SPIRE spectroscopy of the prototypical Orion Bar Photodissociation Region

SPIRE ISM consortium

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As part of the Key project 'Evolution of interstellar dust' (Abergel talk)

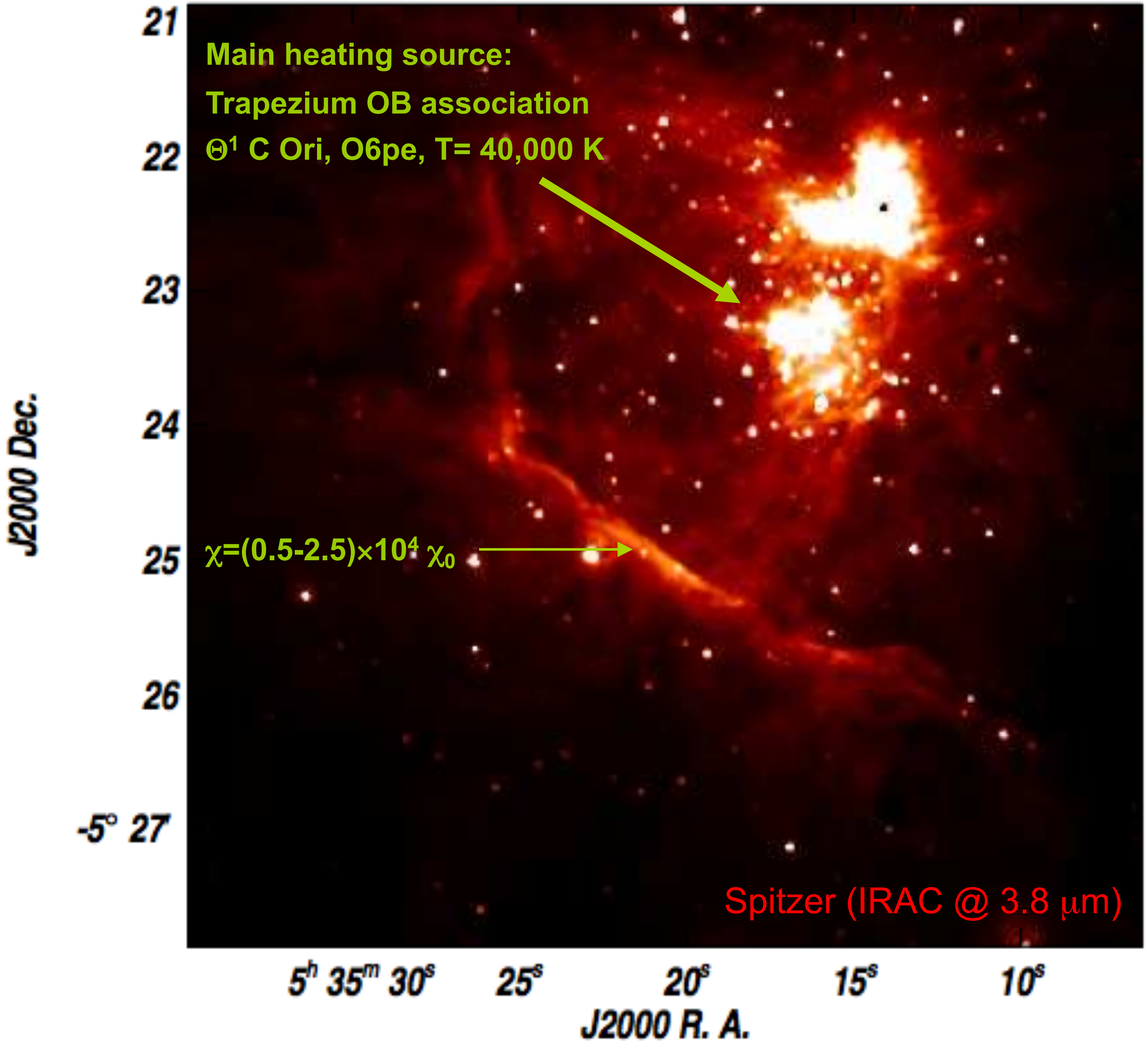
Selected sources in nearby galactic regions,
with precise and well understood excitation conditions and geometry,
in order to derive both the dust and gas properties from the observations

Combination of Mapping and Spectroscopy (SPIRE and PACS),
with a strong emphasis on the spatial information within individual objects

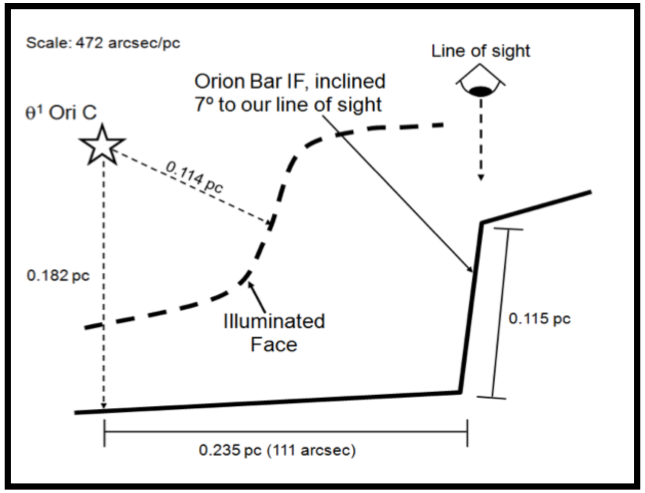
Total SPIRE spectroscopy : 88 hours

10 Classical PDRs	d(pc)	Teff (K), star	SPIRE spectroscopy
Orion Bar	440	40,000, O6	Single+Full Sampling, High+Low resolution 2×6317 s
NGC 2023 N	450	23,000, B1.5V	Single+Full Sampling, High+Low resolution 2×6317 s
NGC 7023	440	17,000, B3Ve	Single+Full Sampling, High+Low resolution 1×6317 s
IC 63	230	30,000, B0.5IV	Single+Full Sampling, High+Low resolution 1×6317 s
Rho Oph	160	22,000, B2V	Single+Full Sampling, High+Low resolution 1×6317 s
Horsehead	450	33,000, O9.5V	Single+Full Sampling, High+Low resolution 3×6317 s
Ced 201	420	10,500, B9.5V	Single+Full Sampling, High+Low resolution 1×6317 s
NGC 7023 E	440	17,000, B3Ve	Single+Full Sampling, High+Low resolution 1×6317 s
IC 59	230	30,000, B0.5IV	Single+Full Sampling, High+Low resolution 3×1769 s
L1721	130	22,000, B2IV	Single+Full Sampling, High+Low resolution 8×641 s
California	3500	37,000, O7	Single+Full Sampling, High+Low resolution 3×1769 s

Orion Bar

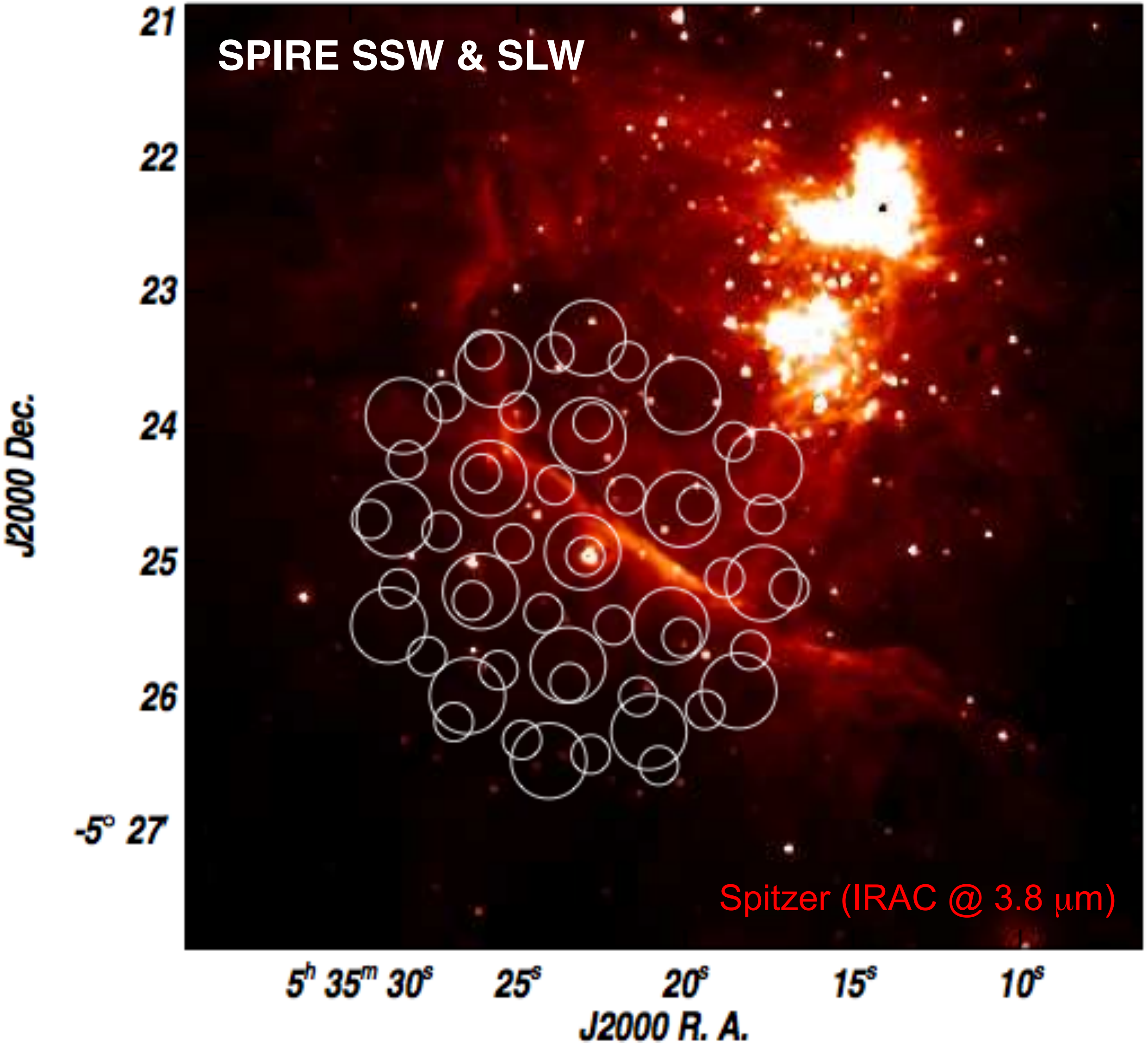


- one of the best-studied PDRs
- exposed to a strong stellar UV flux
- PDR is wrapped around the HII region and changes from a face-on to an edge-on geometry where the emission peak



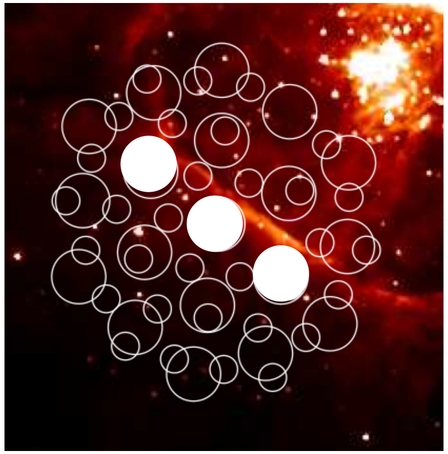
(Pellegrini et al. 2009)

SPIRE/FTS observation



- **Single pointing (coverig all the Bar)**
- **FWHM beam-widths (SSW : 17-21'') (SLW : 29-42'')**
- **High resolution ($\Delta\sigma$=0.04 cm^{-1})**
- **2 scans/repetition**
- **Duration: 266.45 s**

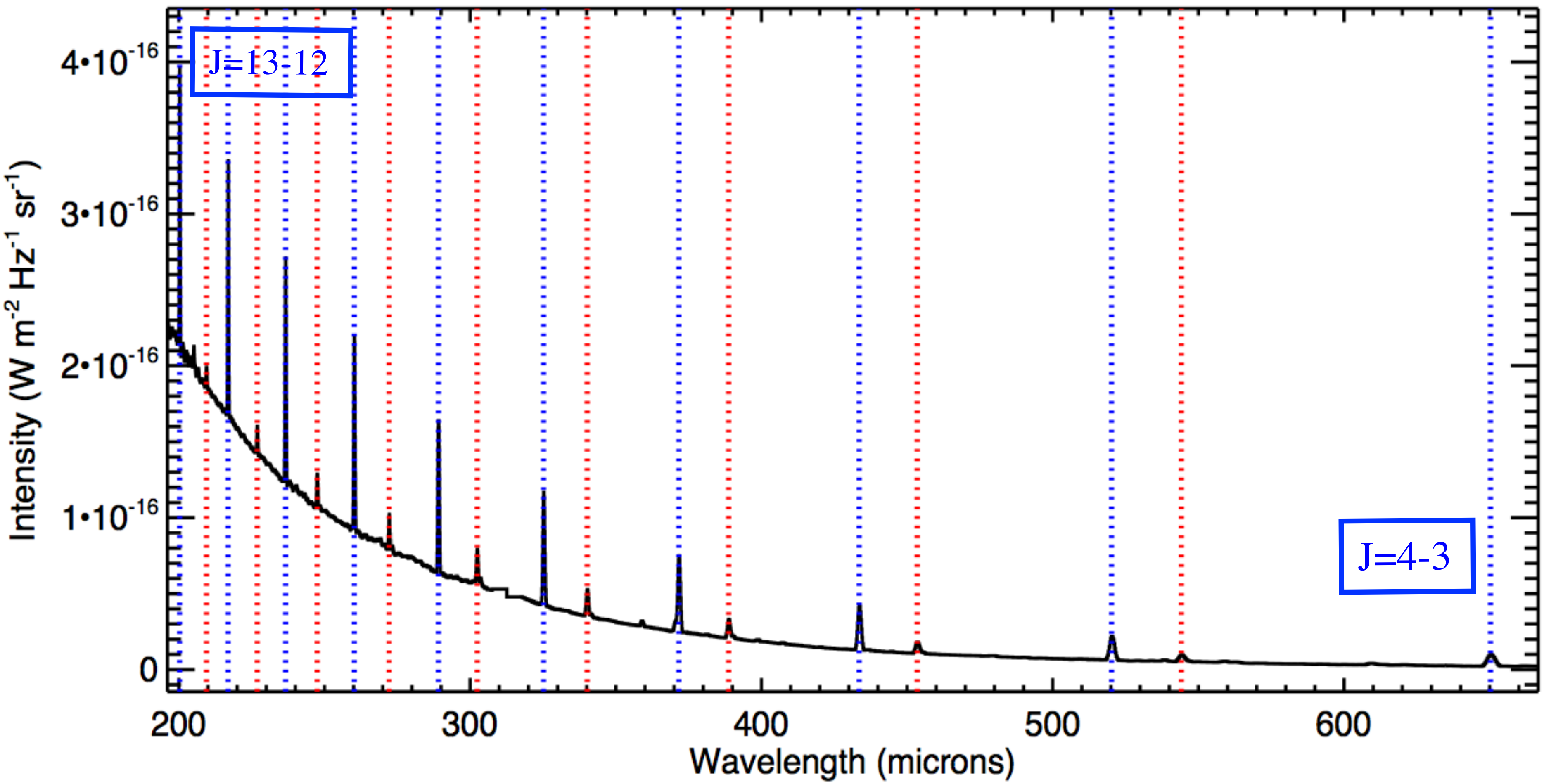
data reduction & line fitting
E. Polehampton, D. Naylor



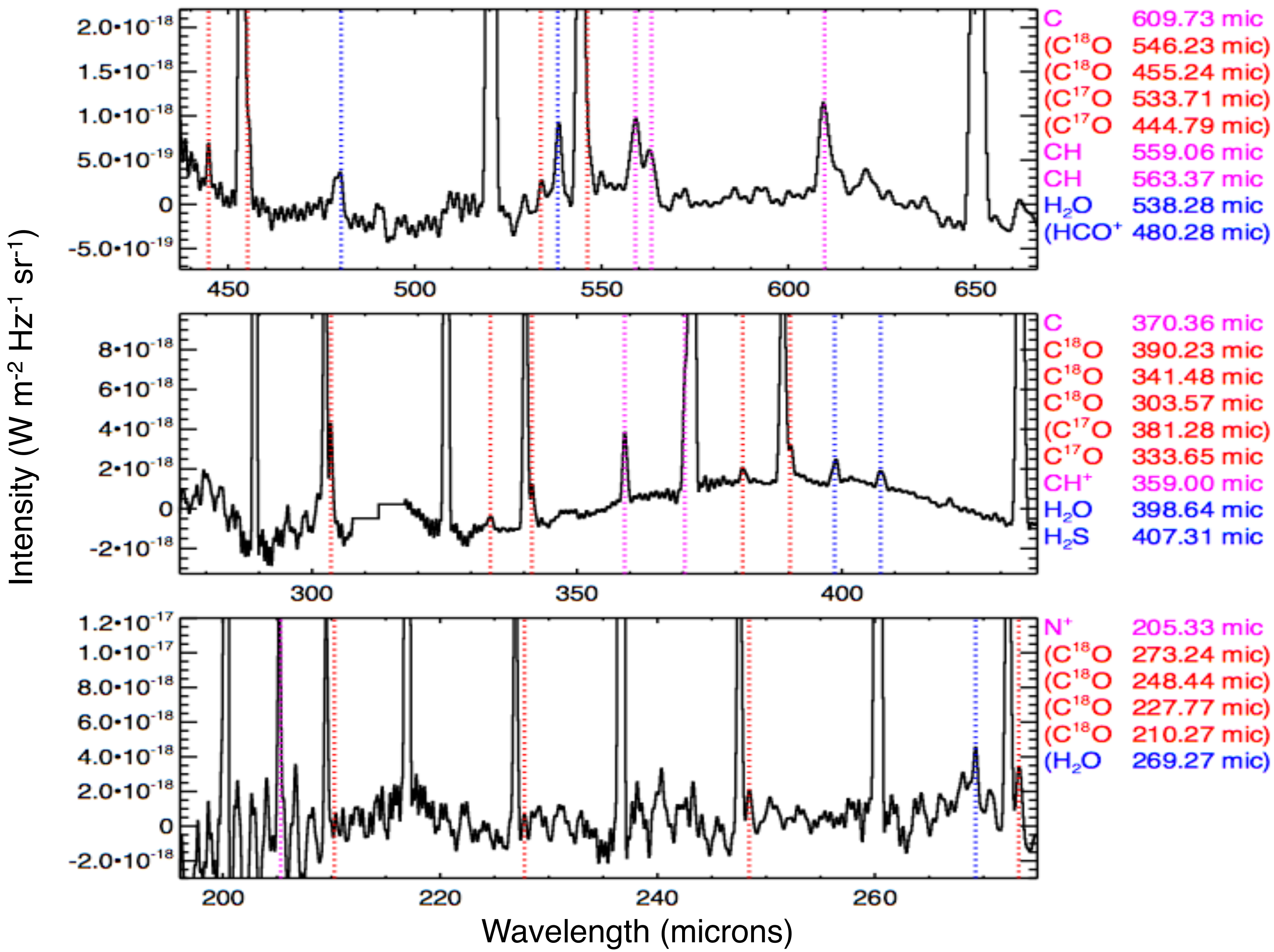
Average apodized spectra on the three arrays on the Bar

(corrected for obliquity effects)

A wealth of bright narrow ^{12}CO & ^{13}CO rotational lines



Zoom of the average apodized spectra



- most of the $C^{18}O$ (blended with ^{13}CO), some $C^{17}O$, fine structure lines of C and N+
- radicals and molecules : CH^+, CH, H_2O, H_2S, HCO^+, (HCl, HCN, CN..) & hydrocarbons (C_2H)

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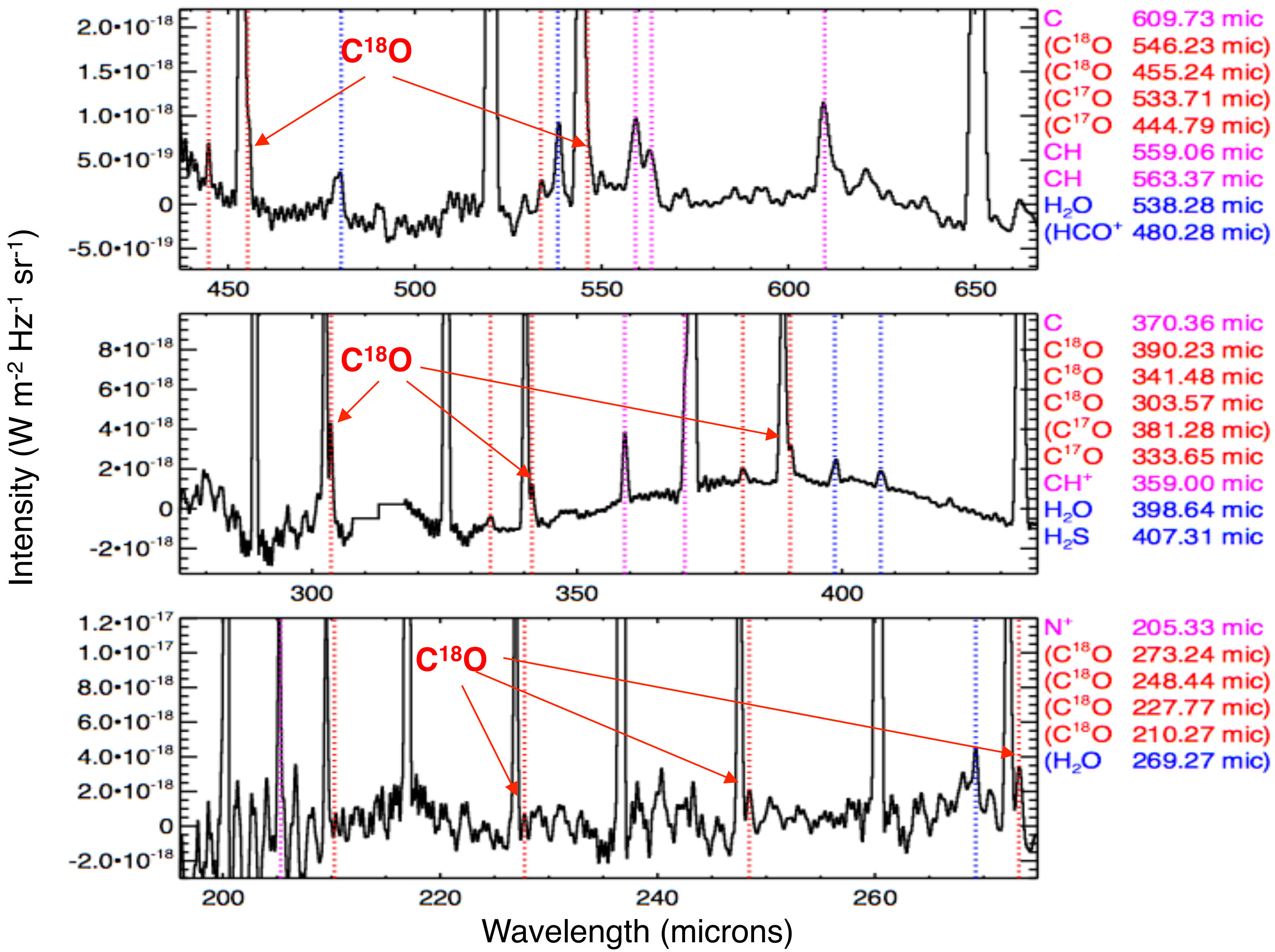

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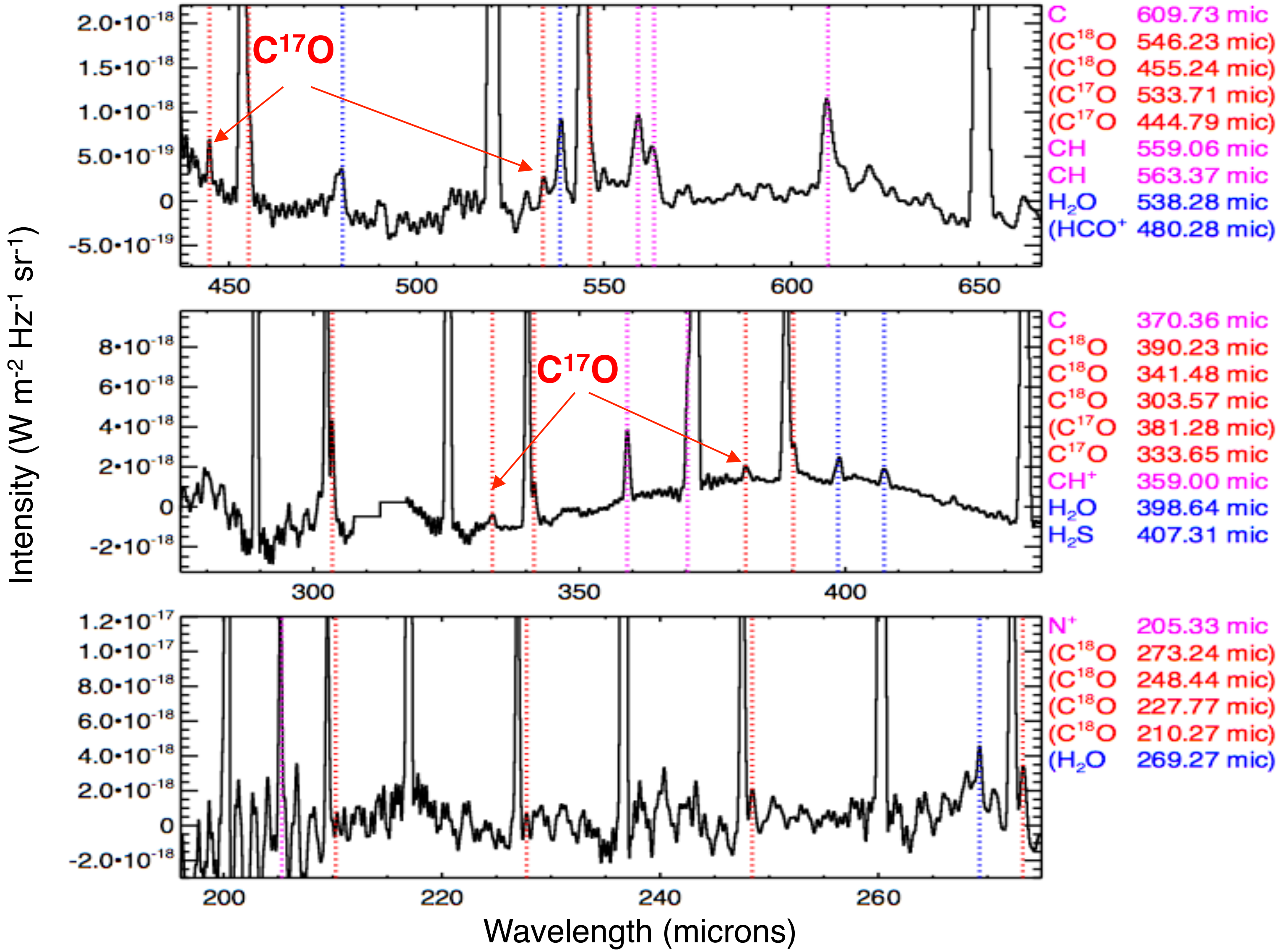

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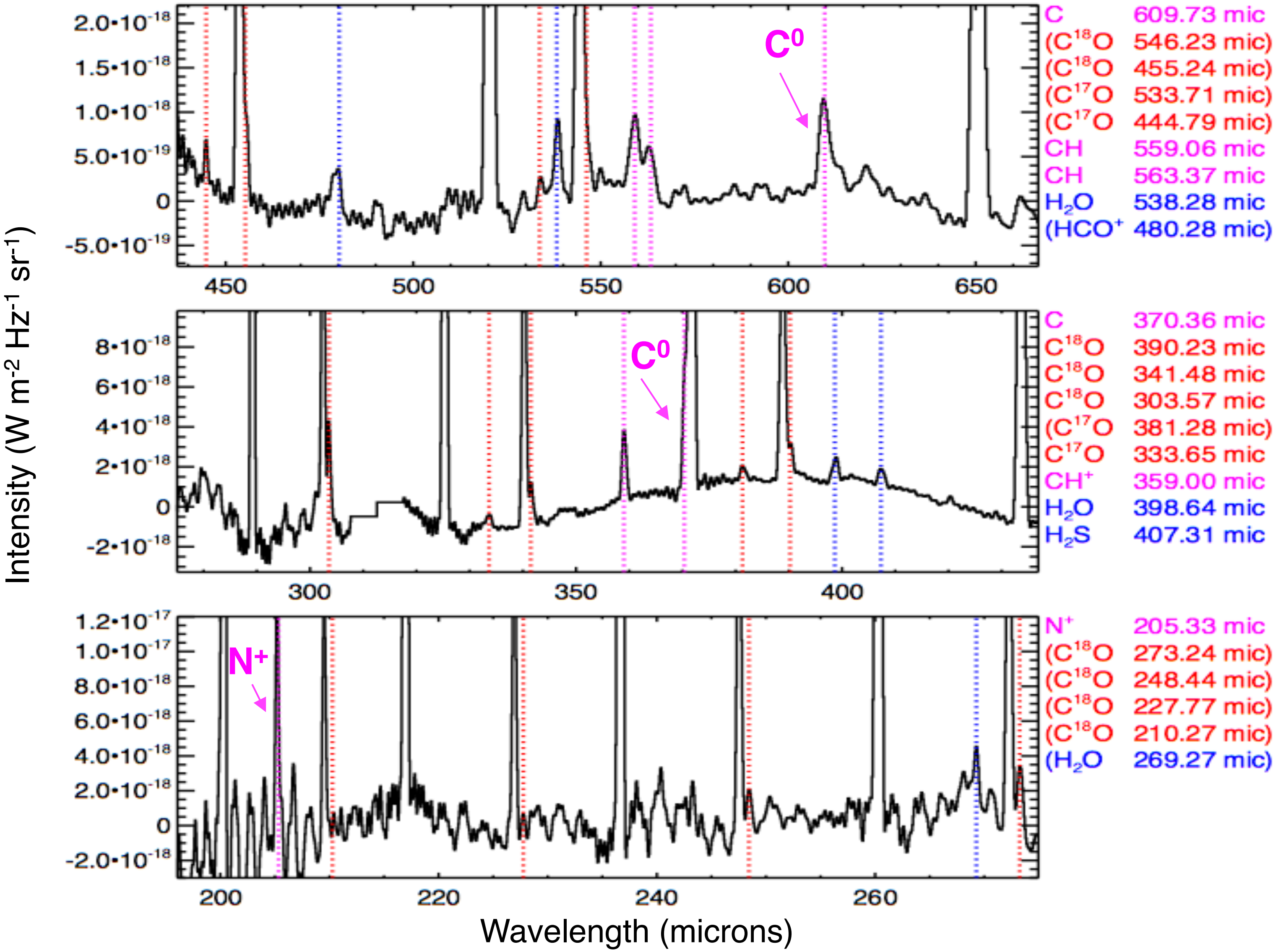

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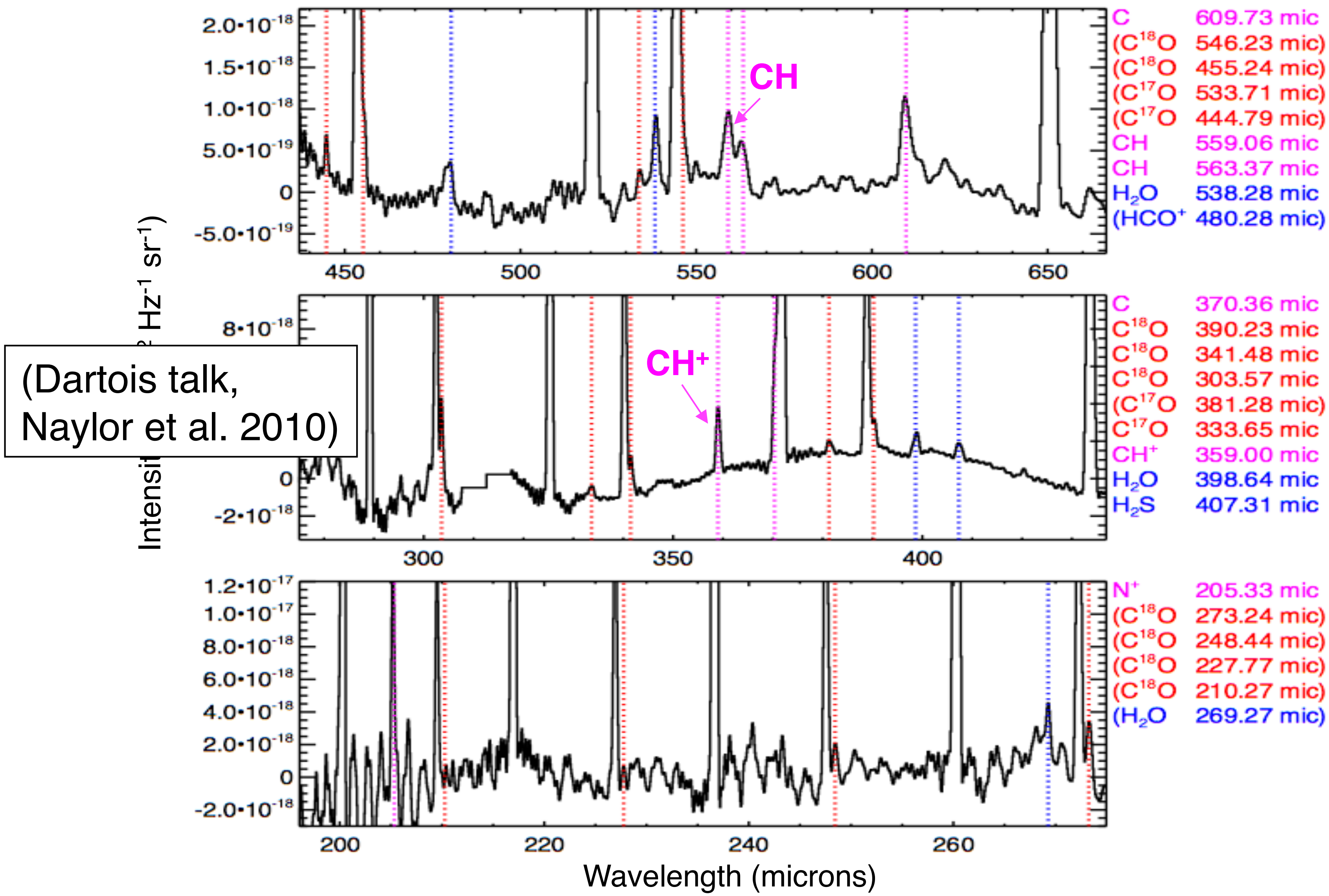

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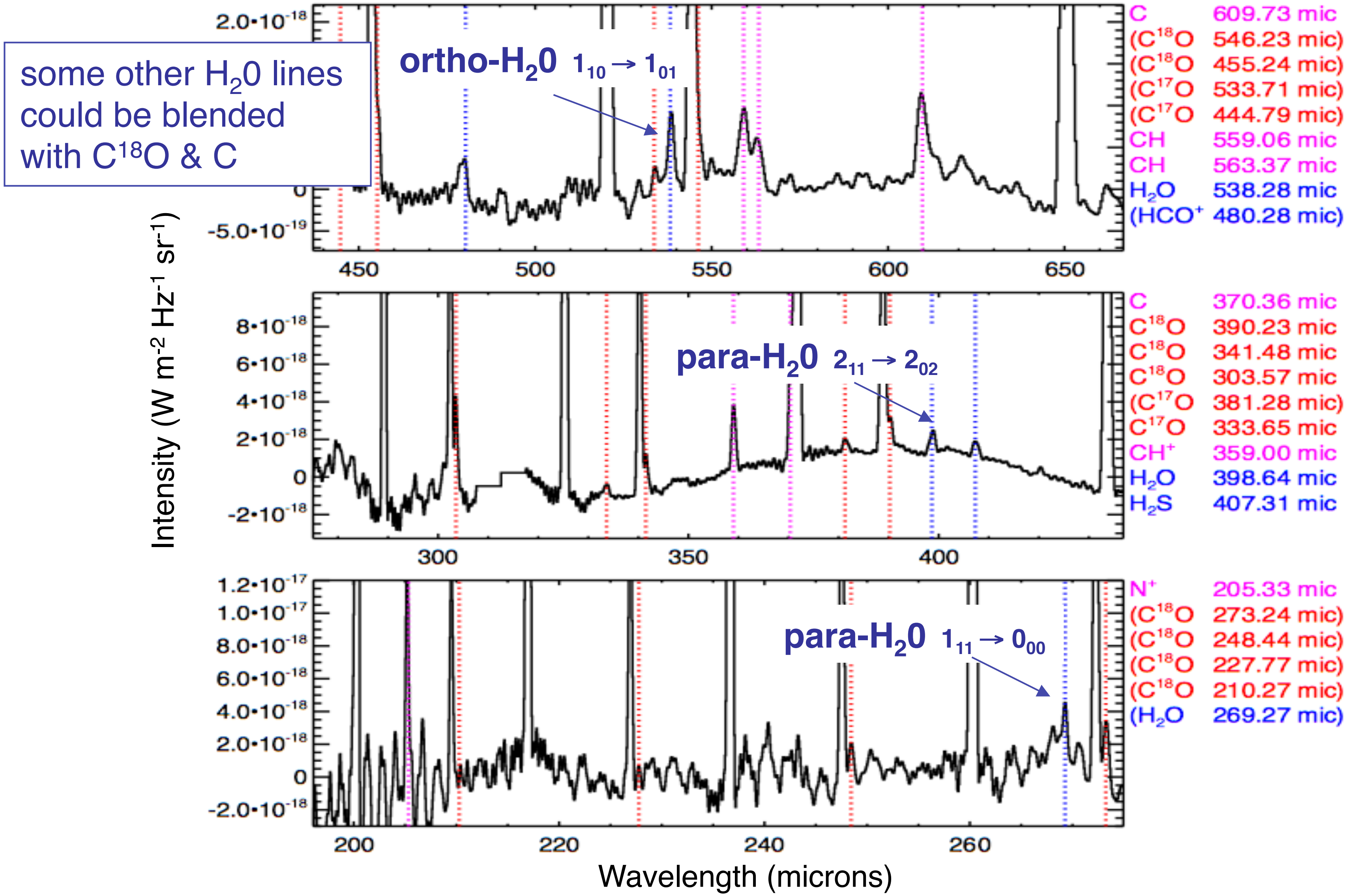

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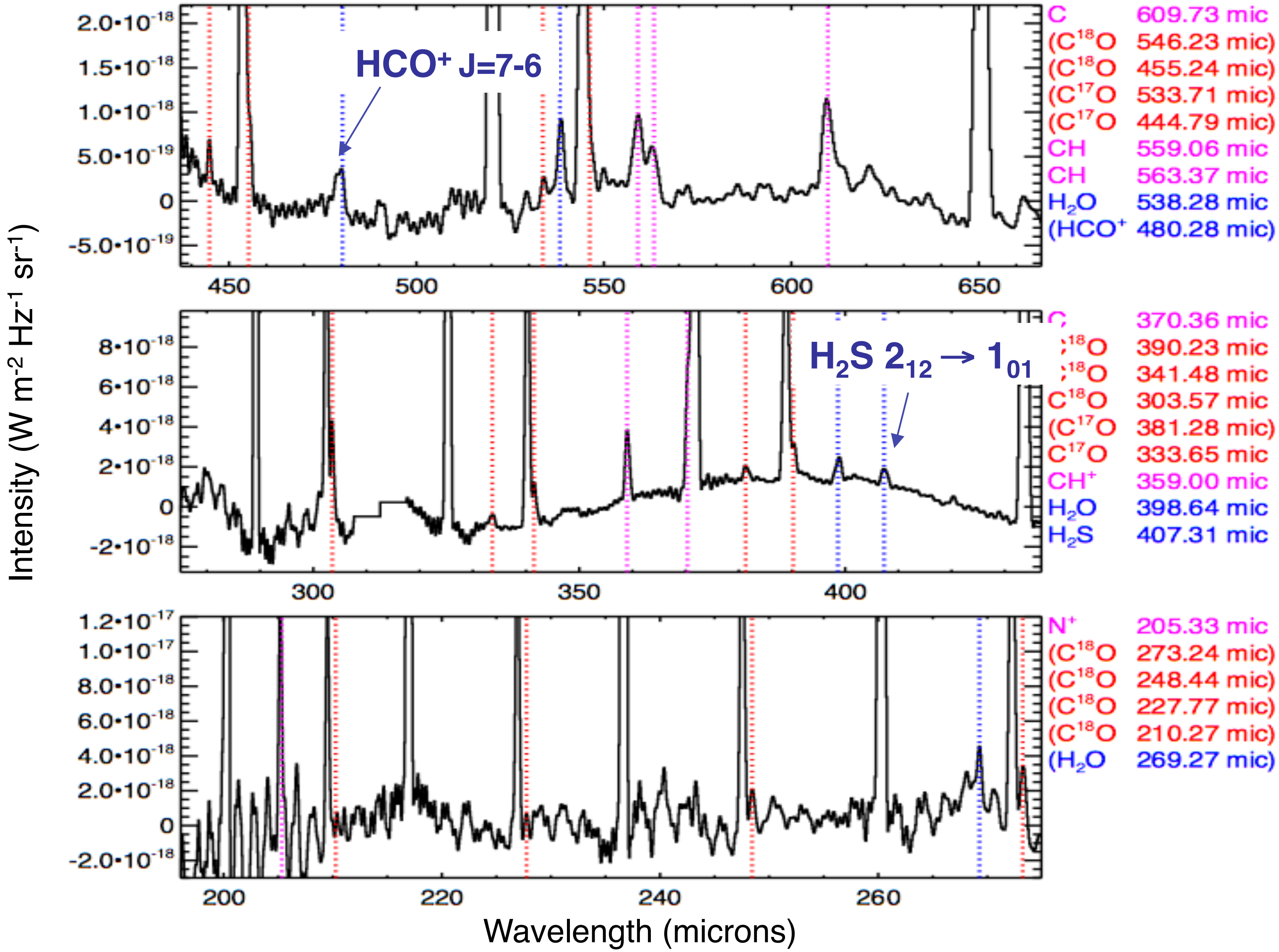
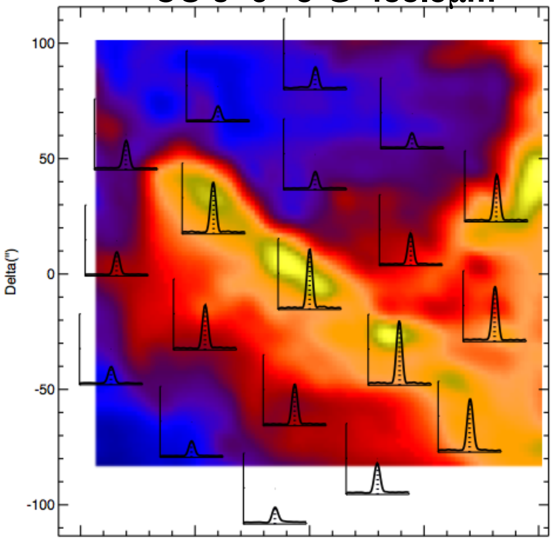


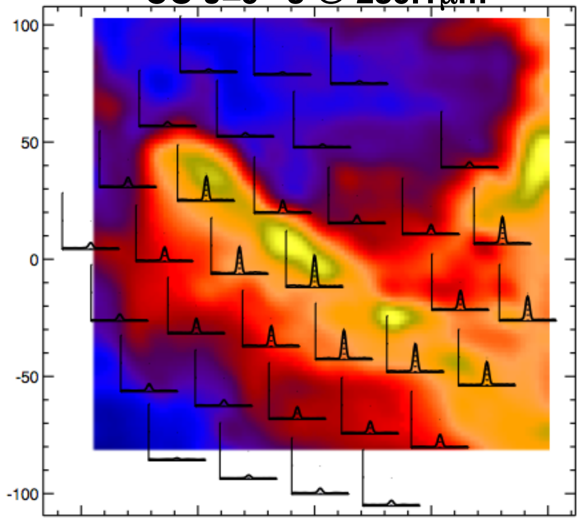
Other fainter lines could be detected but confirmation will be improved with deeper SPIRE observations and HIFI complementary data (which will help to assign some lines that could be merged in the lower resolution SPIRE)

Spectro-imagery in the CO (and isotopes) transitions

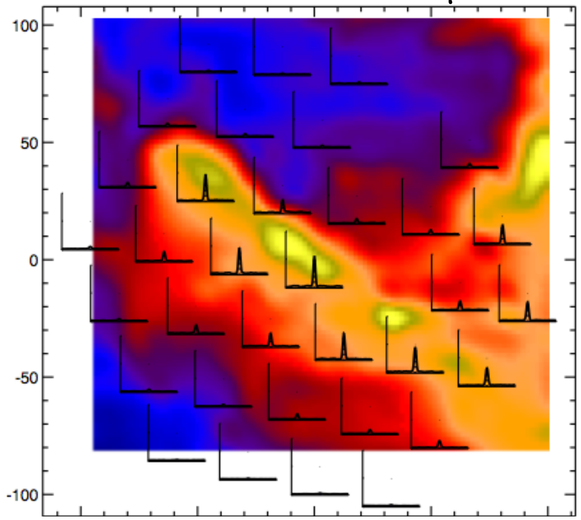
^{12}CO J=6→5 @ 433.5μm



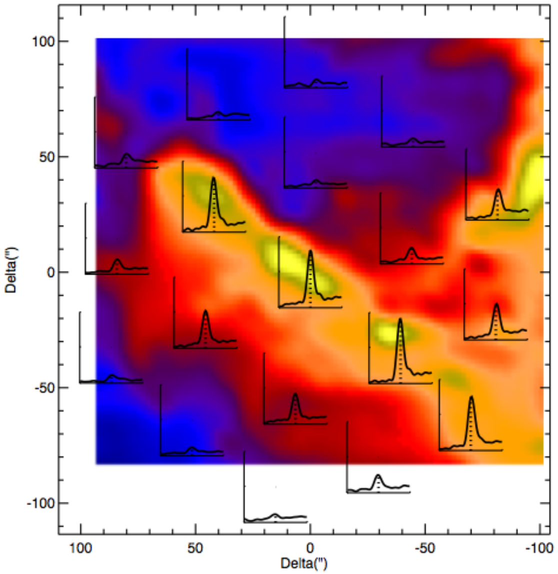
^{12}CO J=9→8 @ 289.1μm



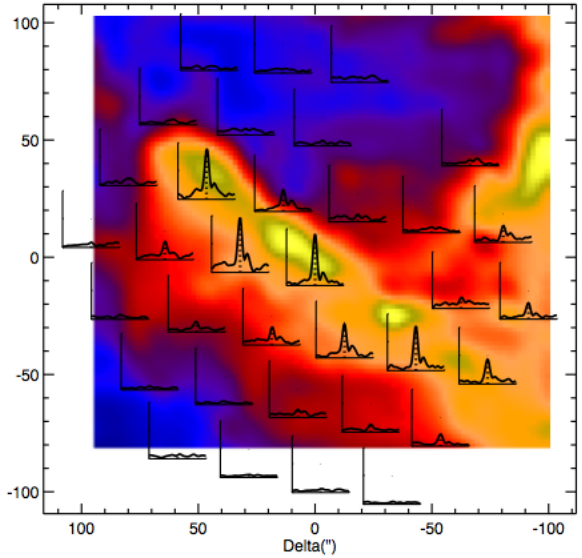
^{12}CO J=12→11 @ 216.9μm



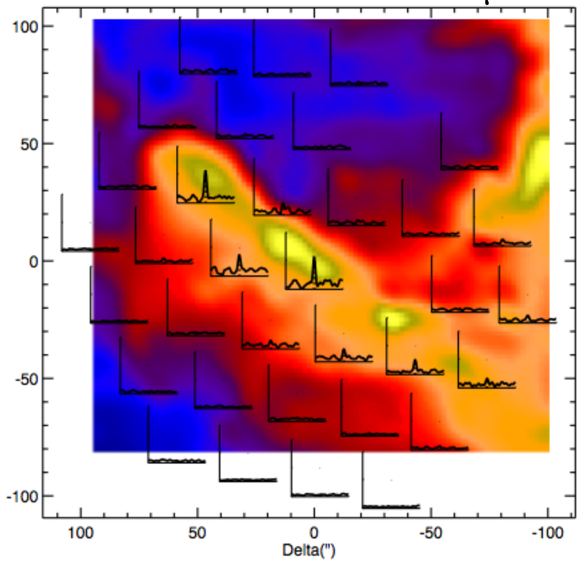
^{13}CO J=6→5 @ 453.5μm (C^{18}O @ 455.2μm)



^{13}CO J=9→8 @ 302.4μm (C^{18}O @ 303.6μm)



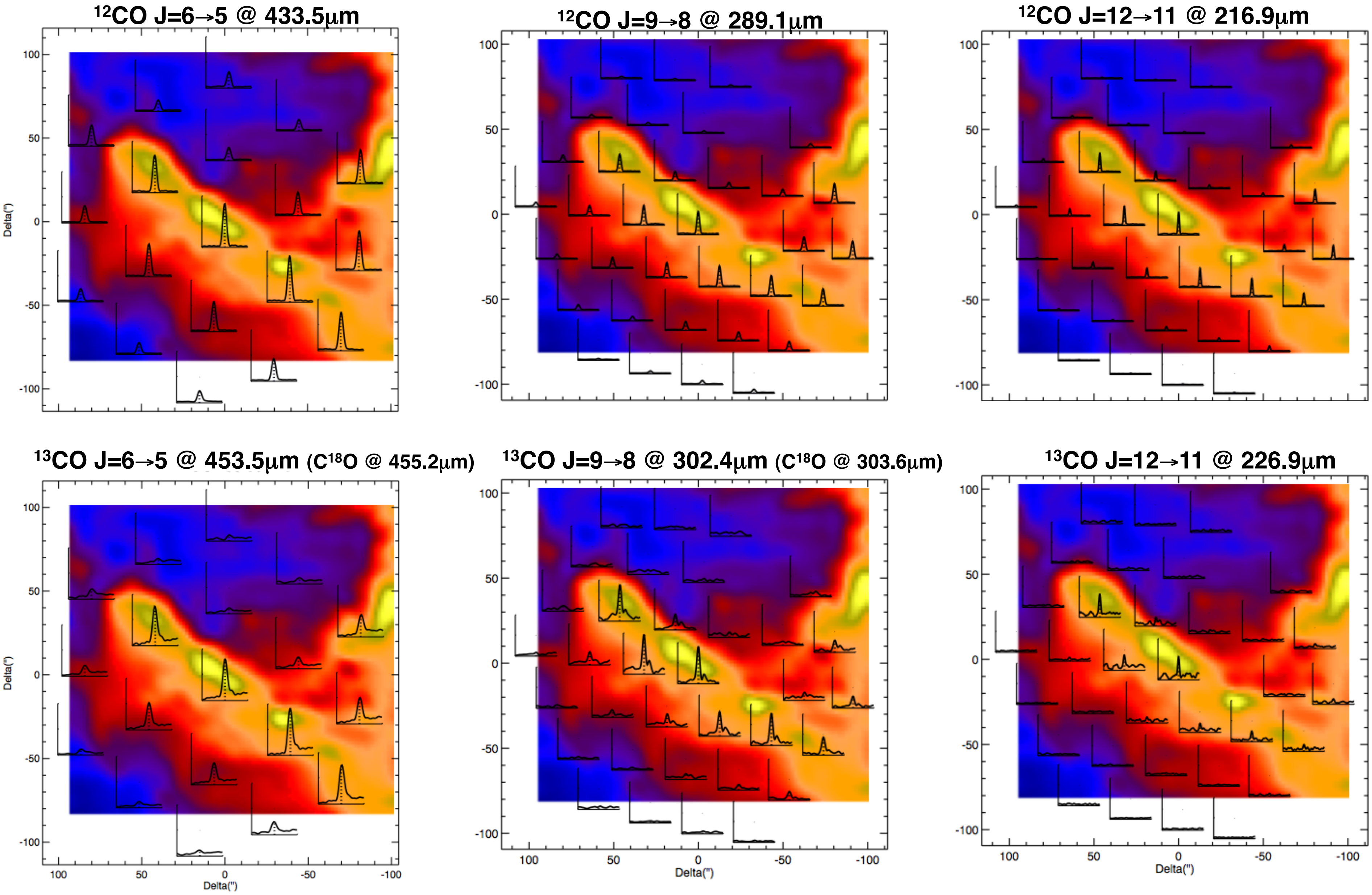
^{13}CO J=12→11 @ 226.9μm



Color map ^{12}CO J=6→5 from the ground (Lis et al. 1998)

Effects of optical depth and excitation

^{12}CO optically thick comes from the surface layers, ^{13}CO less abundant probes the denser shielded regions
Higest rotational lines very sensitive to the density and temperature show strong and peaked emission on the Bar



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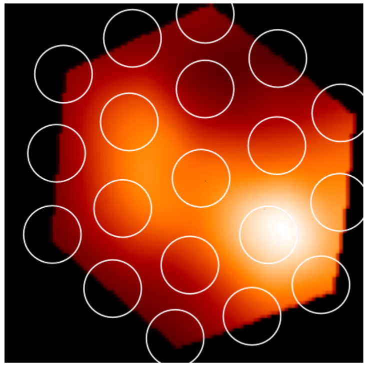
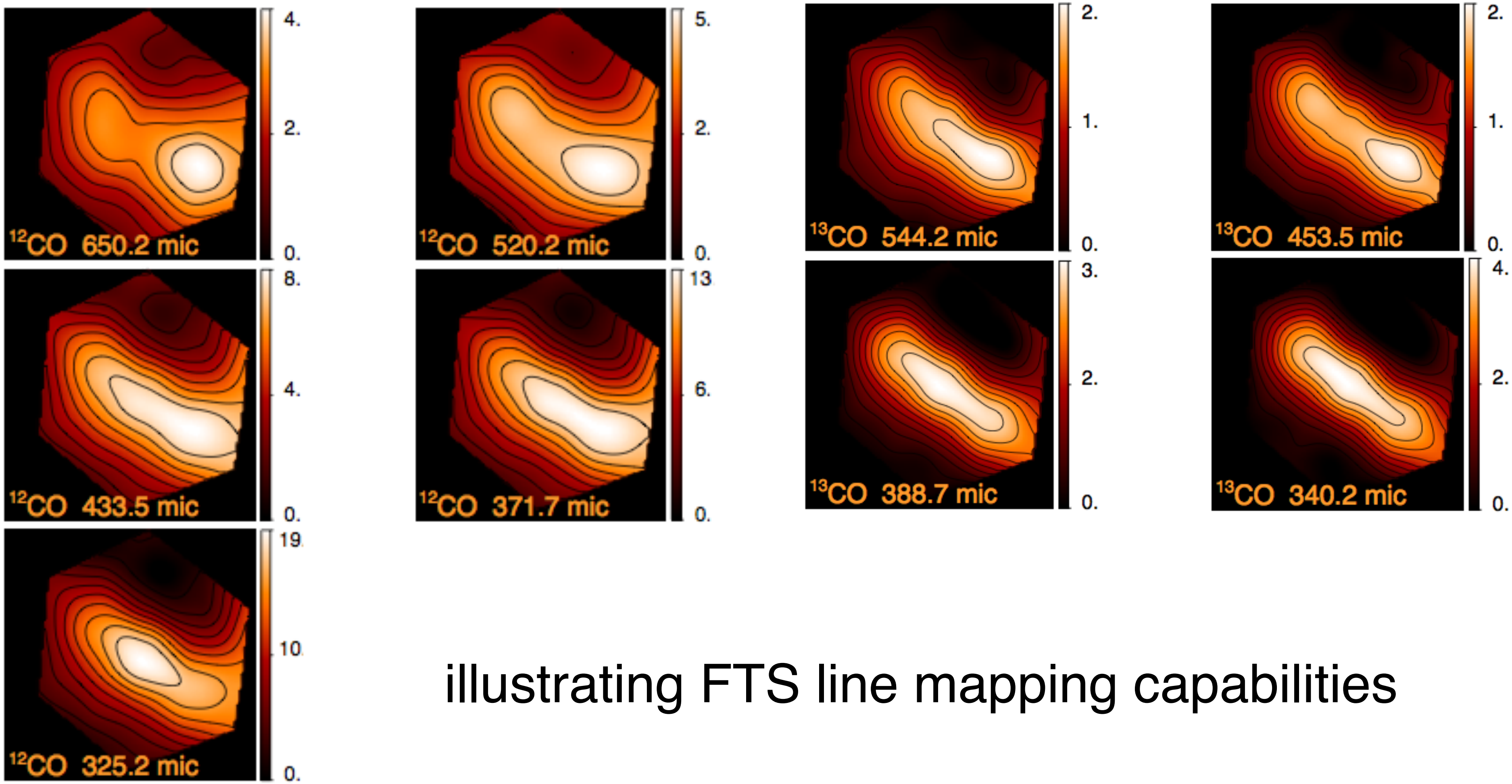


Mapping CO and ^{13}CO lines (SLW)

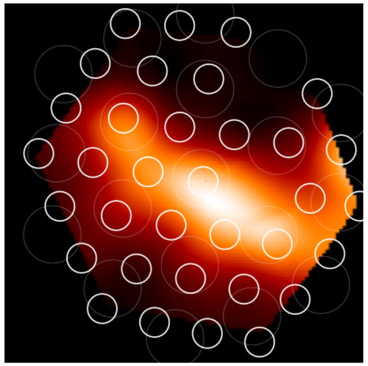
Warning: Unproperly sampled

Full sampling observing mode to be released

Off-axis calibration not guaranteed



illustrating FTS line mapping capabilities



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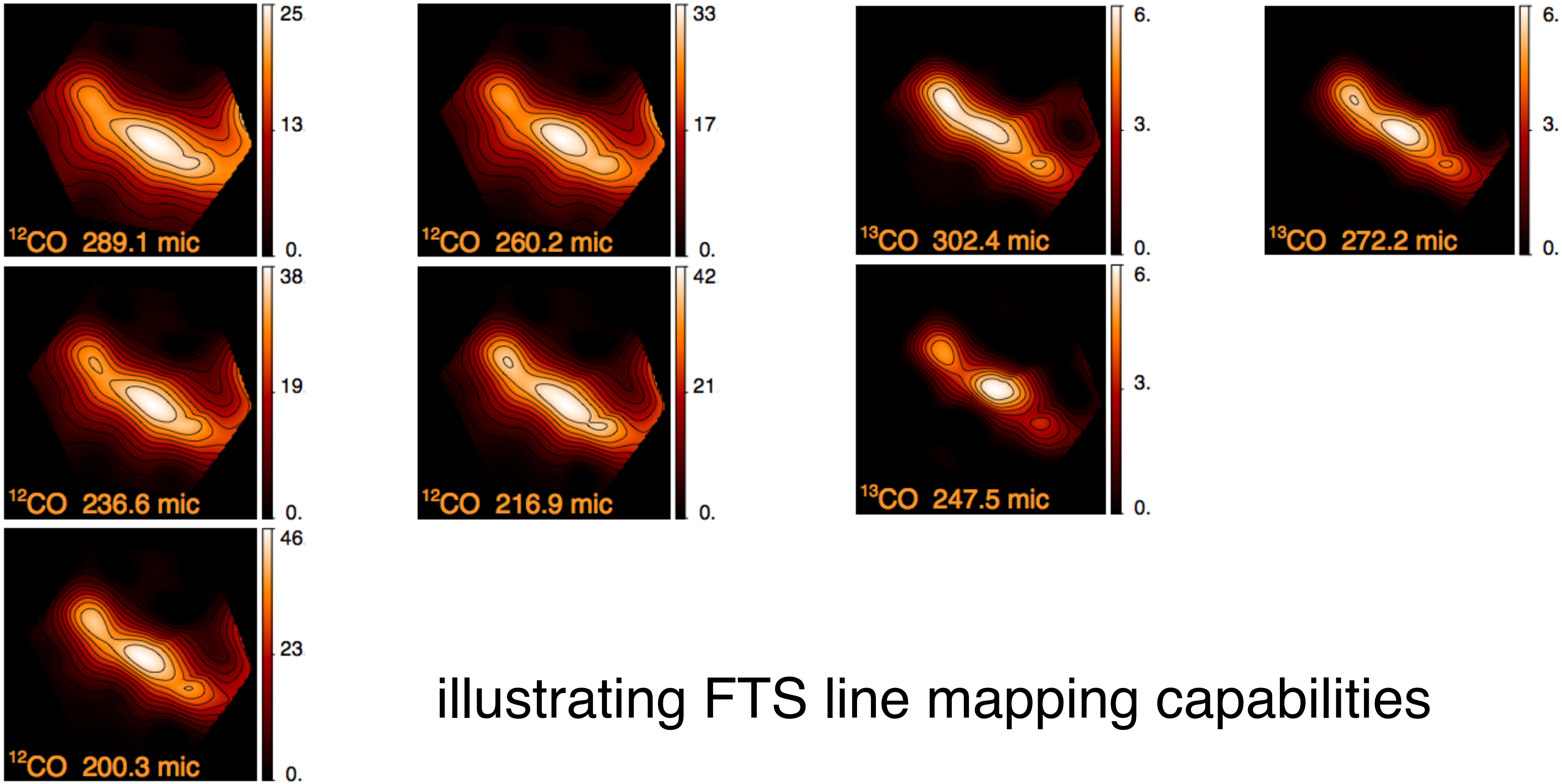
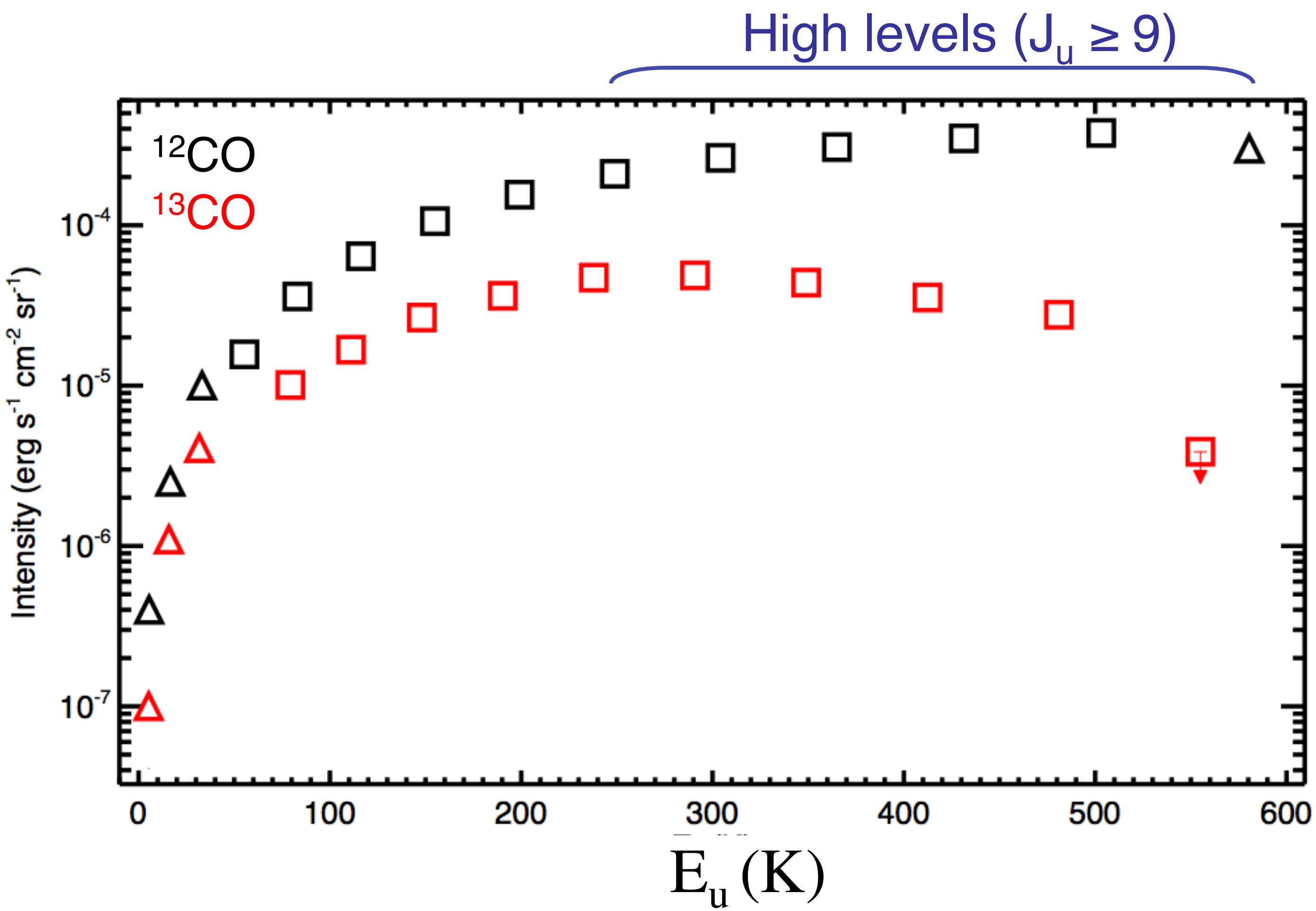


illustrating FTS line mapping capabilities

CO excitation towards the Bar



SPIRE/FTS data

(error bars < symbol size)

Δ Ground data

Stacey et al., 1993

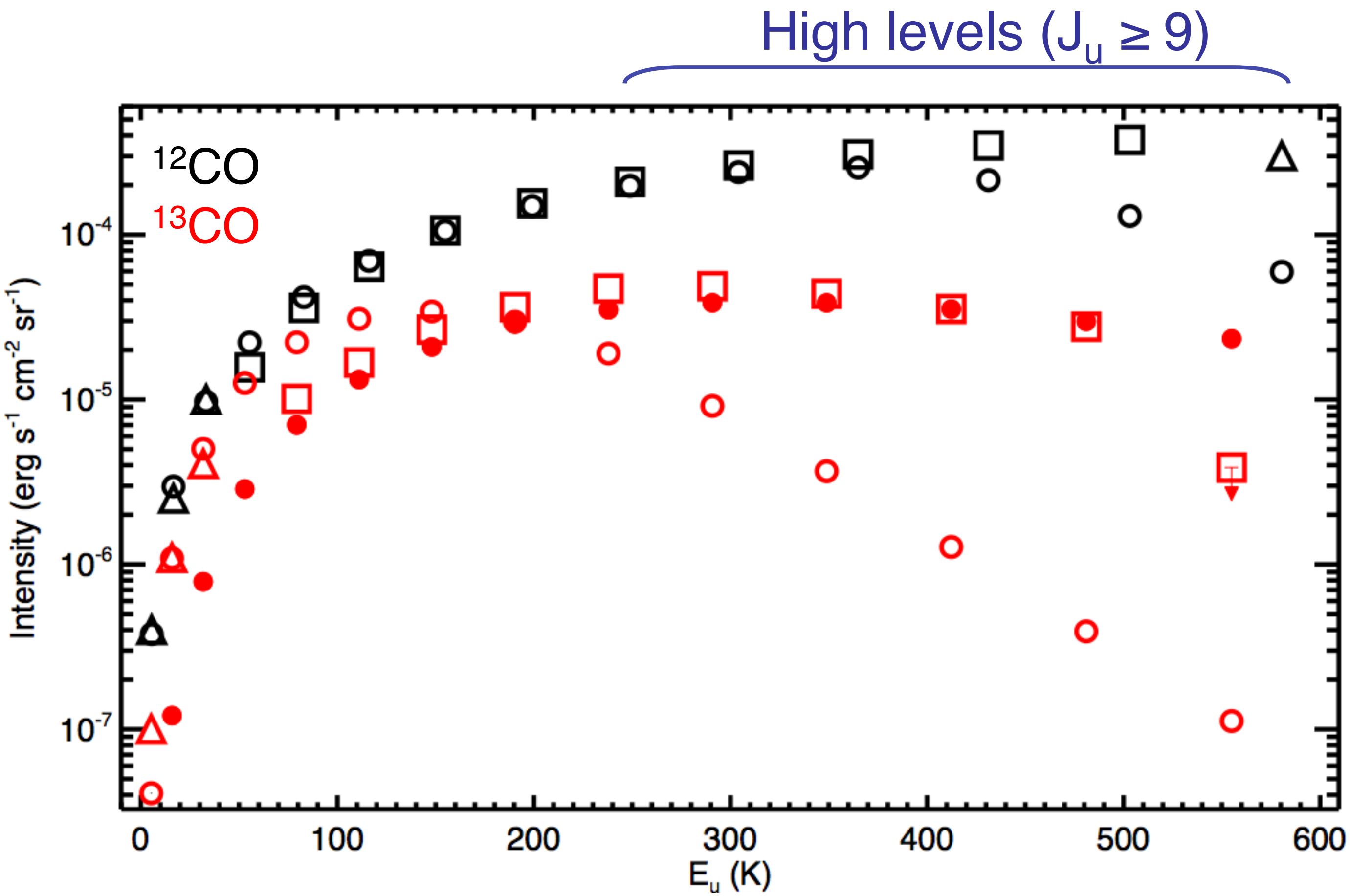
Tauber et al., 1994

White & Sandell, 1995

Hogerheijde et al., 1995

van Der Wiel et al., 2009

CO excitation towards the Bar



SPIRE/FTS data

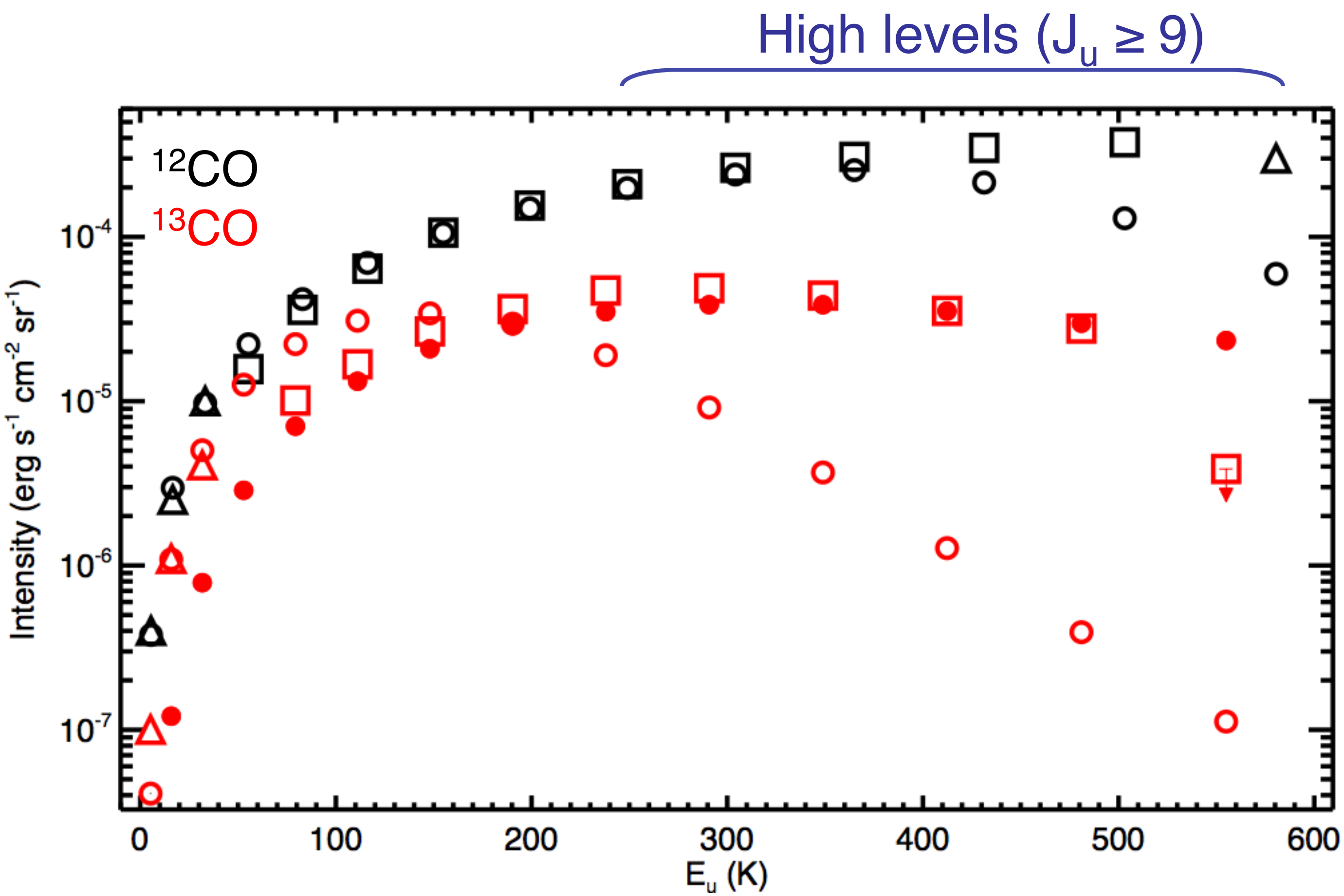
Δ Ground data

○ PDR + RADEX codes
[n=10^5 cm^{-3} ,$\langle T_k \rangle$=85K]
$N(H_2)$=9 10^{22} cm^{-2}

● High-density limit
[n=10^7 cm^{-3} ,$\langle T_k \rangle$=120K]
15% of the total column

- Observed intensities of the optically thick ^{12}CO lines provide an estimate of T~85 K (consistent with many observed transitions from the ground) in agreement with the temperature (50-90K) predicted by PDR model for the CO emitting layers
- However, the high J transitions do not agree with that temperature
- ^{13}CO lines become optically thin for Ju ≥9, while all the ^{12}CO lines are optically thick

CO excitation towards the Bar



SPIRE/FTS data

Δ Ground data

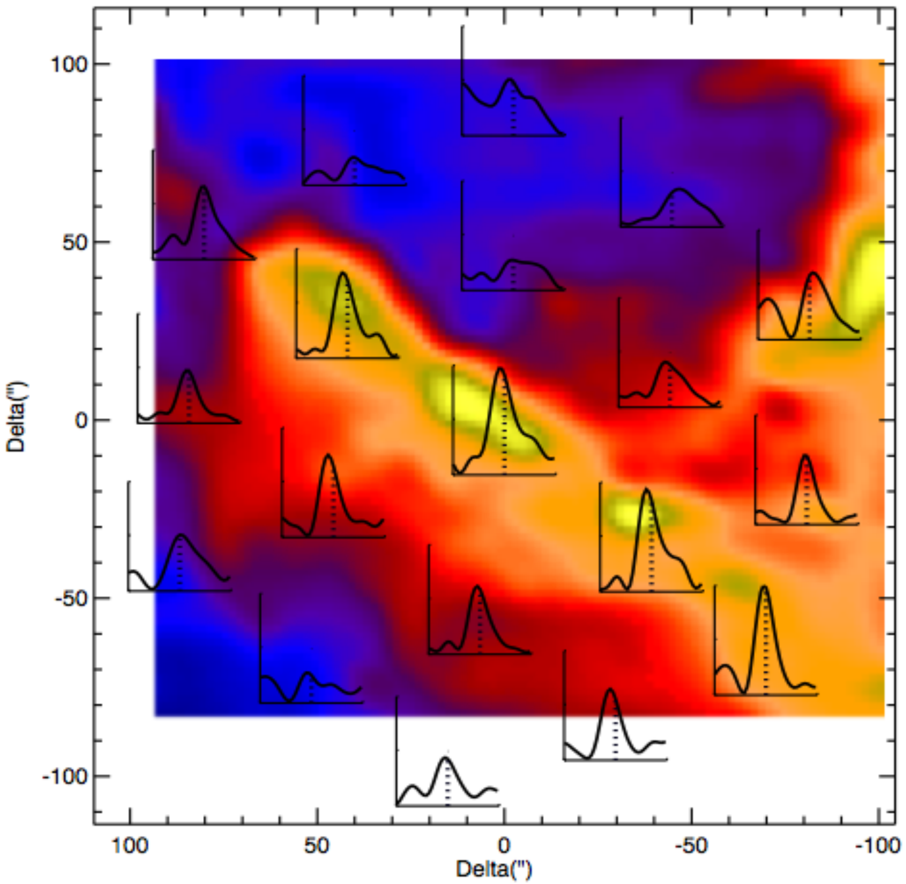
○ PDR + RADEX codes
[n=10^5 cm^{-3} ,<T_k>=85K]
$N(H_2)$=9 10^{22} cm^{-2}

● High-density limit
[n=10^7 cm^{-3} ,<T_k>=120K]
15% of the total column

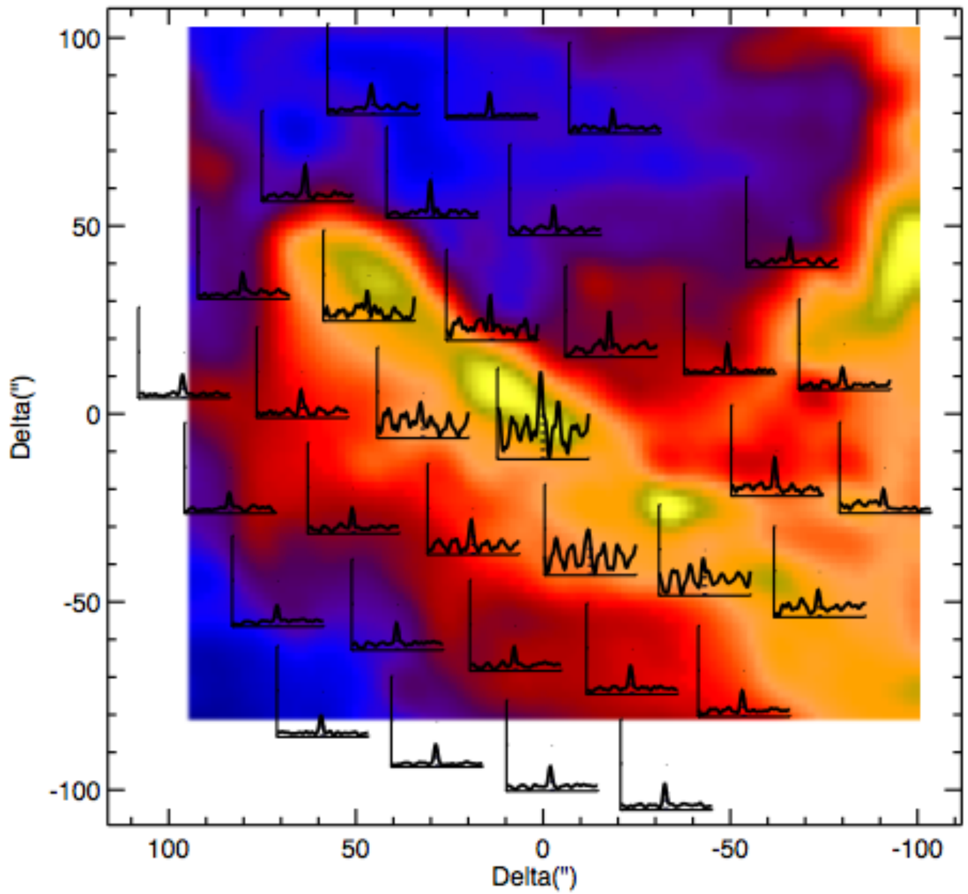
- **Dense & warm component with a significant column density required**
- **Warm CO may originate from dense clumps @ the PDR surface**
- **Out-of-equilibrium effects (advection) could enhance the column of warm CO**
- **Additional heating for the interior like shocks or cosmic rays (Pellegrini et al.) ?**

Spatially extended emission of C^0 and N^+ fine structure lines emission

C^0 $^3P_1 \rightarrow {}^3P_0$ @ 609.7 μm

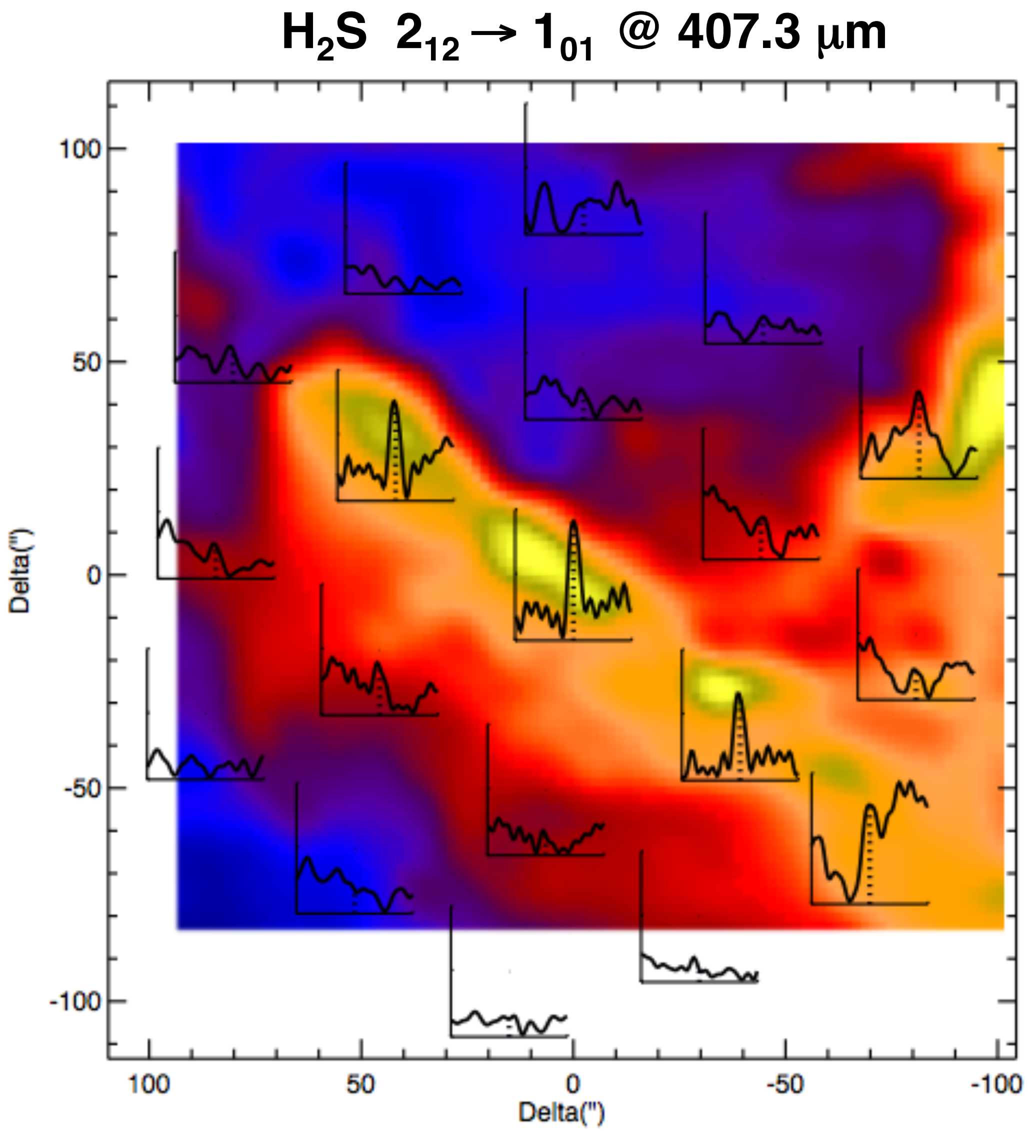


N^+ $^3P_1 \rightarrow {}^3P_0$ @ 205.3 μm



Color map ^{12}CO J=6→5 (Lis et al. 1998)

H_2S line emission



Color map ^{12}CO J = 6 → 5 (Lis et al. 1998)

- **Beam-averaged molecular column densities towards the Bar**

  In the high-density (LTE) limit and Tk~85 K [50-150 K] (probing different PDR regions):

  $N(H_2S)$= 3.1 [2.3-5.2] 10^{13} cm^{-2}

- Our value agrees with previously published value of Leurini et al. (2006) which observes the H_2S $3_{30} \rightarrow 3_{21}$ transition with APEX and deduces $N(H_2S)=(2.5 \pm 1.0)\ 10^{13}\ cm^{-2}$

- Adopting $^{16}O/^{18}O$=500 &$^{16}O/^{17}O$ =1800 (Wilson 1999) and CO/H_2=1.1 10^{-4} (Johnston et al. 2003), $N(H_2)$~9 10^{22} cm^{-2} : **H_2S / H_2 ≤ 3.4 [2.6, 5.8] 10^{-10}**

- High abundances of sulphur species remain an interesting puzzle for interstellar chemistry (i.e., Goicoechea et al., 2006)

- Observed abundance of species such as H_2S are difficult to interpret in models

- **H_2S results from a mixed chemistry involving gas-phase reactions and grain-related processes**

Conclusion

- We have analyzed the FTS complete survey of the Orion Bar spectrum

A wealth of rotational lines of CO (and its isotopologues), fine structure lines of C and N+, and emission lines from radicals and molecules

- We present some maps not fully sampled but illustrating FTS line mapping capabilities

- Next step : fully sampled map will be investigated

- should be associated to HIFI data (help to assign some lines that could be merged in the lower resolution SPIRE spectra and provide missing information on the gas velocity)

- PACS complementary spectroscopic

- High resolution ground based follow-up