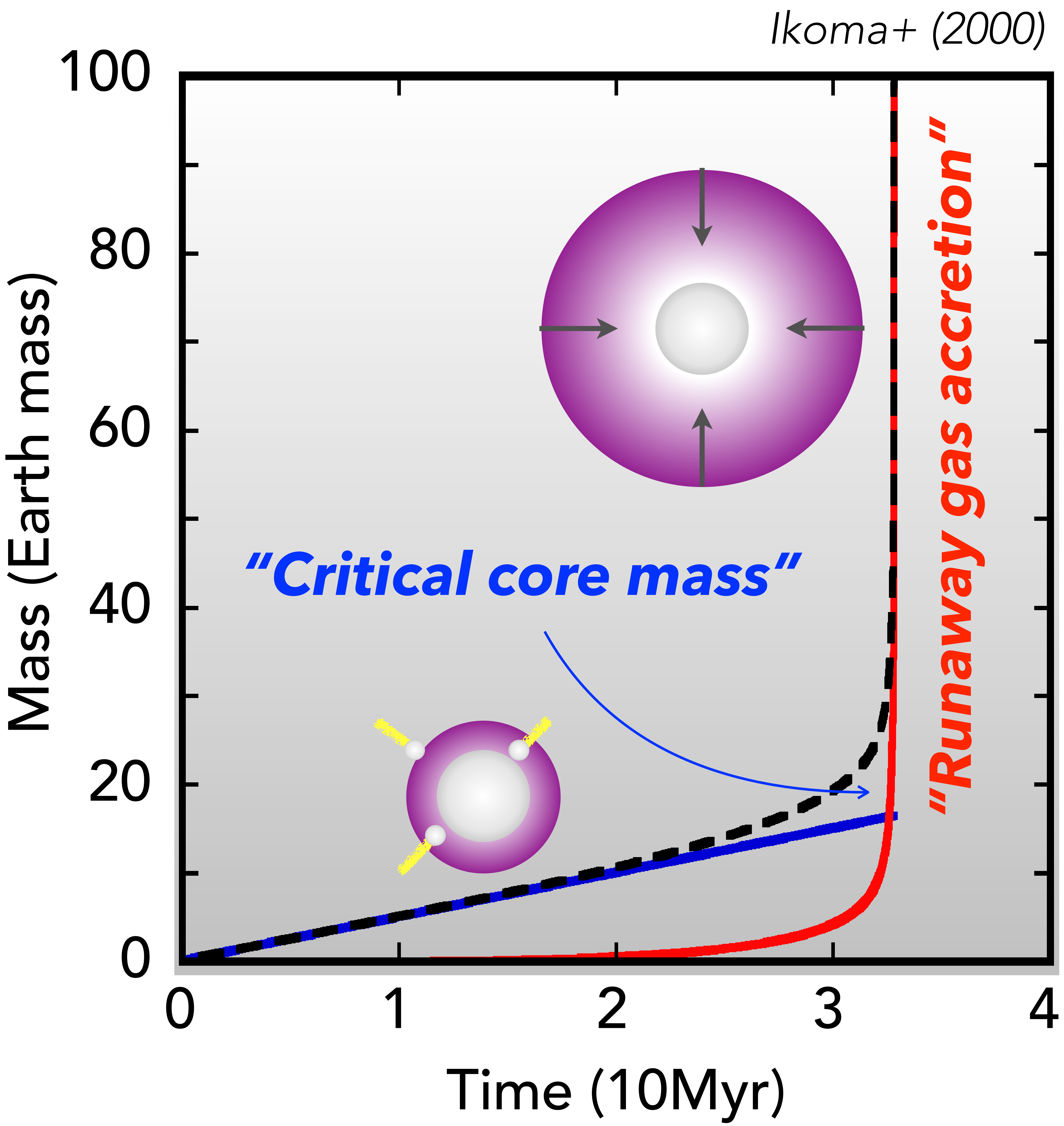
Give support, but

a challenge to

the core accretion model

for giant planet formation

Classic Core Accretion Model



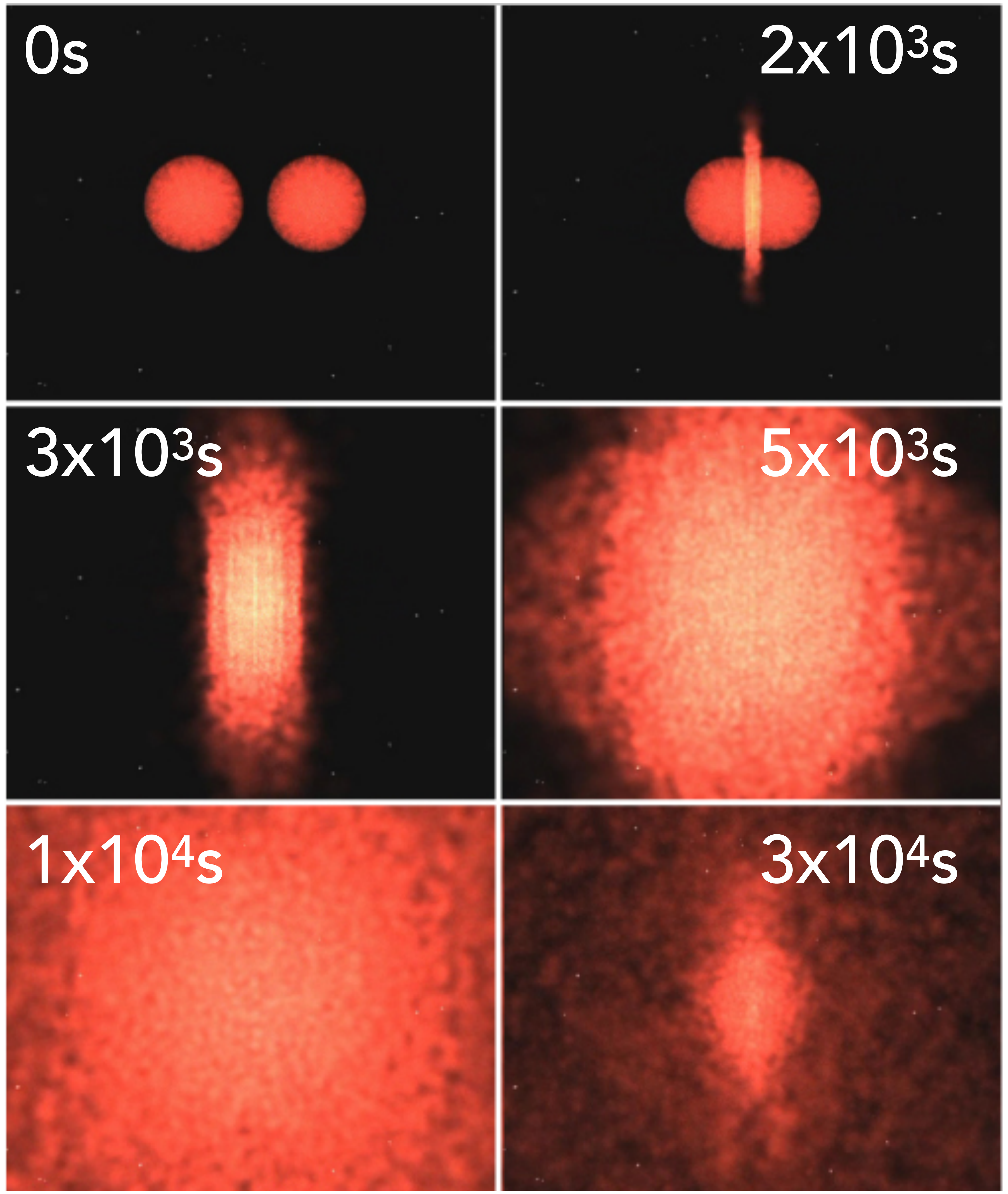
Two-step formation process:
Formation of a critical-mass core followed by runaway gas accretion

Critical core mass is at most 30 M_{Earth}
… recent theories favor smaller cores.

Additional heavy elements must be captured **during and/or after** the runway gas accretion phase.

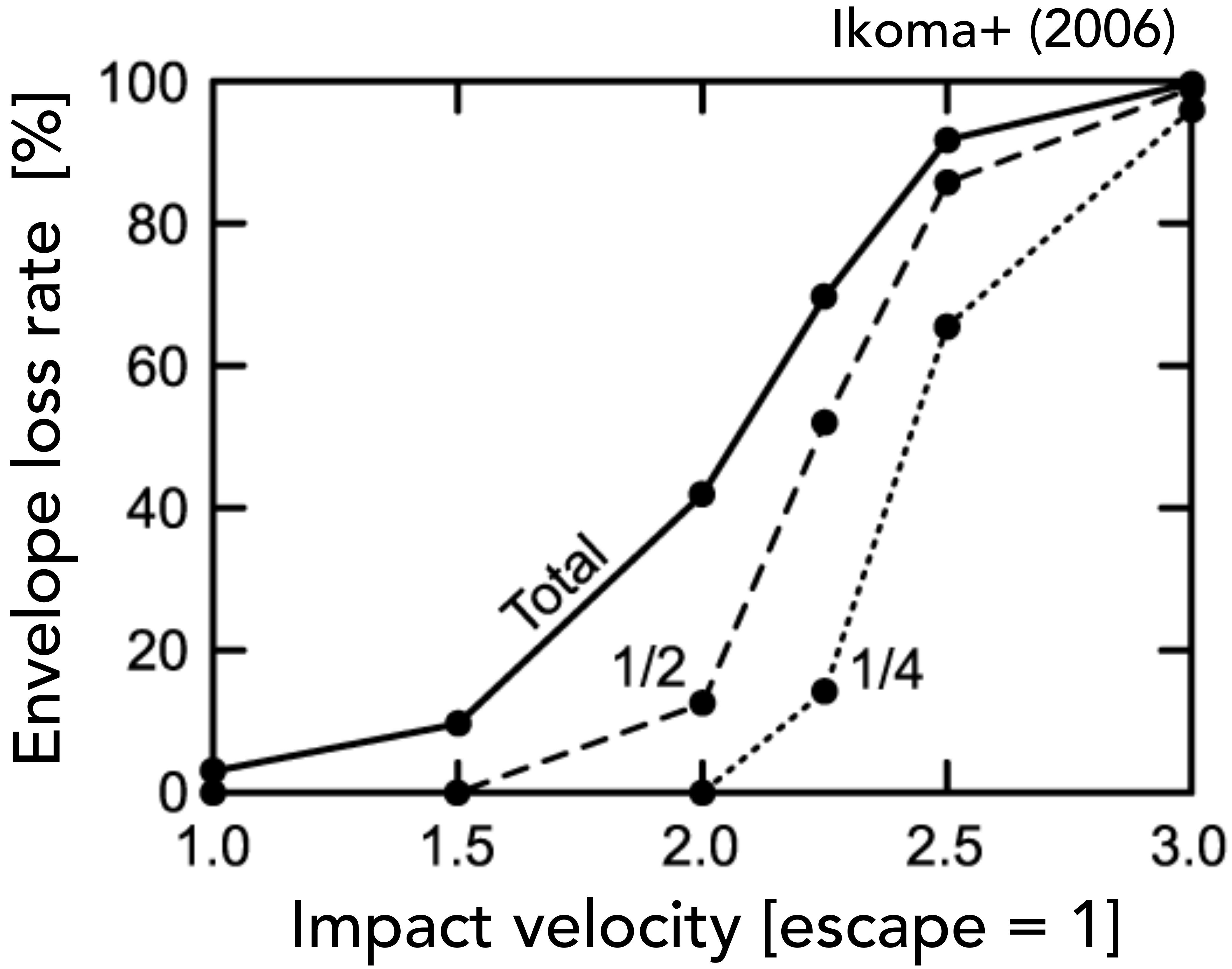
Giant Collision Hypothesis

SPH simulation of collision of two gas giants
(Ikoma+ 2006; Courtesy of H. Genda)



Merger of the cores + Loss of the envelopes

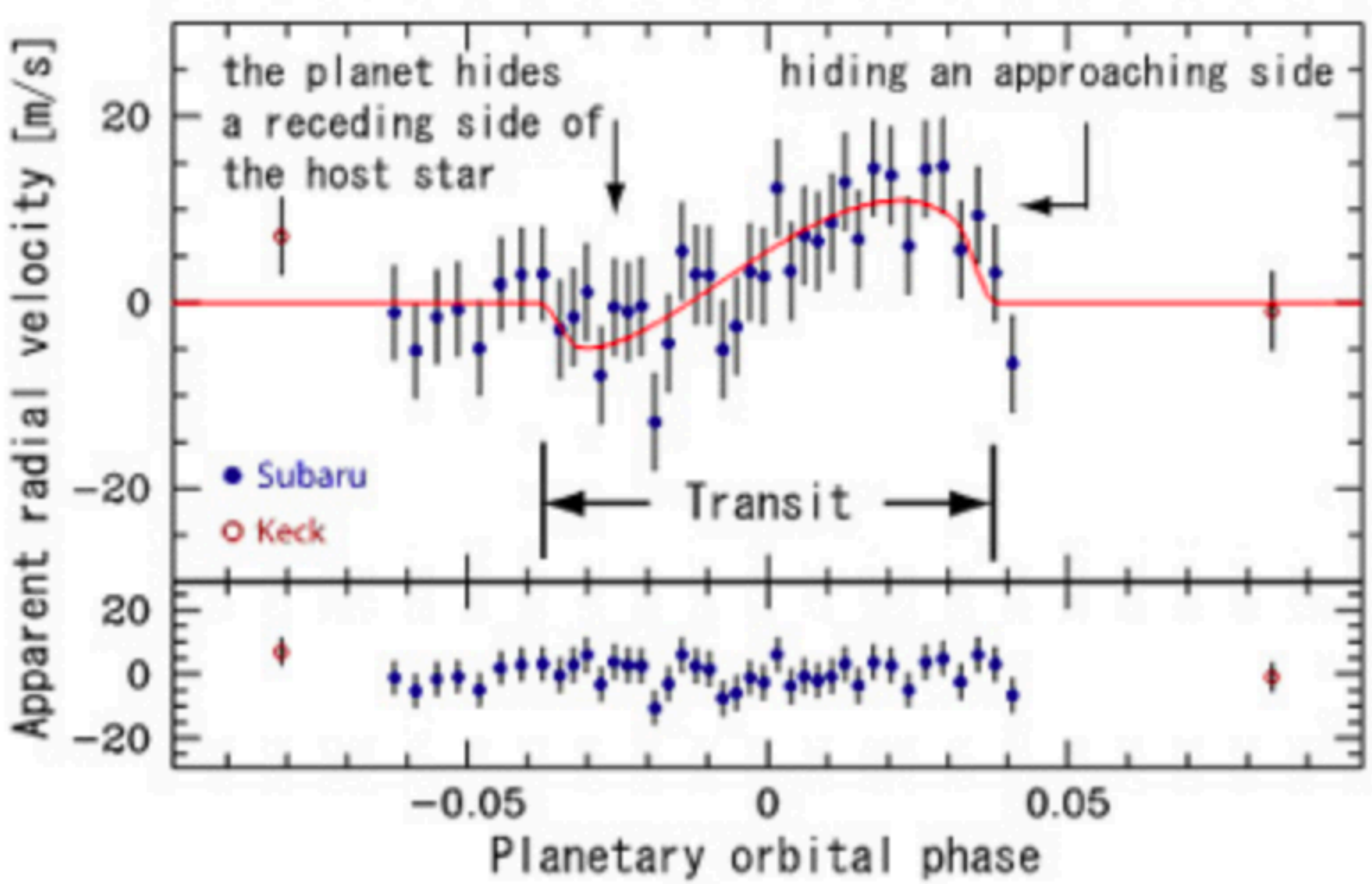
⟶ *Formation of HD149026b-like planets*



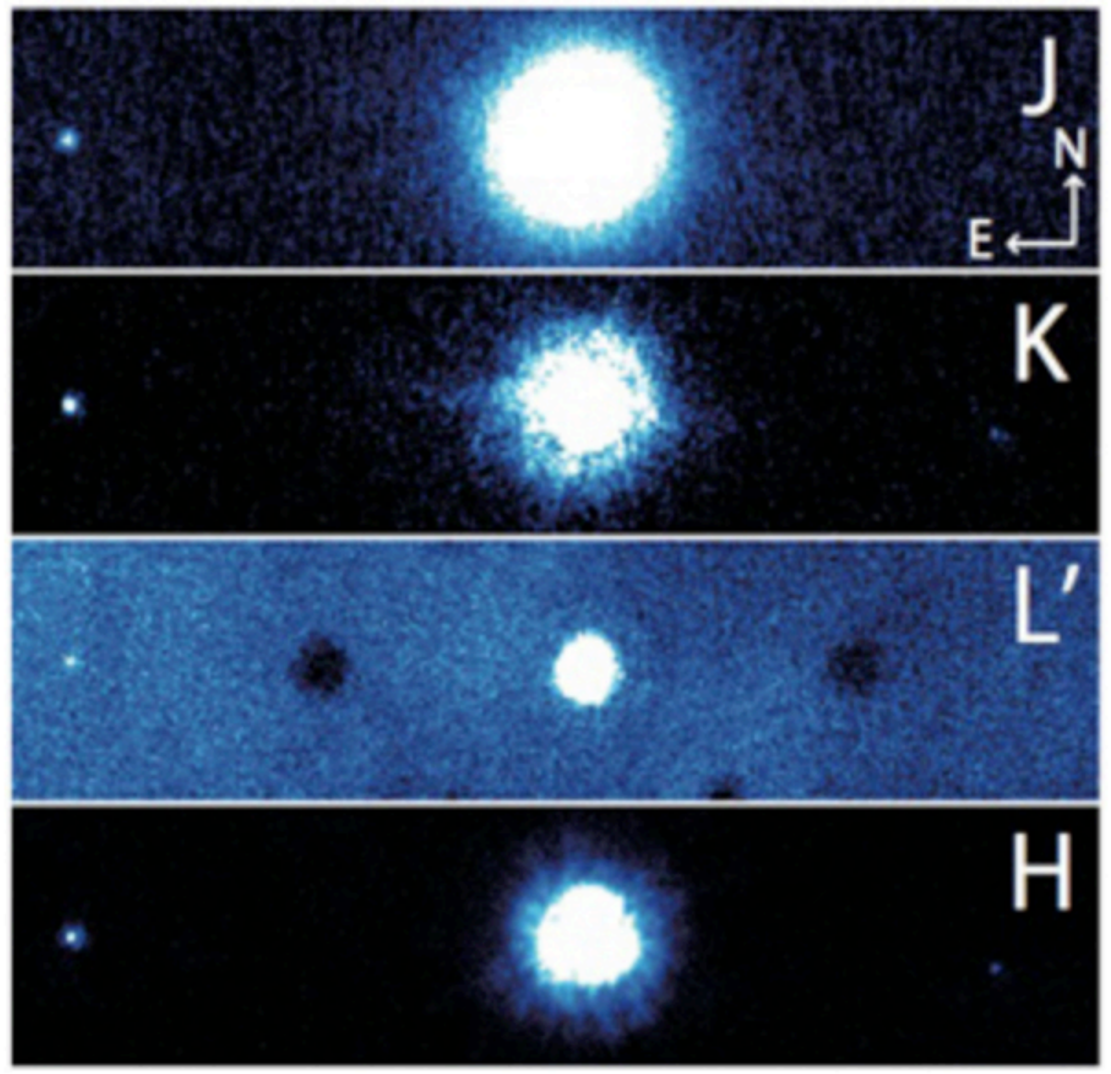
Retrograde or Highly Tilted Planets

Detection of the RM effect with Subaru HDS (Narita et al. 2009)

→ Retrograde-orbit giant planet, HAT-P-7b

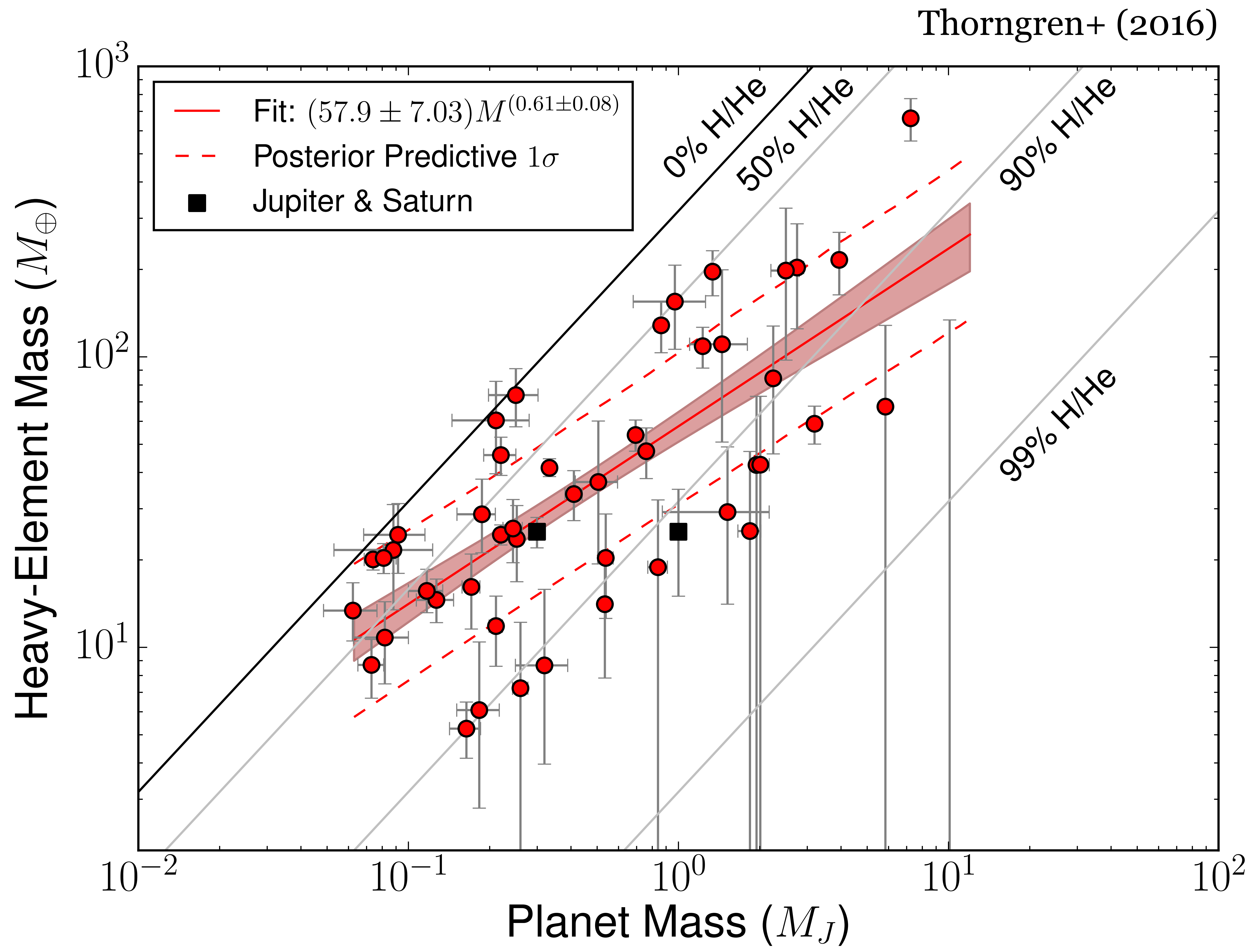


Detection of another gas giant HAT-P-7c with Subaru HDS & a stellar companion 7B with Subaru HiCIAO (Narita et al. 2012)



A piece of the evidence of ***dynamical interaction & migration of gas giants.***

Metallicity of Warm Gas Giants

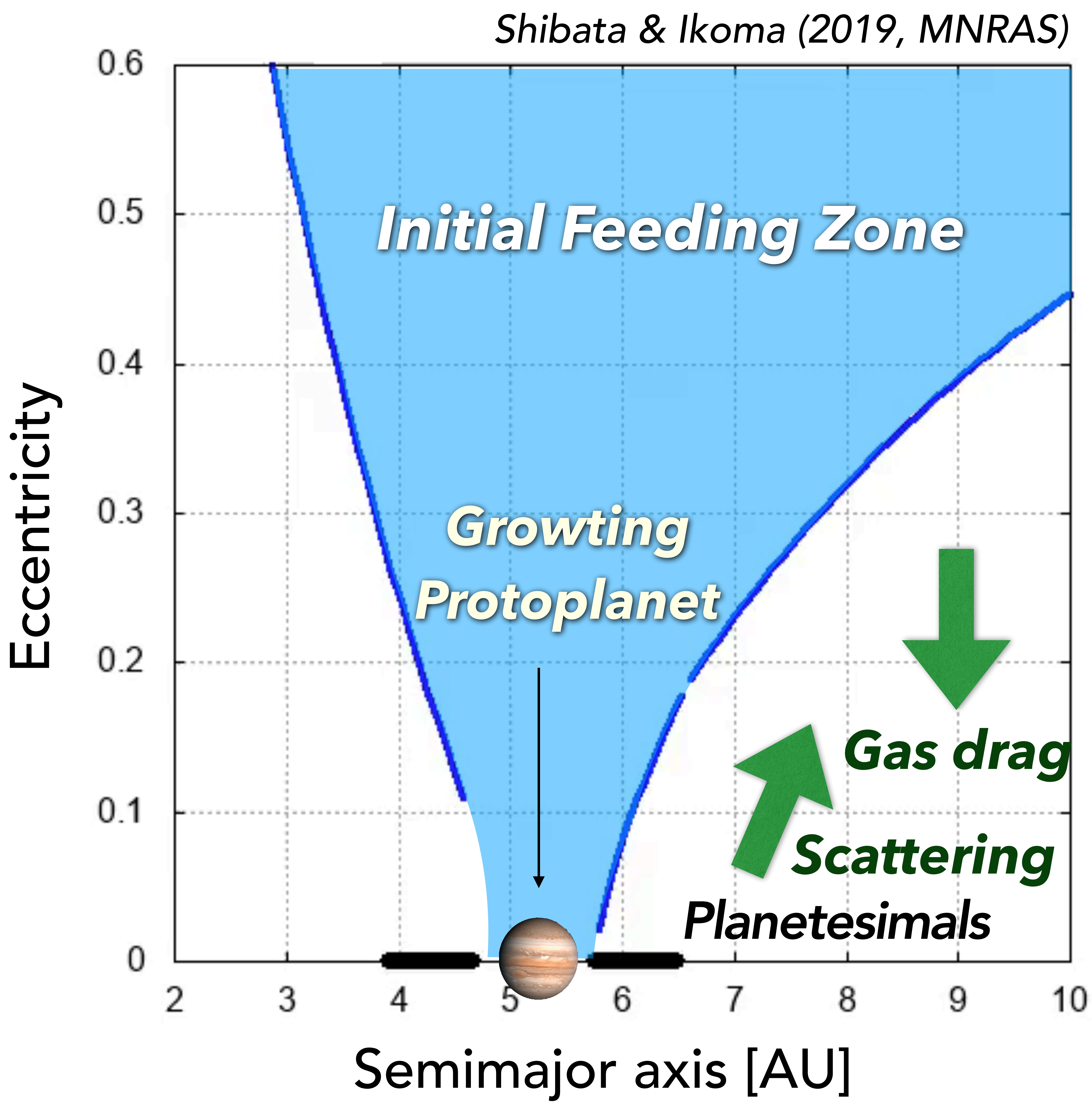


Most of the known ***warm*** Jupiters are enriched with heavy elements relative to their host star.

> ~50 Earth masses !

Late-stage addition of heavy elements may be a common process.

In situ Capture of Planetesimals



Pushing Out of Feeding Zone

Planetesimals are pushed out of the feeding zone by the combined effect of gravitational scattering and eccentricity damping via gas drag.

Planet Growth Helps

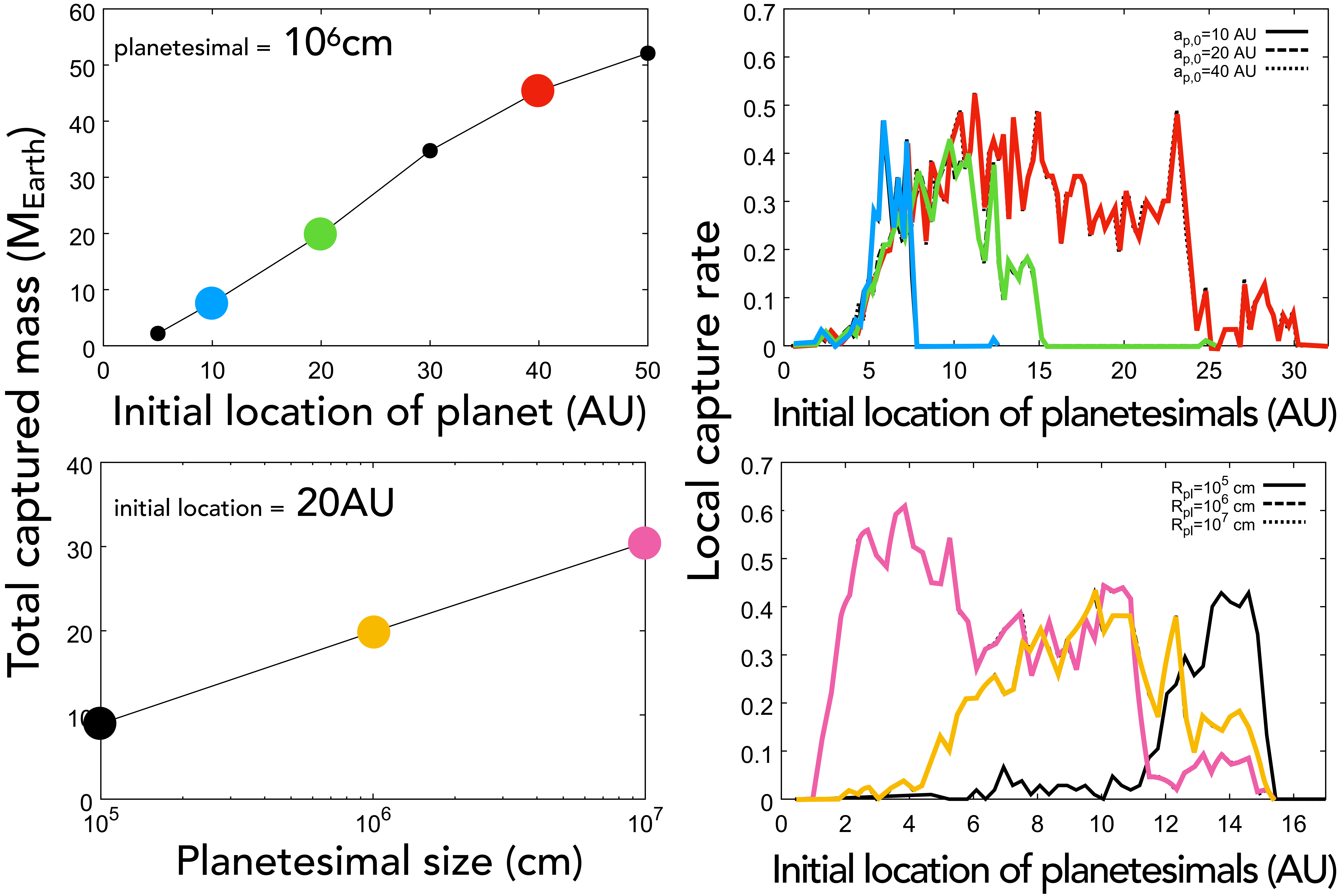
The mass growth of the protoplanet via gas accretion leads to expanding the feeding zone and engulfing some of the surrounding planetesimals.

Low Capture Efficiency

However, the capture efficiency is low:

~ 0% for planetesimal size of 10^4 & 10^5cm
< 5% for 10^6cm, ~20% for 10^7cm

Capture of Planetesimals by a Migrating Planet



Disc-assisted migration helps the planet capture planetesimals.

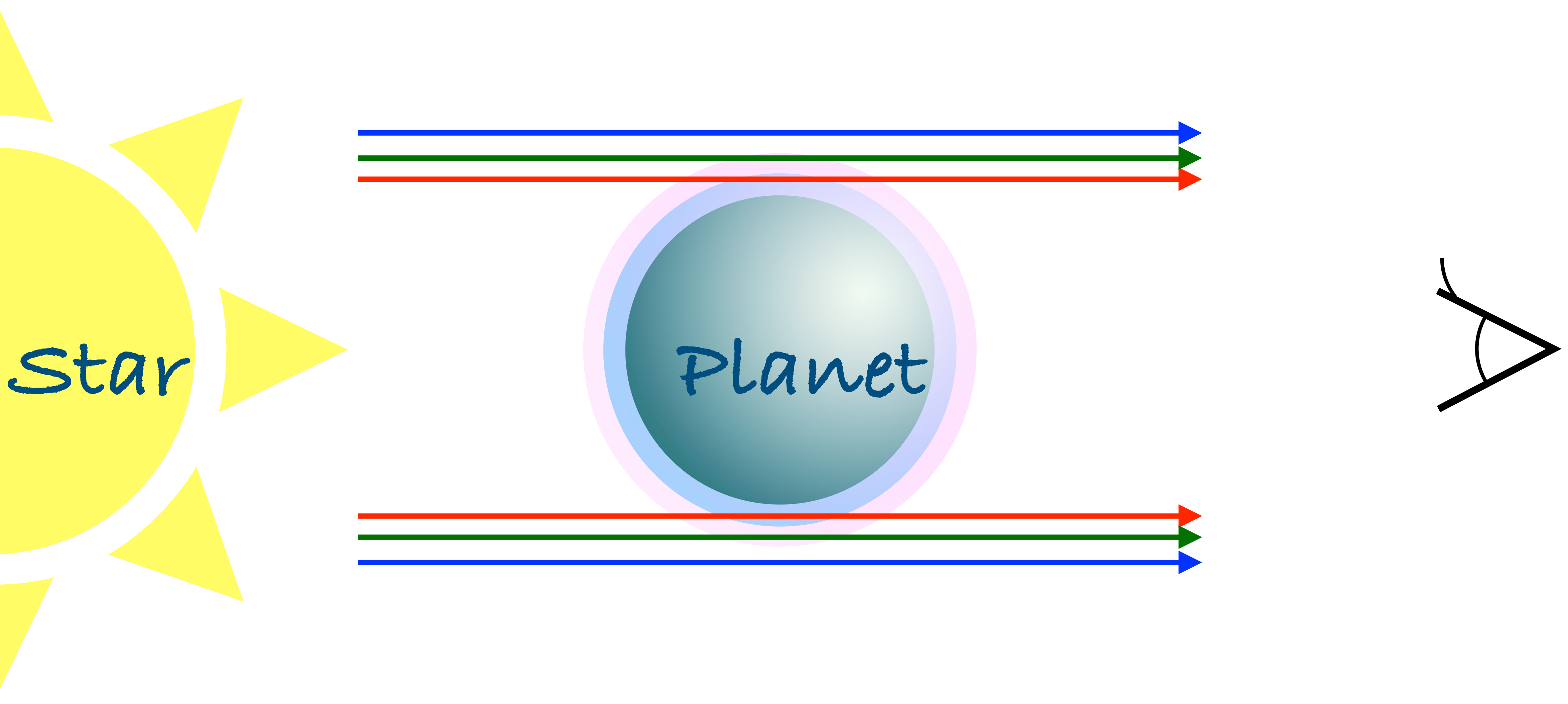
For > 50-100 M_{Earth} of planetesimals to be captured, **Long-distance migration** is need.

The planet captures planetesimals **From limited regions.**
→ important for atmospheric composition

Shibata+ (2019, A&A)

Atmospheric Composition of Hot Jupiters

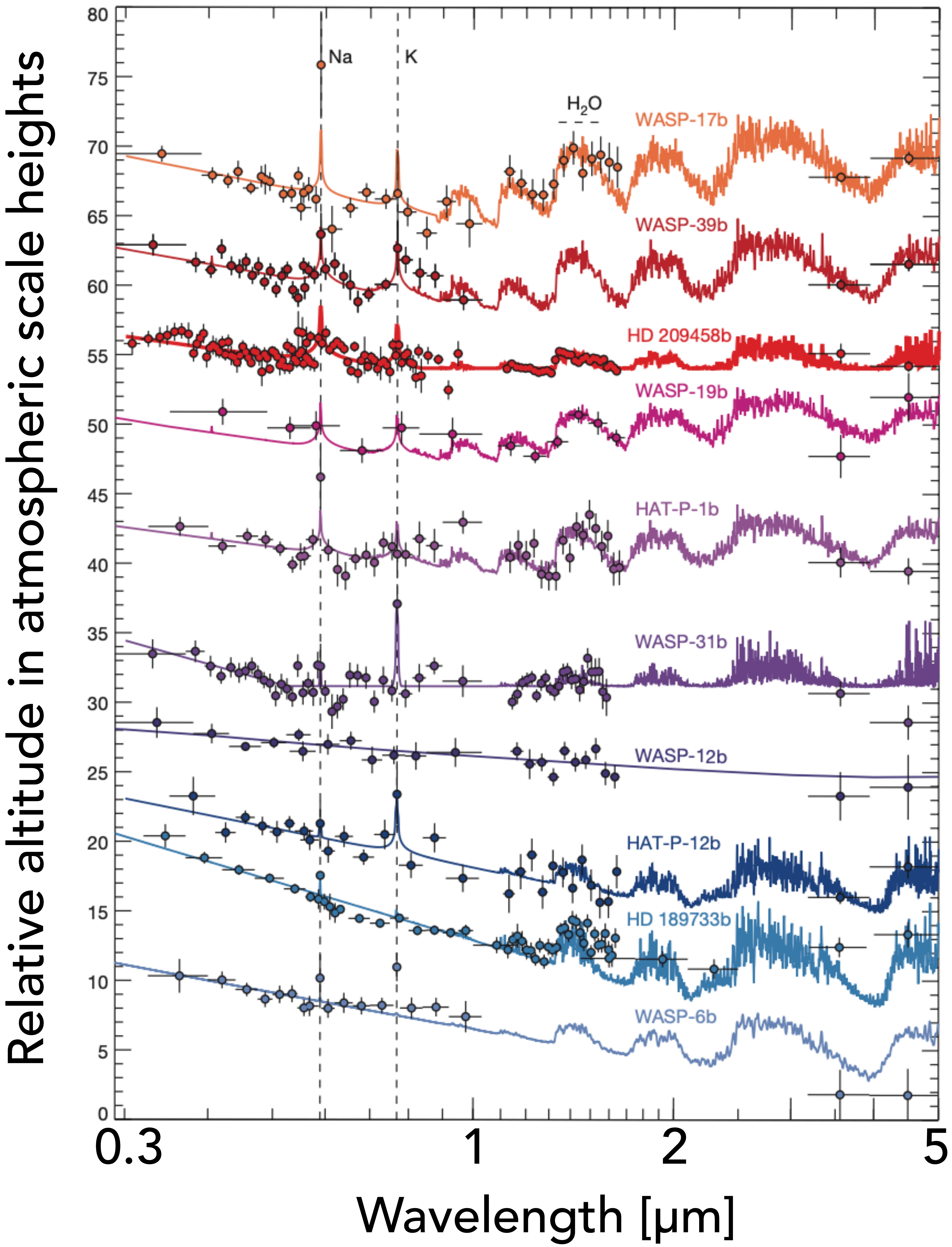
Transmission Spectroscopy for Transiting Planets

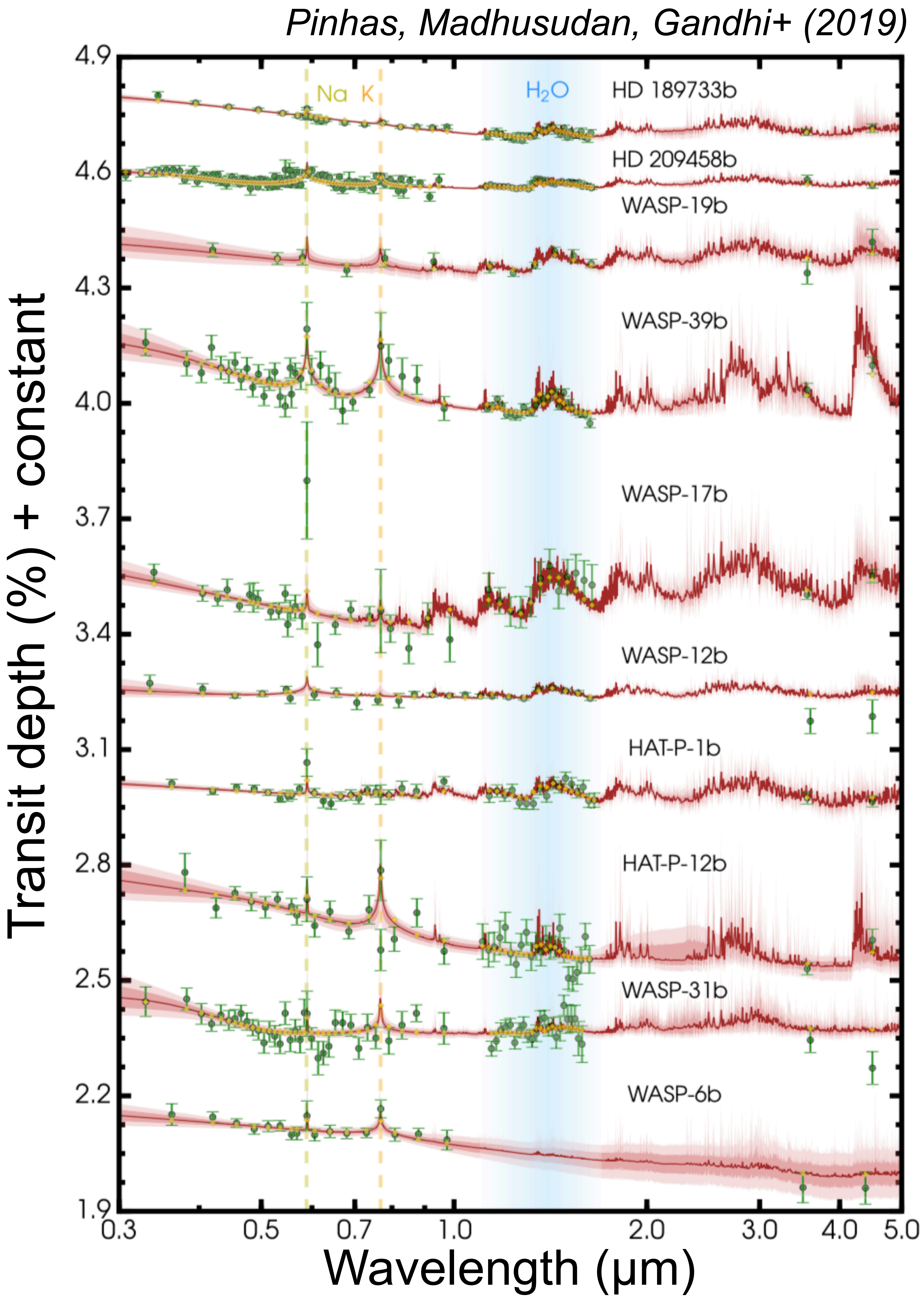


Detect H_2O and some other molecules in atmospheres of hot Jupiters.

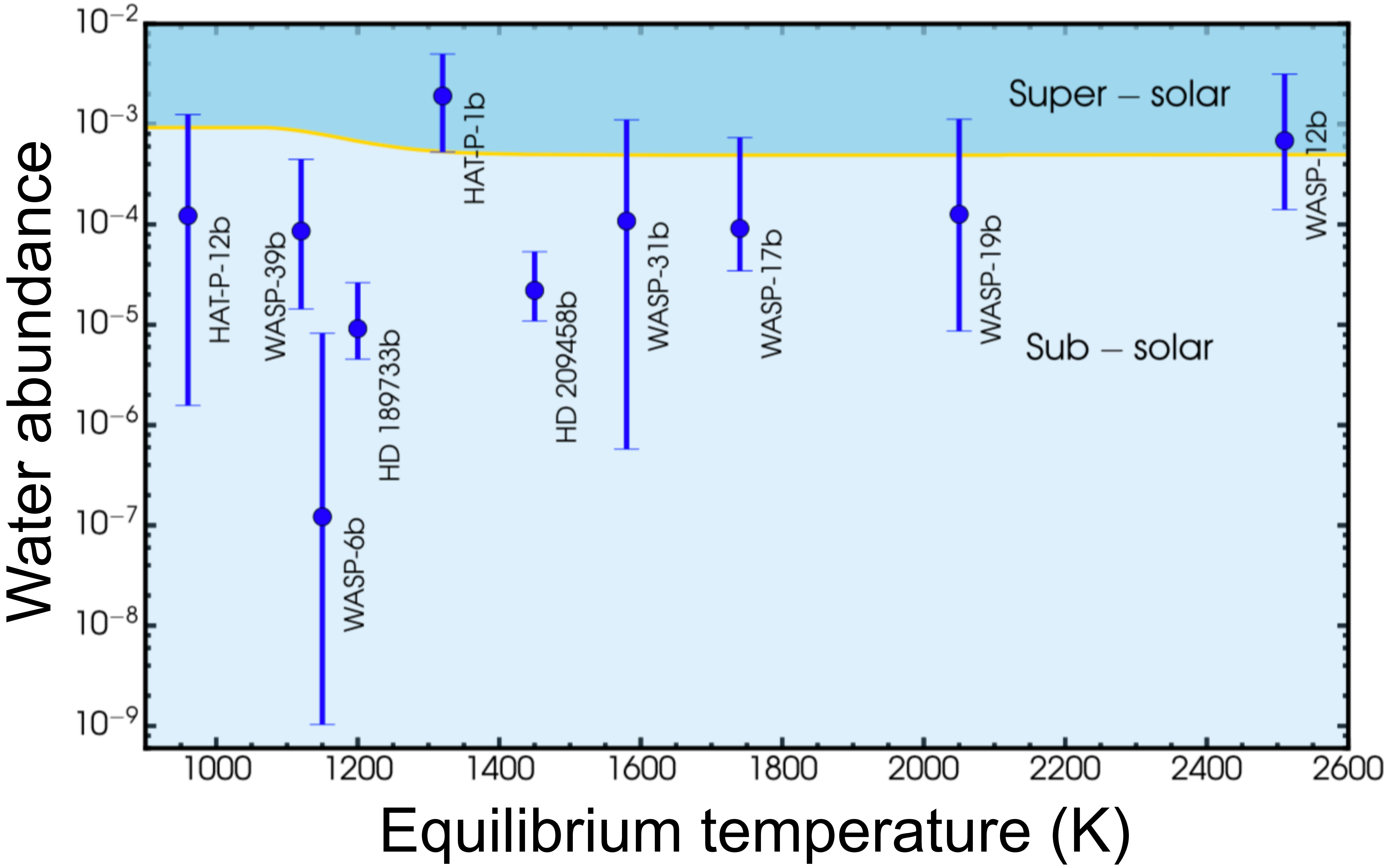
Atmospheric spectra are diverse.

Sing+ (2016)





H_2O in atmospheres of hot Jupiters

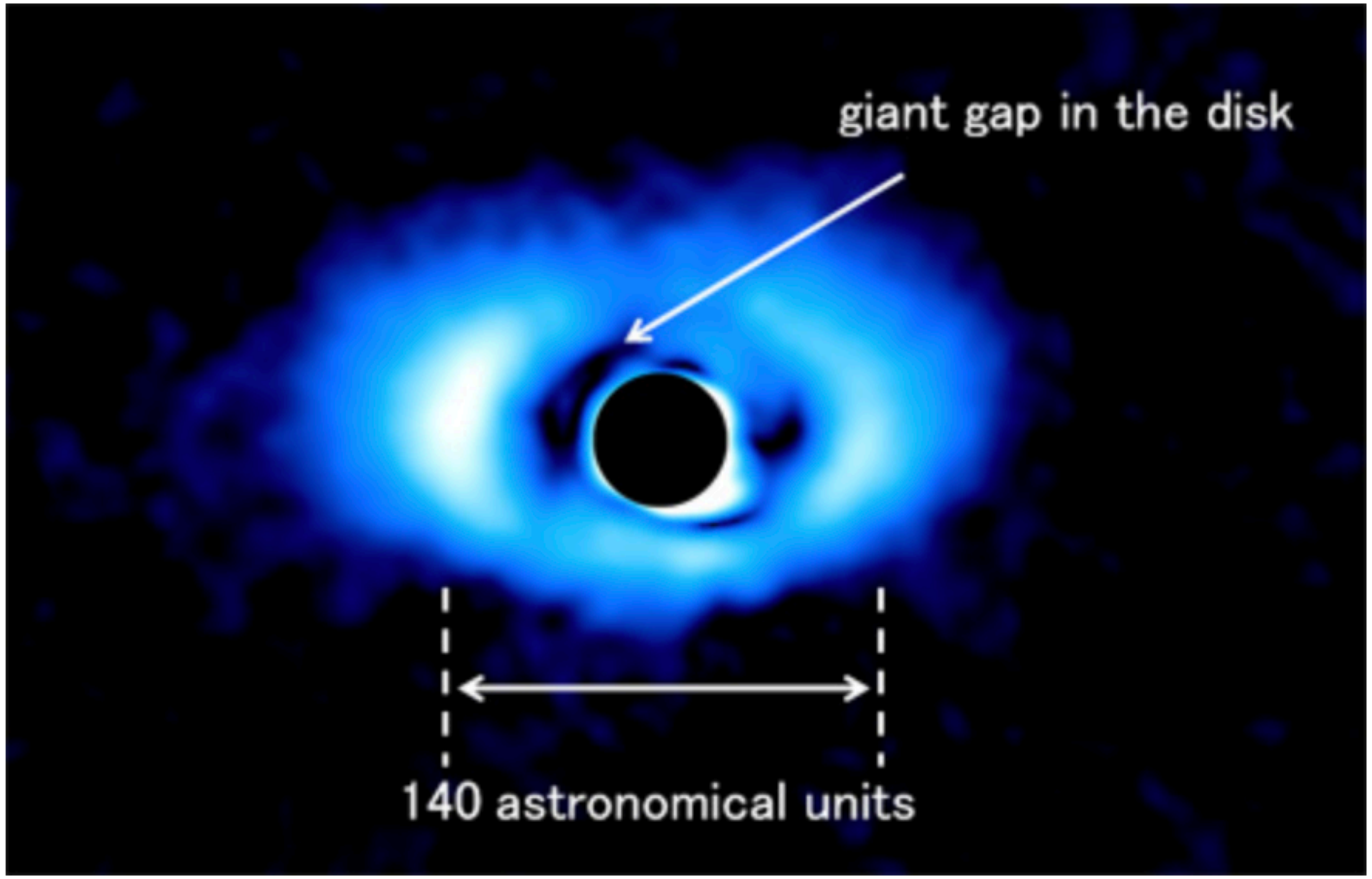


Almost half of the HJ atmospheres are subsolar-H_2O (and thus **substellar H_2O**) abundances.

Haze/clouds possibly obscure the H_2O features.

Growing, Infant Giant Planets

Detection of a giant gap in a cirumstellar disk around PDS 70 with Subaru HiCIAO (Hashimoto+ 2012; Dong+ 2012)

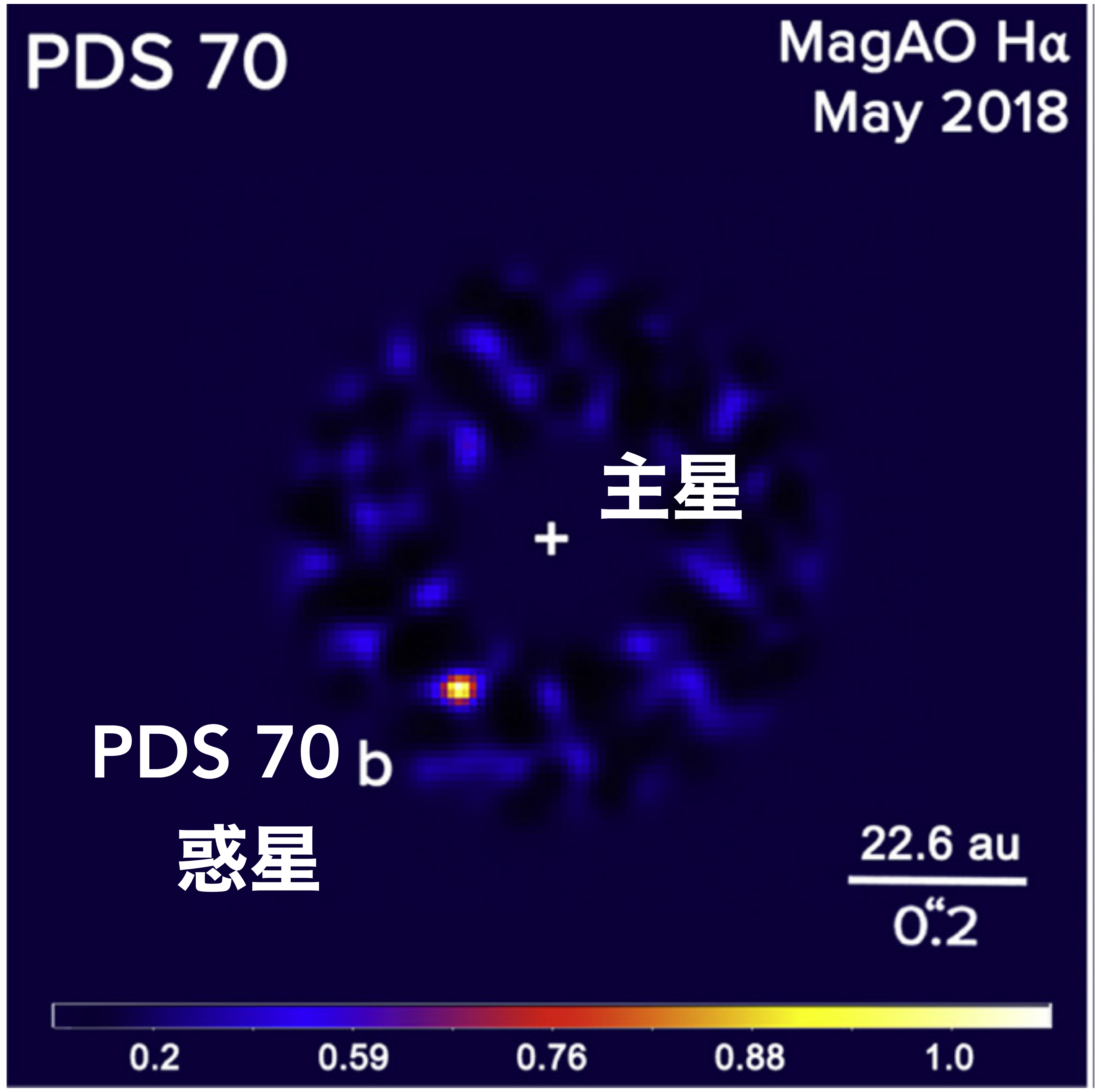


Existence of gas giant planets
which are massive enough to open the gap
were predicted.

Hα emission from Objects in PDS70 Disk

MagAO Hα SDI on 6.5 Mag-Clay telescope

Wanger et al. (2018, ApJL)

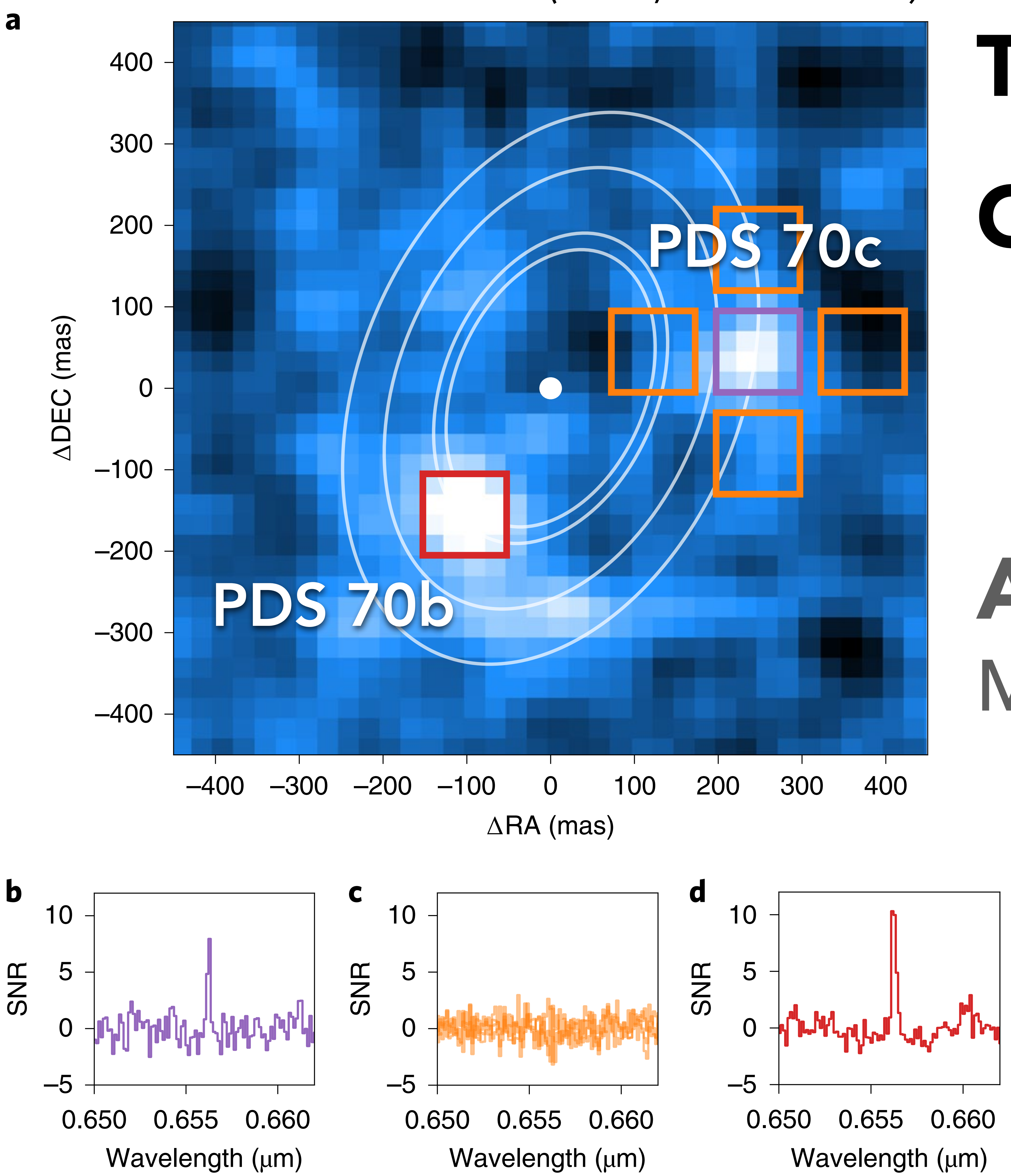


113.43±0.52 pc

5.4±1.0 Myr

LTAO-HRSDI in MUSE@VLT

Haffert et al. (2019, Nat.Astron.)



Two Hα emitters

Observed constraints

Intensities

Line shapes

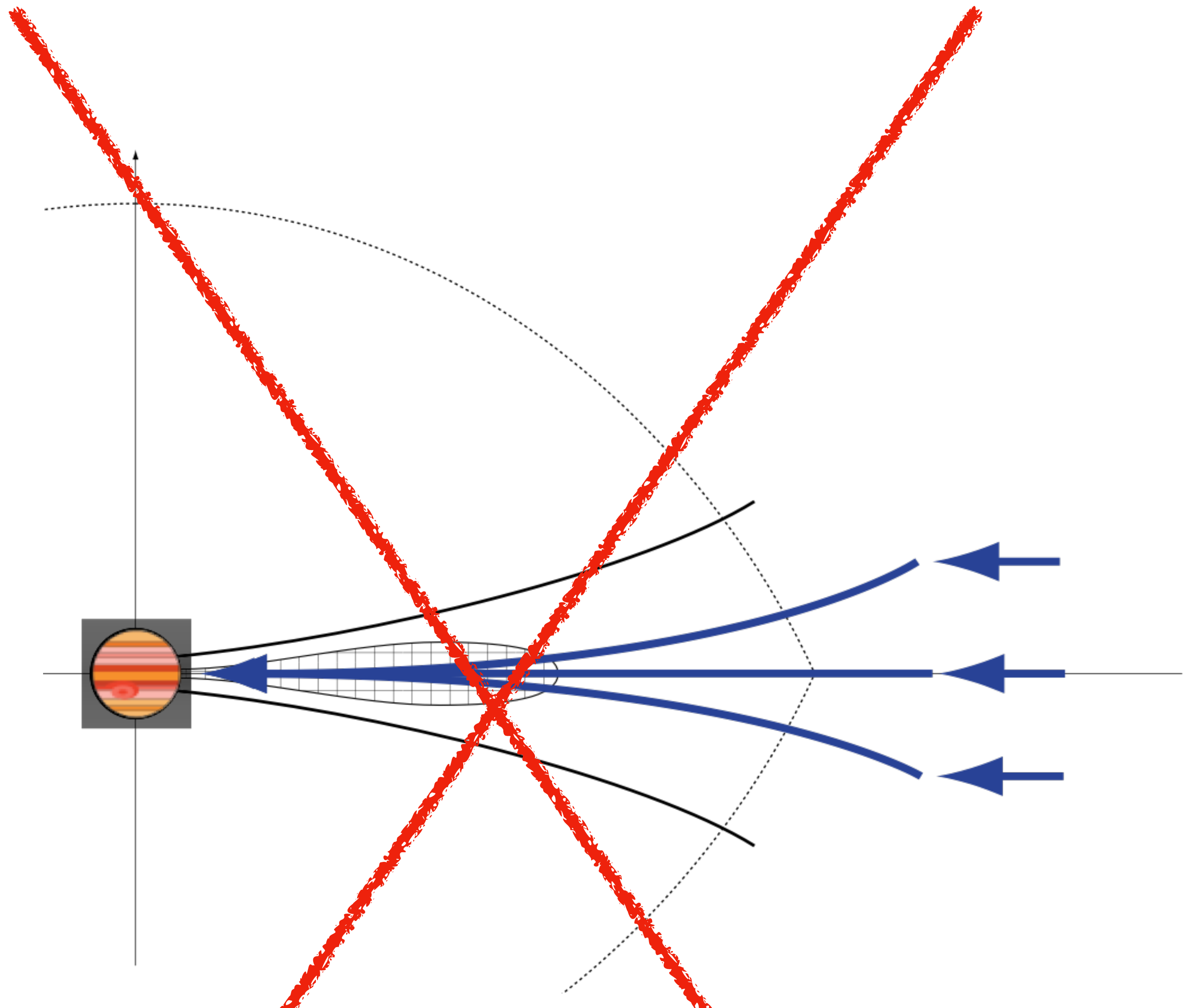
Appear to be near 2:1 MMR -> migration?

What is the origin of Hα emission?

Late Stage Accretion

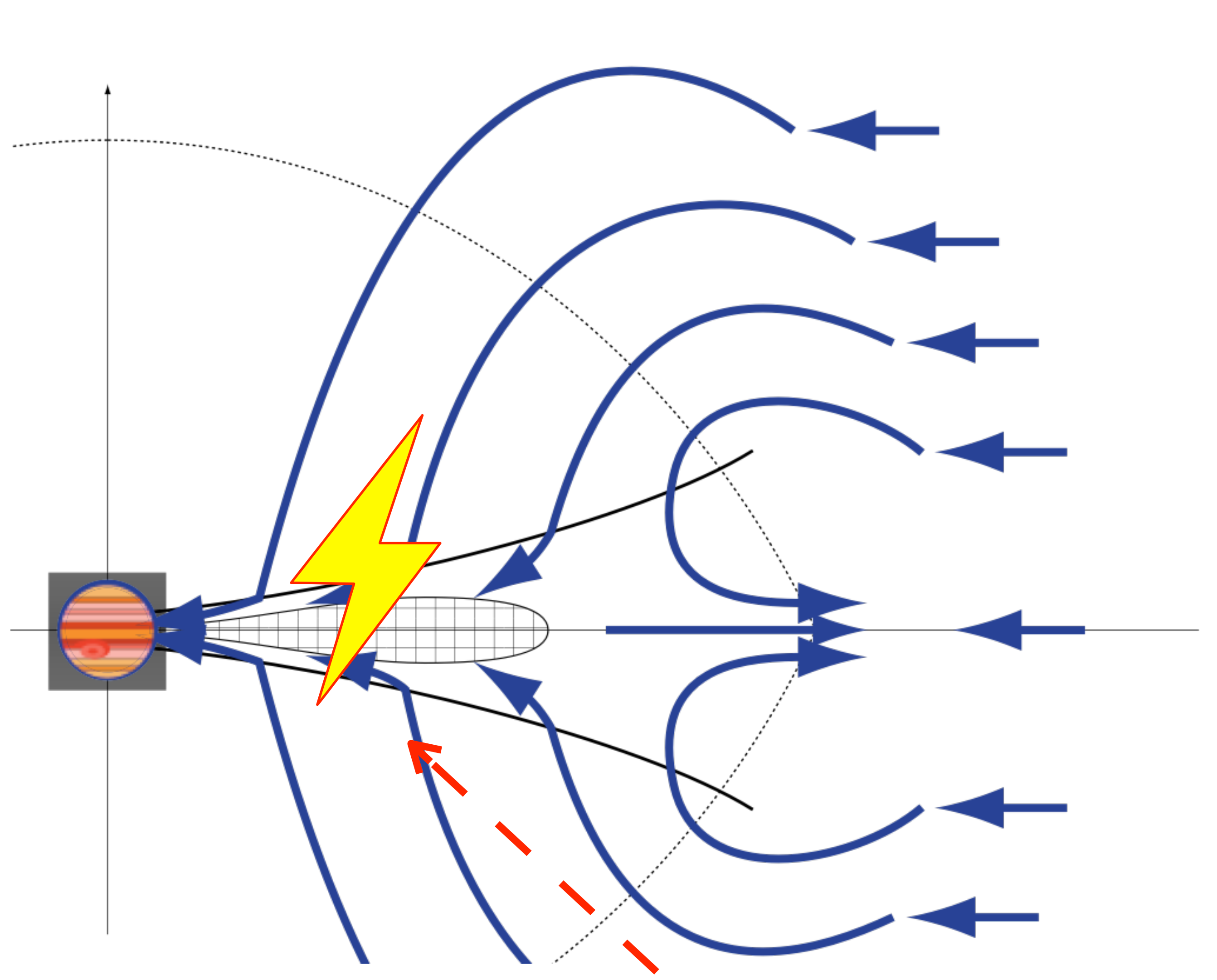
Three different pictures

2D



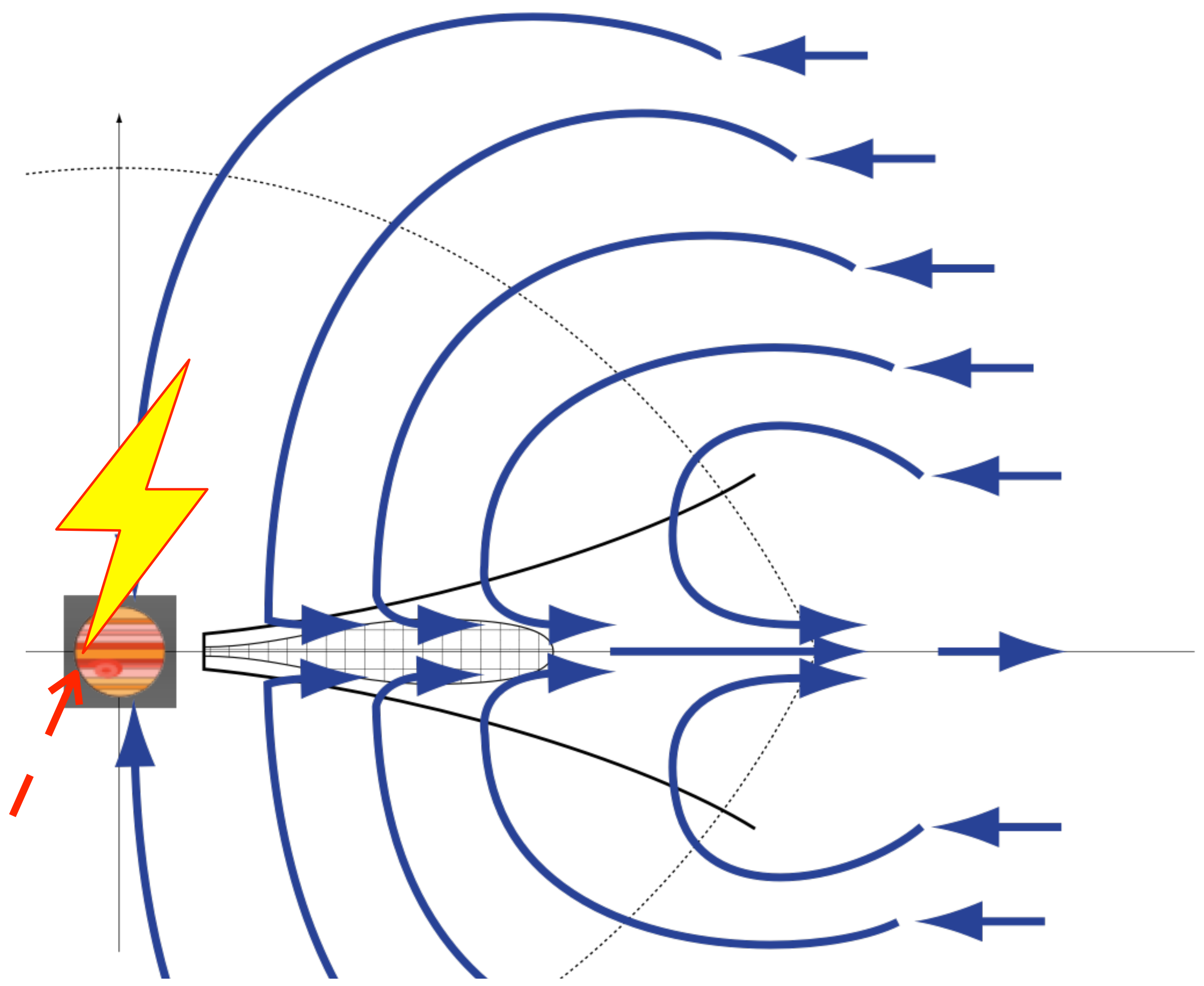
Accretion through a circum-planetary disk (CPD)

3D



Vertical infall +
Accretion through CPD

3D + Magnetic field

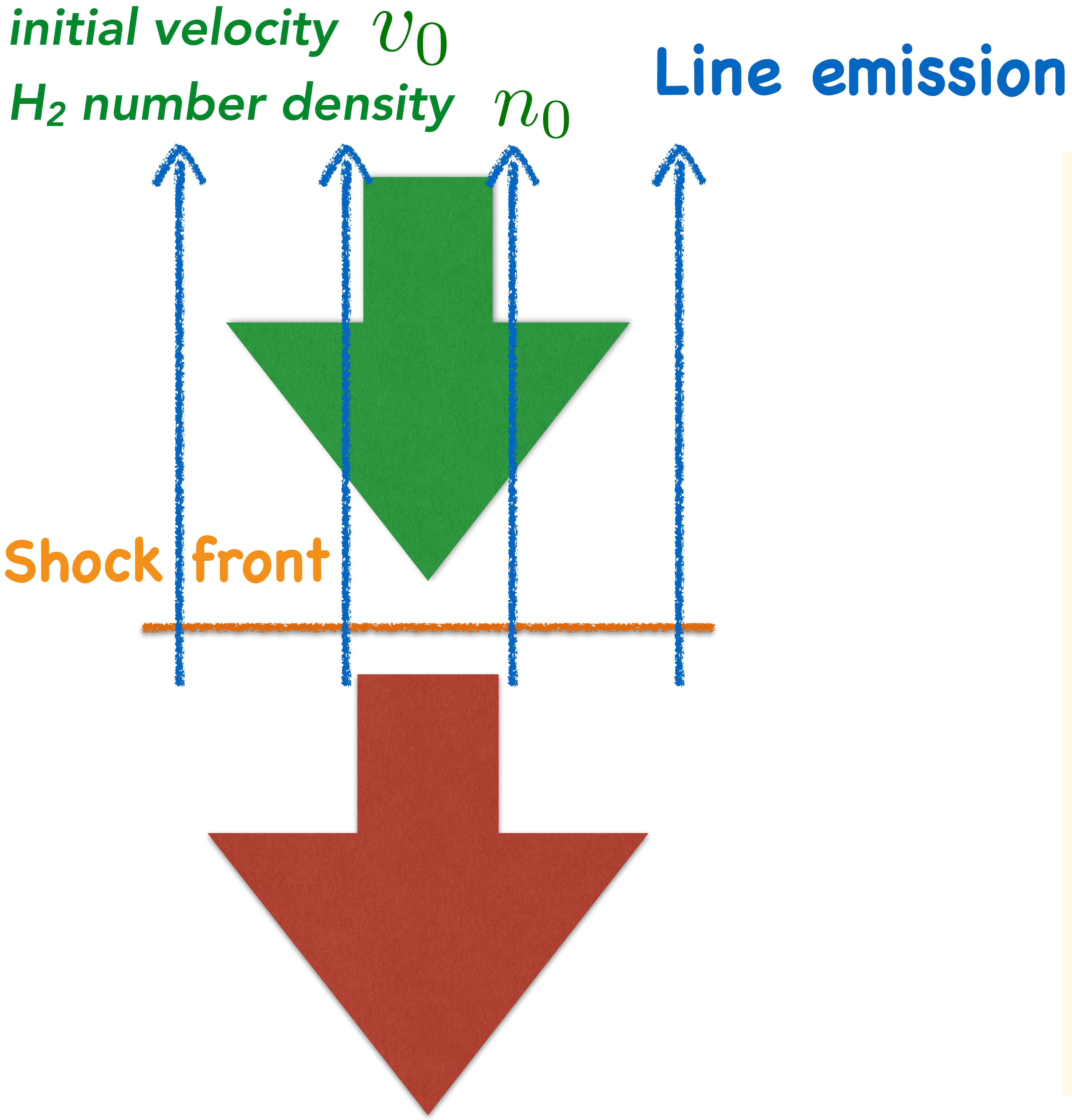


Vertical infall +
Deccretion through CPD

Shock heating + Line emission

1D Radiation Hydrodynamic Model

Aoyama, Ikoma, & Tanigawa (2018, ApJ)



1) Hydrodynamics

- *Eq. of continuity*
- *Eq. of motion*
- *Eq. of energy*

2) Chemical reactions

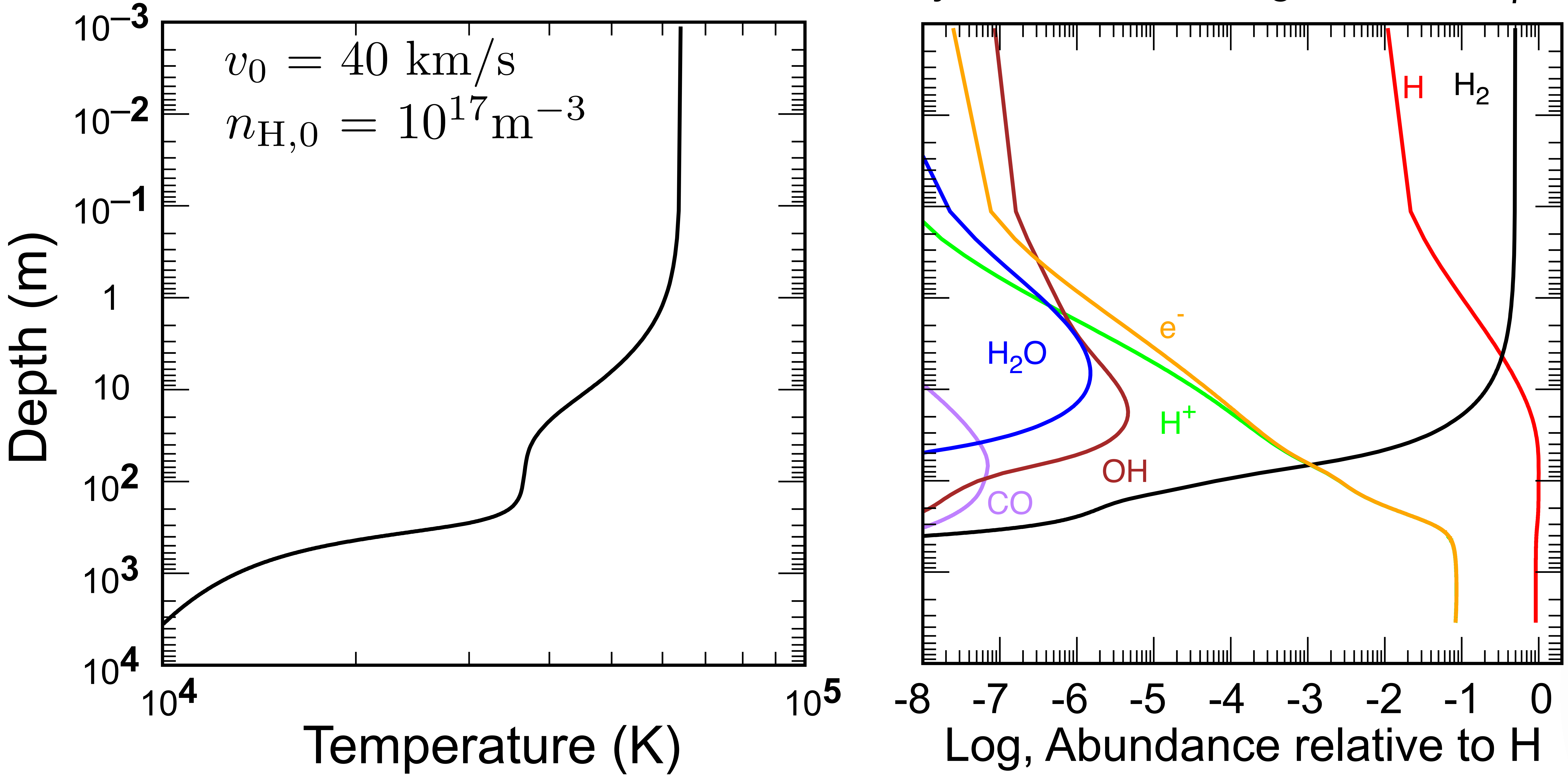
- *H, He, C, O, N, e*
- *60 species & 246 reactions*

3) Electron transitions

- *Collisional excitation*
- *Radiative absorption & emission*

Post-shock Process

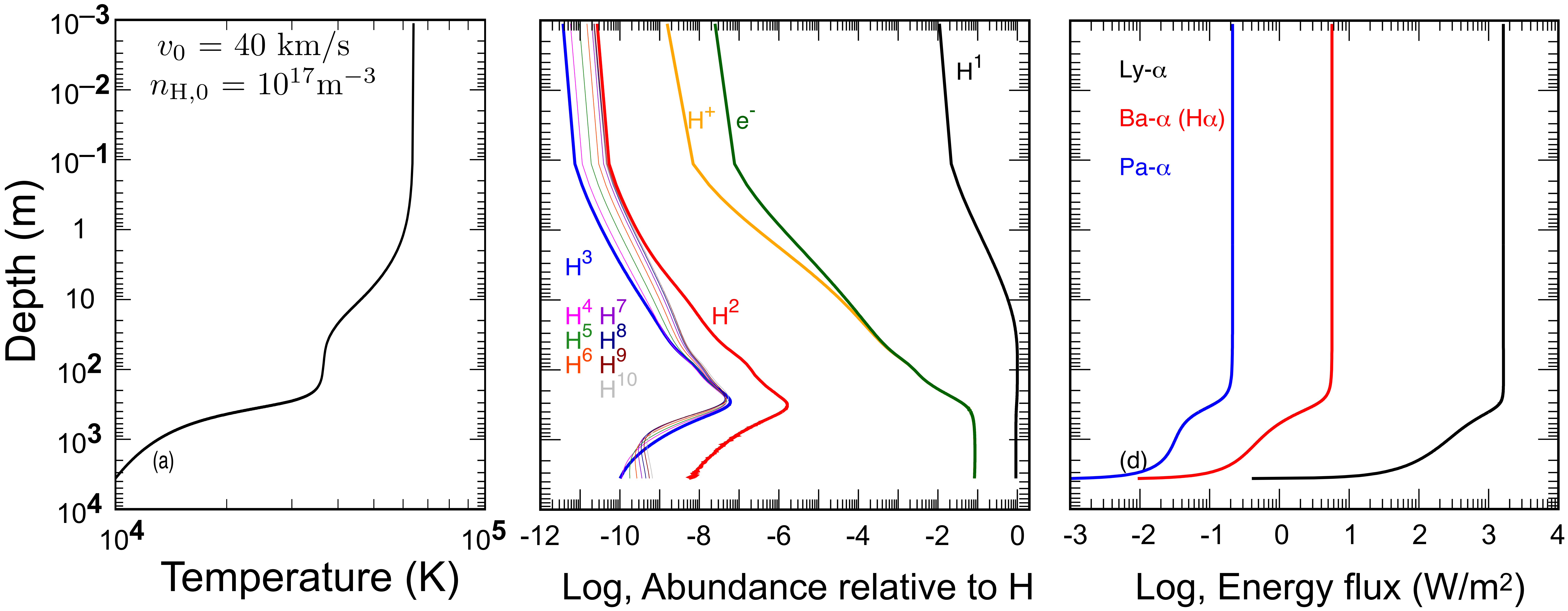
Aoyama, Ikoma, & Tanigawa (2018, ApJ)



The shock-heated gas is hot (~7x10^{4}K) enough to dissociate and also ionize hydrogen, producing a number of electrons.

Post-shock Process

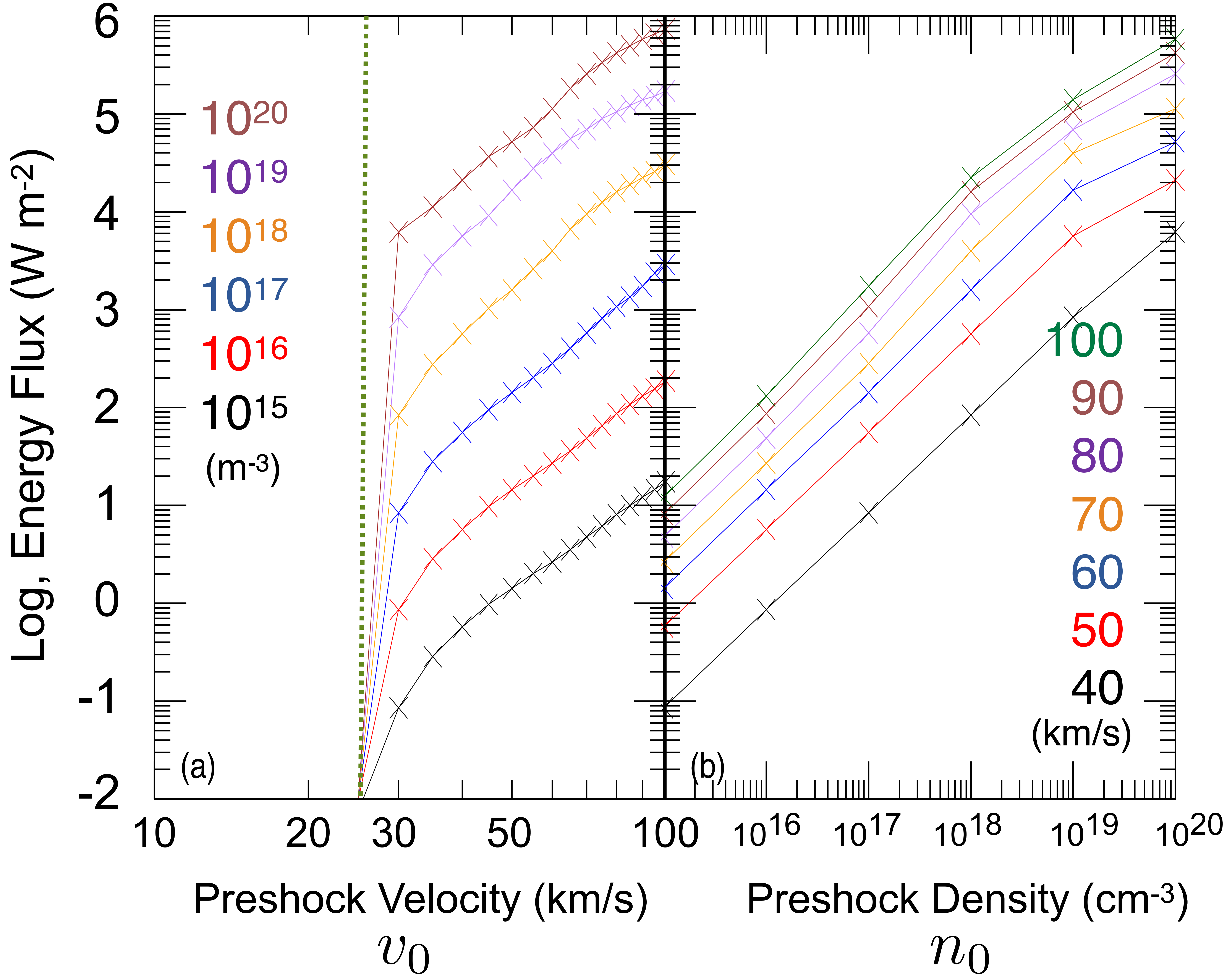
Aoyama, Ikoma, & Tanigawa (2018, ApJ)



Those free electrons collide with and excite hydrogen atoms, resulting in hydrogen line emission.

Hydrogen Line Emission

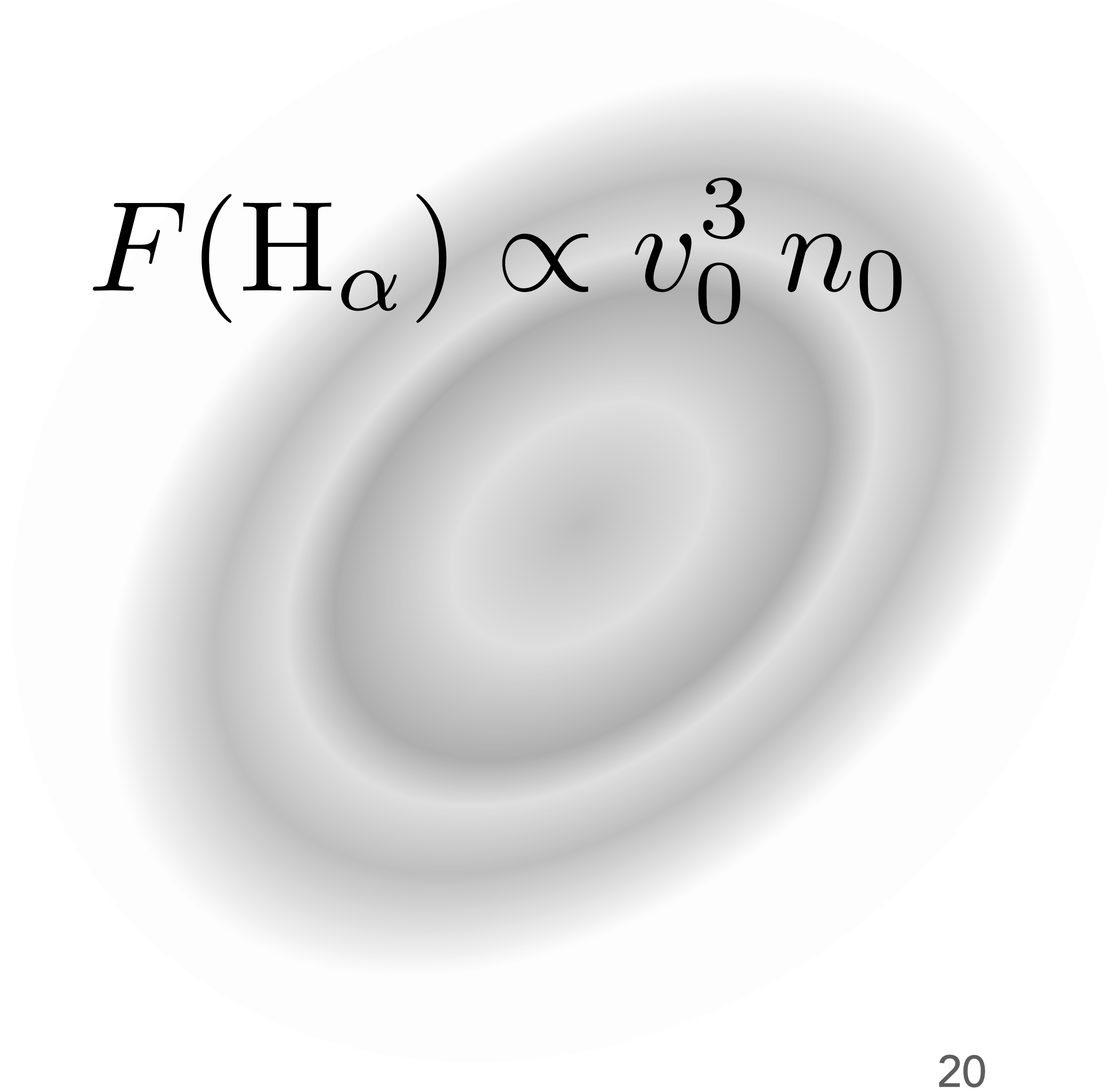
Aoyama, Ikoma, & Tanigawa (2018, ApJ)



Increase with preshock velocity

➡*Decrease with radial distance to the planet*

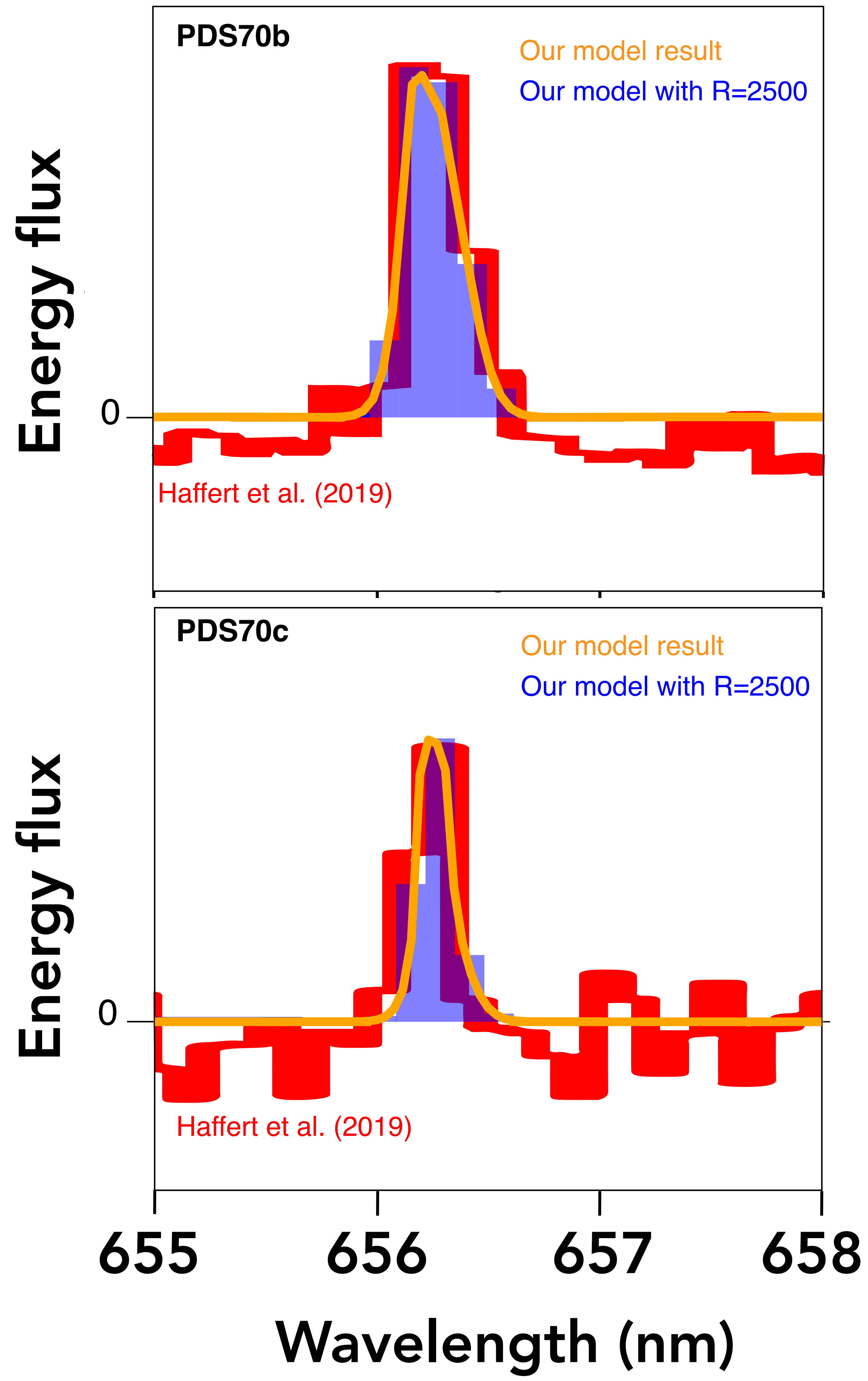
Increase with number density

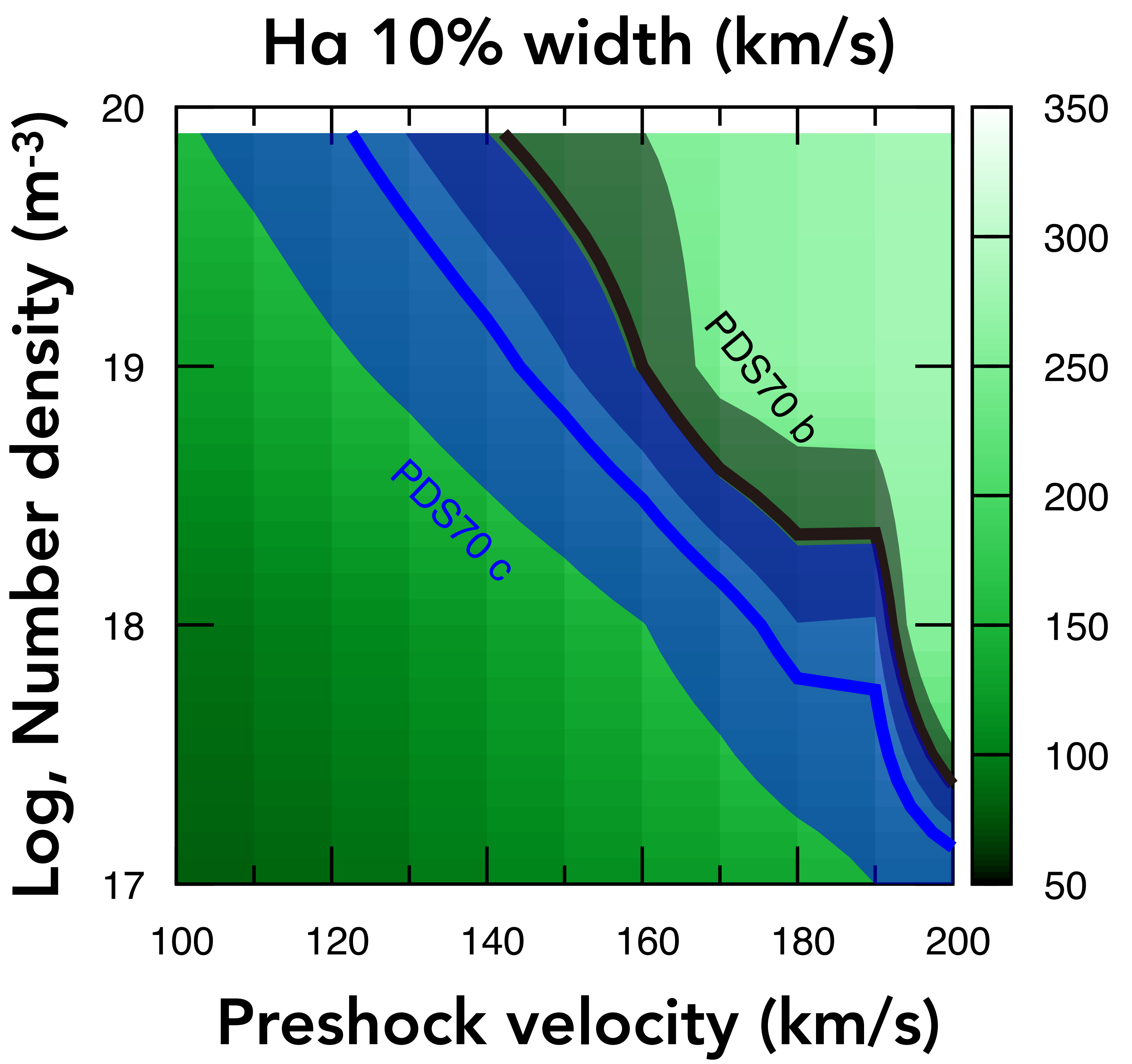


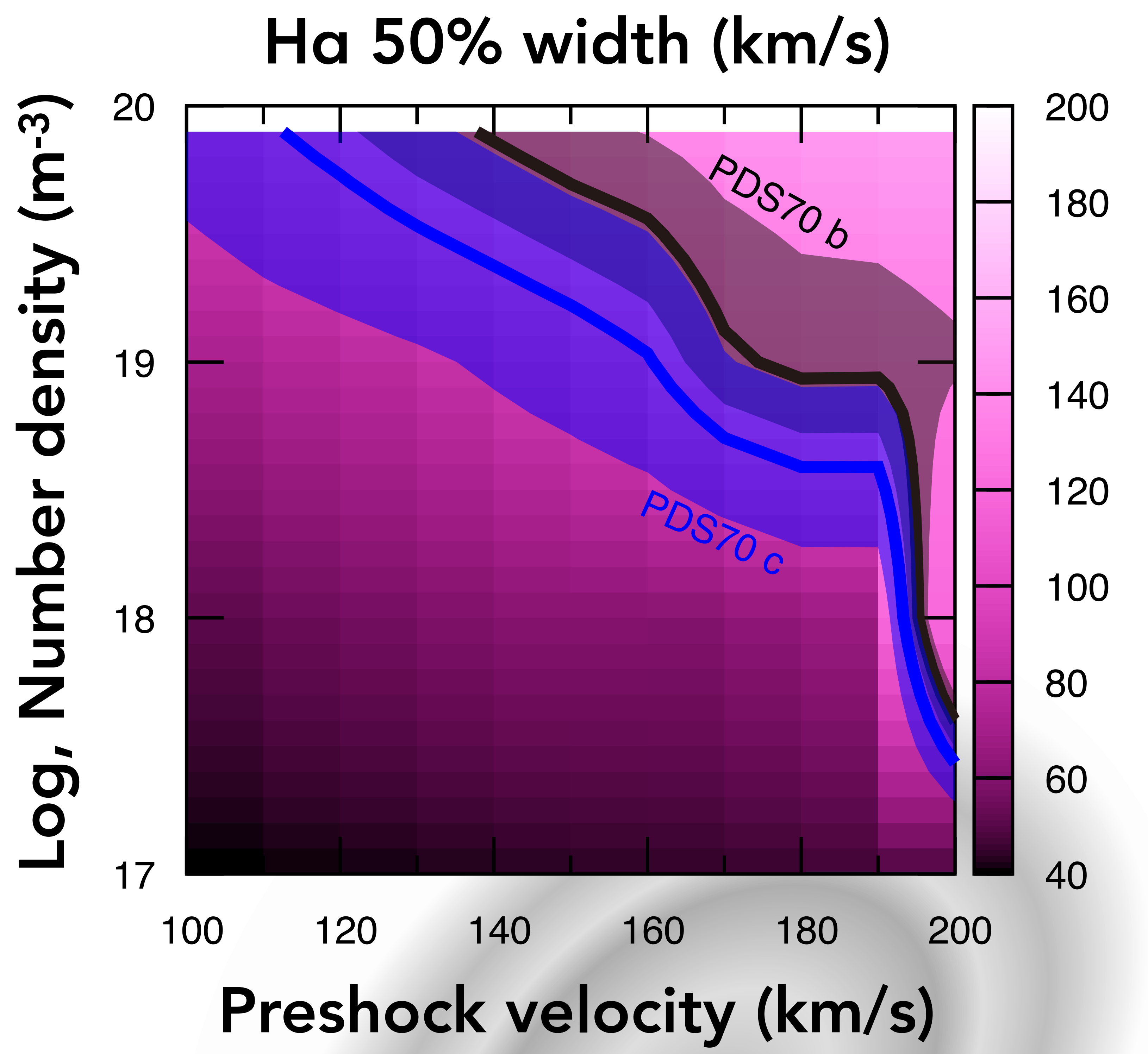
$$F(\mathrm{H}_\alpha) \propto v_0^3\, n_0$$

Comparison with Observed Line Widths

Line Profile







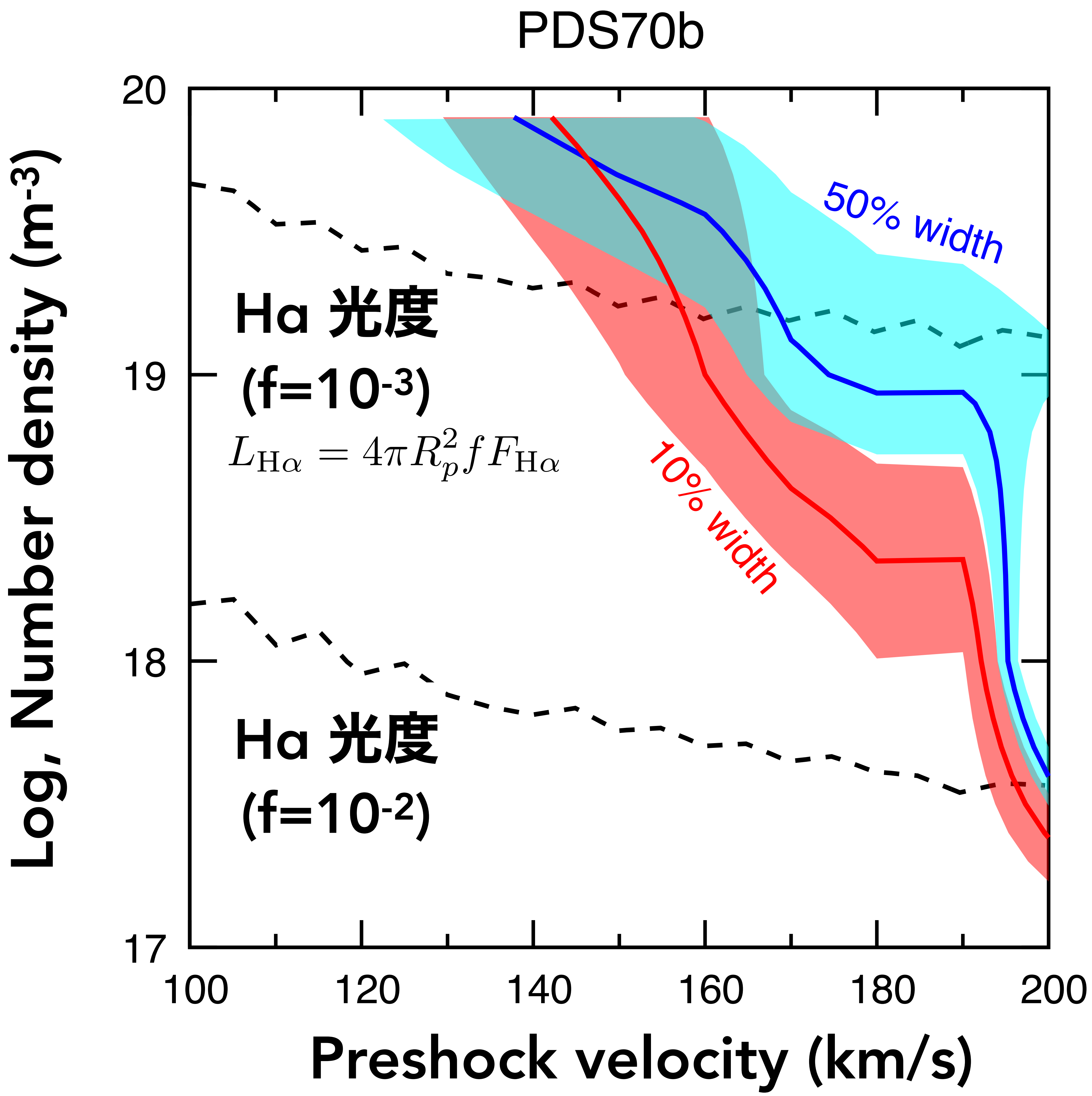
← Our theoretical model reproduces observation.

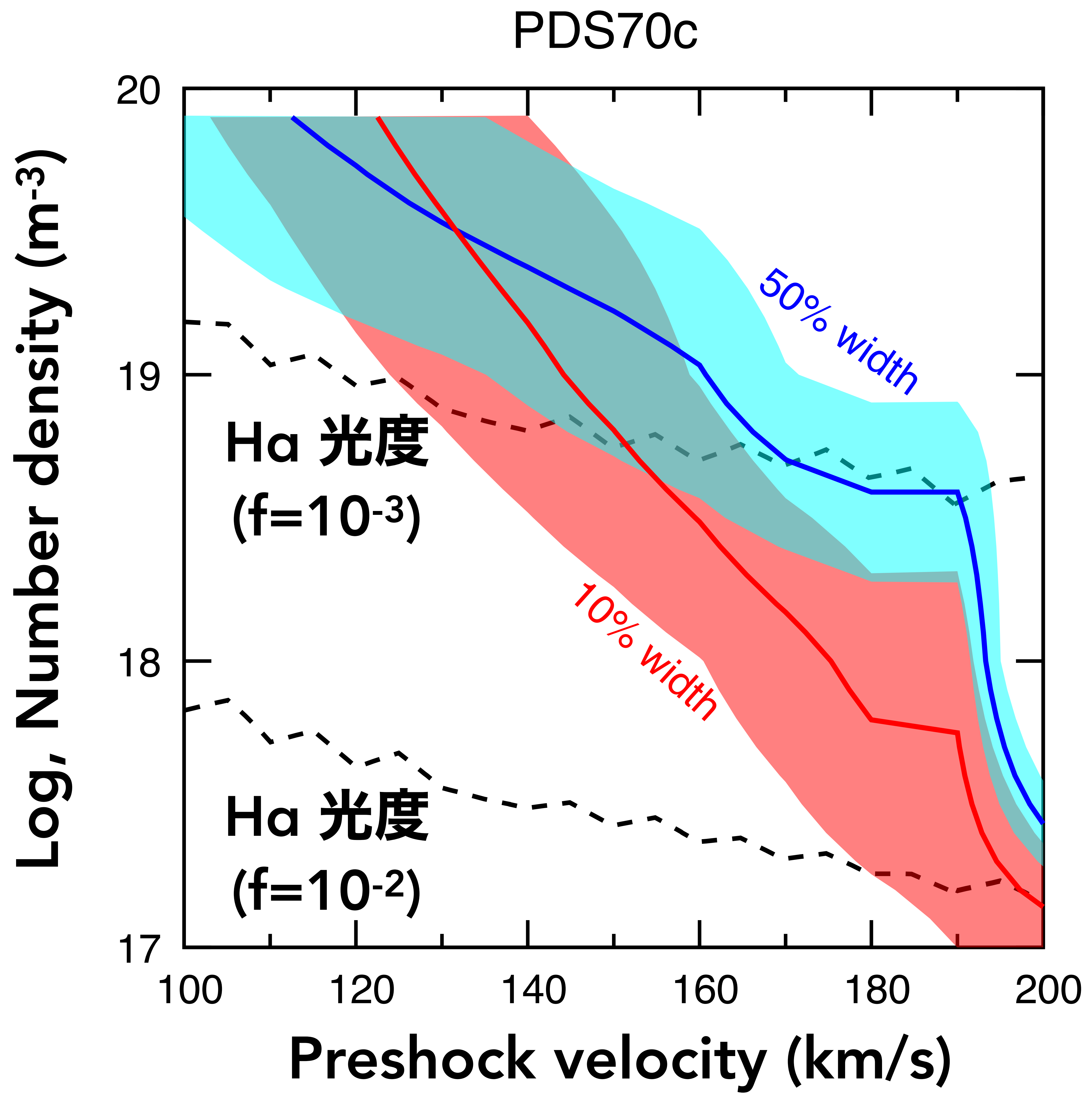
↑Higher velocity yields larger width (Doppler broadening)

↑Higher density yields larger width (Absorption)

Aoyama & Ikoma (2019, ApJL)

Constraints to Accretion Flow Properties

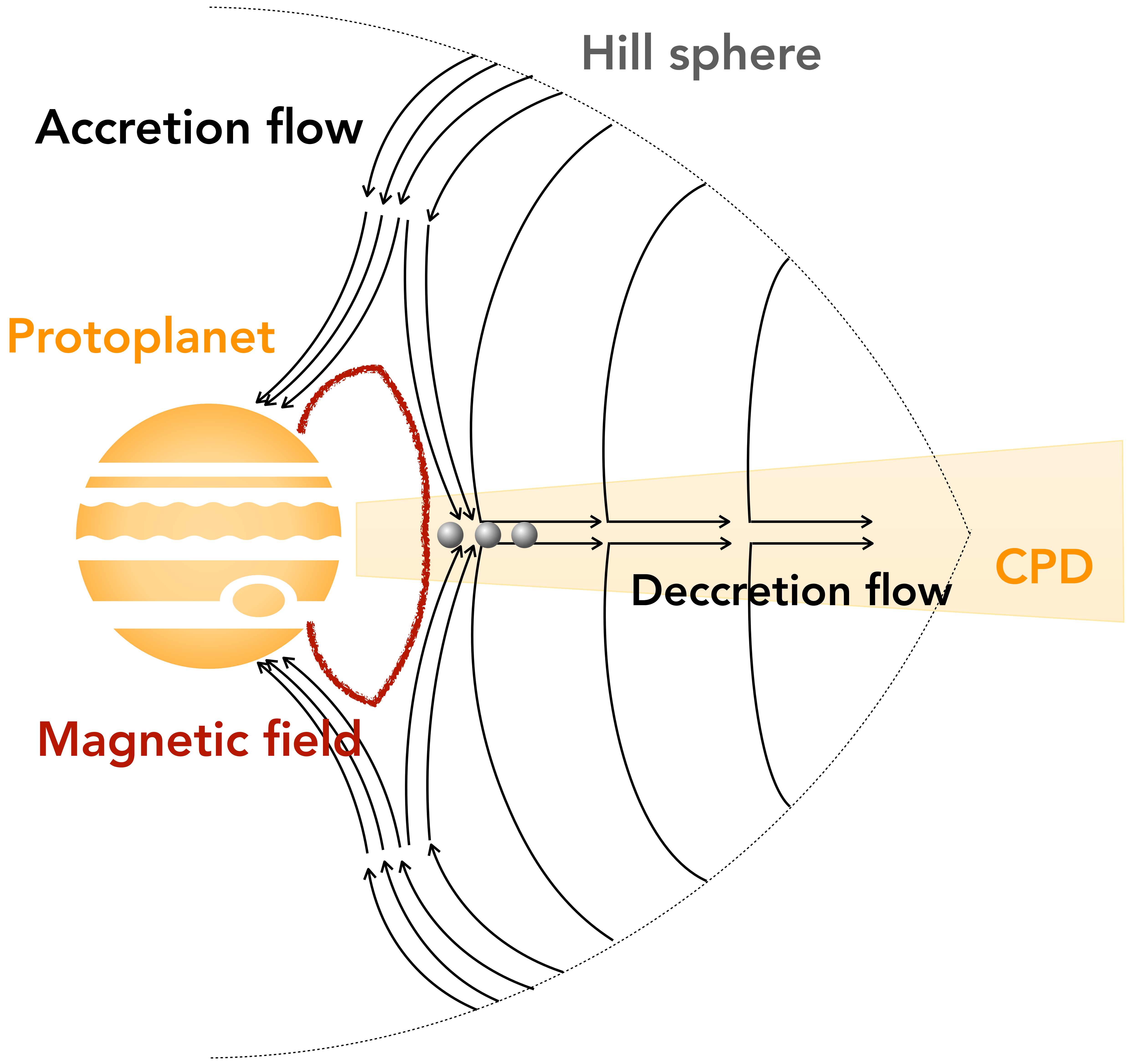




Aoyama & Ikoma (2019, ApJL)

~12 $M_\oplus$	Protoplanet mass	~10 $M_\oplus$
~1x10^{-5} $M_\oplus$/yr	Mass accretion rate	~3x10^{-6} $M_\oplus$/yr
~5x10^{-4}	Filling factor	~3x10^{-4}

Picture of Accretion Flow of PDS70b & c



Vertical Flow onto Protoplanet

Most of the accreting gas flows vertically and directly onto the central protoplanet with the help of the protoplanet's intrinsic magnetic field.

Convergence of Accretion Flow

The accretion flow converges to quite narrow regions of the protoplanetary surface and experiences strong shock heating, resulting in hydrogen line emission.

Issues to Be Examined

- No detailed model of such accretion flow
- More samples other than PDS70 is needed.

Summary

- Subaru has made important contributions to understanding of the formation of giant planets through exoplanet observations.
- The bulk and atmospheric composition of giant exoplanets have been observationally constrained.
- The origin of heavy elements in gas giant planets remains a mystery, which is related to the late-stage accretion and migration.
- Recent observation is capable of accreting gas giants both indirectly and directly, which is of great help in understanding the formation of gas giants.
- Characterization of the atmospheres of gas giants and direct detection of infant gas giants by Subaru are expected.