IR Spectroscopy of Inner Planet-forming Disks

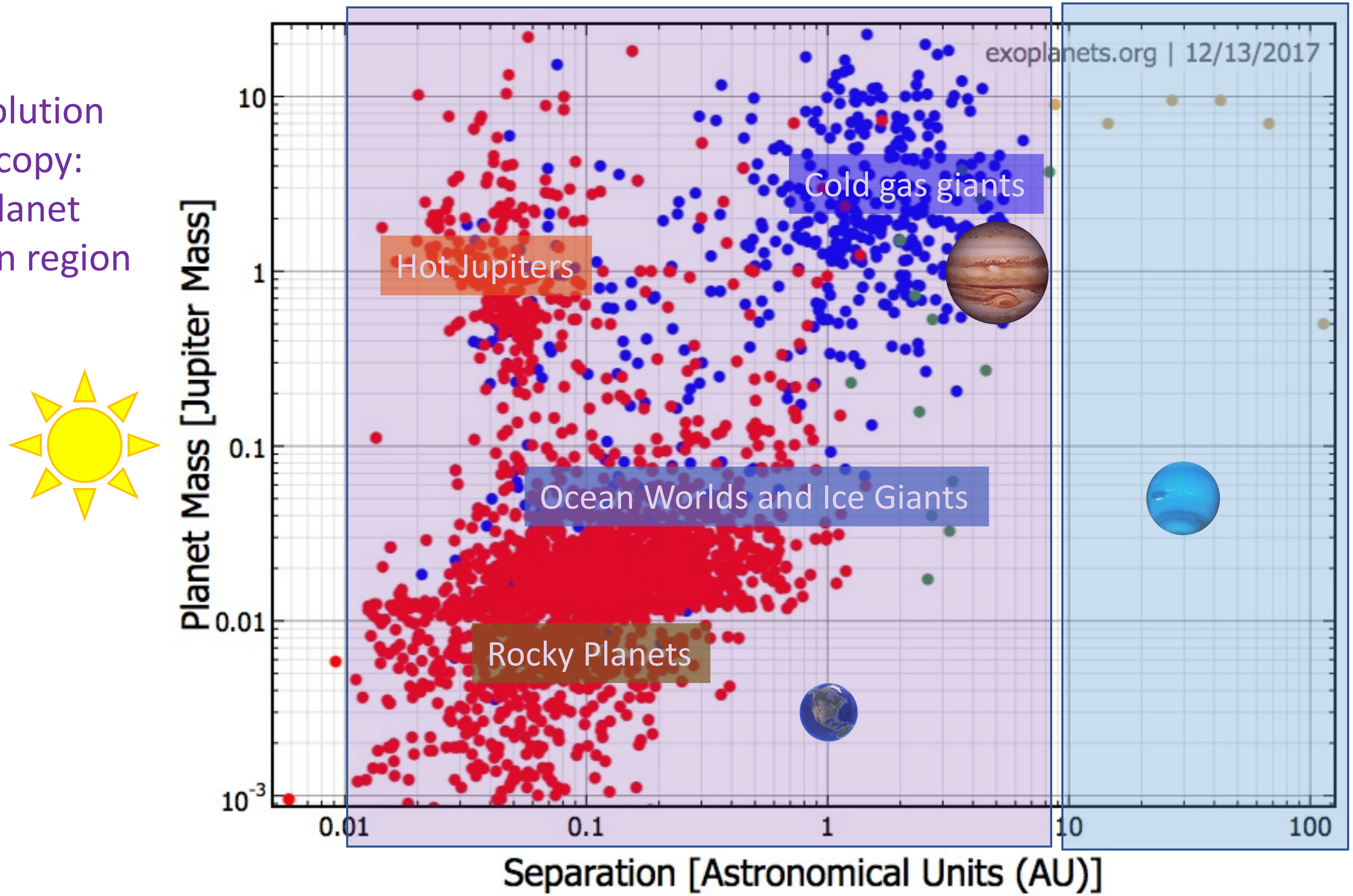
Joan Najita (NOIRLab)

Janus Kozdon, Sean Brittain, John Carr, Jeffrey Fung, Andrea Banzatti, et al.

Stefan Laos, Tom Greene, Keivan Stassun

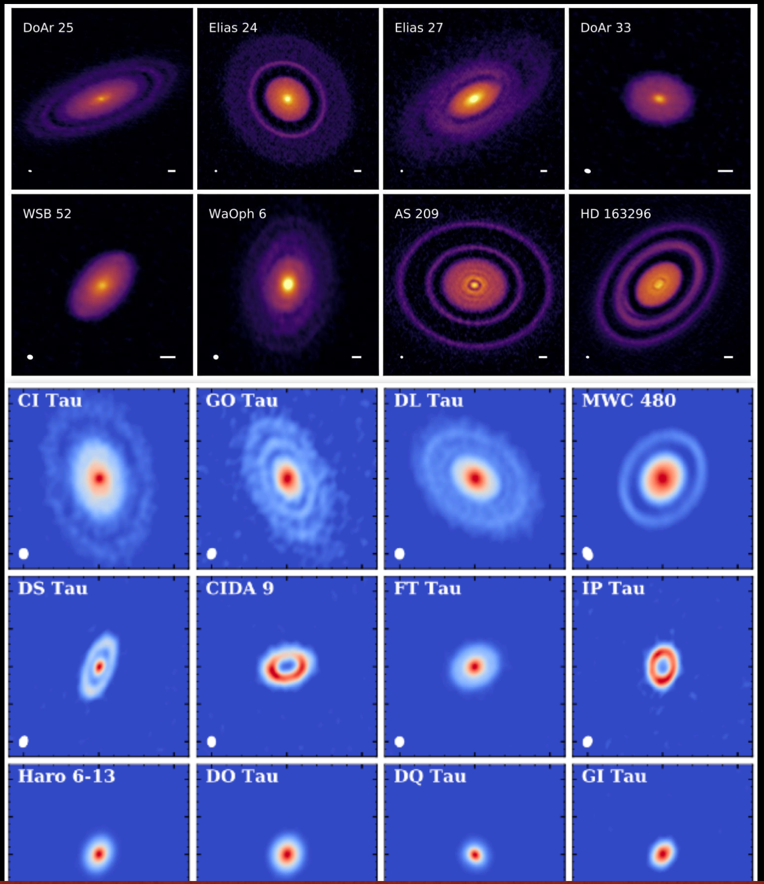
Exoplanet Populations

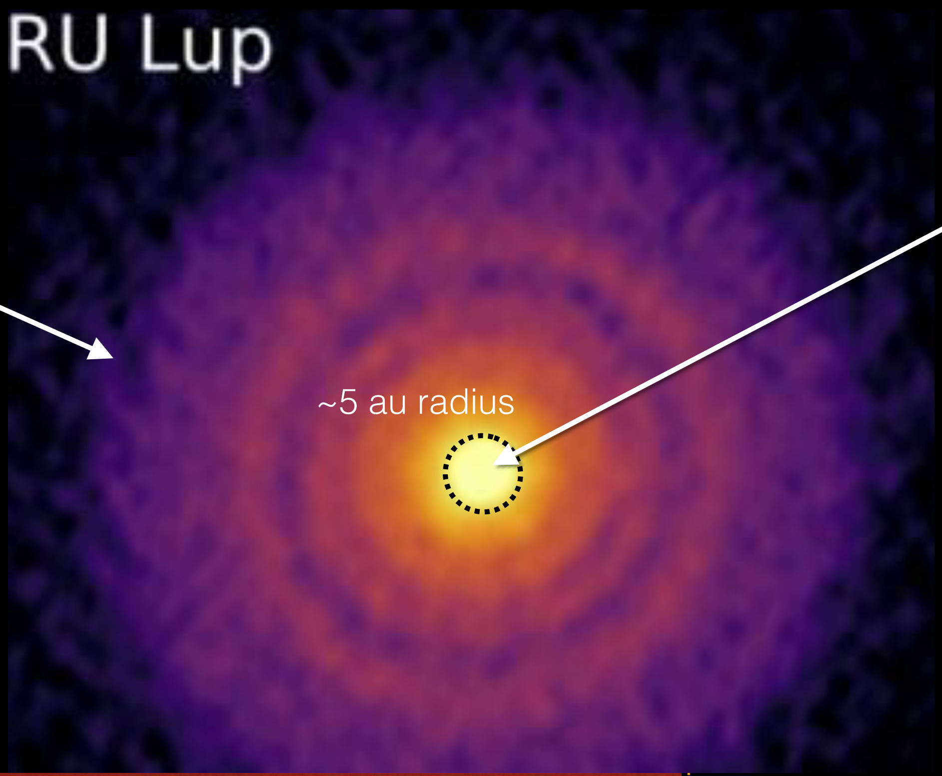
High resolution Spectroscopy: Probes planet formation region

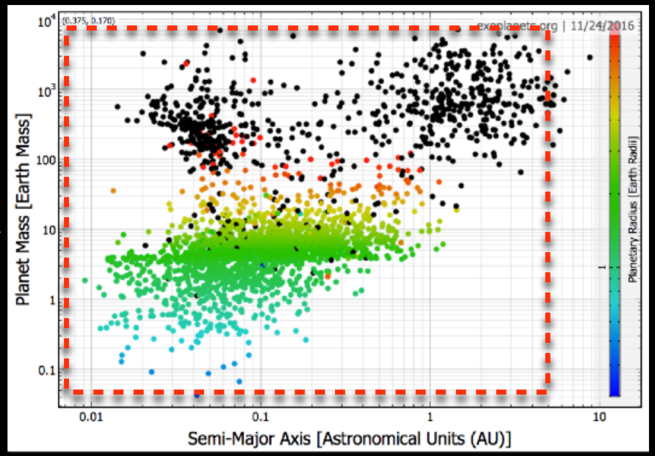


Imaging: ALMA, high contrast NIR

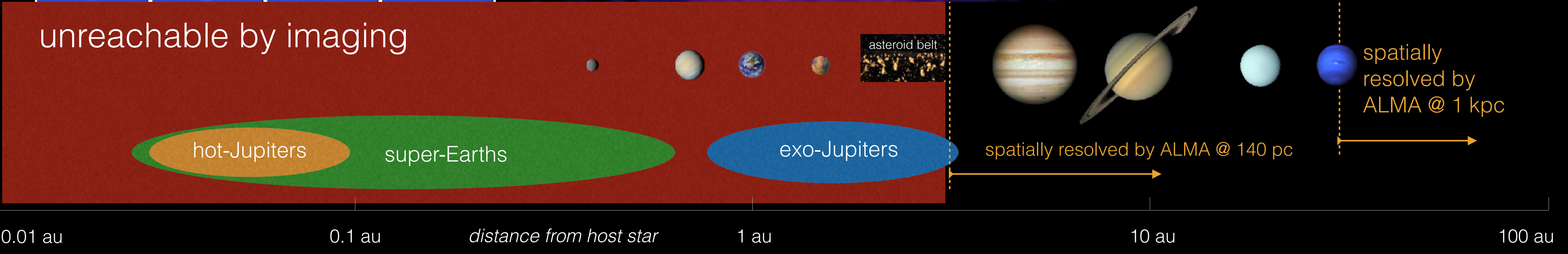
Can we observe disk regions where planets form?



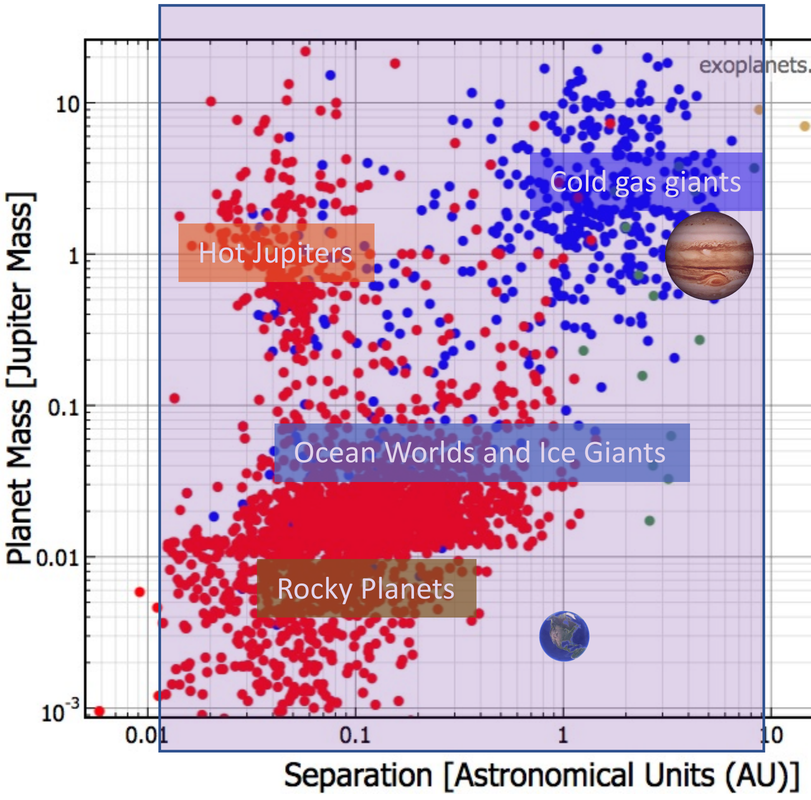




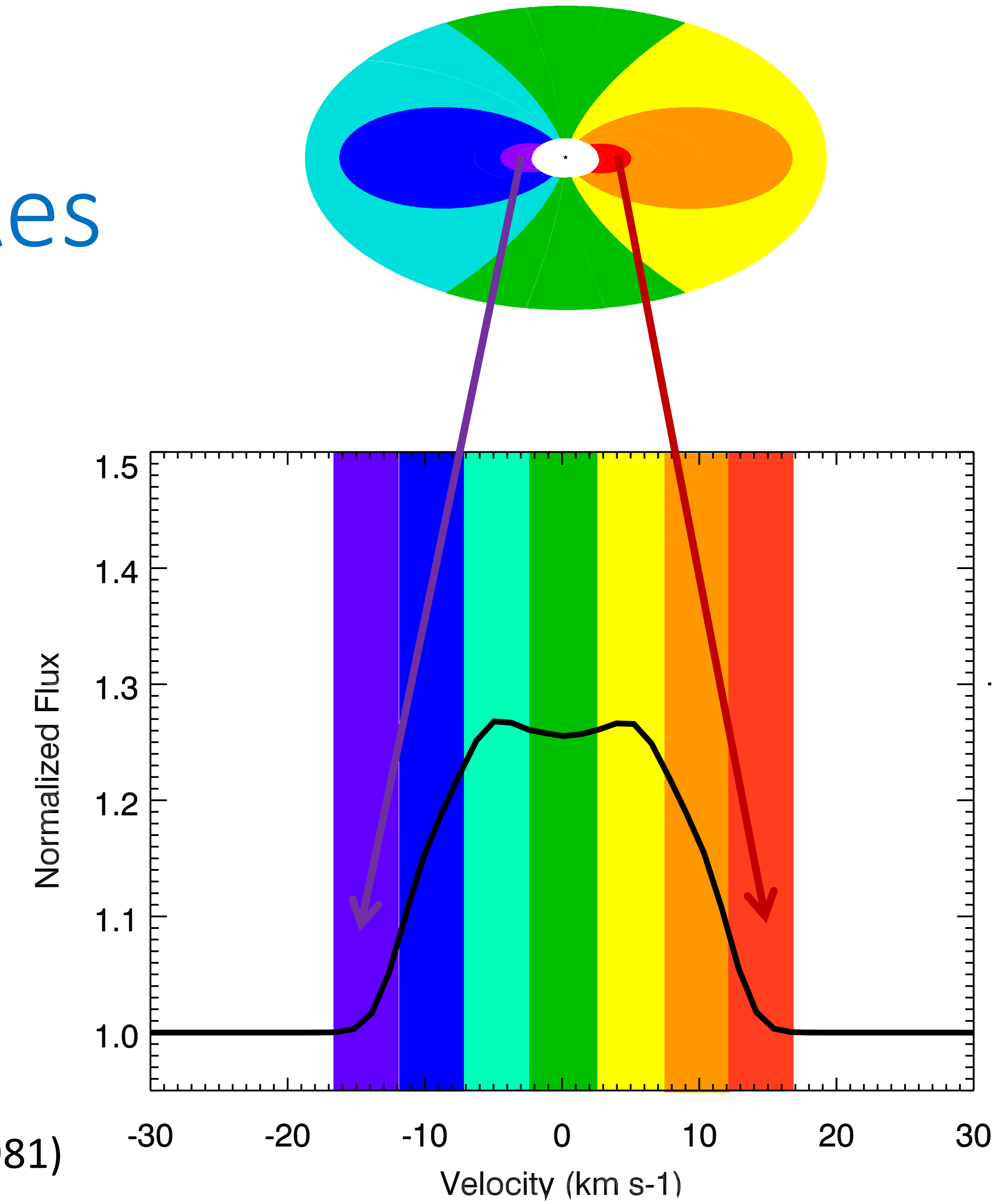
Slide from A. Banzatti



High Spectral Res: Surrogate for High Ang Res



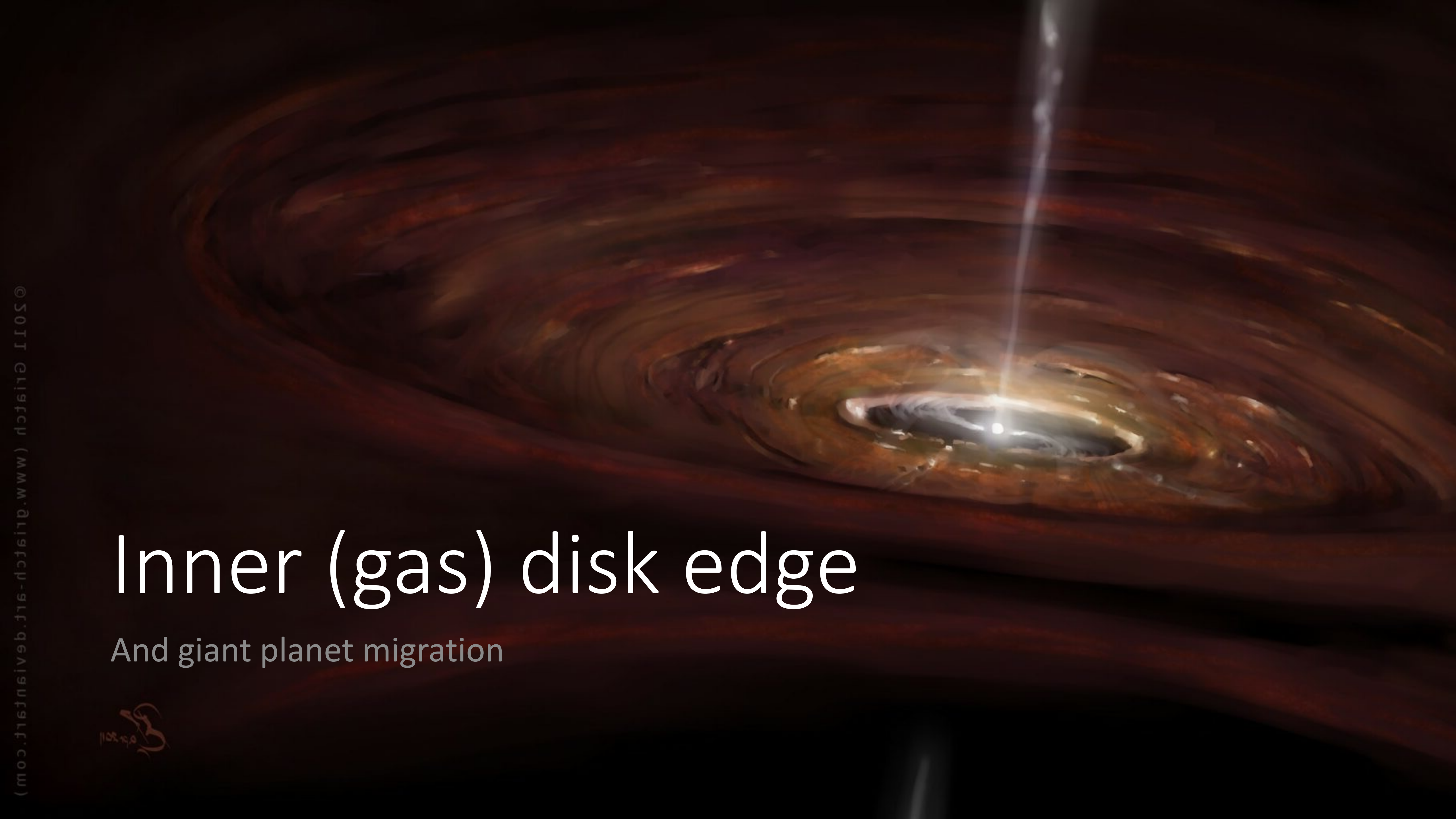
(See Smak 1981)



Graphics Credit: Sean Brittain

3 Quick Stories

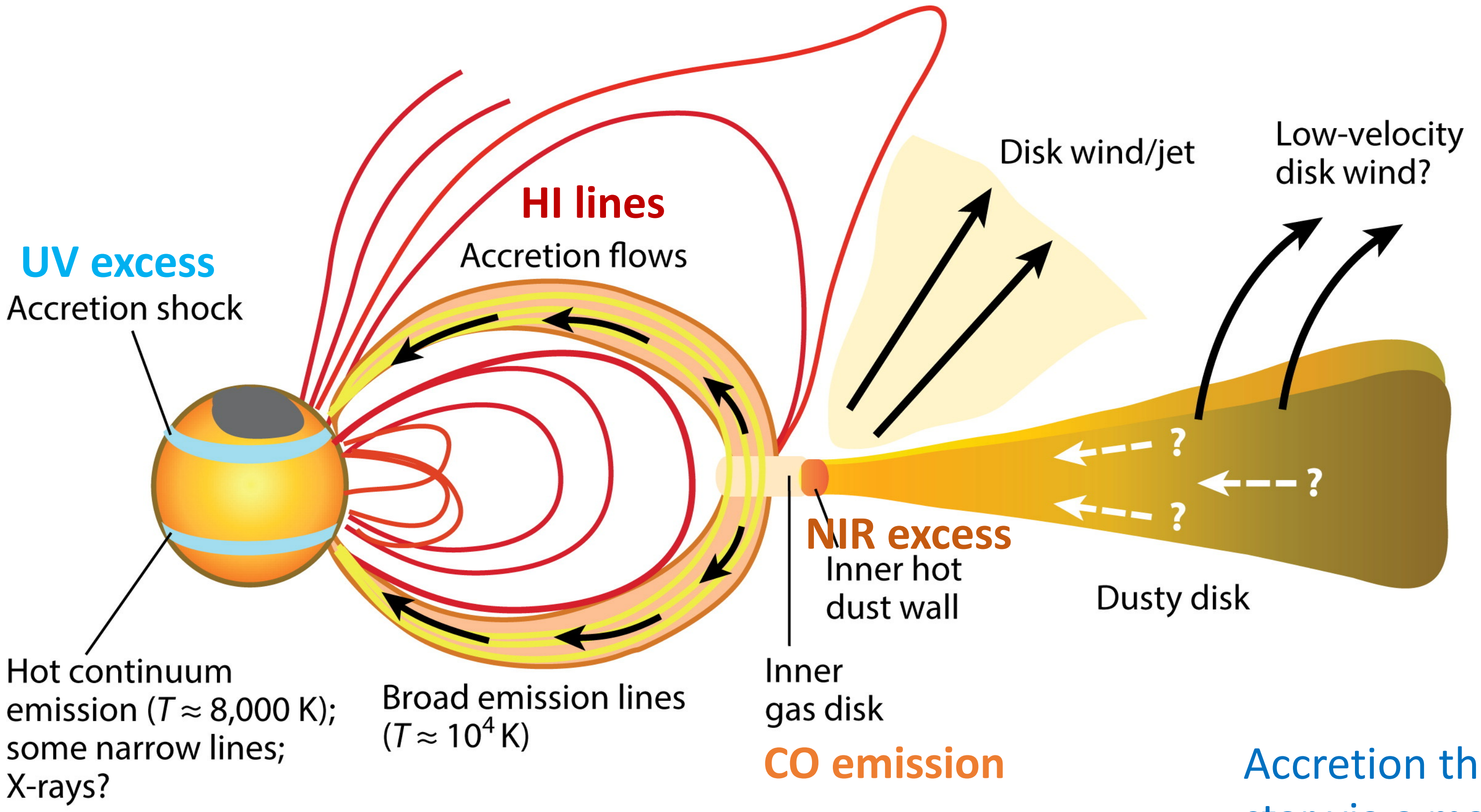
Inner gas disk radii	disk and planet demographics
HD100546	signposts of planet @ 10au
CI Tau	signposts of known planet < 1au



Inner (gas) disk edge

And giant planet migration

The near-stellar environment of T Tauri Stars

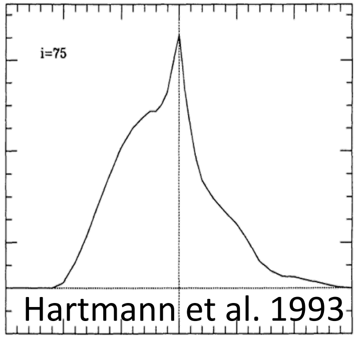


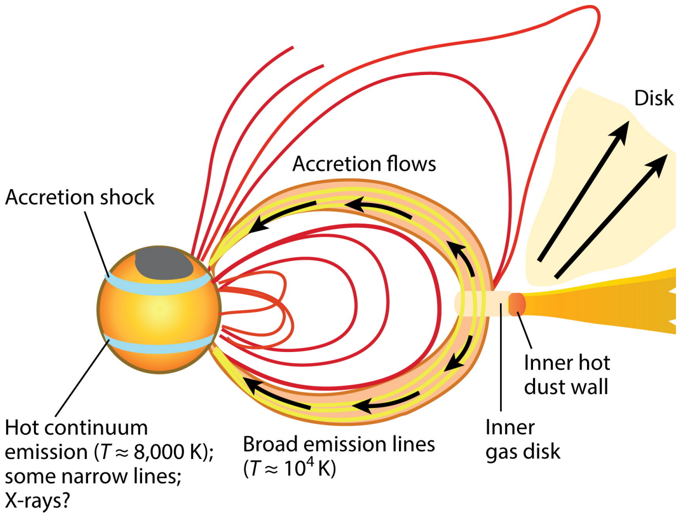
Accretion through disks and onto star via a magnetosphere

Hartmann et al. 2016

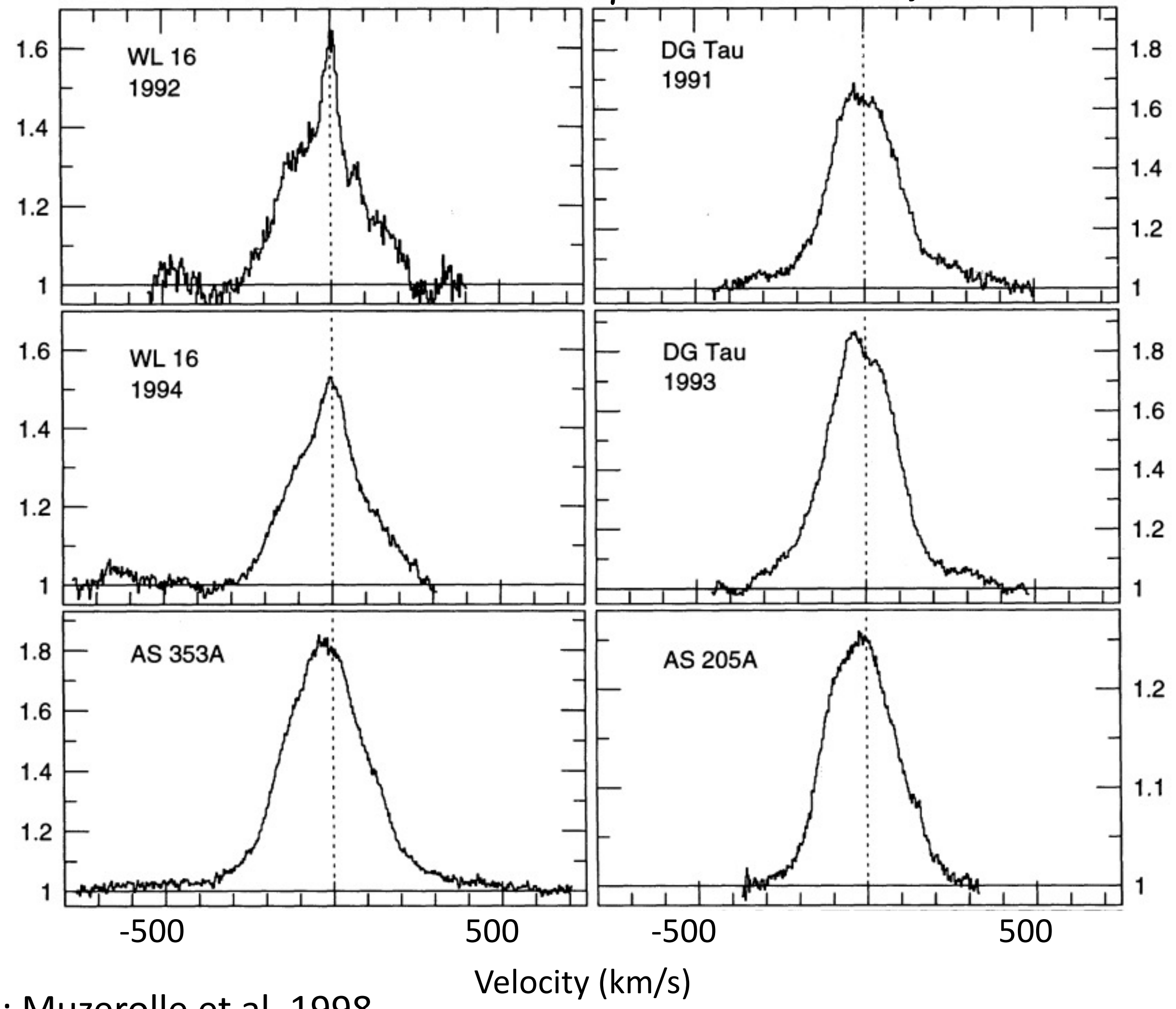
Stellar Accretion via Magnetospheres

Theoretical profiles





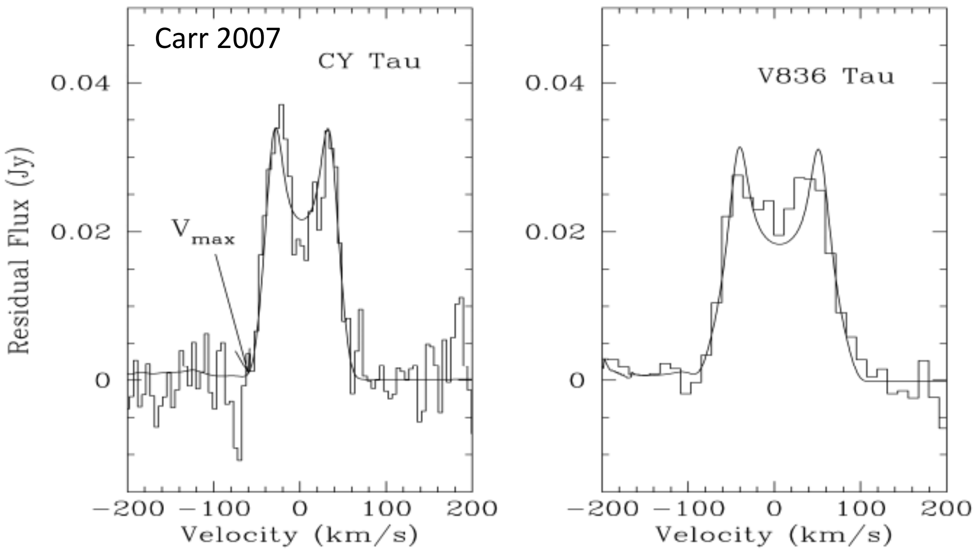
Br γ Najita et al. 1996

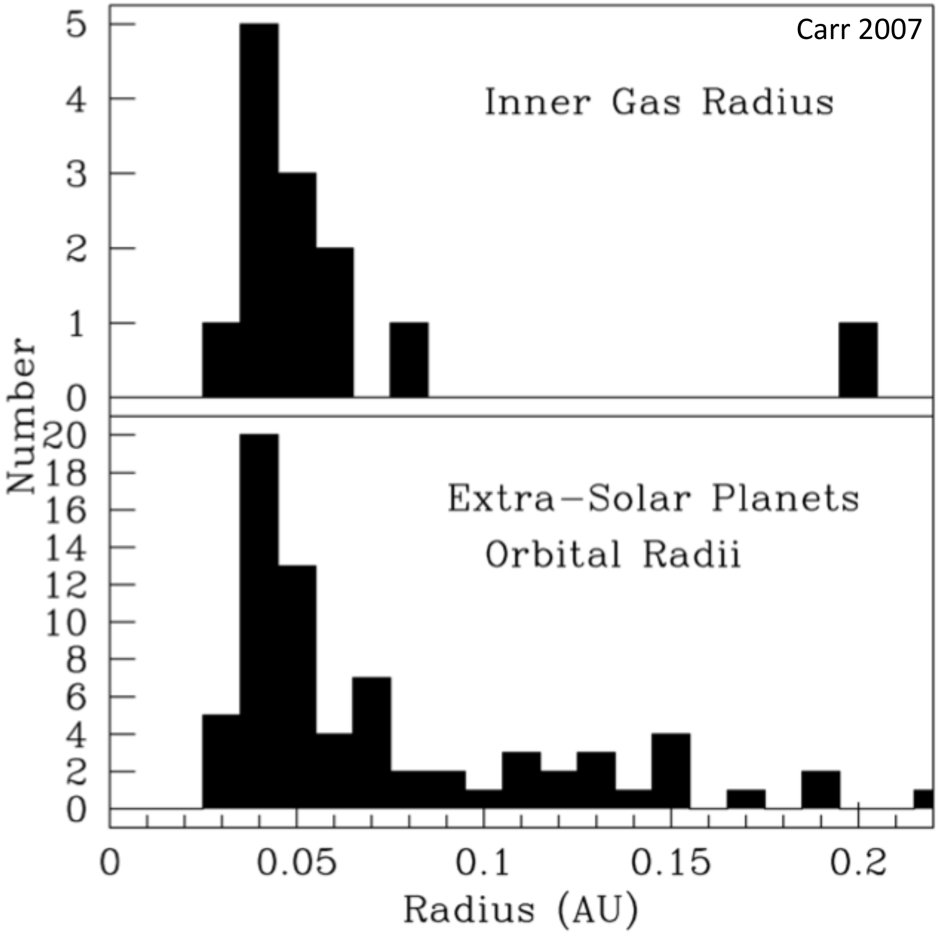


See also Calvet & Hartmann 1992; Hartmann et al. 1994; Muzerolle et al. 1998

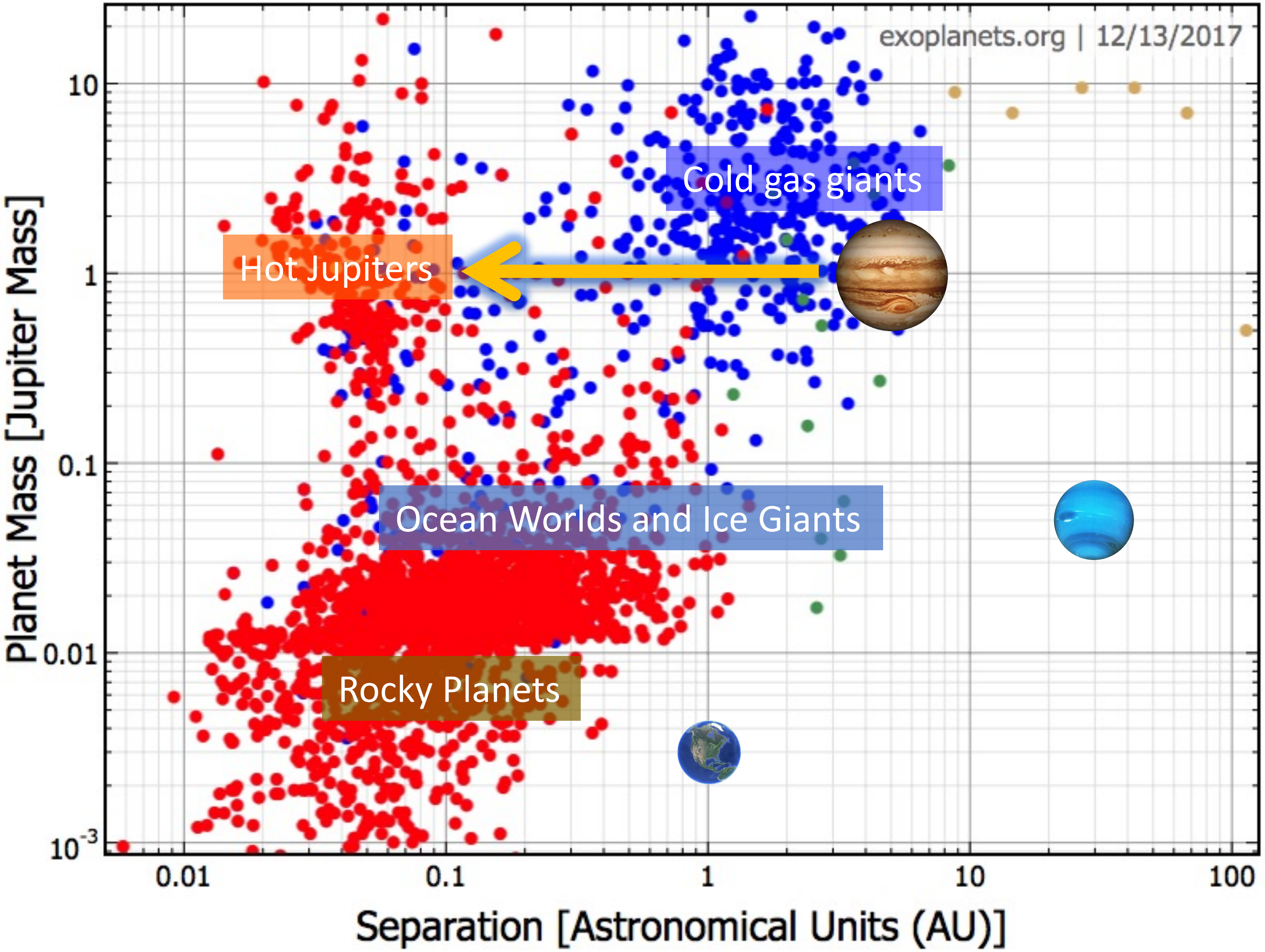
Inner Disk Radii and Exoplanet Orbital Radii

CO fundamental line profiles of Classical T Tauri stars





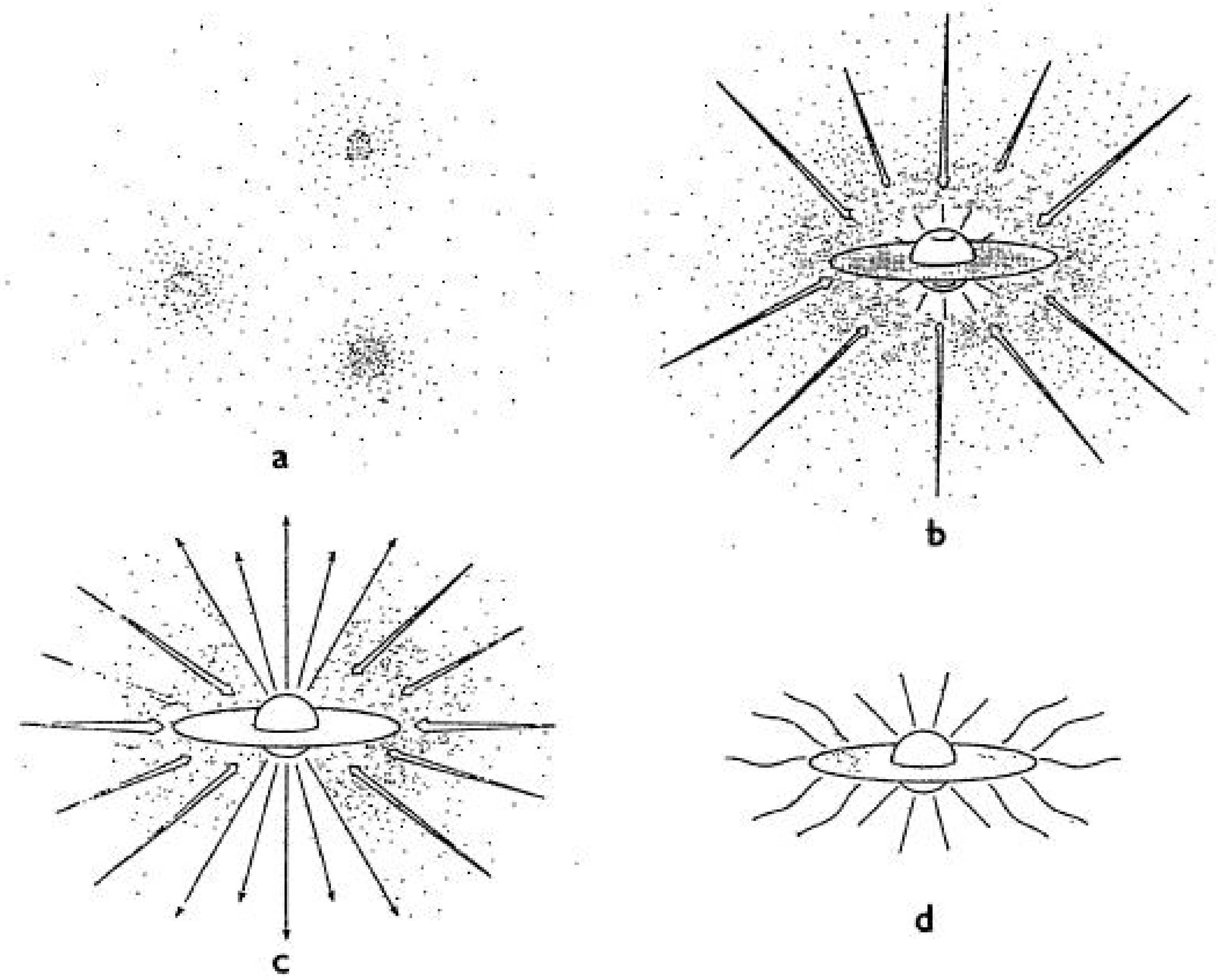
Exoplanet Populations



Gas giants can migrate into the inner disk edge

What about earlier epochs?

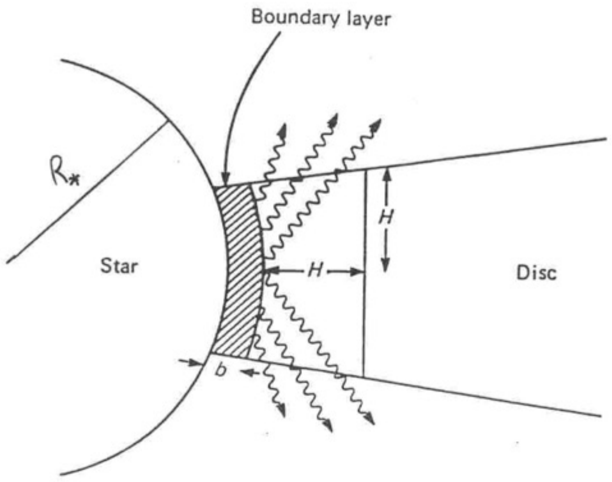
Shu et al. 80's



- Do disks extend up to the star?

Accretion onto Star

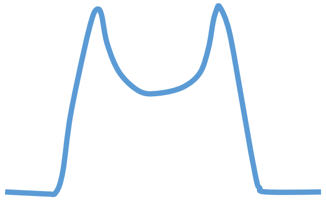
Via a boundary layer?



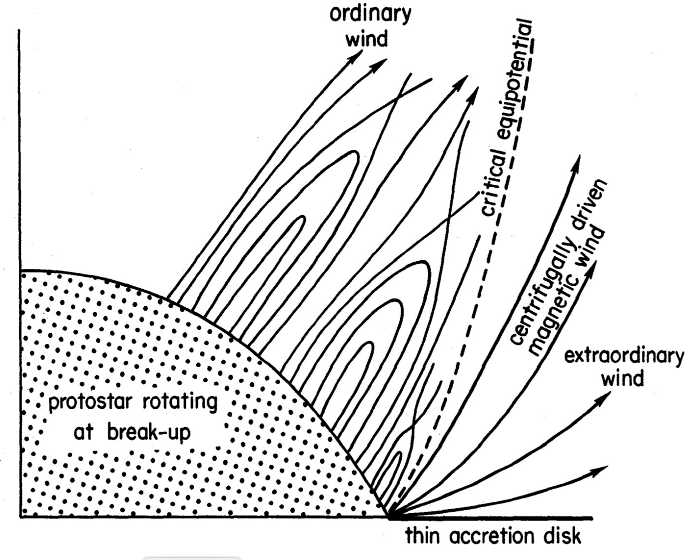
Credit: B. Ryden

$b < H < R_*$

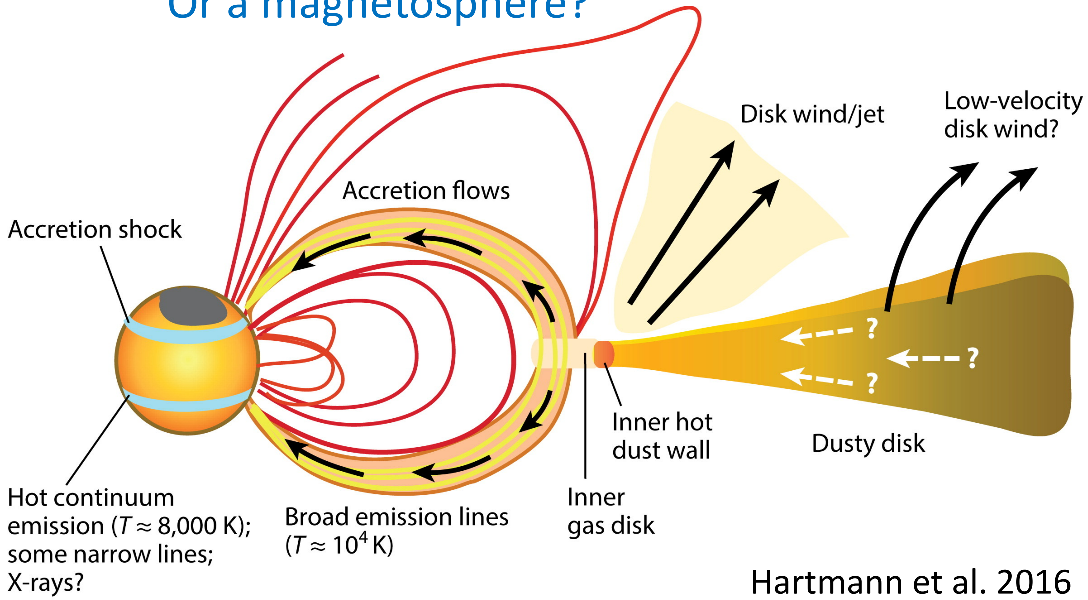
Double-peaked profile from a thin annulus



Spun to break up, equatorial accretion

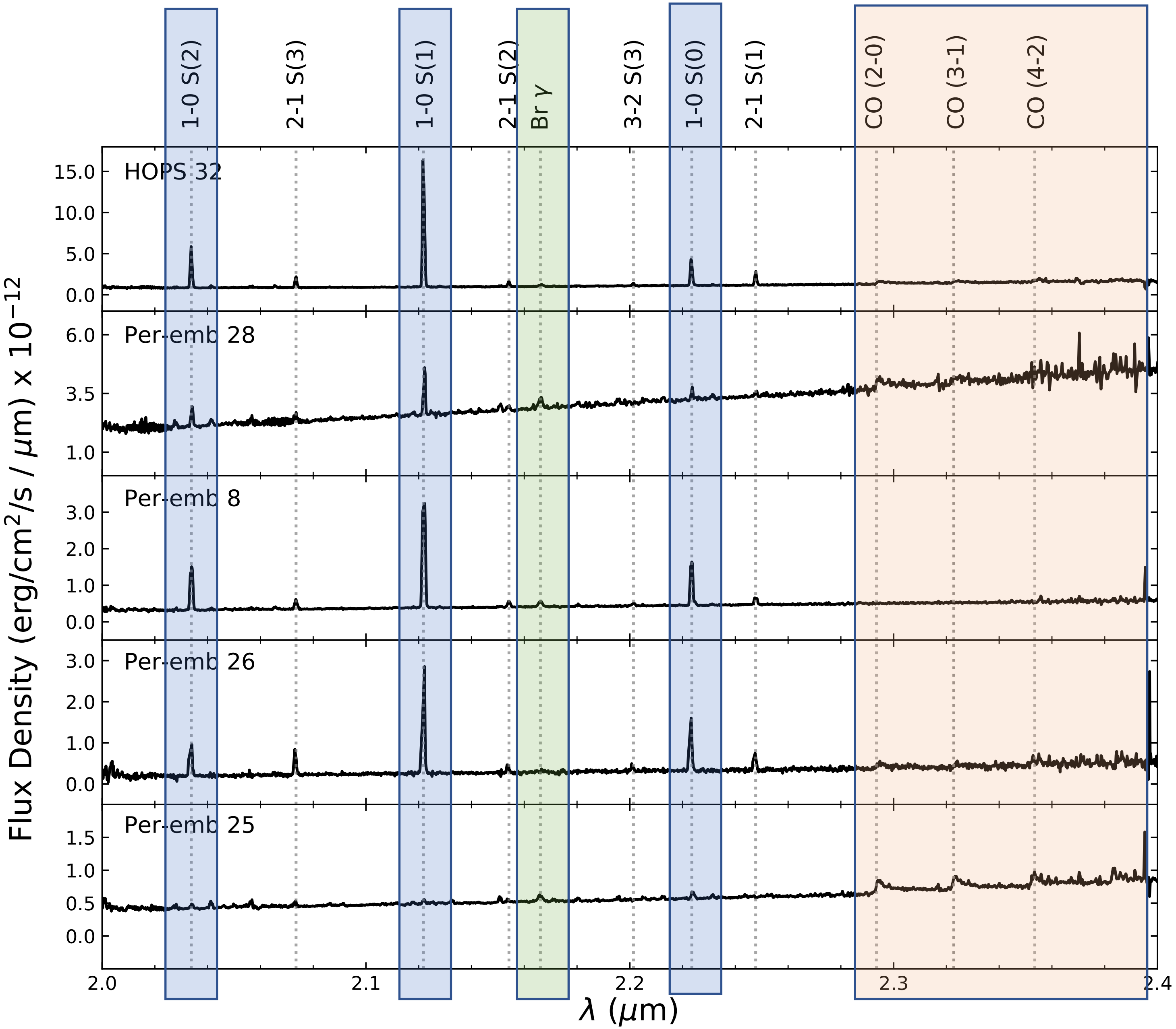


Or a magnetosphere?



Hartmann et al. 2016

NIR Spectroscopy of Class 0 Sources



Stefan Laos + T. Greene, K. Stassun, JN
arXiv:2108.10169

- Keck/MOSFIRE (R=2400)
- Outflow/jets (H_2)
- Disk accretion (CO overtone)
- Stellar accretion (Brγ)

NIR Spectroscopy of Class 0 Sources

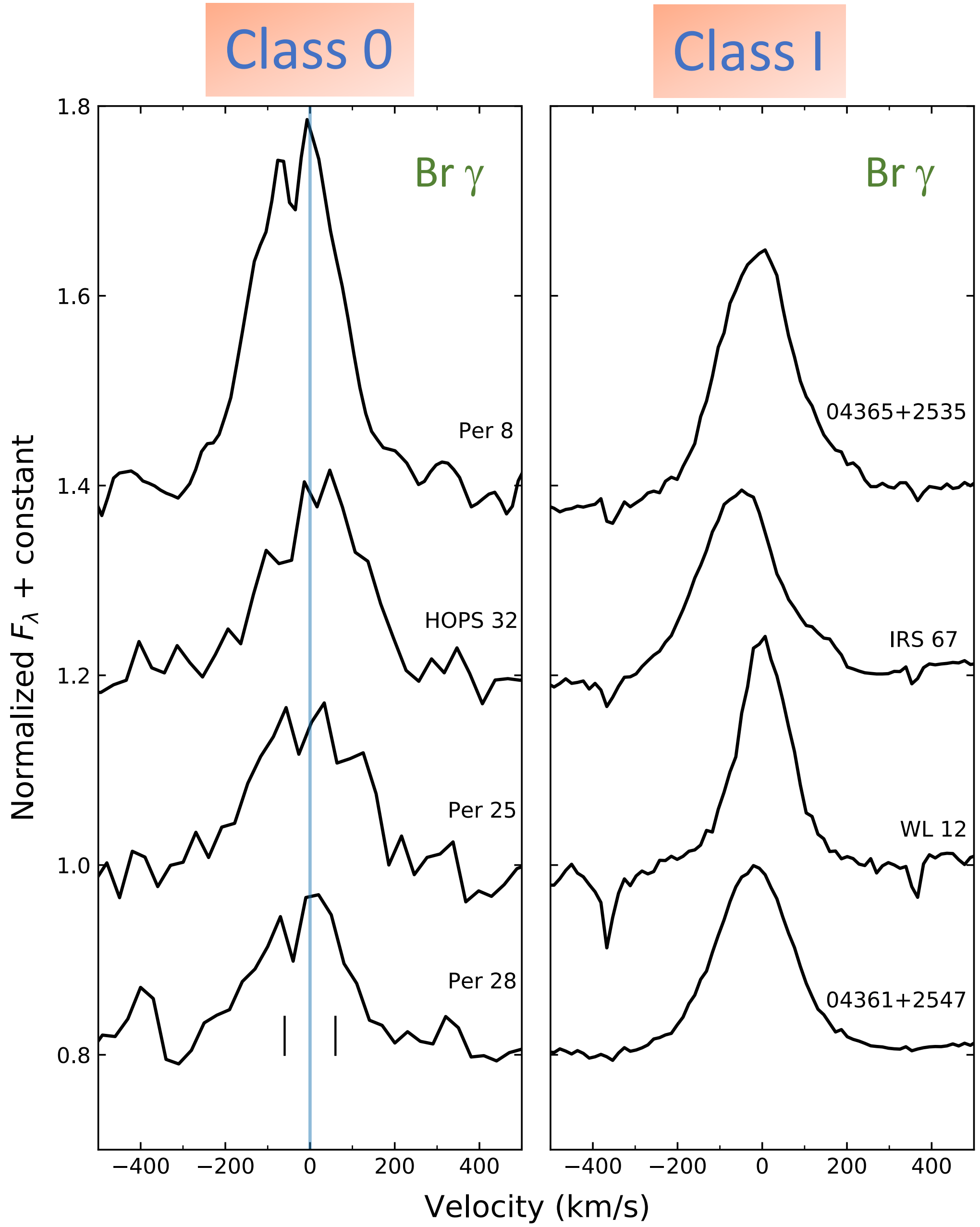
Takeaways:

Can observe Class 0 sources in NIR!

Br γ profiles like Class I/II

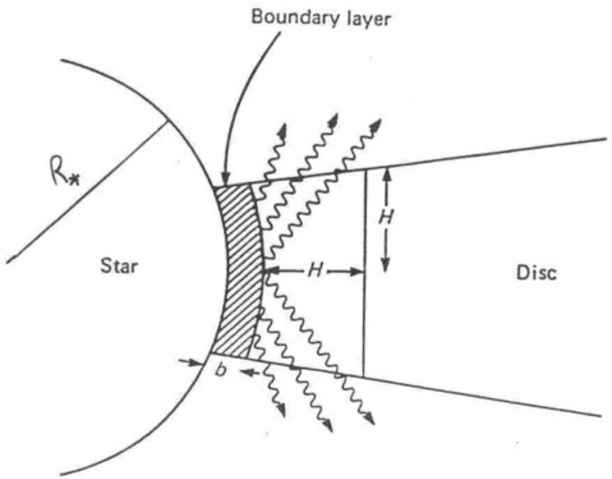
- Organized stellar B forms early
- Star rotates below breakup
- Accretion through magnetosphere

Protostars ”grow up” quickly – feeding behavior established early



Accretion onto Star

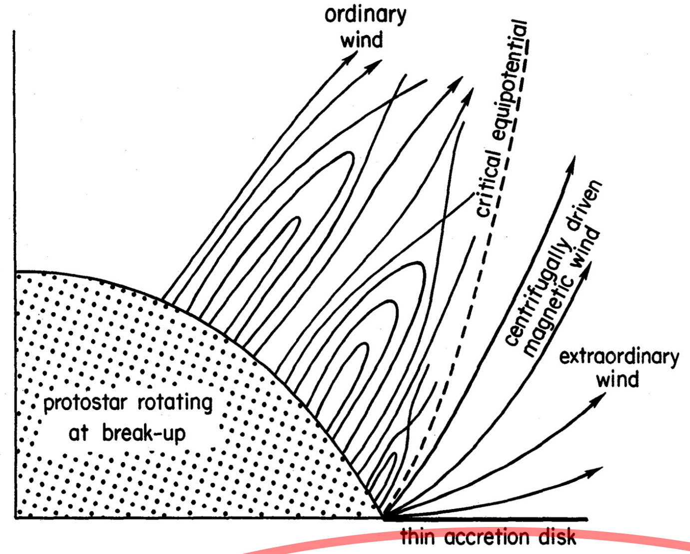
Via a boundary layer?



Credit: B. Ryden

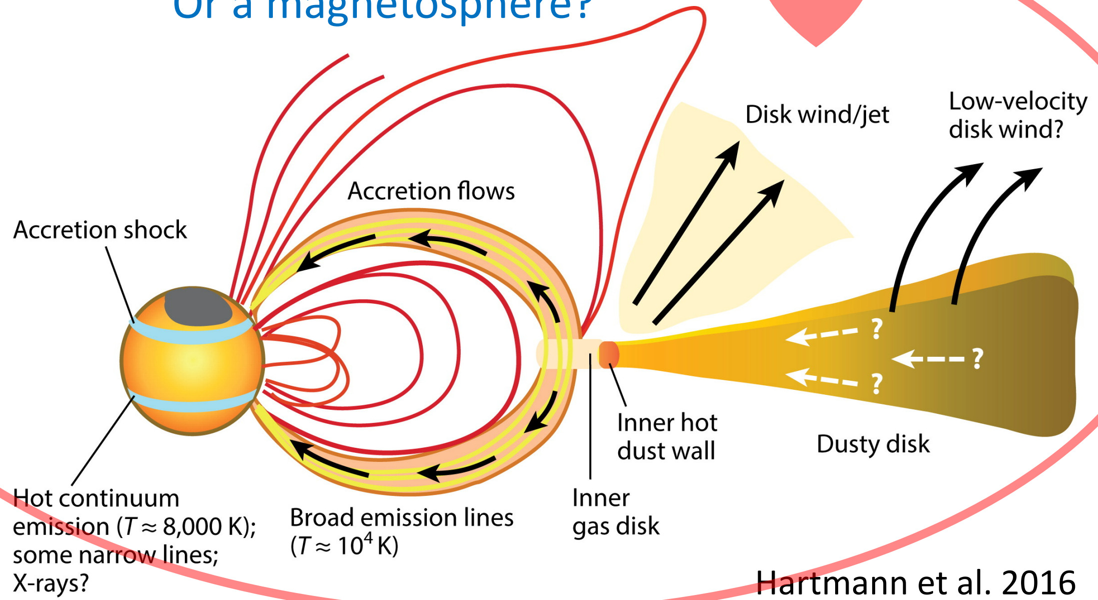
$b < H < R_*$

Spun to break up, equatorial accretion



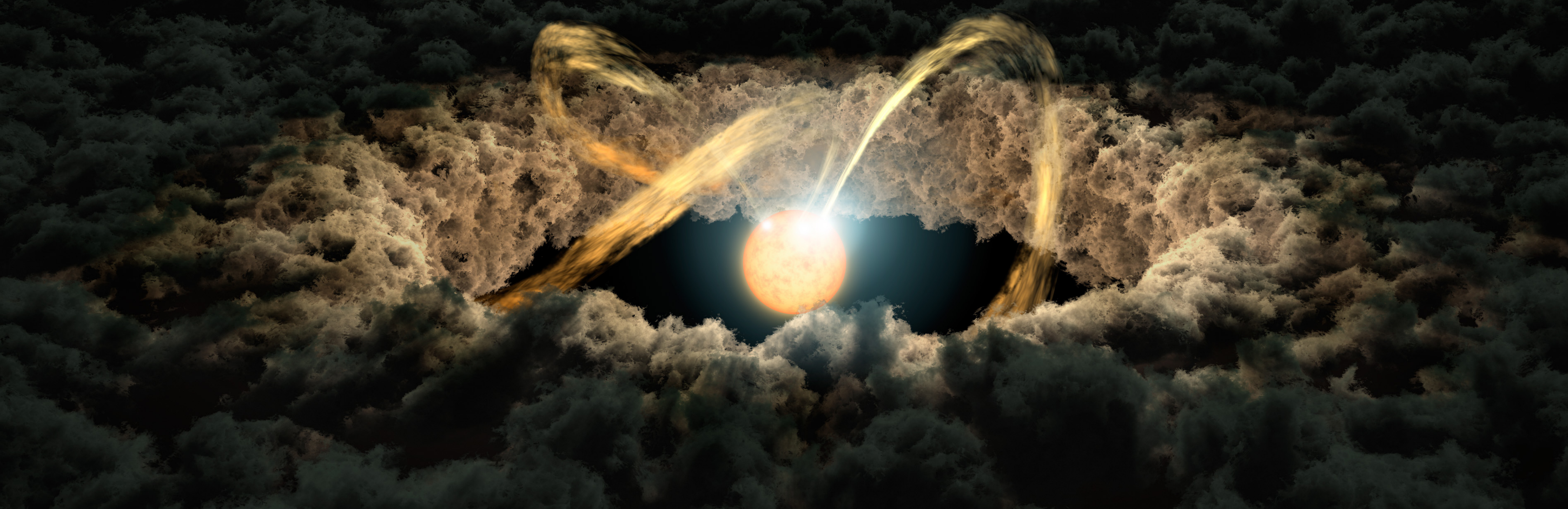
Are magnetospheres always the answer?

Or a magnetosphere?

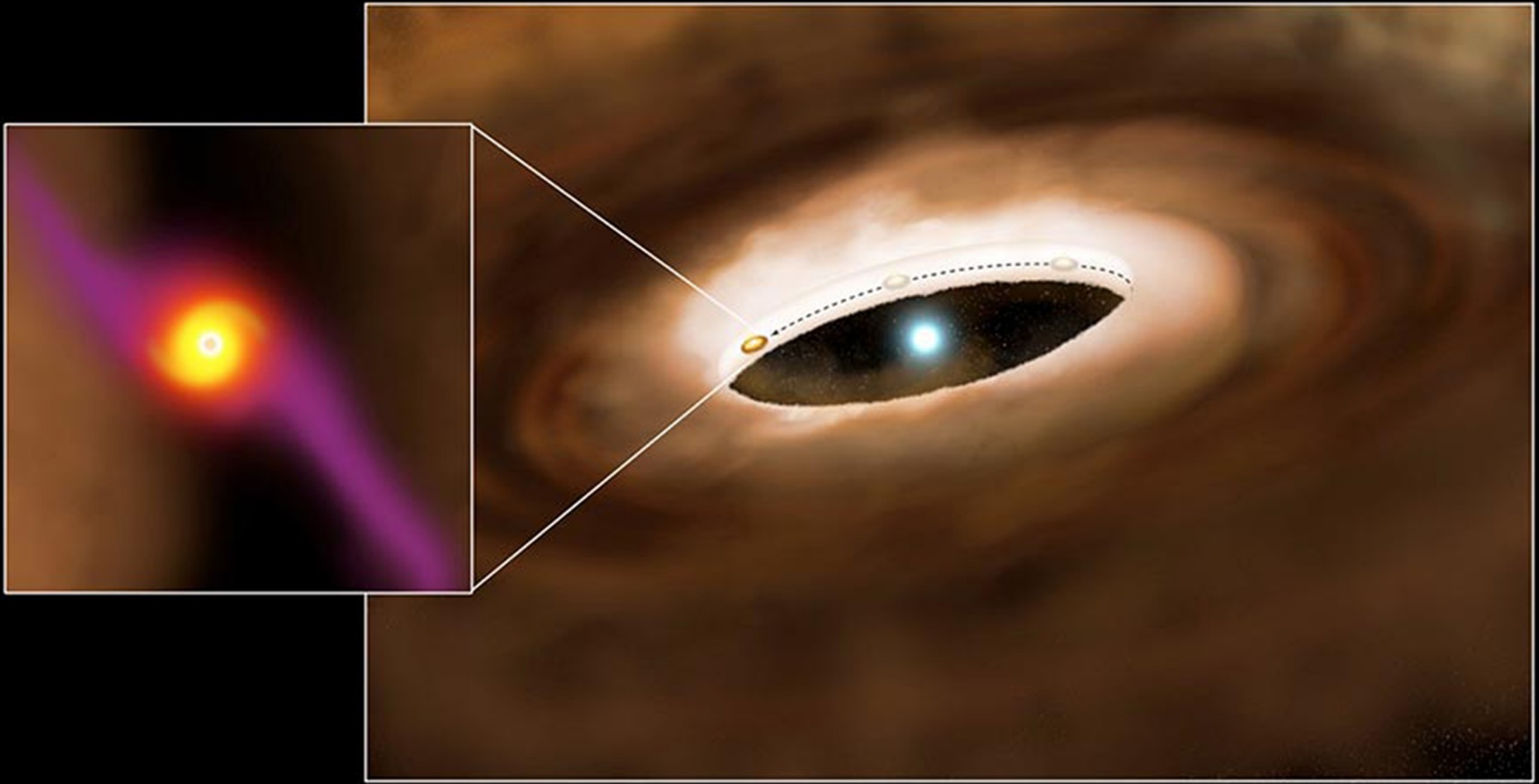


Hartmann et al. 2016

Takeaways



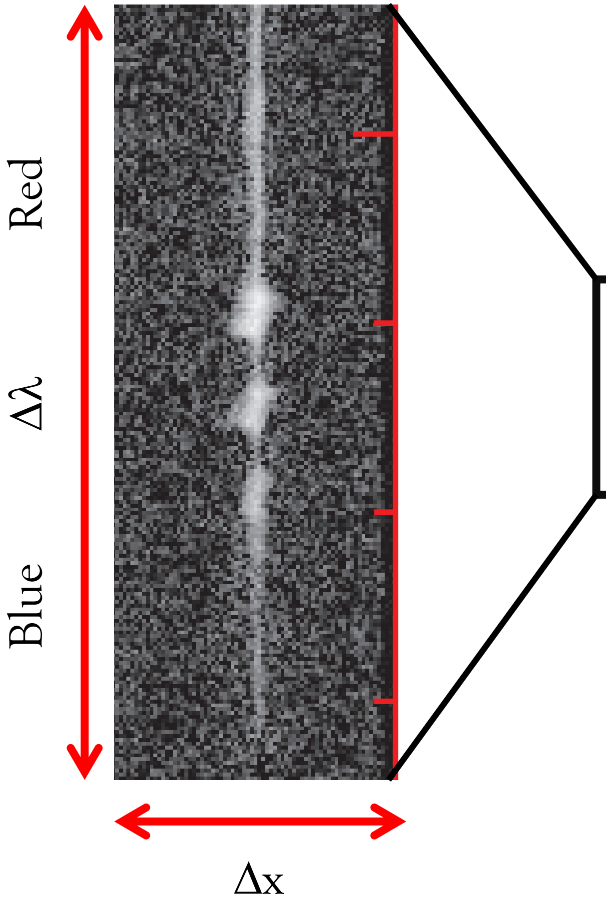
Stars generate magnetospheres early
Establish protective migratory boundary for planets

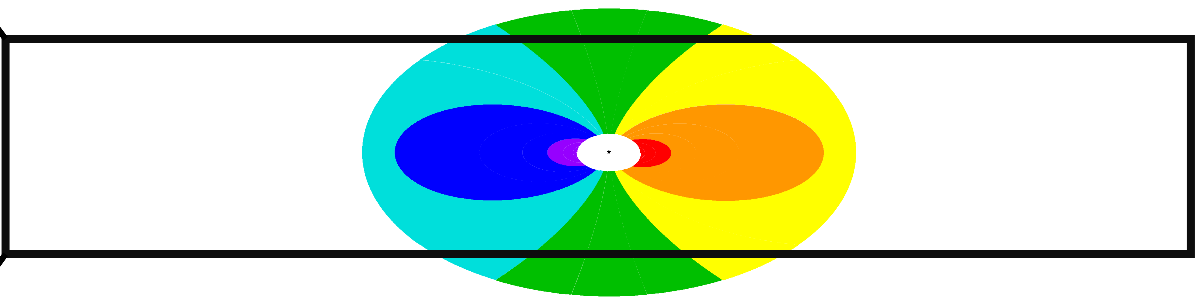


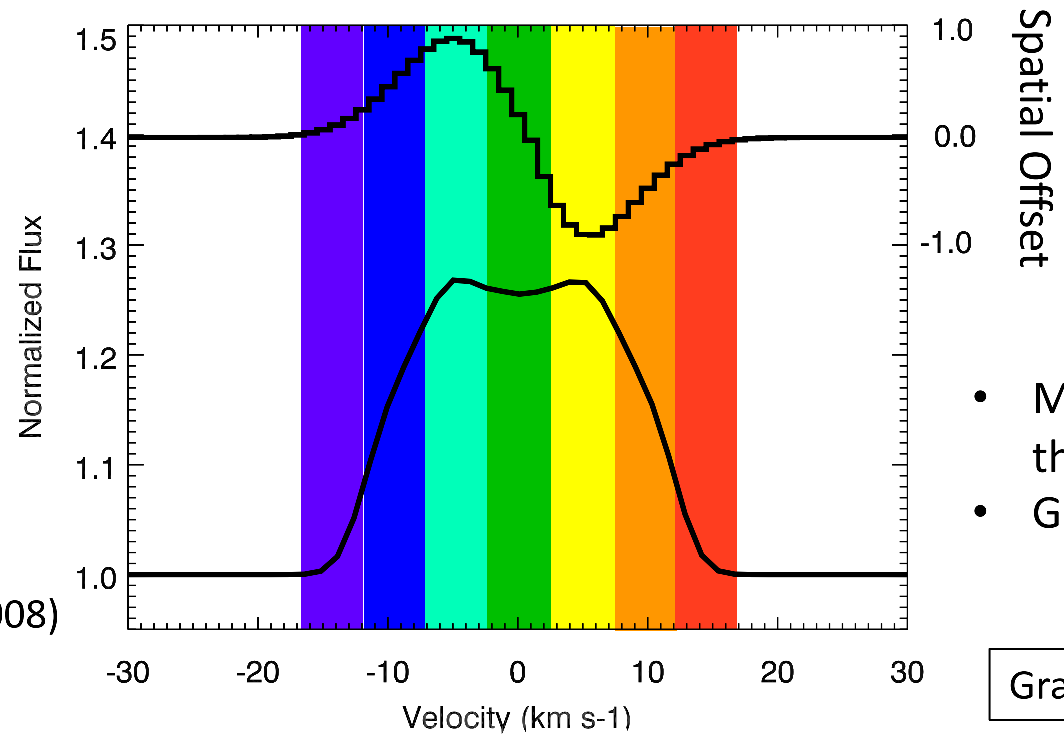
Signposts of giant planet formation

HD100546 @ 10au – Brittain et al. 2013, 2014, 2019

Super-Resolution with Spectroastrometry



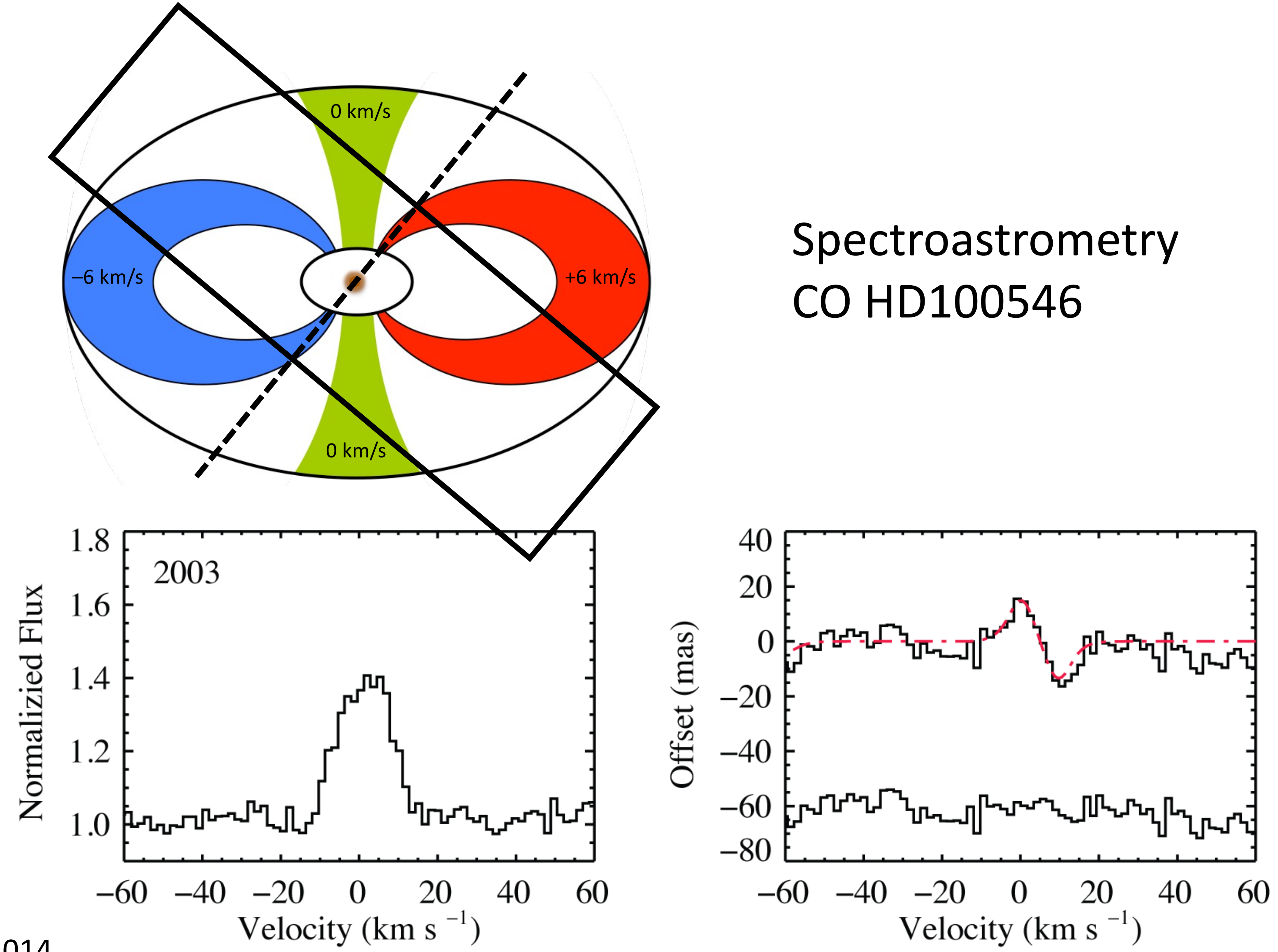




- Magic: spatial centroid more accurate than ang res Δx ~ 0.4 FWHM / SNR
- Good for simple velocity fields

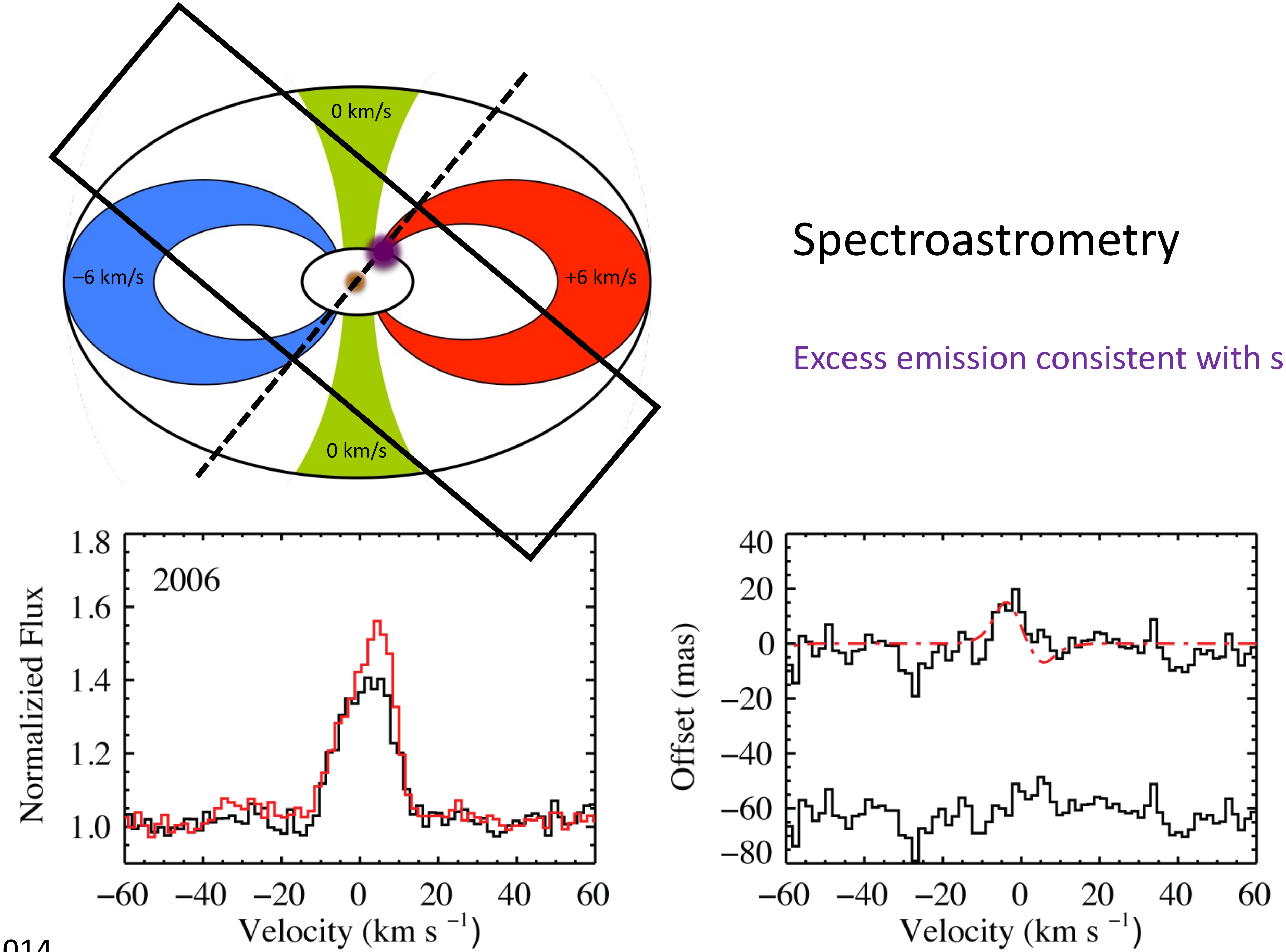
(See Whelan & Garcia 2008)

Graphics Credit: Sean Brittain



Spectroastrometry
CO HD100546

Brittain et al. 2014

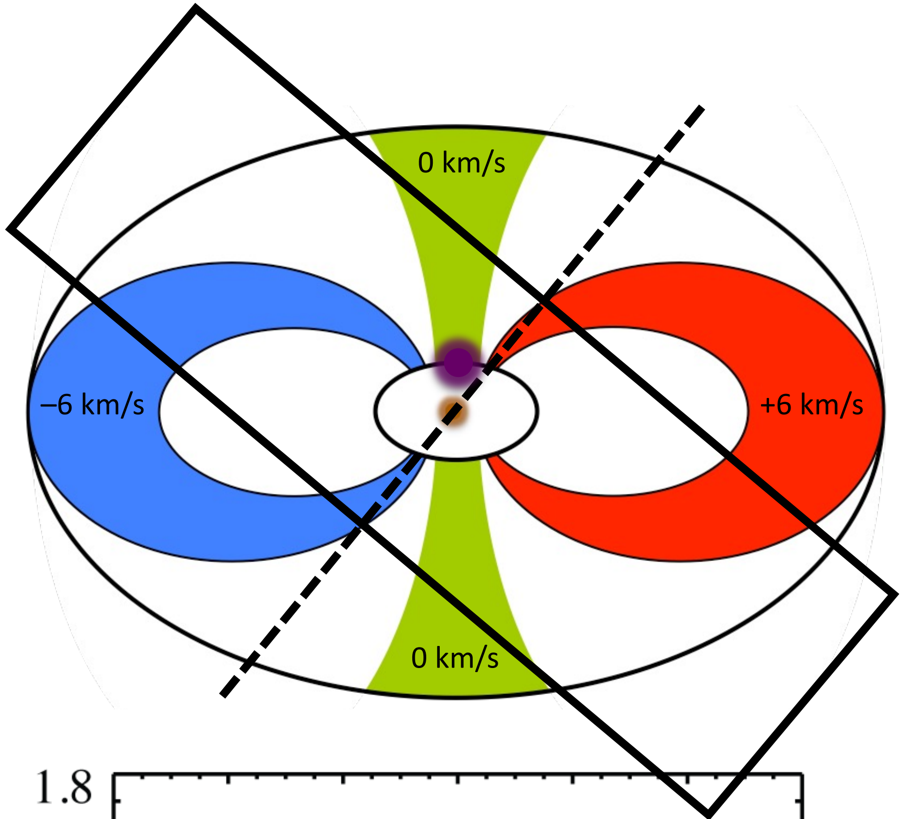


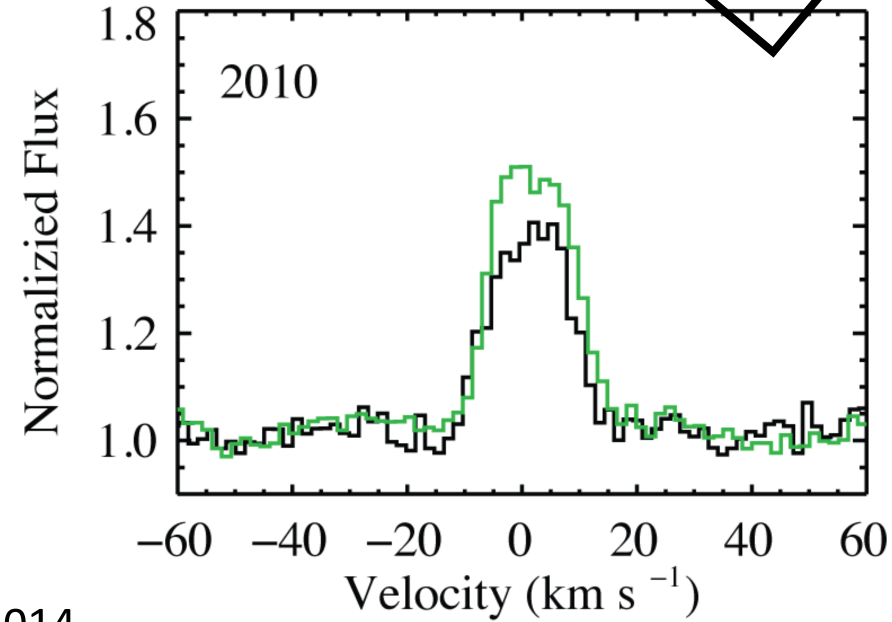
Spectroastrometry

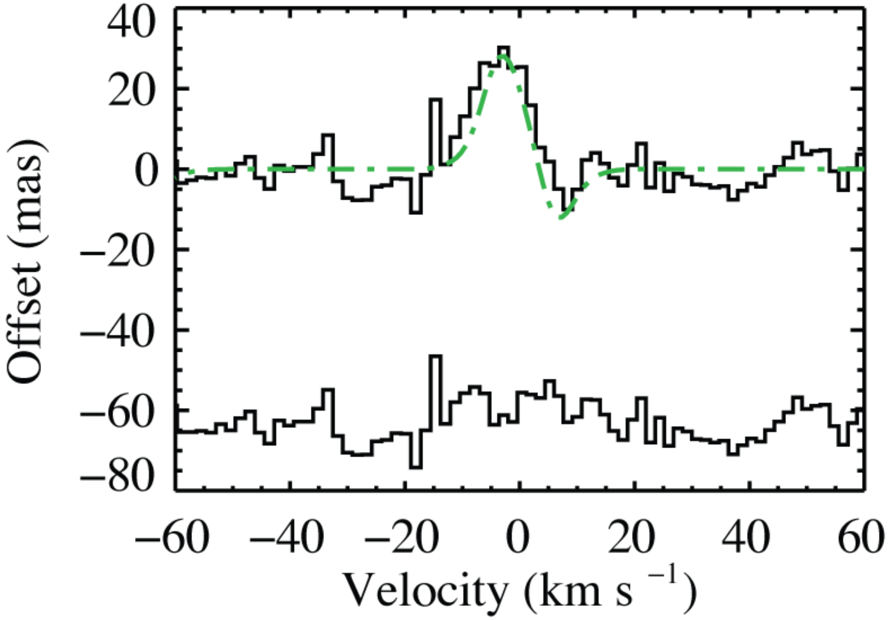
Excess emission consistent with size of CPD

Brittain et al. 2014

Spectroastrometry

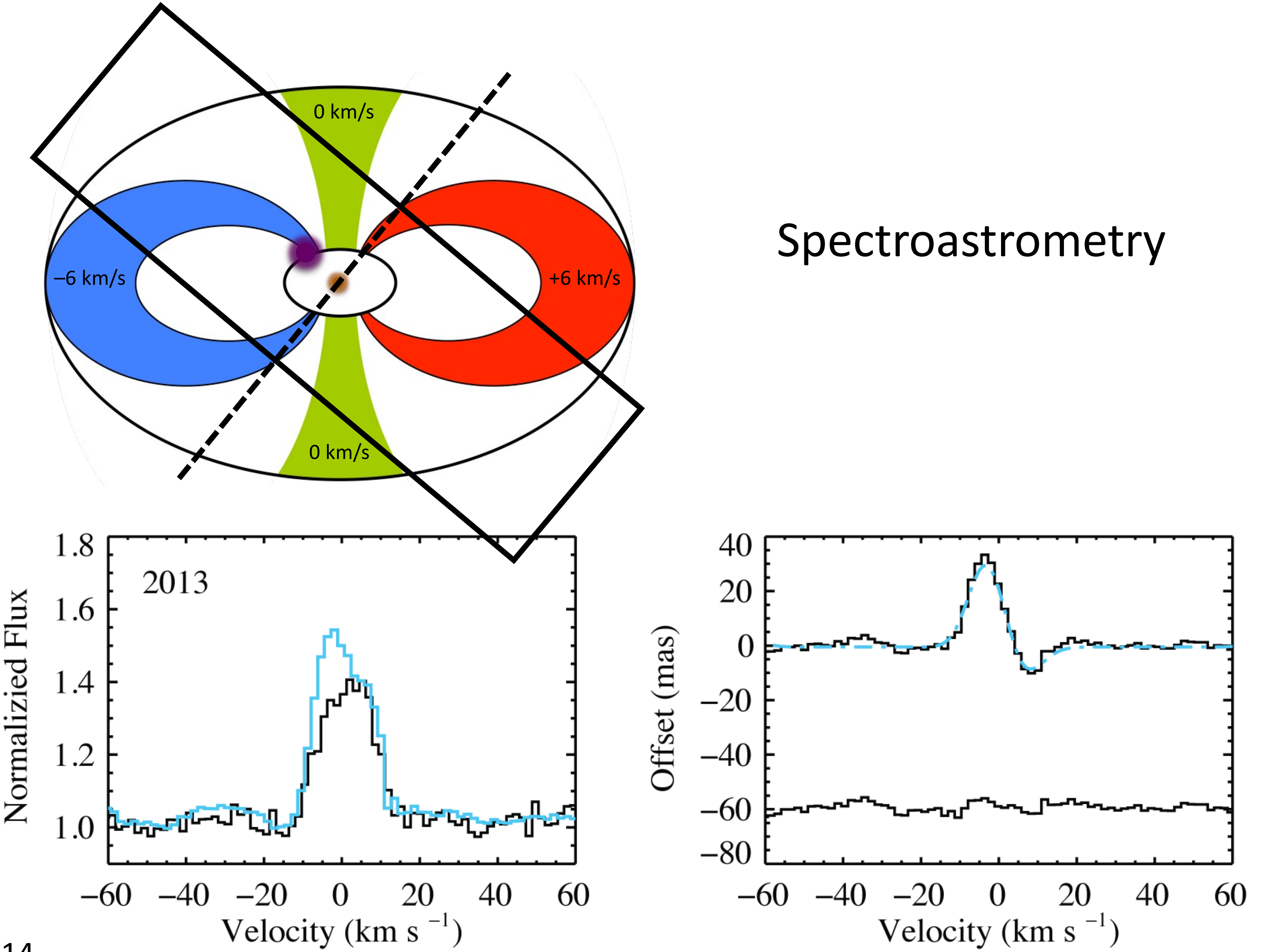






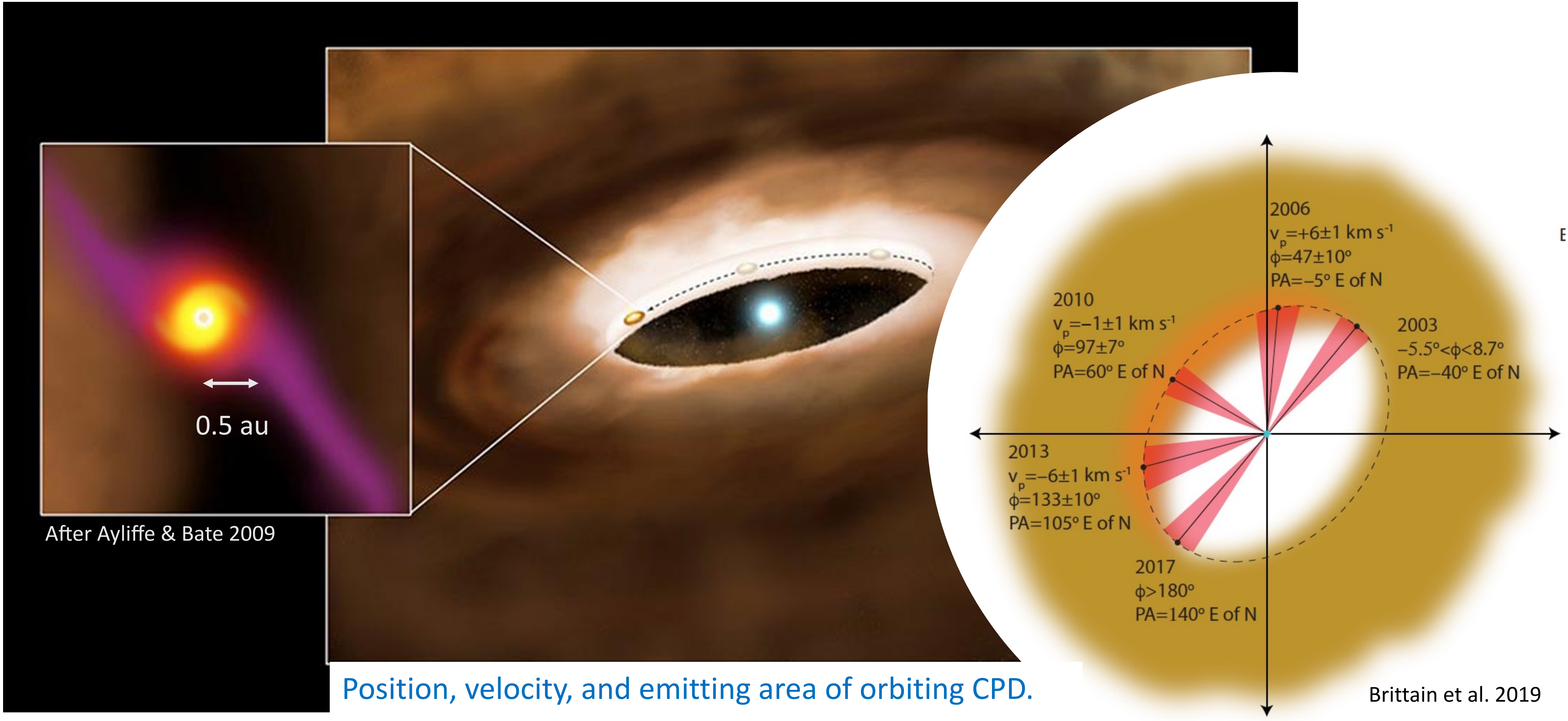
Brittain et al. 2014

Spectroastrometry



Brittain et al. 2014

Orbiting Planet + CPD in HD100546



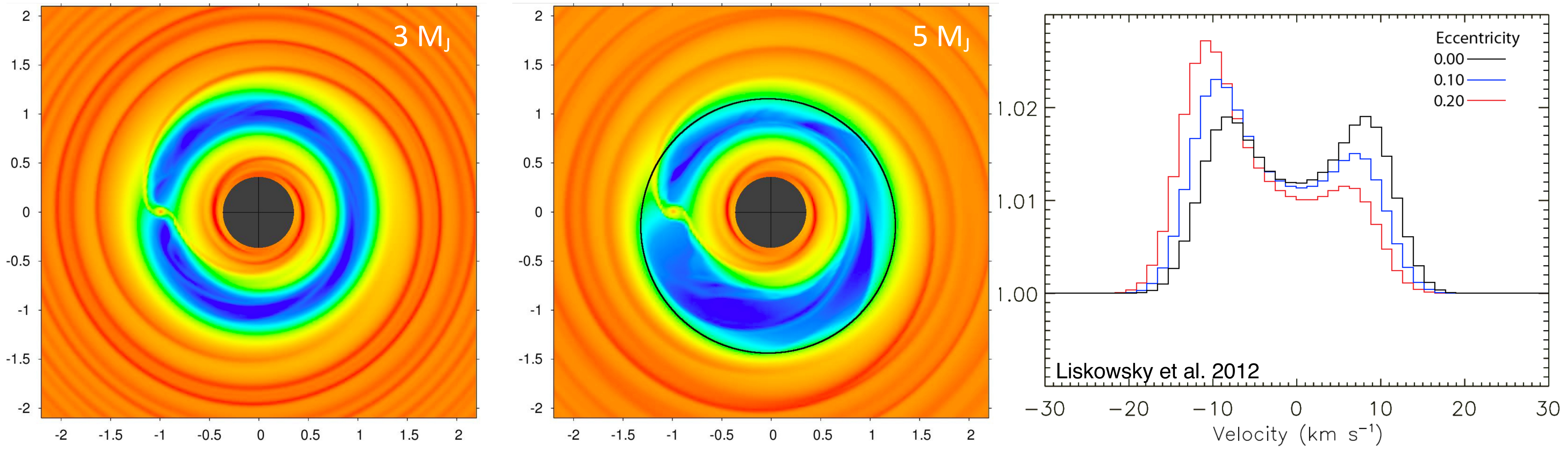
After Ayliffe & Bate 2009

Position, velocity, and emitting area of orbiting CPD.

Brittain et al. 2019

Eccentric inner rim

...induced above a threshold planetary mass

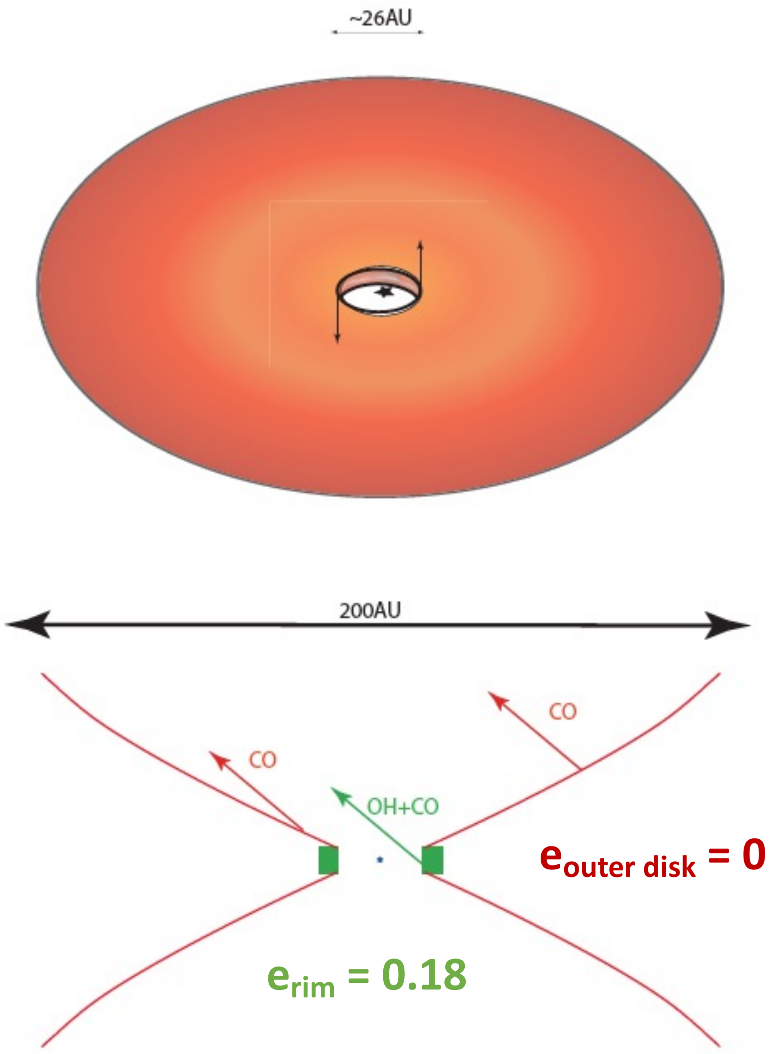


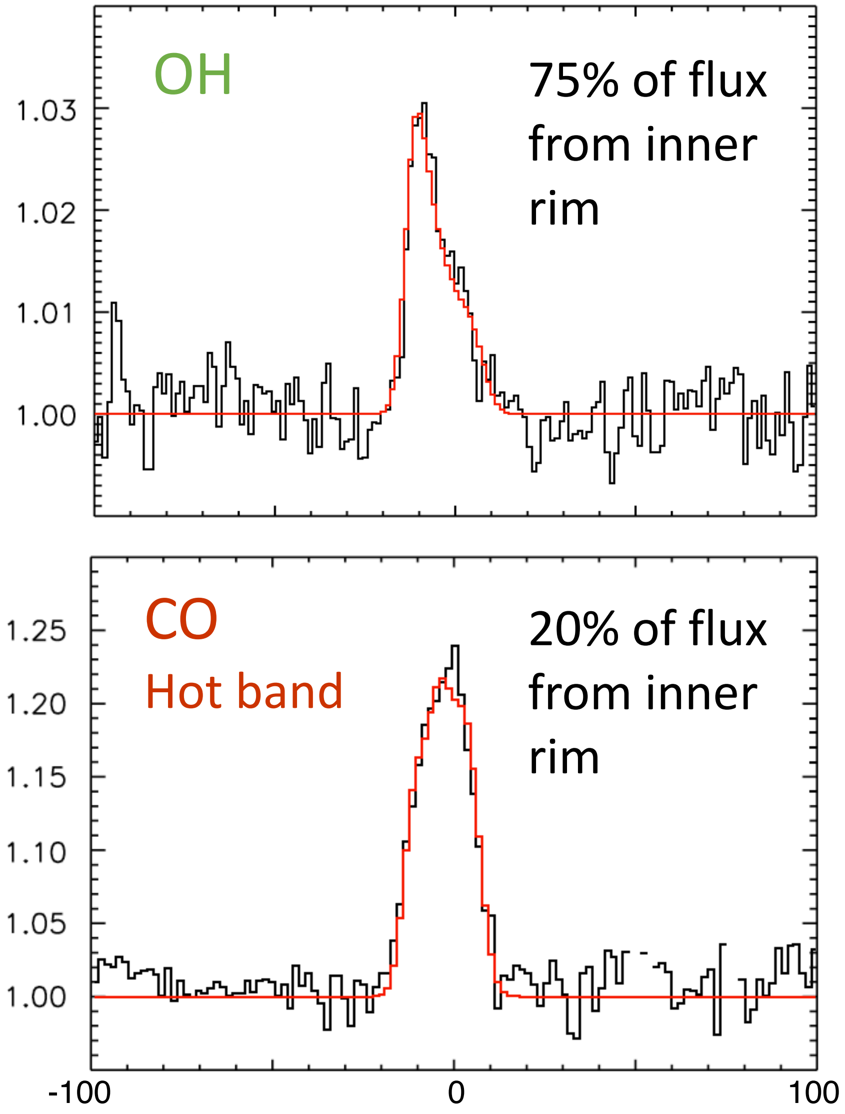
Kley & Dirksen 2006

..produces observable line asymmetry

OH and CO from HD100546

- Radial profile of OH and CO from fluorescence model
- Eccentric inner rim
- Outer disk e=0

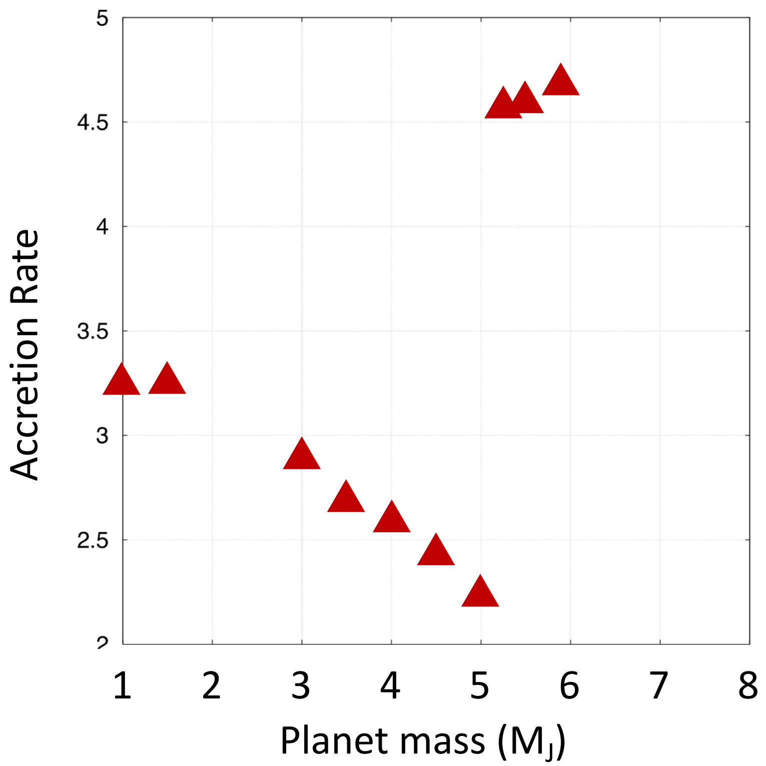


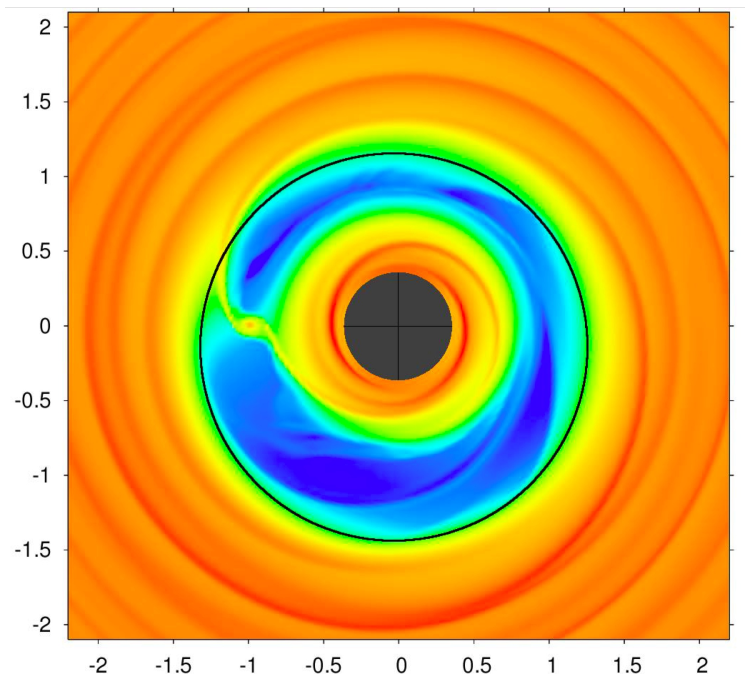


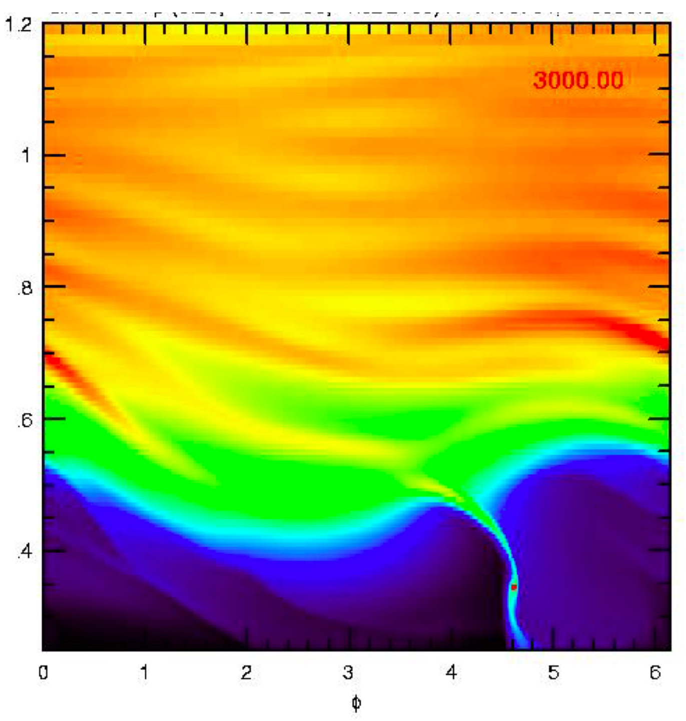
Liskowsky et al. 2012

Eccentric rims enhance accretion

Explain high exoplanet masses?

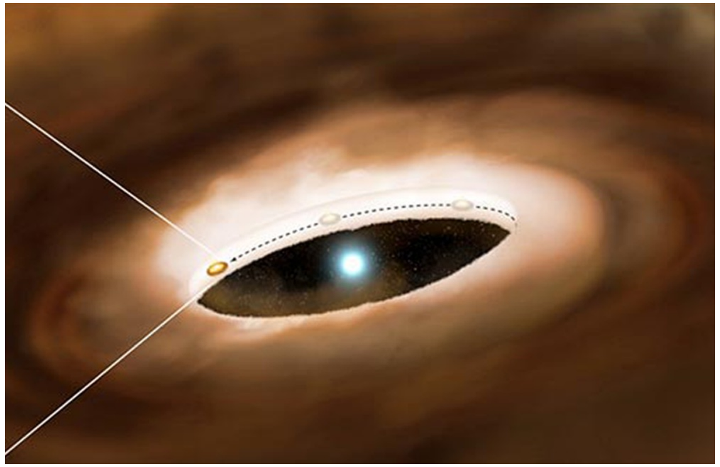




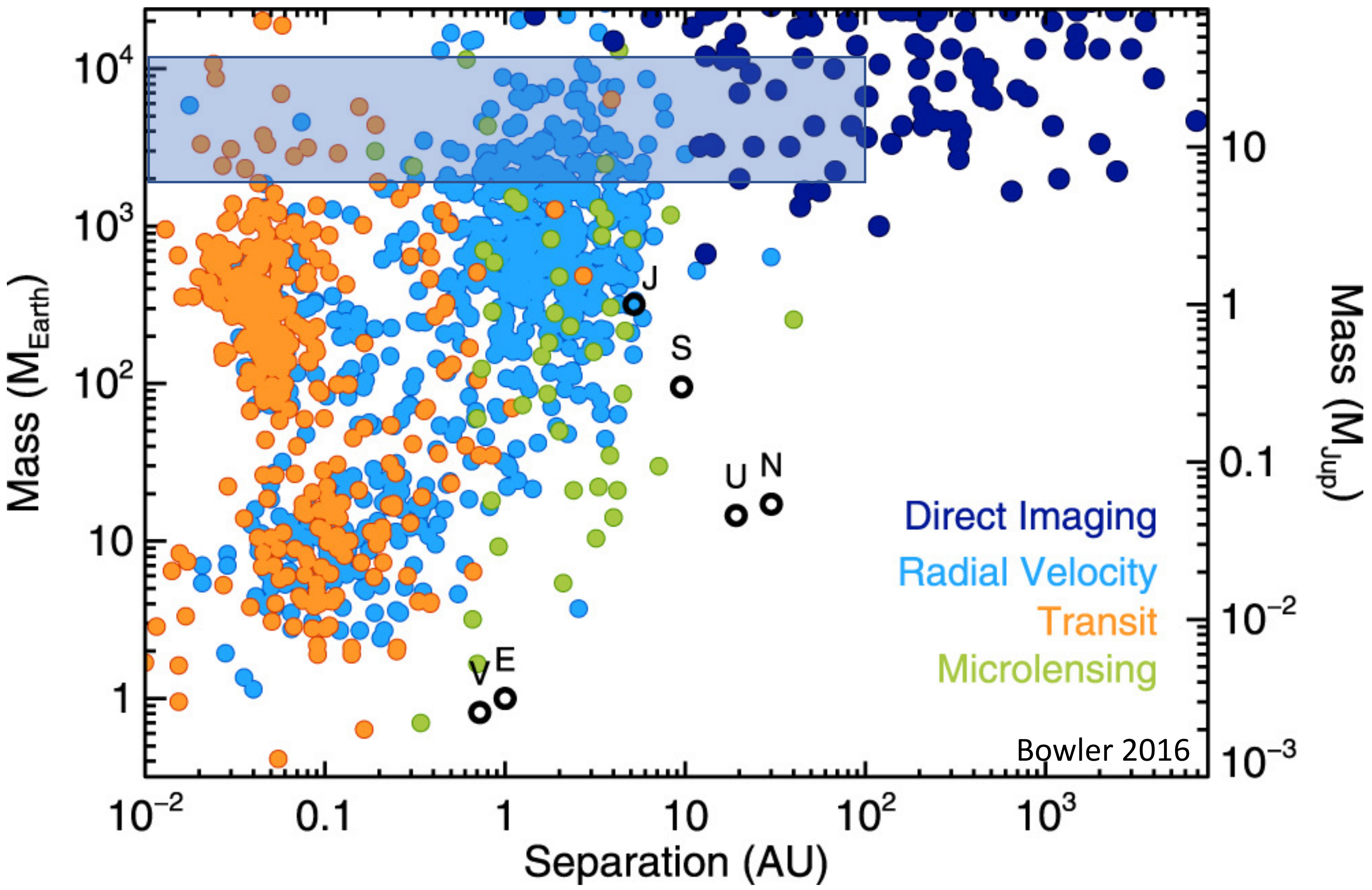


Kley & Dirksen 2006

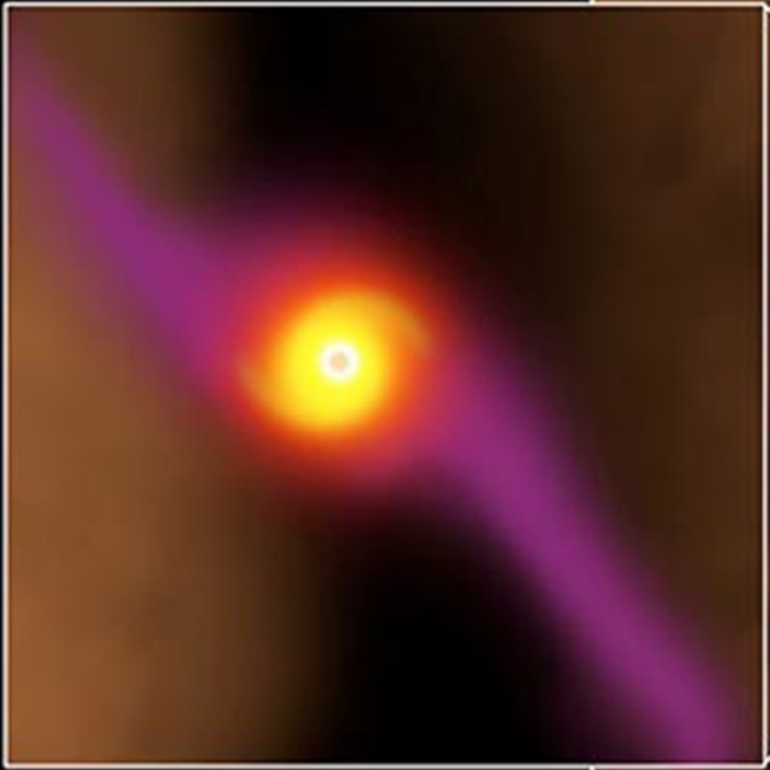
How do very massive planets form?

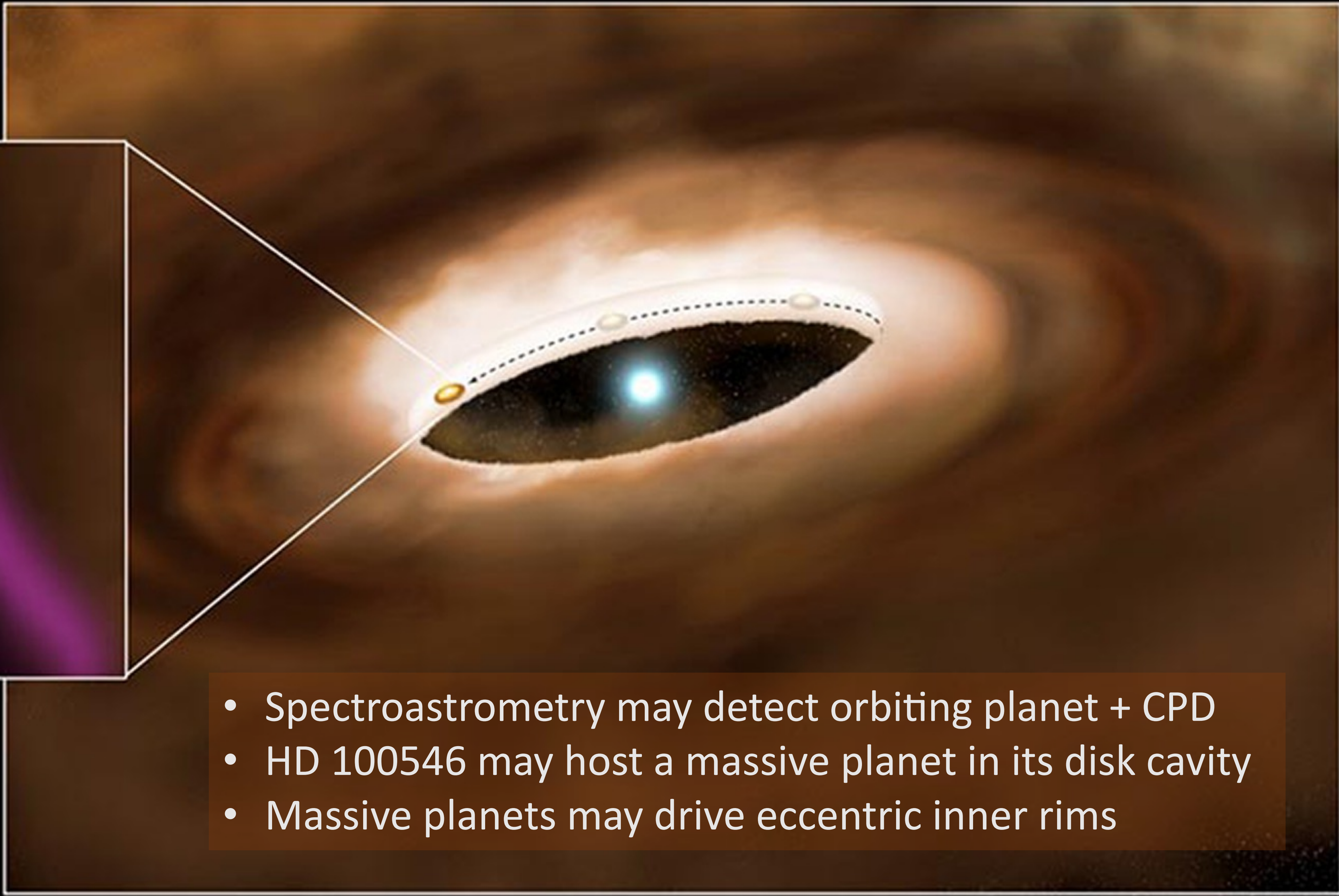


Do planets stop accreting at large masses?



Takeaways



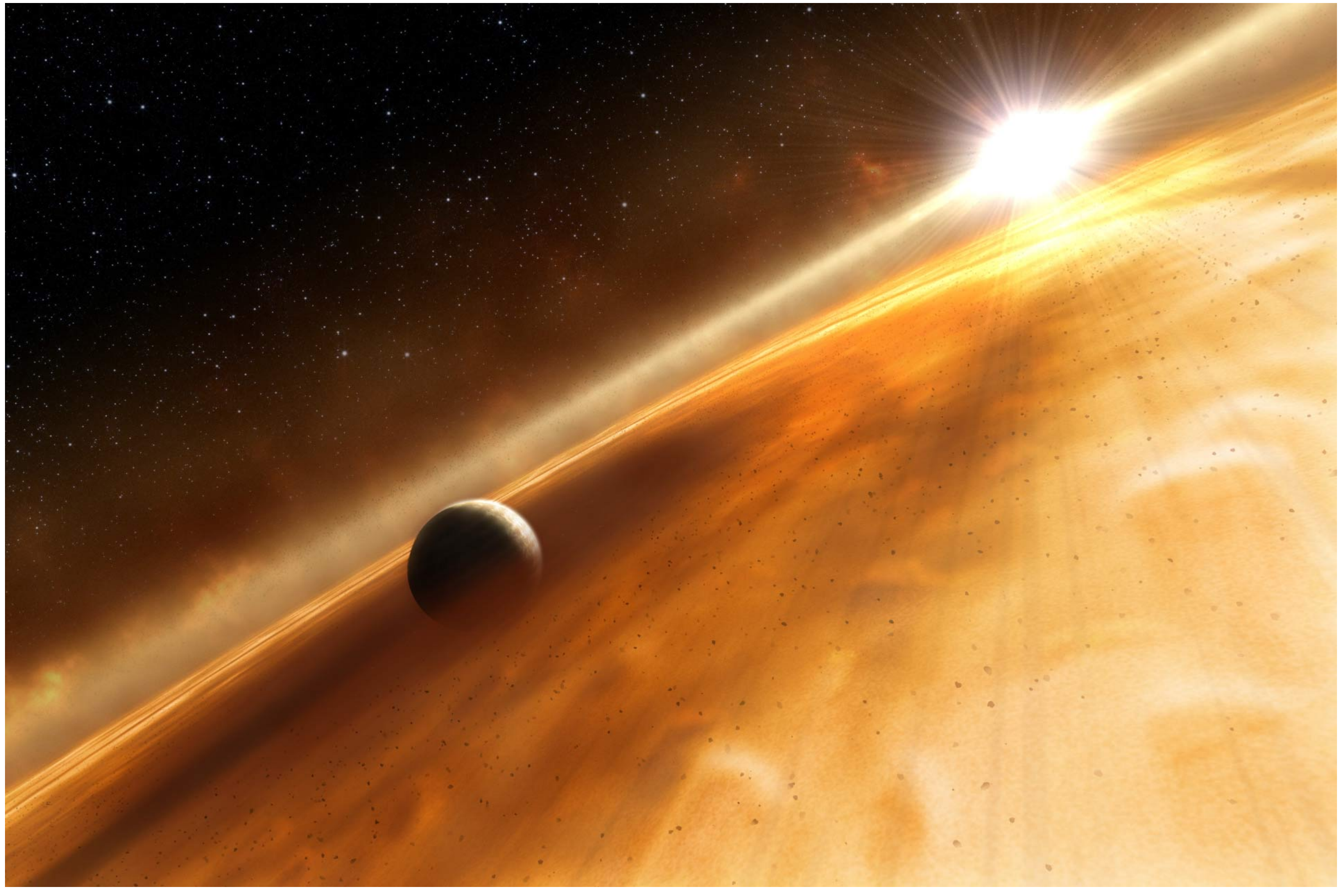


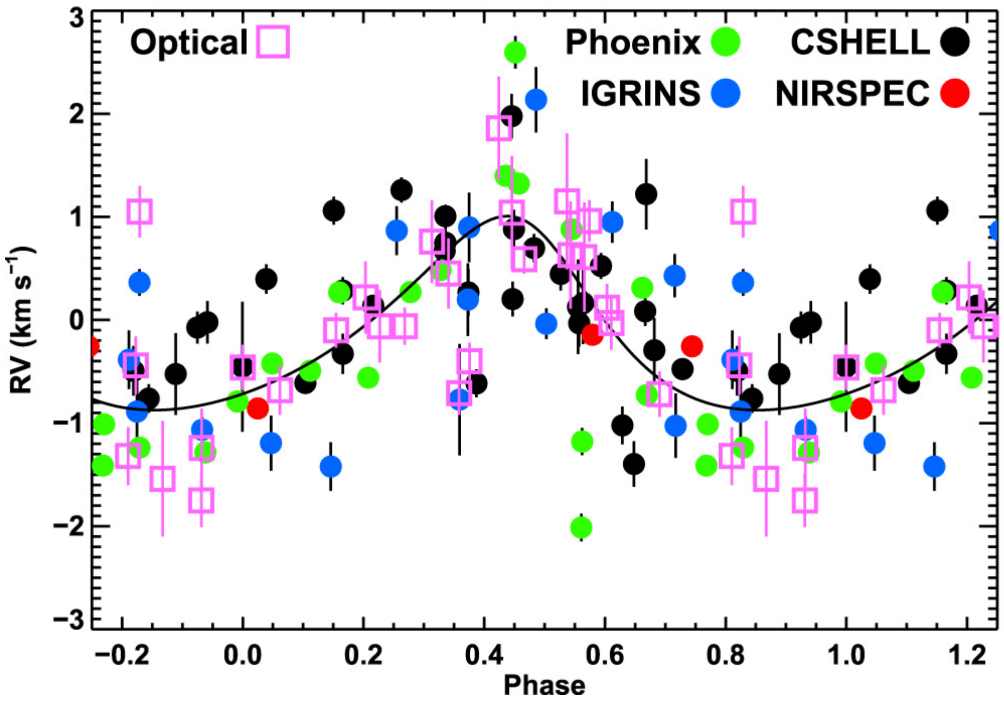
- Spectroastrometry may detect orbiting planet + CPD
- HD 100546 may host a massive planet in its disk cavity
- Massive planets may drive eccentric inner rims

Signatures of close in planets

CI Tau b – Kozdon, Brittain, Fung, Zrake, et al., in prep

CI Tau b



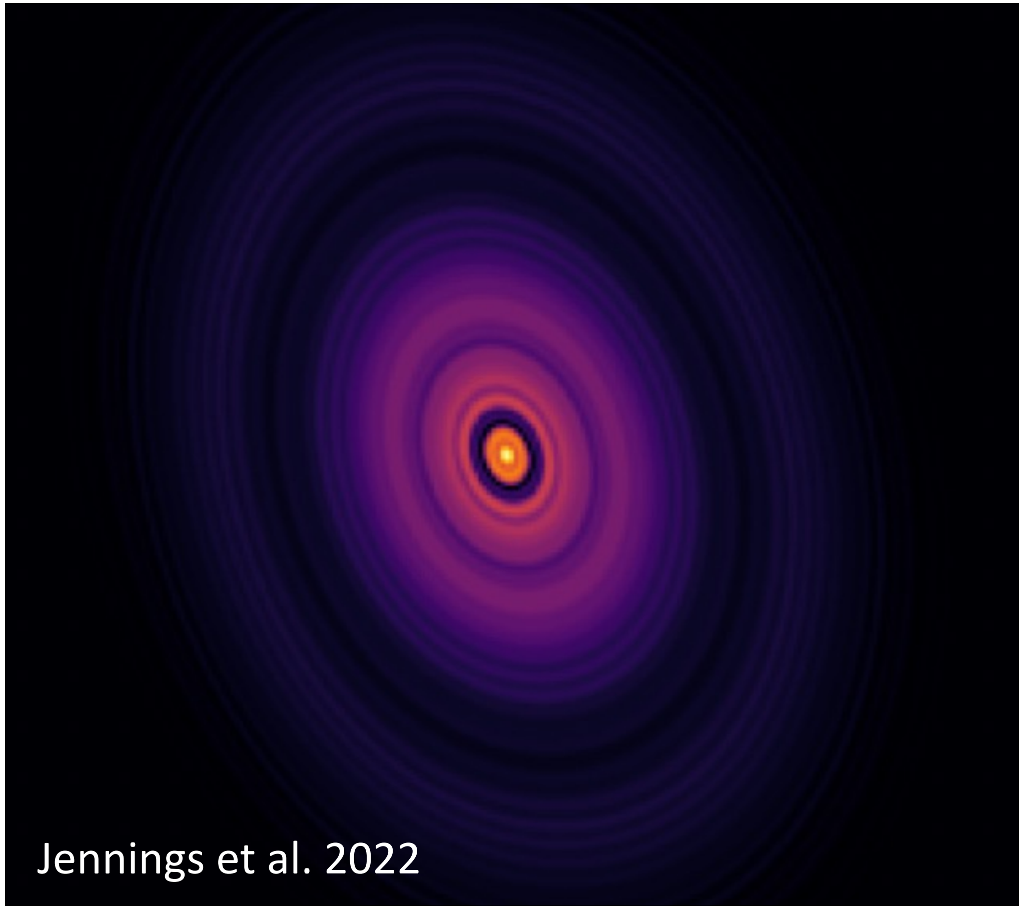


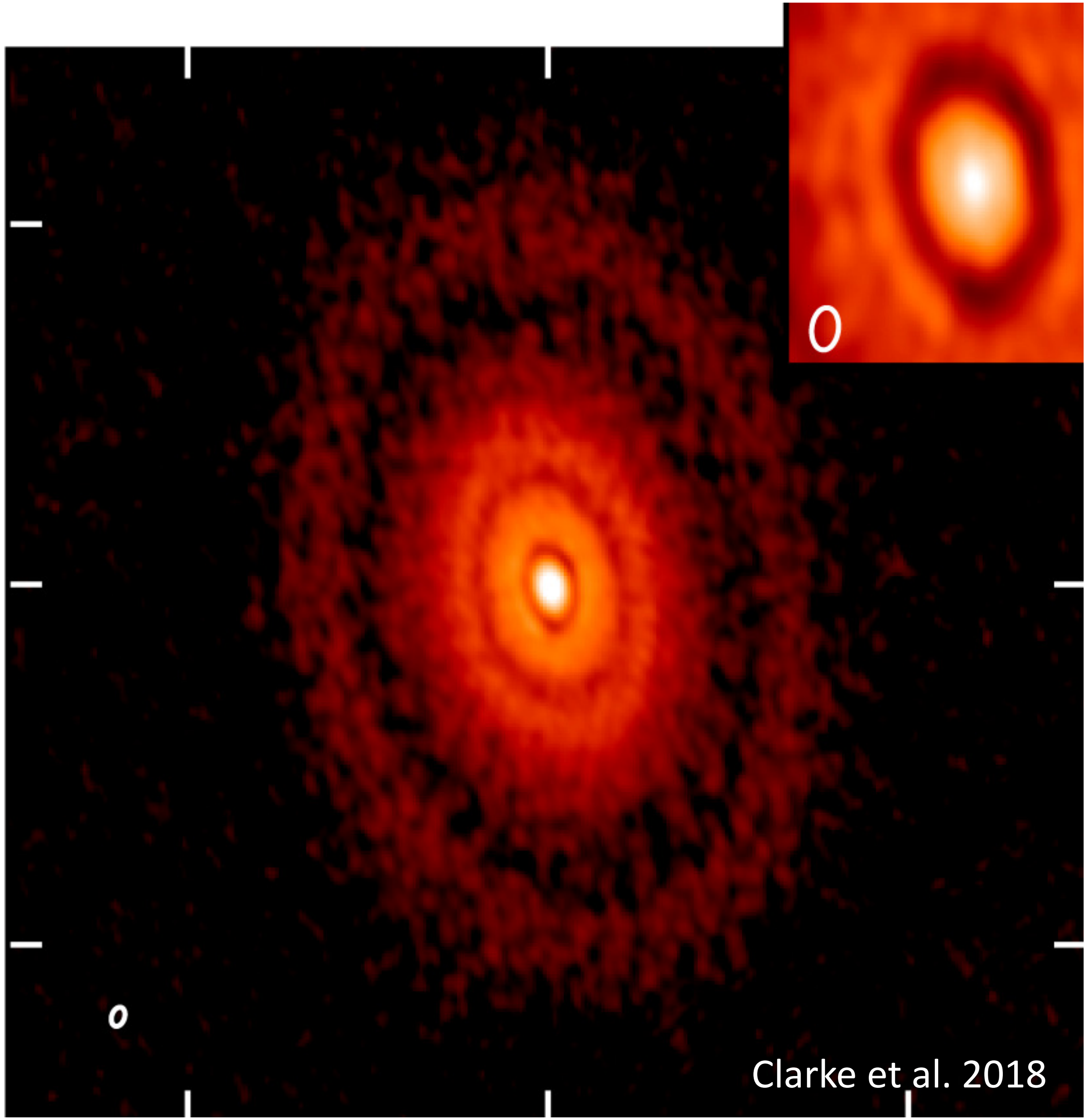
Johns-Krull et al. 2016
Flagg et al. 2019

Age: 2-3 Myr
Orbital period = 9d
Orbital distance: a = 0.08 au
Planet mass ~ 11 M_J
Eccentricity = 0.25

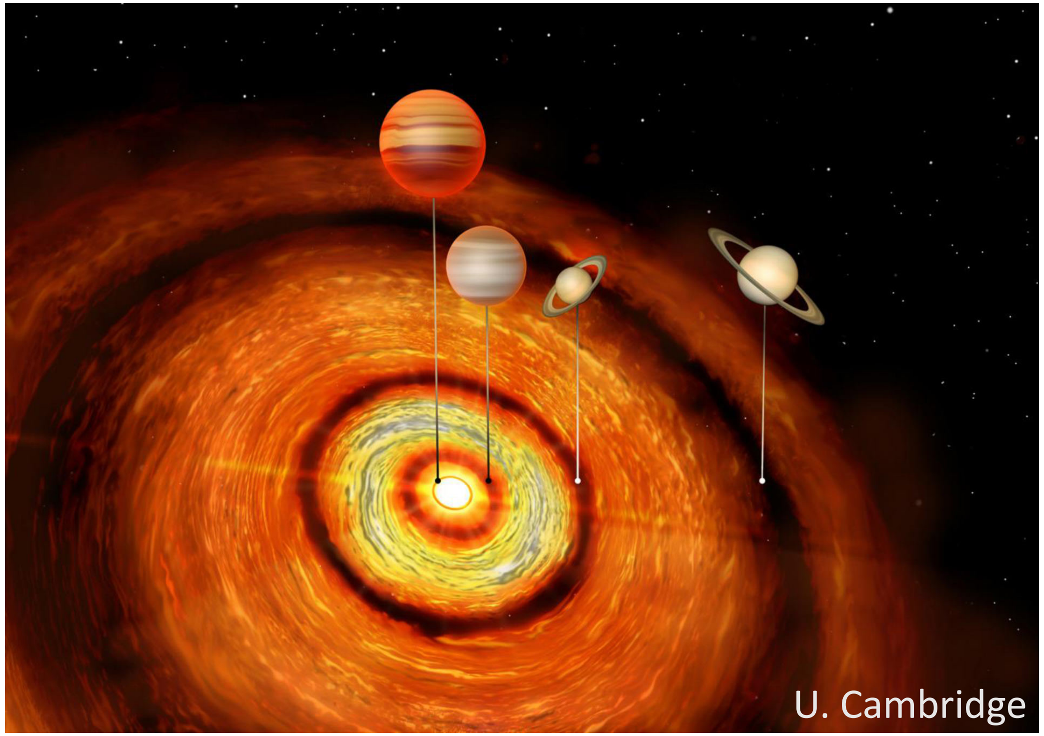
CI Tau with ALMA

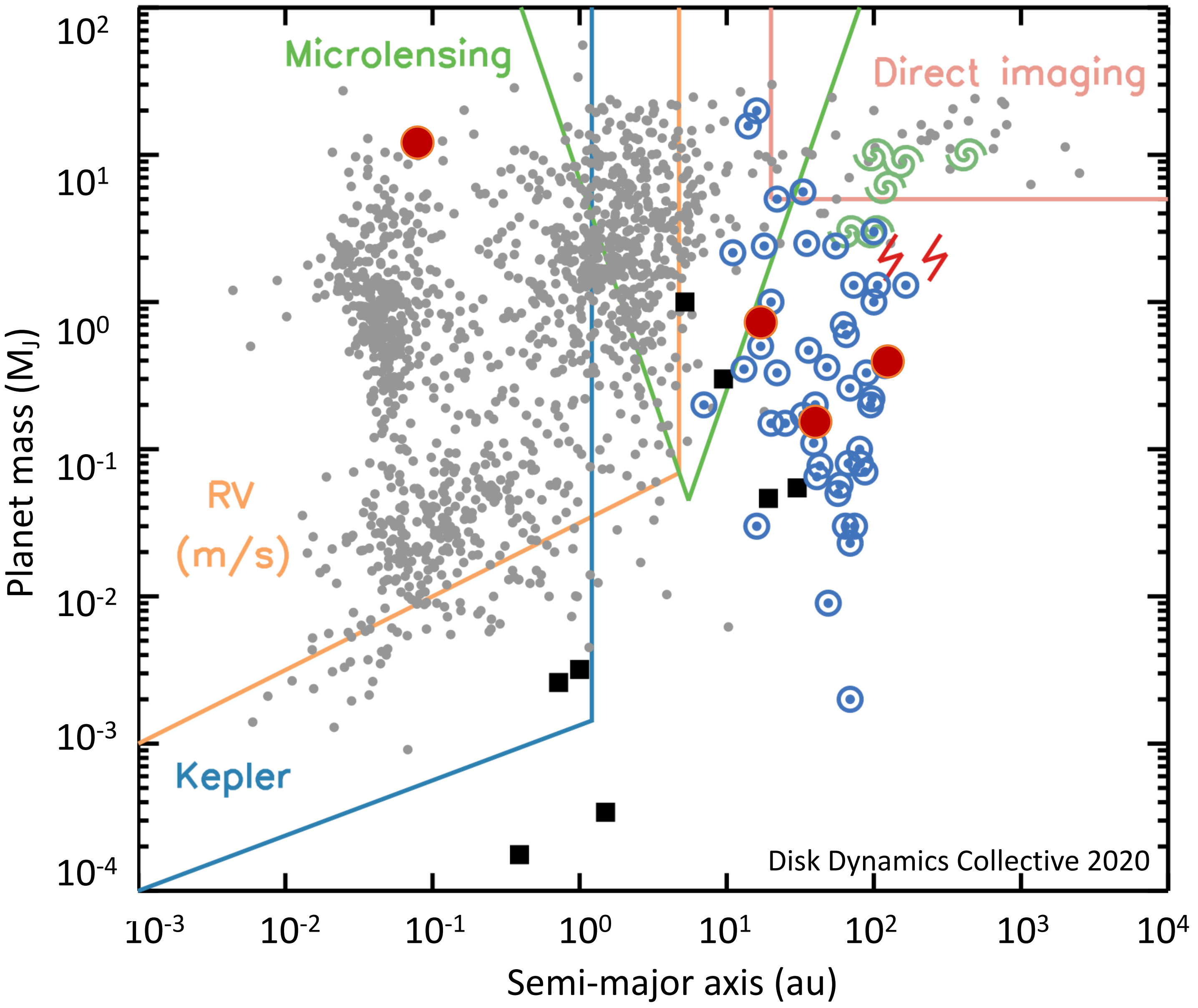
3 distant giants: 0.75 M_J @ 14 au
0.15 M_J @ 43 au
0.4 M_J @ 108 au





CI Tau: 4 giant planets

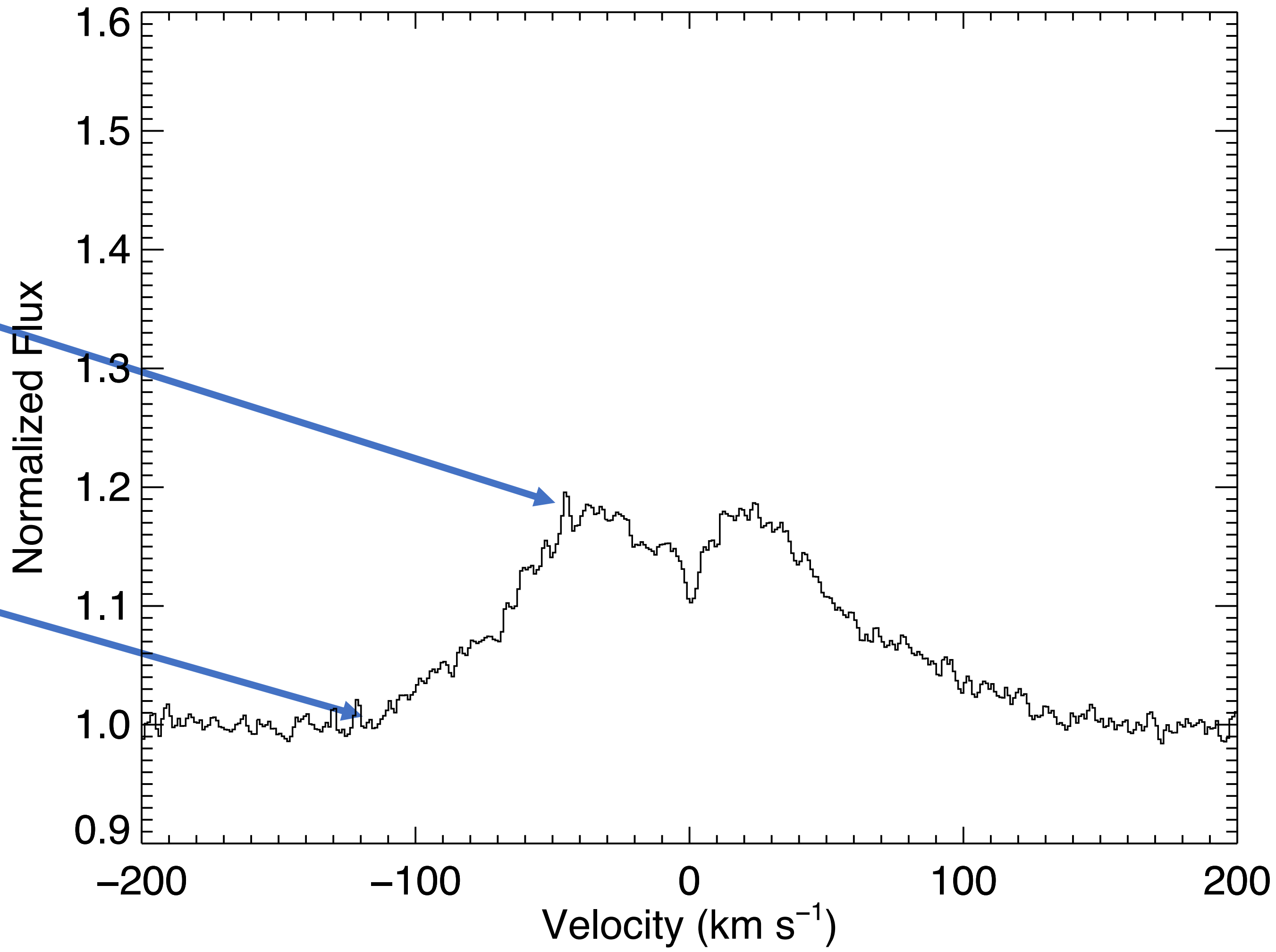




CI Tau: CO fundamental spectroscopy

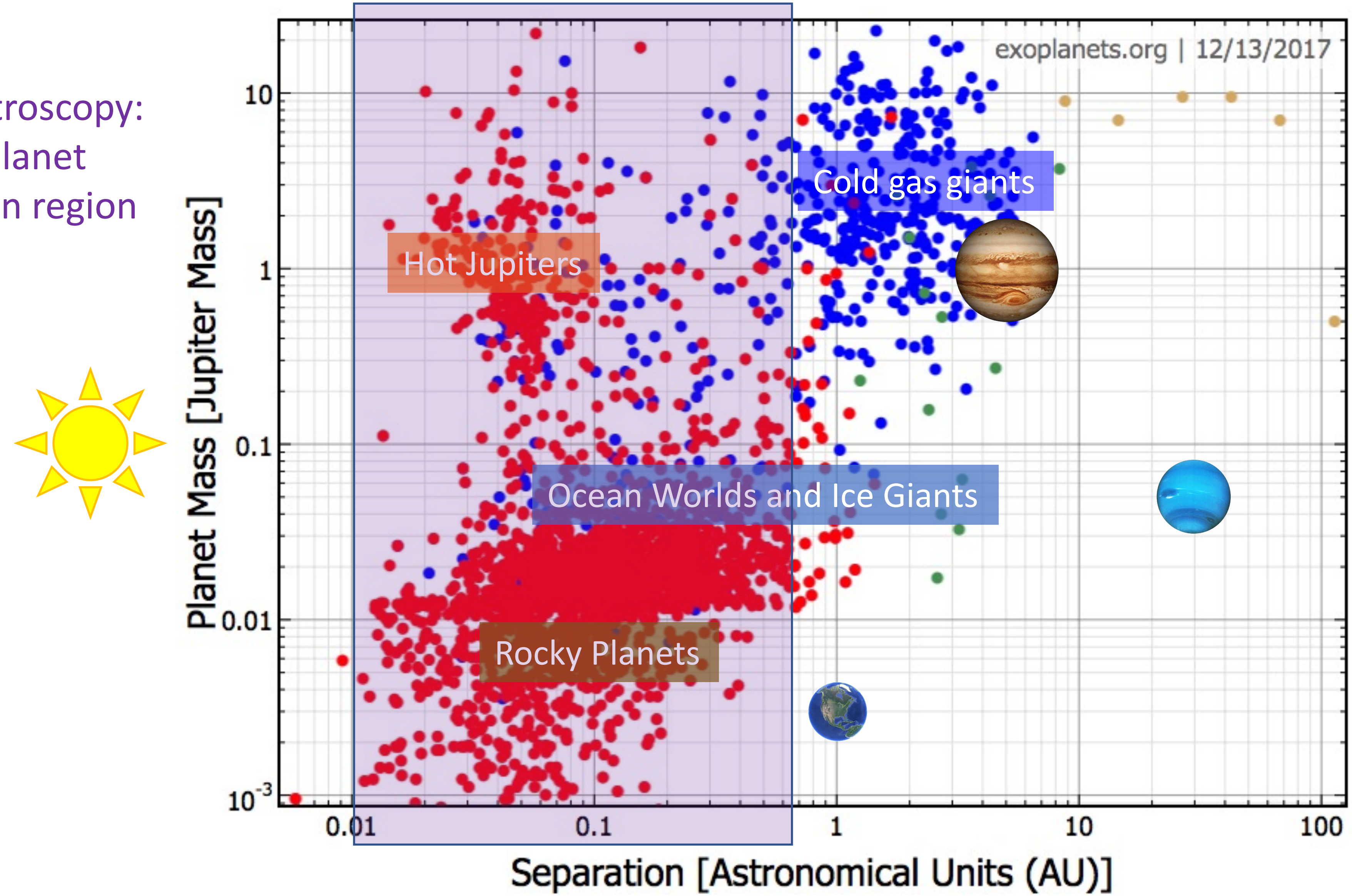
CO outer radius:
~ 0.4 au

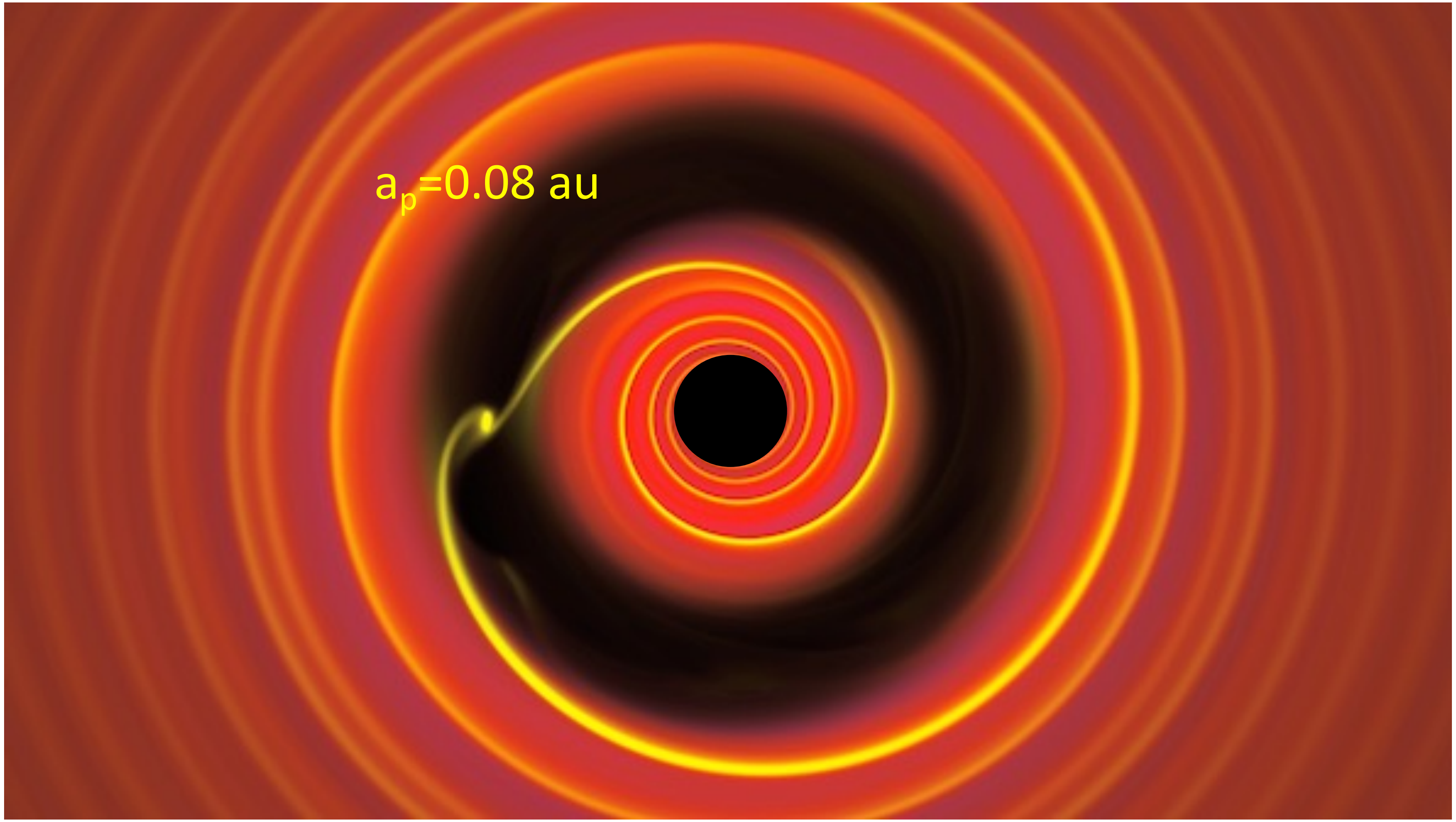
CO inner radius:
0.028 au



Exoplanet Populations

CO spectroscopy: probes planet formation region

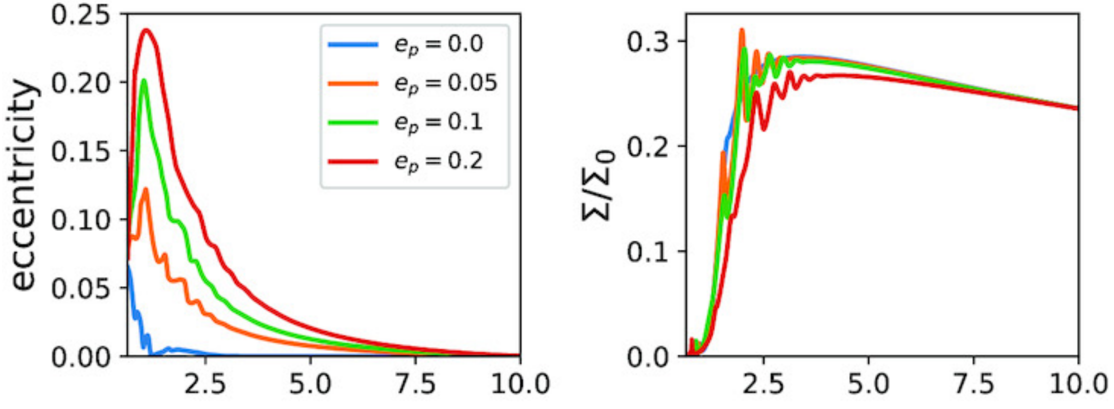


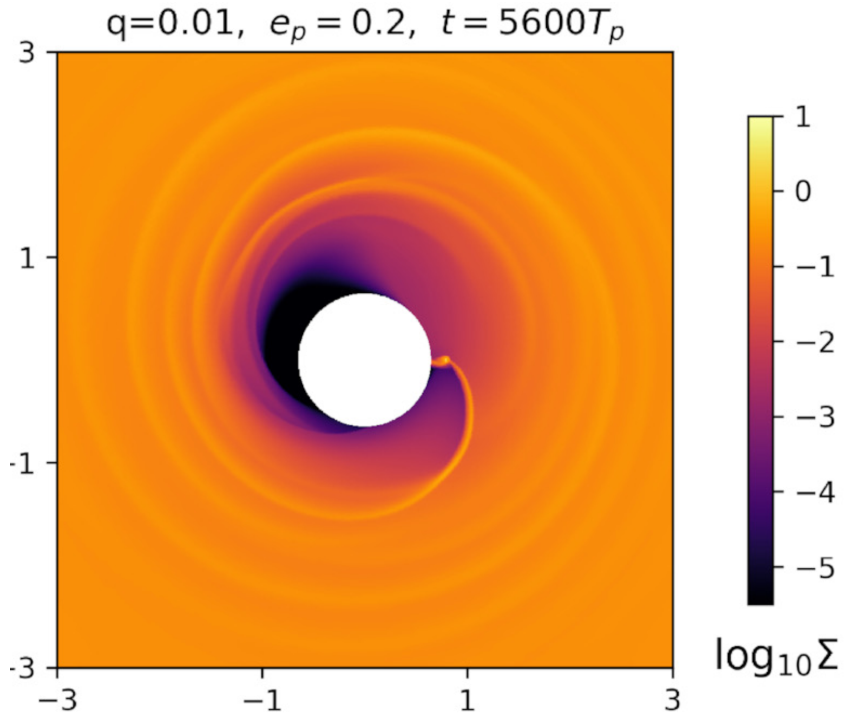


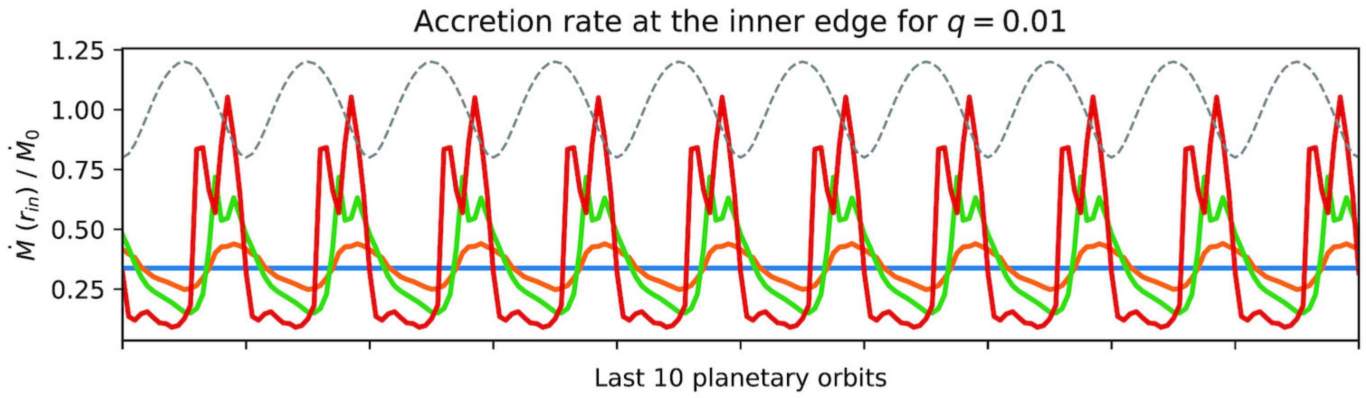
CO probes from ~0.02 au to ~0.6 au

Massive planet on eccentric orbit…

Gap: broader, persistent eccentricity



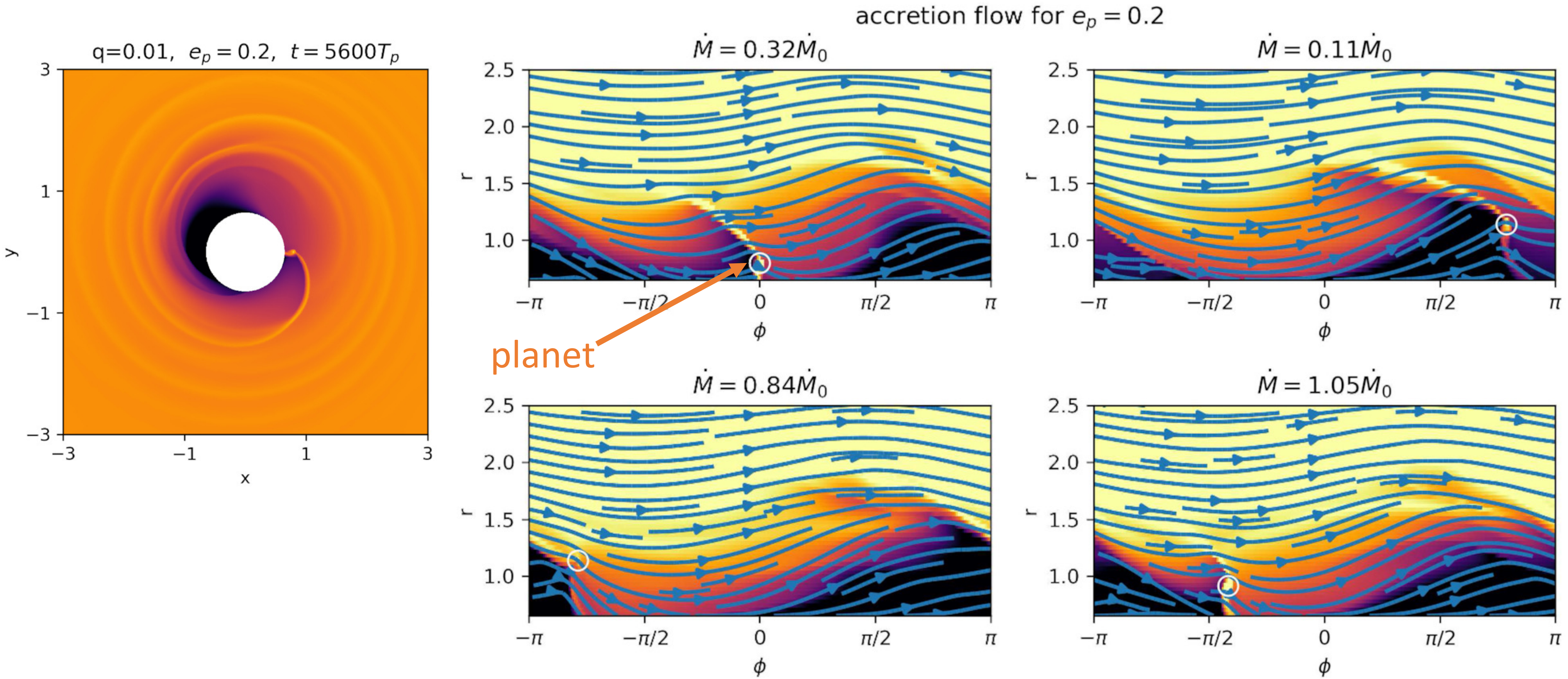




Pulsed accretion at orbital period

Teyssandier & Lai 2020

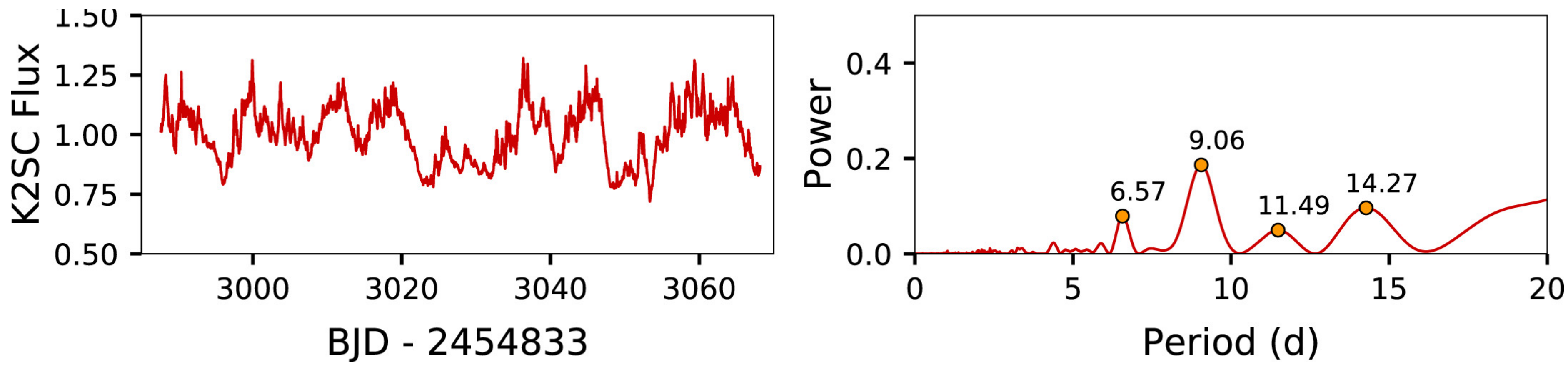
Massive planet on eccentric orbit



Teyssandier & Lai 2020

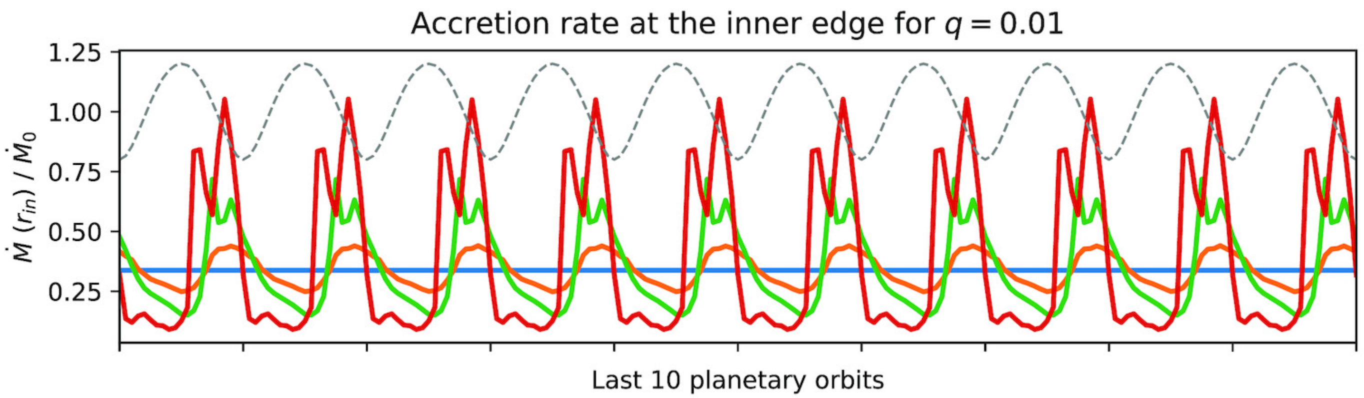
CI Tau b: Variability in optical continuum

K2 photometric variability



Biddle et al. 2018

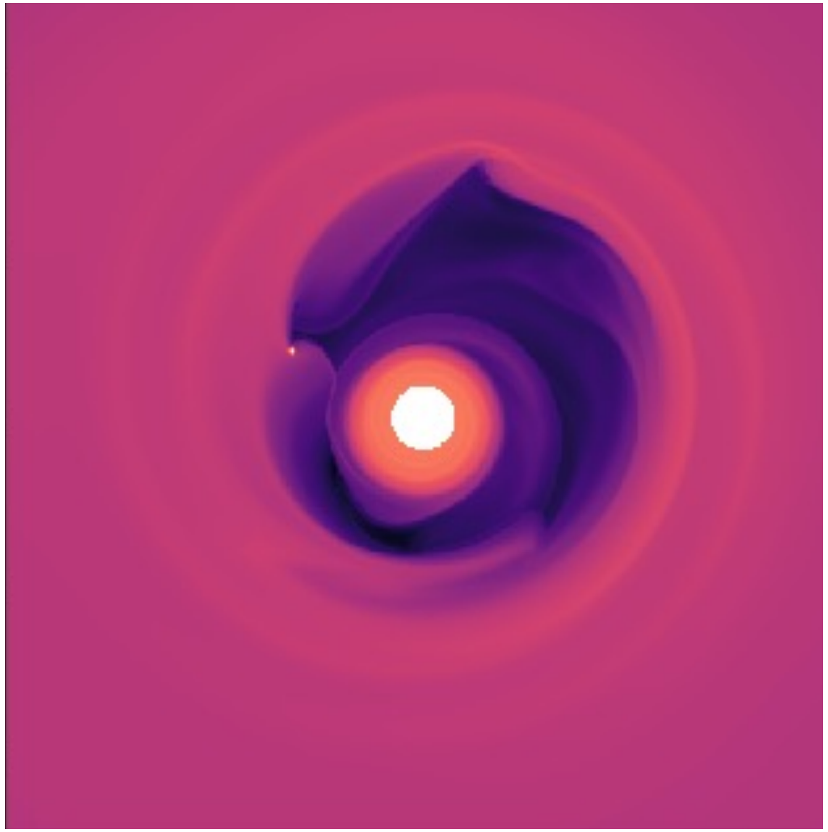
Theory: pulsed accretion at orbital period



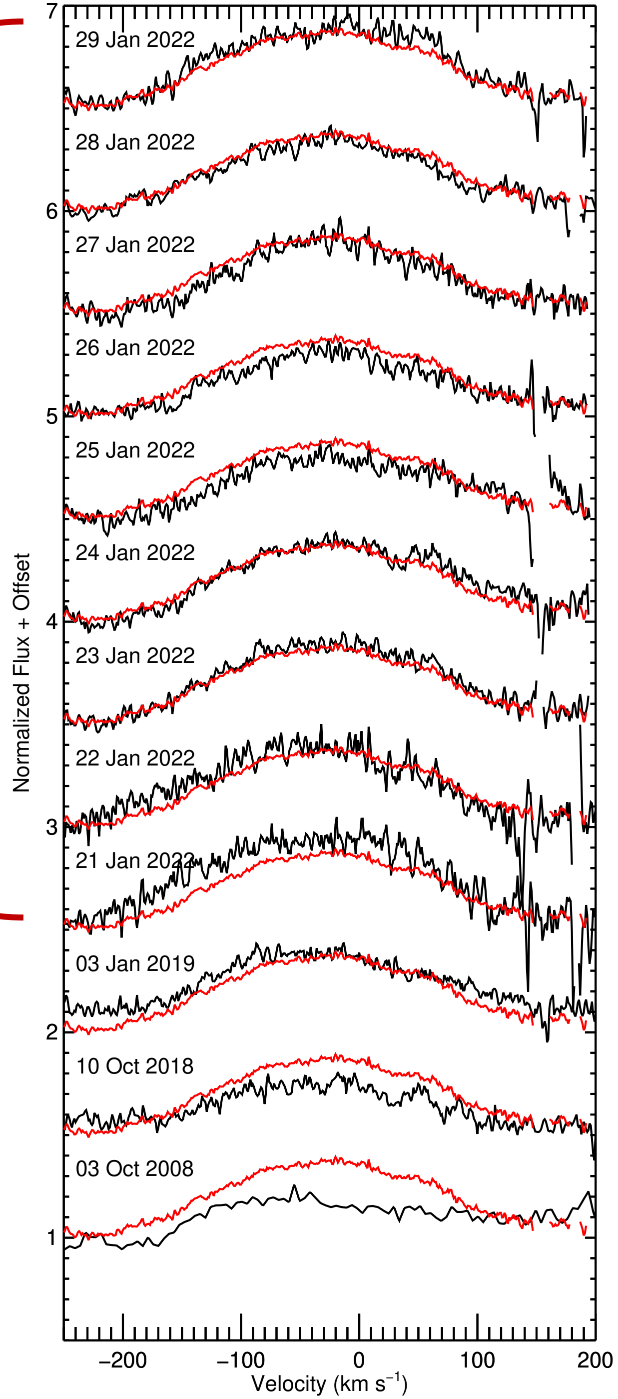
Teyssandier & Lai 2020

CI Tau b: limited Pf β variability

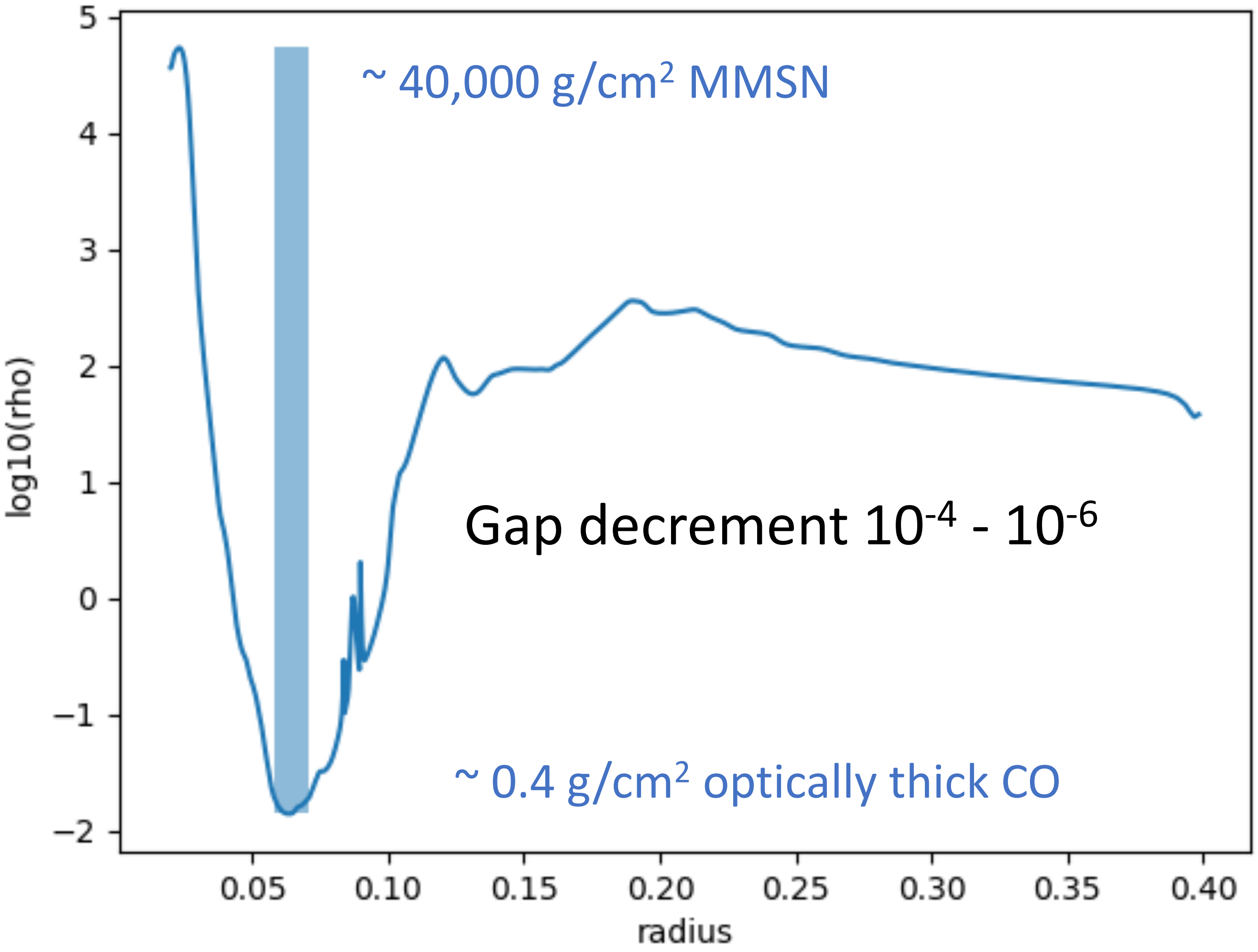
EW: varies by 0.2 dex over orbit



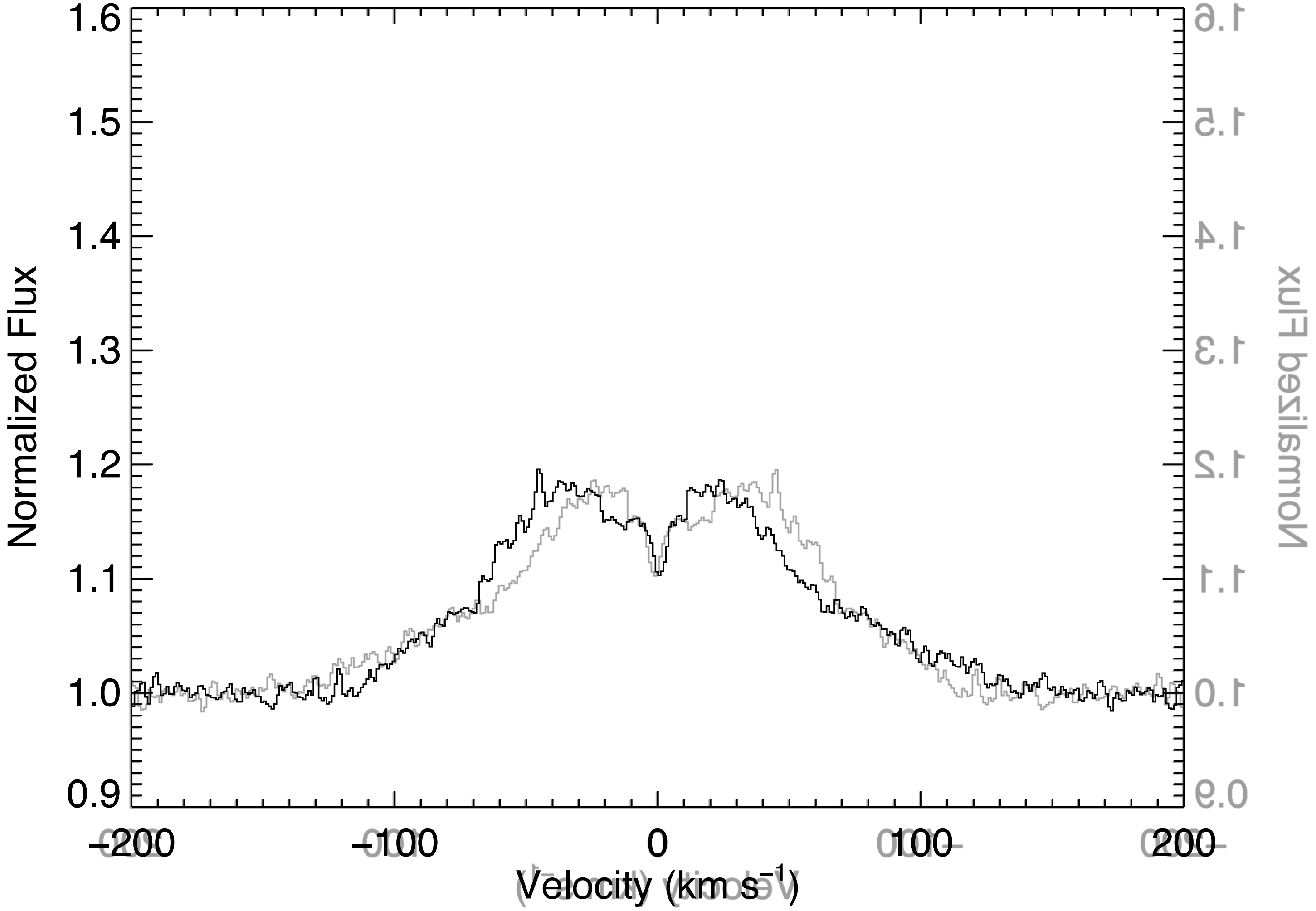
Does inner disk smooth out the predicted pulsed accretion?

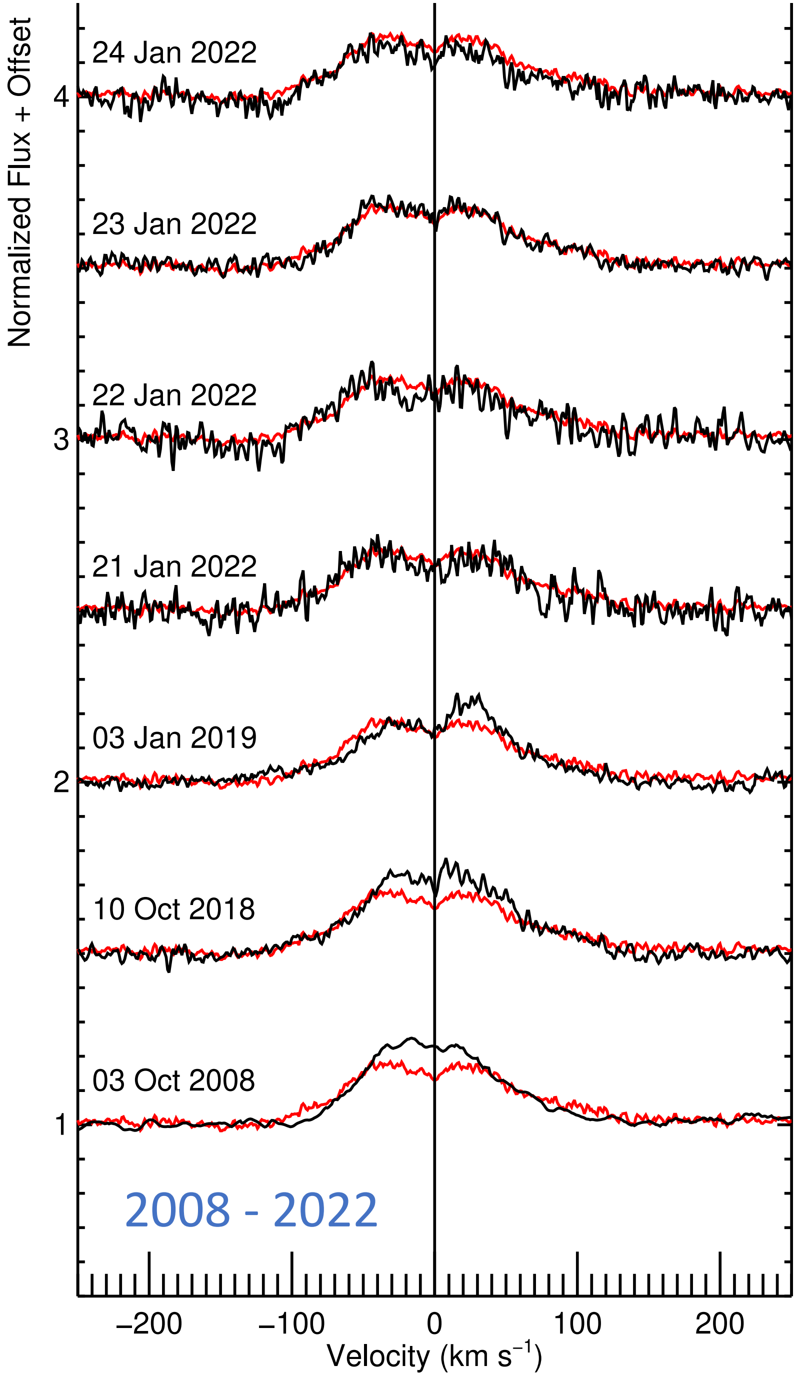


CI Tau b's gap…elusive?

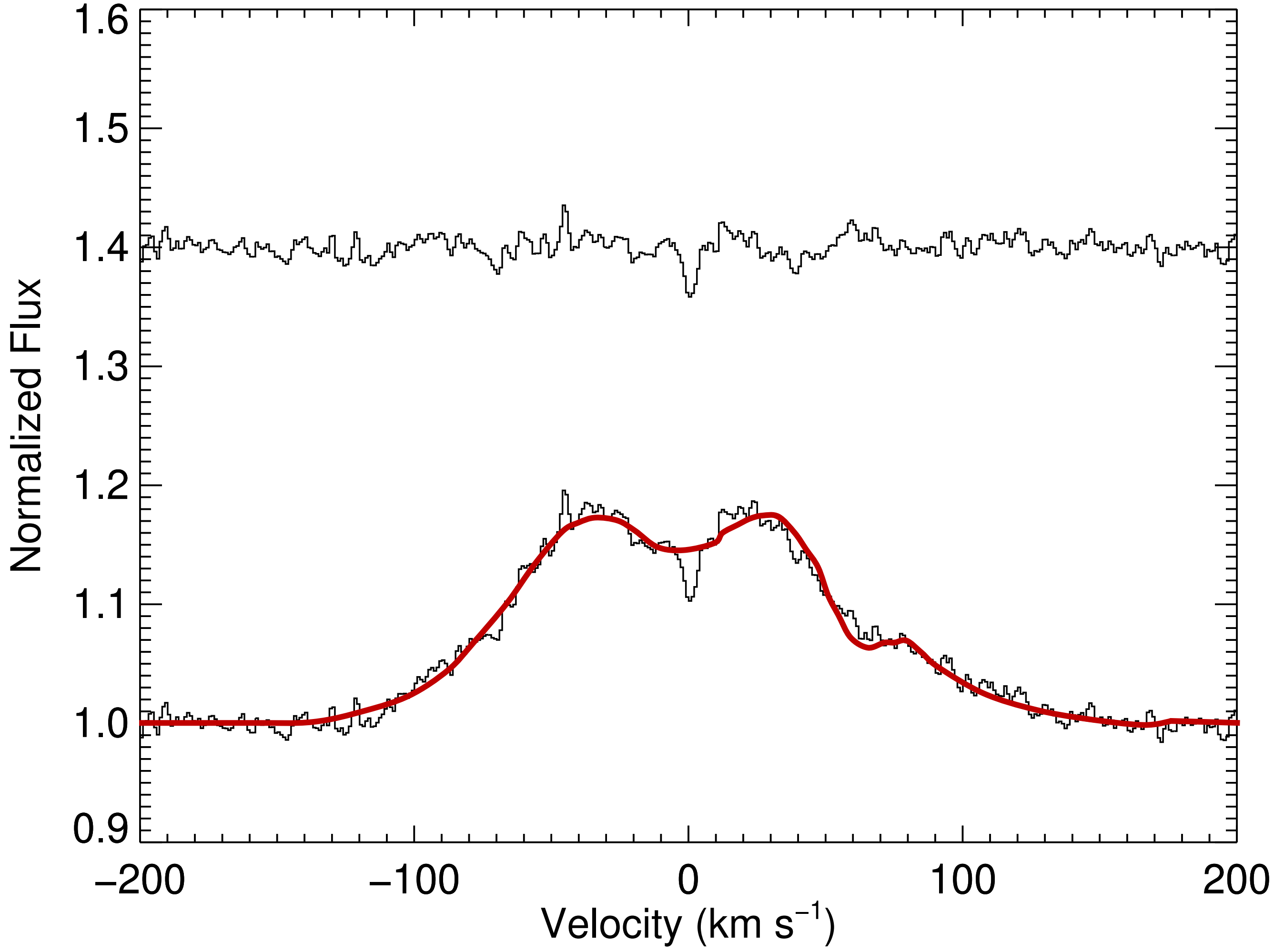


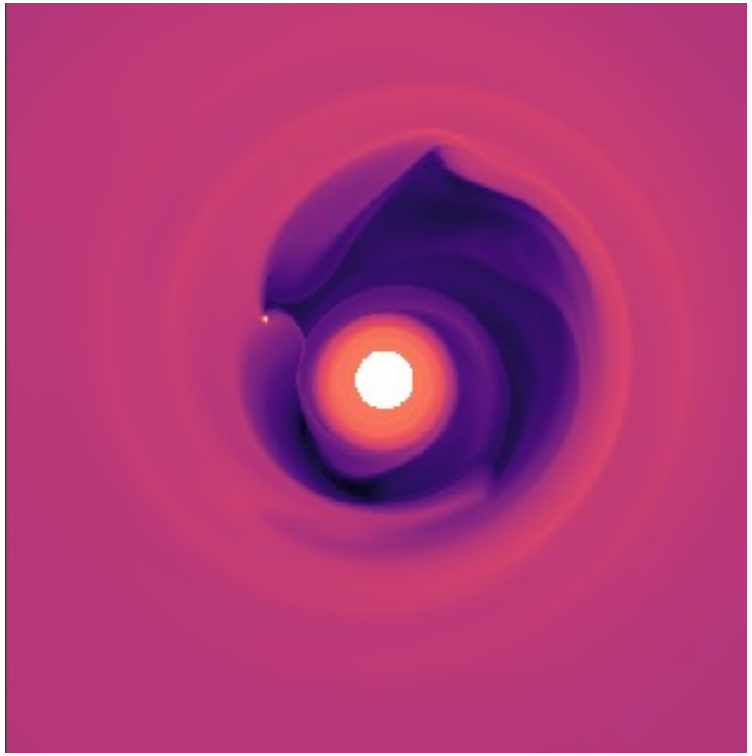
CI Tau b: line profile asymmetry





CI Tau b: CO fit with narrow gap

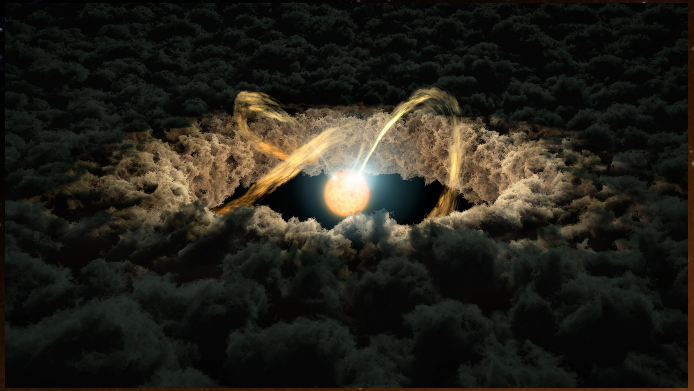


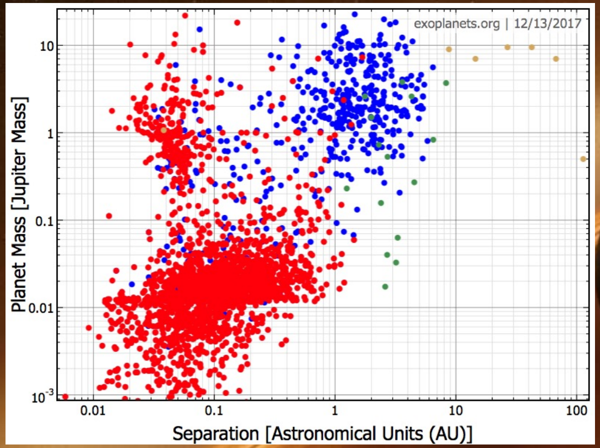


R_{CO} = 0.02 to 2.4 au
e = 0.07 (inner disk)
= 0.13 (outer disk)
Δ_{gap} = 0.009 au

Summary

Protective migratory barrier forms early, leaves imprint on exoplanets

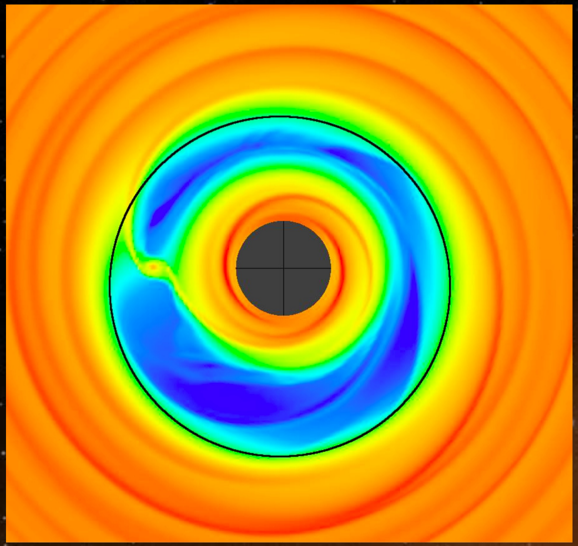


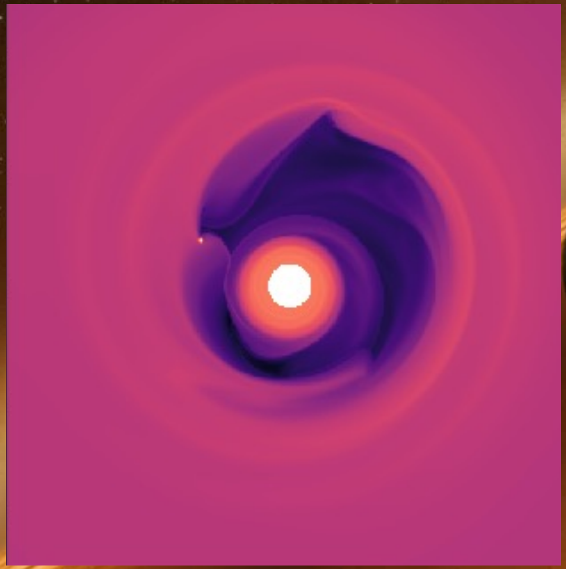


Signposts of (high mass giant) planet formation

Predictions	HD100546	CI Tau
Gap	Yes - CO	Maybe - CO
Circumplanetary disk	Yes - CO	No – low contrast
Persistent asymmetry		
declines from inner rim	Yes – OH, CO	
e (inner disk) < e (outer disk)		Yes - CO
Pulsed stellar accretion	NA	No - inner disk?
Planetary accretion	Unexplored?	Pf β – not apparent

Summary





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