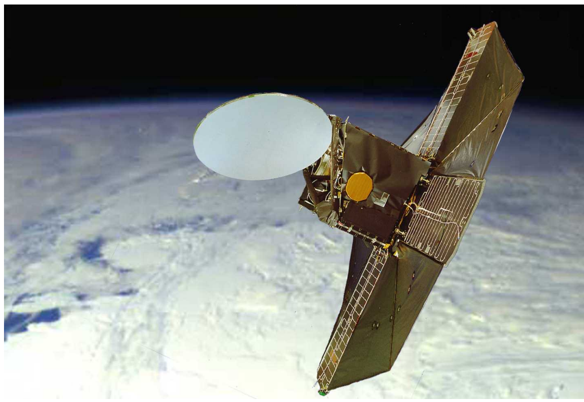
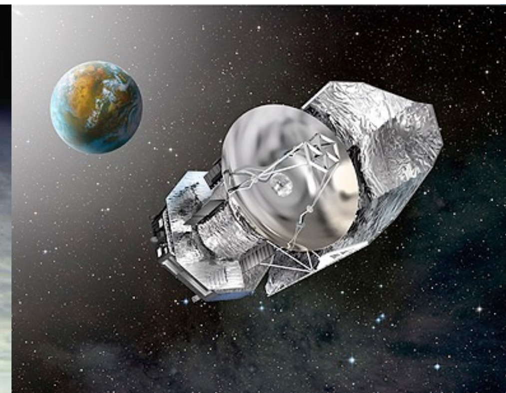
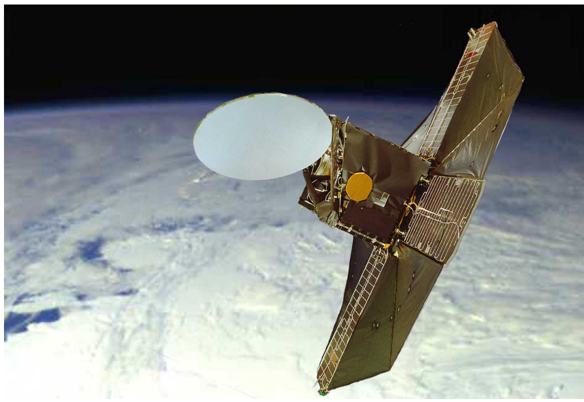
Odin – Herschel – SOFIA

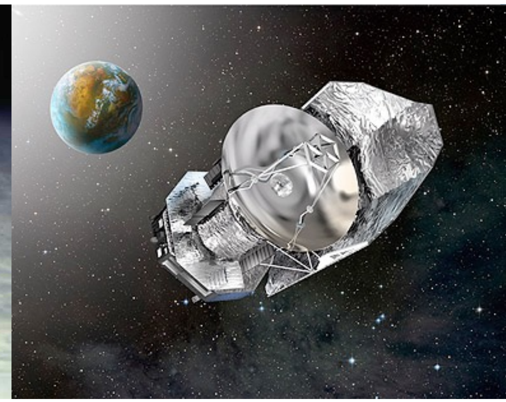




René Liseau Onsala Space Observatory
Chalmers University of Technology, Sweden

Odin – Herschel – SOFIA





René Liseau Onsala Space Observatory
Chalmers University of Technology, Sweden

HERSCHEL

AND THE FORMATION OF STARS AND PLANETARY SYSTEMS

SOC

A. Tielens (chair)
R. Liseau (co-chair)
J.H. Black
M. Griffin
E. Herbst
Th. Henning
M. Meyer
A. Natta
G. Pilbratt
A. Poglitsch
A. Sargent
M. Tafalla
R. Waters

Early Registration until July 15

Late Registration until August 15

GÖTEBORG
SWEDEN
6 - 9
SEPTEMBER
2010

CHALMERS
Chalmers University of Technology

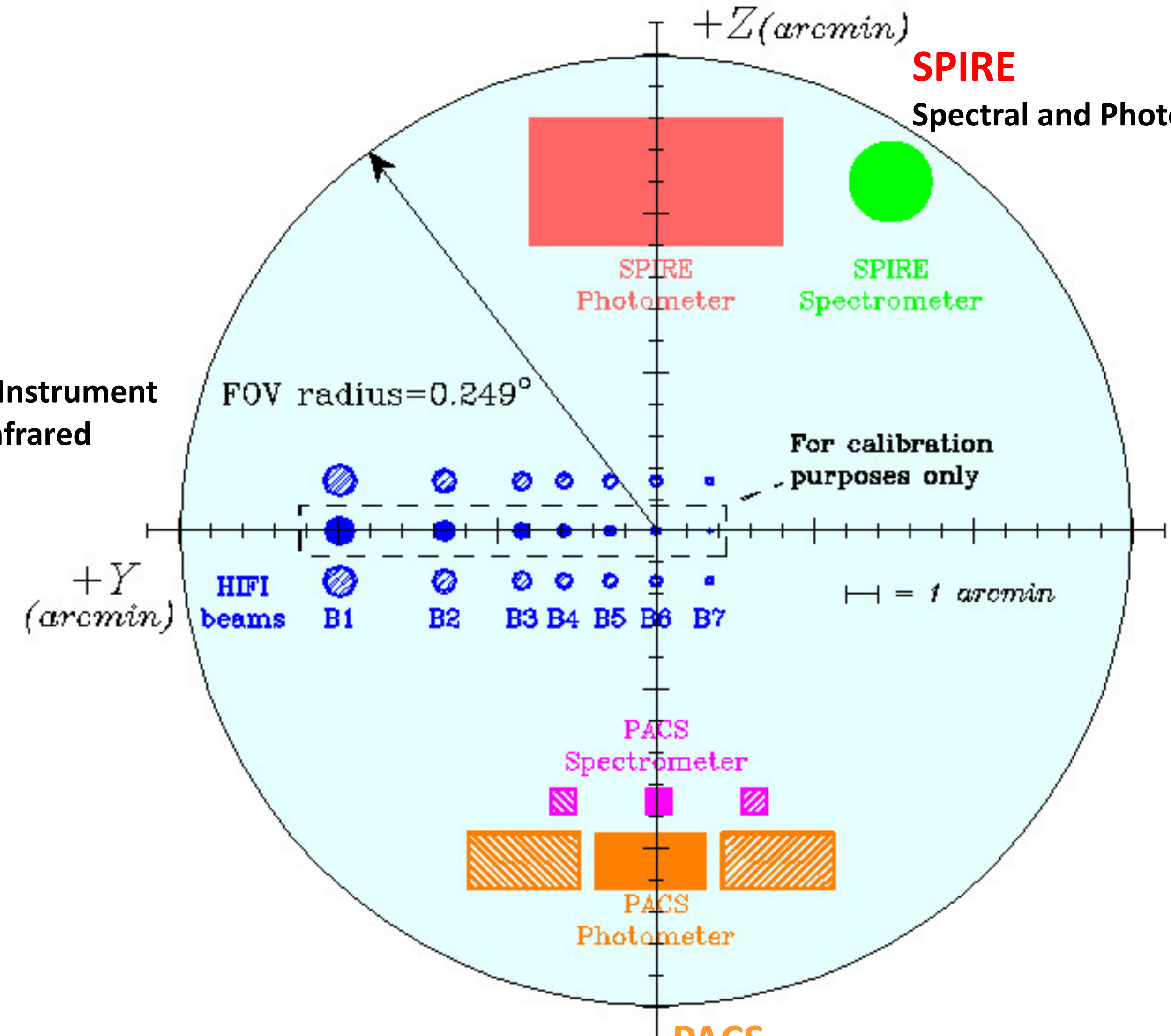
www.chalmers.se/herschel

esa

RYMDSTYRELSEN
Swedish National Space Board

Herschel FOV as seen in the Sky (+X)

Launched in 2009, cryogenic lifetime 3.5 years ➔ ≈20 000 hours (833 days) science observations



SPIRE

Spectral and Photometric Imaging REceiver

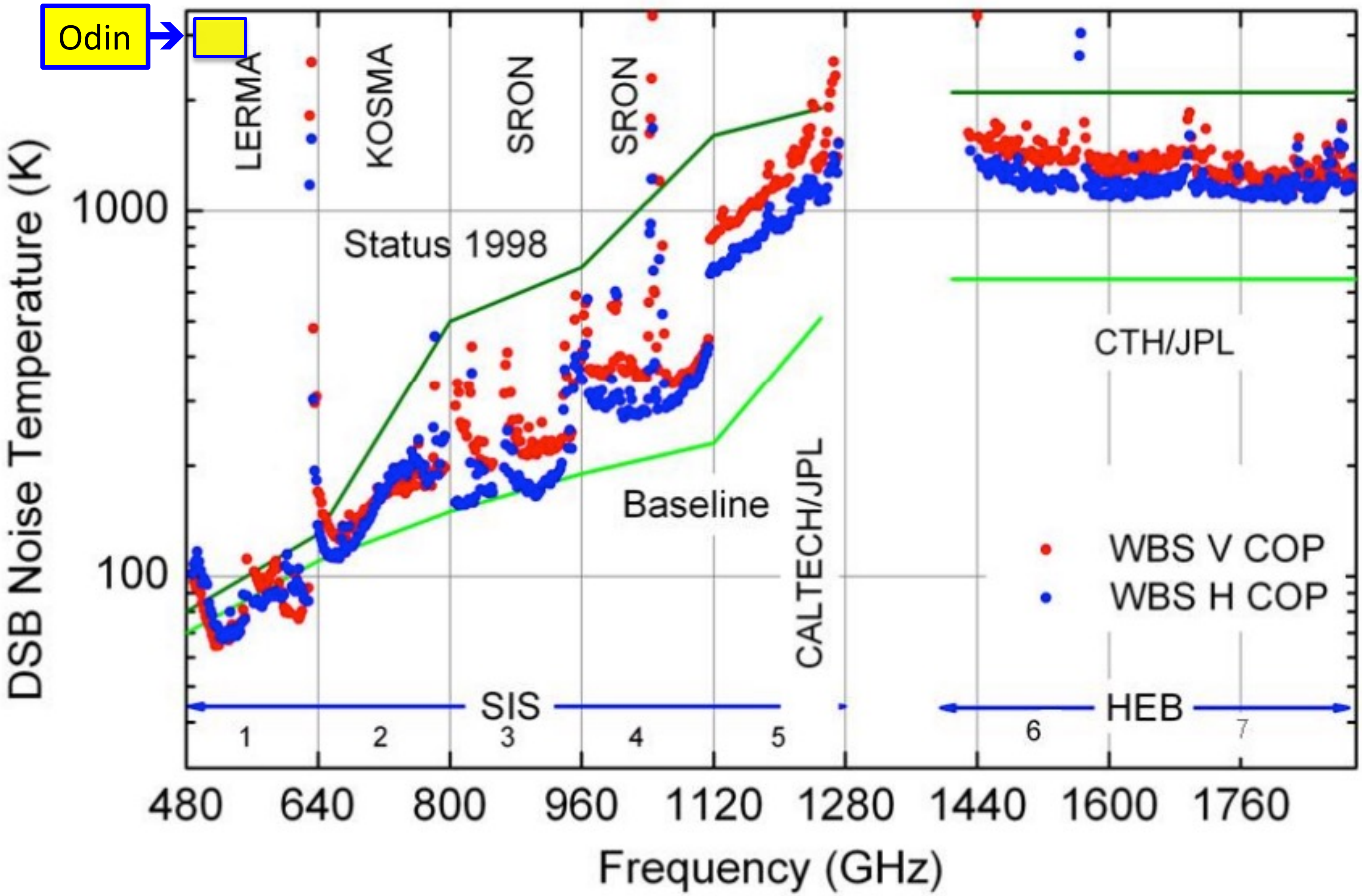
HIFI

Heterodyne Instrument for the Far Infrared

PACS

Photodetector Array Camera and Spectrometer

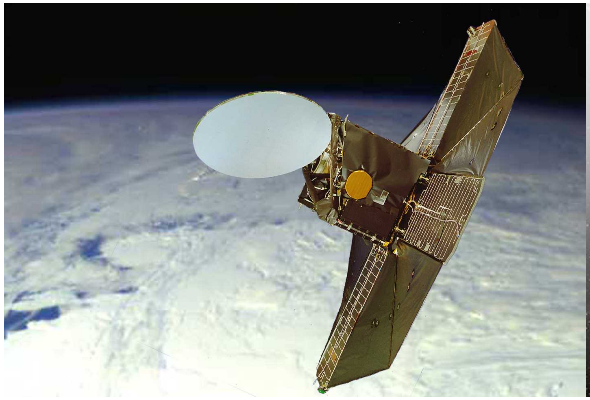
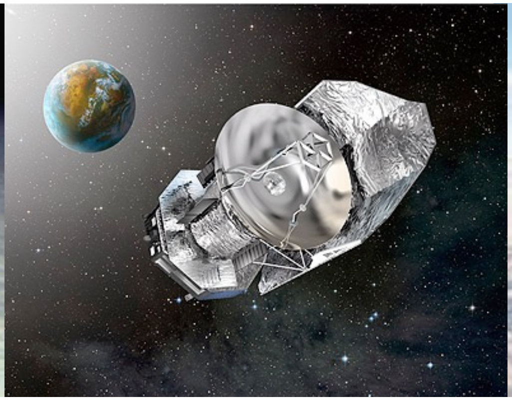
HIFI



Double sideband system temperatures of HIFI mixers (bands 1 to 5 are SIS mixers, bands 6 and 7 are HEB mixers produced by Chalmers,Sweden). System temperatures are based on in-flight measurements using the internal calibrators of HIFI together with the H and V polarizations of the WBS spectrometer. The institutions that created the different mixer subbands are indicated.

Courtesy of M. Olberg, May 2010

Odin – Herschel – SOFIA

Odin is a spectroscopy mission – so we focus here on FIR/submm spectroscopy

of star forming regions in our Galaxy

René Liseau Onsala Space Observatory
Chalmers University of Technology, Sweden

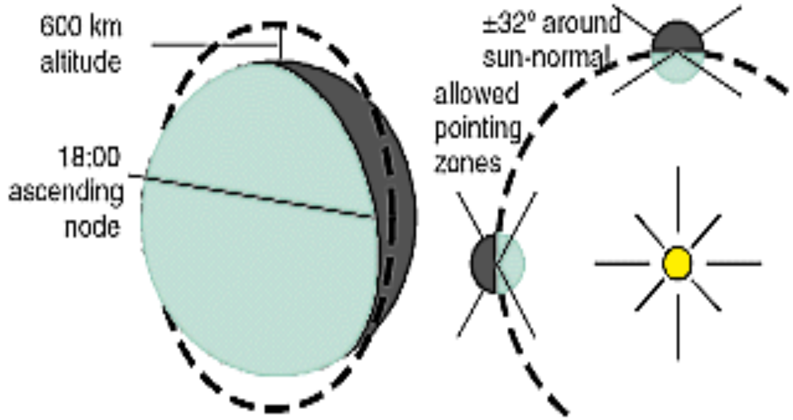
THE ODIN SPACECRAFT

● Platform:	3-axis stabilised w. reaction wheels, star trackers, gyros
● Mass:	250 kg (Bus: 170 kg, Payload: 80 kg)
● Height:	2.0 m, Width: 1.1 m stored/ 3.8 m operational
● Power:	340 W (deployable, fixed arrays)
● Cooling:	120 K (closed cycle Stirling)

■ Datalink:	> 720 kbit/s (Esrange, Sweden)
■ Storage:	> 100 Mbyte (solid state memory)

❍ Telescope:	1.1 m offset Gregorian
❍ Material:	CFRP skins on honeycomb
❍ Surface:	8 µm primary, 5 µm secondary (rms)
❍ Pointing:	15 arcsec (staring), (1.2 arcmin scanning, aeronomy)

☐ Launch:	2001 on Start-1 (Svobodny, Russia)
☐ Orbit:	circular synchronous (620 km, ascending node @ 18:00)
☐ Lifetime:	2 yr (minimum)



Aeronomy & Astronomy on 50/50 share

Start-1 rocket

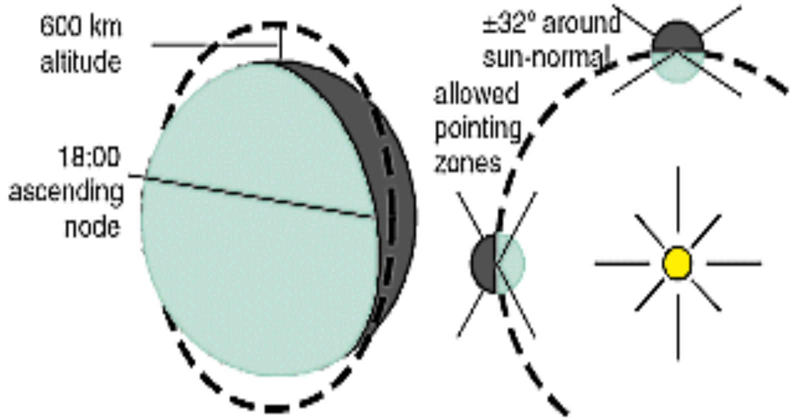
20 February 2001 – Launch from *Svobodny in Siberia*, Russia

Canada Finland France Sweden

odin

http://www.snsb.se/en/Home/Space-Activities-in-Sweden/Satellites/Odin/

God of Nordic mythology: he gave one eye for wisdom



Aeronomy & Astronomy on 50/50 share

Start-1 rocket

20 February 2001 – Launch from *Svobodny in Siberia*, Russia

nominal Lifetime 2 years

JUNE 2010 - after 9 years still operational

(budget constraints → aeronomy only)

Canada Finland France Sweden

odin

http://www.snsb.se/en/Home/Space-Activities-in-Sweden/Satellites/Odin/

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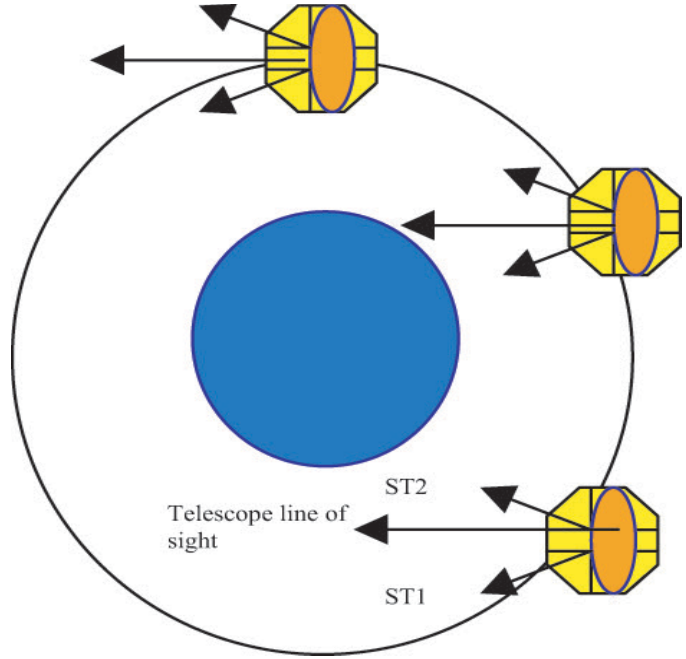
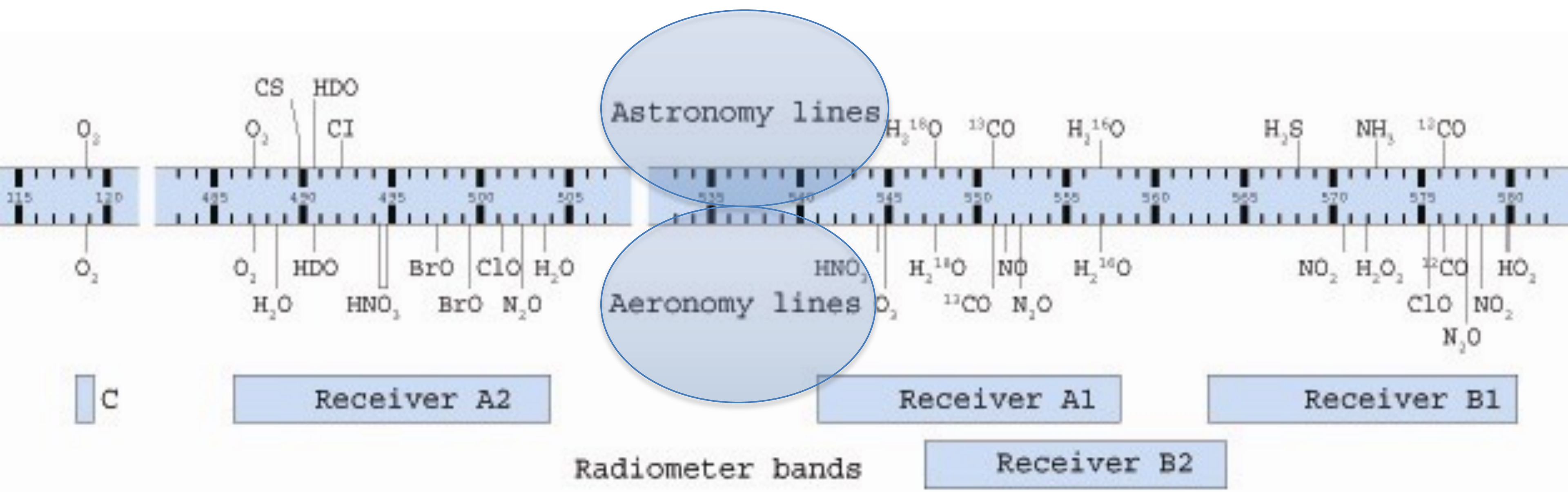

ST2
Telescope line of sight
ST1


Astronomy lines
Aeronomy lines
C
Receiver A2
Receiver A1
Receiver B1
Receiver B2
Radiometer bands

ODIN RECEIVERS & SPECTROMETERS

Front-Ends

- Schottky diodes (120 K, Stirling cooled)
- **480 - 580 GHz: 4 tunable receivers** (17 GHz)
  - System Noise Temperature: 3000 K (SSB)
- **119 GHz: 1 fixed receiver** (InP HEMT)
  - System Noise Temperature: 600 K (SSB)

Back-Ends

- **2 digital hybrid autocorrelators (HAC)**
- **1 acousto-optical spectrometer (AOS)**
- (3 filters - 40 MHz: aeronomy)

Spectrometer	*Bandwidth*	*Resolution*
AOS	1000 MHz	1 MHz
Correlators	4 x 200 MHz	1 MHz
	4 x 100 MHz	500 kHz
	2 x 100 MHz	250 kHz
	1 x 100 MHz	125 kHz

Prime Transitions (ground state lines of oxygen, water and ammonia)

C: 118.24 - 119. 25 GHz

O_2 119 GHz

A2: 486.1 - 503.9 GHz

A1: 541.0 - 558.0 GHz

B1: 568.0 - 580.4 GHz

B2: 547.0 - 564.0 GHz

O_2 487

CS 490

HDO 490

$HD^{18}O$ 493, 502

[C I] ($^3P_1$- $^3P_0$) 492

[^{13}C I] ($^3P_1$- $^3P_0$) 492
(F = 1/2-1/2, 3/2-1/2)

H_2O 557

$H_2{}^{18}O$ 548

$C^{18}O$ (5-4) 549

^{13}CO (5-4) 551

$H_2{}^{17}O$ 552

NH_3 572

CO (5-4) 576

Prime Transitions

in common with SWAS

C: 118.24 - 119. 25 GHz

O_2 119 GHz

A2: 486.1 - 503.9 GHz

O_2 487

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^{13}CO (5-4) 551

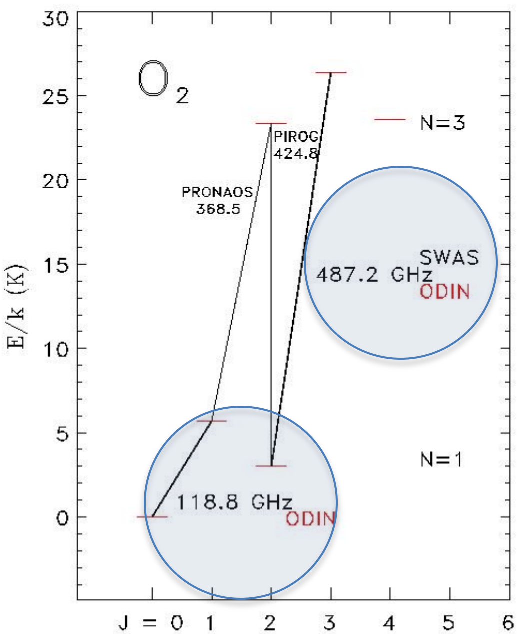
$H_2^{17}O$ 552

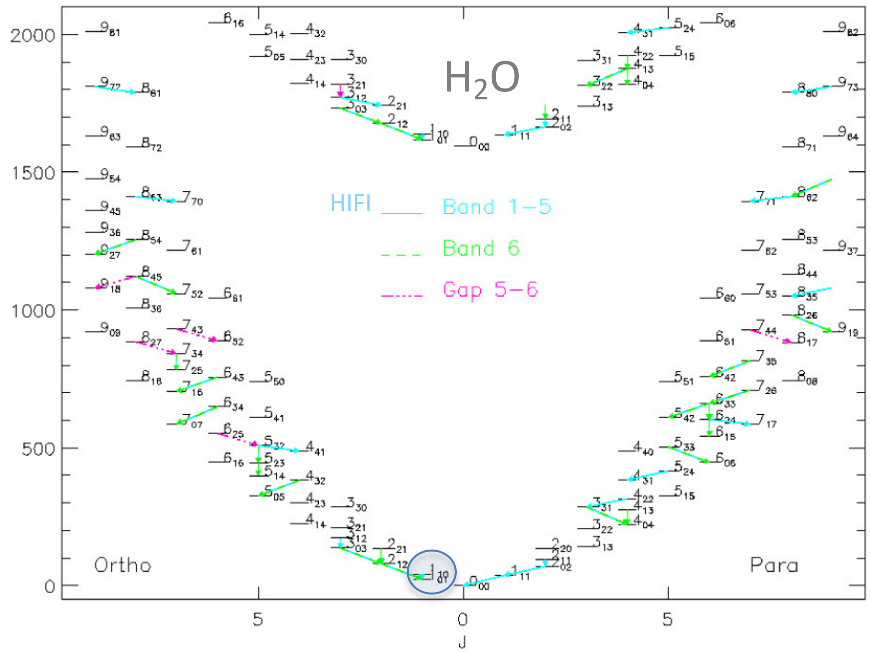
B1: 568.0 - 580.4 GHz

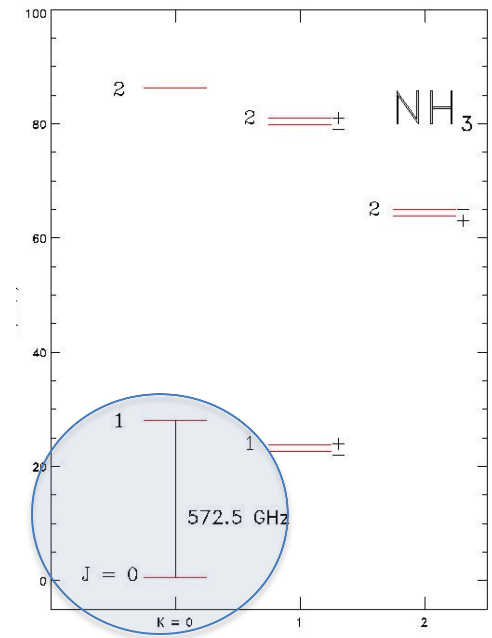
NH_3 572

CO (5-4) 576

some relevant rotational energy levels for O_2 H_2O NH_3







E_{up}/k < 30 K

E_{up}/k < 2000 K

E_{up}/k < 100 K

H_2O and O_2 major oxygen reservoirs, $X \sim 10^{-4}$, and important coolants of the ISM

Goldsmith & Langer, 1978, ApJ 222, 881
Neufeld, Lepp & Melnick, 1995 ApJS 100, 132

O_2 observations of Odin

$(3_3 - 1_2)$ 487 GHz line (2 arcmin beam): no detection

(Olofsson et al. 2007, A&A, 476, 791)

$(1_1 – 1_0)$ 119 GHz line (10 arcmin beam): no detection

(Pagani et al. 2003, A&A, 402, L77)

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(Olofsson et al. 2007, A&A, 476, 791)

$(1_1 – 1_0)$ 119 GHz line (10 arcmin beam): no detection

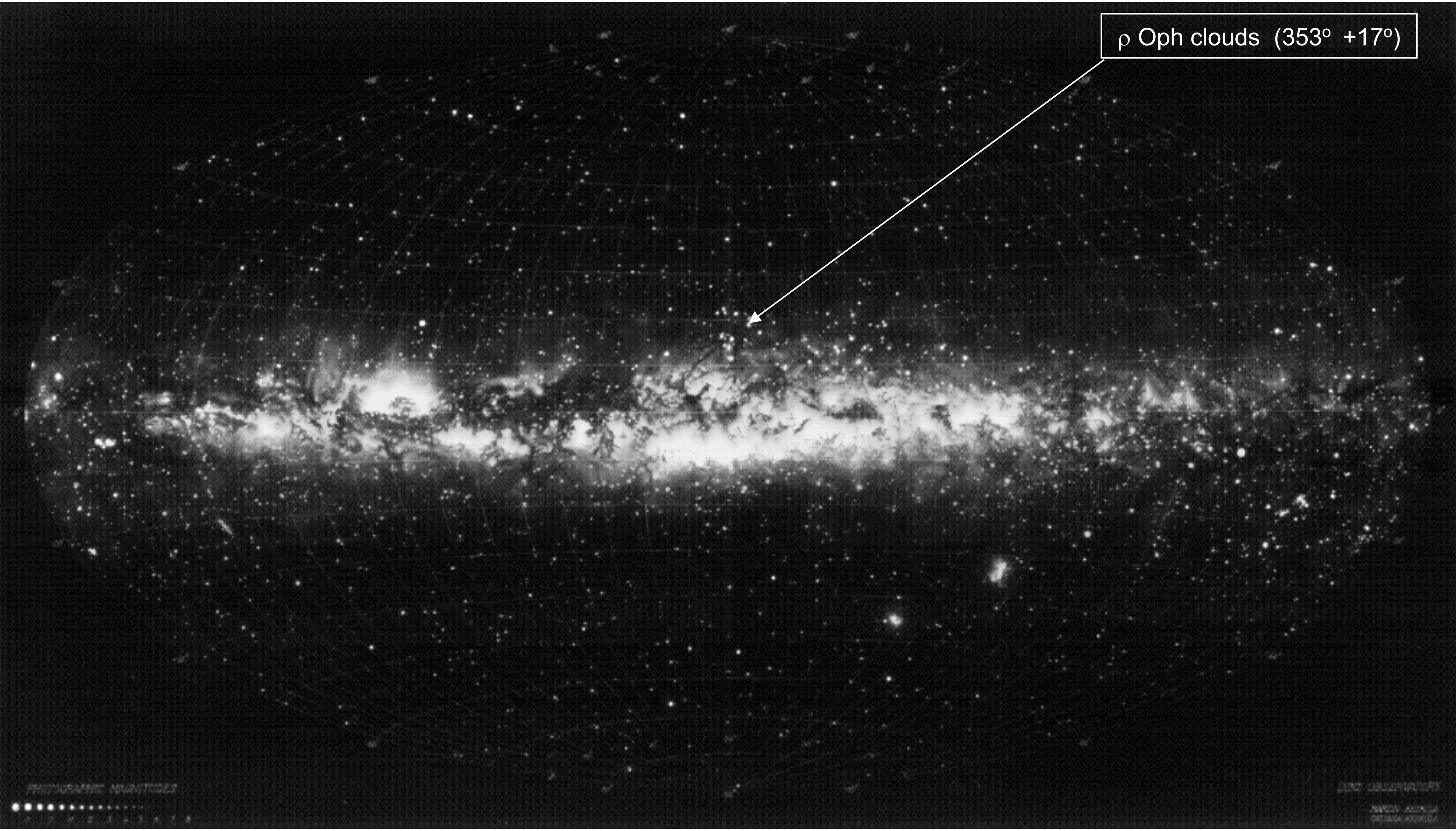
(Pagani et al. 2003, A&A, 402, L77)

with one exception

Courtesy of Axel Mellinger

Toward the ρ Ophiuchi star forming cloud (*D* = 120 pc)

O_2 observations of Odin

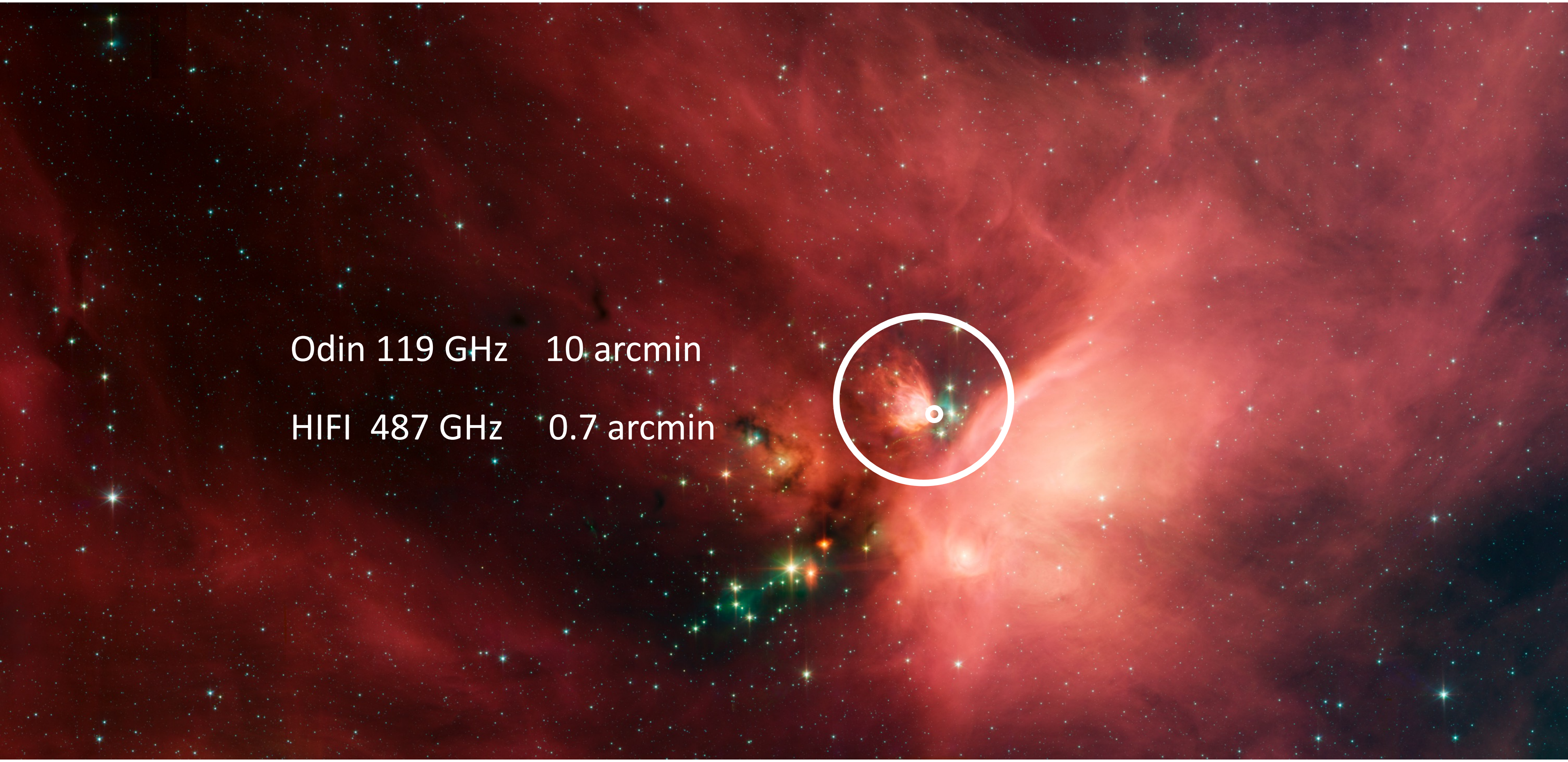


Knut Lundmark et al. 1940s – Lunda Panorama of the Milky Way – Lund Observatory, Sweden

ρ Ophiuchi star forming cloud

Spitzer composite image (IRAC): 3.6 + 4.5 + 5.8 + 8.0 μm

ρ Ophiuchi star forming cloud



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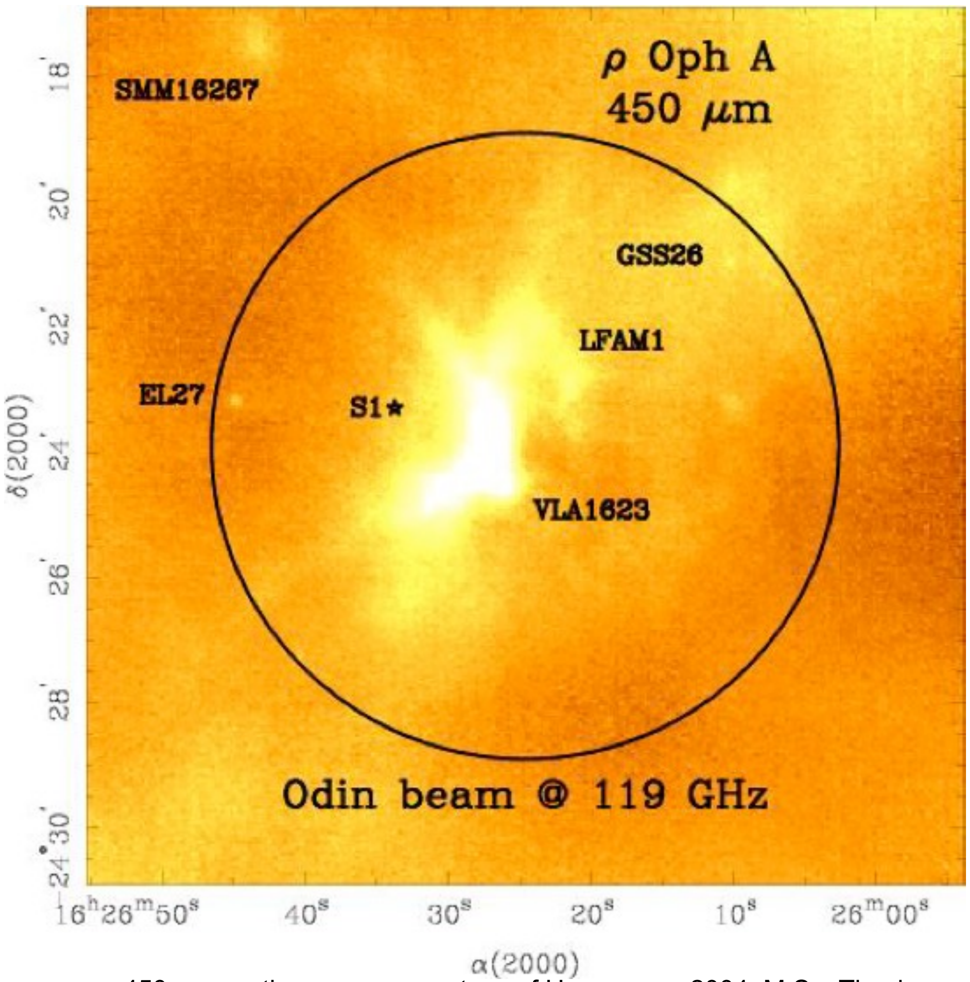
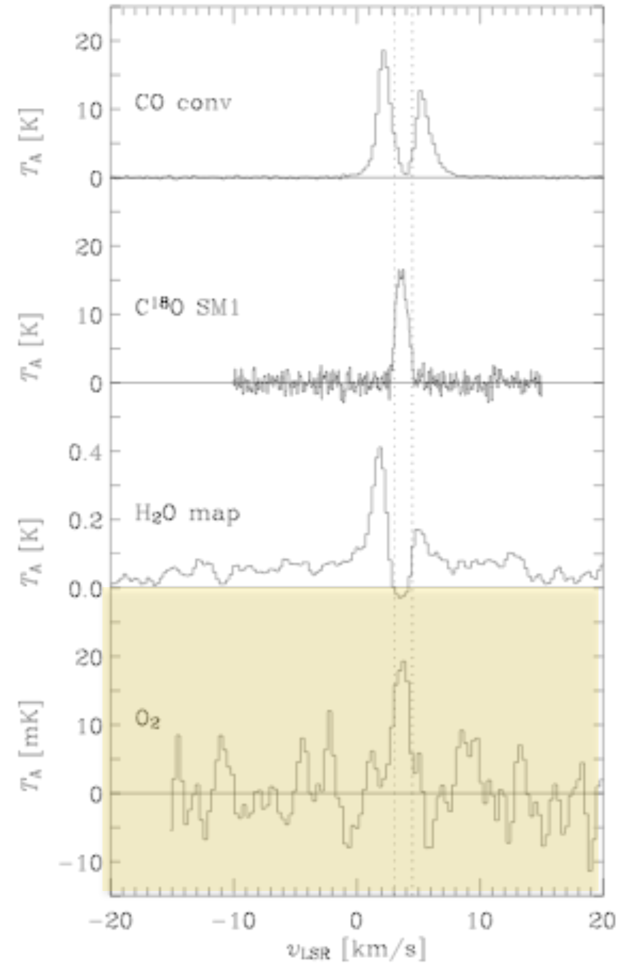
O_2 (1_1-1_0) 119 GHz in ρ Oph A



450 μm continuum map courtesy of Hargreaves 2004, M.Sc. Thesis



Centre velocity and profile as of tracers of cold, high density gas: beam averaged $X(O_2) = 5 \times 10^{-8}$

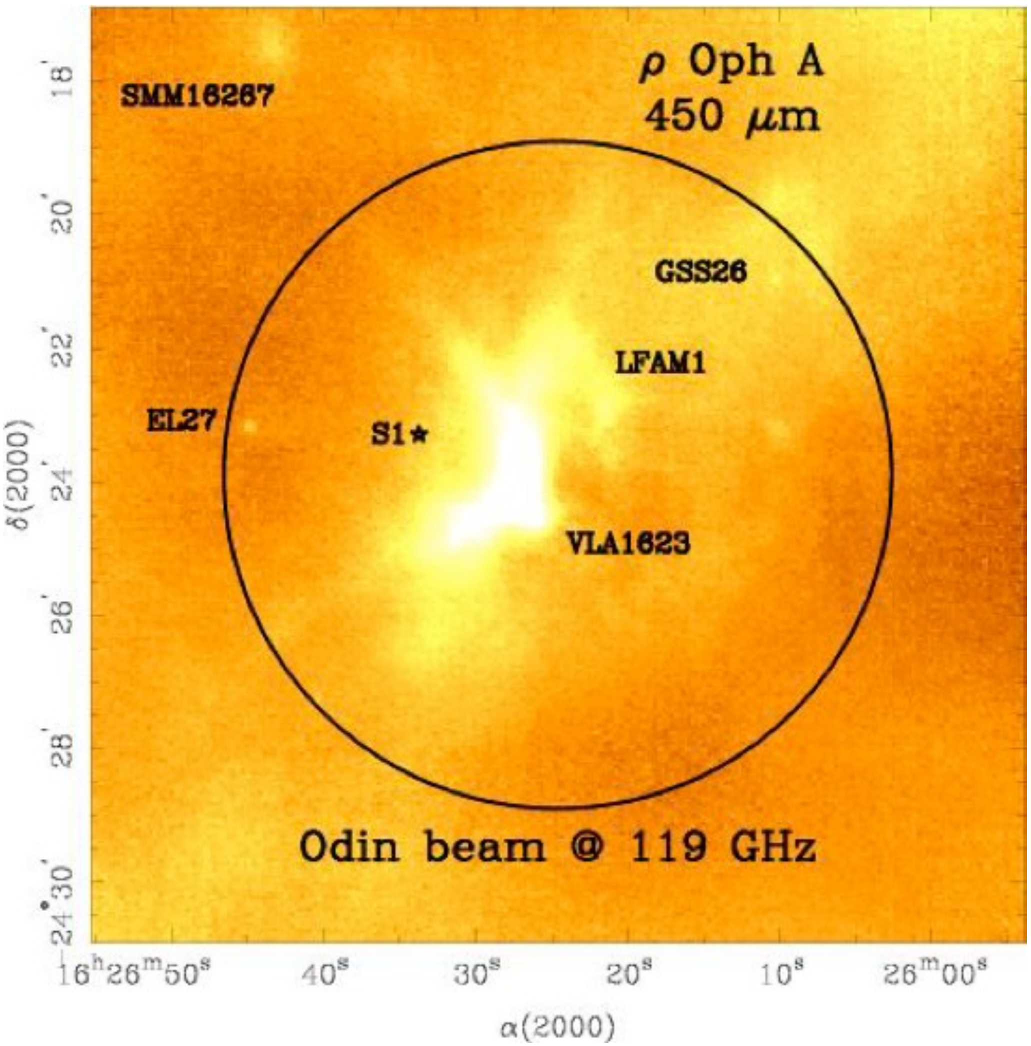
How much diluted in the beam ?

Larsson et al. 2007, A&A, 466, 999

O_2 (1_1-1_0) 119 GHz in ρ Oph A

? Pointlike: ≤ 1 armin

Extended: >> 1 arcmin ?



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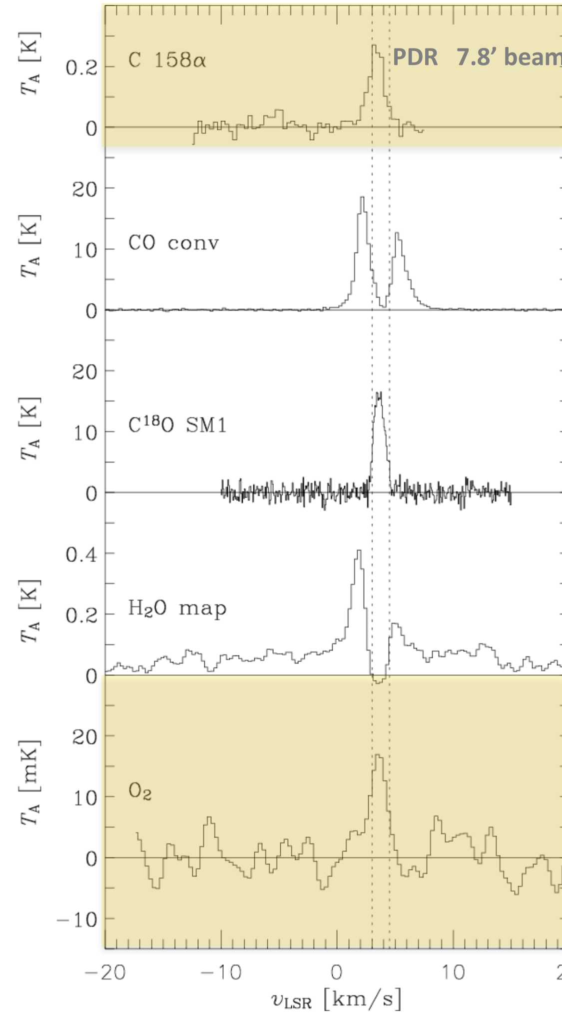
Pankonin & Walmsley 1978, A&A, 64, 333



Oxygen Abundance $X(O_2) \geq 5\times10^{-8}$

Extended O_2 source models – PDR

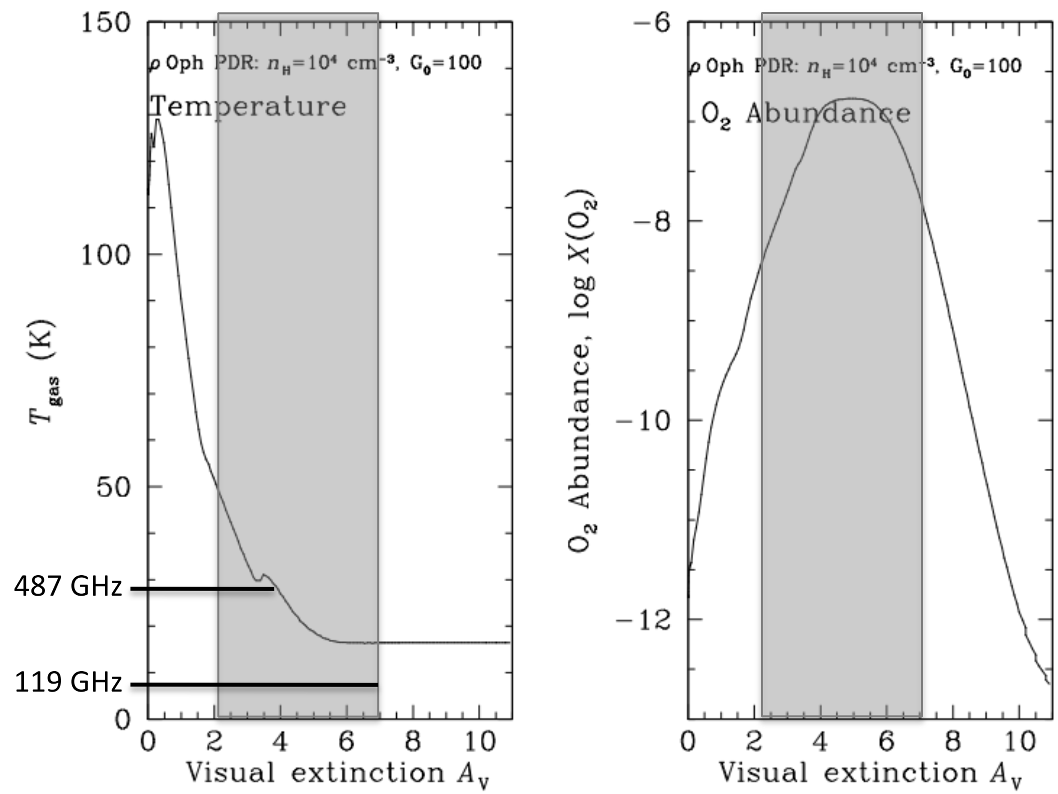
NLTE radiative transfer (Accelerated Lambda Iteration) for Hollenbach et al. PDR models

O_2 model molecule
$E_{up} \leq 300$ K : 18 energy levels
27 radiative transitions
153 collisional transitions

$\xi = 1.0$ km s^{-1} n(H)=1×10^{4} cm^{-3} N(H)=2×10^{22} cm^{-2}

$I_{line} = \int T\, d\upsilon$ (mK km s^{-1})

n(H)=10^4 cm^{-3}	118.75 GHz	487.25 GHz	773.84 GHz	834.15 GHz	424.76 GHz (not HIFI)
G_0 = 100	**8.8**	0.8	0.3	0.1	2.3
G_0=1000	**163**	**11**	2.6	0.8	**33**



Hollenbach, Kaufman, Bergin & Melnick, 2009, ApJ, 690, 1497

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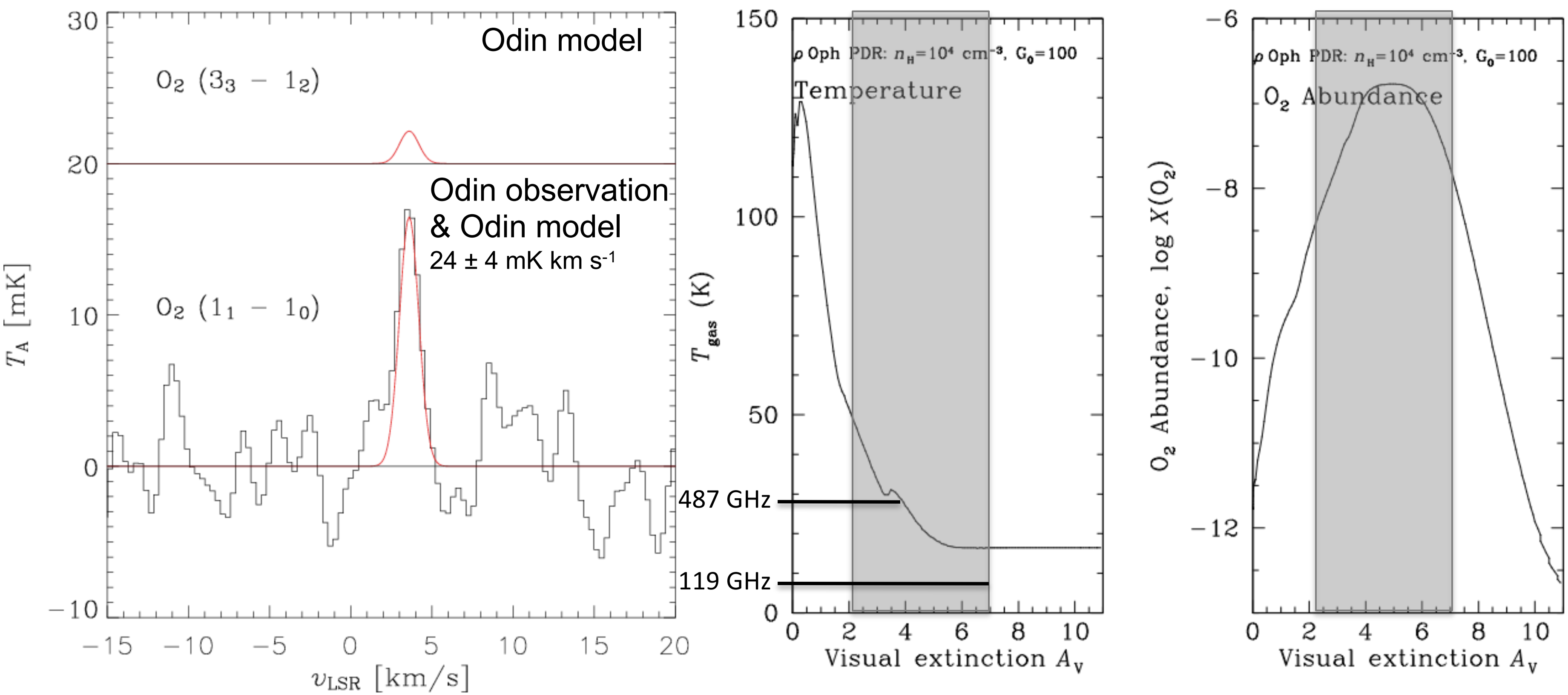

Larsson, Liseau, Pagani et al., 2007, A&A, 466, 999

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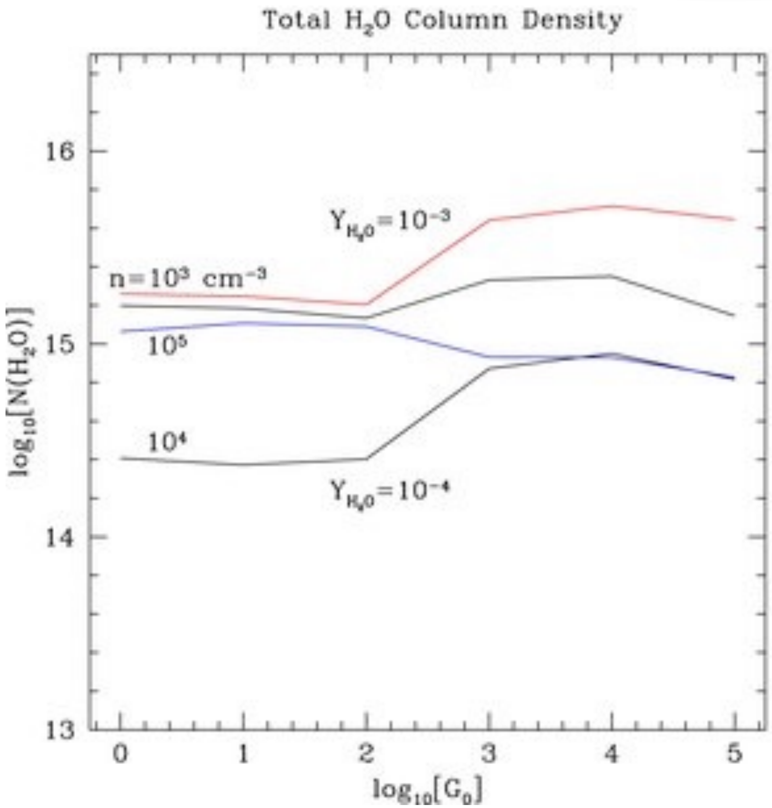

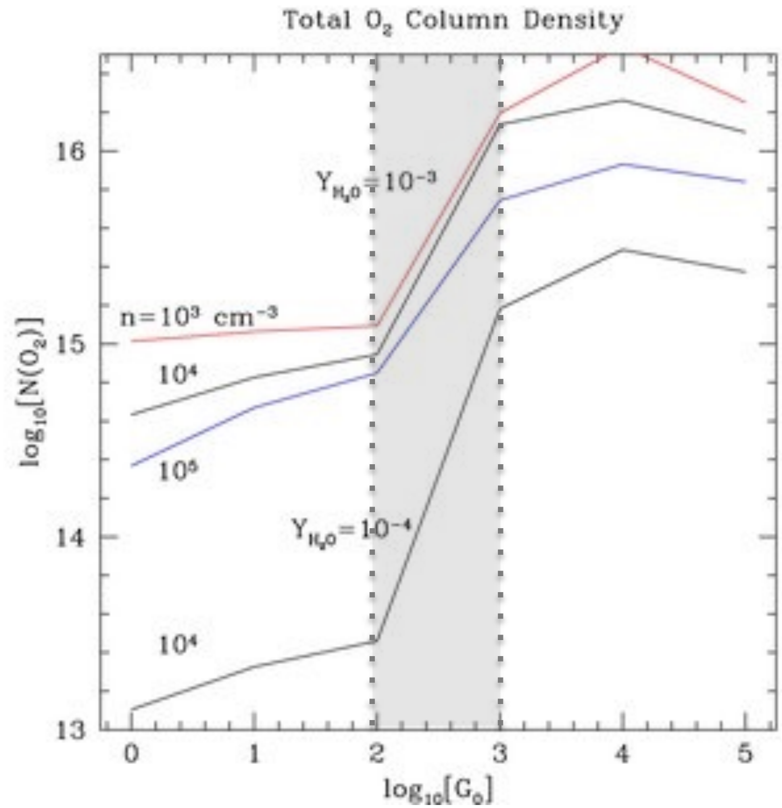

Hollenbach, Kaufman, Bergin & Melnick, 2009, ApJ, 690, 1497

$I_{line} = \int T\,d\upsilon$ (mK km s^{-1})

Radiative transfer ALI (Accelerated Lambda Iteration) for Hollenbach et al. PDR models

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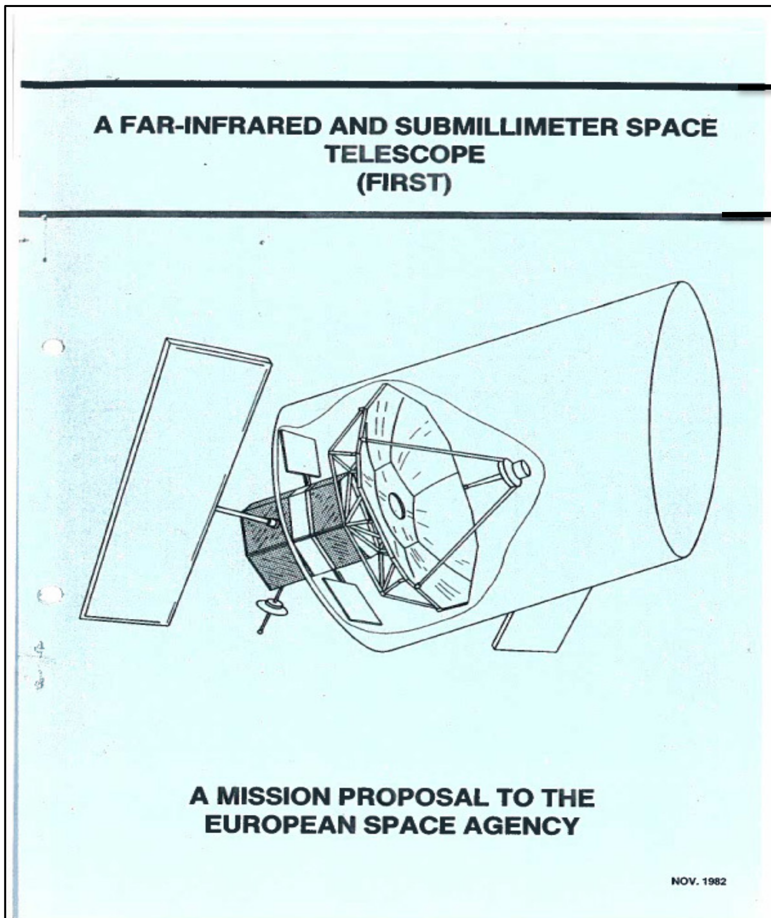
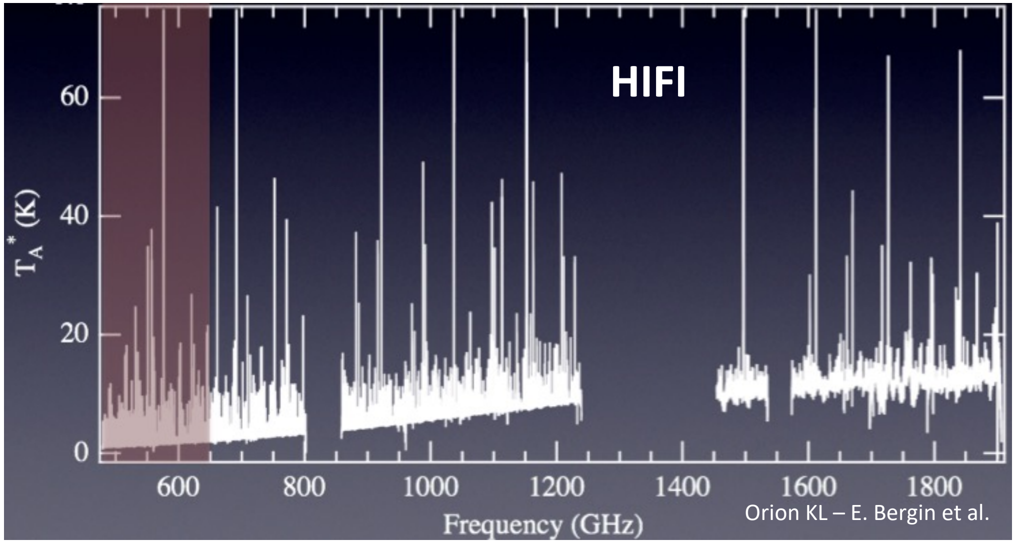


Herschel visibilty 2010

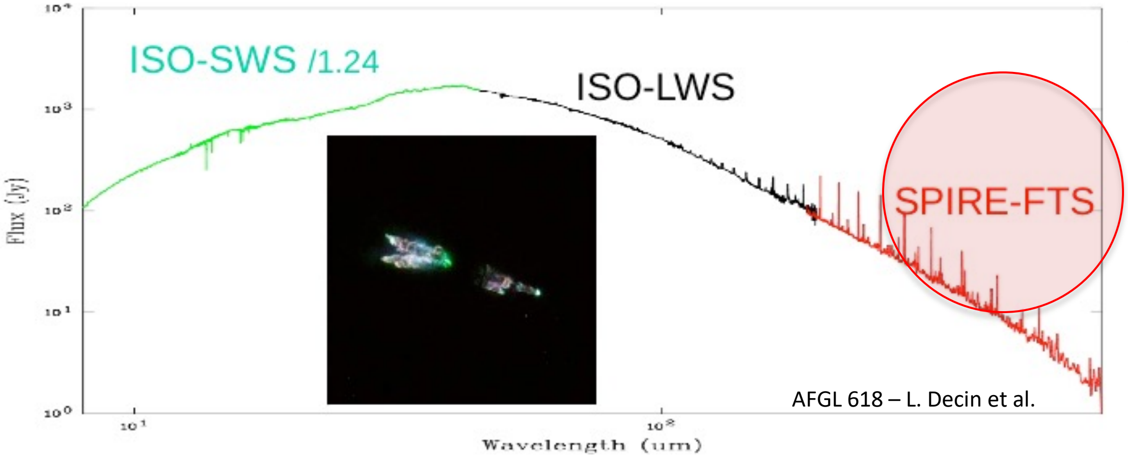
ρ Ophiuchi		
VLA1623	Jan30 - Mar28	Aug2 - Sep30

Soon we will know…

for some early spectacular Herschel results, pls visit http://herschel.esac.esa.int/FirstResultsSymposium.shtml



cf. SOFIA-GREAT



cf. SOFIA-CASIMIR

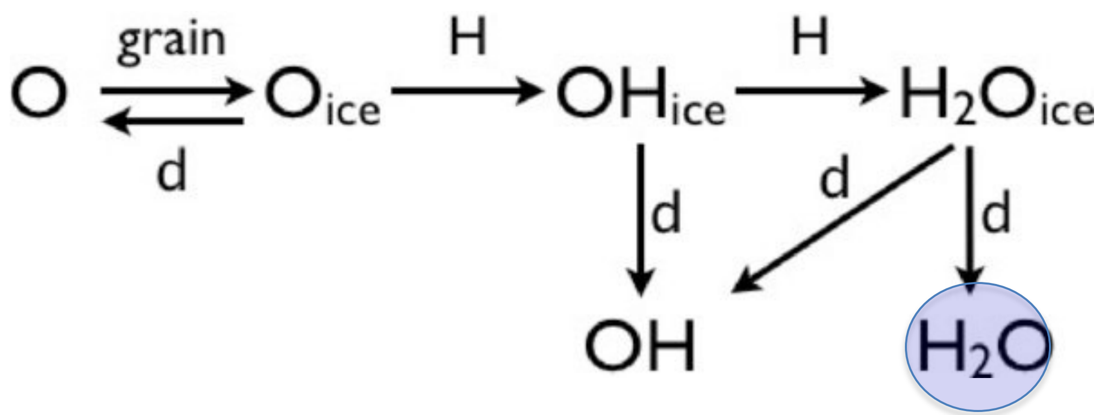
Standard gas phase oxygen and water production

$$O + H_3^+ \rightarrow H_3O^+$$

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

$$O + OH \rightarrow O_2 + H$$

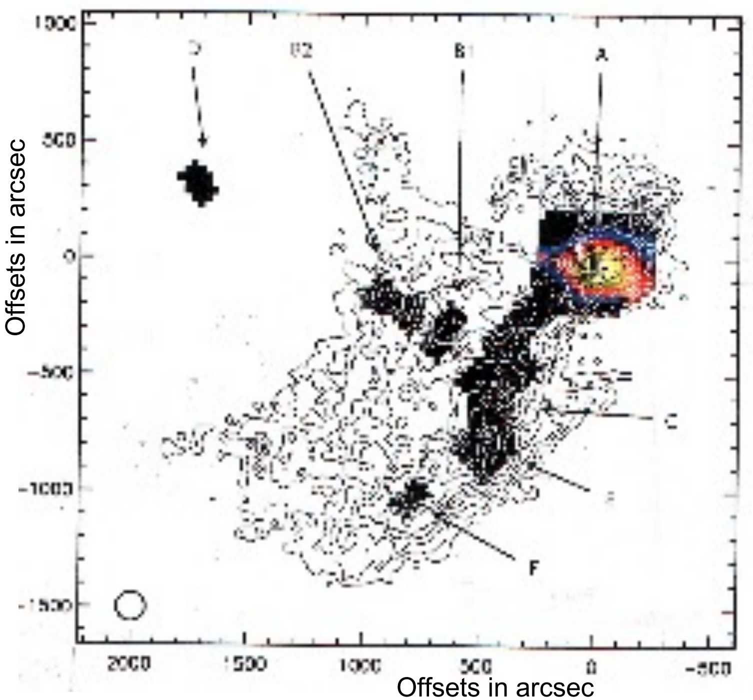
Production on grain surfaces (Hollenbach et al. 2009)



H_2O observations of Odin

ρ Ophiuchi cloud cores A – F

Spectral line image in the H_2O (1_{10}-1_{01}) 557 GHz (2' beam)



Black: non-detections: T_{rms} = 10 – 50 mK

$X(H_2O) << 10^{-7}$

H_2O observations of Odin

ρ Ophiuchi cloud cores A – F

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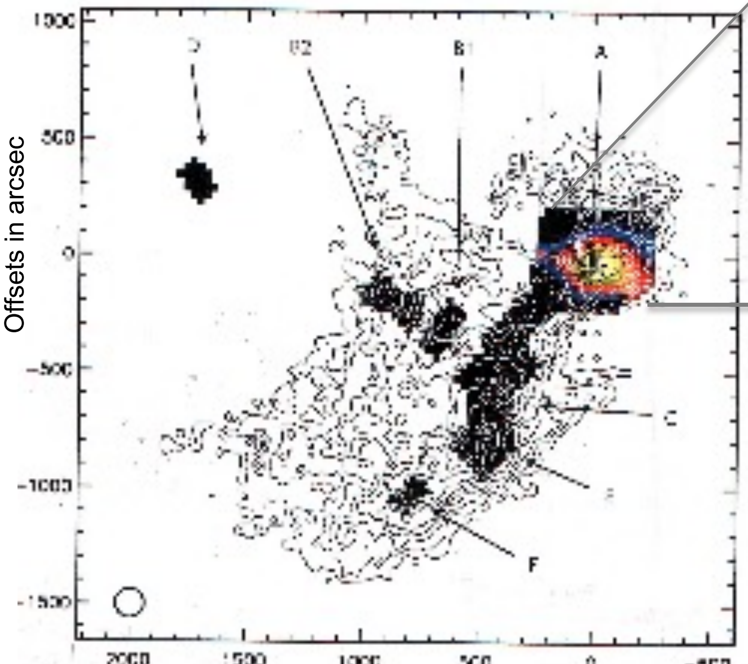
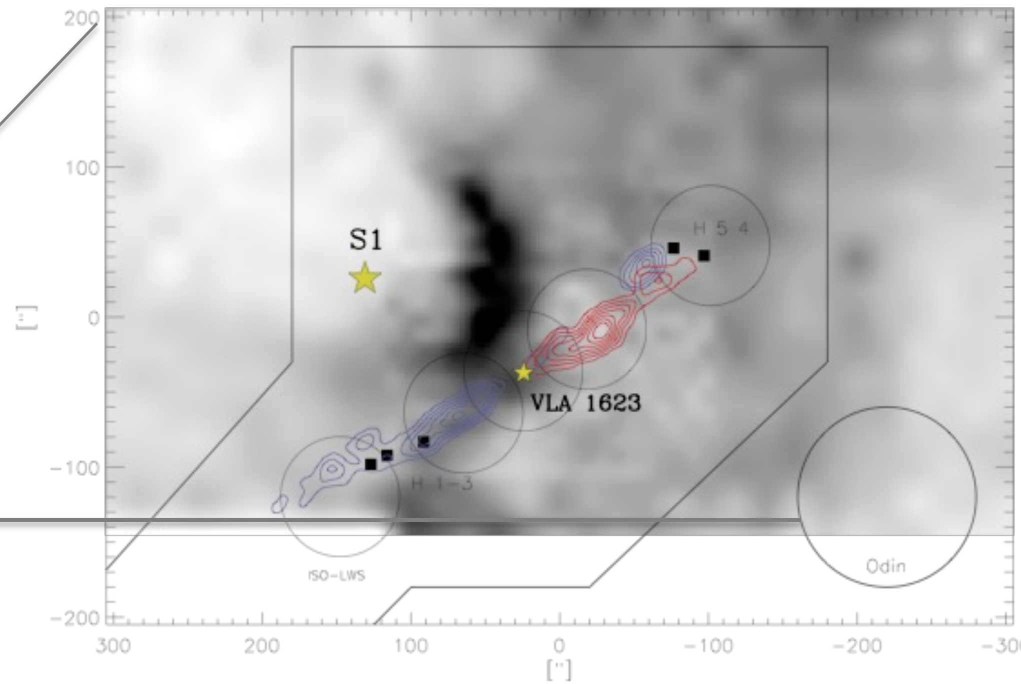




Black: non-detections: T_{rms} = 10 – 50 mK

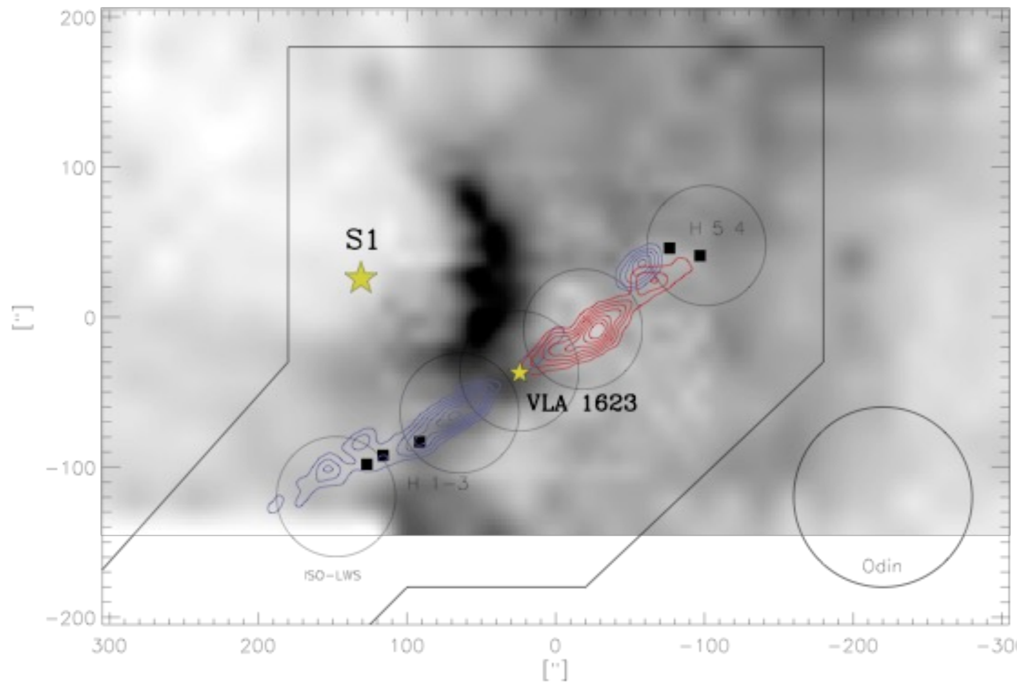
$X(H_2O) << 10^{-7}$

ρ Oph A: water detected in outflow and quiescent gas

8×10^{-6} few $\times10^{-9}$

H2O preliminary result: Larsson & Liseau (in prep.)
Gray: C18O (3-2) Liseau et al. 2010, A&A, 510, 98

Herschel mapping of outflows in H_2O

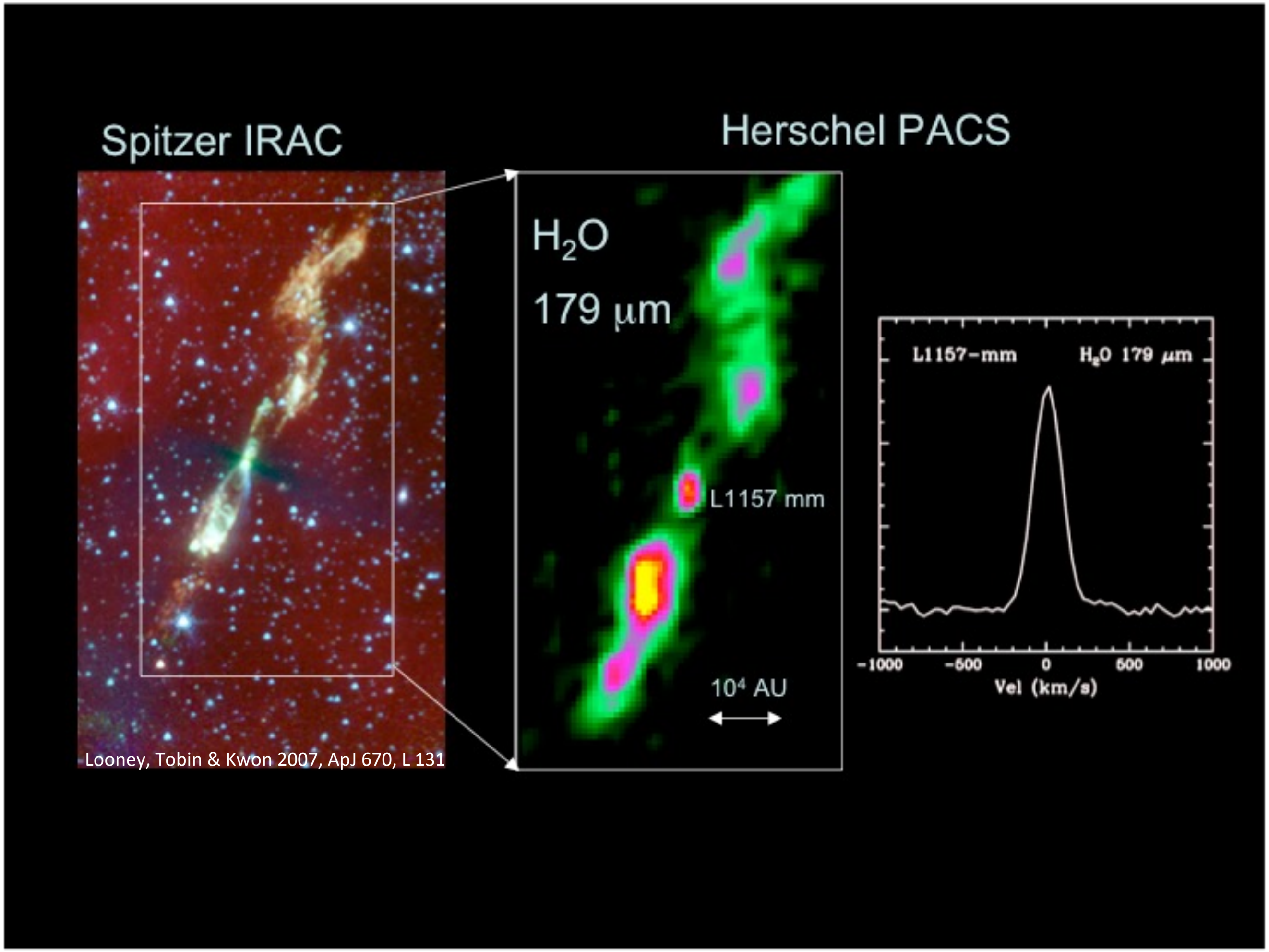


No HIFI data yet for ρ Ophiuchi
Source not visible before August

…but PACS map of H_2O (2_{12} - 1_{01}) 1.7 THz line of L 1157 flow…

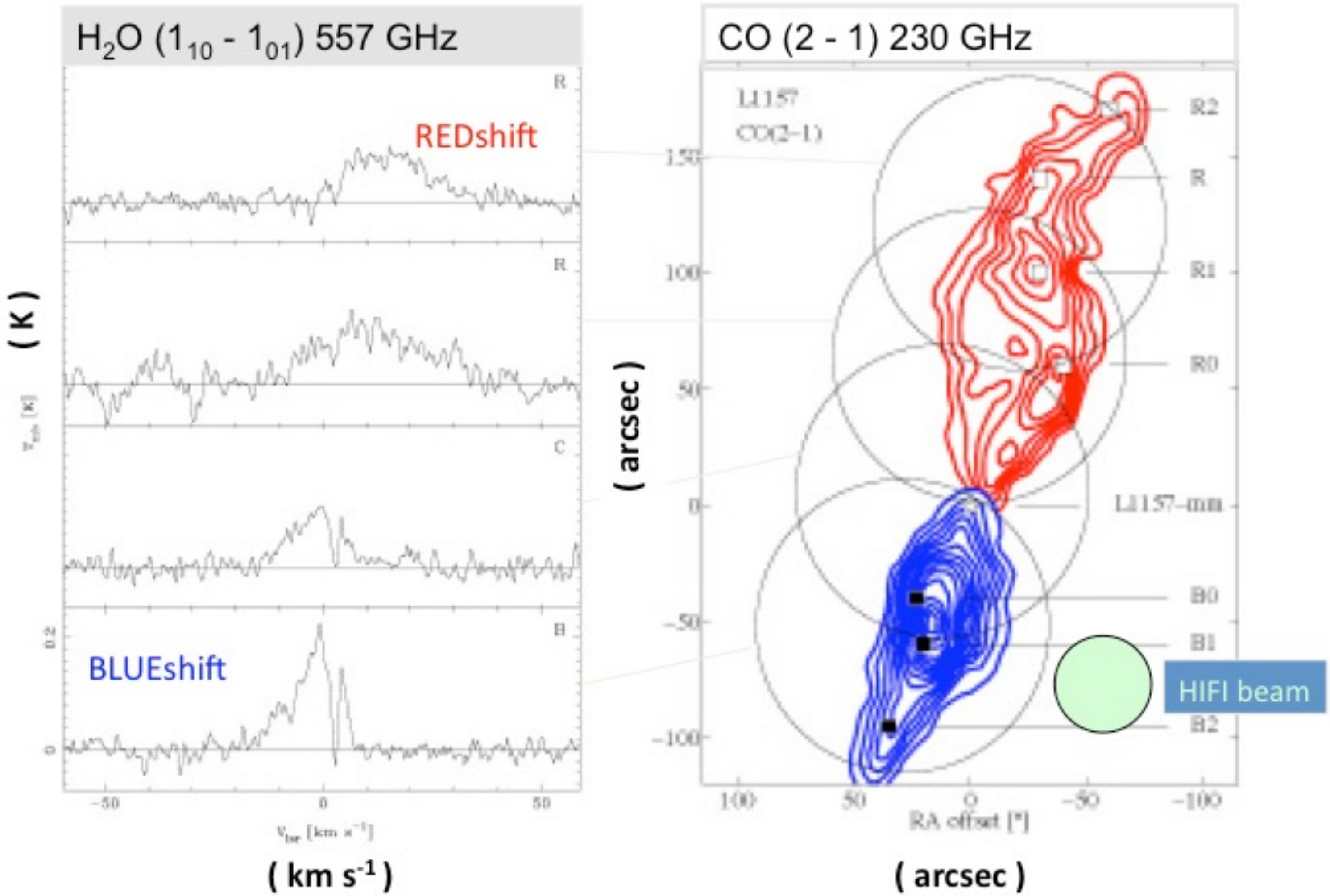
WISH sub-programme OUTFLOWS

Water **I**n **S**tar forming regions with **H**erschel, Guaranted Time Programme, PI Ewine van Dishoeck



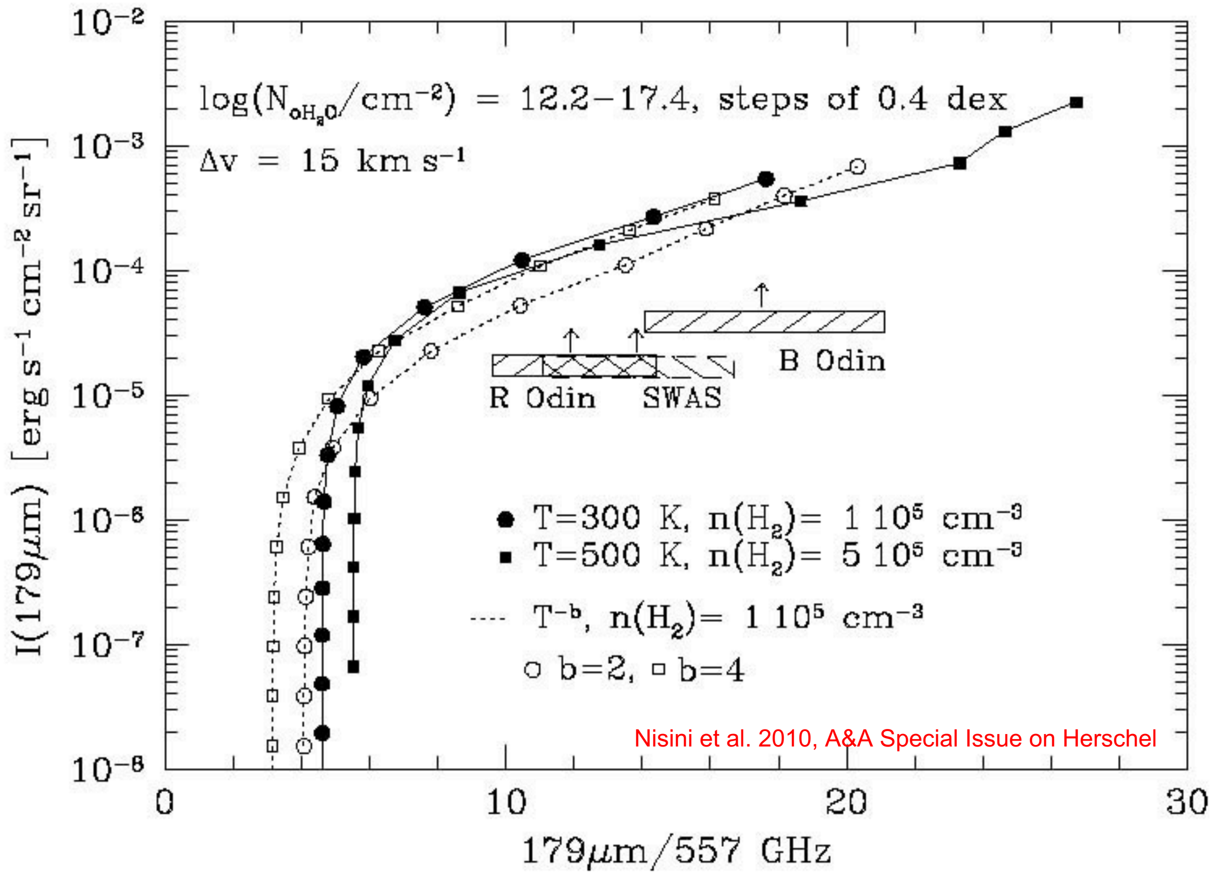
Nisini et al. 2010, Water cooling of shocks in protostellar outflows: Herschel-PACS map of L1157
A&A Special Issue on Herschel

…. previously observed with Odin/SWAS in the 557 GHz line



Bjerkeli et al. 2009, A&A, 507, 1455: Odin H_2O (1_{10}-1_{01}) in 13 outflows + 2 SNRs

combining Odin/SWAS 557 GHz and Herschel 179 μm

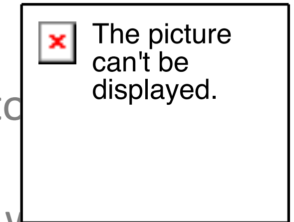


X(H_2O) ≈ 10^{-4} in clumpy flow medium (?)

➔ 557 GHz map data needed !

these initial results based on LVG

(Large Velocity Gradient)



exact solutions to

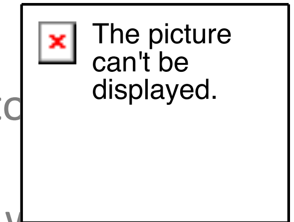
obtainable with ALI

(Accelerated Lambda Iteration)

these initial results based on LVG

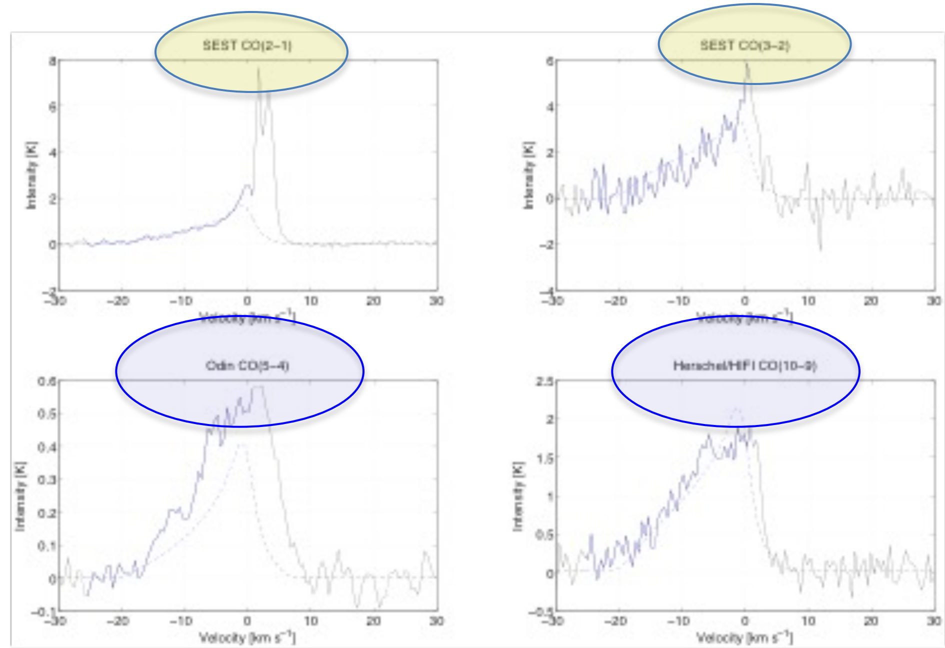
(Large Velocity Gradient)

exact solutions to



obtainable with ALI

(Accelerated Lambda Iteration)



ground

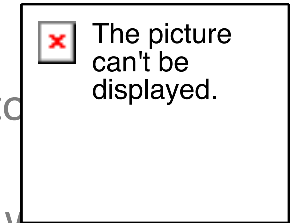
space

Herschel HH54 water data embargoed

P. Bjerkeli 2010, lic. thesis, Chalmers University of Technology

these initial results based on LVG

(Large Velocity Gradient)



exact solutions to

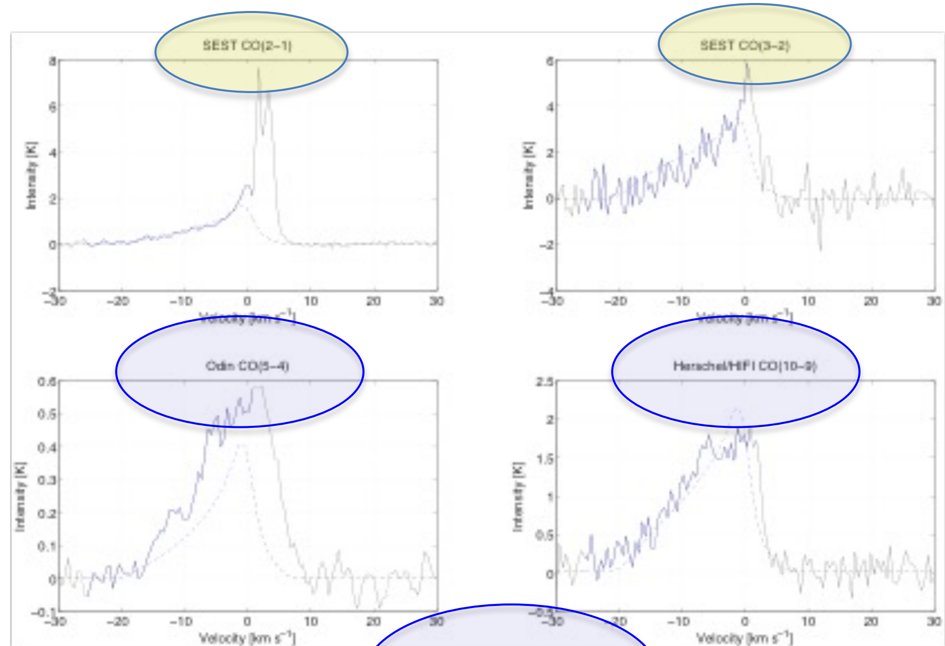
obtainable with ALI

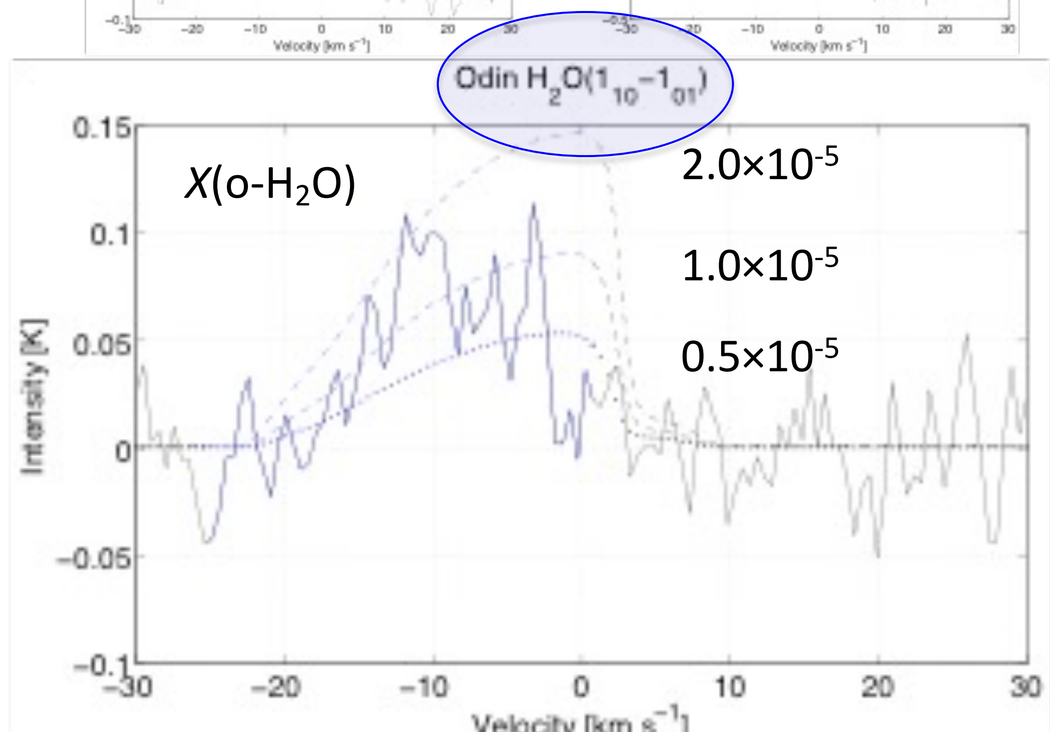
(Accelerated Lambda Iteration)

ground

space

Herschel HH54 water data embargoed





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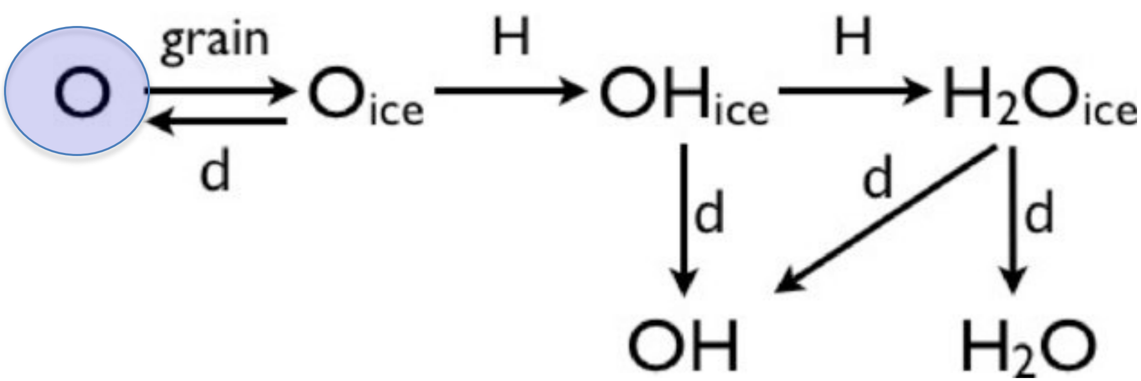
Standard gas phase oxygen and water production

$$O + H_3^+ \rightarrow H_3O^+$$

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

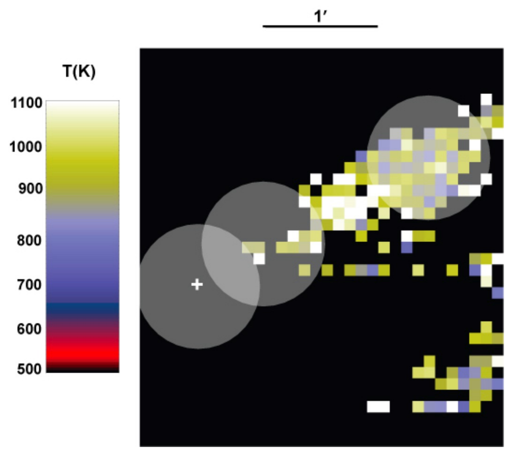
$$O + OH \rightarrow O_2 + H$$

Production on grain surfaces (Hollenbach et al. 2009)

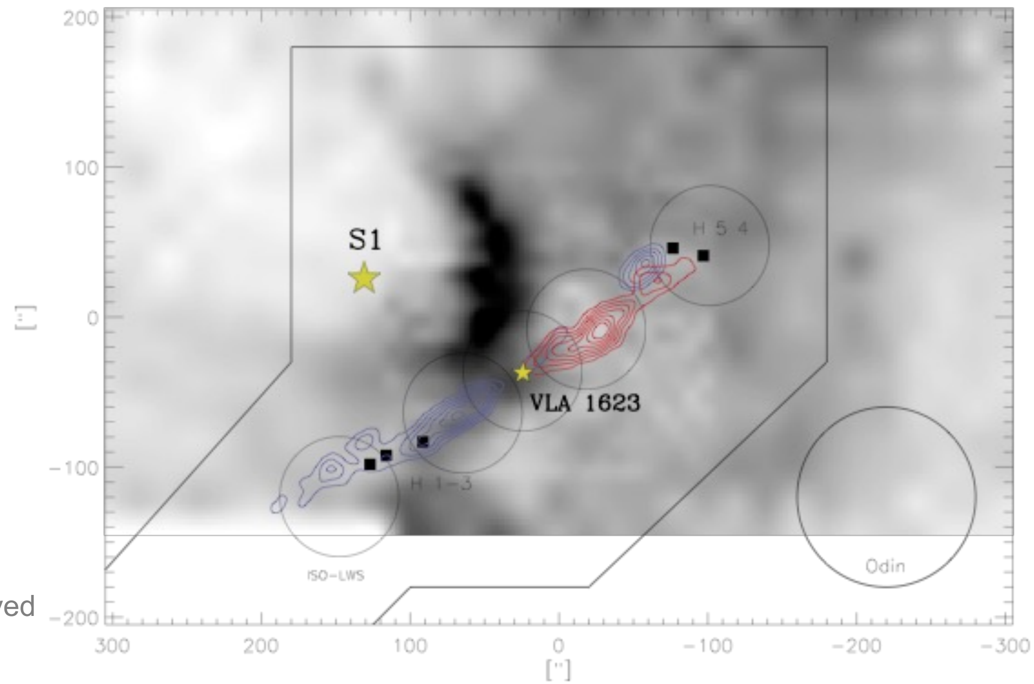


Models assume that **atomic oxygen** is available in the gas phase

Atomic Oxygen: ISO – Herschel – SOFIA



ISOCAM-CVF map with ISO-LWS beams overlayed
(Liseau & Justtanont 2009, A&A, 499, 799)



$N(O) = f(T, n, \tau)$

$X(O) = N(O)/N(H)$

CAM-CVF [6 H_2 lines: v=0, S(2)-S(7)] ➔ T_{gas}(x, y) and $N(H_2)$

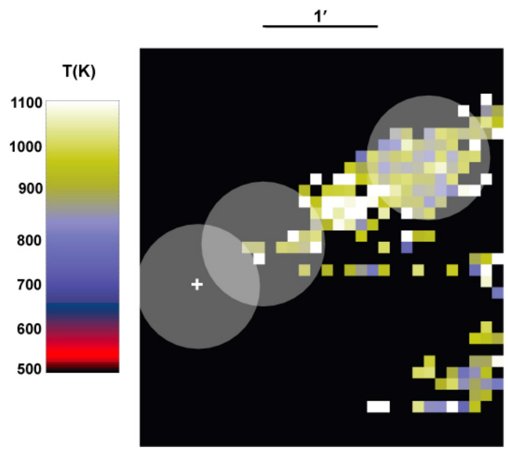
ISO-LWS [2 OI lines: ^3P (1-2) 63 μm, (0-1) 145 μm] ➔ $n(H_2)$ from I_{63}/I_{145} **X(O)**

Sun: 5×10^{-4}

ISM: 3×10^{-4}

ρ Oph A: 2×10^{-5}

Atomic Oxygen: ISO – Herschel – SOFIA



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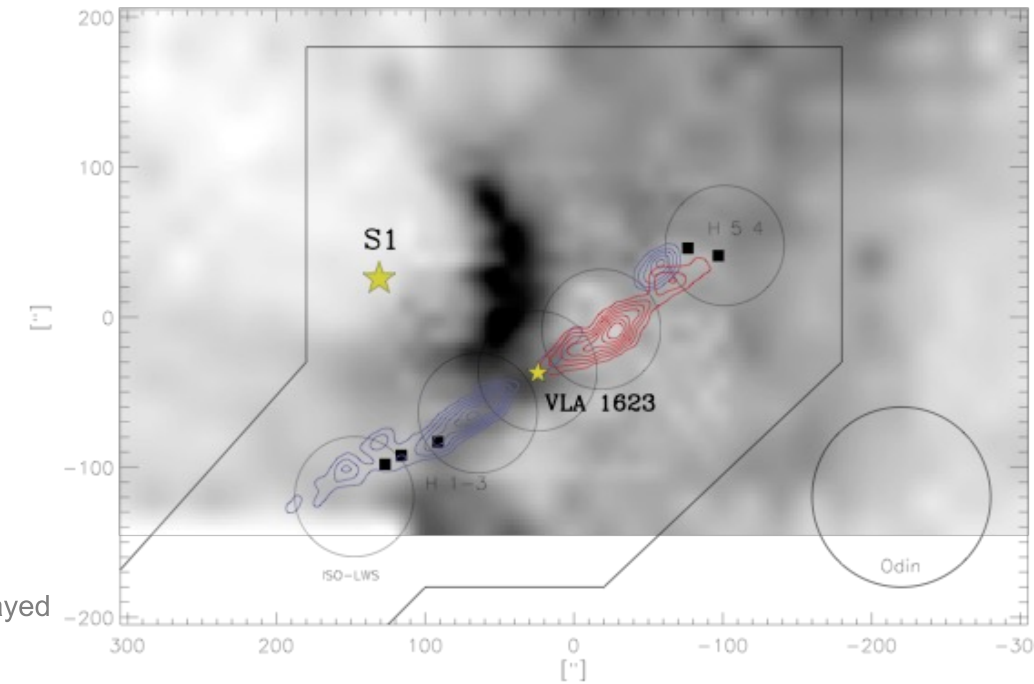

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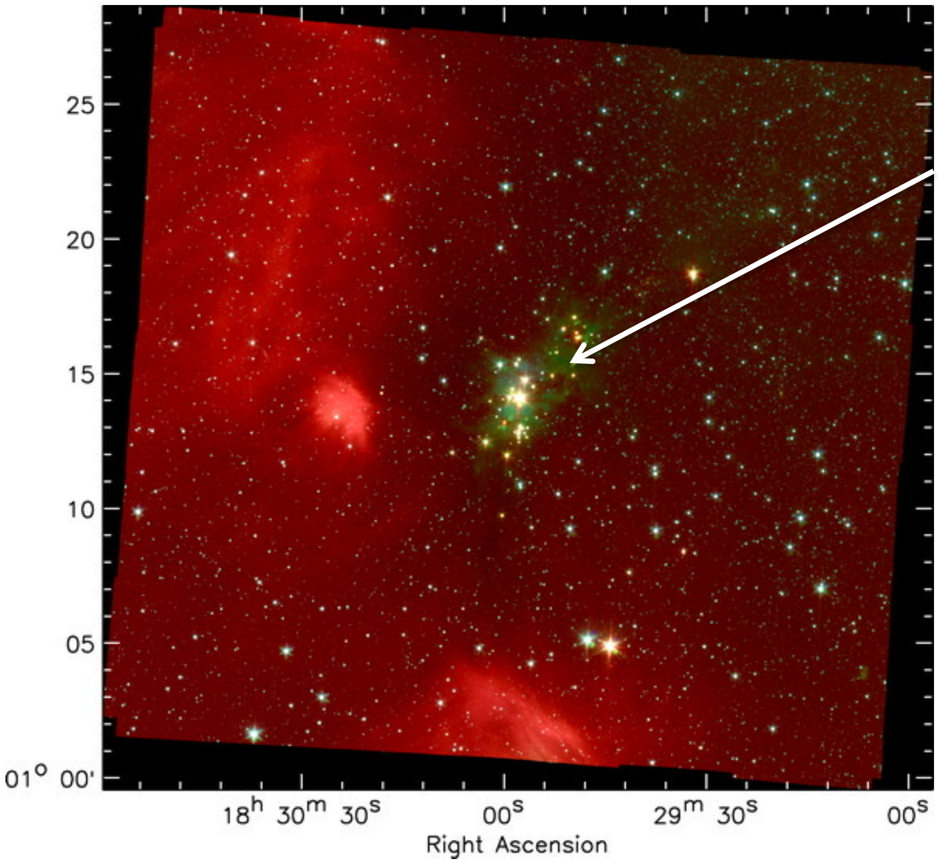
ISO-LWS & Herschel-PACS: low spectral resolution **SOFIA-GREAT: line profiles** **Outflow? Quiescent cloud?**

ISO-LWS & Herschel-PACS: low spectral resolution

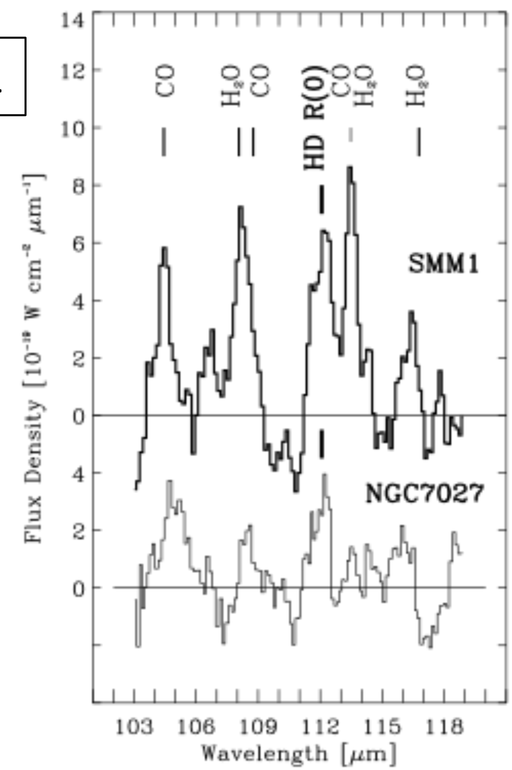


Spitzer IRAC 3.6 μm, 4.5 μm, 8.0 μm image of the Serpens Core
(Winston et al. 2007, ApJ, 669, 493)

SOFIA-GREAT: line profiles

narrow lines & spectral dilution

HD (1-0) 112 μm



Confimation/Disproval
Needs High Spectral Resolution
(Larsson & Liseau, unpublished)

radiative transfer in massive disc

$1.3 \times 10^{-5} \leq D/H \leq 3.8 \times 10^{-5}$

SOFIA will be great for spectroscopy

SOFIA/GREAT - observations already opted for in *Early Science* program

OD (OH)	mixer L1	1.25-1.5 THz (mixer M		2.4-2.7 THz)
p-H_2D^+, o-D_2H^+	mixer L1	1.25-1.5 THz		
[C II], [N II]	mixer L2	1.8-1.92 THz, mixer L1		1.25-1.5 THz
OH	mixer L2	1.8-1.92 THz (mixer M		2.4-2.7 THz)

ISM: oxygen-chemistry – deuteration – PDRs – protoplanetary discs – high mass star formation - shocks

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ISM: oxygen-chemistry – deuteration – PDRs – protoplanetary discs – high mass star formation - shocks

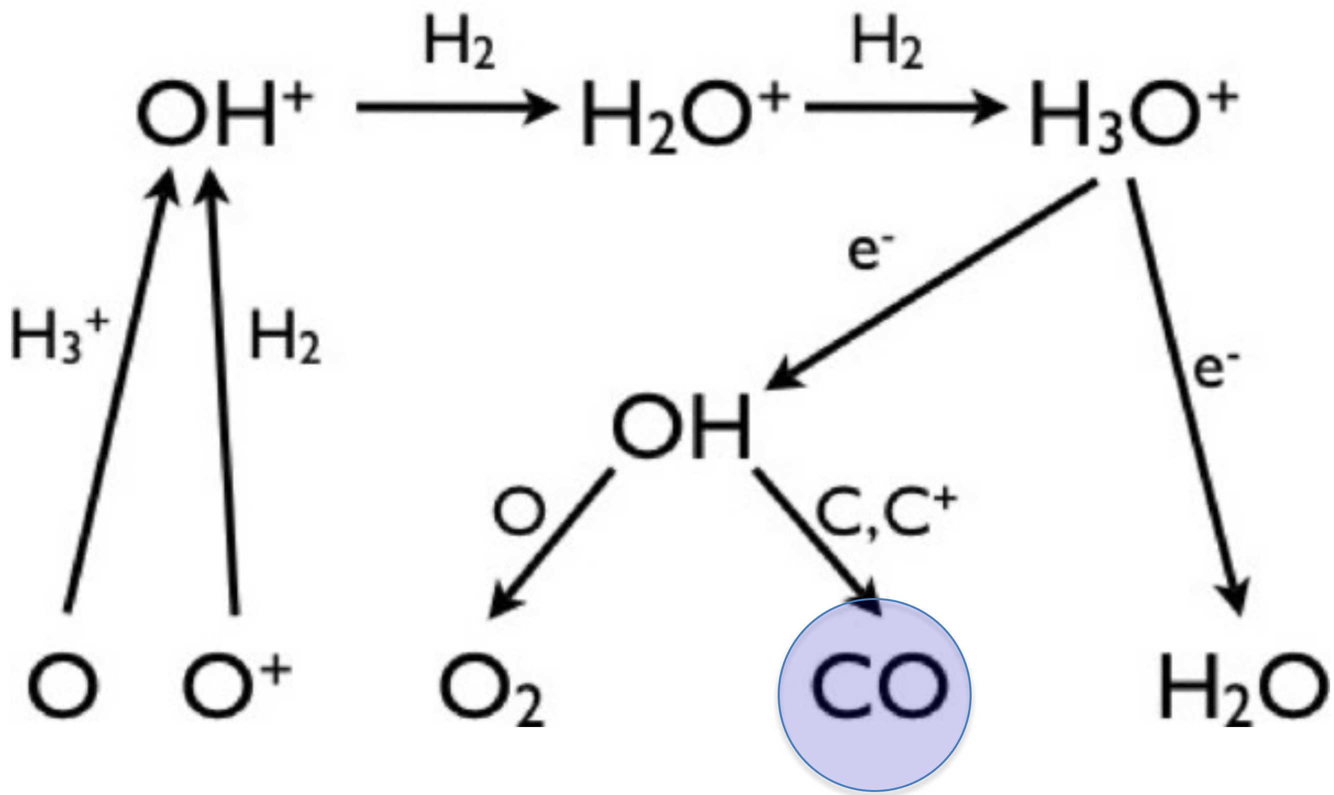
SOFIA/GREAT – future milestones…

[O I] 63 μm observations of outflows/shocks/discs	mixer H	4.7 THz
HD (1-0) 112 μm observations of Class 0 protostars/discs	mixer M	2.4-2.7 THz

Examples:	ρ Oph A	[O I] 63/145 μm	Flux = 2×10^{-14} /5×10^{-15} W m^{-2}	(80´´ beam)
	Ser SMM1	HD 112 μm	Flux = 5×10^{-15} W m^{-2}	(80´´ beam)

High-J CO lines important diagnostics for excitation state and energetics

their kinematics needs spectrally resolved line profiles



Courtesy of Hollenbach et al. 2009

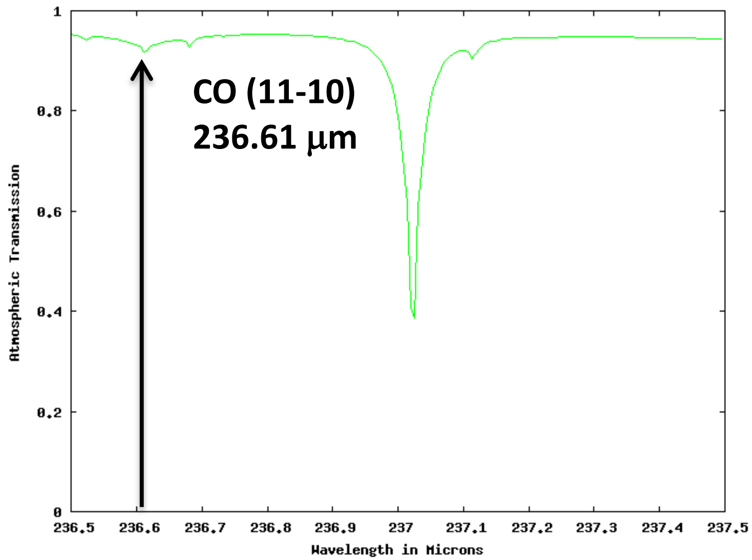
SOFIA will be great for spectroscopy

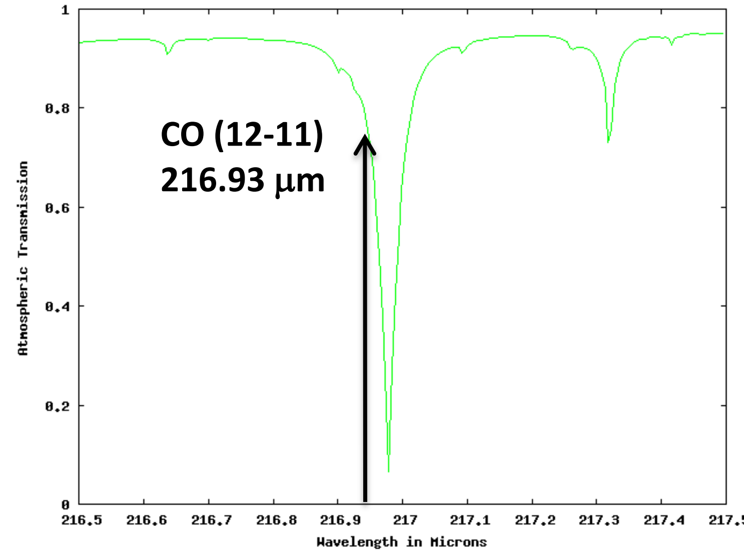
SOFIA/GREAT - but initially one could do

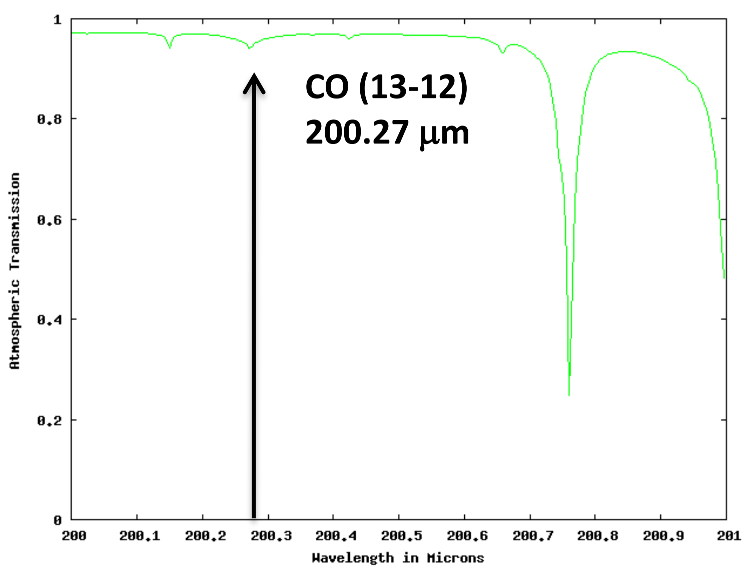
CO (*J*=11-10, 12-11, 13-12)	observations of outflows/shocks/discs	mixer L1	1.25-1.5 THz
CO (*J*=16-15)	observations of Class 0 protostars/discs	mixer L2	1.8-1.92 THz

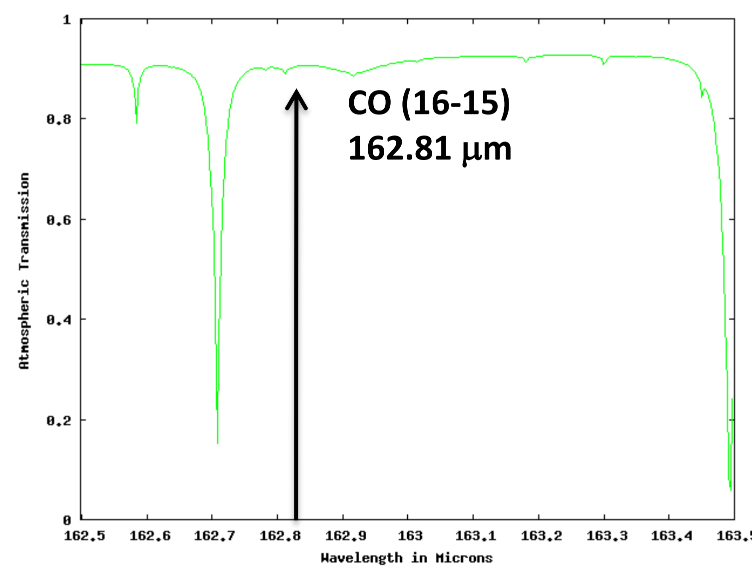
High-*J* CO lines important diagnostics for excitation state and energetics their kinematics needs spectrally resolved line profiles

ATRAN: Observatory Altitude 39000 ft
Observatory Latitude 30°
Number of atmospheric layers 2
Zenith angle of observations 30°









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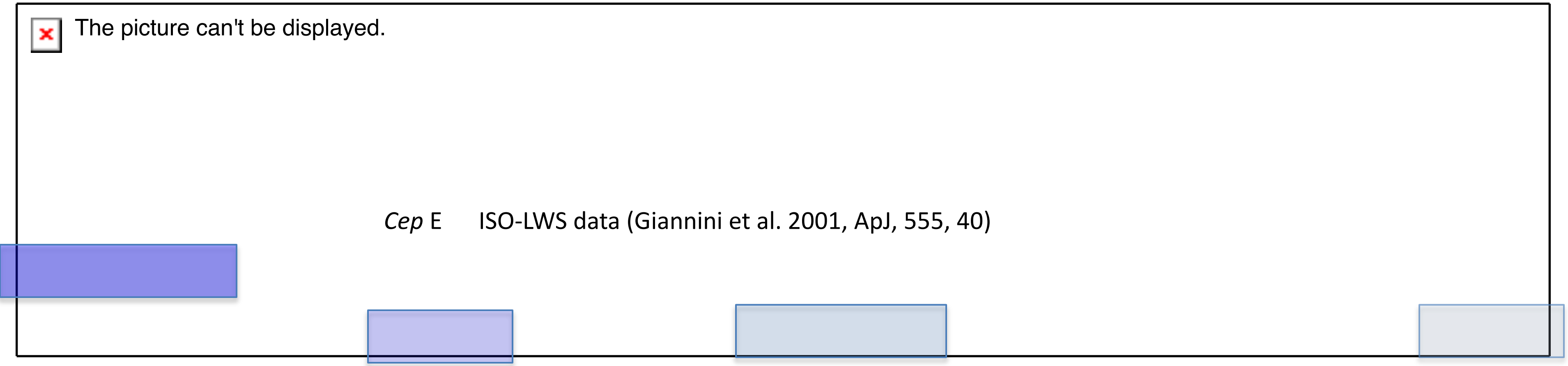
Cep E ISO-LWS data (Giannini et al. 2001, ApJ, 555, 40)



Cep E ISO-LWS data (Giannini et al. 2001, ApJ, 555, 40)

Summarising:

- Odin & Herschel/HIFI capable of obtaining velocity resolved H_2O line spectra

- SOFIA capable of obtaining velocity resolved OI and high-J CO line spectra

➔ Combination a great step forward to understanding oxygen chemistry in the ISM

- As demonstrated, SOFIA not only complementary, but has its own place in THz heterodyne spectroscopy

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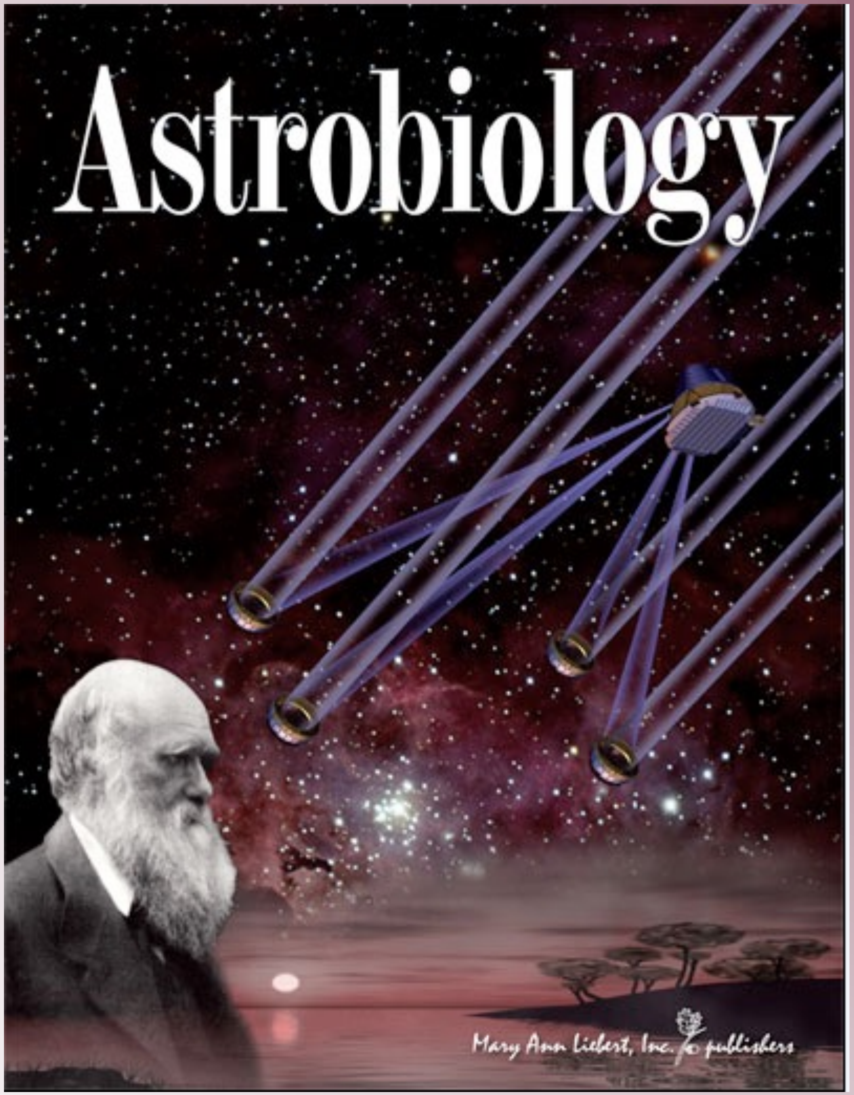
finally, Oxygen is a tracer of Life…

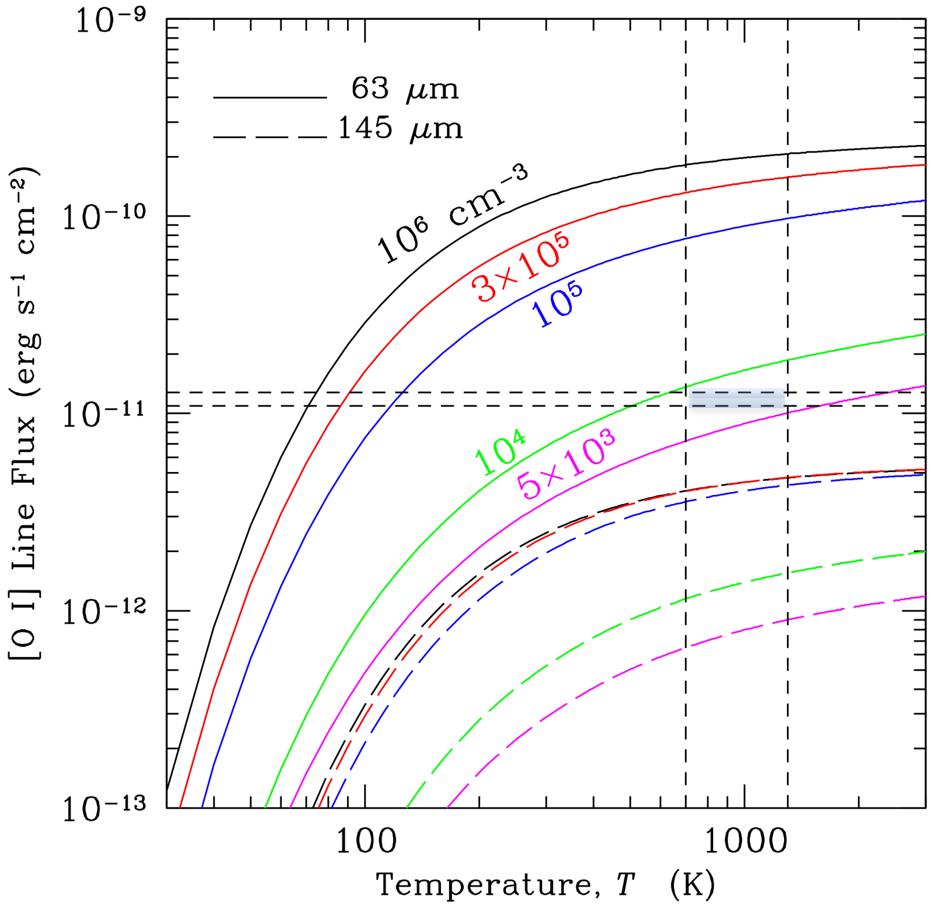


CETERUM CENSEO DARVINUM/TPF ESSE VOLANDUM

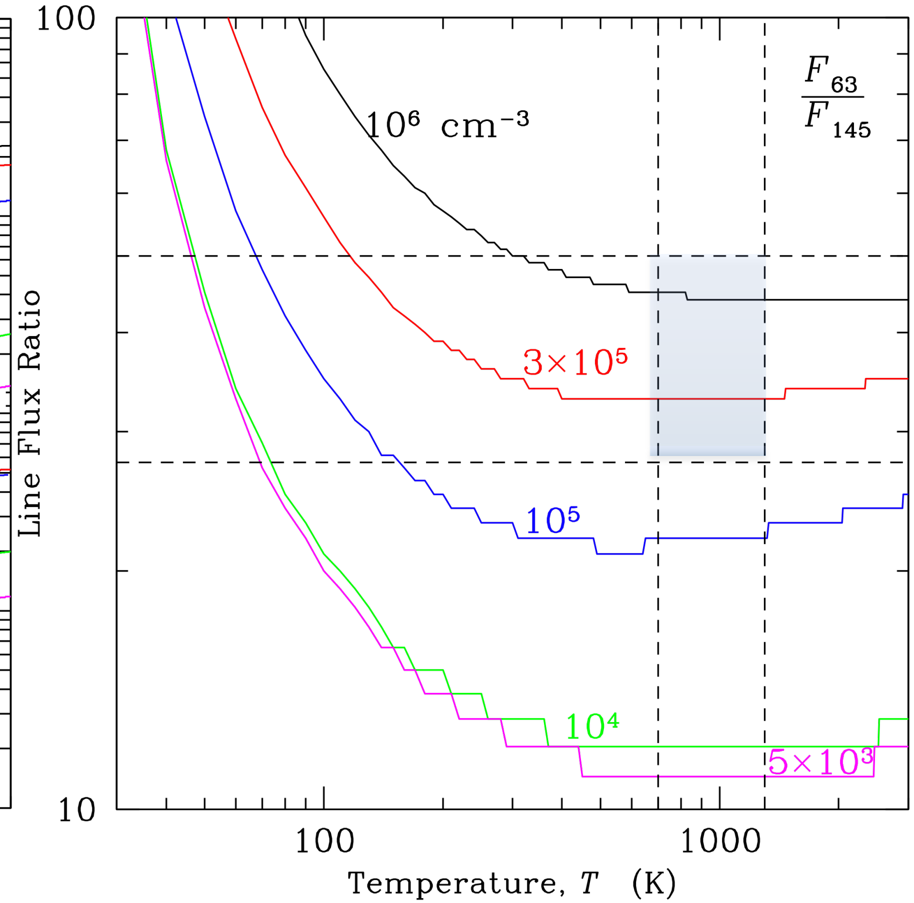
FURTHERMORE, DARWIN/TPF MUST BE FLOWN

ρ Oph A (VLA 1623 Outflow)

[OI] 63, 145 μm Line **Fluxes** (80'' beam)



[OI] 63, 145 μm Line Flux **Ratios**



Models are shown for T = 30 - 3000 K and $n(H_2) = 5\times10^3 - 1\times10^6$ cm^{-3}

Observed values with their error bars within the shaded areas