PDRs Near and Far: The Extraordinary Utility of Photodissociation Region Models

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San José State University

Outline

- A Story
- Some PDR Basics
- Molecular Ions and Cosmic Rays
- Ices
- The challenge of high resolution Galactic observations
- To the Edge of the Universe


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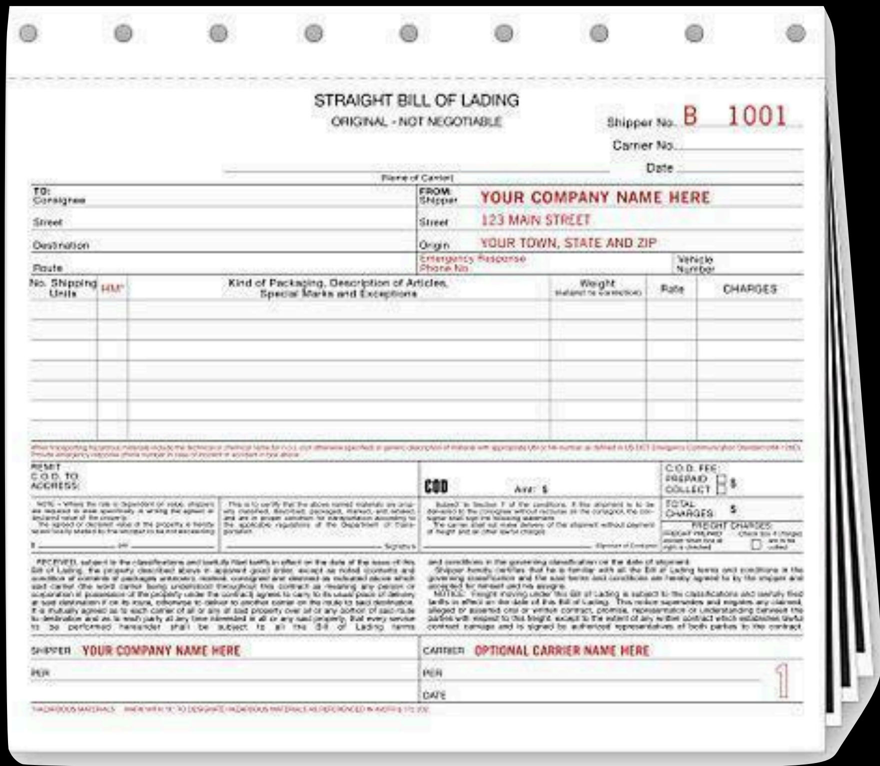
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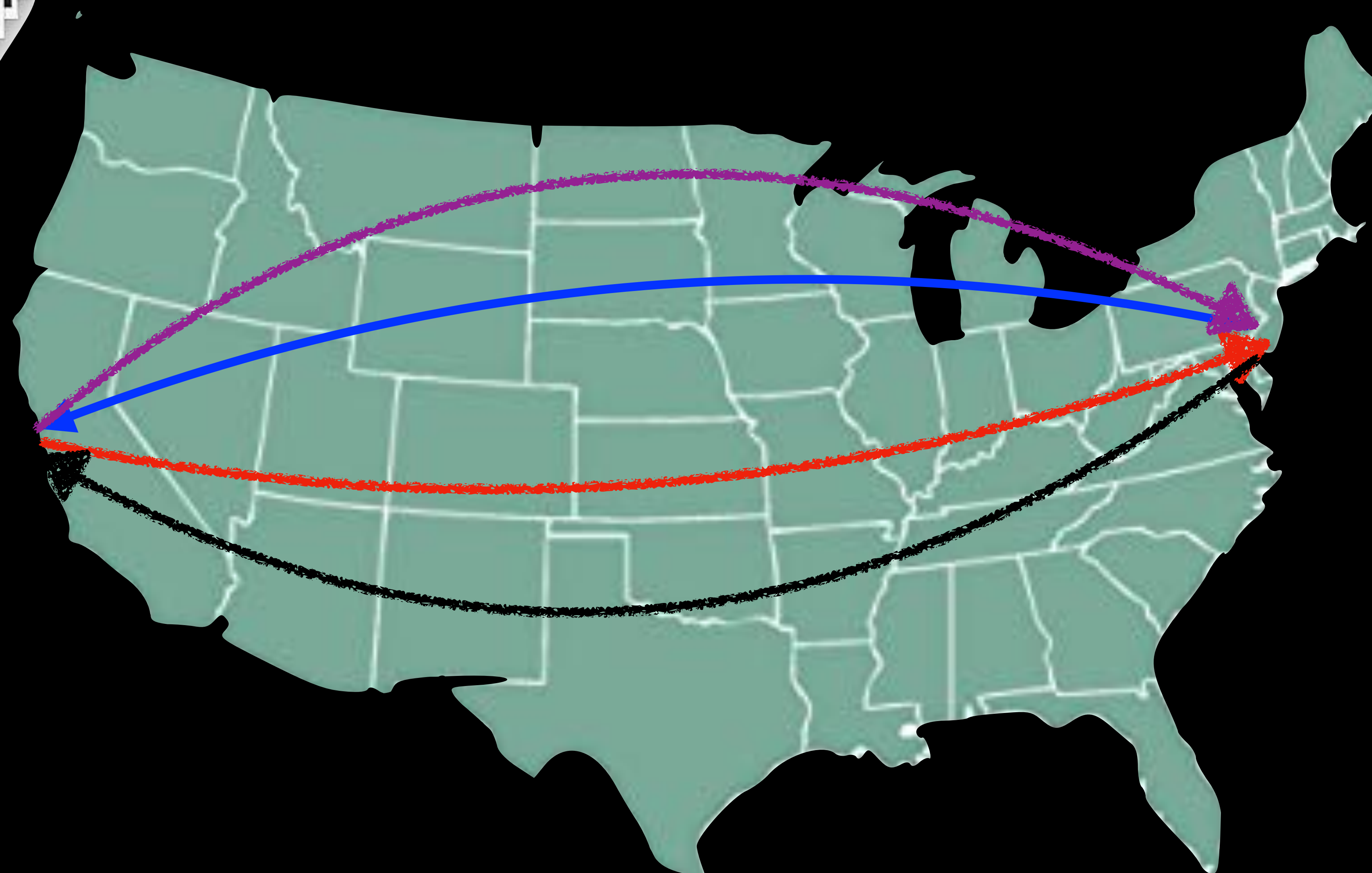

Just put it in your trunk and drive it across the street - nobody will ever know!


A To Z Tree
Specimen Nursery
NASA Ames Research
Center N-254
NASA Ames Intelligent
Systems Division
Stevens Creek
The Golf Club
at Moffett Field
Tee Minus One
Bar & Grill
Santiago Villa
NASA Ames
Fire Department
Moffett Federal
Airfield Hangar 2
Hangar 3
Lockheed Martin
63rd Readiness Division
Carnegie
Mellon
University
Silicon Valley
Moffett Field Historical
Society Museum
San Jose MEPS
NASA Ames
Research Center
Amazon job Lab126
Star One Credit
Union | Sunnyvale
Moffett Blvd
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Microsoft
NORTH
WHISMAN
N Whisman Rd
Specialty's Café & Bakery
Samsung NEXT
Manila Ave
Google Quad Campus
Ellis St
Proofpoint
German International
School of Silicon Valley
Stevens Creek Trail,
Middlefield Entrance
Rotten Robbie
Symantec
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Sunnyvale Municipal
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E Middlefield Rd
Gladys Ave
Synopsys Bldg A
W Maude
View Station
Platform


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Don’t worry about it….
you’ll be long gone before
anybody notices.

PHOTODISSOCIATION REGIONS. I. BASIC MODEL

A. G. G. M. Tielens and David Hollenbach
NASA/Ames Research Center, Moffett Field, California
Received 1984 June 20; accepted 1984 October 31

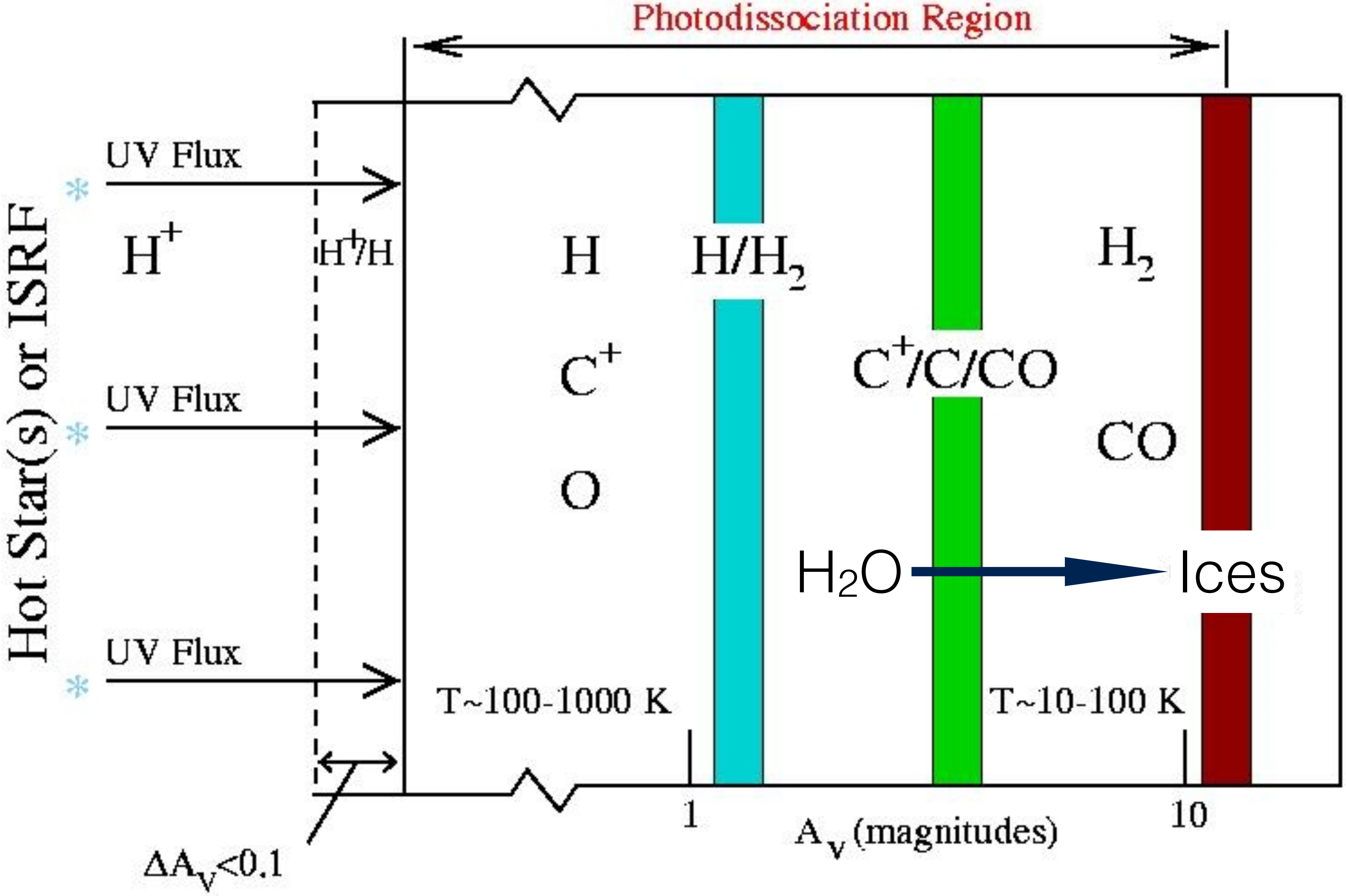
ABSTRACT

We have theoretically modeled the chemistry and heat balance of dense (10^3 cm^{-3} $< n_0 <$ 10^6 cm^{-3}) neutral gas illuminated by far-ultraviolet (FUV) (6 eV $< h\nu <$ 13.6 eV) fluxes 10^3–10^6 times more intense than the ambient interstellar field. The one-dimensional models extend $A_v \sim 10$ into the neutral gas, and are primarily intended to study the FUV illuminated neutral gas (photodissociation regions) between molecular clouds and H II regions. However, the models also apply to neutral shells around planetary nebulae, bright-rimmed molecular clouds, reflection nebulae, regions around protostars, and the center of the Galaxy, and to global studies of external galaxies. The models relate observed line and continuum emission from these regions to interesting physical parameters such as the gas density and temperature, the incident FUV flux, the elemental abundances, and the grain properties. The dense, highly illuminated photodissociation regions generally include a hot ($T > 100$ K) atomic region (H, O, and C^+) near the surface ($A_v \lesssim 3$) where trace H_2 is vibrationally excited by FUV pumping, a warm ($T \sim 100$ K) partially dissociated region (H_2, O, C, and CO) at about $A_v \sim 3$–5, and a cooler ($T < 100$ K) interior region ($A_v \sim 10$) where oxygen is still photodissociated to atomic form (H_2, CO, and O).

The models ….. also apply to neutral shells around Pne, bright-rimmed molecular clouds, reflection nebulae, regions around protostars, … the center of the Galaxy, and to global studies of external galaxies.

Tielens & Hollenbach 85a,b, Hollenbach & Tielens 83

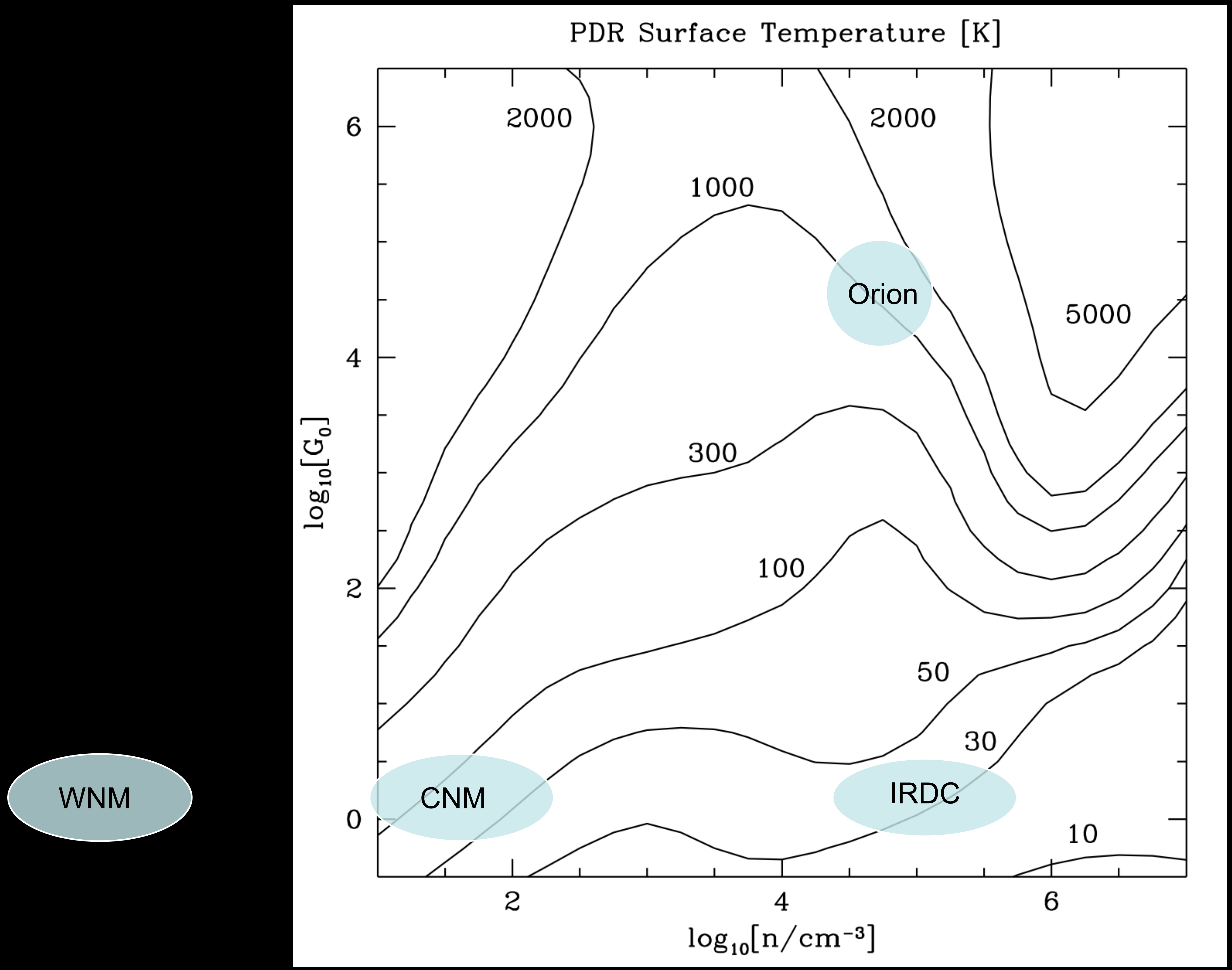
PDR Schematic



Model Grids (Wolfire et al. 1990, Kaufman et al. 1999, 2006; Wolfire & Pound 2008; Hollenbach et al. 2009, 2012)

- Input conditions
  - Grain/PAH properties
  - Chemical abundances
  - FUV spectrum
  - cosmic ray rate
  - total column
  - 1-sided/2-sided illumination
  - Steady state
- Parameter space
  - log(n) =1 - 7 (but possible to fix P instead of n)
  - $\log(G_0)$ = -0.5 - 6.5
- Makes understanding physical processes more straightforward
- Best for trends; individual sources should take details into account

PDR Surface Temperature [K]



PDR Surface Temperature [K]

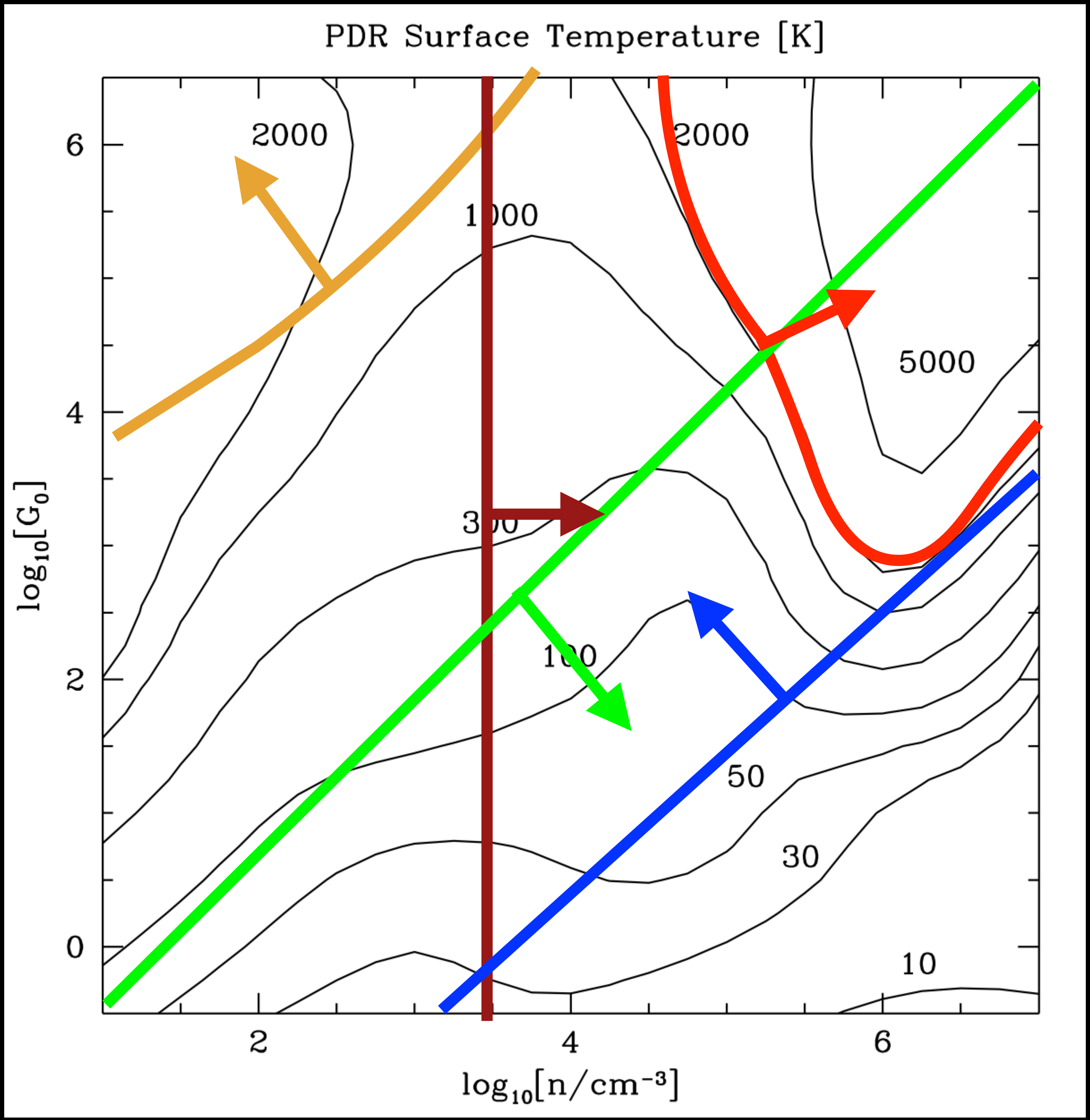
$v_{drift} > v_{th}$

$G_0/n < .03$

$n > n_{cr}^{C}$

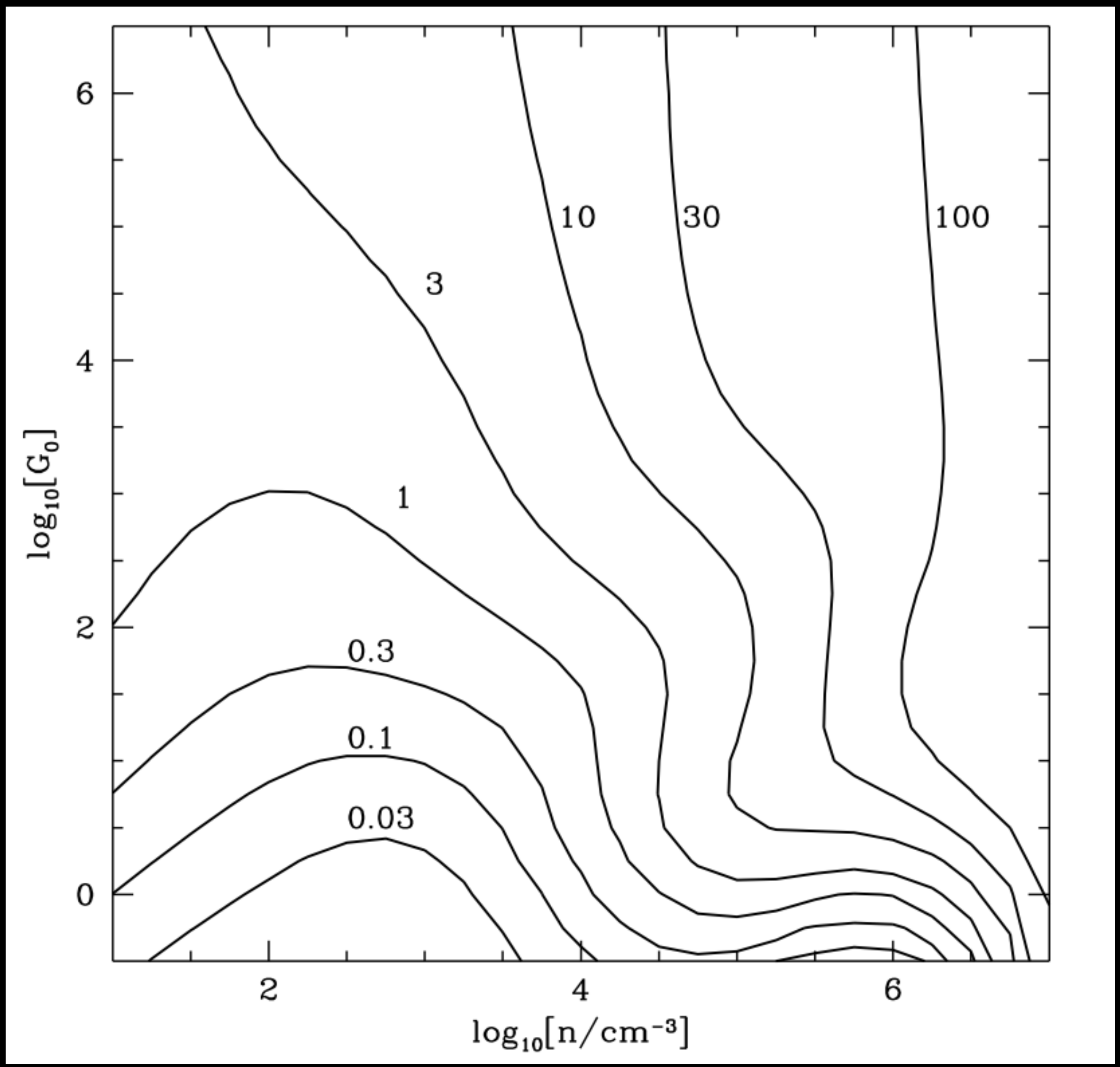
$N(C^+) = 10^{21} x_c$

Vib. Heating

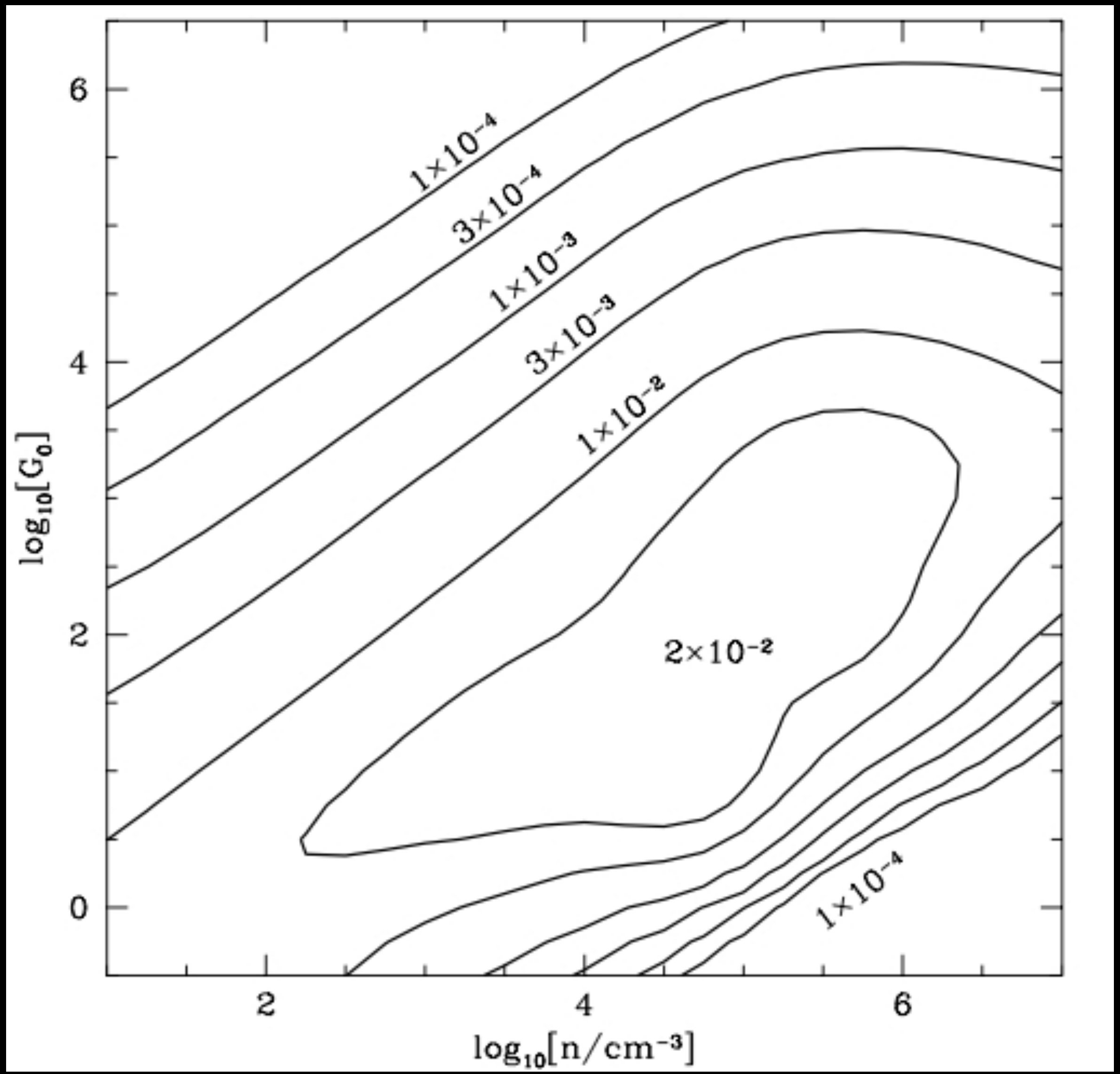


“Classical” Tracers

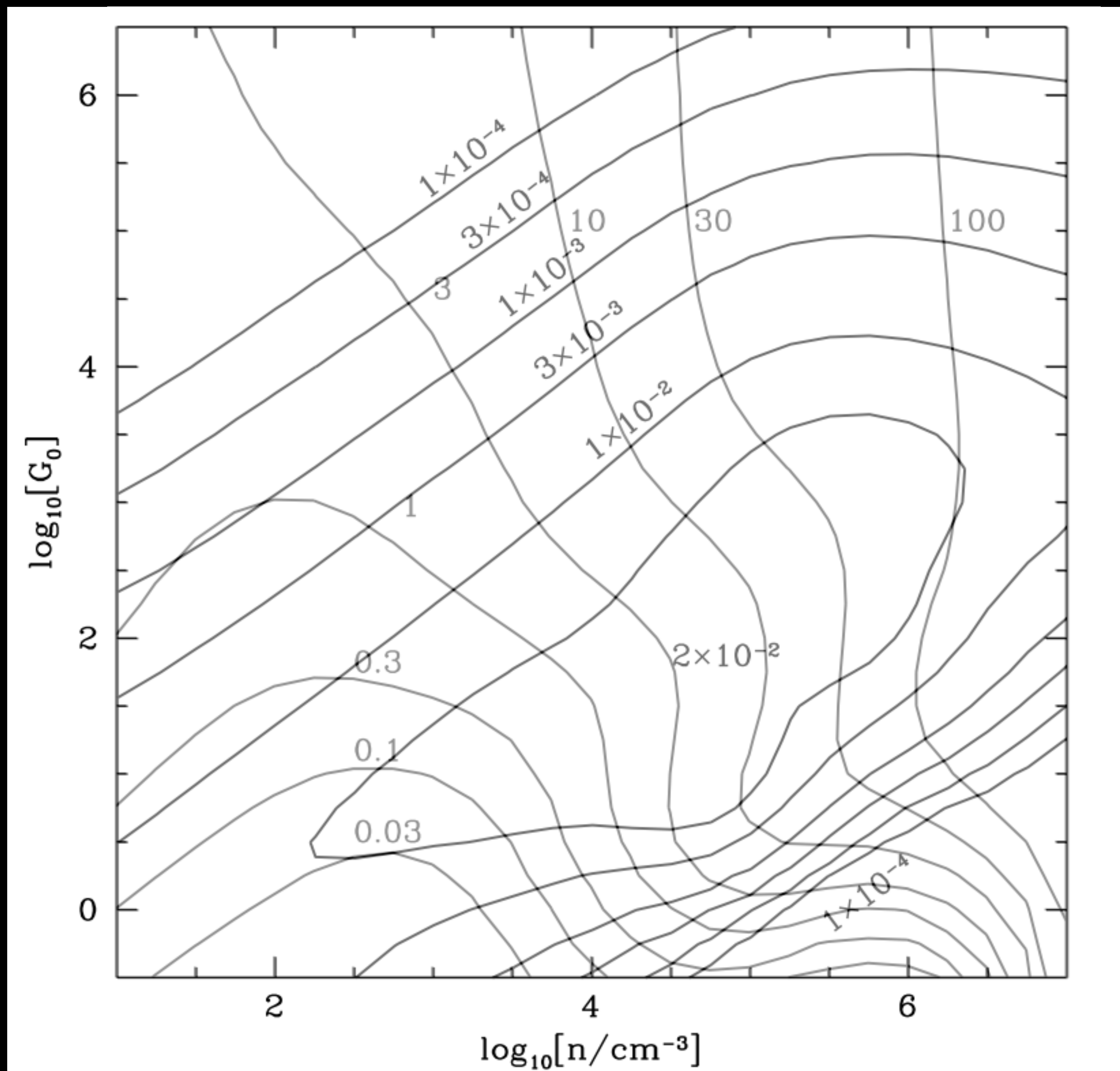
OI 63μm/CII 158μm



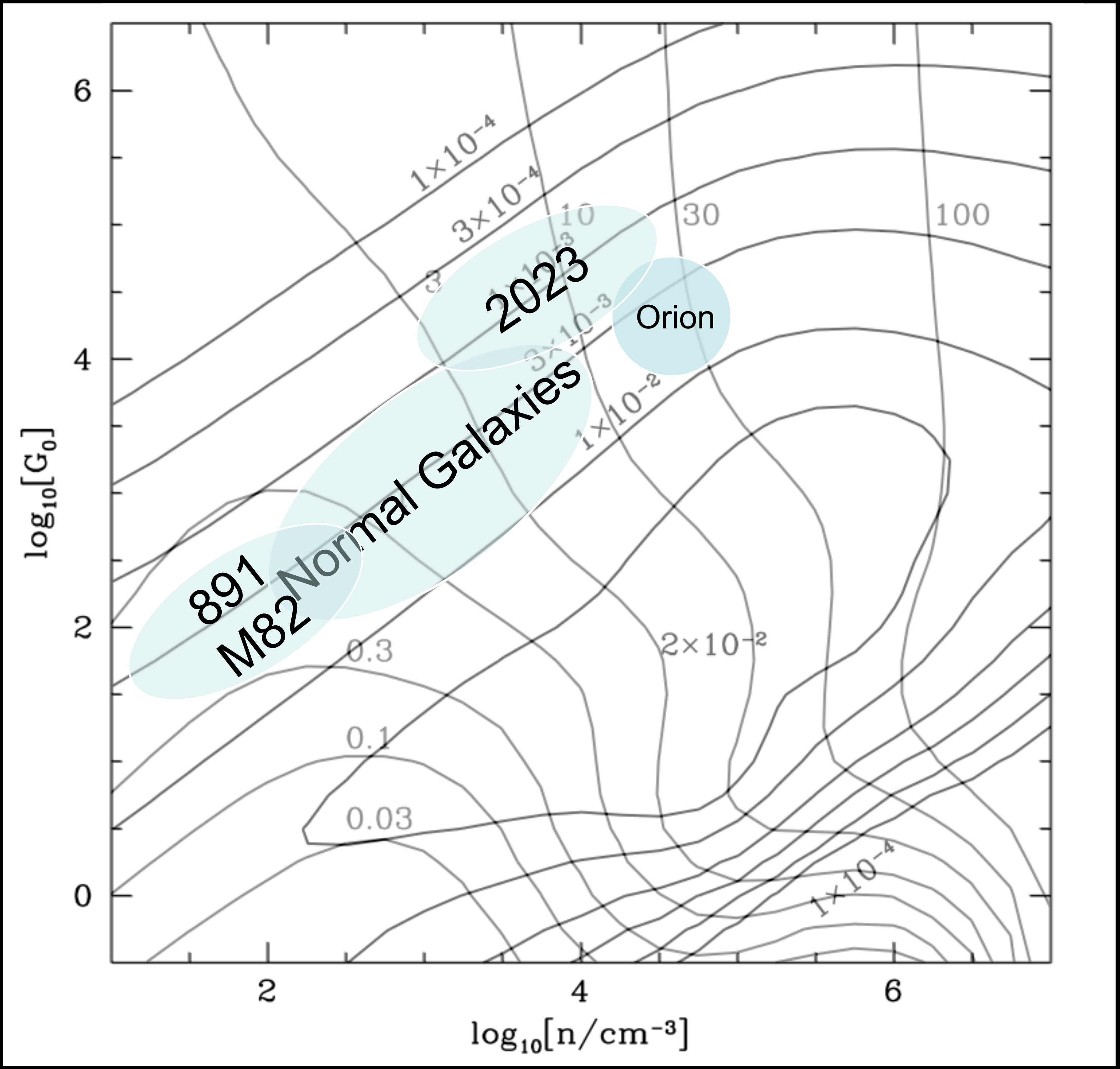
(OI 63μm+CII 158μm)/FIR



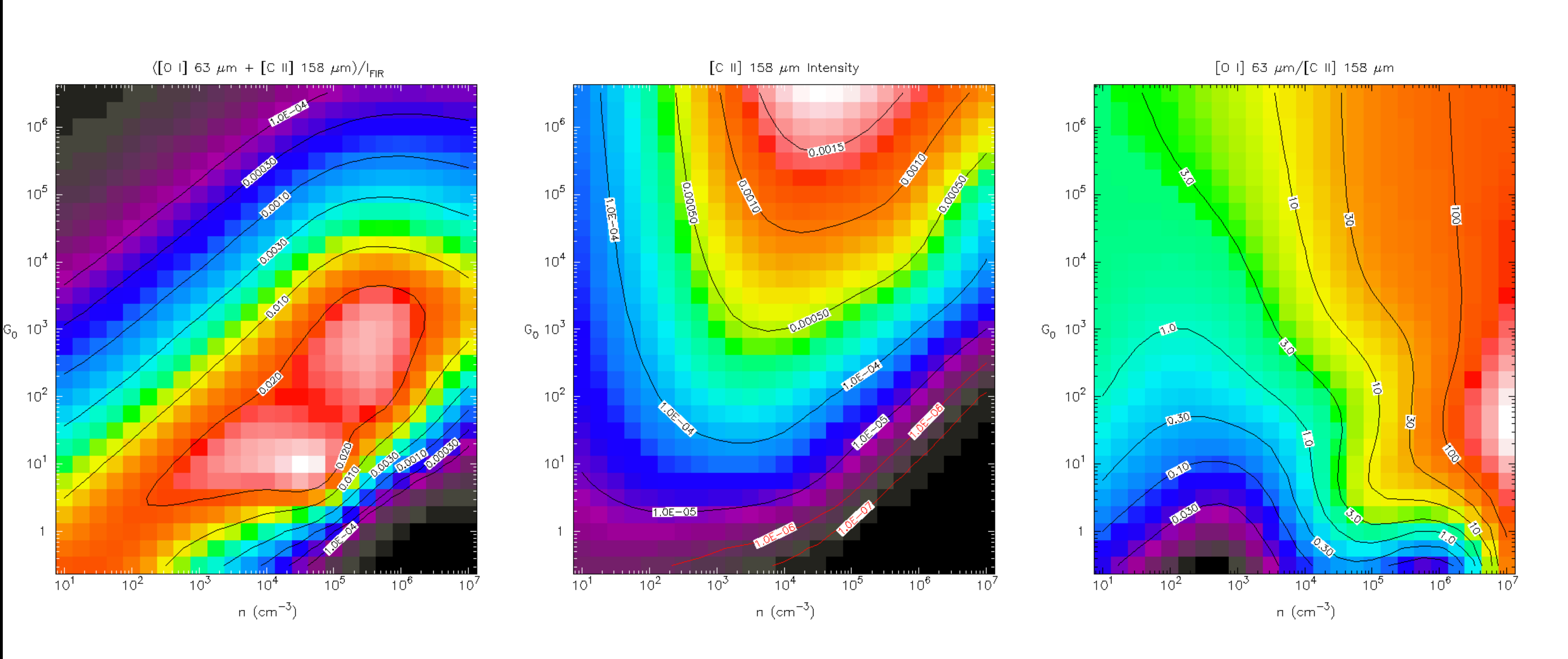
“Classical” Tracers



“Classical” Tracers



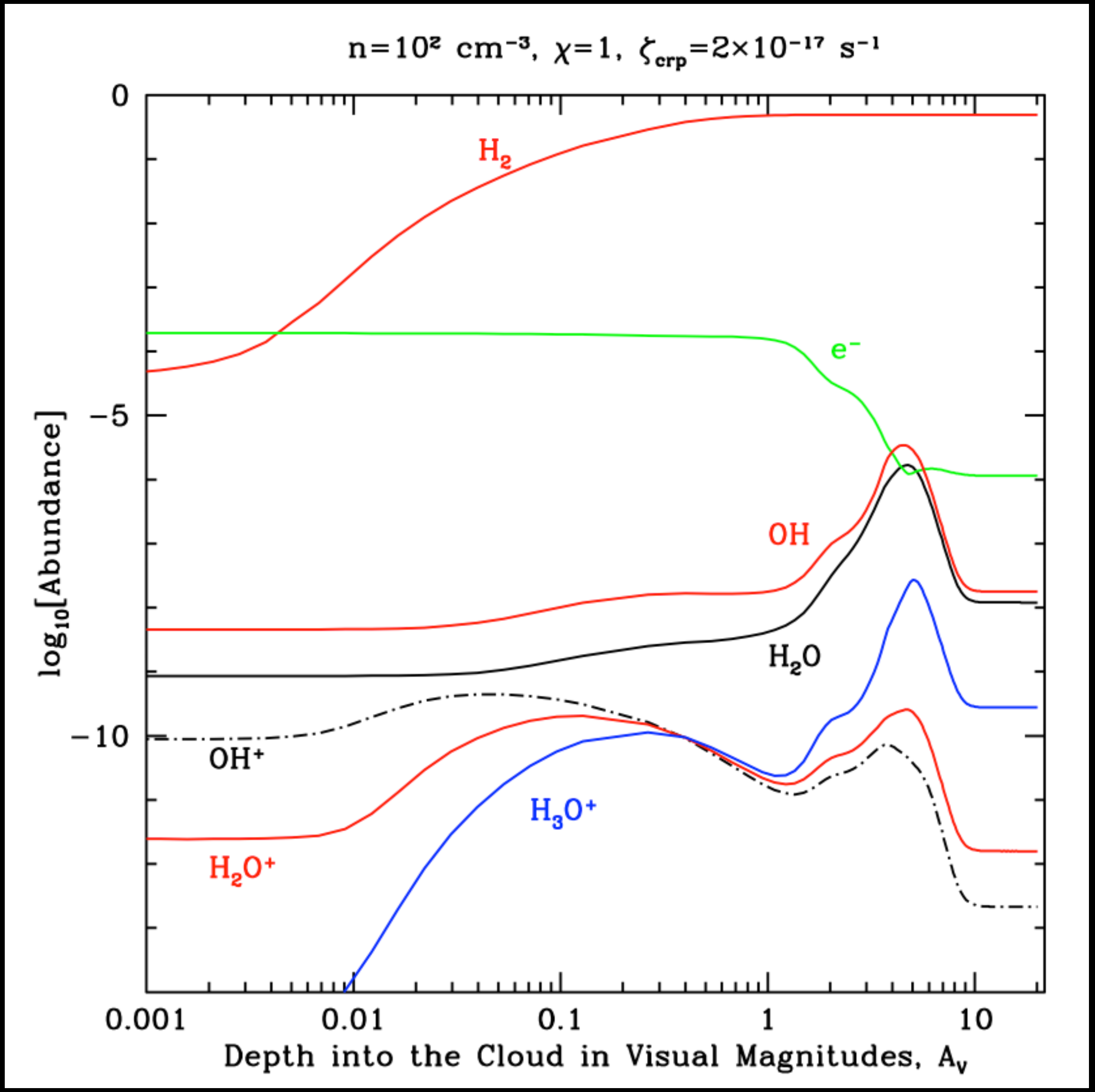
All available from the PDR Toolbox: Precomputed contour plots and best fits to your data



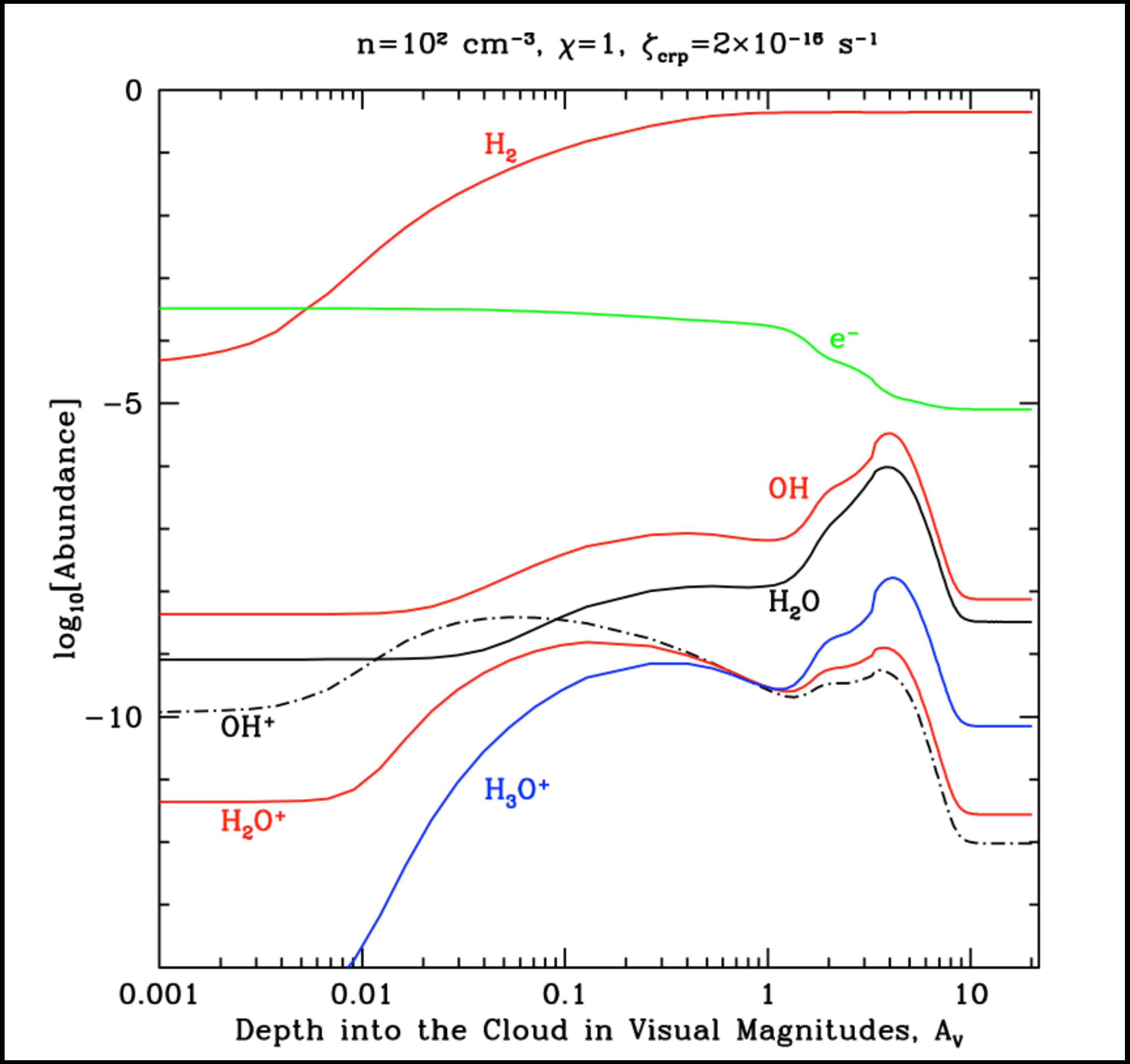
H_2, OI, CII, CI, CO, SiII, FeII, Efficiency, etc.
See Poster by Marc Pound

Molecular Ions in PDRs

$\zeta_{cr} = 2x10^{-17}\ s^{-1}$

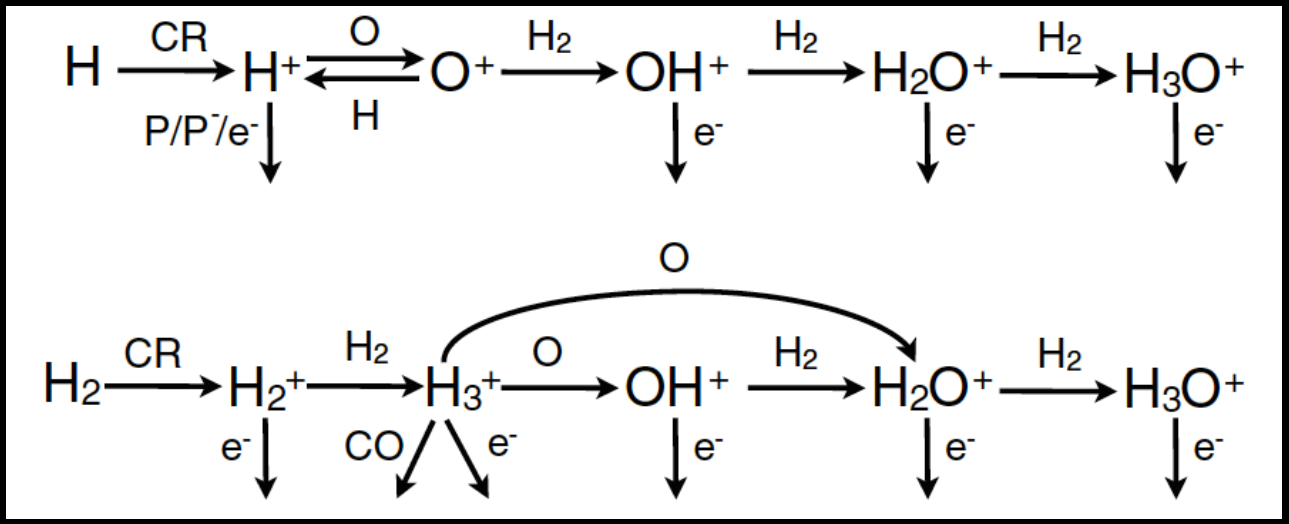


$\zeta_{cr} = 2x10^{-16}\ s^{-1}$

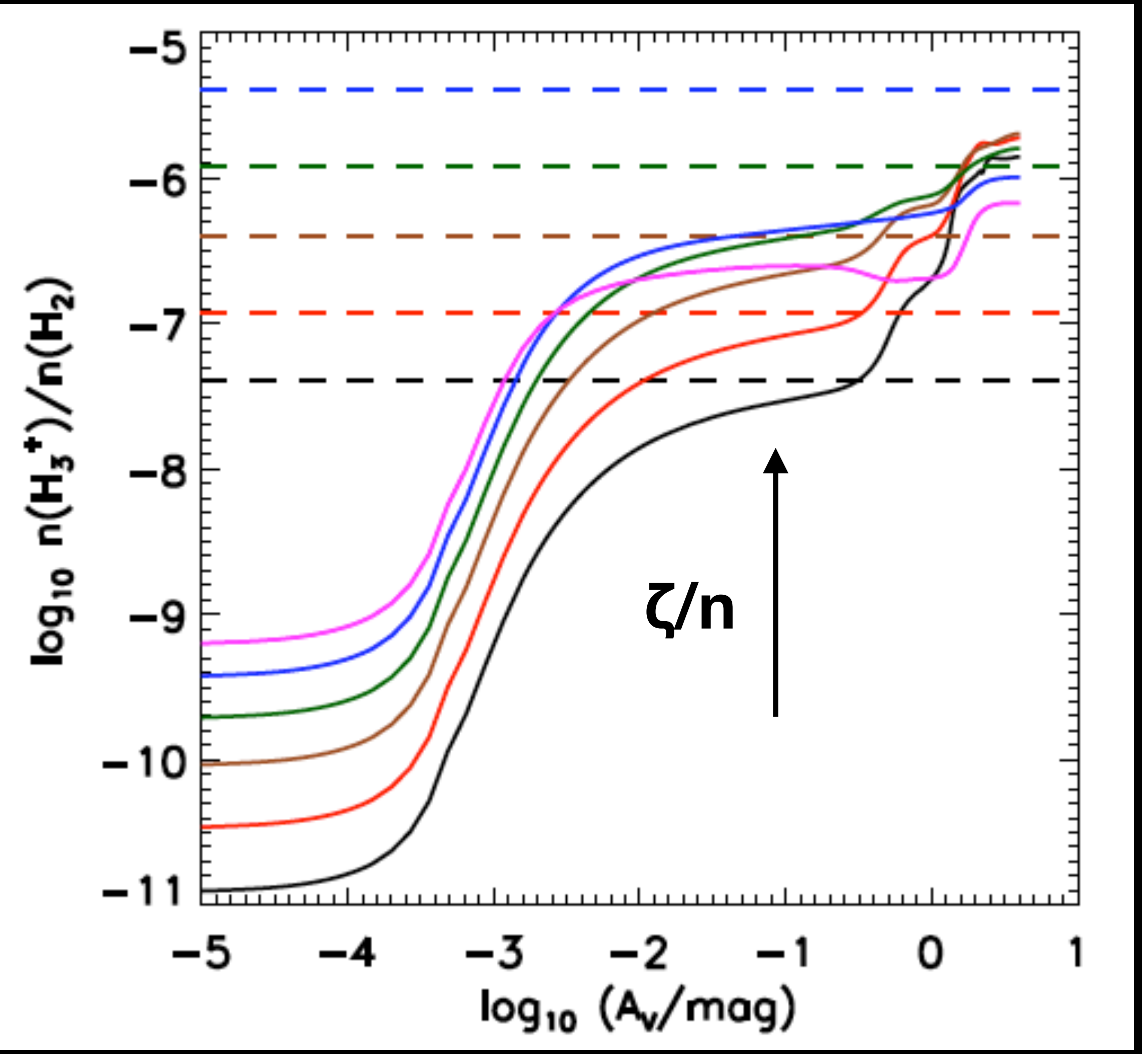


Hollenbach+2012

Cosmic Ray Ionization Rate

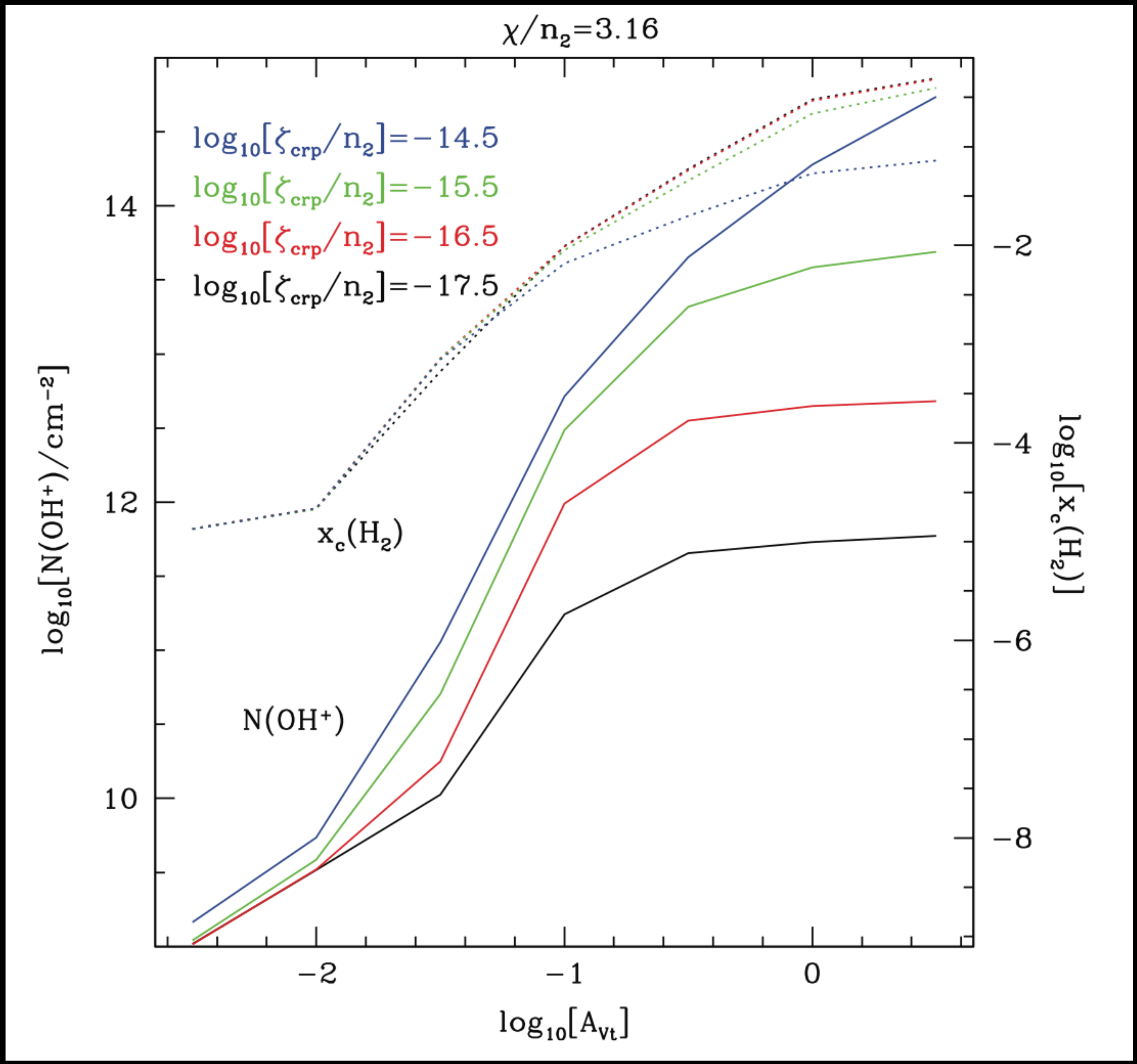


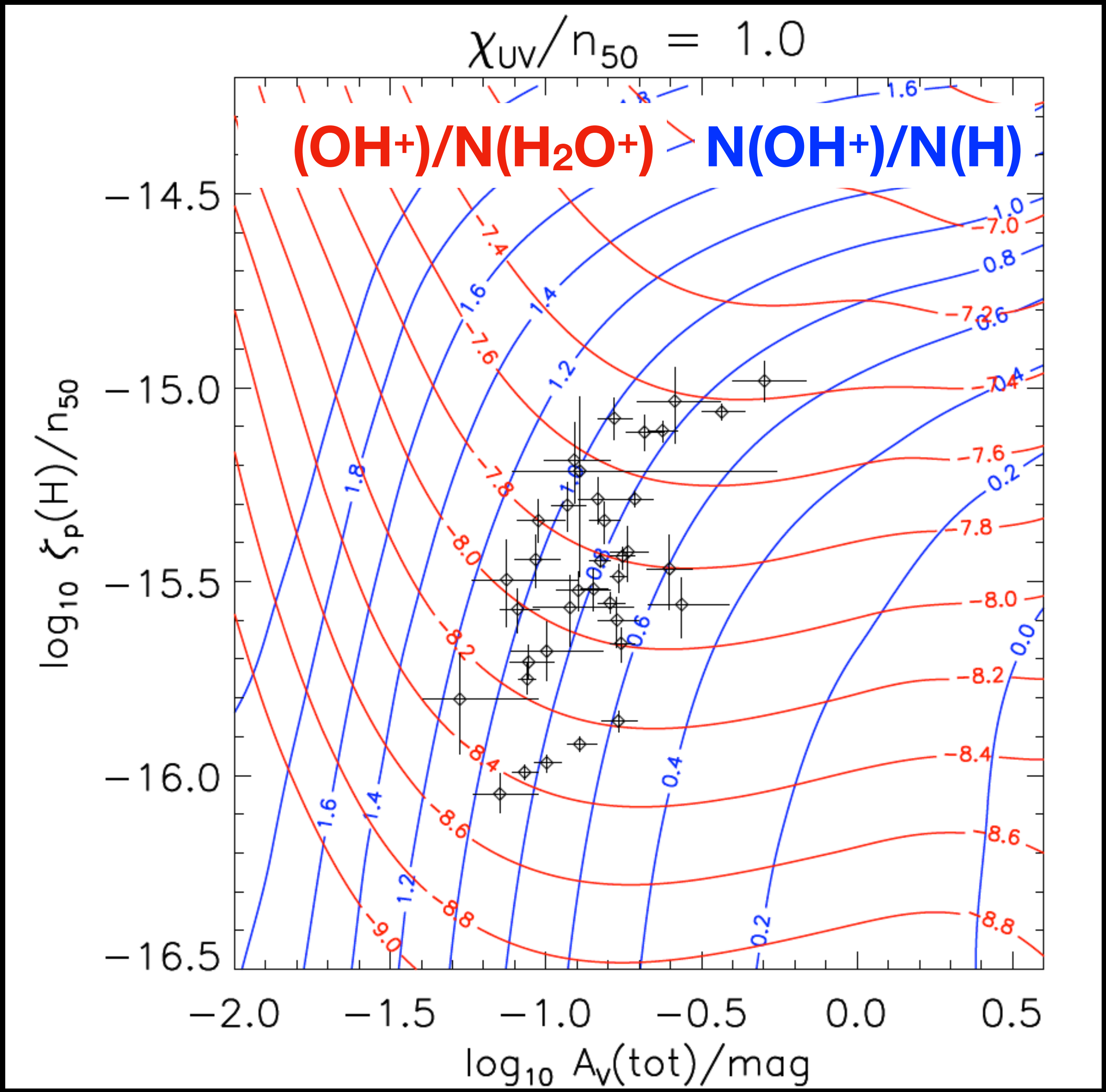
- Herschel absorption line measurements of molecular ions (OH^+, H_2O^+, ArH^+, etc.) + IR measurements of H_3^+
- Simple analytic expressions relate column density ratios to cosmic ray rate (divided by density)
- Detailed PDR modeling of an ensemble of diffuse clouds gives best constraints to date



Neufeld & Wolfire 16, Hollenbach+12, Indriolo & McCall 12

Cosmic Ray Rate Diagnostic

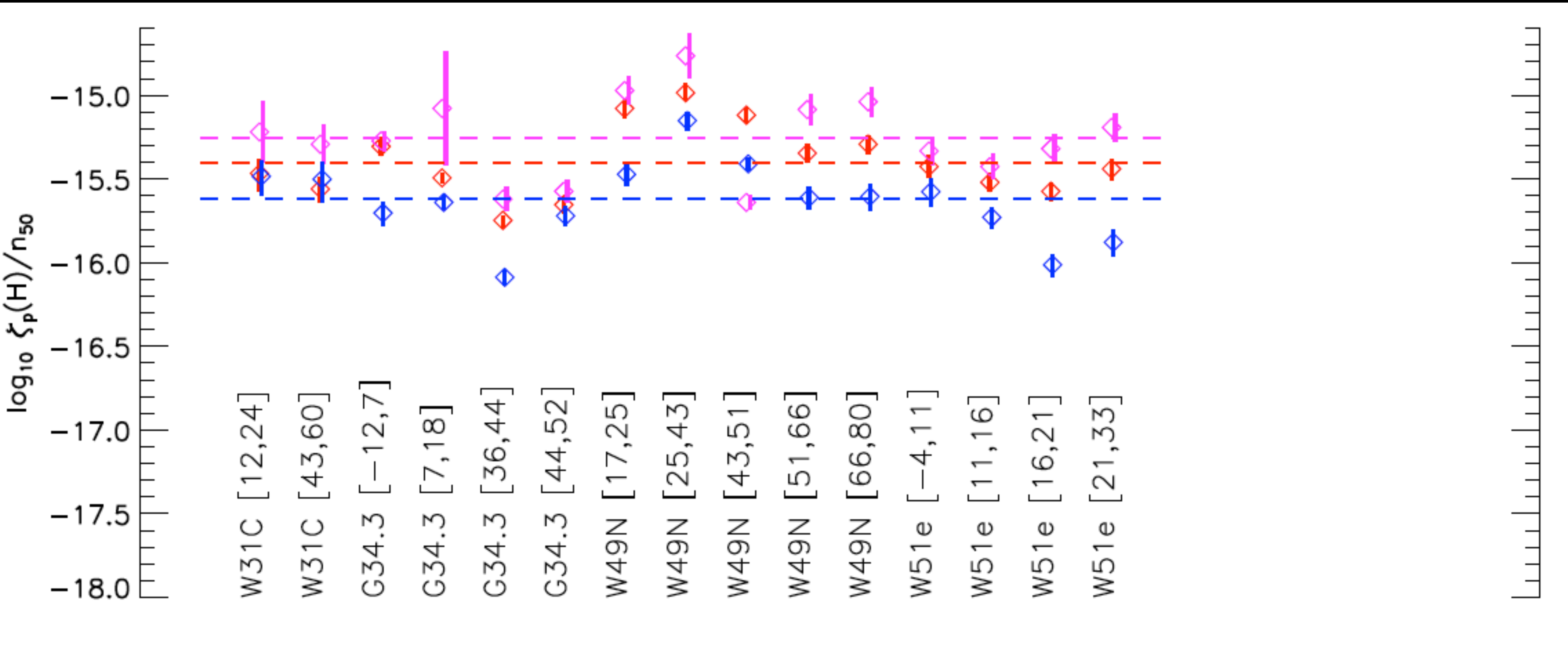




Hollenbach et al. 2012 **Neufeld & Wolfire 2017**

Observed column density ratios along line of sight to diffuse clouds out to 12 kpc ==> constrain ζ/n

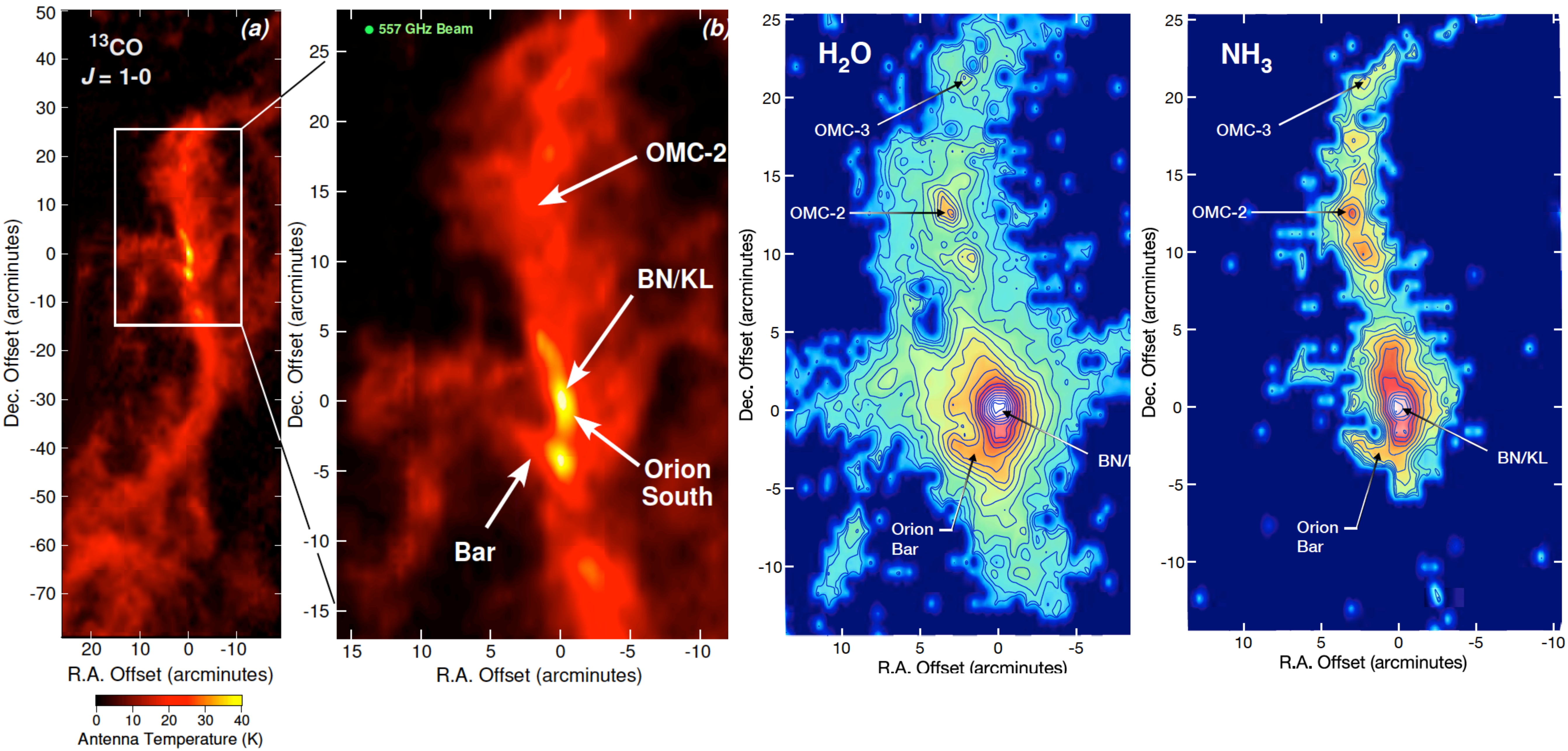
Cosmic Ray Rate Diagnostic



Neufeld & Wolfire 2017

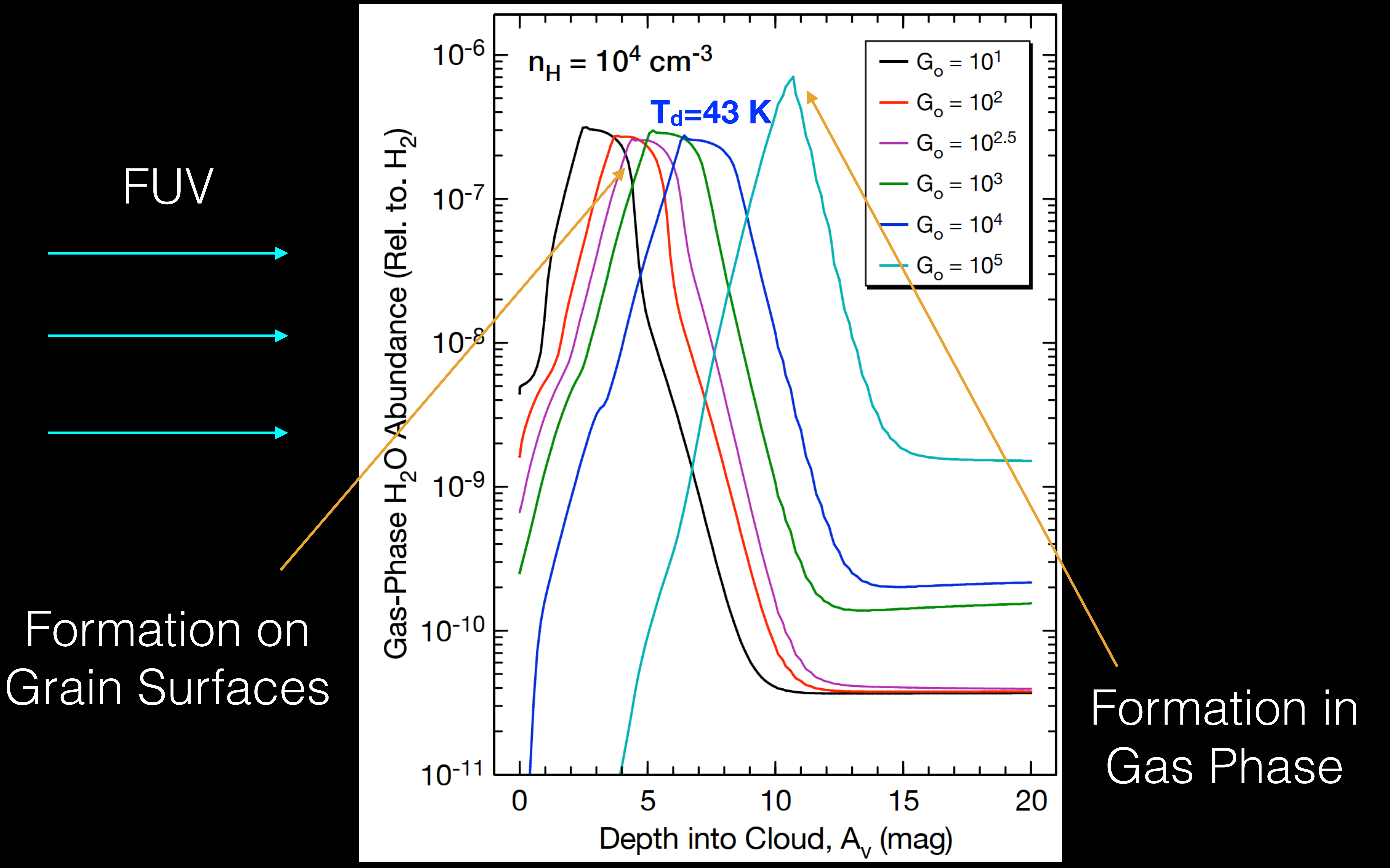
$\zeta_p(H) = (2.2 +/- 0.3)\ \exp[(R_0 - R_G)/4.7\ \mathrm{kpc}]\ \times 10^{-16}\ s^{-1}$

Line Mapping in the Quiescent Ridge: Testing PDR Models with Grain Surface Chemistry

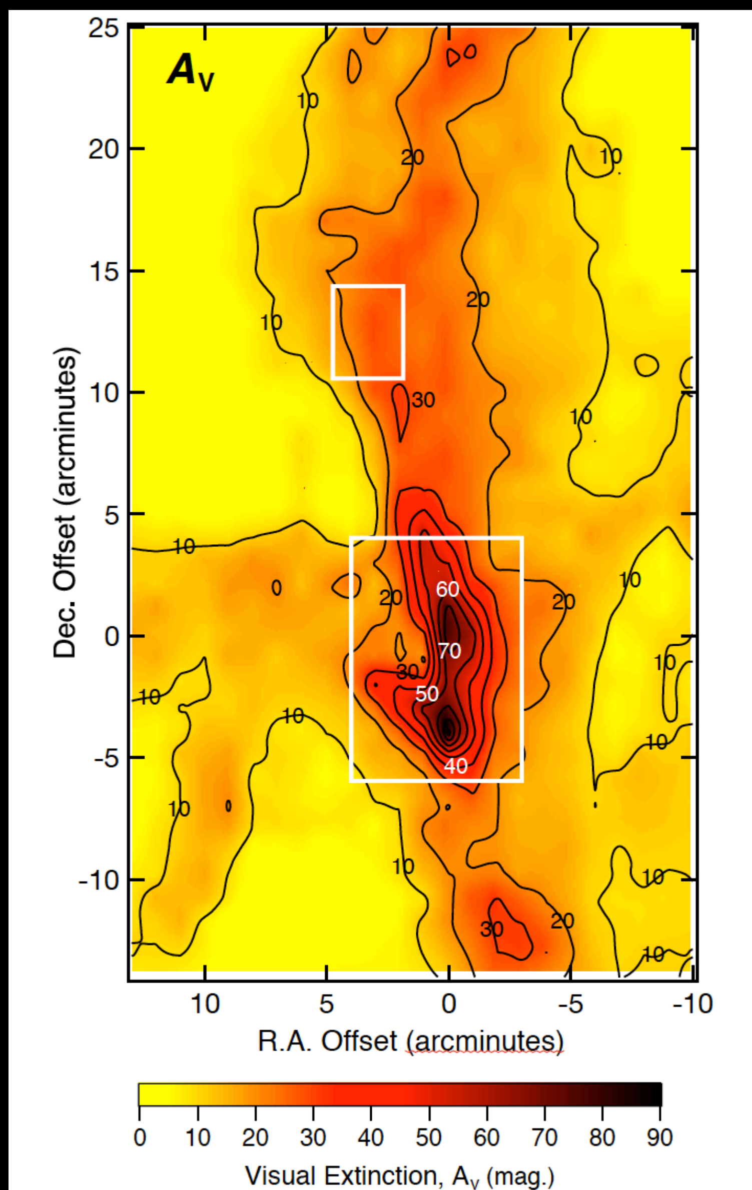


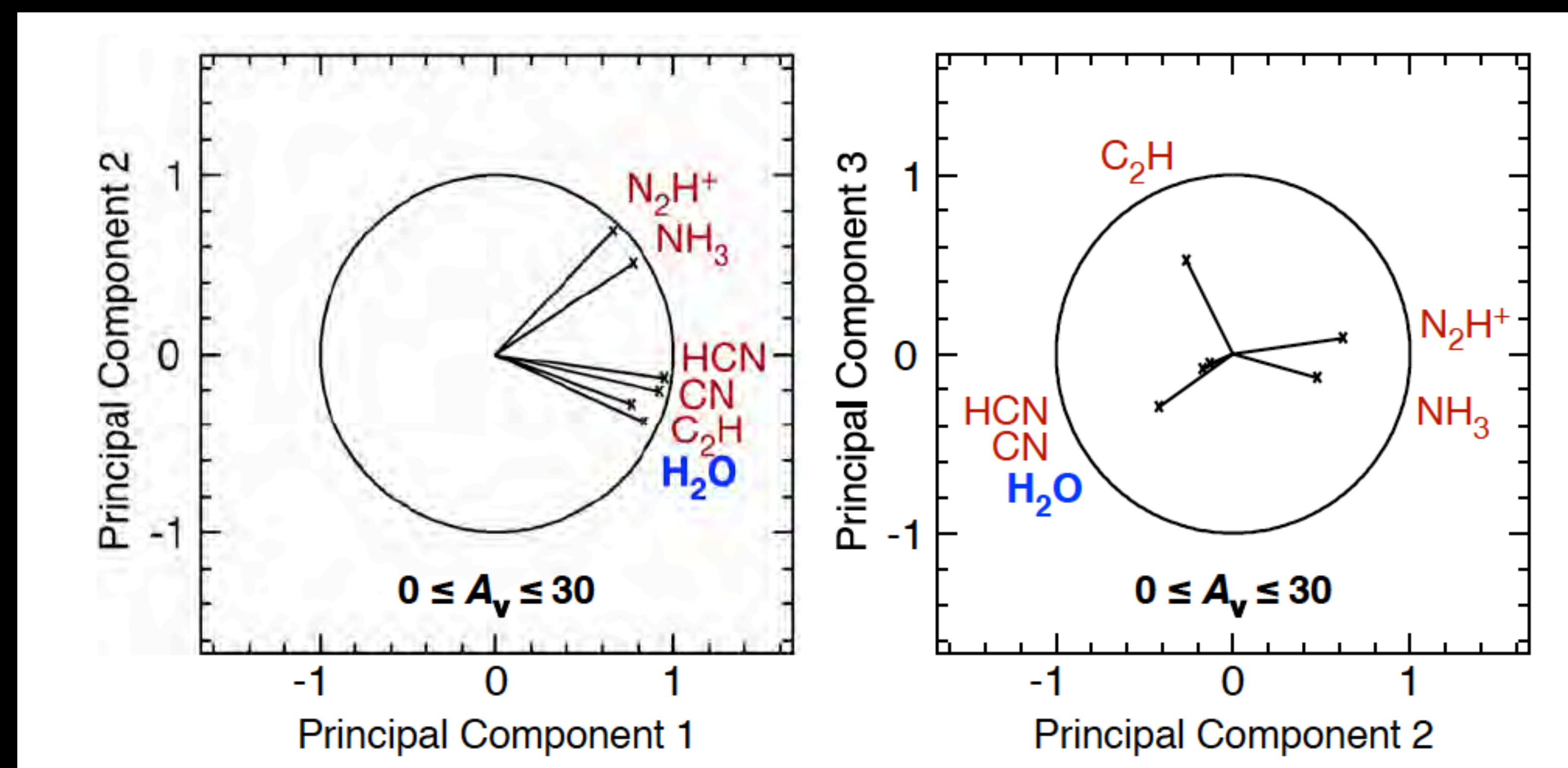
HIFI: H_2O, NH_3 FCRAO: ^{12}CO, ^{13}CO, CN, HCN, C_2H, N_2H^+ Melnick+in prep

Gas-Grain models of PDRs (Hollenbach+09; Melnick+in prep)



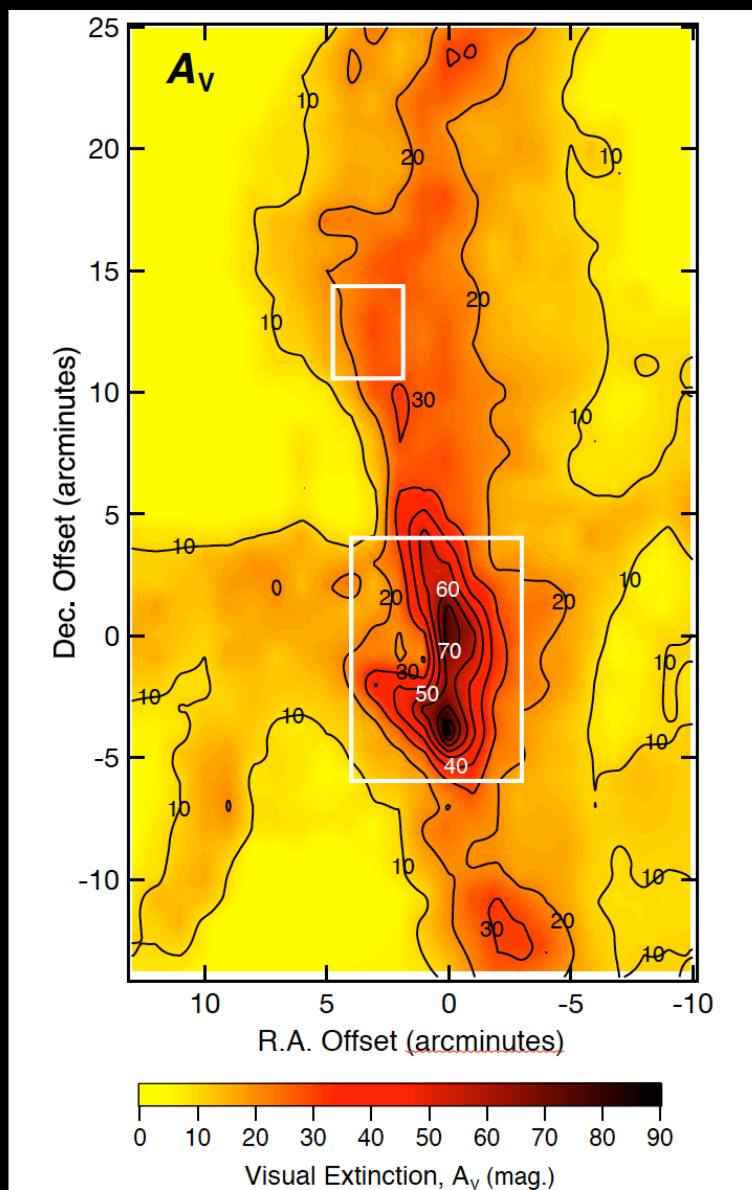
Line Ratios As a Function of Extinction



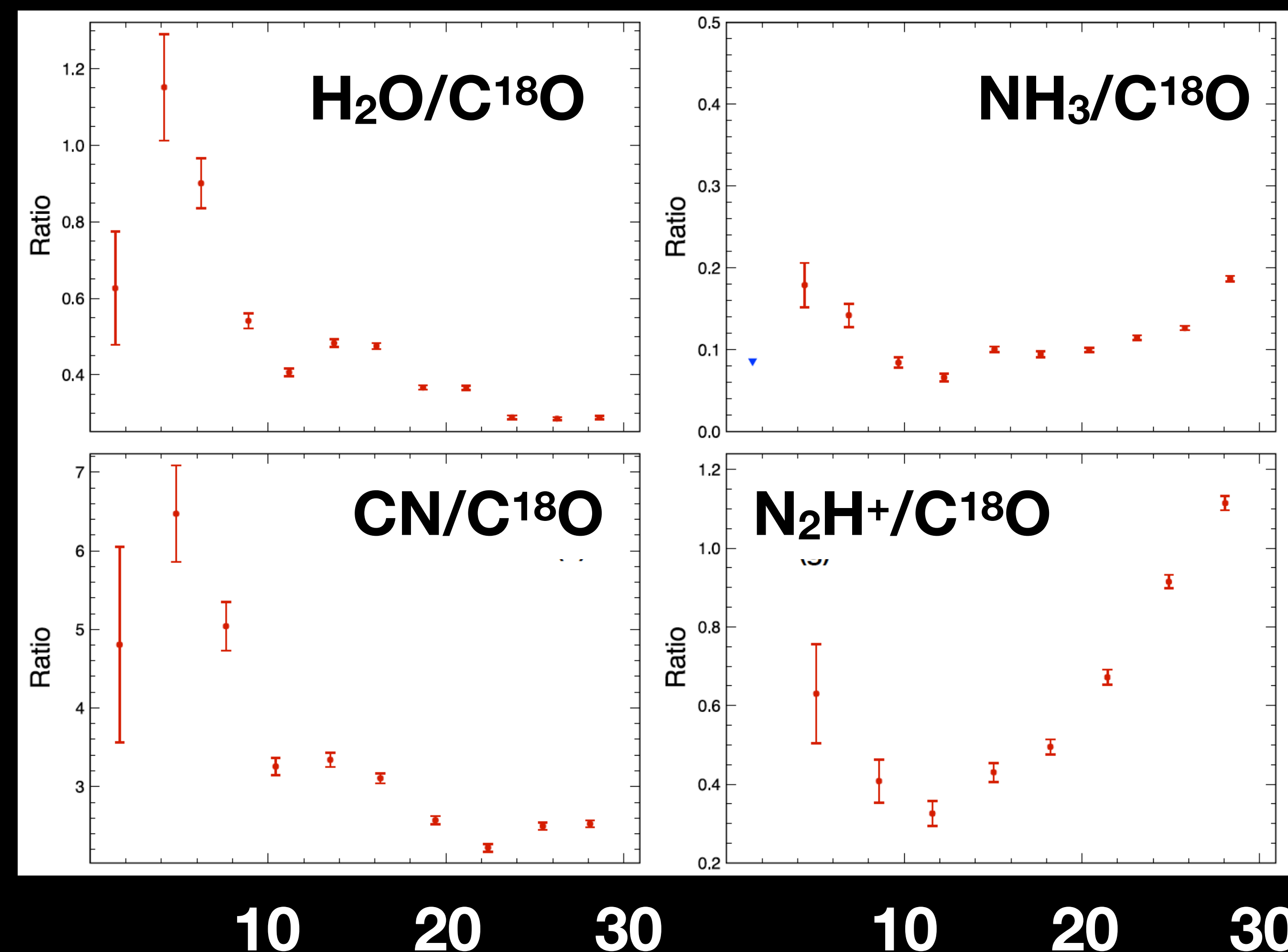


From comparison of $^{13}CO/^{12}CO$ with photometry of background stars (Ripple+13)

Line Ratios As a Function of Extinction



From comparison of $^{13}CO/^{12}CO$ with photometry of background stars (Ripple+13)



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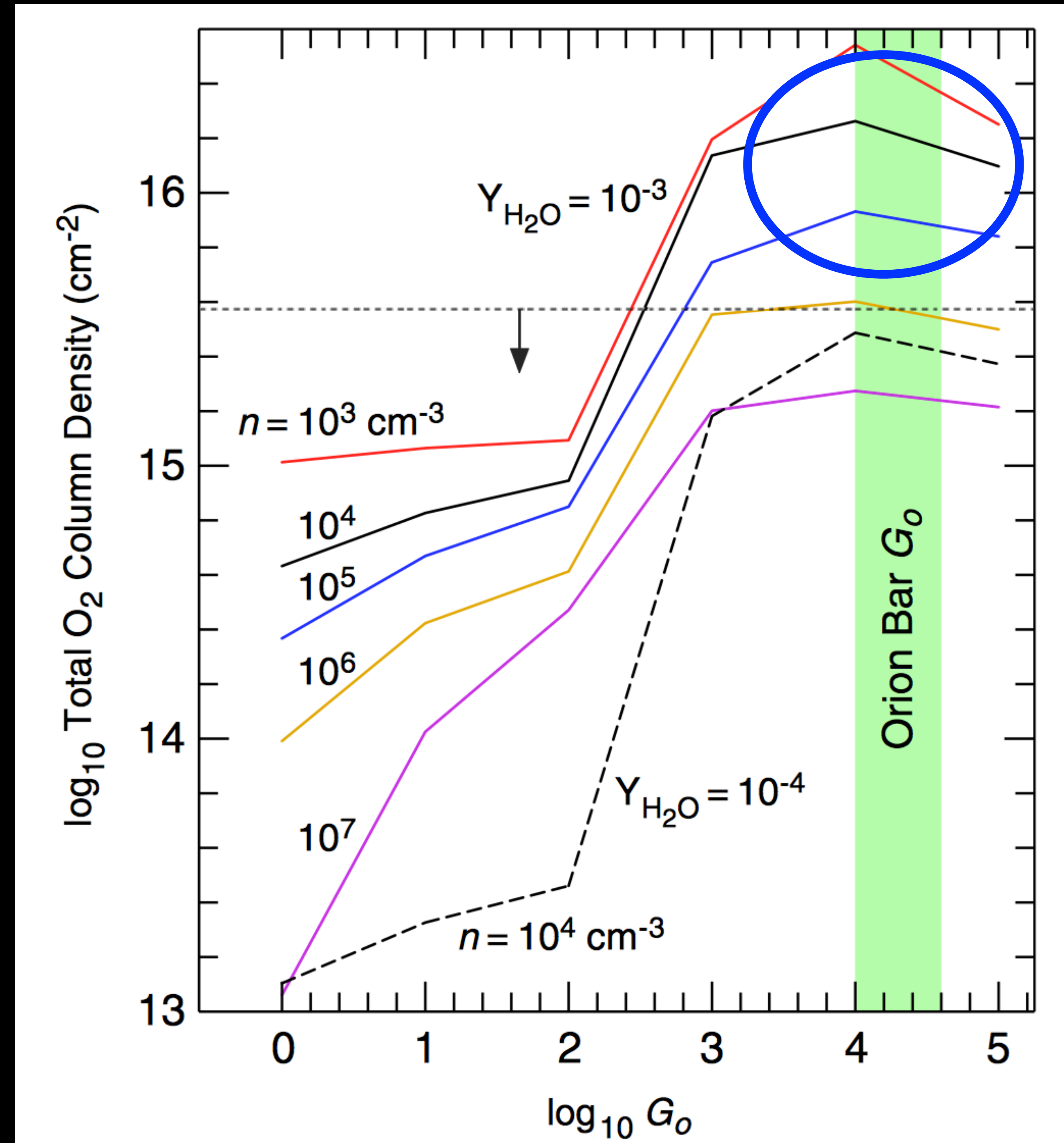
A Search for O_2 in the Orion Bar (Melnick et al. 2012)

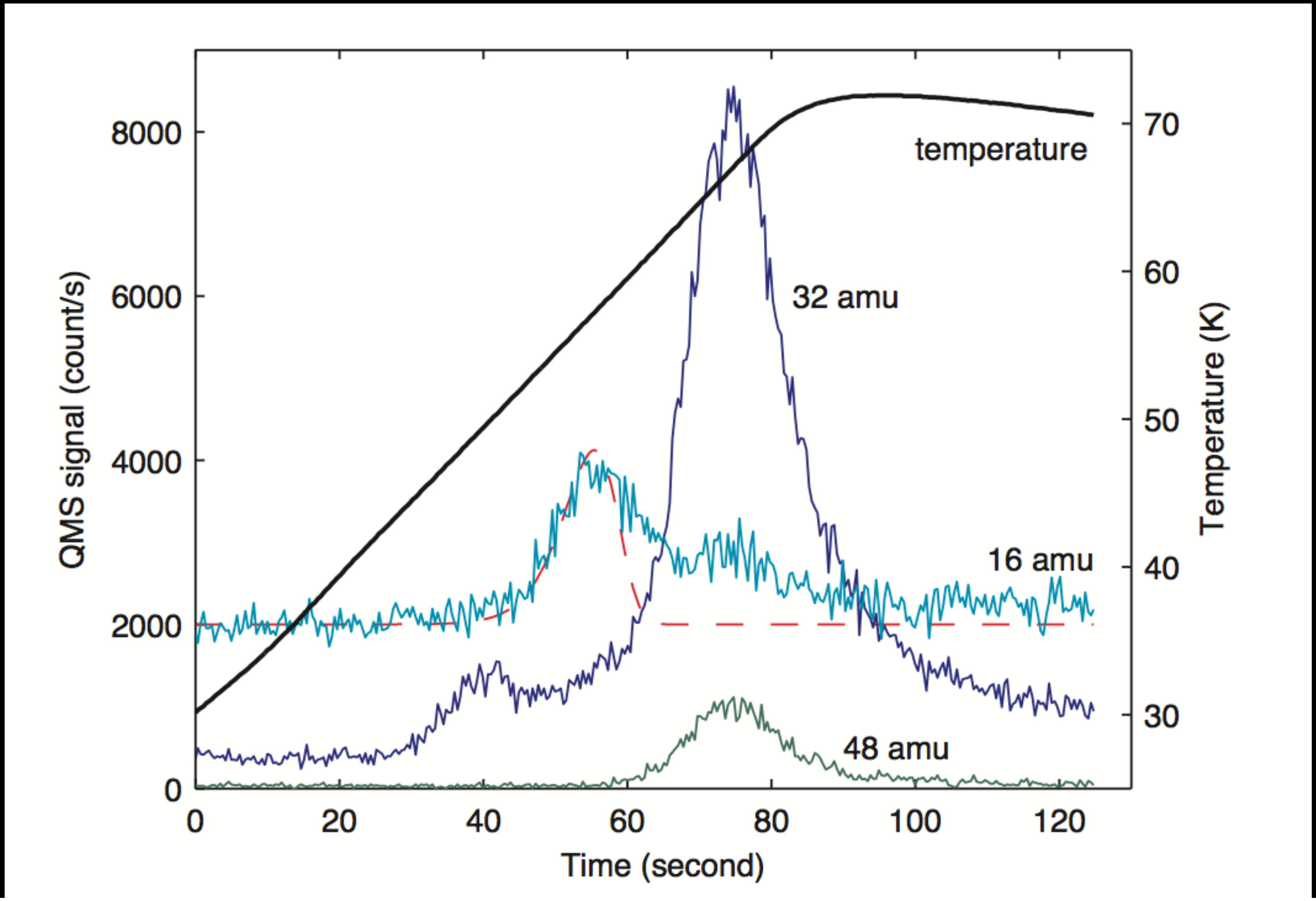
Use the high FUV field to test the model prediction



Upper limits rule out binding energy this low

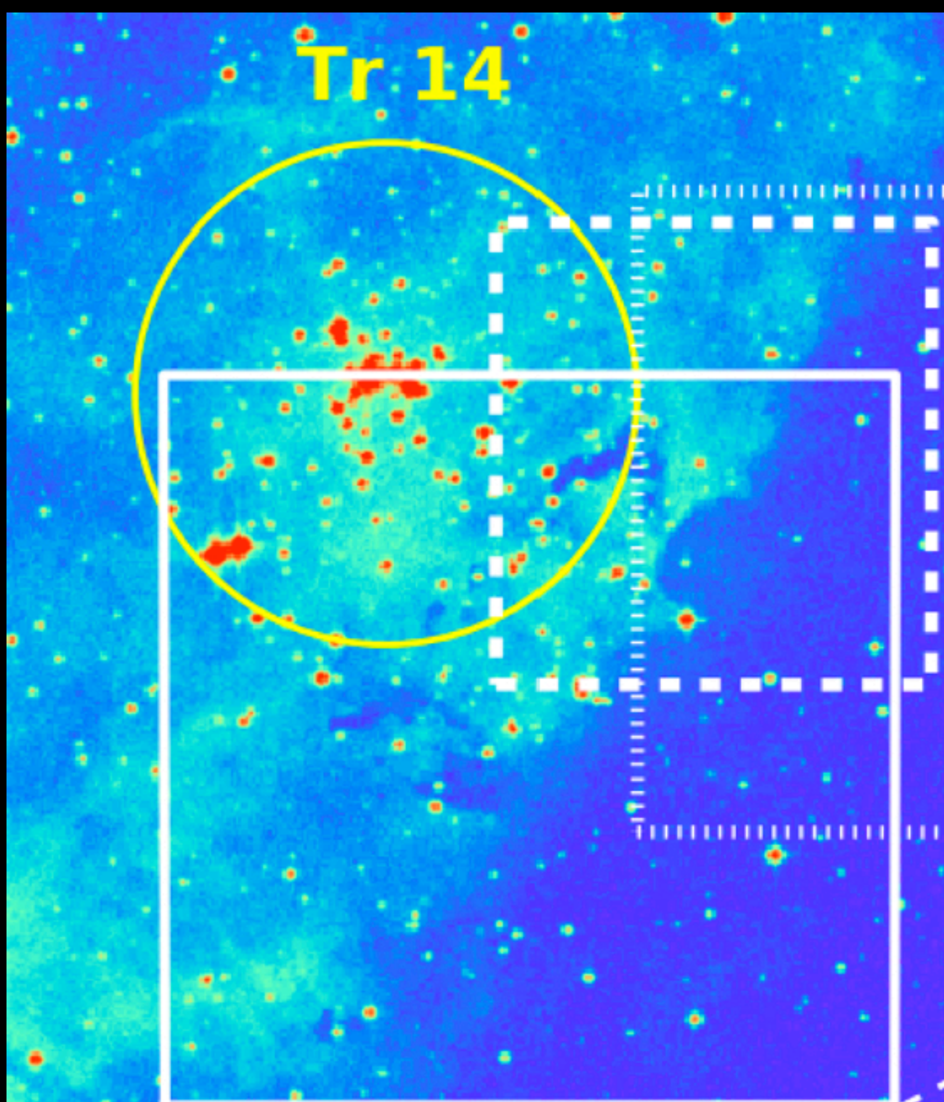
The discrepancy between the model predictions and our observations would be reduced, if not eliminated, if the adsorption energy of atomic oxygen to water ice were greater than 800 K, and possibly as high as 1600 K. A lower value for the photodesorption yield for H_2O would help, but is not supported by fits to other astronomical data or recent theoretical calculations and laboratory measurements. A

New lab results (He et al. 2015)

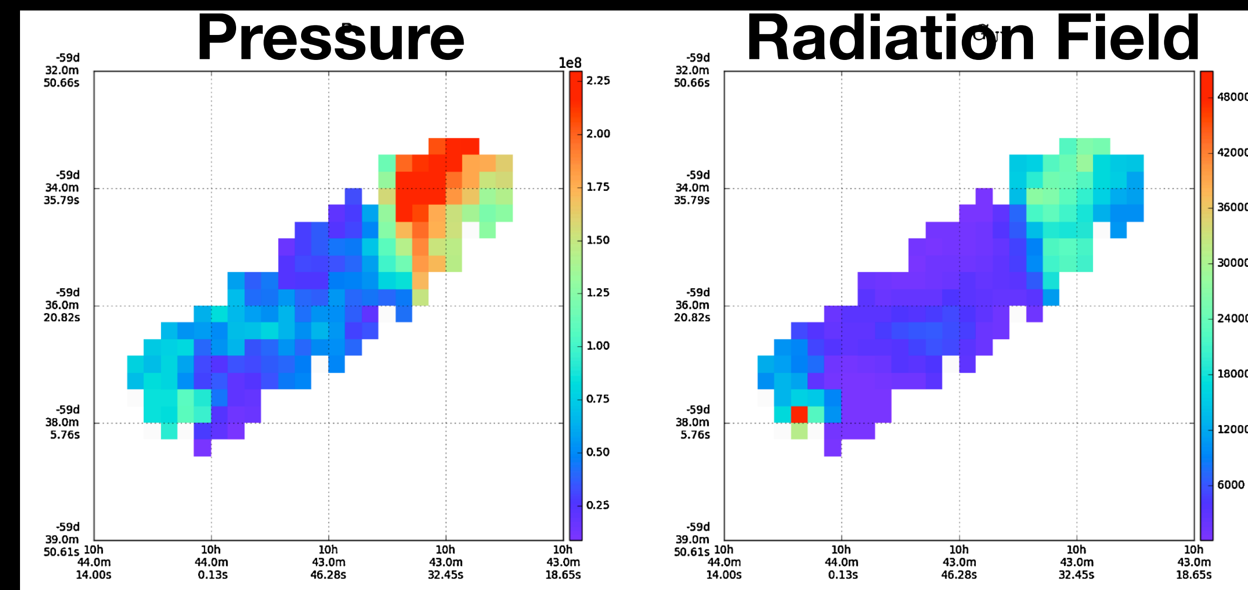


Surface	Desorption Peak Temperature	$E_{des}(O)$
Porous water ice	56±2 K	1660±60 K
Amorphous silicate	64±3 K	1850±90 K

Mapping PDR Conditions on Small Scales

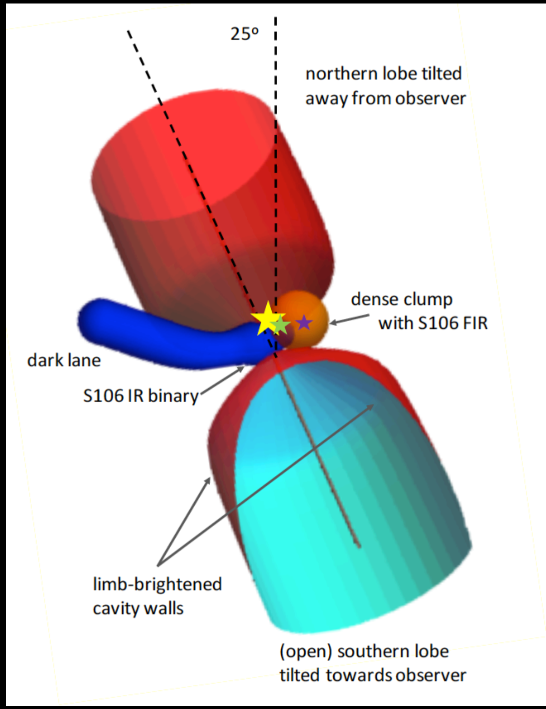


Trumpler 14 PDR - Wu+18
Also: Seo+19

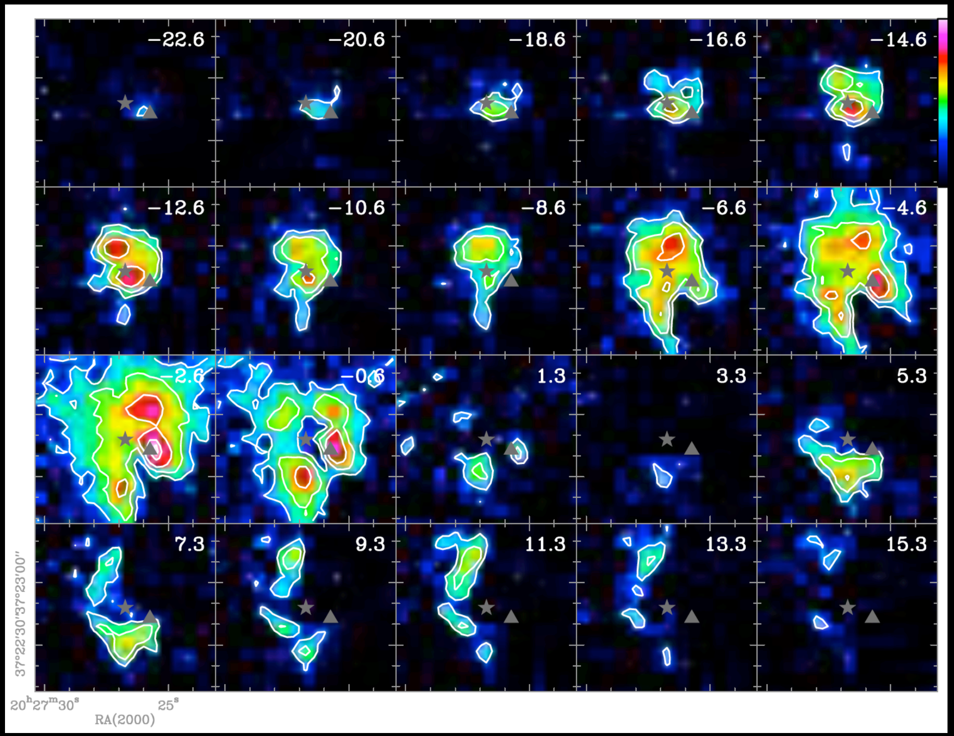


- **SPIRE/FTS: CO 5-4 to 13-12, CI 370 and 610**
- **PACS OI 63, 145 and CII 158**
- **Meudon PDR code fits to CO SLEDS and CI**
- **Matches with OI 63 and CII problematic: need resolved spectra**

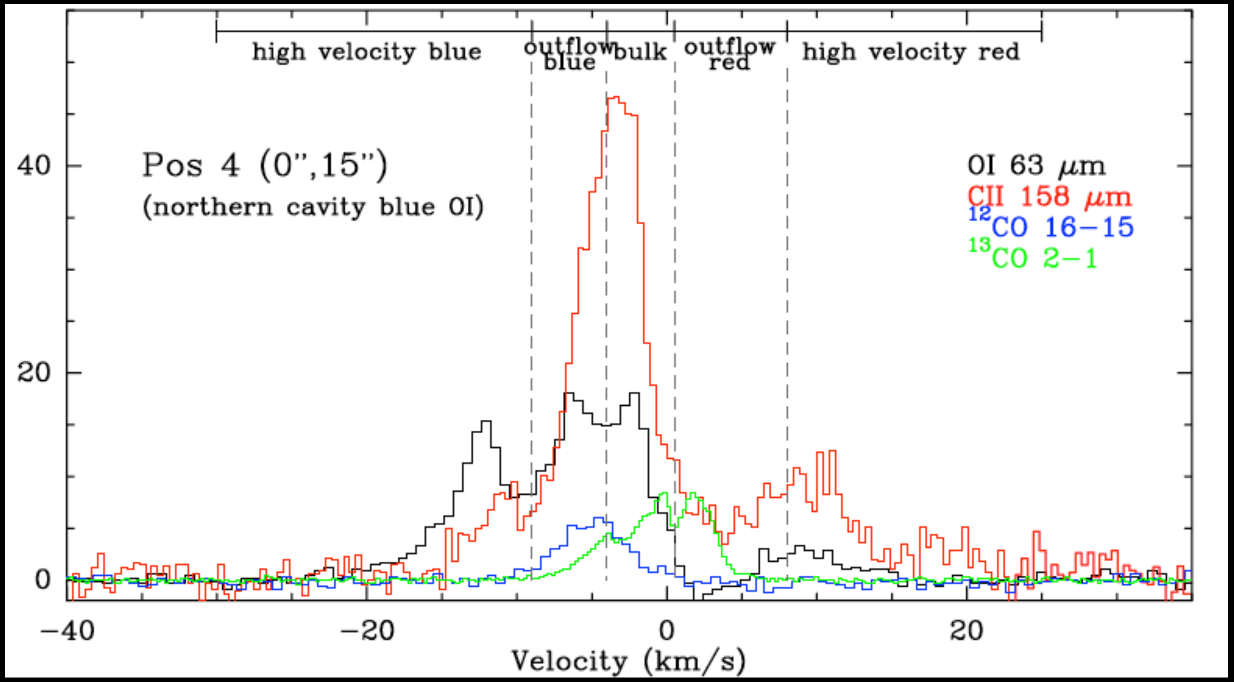
High Spatial and Spectral Resolution Observations of S106: Schneider+18



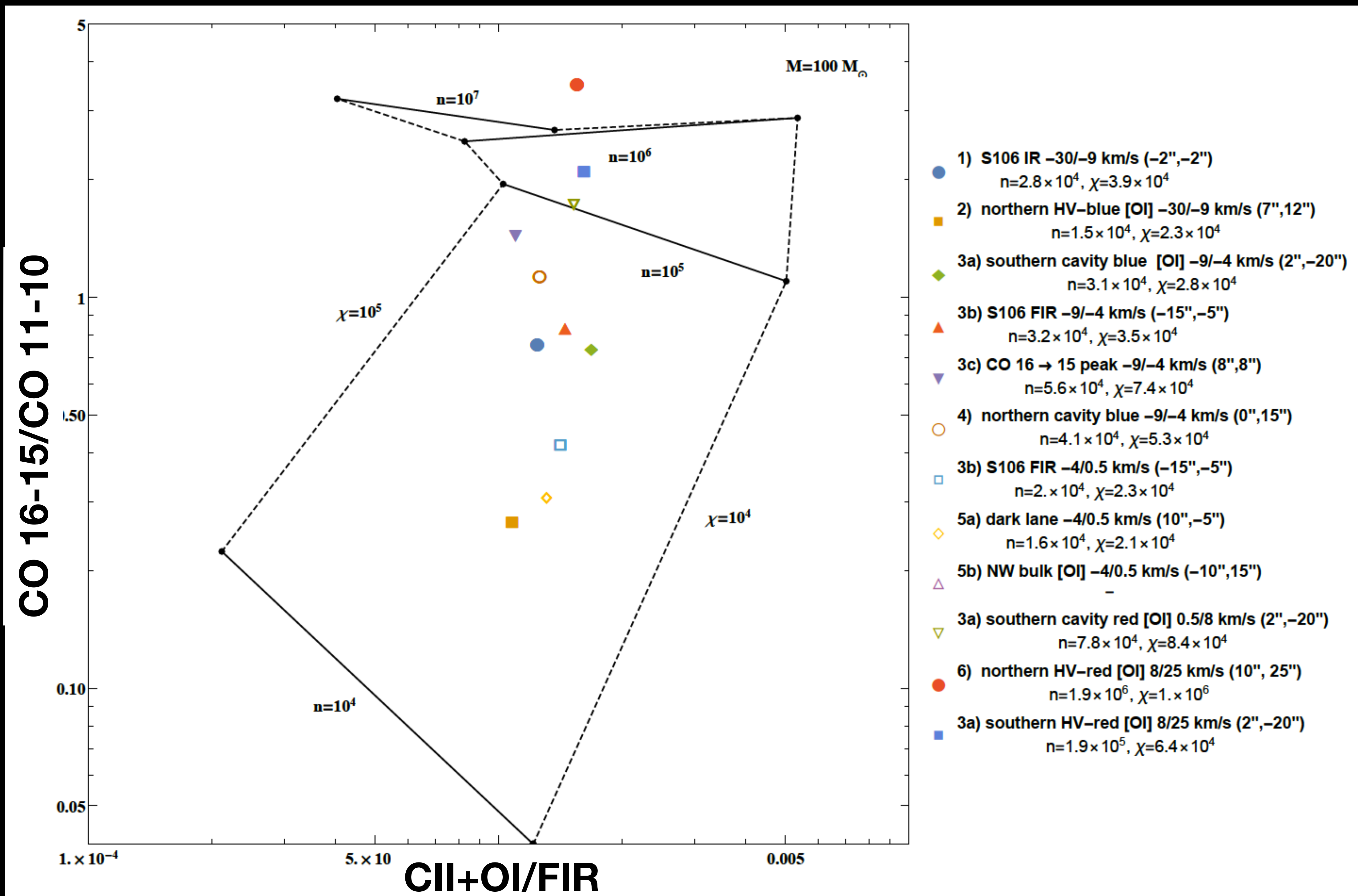
- S106 Massive Star Forming Region
- Binary providing FUV illumination of outflow cavity walls and dense molecular clump
- Observed with SOFIA/GREAT in CII 158, OI 63, CO 16-15
- KOSMA-τ models used to compare intensities in different velocity ranges



SOFIA OI 63μm Channel Maps

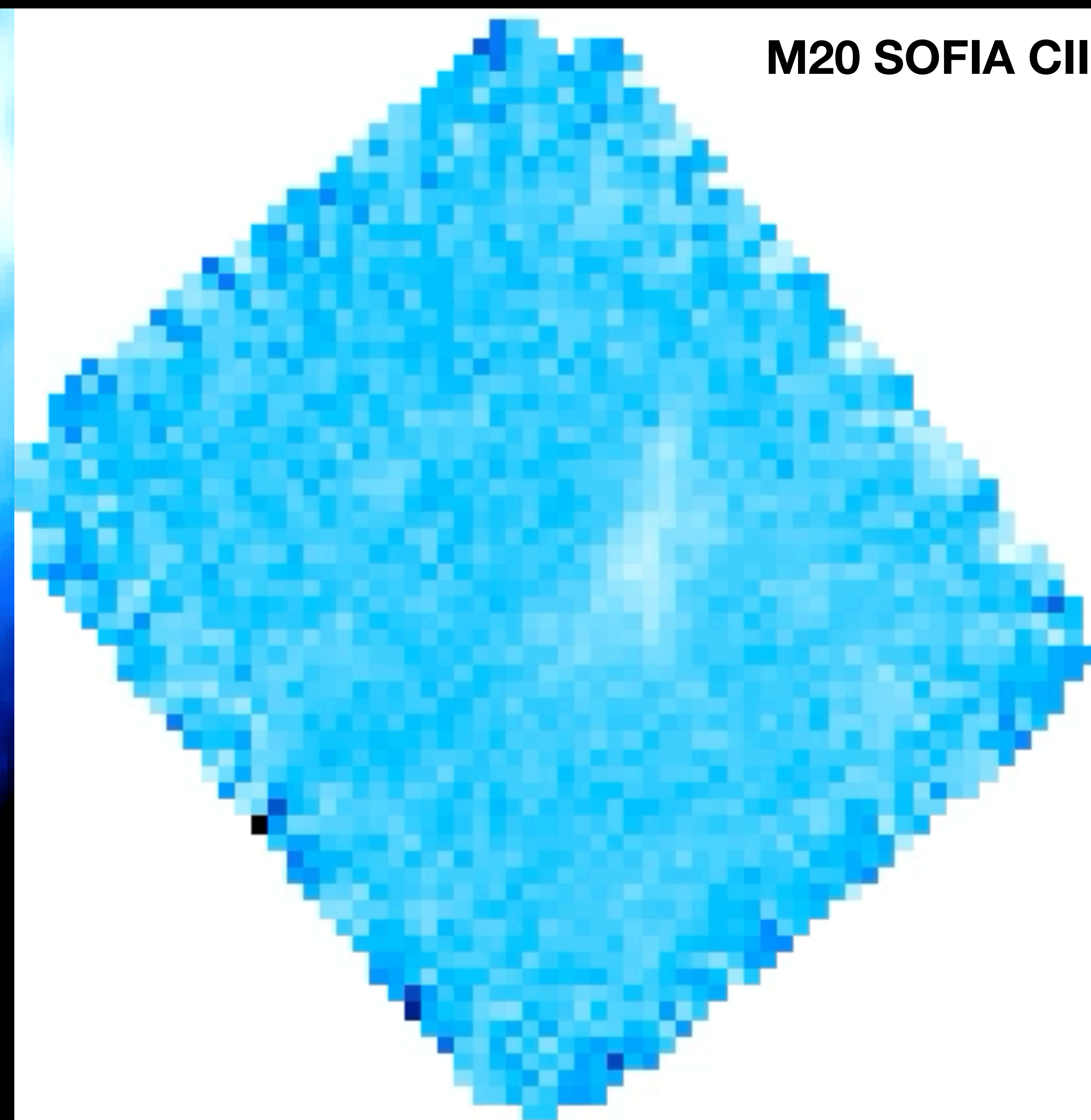


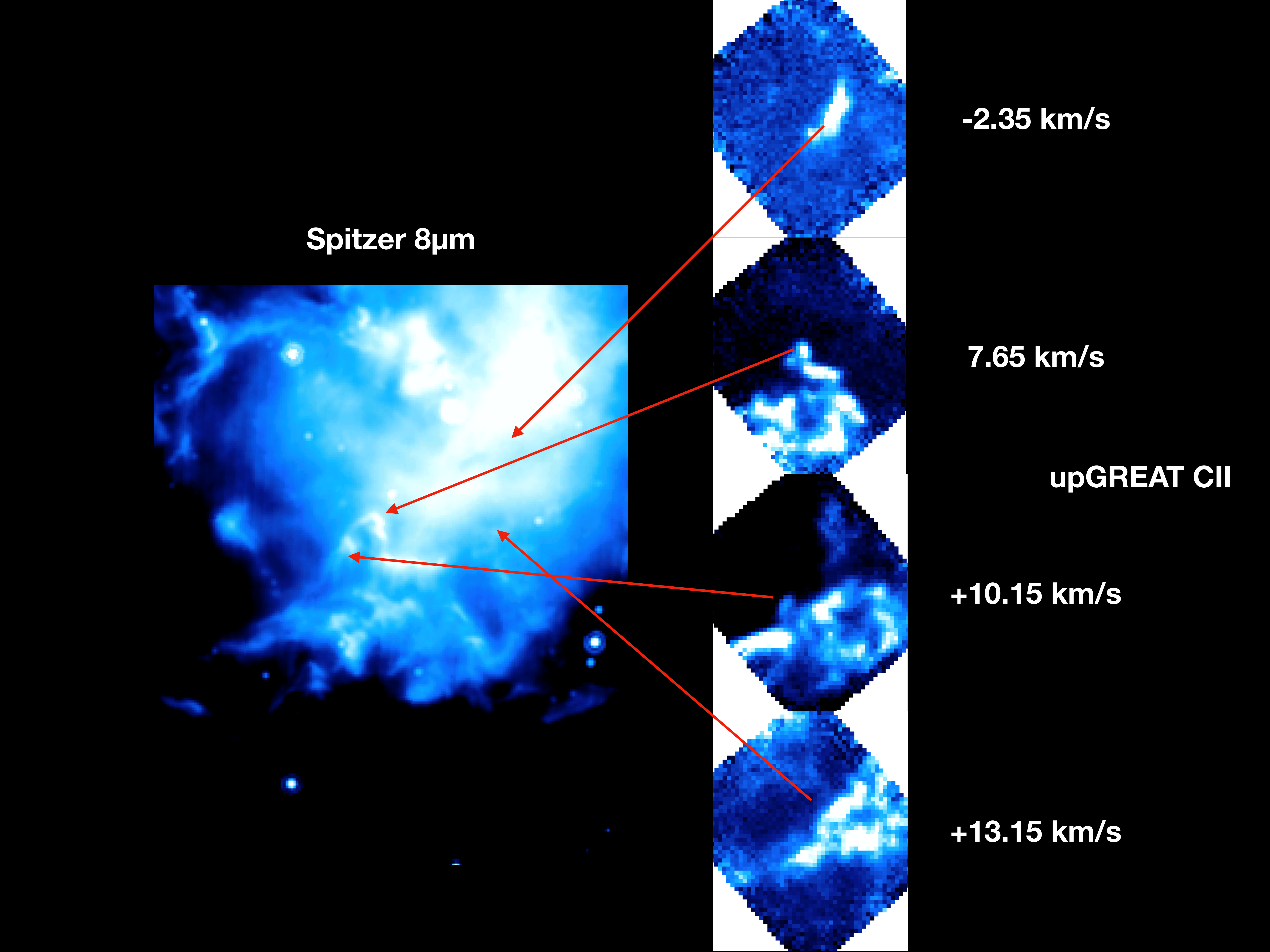
Model Results - Separate Components by Velocity



S106: Schneider+18

Spatially and Spectrally Resolved Galactic PDRs

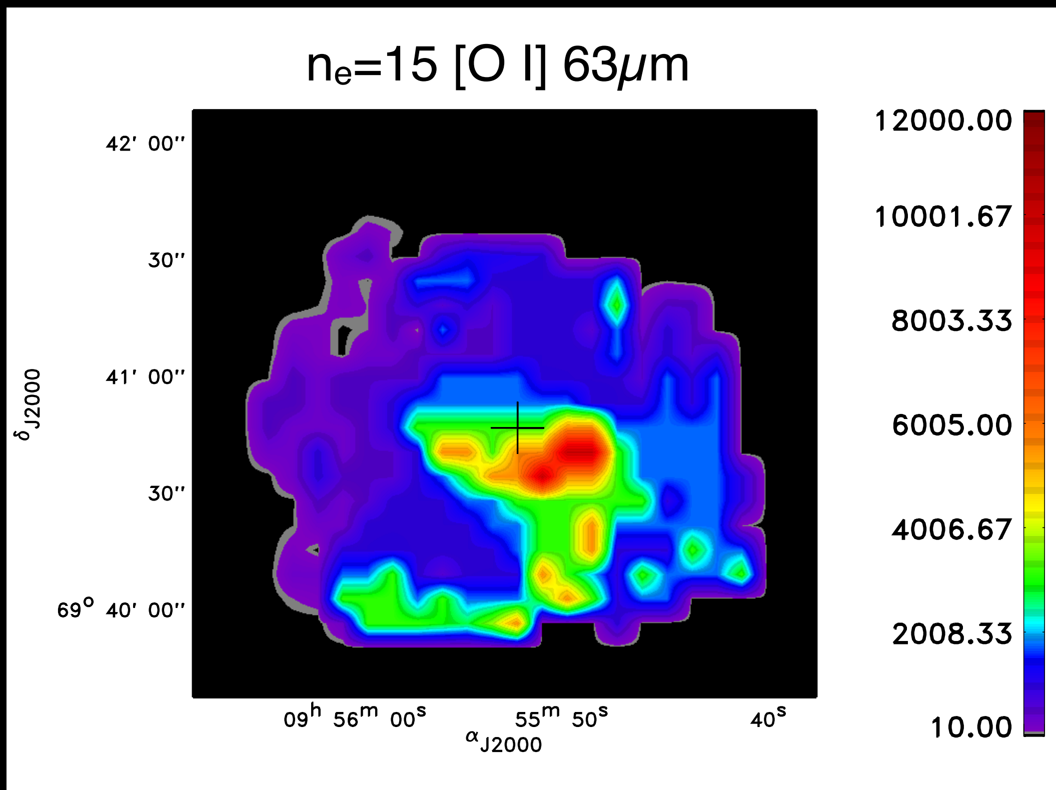




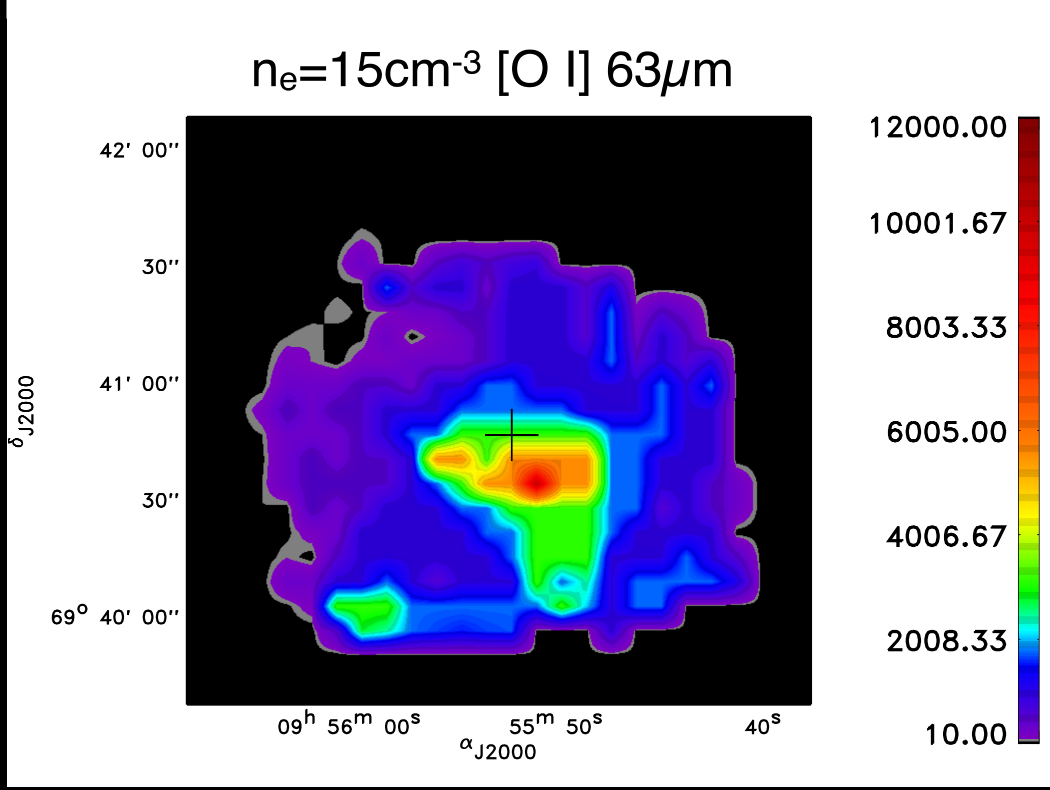
Spitzer 8μm
-2.35 km/s
7.65 km/s
upGREAT CII
+10.15 km/s
+13.15 km/s

Herschel PACS M82 PDR Map: Neutral Gas in Outflows, Disk and Starburst

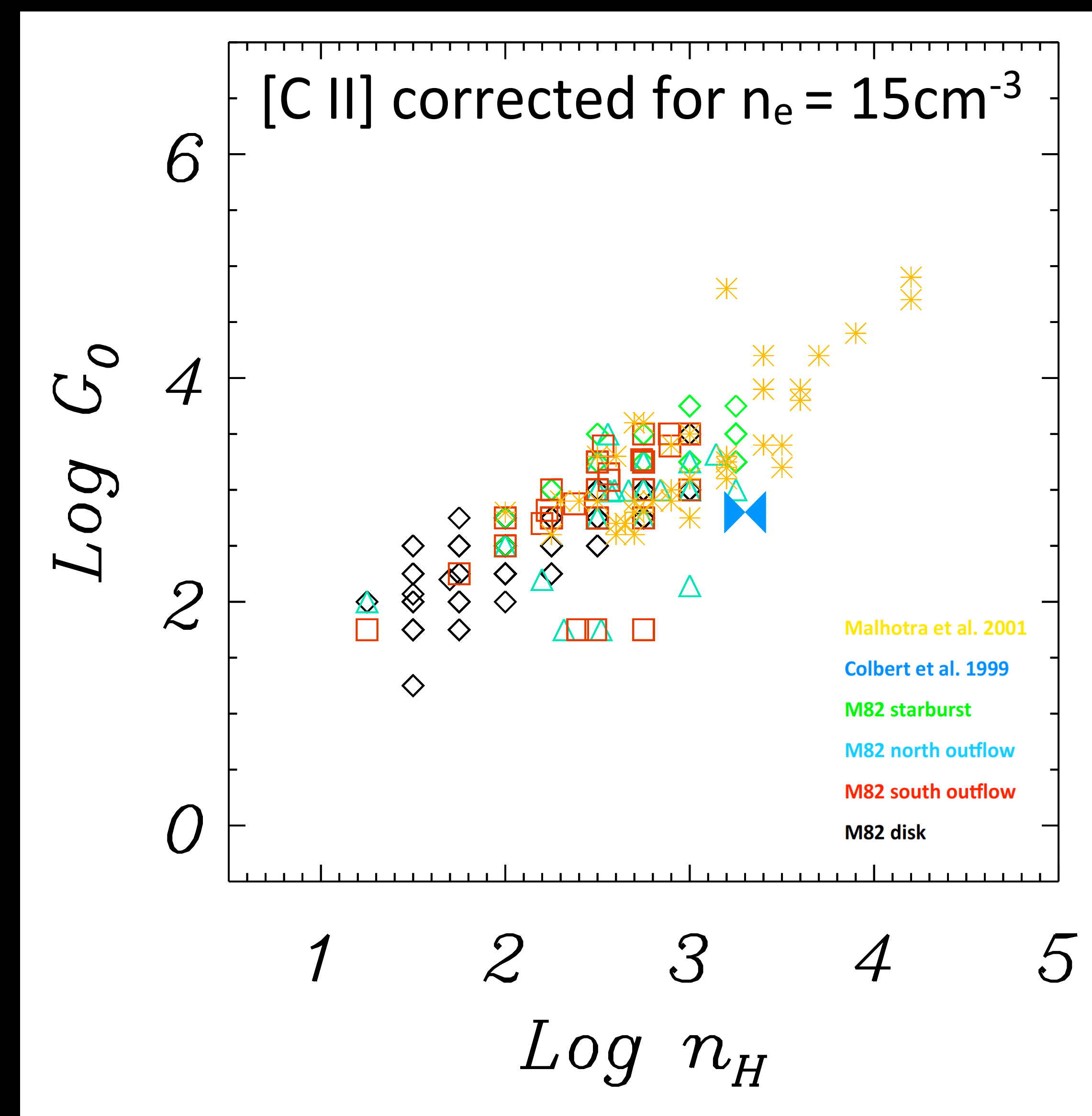
FUV Flux, G_0



Density, n

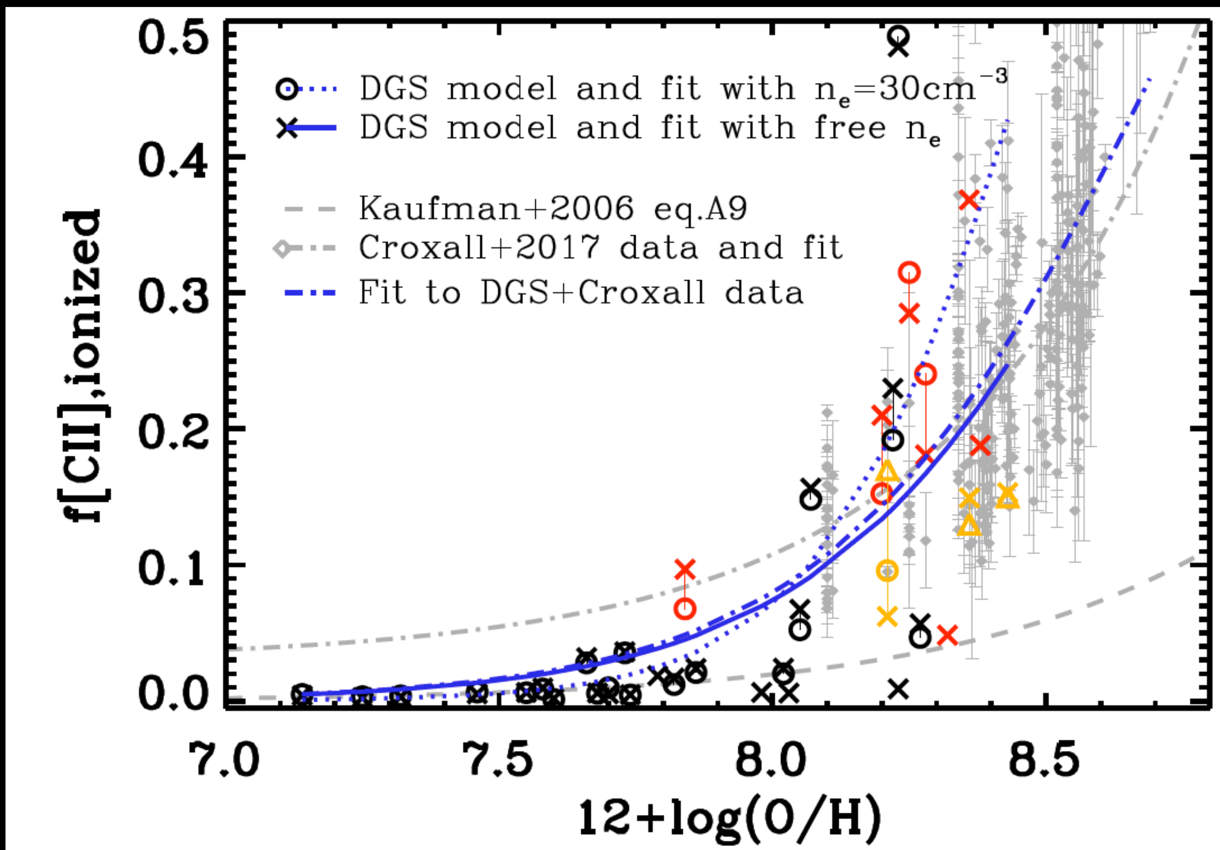


Mapping over ~2kpc of the disk at ~200 pc scale

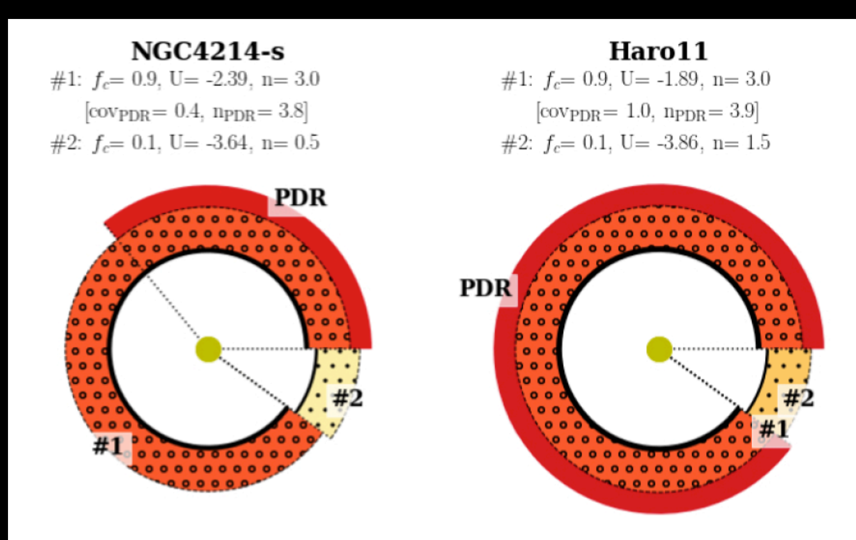


Contursi+2013

Extragalactic Studies: Moving from the General to the Specific

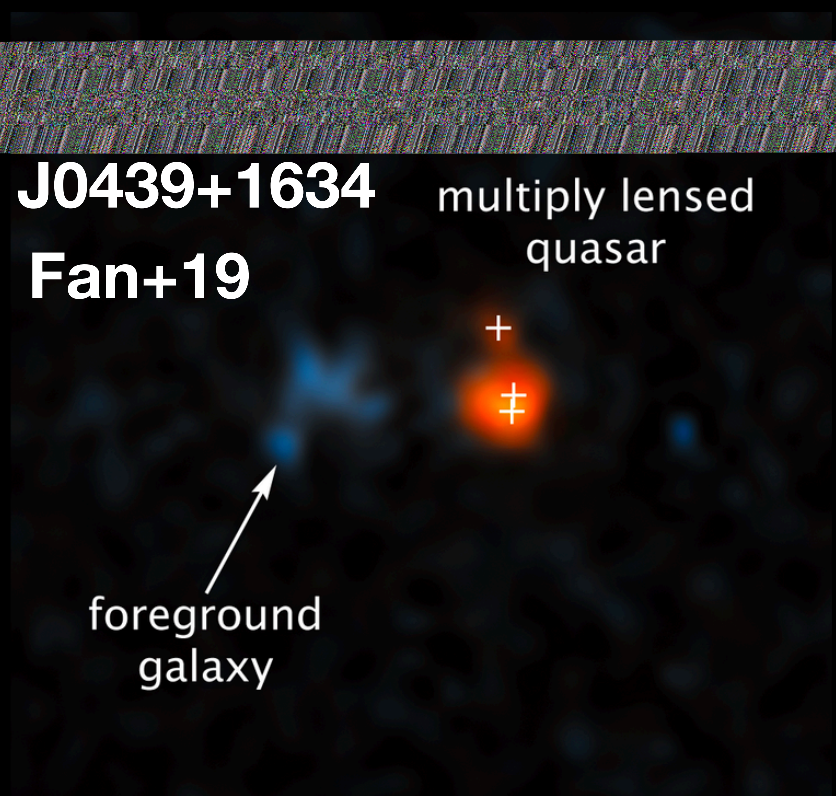


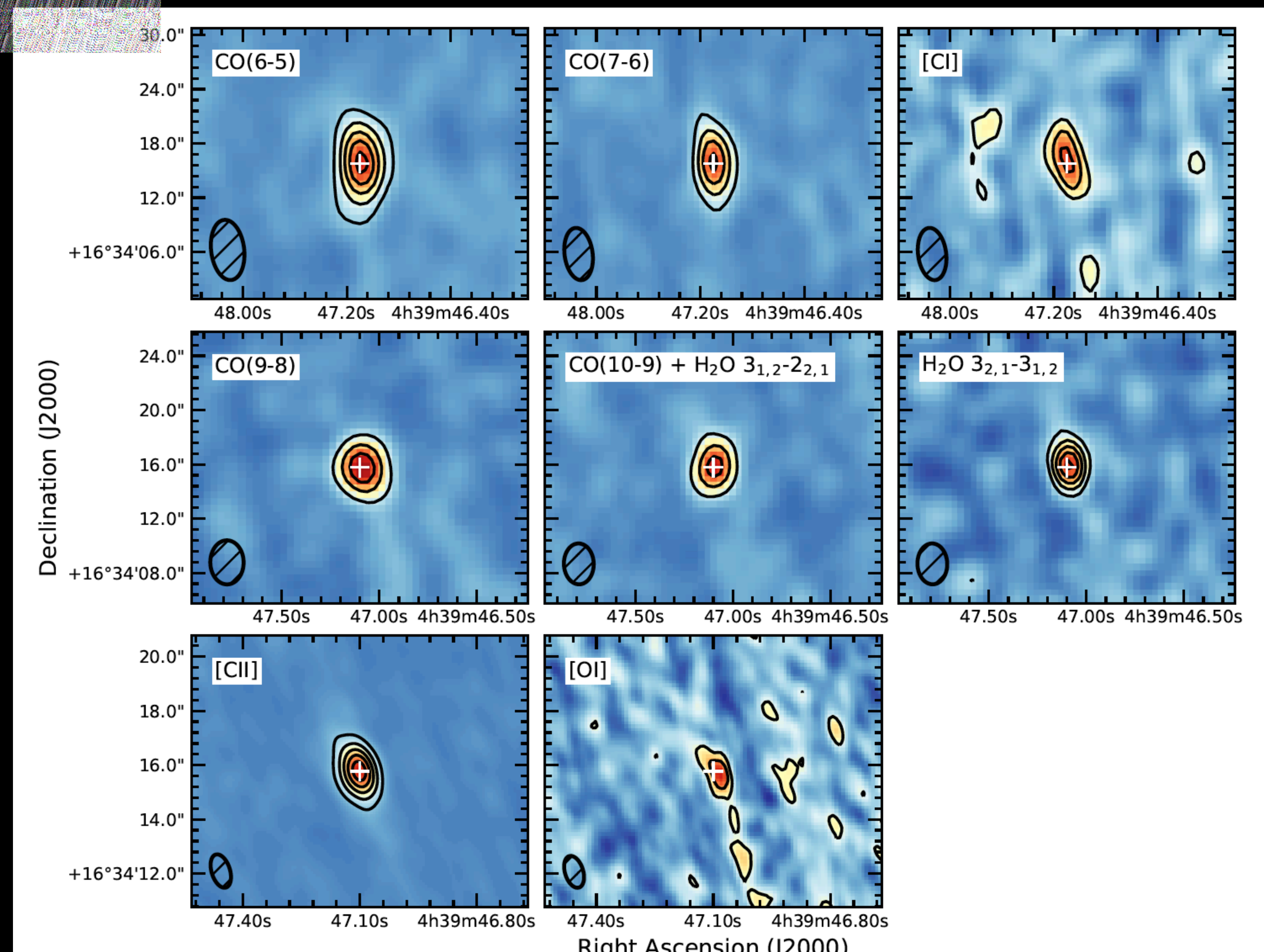
PDRs always dominate [CII] emission
Cormier+19, Croxall+17, Dios-Santos+17



- In low metallicity galaxies, [OIII] emission traces extended ionized gas regions with large volume filling factors
- CII emission is dominated by PDRs, which have thick CII layers surrounding small, weakly emitting CO cores
- CII good for tracing SFR at high redshift

Most Distant Lensed Quasar
z=6.52





Rest-frame FIR/Submm Lines

[CII] 158µm

[CI] 370

[OI] 145

CO 6-5, 7-6, 9-8, 10-9

H_2O $3_{1,2}$-$2_{2,1}$ and $3_{2,1}$-$3_{1,2}$

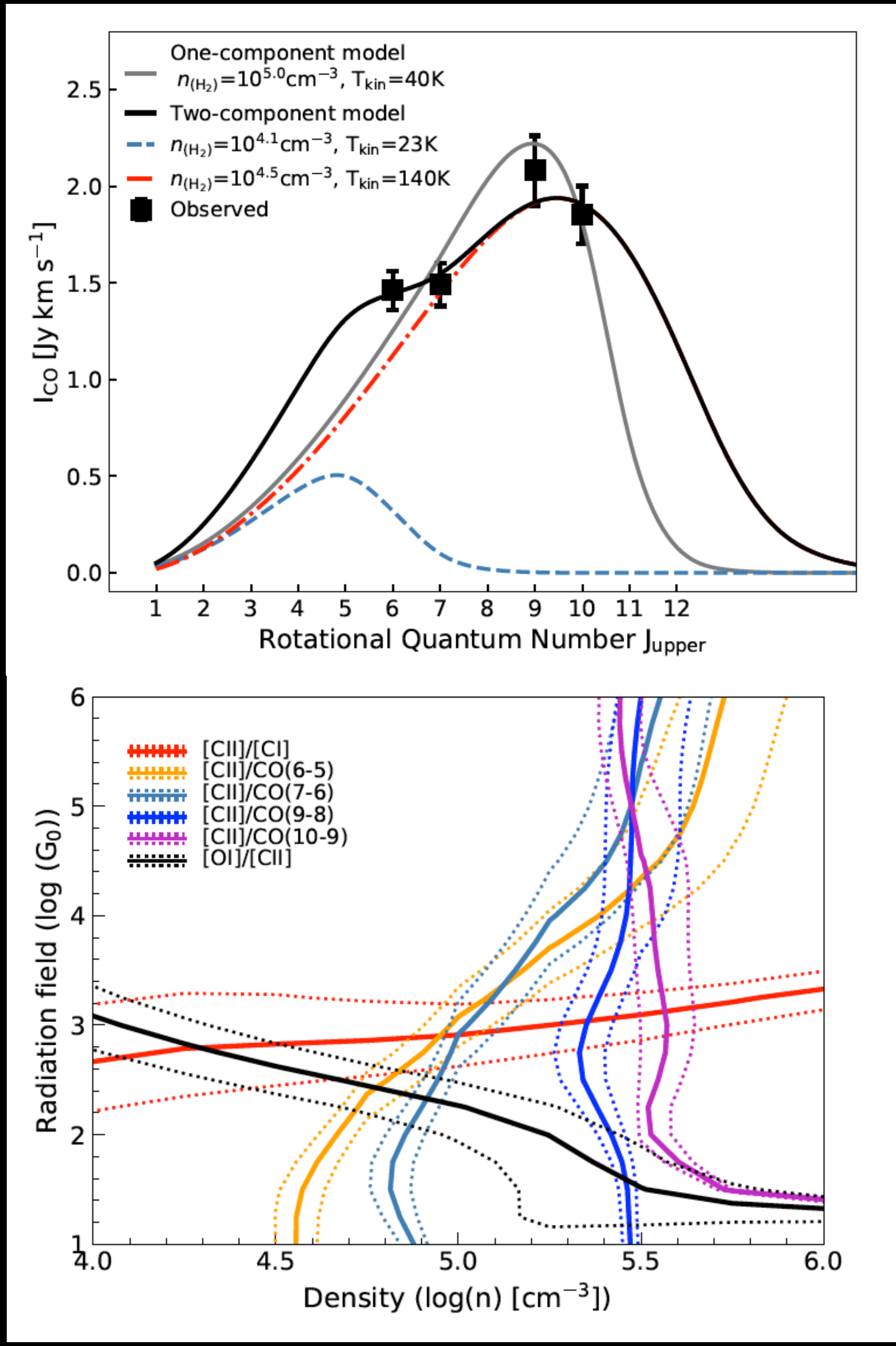
FIR Continuum

Yang+19

Host galaxy magnification ~ 2.6-6.6

Physical Conditions at Very High Redshift

- CO SLED suggests two ISM components
- Comparison with PDR models gives high values of G_0 and n
- CO and CI give molecular gas masses of ~5×10^{10} $M_\odot$
- Strong lensing makes it possible that ALMA can be used to separate components



Yang+19

Conclusions

- PDR Models have been around for ~35 years
- They continue to be useful, even for things Xander didn’t lay claim to
- In “simple” situations, they can be used to make detailed measurements
- In more complex situations, spatial and spectral resolution can help