Protoplanetary Disk
* ELT *

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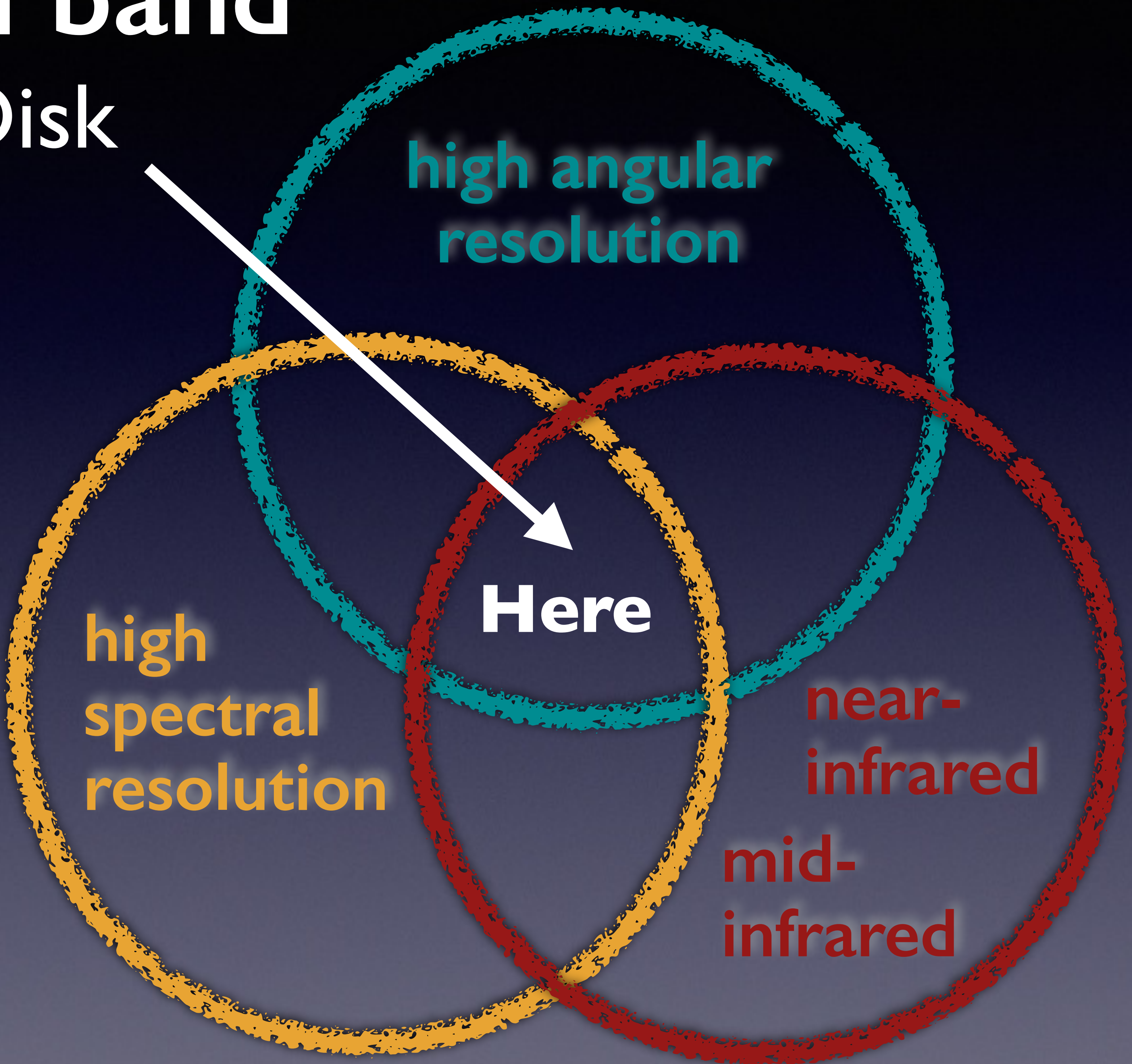
Observing

CO vibrational band

in Protoplanetary Disk



1 angular resolution + IR

warm targets that is barely resolved so far

2 spectral resolution + IR

gas, not ice or dust
molecules
vibrational transitions
kinematics
rotationally quiet molecules even better

H_2, H_3^+, CH_4, C_2H_2 symmetric molecules without permanent dipole moment

What is CO vibrational band ?

Why CO is so special?

Why sub-mm astronomers like it so much?

yes, abundance is high

but, why not OH or H_2O?

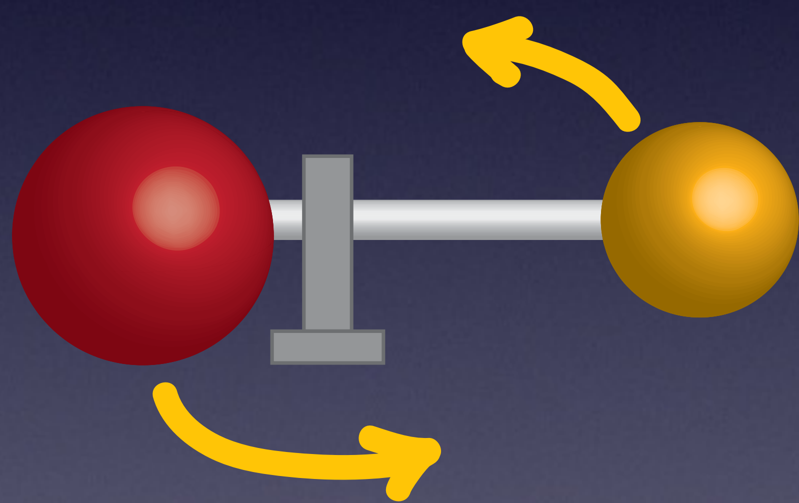
#	Element	Solar photospheric abundance
1	H	12.00
2	He	[10.93]
3	Li	1.05
4	Be	1.38
5	B	2.70
6	C	8.43
7	N	7.83
8	O	8.69
9	F	4.56
10	Ne	[7.93]

Asplund 2009, ARAA

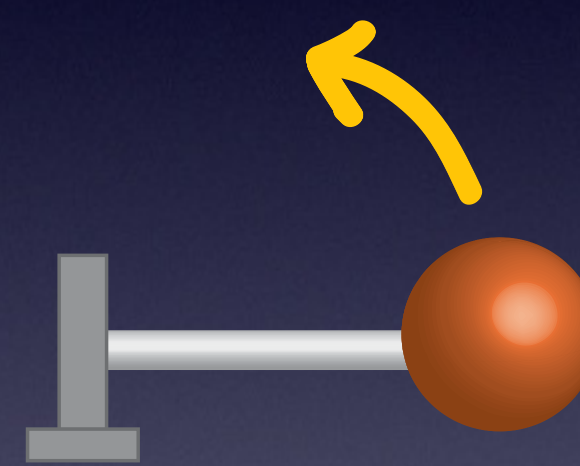
Let us start with rotational transition

reduced mass

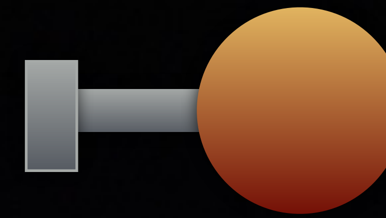
makes this



into this



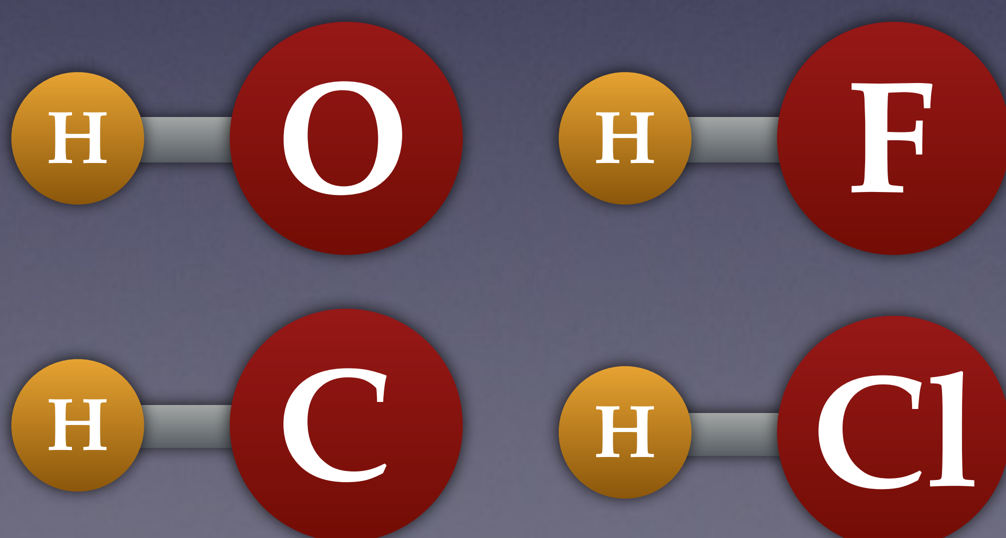
$$\frac{1}{\mu_1} + \frac{1}{\mu_2} = \frac{1}{\mu}$$



$$\frac{1}{\mu_1} + \frac{1}{\mu_2} = \frac{1}{\mu}$$

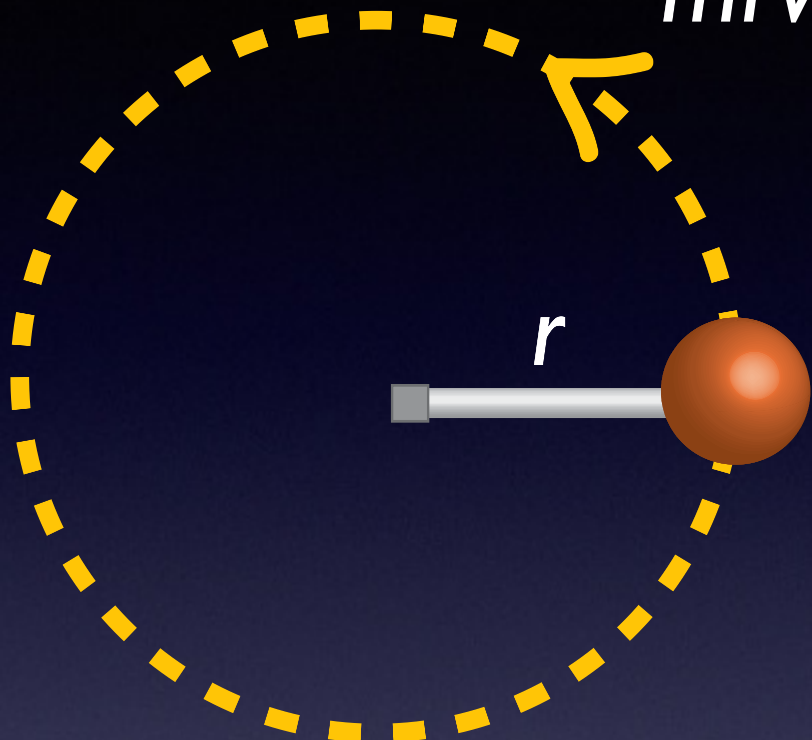
$$\mu_1 \approx \mu_2 \qquad \mu \approx \frac{\mu_1}{2}$$

$$\mu_1 \ll \mu_2 \qquad \mu \approx \mu_1$$ smaller one



all looks
more like H

Rotational Energy levels



$mrv = J$

rotational angular momentum (again…)

$I = \mu r^2$

moment of inertia

$$E = \frac{1}{2} mv^2$$

$$= \frac{m}{2} \left(\frac{J}{mr} \right)^2$$

$$= \frac{J^2}{2mr^2}$$

$$= \frac{J^2}{2I}$$

$$\Delta E = \frac{h^2}{I} \cdot (J+1)$$

the larger μ, the larger I

energy gap is small

easily excited

even at low T → **easy to observe**

$$E = \frac{h^2}{2I} J(J+1)$$

correct answer
… not too bad

- Hydride

	total mass	reduced mass	$\Delta J = 1$ from lowest	ΔE
OH	12 + 1	0.92	83 cm	119 K
HF	1 + 19	0.95	41 cm	59 K
HCl	1 + 35	0.97	21 cm	30 K
HBr	1 + 79	0.99	16 cm	23 K

- non-Hydride

	total mass	reduced mass	$\Delta J = 1$ form lowest	ΔE
CO	12 + 16	6.9	3.8 cm	5.5 K
CS	12 + 32	8.7	1.6 cm	2.3 K

(rule of thumb)

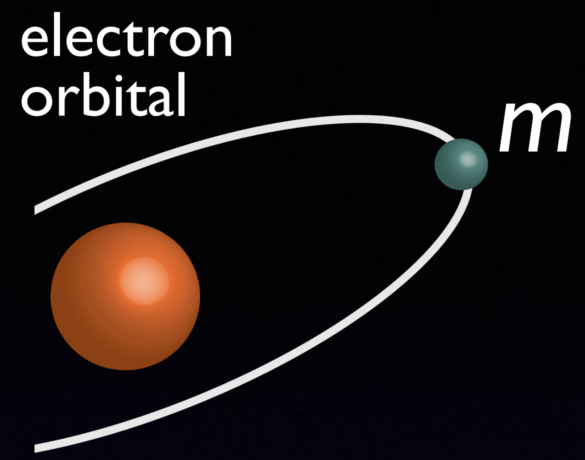
the bigger, the easier to excite

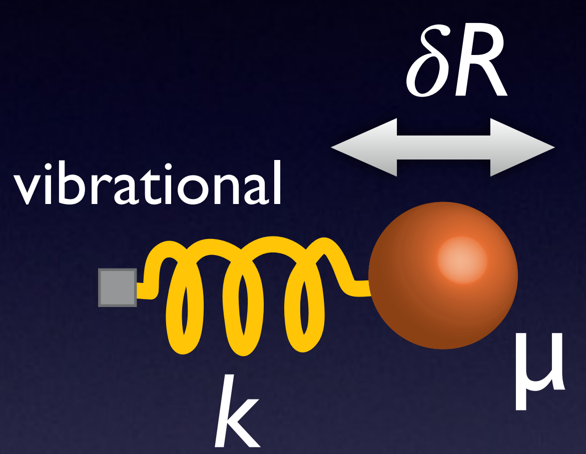
ELT/METIS wrap up

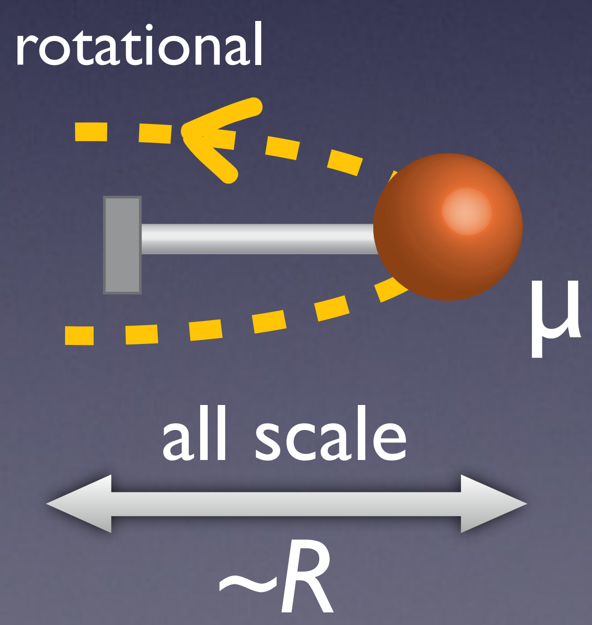
- aperture 39 m

	3 µm	5 µm	8 µm	14 µm
	HD, NH	CO	SO	C
λ/D	16 mas	26 mas	42 mas	74 mas
at 150 pc	2.4 AU	4.0 AU	6.3 AU	11 AU

imaging		3-19 µm	
low-resolution spectroscopy	R=11,000	3-8 µm	
med-resolution spectroscopy	R=10,000	8-14 µm	
high-resolution spectroscopy	R=100,000	3-5 µm	IFU







energy

$$E_{elec} = \frac{1}{2} mv^2 = \frac{1}{2} kR^2 \quad \textbf{1}$$

$$E_{vib} = \frac{1}{2} \mu V_b^2 = \frac{1}{2} k(\delta R)^2 \quad \textbf{2}$$

$$E_{rot} = \frac{1}{2} \mu V_r^2 \quad \textbf{3}$$

angular momentum

$$mRv = \hbar \quad \textbf{4}$$

$$\mu(\delta R)V_b = \hbar \quad \textbf{5}$$

$$\mu RV_r = \hbar \quad \textbf{6}$$

1 2

$$\frac{v}{V_b} \frac{\delta R}{R} = \sqrt{\frac{\mu}{m}}$$

$$\frac{V_r}{V_b} \frac{\delta R}{R} = \sqrt{\frac{m}{\mu}}$$

4 5 6

$$\frac{v}{V_r} = \frac{\mu}{m}$$

proton / electron mass ratio

$$\frac{V_r}{V_b} \frac{R}{\delta R} = 1$$

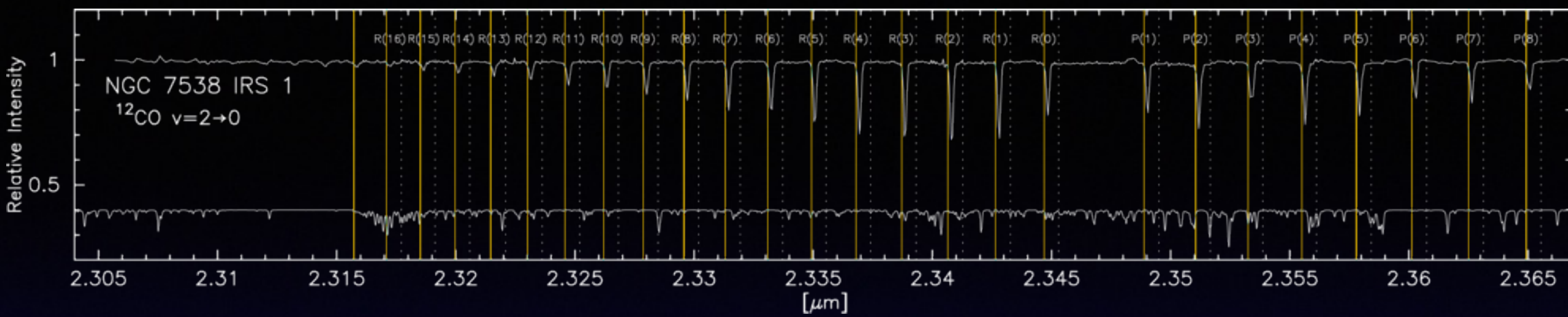
$$\frac{V_r}{V_b} = \left(\frac{m}{\mu}\right)^{1/4} \longrightarrow$$

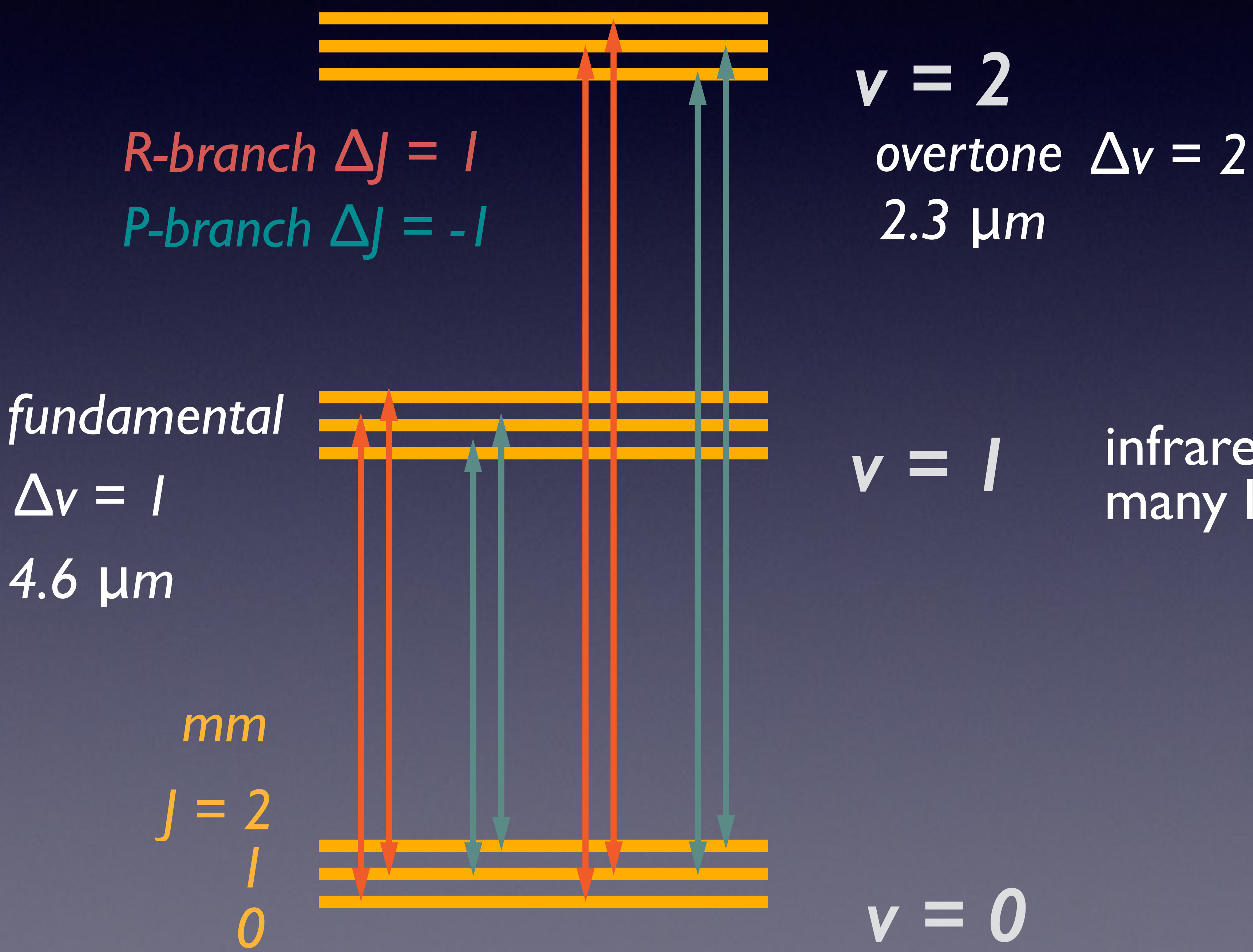
1 mm

$$\frac{E_{rot}}{E_{vib}} = \sqrt{\frac{m}{\mu}} \sim \frac{1}{100}$$

10 μm

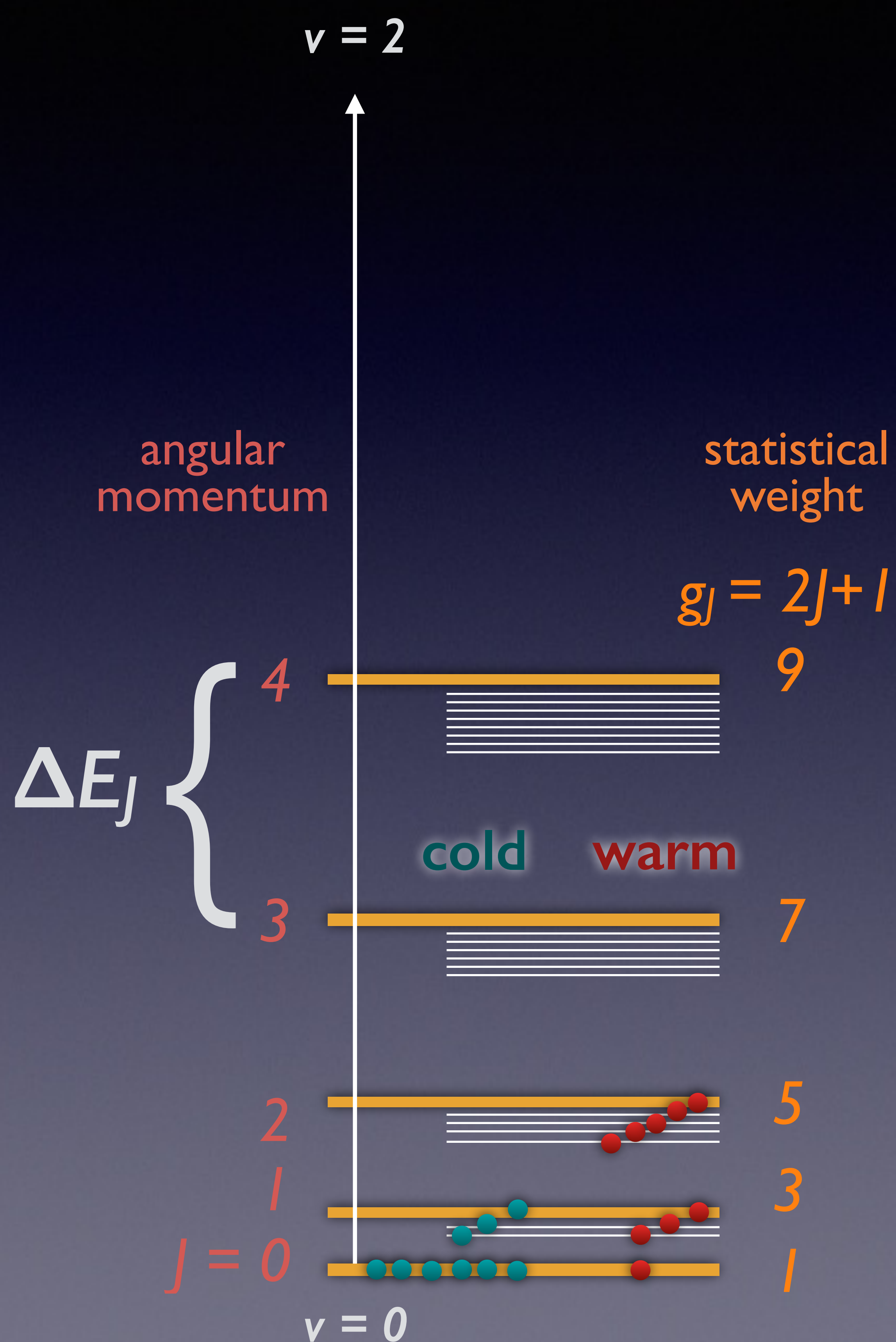
Oka, Takeshi





infrared spectroscopy covers many lines in one shot

Population diagram



Boltzmann distribution

$$\frac{N_J}{g_J} = \frac{N_0}{Qt} \exp\left(-\frac{\Delta E_J}{kT}\right)$$

partition function $Qt = g_J \sum_J exp\left(-\frac{\Delta E_J}{kT}\right)$

just normalization factor so that $N_0 = \sum_J N_J$

$$\ln \frac{N_J}{g_J} = \ln \frac{N_0}{Qt} - \frac{1}{T} \frac{\Delta E_J}{k}$$

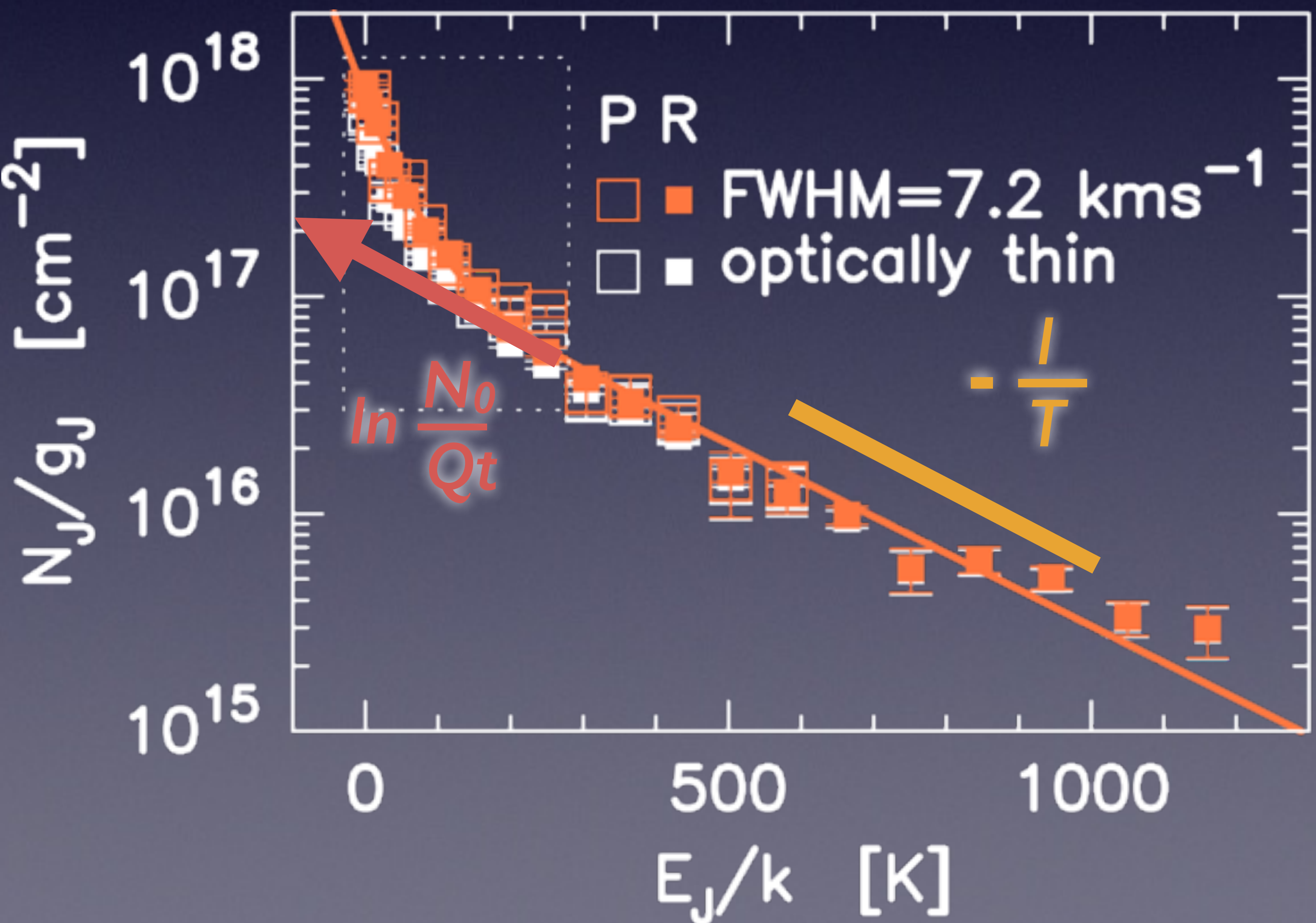
$$y = b - a \cdot x$$

Population diagram

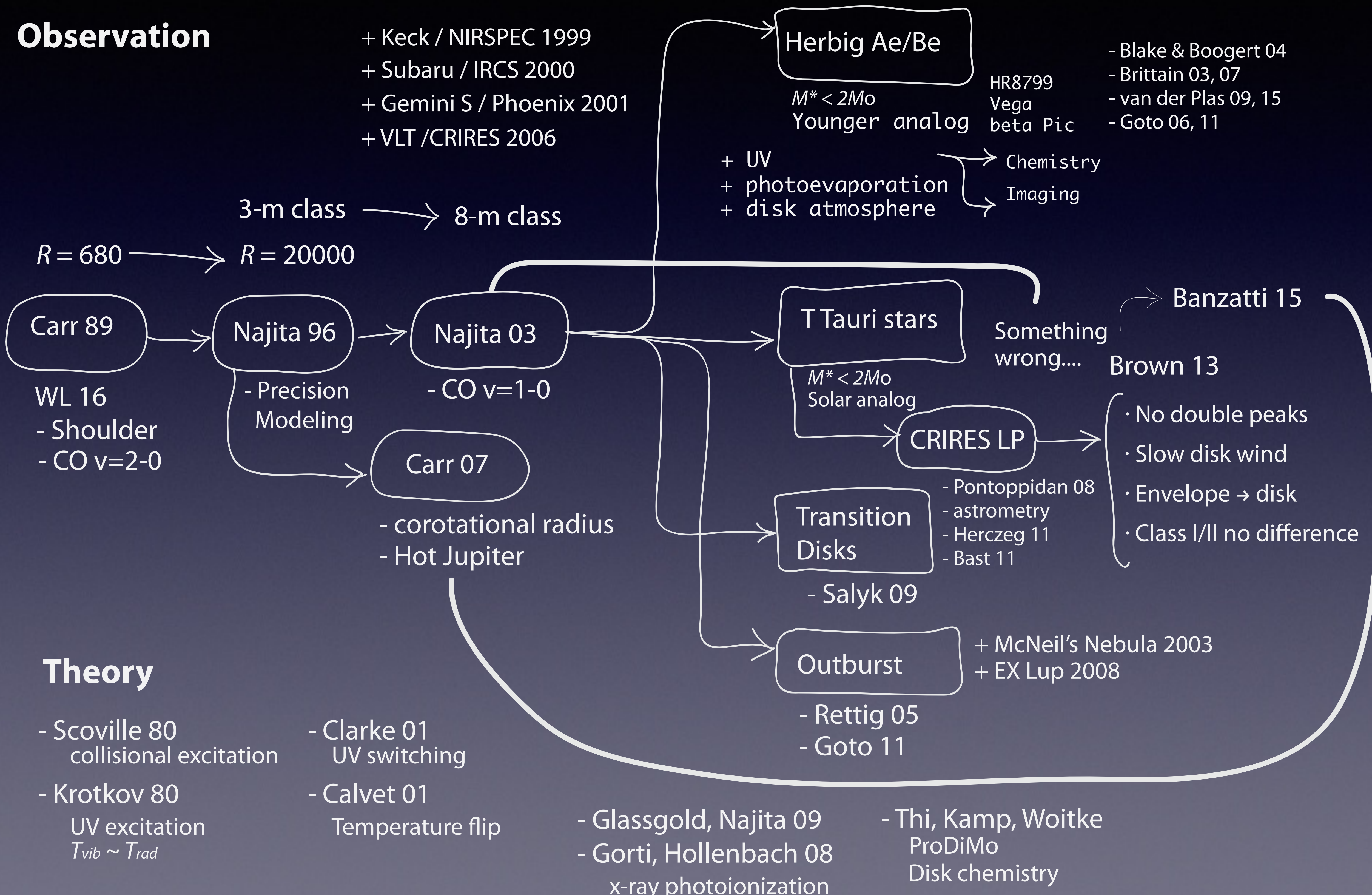
$$\ln \frac{N_J}{g_J} = \ln \frac{N_0}{Qt} - \frac{1}{T} \frac{\Delta E_J}{k}$$

$$y = b - a \cdot x$$

- total column N_0 [cm-2]
- excitation temperature [K]
- LTE+ optically thin or not



Mindmap of CO protoplanetary disks



Techniques

1. spectroscopy λ
2. imaging x
3. monitoring t

2 imaging x

Target spatial scales

1 photoevaporation

gravitational radius $r_g \sim \frac{GM_*}{c_s^2}$

7×10^{-8} cm^3 g^{-1} s^{-2}

2×10^{30} g

10^5 cm/s

$\sim 1.3 \times 10^{14}$ cm

~ 9 AU

2 spiral arms / planet formation

gravitational instability $r_Q = R \cdot \frac{M_d}{M_*}$

0.1

~10 AU

if disk is 100 AU

… so both 0.1” at 100 pc away

ELT is not just bigger and better

The telescope overcomes the **barriers** for the first time

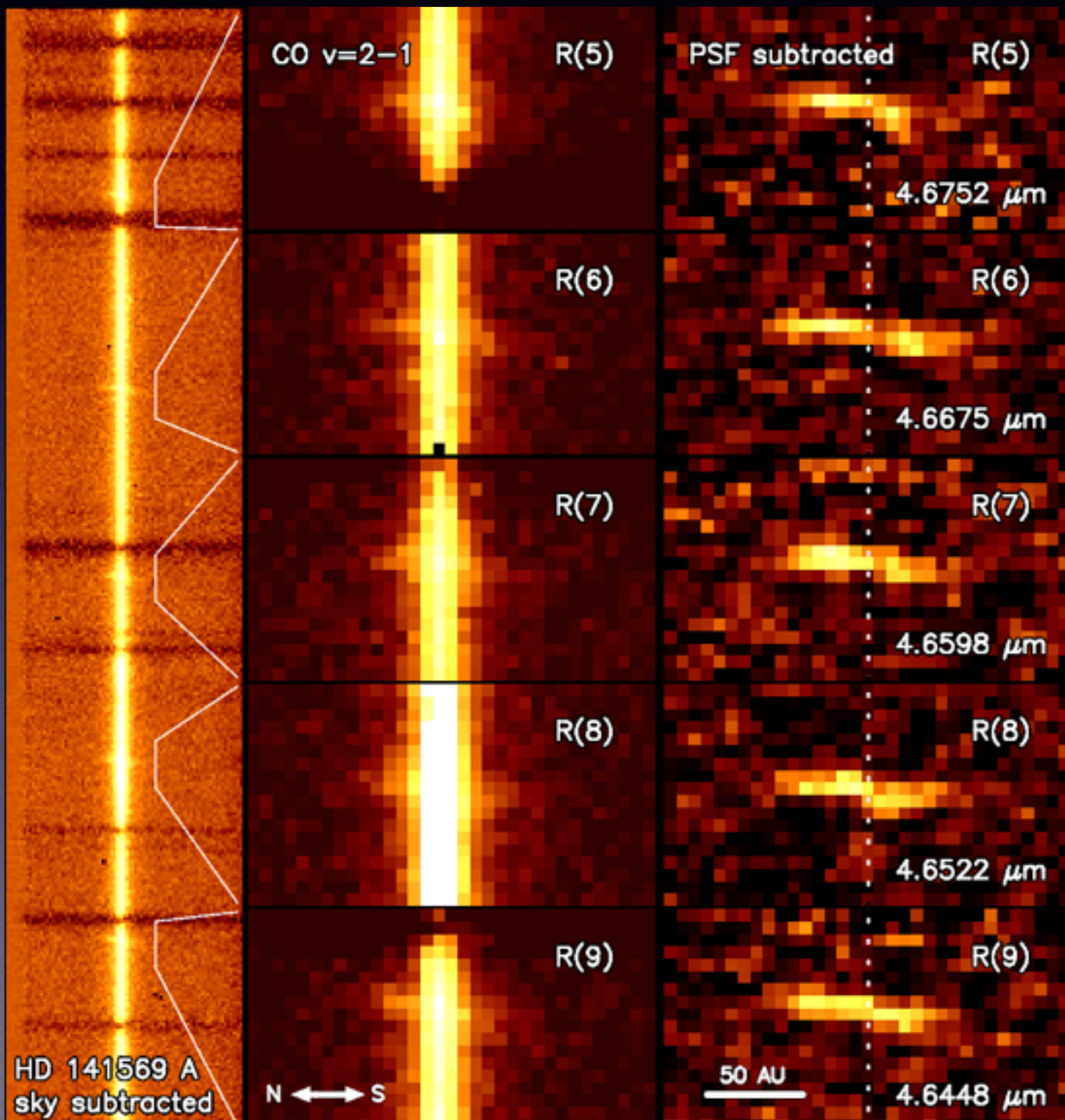
2 imaging x

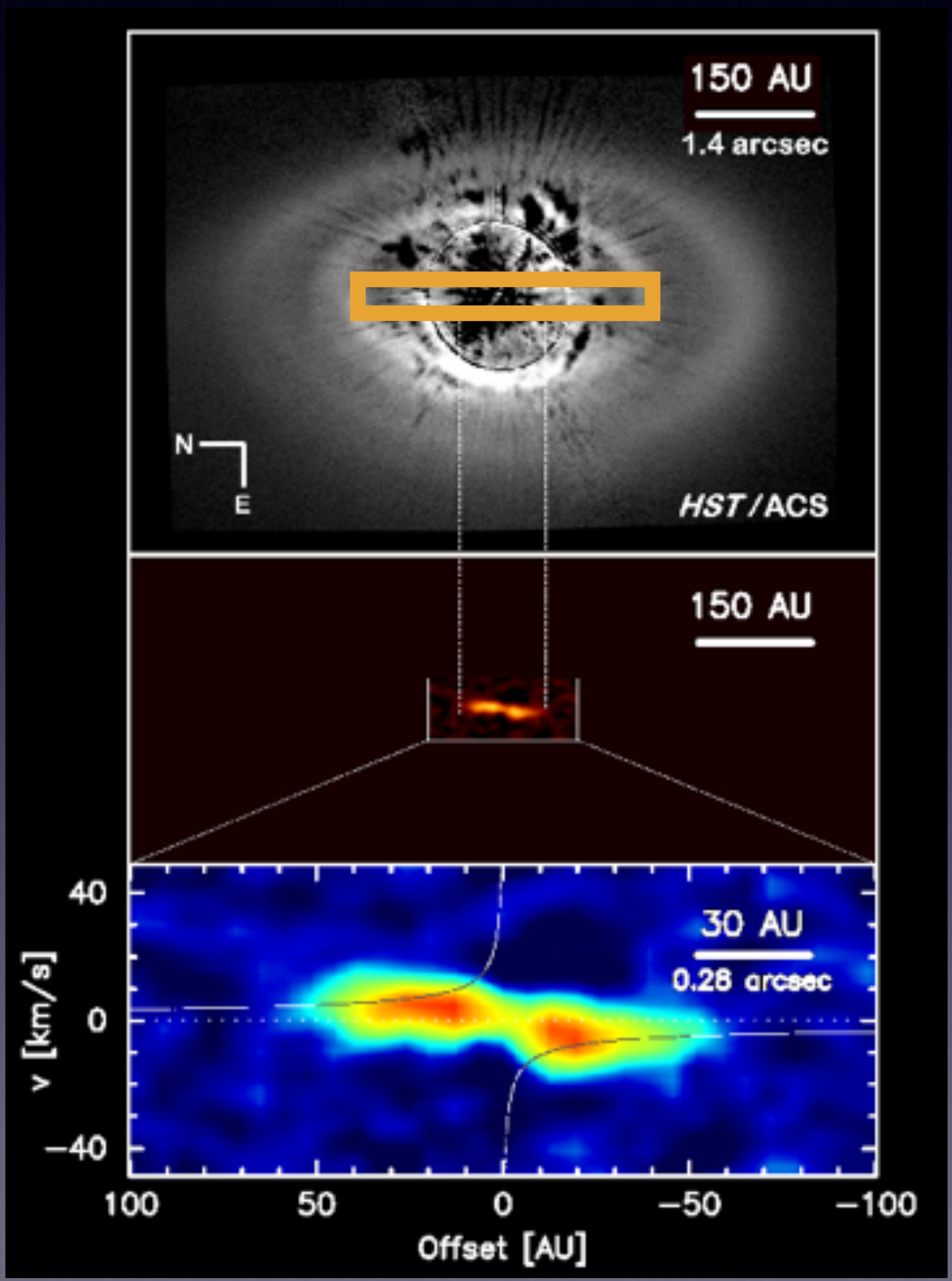
HD 141569 A Herbig Ae/Be

Adaptive Optics, Subaru, R=20000

high resolution spectroscopy

≈virtual coronagraphy





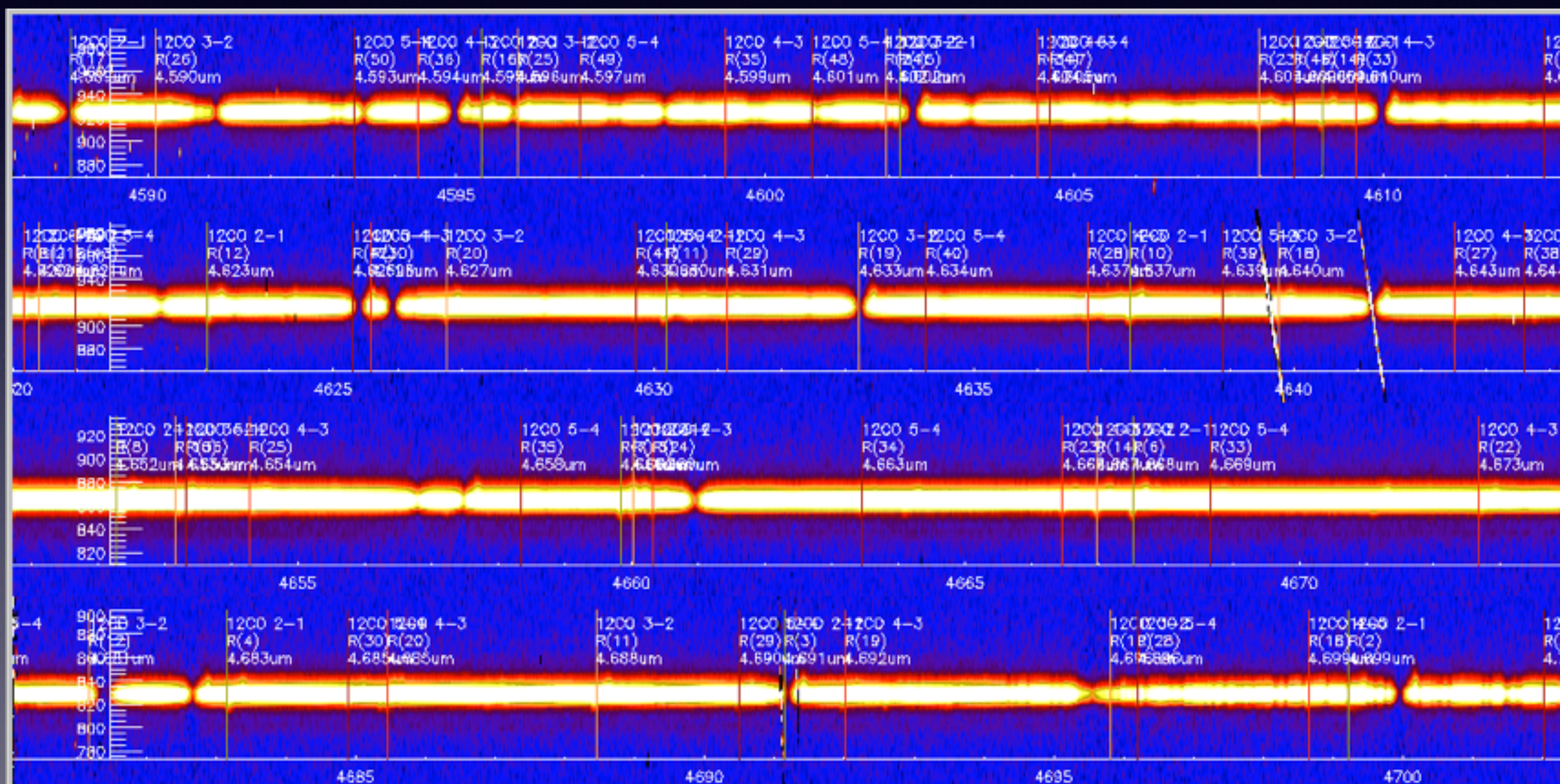
Goto et al. 2006

HD 100546 Herbig Ae/Be

Adaptive Optics

VLT / CRIRES, R=100,000

stellar continuum

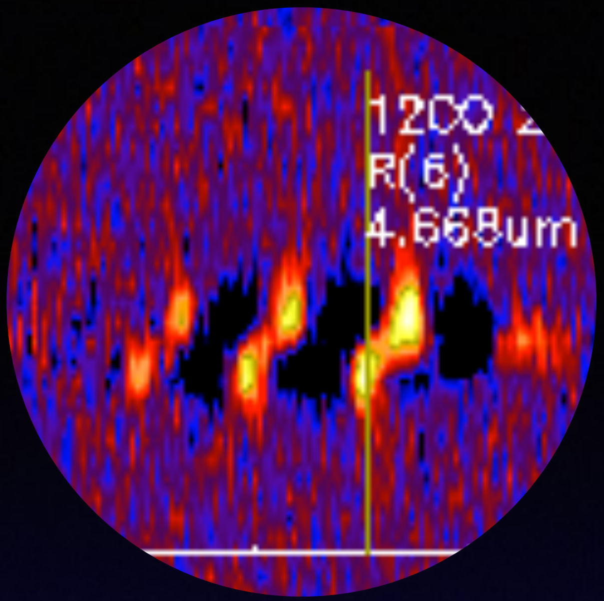


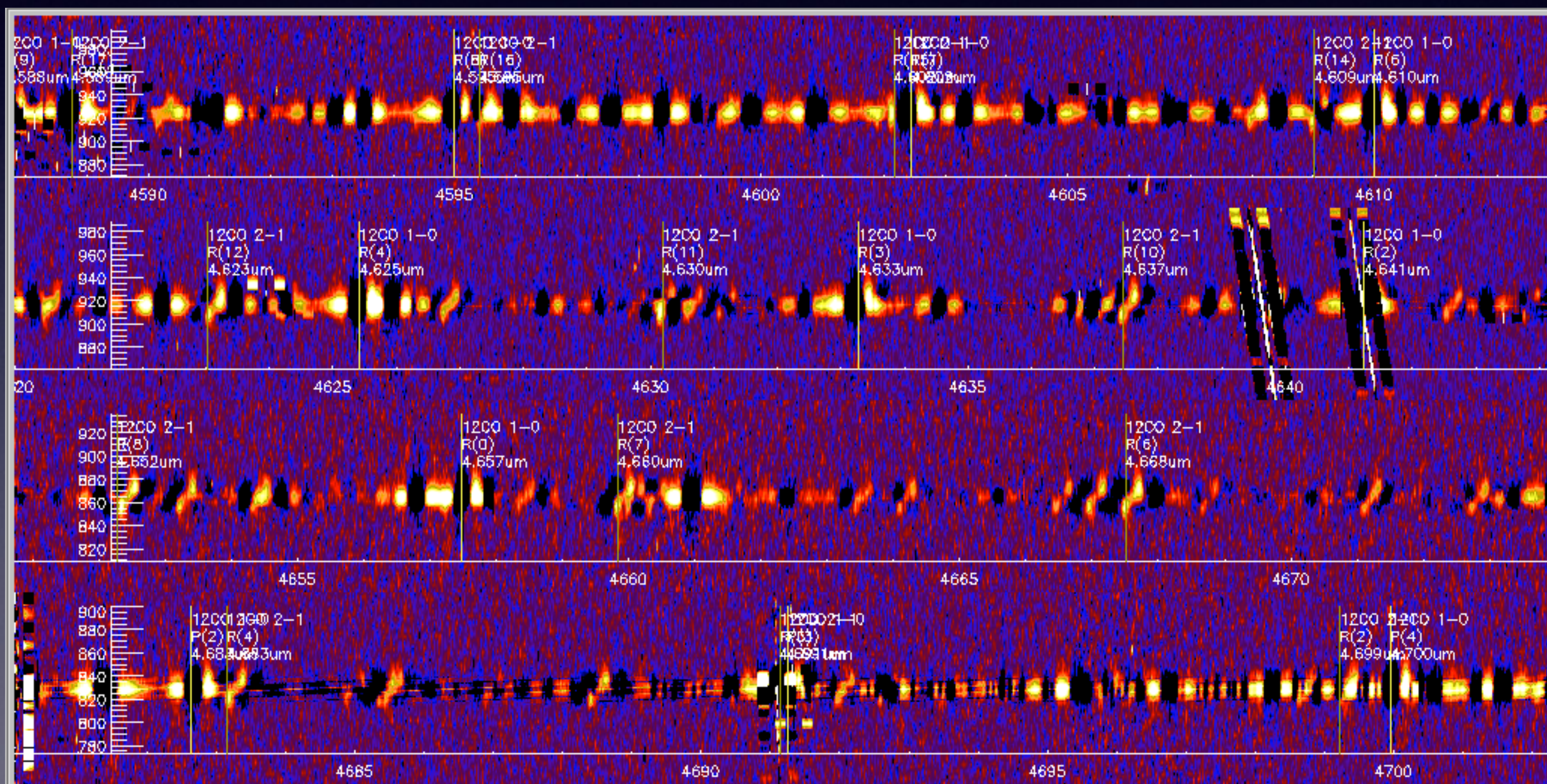
HD 100546 Herbig Ae/Be

Adaptive Optics

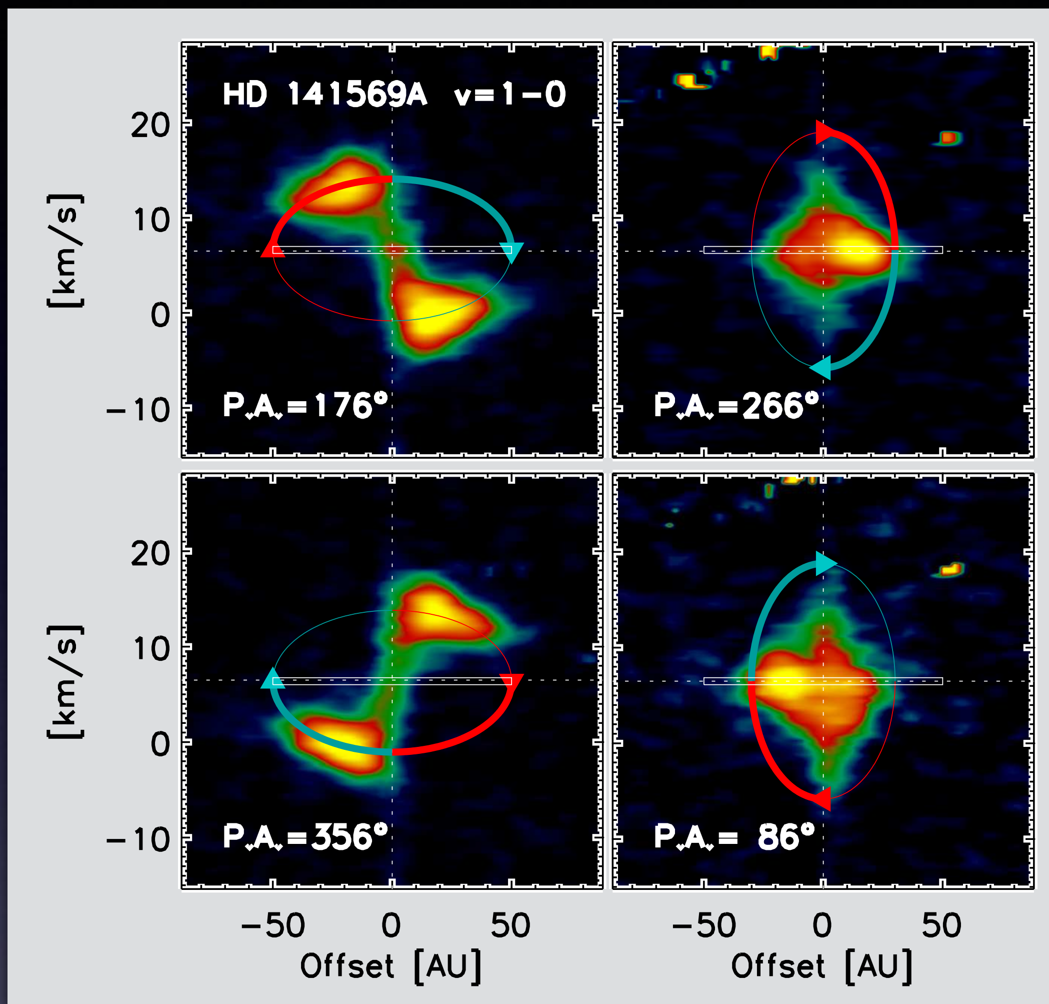
VLT / CRIRES, R=100,000

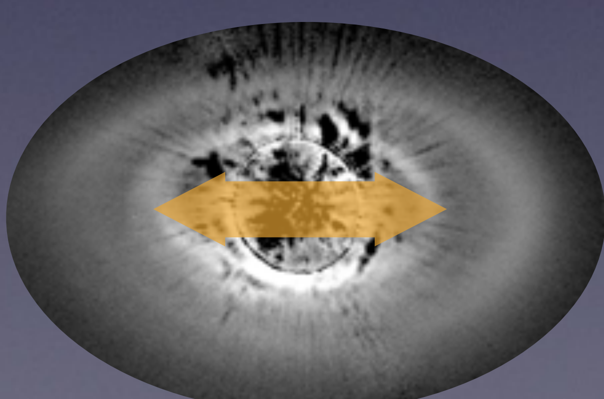
stellar continuum subtracted

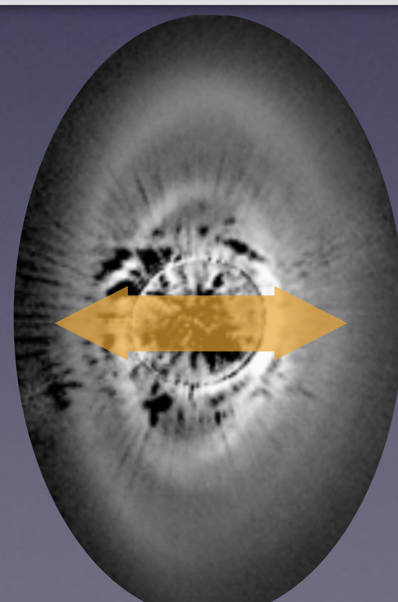




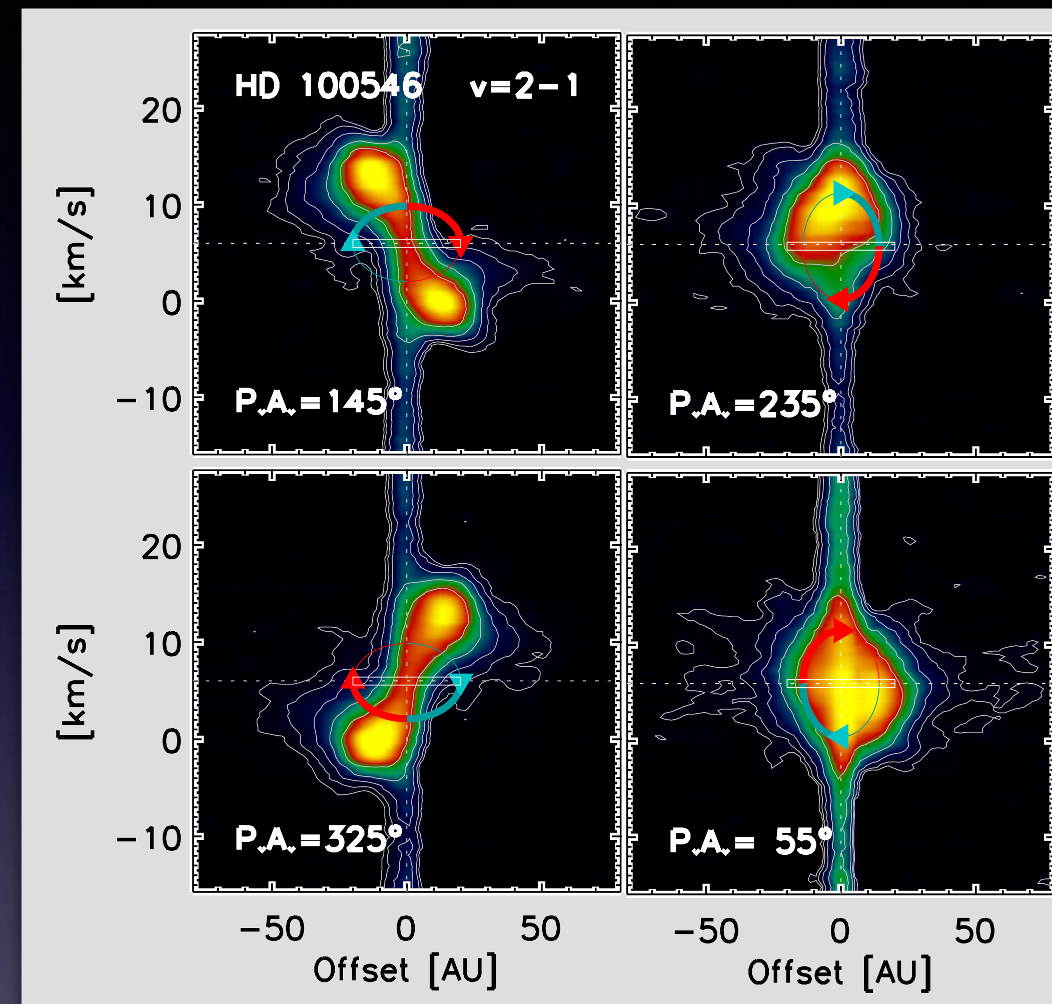
HD 141569A

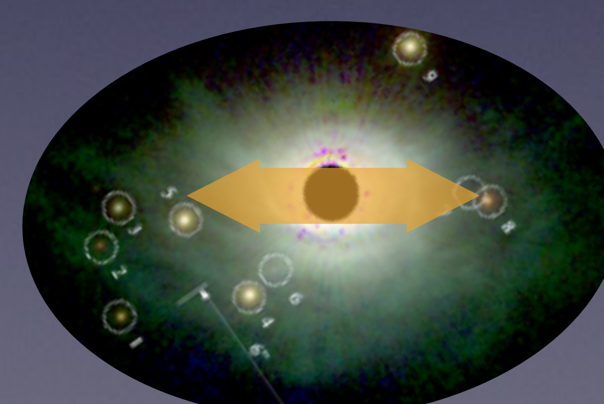


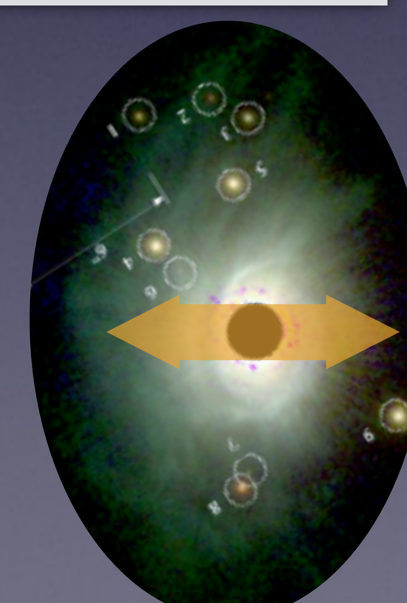




HD 100546



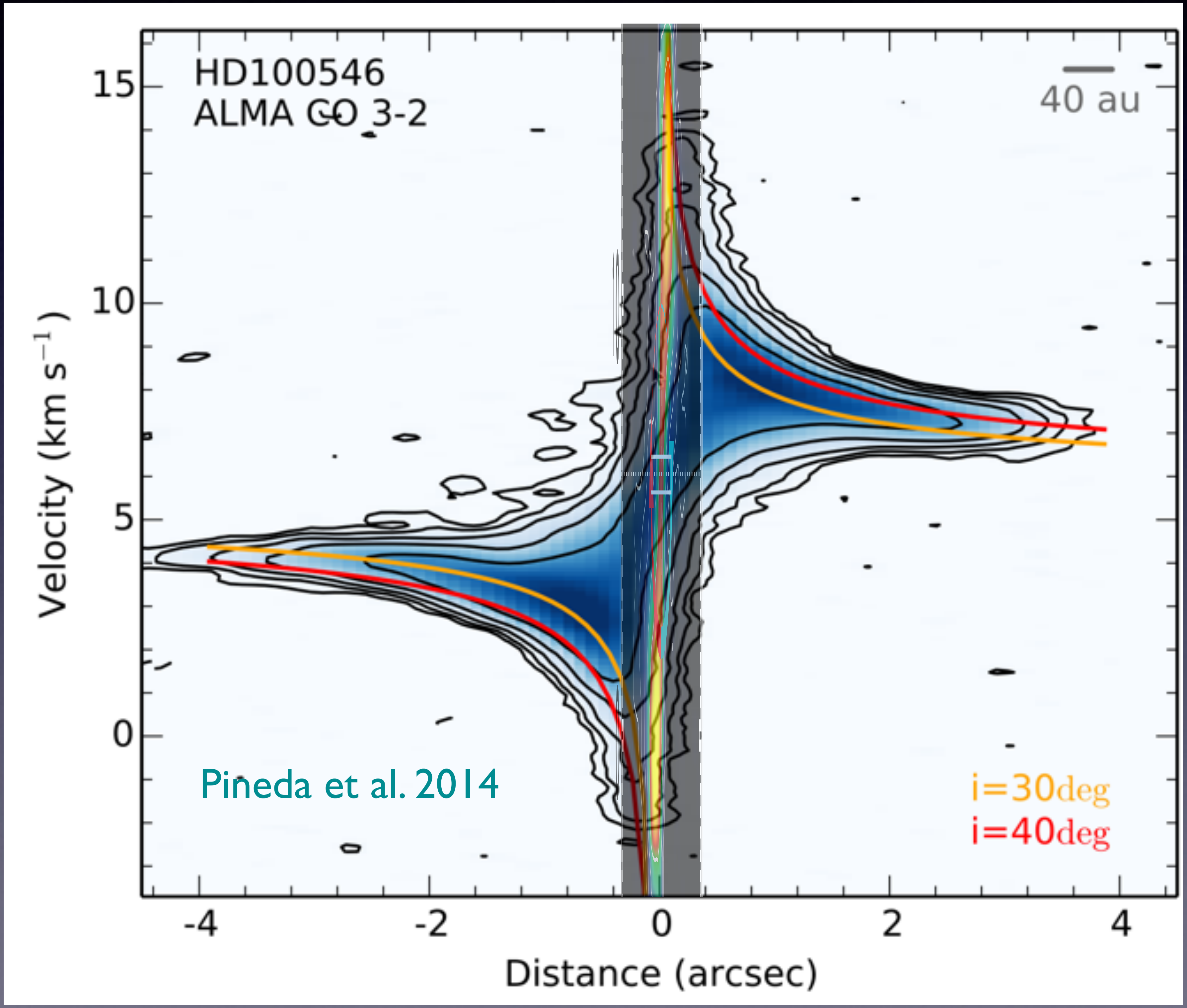




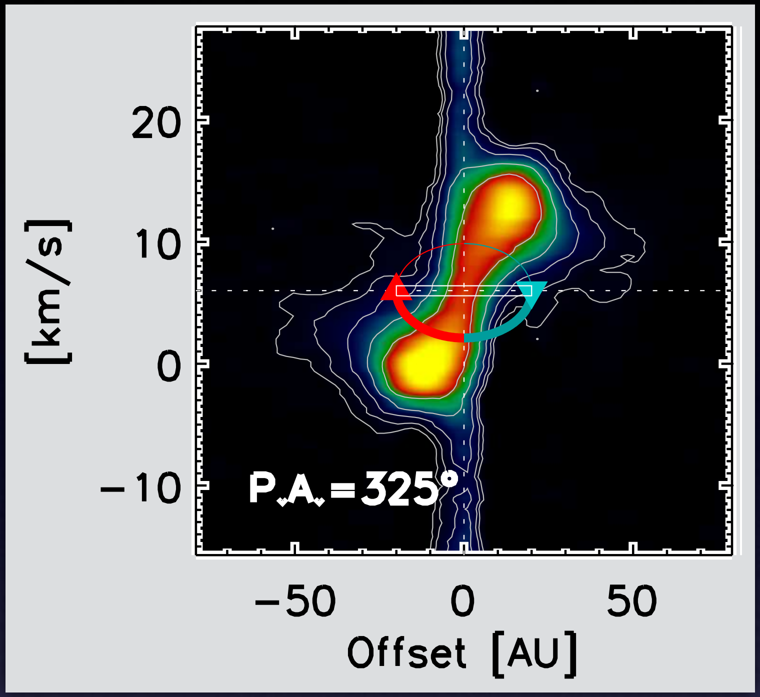
near side brighter

IFU changes life much easer

ALMA vs CRIRES



HD 100546
Herbig Ae star



ALMA / 375m / 870μm

➡ **16000 m**

CRIRES / 8m / 4.6μm

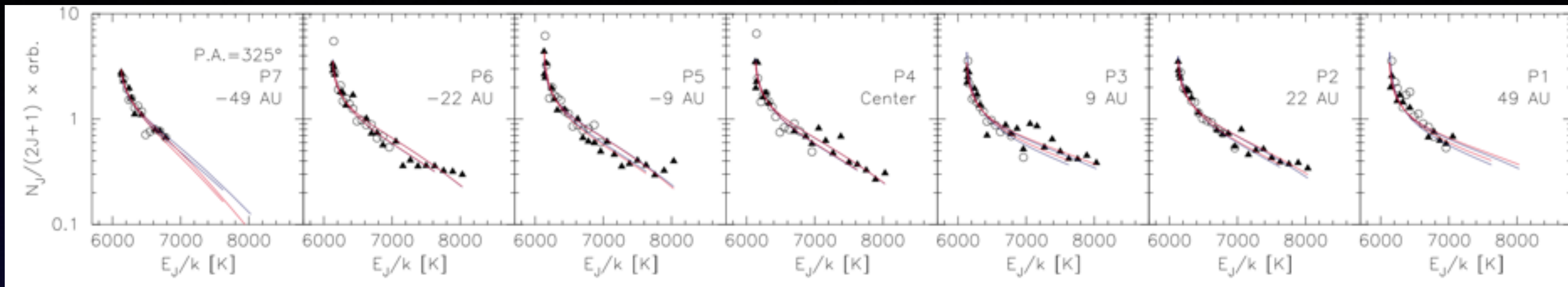
➡ **39 m**

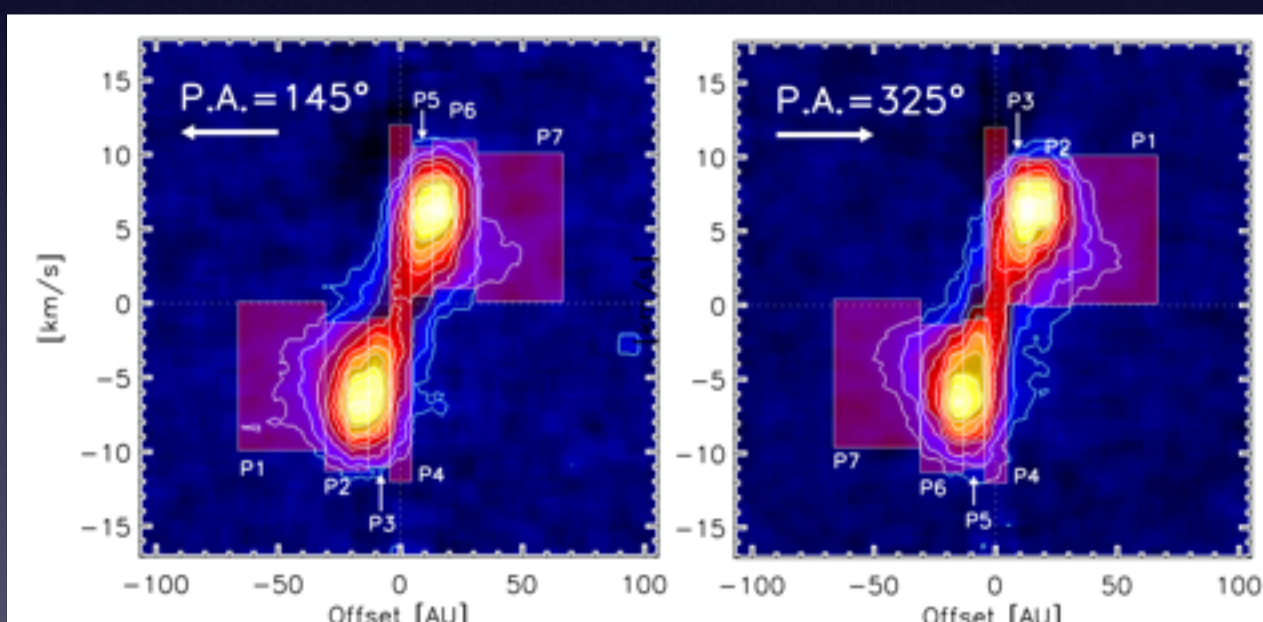
so far CRIRES wins

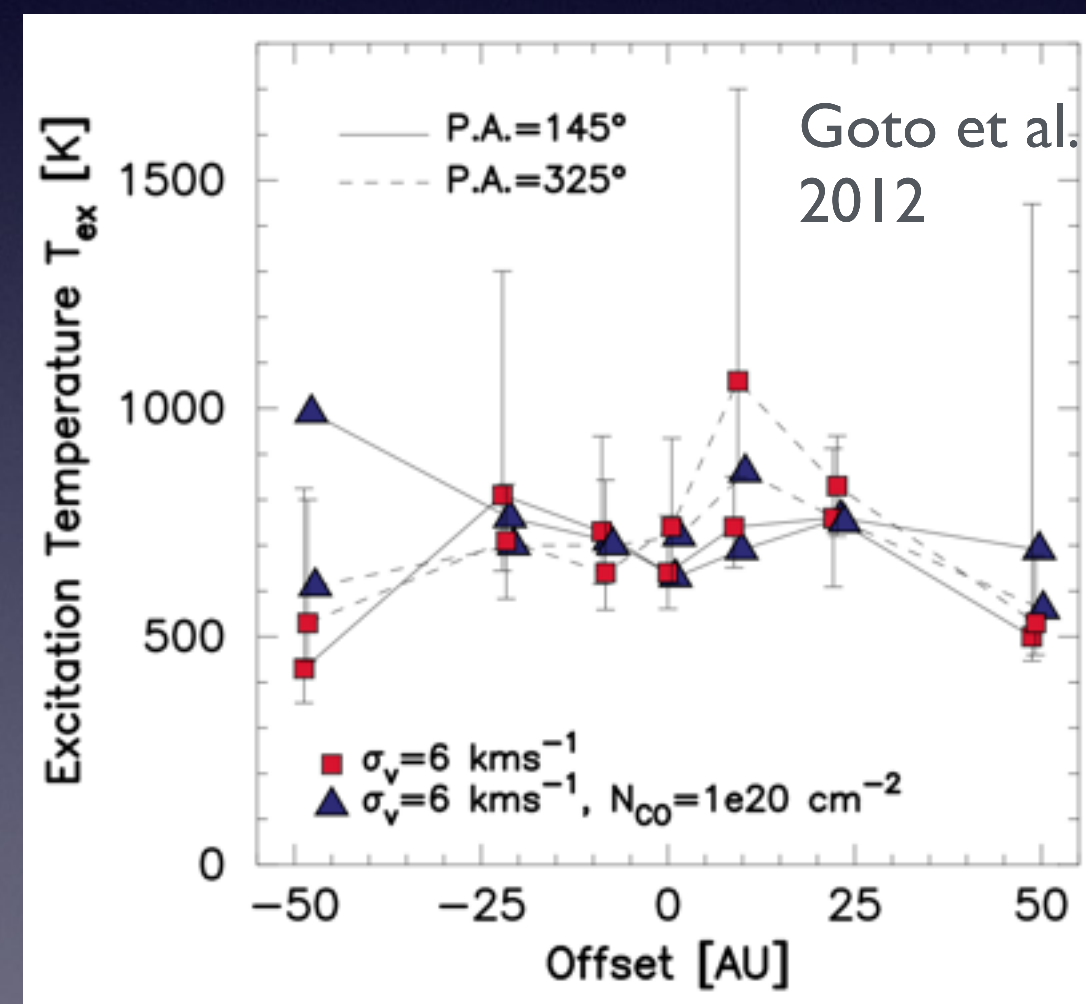
like factor of 3-10

we still have to see

2 imaging x + 1 spectroscopy λ







$T_{eq} < 90$ K

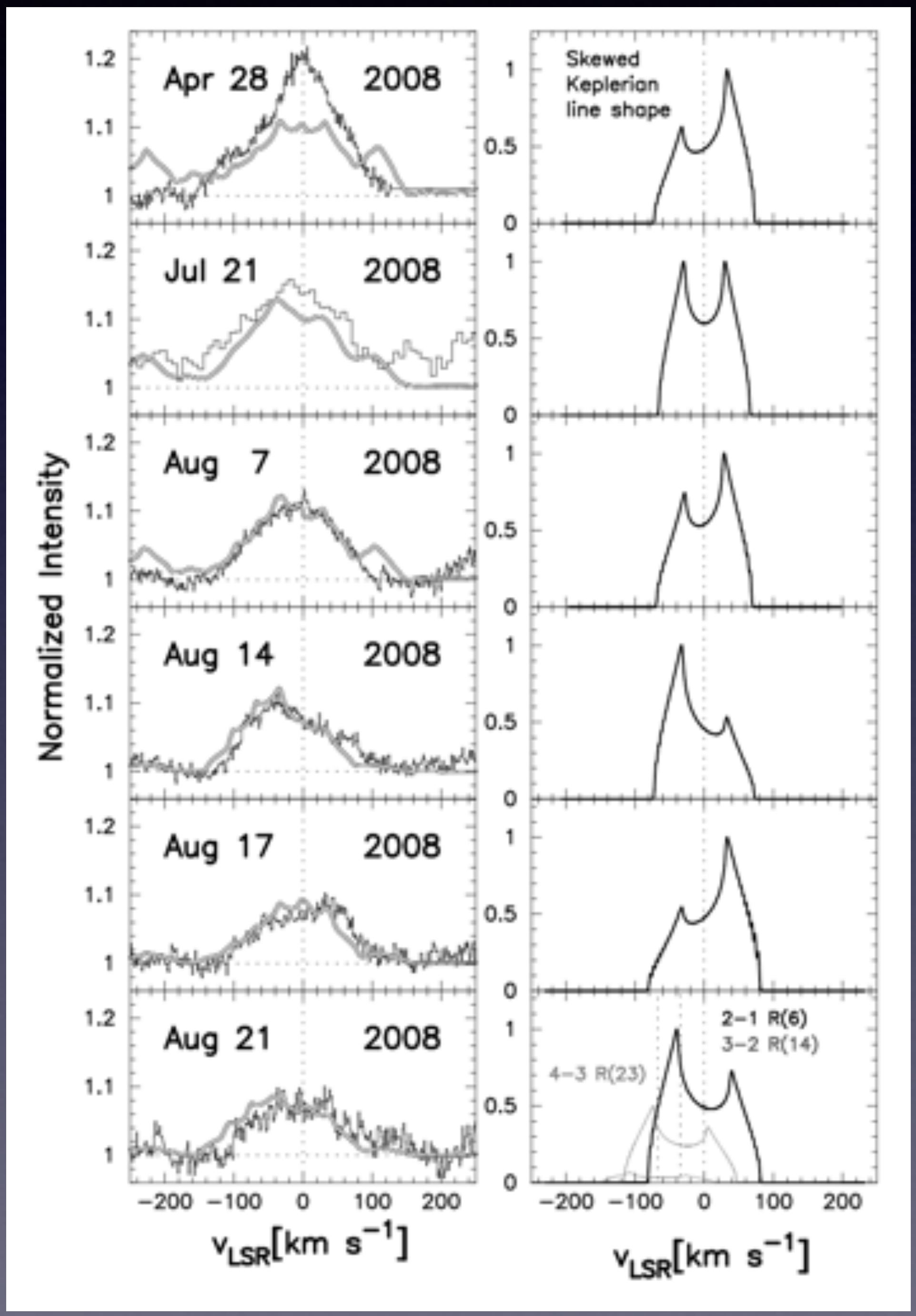
$T_{rot} > 500$ K

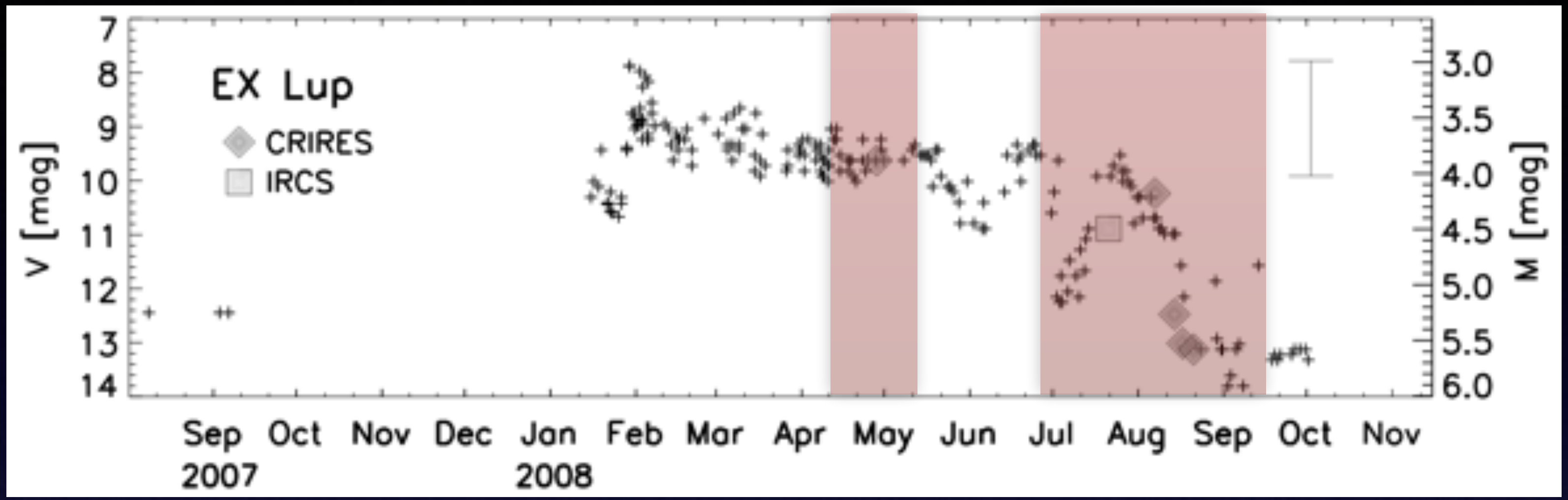
UV fluorescence

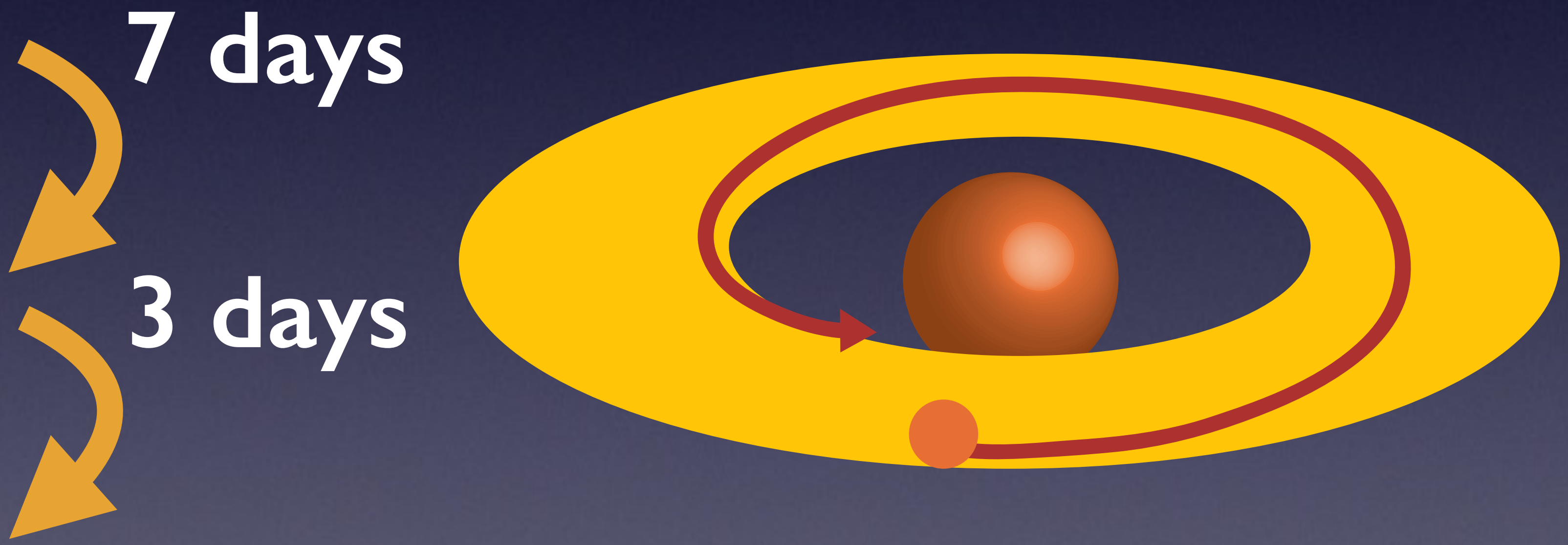
imaging confirmation of hot disk atmosphere

3 monitoring t + 1 spectroscopy λ

EX Lup, 2008 outburst







0.04 - 0.06 AU

Hot spot spiral into the star

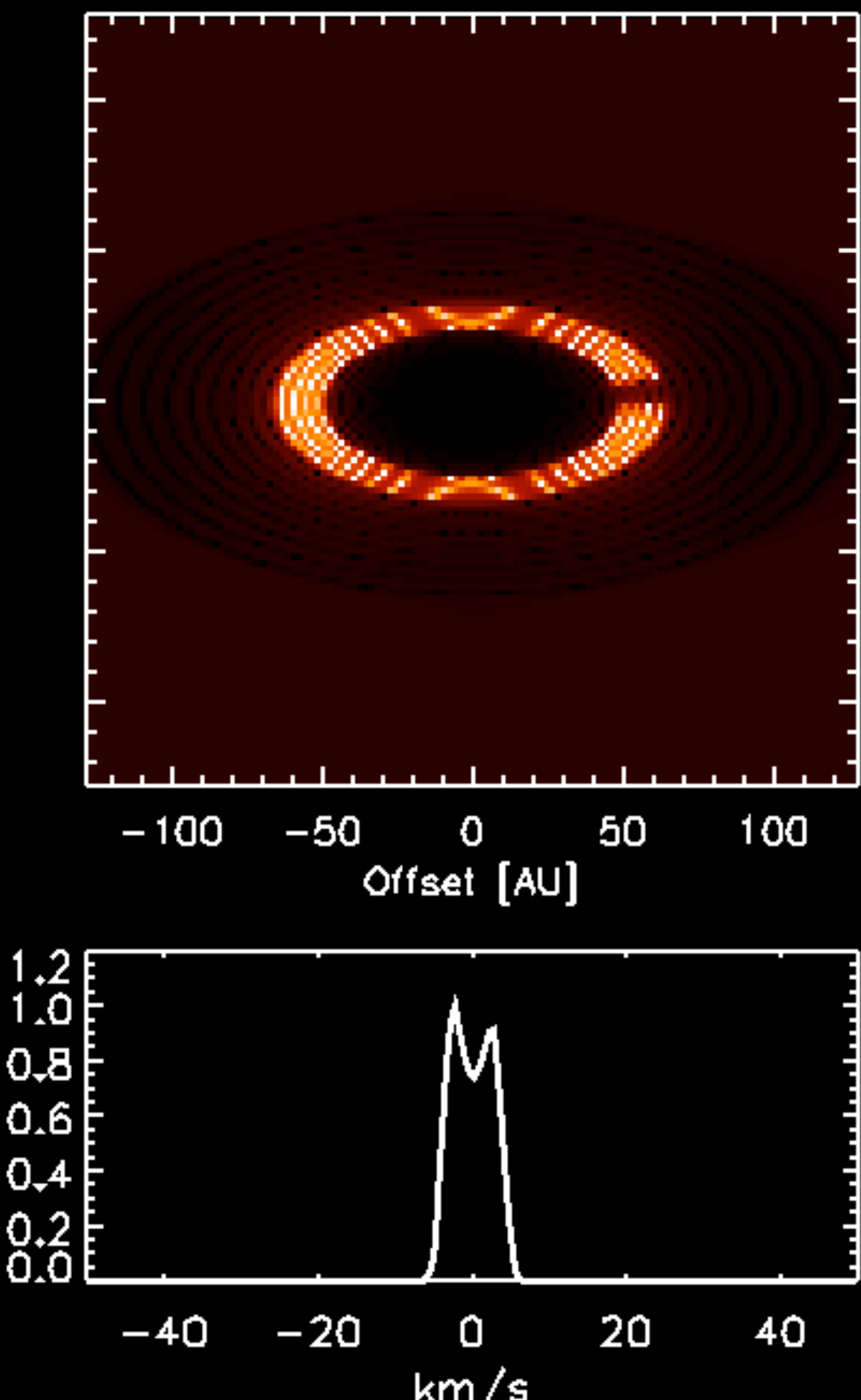
Goto et al. 2011

3 Monitoring

T Tauri star ($1M_\odot$)

Herbig Ae/Be star ($2M_\odot$)

with ELT / METIS



1 spectroscopy λ

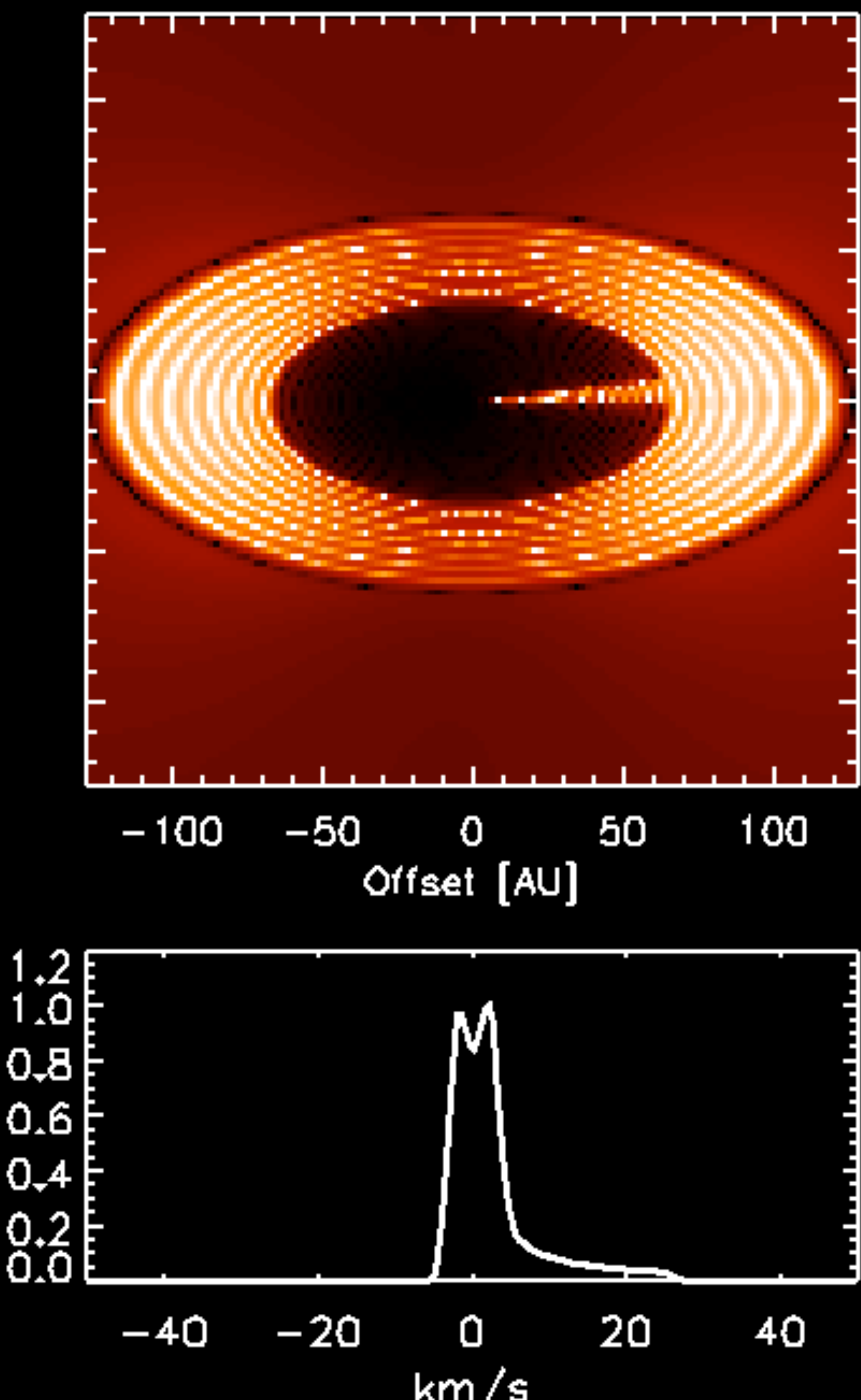
\+

2 imaging x

\+

3 monitoring t

Gap in the disk



1 spectroscopy λ

+

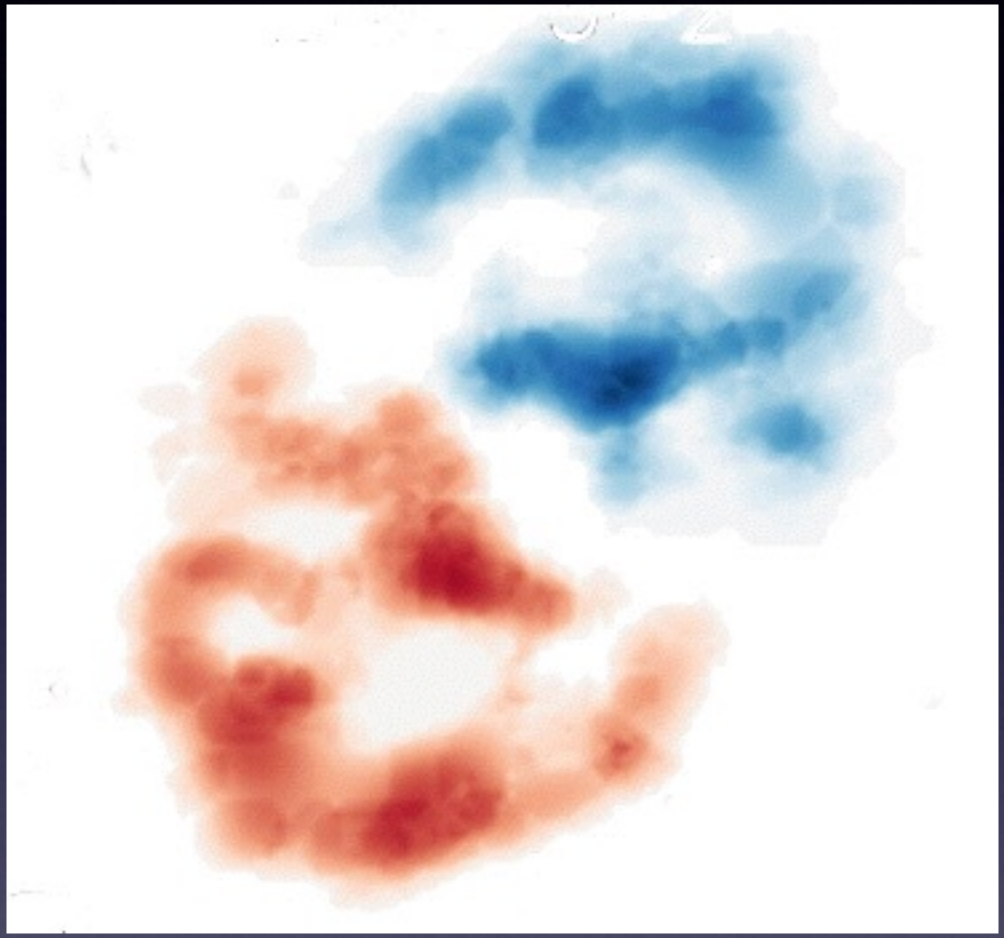
2 imaging x

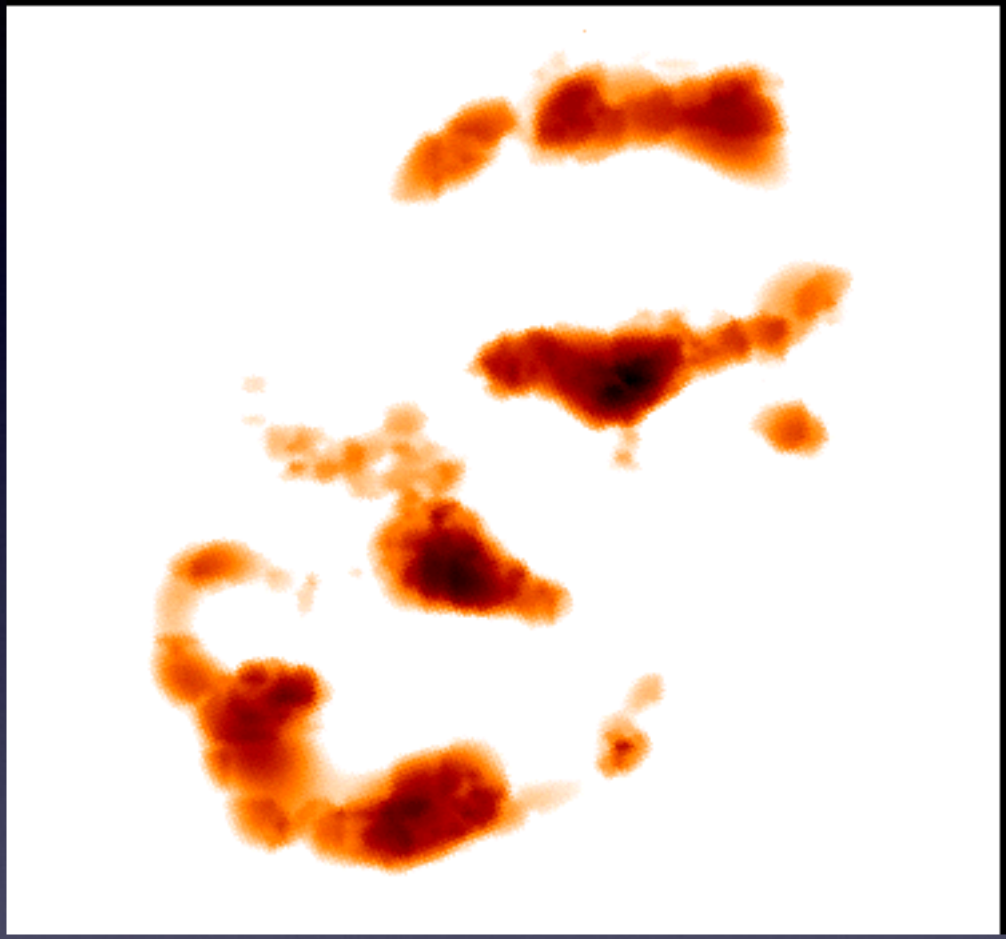
+

3 monitoring t

Bridge in the disk

3 Monitoring





Im Lup, Oeberg 15

ALMA delivered an image

ELT will make it move

thank **you** for your **attention**