Legacy of Herschel: what we have learned about protoplanetary disks

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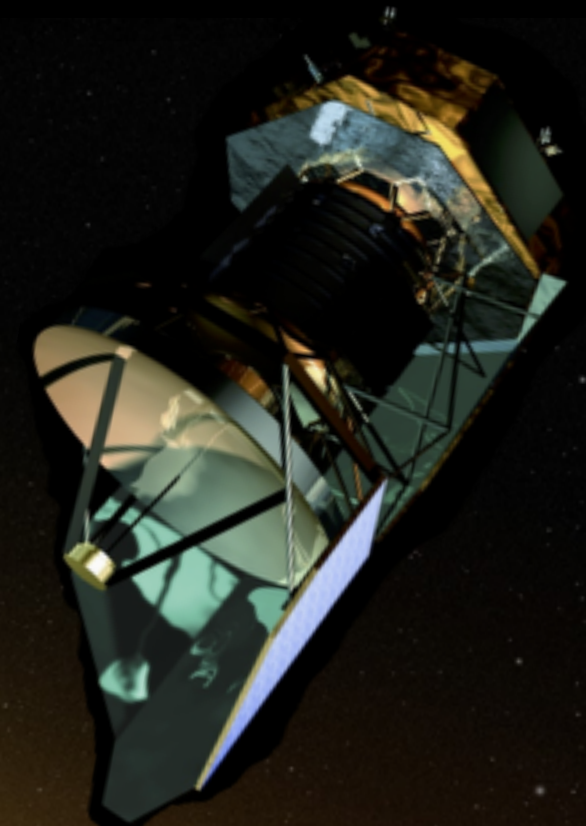


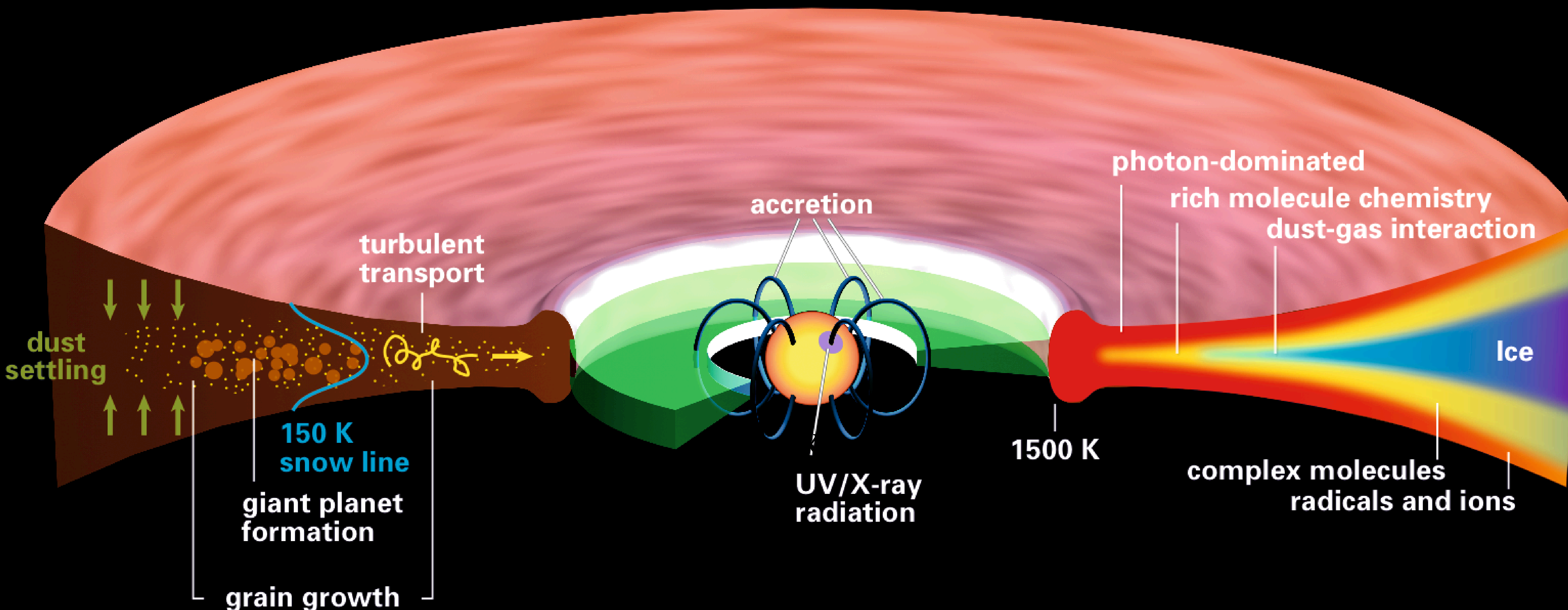
(G. Meeus, W.-F. Thi, D. Fedele, J. Bouwman, M. H. D. van der Wiel)

Credit: ESO/L. Calçada

Outline

- Why disks are interesting?
- Herschel observatory
- Large programs
- Observational results & statistics
- Conclusions

Protoplanetary disks as birth sites of planets

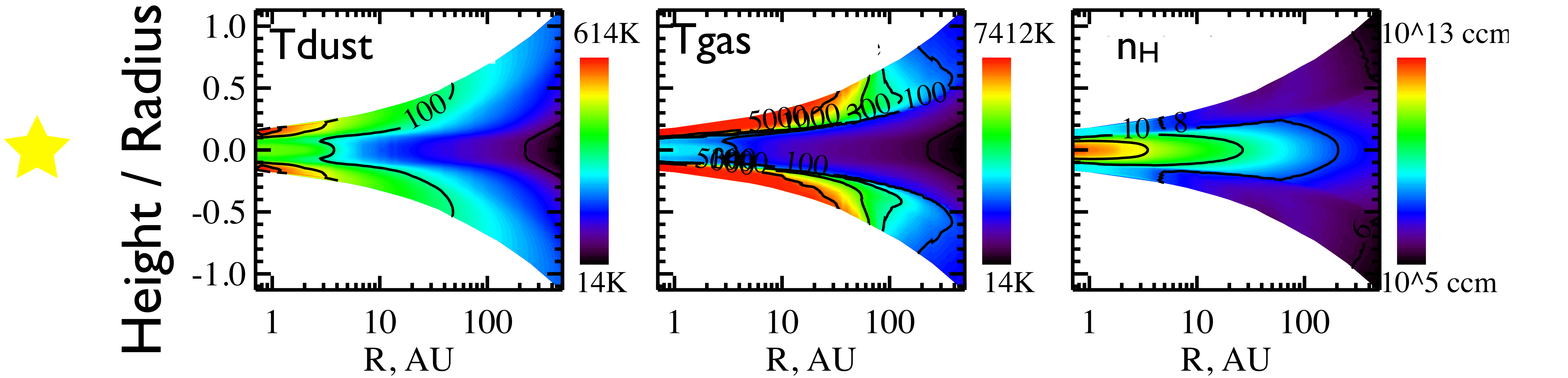


Henning & Semenov 2014, Chem. Reviews

- Strong gradients of physical conditions
- Grain evolution, planet-disk interactions, complex dynamics
- Rich chemistry

Thermochemical models of disk physics

T Tauri systems: T_{eff} ~ 4000 K, L_X ~ 10^{31} erg/s, UV (100 AU) ~ 500 ISM UV



Akimkin et al. (2013), ApJ 766, 8

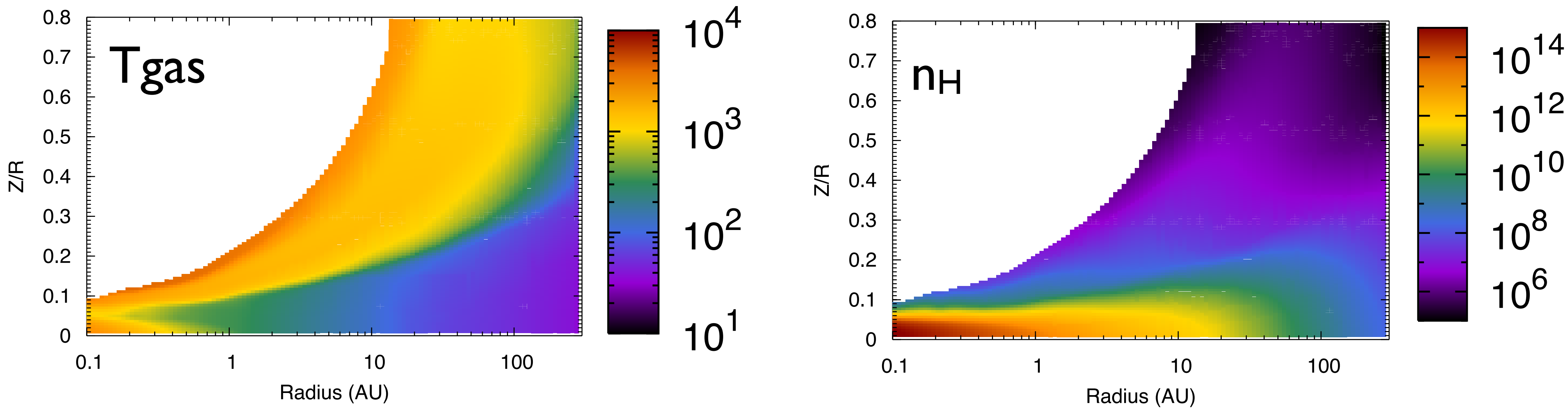
- Heating: dust, PAHs + gas (ro-)vib. absorption
- Cooling: dust + gas (ro-)vib. emission
- Gas-grain collisions: at $n_H > 10^6$ cm^{-3} $T_{dust} = T_{gas}$

Kamp ++ 05; Woitke ++09; Jonkheid ++ 07; Gorti & Hollenbach 08; Nomura ++ 10; Aresu ++12; Bruderer ++ 12

Thermochemical models of disk physics

HAe systems: T_{eff} > 8000 K, L_X ~ 10^{30} erg/s, UV (100 AU) > 10^5 ISM UV

Height / Radius



Nomura & Millar (2005), A&A 438, 923

- Upper layers: $T_{gas} > T_{dust}$
- HAe disks are warmer than TTau disks: T > 20 – 25 K

Kamp ++ 05; Woitke ++09; Jonkheid ++ 07; Gorti & Hollenbach 08; Nomura ++ 10; Aresu ++12; Bruderer ++ 12

Herschel

- Cornerstone ESA mission (with NASA support)
- Large 3.5m mirror
- Cryogenically He-cooled, <2K
- 57–670 μm: imaging & spectroscopy

- Instruments:
  - PACS (Photodetector Array Camera and Spectrometer)
  - SPIRE (SPectral and Photometric Imaging REceiver)
  - HIFI (Heterodyne Instrument for the Far-Infrared)

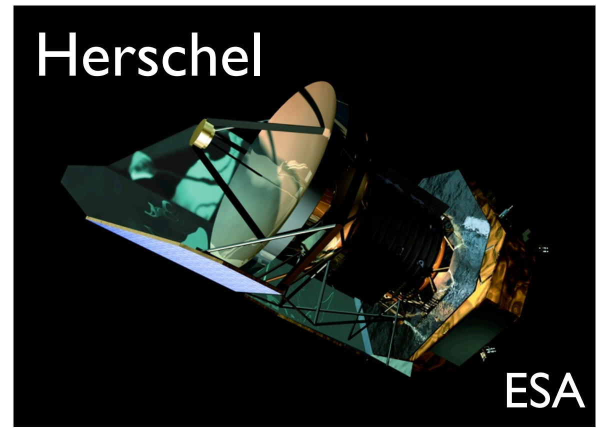
Disks are not spatially resolved

Probing distinct regions: multi-wavelength approach

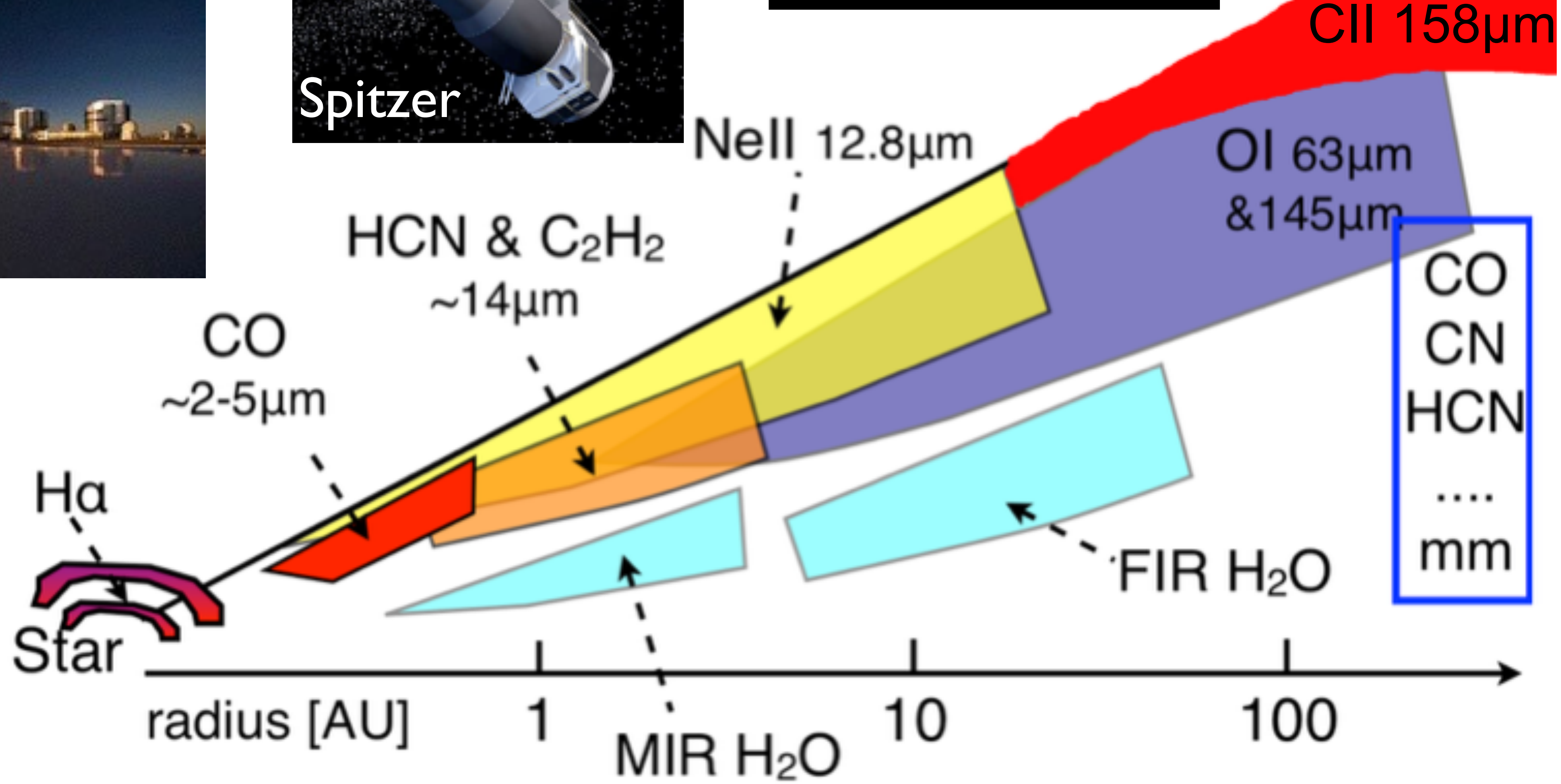
Visual/NIR

NIR/MIR

FIR



Radio

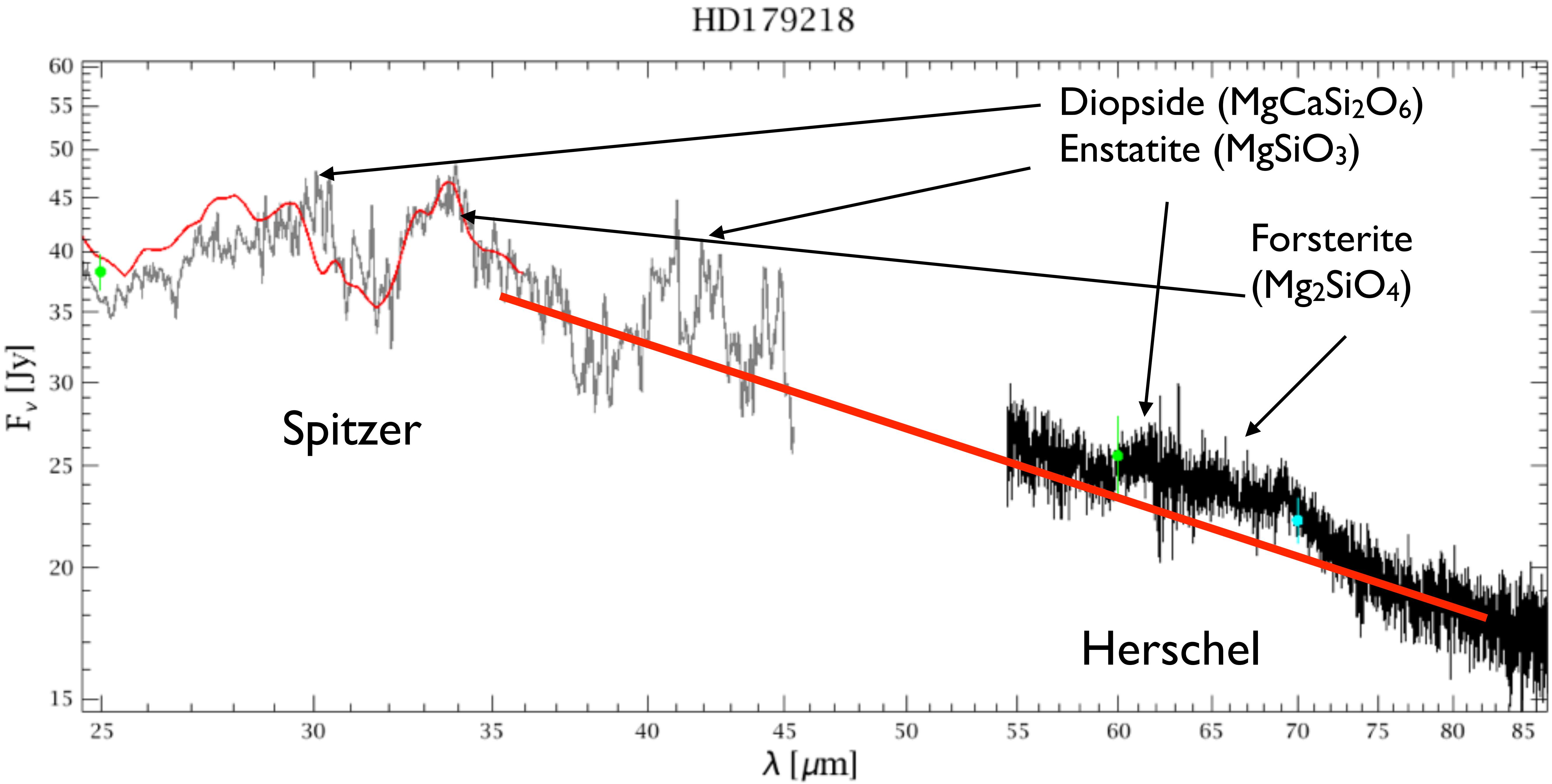


ALMA

Large disk programs

- GAS in Protoplanetary Systems (GASPS; PI Bill Dent):
  - 400 h, 250 disks (PACS)
  - Dust, [CII] 157µm, [OI] 63 & 145µm, water 63.3 & 78 µm, CO lines
- Disk Gas and Ice in Time (DIGIT: PI N. Evans):
  - 250 h, >30 disks (PACS)
  - Gas lines, dust and ice bands
- Water In Star-forming regions with Herschel (WISH; PI E. van Dishoeck):
  - >200 h, many Class 0–II sources
  - OH, H_2O, OH^+, H_2O^+, …
  - Water in disks with HIFI (PI M. Hogerheijde)

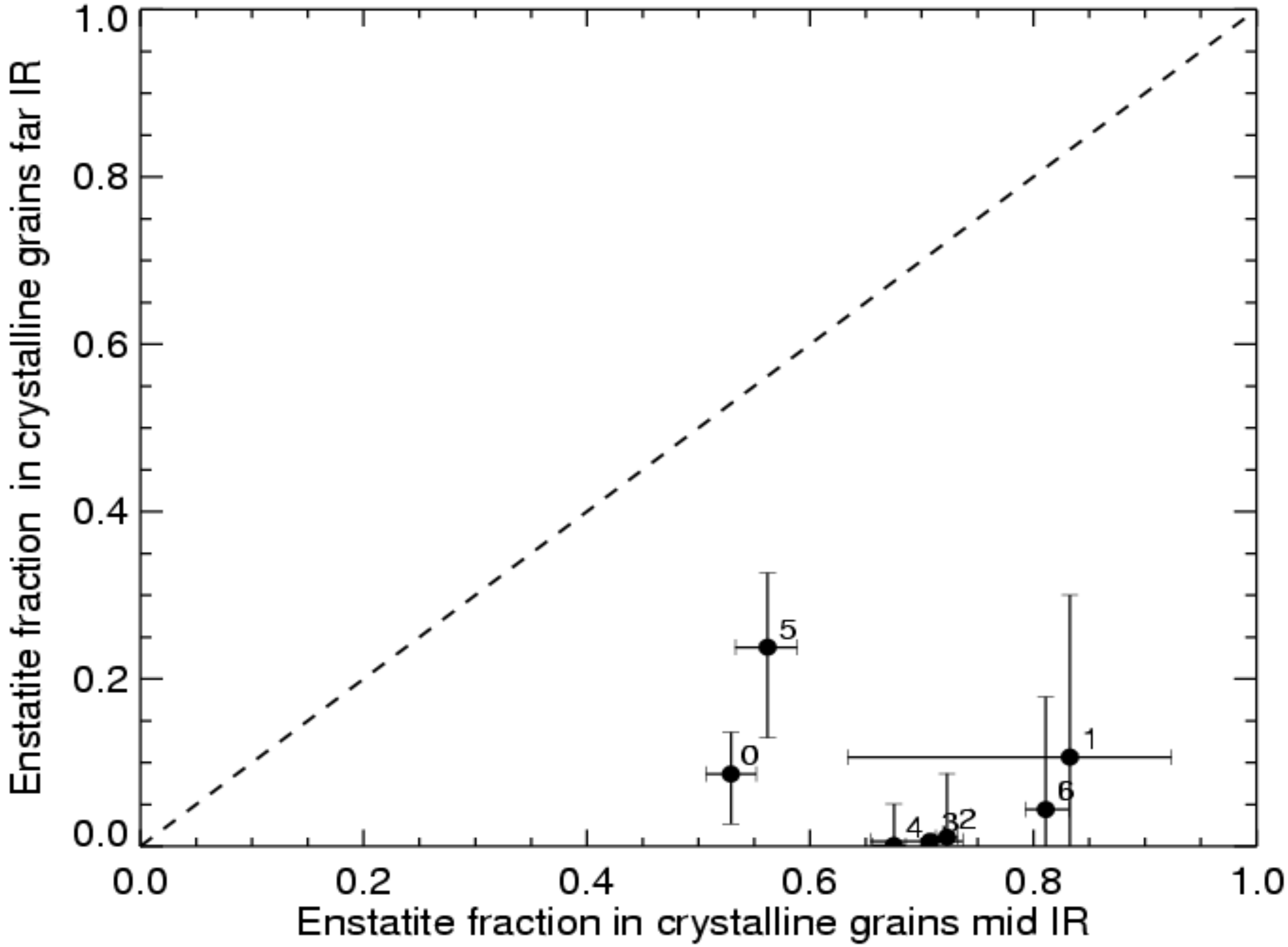
Silicates in protoplanetary disks



- Distinct features, lab. spectra available
- Crystalline and amorphous silicate features (also water)
- Difficulty in setting the continuum slope

J. Bouwman, priv.comm.

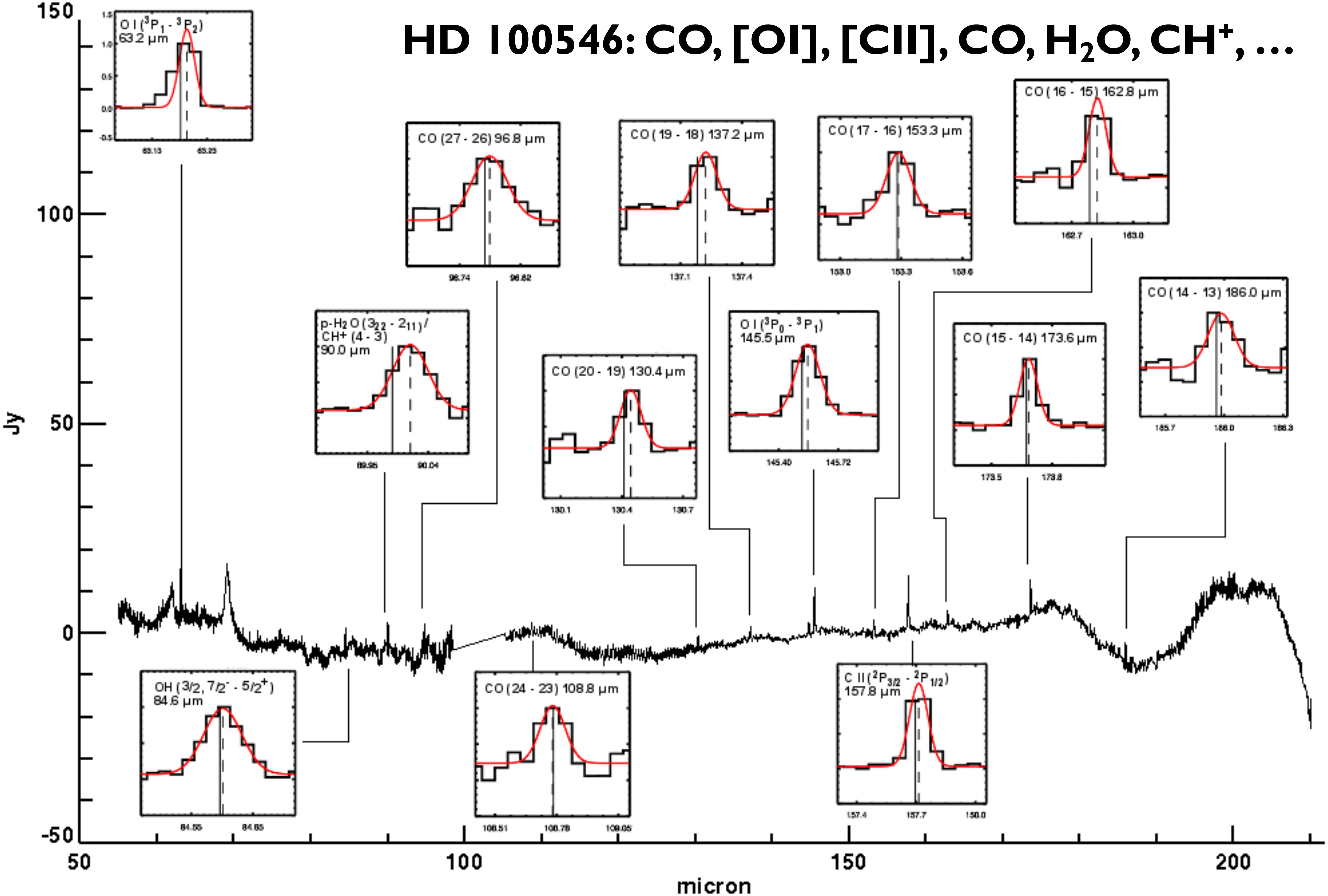
Silicates in protoplanetary disks



- Higher crystallinity fraction in inner disk regions
- Higher Mg-content in inner disks: temperature?

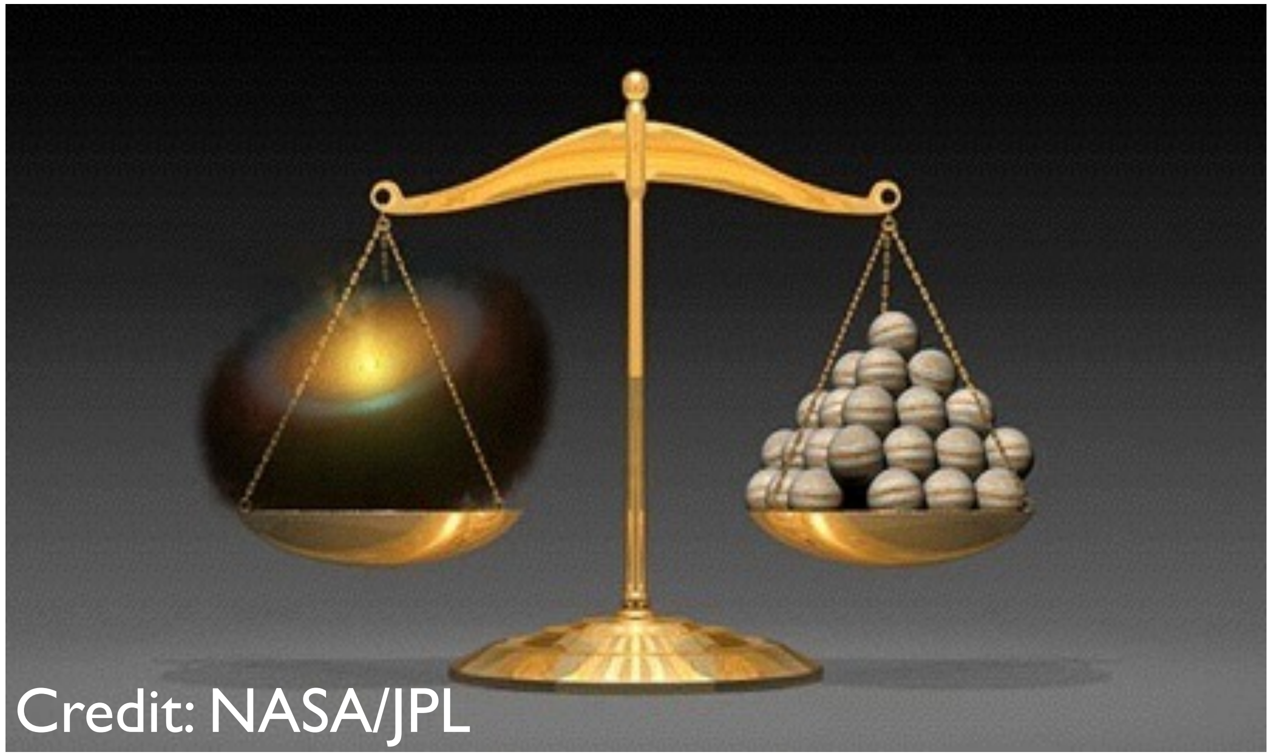
J. Bouwman, priv.comm.

Gas disk diagnostics with Herschel

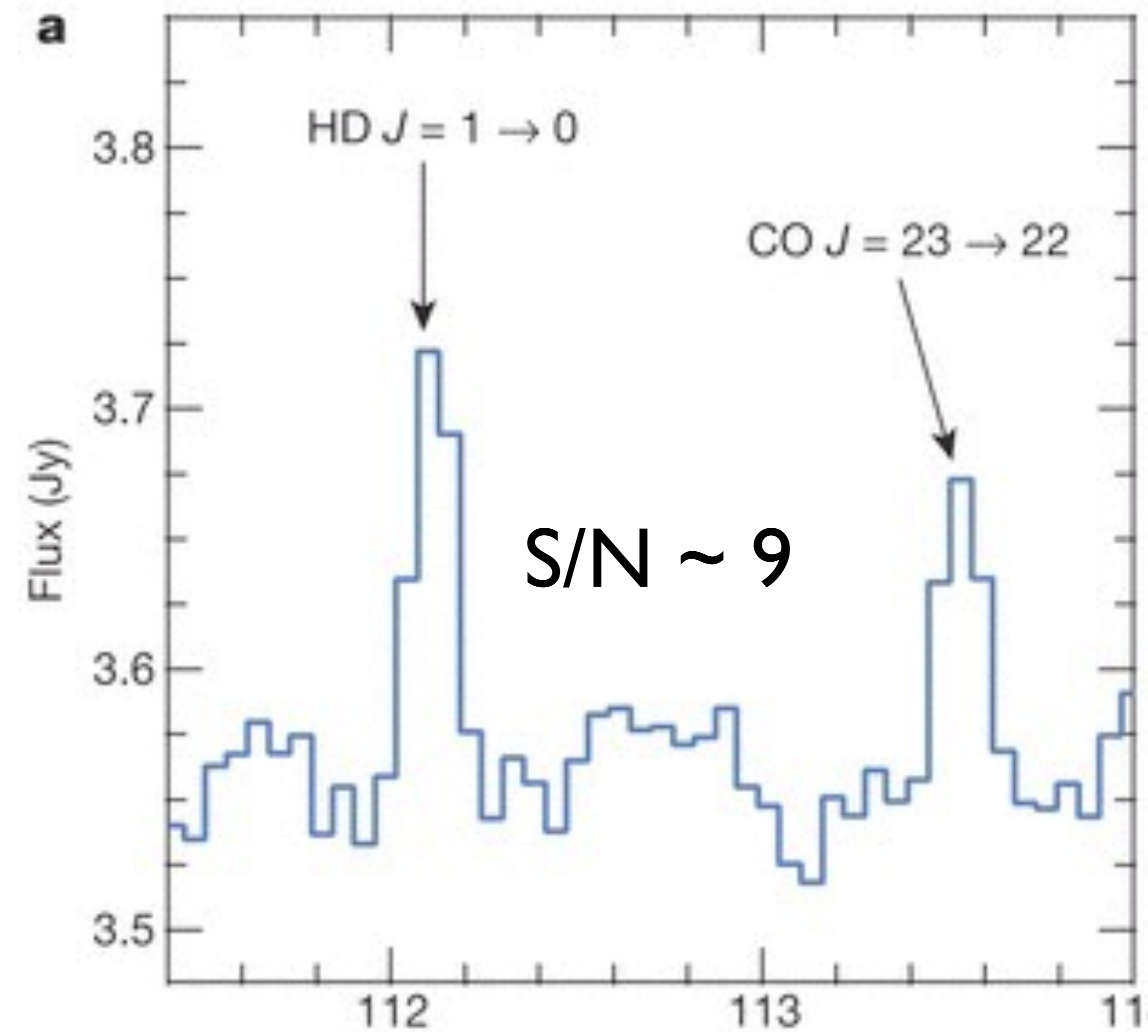


Sturm, Bouwman, Henning et al. (2010; see also Thi et al. 2011)

Herschel PACS detection of HD in TW Hya



Bergin et al. (2013), Nature 493, 644



Direct probe of gas mass:

HD 1–0: T_{ex} > 20–25K

$HD/H_2 \sim 10^{-5} \Rightarrow M_{disk} > 0.05\ M_{sun}$

However: ~20 h of integration time

GASPS: Line detection statistics

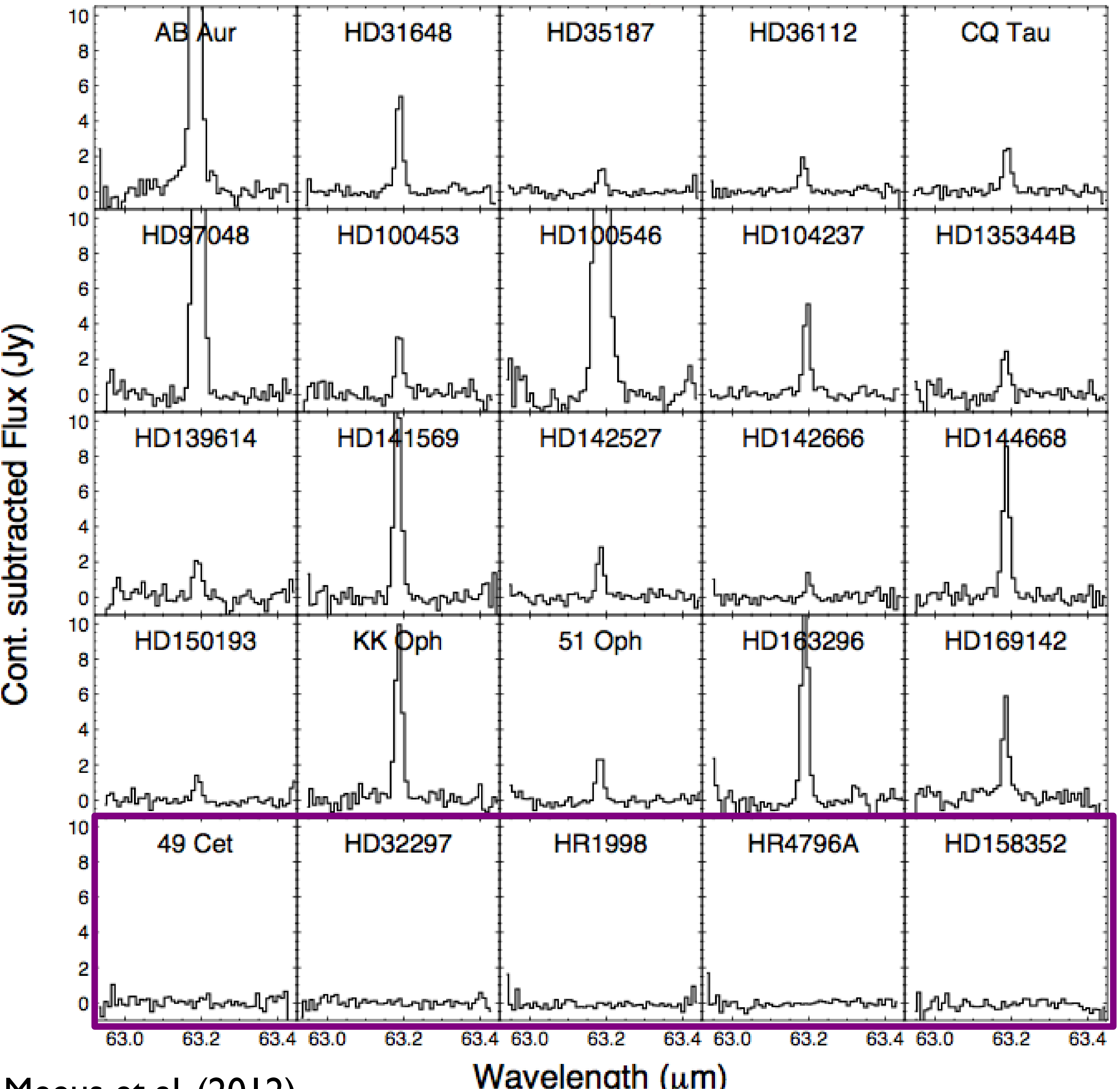
	[OI]63	[OI]145	[CII]157	H_2O 63	CO 18-17
Total	80/164	24/61	19/72	12/164	24/58
HAeBe stars[a]	20/25	5/23	6/25	2/25	10/24
T Tauri stars[b]	60/139	19/38	13/47	10/139	14/34

- [OI]@63 μm / [OI]@145 μm ~ 10 – 20
- [CII] line is weak, often spatially extended ⇒

  surrounding gas/outflows?
- Ortho-H_2O 8_{17}-7_{07} at 63 μm has E_{up} >1000 K ⇒ hot gas
- CO J=18-17 line ⇒ warm gas

Dent et al. (2013), see also Fedele et al. 2012 A&A 544, L9

GASPS: HAe disks at [OI] 63.2 µm

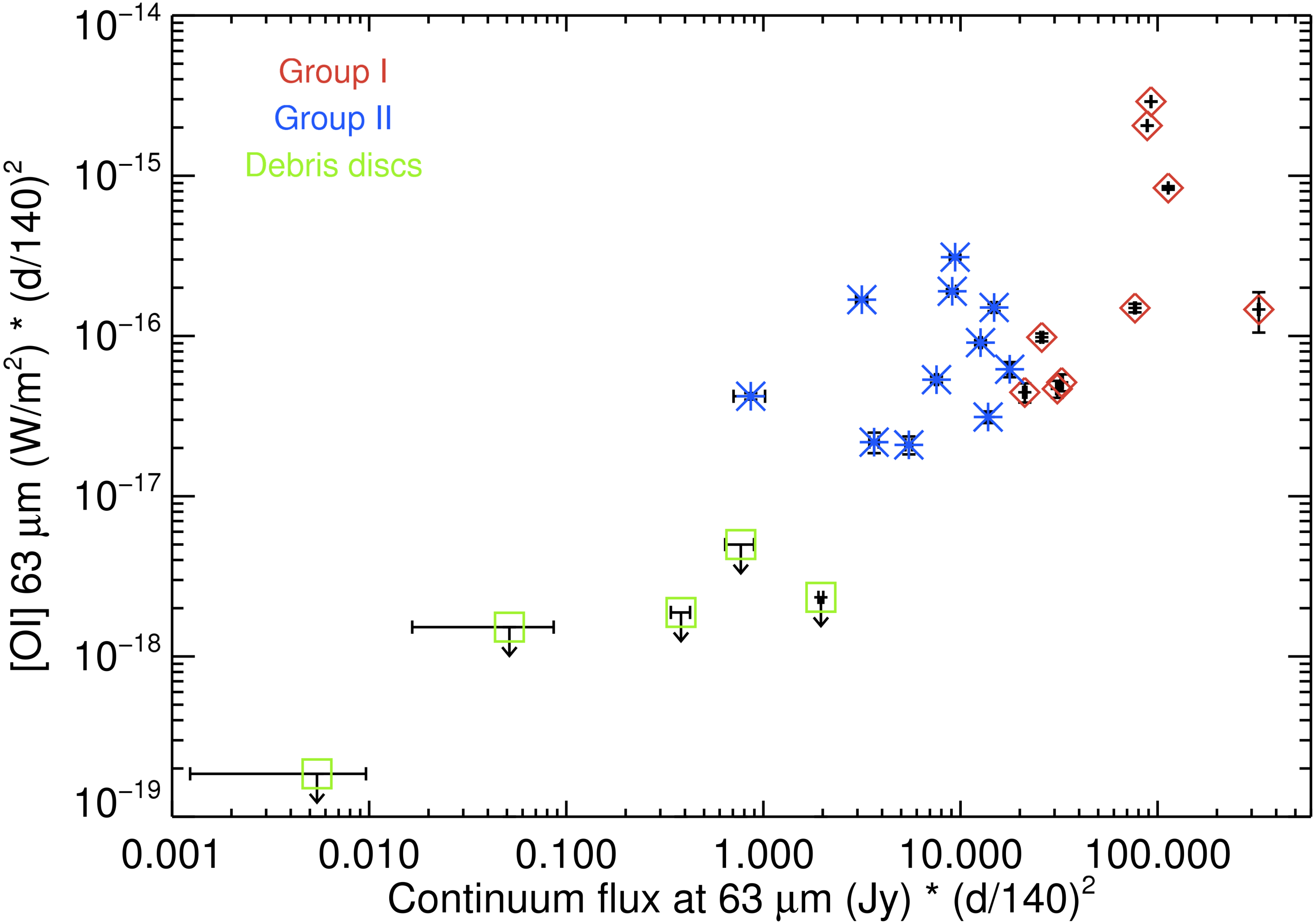


- Variety of line fluxes
- Debris disks are„deserted“

Debris disks

Meeus et al. (2012)

GASPS: Trends with [OI] 63 μm

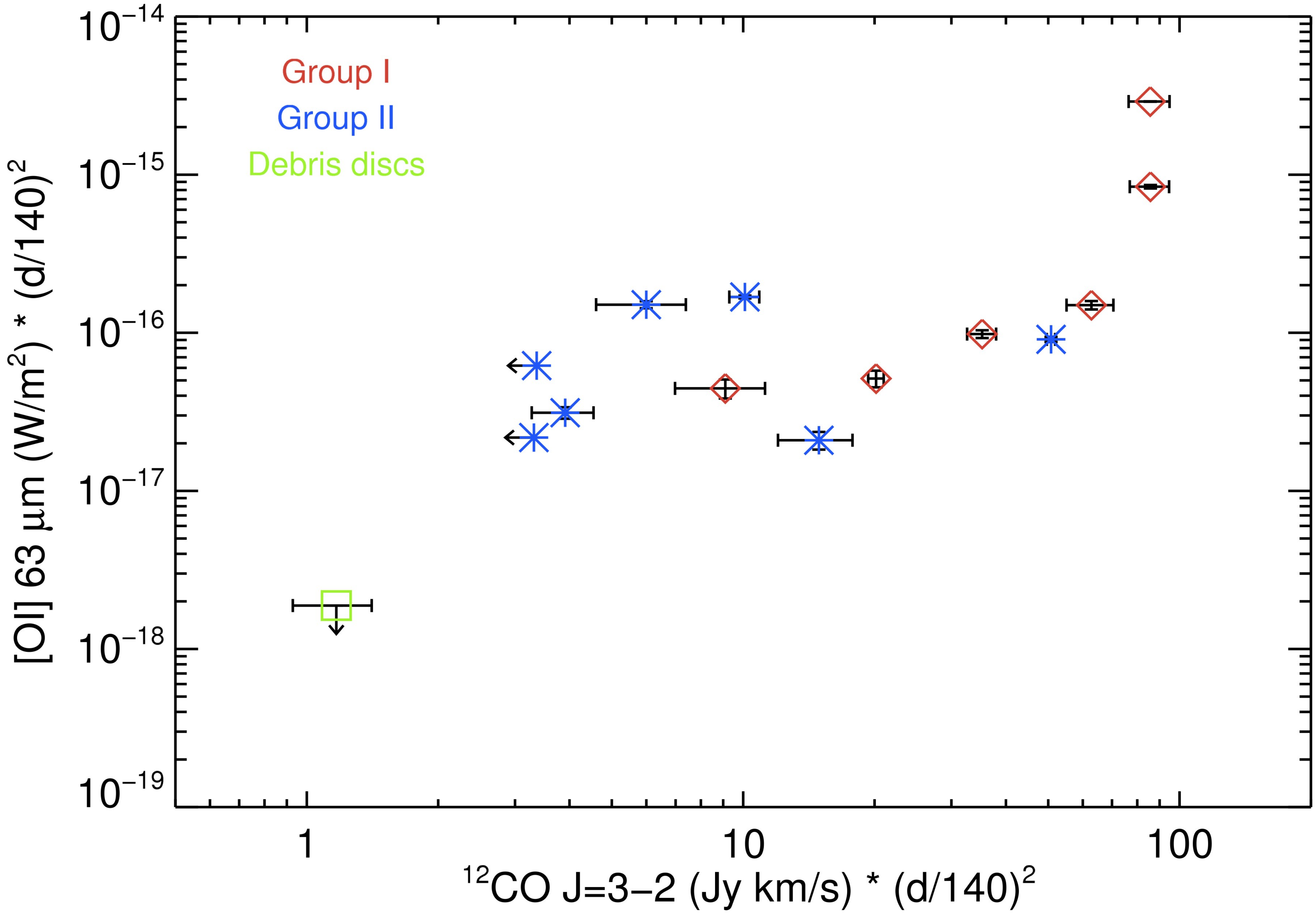


FIR continuum

Dent et al. (2013), PASP, 125, 927, 477

- Higher warm dust mass ⇒ higher warm gas mass

GASPS: Trends with [OI] 63 µm

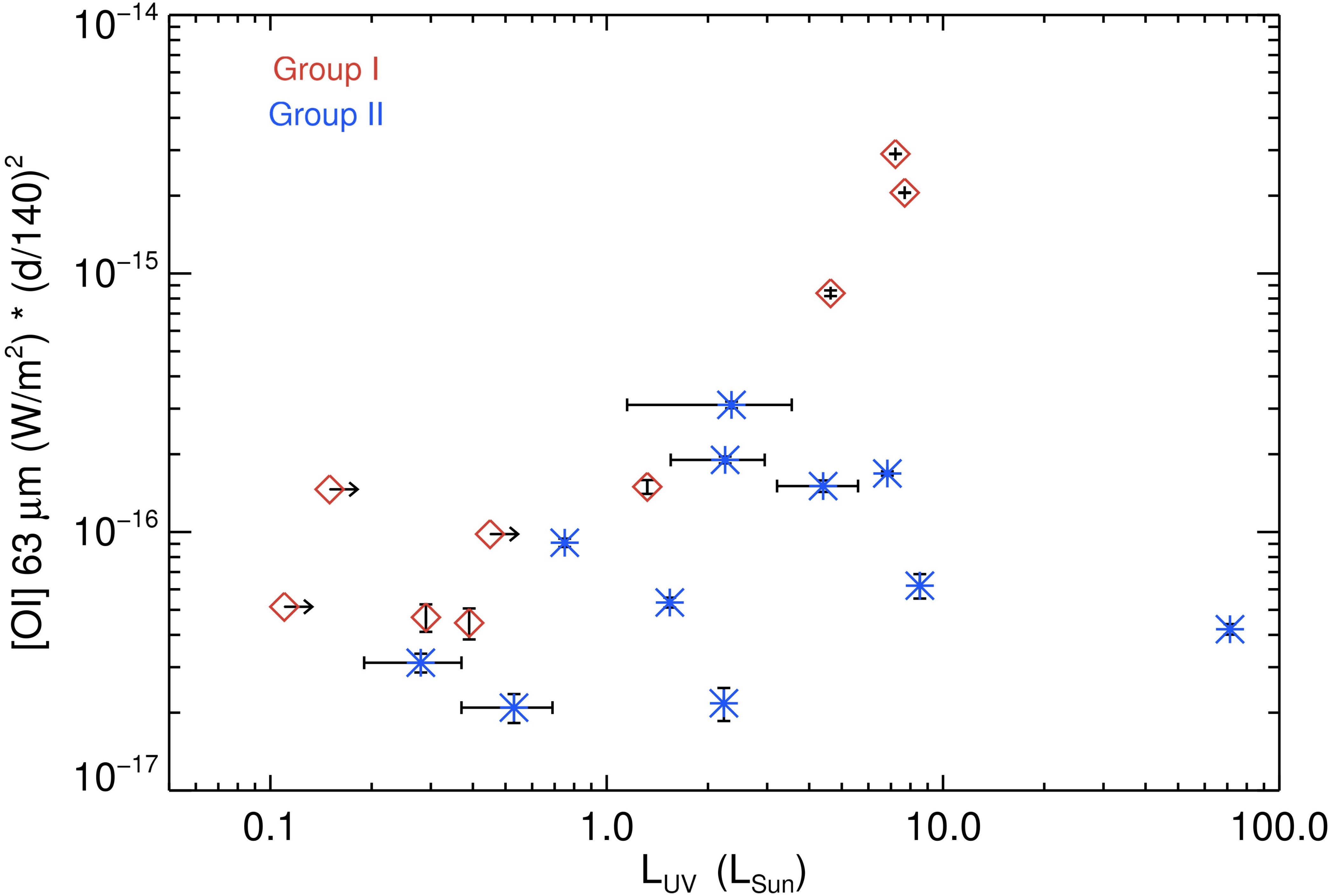


^{12}CO J=3-2 Cold Gas

Dent et al. (2013), PASP, 125, 927, 477

- Higher cold gas mass ⇒ higher gas mass?

GASPS: Trends with [OI] 63 µm

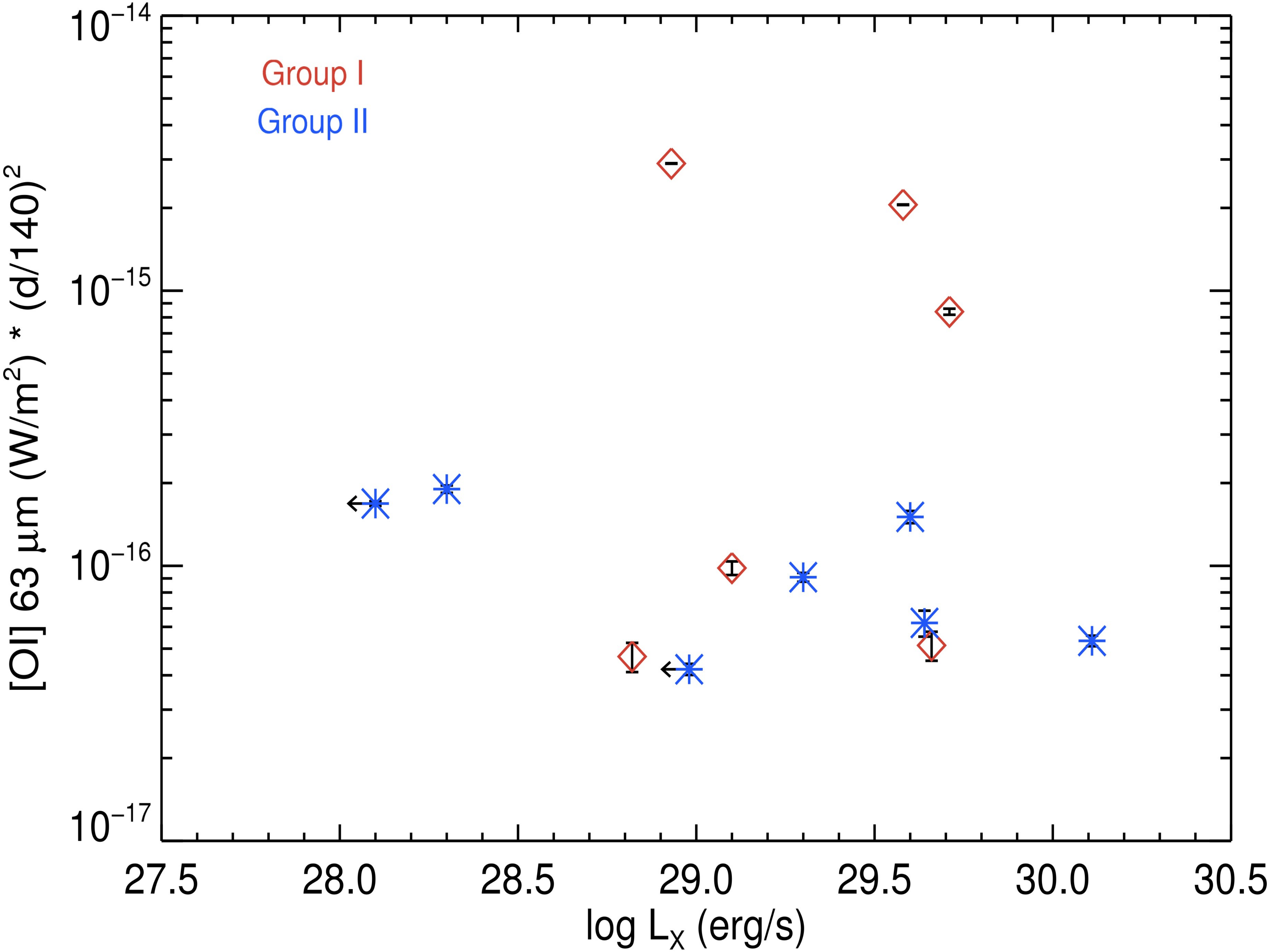


[OI] versus L_{UV}

Dent et al. (2013), PASP, 125, 927, 477

- Self-shadowed disks ⇒ only IS UV matters

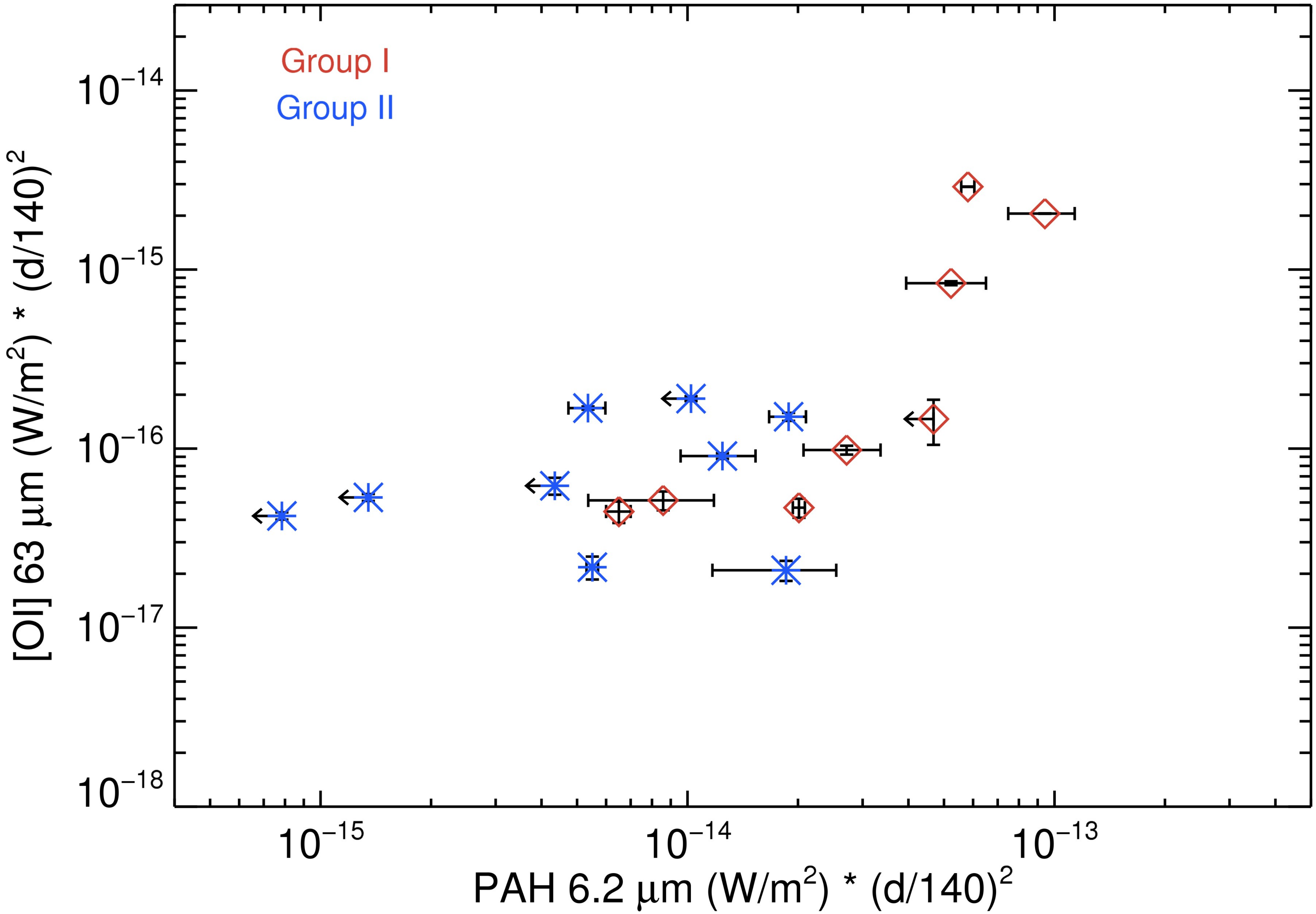
GASPS: [OI] 63 μm vs X-ray luminosity



- No obvious correlation ⇒ UV is more important

Aresu et al. (2011, 2012)

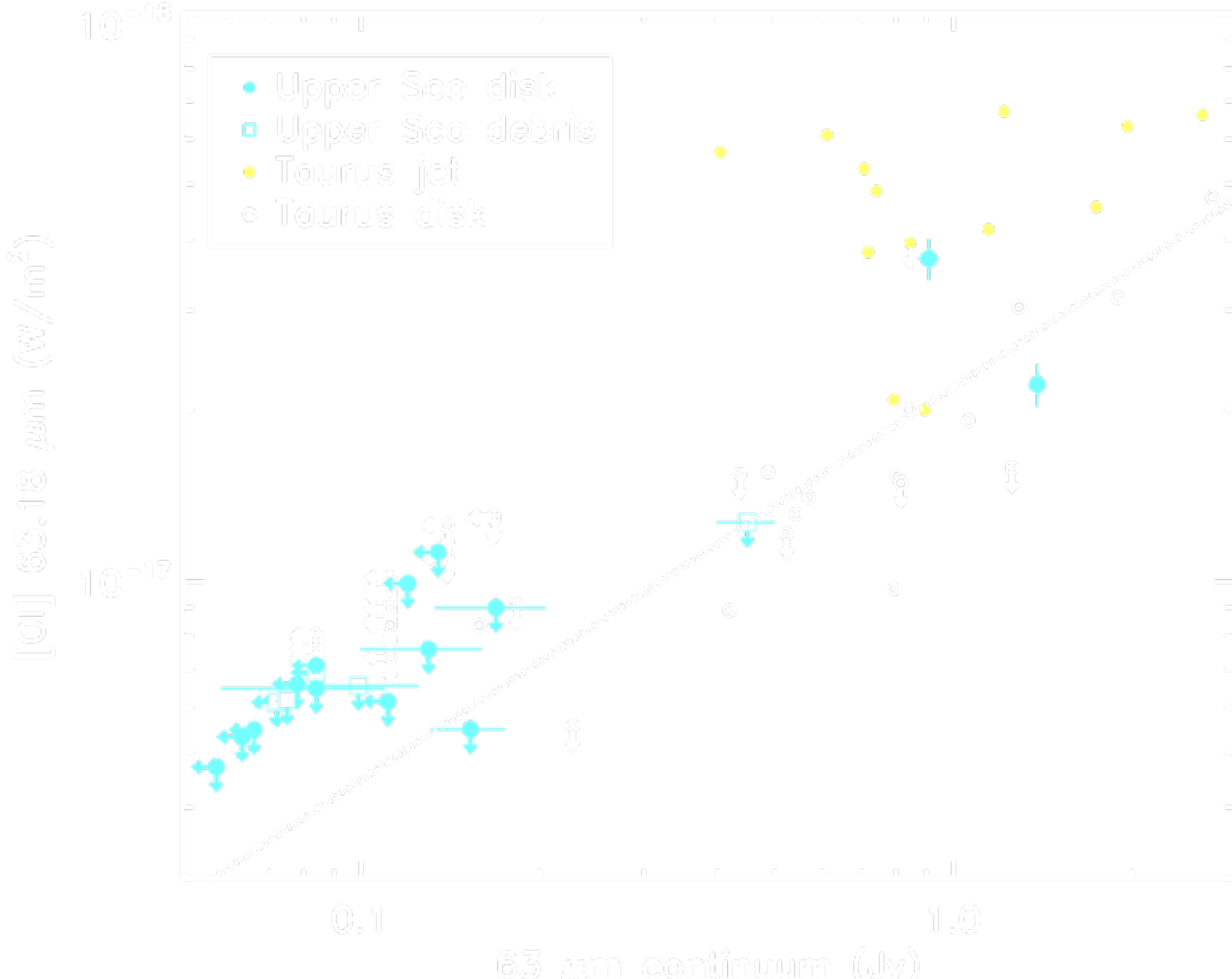
GASPS: Trends with [OI] 63 μm



[OI] versus L_{PAH}

Dent et al. (2013), PASP, 125, 927, 477

- Higher PAH abundance ⇒ more efficient gas heating

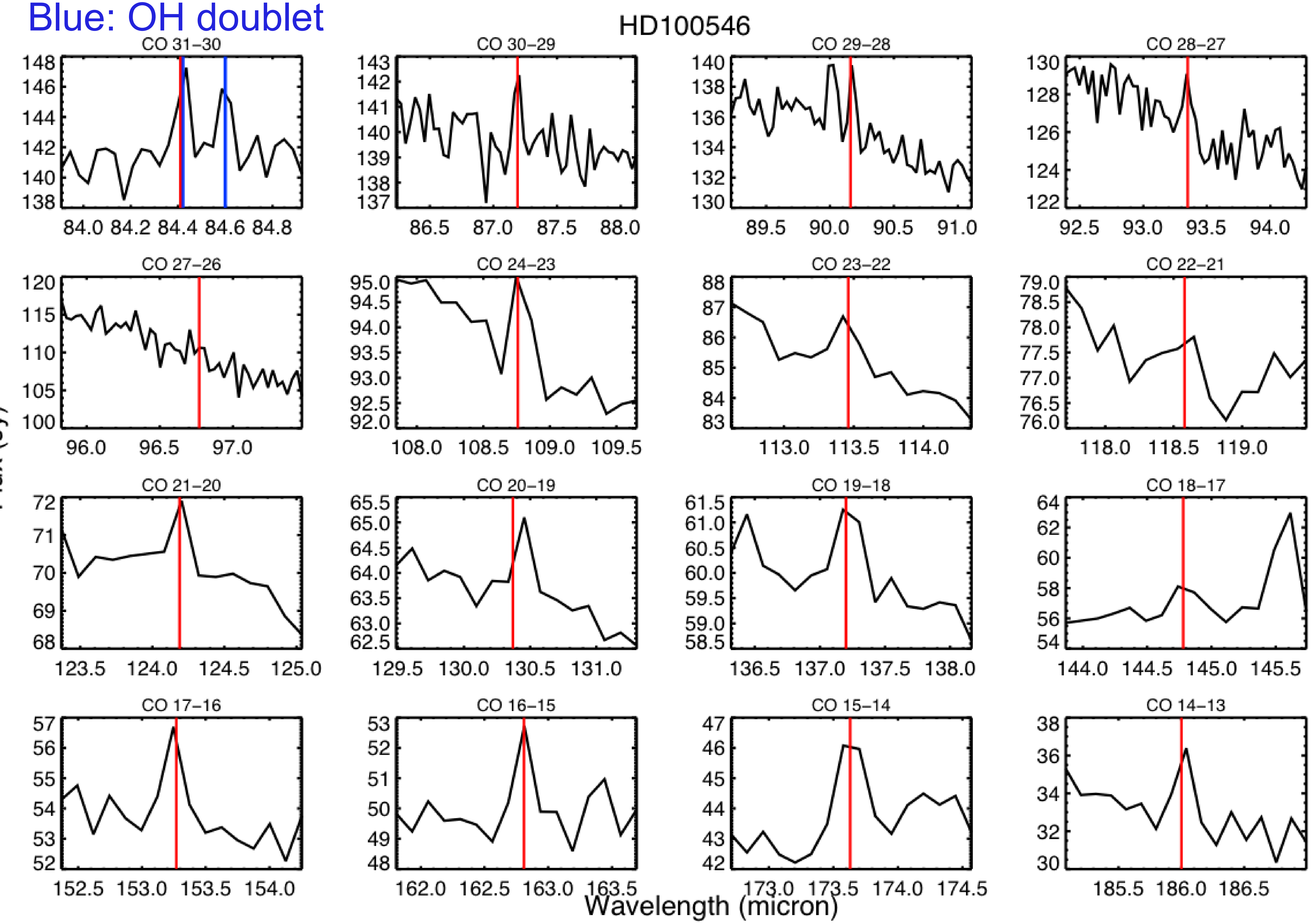


Sources with outflows

Transition disks with inner holes

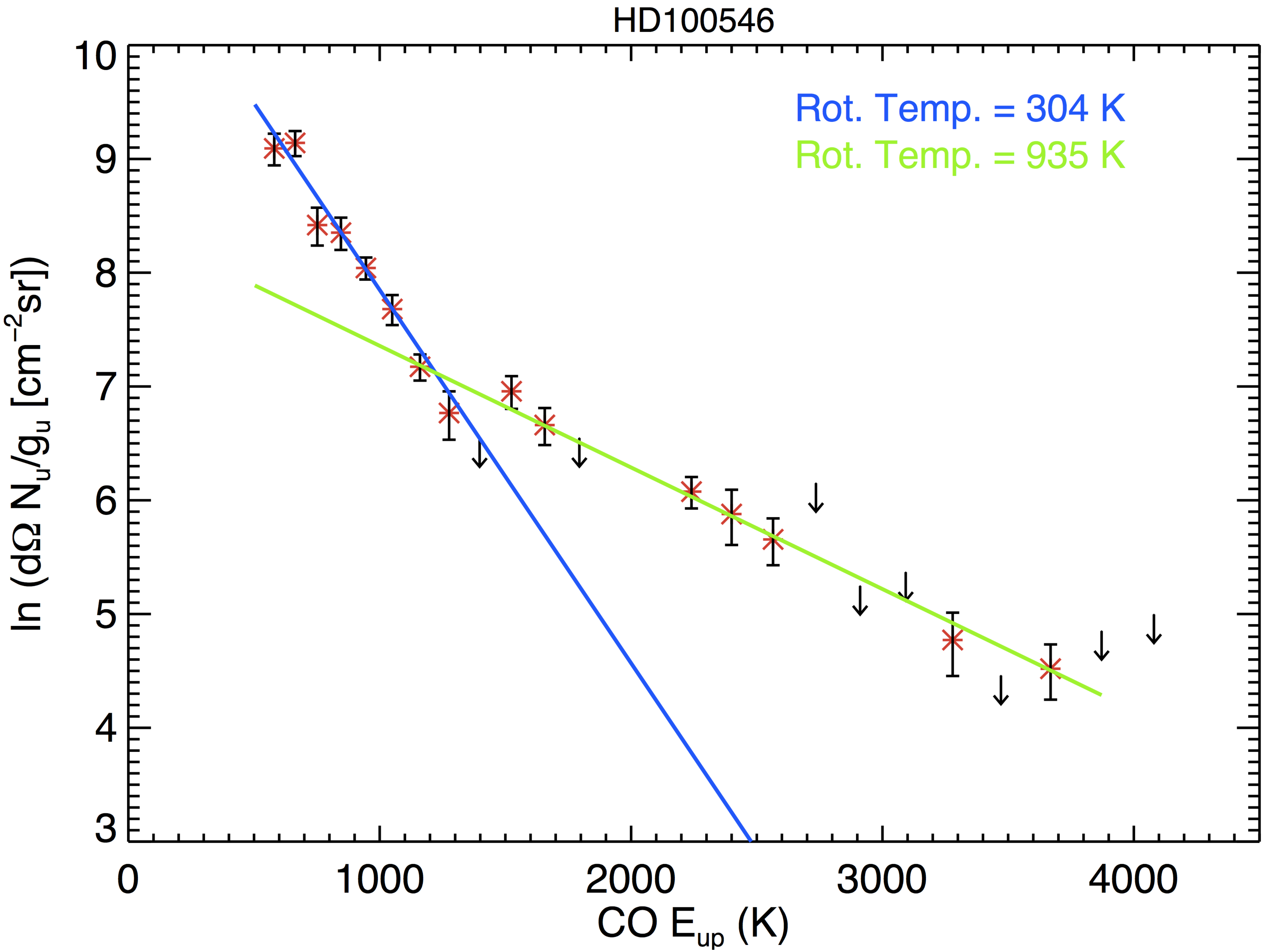
GASPS: Disk diagnostics with CO lines

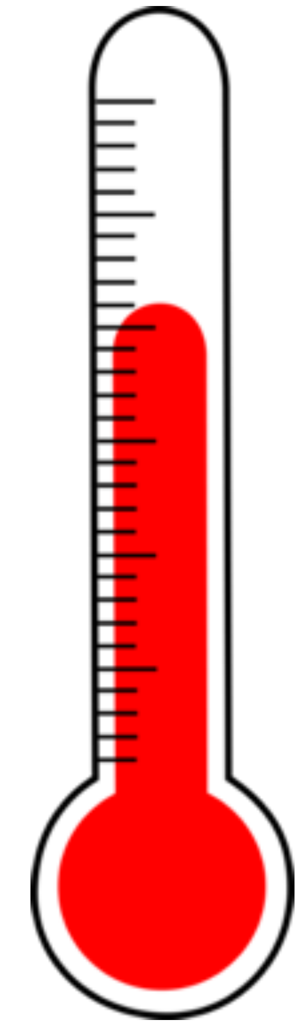
Blue: OH doublet



CO detections: J=30-29 down to 14-13

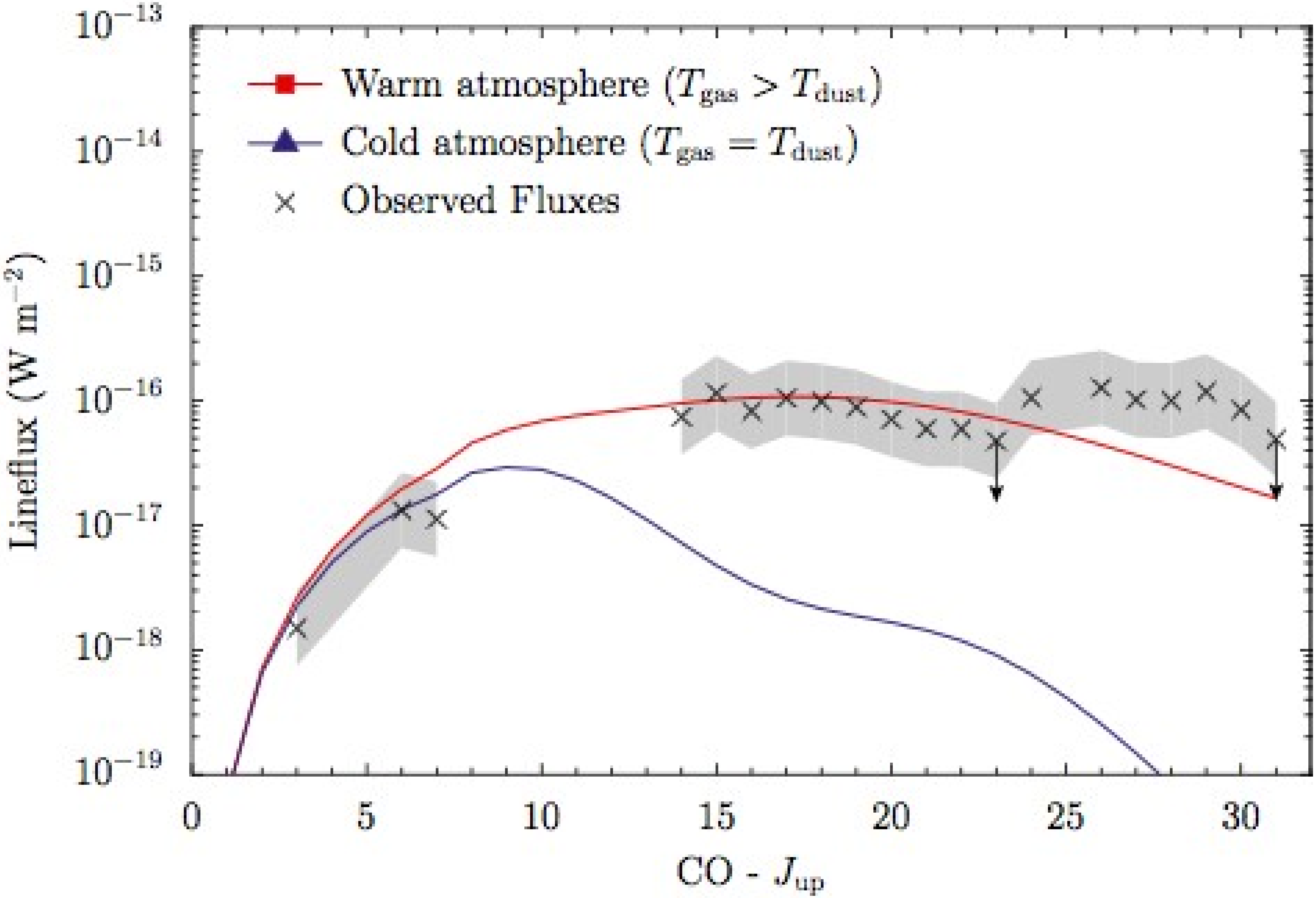
CO rotational diagrams





- Some disks show two components: warm and hot CO gas

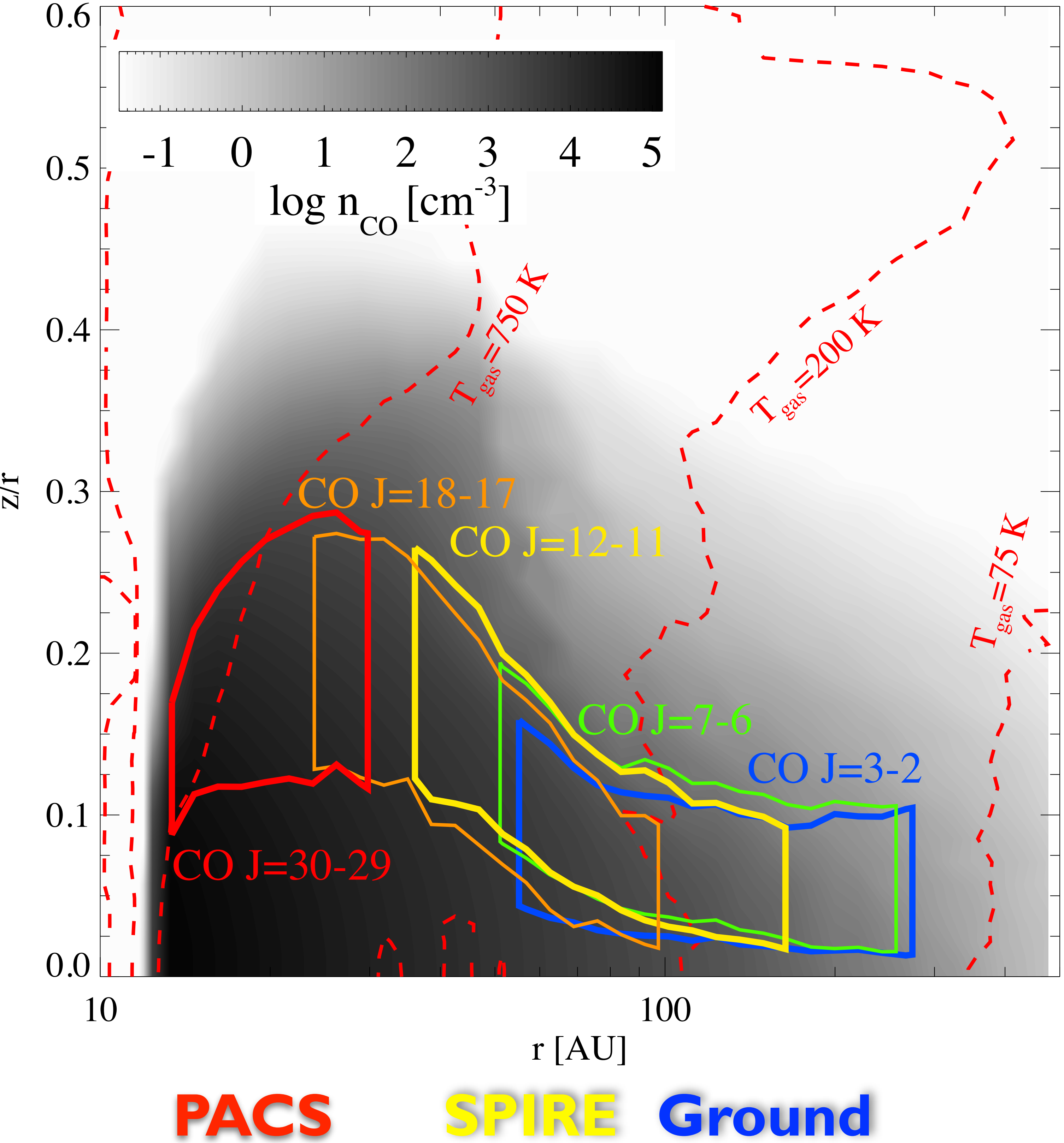
CO line modeling: HD 100546



- Probe disk regions with radii < 30-50 AU
- Mid- and high-J CO lines require $T_{gas} > T_{dust}$

Bruderer et al. (2012)

CO J-line excitation in disks



- CO mid-J lines: E_{up} ~ 50-500 K
- ^{12}CO traces surface
- ^{13}CO traces deeper layers
- Evidence for selective photodissociation

van der Wiel et al. (2014), model from Thi et al. (2011)

CO statistics

- CO mid- to high-J detections:
  - Group I (flared disks): ~40% sources
  - Group II (self-shadowed disks): 0 sources

- Sources with high-J CO detections have high UV fluxes and strong PAH bands

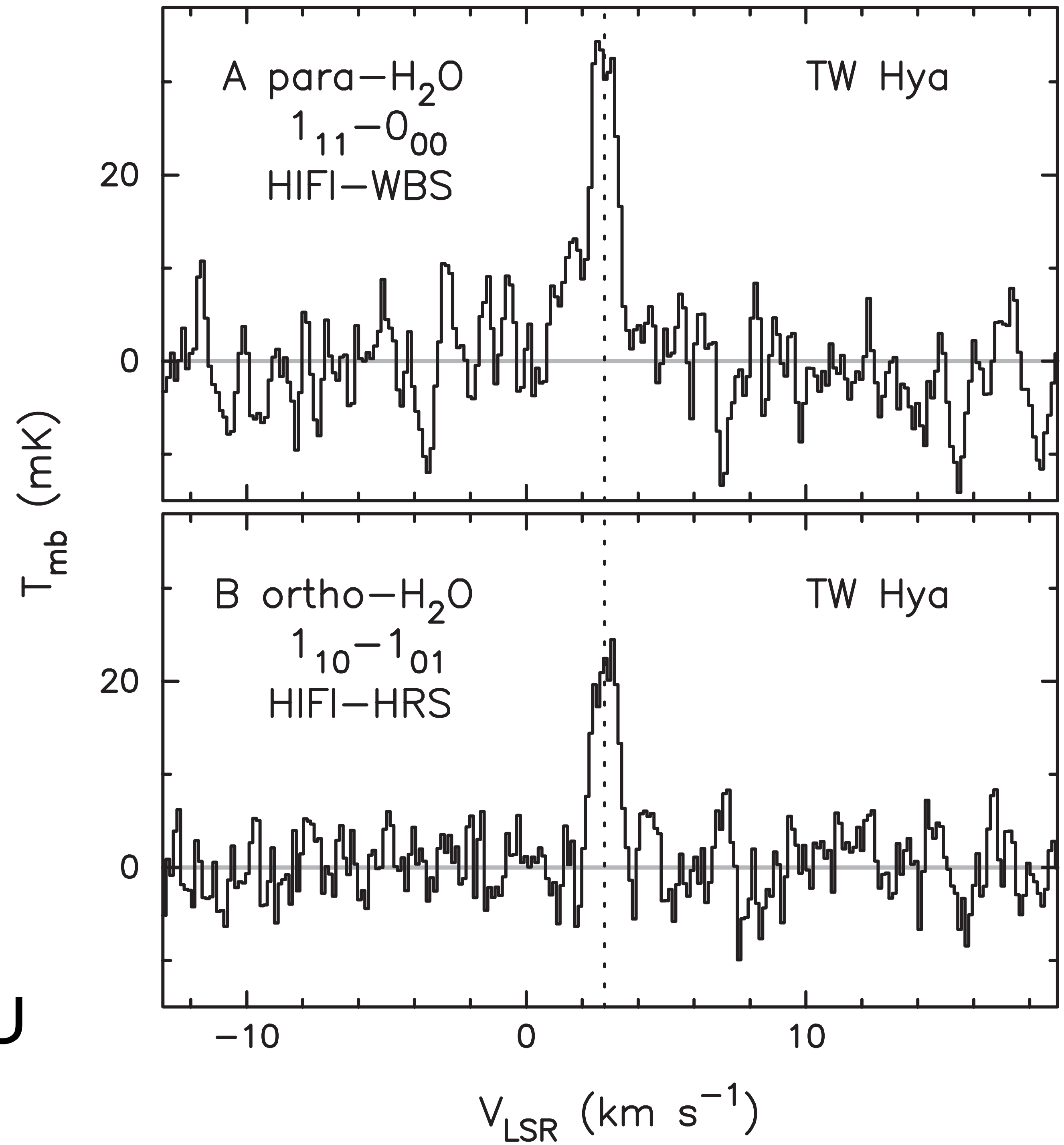
- CO J-lines and [OI]63 line fluxes tend to correlate

- Rotational diagram gives <Trot> = 271 +/- 39 K

- Highest CO-J line found in HD100546: a hot inner wall

WISH: Cold water vapor in TW Hya

- Herschel/HIFI, ortho- and para-water
- o/p ratio ~ 0.8 ⇒ H_2O formed on grains at 10–15 K
- Origin: photodesorption of water ice



- Observations are reproduced when:
  - large, icy grains have settled
  - icy grains have migrated to <60 AU
  - optically thick lines?

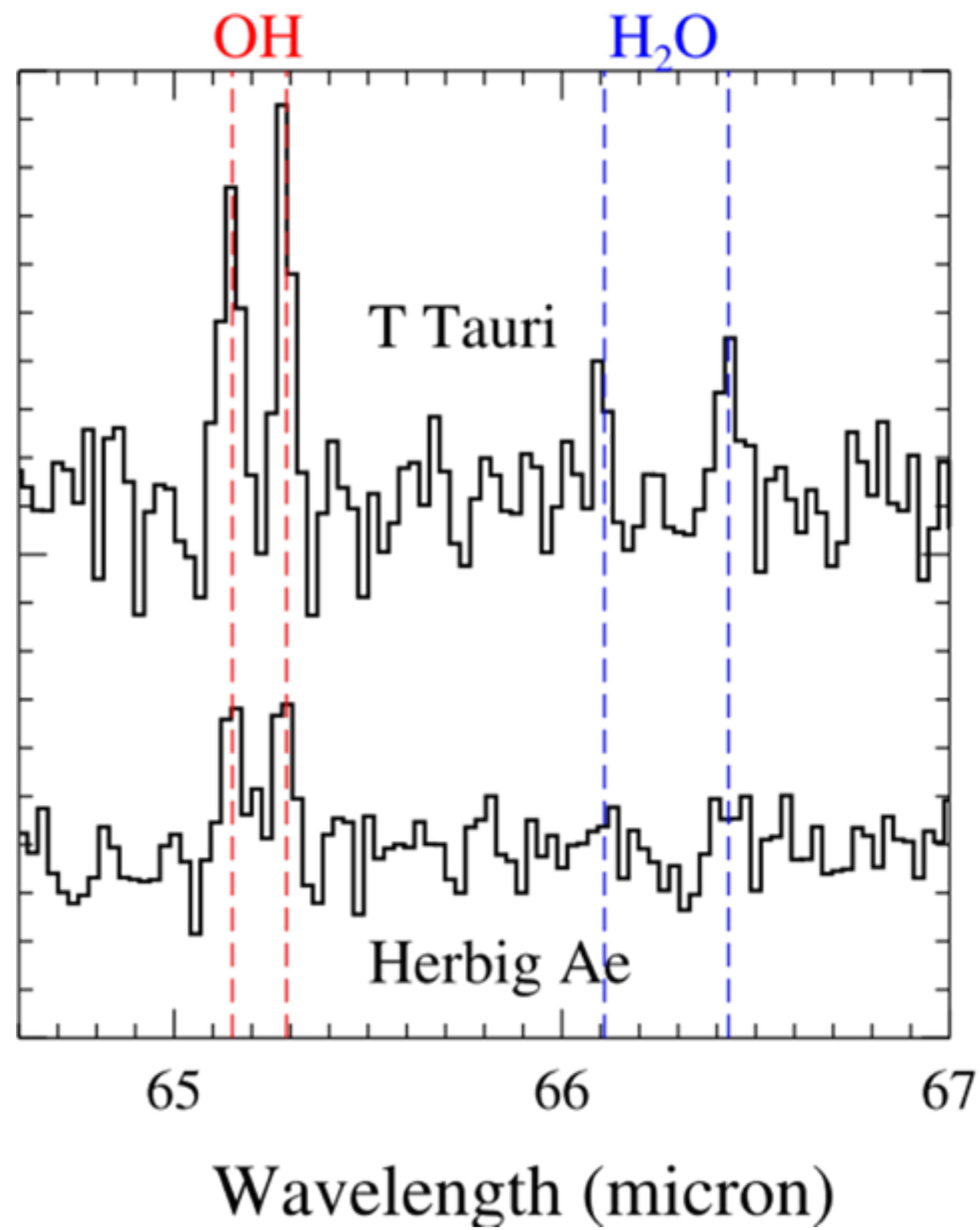
Hogerheijde et al. (2011), Science 334, 338

DIGIT: Warm water content of disks

H_2O / OH depends on stellar mass:

- H_2O / OH >> 1
- $M_{star} < 2\ M_{sun}$

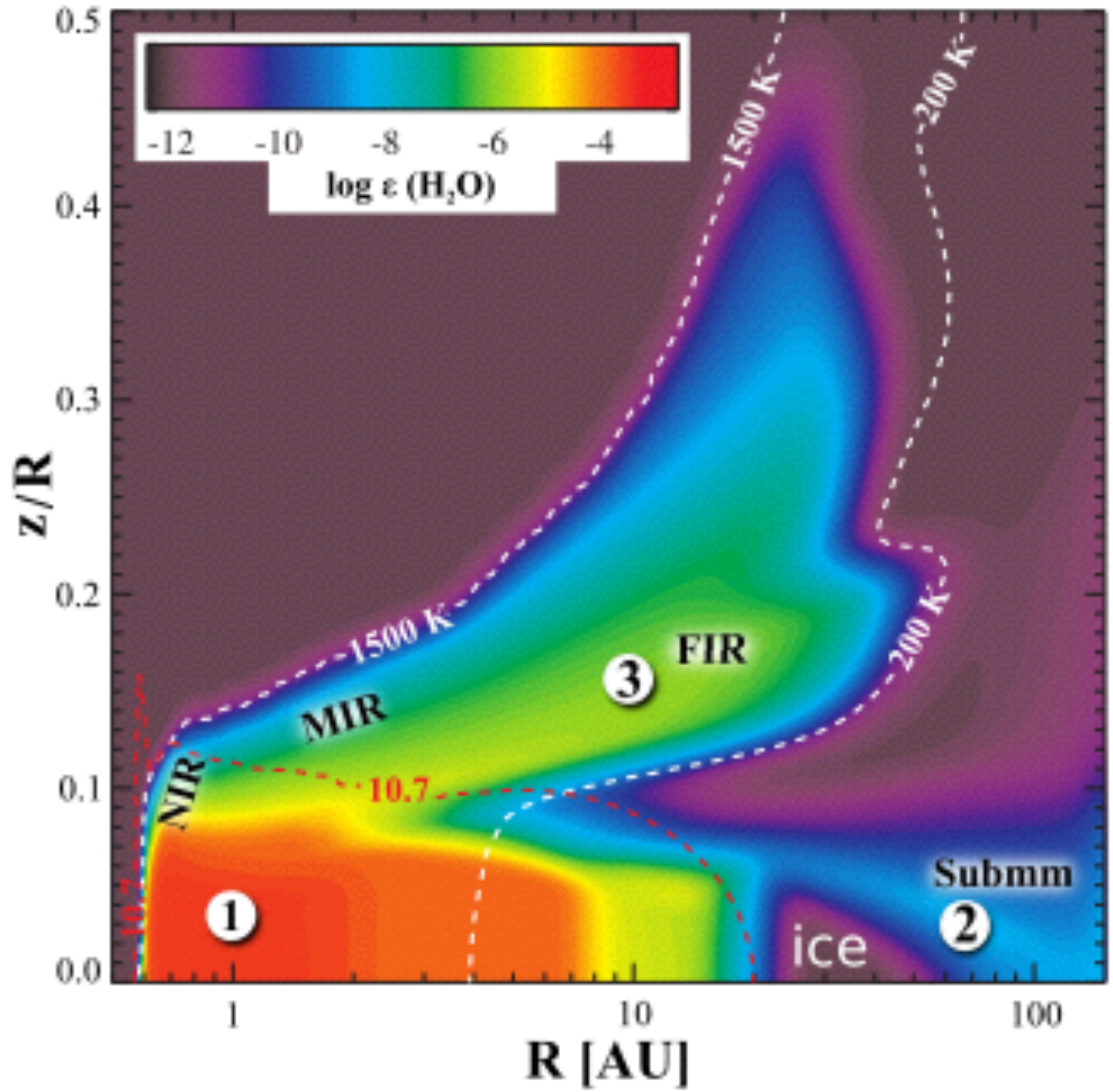
- H_2O / OH < 1
- $M_{star} > 2\ M_{sun}$



Fedele et al. (2013)

Warm water content of disk

- High H_2O abundance in inner disk (< 10 AU)
- Warm H_2O in upper layer
- Low H_2O abundance in outer disk (freeze-out)



ProDiMo model of a Herbig Ae disk

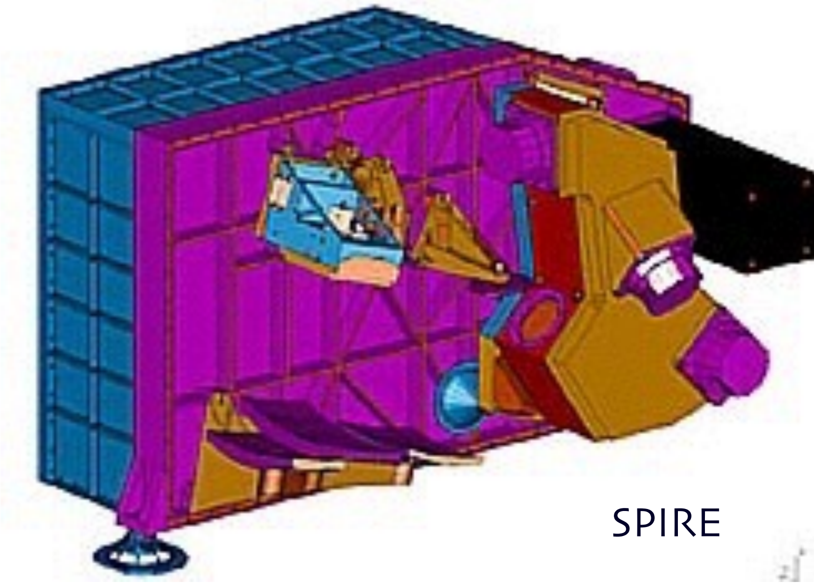
Woitke et al. (2009); Kamp et al. (2013); Fedele et al. (2013),…

Conclusions

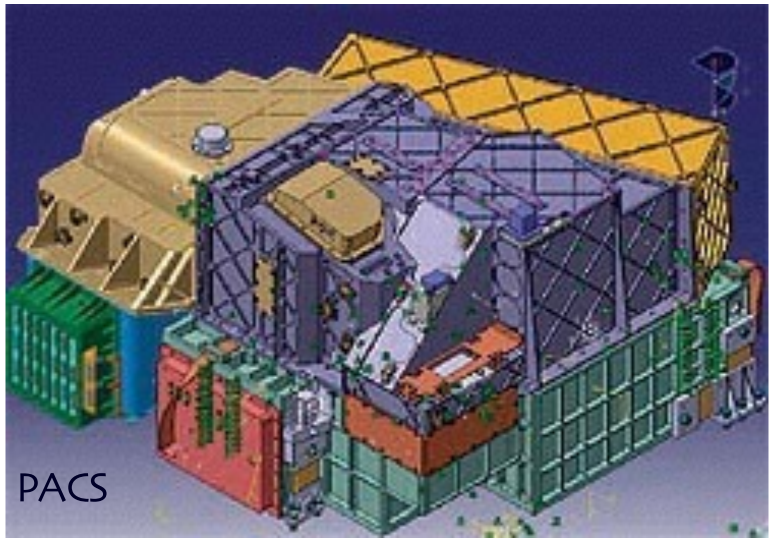
- Surprisingly not that many gas lines detected
- Ratio between line fluxes can be a diagnostic of UV, temperature, PAH abundance, and flaring
- [CII] line is weak in disks: contamination/outflows?
- CO FIR J-lines indicate that $T_{gas} > T_{dust}$
- OH/H_2O depends on stellar mass: UV intensity matters?
- In outer disks water is strongly depleted

Herschel instruments

- SPIRE (photometer & spectrometer):
– ~40 pixels FOV, 194–670µm
– R = 40–1000 (PI: Cardiff Uni., UK)



- PACS (photometer & spectrometer):
– 25 pixels FOV, 60–210µm
– R = 1000–5000 (PI: MPE Garching, DE)



- HIFI (heterodyne spectrometer):
– 1-pixel FOV, 157–212 & 240–625µm
– $R = 10^7$ (PI: SRON, NL)