GREAT science from SOFIA

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Overview

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KOSMA
MPS
DLR-Pf

- SOFIA
  - Telescope
  - Operations
  - Instruments
- (up)GREAT results
  - First detections
  - Velocity-resolved spectra
  - The [OI] ground-state line
  - Gas kinematics and composition
- Outlook

(Disclaimer: Galactic science only here)

SOFIA

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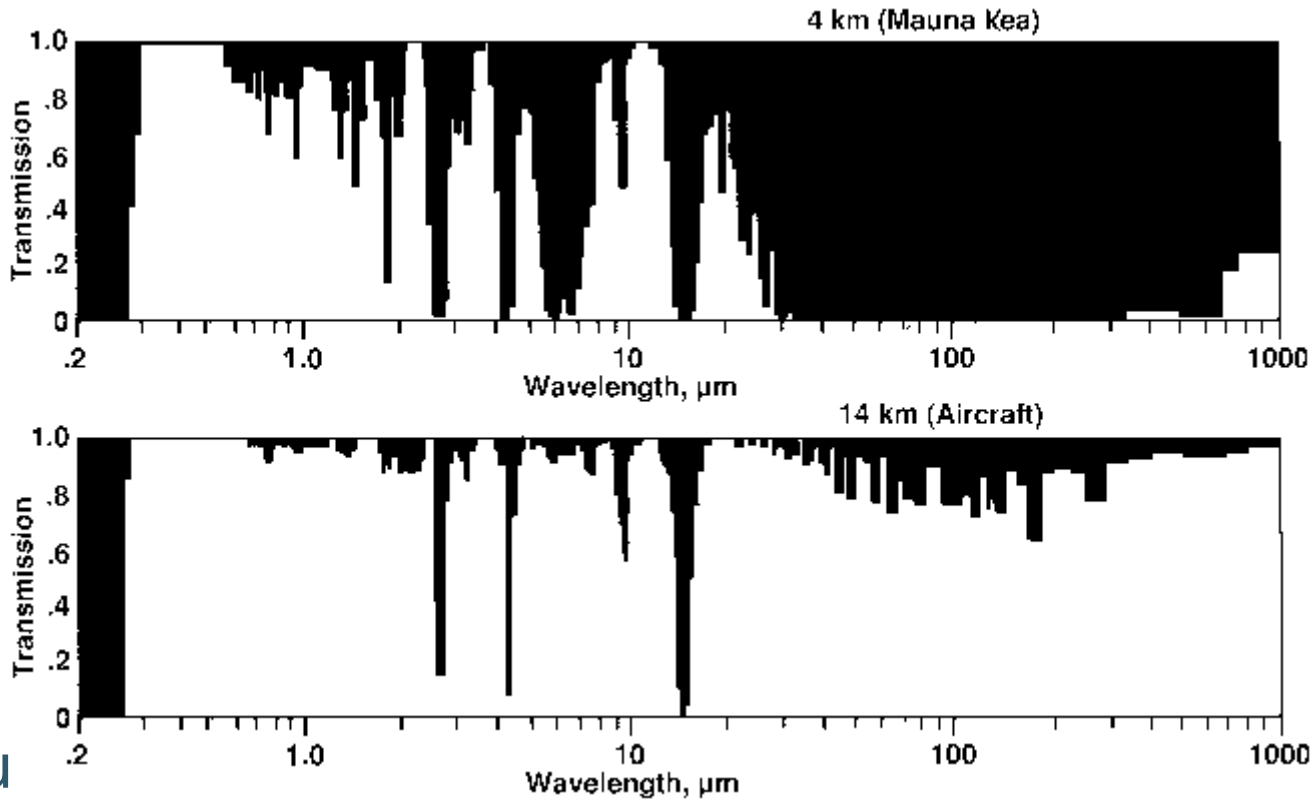
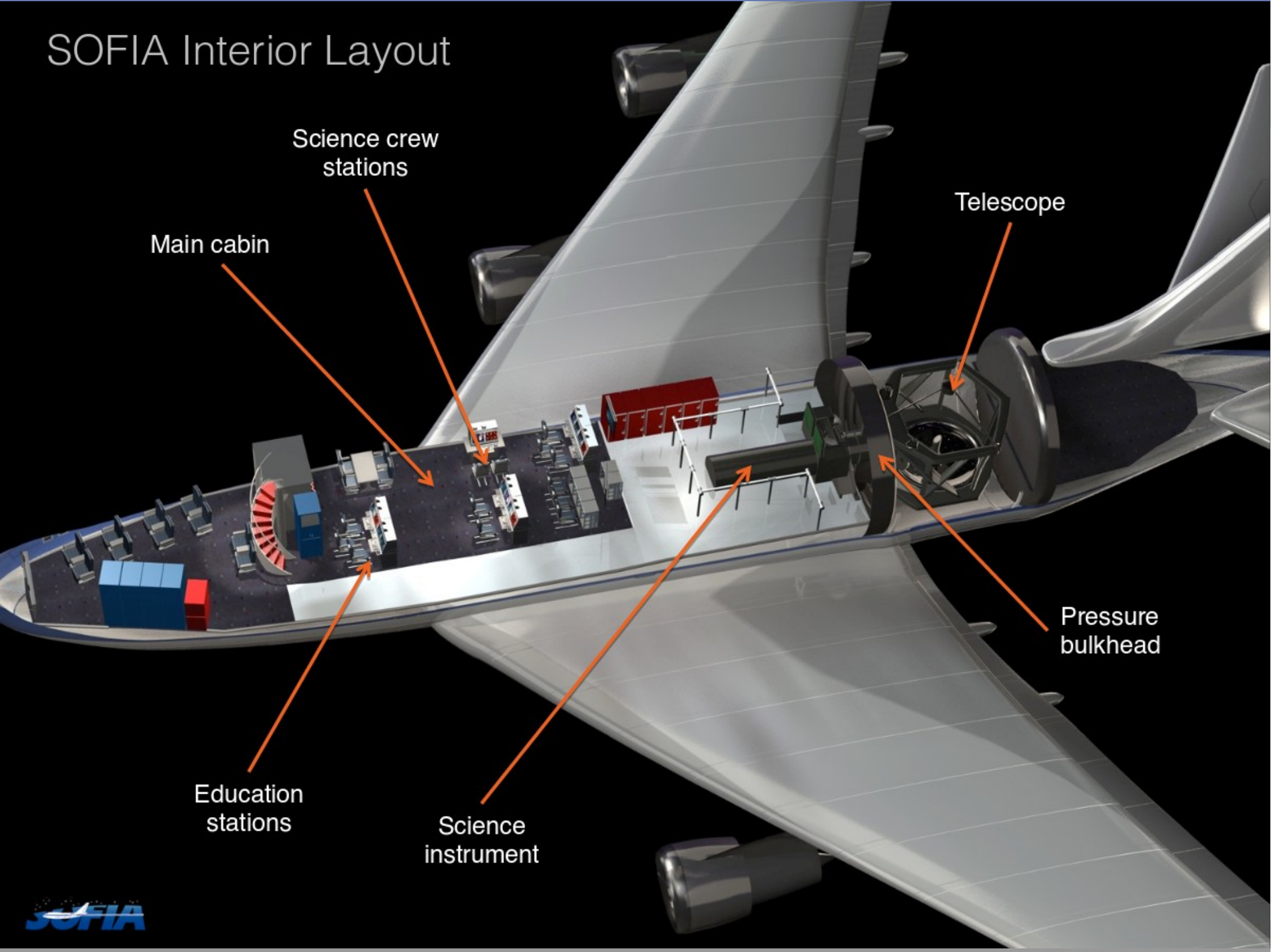
Stratospheric Observatory for Infrared Astronomy

- Boeing 747SP (Special Performance)
- Operating altitude: 11-14km
  - Above 99.8% of the atmospheric water vapor
  - mainly from Palmdale/CA
- US/German project
  - 80/20 in cost & time
- Fully operational since mid 2014
  - > 350 flights so far



http://www.sofia.usra.edu

SOFIA Interior Layout



Telescope

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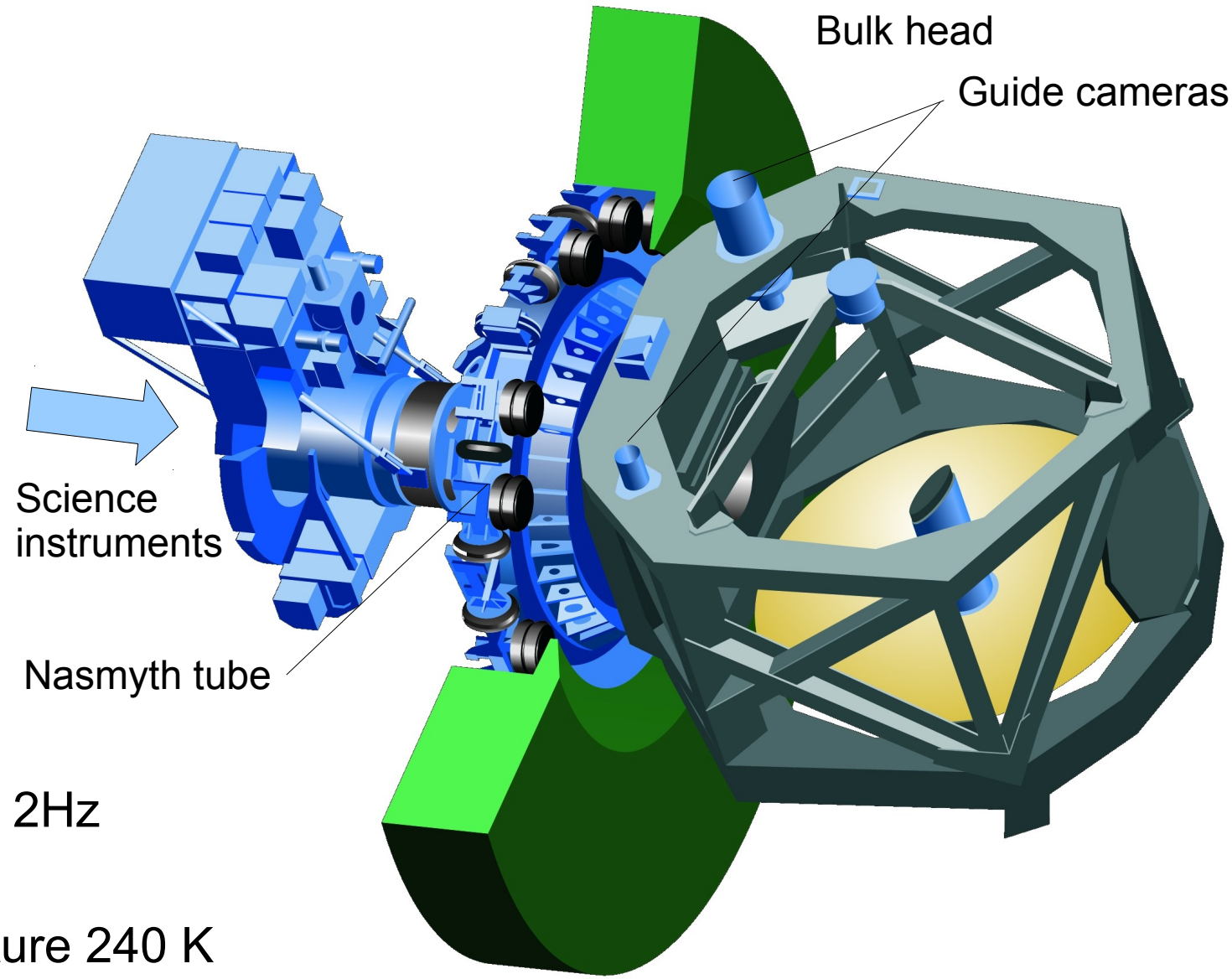
- Telescope:
  - Primary Mirror:
    - 2.7 meters
    - λ > 0.3μm
  - Pointing accuracy ~1"
    - Diffraction limited for λ>20 μm
  - Chopper: 10' at 2Hz
  - optics temperature 240 K



Operations

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- Flexible world wide deployment (Southern sky from New Zealand)
- Typical observing flight duration: 10 hours (8-9 hours at observing altitude)
- 100 flights per year in routine operation
- Planned lifetime 20 years +

- SOFIA Flight Operations Center
  - Armstrong Flight Research Center Dryden, Palmdale, CA

SOFIA Operations:

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Armstrong Flight
Research Center:

Flight planning

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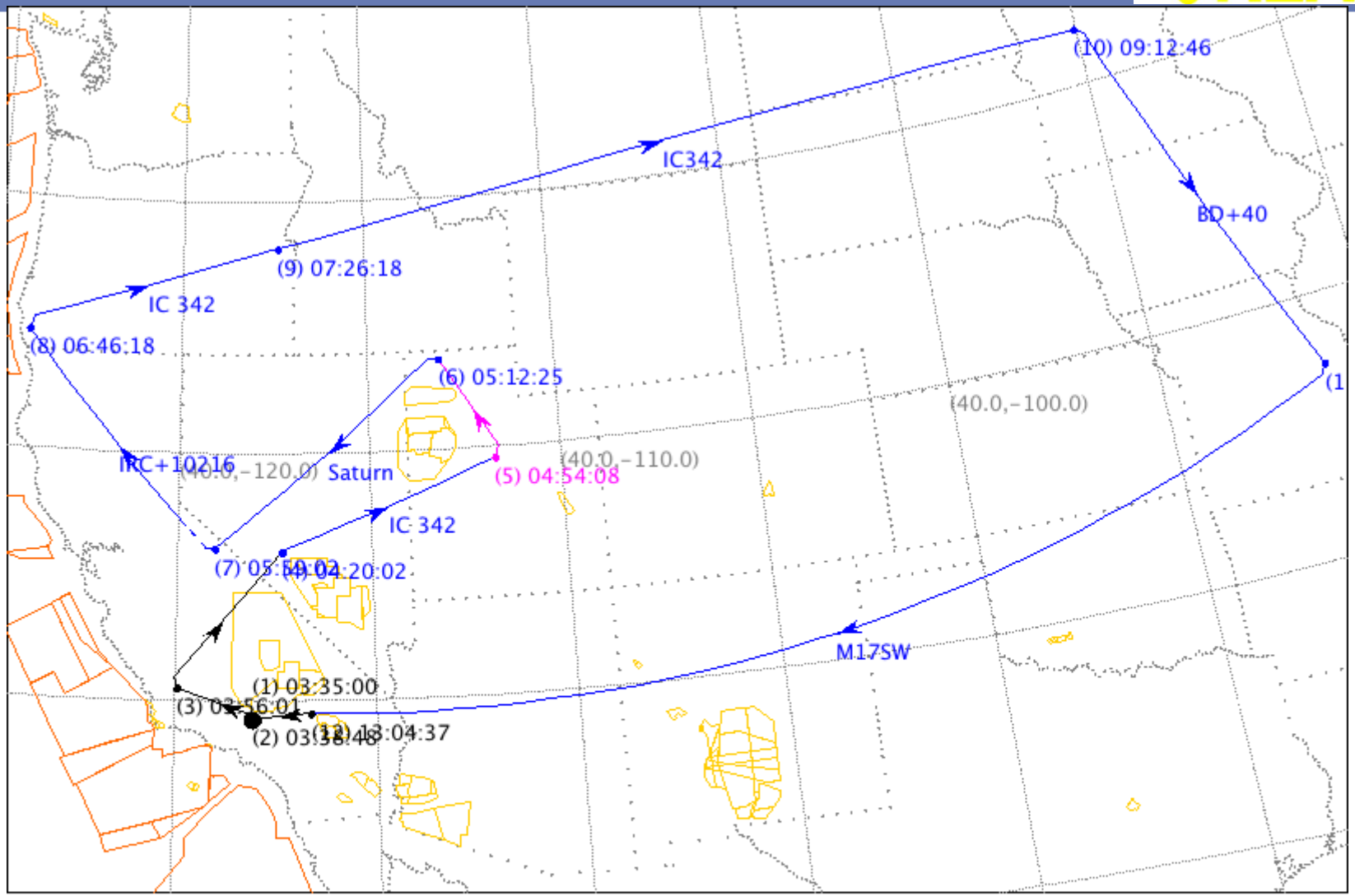

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Est. Takeoff Time: 2011-Apr-06 03:35 UTC
Est. Landing Time: 2011-Apr-06 13:15 UTC
Flight Duration: 09:40
Weather Forecast : 0000 Wed Mar 09 2011 - 1200 Fri Mar 11 2011 UTC
Saved: 2011-Mar-25 18:41 UTC User: rklein

What do we see?

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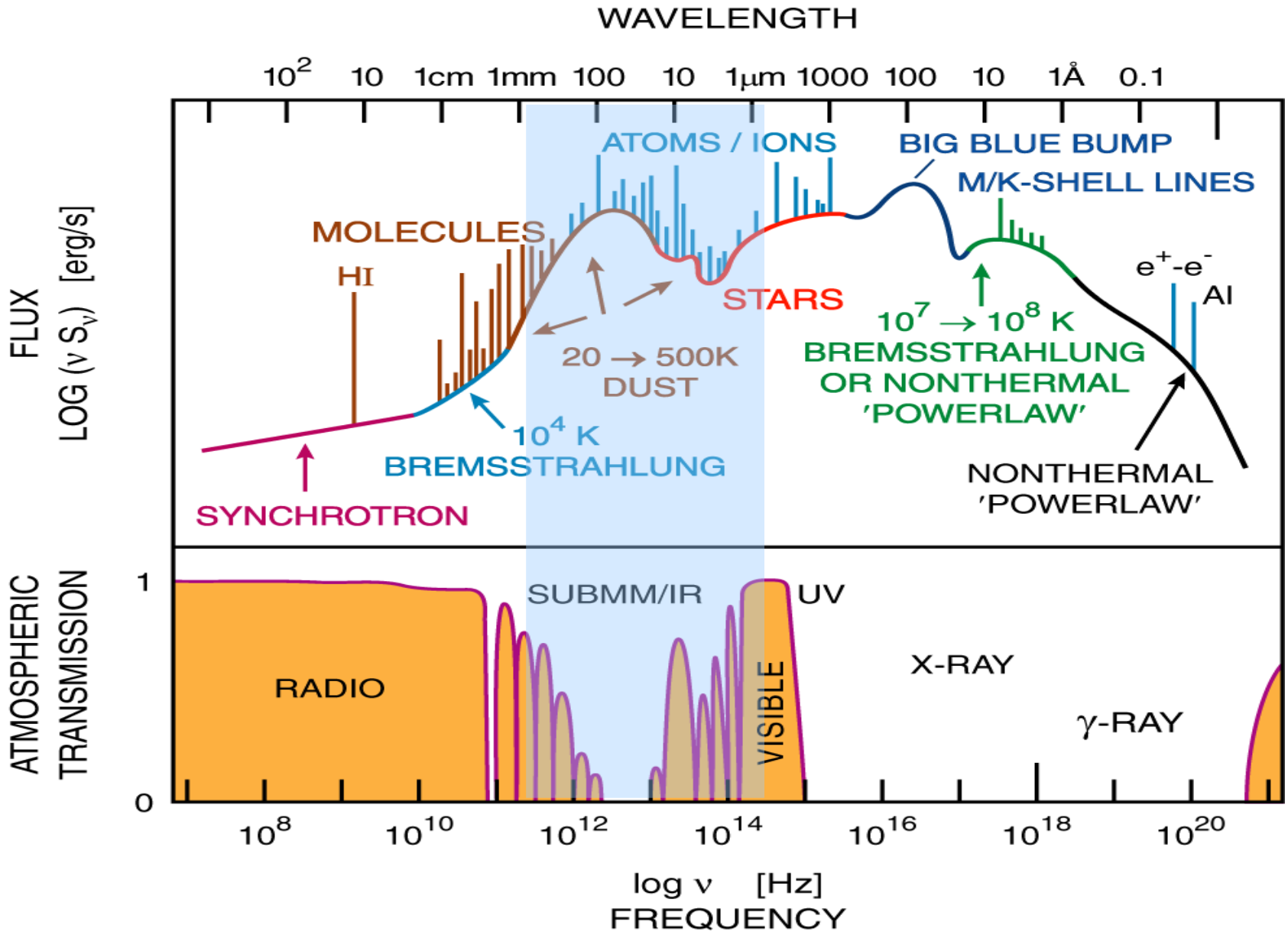
- Spectrum of a star-burst galaxy



Wavelength coverage

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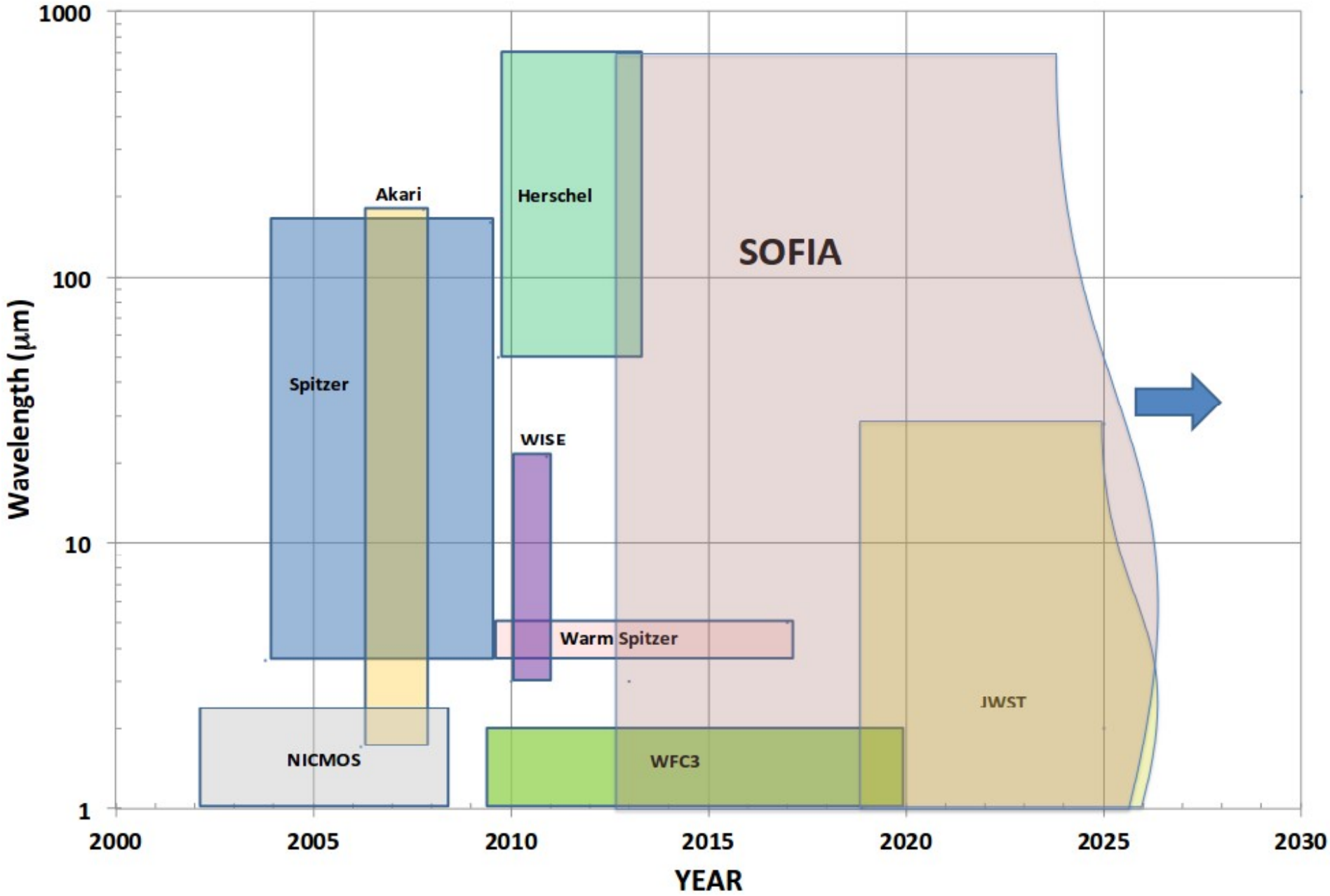

Instruments

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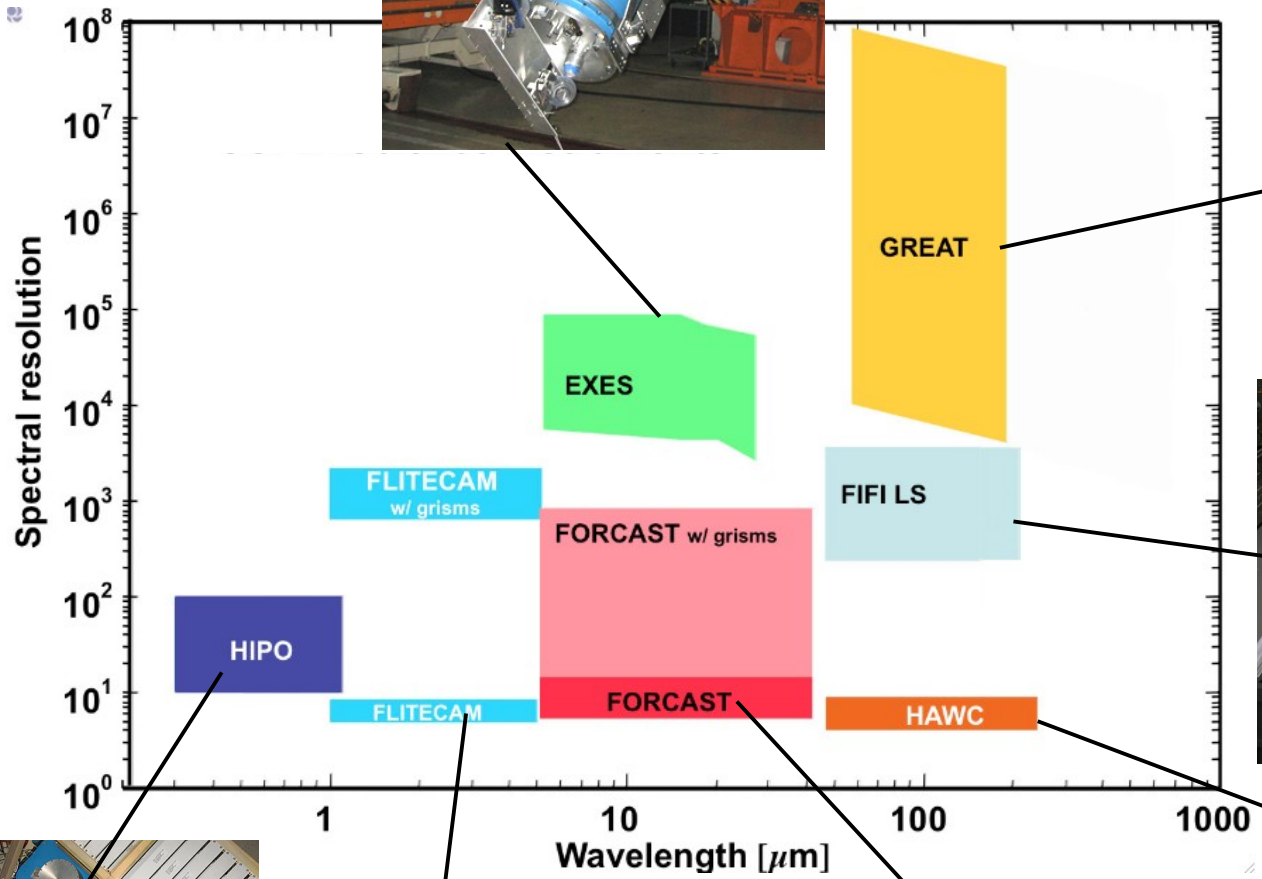

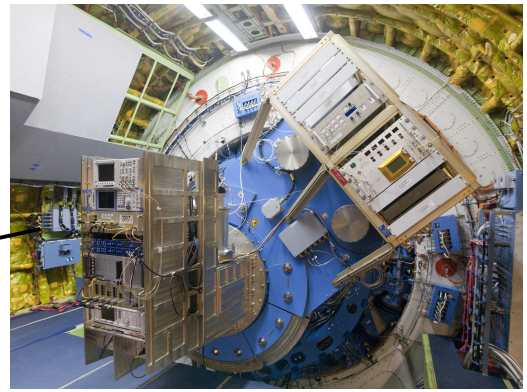

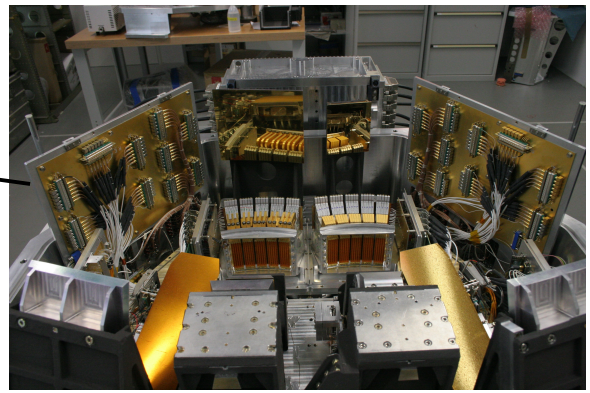

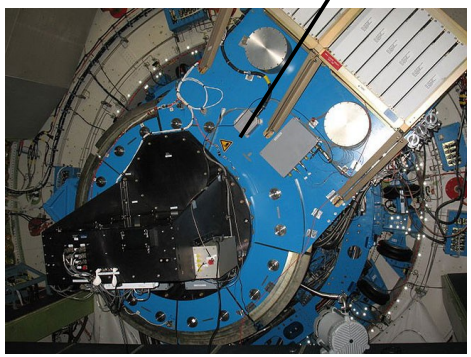

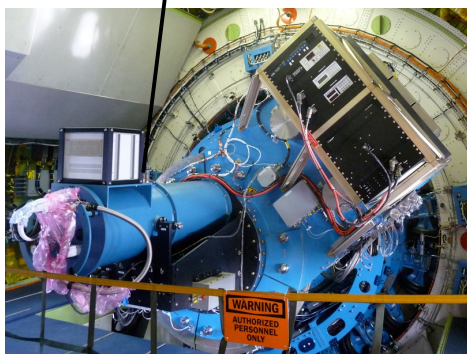

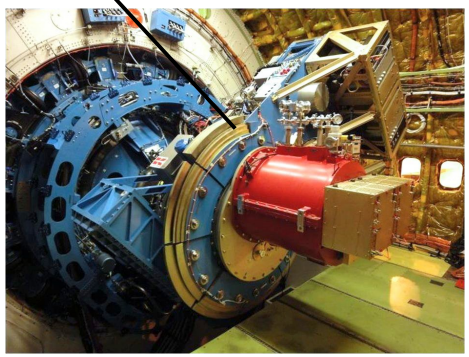

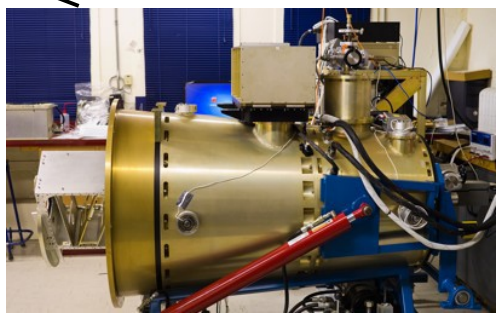

Selected Science Highlights

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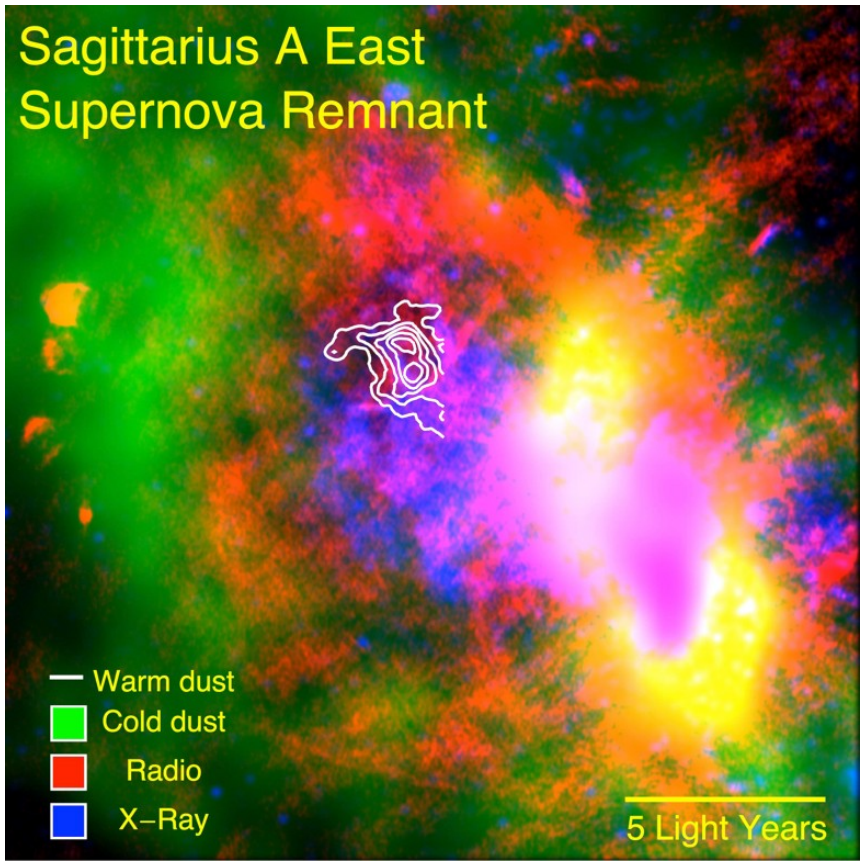
- FORCAST (Faint Object IR Camera for the SOFIA telescope)
  - Simultaneous Dual Channel Imaging and Grism Spectroscopy (5–25 μm and 25–40 μm)
- Dusty circumnuclear ring in the Galactic Center (3 pc diameter)
- Large dust production in Sgr A East supernova remnant (dust surviving shock)

Lau et al. (2013), 19 31 37 micron



Lau et al. (2015)

Selected Science Highlights

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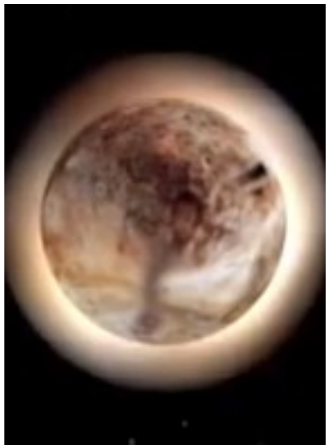
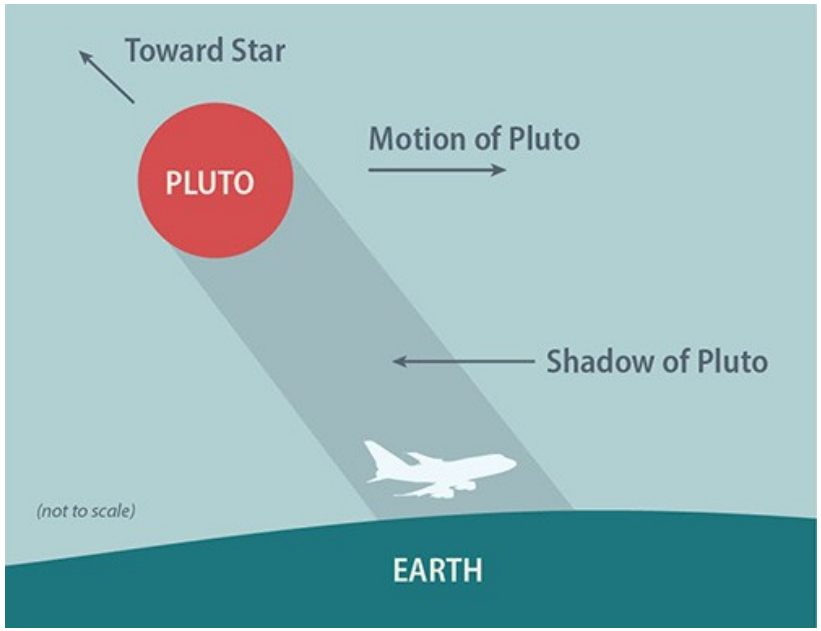
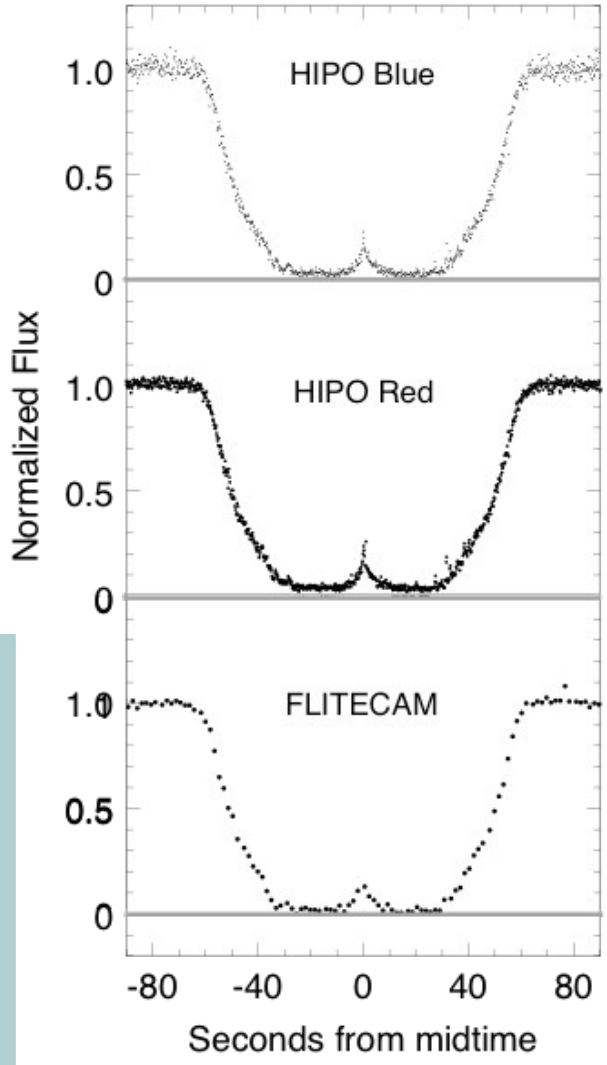
- HIPO (High Speed Imaging Photometer for Occultations)
  - Visible Light High-Speed Camera (0.3–1.1 μm)
  - used in combination with FLITECAM
  - Main purpose: stellar occultations:
    Surface structure of a solar system object
    (planetary atmospheres and rings, comets)



- 2 Pluto occultations (2011, 2015):
  - Density profile and spectroscopy of atmosphere
  - No change since 2011
  - Haze component required to repro-duce light curves





Courtesy of Amanda Bosh, MIT

Selected Science Highlights

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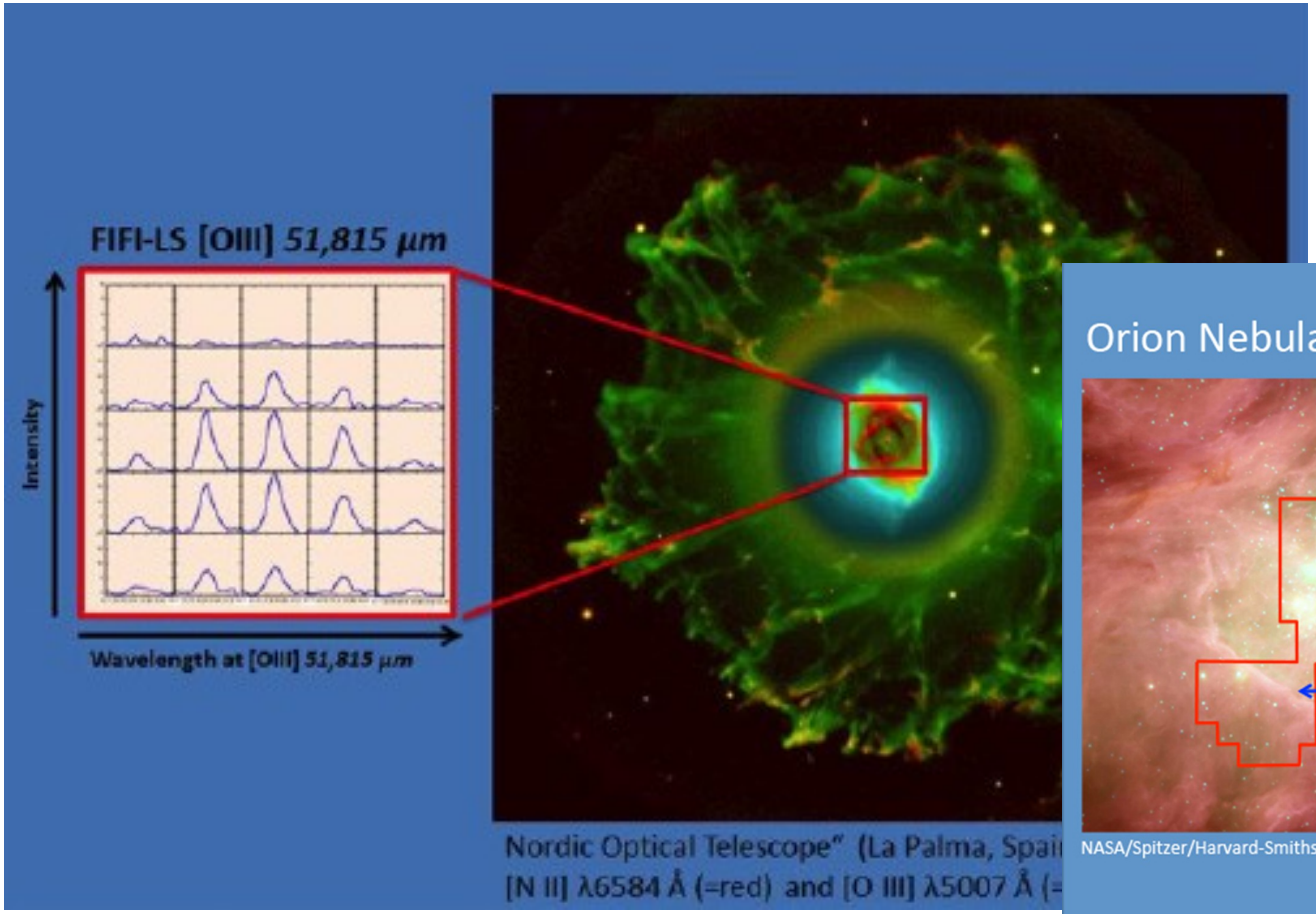
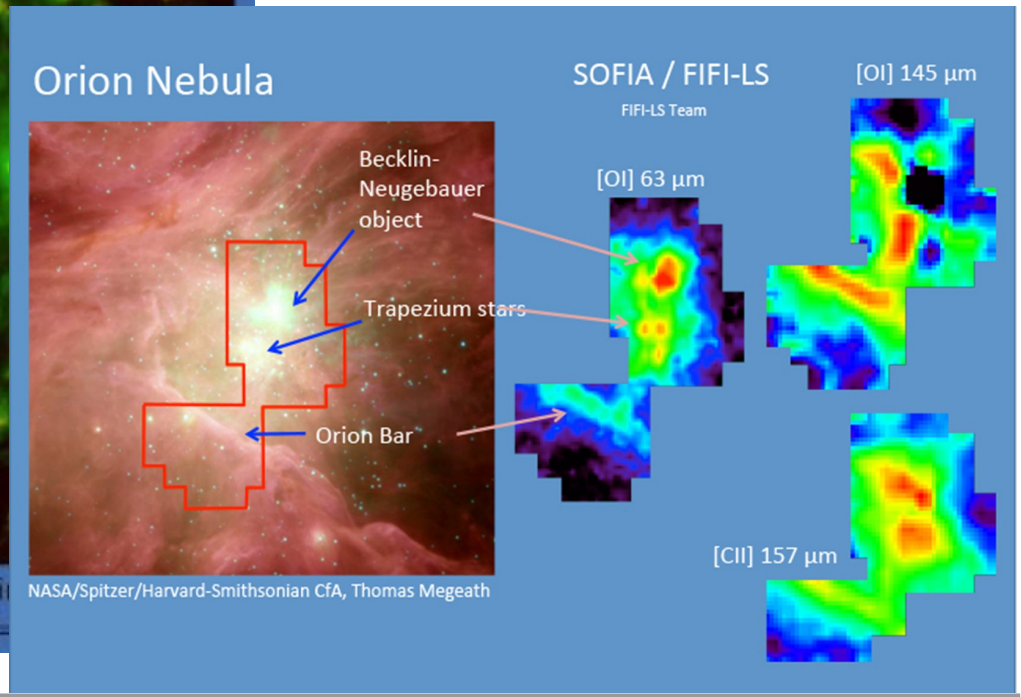
- FIFI-LS (Far Infrared Field-Imaging Line Spectrometer)
  - Dual Channel Integral Field Grating Spectrometer (50–110 µm; 100–200 µm)
  - Spectral line mapping of [CII] 158 µm, [OI] 63, 145 µm, [OIII] 52, 88 µm
  - Absolute atmospheric calibration still being worked on



NGC6543 in [OIII] at 51.8µm

Orion A spectral imaging in [CII] and [OI]:



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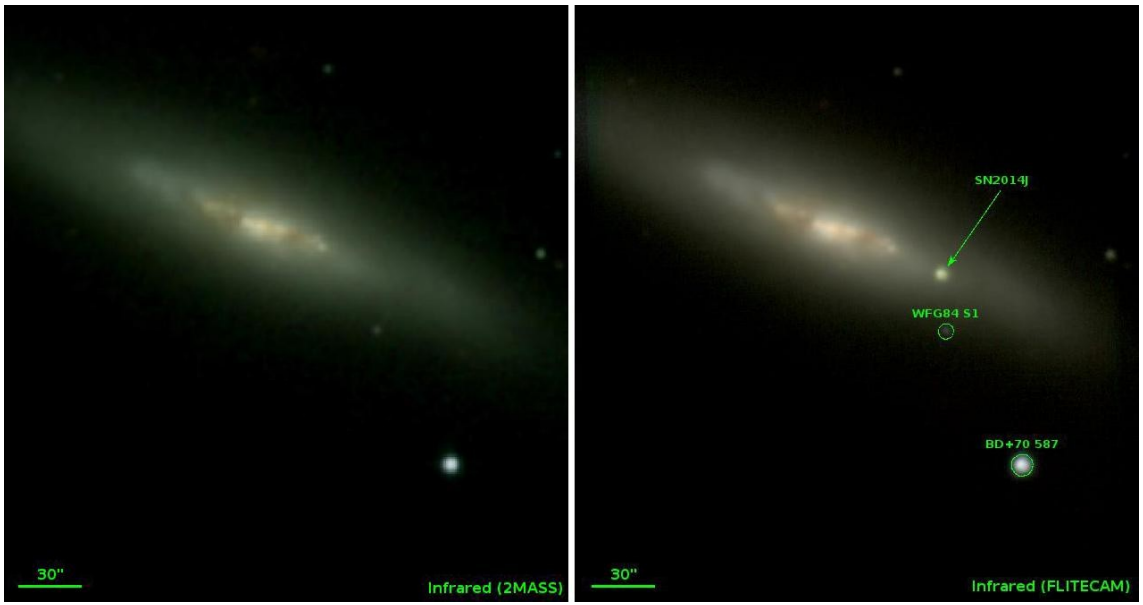
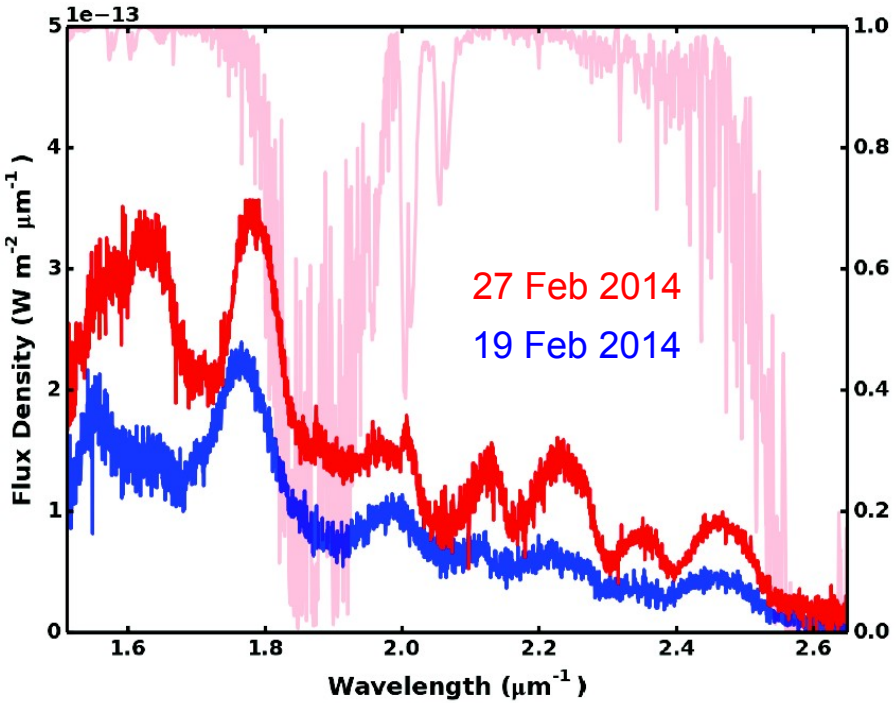
- FLITECAM (First Light Infrared TEst CAMera)
  - Near Infrared Imaging and Grism Spectroscopy (1–5.5 μm)
  - can be used in combination with HIPO
- PAH/Pa α emission and search for Brown Dwarfs
- SN 2014J (M82): near-IR spectrum, evolving with time (ionized Cobalt lines)
- Pluto occultation (June 29, 2015)



Vacca et al. 2015



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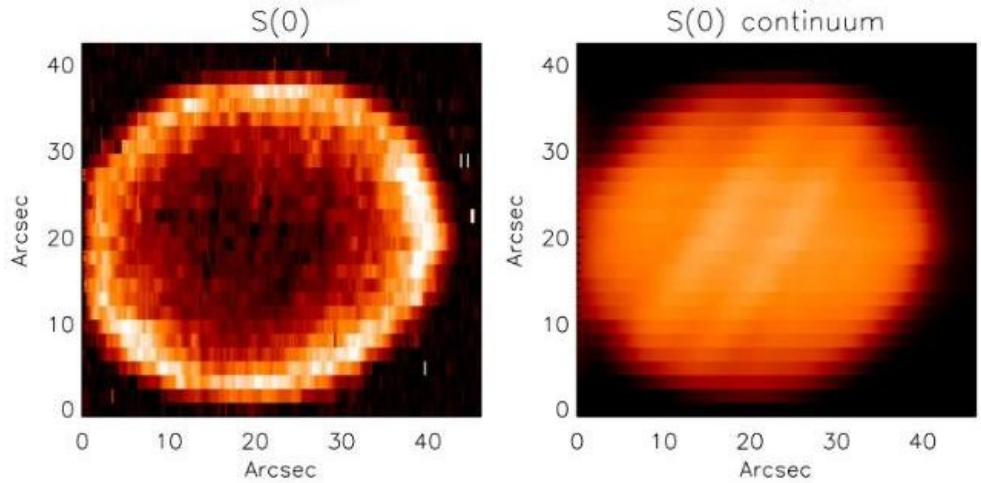
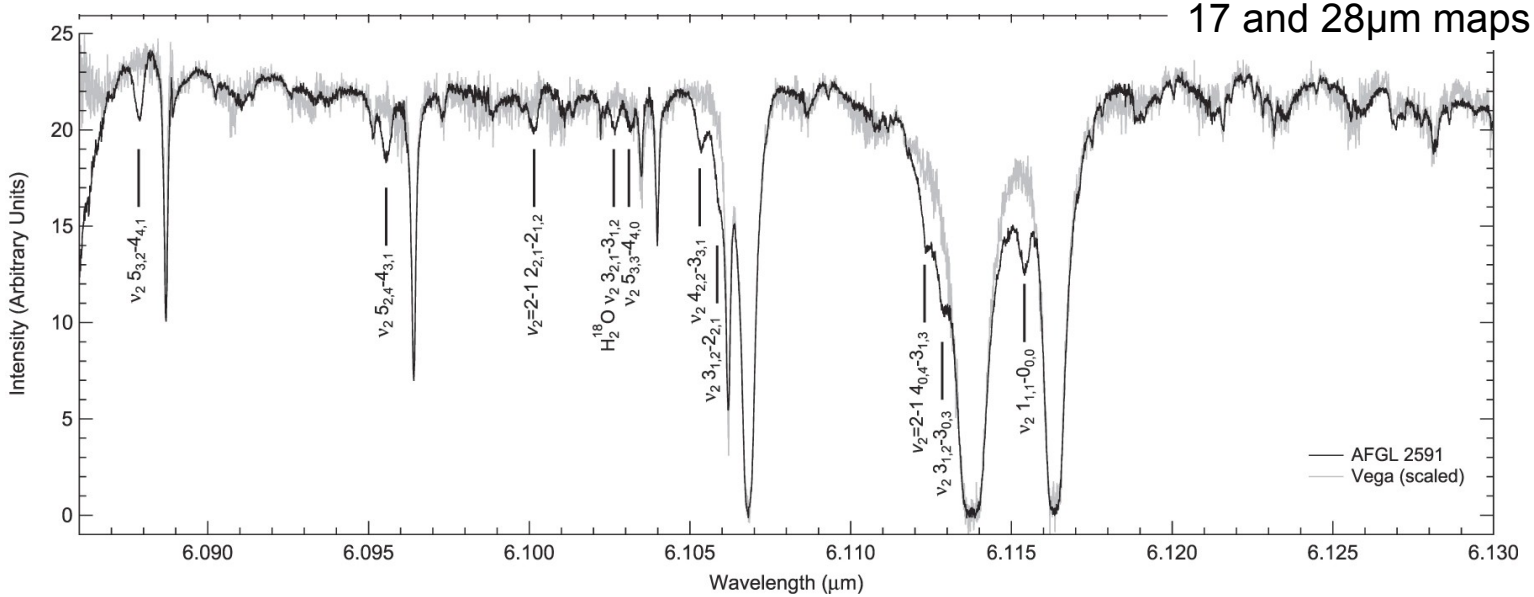
- EXES (Echelon-Cross-Echelle Spectrograph)
  - High Resolution (R=10^5) Echelle Spectrometer (5–28 μm)

- 28/17μm para/ortho-H_2 rotational mapping for Jupiter and several star-forming regions
- Water in protoplanetary disks (AFGL 2591)
  - 10 lines detected, one from $H_2{}^{18}O$
- D/H ratio in water on Mars



17 and 28μm maps of Jupiter (de Witt et al.)



AFGL 2571 water spectrum compared to Vega (Indriolo et al. 2015)

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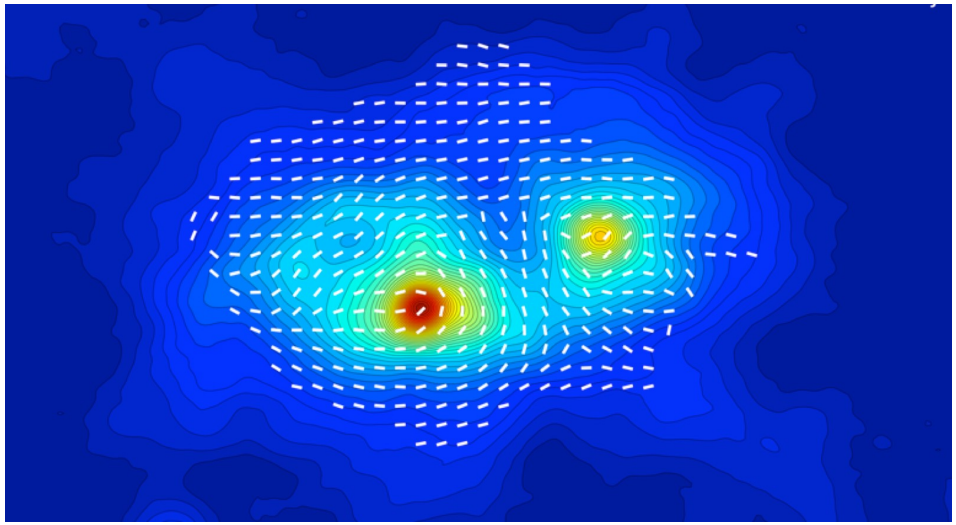
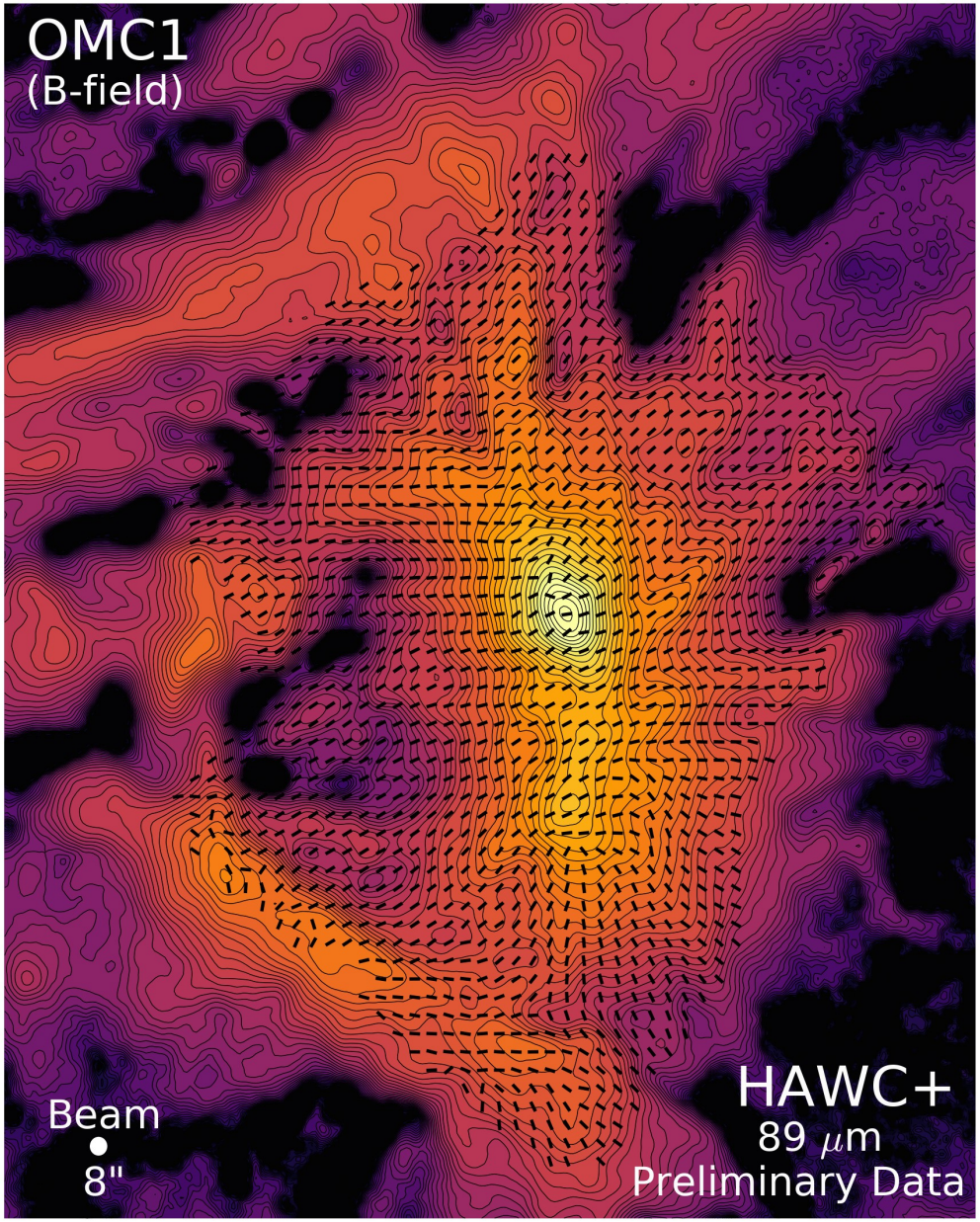
- HAWC+ (High-Angular resolution Wideband Camera)
  - Polarimeter with 5 Channels (53, 63, 89, 154, 214 µm)
- Commissioned 2016
  - Mapping of W3 and OMC1
  - Maximum degree of polarization in the 5 bands: 1.6-2.3%



Linear polarization maps of W3 and the Orion Nebula at 89 µm (Dowell et al. In prep.)



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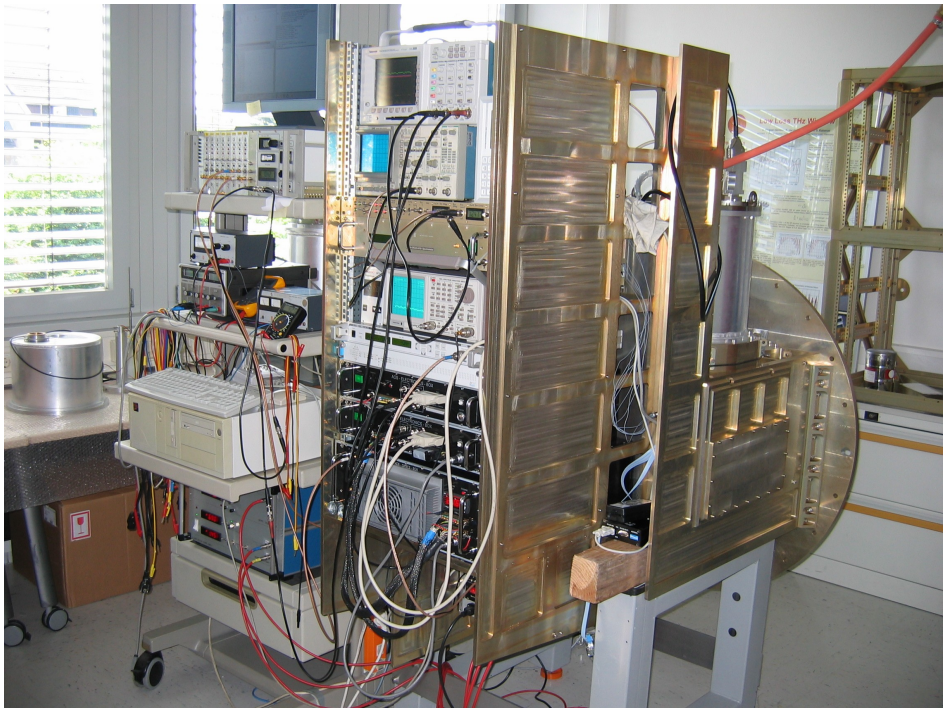
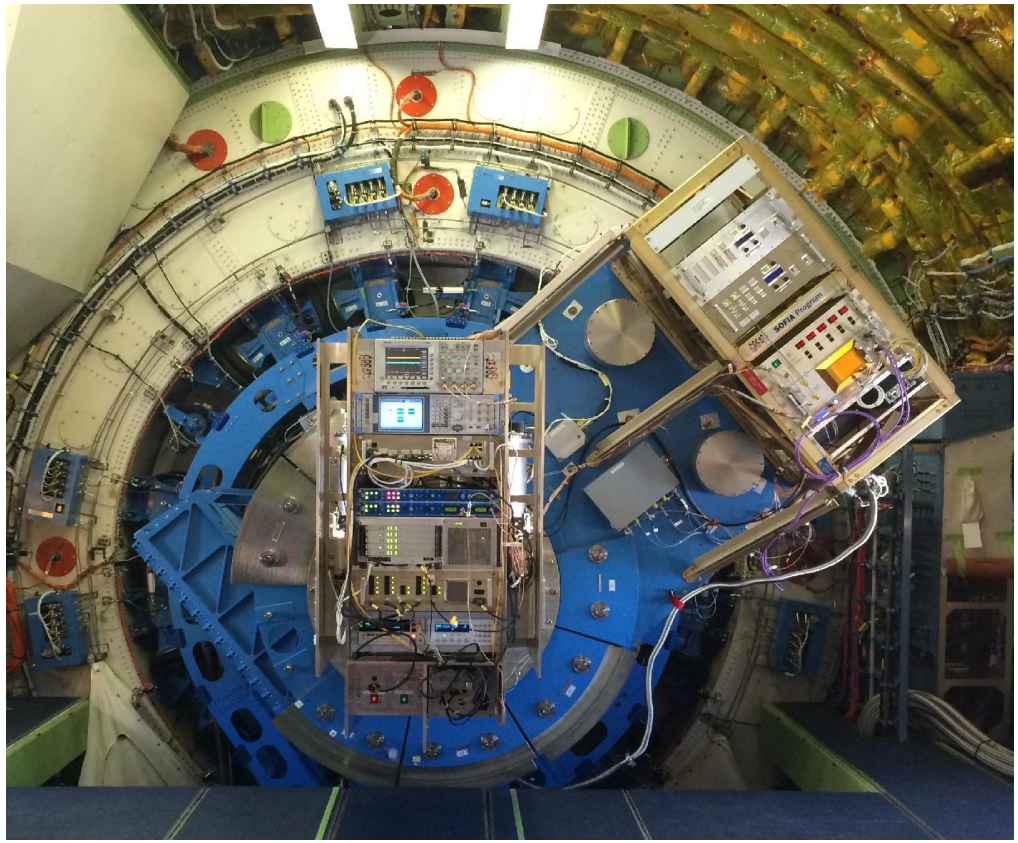
German REceiver for Astronomy at Terahertz-Frequencies

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





- Spectrometers: XFFTS
  - 64000 channels
  - Bandwidth: 2.4GHz
  - Resolution: 44kHz (R = 10^8)

upGREAT: GREAT multiplexed

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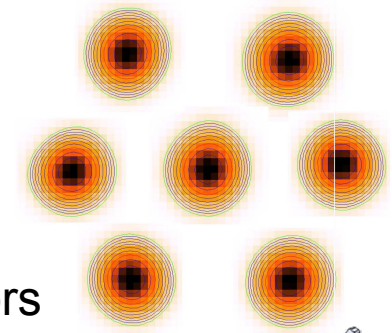
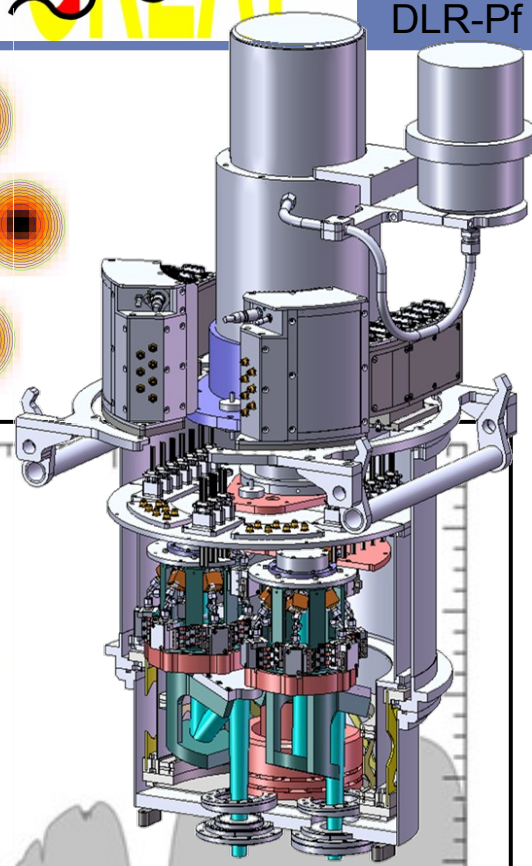
- 2 hexagonal arrays, operating in parallel
  - 2 x 7 low freq. Pixels (LFA)
  - 2 x 7 high freq. Pixels (HFA)
  - or combinations with GREAT single pixel detectors





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Frequencies:

Channel		Frequencies [THz]	Lines of interest	T_{min}[K] / BW_{3dB} [GHz]
low-frequency	L1	1.26 – 1.52	[NII], CO series, OD, H_2D^+	500 / 2.5
low-frequency	L2	1.82 – 1.91	NH_3, OH, CO(16-15), [CII]	700 / 2.5
mid-frequency	Ma/b	2.49 – 2.56, 2.67	$^{(18)}OH(^2\Pi_{3/2})$, HD	1500 / 2.5
high-frequency	H	4.74	[OI]	800 / 2.5
upGREAT	LFA	2x7 (1.9 – 2.5)	CO series, [CII], [OI], OH	1000 / 3.3
upGREAT	HFA	2x7 (4.74)	[OI]	1400 / 3.3

- Beams:
  - 22" (1.26 THz), 6.6" (4.74 THz)
- Future: 4GREAT
  - Additional 2 channels: 0.490 - 0.635 THz, 0.890 - 1.100 THz
  - 4 pixels at simultaneously: new channels + L1 + L2
  - Can be operated in parallel to H or HFA
  - Commissioning: May 2017

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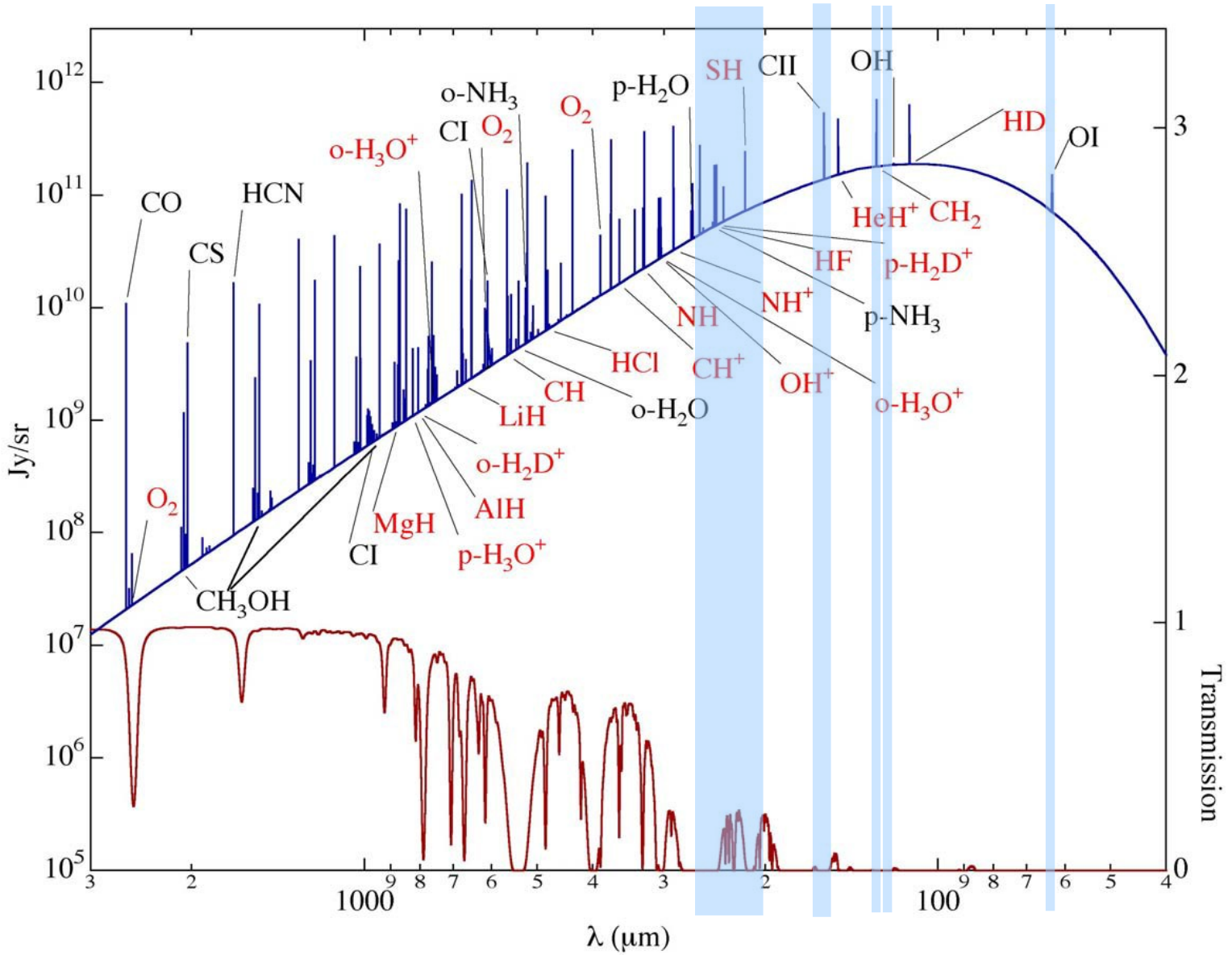
- Focused on main cooling lines:
  - [OI], [CII]
- OH, HD
- High-J CO transitions
- Hydrides
- Covers HIFI-gap



Bergin (2008)

First detections

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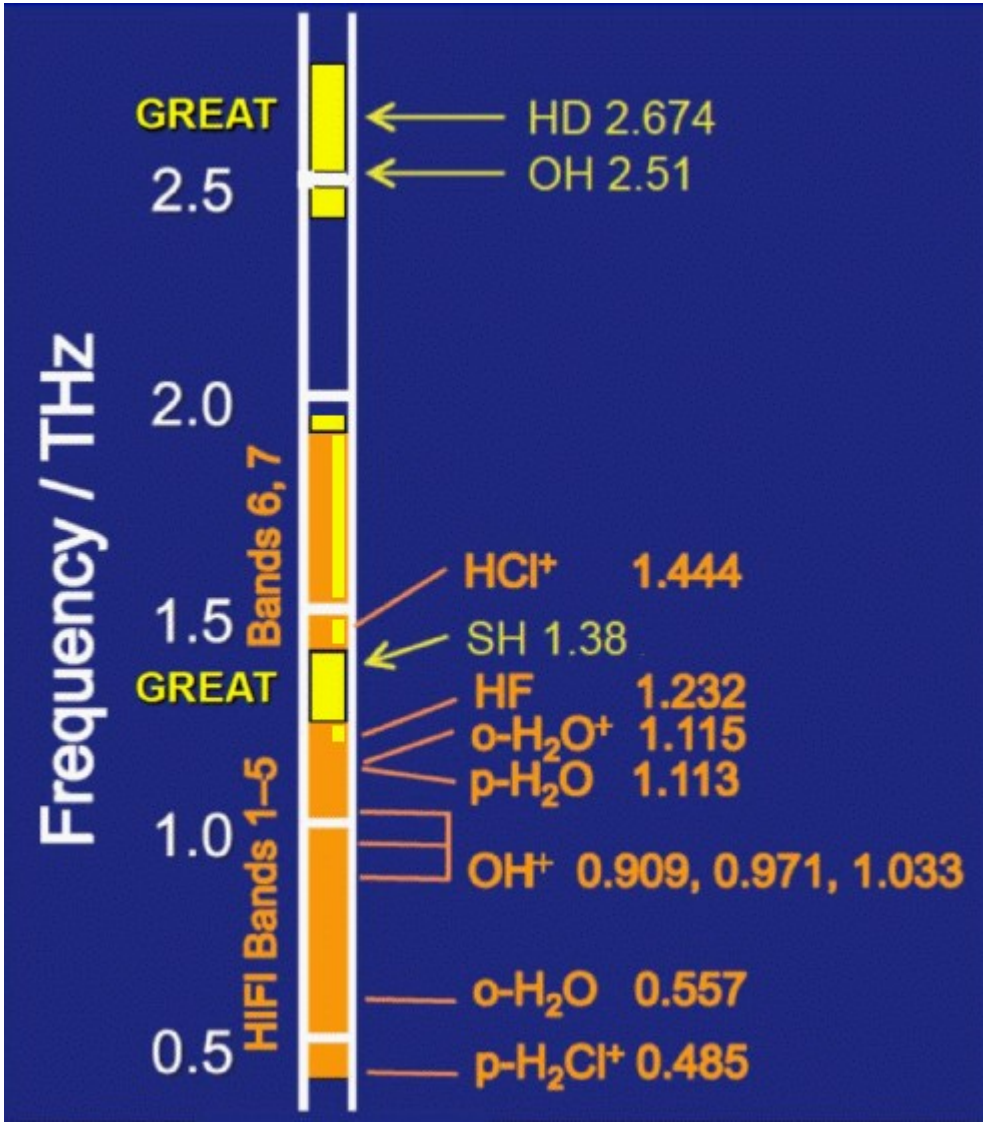
Governed by frequency coverage:

- Gap between HIFI bands
- Frequencies above 1.9THz

- Abundant species:
  - Light Hydrides



Courtesy: Caselli (2015)

First detections

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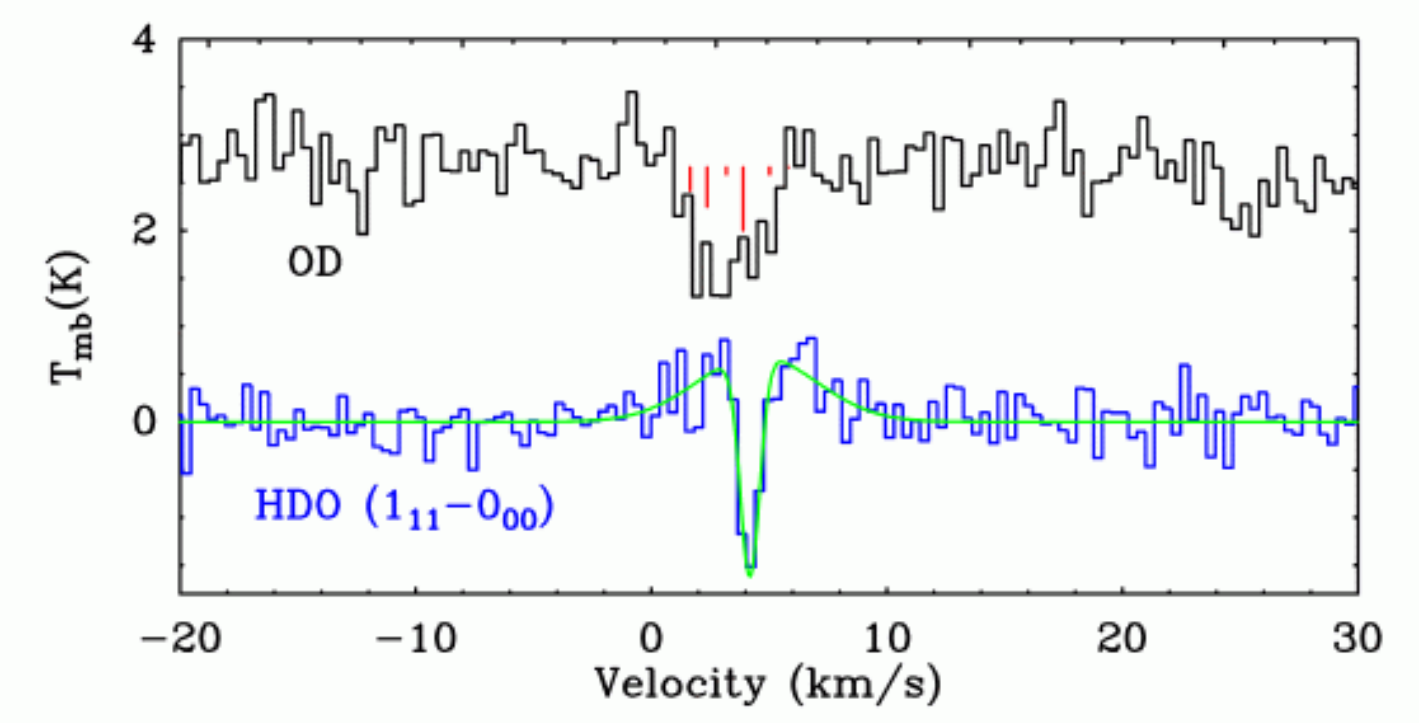
OD:

- IRAS 16293-2422
  - $^2\Pi_{5/2}$ - $^2\Pi_{3/2}$ at 1391.5GHz
  - Hyperfine split of the line



  - Comparison to APEX observations of HDO 1_{11} -0_{00}
  - OD/HDO = 17 … 90 depending on assumed excitation conditions
    - Too high compared to model predictions

Parise et al. (2012)

First detections

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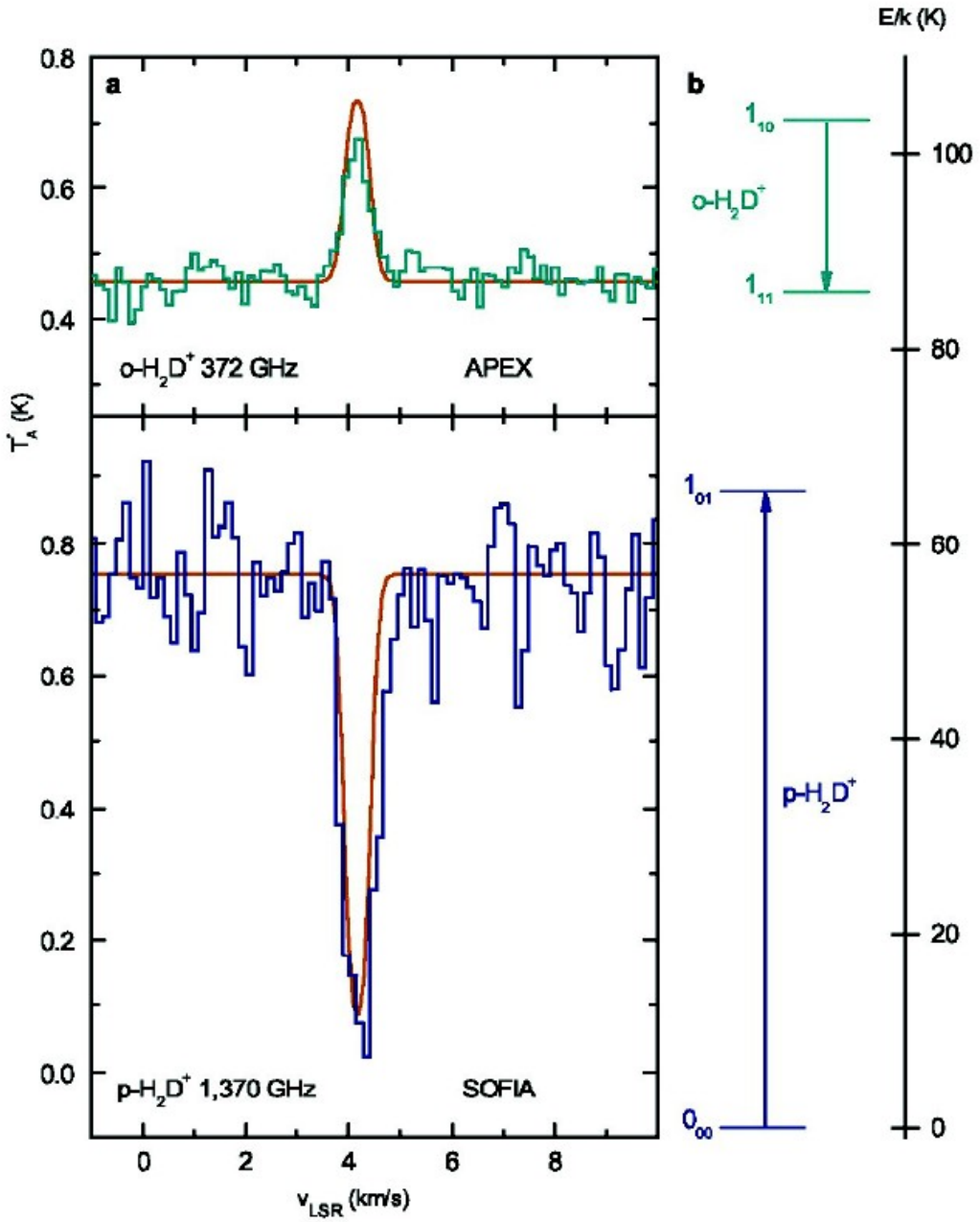
para-H_2D^+:

- IRAS16293-2422
  - Measure o/p ratio in H_2 through o/p of H_2D^+
  - At low T
    $p\text{-}H_2D^+ + o\text{-}H_2 \rightarrow o\text{-}H_2D^+ + p\text{-}H_2$
    dominates over back reaction
  - Chemical clock

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

Brünken et al. (2014)



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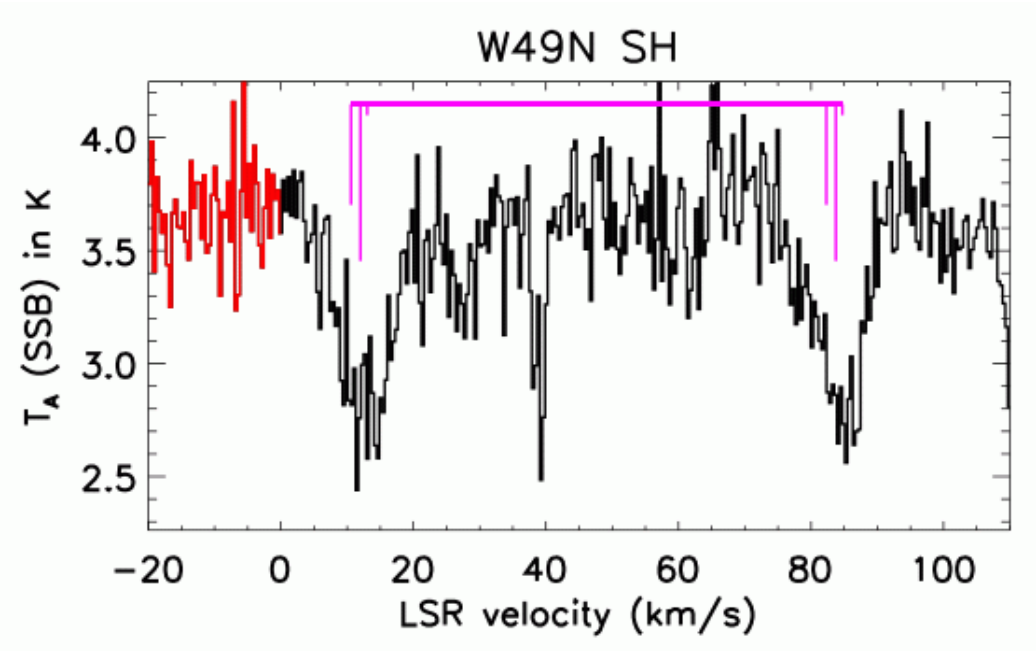
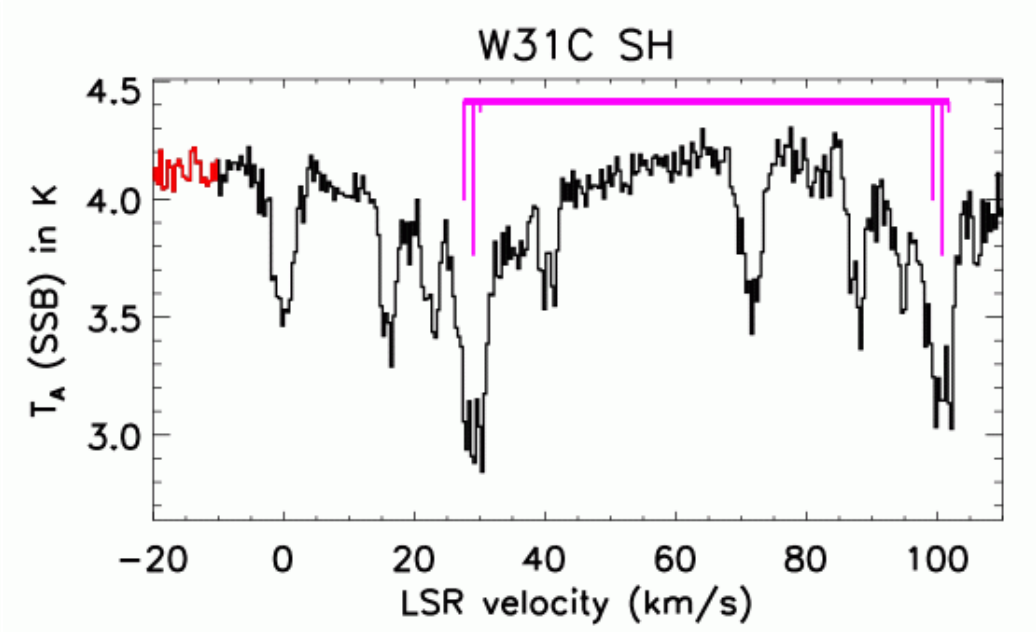
SH:

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





Neufeld et al. (2015): Spectral fingerprint through Λ-doublet and HF split

- Several foreground clouds → spiral structure

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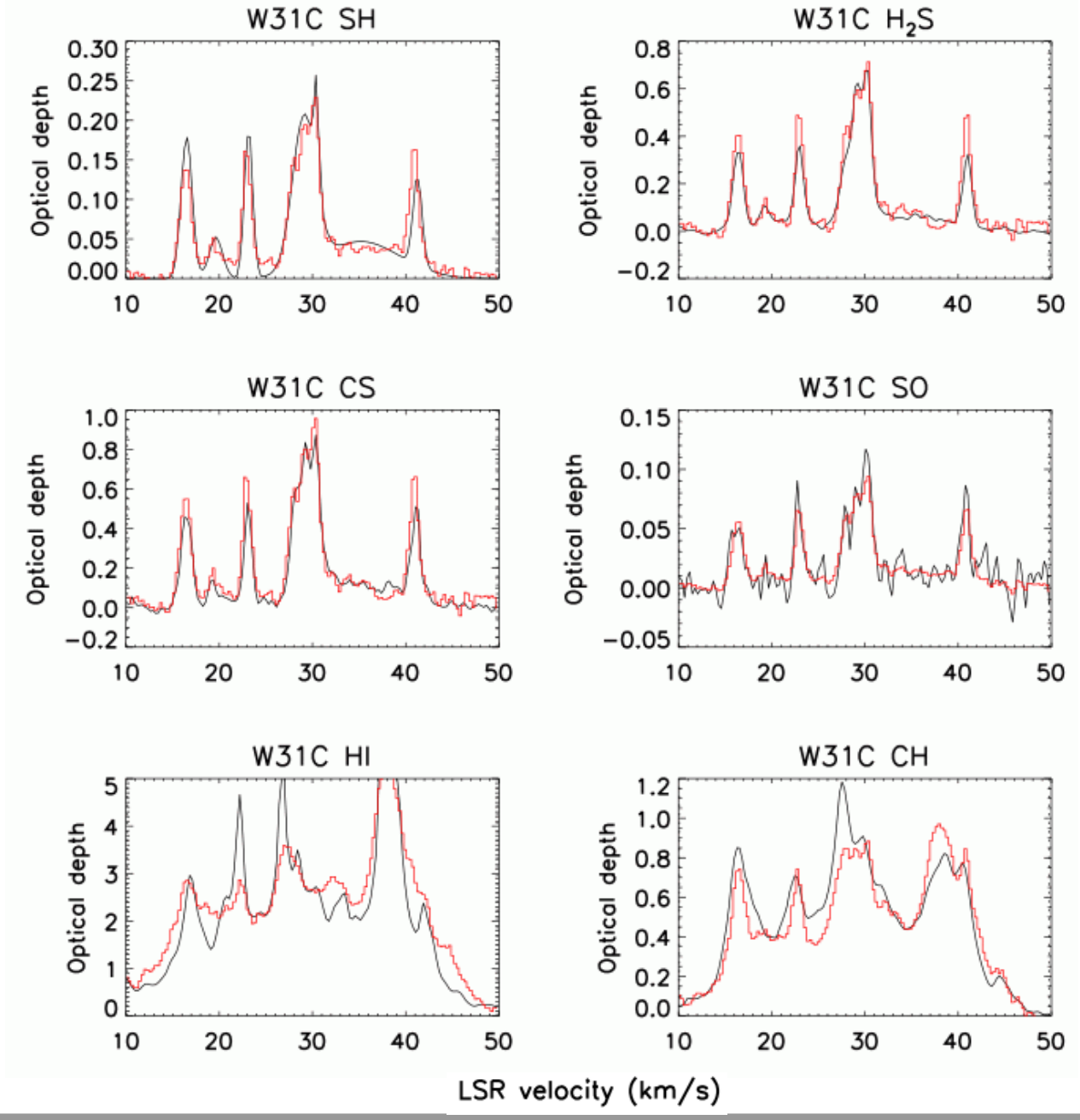
SH:

- $SH/H_2 = 5 \ldots 26\ 10^{-9}$
- Large variation
- SH only produced at elevated temperatures
  - Requires shock or turbulence-dissipation models (TDR)
    - But so far they fail to explain H_2S/SH ratio



Neufeld et al. (2015)

High-resolution spectra

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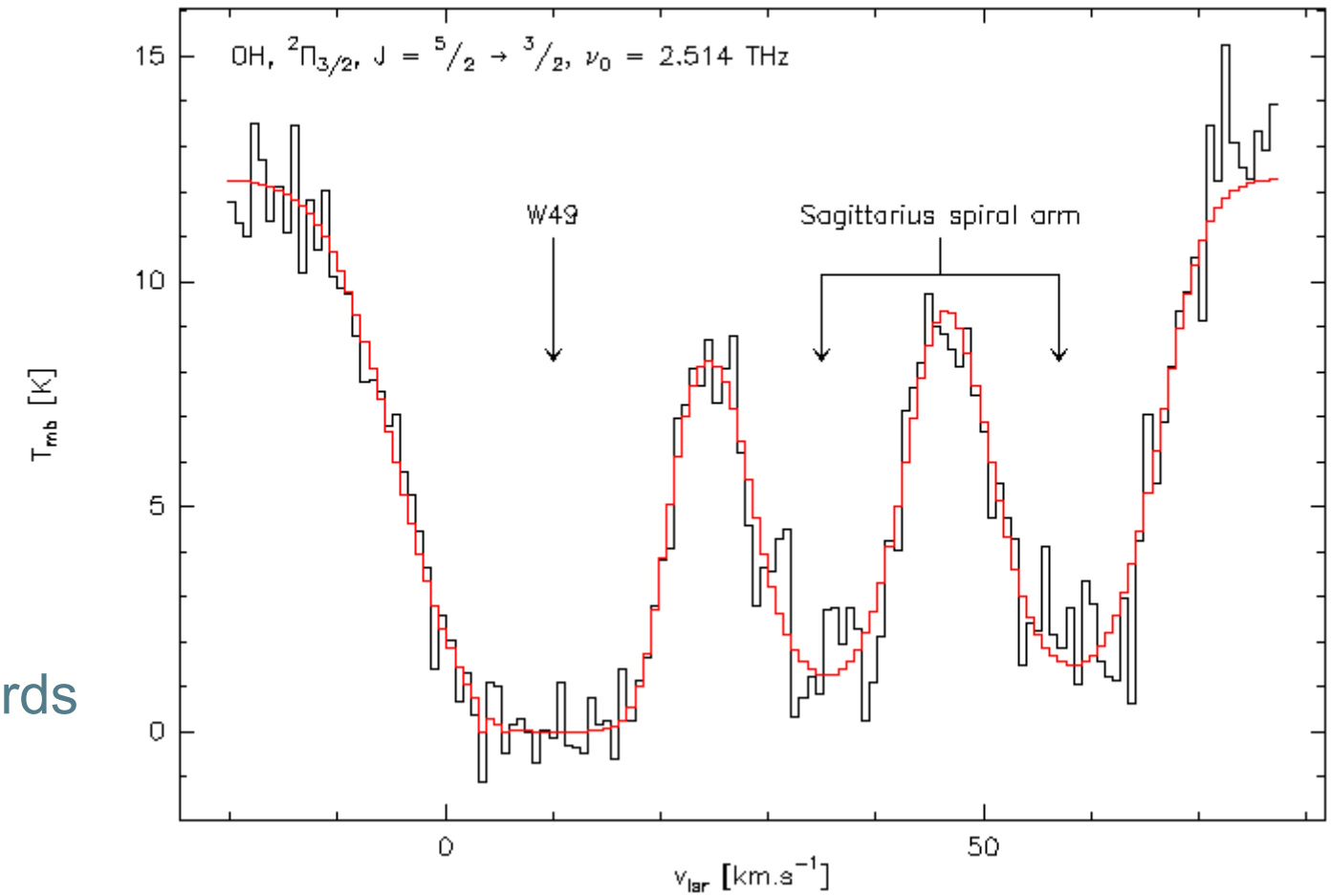
OH absorption:

- 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}

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



[OI] ($^3P_1$ - $^3P_2$ = 63μm)

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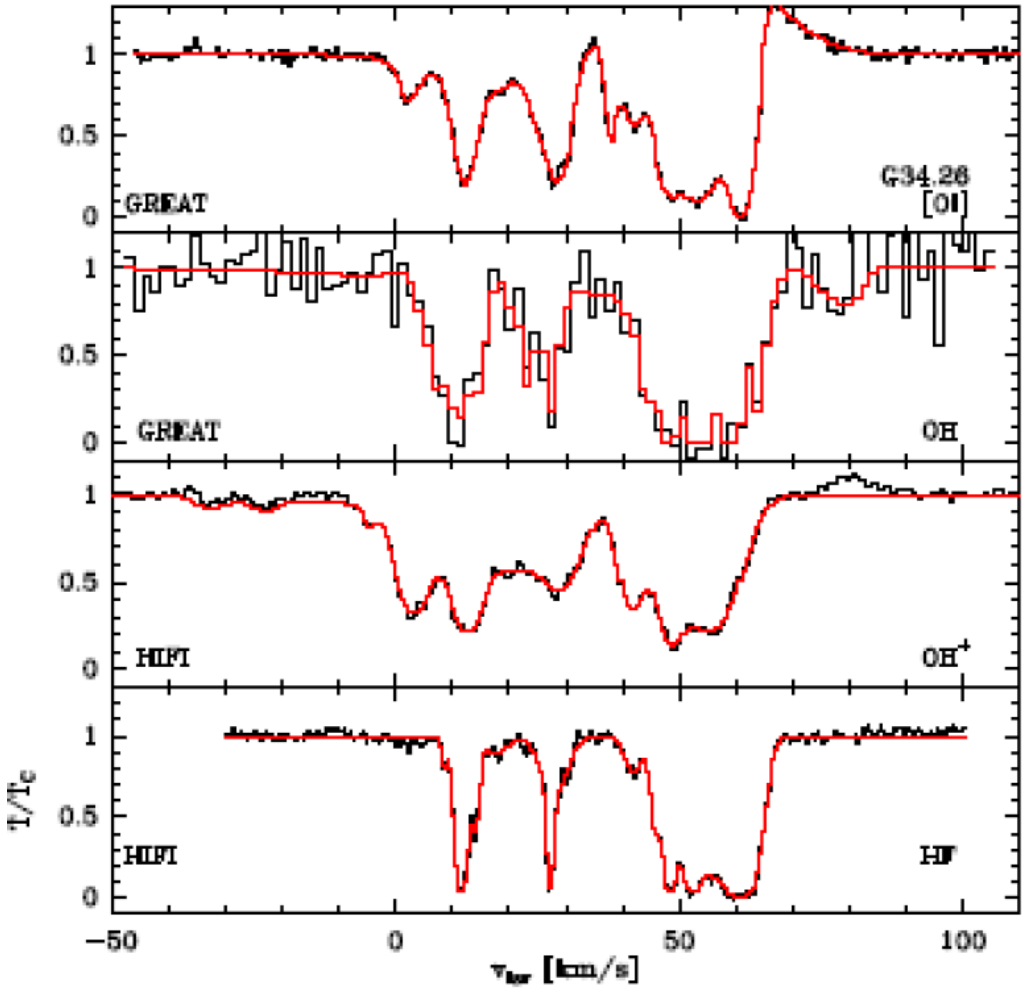
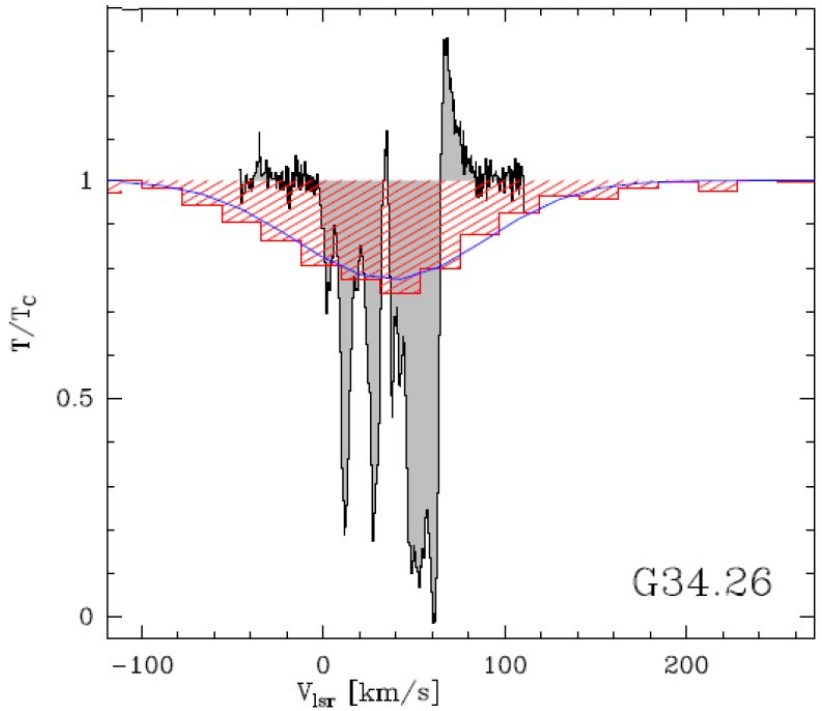
[OI] absorption:

Wiesemeyer et al. (2015)



Complex profiles in most sources



PACS washes out all relevant information

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

[OI] ($^3P_1$ -$^3P_2$ = 63μm)

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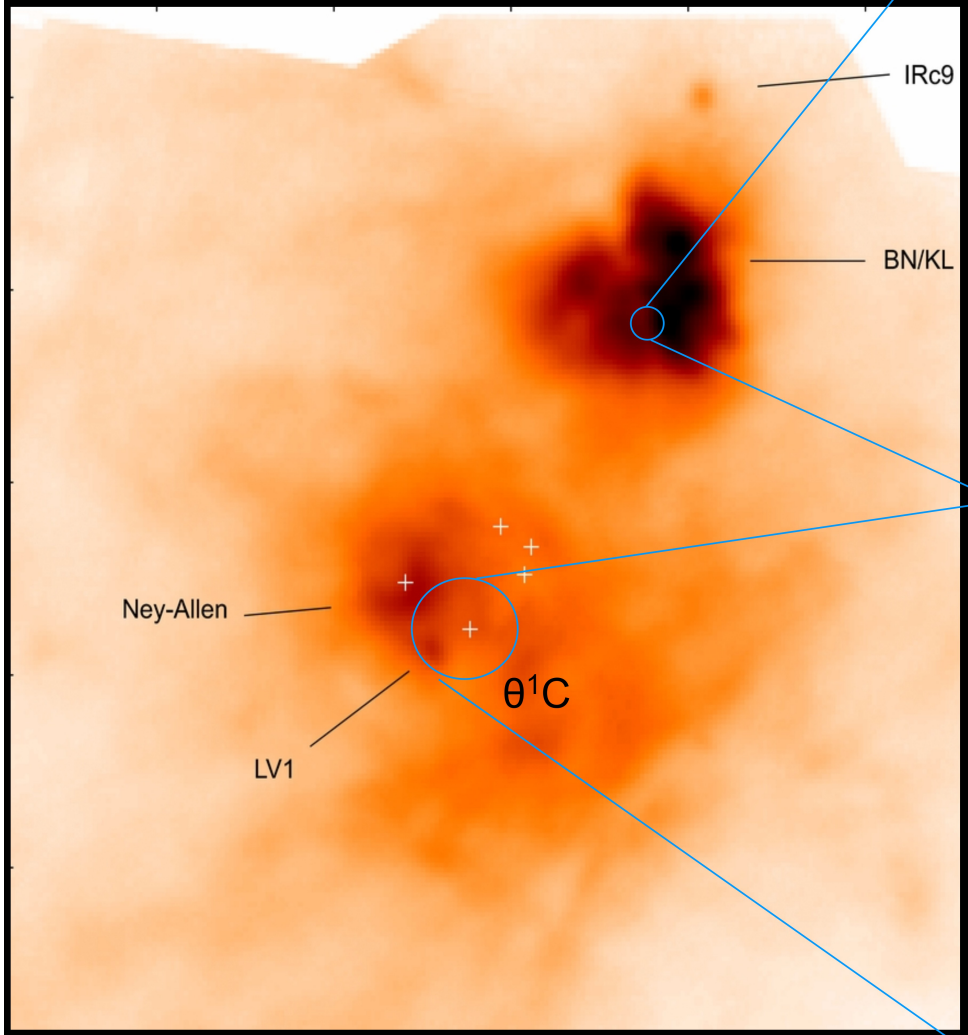
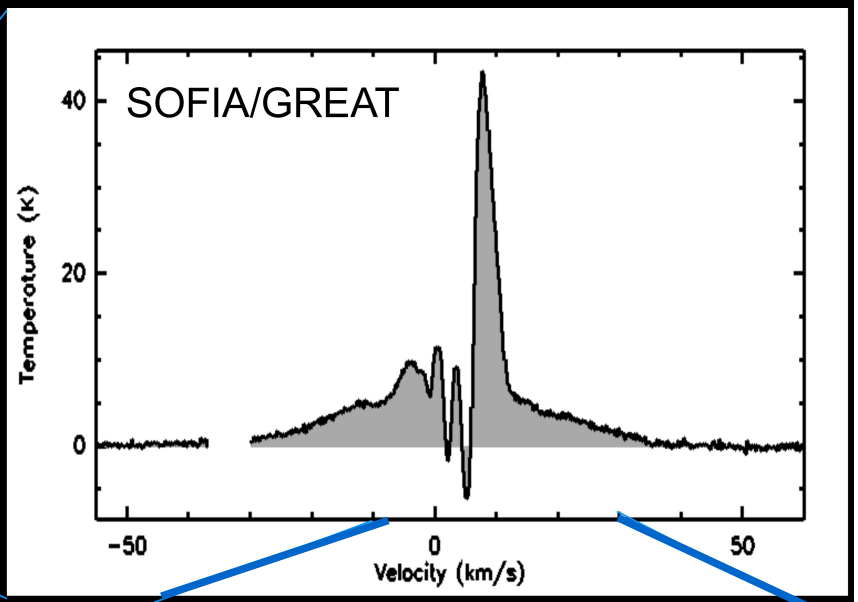
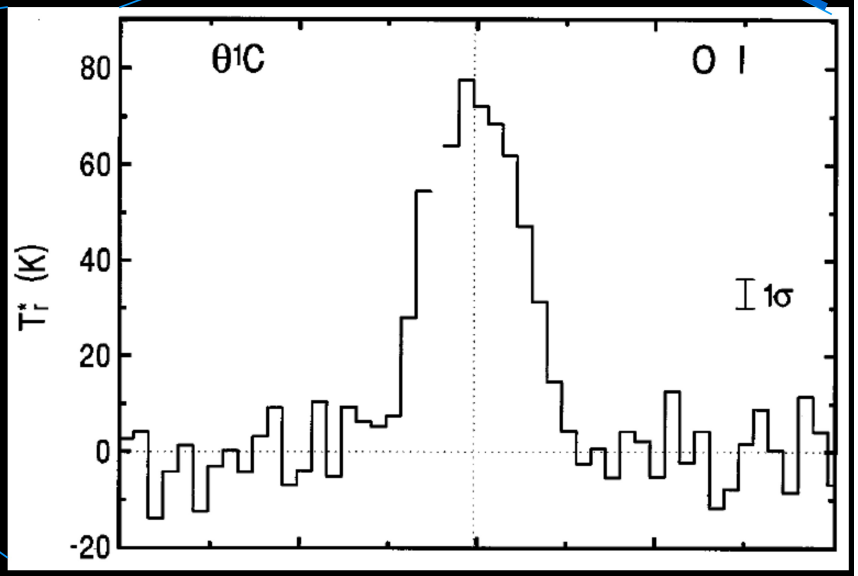
Cooling the gas in the Orion hot core and photodissociation region: Fine-structure O I Line (63 μm)



SOFIA/FORCAST λ19.7 μm)





KAO spectrum (Boreiko & Betz, 1996)

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

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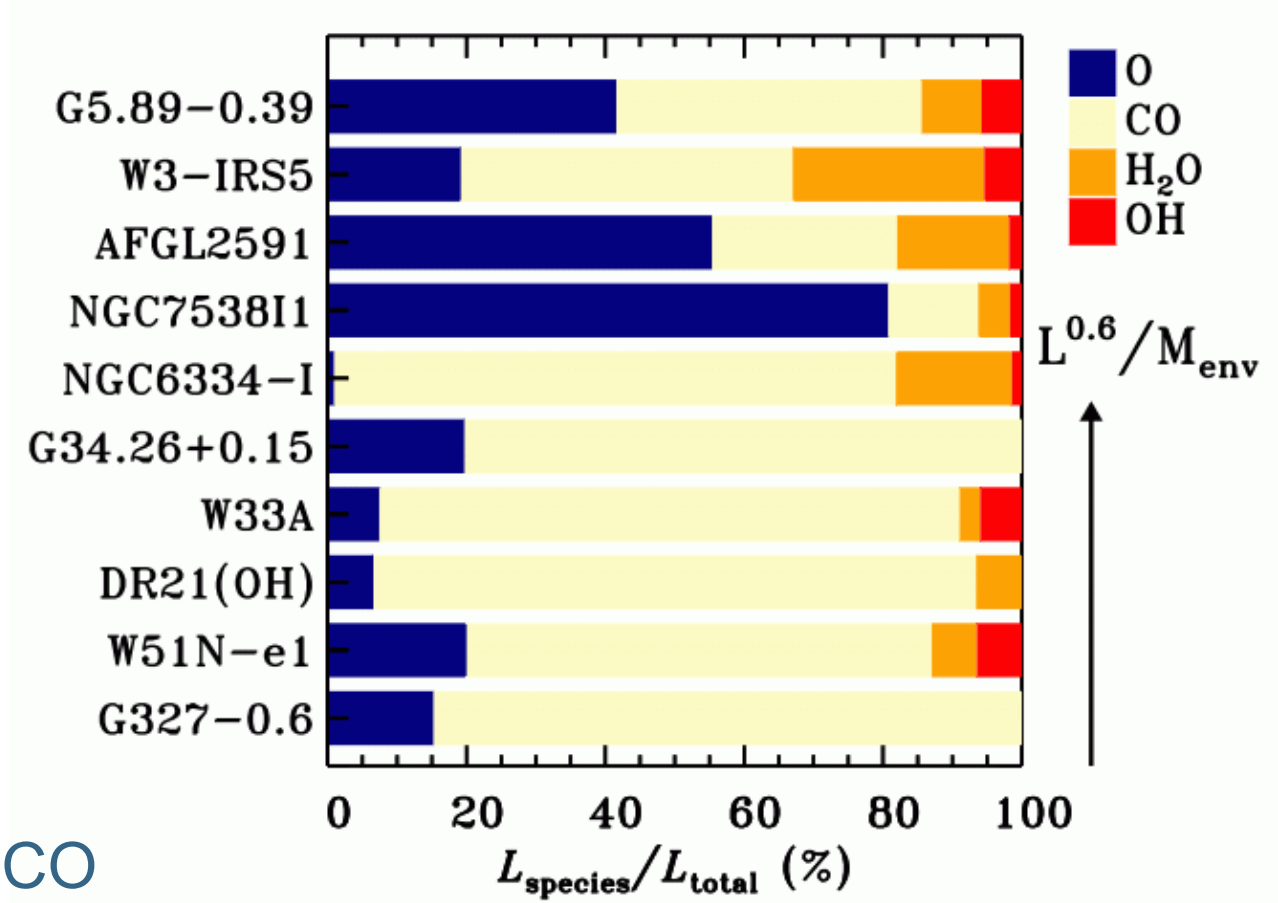
Cooling budget of high mass YSOs:

- The Herschel view: Karska et al. (2014)



- Cooling dominated by CO
- Brightest source: G5.89-0.39

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

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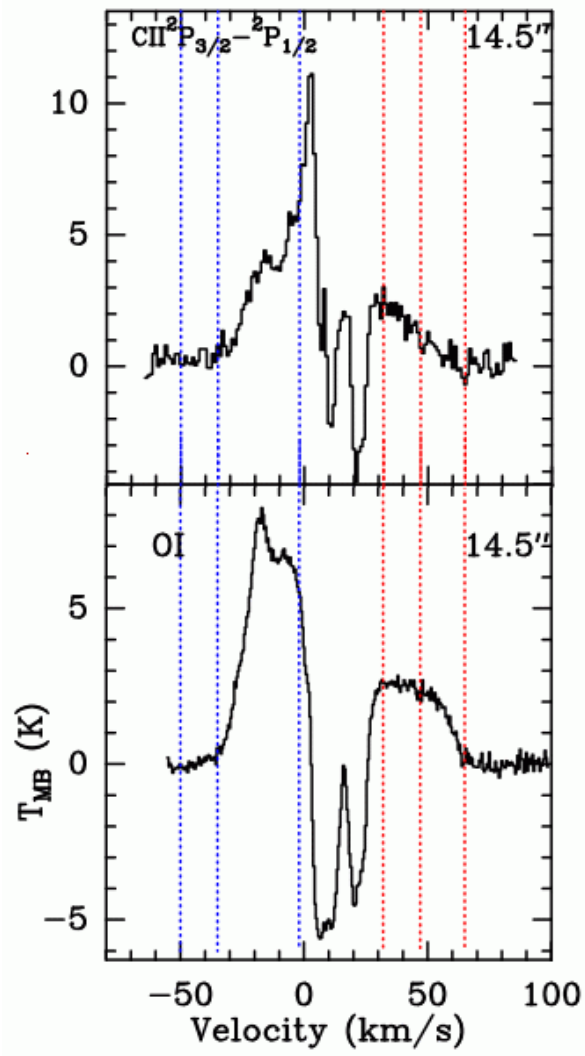
Great observations of G5.89-0.39:

- Complex [OI] profile with broad wings
- [OI] is main coolant:
  - 75% of total line luminosity
  - Strongly self-absorbed
  - High-velocity emission!
- The large scale molecular outflow is driven by atomic jets!
  - 10^{-4} $M_\odot$/a
- Spectral resolution is the key!
  - Explanation of FIR line deficit needs resolved lines



Leurini et al. (2015)

Conclusions

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We are still at the very beginning!

- More new detections with (up)GREAT are to be expected! (e.g. C_3^+...)
- [OI] and [CII] spectra are complex
  - traces velocity structure and foreground in a complex way
  - Emitted from CO-dark molecular gas
  - Gas distribution towards many sources poorly known
  - Large fraction of gas only seen in [CII] and cold OH
- 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 observations!
- Third generation instrument selected:
  - High Resolution Mid-InfrarEd Spectrometer (HIRMES)
  - Spectroscopy at wavelengths between 28 and 112 microns.

Cycle 6 call

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- Observing period: Feb 2018 - Jan 2019
- Call to be expected in March
- Proposal deadline: Probably early July

7 instruments will be offered:

- EXES, FIFI-LS, FLITECAM, FORCAST, upGREAT, HAWC+, HIPO, and the FLITECAM/HIPO combination
- Instruments for Southern deployment to be selected based on requests

- SOFIA Impact Programs solicited
  - Multi-year programs
  - Joint US – German Impact Programs

- Details: http://www.sofia.usra.edu/Science/announcements.html