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The PDR in M17-SW analyzed with FIFI-LS onboard SOFIA

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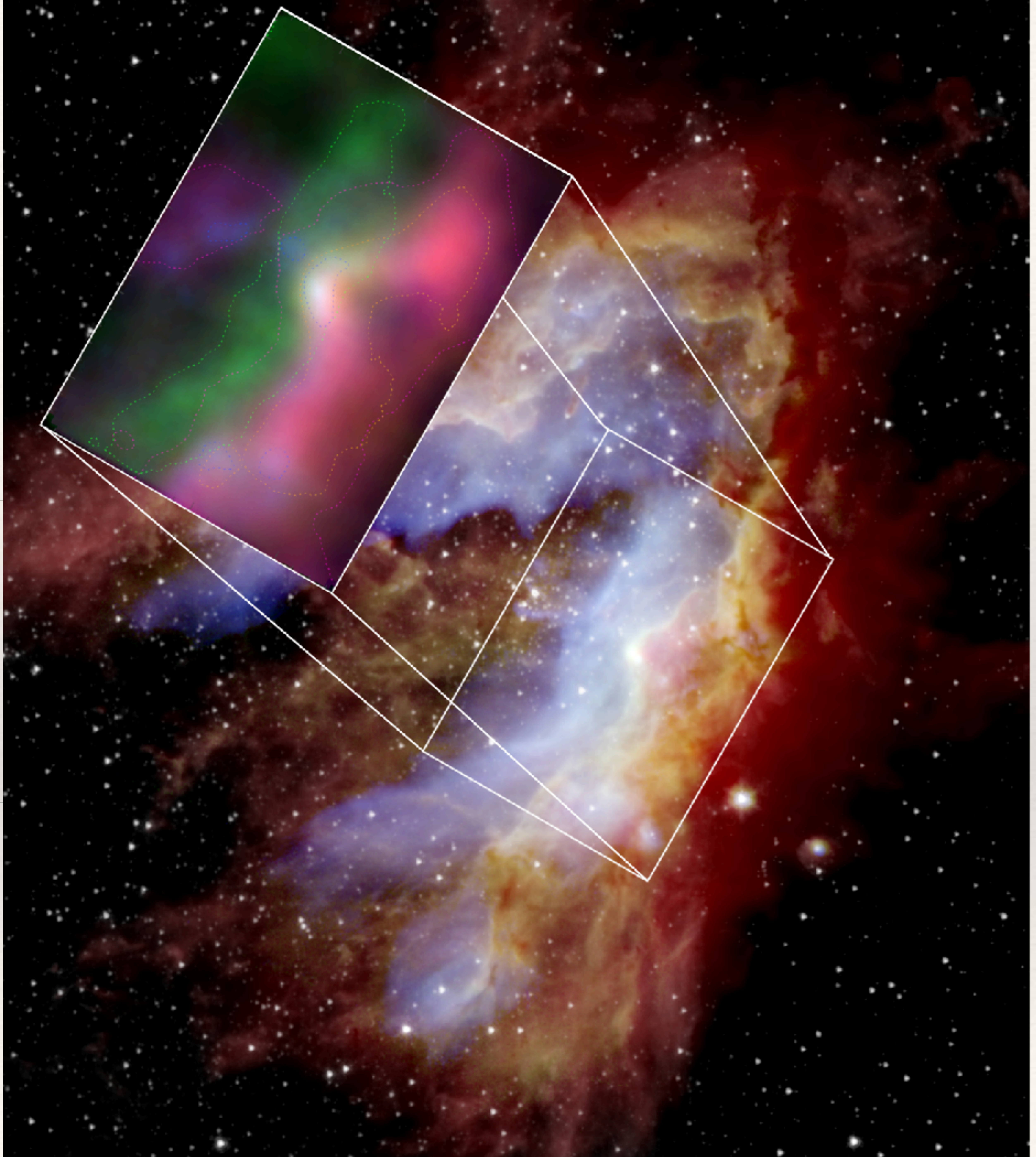
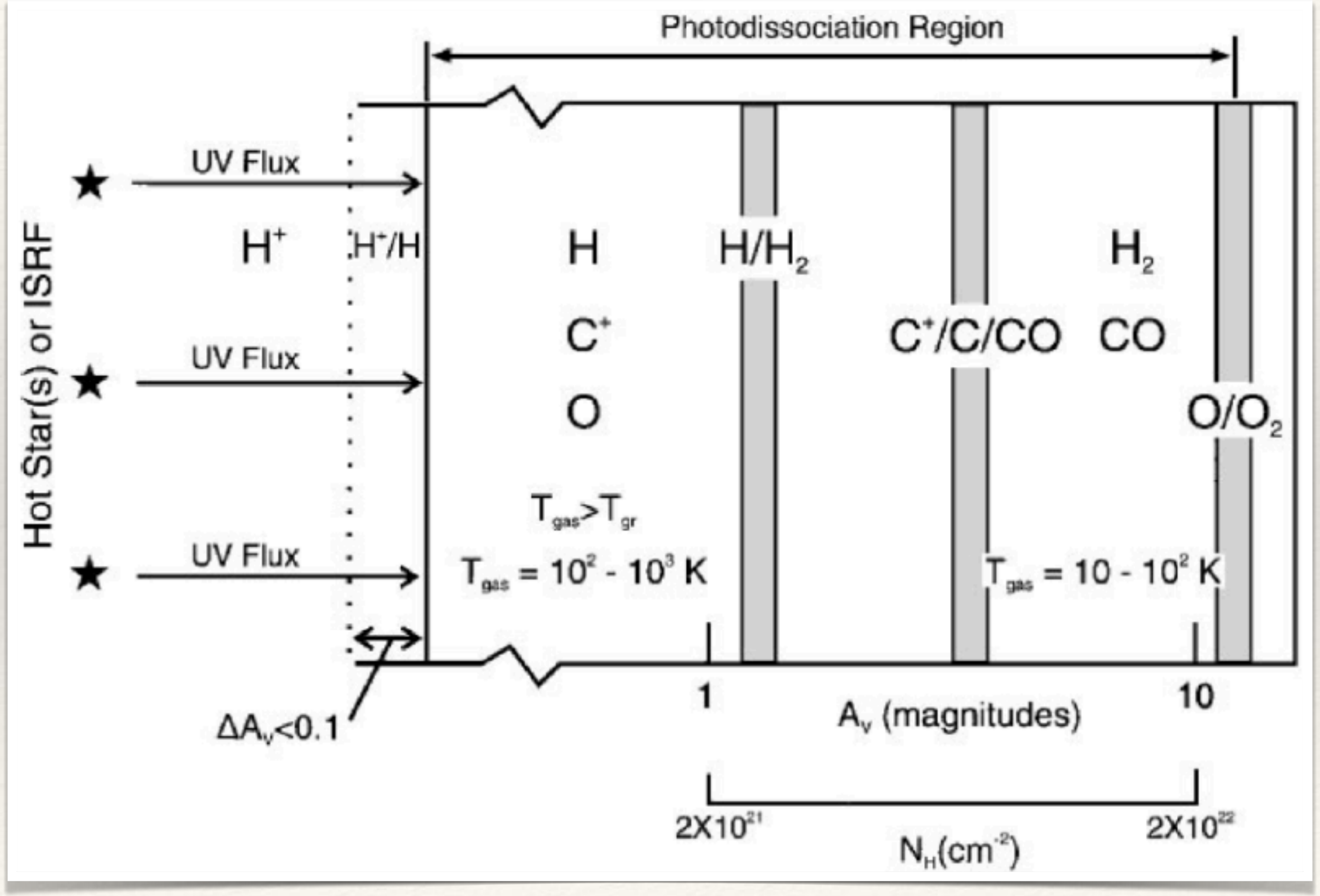


M17 with IRAC, FORCAST, PACS (Lim e al. 2020)

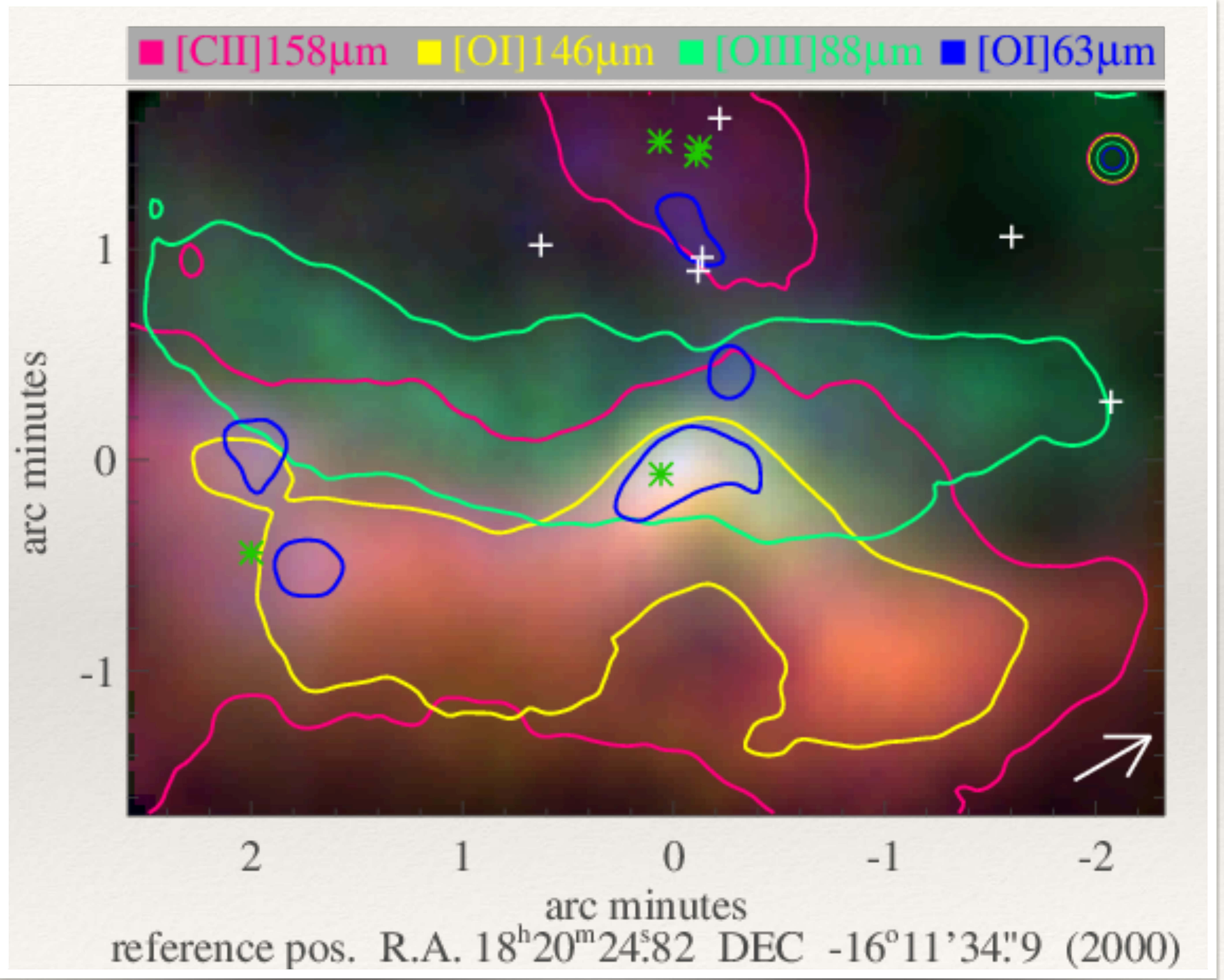
Photodissociation Regions (PDRs)

- The classical schematic of a PDR from Hollenback & Tielens (1997)
- Ionizing stars on the left have created an HII region
- The radiation is eroding a molecular cloud on the right.
- Ionization and photodissociation of different species at different optical depths create various layers.
- The atoms and ions emit fine-structure lines in the far infrared (FIR) largely unaffected by extinction.



Layers of fine-structure lines

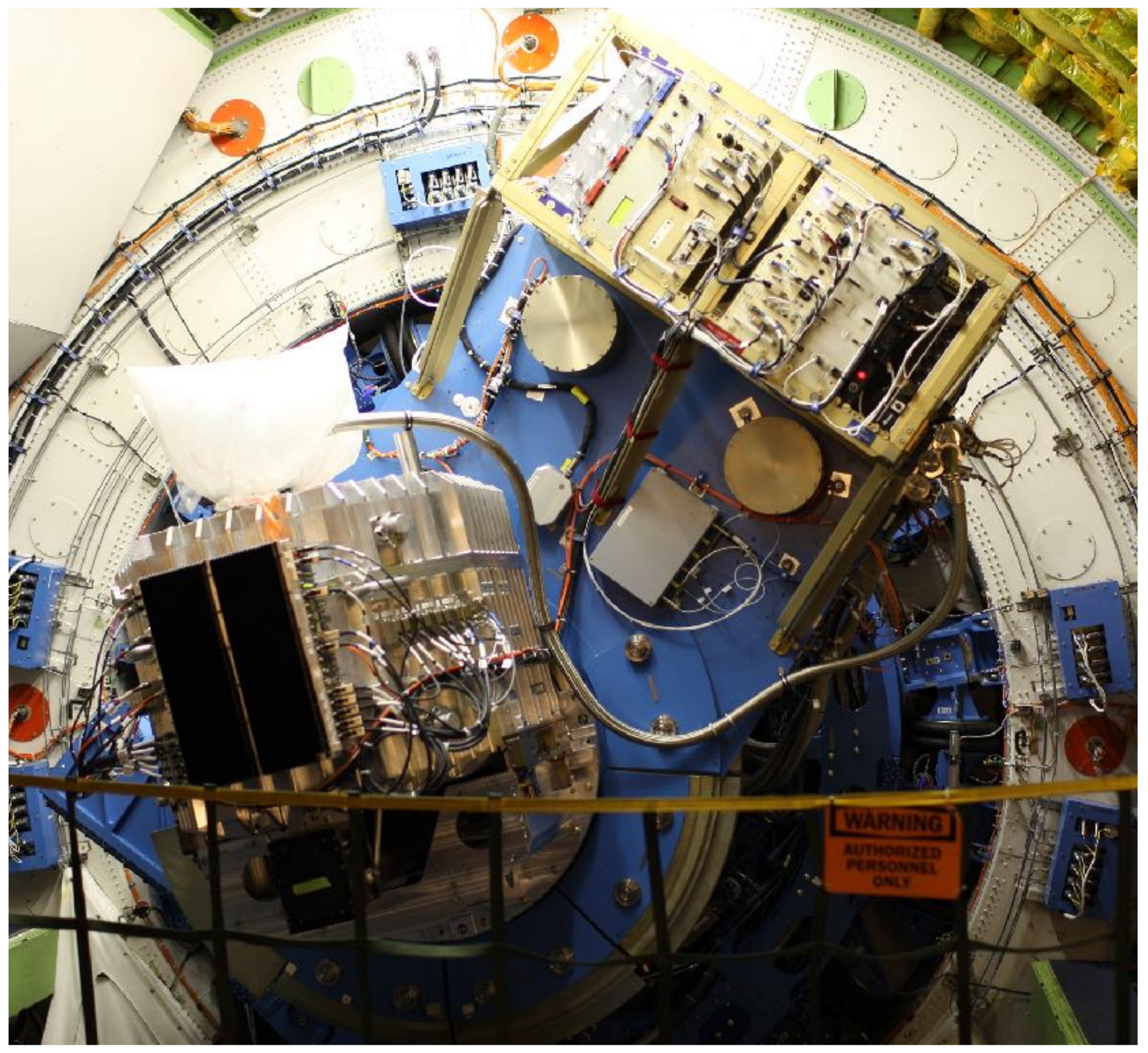
- M17-SW is a well studied edge-on PDR region
- The goal was to create maps of the physical conditions in M17-SW
- We mapped M17-SW in six fine structure lines and three CO lines with FIFI-LS
- Four fine structure lines are shown
- Clear layering of ionized and PDR tracers



[O I]63µm (blue), [O III]88µm (green), [O I]146µm (yellow), and [C II]158µm (magenta); 50% colored contours; circles show respective beam sizes; green stars for spectral types earlier than O9, white crosses for O9 and O9.5 (Hoffmeister et al. 2008); arrow points north

FIFI-LS

- Far Infrared Field-Imaging Line Spectrometer
- Two independent channels in parallel:
  - Blue: 51–125 μm, 5x5 6″ spaxels, 30″ FOV
  - Red: 115–203 μm, 5x5 12″ spaxels, 60″ FOV
- Image slicer rearranges the 25 spaxels onto a pseudo-slit
- Gratings disperse the light onto 16 pixels.
- $R = \lambda / \Delta\lambda = 500$ to 2000.



spaxel = spatial pixel

FIFI-LS

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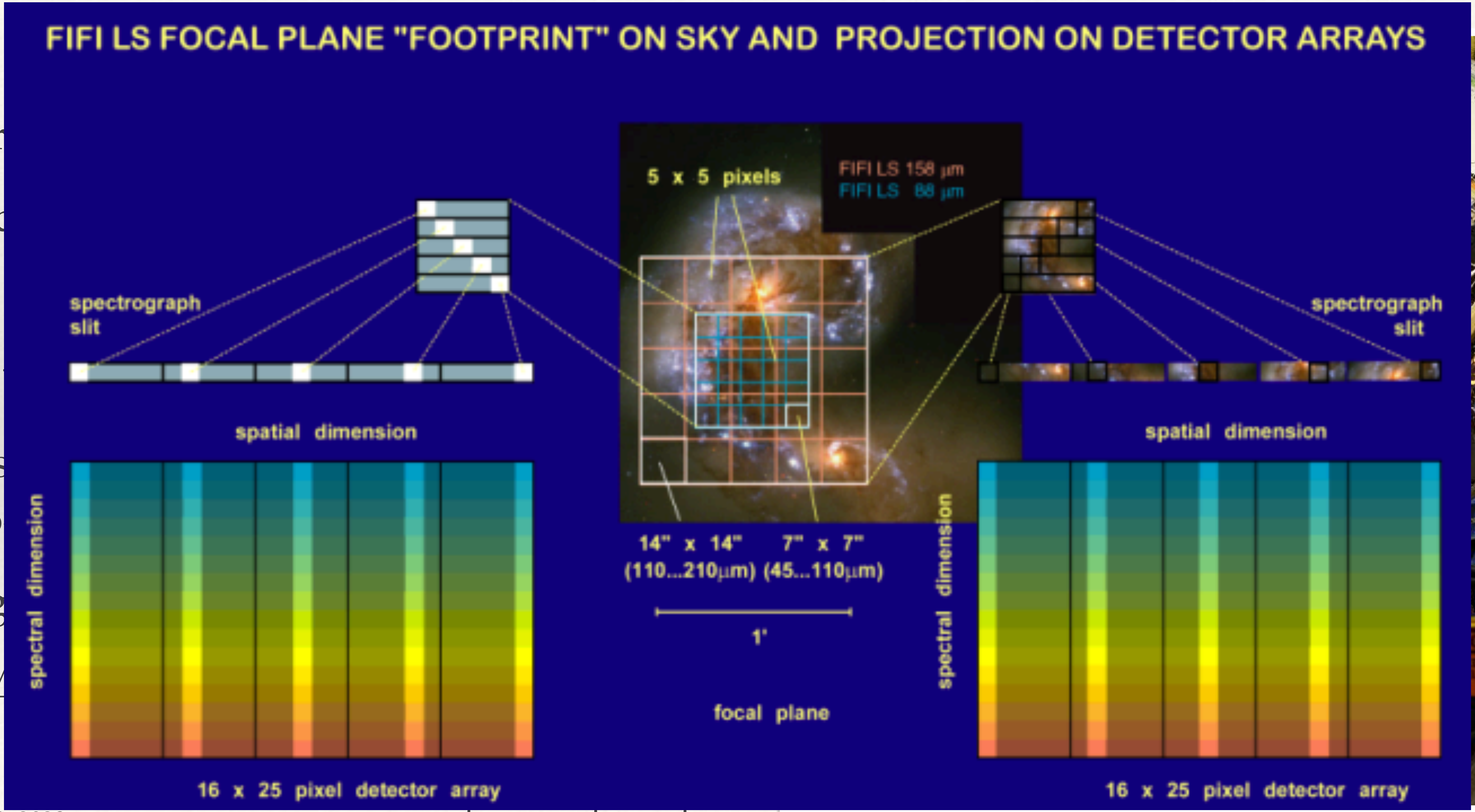
- Two inc
  - Blue:
  - Red:
- Image s pseudo
- Grating
- R = λ/Δ



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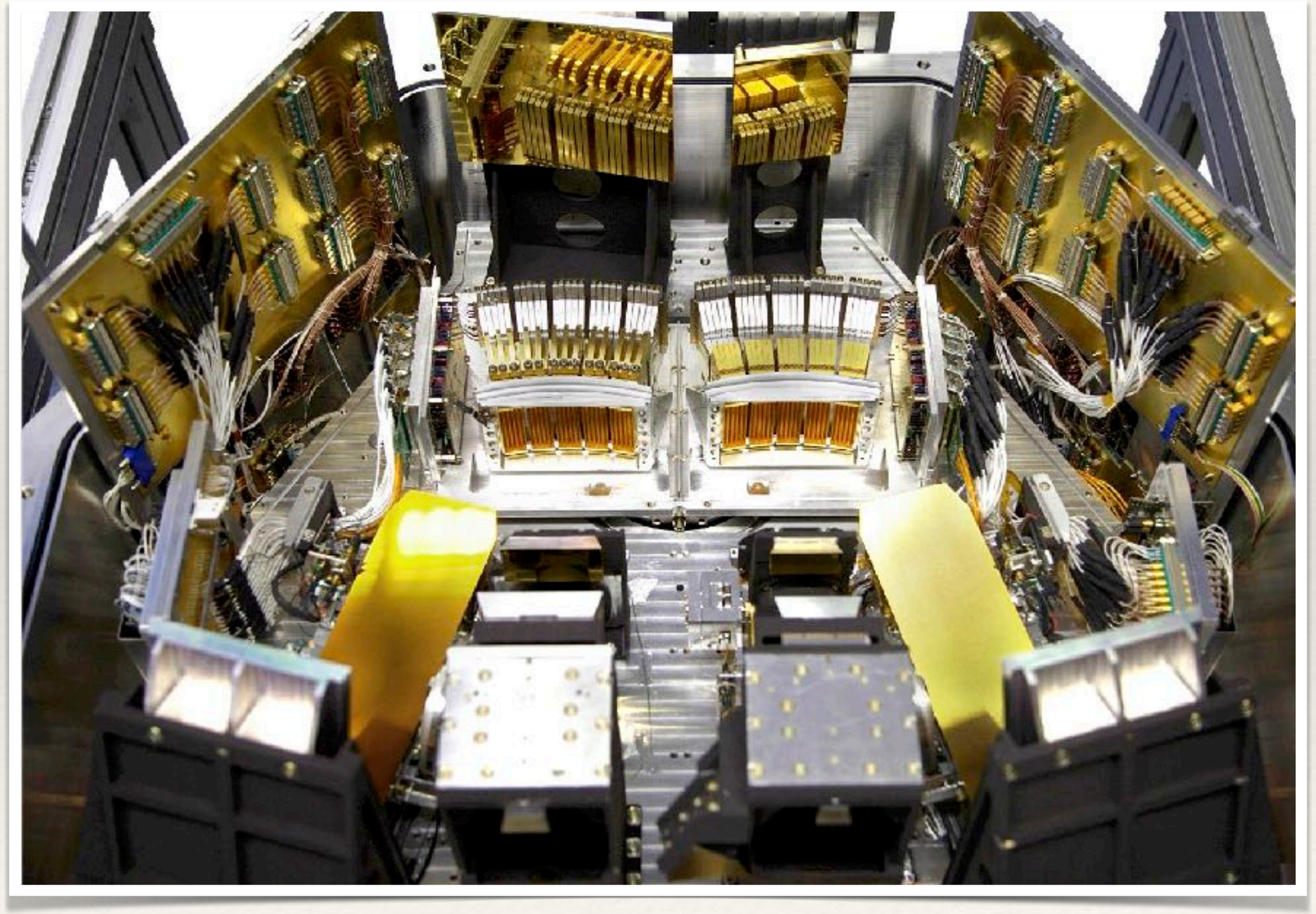


spaxel = spatial pixel

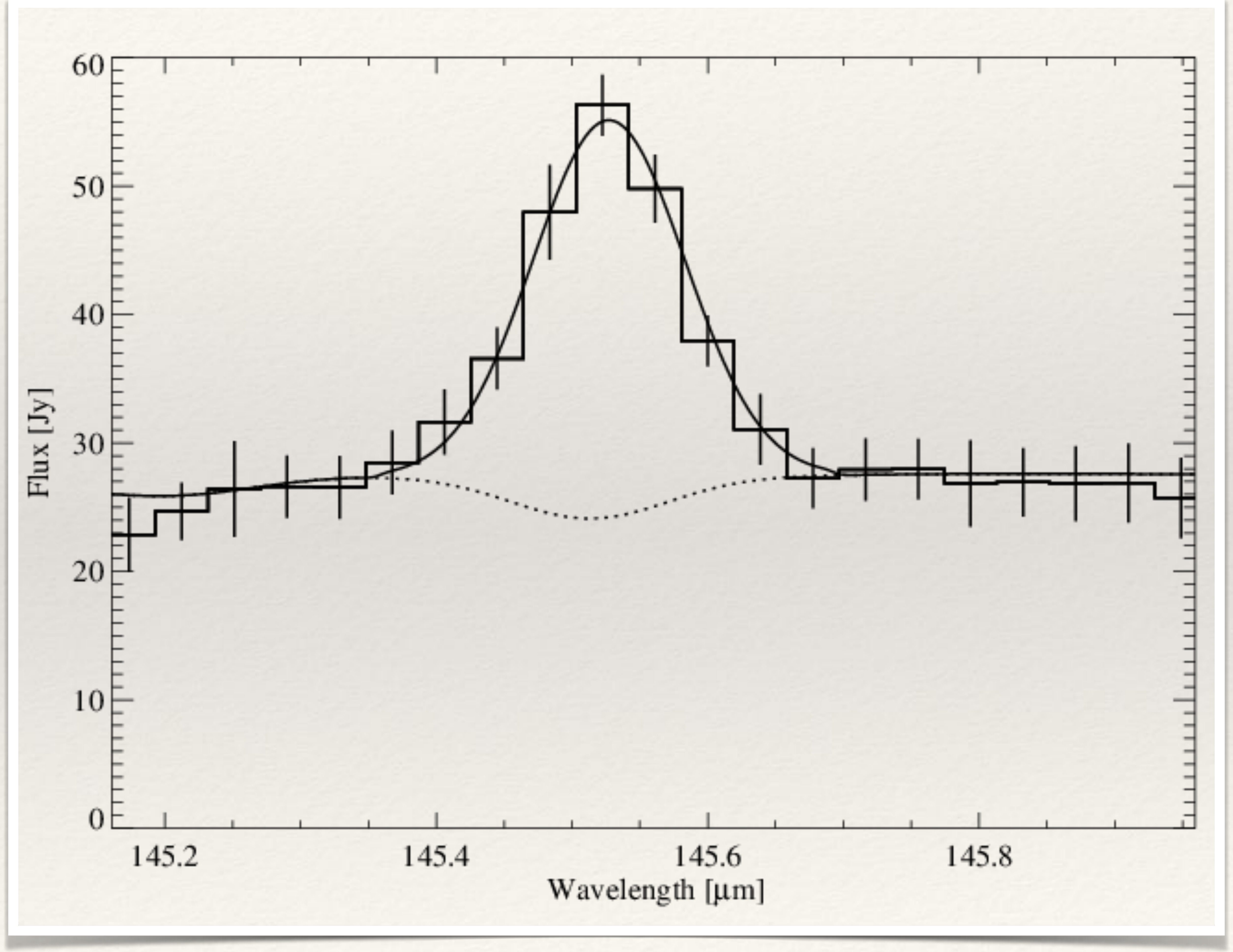
From Data Cubes to Intensity Maps

Simultaneous fitting of:

- Line flux,
- Continuum, and
- Water vapor (main parameter for atmospheric absorption with ATRAN model

Other Parameters set from a-priory knowledge:

- Line center and width
- Altitude and airmass



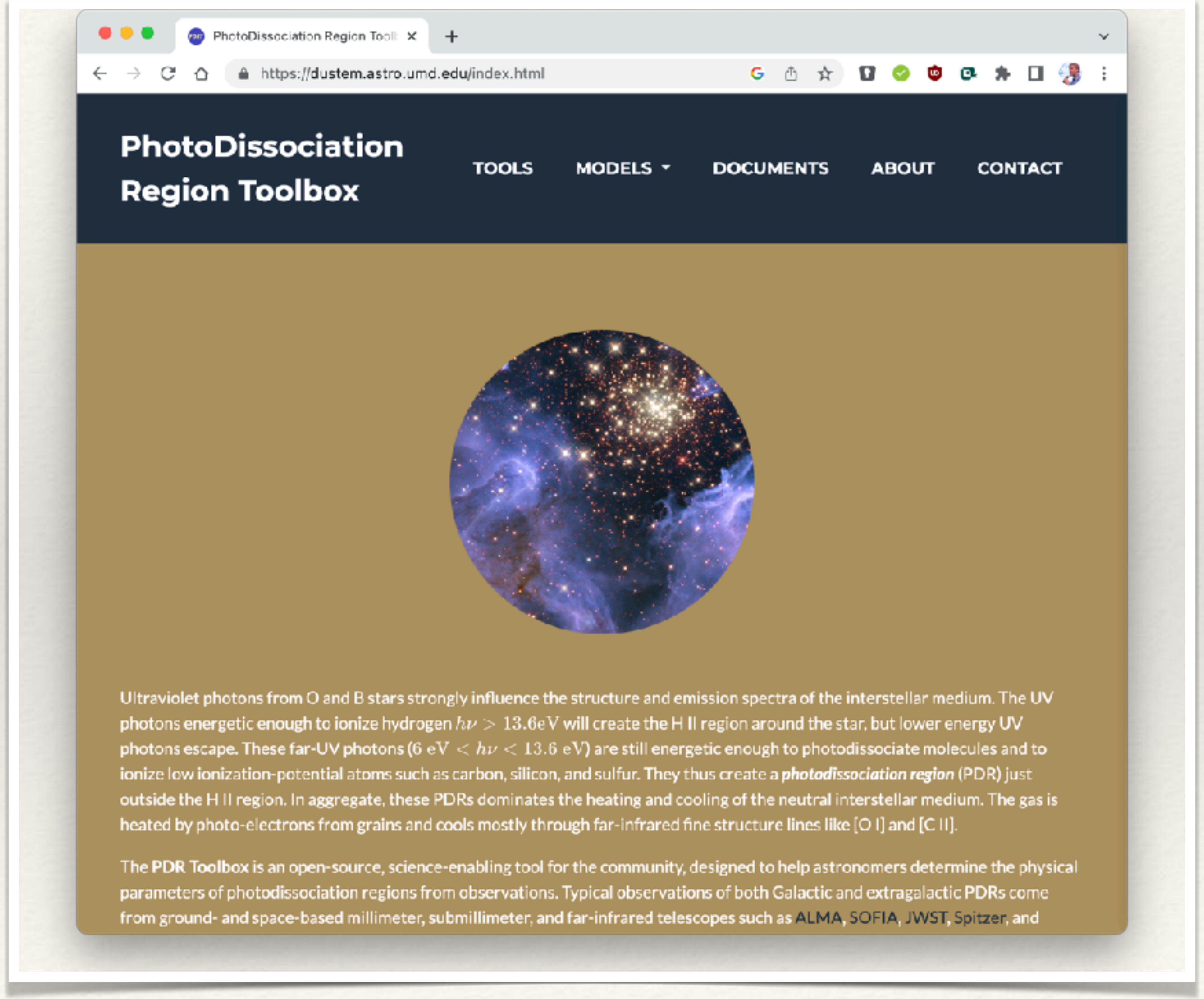
Example fit of an [OI]146μm line

Estimating and Propagating Uncertainties

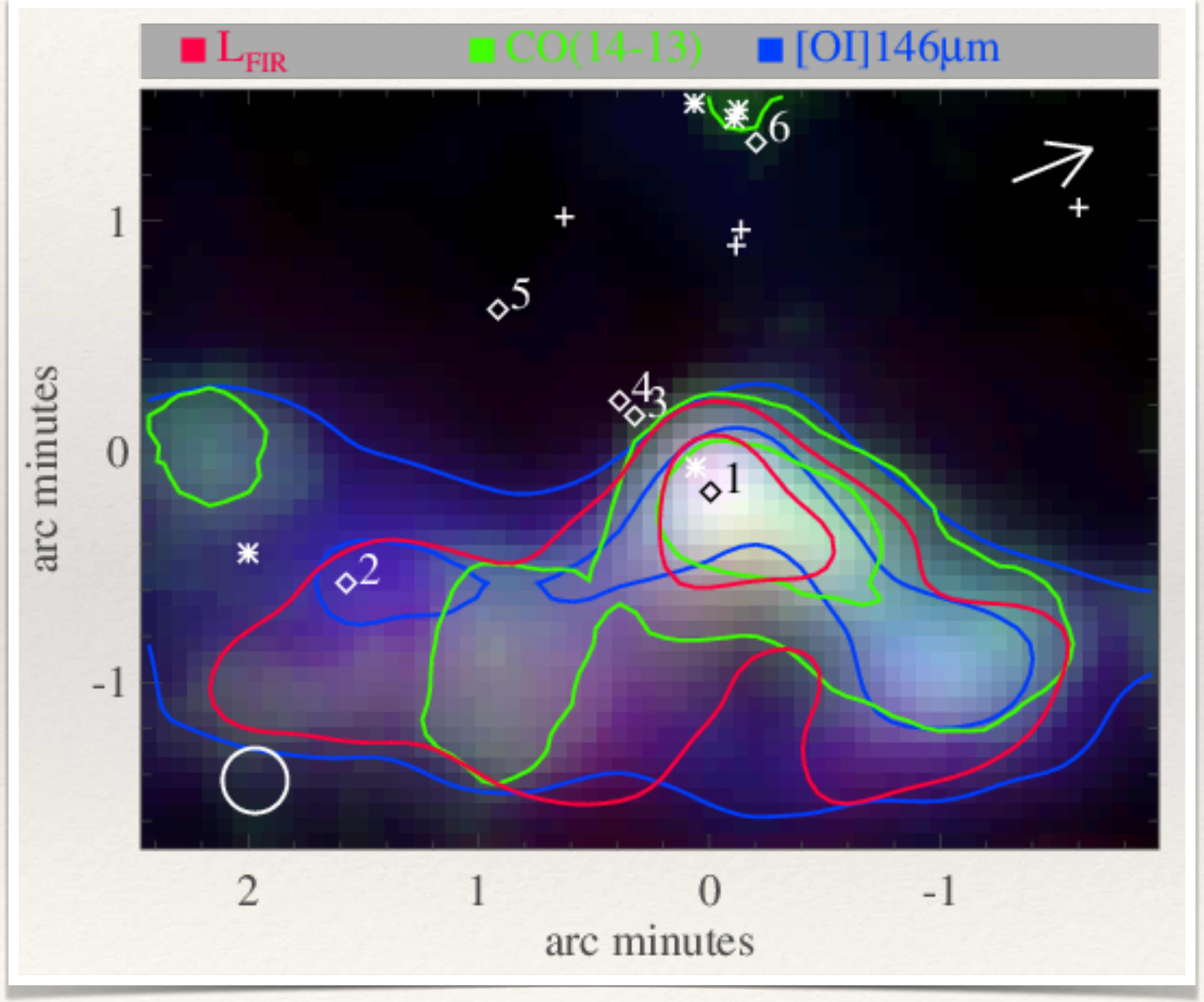
- Data reduction requires re-gridding into a regular data cube
- Uncertainties are estimated from distribution of all measurements around each data cube cell (Dario Fadda, github:darioflute/fifipy/cubik)
  Differs from the pipeline derived uncertainties
- Uncertainties were propagated through the line and continuum fitting
- Data cube is oversampled, thus, neighboring pixels in the data cubes and subsequent maps are correlated on scales of the original beam size
- All the maps have been smoothed to a common spatial resolution for the PDR modeling.
- When smoothing the maps, the noise won't scale down as much as if all pixel were uncorrelated.
- When propagating the uncertainties to the smoothed maps, they were scaled according to their assumed correlation (Klein, R. 2021, RNAAS, 5, 39)

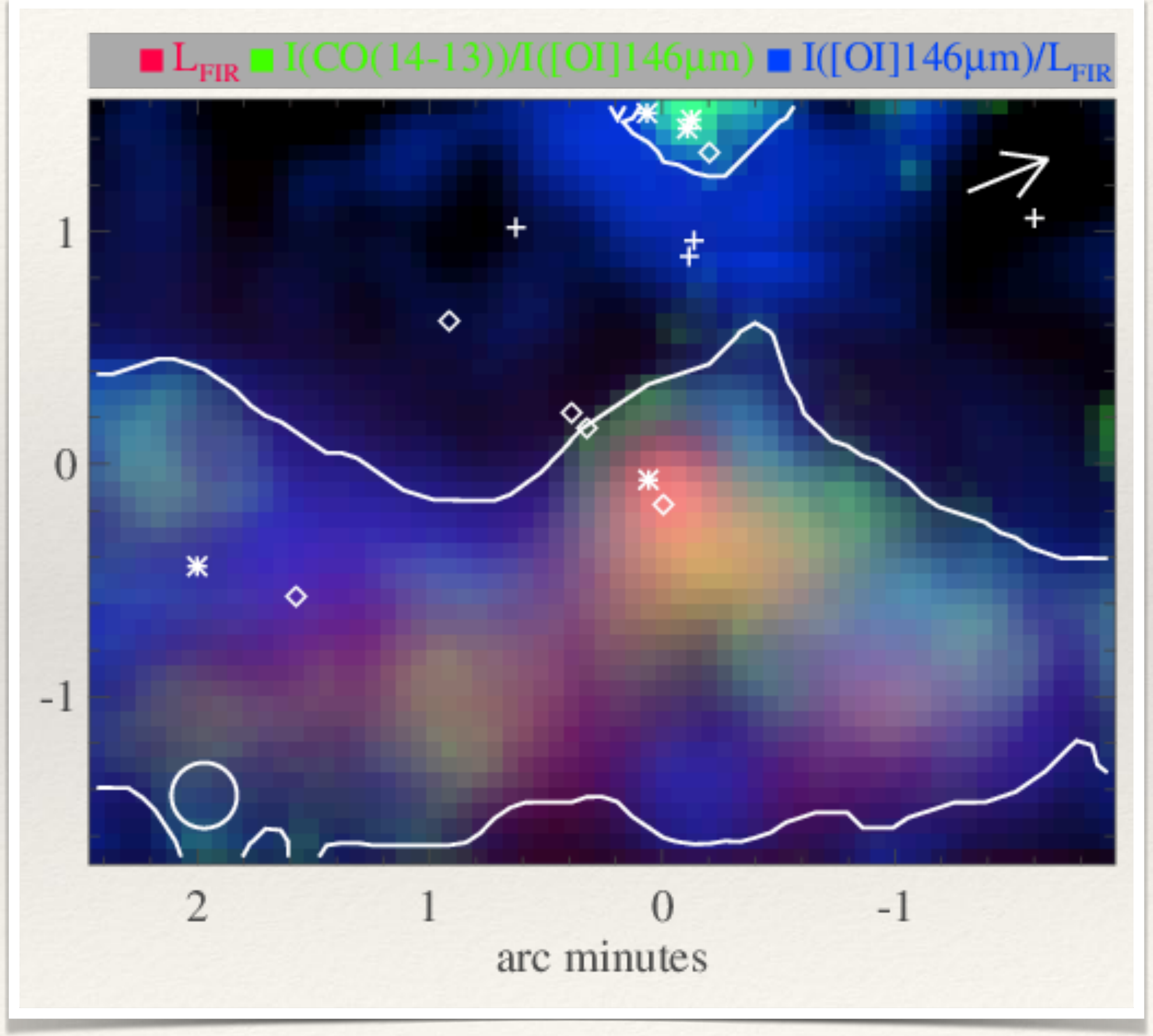
PDR modeling with PDR Toolbox

- PDRT provides pre-computed model grids for PDR models and Python code to fit observations
- While we used it, there was a web interface.
- We downloaded the model (now available as wk2006) and coded the same fitting algorithm in IDL to fit not one point, but the whole maps (point by point)
- The model wk2006 is a one-dimensional face-on model.



Input Quantities





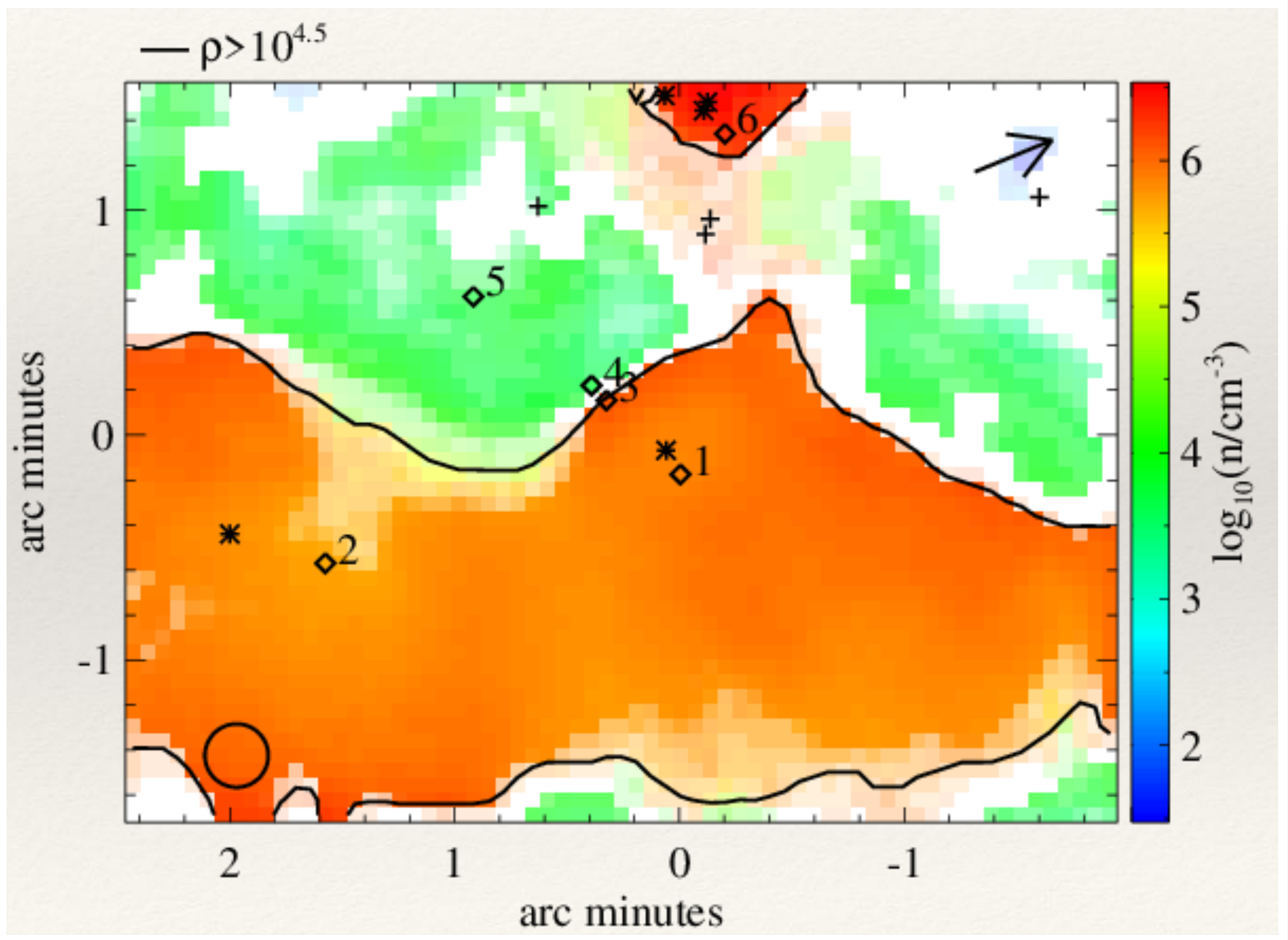
Intensity maps of L_{FIR}, CO(14-13), and [OI]146μm

Only L_{FIR} was used as absolute quantity, ratios were input parameters

PDR Modeling Result

- Hydrogen density map: a clear distinction between
  - a high density (~$10^6 cm^{-3}$) and
  - a low density (~$10^4 cm^{-3}$) solution

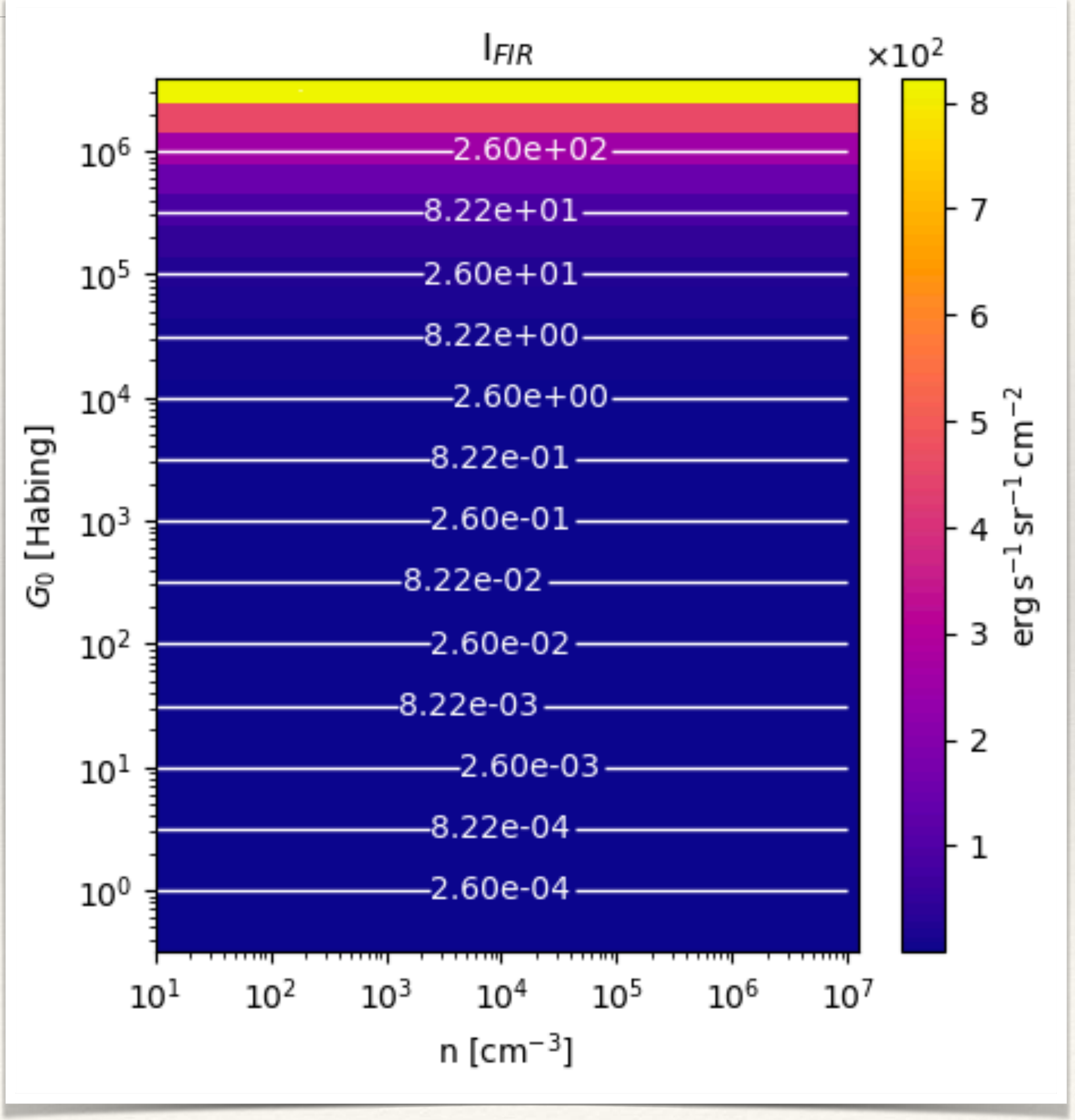
Let's see how this density jump comes about.



The color saturation starts to fade at an uncertainty of 0.2 dex and reaches white at an uncertainty of 1.25 dex.

Anatomy of the PDR Model

- The PDR Toolbox provides predictions of line intensities and ratios as a function of:
  - Density *n*
  - UV intensity G_0
- As a simple example:
  Total infrared intensity
  The IR intensity depends only on G_0, because it is assumed that all of the UV radiation is absorbed in the molecular cloud and reemitted in the IR.



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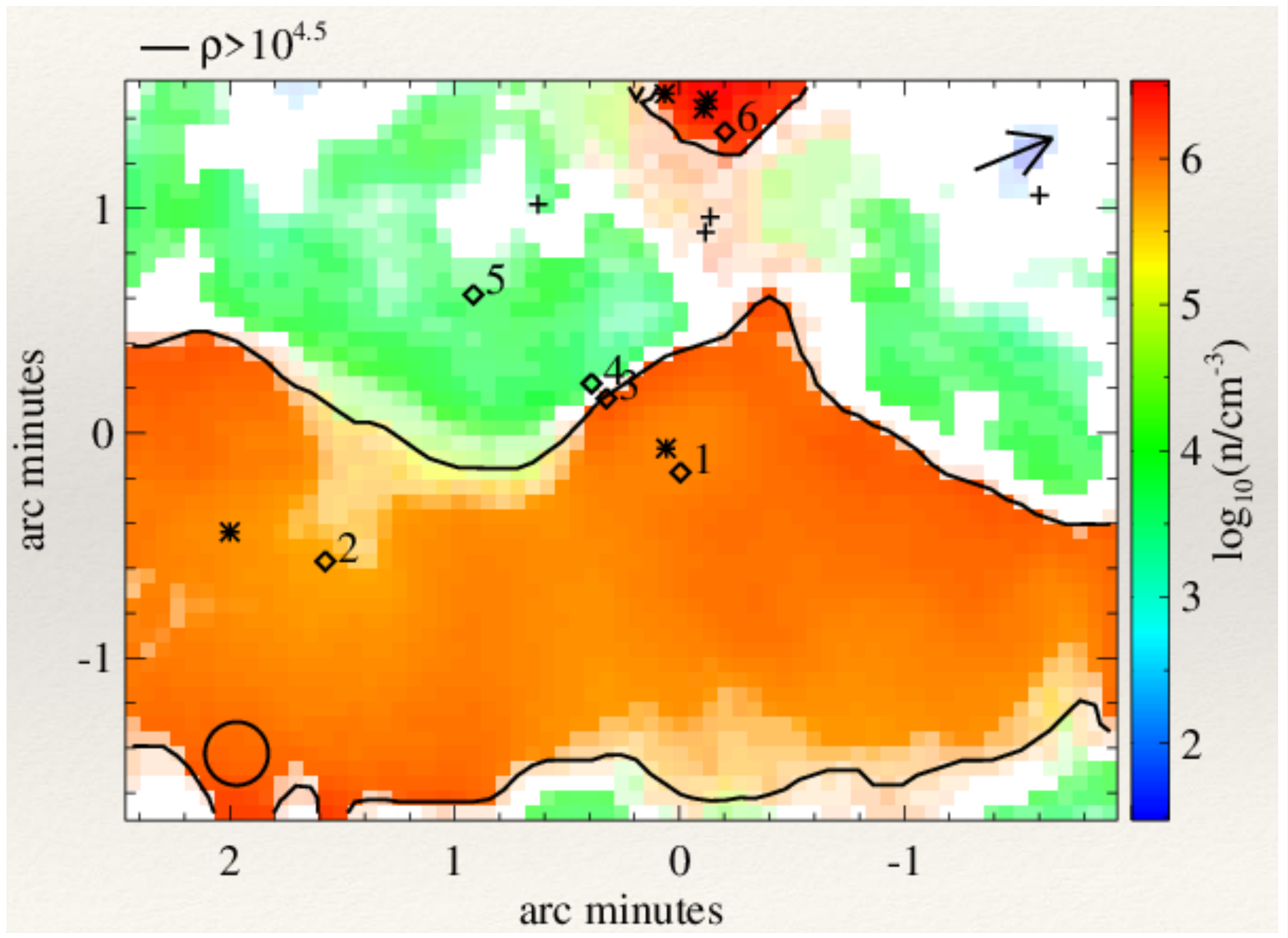
Let's see how this density jump comes about.

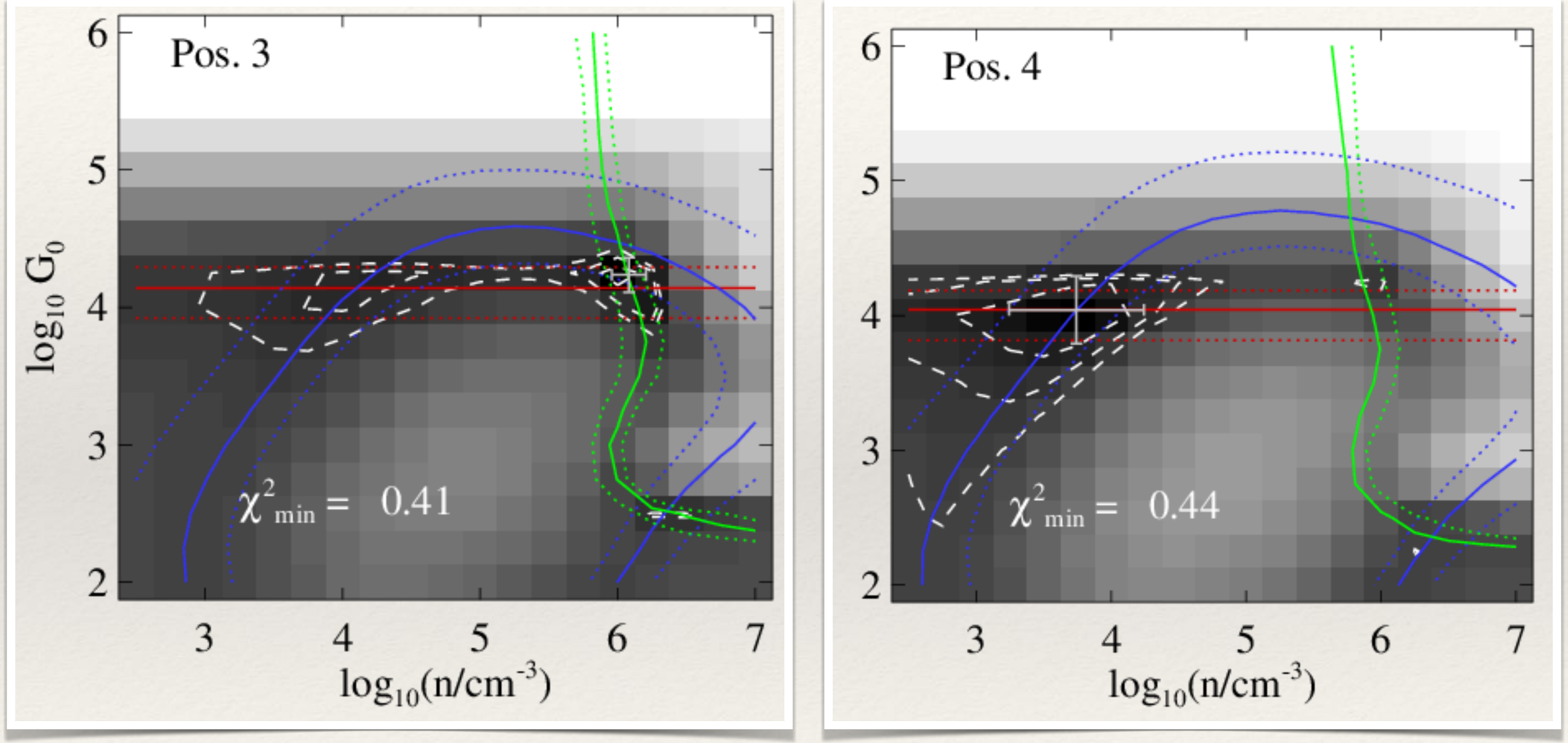
- Let's look at how the solution changes between positions 3 and 4



The color saturation starts to fade at an uncertainty of 0.2 dex and reaches white at an uncertainty of 1.25 dex.

Anatomy of the PDR Model

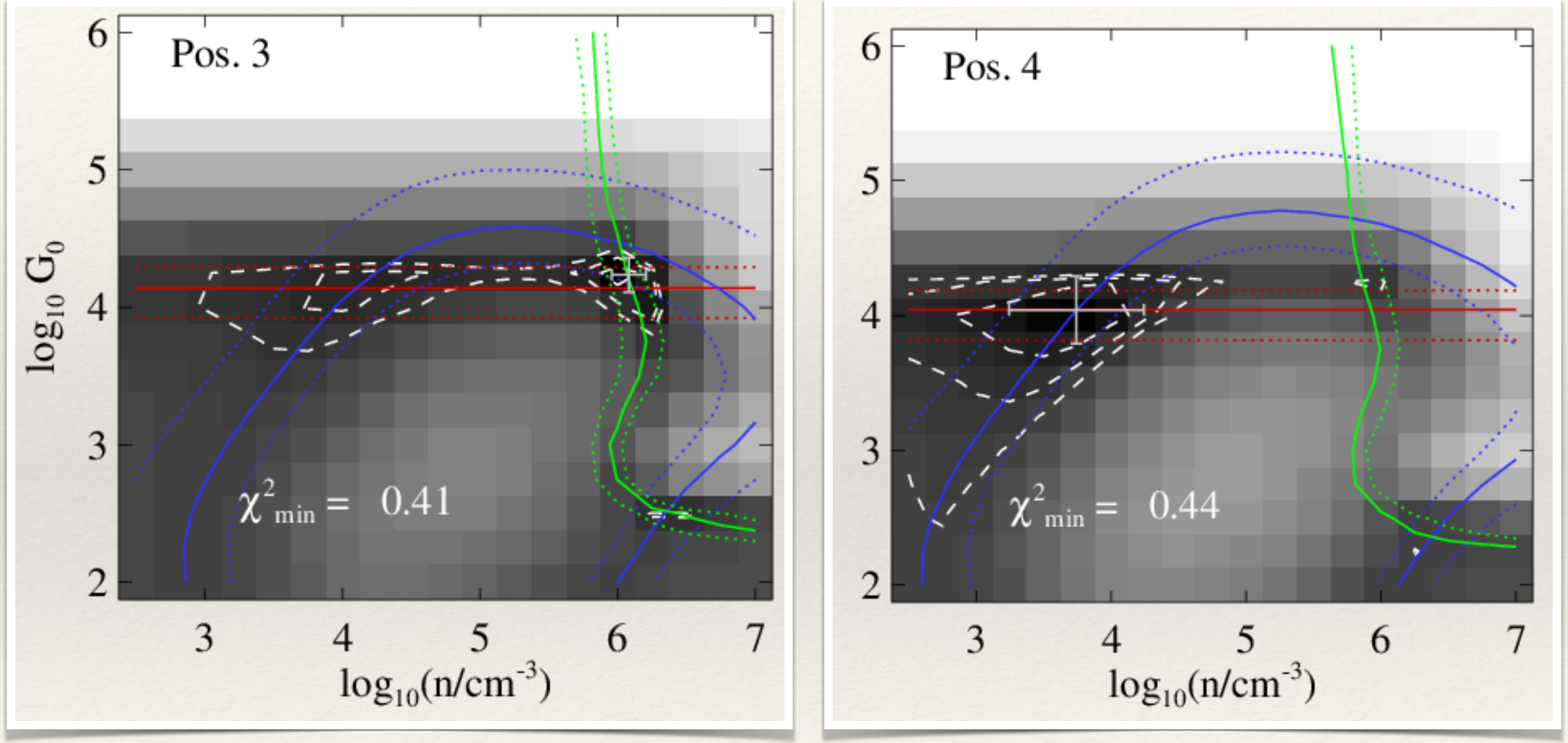
- Solid lines: Where the measured quantity is predicted
- Dotted lines: 1sigma error
- Cross and dashed lines: least chi² and +1 and +3 contour



red: I_{FIR} , green: CO(14 → 13)/[O I]146 μm, blue: [O I]146μm/I_{FIR}

Anatomy of the PDR Model

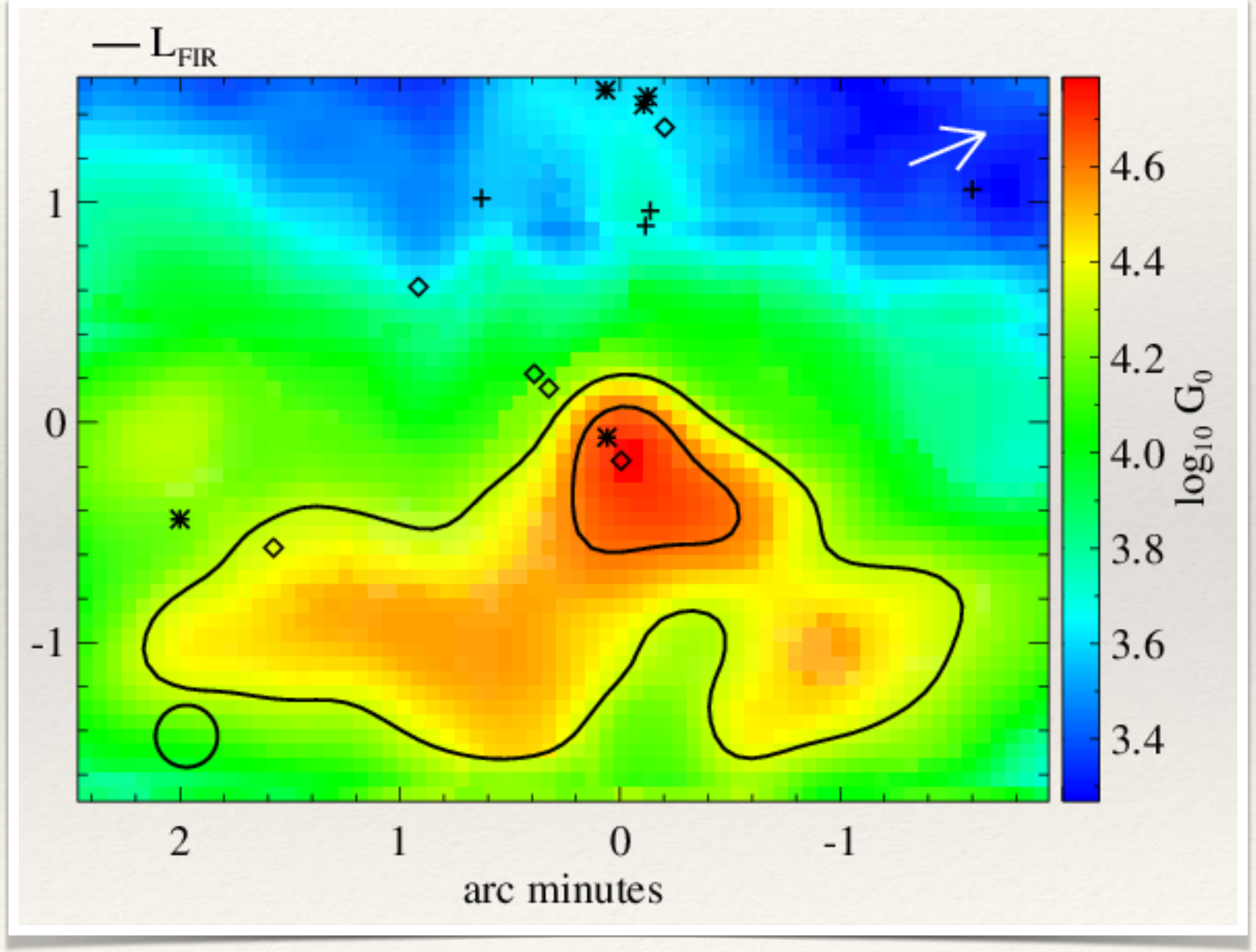
- CO(14 →13)/[OI]146μm is a good density constraint or
upper limit.
- IFIR and OI/IFIR can have two density solutions.
- Density jump results from jumping from one to the other solution.



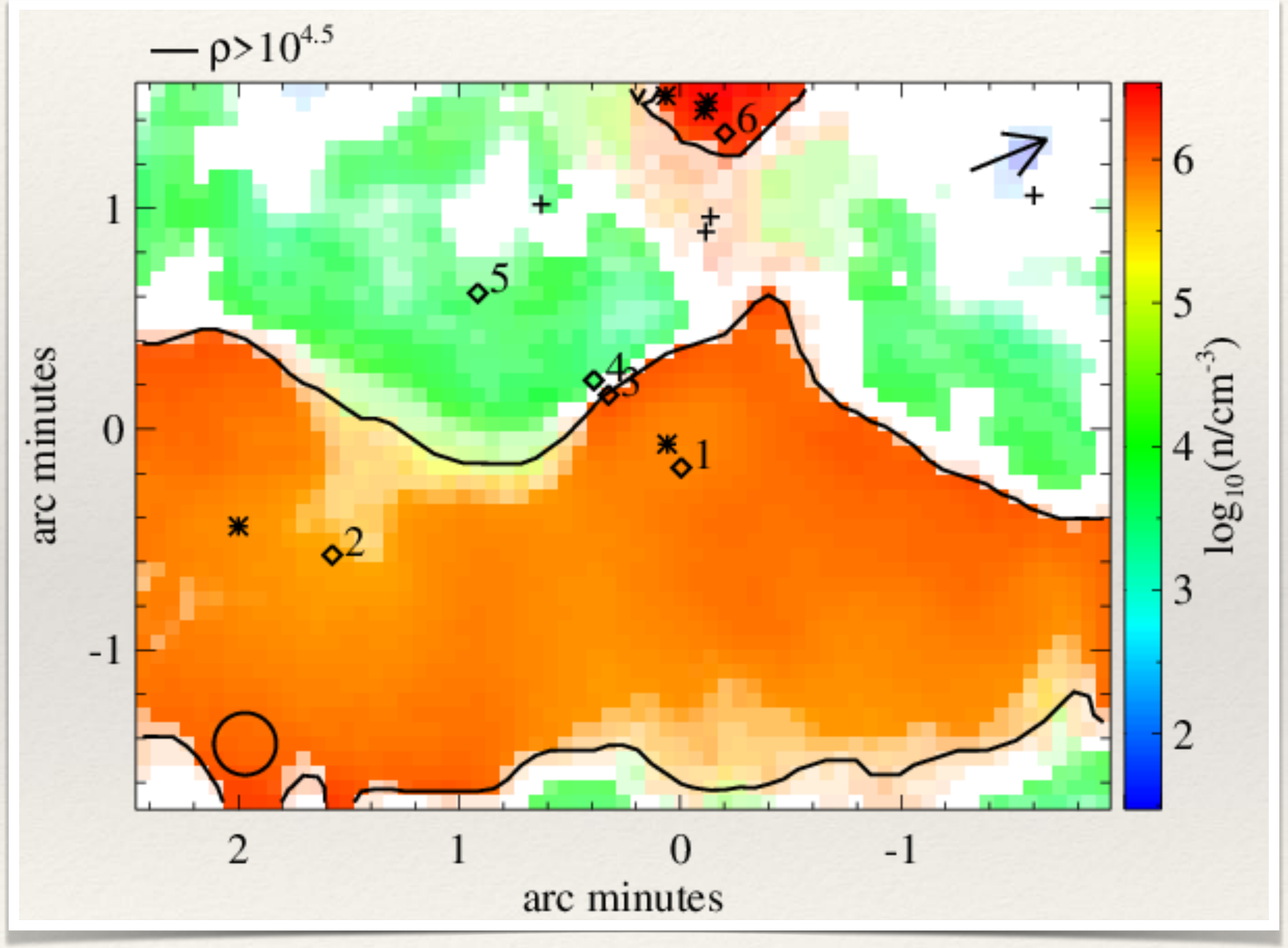
red: I_{FIR} , green: CO(14 → 13)/[O I]146 μm, blue: [O I]146μm/I_{FIR}

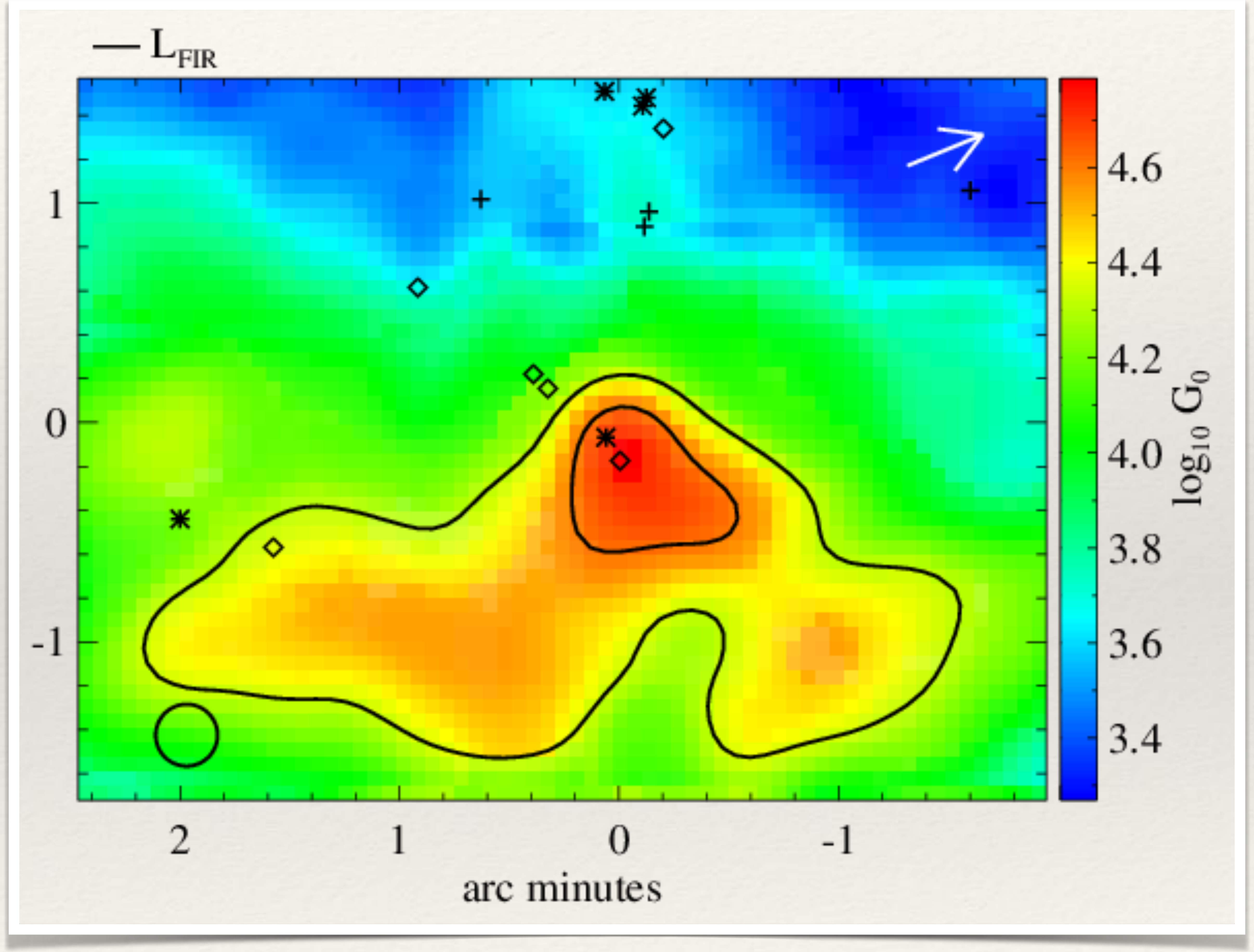
PDR Modeling Result

- The derived UV field follows closely the IR intensity by the models design.
- The black contour is actually the IR intensity while the map is G_0.



PDR Modeling Result





We used a PDR model, but the low density region is a HII region. The model is not applicable there, only in the high density region. The low-density solution is only an upper limit to the density in the HII region.

Why weren't [CII] and [OI]63μm included in the modeling?

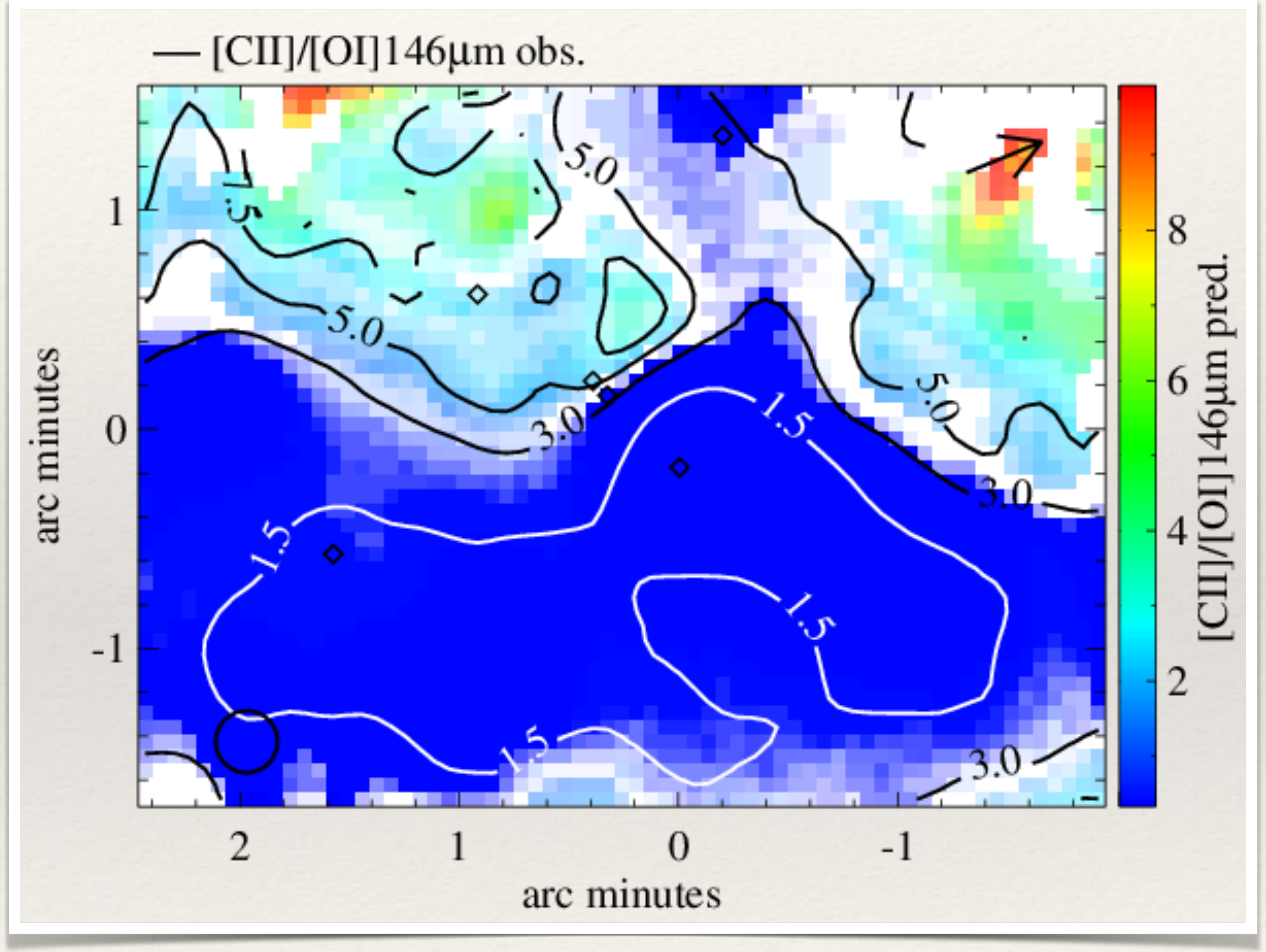
- Optical depth effects!
- The model is face-on, but the M17-SW PDR is edge-on.
- The intensity of potentially optically thick lines as [CII] and [OI]63μm will depend on the depth into the PDR.
- Only optically thin lines and the IR intensity were used for the model as they won't be affected by the depth into the cloud.

But we can compare predictions for the optically thick lines to the observations.

Predictions vs Observations

[CII]/[OI]146μm:

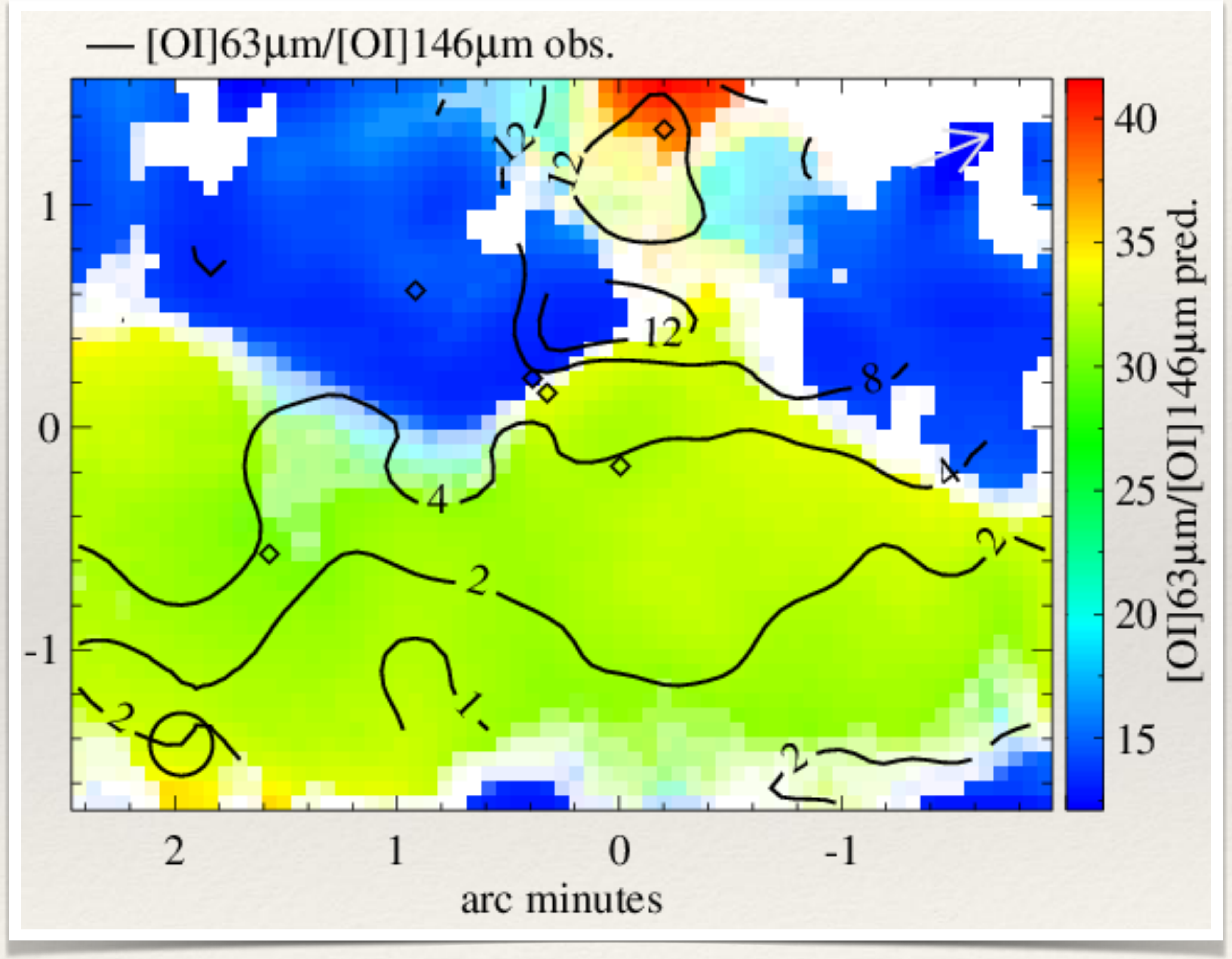
- ~4x more [CII] rel. to [OI] observed than predicted.
- Even when subtracting ubiquitous [CII] foreground emission still ~2x more
- The excess [CII] must be from other phases not associated with the PDR (foreground, HII,…)



Predictions vs Observations

[OI]63μm / [OI]146μm:

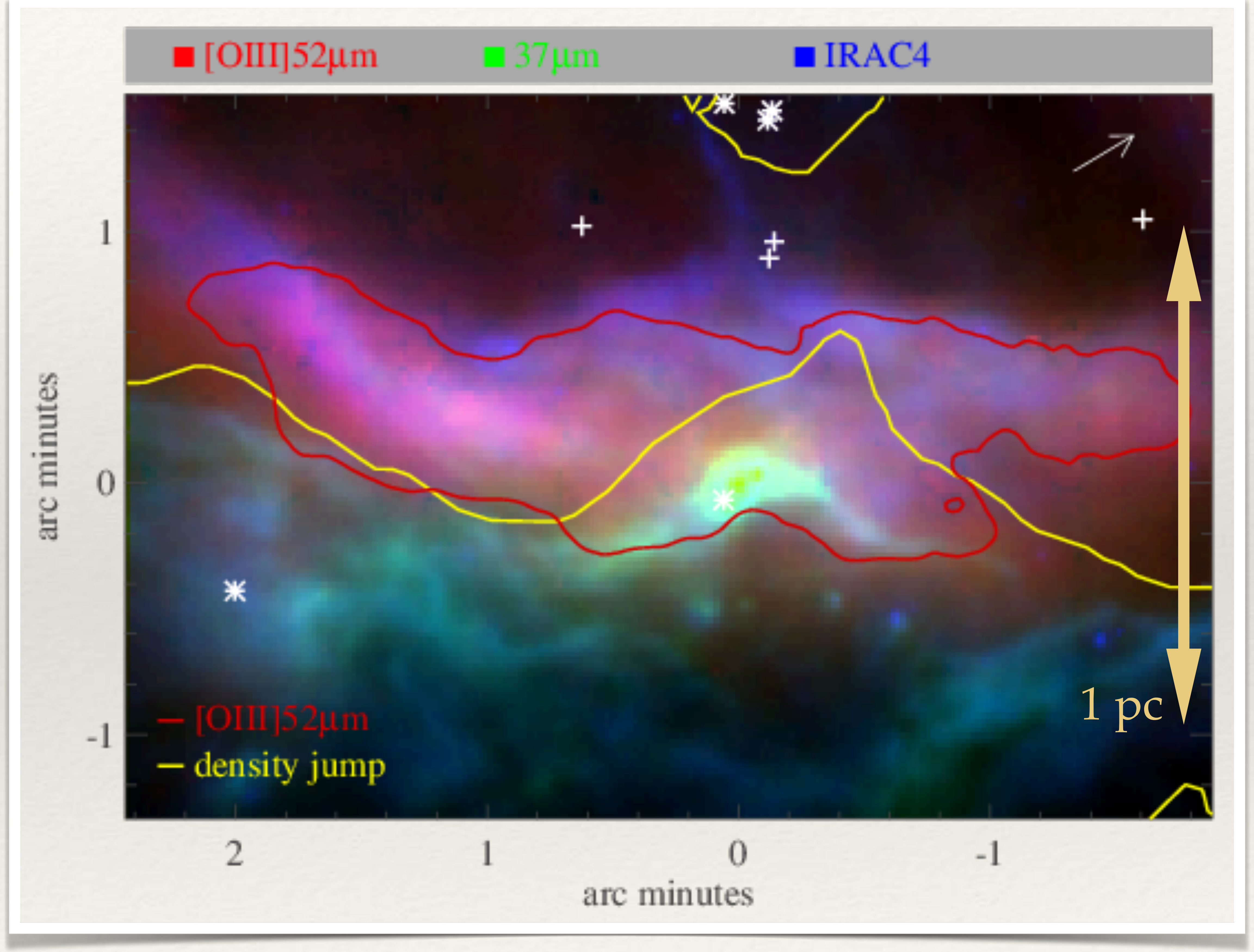
- 63μm line predicted ~30 times stronger than the 146μm line
- Observed ratios in the PDR decrease from ~10 to ~1
- Plausible scenario: A highly self-absorbed 63μm line with increasing optical depth into the PDR
- Note: the lower level of 63μm line is the ground level, while the lower level of the 146μm line is the upper level of the 63μm line. Thus no self-absorption to be expected in the 146μm line.



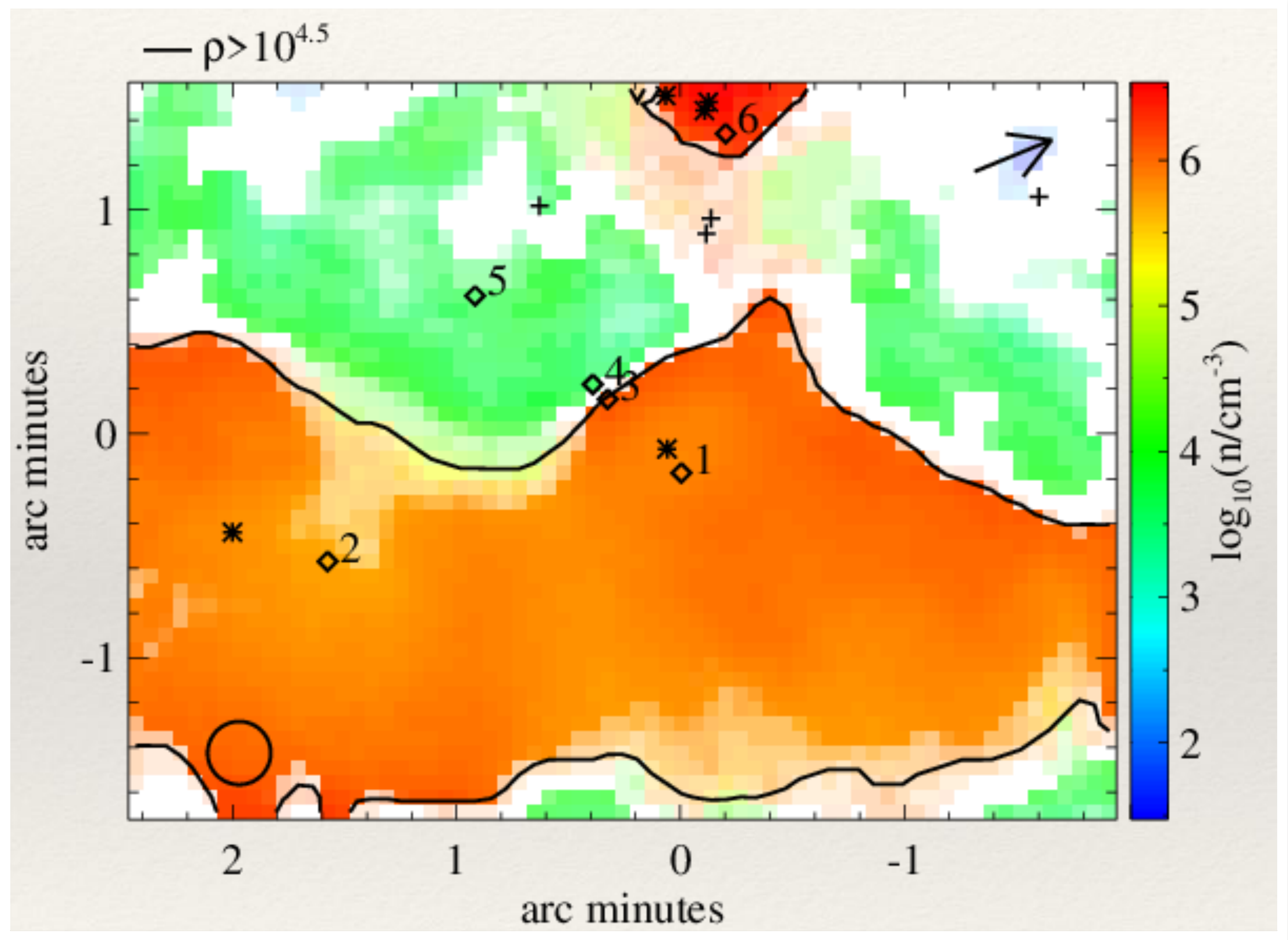
The Fronts

Is the density jump the location of the ionization and photodissociation front?

- The different tracers form layer there.
- A clump with M17-UC1 is poking into the HII region
- Similar sharp layers seen in infrared H_2 and Br_γ observations (Burton et al., 2002)
- With these densities and UV fields the distance between both fronts: 10^{-3}pc to 0pc
- The front should be between the layers about where the model determined the jump.

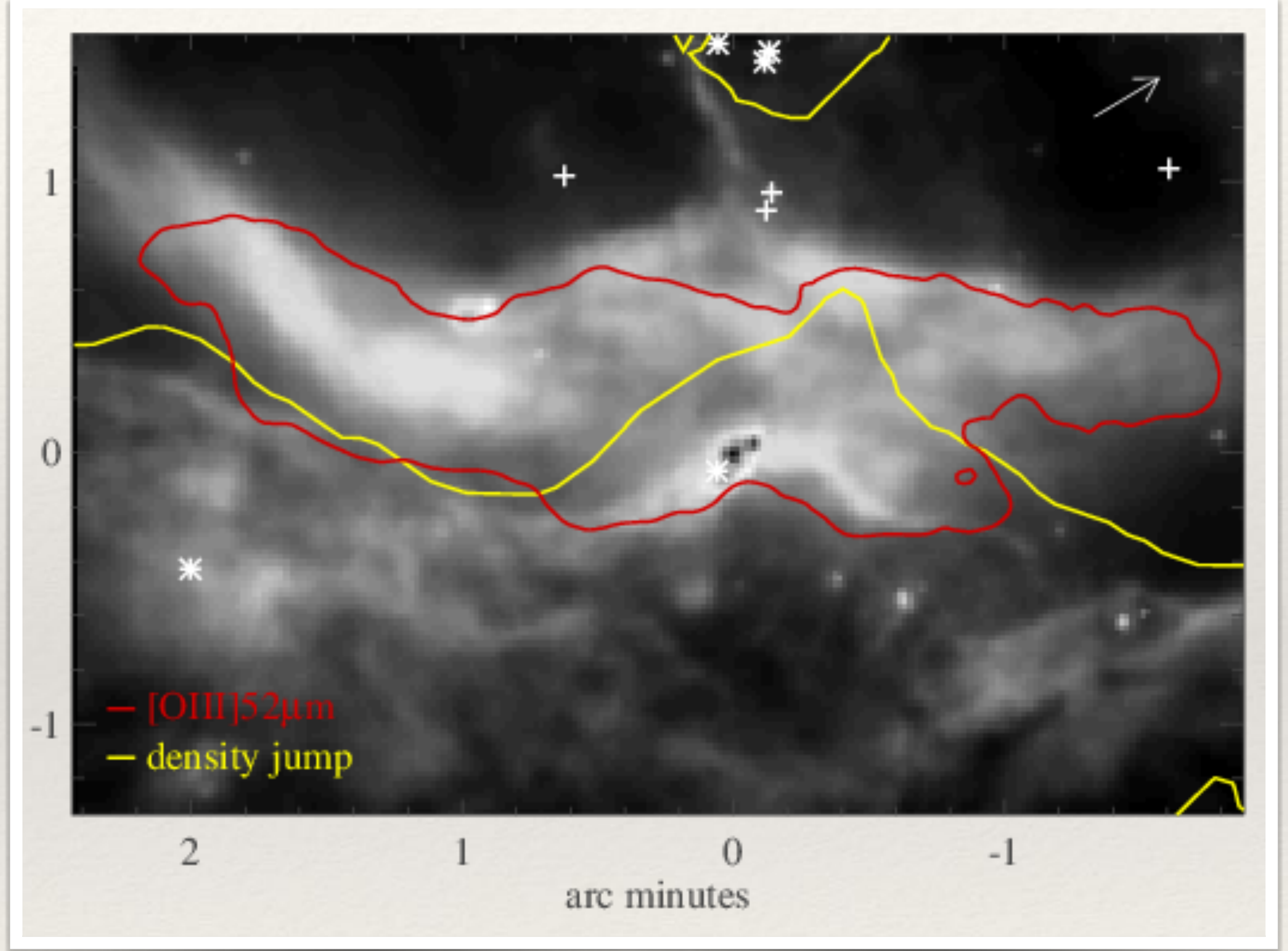


The Pillar



- High density solution extending into the HII region

IRAC 4



- Matches the pillar seen by IRAC and FORCAST (Lim et al., 2020)
- High density ridge irradiated from stars inside the HII region

Summary

We…

- mapped several FIR transitions with FIFI-LS/SOFIA.
- derived H density and UV intensity matching literature values.
- now have maps (0.2pc resolution).
- located the PDR fronts on these maps.
- see ubiquitous [CII] emission and optical depth effects in the [OI]63μm line.
- confirm the presence of an irradiated "pillar" in M17-SW.