Fine structure line deficit in S140

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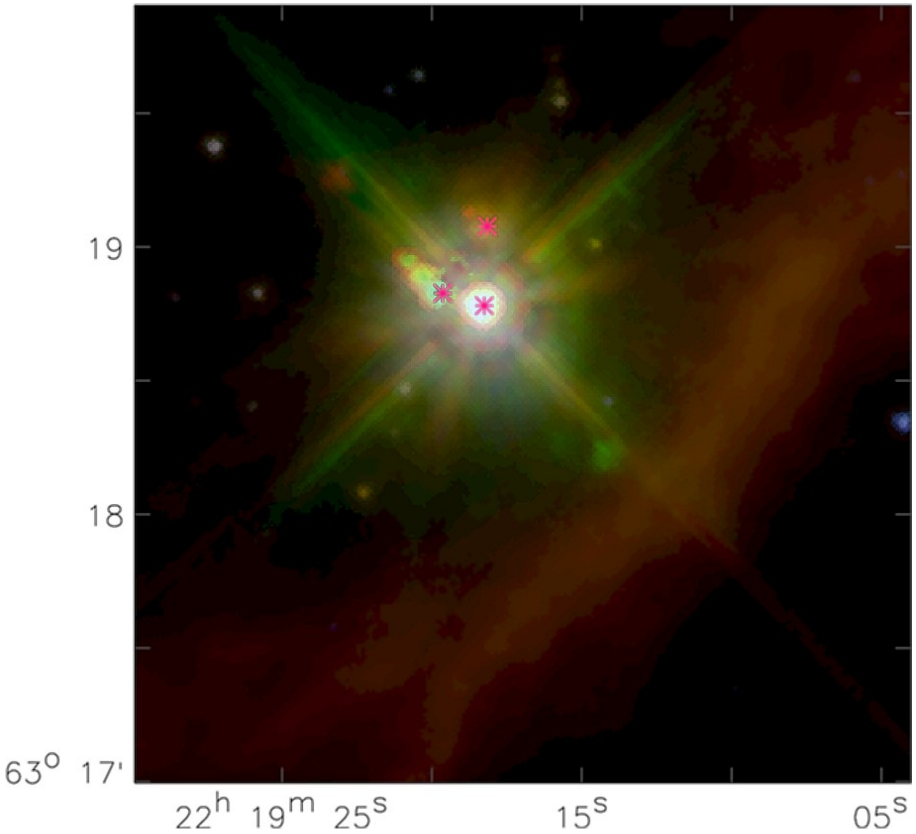
Overview

- S140
- Observational data
  - GREAT observations: [CII], [OI], high-J CO
  - Complementary data
  - Properties of the main emission source
  - The cooling budget
  - The fine-structure line deficit
- PDR modelling
  - Standard plane-parallel models
  - Spherical models and beam filling
  - General explanation for fine-structure line deficit
- Outlook

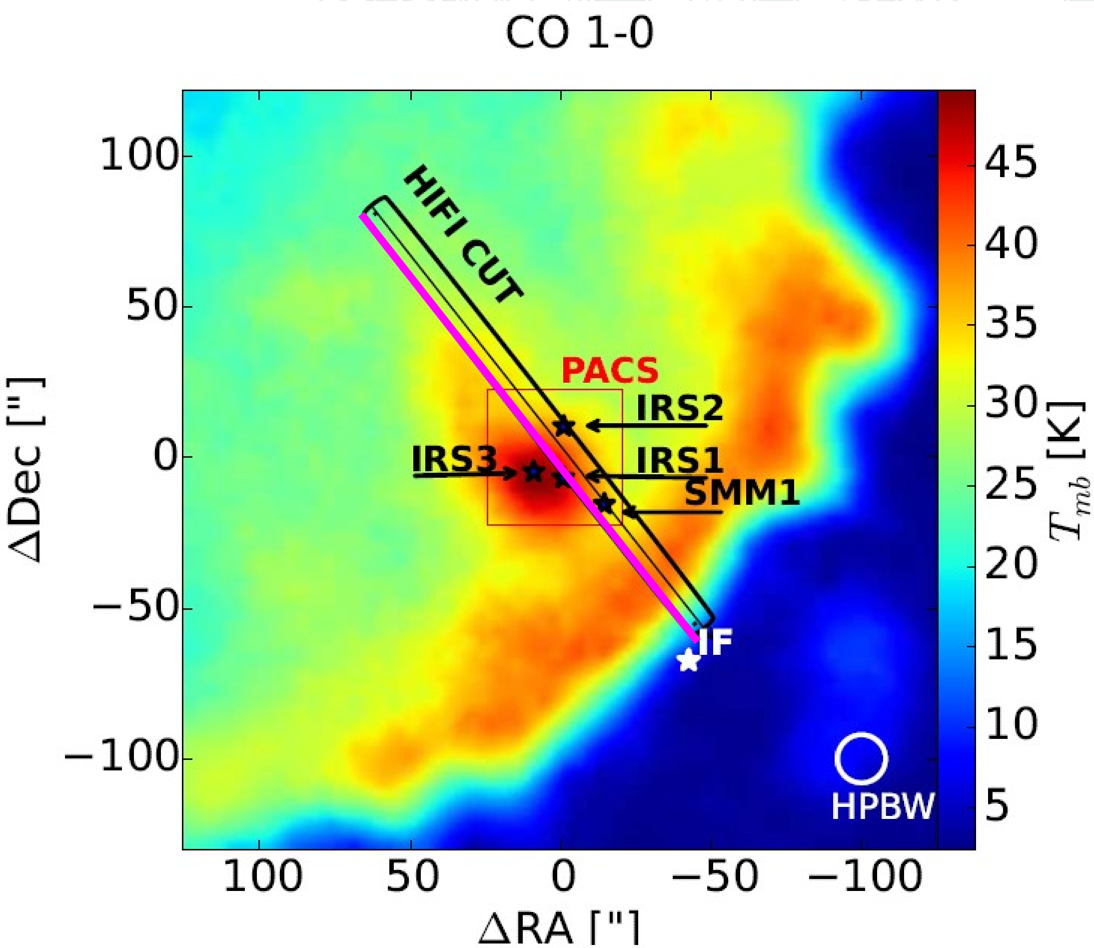
Well-studied molecular cloud:

- **External PDR** (G_0≈300) and deeply **embedded star-formation** (IRS1-3):

IRAC map (3.6, 5.6, 8µm)



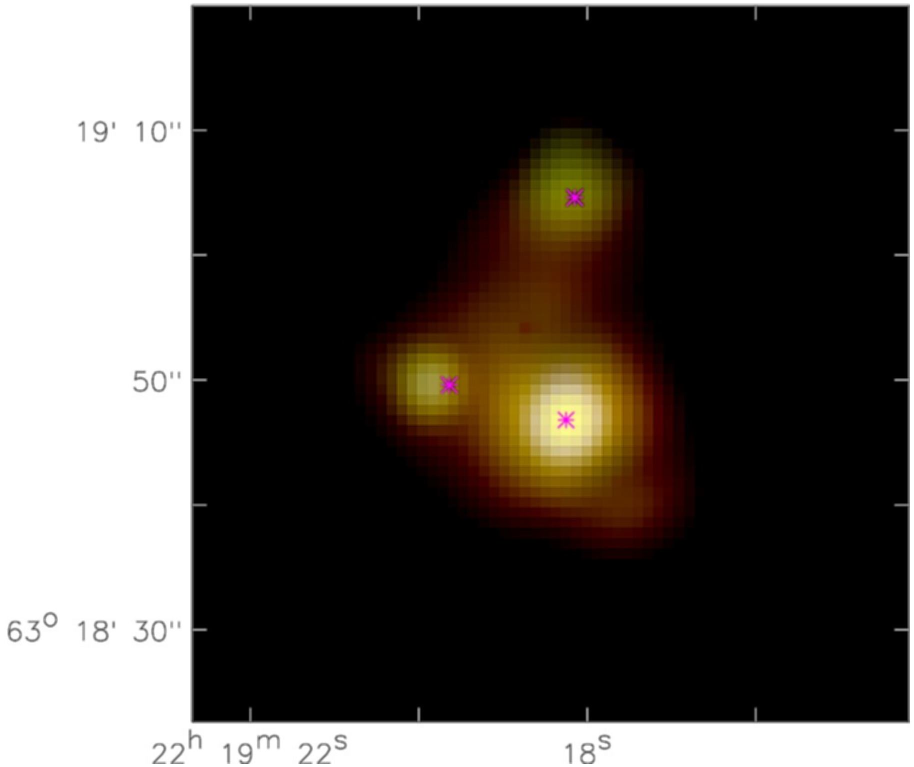
CO 1-0 peak intensity (IRAM)

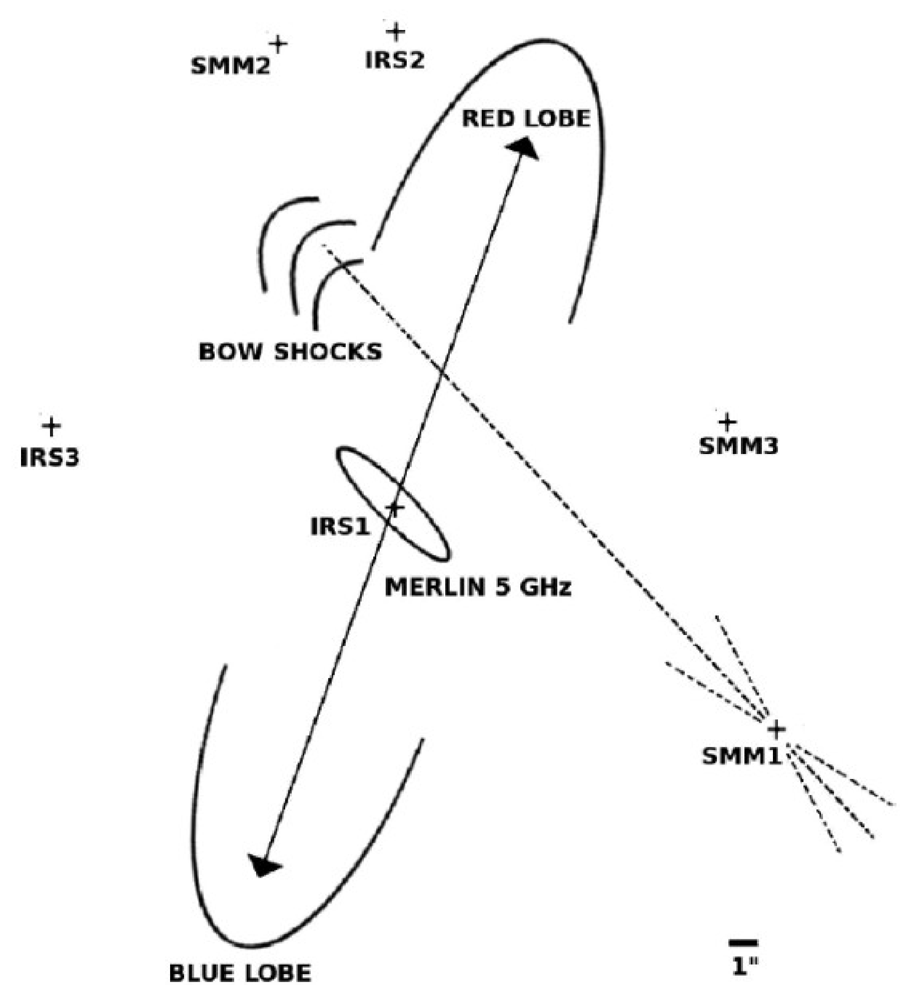


Herschel/PACS and SOFIA/FORECAST observations:

- IRS1 as the central source with 10000$L_\odot$
- Drives molecular outflow (Maud et al. 2013)

FORECAST map (11, 31, 37μm)
(Harvey et al. 2012)

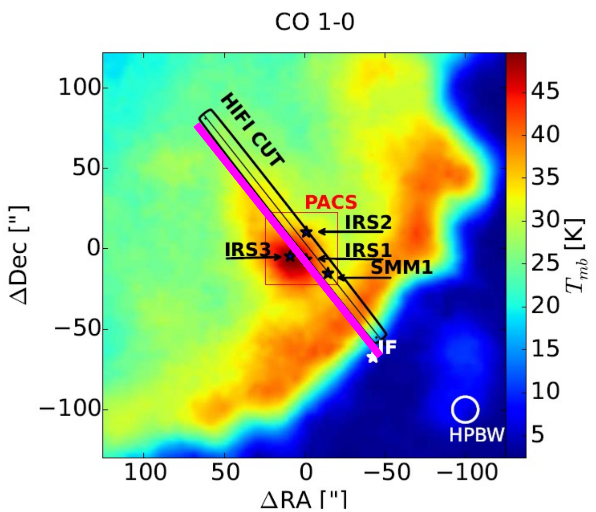


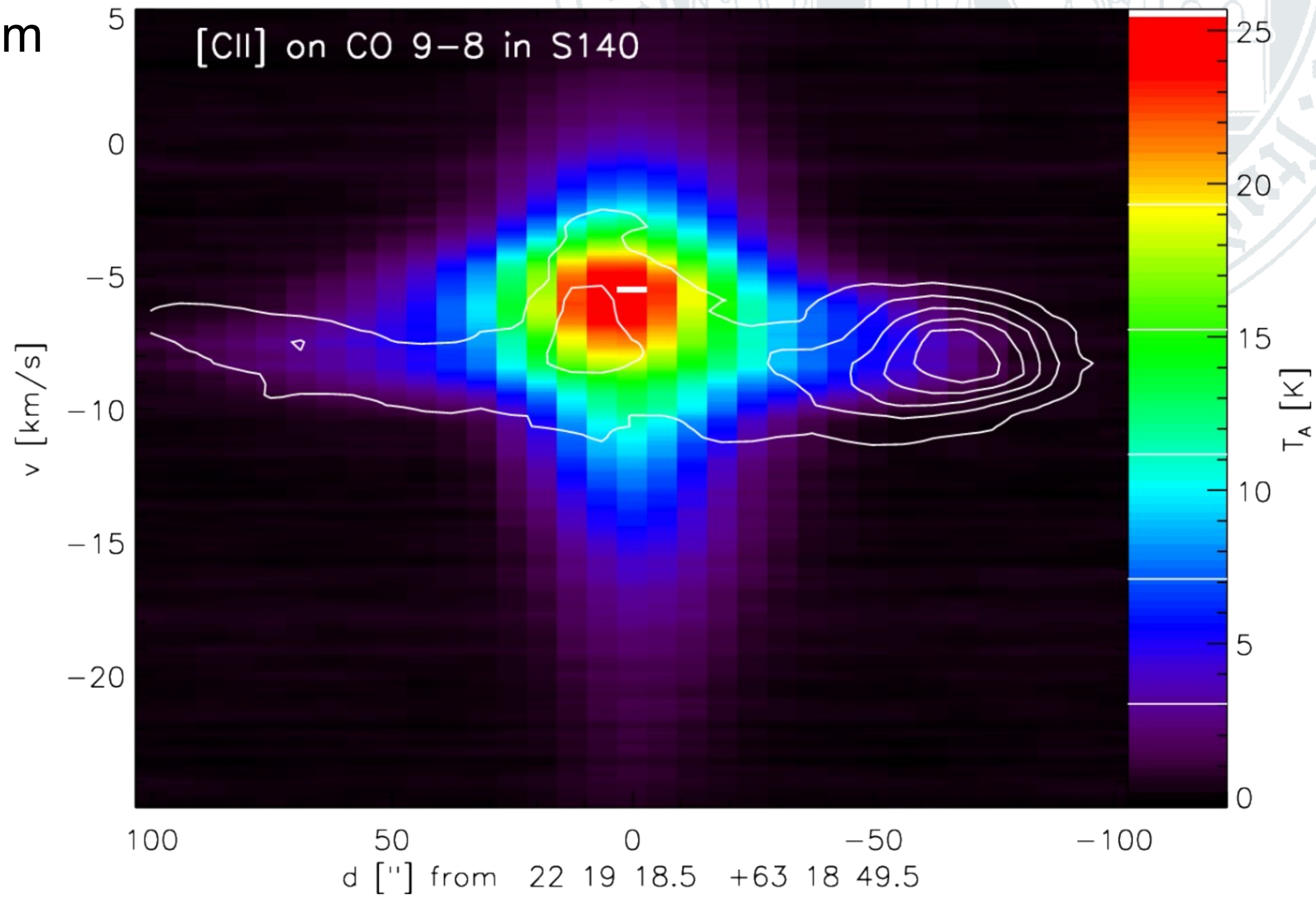


Herschel/HIFI observations of [CII] and many other lines:

- Confirm outflow from IRS1 – prominent on CO
- [CII] strong at interface, weaker, but pronounced at IRS1

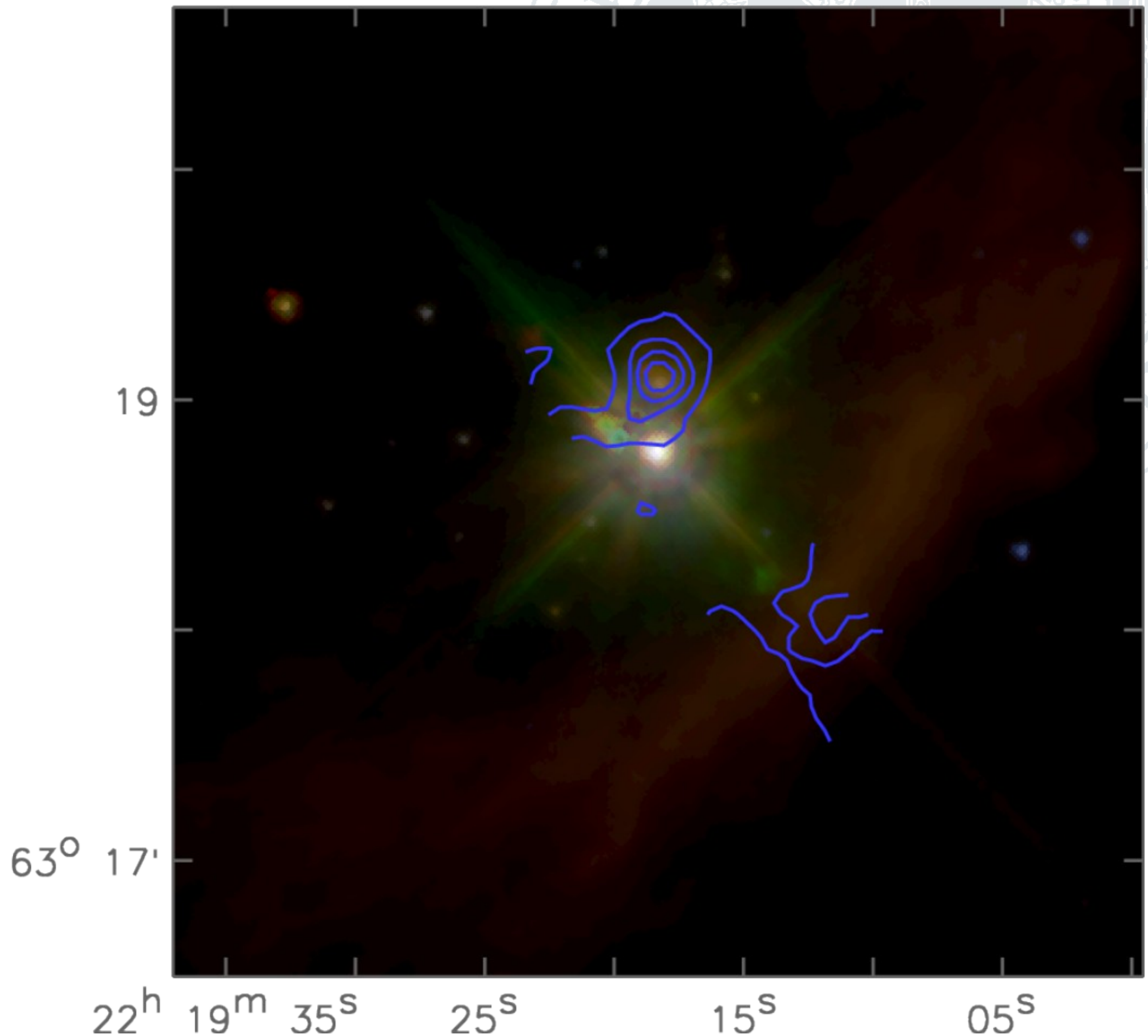
Position-velocity diagram along HIFI cut:





First [OI] 63µm observations - H-channel commissioning 2014:

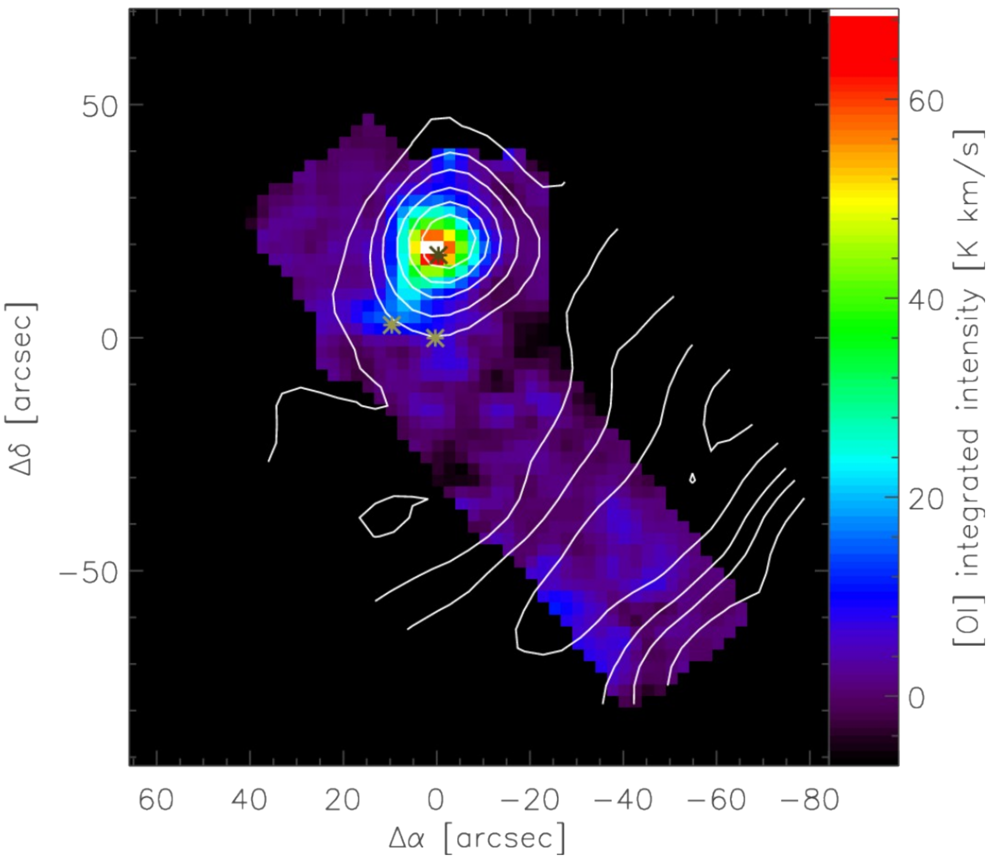
- [OI] strongly peaked, but peak offset by 20'' from IRS1

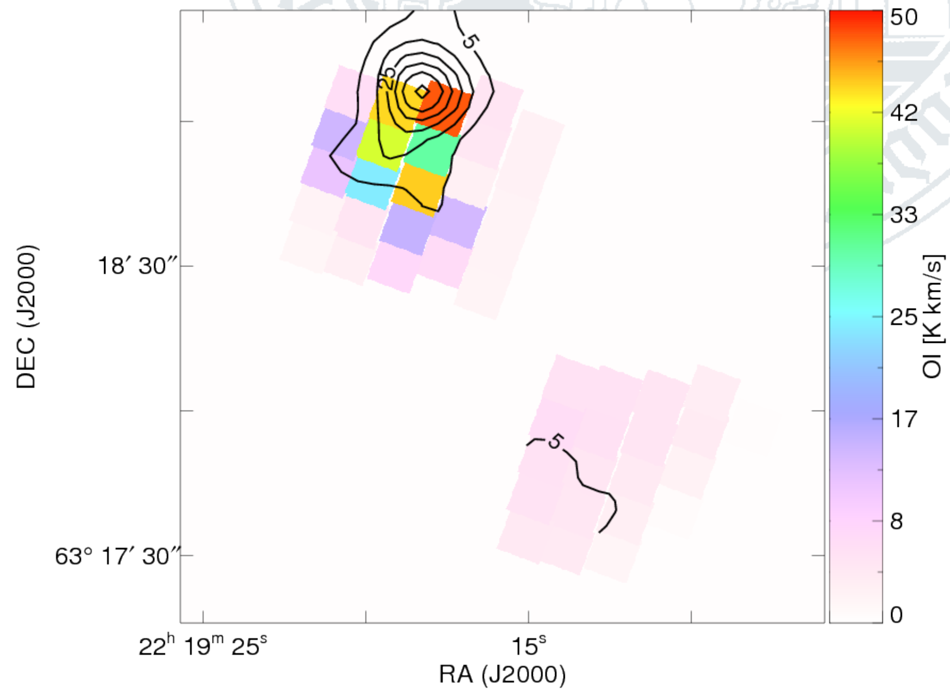


[OI] integrated intensity

[OI] peak confirmed by [CII] map and comparison to PACS:

- Both fine structure lines do **NOT** peak at the main source (IRS1) but 20″ north, close to IRS2

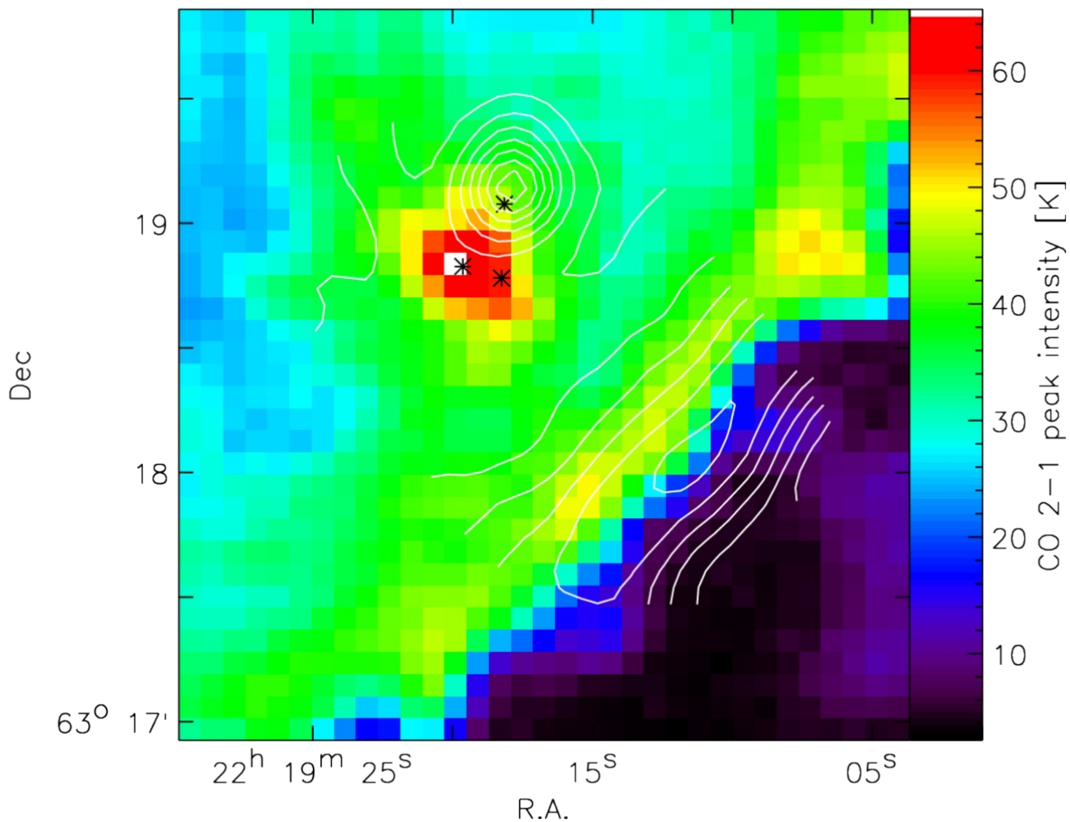




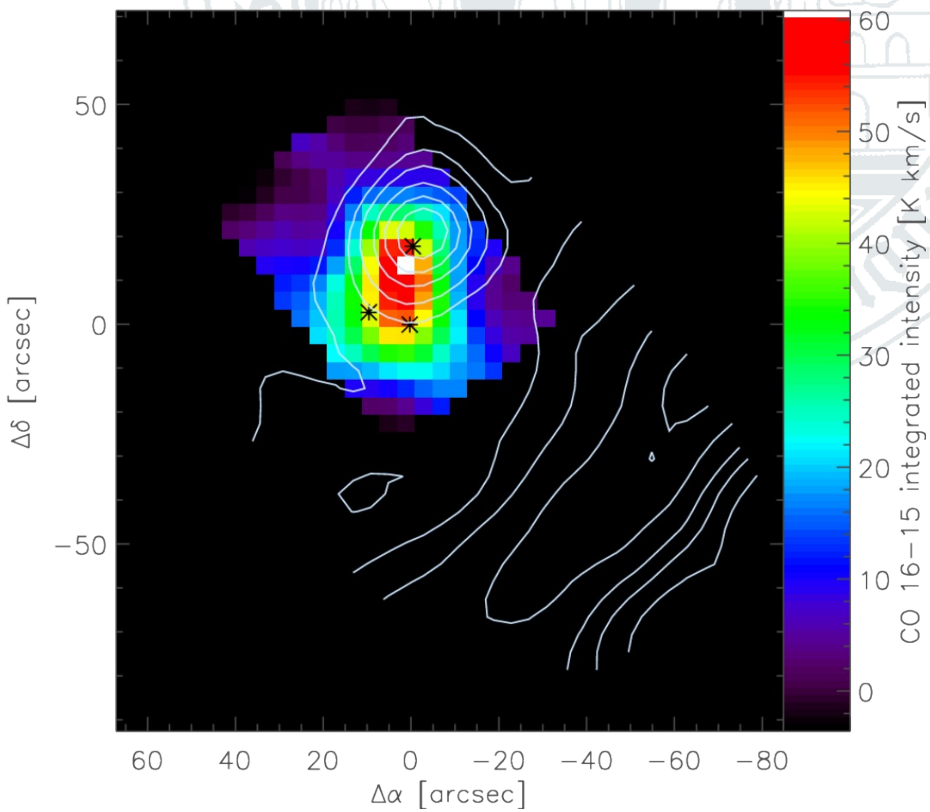
Integrated [OI] (colours) and [CII] contours

GREAT observations of CO 16-15, IRAM 30m maps of low-*J* CO

- Low-*J* lines peak around at IRS1
- CO 16-15 extended between IRS1 and IRS2



CO 2-1 with contours of [CII] (peak intensity) (Koumpia et al. 2015)

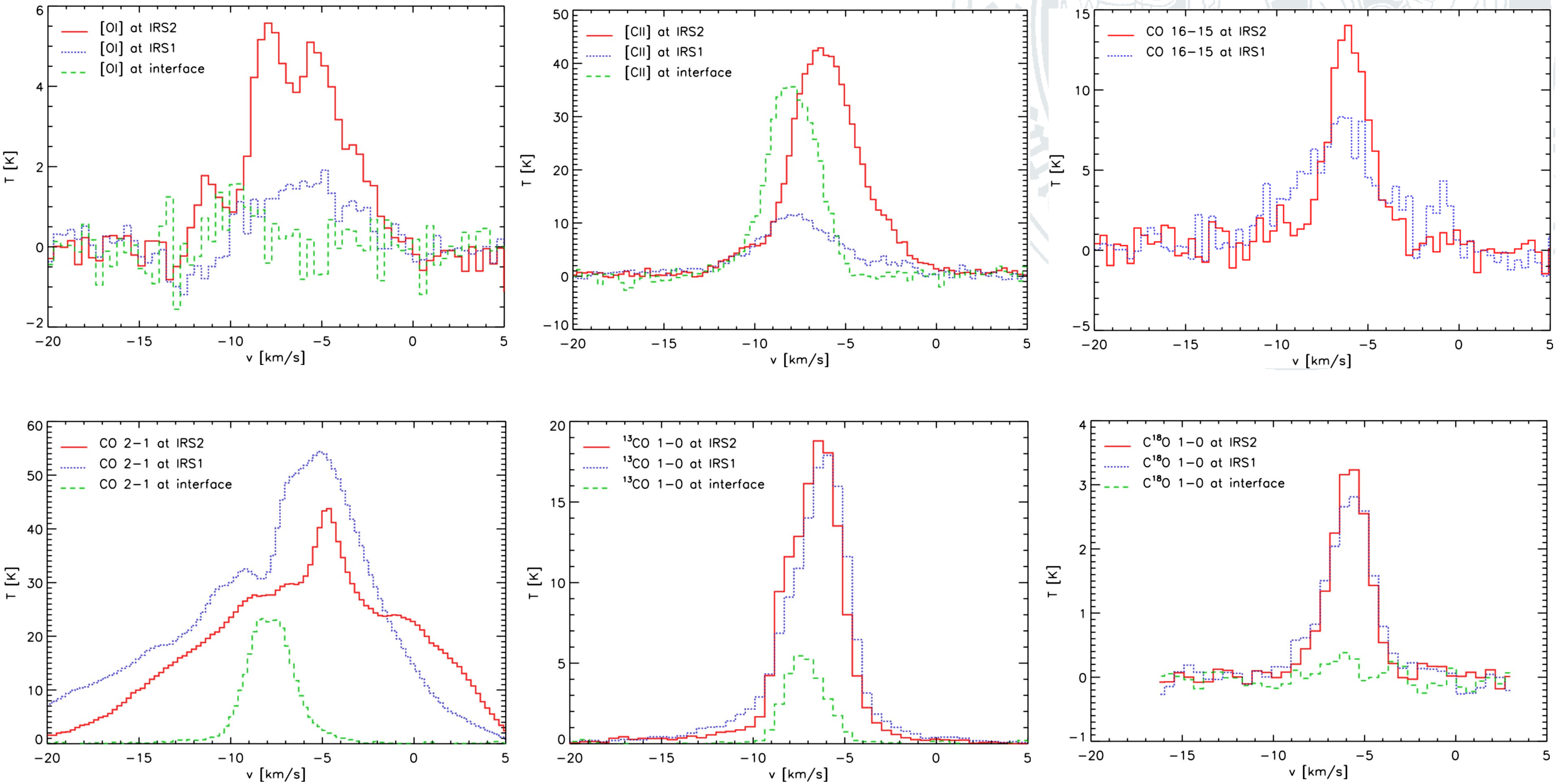


CO 16-15 with contours of [CII] (integrated intensity)

Line profiles

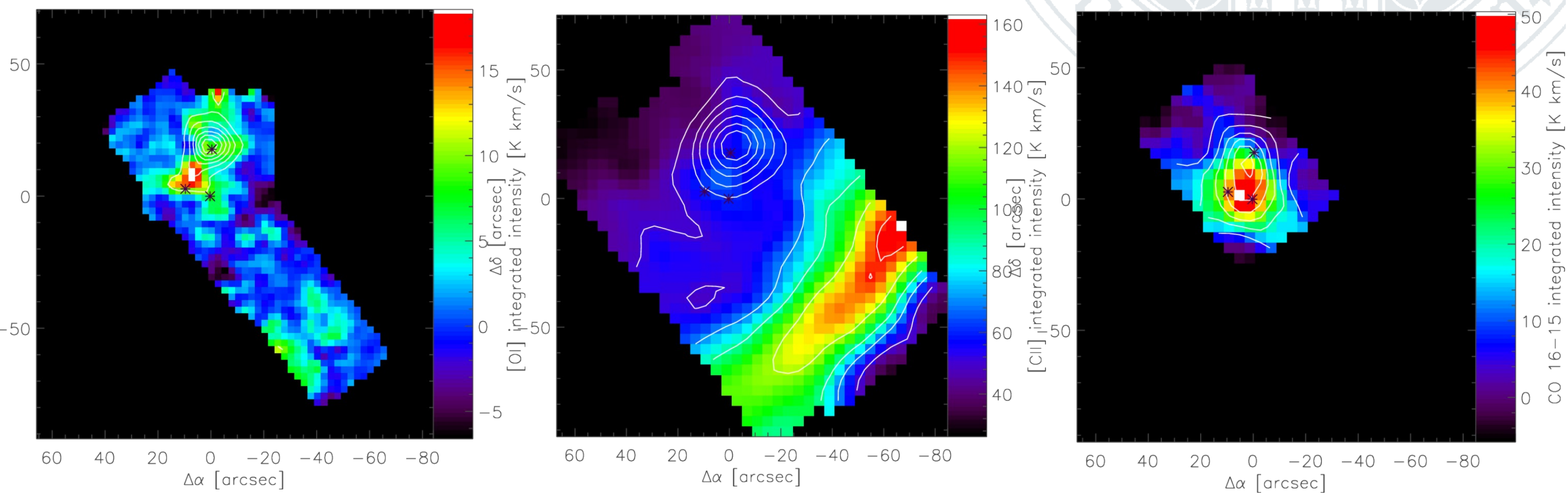
[OI] with clear self-absorption, [CII] also partially optically thick

- Different velocity components towards IRS2 and interface+IRS1



Fit of peak by Gaussian intensity profile

- Resolved in [OI]: FWHM = 8.3" = 0.03pc, M = 2.3 $M_\odot$
  - [OI]: 76 K km/s → 0.28 $L_\odot$
  - [CII]: 212 K km/s → 0.05 $L_\odot$
  - CO 16-15: 46 K km/s → 0.01 $L_\odot$- compare IRS2 luminosity: 2000 $L_\odot$

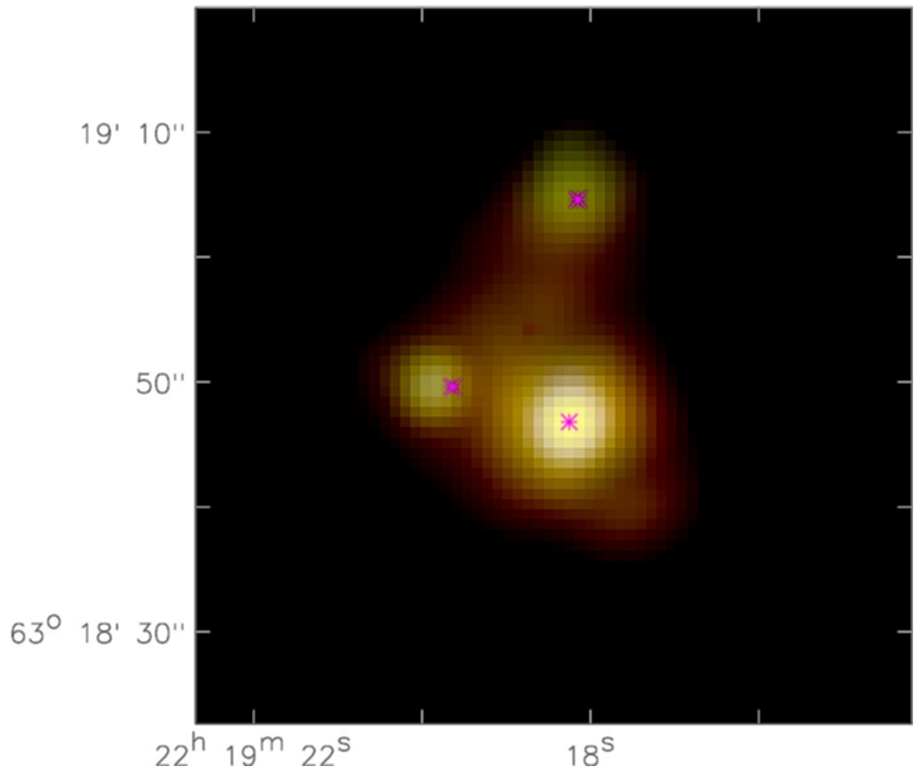


Original maps of [OI], [CII], CO 16-15 (contours) and after source subtraction (colors)

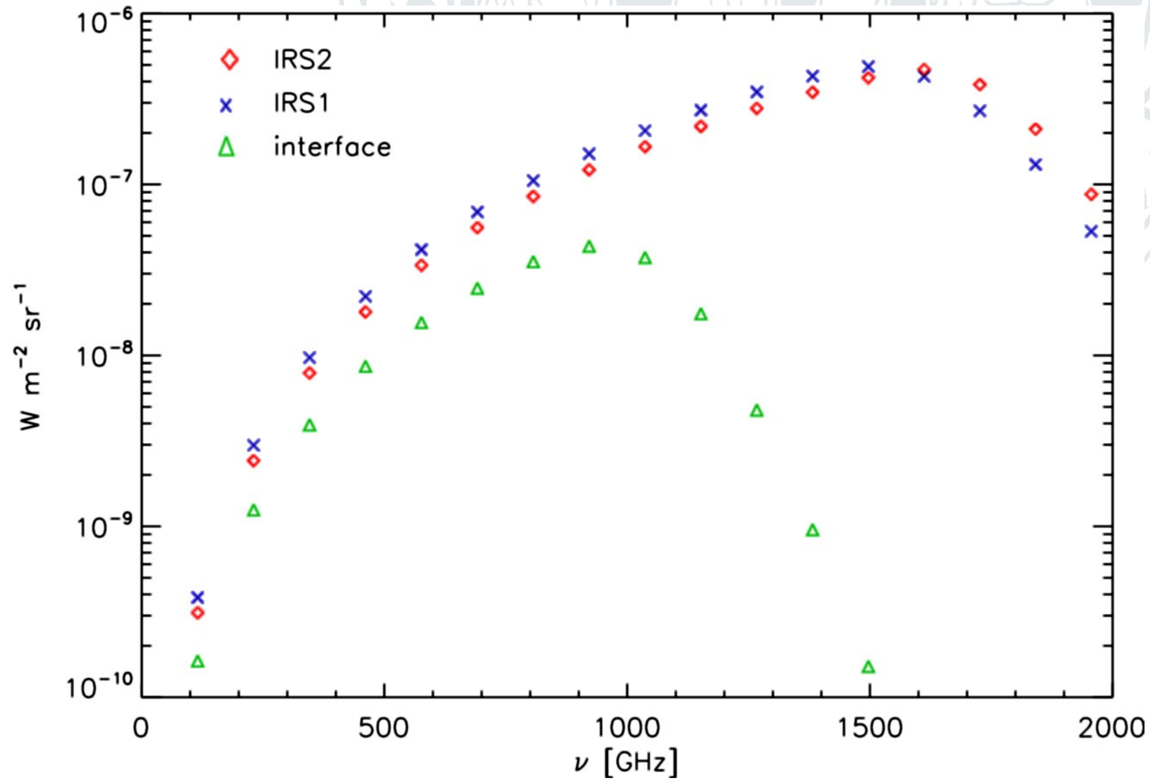
Combination with continuum data

Herschel/PACS, SOFIA/FORCAST, JCMT/SCUBA observations:

- Allow to measure full infrared continuum luminosity
- Access to full energy balance when including CO lines



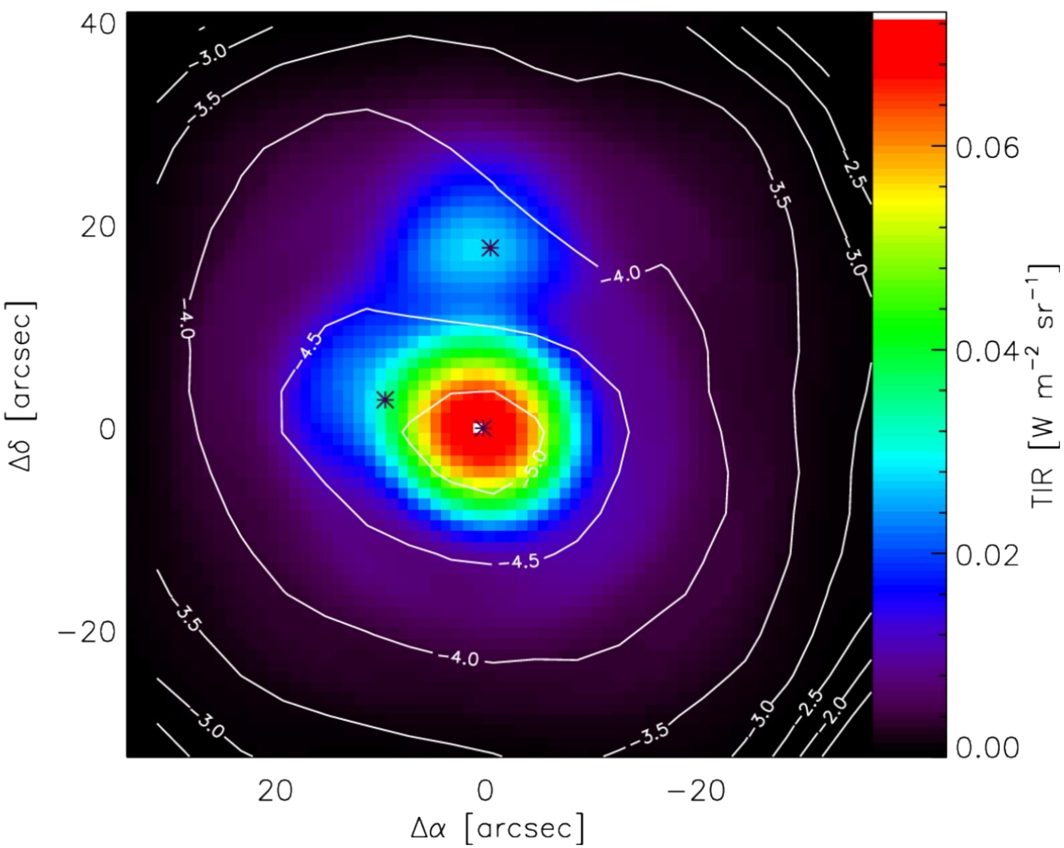
FORCAST map (11, 31, 37µm)

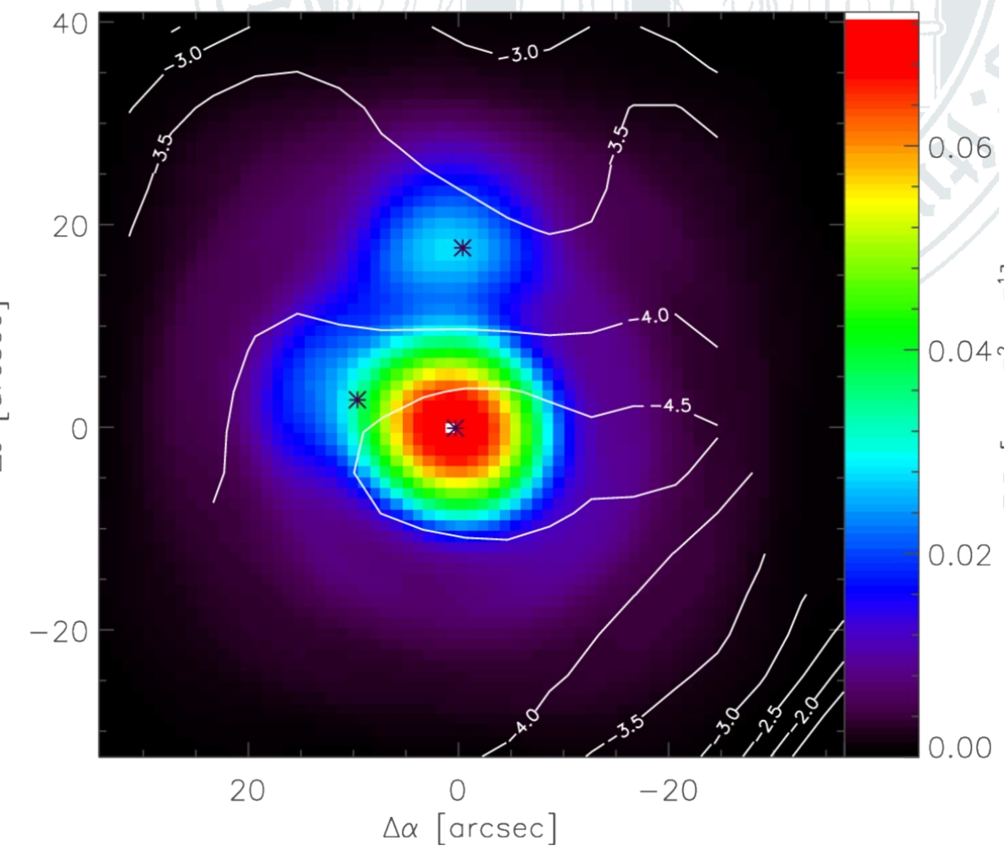


CO line SED from IRAM+HIFI+SOFIA

Ratio between line and continuum cooling

- Should measure gas heating efficiency (typical values: 10^{-3} - 10^{-2})
- IRS1/2/3: **factor 100 lower** than in most Galactic sources
- Matches **line deficit** in ULIRGS





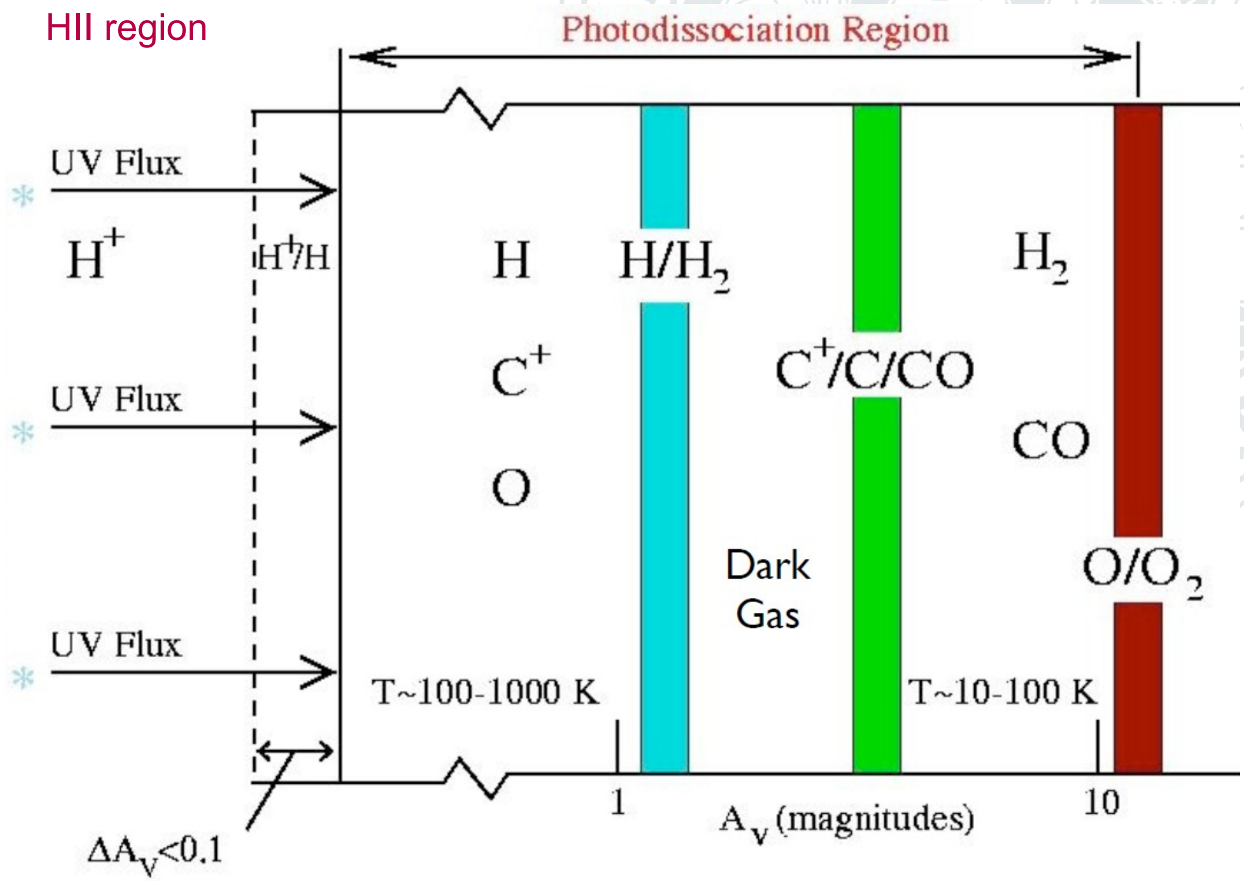
Colours: TIR Contours: $\log_{10}$([CII]/TIR) Contours: $\log_{10}$(([OI]+[CII])/TIR)

Modelling challenge

- IRS1:
  - Main energy source of the region: $L = 10000\ L_\odot$
  - produces almost no [CII] and [OI]
- IRS2:
  - $L = 2000\ L_\odot$
  - Prominent [CII] and [OI] peak, spatially well confined and resolved
  - Velocity offset from main cloud (-6.5km/s instead of -8 km/s)
- Interface:
  - Prominent in [CII]
  - Low [OI], probably due to low density
- Whole cluster:
  - Extremely low line to continuum ratio: **line deficit**

Interpretation in terms of classical PDR model

- C^+ and atomic oxygen produced in UV-illuminated clouds

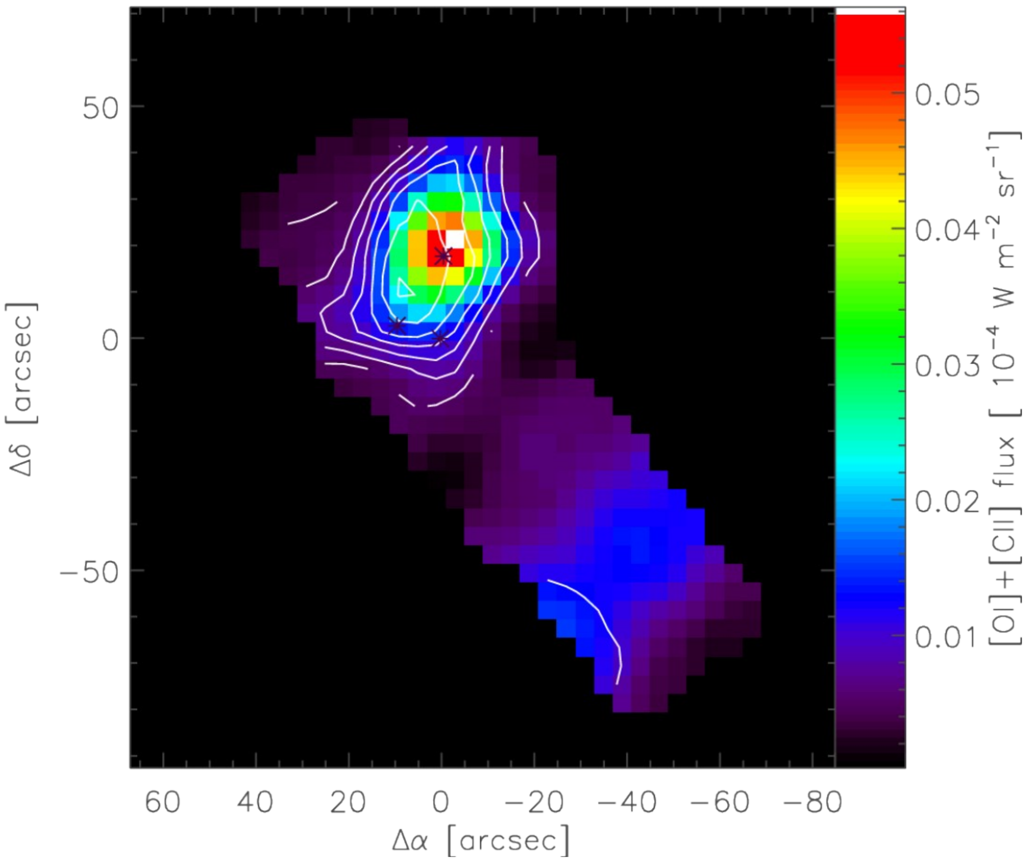


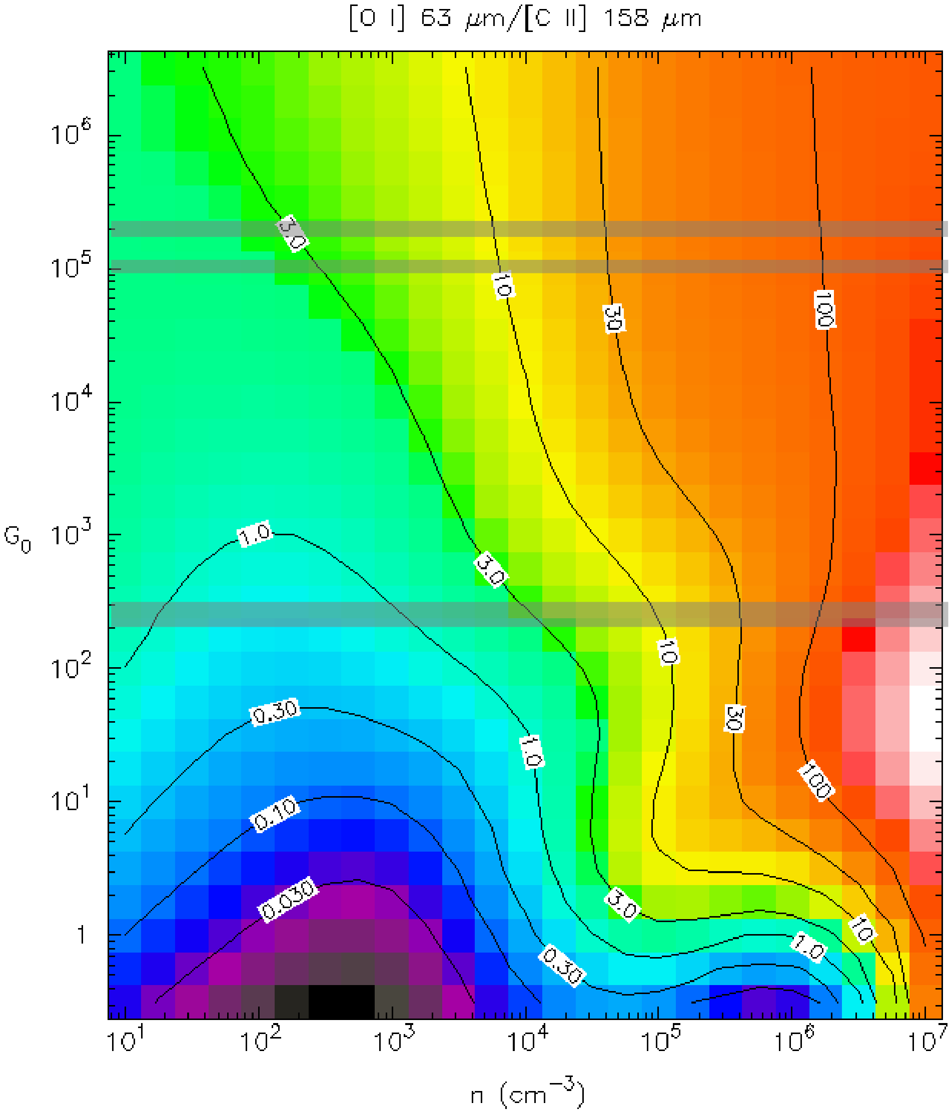
Based on
Hollenbach & Tielens (1999)

- Known radiation fields: **External interface** – G_0= 240
  IRS1 – G_0= 2×10^5
  IRS2 – G_0= 10^5

Comparison with plane-parallel PDR model (Kaufman 1999)

- [OI]/[CII] ratio:
  - 3.0 at IRS1, 2.7 at IRS2
  - 0.3 at interface

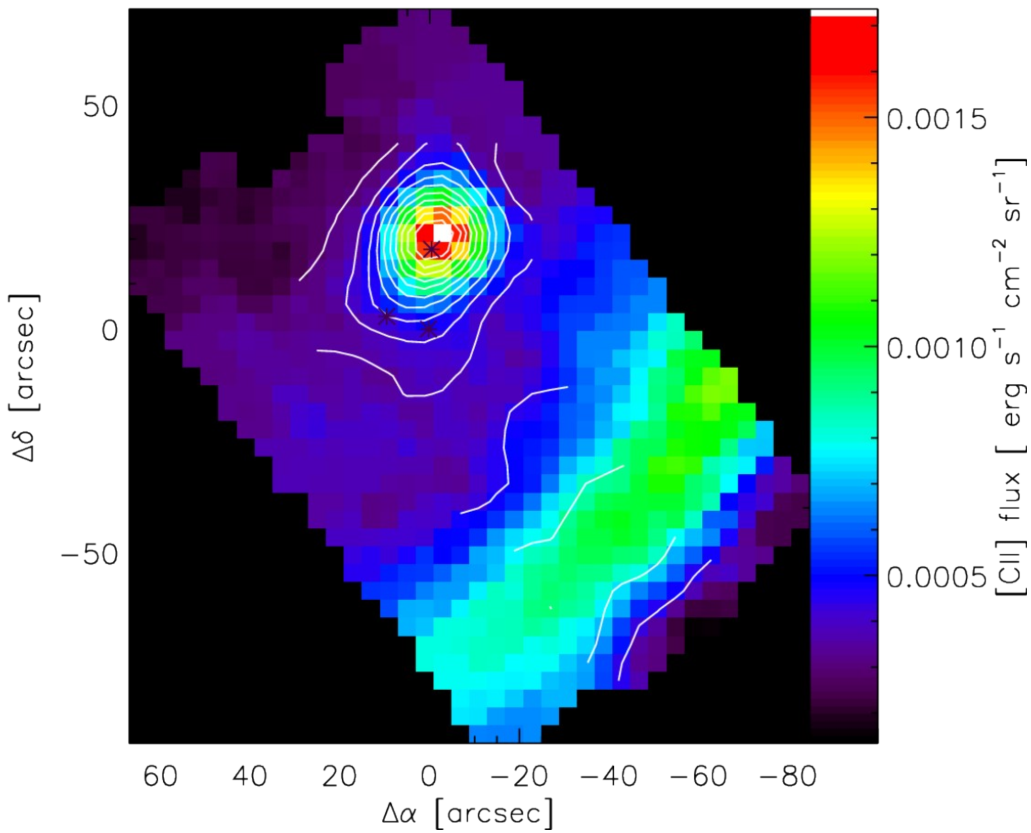


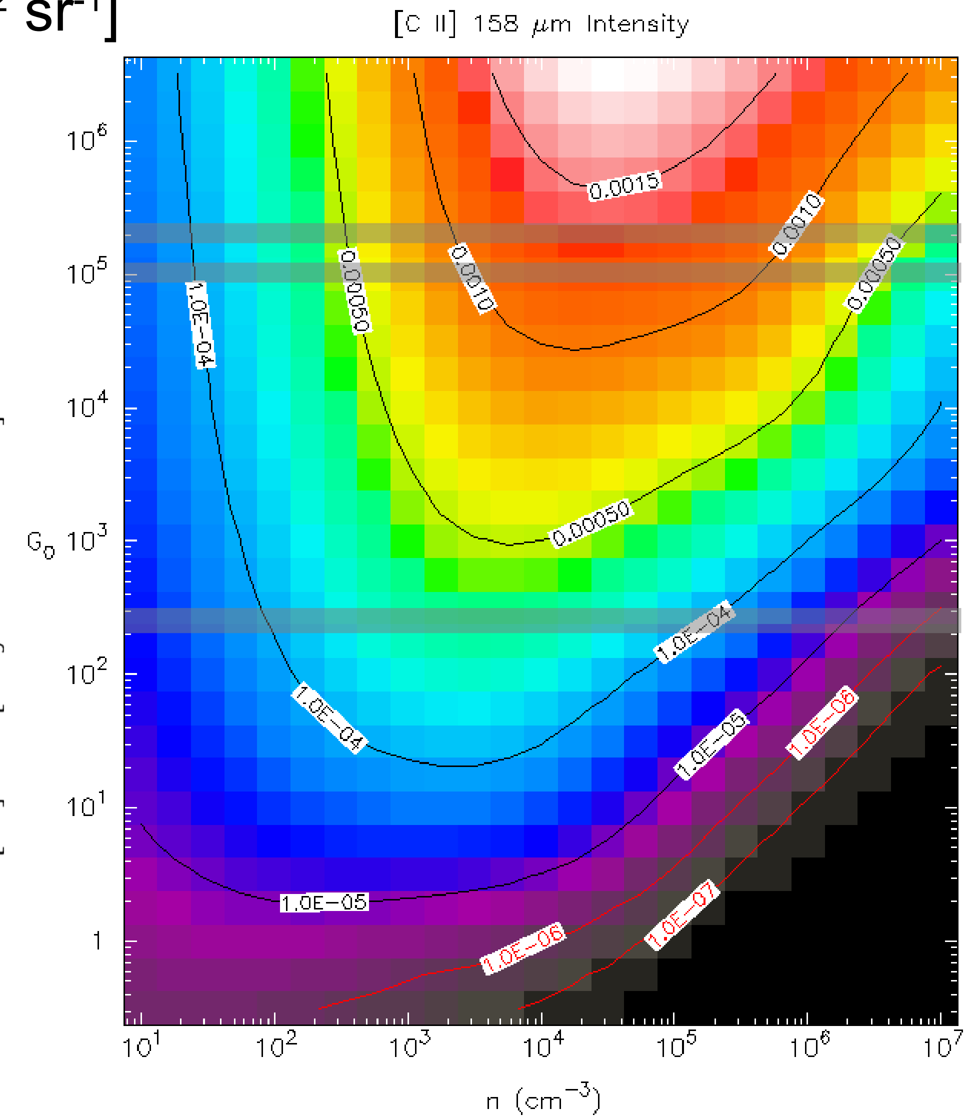


Cooling line strength (colors) [OI]/[CII] ratio (contours from 0.4...2.8)

Comparison with plane-parallel PDR model (Kaufman 1999)

- [CII] integrated intensity [erg s^{-1} cm^{-2} sr^{-1}]
  - 0.0005 at IRS1, 0.0017 at IRS2
  - 0.0011 at interface

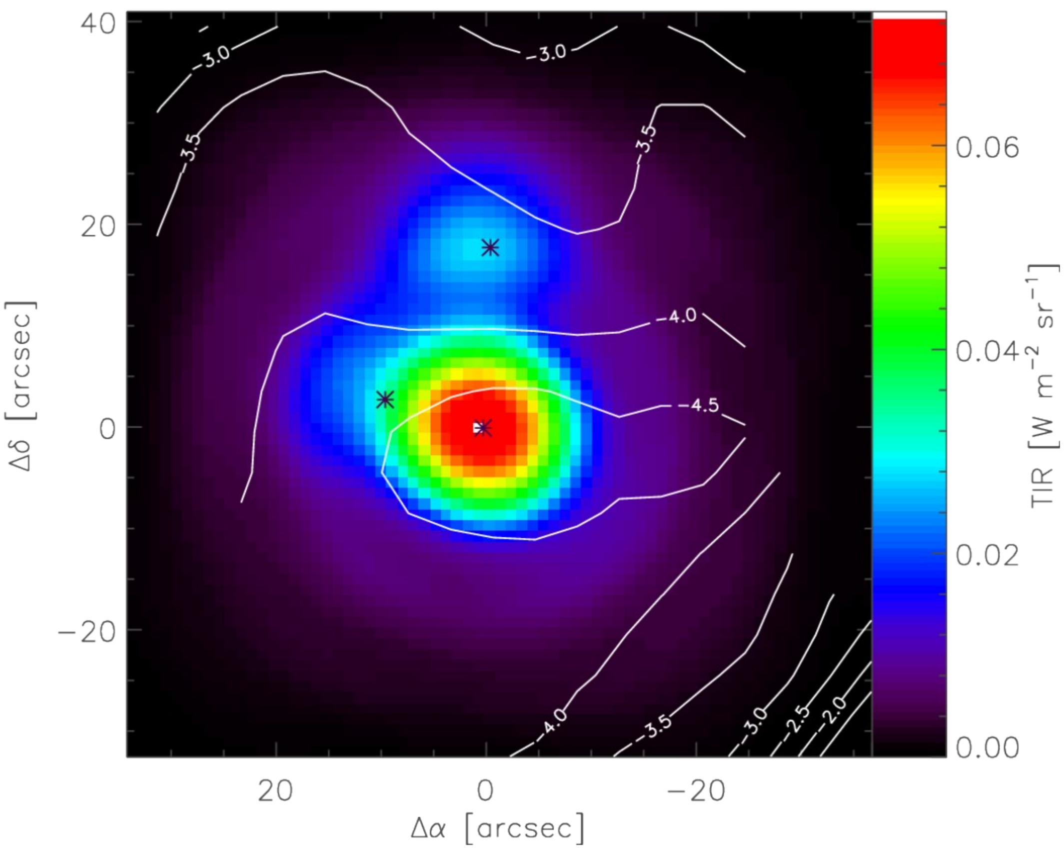


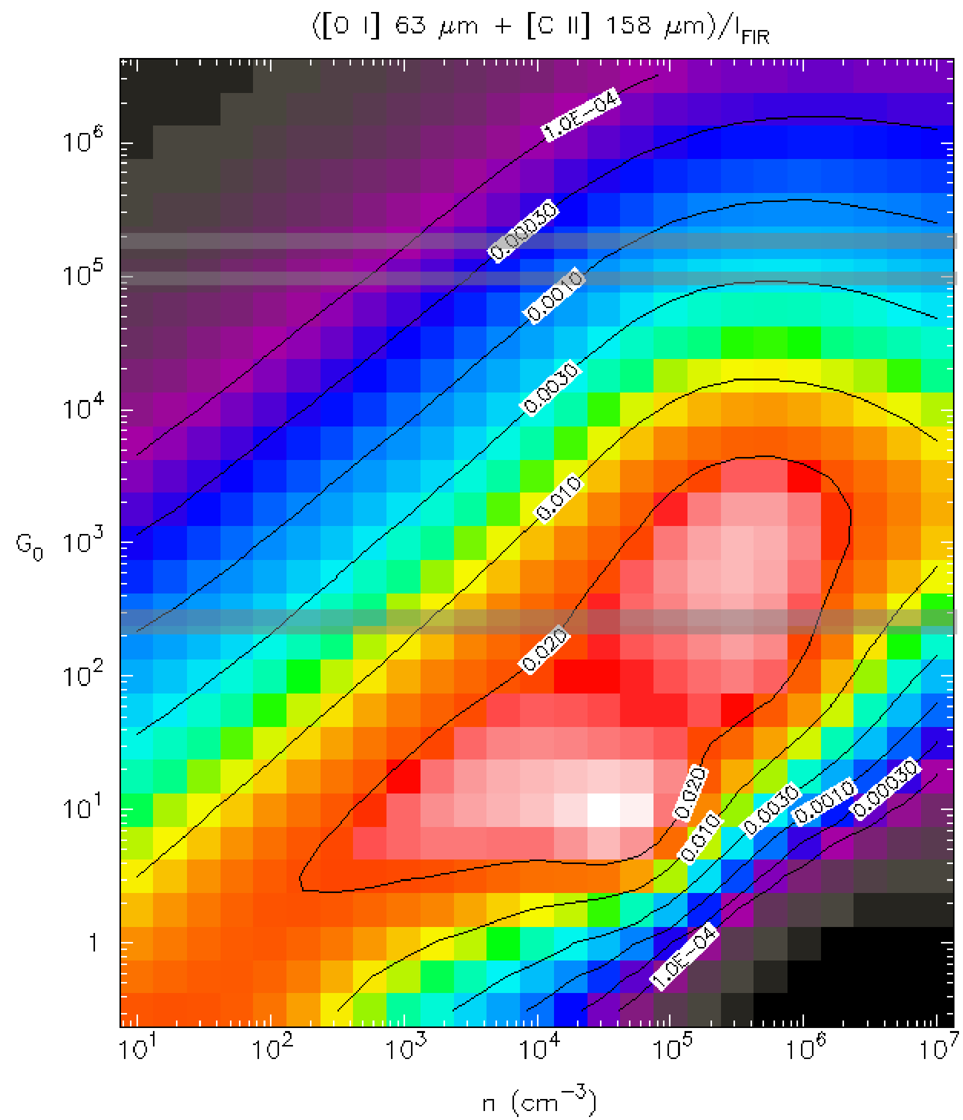


[CII] intensity (colors) and [OI]+[CII] intensity (contours from 0.0005...0.005)

Comparison with plane-parallel PDR model (Kaufman 1999)

- ([CII]+[OI])/FIR
  - $2\ 10^{-5}$ at IRS1, $2\ 10^{-4}$ at IRS2
  - > 0.02 at interface





FIR (colors) and $\log_{10}$(([OI]+[CII])/TIR) (contours)

PDR-model interpretation

- Interface:
  - Inclination by 83° needed to explain strong [CII] emission
  - Consistent with external PDR
    - But requires [OI] density gradient

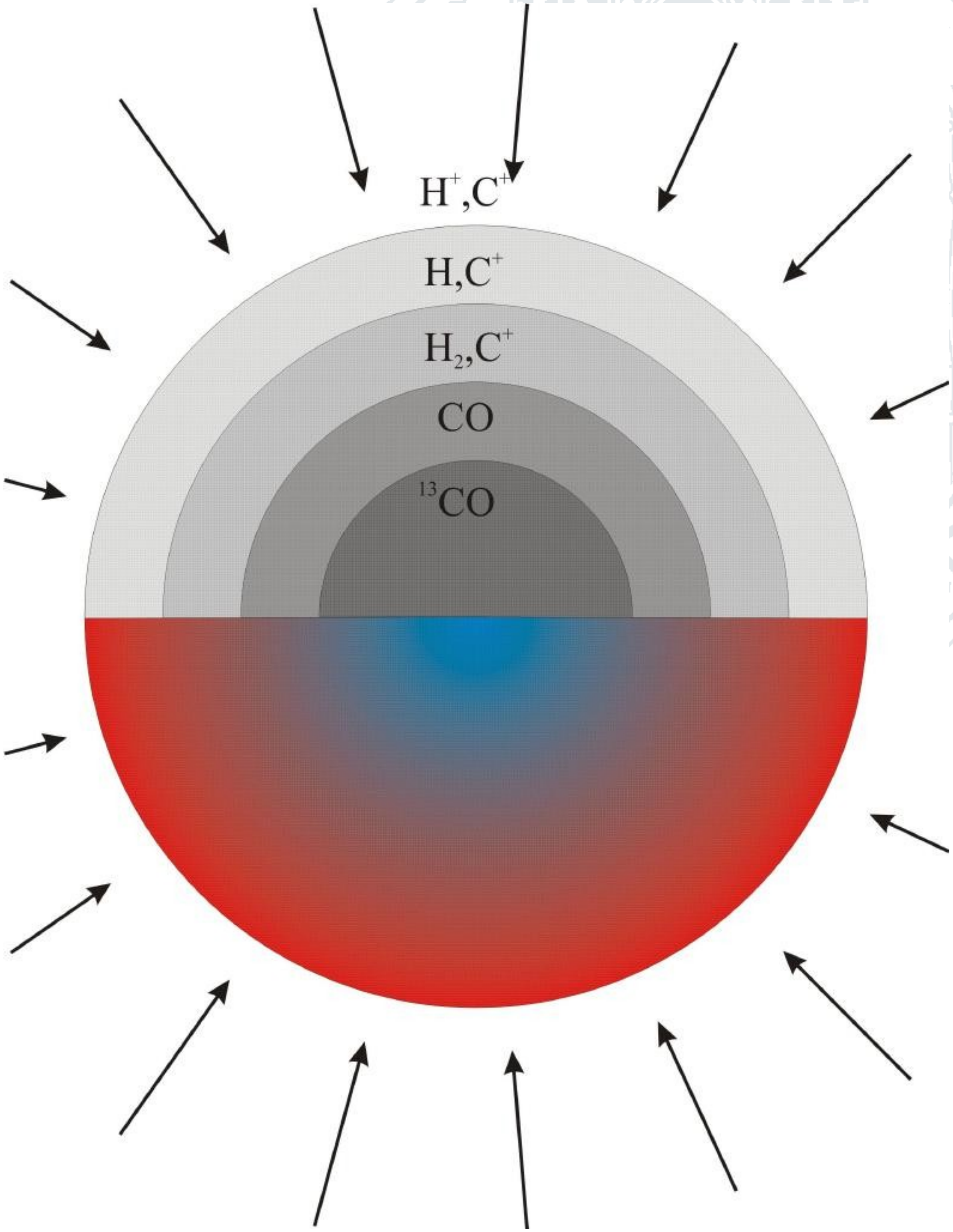
- IRS1:
  - FS lines suggest density of 300 cm^{-3}, dust emission requires 10^6 cm^{-3}

- IRS2:
  - [CII] intensity requires 10^5 cm^{-3}, dust 10^6 cm^{-3}, [OI] 300 cm^{-3}

Explanation: Embedded PDRs not plane-parallel and extended!

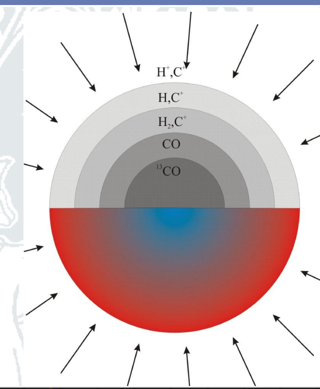
IRS2 PDR shows spherical structure Ø = 6.6''

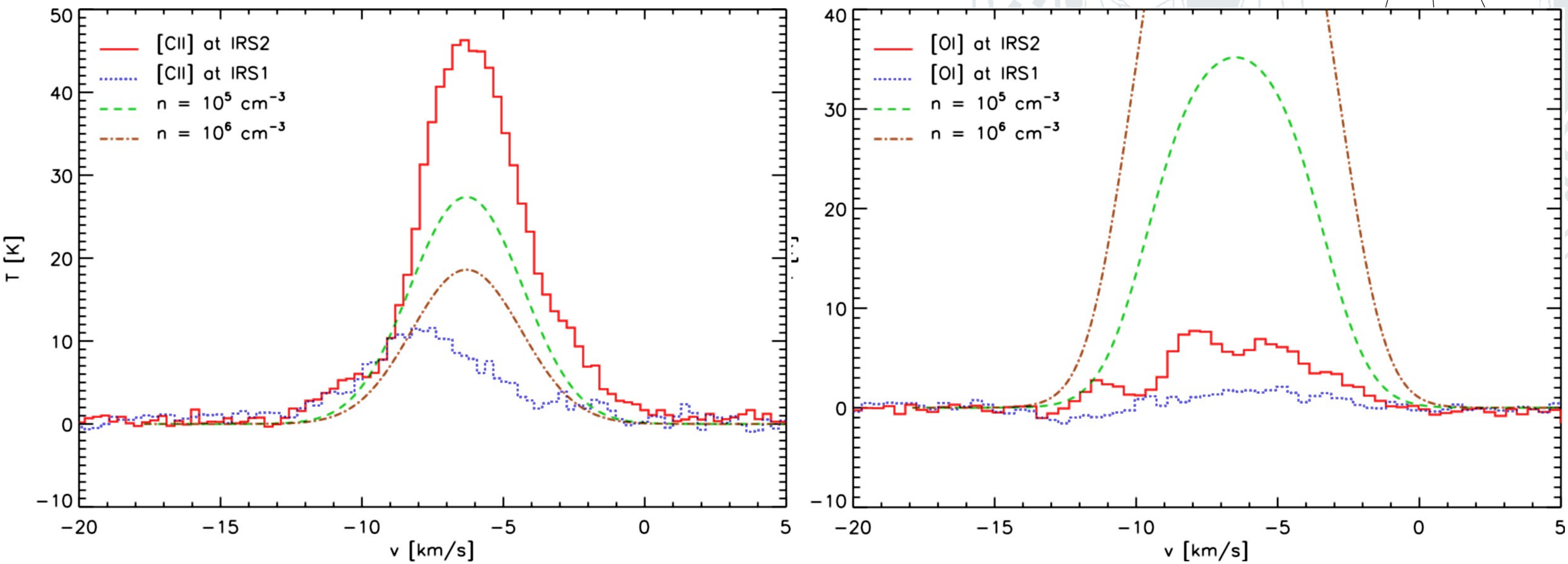
- Compare with spherical PDR model
  - KOSMA-τ:
    - Finite source size - spherical geometry
    - Chemical layering
    - Temperature gradient from energy balance
  - $G_0 = 1.7 \times 10^5$
  - Density constrained by dust continuum: 10^5 cm^{-3} - 10^6 cm^{-3}



Radiative transfer results

- Two limiting KOSMA-τ models: 10^6 cm^{-3} and 10^5 cm^{-3}
- Continuum ignored



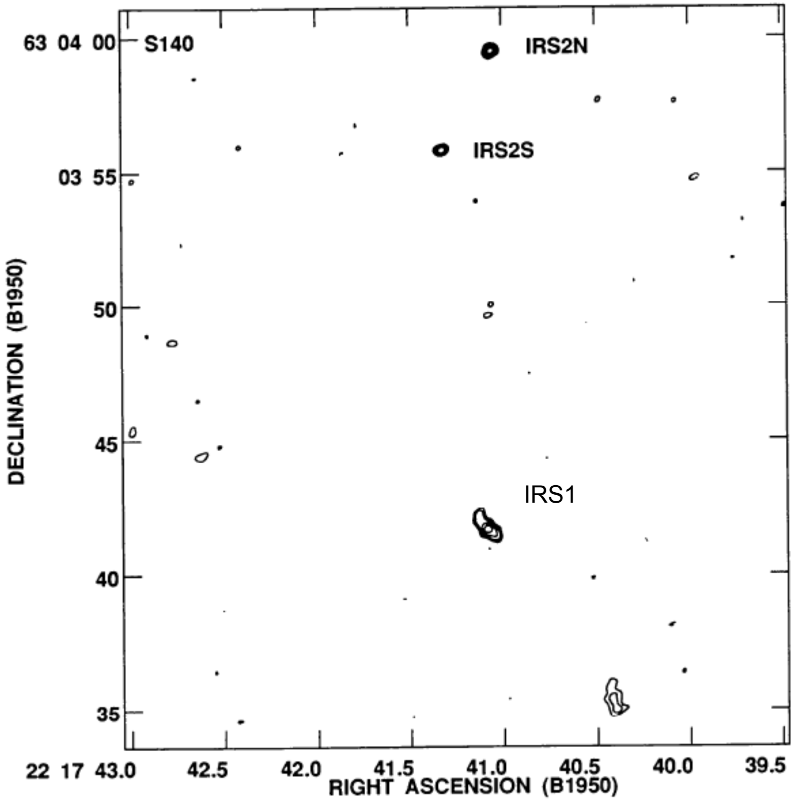


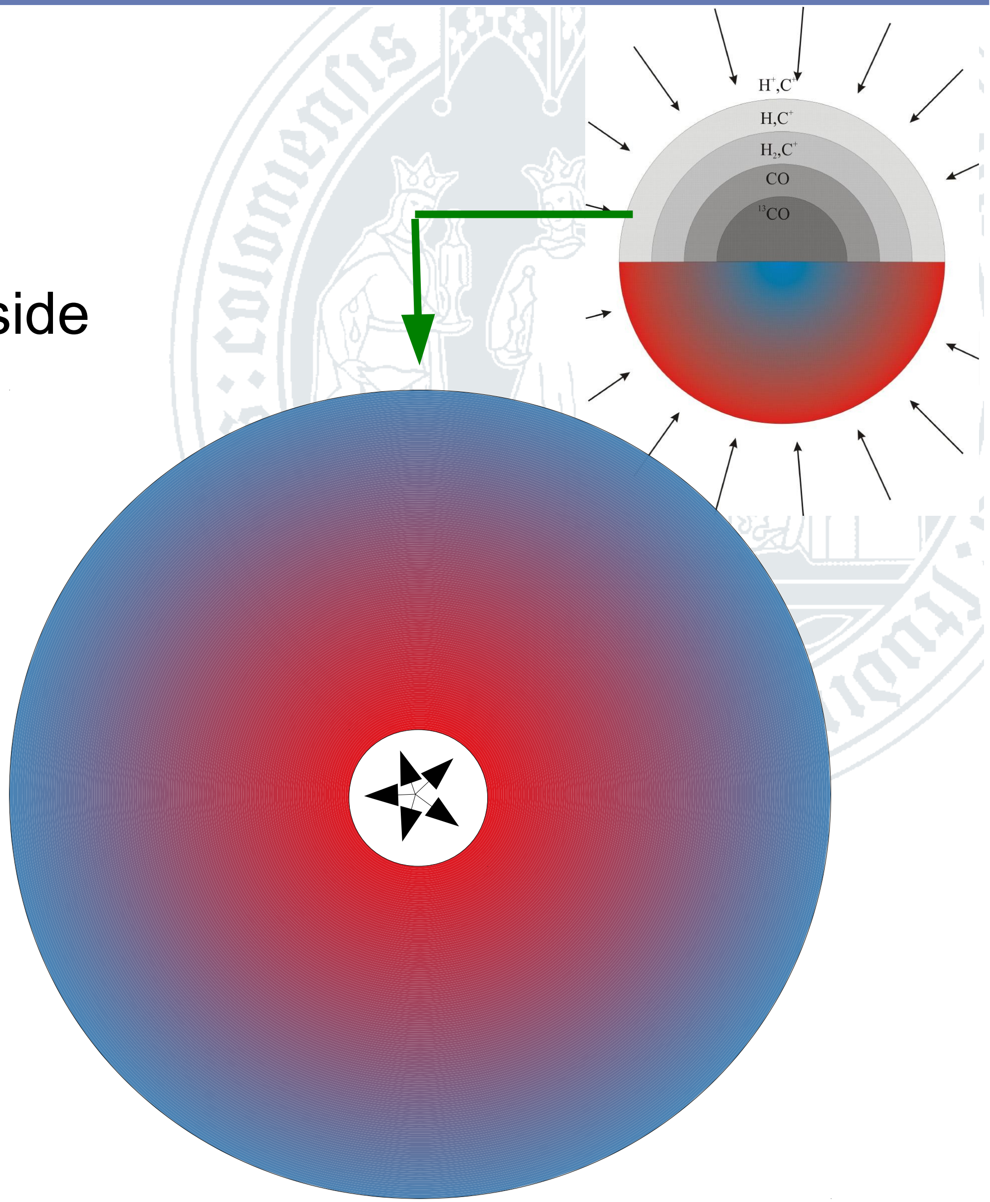
- [CII] stronger than in IRS1, but weaker than in IRS2
  - Main effect: beam filling
- [OI] much stronger than observed

Source geometry

UV field is internal!

- Inverse layering
  - Hot C^+ and oxygen inside, cold outside

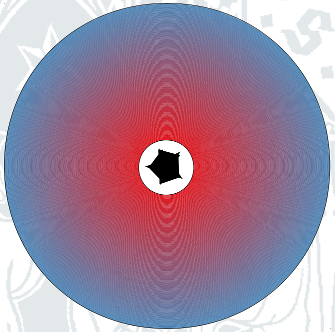




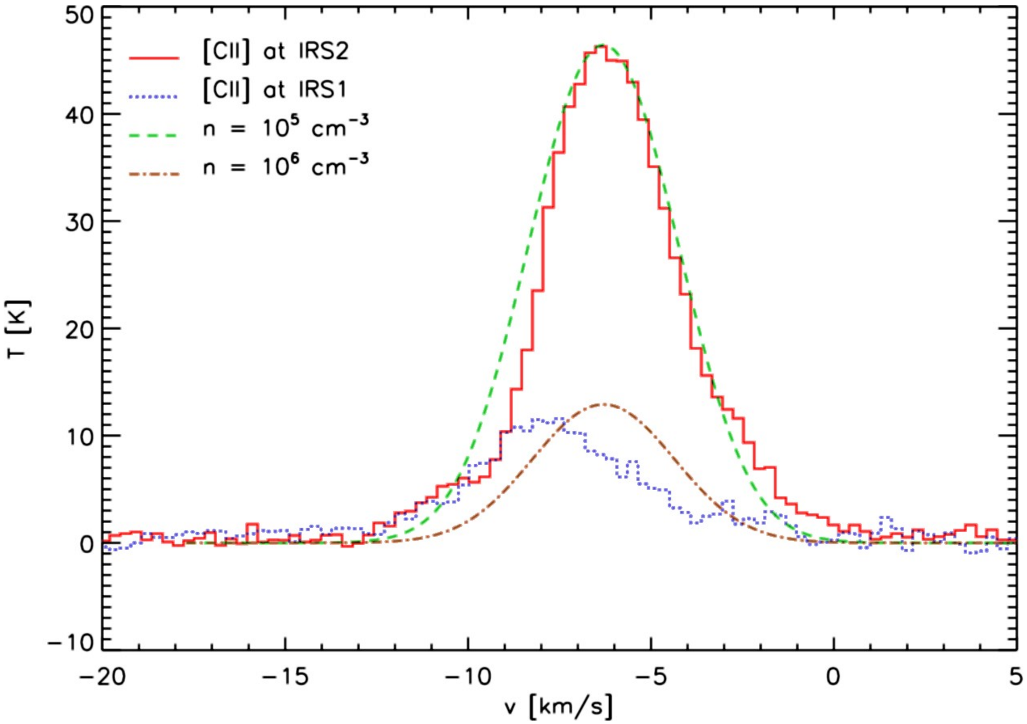
Embedded HII regions from radio continuum: Tofani et al. (1995), Hoare (2006): D ≤ 0.5''

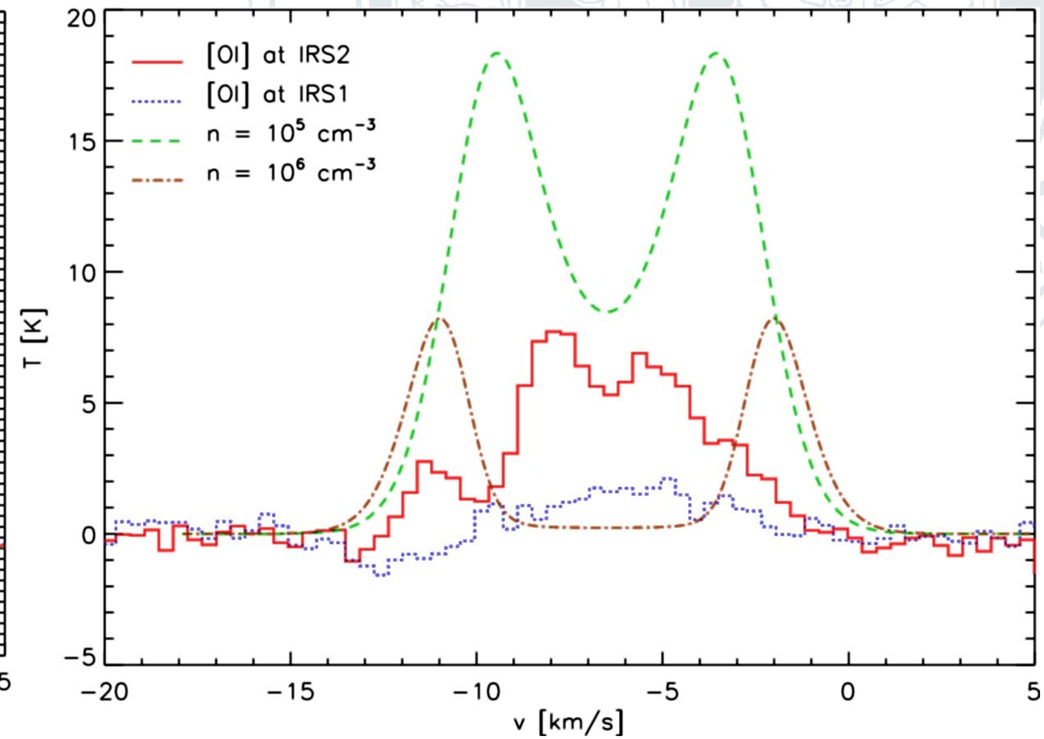
Toy model for internally irradiated PDR: KOSMA-τ with inverse layering

Radiative transfer results



- KOSMA-τ toy model with inverse chemical and temperature layering

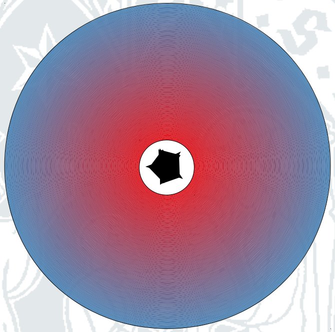


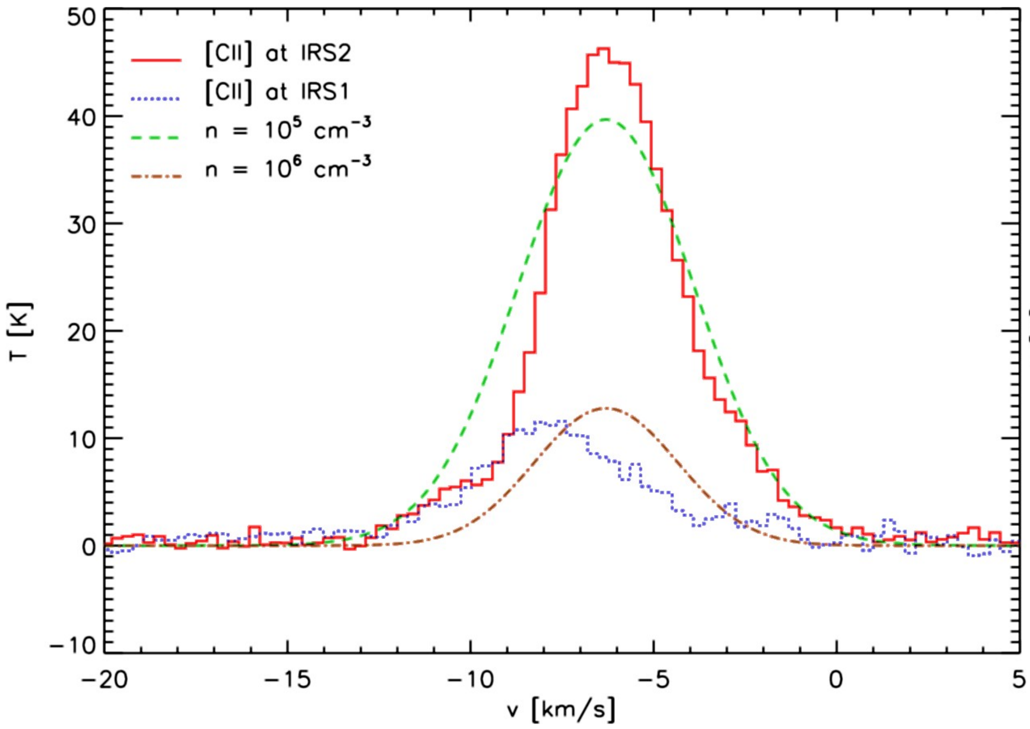


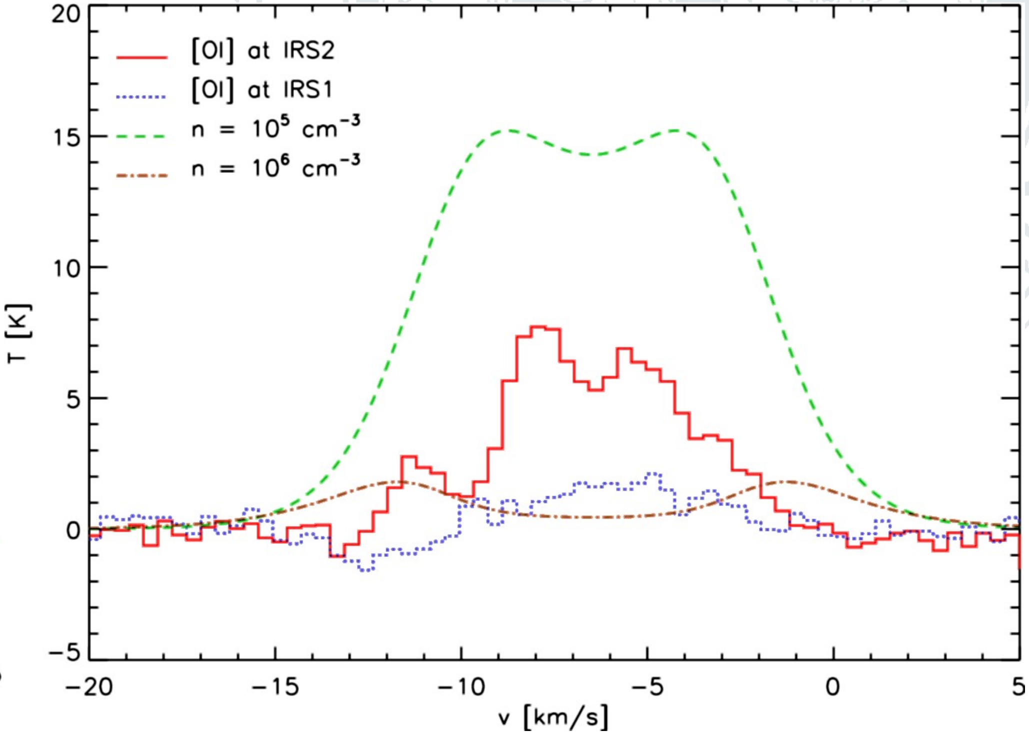
- [CII] perfect match if IRS1 has 10^6 cm^{-3}, IRS2 10^5 cm^{-3}
- Heavy self-absorption in [OI] reduces intensity
  - Profiles not matching yet

With Larson-type velocity dispersion:

- $\sigma_{vel} \sim r^{-0.4}$







- Increasing velocity dispersion avoids sharp self-absorption feature
- [OI] intensity reduced to observed values
- More fine-tuning needed

Comparison to toy model

- Line deficit can be explained by high density and small PDR size
  - No significant UV leakage

- IRS1:
  - Very low line to continuum ratio: **extreme line deficit**
  - Requires denser and smaller PDR than inferred from the dust
    - $R < 0.005$pc, $n > 10^6$ cm^{-3}

- IRS2:
  - Source geometry constrained from resolved spatial structure
    - $R=0.015$pc, $n > 10^5$ cm^{-3}
    - Consistent with observed source properties

- No full match of observed line intensities and profiles yet
  - Parameter fit needed for good match of lines

Conclusion

- S140 modelling → Two-conditions for line deficit:
  - 1) [CII]: PDRs in small dense cores for a low beam filling
    - Size of HII region: $R_s = 0.68\ \mathrm{pc} \left(\frac{Q}{10^{49}\ \mathrm{s}^{-1}}\right)^{1/3} \left(\frac{T_*}{10^4\ \mathrm{K}}\right)^{0.28} \left(\frac{n}{10^3\ \mathrm{cm}^{-3}}\right)^{-2/3}$

      Draine (2011)

      - Consistent with observations (IRS1: ≈ 0.001pc, IRS2: < 0.0005pc)
    - Size of total PDR: $R_S + A_V \approx 2$ layer: $A_{\mathrm{fs}} = \pi \left(R_s + \frac{3.8 \times 10^{21}\,\mathrm{cm}^{-2}}{n}\right)^2$
      - PDR sizes: IRS1: 0.005~pc, IRS2: 0.002~pc
    - Open question: Resolved size of IRS2 somewhat larger
      - Due to multiple sources/PDRs?
  - 2) [OI]: Radial gradient in excitation temperature
    - Zero integrated intensity easily obtained from foreground absorption trunk matching wing emission → Velocity information is crucial!
    - Zero intensity in velocity resolved line needs radially increasing line width

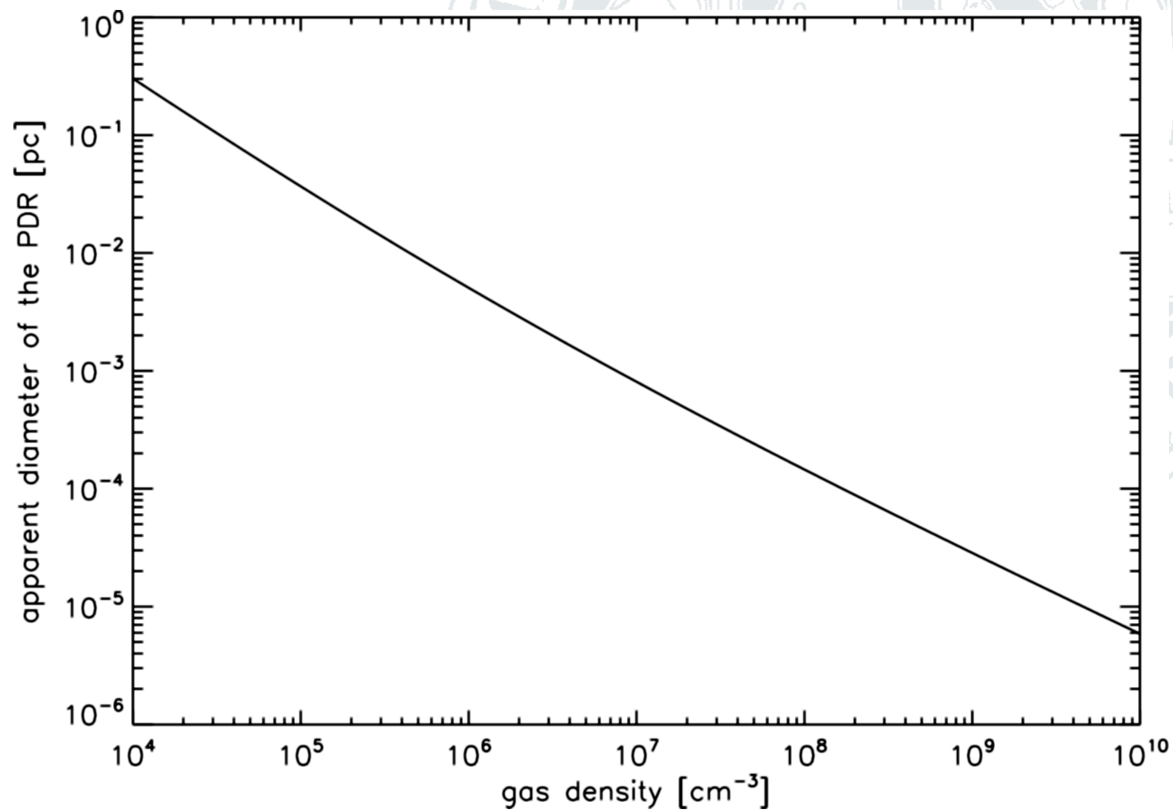
Comparison to toy model

- S140 is an “ultraluminous source” in Galactic context

  → S140 may provide general explanation for line deficit in ULIRGS

- Line deficit explained by high density, small PDR

Size of a PDR fed by a star with $10^{46.5}$ UV photons per second as a function of gas density

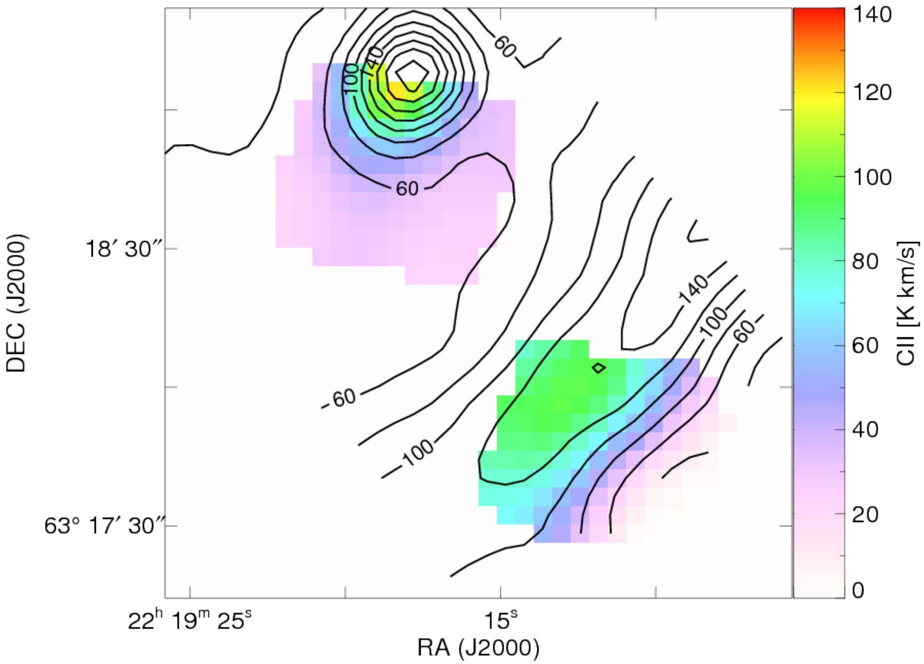


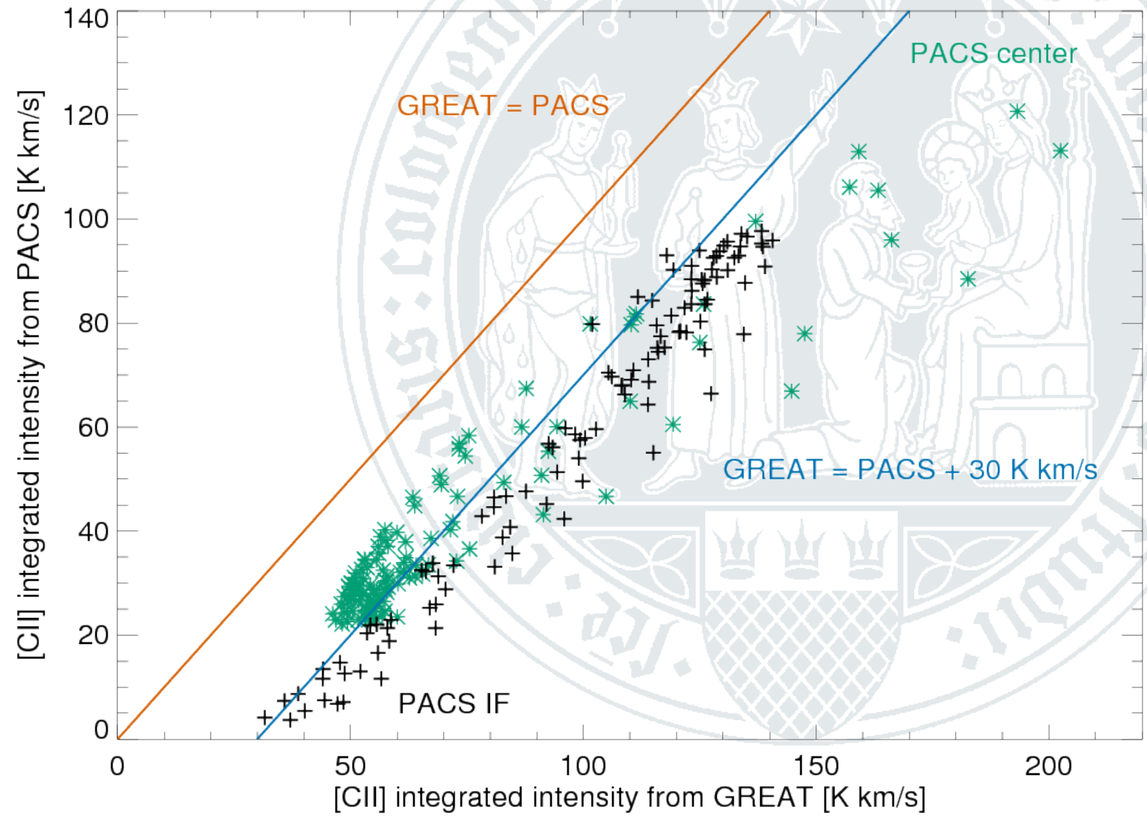
- Main gas cooling in these regions NOT though fine structure lines but
  - Direct recombination
  - Gas-dust collisions with dust continuum emission

Thank you for your attention.

Cross comparison with Herschel

[CII]



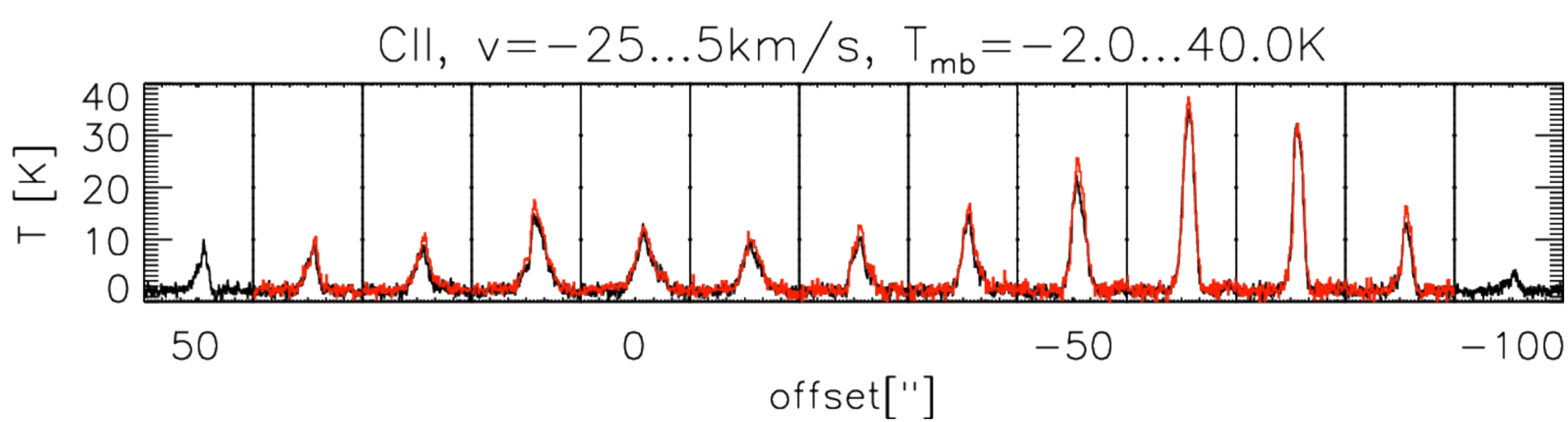


PACS

- OFF contamination

HIFI:

- Agreement better than 15%



Cross comparison with Herschel

[OI]

PACS

- Spatial structure fits
- GREAT intensities tend to be too low