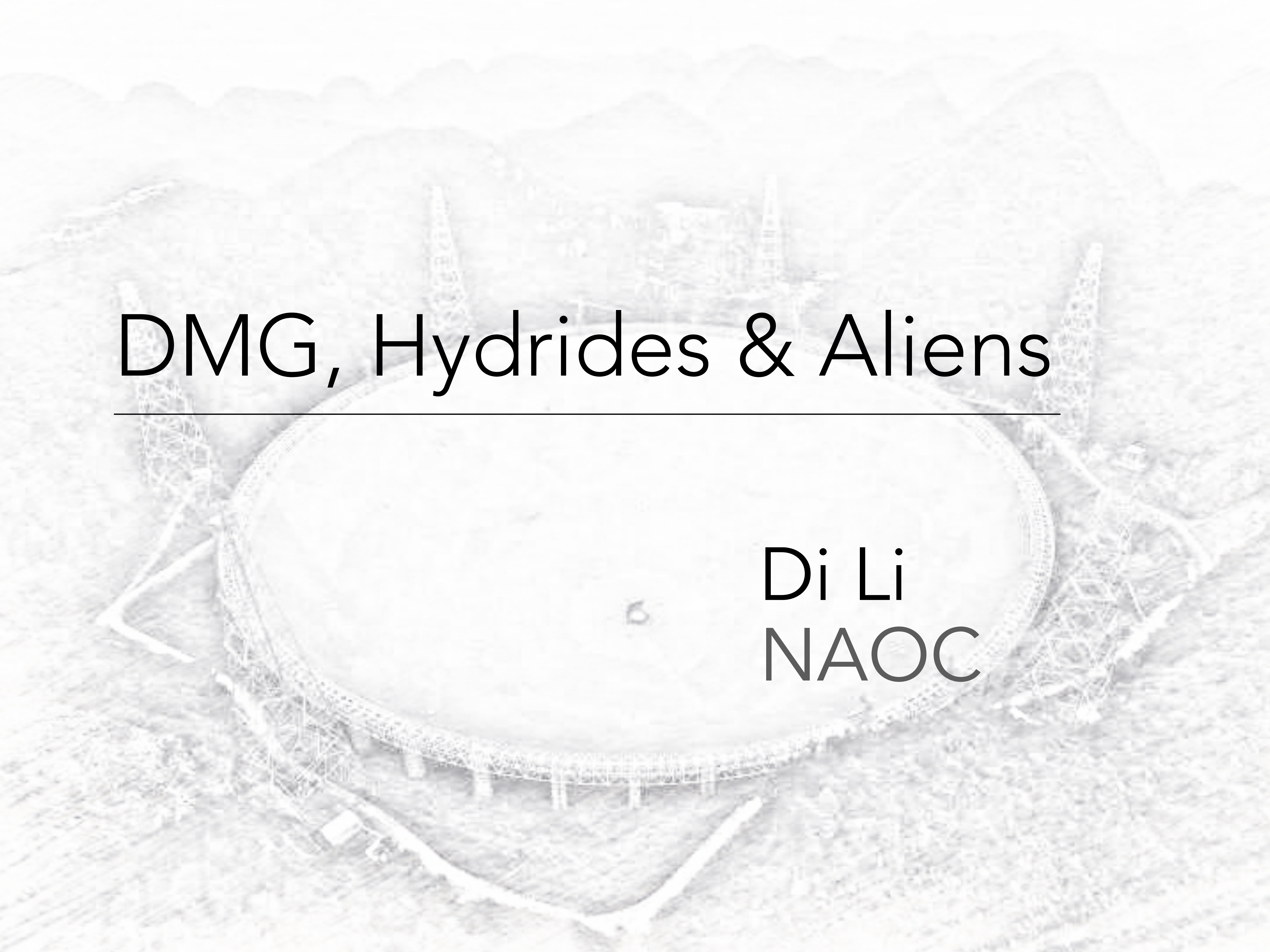
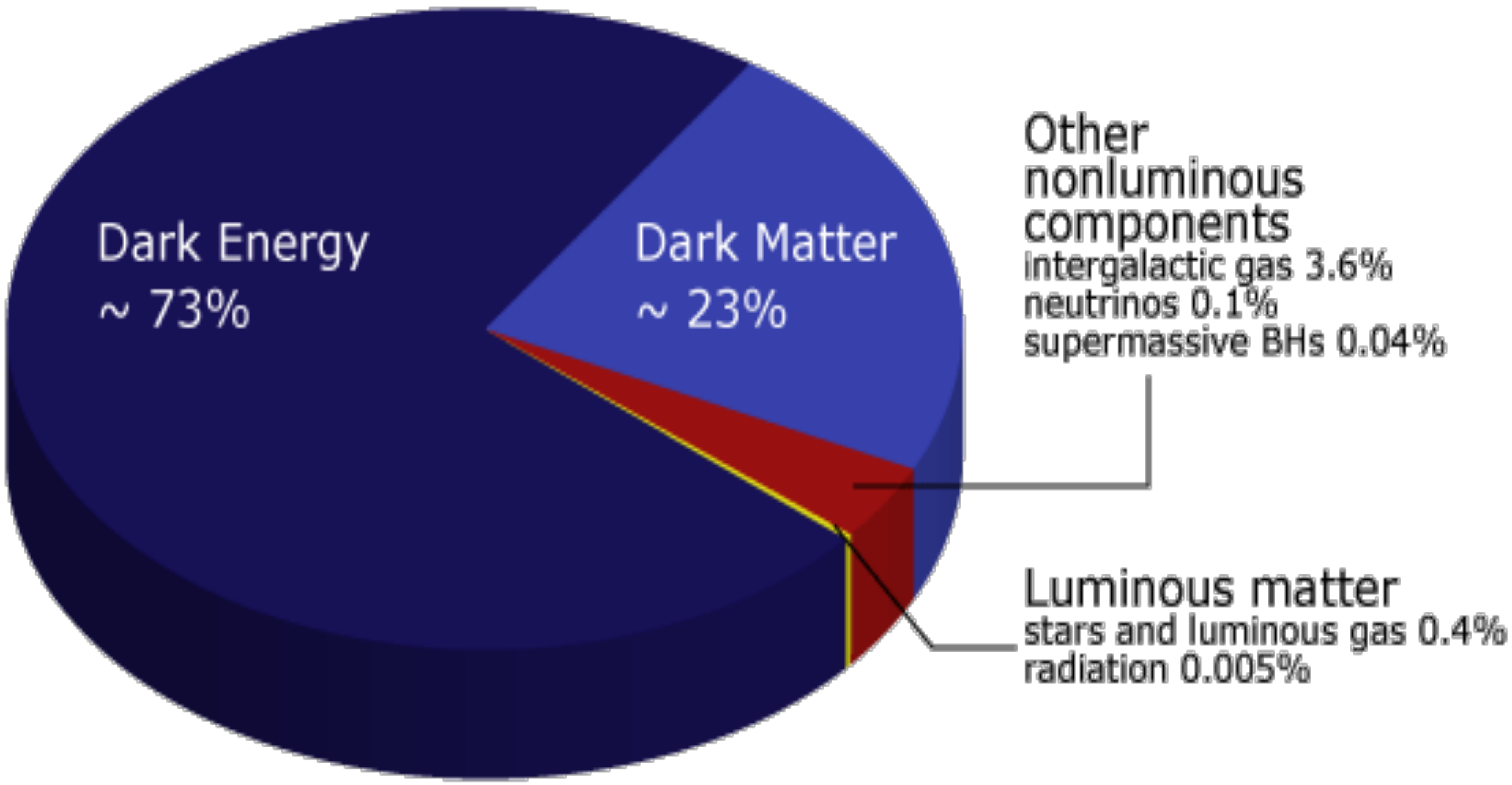
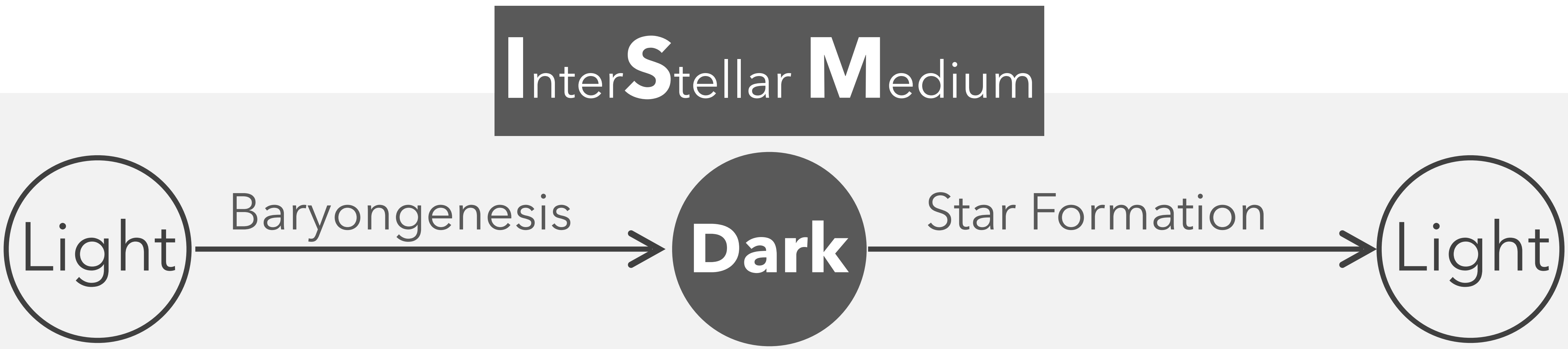


DMG, Hydrides & Aliens

Di Li
NAOC

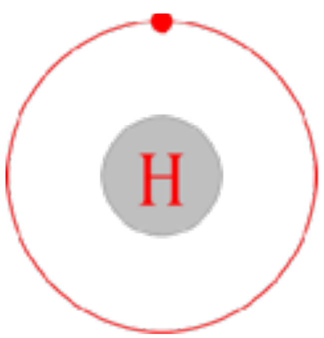

Dark Energy
~ 73%
Dark Matter
~ 23%
Other nonluminous components
intergalactic gas 3.6%
neutrinos 0.1%
supermassive BHs 0.04%
Luminous matter
stars and luminous gas 0.4%
radiation 0.005%


InterStellar Medium
Light
Baryongenesis
Dark
Star Formation
Light

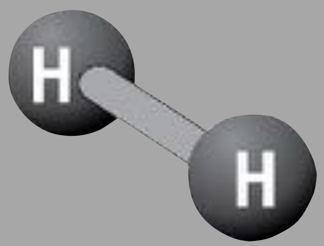
Cosmic Matter Cycle

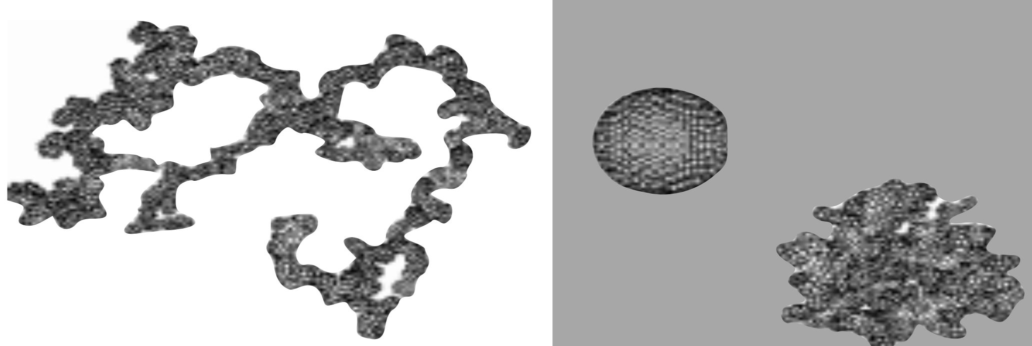
Physics

Chemistry



HI => H_2





star dust

H_2 Formation

- **Hollenbach & Salpeter 1971**: "defect sites"

$$f \equiv (N/N') \exp[-(D' - D)/kT] \ll 1\,; \qquad (1)$$

$$D' - D'_2 \gg k50^\circ\ \mathrm{K} > kT\,. \qquad (2)$$

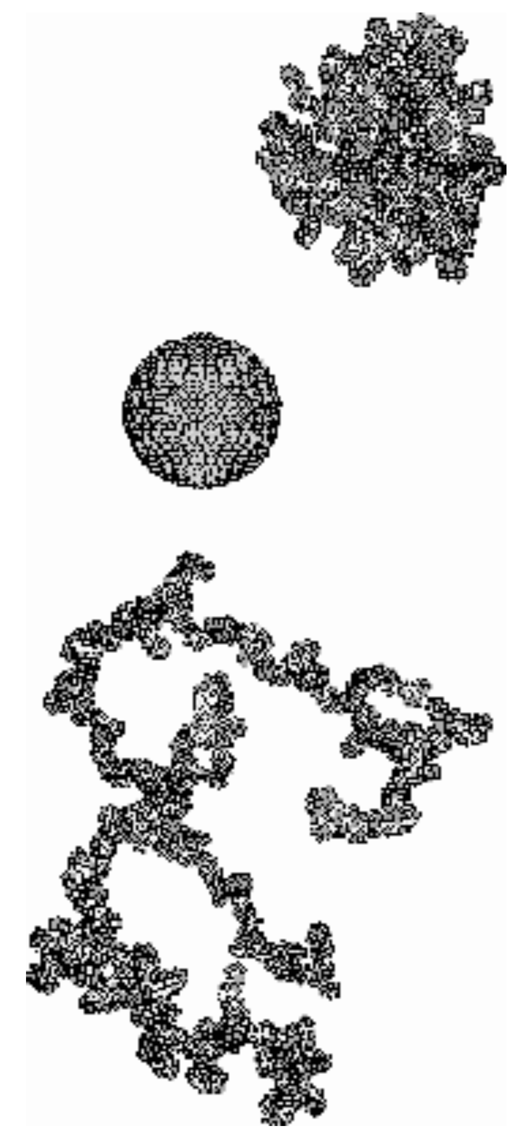
III. THE STICKING COEFFICIENT AND SURFACE MOBILITY

In calculating the recombination efficiency γ for gas atoms on grain surfaces, we first need the "sticking coefficient" S, the fraction of all hydrogen atoms incident on the surface which becomes adsorbed. In principle, S depends on the grain temperature T, the gas temperature T_{gas}, and the adsorption binding energy D. In practice, we are interested only in cases where some inequalities apply,

$$kT < kT_{gas} \ll D\,. \qquad (3)$$

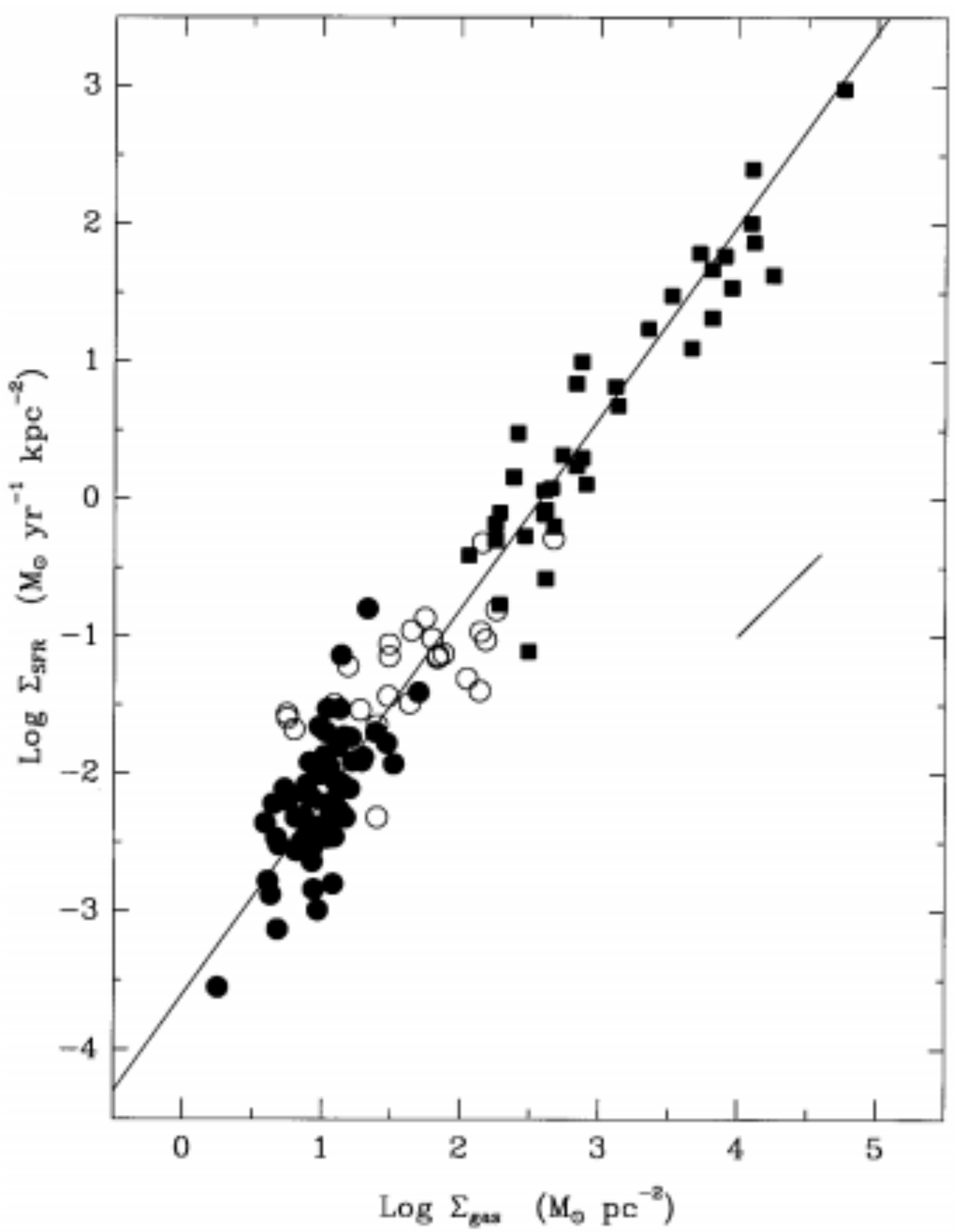
Under these circumstances S is independent of T, and HS showed that its dependence on T_{gas} can be approximated by the relation

$$S(T_{gas}) = \frac{\Gamma^2 + 0.8\,\Gamma^3}{1 + 2.4\,\Gamma + \Gamma^2 + 0.8\,\Gamma^3}\,, \qquad \Gamma \equiv \frac{E_c}{kT_{gas}}\,, \qquad (4)$$

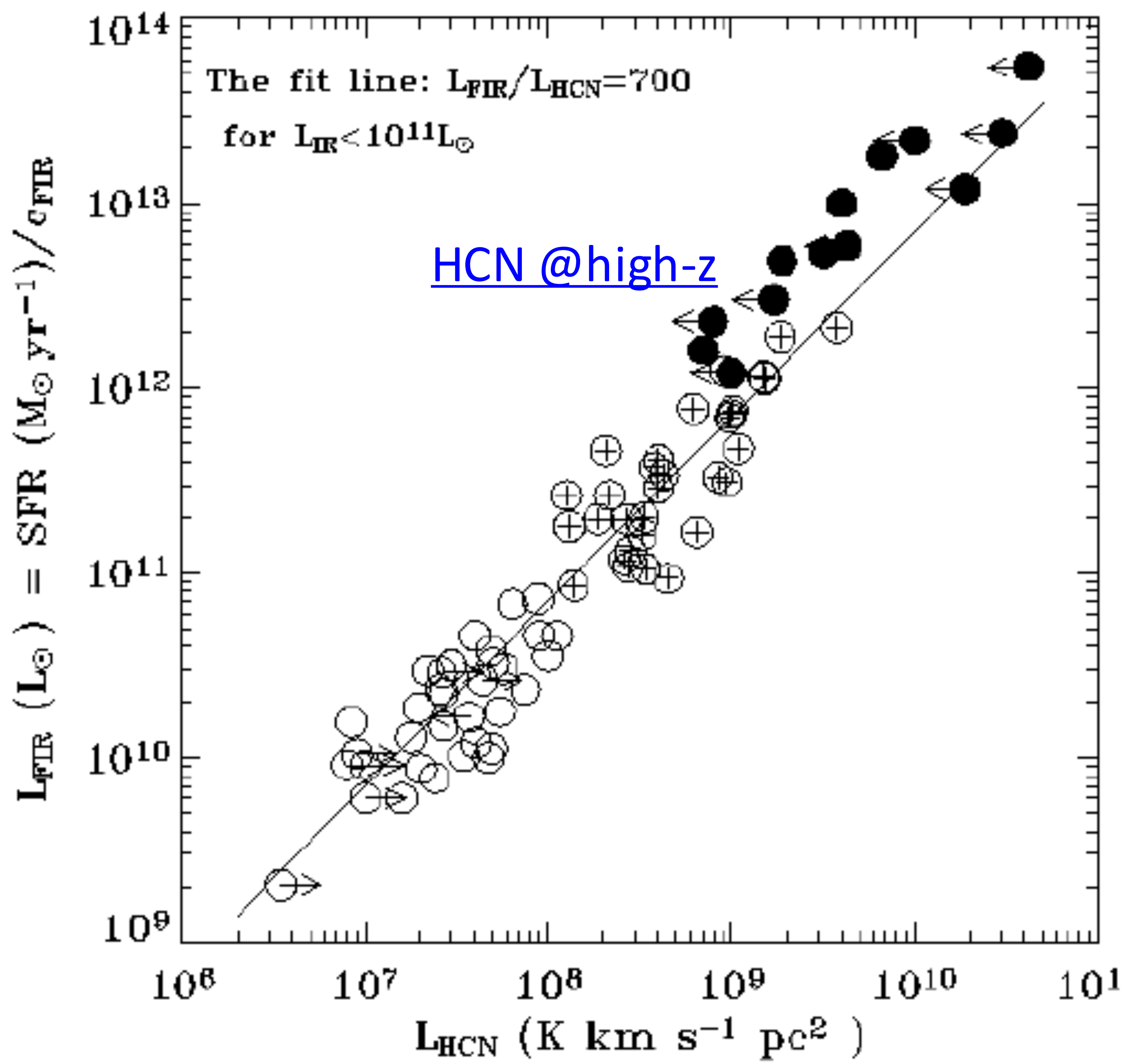


- **Cazaux & Tielens 2002**: Physi+chemi-sorption
- **Katz et al. 1999**: Laboratory

Star Formation 'Law'



Kennicutt 1998
(>3000 citations)

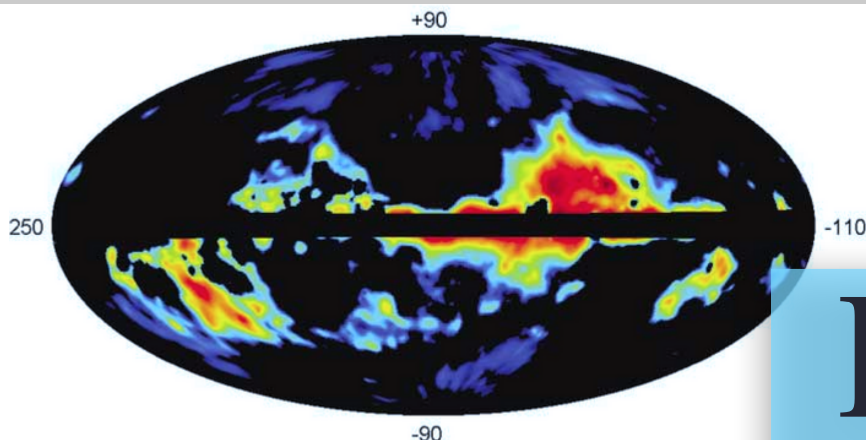


Gao et al. 2007

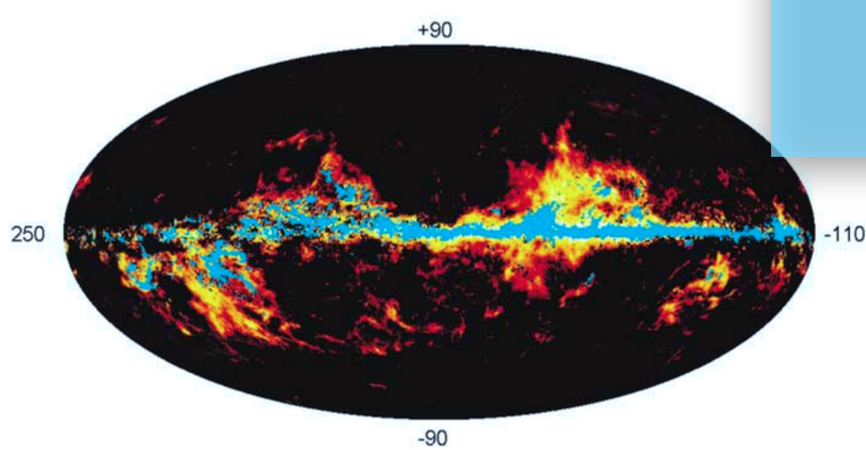
The rise of the *X*-factor

ISM Inventory

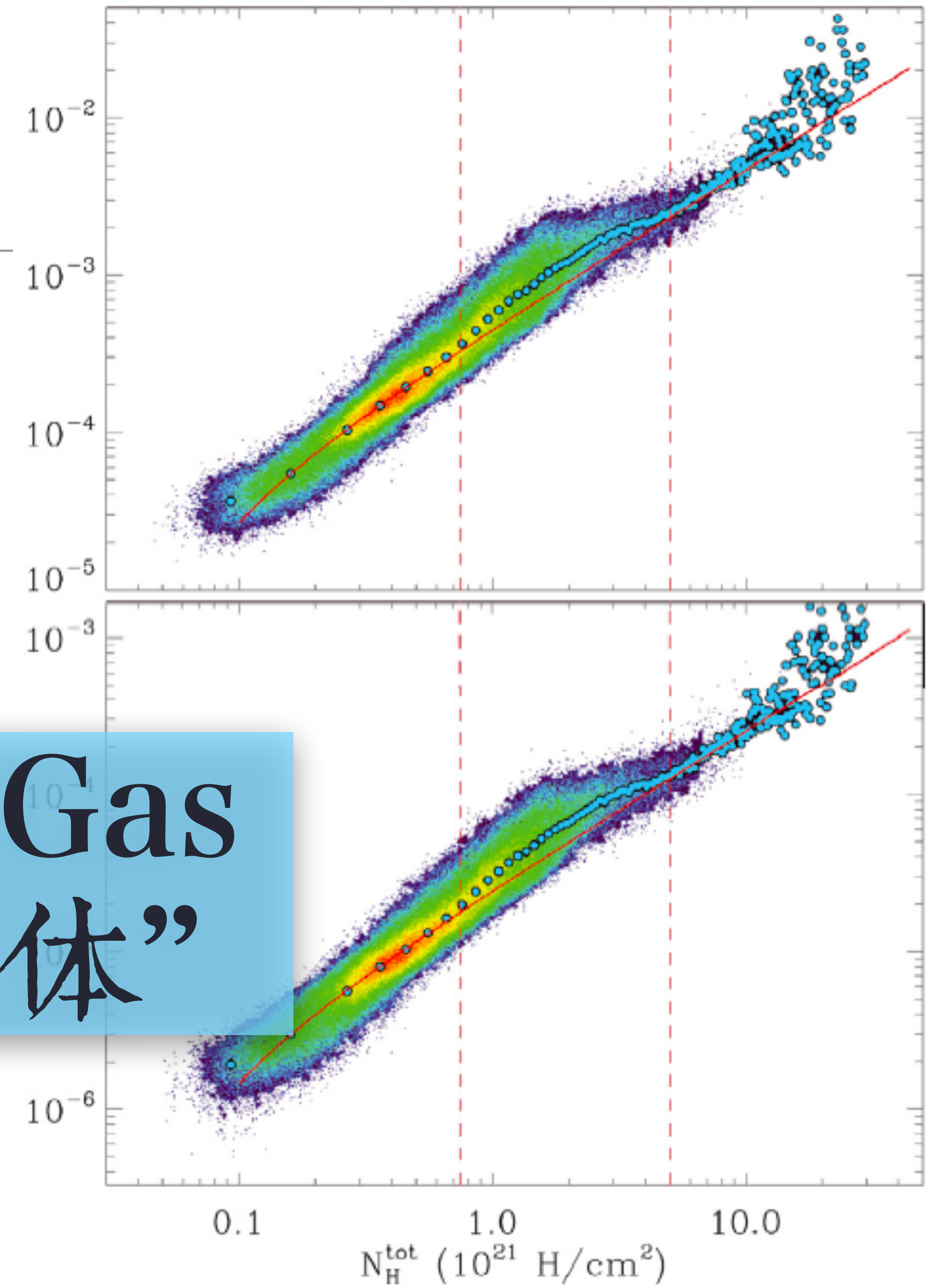
IRAS
[IRAS – (HI + X*CO)]



Dark Gas
“暗气体”

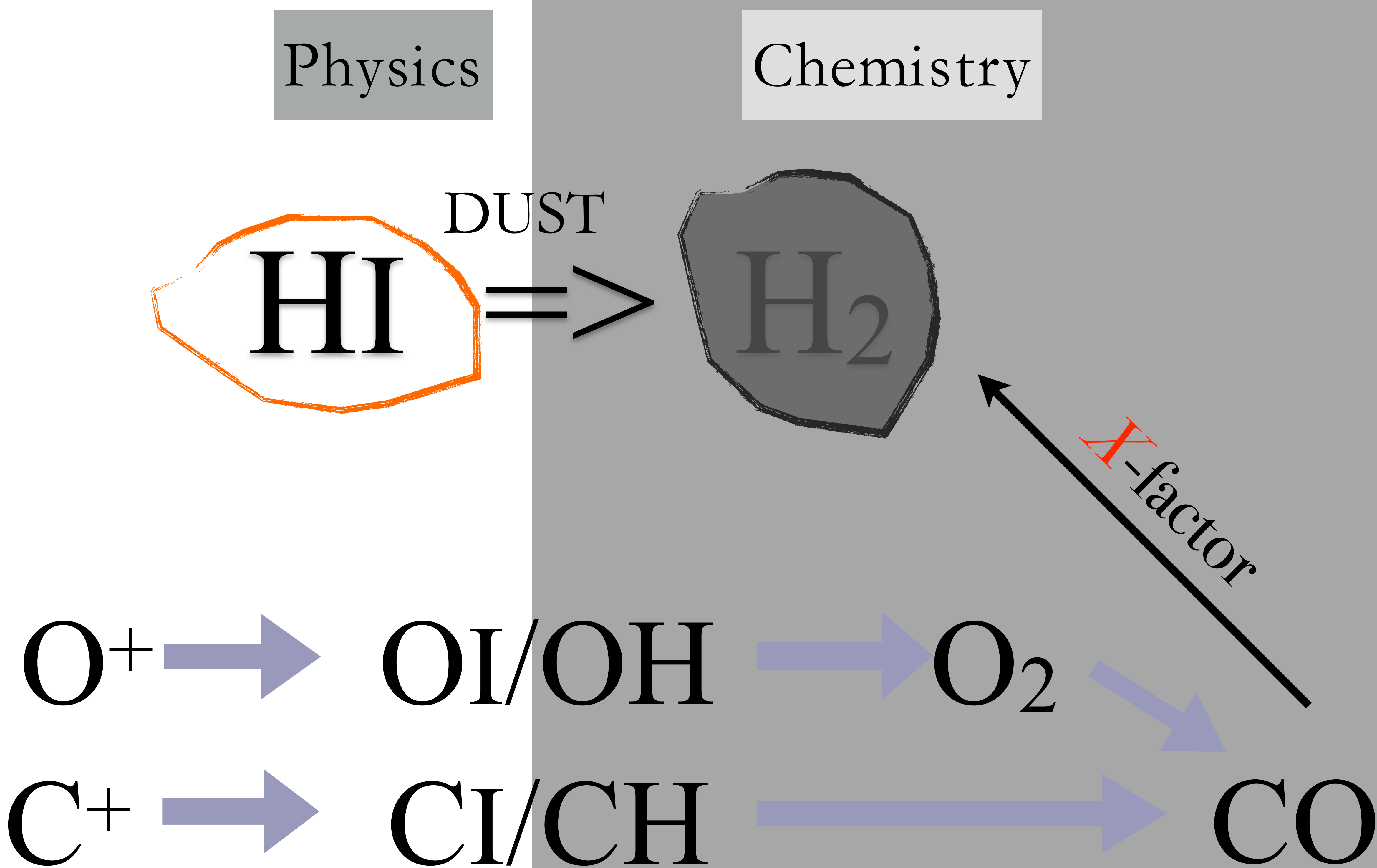


EGRET
[CR/H-nuclei] - (HI + X*CO)
Grenier et al. (2005) **Science**

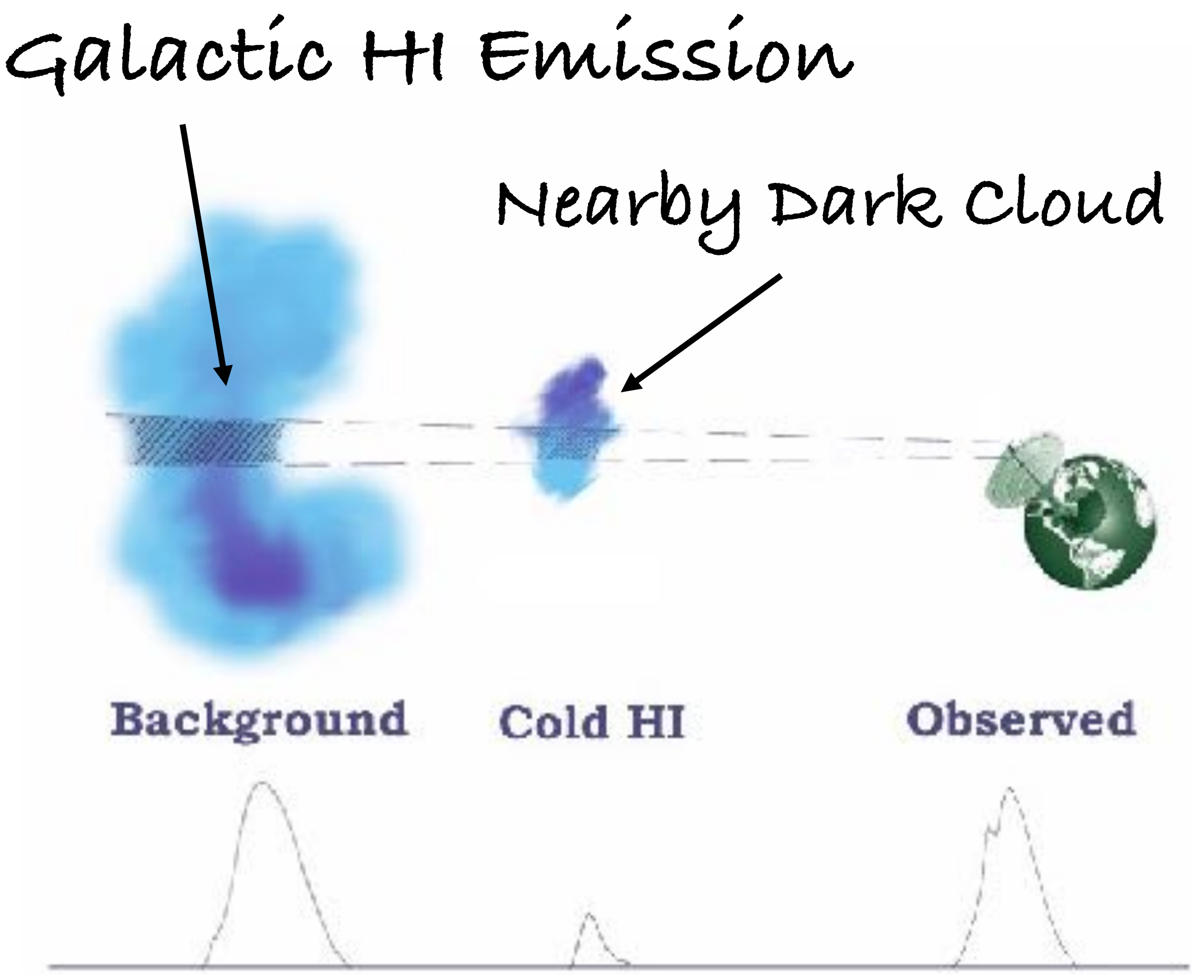


Planck
Dust Opacity vs (HI+X*CO)
Planck Collaboration (2011)

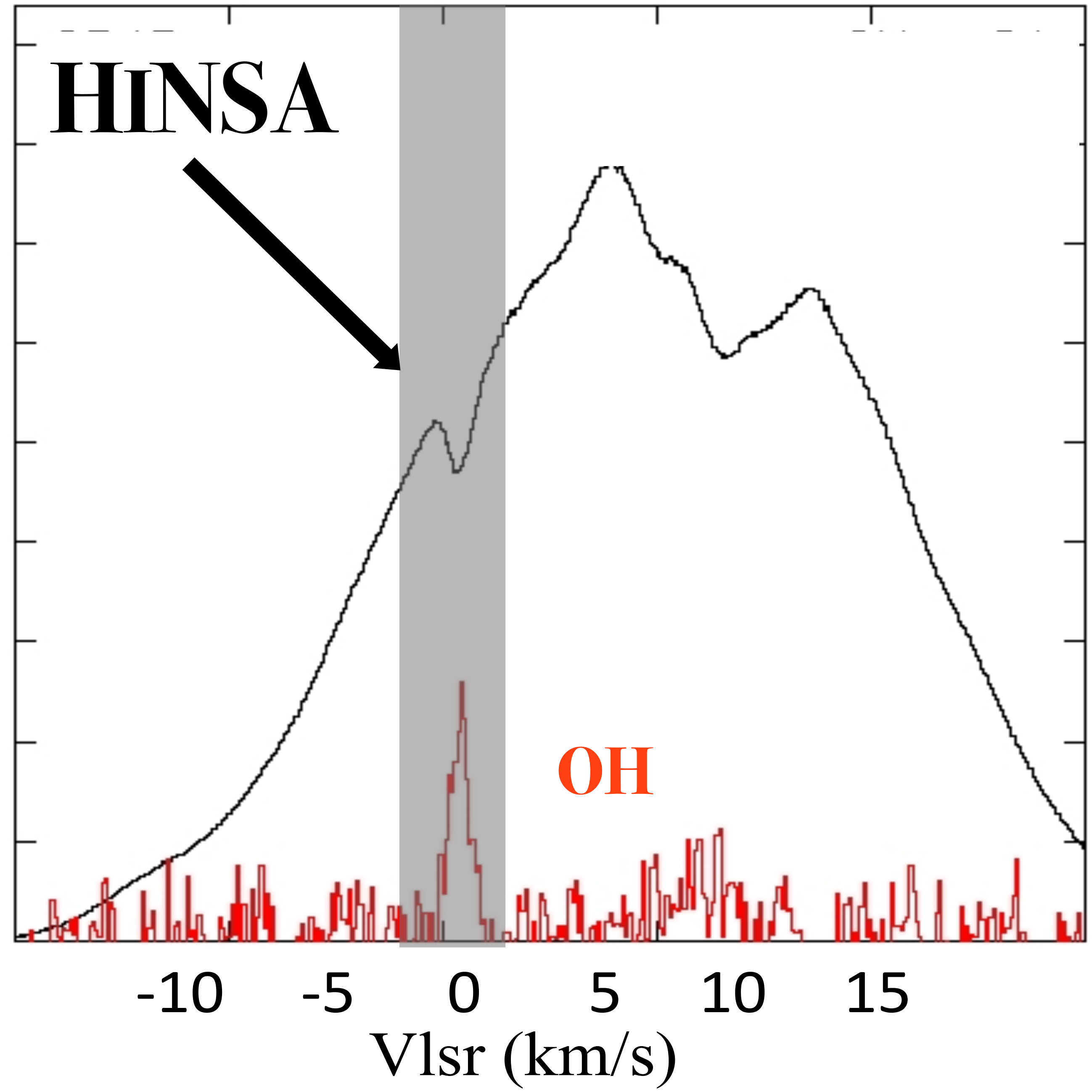
ISM Evolution



HI Narrow Self-Absorption (HINSA)



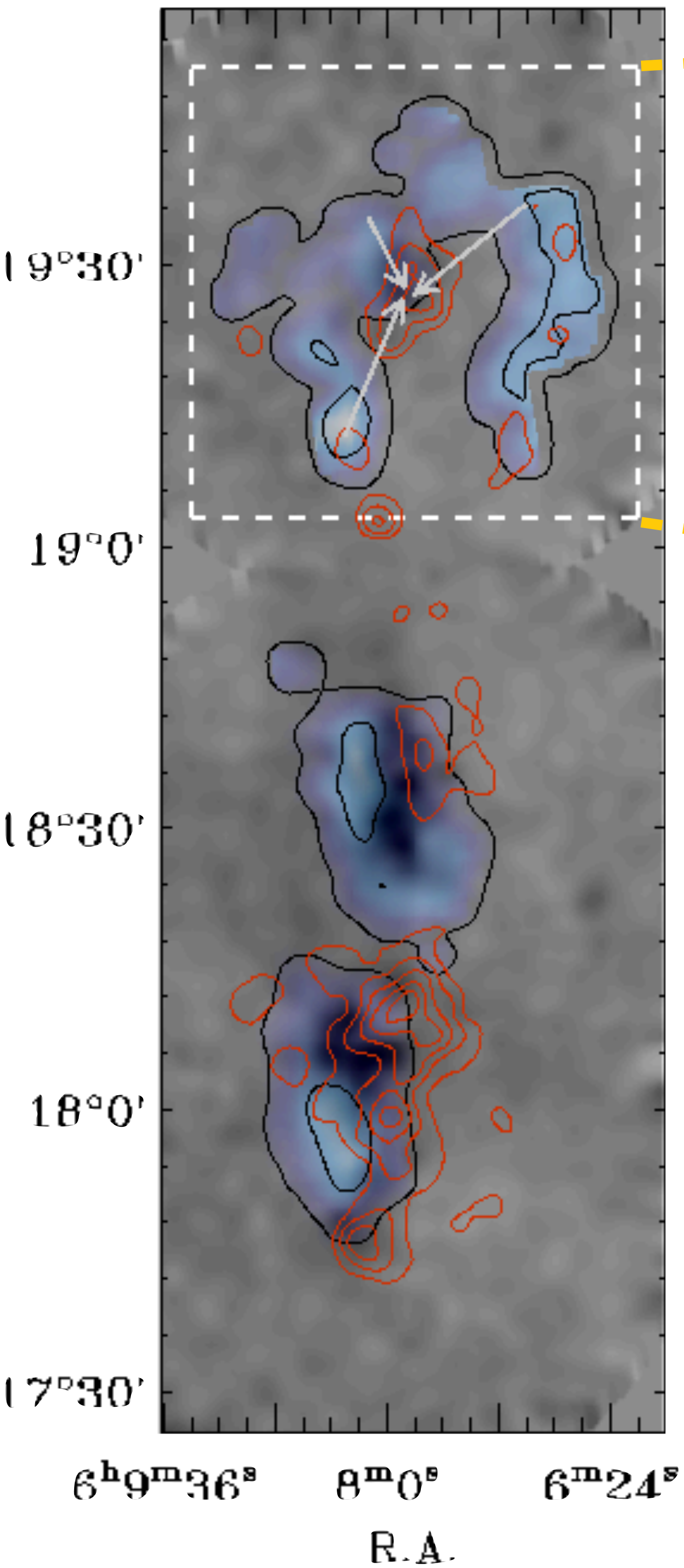
Li & Goldsmith 2003, ApJ
Goldsmith & **Li** 2005, ApJ

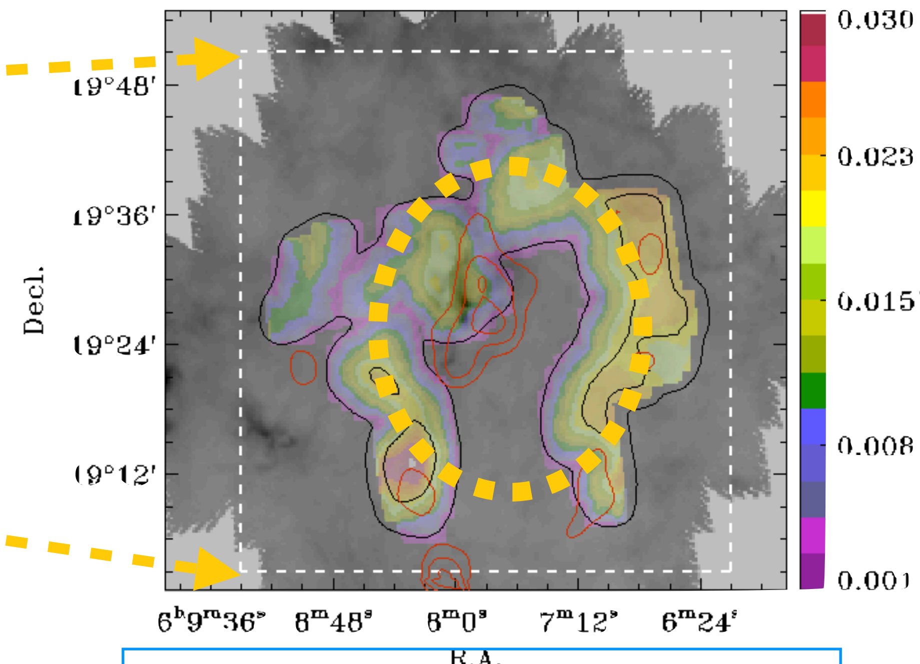


HINSA measures cold HI cooled by collision with H_2, thus providing a rare **robust chemical clock** of molecular formation.

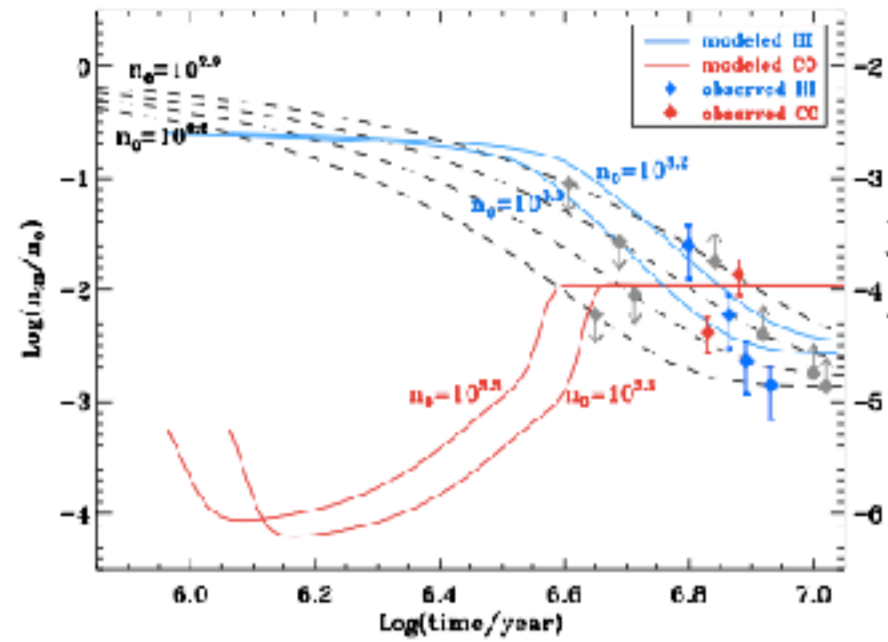
Catching the Birth of a Dark Molecular Cloud for the First Time

Pei Zuo[1,2,3], Di Li[1,2,3], J. E. G. Peek[4,10], Qiang Chang[5], Xia Zhang[5], Nicholas Chapman[6], Paul F. Goldsmith[7], and Zhi-Yu Zhang[8,9]





Herschel OT1 Program
+Arecibo +FCRAO+2Mass

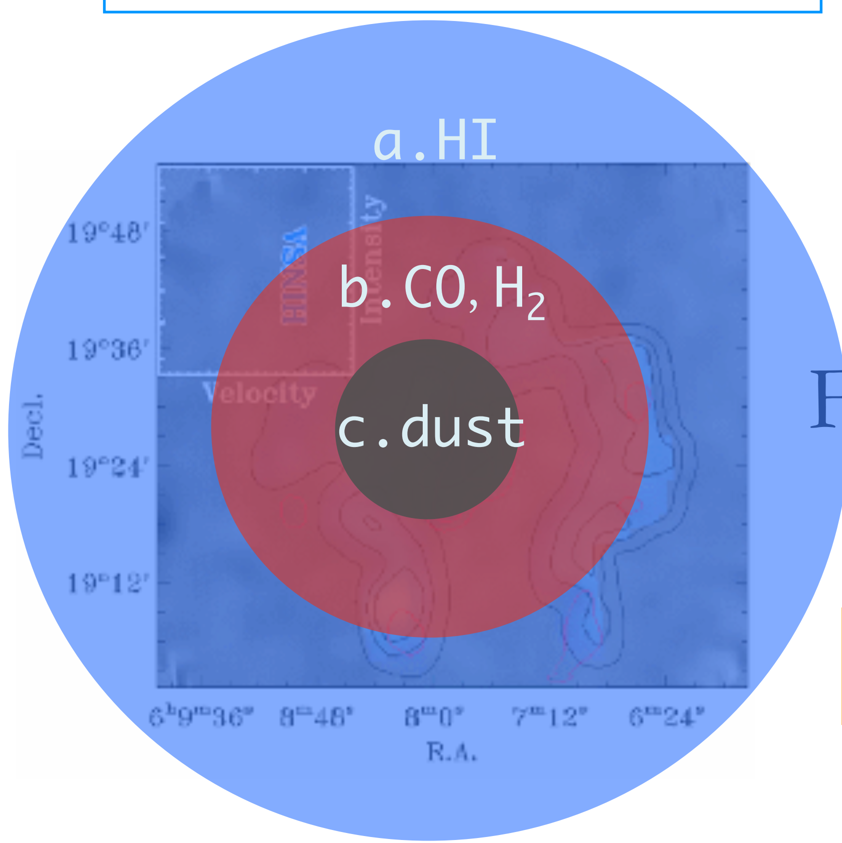


formation

$$R_{H_2} = 2\times10^{-18} n(H) n(HI) \sqrt{T}$$

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

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



Formation Time Scale **> 6 Myr**
(cf. Elmegreen 2000; Glover+ 2009)

Zuo, **Li**, Peek et al. 2018 ApJ

Molecular Cloud Formation

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

$$R_{H_2} = \frac{1}{2} n_g n_1 \sigma v S \eta$$
$$R_{H2} = 2.1\times10^{-18} n n_1 \sqrt{T}$$

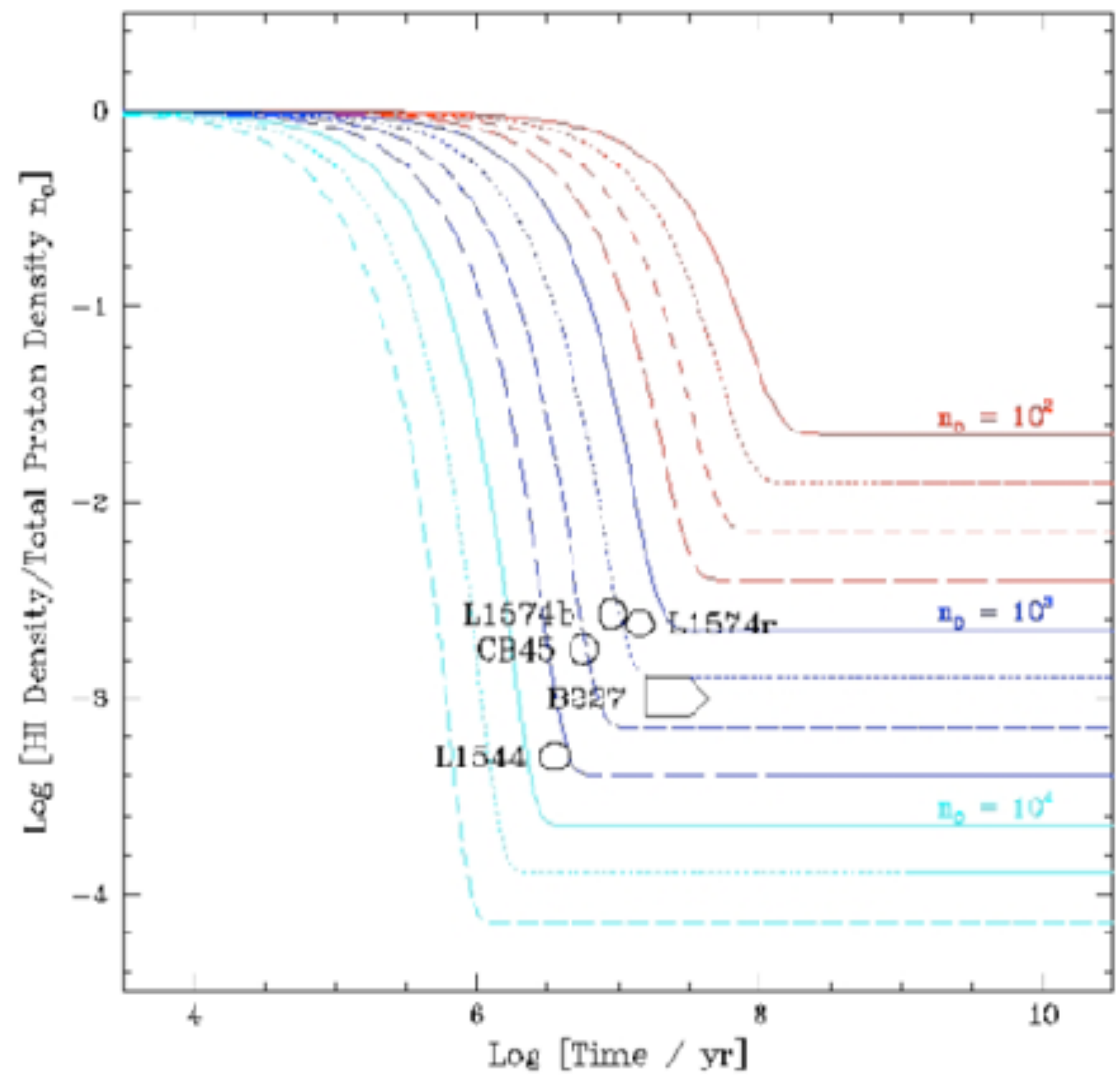
Hollenbach & Salpeter 1970; Buch & Zhang 1991

- 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.



Dark Cloud Age> 10Myr

Goldsmith & **Li** 2005 ApJ

The low abundance [HI]/[H_2] ~ 0.1% **rules out any fast cloud/star formation scenario**, including stochastic H_2 formation in locally enhanced dense spots, and **favors the canonical 'Shu' picture** with ambipolar diffusion.

2018.11

國家天文台首次發現新生暗云

The Astrophysical Journal, 867:13 (7pp), 2018 November 1 https://doi.org/10.3847/1538-4357/aad571

Catching the Birth of a Dark Molecular Cloud for the First Time

Pei Zuo[1,2,3], Di Li[1,2,3], J. E. G. Peek[4,5], Qiang Chang[6], Xia Zhang[6], Nicholas Chapman[7], Paul F. Goldsmith[8], and Zhi-Yu Zhang[9,10]

"A chilly cloud of molecular gas in the Milky Way is giving astronomers a rare look at one of the earliest steps in star formation.

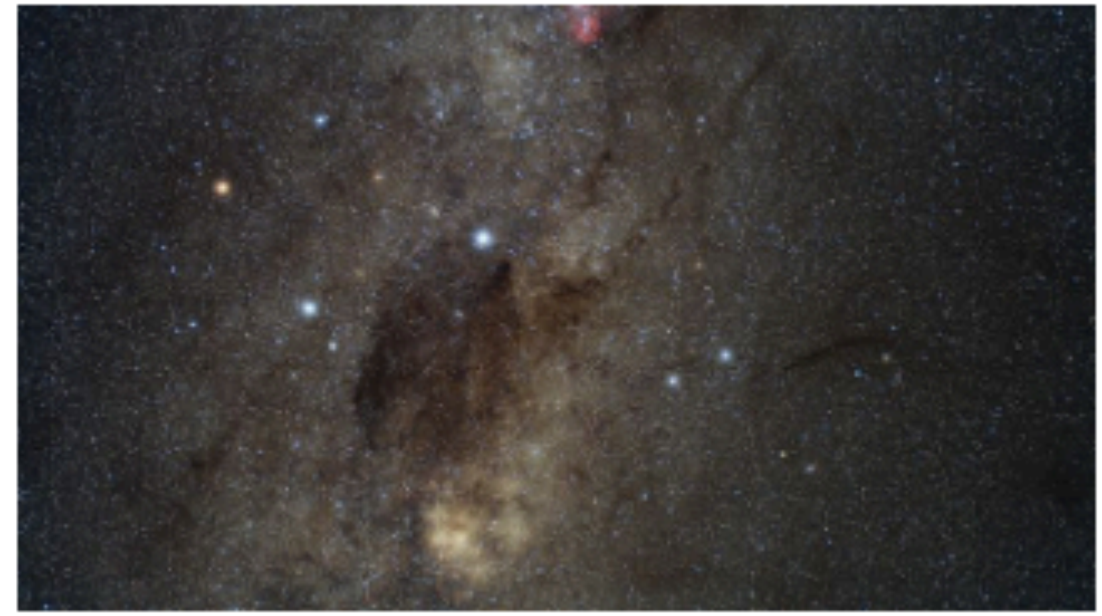
The smallest, most fundamental molecules in the Universe are created when two hydrogen atoms bond to form hydrogen molecules (H2). But the molecule's formation is rarely observed, because it's hard to distinguish atomic and molecular hydrogen from other types of molecules and from each other.

Pei Zuo and Di Li at the National Astronomical Observatories of the Chinese Academy of Sciences in Beijing and their colleagues used the Arecibo radio telescope in Puerto Rico to observe dark clouds in the cosmos. The team found that one cloud had an outer 'shell' of atomic hydrogen that was being converted into molecular hydrogen — the first such detection of a dark cloud's birth.

Further analysis of the rate of H2 formation suggested that the cloud is roughly 6 million years old. This finding could help to constrain models of star, planet and galaxy formation, the authors write. (**Zuo & Li et al. Astrophys. J. 867, 13 (2018)**)

Nature Research Highlight: Nov 2018

MENU nature International journal of science



A dark Galactic cloud similar to the Coalsack nebula (central black blob above) has been seen for the first time in the act of generating molecular hydrogen. Credit: ESO/Digitized Sky Survey 2/Davide De Martin

ASTRONOMY AND ASTROPHYSICS · 02 NOVEMBER 2018

Dark space cloud caught donning halo of hydrogen molecules

For the first time, a Galactic cloud is seen producing an ingredient that is fundamental in star formation.

A chilly cloud of molecular gas in the Milky Way is giving astronomers a rare look at one of the earliest steps in star formation.

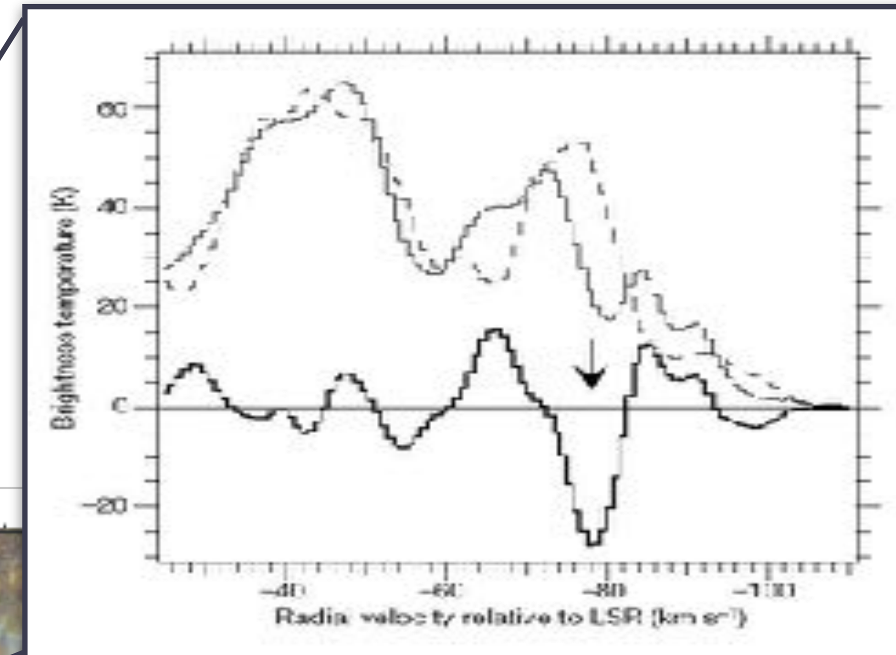
The smallest, most fundamental molecules in the Universe are created when two hydrogen atoms bond to form hydrogen molecules (H_2). This process usually takes place in cold, dark clouds. But the molecule's formation is rarely observed, because it's hard to distinguish atomic and molecular hydrogen from other types of molecules and from each other.

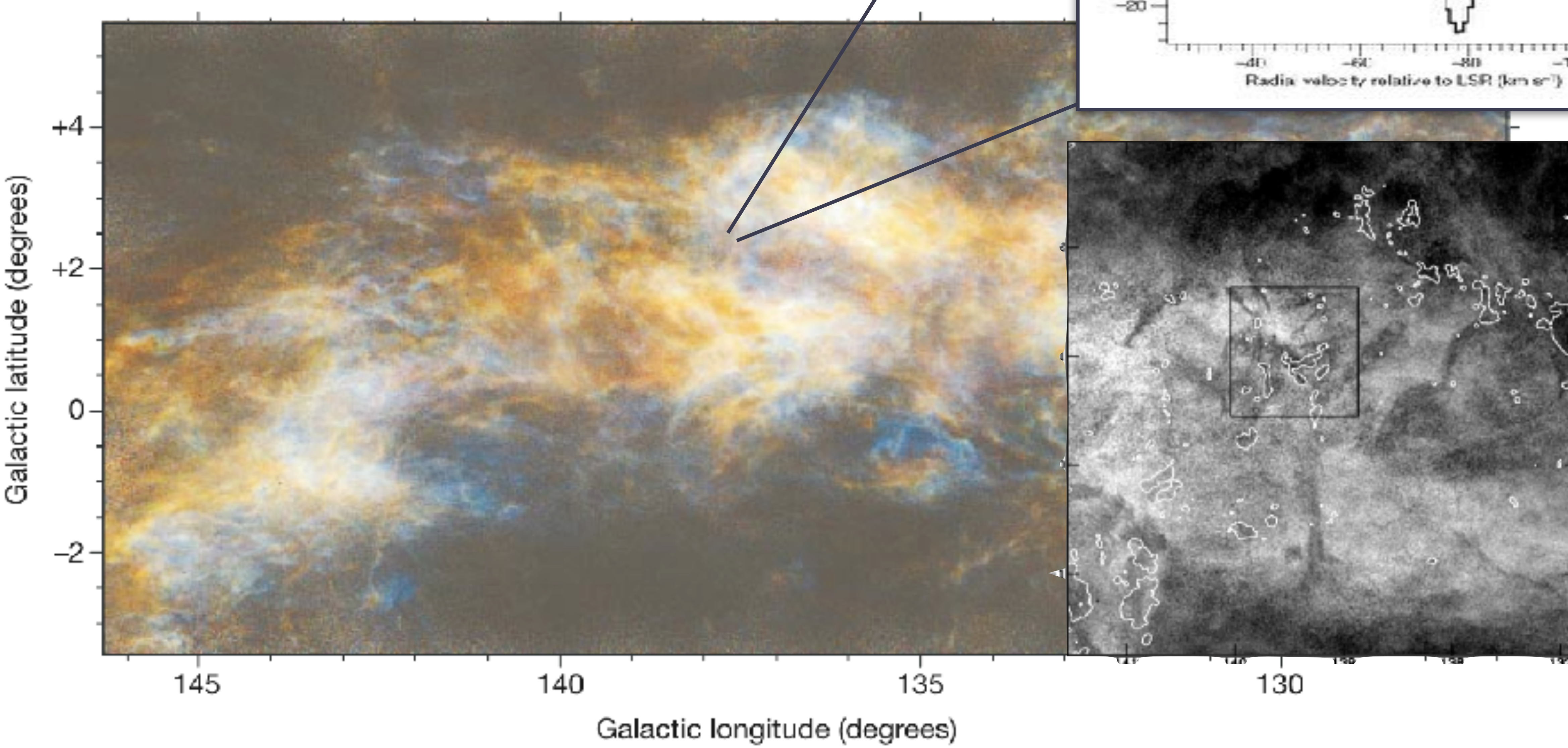
HISA: Cold HI Clouds

DRAO Galactic Plane Survey

Cold features revealed in GSH139-03-69

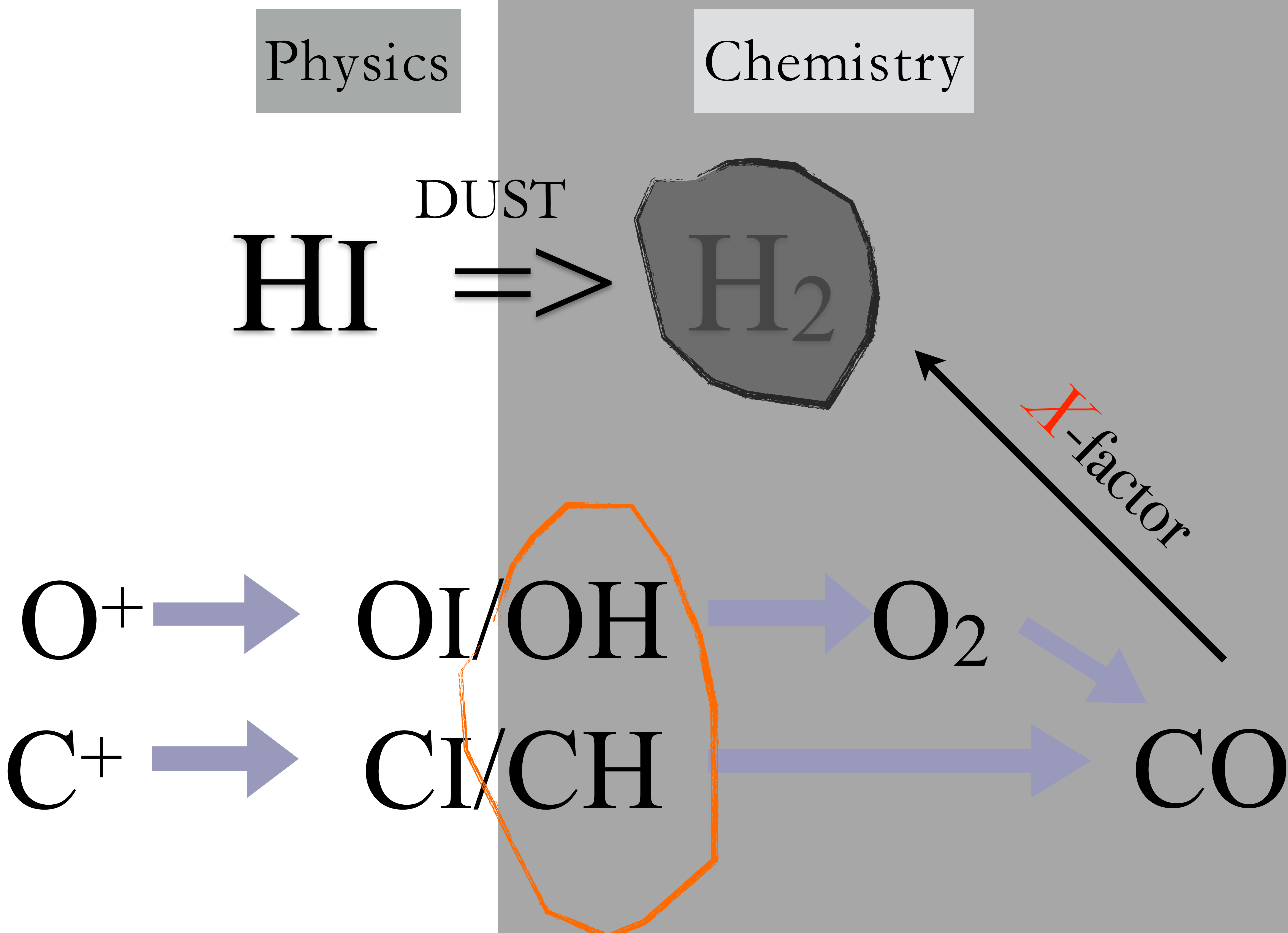
Knee and Brunt, ***Nature***, *2001*





cf. Gibson et al. 2001

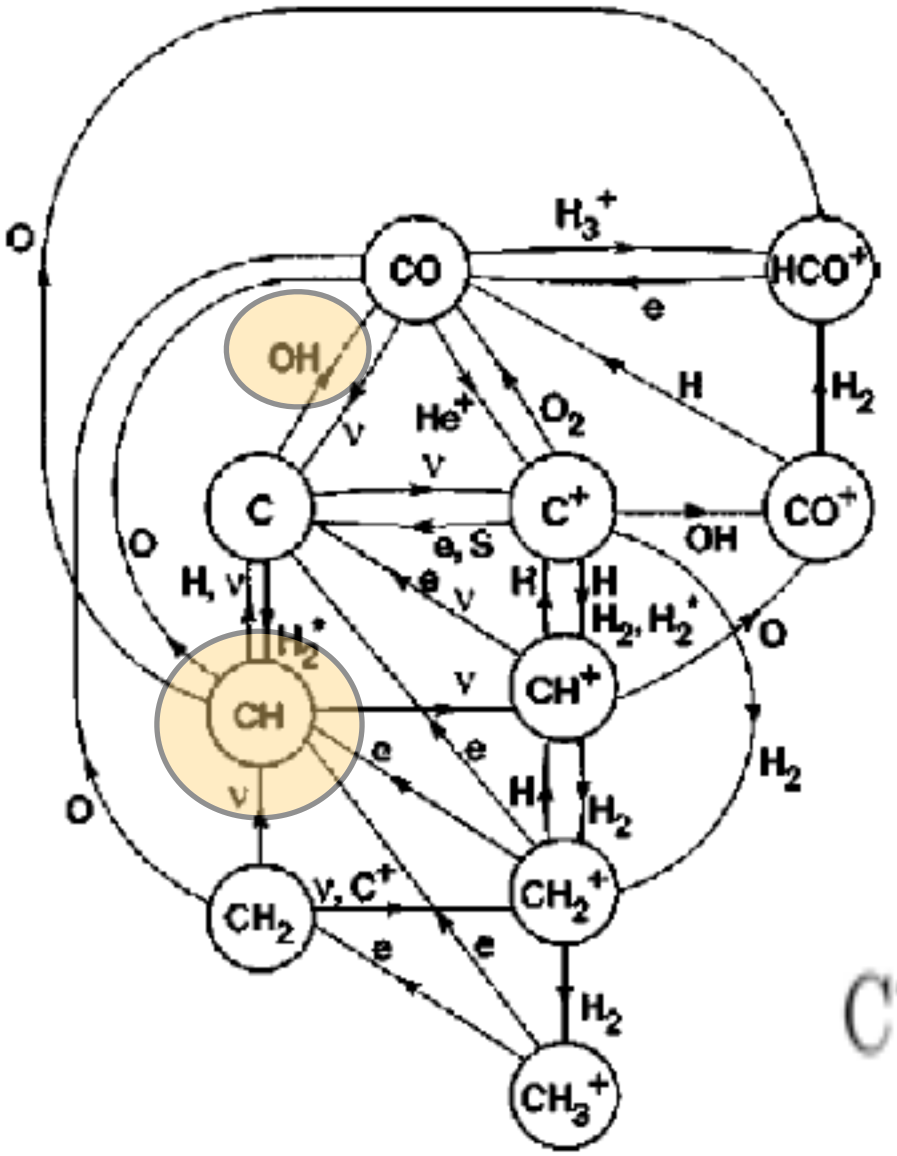
ISM Evolution



The Start of the "Chain"

$$HI + Dust \Rightarrow H_2$$

Tielens 2007



Lucas and Liszt 1996

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

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

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

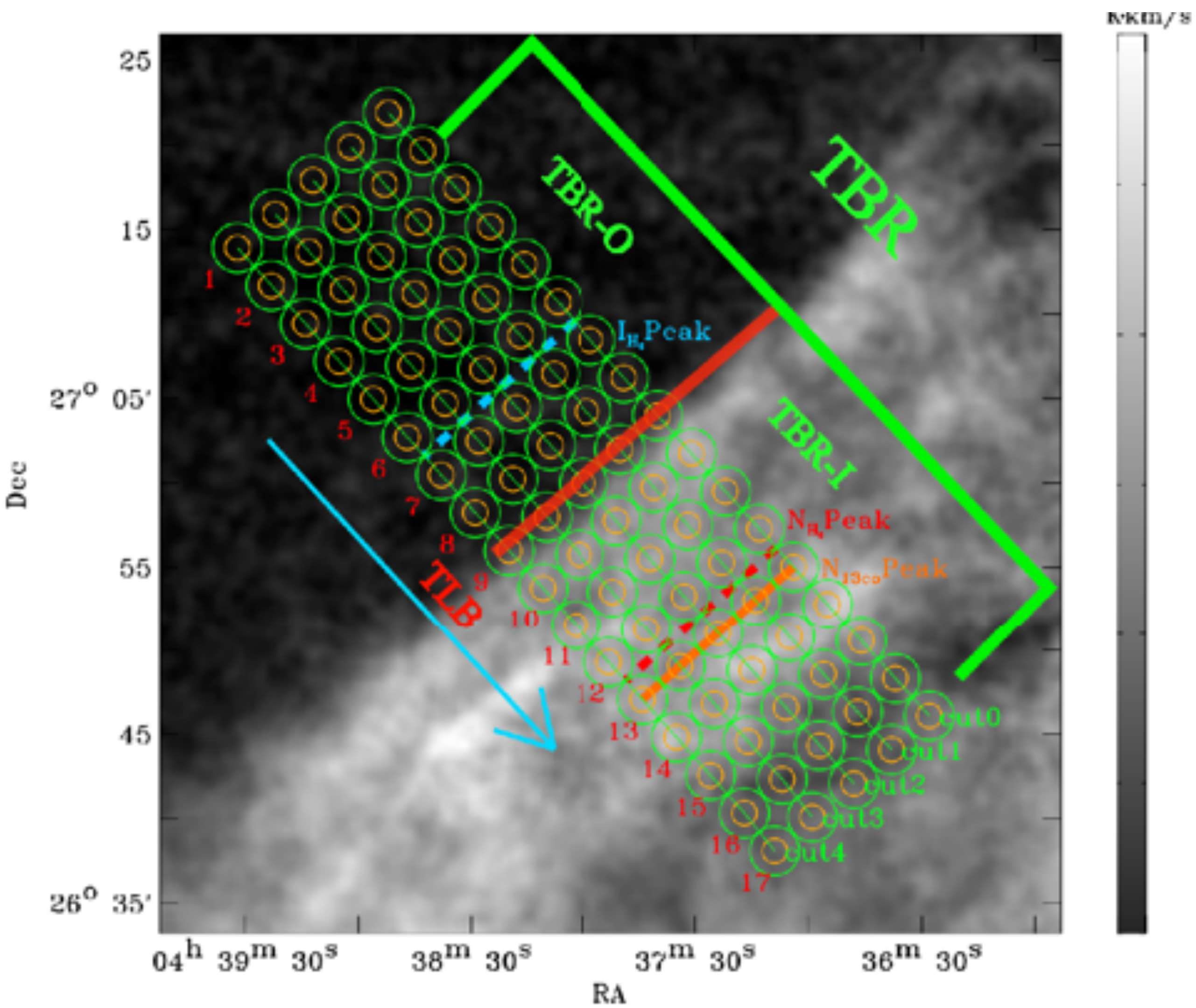
$$OH^+ + H_2 \rightarrow OH_2^+ + H$$

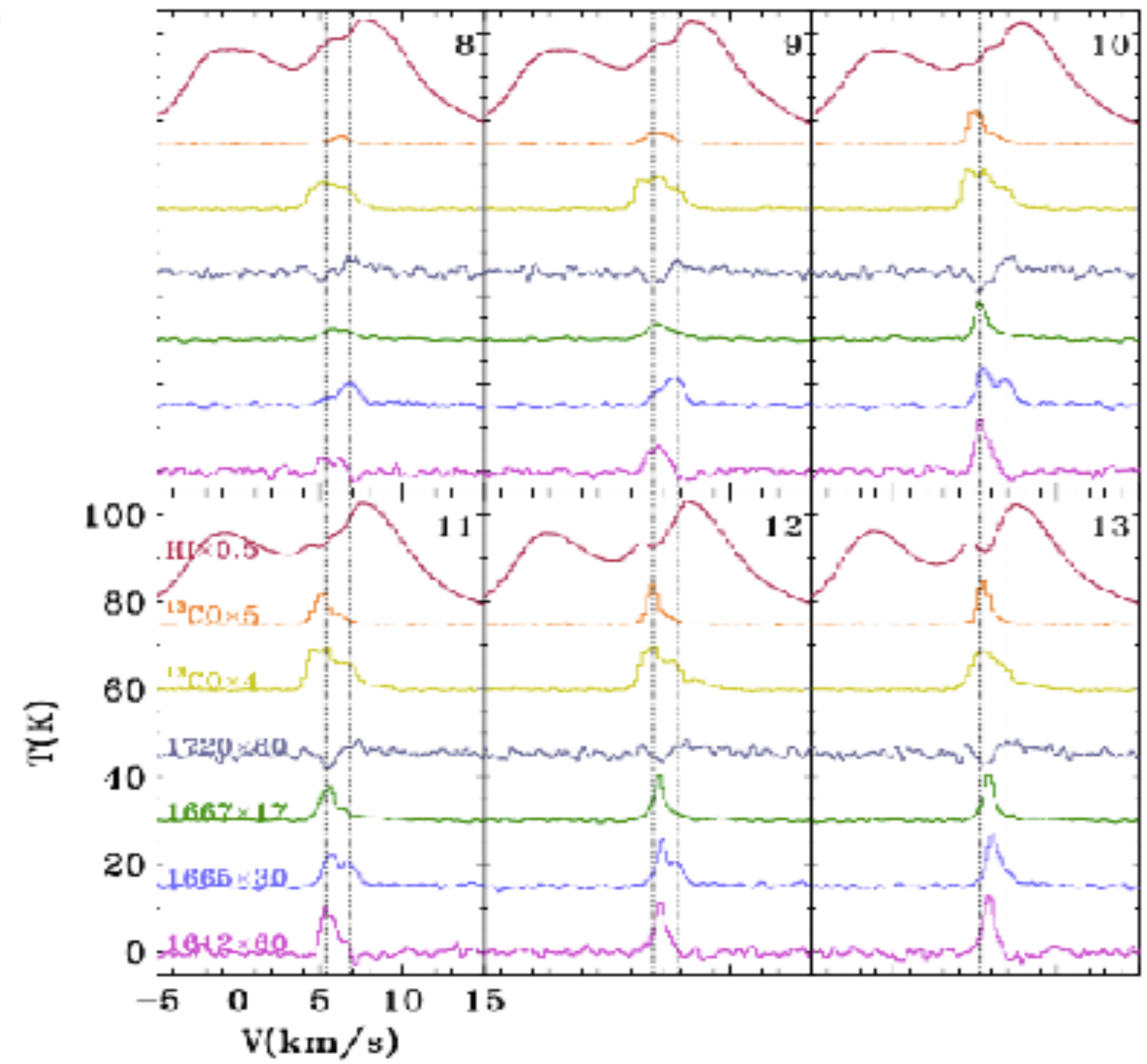
$$OH_2^+ + H_2 \rightarrow H_3O^+ + H$$

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

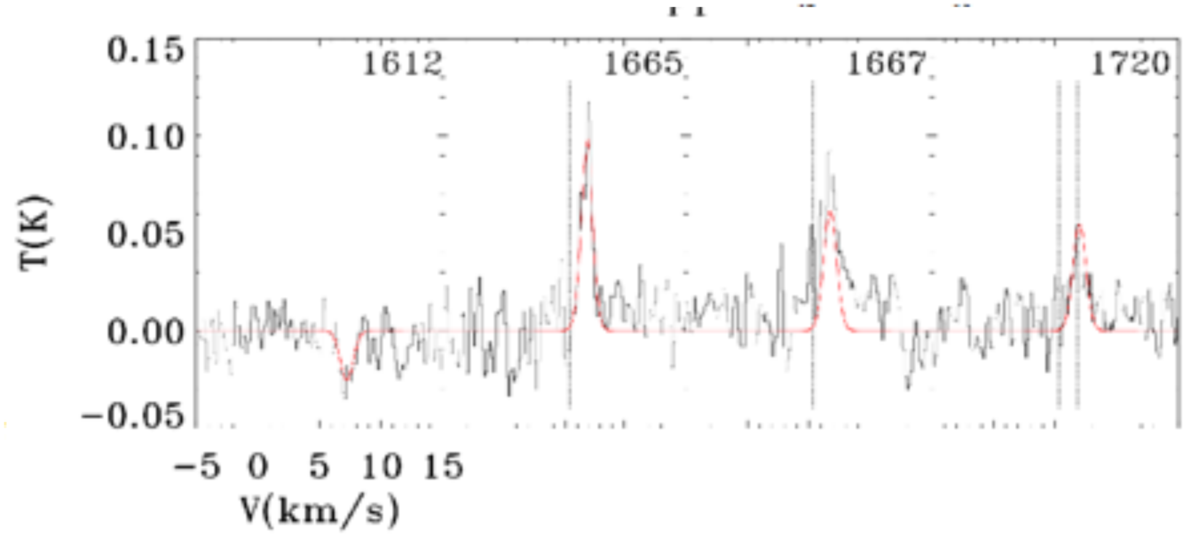
$$C^+ + OH \rightarrow CO^+ + H \quad ; \quad CO^+ + H_2 \rightarrow HCO^+ + H$$

Evolution of **HI, OH, CH** across the **DMG** Zone





Xu, **Li,** Yue+ 2016, ApJ, 819:22



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

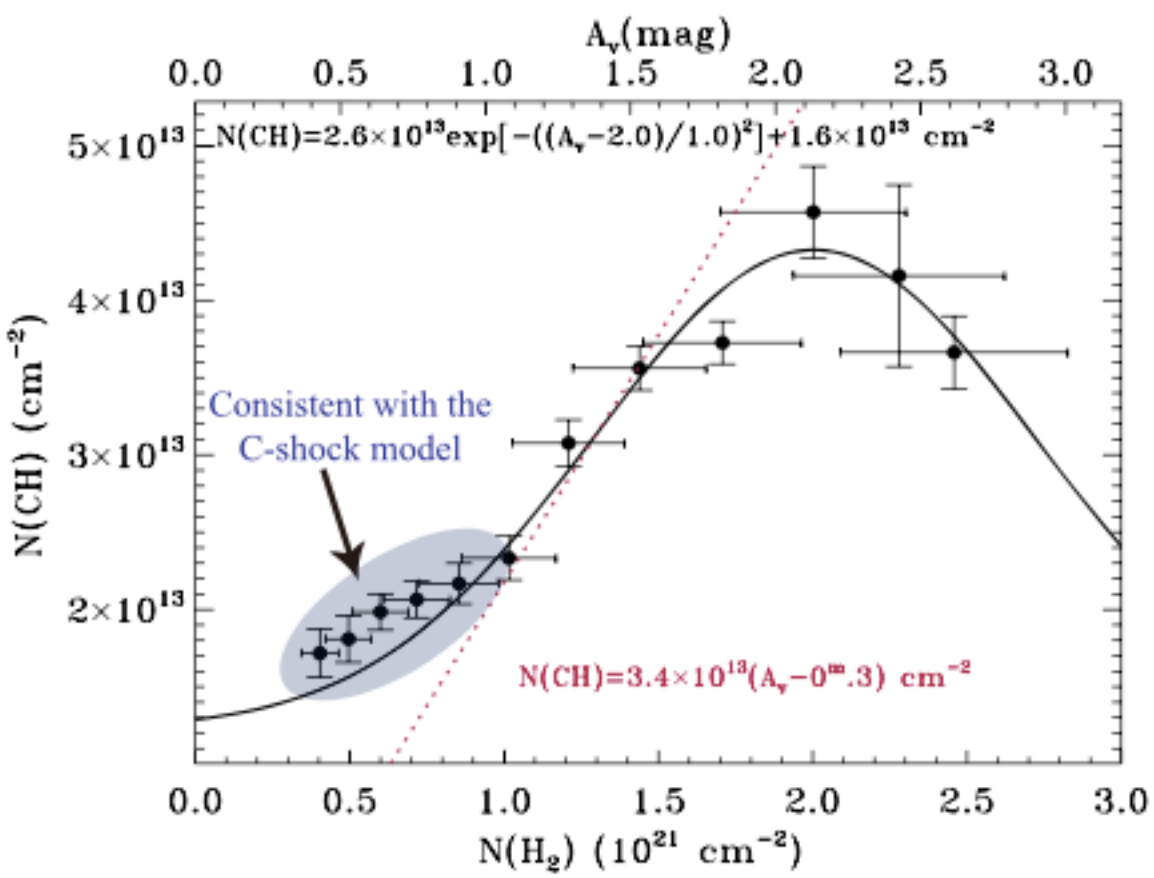
$$[\mathrm{OH}]/[\mathrm{H_2}] = 1.5 \times 10^{-7} + 9.0 \times 10^{-7} \times \exp(-A_v/0.81)$$

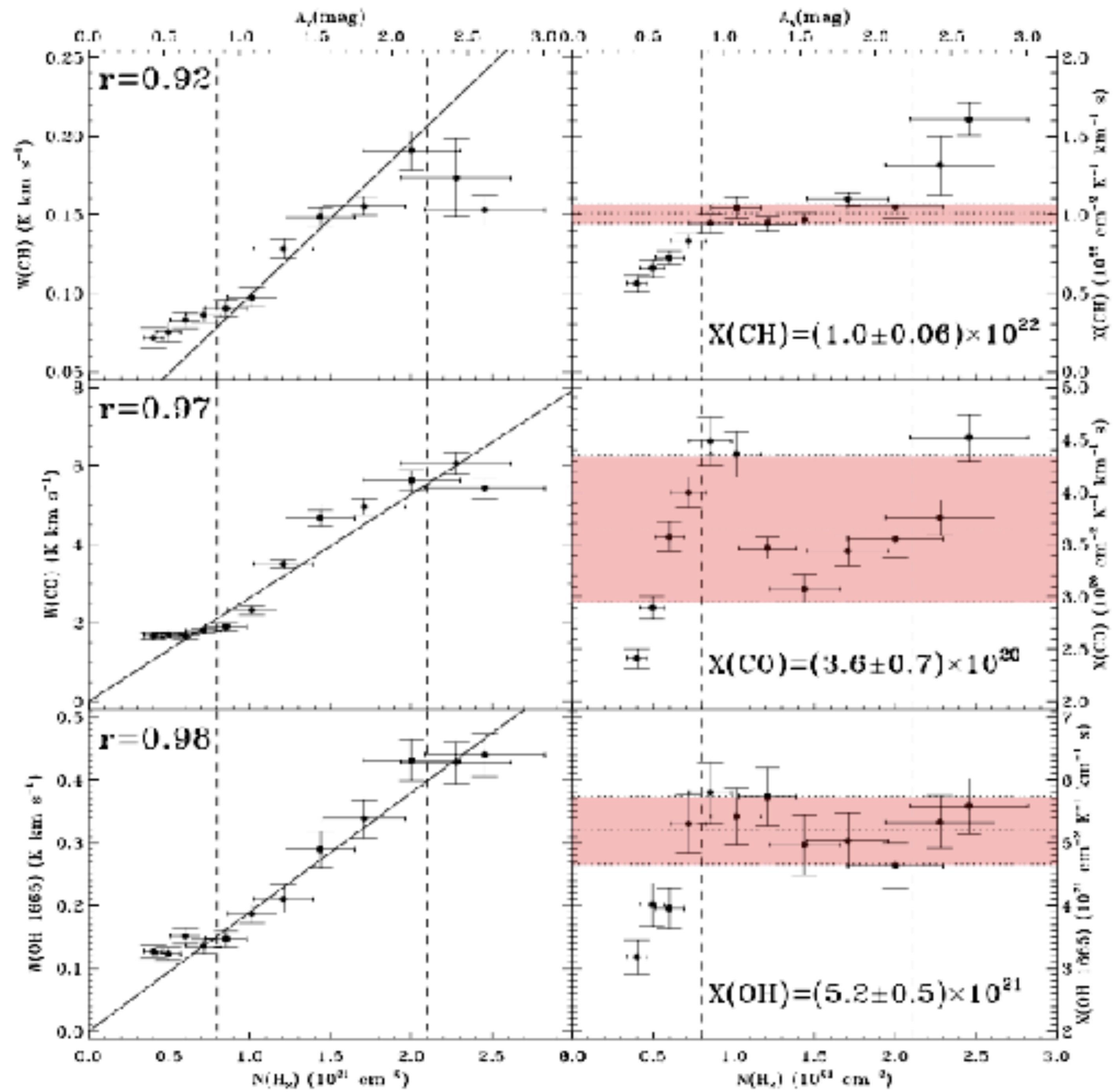
CH AS A MOLECULAR GAS TRACER AND C-SHOCK TRACER ACROSS A MOLECULAR CLOUD BOUNDARY IN TAURUS

Duo Xu(许铎)[1,2,4] and Di Li(李菂)[1,3]

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

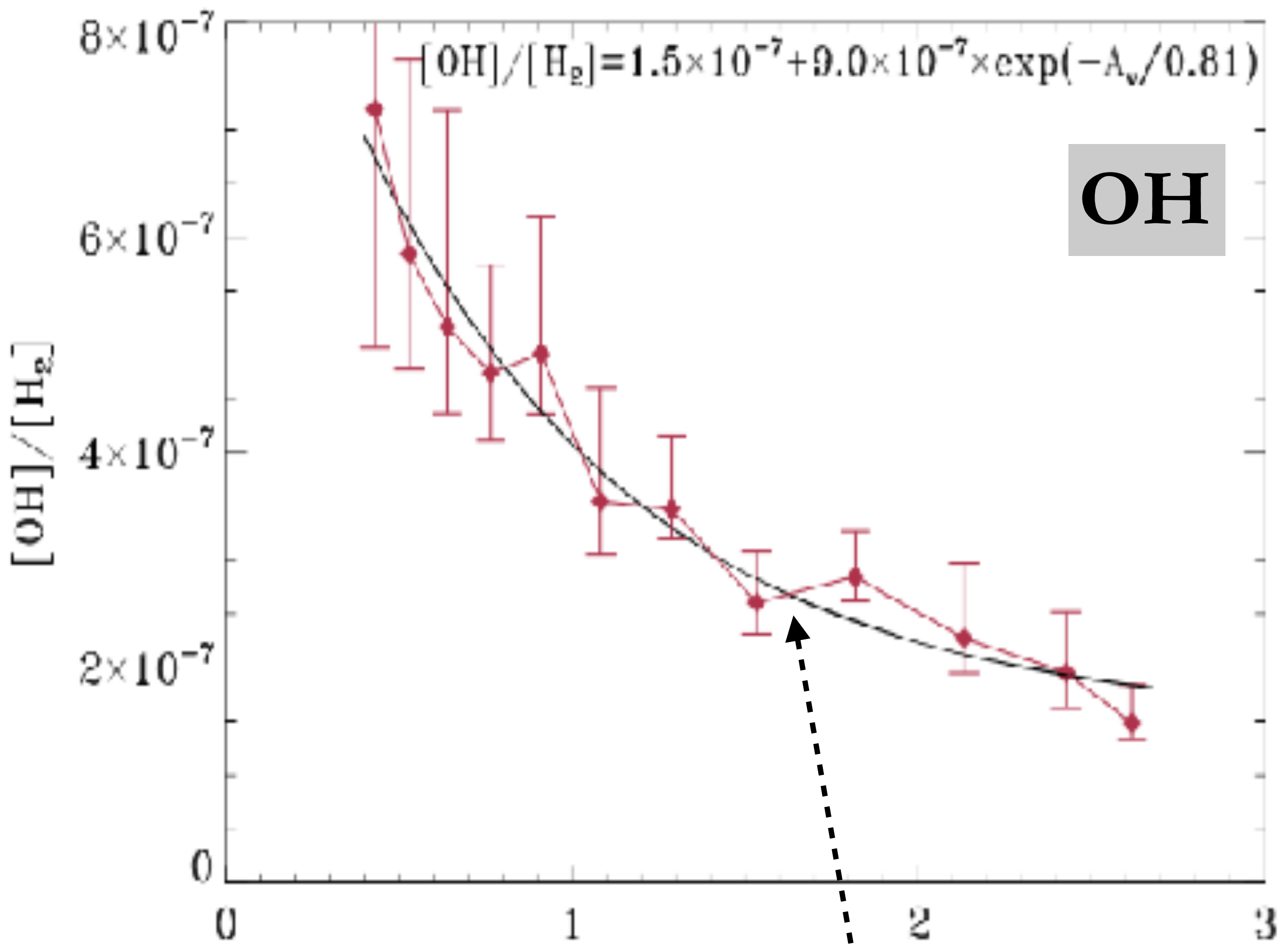
$$C^+ + H \rightarrow CH^+ + h\nu,$$
$$C^+ + H_2 + 0.396\ \mathrm{eV} \rightarrow CH^+ + H,$$
$$CH^+ + e^- \rightarrow CH + h\nu,$$

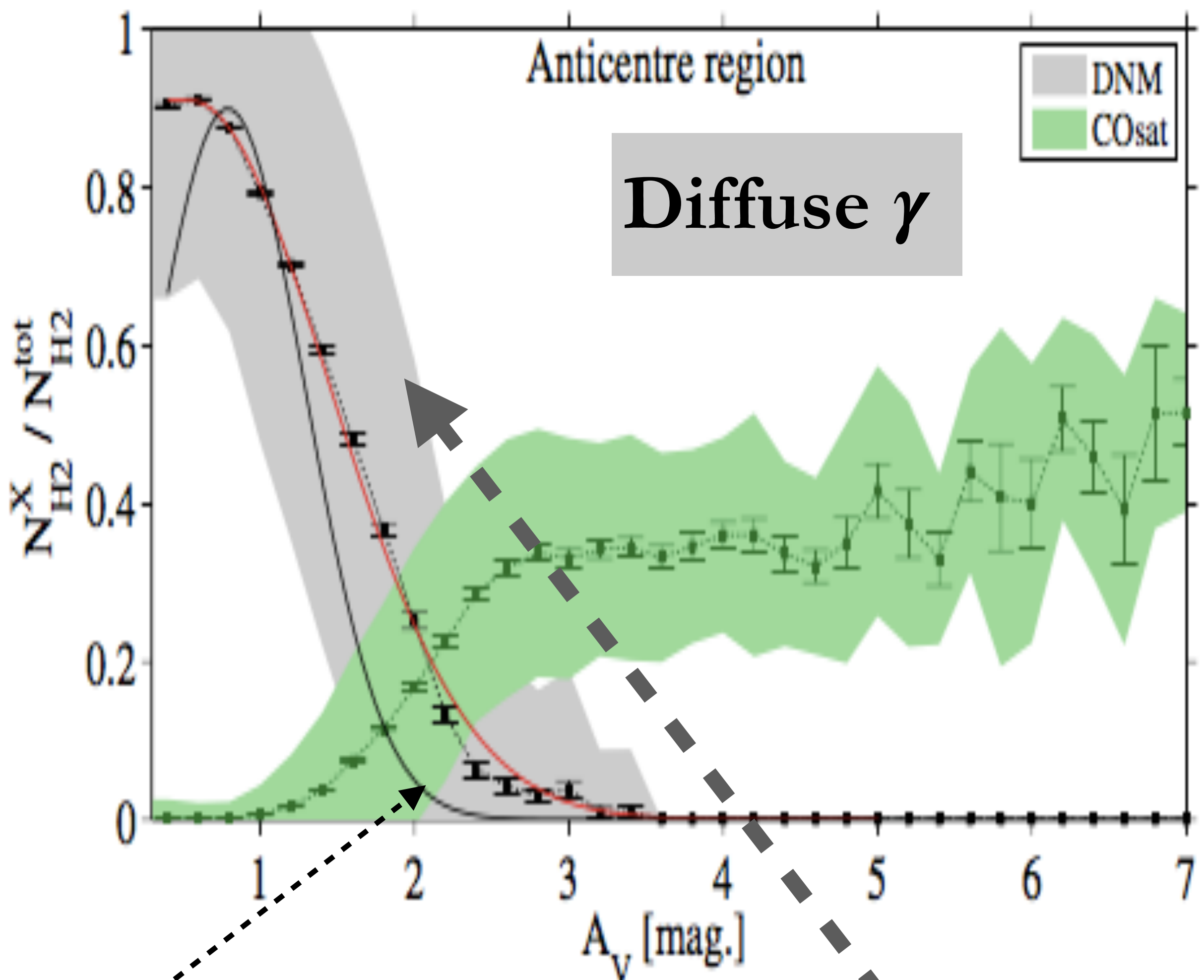




Xu & **Li** 2016, ApJ paper II

DMG & DNM
Intermediate Av ~ 0.1-2





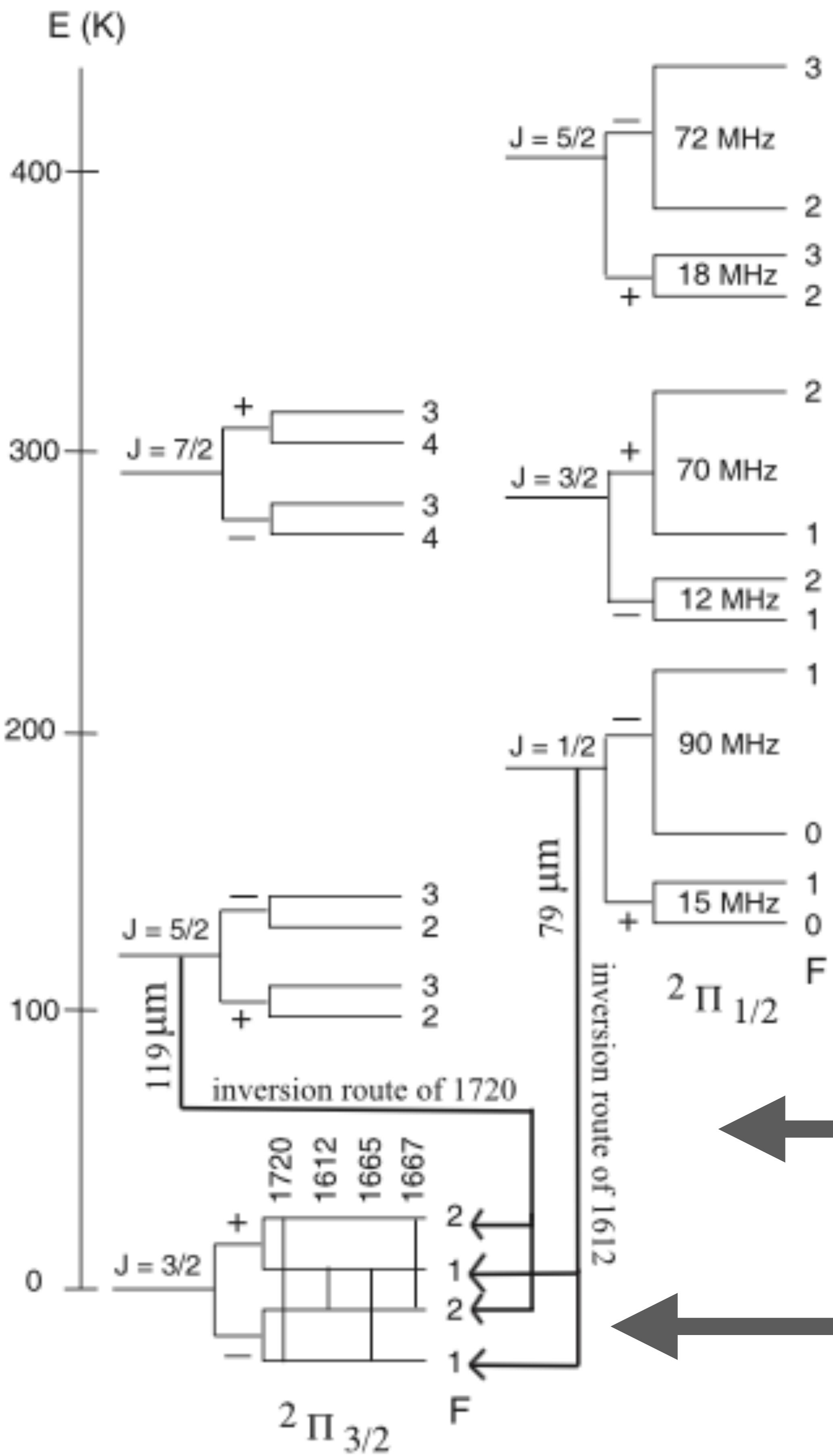
OH abundance co-evolve with CO, N(H), and DGF

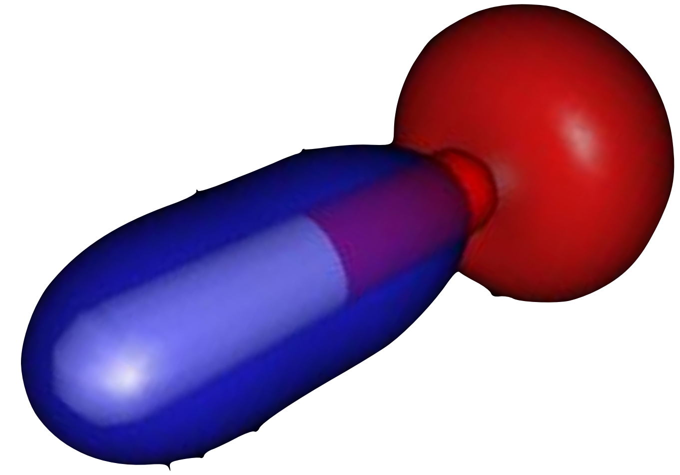
Remy, Grenier et al. 2017
Based on **Fermi**

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

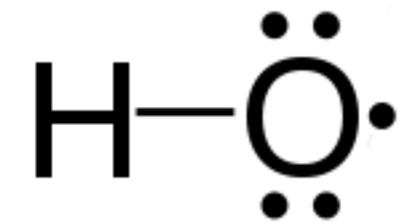
Xu, **Li**+ 2016 ApJ, paper I & II

Xu & Li+ 2016 paper I
based on **Lockett & Elitzur** 2008





Hydroxyl radical



IR

cm

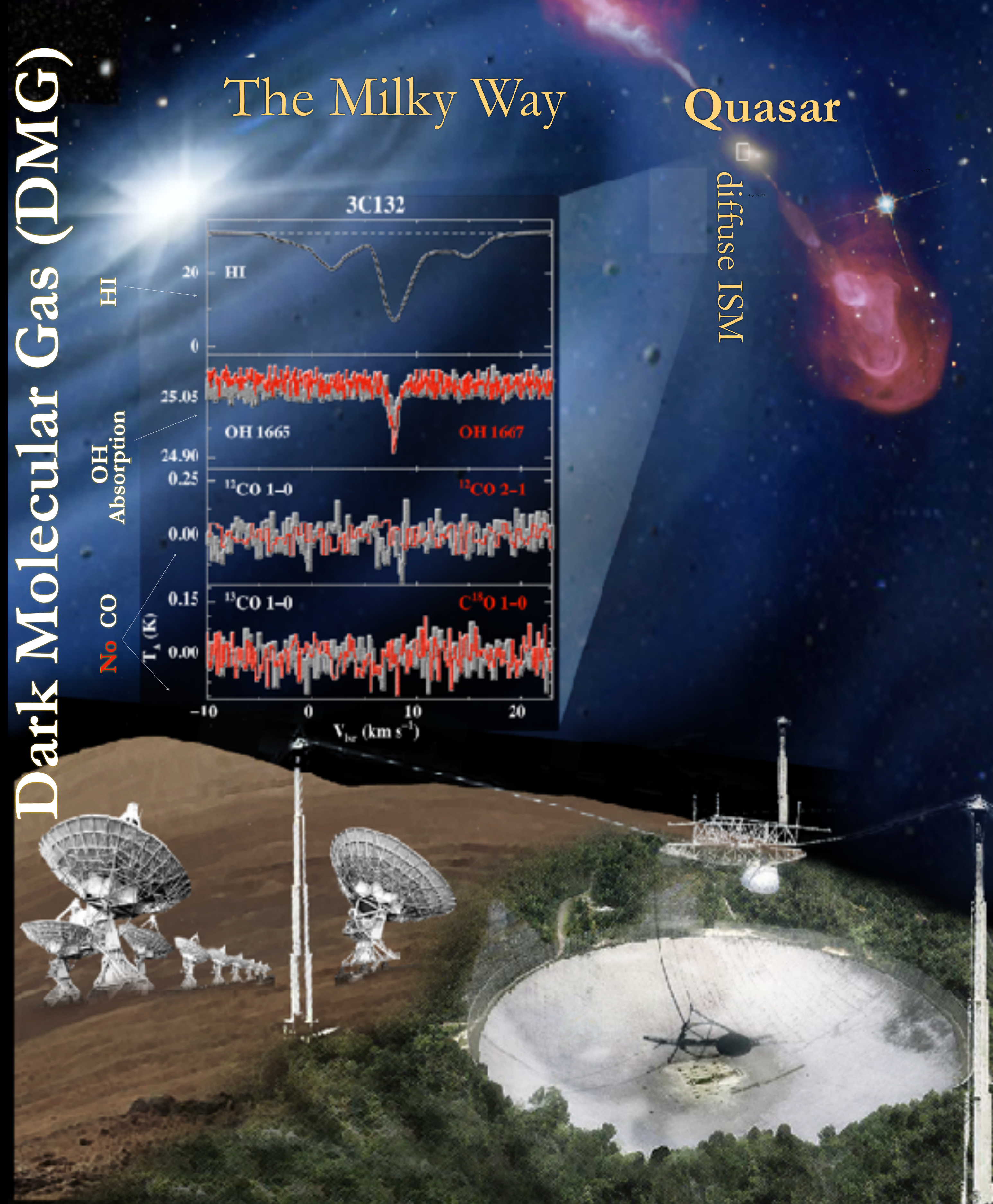
Pacific **R**im **I**nterstellar **M**atter **O**bserver

PRIMO

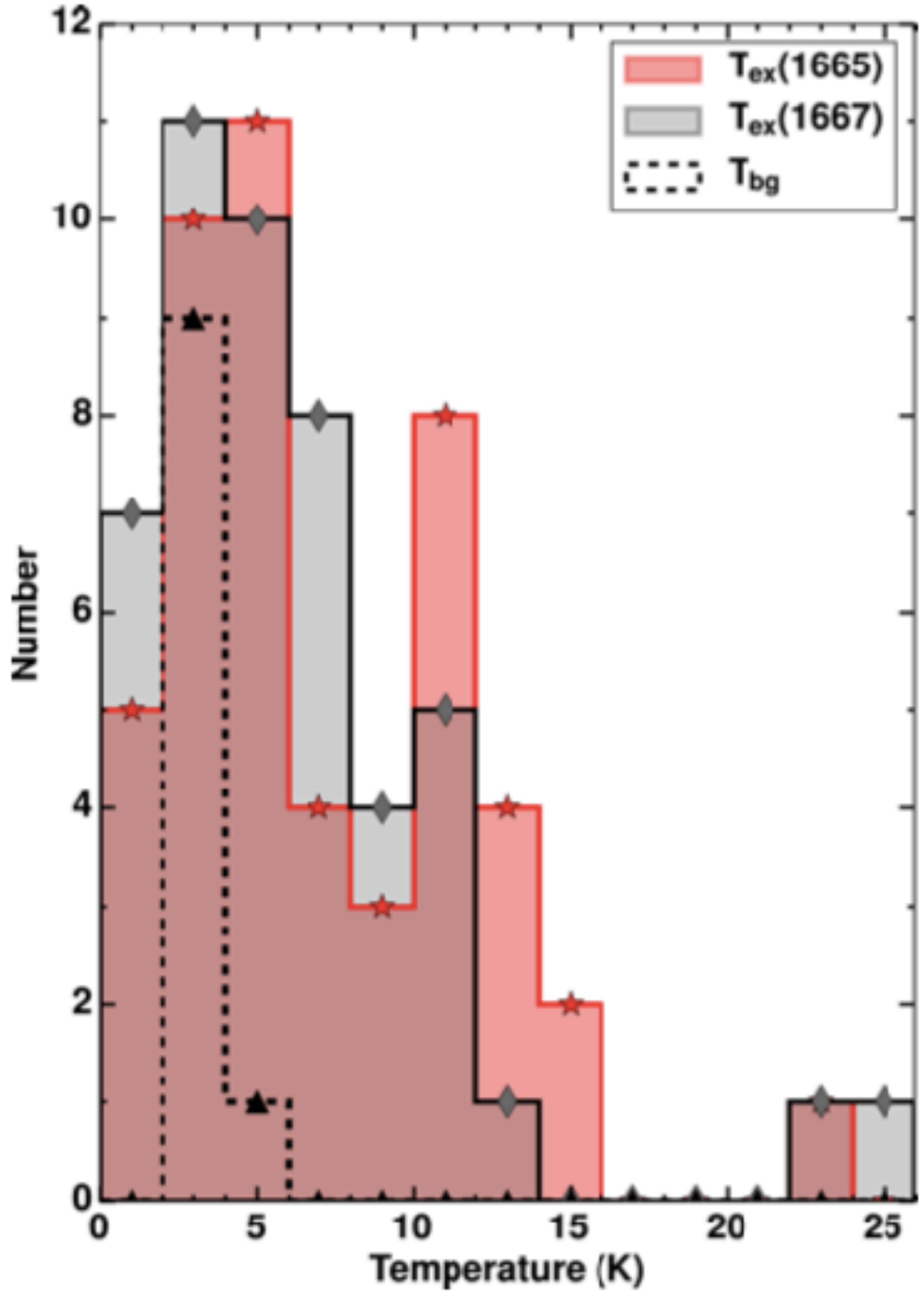
"Where is OH and Does it Trace the Dark Molecular Gas (DMG) ?"
Li, Tang, +**PRIMO**, ApJS, 235,1

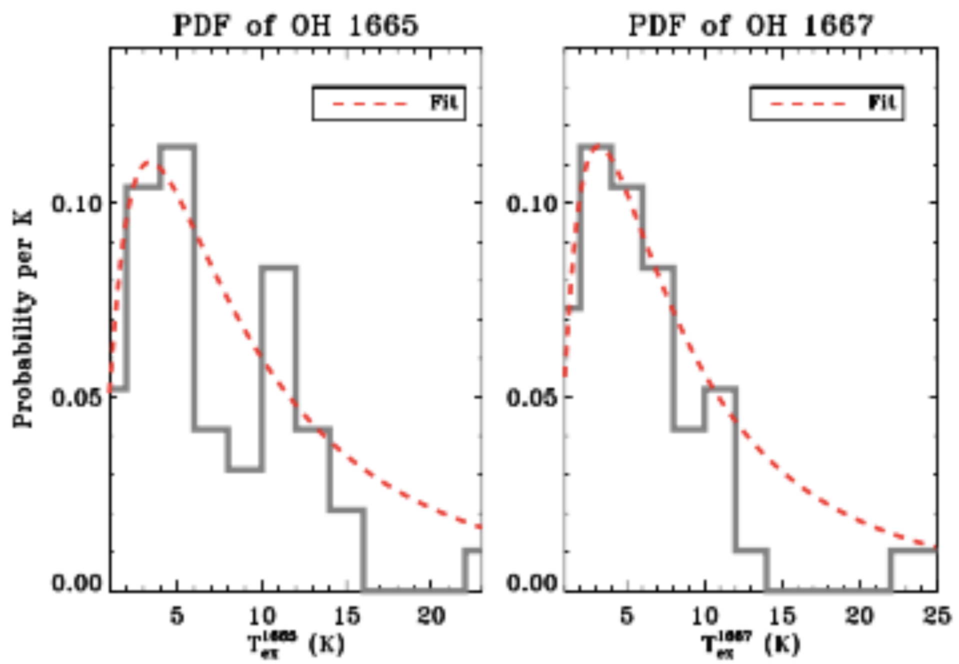
"Dust–Gas Scaling Relations and OH Abundance in the Galactic ISM"
Nguyen, Dawson,+**PRIMO**, ApJ

- OH excitation temperature peaks around CMB
- OH abundance tracks DMG fraction
- **FAST** will supersede Arecibo by x10. Tests underway



OH Excitation



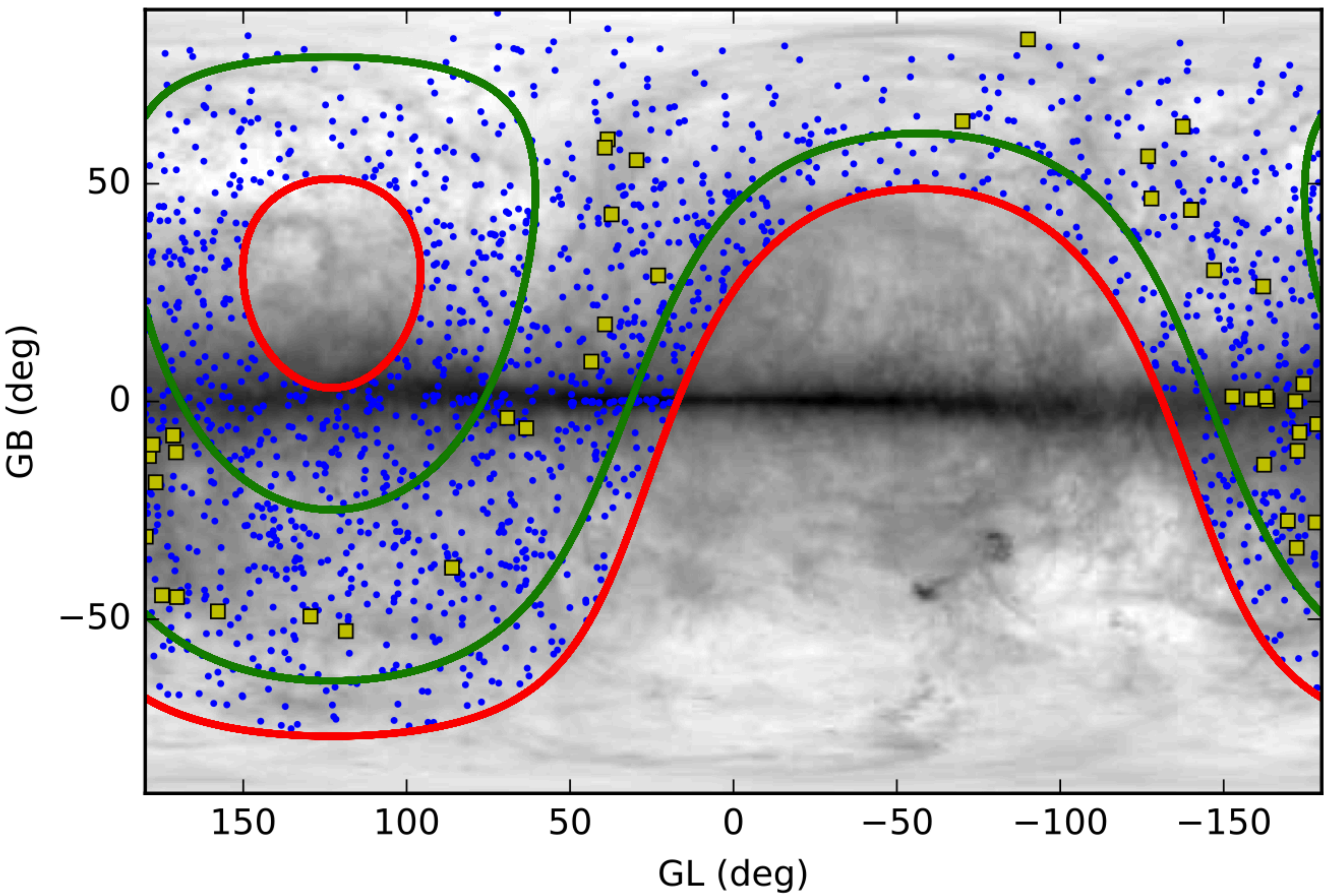


$$f(T_{\rm ex}) \propto \frac{1}{\sqrt{2\pi}\sigma}\exp[-\frac{[\ln(T_{\rm ex})-\ln(3.4\ {\rm K})]^2}{2\sigma^2}]$$

Line	Fitted T^{0}_{ex} [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** (2018)

OH Absorption Survey with FAST



FAST

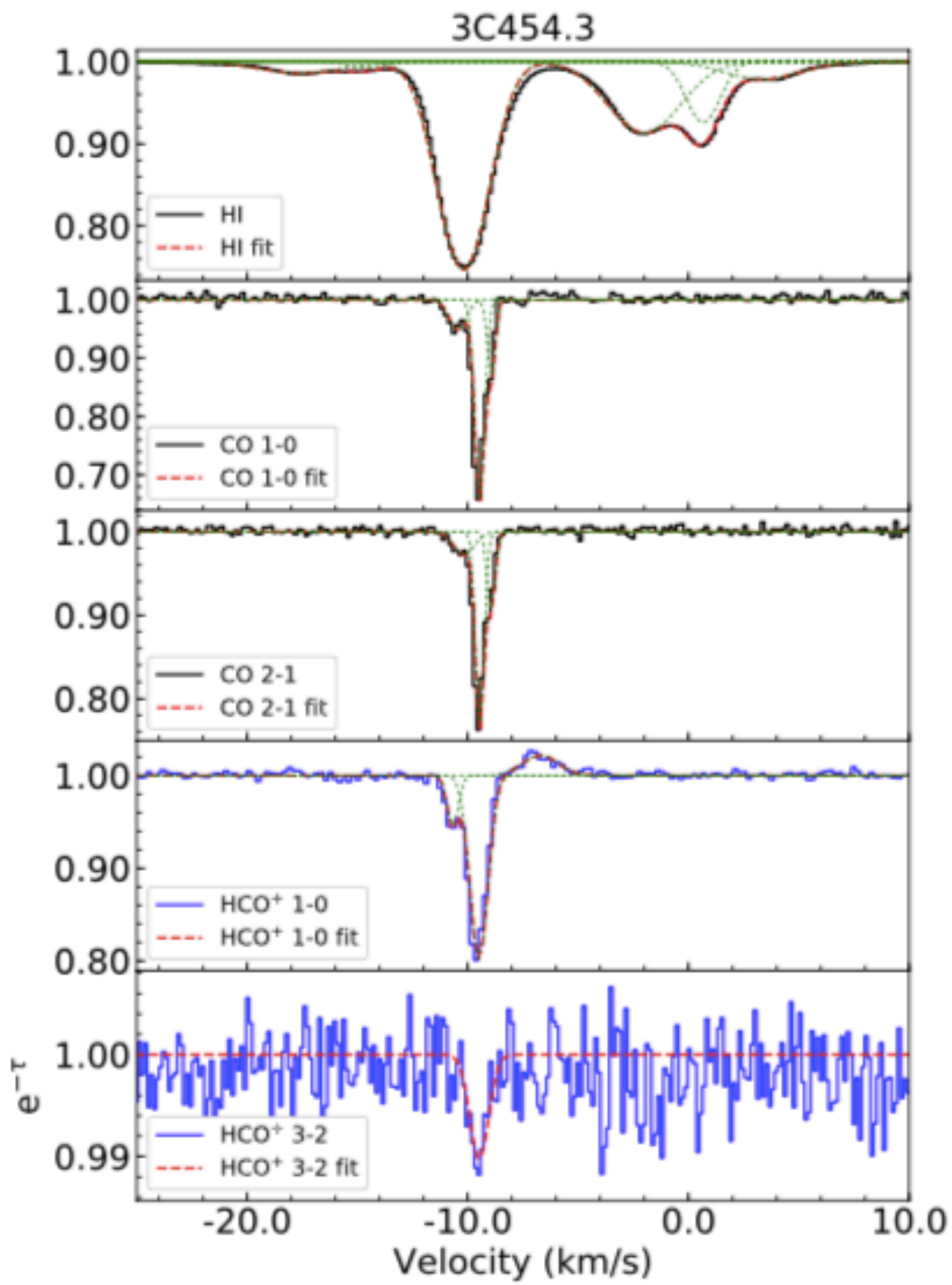
Arecibo

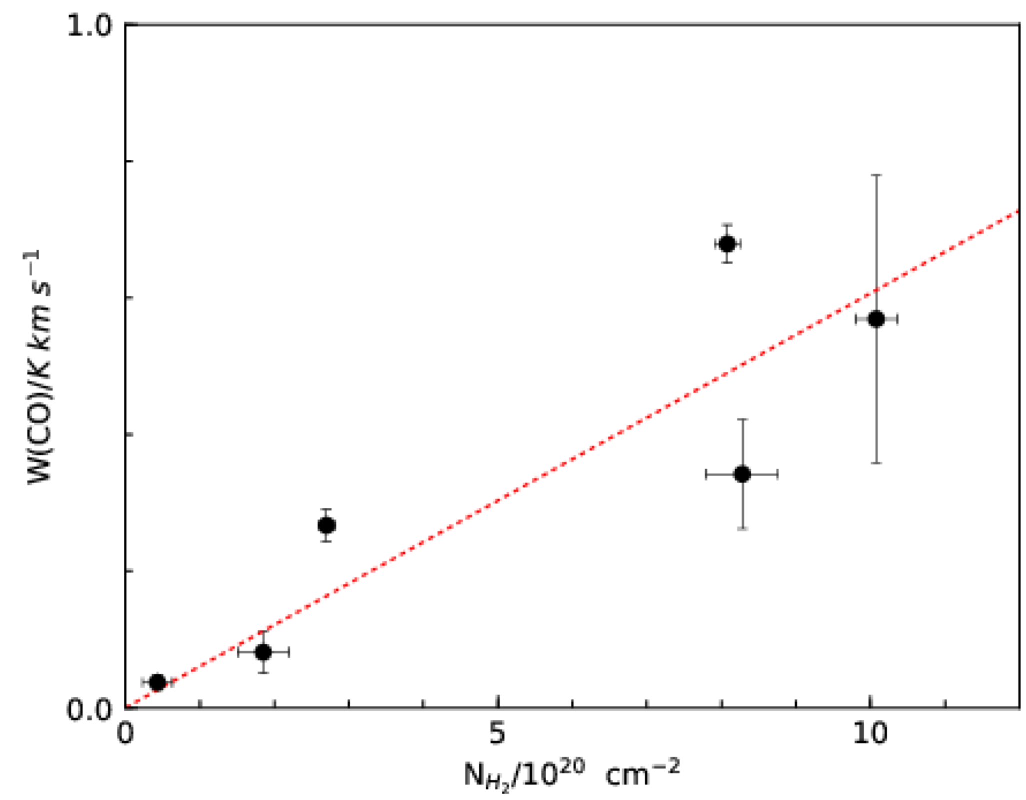
Yellow Millennium sources>2 Jy used for analysis.

Blue FAST sources>0.75 Jy covered. One drift scan allows for 3 sigma detection of OH cloud tau(OH)=0.05

Li, Tang+
PRIMO (2018)

ALMA Absorption





$X_{CO} = 16 \pm 2/10^{20} cm^{-2}\ (K\ km\ s^{-1})^{-1}$

2.1 (Pineda et al. 2010)

2.54 ± 0.13 (Planck Collaboration et al. 2011)

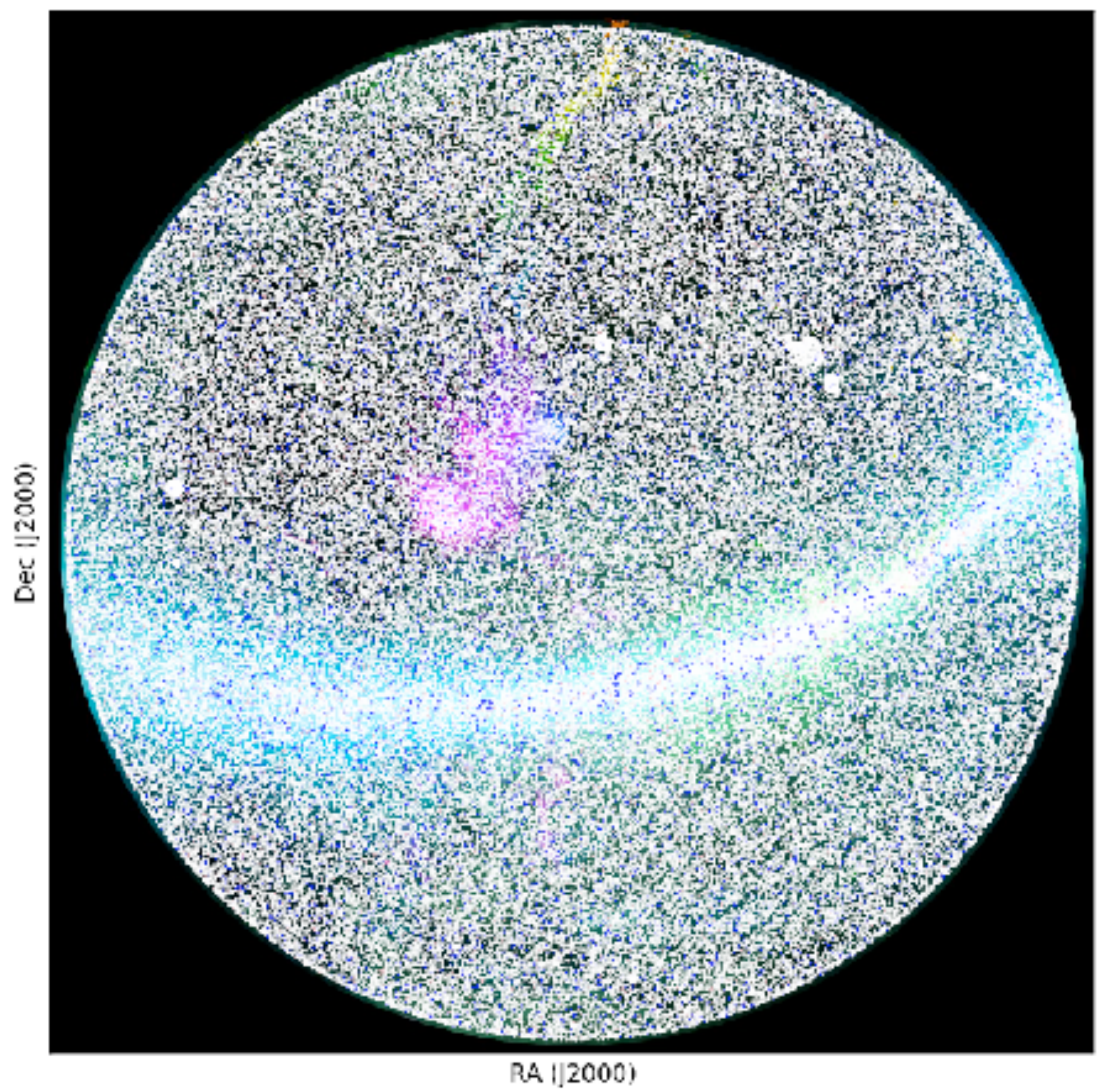
Luo, Tang, DL 2019 in prep.

PROCEEDINGS OF SCIENCE

Galactic and Magellanic Evolution with the SKA

Naomi M. McClure-Griffiths*[1], Snežana Stanimirović[2], Claire E. Murray[2], Di Li[3], John M. Dickey[4], Enrique Vázquez-Semadeni[5], Josh E. G. Peek[6], Mary Putman[6], Susan E. Clark[6], Marc-Antoine Miville-Deschênes[7], Joss Bland-Hawthorn[8], Lister Staveley-Smith[9], on behalf of the H I Science Working Group

Absorption Imaging

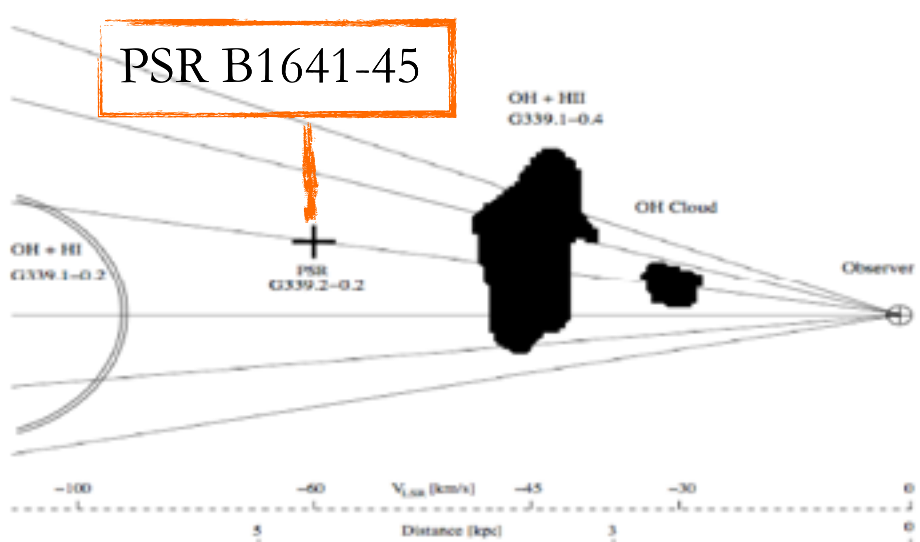


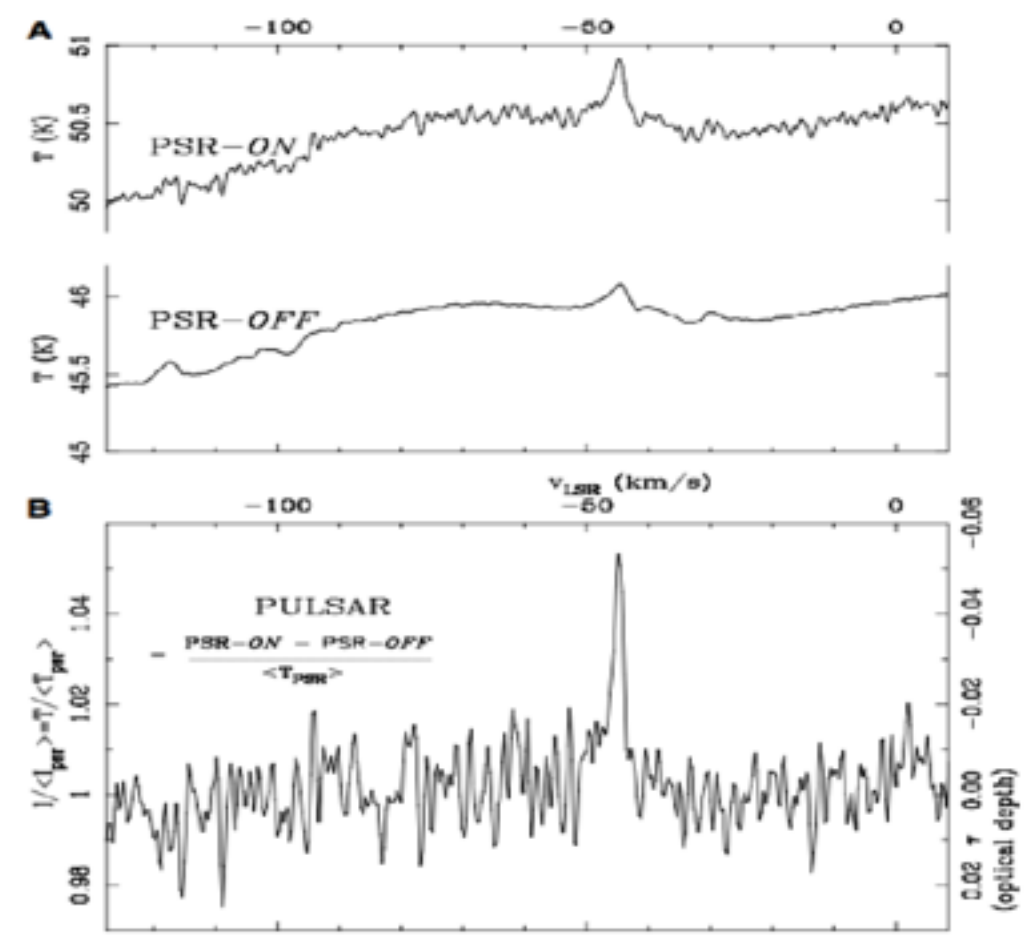
Pulsar-Stimulated Emission

REPORTS

Discovery of Pulsed OH Maser Emission Stimulated by a Pulsar

Joel M. Weisberg,[1,2,3*] Simon Johnston,[2,1] Bärbel Koribalski,[1] Snezana Stanimirović[4]





A Case Study for UWL: **OH + CH** simultaneously

"A Follow-up Study of Stimulated Emission toward PSR B1641-45", **Li** & Hobbs + 2018， 2019 Parkes

Conclusions

- **HINSA** traces cold HI mixed with CO and clock the chemical age of dark clouds at 10 Myr, more consistent with the 'classical' SF picture, which is favored over 'fast/dynamic' star formation (cf. Elmegreen+, Bergin+).

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

$$[\mathrm{OH}]/[\mathrm{H_2}] = 1.5 \times 10^{-7} + 9.0 \times 10^{-7} \times \exp(-A_v/0.81)$$

- All tracers have caveats: OH excitation temperature is close to CMB. Diffuse CO sub-thermally excited. C^+ fine structure line 91K above ground state. Modeling diffuse γ is uncertain.

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