

# **DIRECT OBSERVATIONAL DETECTIONS OF FORMING PLANETS**

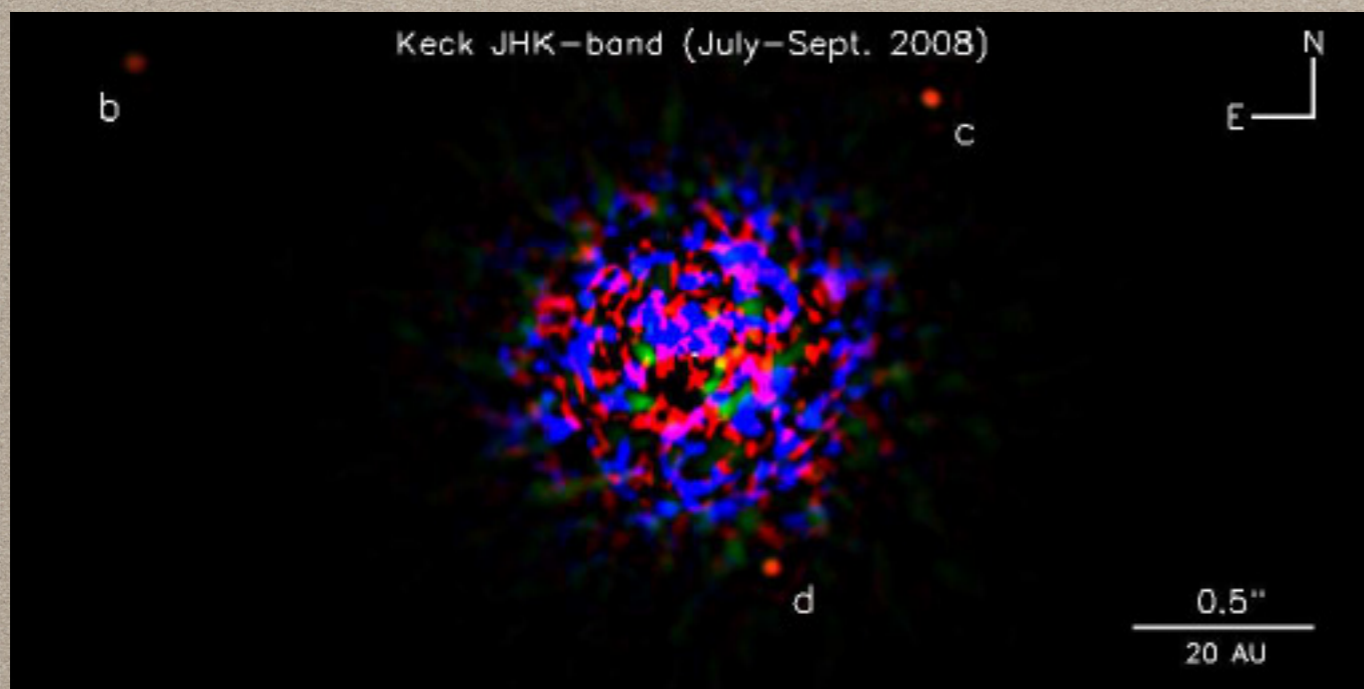
SEAN BRITTAIN<sup>1,2,3</sup>

*1Clemson University*

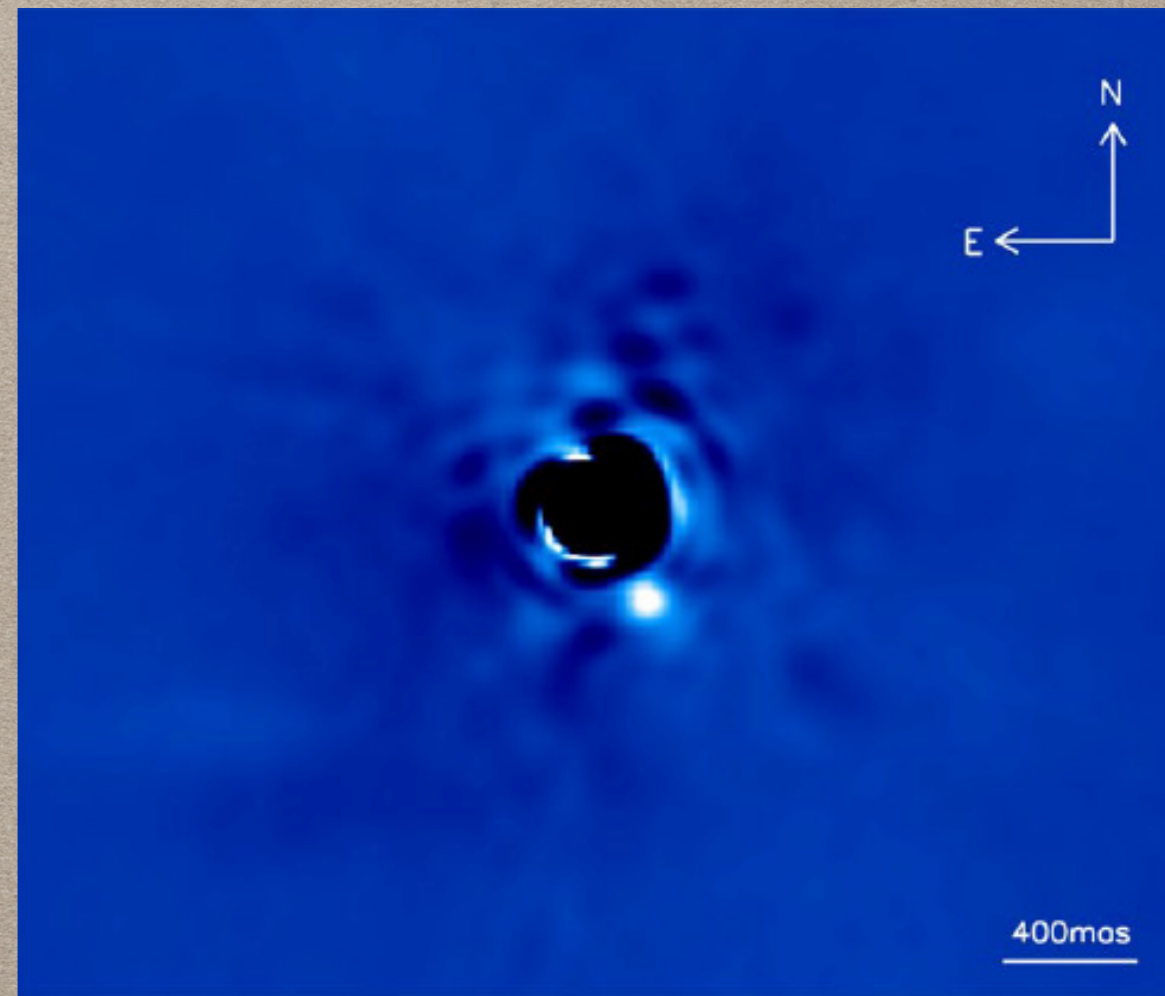
*2NOAO*

*3Funded by NSF/NASA*

# GREAT EXPECTATIONS



MAROIS, ET AL. 2008



LAGRANGE ET AL. 2010

# REALISTIC EXPECTATIONS?

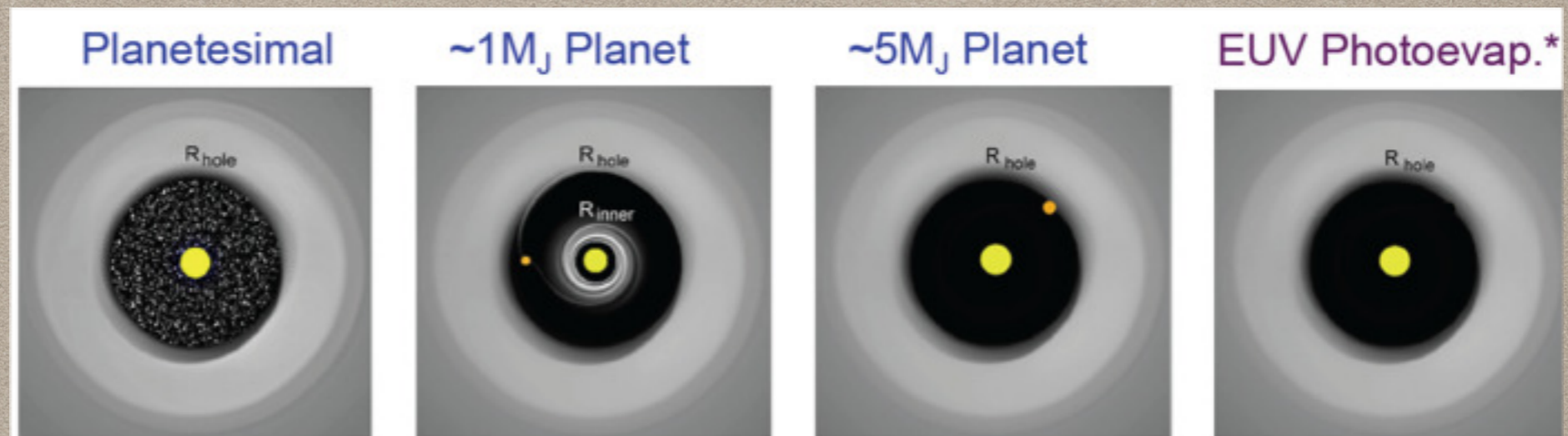
There are few detections of gas giant planets orbiting young, intermediate mass stars from 30-300 au (3/110; Bowler et al. 2016)

Is the **occurrence** rate of gas giant planets from 30-300au a few percent?

What do indirect tracers of planets say?

# UNDERDETERMINATION

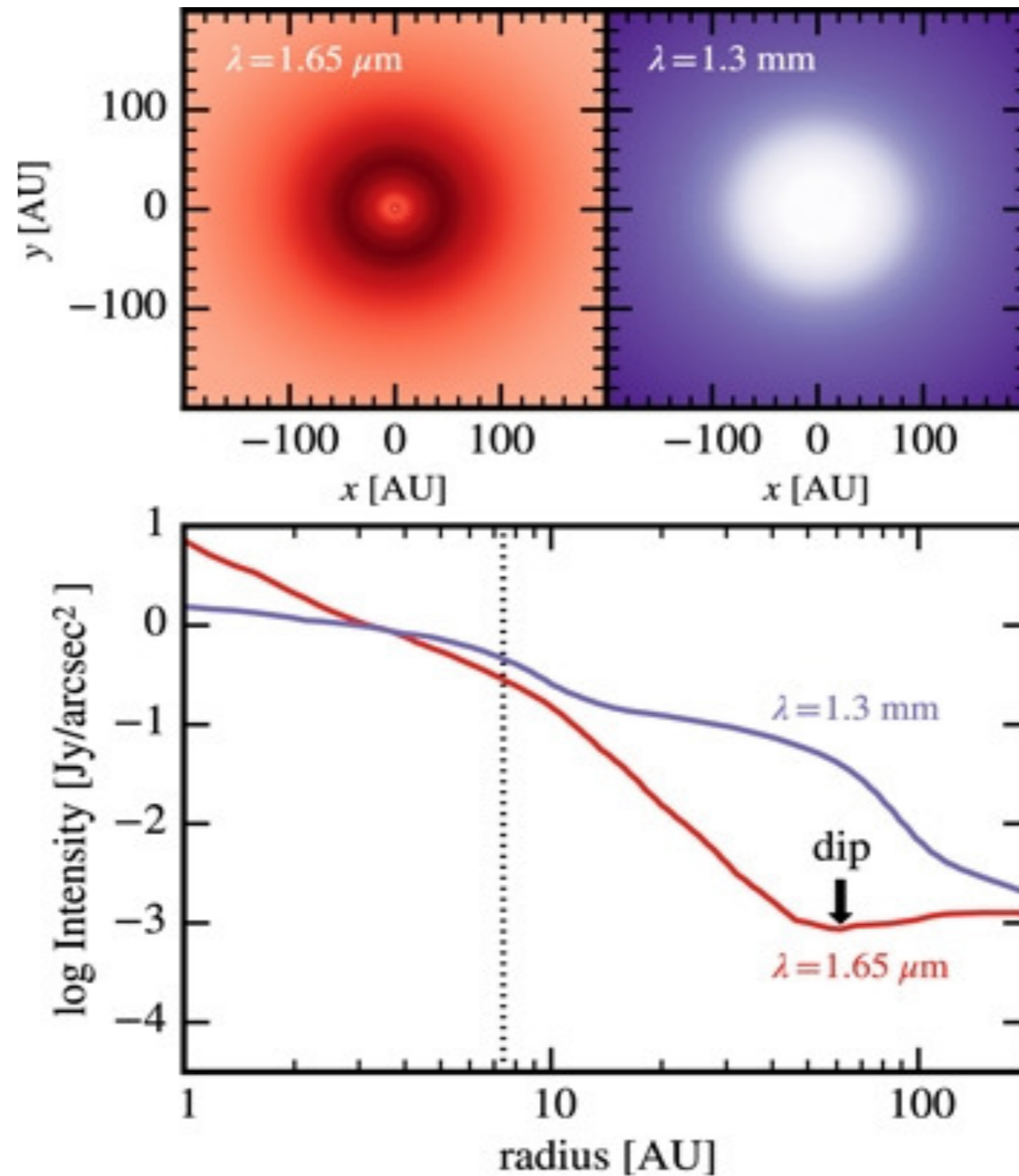
GAPS/HOLES CONDENSATION FRONTS,  
PHOTOEVAPORATION, OR PLANET(S)?



*e.g. Najita+2007*

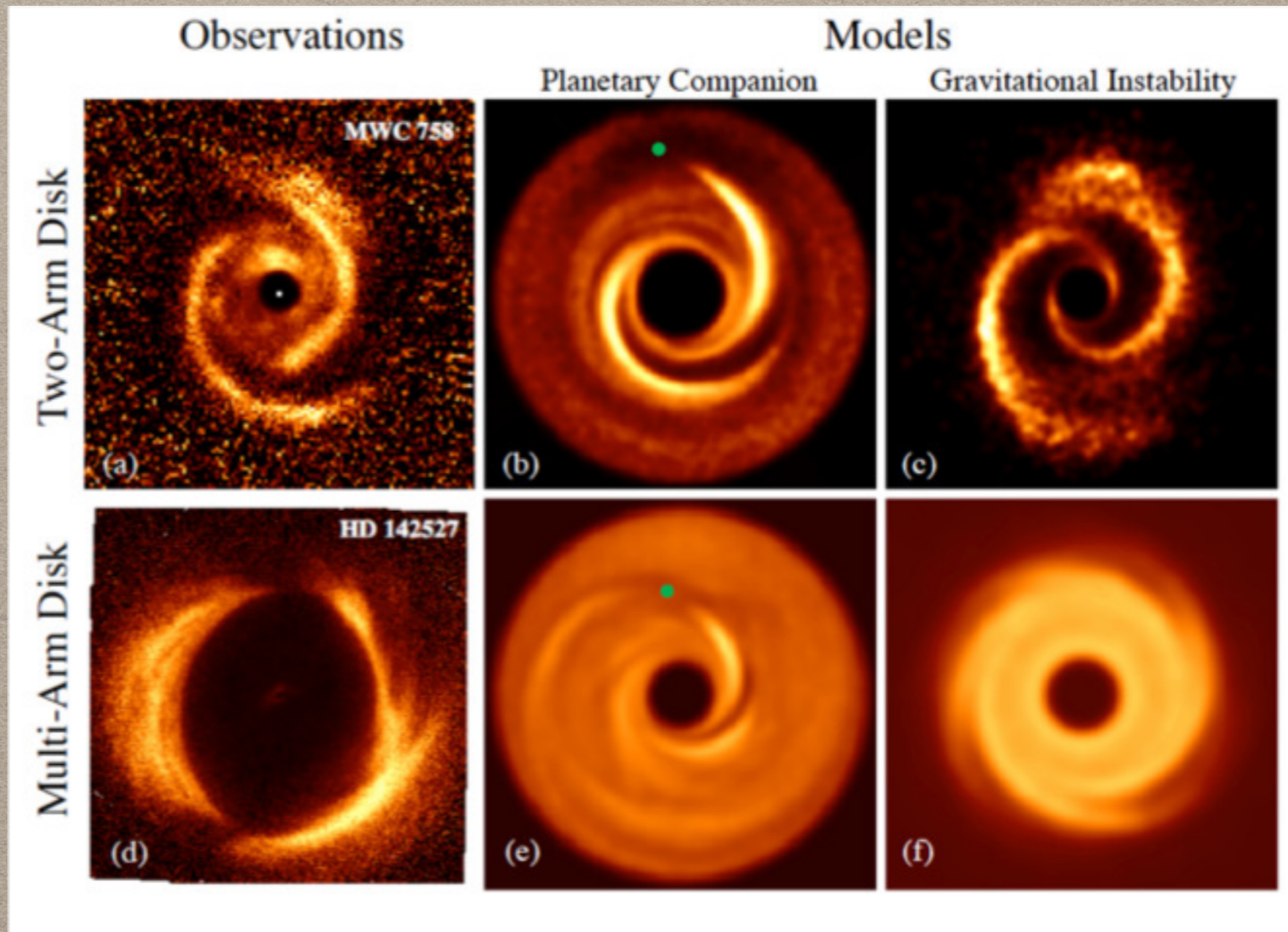
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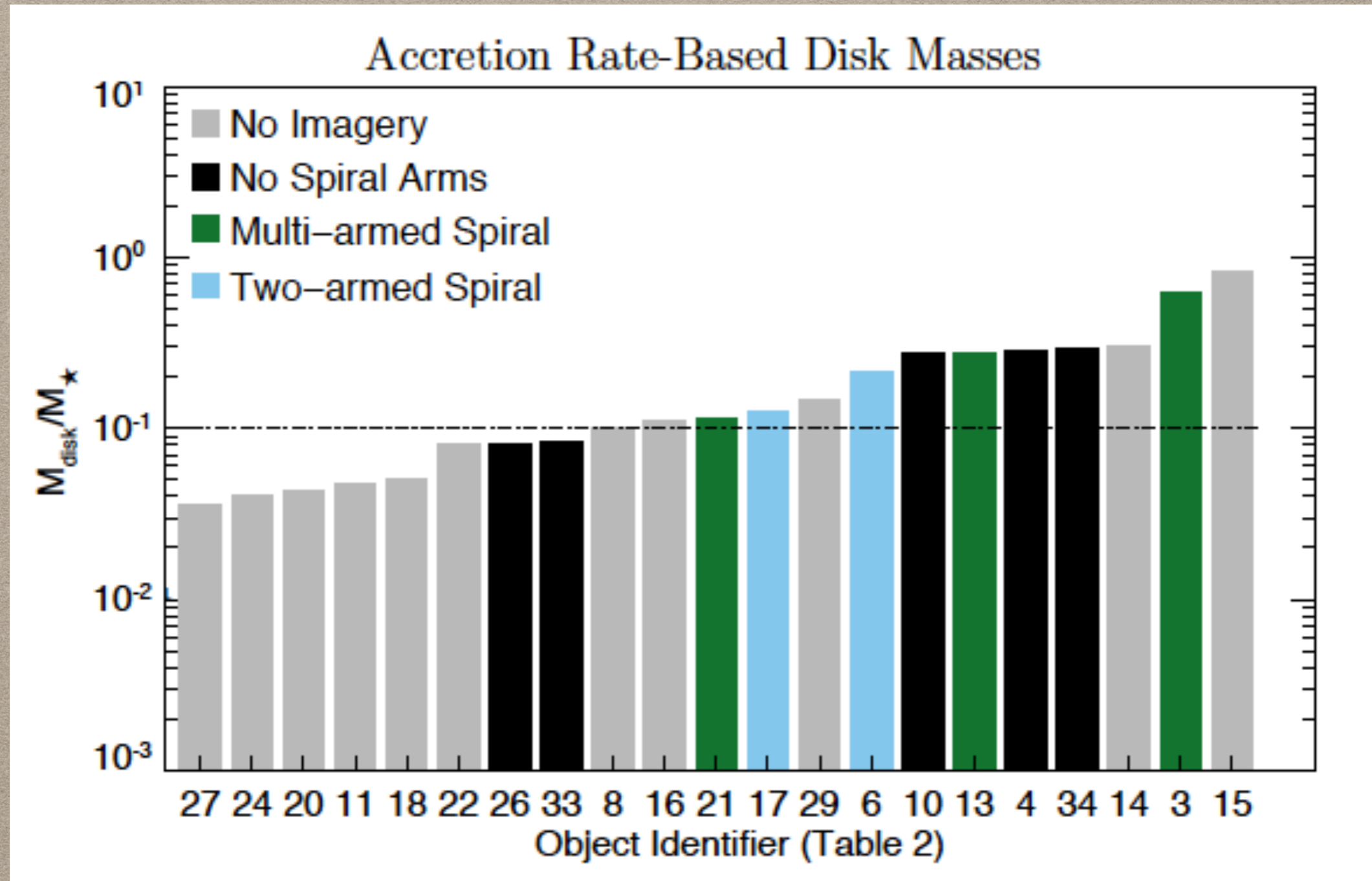
# UNDERDETERMINATION

SPIRAL STRUCTURE CAN BE ACCOUNTED FOR BY GI OR PLANETS AT LARGE RADII



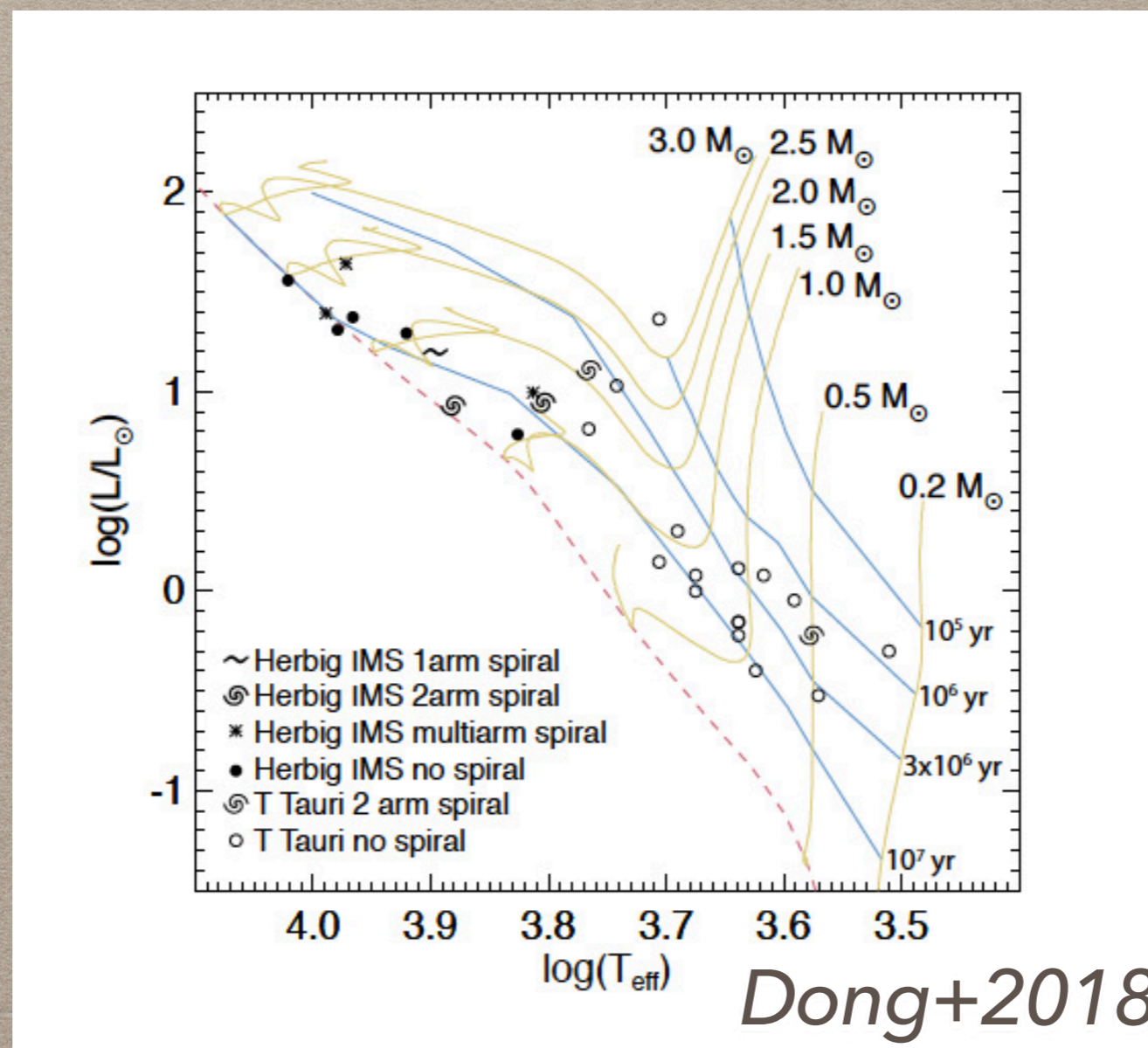
# Can disks around Herbig Ae/Be Stars be gravitationally unstable?

- $M_{\text{Disk}}(M_{\text{Acc}}) \sim 10 \times M_{\text{Disk}}(F_{1.3\text{mm}})$



# INDIRECT SIGNATURES

	All Types of Arms	Two Arms	Multiple Arms
Sources with arms	5	2	3
Arm fraction, well-studied disks	5/10	2/10	3/10
Arm fraction, all disks	$\geq 5/24$	$\geq 2/24$	$\geq 3/24$





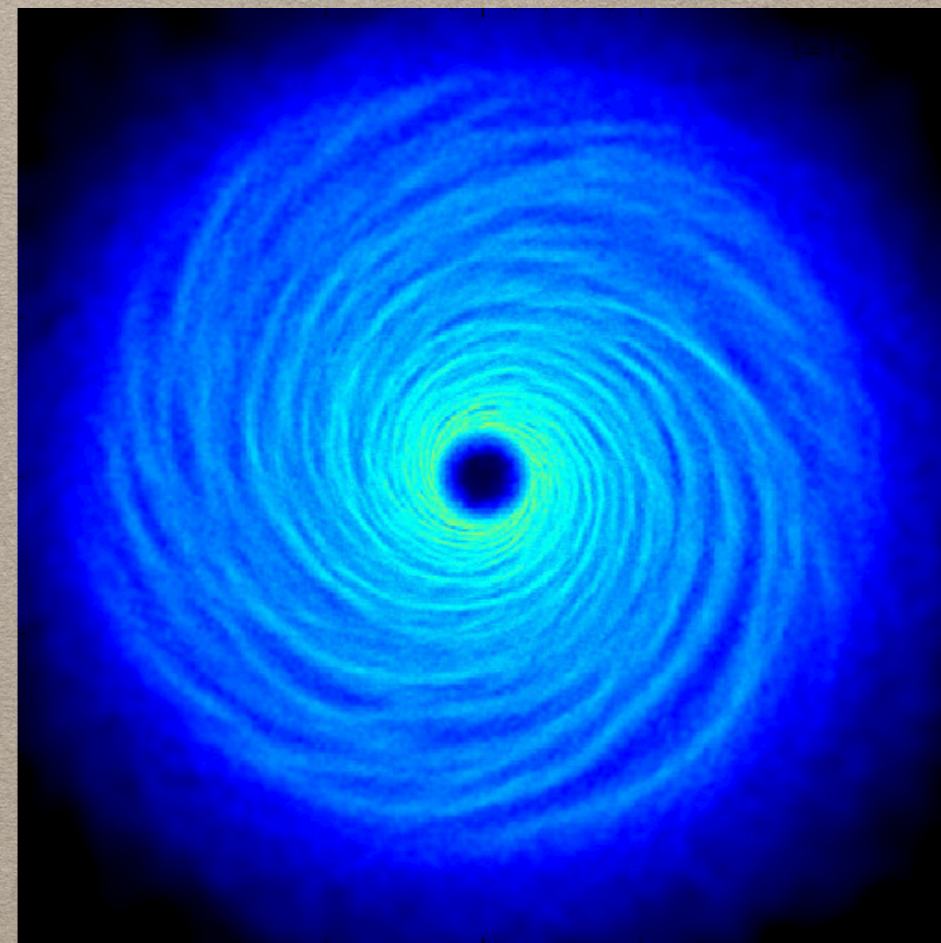
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A volume limited survey of Herbig Ae/Be stars without stellar companions (24 targets) will provide insight to the gas giant occurrence rate from 30-300au at ~few Myr.

How do we rule out the presence of spiral structure?

Is it feasible to get uniform sensitivity on a sample that includes GI and GI sources?



Kratter & Lodato 2016

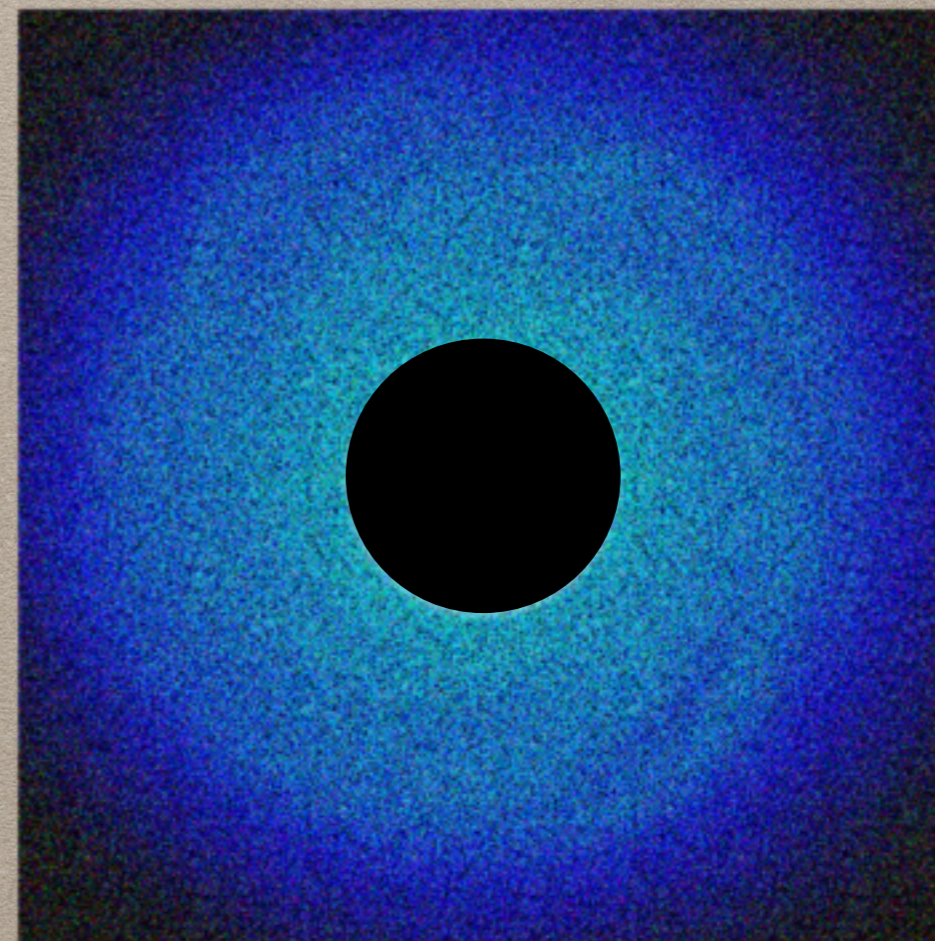
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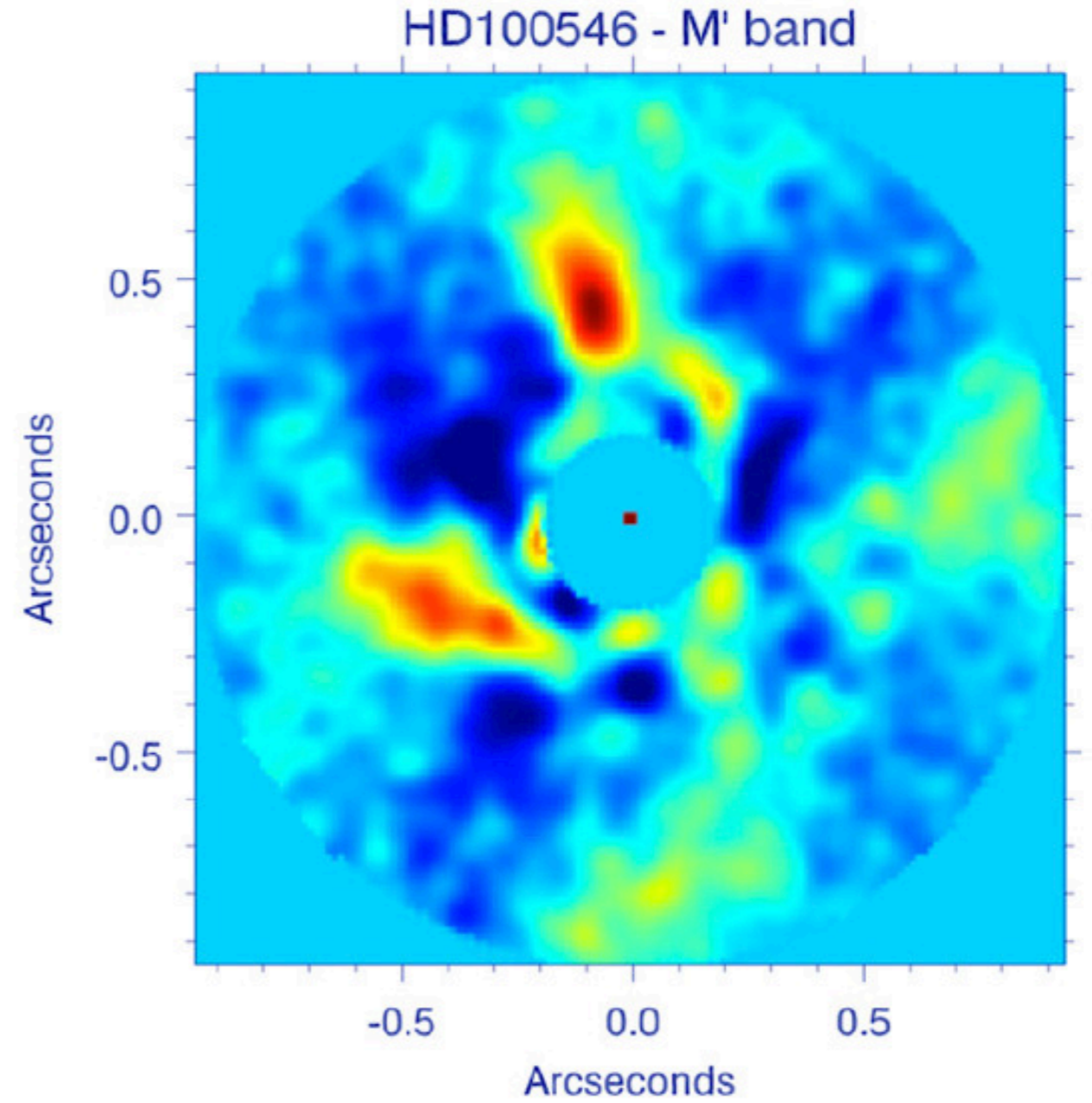
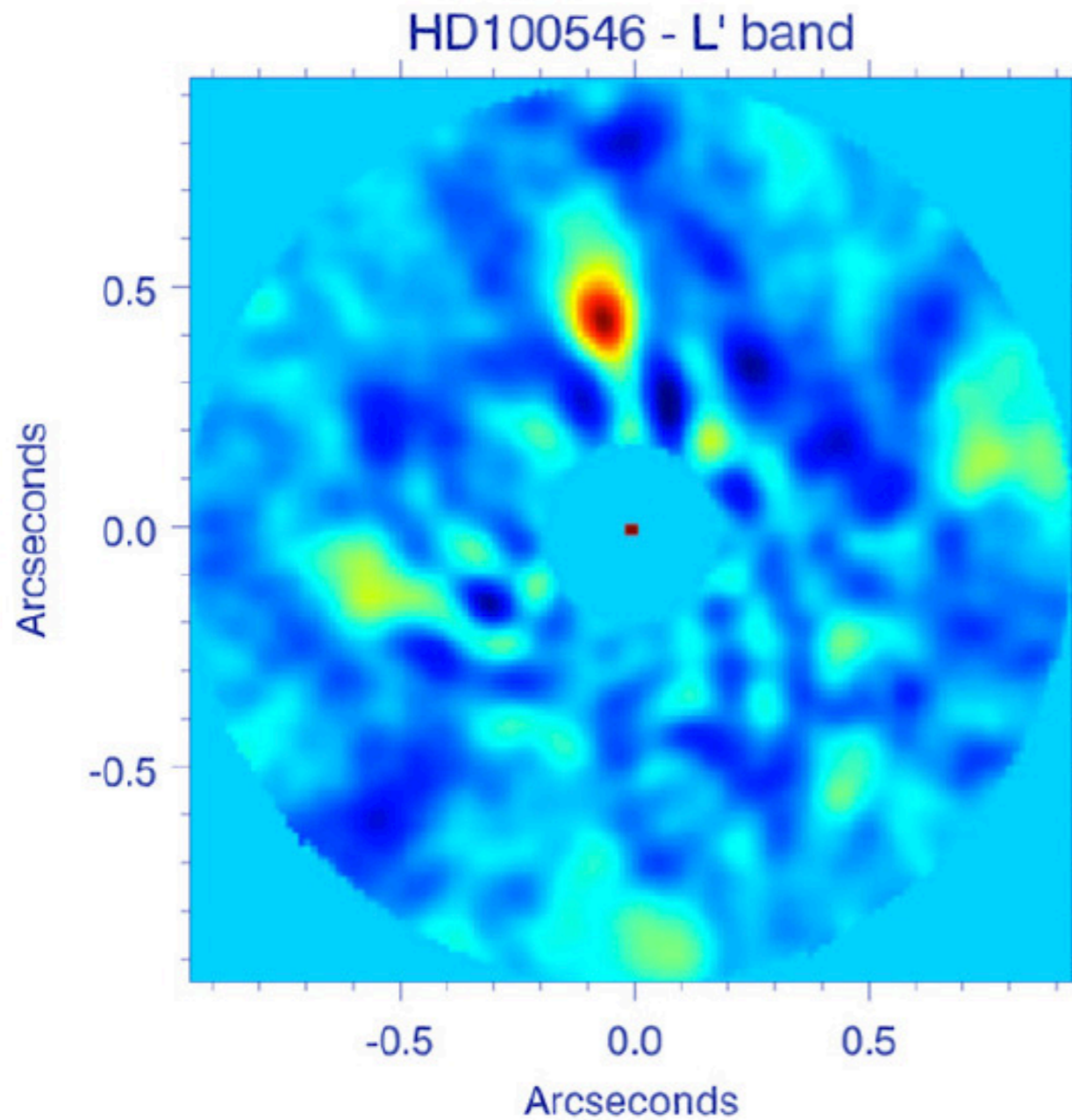
Kratter & Lodato 2016

# IMAGES OF FORMING PLANETS

REPORTED DETECTIONS THUS FAR ARE  
CONTROVERSIAL

*Direct observations of forming planets in protoplanetary discs is the ultimate goal of disc studies. The disc usually outshines the planet, requiring observations at high contrast and angular resolution. Detections by direct imaging have been reported in several discs: HD 100546, LkCa 15, HD 169142, and MWC 758. Yet, most of the detections to date have been subsequently challenged. The quest continues.*  
Pinte et al. 2018 (arxiv1805.10293)

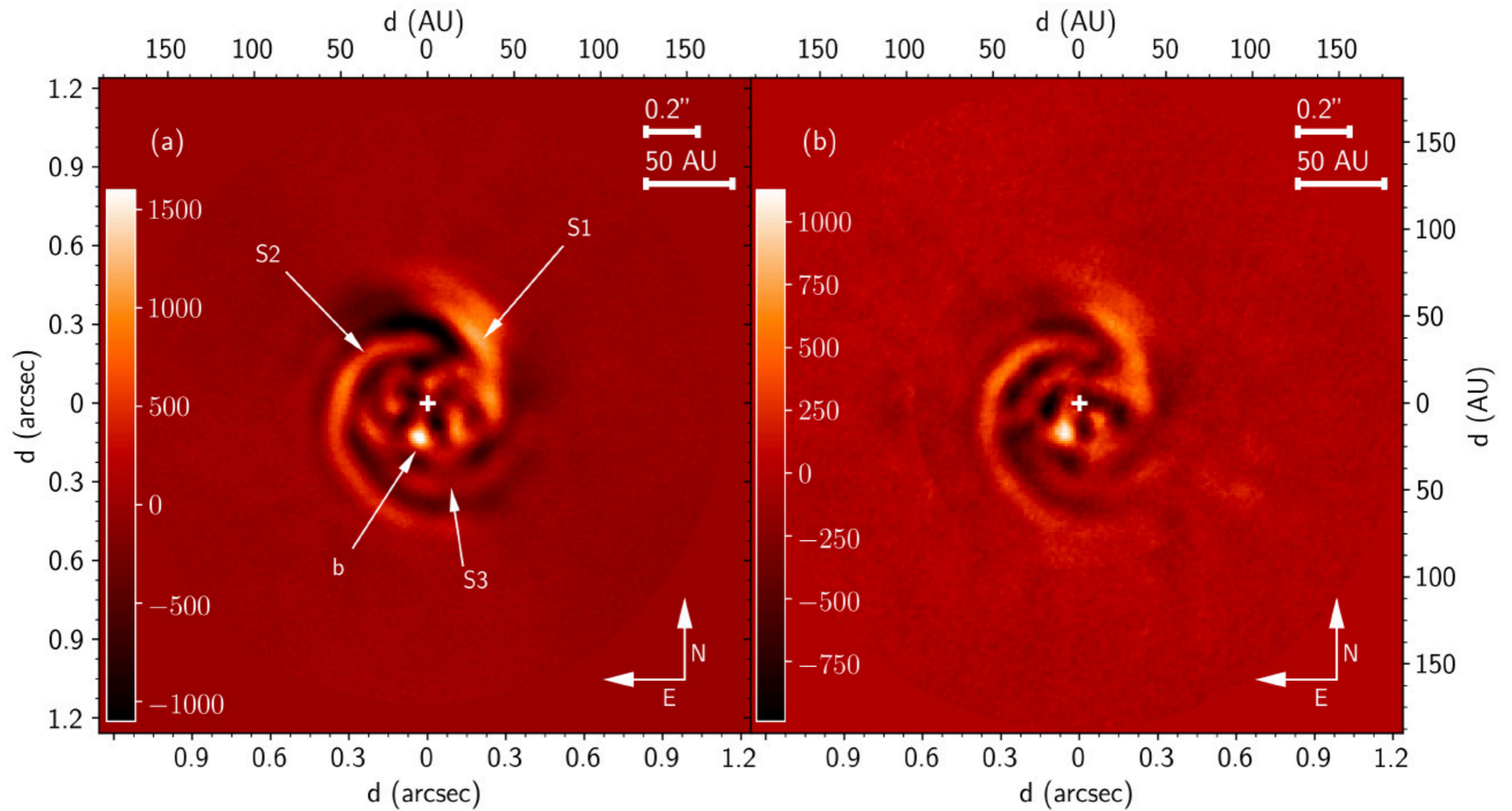
# HD 100546



*Quanz et al. 2015*

**EXTENDED SOURCE DETECTED IN L' AND M BANDS**

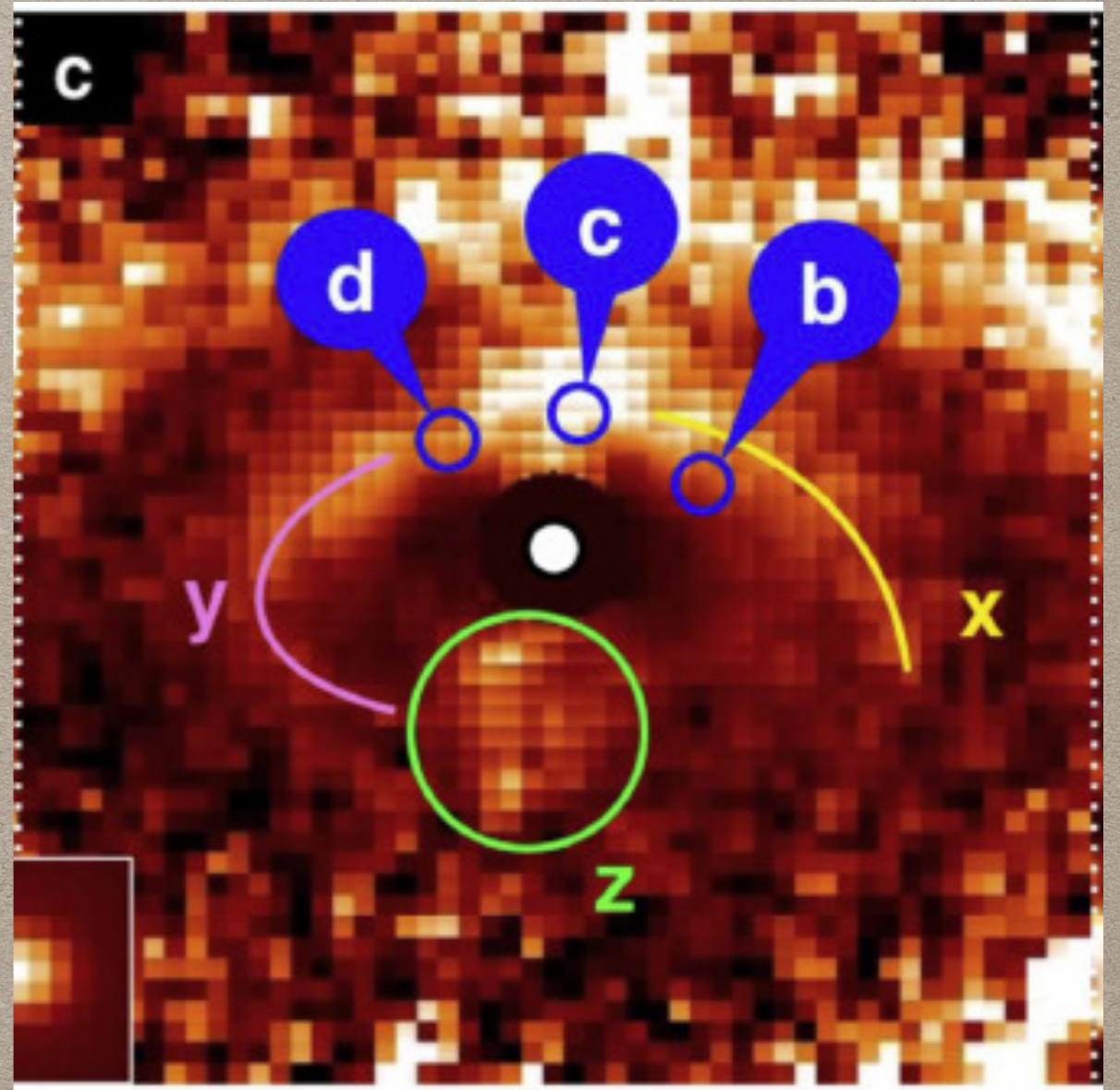
# MWC 758



*Reggiani+ 2017*

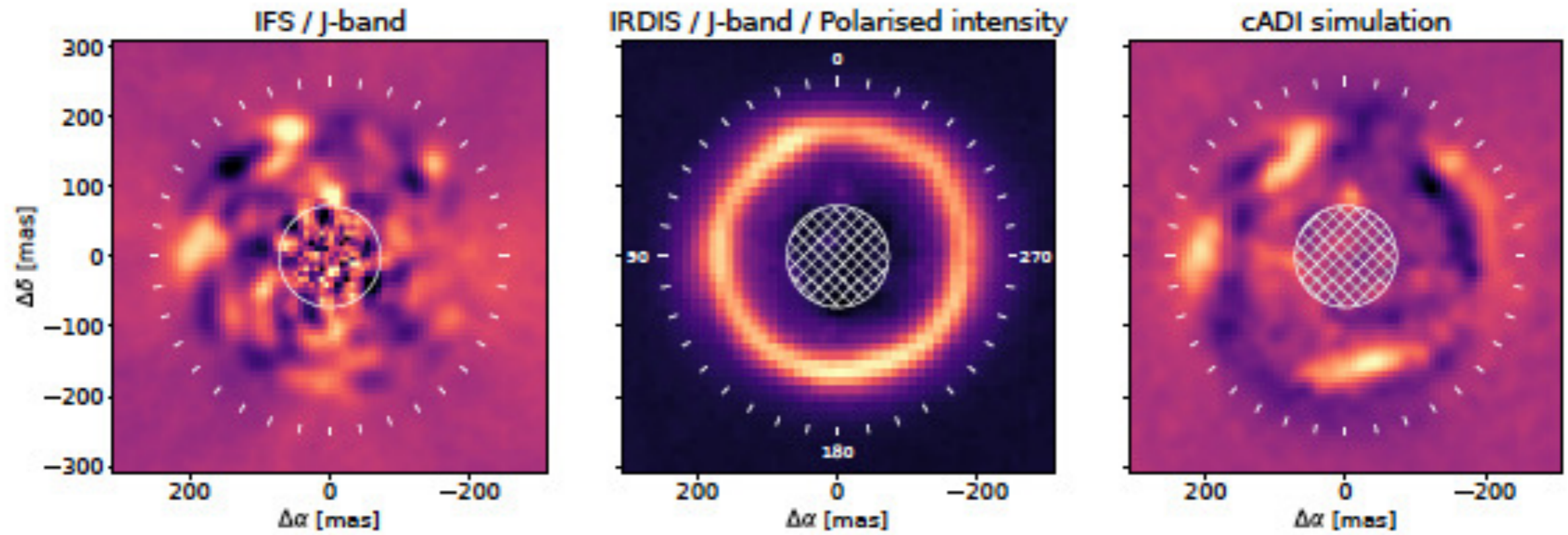
# LkCa 15

- Detection of sources "b", "c", and "d" from disk.
- Detection of H $\alpha$  at position "b" is suggestive?



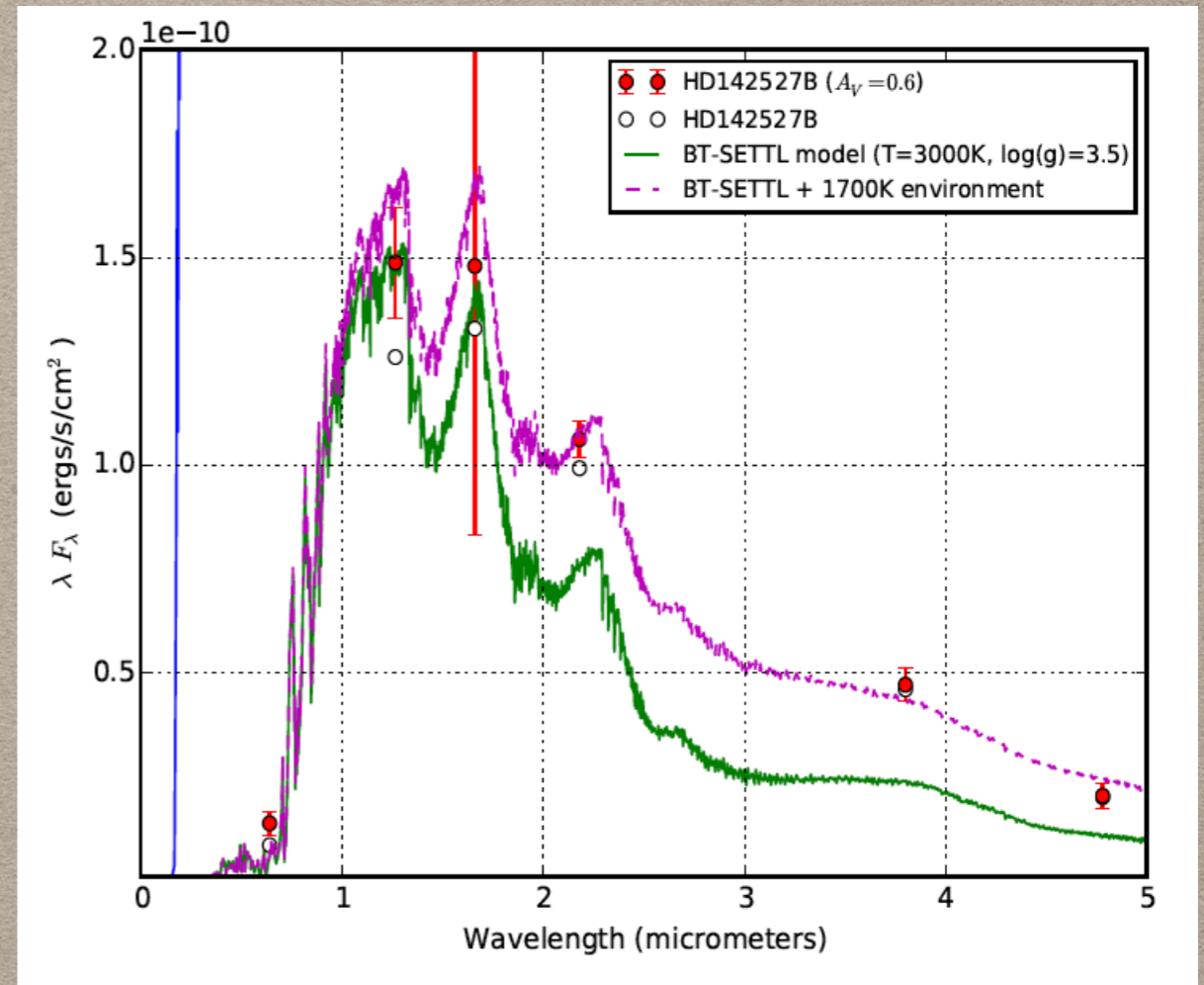
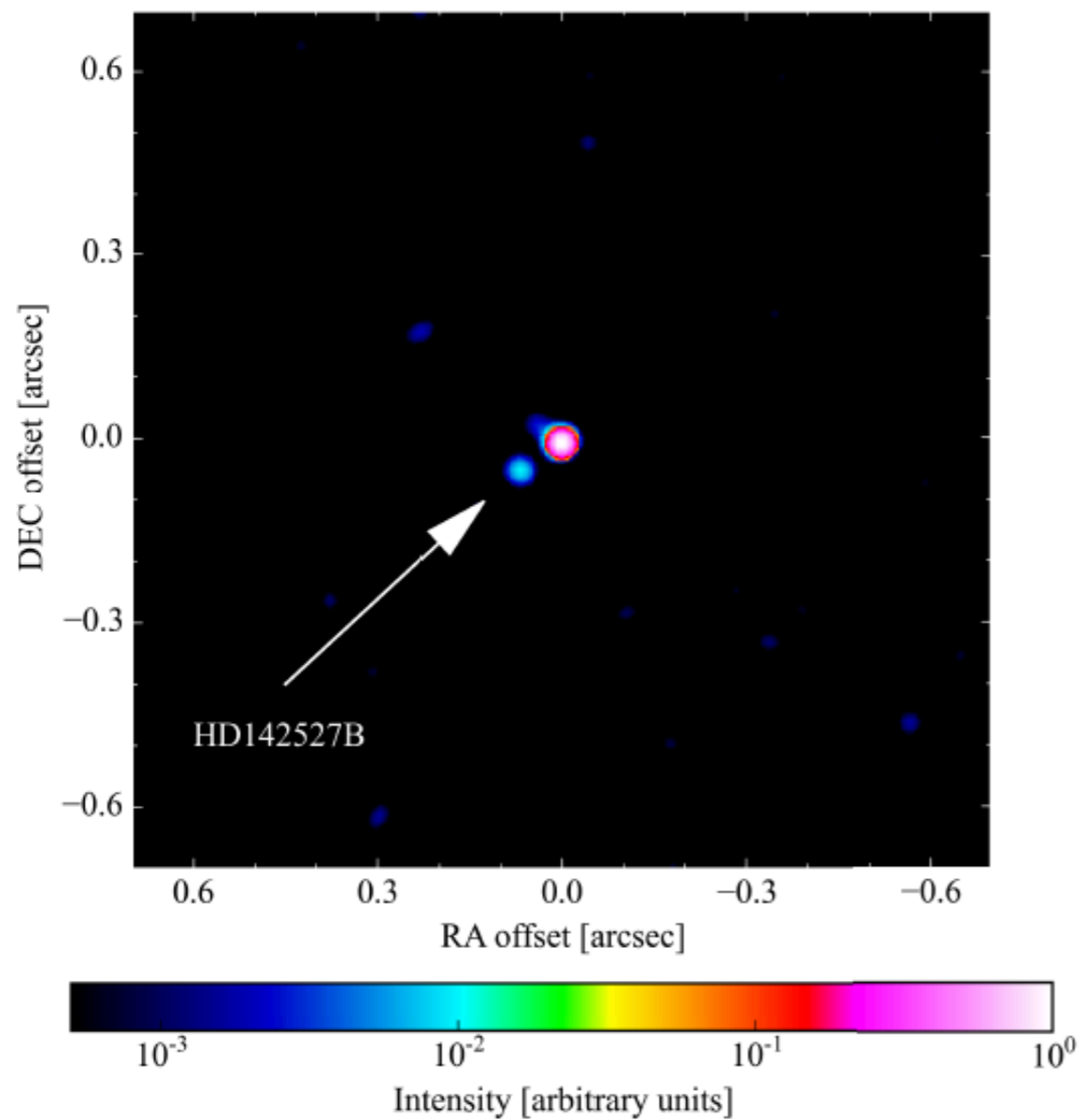
*Thalman et al. 2016*

# HD169142



*Ligi+ 2017*

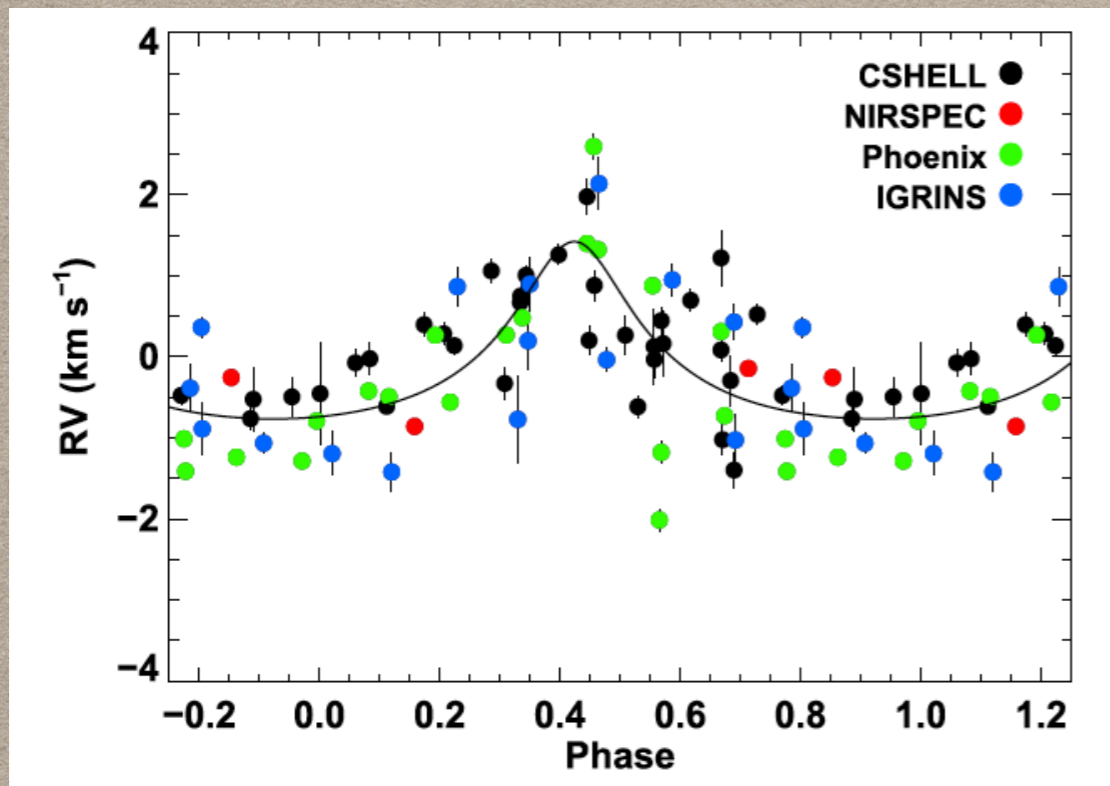
# HD 142527



Lacour+ 2016



# RADIAL VELOCITY



CI Tau b:

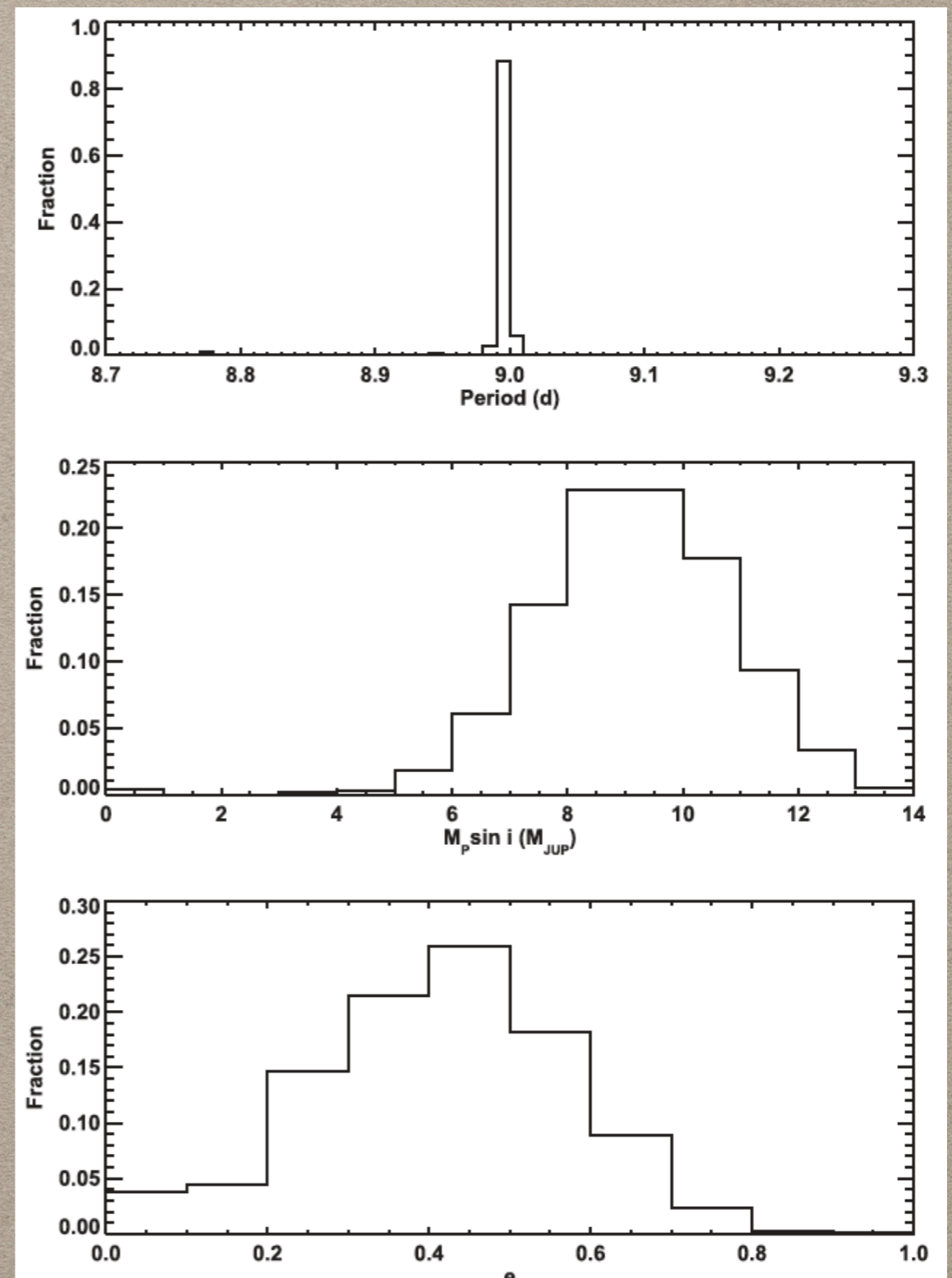
1.  $M=11\pm 2M_{\text{sun}}$

2.  $P=9^{\text{d}}$

3.  $P_{\text{star}}=6^{\text{d}}$

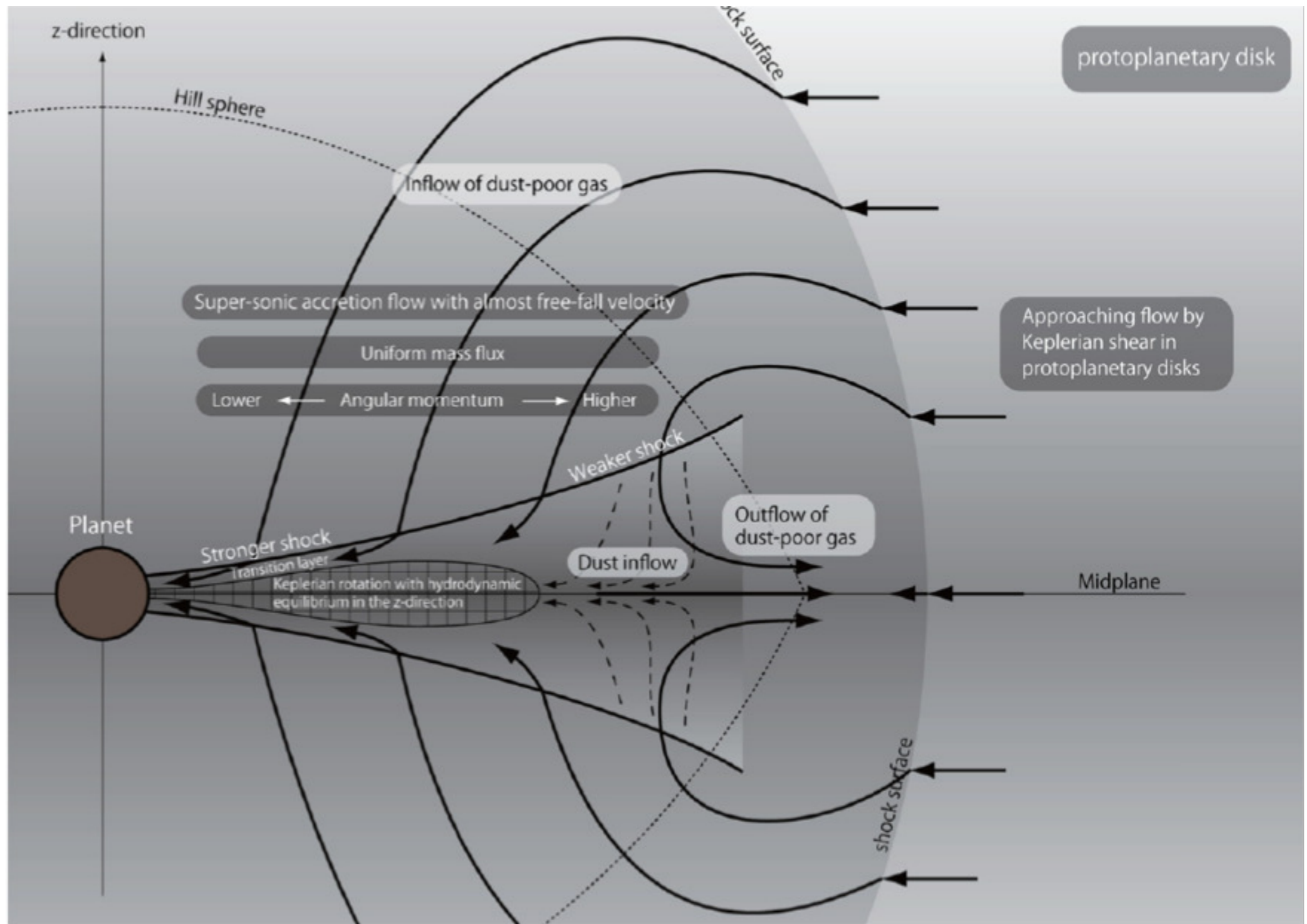
• Johns-Krull et al. 2016

• Biddle et al. 2018



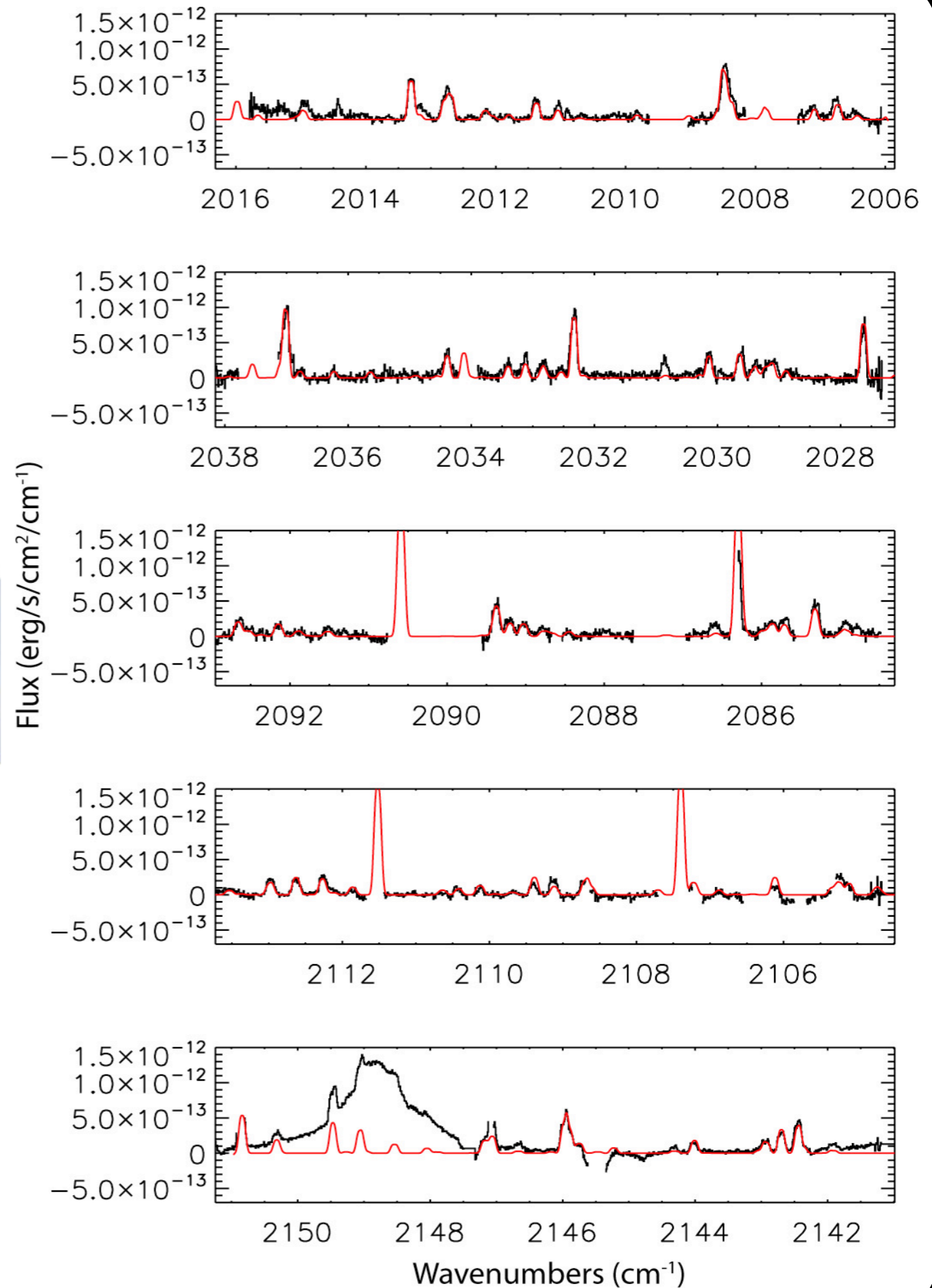
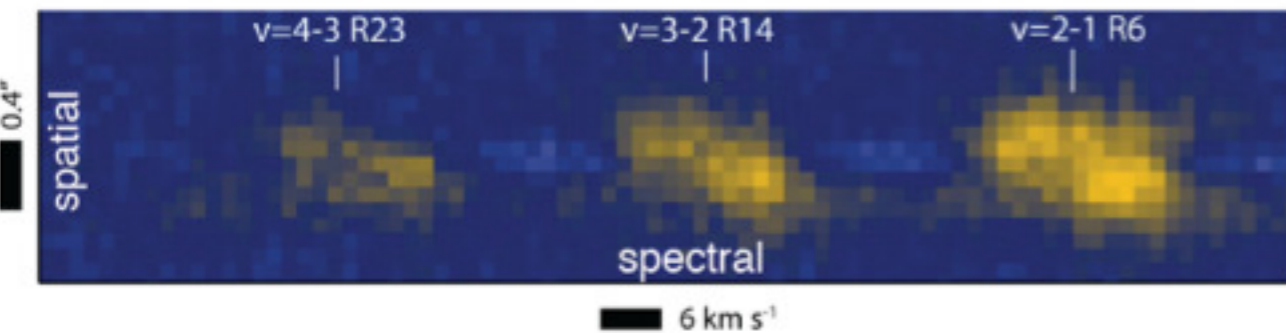
See also *Donati+2016 for WTTs*

# DETECTION OF THE CIRCUMPLANETARY DISK?



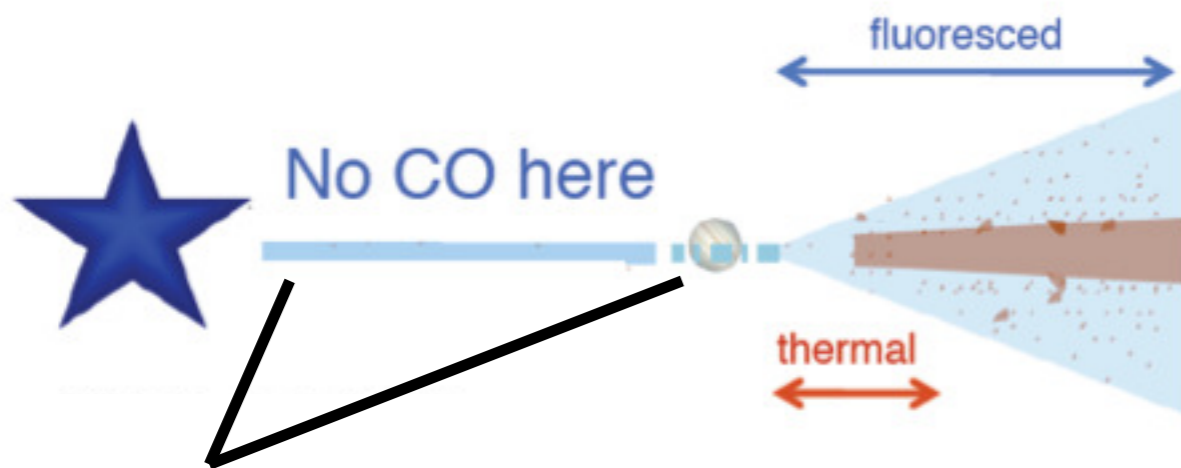
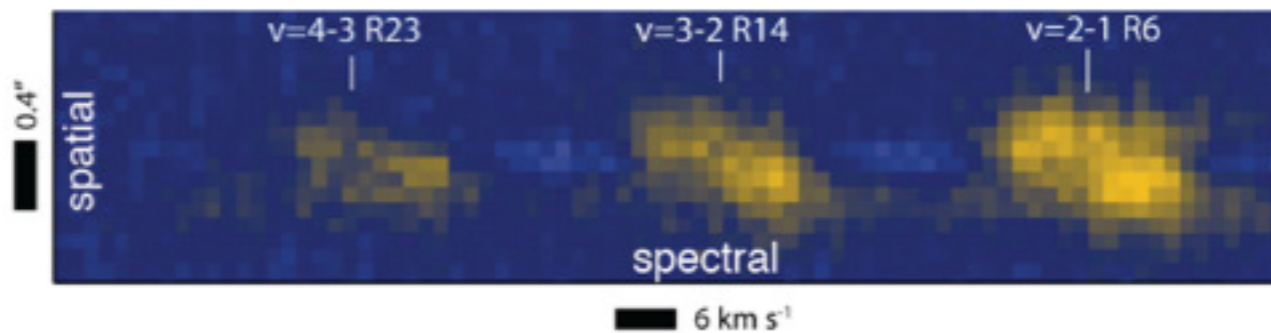
# HD 100546: ro-vib CO

- CO hot bands ( $\Delta v=1, v'>1$ )  
UV fluoresced
- CO  $v=1-0$  also has **thermal** component  
(excited by collisions)
- $R(\text{CO})=13\pm 6\text{AU}$  to  $\sim 50\text{AU}$

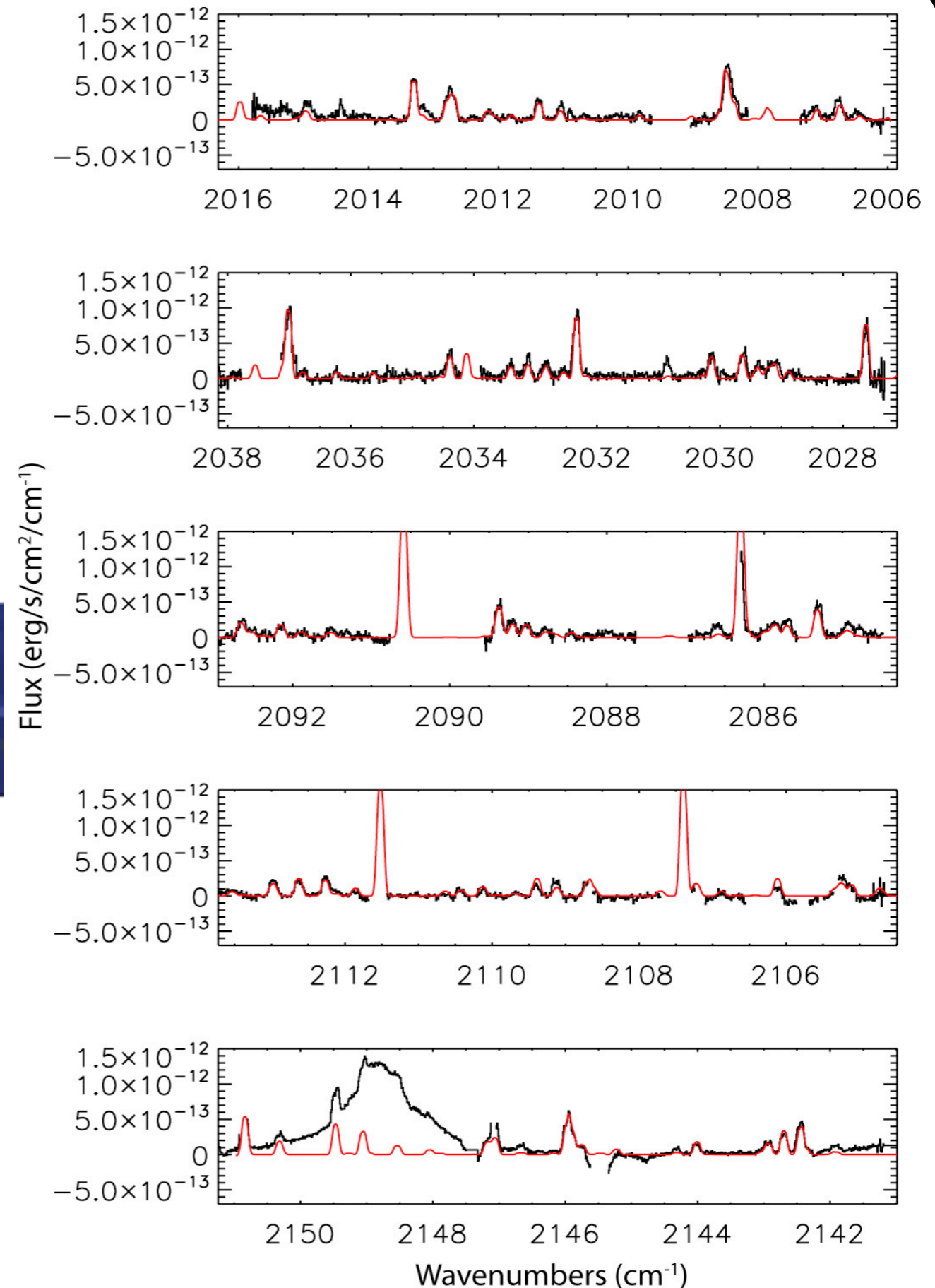


# HD 100546: ro-vib CO

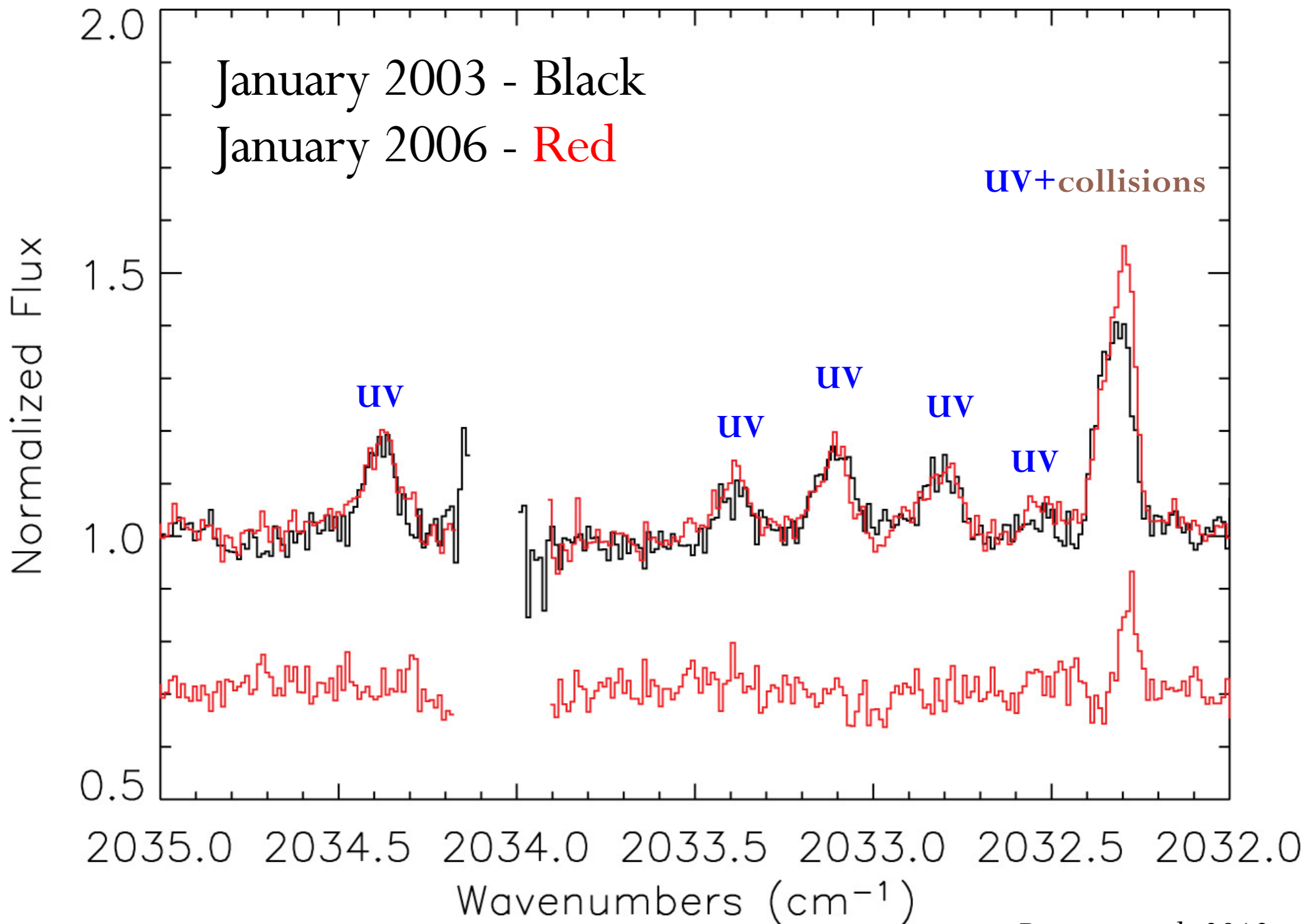
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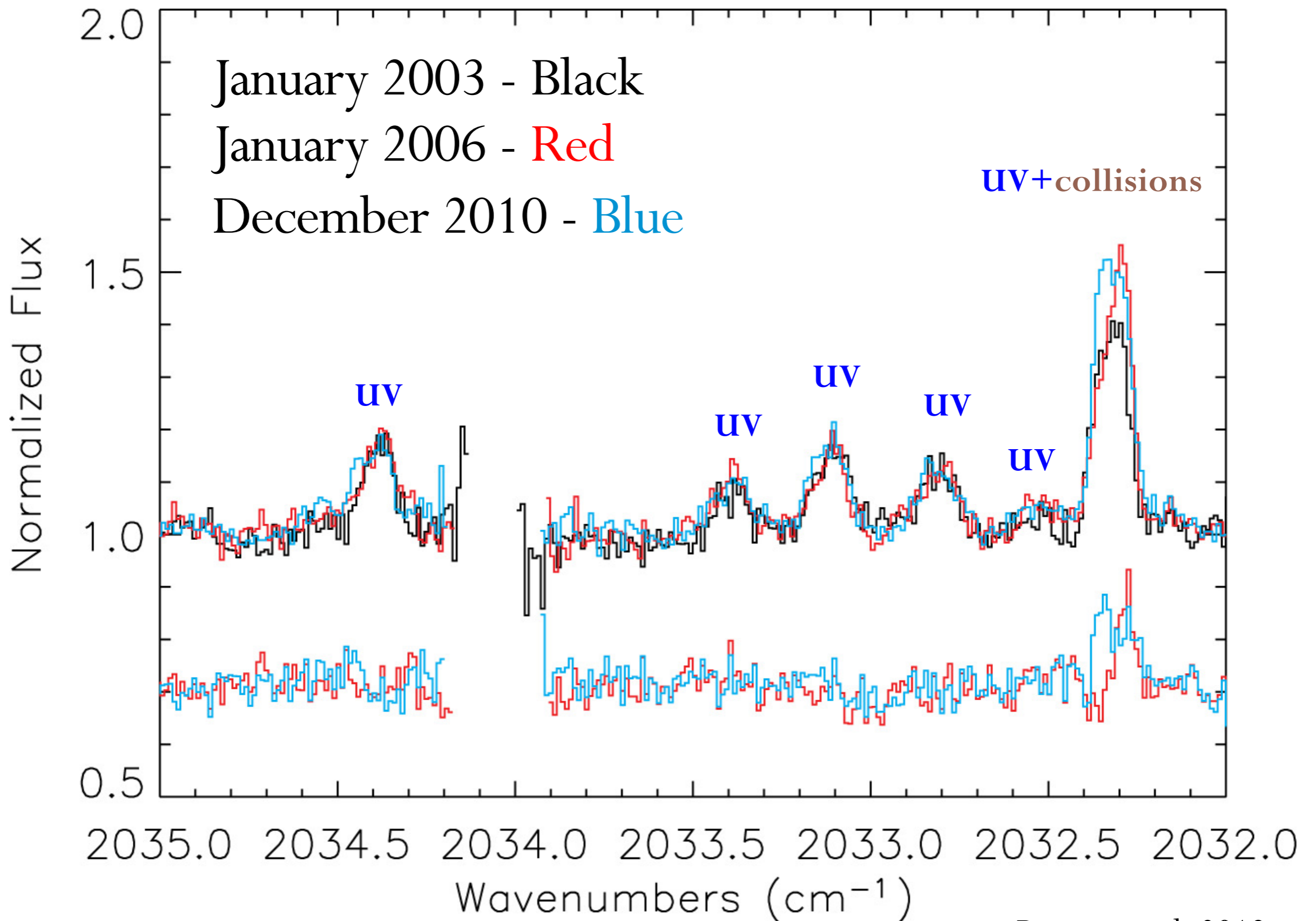
Free of molecules: Habart+ 2006; Brittain+ 2009;  
van der Plas+2009; Carmona+ 2011;  
Liskowsky+2012



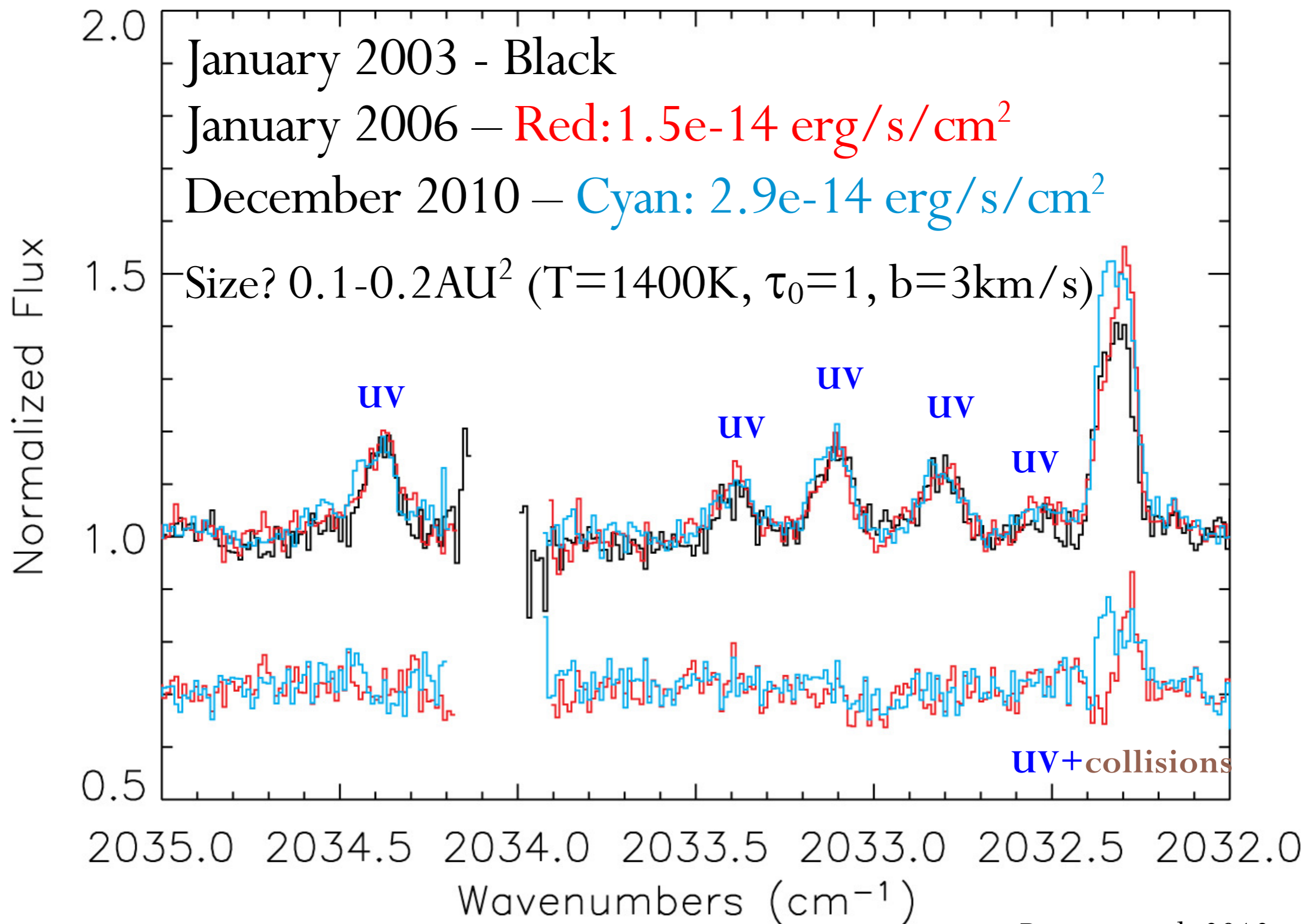
# Variable CO emission



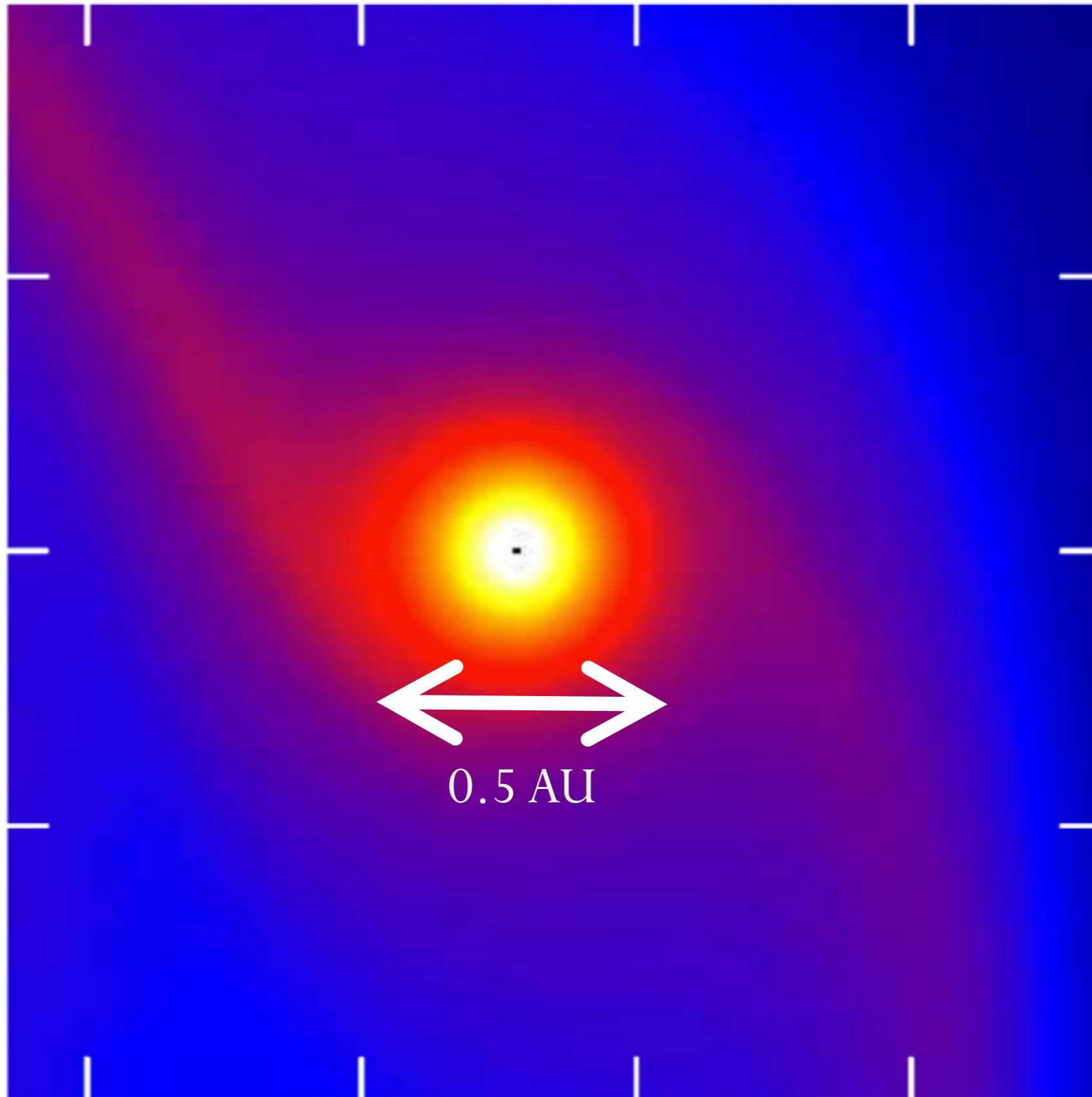
# Variable CO emission



# Variable CO emission



# Signposts of Planet formation: Circumplanetary Disks?

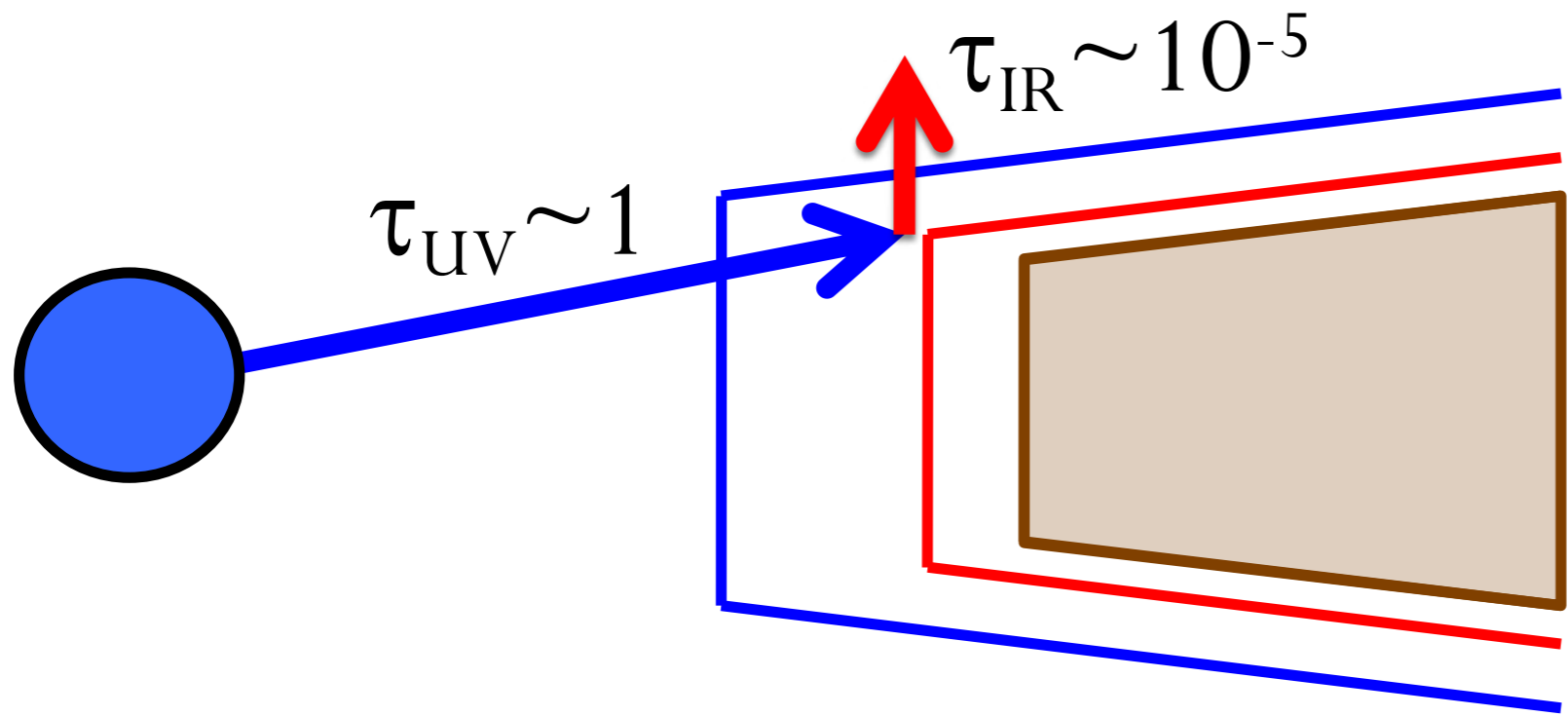


Emission lines from a circumplanetary disk will be Doppler shifted relative to the star.

Ayliffe & Bate 2009, 2012 (see also Quillen & Trilling 1998; Lubow et al. 2011; Tanigawa et al. 2012; Gressel et al. 2013).



# Excitation of gas in disks: UV

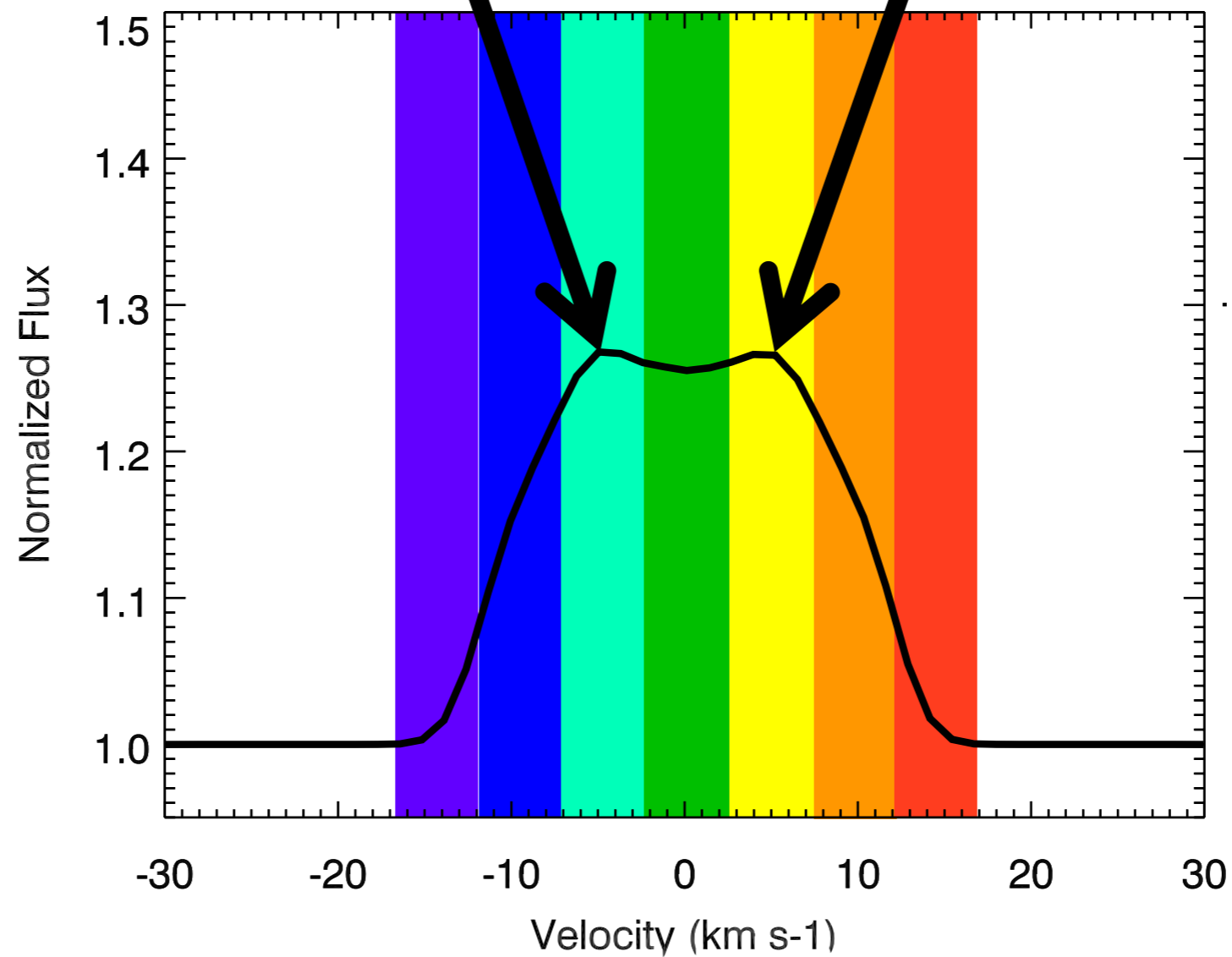
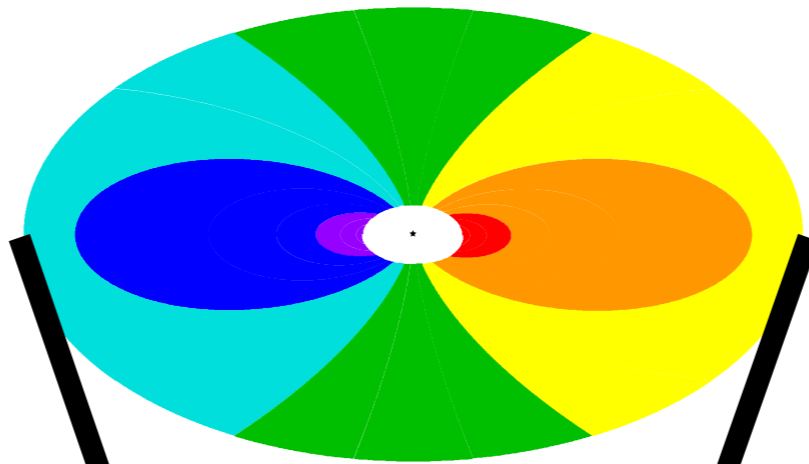


$$L \propto \tau * Area$$

- $5M_J \Rightarrow$  Area of  $\sim 0.1 \text{ AU}^2$
- $\tau \sim 1$  (circumplanetary disk)
- $\tau \sim (10^{-5} \text{ UV fluoresced outer disk})$
- Disk Area  $\sim 10^4 \text{ AU}^2$

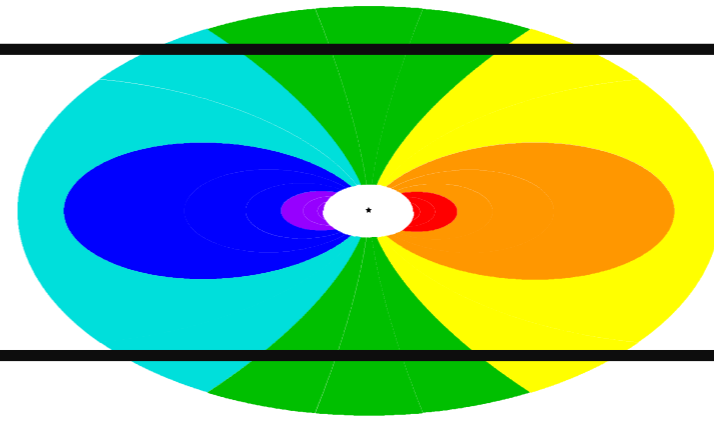
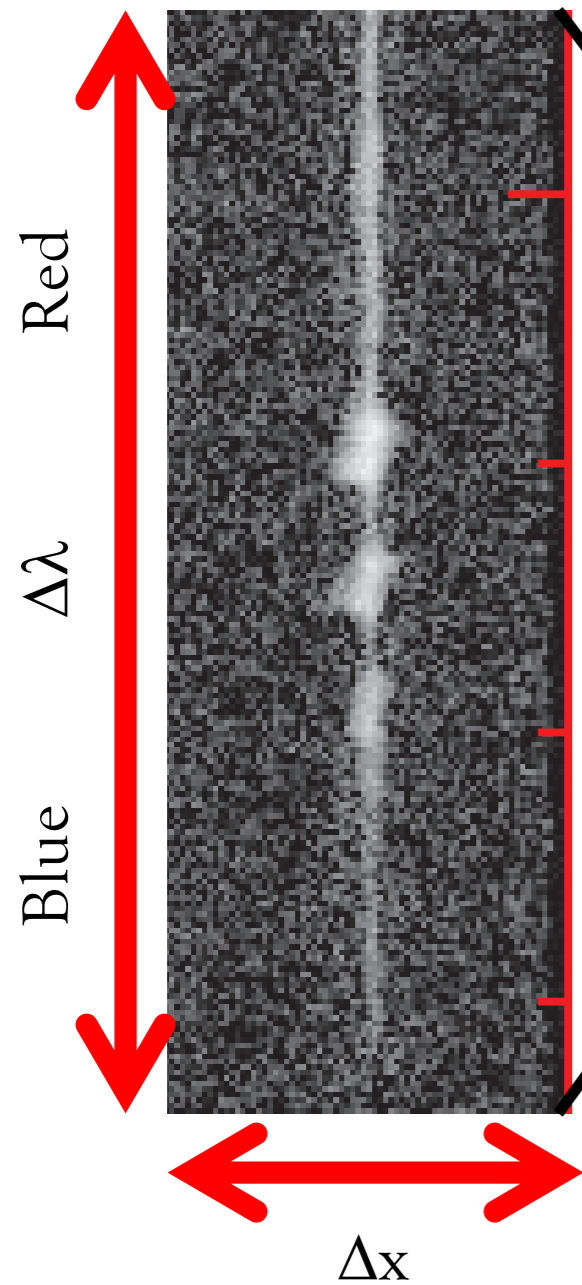
# Spectrally Resolved Lines as Surrogates for High Resolution Imaging

$$v(M_*, i, r) \propto r^{-1/2}$$



(See Smak 1981)

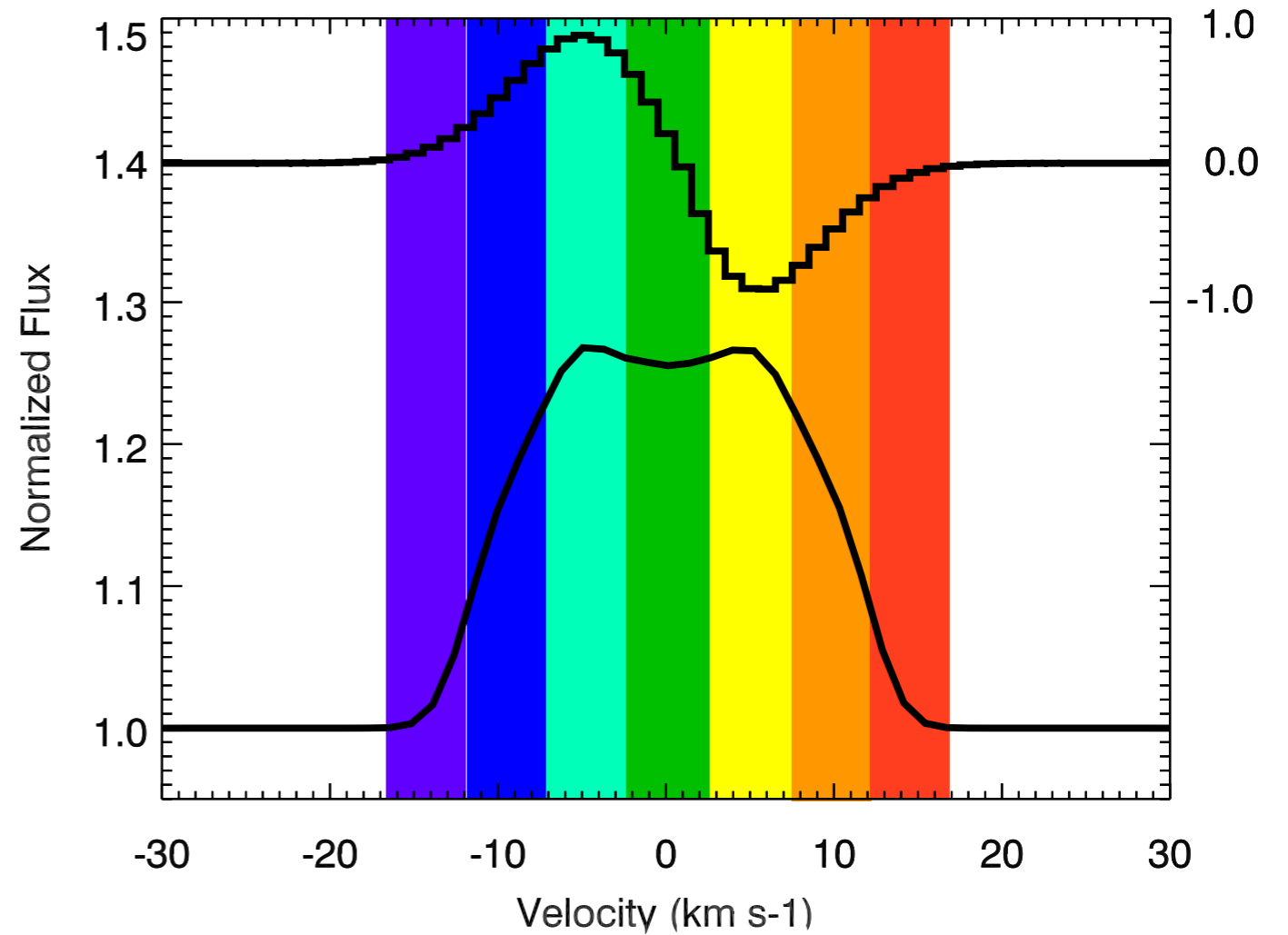
# Spectroastrometry



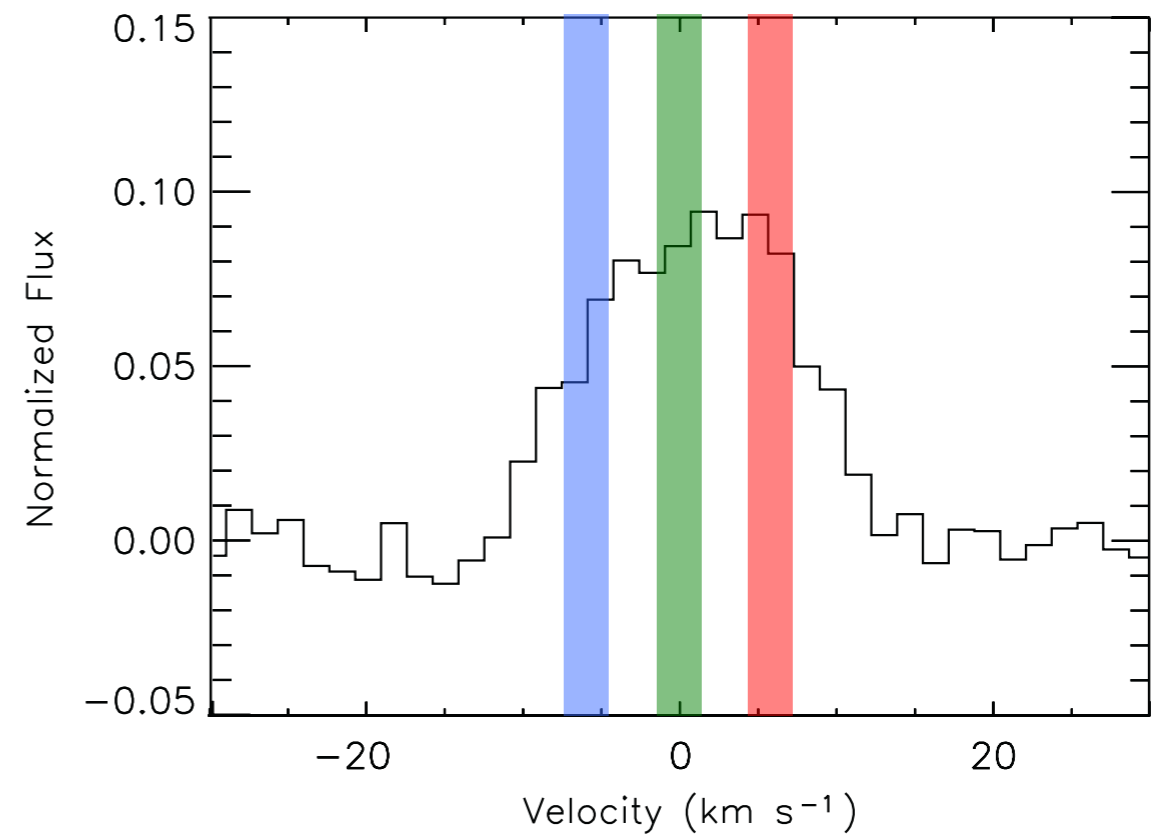
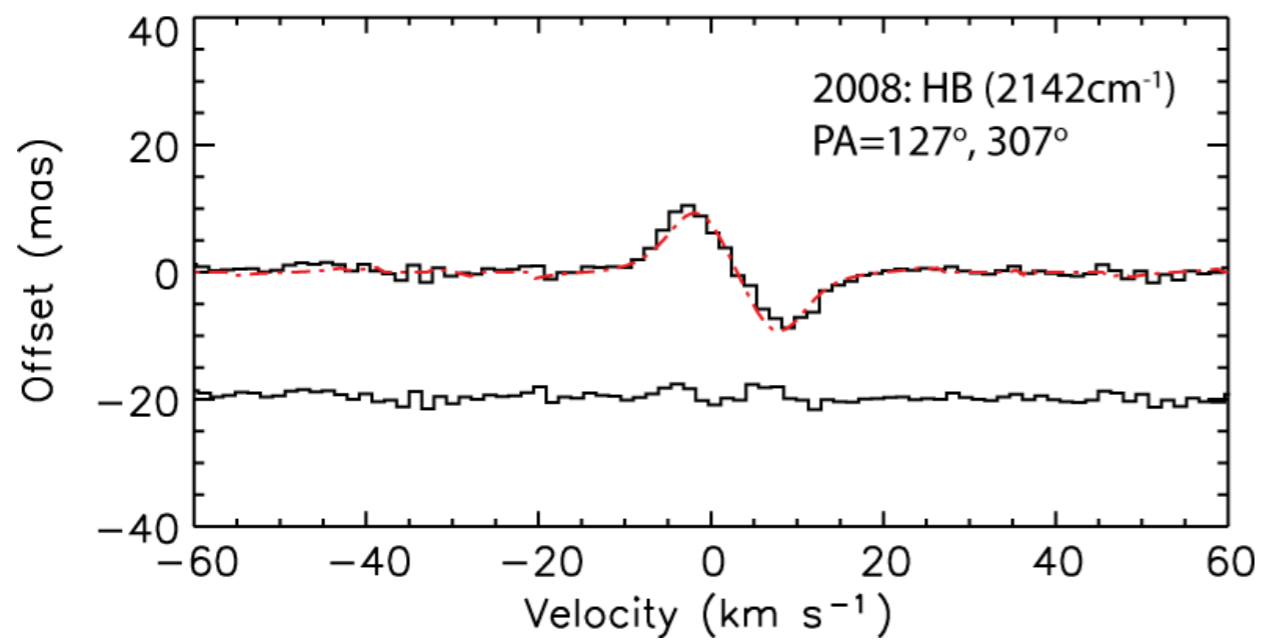
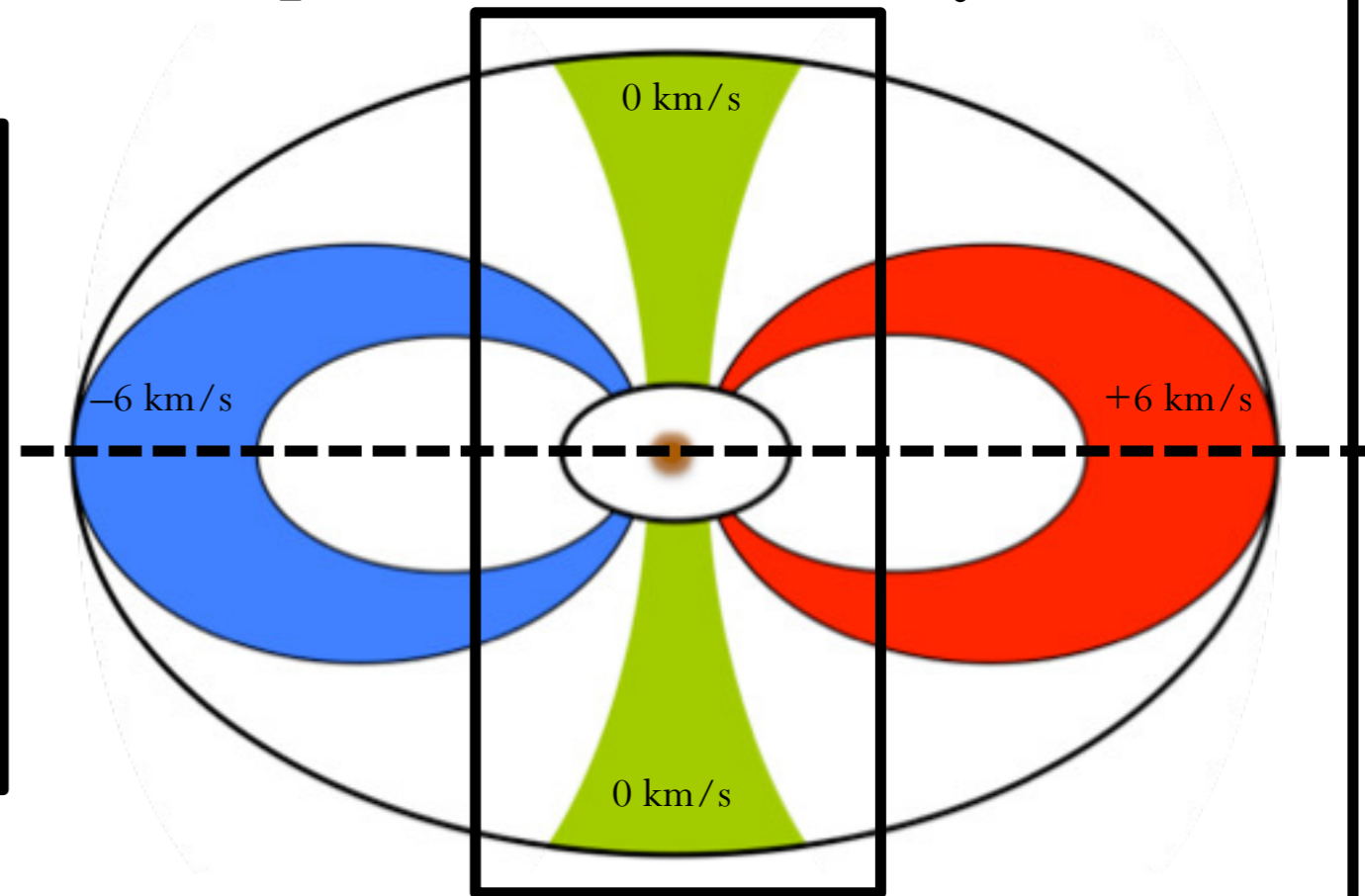
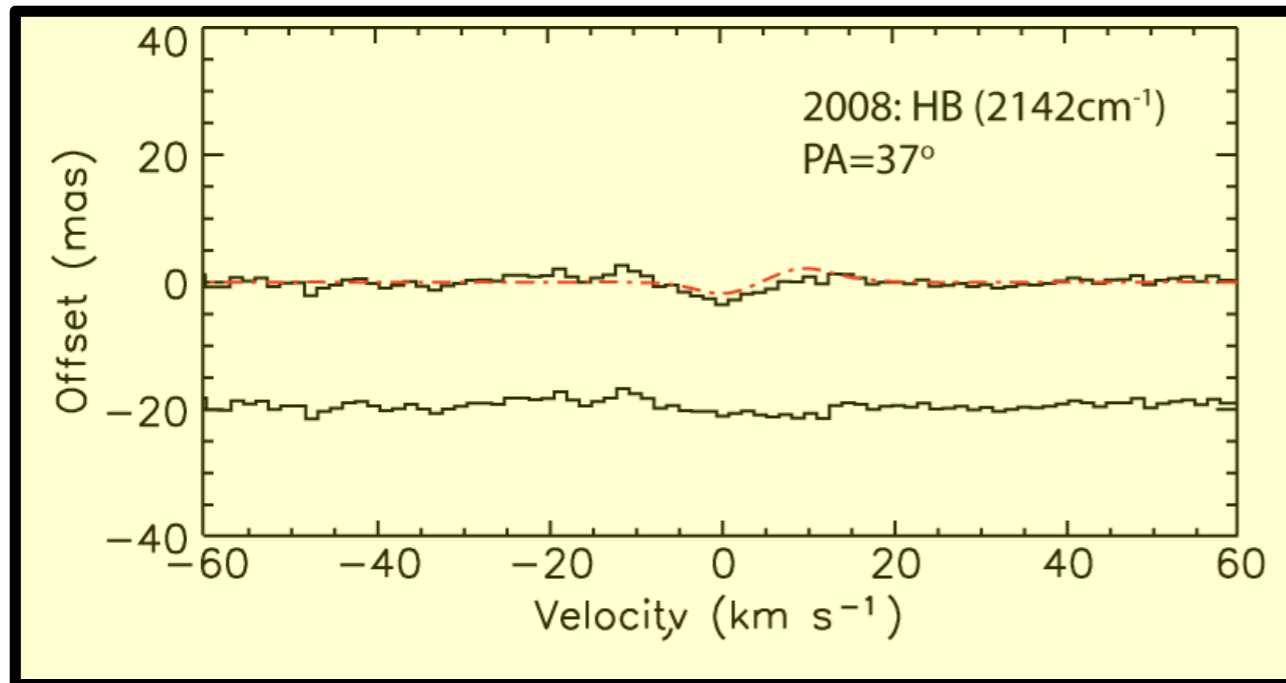
$$\Delta \propto \text{FWHM} / \text{SNR}$$

$$v(M_*, i, r) \propto r^{-1/2}$$

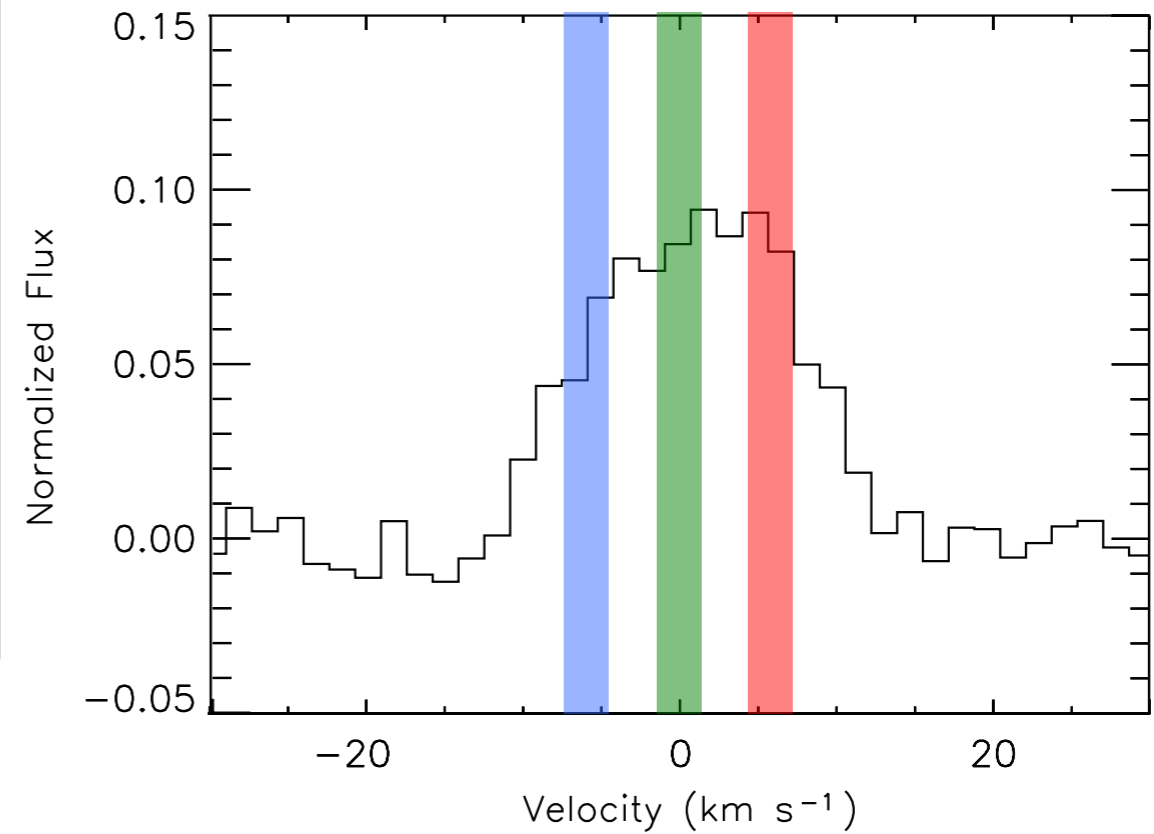
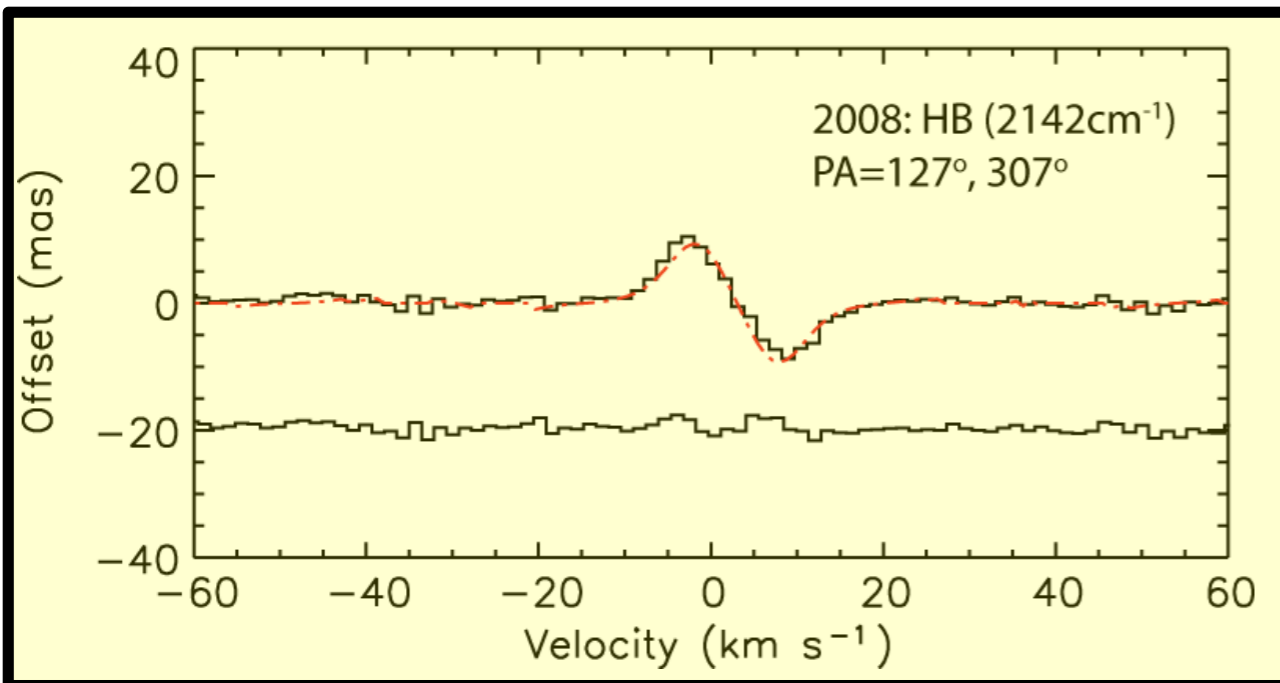
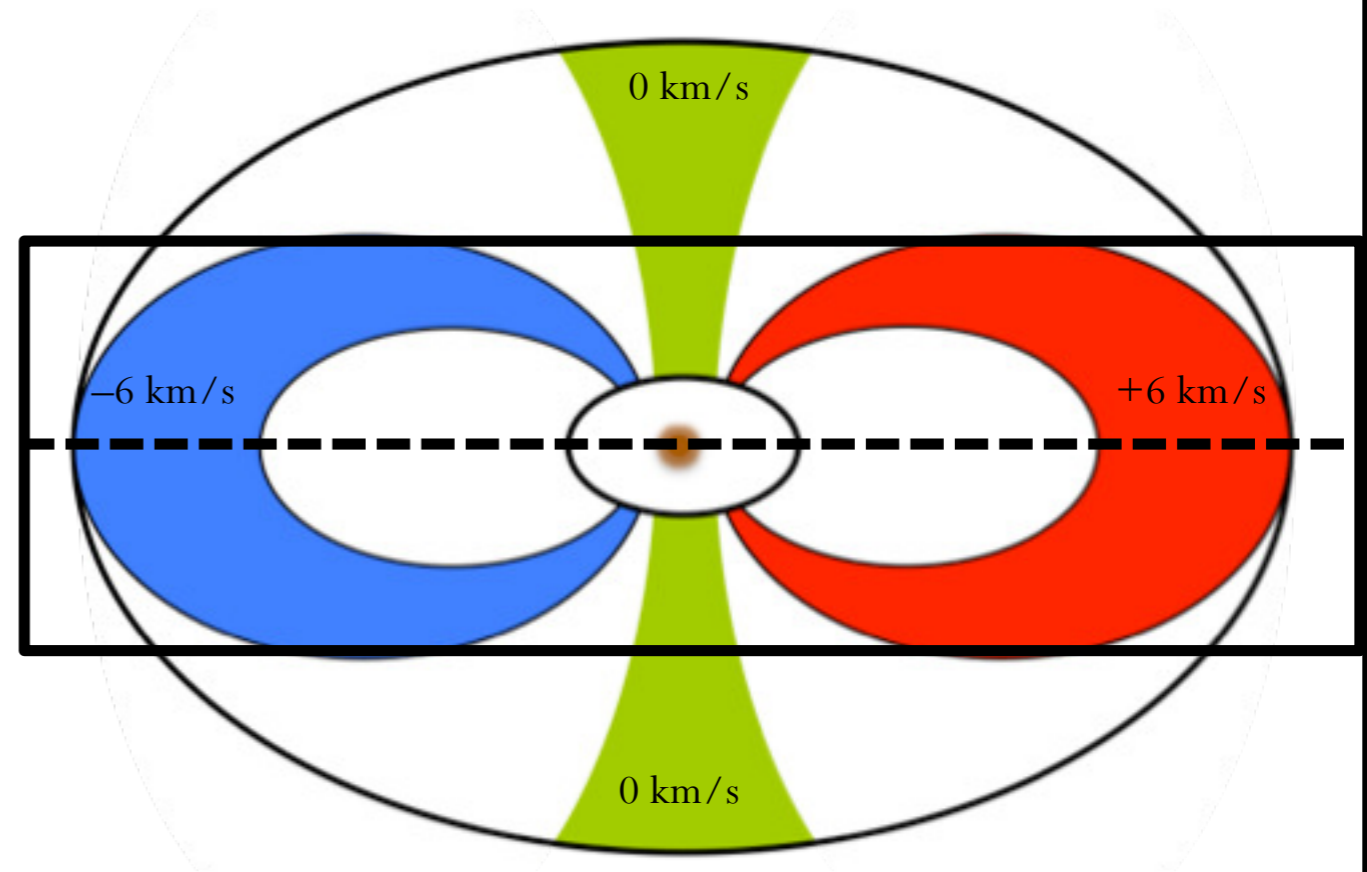
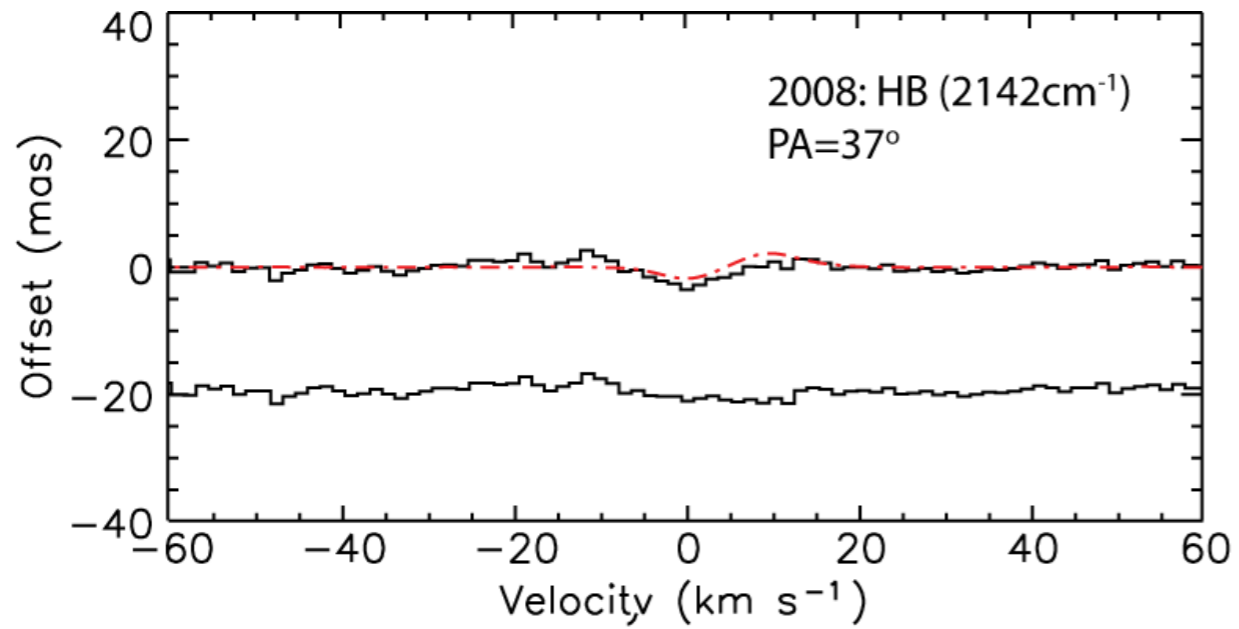
(See Whelan & Garcia 2008)

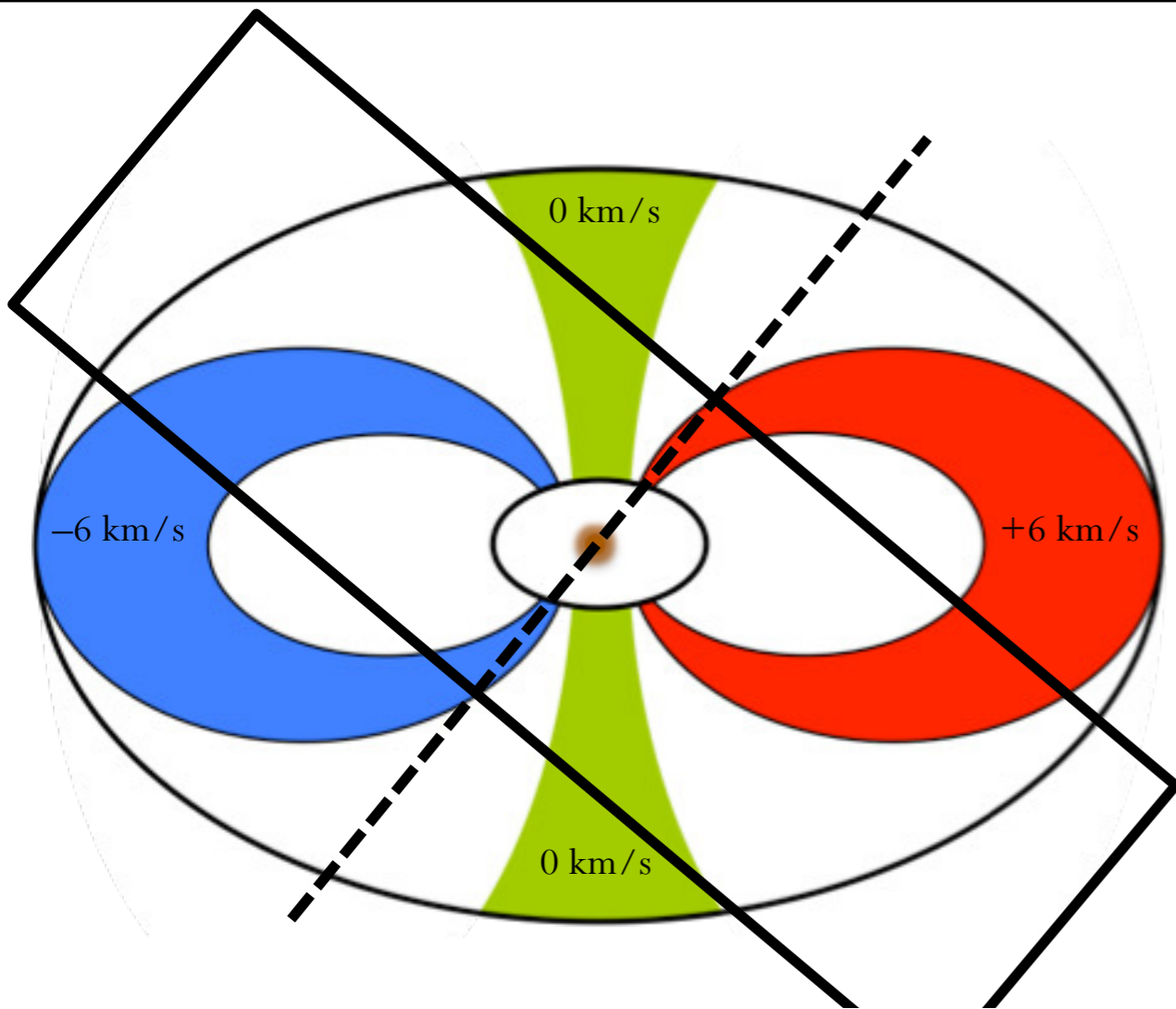


# Spectro-Astrometry

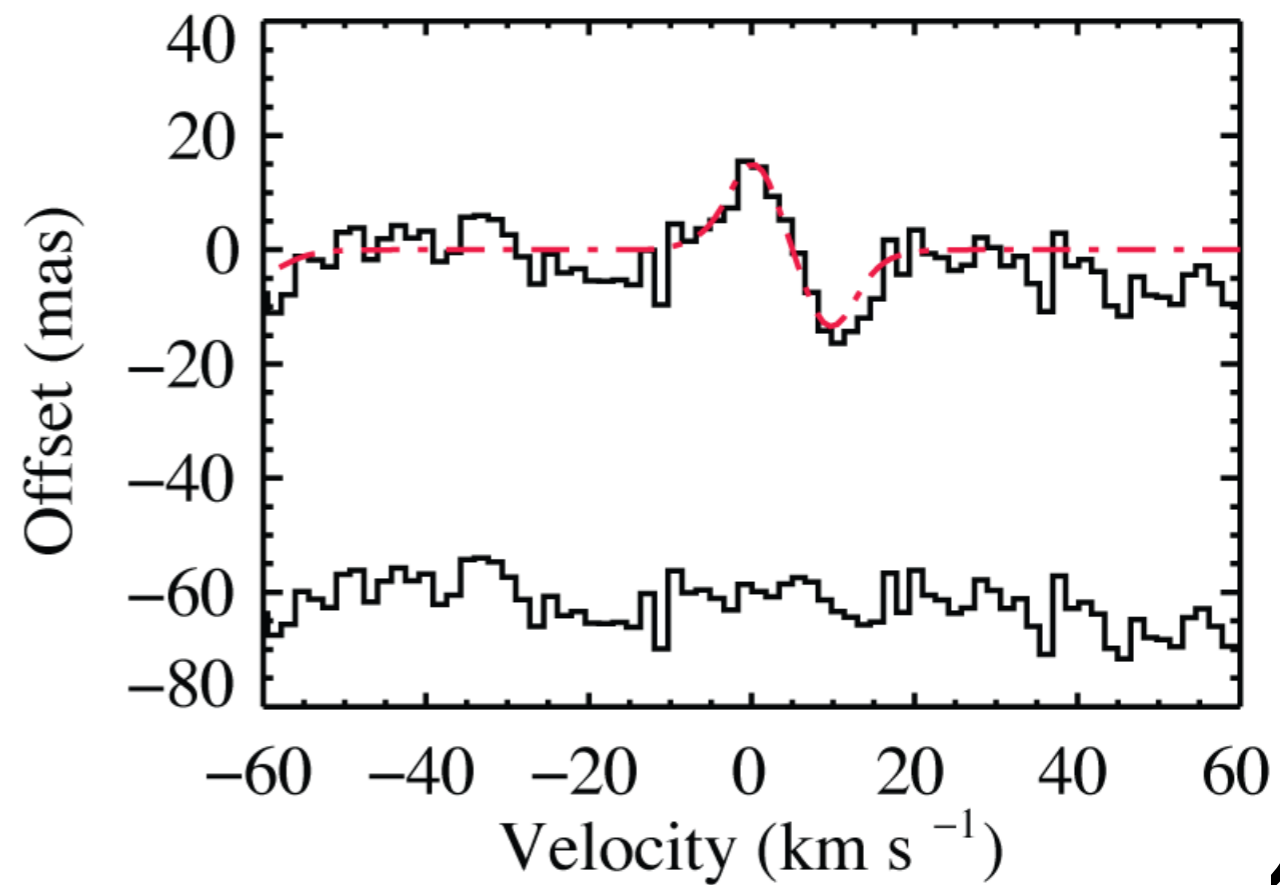
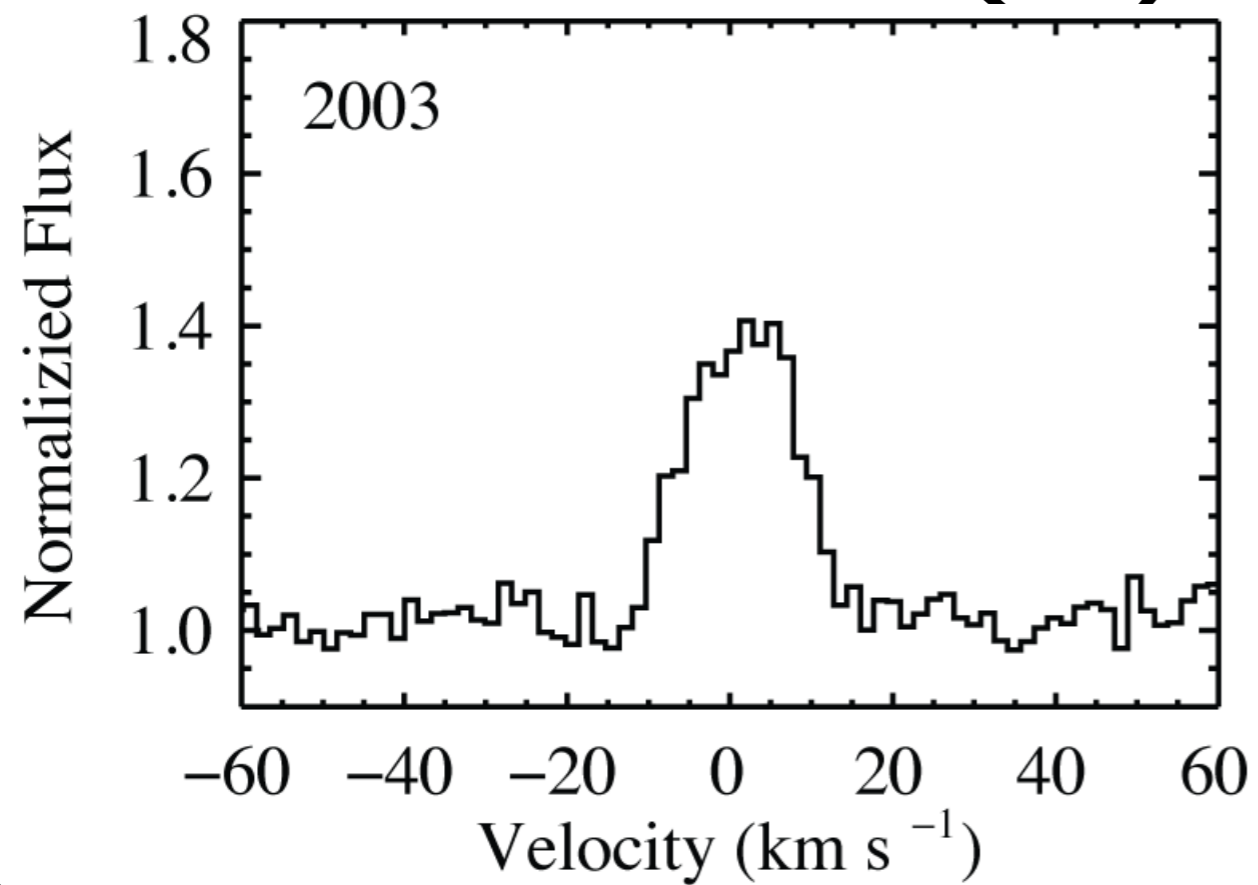


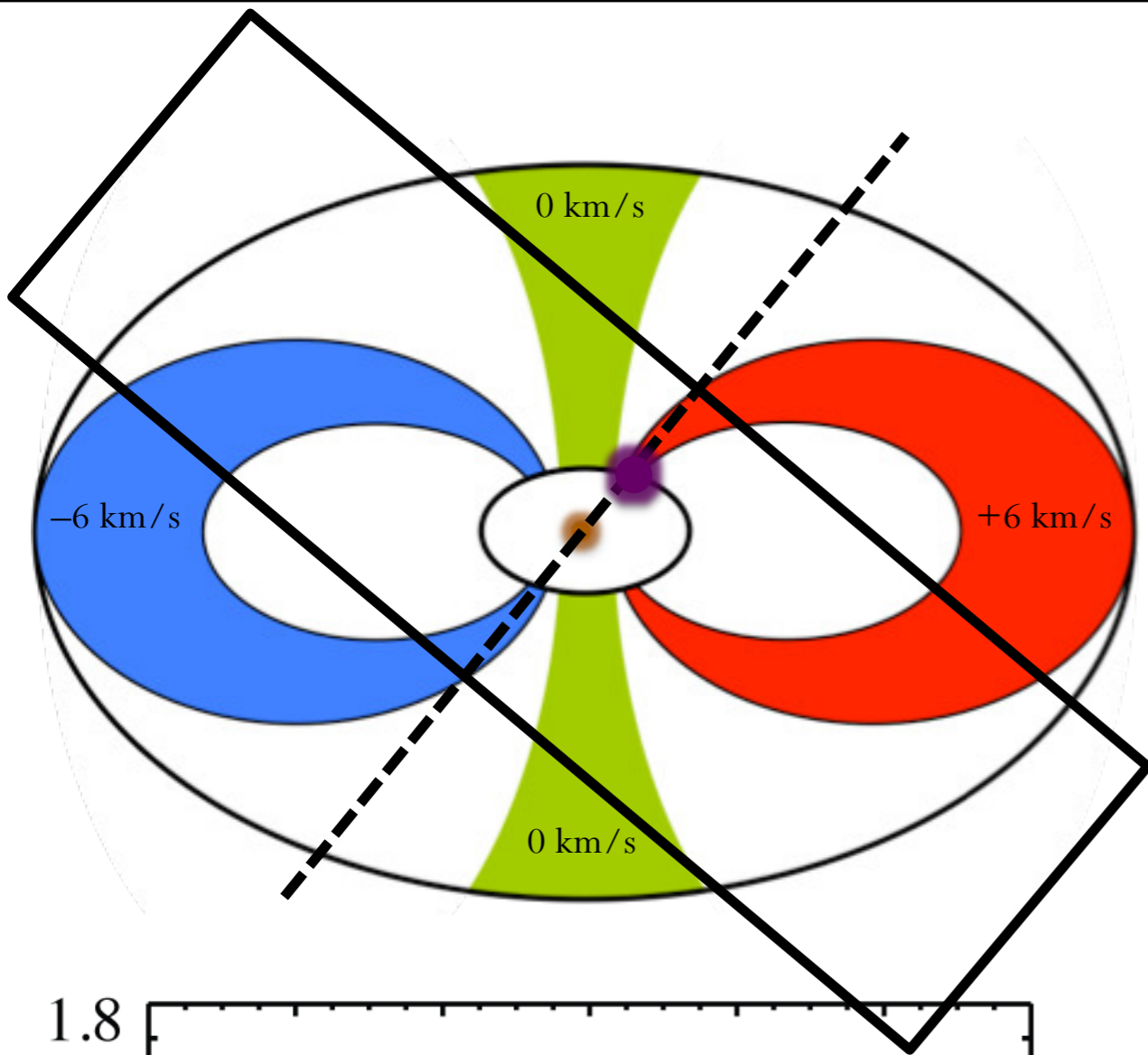
# Spectroastrometry



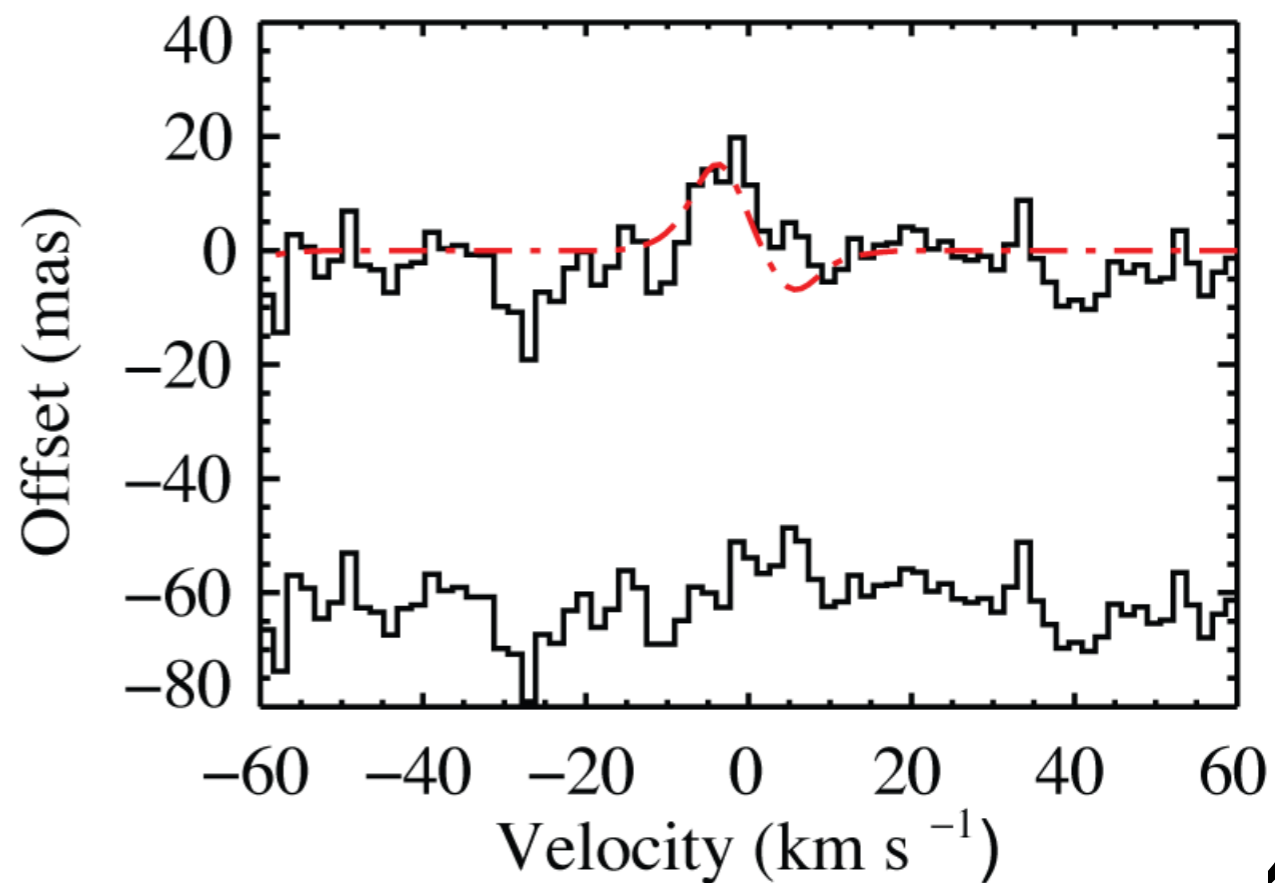
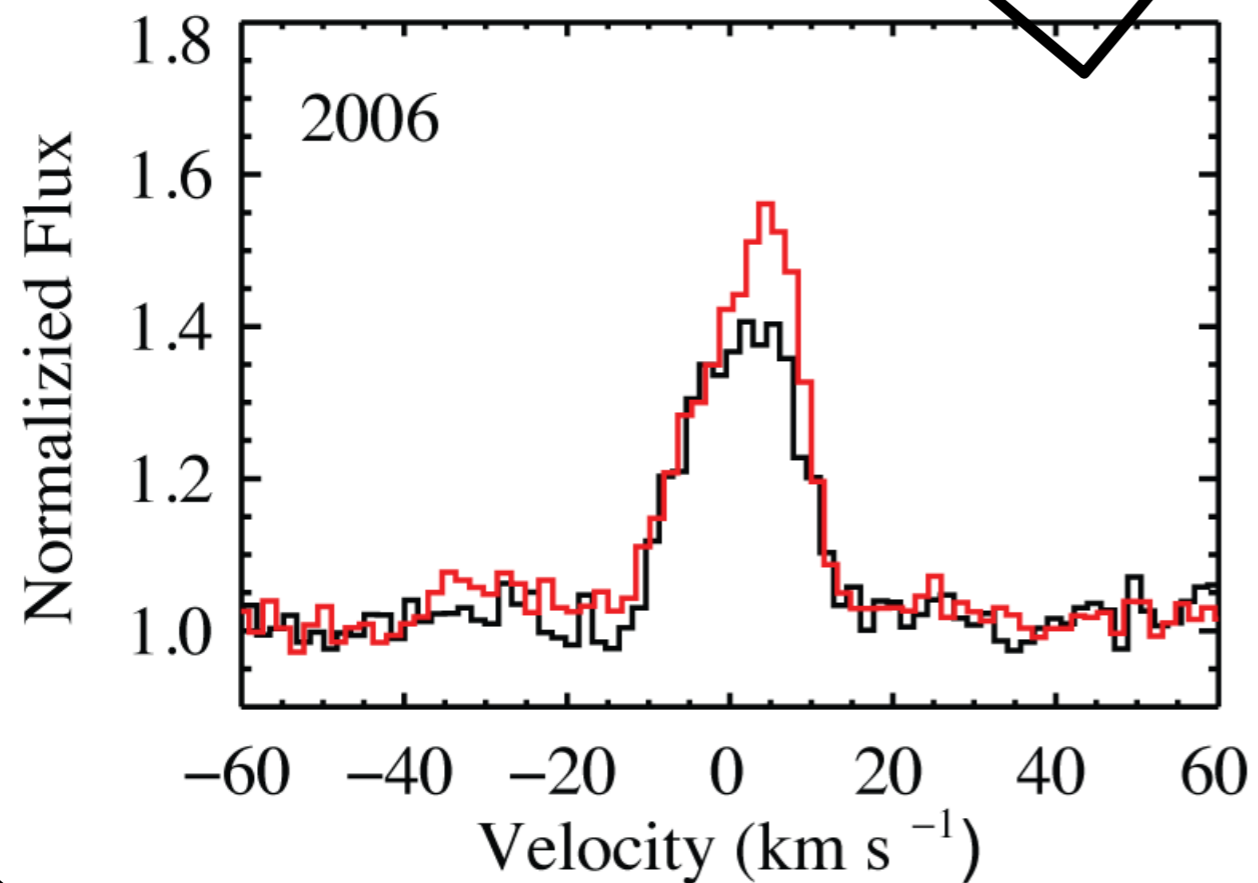


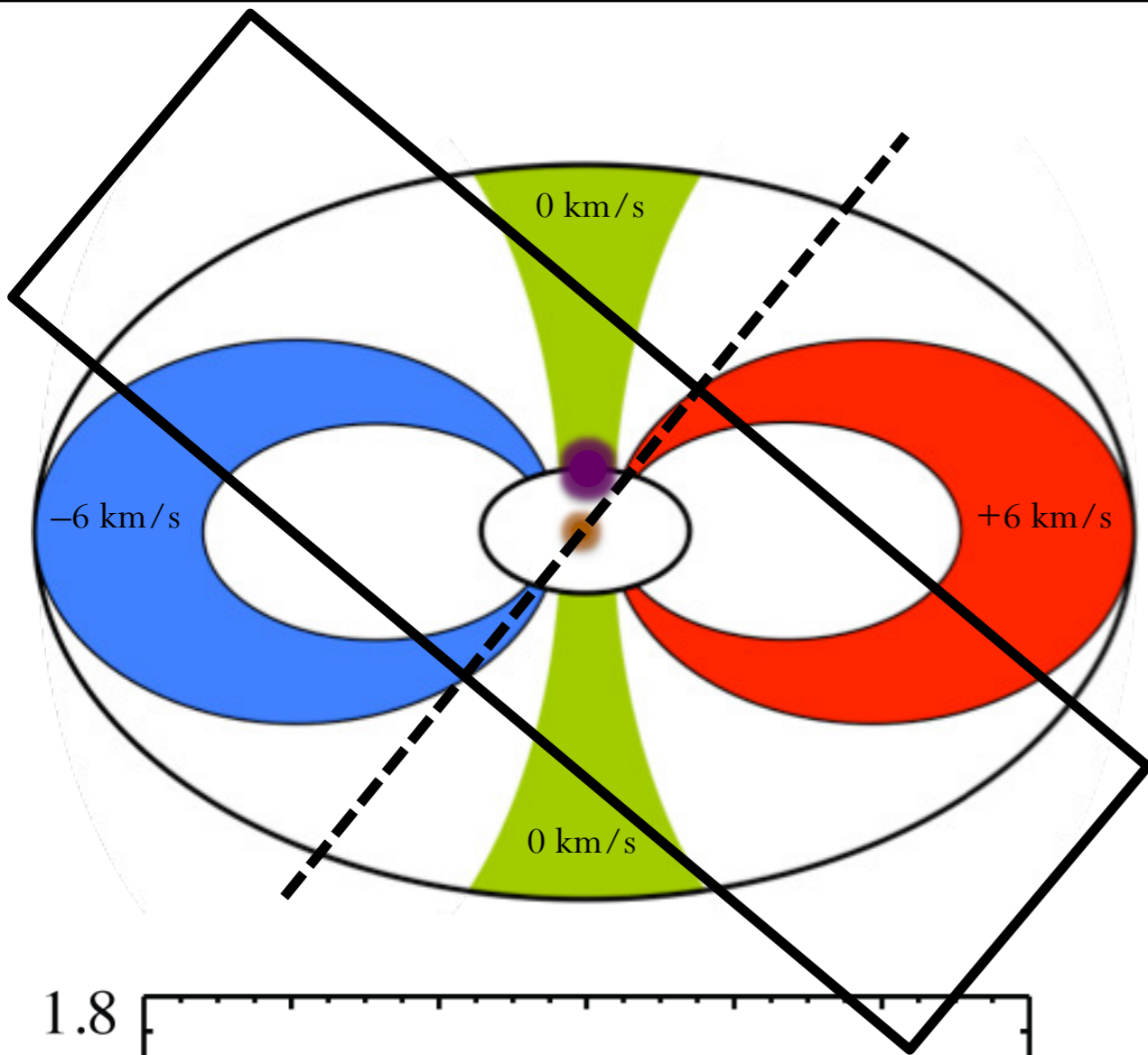
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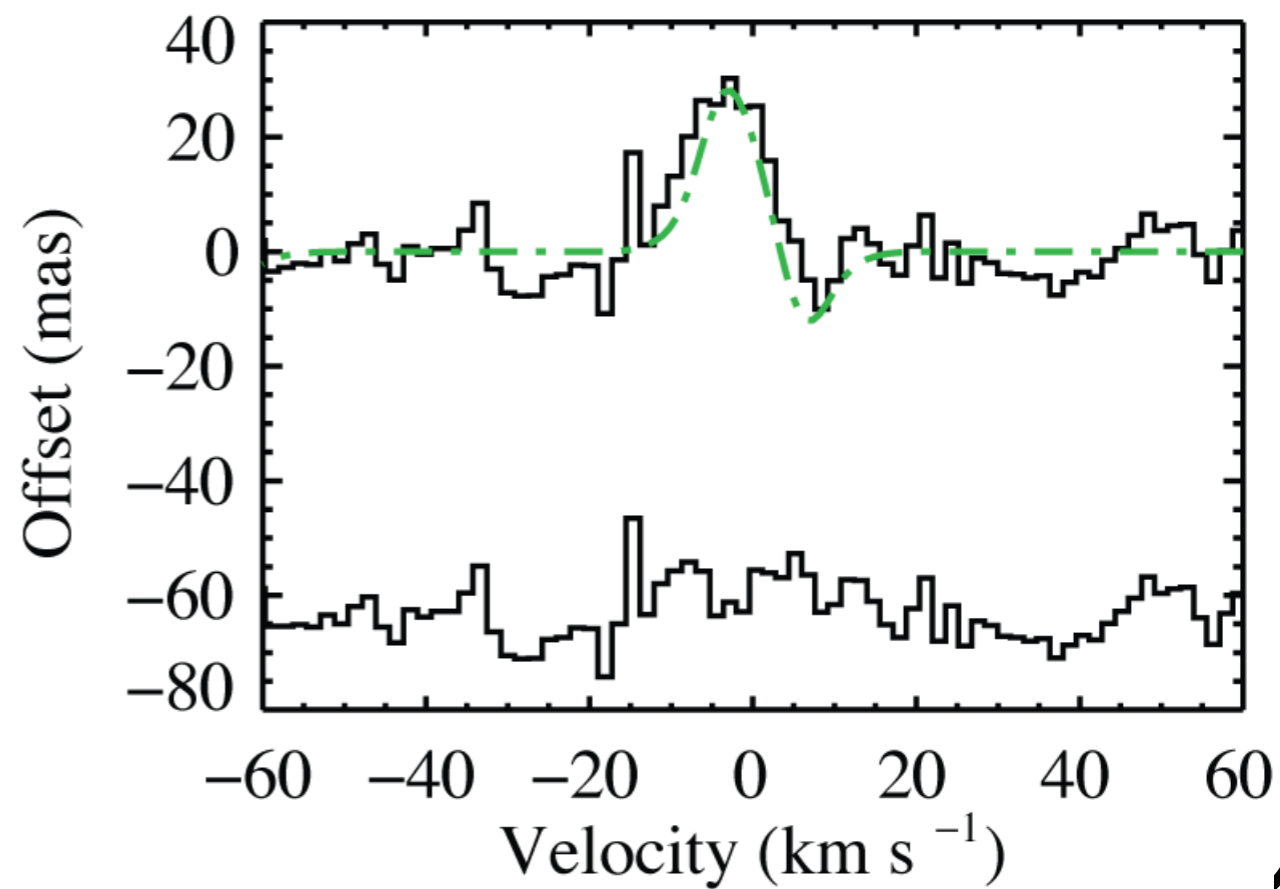
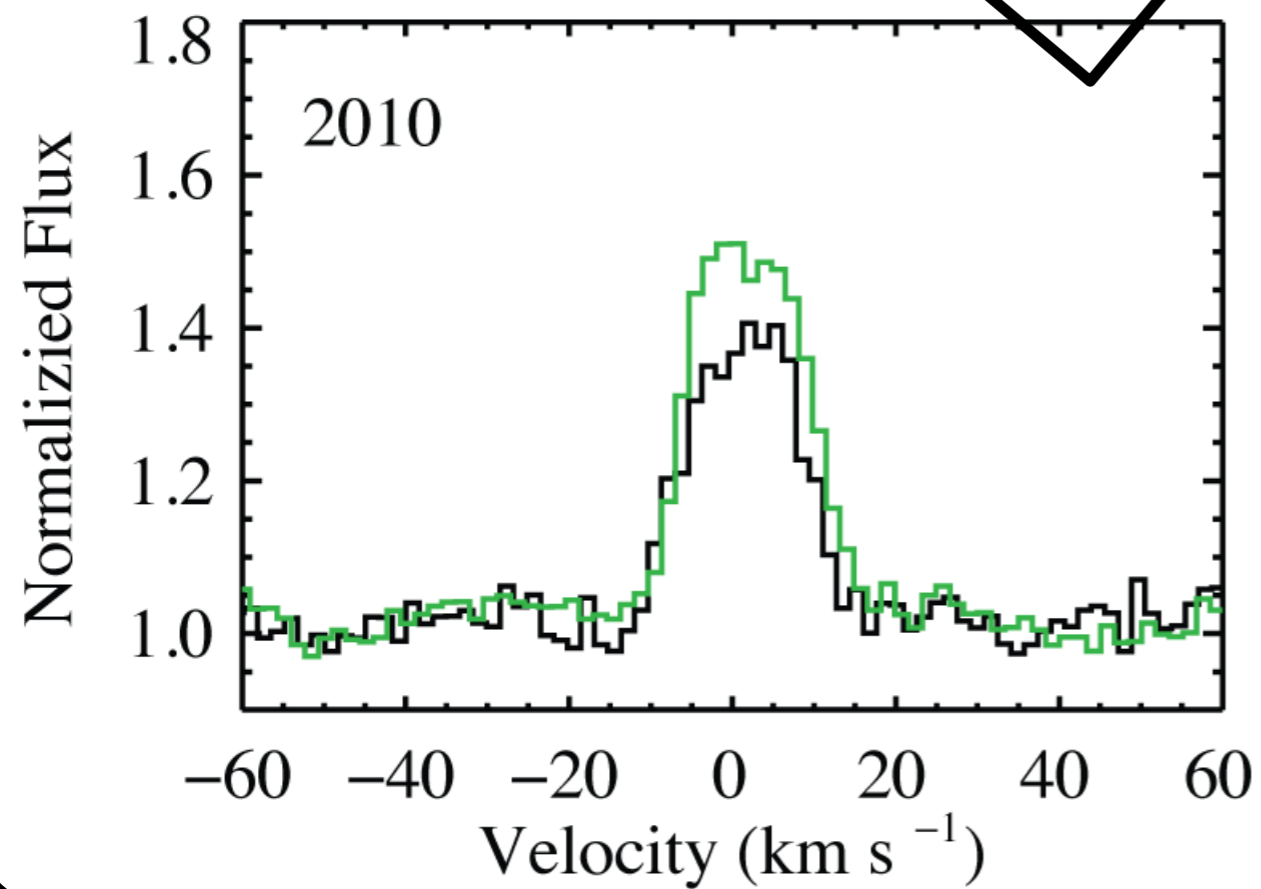


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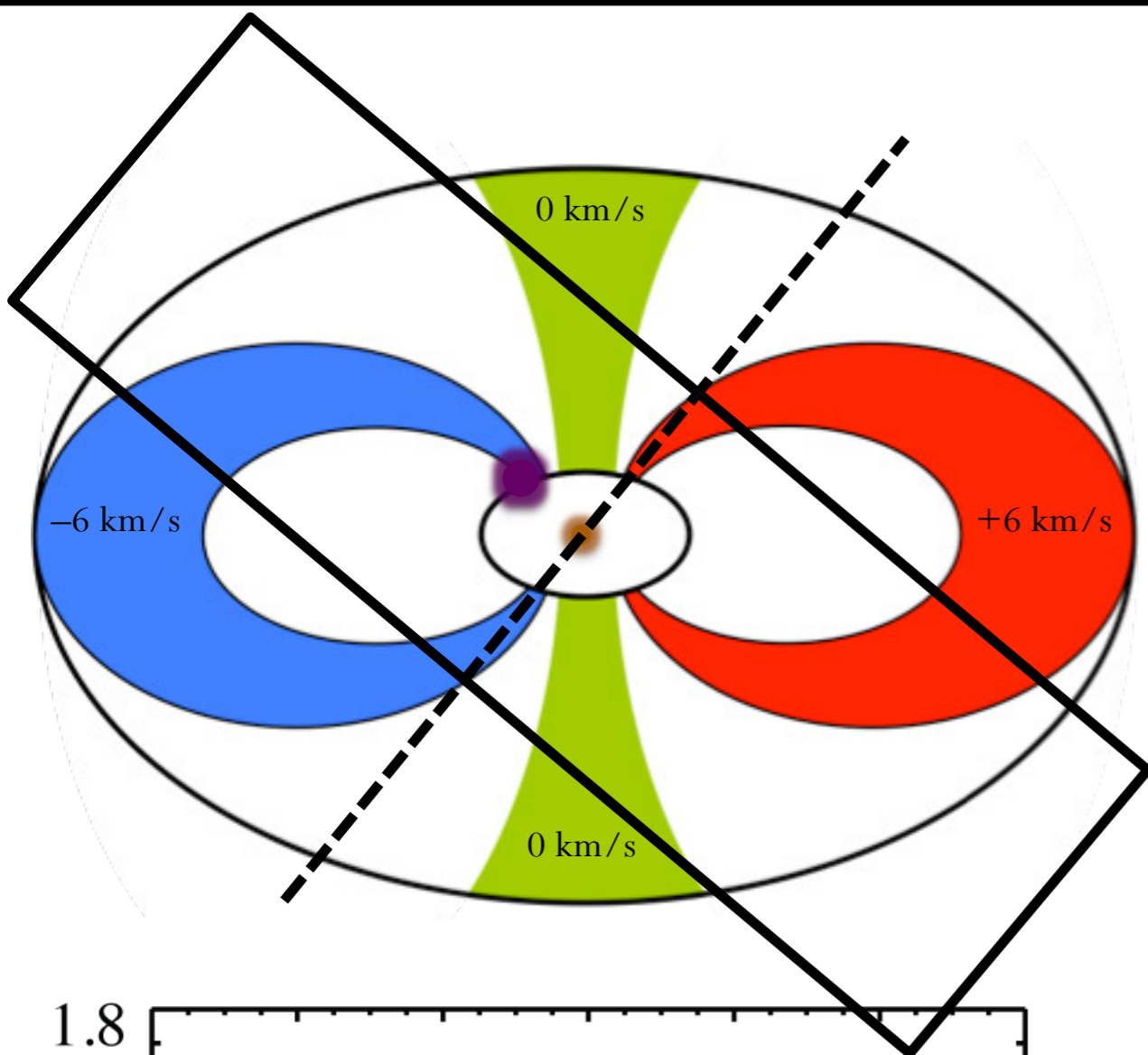




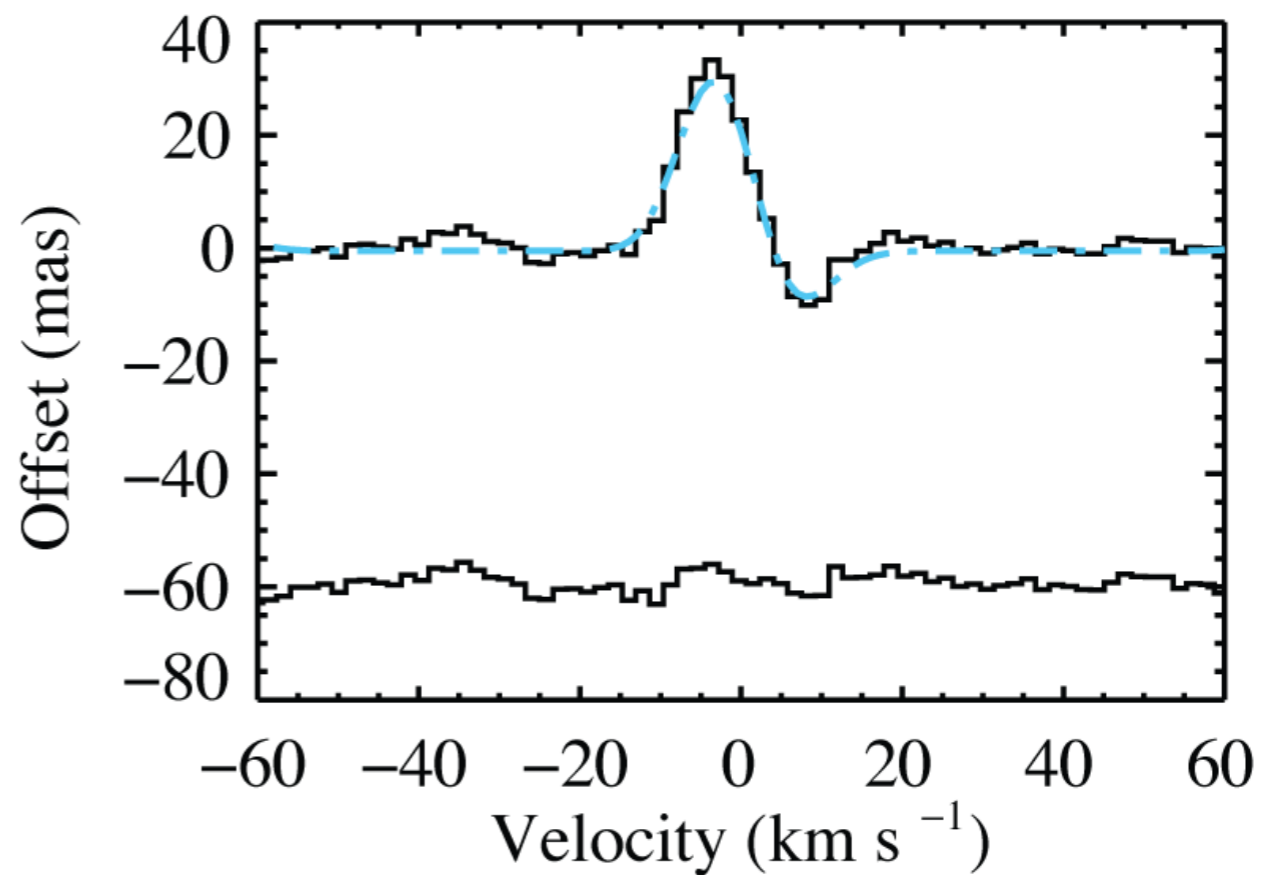
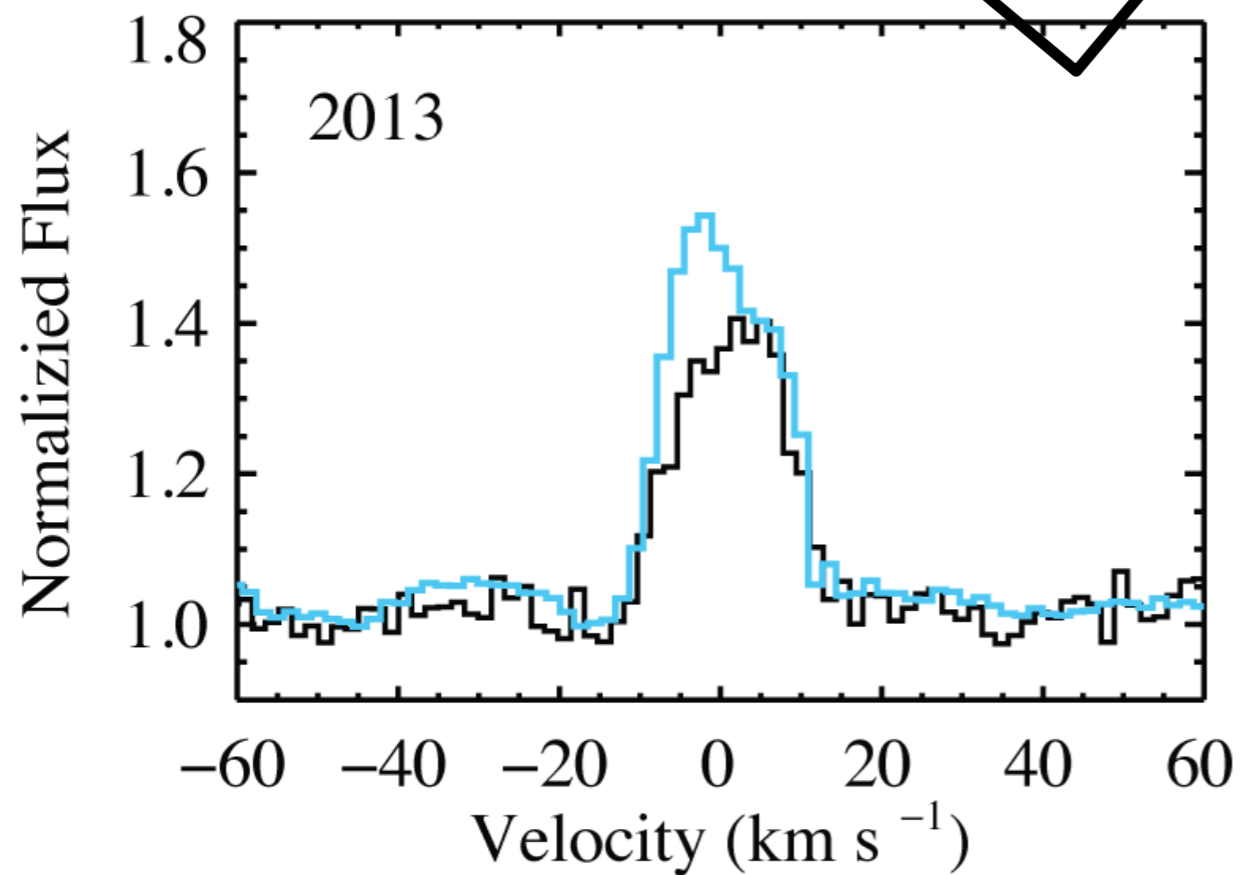
## Spectroastrometry

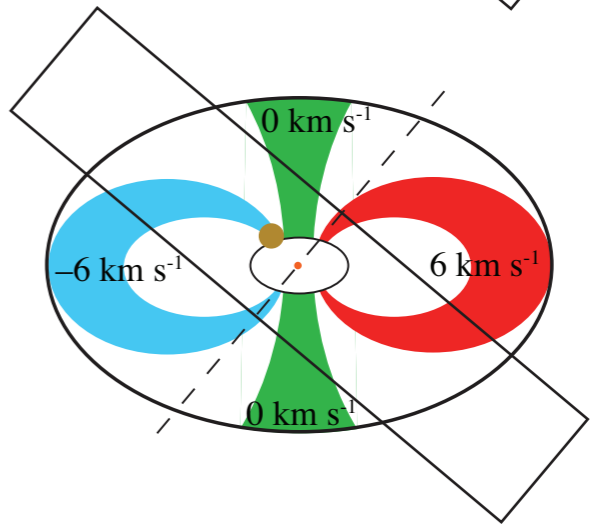
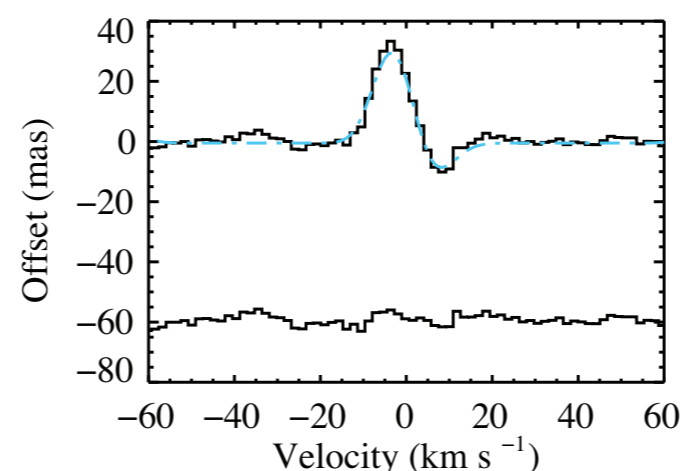
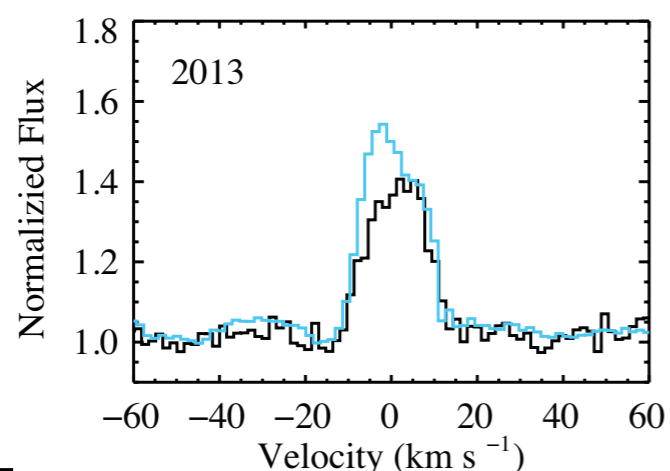
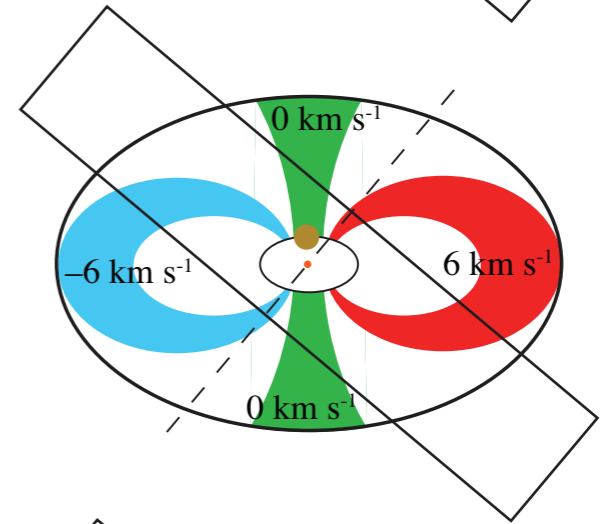
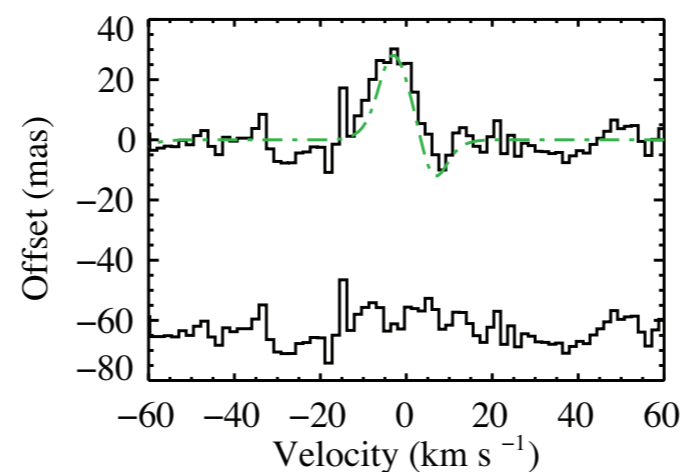
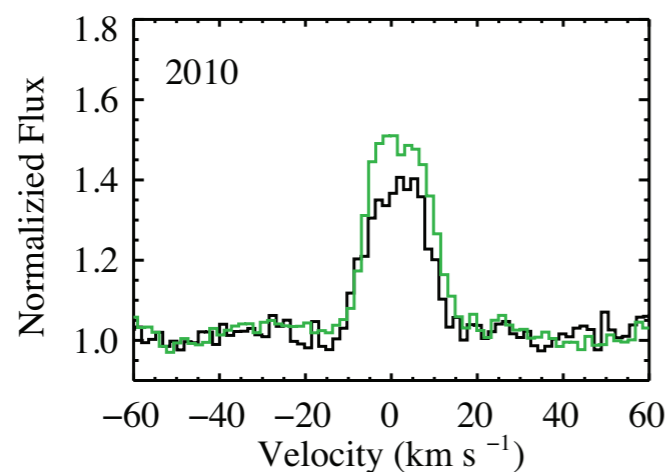
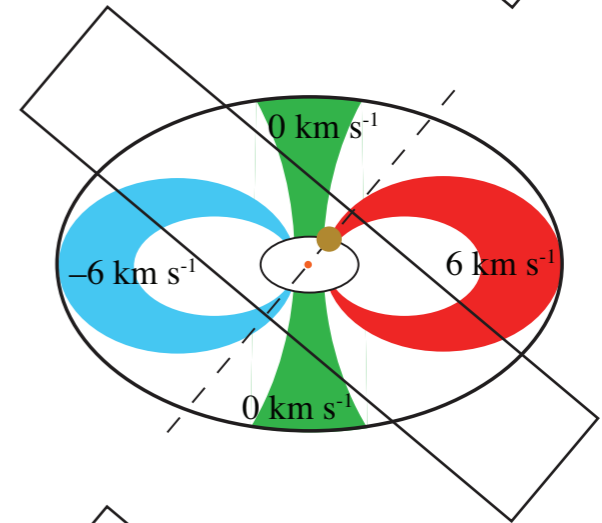
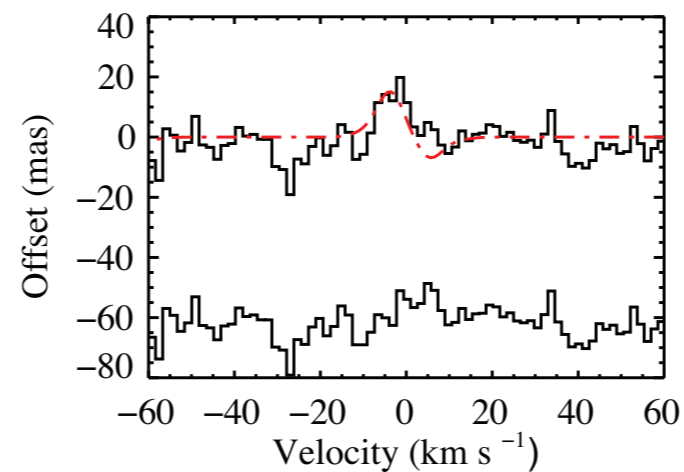
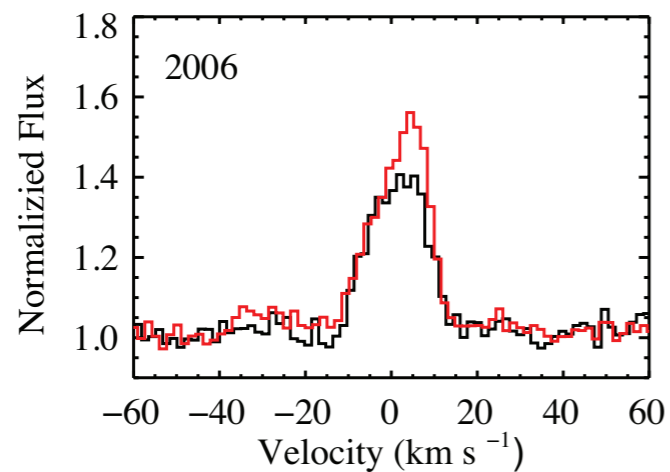
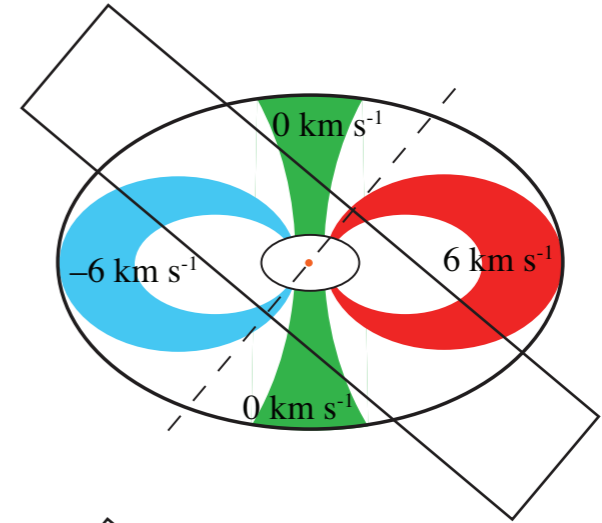
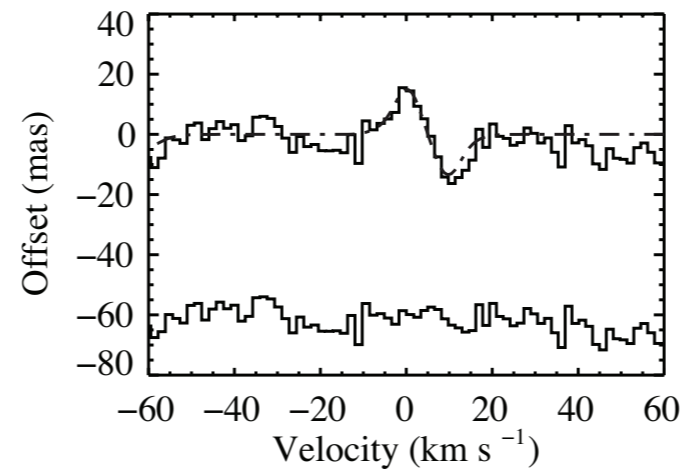
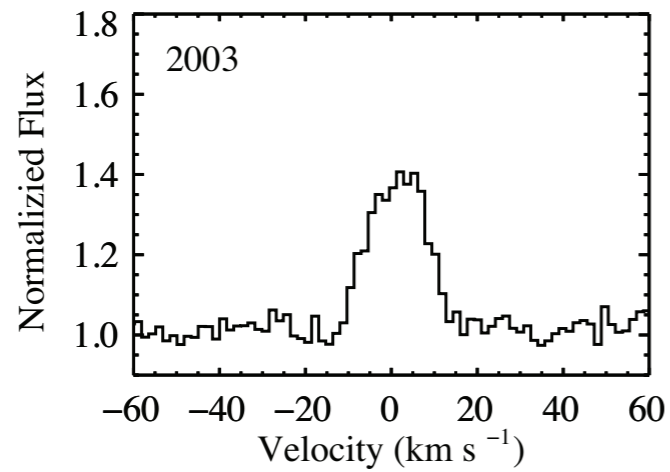




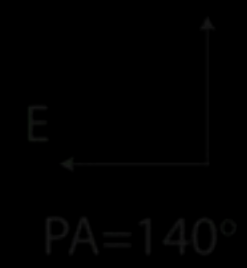
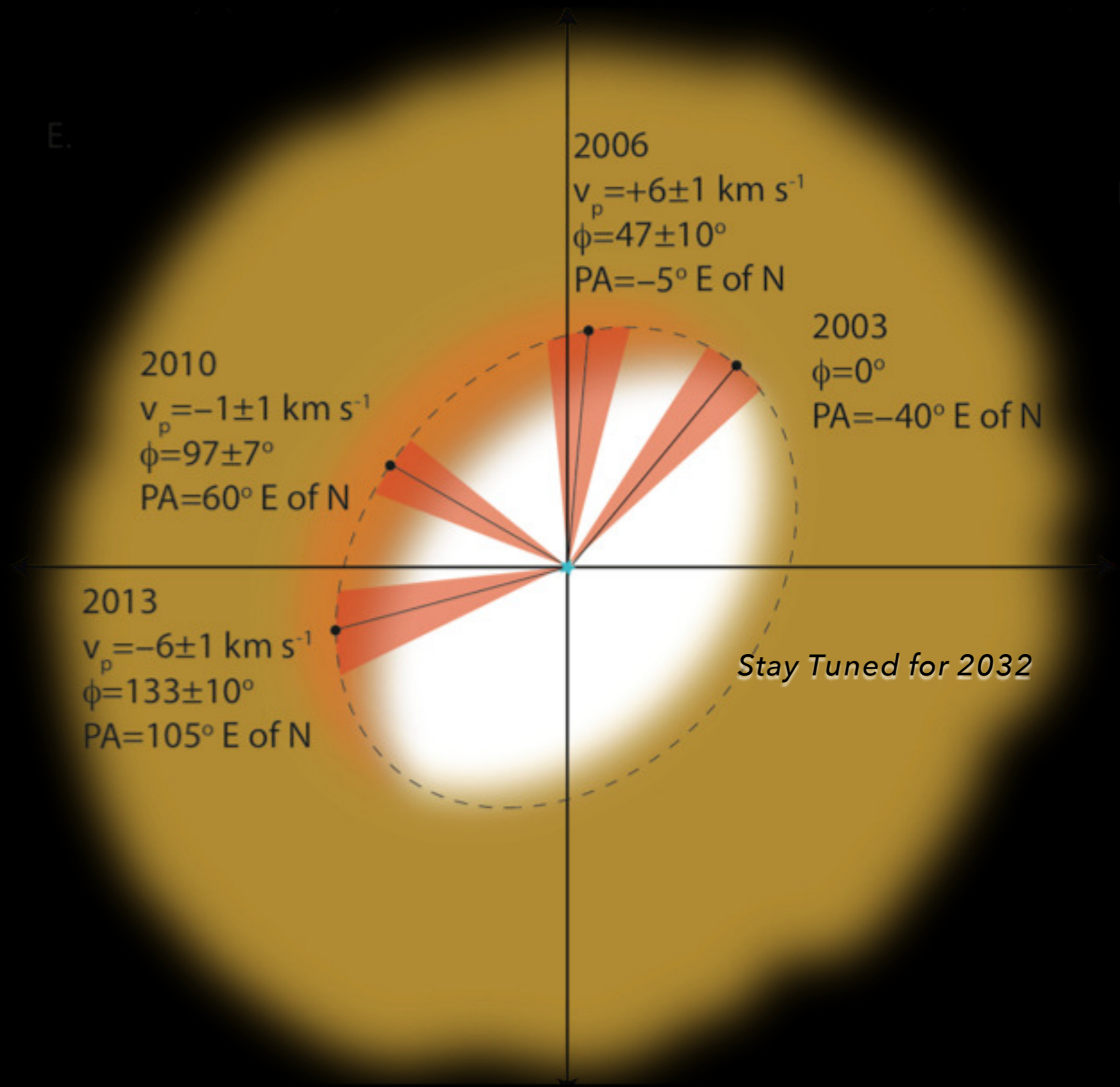


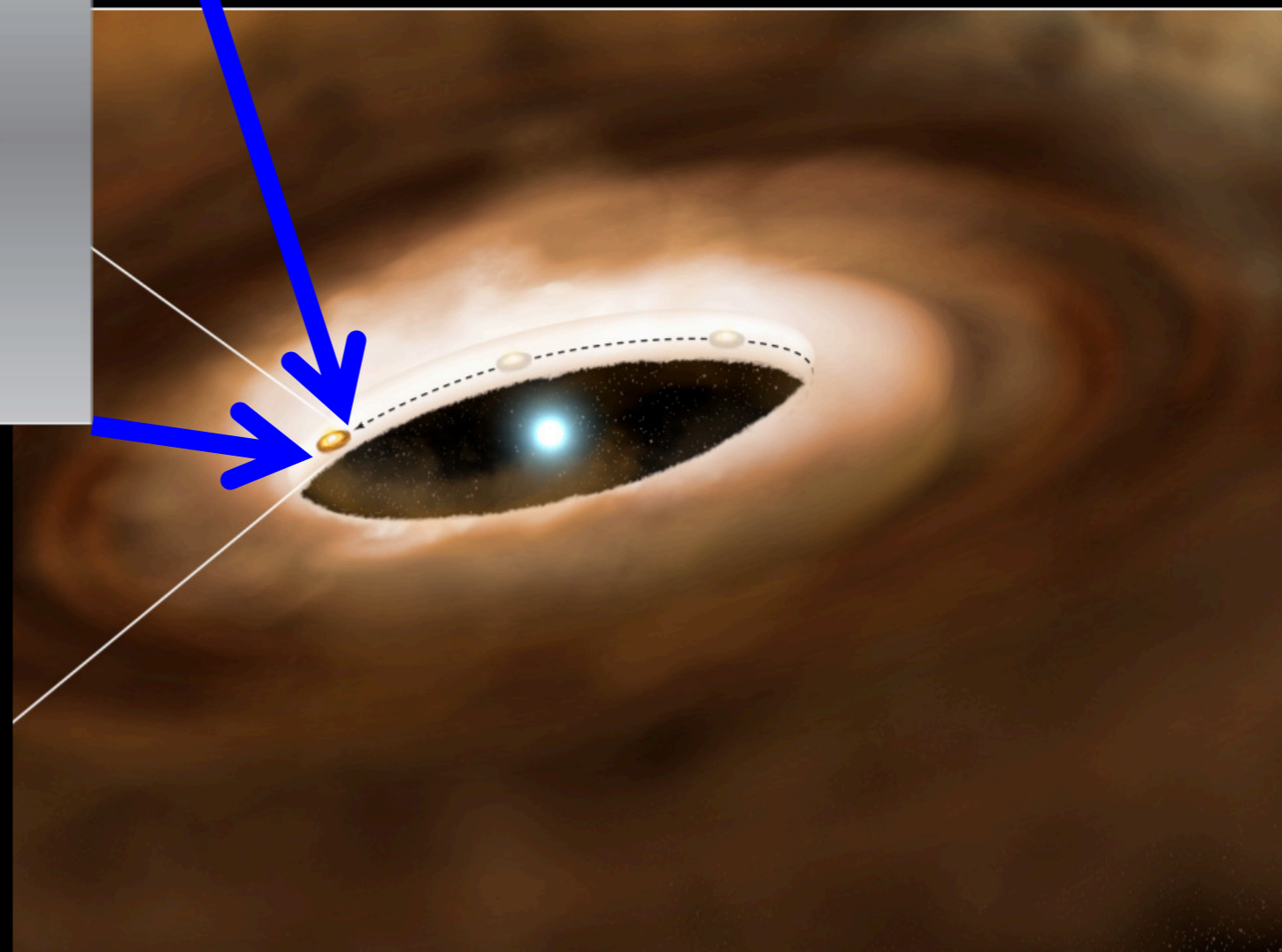
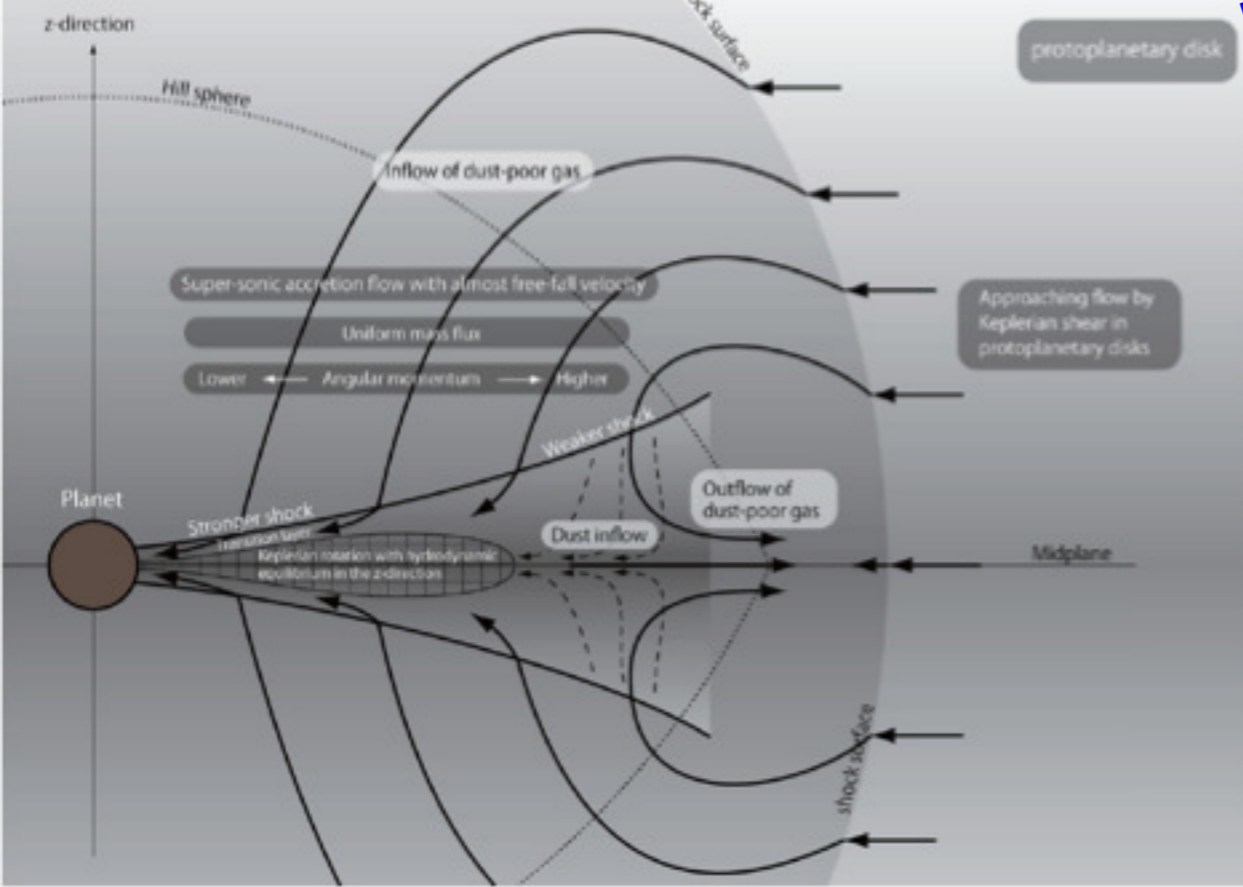
## Spectroastrometry



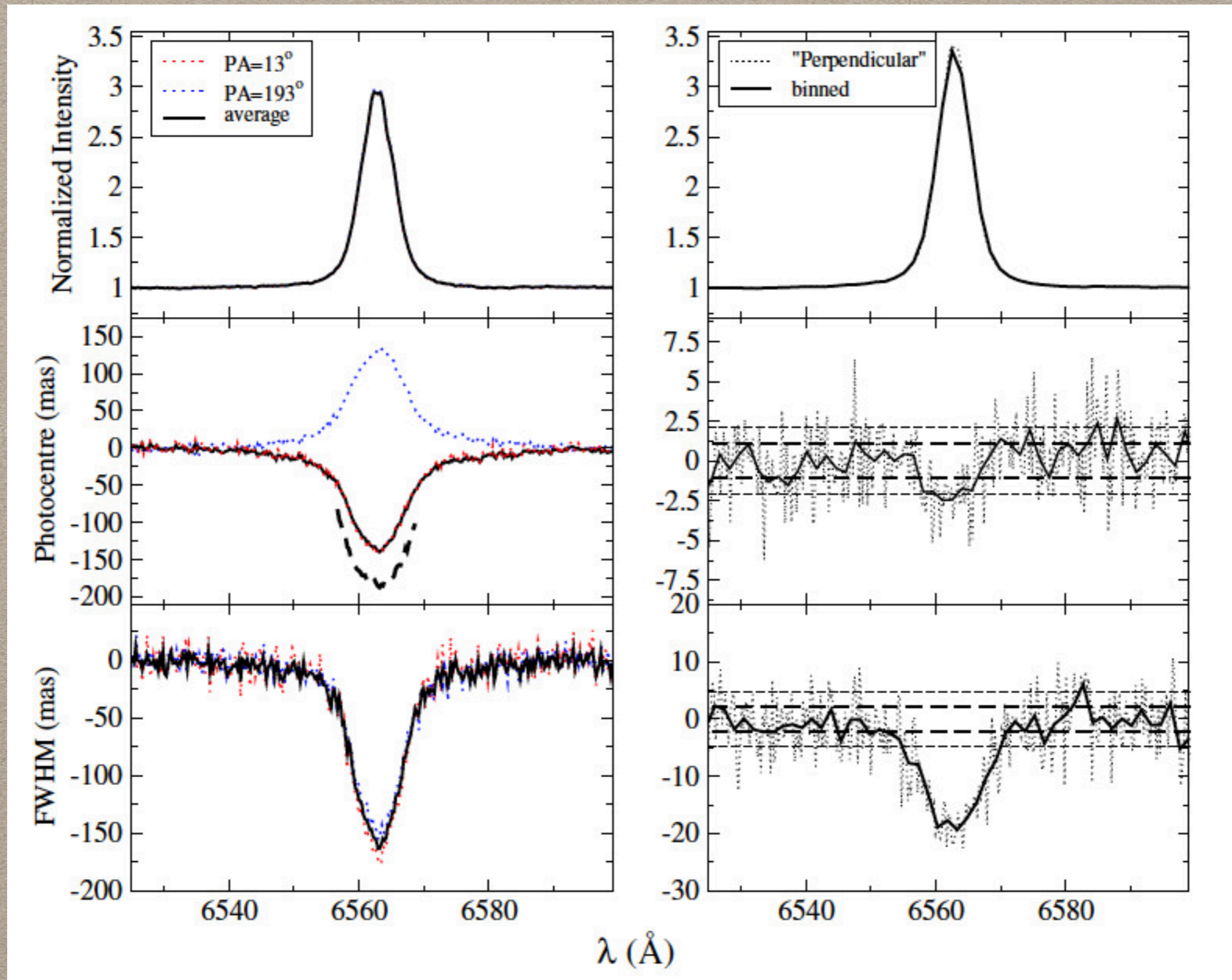


E.



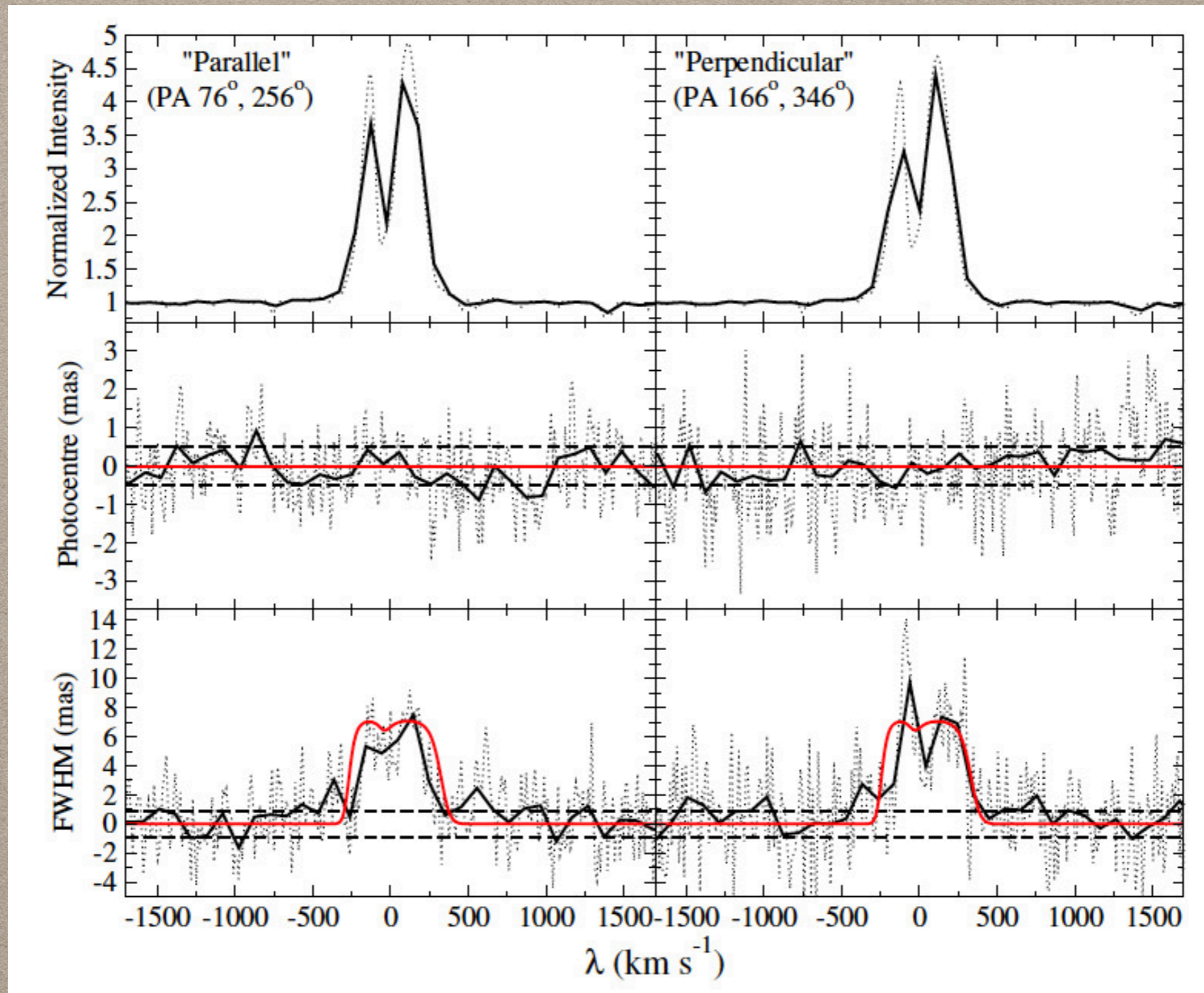


# SPECTROASTROMETRY



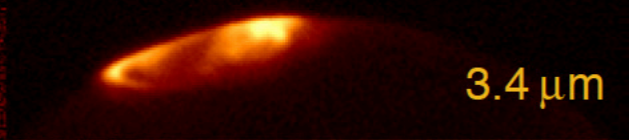
*Ignacio Mendigutia*

# SPECTROASTROMETRY



IRTF/NSFCAM, 29 JUNE 1995

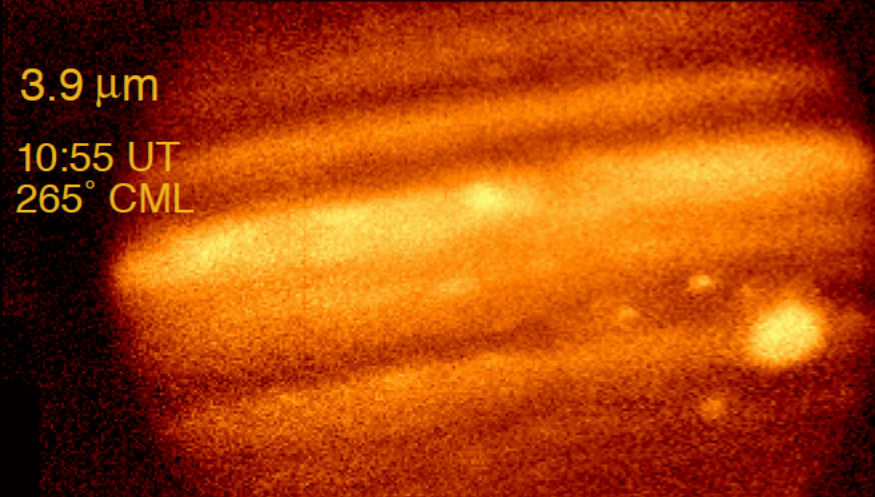
07:57 UT, 155° CML



3.4 μm

3.9 μm

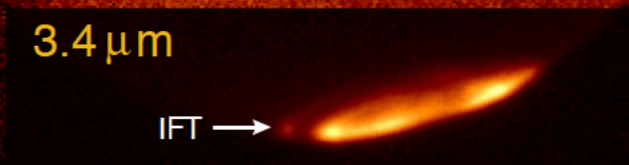
10:55 UT  
265° CML



3.4 μm

IFT →

06:12 UT, 91° CML



Satoh+1999

- Is there a planned volume limited survey
- Is there a planned radial velocity survey
- Application of spectroastrometry to other stars (Mendigutia for other ideas!)
- Monitoring of CO in transition disks is o

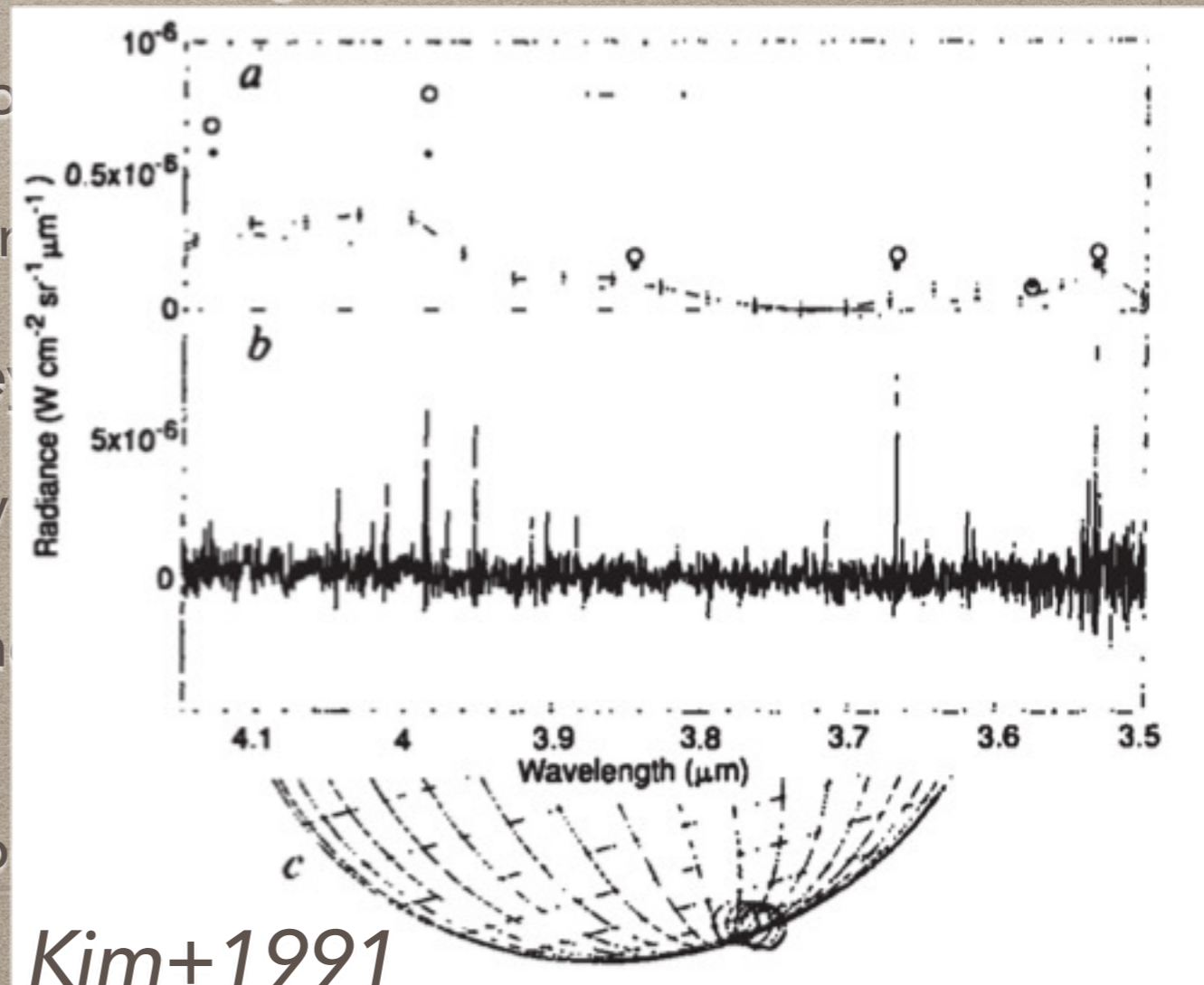
# QUESTIONS

... or are they just rare beyond ~10au?

... detections interesting (are cold/hot start

... variations of the aurora)?

Solar analogs?



Kim+1991

# DETECTION CRITERIA?

- How do we assign upper limits on the presence of a planet in a disk?
- What about ring and spiral "non-detections"?
- How do we encourage publication of complete samples (i.e., non-detections)?
- What criteria allow us to assign "likelihoods" to observations?
- How many disks must we observe before the non-detections become worrisome?