Molecular spectroscopy of protoplanetary disks and evidence for slow disk winds

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Overview of molecular spectroscopy of protoplanetary disks

An observational conundrum: A sub-class of disks not well explained by disk models

Are we seeing disk winds? Pros and cons

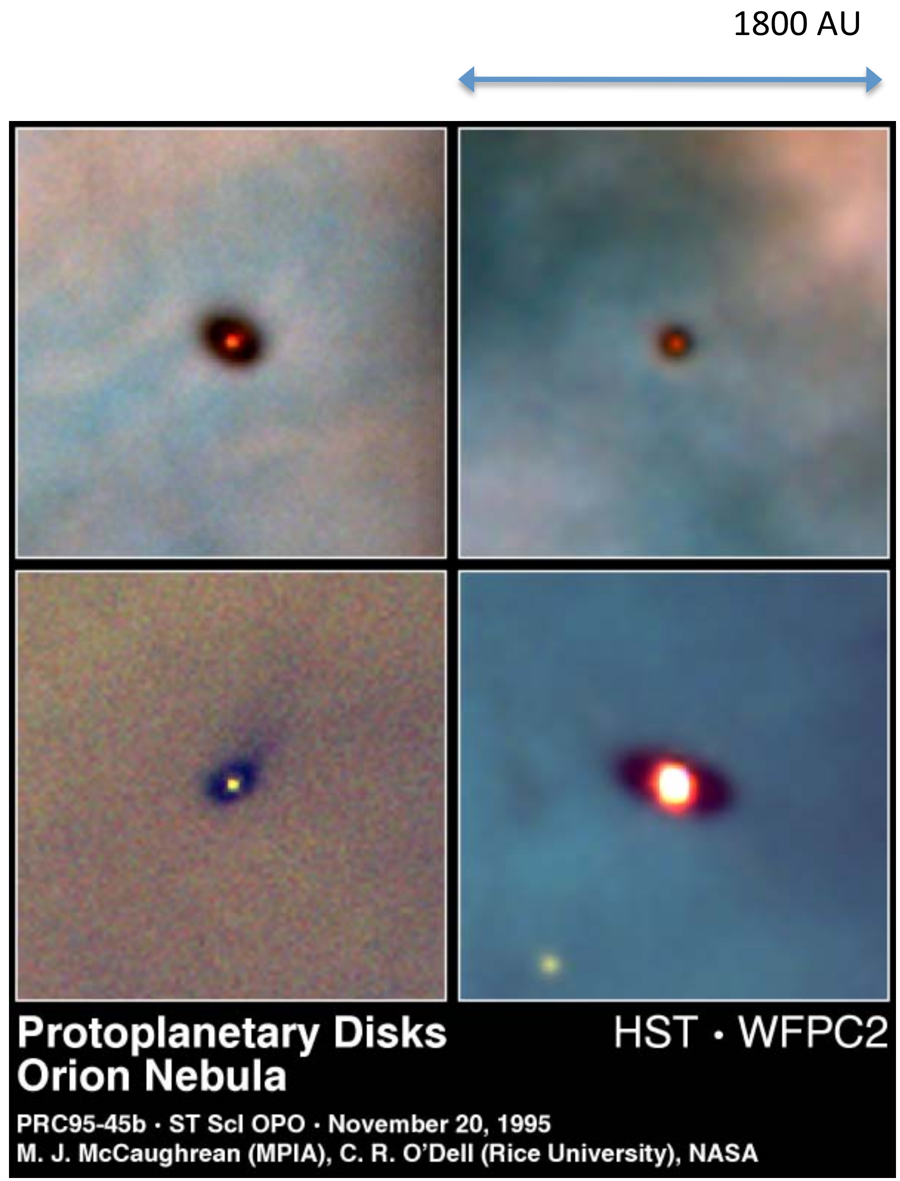
What are the properties of protoplanetary disks?

Disk shaped, composed of gas and dust

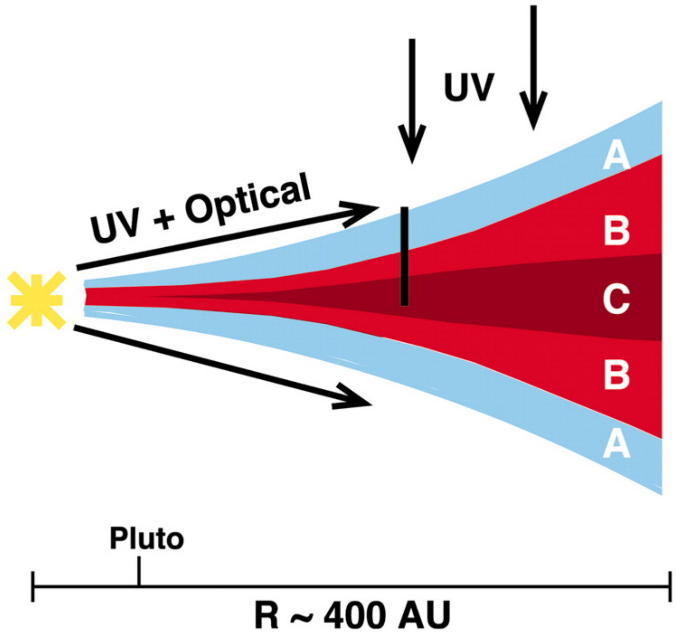
Few 100 AU across (several times Pluto's orbit)

Age ~ a few Myr

Distances > 100 pc (100 AU subtends < 1")



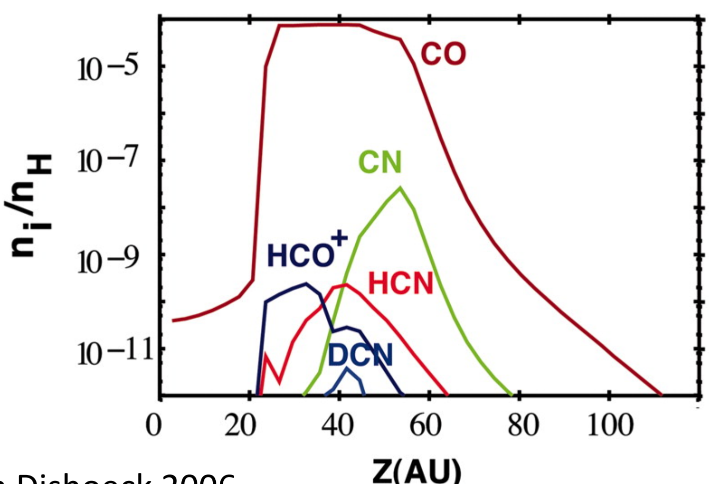
The vertical structure of protoplanetary disks



The PDR layer

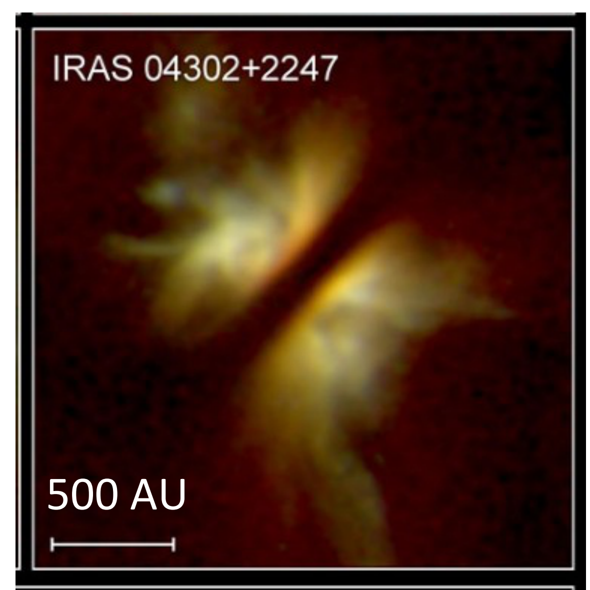
The molecular layer

The icy midplane



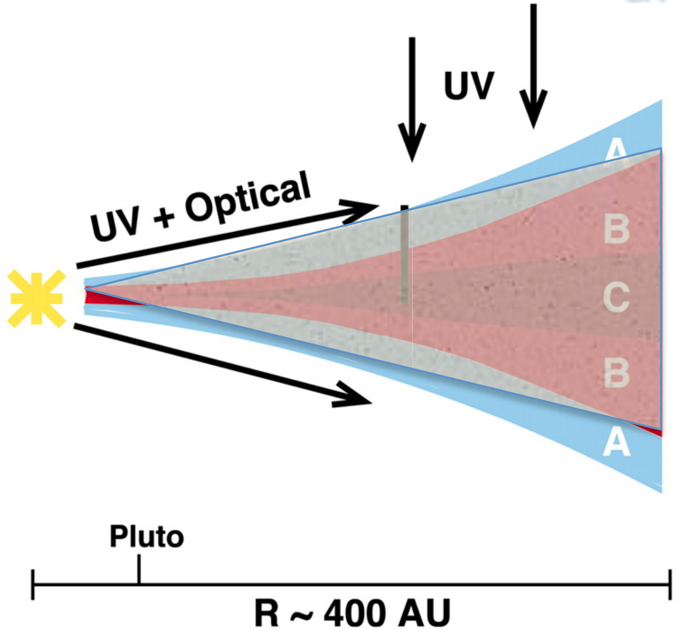
From van Dishoeck 2006

Hubble image



It's not necessarily easy to see molecules in the IR since disks are dusty

(Densities in disk atmosphere < critical densities)



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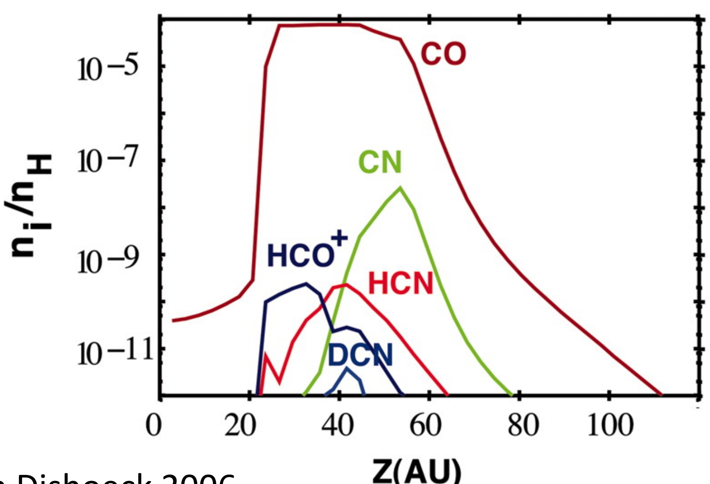
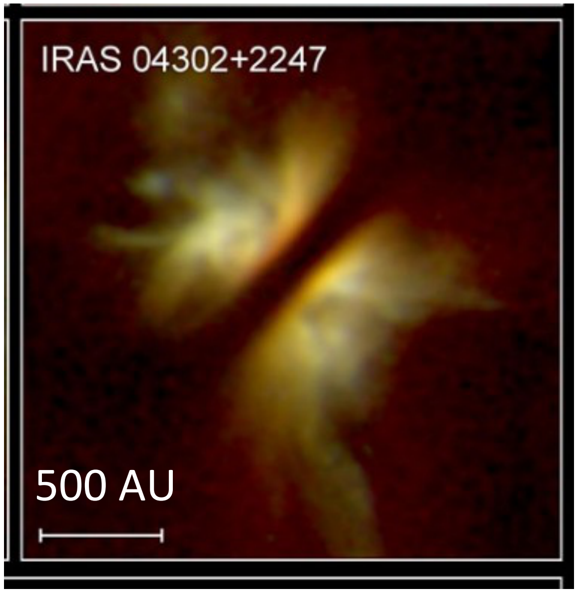
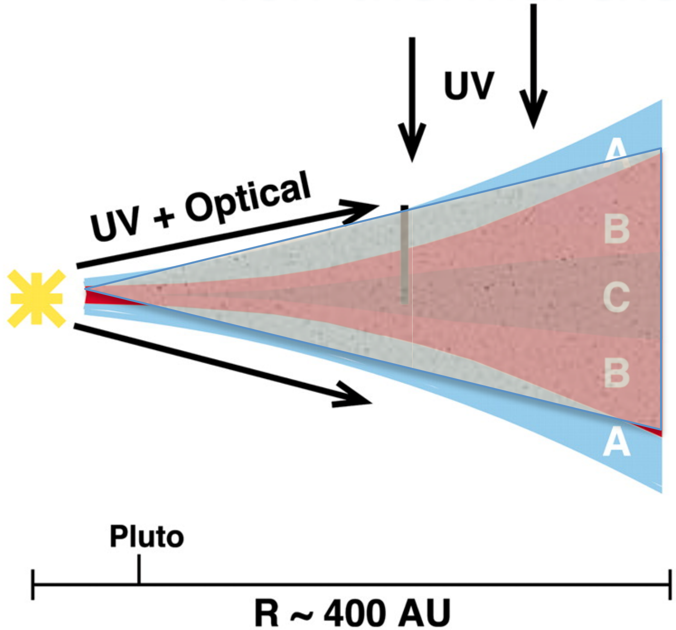


From van Dishoeck 2006

Hubble image



A combination of dust settling/growth, gas heating, and non-thermal excitation make it possible



The PDR layer

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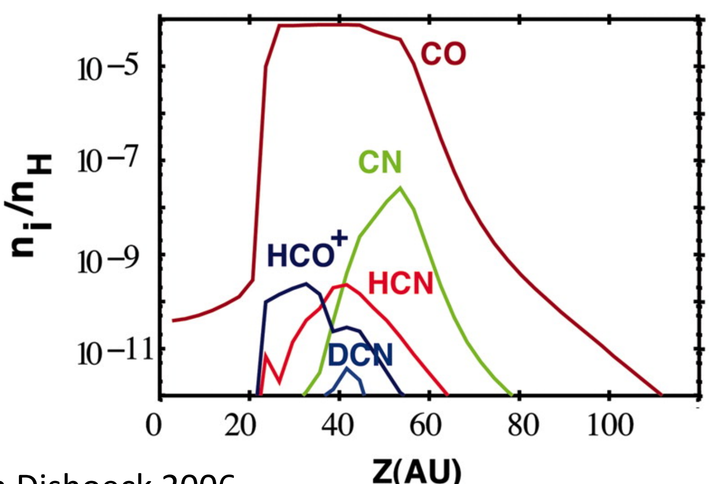
The icy midplane



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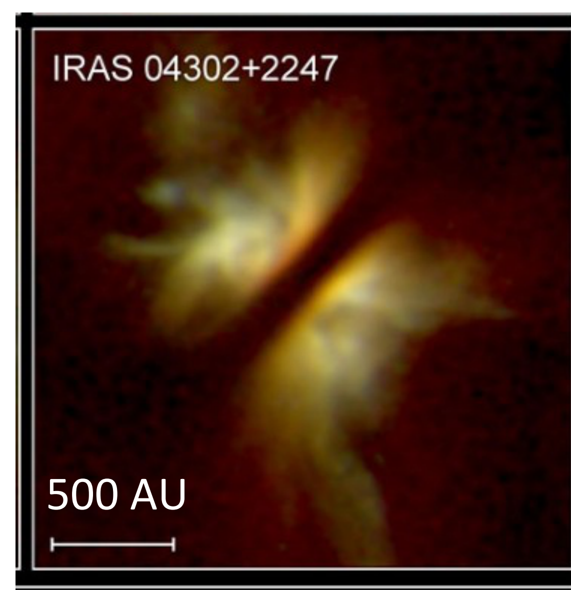
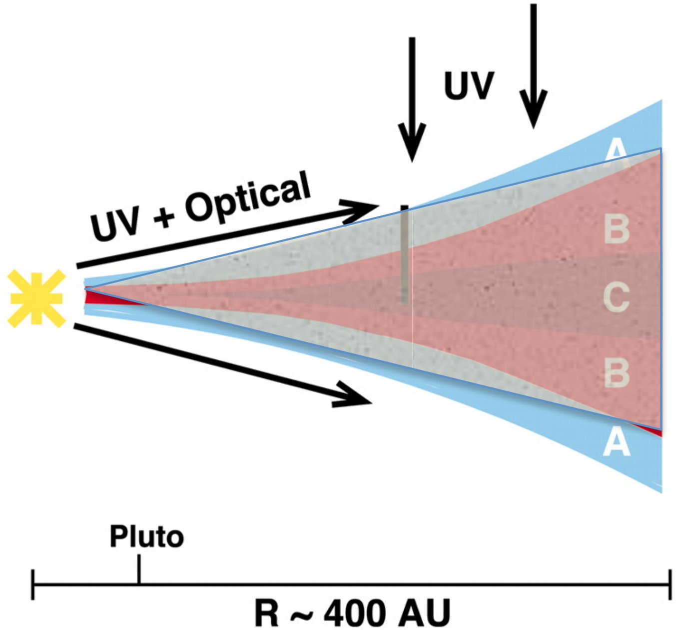
Hubble image



(Also, by millimeter wavelengths, disks become optically thin)



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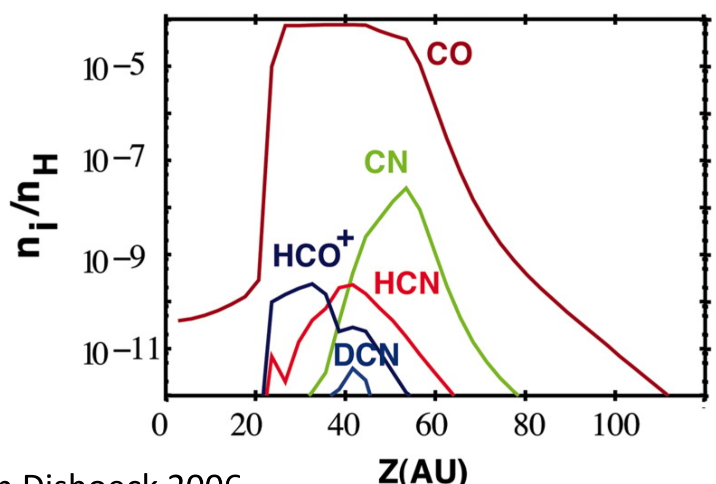
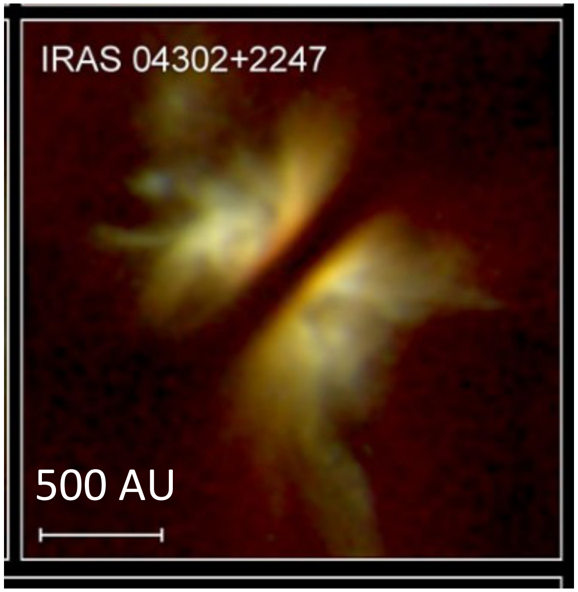


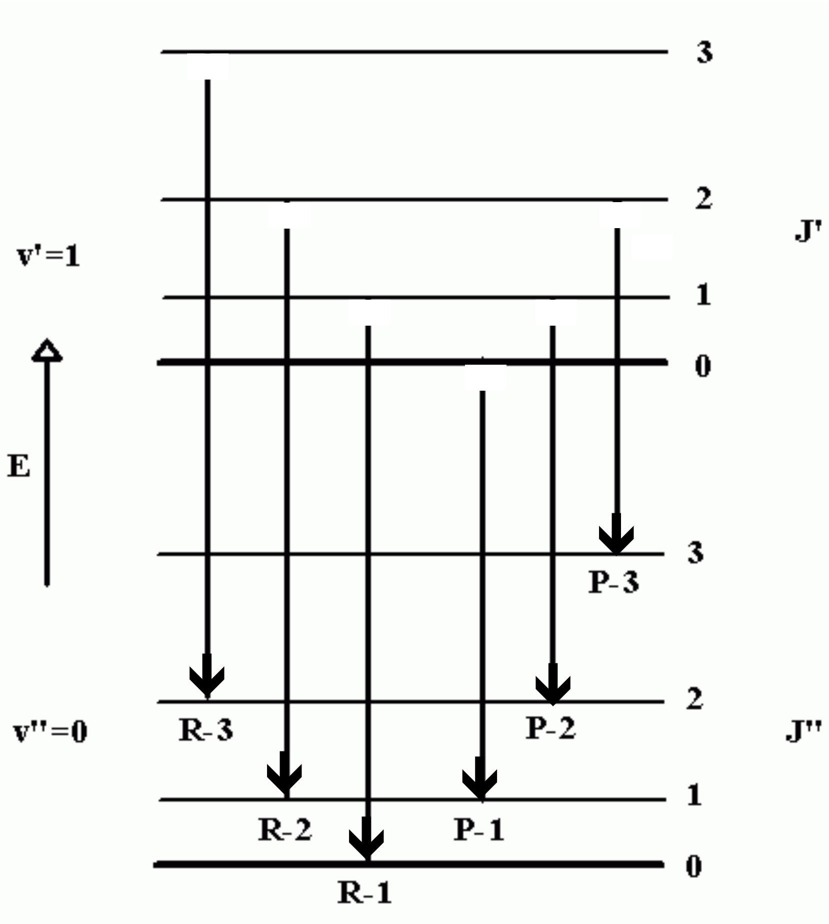
From van Dishoeck 2006

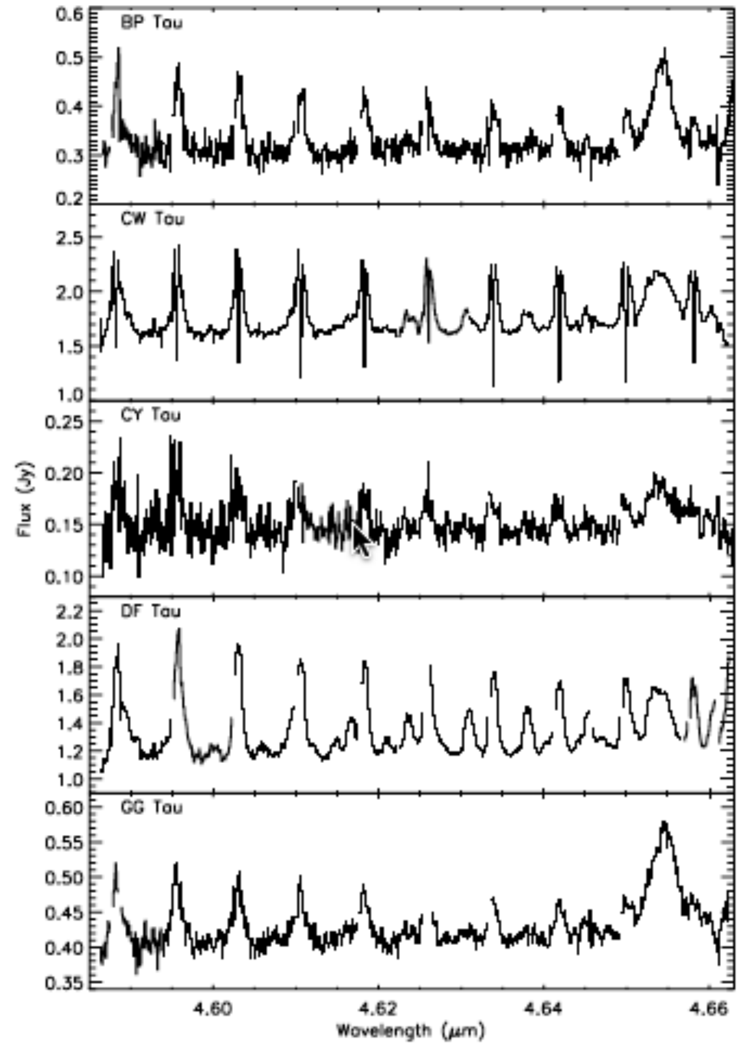
Hubble image



First IR molecular emission detected: CO in near-IR with ground-based spectrographs

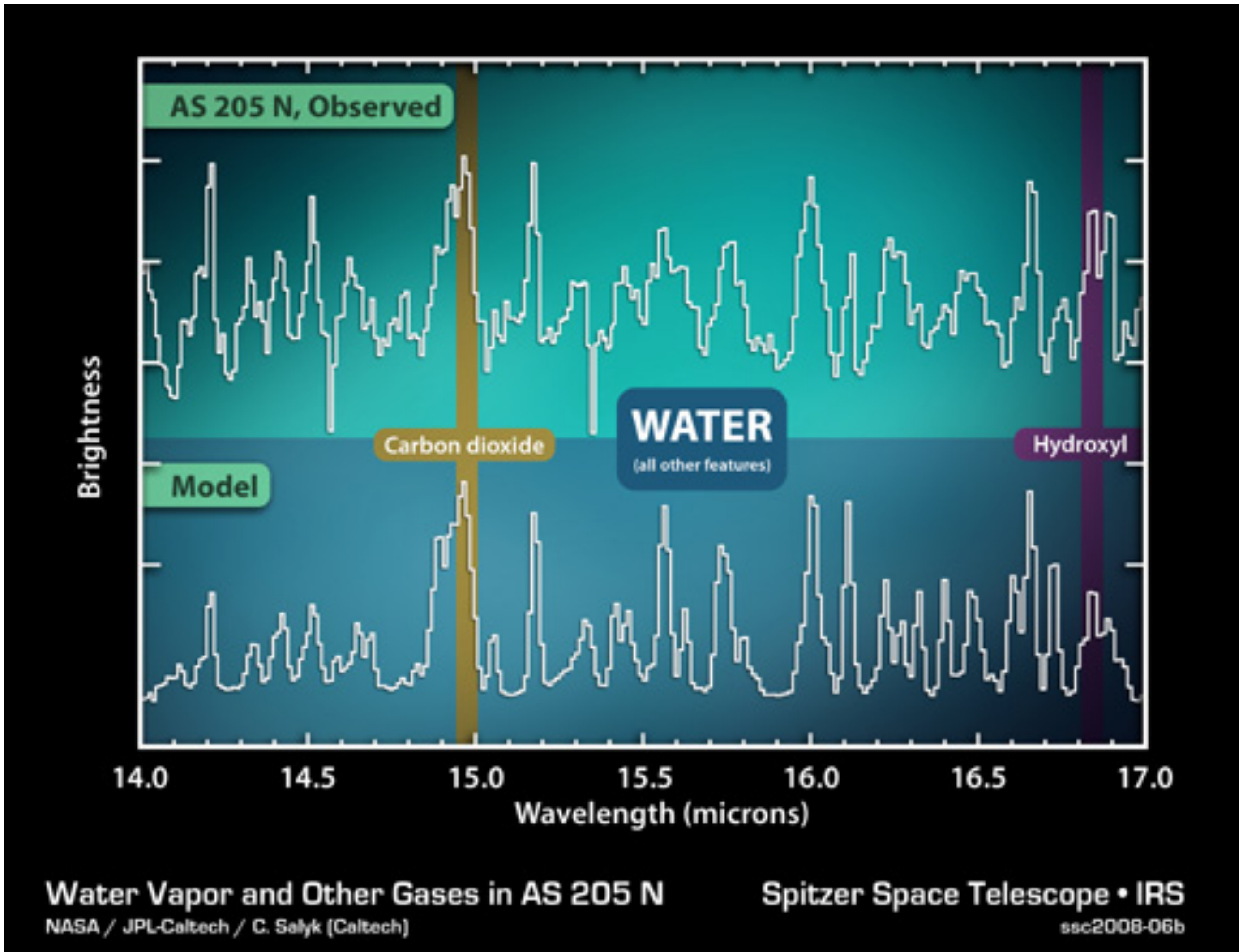
Energy level diagram for CO rovibrational emission



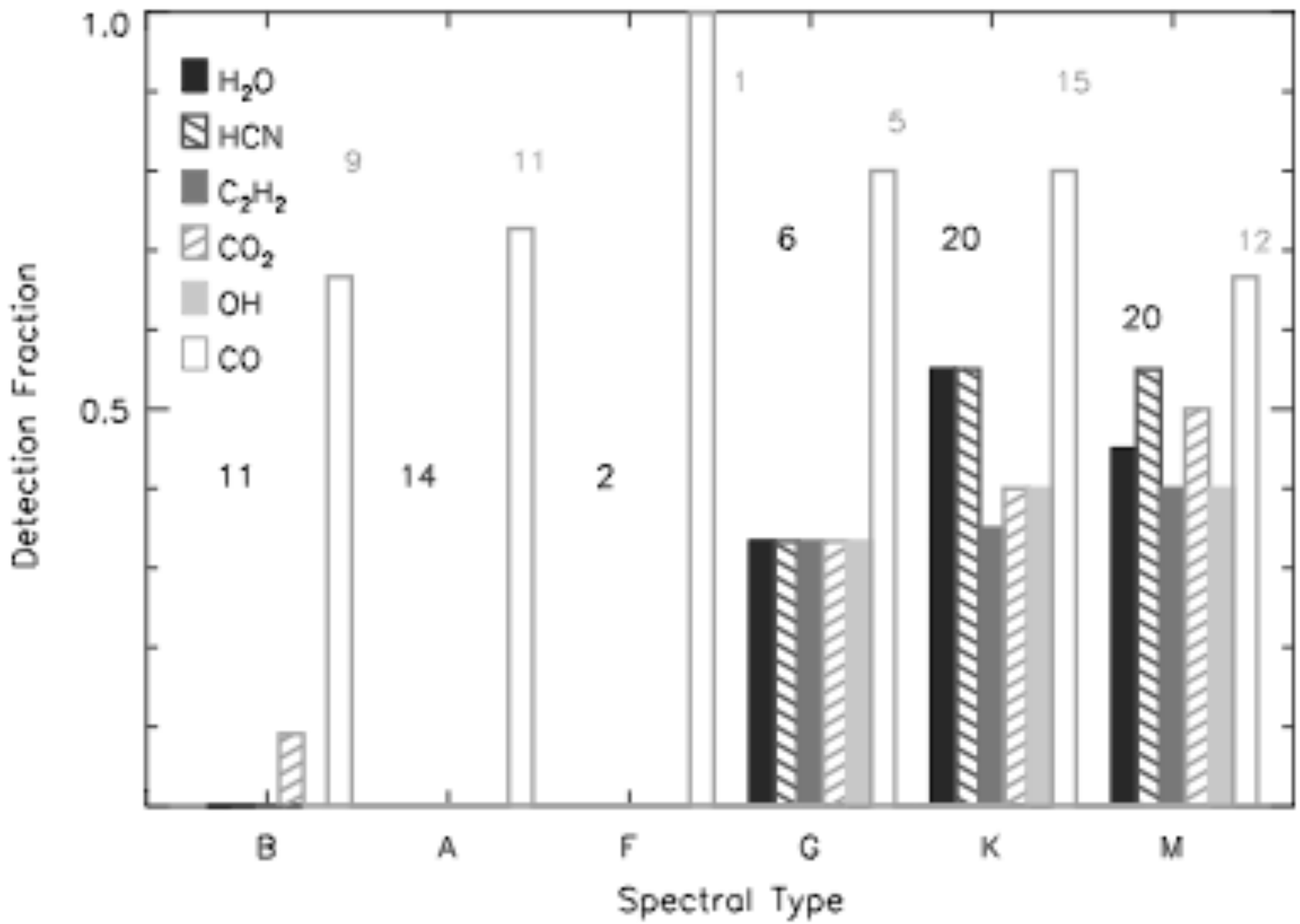


Najita et al. 2003

Other breakthrough: mid-IR molecular detections with Spitzer-IRS (H_2O, HCN, C_2H_2, OH, CO_2)

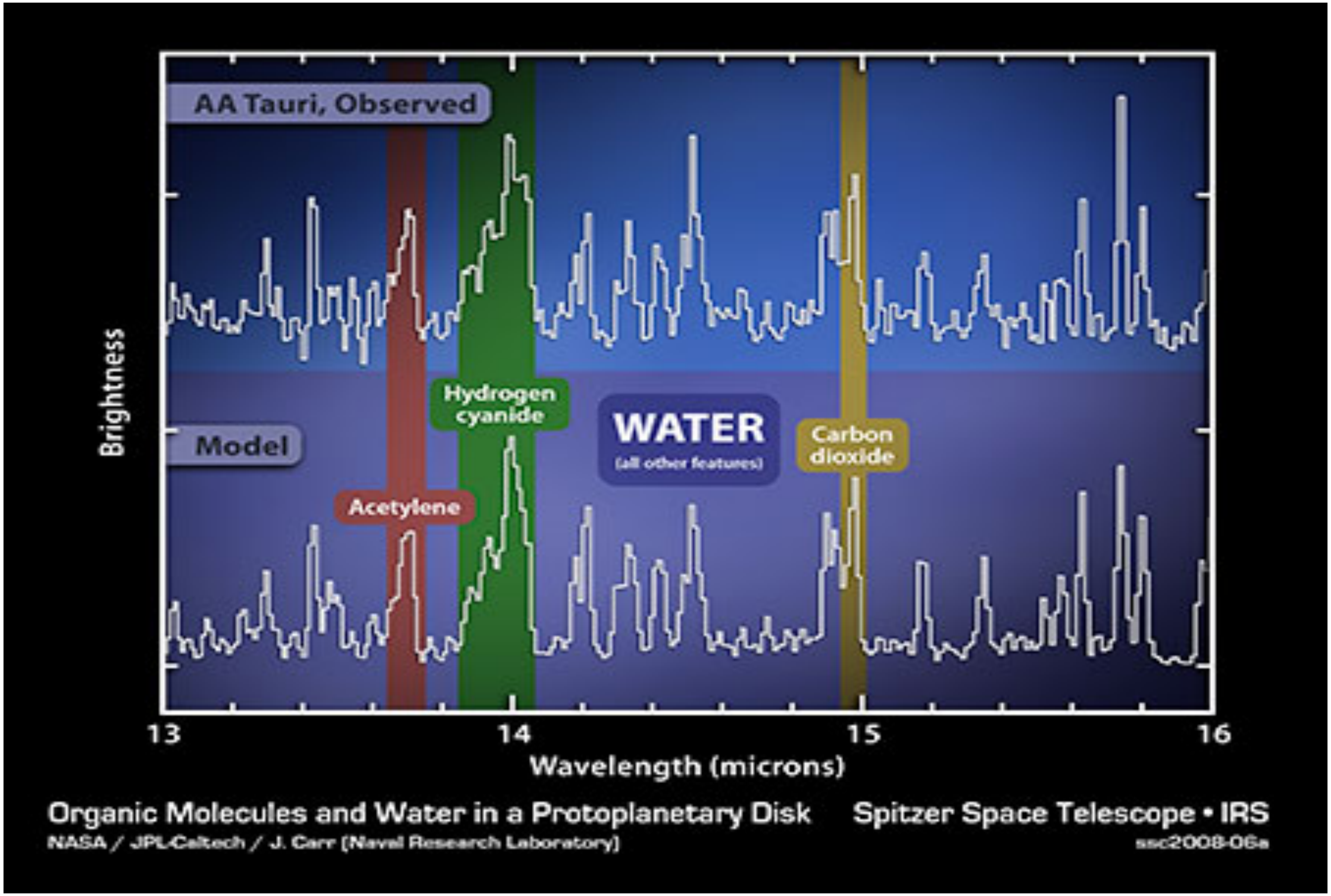


Near-IR and mid-IR emission common around low-mass stars



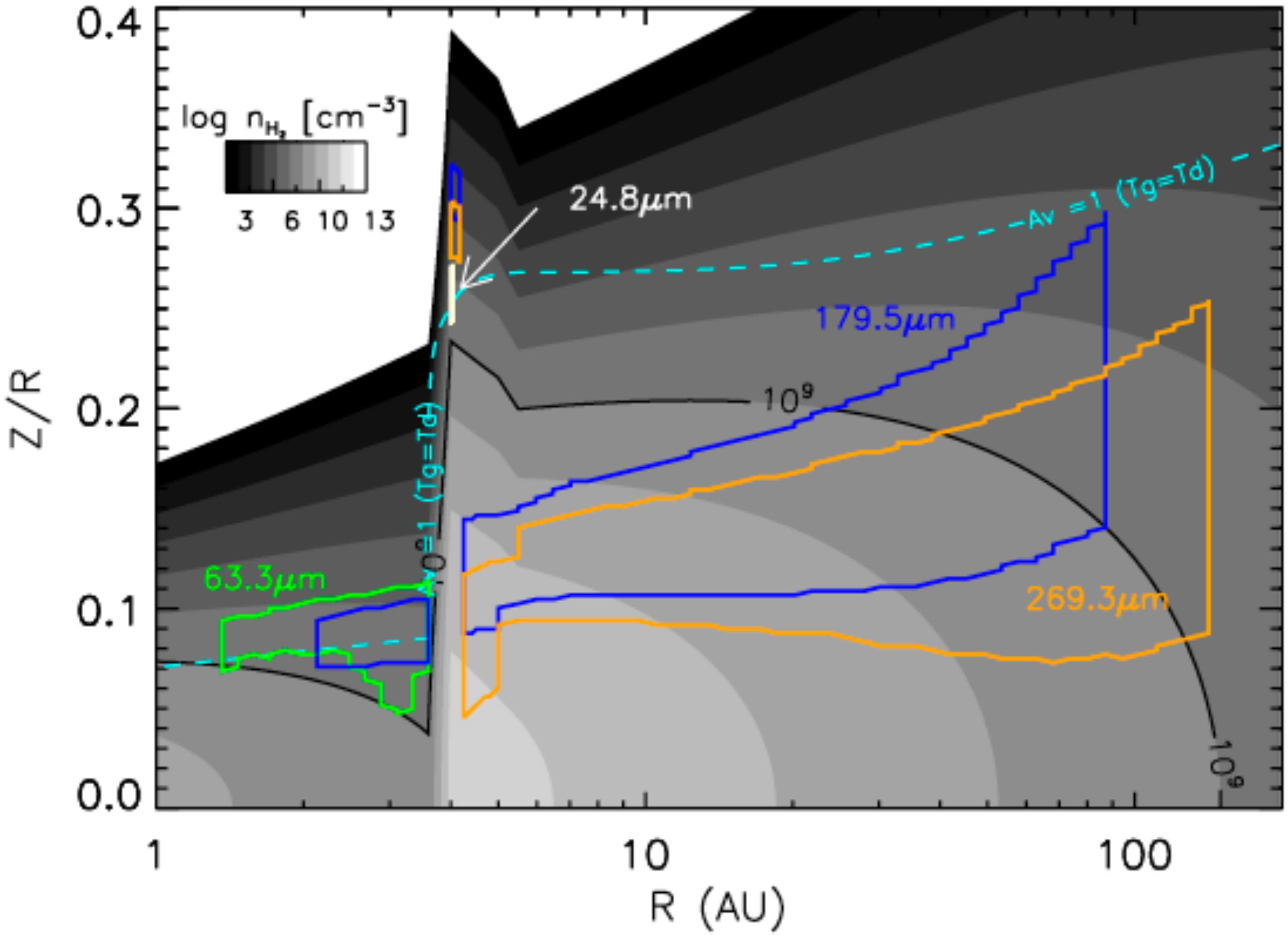
Pontoppidan et al. 2010

What can you do with molecular spectroscopy? Detection of molecules – gas phase chemistry, temperatures, densities



Carr & Najita 2008

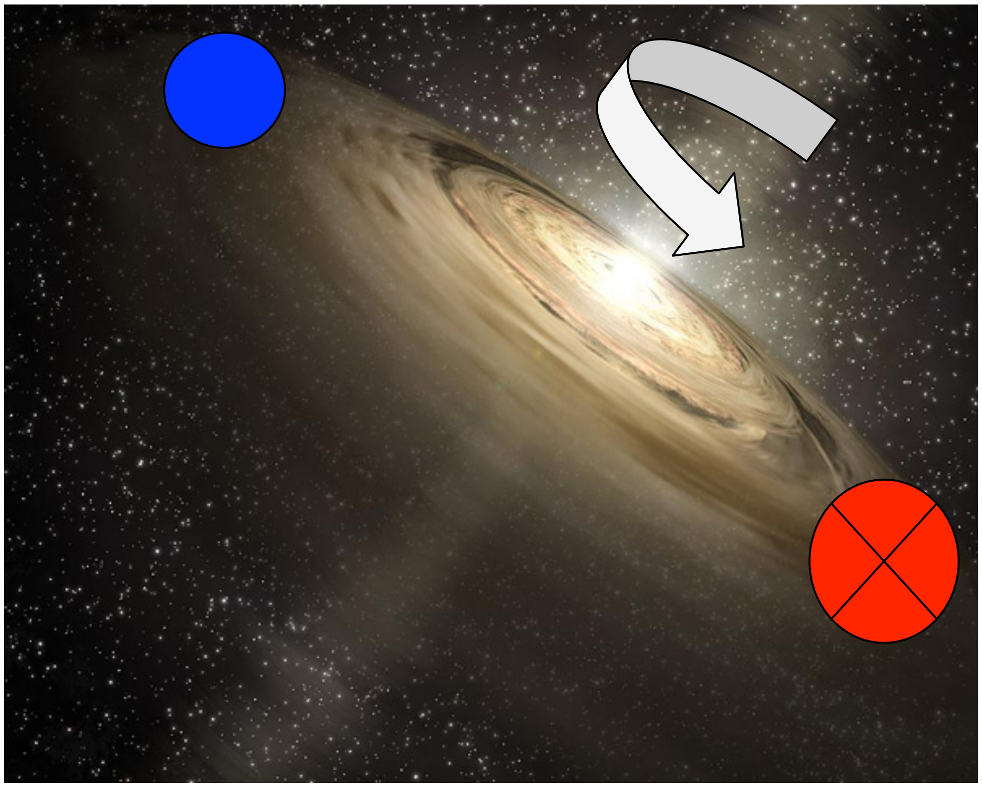
Spatial locating of molecules:
Excitation models + multiple line observations

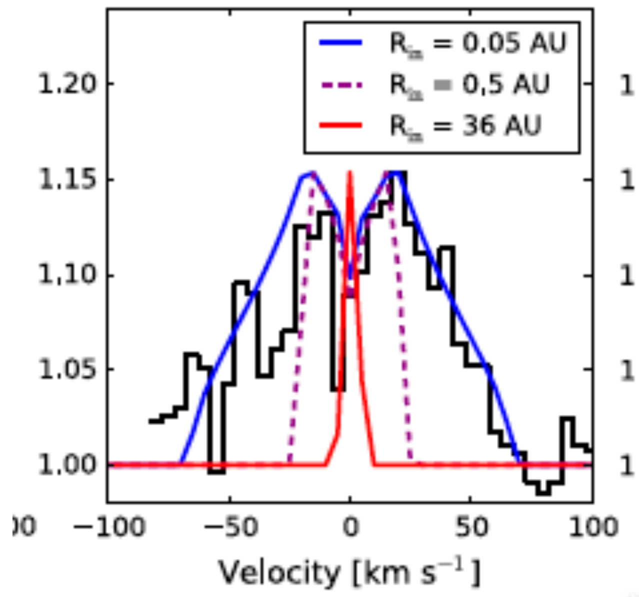


Main contributions to 24, 63, 179 and 269 micron water lines in TW Hya

Zhang… Salyk et al. 2013

Spatial locating of molecules*: Line shapes (Doppler shift + Kepler's 3rd law)



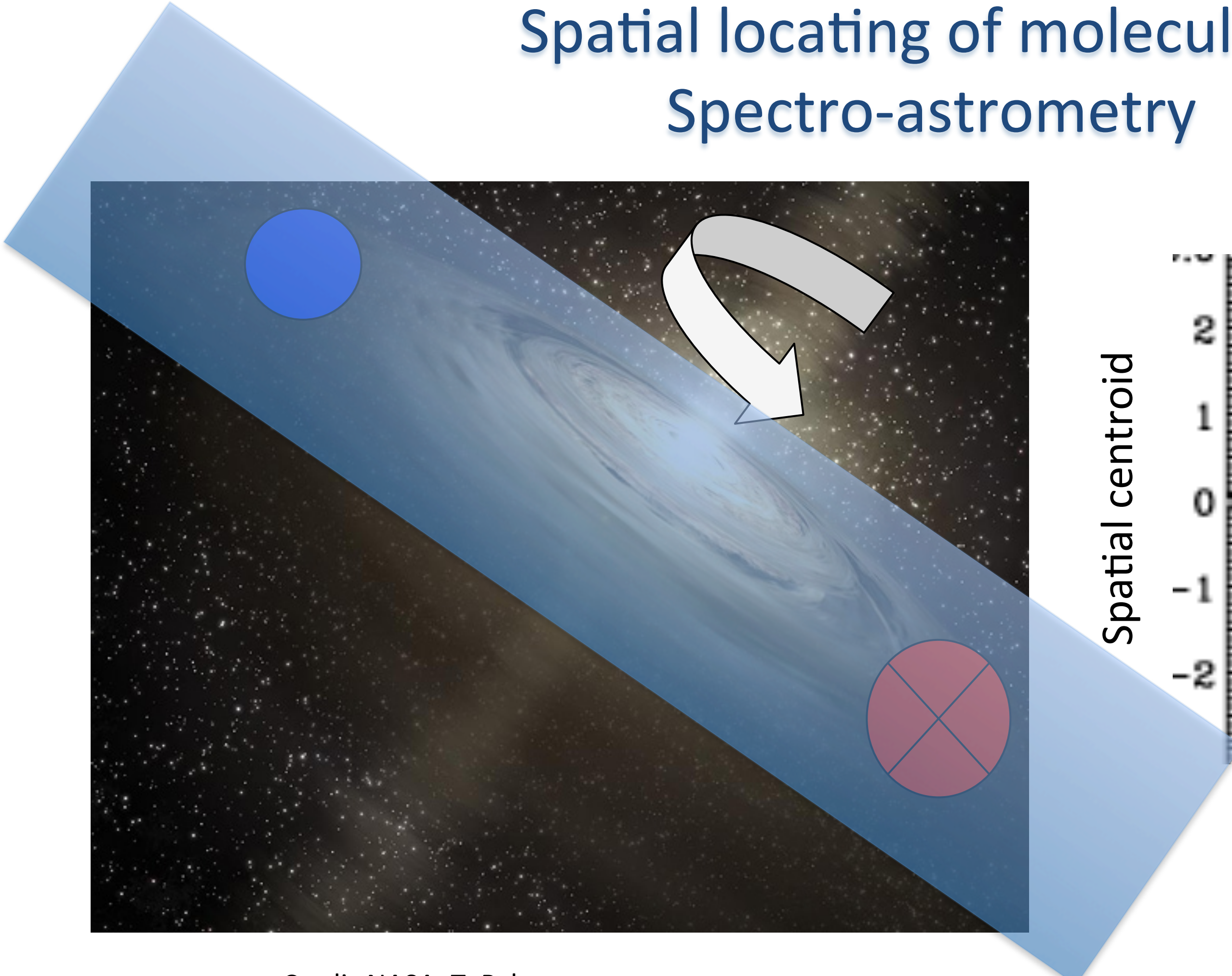


Credit:NASA, T. Pyle

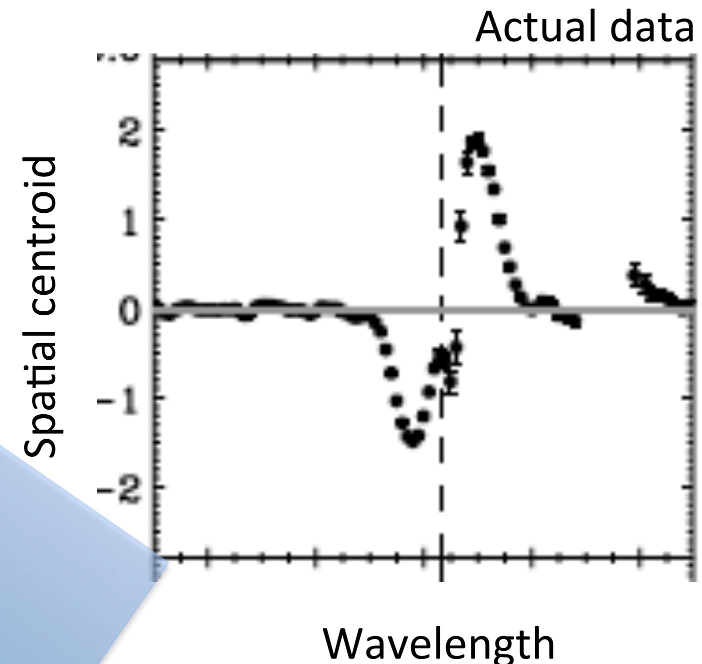
measured **λ** → **v** → **R** inferred

*Requires that lines be spectrally resolved

Spatial locating of molecules*: Spectro-astrometry



Credit:NASA, T. Pyle

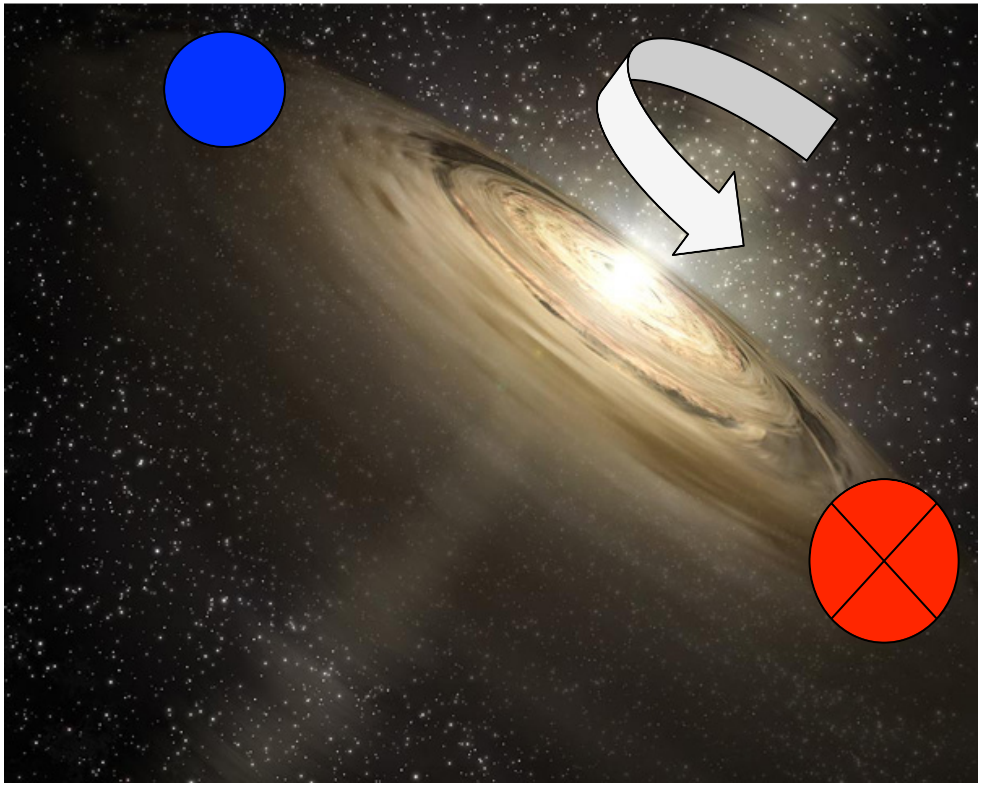


Pontoppidan et al. 2011

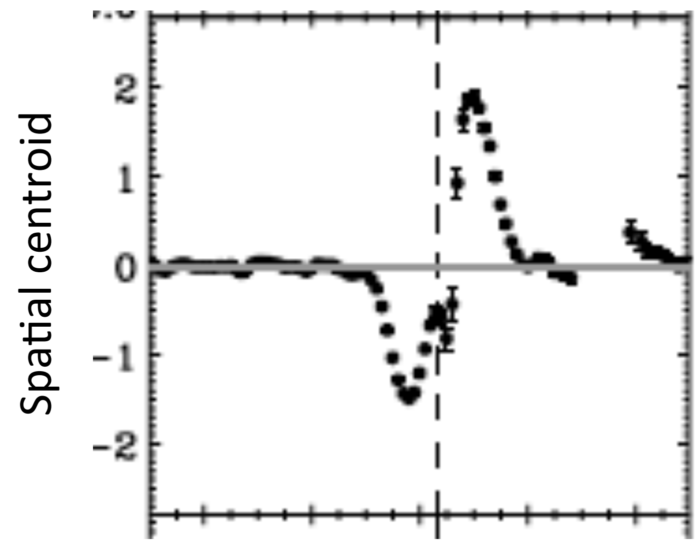
As with other forms of astrometry, spatial accuracy can be *significantly better* than the image FWHM.

*Requires that lines be spectrally resolved

Disk kinematics: Are there deviations from Keplerian motion?*
(And if so, what's causing them?)



Credit:NASA, T. Pyle

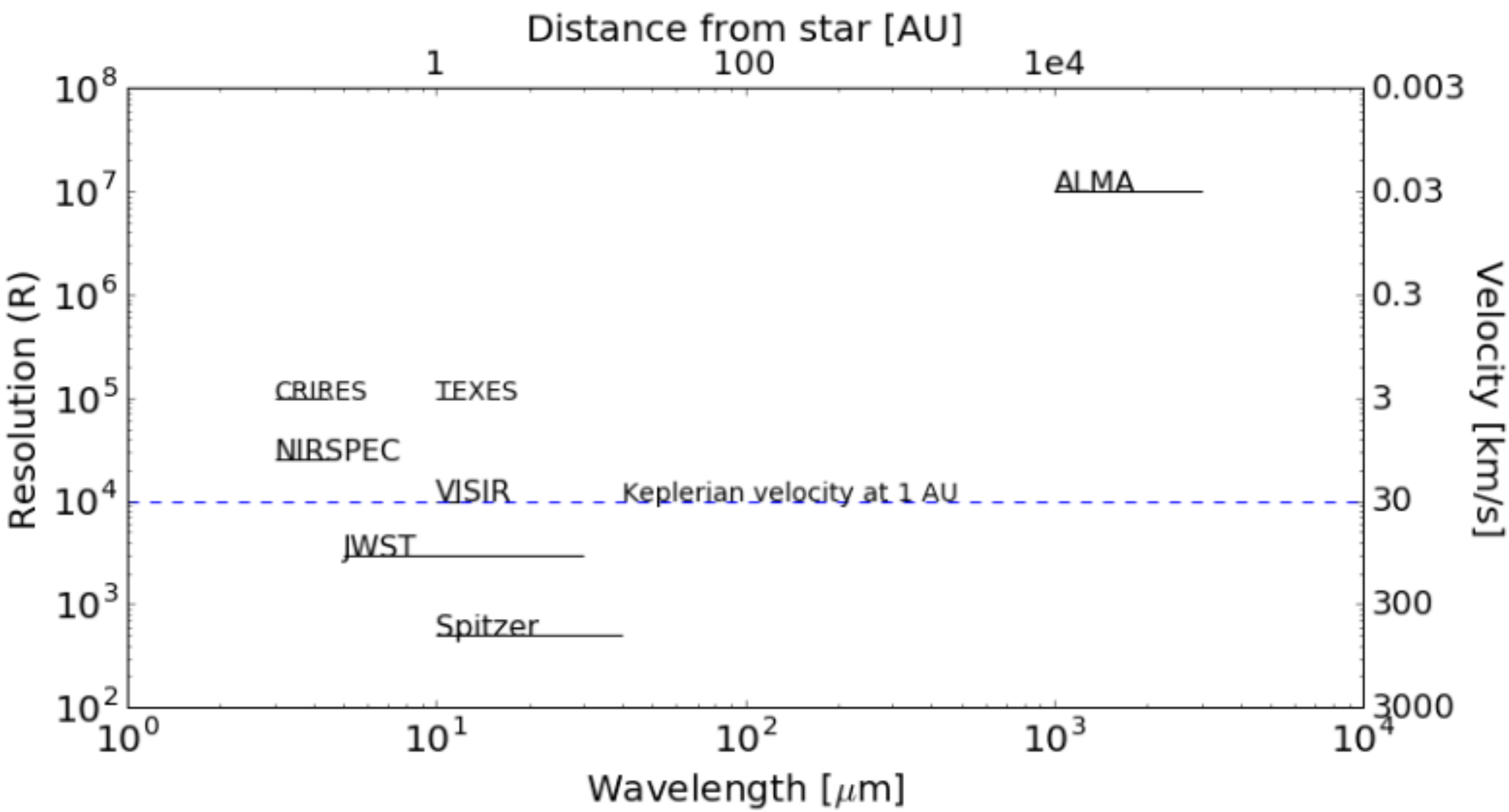


Pontoppidan et al. 2011

*Requires that *deviations* be spectrally resolved

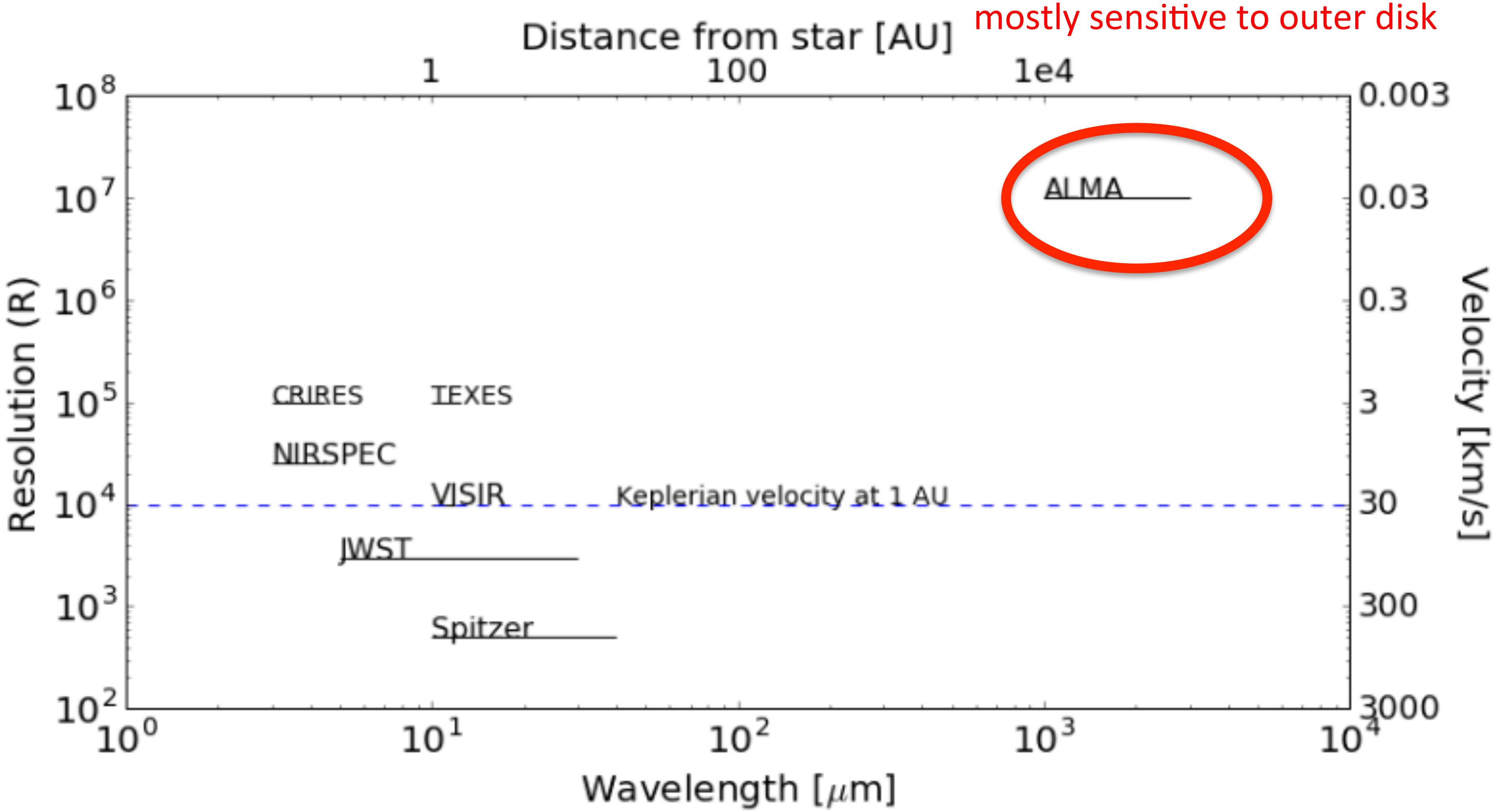
Summary of instruments and disk regimes

(assuming blackbodies at equilibrium temperature)



Summary of instruments and disk regimes

ALMA has extremely high R, but mostly sensitive to outer disk



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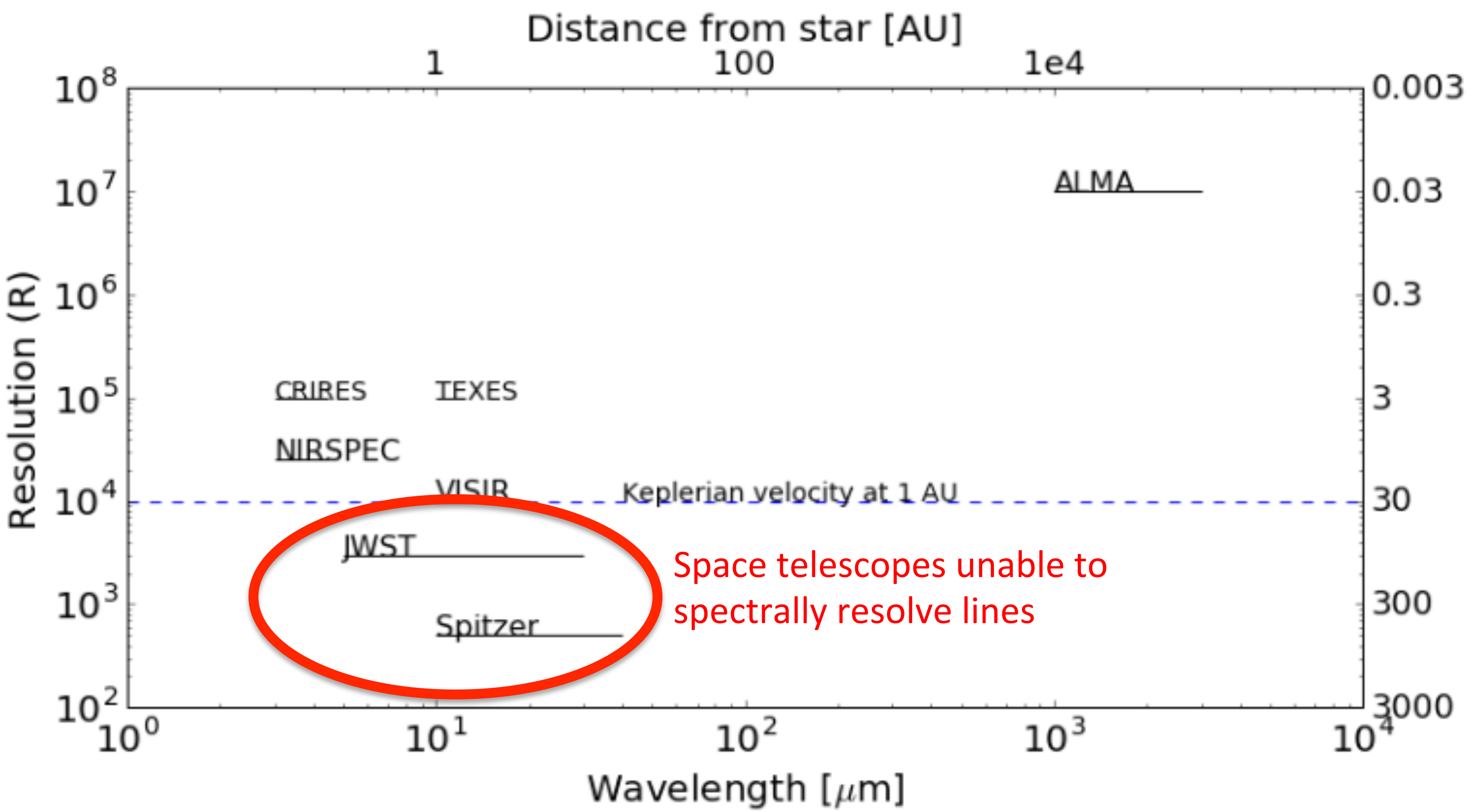

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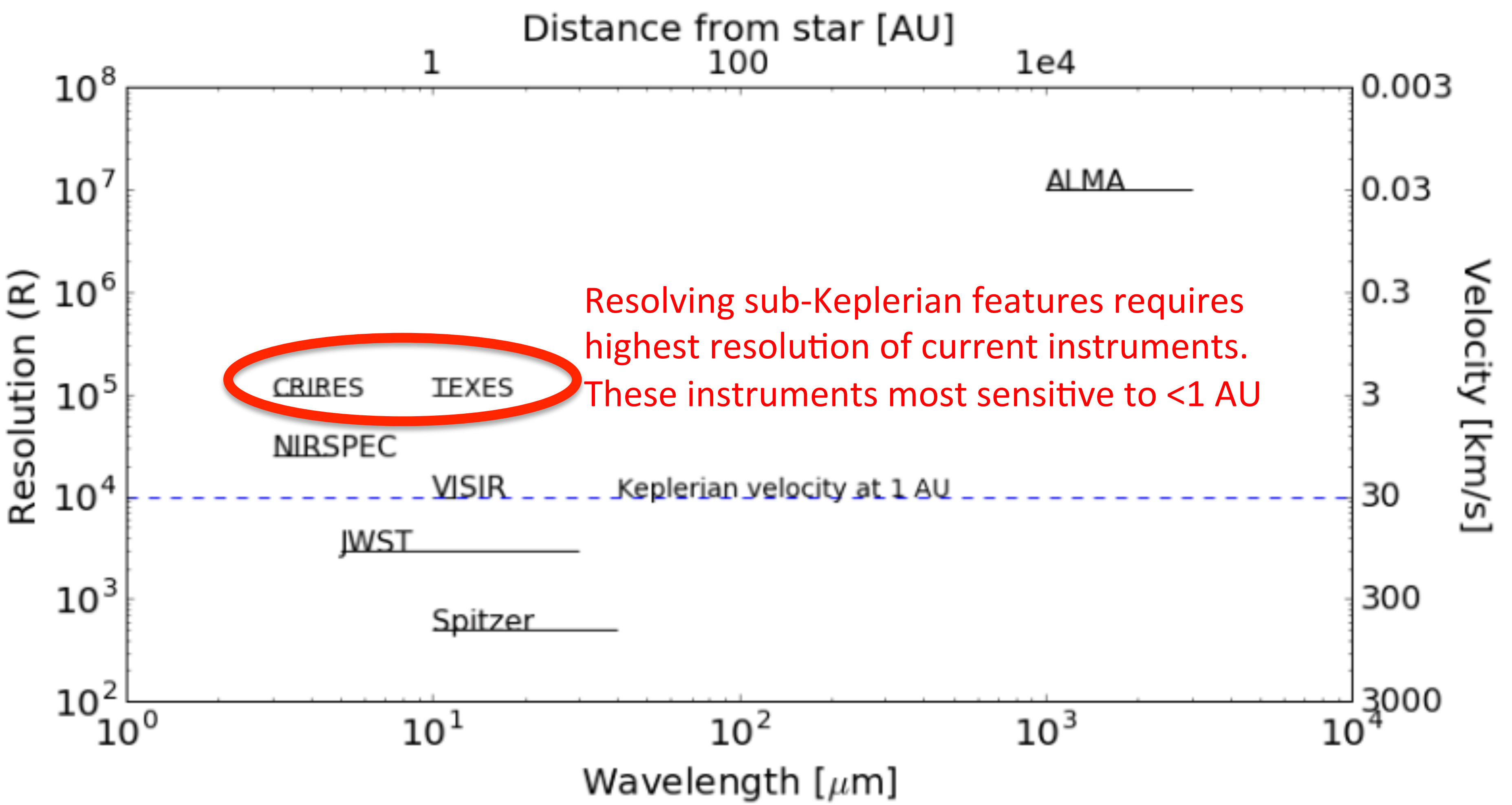


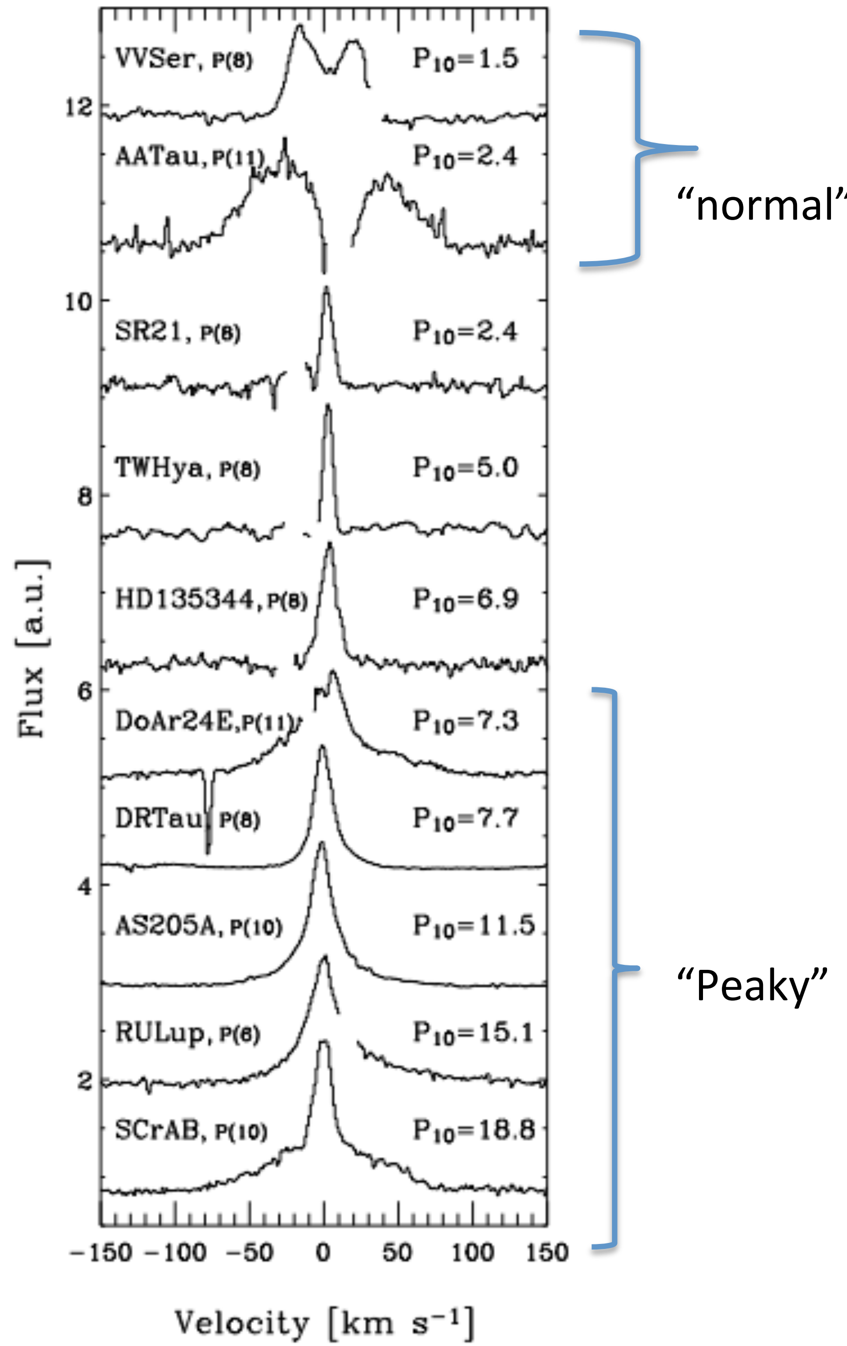
An observationally-motivated conundrum: There is a class of protoplanetary disks with unusual properties that can not be explained with “traditional” disk models.

What is the conundrum?

Some CO molecular emission line profiles are “peaky” (more single peaked than expected).

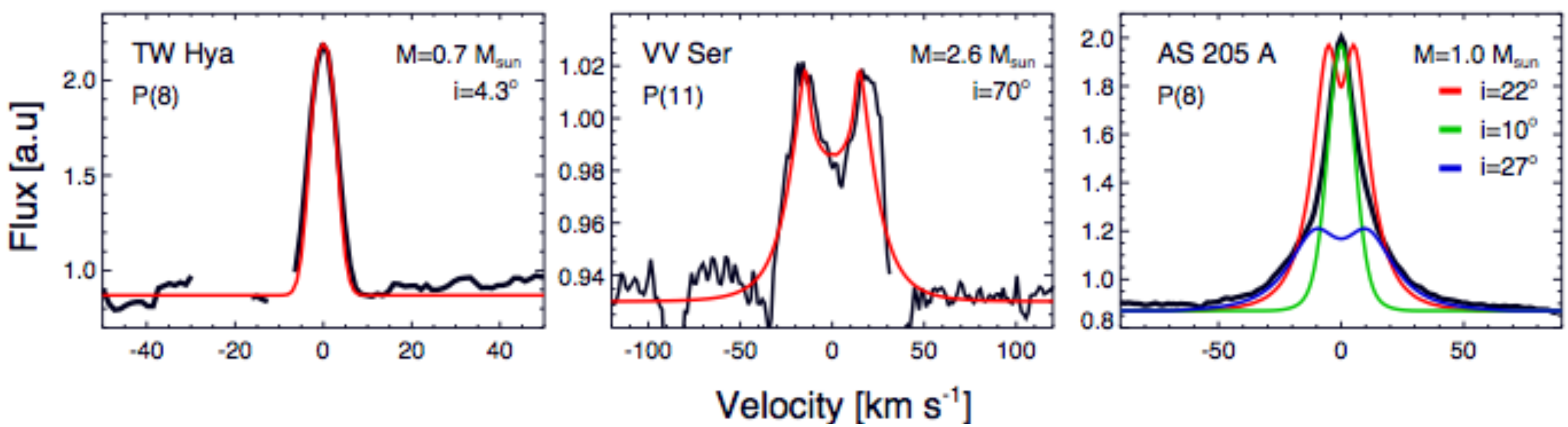
Neither low inclination nor large spatial extent can explain the observations

Bast et al. 2011



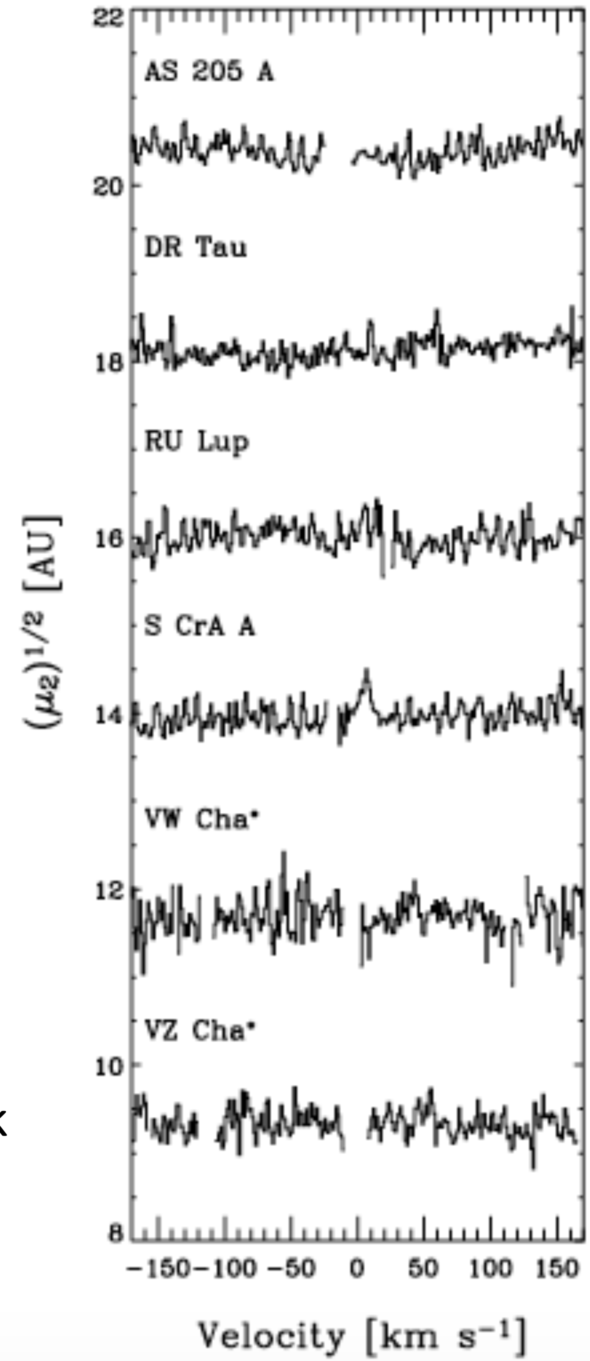
“Peaky” molecular emission line profiles, not fit by inclined disk models

“normal” low inclination “normal” high inclination “peaky”



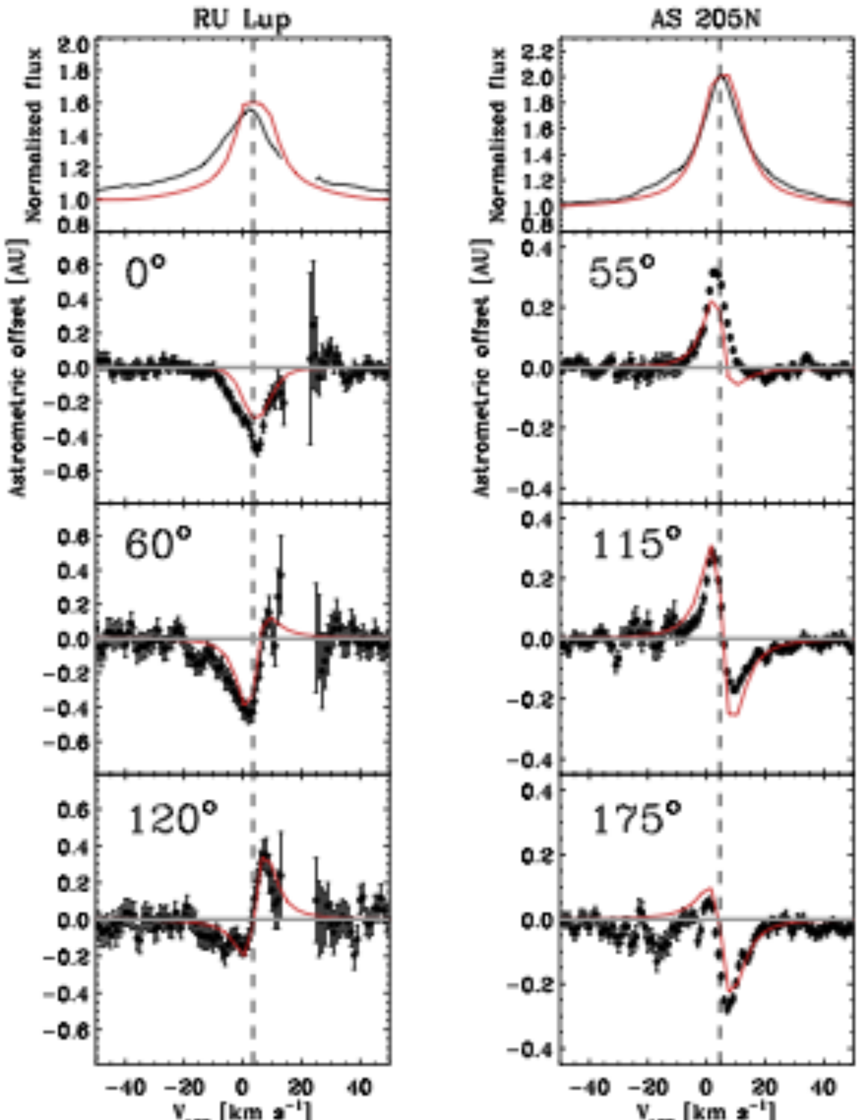
Bast et al. 2011

Since double-peak separation is set by outer radius of emission, models might predict radially extended emission. But emission is actually compact.



2[nd] moment (width) of spatial profile. Extended emission would show up as a peak near v=0.

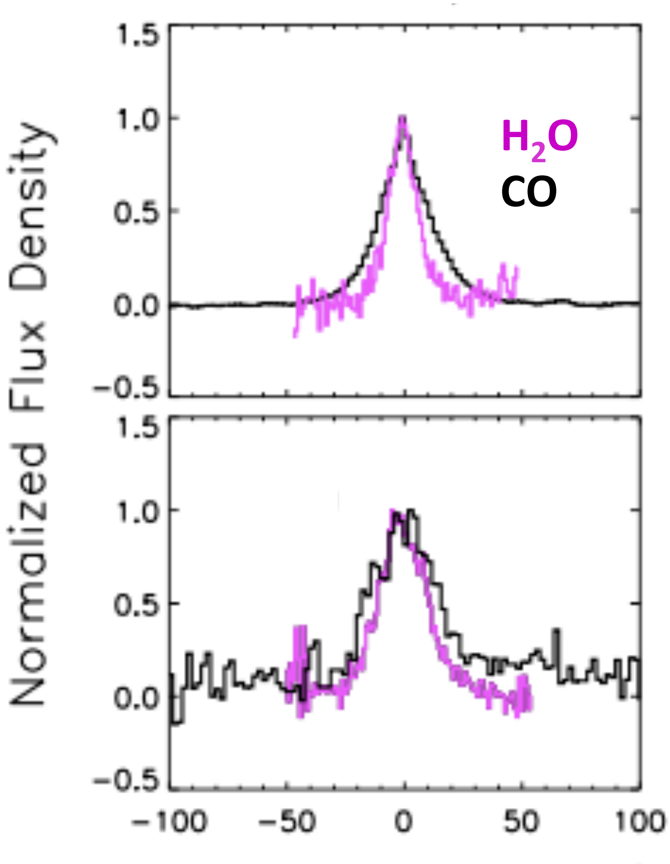
Spectro-astrometric profiles are also asymmetric (suggesting non-Keplerian motion)



Pontoppidan et al. 2011

What else do we know about this odd subclass of disks?

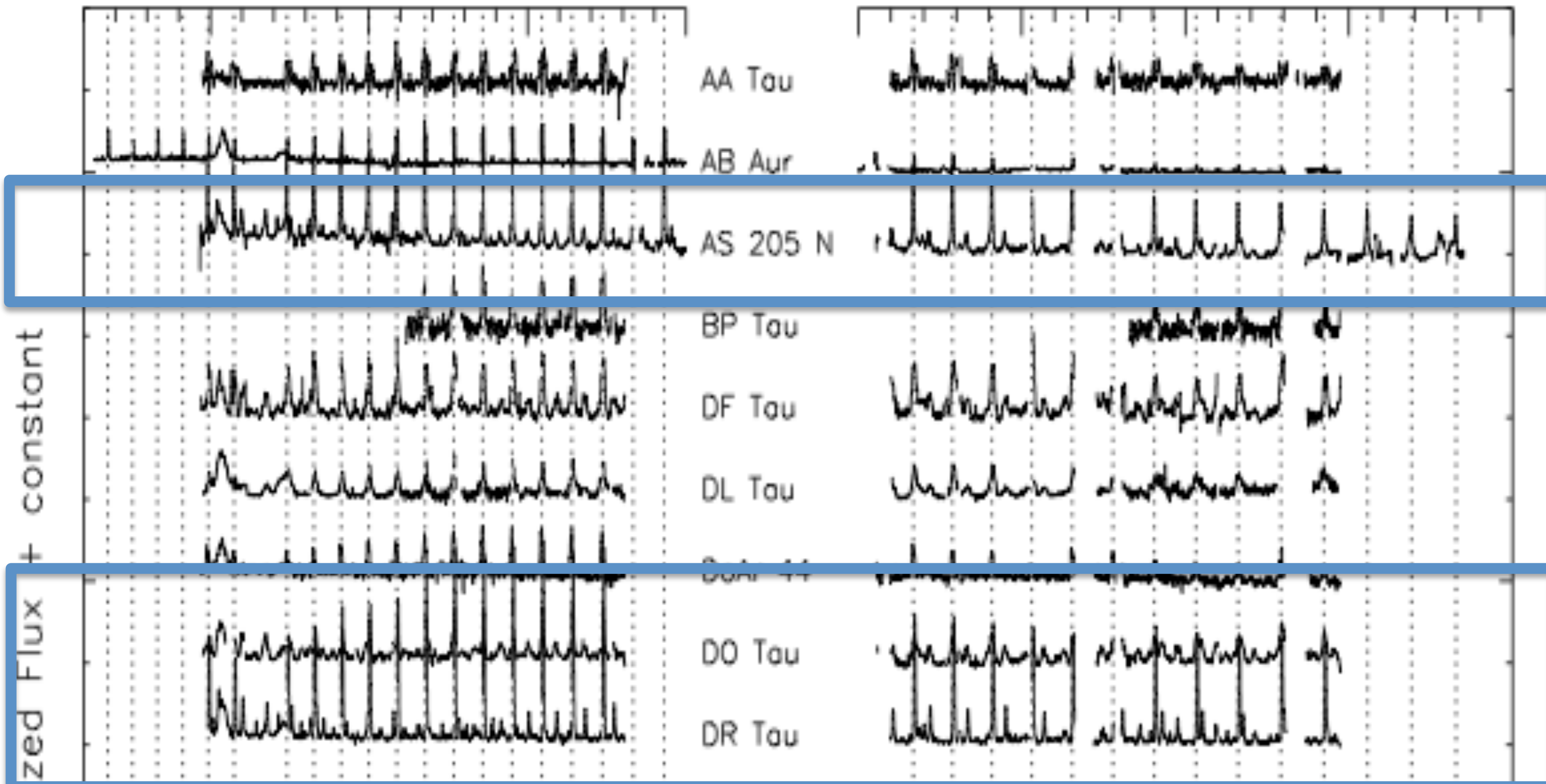
Water lineshapes are also “peaky”



Velocity [km/s]

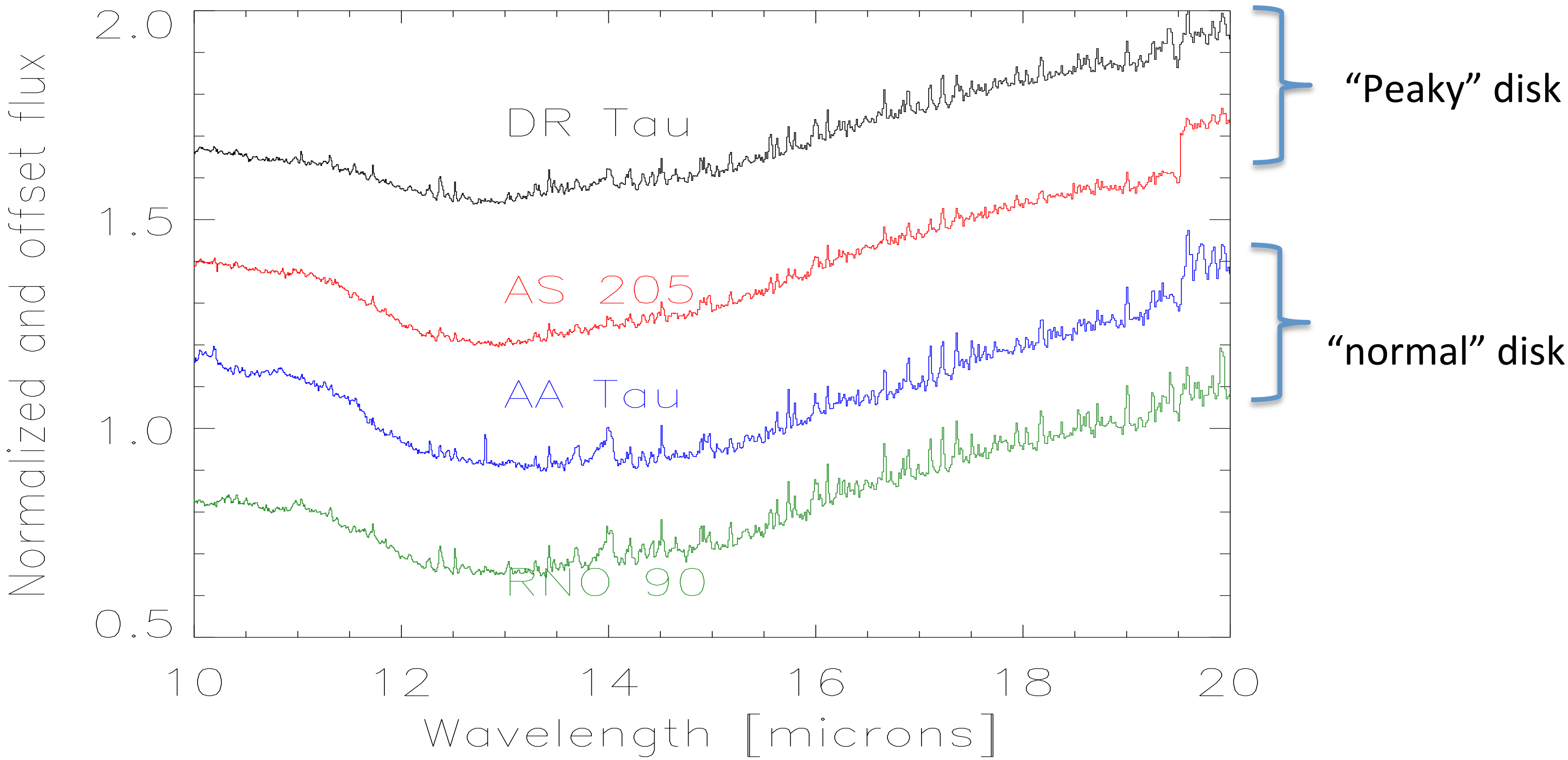
H_2O spectra from TEXES on Gemini,
Salyk et al. work in progress

Near-IR line/continuum ratios are especially high, suggestive of extra gas heating



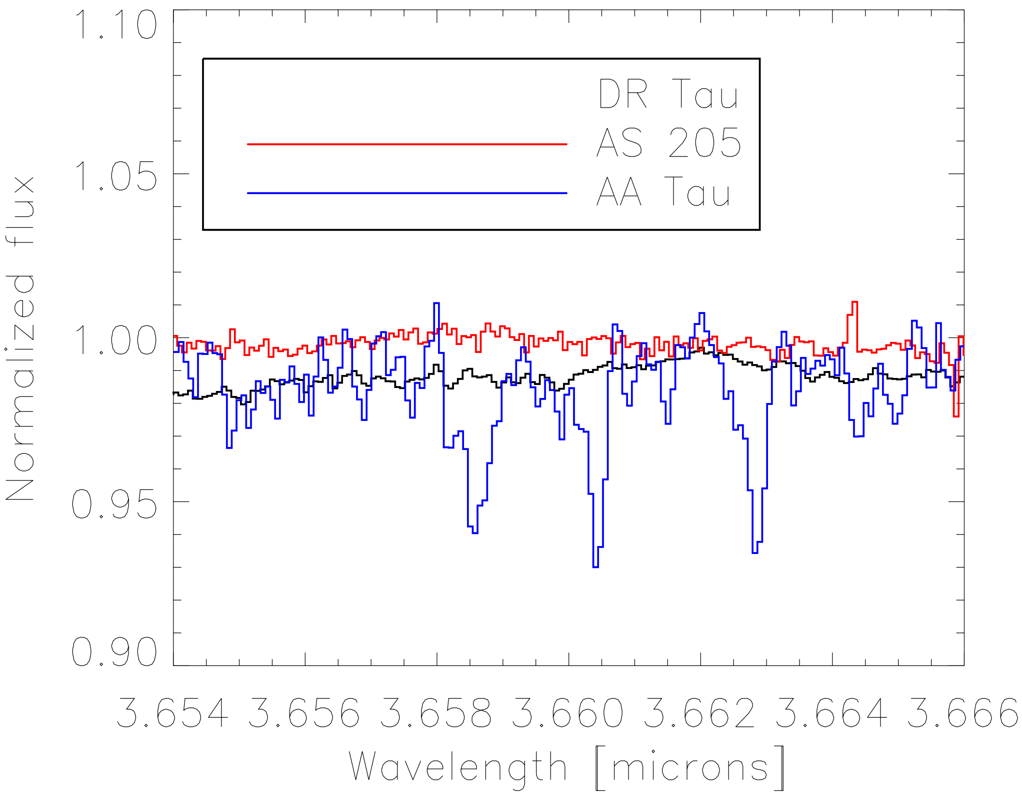
Wavelength [microns]

Not true for mid-IR – perhaps an inner disk phenomenon only?



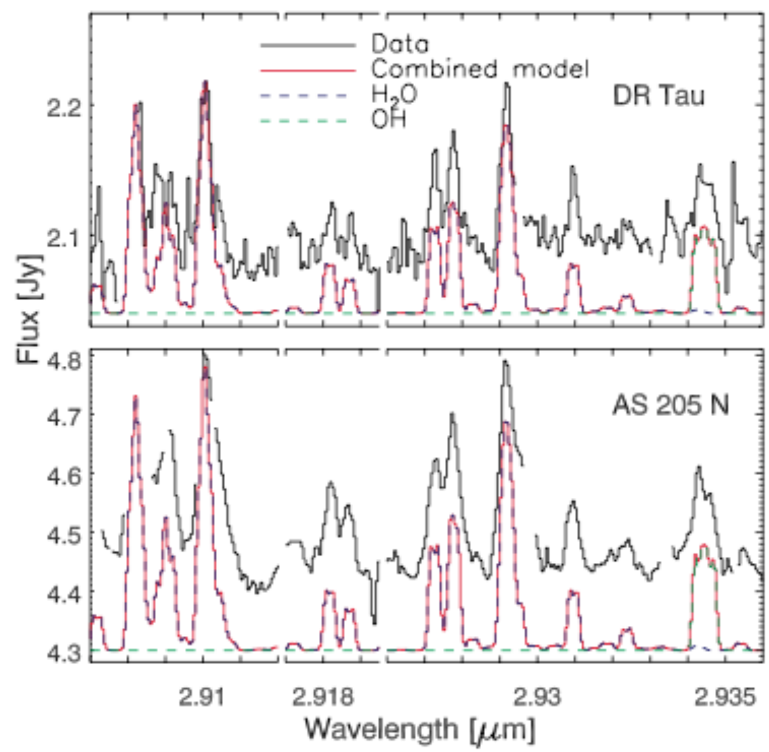
Near-IR veiling is high

Comparison of “peaky” and one other disk



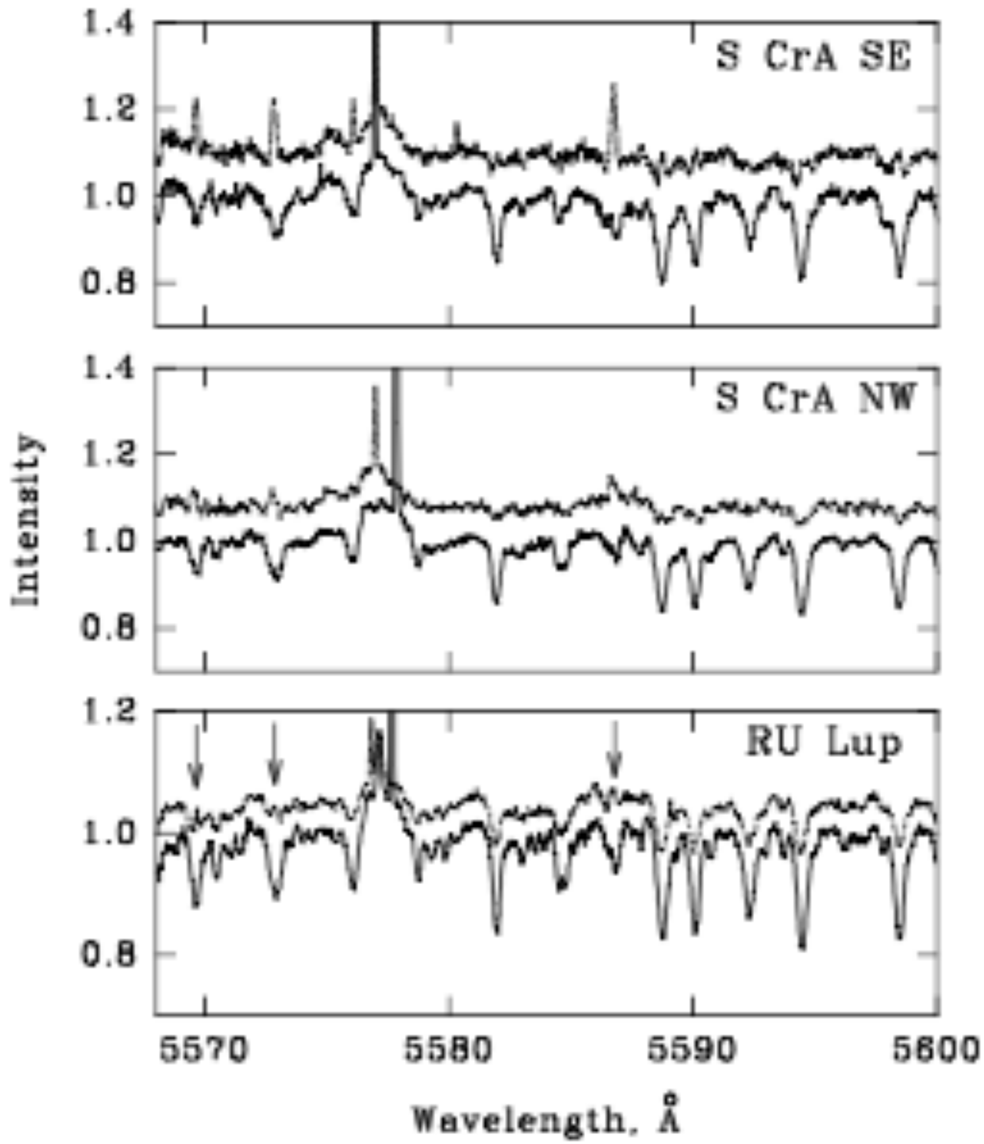
NIRSPEC data

L-band water and OH: 2 “peaky” sources



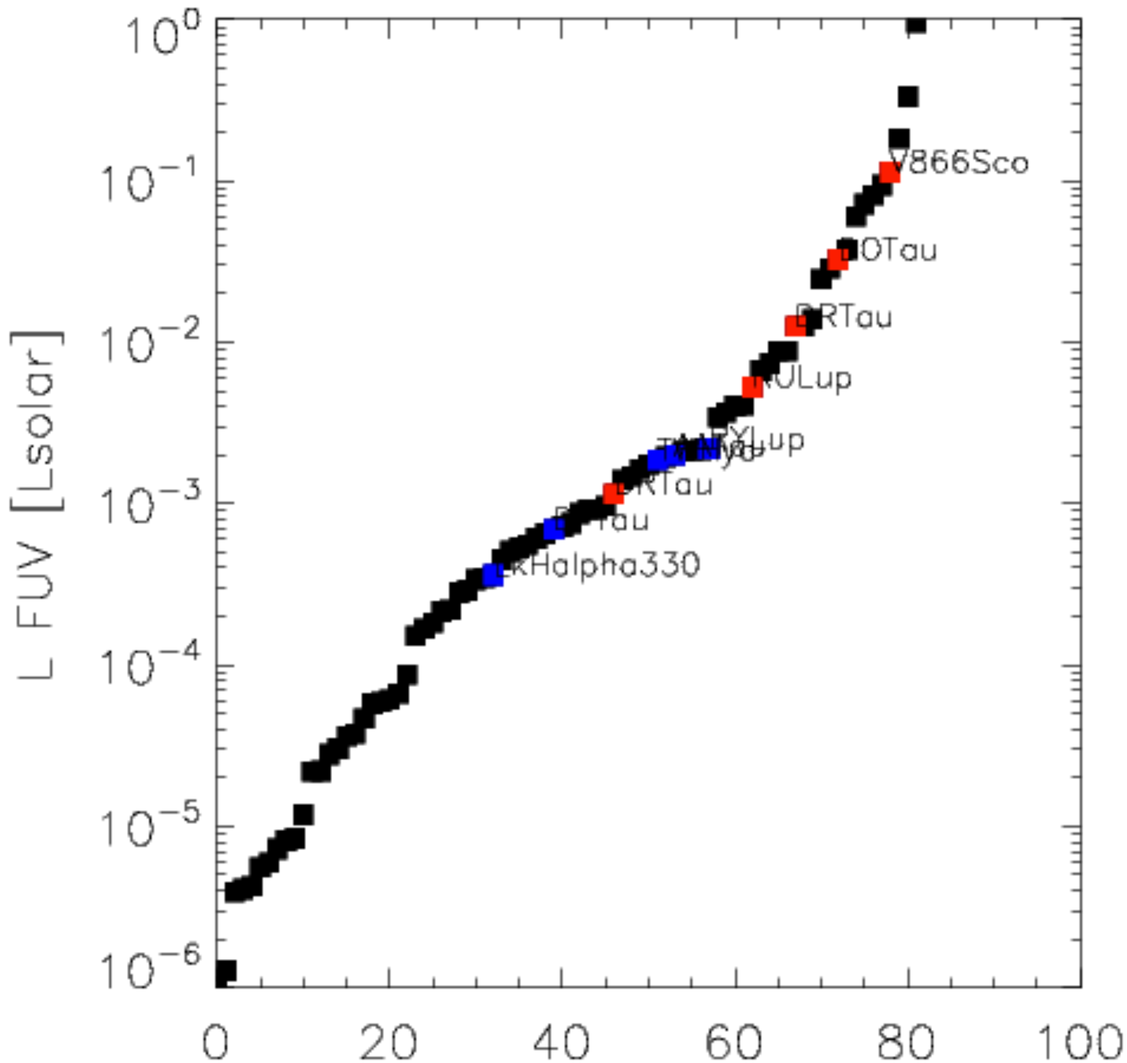
Salyk et al. 2008

Optical veiling is high and highly variable



Gahm et al. 2008

FUV luminosities may be higher than average



Ordered Index

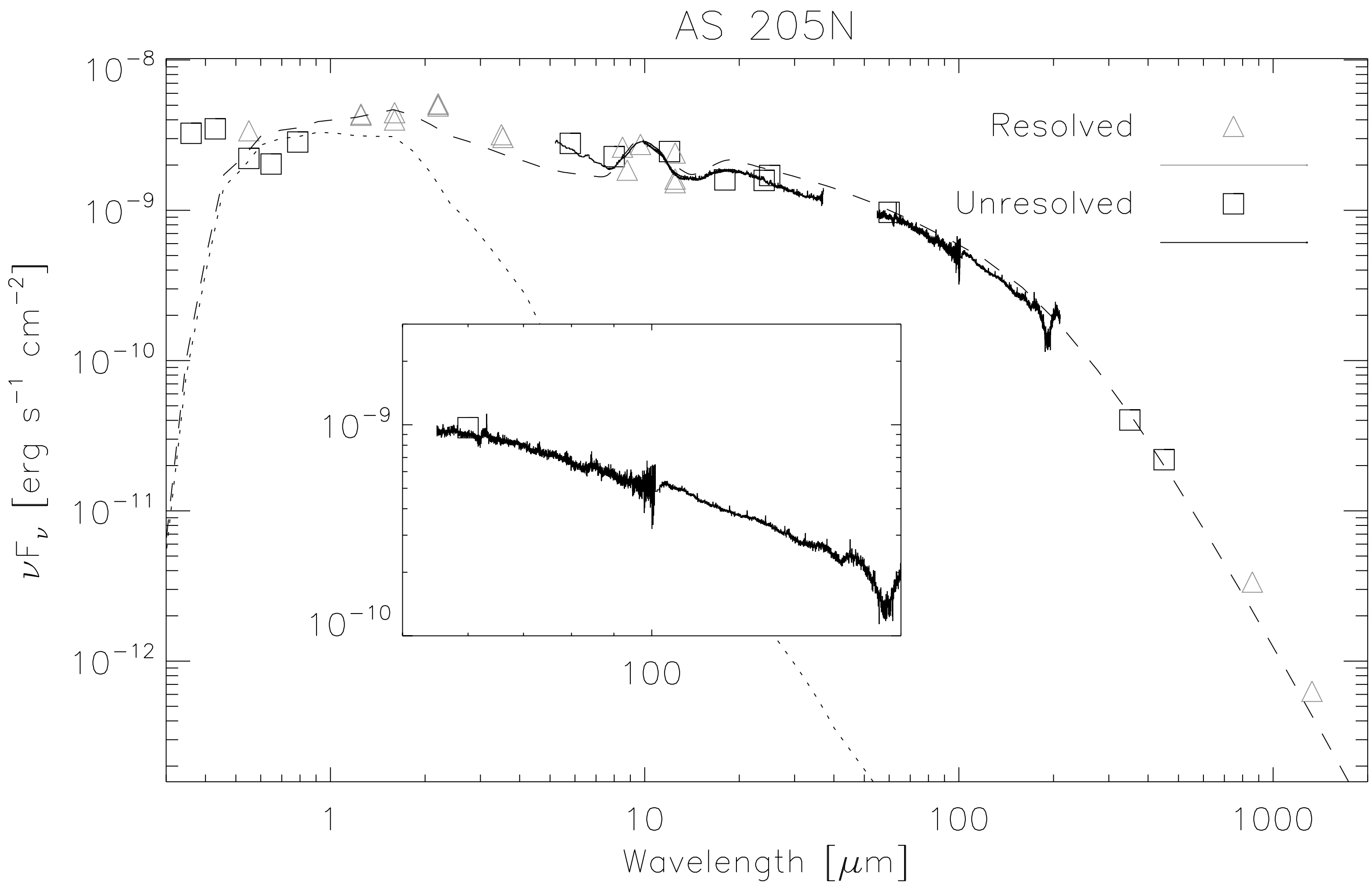
FUV

Red=disk wind

Blue=other

Luminosities from
Yang et al. 2012

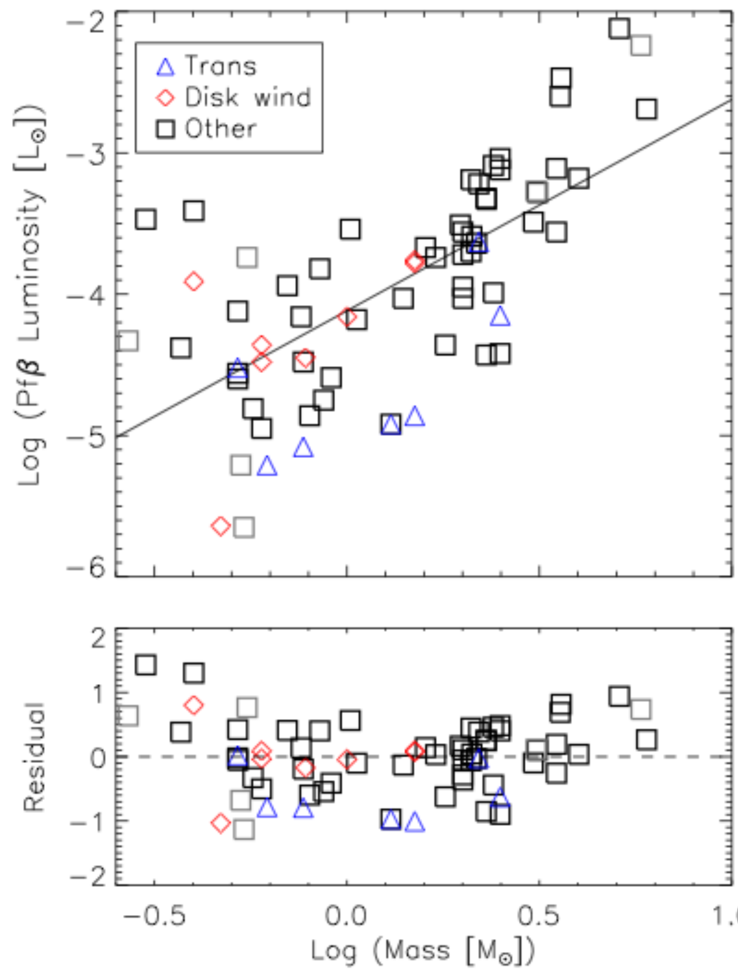
Passive disk models may under-predict near-IR flux



Accretion rates *may* be higher than average… but perhaps not if stellar mass is accounted for

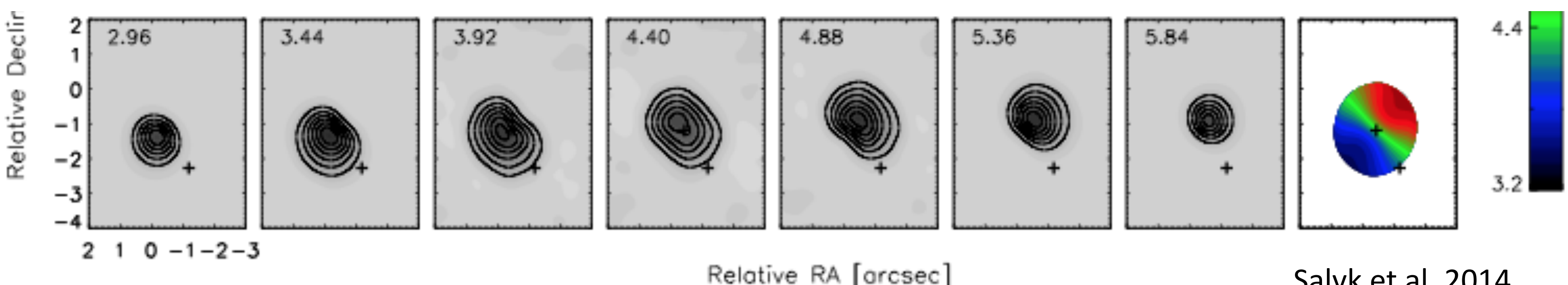
"The average accretion luminosity for those [peaky sources]… is 0.5 L☉. This value is higher than the average accretion luminosity of 0.1 L☉ which is calculated for the rest of the sample of disks"

Bast et al. 2011



Salyk et al. 2013

ALMA observations of only one source so far

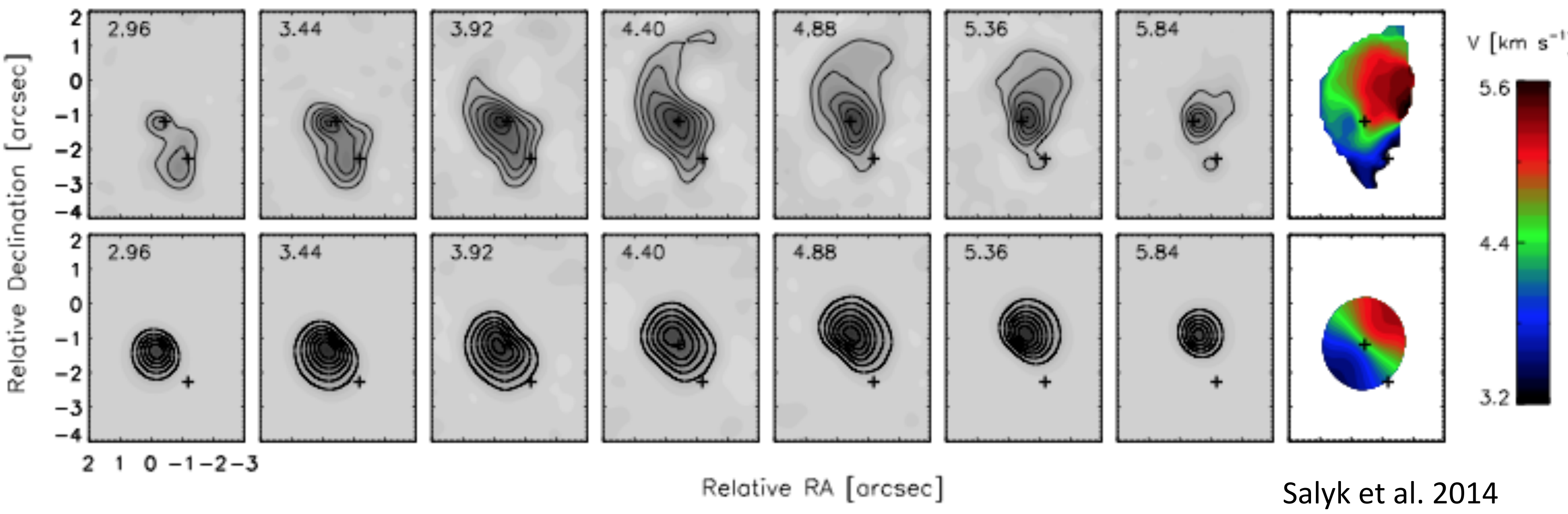


Salyk et al. 2014

Model channel map shows expectation for pure Keplerian disk

ALMA observations of this disk are… strange ^{12}CO shows significant extended, asymmetric emission

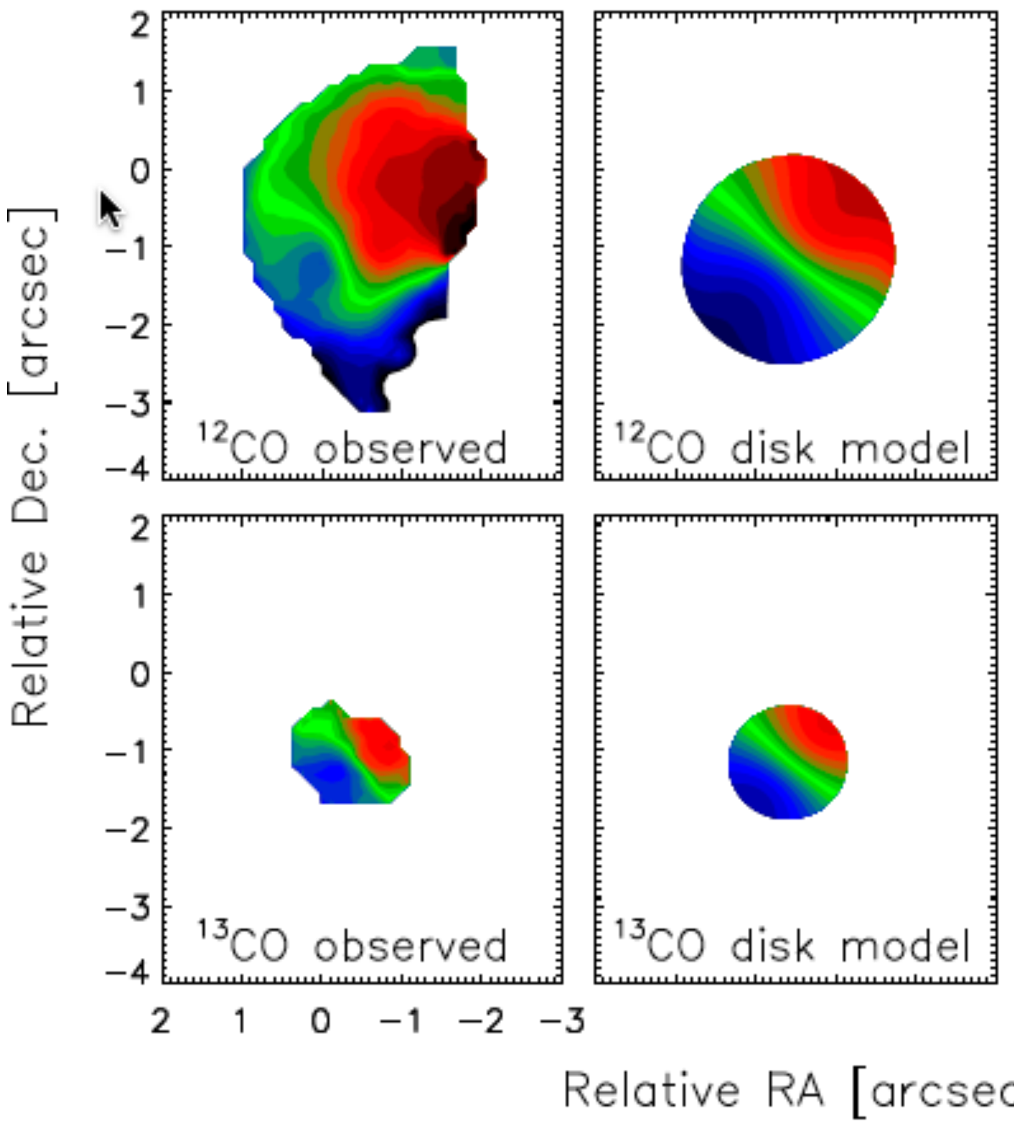
Top: Observed ^{12}CO channel map



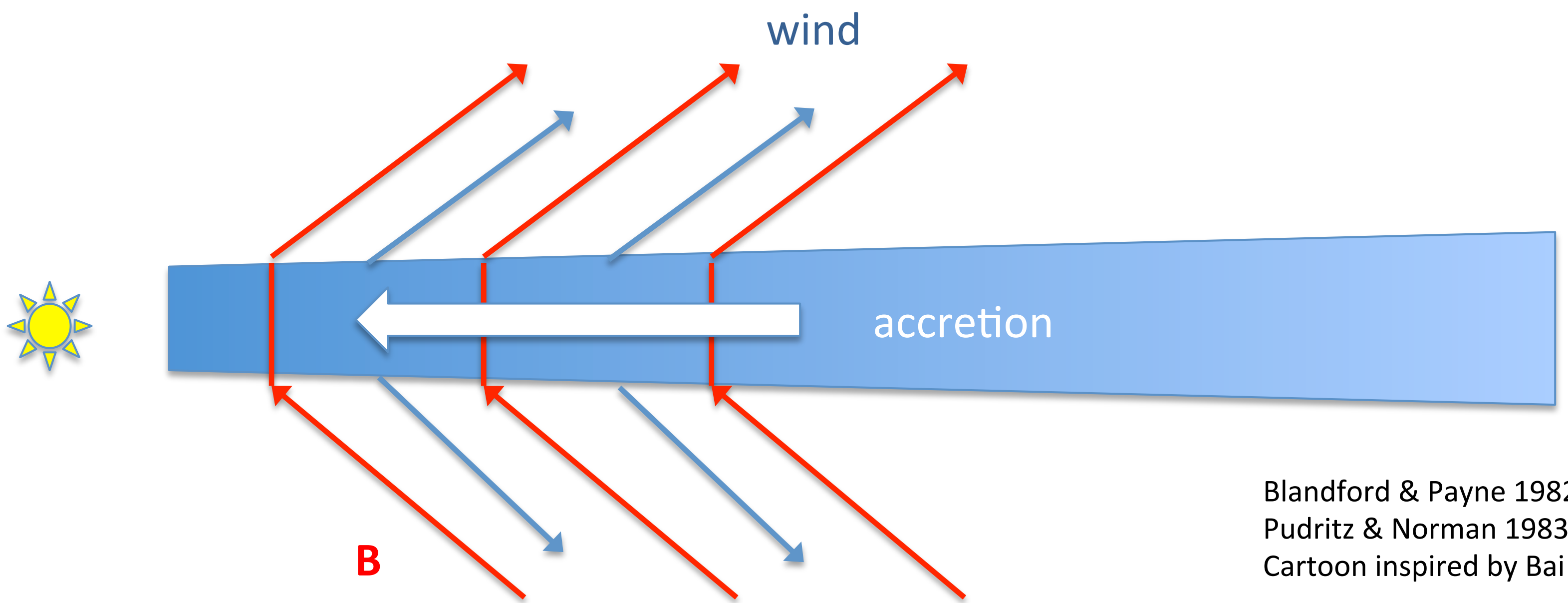
Salyk et al. 2014

Bottom: Model channel map shows expectation for pure Keplerian disk

And both 12CO and 13CO velocity fields are warped



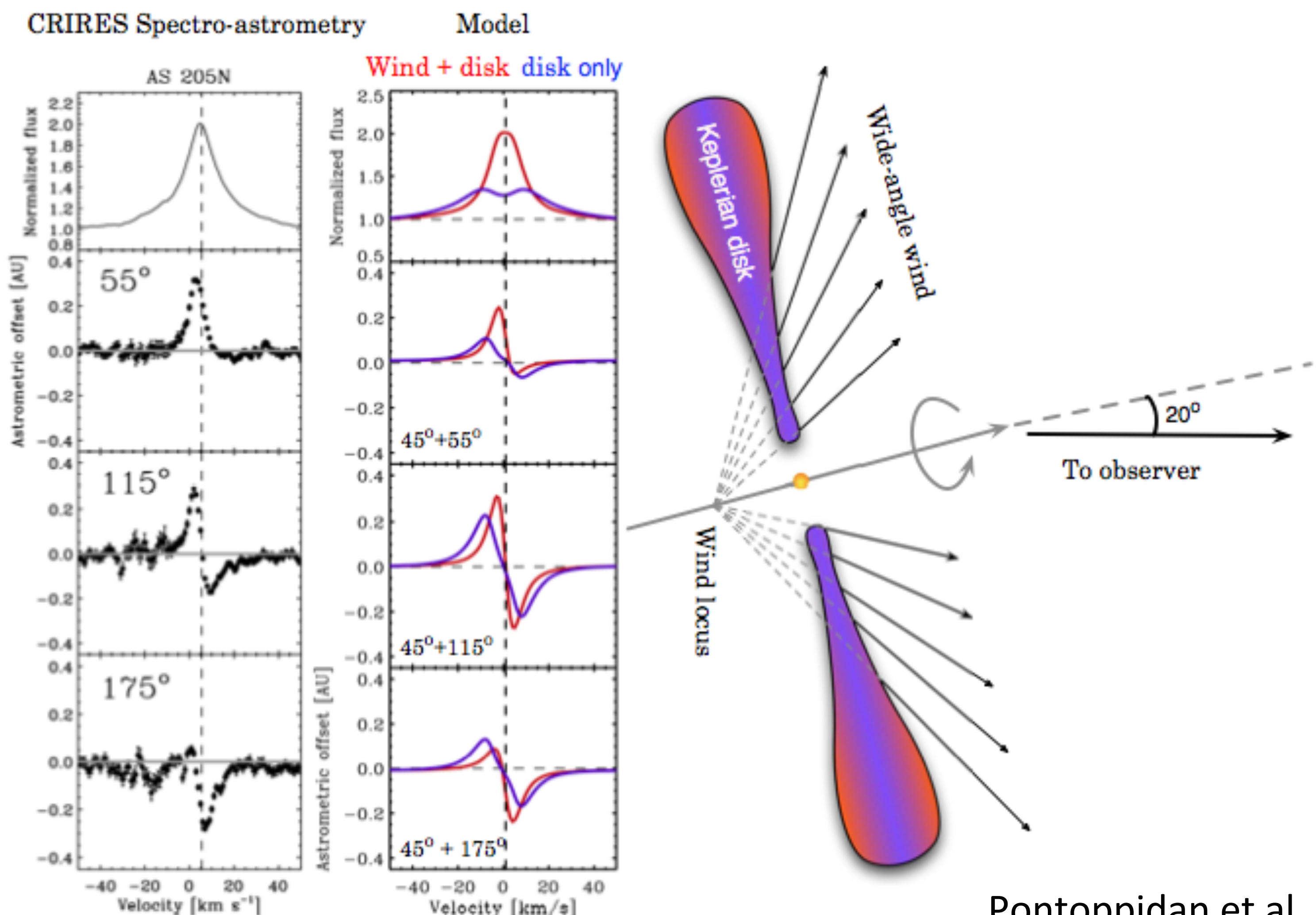
Proposed solution – disk wind?



Blandford & Payne 1982
Pudritz & Norman 1983
Cartoon inspired by Bai et al. 2013

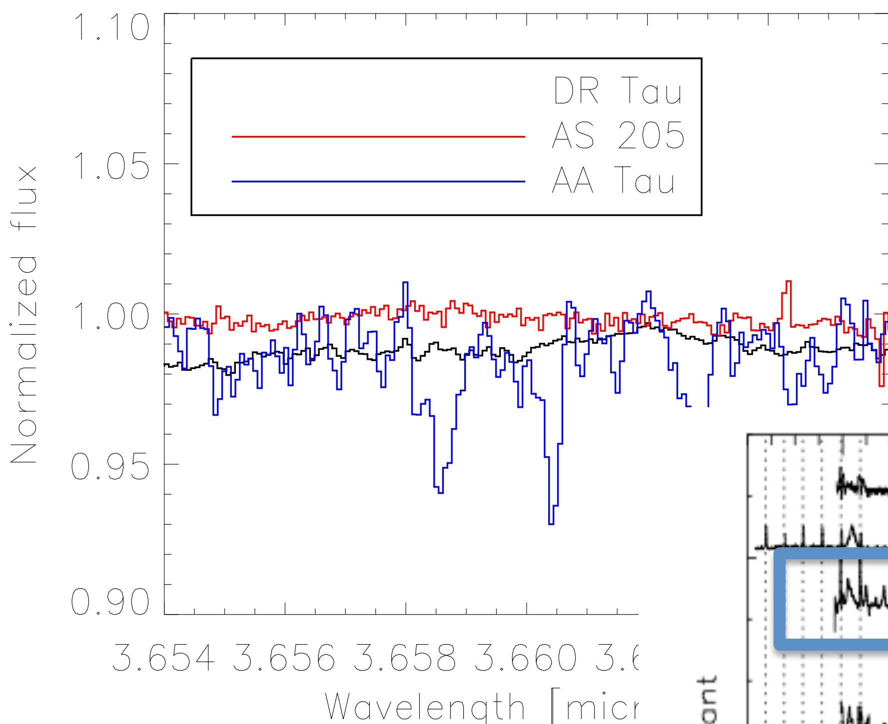
Proposed solution – disk wind?
Pros and cons

Pro: A slow disk wind can produce "peaky" line profiles and asymmetric spectro-astrometric curves



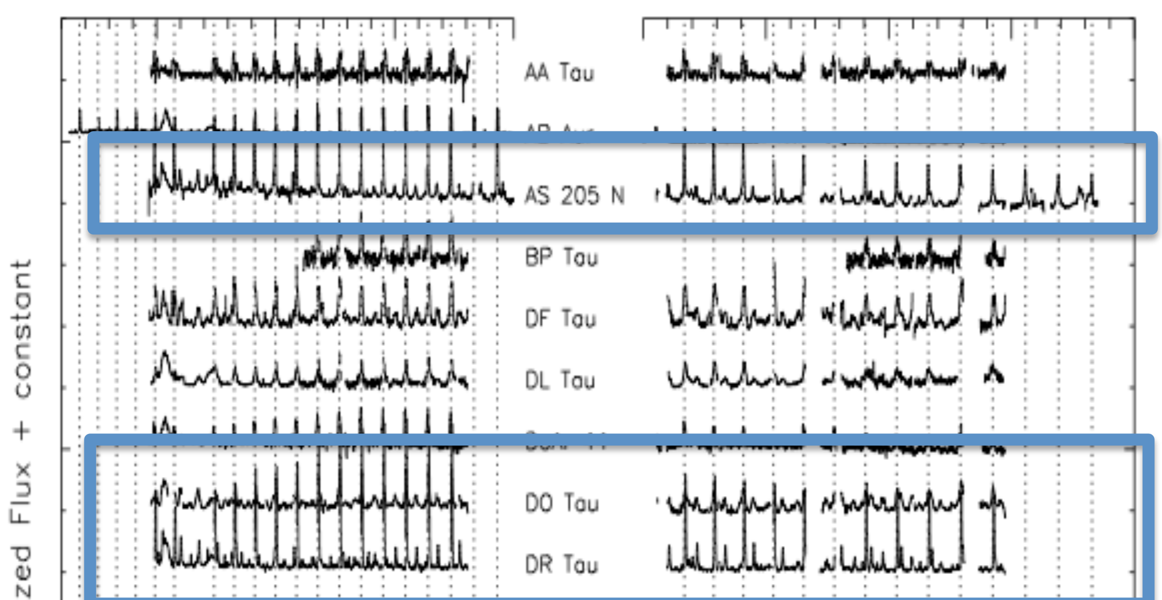
Pontoppidan et al. 2011

Pro: A disk wind might be correlated with more accretion, inner disk heating



High veiling

High line/continuum ratios



Con: best-fit parameters of wind model not physically motivated

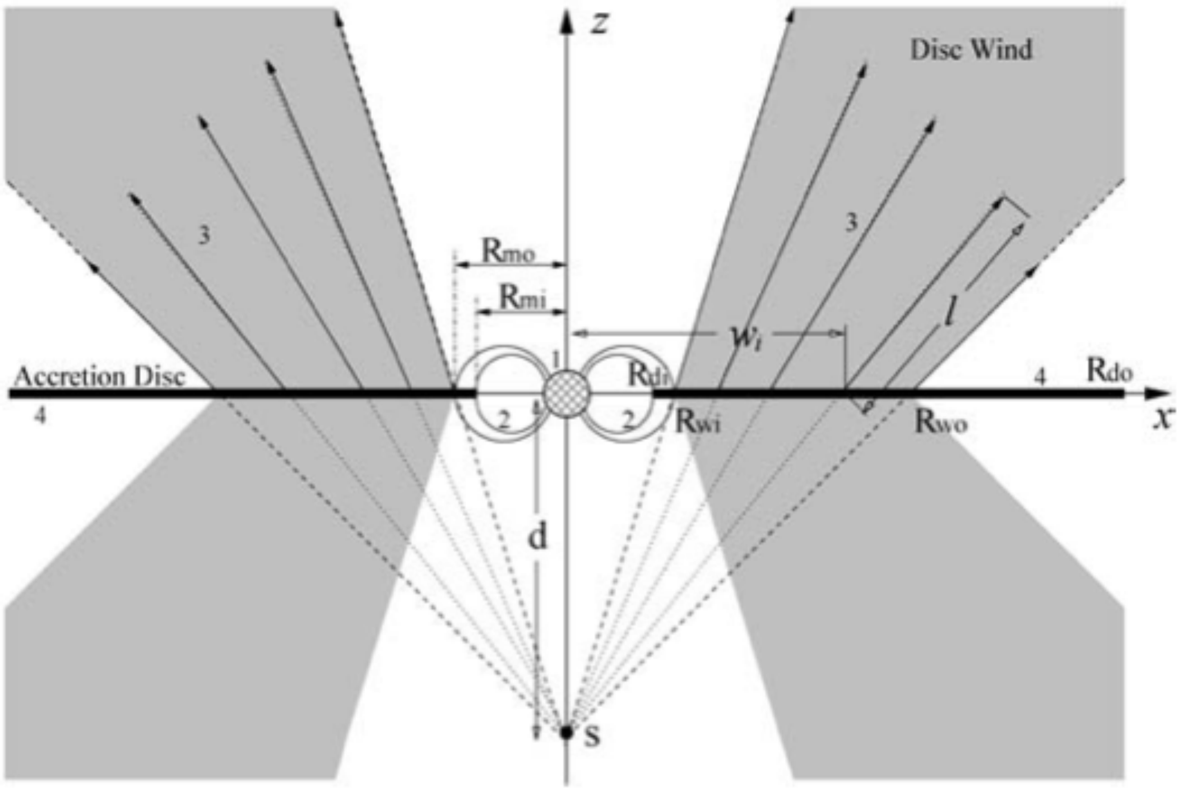
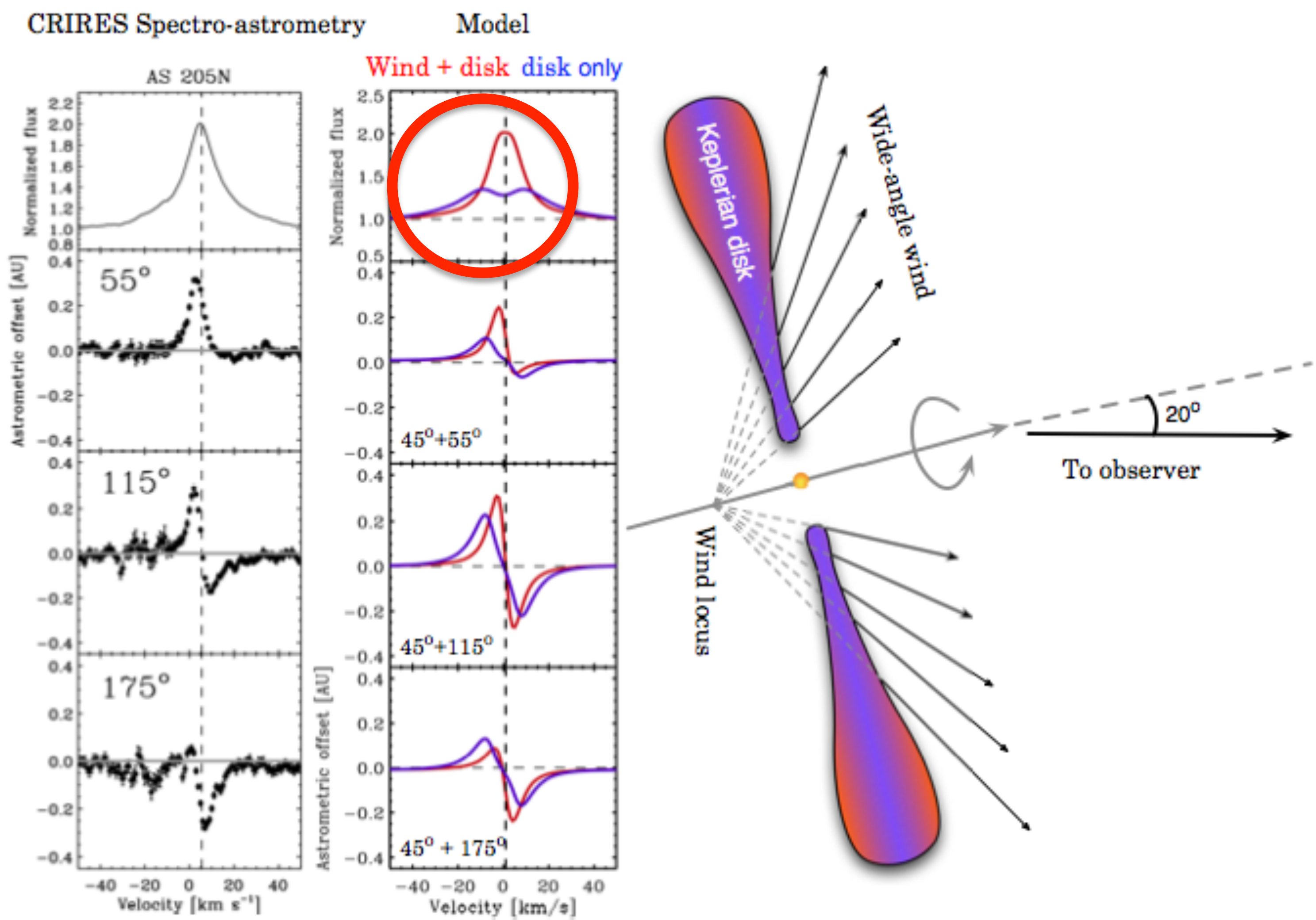


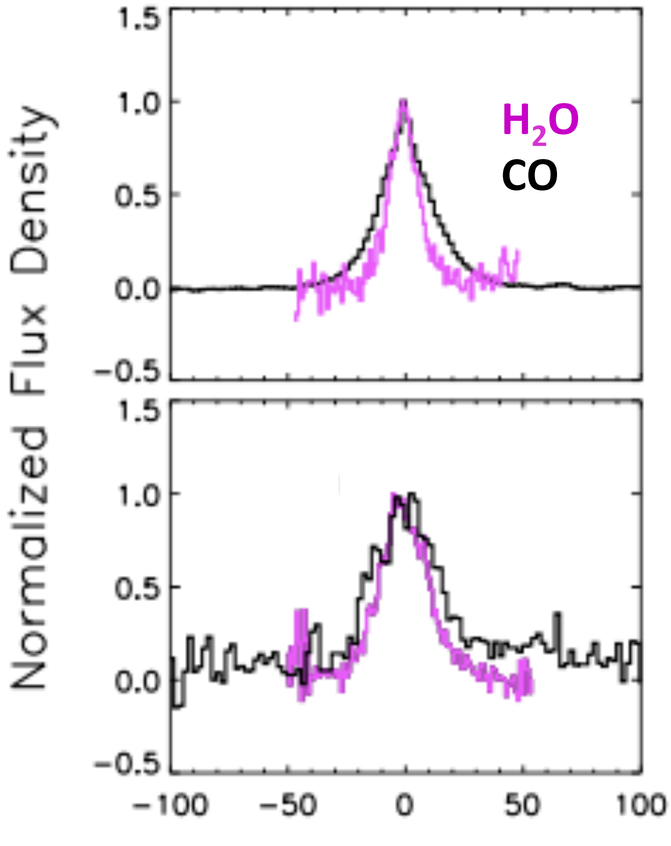
Figure 1. Basic model configuration of the disc-wind-magnetosphere hybrid model. The system consist of four components: (1) the continuum source located at the origin of the cartesian coordinates (x, y, z) – the y-axis is into the paper, (2) the MA flow, (3) the disc wind and (4) the accretion disc. The disc wind originates from the disc surface between $w_i = R_{wi}$ and $w_i = R_{wo}$ where w_i is the distance from the z-axis on the equatorial plane. The wind source points (S), from which the stream lines diverge, are placed at distance d above and below the star. The degree of wind collimation is controlled by changing the value of d.

Kurosawa et al. 2006
"Split-monopole" originally from Knigge, Woods & Drew 1995

Con: Required velocities lower than predicted by wind models/theory



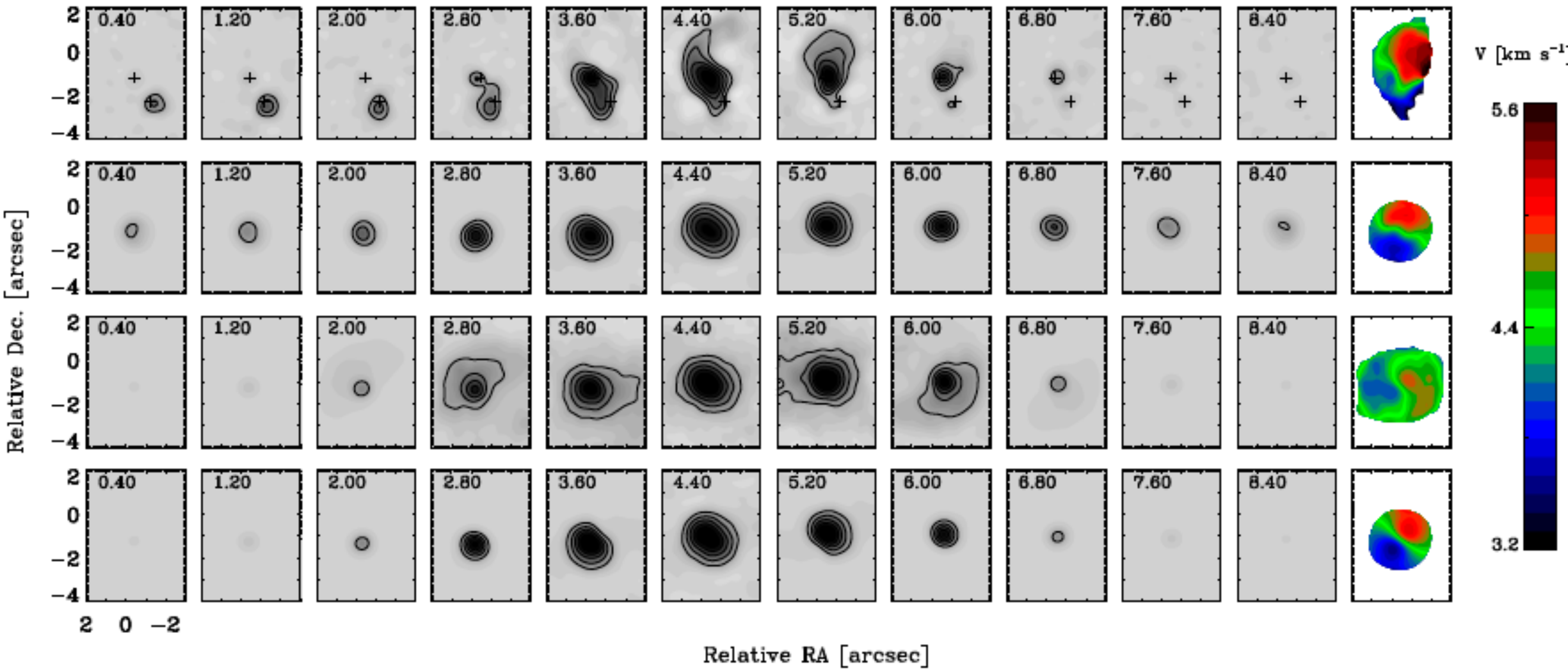
Con: It's not obvious if/how molecules (especially tenuous H_2O) would survive in winds



Velocity [km/s]

H_2O spectra from TEXES on Gemini, Salyk et al. work in progress

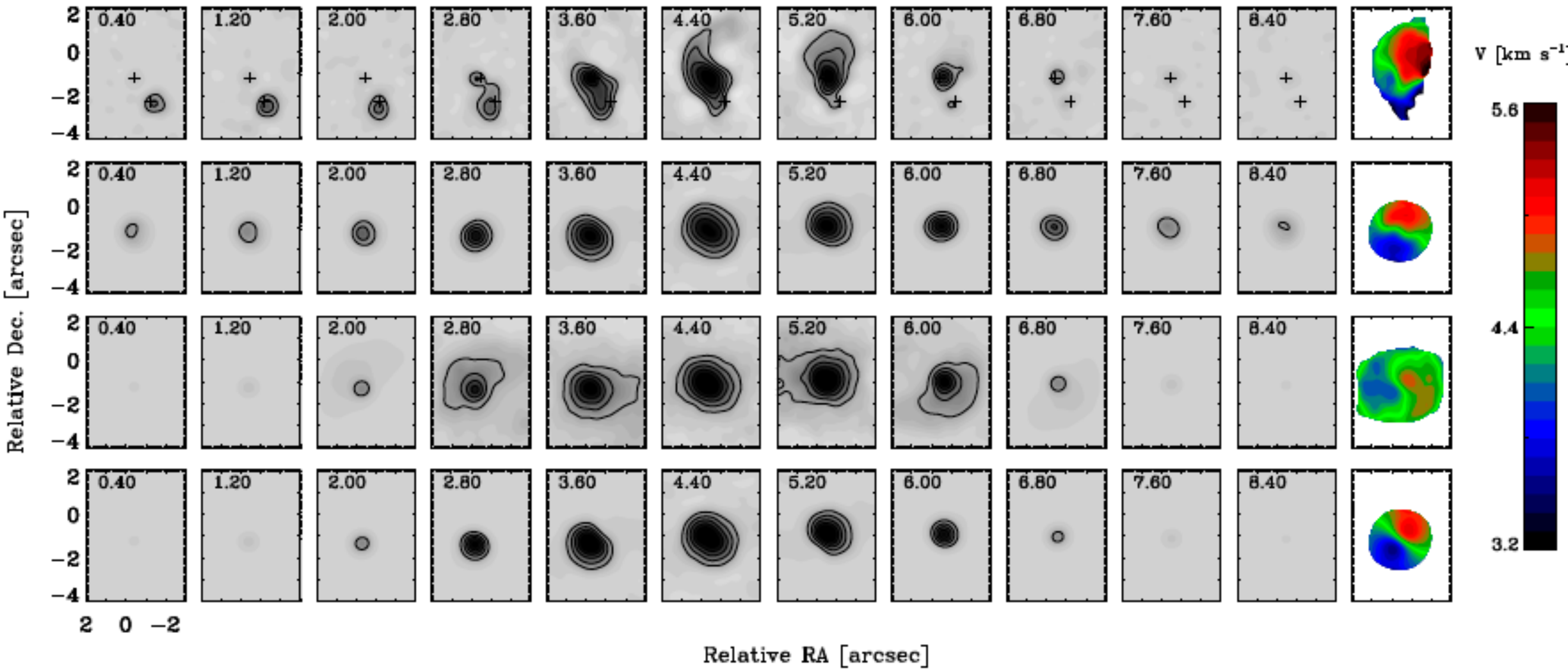
Pro: Warped velocity fields can (sort of) be reproduced with wind models



Salyk et al. 2014

(middle two are disk+wind models)

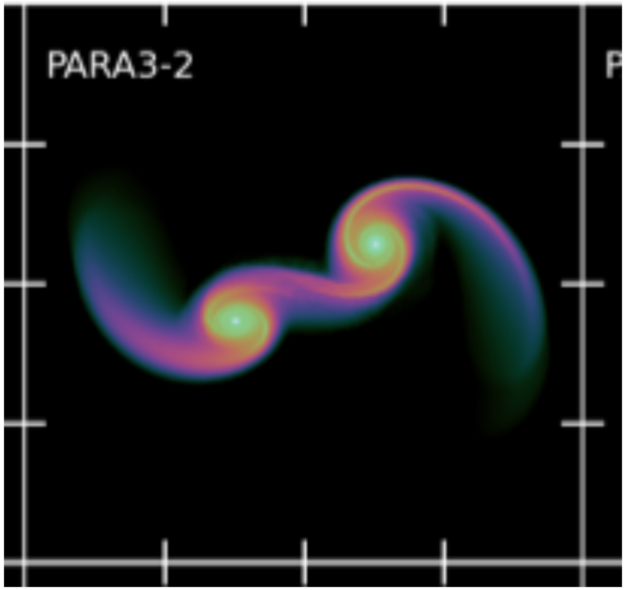
Con: Wind model parameters must be highly "tuned" to fit data



Salyk et al. 2014

(middle two are disk+wind models)

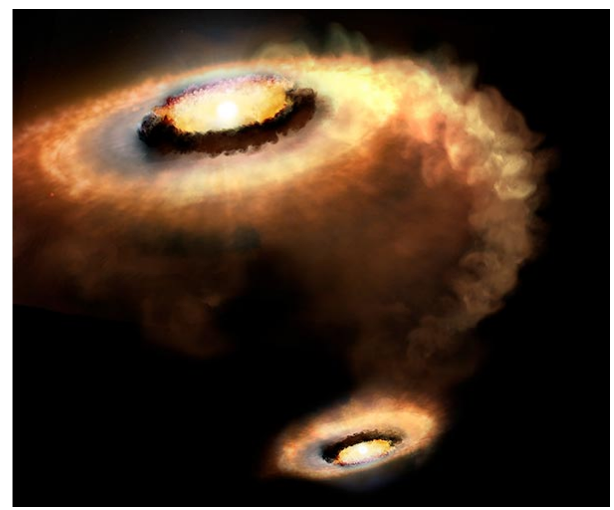
Con: ALMA target AS 205 is also a binary, which could complicate things



Simulations

D. Muñoz, PhD thesis

Artist's rendition



P. Marenfeld

Where do we go from here?

More ALMA data of these disks would determine whether AS 205 N is an exception (wish me luck with ALMA TAC!)

H_2O emission should be modeled more carefully to confirm association with CO phenomenon (work in progress)

We (observers) hope that modelers consider these observational constraints in their work

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I look forward to this week's discussions!