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GMTNIRS and the Promise of High Resolution Spectroscopy in the Infrared: Part 2

Dan Jaffe
The University of Texas at Austin

Today:

Clouds, Cloud chemistry, and Galaxy scale star formation

- Freezeout and excitation, the magic CO ratio
- Photodissoication regions
- Outflows, turbulence, and the destruction of clouds

Evolution of young stellar objects

YSO disks in the planet-forming zone.

H_2 is the most abundant constituent of molecular clouds
H_2 is a homonuclear molecule- no dipole transition
$\Delta J=0,+2,-2$ allowed
H_2 is light=> rotational states far apart

$\Rightarrow$ We trace clouds with CO as substitute.
CO J=1-0 is optically thick
CO may not be excited in cold or low density clouds
CO will freeze onto grains at low temperature.

How good a proxy for H_2 is CO?
=> Measure H_2 ground state using 1-0 S(0) line.

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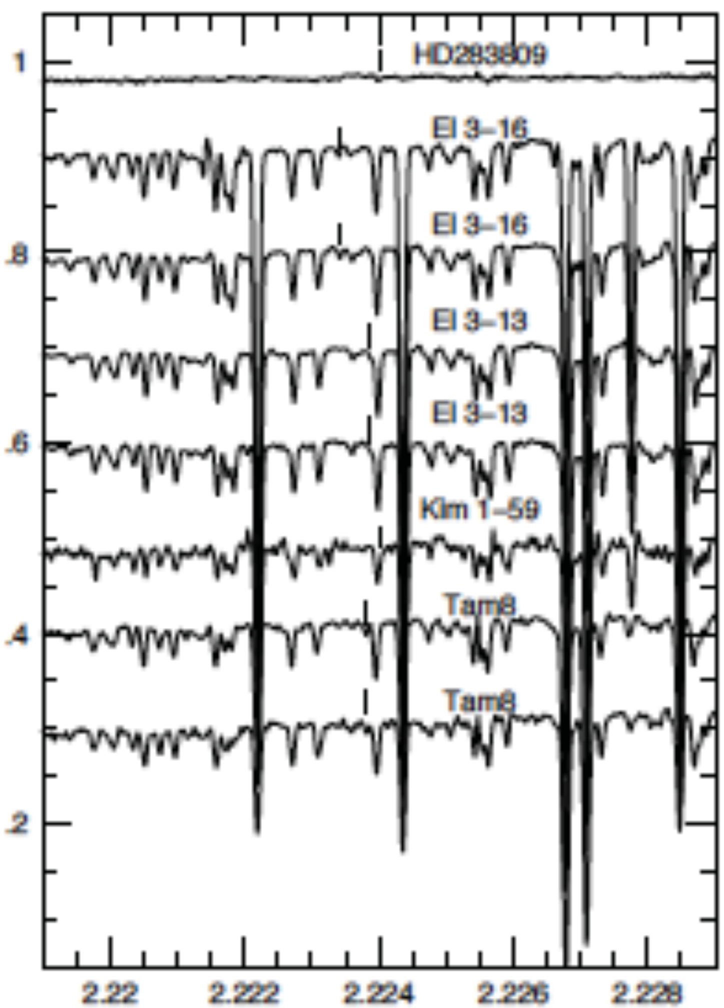
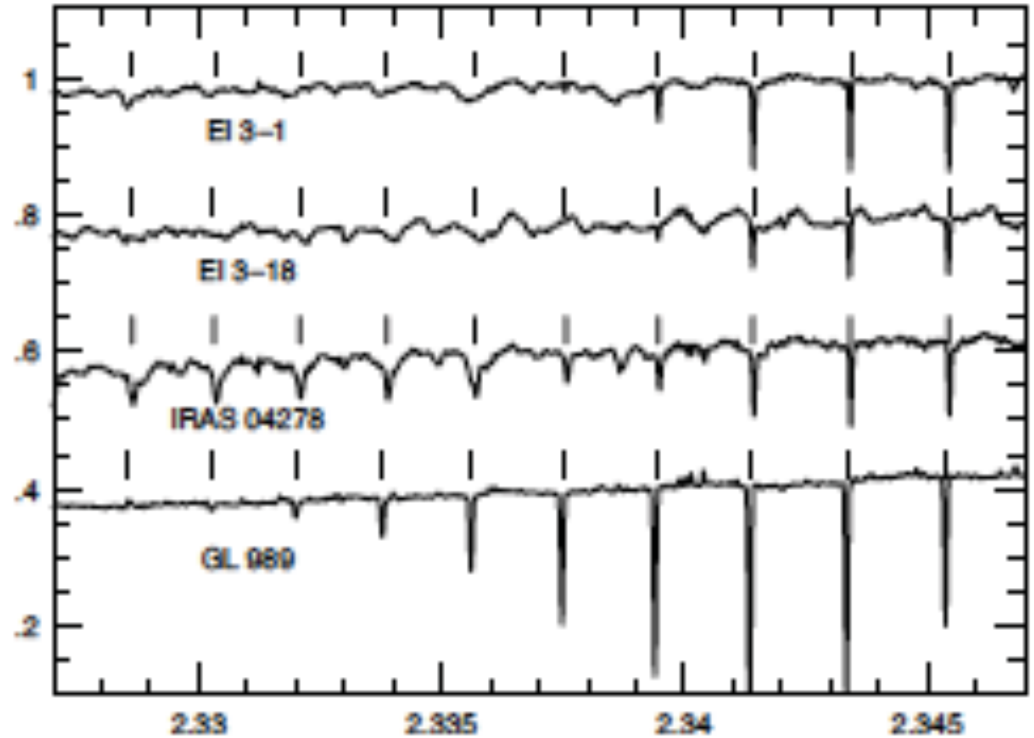
IGRINS spectra of background stars in Taurus





Lacy et al. (2017) derive
N_{CO}/N_{H2}=6000

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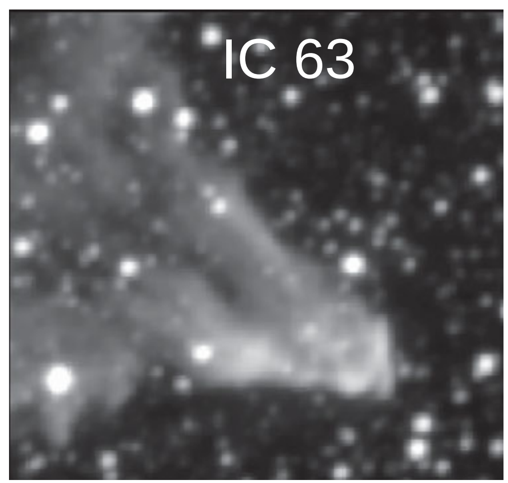
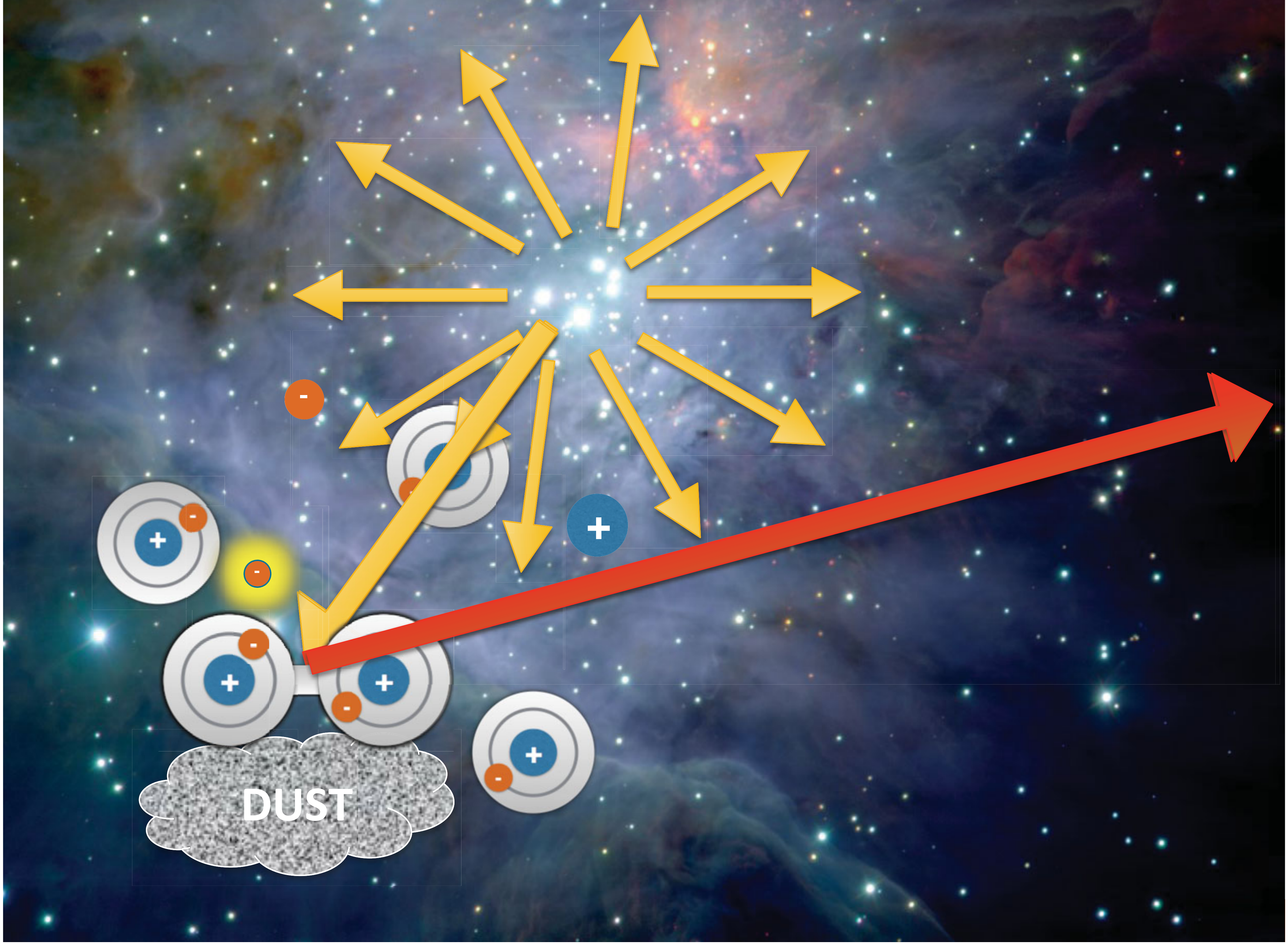
Following Slides from Kyle Kaplan's Thesis 2017

H II Region Edges

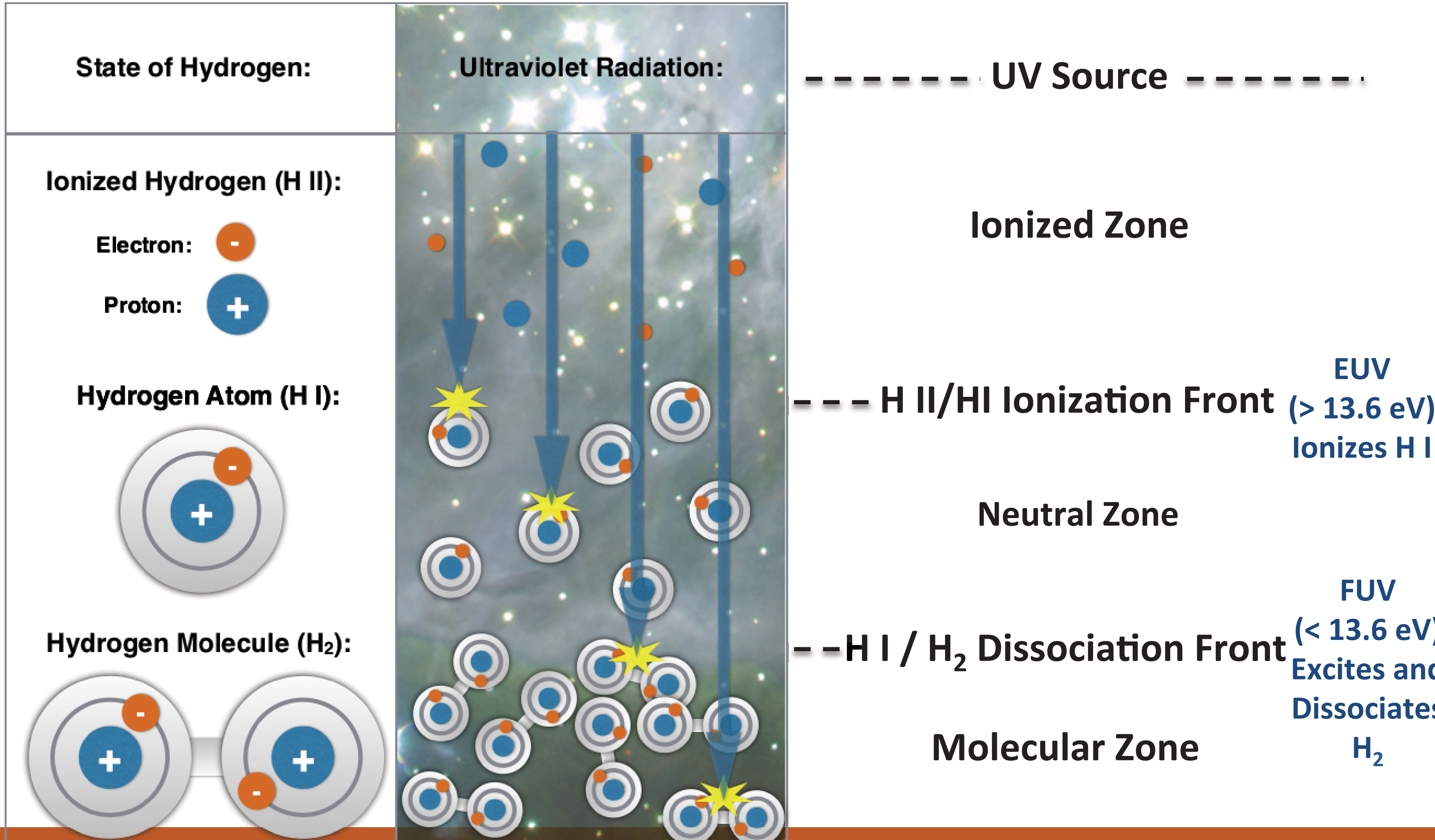
Reflection Nebulae



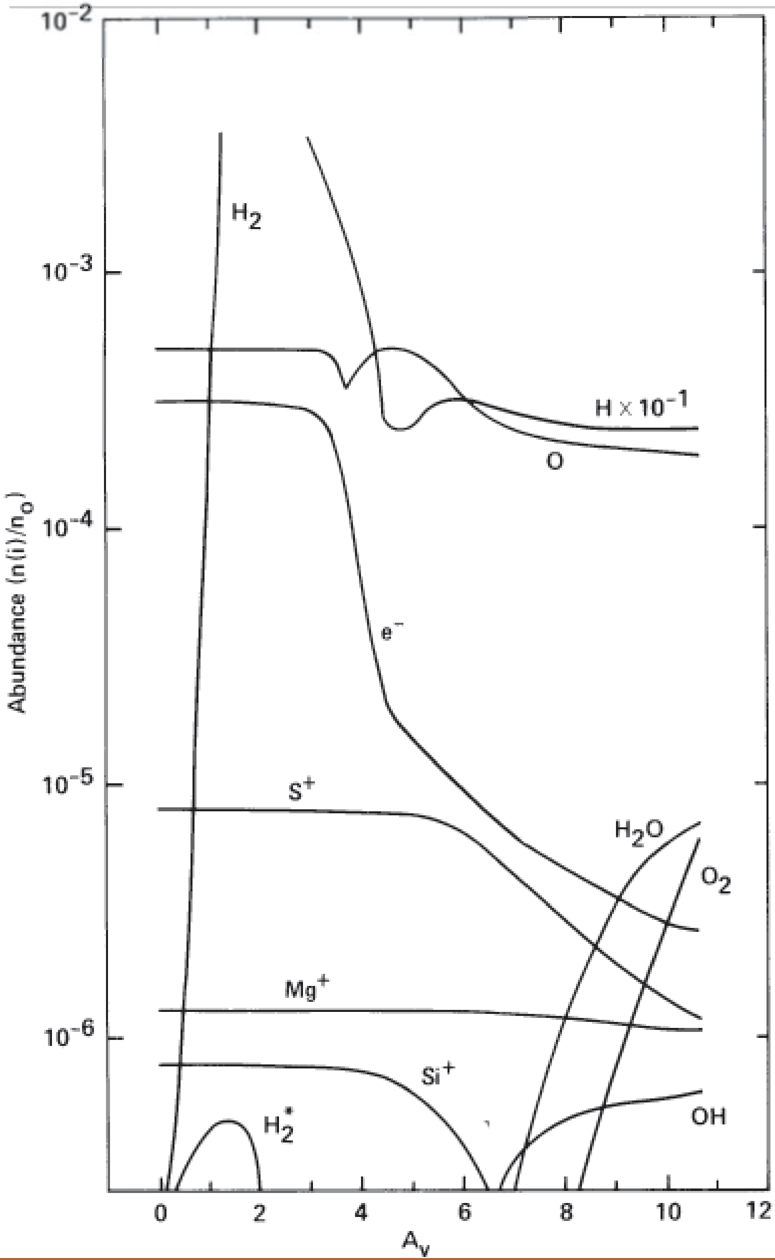
Dark Nebulae

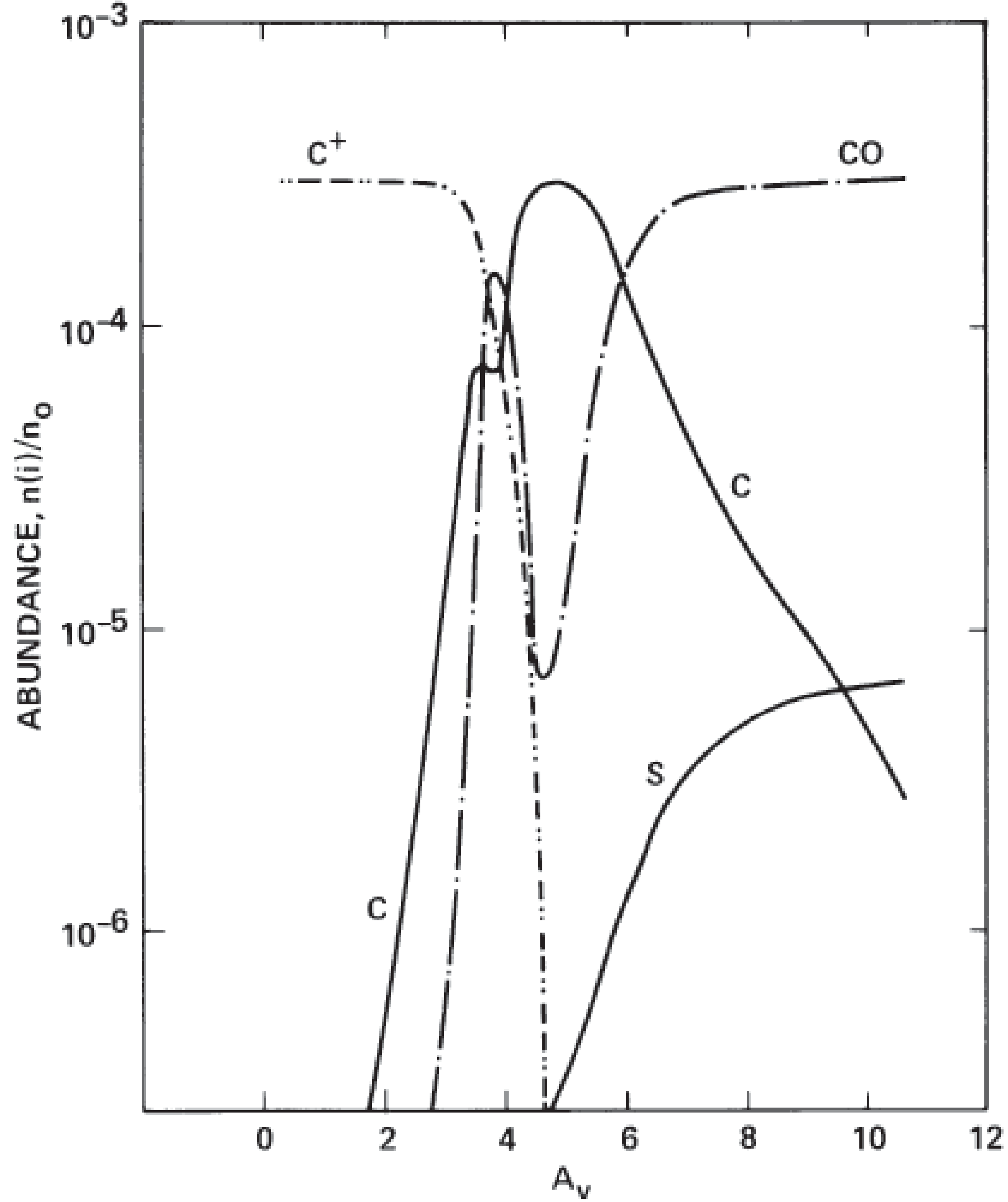

DUST

PDRs (Photodissociation/Photon-dominated Regions)



Tielens, Takahashi, & Hollenbach 1991





Why should we care about PDRs for GMT?

Most of the dense gas in the Galaxy and other spirals is in this form

The AO mode of GMT can see physical effects on interesting scales.

Fluorescent H_2 extends over many parsecs in GMCs- should be able to trace narrow line surfaces of individual GMCs in other galaxies with better than parsec resolution.

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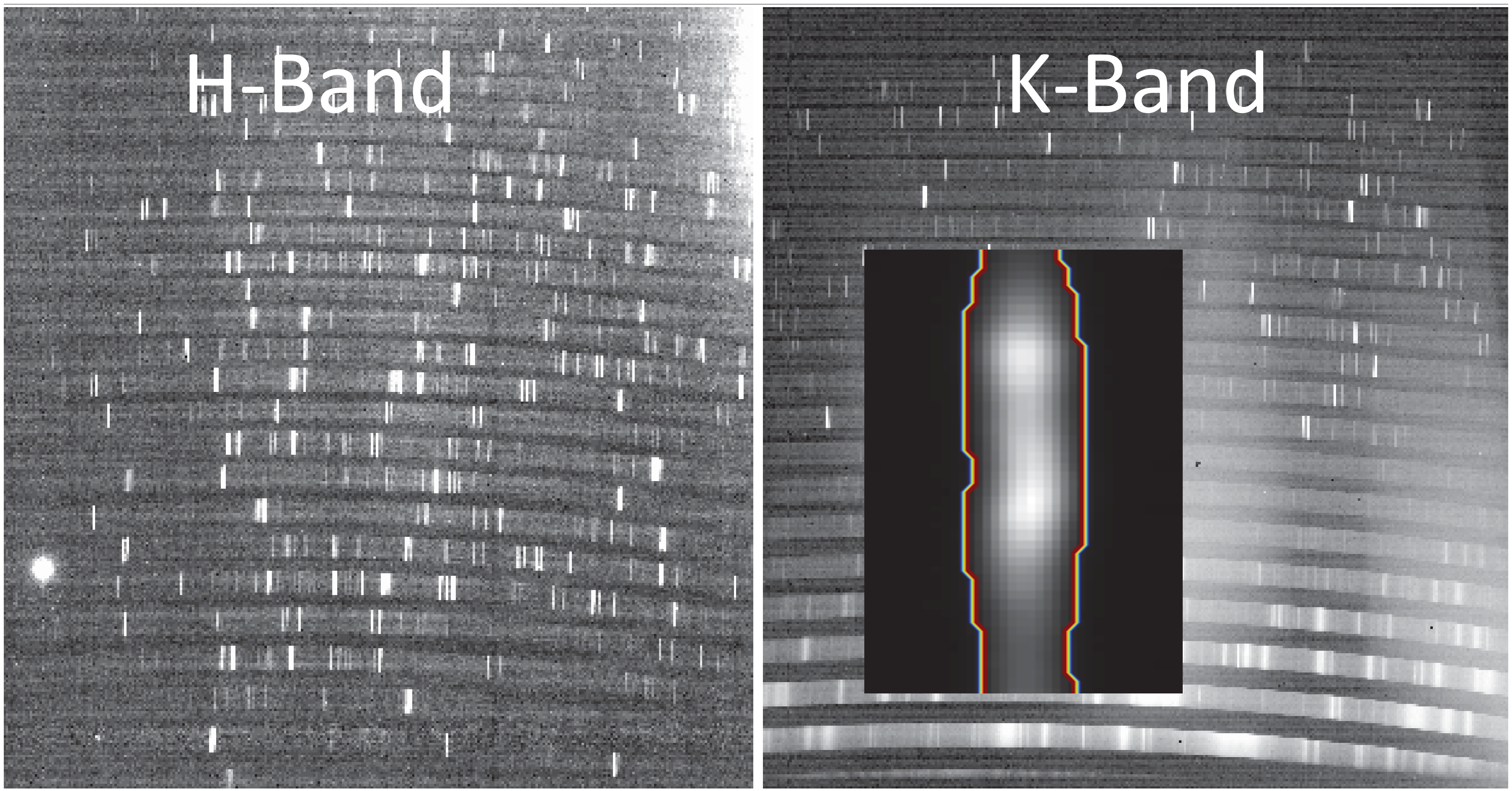
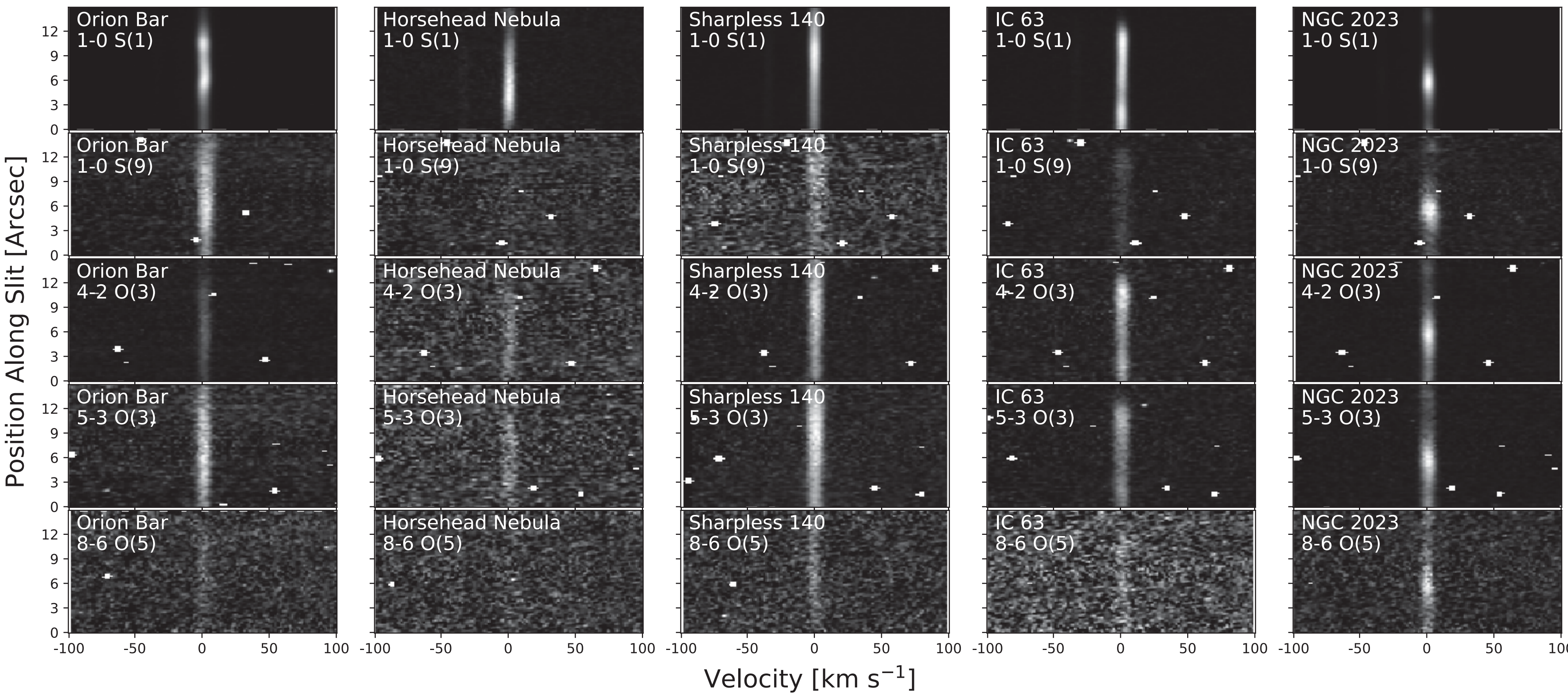
Immersion Grating INfrared Spectrometer (IGRINS)



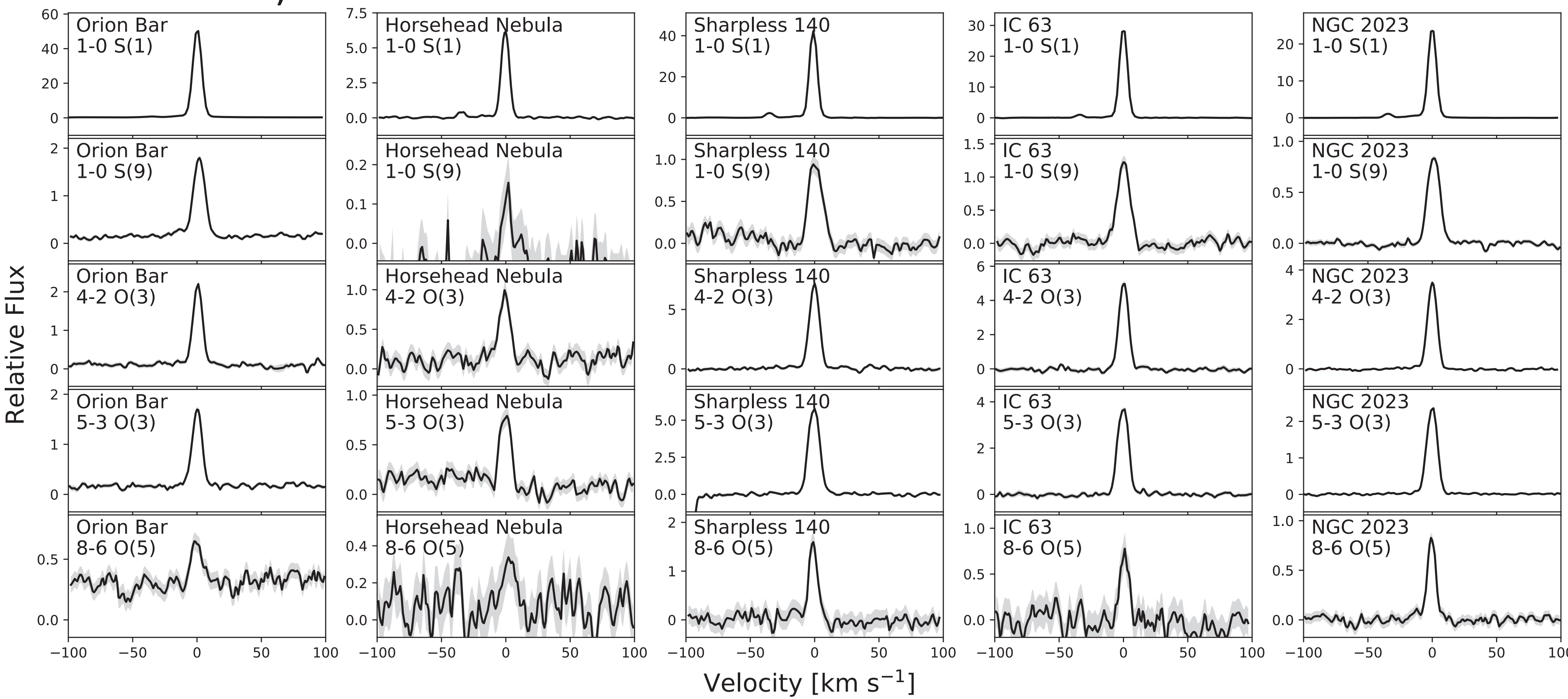
H_2 rovibrational transitions observed with IGRINS

- 2D position-velocity diagrams
- Lines up to high v, J, and excitation energy all visible (typical of UV excitation)
- Lines all narrow
- Gas motions only 1-4 km s^{-1}
- Unlikely shocks



H_2 rovibrational transitions observed with IGRINS

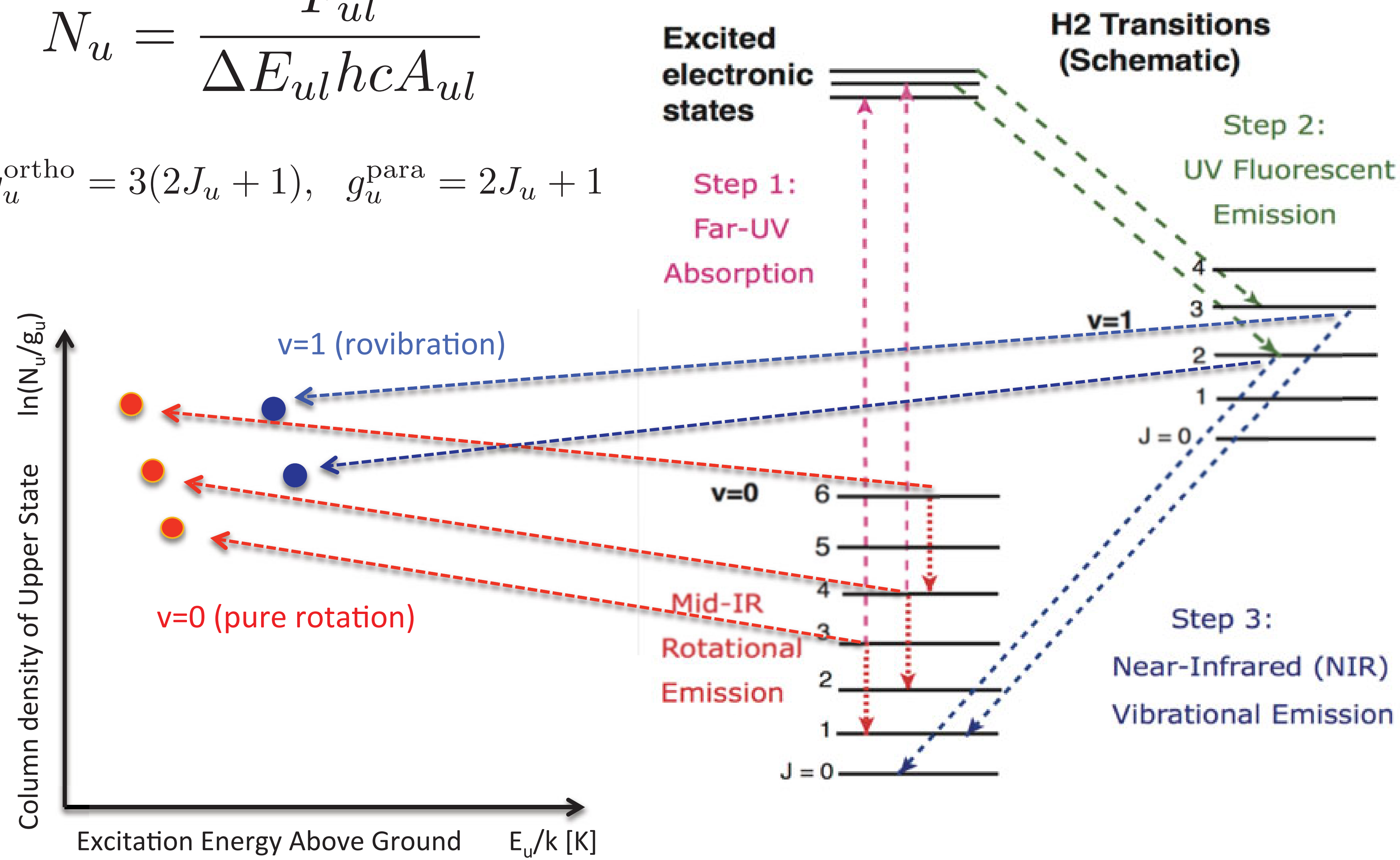
- 1D thumbnails
- Lines up to high v, J, and excitation energy all visible (typical of UV excitation)
- Lines all narrow
- Gas motions only 1-4 km s^{-1}
- Unlikely shocks



The Excitation Diagram

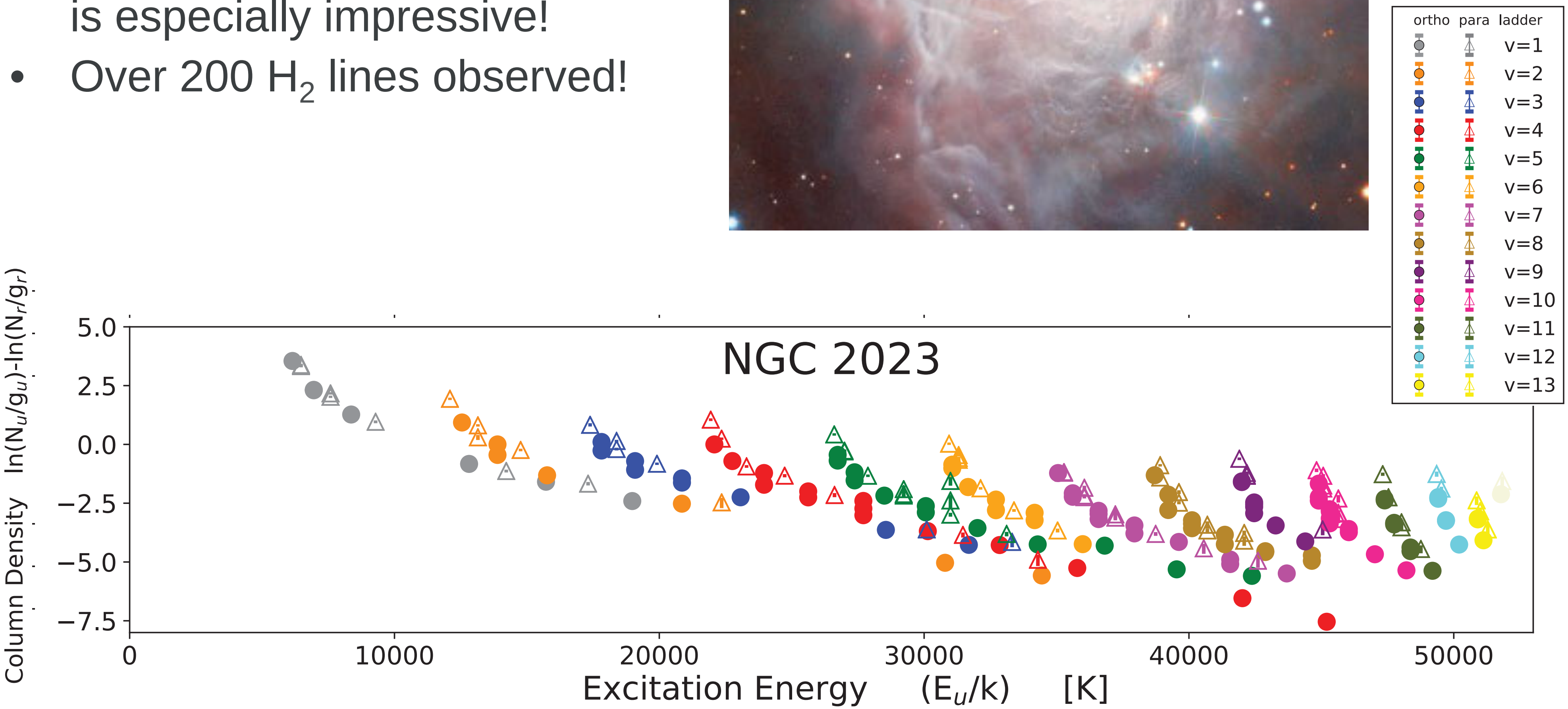
$$N_u = \frac{F_{ul}}{\Delta E_{ul} h c A_{ul}}$$

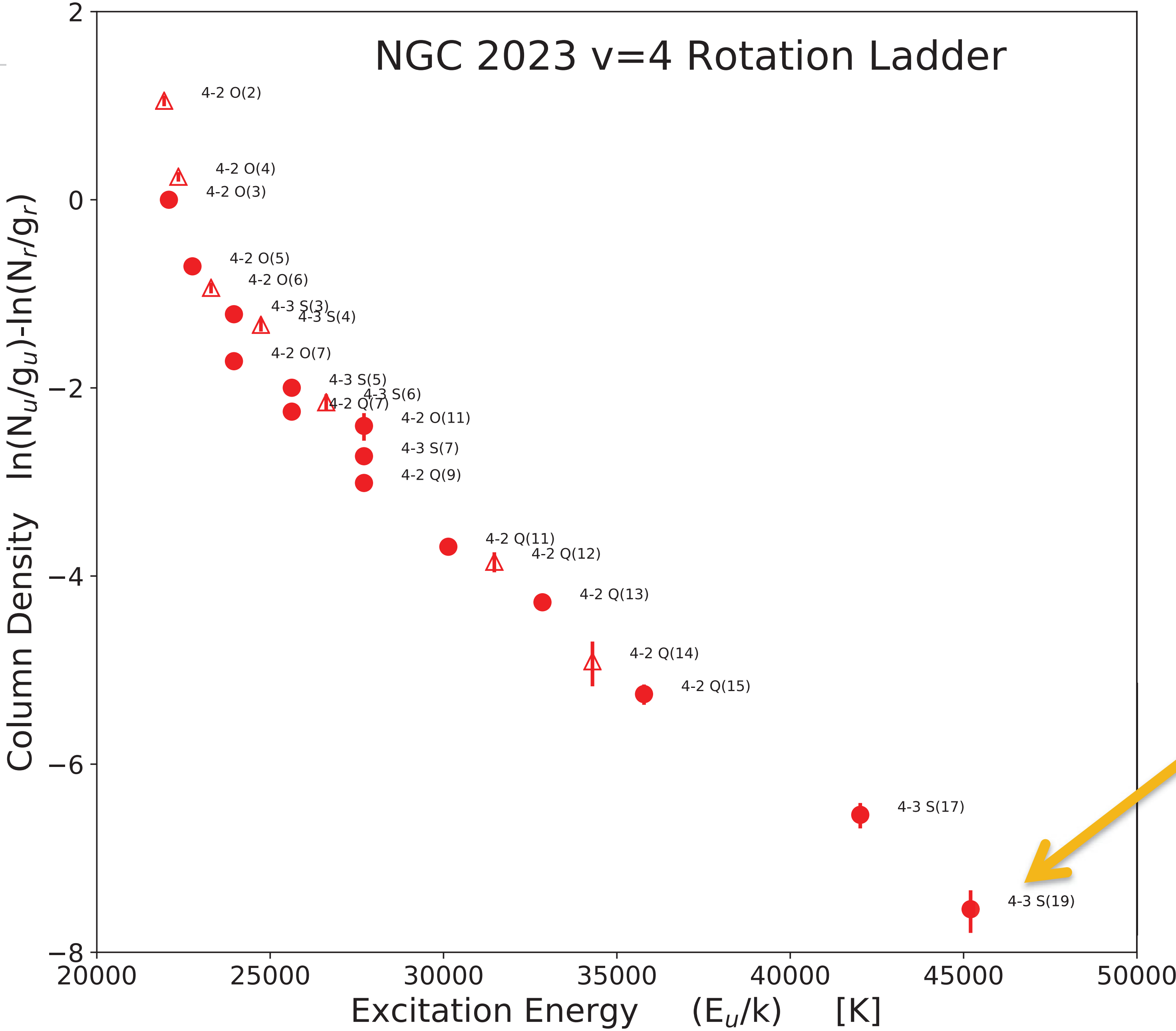
$$g_u^{\rm ortho} = 3(2J_u + 1), \quad g_u^{\rm para} = 2J_u + 1$$



NGC 2023

- High S/N NGC 2023 spectrum is especially impressive!
- Over 200 H_2 lines observed!





The v=4 rotation ladder in NGC 2023 is especially impressive!

v=4, J=21

Outflows, turbulence, and the destruction of clouds

High mass outflows, bullets and the destruction of clouds
Low mass outflows, angular momentum, shocks

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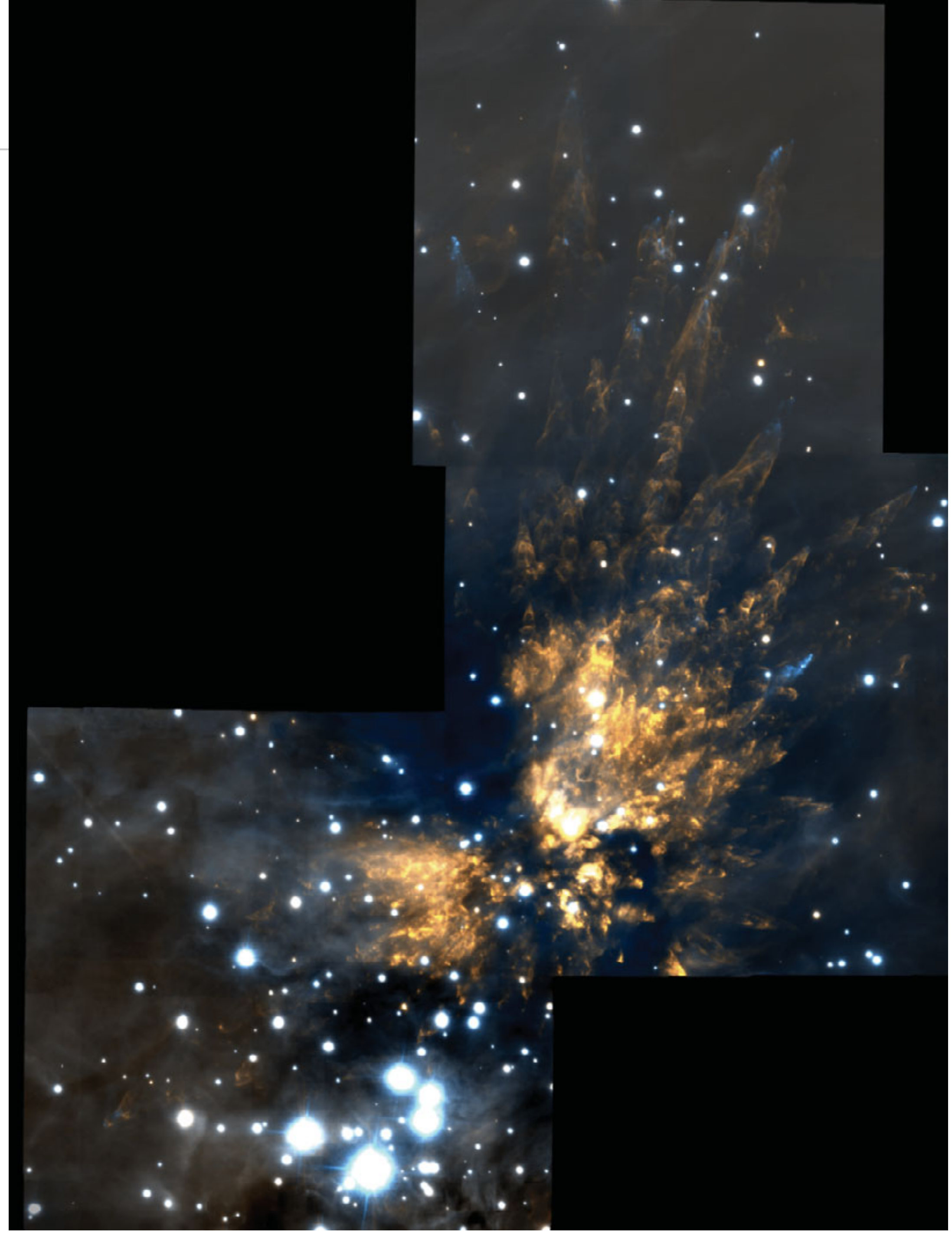
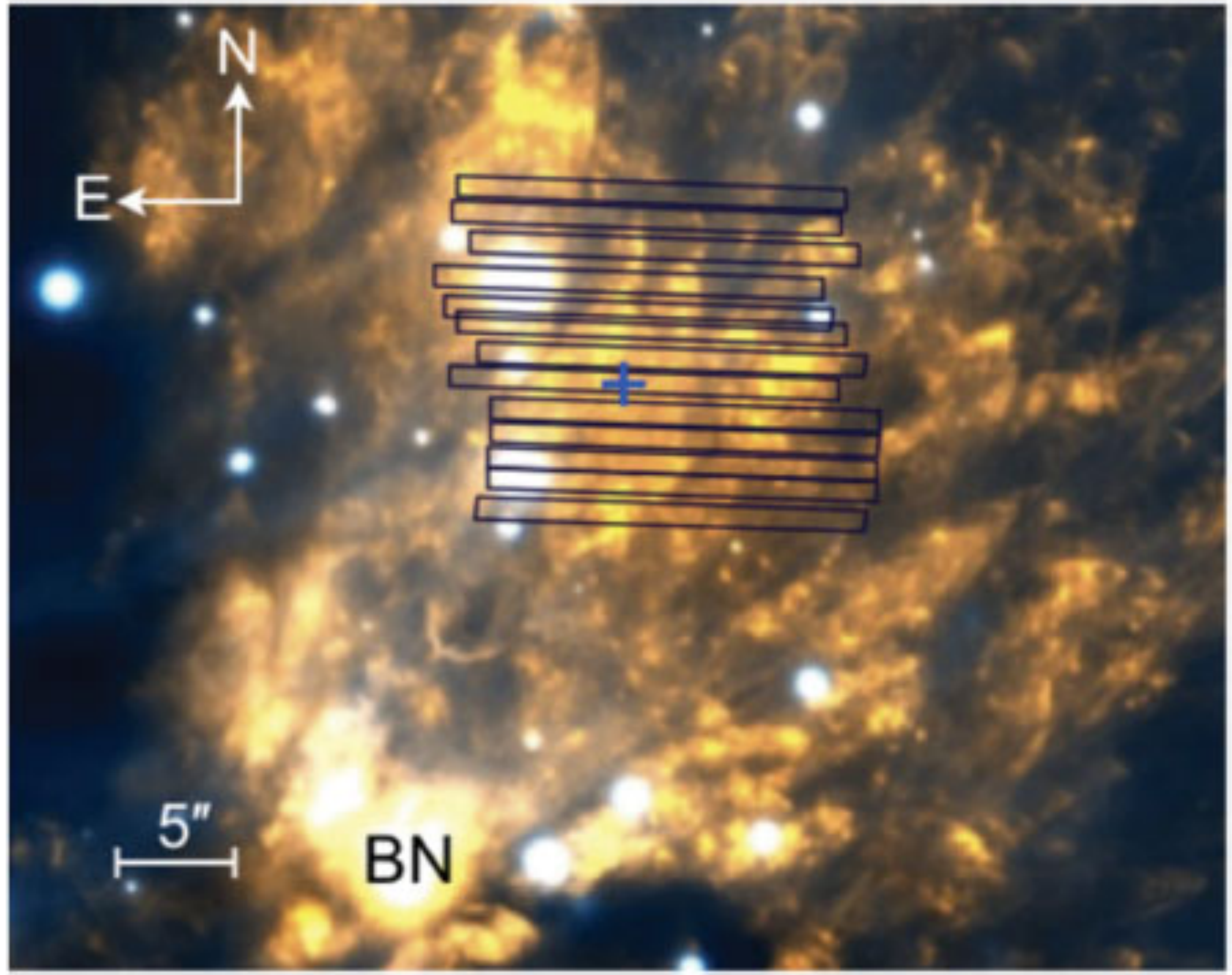
Orion/KL Outflow in H_2

Bally et al. (2015)



Oh et al. 2016, IGRINS map of Orion KL

Slit mapping: the poor person's IFU



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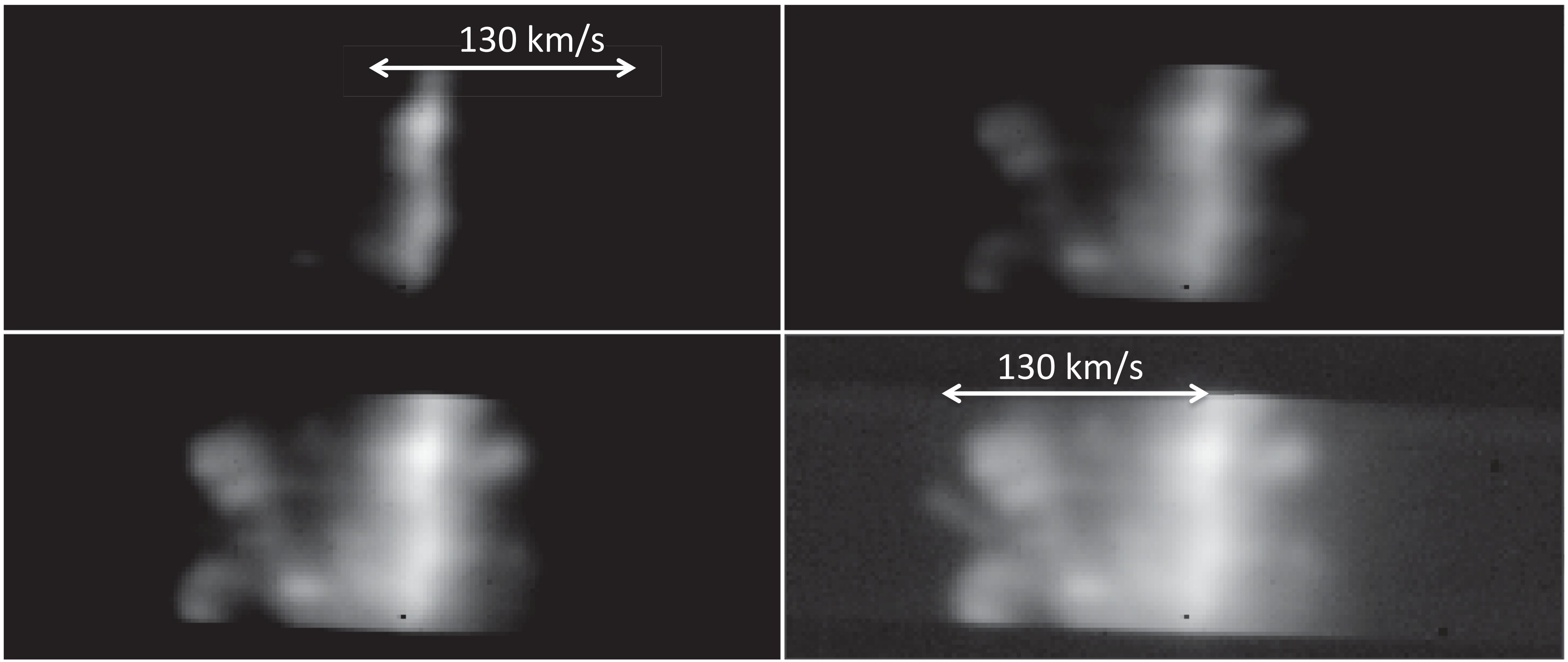
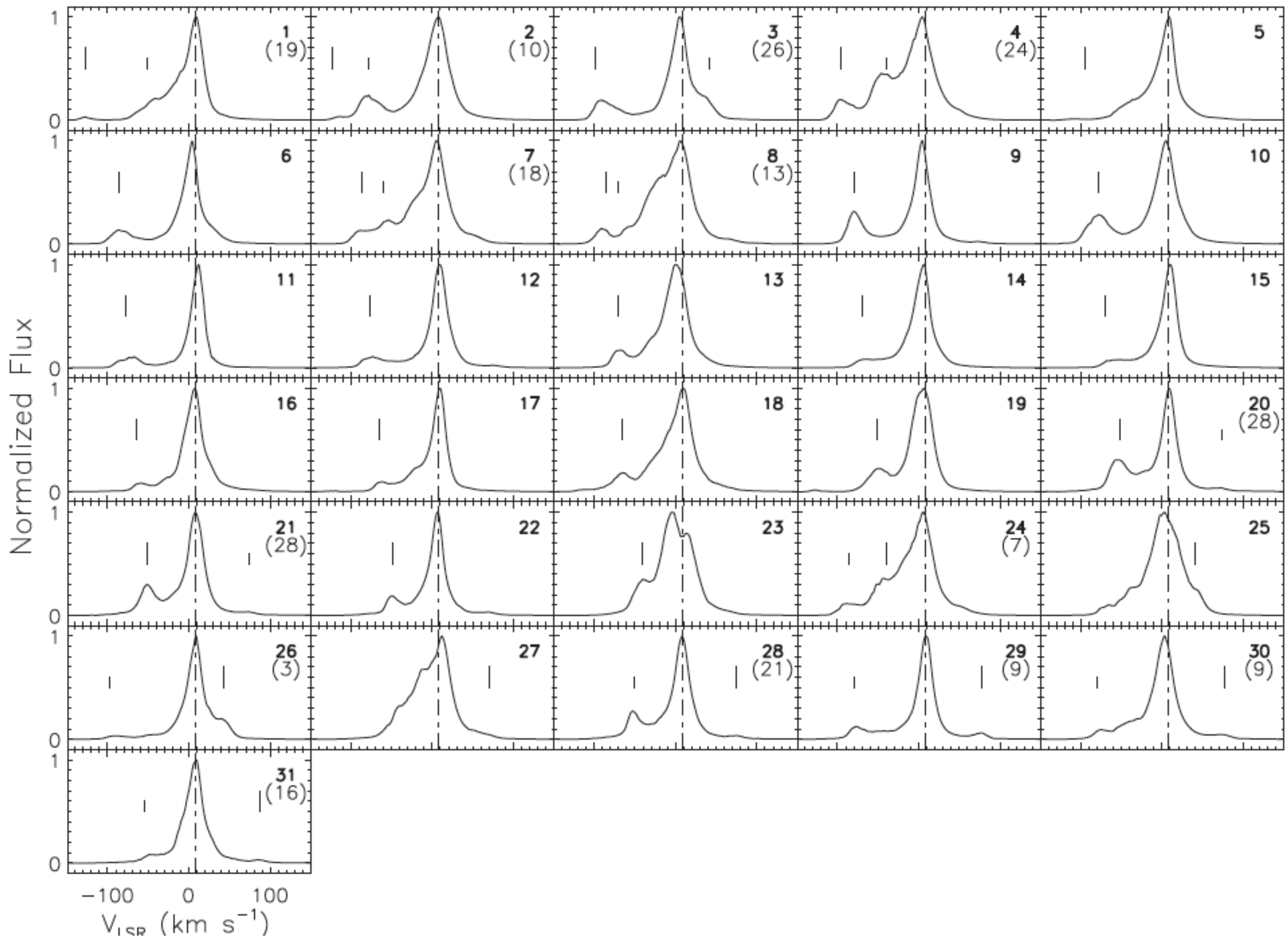
Position-velocity diagrams reveal the kinematics of the bow.
These are all the same slit image but with different greyscales.




Normalized Flux
V_LSR (km s^-1)
−100
0
100
1
0
1 (19)
2 (10)
3 (26)
4 (24)
5
6
7 (18)
8 (13)
9
10
11
12
13
14
15
16
17
18
19
20 (28)
21 (28)
22
23
24 (7)
25
26 (3)
27
28 (21)
29 (9)
30 (9)
31 (16)

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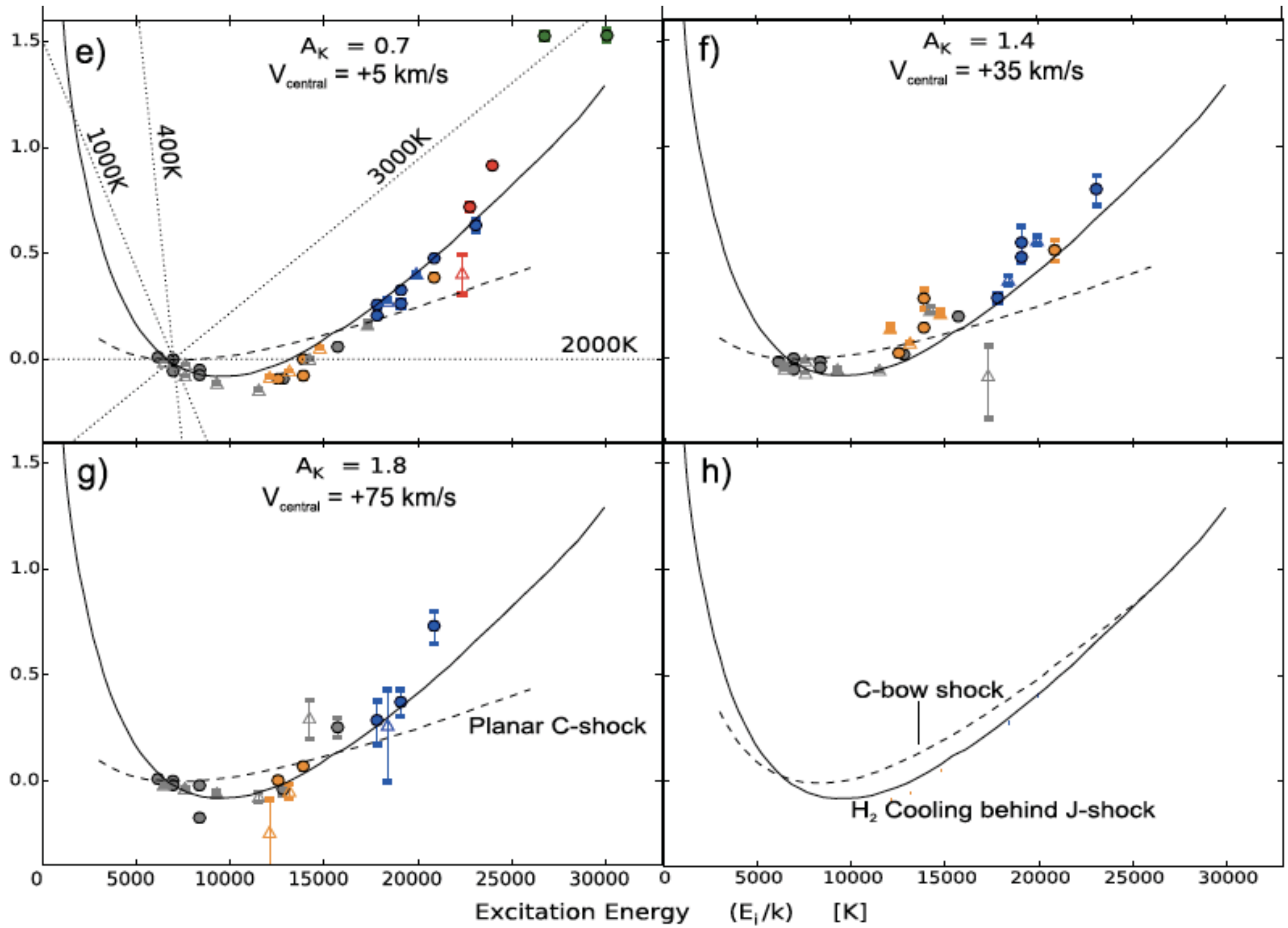
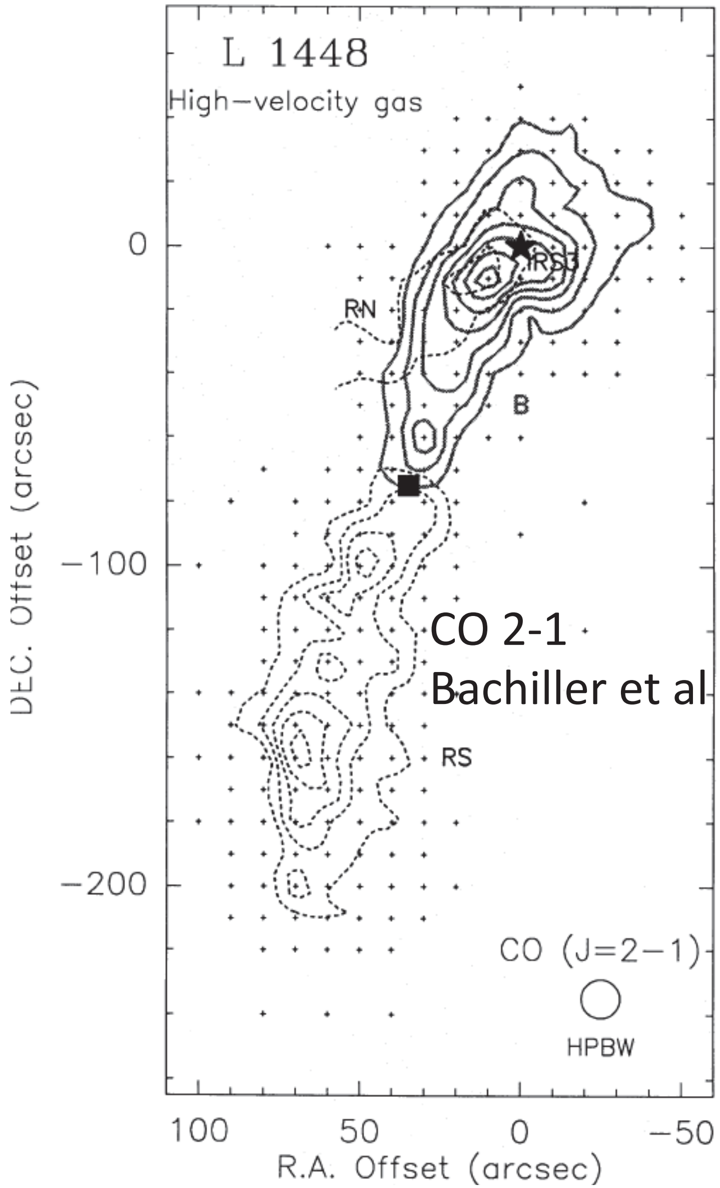
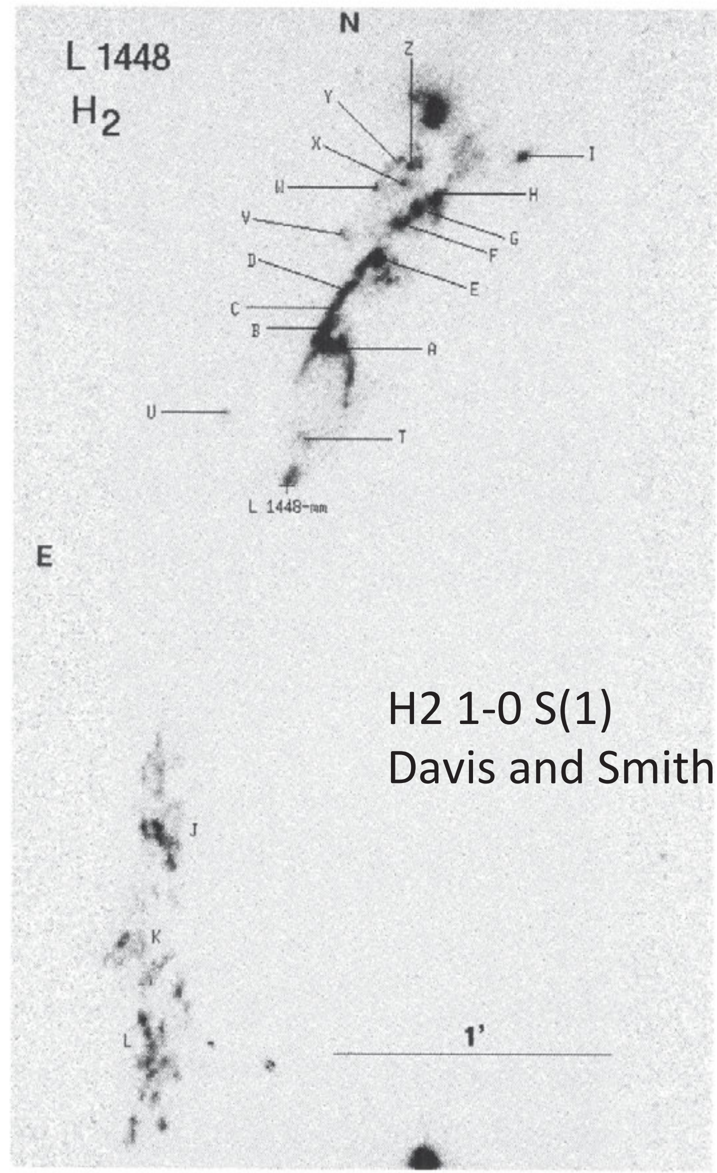


L1448 Low mass Class I YSO with jet

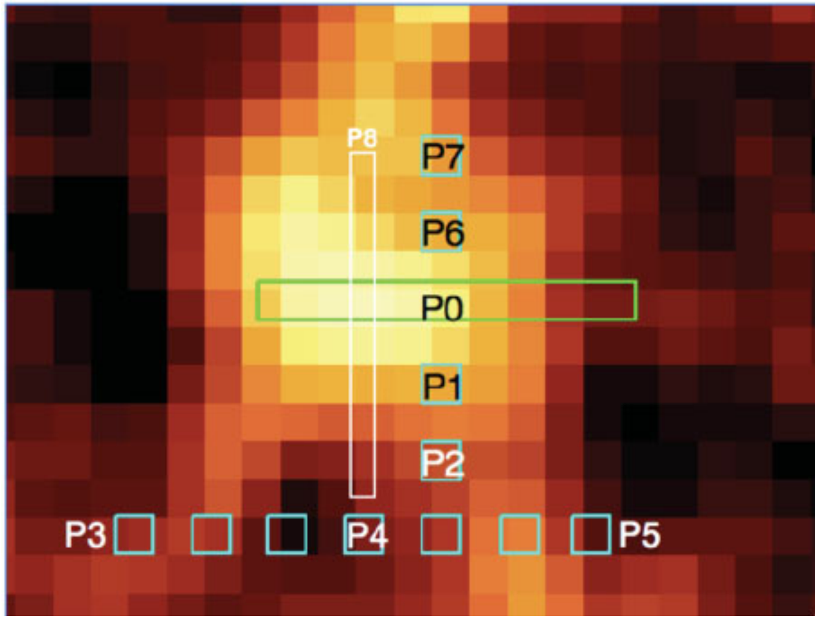


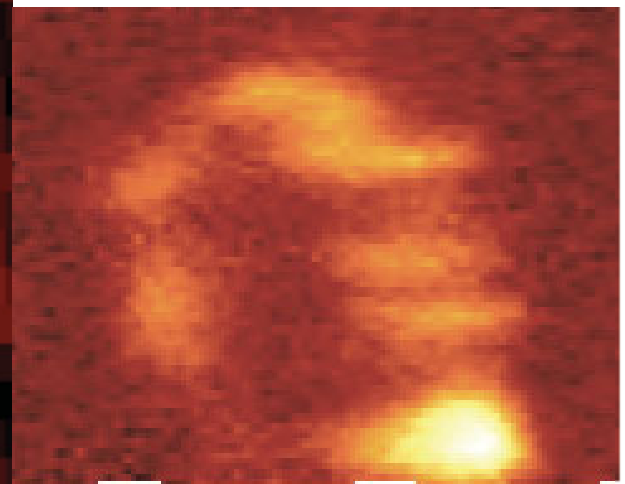
CO 2-1
Bachiller et al 1990

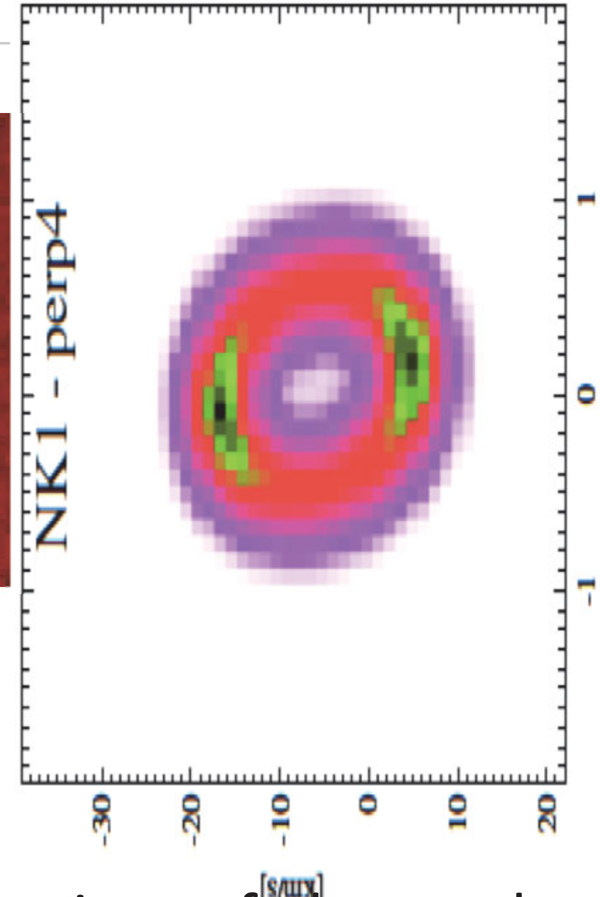


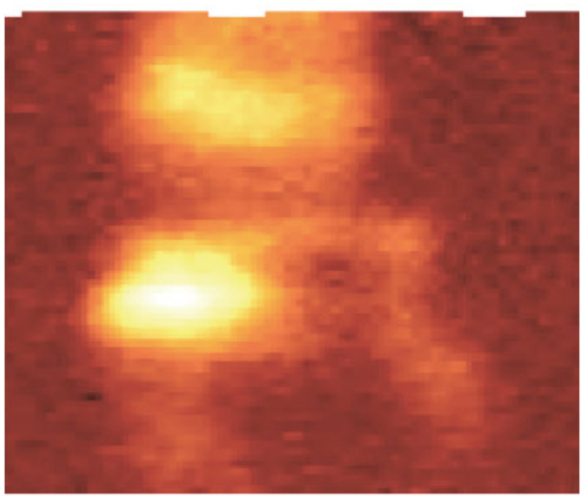
H2 1-0 S(1)
Davis and Smith 1995

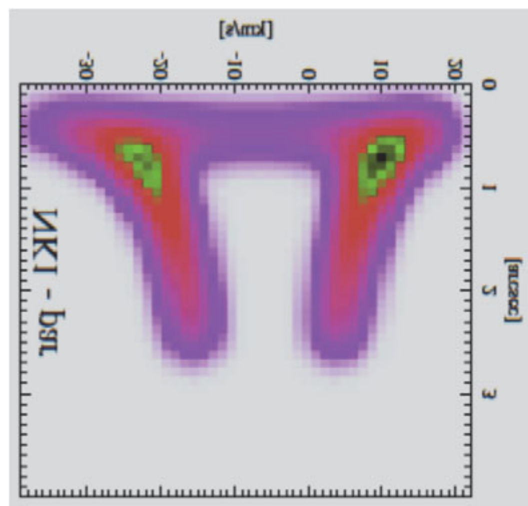
L1448 H2 1-0 S(1) IGRINS-Jaffe et al. in prep











Comparison of observed and model (Correia et al 2009) for position 1 (above) and position 8 (left)

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Evolution of young stellar objects
Problems in measurement
How we can do better logg, B
Two-temperature chromosphere

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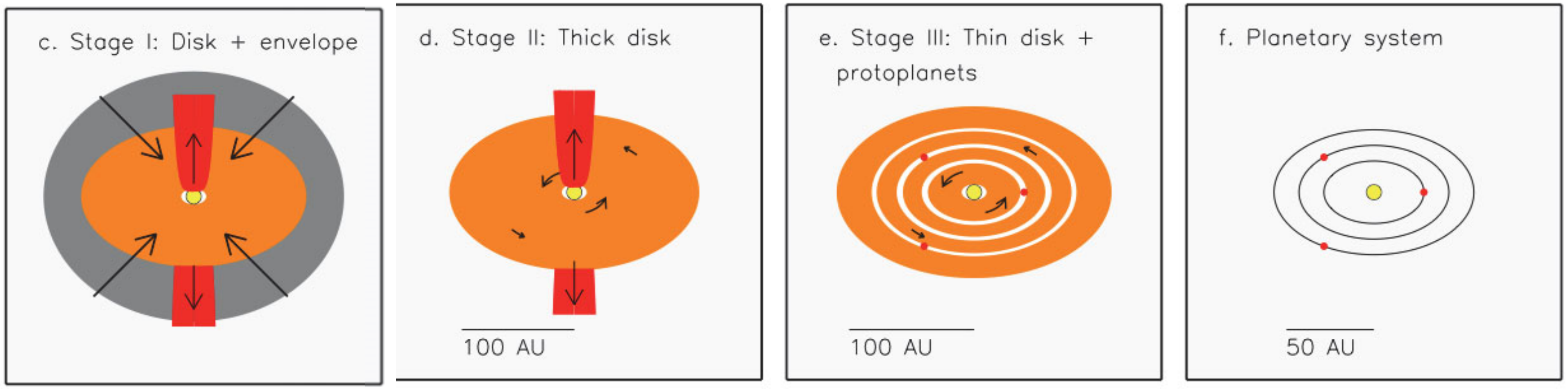
We know that planets are common- Jupiters and even more so terrestrial planets.
We have a kind of cartoon story of how the formation process for planets unfolds,

Physical Stages



Class 0 Far-IR Submm only

Class I Peak in far-IR

Class II Flat spectra in $\lambda F\lambda$

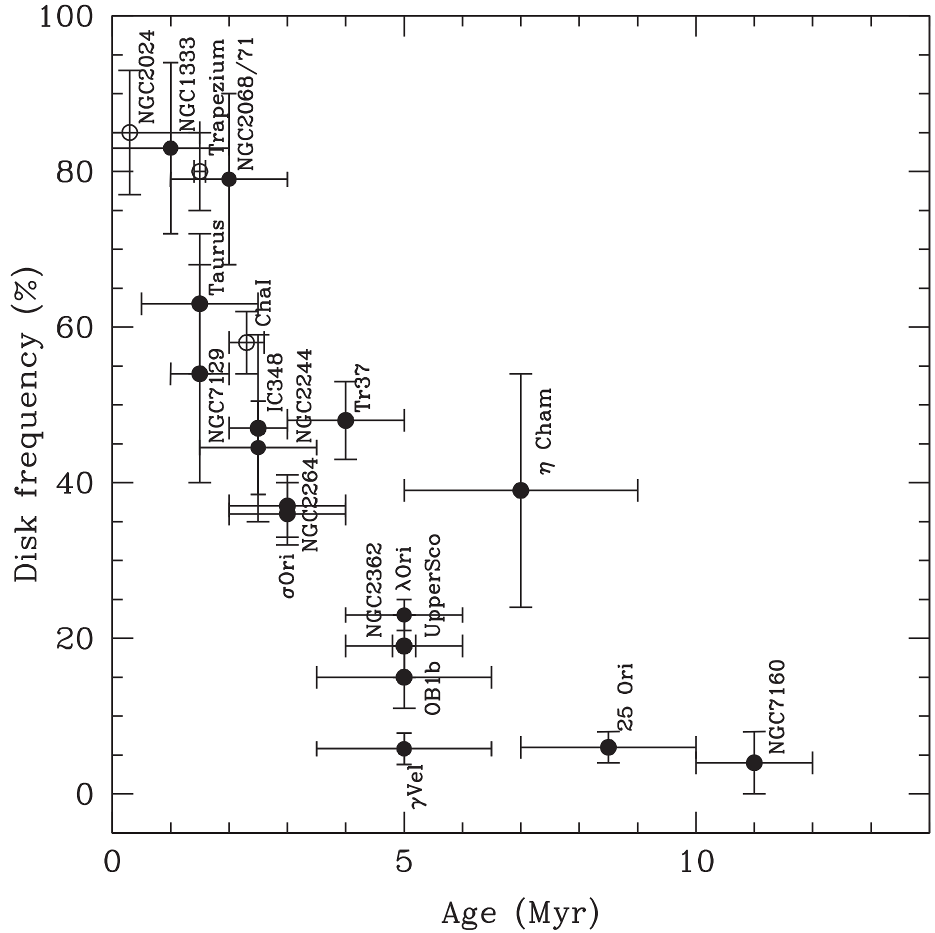
Spectrum with gap

Class III Photospheric "Blackbody"

Spectral Energy Distribution Classes

"At the moment it's just a Notion, but with a bit of backing I think I could turn it into a Concept, and then an Idea." - from Annie Hall

Understanding the timescales is a key element



Hernandez et al. (2008)

Disks disappear, constraining the ability of planets to form.

Is enough attention being paid to the X axis??

Is the scenario right, especially the age-SED relation?
There are many issues still to resolve:

How does the environment affect collapse?
Which protostars form what kind of systems?
How does mass and angular momentum loss feed back to the cloud?
How does angular momentum move through the star-disk-planet system and what is the role of the magnetic field?
Why do some stars lose their disks quickly and others very slowly?
How does accretion interplay with everything else?

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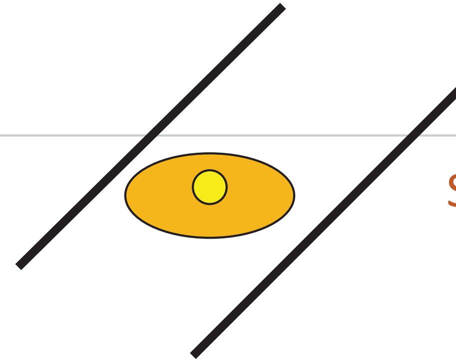
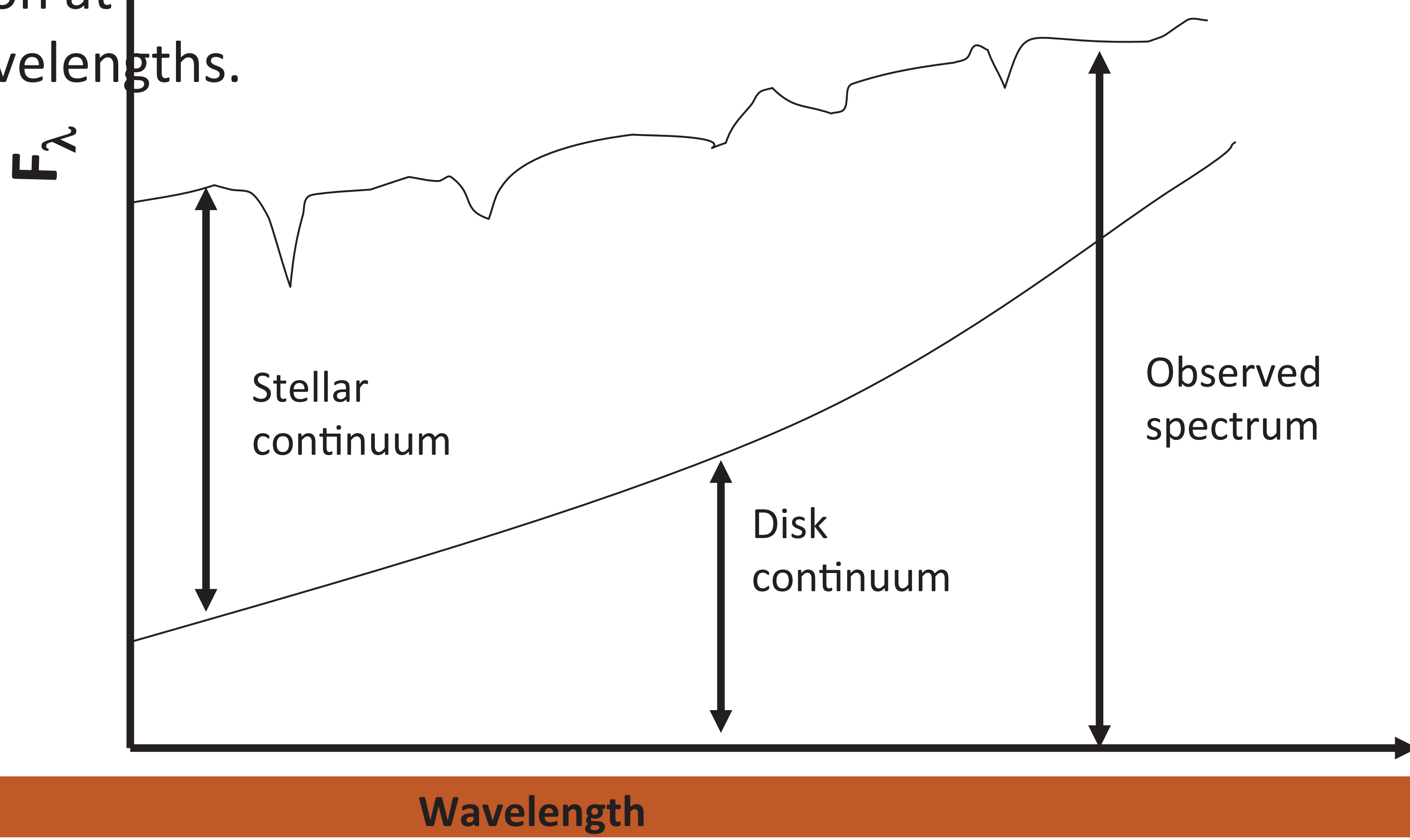
Infrared Excess (also known as Veiling):

$$r_\lambda = (F_{obs}/F_{stellar})-1$$



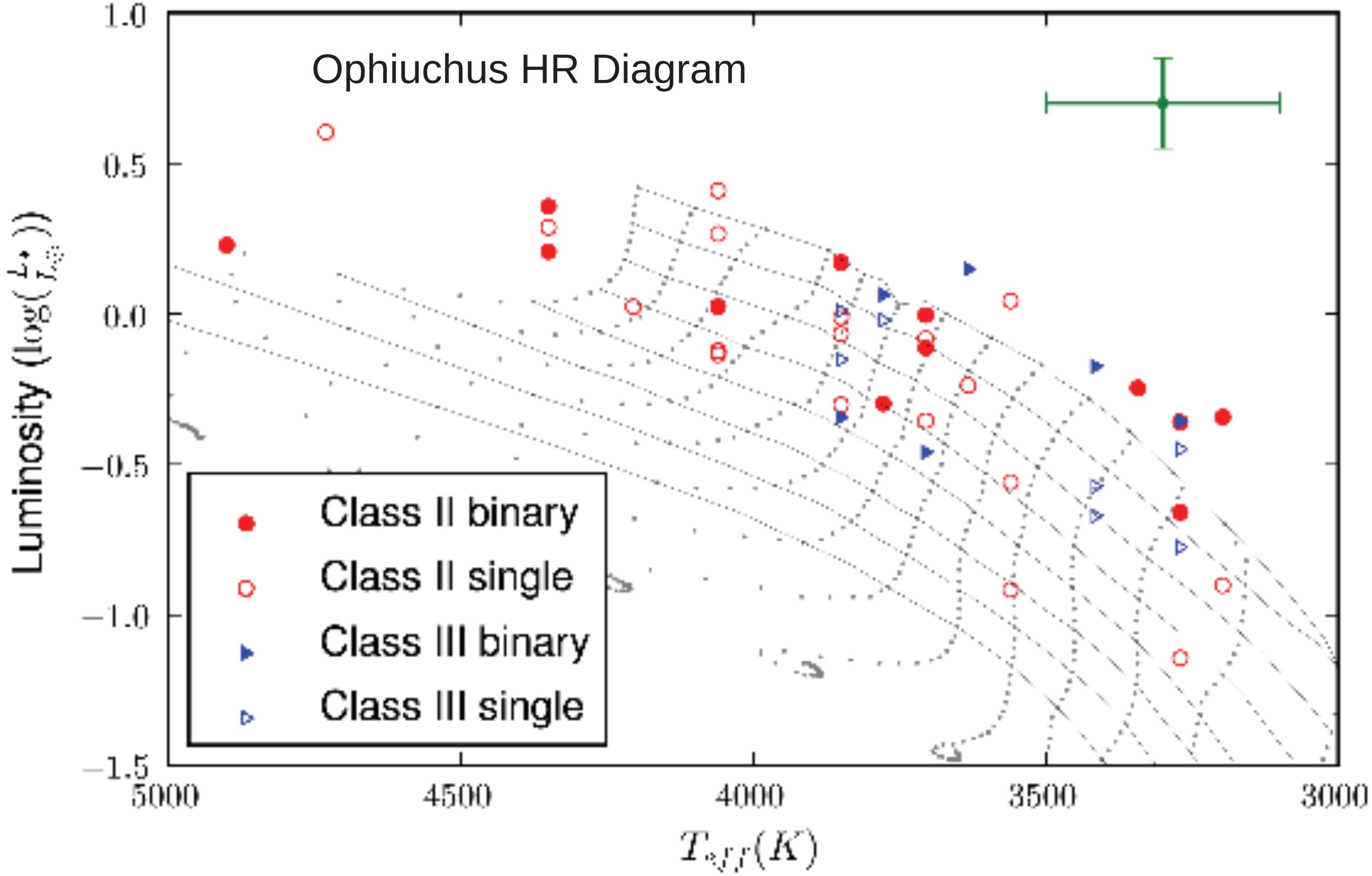
Problem:
There is non-photospheric emission at all wavelengths.



When we use low-resolution spectra, we see considerable age spread. Some theorists argue that this is a physical consequence of accretion. Much of it, however, is measurement uncertainty.

- <disks> = 2.4 +/- 0.3 Myr
- <no disks> = 2.3 +/- 0.5 Myr

Casey Deen PhD Thesis (2012)



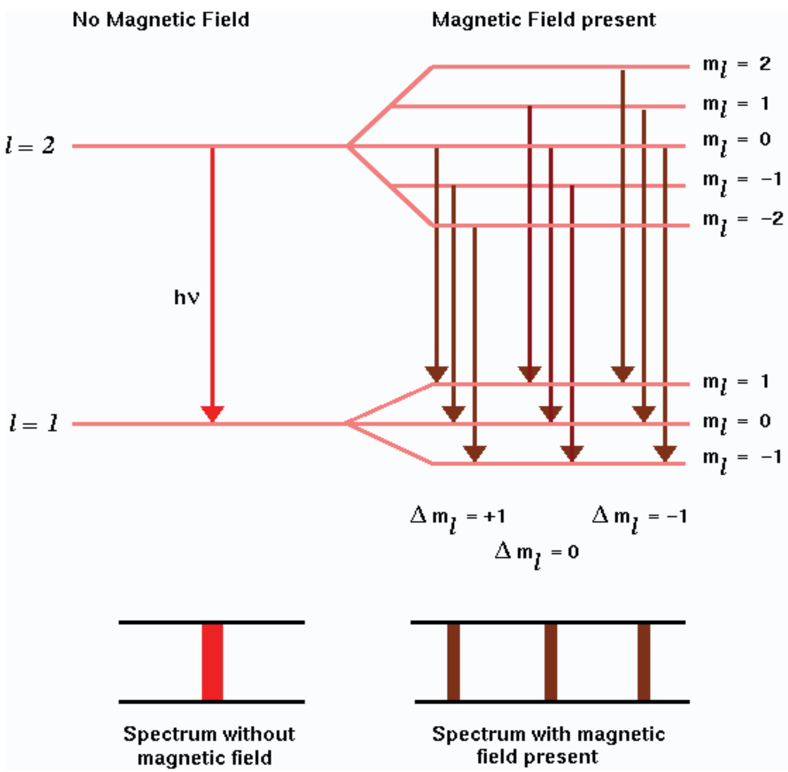
Magnetic Fields:

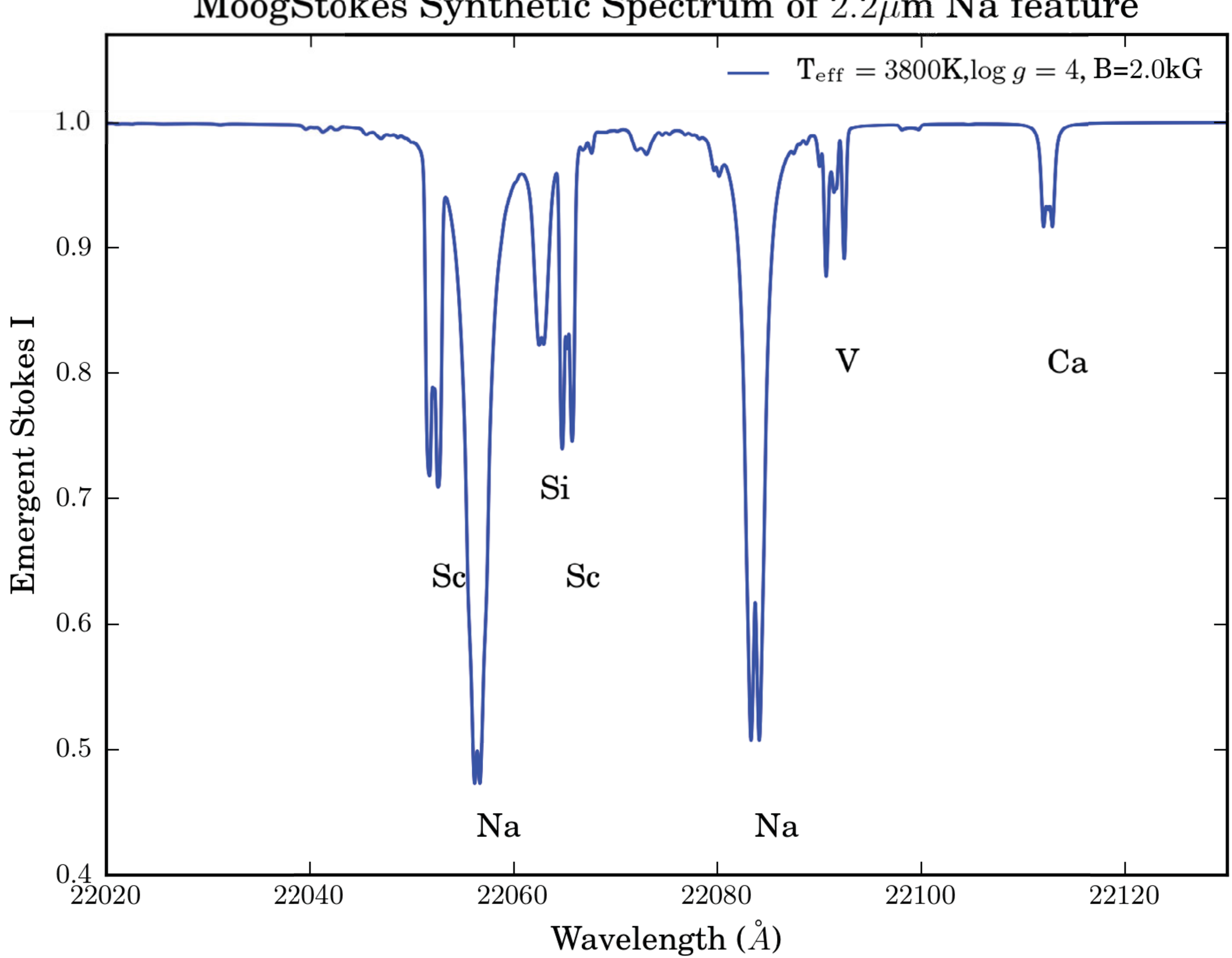
A problem and blessing at high resolution.

- Necessary components of YSO-Disk theories
  - Magnetospheric Accretion
  - Disk locking and Angular Momentum Transport
- Strong Magnetic Fields have already been measured in YSOs
  - Johns-Krull (2007) finds evidence for strong magnetic fields in 15 Taurus YSOs

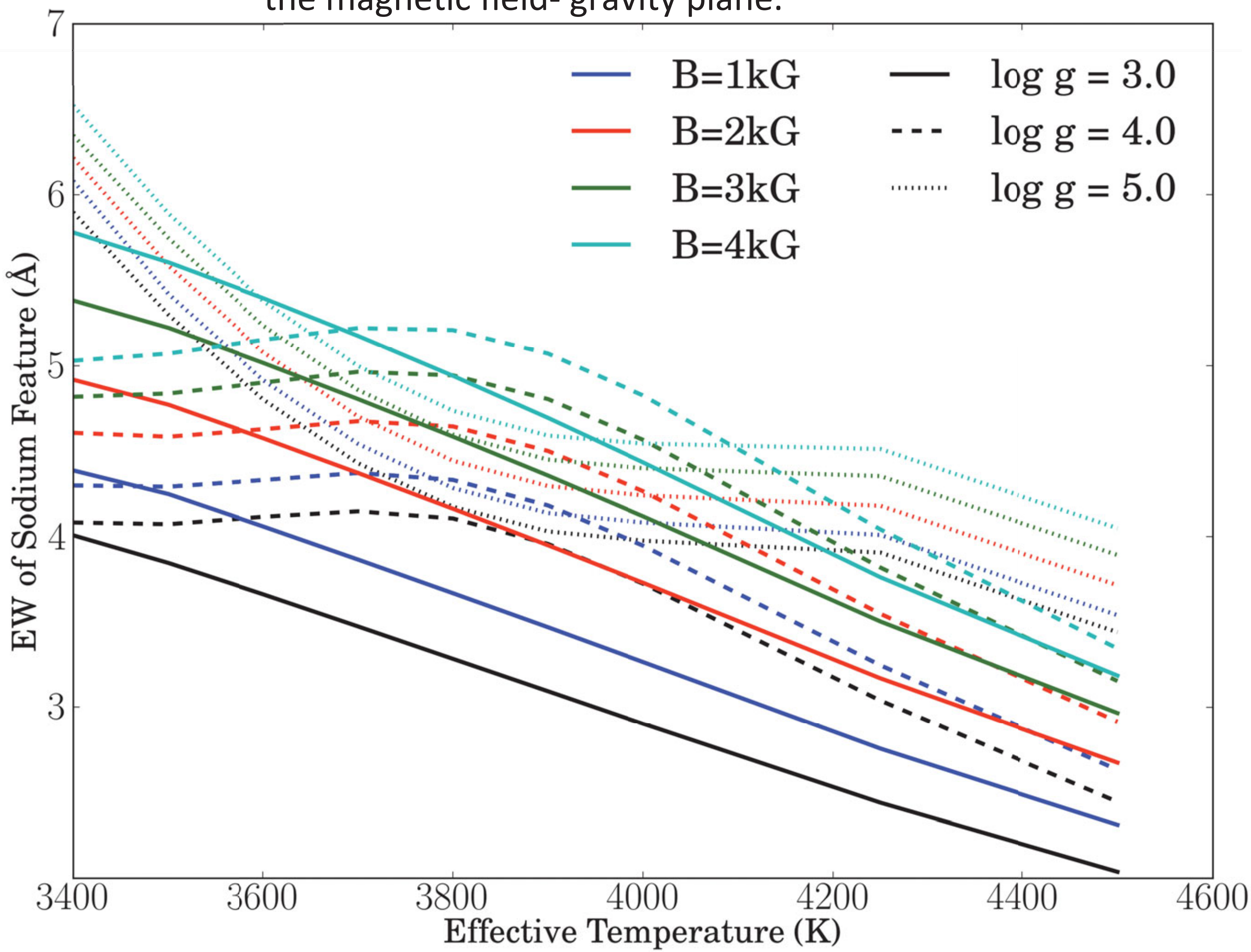
Magnetic Fields- Casey Deen (2013)
MPIA to the rescue

The Zeeman effect will alter the strength of optically thick photospheric lines by spreading their absorptive power over a larger range of wavelengths.




MoogStokes Synthetic Spectrum of 2.2μm Na feature
T_{eff} = 3800K, log g = 4, B=2.0kG
Emergent Stokes I
Wavelength (Å)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
22020
22040
22060
22080
22100
22120
Sc
Na
Si
Sc
Na
V
Ca

Even at a known temperature, equivalent width is degenerate in the magnetic field- gravity plane.



Stokes Vector Equation of Radiative Transf

- Stokes Vector equation of Radiative Transfer:
  - $d\mathbf{I}/d\tau = \mathbf{K}\mathbf{I} - \mathbf{S}$

where $\mathbf{I} = \{I, Q, U, V\}^T$

K = opacity matrix

S = Source function

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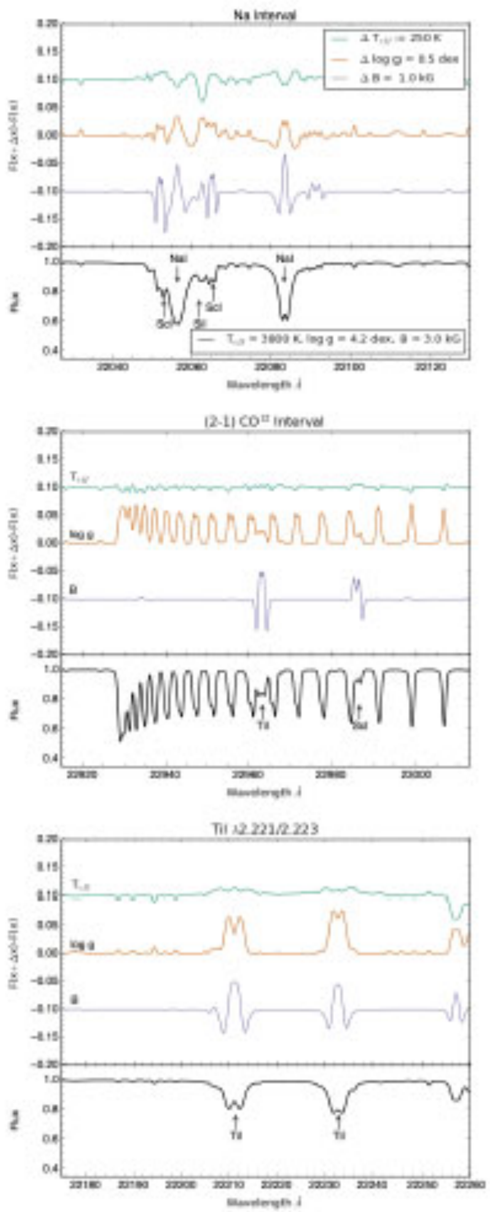
Moog-Stokes modeling of IR Spectra



(Sokal et al.2018)

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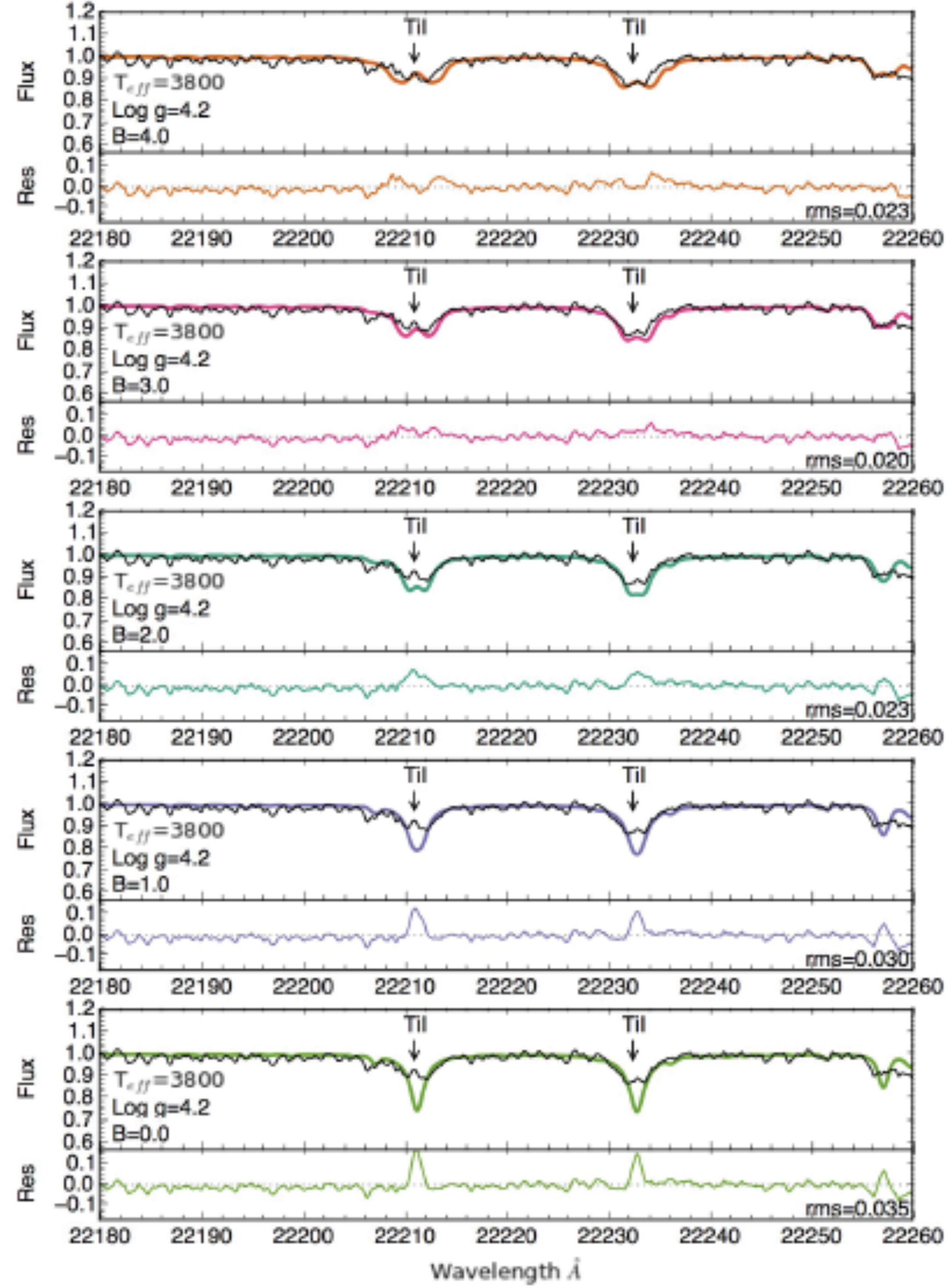
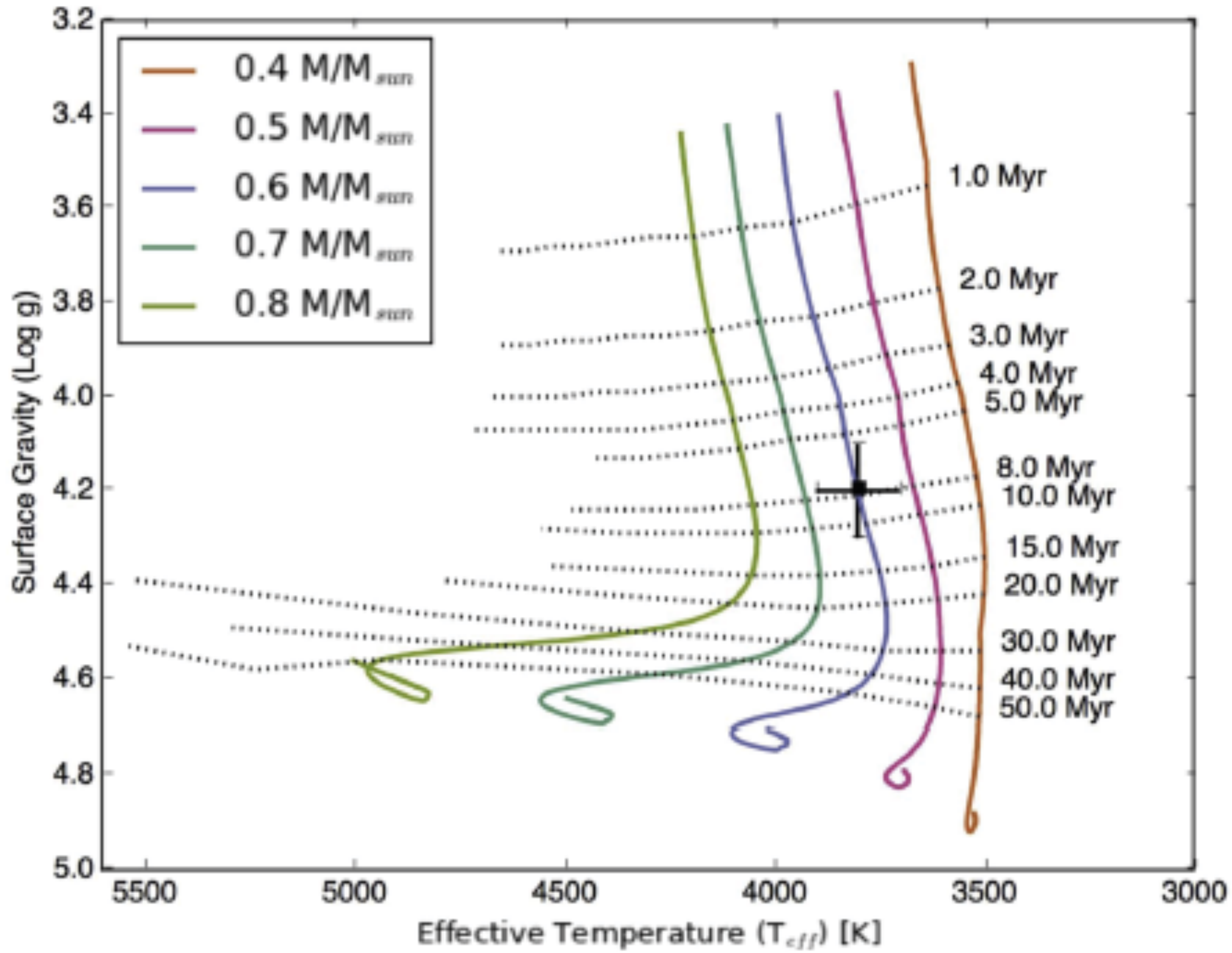
Sokal et al. derivation of B field for TW Hya once temperature and gravity are fixed,



HR diagram position of TW Hya (Sokal et al. 2018)

Derived without any continuum or photometry.



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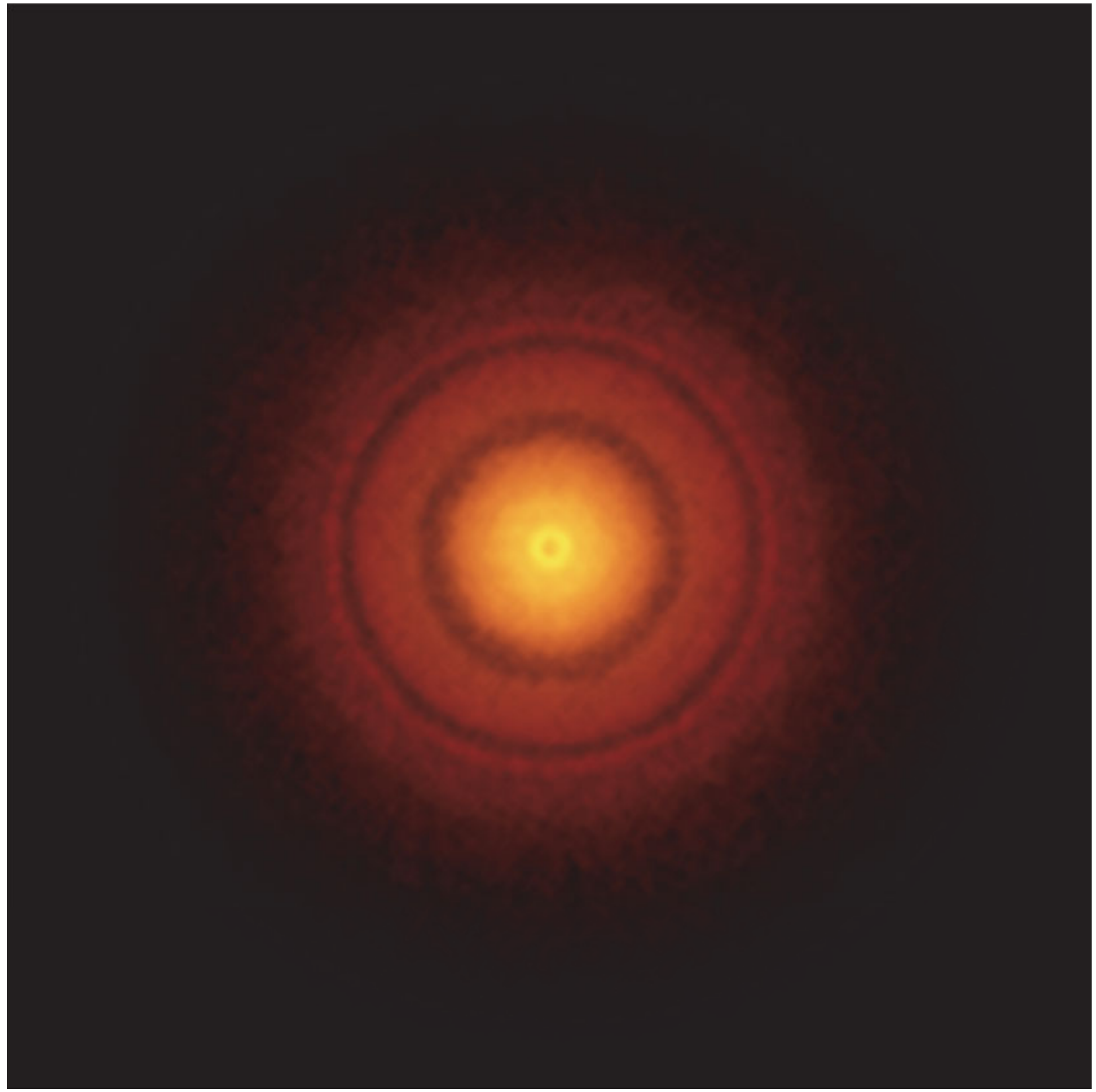
What about all the interesting stuff in the inner disk?

TW Hya with ALMA



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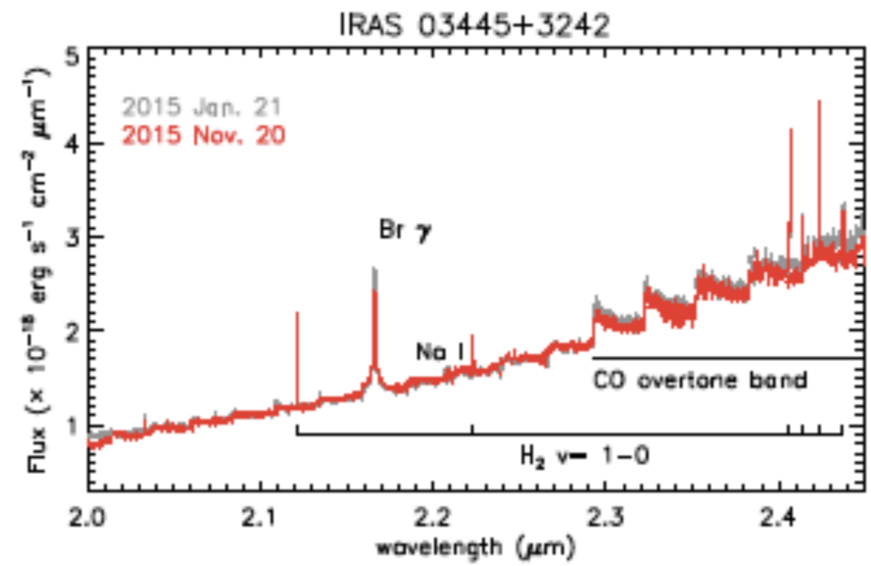
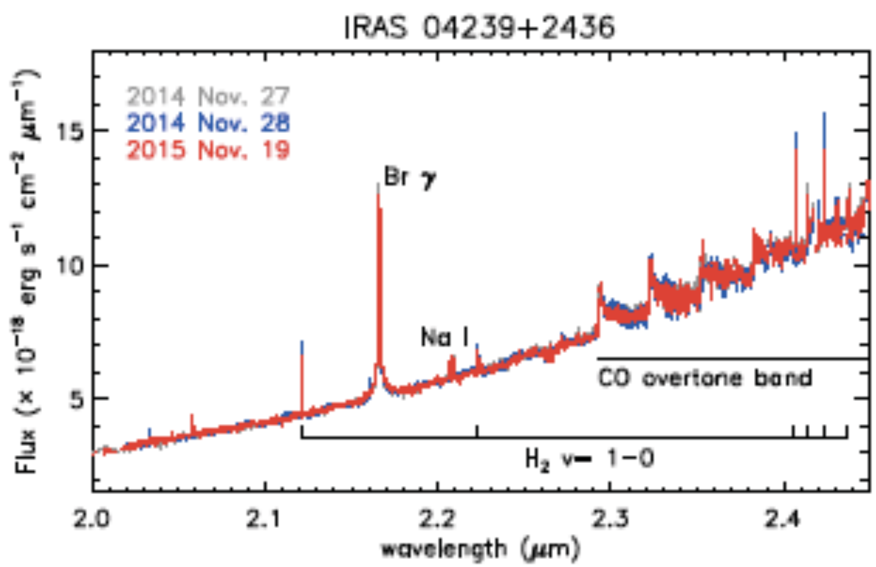
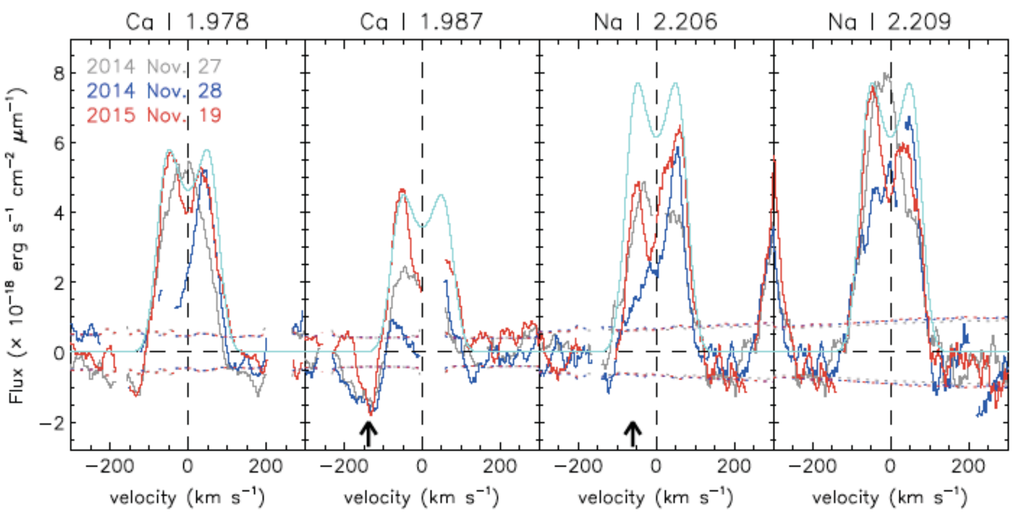
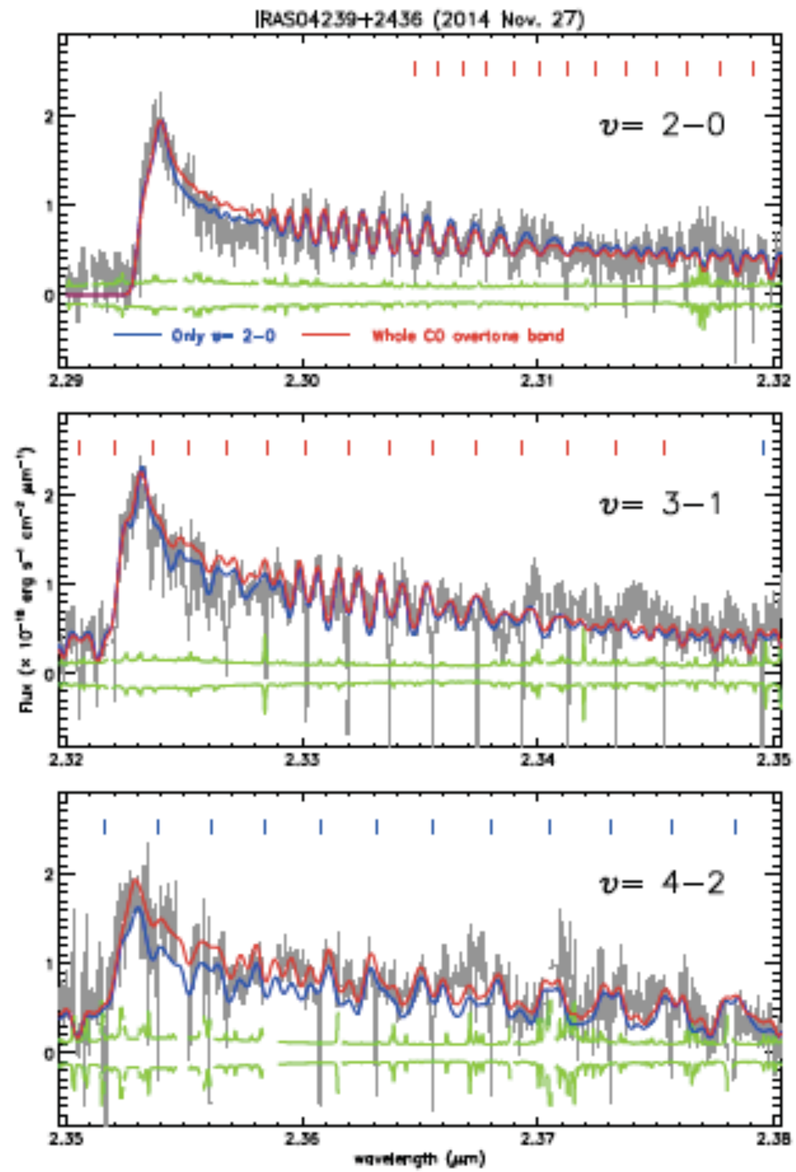
Lee et al. 2016 IGRINS

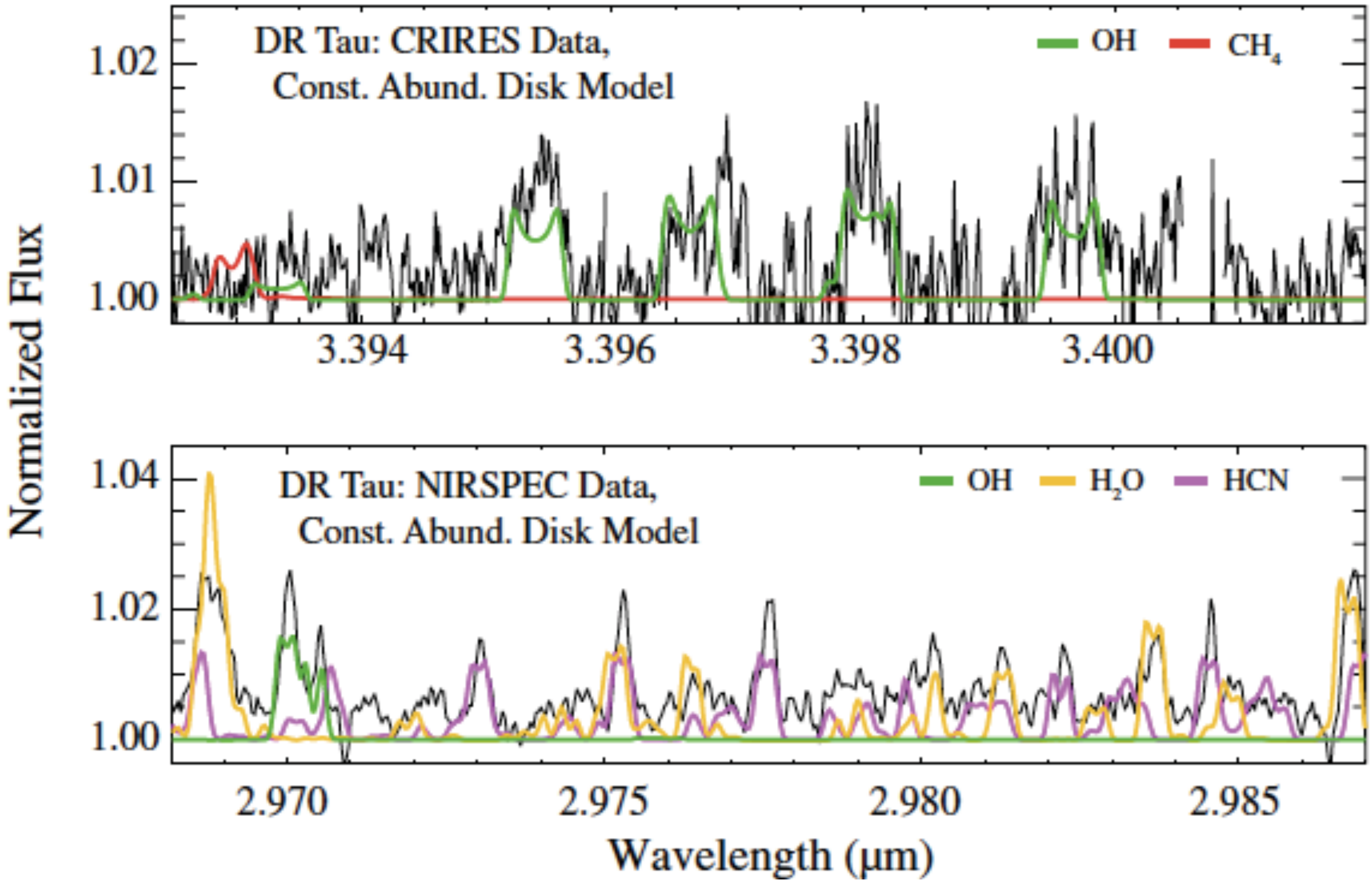




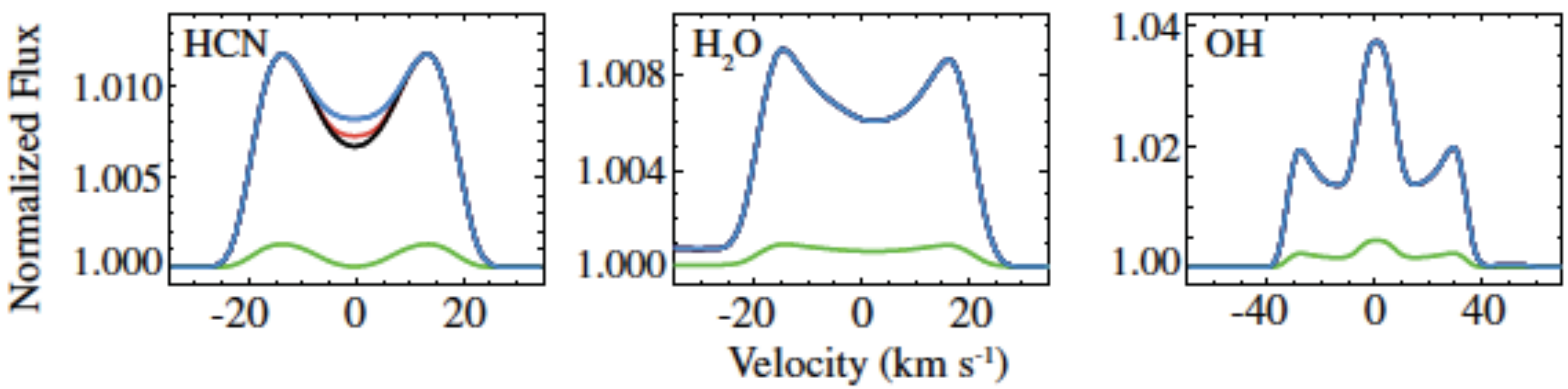

Ca I 1.978
Ca I 1.987
Na I 2.206
Na I 2.209
2014 Nov. 27
2014 Nov. 28
2015 Nov. 19
Flux (× 10⁻¹⁸ erg s⁻¹ cm⁻² μm⁻¹)
velocity (km s⁻¹)


IRAS04239+2436 (2014 Nov. 27)
v= 2−0
Only v= 2−0
Whole CO overtone band
v= 3−1
v= 4−2
Flux (× 10⁻¹⁸ erg s⁻¹ cm⁻² μm⁻¹)
wavelength (μm)

Mandell et al. 2012 Disk Chemistry



Mandell et al. (2012) models including chemistry and freezout – shows how spectral profiles can be used.



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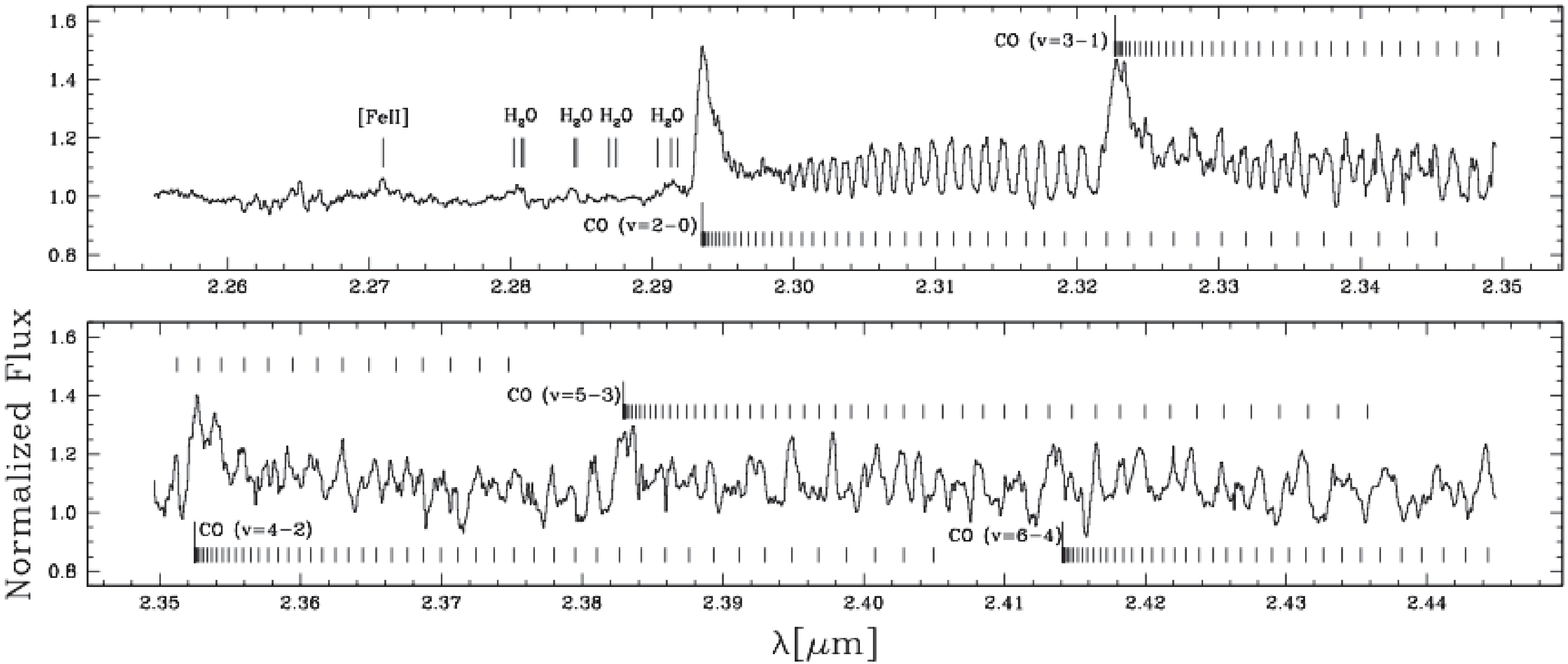
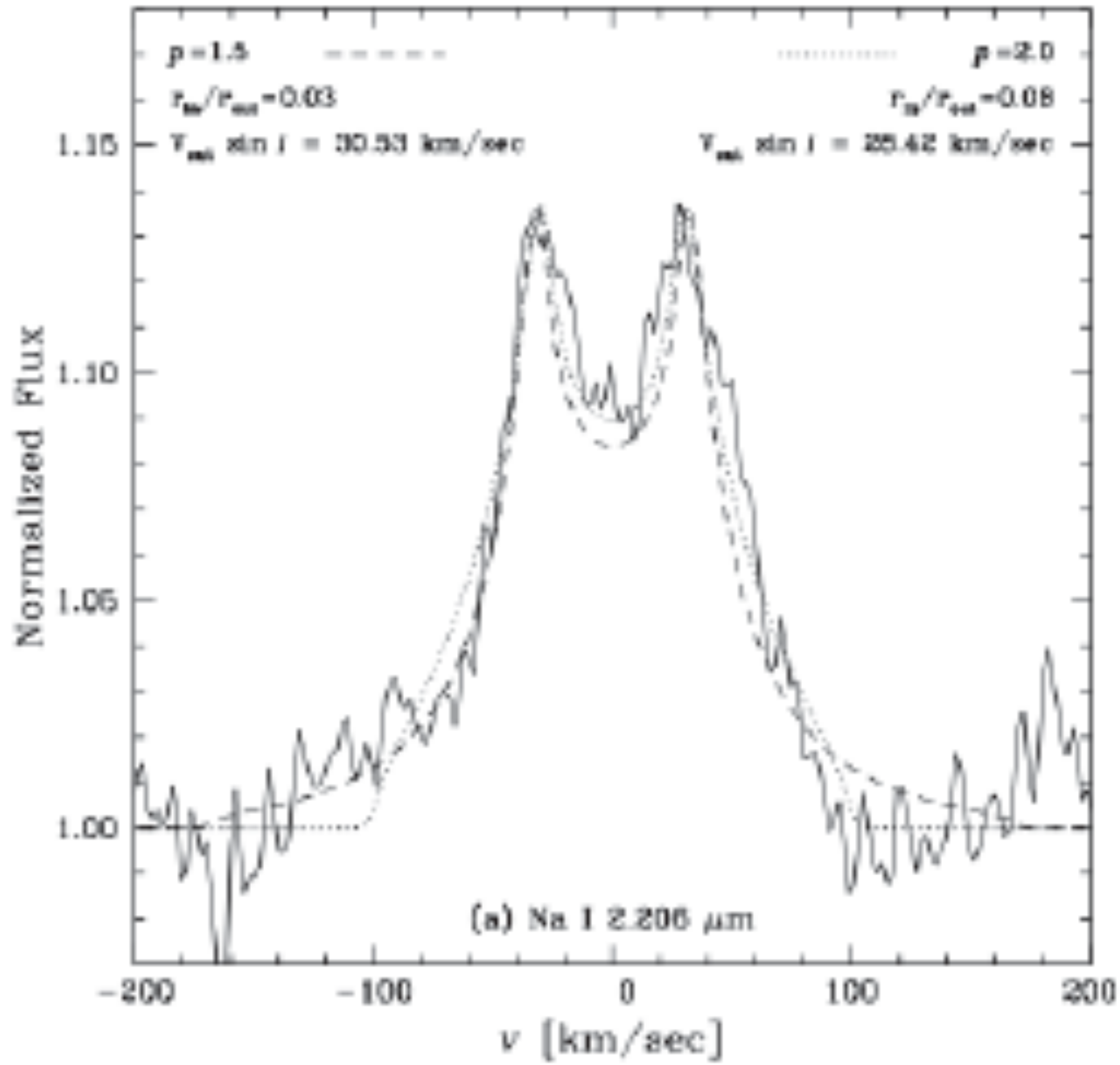
Hα 279A YSO Disk (Lyo et al. 2017, IGRINS)

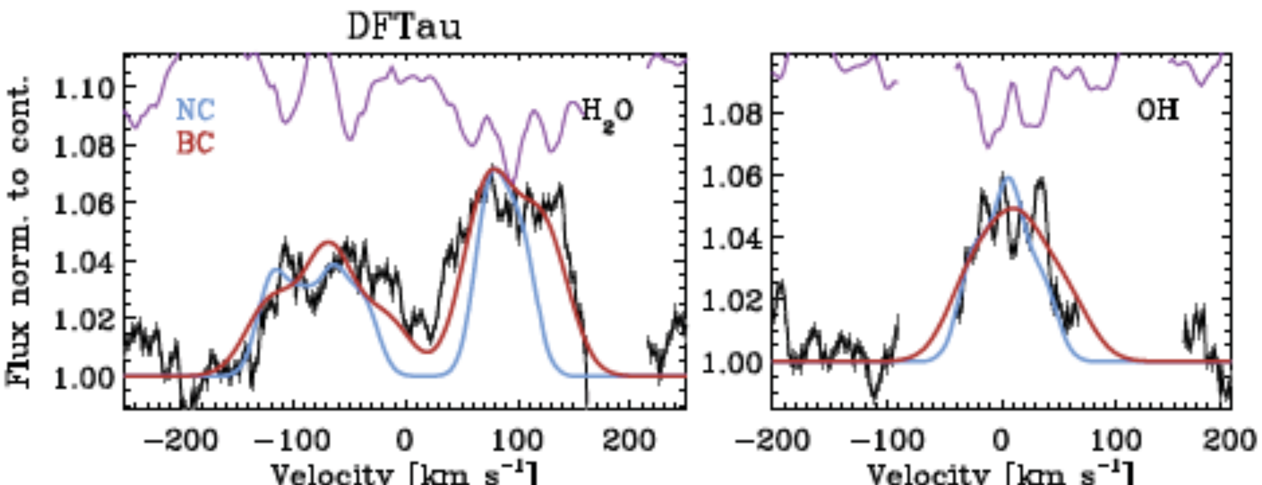


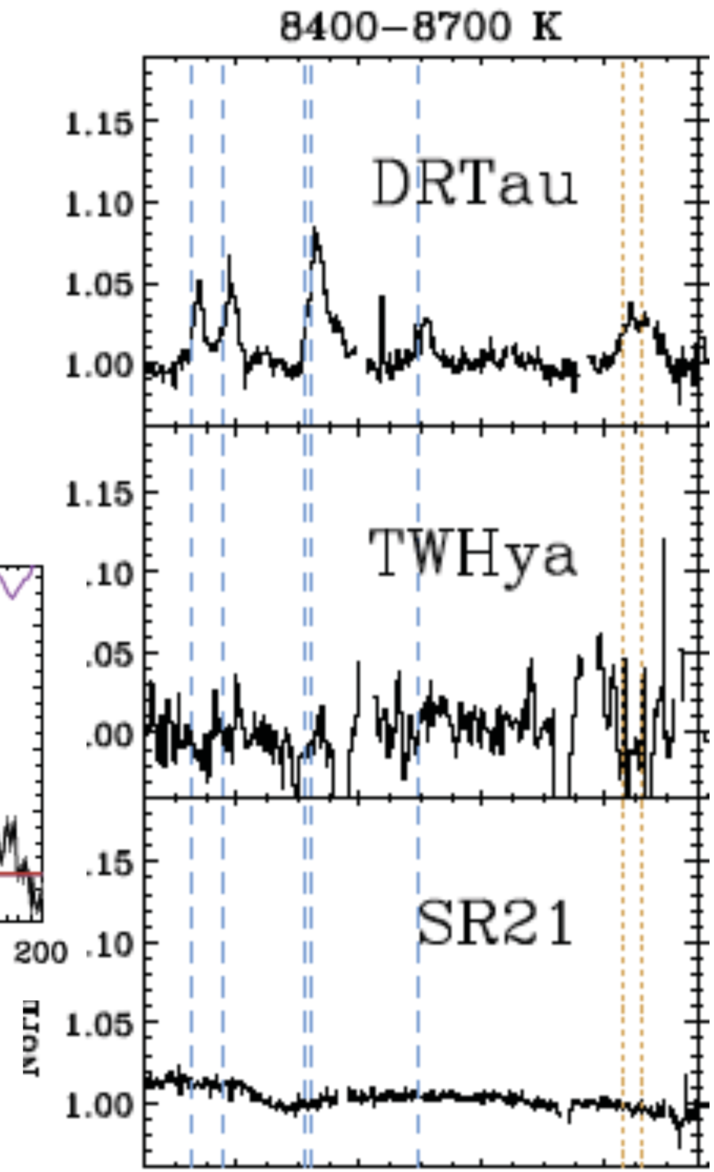
Sodium in the Hα 279A disk



Disk Chemistry cont'd

Banzatti et a. (2017)

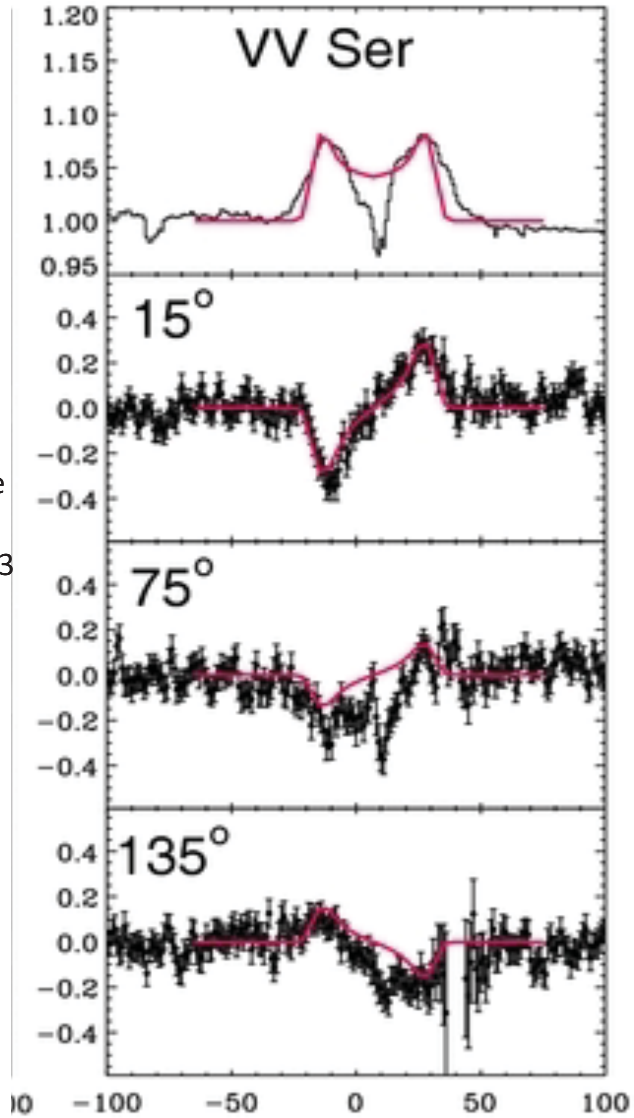


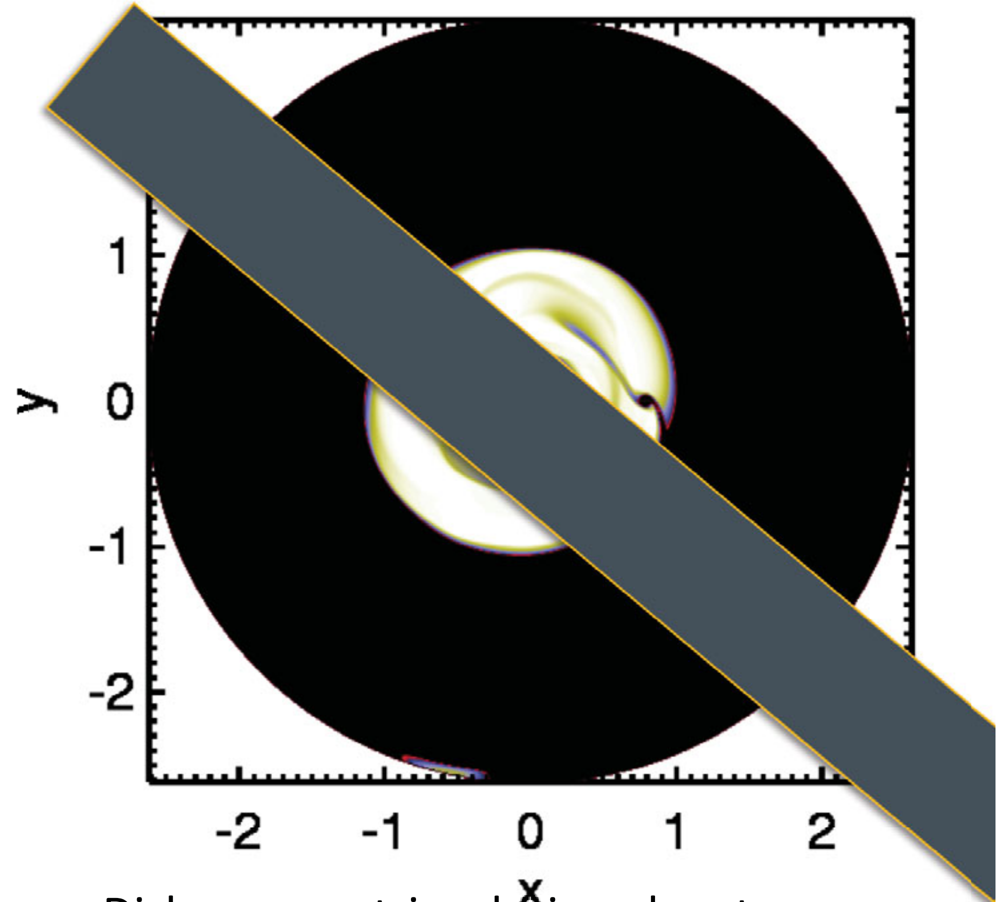


Spectroastrometry allows us to map the 4.6 micron CO lines down to scale sizes of a few AU

Spectroastrometry of disk CO lines to determine distribution below the resolution limit of the observations.

Slit is placed across source and emission at each wavelength from 2.2 to 5.3 microns is centroided relative to continuum.





Disk asymmetries during planet formation. The white regions are optically thin in the continuum near the CO lines (Dodson-Robinson and Salyk 2011).

Klaus M. Pontoppidan et al. 2011 ApJ

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