Study of the S1 PDR in ρOphiuchi
A GREAT/SOFIA View

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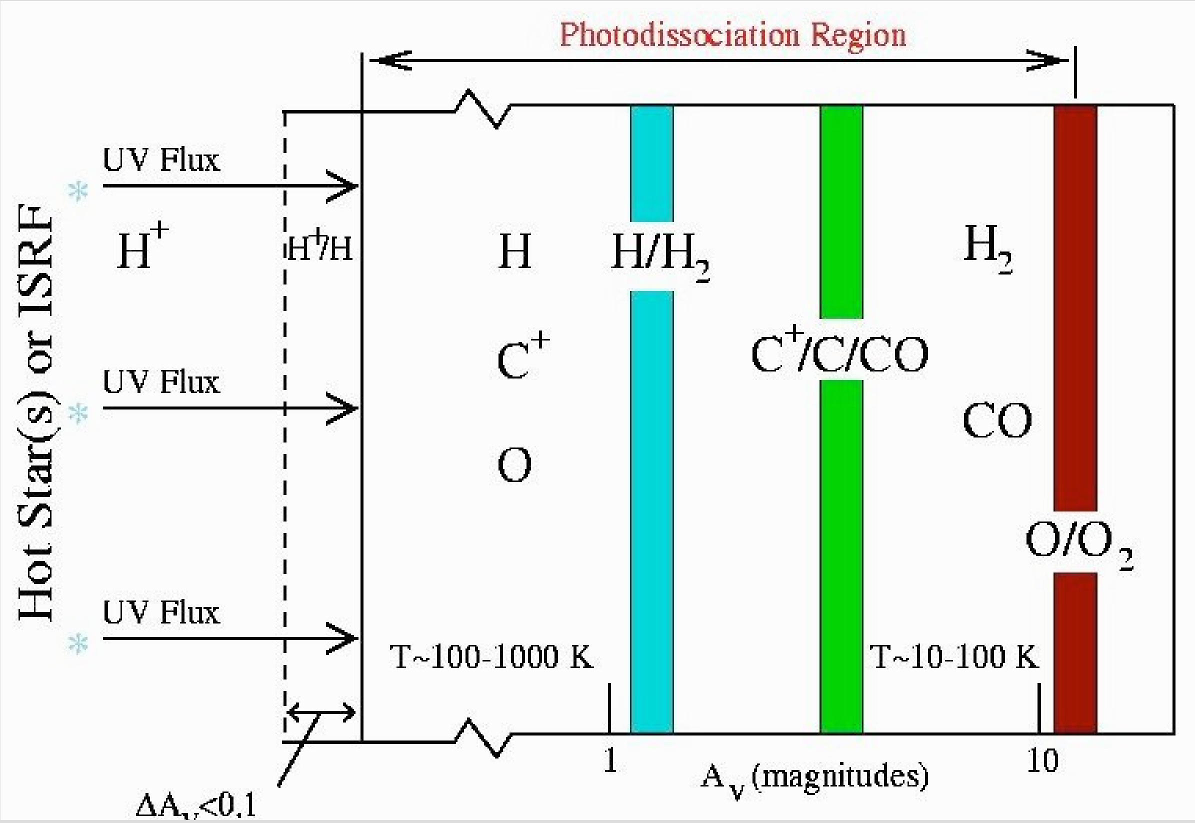
24 October 2018

SOFIA Tele Talk

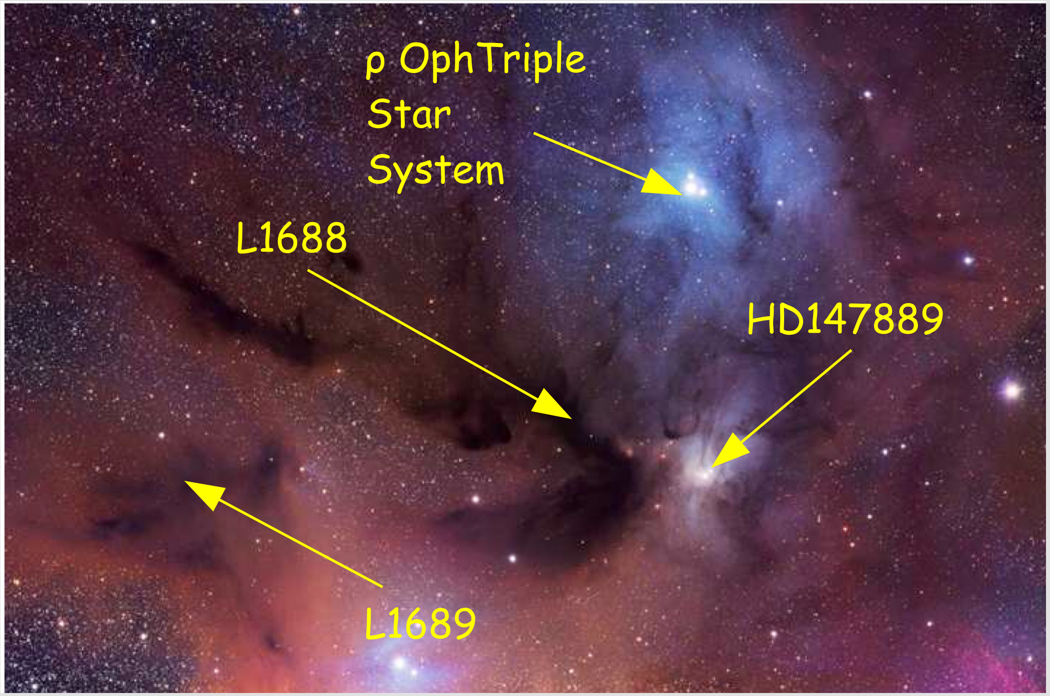
tifr

Photodissociation Regions (PDRs)

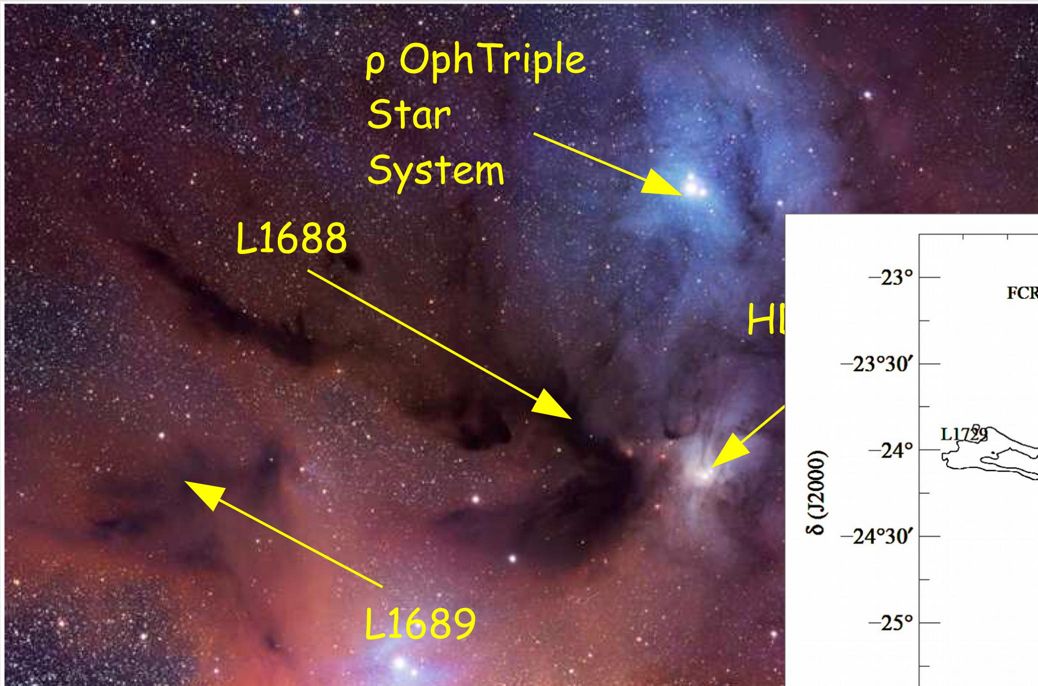


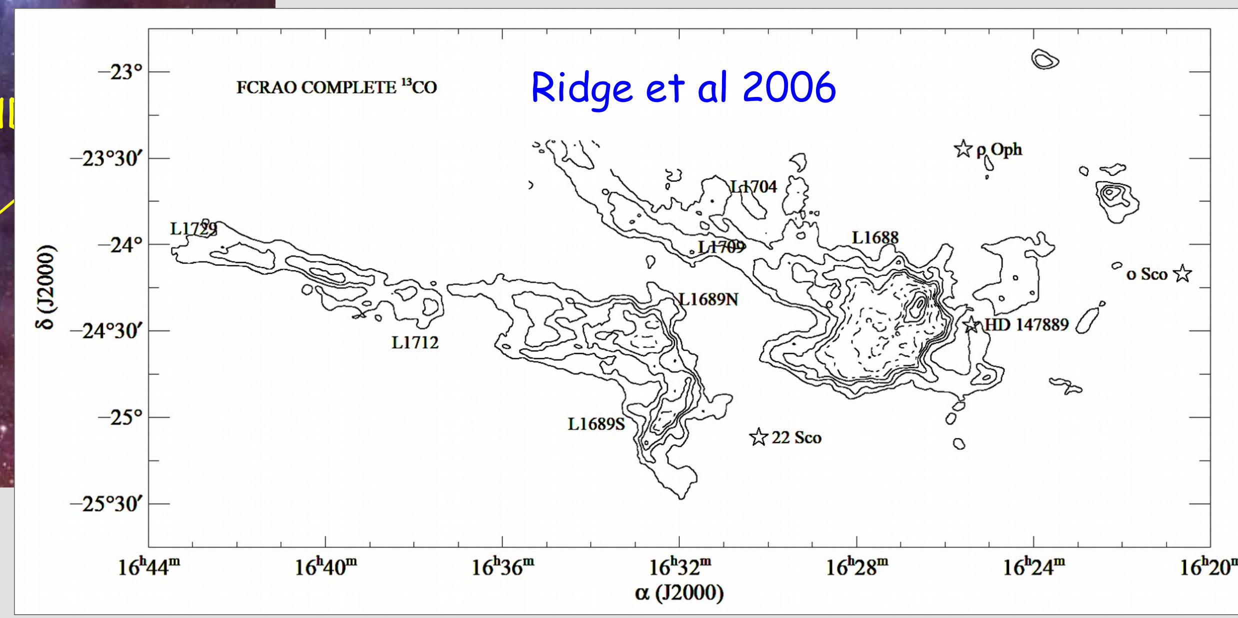
- Prominent & ubiquitous manifestations of the feedback due to radiation from massive stars
- Surfaces of molecular clouds or dense clumps embedded in molecular clouds
- PDRs account for most of the neutral mass of ISM & 90% of Galactic molecular ISM may be photon-dominated
- Emit strongest cooling lines ---> structure formation
- Indicators of star formation and galaxy evolution

Rho Ophiuchi

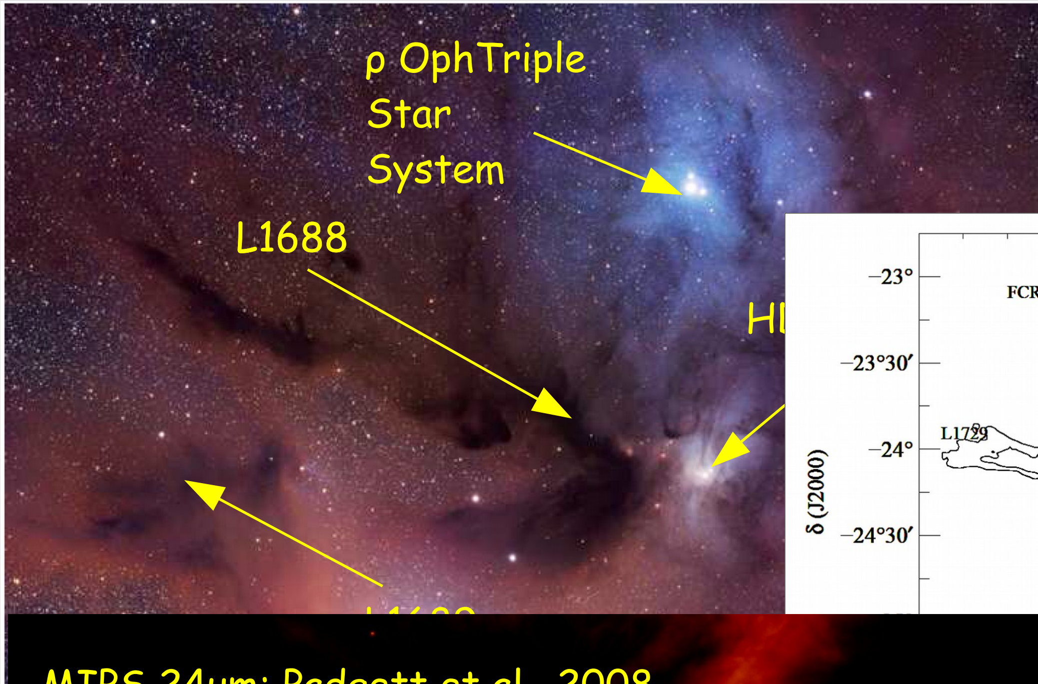


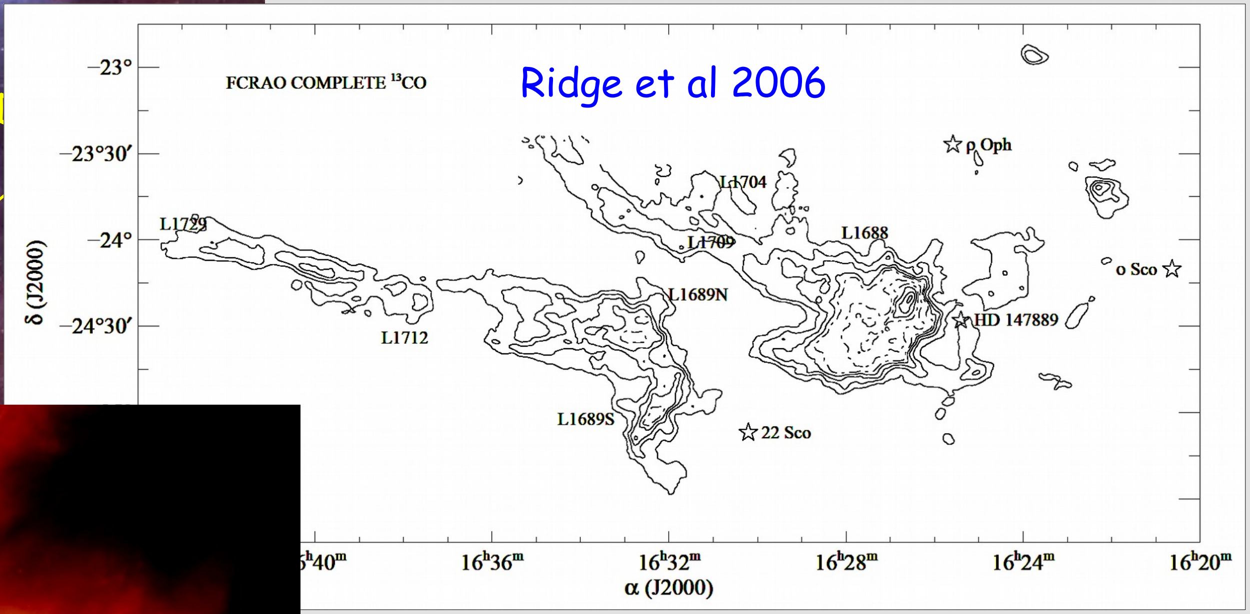
Rho Ophiuchi

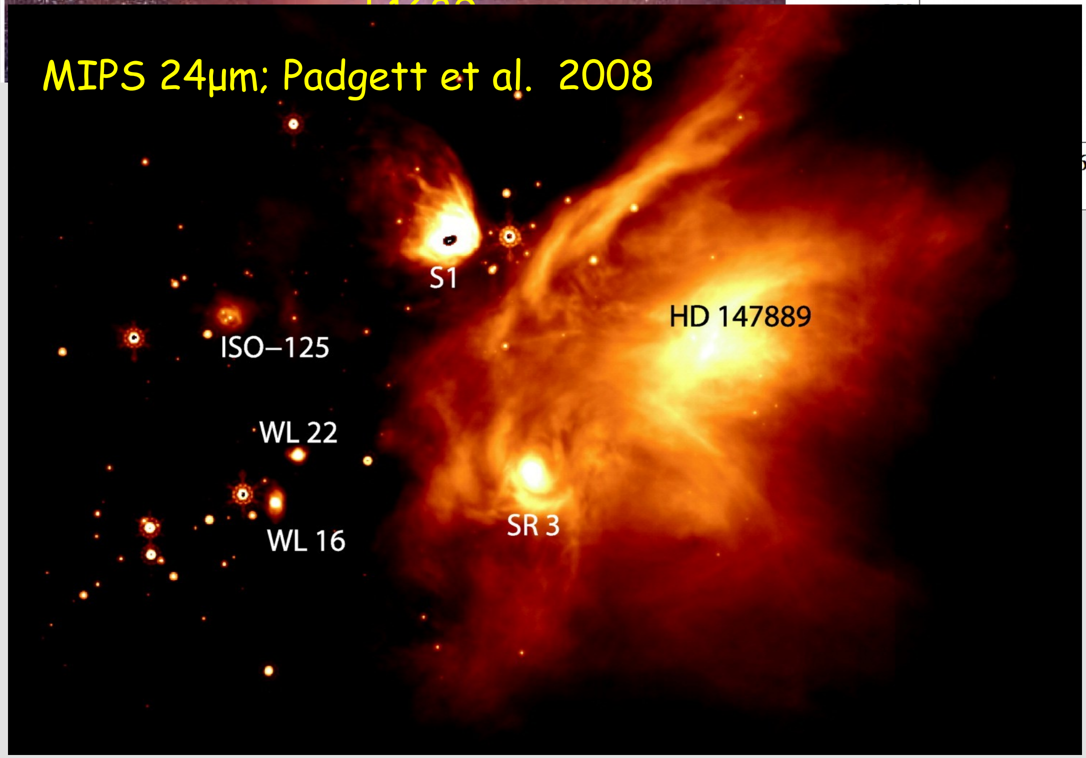




Rho Ophiuchi

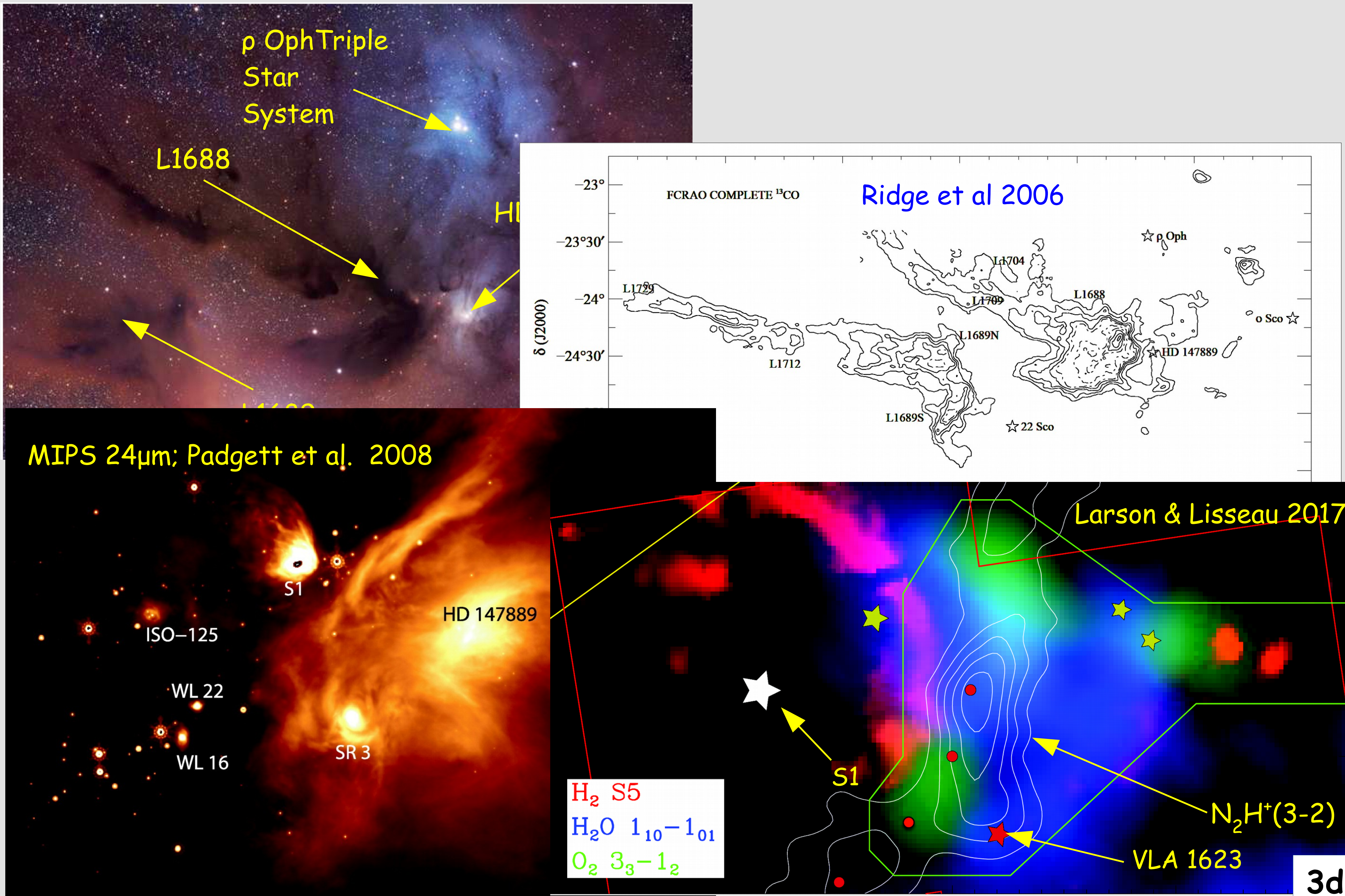






3c

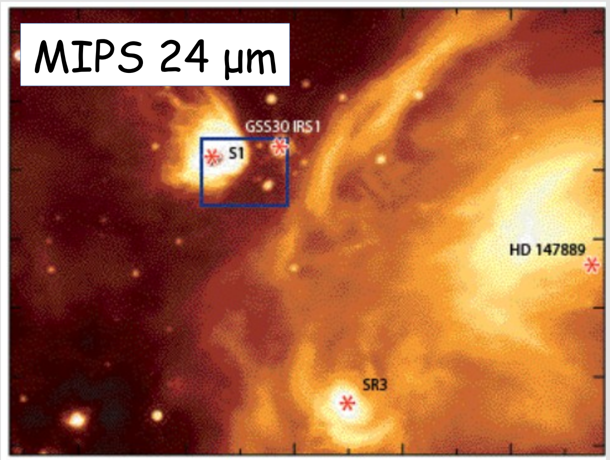
Rho Ophiuchi



Observations & Datasets

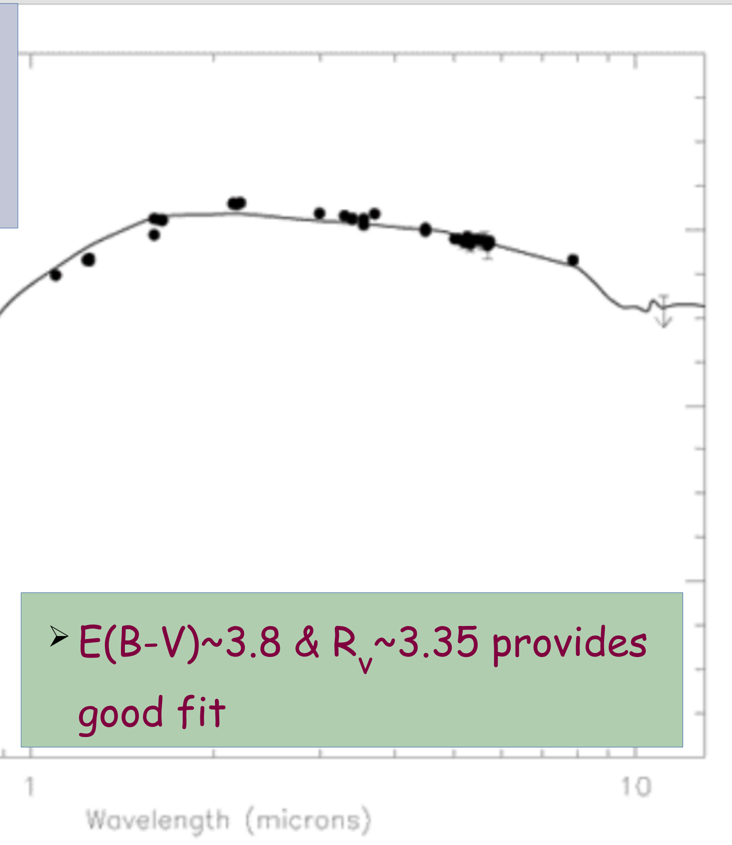
- Retrieved GREAT observations of the $^2P_{3/2}$-$^2P_{1/2}$ fine structure transition of C^+ at 158 μm & the $^3P_1$-$^3P_0$ [N II] line at 205 μm from SOFIA data archive (PI: Di Li) : [N II] was not detected anywhere in the map.
- Retrieved fully processed level 3 SOFIA/FORCAST images from the archive --- S1 not detected
- J=3-2 transitions of CO, ^{13}CO and $C^{18}O$ from JCMT Gould Belt Survey (White et al. 2005); data provided by E. Daubrek-Maunder
- Fully processed ISOCAM image cubes from ISO Data archive
- [O I] 63 and 145 μm PACS fully processed images from Herschel Space Archive ; already published by Larsson & Liseau (2017)

FUV source for the PDR : S1



- S1 too faint in optical (V=16.5 mag)
  - Difficult to classify spectrally
- All observed optical and infrared fluxes : No FORCAST detection

- Teff = 17000 K
- Radius = 4.35 Rsun
- A_V = 12.7 mag



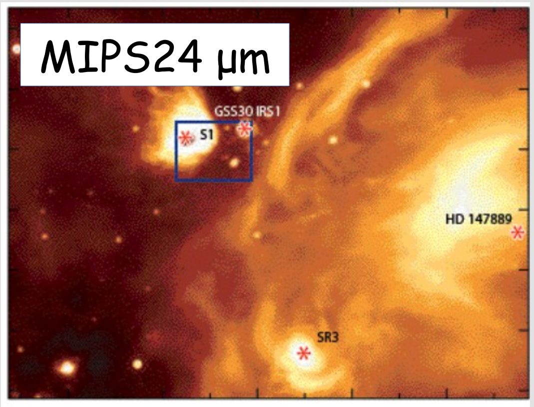
- E(B-V)~3.8 & R_V~3.35 provides good fit

- Fit the SED using a BB function with reddening --> No good fit obtained
- Reddening too large to constrain Teff

- Fix Teff (17000K), Radius (4.35 Rsun) for B4V star; E(B-V) free parameter
- No value of reddening with standard extinction law fits all data

BM,Sandell,Vacca et al 2018, A&A, 616, A31

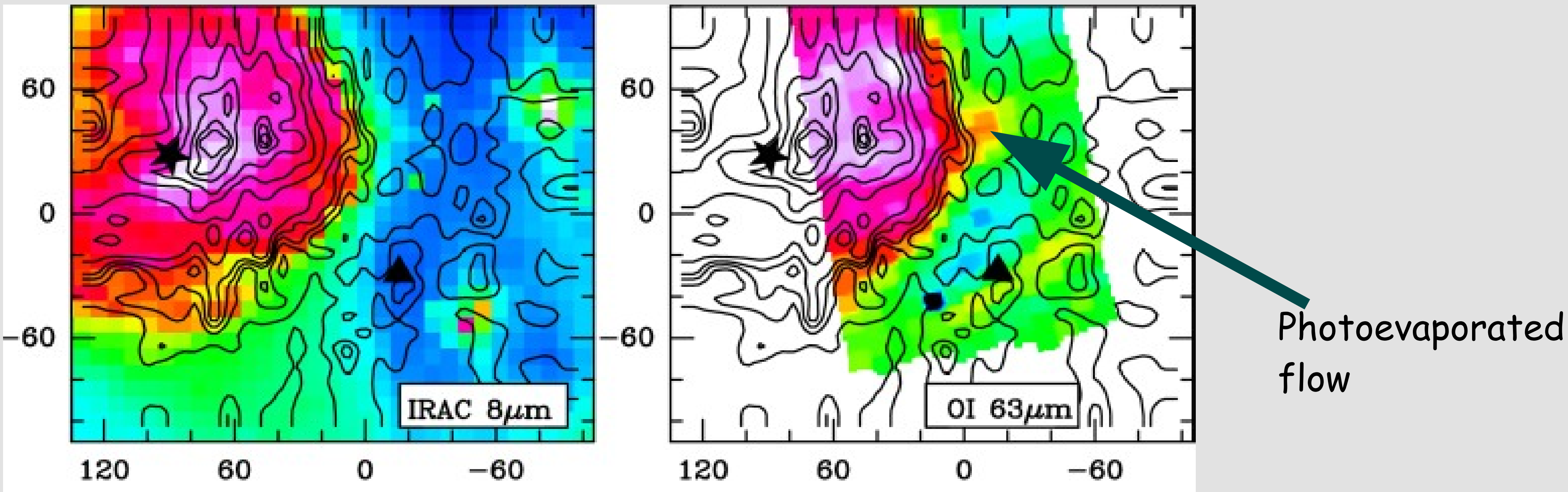
S1 PDR in Rho Ophiuchi: GREAT/SOFIA



- [C II] : Data (PI : D. Li) from SOFIA archives
- [OI] PACS maps at 63 & 145 µm (Larsson & Liseau 2017)

0.01pc resolution

PDR tracers



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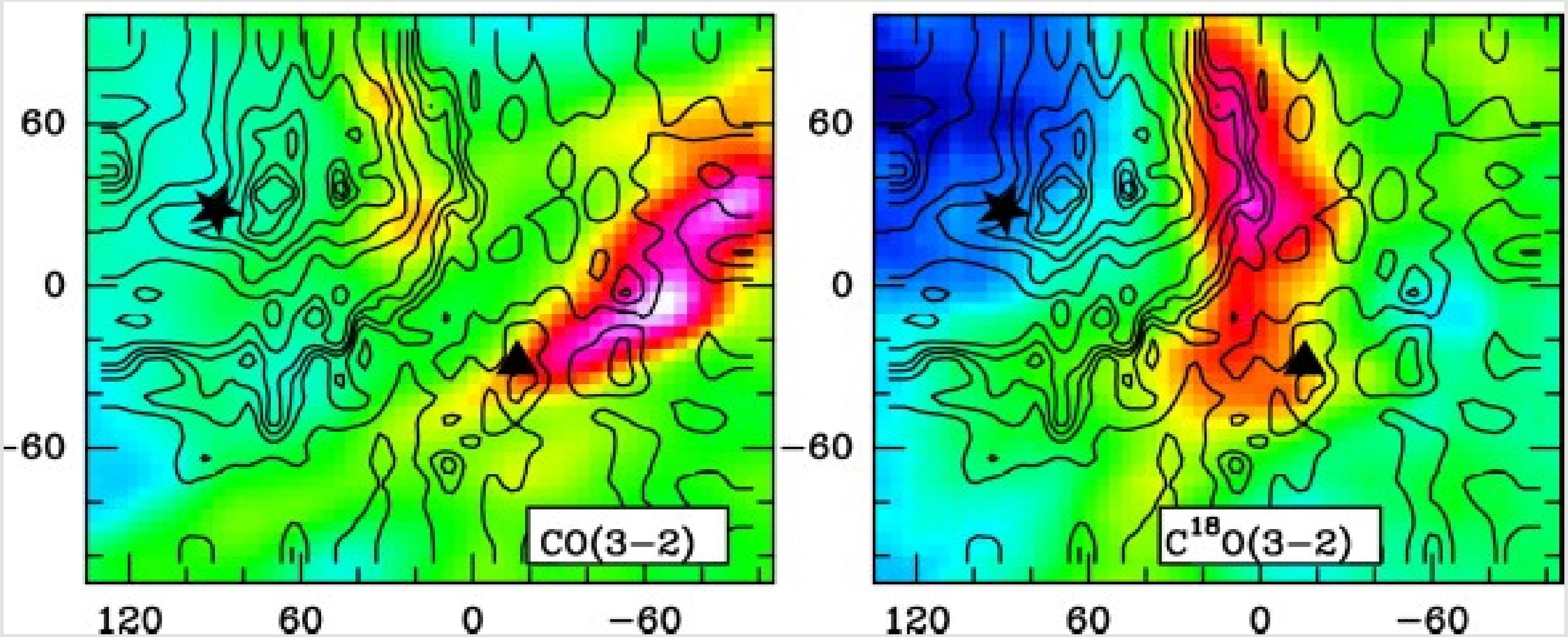
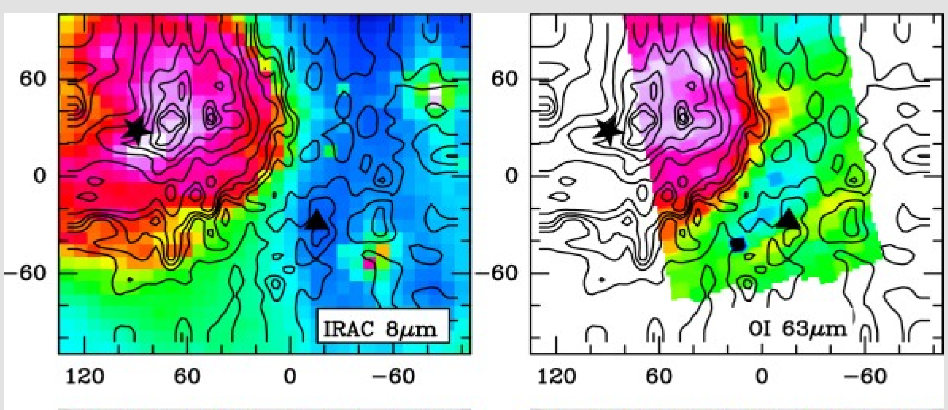
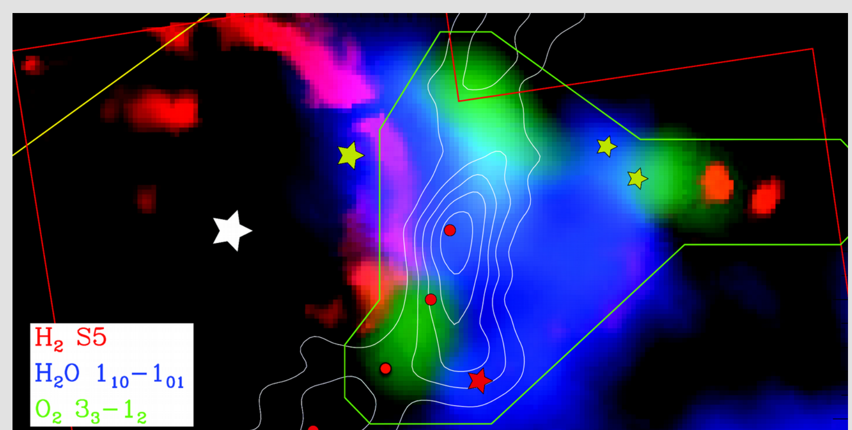
Molecular gas around S1 PDR



- J=3-2 transitions of CO, ^{13}CO and $C^{18}O$ from JCMT Gould Belt Survey (White et al 2015)





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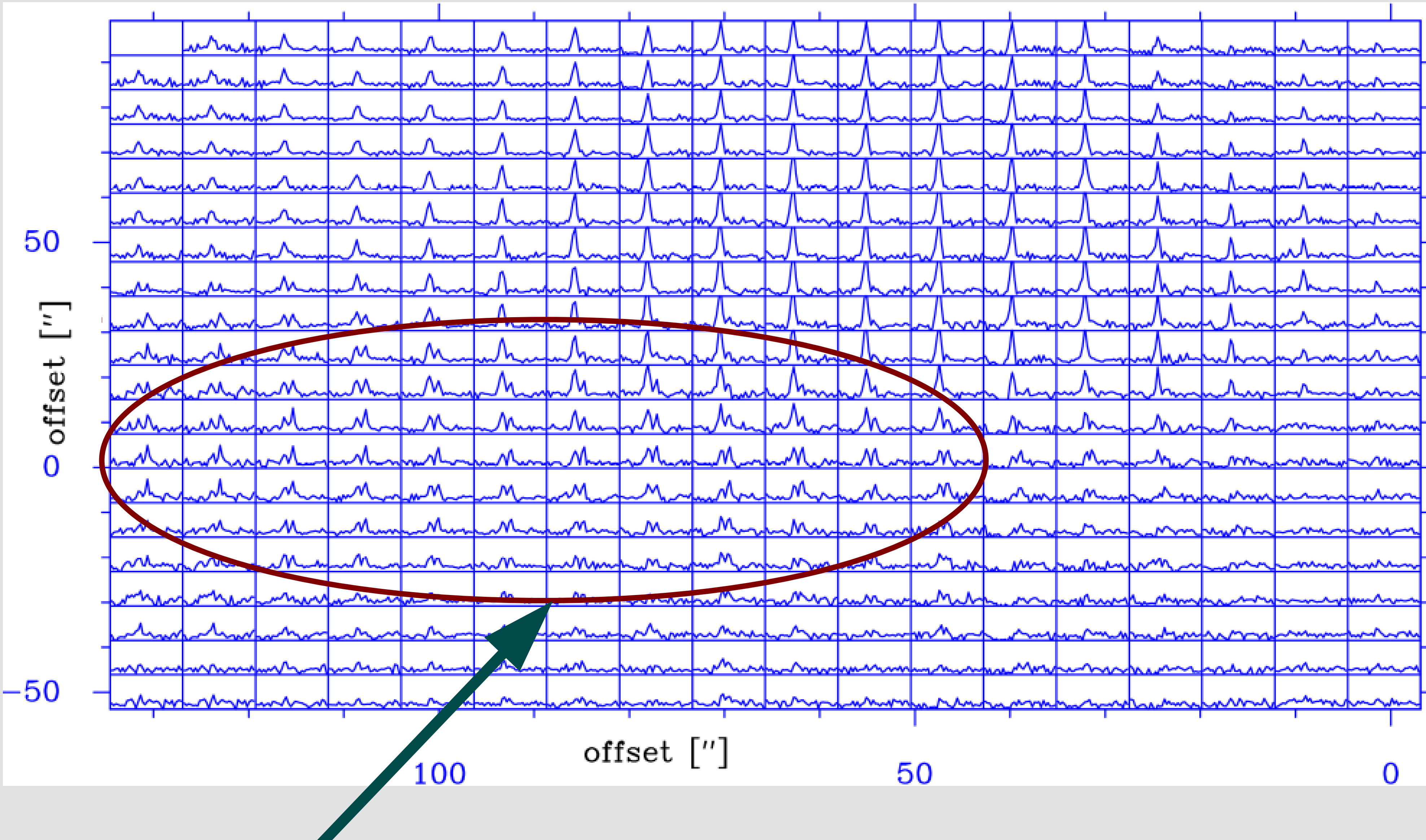
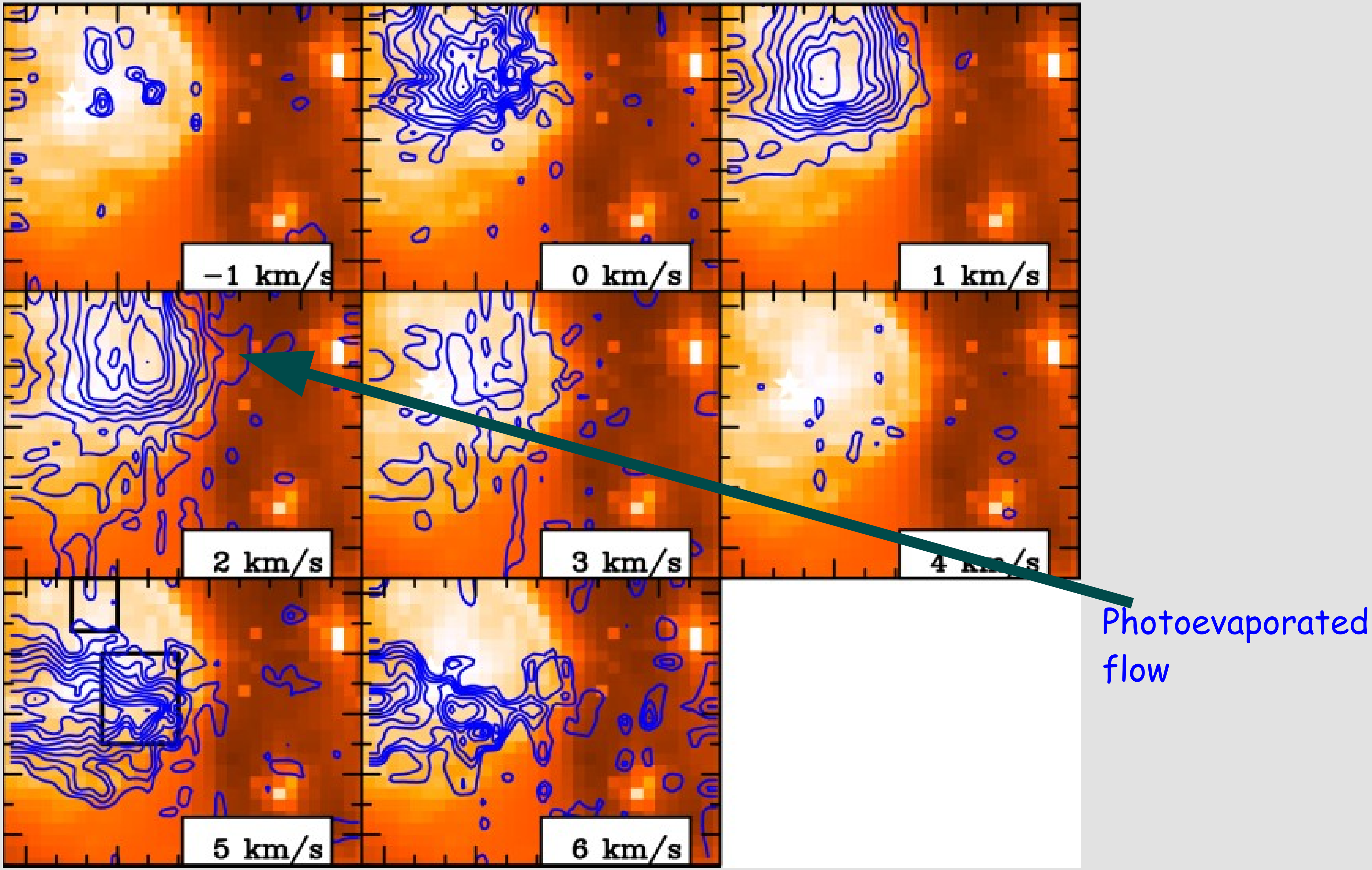
GREAT/SOFIA [C II] 158μm spectral map



Extended Double-peaked/Absorption

BM,Sandell,Vacca et al 2018, A&A, 616, A31

S1 PDR : Velocity Structure of [C II] region



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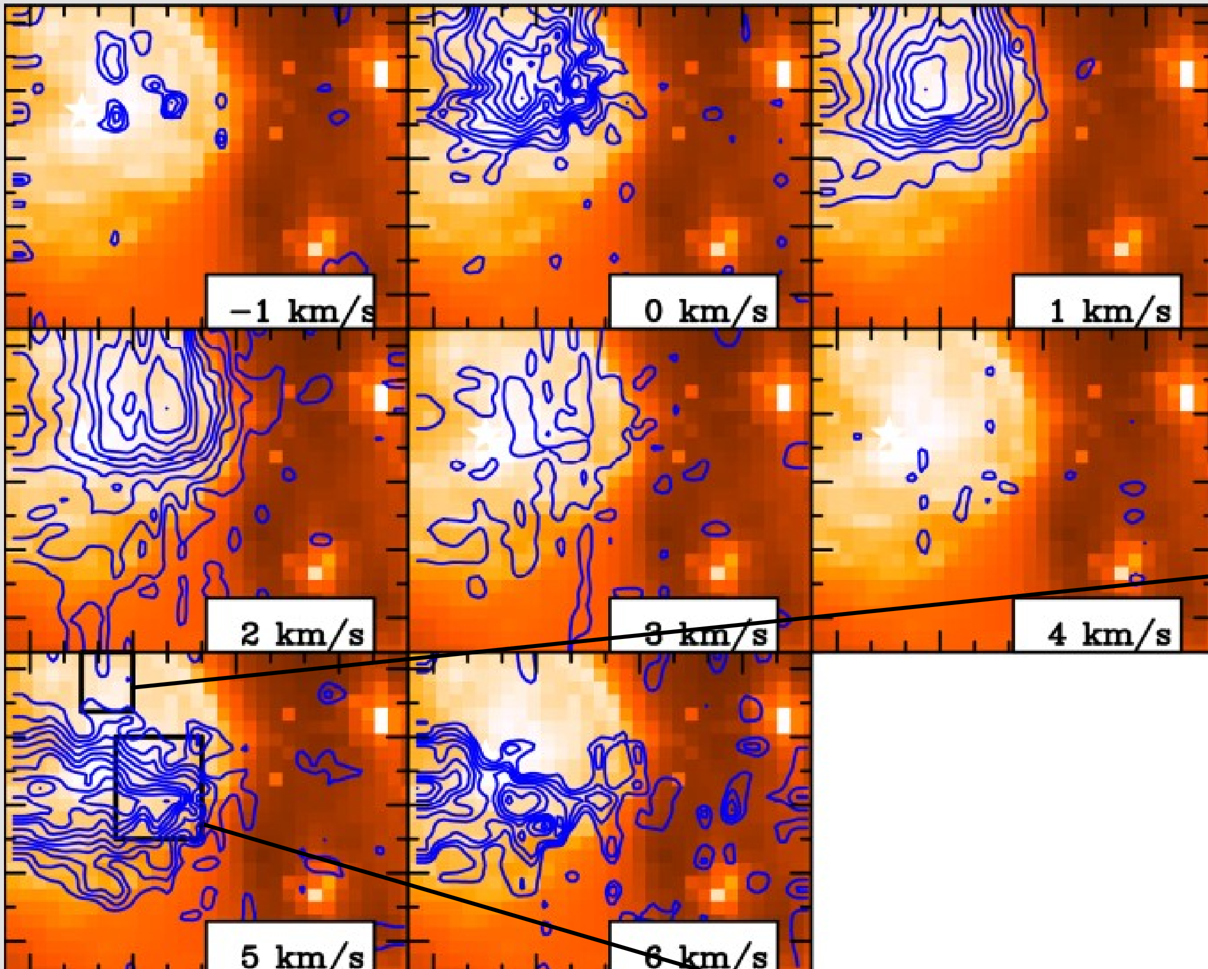
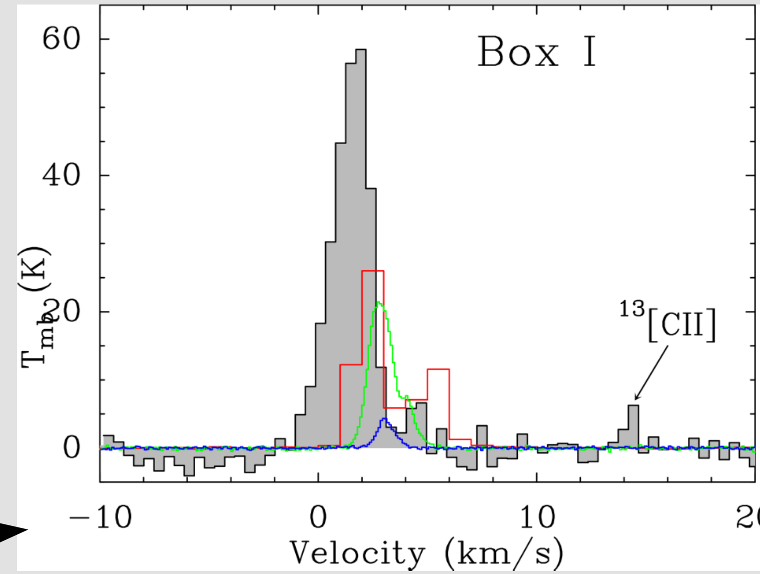
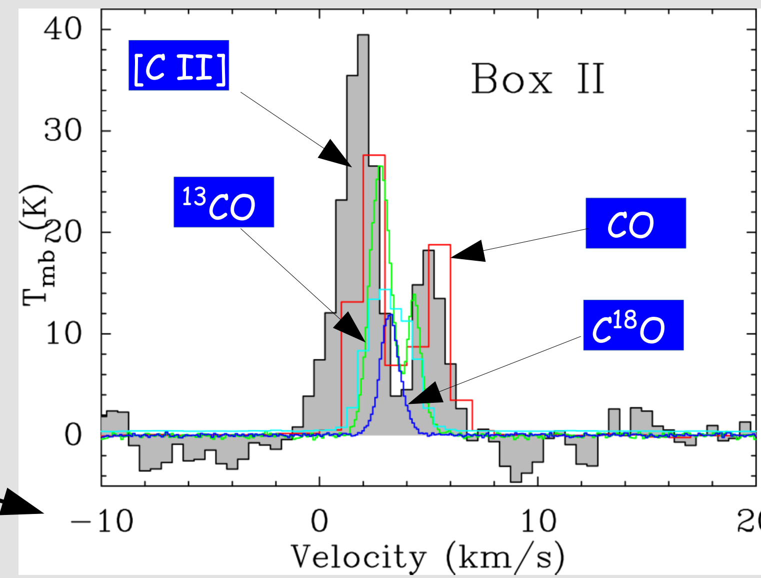
S1 PDR : Velocity Structure of CII region







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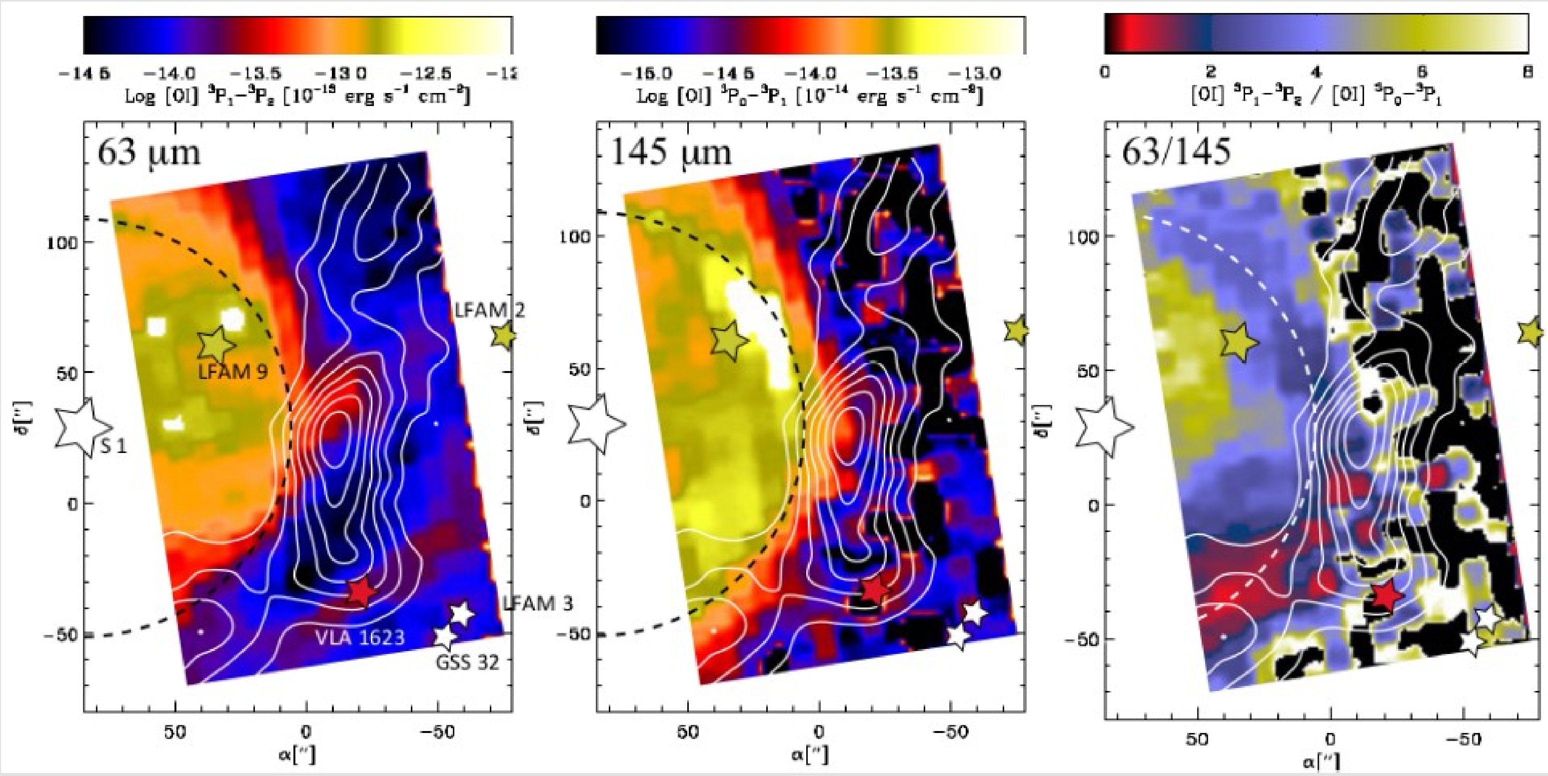
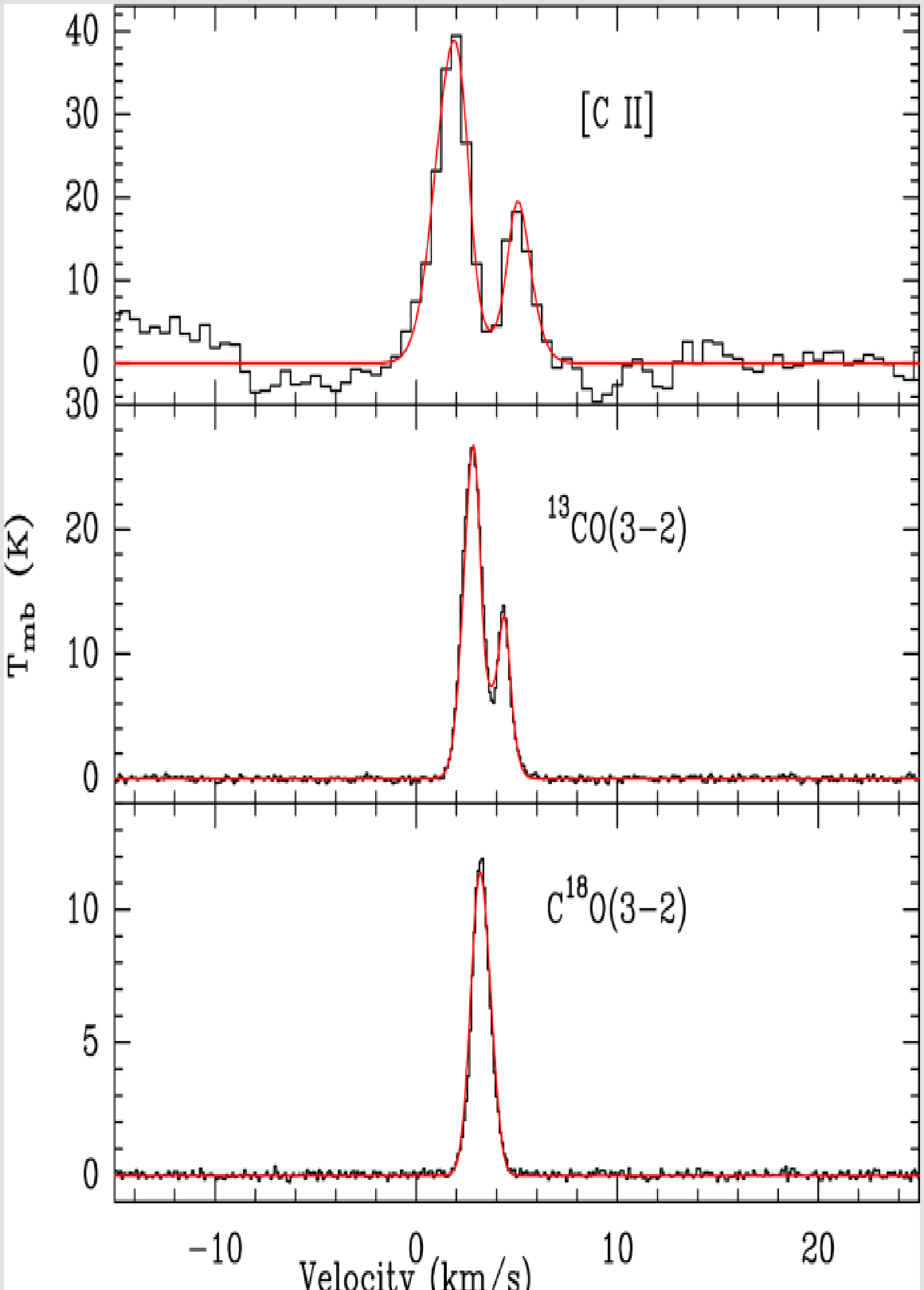
PACS [O I] images of the PDR emission

Larsson & Lisseau 2017



- Observations: F63/F145 ~ 1 to 8, goes down to <1 to the south-east (N6;redstar)
- PDR Models (Kaufman et al. 2006) : OI(63)/OI(145)~ 10 to 20
- Discrepancy too large to be explained by difference in optical depth of the 63 and 145 µm lines
- Foreground cloud absorbing much of the 63 µm flux leaving the 145 µm unaffected.

Double peaked spectra: Shell or Foreground absorption?



- Two-layer Local Thermodynamic Equilibrium model to fit [C II], $^{13}CO(3\text{-}2)$ and $C^{18}O(3\text{-}2)$
- Warmer background component, Colder foreground component
- $^{13}CO/C^{18}O$ = 8.8 for warmer

  = 14 for colder

  -----------> ^{13}CO also optically thick
- $N(H_2)$ for foreground

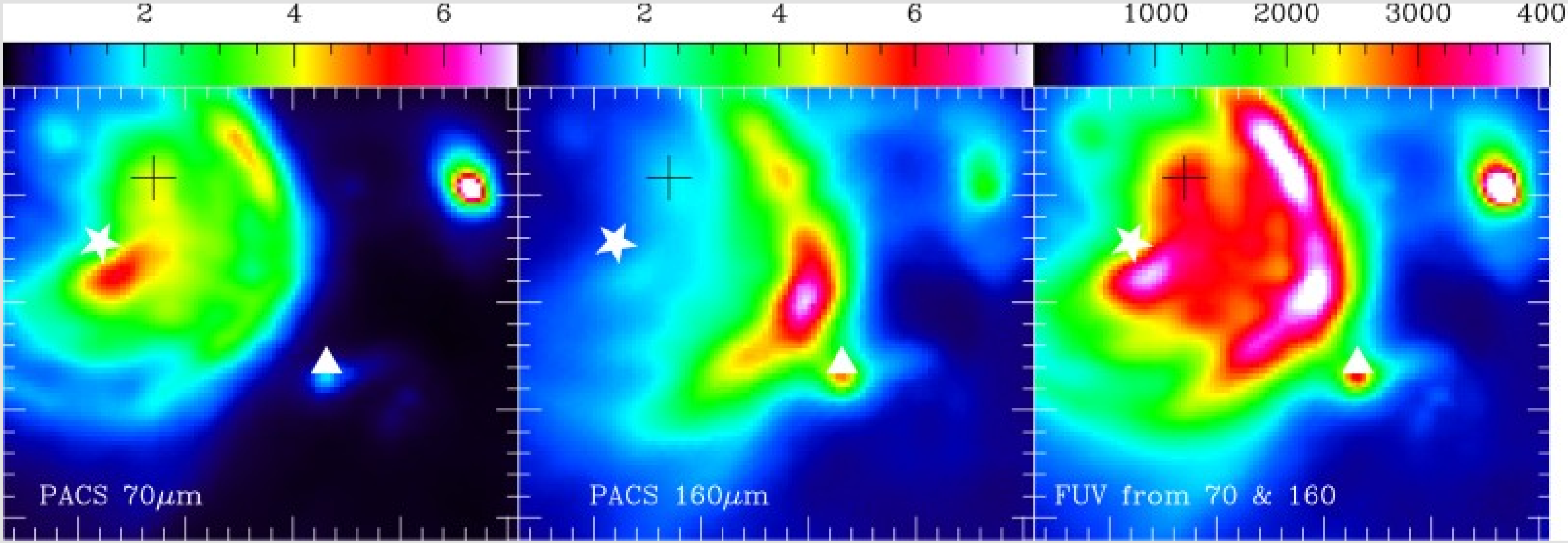
→ From $N(C^{18}O)$, $N(H_2) = 9.3\times10^{21}$ cm^{-2}

-----> A_v=9.9 mag less than estimated reddening toward S1

→ From $N(C^{+})$, $N(H_2) = 5.3\times10^{21}$ cm^{-2}

------> A_v = 5.6 mag assuming $C/H=10^{-4}$

FUV radiation Field & Density of the S1 PDR



- I_{FIR} from the PACS 70 and 160 μm maps ; $I_{FUV} = \frac{4\pi I_{FIR}}{1.6 \times 10^{-3} ergs^{-1} cm^{-2}}$

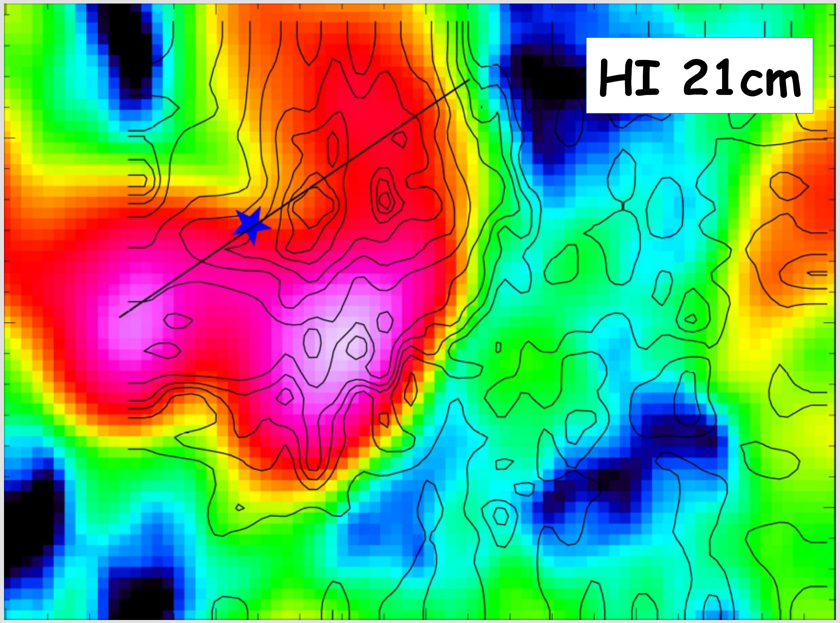
- At the marked position I_{FUV} = 3100 G_0 & observed [OI (145)]/[OI (63)] = 0.15
- Optically thin lines; [OI(145)]/[OI(63)]~0.05-0.1 (PDR model; Kaufmann et al. 2006)
- Observed [OI(145)]/[C II] = 0.27 ---> for FUV = 3000 G_0 ---> n=3000 cm^{-3}
- Critical density of [OI (145)] > 10^6 cm^{-3}
- PDR Clumps emitting [OI] & [CII] embedded in diffuse PDR gas emitting only [CII]

Results & Discussion

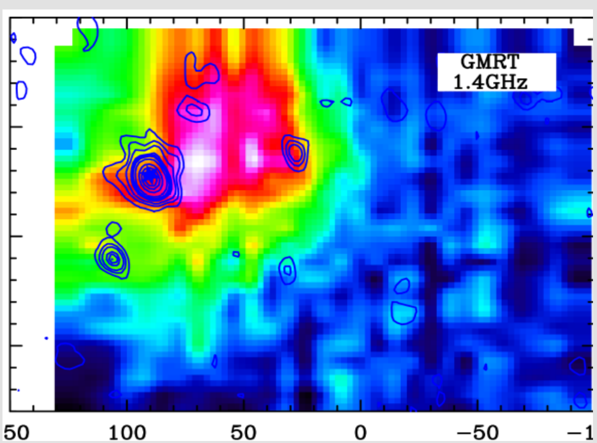
- The PDR close to S1 is primarily illuminated by S1 with negligible contribution from the nearby B2V star HD 147889.
- The PDR appears to be a slightly asymmetric sphere which is pressure-bound to the south and west due to enhanced density of the dense cloud
- The [C II] emission certainly extends further to the north-east – not mapped
- We detect optically thick [C II] lines with strong absorption dips at the center of the line
- Based on the velocity of the singly peaked $C^{18}O$ and [^{13}CII] at the velocity of the absorption we conclude that the dip is due to absorption from a foreground cloud
- We used a two-component (warm and cold) LTE gas model to interpret the line profiles.

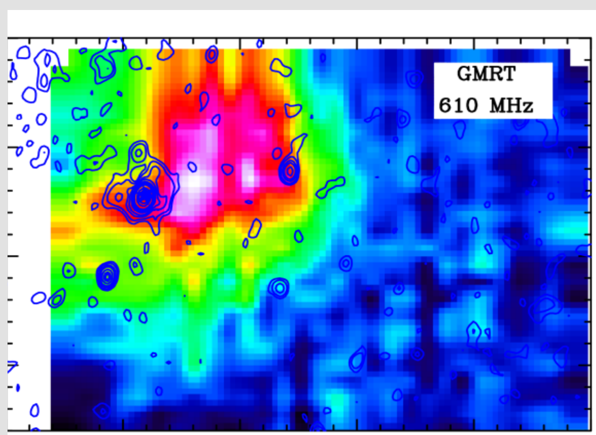
S1 PDR with uGMRT (July 2018)

BM,Veena,Sandell et al



Compare spectral features to separate out kinematic components in neutral gas

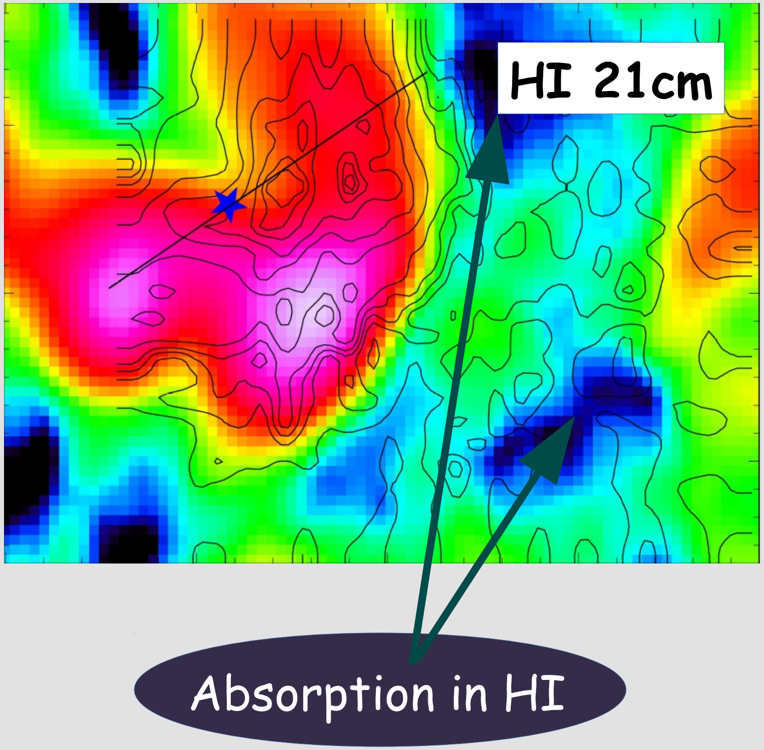




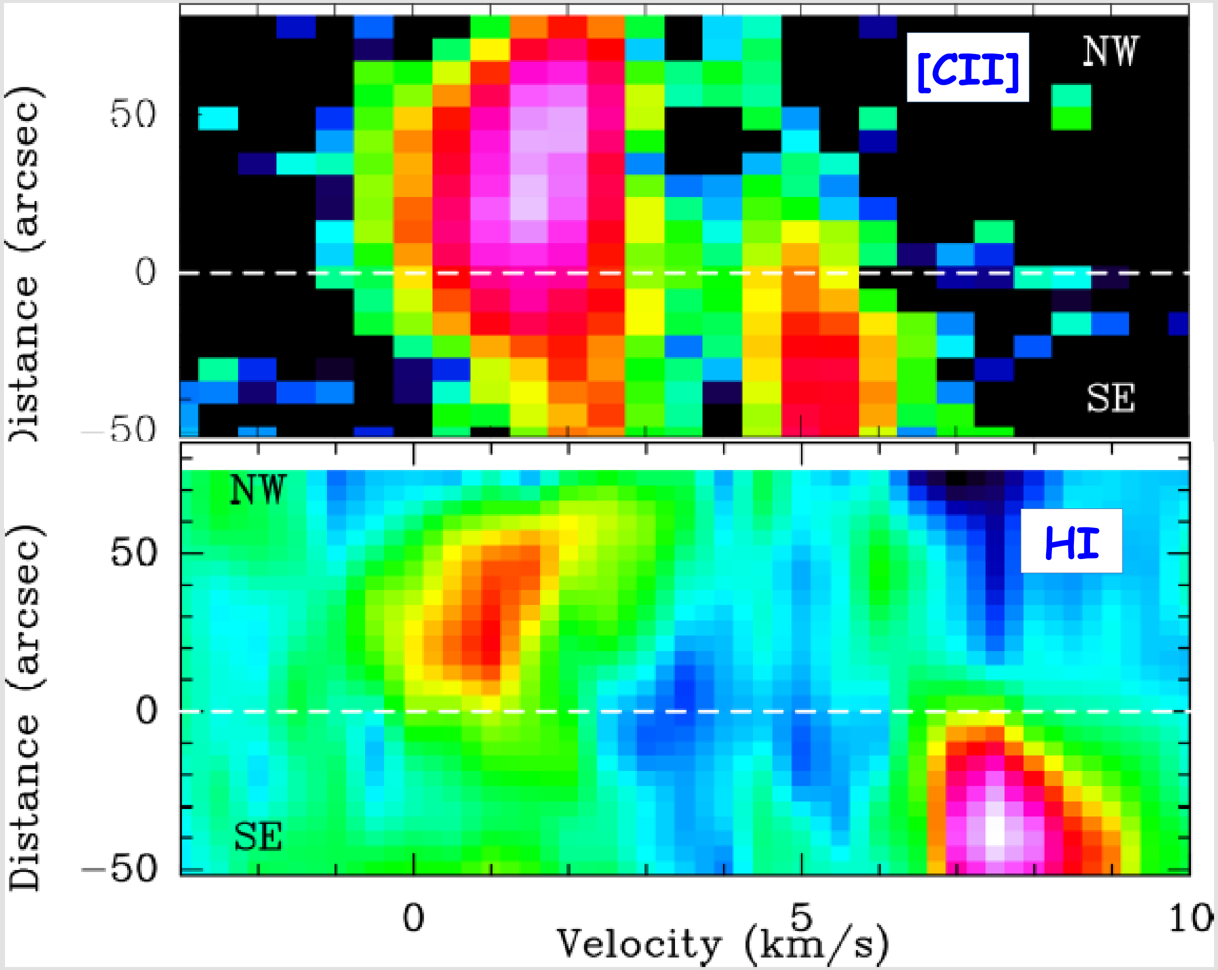
Characterize the radio SED to derive electron density, and use it to estimate the [C II] emission from the ionized gas

- Construct a physical model for the region using multiple tracers:
  - Expanding PDR shell
  - Compressing molecular cloud? --triggering star formation

Velocity Features in atomic gas emission

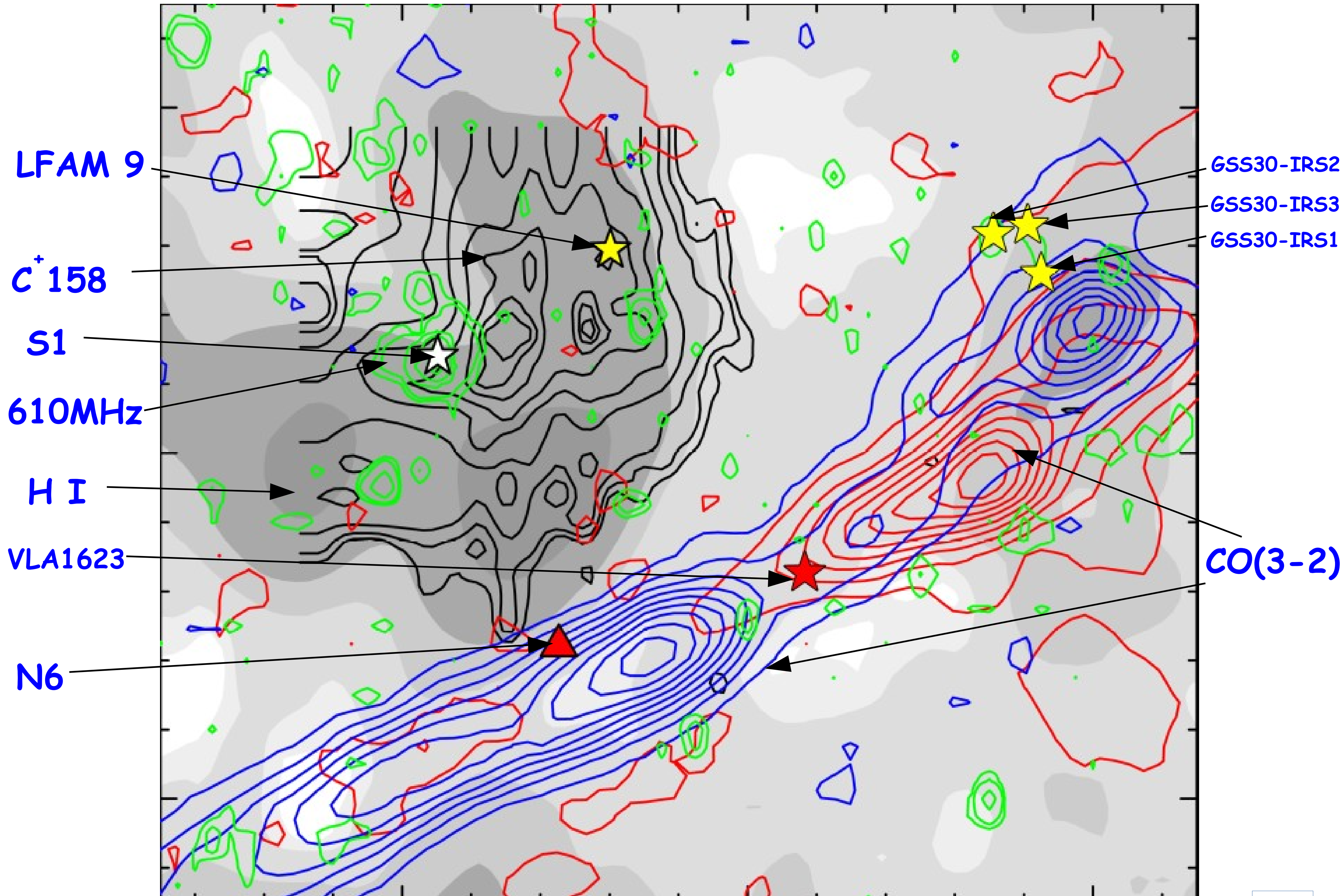


PV diagram along a cut with PA = -45° through S1



- 21 cm HI emission distribution looks more similar to [C II]
- Double lobed structure in PV diagram seen in both tracers

Interpretation of HI 21 cm emission complicated by absorption



BM,Veena,Sandell et al

Outlook

- Located at 138 pc and being edge-on the S1 PDR provides a good opportunity
- [C II] 158 µm emission is similar to emission from the atomic gas and other PDR tracers. High-J CO observations needed to detect the hot molecular gas in the sphere around S1
- Complete analysis of the uGMRT data is in progress and will characterize the atomic and ionized gas in the region.
- For complete disentanglement of the contribution from the low and high-density (traced by [O I] lines) PDRs velocity-resolved [O I] observations are needed
- Extension of the [C II] map to the north-east to understand the complete geometry of the region and deeper integration to detect the [^{13}CII] line at individual positions to obtain an estimate of the variation of optical thickness of the main isotope over the map is needed