GREAT results from SOFIA

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Overview

- SOFIA
- GREAT
- (Galactic) Science with GREAT
  - First detections
  - Velocity-resolved spectra
  - The [OI] ground-state line
  - Gas kinematics and composition
  - The ISM cooling balance
- Outlook: upGREAT

SOFIA

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DLR-Pf

Stratospheric Observatory for Infrared Astronomy

- Boeing 747SP (Special Performance)
- Operating altitude: 11-14km
  - above 99.8 percent of the Earth's atmospheric water vapor
  - mainly from Palmdale/CA
- US/German project
  - 80/20 in cost & time
- Telescope:
  - Primary Mirror:
    - 2.7 meters
    - λ > 0.3µm
  - Chopper: 10' at 2Hz
  - Pointing ~ 1"

Instruments

Science Instrument	Type*	Developing Institution	Principal Investigator	Instrument Description
FORCAST	FSI	Cornell University	Herter	Simultaneous Dual Channel Imaging and Grism Spectroscopy (5-25 μm and 25-40 μm)
GREAT	PSI	Max Planck Institute, Bonn	Güsten	High Resolution (R > 10^6) Heterodyne Spectrometer (1.25-1.9THz; 2.5-2.7THz; 4.7 THz)
HIPO	SSI	Lowell Observatory	Dunham	Visible Light High-Speed Camera (0.3-1.1 μm)
FLITECAM	FSI	UCLA	McLean	Near Infrared Imaging and Grism Spectroscopy, (1-5.5 μm); Can be used in combination with HIPO
FIFI-LS	PSI → FSI	University of Stuttgart	Krabbe	Dual Channel Integral Field Grating Spectrometer (42-110 μm; 100-210 μm)
EXES	PSI	UC Davis	Richter	High Resolution (R > 10^5) Echelle Spectrometer (5-28 μm)
HAWC → HAWC+	FSI	University of Chicago → JPL	Harper → Dowell	High-Angular Resolution Wide-Band Camera with 4 Channels (50 μm, 100 μm, 160 μm, 200 μm)

Instruments

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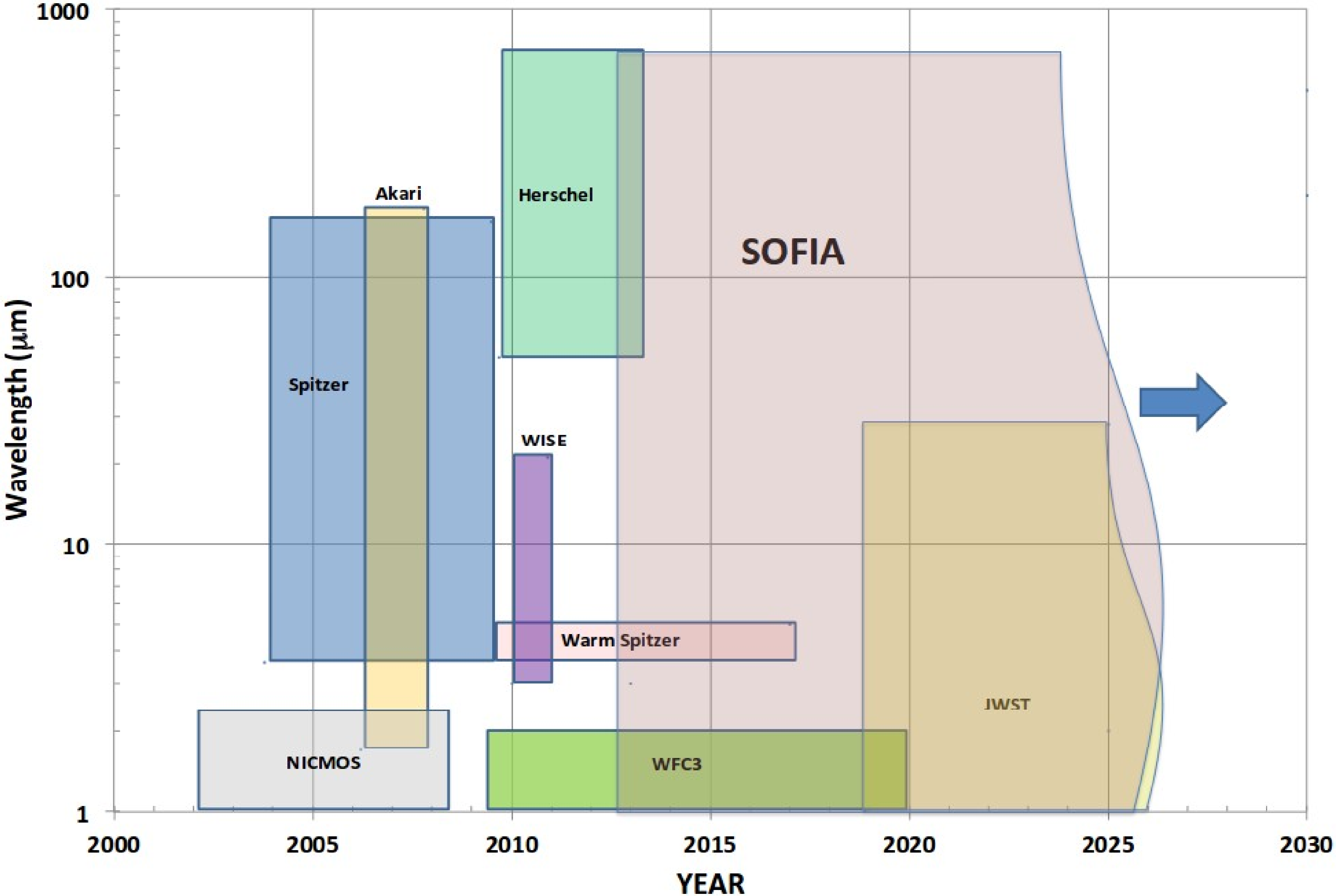

Cycle 4 call

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- Observing period: Feb 2016 - Jan 2017
- All 7 instruments offered:
  - EXES, FIFI-LS, FLITECAM, FORCAST, GREAT, HAWC+, HIPO, and the FLITECAM/HIPO combination
  - Instruments for Southern deployment tbd., based upon requests
- SOFIA Impact Programs solicited
  - Multi-year programs
  - Joint US – German Impact Programs
- Deadline:
  - July 10
- http://www.dsi.uni-stuttgart.de/observatorium/proposals/cycle04/index.html (D)
- http://www.sofia.usra.edu/Science/proposals/cycle4/index.html (US)

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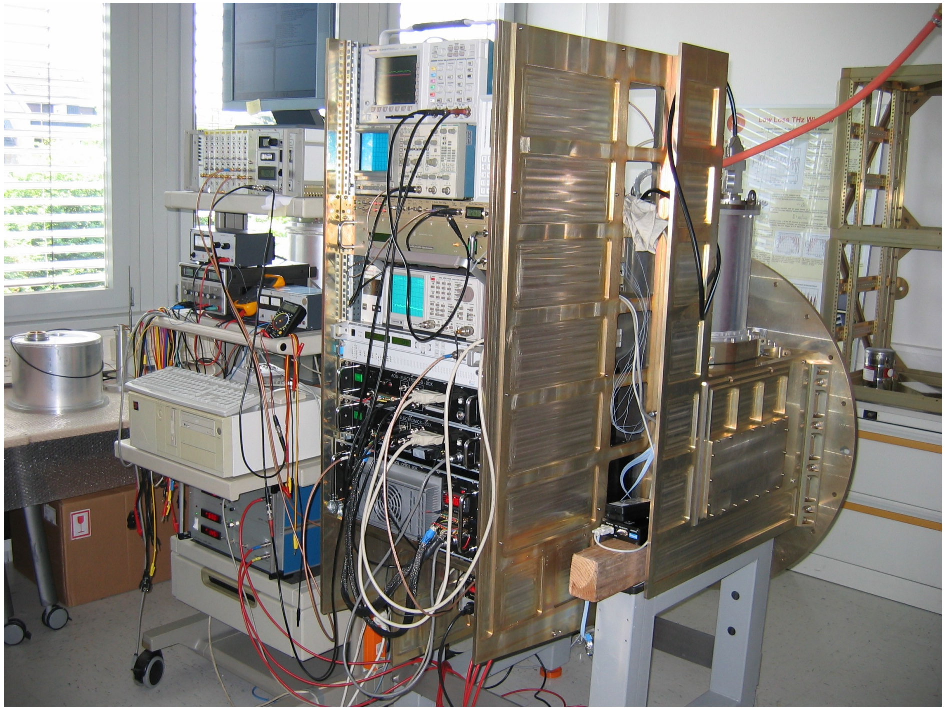
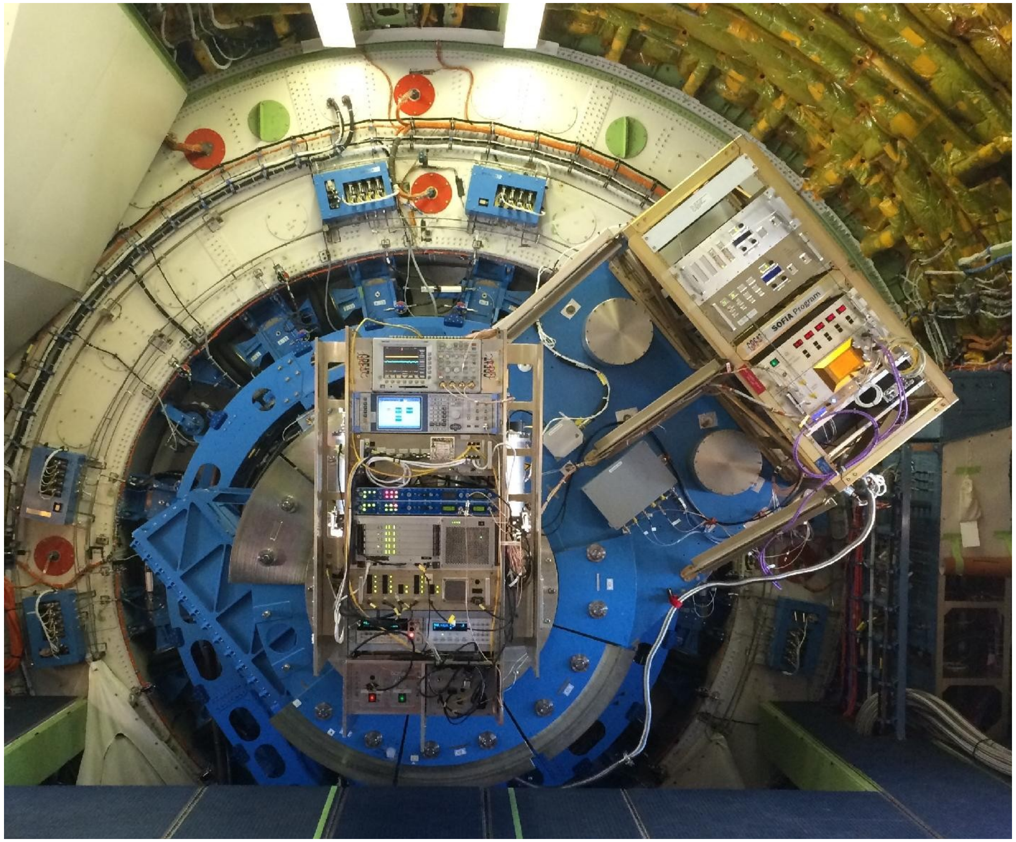
German REceiver for Astronomy at Terahertz-Frequencies

- Heterodyne receiver
  - Single pixel
  - Dual channel
    - Two frequencies simultaneously
  - 1.2 – 4.7 THz
    - in 5 frequency-bands





- XFFTS
  - 64000 channels
  - Bandwidth: 2.5GHz
  - Resolution: 44kHz (R = 10^8)

Frequencies:

Channel		Frequencies [THz]	Lines of interest
low-frequency	L1	1.26 – 1.52	[NII], CO series, OD, H_2D^+
low-frequency	L2	1.82 – 1.91	NH_3, OH, CO(16-15), [CII]
mid-frequency	Ma	2.49 – 2.56	$^{(18)}OH(^2\Pi_{3/2})$,
	Mb	2.67	HD
high-frequency	H	4.74	[OI]

- System temperature (DSB):
  - 700 - 800K in L1 and L2 channels
  - 2000 - 2500K in M and H channels
- Beam:
  - 22" (1.26 THz)
  - 6.6" (4.74 THz)

GREAT science

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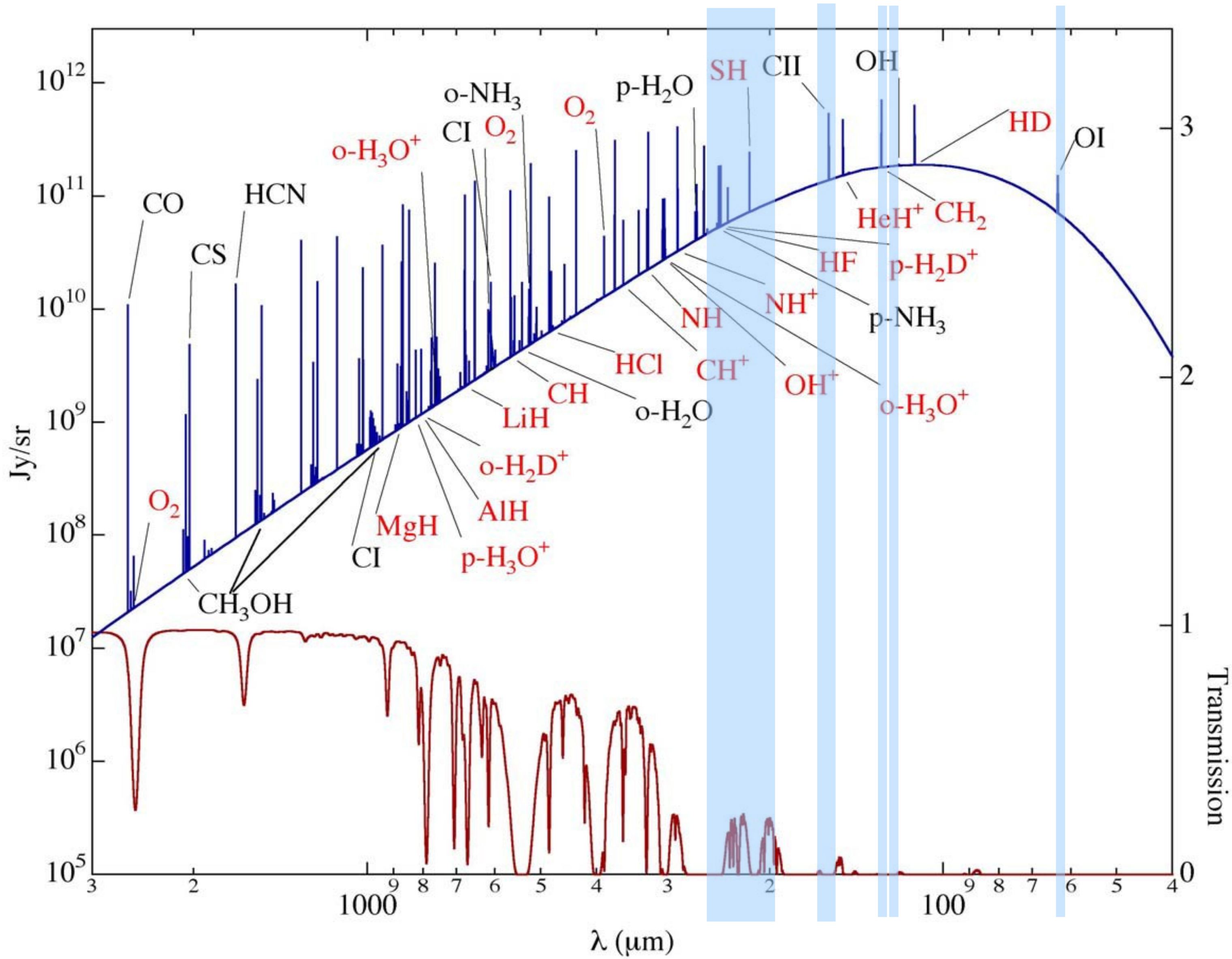
- Focused on main cooling lines:
  - [OI], [CII]
- OH, HD
- High-J CO transitions
- Hydrides
- Covers HIFI-gap



Bergin (2008)

First detections

HD detection:

- Sgr B2
  - Previously claimed detection (Polehampton et al. 2002, LWS: 55K km/s) very unlikely
  - Narrow line

Güsten et al. in prep.

HD detection towards SgrB2 (M)

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Should allow to constrain D abundance

→ Deuteration history of the universe!

But: complex structure in the beam

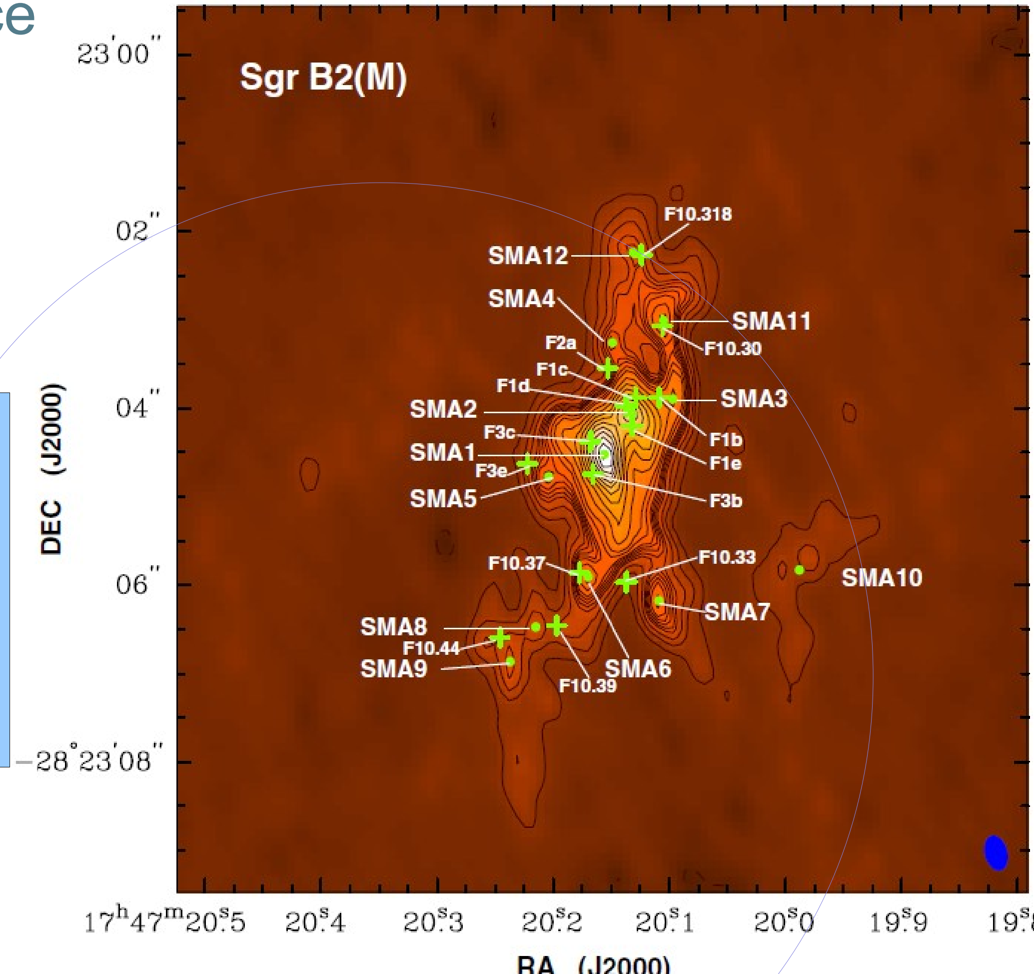
- Kinematics → SMA2 (F1) hot core

- HD abundance:

  N(HD): 2 (±.2) 10^{18} cm^{-2}

  N(H_2): $10^{23.8}$ – $10^{24.4}$ cm^{-2}

  → [HD]/[H_2] = 0.8 – 3.3 10^{-6}



Qin et al. (2011, SMA 850 µm continuum)

First detections

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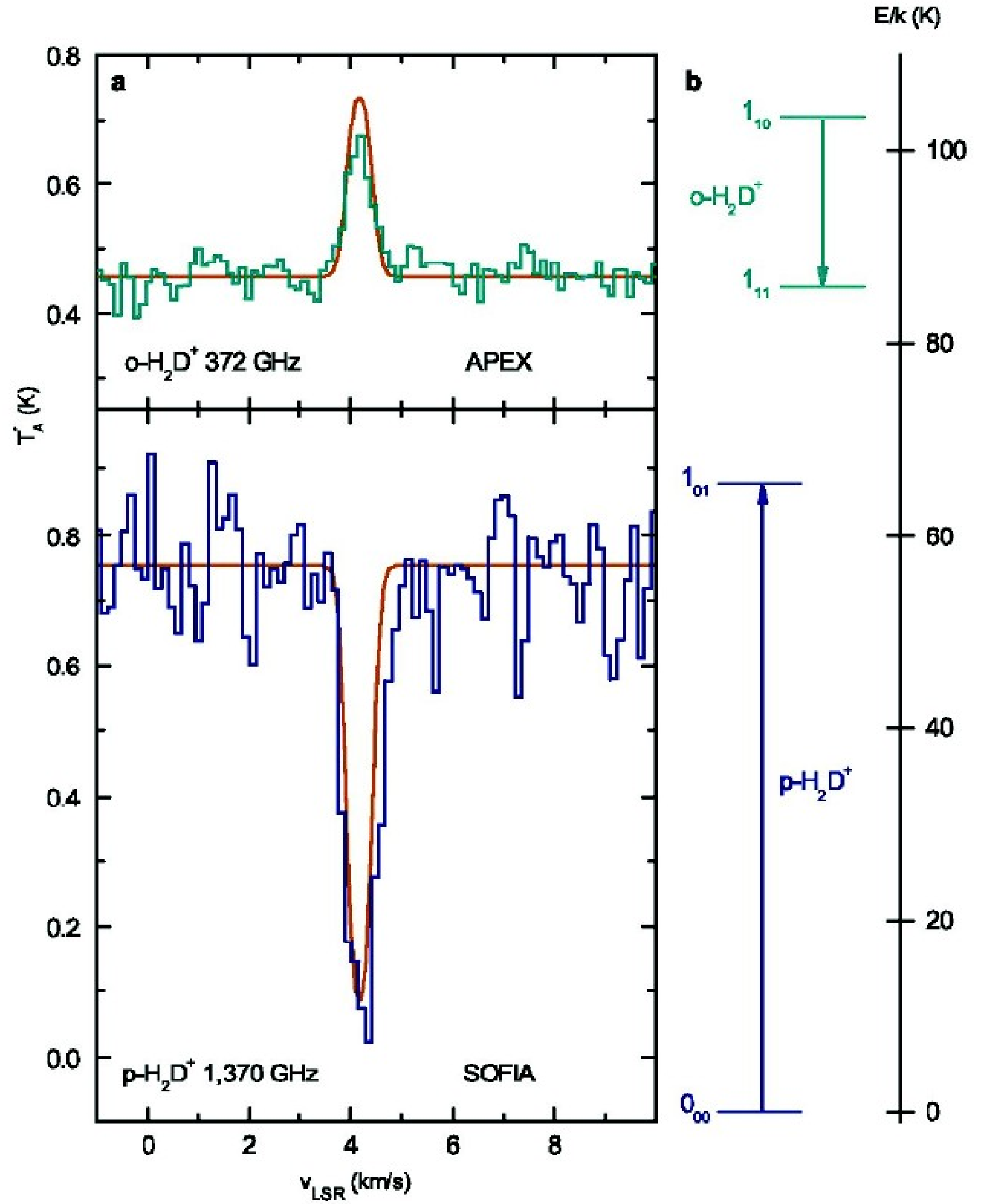
para-H_2D^+ detection:

- IRAS16293-2422
  - Measure o/p ratio in H_2 through o/p of H_2D^+
  - At low T
    p-H_2D^+ + o-H_2 → o-H_2D^+ + p-H_2
    dominates over back reaction
  - Chemical clock

    → Cold gas in dense envolope for 5 10^5 - 5 10^6 a

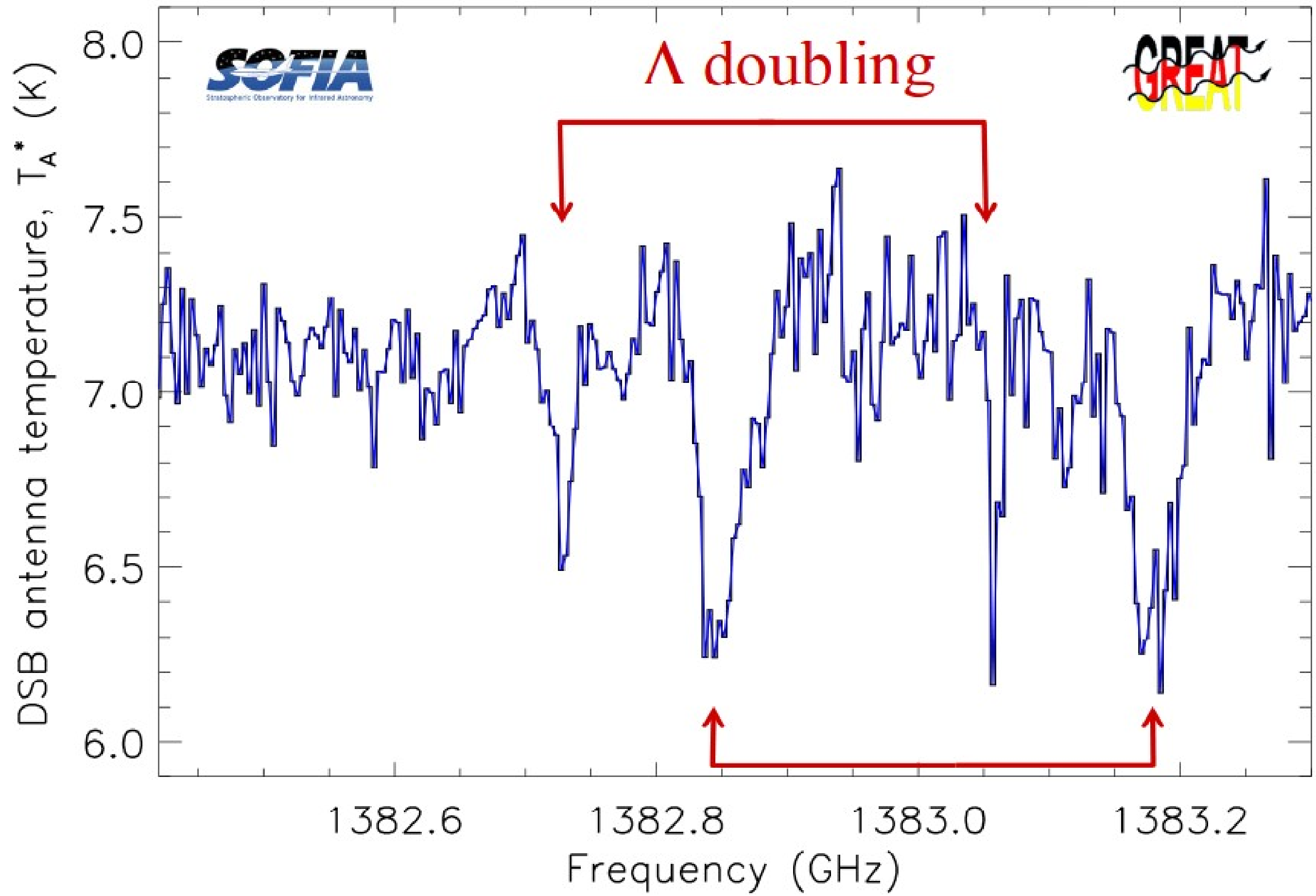
Brünken et al. (2014)



First detections

SH detection:

- In absorption towards W49N, W31C, W51, G29.96-0.02, G34.3+0.1

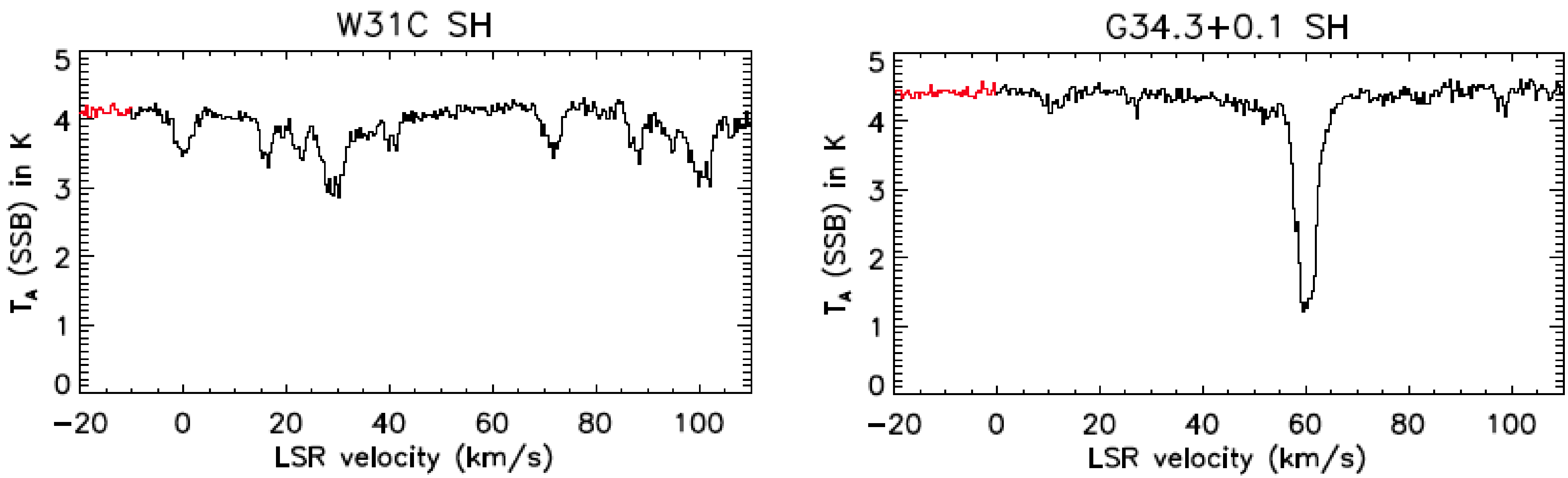


W49N
Neufeld et al. (2014)

- Several foreground clouds → spiral structure

First detections

SH detection:



- SH is only produced at elevated temperatures
  - Key tracer for warm diffuse chemistry
  - Requires shock or TDR models
    - But so far they fail to explain H_2S/SH ratio

Neufeld et al. (2014)

High-resolution spectra

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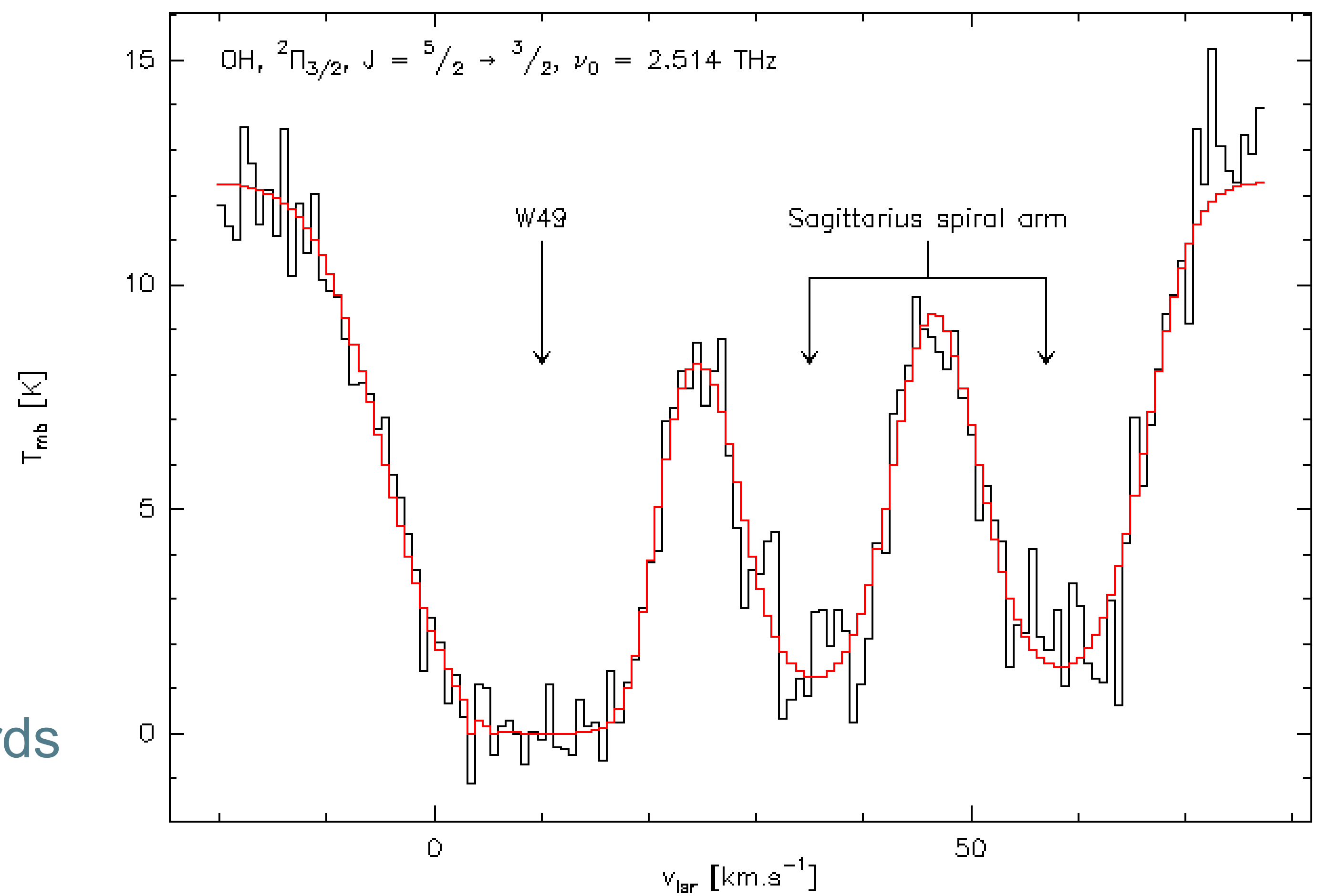
OH absorption:

H. Wiesemeyer - A&A 542 L7 (2012)

- 119µm ground state transitions
  - First >2THz spectroscopy
  - Absorption towards W49N
  - Spectral features of Sagittarius arm
  - Discovery of ^{18}OH
  - OH saturated towards W49N
  - X(OH)=10^{-7} – 10^{-8}



Wiesemeyer et al. (2012)

OH absorption

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Systematics (G10.47, G34.26, W31C, W49N, G327.29, G351.58):

- OH^+ traces atomic, OH rather molecular diffuse gas:
  - OH^+ has lower arm/interarm contrast than OH
  - $[OH]/[OH^+]$ correlated with H_2: bottleneck $OH + H_2 \rightarrow H_2O + H$
  - H_2O/OH ratio to be explained by TDR model

Wiesemeyer et al. in prep.

[OI] ($^3P_1$ -$^3P_2$ = 63µm)

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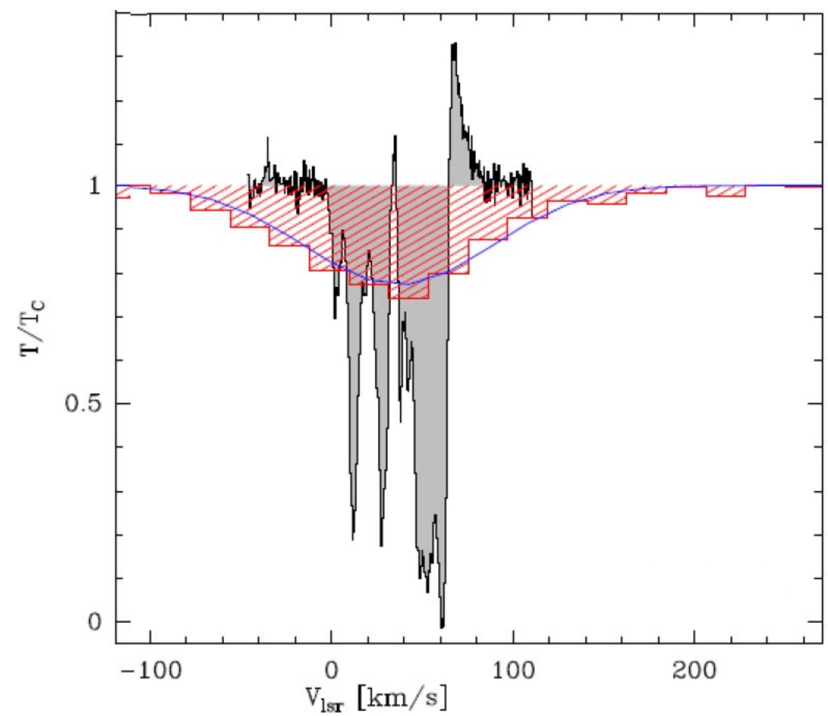
[OI] absorption:

Wiesemeyer et al. in prep.

- Complex profiles in many sources



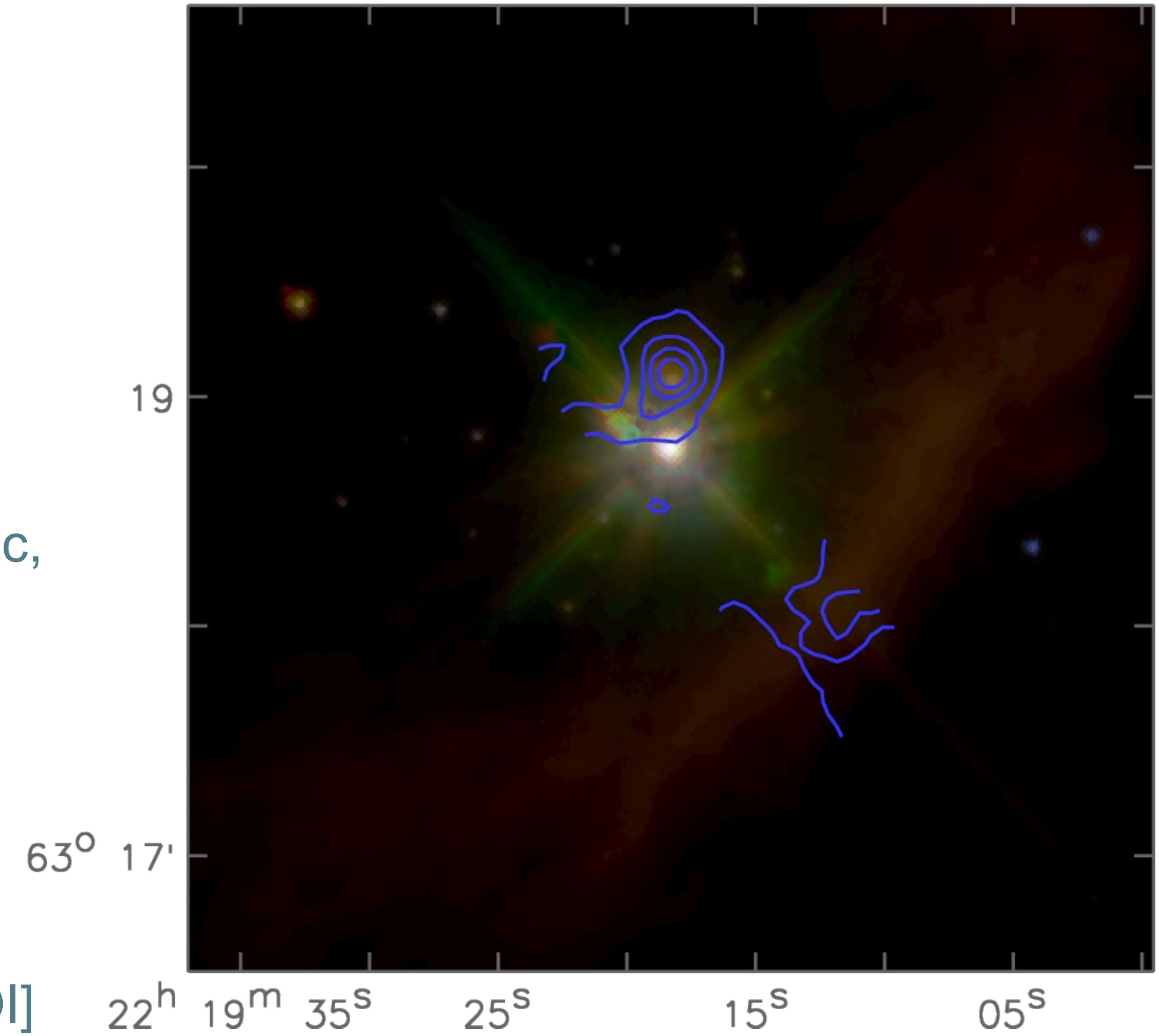
- PACS washes out all relevant information

- [OI] traces both atomic & molecular diffuse gas, up to A_V ~ 1 mag

[OI] $^3P_1$ -$^3P_2$

S140:

- First [OI] 63μm observations with H-channel
- [OI] strongly peaked, but at IRS2, not IRS1
  - Resolved in [OI]: FWHM = 8.3" = 0.03pc, $L([OI])=0.05\ L_\odot$, $L([CII])=0.28\ L_\odot$, $L(dust)=2000\ L_\odot$
  - IRS1, the main energy source of the region produces almost no [CII] and [OI]



Ossenkopf et al. subm.

Line profiles

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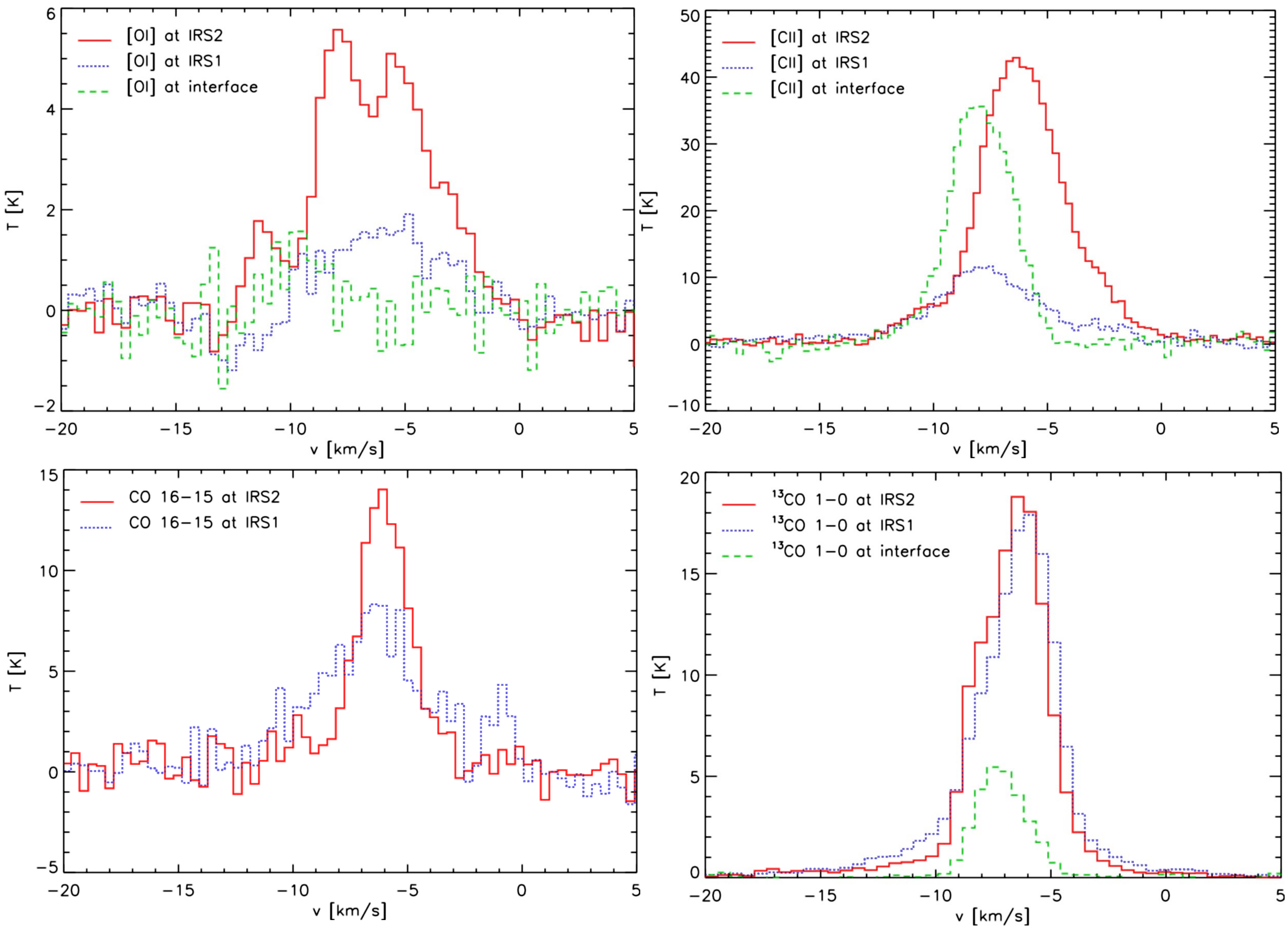
[OI] with moderate self-absorption, [CII] partially optically thick



- 1.5km/s velocity difference between IRS2 and bulk of cloud
- PDR model fits:

  [CII] intensity requires 10^5 cm^{-3}, dust 10^6 cm^{-3}, [OI] 300 cm^{-3}
- Nature of the source:

  Big puzzle!

[OI] $^3P_1$ -$^3P_2$

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G5.89-0.39:

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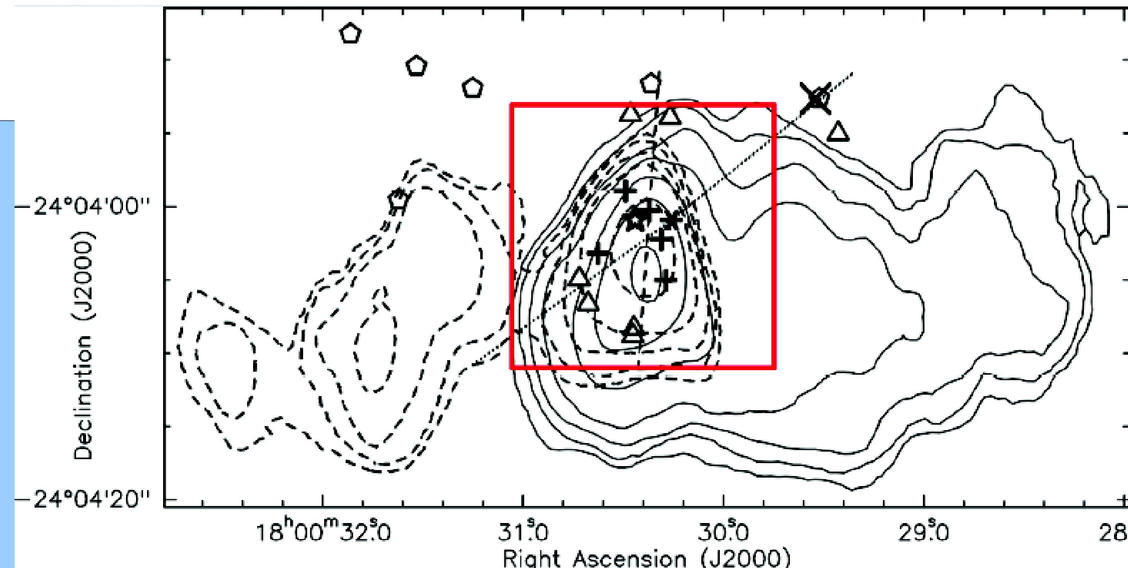

Hunter et al. (2008)

- Massive star-forming region
- hosts O8 star with UCHII and massive outflow
- Complex [OI] with very broad wings

Leurini et al. subm.

[OI] $^3P_1$ -$^3P_2$

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G5.89-0.39:

- [OI] is main coolant:
  - 75% of total line luminosity
  - Dominates cooling budget
  - Strongly self-absorbed
  - High-velocity emission!
- The large scale molecular outflow is driven by atomic jets!
  - $10^{-4}\ M_{\odot}/a$

Leurini et al. subm.

NGC 2024

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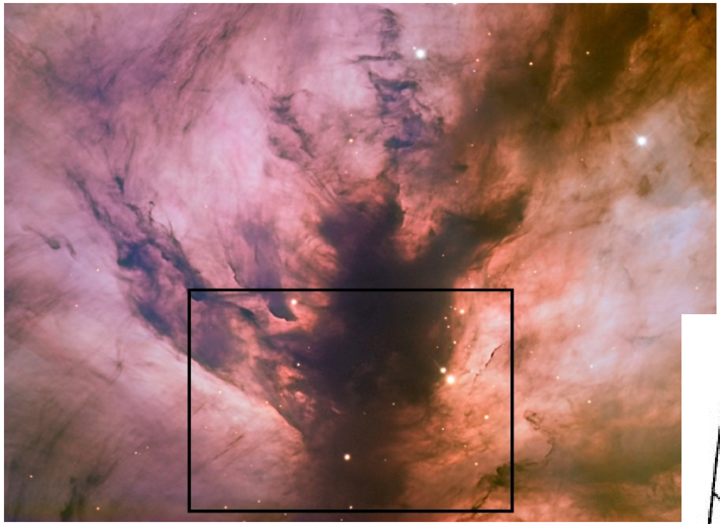
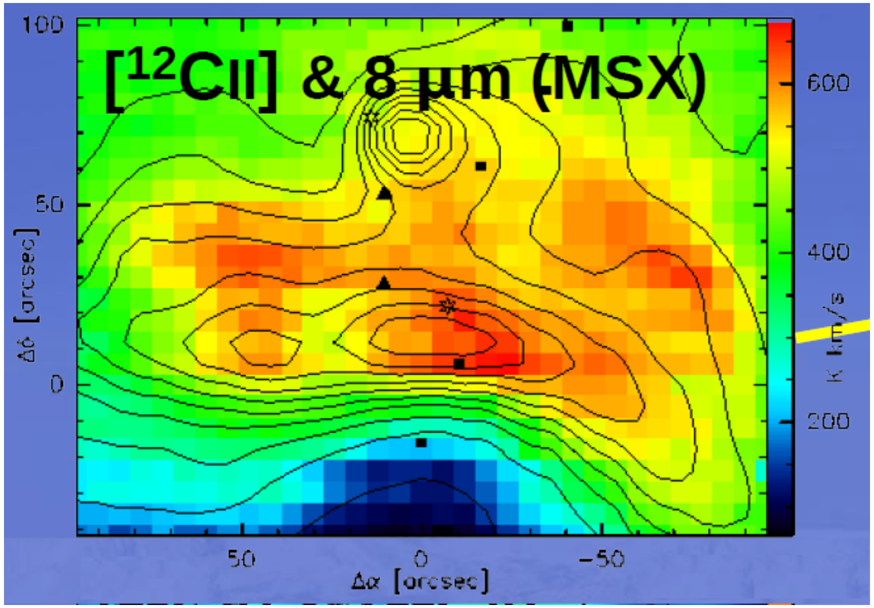
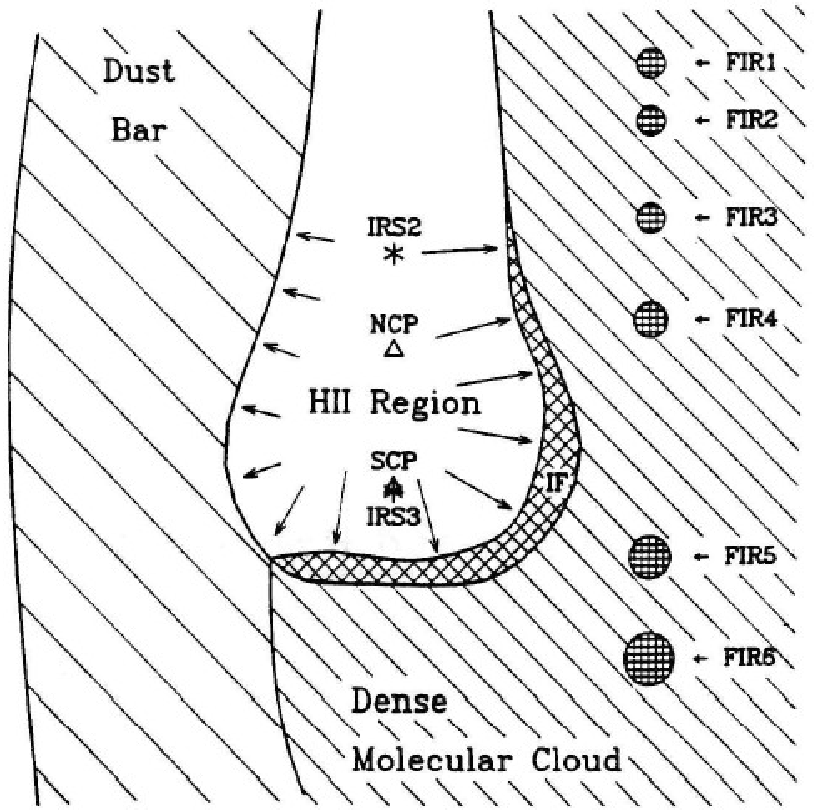
- HII region shadowed by optically opaque dust lane
- [CII], [^{13}CII], and [OI] mapped by GREAT

Graf et al. (2012)







[OI] $^3P_1$ -$^3P_2$

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NGC2024:

- 85% of [OI] emission obscured by foreground
- Consistent with foreground hydrogen column density 10^{22} cm^{-2}
- Background [OI] / [CII] intensity ratio ~ 5 indicates substantial density and radiation field
- Full model still pending

Graf et al. in prep.

NGC 2024

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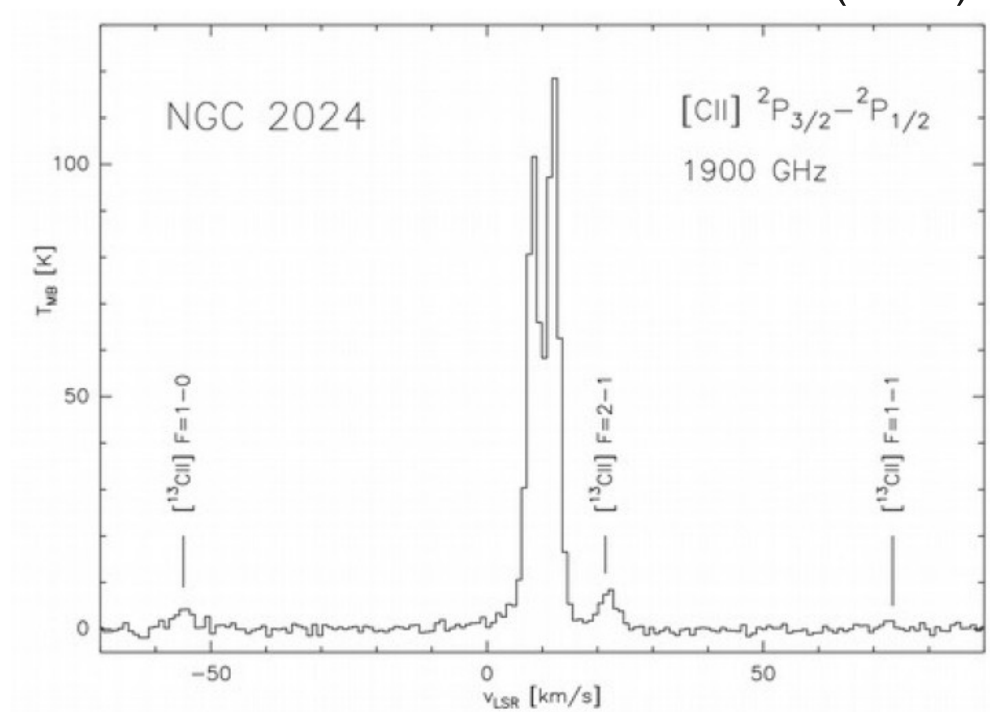
- [CII] and [^{13}CII]

- [^{13}CII] emission requires $N(^{13}C^{+}) \sim 2.6\text{x}10^{17}$ cm^{-2} $\rightarrow N(H) \sim 1.6\ 10^{23}$ cm^{-2}
- This is as high as the total column density deduced from CO!

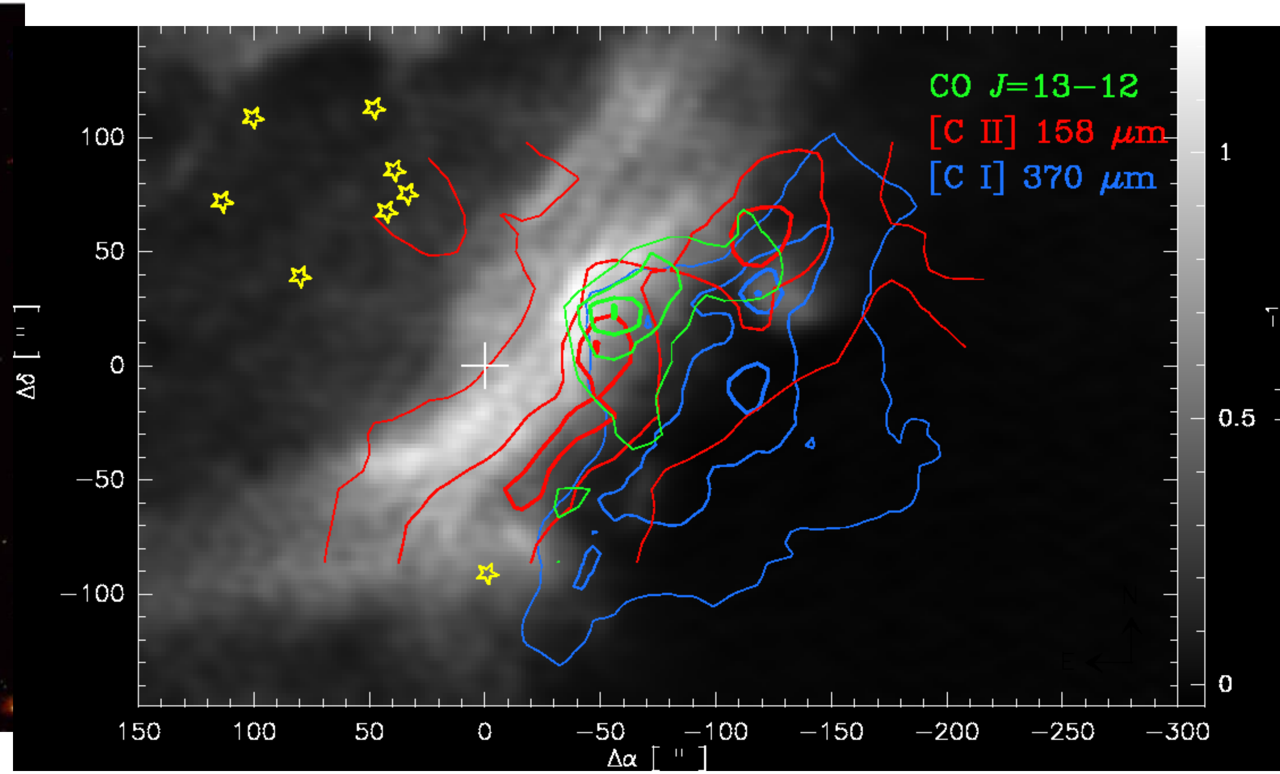
Graf et al. (2012)



Gas composition and kinematics

M17SW (Clumpy PDR):

- GREAT mapping of the cloud in [CII], CO 13-12 and 16-15
- Many complementary observations with APEX



Clear PDR stratification with layering structure between HII (radio continuum), [CII], hot CO and [CI]

Perez-Beaupuits et al. (2015)

M17 SW

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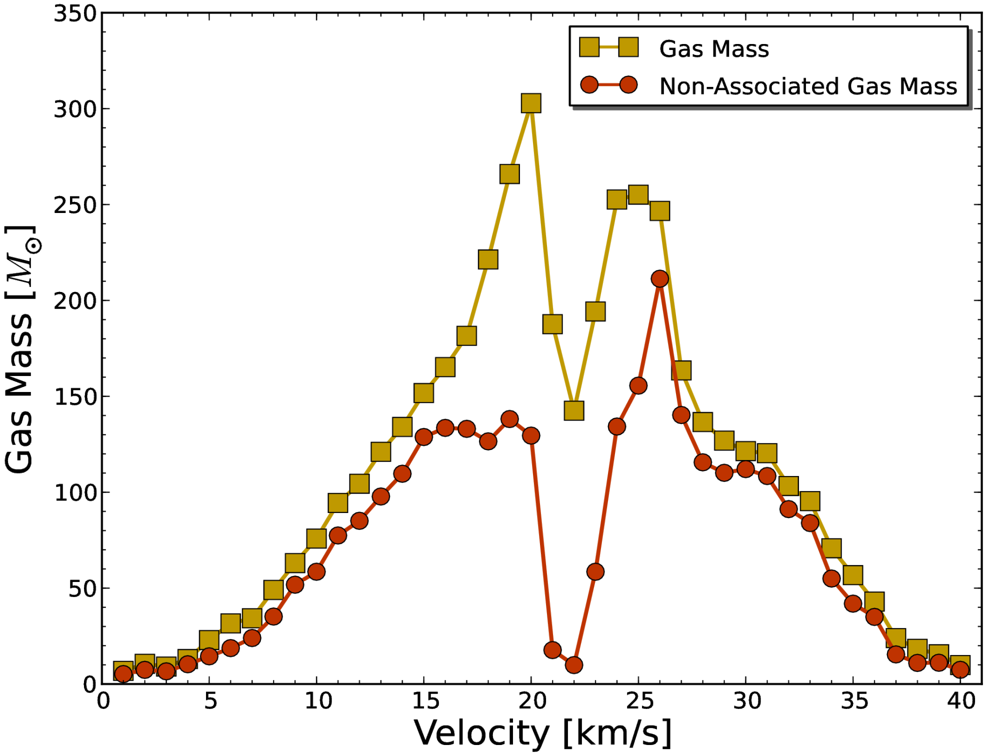
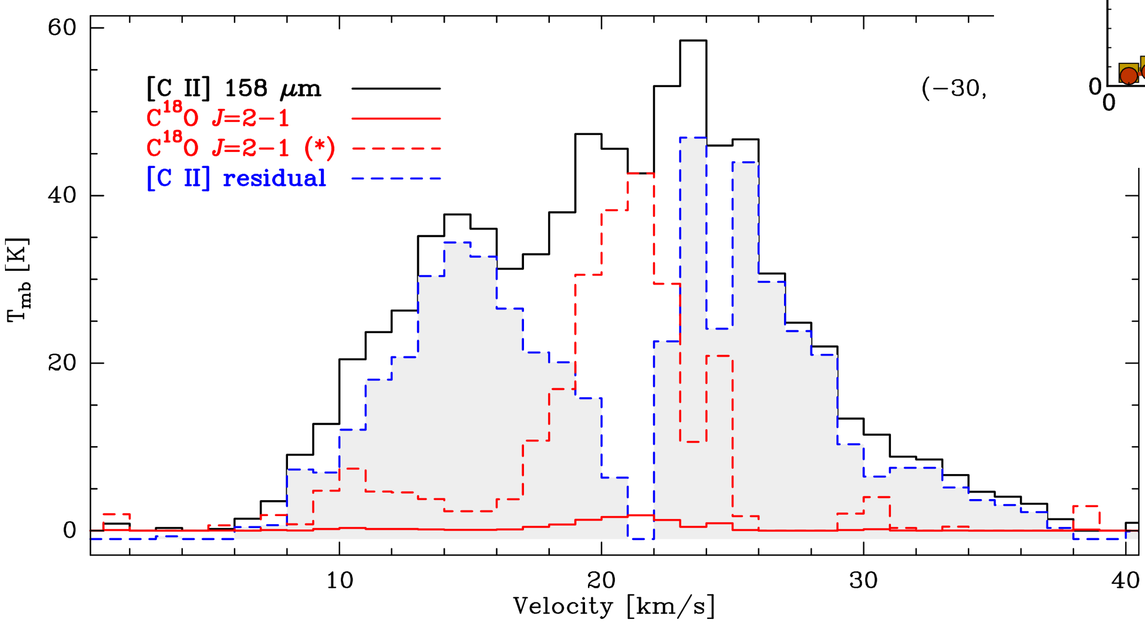
DLR-Pf

- 64% of the mass traced by [C II] is not associated with star-forming material traced by [CI] and $C^{18}O$
- Assignment to phases:
  - 36% - HII
  - 17% - HI
  - 47% - H_2





- Most [CII] at velocities far from the cloud velocity has no high-density counterpart
- Large-scale flows and photo-evaporation

Perez-Beaupuits et al. (2015)

Cooling balance

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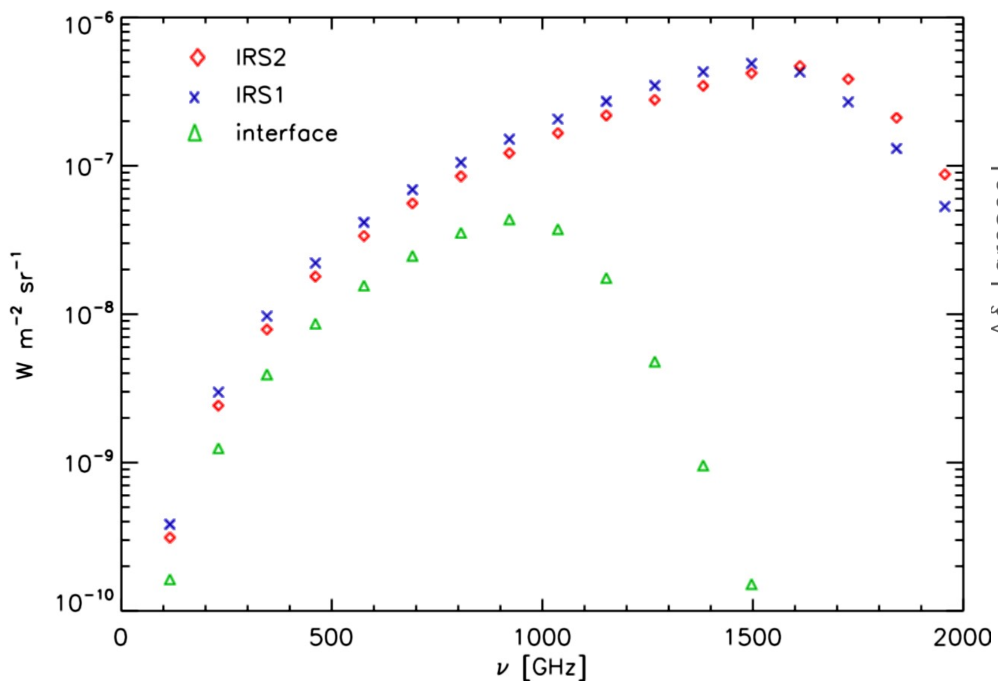
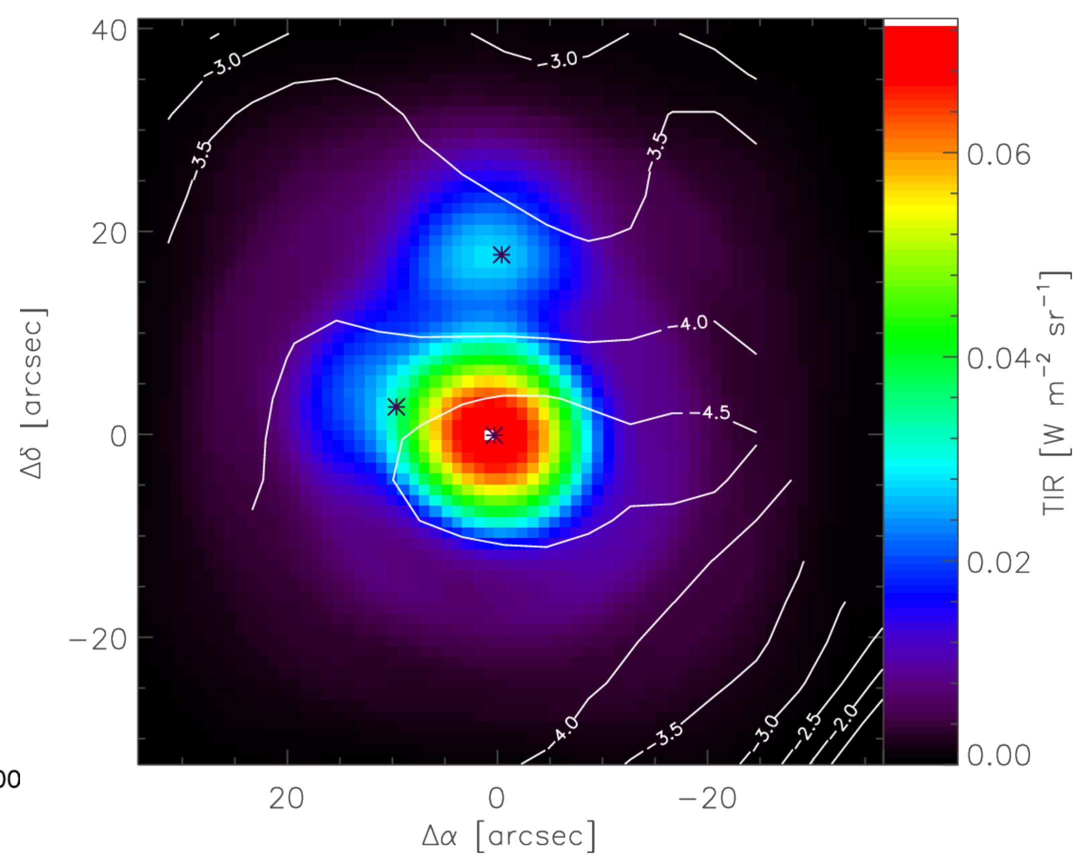
- [OI] and [CII] are main cooling lines of the dense ISM
- CO ladder also traced by GREAT observations
- Line to continuum ratio should measure gas heating efficiency

S140:

- **Factor 100 lower** than in PDRs
- Similar to line deficit in ULIRGS



$\log_{10}(([OI]+[CII])/TIR)$



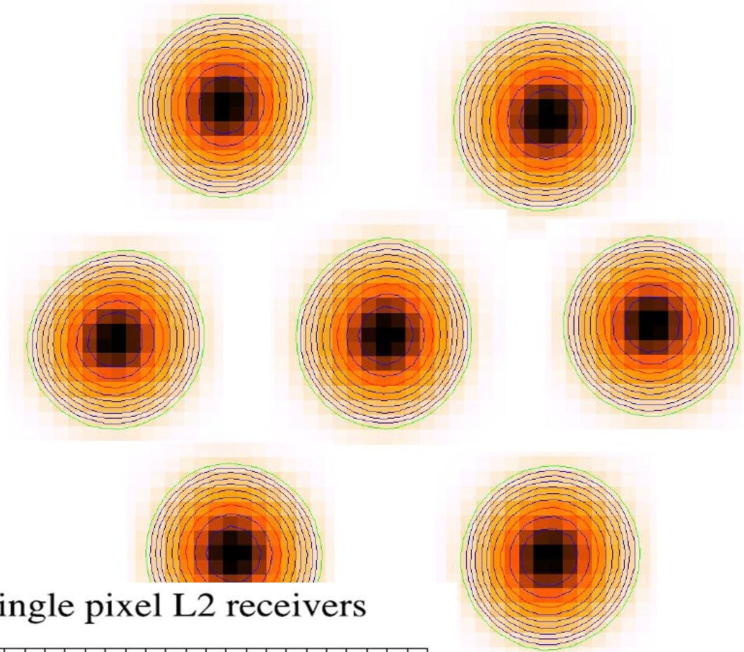
Conclusions

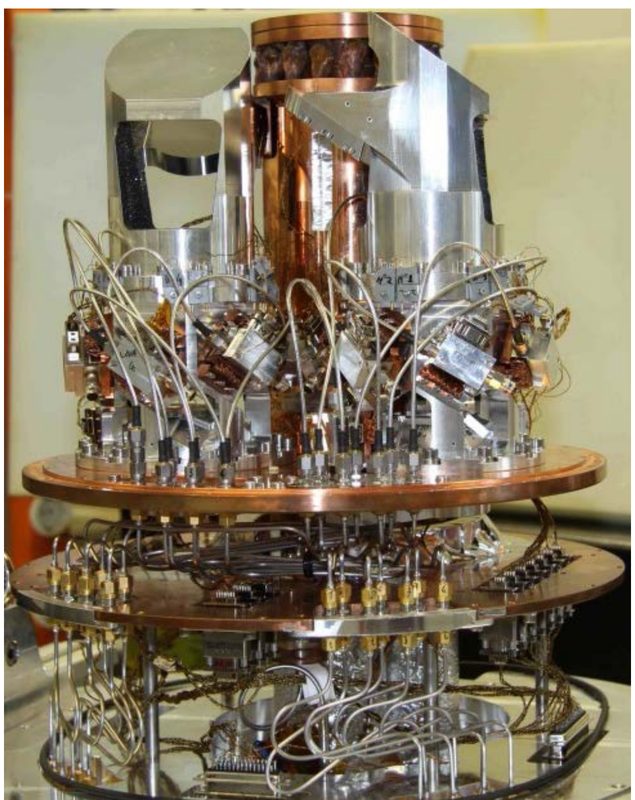
We are still at the very beginning!

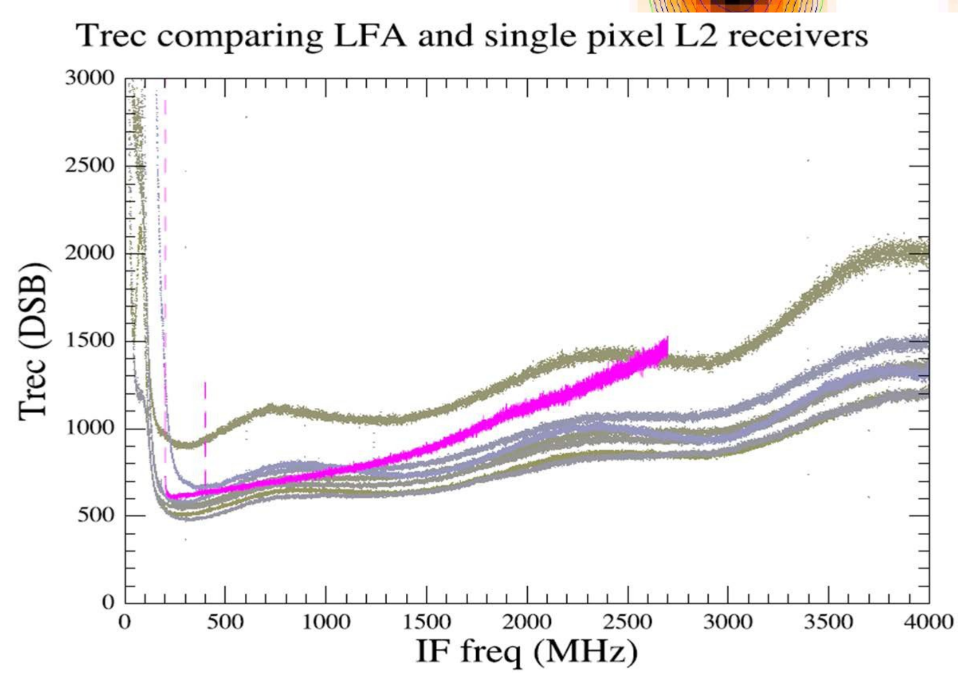
- More new detections with GREAT are to be expected! (e.g. C_3^+...)
  - Constraints on TDR models from several hot-chemistry tracers
  - OH allows to assess H_2 fraction
- [OI] traces velocity structure and foreground in a complex way
  - [CII] + [OI] to FIR continuum cooling between $10^{-4.5}$ and 10^{-2}
  - No clear correlation between line deficit and self-absorption
  - Gas distribution towards many sources poorly known
  - Large fraction of gas only seen in [CII]
- Assessment of the full gas reservoir only from velocity-resolved observations of many species: at least CO, CI, CII, OI, OH, and OH^+
- We need more large-scale mapping projects

Outlook

- **UpGREAT**
  - LFA (1.9-2.5THz): 2x7 pixels
    HFA (4.7THz): 7 pixels
  - Sucessfully commissioned yesterday!
  - Performance as good as single-pixel







Outlook

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- **UpGREAT**
  - **Cycle 4 call is updated to include LFA at 1.9THz !**

	Low Frequency Array (LFA)	High Frequency Array (HFA)
RF Bandwidth	1.9-2.5 THz (goal)	~4.745 THz
IF Bandwidth	0.2-4 GHz	0.2-4 GHz
HEB technology	Waveguide-based HEB NbN on Si membrane	Waveguide-based HEB NbN on Si membrane
LO technology	Cooled photonic mixers (goal) / solid-state chains (baseline)	Quantum cascade lasers (QCL)
LO coupling	Beamsplitter	Beamsplitter
Array layout	2x7 pixels for orthogonal polarizations in hexagonal configuration with central pixel	1x7 pixels in hexagonal configuration with a central pixel
Expected T_{REC}	~600-1200K DSB 0-4GHz IF	~800-1600K DSB 0-4GHz IF
Backends	0-4 GHz with 16k channels	0-4 GHz with 16k channels

Cycle 4 call

- Deadline:
  - July 10
- http://www.dsi.uni-stuttgart.de/observatorium/proposals/cycle04/index.html (D)
- http://www.sofia.usra.edu/Science/proposals/cycle4/index.html (US)