Modeling the fine-structure lines in S140

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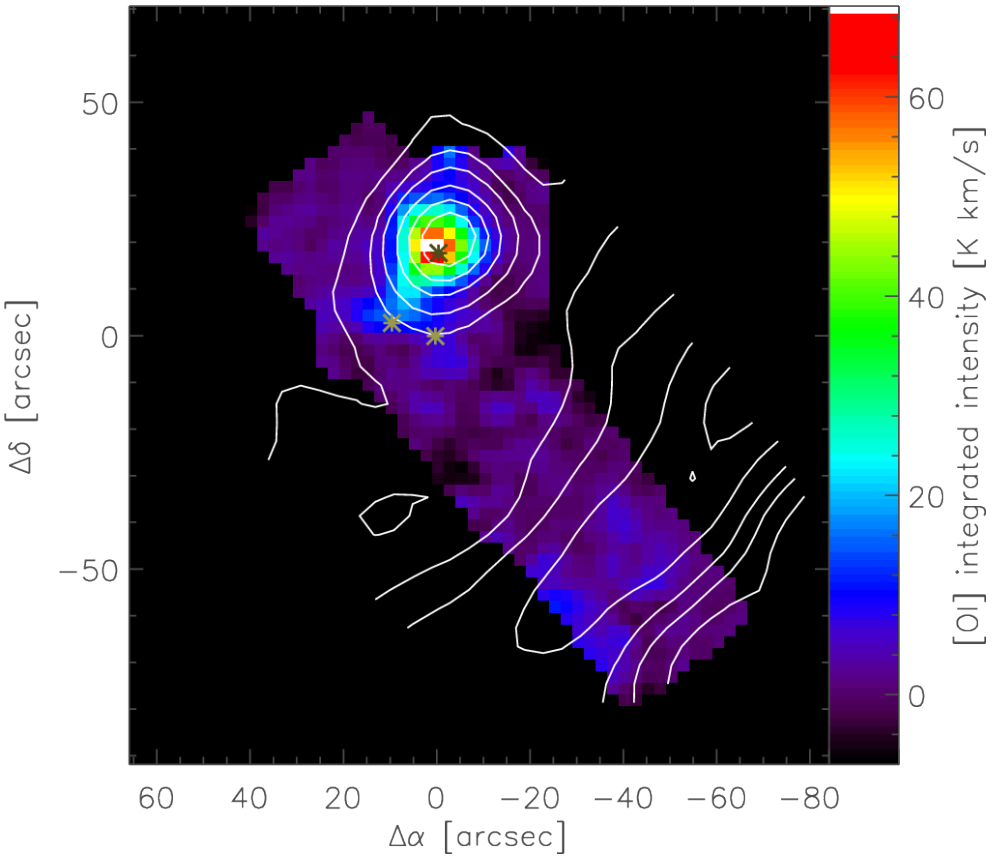
Overview

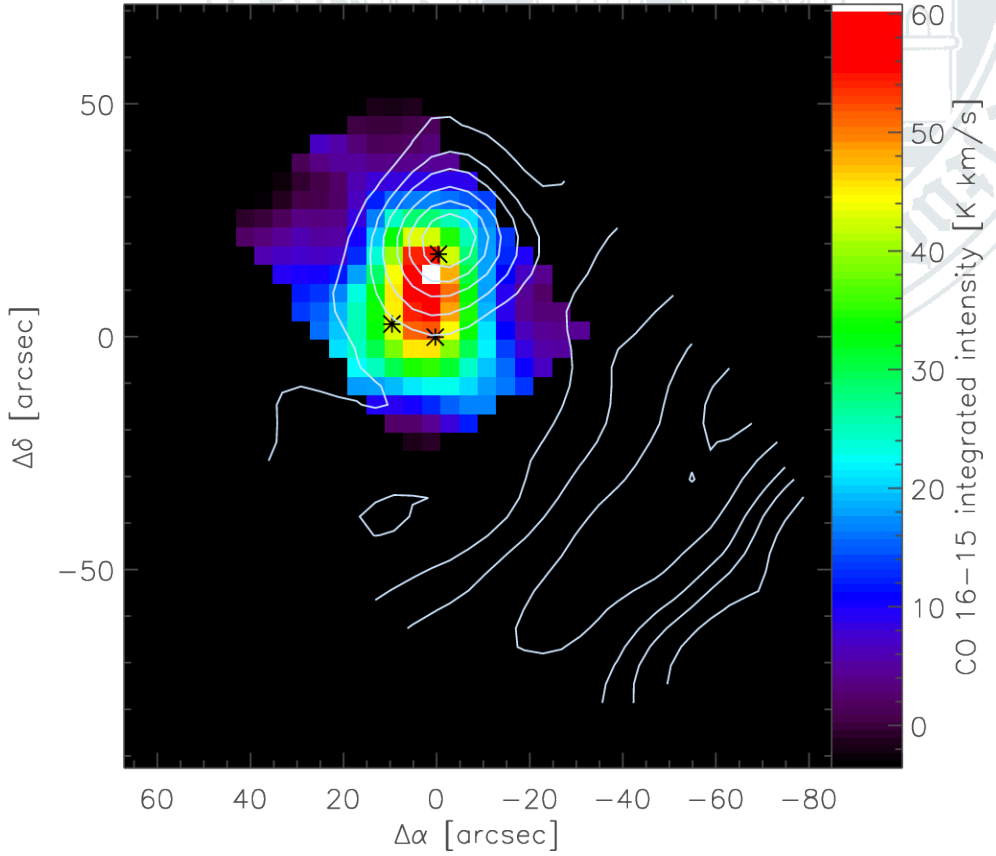
- Starting point:
  - SOFIA observations
  - Continuum and the cooling budget
    - The fine-structure line deficit
- PDR modeling
  - Standard plane-parallel models
  - Spherical models and beam filling
  - Centrally heated models
- Conclusion: S140 = template for ULIRG with line-deficit

GREAT observations

- [OI] (63μm) and [CII] do **NOT** peak at the main source (IRS1) but 20" north, close to IRS2
- Low-*J* CO peaks around at IRS1, CO 16-15 between IRS1 and IRS2



Colors: [OI] (line integrated)

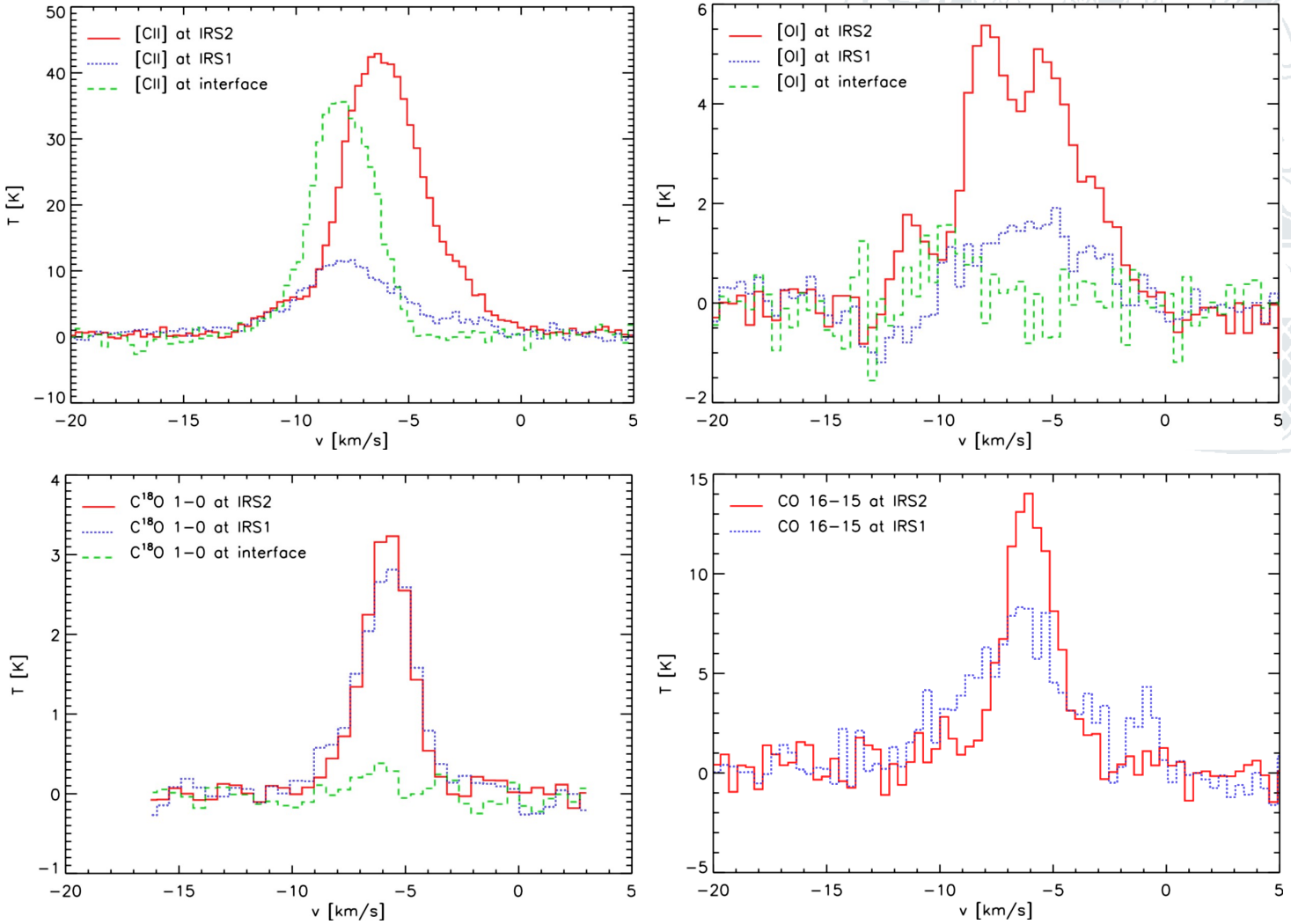


CO 16-15 Contours: [CII]

Line profiles

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

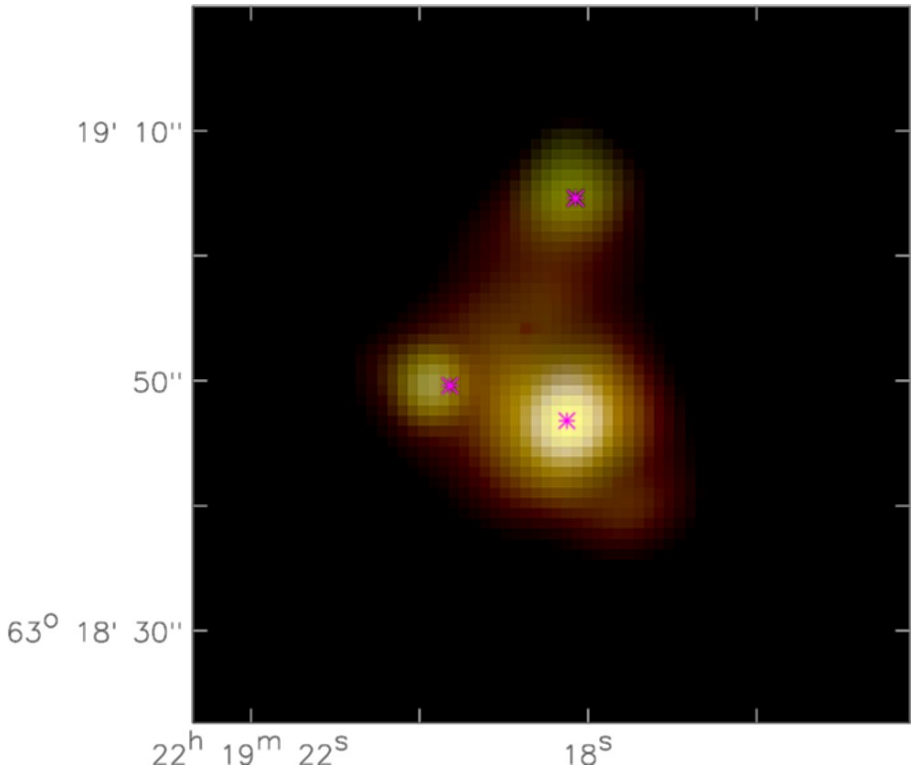
- Different velocity at IRS2 compared to main cloud/IRS1



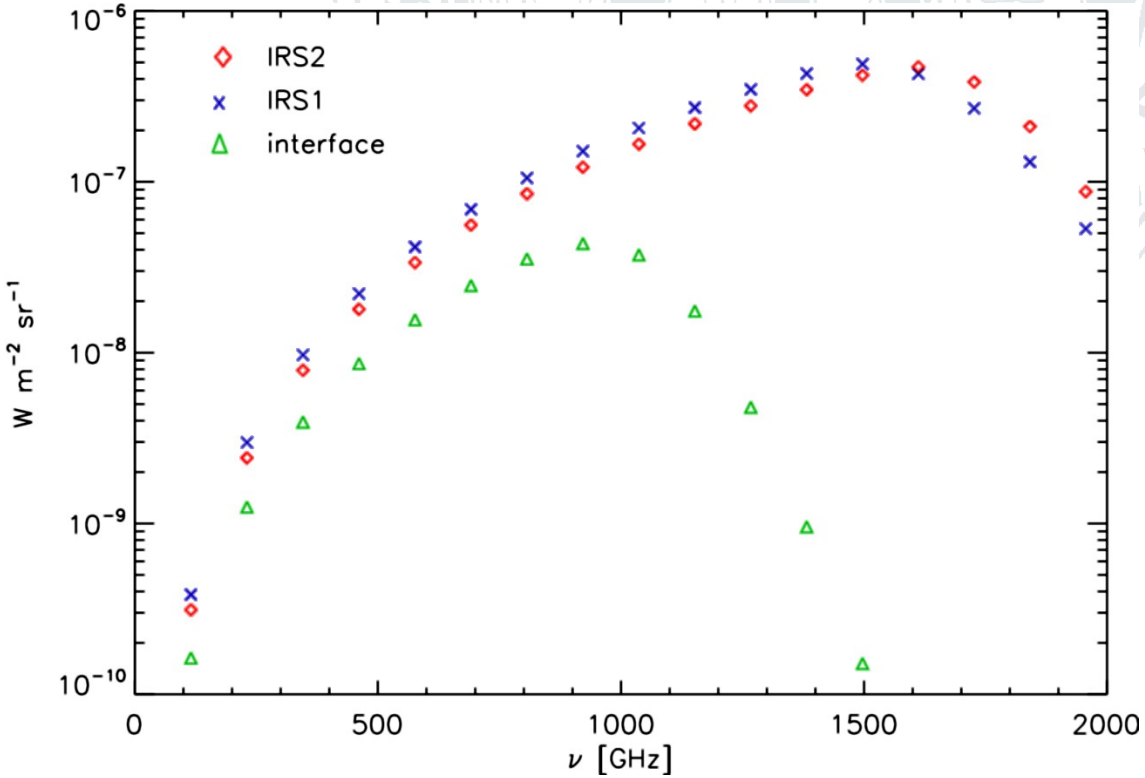
Combination with complementary data

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)

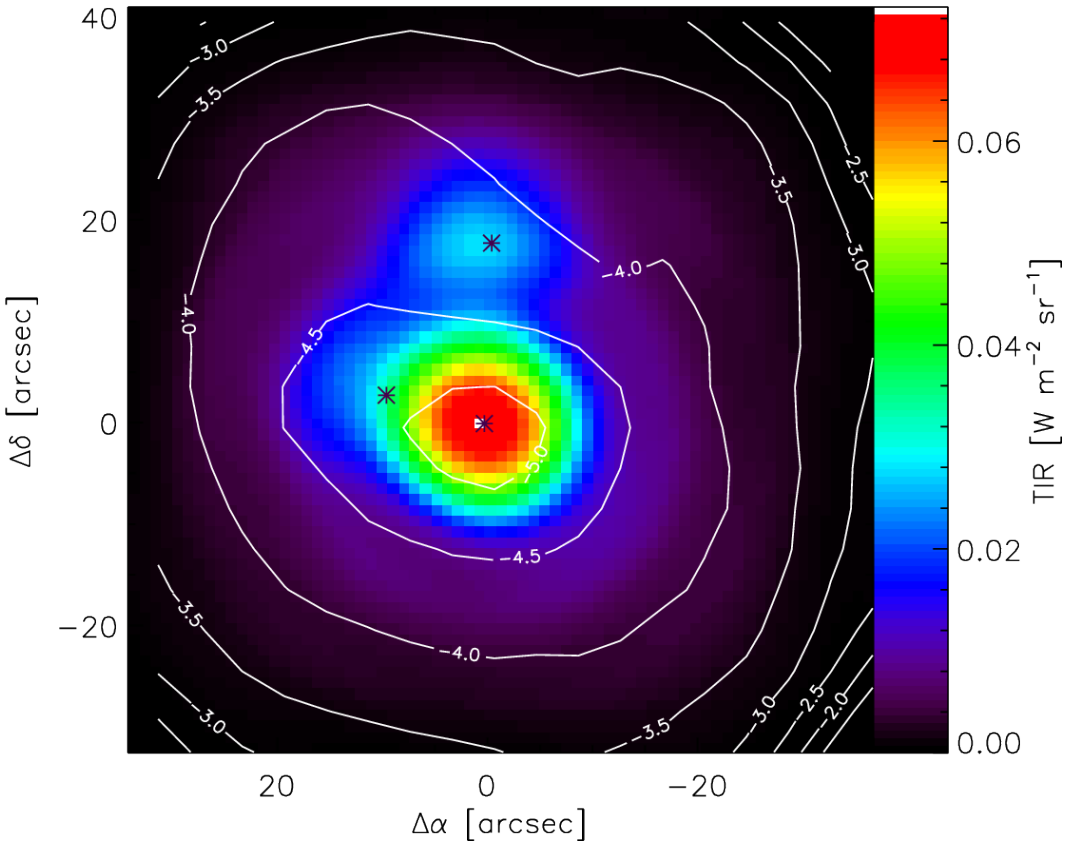


CO line SED from IRAM+HIFI+SOFIA

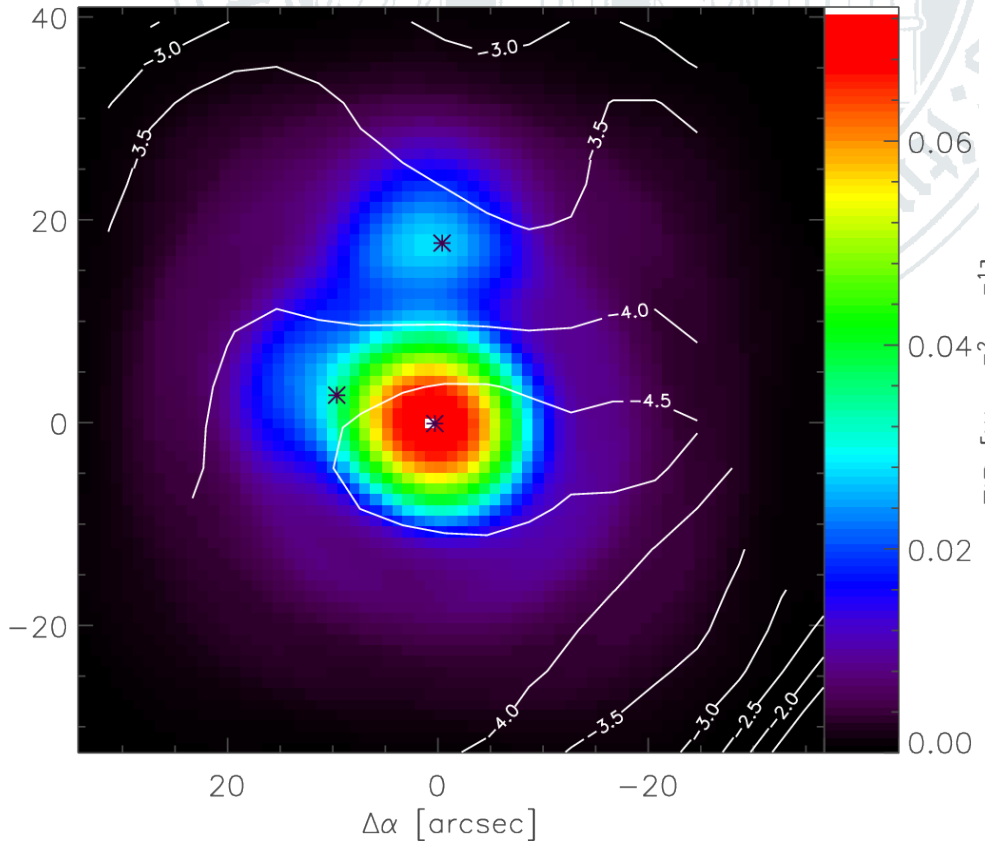
Cooling balance

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
- Reminiscent of **line deficit** in ULIRGS



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



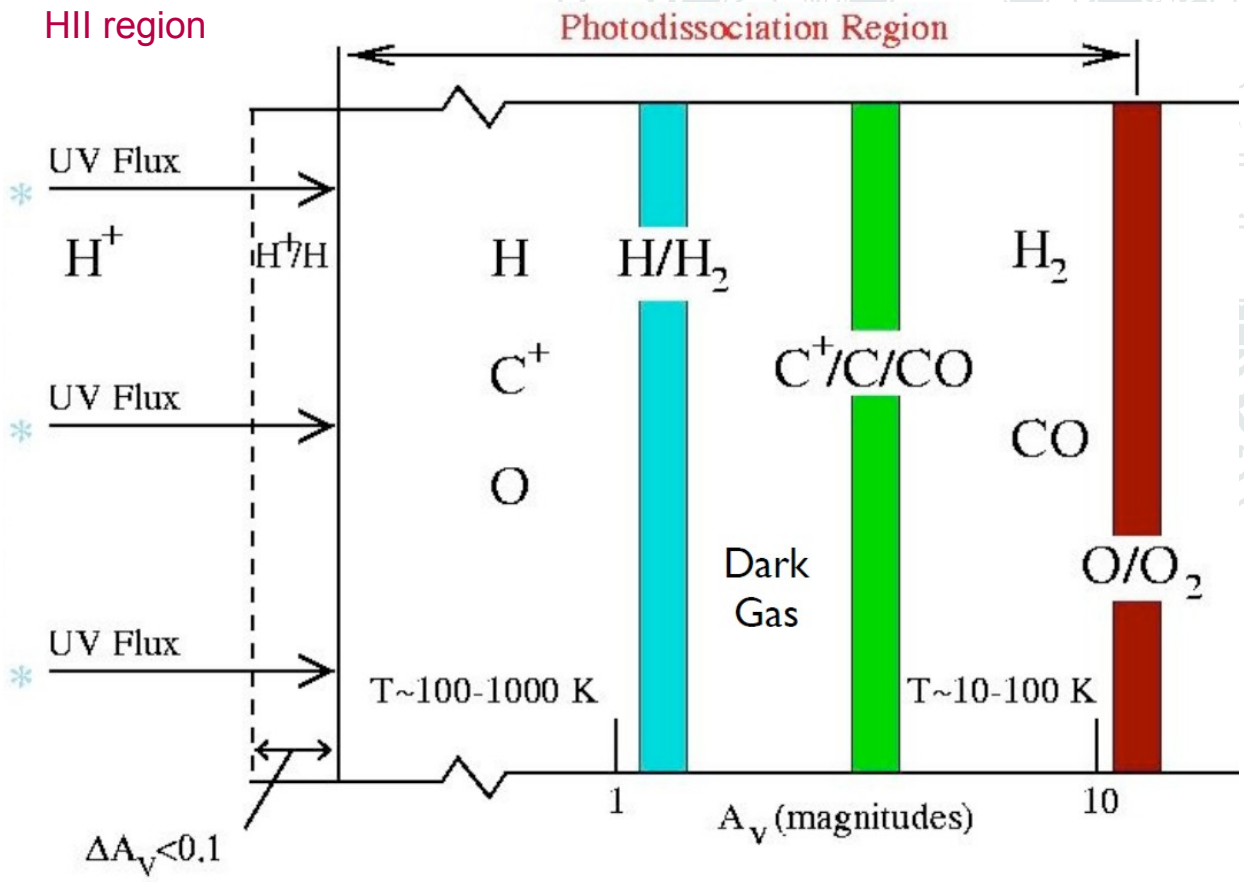
Contours: $\log_{10}$(([OI]+[CII])/TIR)

Starting facts

- 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
  - Velocity offset from main cloud (-6.5km/s instead of -8 km/s)
- Whole cluster:
  - Extremely low line to continuum ratio: **line deficit**

Interpretation as classical photon-dominated region (PDR)

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

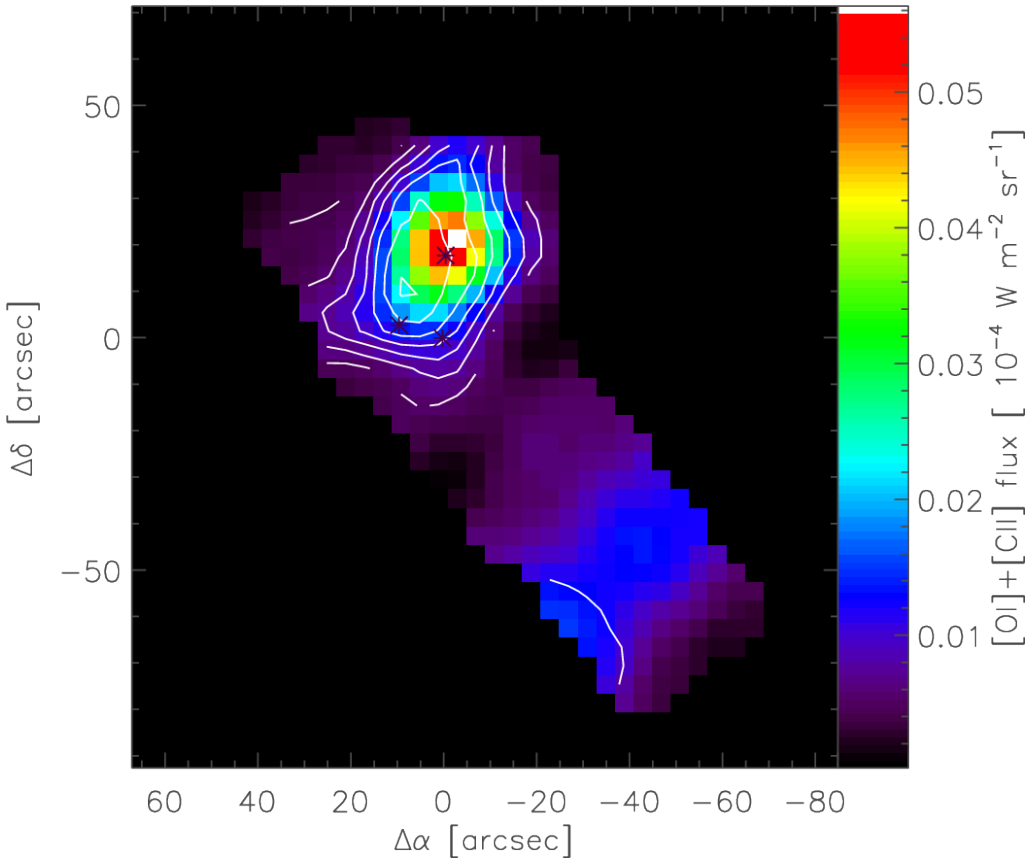


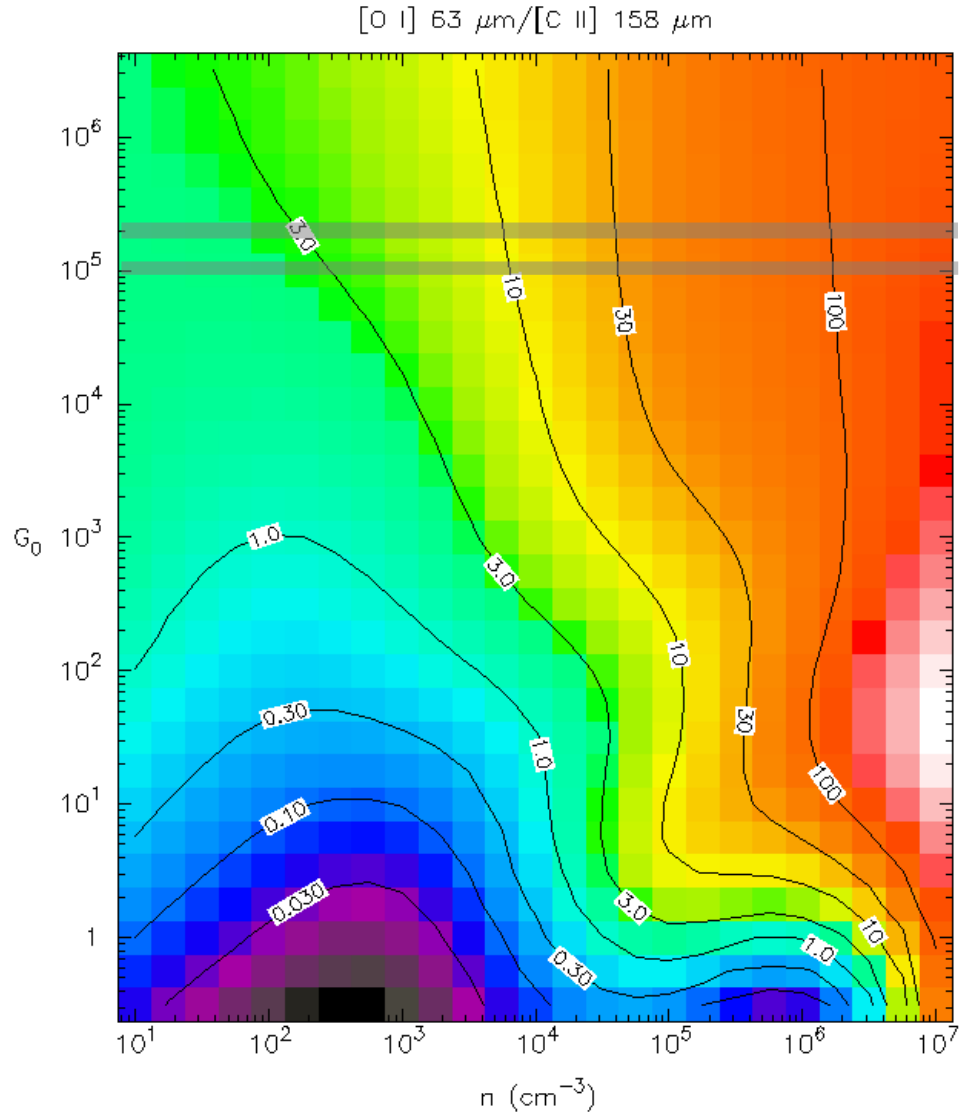
Based on
Hollenbach & Tielens (1999)

- Known radiation fields: **IRS1** – $G_0 = 2\times10^5$
  IRS2 – $G_0 = 10^5$

Comparison with plane-parallel PDR model (Kaufman 1999)

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

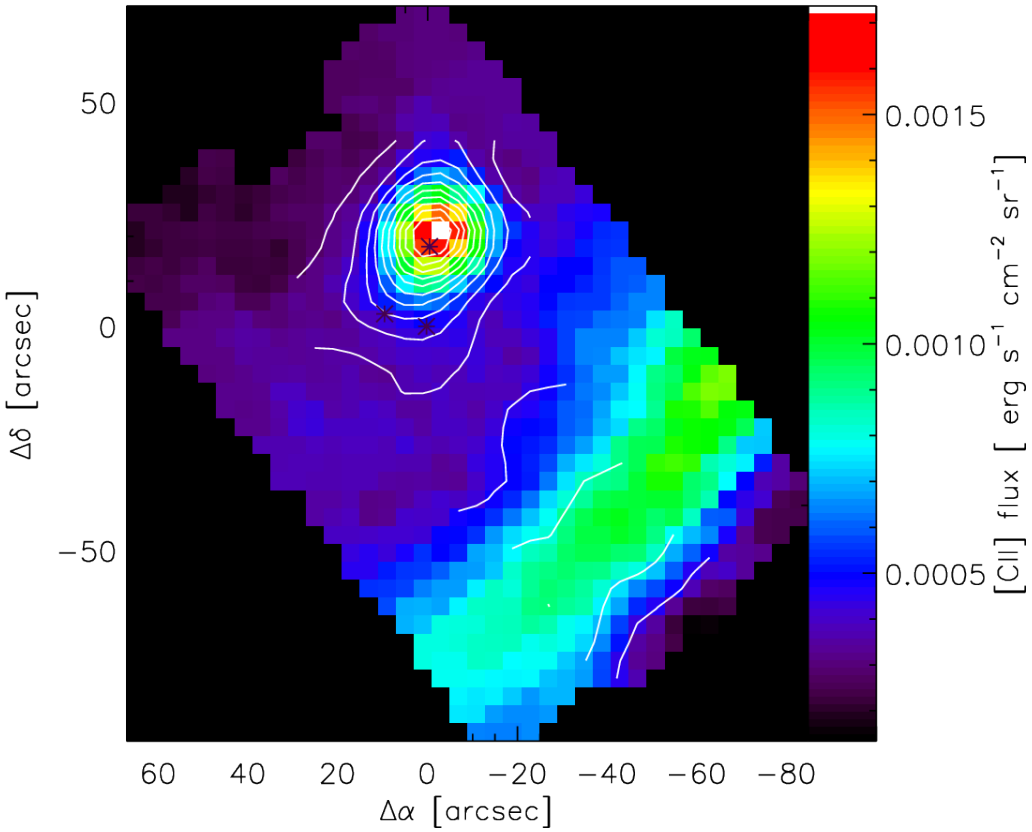


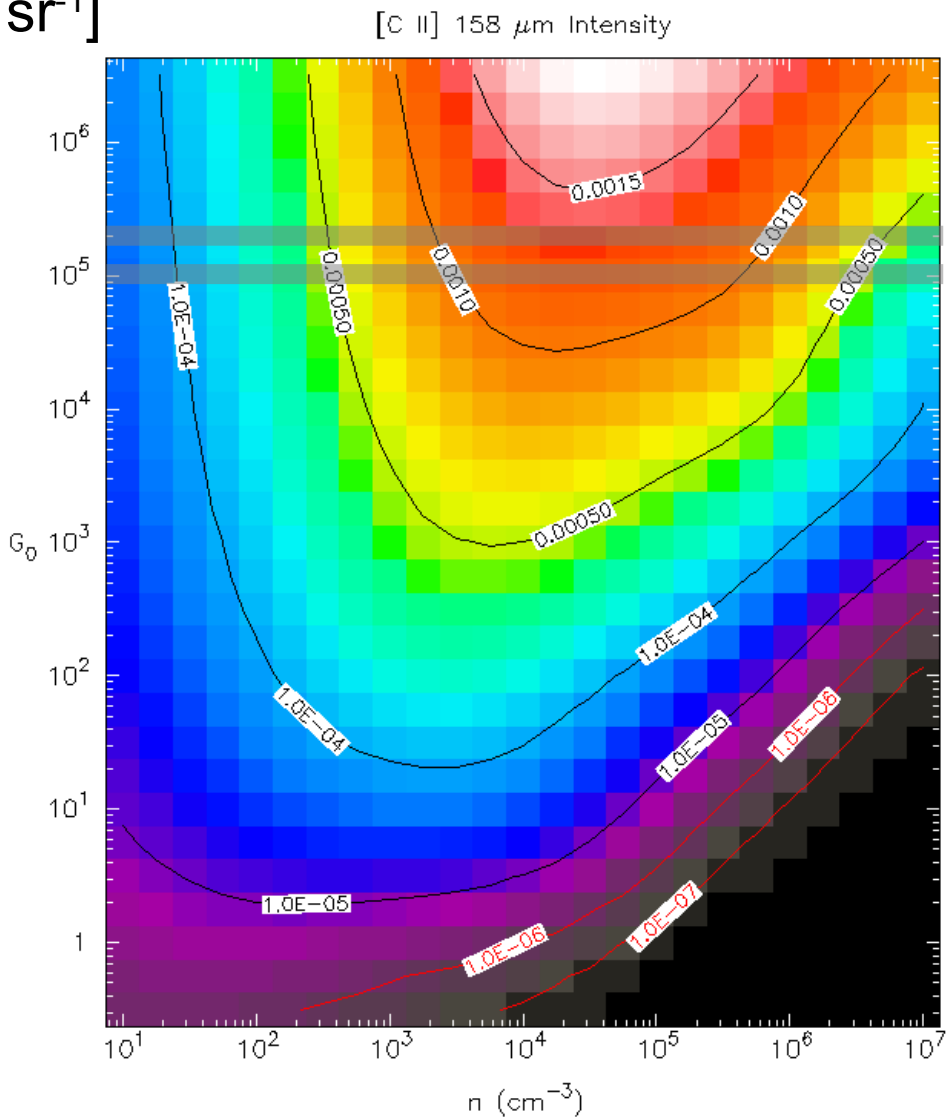


Cooling line strength (colors) [OI]/[CII] ratio (contours from 0.4...2.8)

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

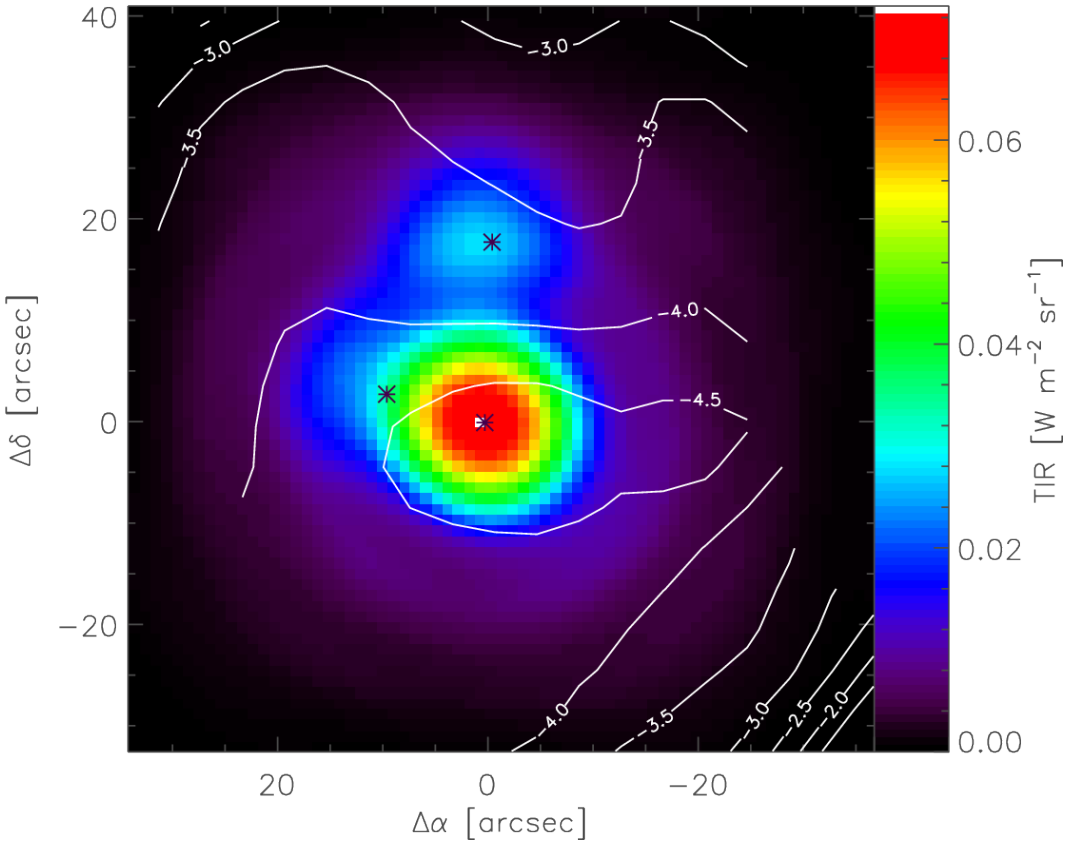


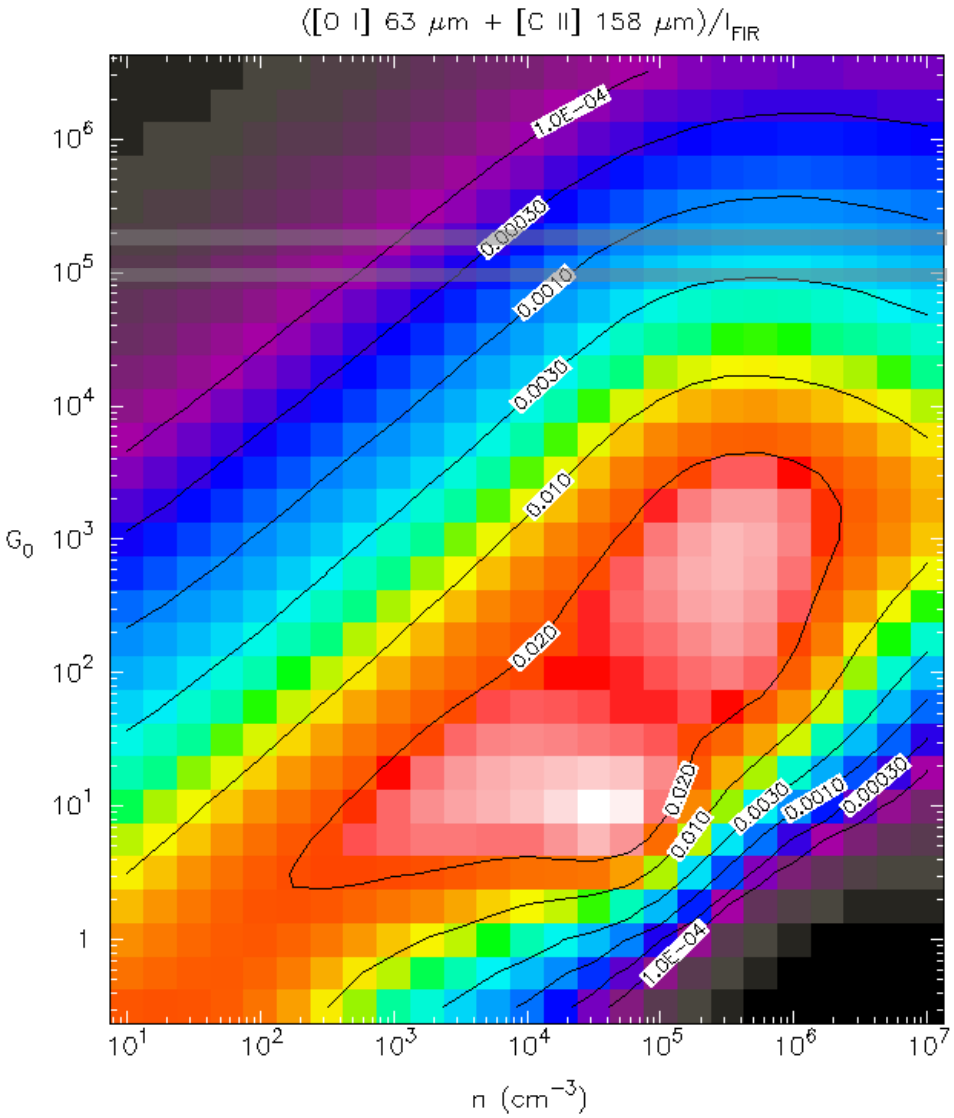


[CII] intensity (colors) and [OI]+[CII] intensity (contours from 0.0005...0.005)

Comparison with plane-parallel PDR model (Kaufman 1999)

- ([CII]+[OI])/FIR
  - 2 10^{-5} at IRS1
  - 2 10^{-4} at IRS2





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

PDR-model interpretation

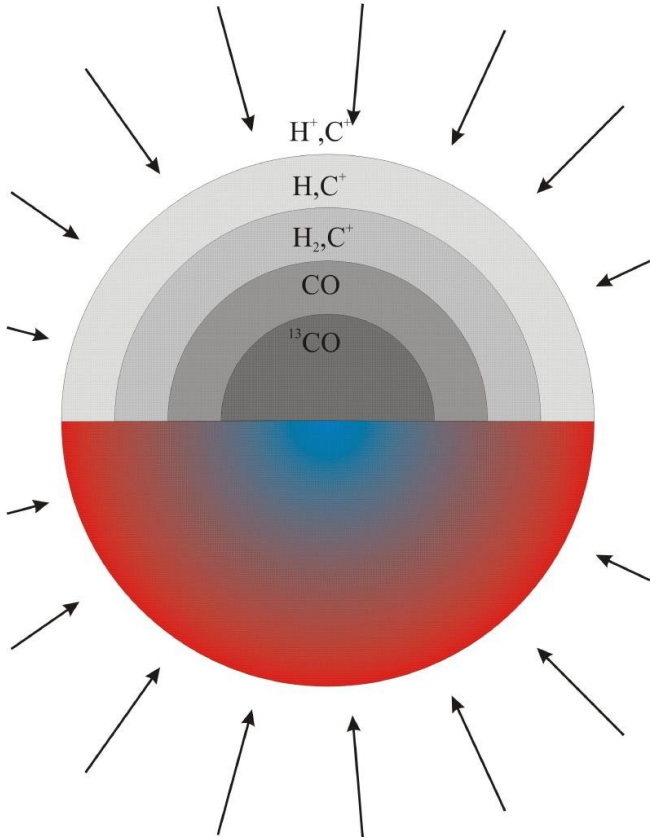
- IRS1:
  - [OI]/[CII] and [CII] intensity suggest density of 300 cm^{-3}
  - line-to-continuum ratio requires < 1 cm^{-3}
  - dust emission requires 10^6 cm^{-3}
- IRS2:
  - [OI]/[CII] and cooling balance require 300 cm^{-3}
  - [CII] intensity and dust emission require 10^5 cm^{-3}

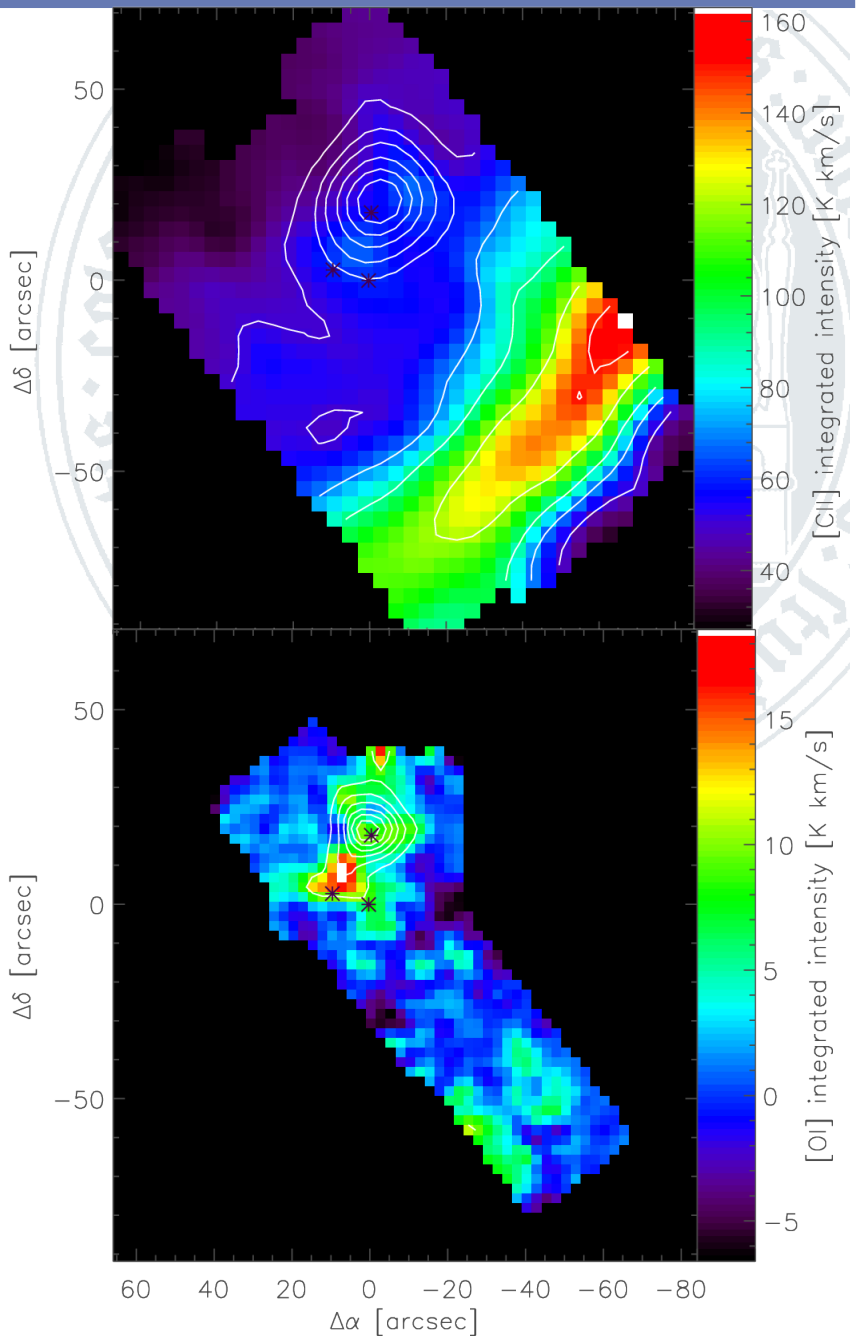
Explanation: Embedded PDRs neither plane-parallel nor extended!

Source geometry

Resolved in [OI] at 6.6"

- Fit by Gaussian intensity profile:
  - FWHM = 8.3" = 0.03pc
  - Identical for [OI] and [CII]
- Compare with spherical PDR model
  - KOSMA-τ



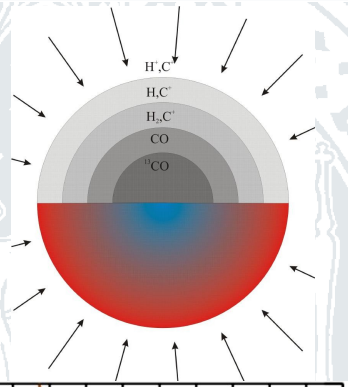


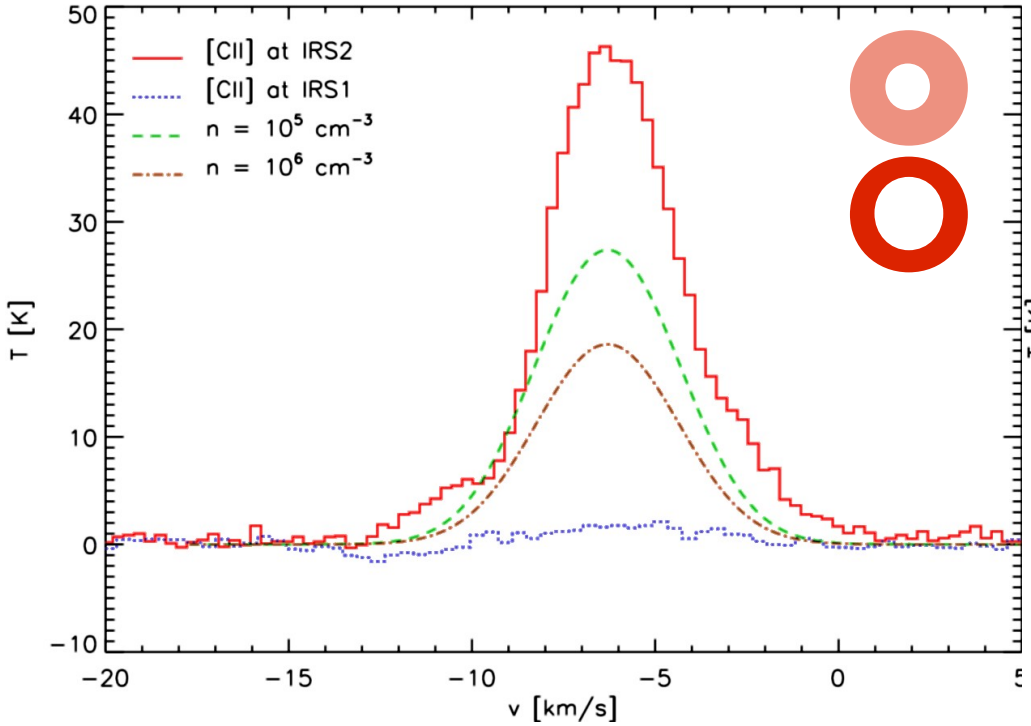
Original [OI], [CII] maps(contours), after source subtraction (colors)

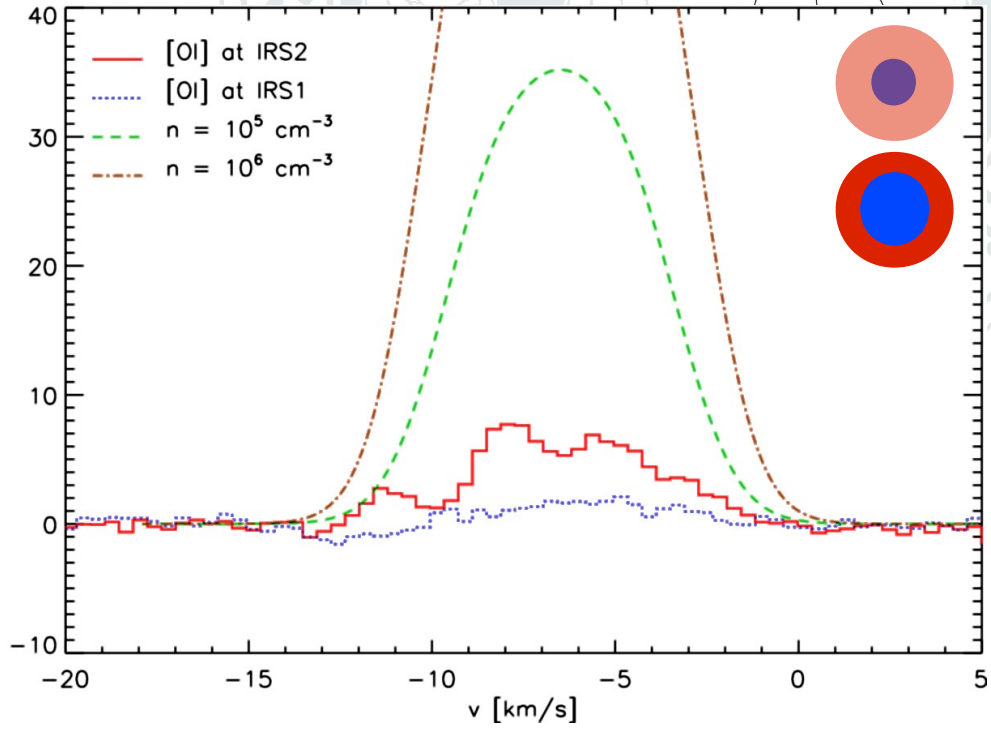
Spherical PDR

Toy model:

- $G_0 = 1.7 \times 10^5$
- n = 10^6 cm^{-3} and n = 10^5 cm^{-3}





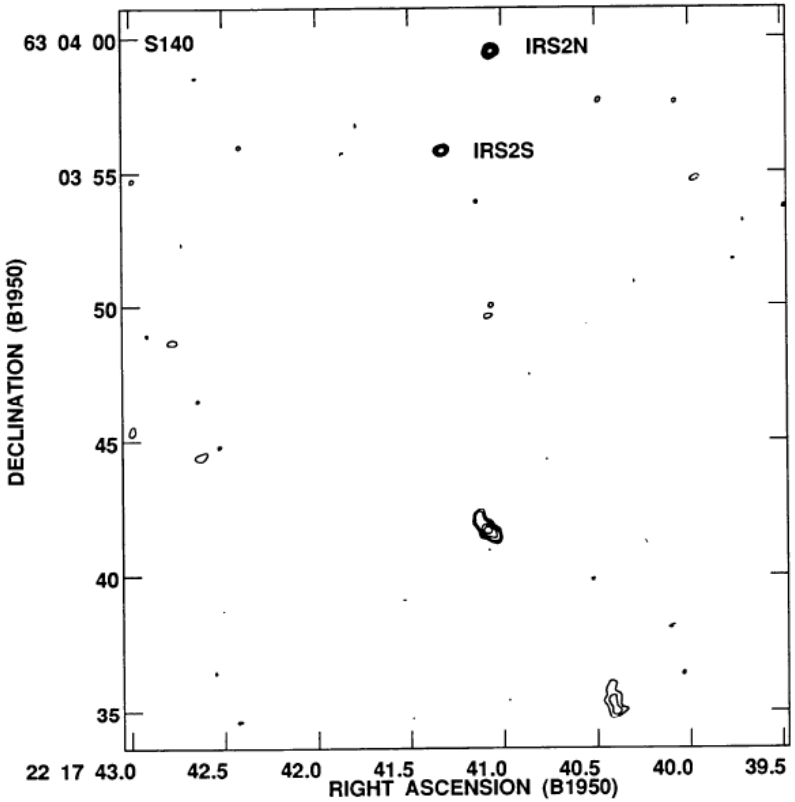


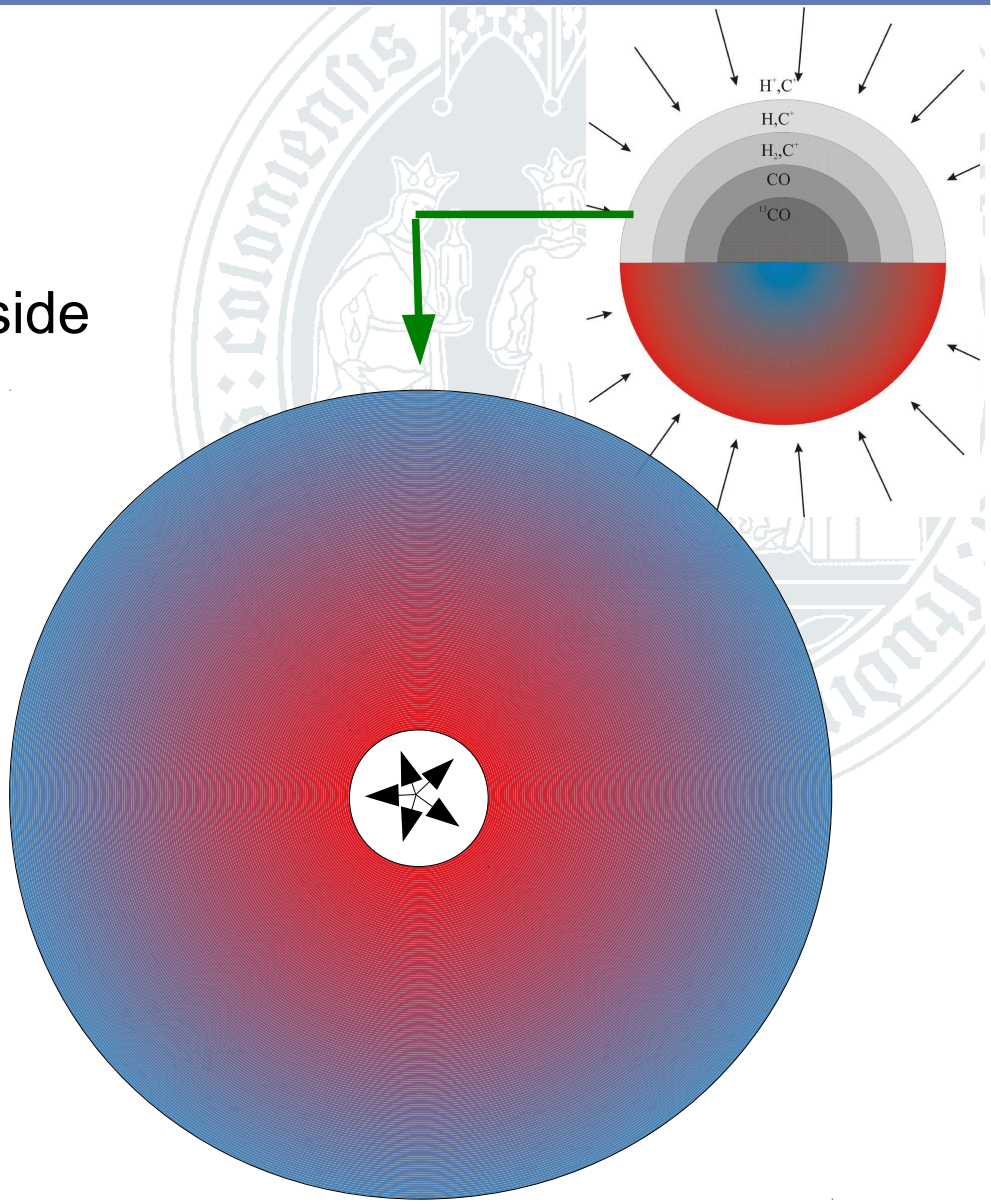
- [CII] stronger than in IRS1, but weaker than in IRS2
  - Main effect: beam filling
- [OI] much stronger than observed

Source geometry

UV field is internal!

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





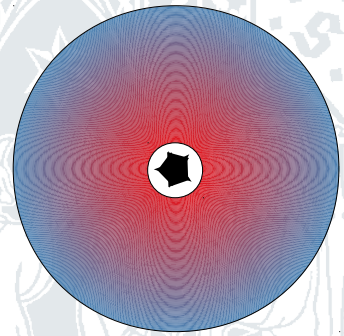
Embedded HII regions from radio continuum:
Tofani et al. (1995), Hoare (2006): D ≤ 0.5"

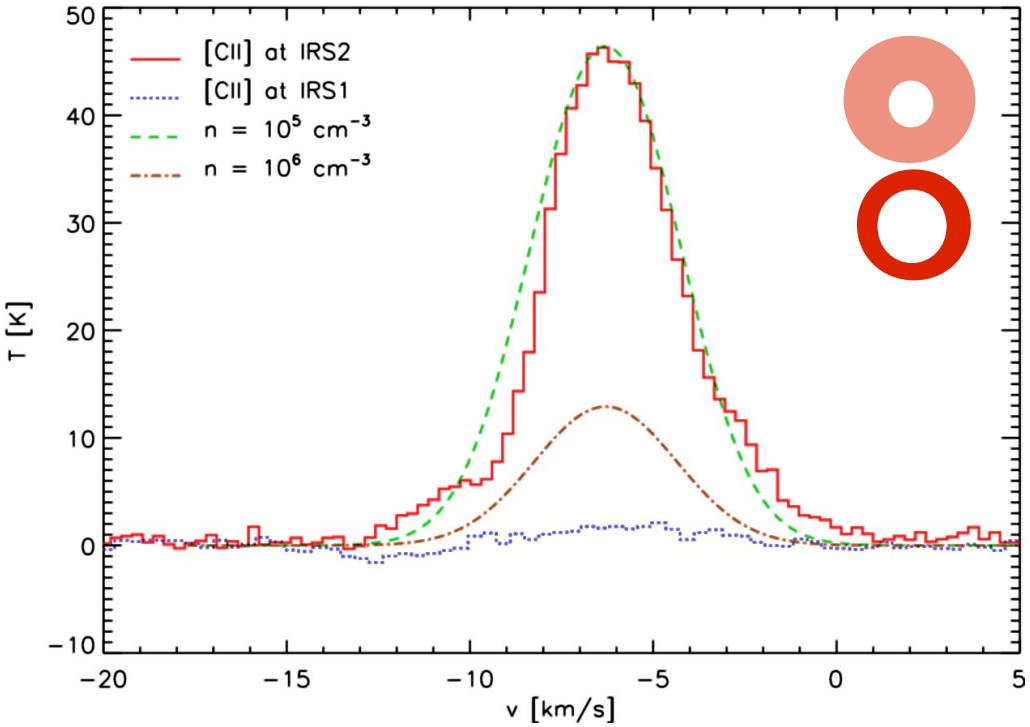
Toy model for internally irradiated PDR:
KOSMA-τ with inverse layering

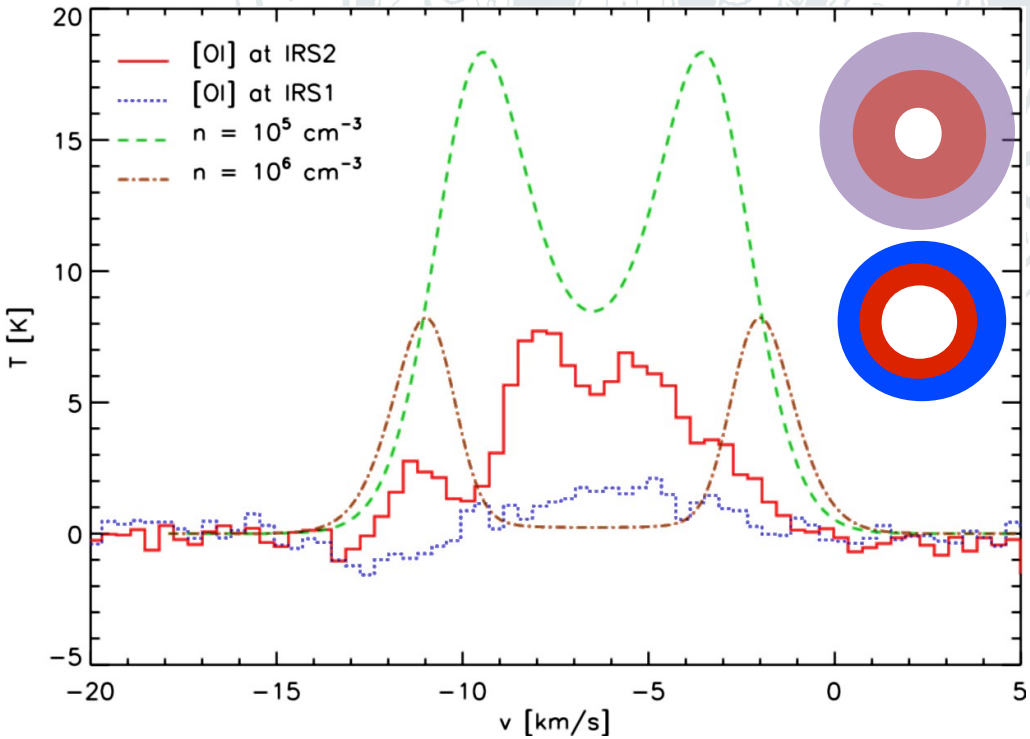
Central heating

Toy model:

- $G_0 = 1.7 \times 10^5$
- n = 10^6 cm^{-3} and n = 10^5 cm^{-3}



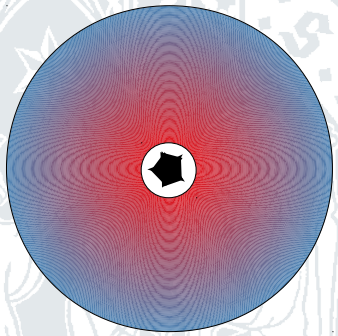


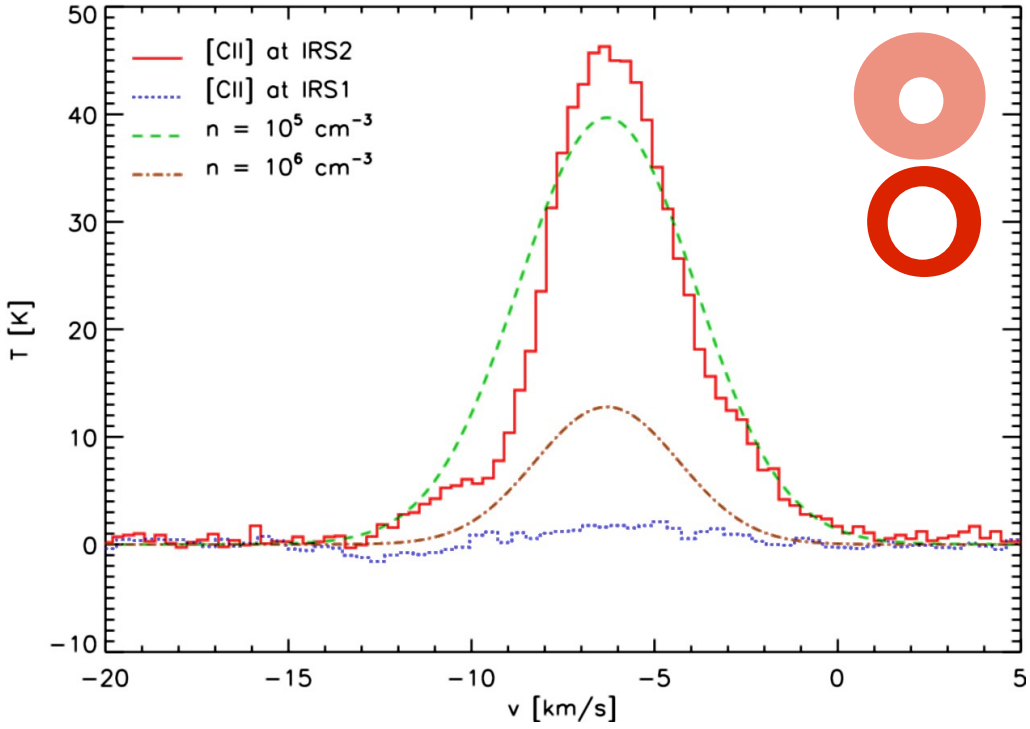


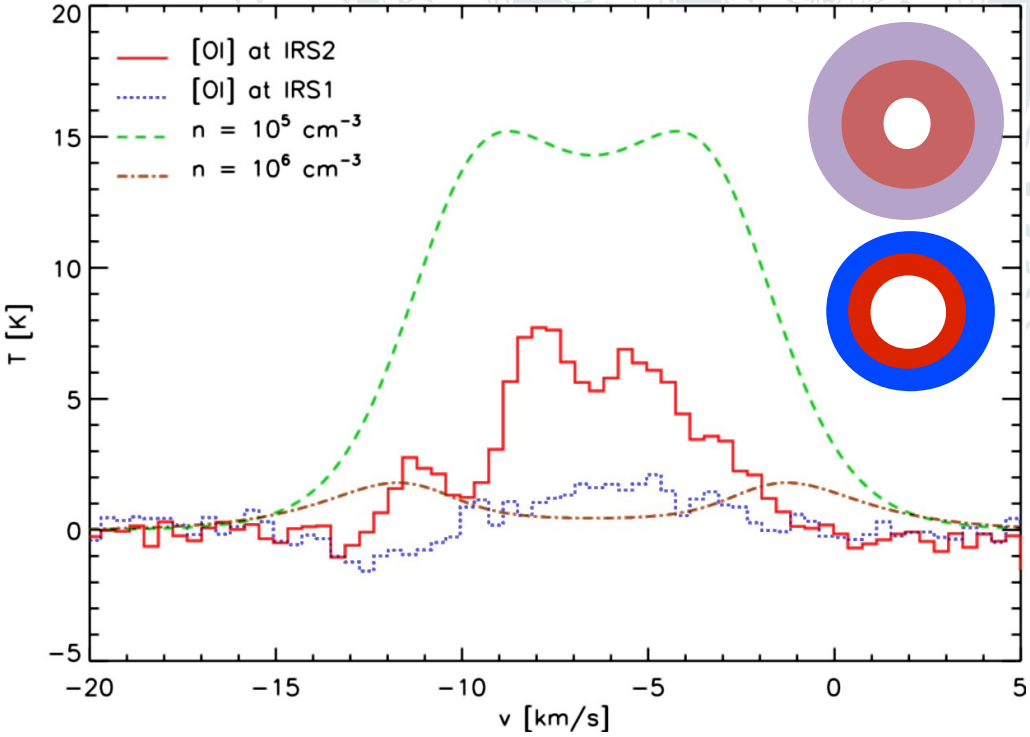
- [CII] perfect match for IRS2, too strong for IRS1
- Heavy self-absorption in [OI] reduces intensity
  - Profiles not matching yet

With Larson-type velocity dispersion:

- σ_{vel} ~ r-0.4







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

Summary

- **Two-conditions to produce line deficit:**
  - **PDRs in small dense cores for low [CII] beam filling – NOT clumpy!**
  - **Outwards gradient in excitation temperature of [OI]**
    - Zero intensity in velocity resolved line only with increasing line width
    - Zero **integrated** intensity easily when absorption trunk compensates for wing emission – velocity information is crucial!
- IRS2:
  - Source geometry constrained from resolved spatial structure
    - R=0.015pc, n > 10^5 cm^{-3}
- IRS1:
  - Very low line to continuum ratio: **extreme line deficit**
  - Requires denser and smaller PDR than inferred from the dust
    - R < 0.005pc, n > 10^6 cm^{-3}
- No match of observed line intensities and profiles yet
  - Parameter fit needed for good match of lines