Absorption Tomography of Chemistry in the Milky Way

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Probing the Diffuse ISM with Submillimeter Absorption Spectroscopy

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Diffuse atomic/molecular to translucent molecular clouds

Table 1 Classification of Interstellar Cloud Types

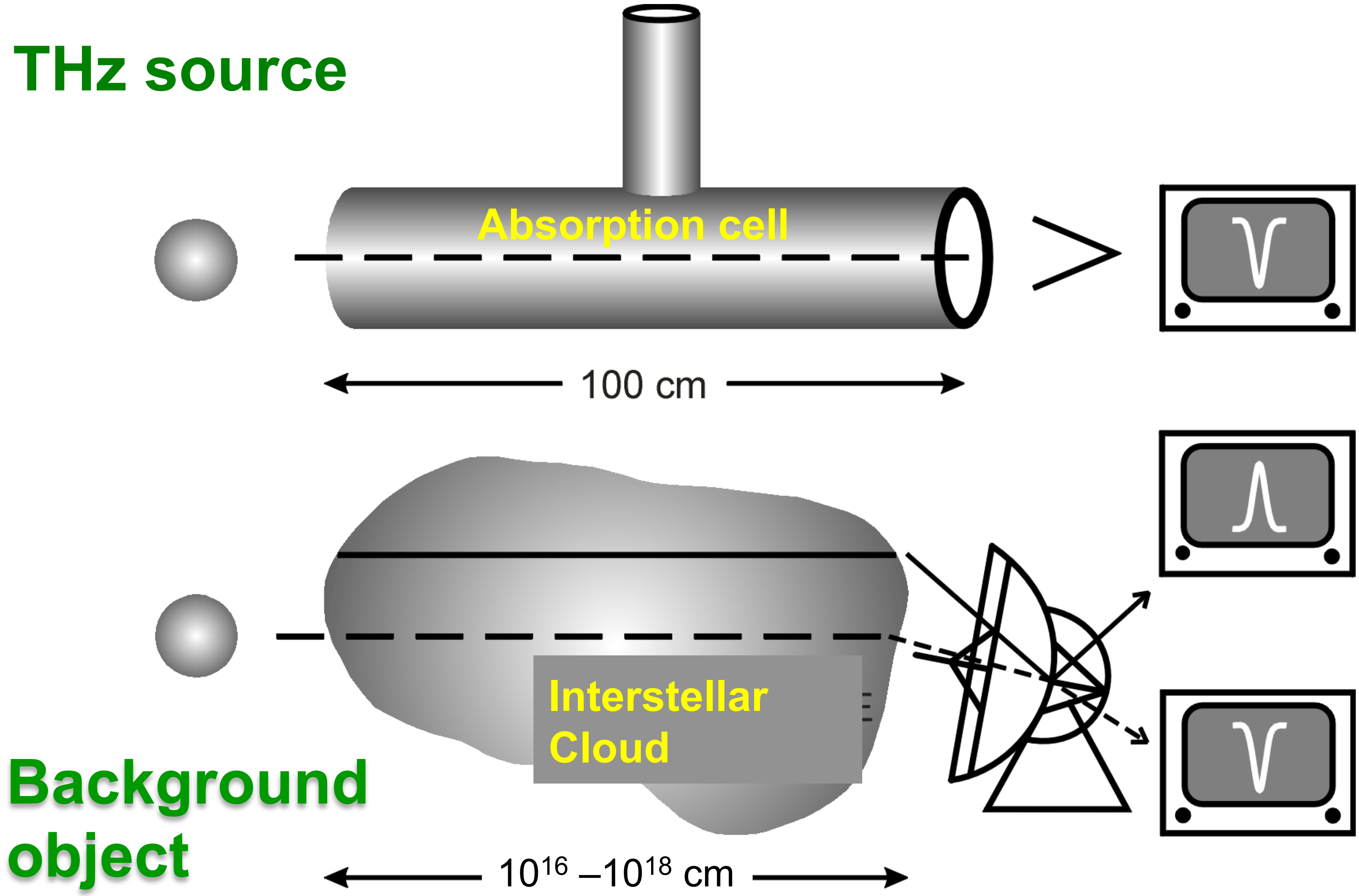
	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^n{}_{H_2} < 0.1$	$f^n{}_{H_2} > 0.1$ $f^n{}_{C+} > 0.5$	$f^n{}_{C+} < 0.5$ $f^n{}_{CO} < 0.9$	$f^n{}_{CO} > 0.9$
A_V (min.)	0	~0.2	~1–2	~5–10
Typ. n_H (cm^{-3})	10–100	100–500	500–5000?	$>10^4$
Typ. T (K)	30–100	30–100	15–50?	10–50
Observational Techniques	UV/Vis H I 21-cm	UV/Vis IR abs mm abs	Vis (UV?) IR abs mm abs/em	IR abs mm em

Snow & McCall, ARA&A 2006

n(H) <100–a few 1000 cm^{-3}

N(H) = ~10^{20}–a few 10^{21} cm^{-2}

T ~ 100–15 K



Lab: $n(X) = 10^{12} - 10^{13}\ cm^{-3} \Rightarrow N = 10^{14} - 10^{15}\ cm^{-2}$

"column density"

ISM: $n(X) = 10^{-5} - 10^{-2}\ cm^{-3} \Rightarrow N = 10^{13} - 10^{16}\ cm^{-2}$

Light Hydrides before Herschel

• Building blocks of larger molecules

Needs bright optically visible stars as background sources → Restricted to a few kpc from Sun

lines from CH, CH^+ and CN have
ranslucent interstellar clouds

• H_2 (UV 1970)

• HD (UV)

Then came radio/mm (1960s/70s)

• OH (1963), NH_3 (1968), H_2O (1969), CH (1973), HDO, H_2S

1980s)

Needs radio/(sub)mm background sources → Can be done Galaxy-wide

H_3^+ (NIR 1996)

rly 2010s:
rschel/HIFI rules!

• HDO, D_2O, H_3O^+

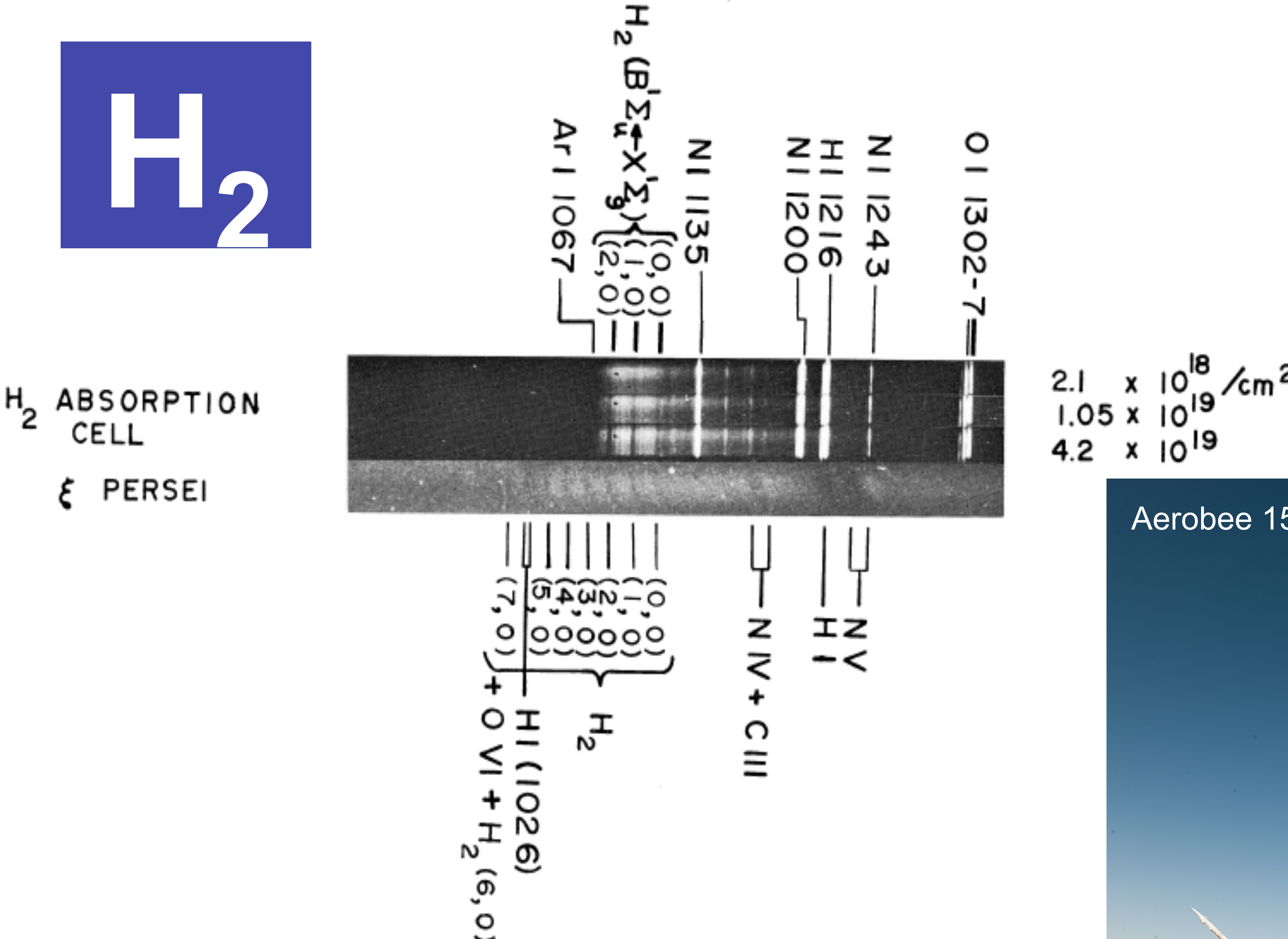
Now:
SOFIA

After 2000:

• CH_2 (ISO)

• HF (ISO)

H_2



Carruthers 1971

Absorption lines

$$N_l = \frac{8\pi}{c^3 A_{ul}}\left(1 - e^{-h\nu/kT_{ex}}\right)\int \tau\, dv$$

$$\tau \propto N_l T_{ex} A_{ul} / \Delta v$$

$$\left(N_u / g_u\right) / \left(N_l / g_l\right) = e^{-\frac{E_u - E_l}{kT_{ex}}}$$

$$N_{tot} = \frac{N_u}{g_u} e^{E_u/kT_{rot}} Q\left(T_{rot}\right)$$

Common assumption: LTE

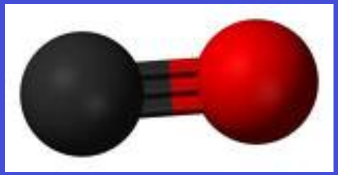
$$T_{ex} = T_{rot} = T_{kin}$$

High density gas

$$= T_{CMB} (= 2.728\,\mathrm{K})$$

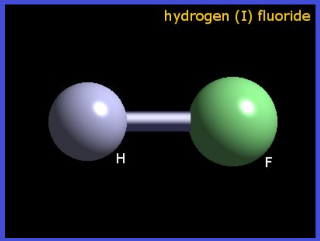
low density gas

CO

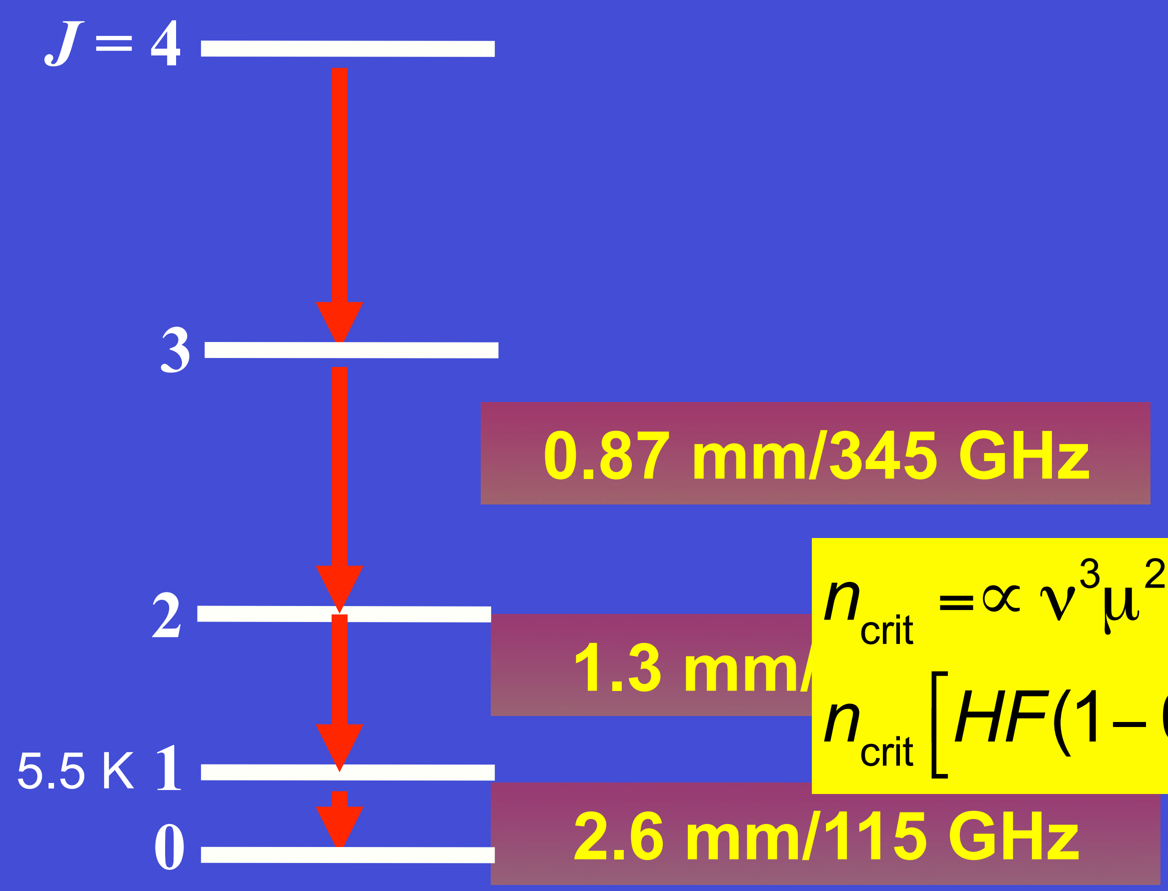


$$E_{rot} = \frac{\hbar^2}{2I} J(J+1)$$

HF



$$\nu \propto J$$



$$n_{crit} = \propto \nu^3 \mu^2$$

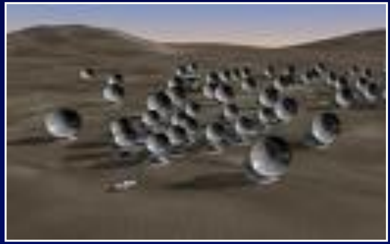
$$n_{crit}\left[HF(1-0)\right] \approx 5 \times 10^6 \, n_{crit}\left[CO(1-0)\right]$$

For compact sources, large collecting area makes the difference!

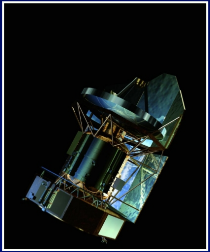
$$S_L = -\eta_{\mathrm{cov}} S_C \left(1 - e^{-\tau}\right) \approx -\eta_{\mathrm{cov}} S_C \tau \text{ (for } \tau << 1\text{)}$$

$$S_C \propto \eta_S T_C^B \nu^2 = \frac{\Omega_S}{\Omega_S + \Omega_B} T_C^B \nu^2 \propto \frac{\Omega_S}{\Omega_B} T_C^B \nu^2$$

$$|\mathrm{T_L}| \propto \mathrm{S_C} \times \mathrm{A_{eff}}$$



=  x 50



=  x 35

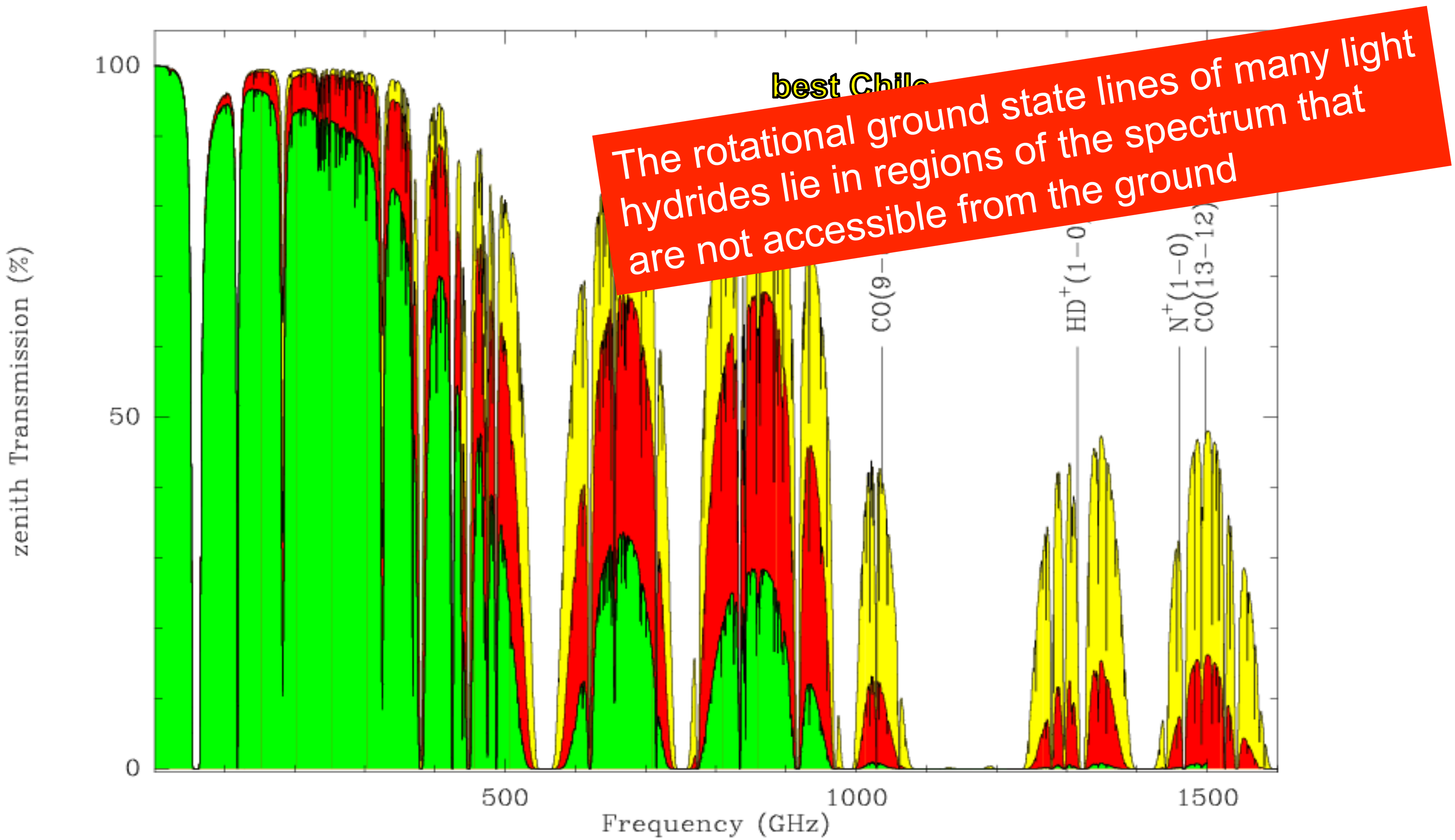
Transmission on a 5000m high site unter good, very good, and **extremely good** weather conditions

1200µm 250 GHz

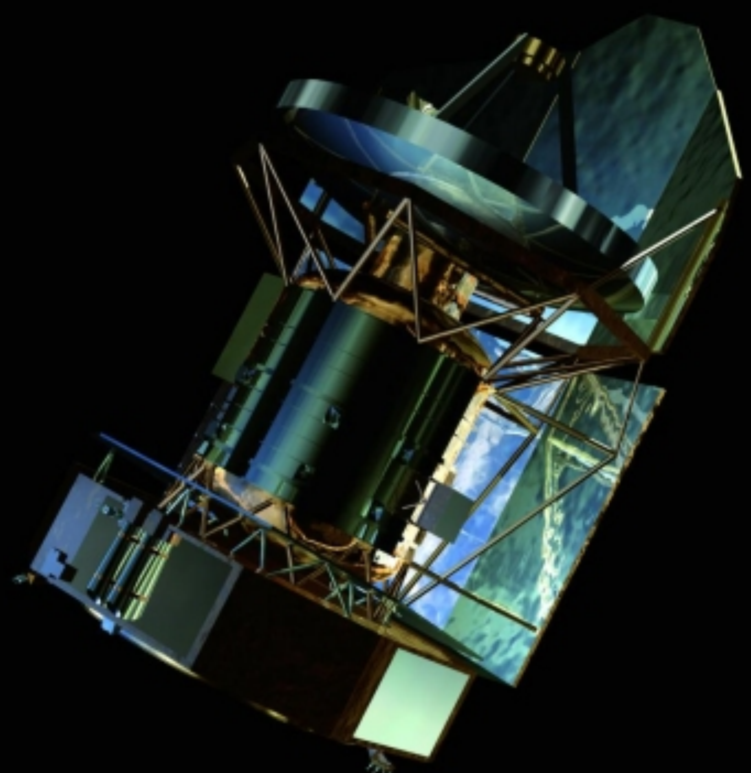
450µm 660 GHz

350µm 860 GHz

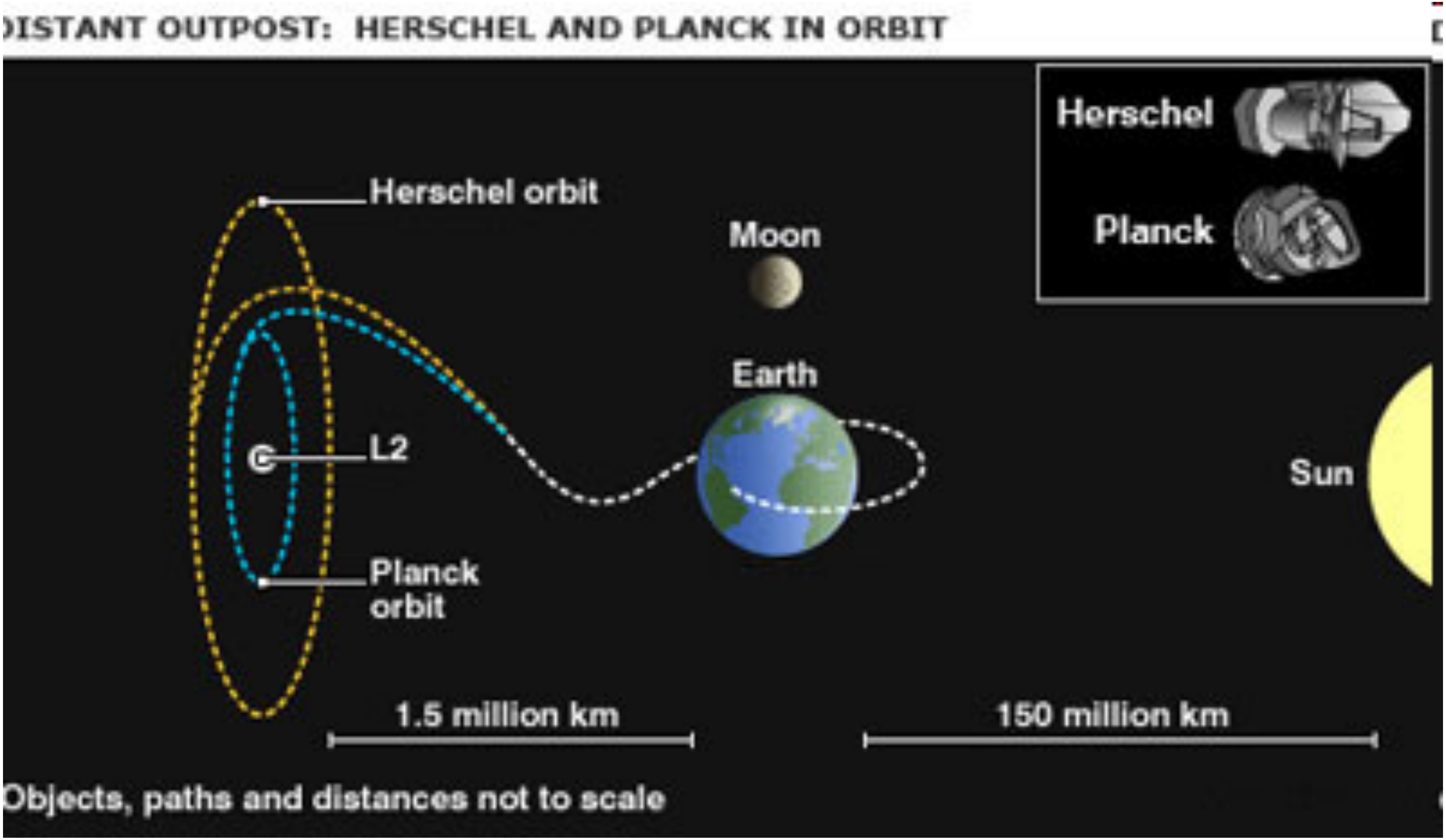
200µm 1.5 THz



HERSCHEL

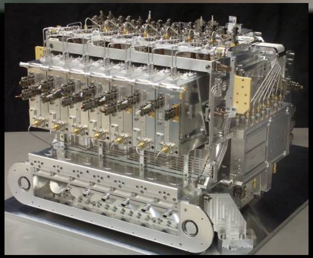


14 May 2009 –29 April 2013

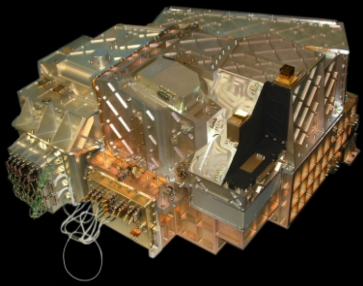


Systems must by completely autonomous

HERSCHEL



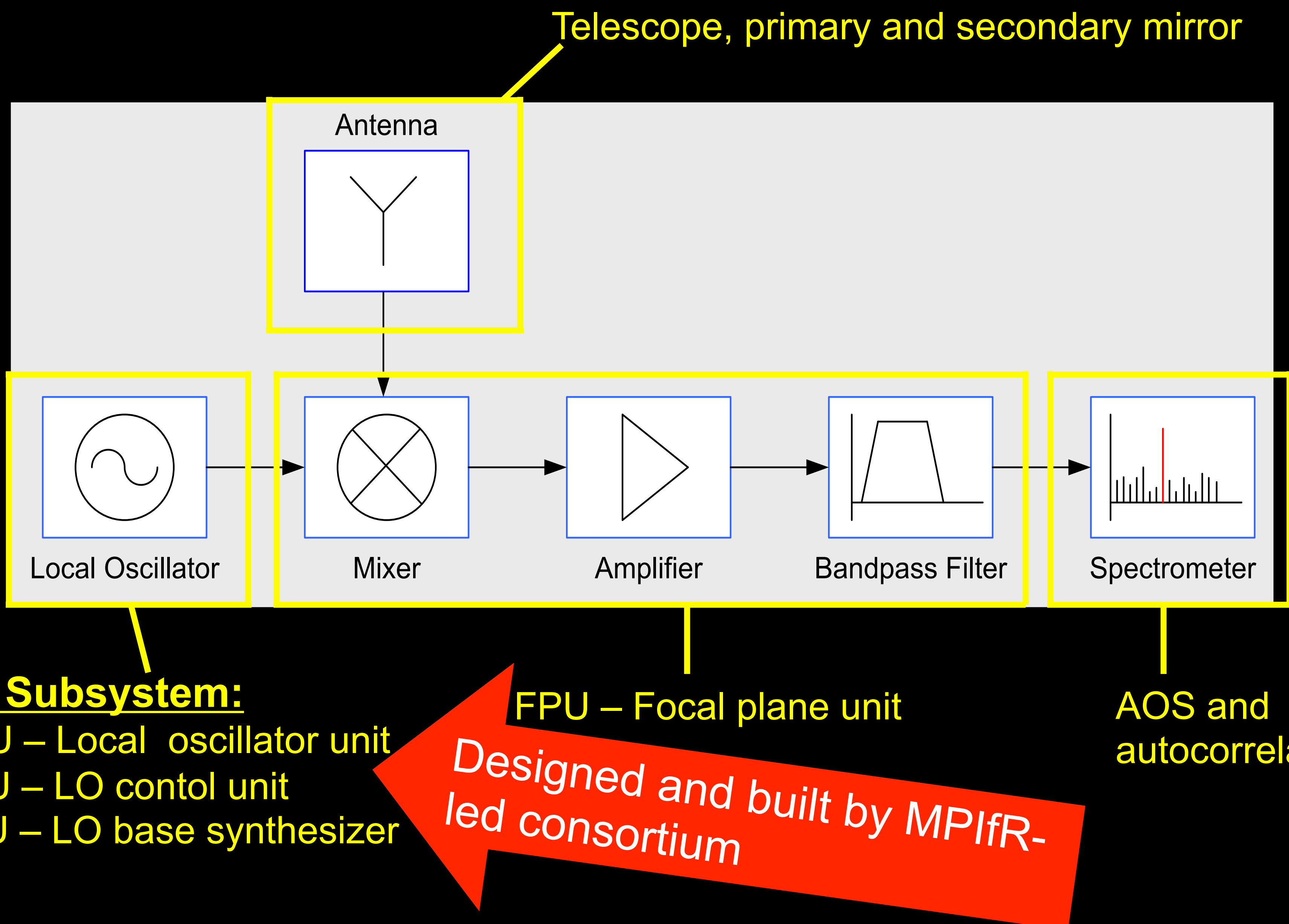
HIFI (Heterodyne Instrument for the Far Infrared)
480 – 1910 GHz, 7 bands
Very high resolution heterodyne spectrometer



PACS (Photodetector Array Camera and Spectrometer)
1.4 – 5 THz: photom. 1.75 x 3.5' / spec 50×50" @ 5"
Imaging photometer / medium resolution grating spectrometer

SPIRE (Spectral and Photometric Imaging Receiver)
0.58, 0.83, 1.2 THz, 4'×4'
Imaging photometer / imaging Fourier transform spectrometer

HIFI Heterodyne Instrument for the Far-Infrared



LO Subsystem:

LOU – Local oscillator unit

LCU – LO contol unit

LSU – LO base synthesizer

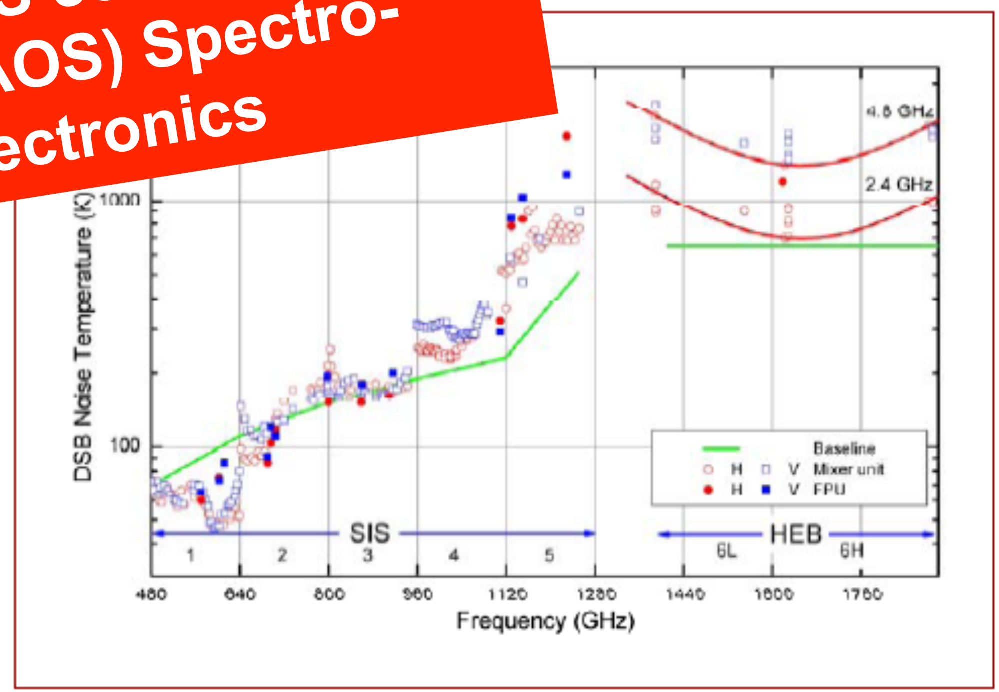
Table 1. Overview of frequeny ranges and technologies for the HIFI mixer bands. See a.o.[4,5,6,7,8,9].

Mixer band	Frequency range	Mixer Element	Matching circuit	Feed/coupling structure	Mixer Development Laboratory
1	480 – 640 GHz	SIS Nb-Al2O3-Nb	Nb on Nb microstrip	corrugated horn and waveguide	LERMA Paris, France
2	640 – 800 GHz	SIS NbTiN-Al2O3-Nb	Al on NbTiN microstrip	corrugated horn and waveguide	KOSMA Koeln, Germany
3	800 – 960 GHz	SIS NbTiN-Al2O3-Nb	Al on NbTiN microstrip	corrugated horn and waveguide	SRON Groningen, Netherlands
4	960 – 1120 GHz	SIS NbTiN-Al2O3-Nb	Al on NbTiN microstrip	corrugated horn and waveguide	SRON Groningen, Netherlands
5	1120 – 1250 GHz	SIS NbTiN-AlN-NbTi	Al on NbTiN microstrip	lens and twin slot antenna	CalTech/JPL Pasadena, USA
6L	1410 – 1703 GHz	HEB NbN phonon cooled	Al co-planar waveguide	lens and twin slot antenna	Chalmers Univ. Gothenborg, Sweden
6H	1703 – 1910 GHz	HEB NbN phonon cooled	Al co-planar wavegui…	…ntenna	Chalmers Univ. Gothenborg, Sweden

KOSMA + MPS contributed Wide Band (AOS) Spectro-meter and electronics

HIFI:

480–1250 and 1410–1910 GHz seamless coverage



De Graauw+ 2010

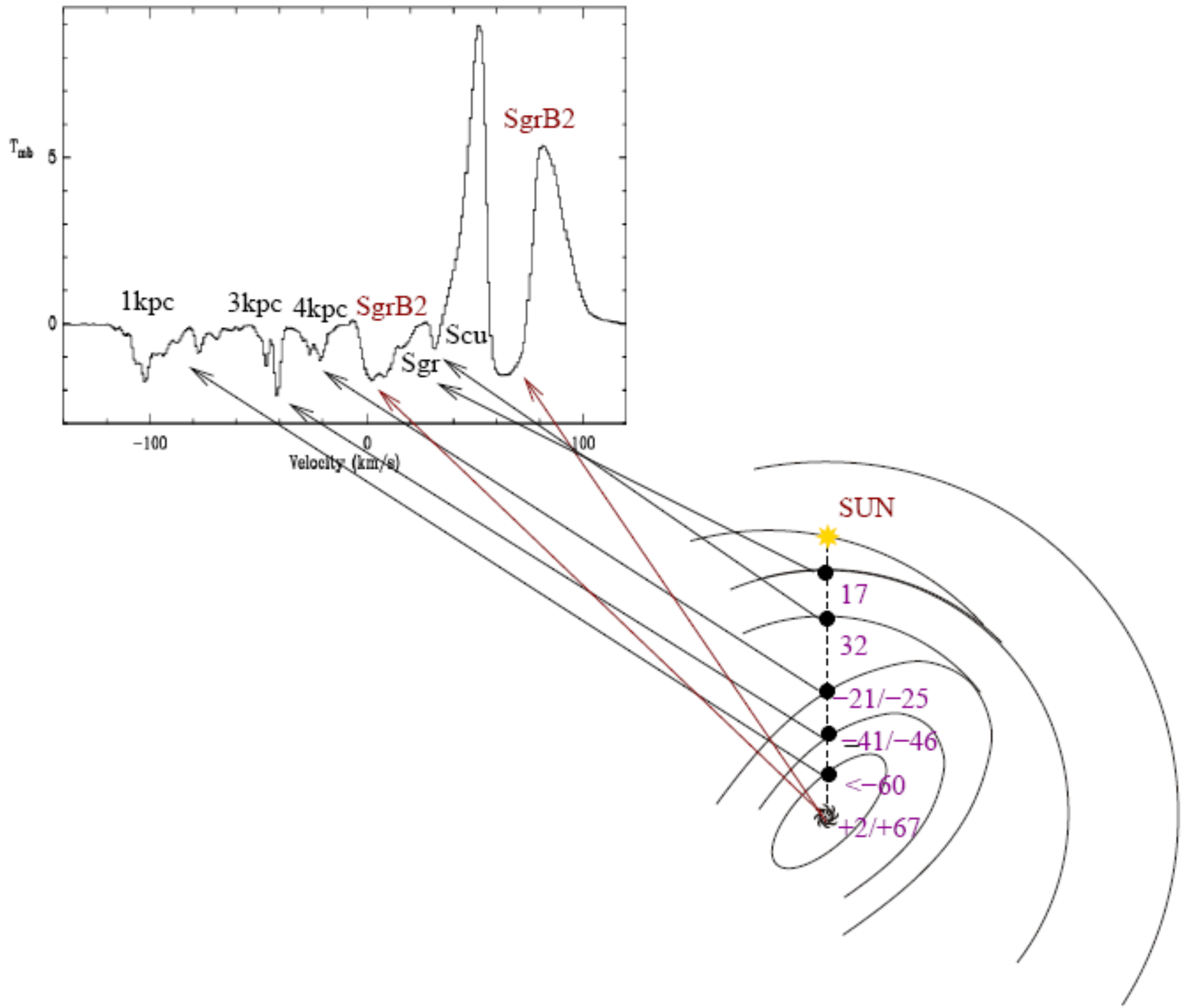
Herschel/HIFI Guaranteed Time Key Programmes

HEXOS: Herschel/HIFI Observations of EXtraOrdinary Sources

- Complete line surveys of 5 positions in the Orion- KL and Sgr B2 molecular clouds
- PI: E. Bergin (U. Michigan, Ann Arbor)

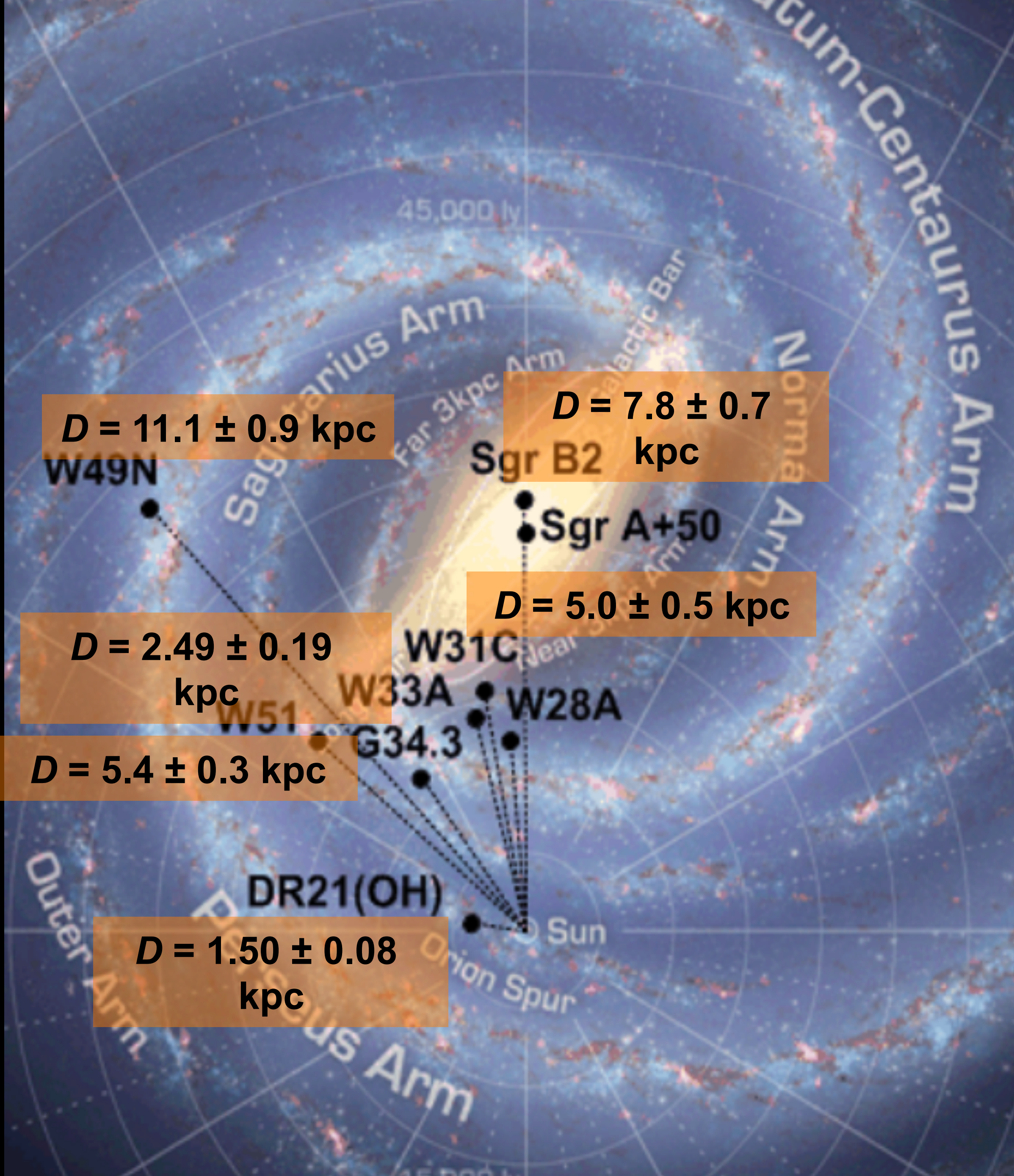
PRISMAS: PRobing Interstellar Molecules with Absorption Line Studies

- (Mostly) rotational ground-state transitions of O-, C-, and N-bearing hydrides toward selected SFRs
- PI: M. Gerin (LERMA Obs. de Paris/ENS)



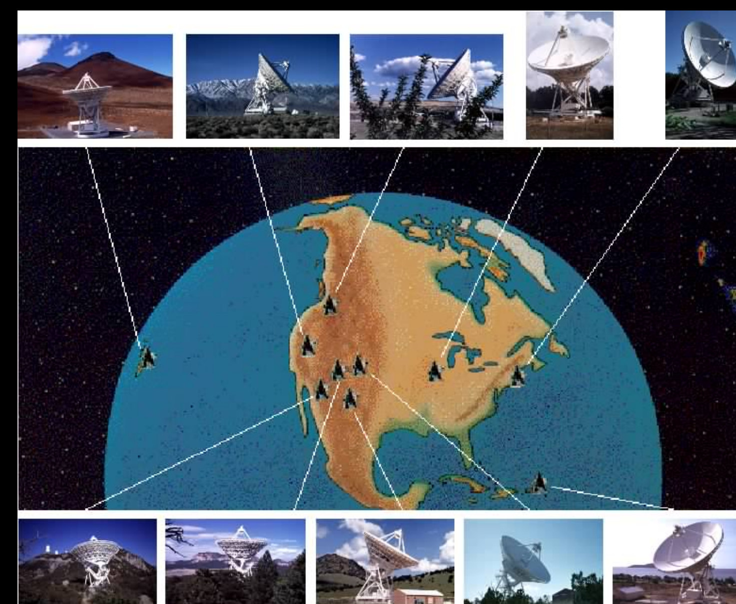
C. Hieret, Diploma Thesis, MPIfR

Observing geometry



Distances from:

http://bessel.vlbi-astrometry.org



Formation of gaseous water

$$H_2 + \text{cosmic rays} \rightarrow H_2^+ + e$$

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

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

$$OH^+ + H_2 \rightarrow H_2O^+ + H$$

$$H_2O^+ + H_2 \rightarrow H_3O^+ + H$$

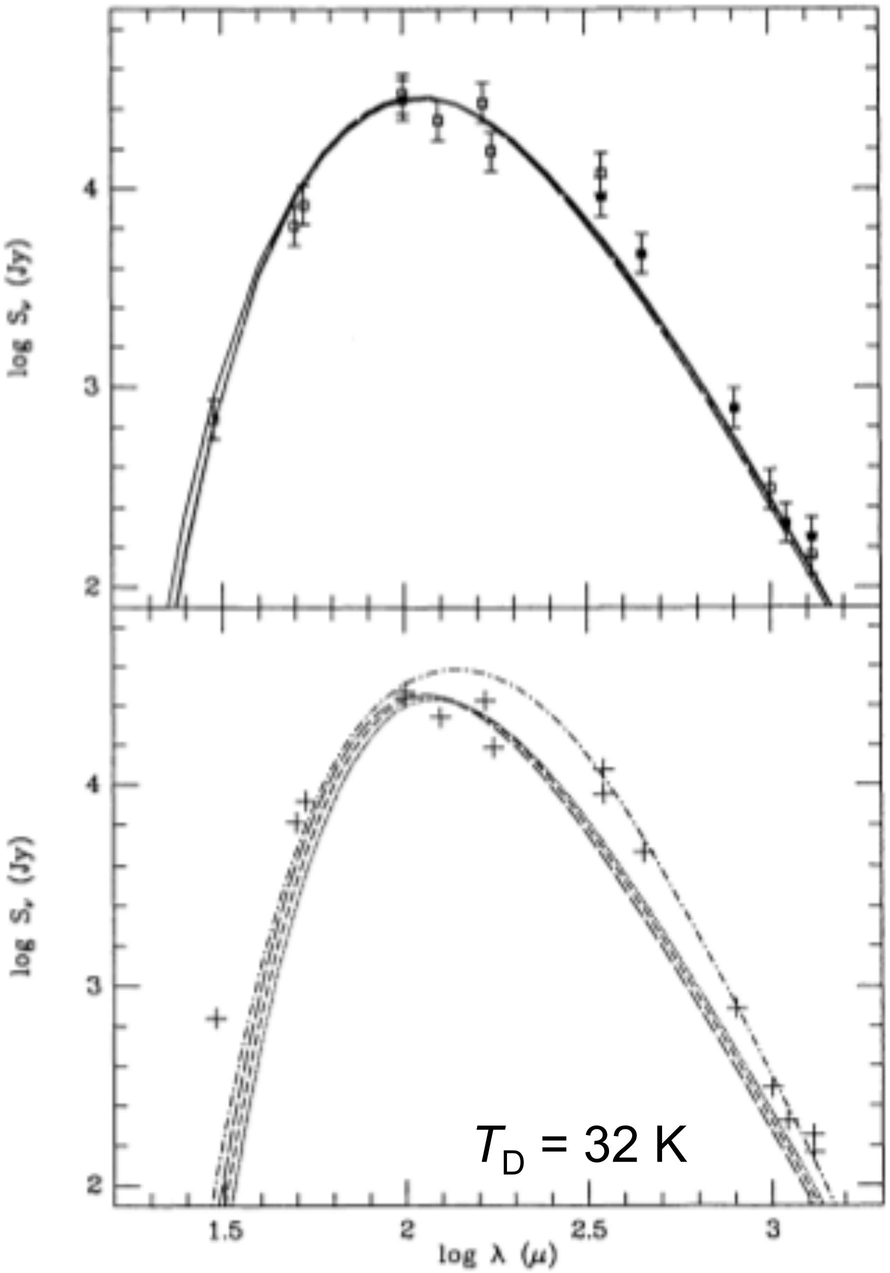
$$H_3O^+ + e \rightarrow H_2O + H$$

$$\text{or } OH + H$$

Before 2009:

not	observed
poorly	observed

The Background Sources:
Cold or Warm Dust from
Protostellar Condensations



Sgr B2 – Lis & Goldsmith 1990

ATLASGAL
(APEX Telescope Large Survey: The Galaxy)

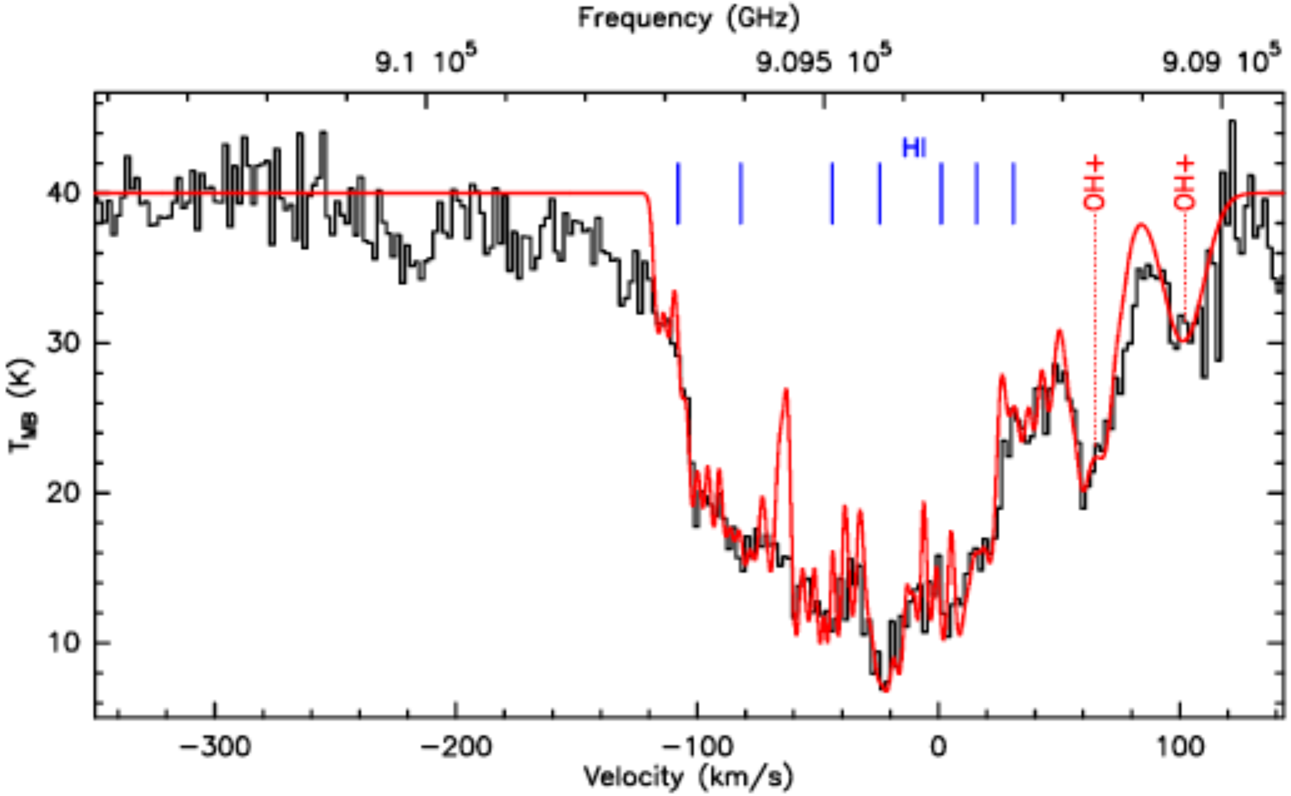
- Main goals:
  - To have a complete 350 GHz census of high mass star formation in the Galaxy (= whole part of Galactic plane visible with APEX)
  - To detect protostellar condensations down tens of $M_\odot$ throughout the Milky Way

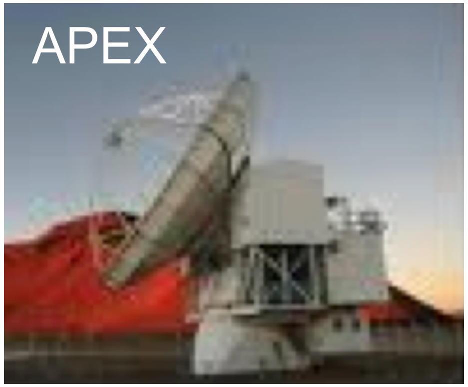
Total observing time: ~1000 hours

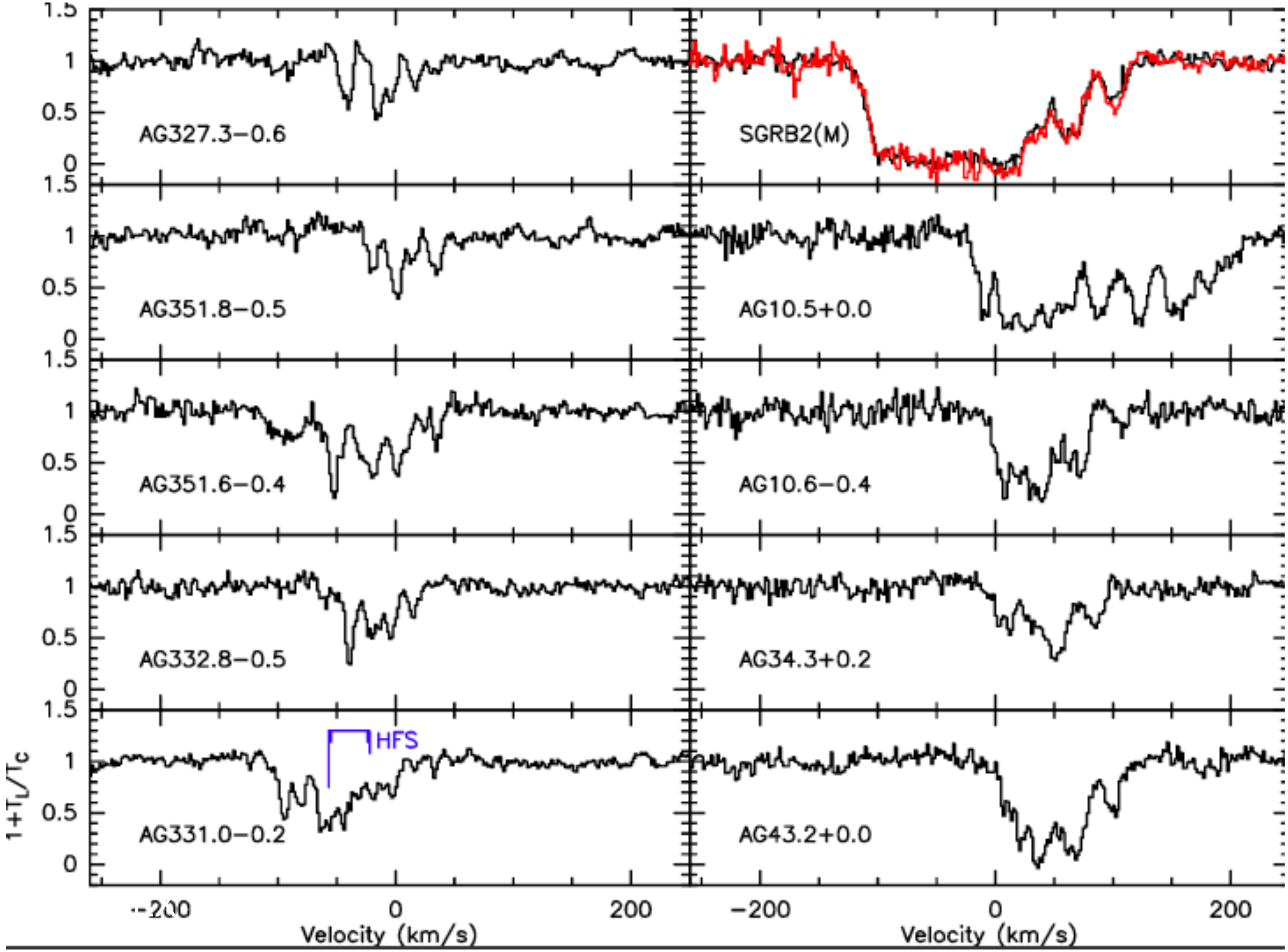
Schuller et al. 2009

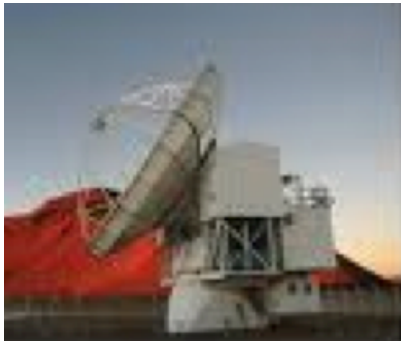
First interstellar detection of OH^+

F. Wyrowski[1], K. M. Menten[1], R. Güsten[1], and A. Belloche[1]





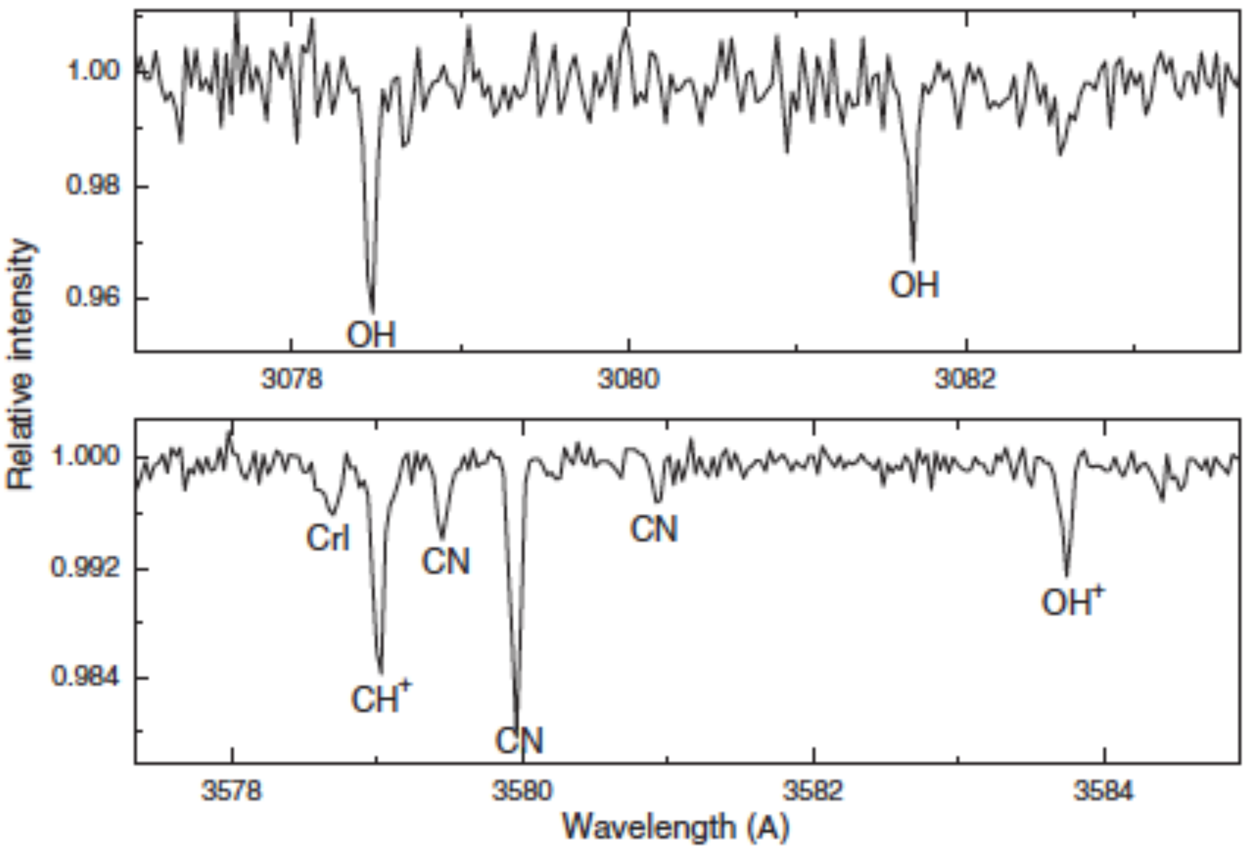


(Much) more OH^+ with 

Wyrowski et al. (in prep.)

HYDROXYL CATION IN TRANSLUCENT INTERSTELLAR CLOUDS*

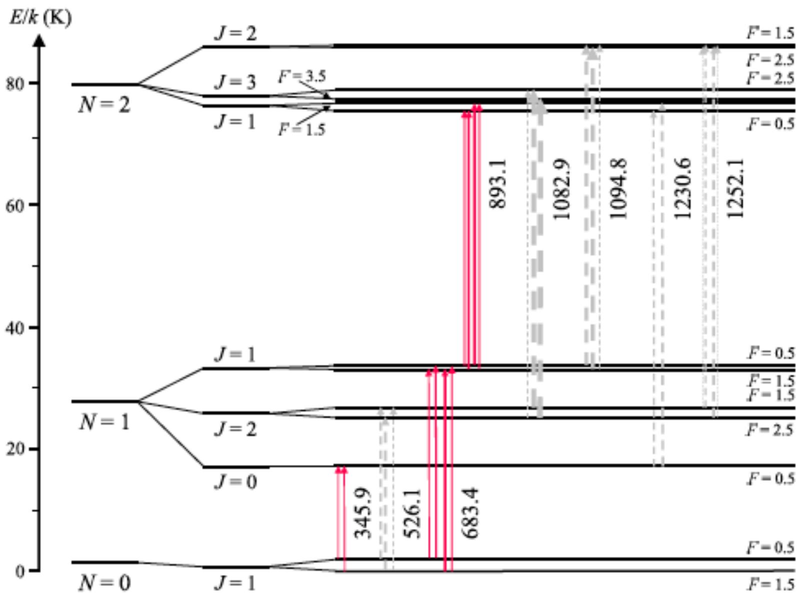
J. KREŁOWSKI[1], Y. BELETSKY[2], AND G. A. GALAZUTDINOV[3] 2010

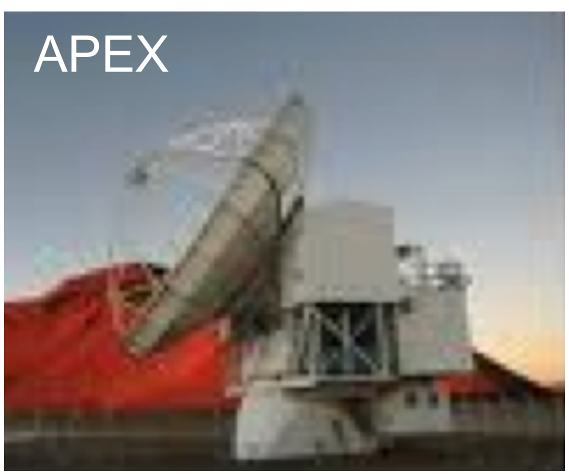


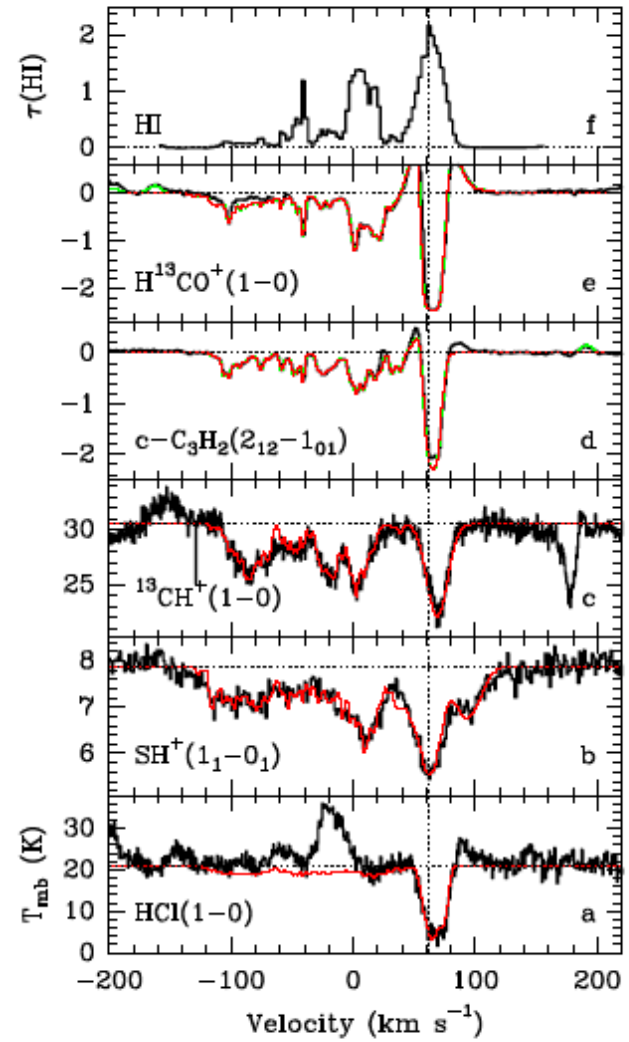
average over man l.o.s.

Submillimeter absorption from SH^+, a new widespread interstellar radical, $^{13}CH^+$ and HCl

K. M. Menten[1], F. Wyrowski[1], A. Belloche[1], R. Güsten[1], L. Dedes[1], and H. S. P. Müller[2]







How to get H and H_2 column densities

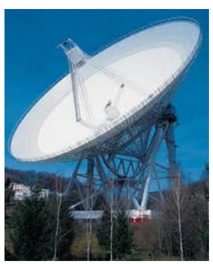
- Direct determination of HI column density by interferometry (+ emission mapping) of 21 cm line
- mm absorption interferometry of lines of H_2 column density proxies and other "interesting" species

Complementary:

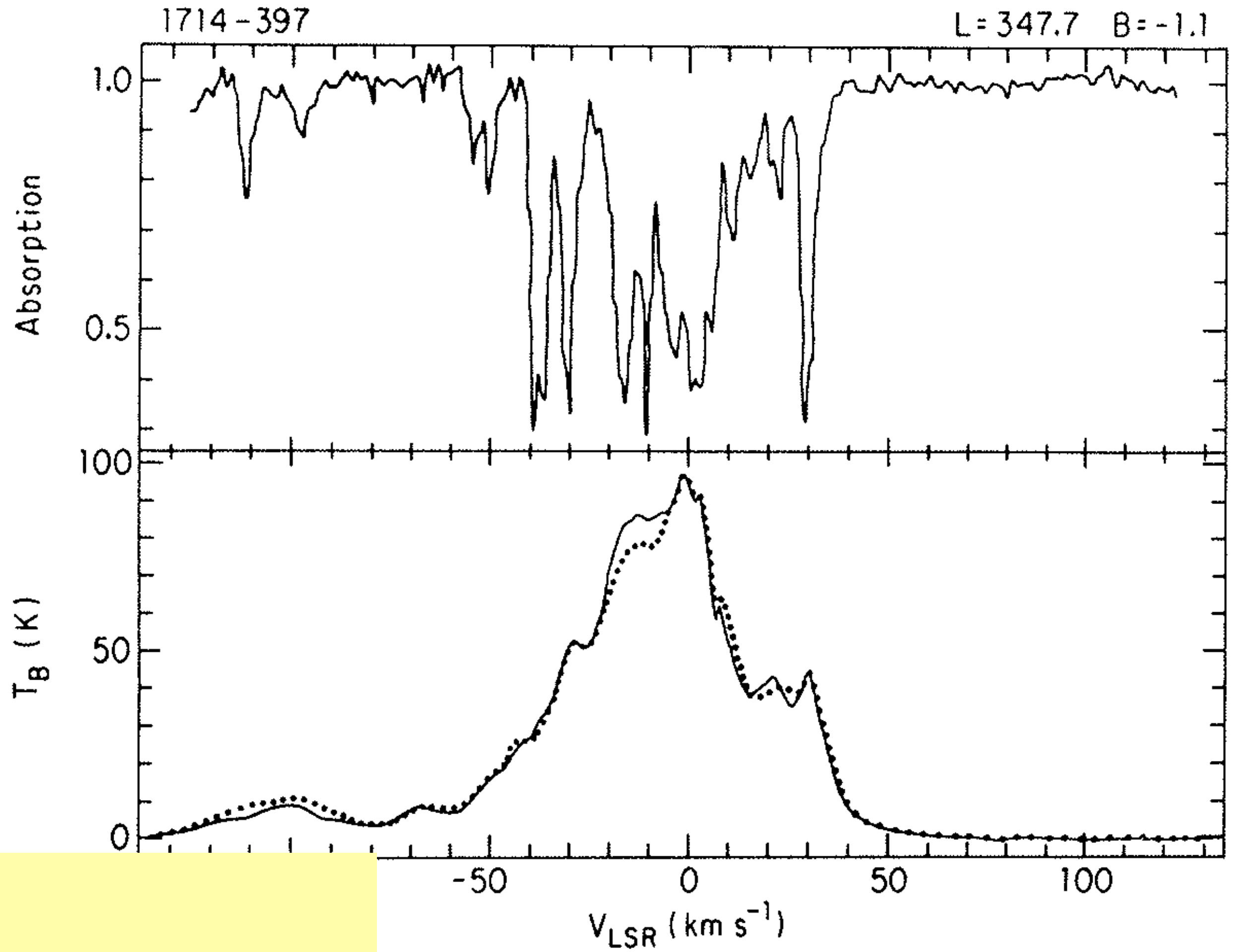
- cm absorption interferometry of (near) ground state lines from:
  - OH (1612, 1665, 1667, and 1720 MHz)
  - CH (3264, 3335, and 3349 MHz
  - H_2CO (4830 and 14488 MHz)
  - C_3H_2 (18343 MHz)
  - …

Determination of HI Column Densities with the Lazareff (1975) Technique

delivers τ



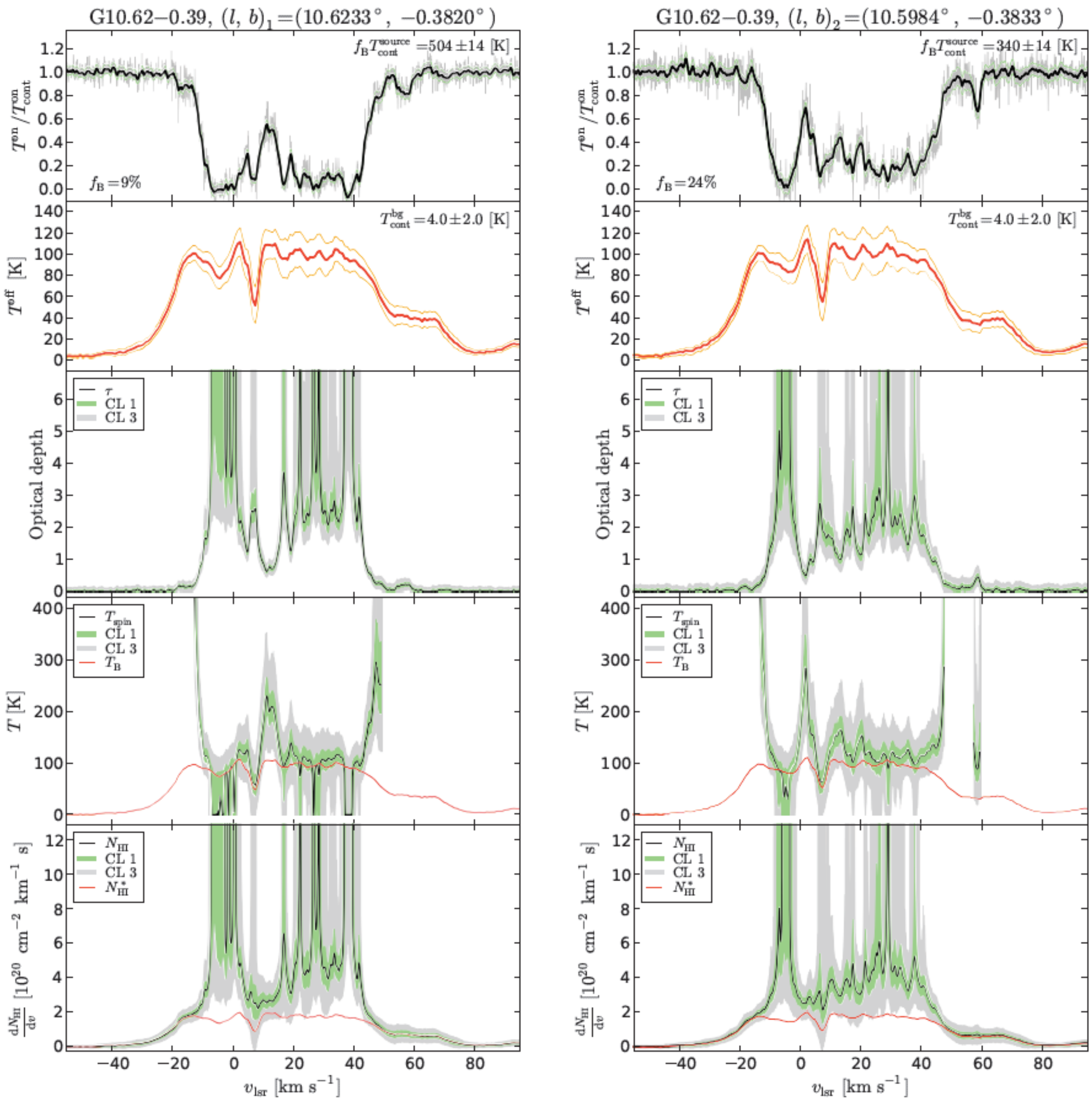
delivers T_B



Dickey et a. 1983

$$T_s(\mathrm{v}) = T_B\left[1 - \exp\left(-\tau_{\mathrm{v}}\right)\right]$$

$$N_H\left(cm^{-2}\right) = 1.7 \times 10^{18} \int \tau T_s(K) d\mathrm{v}\left(km\ s^{-1}\right)$$



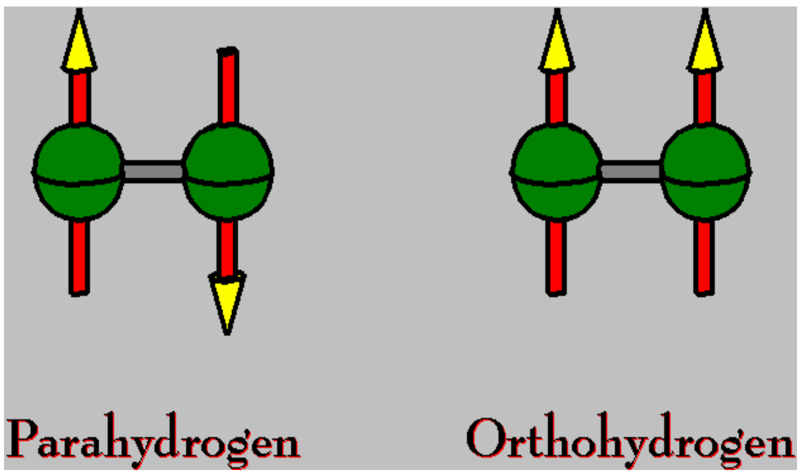
HI Column densities for PRISMAS sources

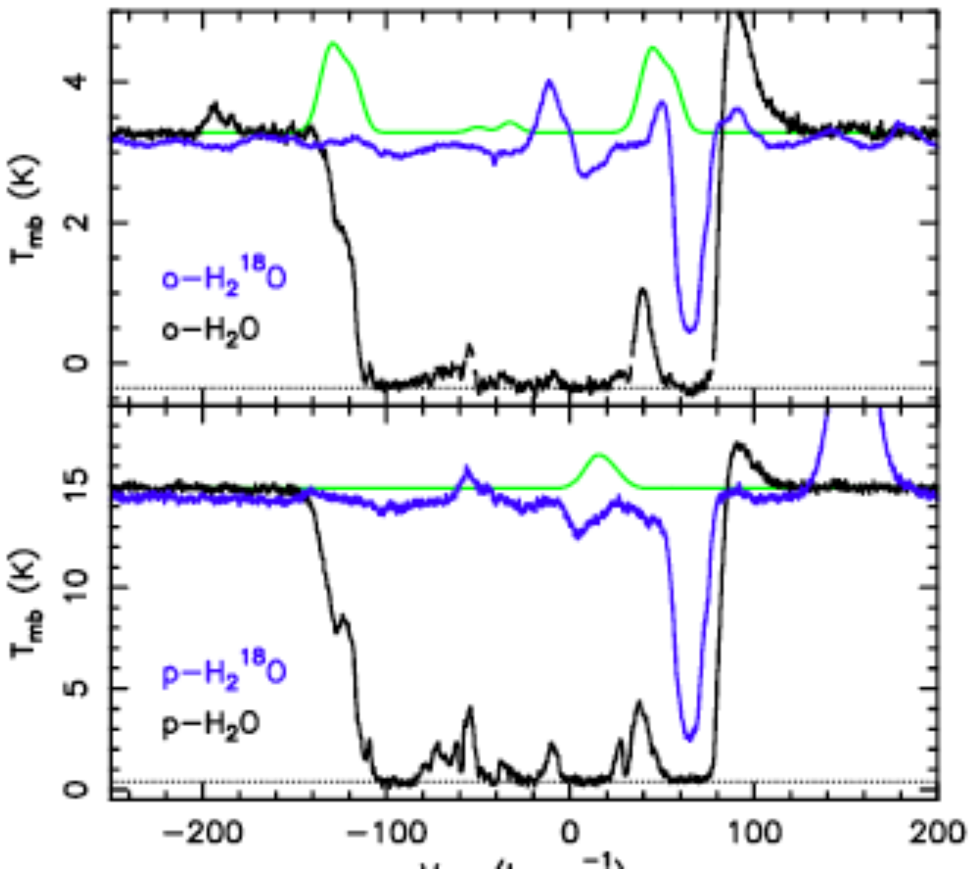
Winkel et al. 2014

Herschel/HIFI measurements of the ortho/para ratio in water towards Sagittarius B2(M) and W31C⋆

D. C. Lis[1], T. G. Phillips[1], P. F. Goldsmith[13], D. A. Neufeld[3], E. Herbst[14], C. Comito[8], P. Schilke[8,12], H. S. P. Müller[12],

26 (2010)





$[O(H_2O)]/[P(H_2O) = 2.5$

$\Rightarrow T = 27$K

Interstellar OH^+, H_2O^+ and H_3O^+ along the sight-line to G10.6–0.4⋆,⋆⋆

M. Gerin[1], M. De Luca[1], J. Black[2], J. R. Goicoechea[3], E. Herbst[4], D. A. Neufeld[5], E. Falgarone[1], B. Godard[1,8],

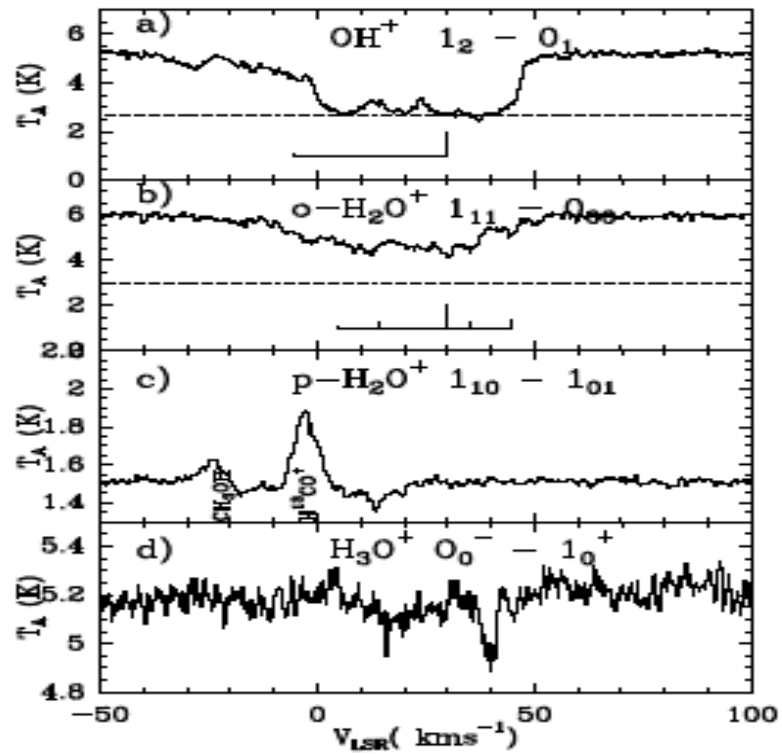
+ 44 others
Strong involvement of laboratory people

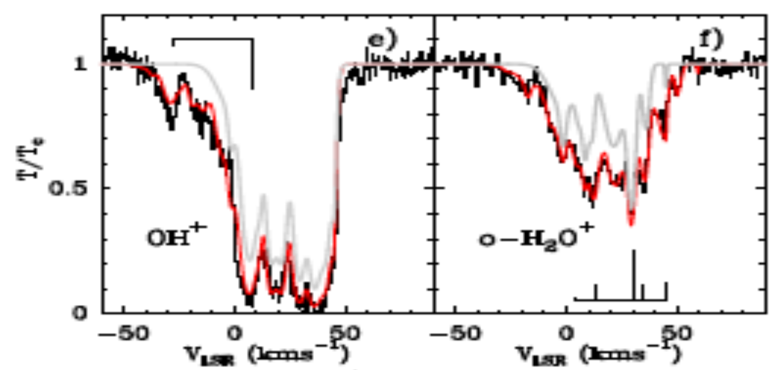
Table 1. Transition spectroscopic pa[...]

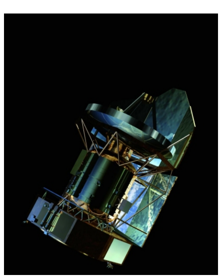
Transition	Frequency MHz				
OH^+ $N = 1 - 0$					
2, 5/2–1, 3/2	971803.8	1.5	0.0	1.82	1
2, 3/2–1, 1/2	971805.3	1.5	0.0	1.52	1
2, 3/2–1, 3/2	971919.2	1.0	0.0	0.30	1
o-H_2O^+ $1_{1,1}–0_{0,0}$					
3/2, 3/2–1/2, 1/2	1115122.0	10	0.0	1.71	2
3/2, 1/2–1/2, 1/2	1115158.0	10	0.0	2.75	2
3/2, 5/2–1/2, 3/2	1115175.8	10	0.0	3.10	2
3/2, 3/2–1/2, 3/2	1115235.6	10	0.0	1.39	2
3/2, 1/2–1/2, 3/2	1115271.6	10	0.0	0.35	2
p-H_2O^+ $1_{1,0} - 1_{0,1}$					
3/2, 3/2–3/2, 3/2	60720[illegible]	[illegible]	20.9	0.60	2
H_3O^+					
$0_0^- - 1_0^+$	984711.9	[illegible]	[illegible]	2.3	3

References. 1, Müller et al. (2005) & CD[...] [...]han et al. (1986), Ossenkopf et al. (2010); 3 Yu et al. (2009) & [...]

Hyperfine structure

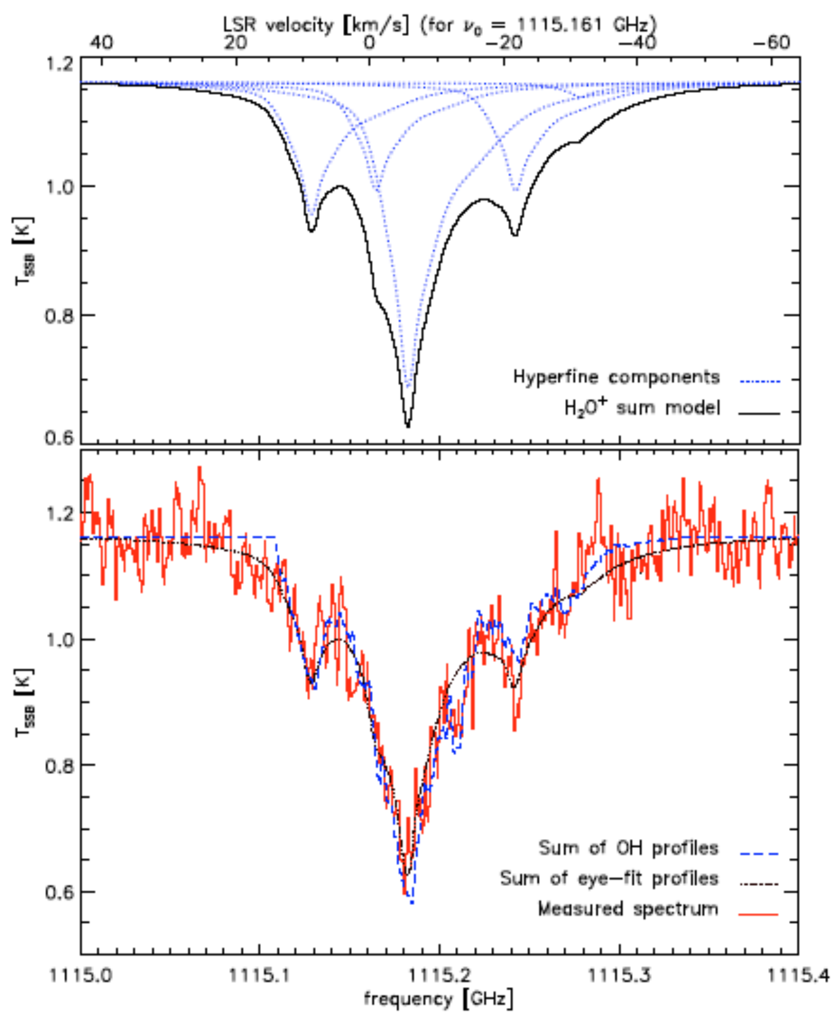






Detection of interstellar oxidaniumyl: Abundant H_2O^+ towards the star-forming regions DR21, Sgr B2, and NGC6334★

V. Ossenkopf[1,2], H. S. P. Müller[1], D. C. Lis[3], P. Schilke[1,4], T. A. Bell[3], S. Bruderer[8], E. Bergin[5], C. Ceccarelli[6],



H_2O^+ toward DR 21

- Detected during HIFI science verification

Nitrogen hydrides in interstellar gas

Herschel★/HIFI observations towards G10.6-0.4 (W31C)★★

C. M. Persson[1], J. H. Black[1], J. Cernicharo[2], J. R. Goicoechea[2], G. E. Hassel[3], E. Herbst[4], M. Gerin[5], M. De Luca[5],

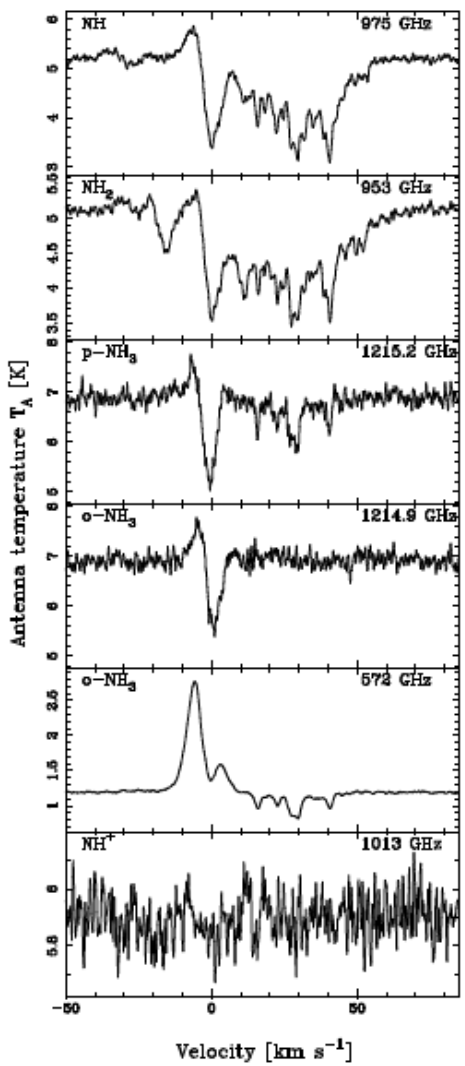


Table 1. Observed transitions.

Species[a]	Frequency (GHz)	Band[b]	T_{sys}[c] (K)	t_{int}[d] (s)	Transition
NH^+	1012.540	4a	385	47	$^2\Pi_{1/2}\ J = 3/2 \leftarrow 1/2$
NH	974.478	4a	339	30	$N = 1 \leftarrow 0\ J = 2 \leftarrow 1$
o-NH_2	952.578	3b	230	15	$1_{1,1}$–$0_{0,0}$
o-NH_3	572.498	1b	83	276	1_0–0_0
	1214.859	5a	1012	49	2_0–1_0
p-NH_3	1215.245	5a	1012	49	2_1–1_1

Species x	N^a (cm^{-2})	$X = N_x/N_H$
NH	1.5×10^{14}	5.6×10^{-9}
NH_2	8.0×10^{13}	3.0×10^{-9}
NH_3	8.7×10^{13}	3.2×10^{-9}
NH^+	$\lesssim 2 \times 10^{13}$	$\lesssim 8 \times 10^{-10}$

Excitation and abundance of C_3 in star forming cores

Herschel/HIFI⋆ observations of the sight-lines to W31C and W49N⋆⋆

B. Mookerjea[1], T. Giesen[2], J. Stutzki[2], J. Cernicharo[3], J. R. Goicoechea[3], M. De Luca[4], T. A. Bell[5], H. Gupta[6],

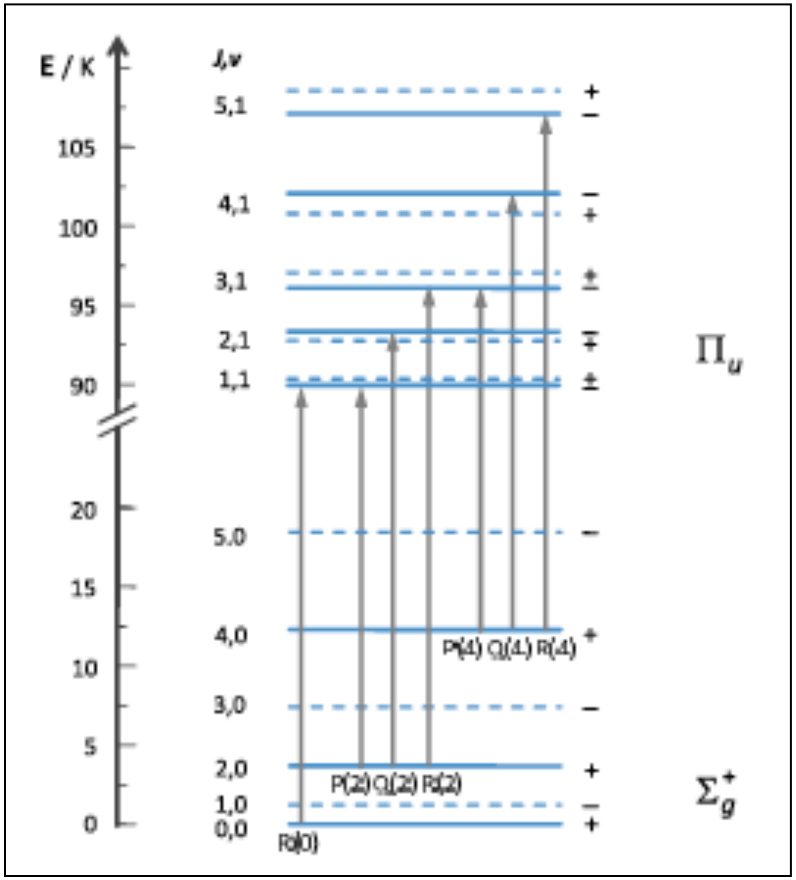
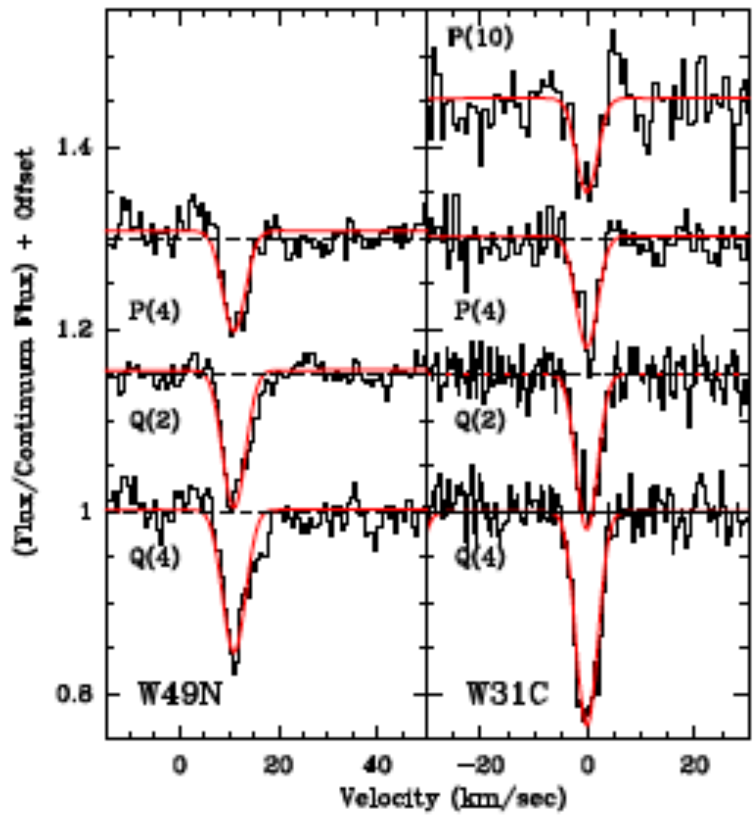


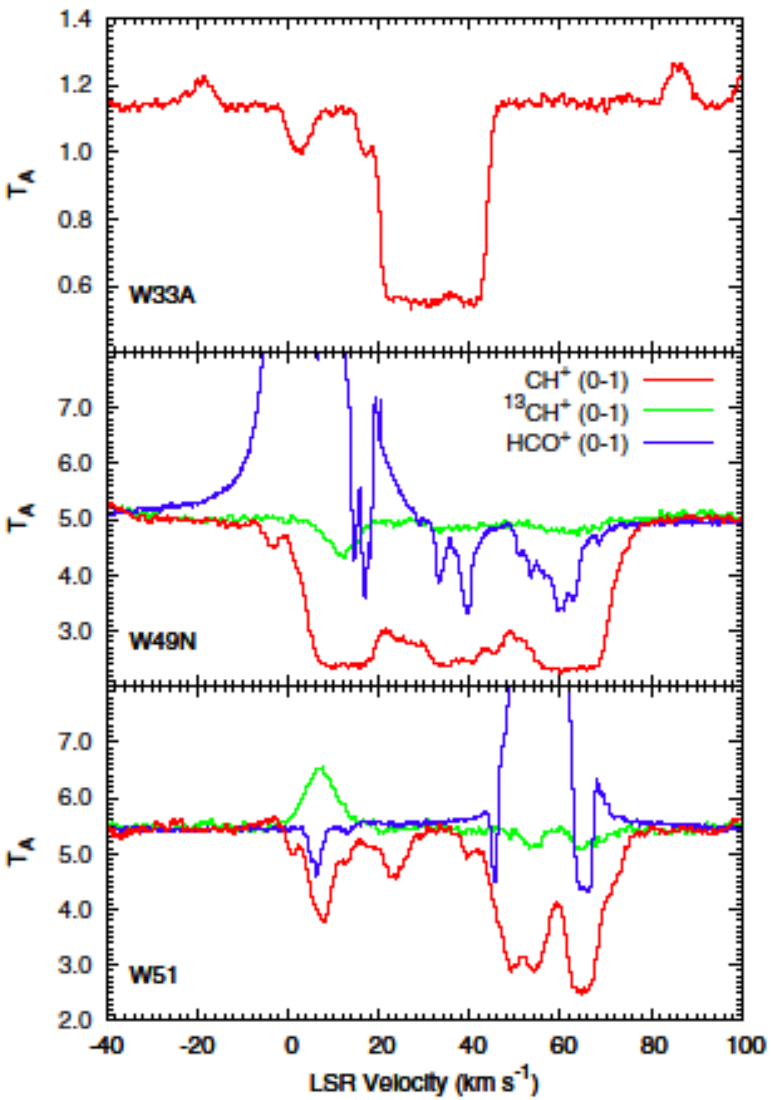
Table 1. Spectroscopic parameters for the observed C_3 transitions.

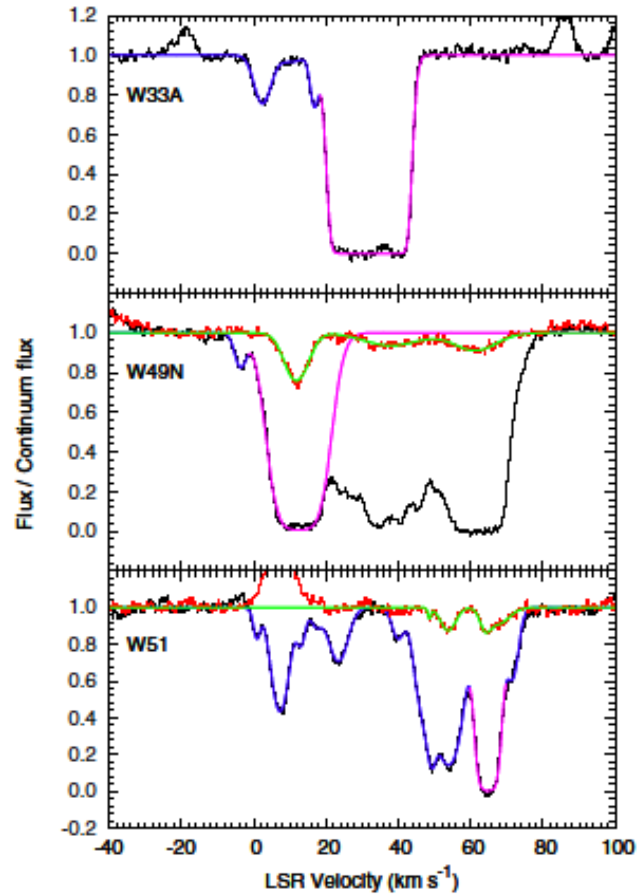
Name	Transition $(J', v')\leftarrow(J, v)$	Frequency[a] [MHz]	A-coeff 10^{-3} s^{-1}	E_l [K]
$P(10)$	(9, 1)←(10, 0)	1654081.66(4.68)[b]	2.38	47.3
$P(4)$	(3, 1)←(4, 0)	1787890.57(6.90)	2.72	8.6
$Q(2)$	(2, 1)←(2, 0)	1890558.06(0.25)	7.51	2.6
				8.6

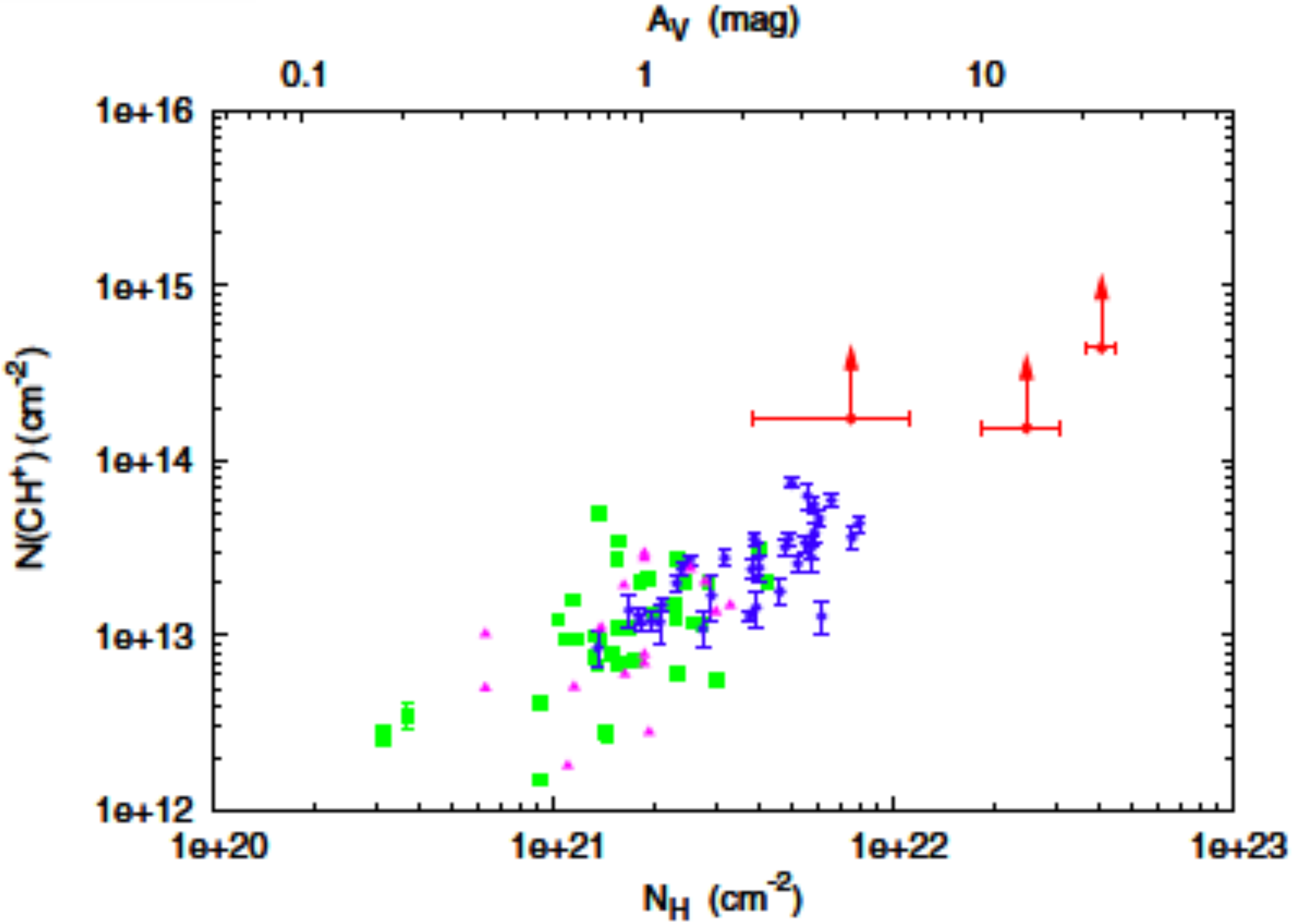


$CH^+(1\text{–}0)$ and $^{13}CH^+(1\text{–}0)$ absorption lines in the direction of massive star-forming regions★,★★

E. Falgarone[1], B. Godard[8,1], J. Cernicharo[3], M. De Luca[1], M. Gerin[1], T. G. Phillips[7], J. H. Black[2], D. C. Lis[7],







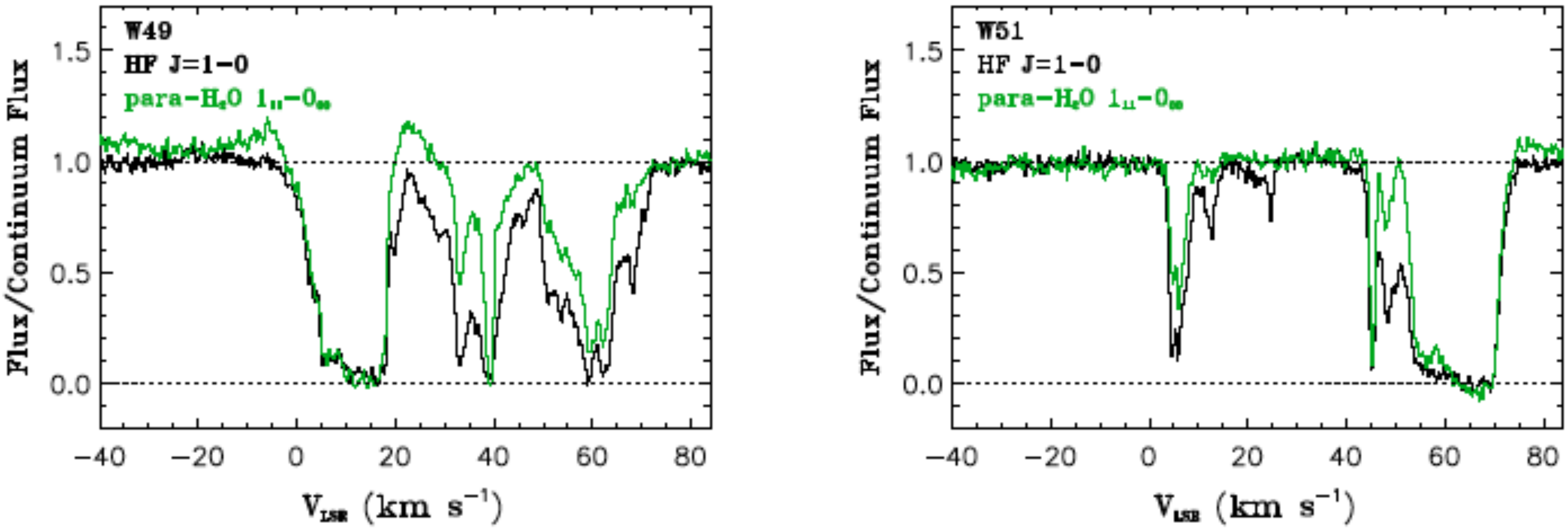
The interstellar CH^+ abundance problem even gets aggravated!

$$C^+ + H_2 \rightarrow CH^+ + H$$

0.4 ev (4600 K)

Detection of hydrogen fluoride absorption in diffuse molecular clouds with *Herschel*/HIFI: an ubiquitous tracer of molecular gas★

P. Sonnentrucker[1], D. A. Neufeld[1], T. G. Phillips[2], M. Gerin[3], D. C. Lis[2], M. De Luca[3], J. R. Goicoechea[4],

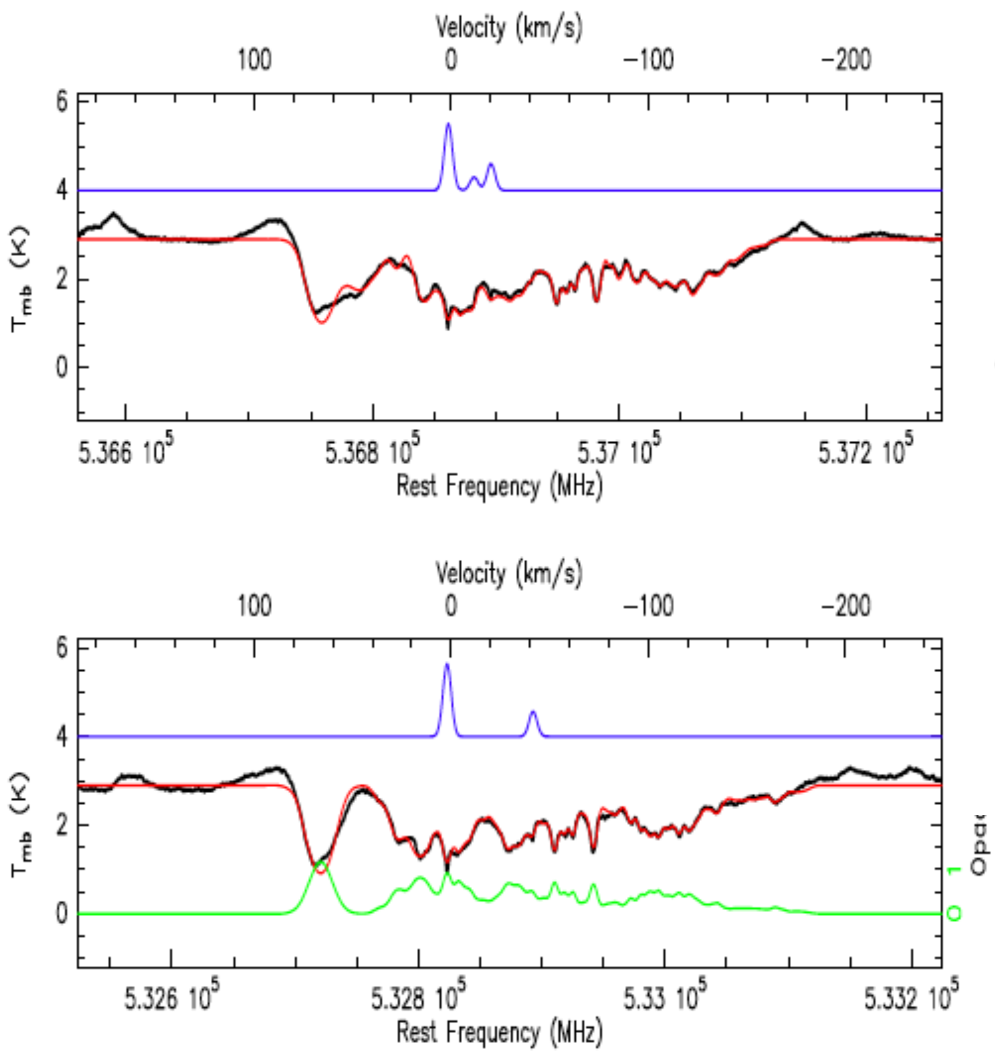


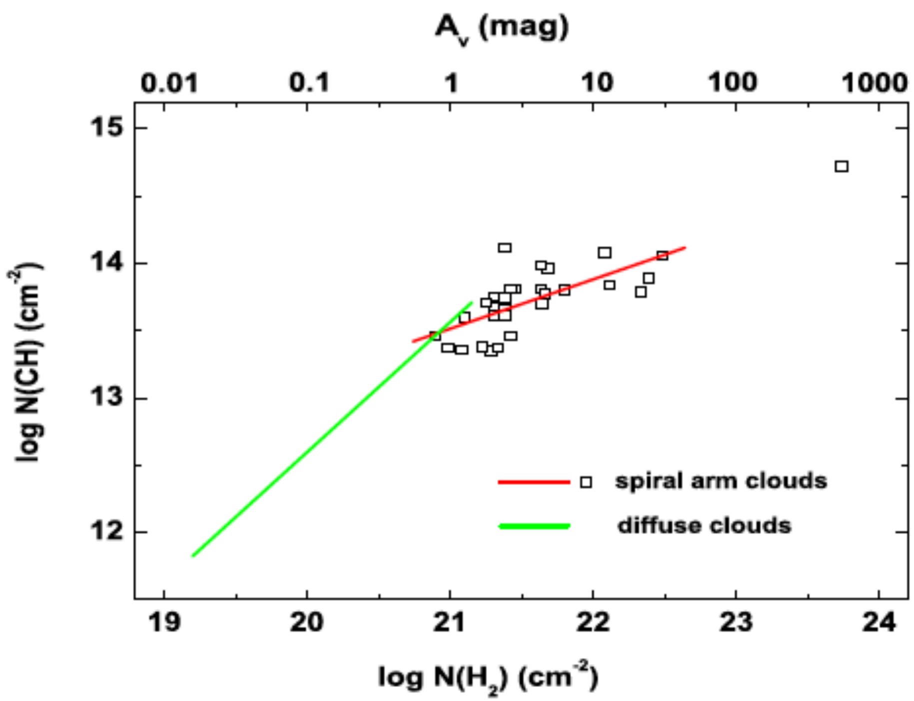
- Fluorine is the only atom that can react **exothermically** with H_2 to form a diatomic hydride
- HF is destroyed very slowly
- HF is expected to be the dominant reservoir of gas-phase fluorine.

→ HF may be used as a valuable surrogate **tracer for molecular hydrogen**

Herschel observations of EXtra-Ordinary Sources (HEXOS): detecting spiral arm clouds by CH absorption lines★

S.-L. Qin[1], P. Schilke[1,2], C. Comito[2], T. Möller[1], R. Rolffs[2], H. S. P. Müller[1], A. Belloche[2], K. M. Menten[2], D. C. Lis[3],





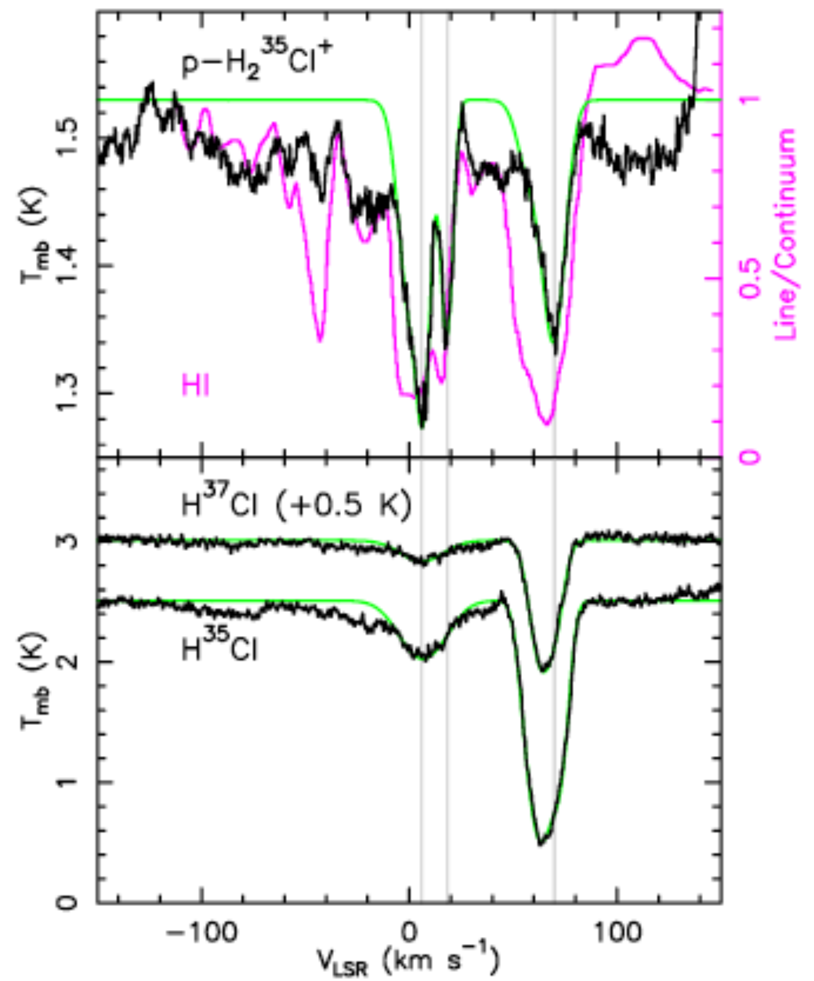
Another good proxy for the H_2 column density

Herschel/HIFI discovery of interstellar chloronium (H_2Cl^+)★,★★

D. C. Lis[1], J. C. Pearson[13], D. A. Neufeld[3], P. Schilke[8,12], H. S. P. Müller[12], H. Gupta[13], T. A. Bell[1], C. Comito[8],

Exotica I: H_2Cl^+

$[H_2Cl^+] \sim [HCl]$



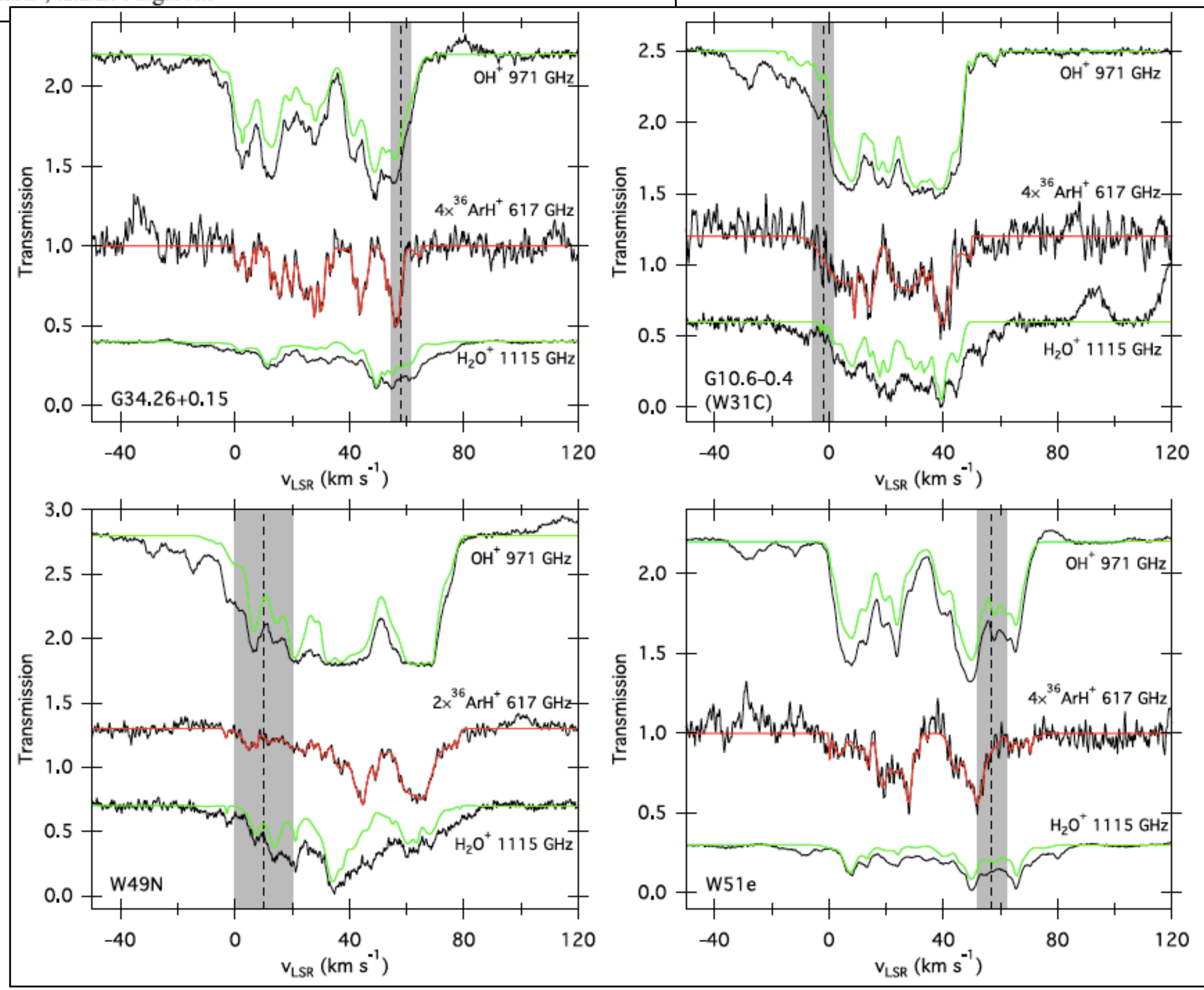
A&A 566, A29 (2014)
DOI: 10.1051/0004-6361/201423727

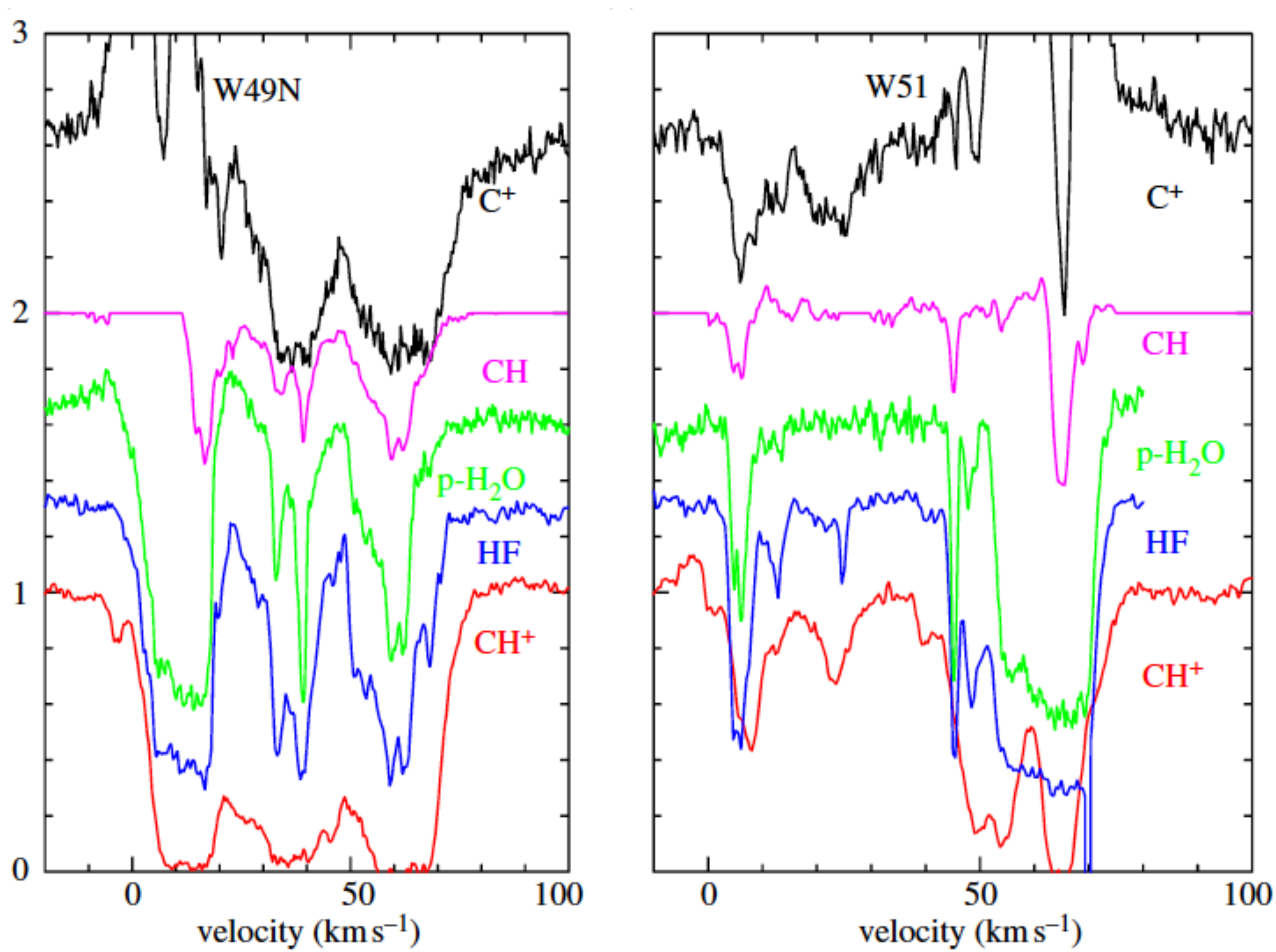
Astronomy & Astrophysics

Exotica II: ArH^+

Ubiquitous argonium (ArH^+) in the diffuse interstellar medium: A molecular tracer of almost purely atomic gas

P. Schilke[1], D. A. Neufeld[2], H. S. P. Müller[1], C. Comito[1], E. A. Bergin[3], D. C. Lis[4,5], M. Gerin[6], J. H. Black[7], M. Wolfire[8], N. Indriolo[2], J. C. Pearson[9], K. M. Menten[10], B. Winkel[10], Á. Sánchez-Monge[1], T. Möller[1], B. Godard[6], and E. Falgarone[6]





Compilation: Gerin et al. 2012

Results so far and future developments:

Submillimeter observations of rotational ground-state transitions

- have greatly enhanced our view of diffuse ISM chemistry
- added important missing pieces in reaction network
- have extended chemistry studies throughout the Galaxy
- delivered new HI/H_2 tracers

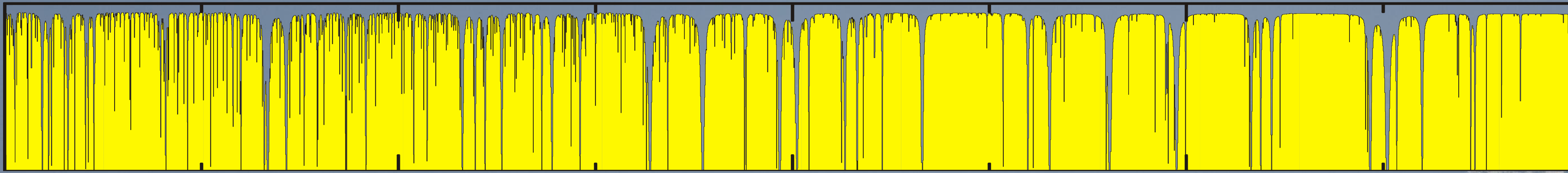
This new information will allow addressing questions on

- Galactocentric abundance gradients
- effects of lower metallicity in Outer Galaxy
- …

Galactic molecular absorption spectroscopy after Herschel

Stratospheric Observatory for For Infrared Astronomy (SOFIA)

- 2.7 m telescope
- US/German (NASA/DLR) 80%/20% joint project
- 0.3 - 1600 μm (0.2 – 2500 THz) wavelength/frequency range
- GREAT und STAR instruments from Bonn/Köln/Berlin-Adlershof
- First science flight
- Project duration > 20 years



ATM 1-5 THz, 14 km altitude

German Receiver for Astronomy at THz Frequencies

GREAT

Modular dual-channel heterodyne receiver for high-resolution spectroscopy with SOFIA

GREAT - the Consortium

MPIfR
KOSMA
MPS
DLR-Pf

PI-Instrument funded and developed by

- MPI Radioastronomie (2.7 THz channel)
  - R. Güsten (PI)
  - S. Heyminck (system engineer)
  - B. Klein (FFT spe ctrometer)
  - I. Camara, T. Kle 7 THz LO)

Talk by Rolf Güsten/
Karl Jacobs

- .4/1.9THz channels)
  - U. Graf (1.4 &1.9 LO, Optics)
  - K. Jacobs (HEB ixers up to 2.7 THz)
  - R. Schieder (array-AOS)
- DLR Planetenforschung (4.7 THz channel)
  - H-W. Hübers (Co-PI: 4.7 THz HEB, IF, cal unit)
- MPI Sonnensystemforschung
  - P. Hartogh et al. (CO-PI: CTS)

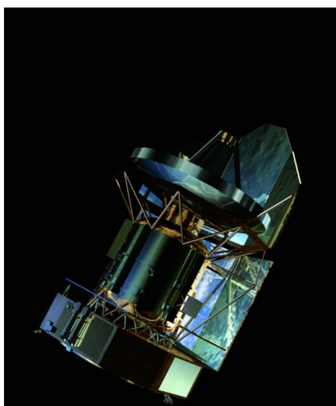
A&A 542, L5 (2012)
DOI: 10.1051/0004-6361/201218784

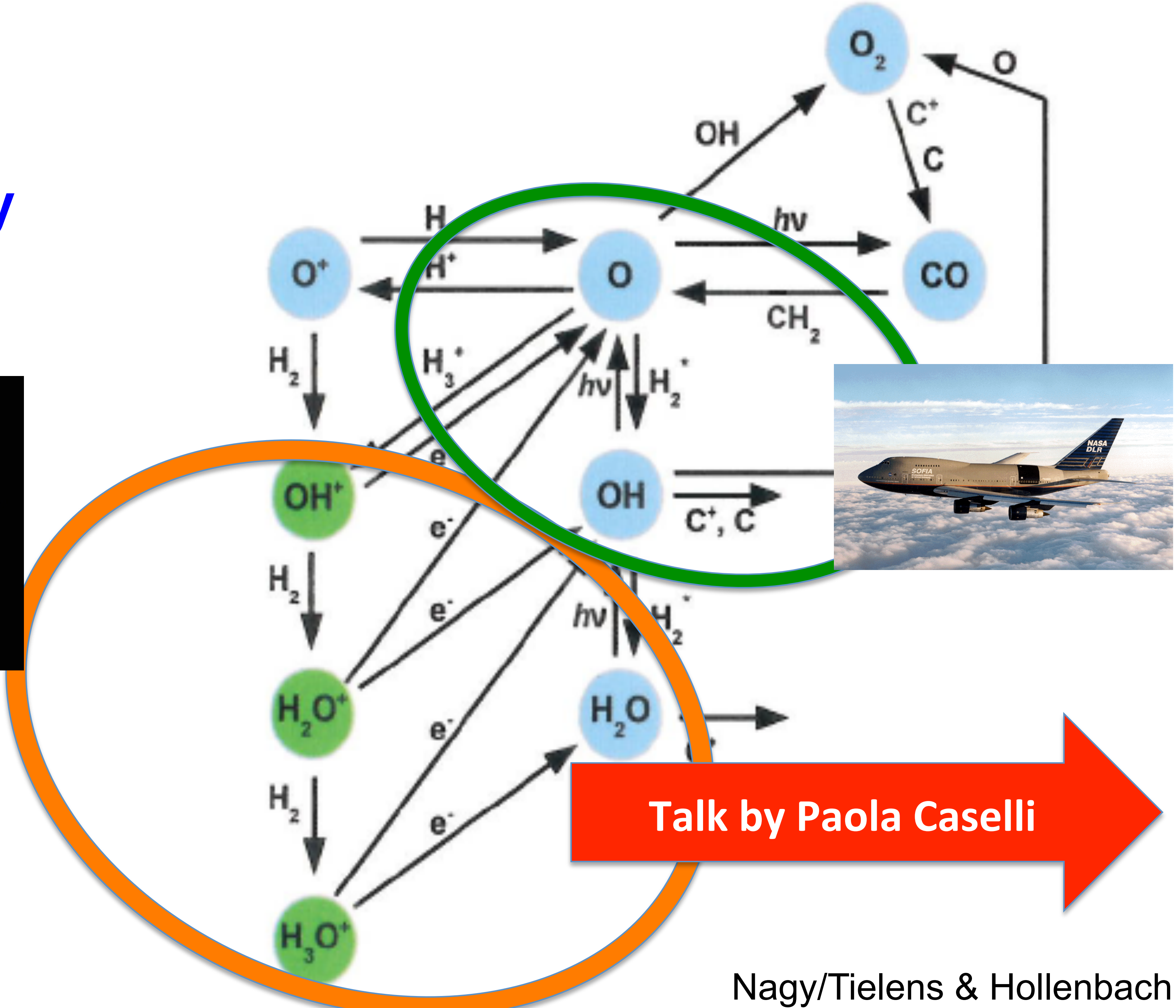
GREAT: early science results

Astronomy & Astrophysics
Special feature

Front-end	Frequencies [THz]	Astronomical [illegible]es of interest
low-frequency L1a	1.250 – 1.392	CO(12-11), [illegible](12-11), OD, SH, H_2D^+, HCN; HCO^+
low-frequency L1b	1.417 – 1.520	CO(13-12[illegible]II],
low-frequency L2	1.815 – 1.920	NH_3(3-2), OH($^2\Pi_{1/2}$), CO(16-15), [CII]
mid-frequency Ma	2.507 – 2.514	$^{(18)}$OH($^2\Pi_{3/2}$)
mid-frequency Mb	2.670 – 2.680	[illegible]D(1-0)
high-frequency H	4.750 – 4.7[illegible]	[OI]

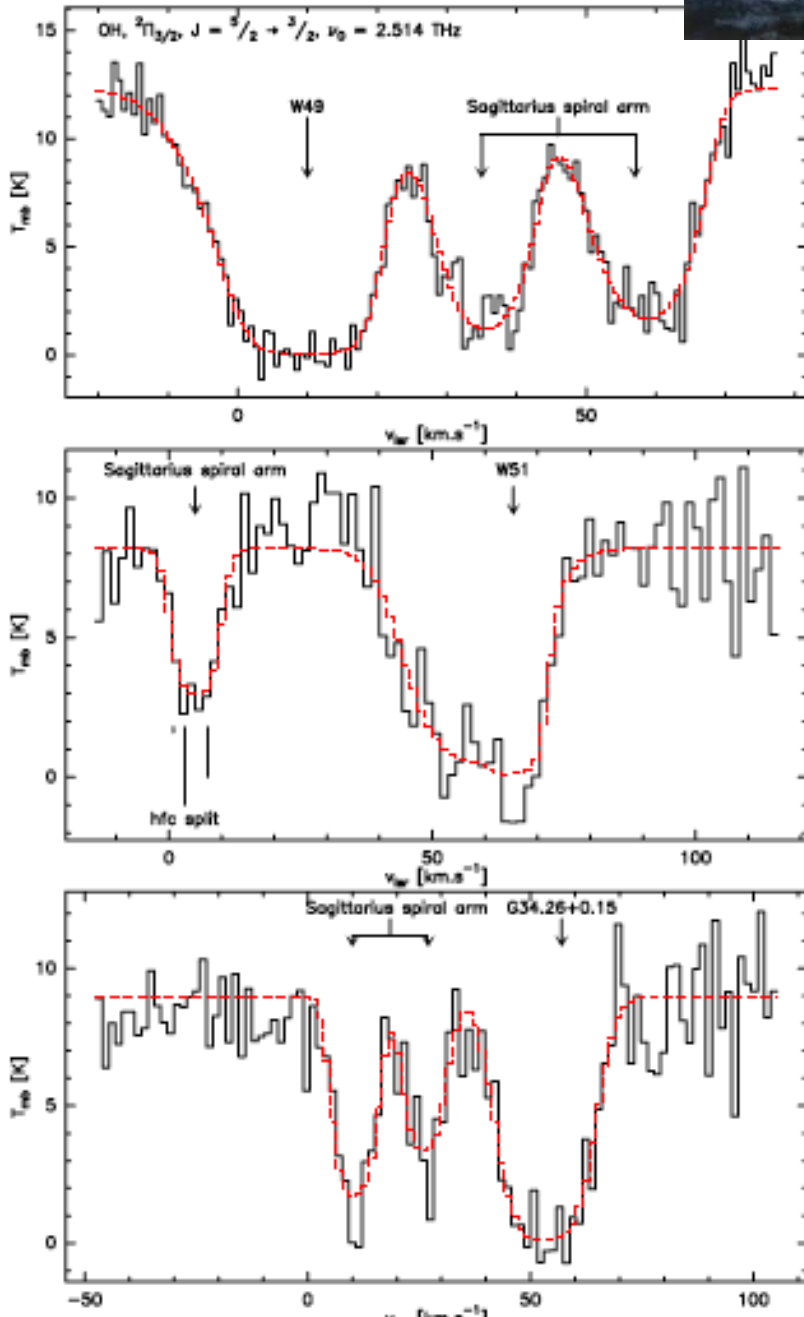
Basic Oxygen Chemistry



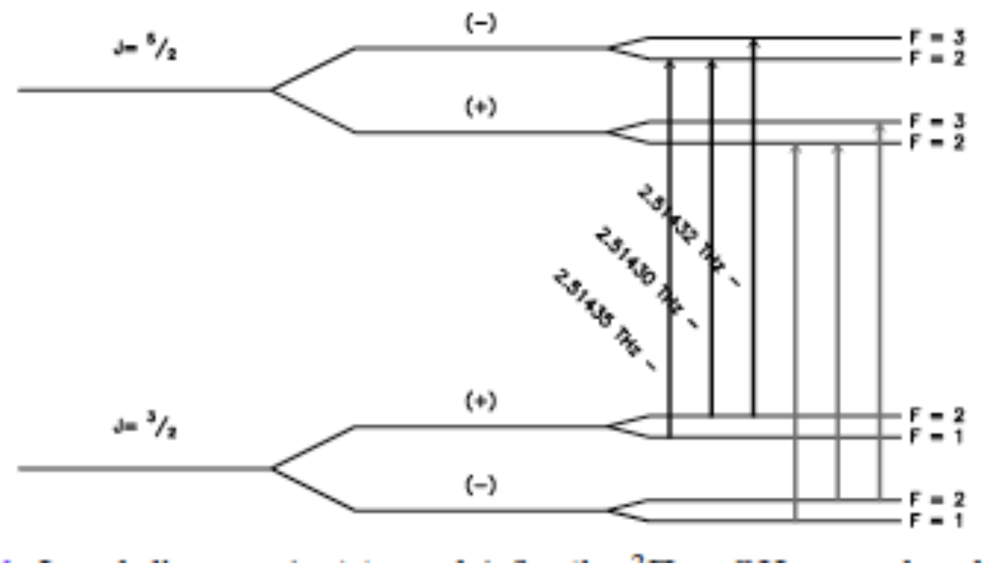


Talk by Paola Caselli

Nagy/Tielens & Hollenbach



Transition	Frequency [GHz][a]	A_E [s^{-1}][b]
OH, $^2\Pi_{3/2}, J = 5/2 \leftarrow 3/2$		
$F = 2^- \leftarrow 2^+$	2514.298092	0.0137
$F = 3^- \leftarrow 2^+$	2514.316386	0.1368
$F = 2^- \leftarrow 1^+$	2514.353165	0.1231
^{18}OH, $^2\Pi_{3/2}, J = 5/2 \leftarrow 3/2$		
$F = 2^+ \leftarrow 2^-$	2494.68092	0.0136
$F = 3^+ \leftarrow 2^-$	2494.69507	0.1356
$F = 2^+ \leftarrow 1^-$	2494.73421	0.1221



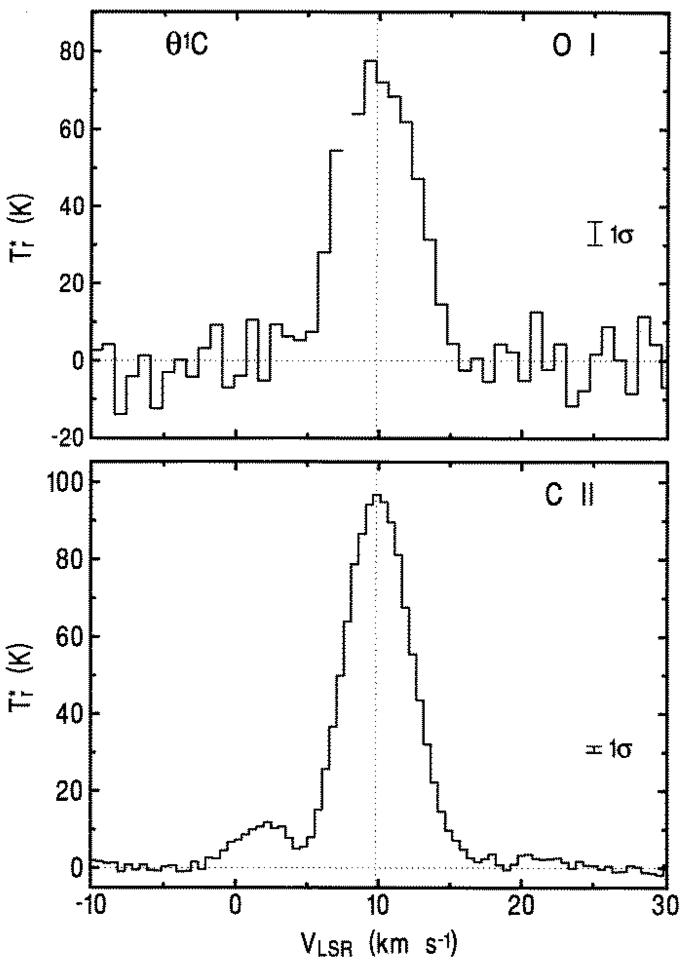
Wiesemeyer et al. 2012

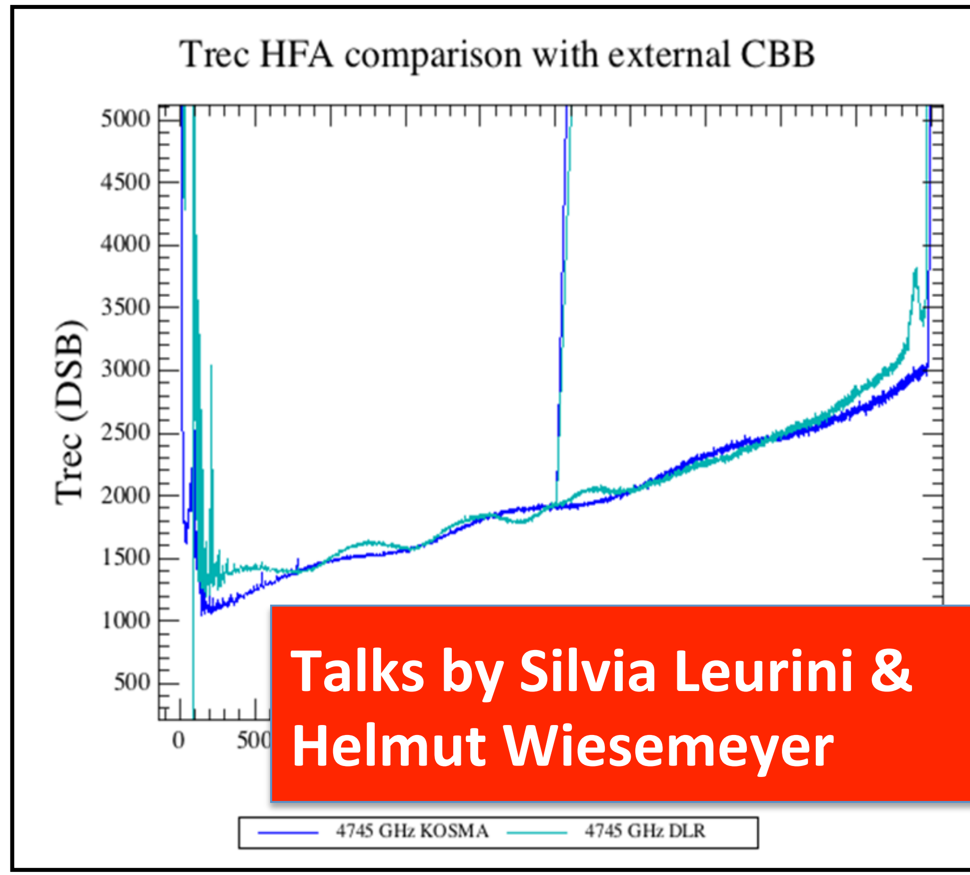
The 4.75 THz (63 μm) OI ground-state fine structure line

First H/D detection in M42

- T_{sys}(DSB) = 70000 K

Boreiko & Betz 1996





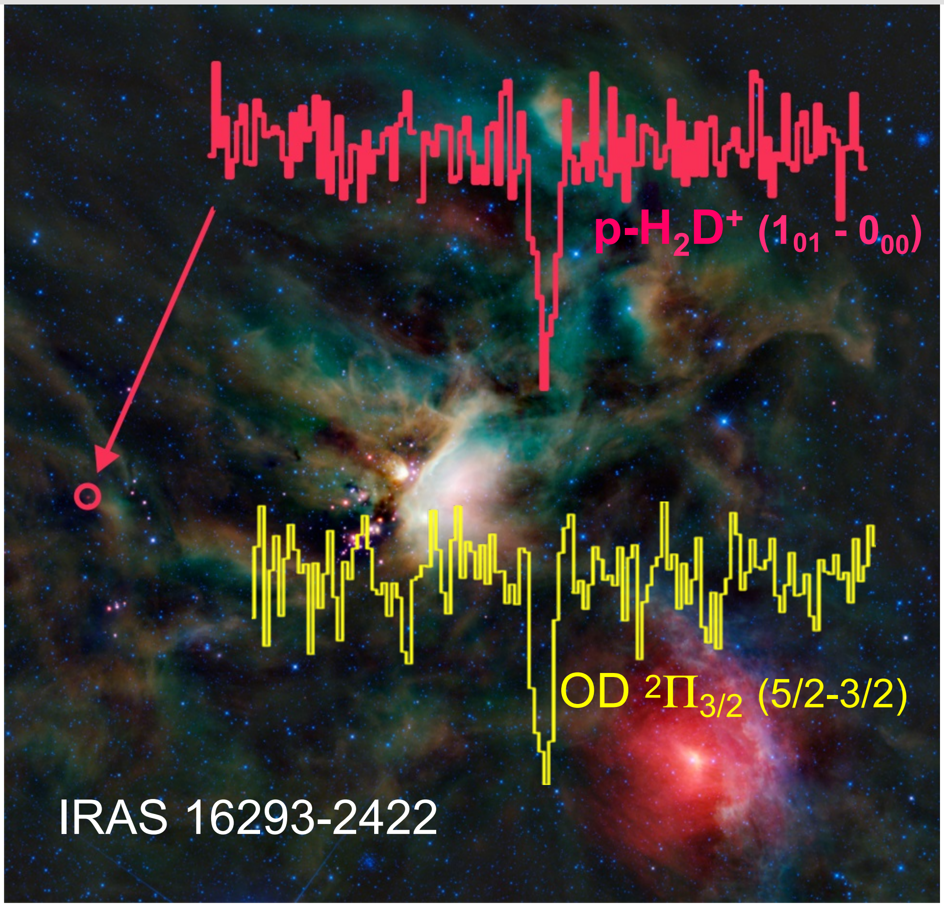
Talks by Silvia Leurini & Helmut Wiesemeyer

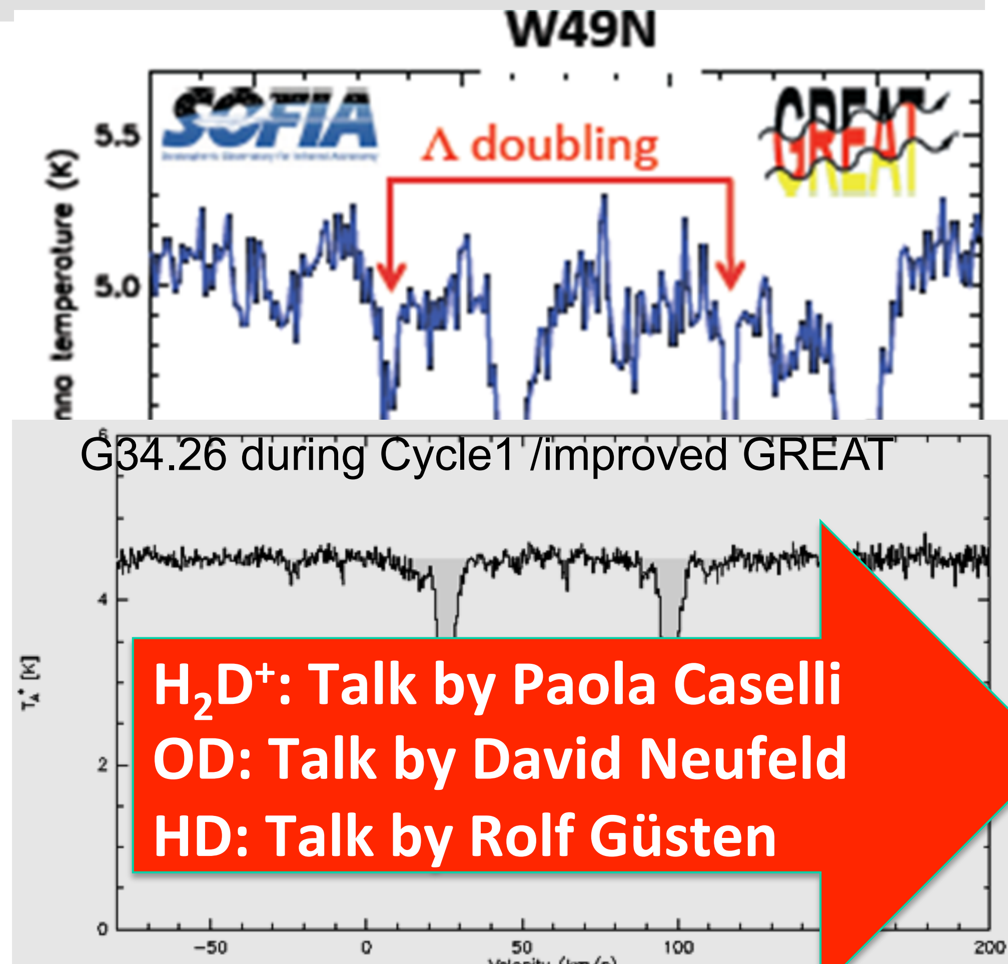
2013:

- T_{sys}**(DSB, KOSMA, Jacobs) ≈** T_{sys}**(DSB, DLS-Pf, Hübers) = 1500 K**

New light hydrides with SOFIA

Searches for light hydrides have been very succesful: SH, OD, p-H_2D^+

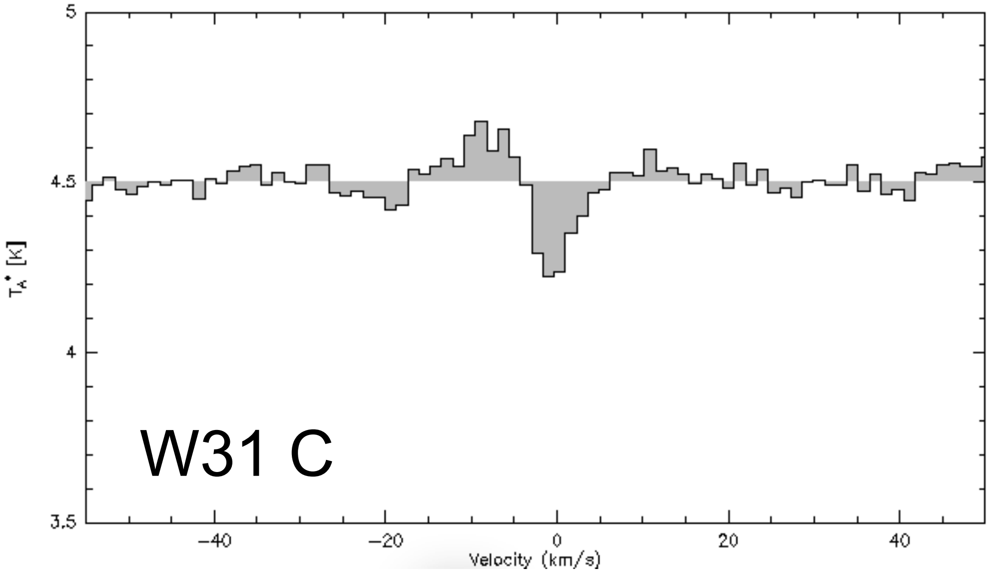


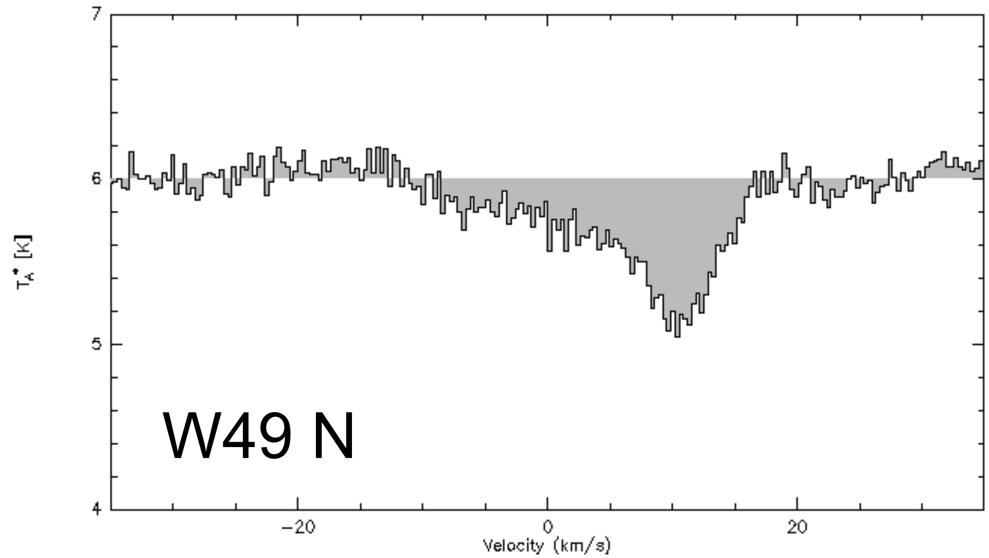


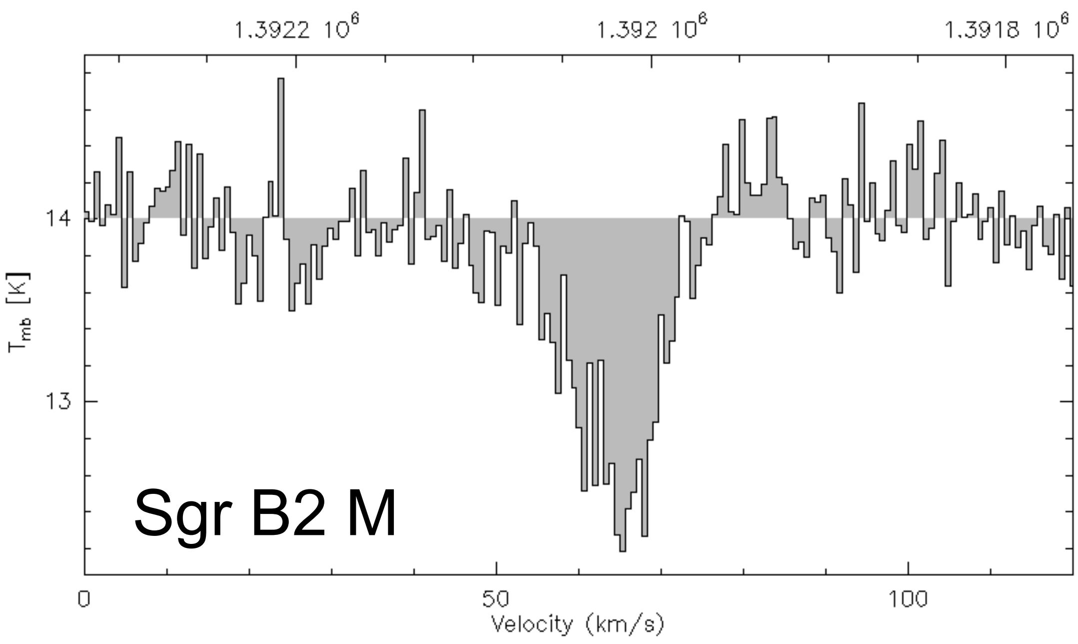
H_2D^+: Talk by Paola Caselli
OD: Talk by David Neufeld
HD: Talk by Rolf Güsten

Detection of OD ground-state (1.39 THz) during Basic Science (Parise et al. 2012). p-H_2D^+ ground-state during Cycle 1 (New Zealand – Brünken et al. 2013). SH Λ-doublet detected in BS, follow-up during Cycle 1 on half dozen targets (Neufeld et al 2012.)

More OD







K. Menten/H. Wiesemeyer

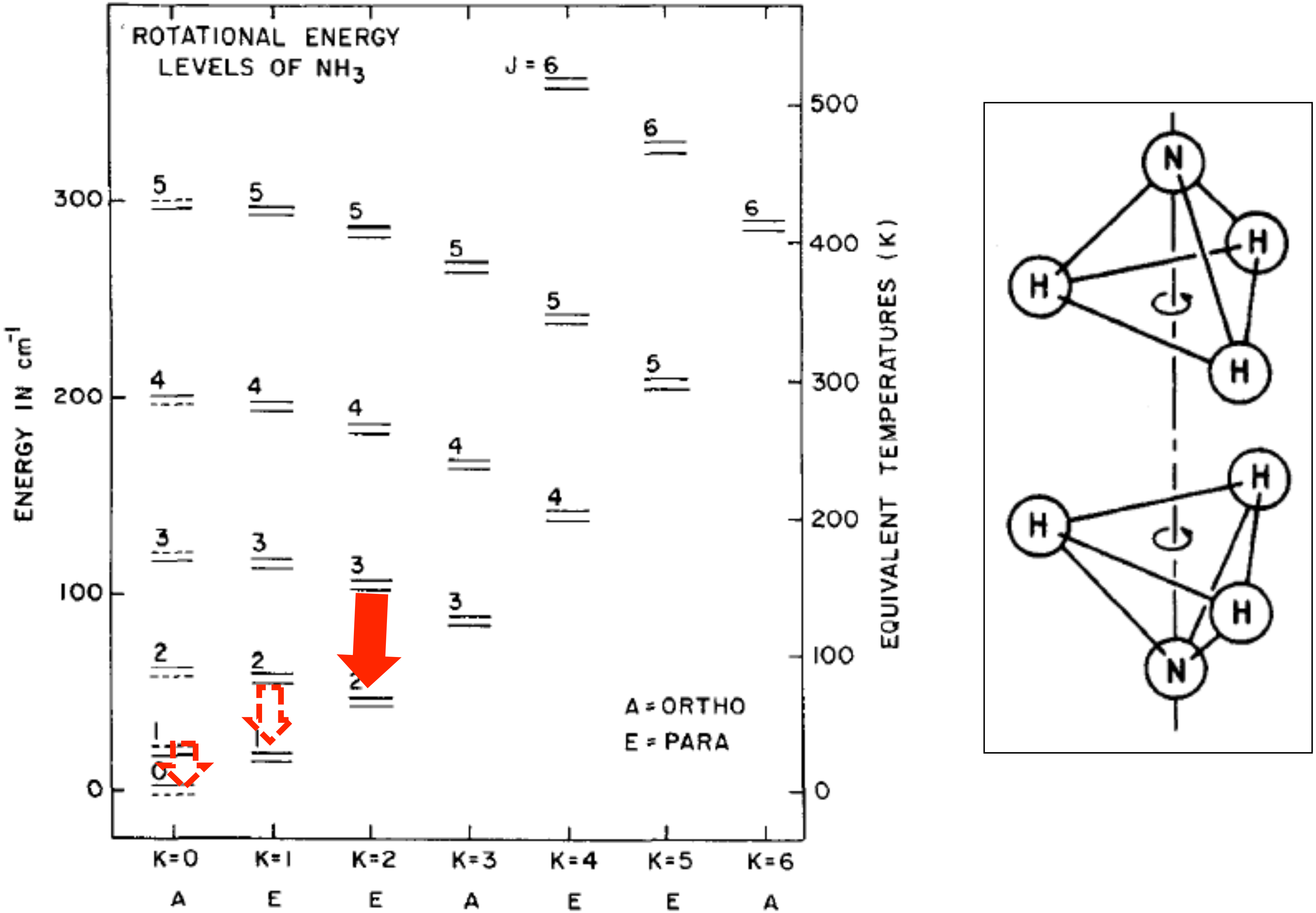
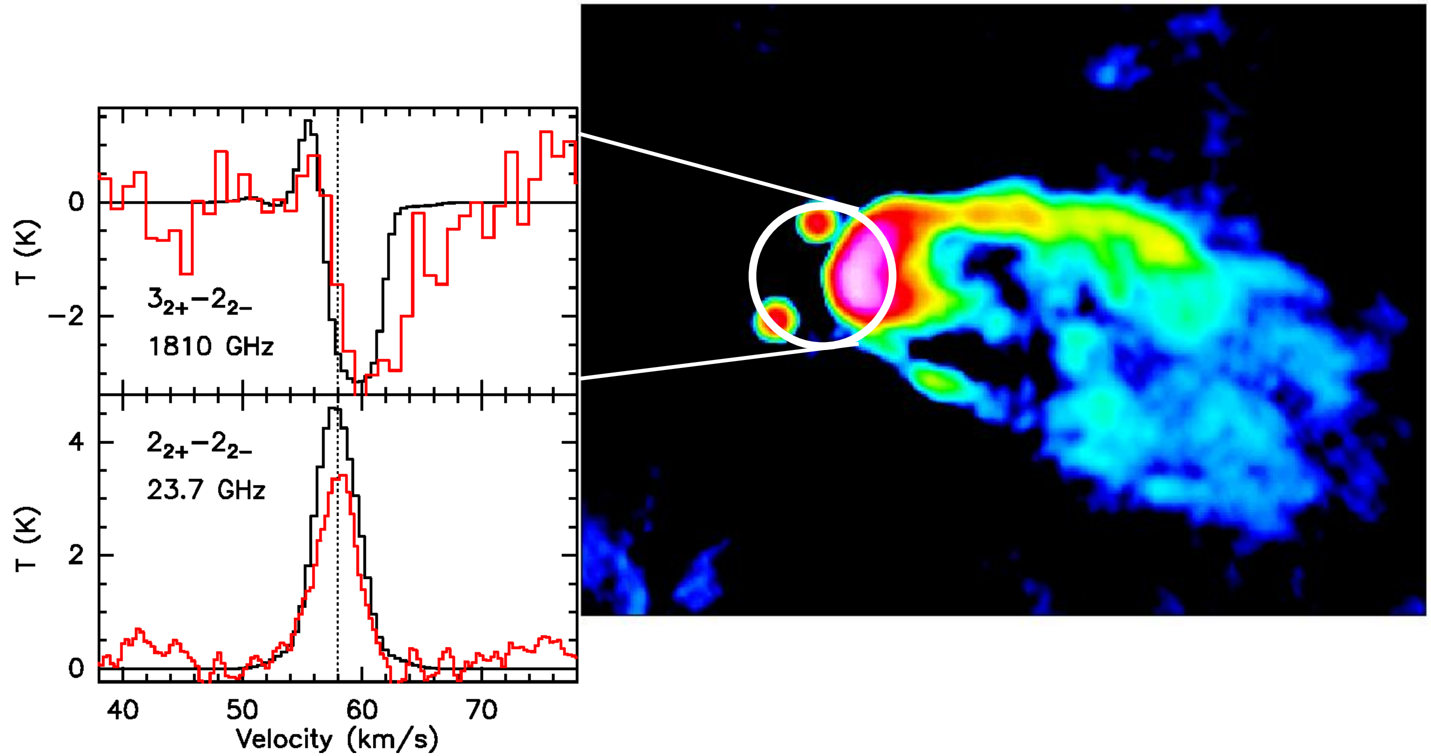


Figure 1 Energy level diagram of rotation-inversion states. J is the total angular-momentum quantum number, and K is the projected angular momentum along the molecular axis.

Ammonia/1.8 THz: Probing infall



- 3 absorption line detections
- All redshifted with respect to v_{sys}
  $\tau \sim 1$
- RATRAN modeling

→Mass infall rates:

$3–10\ 10^{-3}\ M_{sun}/y$

Poster by Ka Tat Wong

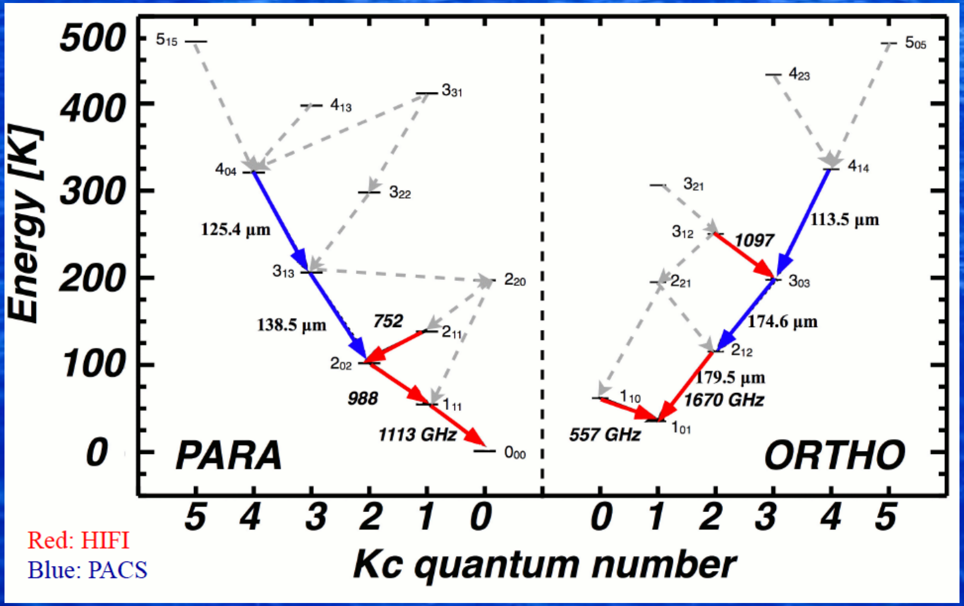
Wyrowski et al. 2012

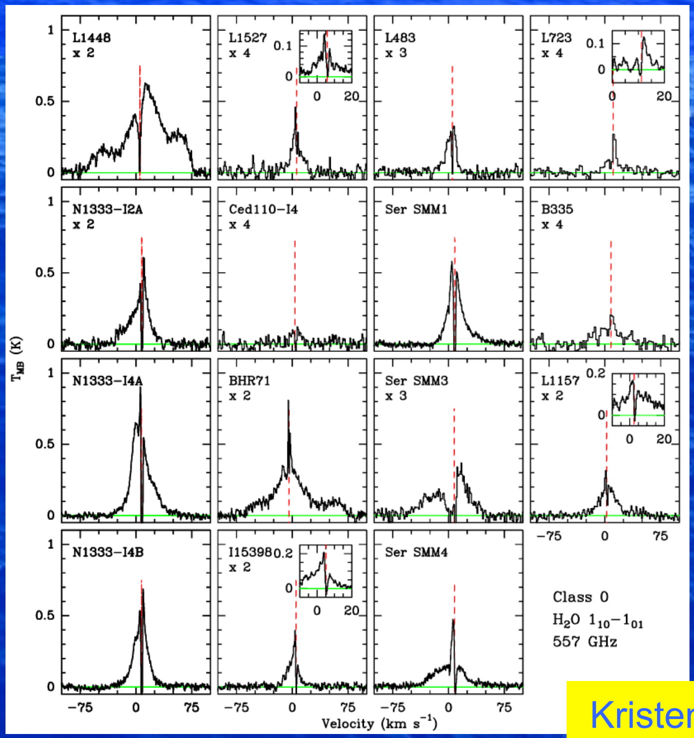
Impossible for SOFIA: H_2O

Water in Star-Forming Regions

- Herschel/HIFI GTKP/PI E. van Dishoeck
- H_2O abundance shows large variations in SF regions: $<10^{-8}$ (cold) – 3 10^{-4} (warm) → unique probe of different physical regimes
  ---> Natural filter of warm gas

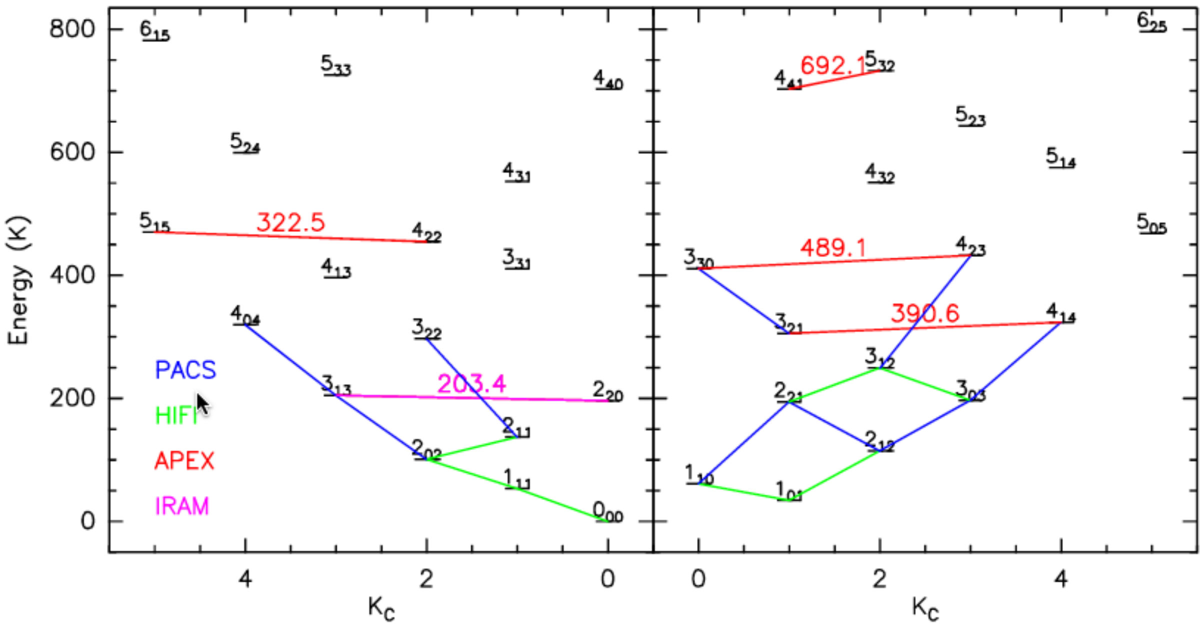
- Main reservoir of oxygen → affects chemistry of all other species. Traces basic processes of freeze-out onto grains and evaporation, which characterize different stages of evolution



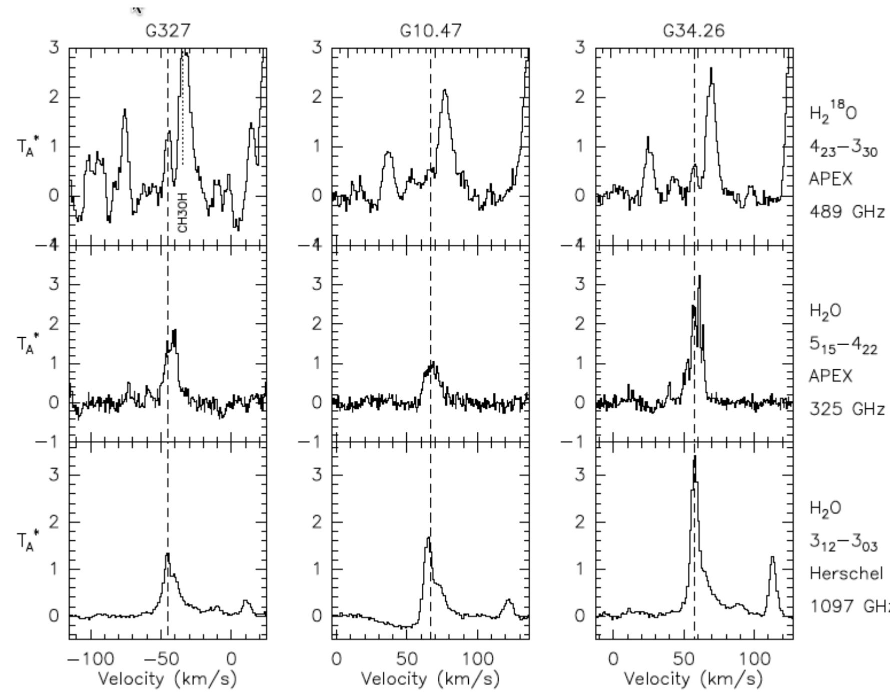


Kristensen et al. 2012

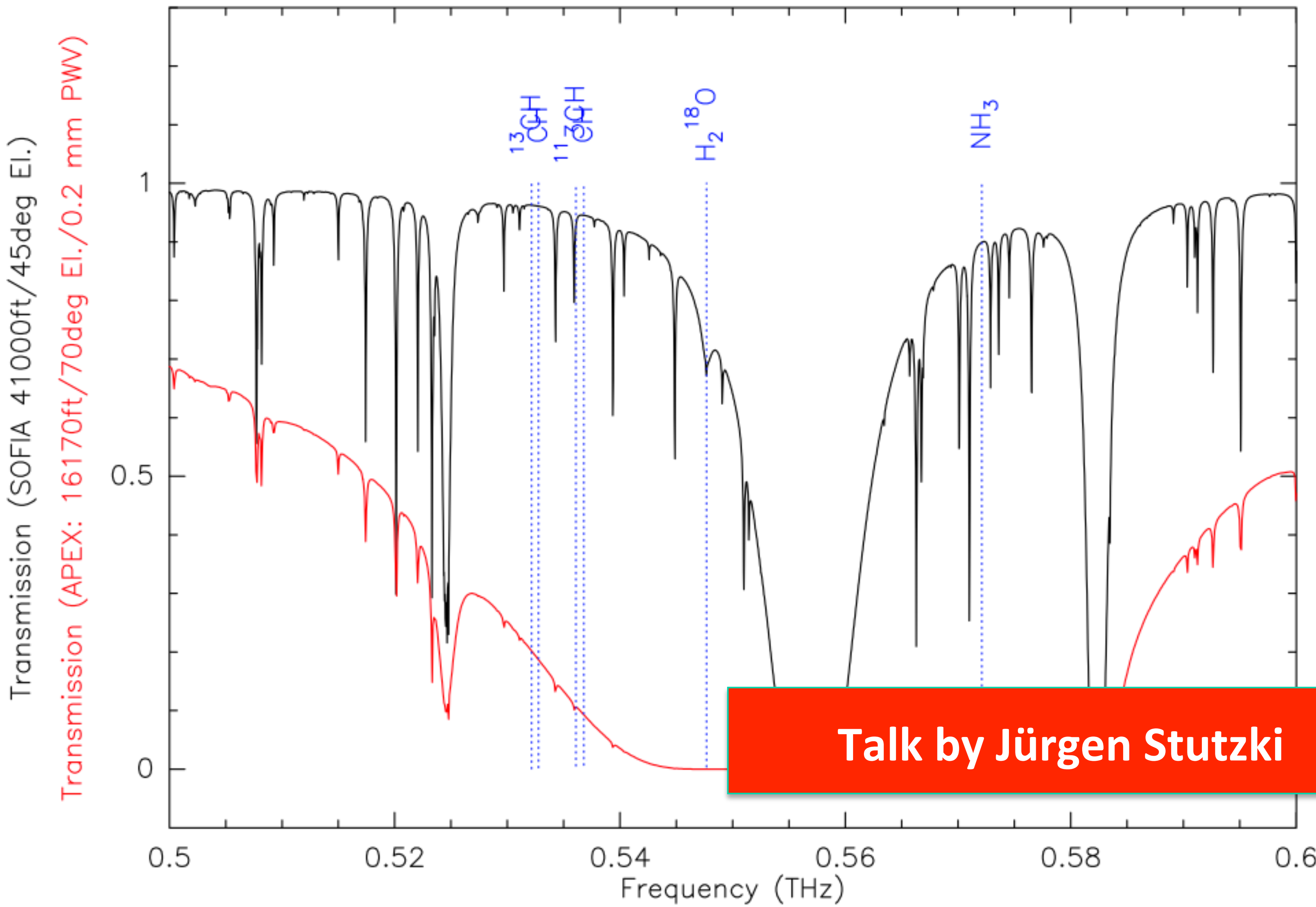
$H_2^{18}O$ can also be observed from the ground!



Molecule	Transition	Frequency (GHz)	RX	T_l (K)	dT (K)	Tint (min)	PWV (mm)
$H_2^{18}O$	$5_{32}-4_{41}$	692.1	CHAMP+	0.4	0.04	33	0.5
$H_2^{18}O$	$4_{14}-3_{21}$	390.6	FLASH	0.5	0.05	20	1.0
$H_2^{18}O$	$4_{23}-3_{30}$	489.1	FLASH	0.7	0.1	44	0.5
$H_2^{18}O$	$5_{15}-4_{22}$	322.5	FLASH	0.2	0.02	18	0.5
H_2O	$5_{15}-4_{22}$	325.1	FLASH	–	0.1	20	0.5



… but SOFIA can even observe the ortho-$H_2^{18}O$ ground-state line!



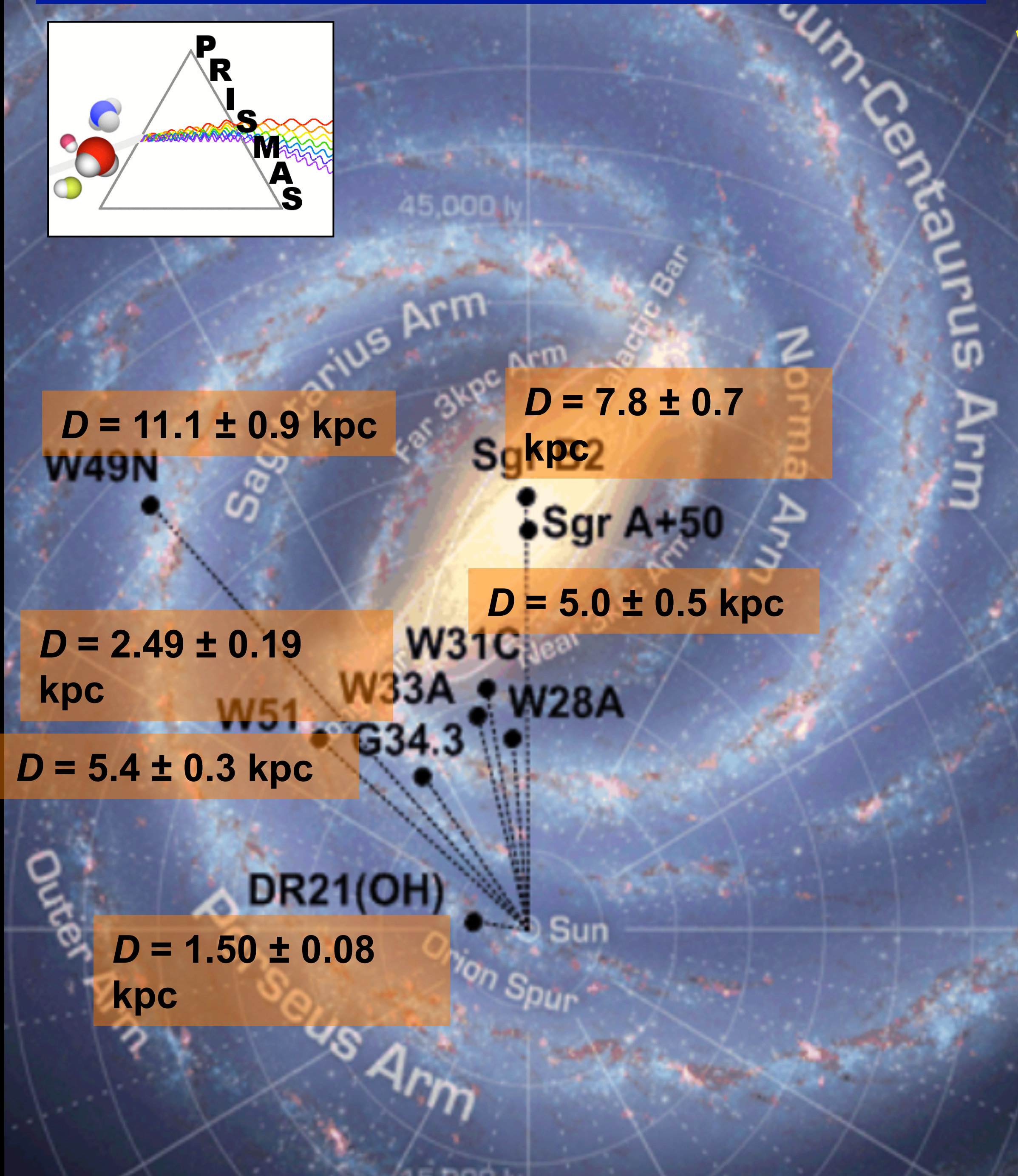
Talk by Jürgen Stutzki

Some Conclusions:

- High spectral resolution molecular (sub)millimeter absorption spectroscopy has transformed our knowledge of diffuse ISM chemistry and expanded our reach from ~ 1 kpc to the whole of the Galaxy
- Herschel has left a rich heritage on which we can build with SOFIA and ground based observatories…

  … and at high redshift with ALMA!
- Together with directly measured distances to the absorption sources (= MSFRs) we can determine galactocentric atomic, molecular and isotopic abundance gradients

Distances to PRISMAS Sources

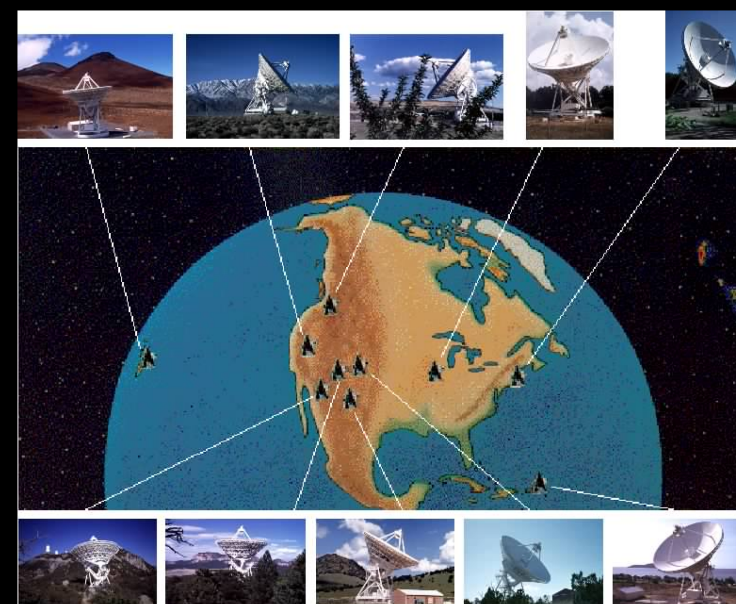


Distances for all interesting sources from:

BESSEL

Bar and Spiral Structure Legacy Survey, a VLBA Key Science Project

http://bessel.vlbi-astrometry.org



SOFIA's central role in diffuse ISM science

SOFIAS's highly diverse high resolution spectroscopy program addresses fundamental questions of diffuse and dense ISM astrochemistry and physics

It enjoys broad synergies with ground-based observations from the cm to the (sub)mm range and also at IR wavelengths

The highly modular GREAT receiver system can be continuously extended – in both frequency and spatial coverage – to address newly emerging interests:

- **upGREATs will provide access to ground-state transitions to some of the most important diffuse ISM tracers: CH, HF, $H_2{}^{18}O$, OI and NH_3**
- **Receiver arrays will multiply imaging efficiency**


Thanks for your attention