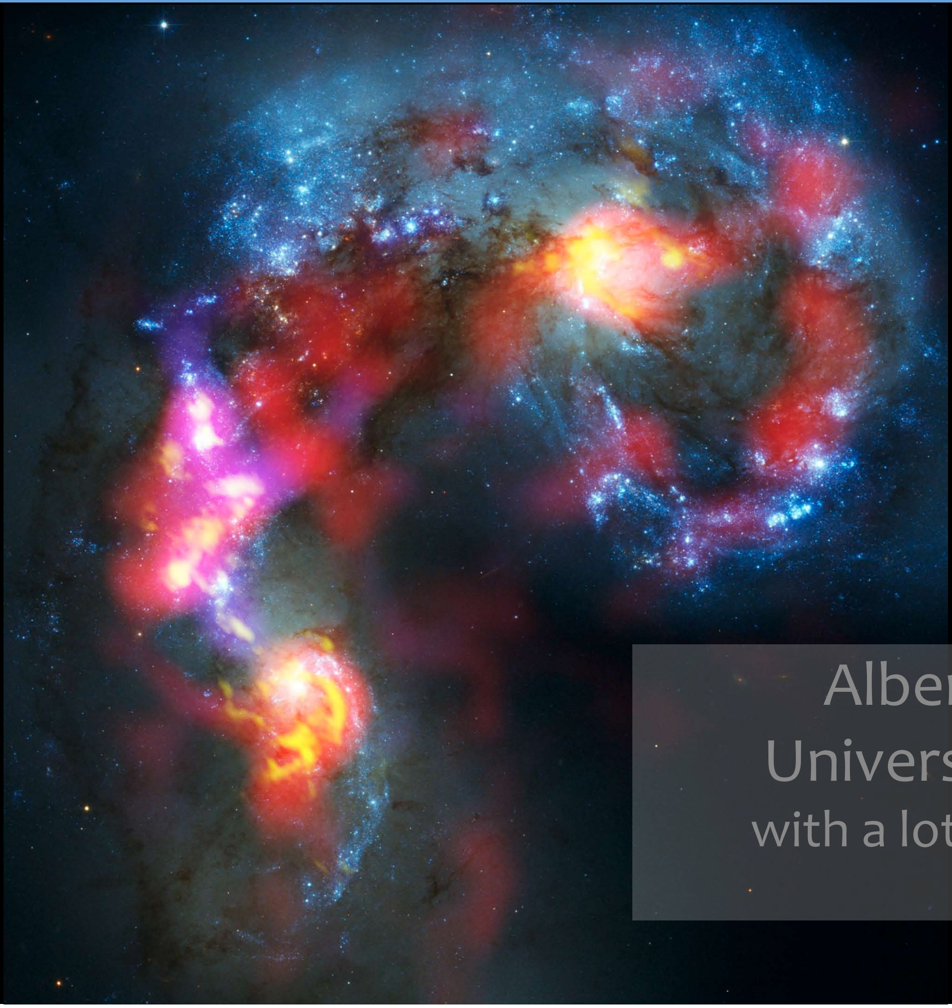
Molecular Masses from CO Observations



Alberto D. Bolatto
University of Maryland
with a lot of help from many people…

Google's version

Outline

1. Background: The structure of molecular clouds
2. Overview:
    I. The Milky Way
    II. Low Metallicities
    III. LIRGs and ULIRGs
    IV. High-z
3. Summary

Some definitions

$$N(H_2)\,[\mathrm{cm}^{-2}] = X_{co}\; I_{co}\,[\mathrm{K\ km\ s}^{-1}]$$

$$M(H_2)\,[M_\odot] = \alpha\; L_{co}\,[\mathrm{K\ km\ s}^{-1}\ \mathrm{pc}^2]$$

(should include 36% correction due to He)

$$\left.\begin{array}{l} X_{co} \sim 2\times10^{20}\ \mathrm{cm}^{-2}(\mathrm{K\ km\ s}^{-1})^{-1} \\ \alpha \sim 4.3\ M_\odot\ (\mathrm{K\ km\ s}^{-1}\ \mathrm{pc}^2)^{-1} \\ \quad (3.2\ \text{if no He correction}) \end{array}\right\}$$

approximate for the Milky Way disk

For self-gravitating entities

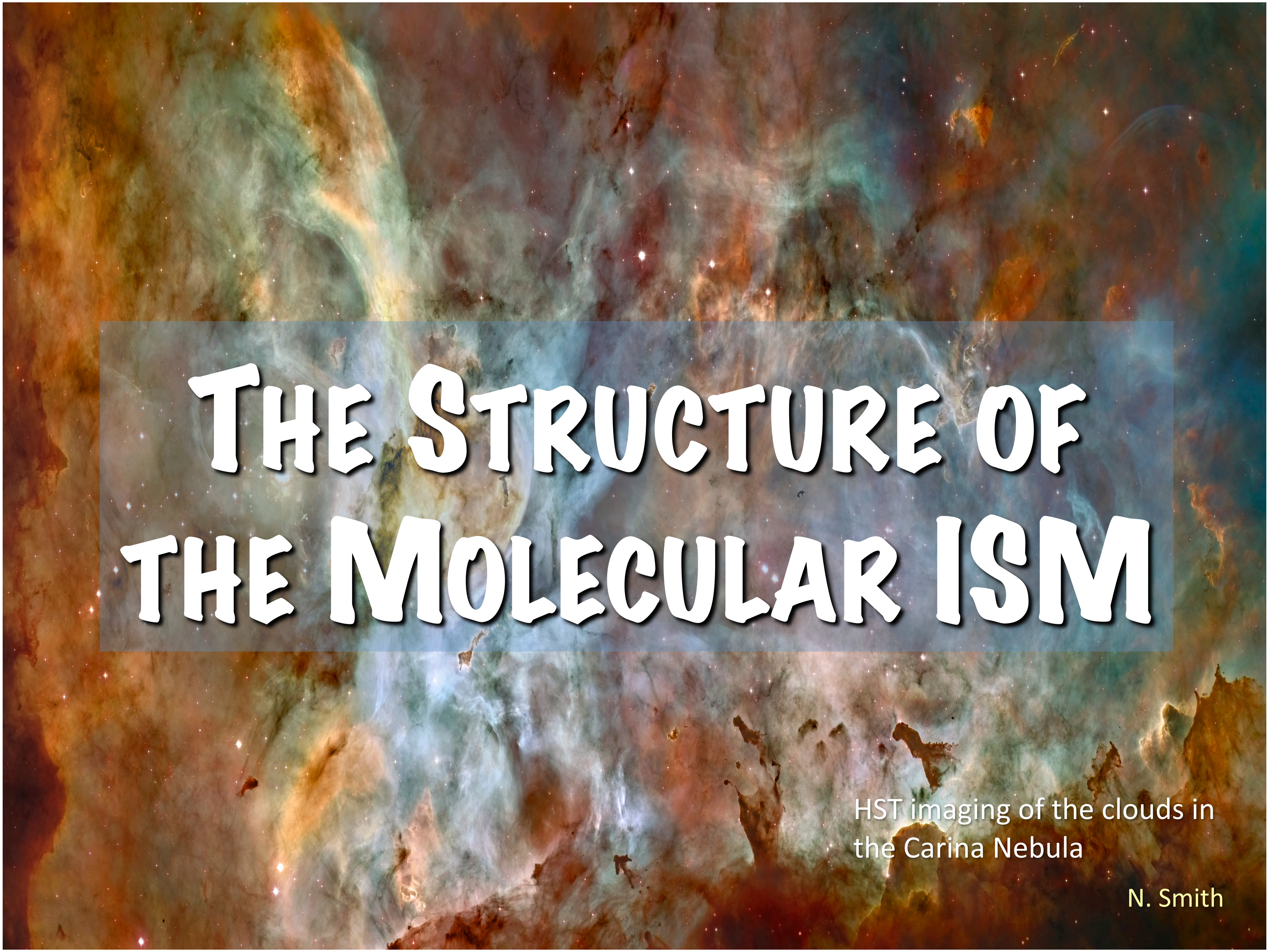
- $M \sim R\,(\Delta v)^2$ ➔ $R^3 n \sim R\,(\Delta v)^2$ virial theorem
- size-linewidth relation $\Delta v \sim R^{1/2}$ ➔ $\Delta v \sim n^{-1/2}$
- $T_b \sim T_k$ for $\tau >> 1$

So $I_{co} = T_b\,\Delta v \sim T_k\, n^{-1/2}$ ➔ $\boxed{X_{co} \sim n^{1/2} / T_k}$

Similarly $\boxed{\alpha_{CO} \sim L_{CO}^{-0.2} T_B^{-0.8}\, \Sigma_{GMC}^{0.6}}$

The basis for Xco

- How can we use an optically thick transition as a mass tracer?
  - The "mist" model (Dickman et al. 1986)
    1. CO emission arises from an ensemble of clouds
    2. Each cloud is virialized, linewidth reflects its mass
    3. The mean density of the clouds is the same
    4. Clouds do not shadow each other: "mist" is optically thin even though the droplets are not
    5. There is a narrow range of densities and temperatures
  - $\alpha_{CO}=M_{gas}/L_{CO} \sim n^{1/2}/T_k$



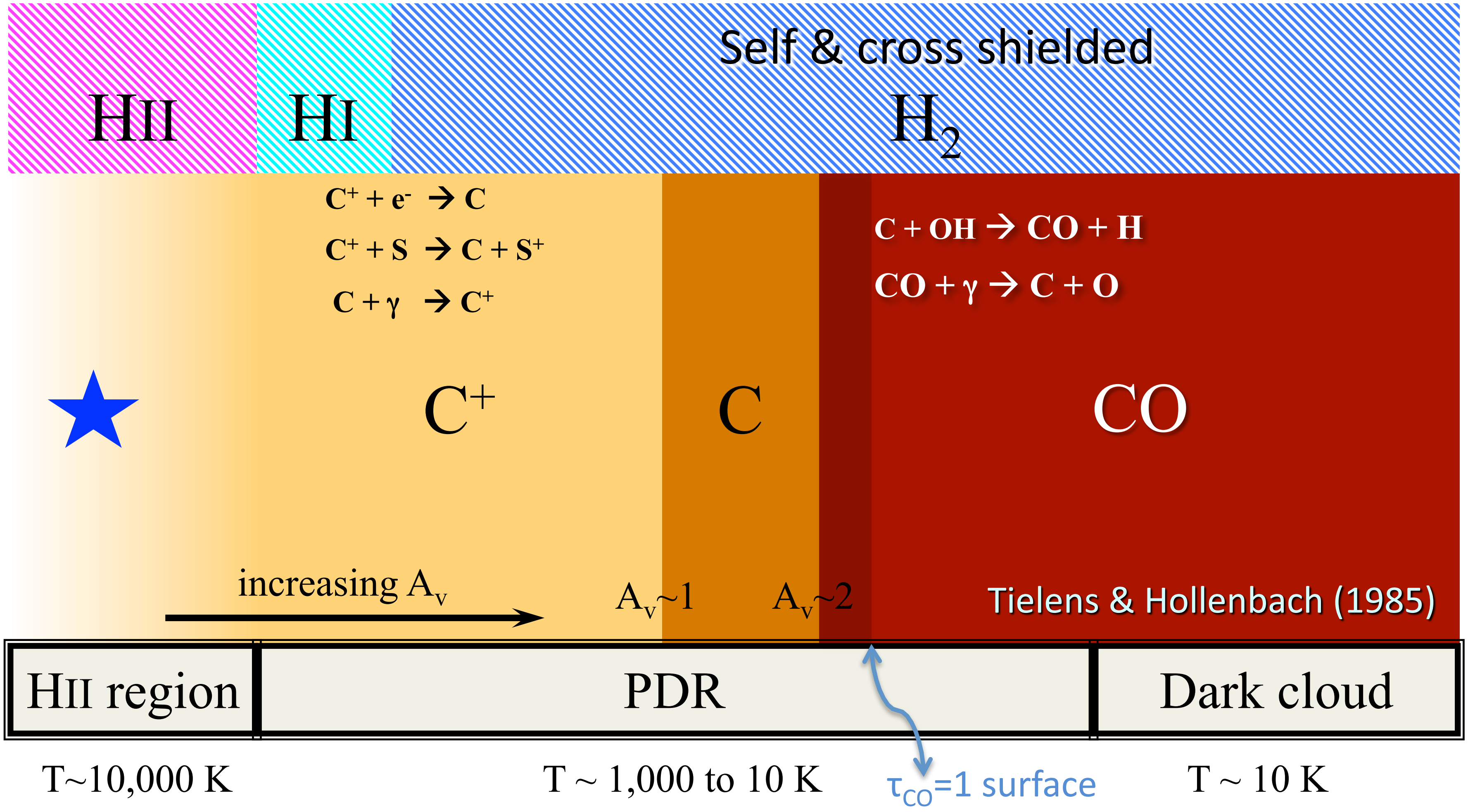
The Structure of the Molecular ISM

HST imaging of the clouds in the Carina Nebula

N. Smith

Structure of PDRs

Dust controls UV extinction and physical sizes



Self & cross shielded

HII HI H_2

$C^+ + e^- \rightarrow C$

$C^+ + S \rightarrow C + S^+$

$C + \gamma \rightarrow C^+$

$C + OH \rightarrow CO + H$

$CO + \gamma \rightarrow C + O$

C^+ C CO

increasing A_v

A_v~1 A_v~2

Tielens & Hollenbach (1985)

HII region | PDR | Dark cloud

T~10,000 K

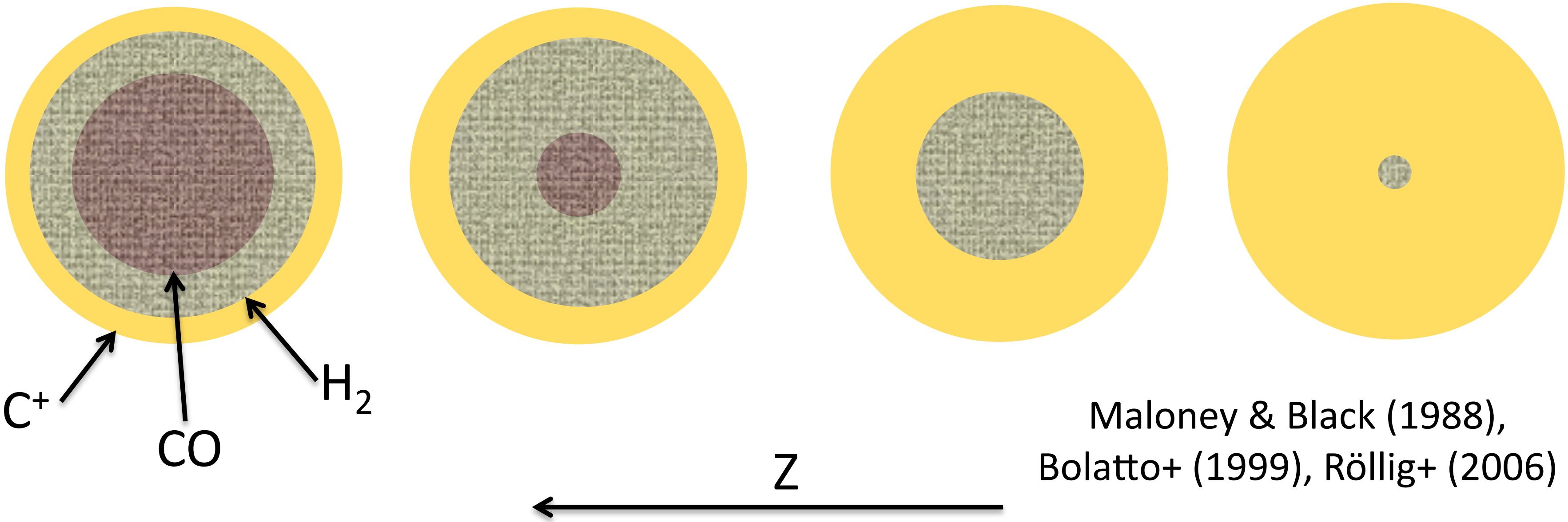
T ~ 1,000 to 10 K

τ_{CO}=1 surface

T ~ 10 K

Metallicity/dust effects

- As metallicity and dust-to-gas ratios decrease, A_V~1 moves deeper into clumps of constant column density
- CO disappears when A_V<2 through a clump, but H_2 exists to much lower extinctions
- The relative amount of CO and H_2 is set by the distribution of column densities in the ISM

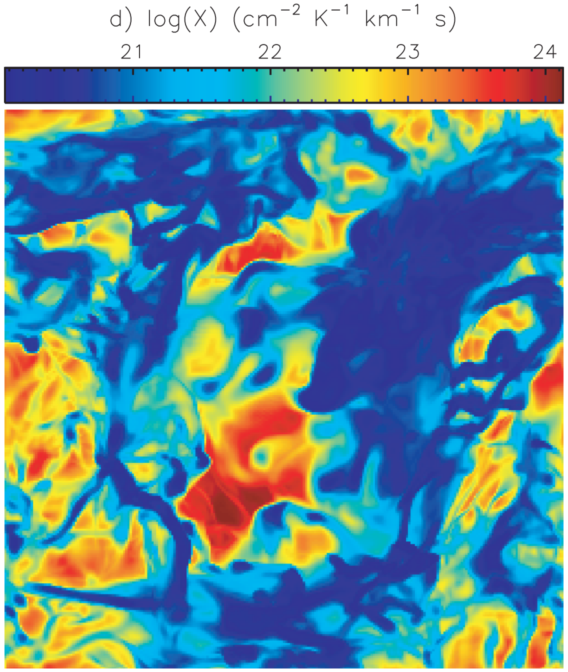


Maloney & Black (1988),
Bolatto+ (1999), Röllig+ (2006)

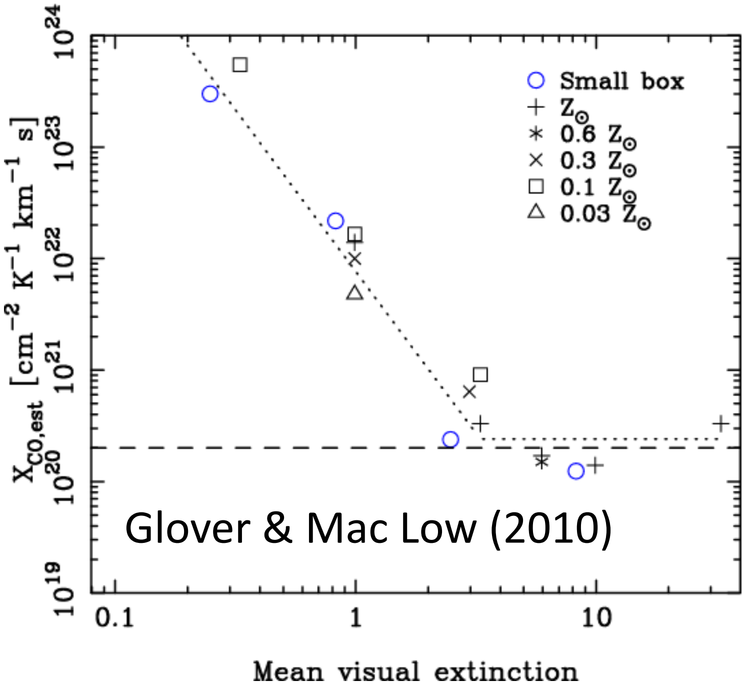
Gas in a box: CO-to-H_2

Simulations of time-dependent chemistry in a turbulent box, illuminated by UV, probing a range of metallicities

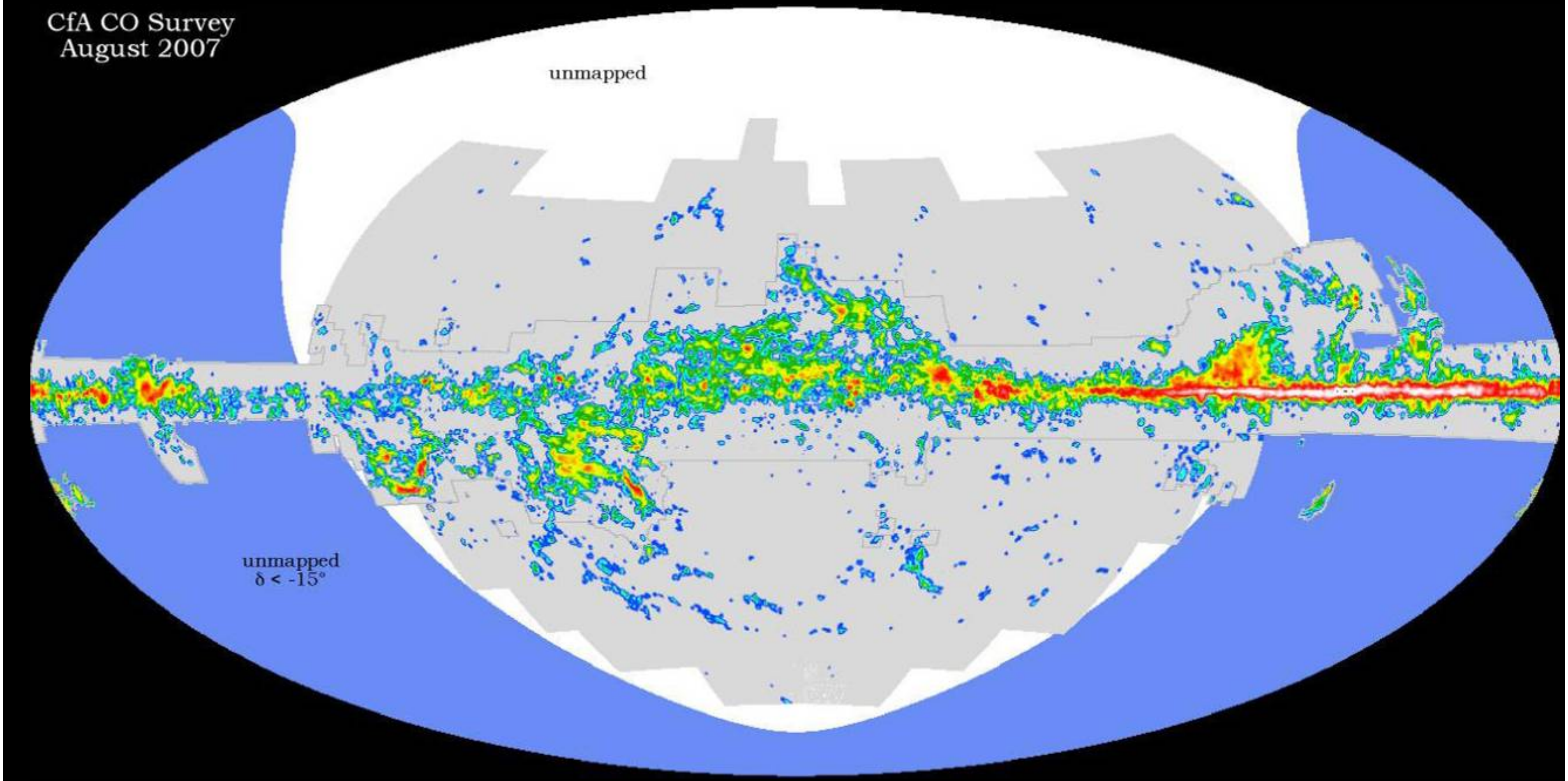
- The CO-to-H_2 conversion, X_{CO} , depends mostly on A_V, and only indirectly (through the dust-to-gas ratio) on metallicity
- Corollary: X_{CO} is due to the combined effect of the N(H) PDF and the DGR(Z)



Shetty+(2011a,b); see also Wolfire+(2010), Feldmann+ (2011)



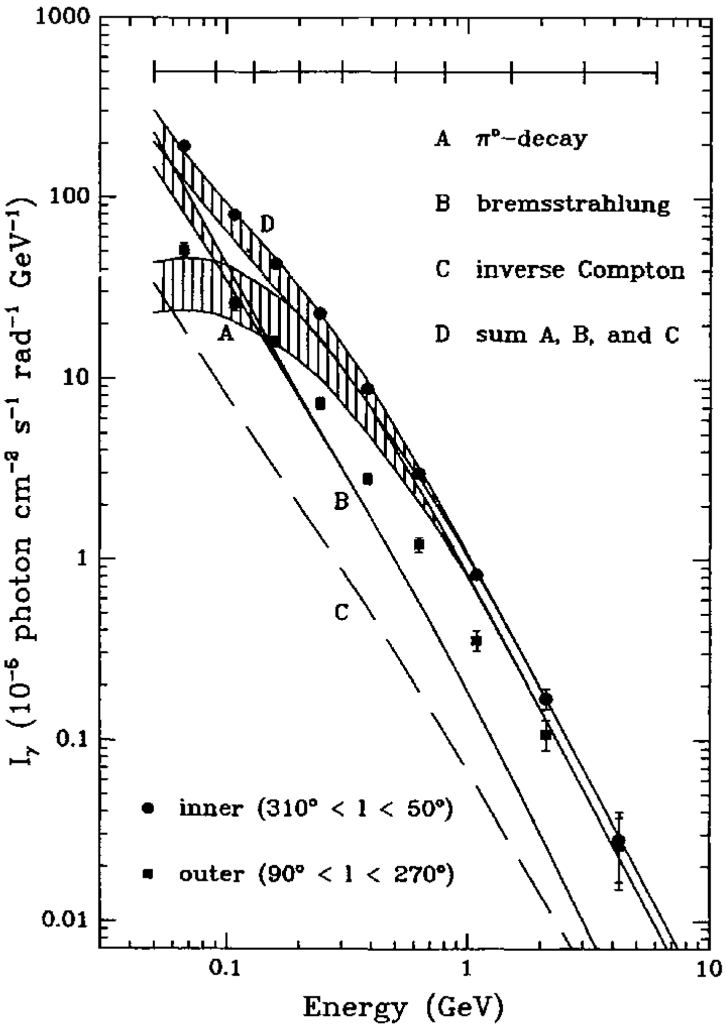
Glover & Mac Low (2010)



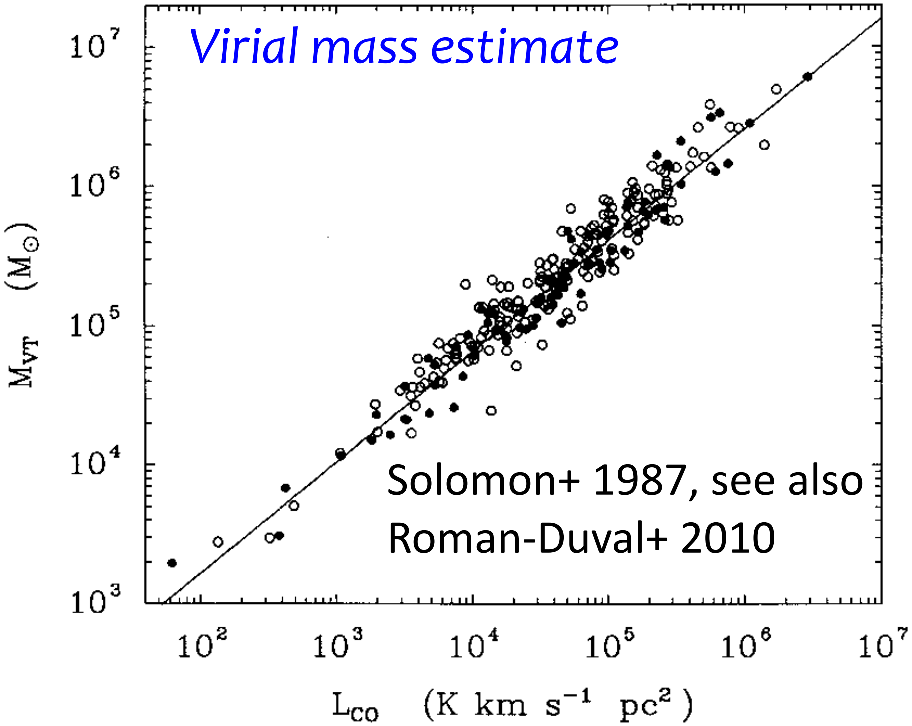
Xco in the Milky Way

Xco in the Milky Way

Diffuse γ-ray emission to estimate proton column density



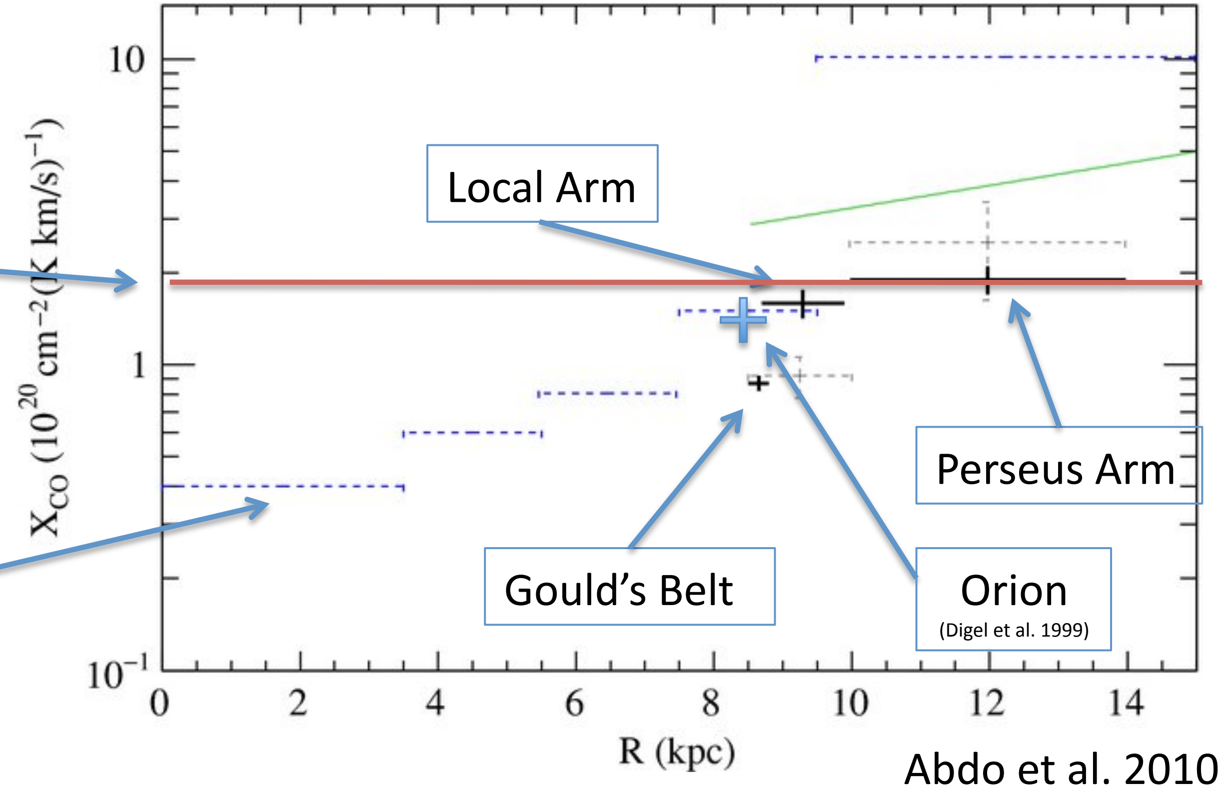
Bloemen 1989, see also
Ackerman+ 2011,2012



Virial mass estimate

Solomon+ 1987, see also
Roman-Duval+ 2010

FERMI analysis



Strong & Mattox (1996), Strong et al. (2000) single value EGRET analysis

Strong et al. (2004) EGRET analysis

Local Arm

Gould’s Belt

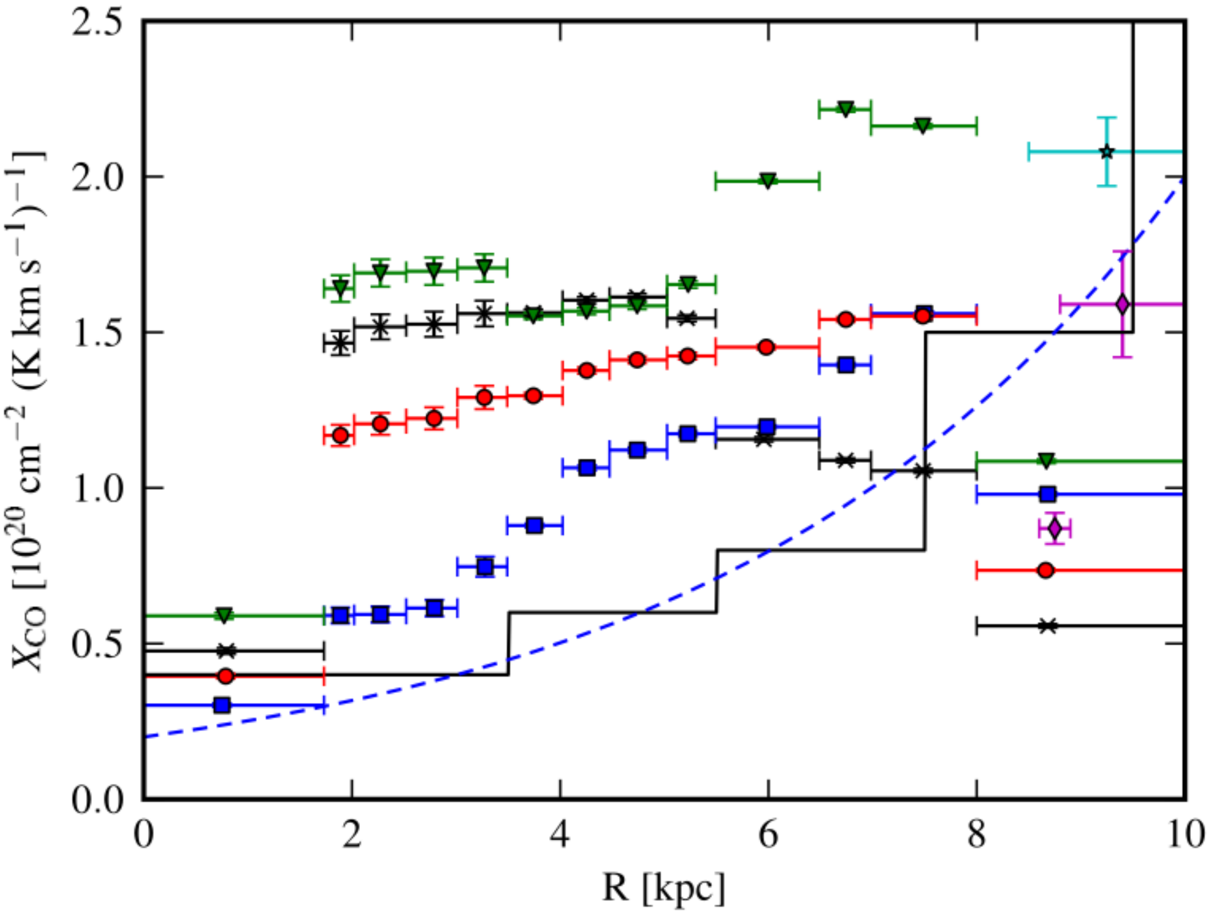
Orion (Digel et al. 1999)

Perseus Arm

Abdo et al. 2010

- Need to solve simultaneously for the cosmic ray distribution and Xco
- Fundamental assumption is that cosmic rays are not rejected from cloud centers
- Very good agreement with virial mass method over mean values
- Low value for GC is robust, gradient is not (Ackermann+ 2012)

FERMI analysis



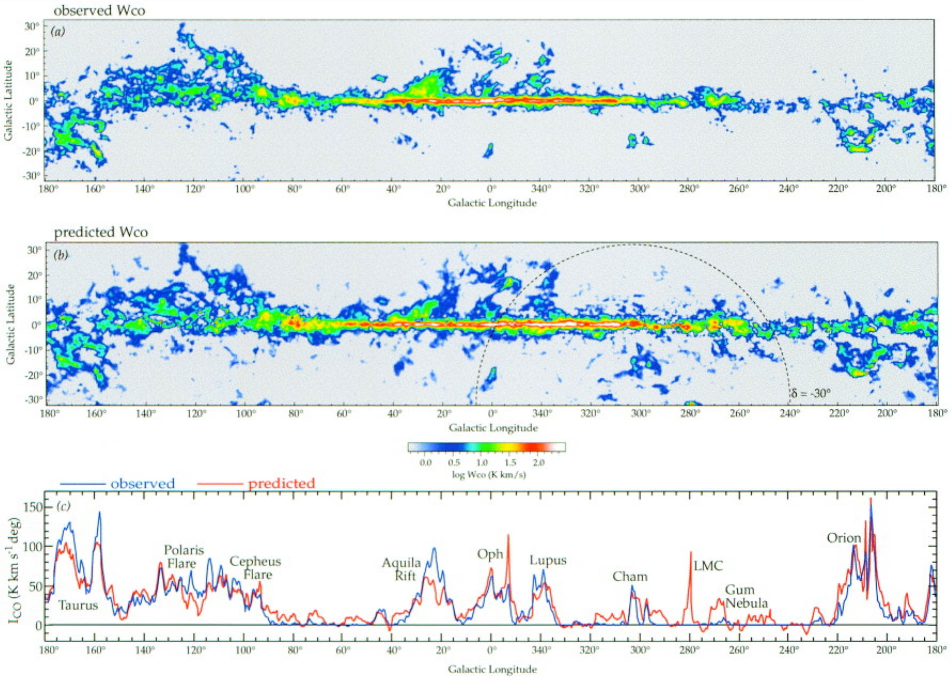
Ackermann et al. 2012

Using dust to trace H_2

FIR dust emission offers a view of the molecular component that is independent of CO and its chemistry.

Traces the total gas (HI + H2) column.

Matches Gamma Ray and CO results well.



Dame, Hartmann, and Thaddeus (2001)

Method:

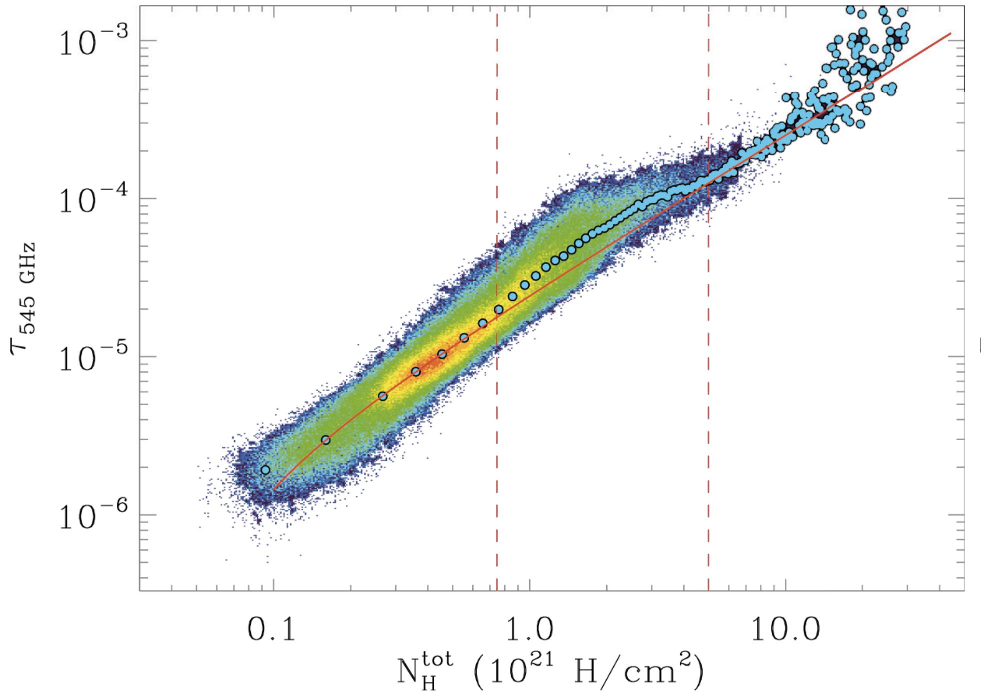
$$2N_{H2} = (\tau_{dust} \times [N_H/\tau_{dust}]_{mean}) - N_{HI}$$

From FIR modeling

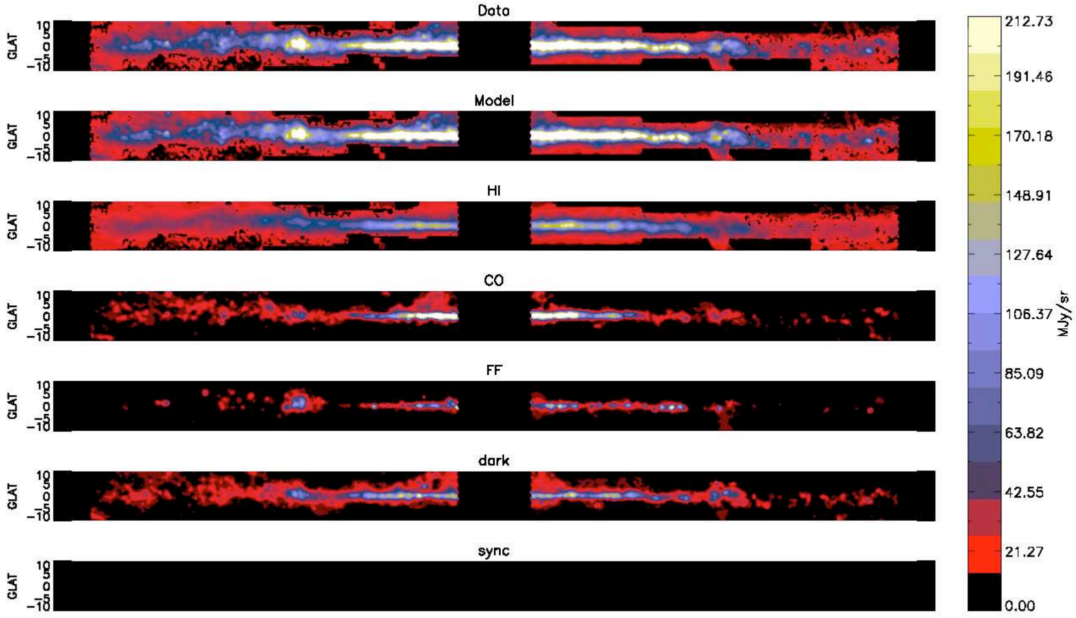
Self-consistent determination (e.g., along atomic-dominated LOS)

From 21cm map

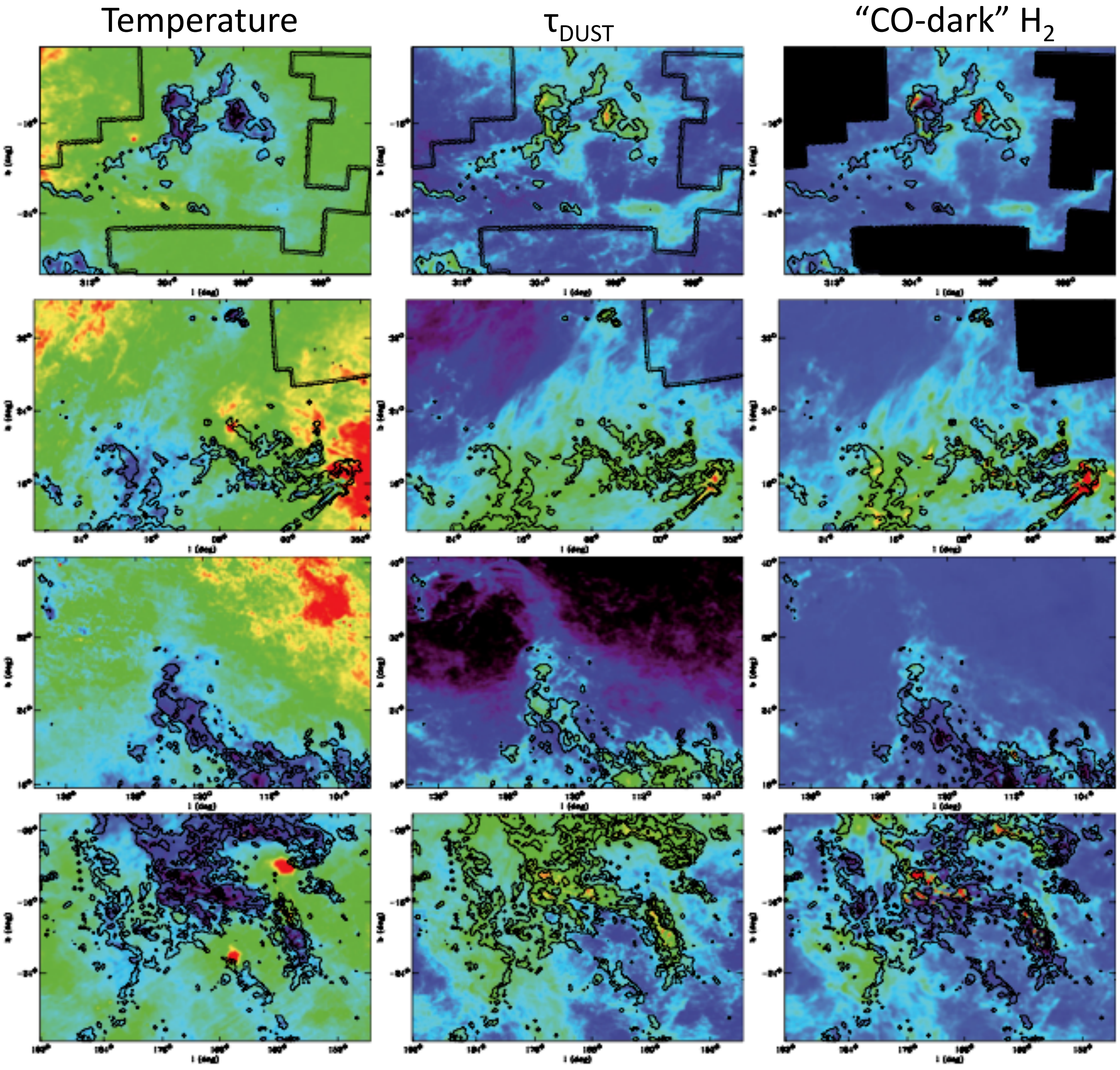
Planck Results



- Xco~2.54×10^{20} (but mind τ_{HI})
- CO-dark H_2 for A_V~0.4-2.5
- CO-dark H_2 dominant at Solar circle? (118% of H_2)
- No τ_{dust}/N_H difference between phases
- No radial trends in τ_{dust}/N_H

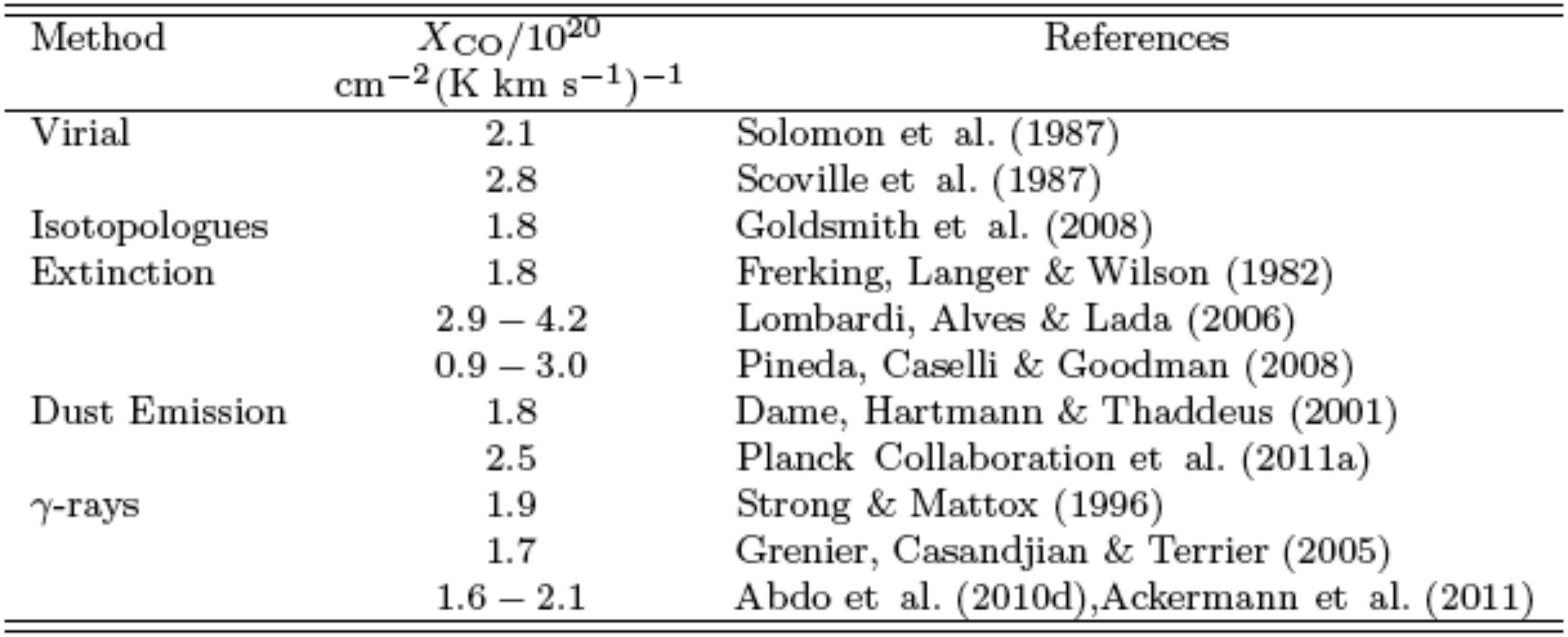


Planck Collaboration (2011, a number of papers)



Planck results: "dark" gas in the MW (Planck Collaboration XIX)

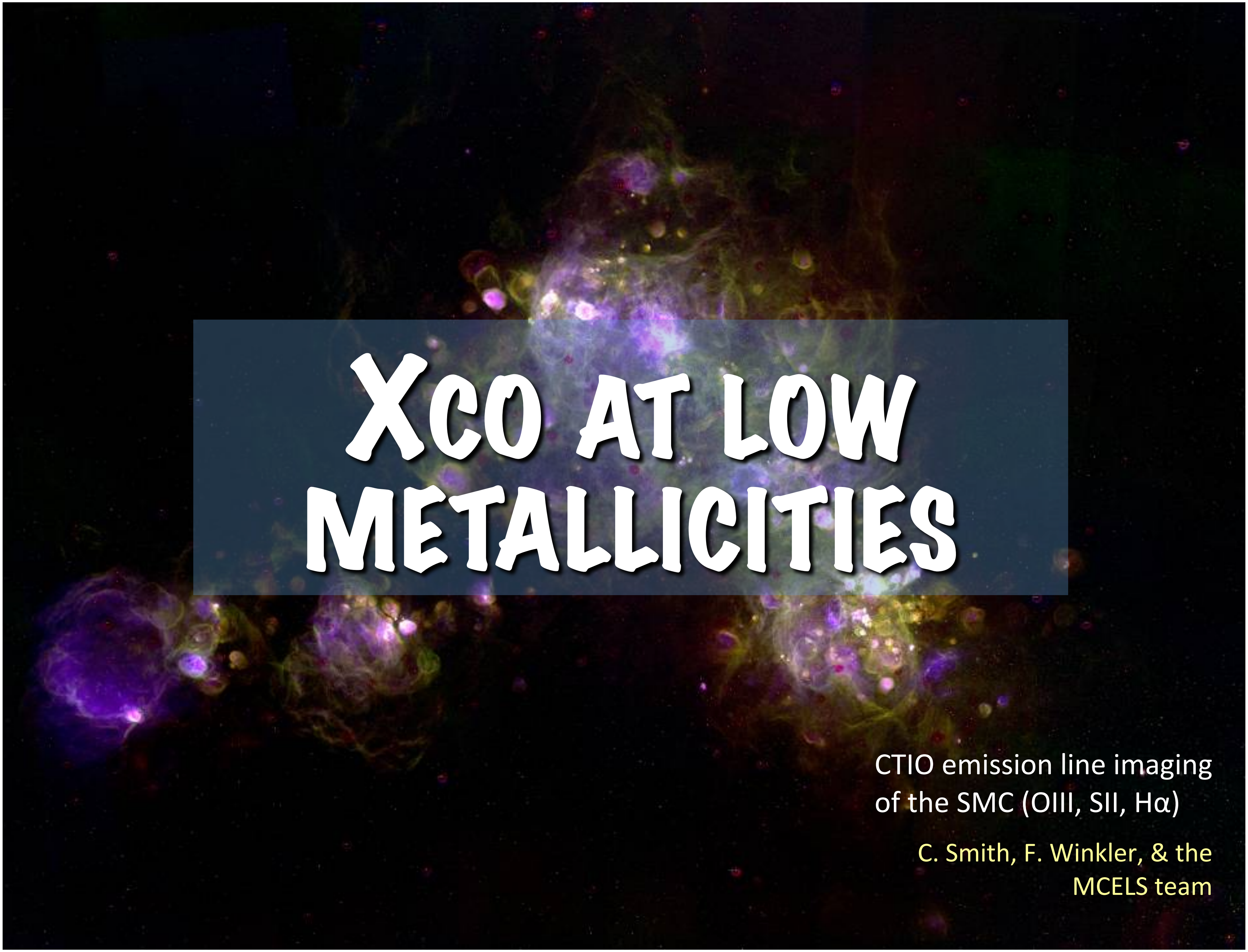
X_{CO} in the Milky Way



Method	$X_{CO}/10^{20}$ $\mathrm{cm^{-2}(K\ km\ s^{-1})^{-1}}$	References
Virial	2.1	Solomon et al. (1987)
	2.8	Scoville et al. (1987)
Isotopologues	1.8	Goldsmith et al. (2008)
Extinction	1.8	Frerking, Langer & Wilson (1982)
	2.9 – 4.2	Lombardi, Alves & Lada (2006)
	0.9 – 3.0	Pineda, Caselli & Goodman (2008)
Dust Emission	1.8	Dame, Hartmann & Thaddeus (2001)
	2.5	Planck Collaboration et al. (2011a)
γ-rays	1.9	Strong & Mattox (1996)
	1.7	Grenier, Casandjian & Terrier (2005)
	1.6 – 2.1	Abdo et al. (2010d),Ackermann et al. (2011)

Karin Sandstrom's talk about Xco in other galaxy disks!

Bolatto, Wolfire, & Leroy
(ARAA, in prep)



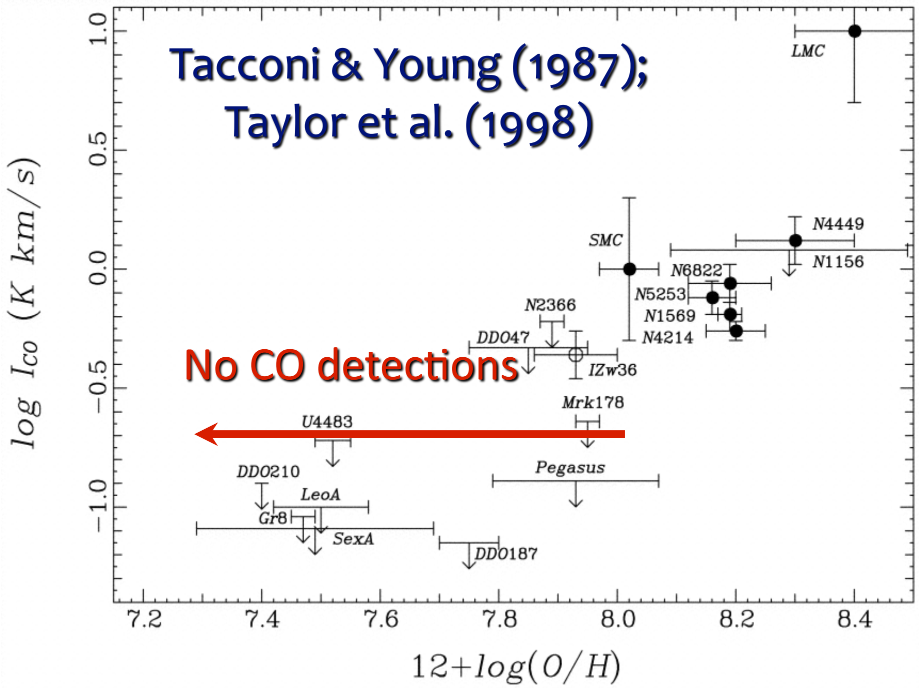
XCO AT LOW METALLICITIES

CTIO emission line imaging of the SMC (OIII, SII, Hα)

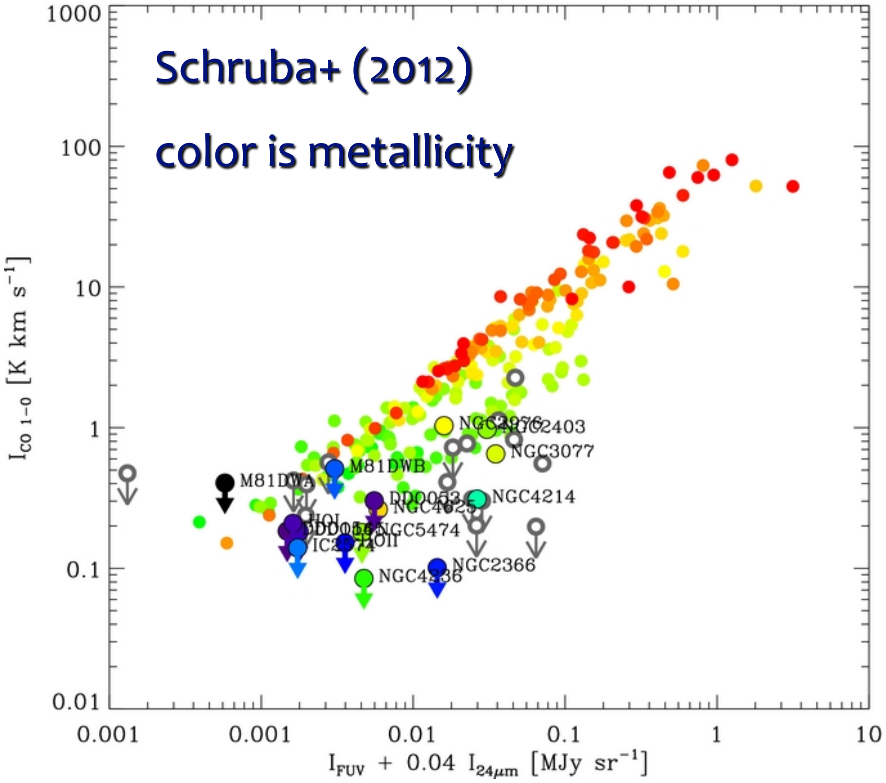
C. Smith, F. Winkler, & the MCELS team

No CO but Active Star Formation

- Faint CO below O/H~1/5 Solar
- But plenty of SF


Tacconi & Young (1987); Taylor et al. (1998)

No CO detections

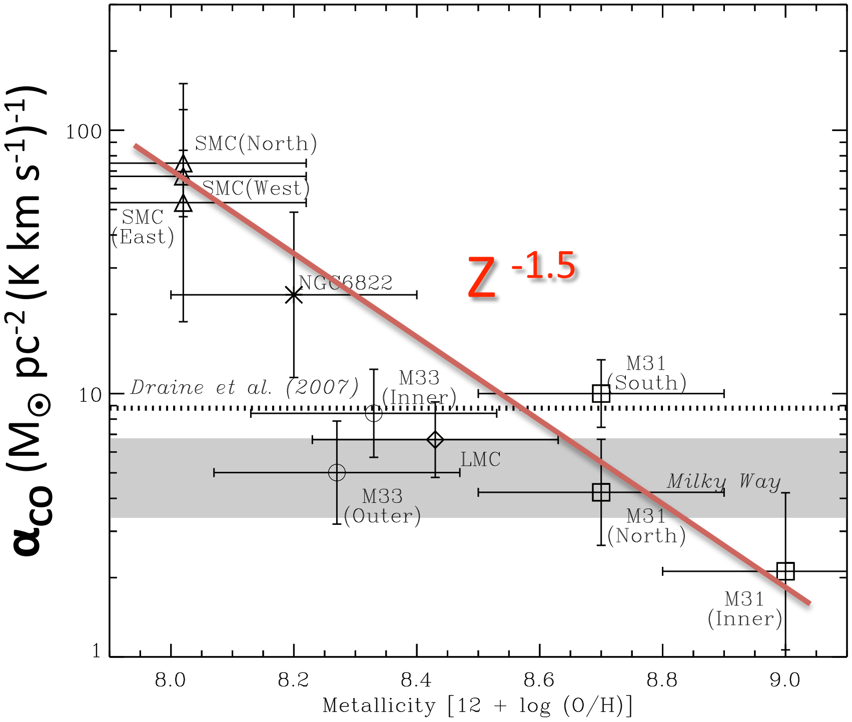

Schruba+ (2012)

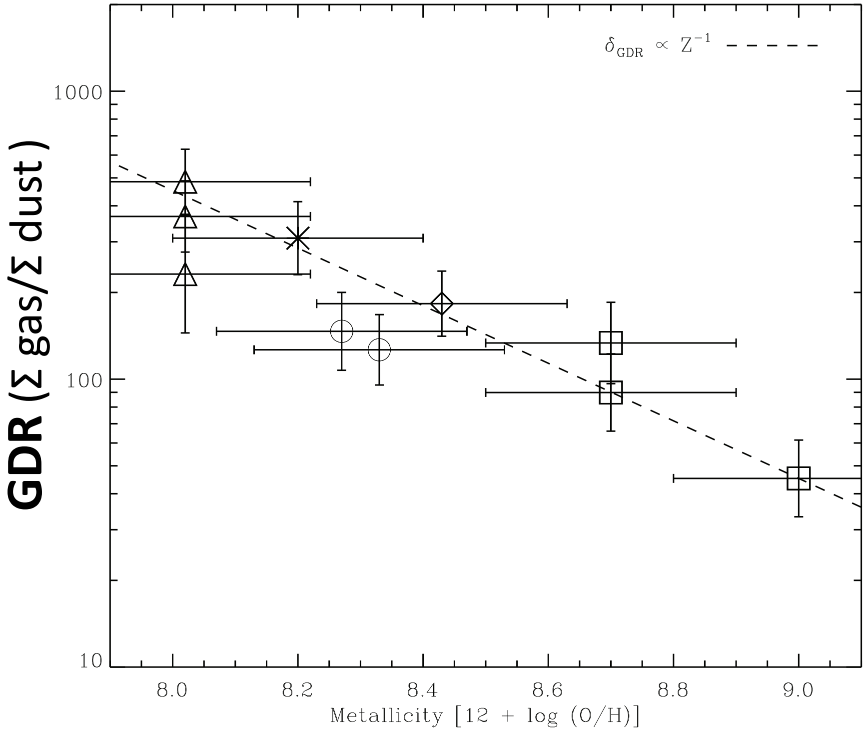
color is metallicity

CO/H_2 in the Local Group

- Obtain α_{CO} and GDR by minimizing $\alpha\ I_{CO} + \Sigma_{HI} - \mathrm{GDR}\ \Sigma_{dust}$
- Sharp increase in X_{CO} at low Z: plenty of H_2

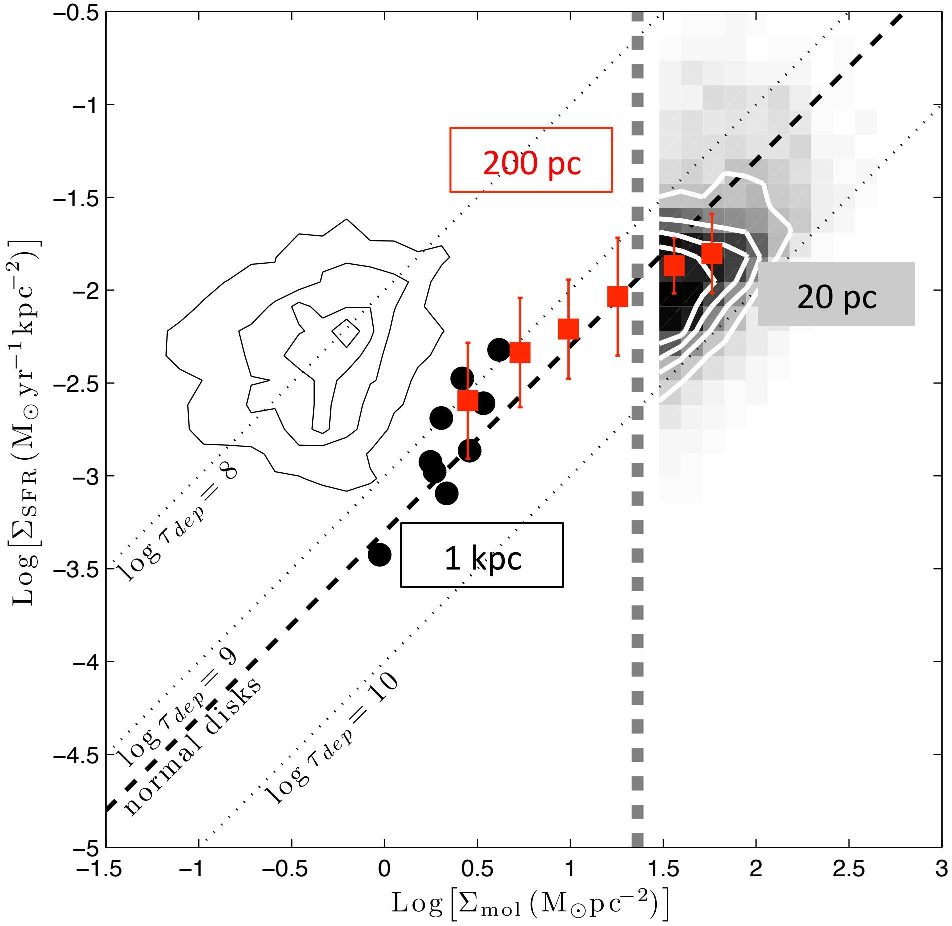
Leroy et al. (2011); see also Israel (1997)





Relation between H_2 and Star Formation in the SMC

- Looks just like the high metallicity version
- No major metallicity effects
- Except for the CO intensity

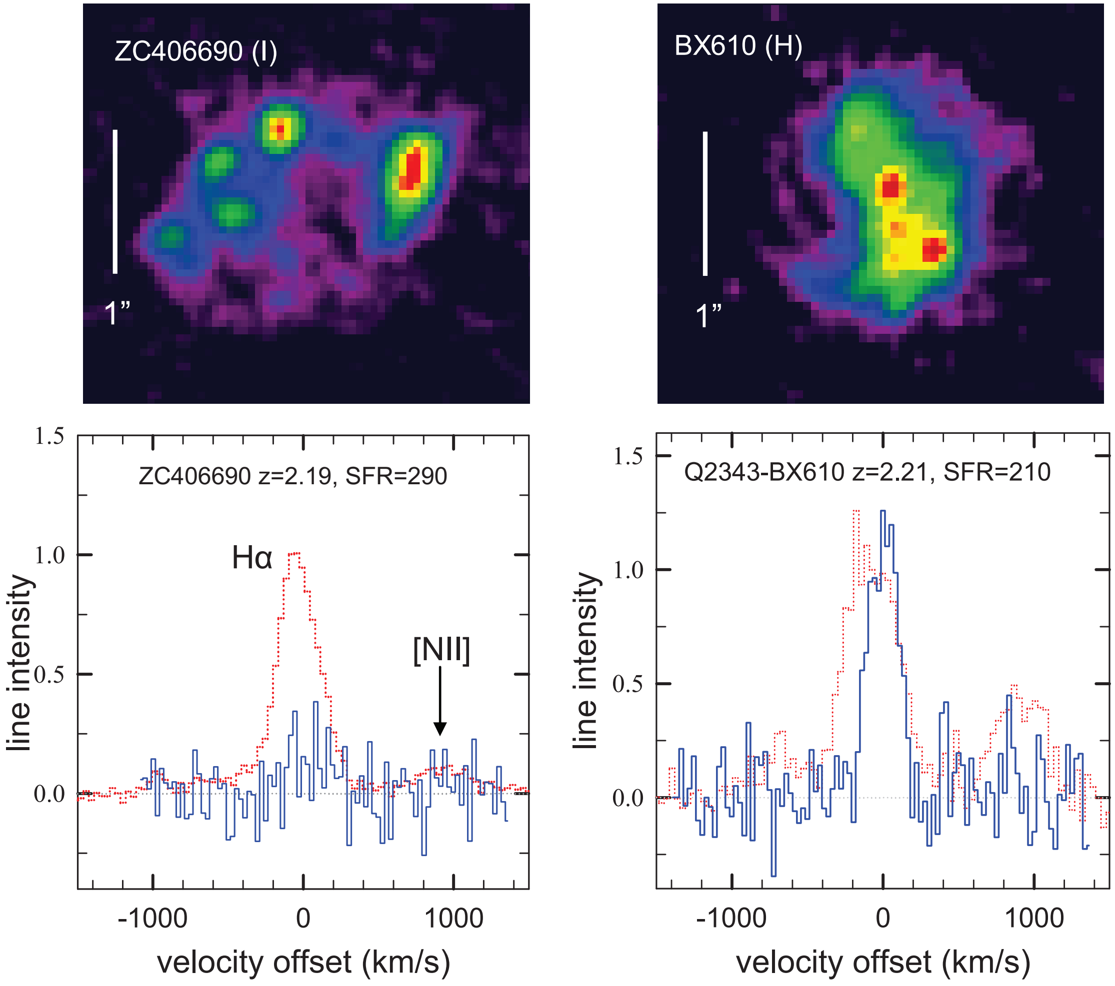


Bolatto et al. (2011)

Metallicity effects also at high-z !

- z~2 glaxies with similar SFR, very different CO and metallicity
- Not dwarfs !!!!
- Likely to become a key issue for lower luminosity high-z galaxies

Genzel+(2011)



Xco in Starbursts

IRAS 19297-0406

HST combined UV,V,NIR

Ultra-Luminous IR Galaxies/mergers

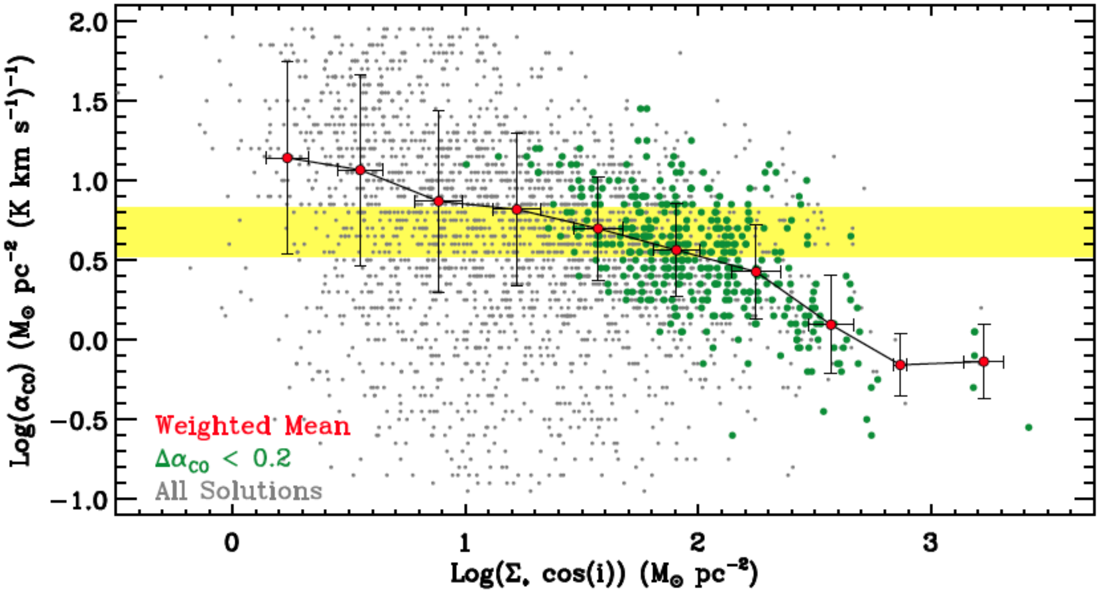
- Problem: the H_2 mass is uncomfortably large compared the dynamical mass for a "normal" Xco (Downes+ 1993)
  - Virialization assumption breaks down? Velocity dispersion reflects the overall potential of the galaxy (Downes+ 1993, Solomon et al. 1997, Downes & Solomon 1998)

    $M_{gas}\, M_{dyn} \sim (\alpha\, L_{CO})^2\ ,\ M_{gas}/L_{CO} \sim \alpha\, (M_{dyn}/M_{gas})^{1/2}$

  - Downes & Solomon (1998) conclude α~1/5 of MW (α=0.8) and M_{gas}~1/6 M_{dyn}.
  - Mostly this is a "plausibility" argument (M_{dyn} limit, CO excitation, CO region size, CO/H_2 abundance, T_{gas}~T_{dust})
  - Likely, α~ 0.8 – 2 (Scoville+ 1997; Bryant et al. 1999; Bothwell et al. 2009)

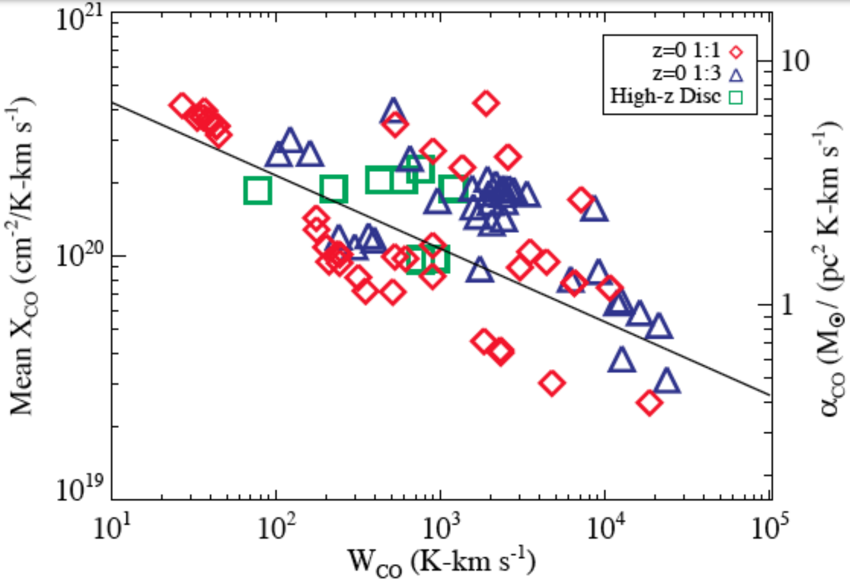
Galaxy Centers

- Virial/γ-ray shows that MW GC clouds have high surface densities and low Xco (Oka et al. 1998, 2001, etc)
- Evidence from multiline CO analysis: hot gas, Xco~ a few times smaller than Galactic (Israel & Baas 2003,2006)
- Dust modeling of KINGFISH sample shows α_{CO} depression in the center of 10/26 galaxies: virialization break-down? hotter clouds? (Sandstrom+, in prep.; see also Magrini+ 2011)

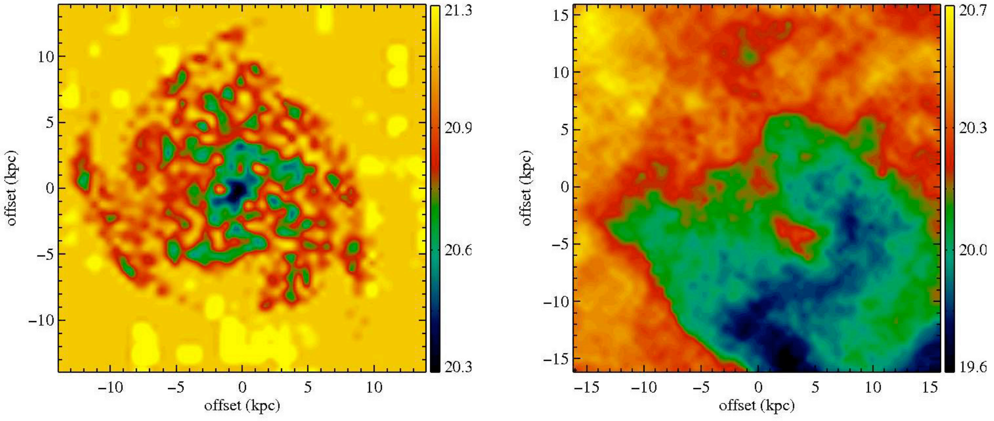


ULIRGs/mergers modeling

- SPH simulation coupled with radiative transfer (Narayanan+ 2011,2012)
- In mergers, GMC surface density and volume density increase occur, together with an increase in velocity dispersion
- Higher density leads to efficient dust-gas thermal coupling
- Together with increase in SFR, this leads to hotter gas with larger linewidths, decreasing Xco by factors of 2-10



Narayanan et al. (2011,2012)



Xco at High Redshifts

Hubble UDF

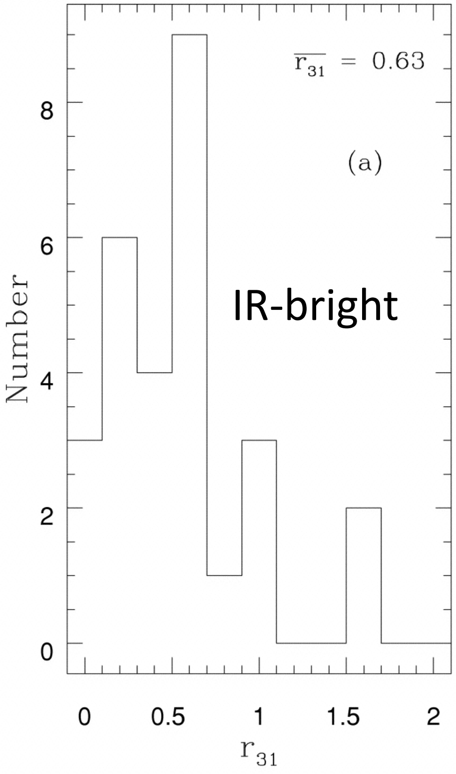
Excitation

- SLUGS (Yao et al. 2003), LIGS (Leech et al. 2010): CO (3-2)/CO (1-0) ~ 0.5-0.6

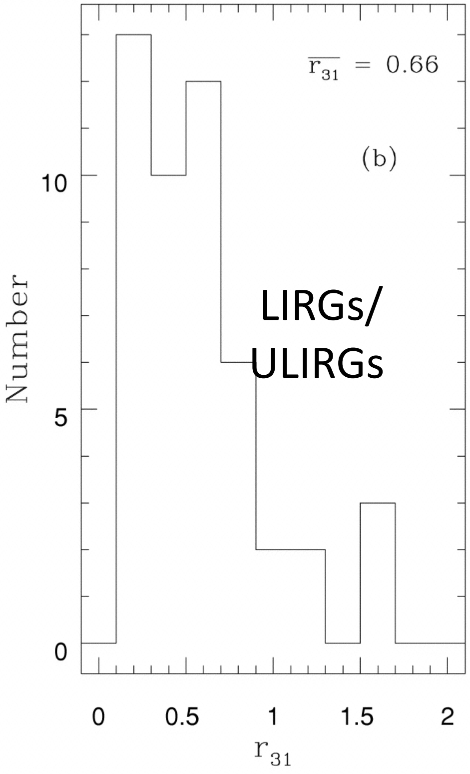
- r_{31} distribution is similar in ULIRGs and less bright galaxies

- Normal galaxies have r_{31}~0.3-0.4 (Wilson et al. 2009)

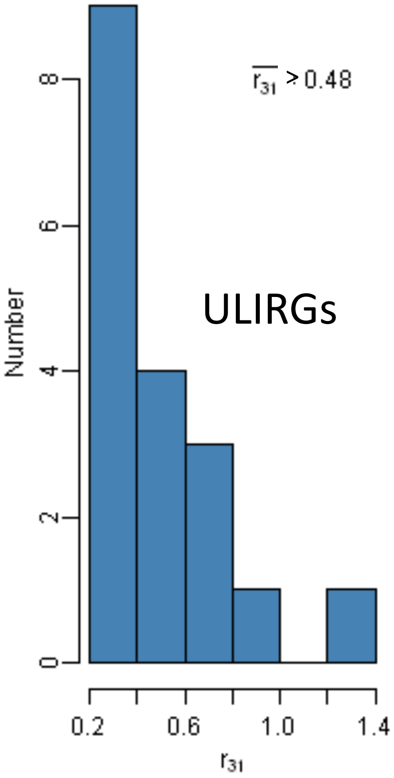
- Large CO(1-0) reservoirs in some z~3 galaxies, but not in z~4 QSOs (Riechers+2011a,b)



Mauersberger et al. (1998)

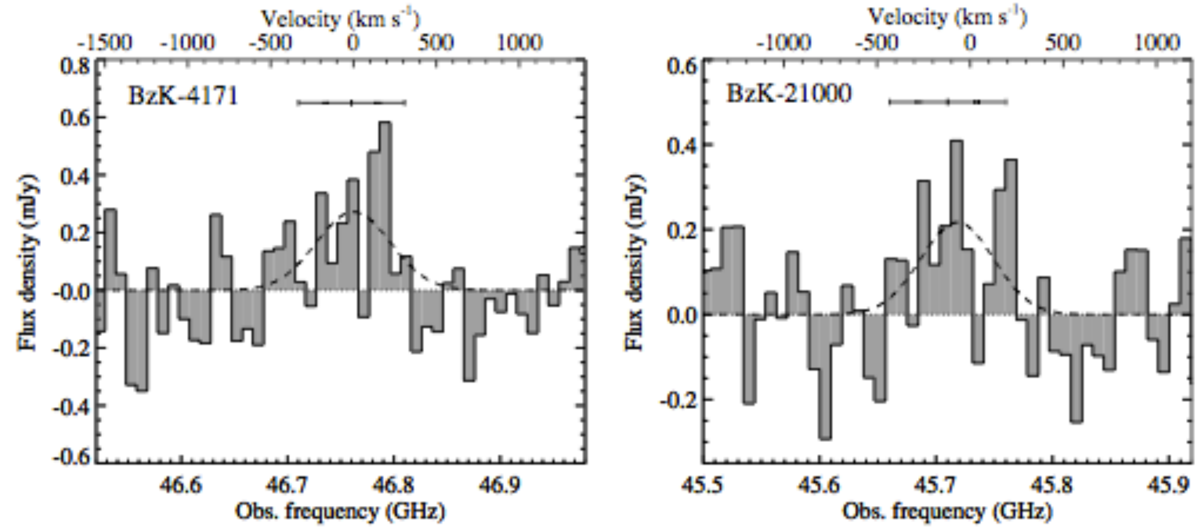


Yao et al. (2003)



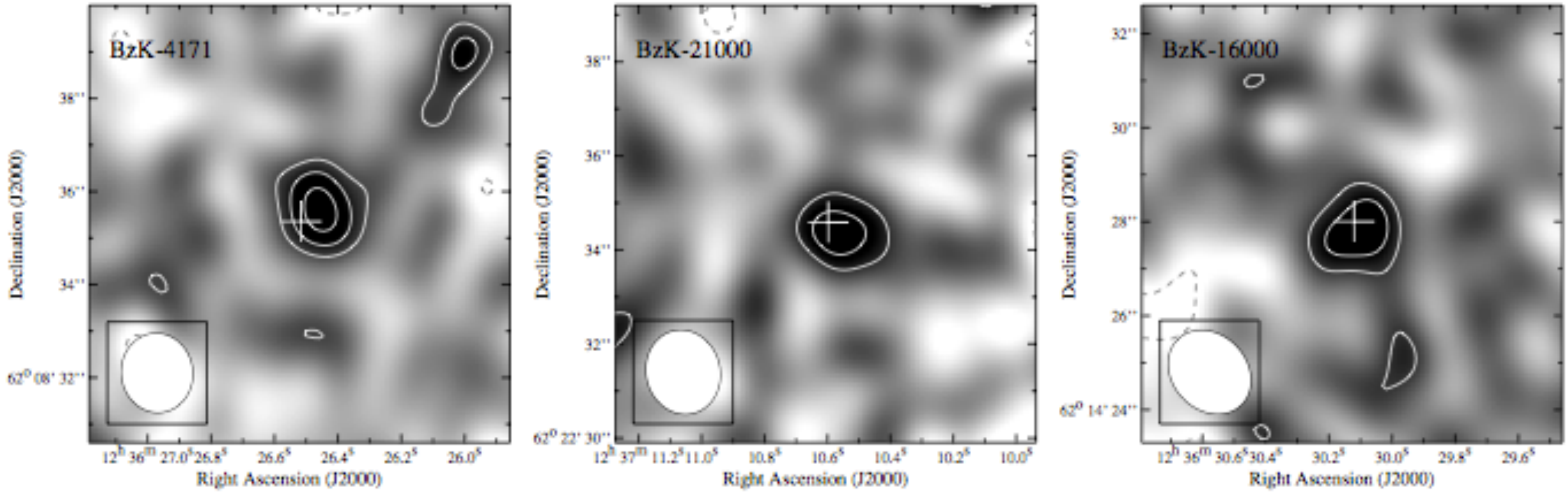
Iono et al. (2009)

“Normal” Galaxies and Low J



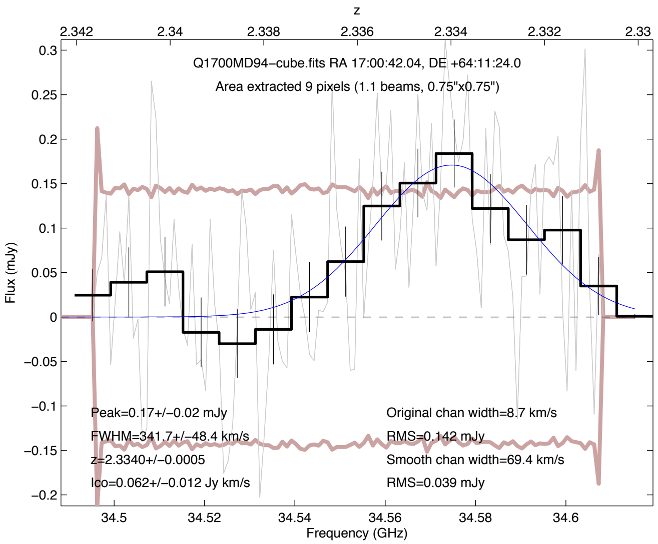
BzKs in CO (2-1) at z~1.5

Aravena+ (2010,2012); see also Dannerbauer+ (2009)

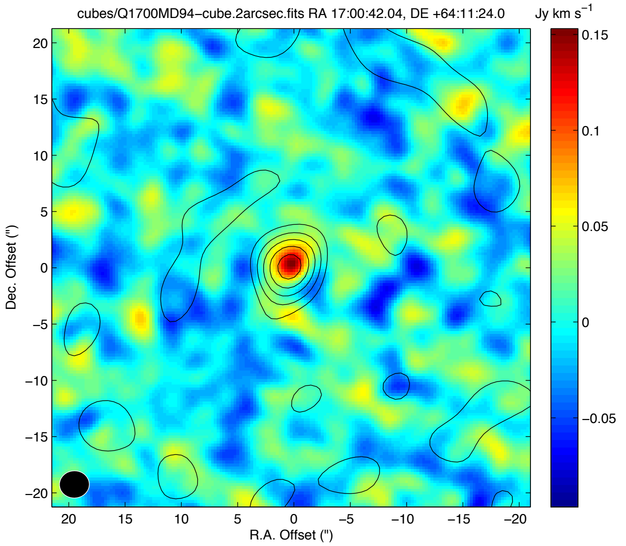


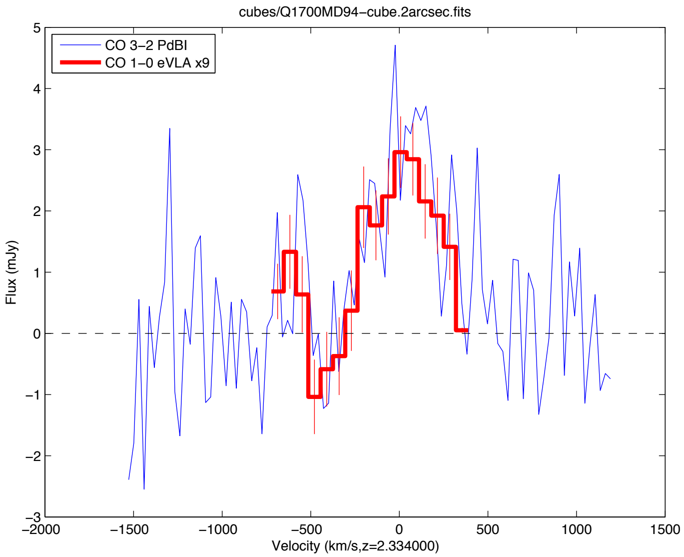
“Normal” Galaxies and Low J

- CO (1-0) at z~2.3 in K_a
- Lines are faint, very challenging even with JVLA
- S_{31}/S_{10}~9



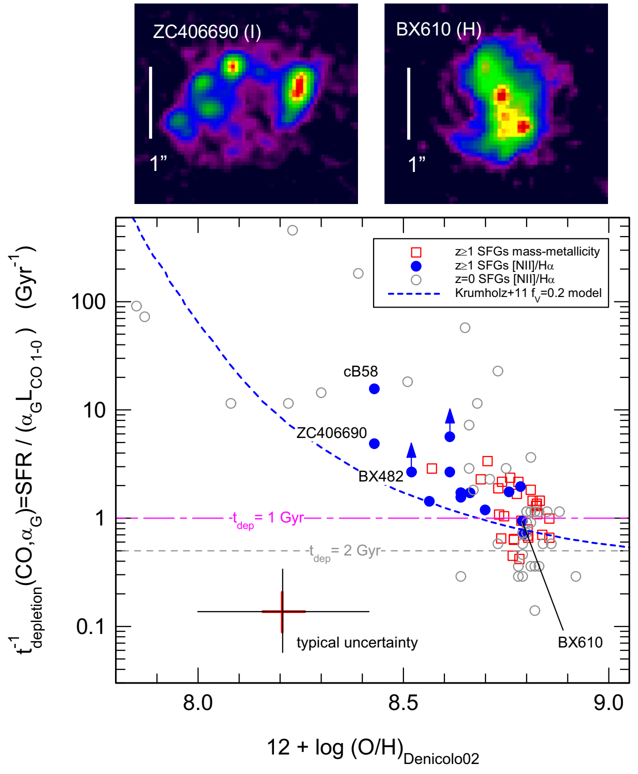
Bolatto, Leroy, Tacconi, Genzel, + (in prep.)

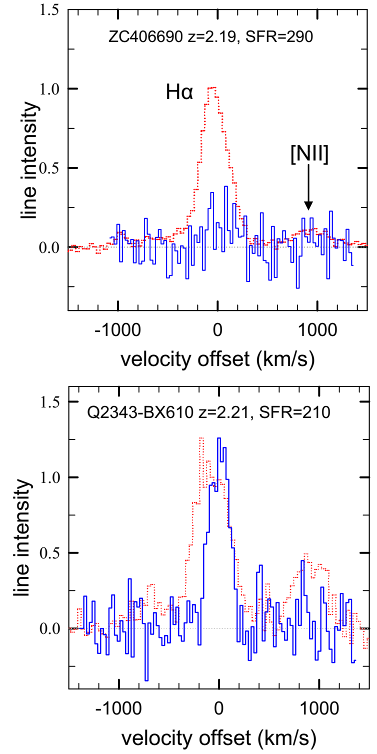


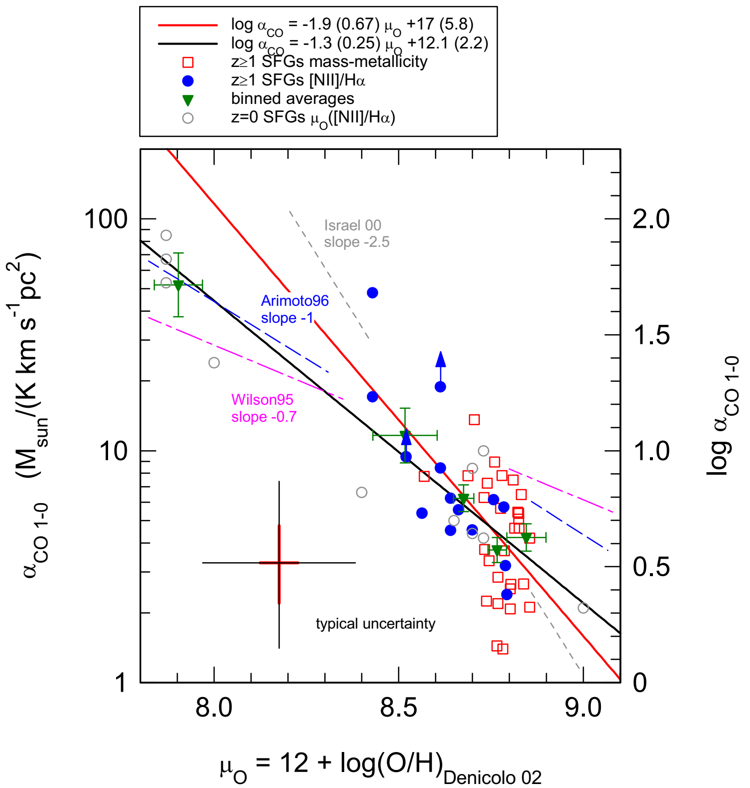


Metallicity Effects at High-z

- It's almost impossible to directly measure Xco at high redshifts
- But we can make an indirect argument, based on the link between $M(H_2)$ and SFR
- It suggests a steep $Z^{-1.9}$ - $Z^{-1.3}$ dependency, similar to the one from Leroy et al. (2011)

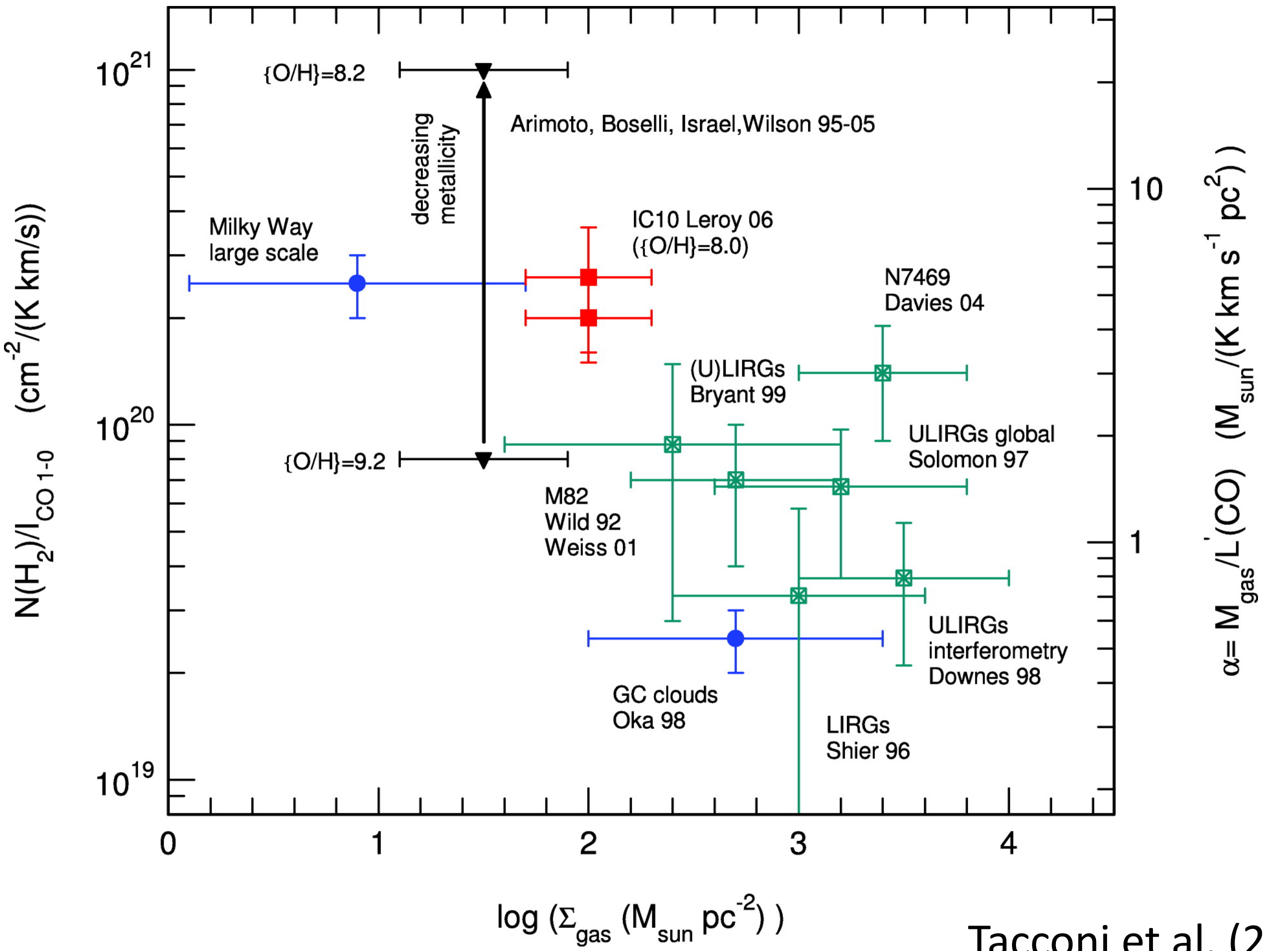






Genzel, Tacconi, Combes, et al. (2011)

Putting it all together



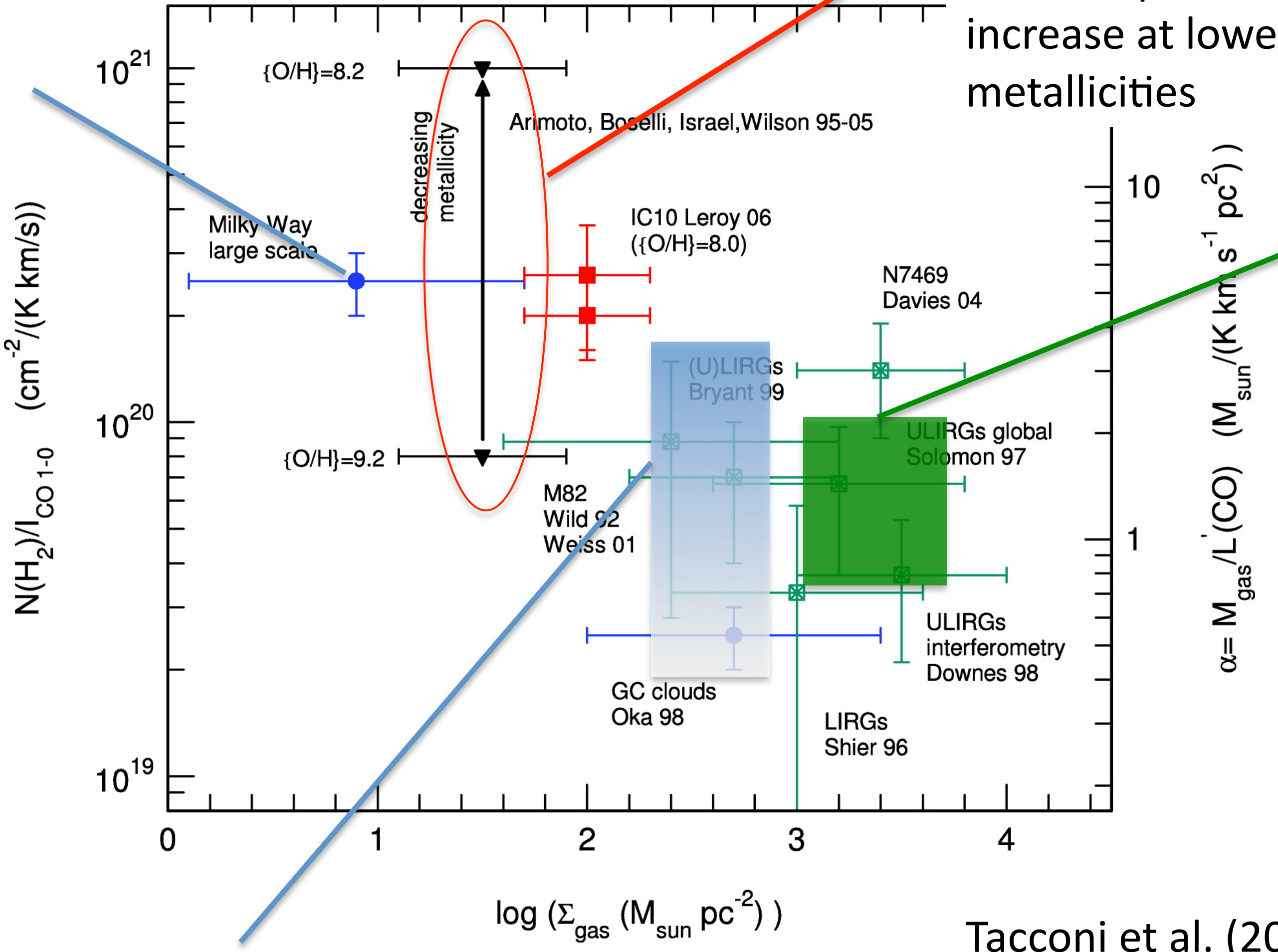
Tacconi et al. (2008)

Putting it all together

Gradients?

Probably “normal” to Z~0.5, expect sharp increase at lower metallicities

ULIRGs/SMGs



Tacconi et al. (2008)

Galaxy centers
Molecular outflows?

Summary

We know quite a bit about the CO-to-H_2 conversion factor

1. X_{CO} is more than a single number
   - it depends on the physical conditions
   - spatial scale is important (local vs. global)
2. Agreement for MW and other galaxy disks (within ~50%)
   - Gradient and outer disk values still open questions
3. Rapid increase for decreasing metallicity
   - Likely about MW up to Z~0.5 (12+log[O/H]~8.4)
4. But not just a function of metallicity
   - For example galactic centers, ULIRGs
   - Velocity dispersion, τ of medium, excitation, coupling to U
5. High-z frontier: dust/[CII] in resolved galaxy disks, low J observations, multi-transition modeling
6. Need to understand Z enrichment **and** dust creation in the cosmological context