Probing the diffuse interstellar gas with observations of simple hydrides

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and the PRISMAS GTKP team (PI, M. Gerin)

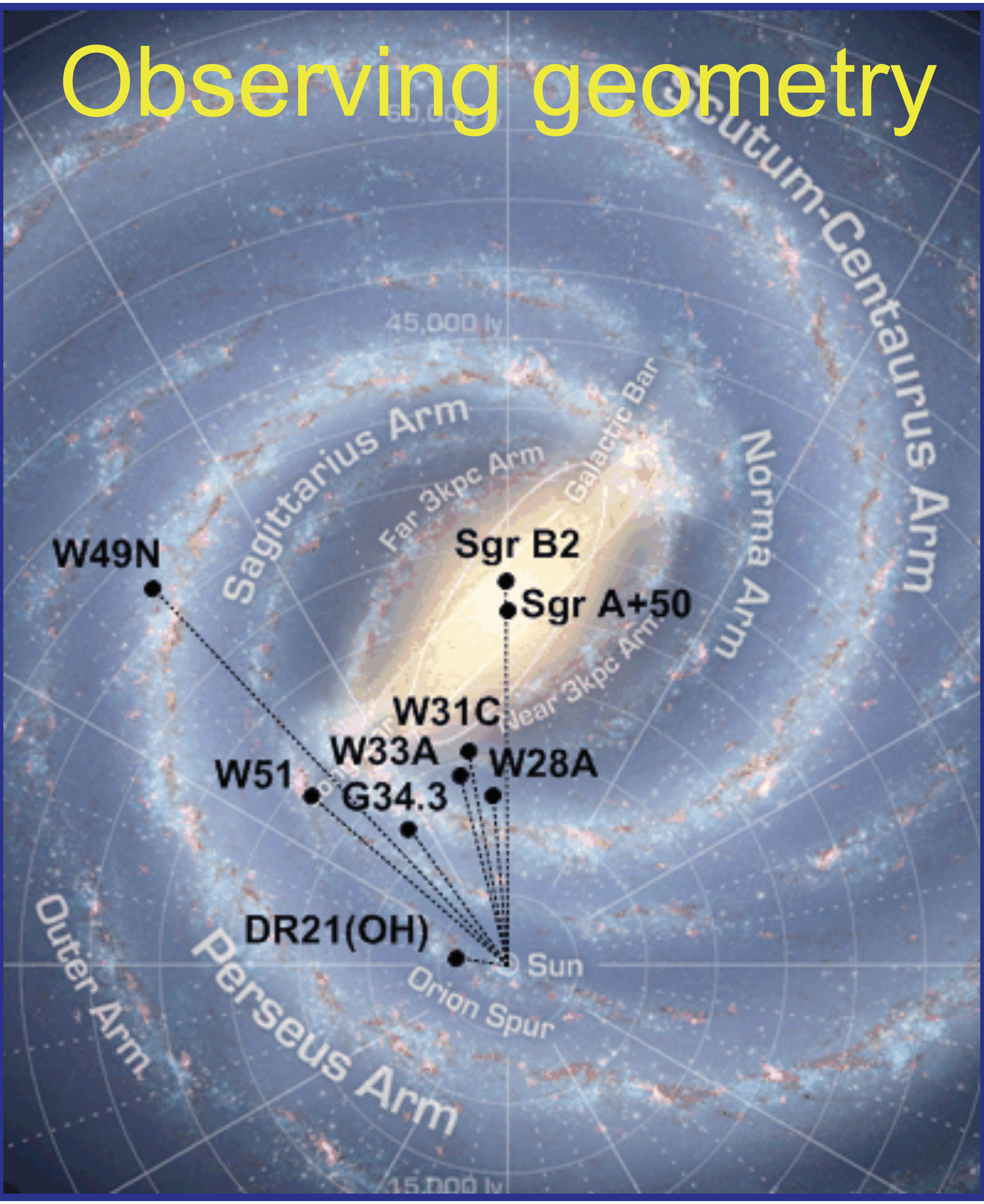
Outline

- Introduction: interstellar hydrides
- Case studies with Herschel
  - Hydrogen fluoride (HF)
  - Hydroxyl and water cations (OH^+ and H_2O^+)
  - Chloronium (H_2Cl^+)
- The future: studying molecules with ALMA and SOFIA

Interstellar hydrides

- Given the elemental abundances in our Universe, it is natural to expect that hydrides will be abundant constituents of the ISM
- Herschel/HIFI provides a unique opportunity to study interstellar hydrides with large rotational constants
- The PRISMAS key program (PI, M. Gerin) has carried out absorption line studies of foreground clouds along the sight-lines to bright Galactic continuum sources

Observing geometry



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Interstellar hydrides

- Herschel/HIFI observations, of very short duration, quickly provided spectacular spectra that reveal the presence in diffuse clouds of:

CH, CH^+ (Gerin et al., Falgarone et al.)

NH, NH_2, NH_3 (Persson et al.)

OH^+, H_2O^+, H_3O^+, H_2O (Gerin et al., Neufeld et al.)

HF (Neufeld et al., Sonnentrucker et al.,, Monje et al.)

SH^+ (Falgarone et al. in preparation)

H_2Cl^+ (Lis et al.)

HCl (Monje et al. in preparation)

HCl^+ ? (de Luca et al.)

Note also APEX observations of OH^+ (Wyrowski et al. 2010) and SH^+ (Menten et al. 2010); VLT observations of OH^+ (Krelowski et al 2010)

Interstellar hydrides

Absorption line observations of foreground clouds provide *extremely robust* estimates of the column densities that are almost independent of

gas temperature

density

collisional excitation rates

the details of radiative transfer

This is a particularly “clean” experiment

Interstellar hydrogen fluoride:

a surrogate for molecular hydrogen

Dissociation energy of the diatomic hydrides (eV)

H_2 4.48							
LiH 2.41	BeH 2.24	BH 3.44	CH 3.49	NH 3.22	OH 4.39	HF 5.87	
NaH 2.04	MgH 1.99	AlH 2.95	SiH 2.98	PH 2.87	SH 3.65	HCl 4.43	
KH 1.87	CaH 1.77	GaH 2.78	GeH 2.73	AsH 2.66	SeH 3.11	HBr 3.76	

ScH 2.09	TiH 2.08	VH 1.67	CrH 2.27	MnH 1.27	FeH 1.59	CoH 1.97	NiH 2.57	CuH 2.64	ZnH 0.83

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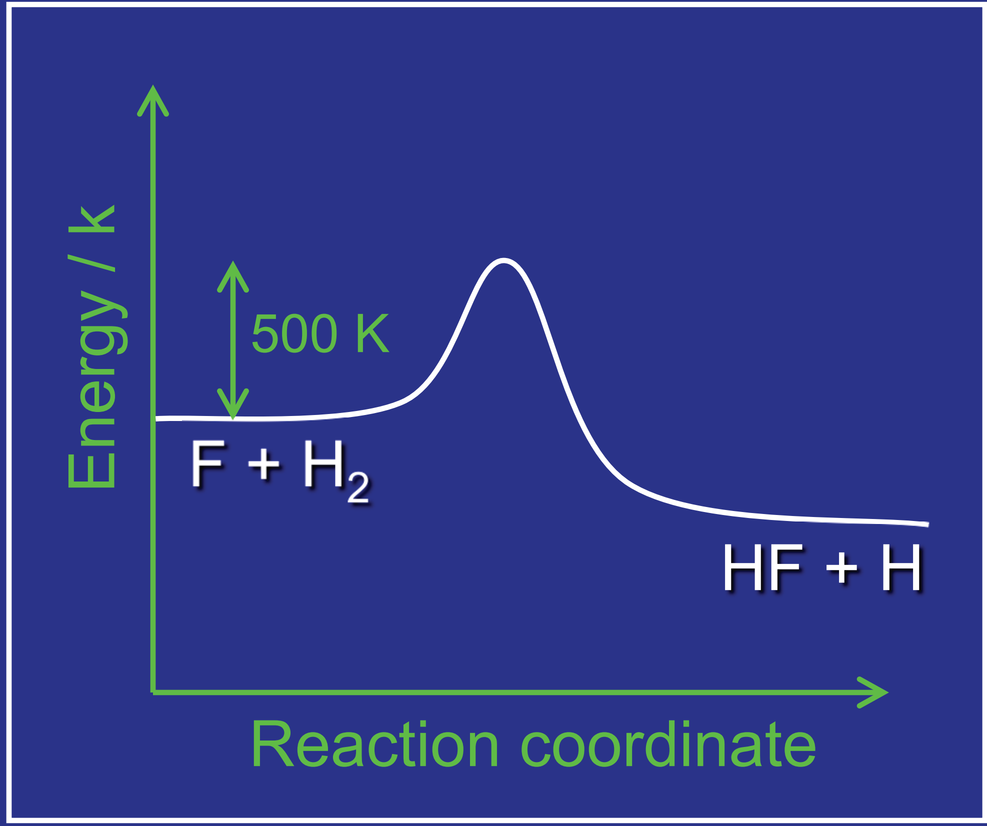
Neufeld and Wolfire 2009, ApJ

Reaction of H_2 with F

One of the most extensively studied bimolecular chemical reactions

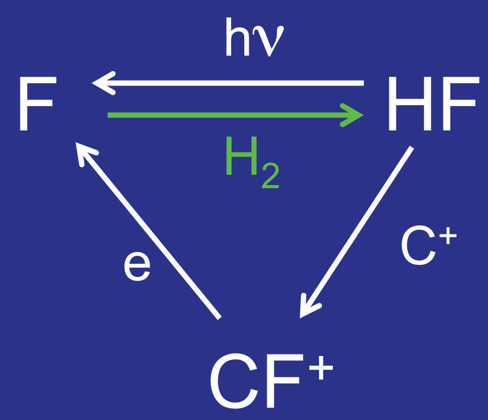
Room temperature experiments suggest a barrier, E_A/k ~ 500 K

Theory suggests a substantial tunneling probability at low T

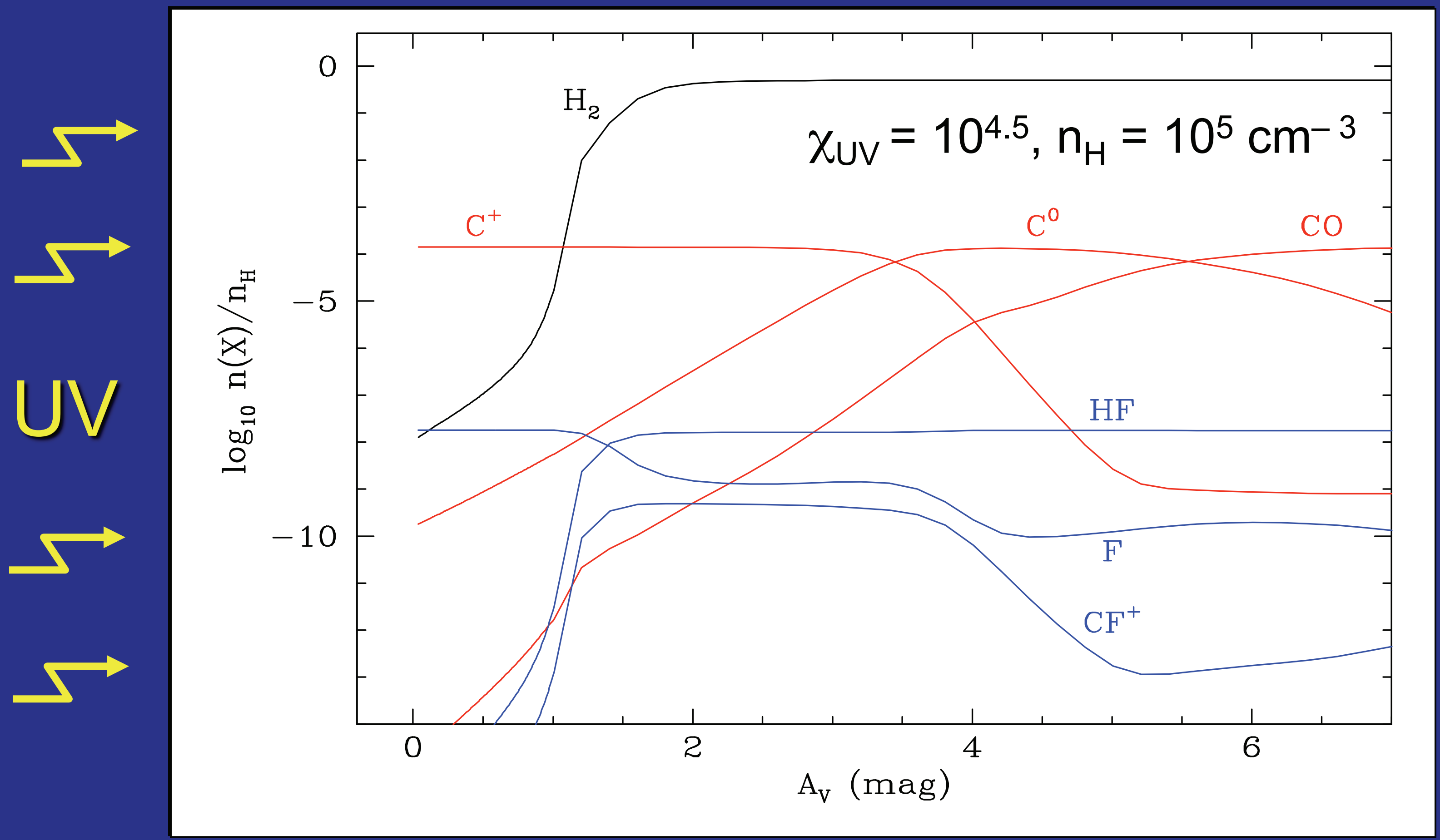


Chemistry of interstellar fluorine

- Fluorine chemistry is very simple



Predicted abundance profiles
(Neufeld, Wolfire & Schilke 1995)



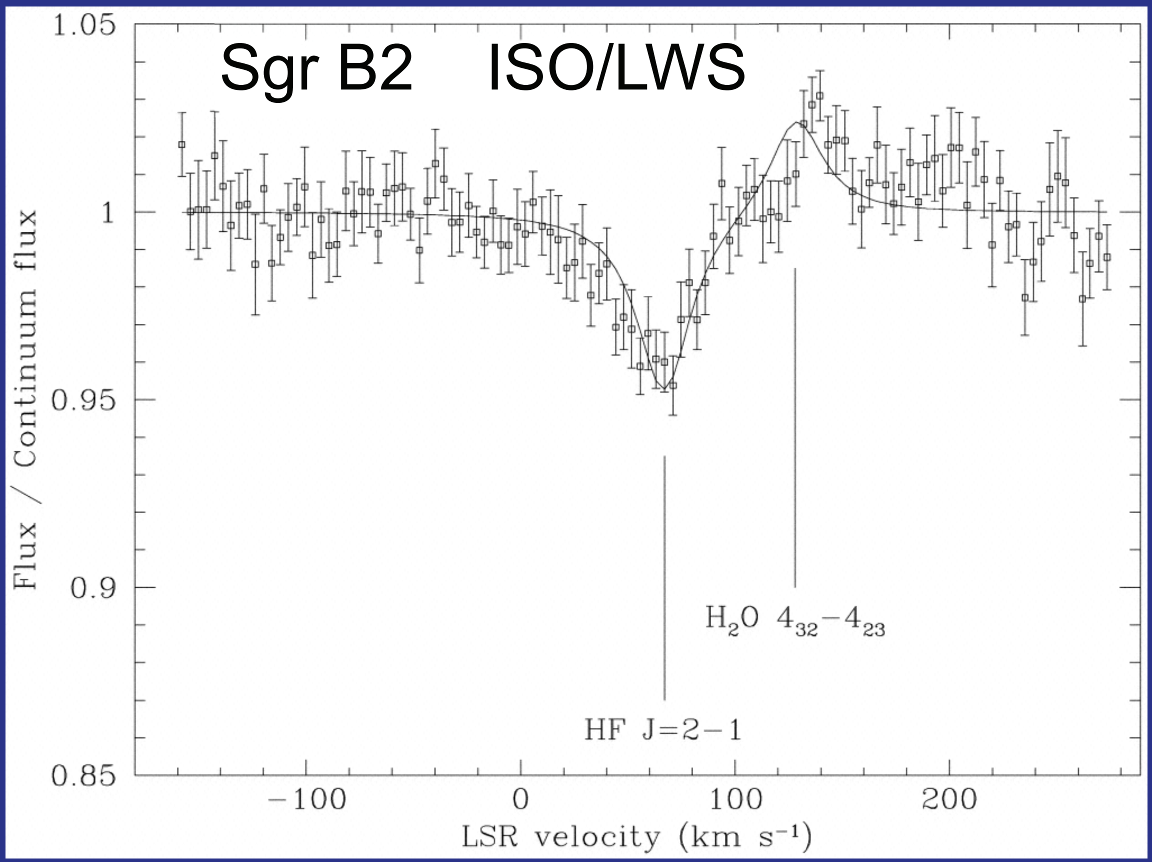
Chemistry of interstellar fluorine

- Once H_2 becomes abundant, HF is produced rapidly
- HF is destroyed slowly by photodissociation and reaction with C^+
- HF becomes the dominant reservoir of fluorine:
  - Unobservable from the ground, however: the J = 1– 0 transition is at 1.232 THz

Discovery of interstellar HF

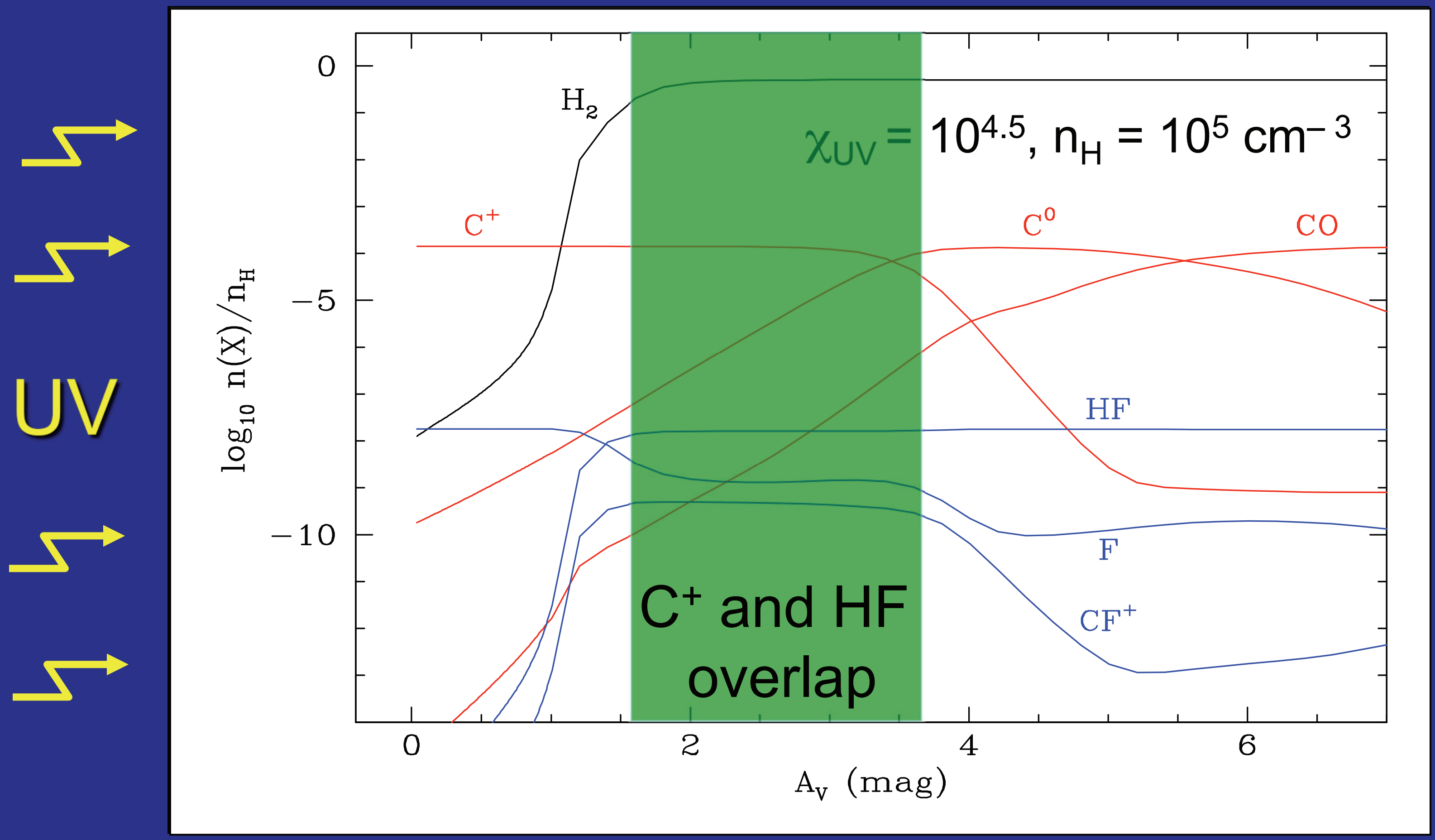
J = 2 – 1 transition discovered by ISO

(Neufeld, Zmuidzinas, Schilke and Phillips 1997)



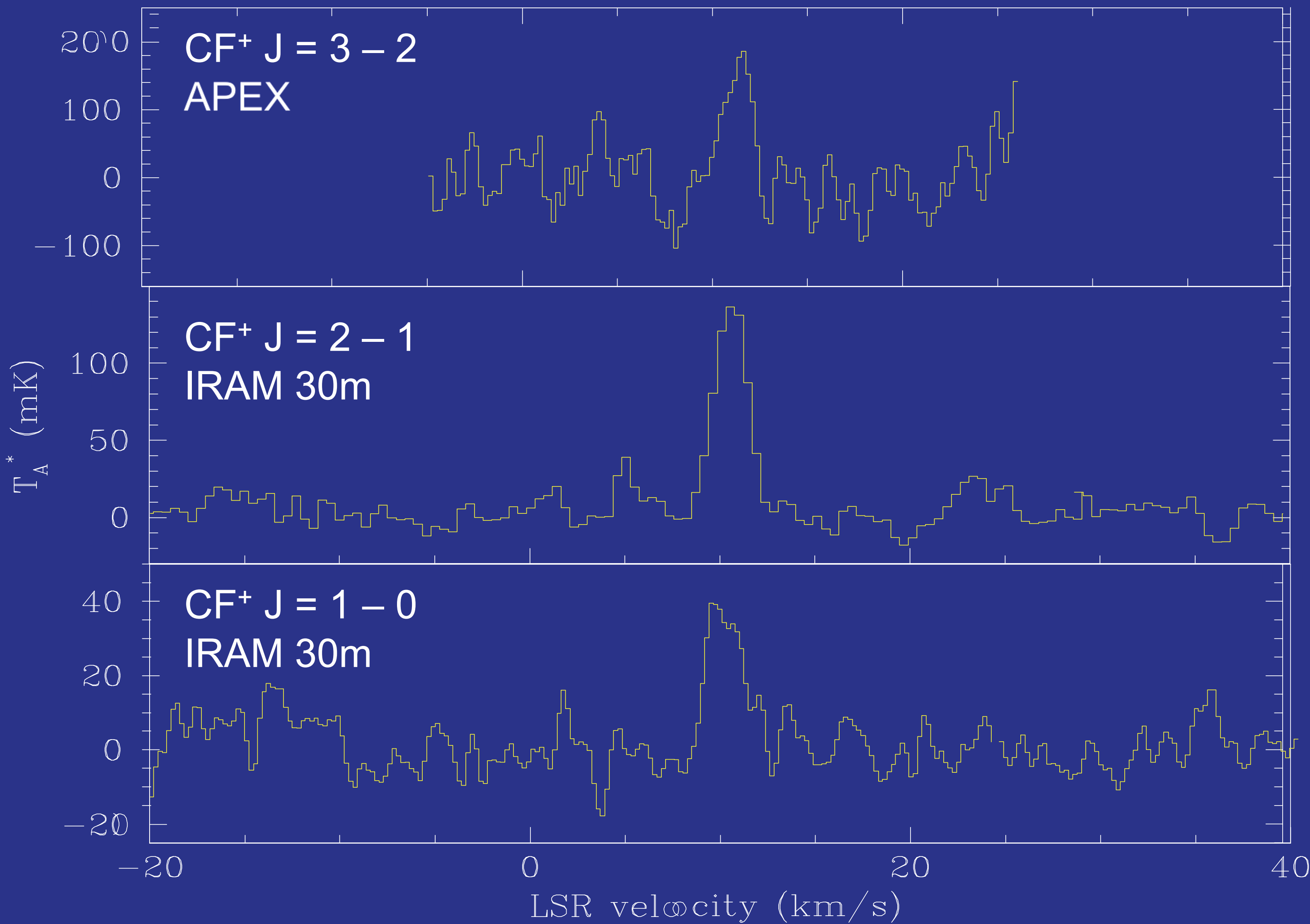
Lacking access to the J = 1 – 0 transition, ISO was unable to probe HF in any source other than Sgr B2

Predicted abundance profiles
(Neufeld, Wolfire & Schilke 1995)



CF$^+$ spectra toward the Orion Bar

(Neufeld et al. 2006, A&A)



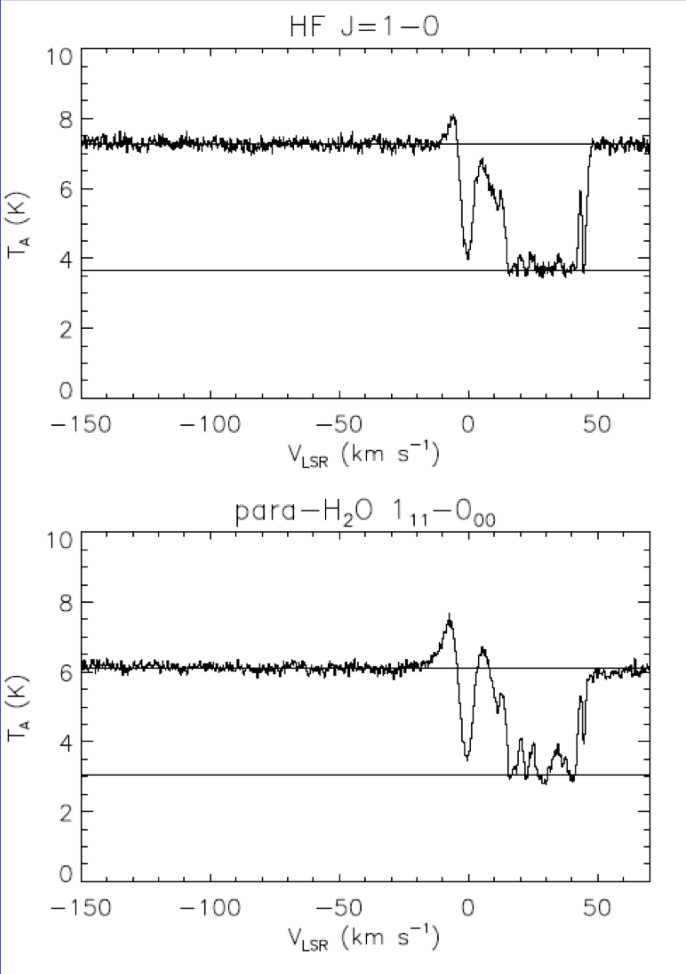
Herschel/HIFI observations of HF J = 1 – 0

- As part of the "PRobing InterStellar Molecules with Absorption line Studies (PRISMAS)" Key Program, we have observed the HF J = 1 – 0 transition toward three strong continuum sources with sight-lines that are intersected by foreground clouds:

G10.6 – 0.4 (W31C), W49, W51

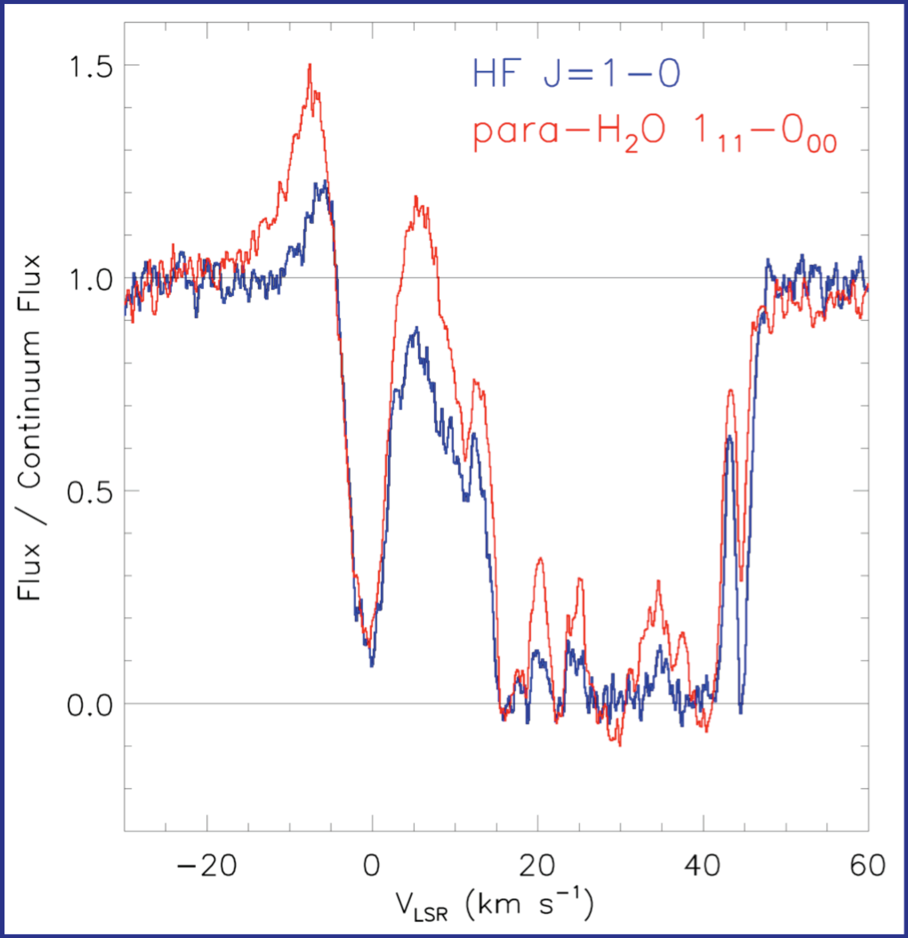
Strong HF absorption observed toward G10.6 – 0.4 (W31C)

- We observed the HF J = 1 – 0 and para-H_2O $1_{11} – 0_{00}$ transitions in mixer band 5a
- The on-source integration times were 225 s and 117 s, respectively
- The spectra are double-sideband spectra ➔ the complete absorption of radiation reduces the apparent antenna temperature by one-half (for a sideband gain ratio of unity)



Neufeld et al. 2010, A&A

Strong HF absorption observed toward G10.6 – 0.4 (W31C)



Neufeld et al. 2010, A&A

Strong HF absorption observed toward G10.6 – 0.4 (W31C)

Remarkably, the optical depth for HF is larger than that for para-H_2O, even though the elemental abundance of fluorine is 10^4 times smaller than that of oxygen

$\tau(HF) / \tau(p\text{–}H_2O) \sim 2 – 3$

➔ $N(HF) / N(H_2O) \sim 1$

for an assumed H_2O ortho-to-para ratio of 3

Strong HF absorption observed toward G10.6 – 0.4 (W31C)

- Inferred column density and abundance

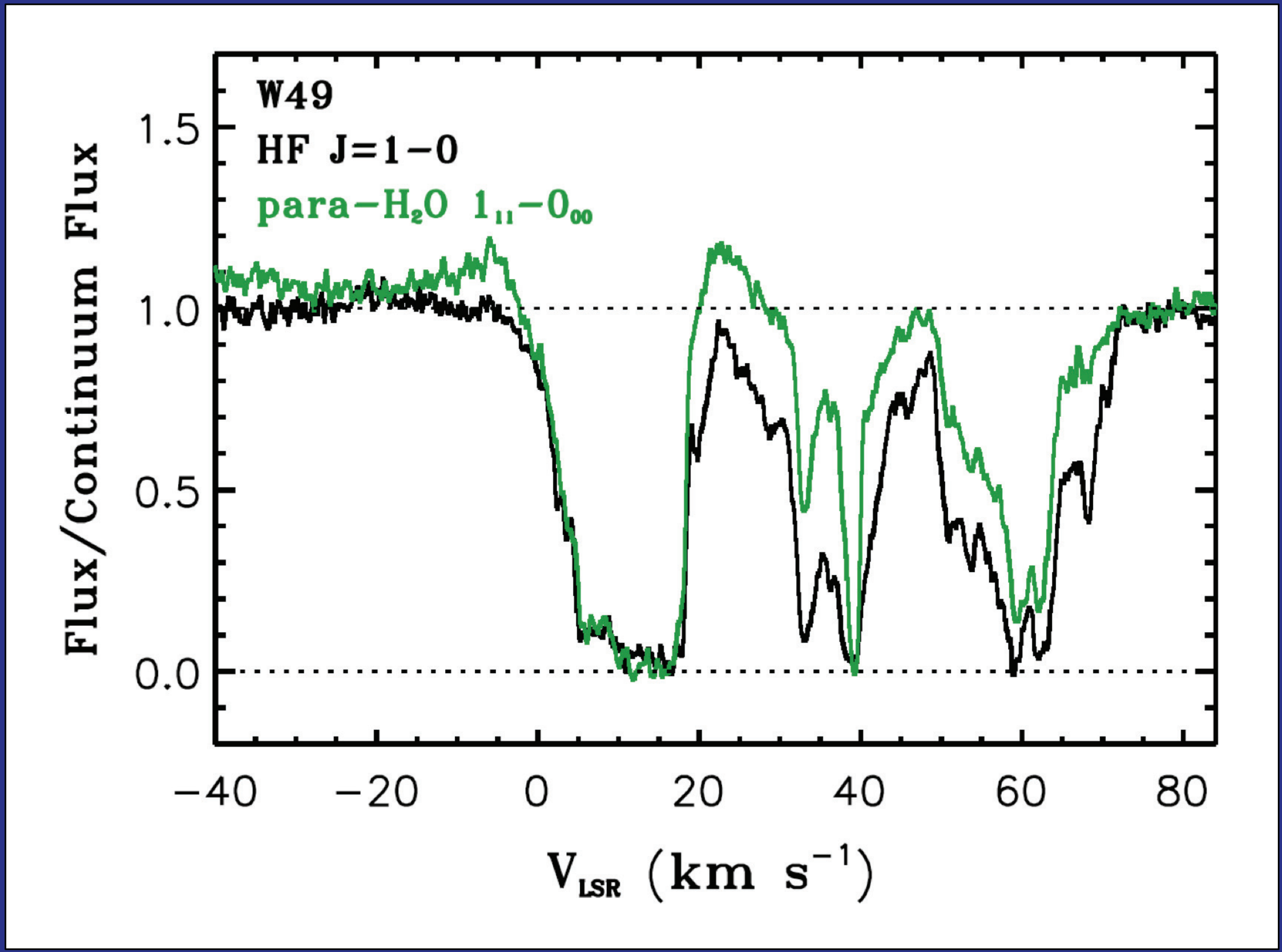
$N(HF) > 1.6 \times 10^{14}$ cm^{-2} (lower limit, because the optical depth is large)

Along this sight-line, $N_H = N(H) + 2\,N(H_2) \sim 2.7 \times 10^{22}$ cm^{-2} (based on extinction estimates)

$N(HF)/N_H > 6 \times 10^{-9}$

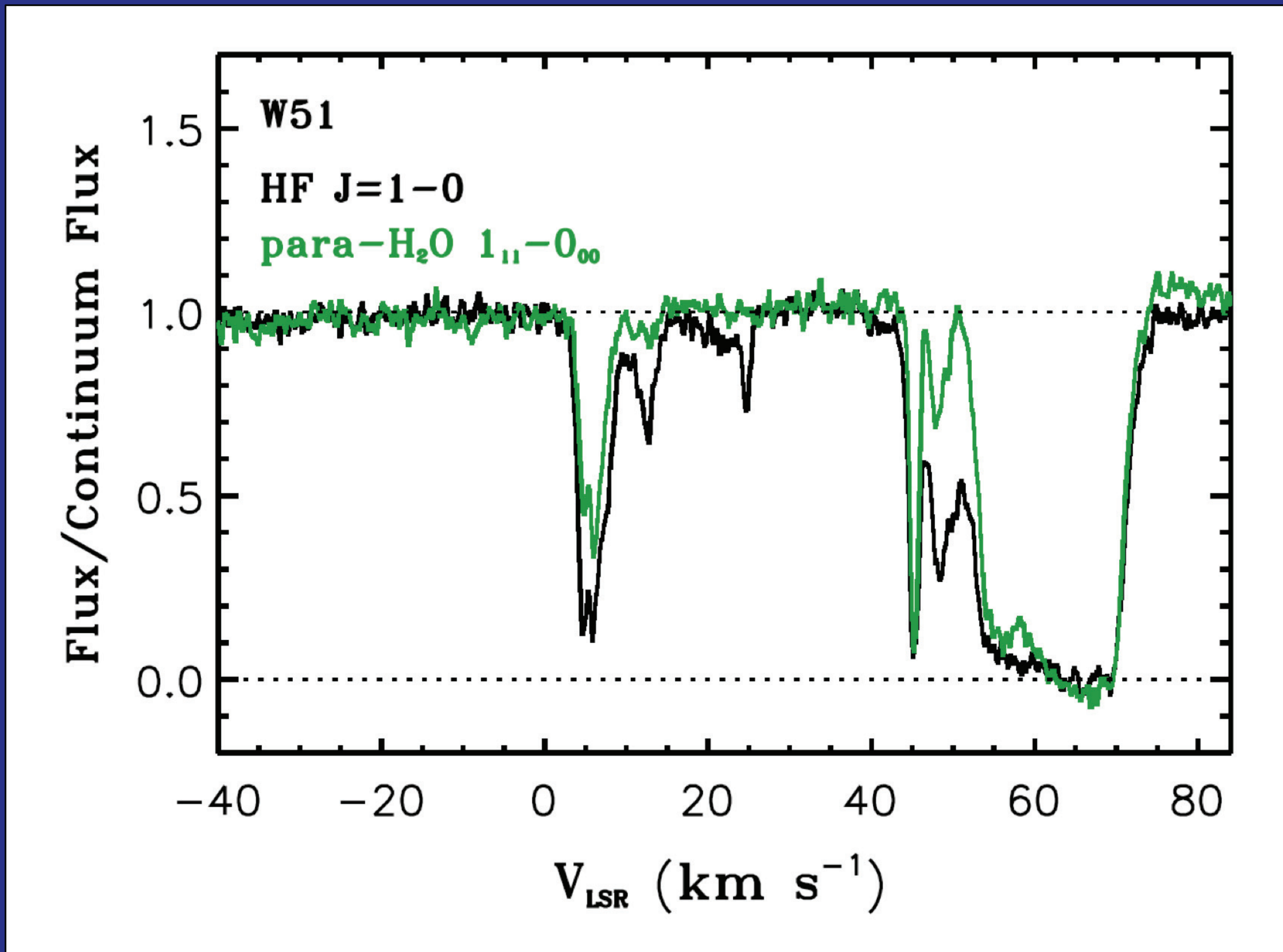
➔ HF accounts for 30 – 100% of fluorine in the gas phase

HF absorption also detected toward W49



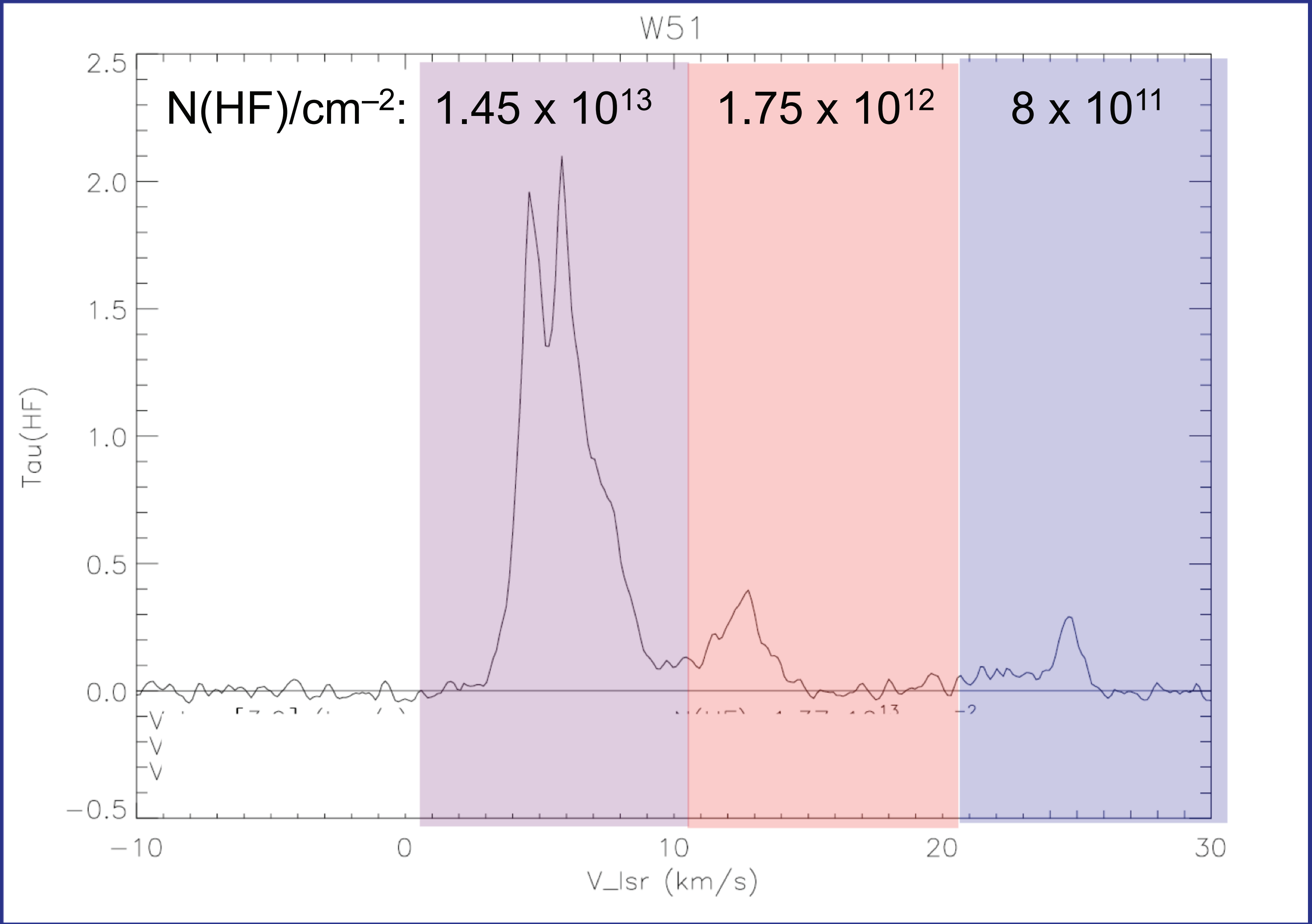
Sonnentrucker et al. 2010, A&A

…….and toward W51



Sonnentrucker et al. 2010, A&A

W51 exhibits some *optically-thin* absorption clouds



W51 absorption

Total HF column density at LSR velocities between 3 and 27 km s^{-1}: 1.7×10^{13} cm^{-2}

(a *measurement*, not a lower limit)

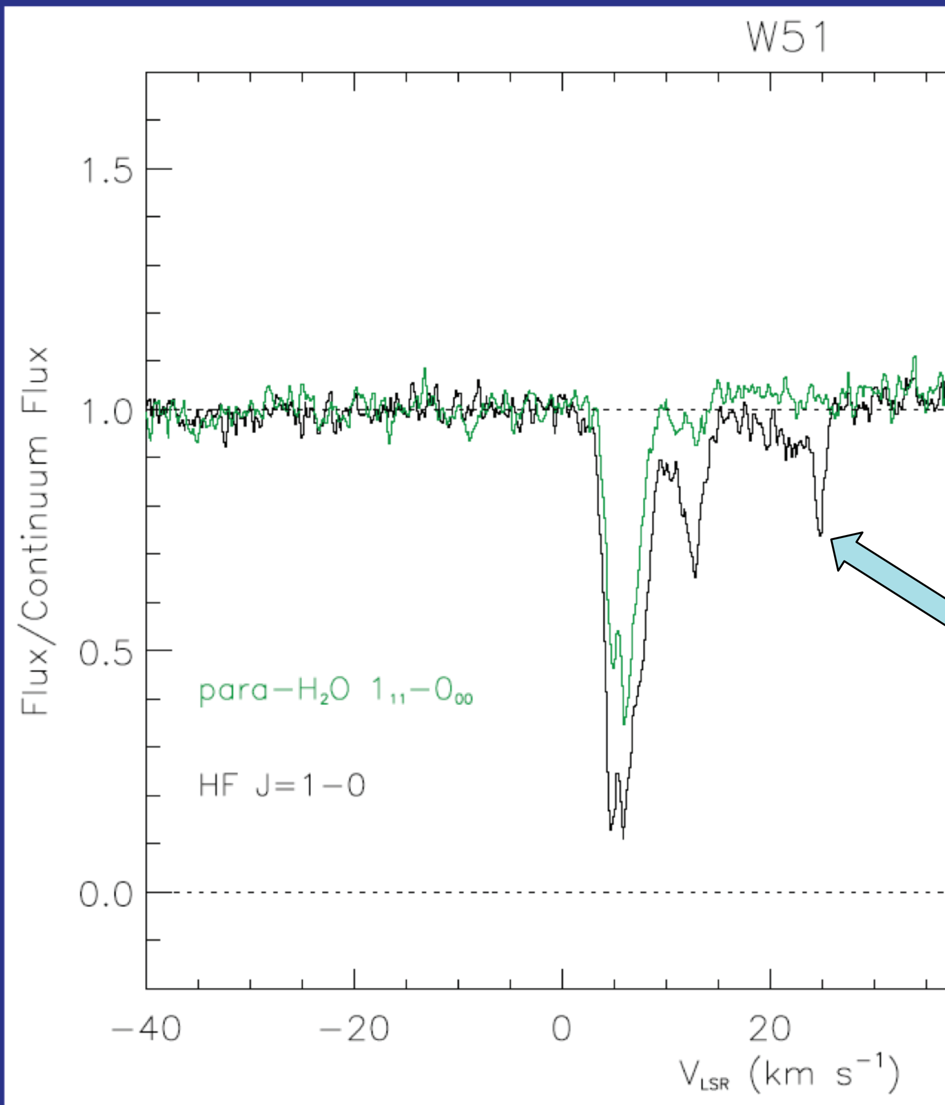
Corresponding H_2 column density ~ 6×10^{20} cm^{-2}

(based upon observations of CH by Gerin et al. 2010, and assuming $CH/H_2 = 3.5 \times 10^{-8}$)

$N(HF)/N(H_2) \sim 3 \times 10^{-8}$

By comparison: average $N_F/N_H = 1.8 \times 10^{-8}$ in diffuse atomic clouds (Snow et al. 2007)

W51 absorption

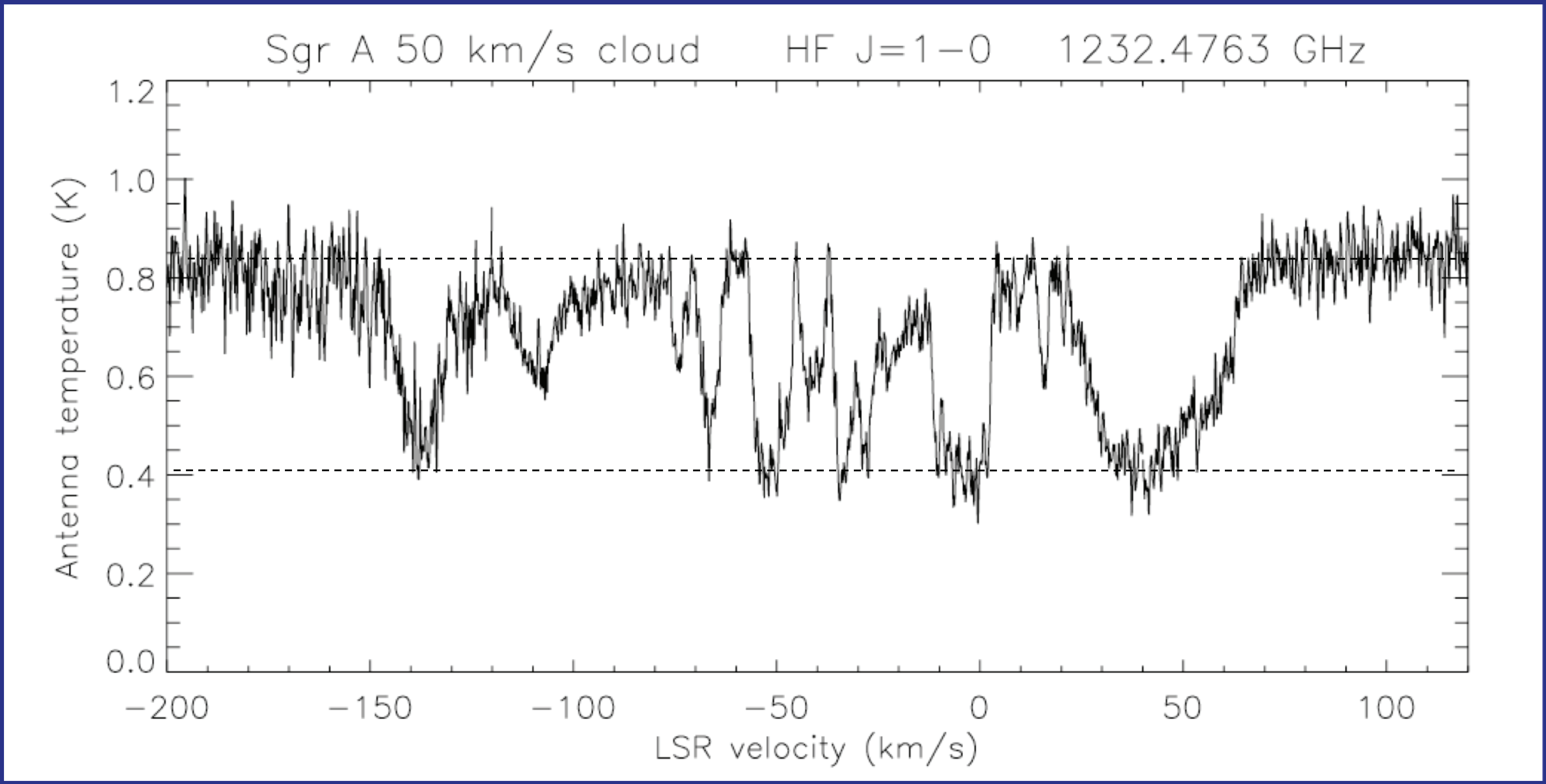


Additional note:

This weak HF absorption feature at an LSR velocity of +25 km/s is not detected in the absorption spectrum of any other molecule detected before Herschel.

This cloud was also detected in CH^+ J = 1 – 0 (Falgarone et al. 2010)

HF toward the Galactic Center



Future prospects

Hydrogen fluoride could prove to be a valuable surrogate for H_2

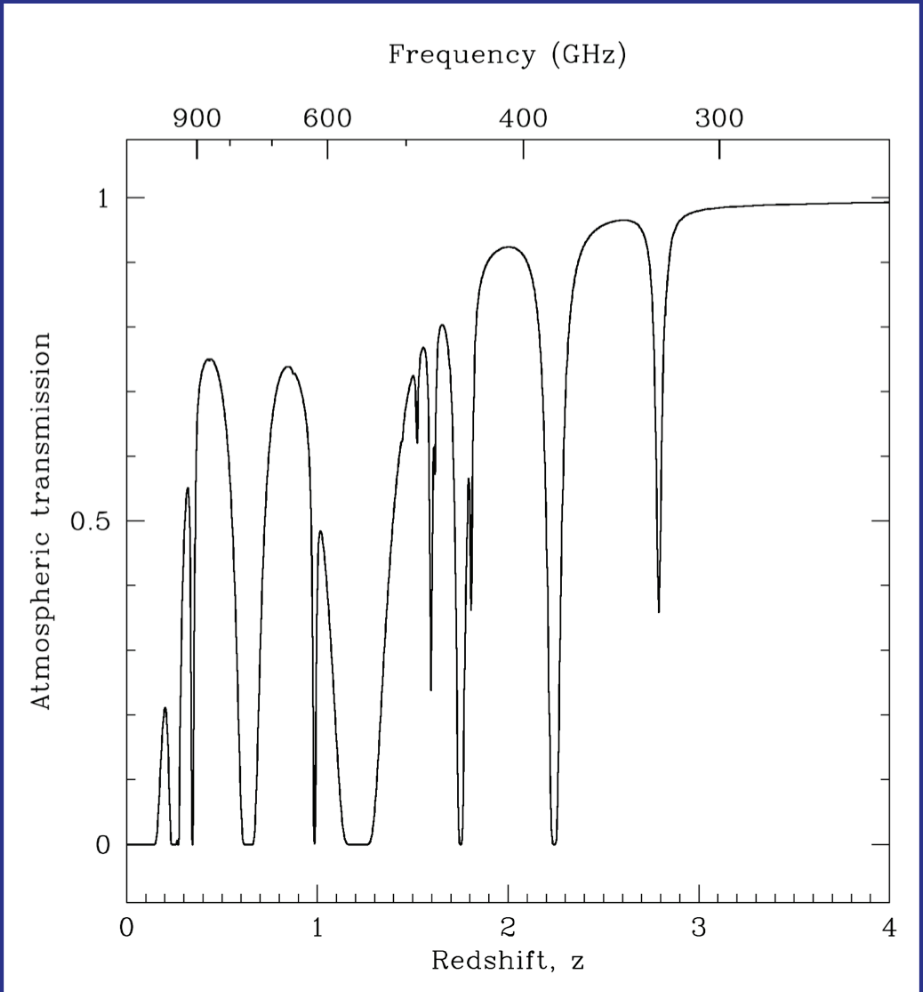
- Initial observations of diffuse clouds confirm the theoretical prediction that $N(HF)/2N(H_2)$ = gas phase elemental F/H ratio
- HF J = 1 – 0 can trace clouds of very small H_2 column density (< 10^{20} cm $^{-2}$) that are difficult to detect by other means
- In the observations presented here, the on-source integration time was only 4 minutes

  ➔ substantial sensitivity improvement will be achievable in longer integrations

Future prospects

Observations of HF
J = 1 – 0 absorption might prove valuable in probing molecular hydrogen at high redshifts (e.g. in absorption toward a quasar)

Atmospheric windows appear at redshifts > 0.2



Neufeld, Wolfire & Schilke 2005, ApJ

Interstellar OH^+ and H_2O^+:

probing the cosmic ray ionization rate in clouds of low molecular fraction

Dissociation energy of the diatomic hydrides (eV)

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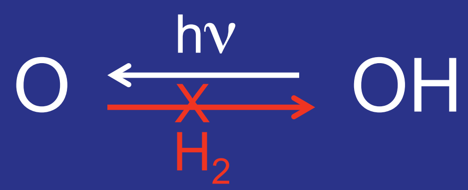
Neufeld and Wolfire 2009, ApJ

Chemistry of interstellar oxygen

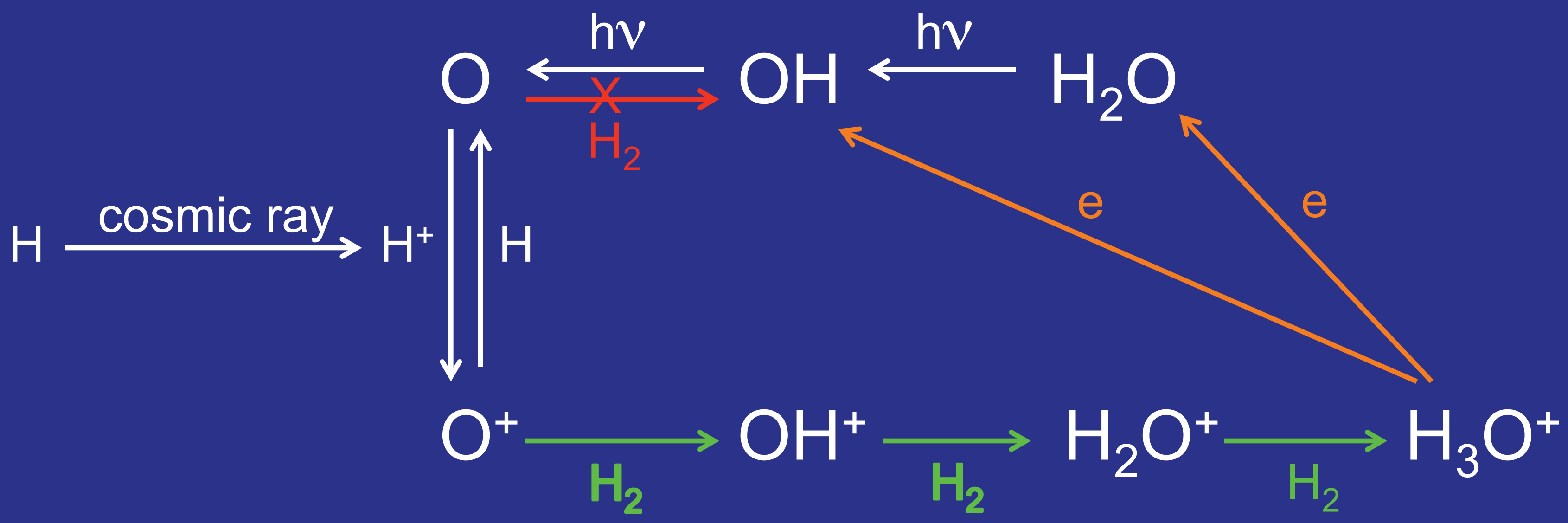
- Oxygen differs from fluorine



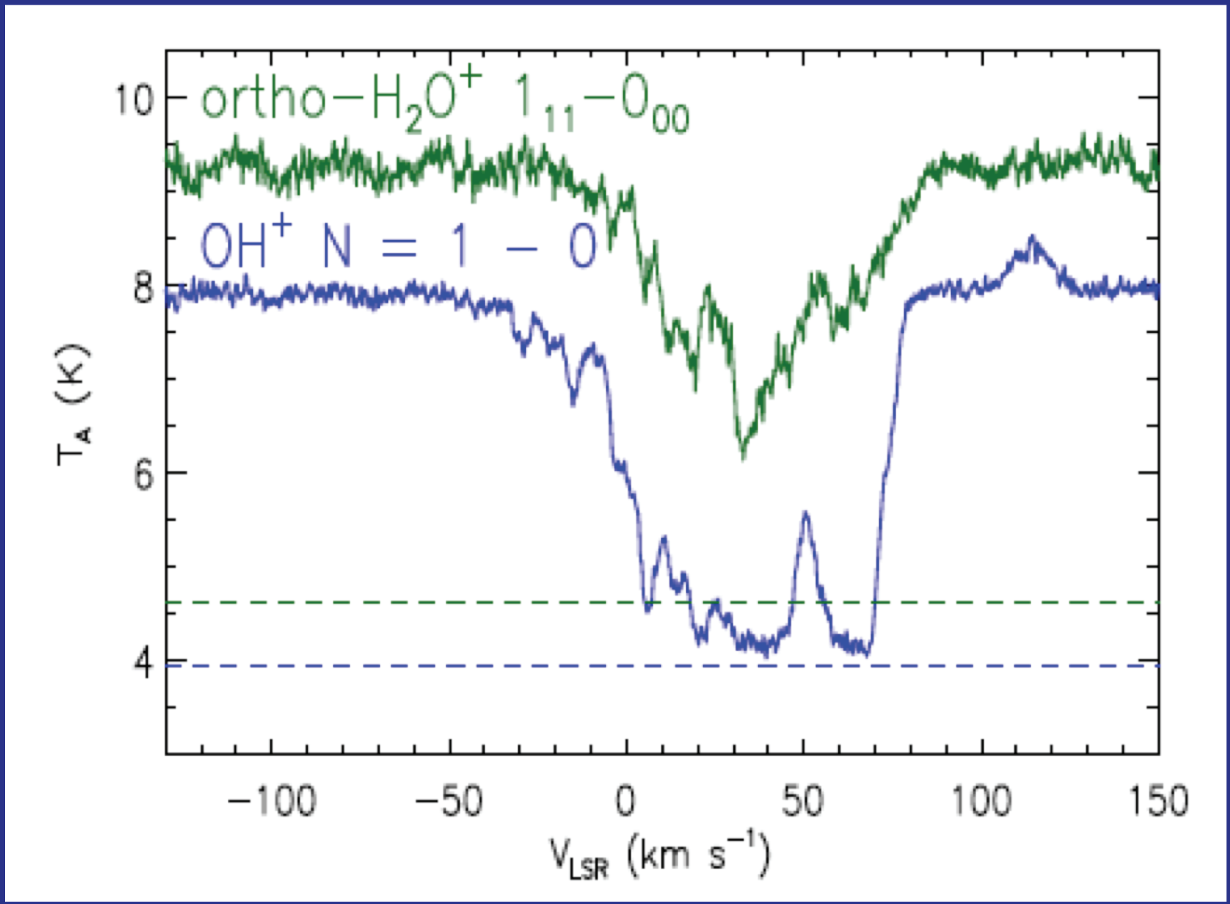
O cannot react with H_2 except at high temperature (> 300 K)

Chemistry of interstellar oxygen

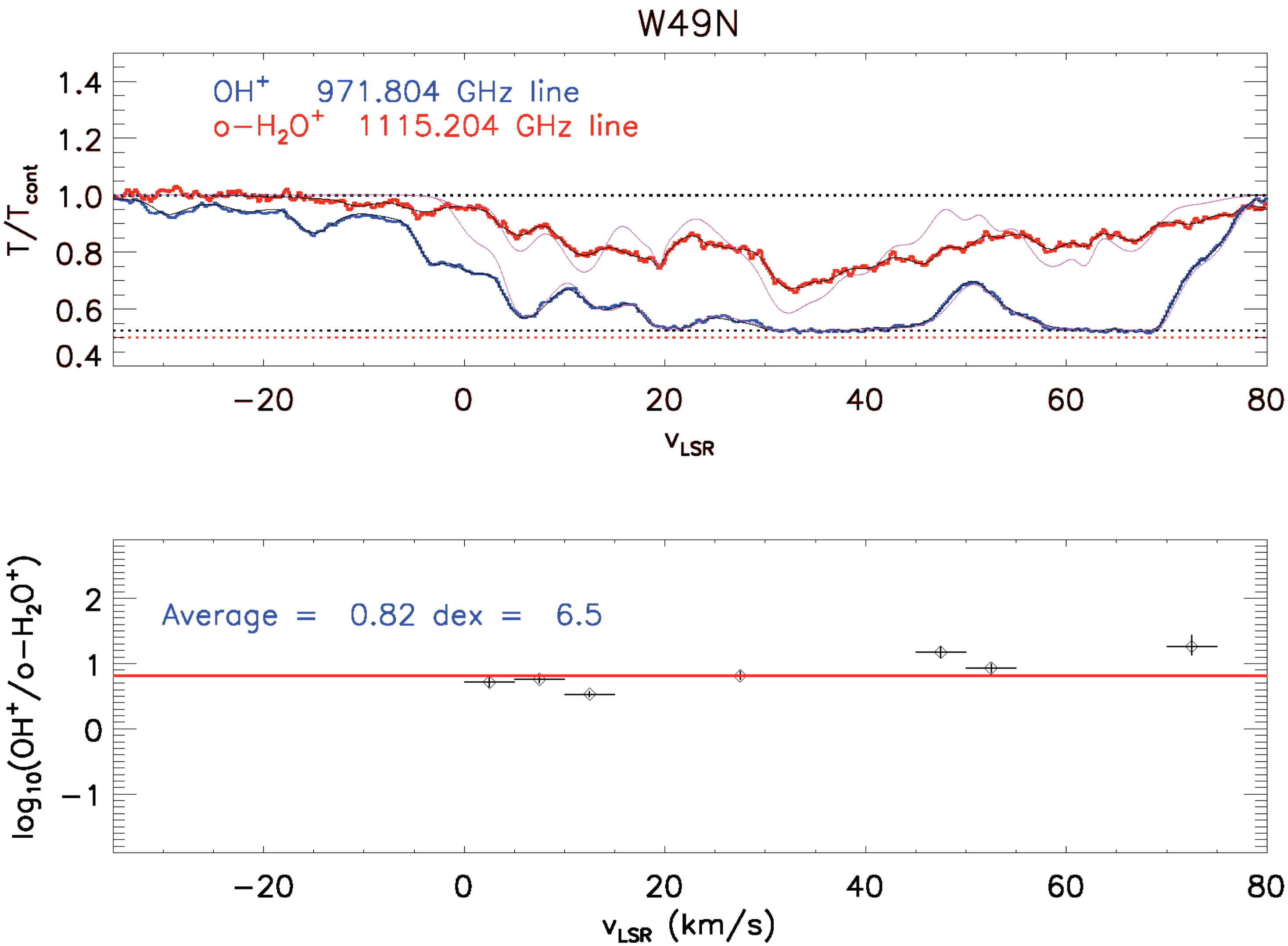
- Chemistry is initiated by cosmic rays



OH^+ and H_2O^+ along the sight-line to W49N



Neufeld, Goicoechea, Sonnentrucker et al. 2010, A&A


W49N
OH+ 971.804 GHz line
o−H2O+ 1115.204 GHz line
T/Tcont
1.4
1.2
1.0
0.8
0.6
0.4
−20
0
20
40
60
80
vLSR
Average = 0.82 dex = 6.5
log10(OH+/o−H2O+)
2
1
0
−1
−20
0
20
40
60
80
vLSR (km/s)

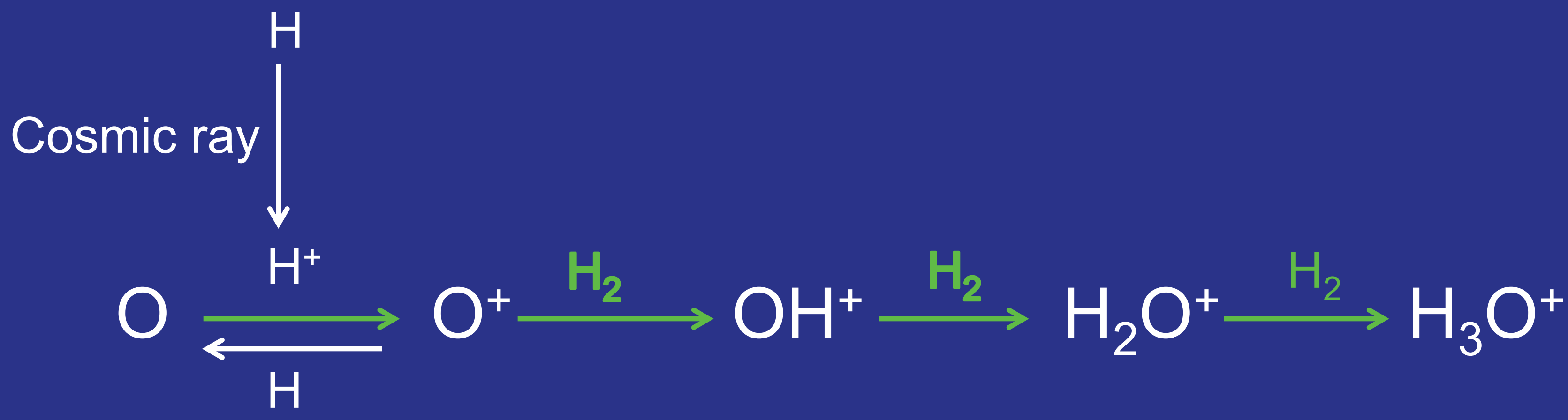
OH^+ and H_2O^+ along the sight-line to W49N

Rather surprising result:

$OH^+/H_2O^+ = 3 – 15$

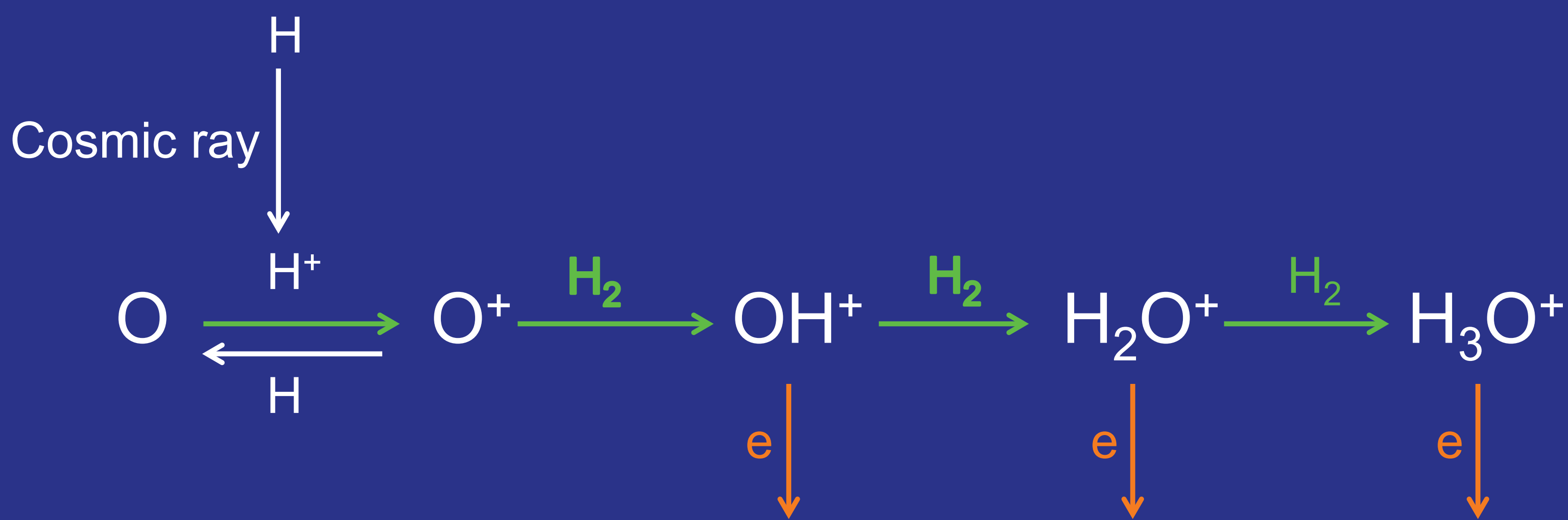
We would have expected a ratio ~ 1 if reaction with H_2 dominated the destruction of H_2O^+

The oxygen pipeline



The large OH^+/H_2O^+ ratio implies that the pipeline is leaky

The oxygen pipeline



The large OH^+/H_2O^+ ratio implies that the pipeline is leaky – electrons are competing with H_2 in destroying molecular ions

Implication: the molecular fraction is only 2 – 8 %

OH^+ and H_2O^+ along the sight-line to W49N

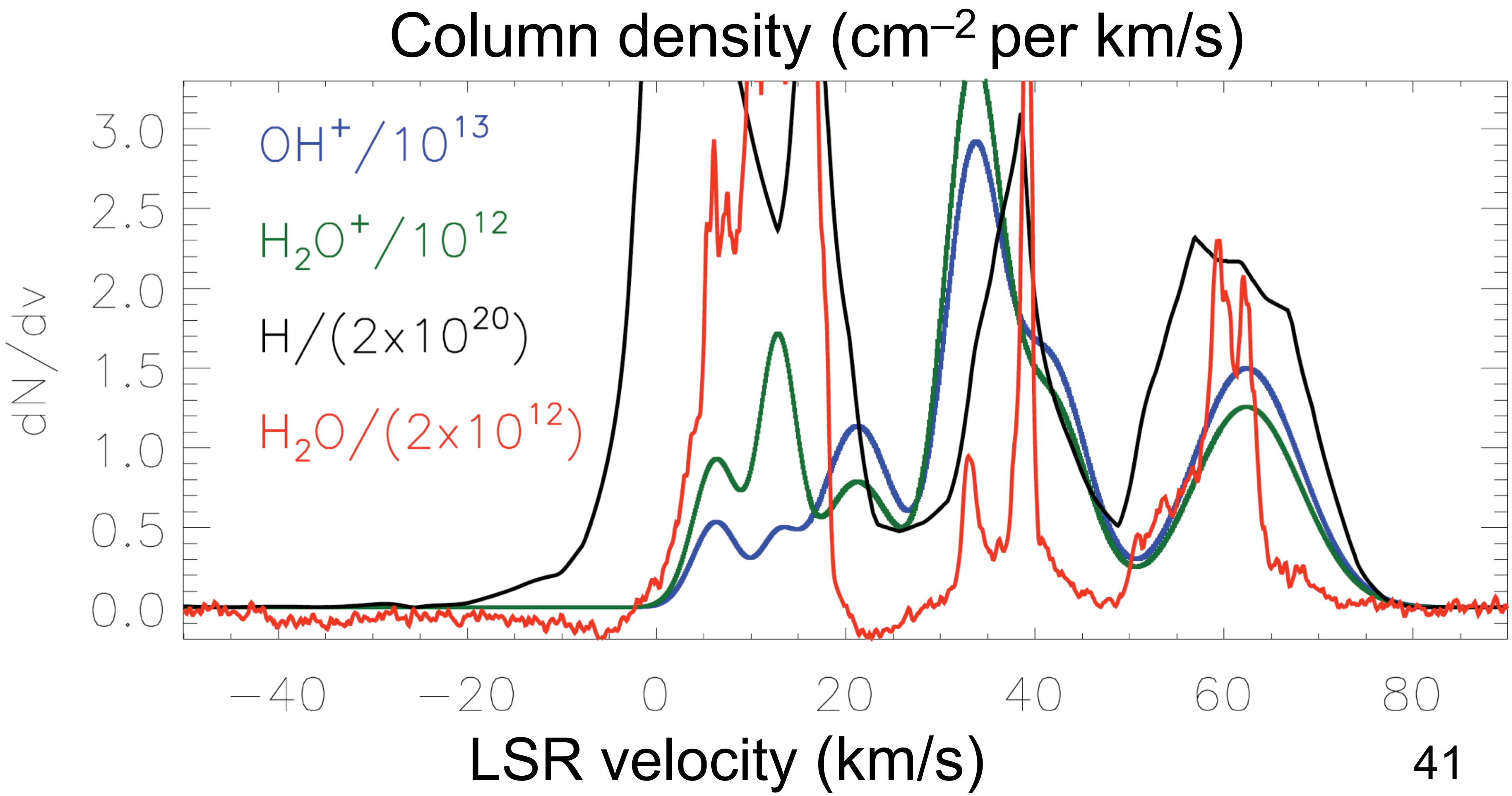
Two important implications:

(1) OH^+/H_2O^+ ratio → low molecular fraction

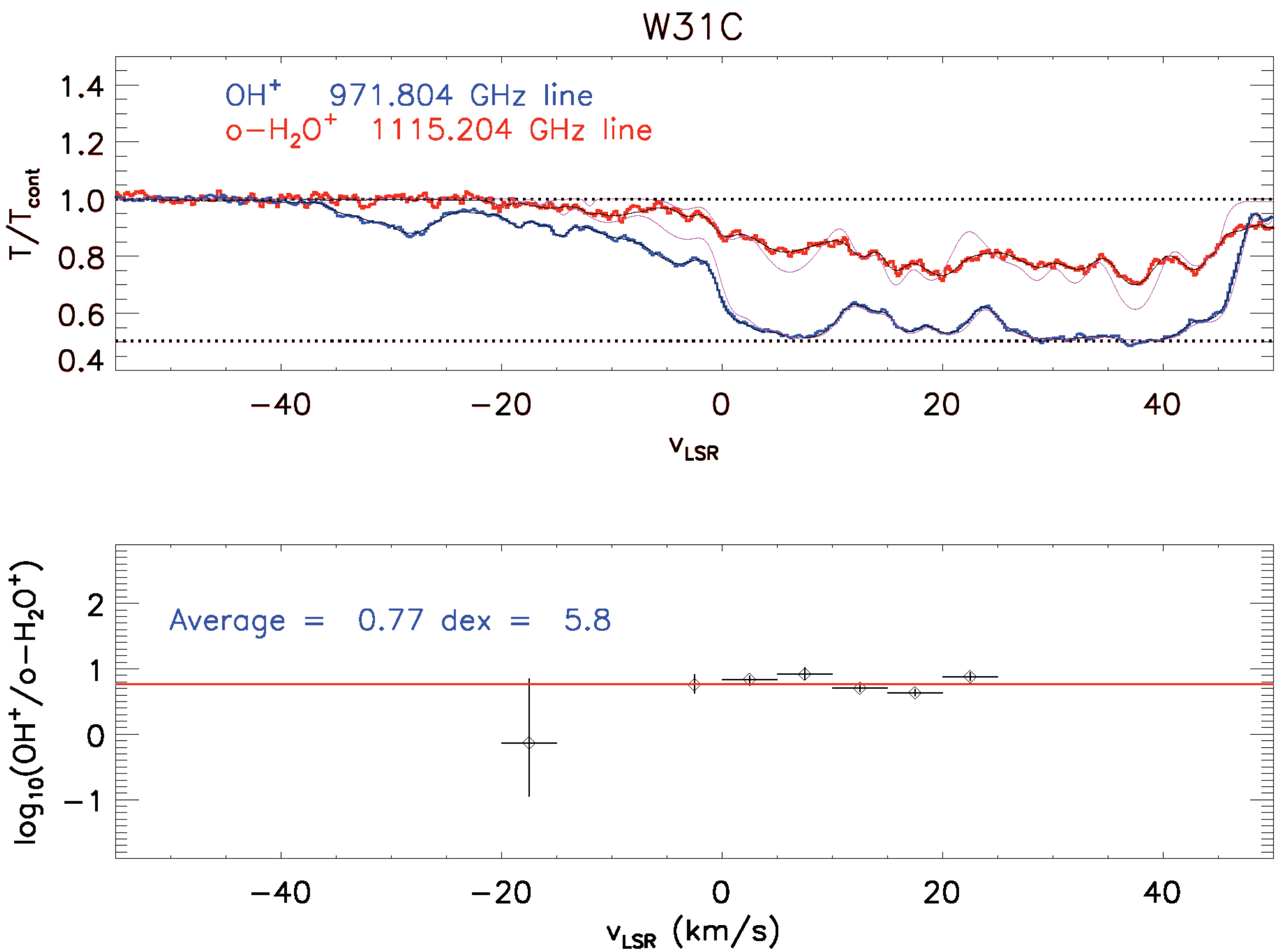
Many small clouds along the sight-line (weakly shielded), or could represent departure from steady state

We may be witnessing the transition from atomic to molecular clouds

The OH^+ and H_2O^+ distributions follow that of HI (Fish et al. 2003) rather than H_2O



Similar results for OH^+/H_2O^+ are obtained toward other sources



Gerin et al. 2010

OH^+ and H_2O^+ along the sight-line to W49N

Two important implications:

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We may be witnessing the transition from atomic to molecular clouds

OH^+ and H_2O^+ along the sight-line to W49N

Two important implications:

(2) OH^+ column density → cosmic ray ionization rate

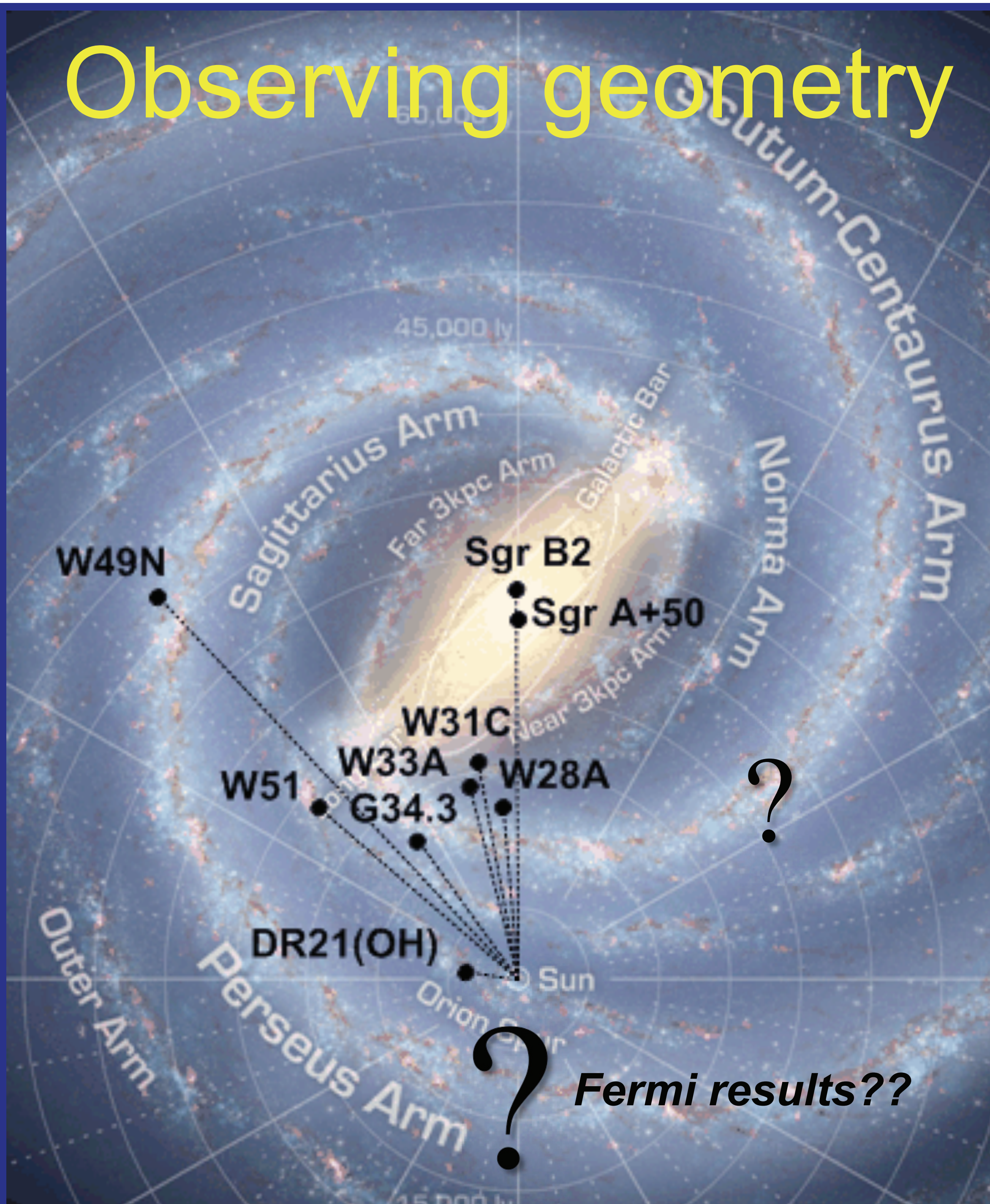
Preliminary estimate: $\zeta_H = 0.5 - 3 \times 10^{-16}\ s^{-1}$ in W49N

Confirmation of new larger values inferred by Indriolo, Geballe, Oka, & McCall from observations of H_3^+

Next steps:

- more detailed analysis of chemistry
- investigate variation with position in the Galaxy

Observing geometry



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Interstellar HCl^+ and H_2Cl^+:

yet a third type of chemistry

Chlorine chemistry

Just like with oxygen,

$Cl + H_2 \rightarrow HCl + H$ is endothermic

$Cl^+ + H_2 \rightarrow HCl^+ + H$ is exothermic

BUT,

Cl has an ionization potential of 13.0 eV, smaller than that of hydrogen (13.6 eV)

and THUS, UV photoionization creates Cl^+

$Cl + h\nu \rightarrow Cl^+ + e$

Subsequent reactions form H_2Cl^+ and HCl

$HCl^+ + H_2 \rightarrow H_2Cl^+ + H$

$H_2Cl^+ + e \rightarrow HCl + H$

Chlorine chemistry

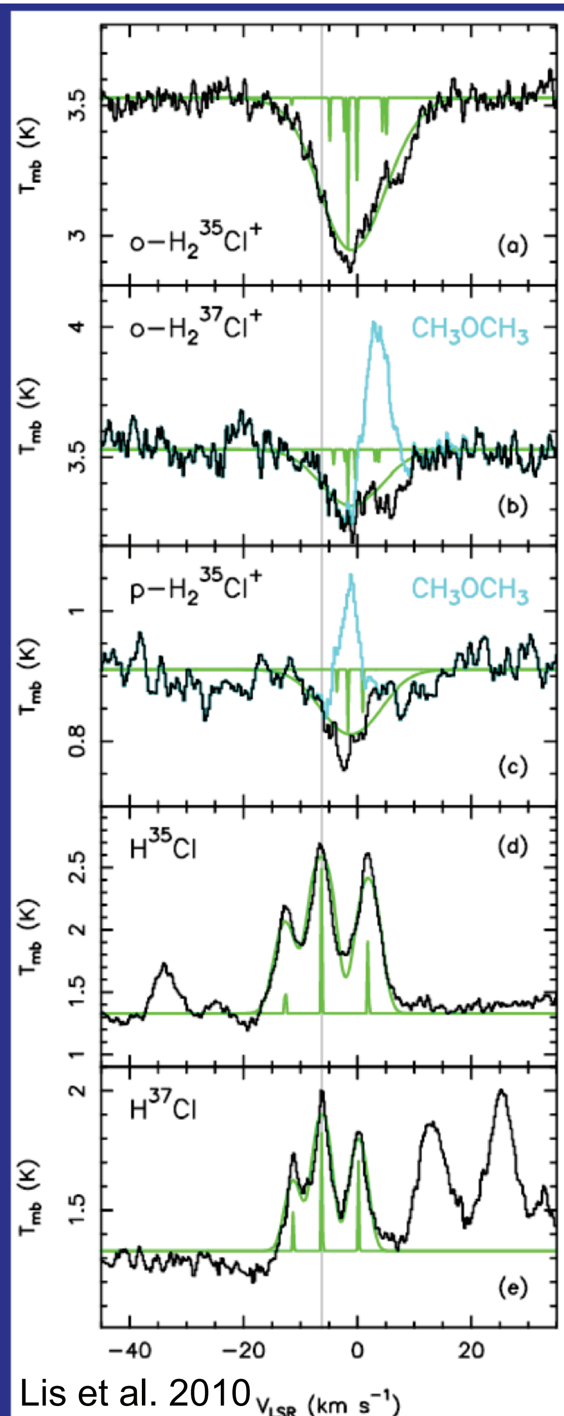
H_2Cl^+ detected by Lis et al. (2010) along the sight-line to NGC 6334I

Column density ~ 1.7×10^{13} cm^{-2} appears to require an enhanced UV radiation field to drive photoionization of Cl

Additional Herschel detections are currently being analysed

HCl^+ has been tentatively detected at 1.444 THz toward W31C (poster paper by de Luca et al. at IAU Symposium 280 last week)

Improved laboratory spectroscopy is needed to confirm the identification



Lis et al. 2010

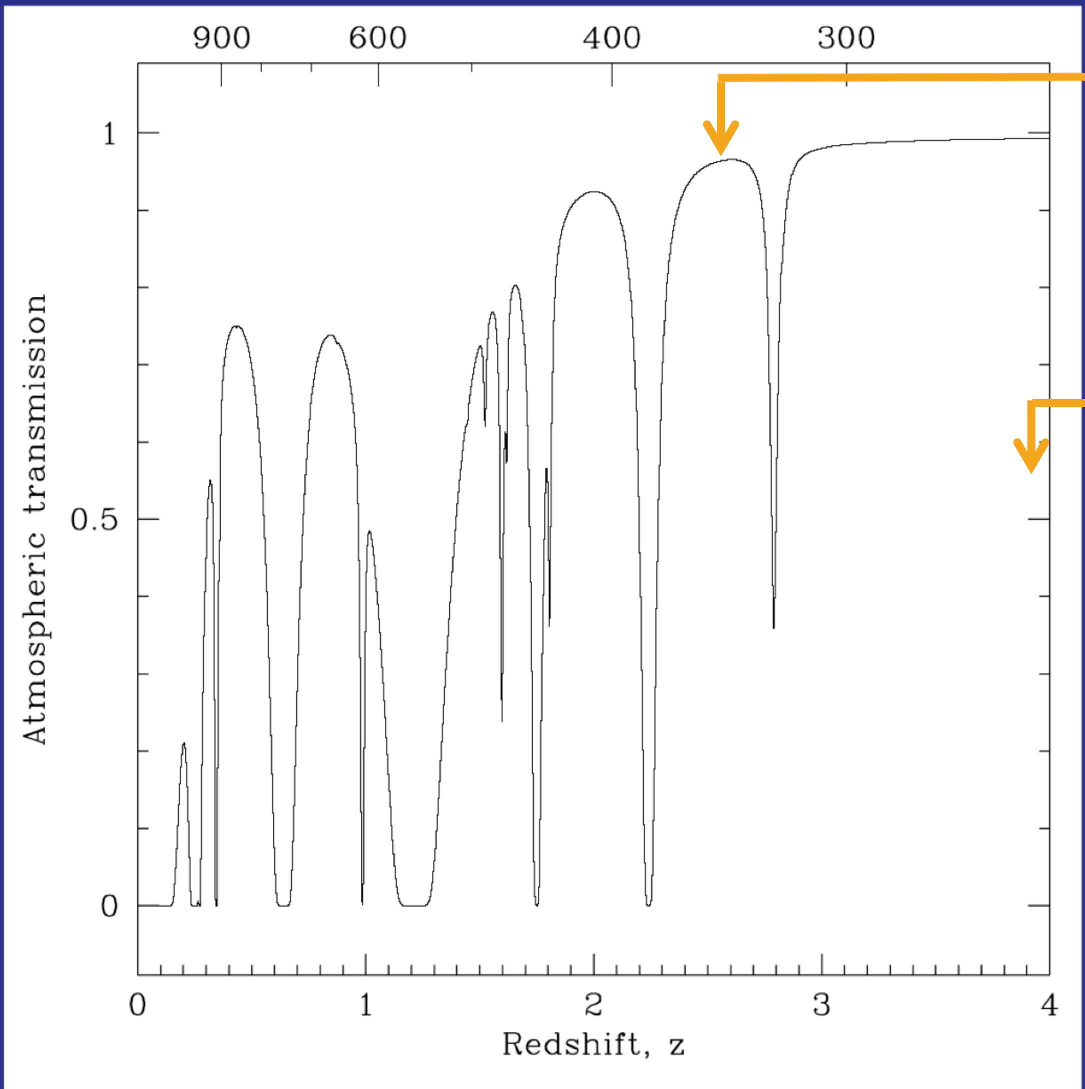
The future of high-resolution molecular spectroscopy, after Herschel

ALMA will be able to access – in high-redshift galaxies – transitions of molecules that are inaccessible from the ground

ALMA collecting area / Herschel collecting area = 50 x $(12/3.5)^2$ ~ 600

Photo credit: ALMA (ESO/NAOJ/NRAO), J. Guarda (ALMA)

Accessibility of HF J = 1–0 from the ground at high-z



Tentative detection in the Cloverleaf at z=2.56 (T. Phillips at IAU Symposium 280)

Non detection in APM At z = 3.91 (Lis, Neufeld, Phillips et al. 2011, ApJL, submitted)

Neufeld, Wolfire & Schilke(2005), based on the atmospheric model of Pardo et al. (2001; for the ALMA site with 0.4 mm PWV)

The future of high-resolution molecular spectroscopy, after Herschel

SOFIA can push high resolution spectroscopy to higher frequencies

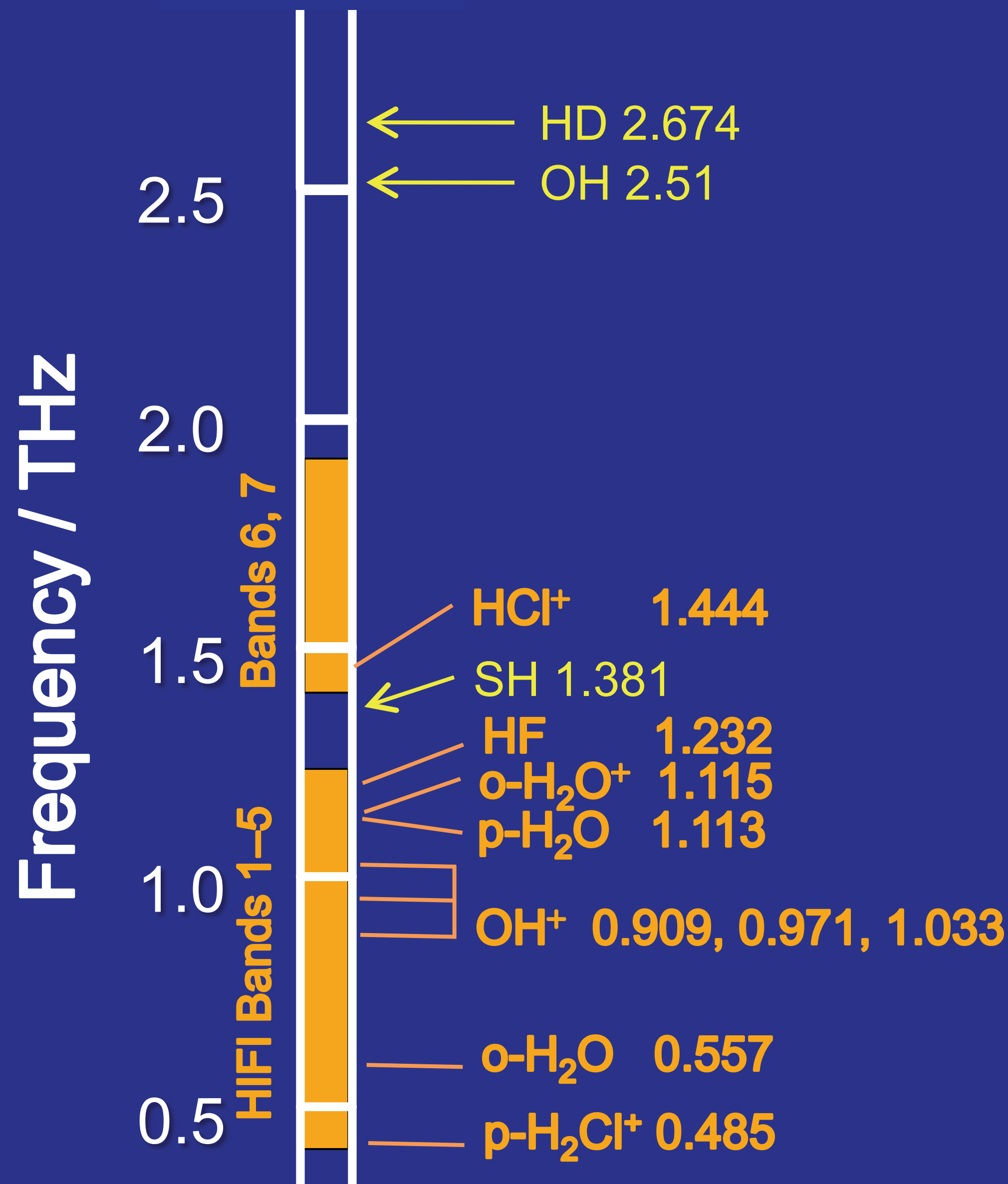
GREAT: access to

HD $J = 1 – 0$

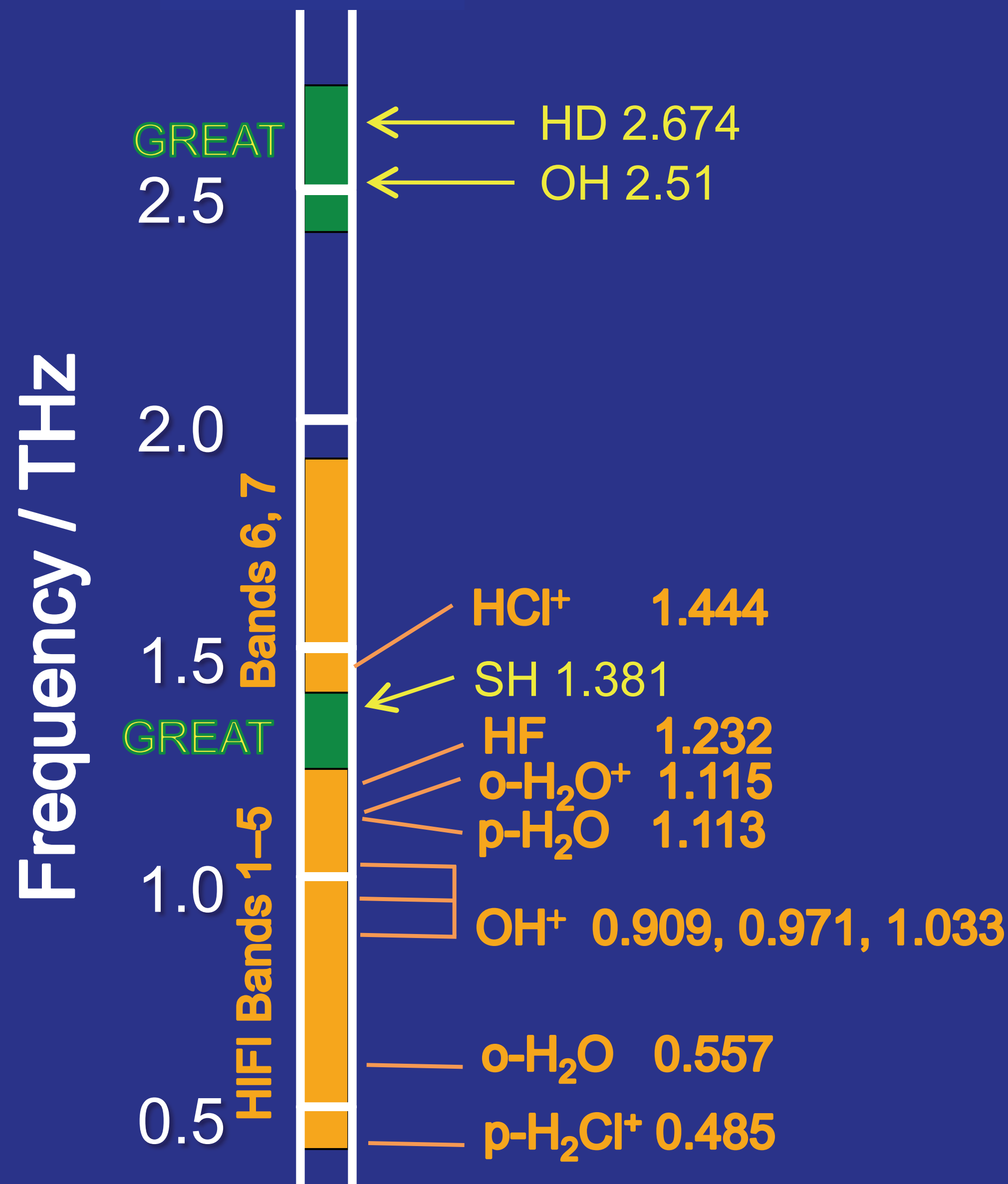
OH $^2\Pi_{3/2}$ $J = 5/2 – 3/2$

SH $^2\Pi_{3/2}$ $J = 5/2 – 3/2$

Frequencies of selected hydride transitions originating in the ground state



Frequencies of selected hydride transitions originating in the ground state



Search for interstellar mercapto radicals (SH) with SOFIA (upcoming Basic Science program)

SH is potentially a powerful probe of turbulent dissipation regions in which the gas is heated, giving rise to a “warm chemistry”

Like the reactions proposed to explain the observed abundances of CH^+ and SH^+,

$$S + H_2 \rightarrow SH + H$$

is somewhat endothermic, with a rate that increases rapidly with temperature

The future of high-resolution molecular spectroscopy, after Herschel

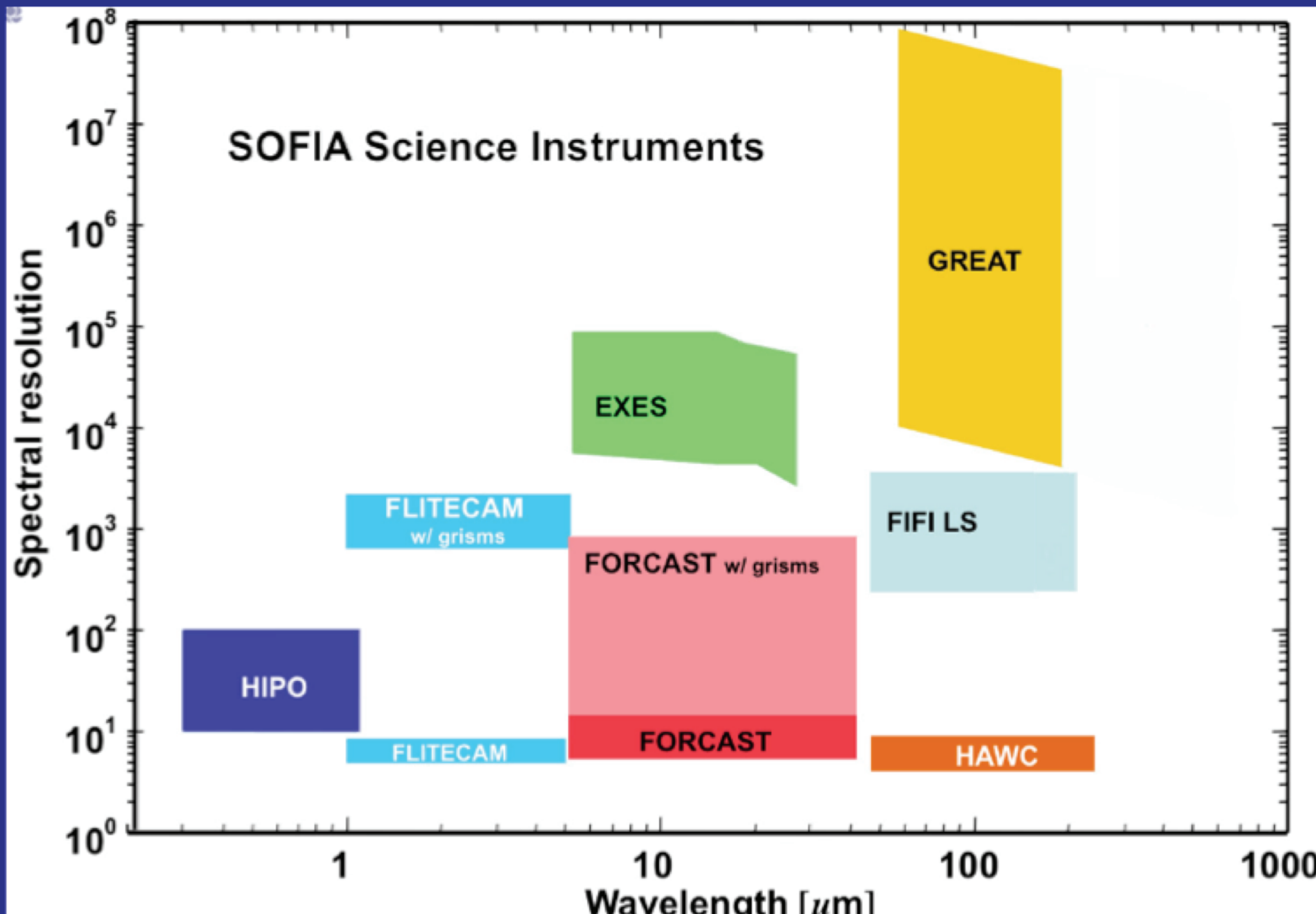
SOFIA can push high resolution spectroscopy to higher frequencies

EXES: access to the 4.5 – 28.3 μm range at $R = 10^5$

Rotational transitions of H_2

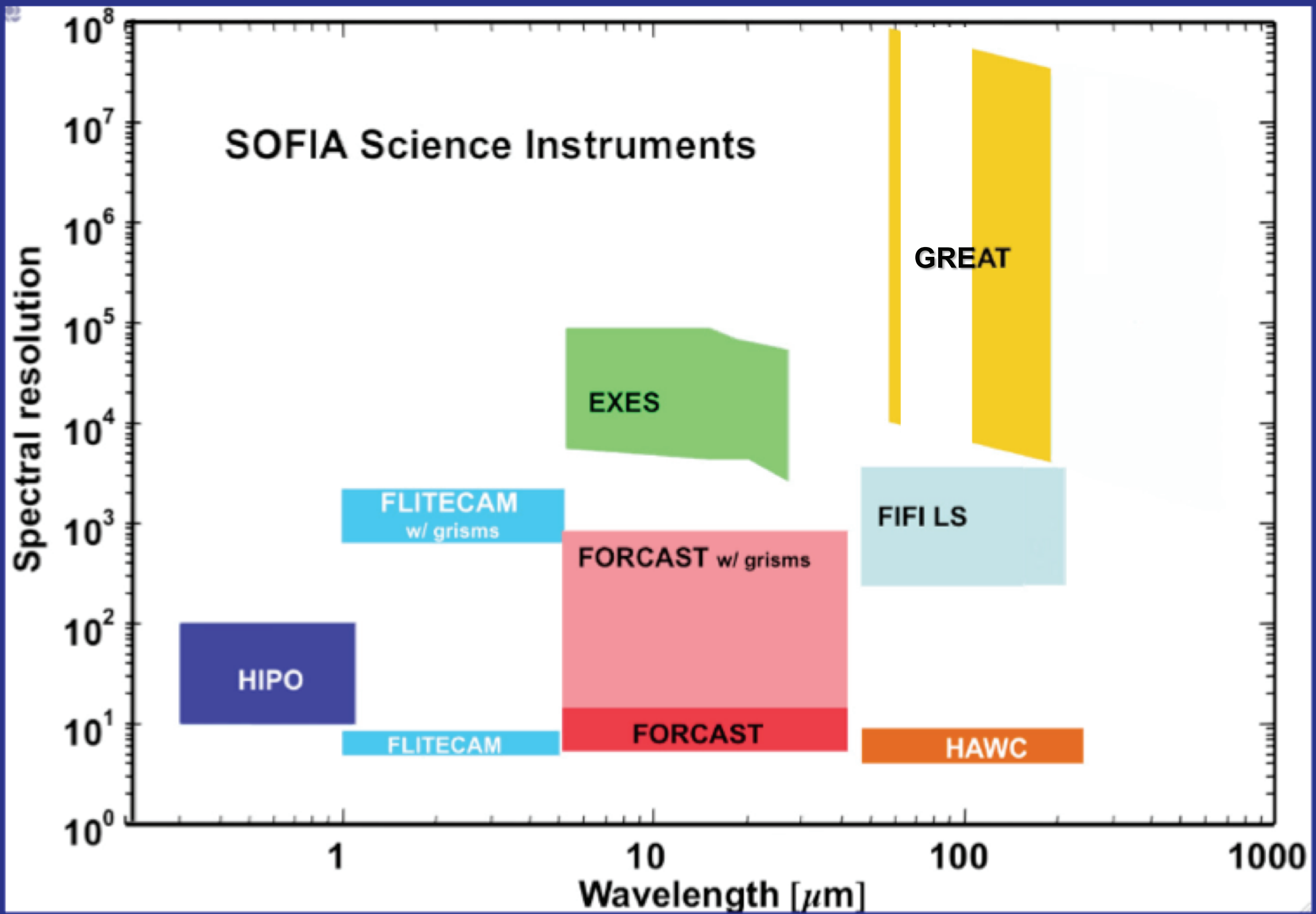
Vibrational transitions

First generation instruments



Credit: SOFIA science center

First generation instruments



Credit: SOFIA science center

Second generation instruments?

- High spectral resolution
  - important for absorption line spectroscopy in Galactic sources
  - a good use of a warm infrared telescope looking through a warm atmosphere
- Unexploited capabilities of SOFIA
  - Spatial multiplexing with heterodyne arrays
  - High resolution spectroscopy in the 28 – 110 μm region (i.e. the gap between EXES and GREAT), which is uncovered except at 63 micron