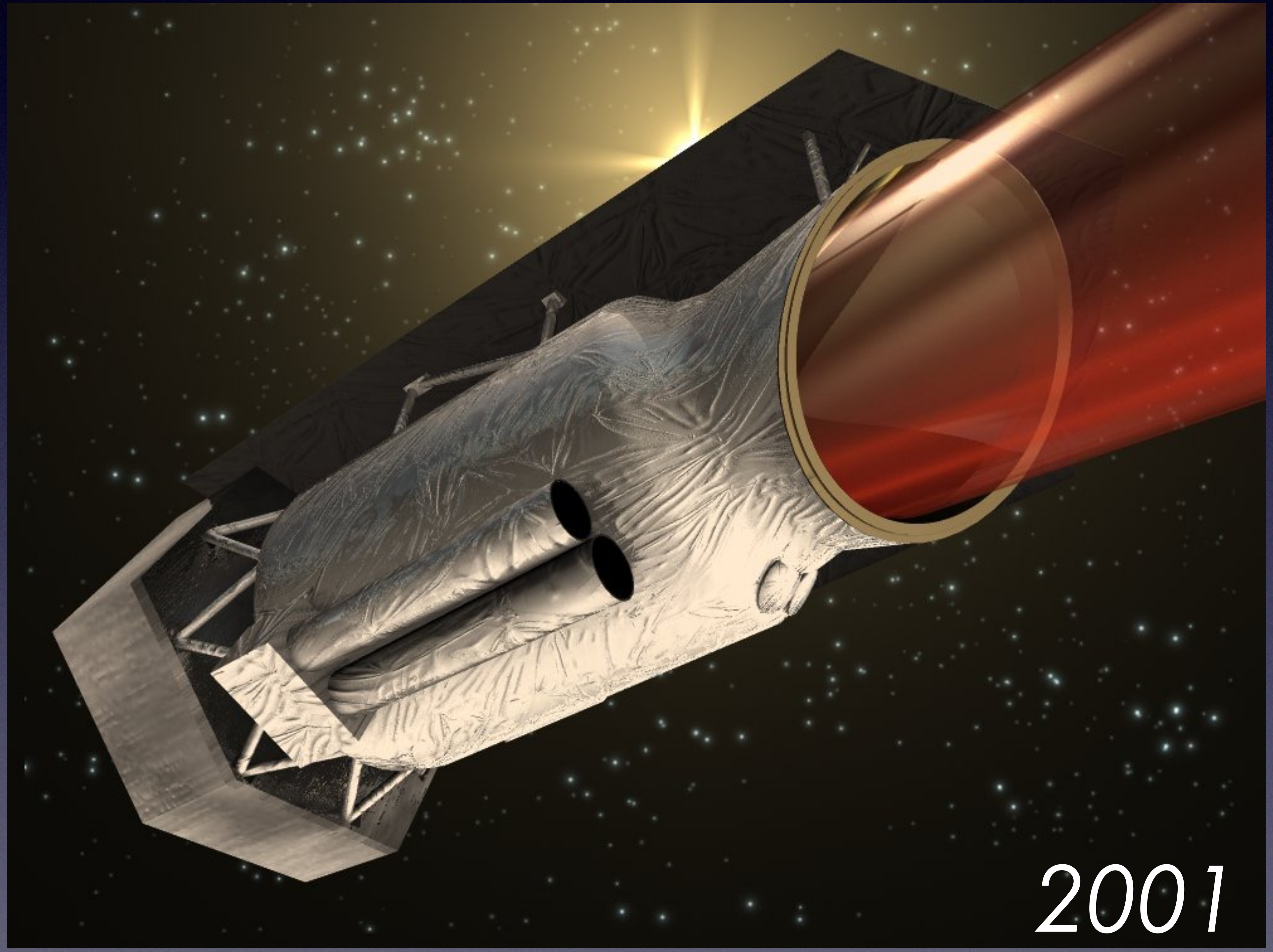
Atomic Oxygen Abundance Toward Sagittarius B2



Jet Propulsion Laboratory
California Institute of Technology

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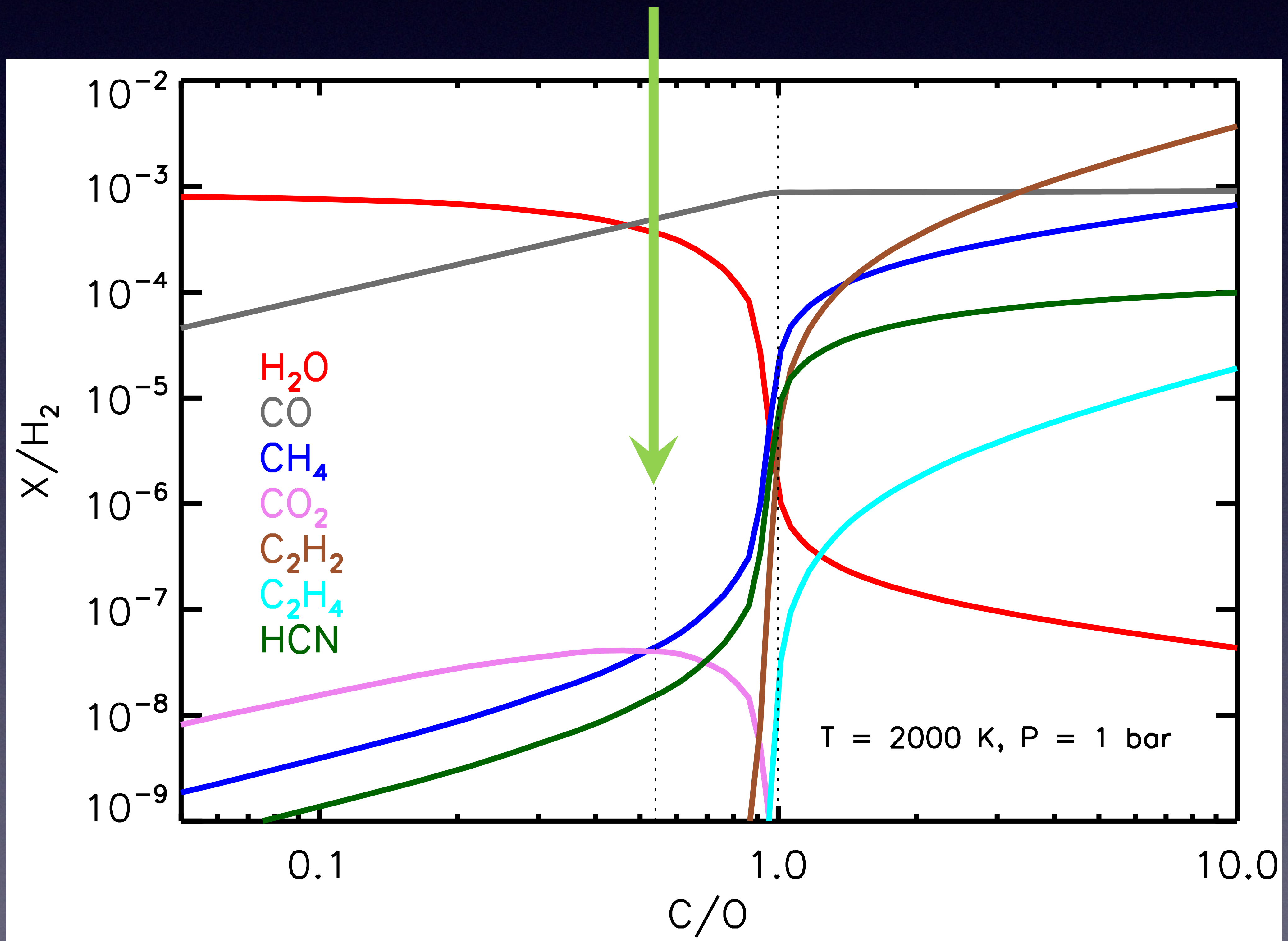
P. Schilke, H. Wiesemeyer, Y. Seo, and M. Werner

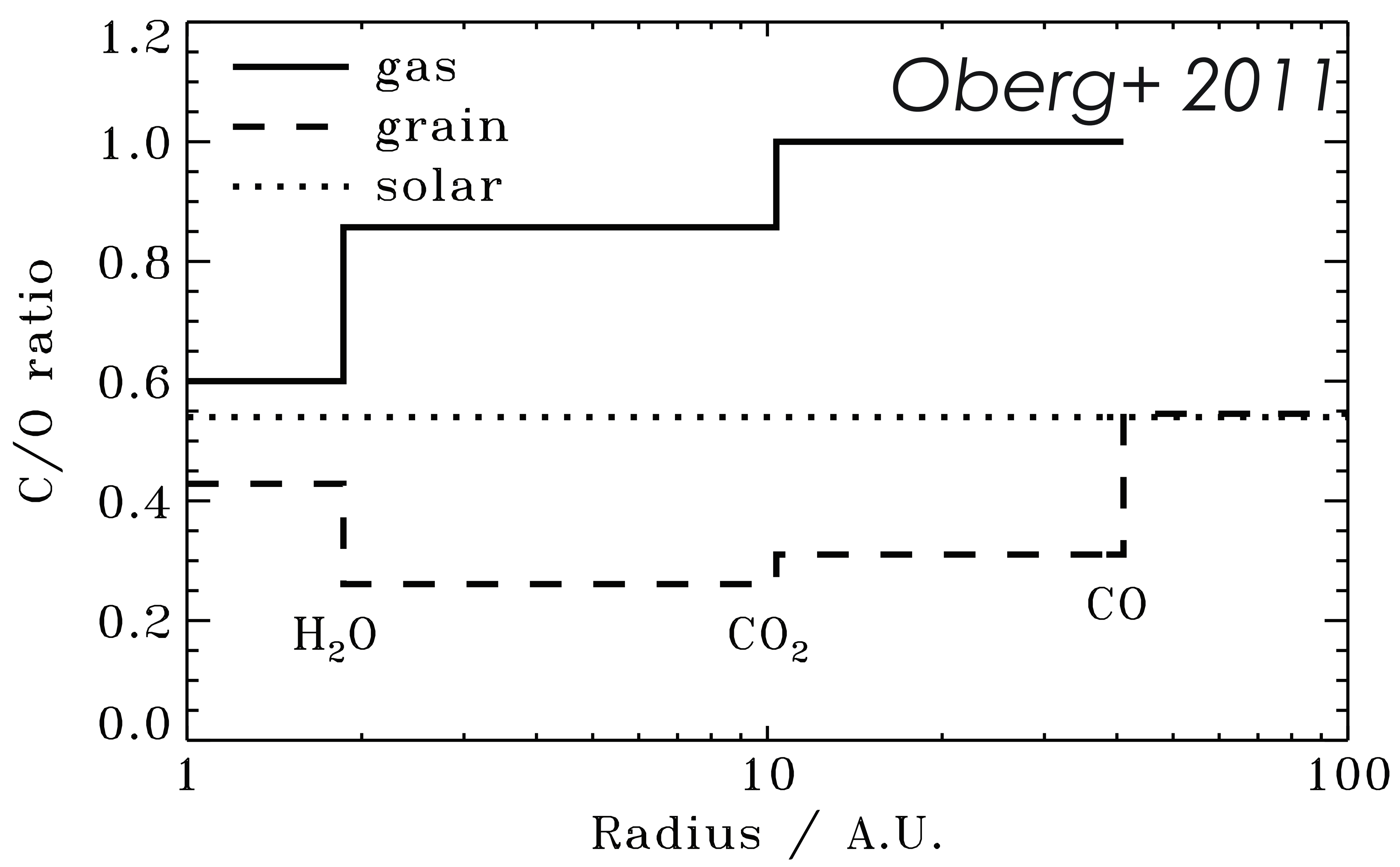
SOFIA TeleTalk, April 5, 2023

C/O Ratio

Solar C/O=0.54



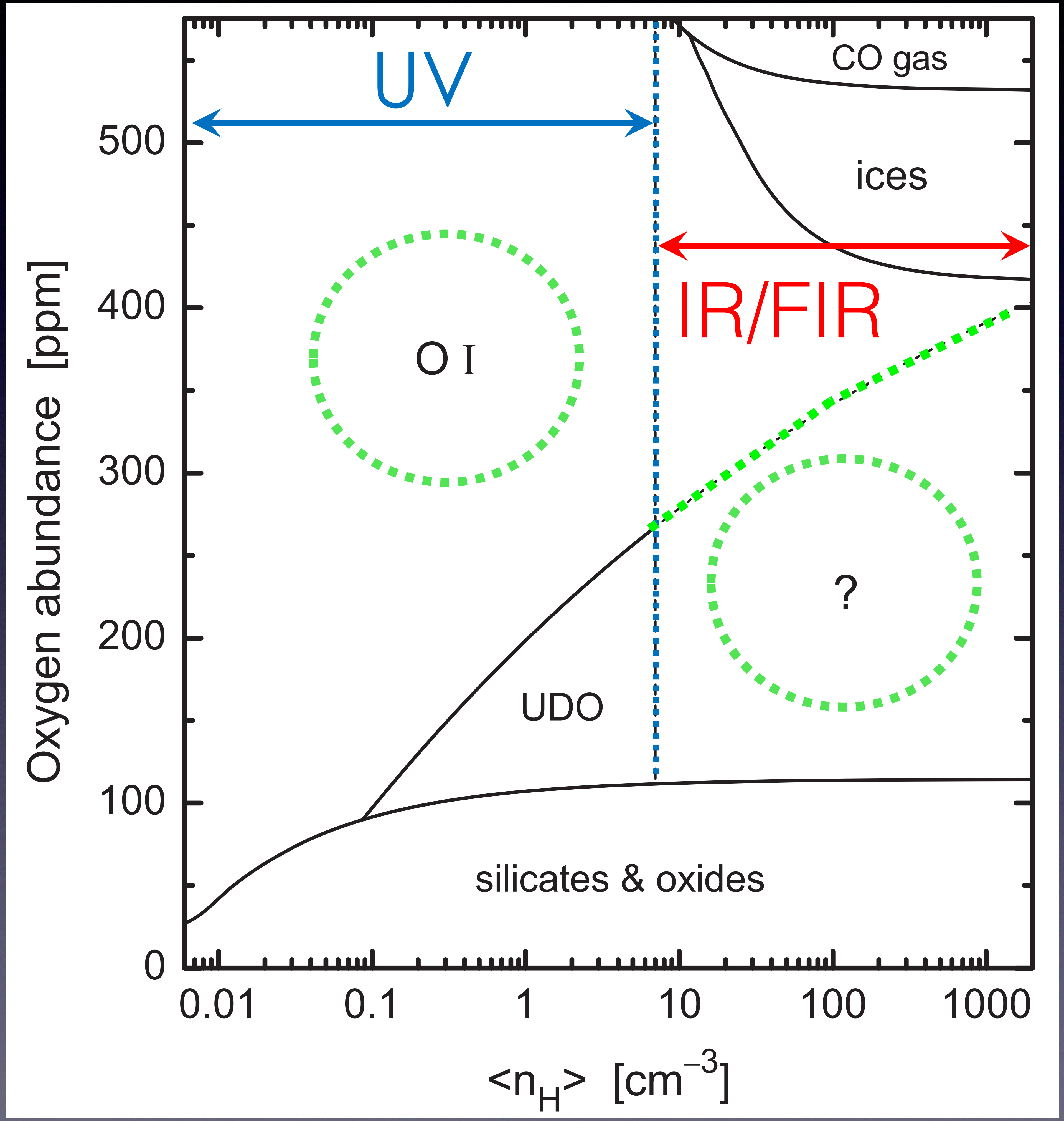
Madhusudhan 2012



Oberg+ 2011

- C/O ratio controls the nature of terrestrial planets
- A high C/O ratio implies that elements such as Ca, Fe and Ti are locked up during condensation as carbides, sulfides and nitrides rather than silicates and oxides
- The internal oxidation state then strongly influences the formation and evolution of the core, mantle, and crust of differentiated (exo)planets
- The overall C/O ratio is an important parameter for characterizing exoplanetary atmospheres
- ISM observations allow the determination of the initial C/O elemental ratio in planet-forming disks

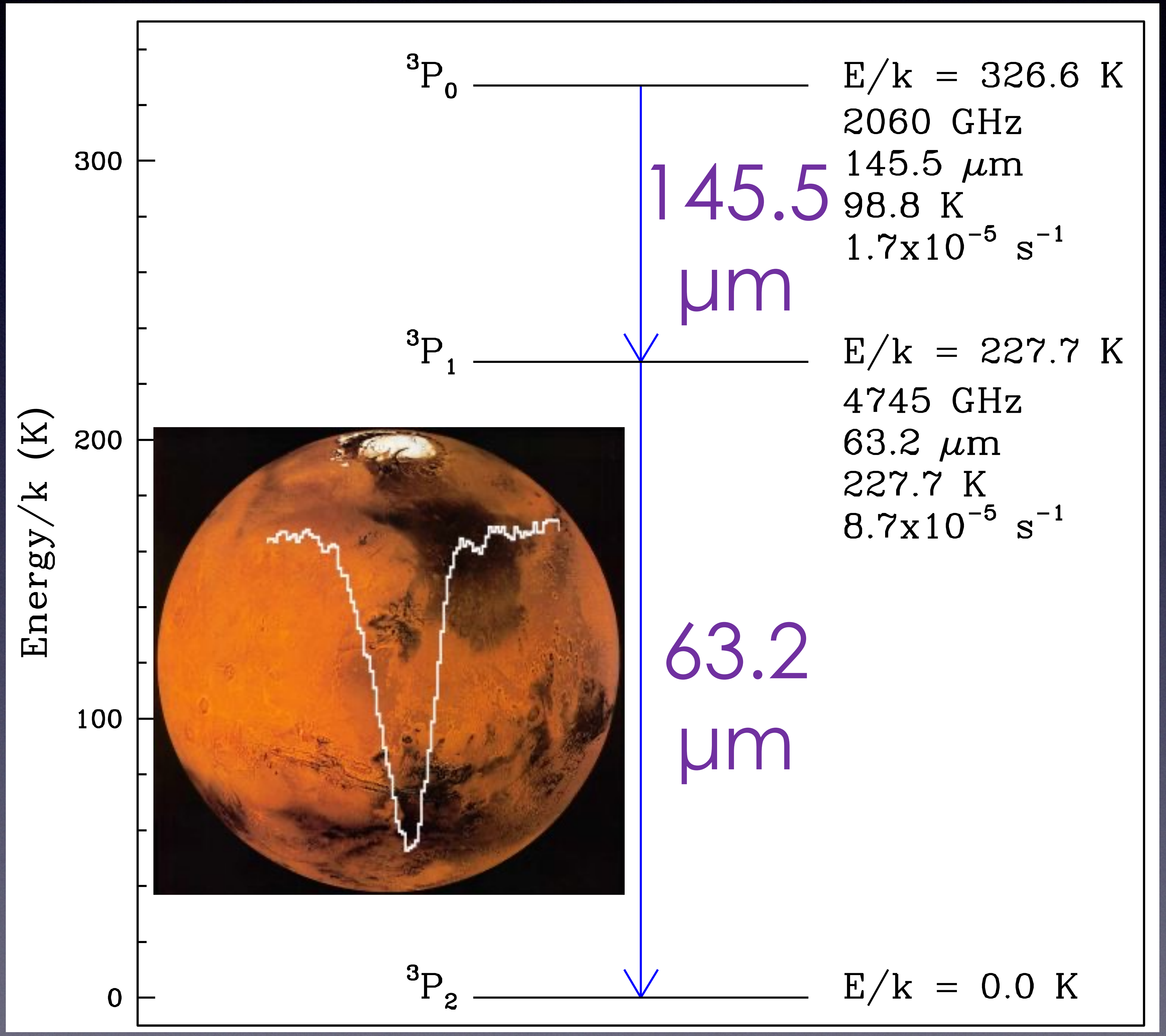
Gas-Phase Abundances of C and O



Whittet 2010 – Goldsmith+ 2011, Liseau+ 2012, van Dishoeck+ 2021

- First ion-molecule reaction schemes (Herbst & Klemperer, Dalgarno & Black): fundamental reservoirs CO, H_2O, and O_2
- C/O~ 0.5: nearly all C should be in CO, with plenty of O left over for H_2O and O_2
- CO was confirmed by mm spectroscopy at ~10^{-4} of H_2
- *Herschel* observations showed that H_2O abundance is universally low at ~10^{-6}, and O_2 even lower $<5\times10^{-8}$
- Within simple chemistry models the only solution is to have a short pre-stellar phase (0.1 Myr) to prevent all oxygen from being turned into water
- O may be in some refractory form (unidentified depleted oxygen or UDO), that does not vaporize or atomize even in strong shocks
- Atomic oxygen is an important part of the O budget

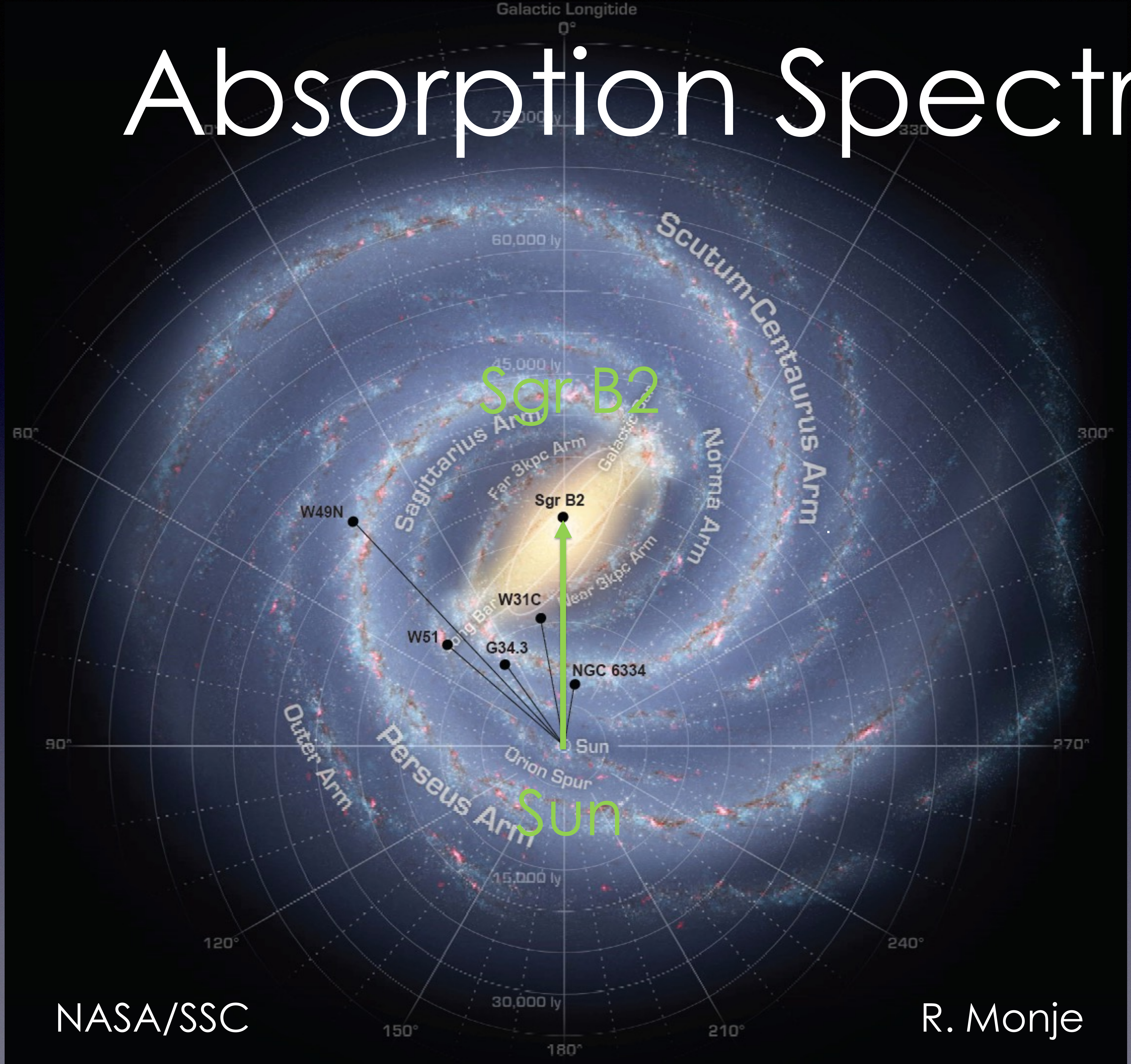
FIR Spectroscopy of [OI]



Goldsmith+ 2019, Rezac+ 2015

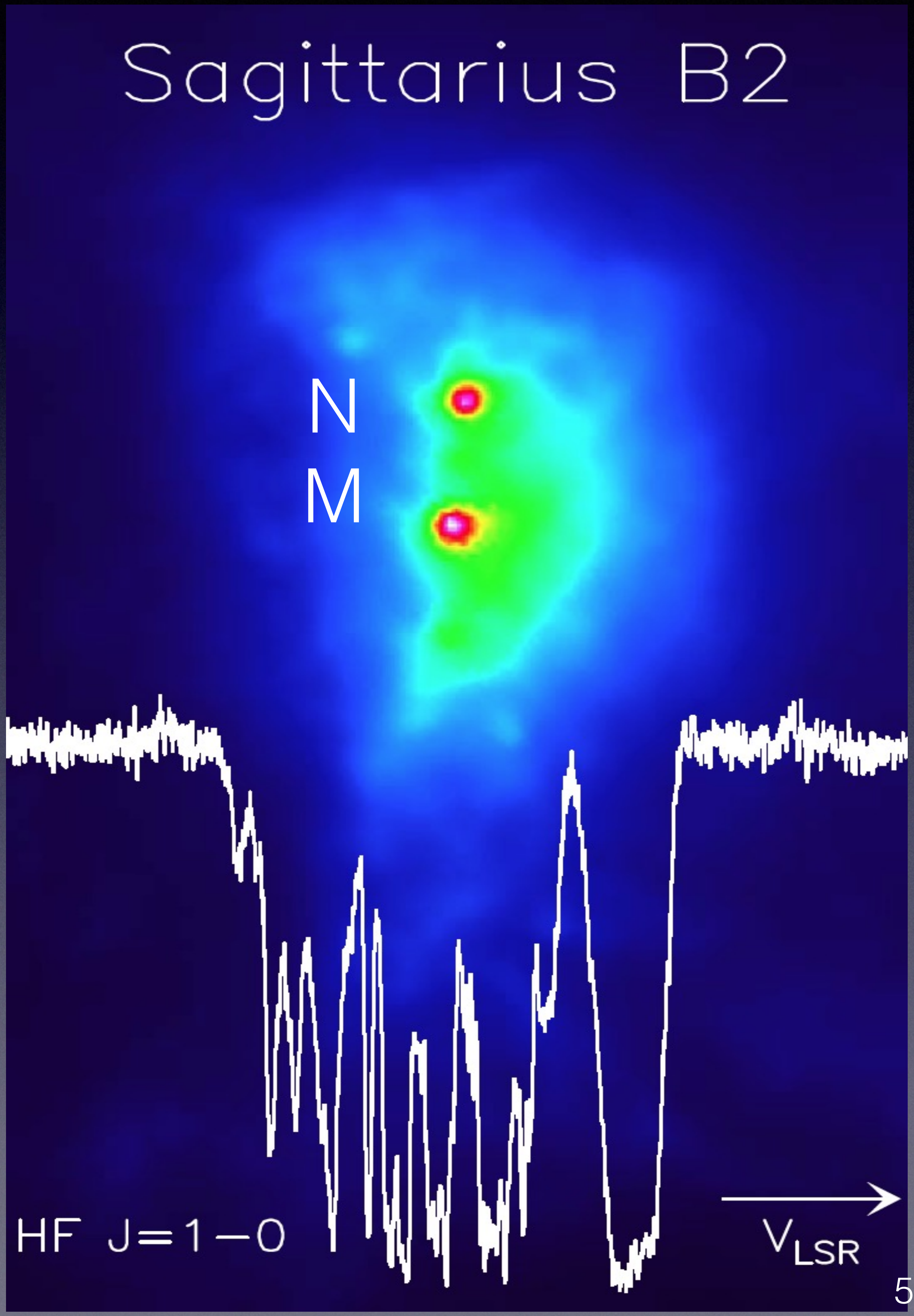
- Atomic oxygen in the ground electronic state is a simple 3-level system with two fine-structure transitions at 63.2 μm and 145.5 μm
- The critical density of the ground state transition is 5.0×10^5 cm^{-3} for collisions with H_2 and 7.8×10^5 cm^{-3} for collisions with H
- In diffuse and translucent clouds, the population is in the ground state and the 63.2 μm transition is an excellent target for absorption spectroscopy

Absorption Spectroscopy

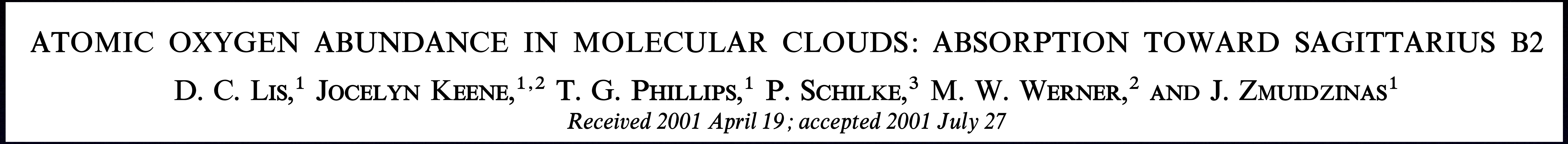


NASA/SSC

R. Monje



ISO Observations of OI toward Sgr B2



ATOMIC OXYGEN ABUNDANCE IN MOLECULAR CLOUDS: ABSORPTION TOWARD SAGITTARIUS B2

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Received 2001 April 19; accepted 2001 July 27

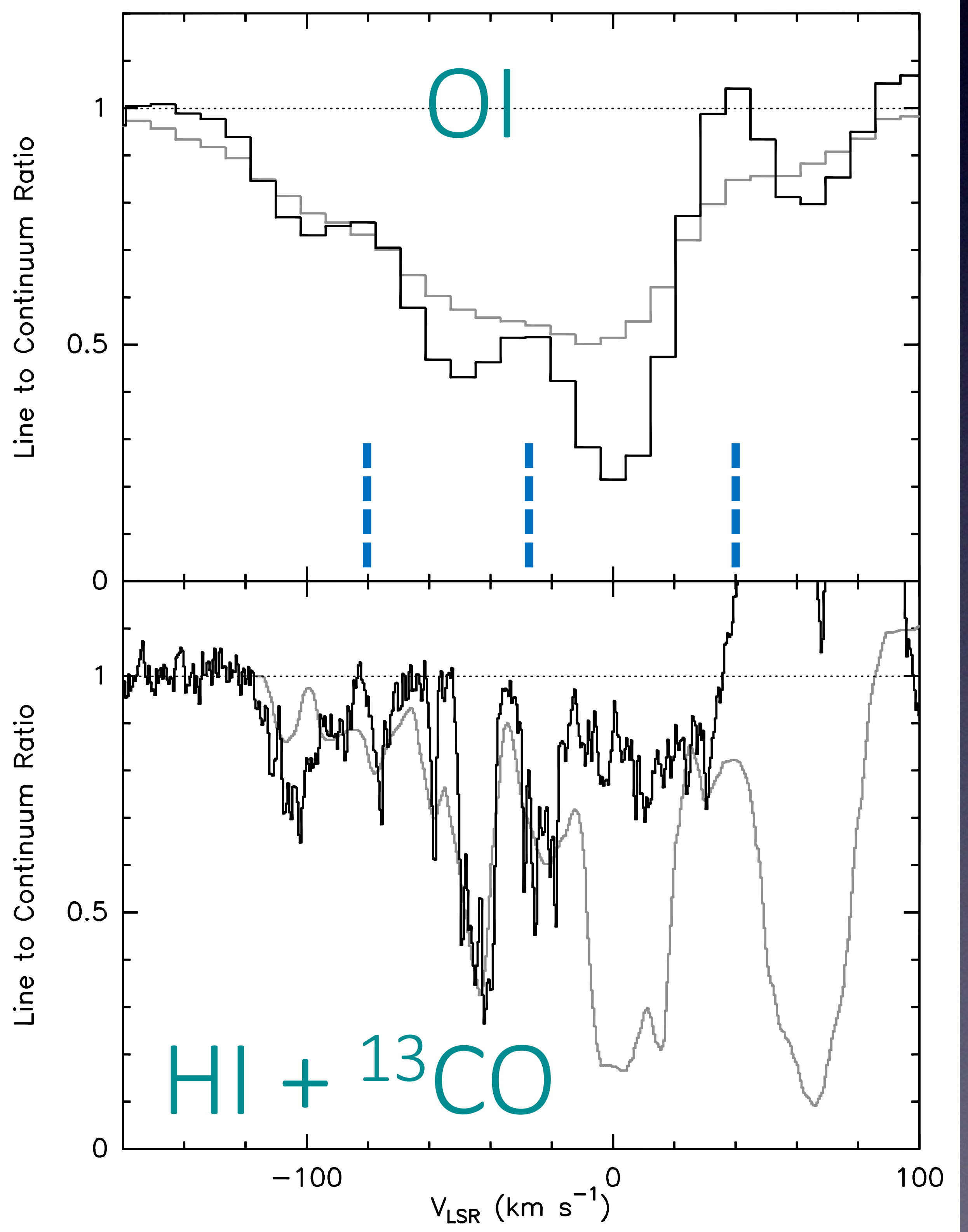


FIG. 3.—*Top:* Observed O I (63 μm) Fabry-Perot spectrum (~35 km s^{-1} resolution; *gray line*) and MEM-deconvolved spectrum (~10–15 km s^{-1} resolution; *solid black line*). *Bottom:* H I and ^{13}CO (1–0) absorption spectra toward Sgr B2(M) (*gray and black lines, respectively*). The ^{13}CO spectrum toward the central position has been corrected for the cloud emission averaged over a 40″ square frame.

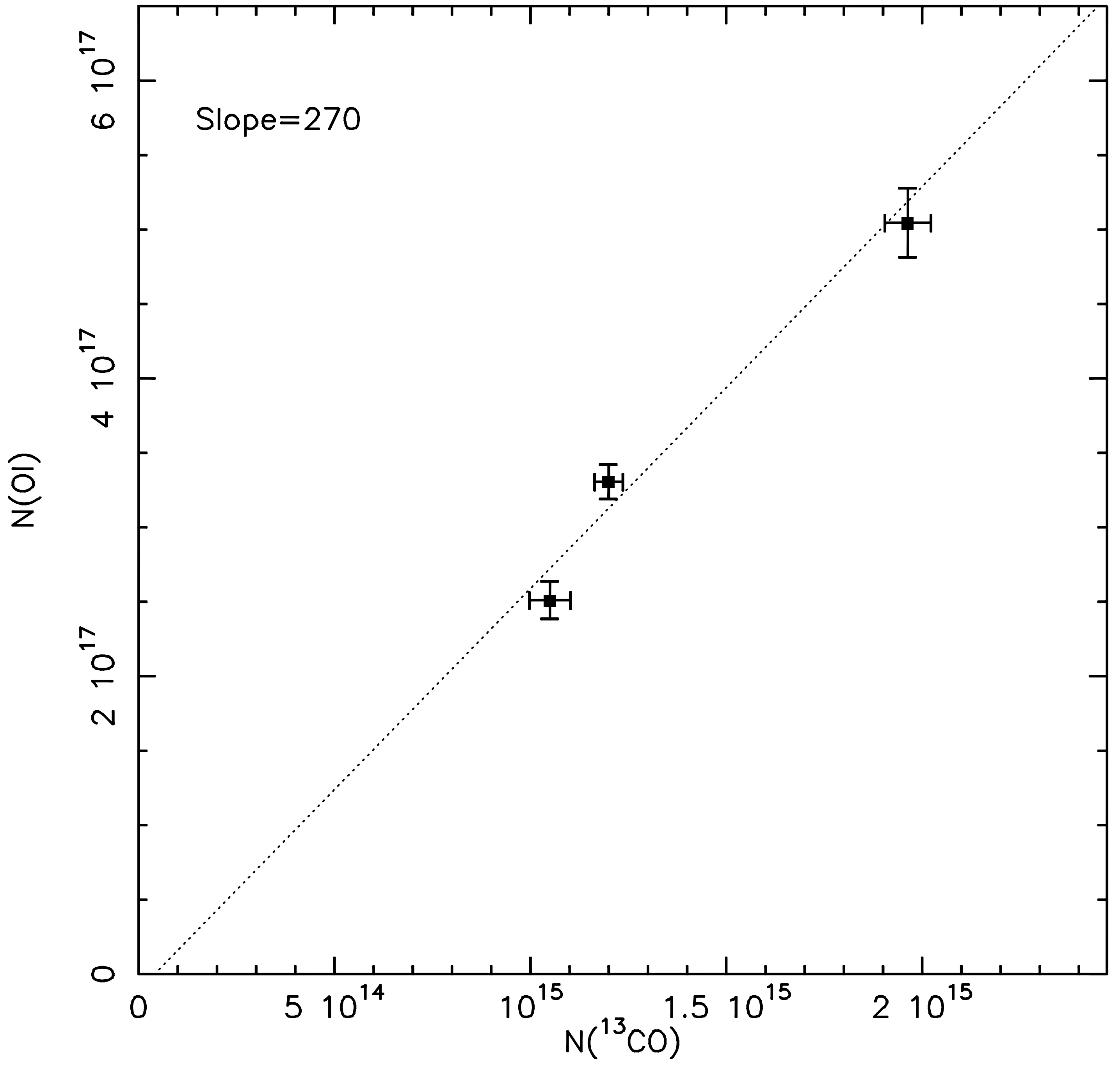
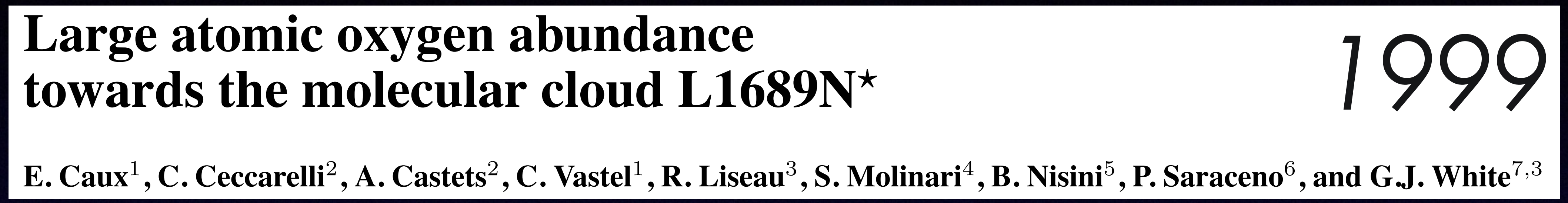


FIG. 4.—O I column density as a function of ^{13}CO column density per ^{13}CO velocity component for the three velocity ranges that are distinguishable in the MEM-deconvolved O I spectrum. Error bars correspond to 1 σ statistical uncertainties for O I and ^{13}CO column densities. A least-squares fit to the data gives a slope of 270 ± 35 (1 σ statistical uncertainty). The intercept is $(-1.1 \pm 4.6) \times 10^{16}$ cm^{-2} (1 σ). This indicates that the O I and ^{13}CO emission come from the same region and there is little or no excess O I emission from the PDR interface where hydrogen is already molecular, but ^{13}CO is photodissociated (region B in Fig. 1*b*).

- ISO/LWS Fabry-Perot instrument, R=10,000 (30 km s^{-1} ➡ 10 km s^{-1} with MEM)
- Foreground absorption separated into 3 velocity components
- Use ^{13}CO as a proxy for H_2 and HI 21 cm as a tracer of atomic gas
- Atomic oxygen column density correlated with ^{13}CO
- O^0/CO ~ 9
- Abundance $X(O^0) = 2.7 \times 10^{-4}$ with respect to H nuclei
- Moderate oxygen depletion

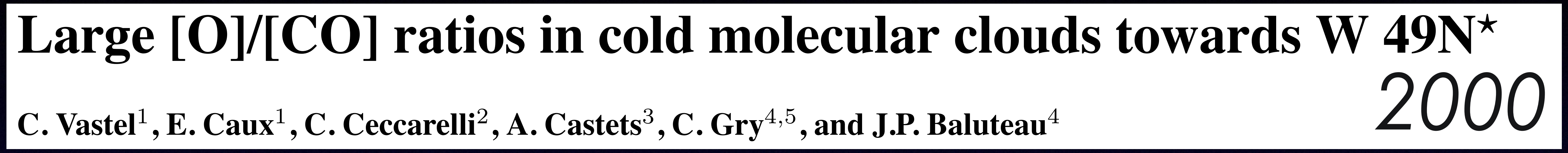
Other ISO Observations of [OI]



Large atomic oxygen abundance towards the molecular cloud L1689N⋆

1999

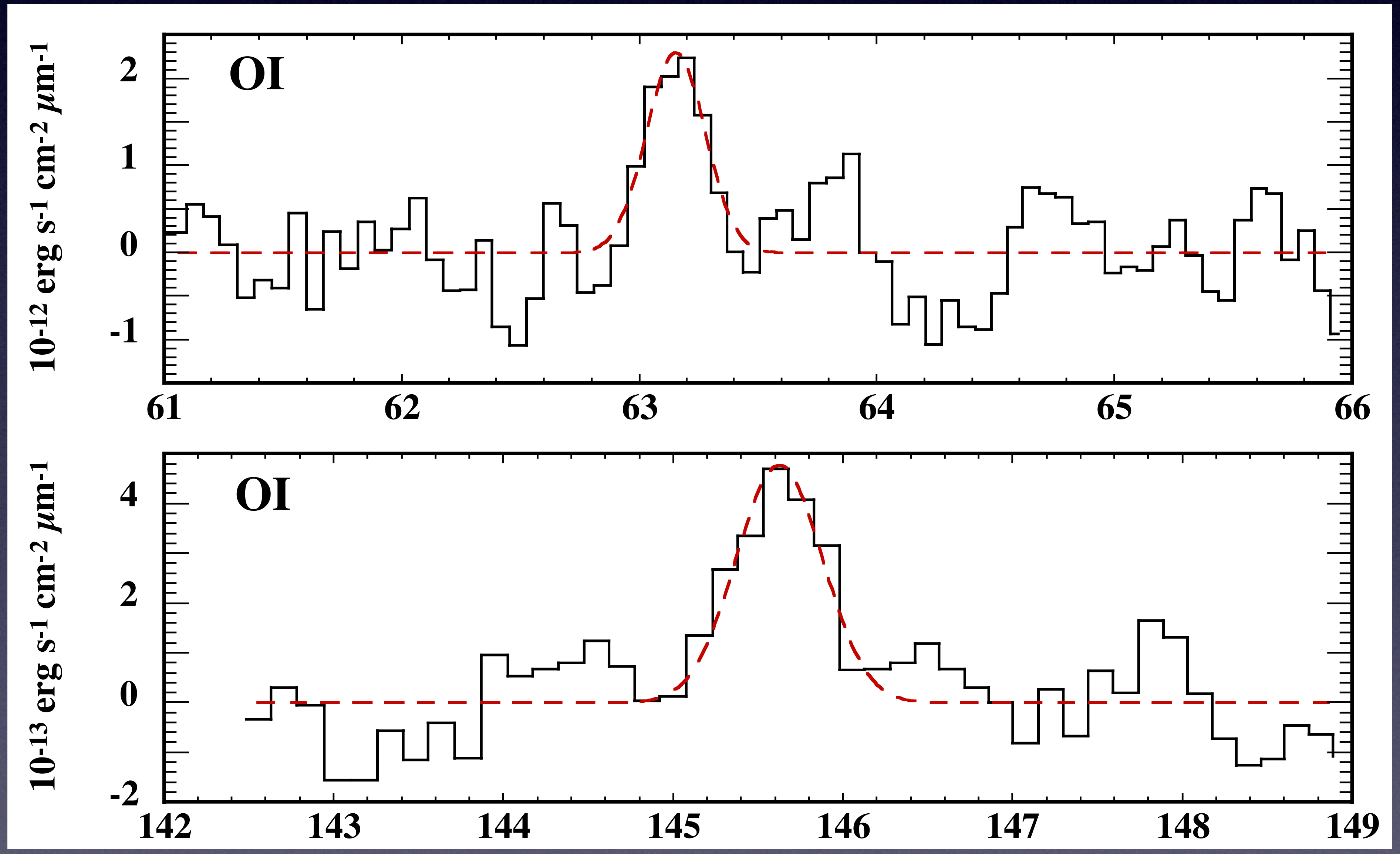
E. Caux[1], C. Ceccarelli[2], A. Castets[2], C. Vastel[1], R. Liseau[3], S. Molinari[4], B. Nisini[5], P. Saraceno[6], and G.J. White[7,3]

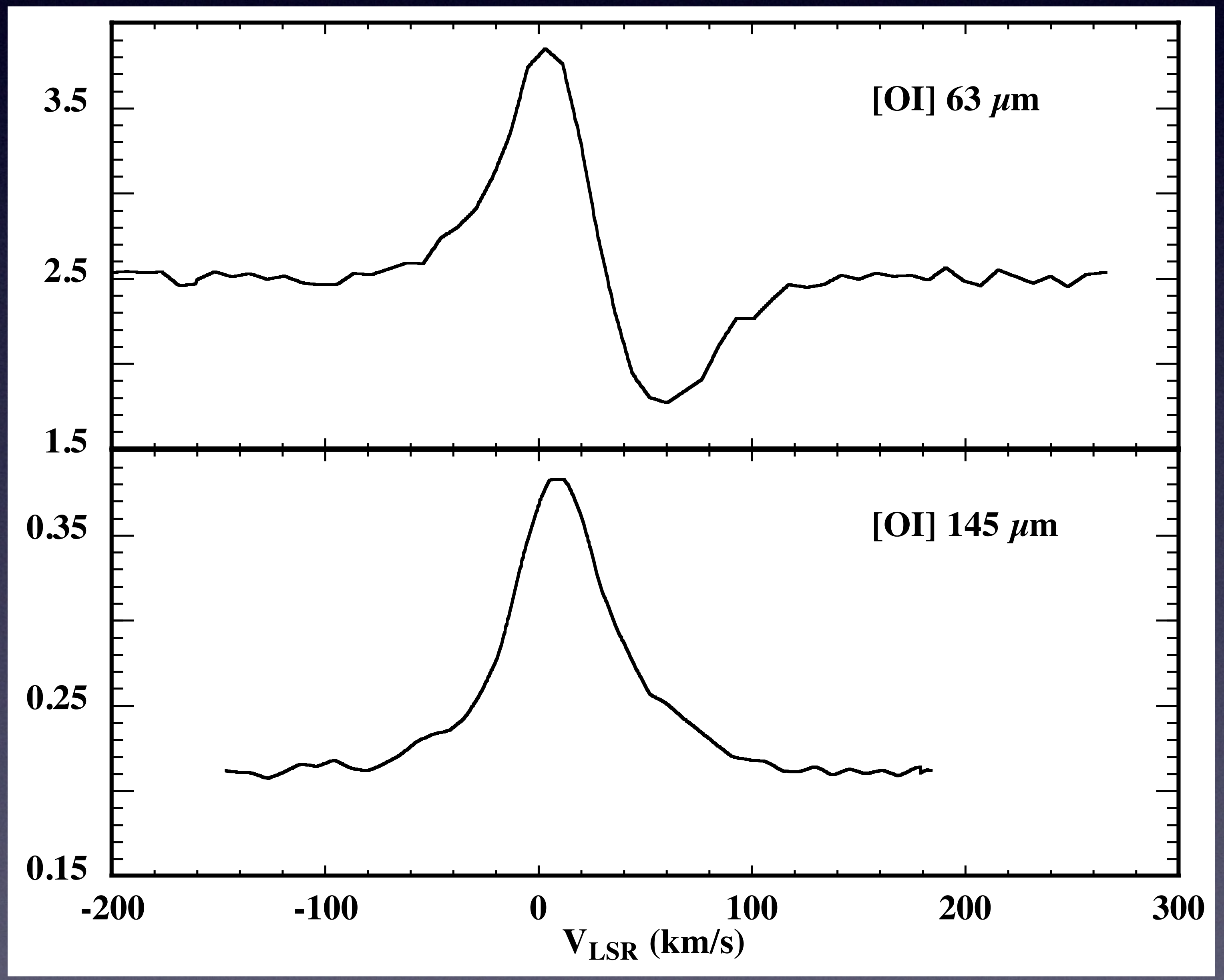


Large [O]/[CO] ratios in cold molecular clouds towards W 49N⋆

2000

C. Vastel[1], E. Caux[1], C. Ceccarelli[2], A. Castets[3], C. Gry[4,5], and J.P. Baluteau[4]

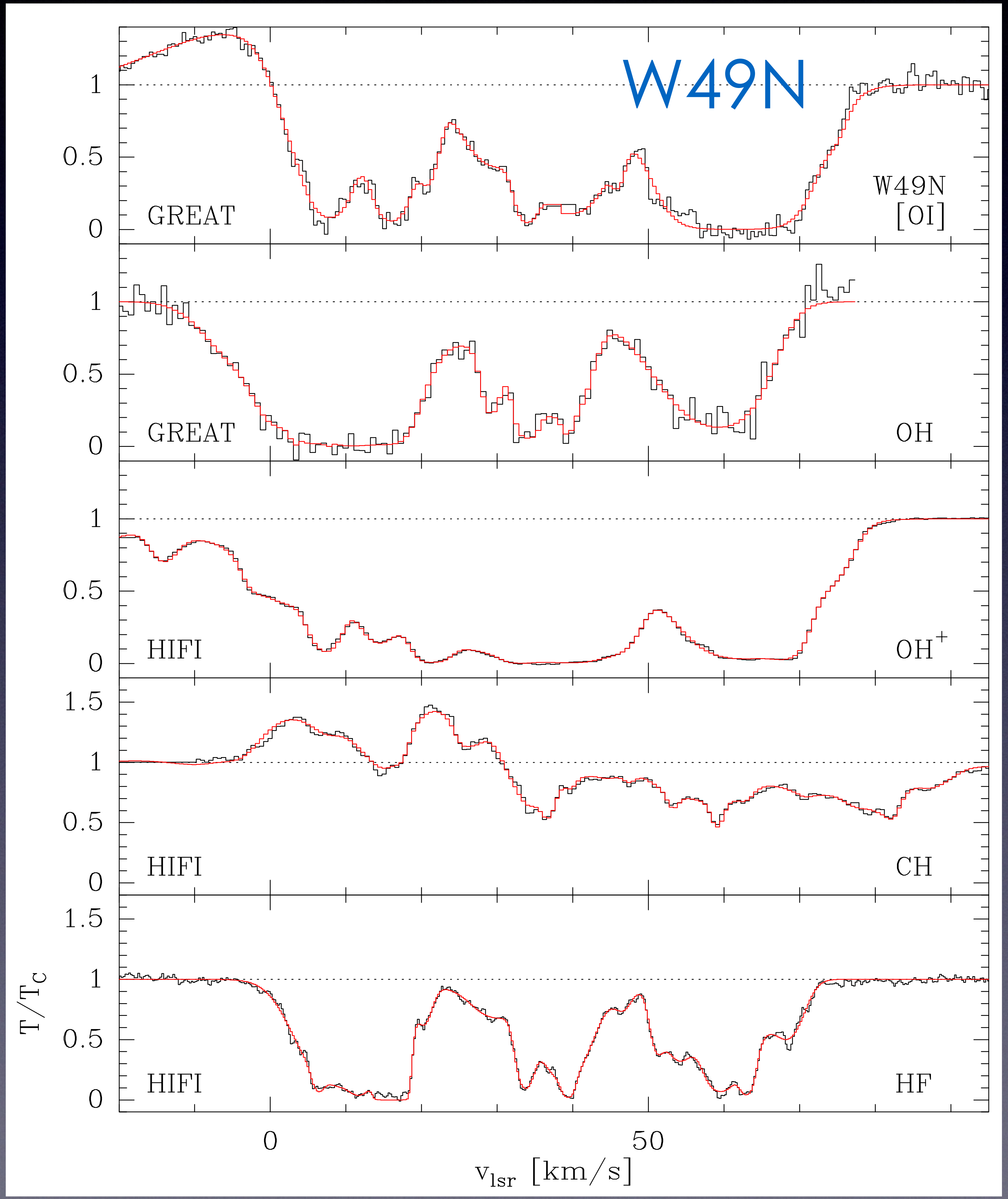




- Environment of the IRAS 16293 protostar
- O/C ~ 50
- 98% of atomic oxygen is in the gas phase
- C depleted by more than a factor of 24

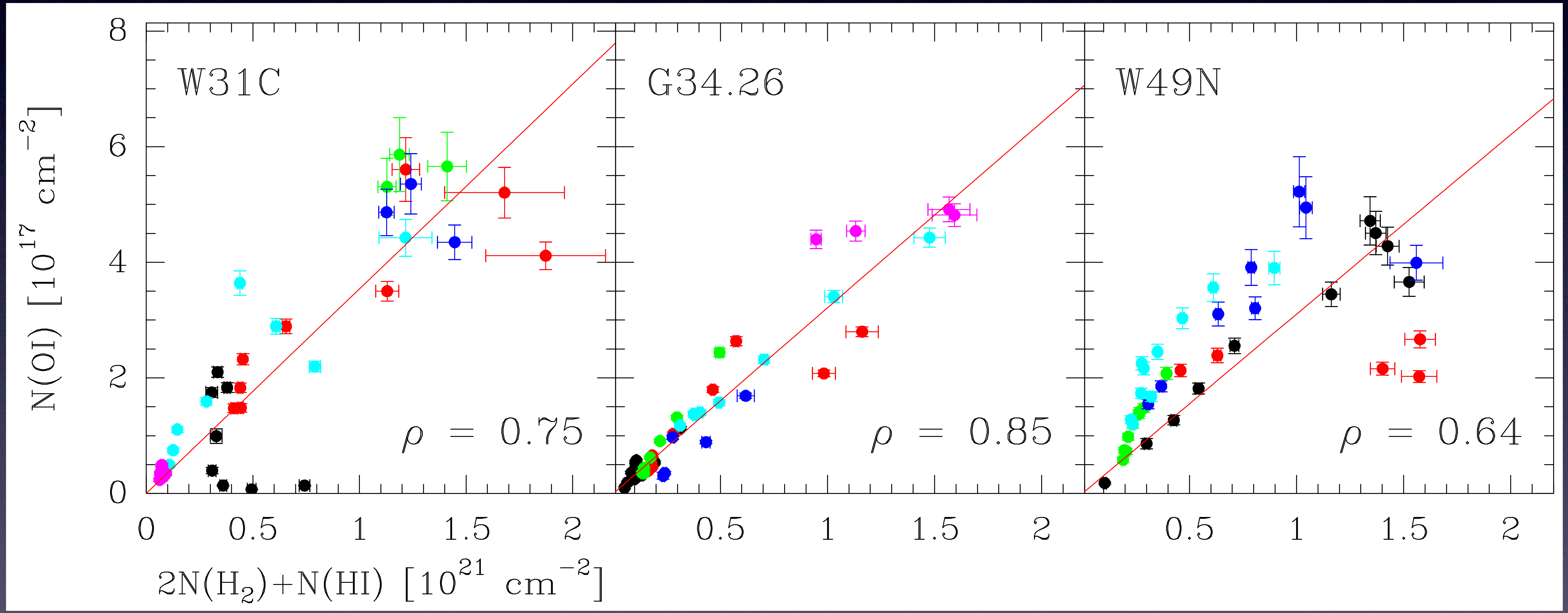
- Foreground absorption toward W49N
- O/C > 15 to account for the 63 μm absorption
- C deficiency > 6 compared to the cosmic abundance

SOFIA Observations of [OI]



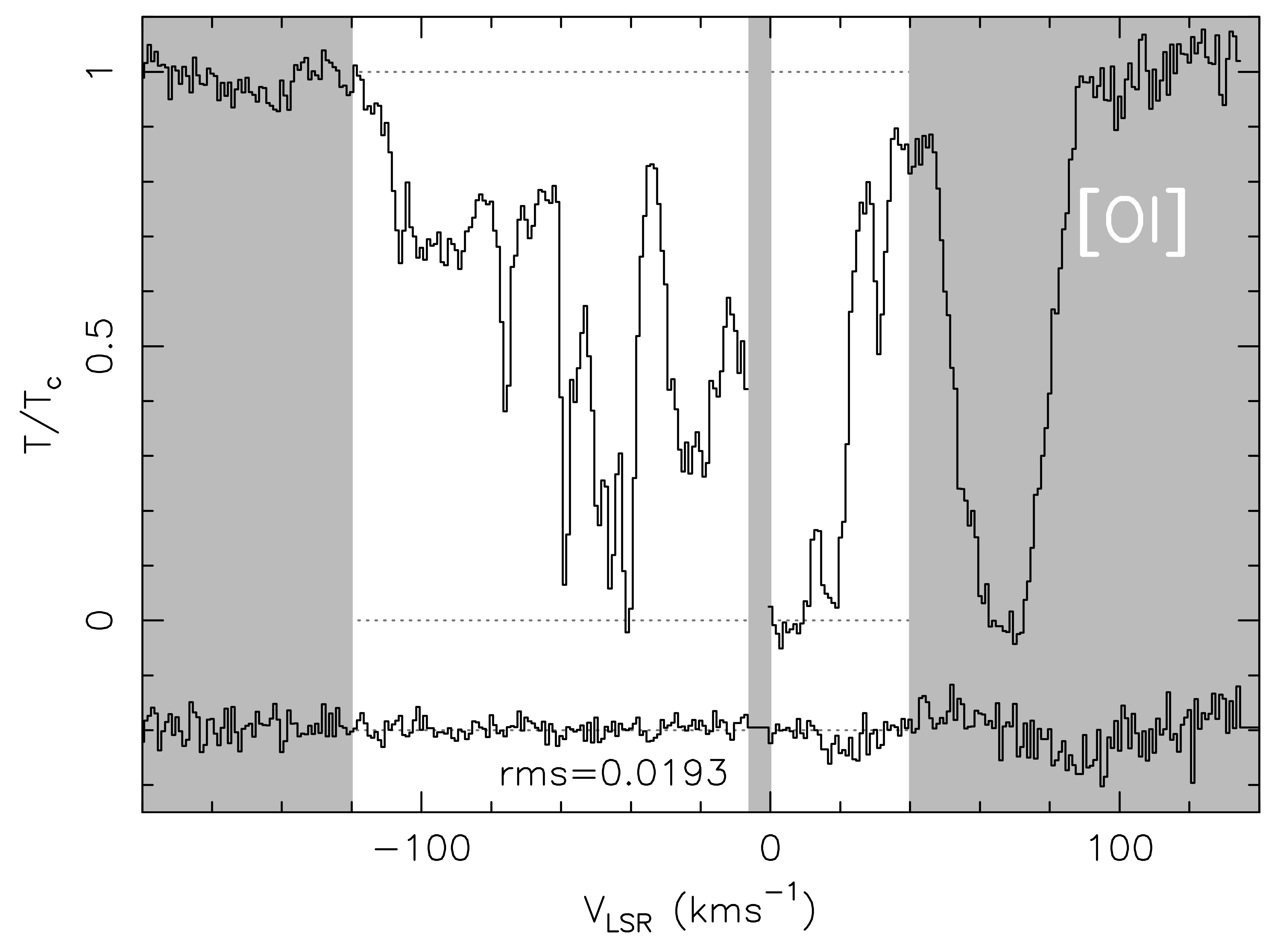
Wiesemeyer+ 2016

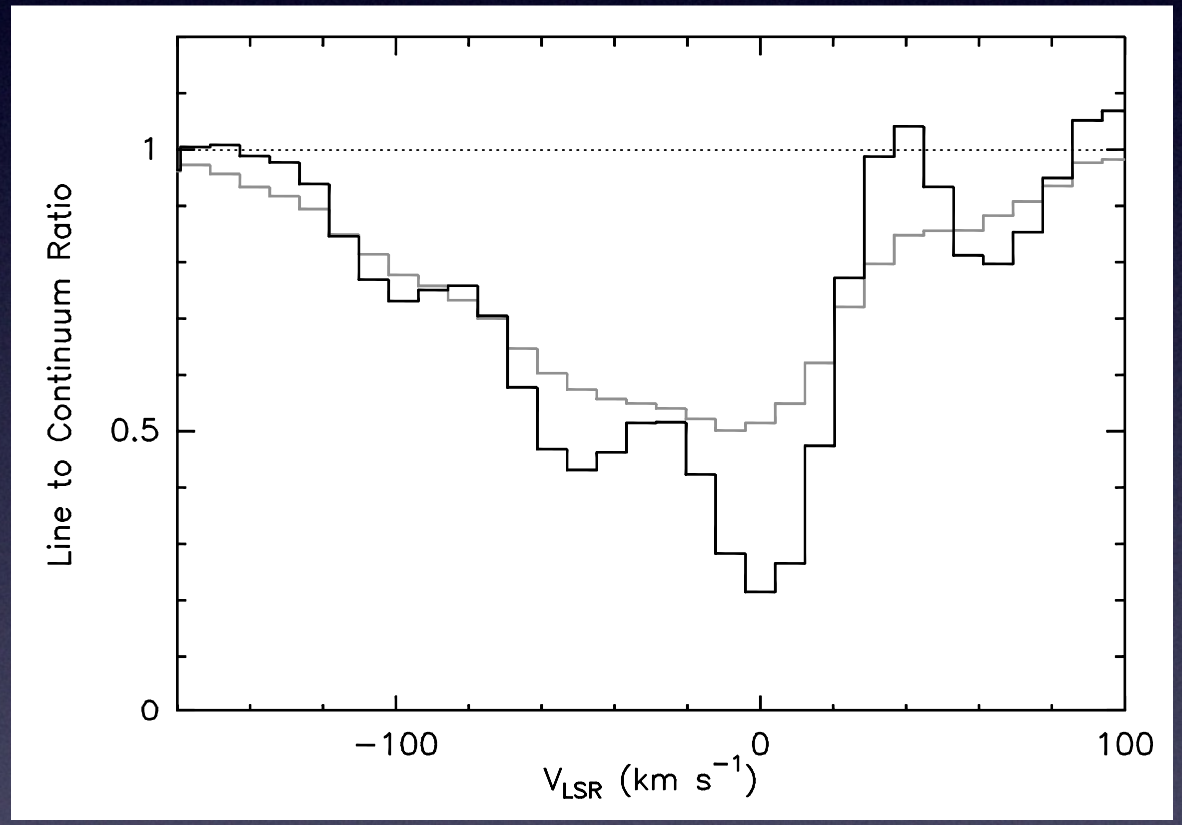
W31C G34.26 W49N



- Average atomic oxygen abundances confined to a narrow range of 3.1 – 3.5 × 10^{-4}

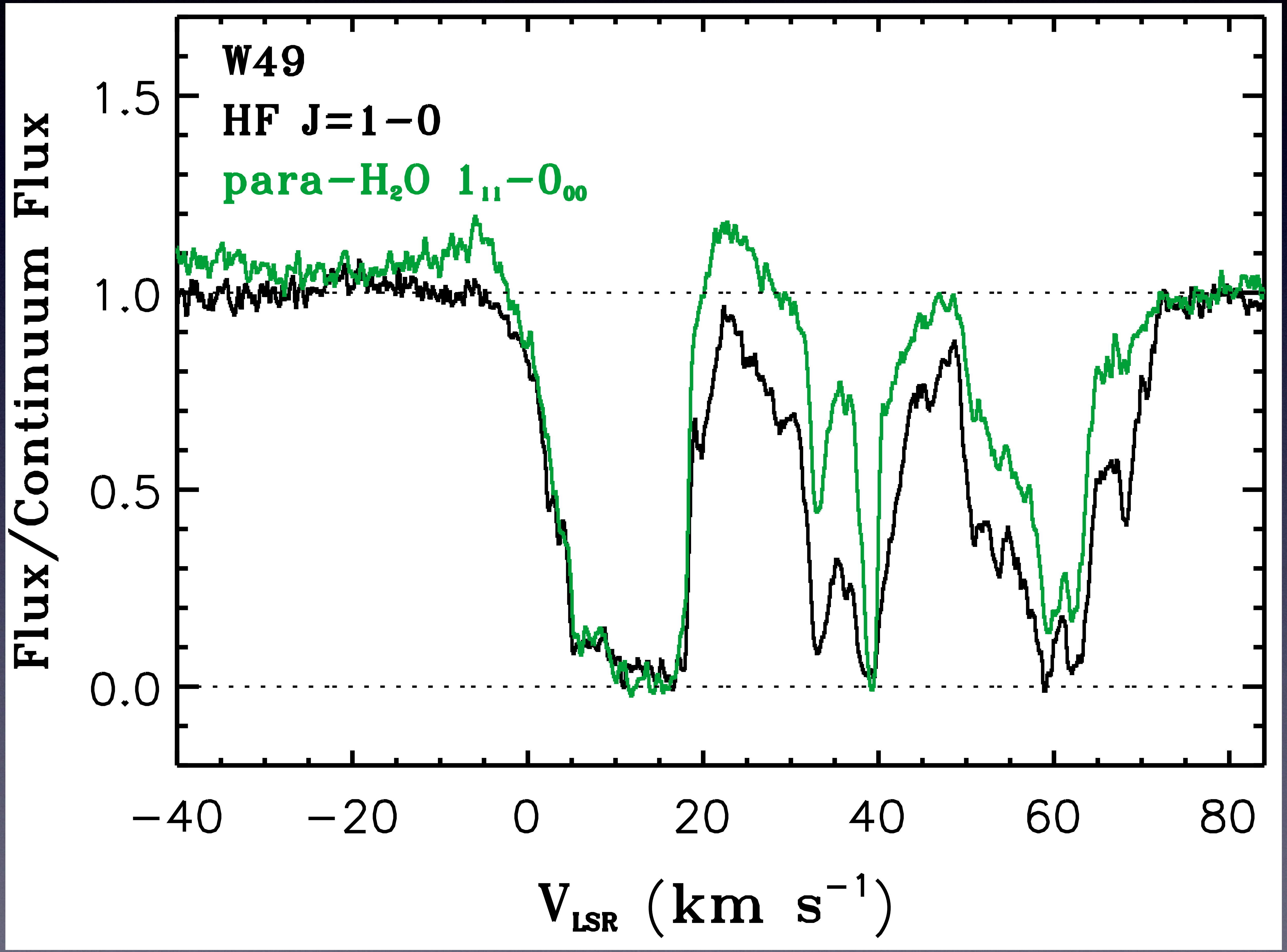
[OI] Observations toward Sgr B2





- Use archival SOFIA observations using the GREAT Heterodyne instrument ($R=1.2\times10^6$ or 0.25 km s^{-1})
- The high SNR gives a good handle on the uncertainties

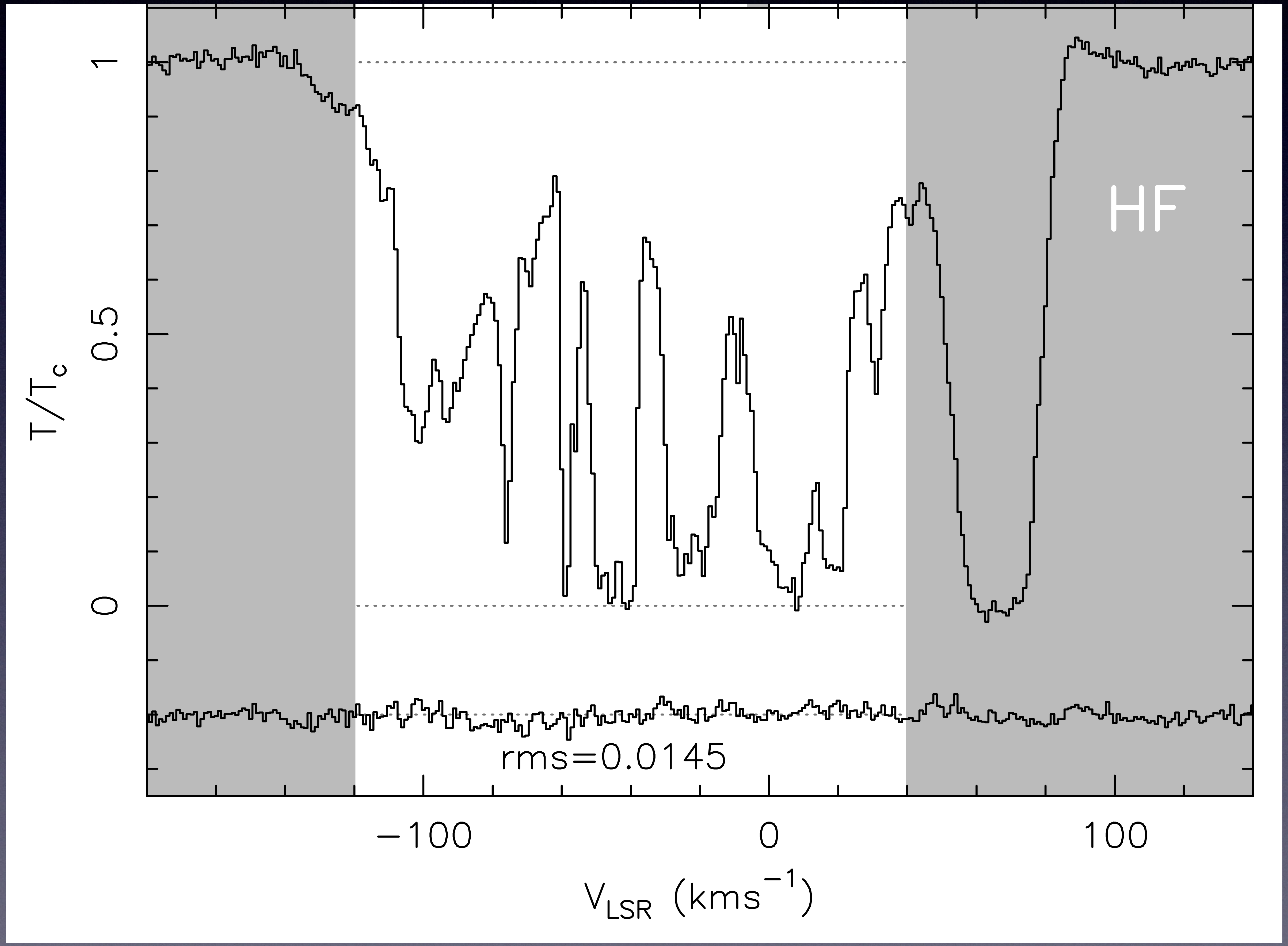
HF as a Proxy for H_2



- Fluorine reacts exothermically with H_2 to produce HF
- HF extensively studied by *Herschel*/HIFI
- Abundance calibrated with respect to CH
- In diffuse/translucent clouds X(HF) = $(1.4 \pm 0.17) \times 10^{-8}$ with respect to H_2
- HF depletion at higher densities, e.g, Orion KL outflow ~3×10^{-10}
- Use multiple archival *Herschel*/HIFI observations toward Sgr B2 to estimate the uncertainties

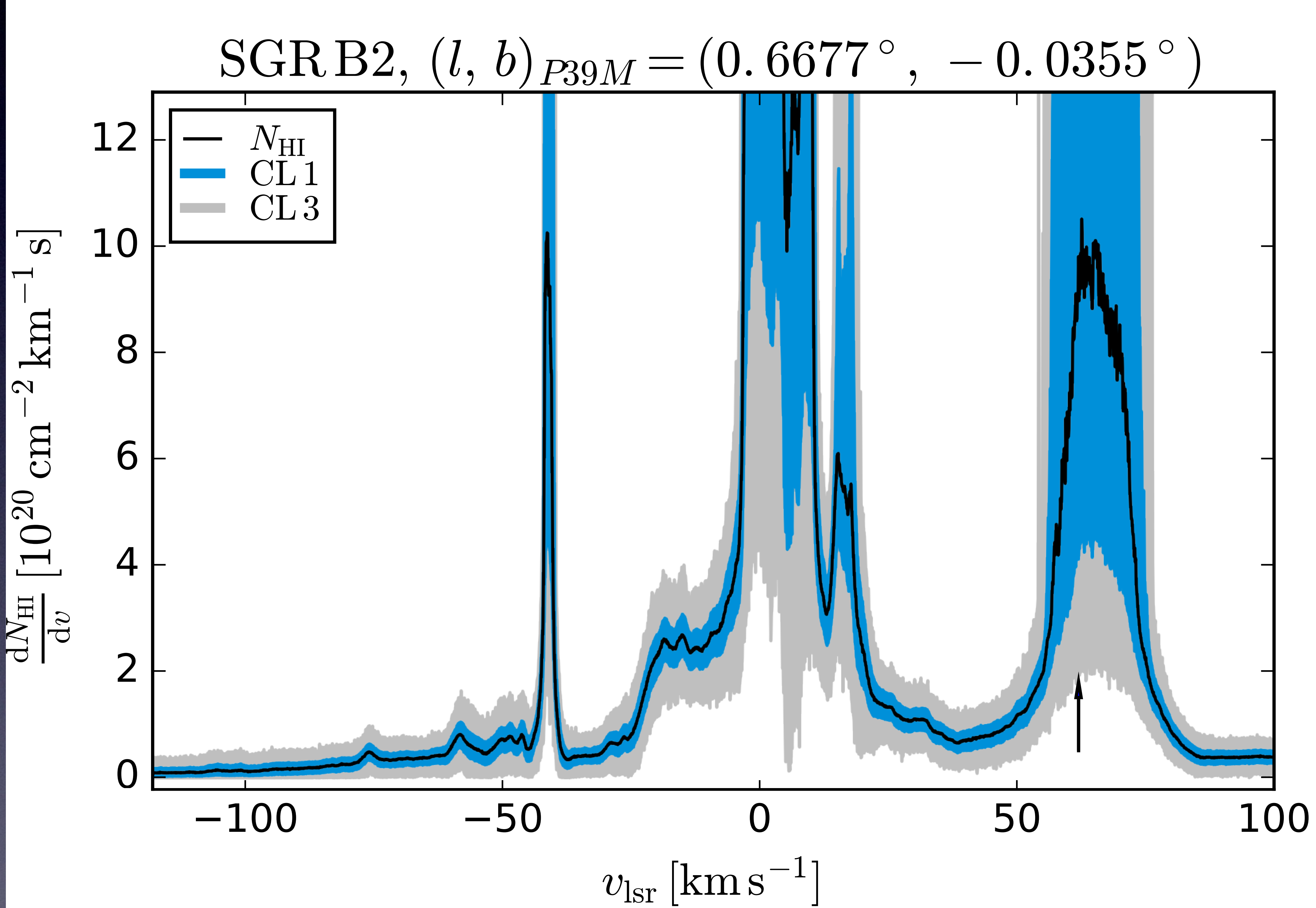
Phillips+ 2010, Neufeld+ 2010, Sonnentrucker+ 2010, Monje+ 2011, Emprechtinger+ 2012

HF toward Sgr B2

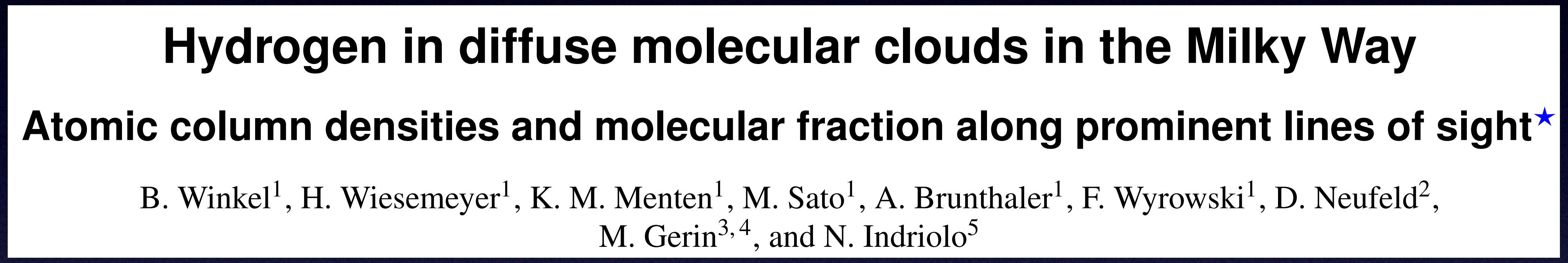


- Use multiple independent archival *Herschel*/HIFI observations of HF toward Sgr B2 to estimate the uncertainties

HI 21-cm Observations



Winkel+ 2017



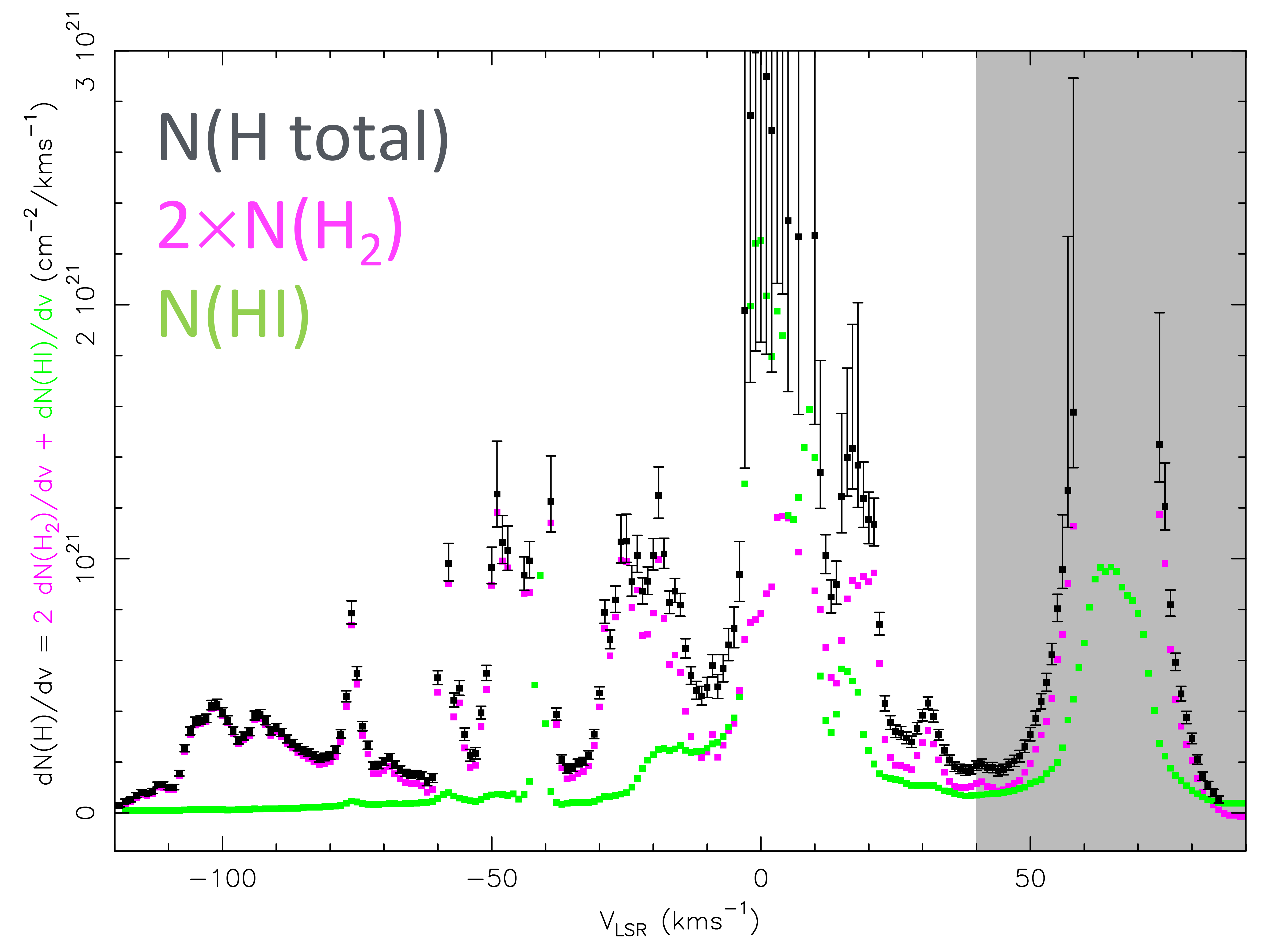
Hydrogen in diffuse molecular clouds in the Milky Way

Atomic column densities and molecular fraction along prominent lines of sight★

B. Winkel[1], H. Wiesemeyer[1], K. M. Menten[1], M. Sato[1], A. Brunthaler[1], F. Wyrowski[1], D. Neufeld[2], M. Gerin[3,4], and N. Indriolo[5]

- Jansky VLA HI 21-cm observations
- Several lines of sight, including Sgr B2
- Provides HI column density as a function of velocity, along with 1 and 3-σ confidence levels

Column Densities



- Resample spectra to 1 km s^{-1}
- Use established absorption spectroscopy techniques

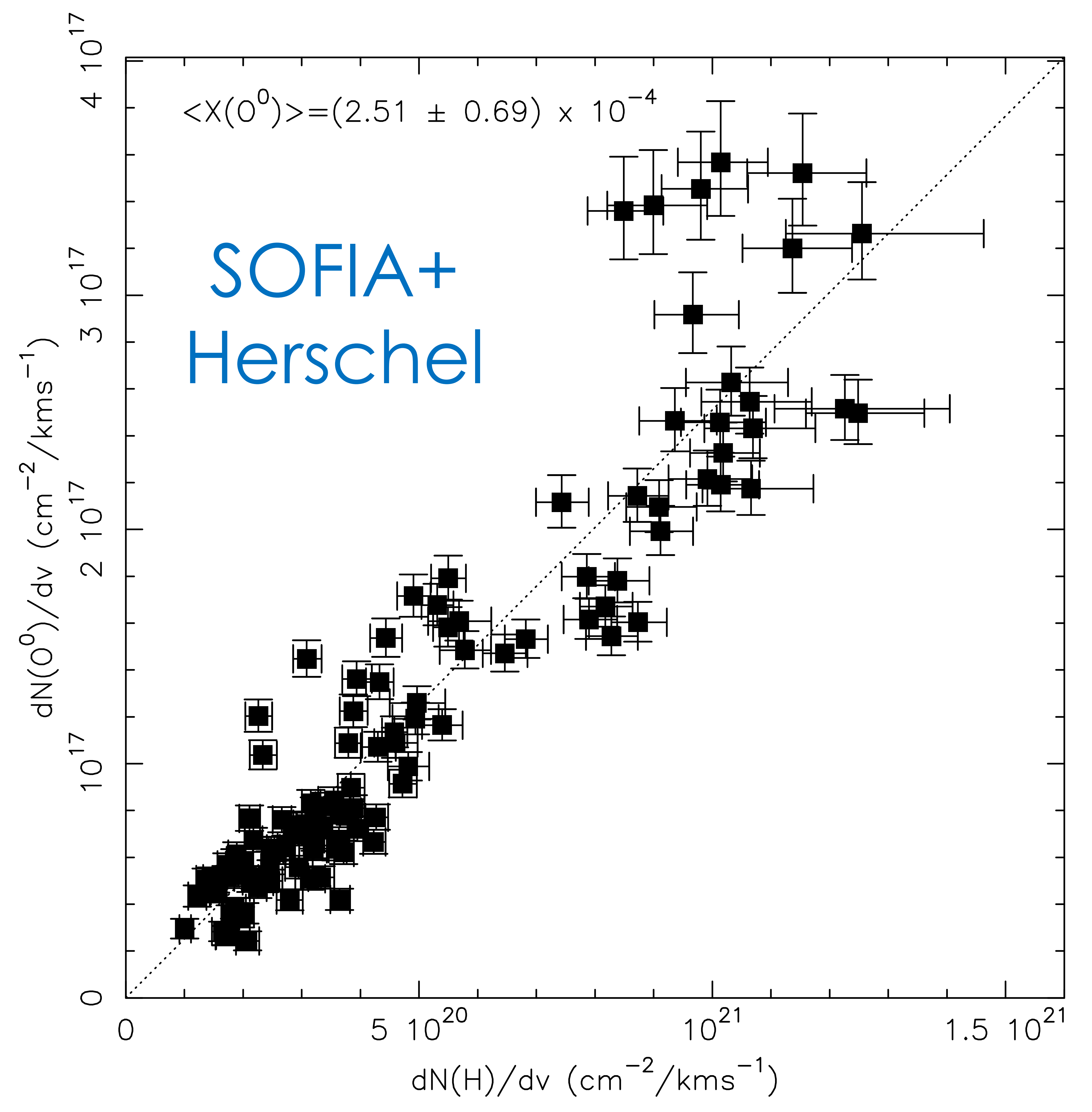
$$\tau = -ln[1 - T_L/T_C]$$

$$\int \tau \mathrm{d}v = \frac{A_{\mathrm{ul}} g_{\mathrm{u}} \lambda^3}{8\pi g_{\mathrm{l}}} N(\mathrm{O}^0) = 5.365 \times 10^{-18} N(\mathrm{O}^0)\ \mathrm{cm}^2\,\mathrm{km\,s}^{-1},$$

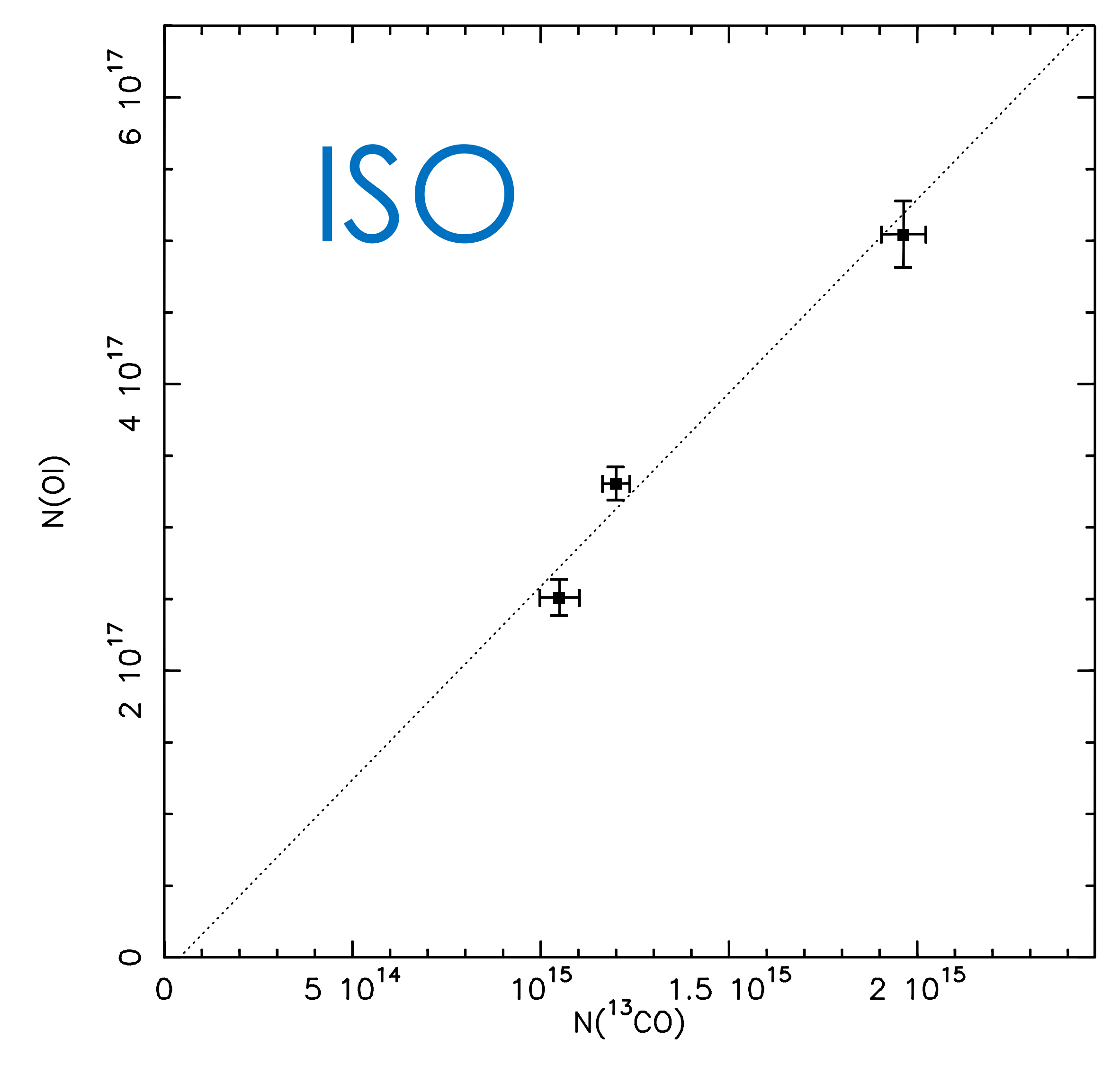
$$\int \tau \mathrm{d}v = \frac{A_{\mathrm{ul}} g_{\mathrm{u}} \lambda^3}{8\pi g_{\mathrm{l}}} N(\mathrm{HF}) = 4.157 \times 10^{-13} N(\mathrm{HF})\ \mathrm{cm}^2\,\mathrm{km\,s}^{-1},$$

- Propagate the uncertainties

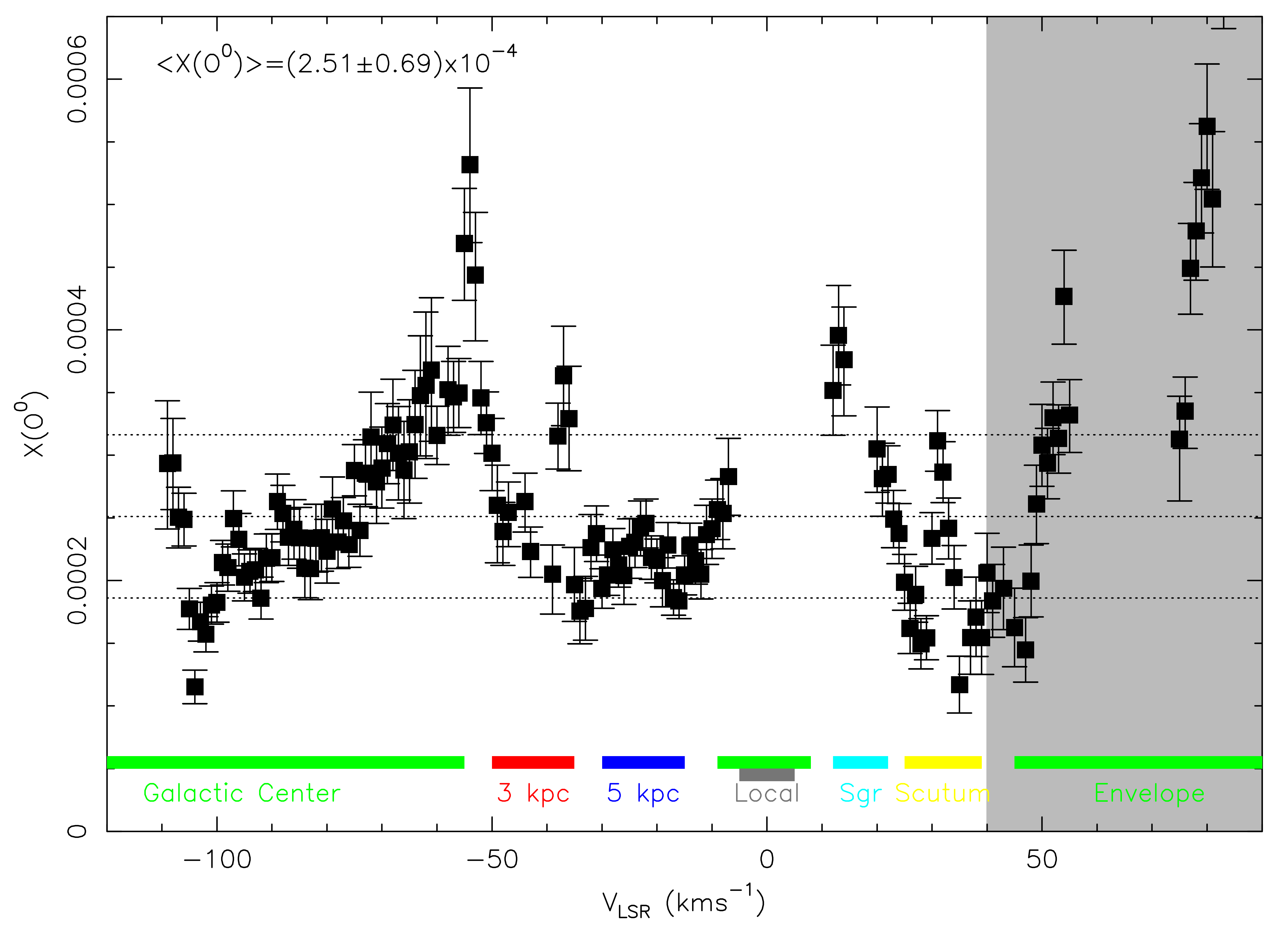
O^0 vs. H Column Density



- Good correlation between O^0 and total H nuclei column densities
- Pearson's correlation coefficient 0.85
- Confirms the early ISO results



Atomic Oxygen Abundance



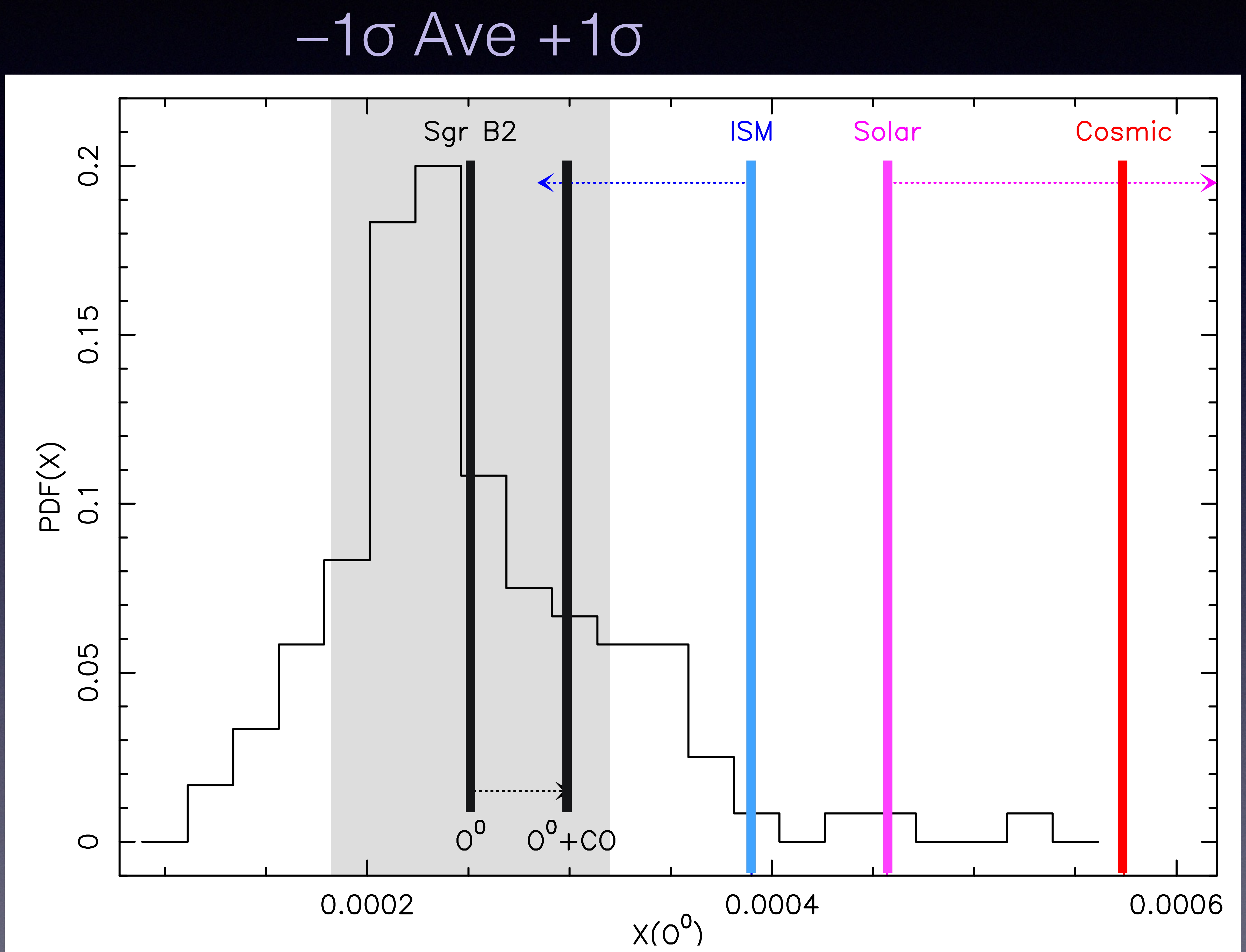
+1σ

Ave

−1σ

- Average gas-phase atomic oxygen abundance with respect to H nuclei $(2.51\pm 0.69)\times10^{-4}$
- Excellent agreement with the ISO results 2.7×10^{-4}
- Dispersion computed from the 120 individual velocity channels is higher than the uncertainty of individual measurements
- Indicates variations in the oxygen abundance among different velocity channels

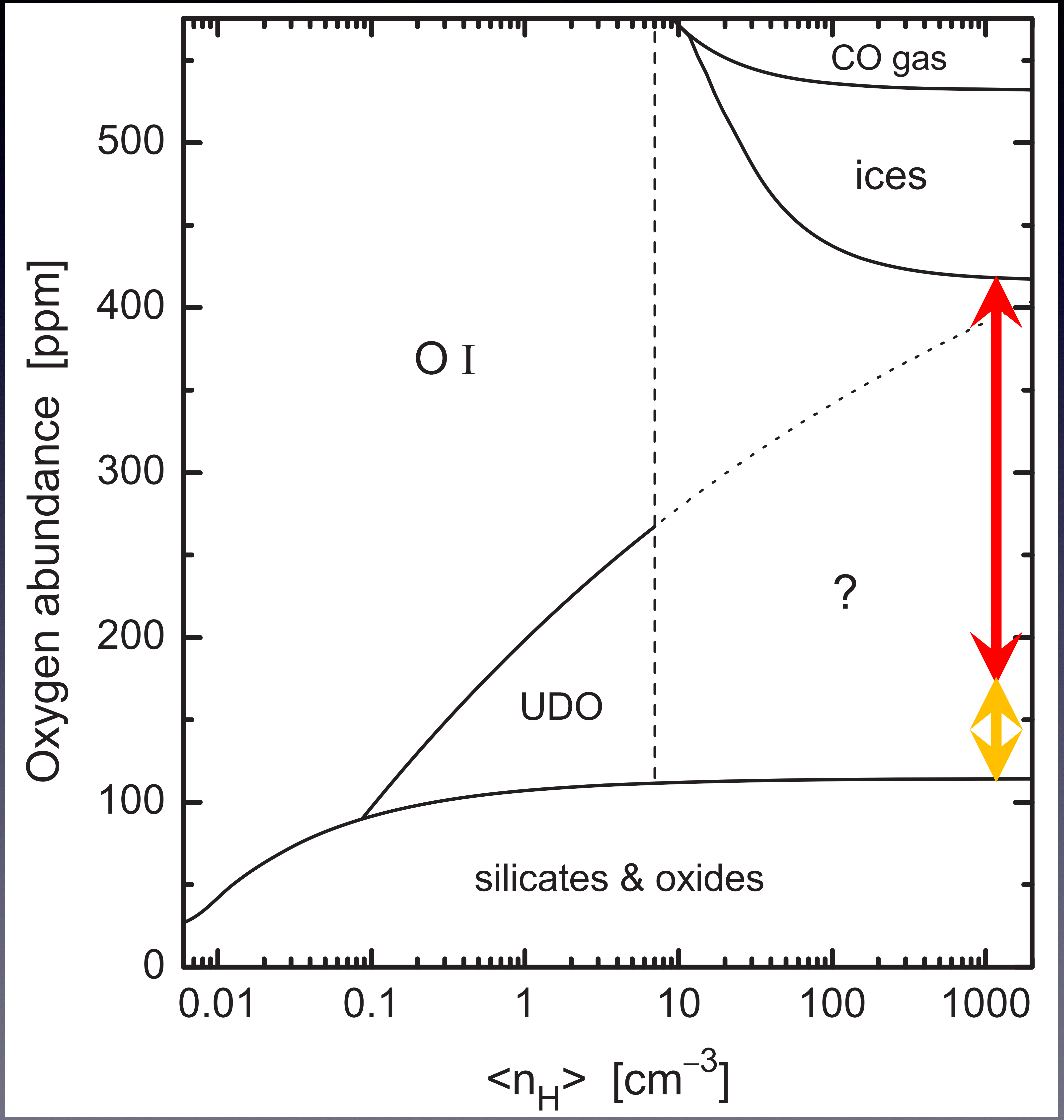
Atomic Oxygen Abundance



- Normalized PDF of atomic oxygen abundances is non-Gaussian and double-peaked
- A narrow peak around 2.25×10^{-4}
- Broader shoulder around 3.15×10^{-4}
- Vertical lines show reference cosmic (5.75×10^{-4}), solar (4.57×10^{-4}, 6.76×10^{-4}), and diffuse ISM (3.9×10^{-4} in the low-density warm gas) values
- O^0+CO = 3×10^{-4} : moderate gas-phase oxygen depletion of ~25% compared to the diffuse ISM

Przybilla+ 2008, Asplund+ 2005, Grevesee & Sauval 1998, Cartledge+ 2004

Oxygen Budget Toward Sgr B2



50 ppm CO gas

125 ppm ices

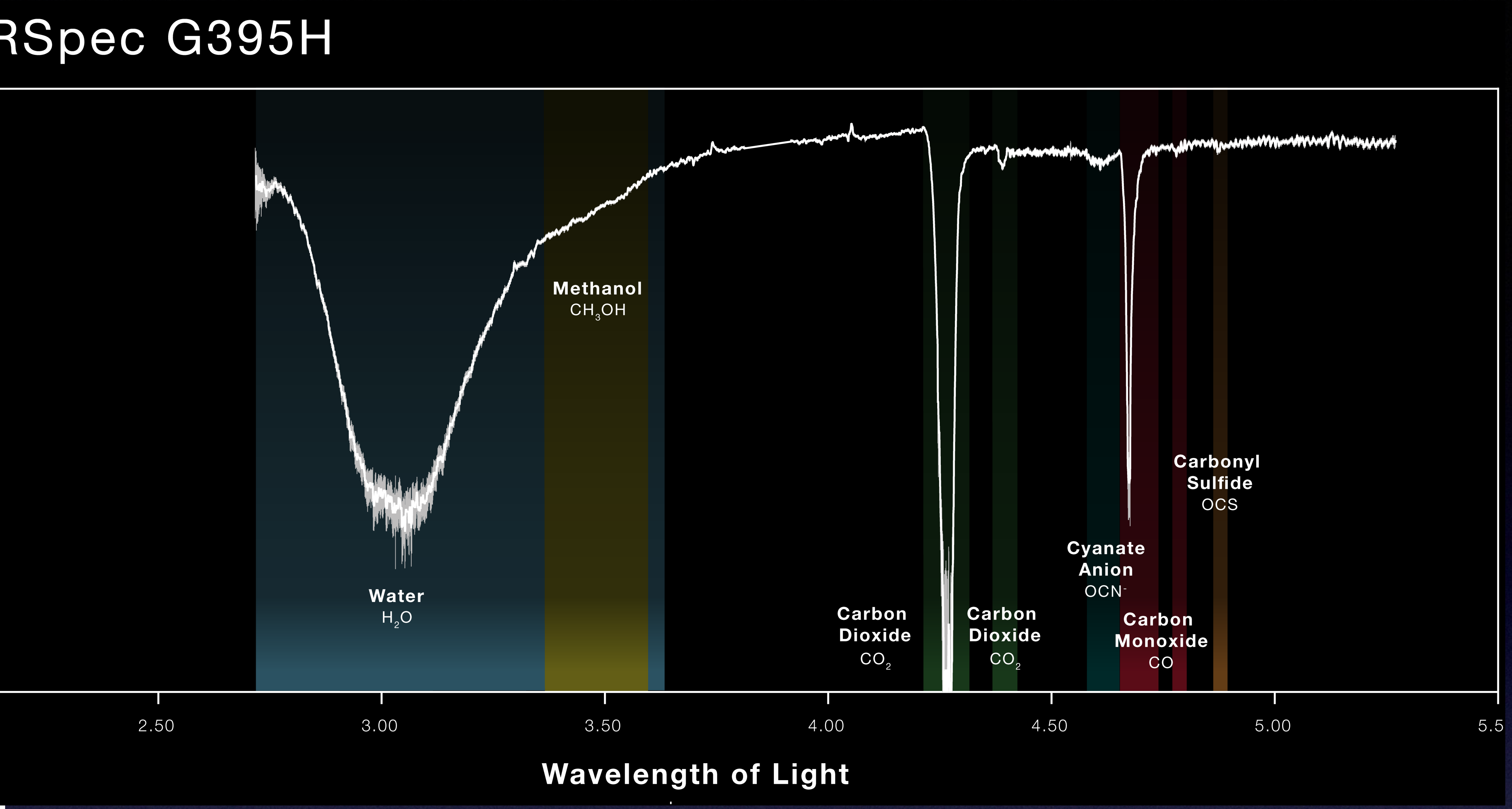
250 ppm O^0 gas (SOFIA)

Little room for UDO!

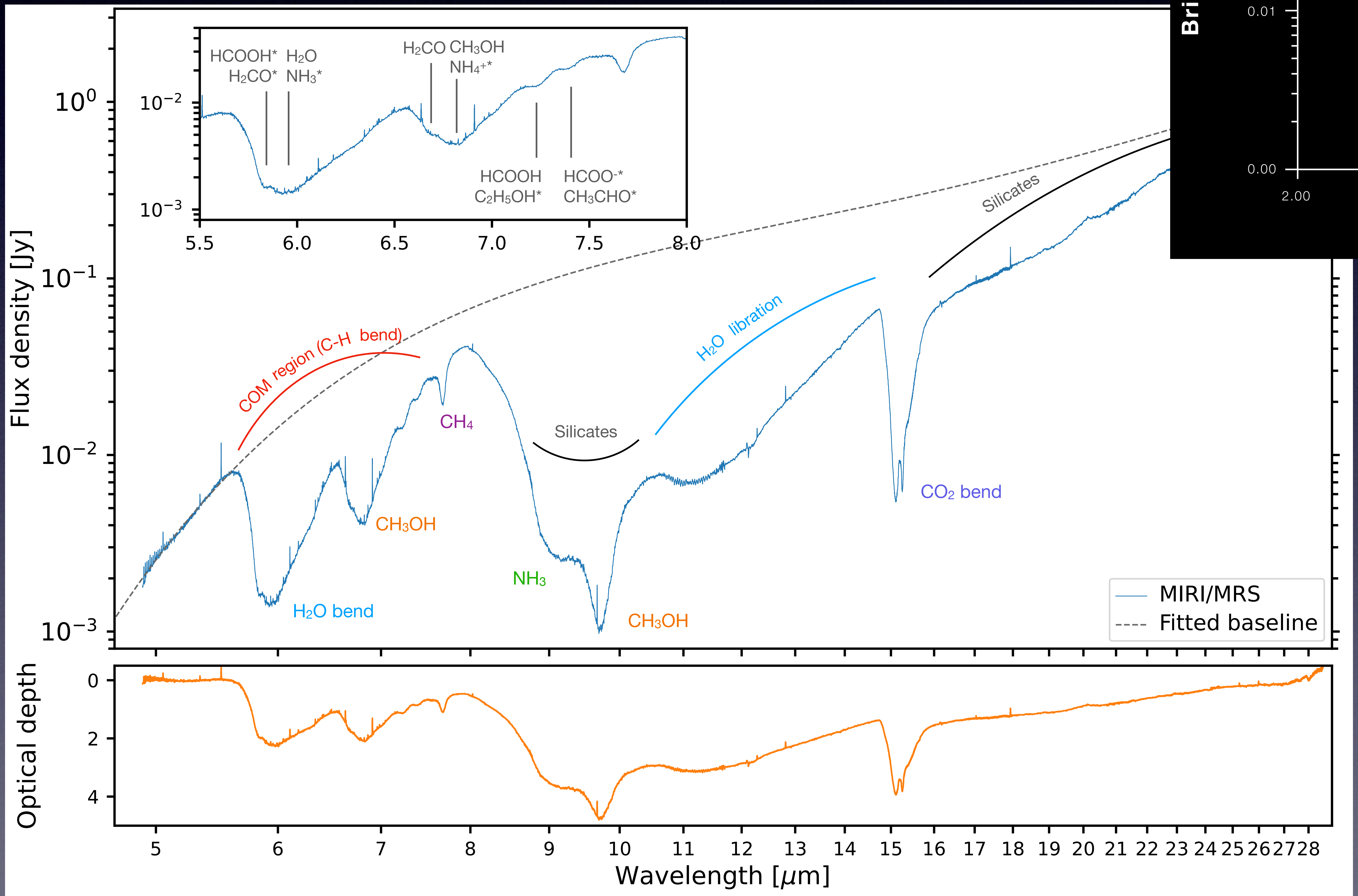
100 ppm silicates

Whittet 2010

Next Step: The Ices



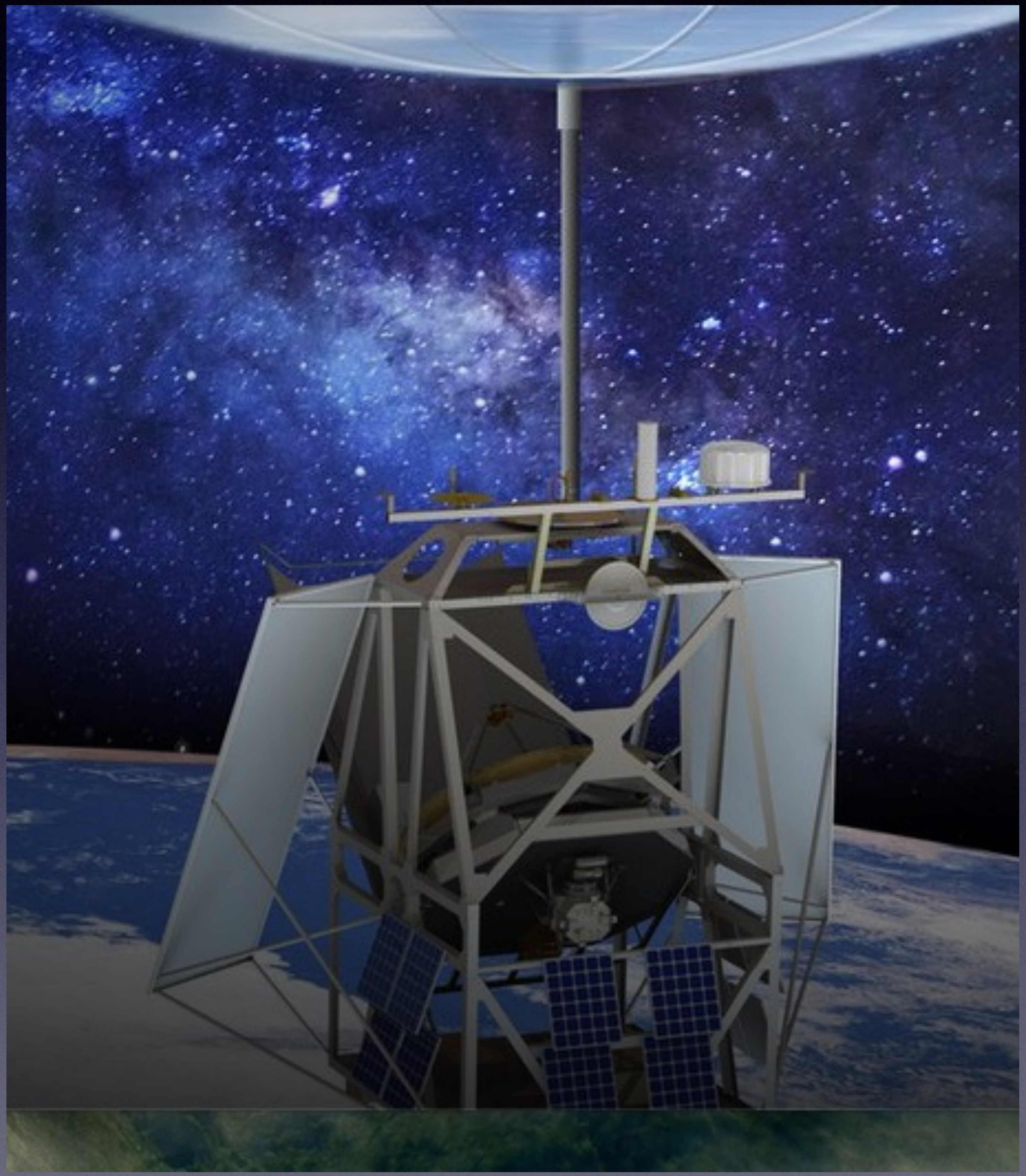
A$_V$=60 Star, NIRSEC FS, McClure et al. 2023



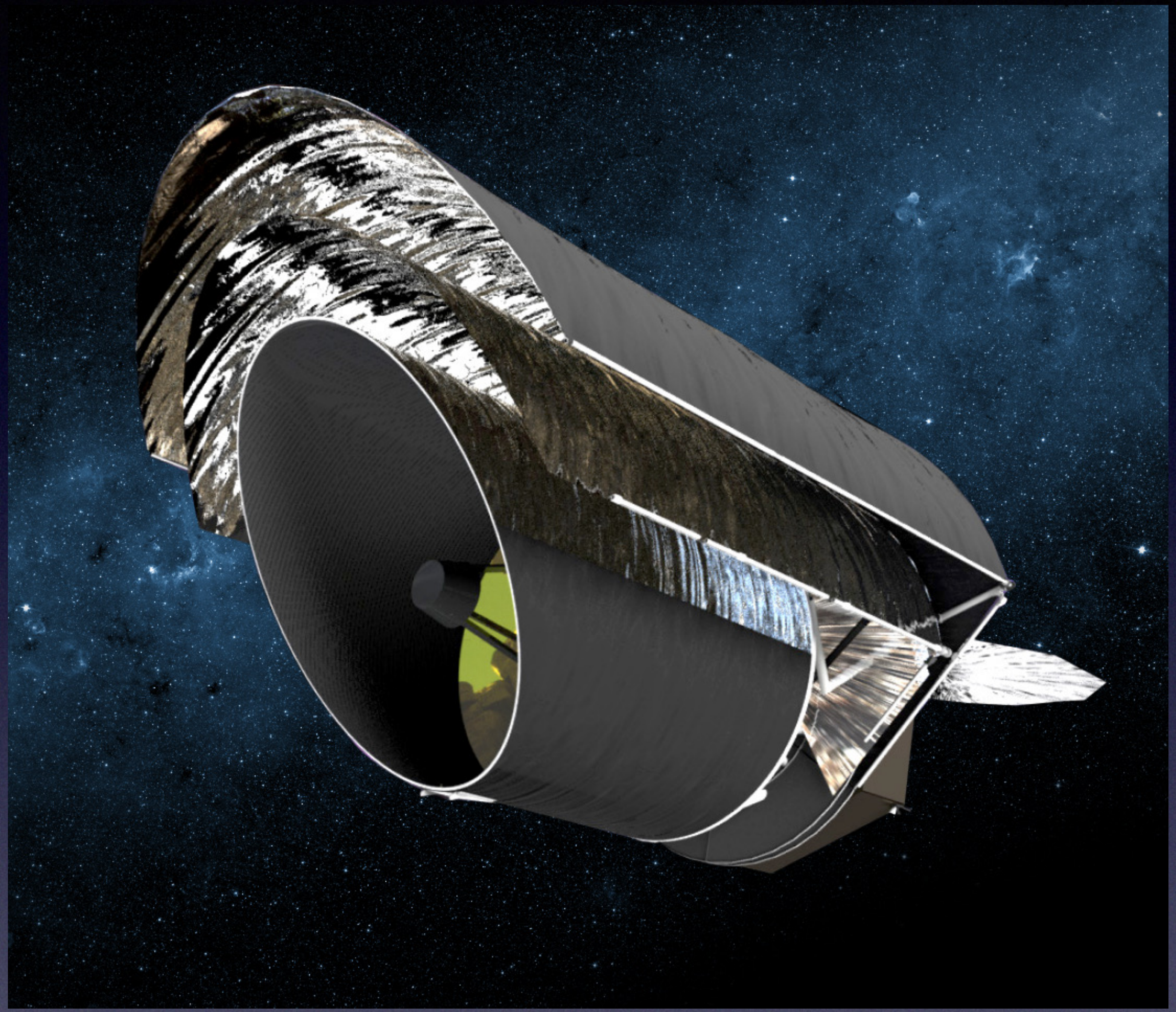
IRAS 15398, MIRI MRS, Yang et al. 2022

- We have to better characterize the ice oxygen content
- James Webb observations of the ice bands of water, CO, CO_2, methanol…
- Confounding factor: blending of different velocity components

Future Prospects



- No current FIR facilities that enable velocity-resolved spectroscopy of [OI]
- Near future: balloons (GUSTO, ASTHROS)
- Astrophysics Probes
- Very distant future: FIR Flagship (*Origins*)



- Archival work: characterize differences in the physical conditions between the two peaks in the O^0 abundance PDF using other molecular tracers :
  - OH^+, H_2O^+, H_3O^+ (constrain molecular fraction and cosmic ray ionization)
  - ArH^+ (tracer of purely atomic gas)

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