[CII] and [OI] as star-formation tracers?

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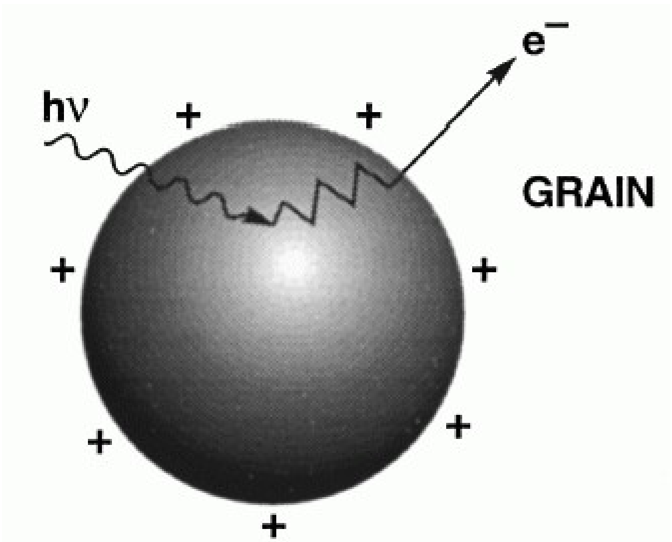
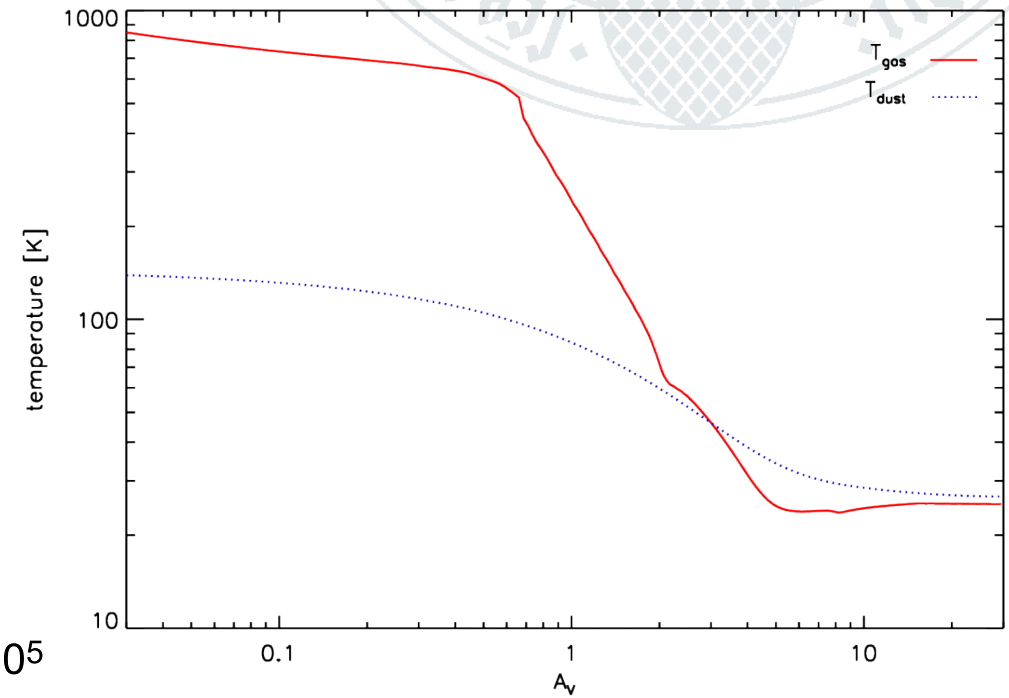
The naïve view

- Star-formation always deeply embedded
- Interaction with the environment
  - Formation of Photon-Dominated Regions (PDRs)
  - Photoelectric effect



→ Hot gas

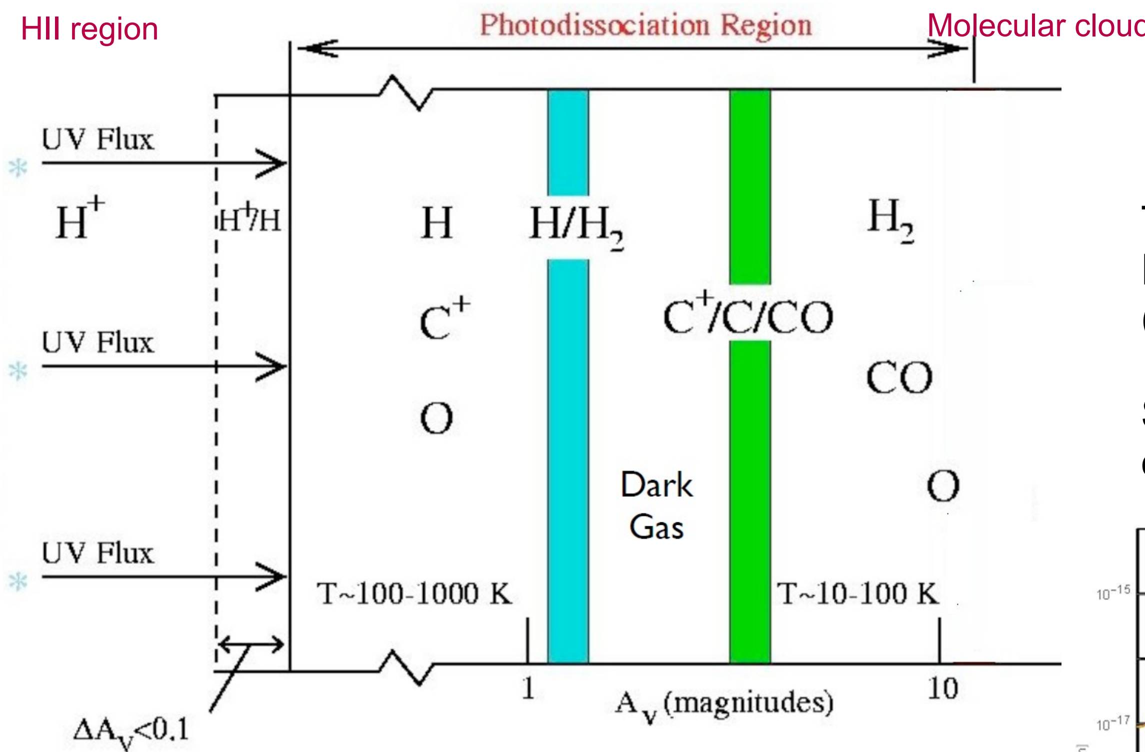
Herschel map of Aquila (HOBYS project)



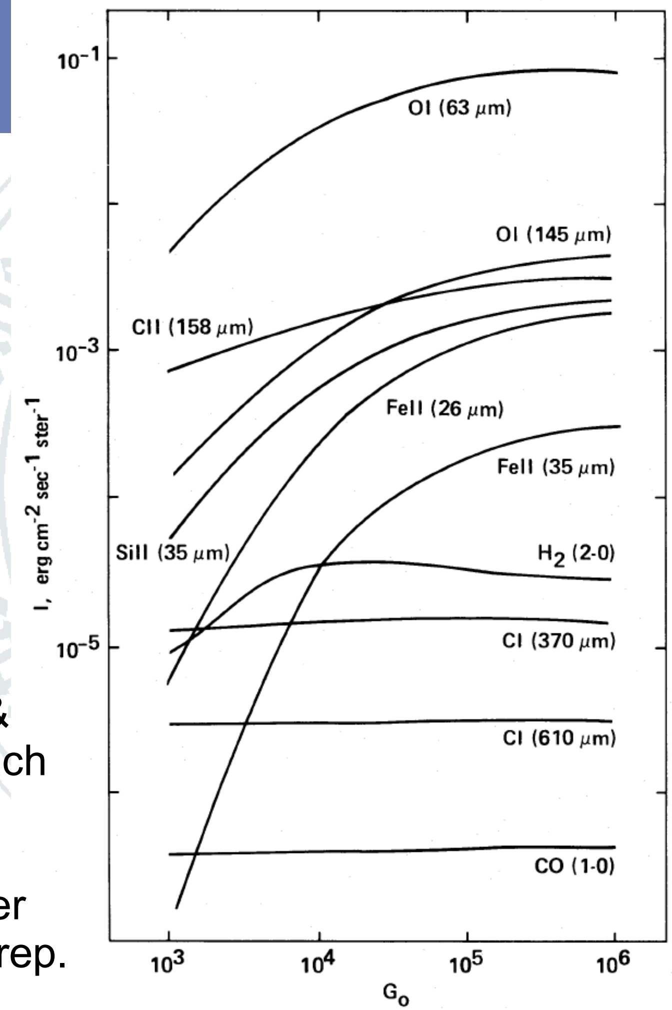
Temperature structure of a PDR exposed to $G_0=10^5$

The naïve view

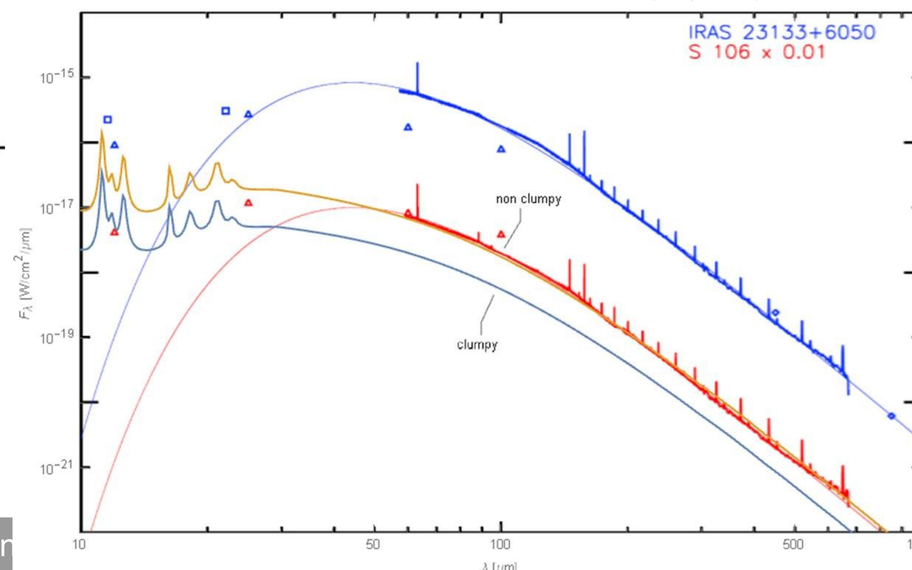
- Formation of Photon-Dominated Regions (PDRs)
  - ➢ Chemical differentiation



Tielens & Hollenbach (1985)



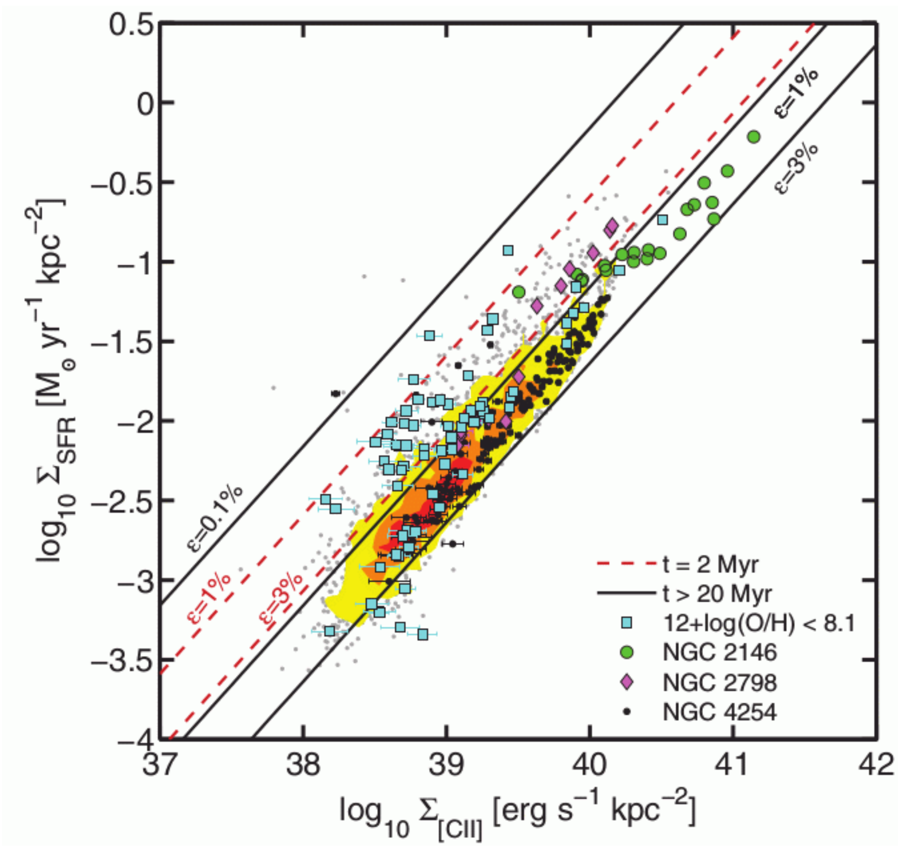
Schneider et al in prep.

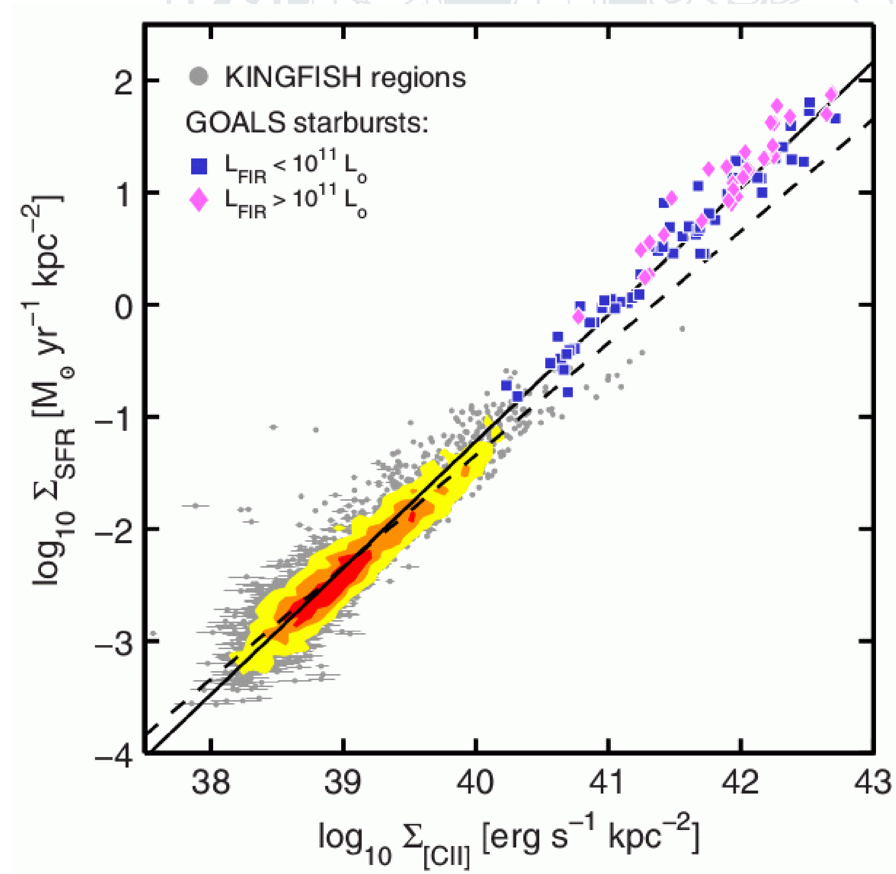


- ➢ Brightest lines / main cooling:
  Fine structure lines of [OI] and [CII]
  - Measure strength of UV radiation field

Systematics

- [CII] as star-formation tracer
  - Significant correlation in nearby and distant galaxies
  - But scatter by more than a factor 10



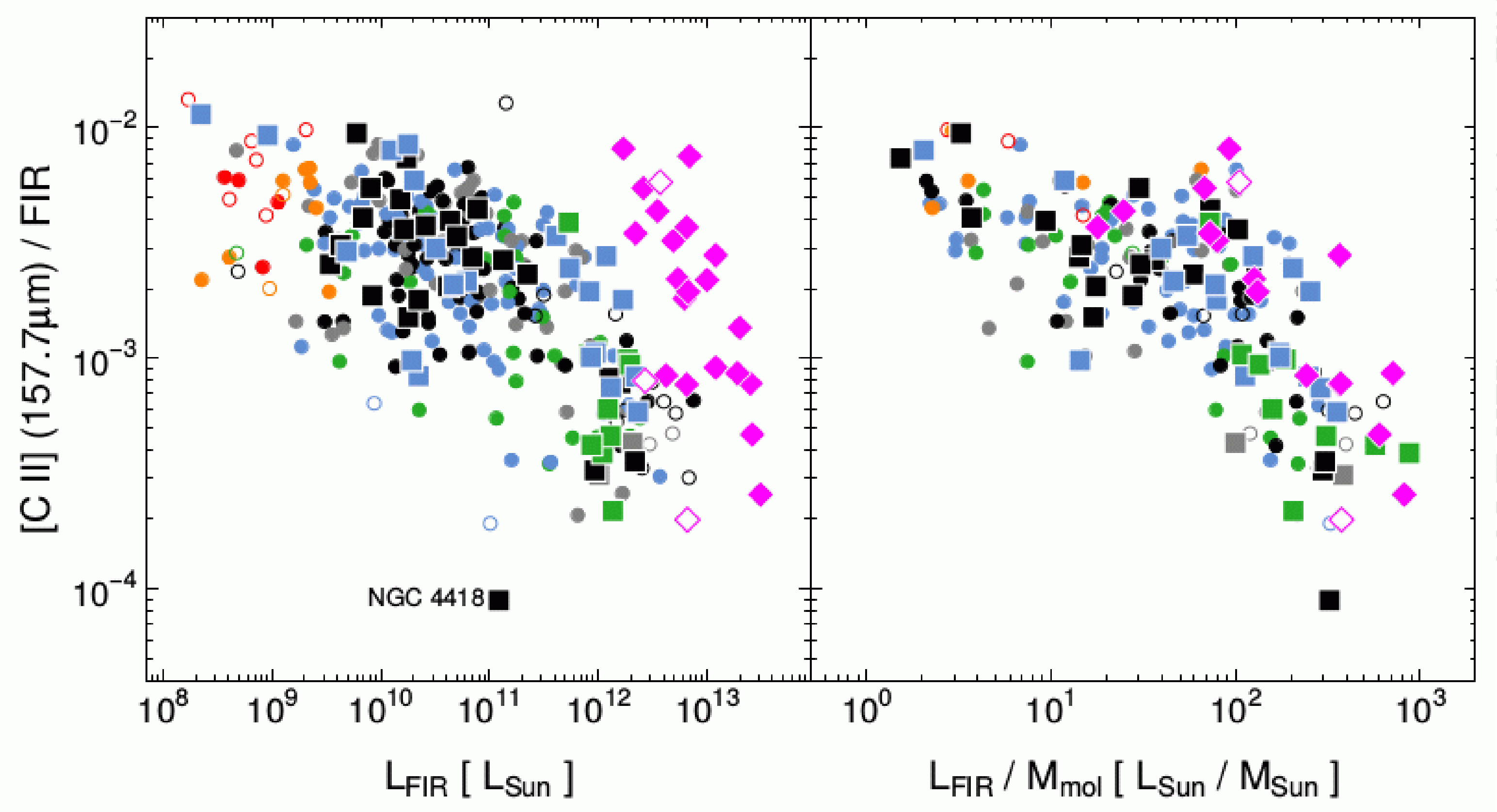


– Requires careful color correction

Herrera-Camus et al (2015)

Systematics

- [CII] as star-formation tracer
  - Scatter



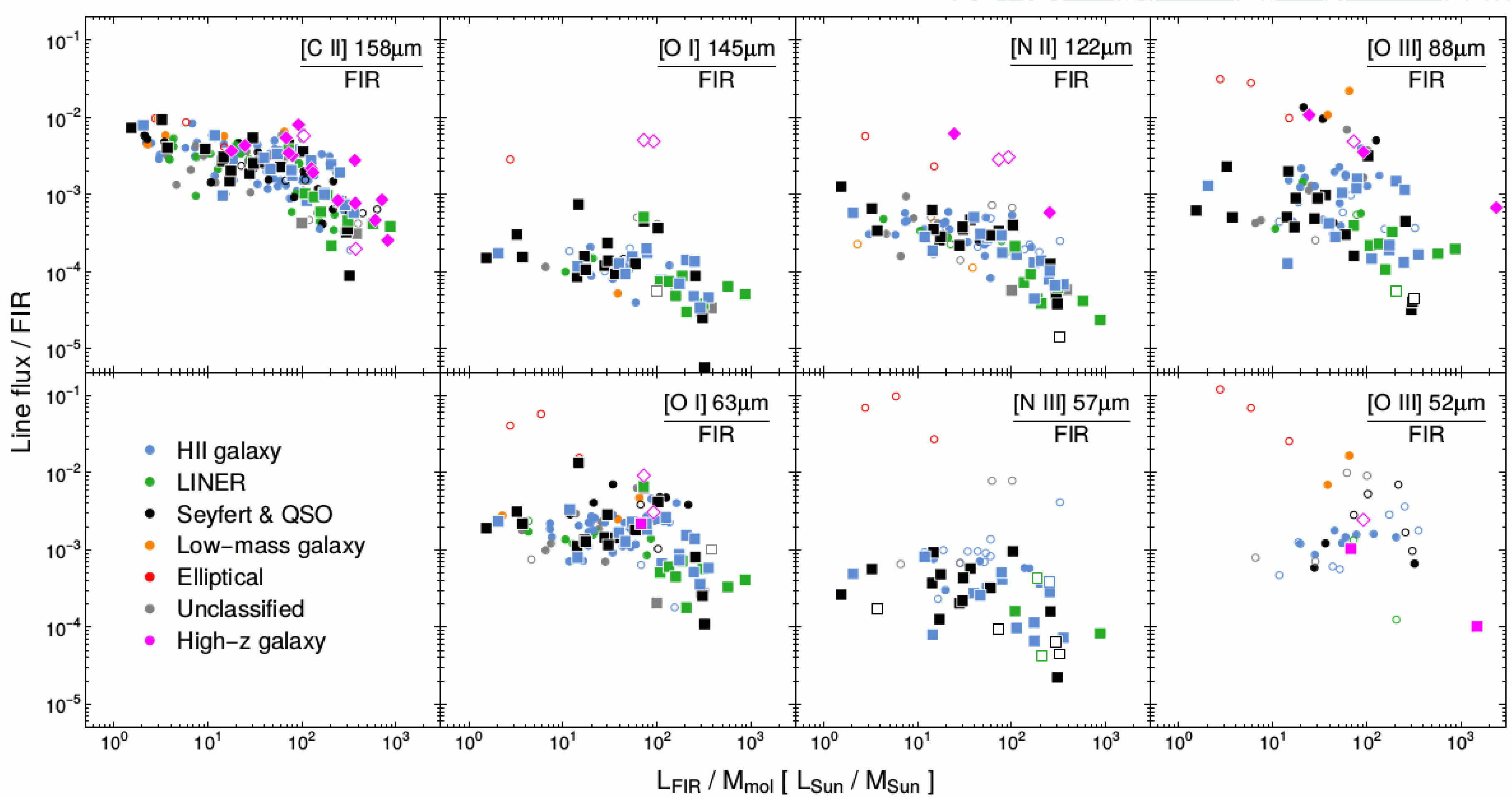
  - Good correlation when normalized to star-formation efficiency L_{FIR}/M_{mol}
  - Lower line strength relative to continuum for FIR bright sources

→ [CII] line deficit

Gracia-Carpio et al. (2011)

Systematics

- Fine structure lines as star-formation tracer



  - Same trend for other FIR fine-structure lines

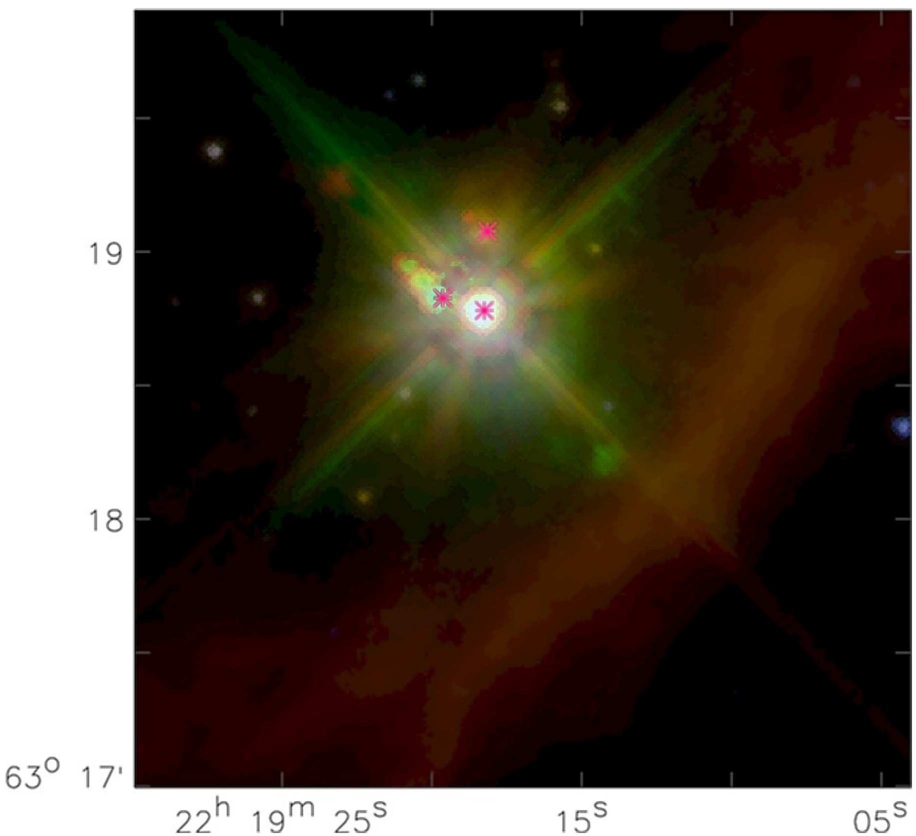
→ fine-structure line deficit

Gracia-Carpio et al. (2011)

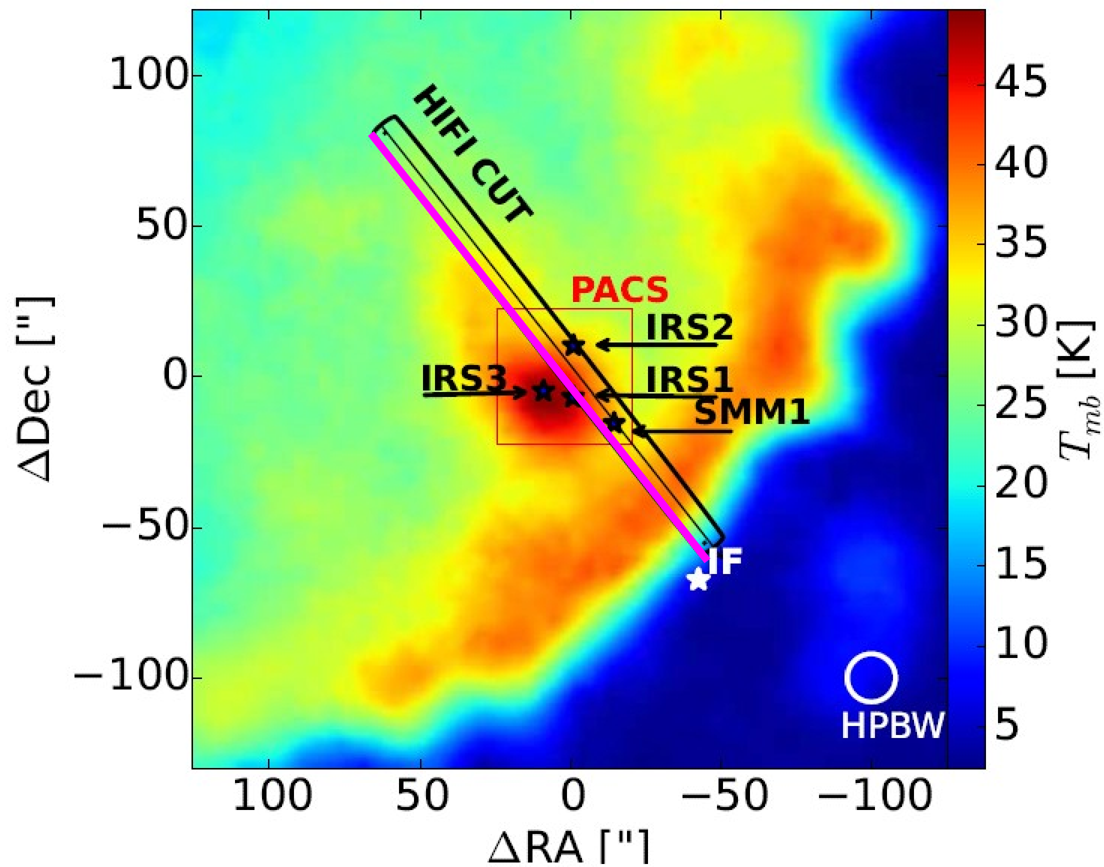
Search for a Galactic template

- **Ultraluminous Infrared Source**
  - **S140**: $L_{FIR} \approx 13000 L_\odot$, $M_{mol} \approx 100 M_\odot$ (Koumpia et al. 2015)
- External PDR ($G_0 \approx 300$) and deeply embedded star-formation (IRS1-3):

IRAC map (3.6, 5.6, 8µm)

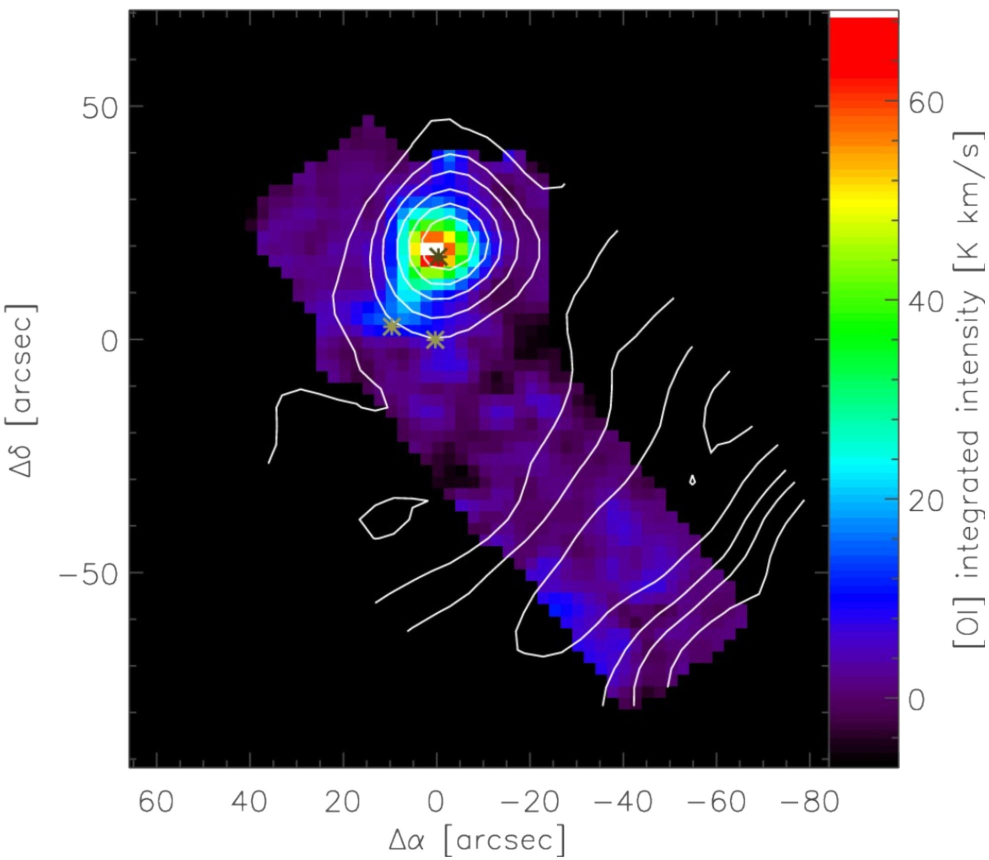


CO 1-0

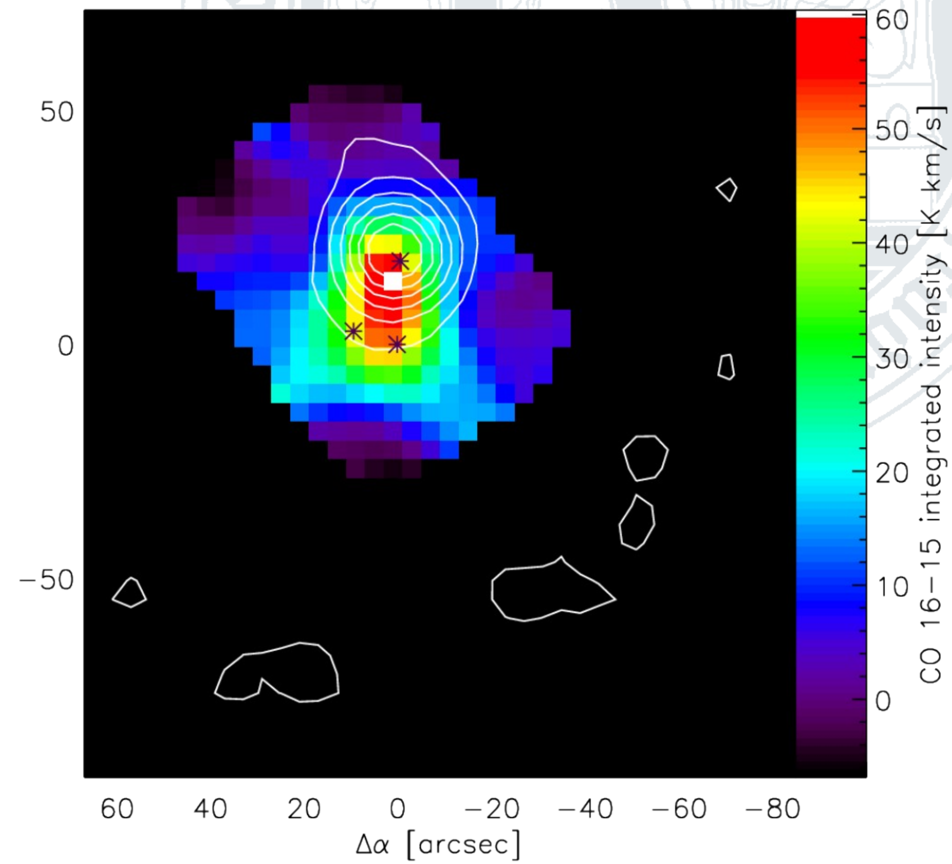


SOFIA/GREAT observations of [OI] and [CII]

- [OI] (63µm, 145µm) and [CII] do **NOT** peak at the main source (IRS1, 10000L$_\odot$) but 20" north, at IRS2 (2000L$_\odot$)
- Low-*J* CO peaks around at IRS1, CO 16-15 between IRS1 and IRS2



Colors: [OI $^3P_1$-$^3P_2$], Contours: [CII]



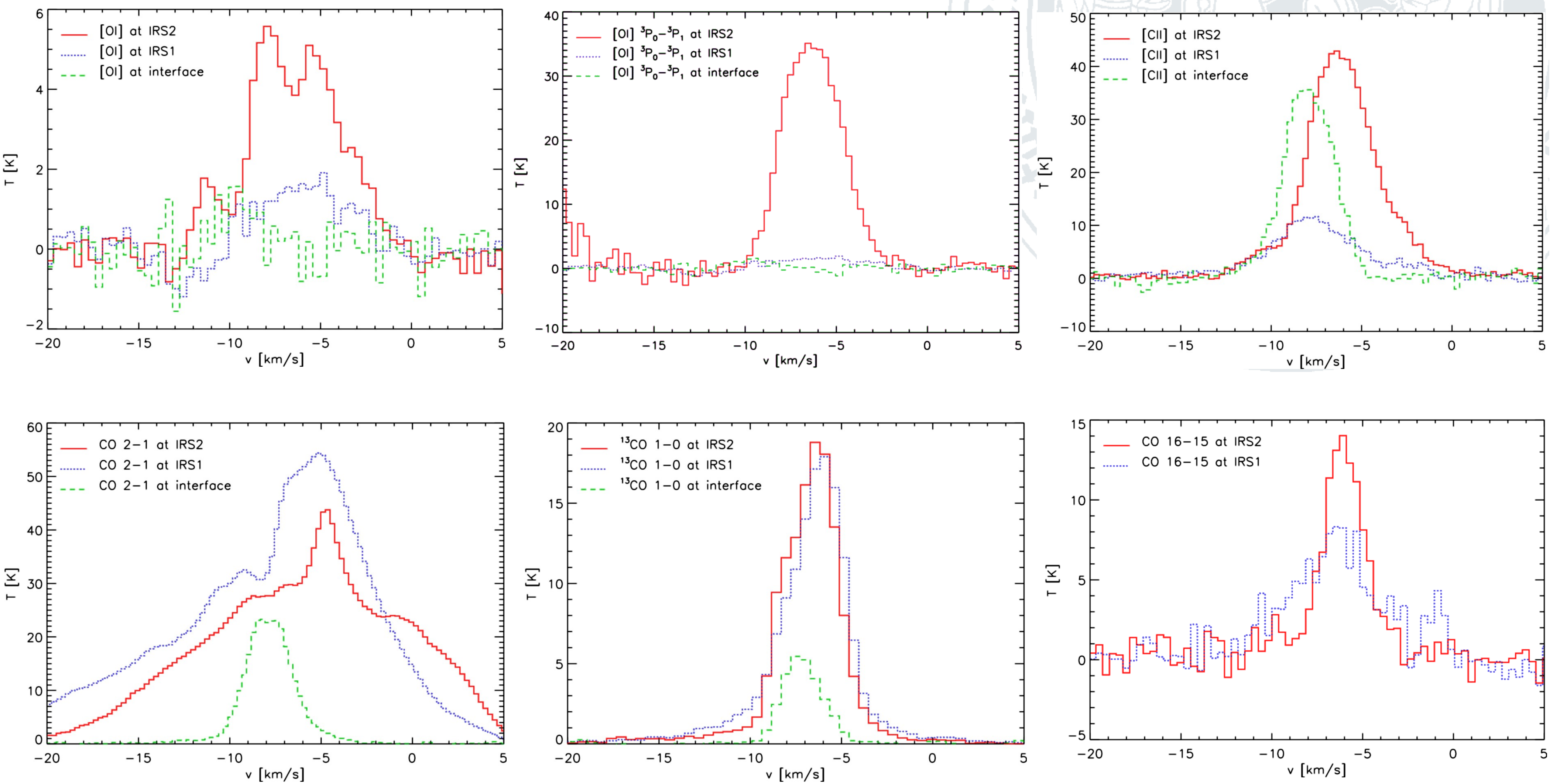
Colors: CO 16-15, Contours: [OI $^3P_0$-$^3P_1$]

(line integrated)

Line profiles

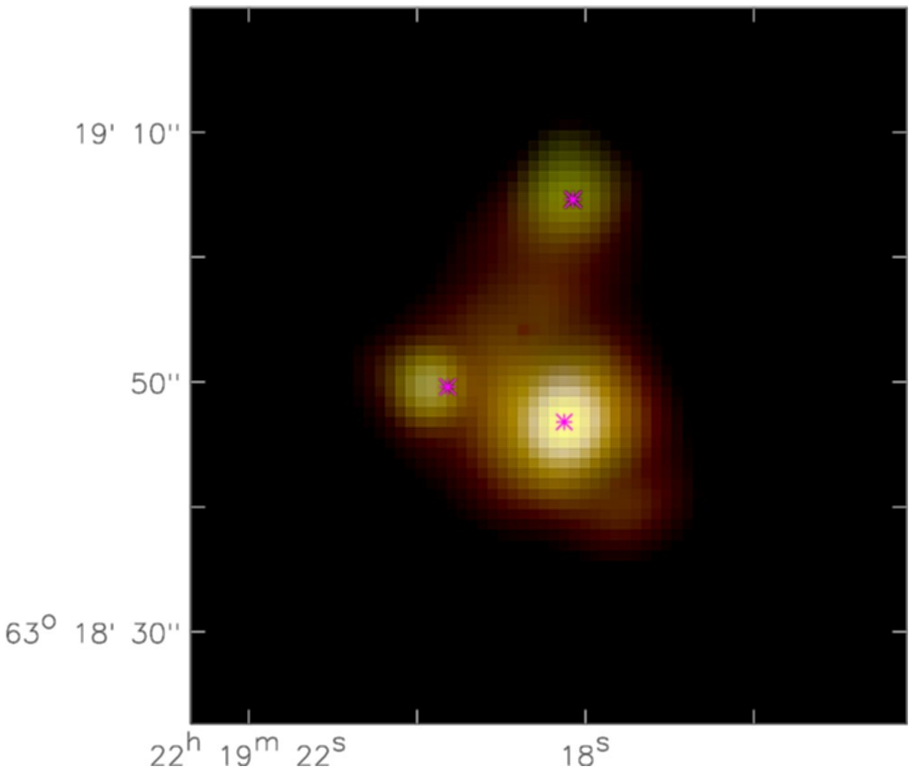
[OI] 63µm with clear self-absorption, [CII], [OI] 145 µm partially optically thick

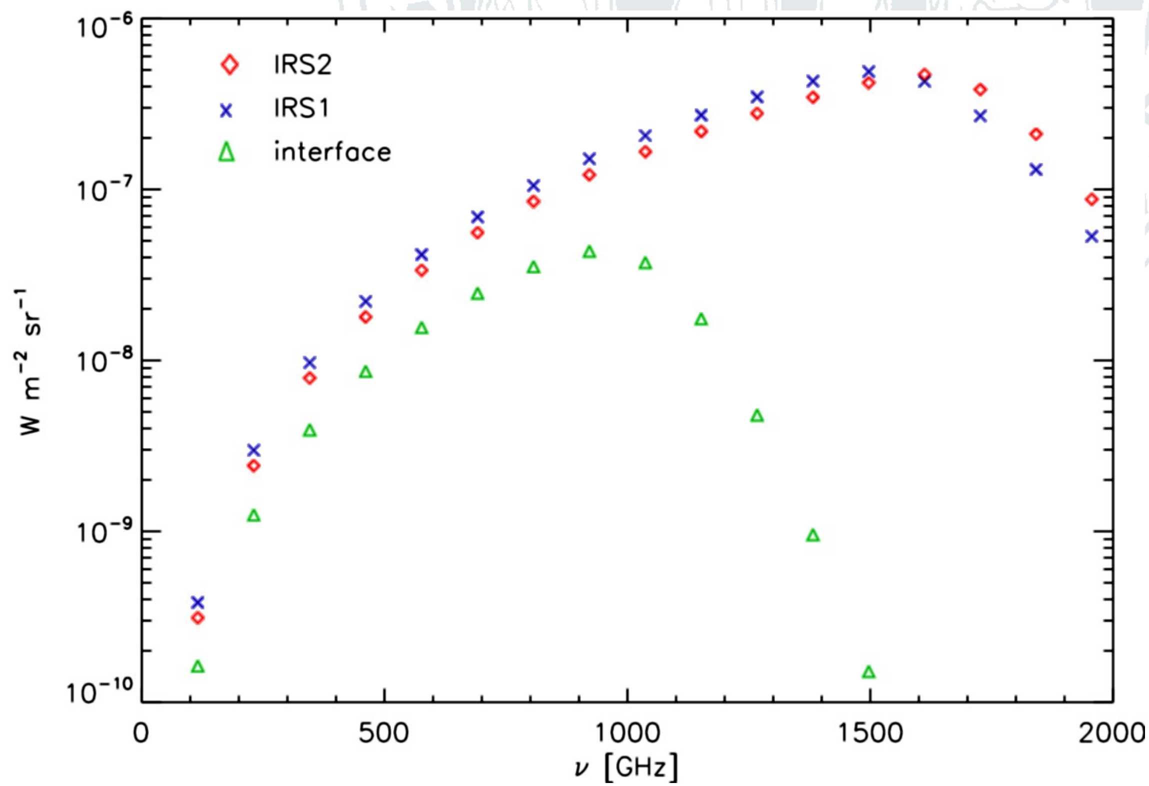
- Different velocity components towards IRS2 and interface+IRS1



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

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





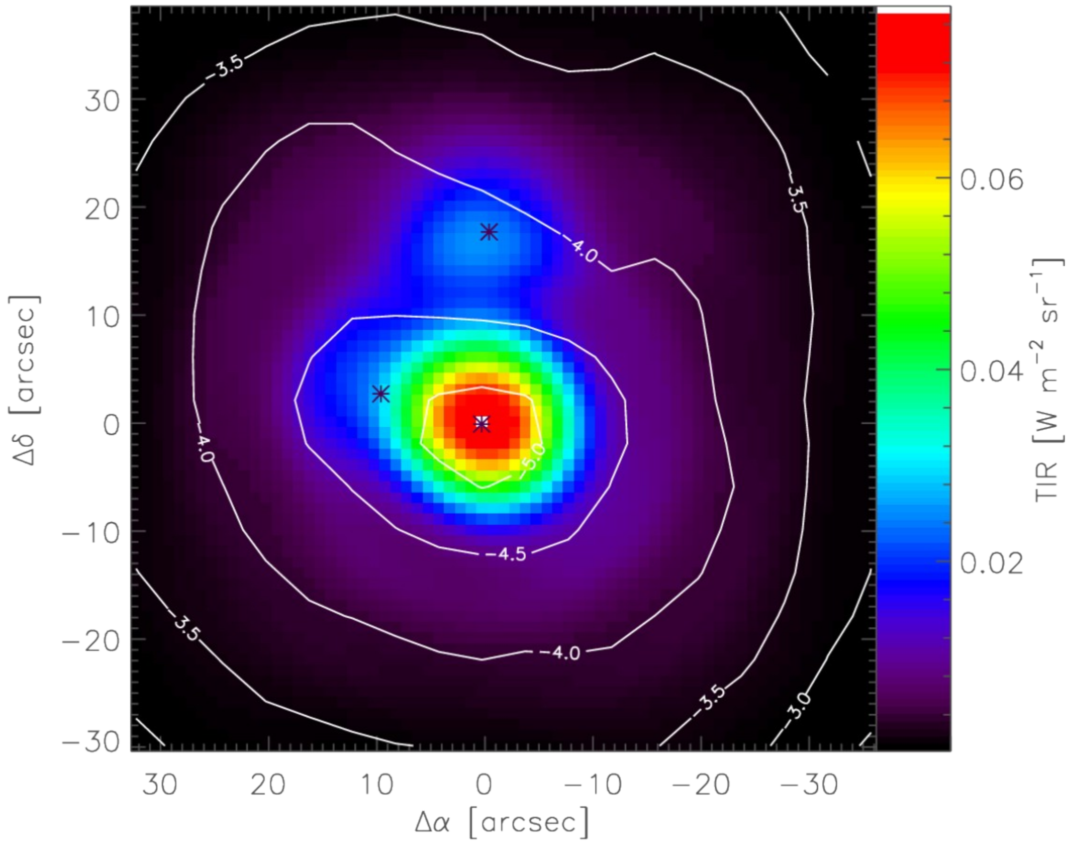
FORCAST map (11, 31, 37μm)

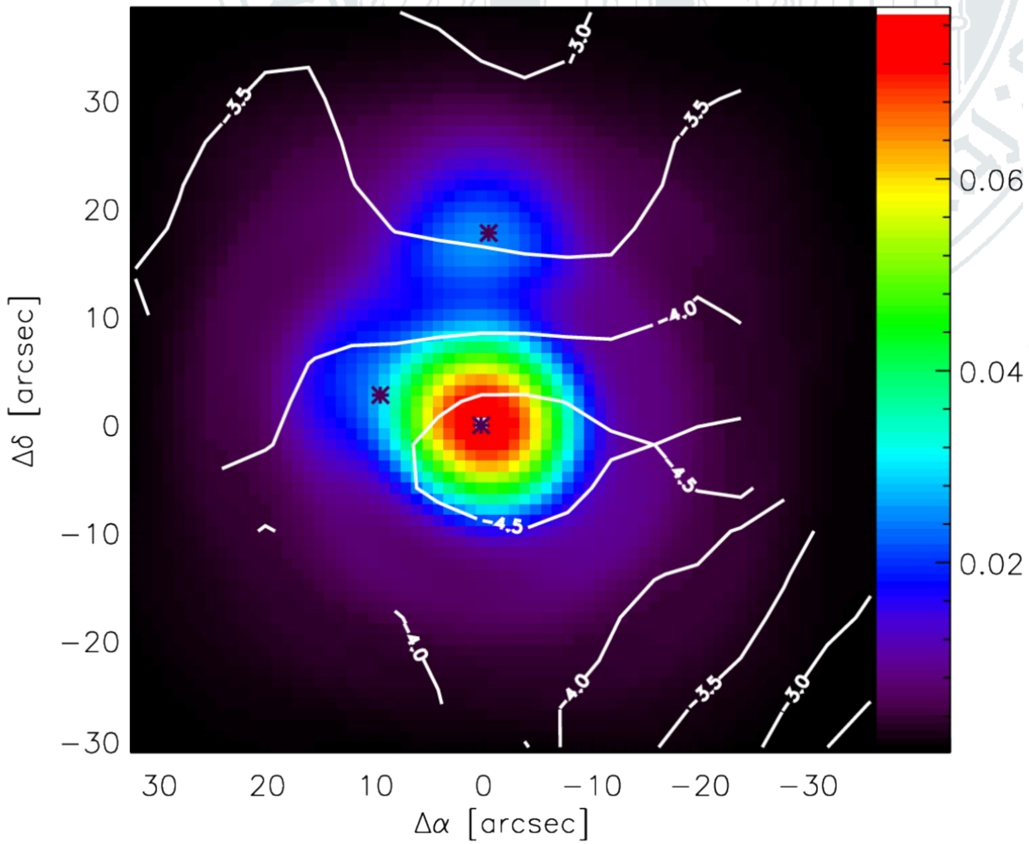
CO line SED from IRAM+HIFI+SOFIA

Line deficit?

Ratio between lines and FIR continuum

- IRS1: **factor 100 lower** than typical Galactic sources (values: 10^{-3} – 10^{-2})
- IRS2: **factor 10 lower** (IRS3 inbetween)
- Matches **line deficit** in ULIRGS

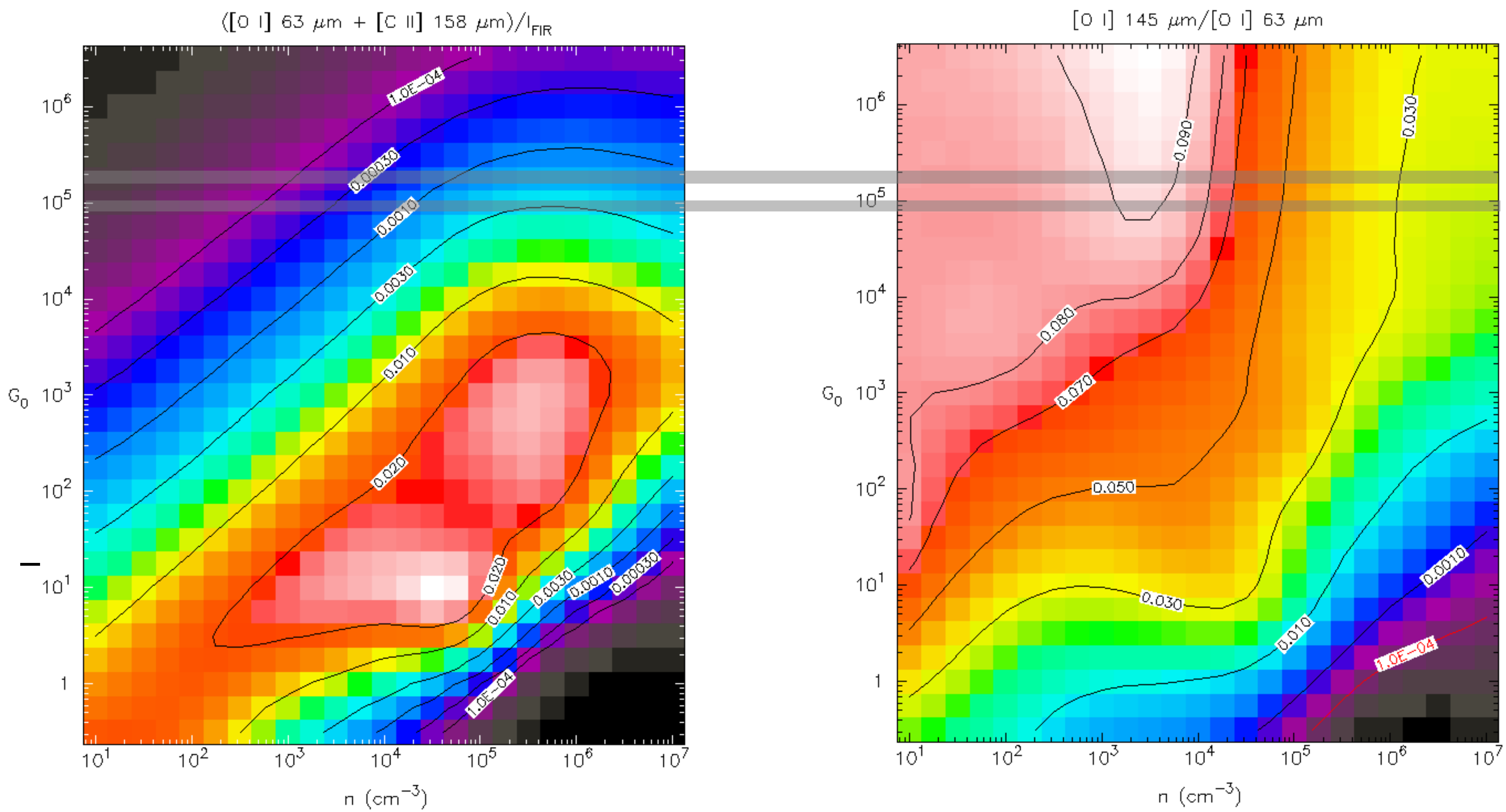




Colours: TIR   Contours: $\log_{10}$([CII]/TIR)   Contours: $\log_{10}$(([OI]+[OI]+[CII])/TIR)

Comparison to PDR model (Kaufman 1999)

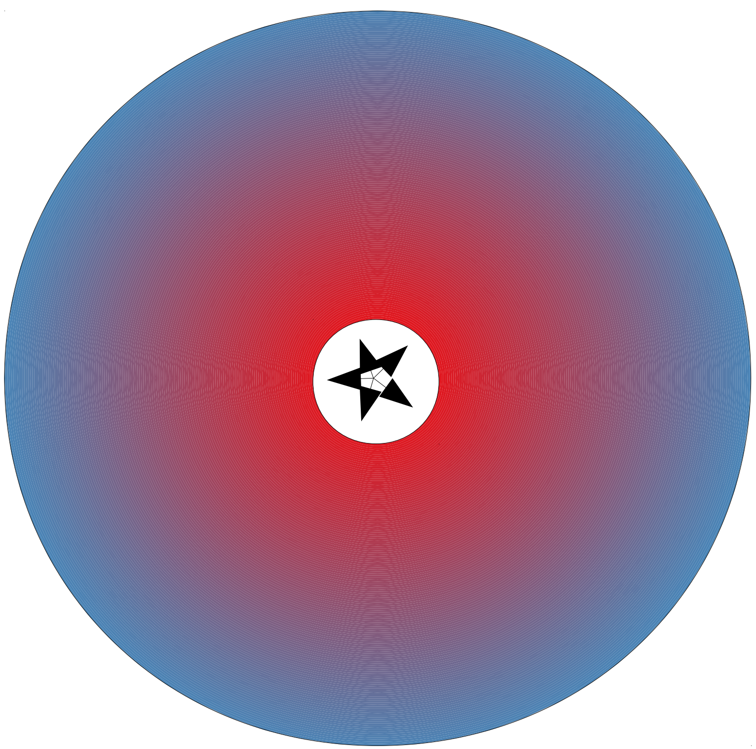
- Radiation field known: **G_0= 2×10^5** (IRS1), **G_0= 10^5** (IRS2)
- ([OI]+[OI]+[CII])/FIR = **2 10^{-5}** (IRS1), **3 10^{-4}** (IRS2)
- [OI] 145µm/ [OI] 63µm = **0.3** (IRS1), **0.05** (IRS2)



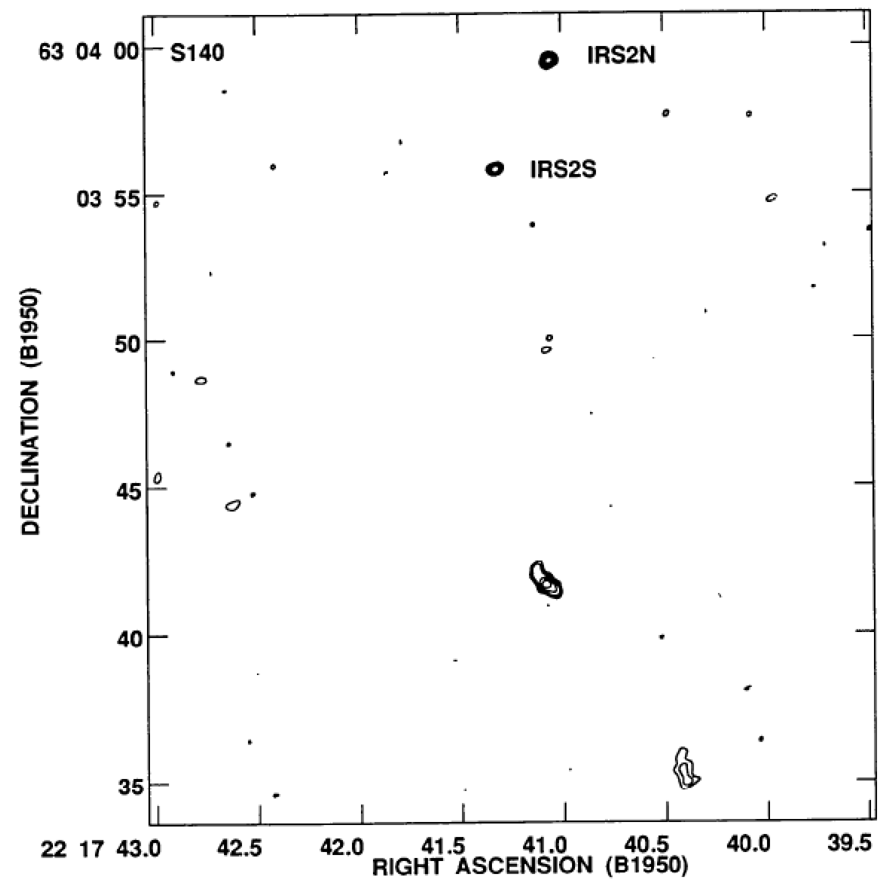
Source geometry

Plane-parallel PDR model does not make sense

- Internal PDR – geometrical dilution
  - Hot C^+ and oxygen inside, cold outside
  - No UV leaking at high densities



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



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

Internal PDR

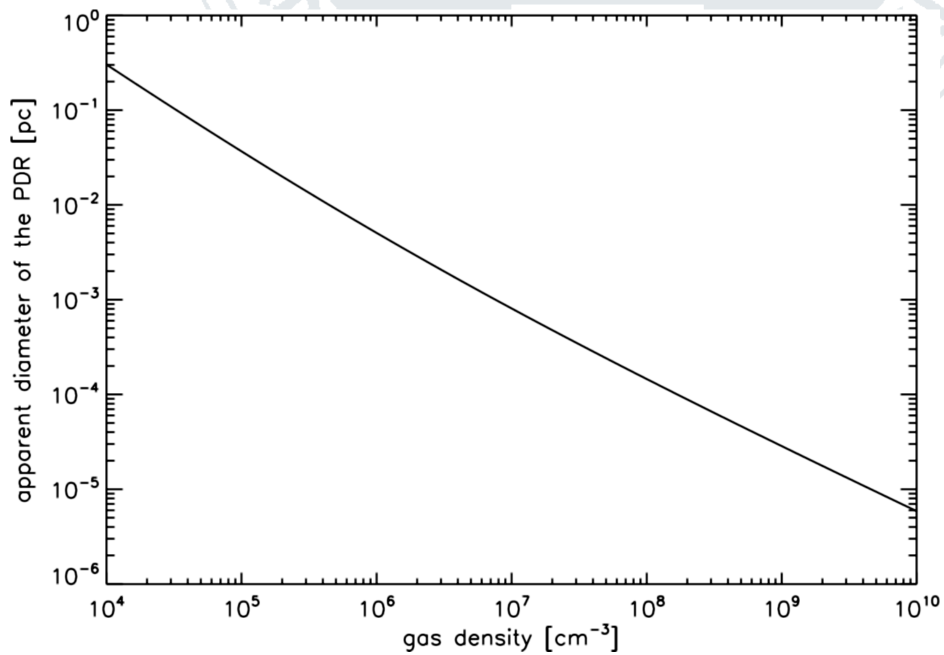
- **Line radiation comes from tiny UV- illuminated volume**
- **FIR continuum comes from large volume heated by NIR/MIR**
  - Size of HII region: $$R_s = 0.68\ \mathrm{pc}\left(\frac{Q}{10^{49}\ \mathrm{s}^{-1}}\right)^{1/3}\left(\frac{T_*}{10^4\ \mathrm{K}}\right)^{0.28}\left(\frac{n}{10^3\ \mathrm{cm}^{-3}}\right)^{-2/3}$$

    Draine (2011)

    - Consistent with observations (IRS1: ≈ 0.001pc, IRS2: < 0.0005pc)
  - Size of total PDR: $R_S + A_V \approx 2$ layer:

$$A_{\mathrm{fs}} = \pi\left(R_s + \frac{3.8\times10^{21}\mathrm{cm}^{-2}}{n}\right)^2$$

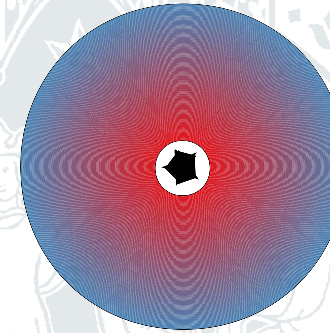
    - IRS1: 0.005~pc, IRS2: 0.002~pc (IRS1 not resolved, IRS2 slightly larger)



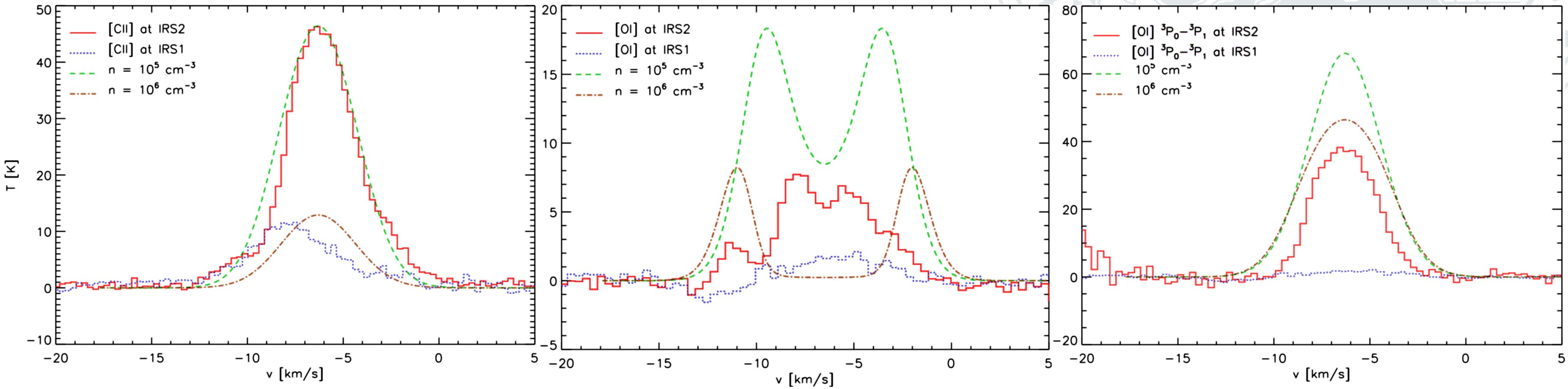
Size of a PDR fed by a star with $10^{46.5}$ UV photons per second as a function of gas density

- Line deficit qualitatively explained by high density, small PDR

Quantitative toy model



- KOSMA-τ PDR model with inside-out chemical and temperature layering
- Two models tested: 10^6 cm^{-3} and 10^5 cm^{-3}
  - No fine tuning of parameters yet
  - Radiative transfer results:



- Reasonable match for IRS2 at 10^5 cm^{-3}, weak 145µm in IRS1 not explained yet
- [OI] 63µm always heavily self-absorbed
  - Estimate only from velocity resolved profiles

Summary

- S140 is an "ultraluminous source" in Galactic context

  → may provide general explanation for line deficit in ULIRGS

  - Here we can exclude other "extragalactic explanations" for line deficit
- Explanation for line deficit in S140:
  - PDRs in small dense cores

    → low beam filling of fine-structure lines relative to continuum

    → negative gradient in excitation temperature for self-absorption

    - Zero integrated intensity possible in case of absorption trunk
    - Correlation with OH absorption expected
      – velocity information is crucial!

- Disclaimer!:
  - No detailed quantitative model yet!
    - IRS2: Source somewhat larger than predicted: Multiple sources/PDRs?
    - IRS1: no fit of **extreme line deficit** yet → requires further modelling efforts

Fine structure lines as star-formation tracers?

- [OI] 63μm is totally useless
  - Various geometries allow for self-absorption as high 98%
  - With strong continuum one will often see negative integrated intensities
- [CII] and [OI] 145μm can be optically thick
  - Only “wrong” by factors 2-5
- The beam-filling problem limits the fine-structure lines as star-formation tracers to sources with known density
  - High density, small PDRs always create a line deficit
  - Predicts an observable age dependence:
    - After 10-50 Ma, the environment should be sufficiently eroded to allow for some UV leakage → line deficit should disappear

- Gas in ULIRG conditions: Main gas cooling NOT though fine structure lines but
  - Direct recombination
  - Gas-dust collisions with dust continuum emission