The CI lines: probes of H_2 gas conditions and mass

…a brief history

Phillips & Huggins 1981, ApJ, 251, 533

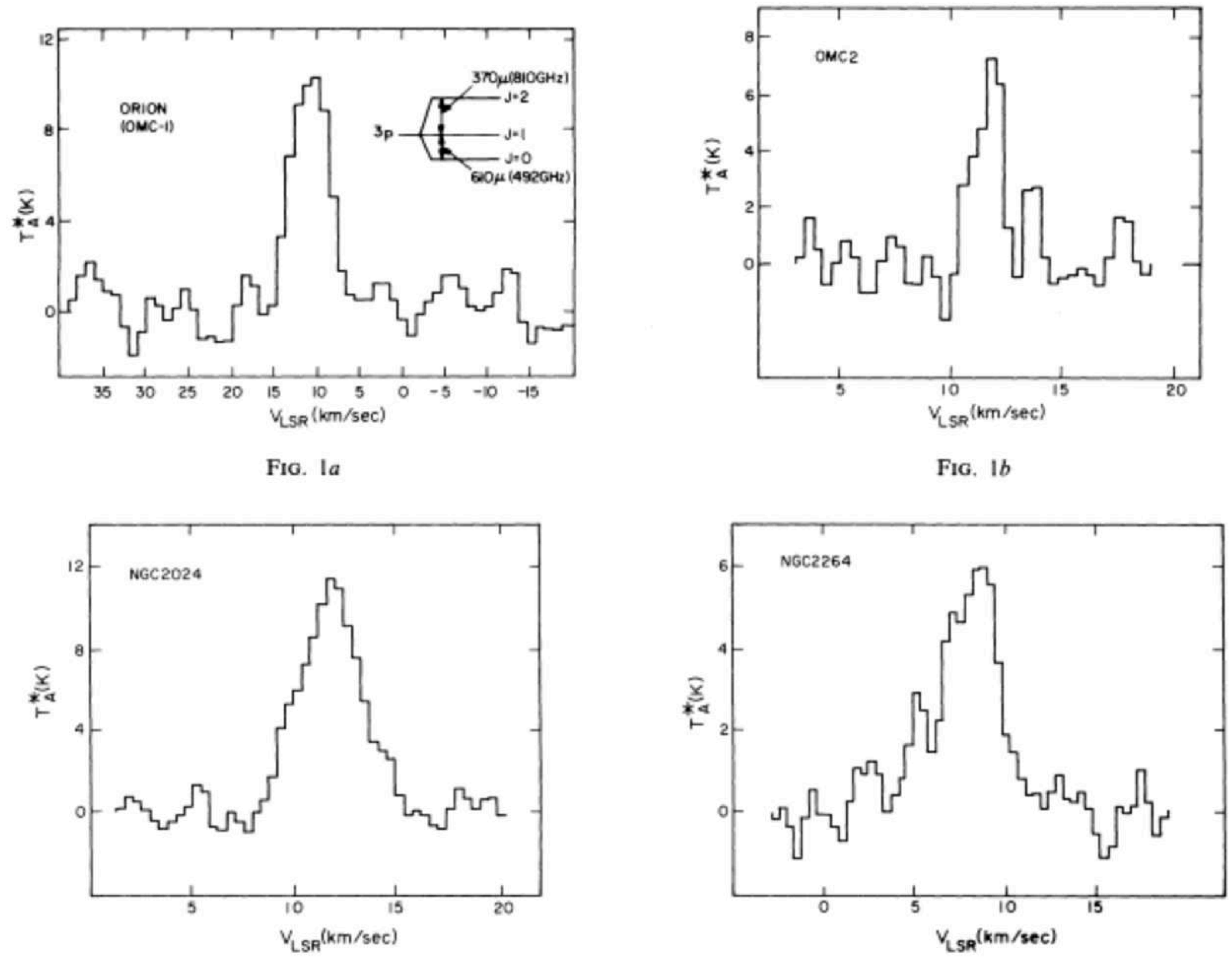


FIG. 1*a* FIG. 1*b* FIG. 1*c* FIG. 1*d*

Three seminal papers…

Tielens & Hollenbach 1985: Photodissociation regions. I.
Basic Model
(Astrophysical Journal, 291, 722)

Tielens & Hollenbach 1985: Photodissociation regions. II.
A model for the Orion photodissociation region.
(Astrophysical Journal, 291, 747)

Hollenbach, Takahashi & Tielens 1991: Low density PDRs
(Astrophysical Journal, 377, 192)

$G_o=10^5$
$n = 2 \times 10^5 \ cm^{-3}$
(Orion-type PDR)

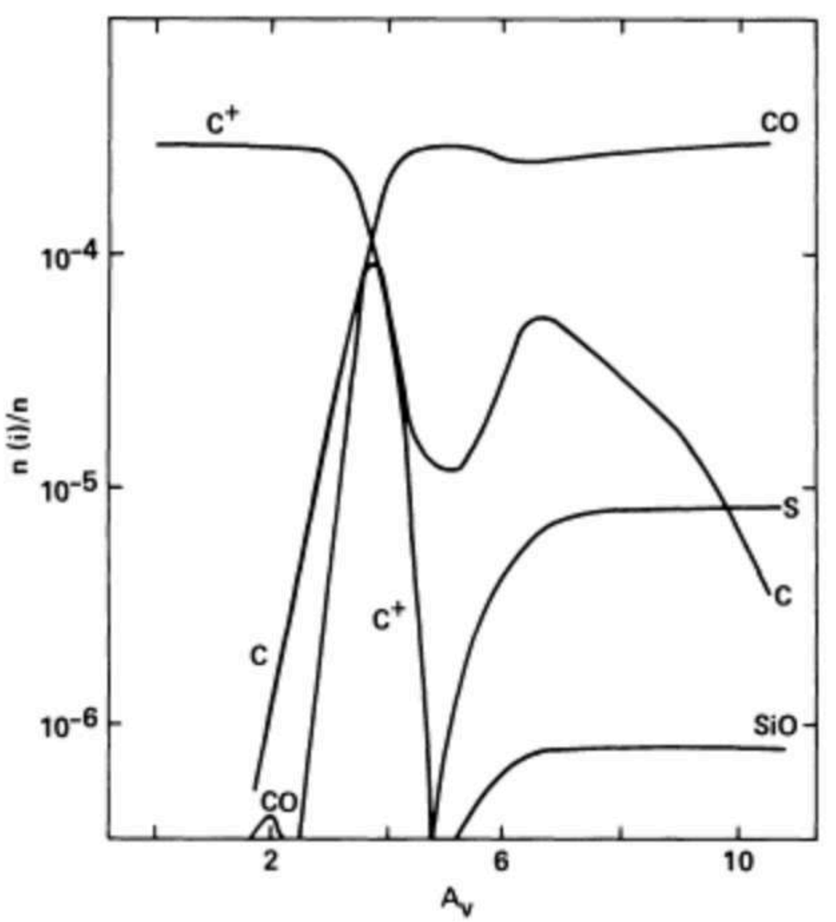


FIG. 9b

$G_o=10^3$
$n=10^3 \ cm^{-3}$ (low-density PDR)

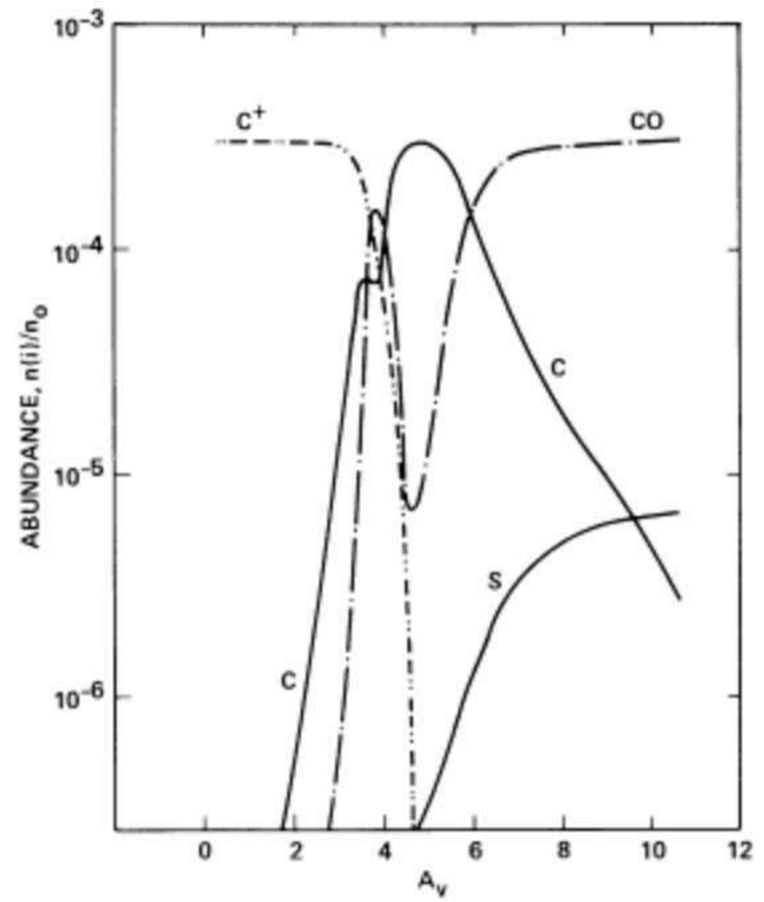
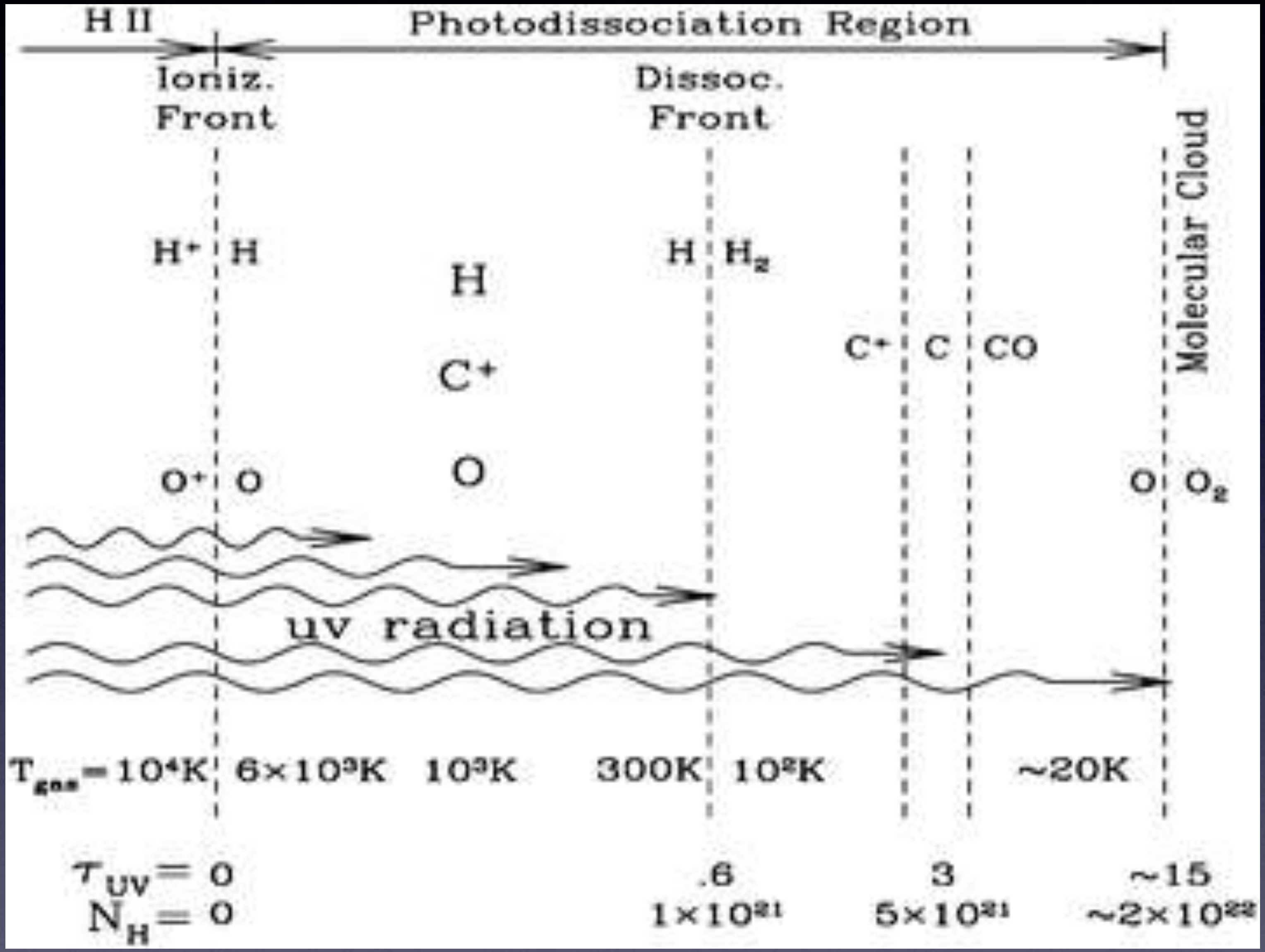


FIG. 4b

C exists only within a transition layer in FUV-irradiated H_2 clouds…



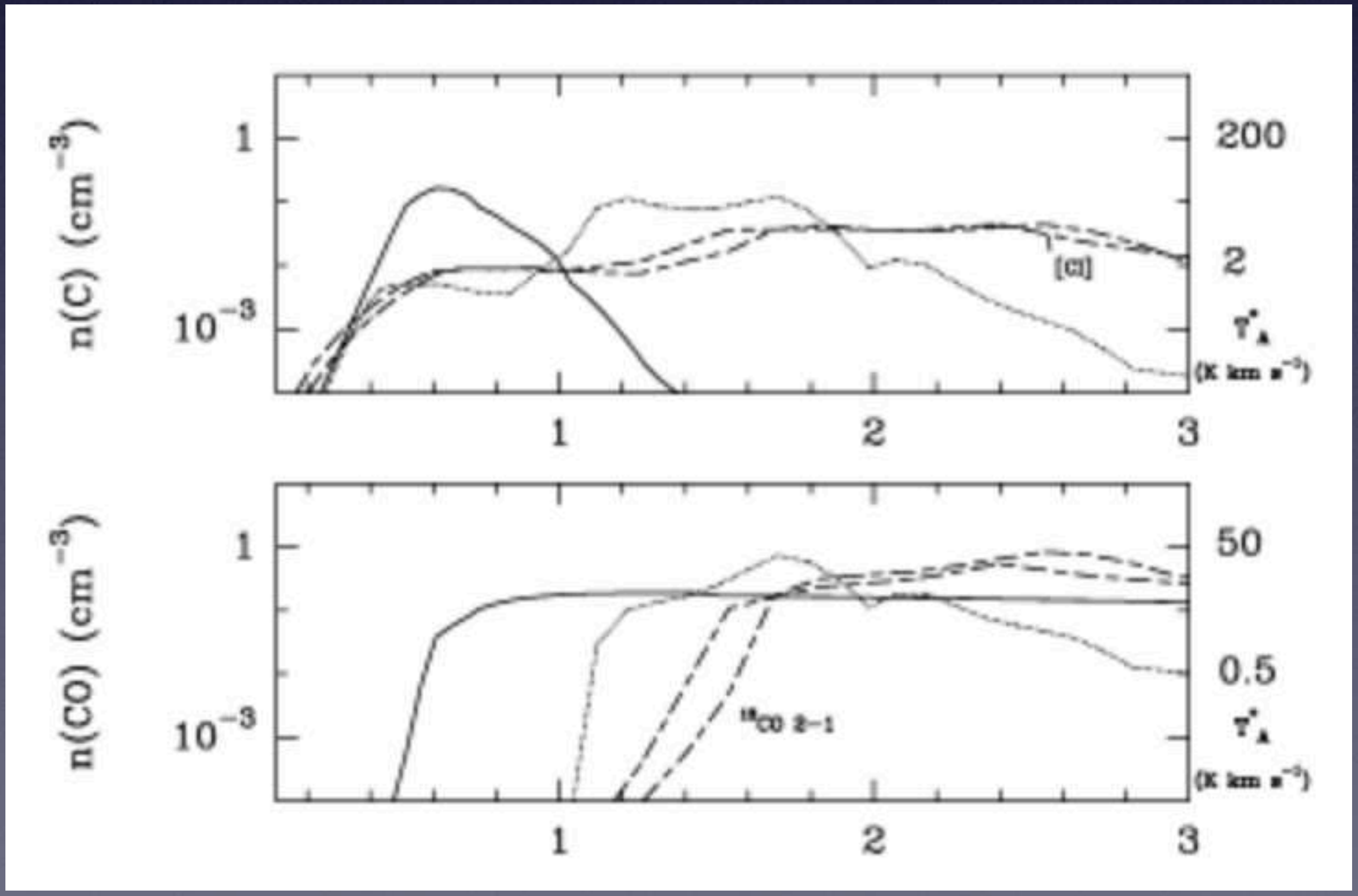
…hence it cannot be used to trace bulk H_2 gas mass or probe its physical conditions.

…a few last refinements

Clumpy PDRs….

Meixner & Tielens 1993, ApJ, 405, 216

Spaans & van Dishoeck 1997, A&A, 323, 953



…bulletins from little corners of astro-history

55.10

The Distribution of Atomic Carbon in the Rho Ophuichi Dark Cloud

J. Keene, G. A. Blake, and T. G. Phillips (Caltech)

We have obtained spectra and spatial scans of the $^3P_1 \rightarrow {}^3P_0$ transition of neutral atomic carbon [CI] in the ρ Oph dark cloud. The peak emission ($T_A^* \cong 9$ K measured in a 3' beam) is found at the position of the molecular condensation ρ Oph A which is near a luminous star (1500 $L_\odot$) and an associated FIR source. However the emission is also quite strong ($T_A^* \cong 6$ K) far from any bright embedded or external sources. In particular, the dense but cold condensation ρ Oph B is evident in the spatial scans. The widespread and fairly uniform distribution of CI in the ρ Oph dark cloud may be related to the presence of numerous embedded low-luminosity stars.

Bulletin of the American Astronomical Society, 1986, Vol 18, pg 637

Odd but inconspicuous news….

1985, ApJ, 299, 967

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Received 1984 December 10; accepted 1985 June 17

ABSTRACT

We have observed the 492 GHz ground-state line of atomic carbon in the edge-on ionization fronts in M17 and S140. We find that, contrary to expectation, the C I emission peaks farther into the molecular cloud from the ionization front than does the CO. In fact the peak C I abundance in M17 occurs more than 60 mag of visual extinction into the cloud from the ionization front. Calculations of the ratio of C I to CO column densities yield values of 0.1–0.2. These observations do not support chemical models which predict that neutral atomic carbon should be found only near the edges of molecular clouds. Other models are discussed which may explain the observations.

Subject headings: interstellar: abundances — interstellar: matter — nebulae: abundances —

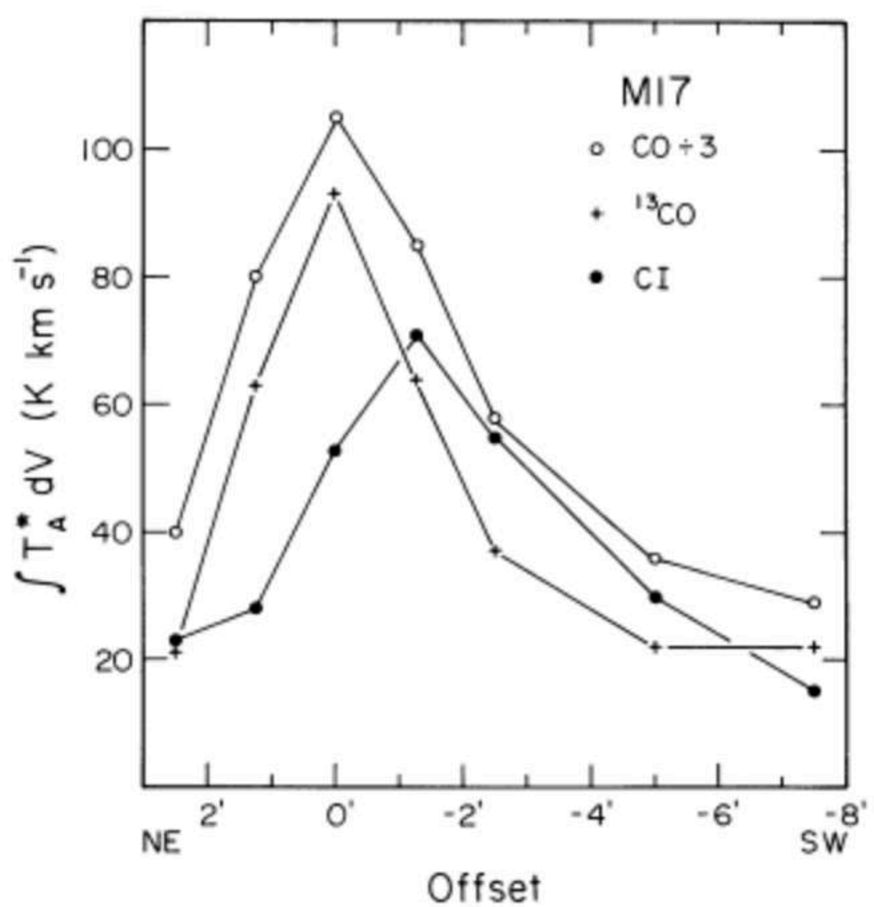


FIG. 4.—Comparison of C I and CO antenna temperatures in M17 integrated over velocity. The ionization front is again to the left. The C I and ^{13}CO are on the same scale; the ^{12}CO temperatures have been divided by 3.

Keene et al 1997, IAU 178

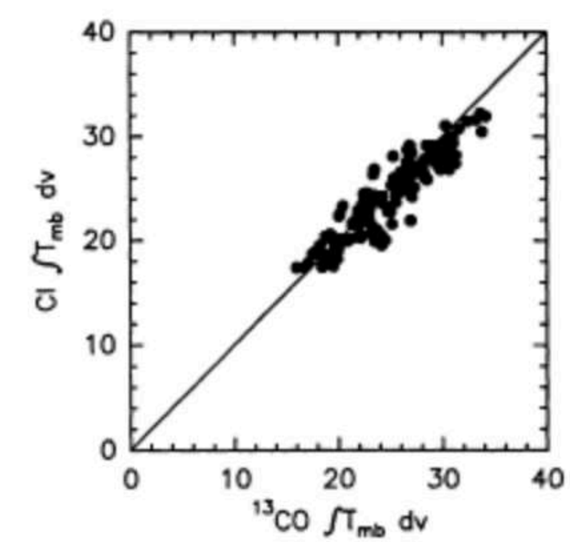


Figure 6. Correlation of the ^{13}CO and [C I] maps of the Oph A region. The [C I] intensities have been smoothed to the 33″ resolution of the ^{13}CO map.

Plume, R., Jaffe, D. T., & Keene, J. 1994, ApJL 425, L49: CI line emission well past the PDR fronts (S140)

Tatematsu et al. 1999, ApJ, 526, 295: CI line emission in FUV-shielded dark clouds

Oka et al. 2001, ApJ, 558, 176: CI line emission in mid-IR dark clouds

Ojha et al. 2001, ApJ, 548, 253: CI imaging of the Galactic Center

Ikeda et al. 2002, ApJS, 139, 467: CI imaging of Orion A and B clouds

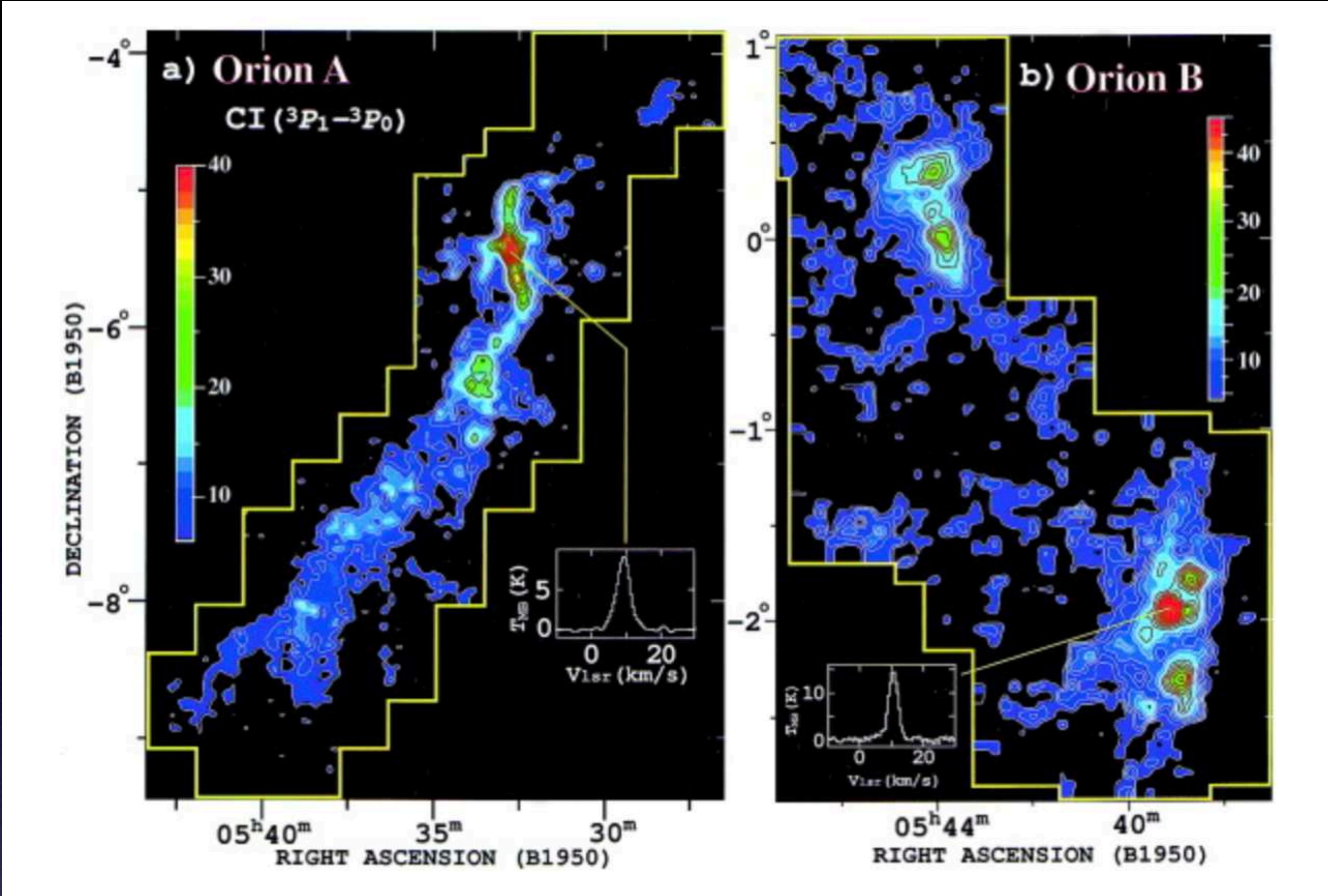
White et al. 1994, A&A, 284, L23: CI imaging of inner starburst of M82

Israel, White & Baas 1995, A&A, 302, 343: CI imaging of starburst NGC 253

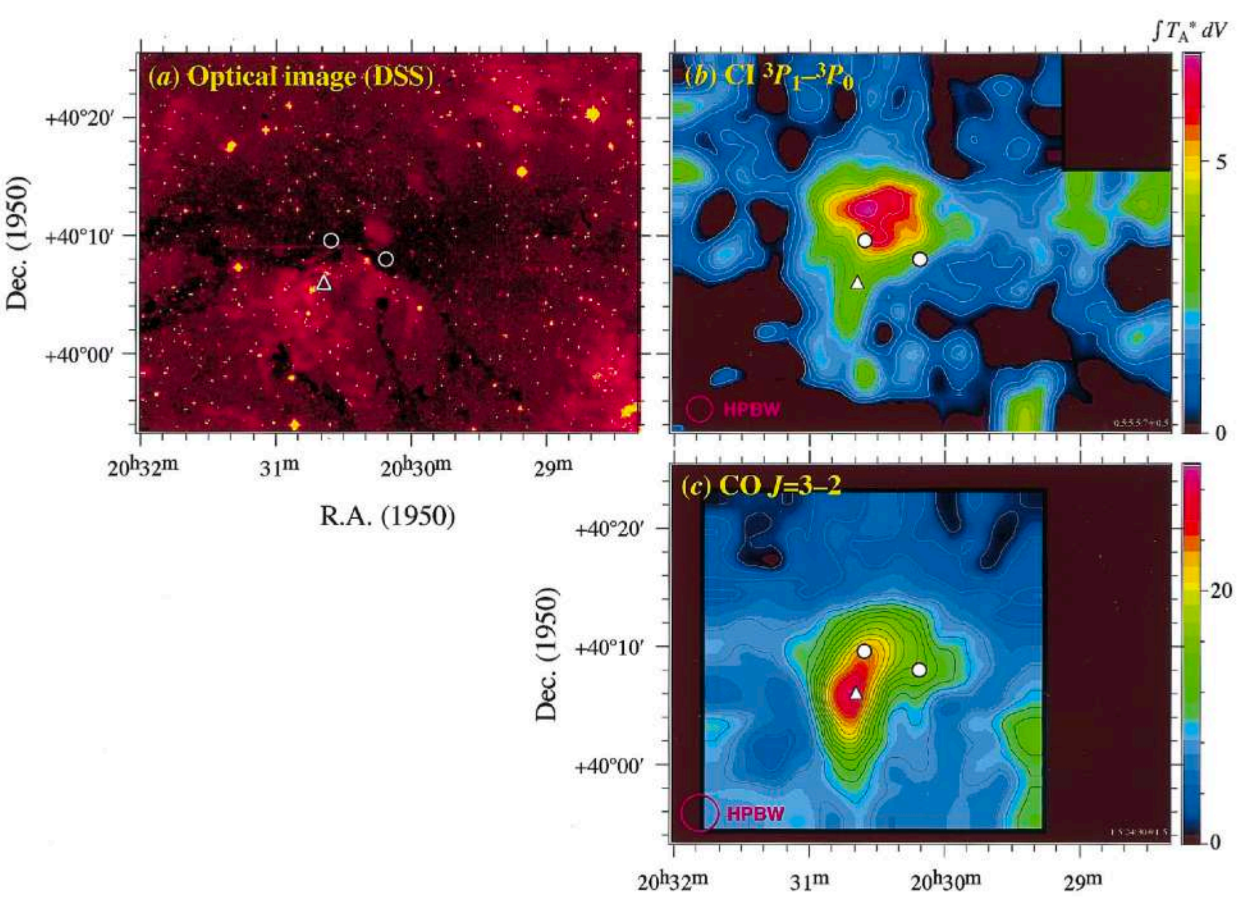
Israel, Tilanus, & Baas 1998, A&A, 339, 398: CI detection in a cold dark cloud in M31!

Weiss et al. 2003, A&A, 409, L41: CI 1-0, 2-1 at a lensed QSO at $z=2.5$!

Papadopoulos & Greve 2004, ApJL, 615, L29: CI lines in ULIRGs



Ikeda et al. 2002



DR15 dark cloud
(Oka et al. 2001)

…where did all this leave us back in 2004?

- Excellent spatial correspondence between CI CO, and ^{13}CO line emission at all scales.
- Small variation in the I(CI)/I(CO, ^{13}CO) intensity ratios across a wide range of conditions (even in the Galactic Center!)
- Good agreement between CI, CO, and ^{13}CO line profiles on molecular cloud scales.

…a non-PDR origin for the bulk of CI line emission in the ISM, and…

CO and CI are concomitant at all scales, and trace the same H_2 gas phase

so one can use the two CI lines for:

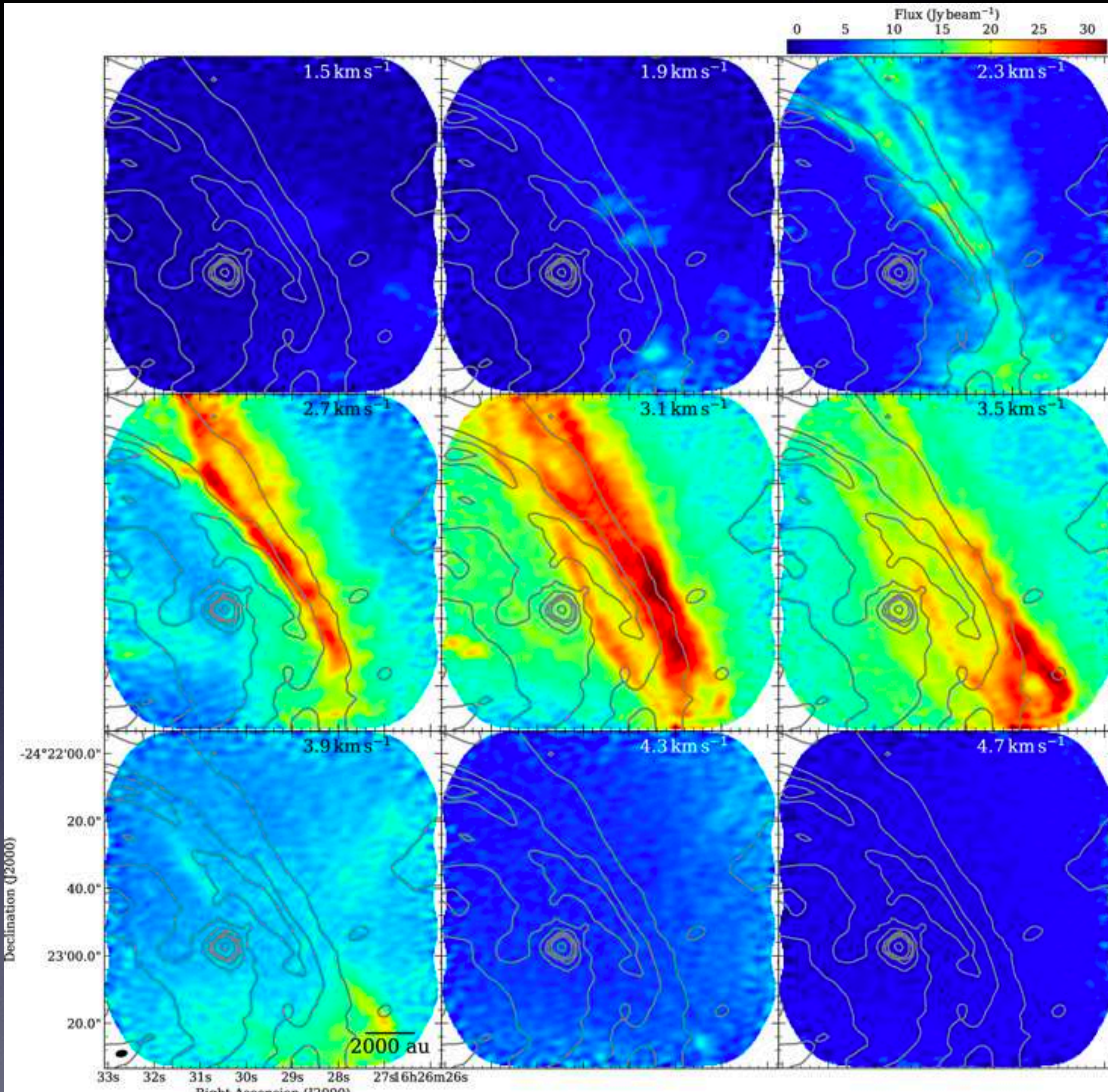
a) H_2 gas mass tracing across the Universe (with some advantages CO lines do not have)

b) a simple T_{kin} probe (in LTE via the CI 2-1/1-0 ratio)

(Papadopoulos, Thi & Viti 2004)

Yes but after ~2004 lack of high-frequency receivers (except in a few special places) meant no new CI line data ….

(…and good models die hard)



Soft PDR ρOphiouchi
(Be star, closest PDR)

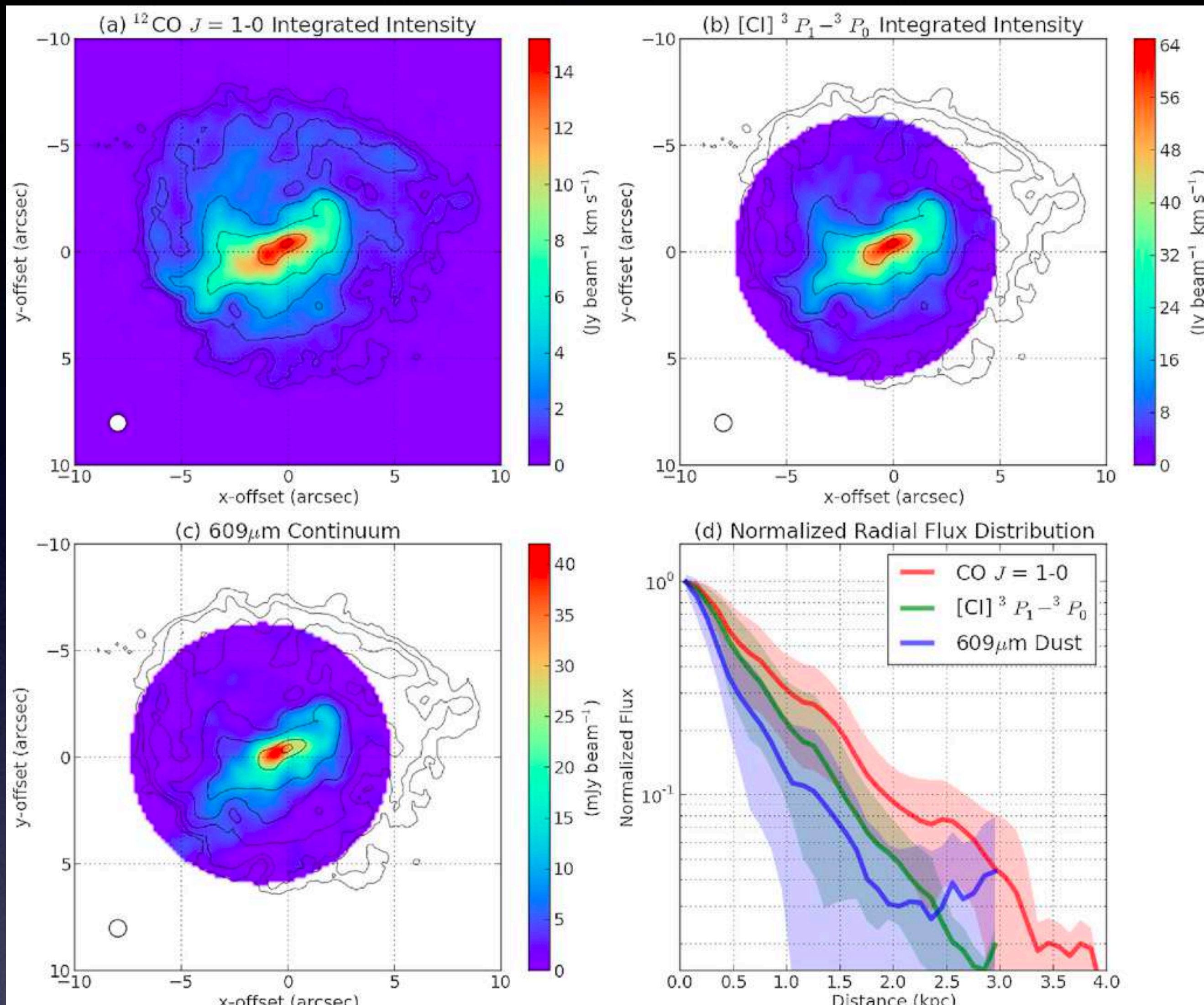
Yamagishi et al. 2021

ACA + TP mode!

Contours: 4.5μm emission (Spitzer)

PDR-related CI but also an extended component with N(CI)/N(CO)~2

An ALMA-driven explosion of CI line imaging data!

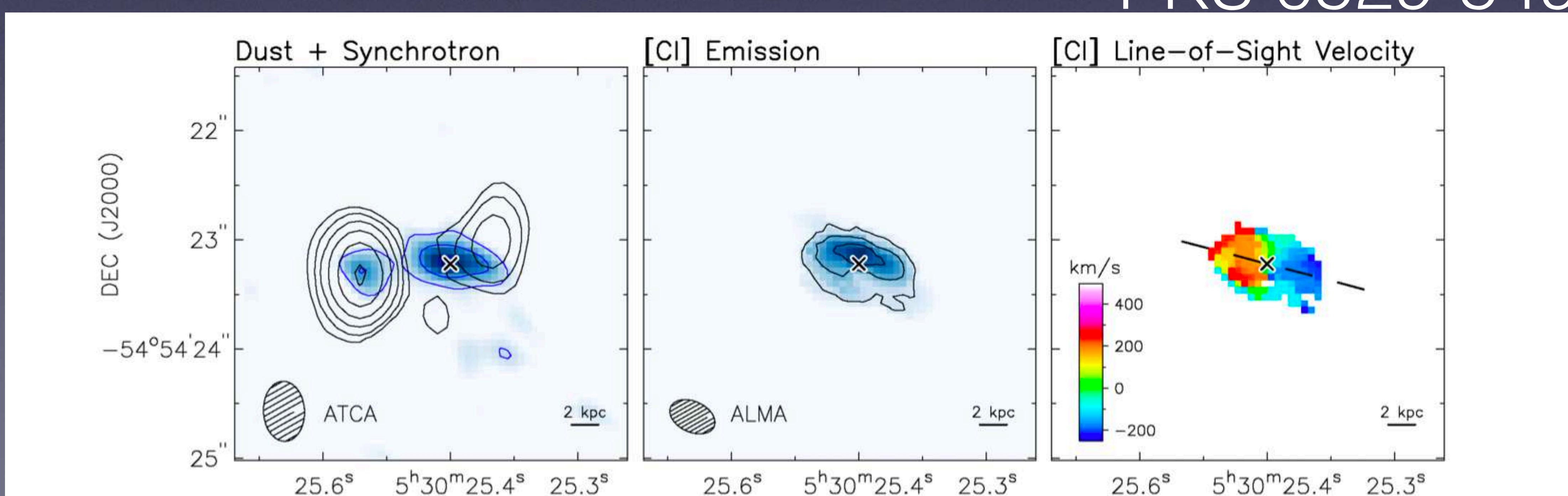


Saito et al. 2020

IRAS F18293-3413

Lelli et al. 2018, z=2.6

PKS 0529-549



How could all this “extra” CI could come about?

Cosmic Rays + Non-steady state Chemistry + Turbulent mixing

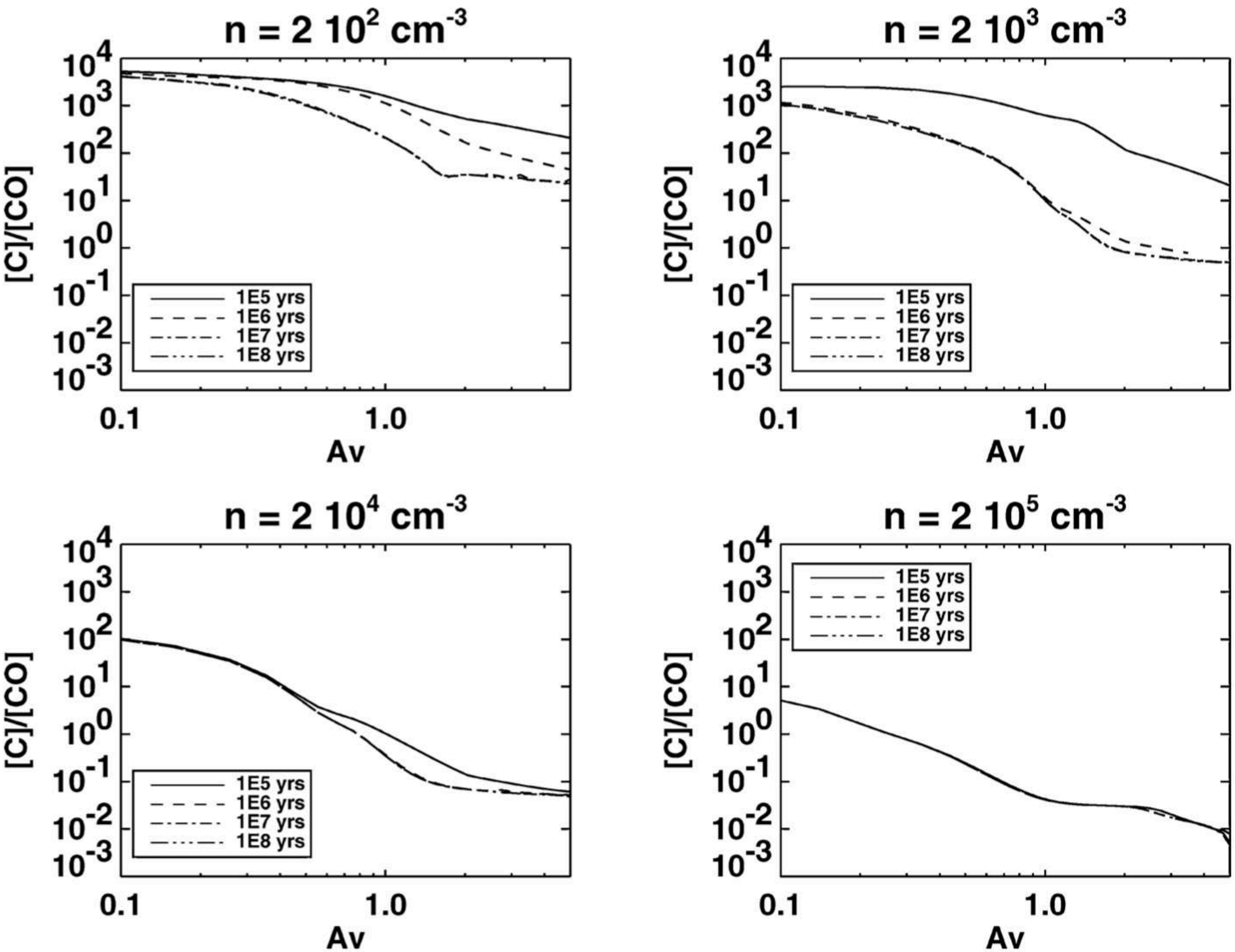


Figure 1. Results from a time-dependent PDR code (see text) for an initially atomic cloud with one-sided illumination by a unidirectional FUV field and densities shown at the top of each frame. The assumed metallicity is solar ($Z = 1$) and the incident radiation field is $G_0 = 1/2$, (corresponding to one-sided illumination by a Habing field). The well-known [C]/[^{12}CO] enhancement in low-density gas with respect to denser gas is clearly discernible.

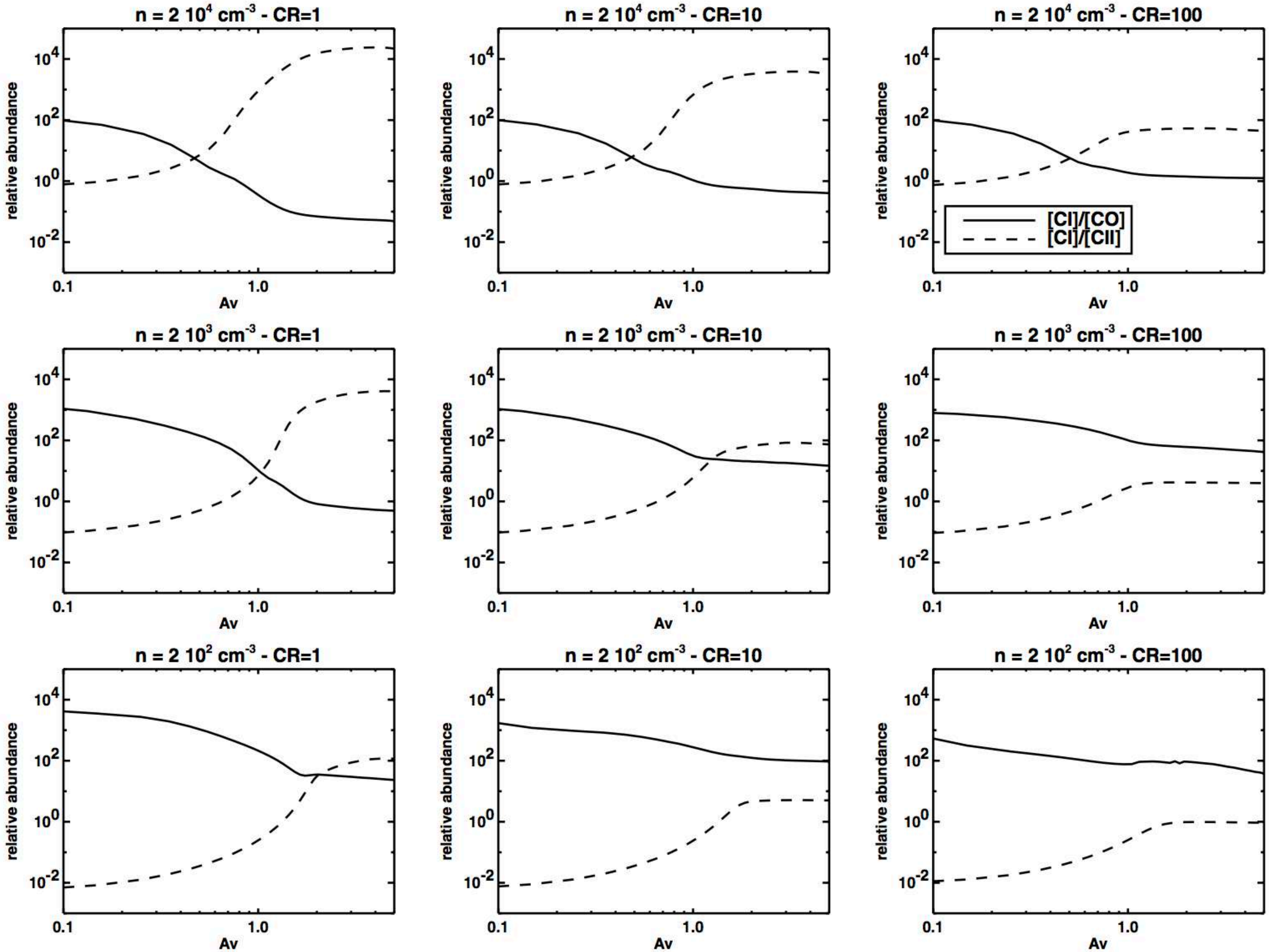


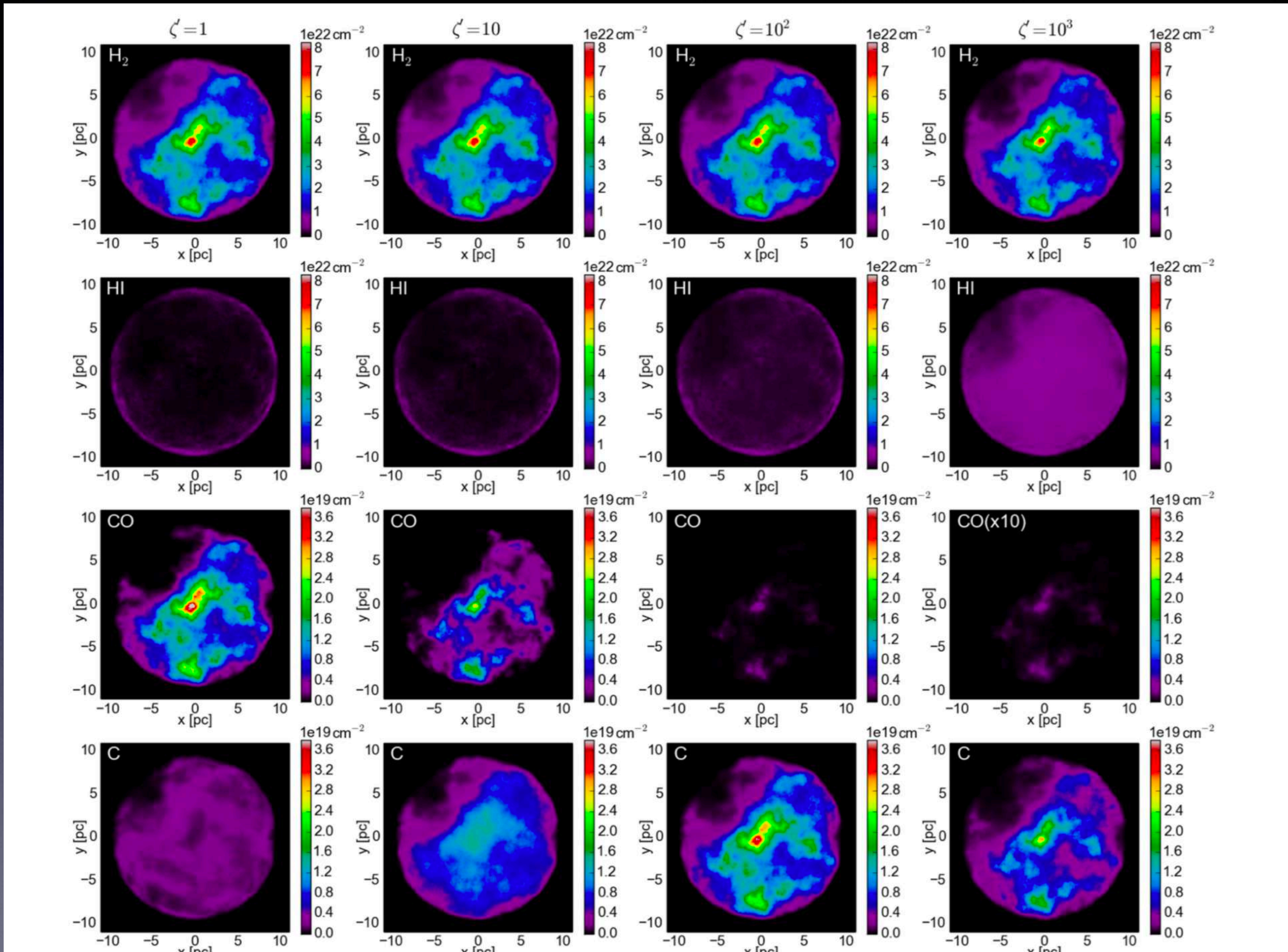
Figure 2. Abundance distributions at $t = 10^7$ yr, for identical initial conditions as in Fig. 1. The values of $F_{\rm CR}$ are indicated in the panels, normalized to the Galactic value. The ambient $G_0 = 1/2$, corresponding to one-sided cloud illumination by a Habing field. In most cases [C I]/[C II]$\gtrsim 1$ for $A_v \gtrsim 1$. The density range chosen characterizes the bulk of H_2 in typical GMCs.

Papadopoulos, Thi & Viti 2004

So nature does it mostly the CR-way, then turbulently "stirs" it up, and has only ~ 10^7 yrs to do it all before another H_2—>HI—>H_2 far-UV/pressure-driven (re)cycle

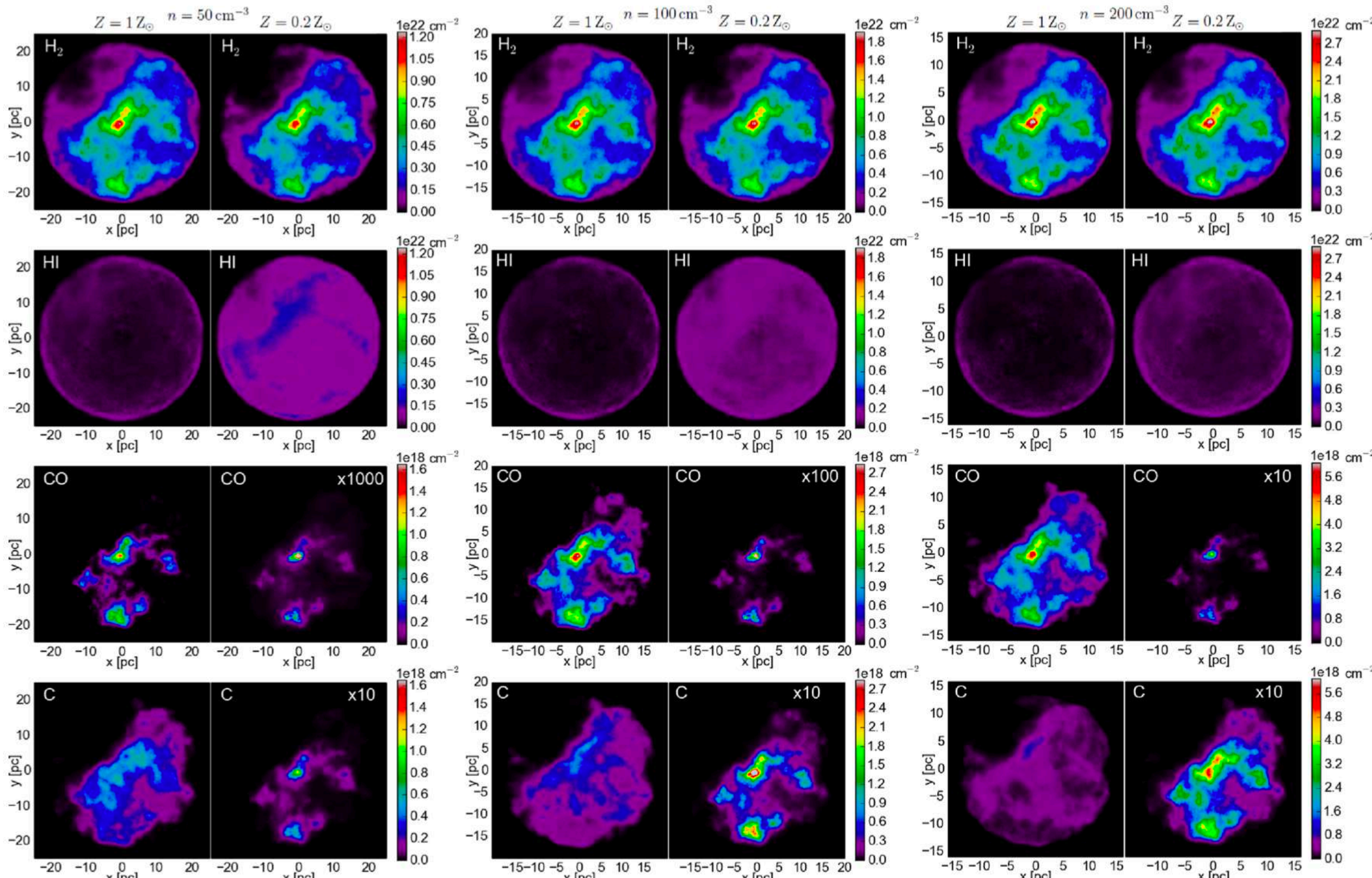
So are we done?
(any **predictions** from this new framework?)

The inhomogeneous cloud case (Bisbas, van Dishoeck, Papadopoulos et al. 2017)



We could be missing H_2 gas in galaxies
(within them, and maybe in entire classes)
and CI lines maybe a way to trace it…

MNRAS, 2018



$Z = 1\,Z_\odot$ $n = 50\,\mathrm{cm^{-3}}$ $Z = 0.2\,Z_\odot$
$Z = 1\,Z_\odot$ $n = 100\,\mathrm{cm^{-3}}$ $Z = 0.2\,Z_\odot$
$Z = 1\,Z_\odot$ $n = 200\,\mathrm{cm^{-3}}$ $Z = 0.2\,Z_\odot$
H_2
HI
CO
C
x1000
x100
x10
1e22 cm^{-2}
1e18 cm^{-2}
x [pc]
y [pc]

Wherever in the Universe, you have a high-CR/low-n H_2 gas phase (inside galaxies, outside) it may be CO-poor/CI-rich (..even in the Milky Way..)

BUT….

You better have very good line **brightness** sensitivity to extended CI line emission if you want to get it…

(ALMA+ACA+TP…)

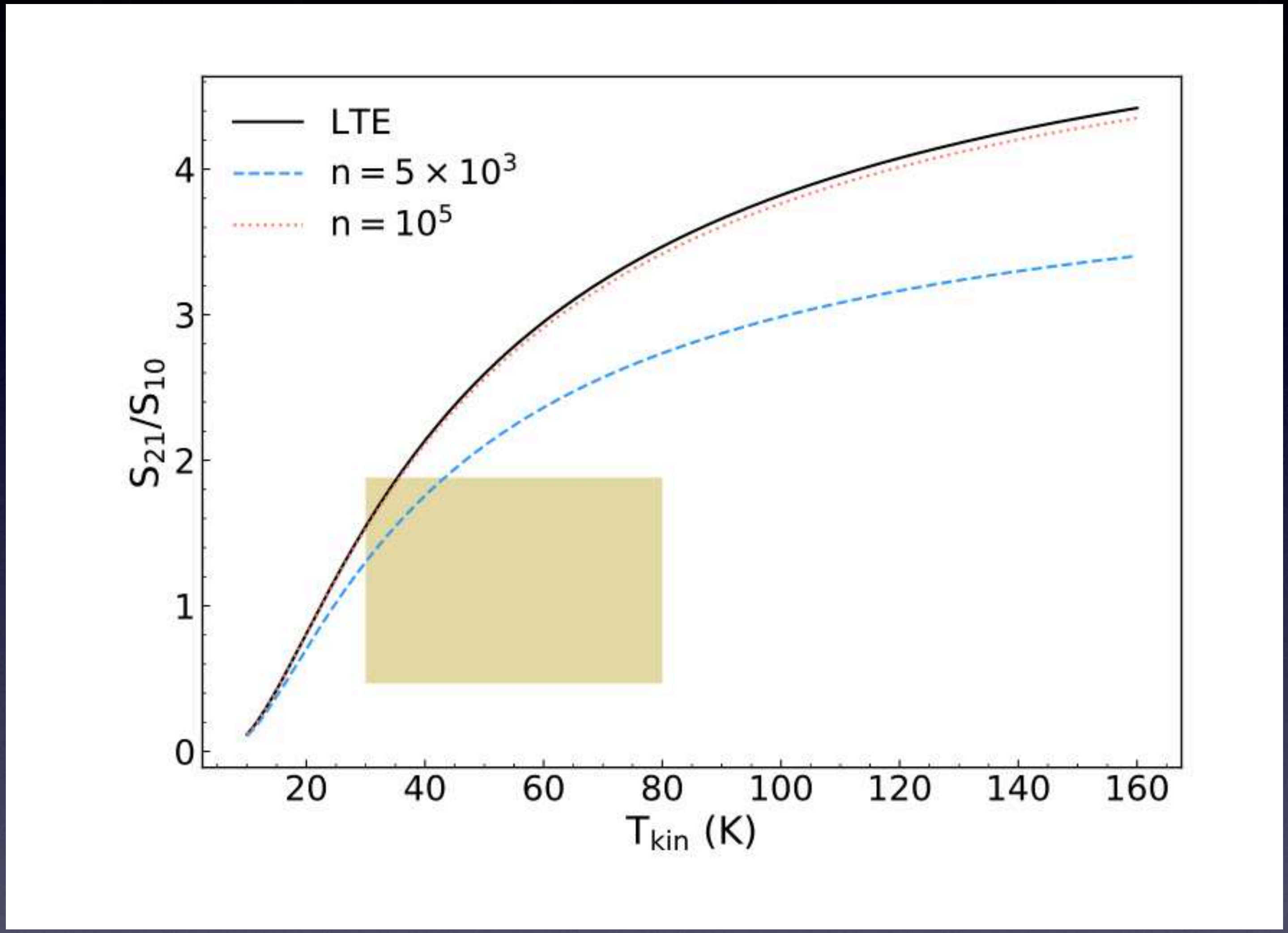
…a new development

Using the CI 2-1/1-0 (LTE) line as a simple T_k probe

Walter et al. 2011, ApJ, 730, 18
Kamenetzky et al. 2014, 795, 174
Valentino et al. 2018, ApJ, 869, 27
Valentino et al. 2020, ApJ, 890, 24
…and many many others…

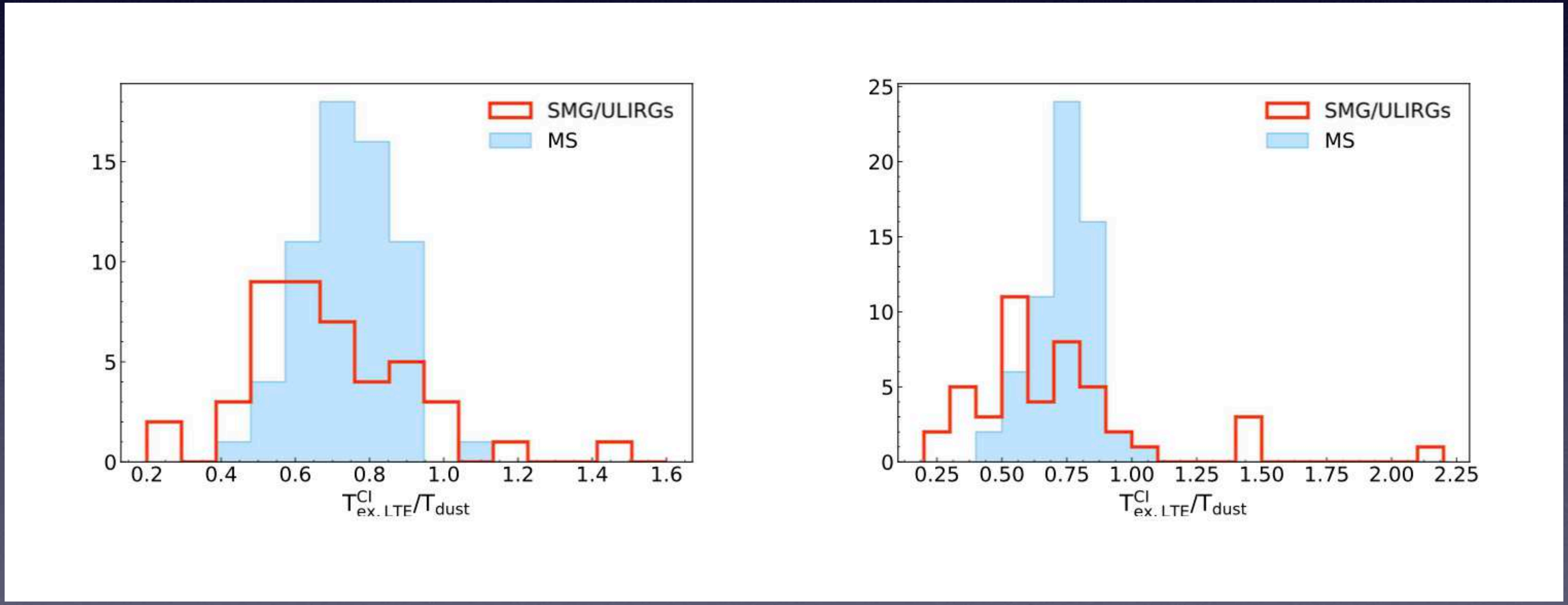
…find a curious clustering around 25-26 K.

Papadopoulos, Dunne & Maddox 2021 (MNRAS)



Shaded area:
The range of observed CI 2-1/1-0 line ratios vs the average expected T_{kin} (N=108 galaxies)

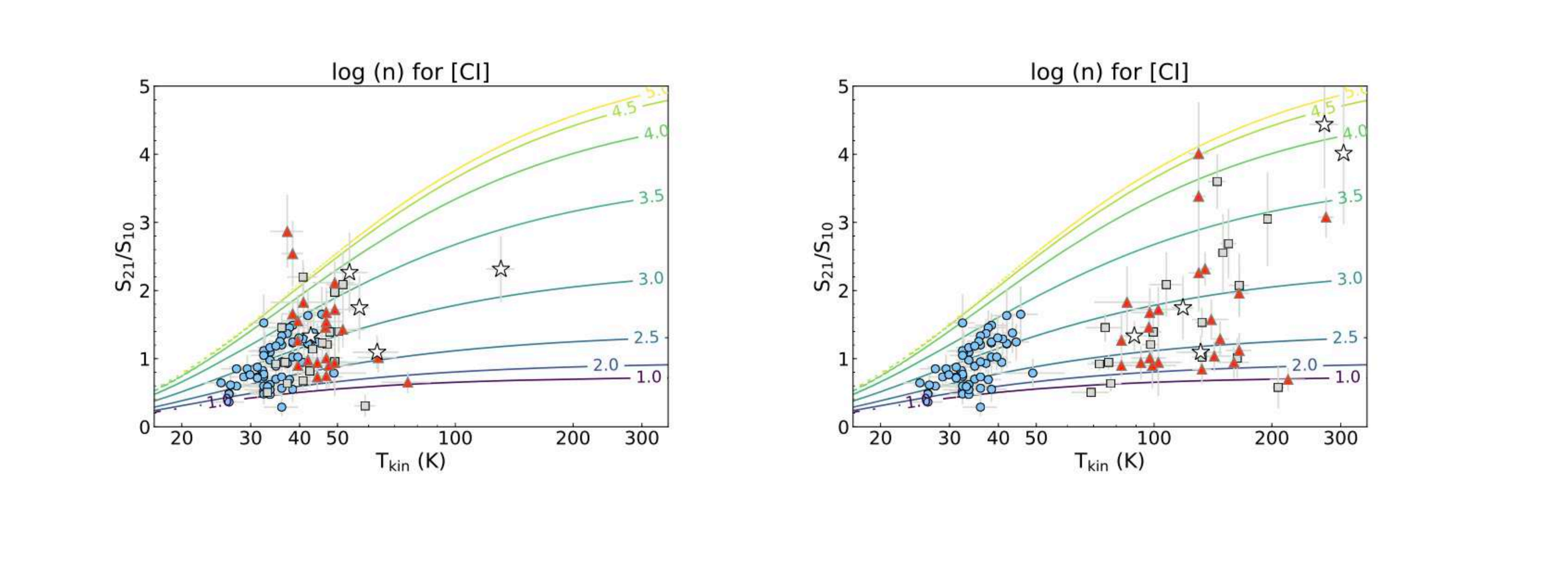
CI line excitation NOT in LTE for the bulk of H_2 gas mass reservoirs in galaxies!


SMG/ULIRGs
MS
$T^{CI}_{ex,LTE}/T_{dust}$
SMG/ULIRGs
MS
$T^{CI}_{ex,LTE}/T_{dust}$

$$R^{(ci)}_{21/10} = F(n, T_{kin})$$

(Analytically computed)

T_{kin}=a T_{dust} $a \geq 1$



The CI 2-1/1-0 factor is now …much more useful! (as part of joint CO/CI SLED and dust SED fits)

1) It can be solved analytically (unlike CO models)
2) It is optically thin (no need for LVG assumptions)
3) Sensitive to both $n(H_2)$ and T_{kin}

…it may thus break well-known CO SLED fit degeneracies!

and can help also derive more robust $a=T_{kin}/T_{dust}$ values (see Harrington et al. 2021 for a recent result)

$a \geq 1:$ Far-UV photons can do it…

$a \gg 1:$ CRs and/or shock are necessary

… an indicator of the dominant power source of the ISM

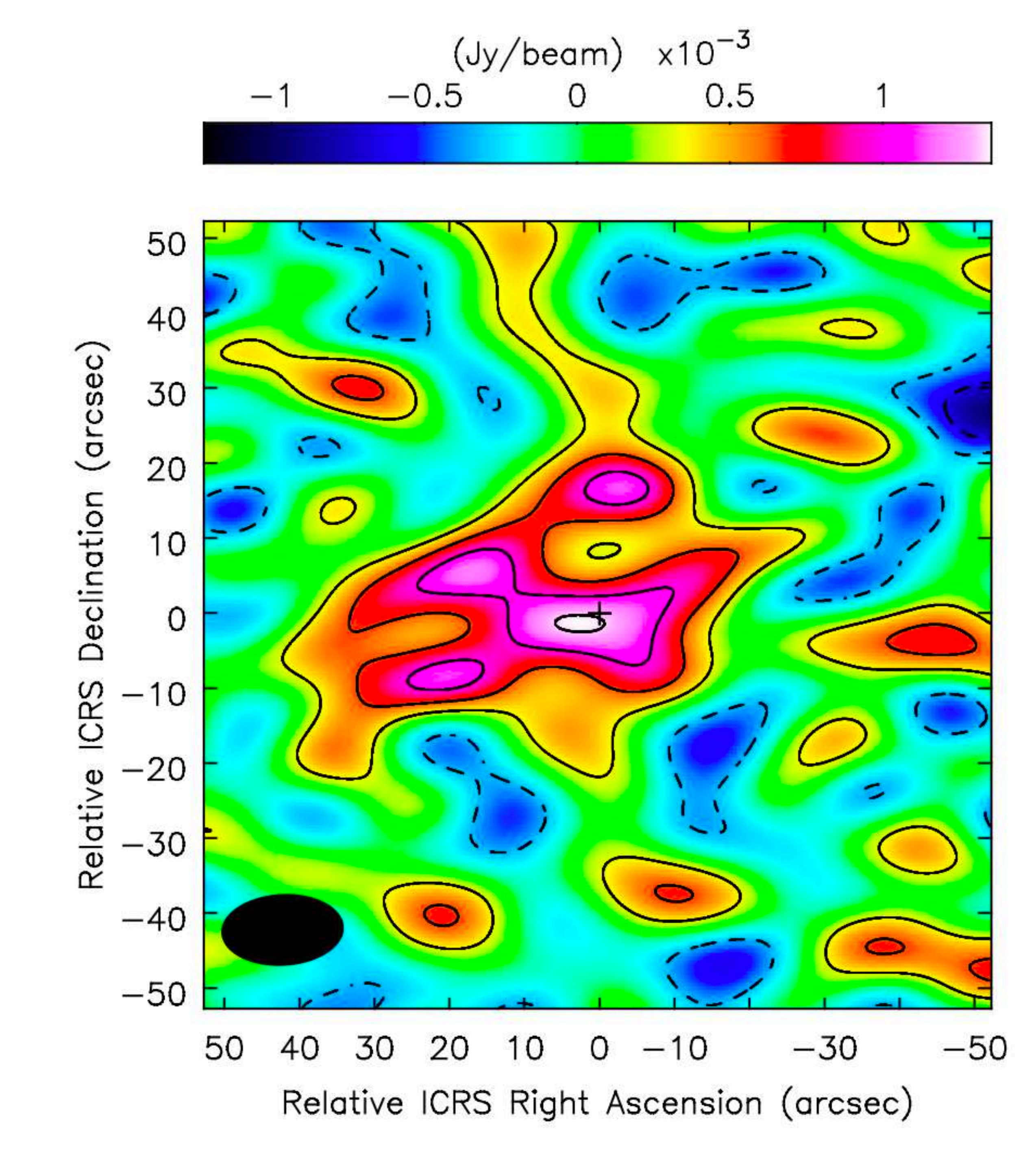
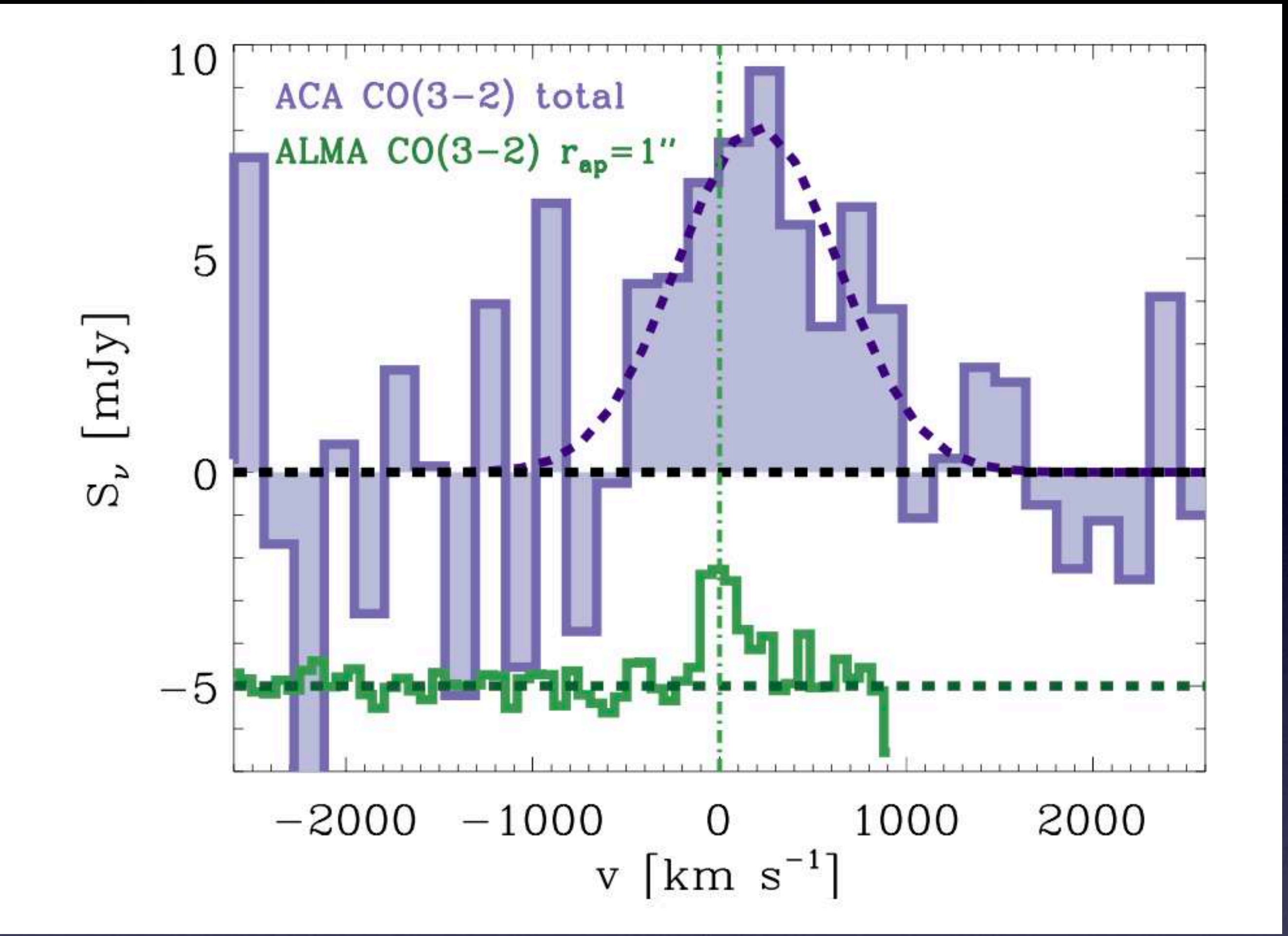


Fig. 1: ACA map obtained by integrating the CO(3-2) line emission within $-400 < v[\mathrm{km\ s^{-1}}] < 1000$. For visualization pur-

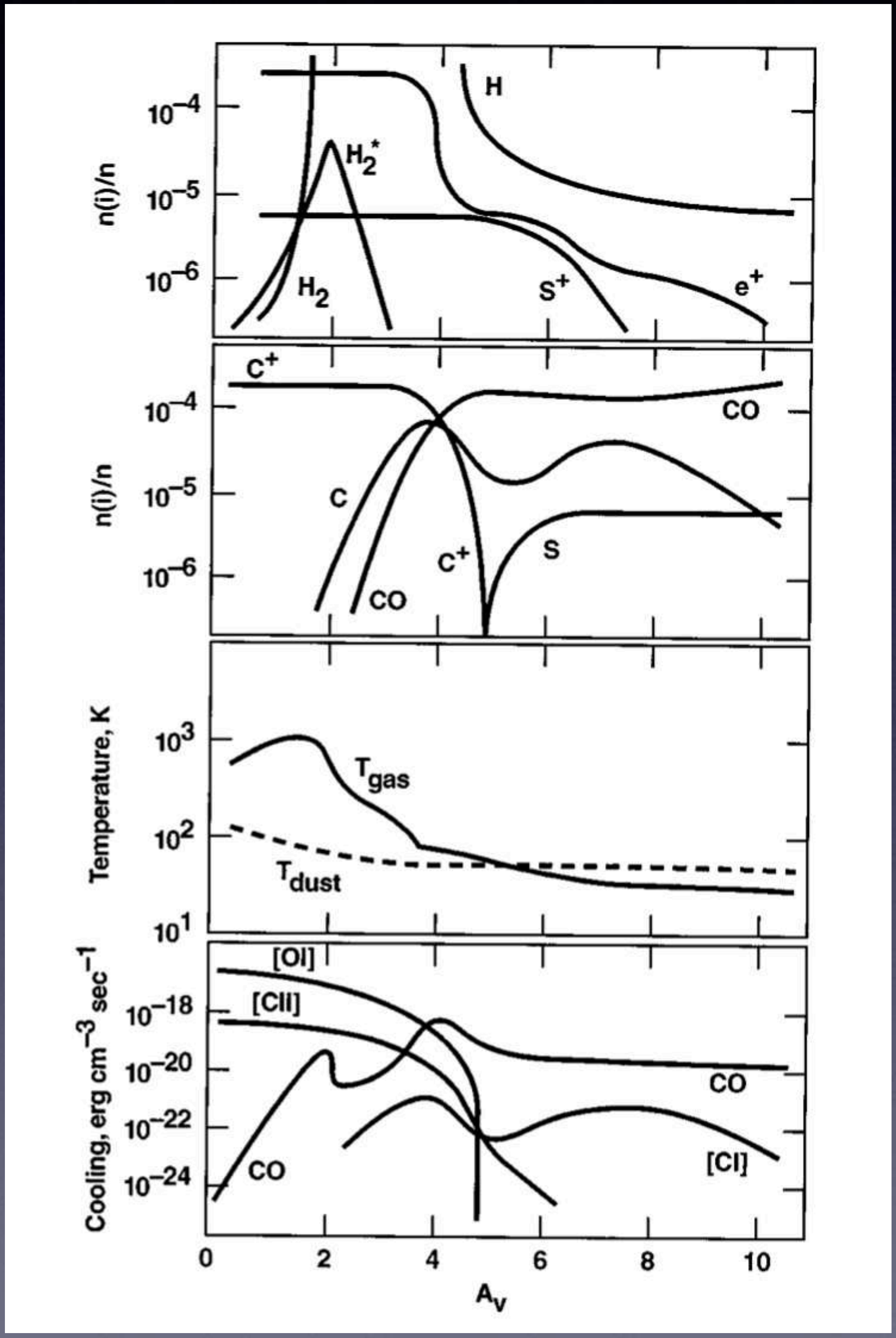


In a z=2 QSO, at r=200 kpc beyond/around the host, at least ~$10^{10} M_{sol}$ of H_2 mass..

Cicone et al. 2021, (arXiv 2109.02269)

The question now is:
How much more, and where…?

THANK YOU!



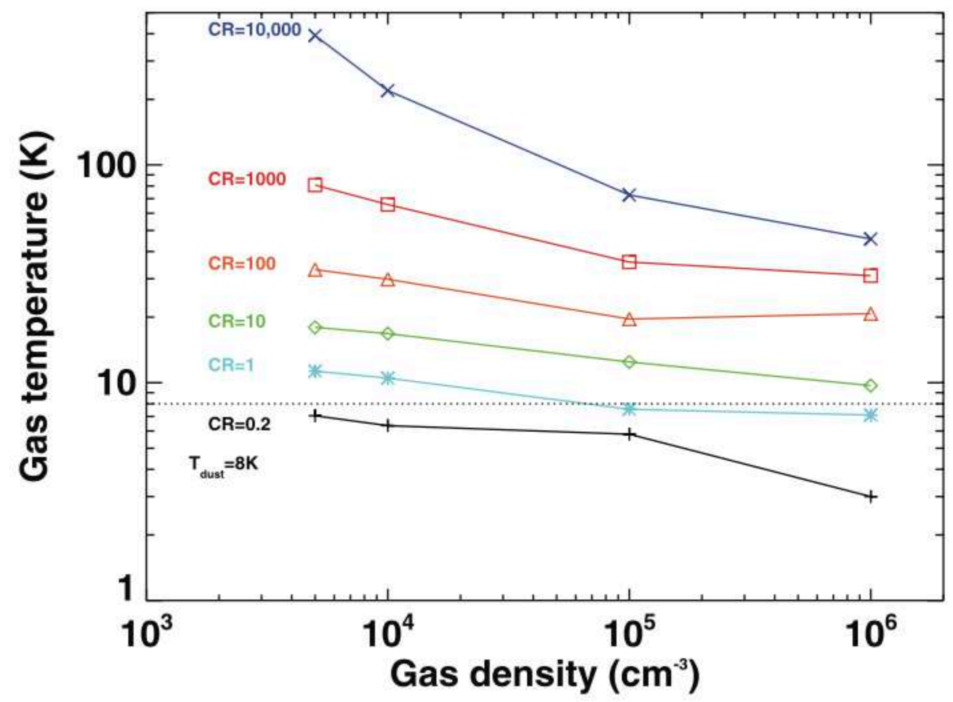


Figure 1. The temperature of UV-shielded dense gas cores computed from equation (2) for the range of densities typical in molecular clouds. The CR energy densities range from the quiescent environment of the Galaxy $[U_{CR} = (0.2–1) \times U_{CR,Gal}]$ to those in extreme CRDRs $[U_{CR} \sim (10^3–10^4) \times U_{CR,Gal}$; Papadopoulos 2010]. A dust temperature $T_{dust} = 8\,K$ and a Galactic CR ionization rate of $\zeta_{CR} = 5 \times 10^{-17}\,s^{-1}$ have been assumed.

What is so important about the $a = T_{kin}/T_{dust}$ gas-dust thermal decoupling parameter?