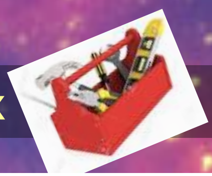
Future Observations of Hydrides

Karl M. Menten

Max-Planck-Institut für Radioastronomie



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 (

• HD

Vastly expanded new view of diffuse ISM chemistry since 2010!

Ther

• OH

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

(NIR 1996)

rly 2010s: rschel/HIFI rules!

Now: SOFIA+APEX

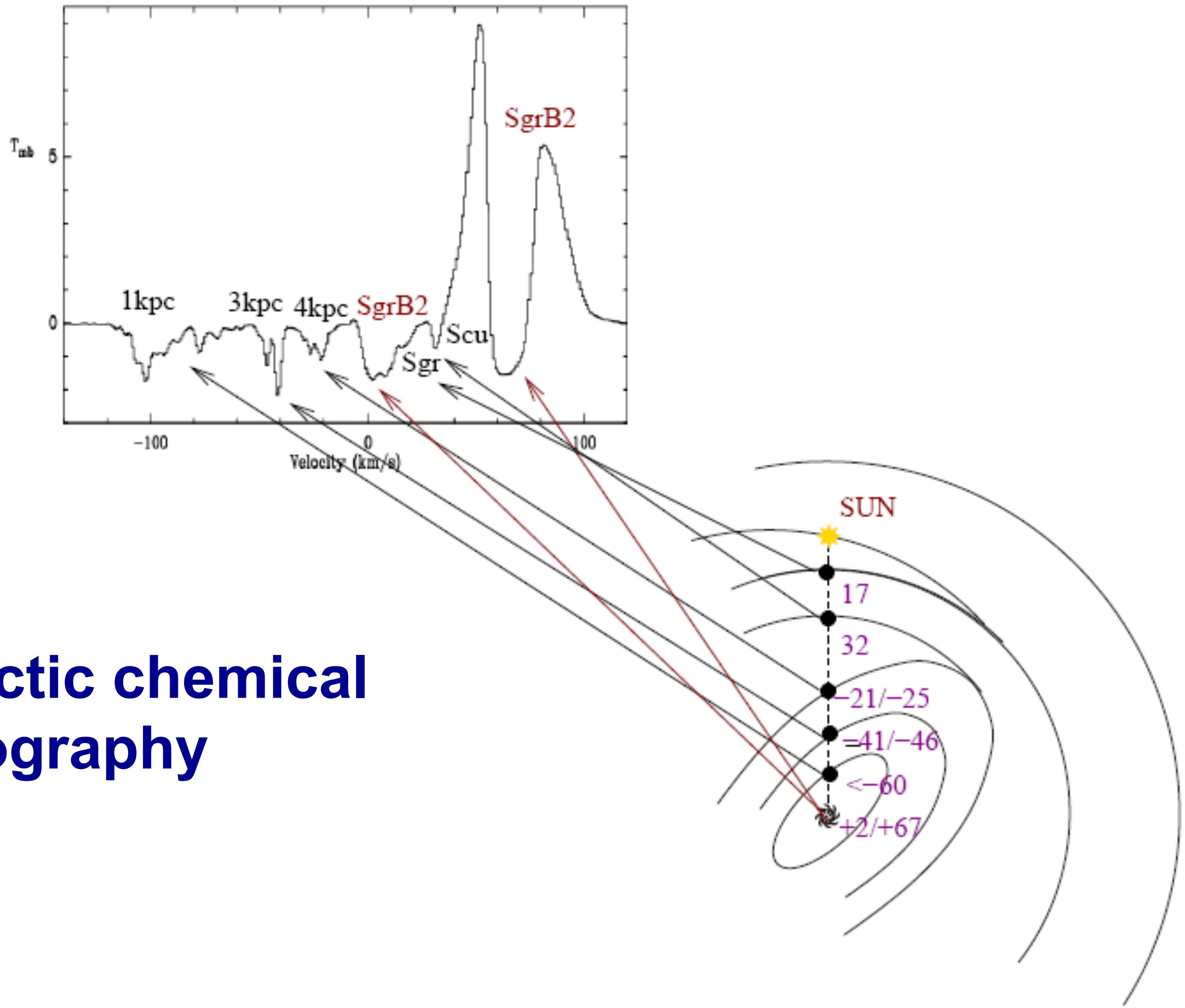
Plus: Radio

• HDO, D_2O, H_3O^+

After 2000:

• CH_2 (ISO)

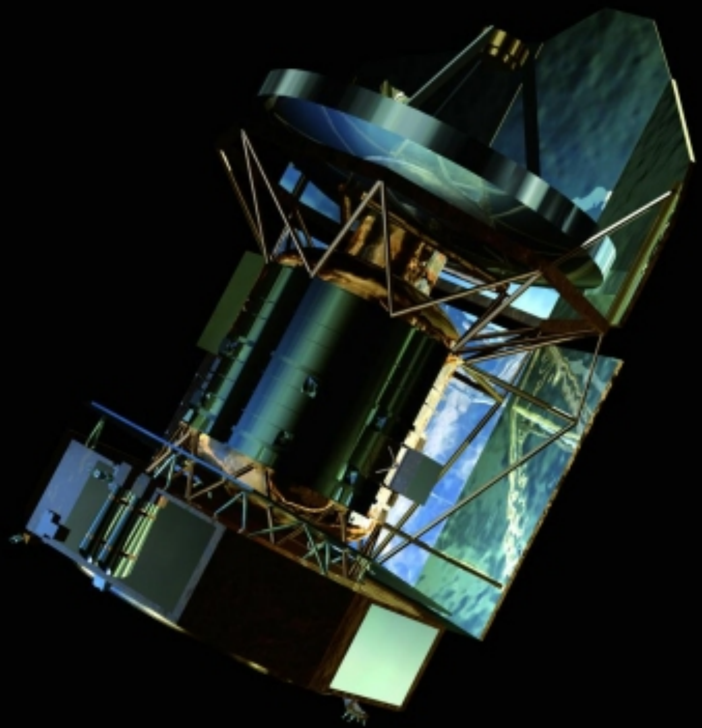
• HF (ISO)



Galactic chemical tomography

C. Hieret, Diploma Thesis, MPIfR

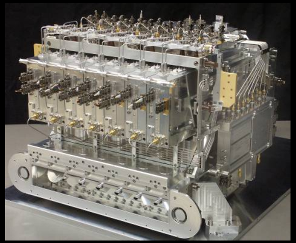
HERSCHEL



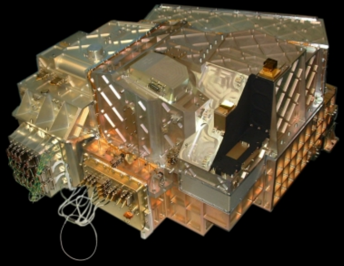
Launch: 14 May 2009

R.I.P. 17 June 2013

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 spectromete

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

Herschel/HIFI Guaranteed Time Key Programmes

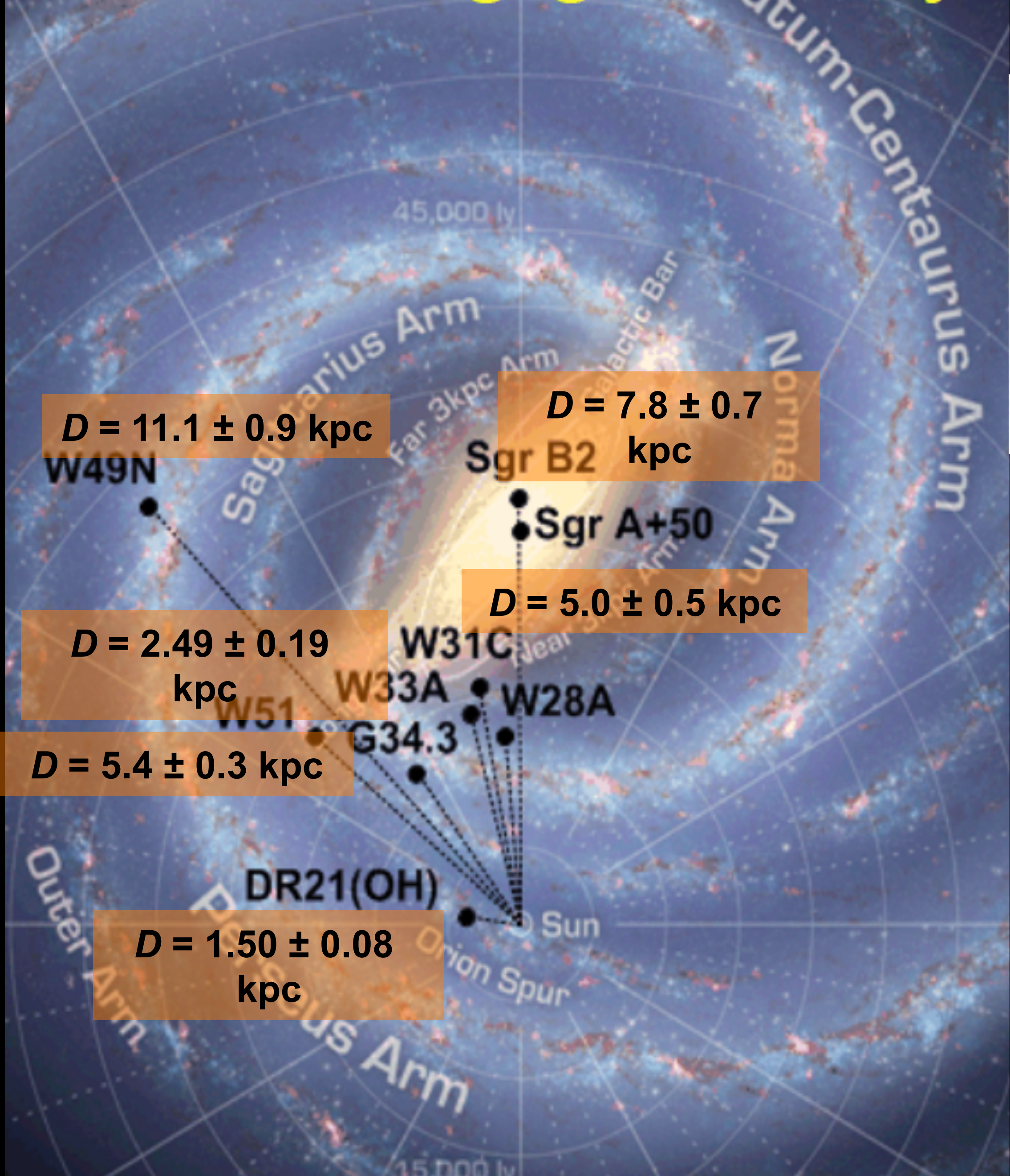
HEXOS: Herschel/HIFI Observations of EXtraOrdinary Sources

- 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)

Observing geometry

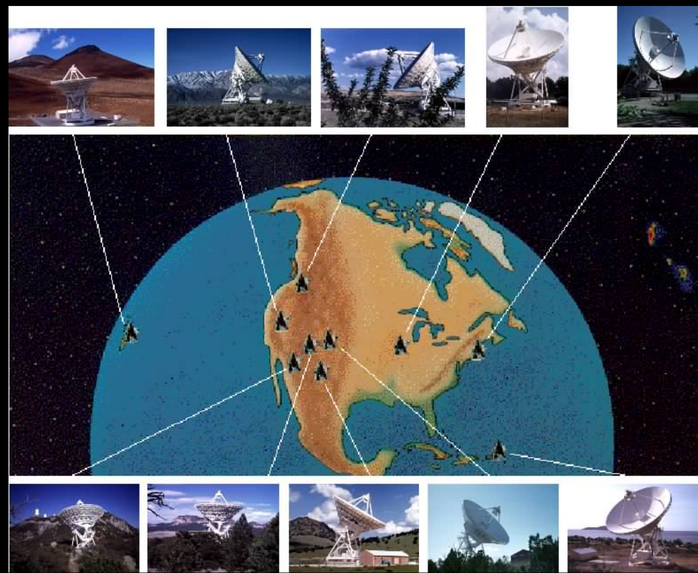


Distances from:

BESSEL

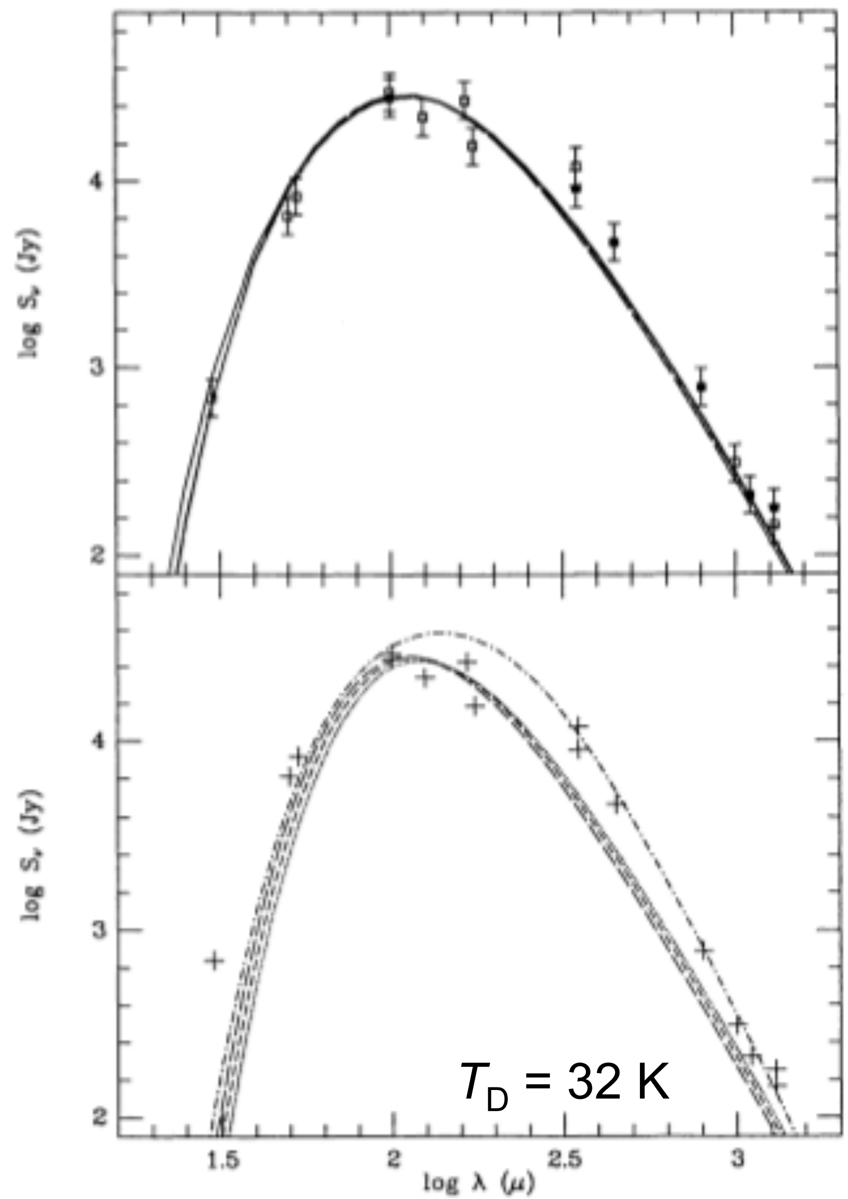
Bar and Spiral Structure Legacy Survey, a VLBA Key Science Project

http://bessel.vlbi-astrometry.org



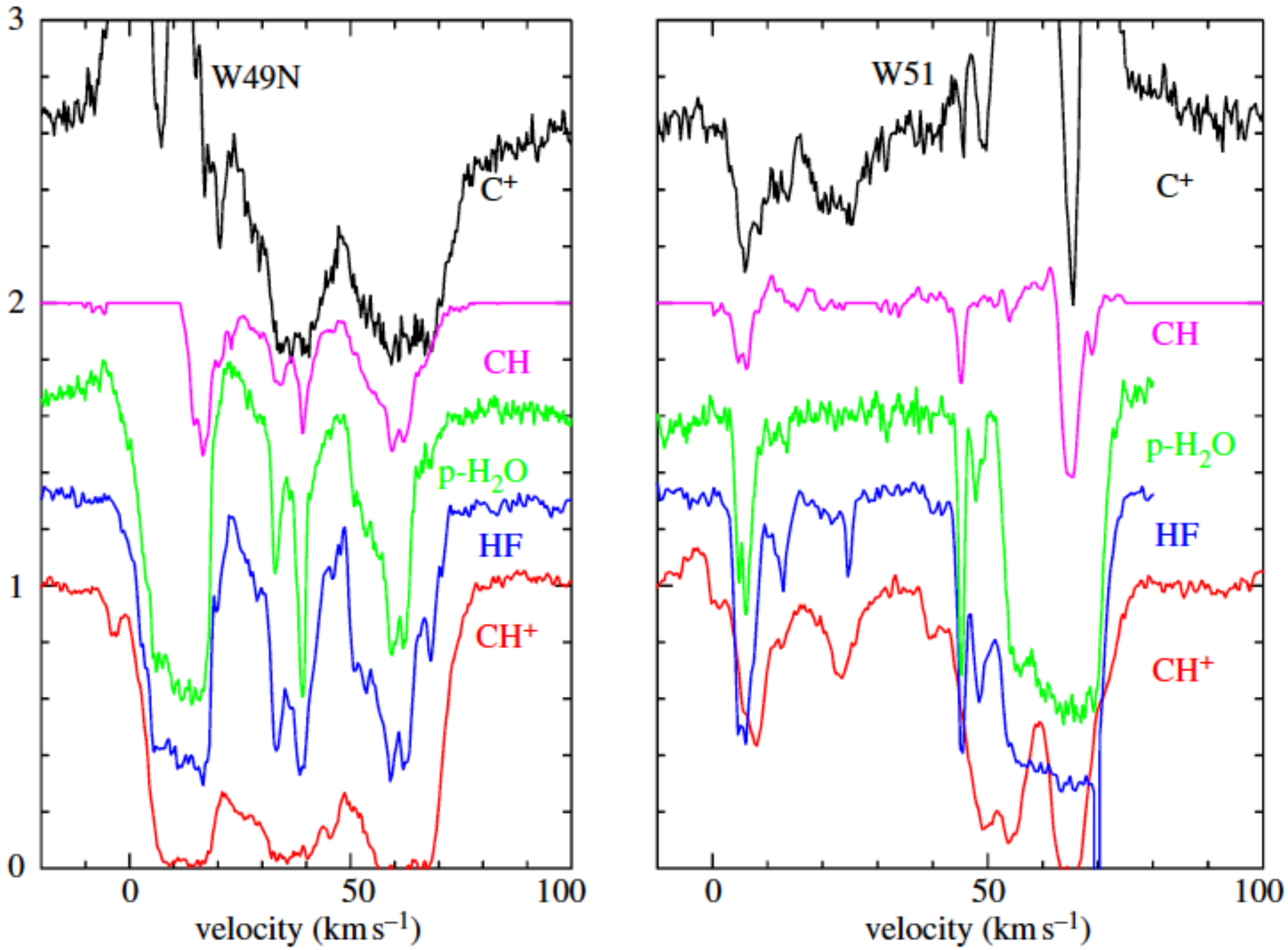
PI: Mark Reid (CfA)

The Background Sources:
Cold or Warm Dust from
Protostellar Condensations



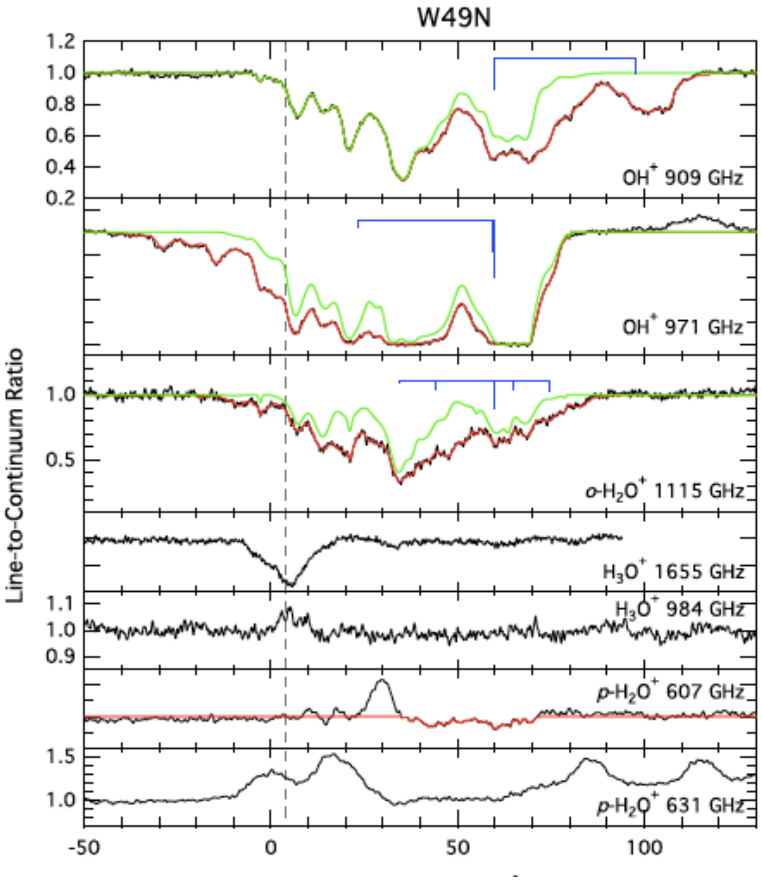
Sgr B2 – Lis & Goldsmith 1990

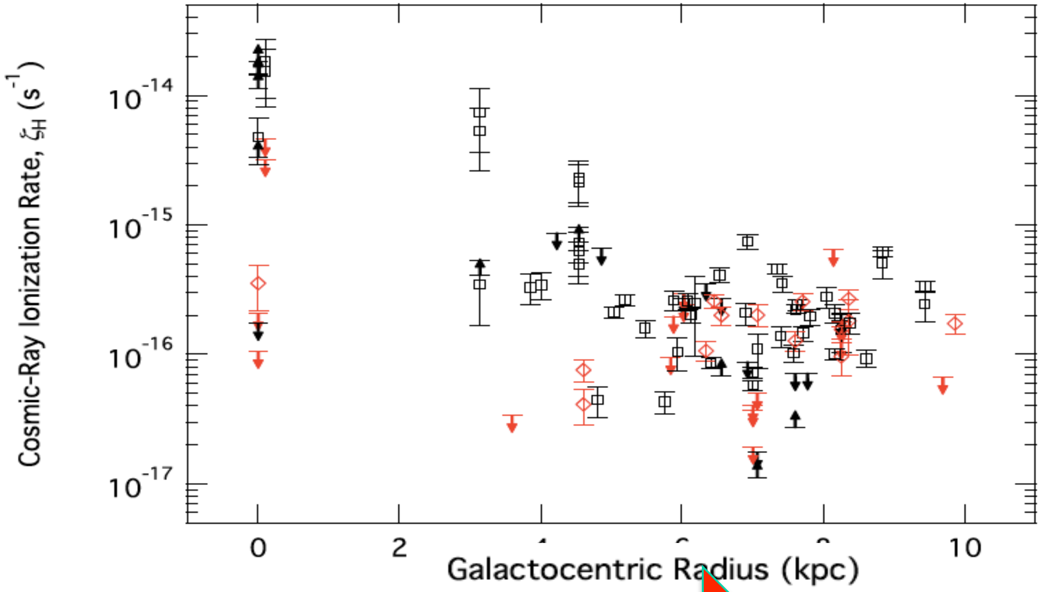
PRISMAS: PRobing Interstellar Molecules with Absorption Line Studies



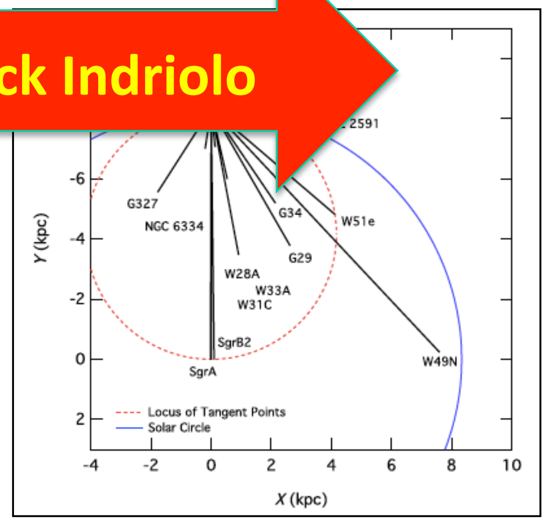
Compilation: Gerin et al. 2012

The cosmic ray ionization rate over the whole Galaxy





Talk by Nick Indriolo



$$\epsilon\zeta_{\rm H} = \frac{N({\rm OH^+})}{N({\rm H})} n_{\rm H} x_e \left[\frac{k_7}{N({\rm OH^+})/N({\rm H_2O^+}) - k_6/k_4} + k_5 \right]$$

Indriolo+ 2015

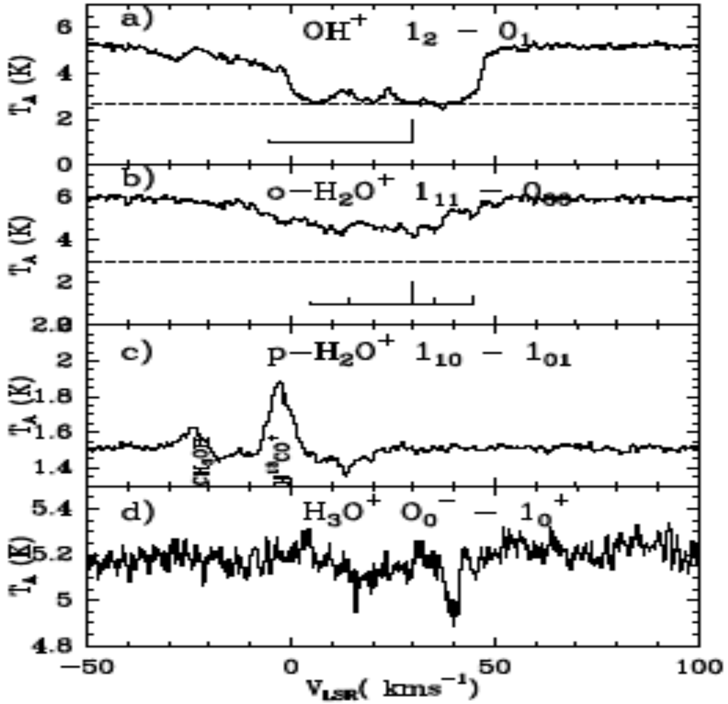
Interstellar OH^+, H_2O^+ and H_3O^+ along the sight-line to G10.6–0.4⋆,⋆⋆

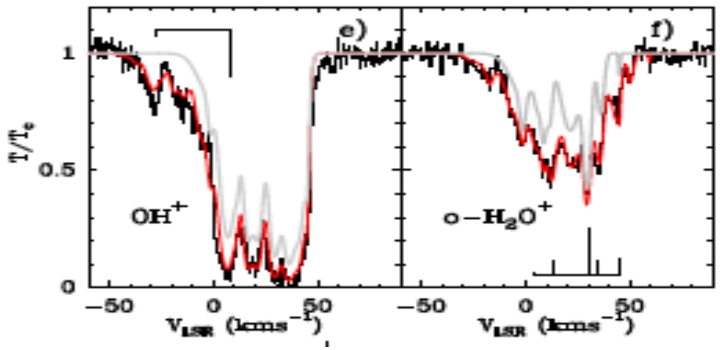
M. Gerin[1], M. De Luca[1], J. Black[2], J. R. Goicoechea[3], E. Herbst[4], D. A. Neufeld[5], E. Falgarone[1], B. Godard[1,8],

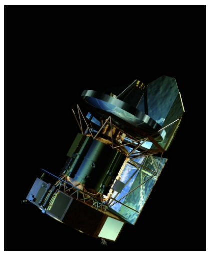
Table 1. Transition spectroscopic parameters.

Transition	Frequency MHz	Error MHz	E_l cm^{-1}	A $10^{-2}\,s^{-1}$	Ref.
$OH^+ N = 1-0$					
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	607207.0	20	20.9	0.60	2
H_3O^+					
$0_0^- - 1_0^+$	984711.9	0.3	5.1	2.3	3

References. 1, Müller et al. (2005) & CDMS; 2, Strahan et al. (1986), Ossenkopf et al. (2010); 3 Yu et al. (2009) & JPL catalog.

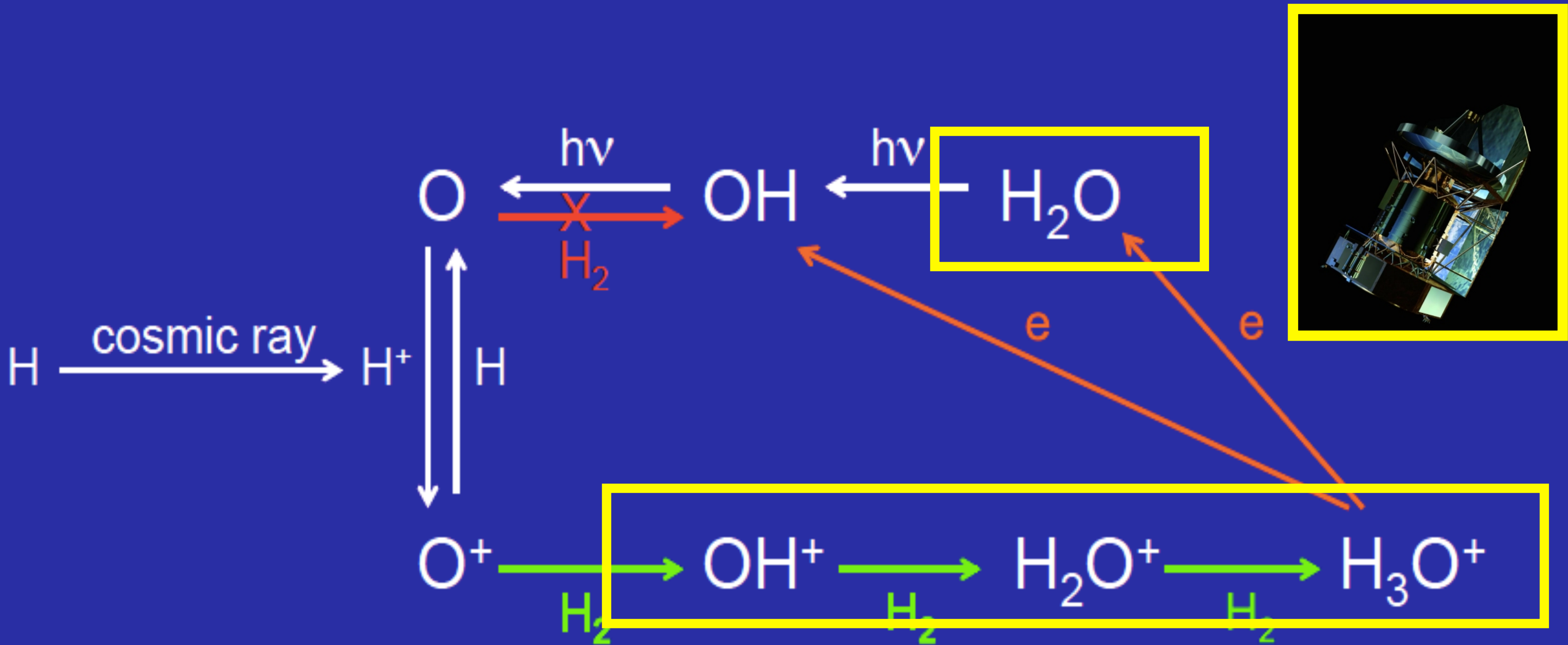






Chemistry of interstellar oxygen

- Chemistry is initiated by cosmic rays



D. Neufeld

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

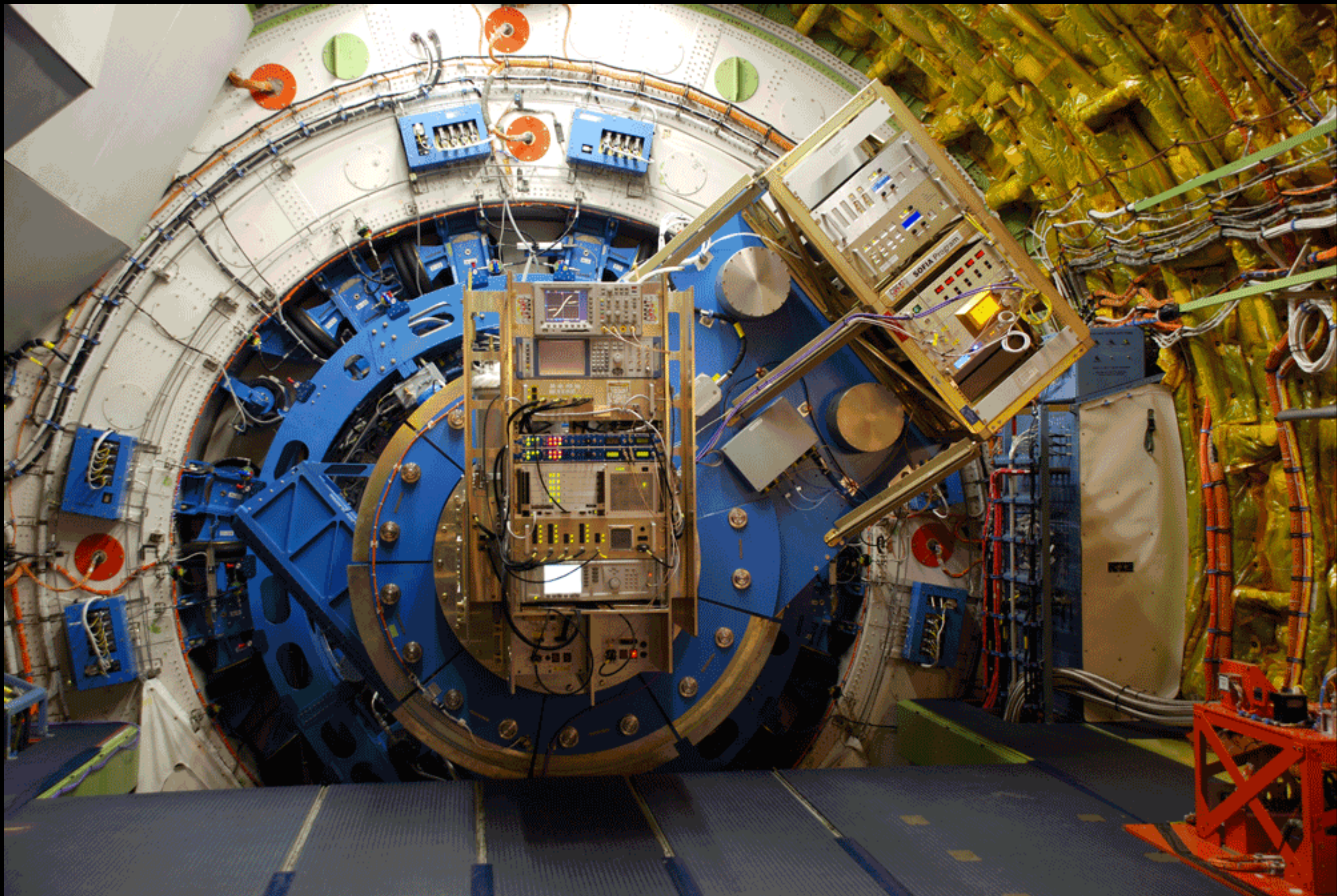
GREAT - the Consortium

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 spectrometer)
  - I. Camara, T. Klein (2.7 THz LO)
- Univ. zu Köln, KOSMA (1.4/1.9THz channels)
  - J. Stutzki (Co-PI)
  - U. Graf (1.4 &1.9THz LO, Optics)
  - K. Jacobs (HEB mixers 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)

GREAT constantly gets re-invented



Herschel/HIFI: 480–1250 and 10–1910 GHz

Mixer band	Frequency range	Mixer Element	Ma ci	Feed/coupling structure	Mixer Development Laboratory
1	480 – 640 GHz	SIS Nb-Al2O3-Nb	N	horn and	LERMA Paris, France
2	640 – 800 GHz	SIS NbTiN-Al2O3-Nb		d	KOSMA ln, Germany
3	800 – 960 GHz	SIS NbTiN-Al2O3-Nb			lands
4	960 – 1120 GHz	SIS NbTiN-Al2O3-Nb			
5	1120 – 1250 GHz	SIS NbTiN-AlN-NbTi			
6L	1410 – 1703 GHz	HEB NbN phonon cooled			
6H	1703 – 1910 GHz	HEB NbN phonon cooled	Al co-planar		

SOFIA/GREAT receivers

- out-perform HIFI in every metric (T_{RX}, bandwidth, multiplexing)
- Modular approach
- Everything but H_2O

SOFIA/GREAT: 1.25 –2.5 THz + 4.7 THz

Channel	Frequencies (THz)	Lines of Interest
low-frequency L1 a,b	1.25-1.50 (single pixel)	[NII], CO series, OD,HCN,H_2D^+
low-frequency L2	1.81-1.91 (single pixel)	NH_3,OH,CO(16-15),[CII]
mid-frequency M a,b	2.5 – 2.7 (single pixel)	OH($^2\Pi_{3/2}$),HD
high-frequency H	4.7 (single pixel)	[OI]
upGREAT Low Frequency Array (LFA)	1.9 – 2.5 (14 pixels)	OH lines, [CII],CO series, [OI]
upGREAT High Frequency Array (HFA)	4.7 (7 pixels)	[OI]

http://www3.mpifr-bonn.mpg.de/div/submmtech/heterodyne/upgreat/upgreatmain.html

Max-Planck-Institut
für Radioastronomie

FFTS4G @ upGREAT / SOFIA

digital Signal Processing
dSP

upGREAT
extension of GREAT into heterodyne arrays for SOFIA

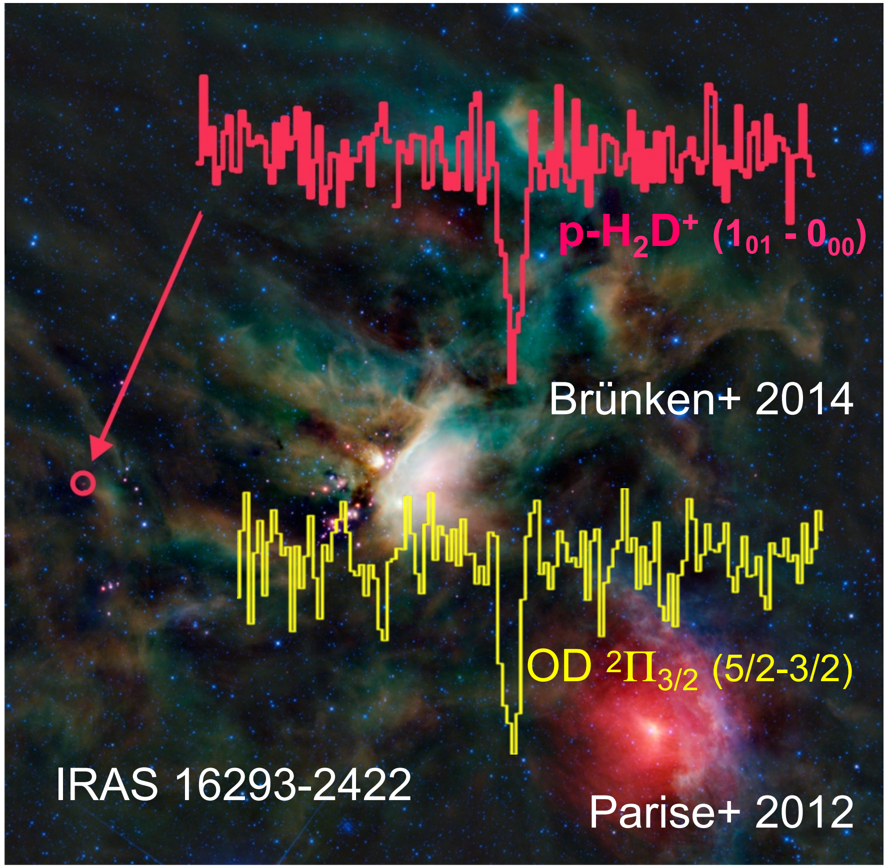
FFTS4G:

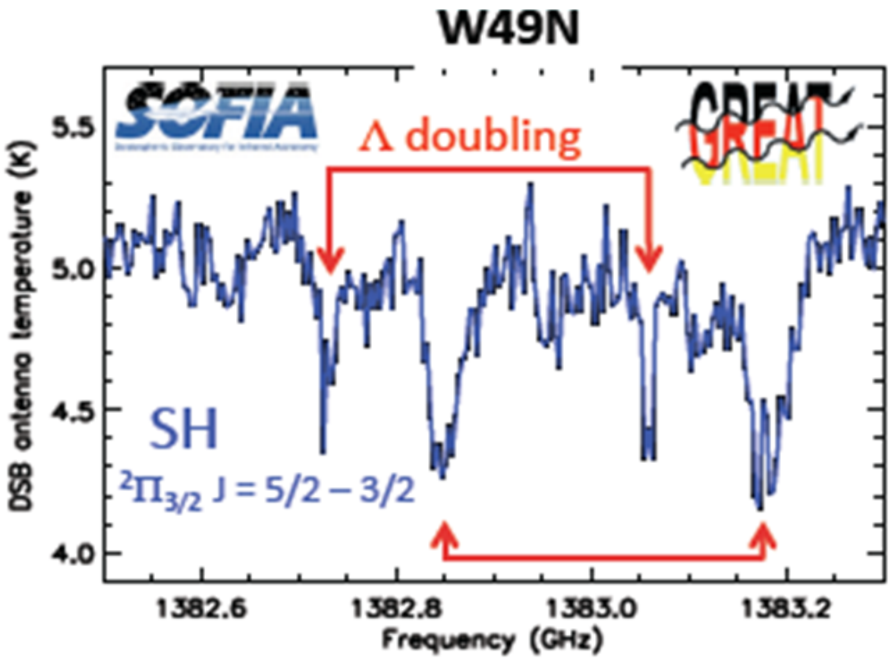
- *16 x FFTS4G boards*
- *64 GHz total bandwidth*
- *512k spectral channels*
- *142 kHz spectral resolution*

IF-Processor

New light hydrides with SOFIA

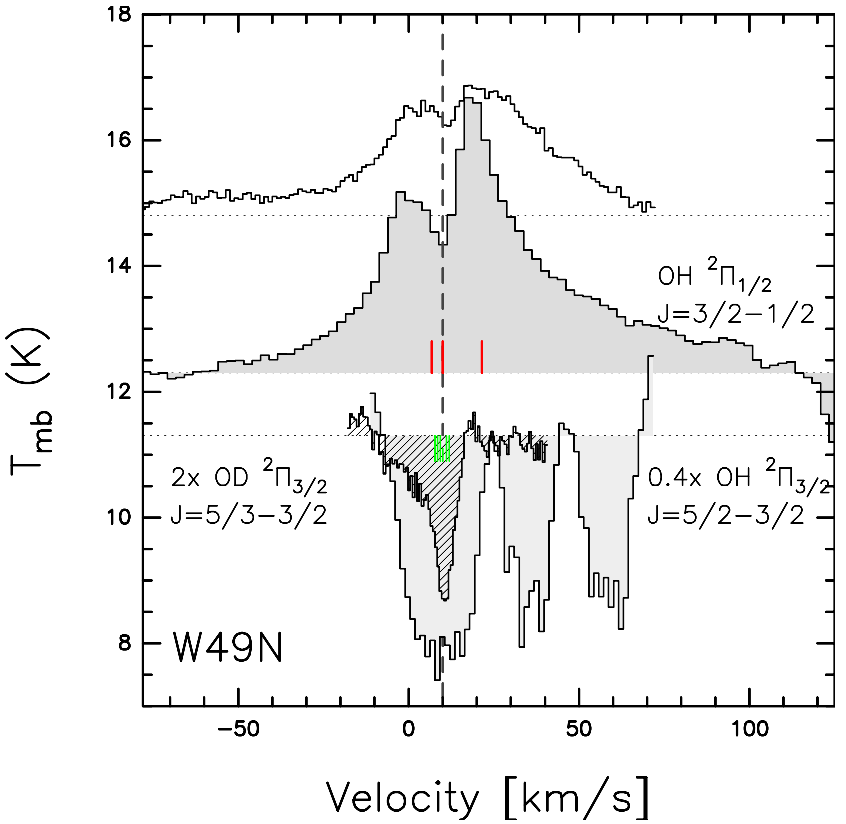
Searches for light hydrides have been very succesful: SH, OD, p-H_2D^+

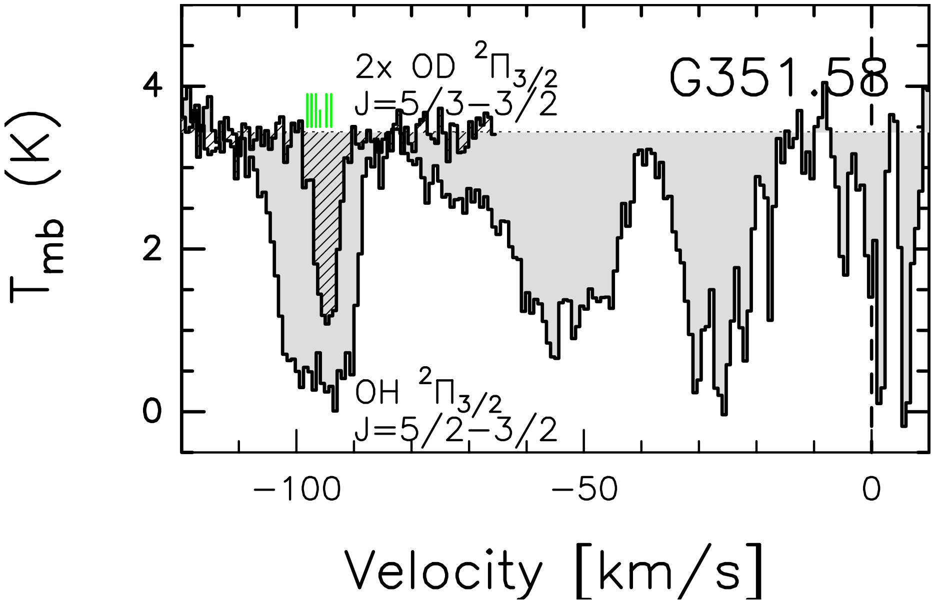




Neufeld+ 2012

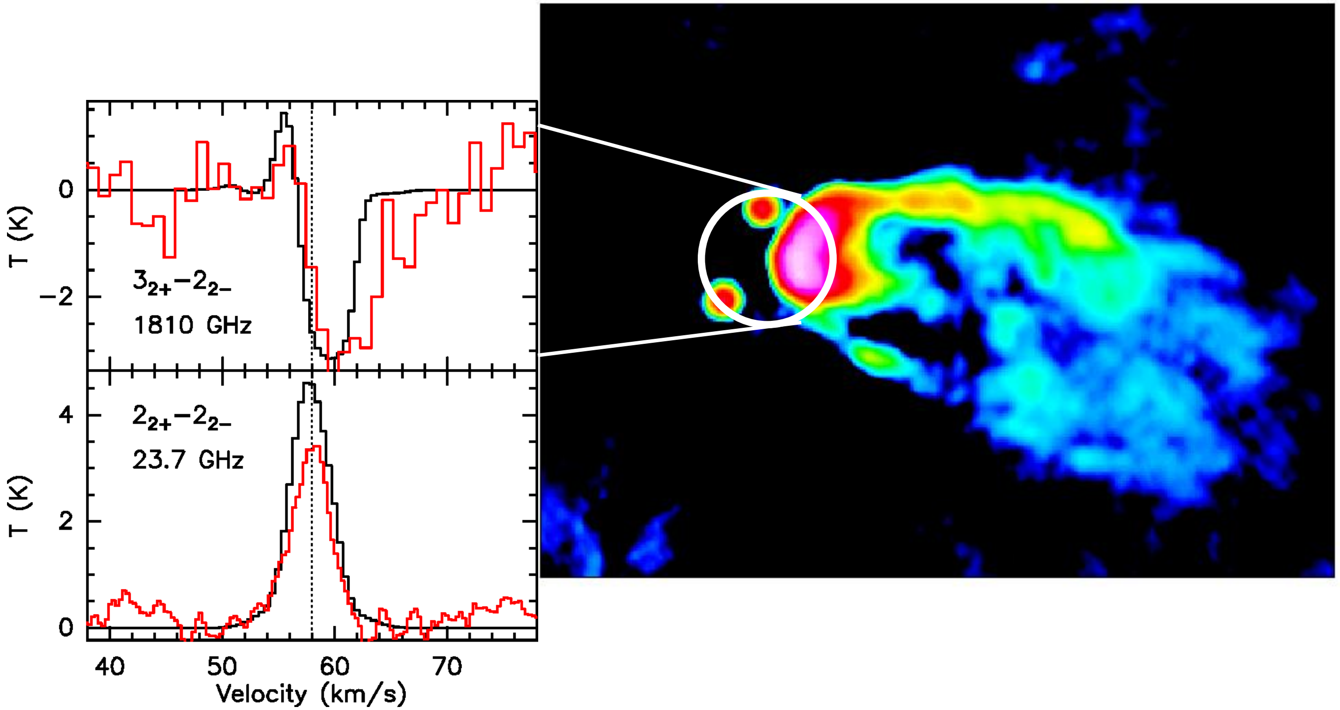
OD resides in the envelopes of massive star-forming regions





Menten, Csengeri, Wiesemeyer, Wyrowski, Güsten

Ammonia/1.8 THz: Probing infall



→ Mass infall rates:
a few x 10^{-3} $M_{\odot}$/yr

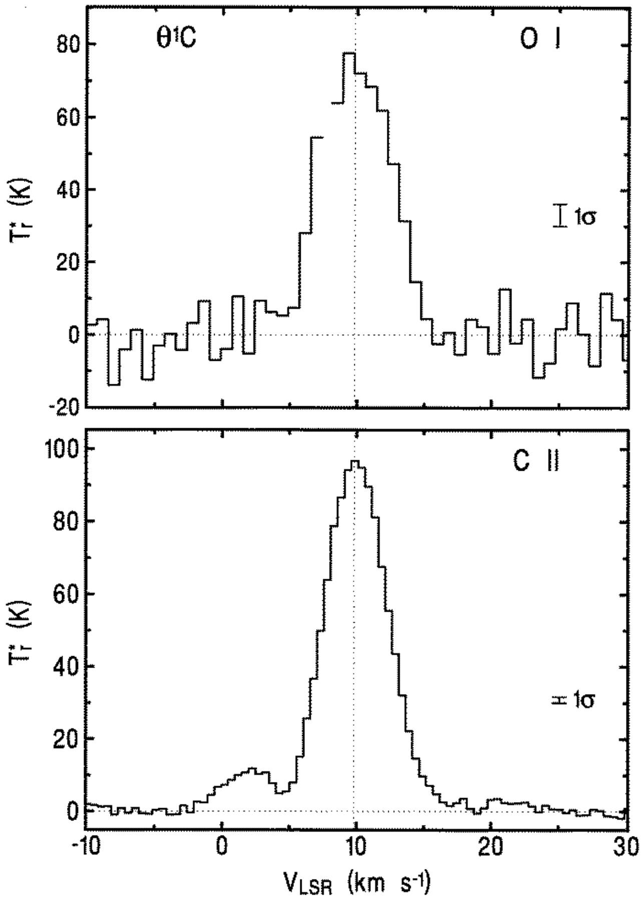
Wyrowski + 2012, 2016
See also Hajigholi+ 2016 (Herschel/HIFI)

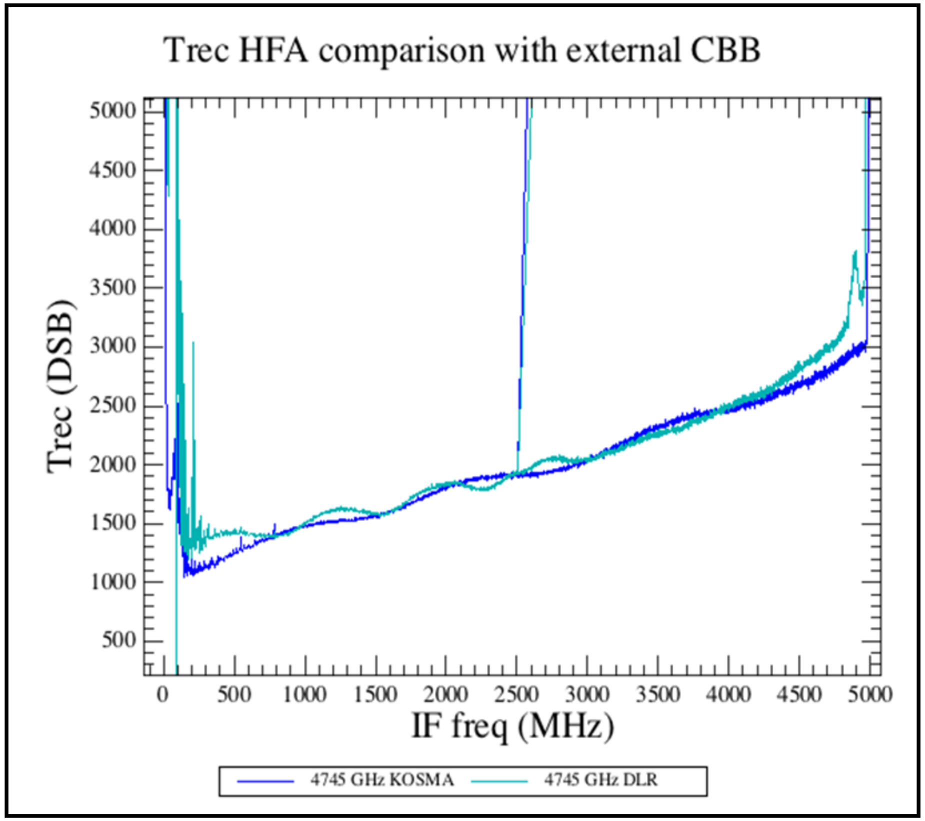
The 4.75 THz (63 µm) OI ground-state fine structure line

First H/D detection in M42

- T_{sys}(DSB) = 70000 K

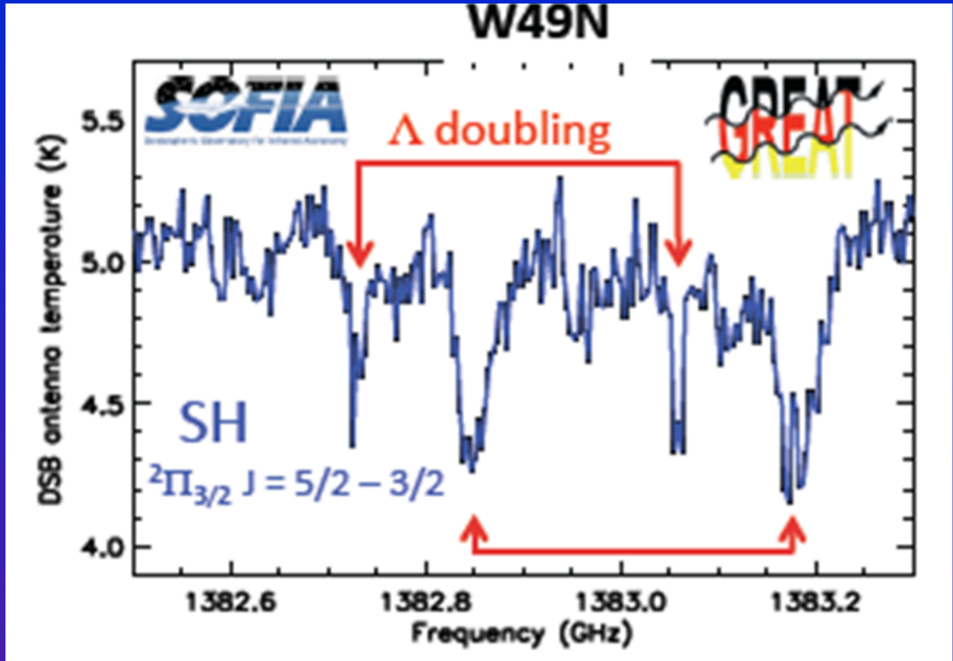
Boreiko & Betz 1996



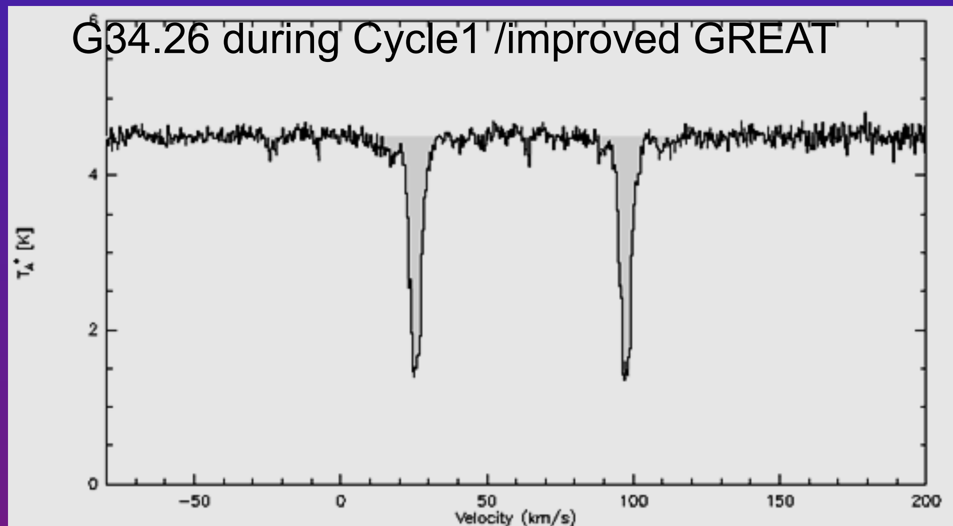


2013:

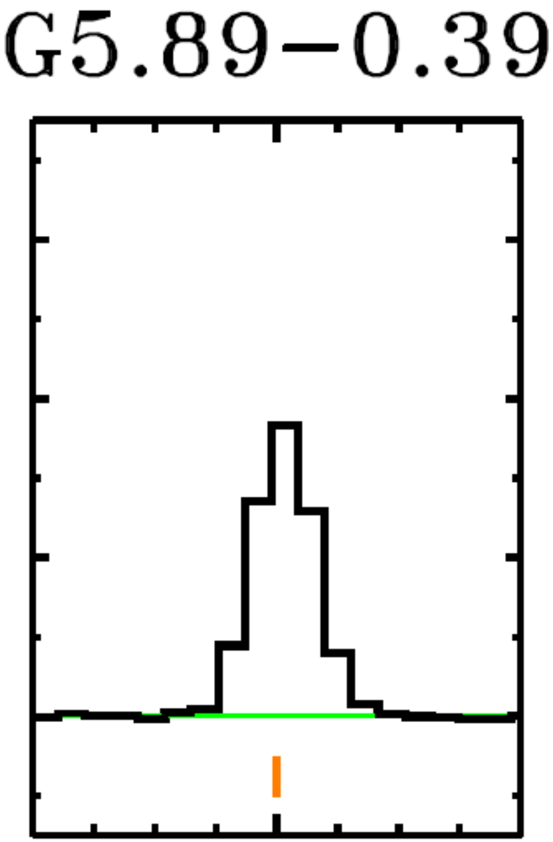
- T_{sys}(DSB, KOSMA, Jacobs) ≈ T_{sys}(DSB, DLS-Pf, Hübers) = 1500 K



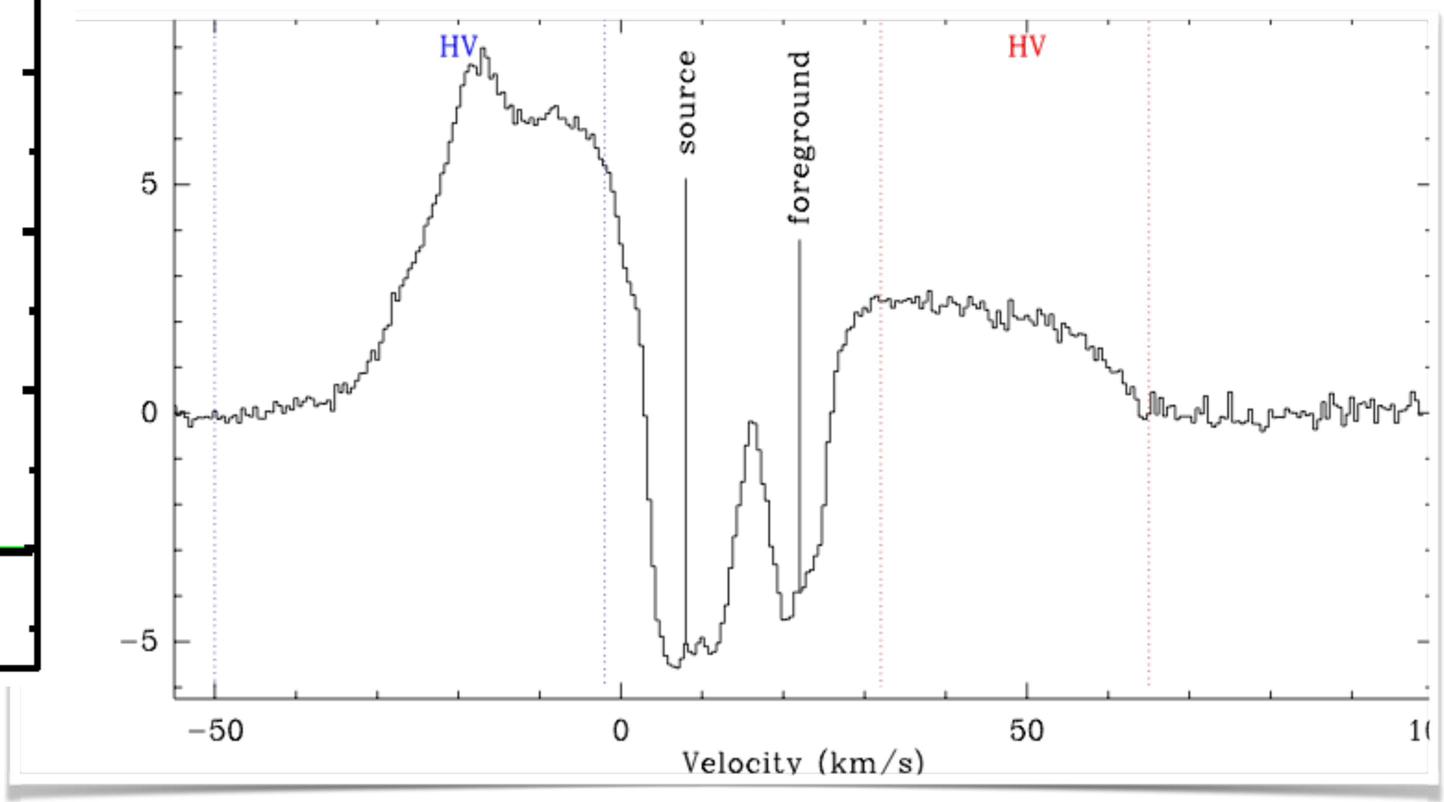
Neufeld et al. 2012



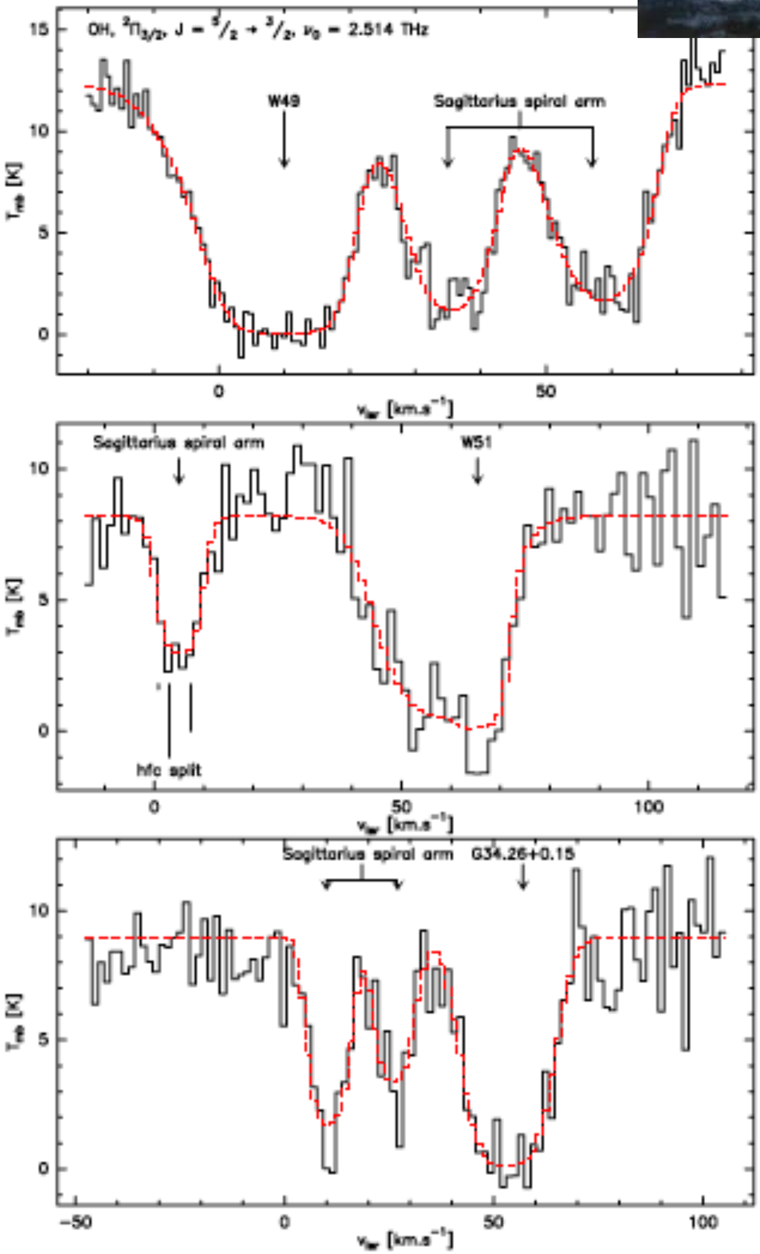
[OI] 63 μm: from PACS to GREAT



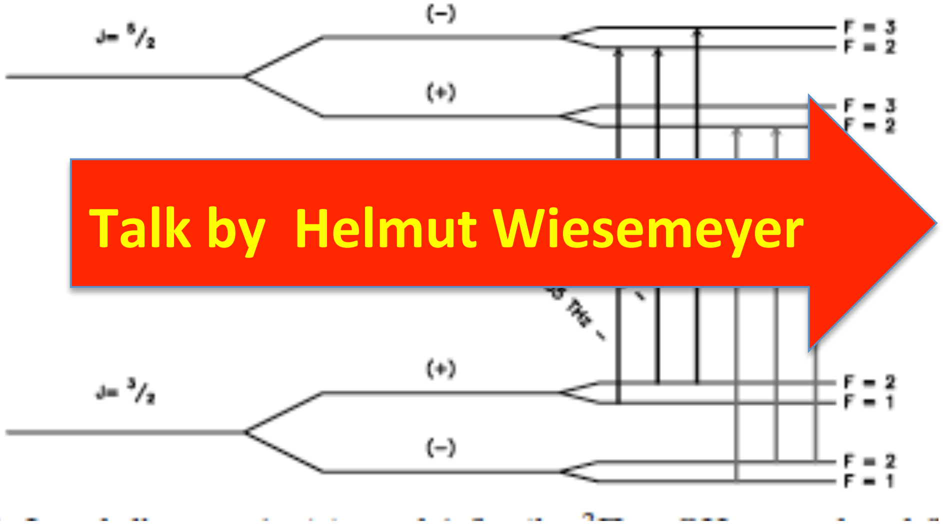
Karska+2013



Leurini+2015



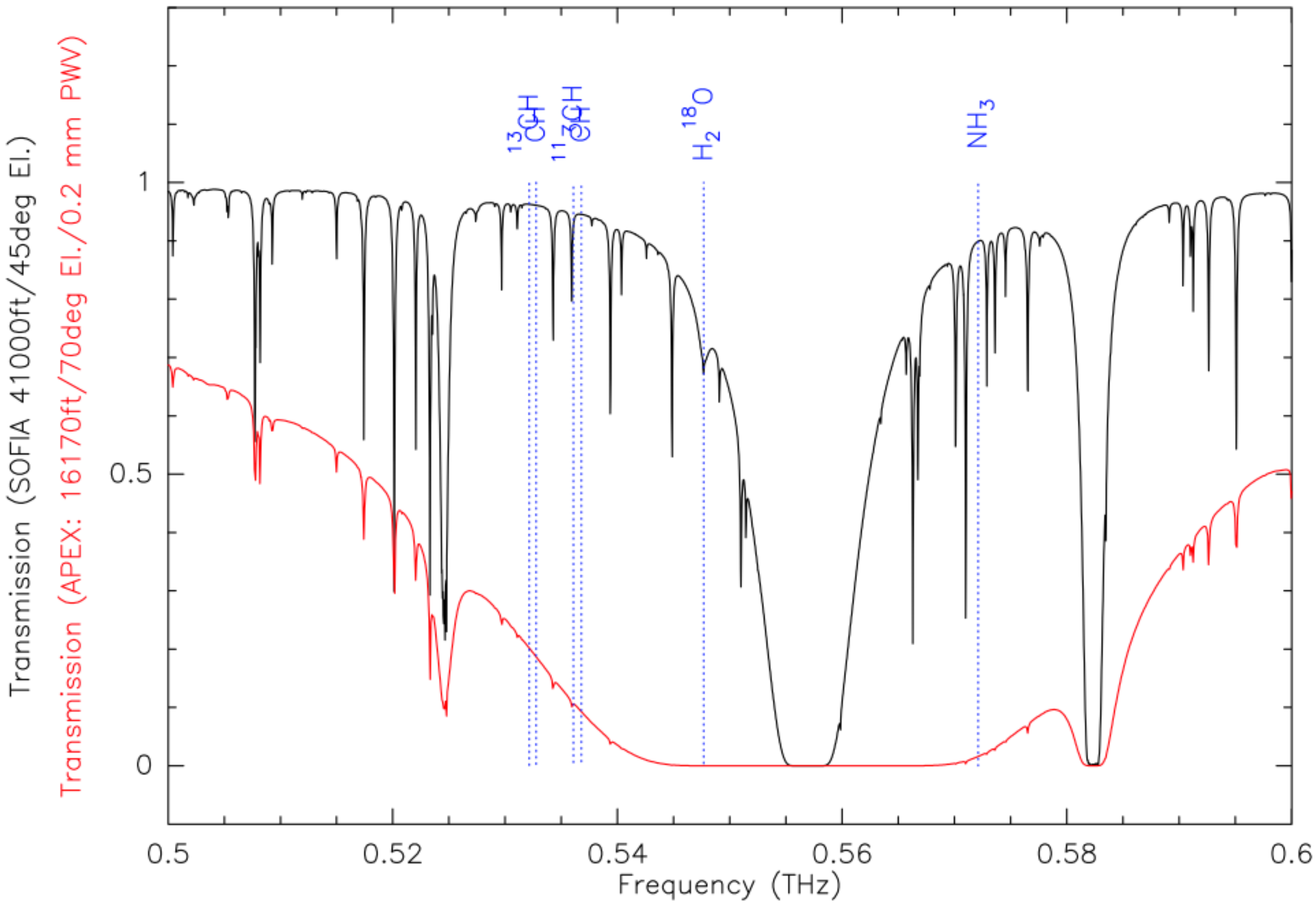
Transition	Frequency [GHz][a]	A_E [s^{-1}][b]
OH, $^2\Pi_{3/2}, J = 5/2 \leftarrow 3/2$		
$F = 2^- \leftarrow 2^+$	2514.298092	0.0137
$F = 3^- \leftarrow 2^+$	2514.316386	0.1368
$F = 2^- \leftarrow 1^+$	2514.353165	0.1231
^{18}OH, $^2\Pi_{3/2}, J = 5/2 \leftarrow 3/2$		
$F = 2^+ \leftarrow 2^-$	2494.68092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



Talk by Helmut Wiesemeyer

Wiesemeyer et al. 2012

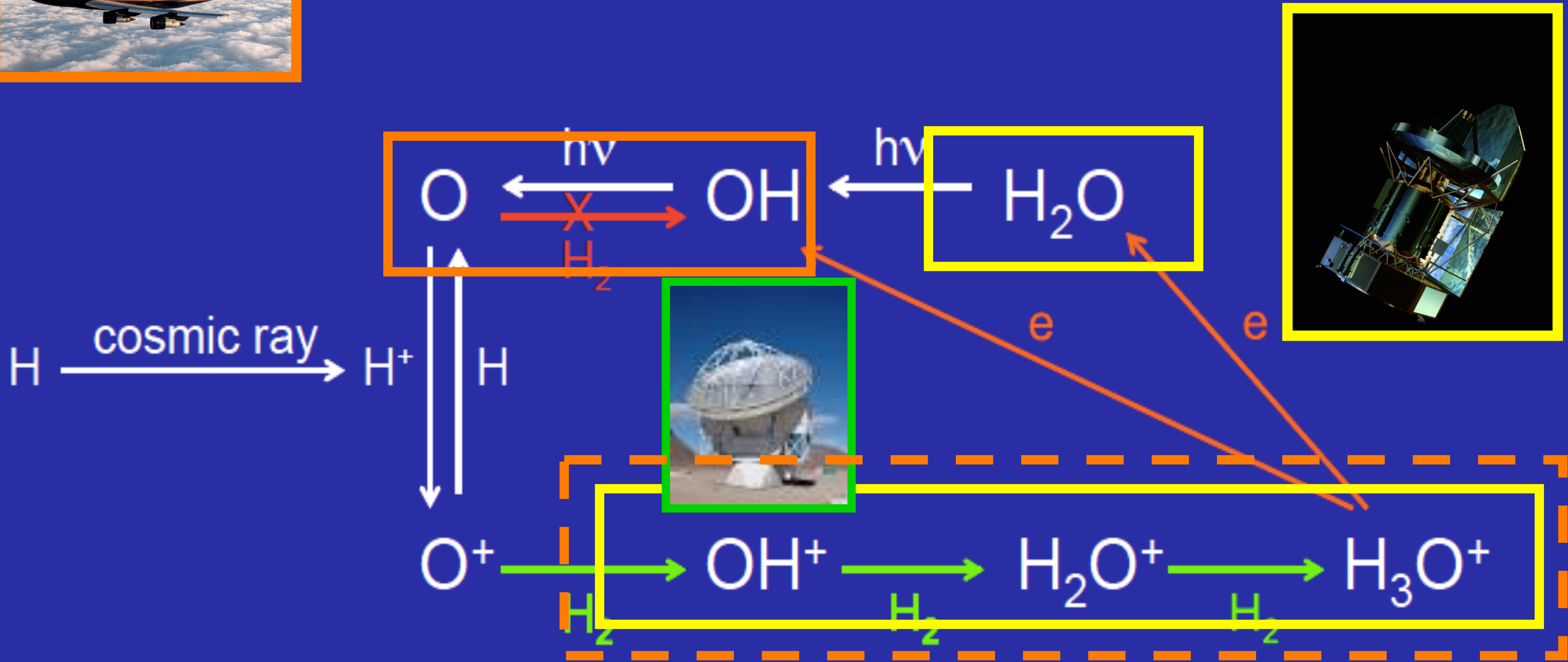
4GREAT will increase SOFIA's hydride coverage



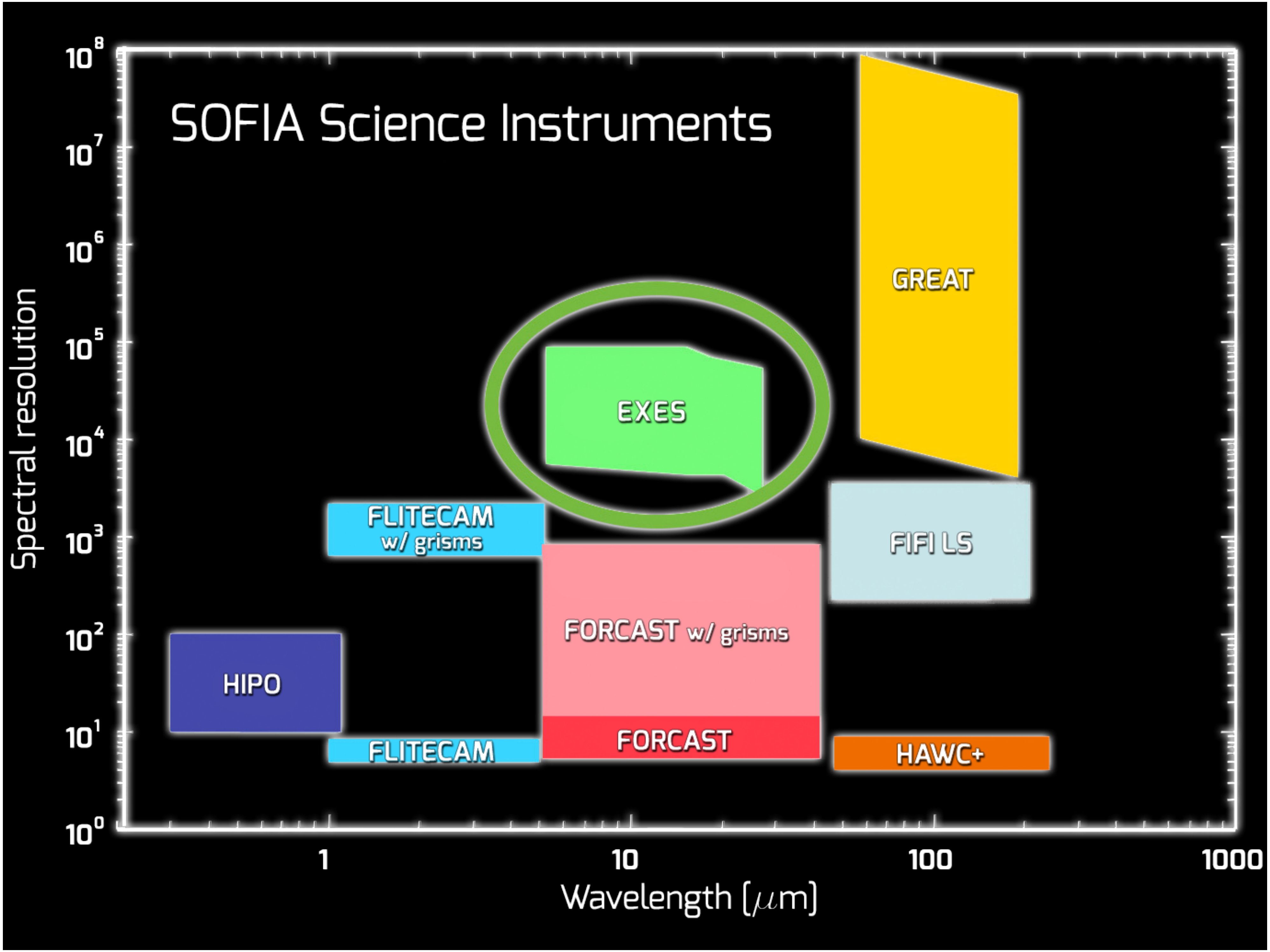
+ p-H_2O^+ 606/607 GHz

Chemistry of interstellar oxygen

mistry is initiated by cosmic rays

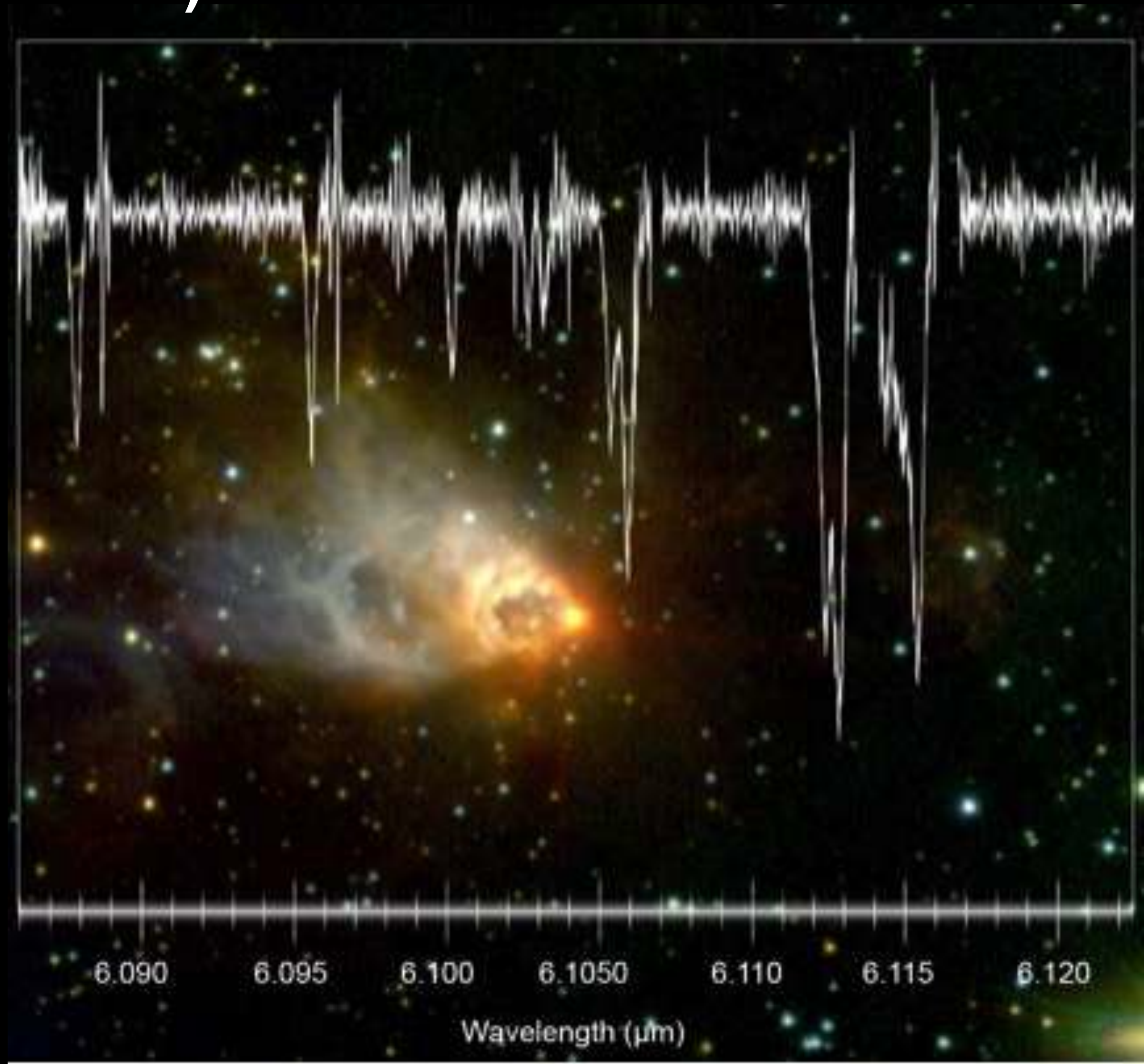


D. Neufeld

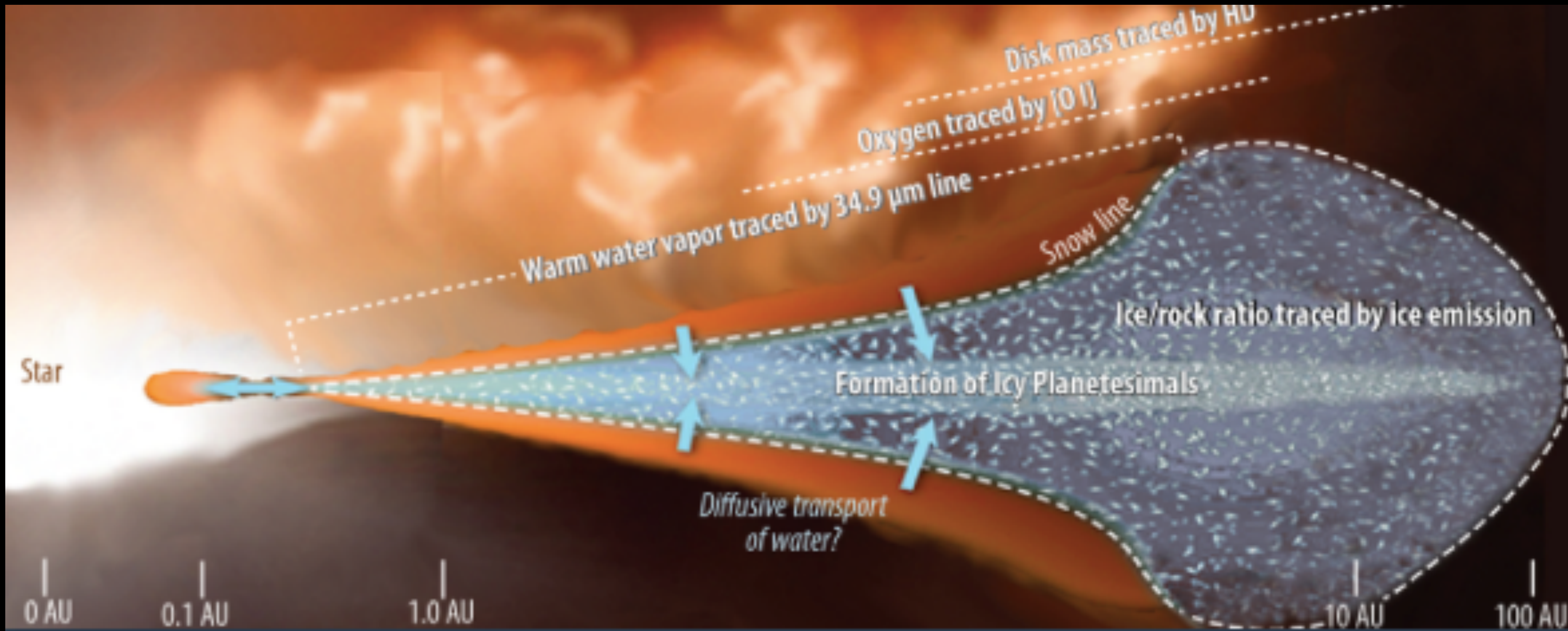


SOFIA Science Instruments
Spectral resolution
Wavelength [μm]
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
1
10
100
1000
GREAT
EXES
FLITECAM w/ grisms
FIFI LS
FORCAST w/ grisms
HIPO
FLITECAM
FORCAST
HAWC+

Hot (> 600 K) water in AFGL 2591



SOFIA/EXES   Indriolo+2015



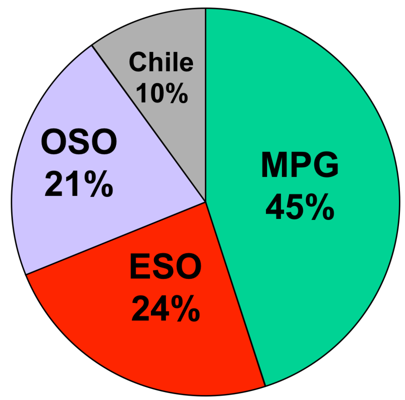
High Resolution Mid-InfrarEd Spectrometer (HIRMES)

Talk by K. Pontoppidan

The Atacama Pathfinder Experiment (APEX)

Built and operated by

• Max-Planck-Institut fur Radioastronomie
• Onsala Space Observatory
• European Southern Observ[atory]

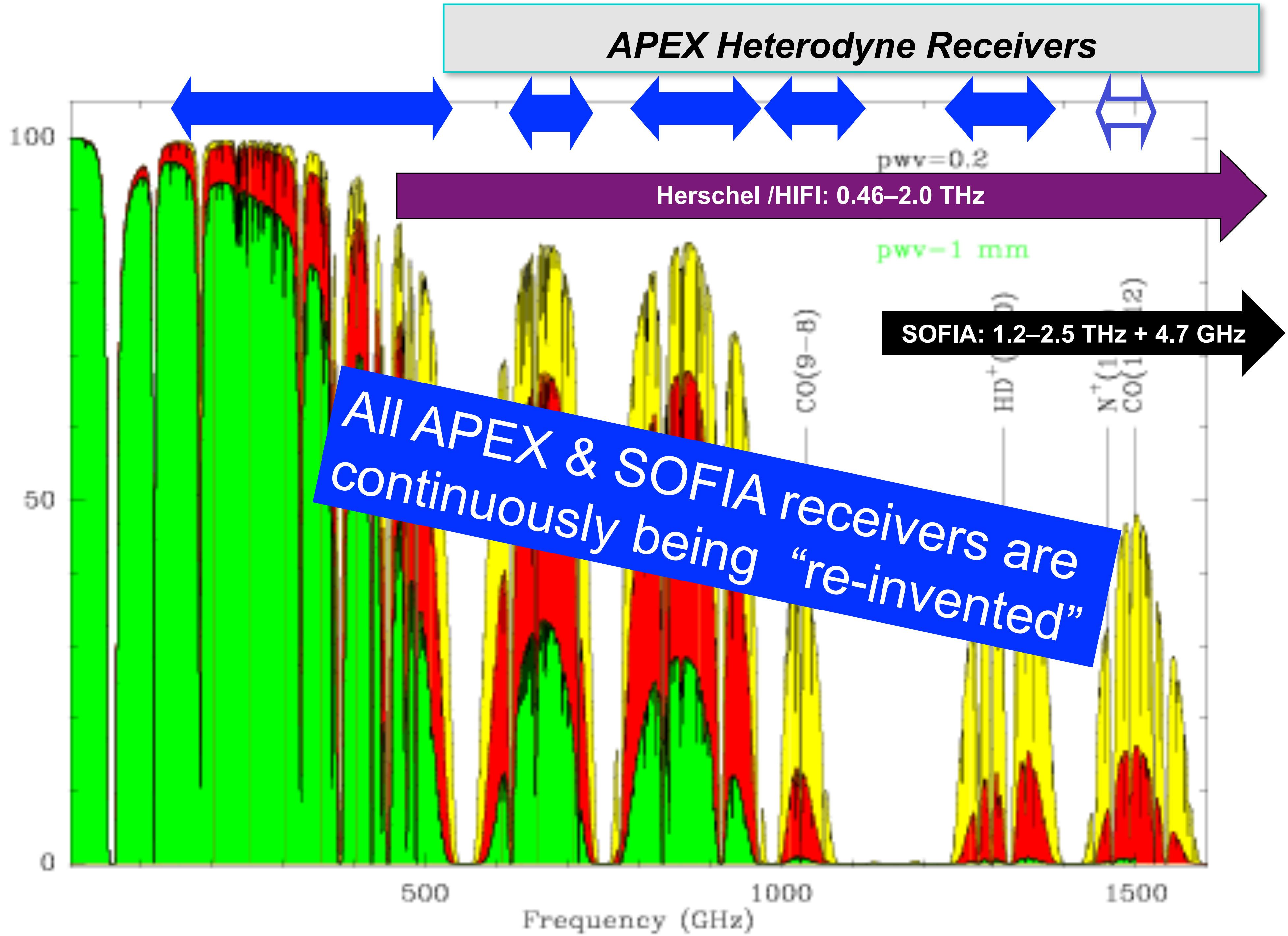


on

Llano de Chajnantor (Chile)
Longitude: 67° 45′ 33.2″ W
Latitude: 23° 00′ 20.7″ S
Altitude: 5098.0 m

- ∅ 12 m
- λ = 200 μm – 2 mm
- 15 μm rms surface accuracy
- PI and facility instruments: H/D RXs cover complete (accessible) frequency range from from 160–1100 GHz
- In operation since July 2005 / Just extended until 2022

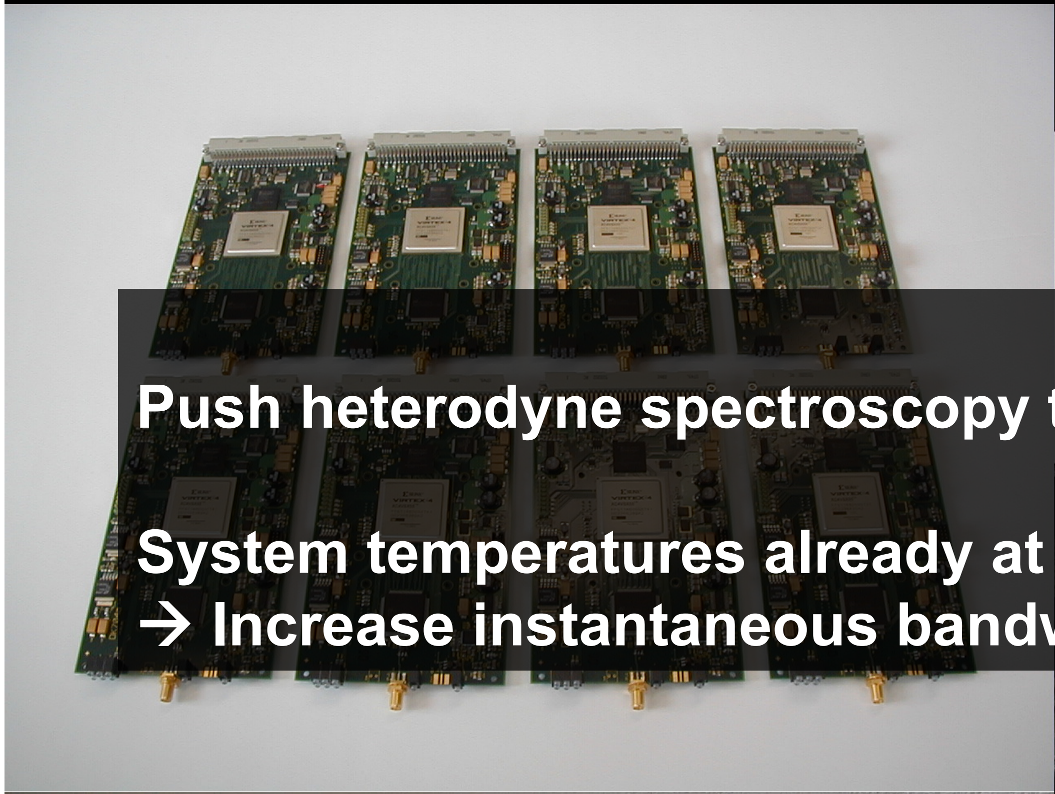
http://www.mpifr-bonn.mpg.de/div/mm/apex/

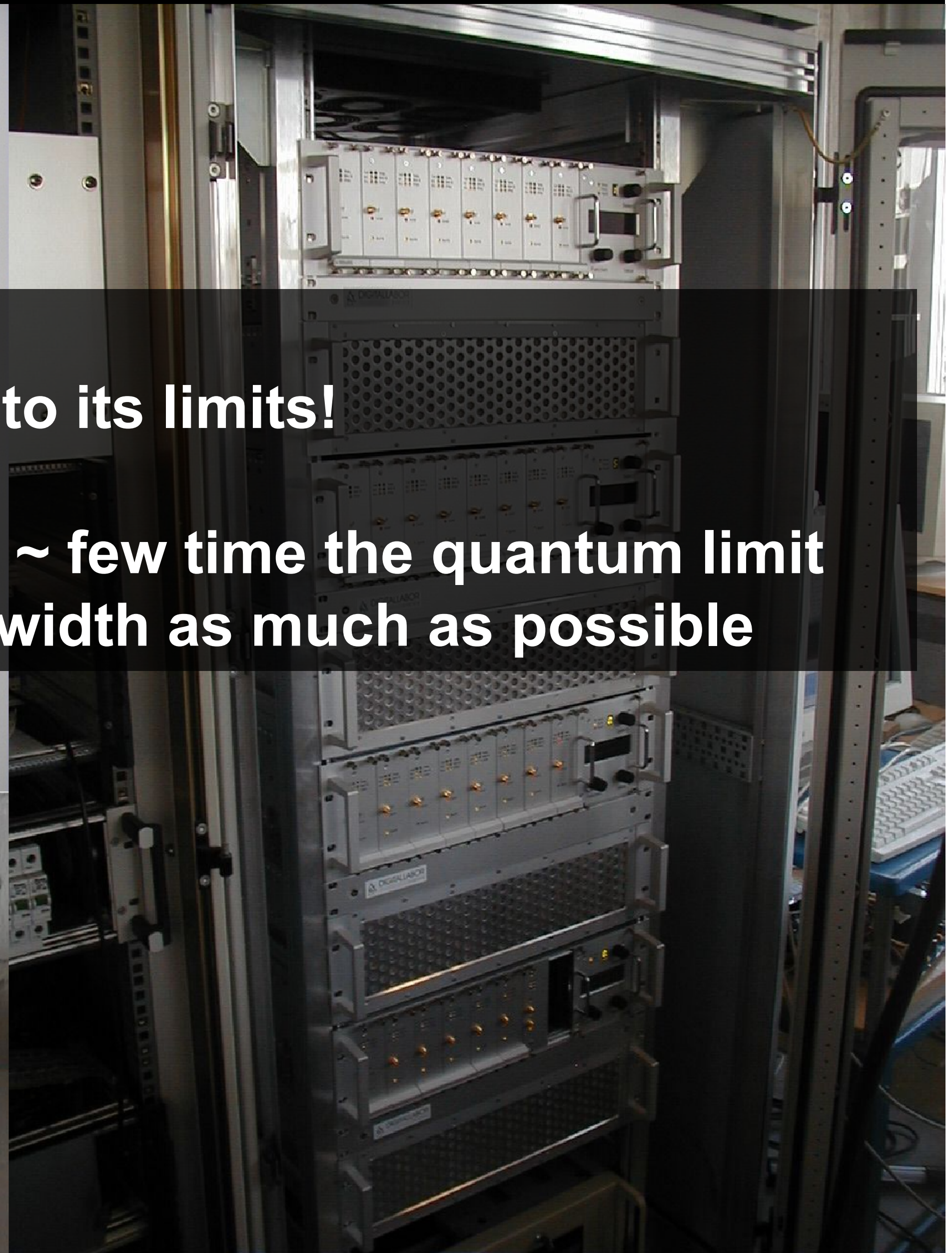

APEX Heterodyne Receivers
Herschel /HIFI: 0.46–2.0 THz
SOFIA: 1.2–2.5 THz + 4.7 GHz
All APEX & SOFIA receivers are continuously being "re-invented"
pwv=0.2
pwv=1 mm
CO(9–8)
100
50
0
500
1000
1500
Frequency (GHz)

Massive MPIfR digital electronic development

APEX Array Fast Fourier Transform Spectrometer: 4 × 8 × 1.5 GHz = 48 GHz/262144 channels

Massive MPIfR digital electronic development





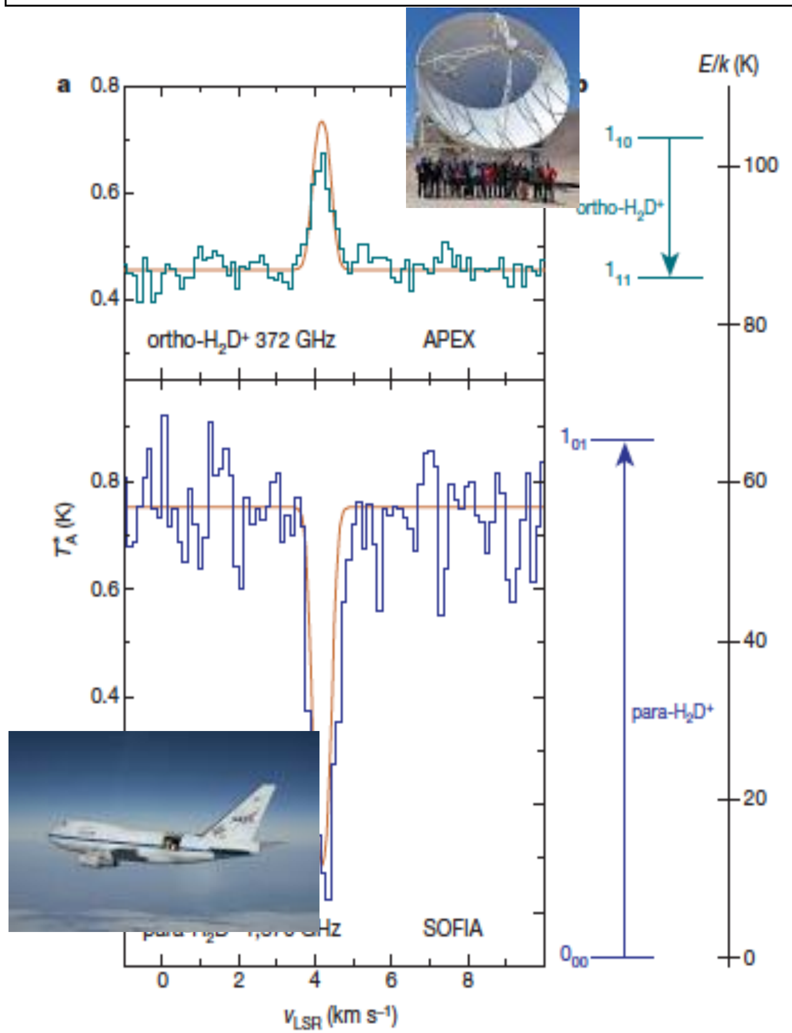
Push heterodyne spectroscopy to its limits!

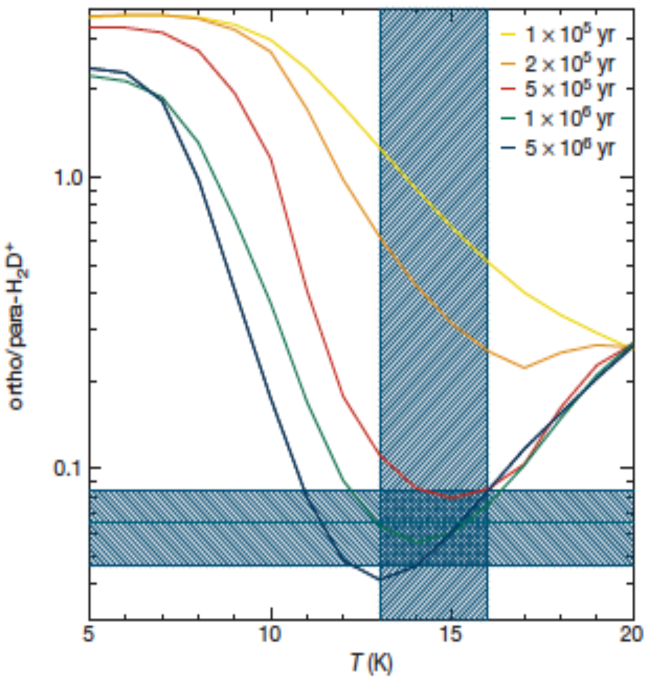
System temperatures already at ~ few time the quantum limit
→ Increase instantaneous bandwidth as much as possible

APEX Array Fast Fourier Transform Spectrometer: 4 × 8 × 1.5 GHz = 48 GHz/262144 channels

H_2D^+ observations give an age of at least one million years for a cloud core forming Sun-like stars

Sandra Brünken[1], Olli Sipilä[2,3], Edward T. Chambers[1], Jorma Harju[2], Paola Caselli[3,4], Oskar Asvany[1], Cornelia E. Honingh[1], Tomasz Kamiński[5], Karl M. Menten[5], Jürgen Stutzki[1] & Stephan Schlemmer[1]

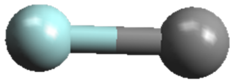




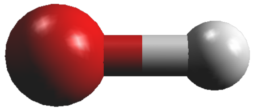
Talk by Paola Caselli

Nature, 516, 219 (2014)

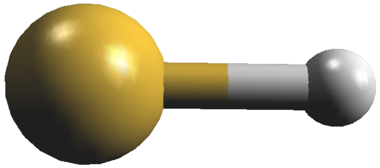
APEX Molecules



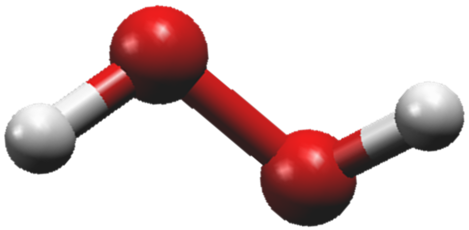
CF^+ — Neufeld et al. 2006



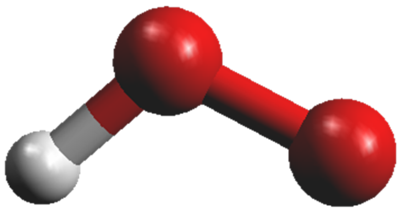
OH^+ — Wyrowski et al. 2010



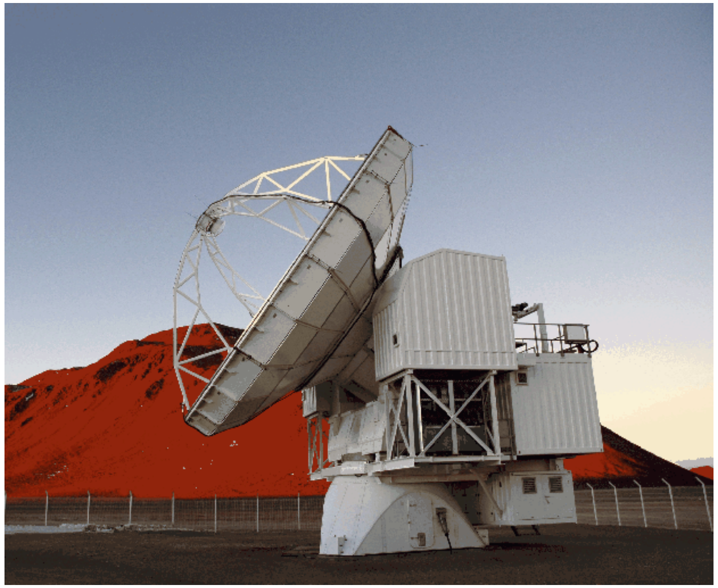
SH^+ — Menten et al. 2011



H_2O_2 — Bergman et al. 2011

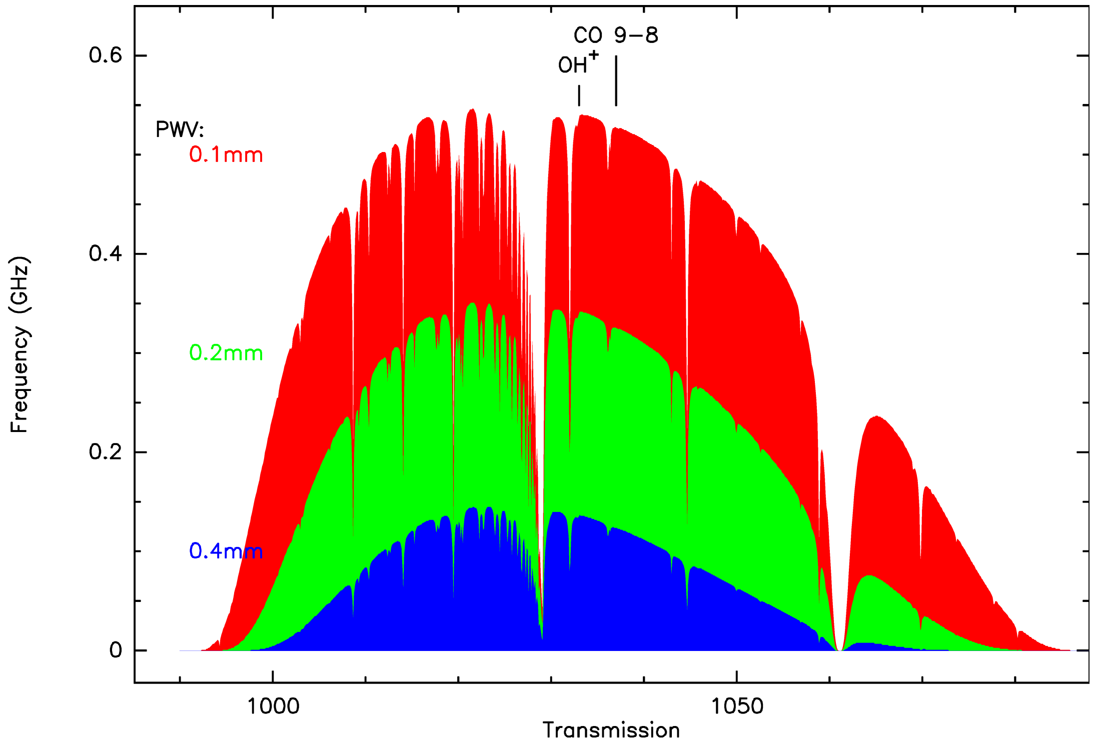


HO_2 — Parise al. 2012

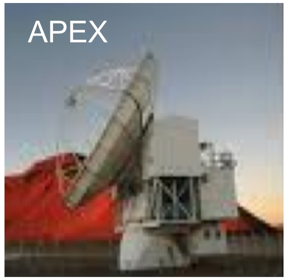


OH^+ towards strong submm sources

- Study distribution using continuum from MSFRs ras background candle
- strongest OH+ fine structure line @ 1033GHz with MPIfR THz RX (Leinz +2010)

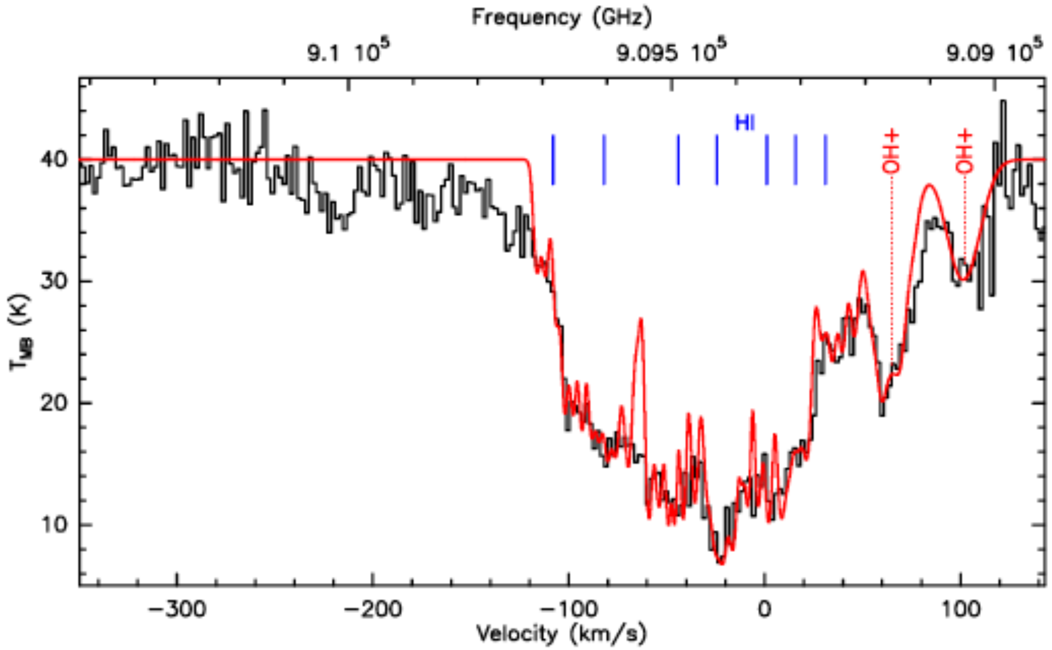


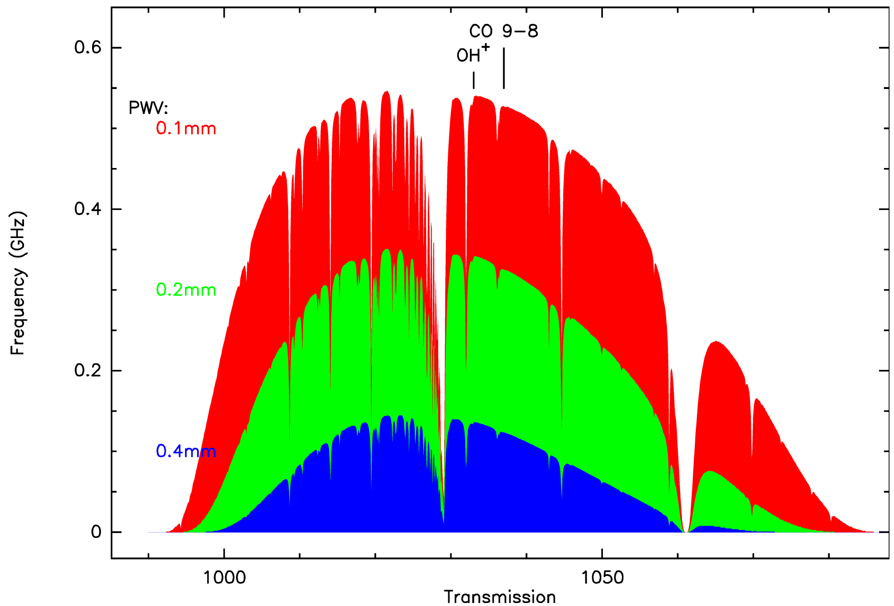
Wyrowski+ in prep.

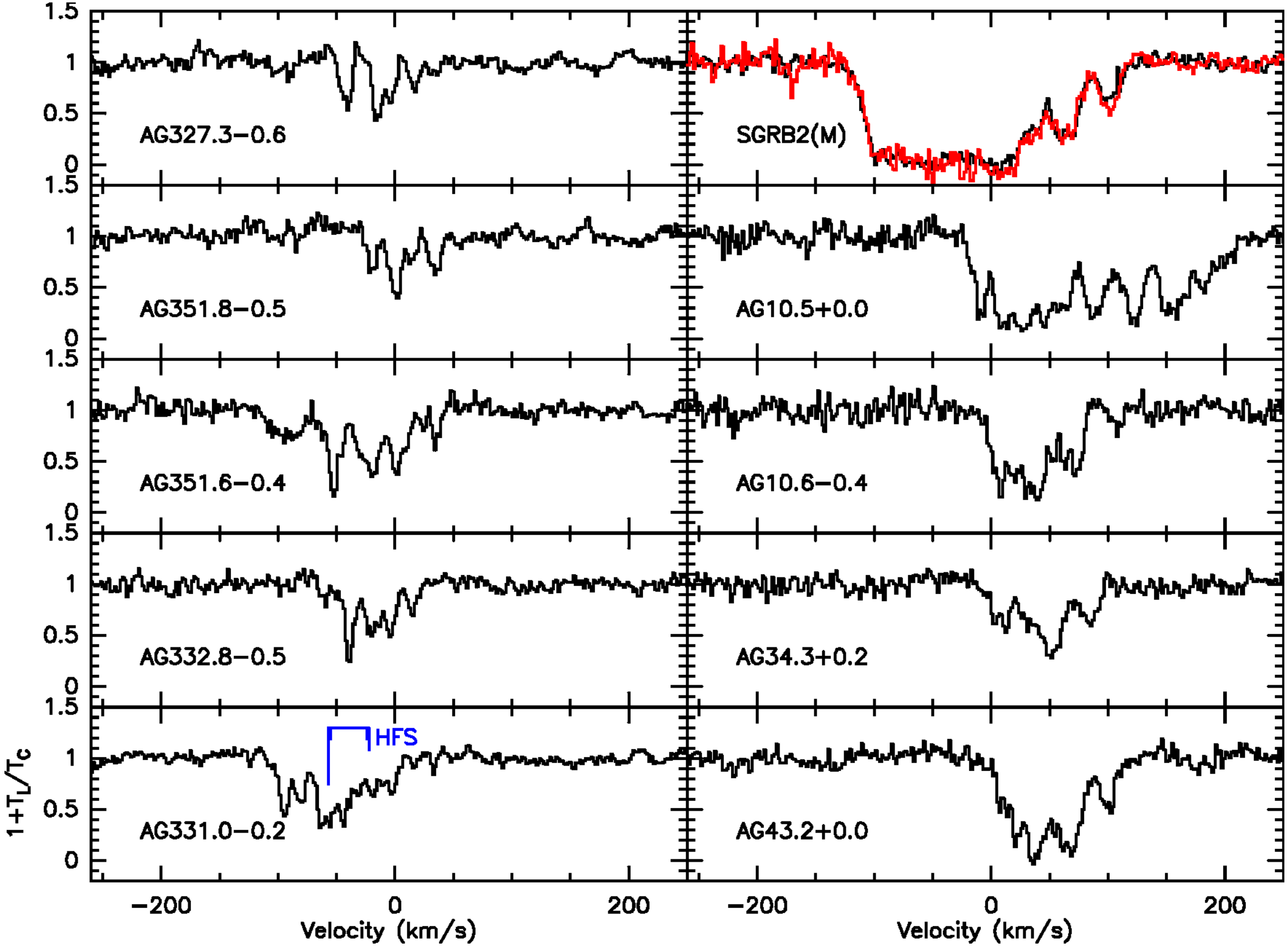


First interstellar detection of OH^+

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

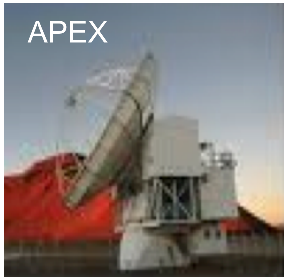


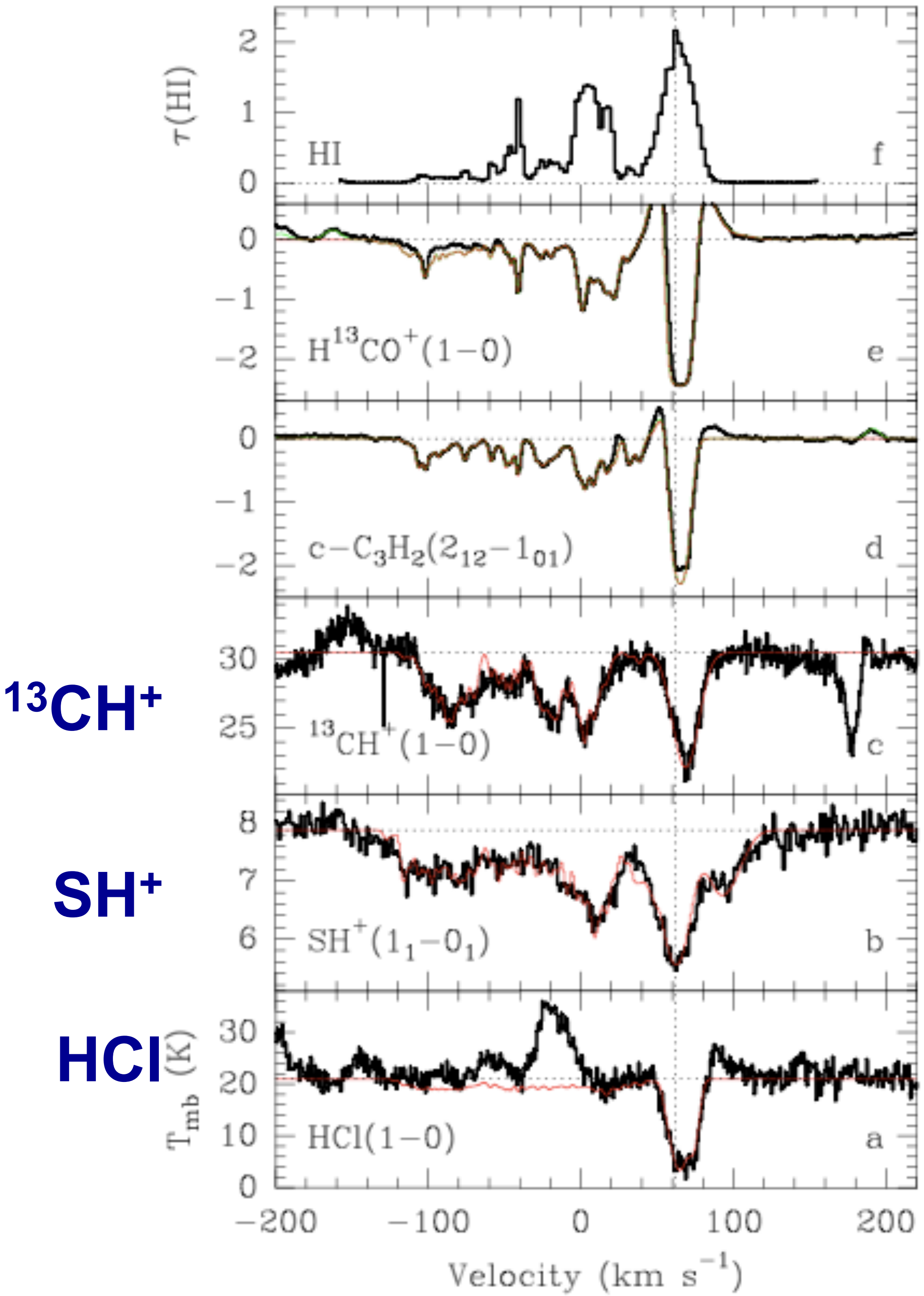




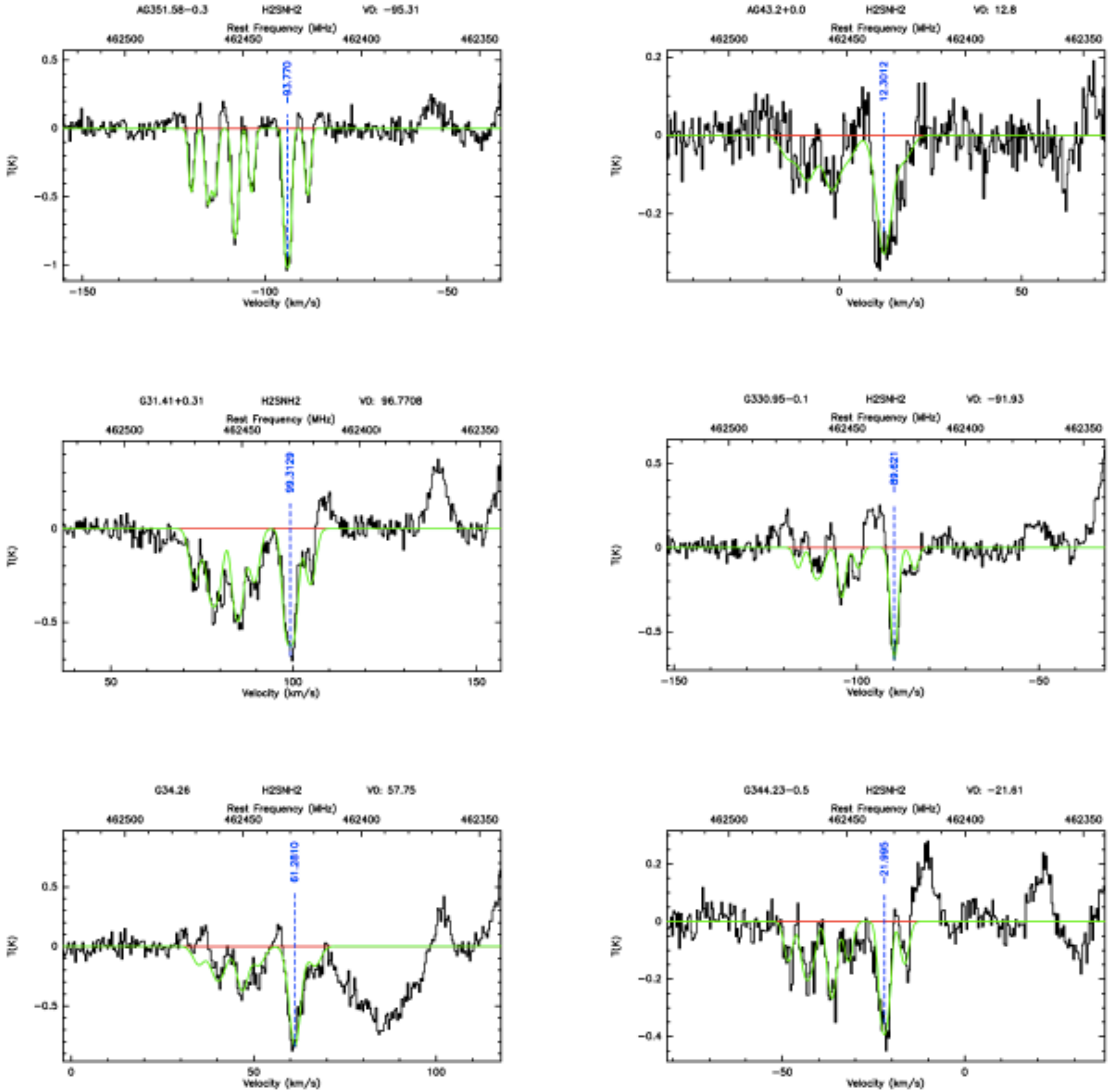
Ubiquitous OH^+ absorption.

Wyrowski+ in prep.


APEX


13CH+
SH+
HCl
τ(HI)
HI
f
H13CO+(1−0)
e
c−C3H2(212−101)
d
13CH+(1−0)
c
SH+(11−01)
b
HCl(1−0)
a
Tmb (K)
Velocity (km s−1)

Menten+ 2011



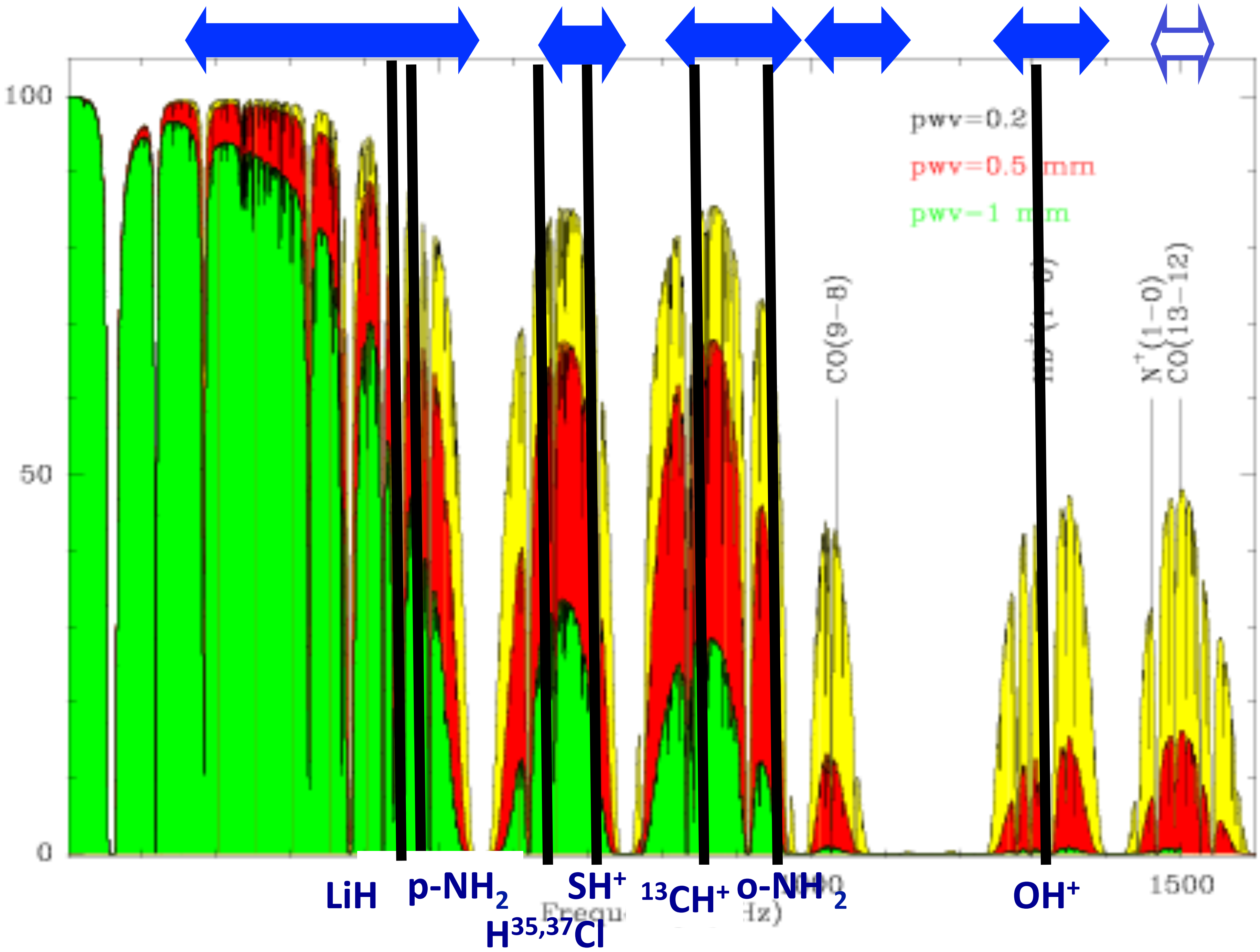
NH_2

$J = 3/2 – 3/2$

NH_2 462.4 GHz

C. Gette MSc thesis

Hydrides with APEX



Results so far and future developments:

Submillimeter observations of rotational ground-state transitions

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

This new information will allow addressing questions on

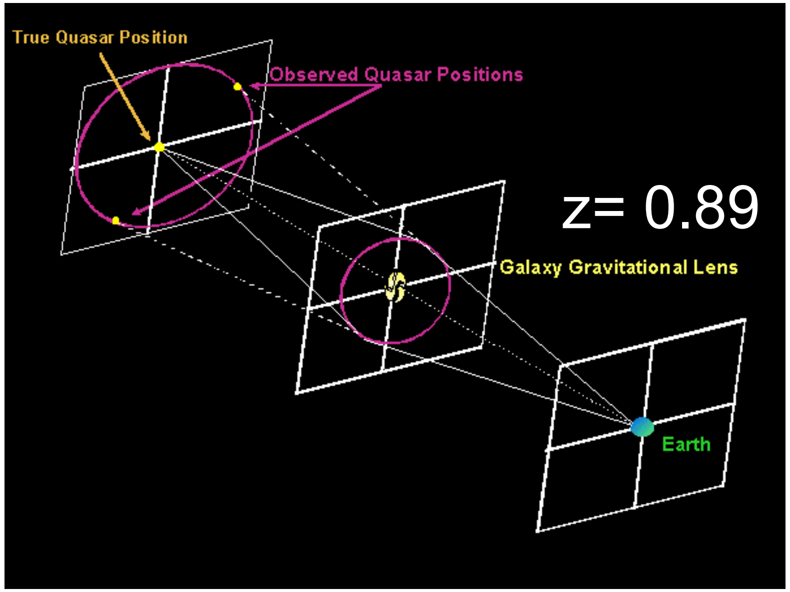
- Galactocentric abundance gradients
- effects of lower metallicity in Outer Galaxy
- …

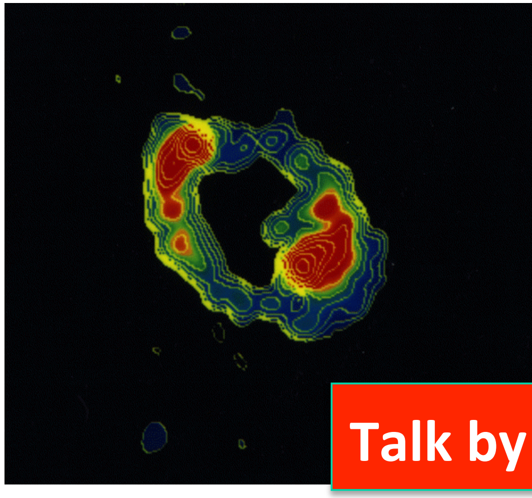
The Future is here!

Atacama Large Millimeter/submillimeter Array

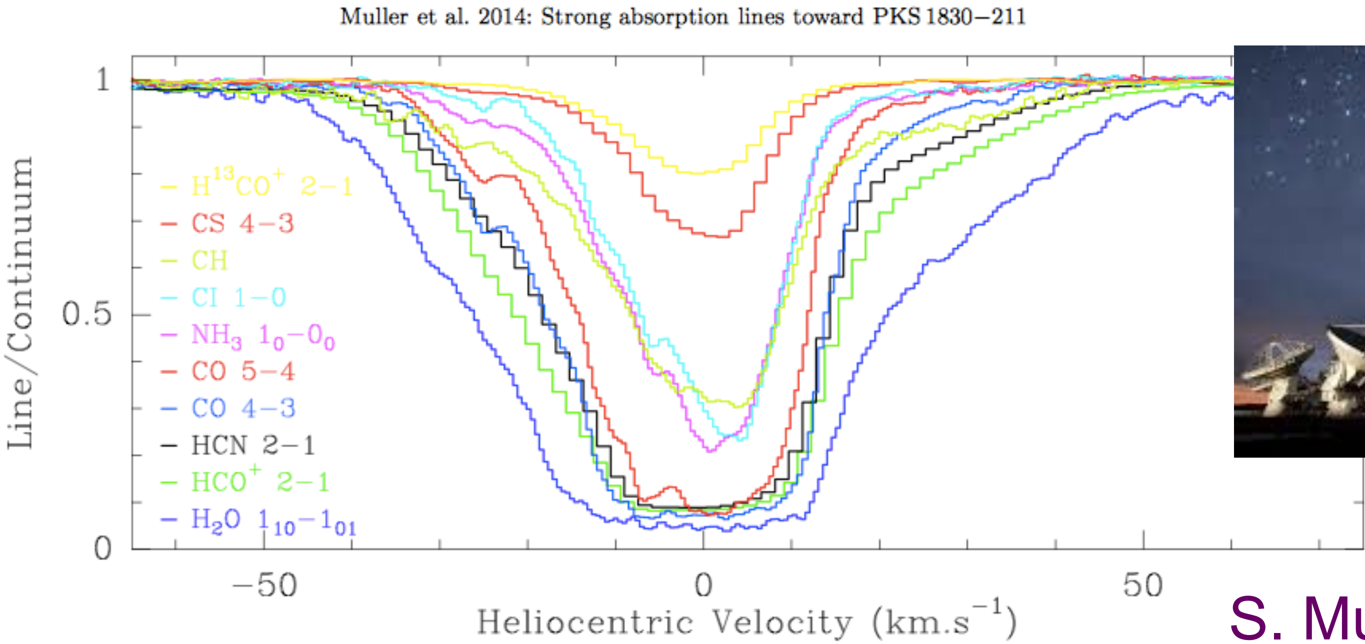
- 50 x 12 m ∅ antennas + 12 x 7 m ∅ antennas
- Interferometer
- maximal resolution 0.01" (1000 times higher than APEX)
- European-North-American-Japanese project

From the Local Truth to the distant Universe

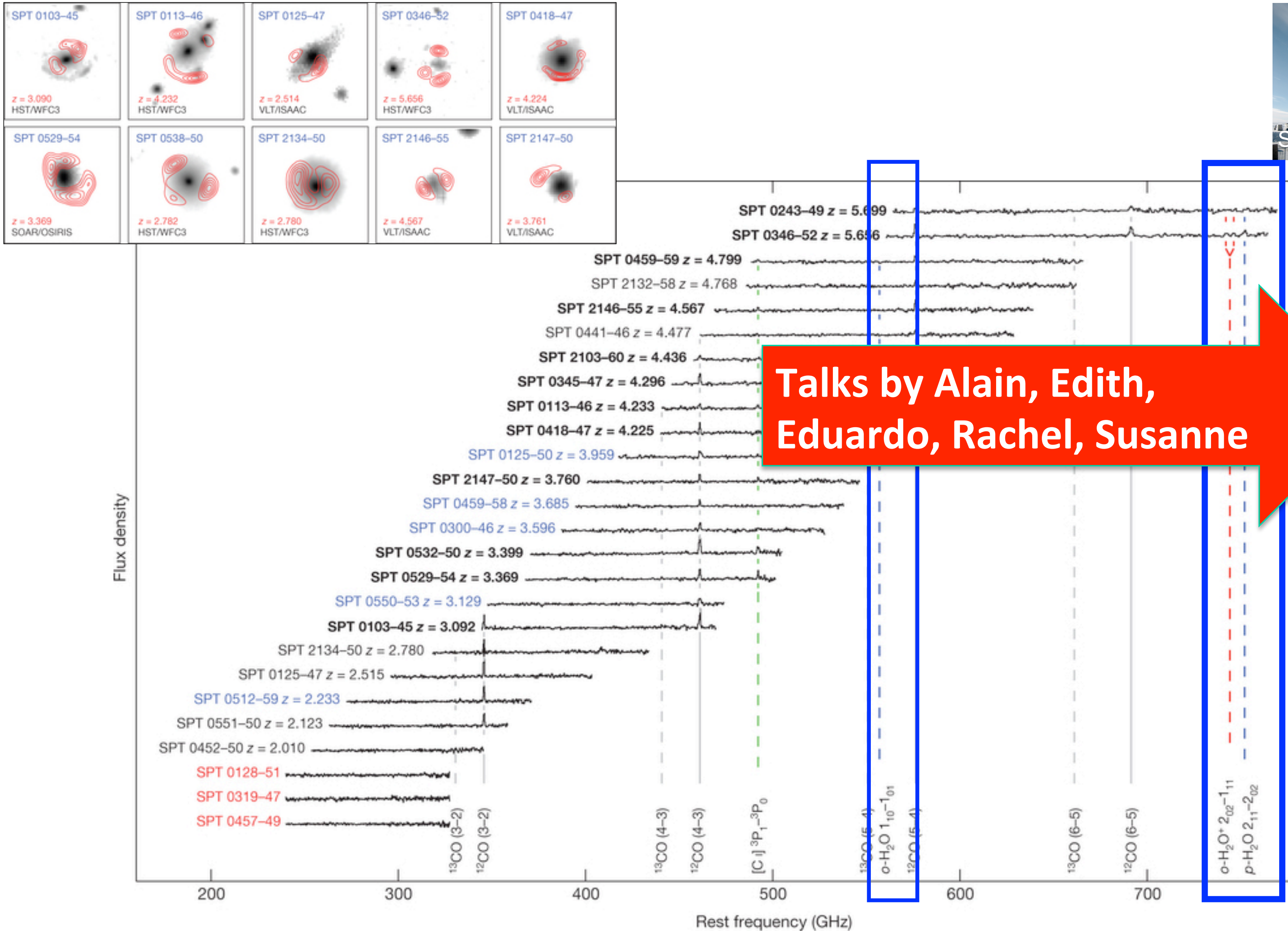




Talk by Sebastien Muller



S. Muller+ 2014,15,16



Talks by Alain, Edith, Eduardo, Rachel, Susanne

Vieira et al. 2013

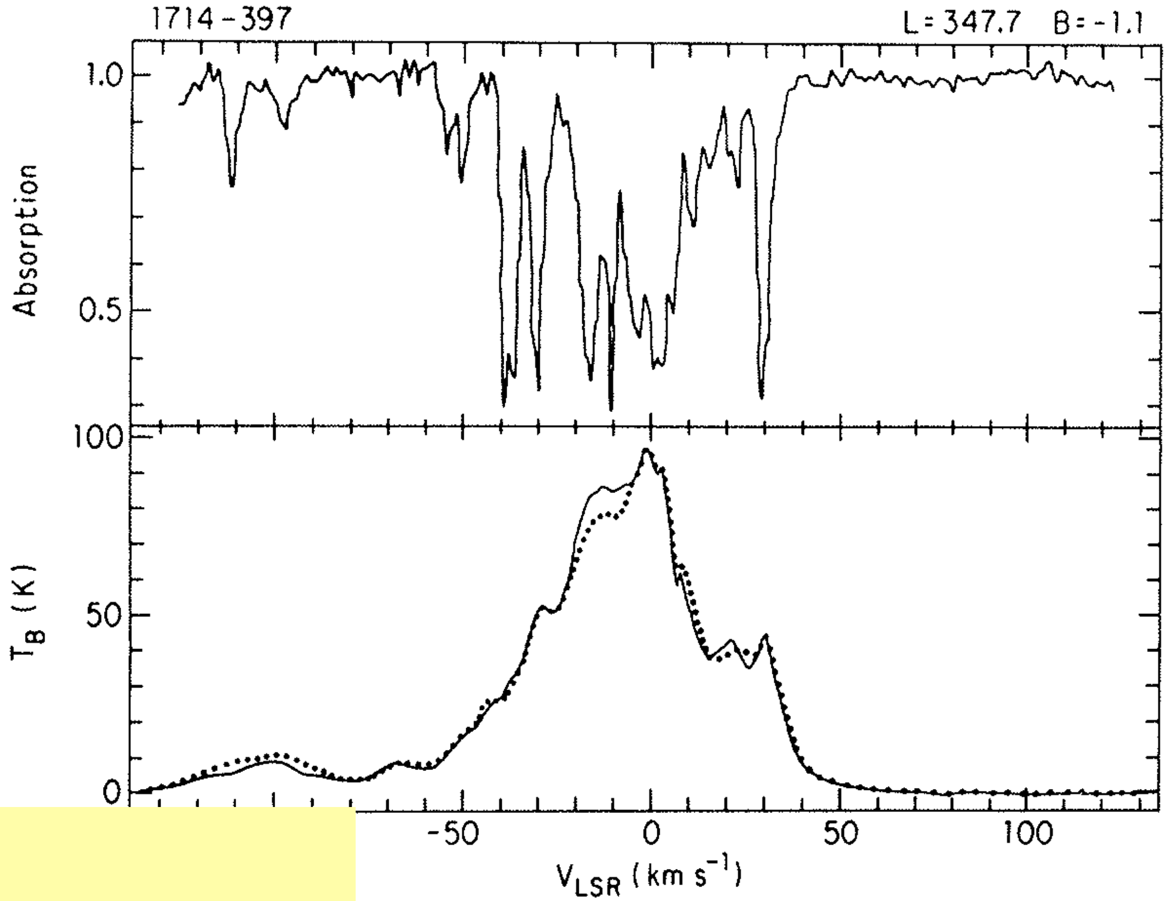
Reconsidering radio:

cm-wavelength Galactic molecular (and atomic) absorption spectroscopy

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

delivers τ

delivers T_B

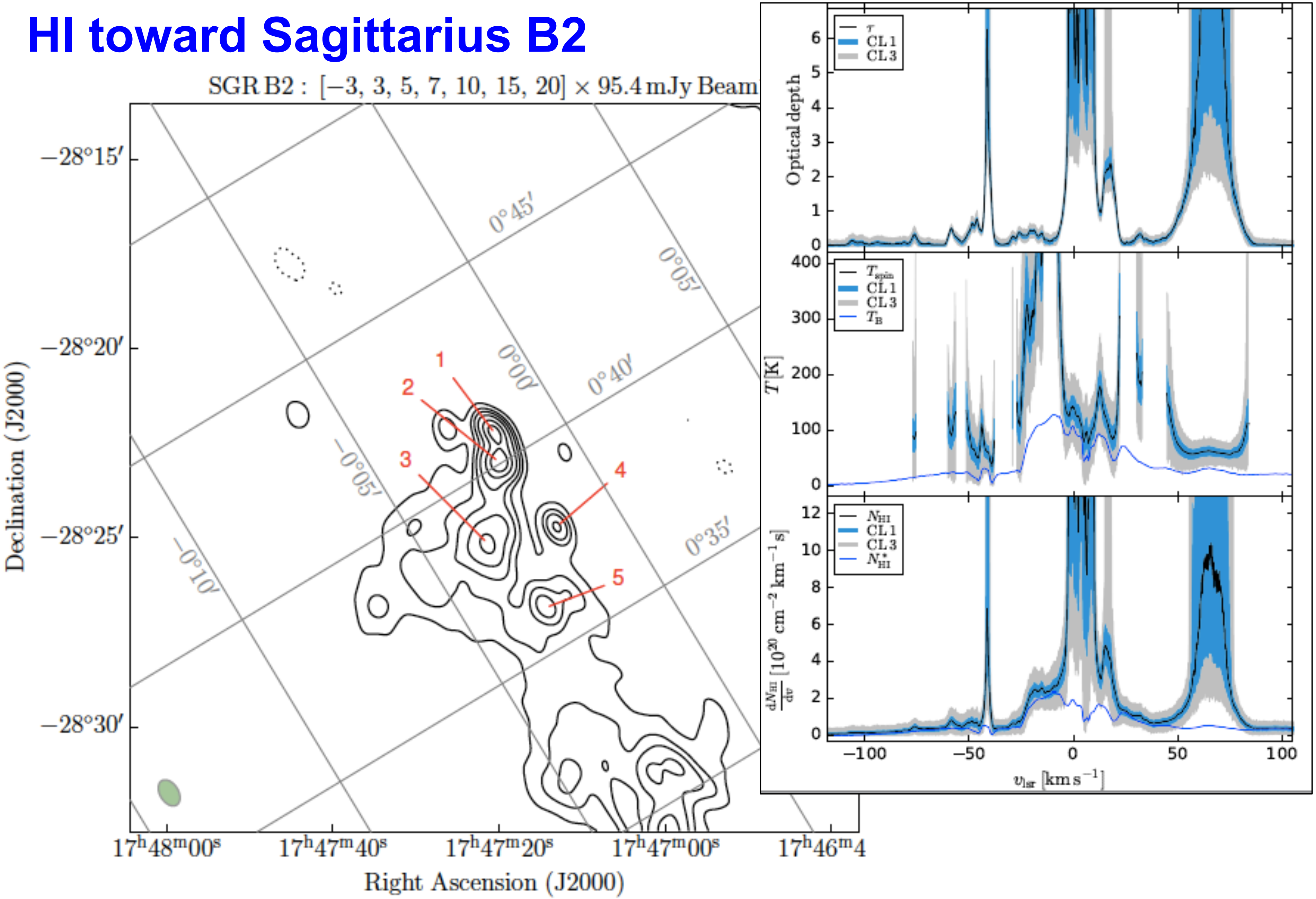


Dickey et a. 1983

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

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

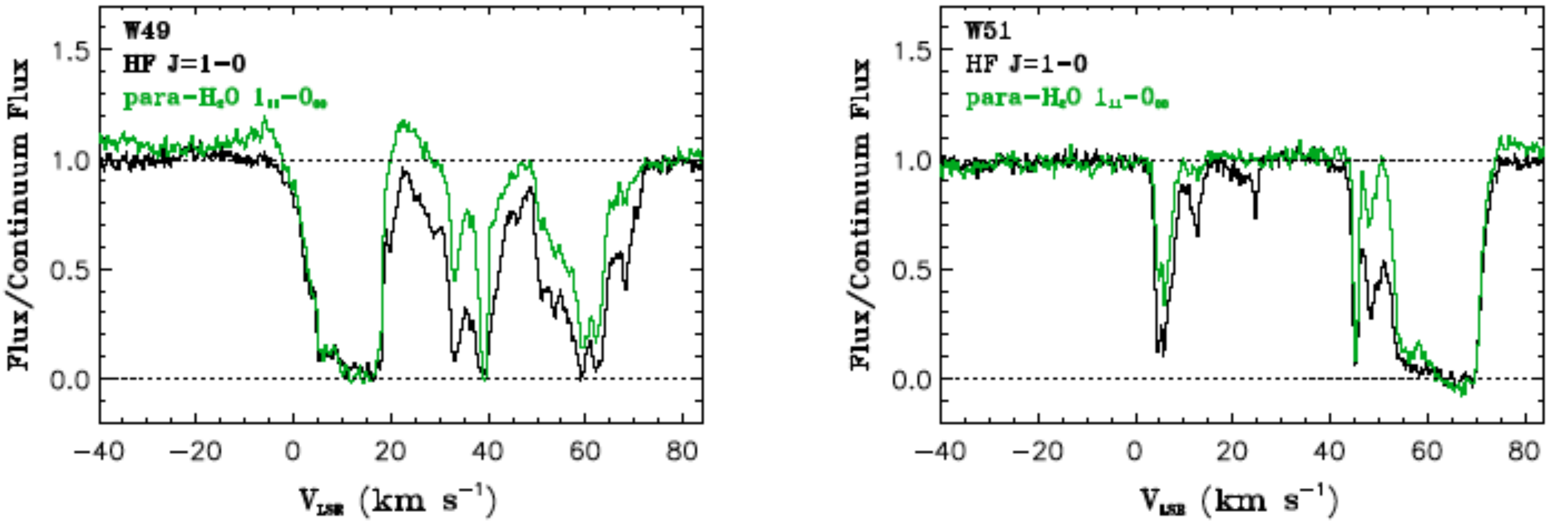
HI toward Sagittarius B2



PRISMAS Sources+: Winkel+ 2017

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],

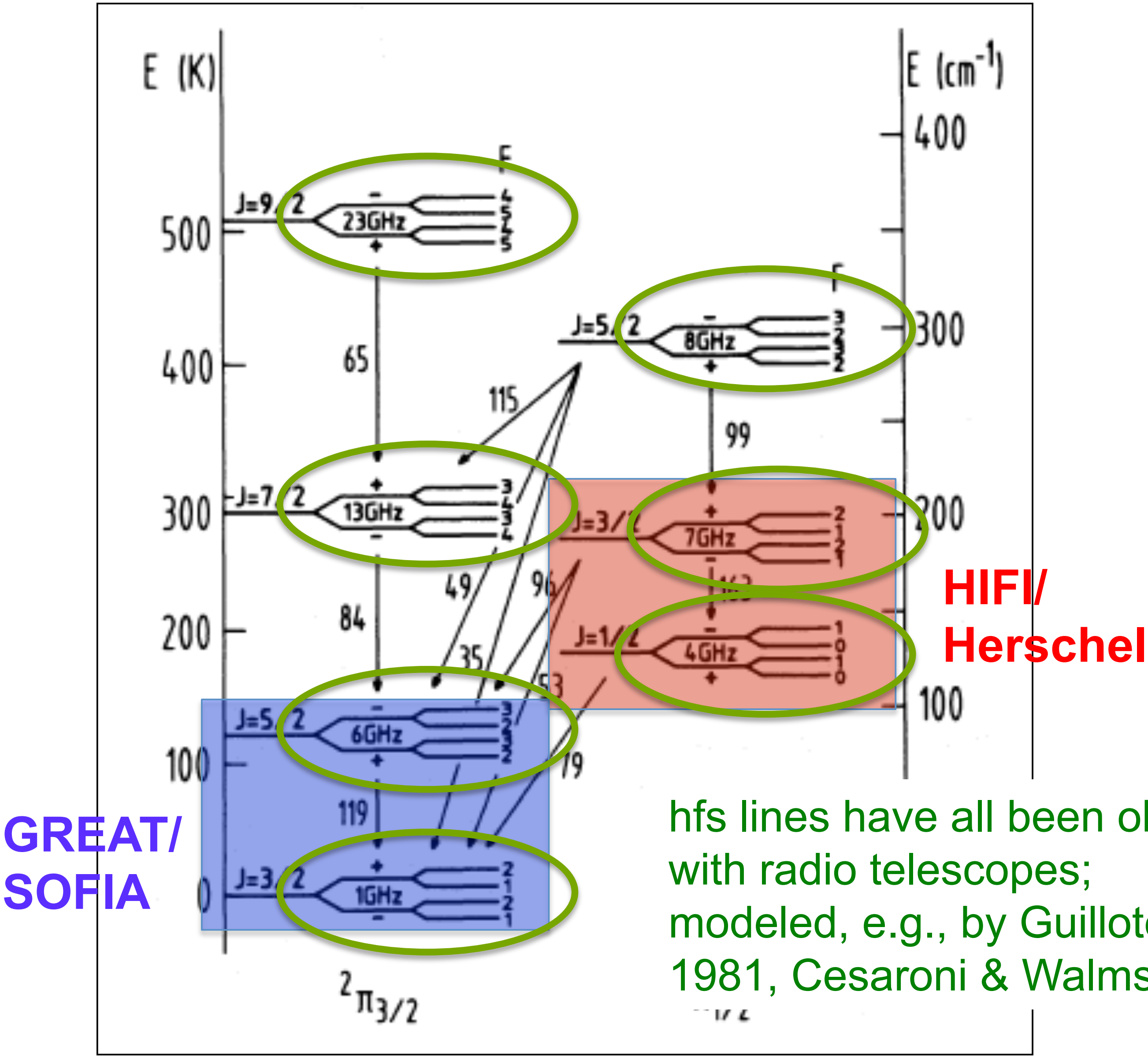


Two of the most fundamental hydrides can easily be observed from the ground:
Hyperfine structure line emission from

- **OH (near 1.7 GHz)**
- **CH (near 3.3 GHz)**
- **+ hfs emission from within rotationally exited states**

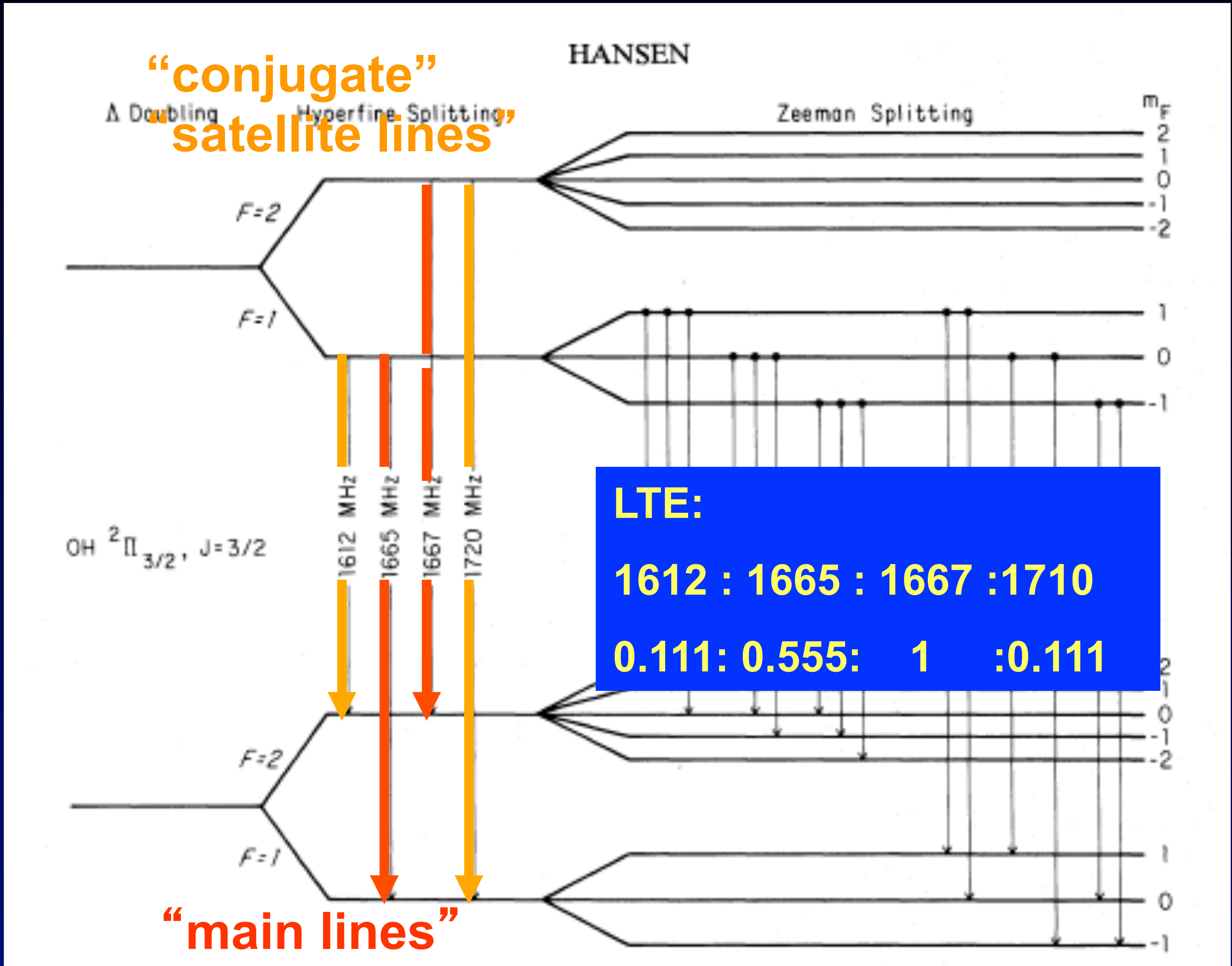
Caveat: Lines are non-thermally excited (**inverted** or overcooled)

OH Energy Levels



hfs lines have all been observed with radio telescopes;
modeled, e.g., by Guilloteau+ 1981, Cesaroni & Walmsley 1990

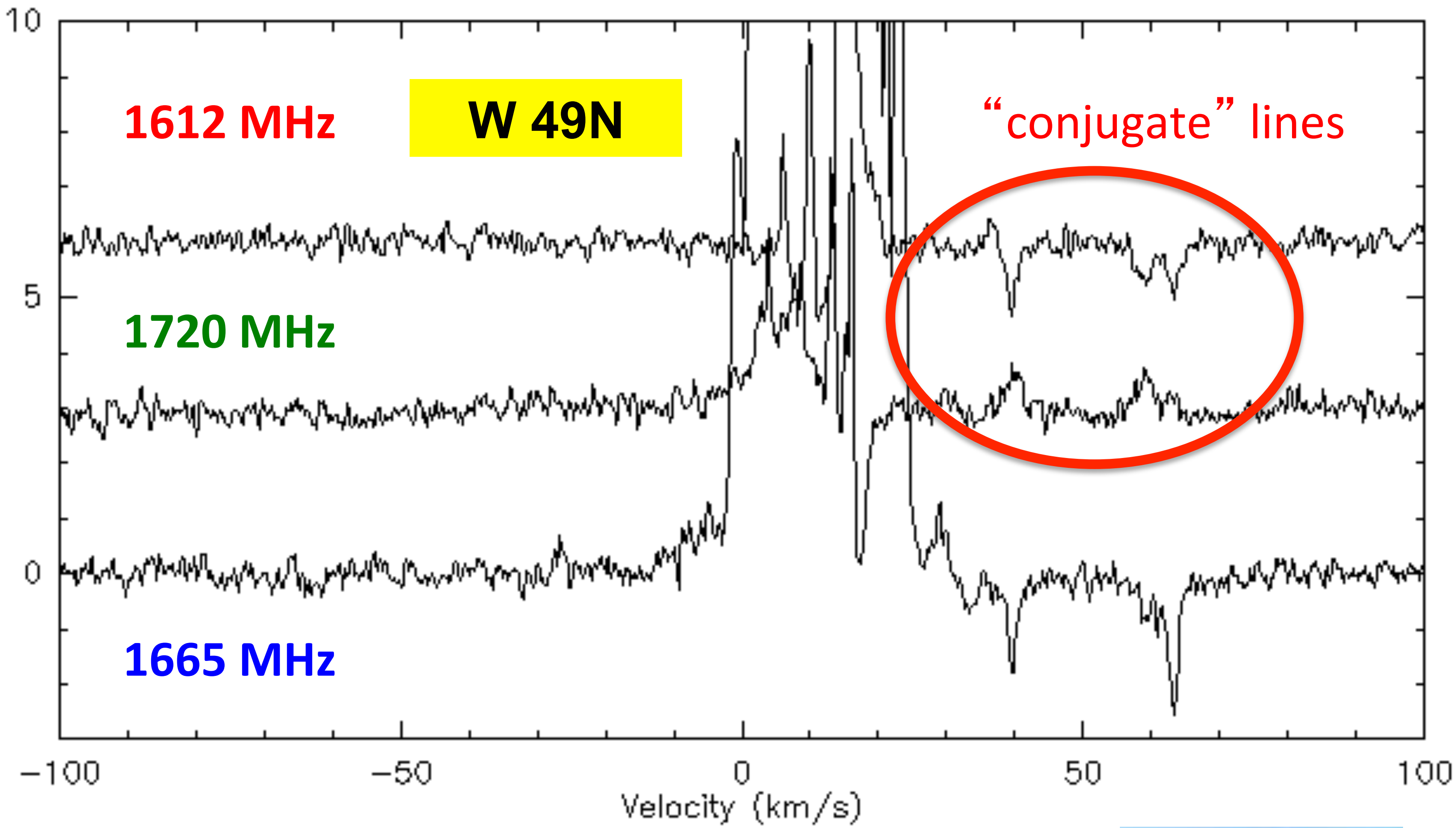
OH $^2\Pi_{3/2}$ ground-state transitions



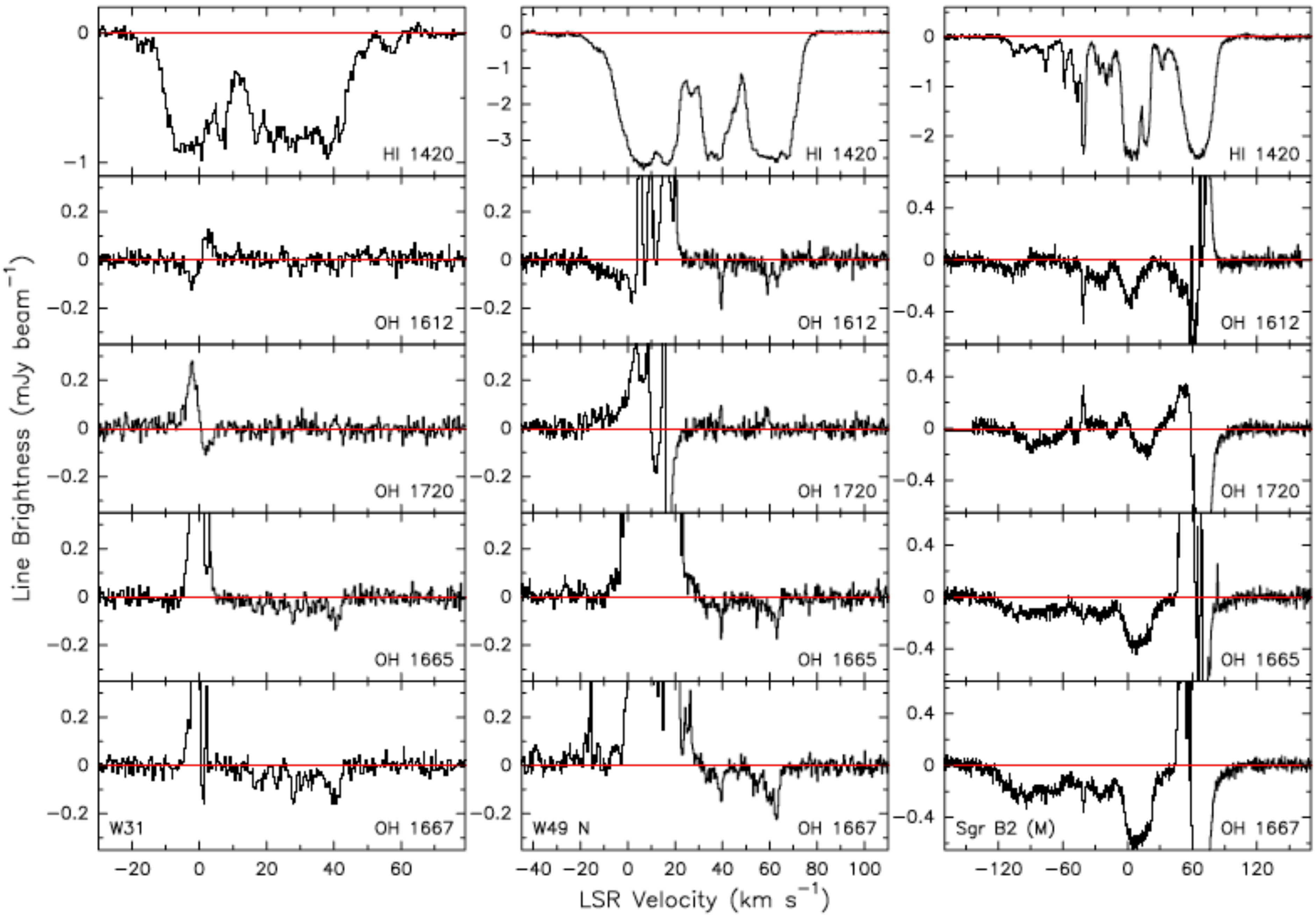
LTE:

1612 : 1665 : 1667 :1710

0.111: 0.555: 1 :0.111

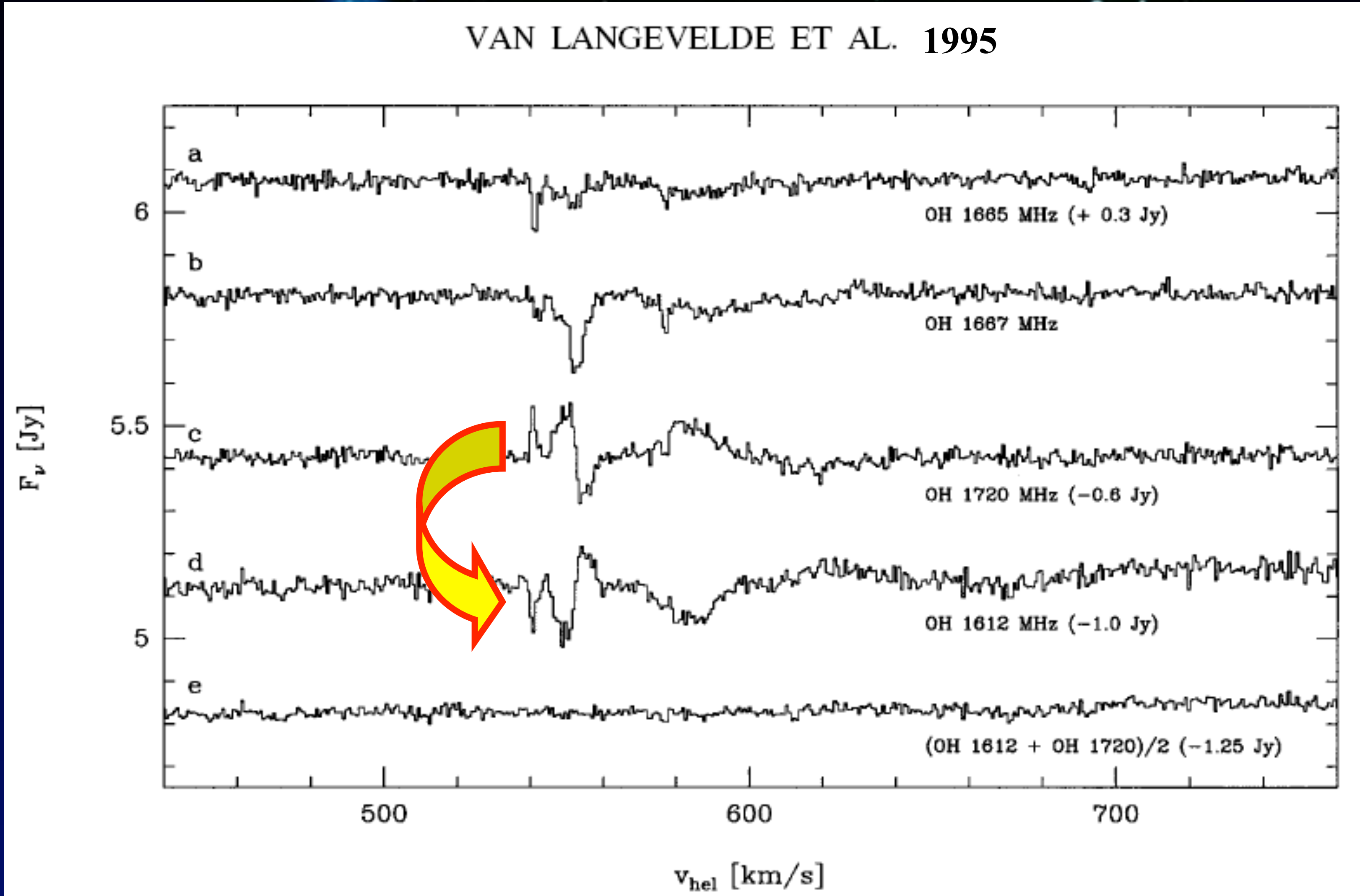


$$\text{OH } {}^2\Pi_{3/2} J = \frac{1}{2} \ (1612,\ 1665,\ 1720 \text{ MHz})$$



Line Brightness (mJy beam^{-1})
LSR Velocity (km s^{-1})
HI 1420
OH 1612
OH 1720
OH 1665
OH 1667
W31
W49 N
Sgr B2 (M)

The "conjugate" OH ground-state satellite lines



Centaurus A

The “conjugate” OH ground-state satellite lines

Selection rules:

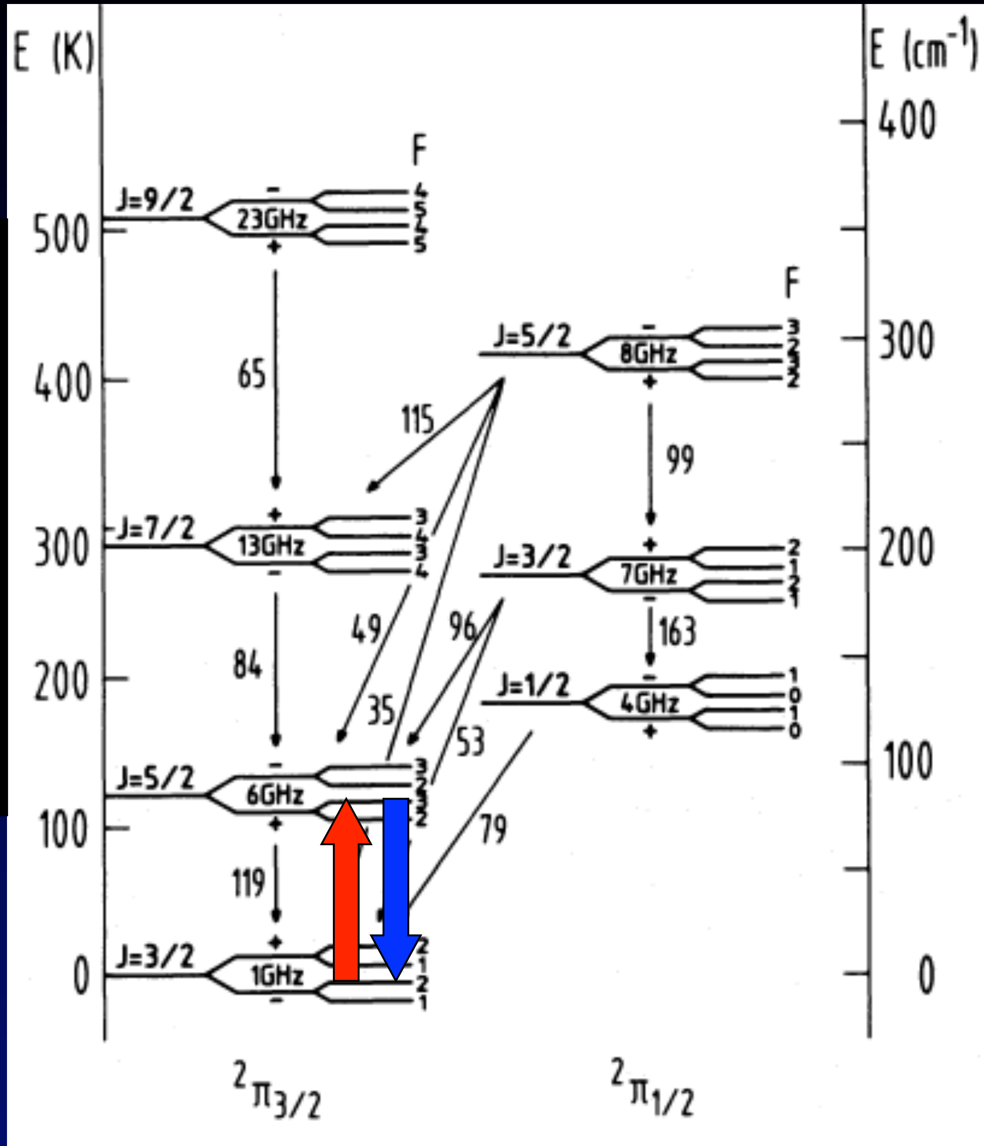
- parity must change
- |F| = 0, 1

⇒More transitions lead to J = 3/2, F=2$^+$ than 1$^-$ and more to F=2$^-$ than 1$^+$

⇒Overpopulation of F= 2 levels

⇒F = 2→ 1 maser

⇒F = 1 → 2 cooling



Constraining physical conditions with the 18 cm OH hfs lines

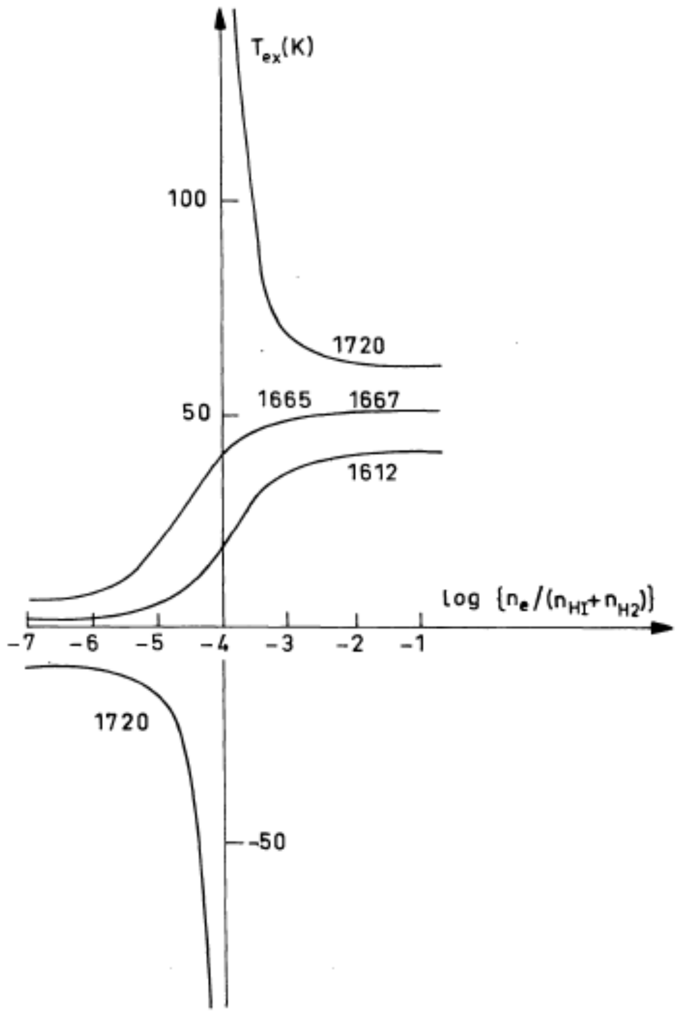
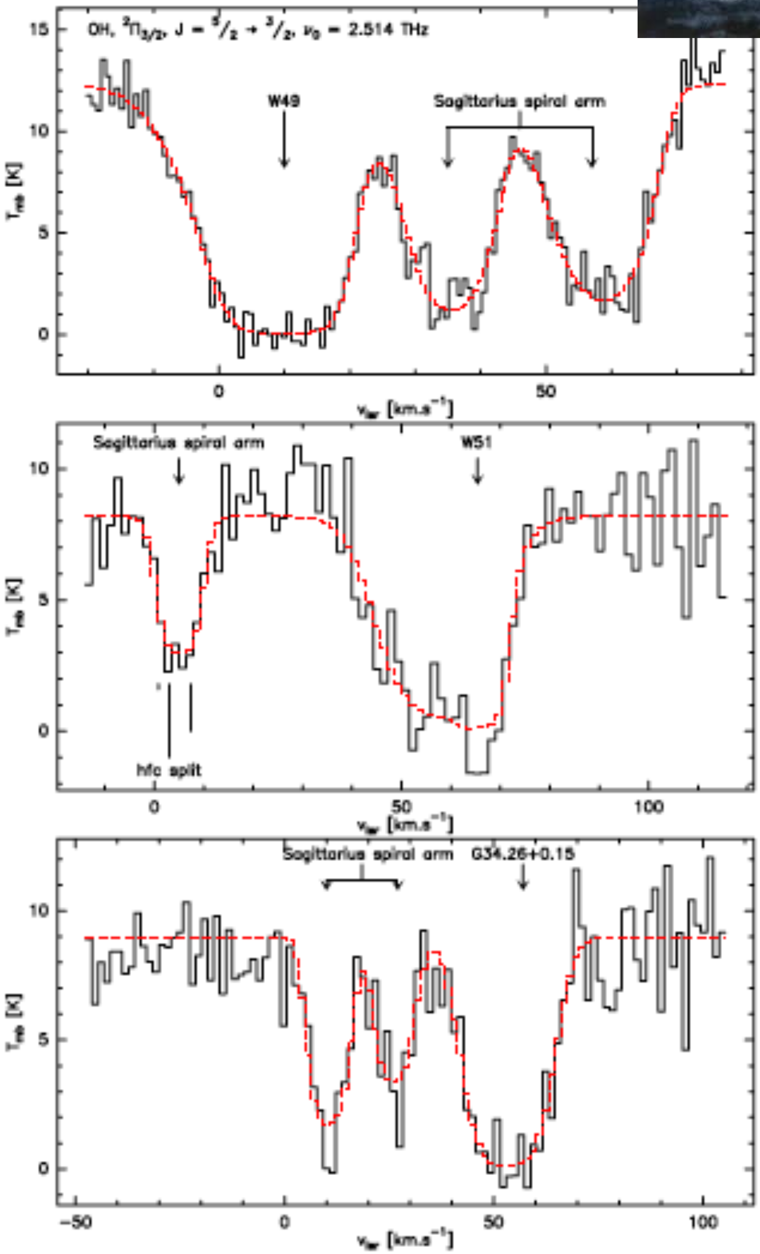


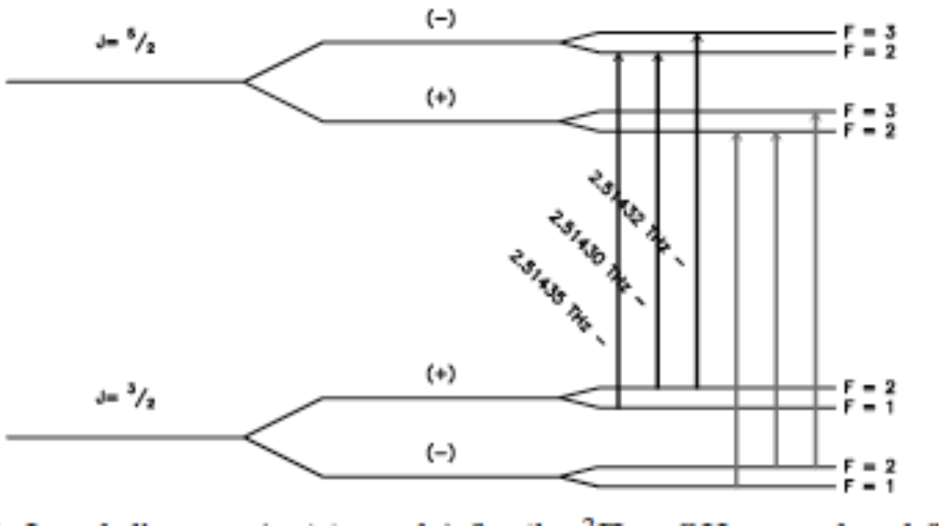
Fig. 4. Variation of the OH excitation temperatures as a function of the fractional ionization

$T_g = 10$ K; $W = 10^{-4}$; $p = 2$
$n_{HI} + n_{H_2} = 200\ cm^{-3}$; $T_K = 50$ K
$N_{OH}/V = 6\cdot10^{-5}\ cm^{-3}$ pc km^{-1} s
($N_{OH} \sim 5\cdot10^{14}\ cm^{-2}$)

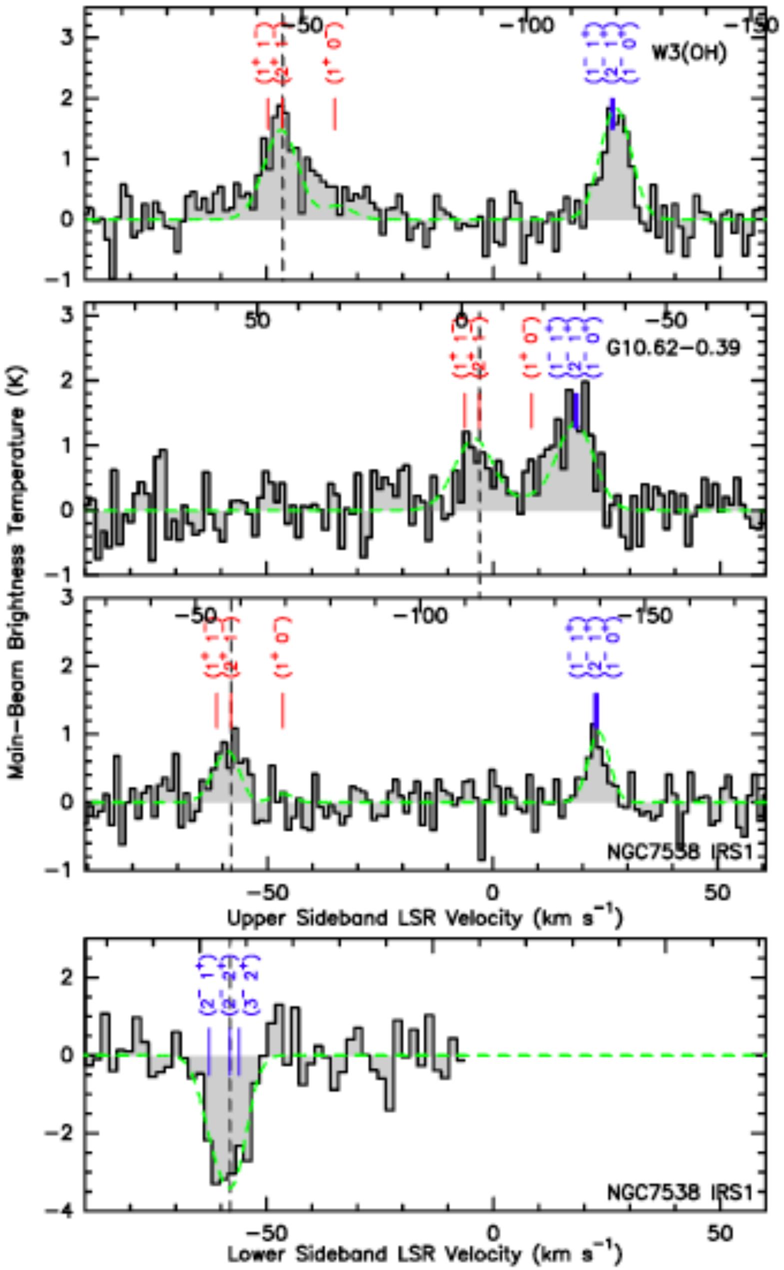
Guibert et al. 1978

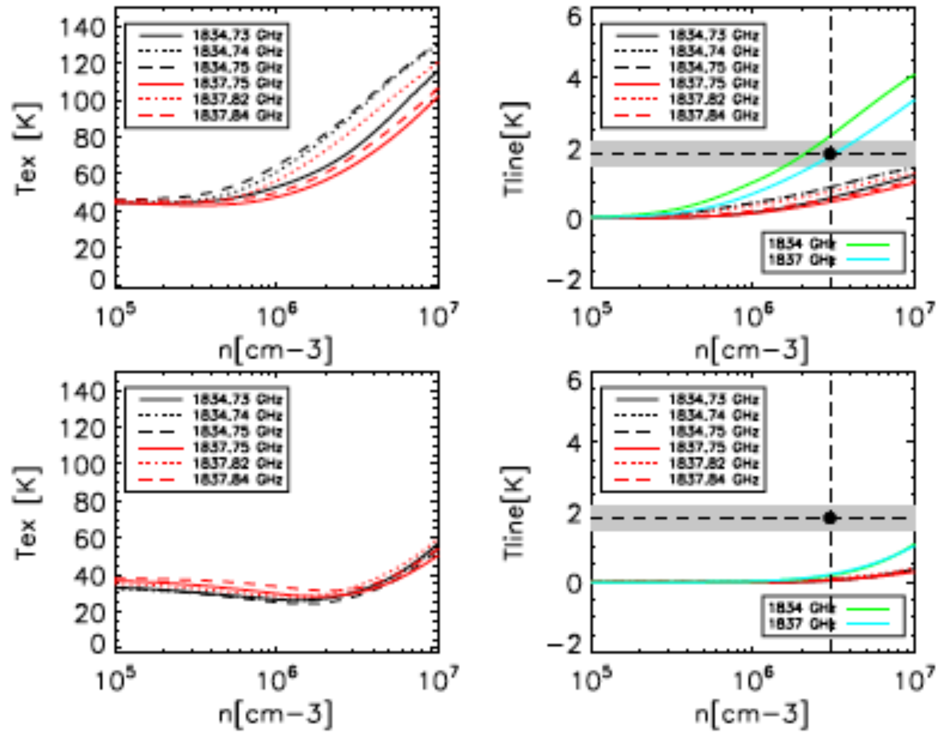


Transition	Frequency [GHz][a]	A_E [s^{-1}][b]
OH, $^2\Pi_{3/2}, J = 5/2 \leftarrow 3/2$		
$F = 2^- \leftarrow 2^+$	2514.298092	0.0137
$F = 3^- \leftarrow 2^+$	2514.316386	0.1368
$F = 2^- \leftarrow 1^+$	2514.353165	0.1231
^{18}OH, $^2\Pi_{3/2}, J = 5/2 \leftarrow 3/2$		
$F = 2^+ \leftarrow 2^-$	2494.68092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



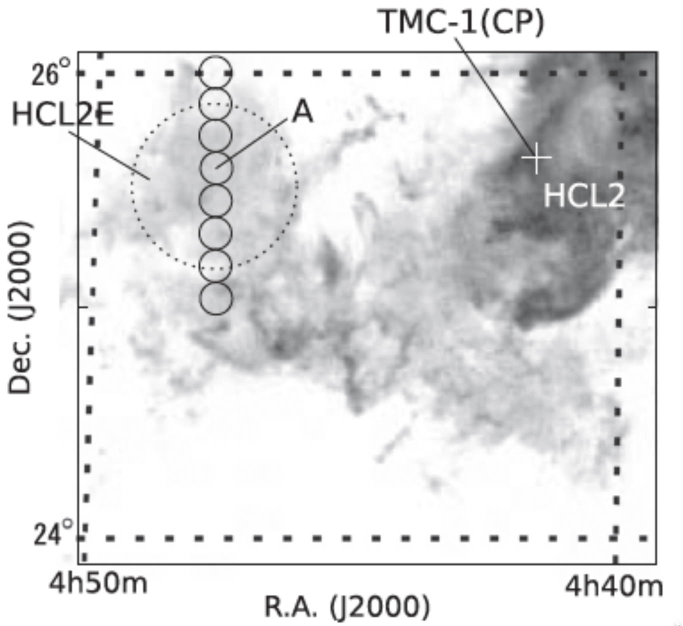
Wiesemeyer et al. 2012

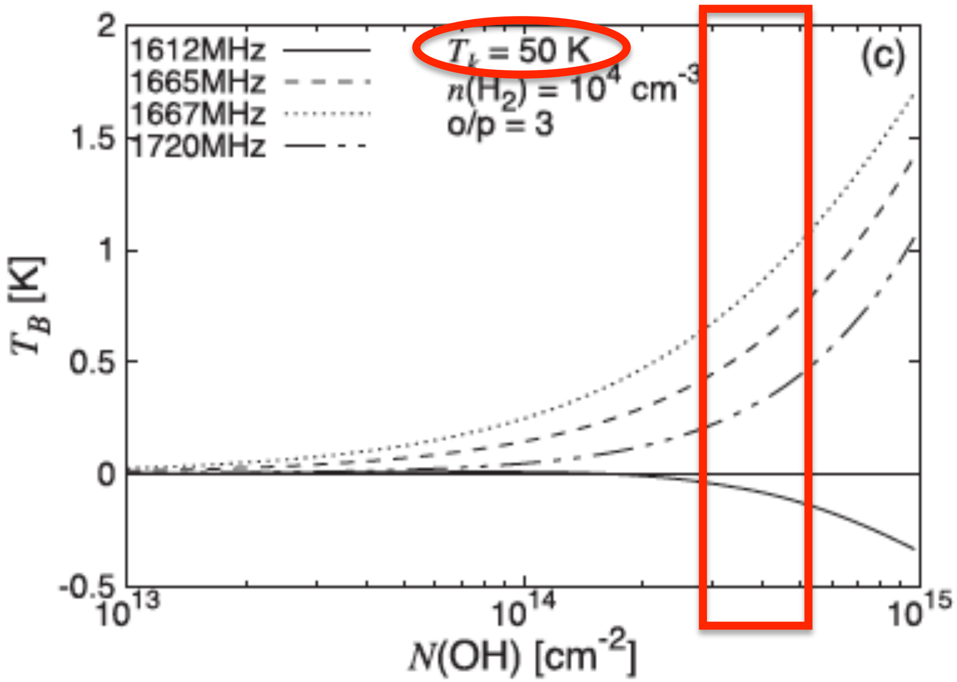


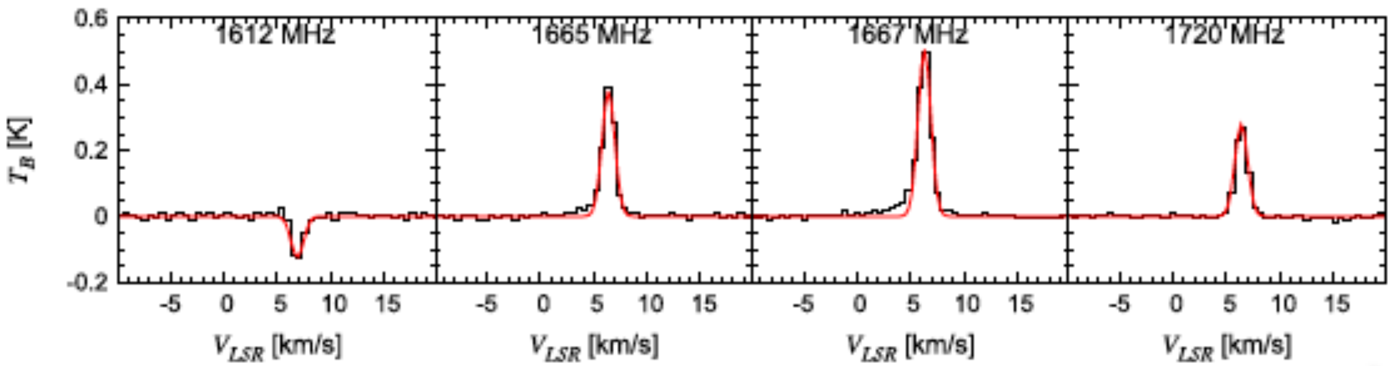


LVG Modeling with program from Cesaroni & Walmsley 1990

Csengeri, Menten, et al. 2012







Poster by Y. Ebisawa

Ebisawa+ 2105

To model the radio lines of OH and CH, accurate hyperfine structure selective collisional rate coefficents are of crucial importance!

Example: OH

Flower 1989

- Only OH–para-H_2
- hfs splitting not take into account →make guesses, use (rough) propensity rules (ΔF =0 preferred, Corey & Alexander 1988)

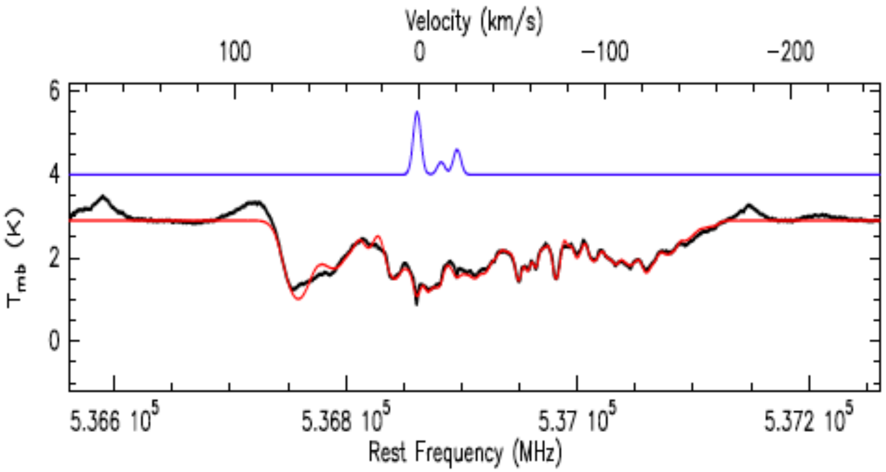
Offer+ 1994

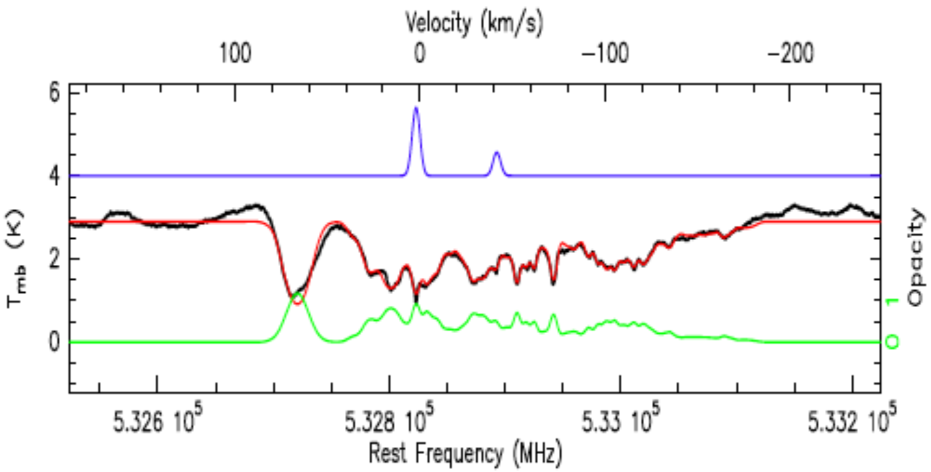
- OH–ortho- and para-H_2
- hfs-resolved cross sections

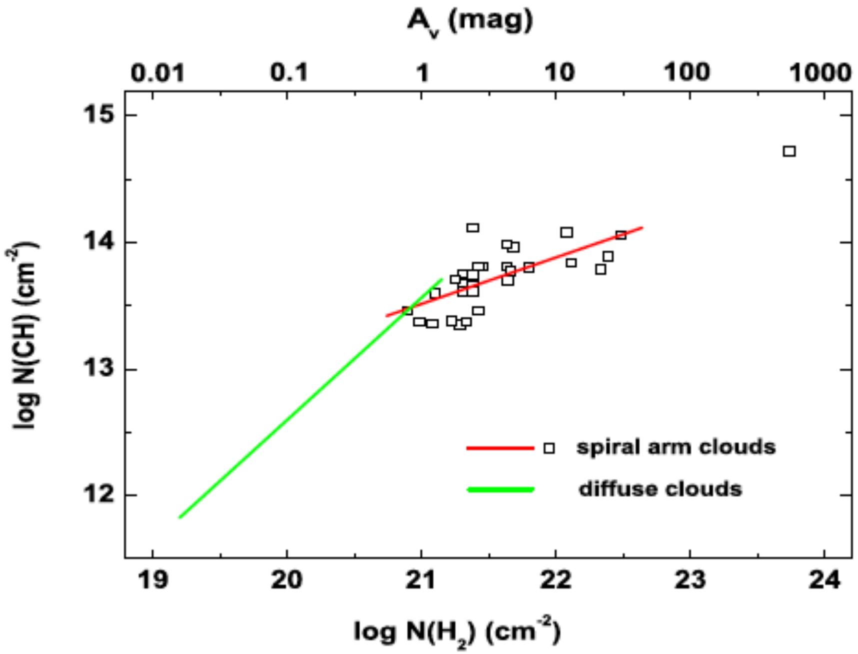
New calculations by Faure+

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],

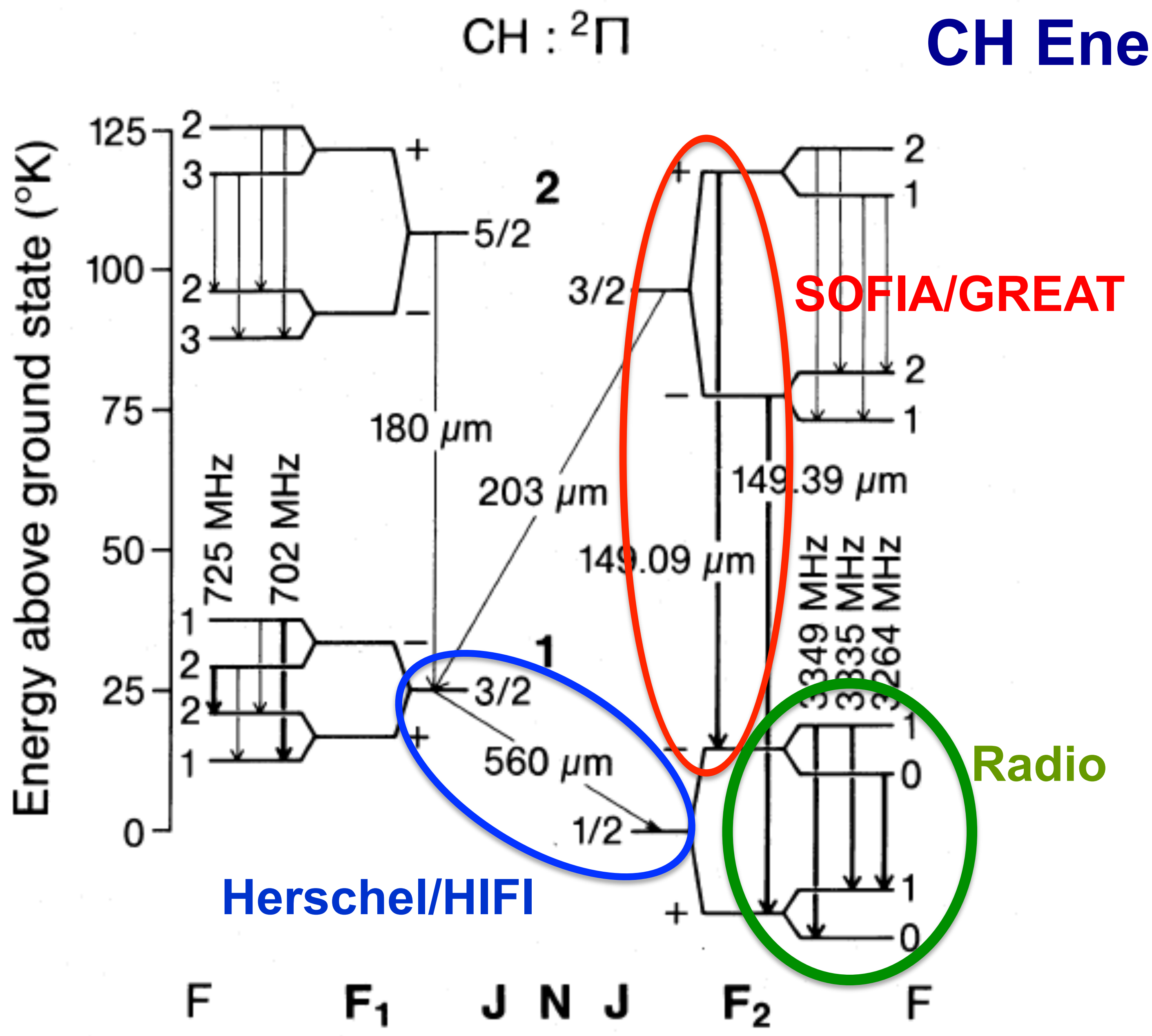






Methylidyne CH

CH Energy Levels



NATURE VOL. 246 DECEMBER 21/28 1973

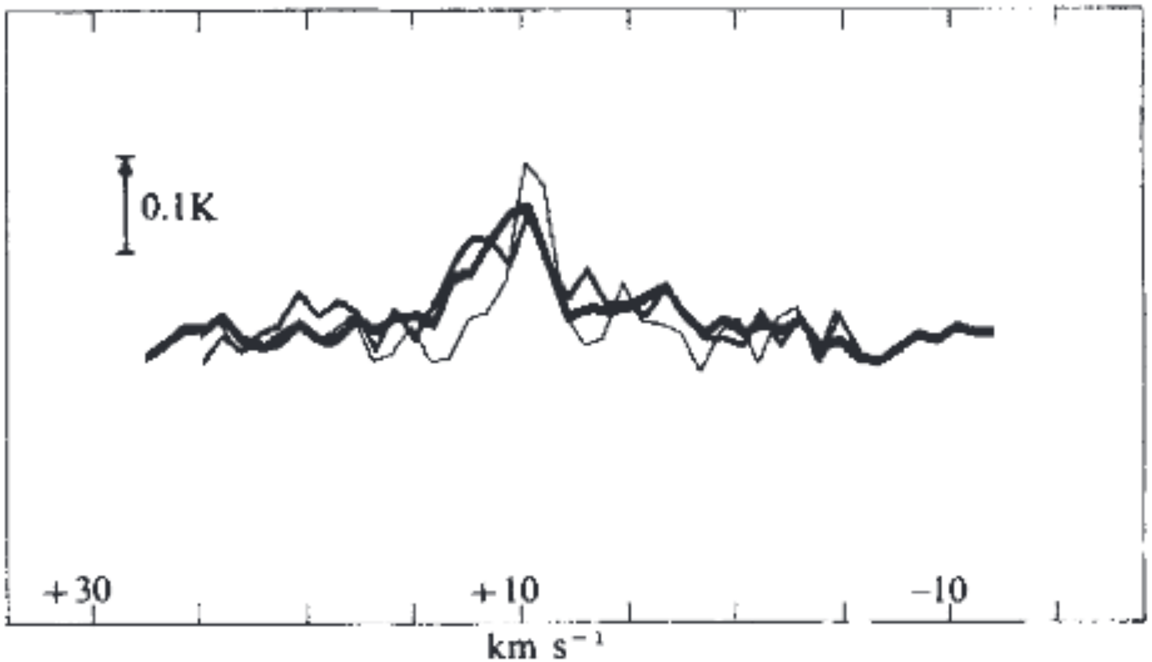
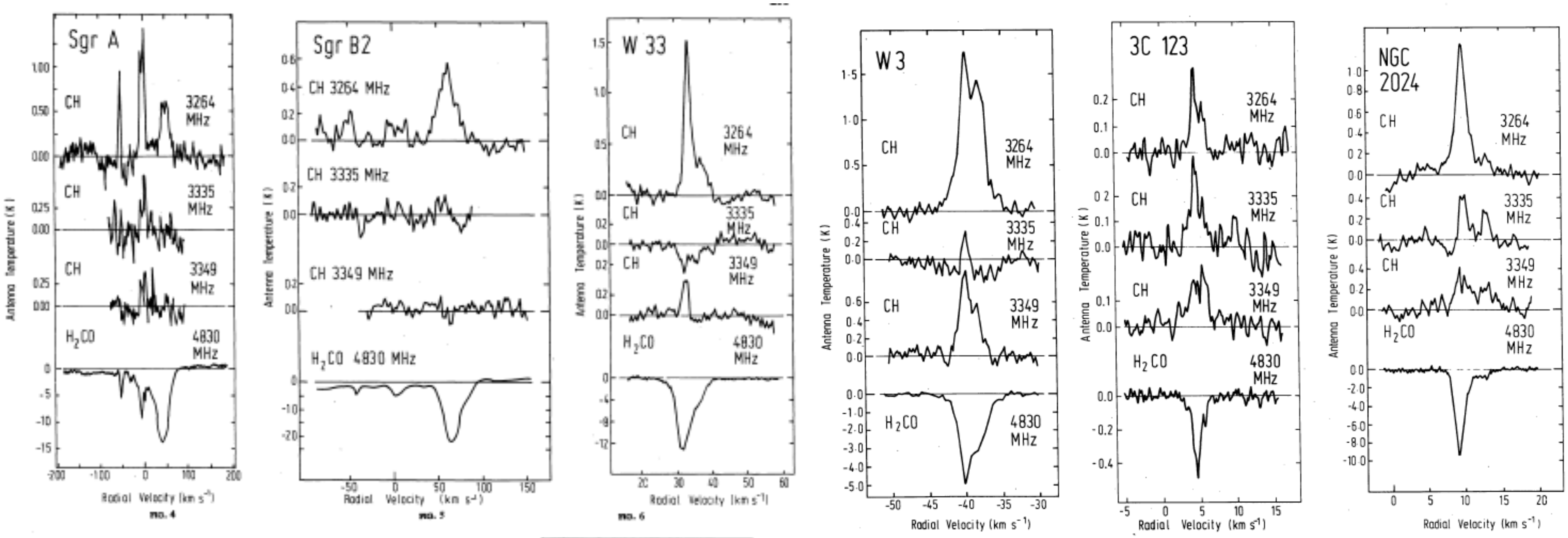
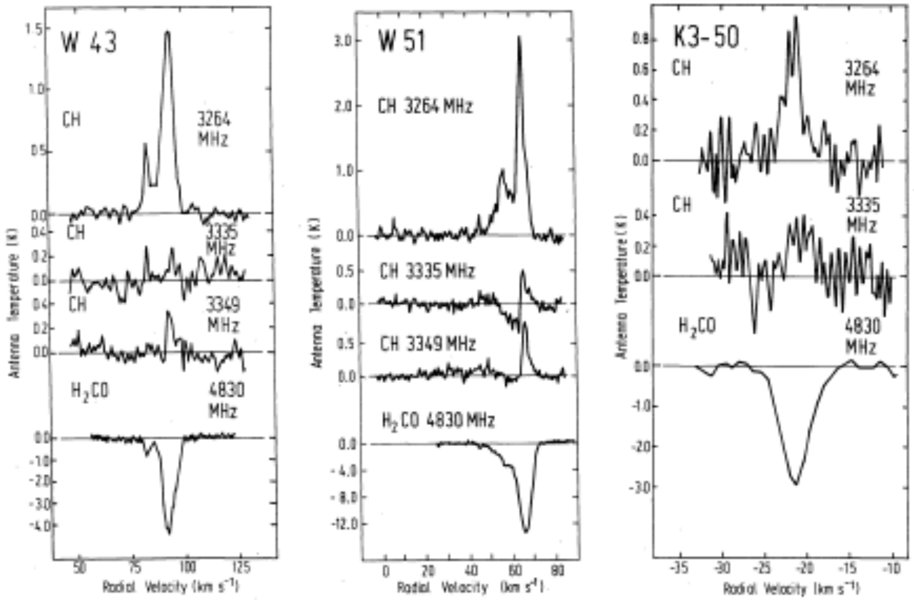


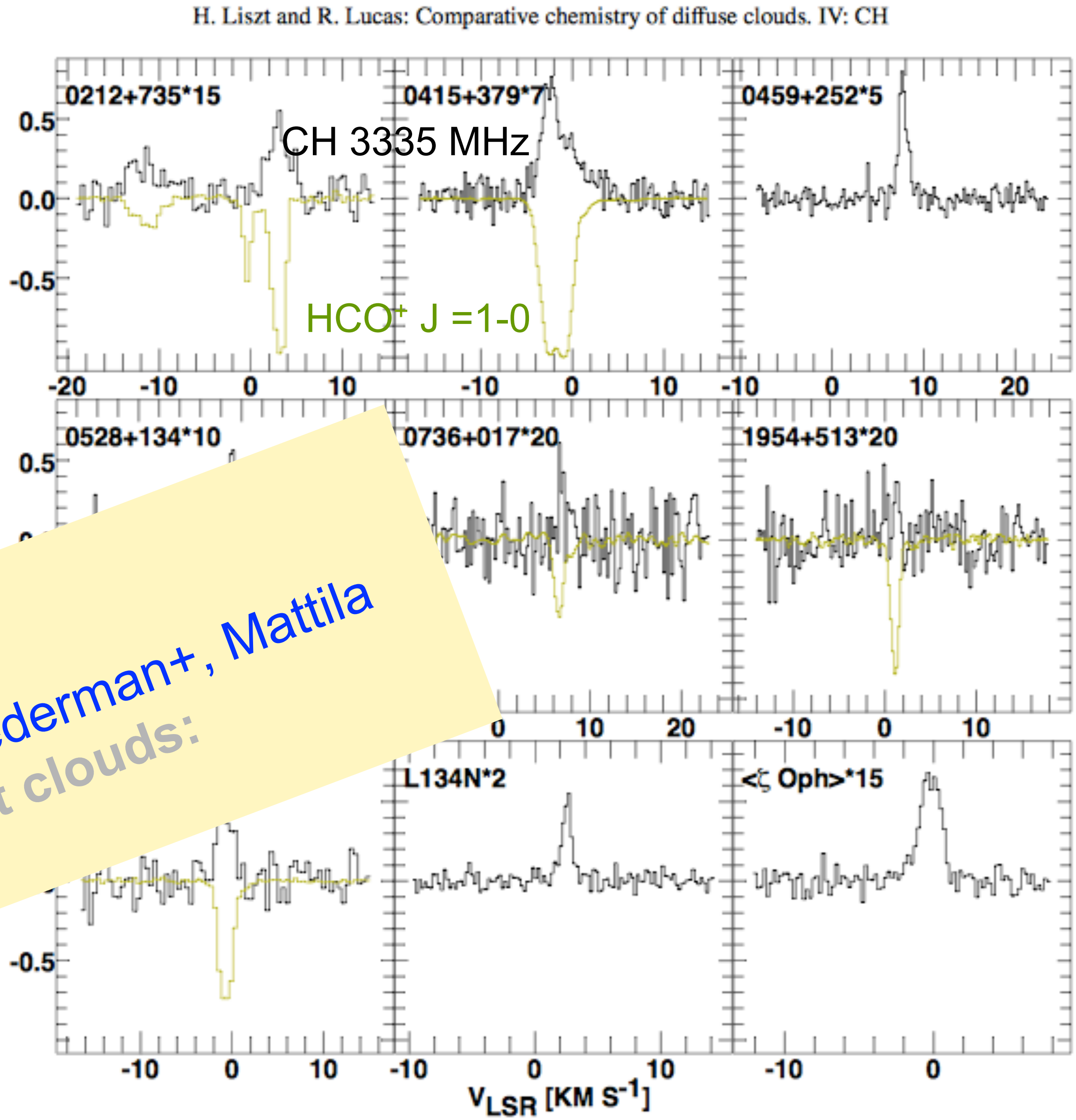
Fig. 8 Emission spectra of the ν_{11} (heavy line), ν_{10} (medium), and ν_{01} (light) lines of the CH ground state Λ doublet, as seen in the direction of W12.

Rydbeck, Elldér & Irvine 1973


Sgr A
Sgr B2
W 33
W 3
3C 123
NGC 2024
CH 3264 MHz
CH 3335 MHz
CH 3349 MHz
H2CO 4830 MHz
Antenna Temperature (K)
Radial Velocity (km s⁻¹)

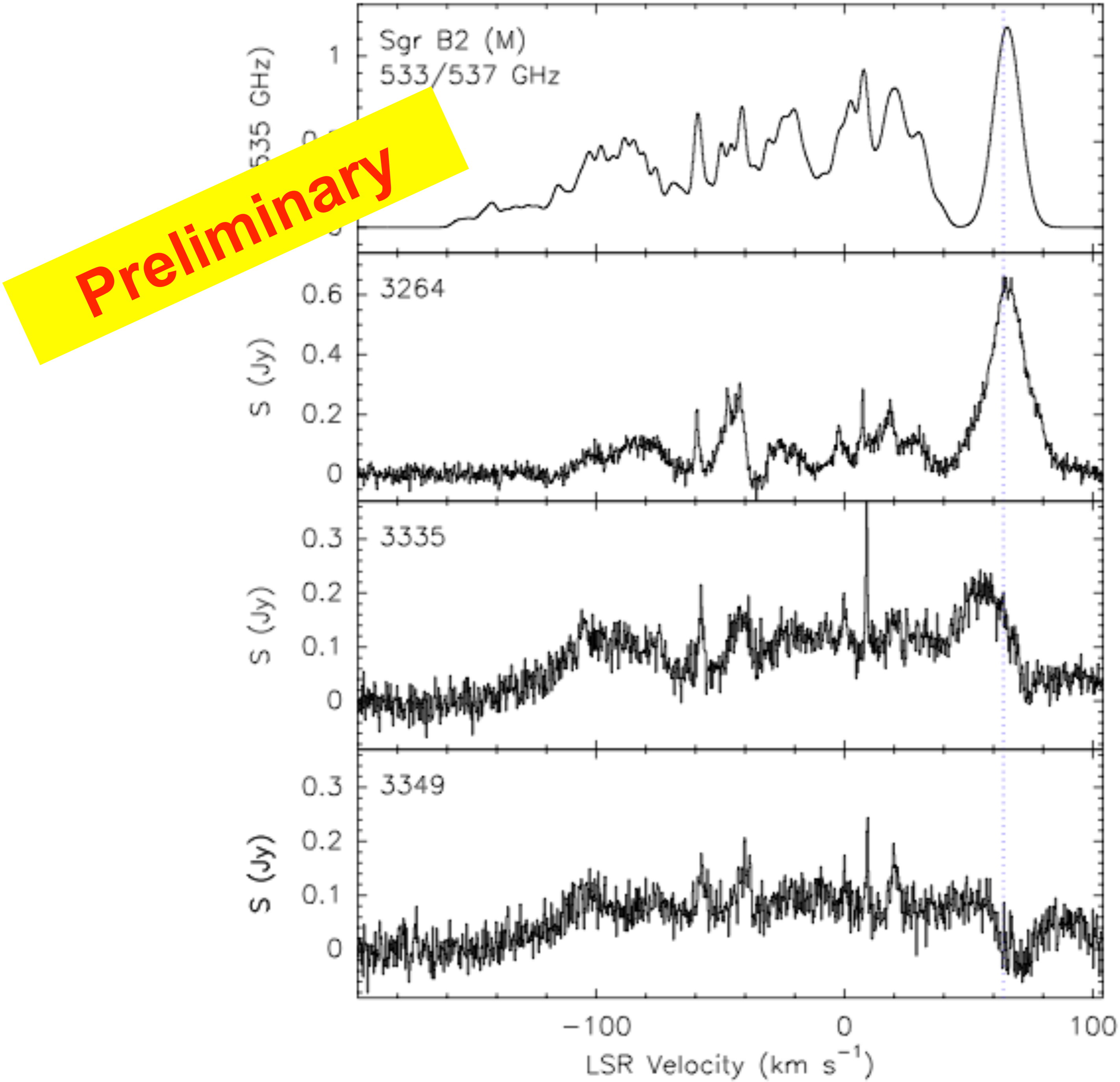

W 43
W 51
K3-50
CH 3264 MHz
CH 3335 MHz
CH 3349 MHz
H2CO 4830 MHz
Antenna Temperature (K)
Radial Velocity (km s⁻¹)

Genzel+ 1979



Radio CH in
Dark clouds:
Rydbeck+,Federman+, Mattila
Translucent clouds:
Magnani+

Liszt & Lucas 2002



LTE Ratios

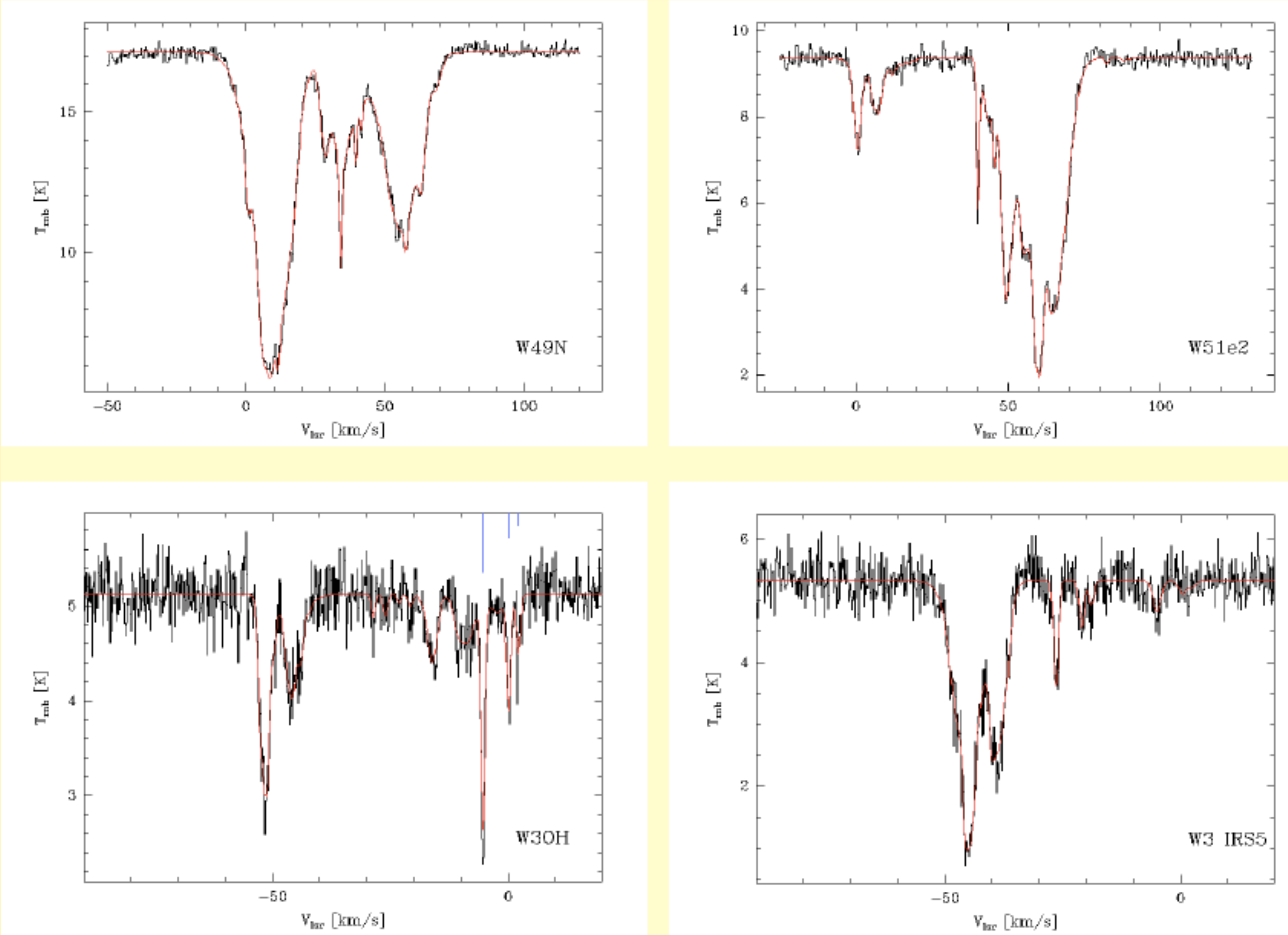
0.5

1

0.5

Transition	Frequency (Hz)
$(1/2^+, 1) - (1/2^-, 1)$	3335479356 ± 3
$(1/2^+, 0) - (1/2^-, 1)$	3349192556 ± 3
$(1/2^+, 1) - (1/2^-, 0)$	3263793447 ± 3
$(3/2^+, 2) - (3/2^-, 2)$	701677682 ± 6
$(3/2^+, 1) - (3/2^-, 1)$	724788315 ± 16
$(3/2^+, 1) - (3/2^-, 2)$	703978340 ± 21
$(3/2^+, 2) - (3/2^-, 1)$	722487624 ± 16

Truppe+ 2014



CH $^{2}\Pi_{/2}$ J = 3/2 – 1/2
2011 GHz/SOFIA/4GREAT

H. Wiesemeyer, R. Güsten, V. Thiel,
A. Jacob (MSc), C. Durán (PhD)

CH Collisional Rate Coefficents

- P. Dagdigian 2016, 2017:
  - Ab initio potential energy surfaces describing the interaction of CH($X\ ^2\Pi$) with H_2
  - CH –H2 collisional rate coefficients

- Ongoing:
  - Faure+: CH –H_2 collisional rate coefficients
  - Lique+: CH –H collisional rate coefficients

The potential of cm-wavelength hfs line observations

- Modeling their relative line intensities can deliver densities, temperature, o/p ratios
  → **Reliable hfs sensitive collisional rate coefficients absolutely mandatory**
- In HMSFs, their regions with absorption (OH) and emission (CH): HII region free-free
  - Have comparable size as the submm background sources
  - Can be imaged (VLA, MeerKAT) with similar resolution as 21 cm HI and the submm lines (Herschel/SOFIA)
- Their **low critical densities** allow observations of **emission**, probing region inaccessible to (rotational) submm absorption
  → Dark clouds, SNR-GMC interactions, …

Low frequency line observations are expensive!

- Emission lines are weak
- Absorption lines

$$T_L = -\eta_{\mathrm{cov}} T_C \left(1 - e^{-\tau}\right) \approx -\eta_{\mathrm{cov}} T_C \tau$$

But:

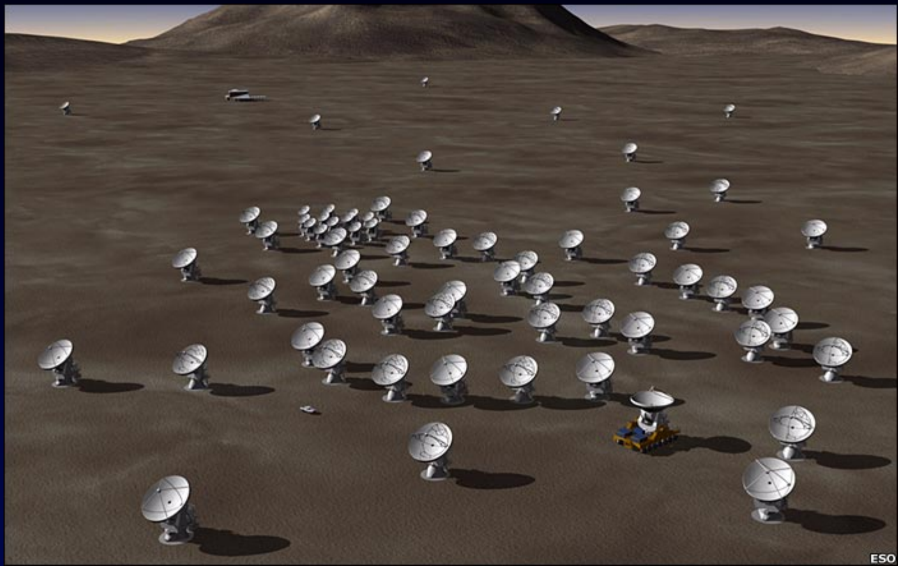
$$\Delta T_L \approx \frac{T_{sys}}{\sqrt{\delta\nu \times t_{int}}}$$

Often: $T_C >> T_{RX}$

$$T_{sys} = T_{RX} + T_C$$

$$\delta\nu = \delta \mathrm{v} \frac{\nu}{c}$$

Much higher signal-to-noise ratios!



Atacama Large Millimeter Array

$$T_A \propto A_{eff} S$$

Talk by M. Krco

FAST

D. Li, R. Nan & Z. Pan

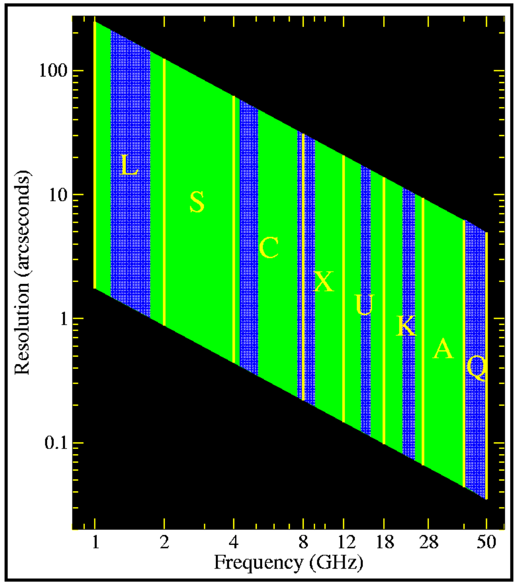
Table 1. Main technical specifications of FAST.

Spherical reflector: Radius = 300m, Aperture = 500m
Illuminated aperture: D_{ill} = 300m
Focal ratio: f/D = 0.4611
Sky coverage: zenith angle 40
Frequency: 70MHz - 3GHz
Sensitivity (L-Band): A/T ~2000, system temperature T_{sys} ~20K
Resolution (L-Band): 2.9′
Multi-beam (L-Band): beam number = 19
Slewing time: <10 minutes
Pointing accuracy: 8″

CH: 3.3 GHz
H_2CO: 4.8 GHz
CH_3OH: 6.7 GHz

Powerful New Radio Interferometer Arrays

Karl G. Very Large Array:
2011- /27 x 25 m
1–50 GHz



GMRT:
30 x 45 m

MPIfR contributes 1.7 –3.3 GHz band

MeerKAT:
2017- /64 x 13.5 m
0.6–1.75 + 8–14 GHz

Space

Presently, both in the US and in Europe, space missions are being discussed that feature high resolution spectroscopy:

NASA FIR Surveyor/Origins Space Telescope

ESA FIRSPEX:

- 4 Bands: [CII] 158 μm (1.9 THz), [NII] 205 μm (1.46 THz), [CI] 370 μm (0.89 THz), CO(6-5) 433 μm (0.69 THz)

The next submm/FIR space observatory will happen in the far future

→ **big problem of losing your community**

→ **important issue when planning for future space missions, e.g., NASA FIR Surveyor, Origins ST, FIRSPEX**

→ **High resolution spectroscopy may fall between the cracks**

→ **Keep SOFIA flying!**


Long duration balloon flights

MORE STORIES

Dec. 9, 2016

Balloons on Ice: Final Flight Launches in Antarctica

The third and final NASA scientific balloon flight from Antarctica's Ross Ice Shelf near McMurdo Station was successfully launched at 3:53 p.m. EST Dec. 8.

The balloon is carrying the Stratospheric Terahertz Observatory (STO-II) from the University of Arizona. The instrument is designed to better understand the life cycle of the interstellar medium, which is the matter that fills the space between stars in the galaxy. Studying the interstellar medium will help us understand more about the life cycle of stars.

"This has been the earliest in an Antarctica campaign that all the planned missions were successfully launched," said Gabe Garde, NASA project manager. "The science and balloon teams and personnel with the National Science Foundation's United States Antarctic Program, all came together for the launches to be conducted early in the launch window."

Far Infrared

Kuiper Airborne Observatory:
1974-1995/D = 0.915 m

Radio

Very Large Array:
1980-2011/27 x 25 m

Very long time span without a significant new observatory

Herschel:
2009-2013/
D = 3.5 m

SOFIA
2011+/D = 2.5 m

Karl G. Very Large Array:
2011- /27 x 25 m

Submillimeter hydride absorption spectroscopy delivers crucial information on diffuse cloud and PDR chemistry

SOFIA and APEX are carrying on

Great potential of adding radio wavelength data

Powerful new radio facilities

APEX and SOFIA Workshops (in alternating years)

- at Ringberg Castle, Bavaria
- organized by Friedrich Wyrowski
- Next SOFIA workshop March 5-8, 2017


Thanks for your
attention