GREAT science from SOFIA

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Overview

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KOSMA
MPS
DLR-Pf

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

SOFIA

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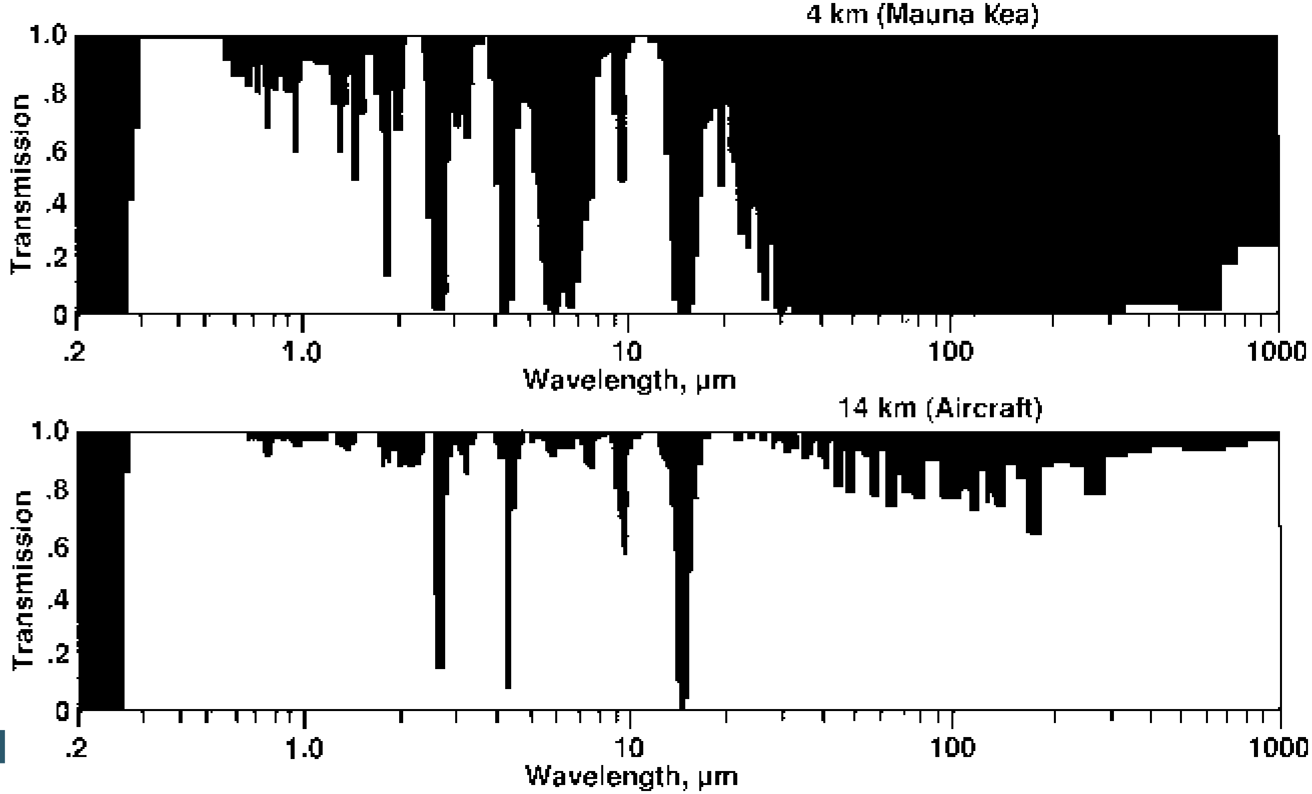
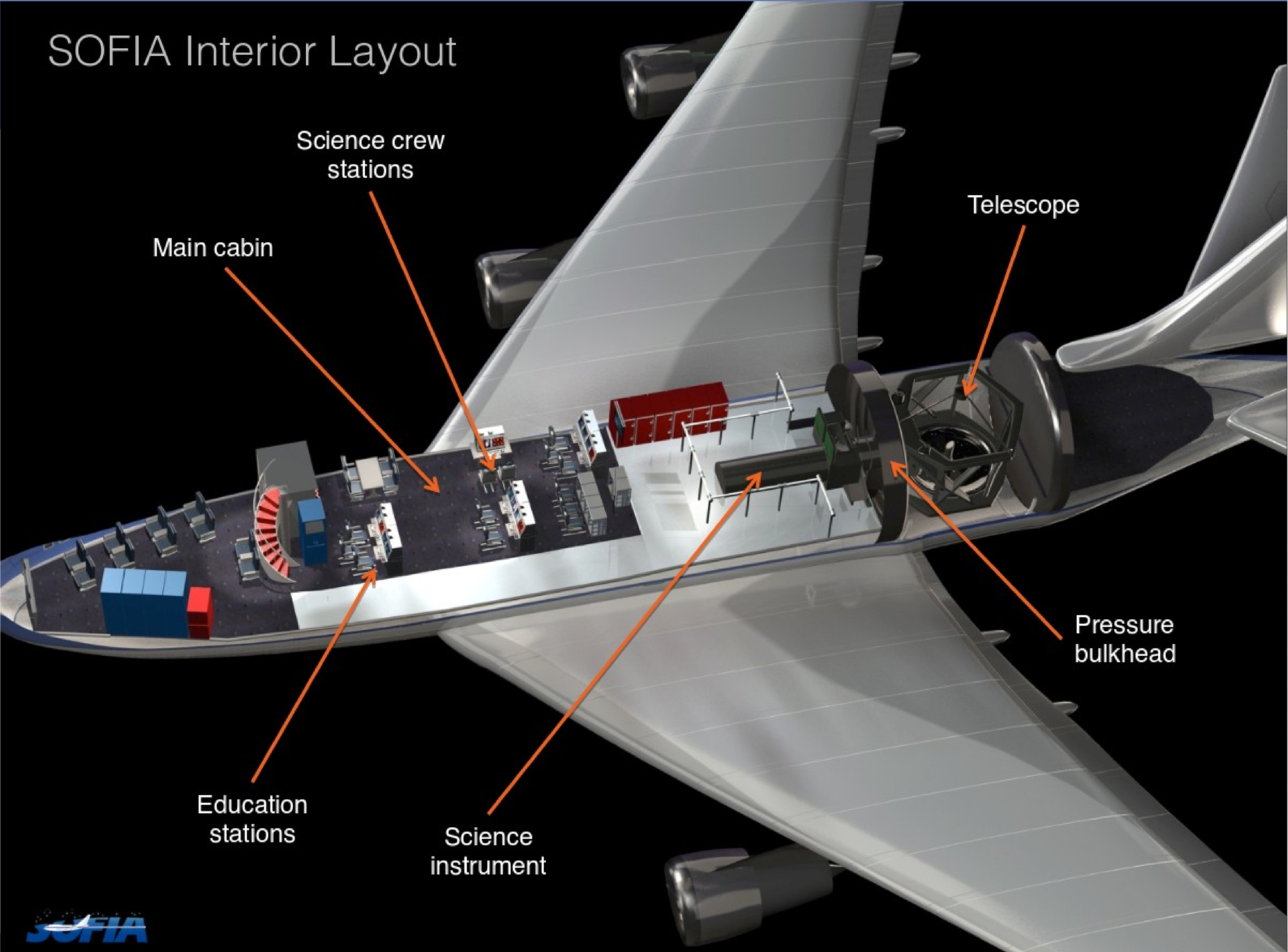
Stratospheric Observatory for Infrared Astronomy

- 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



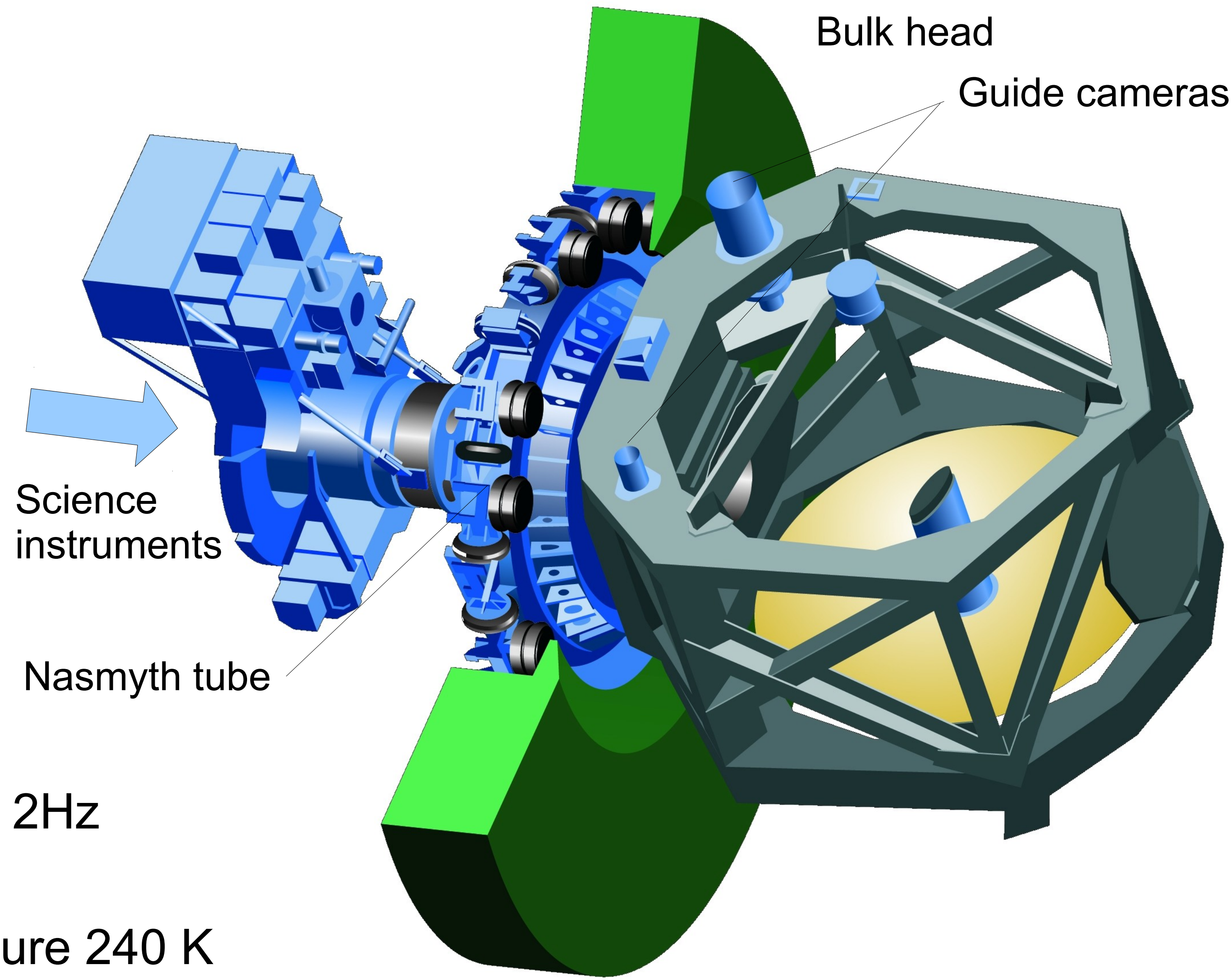
http://www.sofia.usra.edu

SOFIA Interior Layout



Telescope

- Telescope:
  - Primary Mirror:
    - 2.7 meters
    - λ > 0.3μm
    - Diffraction limited for λ>20 μm
  - Pointing accuracy ~1"
  - 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 plus

- 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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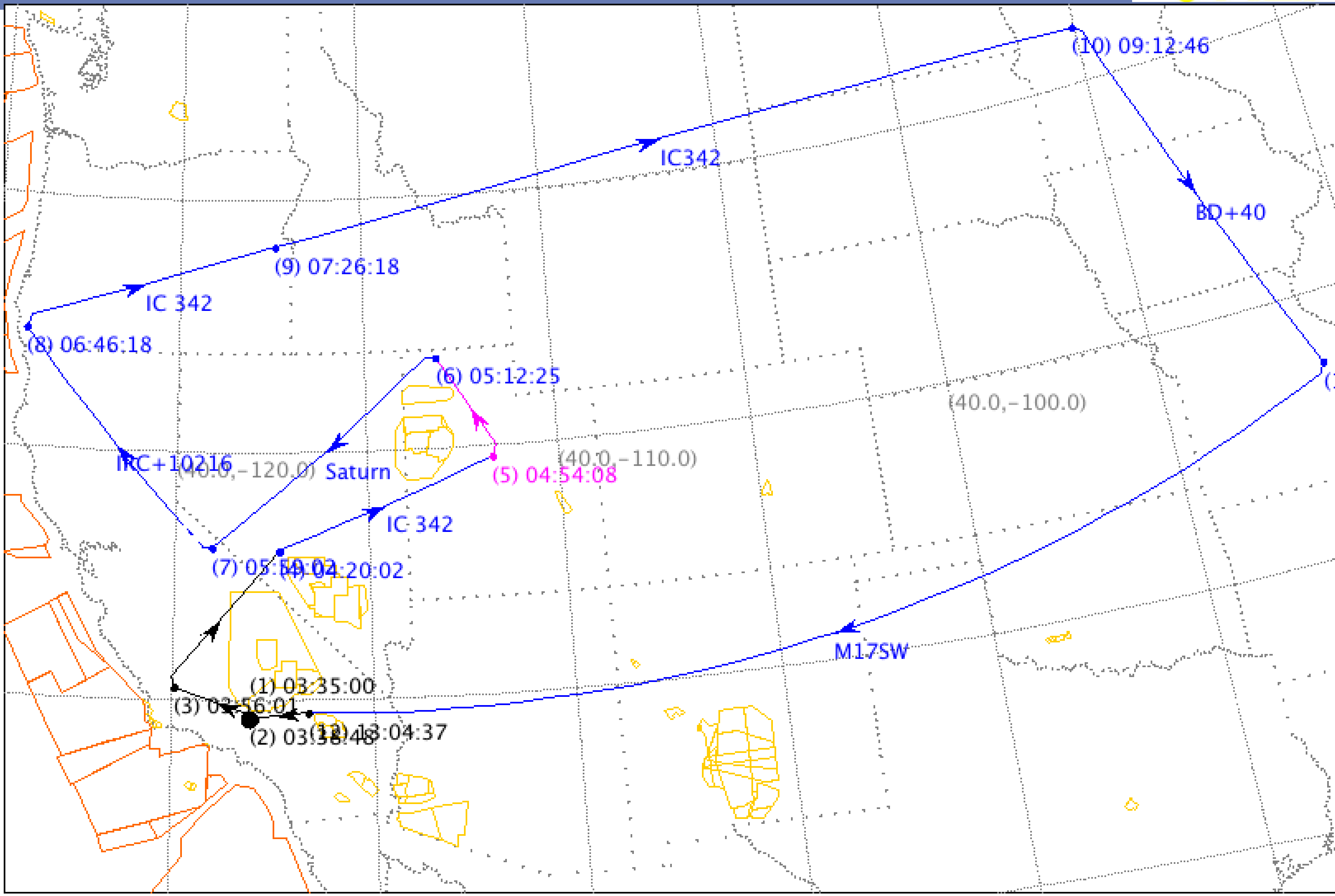

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Flight ID: 2011/04/06
Est. Takeoff Time: 2011-Apr-06 03:35 UTC
Est. Landing Time: 2011-Apr-06 13:15 UTC
Flight Duration: 09:40
Weather Forecast : 0000 Wed Mar 09 2011 - 1200 Fri Mar 11 2011 UTC
Saved: 2011-Mar-25 18:41 UTC User: rklein

Why Stratosphere and why far-IR?

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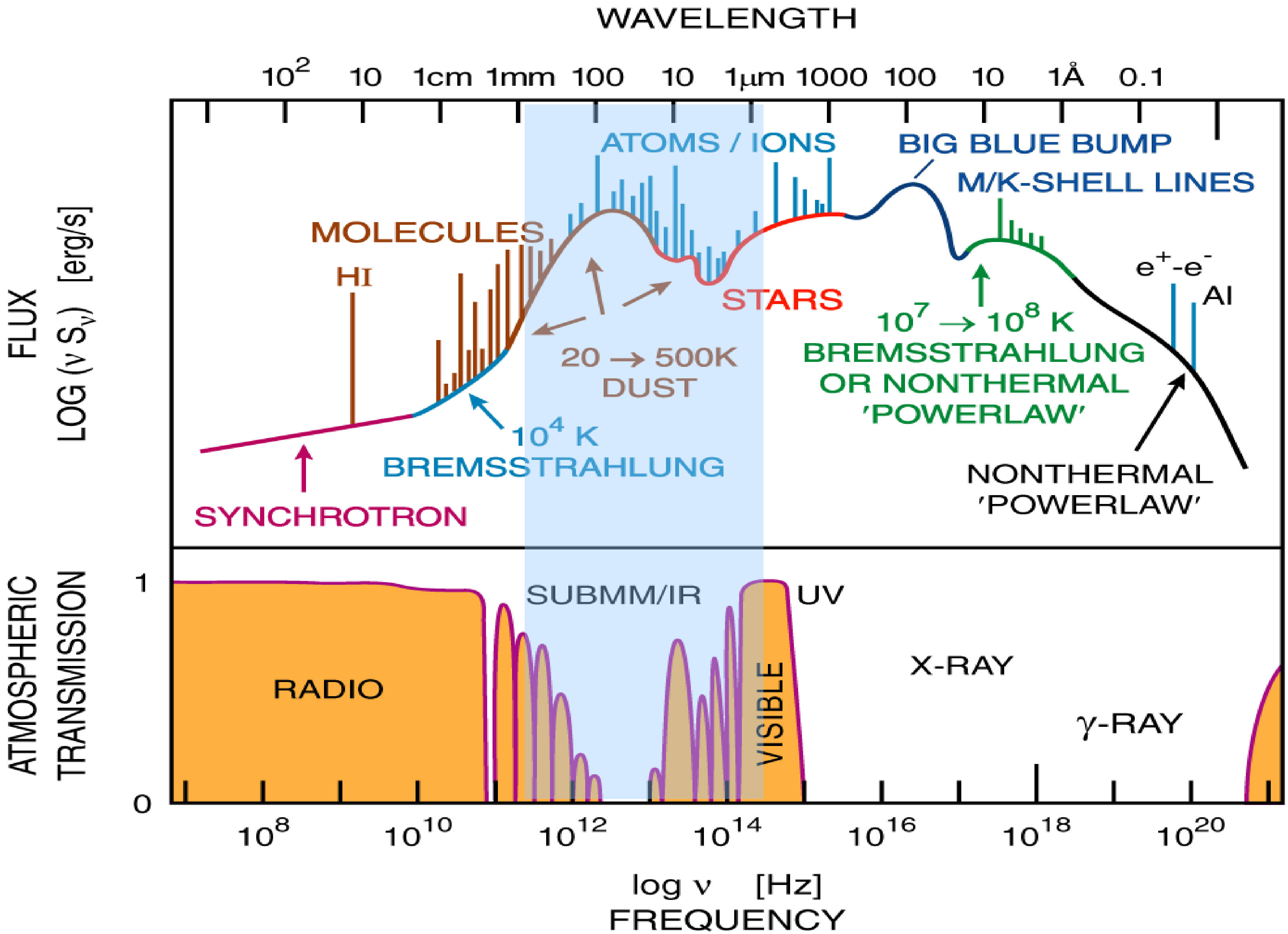
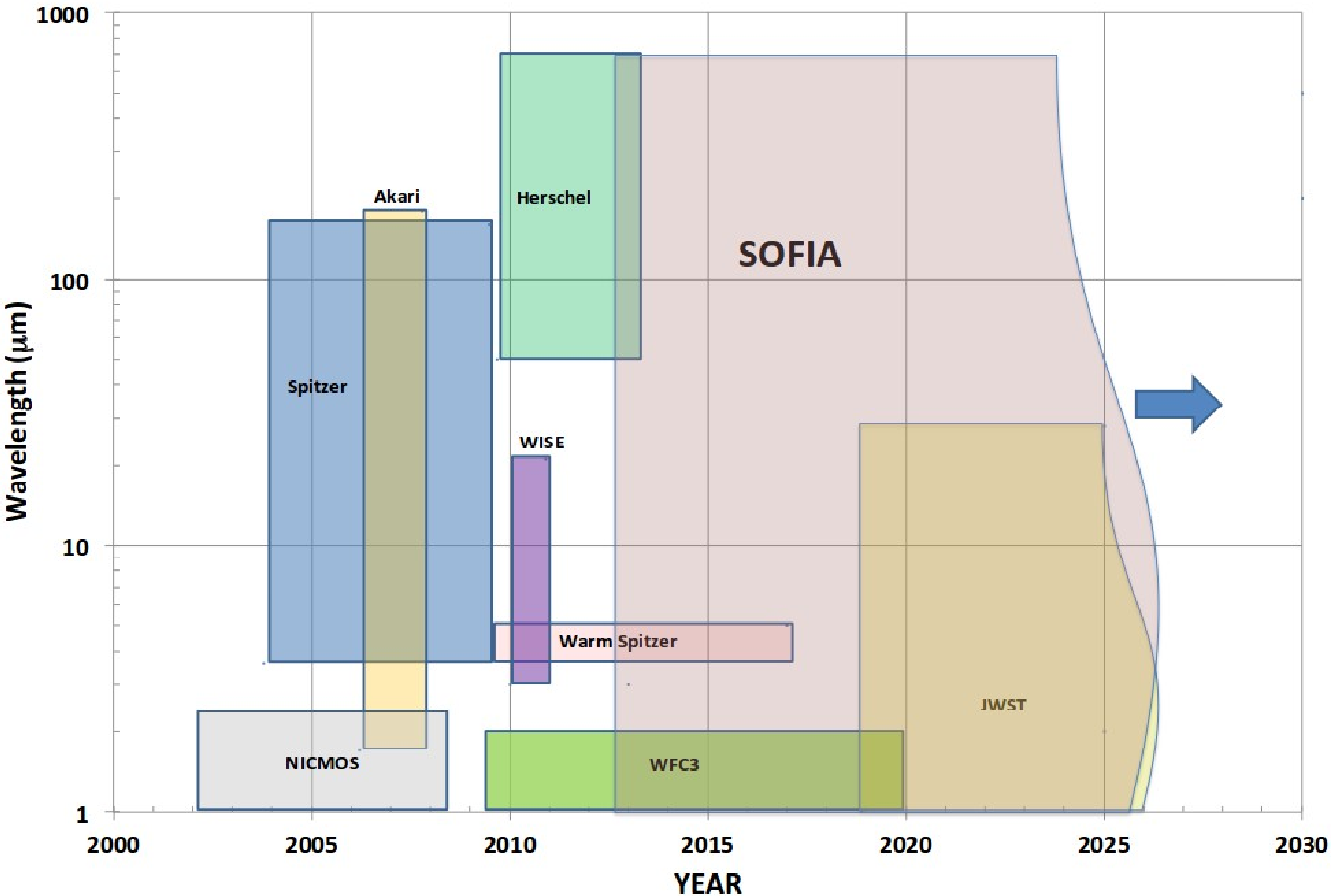
- Spectrum of a star-burst galaxy



Wavelength coverage



Instruments

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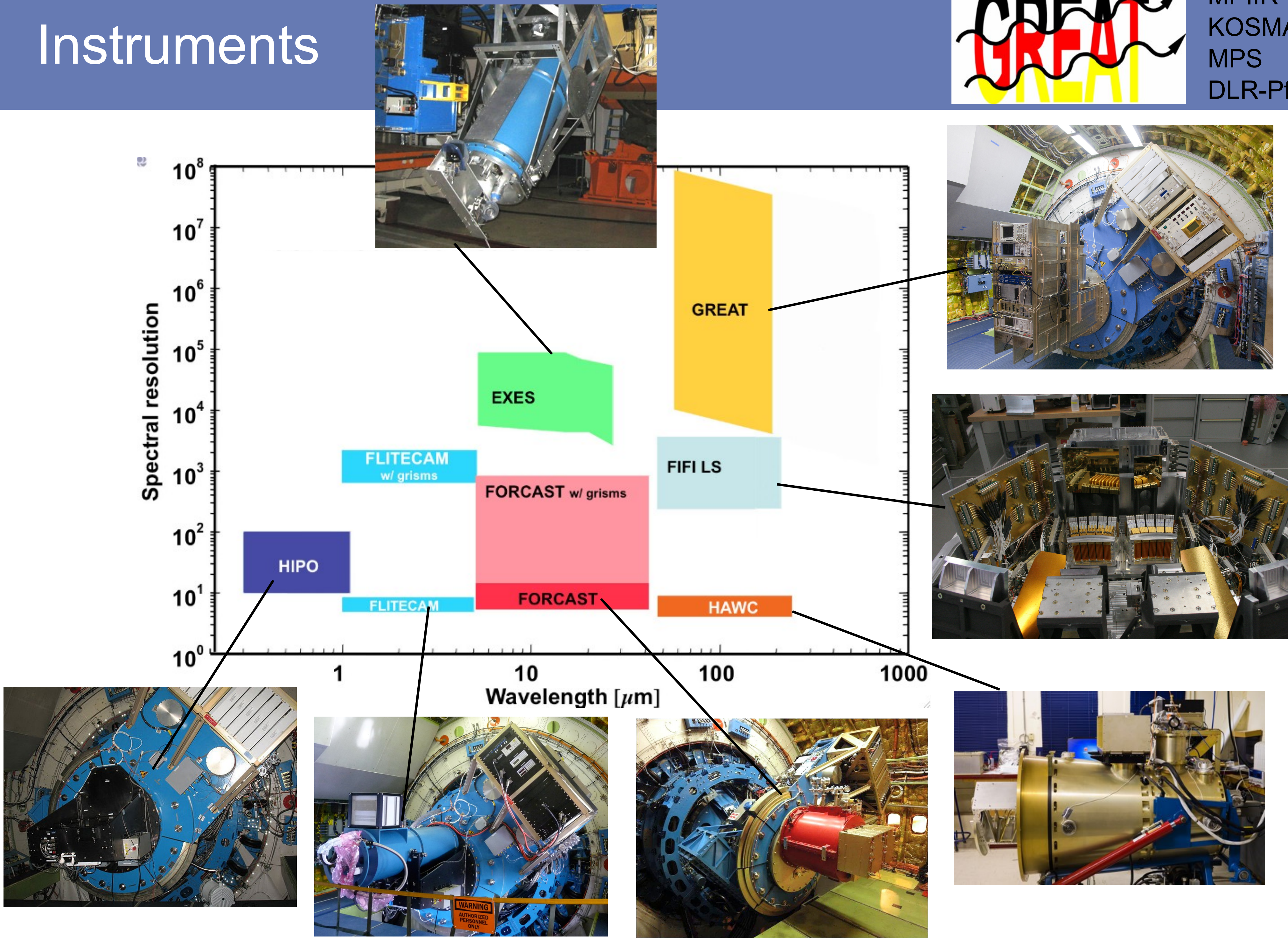
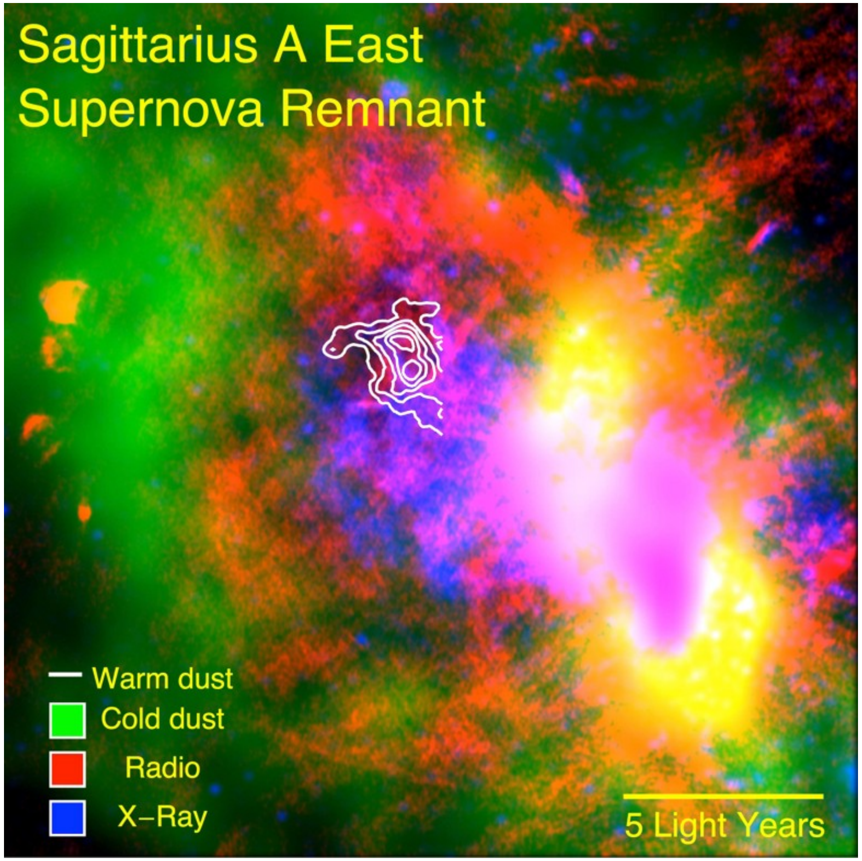


Selected Science Highlights

- 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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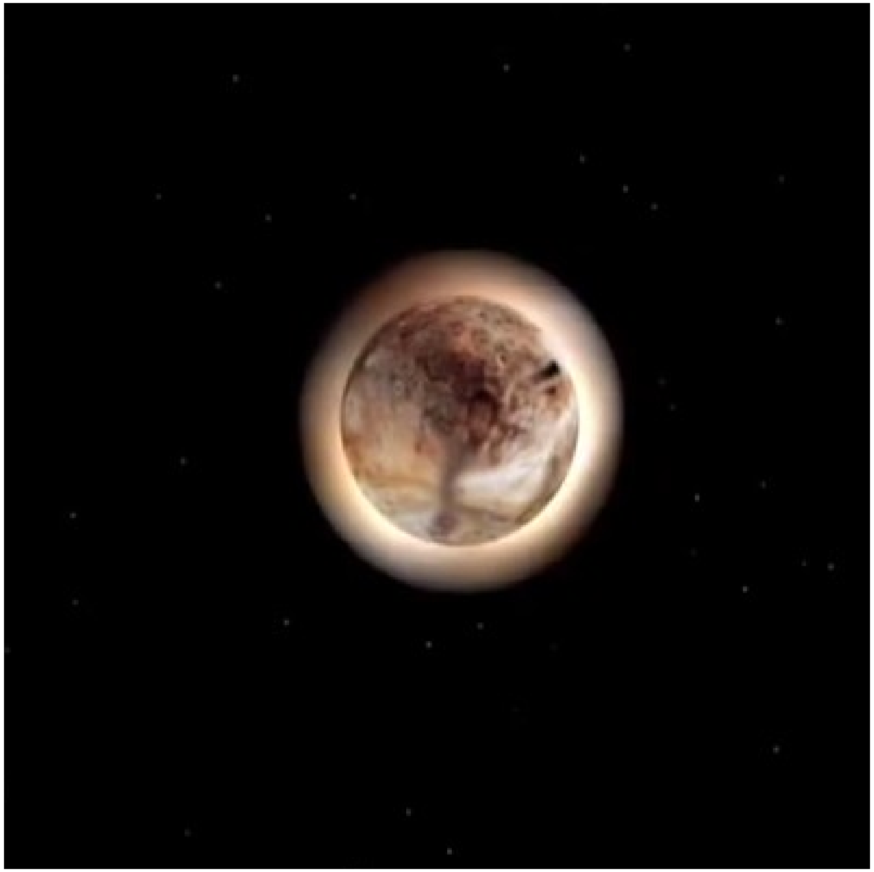
- HIPO (High Speed Imaging Photometer for Occultations)
  - Visible Light High-Speed Camera (0.3–1.1 μm)
  - used in combination with FLITECAM
  - Main purpose: stellar occultations: Surface structure of a solar system object (planetary atmospheres and rings, comets)
- 2 Pluto occultations (2011, 2015):
  - Density profile and spectroscopy of Pluto atmosphere



Selected Science Highlights

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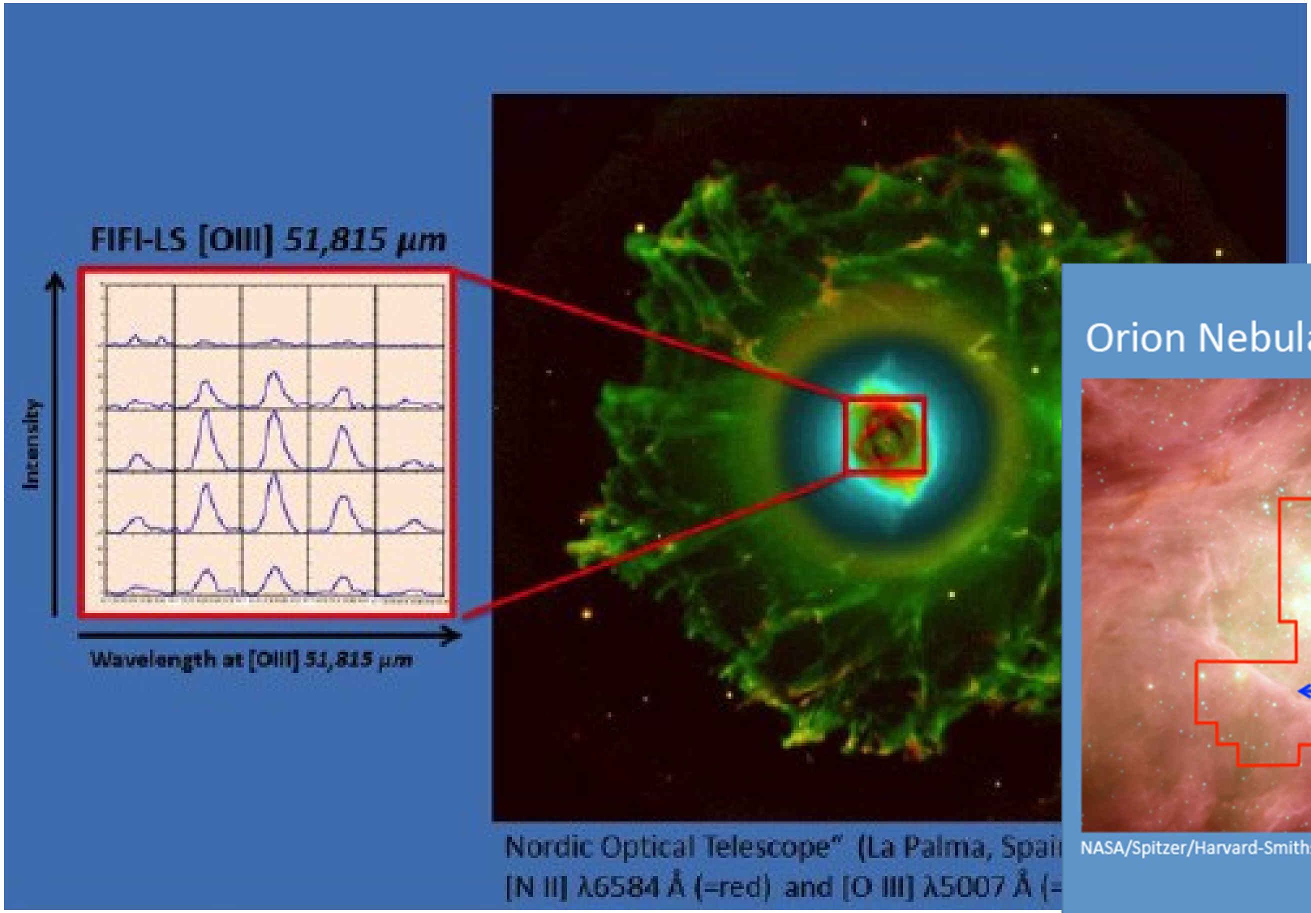
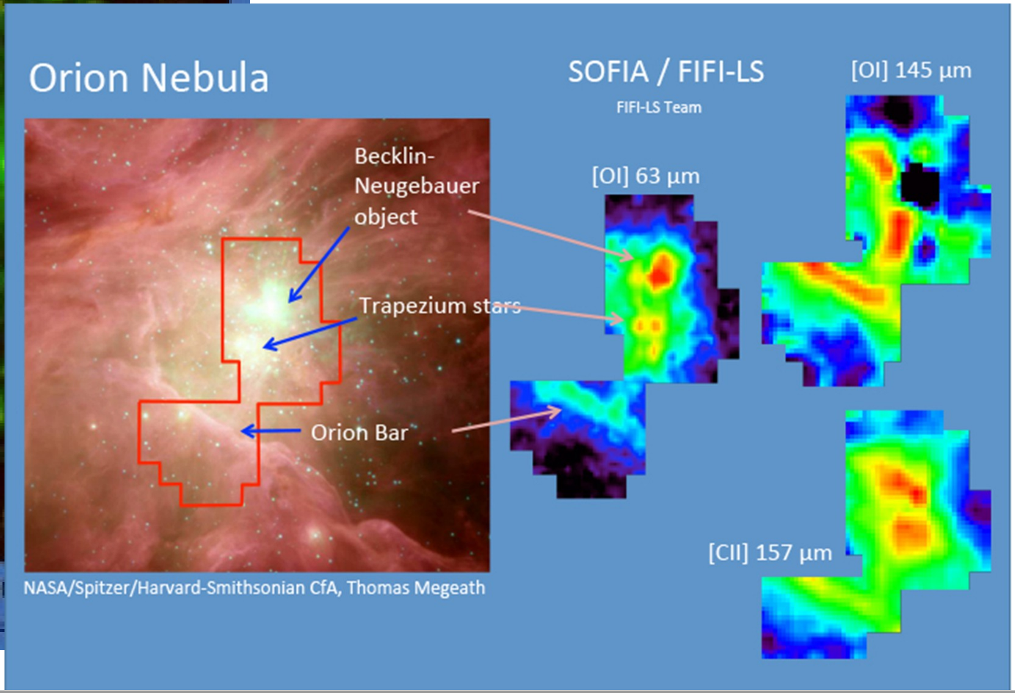
- FIFI-LS (Far Infrared Field-Imaging Line Spectrometer)
  - Dual Channel Integral Field Grating Spectrometer (50–110 µm; 100–200 µm)
  - Spectral line mapping of [CII] 158 µm, [OI] 63, 145 µm, [OIII] 52, 88 µm
  - Absolute atmospheric calibration still being worked on



NGC6543 in [OIII] at 51.8µm

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



Selected Science Highlights

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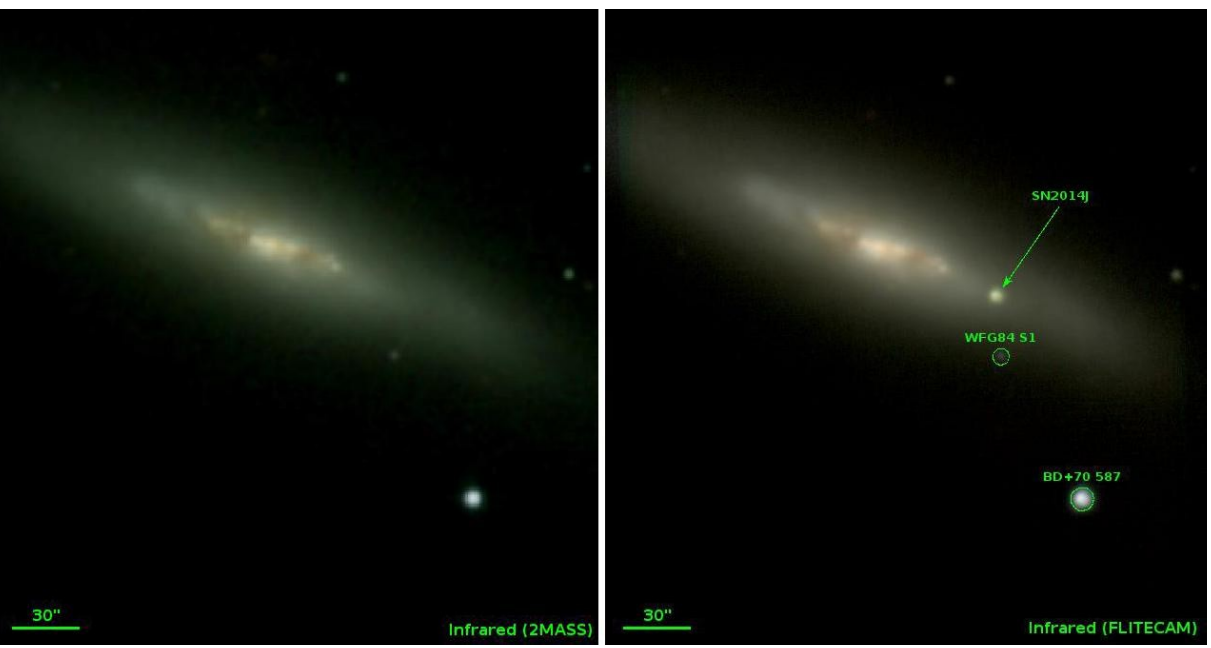
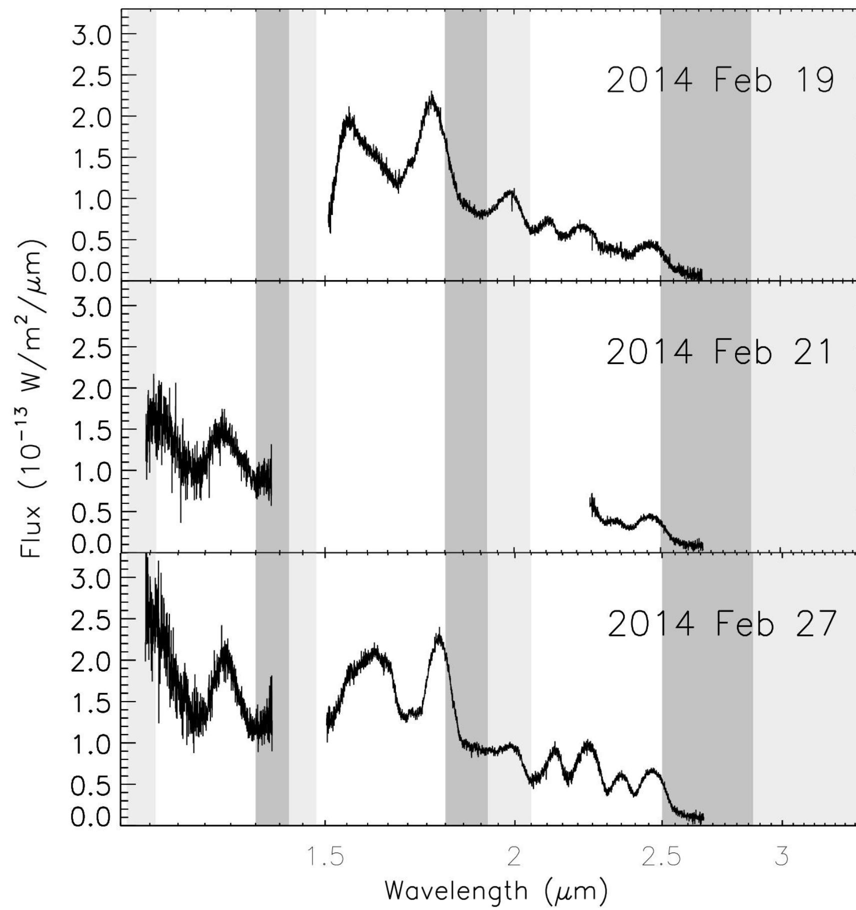
- FLITECAM (First Light Infrared TEst CAMera)
  - Near Infrared Imaging and Grism Spectroscopy (1–5.5 µm)
  - can be used in combination with HIPO
- SN 2014J (M82): near-IR spectrum, evolving with time (ionized Cobalt lines)
- Pluto occultation (June 29, 2015)





Selected Science Highlights

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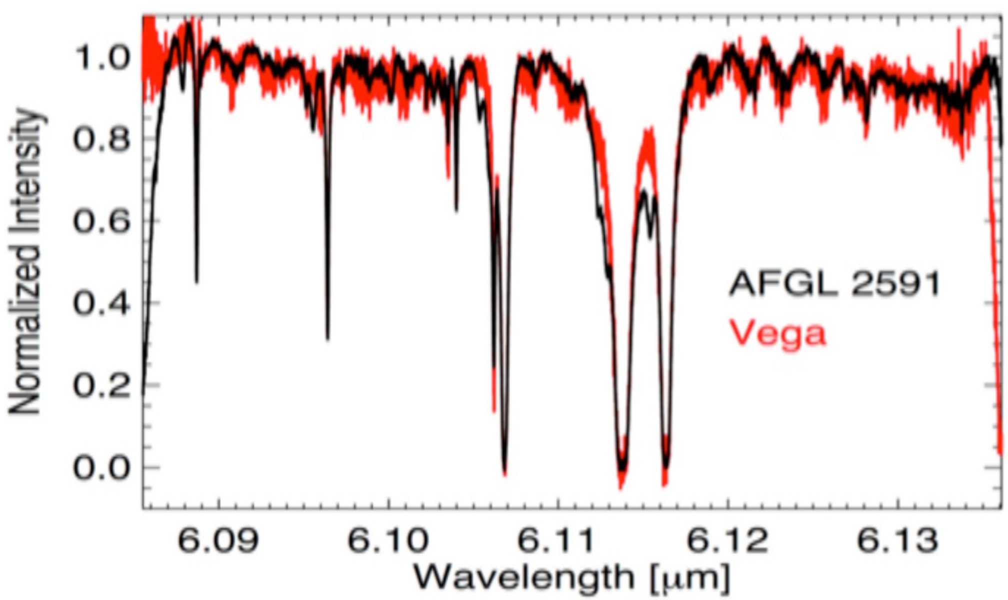
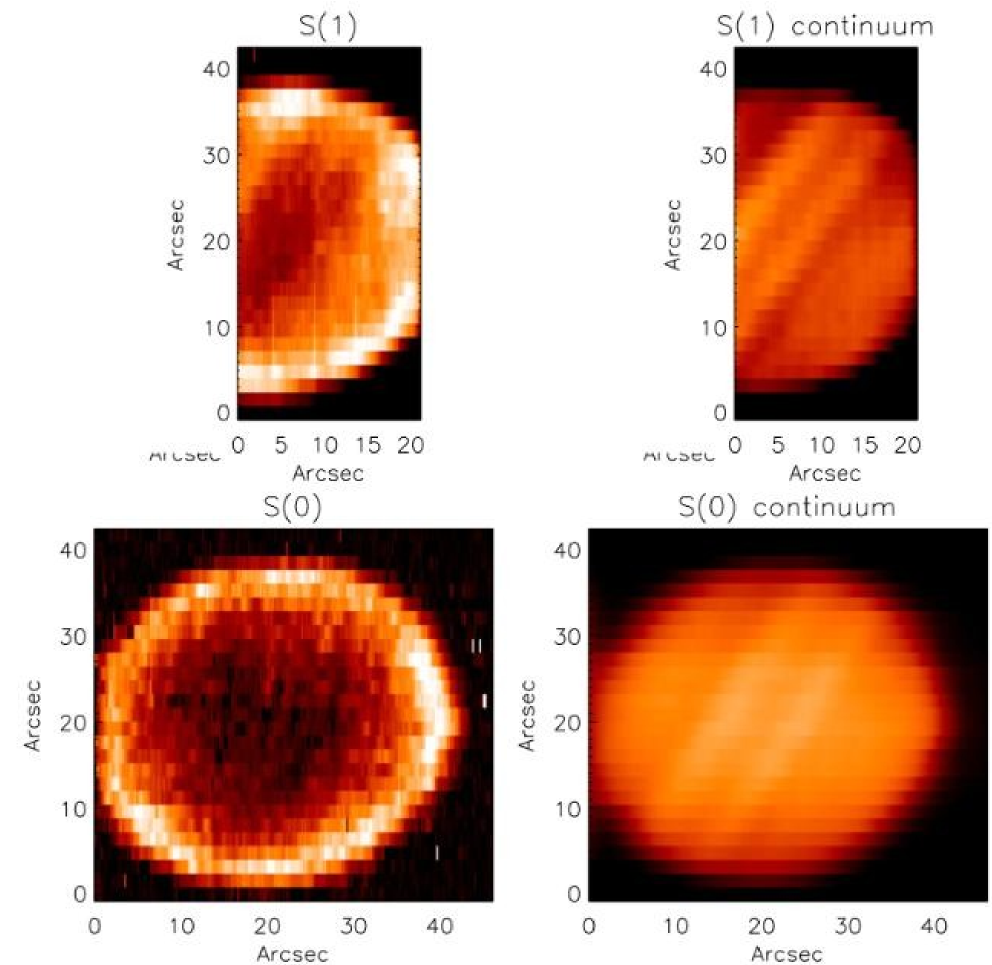
- EXES (Echelon-Cross-Echelle Spectrograph)
  - High Resolution ($R=10^5$) Echelle Spectrometer (5–28 μm)

- 28/17μm para/ortho H_2 mapping for Jupiter and several star-forming regions
- Water in protoplanetary disks (AFGL 2591)



Indriolo et al.



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

Selected Science Highlights

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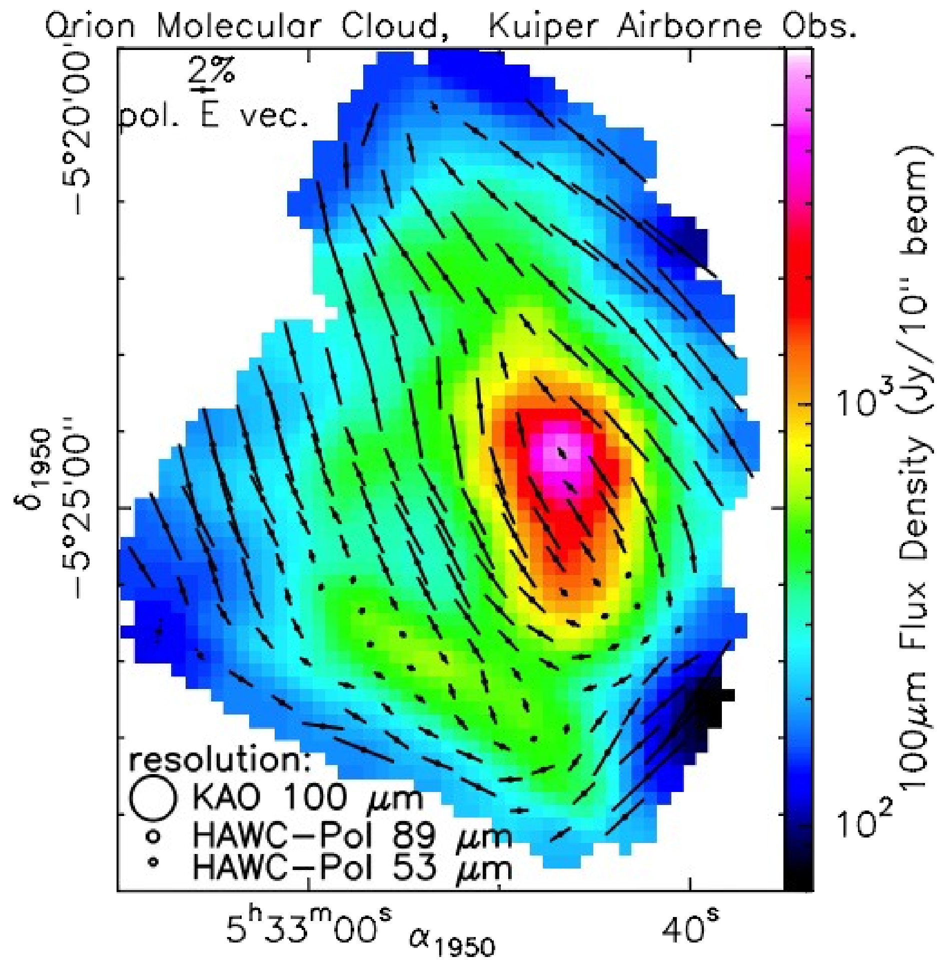
- HAWC+ (High-Angular resolution Wideband Camera)
  - High-Angular Resolution Wide-Band Camera
  - Polarimeter with 5 Channels (53, 62, 88, 155, 215 μm)
  - Currently being commissioned
- No results yet
  - Expectations based on KAO results



Linear polarization of the Orion Nebula at 100 μm measured with the KAO by Schleuning (1998). Beam sizes of the KAO polarimeter and HAWC upgrade. (Dowell et al. 2007)

GREAT

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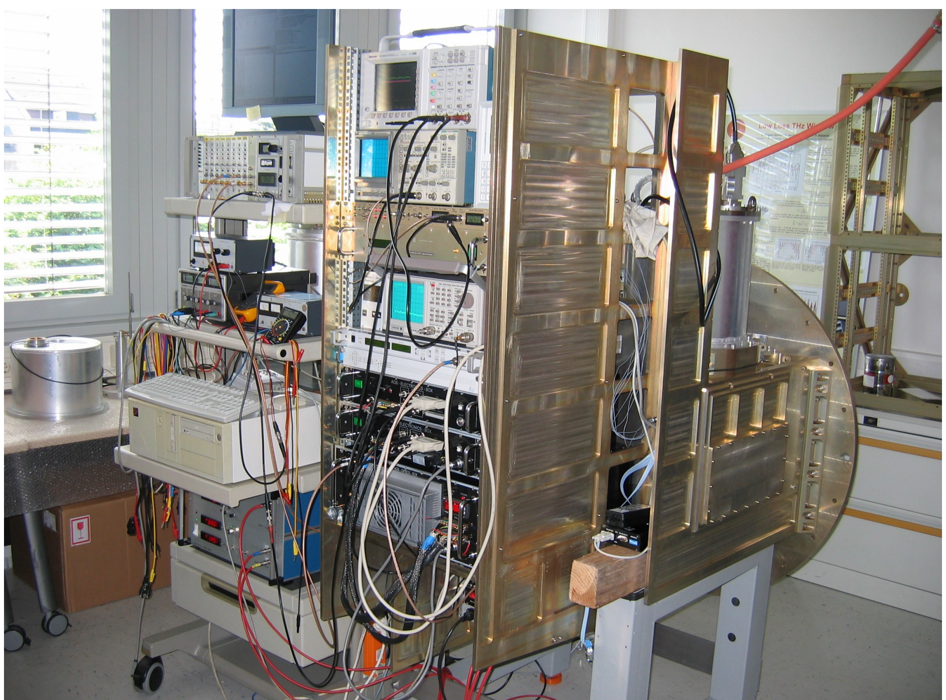
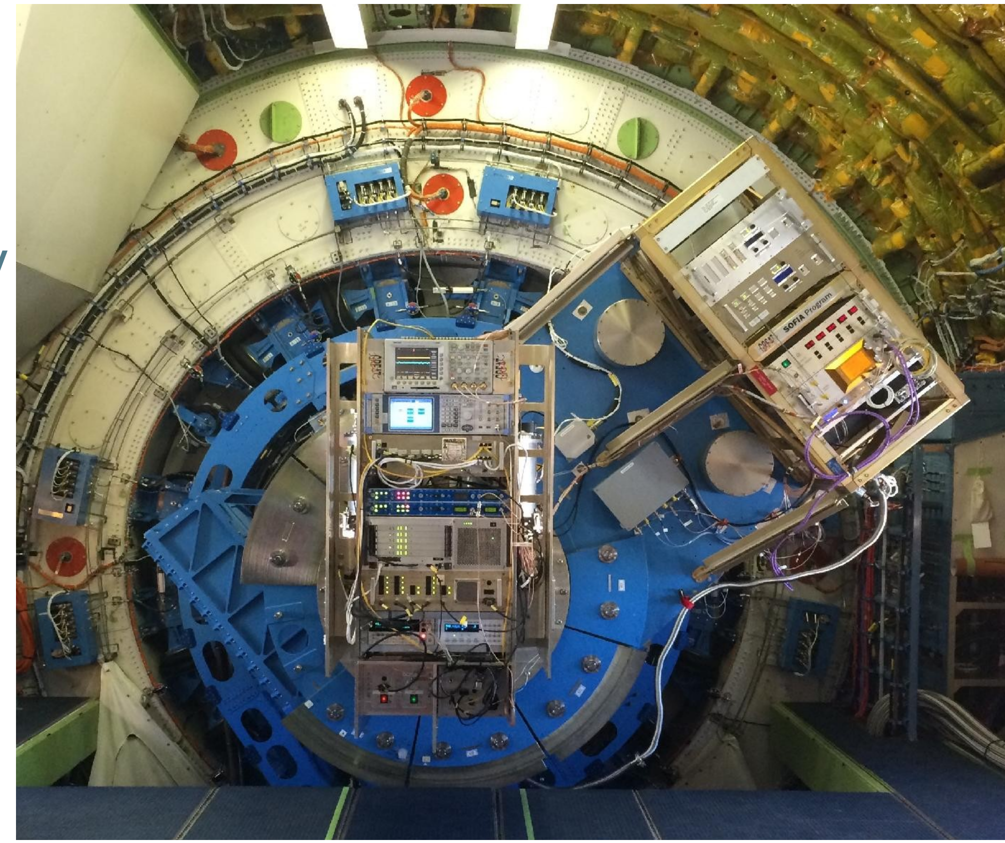
German REceiver for Astronomy at Terahertz-Frequencies

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





- XFFTS
  - 64000 channels
  - Bandwidth: 2.4GHz
  - 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)

upGREAT: GREAT multiplexed

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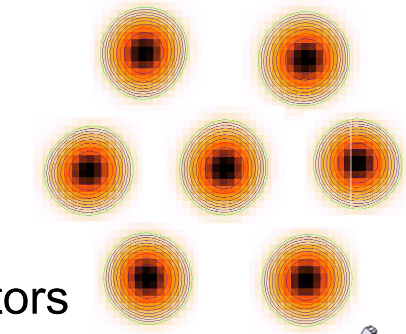
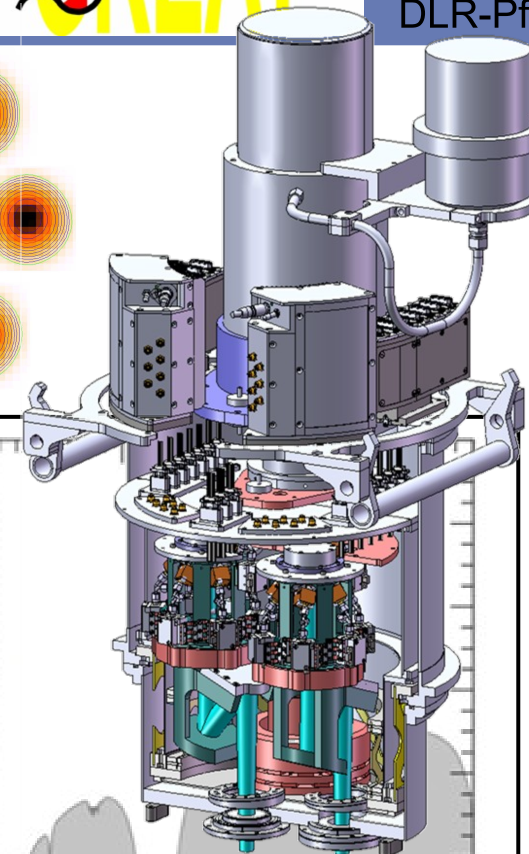
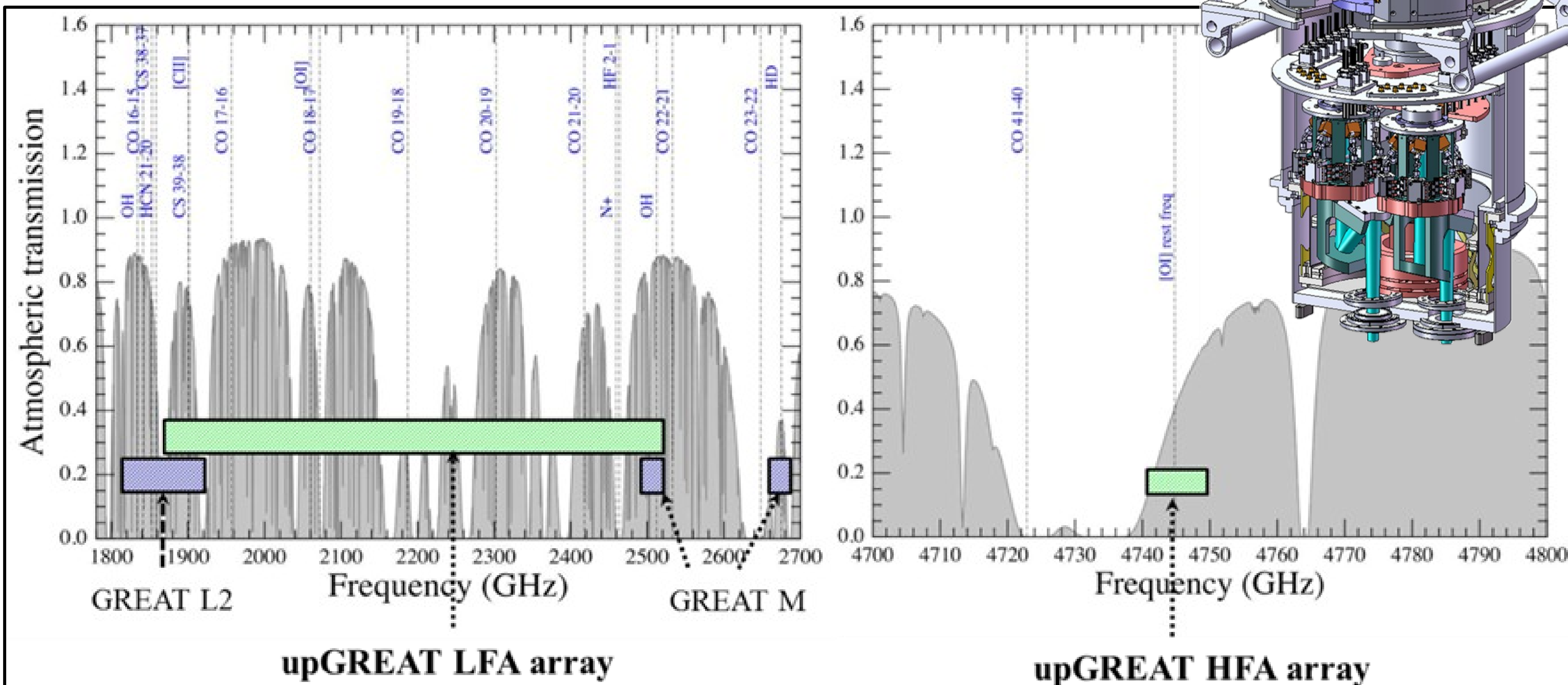
- 2 hexagonal arrays, operating in parallel
  - 2 x 7 low freq. Pixels (LFA)
  - 1 x 7 high freq. Pixels (HFA)
  - Or combinations with GREAT single pixel detectors







GREAT science

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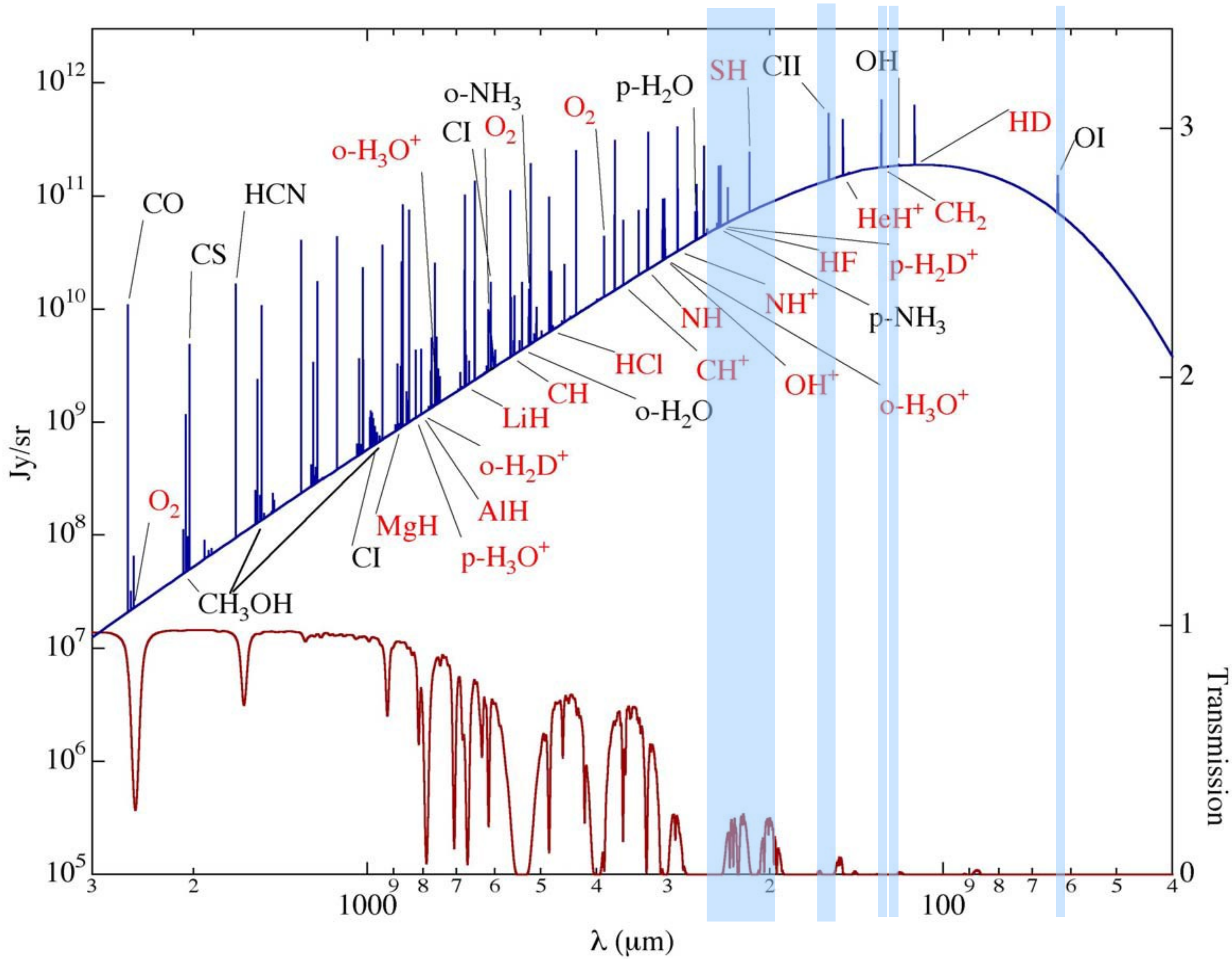
- Focused on main cooling lines:
  - [OI], [CII]
- OH, HD
- High-J CO transitions
- Hydrides
- Covers HIFI-gap



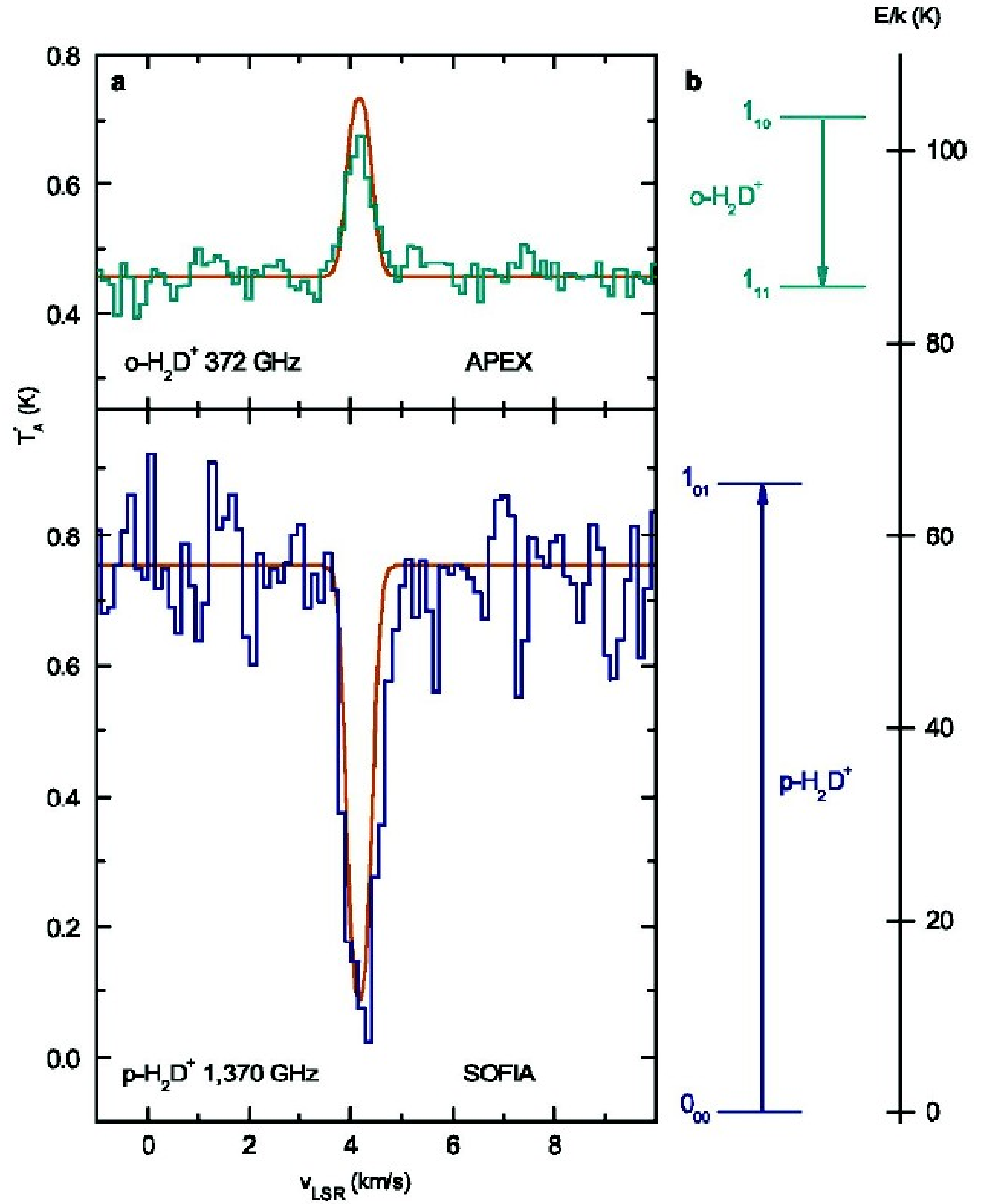
Bergin (2008)

First detections

para-H_2D^+ detection:

- 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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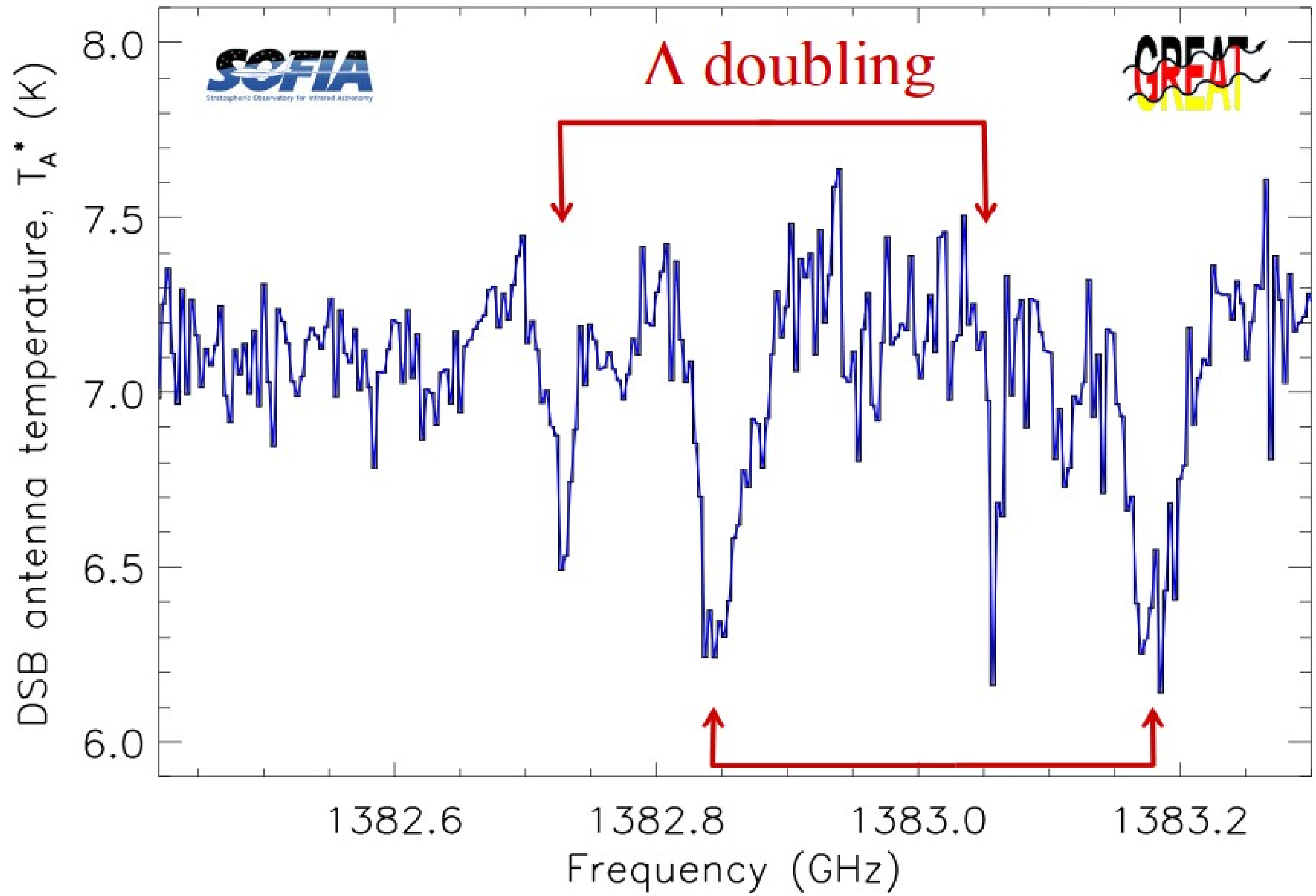
SH detection:

- 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

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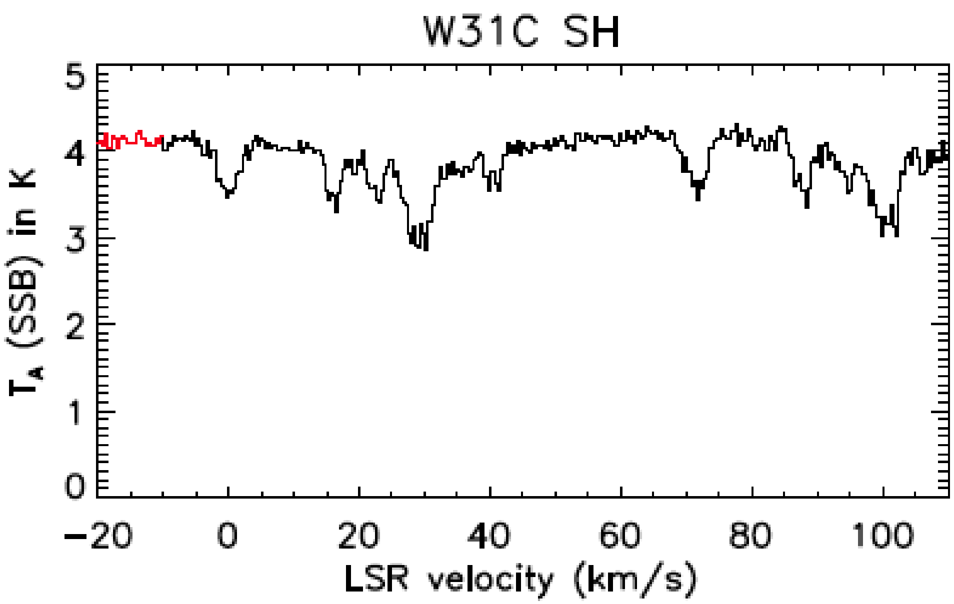
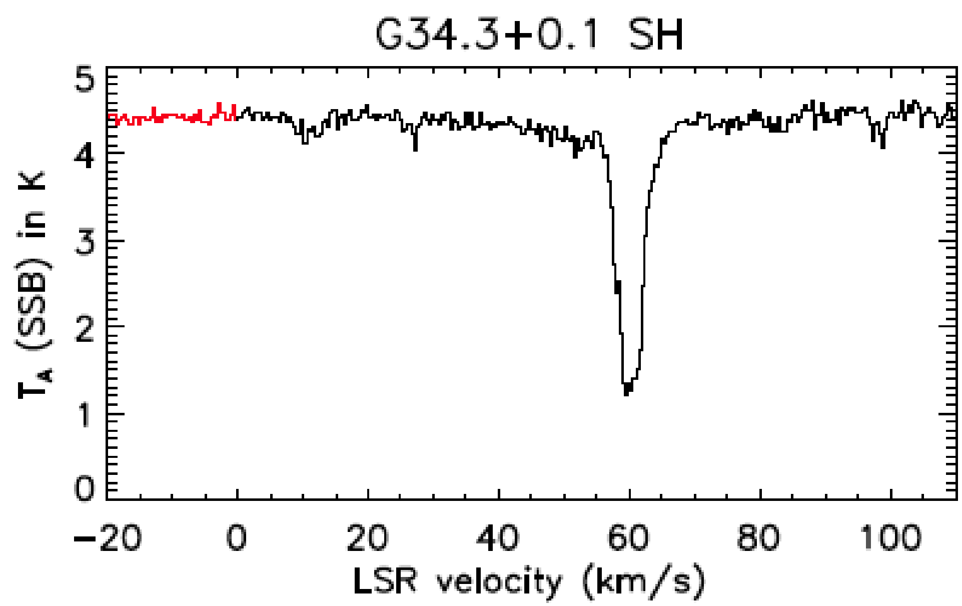
SH detection:





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

Neufeld et al. (2014)

High-resolution spectra

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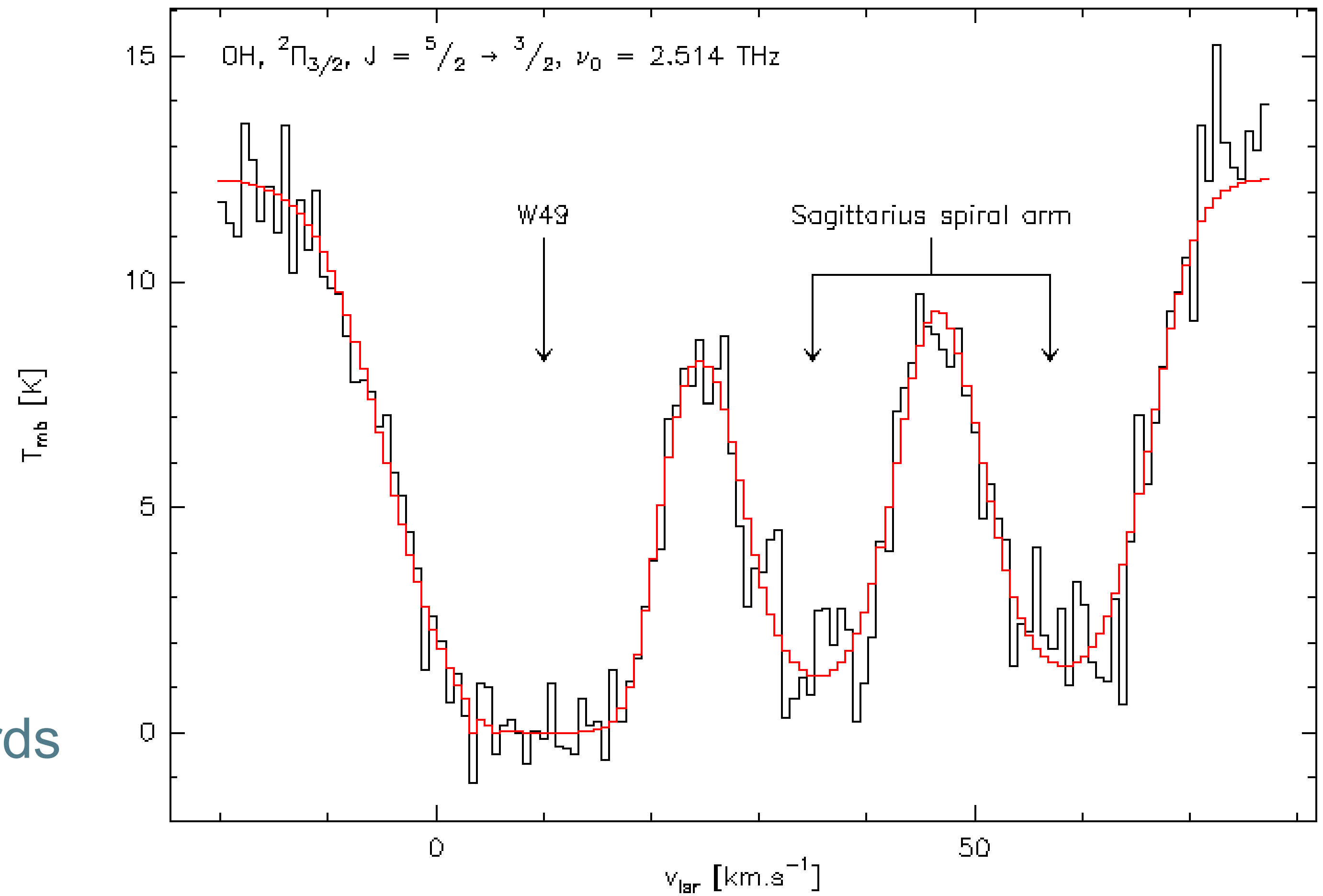
OH absorption:

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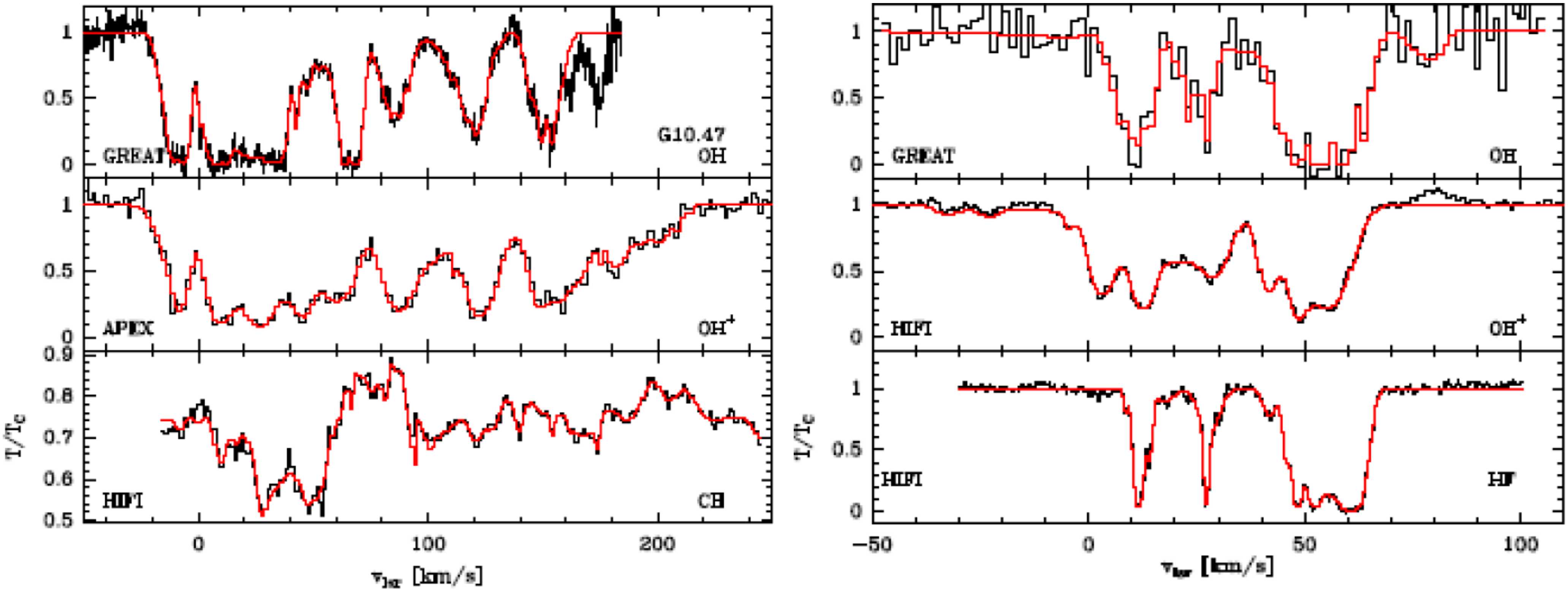
Systematics (G10.47, G34.26, W31C, W49N, G327.29, G351.58):



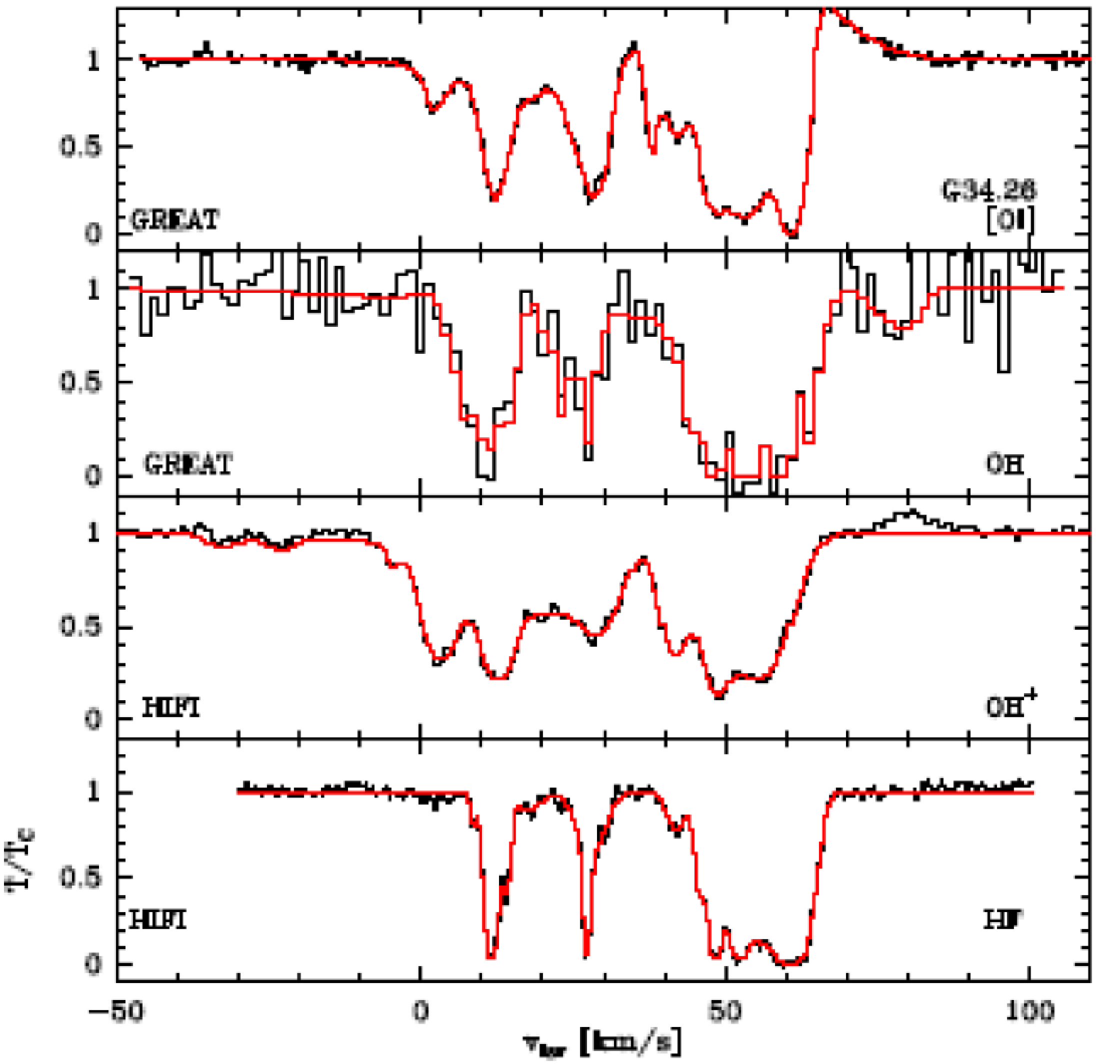
- OH^+ traces atomic, OH rather molecular diffuse gas:
  - OH^+ has lower arm/interarm contrast than OH
  - $[OH]/[OH^+]$ correlated with H_2: bottleneck $OH^+ + H_2 \rightarrow H_2O + H$
  - H_2O/OH ratio to be explained by TDR model

Wiesemeyer et al. (2015)

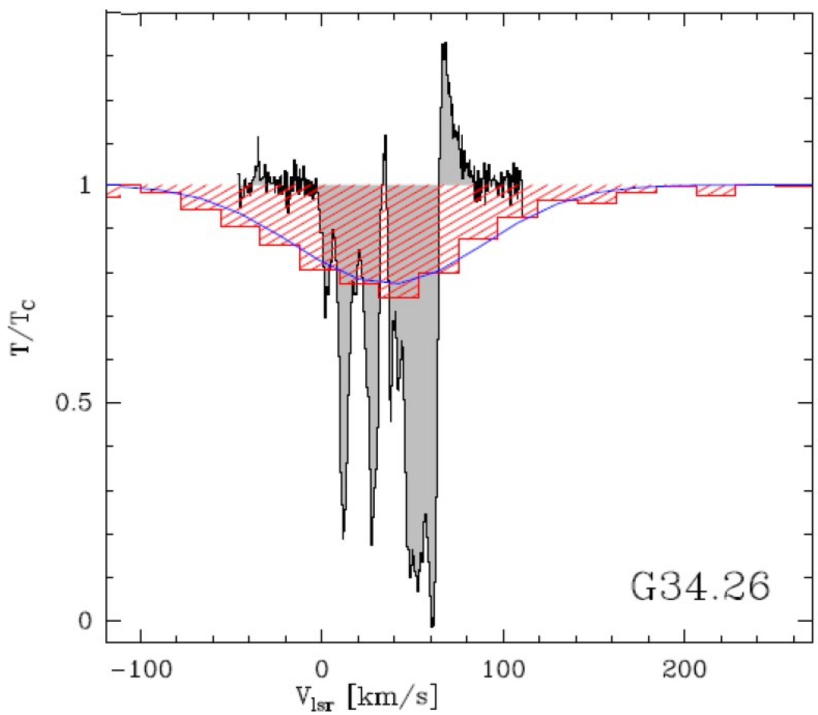
[OI] ($^3P_1$ -$^3P_2$ = 63µm)

[OI] absorption:

Wiesemeyer et al. (2015)



- 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] $^3P_1$ -$^3P_2$

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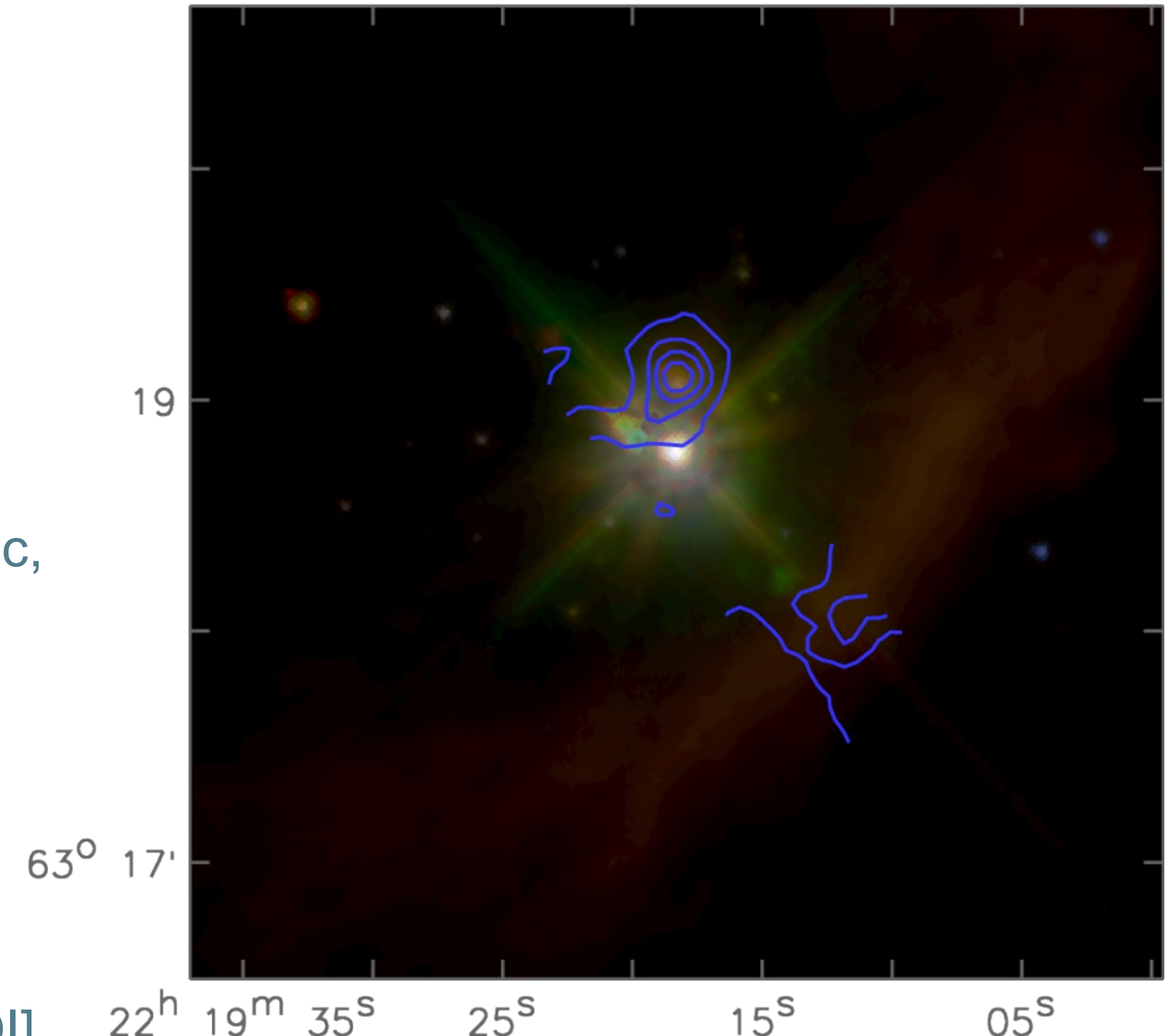
S140:

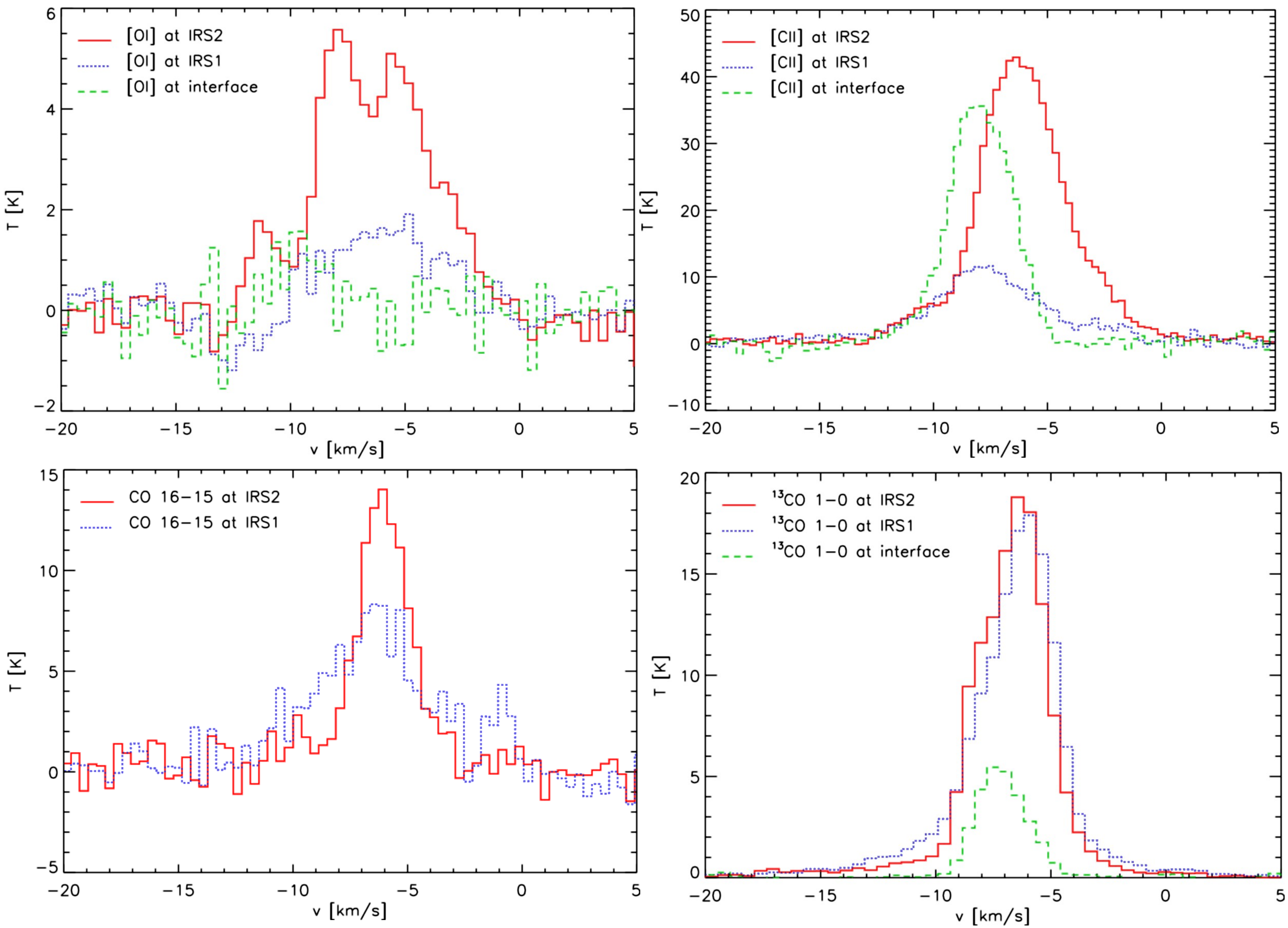
- First [OI] 63µm observations with H-channel
- [OI] strongly peaked, but at IRS2, not IRS1
  - Resolved in [OI]: FWHM = 8.3" = 0.03pc, L([OI])=0.05 $L_\odot$, L([CII])=0.28 $L_\odot$, L(dust)=2000 $L_\odot$
  - IRS1, the main energy source of the region produces almost no [CII] and [OI]



Ossenkopf et al. (2015)

Line profiles

[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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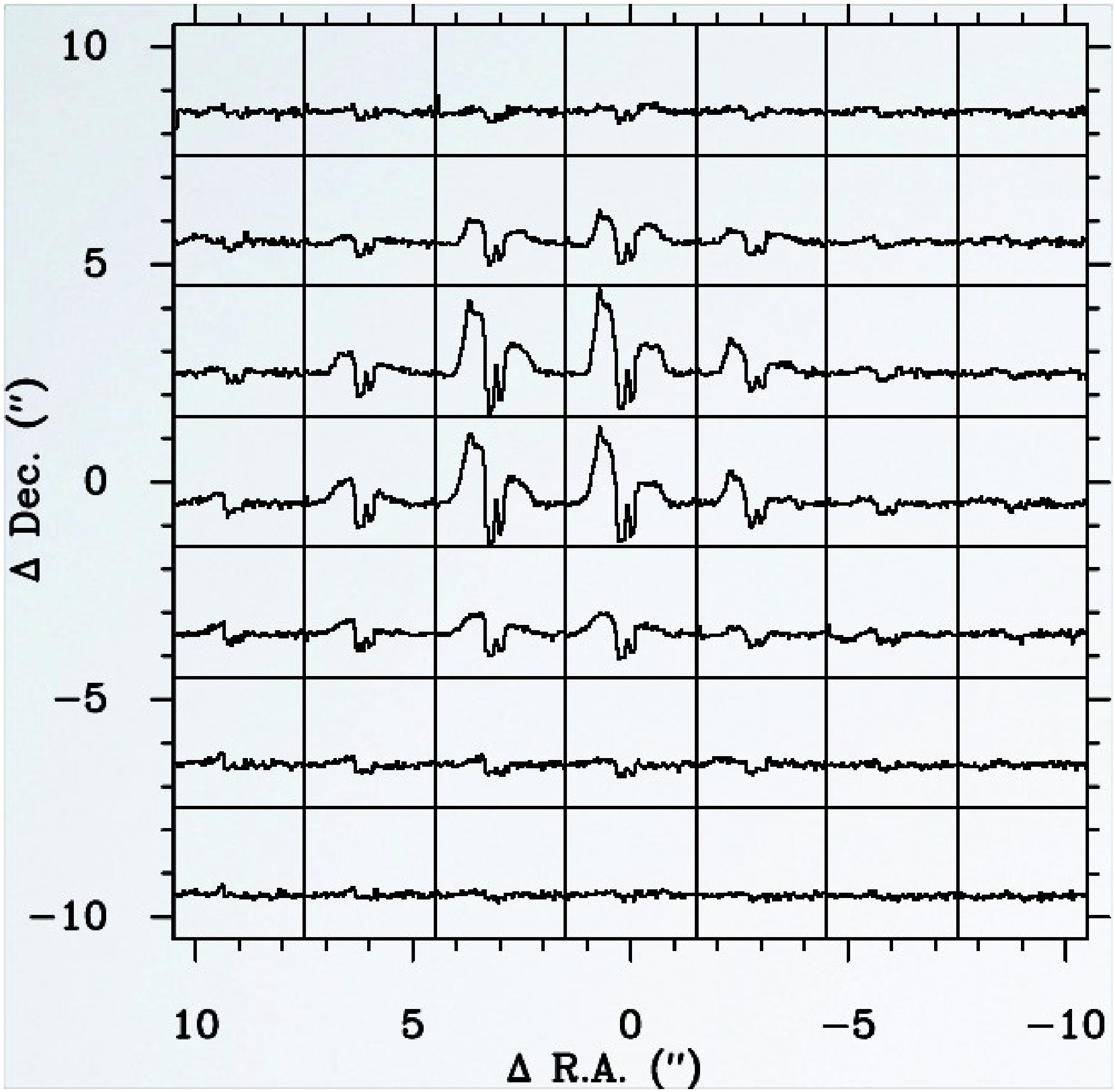
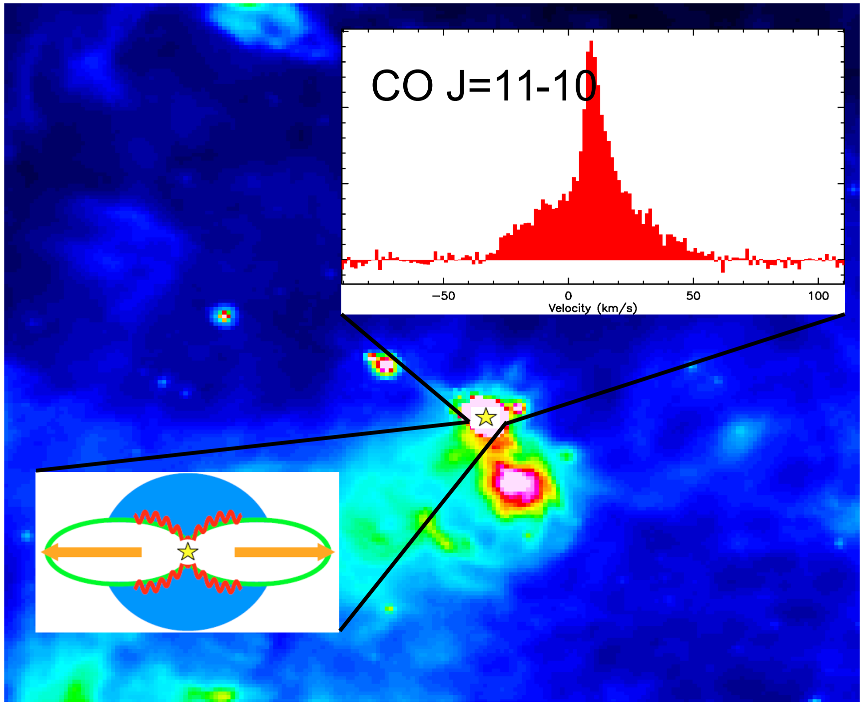
G5.89-0.39:





Güsten & Gusdorf in prep.

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

Leurini et al. (2015)

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

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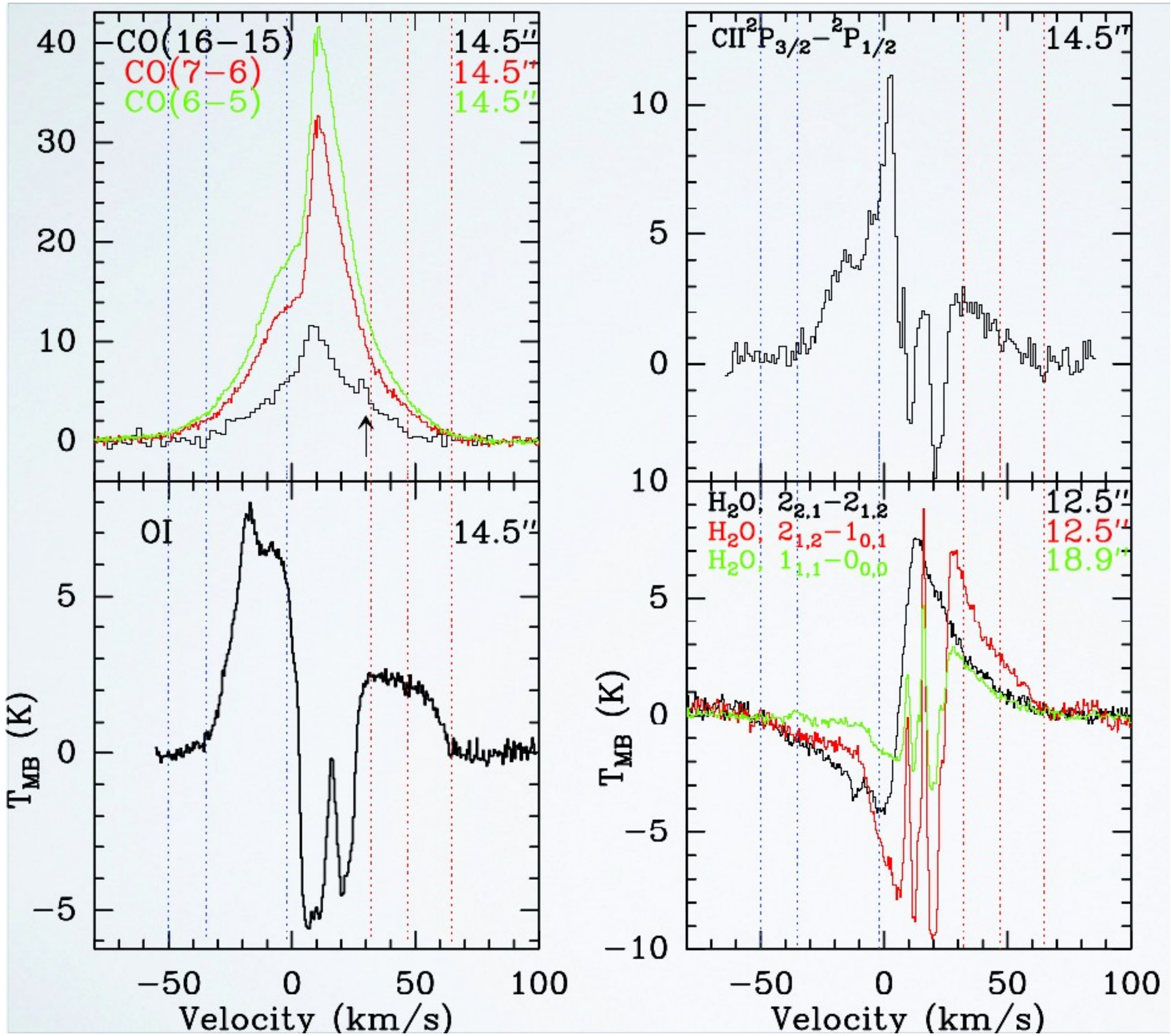
G5.89-0.39:

- [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. (2015)

(up)GREAT mapping

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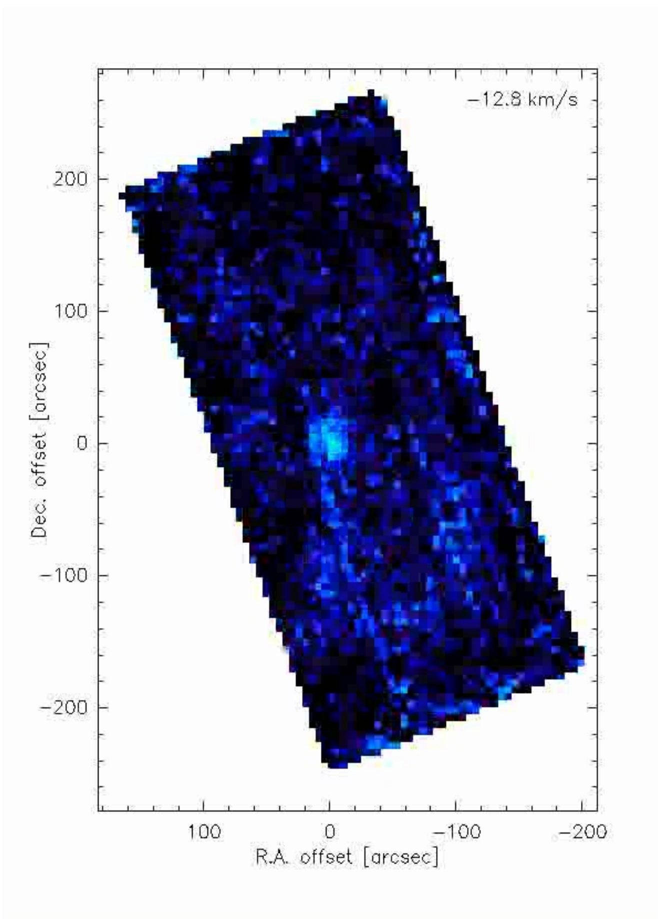
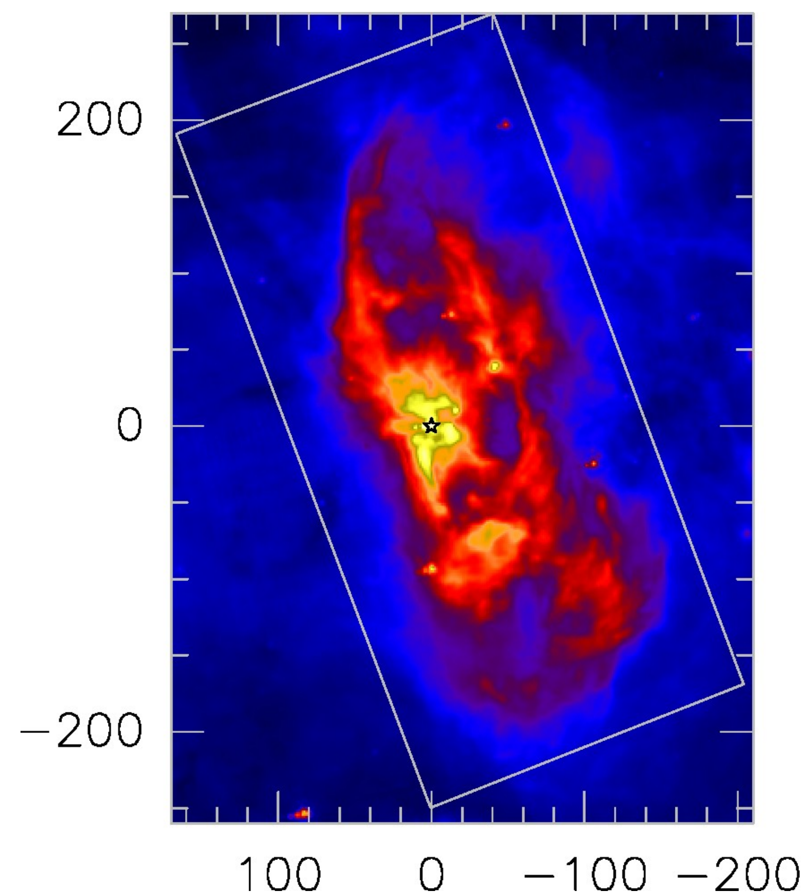
- The first [CII] map observed with upGREAT: S106
  - 7 pixels, 1 hour flight leg, commissioning flight in May 2015
  - 3 x bigger map, 4 – 7 x better noise, 2 x faster (than GREAT)

upGREAT



IRAC 8 μm



Gas composition and kinematics

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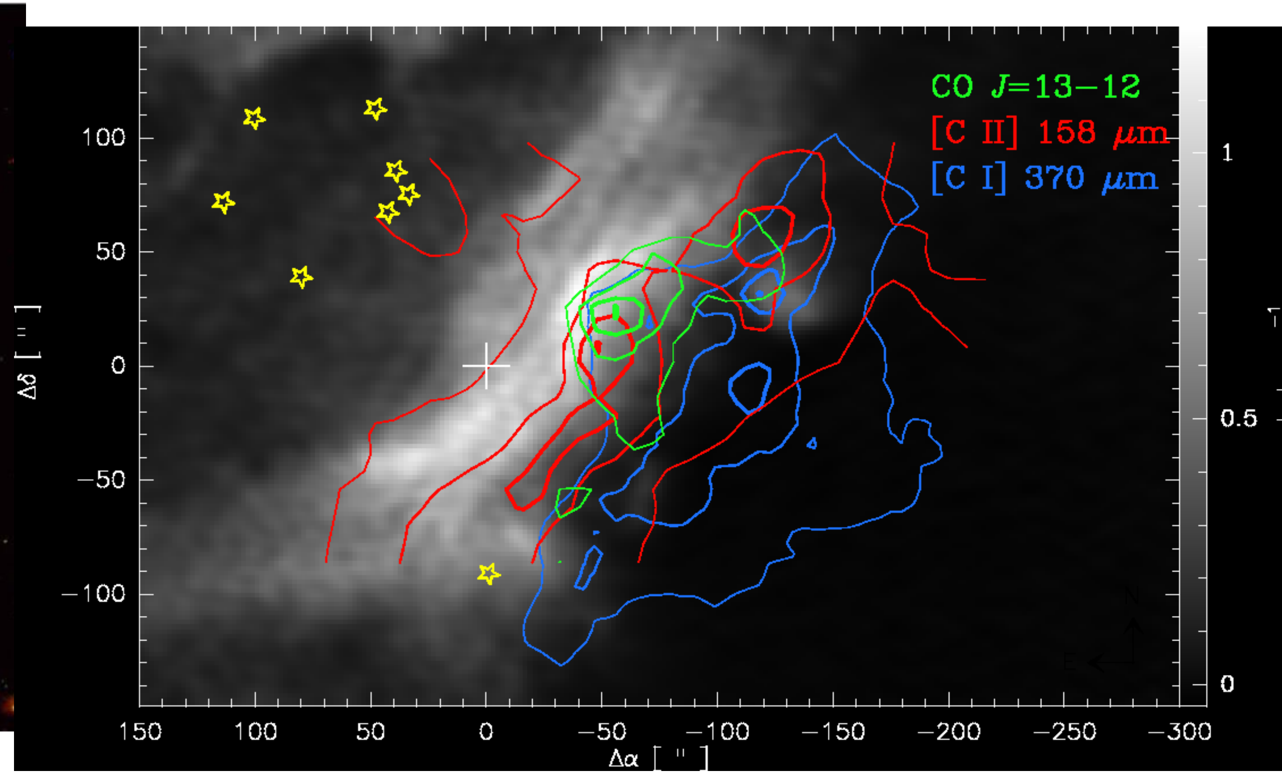
M17SW (Clumpy PDR):

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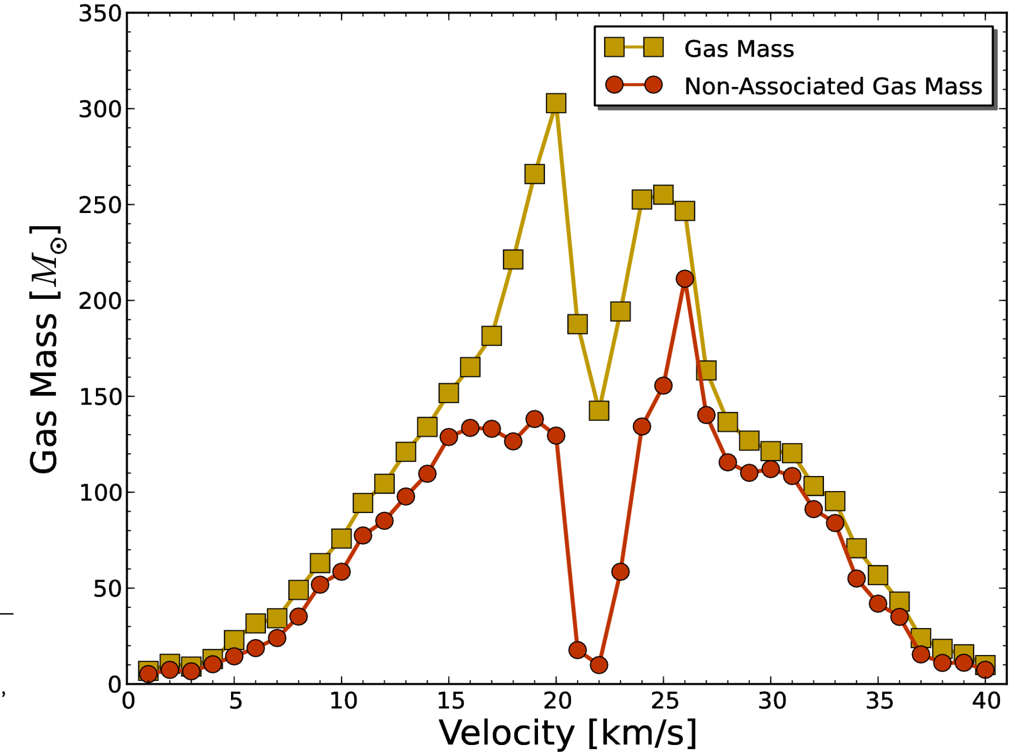
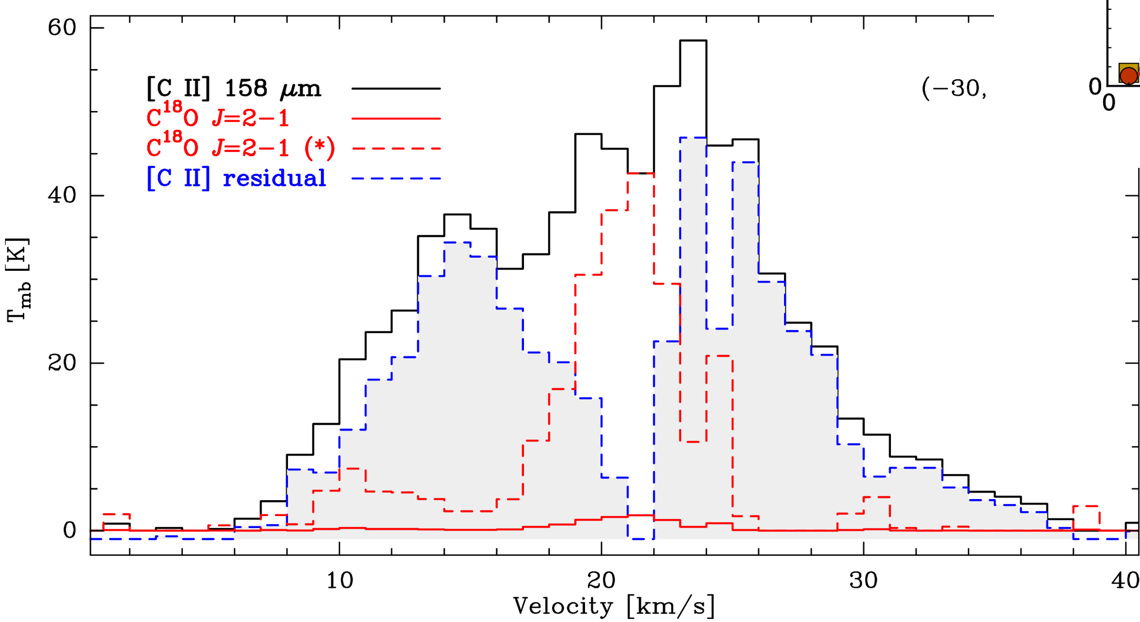
- 64% of the mass traced by [C II] is not associated with star-forming material traced by [CI] and $C^{18}O$
- Assignment to phases:
  - 36% - HII
  - 17% - HI
  - 47% - H_2





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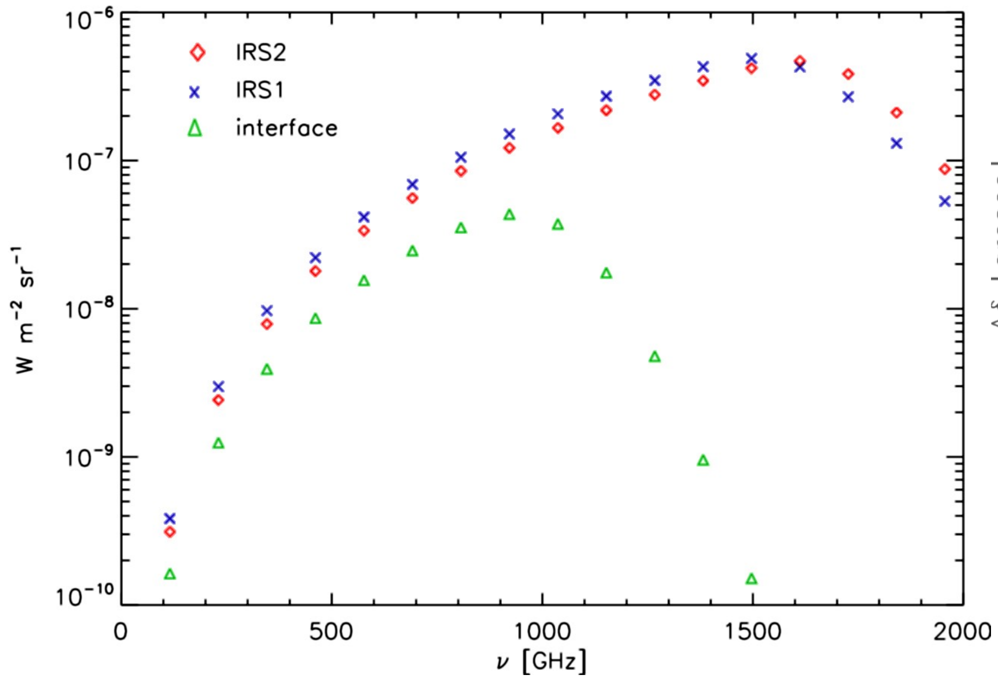
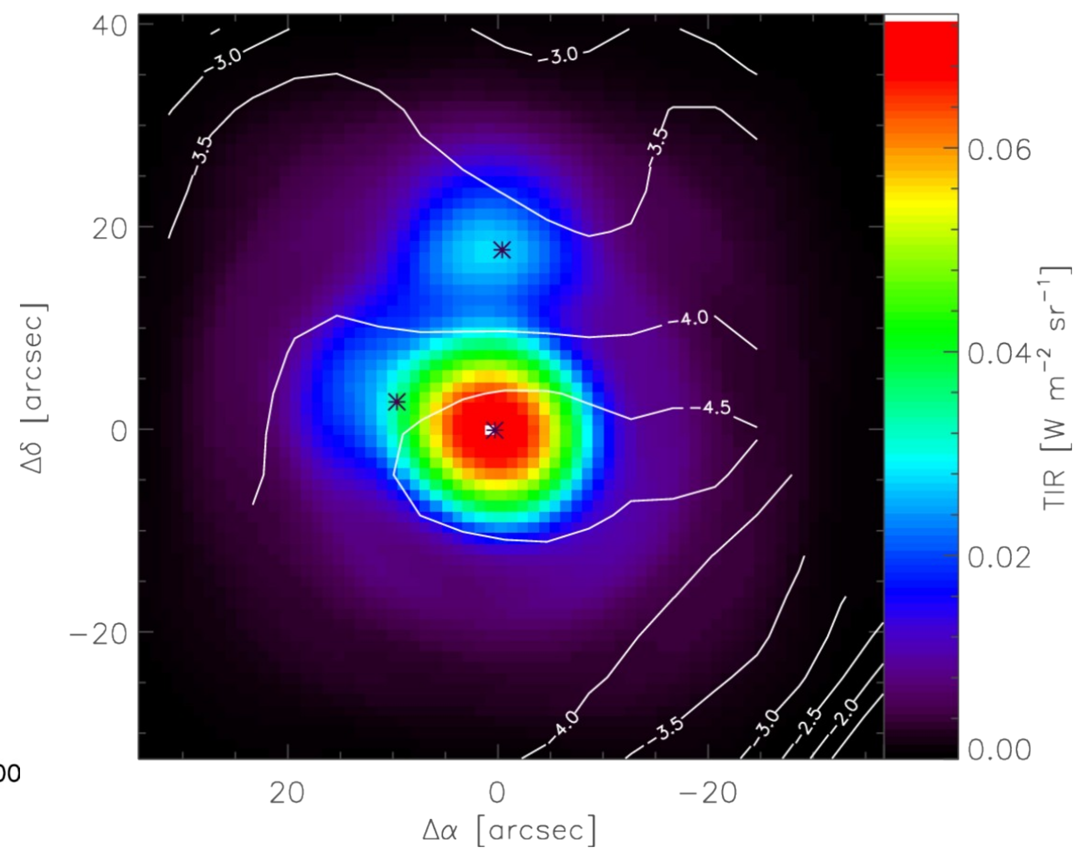
- [OI] and [CII] are main cooling lines of the dense ISM
- CO ladder also traced by GREAT observations
- Line to continuum ratio should measure gas heating efficiency

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 (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^+
- Energy balance of the interstellar gas still not understood
  - [CII] + [OI] to FIR continuum cooling between $10^{-4.5}$ and 10^{-2}
  - No clear correlation between line deficit and self-absorption
- We need more observations!

Cycle 5 call

MPIfR
KOSMA
MPS
DLR-Pf

- Observing period: Feb 2017 - Jan 2018
- Call to be expected in March
- Proposal deadline:
  - Probably July 8
- 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
- Follow: http://www.sofia.usra.edu/Science/announcements.html (open time)