How to Measure H_2 Formation?

Li, Heiles, Goldsmith, Dawson

+PRIMO
Tang, Nguyen, Xu, McClure-Griffith, Dickey, Yue, Stanimirovic, Murray, Dickey, Burton, Robishaw, Koo, Bronfmann, Mardones, Finger etc.

radio973.bao.ac.cn

Stars and Molecules

SF: Complex Processes involving gravity, radiation, turbulence, magnetic field, and feedback

- Chemical evolution
- Heating / cooling
- Environmental and Initial Conditions
- Gas accretion
- Energy dissipation

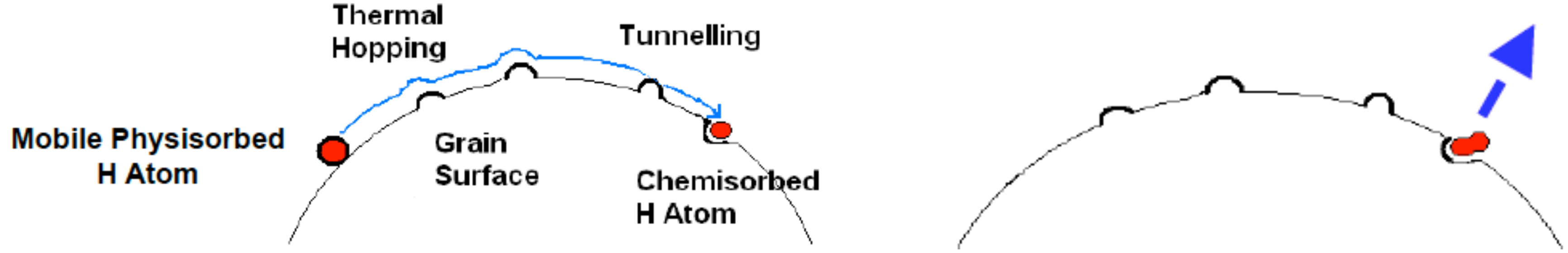
"I write about molecules with considerable diffidence, having not yet rid myself of the tradition that "atoms are physics, but molecules are chemistry。"

---A.S. Eddington， 1937

Formation of H_2

Formation on grains by one of various processes all of which depend on the grain surface area and the density of atomic H.

(1) An H atom hits and sticks to grain
(2) Another H atom does the same
(3) H atoms hop or tunnel around grain surface until find another
(4) Two H atoms form H_2 , then desorb from grain surface



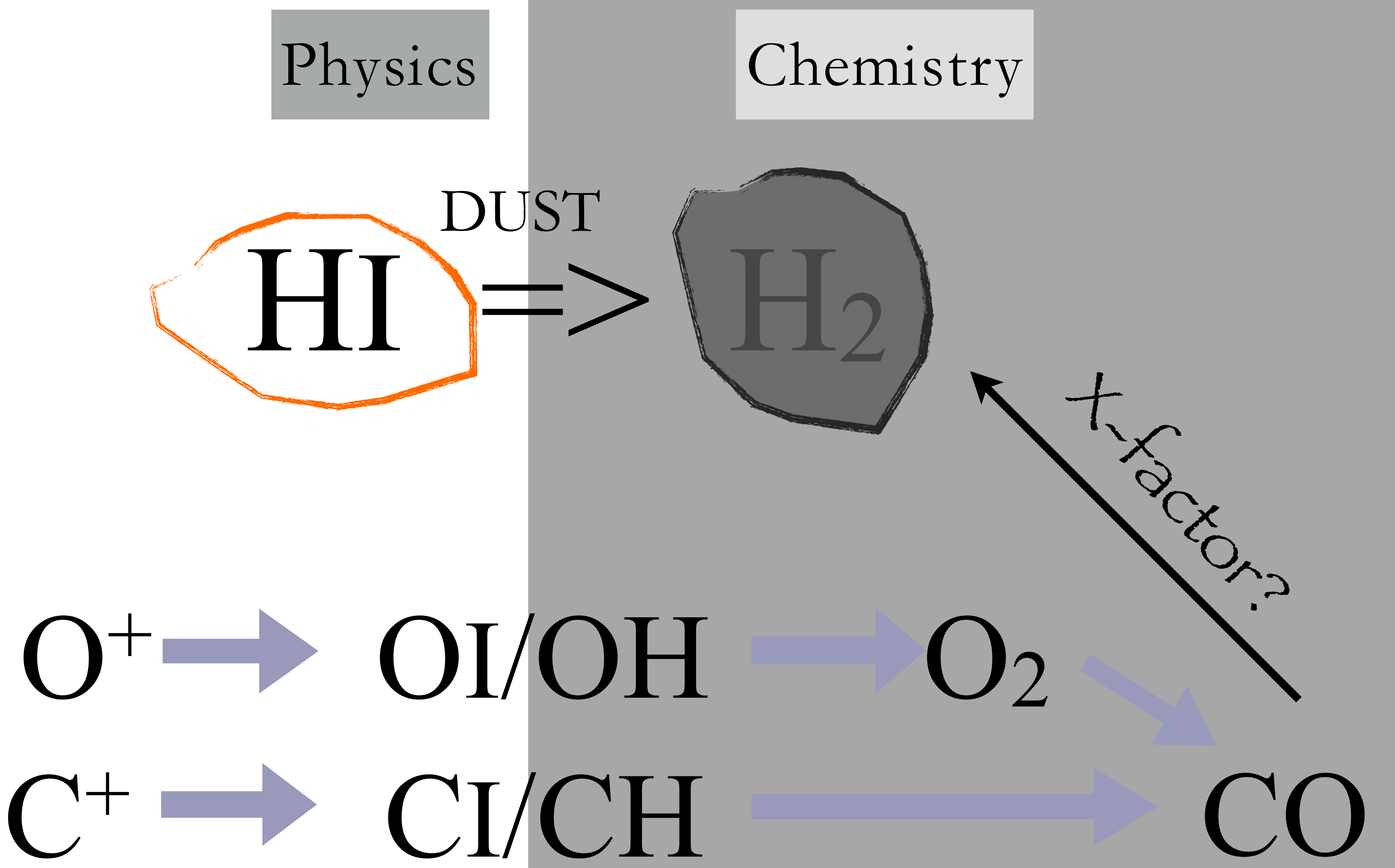
Destruction

(1) Cosmic rays rate $\zeta \sim 5\text{x}10^{-17}\ \text{s}^{-1}$ within well-shielded regions, though may be greater at cloud edges/diffuse clouds

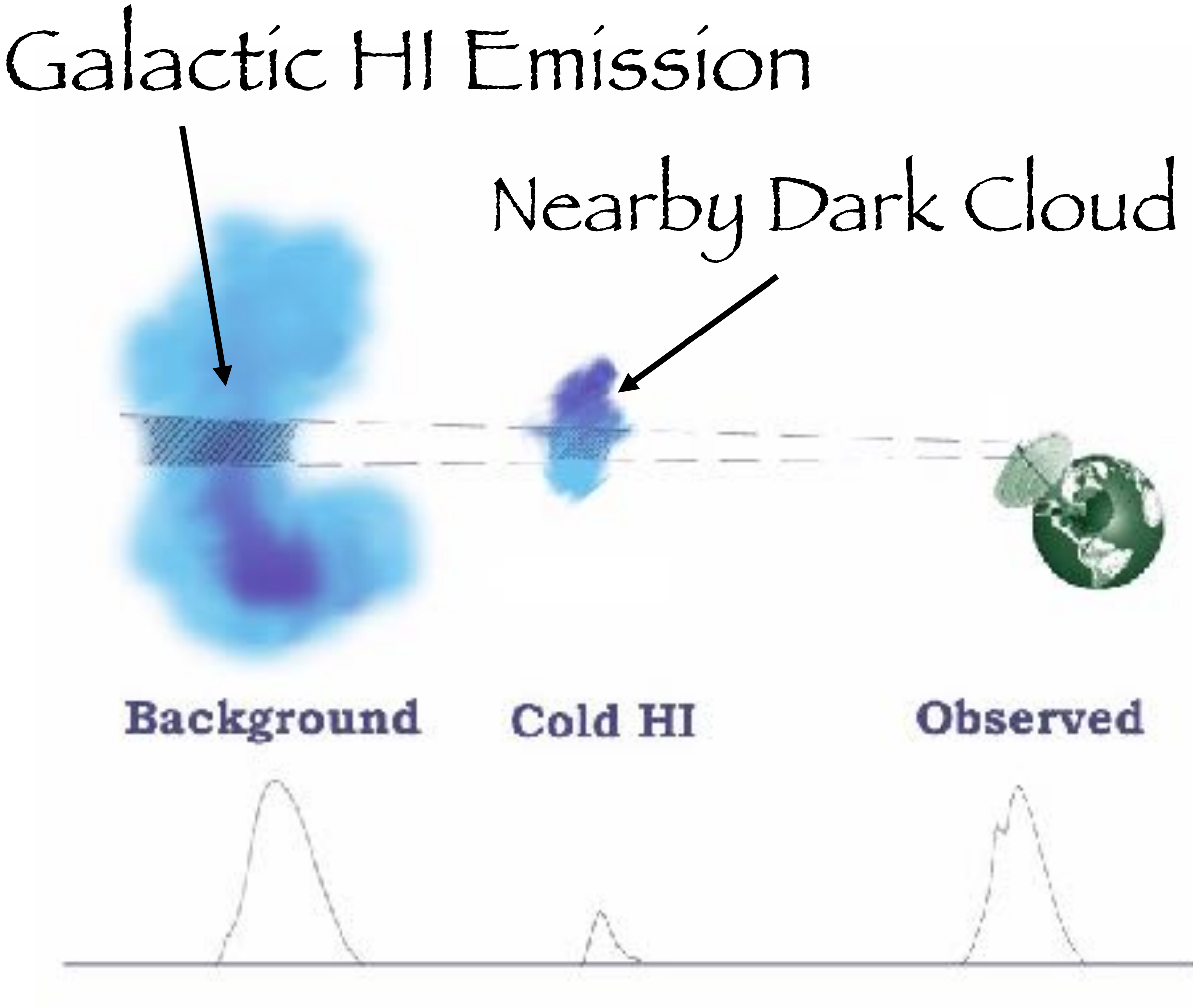
(2) UV at cloud edges and in translucent/diffuse clouds. Critical parameters are the UV enhancement relative to ISRF and the total H column density. The latter is critical due to self-shielding.

H_2 Formation time scale ~ $10^9/n_H$

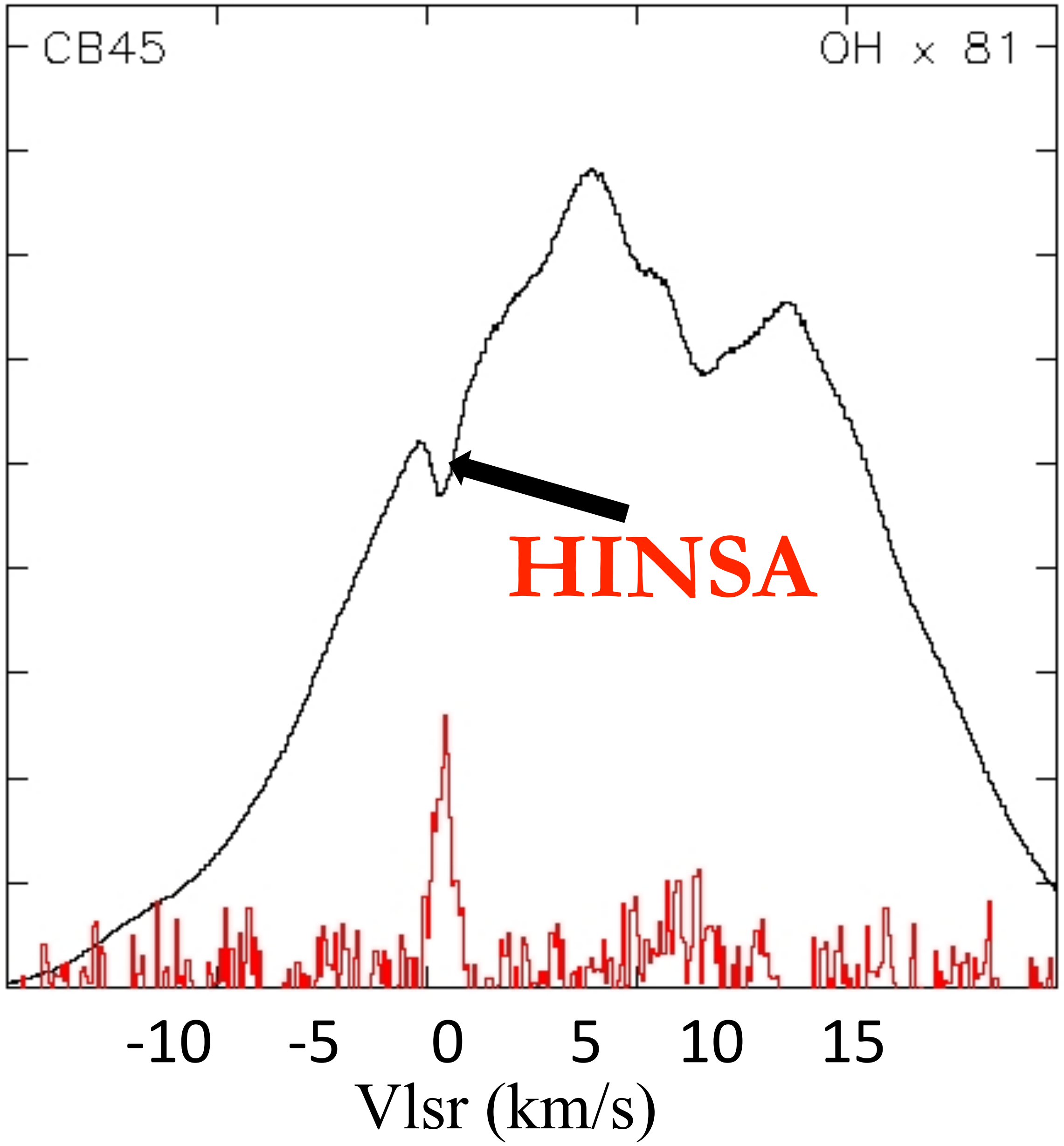
ISM Evolution



HINSA Reveals Cold HI

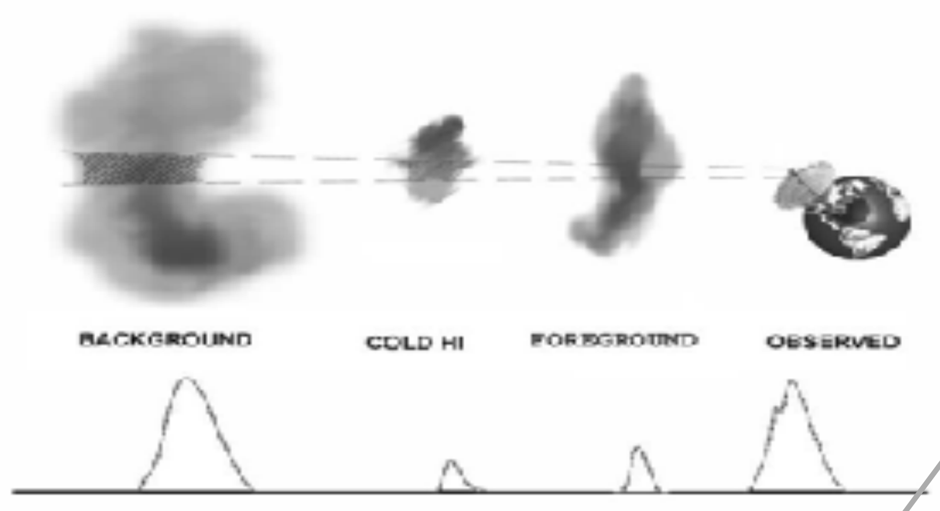


Li & Goldsmith 2003, ApJ

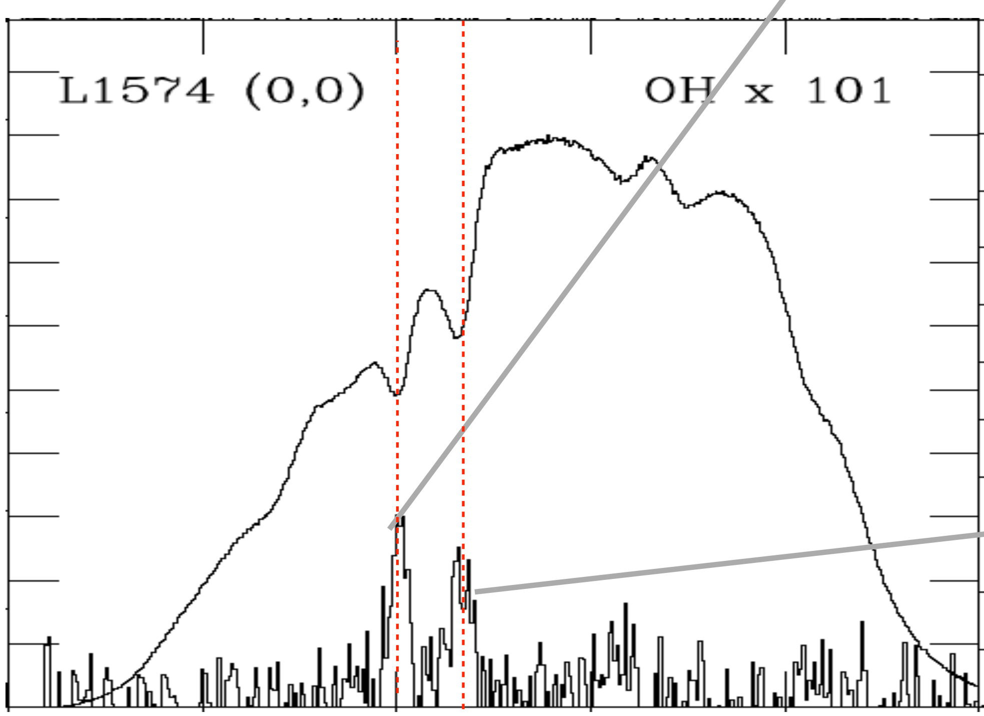


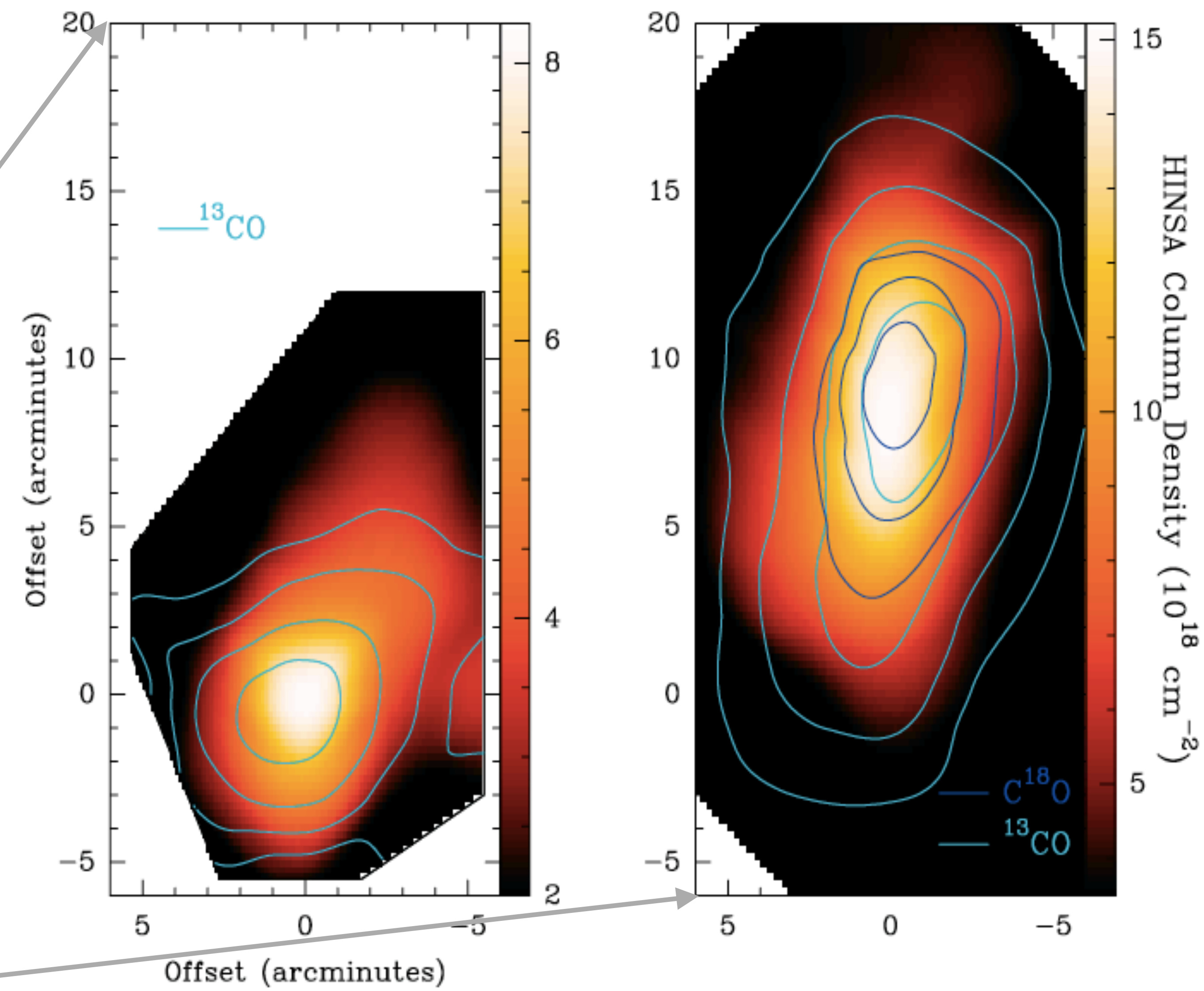
HI Narrow Self Absorption

2 in 1
HI Narrow Self-Absorption



Li & Goldsmith 2003





Goldsmith & **Li** 2005
Goldsmith, **Li** & Krco 2007

Molecular Cloud Formation

- H_2 Formation On Dust Grains
  Production rate ($s^{-1}cm^{-3}$)

$$R_{H_2} = \frac{1}{2} n_g n_1 \sigma v S \eta$$

$$R_{H2} = 2.1\times10^{-18} n n_1 \sqrt{T}$$

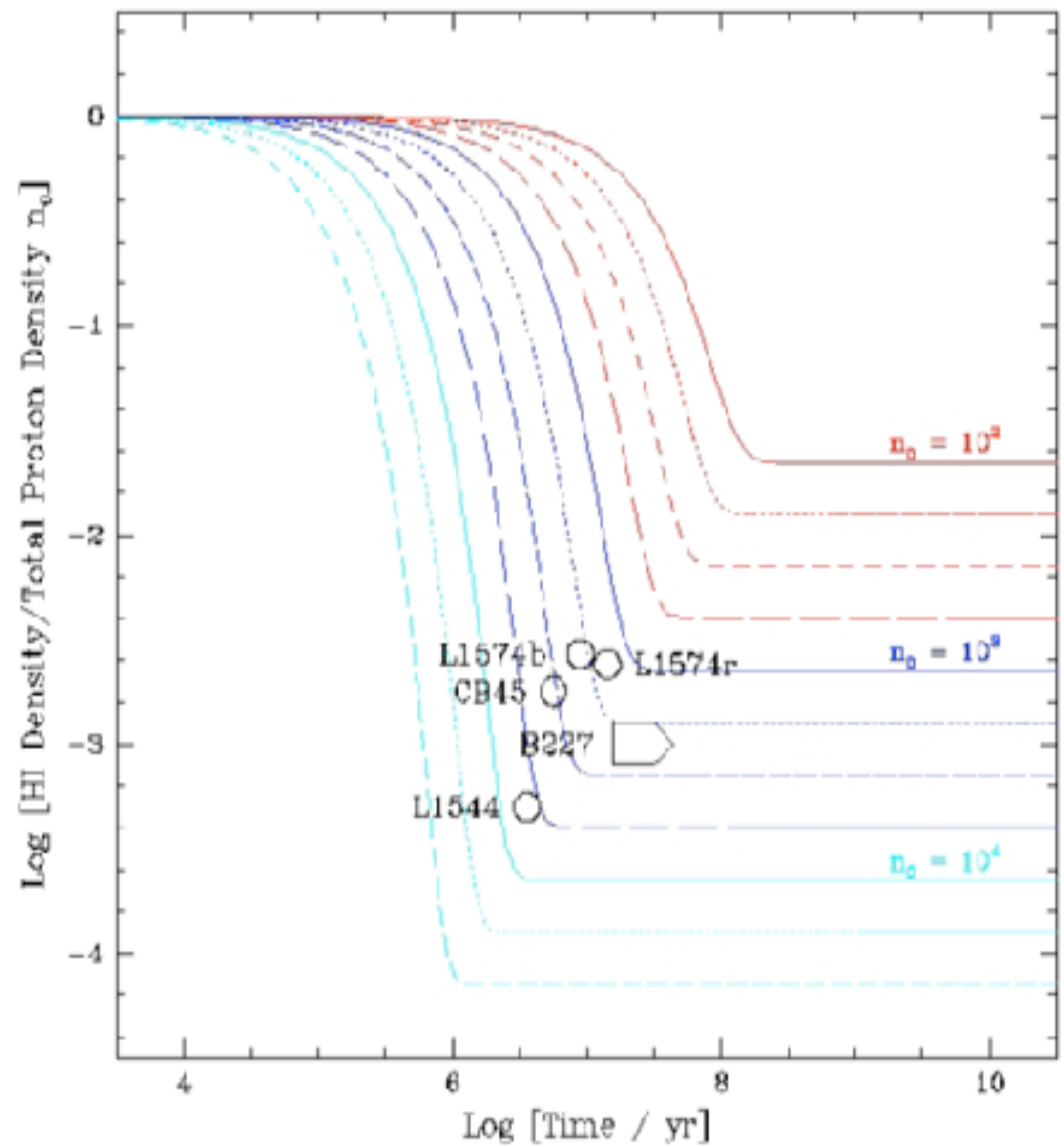
Hollenbach & Salpeter 1970; Buch & Zhang 1991

- H_2 Dissociation By Cosmic Rays
  Destruction Rate($cm^{-3}\ s^{-1}$)

$$D_{H_2} = \xi n_2,$$

where $\xi \approx 3\times10^{-17} s^{-1}$

is the cosmic ray ionization rate.

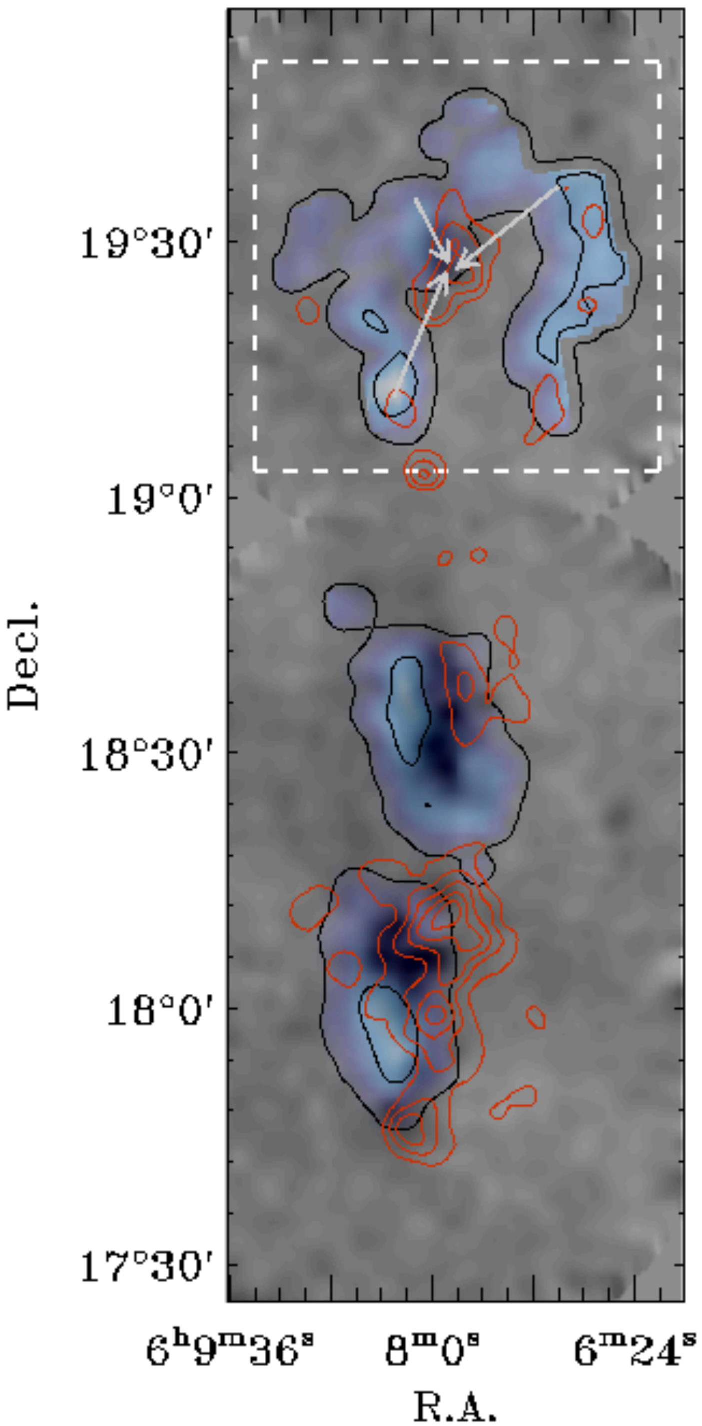


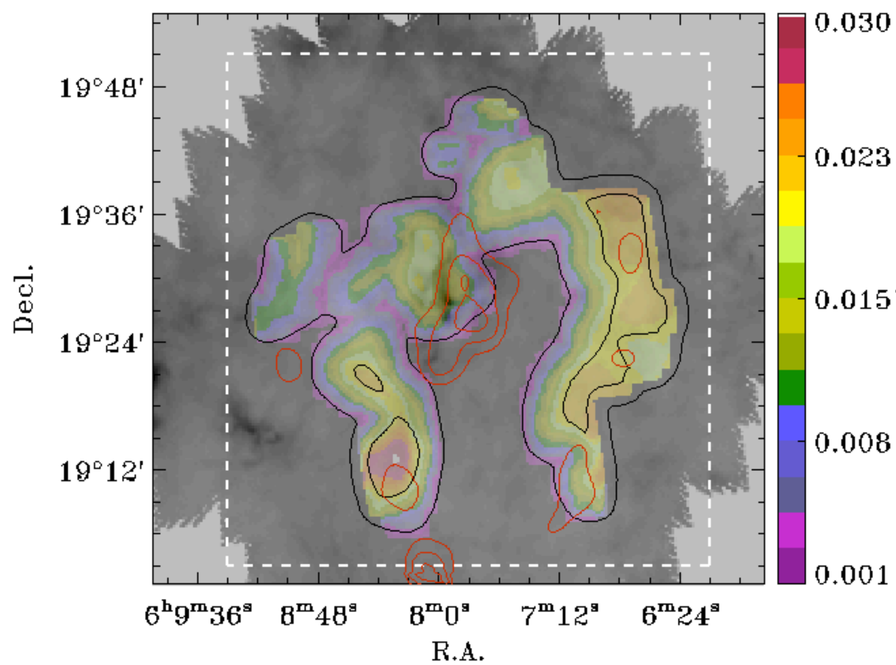
Goldsmith and **Li** 2005 ApJ

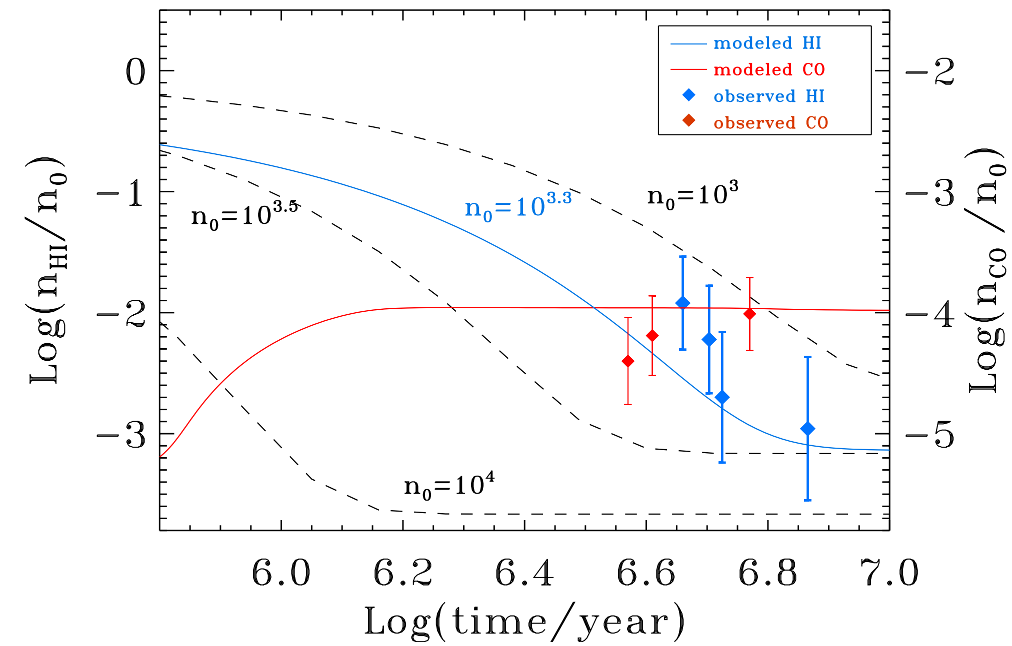
Dark Cloud Age> 10Myr

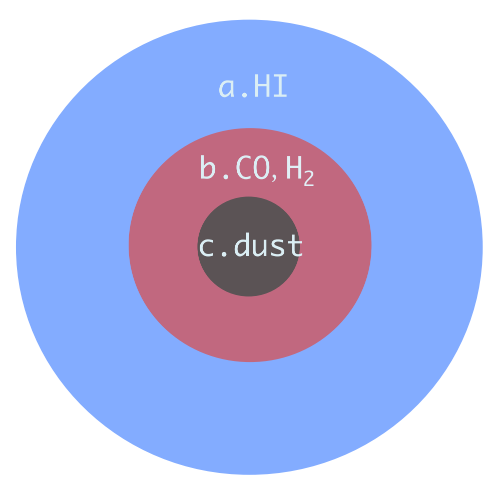
Confirming the Classical Picture of H_2 Formation in A Young Dark Cloud

Zuo, Li, Peek et al. 2017 submitted









$$R_{H_2} = 2\times 10^{-18} n(H) n(HI)\sqrt{T}$$

$$D_{H_2} = \zeta n(H_2)$$

$$[HI]/[H_2]: 0.2\% - 2\%$$

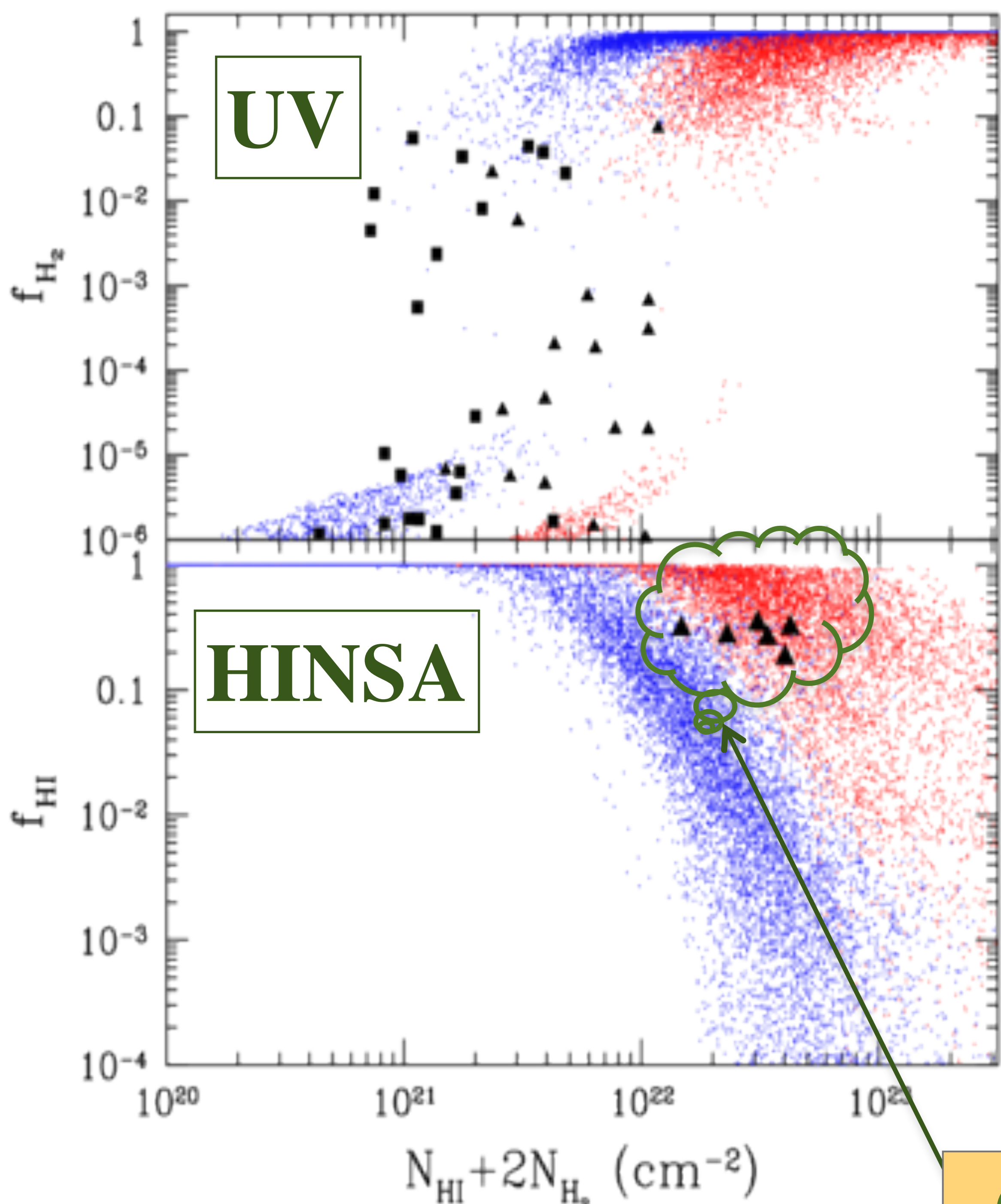
$$Timescale: 5\times 10^{6}\, yrs$$

Herschel OT1 Program: **Li (PI)**
\+ Arecibo +FCRAO +Delinha +2Mass

HINSA Constrains

Cosmological Simulations

ΛCDM+H_2 formation



Gnedin & Kravtsov 2010

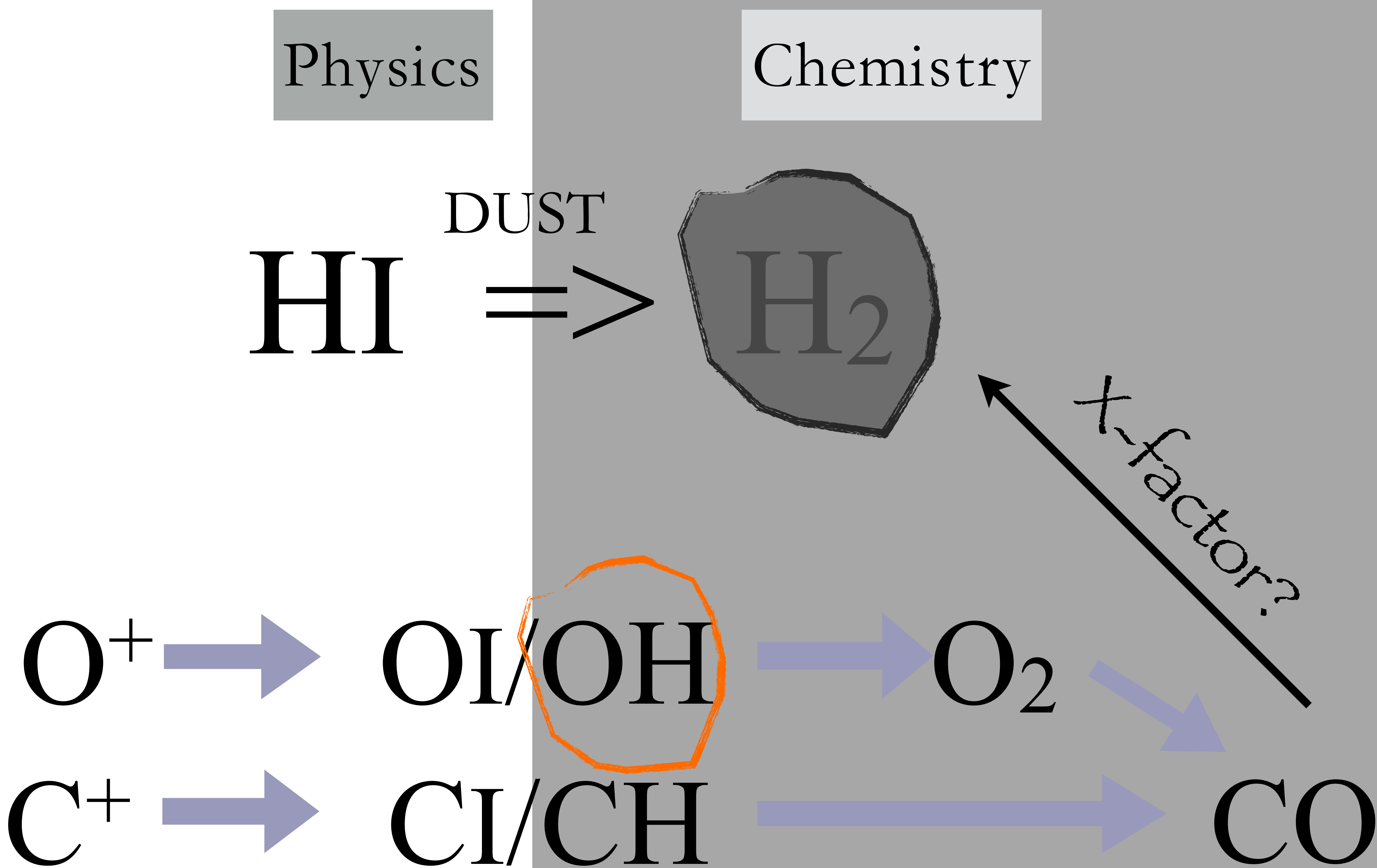
"The Impact of Baryon Physics on the Structure of High-redshift Galaxies"

Zemp et al. 2012

- Li & Goldsmith et al. 2003 ApJ
- Goldsmith & Li et al. 2005 ApJ
  cited as a "robust clock" by McKee & Ostriker ***ARA&A*** 2007
- Goldsmith, Velusamy & Li et al. 2010 ApJ
  selected as the astronomy highlight on the June 2010 NATURE
- Goldsmith, Marko & Li 2007 ApJ
- Krco & Goldsmith 2016 ApJ
- Zuo, Li, Peek+ 2017 submitted

Goldsmith & **Li** 2005

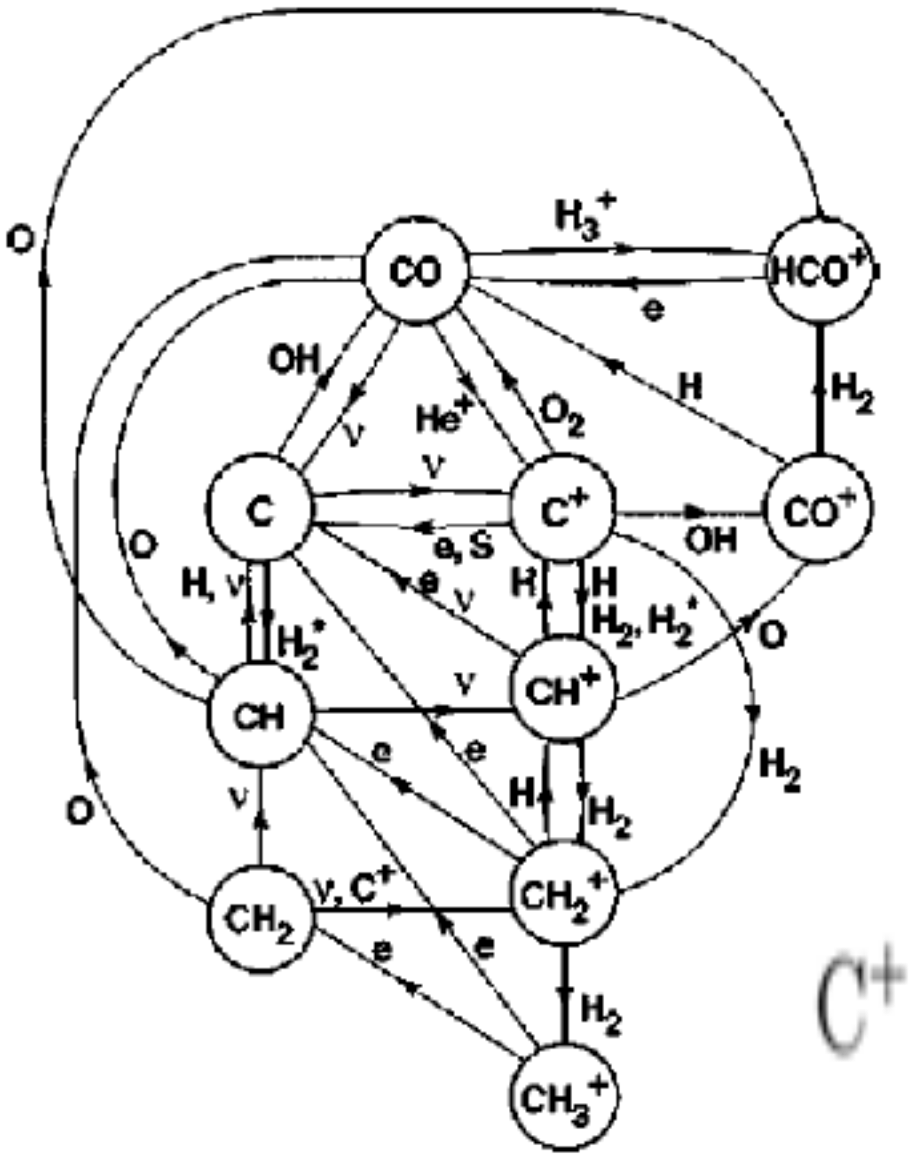
ISM Evolution



The Start of the "Chain"

HI + Dust => H_2

Tielens 2007 **Lucas and Liszt 1996**



$$H_2 + cosmicray \rightarrow H_2^+ + e^-$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

$$H_3^+ + O \rightarrow H_2 + OH^+$$

$$OH^+ + H_2 \rightarrow OH_2^+ + H$$

$$OH_2^+ + H_2 \rightarrow H_3O^+ + H$$

$$H_3O^+ + e^- \rightarrow OH + H_2$$

$$C^+ + OH \rightarrow CO^+ + H \quad ; \quad CO^+ + H_2 \rightarrow HCO^+ + H$$

Dark Molecular Gas (DMG)

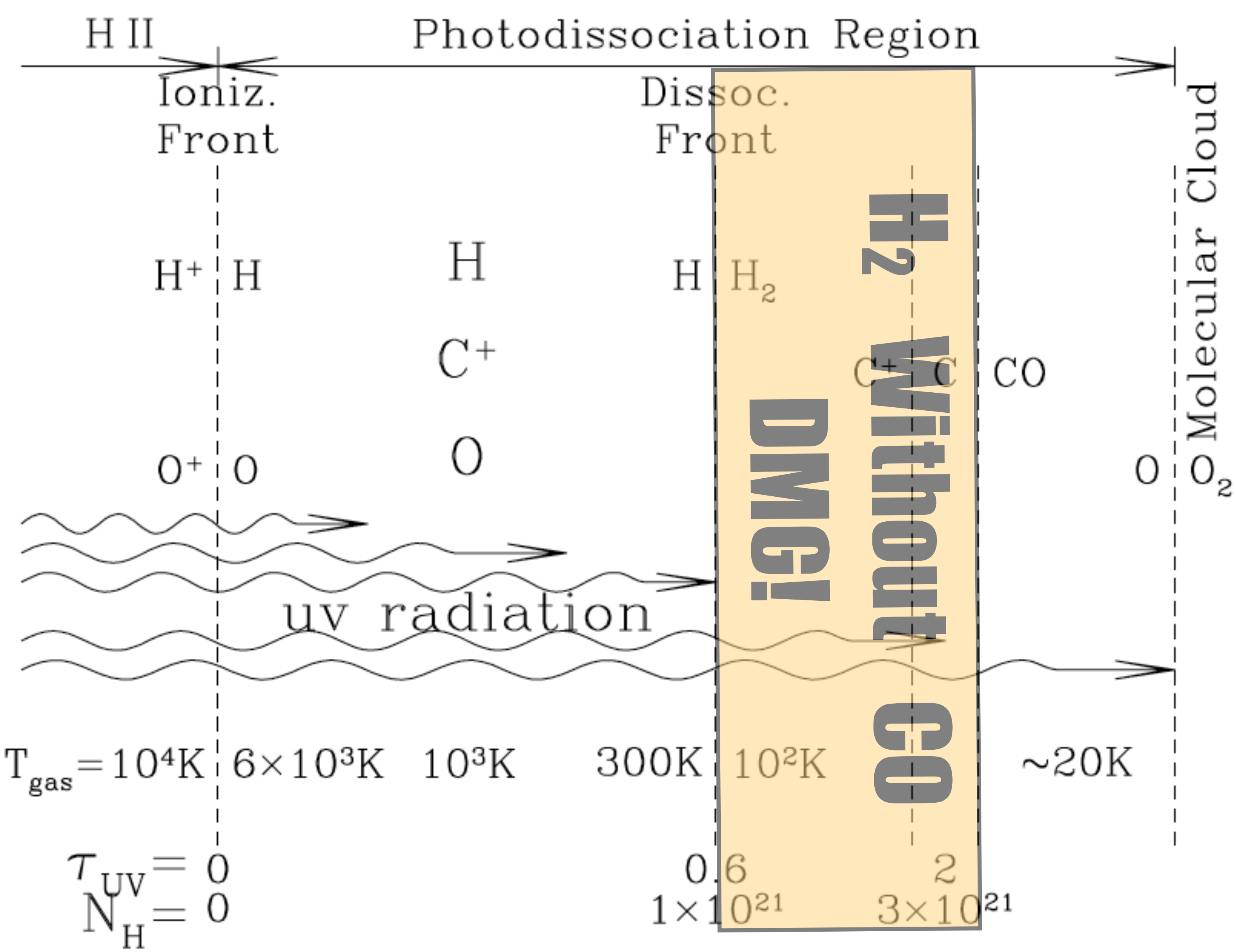
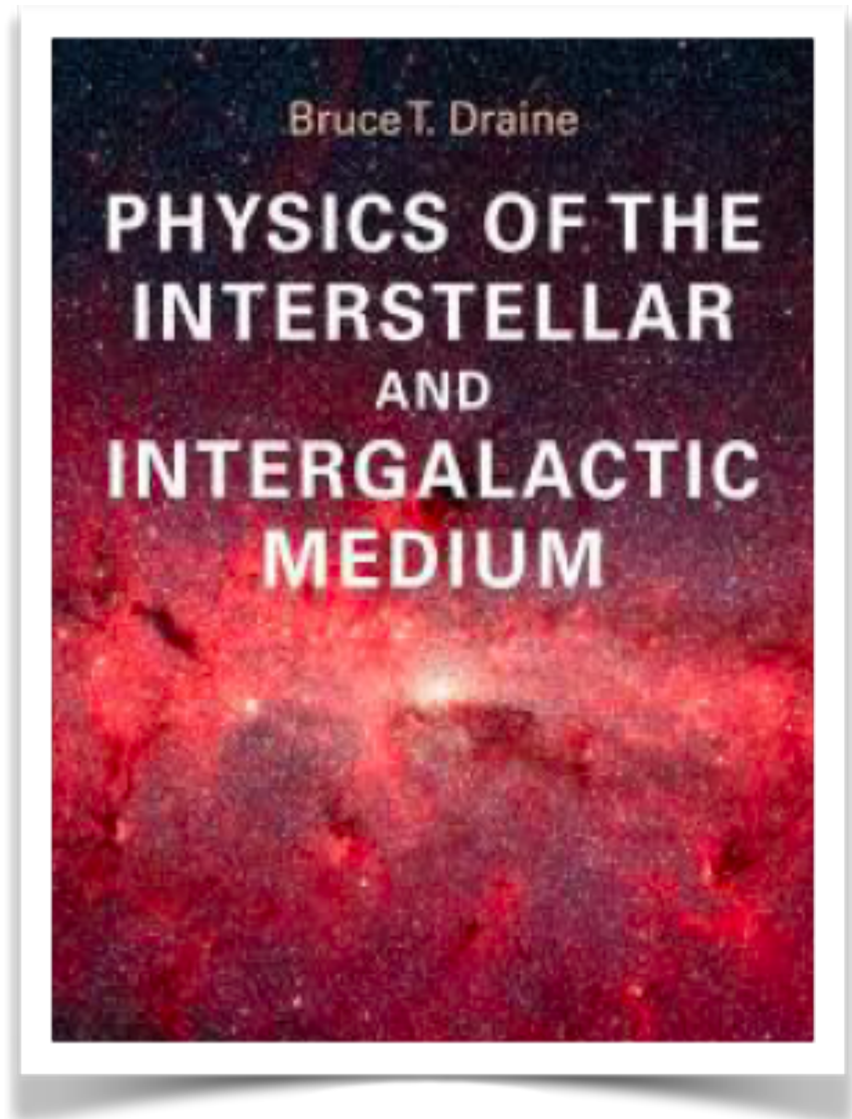


Figure 31.2 Structure of a PDR at the interface between an H II region and a dense molecular cloud.

the prevalence of C^+



PDR
Schematic Diagram

“Missing” OH?

A SEARCH FOR THERMAL HYDROXYL EMISSION IN NEARBY GALAXIES

Emisson $T_A = [T_x - T_{bg}](1 - e^{-\tau})$

Absorption $T_{ab} = T_C - T_A$

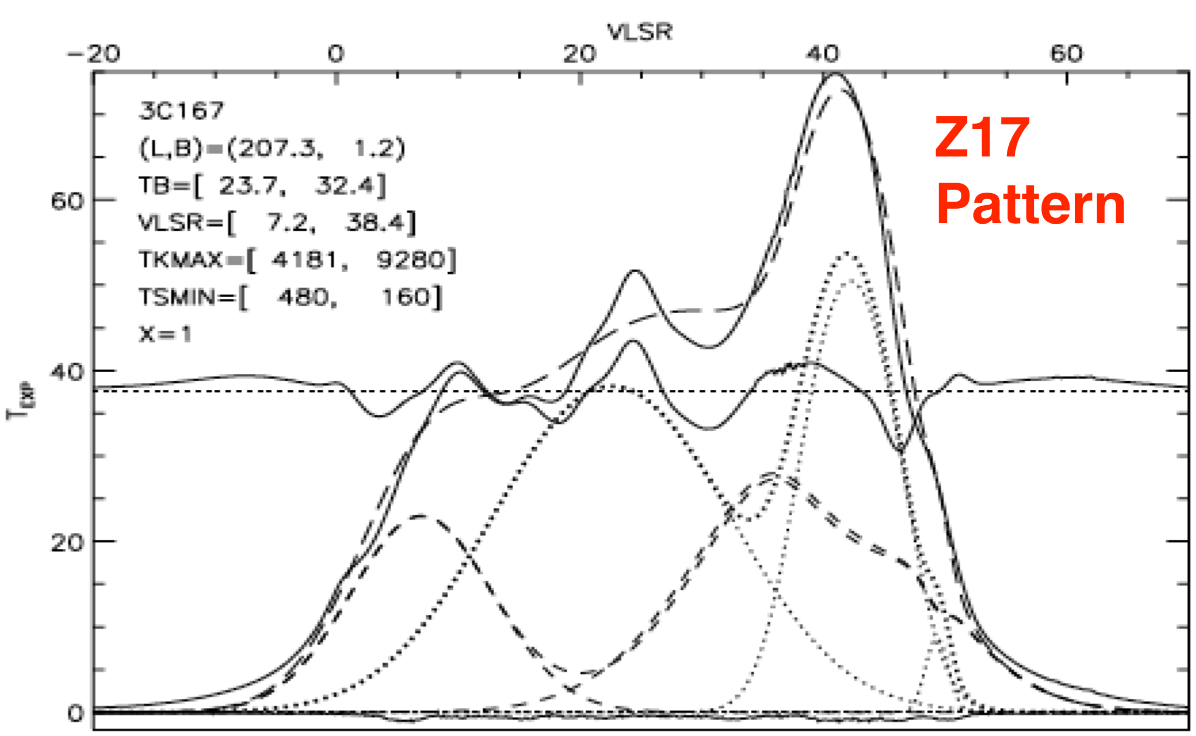
$= [T_C - T_x](1 - e^{-\tau})$

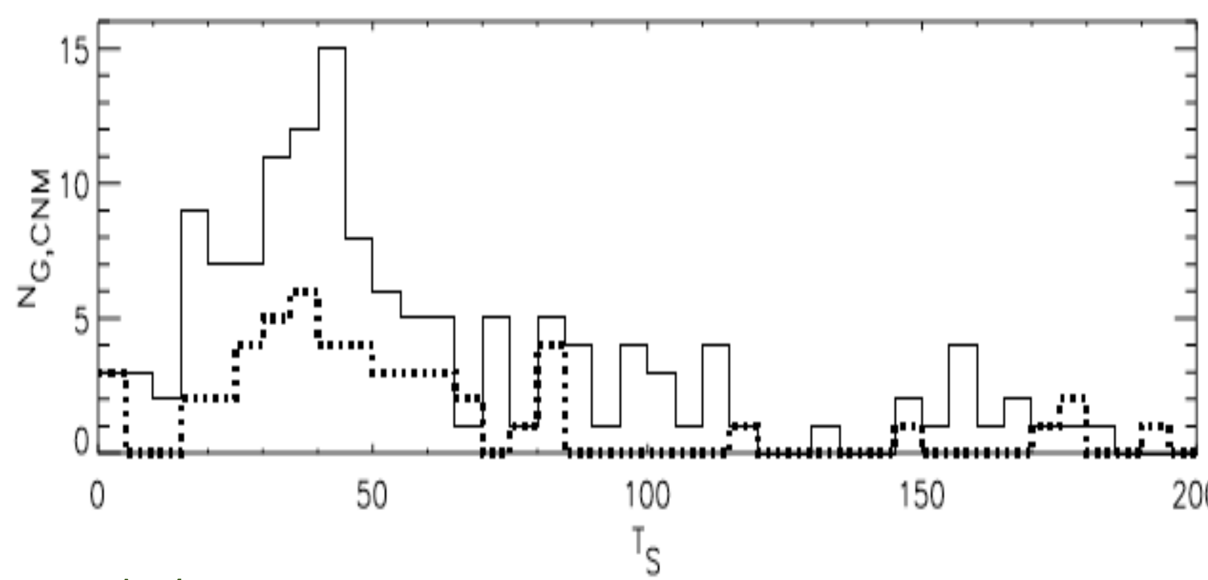
J. T. Schmelz
Applied Research Corporation, 8201 Corporate Drive, Landover, Maryland 20785
W. A. Baan
Arecibo Observatory,[a] P.O. Box 995, Arecibo, Puerto Rico 00613

Received 5 August 1987; revised 24 November 1987

ABSTRACT

A survey of 63 nearby spiral galaxies for hydroxyl emission has been completed using the 305 m telescope of the Arecibo Observatory. We were hoping to detect the main lines at 1667 and 1665 MHz in LTE emission as observed in dark clouds and most GMCs in our own galaxy. No OH emission was detected, but limits have been set on the OH column densities of these galaxies.





The “Millennium Survey”
Heiles & Troland 2003

PRIMO
Pacific Rim Interstellar Matter Observers

PRIMO

2015**年创建**“环太平洋暗气体探测”
国际合作团队

Arecibo, VLA, ATCA, ALMA

国际团队计划FAST观测
扩大样本数量x10倍

FAST: 800 quasars in 5 years

设于国家天文台的合作团队主页

Publication:

1. **Li** et al. 2015, *Quantifying Dark Gas, PKAS*
2, Tang, **Li***, Heiles et al. 2016 A&A, *Physical Properties of CO-dark Molecular Gas Traced by C^+*
3. Tang, **Li*** … Dawson et al. 2016 ApJ, *Pilot OH Survey along Sightlines of Galactic Observations of Terahertz C+*
4. Xu, **Li** *, Yue, N. & Goldsmith, P. F. 2016, ApJ *"Evolution of OH and CO-Dark Molecular Gas Fraction across a Molecular Cloud Boundary in Taurus"*
5. **Li**, Tang, Dawson, Heiles, McClure-Griffitth and PRIMO 2017 in prep., *Does OH Absorption Traces Dark Molecular Gas (DMG)?*

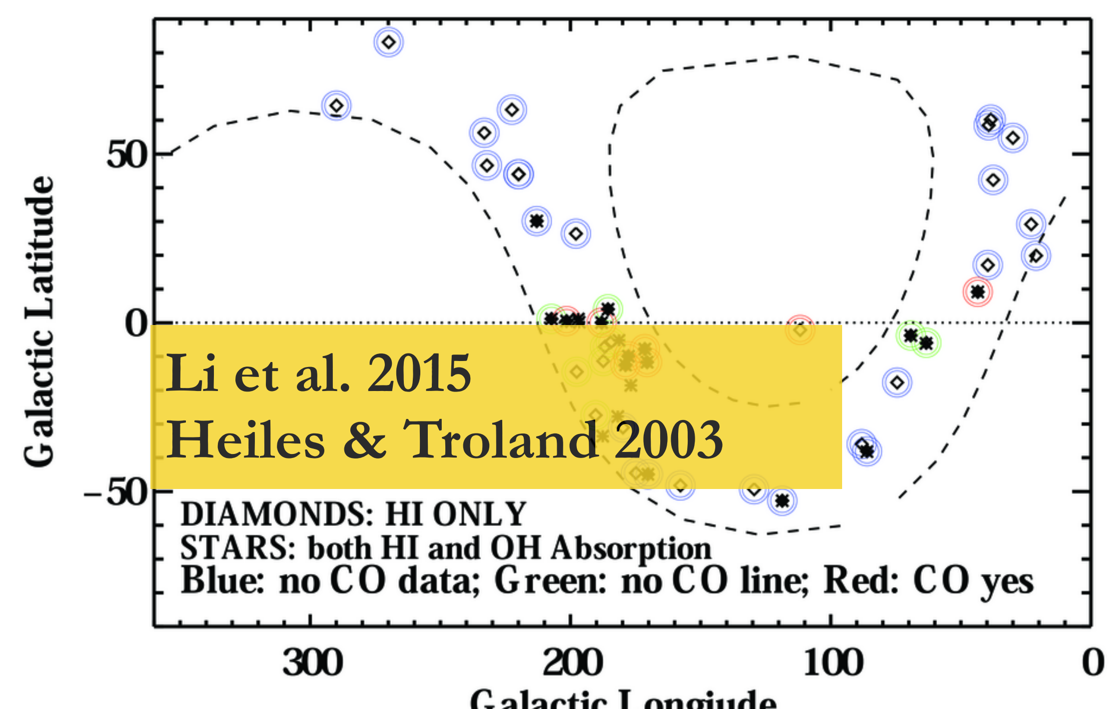
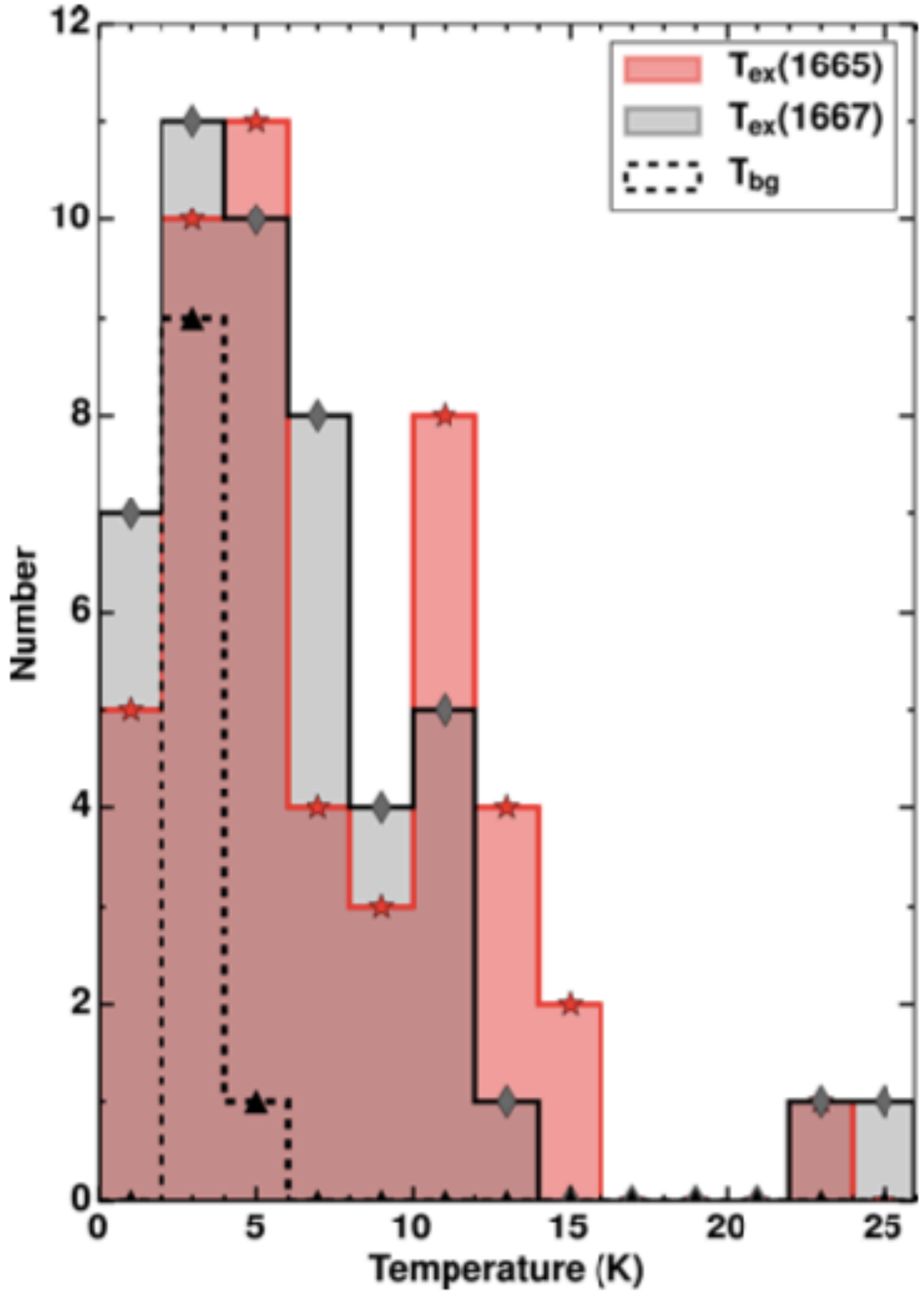
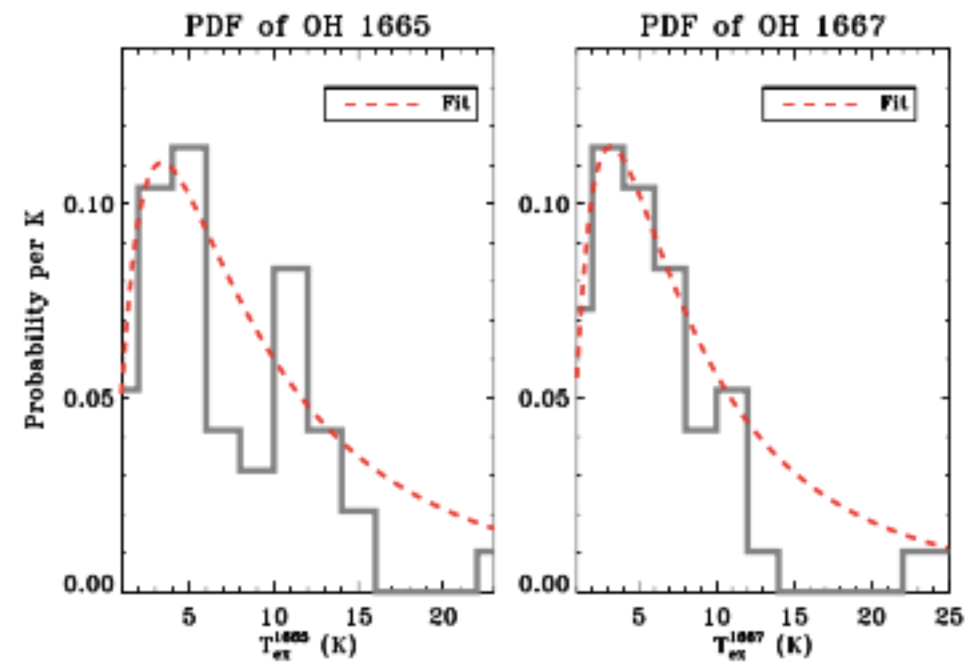


Fig. 5.— Map of sources observed in the Millennium survey. Diamonds are sources showing HI absorption

OH Excitation





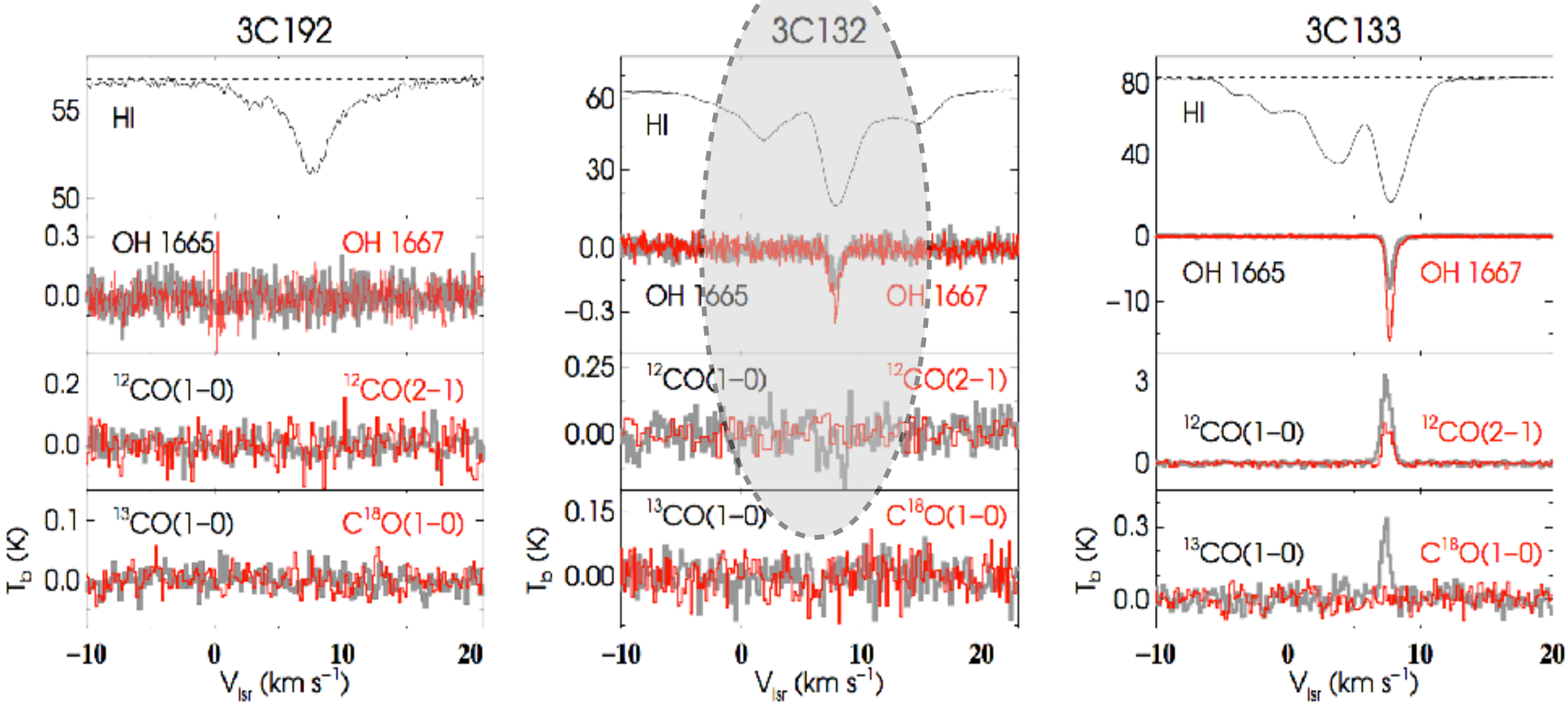
$$f(T_{\rm ex}) \propto \frac{1}{\sqrt{2\pi}\sigma}\exp[-\frac{[\ln(T_{\rm ex}) - \ln(3.4\ {\rm K})]^2}{2\sigma^2}]$$

Line	Fitted T_{ex}^{0} [a]	Fitted σ [a]
OH 1665	3.4	0.98
OH 1667	3.2	0.96
OH average	3.3	0.97

Li, Tang, Nguyen, Dawson, +**PRIMO** 2017

Dark Gas Probe: **HI+OH+CO**

Li, Tang, Nguyen, Dawson, +**PRIMO** 2017

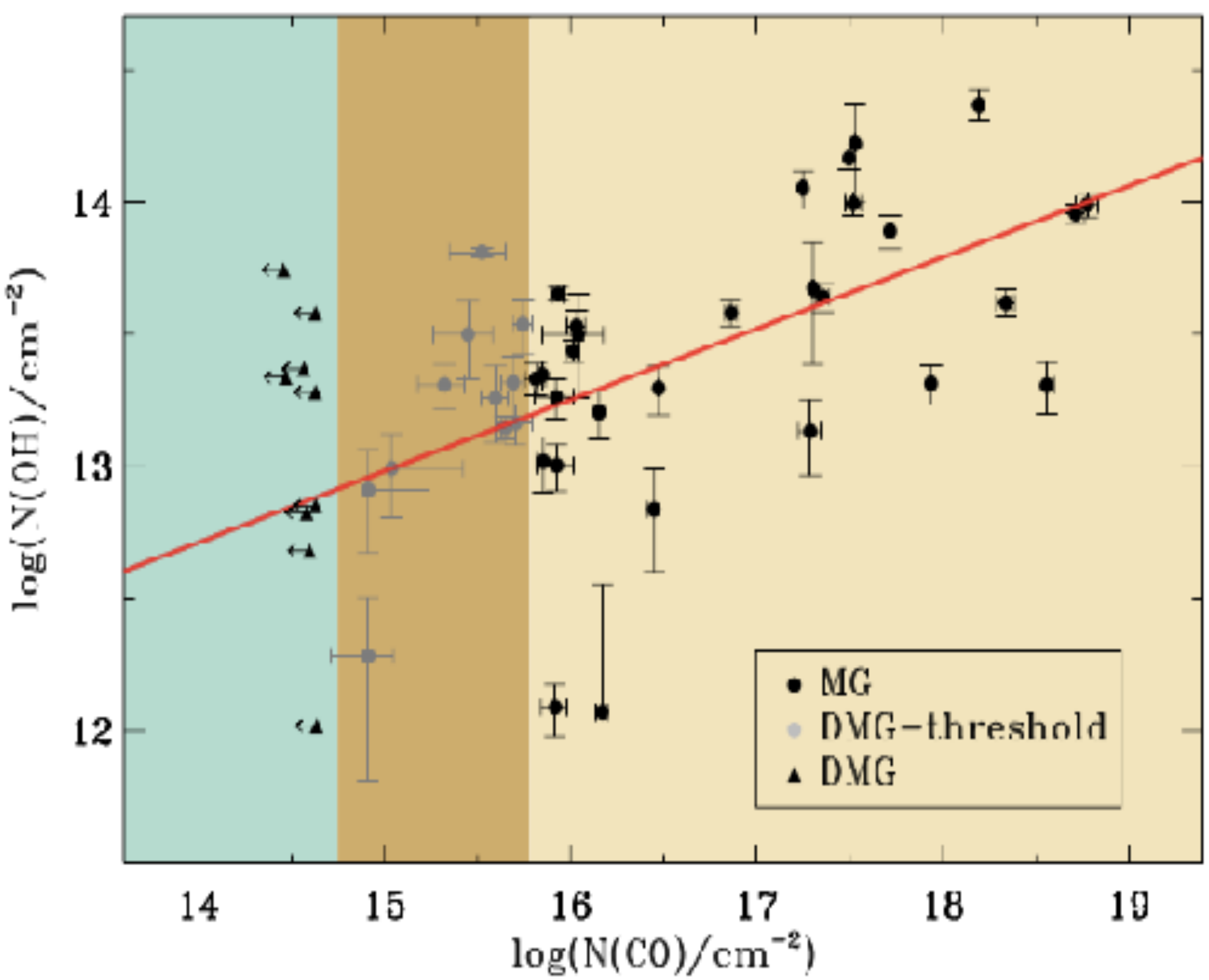


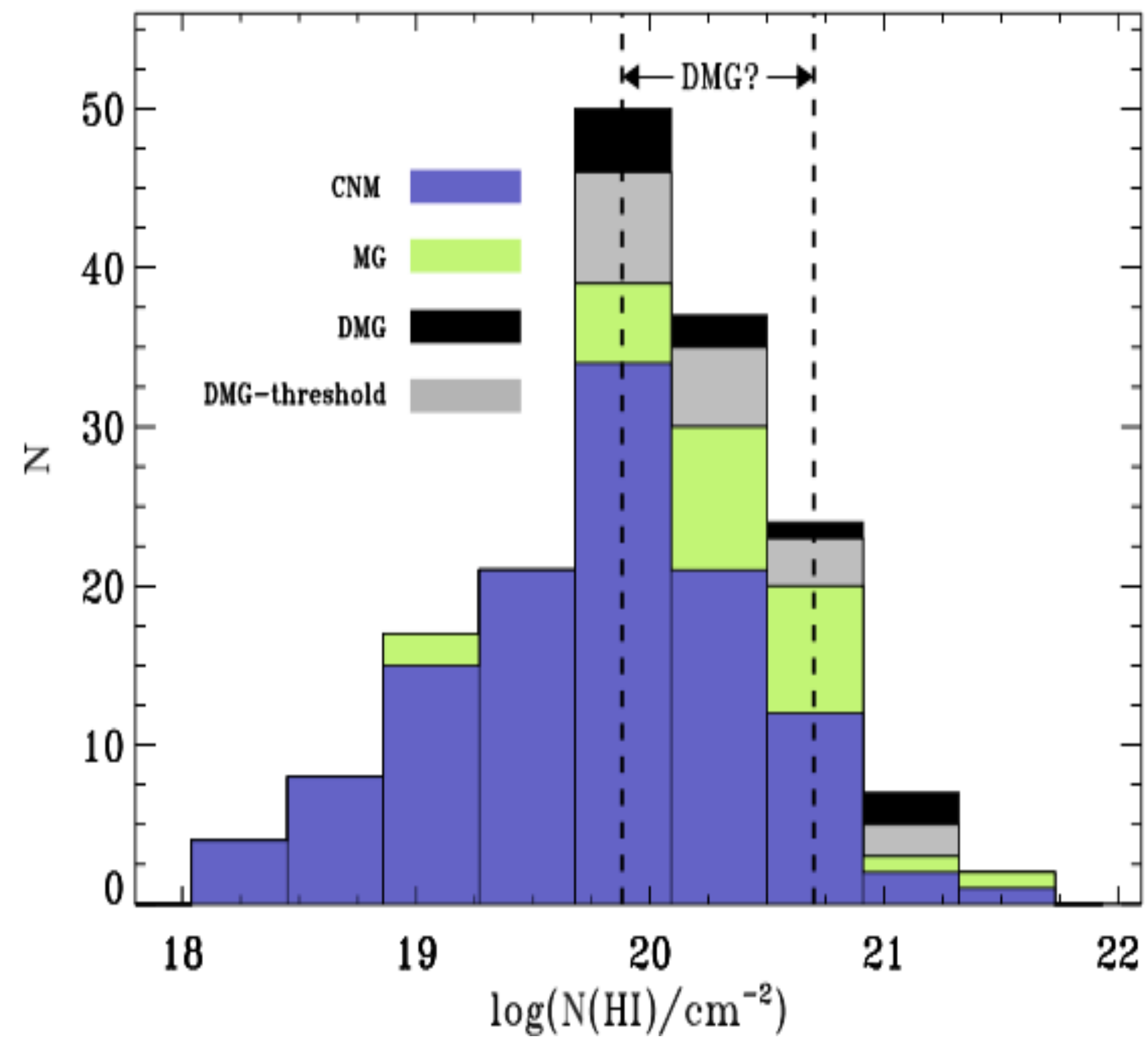
CNM

Dark Gas (DMG)

Molecular Cloud

DMG Statistics





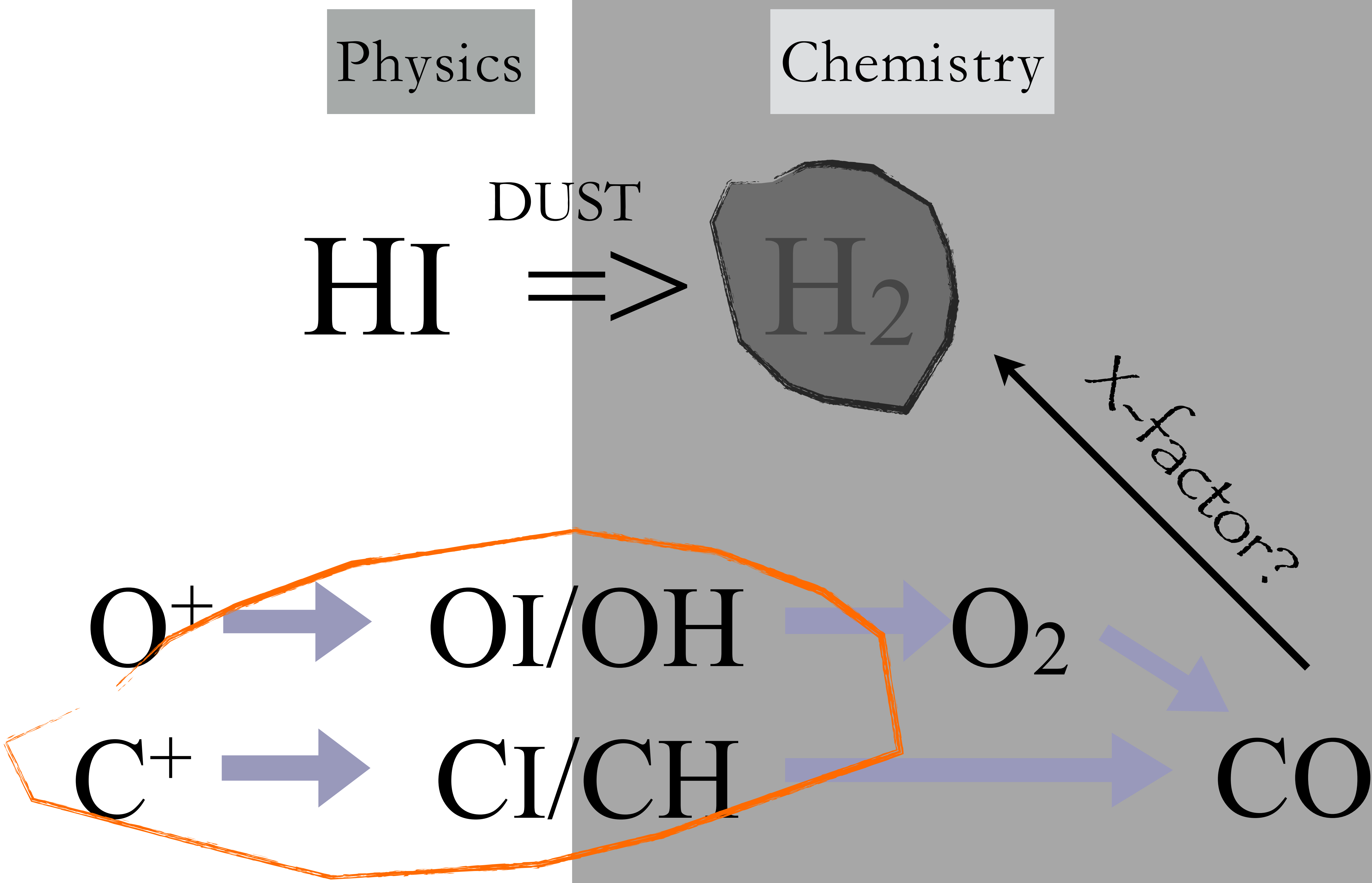
DMG Tex=10 K, 2*sigma rms in units of K km/s (0.14 K per 0.16 km/s FWHM=1.0 km/s

DMG-threshold darkgas-threshold: clouds that is less than 2*sigma rms (=0.5 K*0.65 km/s) in CFA CO survey

"Textbook" example of the HI-H_2 transition zone chemistry.

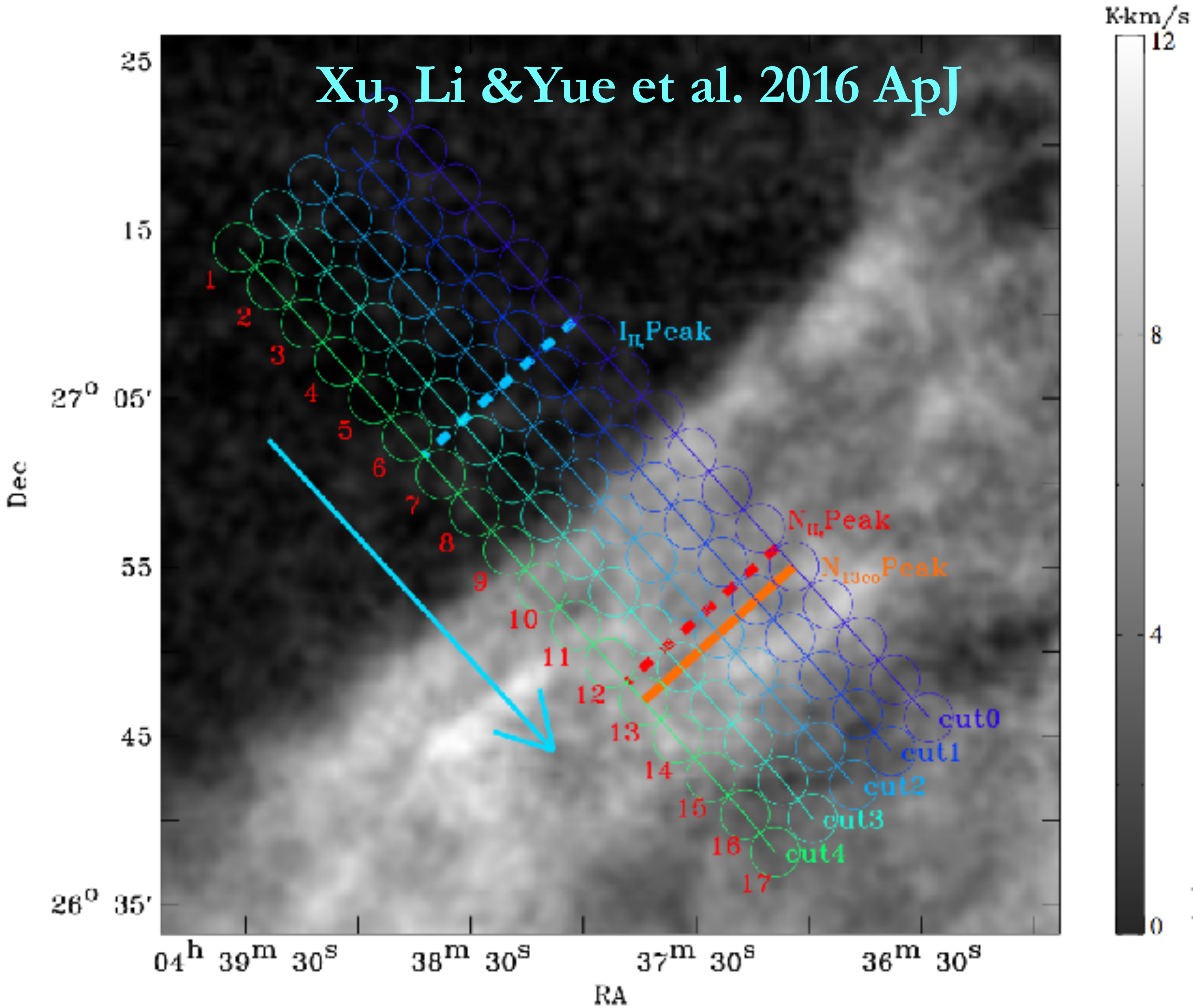
Li, Tang, Nguyen, Dawson, +**PRIMO** (2017)

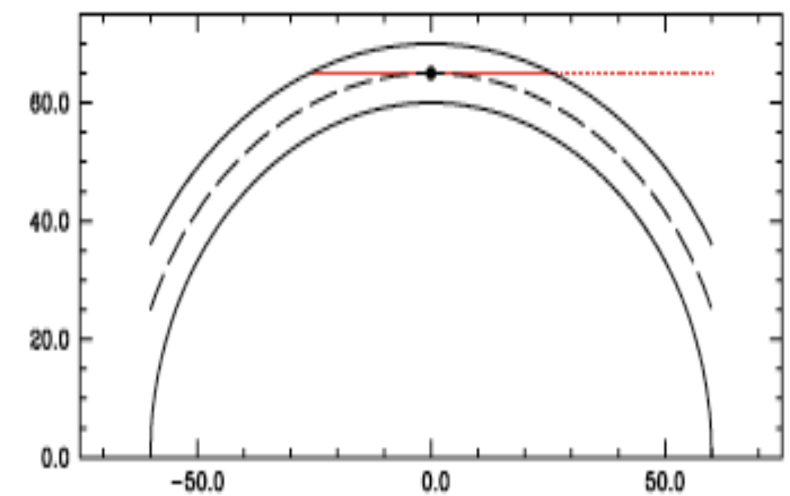
ISM Evolution



Taurus Edge

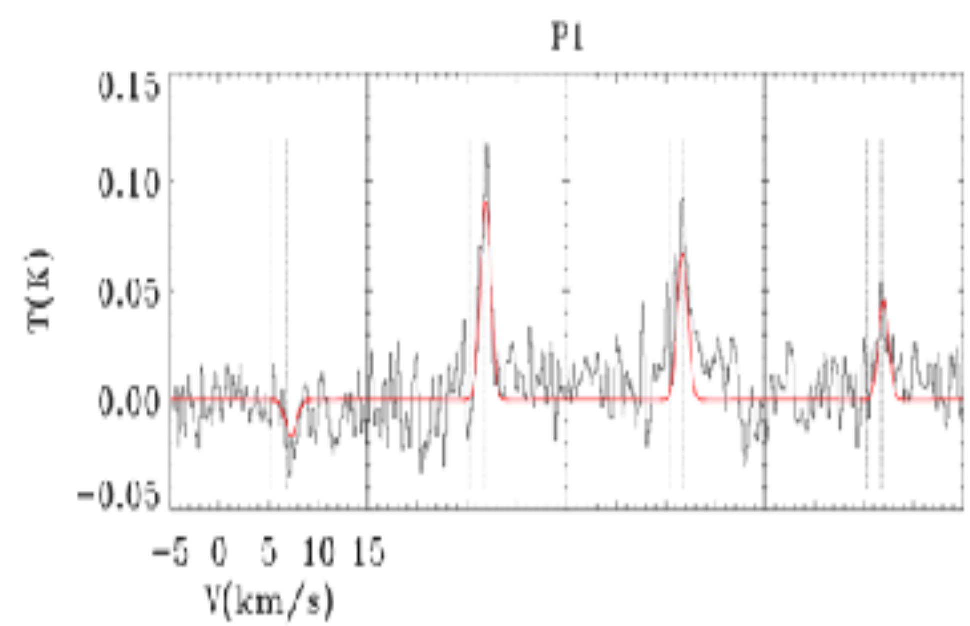
Catching the HI-H_2 Transition





H_2 , CI, CO, Dust

Goldsmith et al. 2008
Goldsmith et al. 2010
Orr et al. 2013

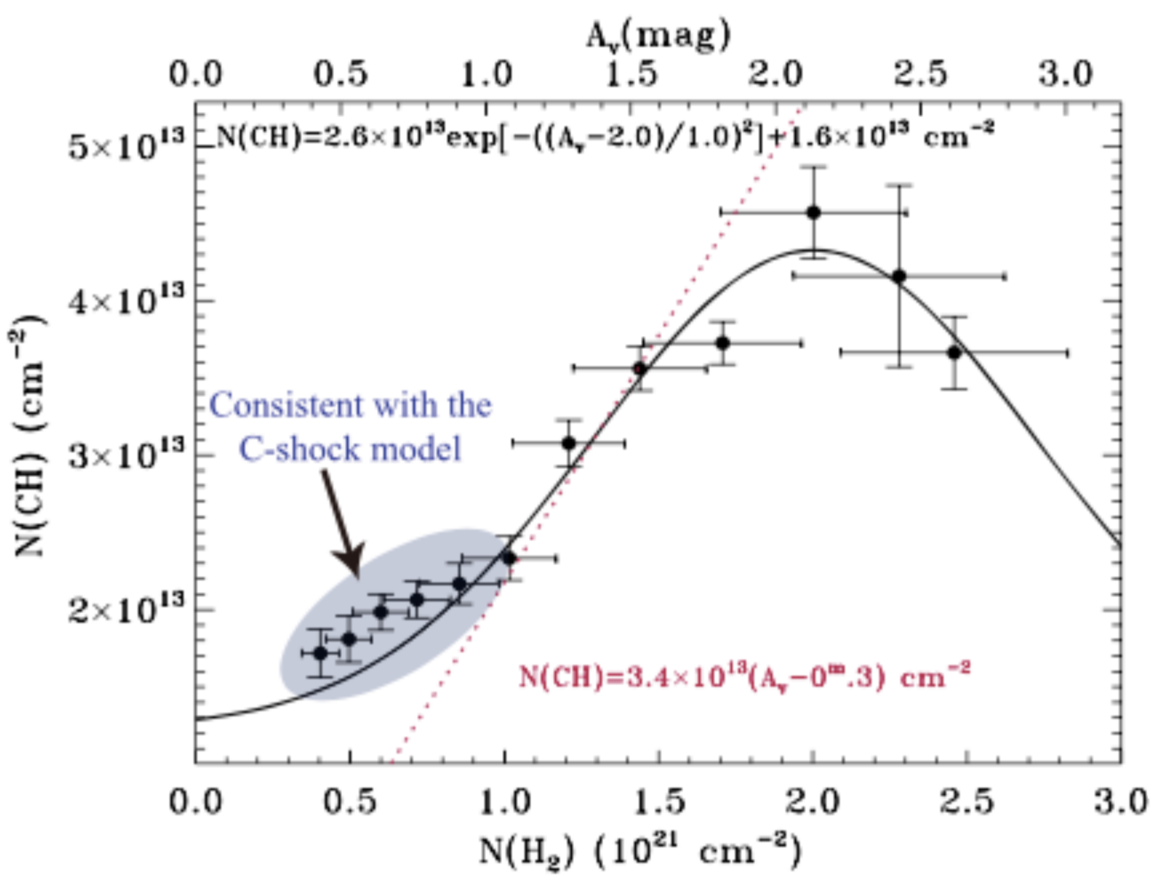


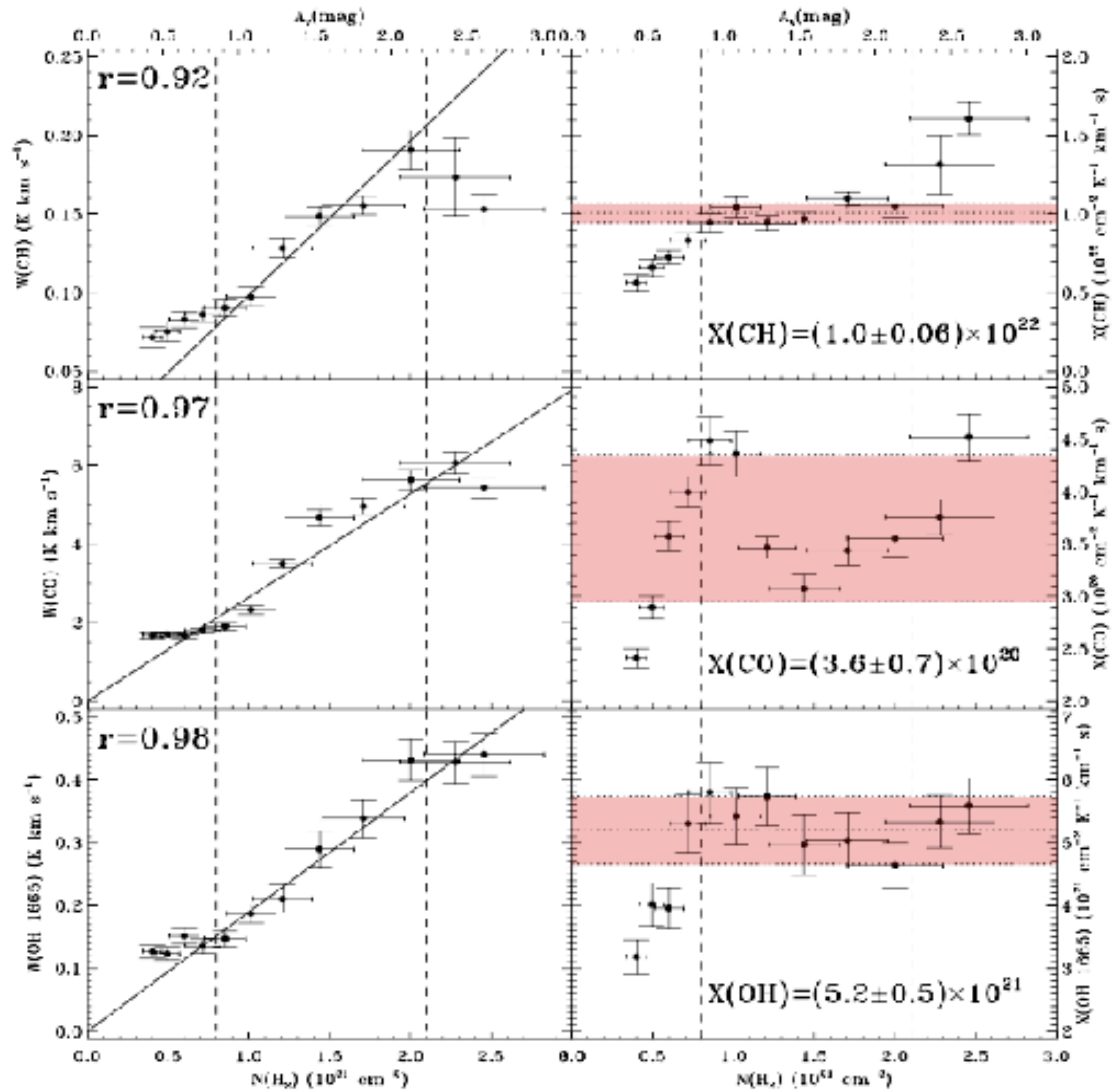
CH AS A MOLECULAR GAS TRACER AND C-SHOCK TRACER ACROSS A MOLECULAR CLOUD BOUNDARY IN TAURUS

Duo Xu(许铎)[1,2,4] and Di Li(李菂)[1,3]

$$C^+ + H_2 \rightarrow CH_2^+ + h\nu,$$
$$CH_2^+ + H_2 \rightarrow CH_3^+ + H,$$
$$CH_2^+ + e^- \rightarrow CH + H,$$
$$CH_3^+ + e^- \rightarrow CH + H_2.$$

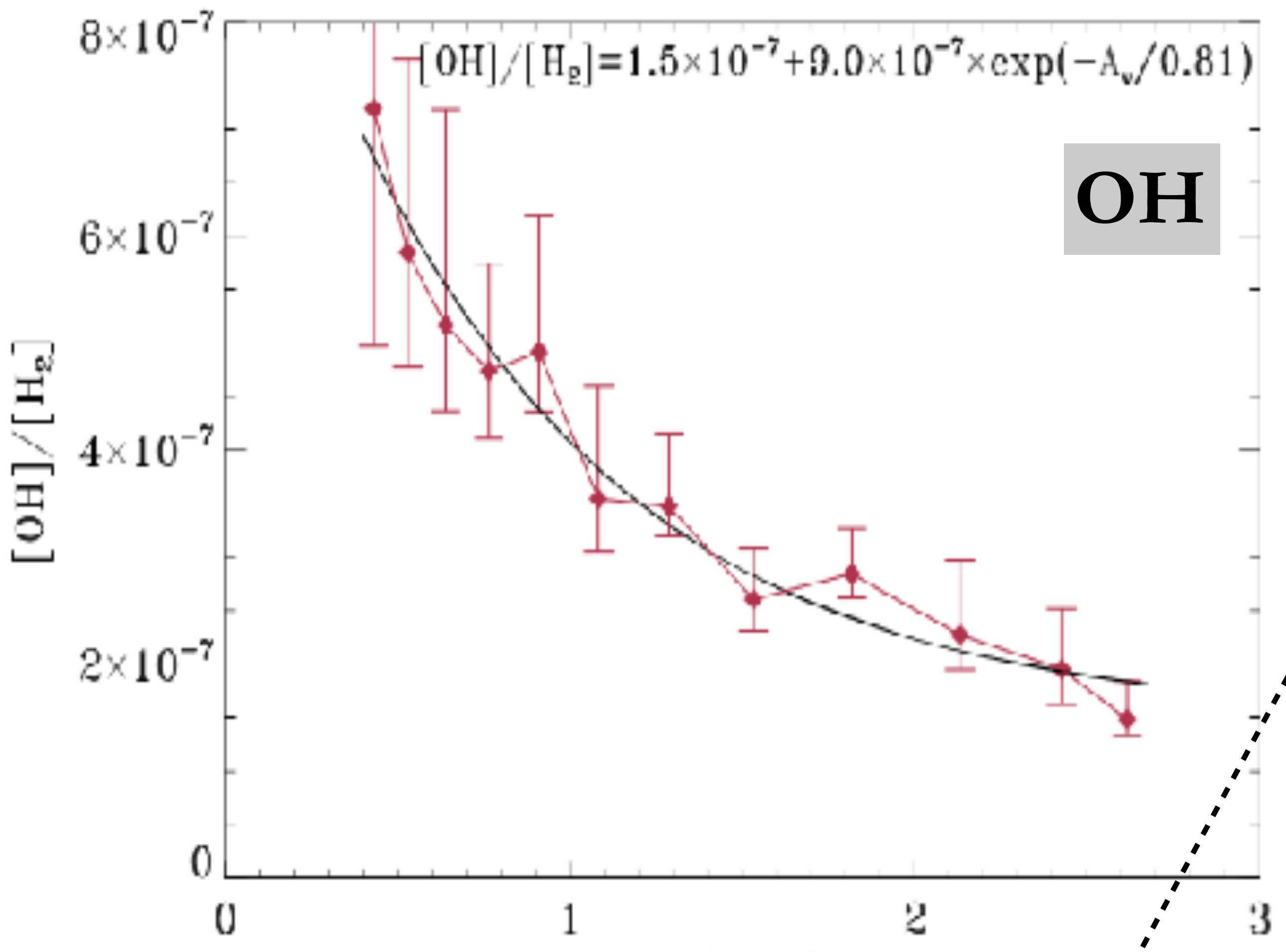
$$C^+ + H \rightarrow CH^+ + h\nu,$$
$$C^+ + H_2 + 0.396\ \mathrm{eV} \rightarrow CH^+ + H,$$
$$CH^+ + e^- \rightarrow CH + h\nu,$$

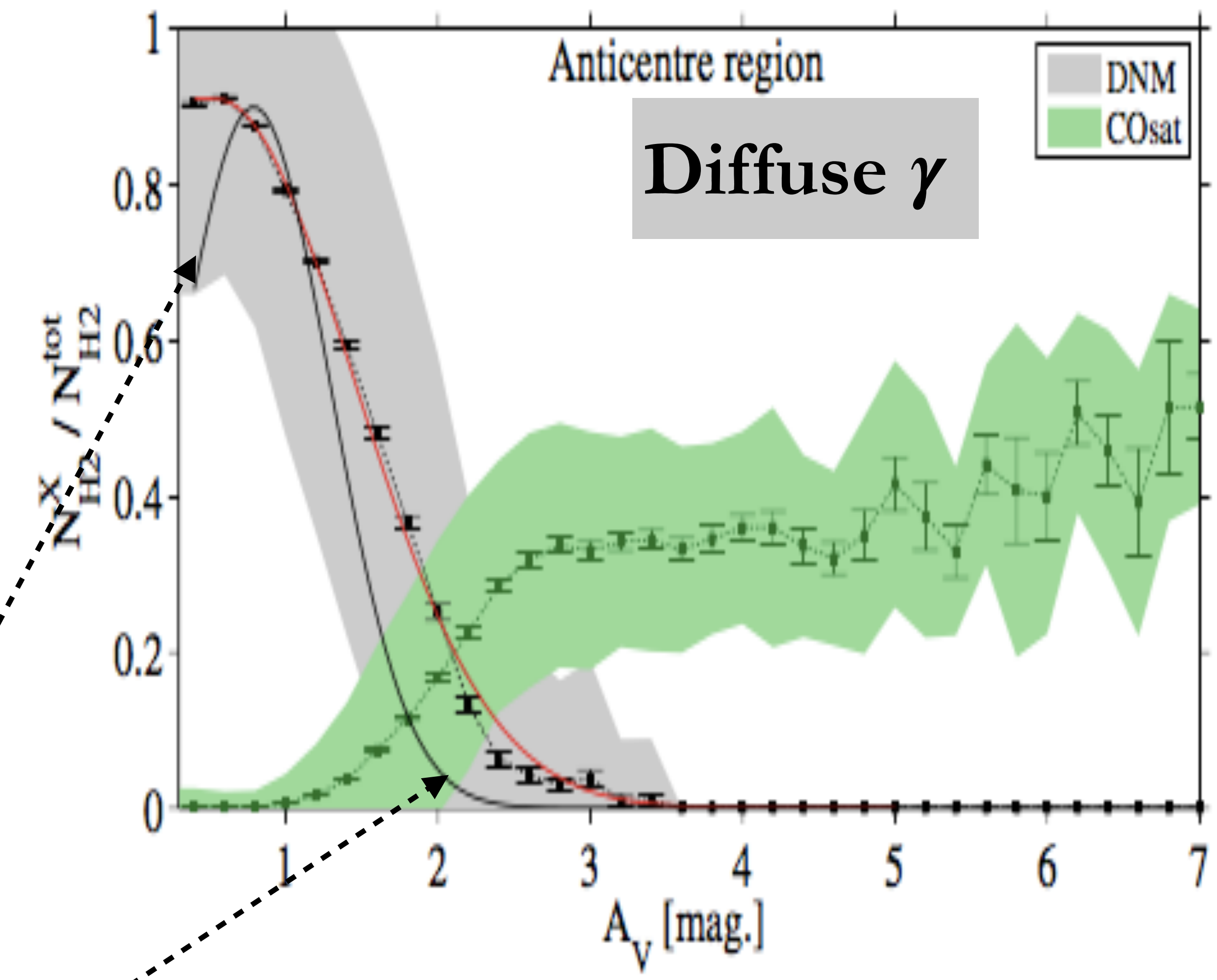




Xu & **Li** 2016, ApJ

DNM (Intermediate Av ~ 0.1-2)
Gas Evolution





OH abundance co-evolve with CO, N(H), and DGF

Remy et al. 2017 Submitted

$$\mathrm{DGF} = 0.90 \times \exp\left(-\left(\frac{A_v - 0.79}{0.71}\right)^2\right).$$

Xu, **Li**, Yue et al. 2016 ApJ

Conclusions

- HINSA traces cold HI mixed with CO and clock the chemical age of dark clouds at 10 Myr

- Dark Molecular Gas (DMG) dominates intermediate extinction gas (Av 0.2 - 1.5)

$$\mathrm{DGF} = 0.90 \times \exp\left(-\left(\frac{A_v - 0.79}{0.71}\right)^2\right).$$

- Simple hydrides, OH and CH, are better tracers of H_2 than CO.

$$X_{CH} = 1.0 \times 10^{22}\ \mathrm{cm^{-2}/(K\ kms^{-1})}$$
$$X_{OH} = 5.2 \times 10^{21}\ \mathrm{cm^{-2}/(K\ kms^{-1})}$$

- Absorption measurements from *Arecibo, FAST, ATCA, VLA, ALMA, and SKA* will quantify 'cold' ISM, including both CNM and DMG.