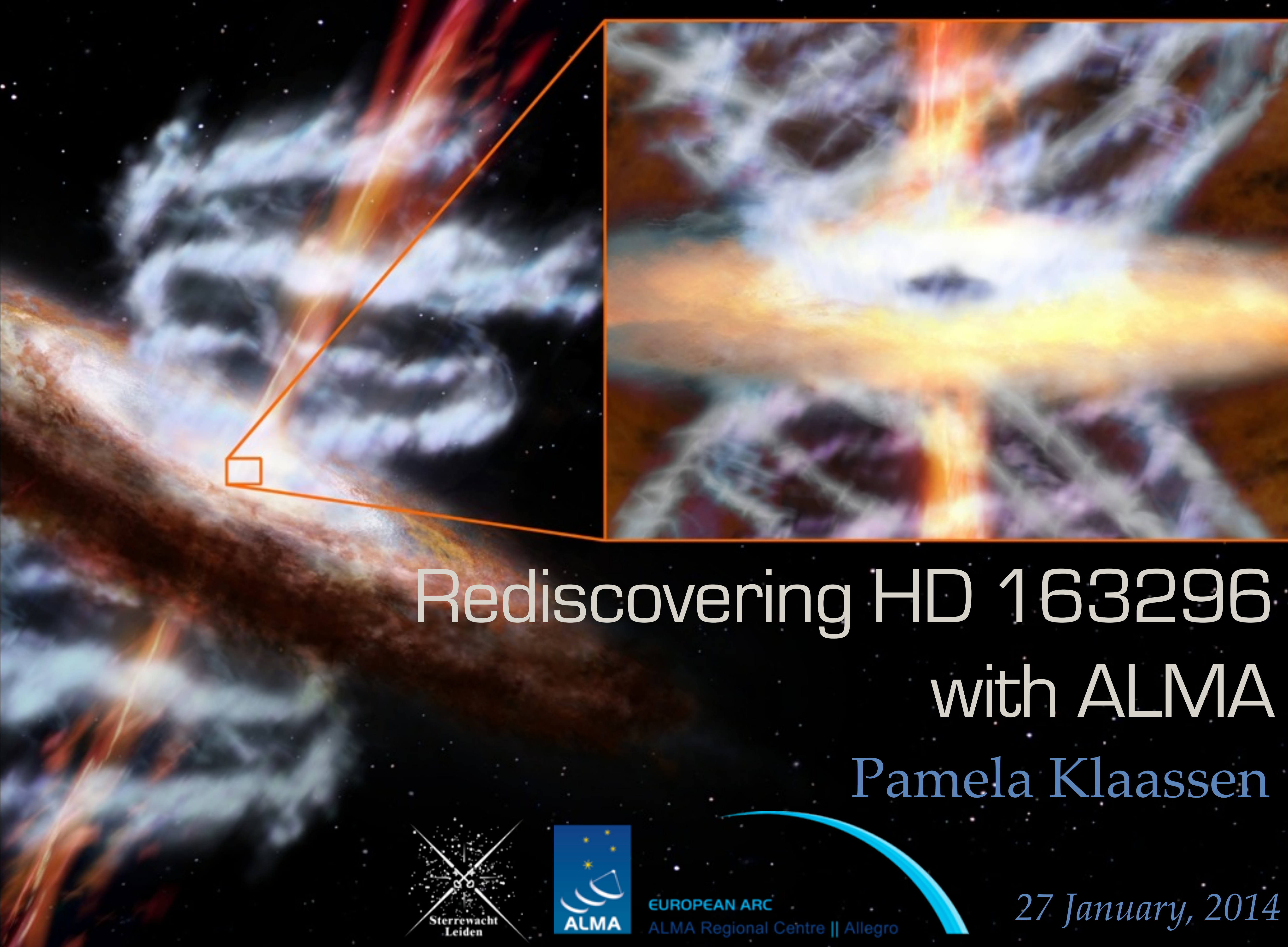

ESA/AOES Medialab

Rediscovering HD 163296 with ALMA

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Sterrewacht Leiden

ALMA

EUROPEAN ARC

ALMA Regional Centre || Allegro

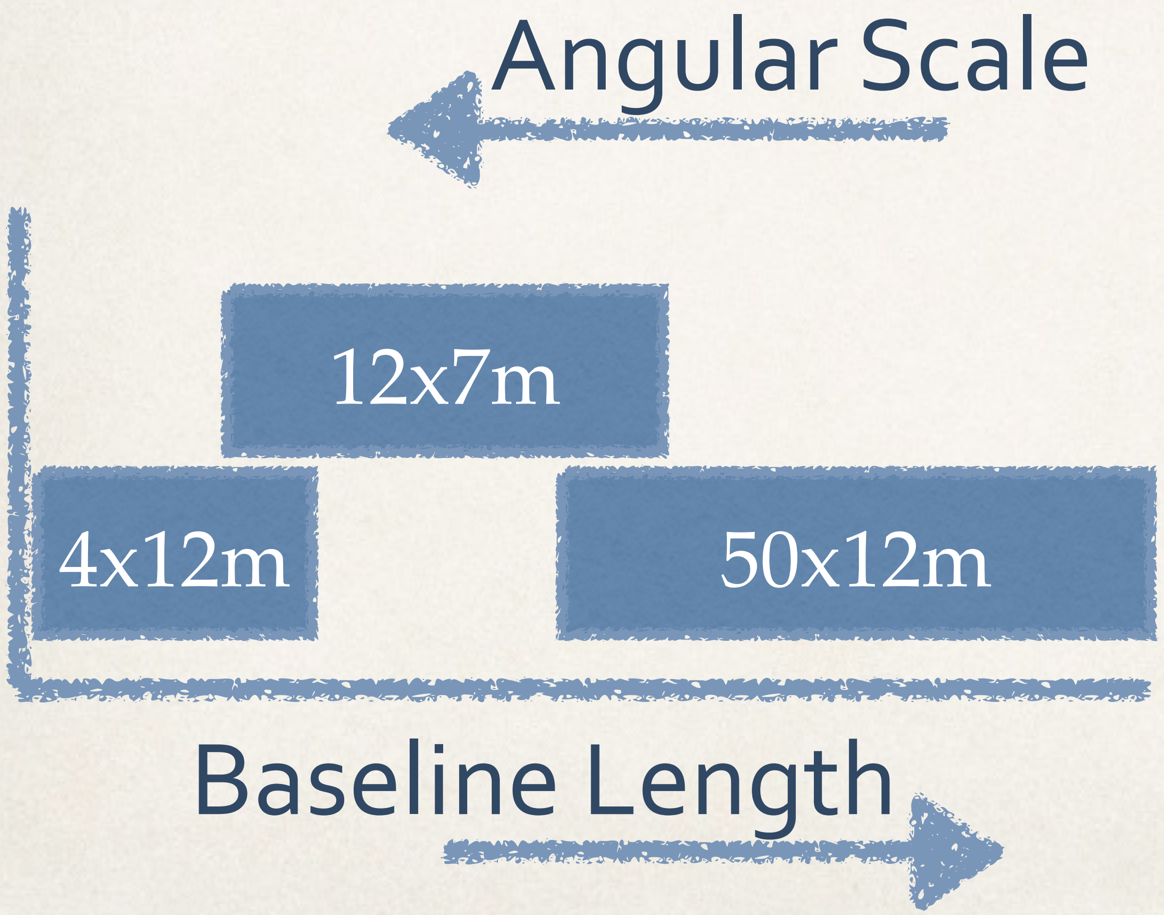
27 January, 2014

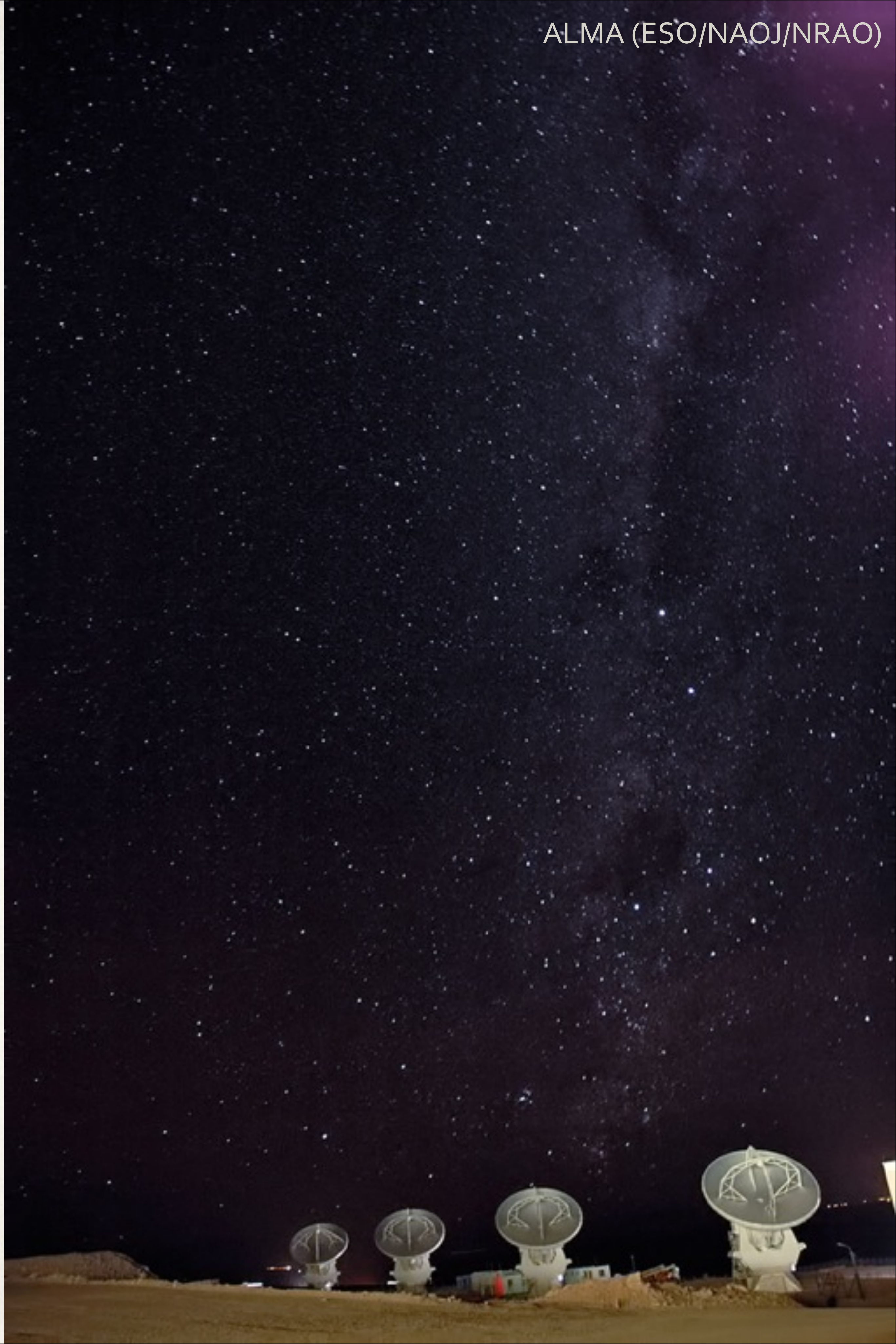
Outline

- ALMA and Science Verification
- The Role of Disks in Star Formation
- Herbig Ae stars and the HD 163296 System
- What we knew before
- What we know now:
    - The vertical structure of the disk
    - The location of the CO snow line
    - The presence of a magnetic disk wind

ALMA

- High (Dry) site in Northern Chile
- 84-720 GHz
- 0 - 16 km baselines (when finished)

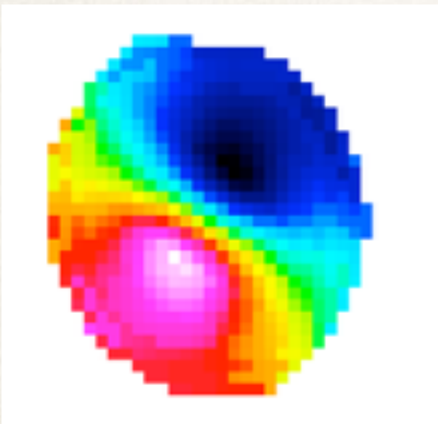




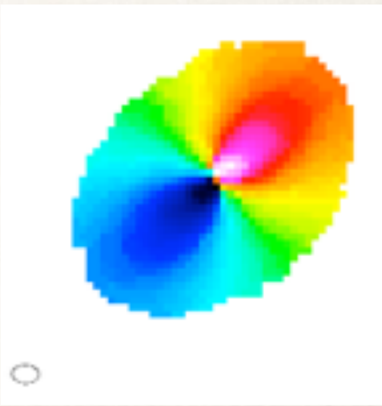
almascience.eso.org/alma-data/science-verification

Science Verification

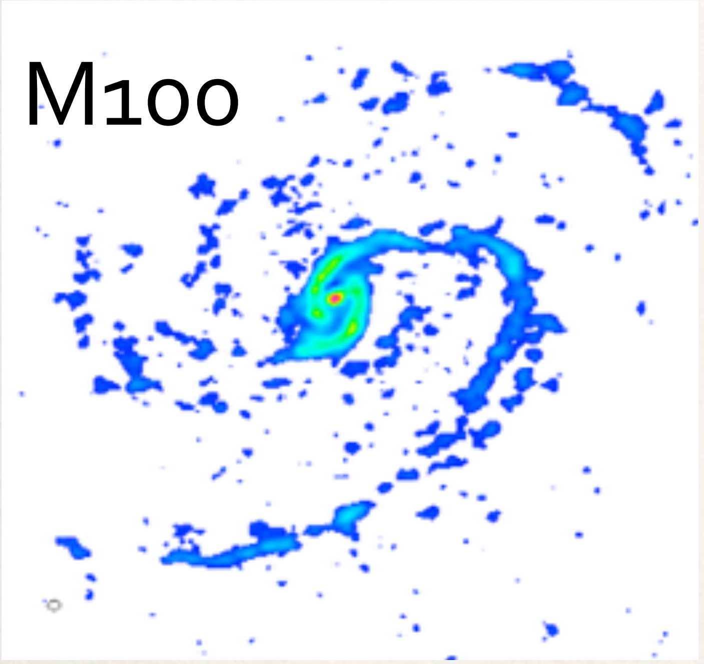
TW Hydra

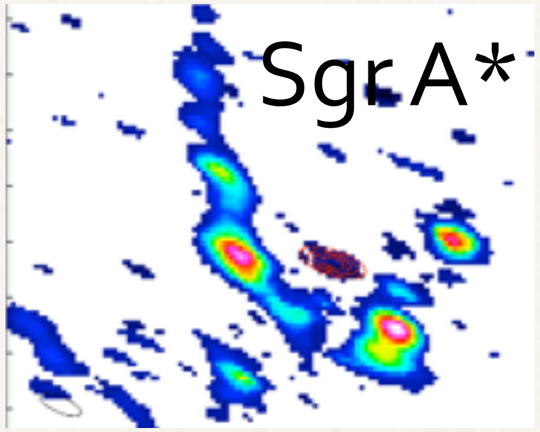


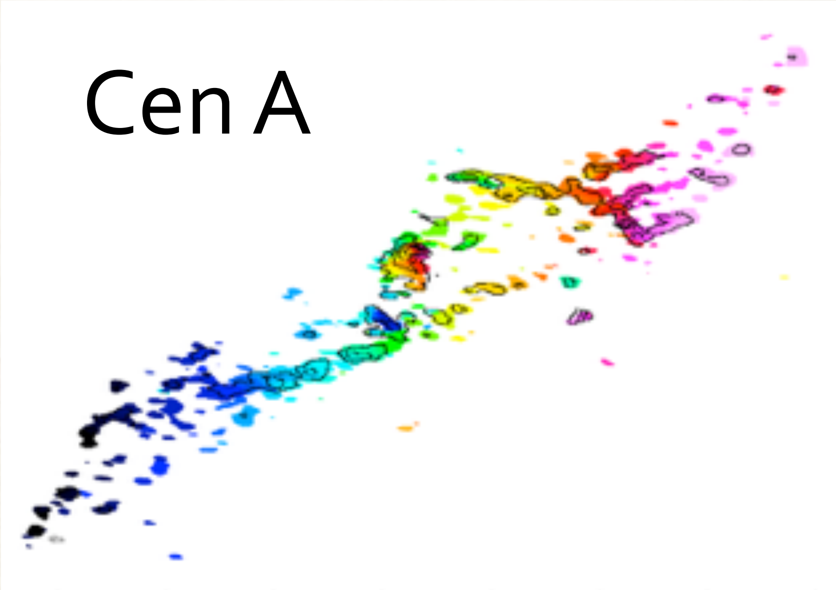
Observations of well studied objects to make sure ALMA is working properly



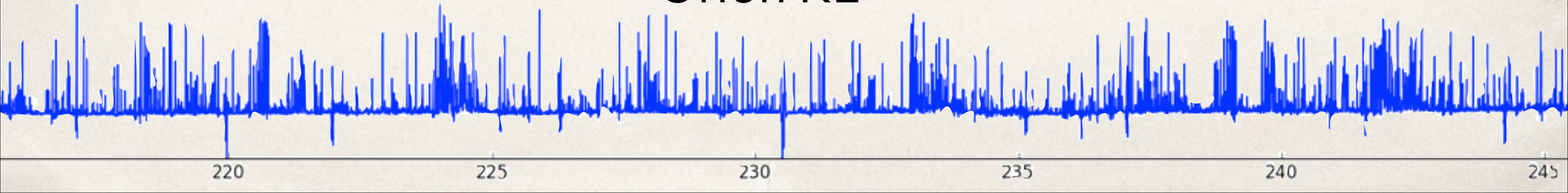
HD 163296





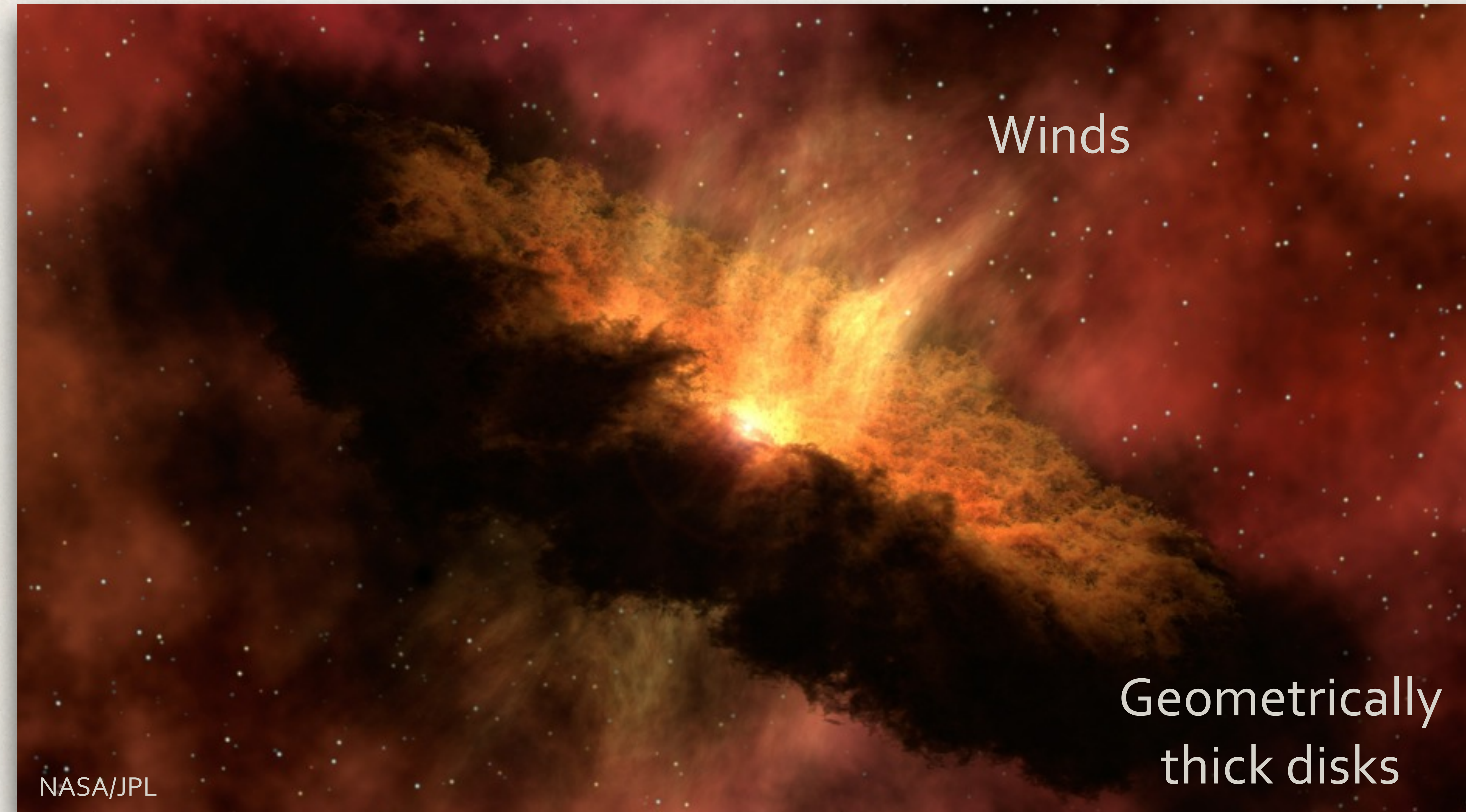


Orion KL




A wind releases angular momentum
An over density begins to collapse

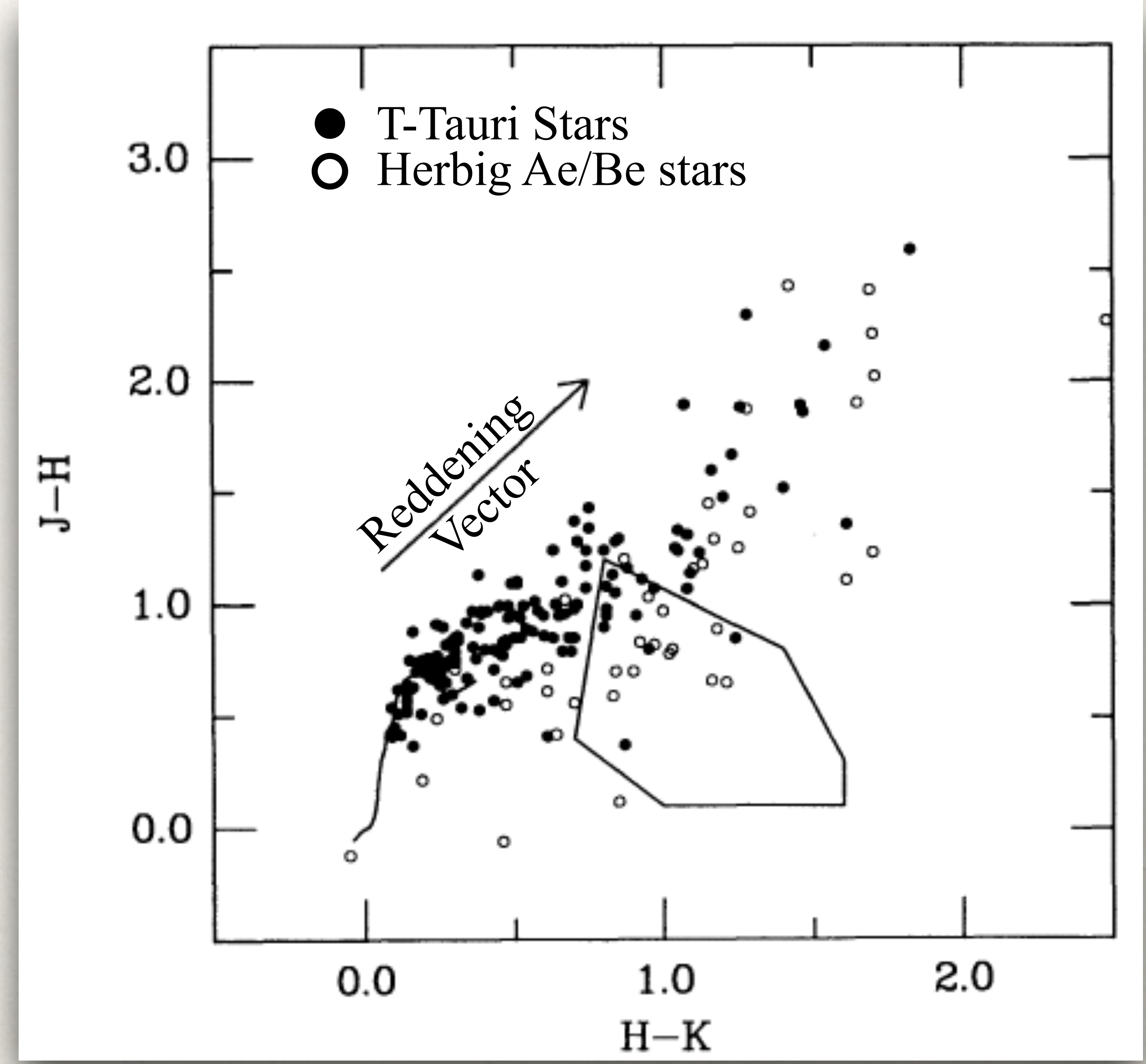
Protostellar Disks



Herbig AeBe stars

Hartmann et al. 1993

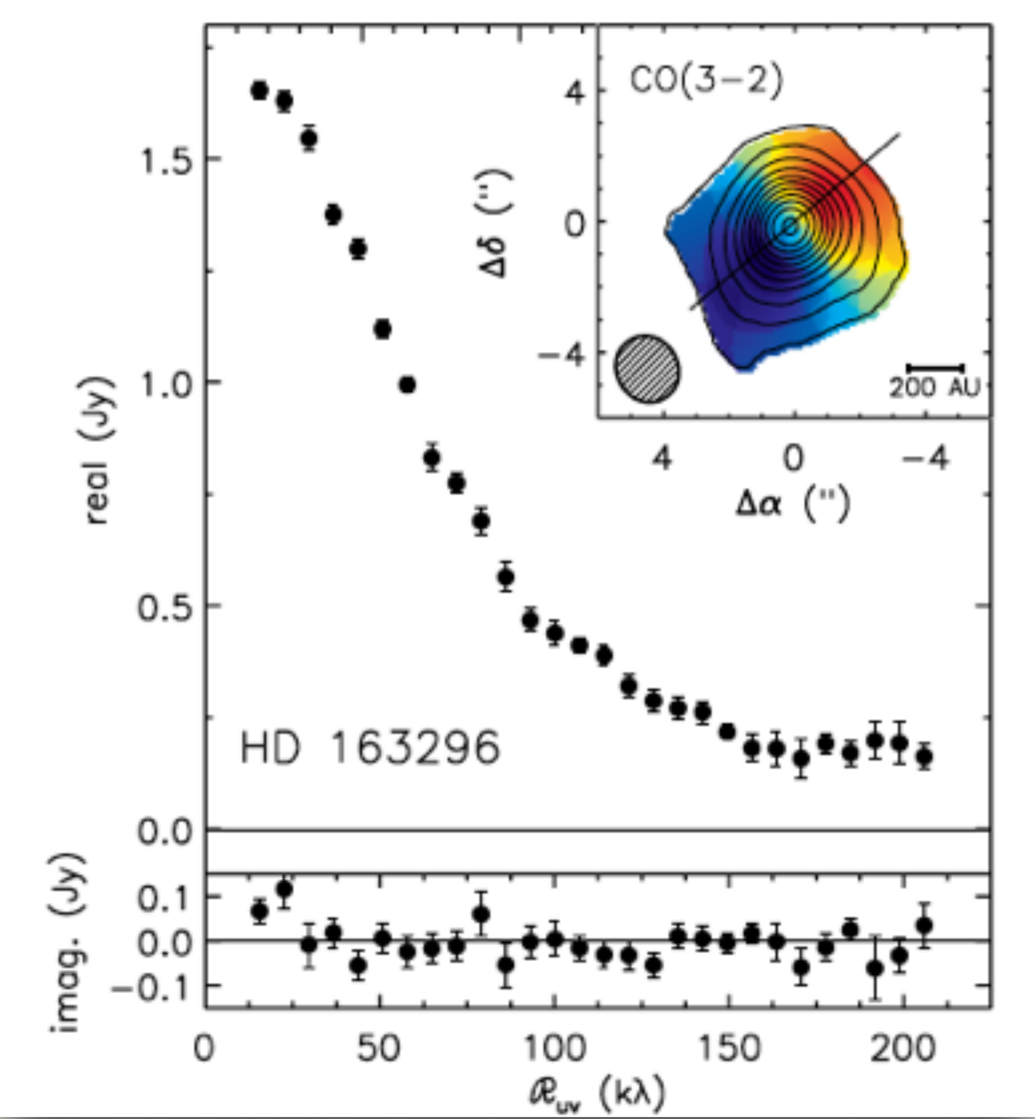
- Slightly higher mass equivalent of T-Tauri stars
  - Intermediate Mass (2-8 $M_\odot$)
  - Still forming
  - Brighter
  - Larger disks



HD 163296

Spectral Type	A1
Temperature	9333 K
Mass	2.3 M
Distance	122 pc
Disk Mass	0.089 M
Outer Radius	> 500 au

- Well studied Herbig Ae star
- Favourably inclined for imaging disk structures
- Extended
- BRIGHT



Hughes et al. 2009

Science Verification

	SV	Now
	June 2012	Jan 2014
Antennas	16	28
Longest Baseline	400m	~1km

CO ^{13}CO C^{18}O

Less abundant →

HCO^+ $H^{13}CO^+$ DCO^+

HD 163296

- ~4 hr on source (each in bands 6&7)
- 0.1-0.5 km/s spectral resolution
- 0.4-0.7″ spatial resolution

Protostellar Disks

- Three things that were suspected / predicted by models
  - Disks have vertical structures

    Chiang & Goldreich 1997
  - Molecular snow lines (i.e. CO, H_2O)

    Sasselov & Lecar 2000
  - Magnetically driven winds

    Pudritz & Norman 1983

HD 163296 with ALMA SV

The focus today is on

Unveiling the gas-and-dust disk structure in HD 163296 using ALMA observations

I. de Gregorio-Monsalvo[1,6], F. Ménard[2,3], W. Dent[1,10], C. Pinte[3], C. López[1,5], P. Klaassen[4], A. Hales[1,5], P. Cortés[1,5], M. G. Rawlings[5], K. Tachihara[1,9], L. Testi[6,7], S. Takahashi[1,8], E. Chapillon[8], G. Mathews[4], A. Juhasz[4], E. Akiyama[9], A. E. Higuchi[1,9], M. Saito[1,9], L.-Å. Nyman[1,10], N. Phillips[1,10], J. Rodón[10], S. Corder[1,5], and T. Van Kempen[1,4]

ALMA imaging of the CO snowline of the HD 163296 disk with DCO^{+}★

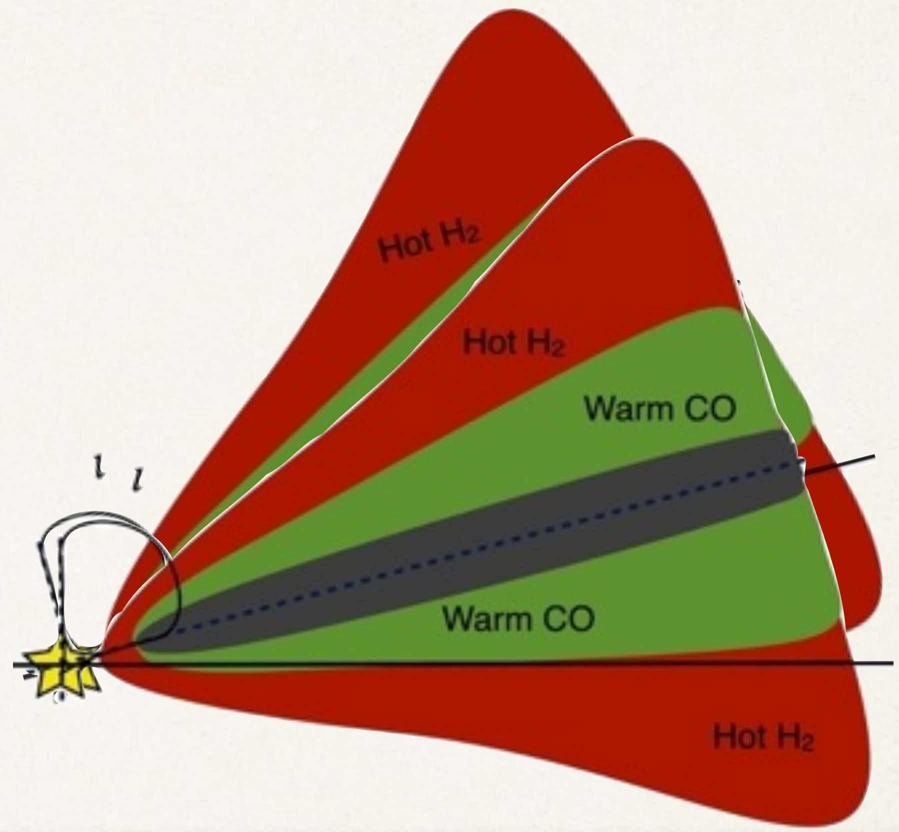
G. S. Mathews[1], P. D. Klaassen[1], A. Juhász[1], D. Harsono[1,2], E. Chapillon[3], E. F. van Dishoeck[1,4], D. Espada[5,6], I. de Gregorio-Monsalvo[7,8], A. Hales[8], M. R. Hogerheijde[1], J. C. Mottram[1], M. G. Rawlings[9], S. Takahashi[8,5,3], and L. Testi[7,10]

ALMA detection of the rotating molecular disk wind from the young star HD 163296

P. D. Klaassen[1], A Juhasz[1], G. S. Mathews[1], J. C. Mottram[1], I. De Gregorio-Monsalvo[2,3], E. F. van Dishoeck[1,4], S. Takahashi[5], E. Akiyama[6], E. Chapillon[5], D. Espada[6], A. Hales[2], M. R. Hogerheijde[1], M. Rawlings[7], M. Schmalzl[1], and L. Testi[3,8]

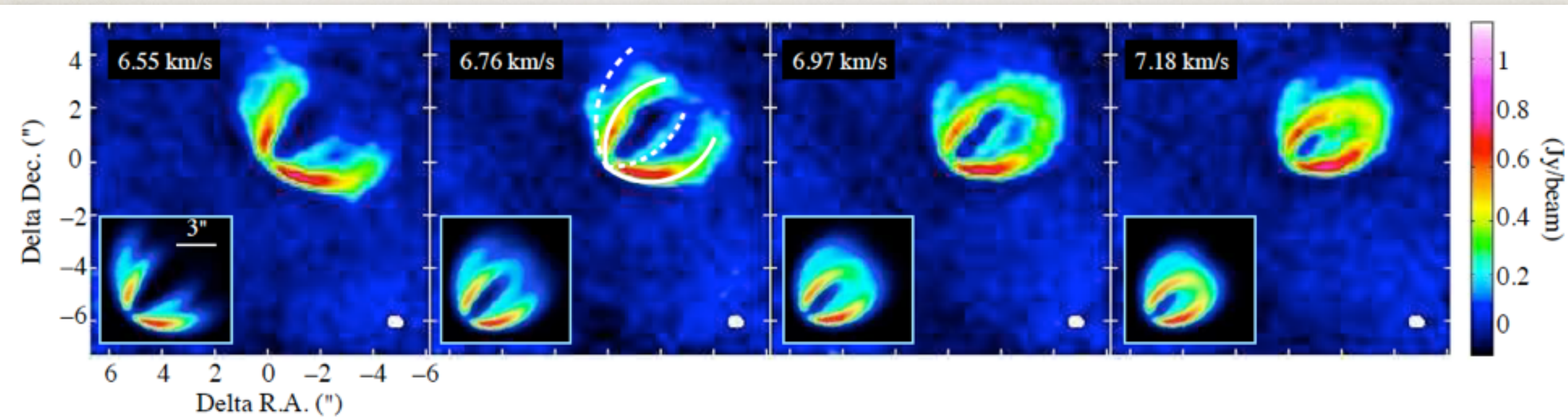
The Disk

- First time we've seen the vertical structure and both the front and back sides of the disk



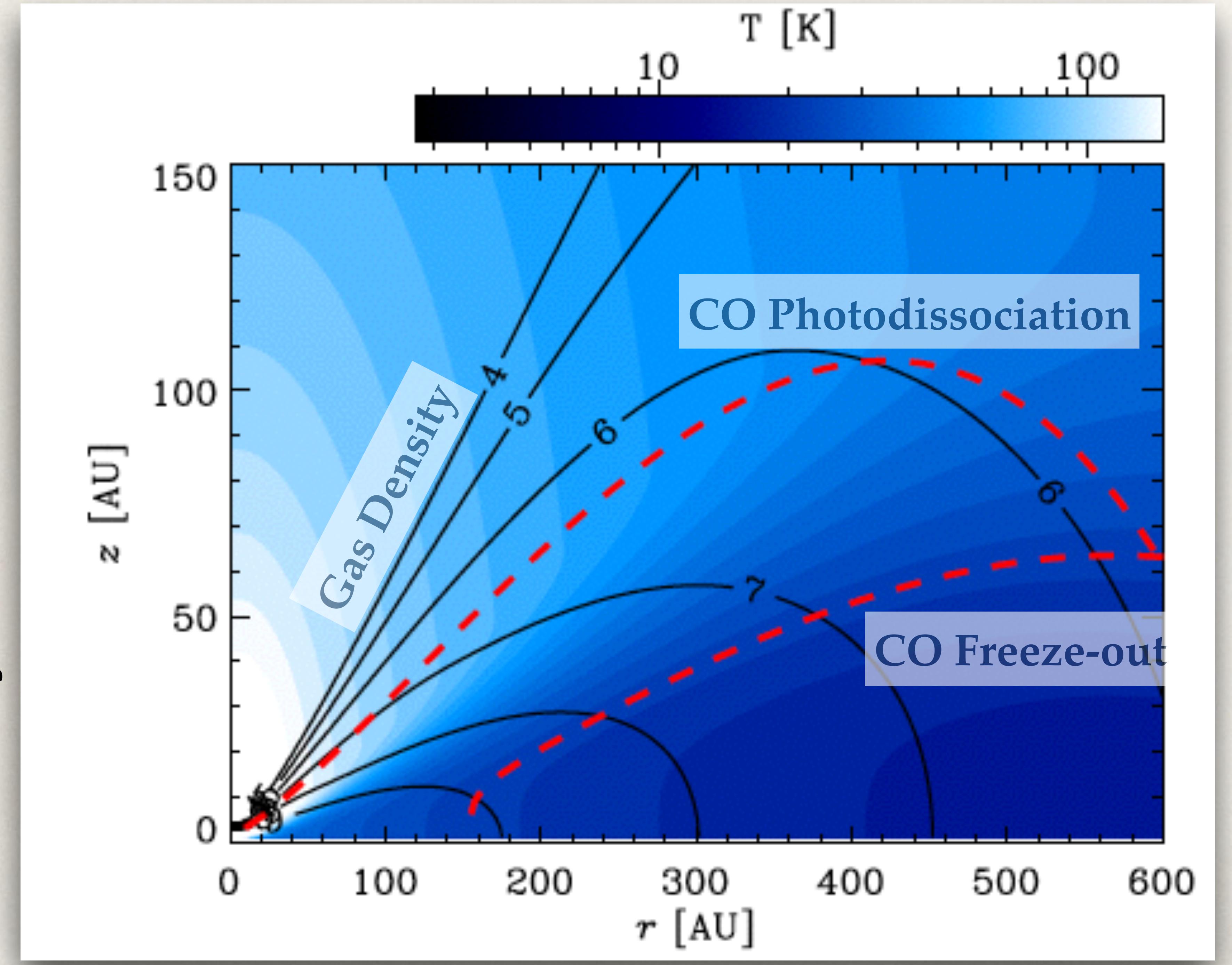
Modified from McJunkin et al. 2013

- We're seeing the layered structures within the disk
- Because of the rotation, we are also able to see the front and back sides of the disk



de Gregorio-Monsalvo et al. 2013

Disk Vertical Structure

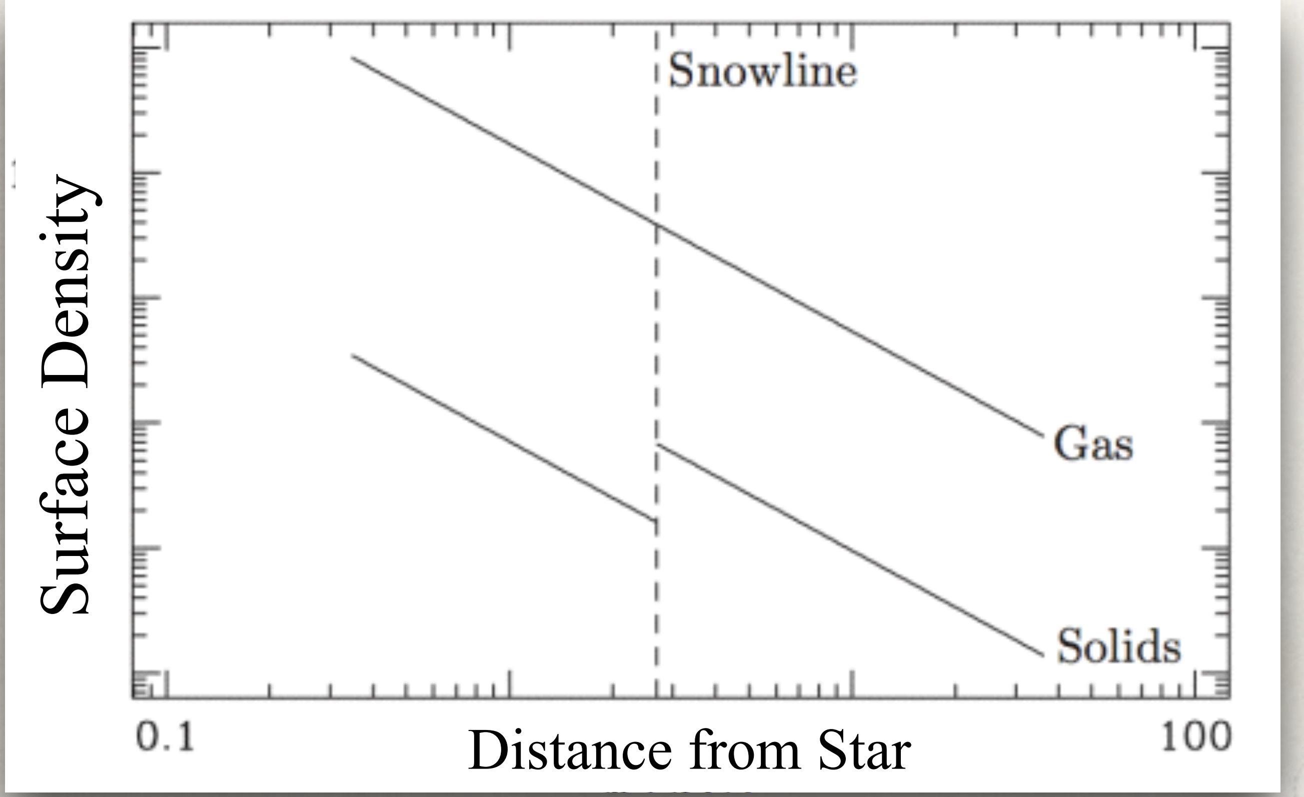


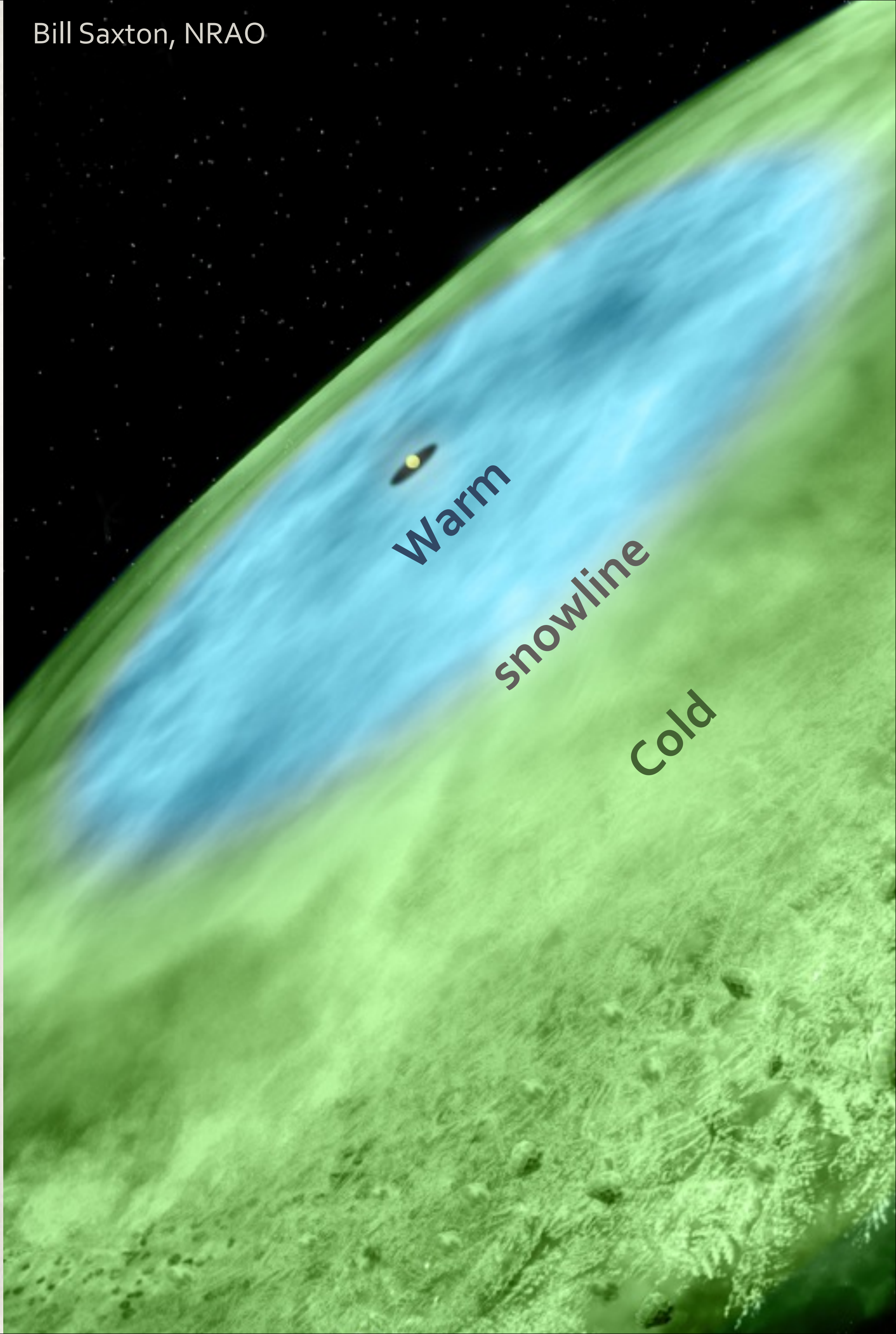
Rosenfeld et al. 2013

- From this we understand how the disk is vertically stratified
  - in density AND temperature
- How can we confirm this?

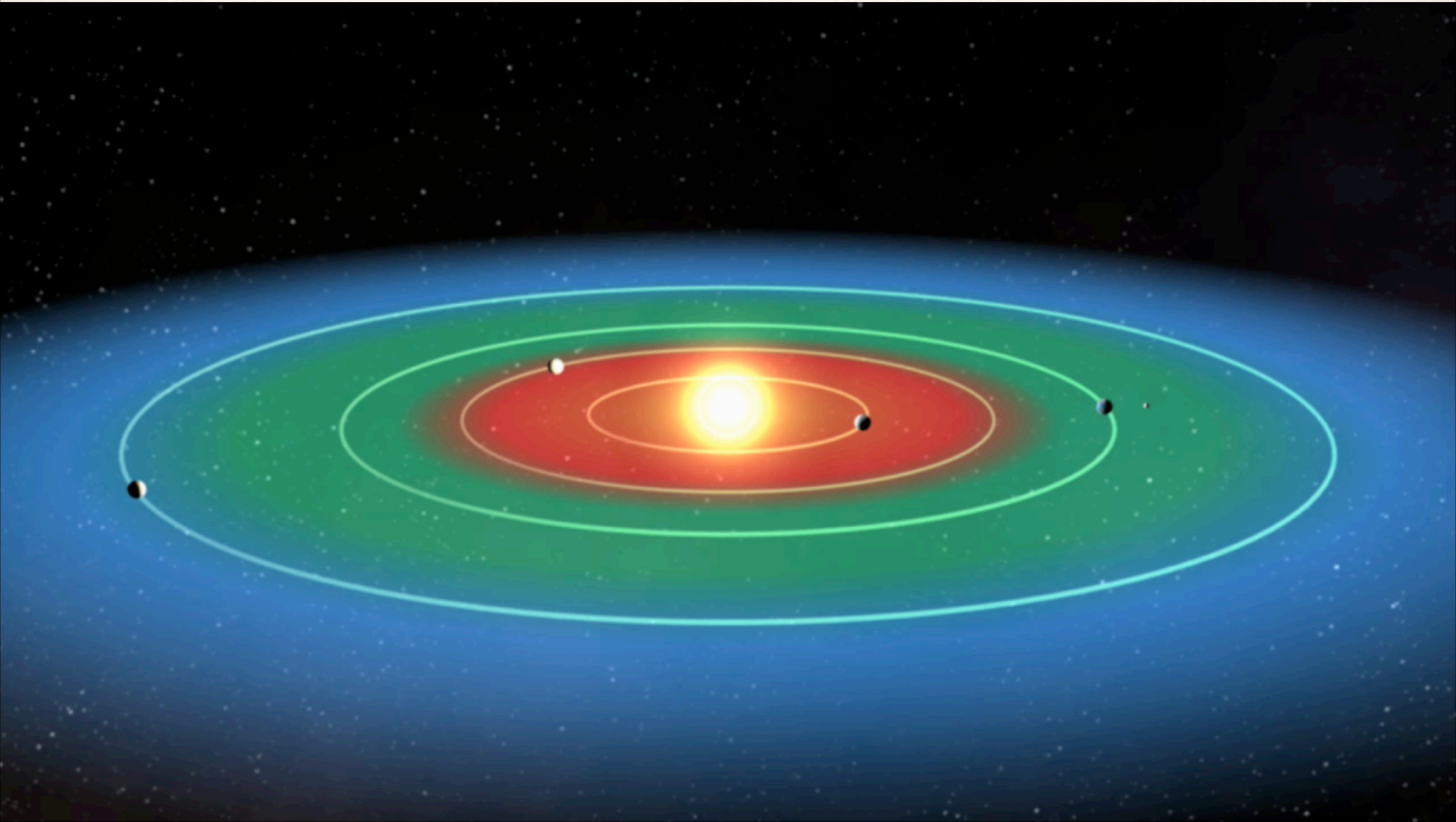
Snowline

- Different types of chemistry take over
- **Inside**: most molecules are gaseous
- **Outside**: most molecules are frozen out onto dust grains



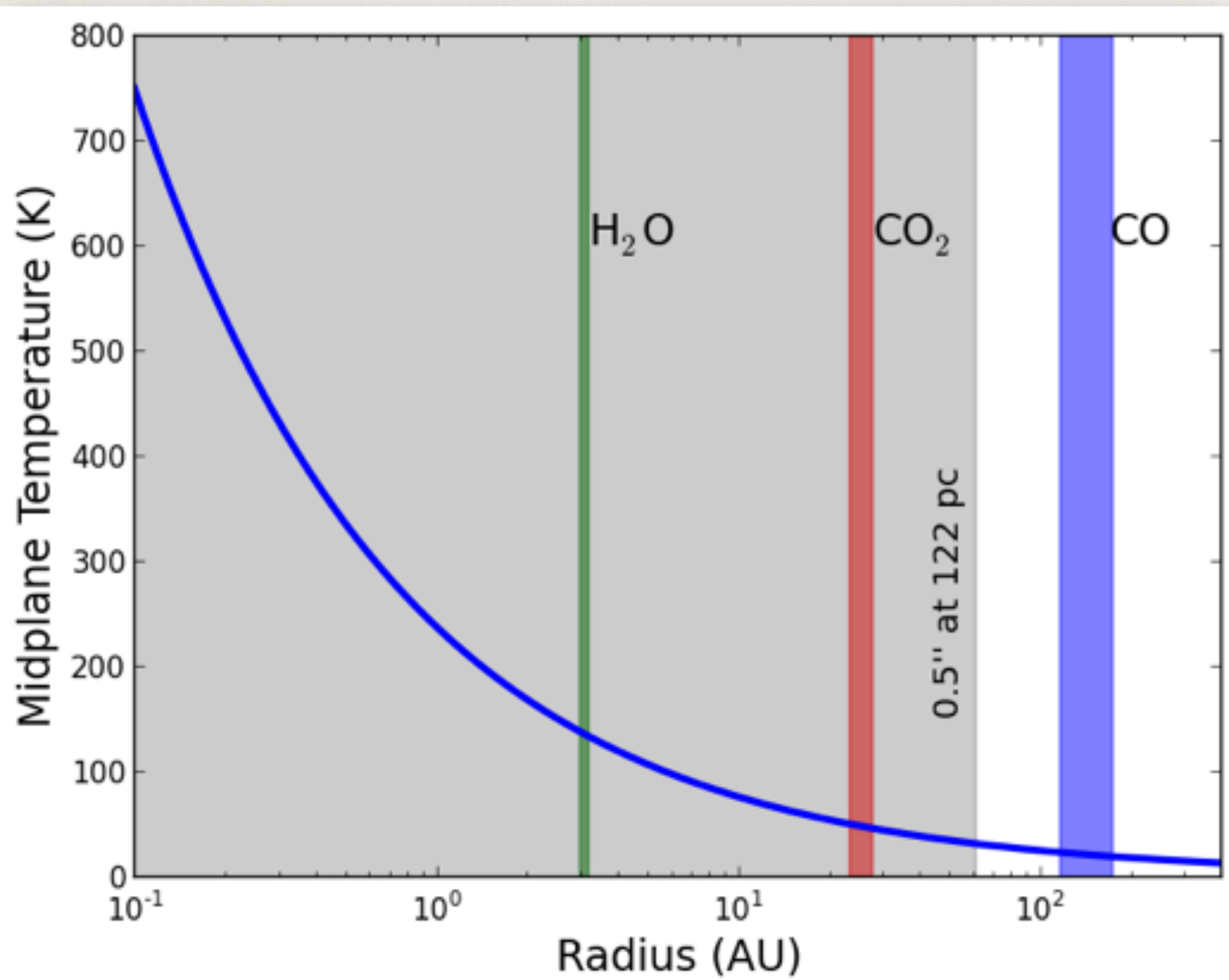


Snowline



Snowline

- Different species freeze out at different temperatures



Species	T_{evap} [a] (K)
CO	18–22 (20)
CO_2	42–52 (47)
H_2O	120–150 (135)

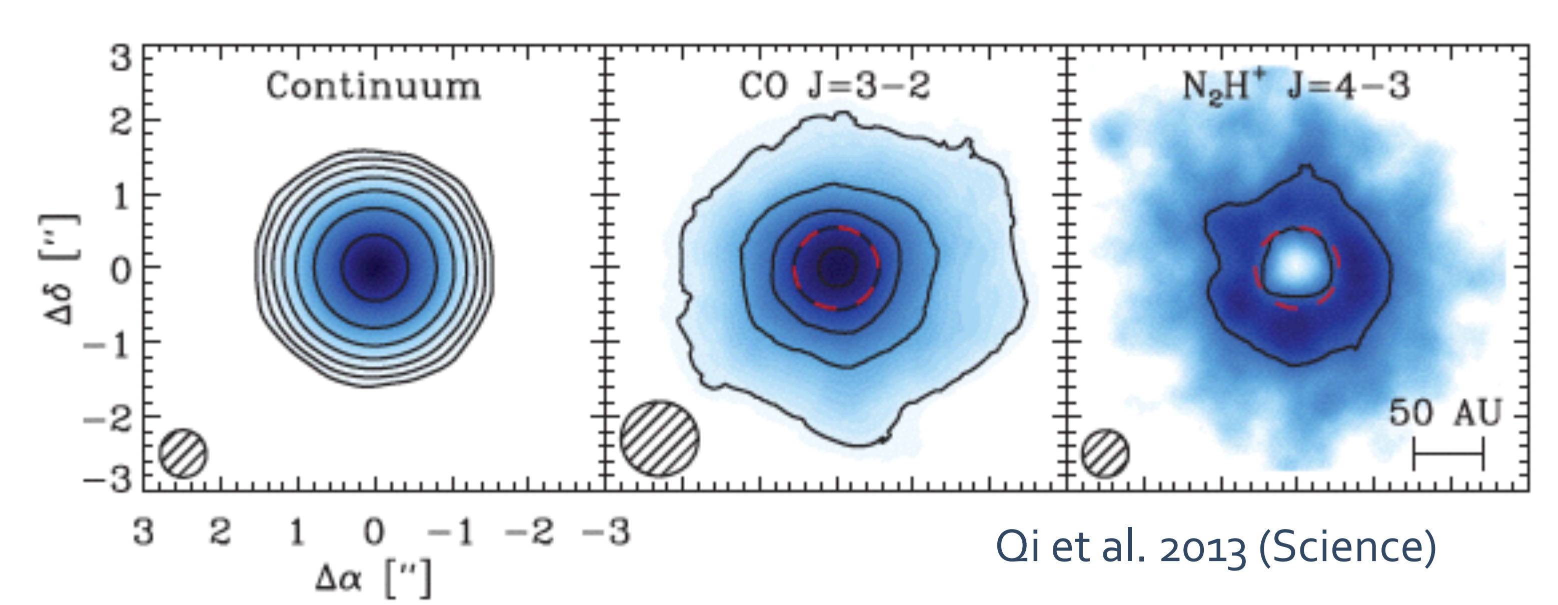
Oberg et al. 2011

To see the water snow line in HD 163296 would require a spatial resolution of <0.02"

- CO is the easiest to observe because it occurs furthest out

CO snowline

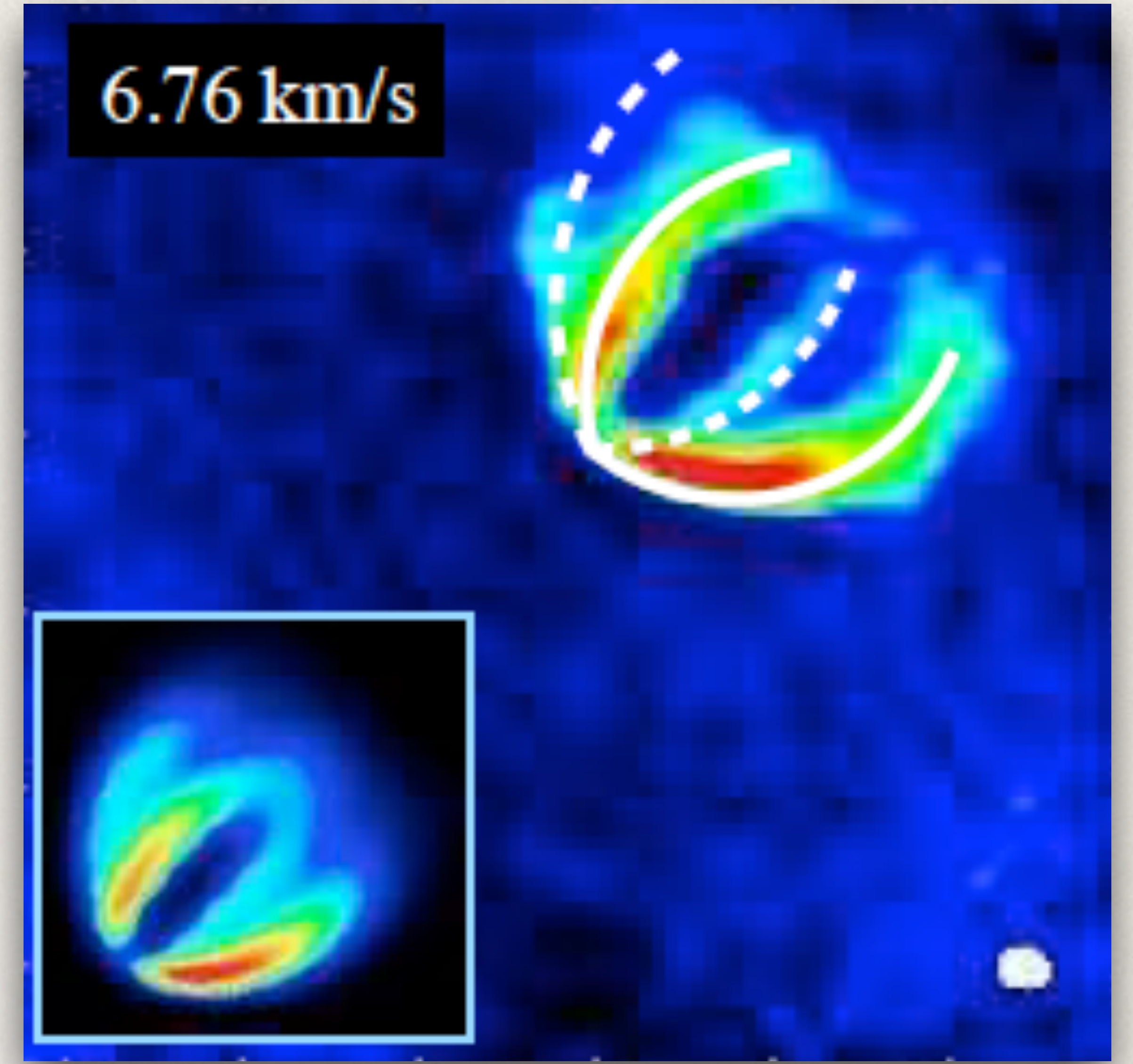
- Because HD 163296 is an A star, its snow line is much further out than the equivalent in a solar type star
- Qi et al. (2011) inferred the location of the CO snow line in HD 163296 from SMA observations (~150 au)
- Qi et al. (2013) resolved the snow line in TW Hydra



Qi et al. 2013 (Science)

Tracing the CO snow line

- We can see that there is a lack of CO in the mid plane of the disk
- But that doesn't exclusively mean that the CO is frozen out
  - The abundance could drop?
  - There may be a gap?
  - It could be optically thick?



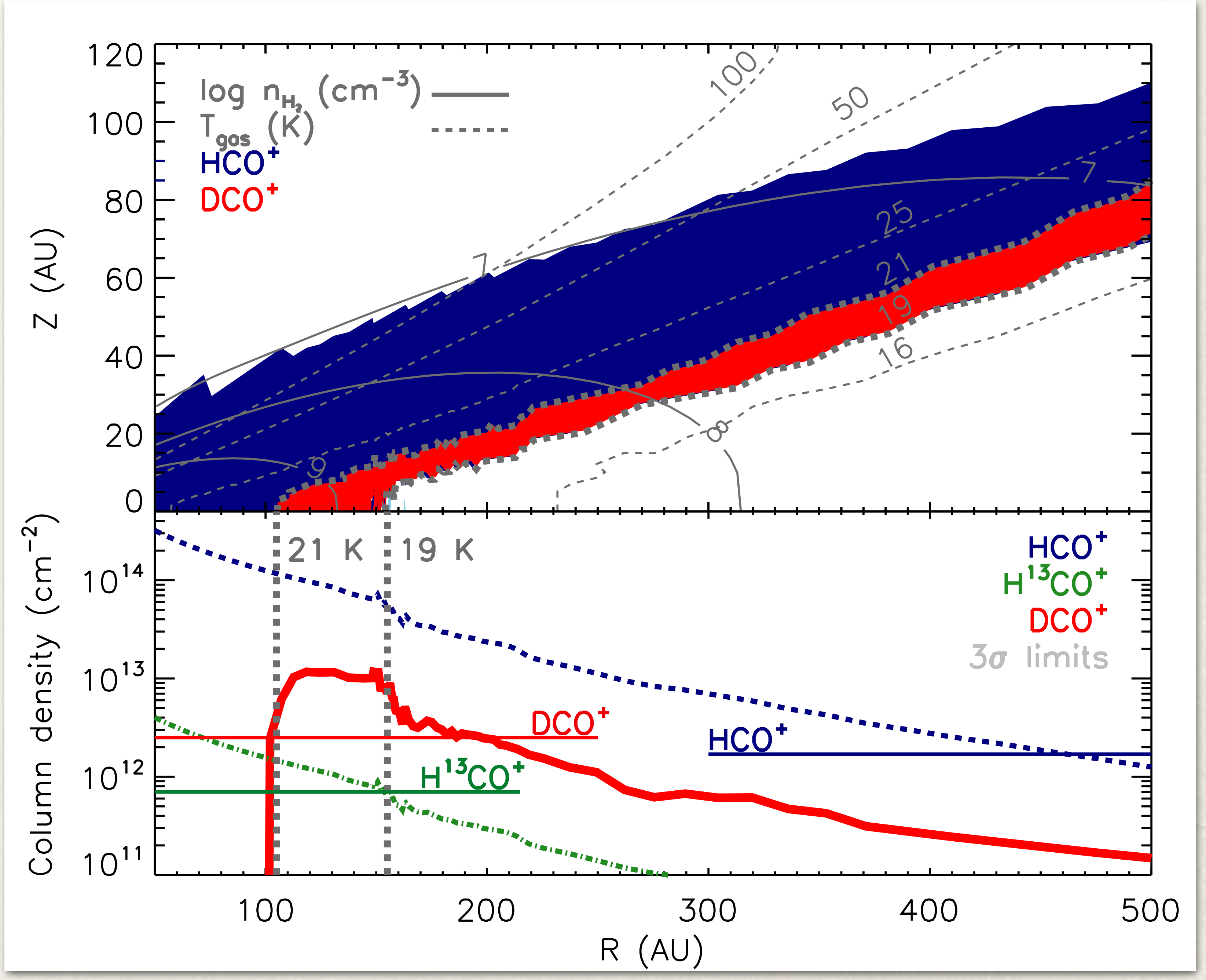
de Gregorio-Monsalvo et al. 2013

- Because of the inclination, there could also be 'atmospheric' CO masquerading as mid plane CO
  - We need an independent tracer of cold gas whose chemistry is linked to that of CO

Why DCO+

A lack of CO doesn't necessarily mean CO freeze-out.

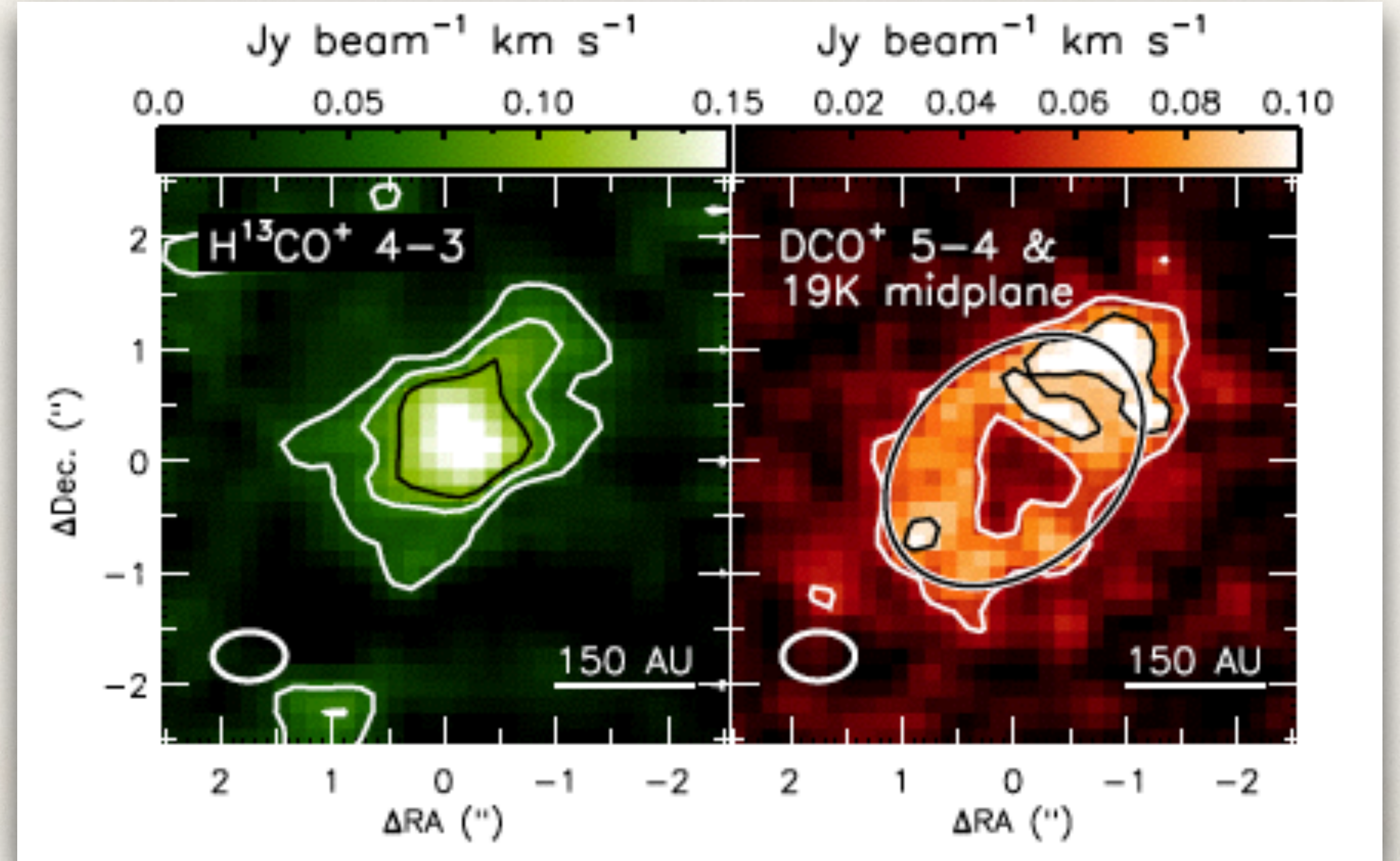
- Its chemistry is intricately linked with that of CO
- There is a temperature sweet spot where:
  - There is still enough CO to form DCO+
  - The temperature is low enough to enhance deuteration



Mathews, Klaassen et al. 2013

Snowline

The DCO^+ emission has a different spatial structure than the $H^{13}CO^+$



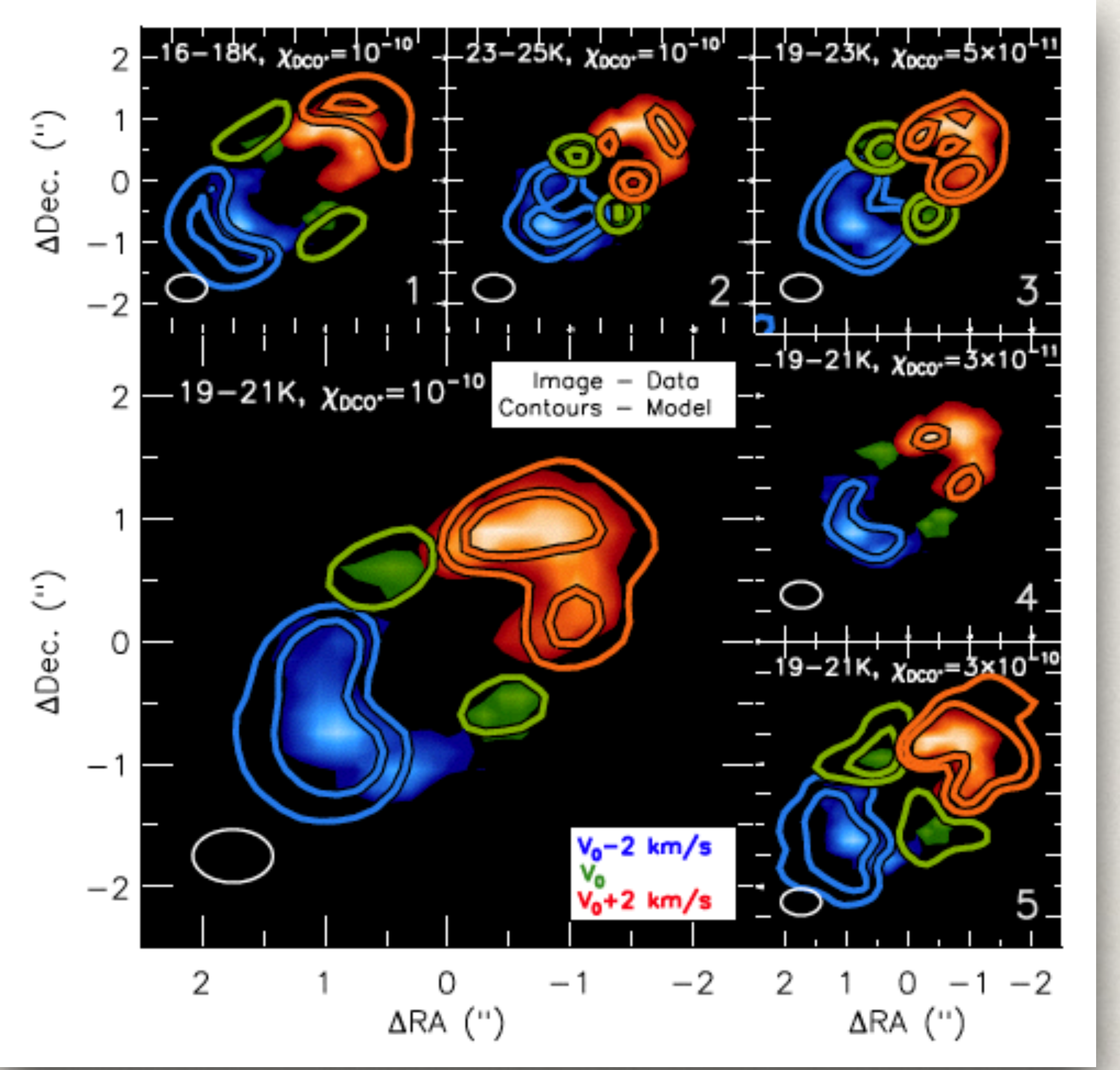
Mathews, Klaassen et al. 2013

Varying the parameters

- Changing the temperature or abundance moves the modelled position of the snowline.

  T=20±1, $[DCO^+]/[H_2] = 10^{-10}$

- This suggests the vertical structure models are right/predictive



Mathews, Klaassen et al. 2013

Protostellar Disks

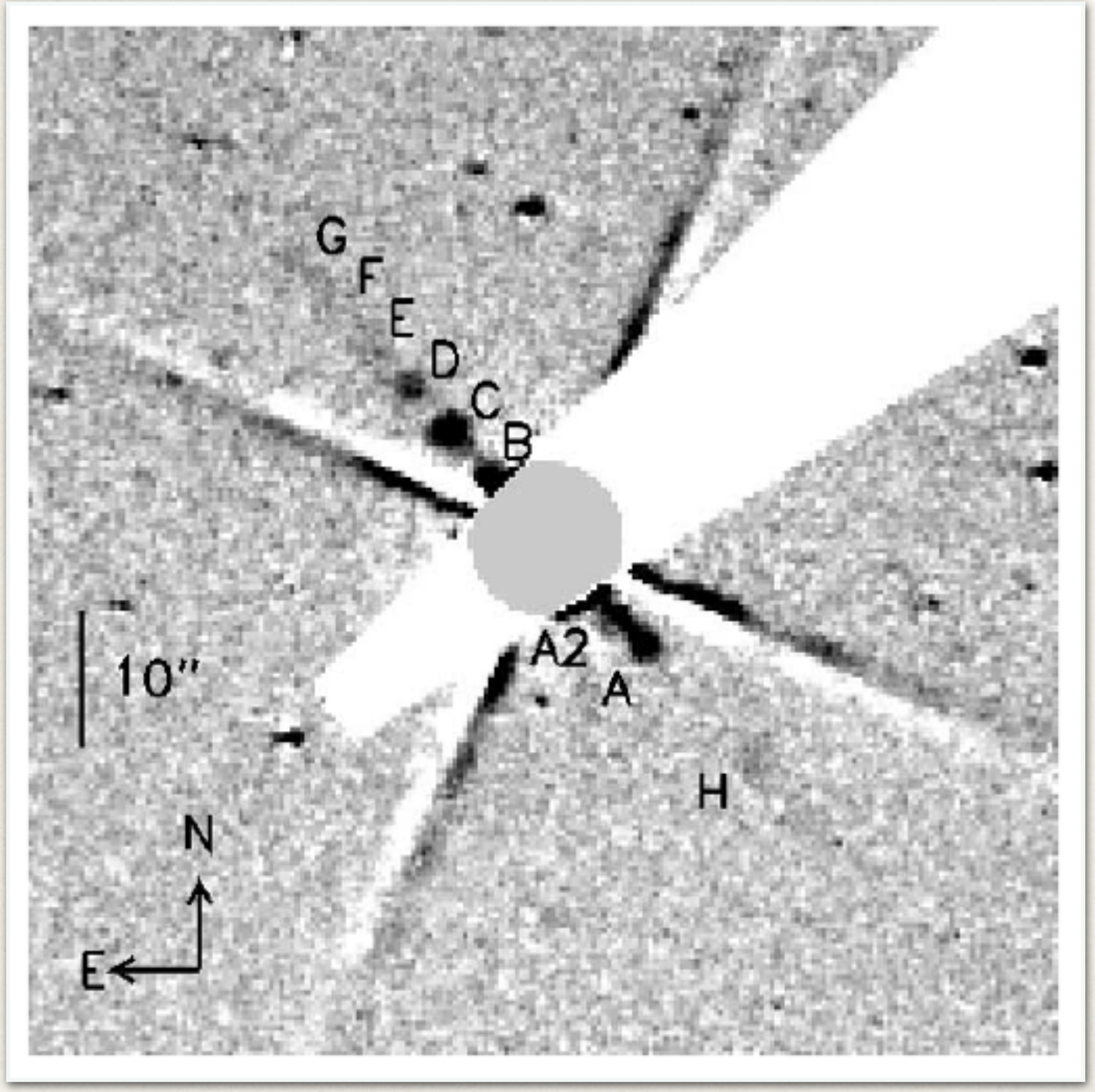
Material falls in, onto the disk

Winds are blown off

Removing momentum from the disk

- Now that we understand the structure of the disk.
- How are the internal dynamics regulated?
  - Episodic accretion (seen in the HH object)
  - Angular momentum released along magnetic field lines
    - A magnetically driven disk wind.

HH 409



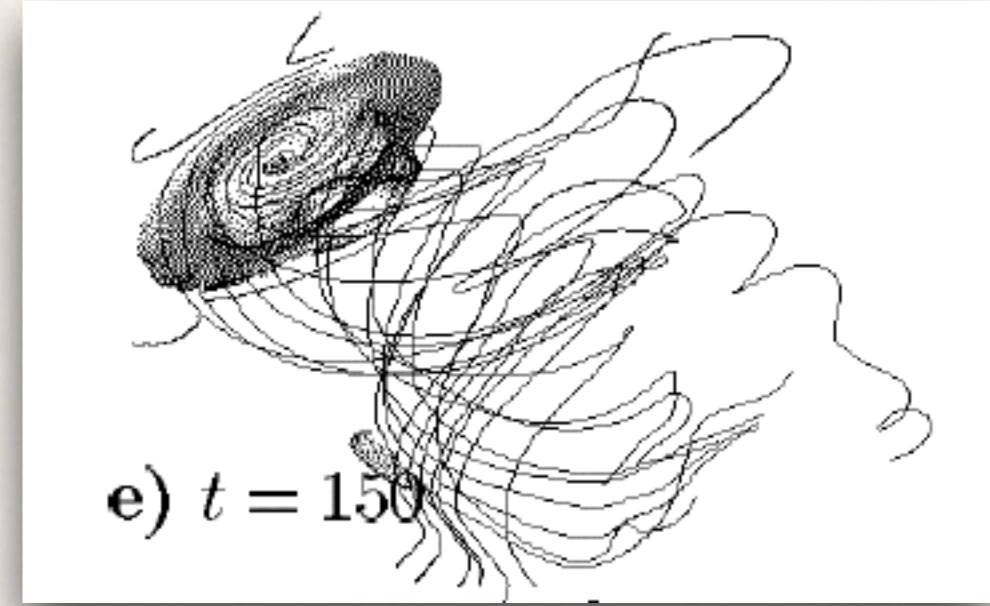
Wassell et al. 2006

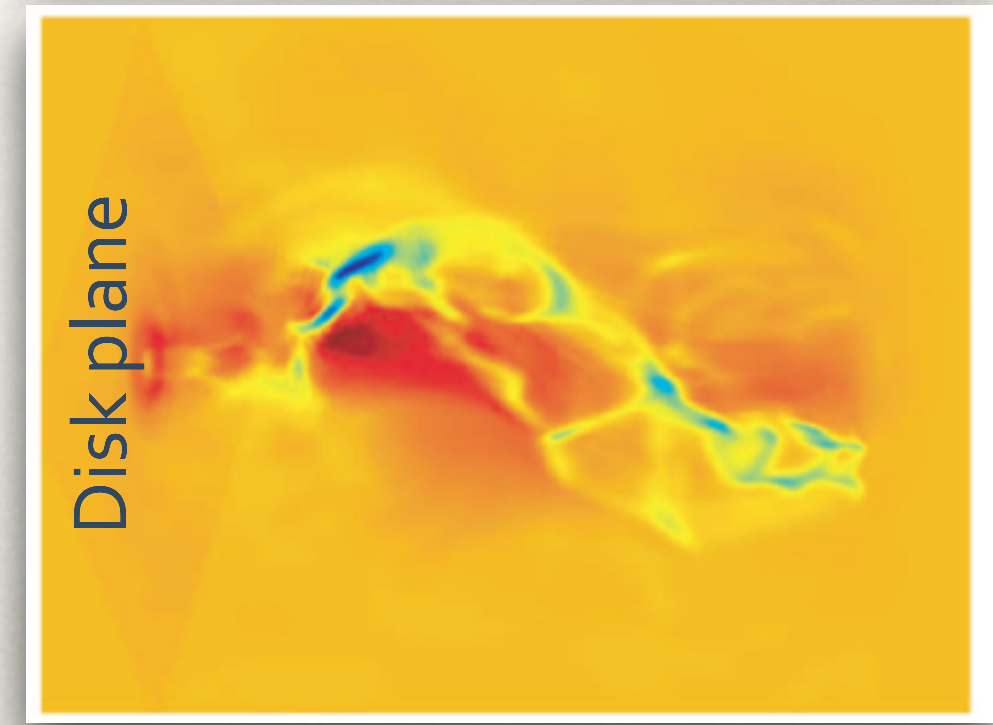
- HH 409 is associated with this disk
- Proper motion of the knots has been measured
- G and H are bow shocks at the ends of the object

Knot proper motions link back to likely ejection events

Magnetic field

- Material can be lifted off of the disk by the magnetic field
    - think of it as a bead on a wire
- This process acts to release the angular momentum in the disk, and allows material to flow onto the star





Ouyed et al. 2003

Theories of Winds

Before ALMA, disk winds had never conclusively been imaged

Disk winds predicted since the early 1980's

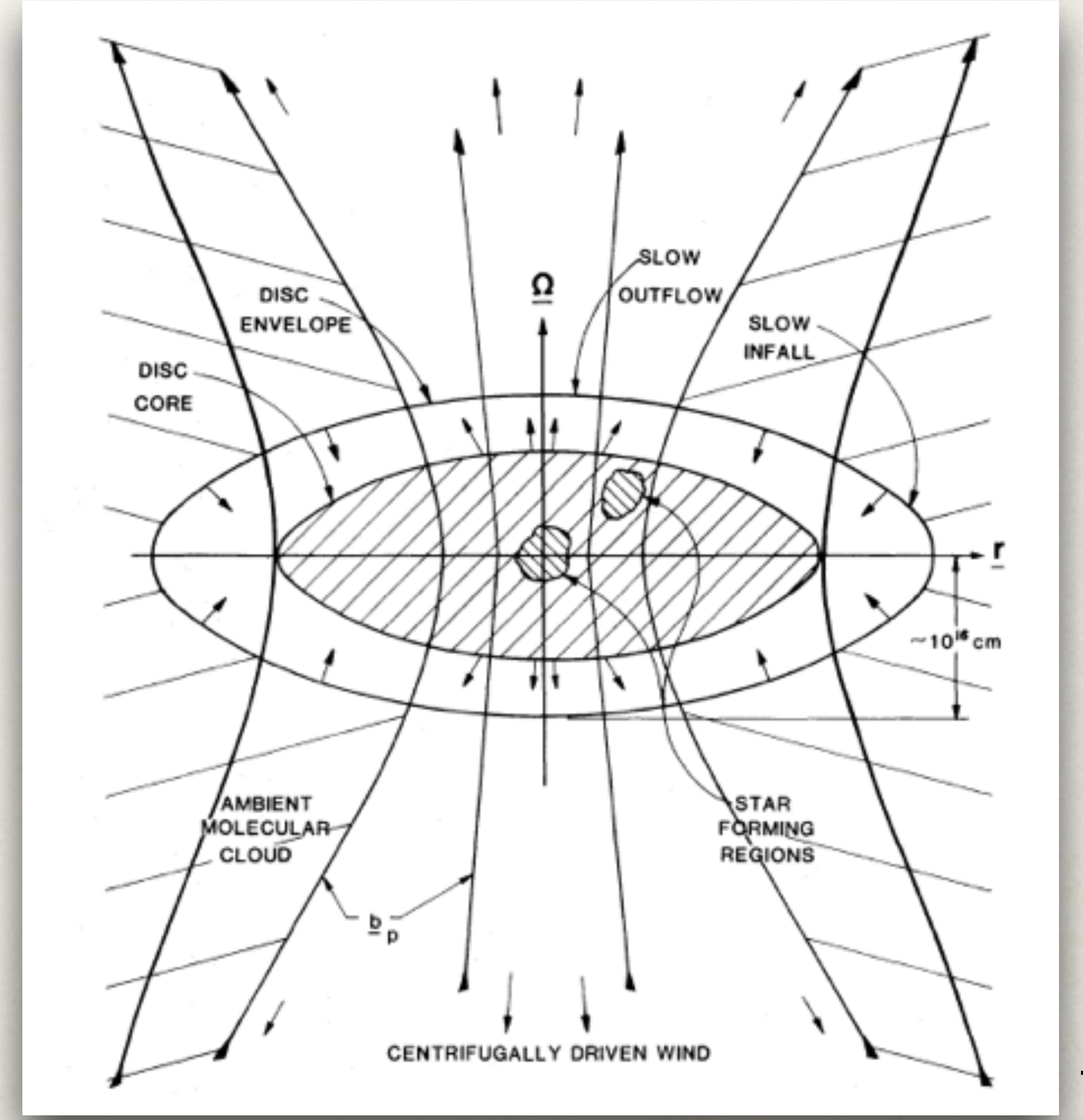
- They're produced differently than:
- Canonical Outflows

  Ambient material entrained around the jet (Jet launched from protostar)

  Snell 1980
- Photoevaporative flows

  Material being photo evaporated off the disk (and is therefore too hot to be molecular)

  Alexander 2006



Pudritz & Norman 1983

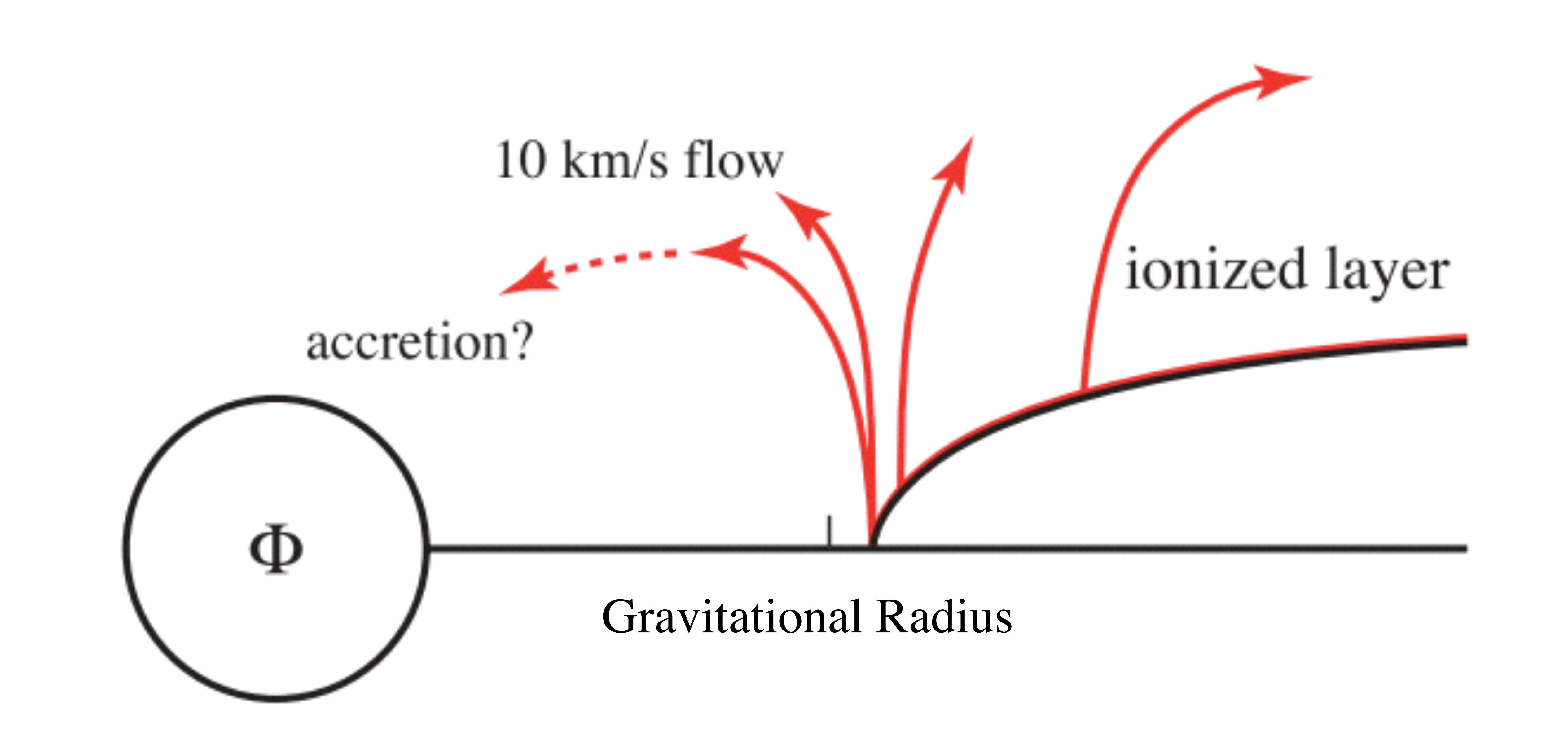
Jet/Outflow

NTT: Optical Image
ALMA: green/orange emission

- Jet launched from very close to the star
- Outflow is entrained from the material surrounding the jet
- Releases angular momentum, but from very small radii

Photoevaporative winds

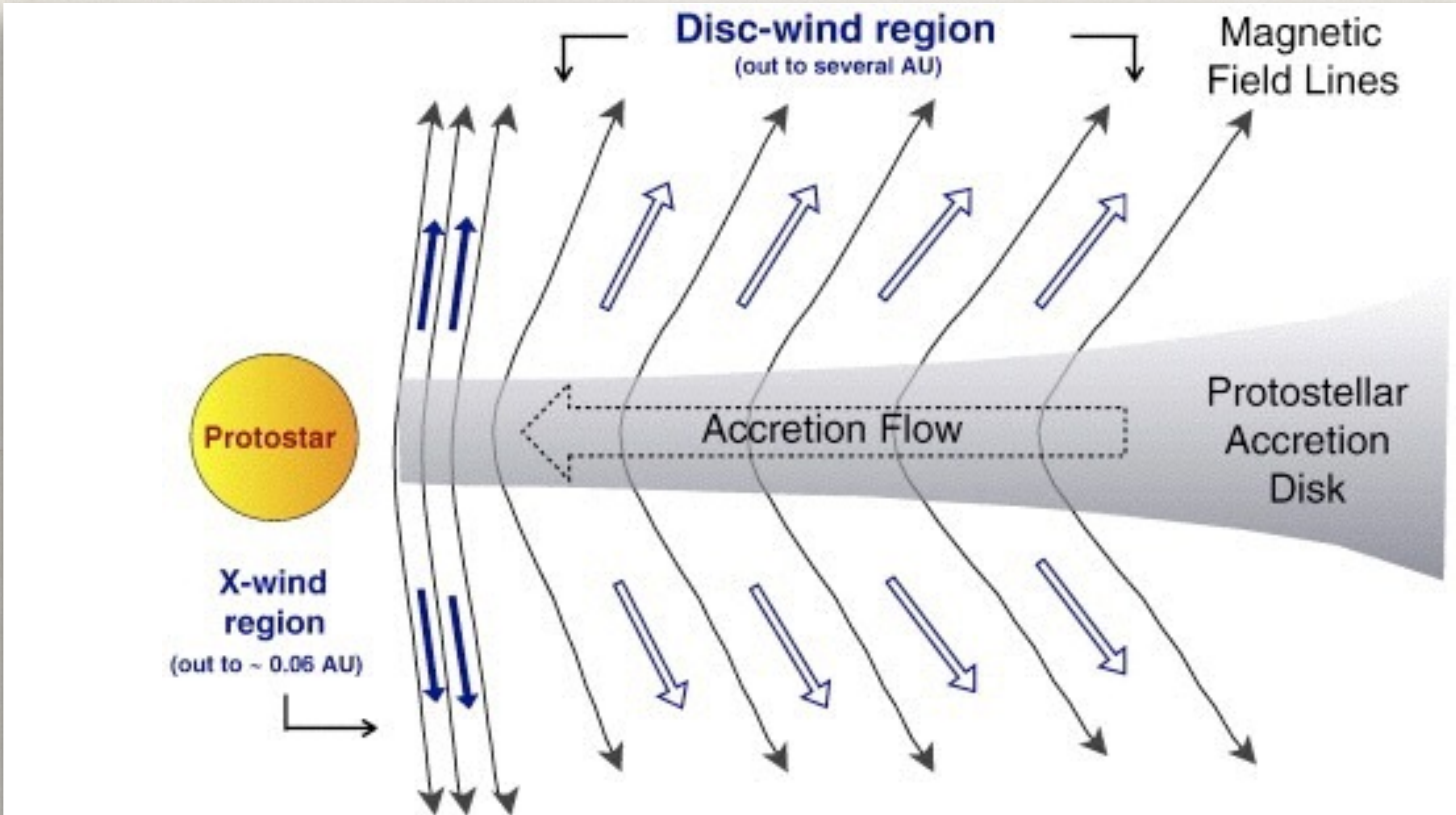
- Material being evaporated off of the disk surface
- Ionised gas - not molecular



Alexander et al. 2006

Theory of Disk Winds

Disk winds should show signs of rotation



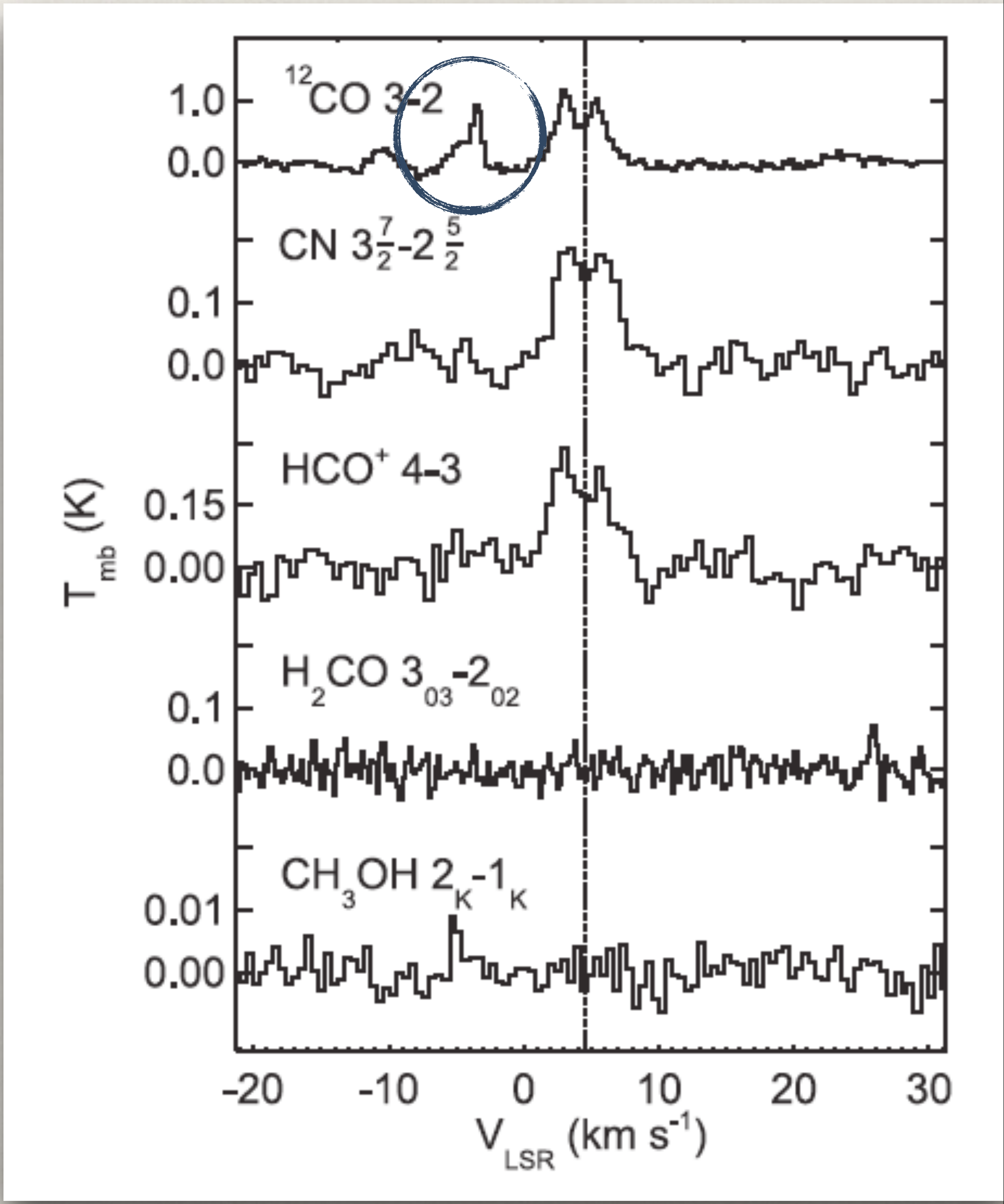
Salmeron & Ireland (2011)

Thi et al. (2004)

Previous Observations

- This wind hasn't been imaged before because previous observations weren't sensitive enough at high resolution

It has been seen in CO with single dish telescopes



Brief interlude into interferometry

- Interferometers can see at high resolution by having long baselines
- But, they are *insensitive* to large scale structures

The largest detectable scale is based on how tightly the antennas can be packed

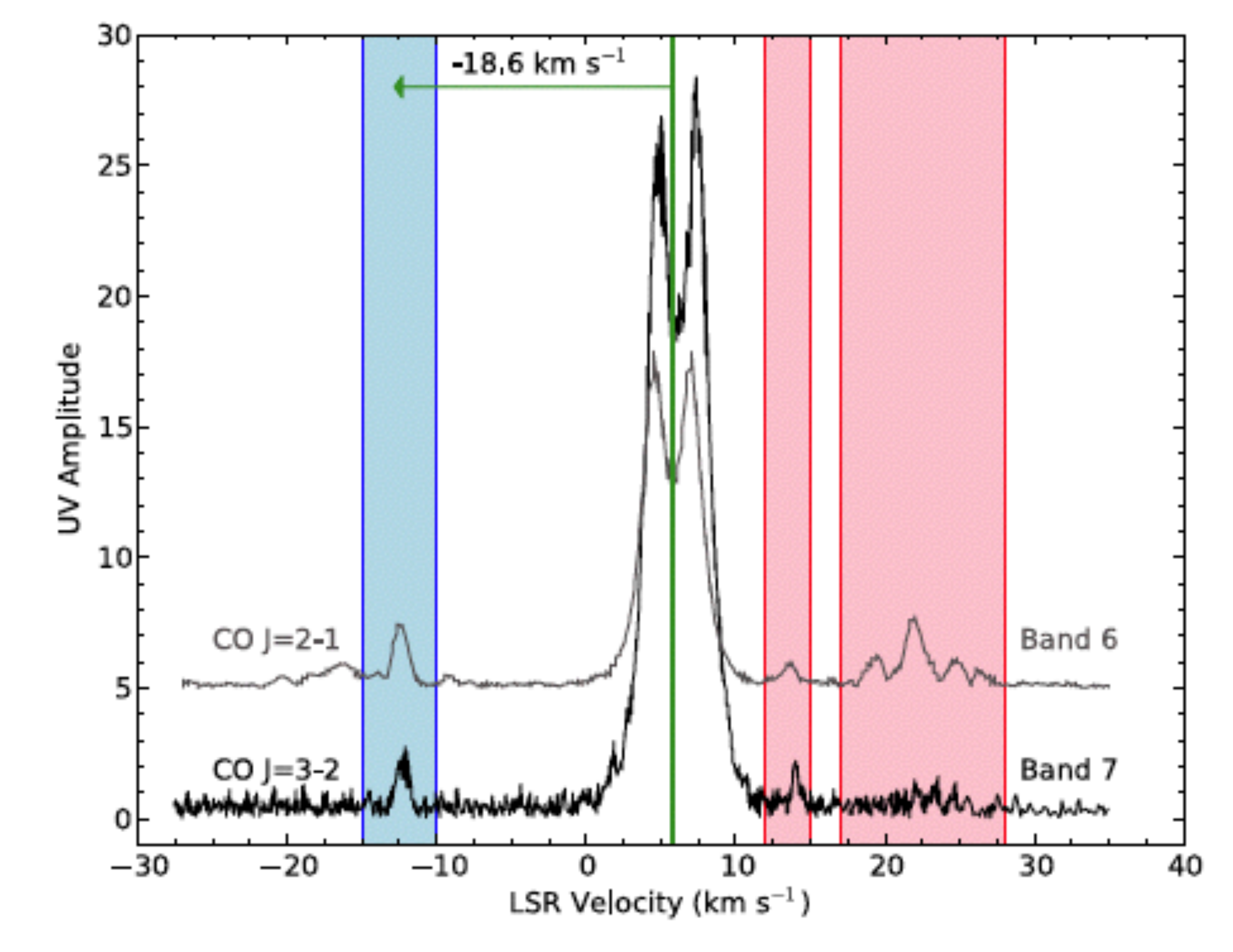
$$\theta = \frac{1.2\lambda}{L}$$

Baseline length = L

Wind from HD 163296

- First look at the *uv* plane spectra
  - Shortest baselines only
  - Red emission is filtered out (it cannot be imaged)
- There appear to be species emitting *near* CO
  - In *two* bands

Klaassen et al. 2013

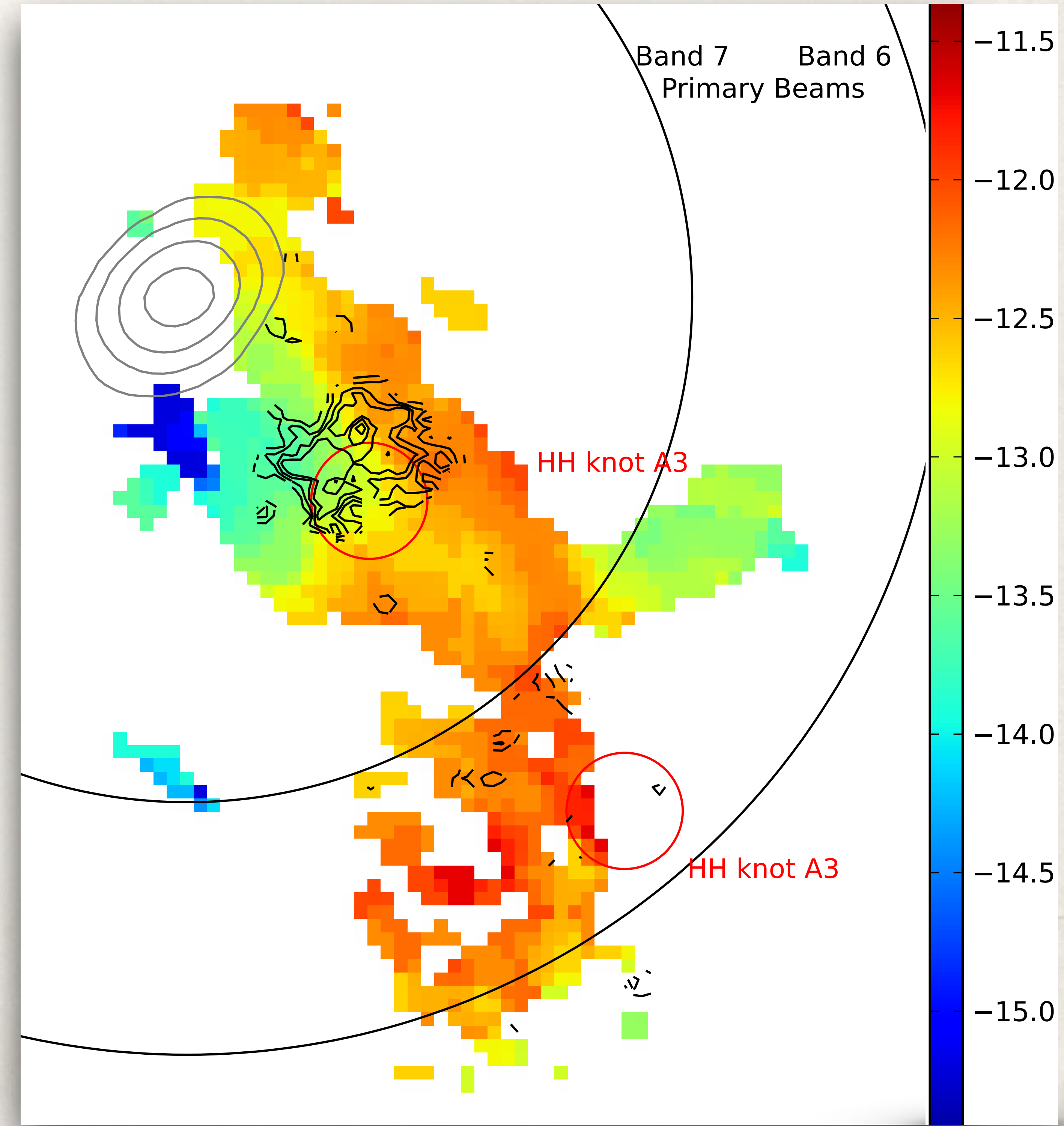


These spectra are 'filtered' to only show the largest scale structures

Disk Wind

Klaassen et al. 2013

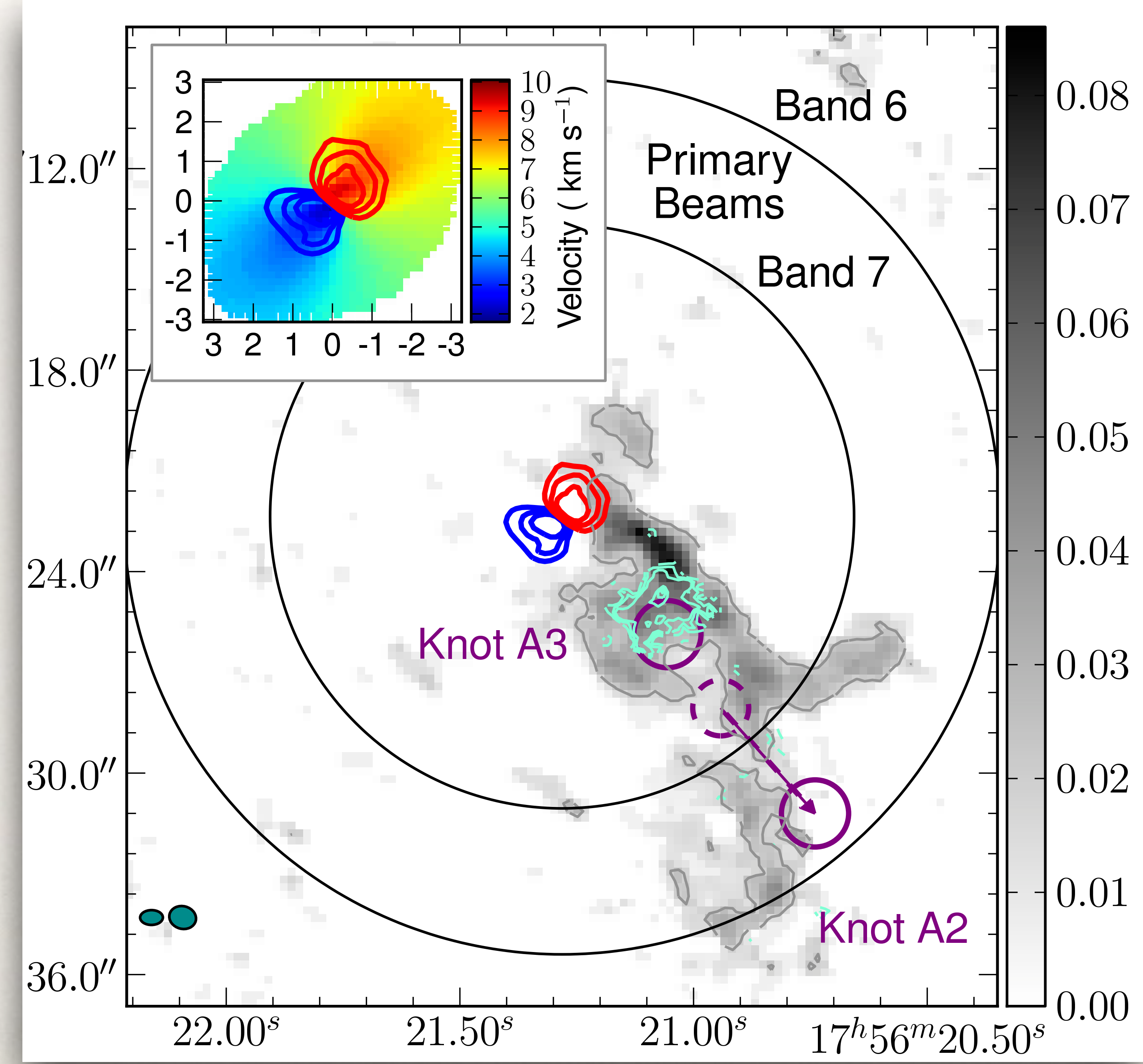
- It turns out that high velocity emission is extended
  - which is why it only shows up on short baselines
- More so in the Band 6 (CO J=2-1) data
  - this has to do with the spatial filtering of the interferometer



Disk Wind

- Why do we see only one lobe?
- Why is the CO J=3-2 so sparse?
- What is the relation to HH 409?

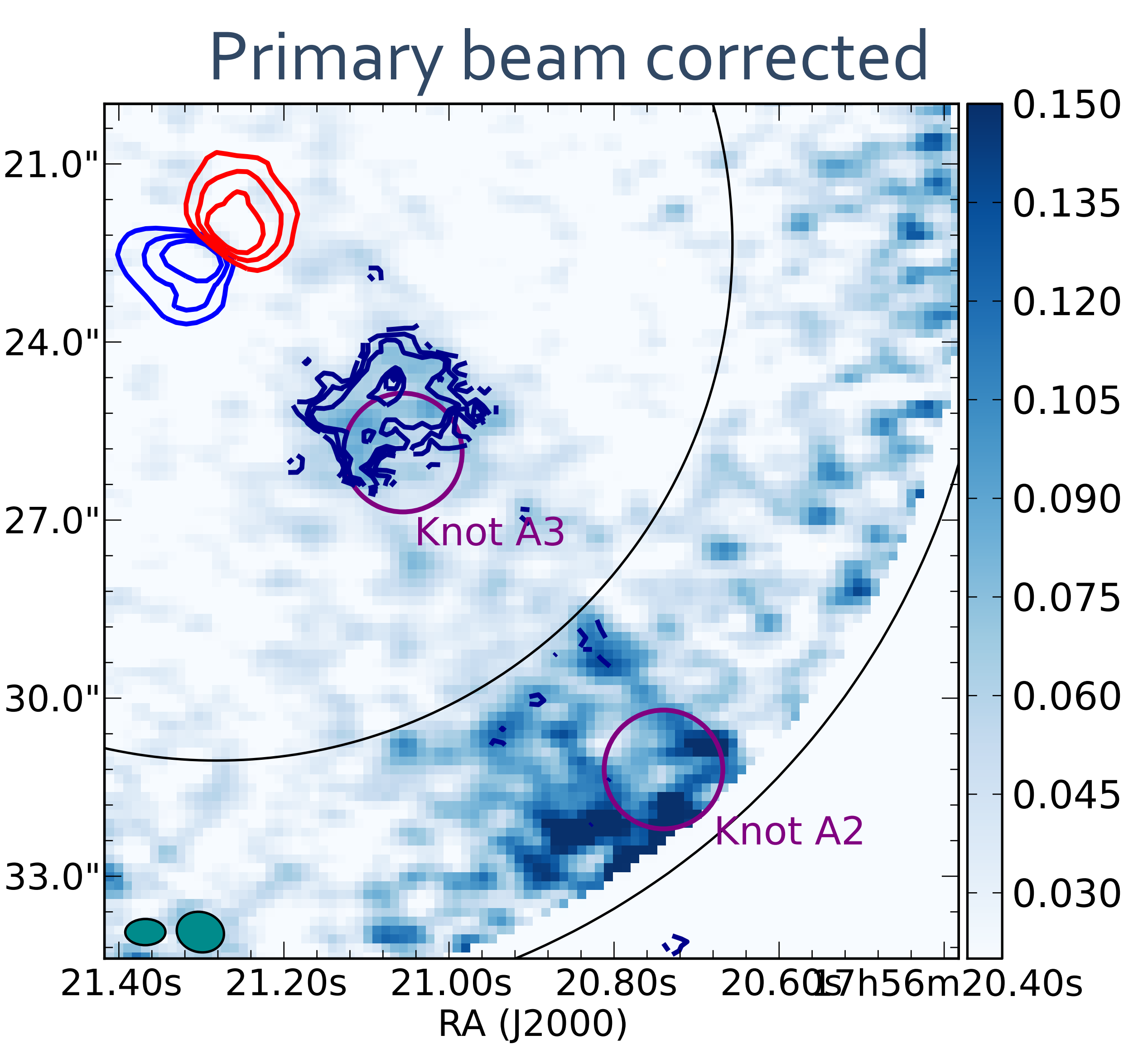
This is pretty neat actually



Klaassen et al. 2013

Klaassen et al. 2013

Interaction with HH 409



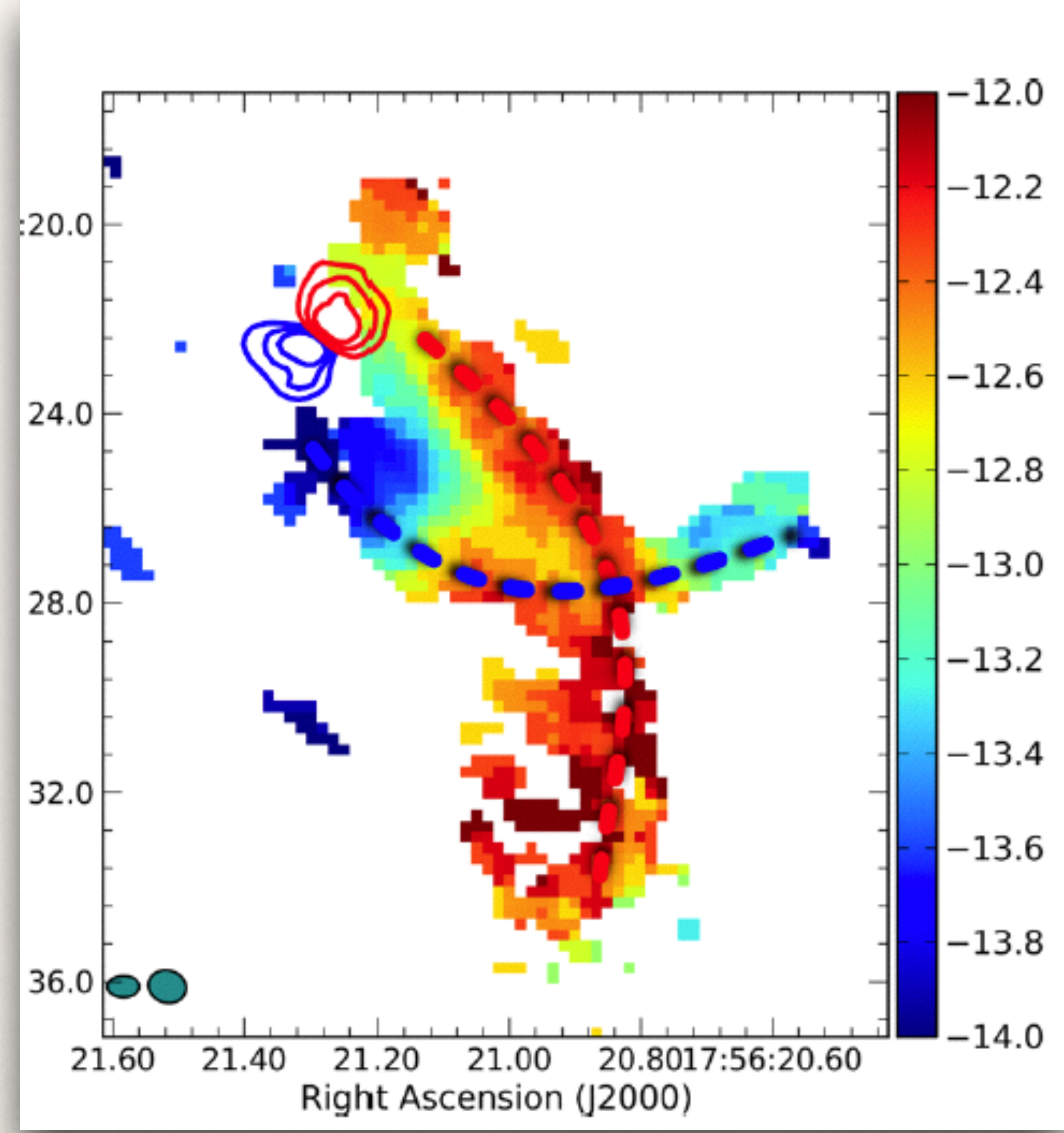
- We're only seeing the CO J=3-2 where the disk wind is interacting with the HH object
- The data show bright (hot) knots of molecular emission behind (downstream) the HH knots suggesting the wind and jet interact

Because the band 7 observations were only sensitive to smaller scales, we were only able to pick up bright knots of emission - not the bulk of the gas

Wind Rotation

- The wind appears to have two arms
  - they're at slightly different velocities
  - this suggests a double corkscrew

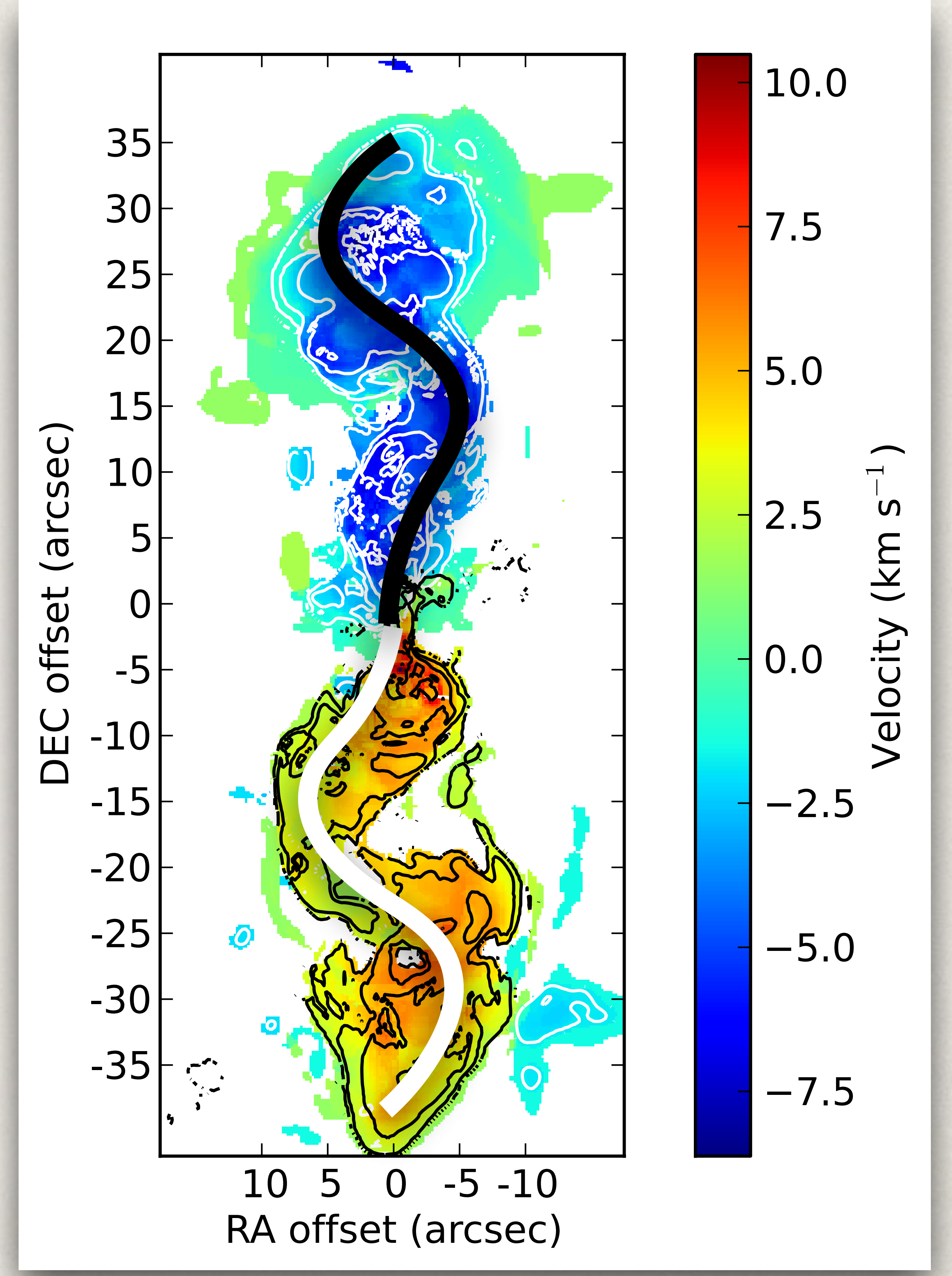
We need further observations to observe the second crossing of the arms to confirm this hypothesis



Peters, Klaassen et al. 2014

Corkscrew

- Some models to predict the corkscrew morphology
- It is driven by an instability in the disk

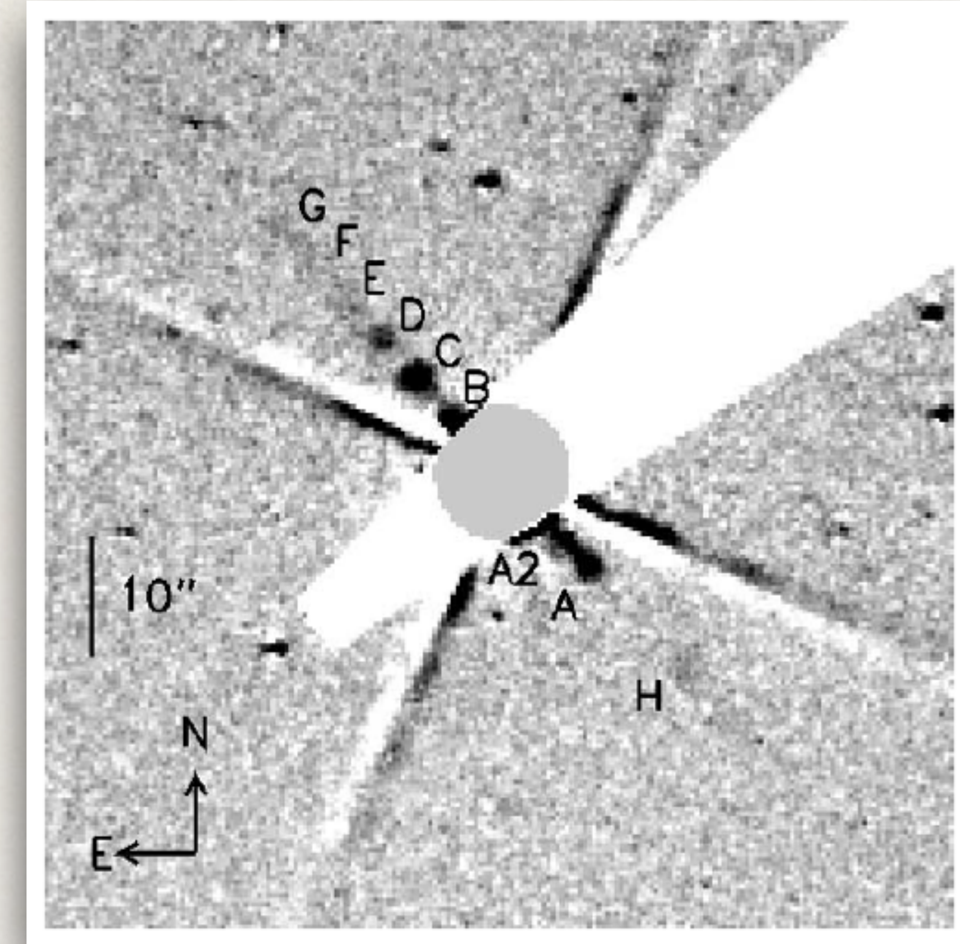


Peters, Klaassen et al. 2014

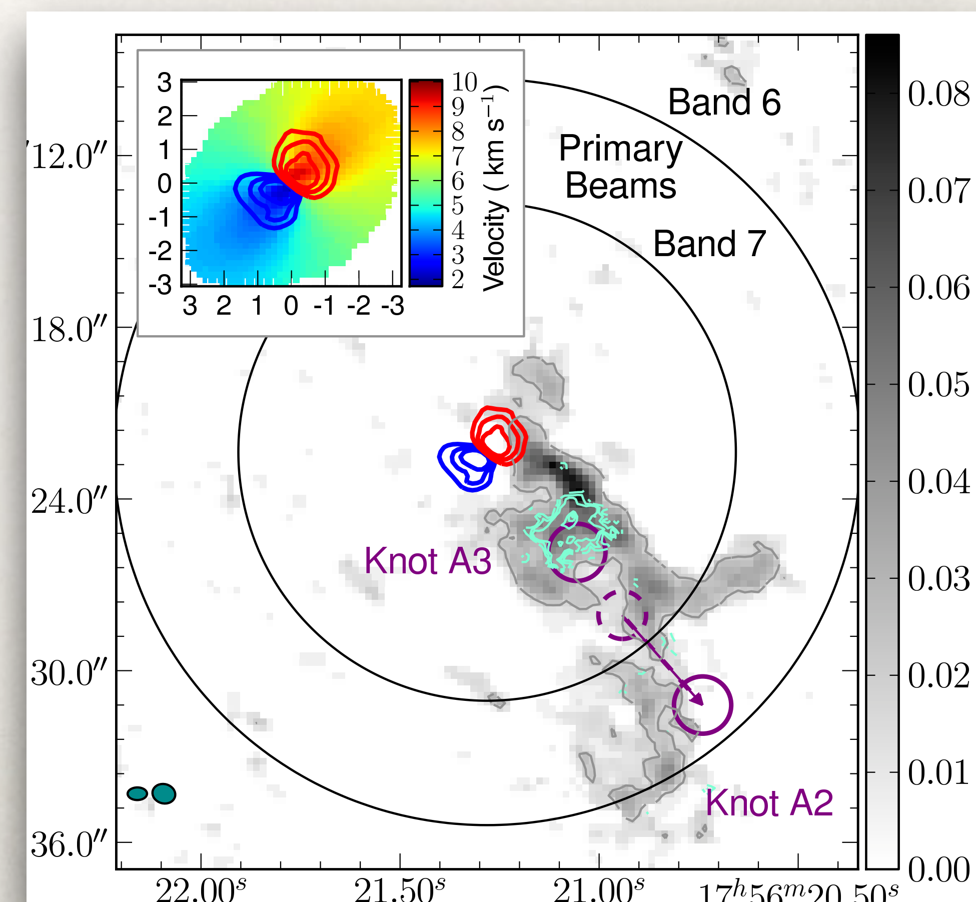
What's Next?

- Why could we only recover the blue shifted wind?
  - because the red lobe was too extended?
- What is the full extent of the wind?
- Is this something we could detect in other systems?

Hopefully we can answer these questions with Cycle 2 data



Wassell et al. 2006



Klaassen et al. 2013

Summary

- With Science Verification data, we've already:
  - Seen the vertical structure of the disk
  - Resolved the location of the CO snow line
  - Discovered a molecular disk wind

And all this for a system we thought we knew well

ALMA is already answering questions we hadn't even asked yet!

de Gregorio-Monsalvo et al. 2013 A&A 557 133
Mathews et al. 2013 A&A 557 132
Klaassen et al. 1013 A&A 555 73