Understanding the Orion Bar stratification

"KOSMA-τ-3D"

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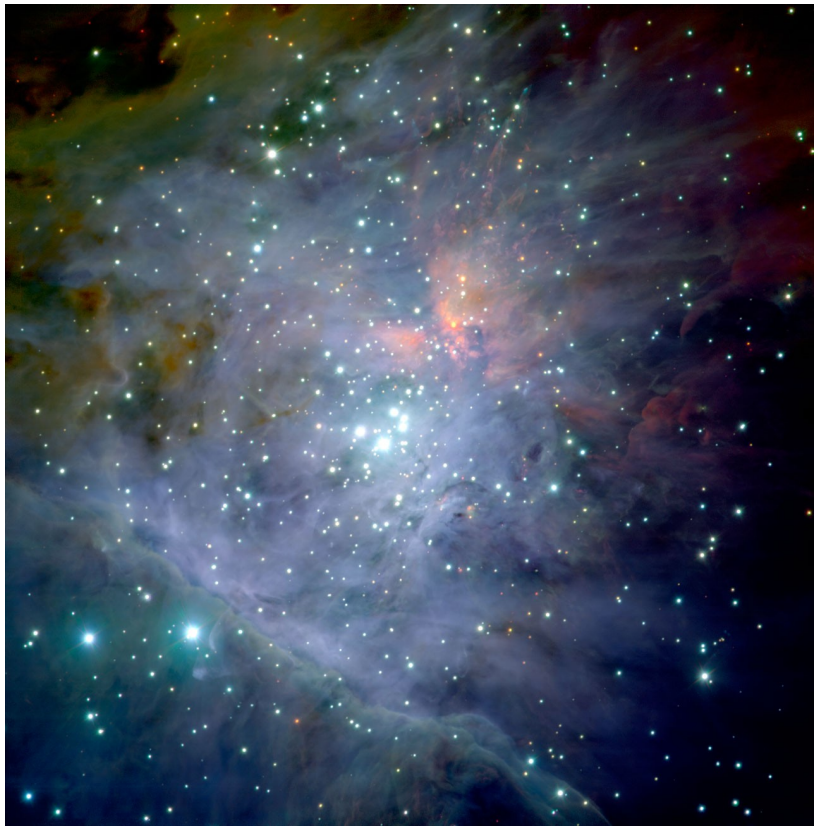
Main characteristics:

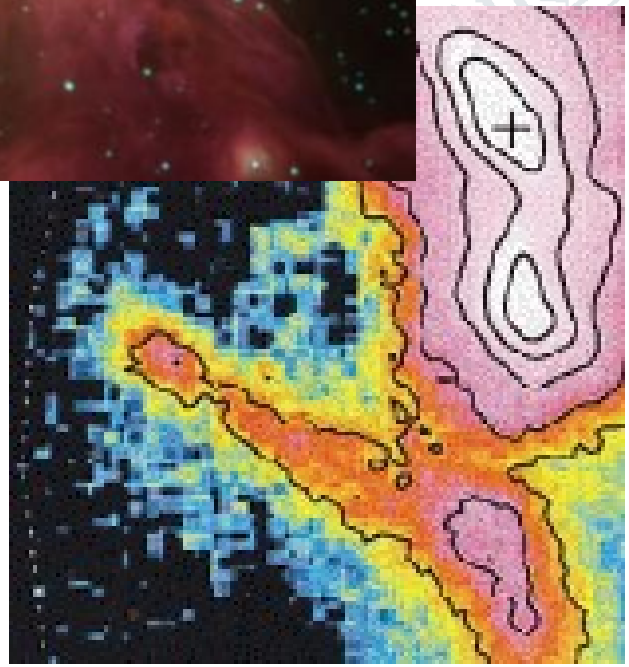
- **The PDR prototype**
- Edge-on geometry
- Exposed to high UV field from Θ^1Ori C



Spitzer/IRAC (NIR/MIR)

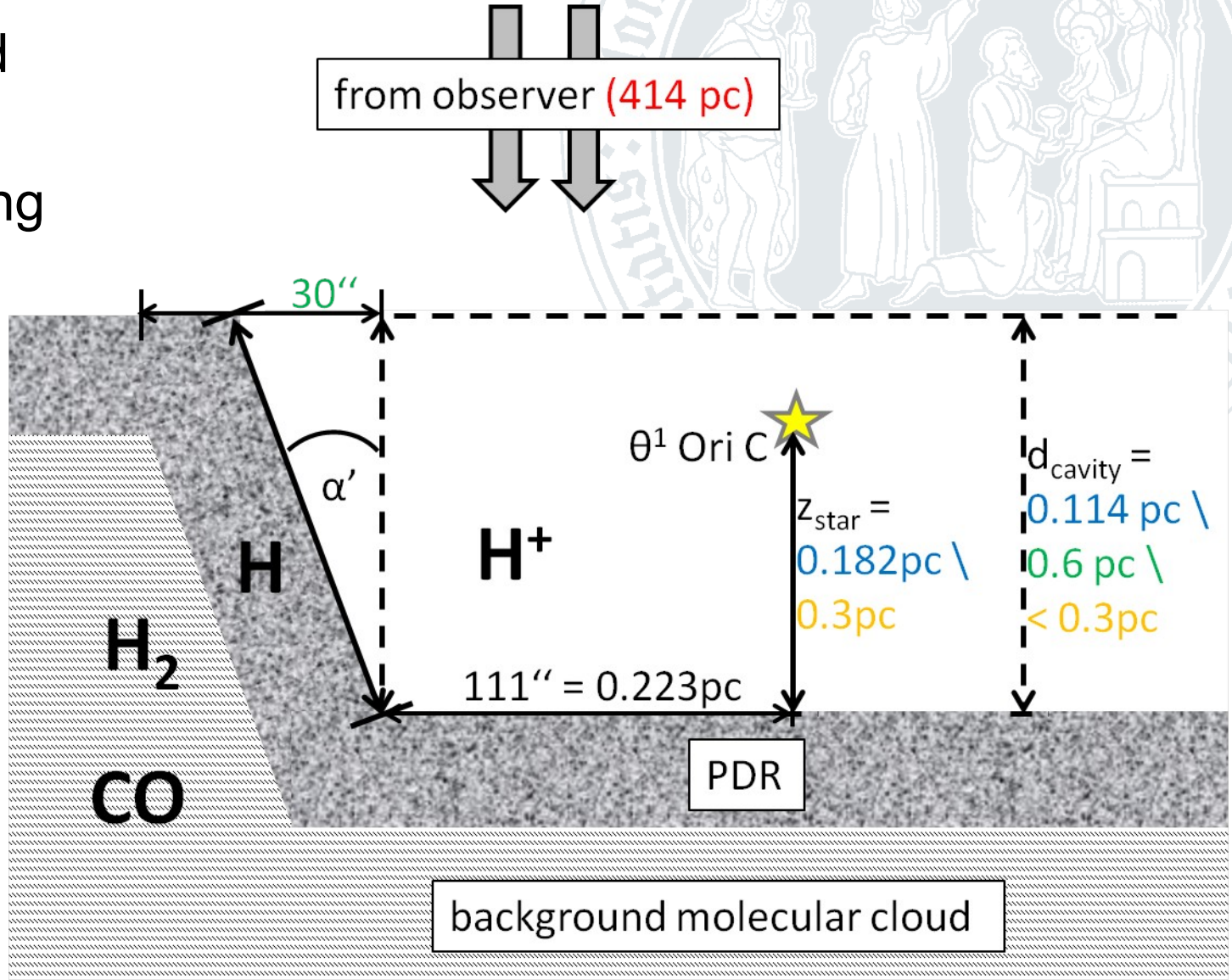
ESO/VLT (VIS/NIR)

CSO/350μm (FIR)



Overall geometry:

- HII region around Trapezium stars
- Cavity wall forming the Orion Bar

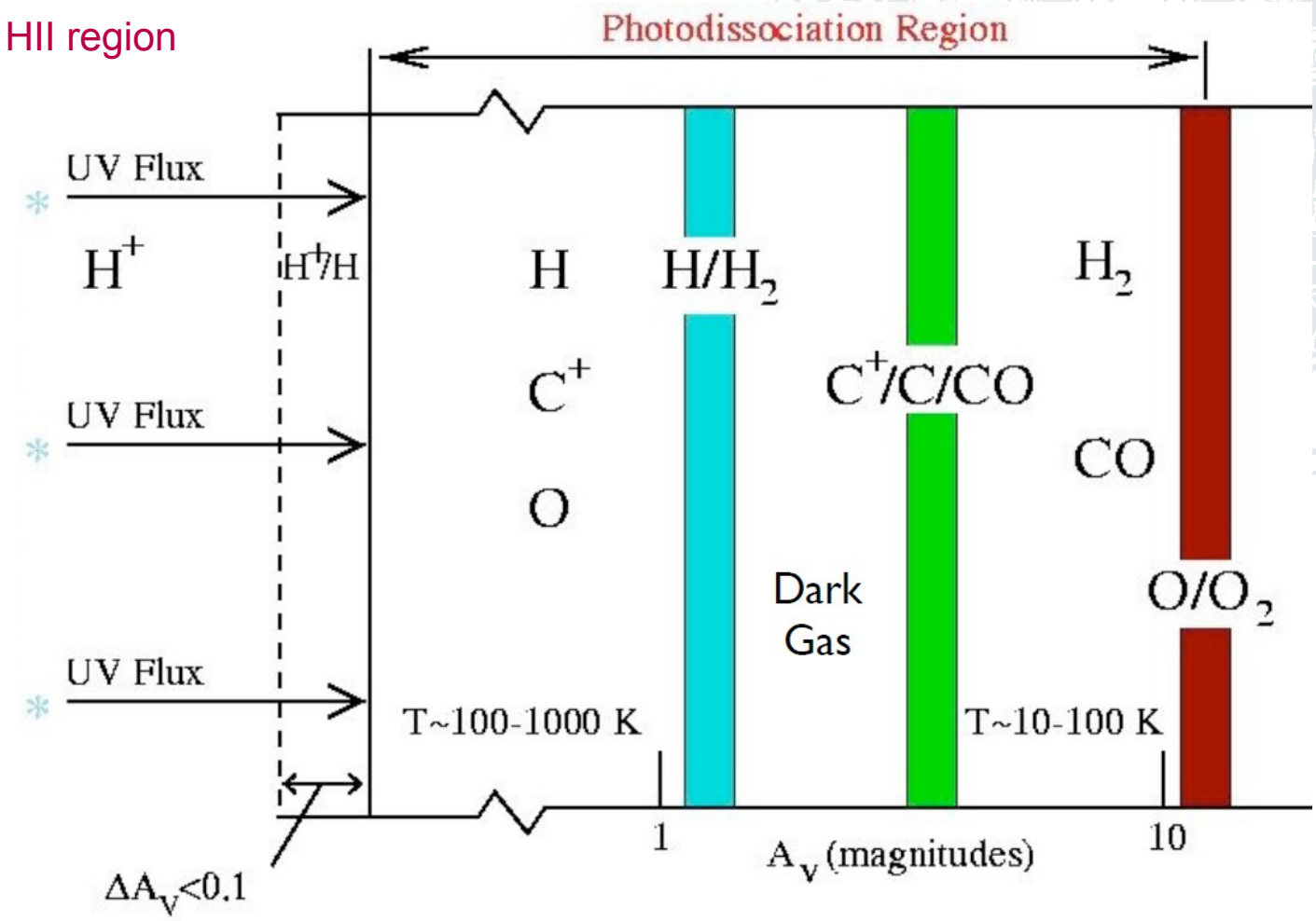


Distances from

Hogerheijde et al. (1995), Menten et al. (2007), Pellegrini et al. (2009), van der Werf et al. (2013)

Stratified structure

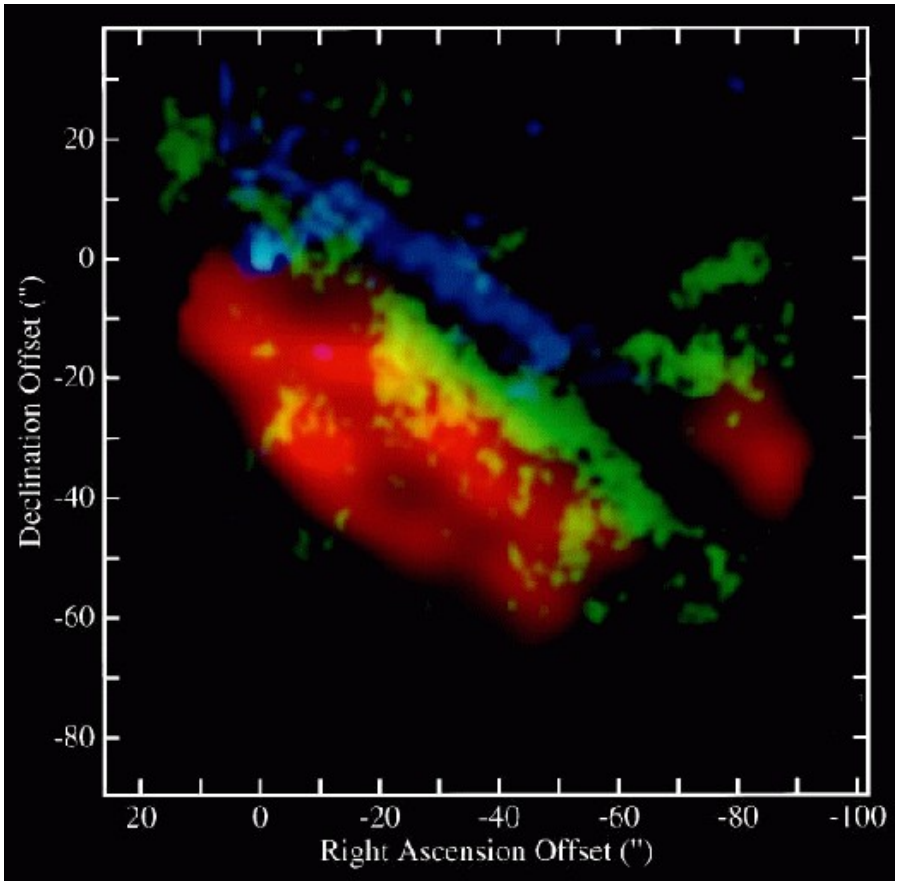
- Layering of chemical transitions and temperatures across the PDR:

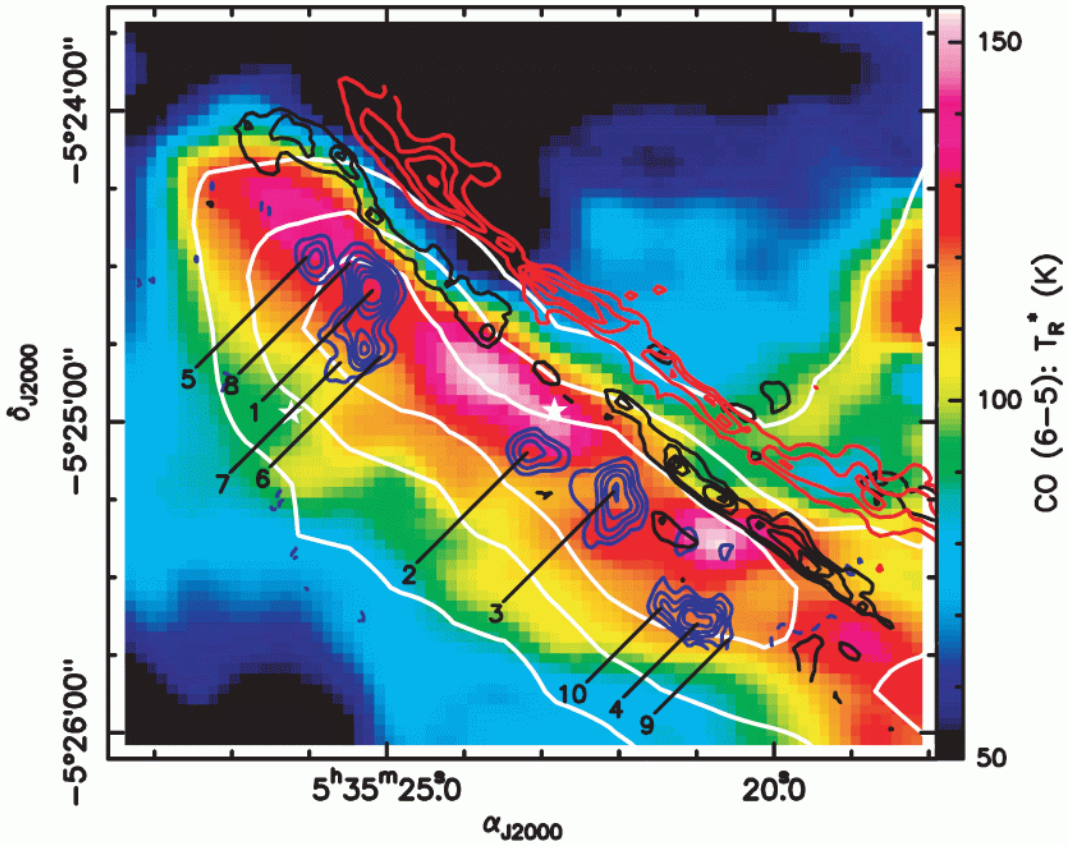


Based on Hollenbach & Tielens (1999)

Stratified structure observationally confirmed

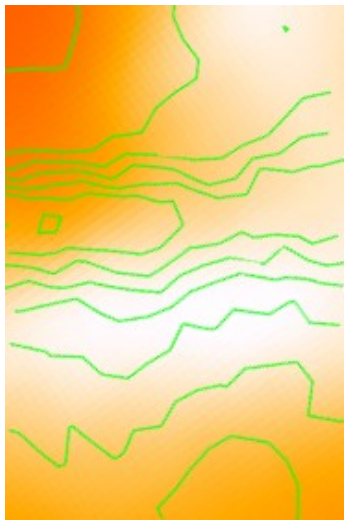
3.3μm PAHs (blue), H_2 v=1-0 S(1) (green), CO 1-0 (red)
(Hollenbach & Tielens 1999)



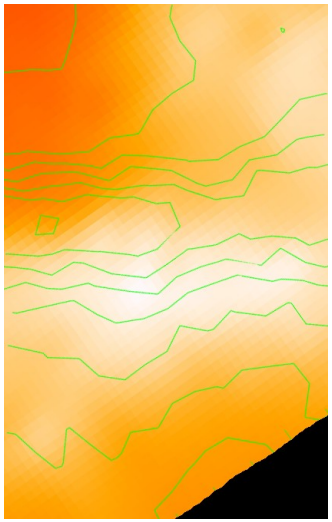


OI 1.32μm (red), H_2 v=1-0 S(1) (black), CO 6-5 (color), ^{13}CO 3-2 (white contours), H^{13}CN 1-0 (blue) *(Lis & Schilke 2003)*

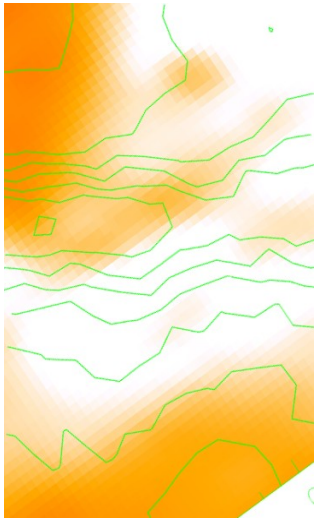
New Herschel observations (Combined with ground-based data)



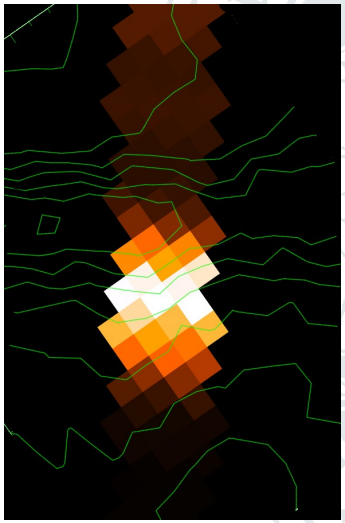
CO 2-1



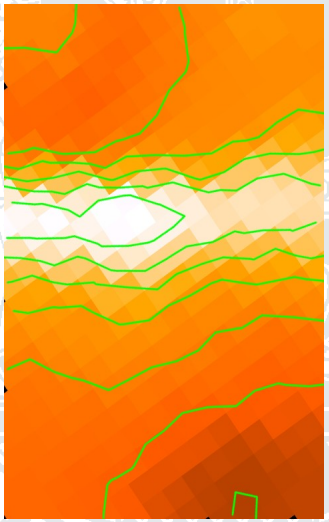
3-2



6-5

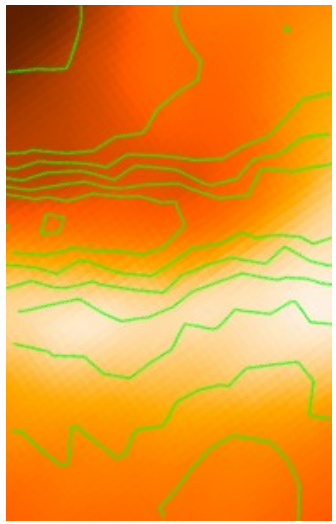


16-15

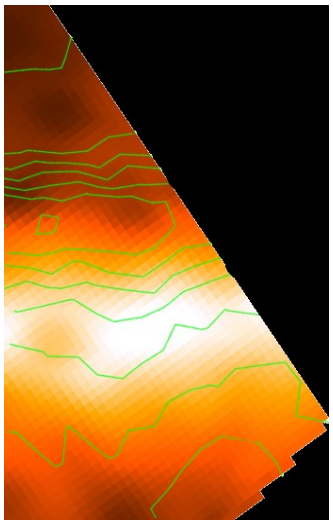


[CII]

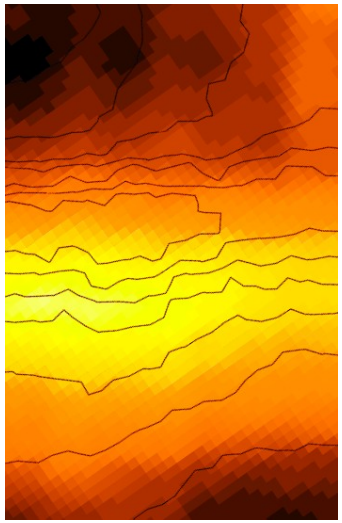
Reference: [CII] in contours



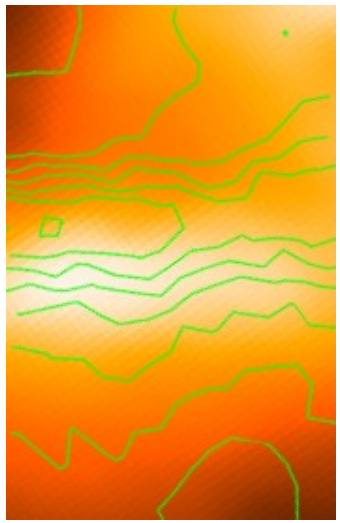
^{13}CO 2-1



6-5

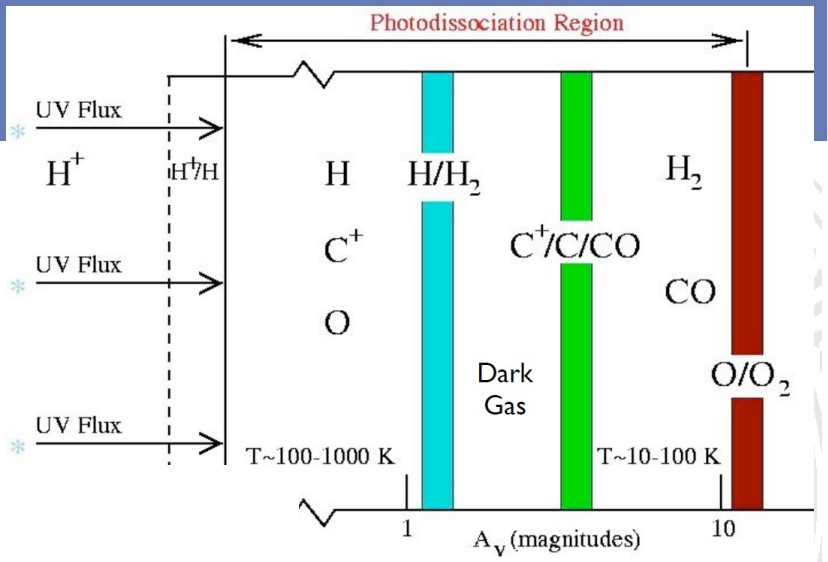


10-9



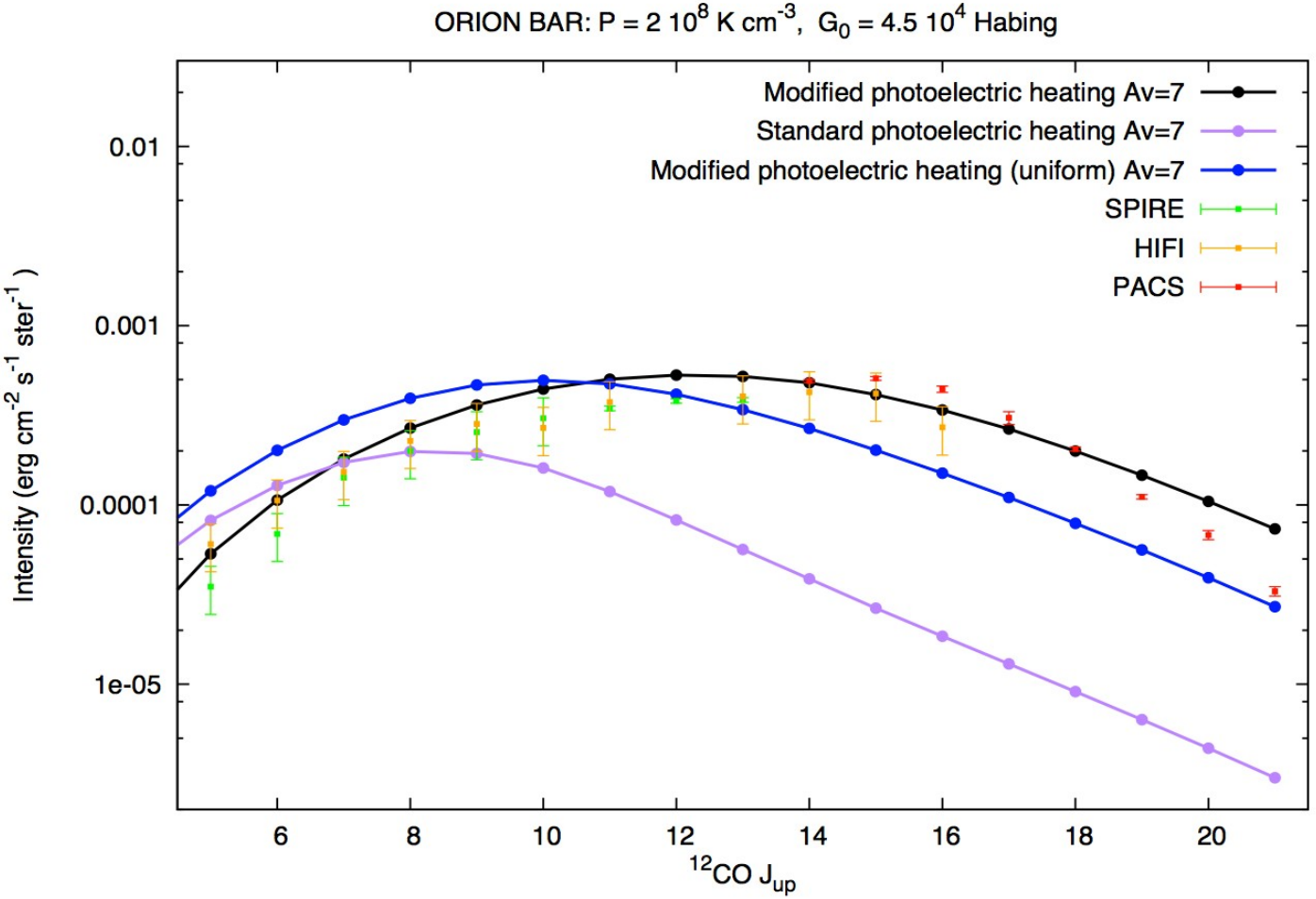
HCO$^+$ 3-2

6-5



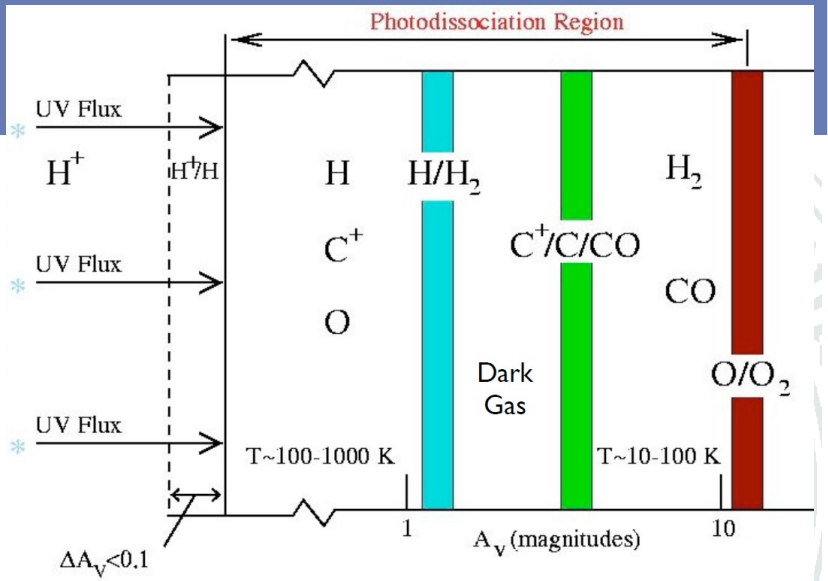
Fit with Meudon PDR model
(Version 1.5.2)

- Model with p = 2 10^8 K cm^{-3}

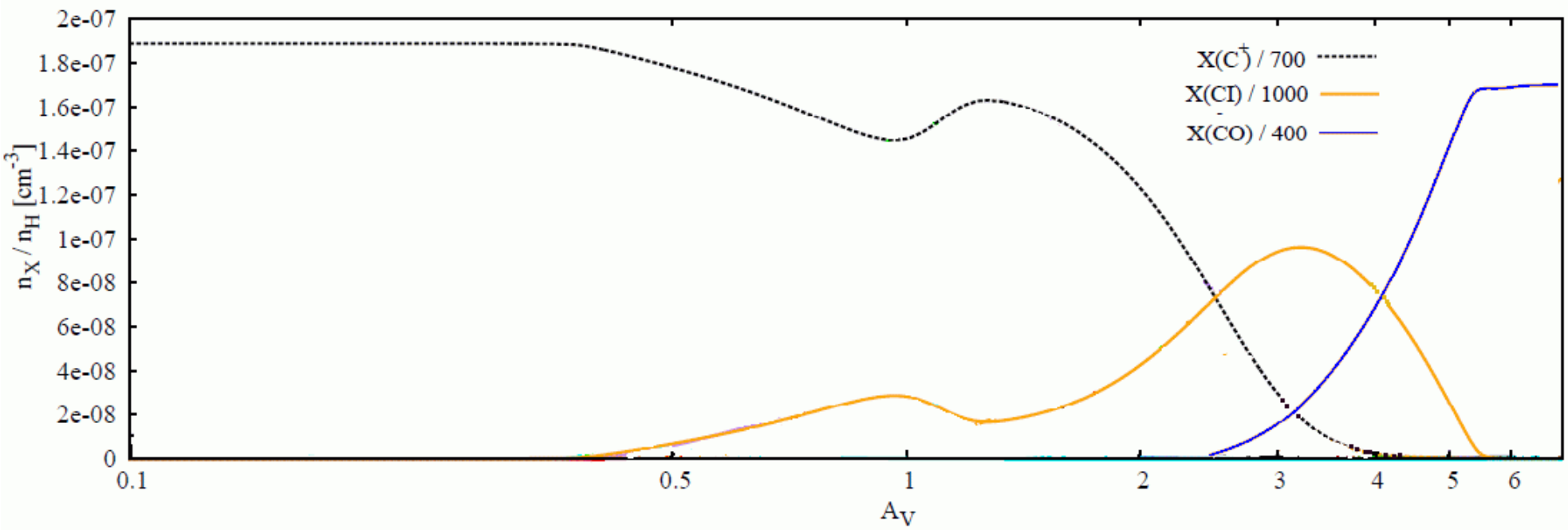


Joblin et al. (2013)

Fit with Meudon PDR model



Corresponding abundance distribution of main C-bearing species:

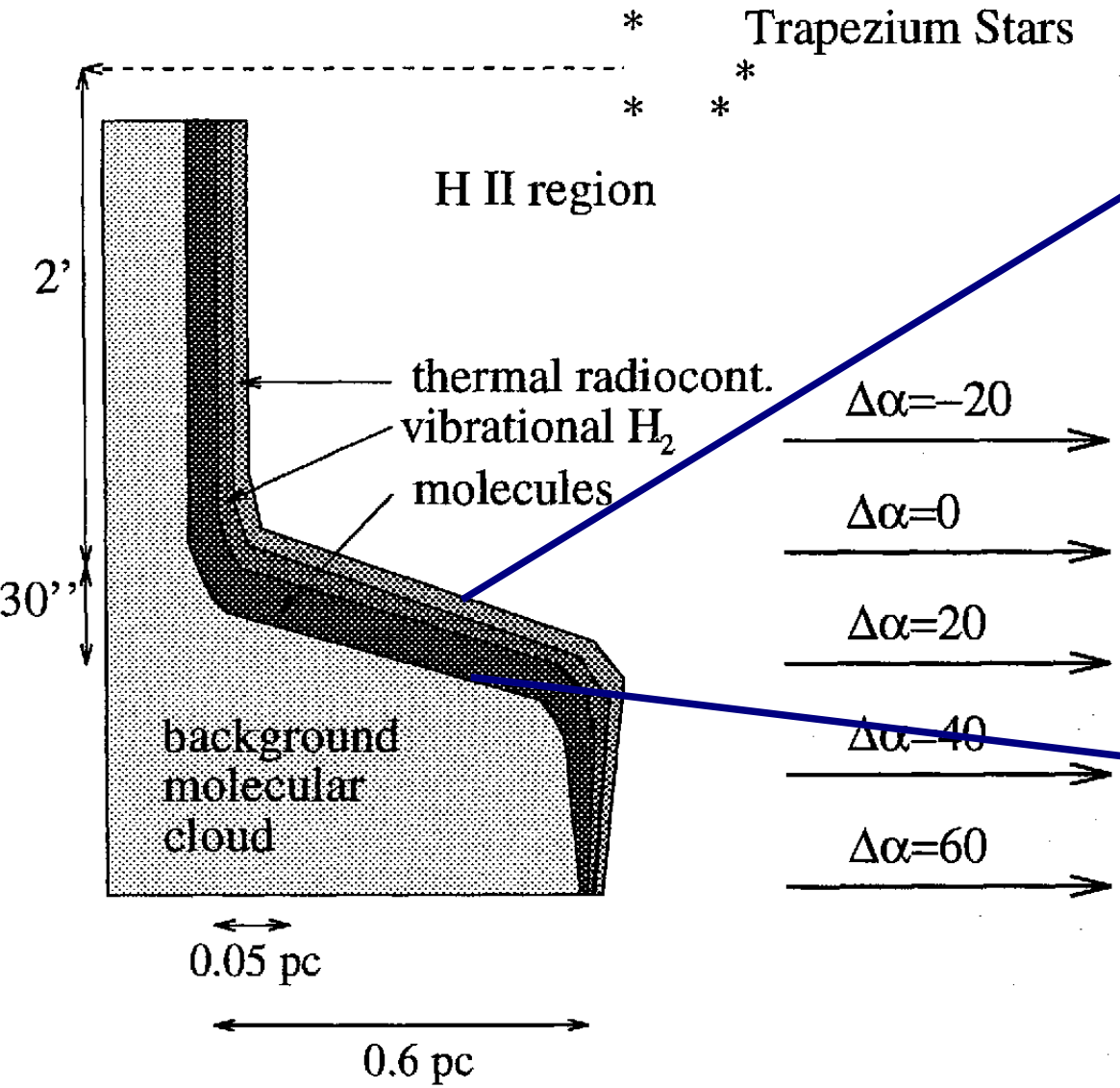


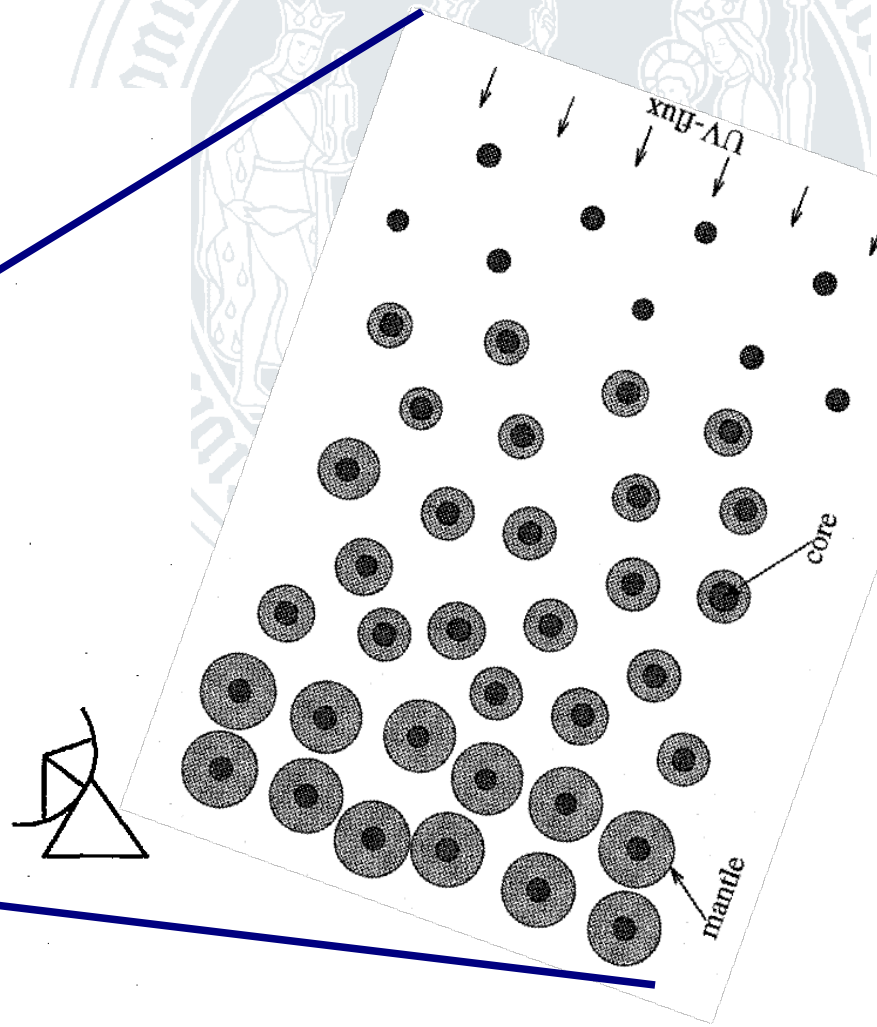
0.002pc = 1"

The PDR stratification in such a model would not be observable!

Clumpy medium

- Allows deeper penetration of UV radiation



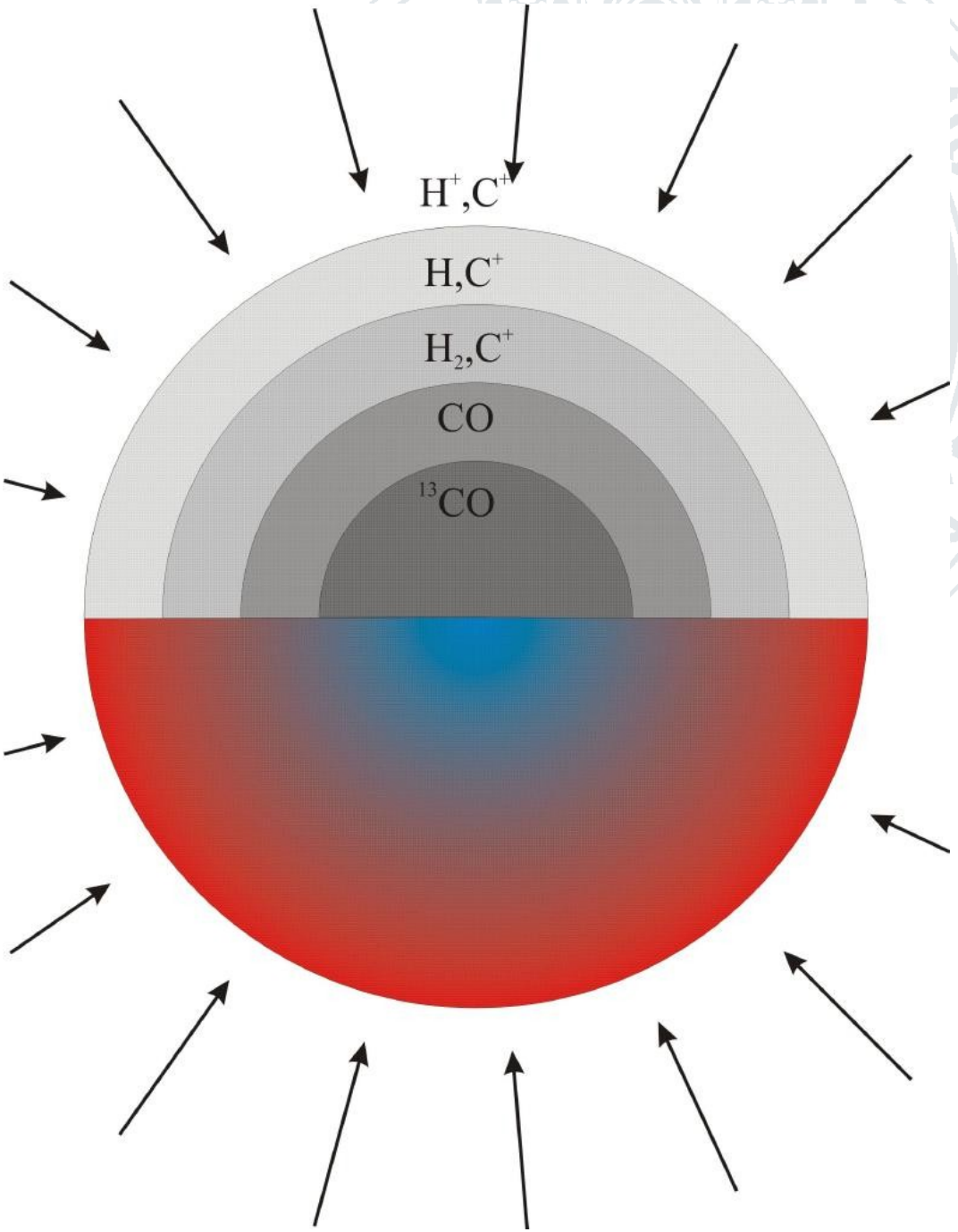


Hogerheijde et al. (1995)

KOSMA-τ PDR Code

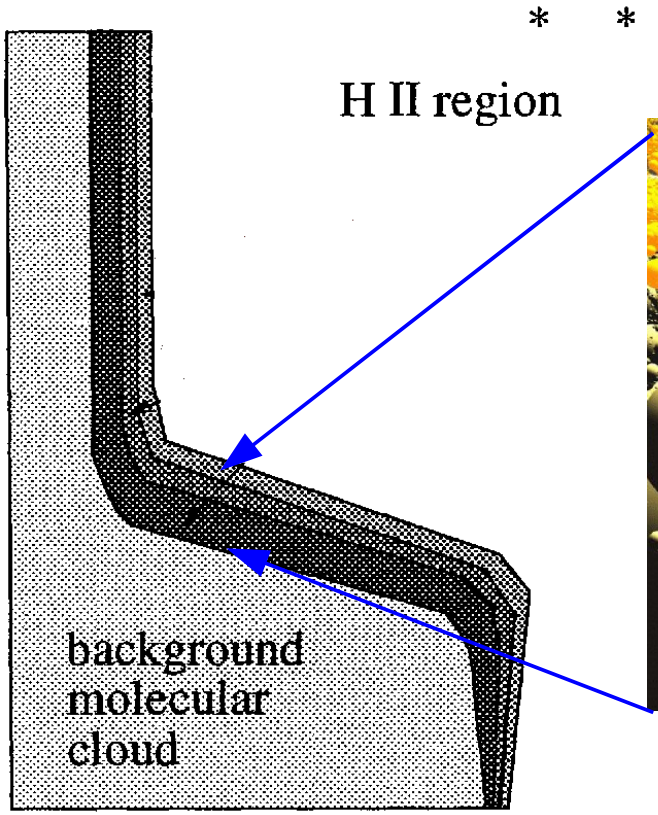
- **Individual spherical clumps**
  → Layering of chemical species and excitation around each clump

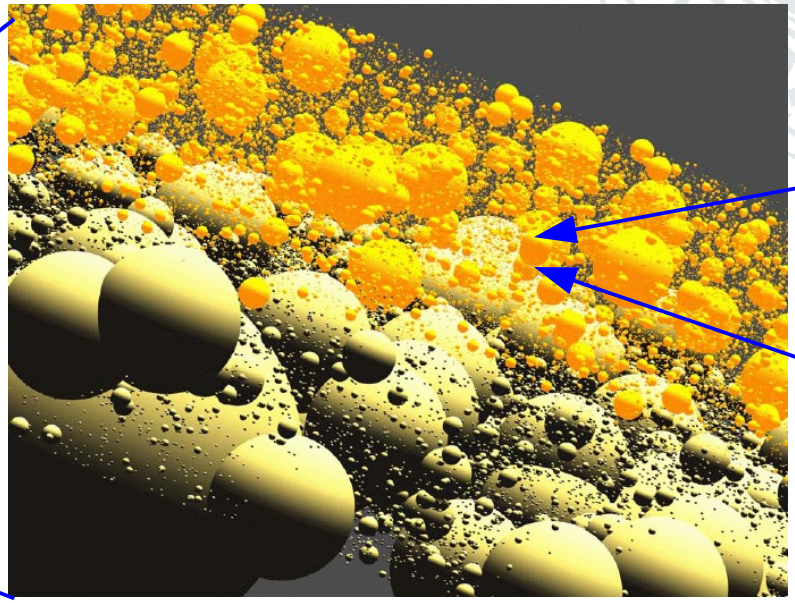
- **Recent improvements:**
  - Eley-Rideal H_2 formation
  - Arbitrary dust properties
  - Dust surface chemistry
  - Full isotopologue network

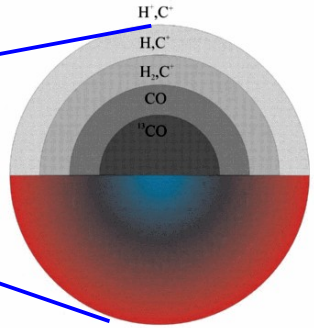


KOSMA-τ-3D

- Simulate PDR by clump ensembles with full size distribution (embedded in interclump medium)
- Individual clumps computed by KOSMA-τ



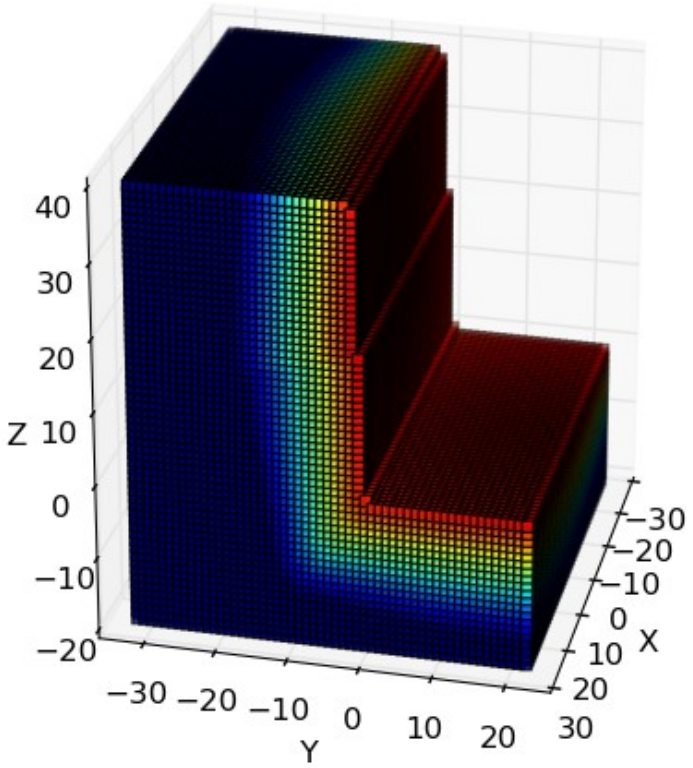


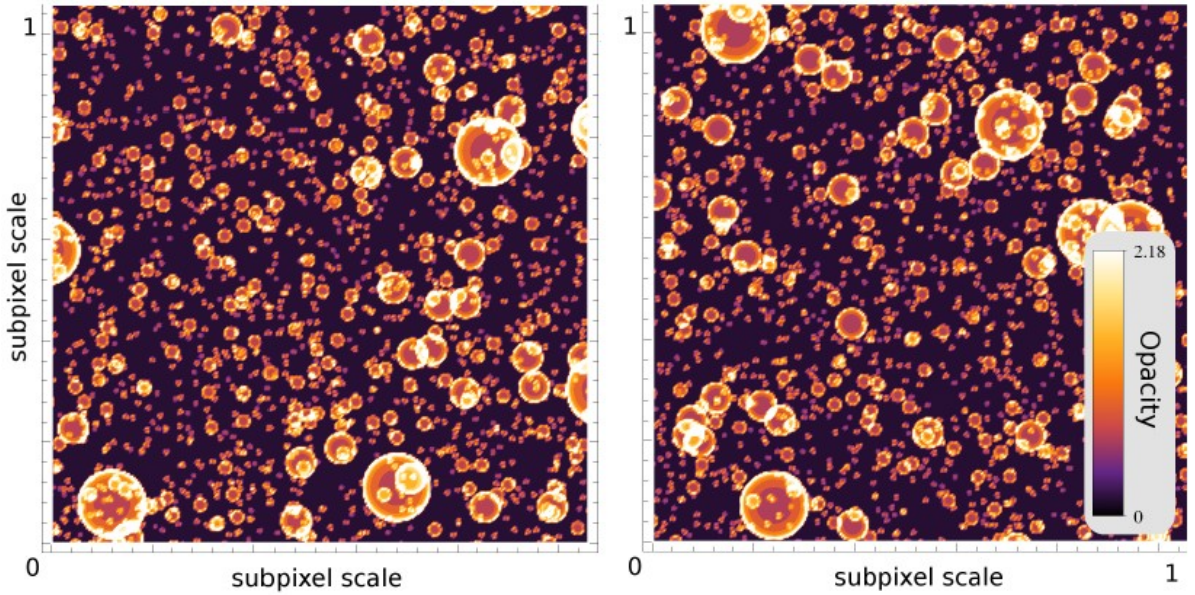


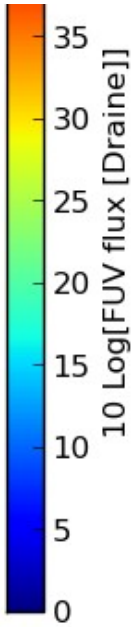
UV field attenuated in the cloud by foreground clumps

Radiative transfer

- Probabilistic approach for optical depths
- Common approach for UV extinction and line emission







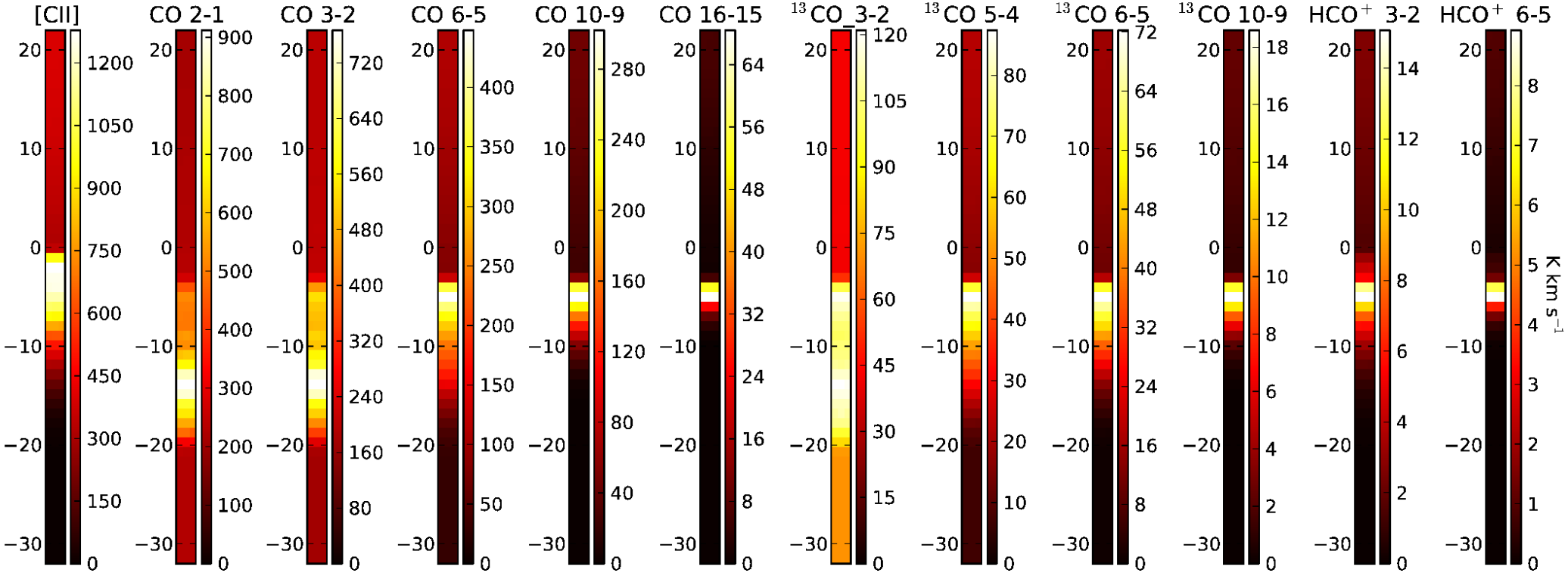
Random maps of [CII] line peak opacities in scaled voxels.

Probability distribution for line-of-sight optical depths: $p\left(e^{-\tau}\right)$

for each pixel

Resulting FUV flux distribution in the best fitting Orion Bar model.

Simultaneous fit of line intensities and stratification profile



- **Decent match of the observations**
  - Large number of free parameters in a 2D model
    - Variation along the Bar ignored here
  - No fit in χ^2 sense performed yet, due to huge parameter space

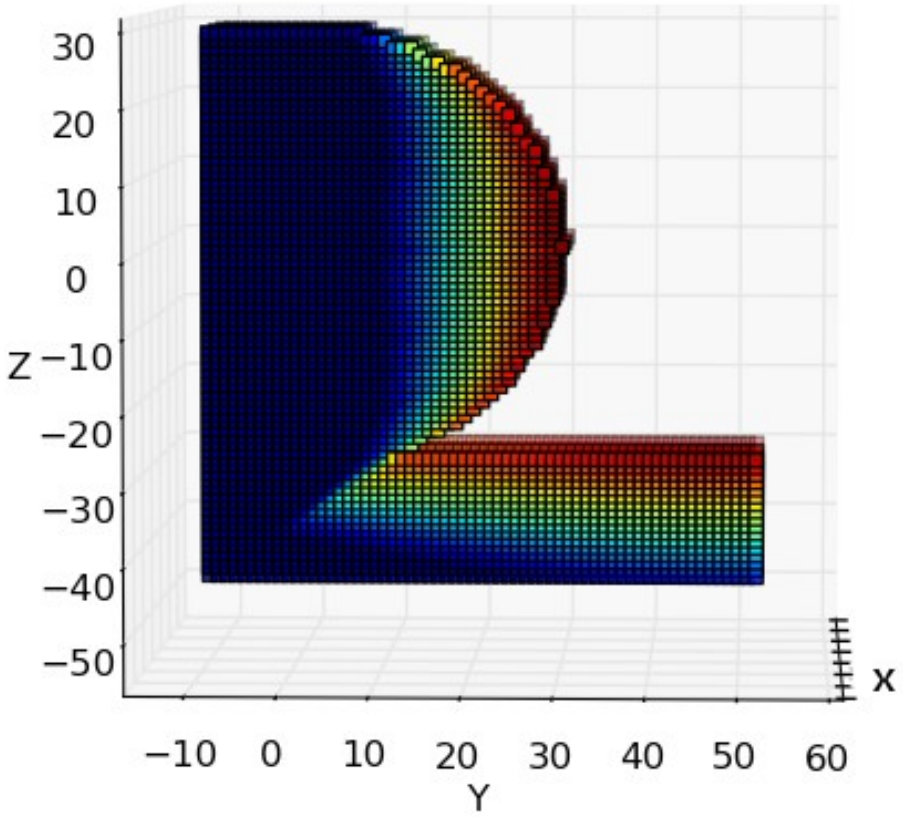
What is the Orion Bar?

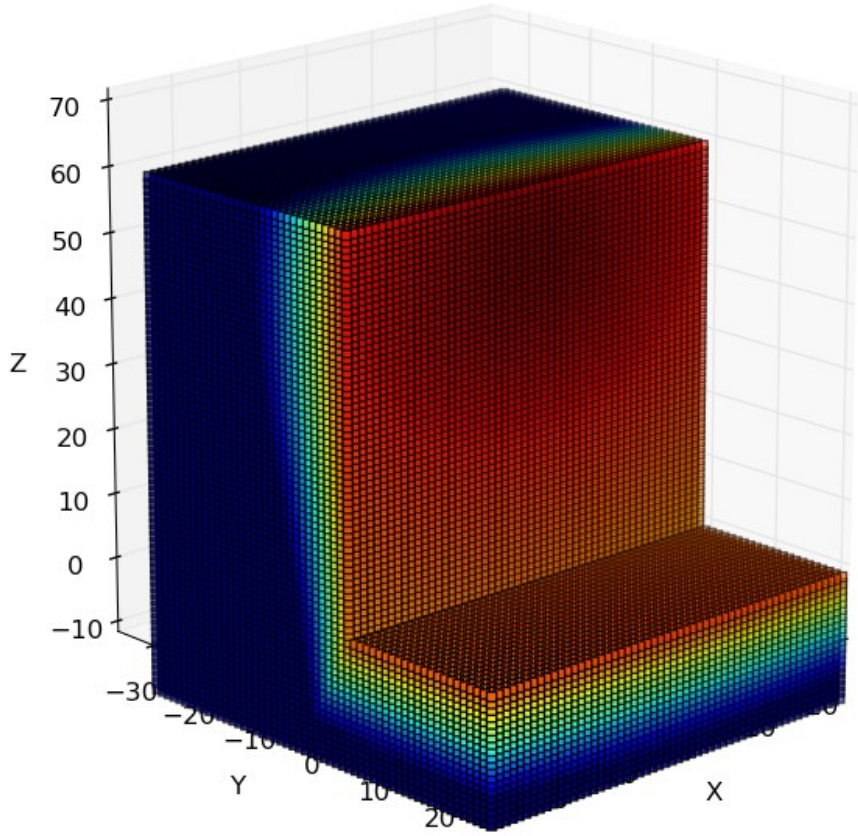
- A successful fit does not prove that we found the true geometry and parameters of the PDR

- **But:**
  - We can exclude scenarios if it turns impossible to reproduce the observed properties in them.

→ **We do not know what the Orion Bar is, but we know what it is not:**

Geometry

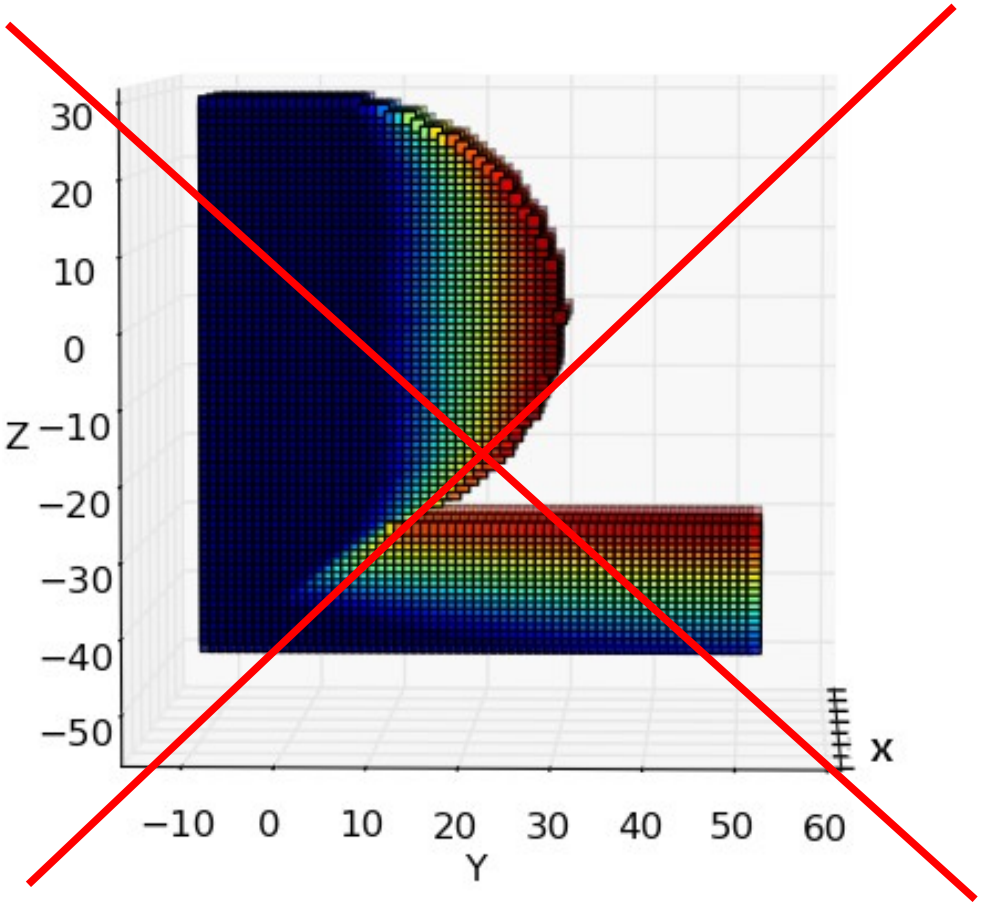


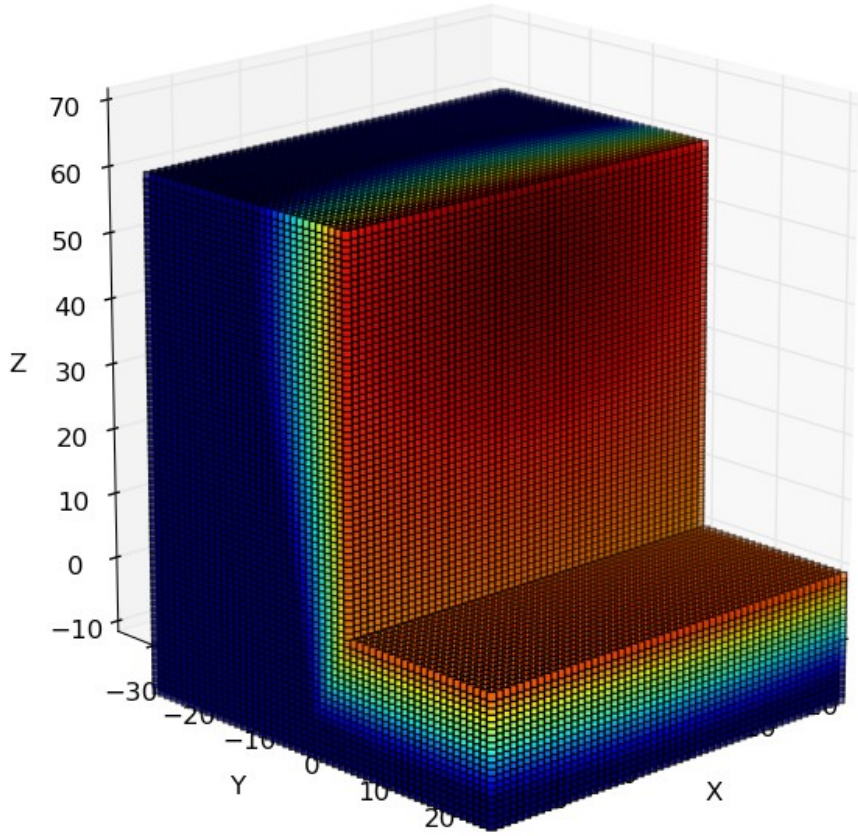


Orion Bar = (cylindrical) filament (Walmsley et al. 2000, Arab et al. 2012)

Orion Bar = (straight or concave) cavity wall (Hogerheijde et al. 1995, Pellegrini et al. 2009, Bernard Salas et al. 2012, van der Werf et al. 2013)

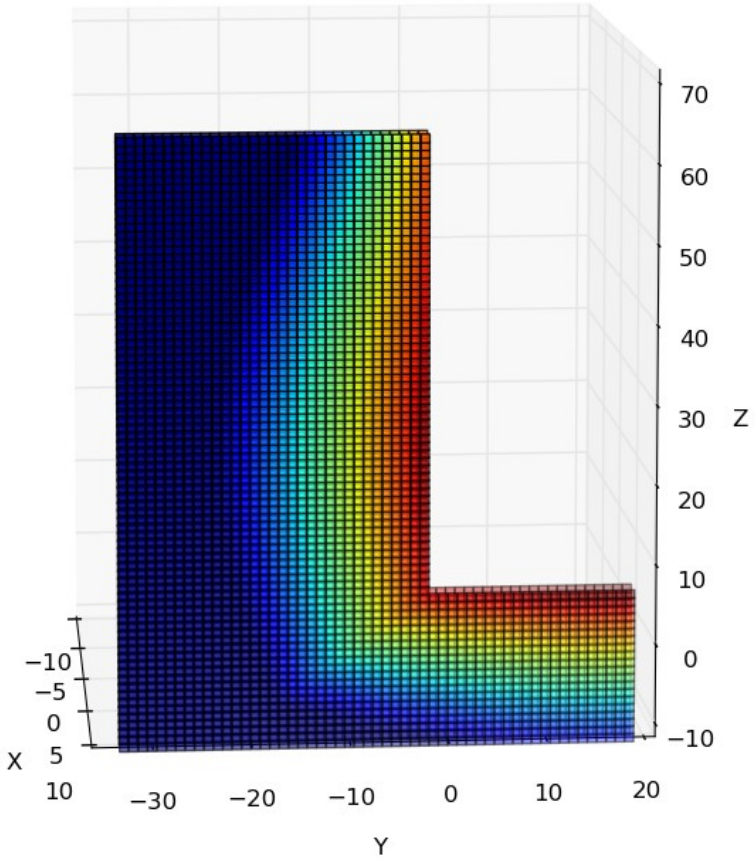
Geometry



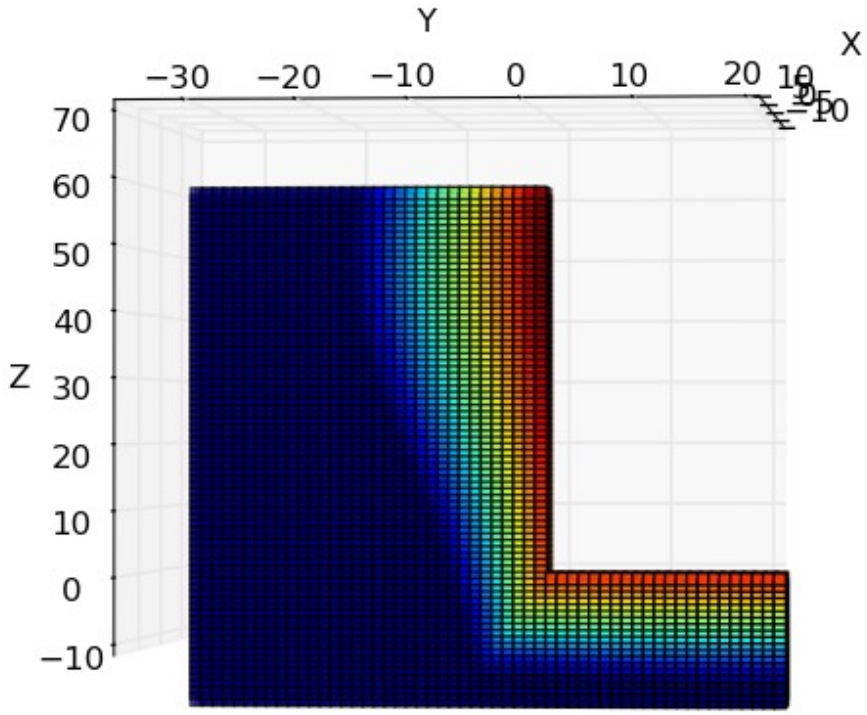


Convex structures provide no layering of high-density tracers

Illumination

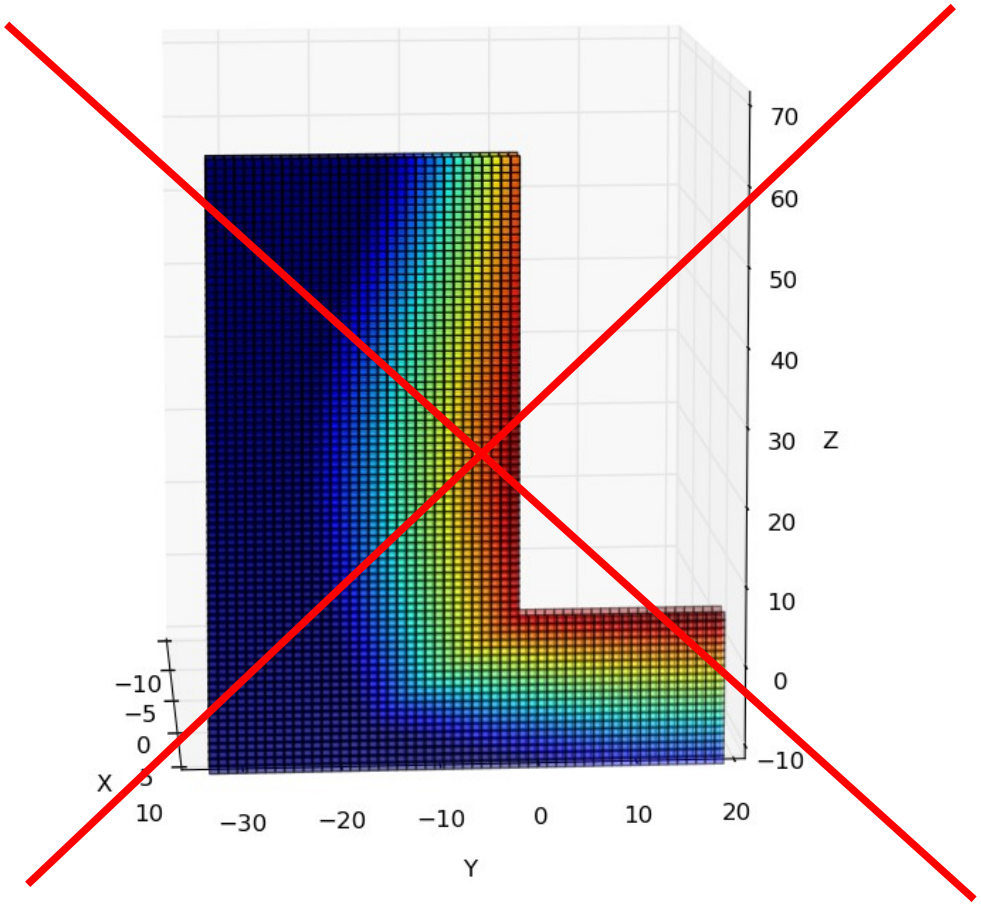


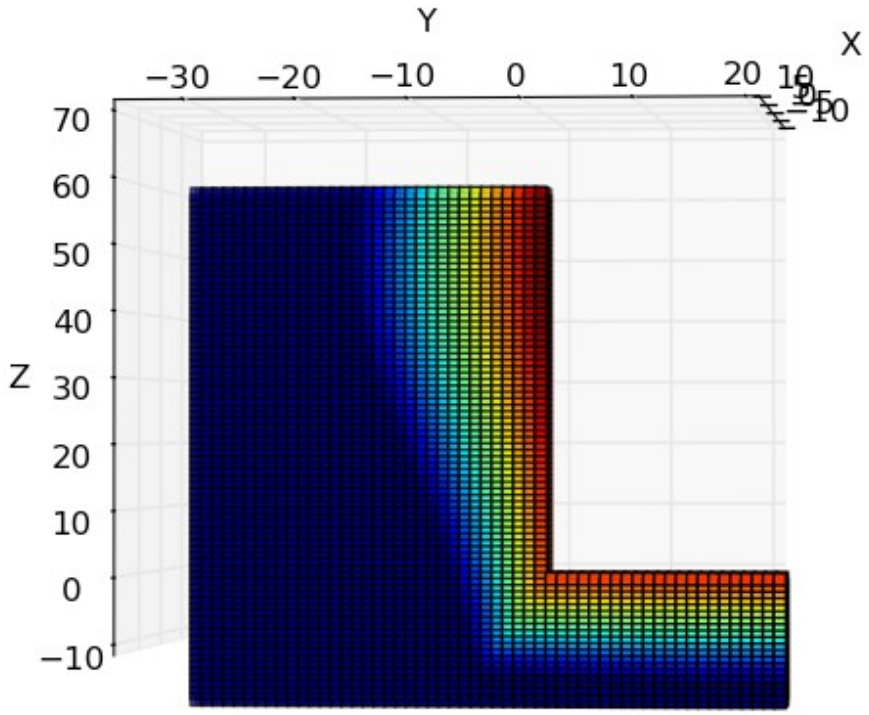
Θ¹Ori C deep in the cavity
(Jansen et al. 1995, implicite)



Θ¹Ori C at the cavity upper edge
(Pellegrini et al. 2009, van der Werf et al. 2013)

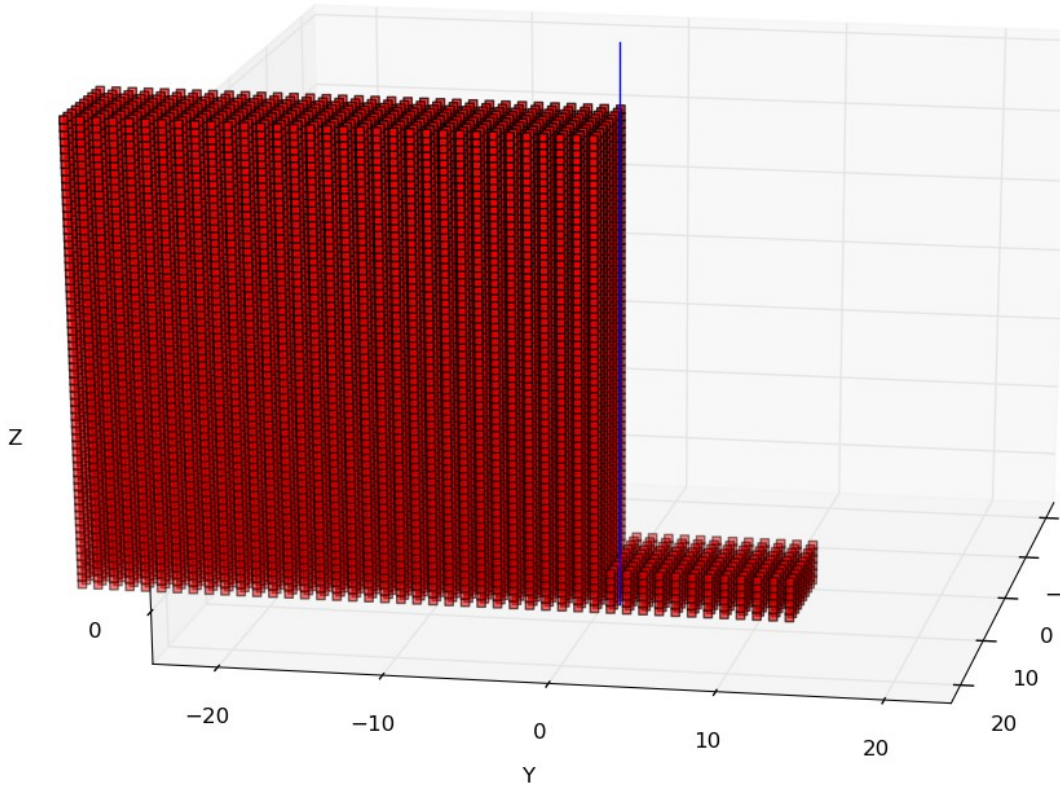
Illumination

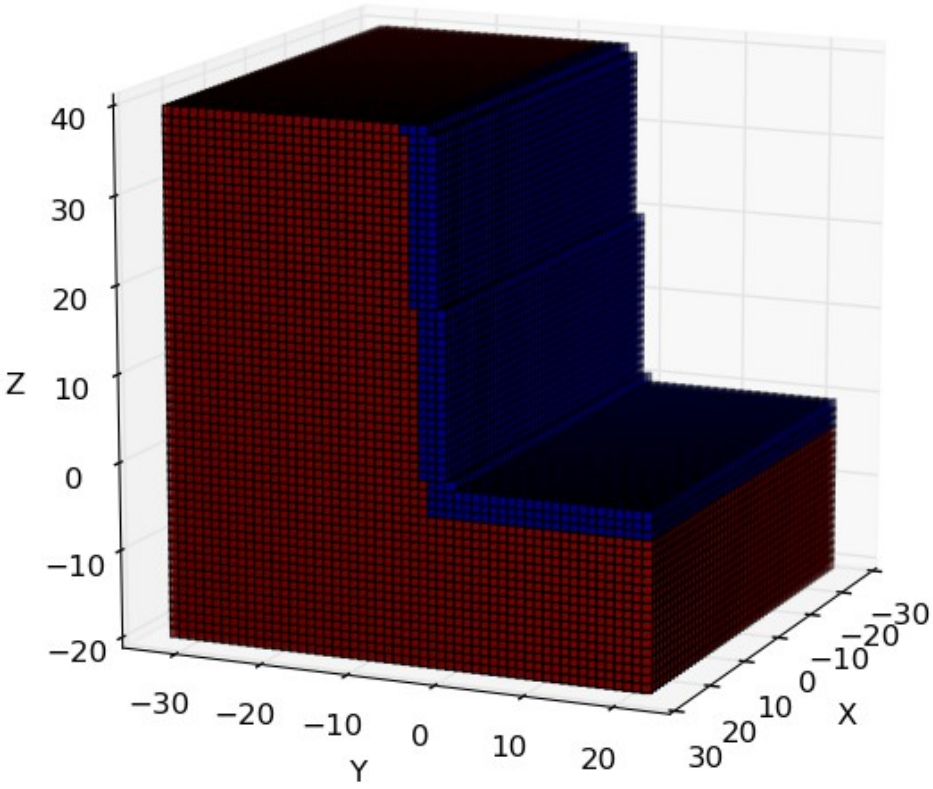




Location deep in the cavity produces foreground self-absorption

Density structure

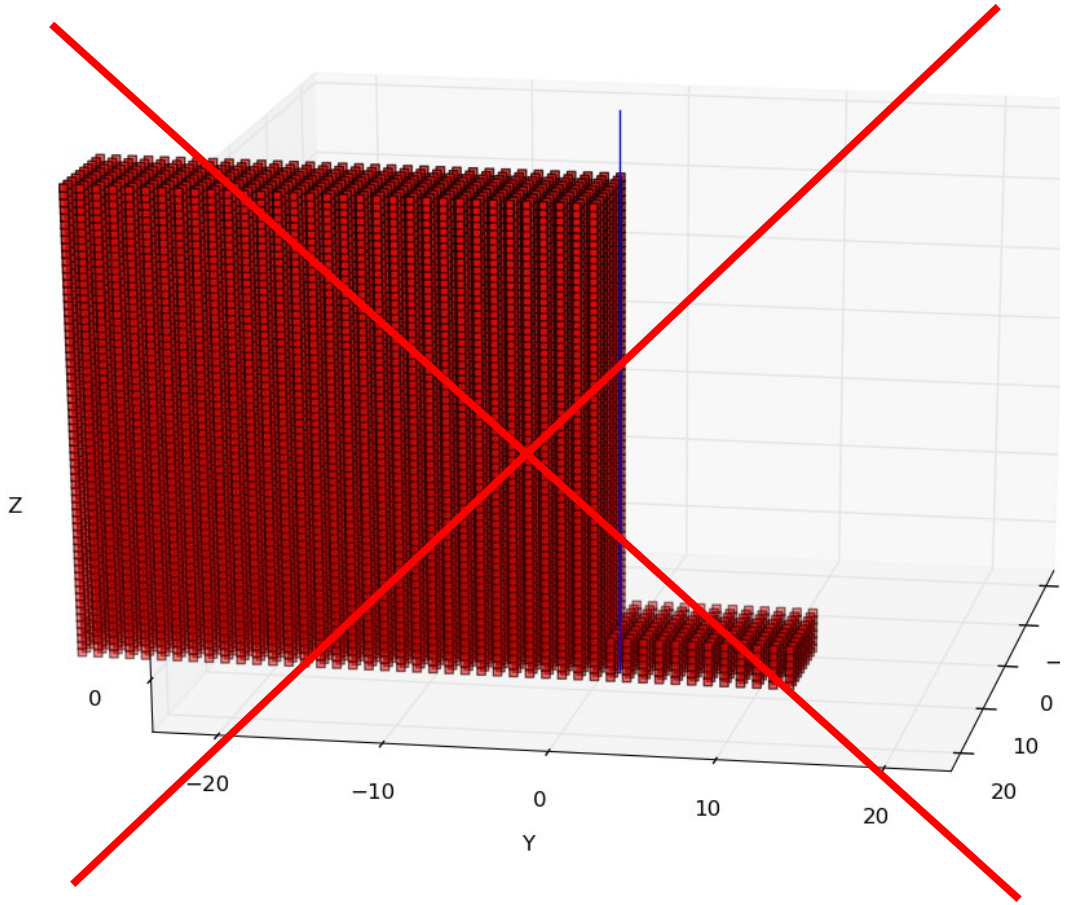


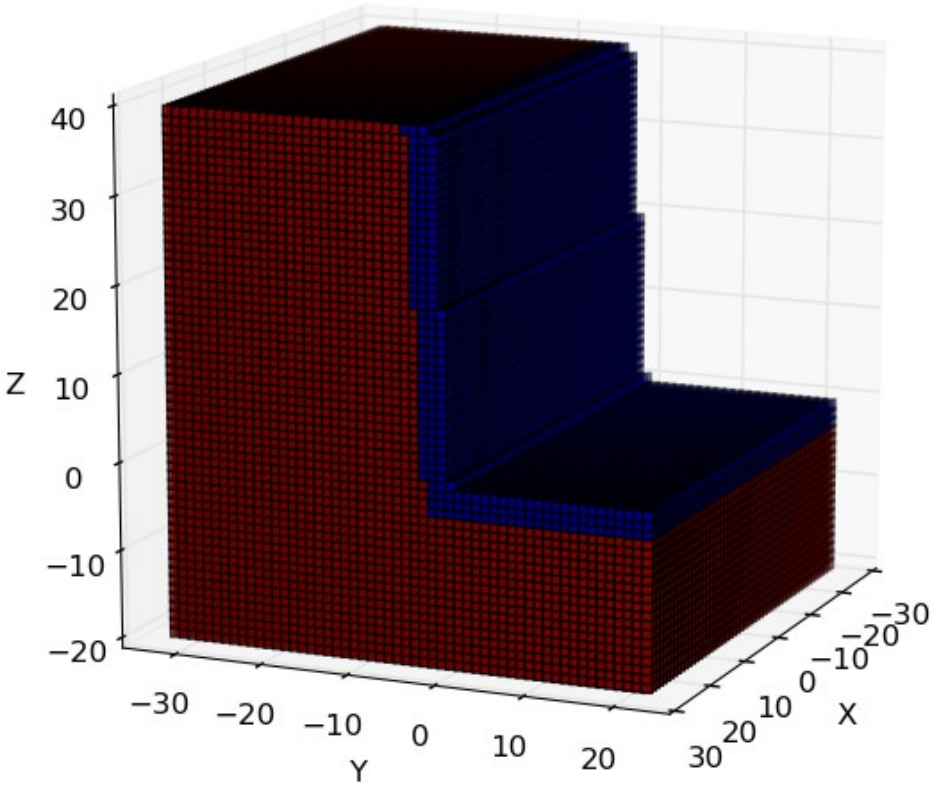


Homogeneous mixture of clumps and interclump medium
(simplicity first)

Deficiency of dense clumps at the PDR surface
(Parmar et al. 1991, Hogerheijde et al. 1995, Young Owl et al. 2000)

Density structure





Stratification between [CII] and HCO^+ requires thin medium in front of dense clumps

Other parameters

- **Overall, the scenario proposed by Hogerheijde et al. (1995) matches well**
  - FUV flux 4 10^4 χ_0 confirmed
- **Deviations:**
  - The cavity is only around 0.3pc deep (compared to 0.6pc)
  - Consequently, the mass per voxel is higher by a factor 2.5
  - The clump-to-interclump mass ratio is 4:2 (compared to 1:9)
  - Dense clump and interclump medium densities are slightly higher:
    - 4 10^6 and 4 10^4 cm^{-3}