Initial Results from the Herschel Space Observatory Open Time Key Project

Herschel Oxygen Project

"HOP"

Paul F. Goldsmith
Jet Propulsion Laboratory, California Institute of Technology

for the HOP Team

with special thanks to Tom Bell, John Black, David Hollenbach, Michael Kaufman, Bengt Larsson, Di Li, Tom Phillips, Aage Sandqvist, & Ewine van Dishoeck

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Herschel Oxygen Project

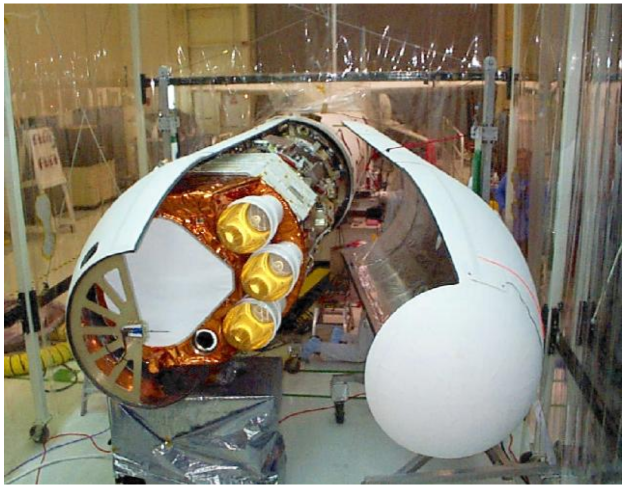
Paul Goldsmith (NASA JPL), *U.S. PI*; René Liseau (Chalmers Univ.), *European PI*

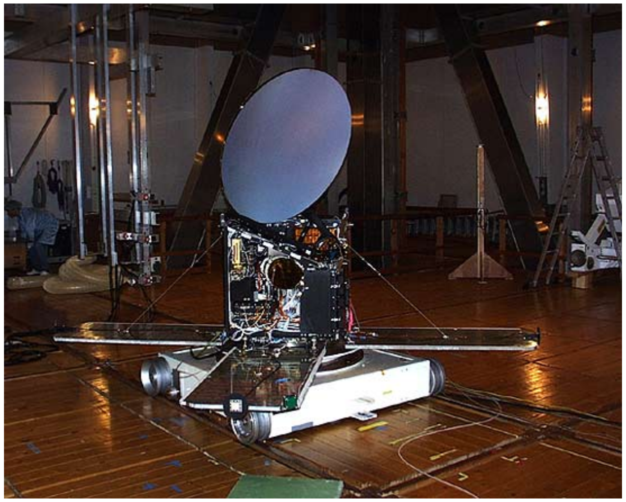
Tom Bell	Astrobiology Inst. Madrid	Franck Le Petit	Obs. Paris
Arnold Benz	ETH, Zurich	Di Li	NASA JPL
Edwin Bergin	Univ. Michigan	Darek Lis	Caltech
John Black	Chalmers Univ.	Gary Melnick	Center for Astrophys.
Simon Bruderer	ETH, Zurich	Zsofia Nagy	SRON, Groningen
Paola Caselli	Univ. Leeds	David Neufeld	Johns Hopkins Univ.
Emmanuel Caux	CESR Toulouse	Henrik Olofsson	Obs. Paris
Jo-Hsin Chen	NASA JPL	Laurent Pagani	CNRS, Paris
Pierre Encrenaz	Univ. Paris	Evelyne Roueff	Obs. Paris
Edith Falgarone	CNRS, Paris	Aage Sandqvist	Stockholm Univ.
Maryvonne Gerin	CNRS, Paris	Ronald Snell	Univ. Massachusetts
Javier Goicoechea	Obs. Paris	Floris van der Tak	SRON, Groningen
Ake Hjalmarson	Onsala Space Obs.	Ewine van Dishoeck	Leiden Univ.
David Hollenbach	NASA Ames	Charlotte Vastel	CESR, Toulouse
Michael Kaufman	San Jose State Univ.	Serena Viti	Univ. College London
Bengt Larsson	Stockholm Obs.	Umit Yildiz	Leiden Observatory
Jacques Le Bourlot	Univ. Paris		

Why O_2 and Why at Submillimeter Wavelengths?

- **Astrophysical Importance** – O_2 is a simple molecule whose gas-phase chemistry is thought to be well understood
- **Large predicted abundance** - in relevant situations should be as large as $X(O_2) = n(O_2)/n(H_2) = 3x10^{-5}$ making O_2 a major oxygen reservoir
- **Critical transitions** fall in THz range
- **O_2 was major objective** of SWAS and Odin satellites, which yielded very surprising results

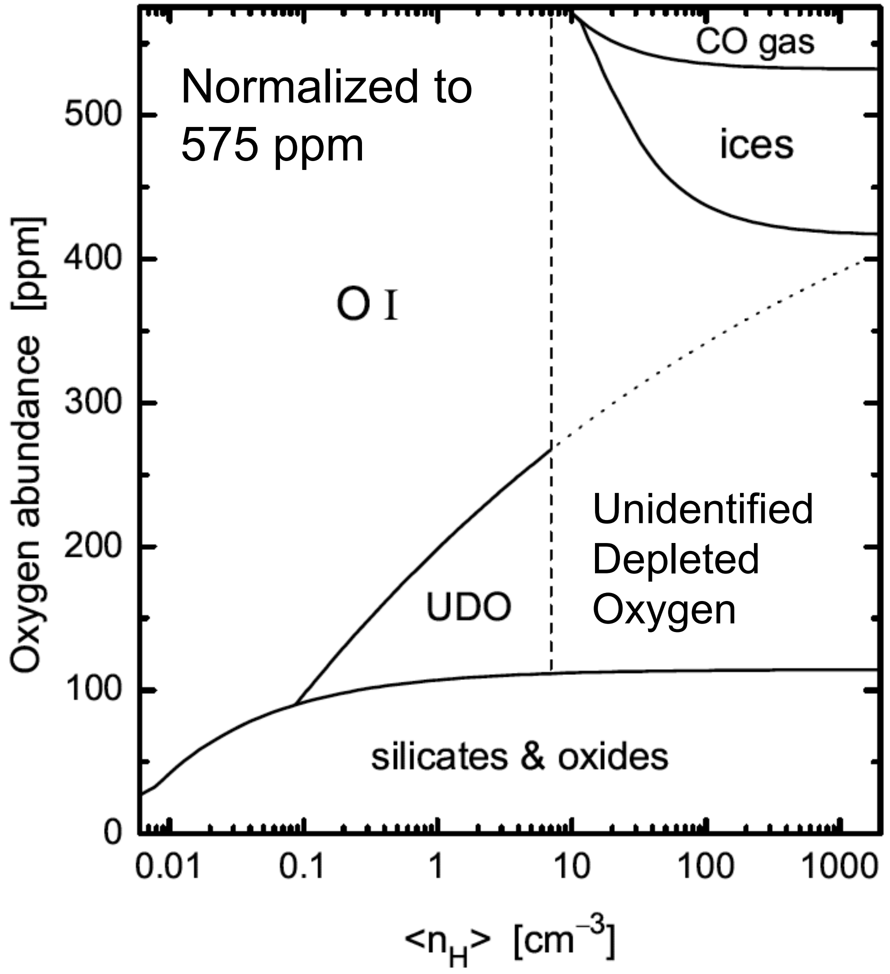
➔O_2 is a target of Herschel projects (GTKP & OTKP)





Part of a Bigger Question: Where is the Oxygen in the Dense ISM?

- Oxygen is the 3rd most abundant element
- Its form in the Dense ISM is very unclear
- Should O_2 be in this figure?



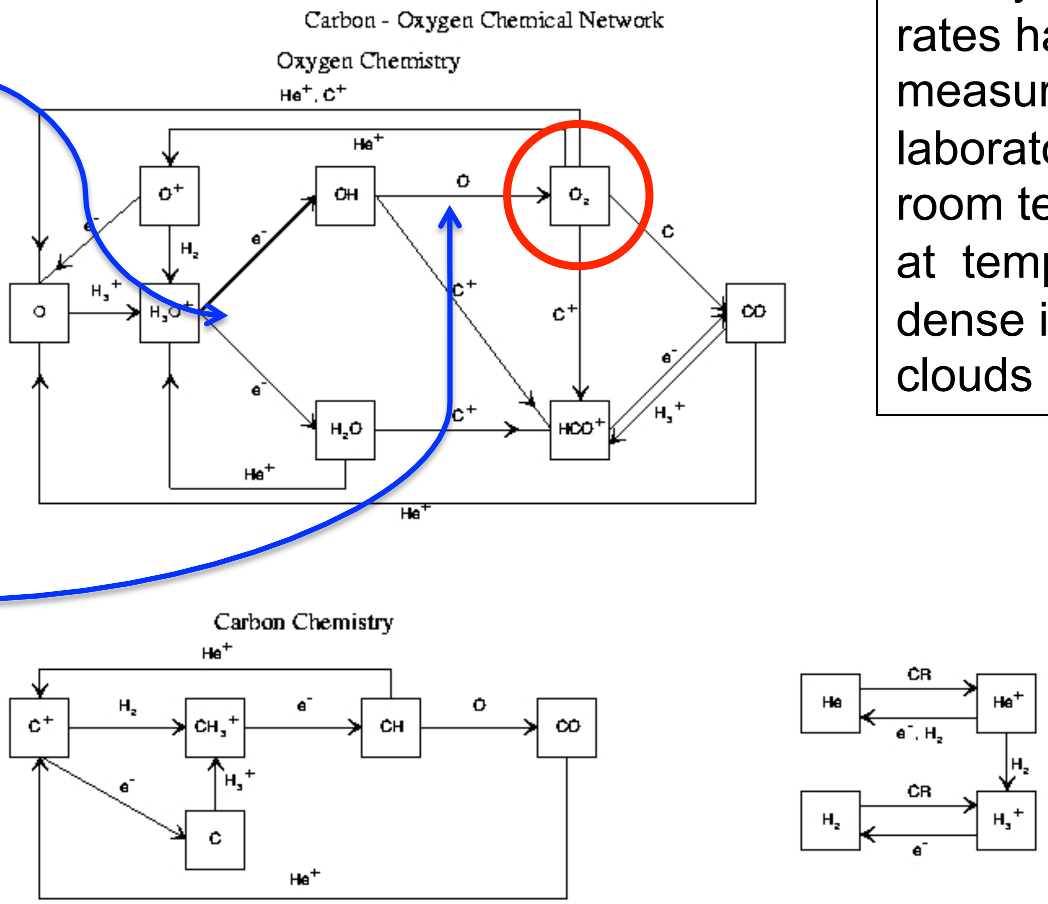
D. Whittet (ApJ 2010)

Gas Phase Chemistry for O, H_2O, O_2 and CO is Relatively Simple

Branching ratio measured by ASTRID and CRYRING experiments (Jensen et al. 2000; Neau et al. 2000) $f(H_2O):f(OH) = 0.25:0.75$

OH + O –> O_2 is an endothermic neutral-neutral reaction

Measurements (Carty et al. (2006) and full quantum calculations (Lique 2010) indicate ~ temp-indep. rate from 300 K to very low temperatures ≅ 4×10^{-11} $cm^3 s^{-1}$



Carbon - Oxygen Chemical Network

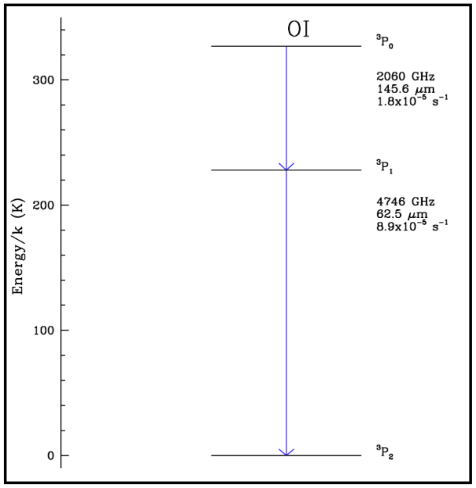
Oxygen Chemistry

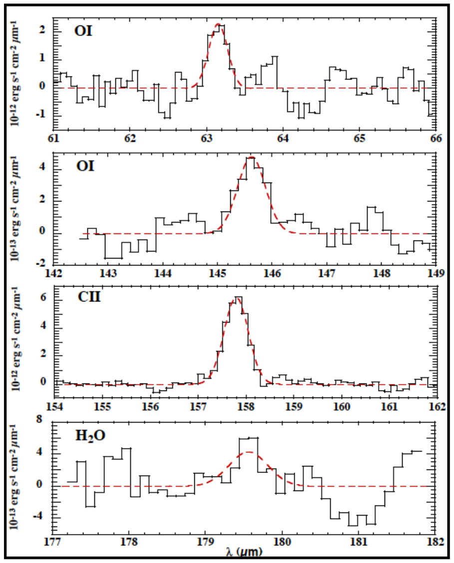
Carbon Chemistry

All key reaction rates have been measured in laboratory, both at room temperature & at temperatures of dense interstellar clouds

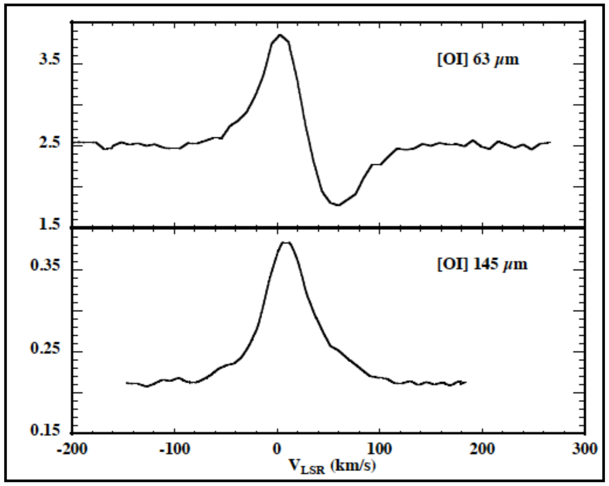
OI: Suggestions From ISO LWS Fabry-Perot are that X(OI) >> X(CO) in Dense Gas

- ~30 km/s velocity resolution allows separation of foreground absorption from hot core emission
- Caux et al. (1999), L1689N: [OI]/CO~50
  - 98% of the oxygen is in atomic form in the gas phase!
- Vastel et al. (2000), W49N: atomic clouds responsible for only fraction of the absorption
  - At least 15 times more O than CO has to be present in molecular cloud interiors!
- These conclusions would dramatically alter astrochemical modeling if confirmed, but to do so will require heterodyne resolution and mapping of extended sources





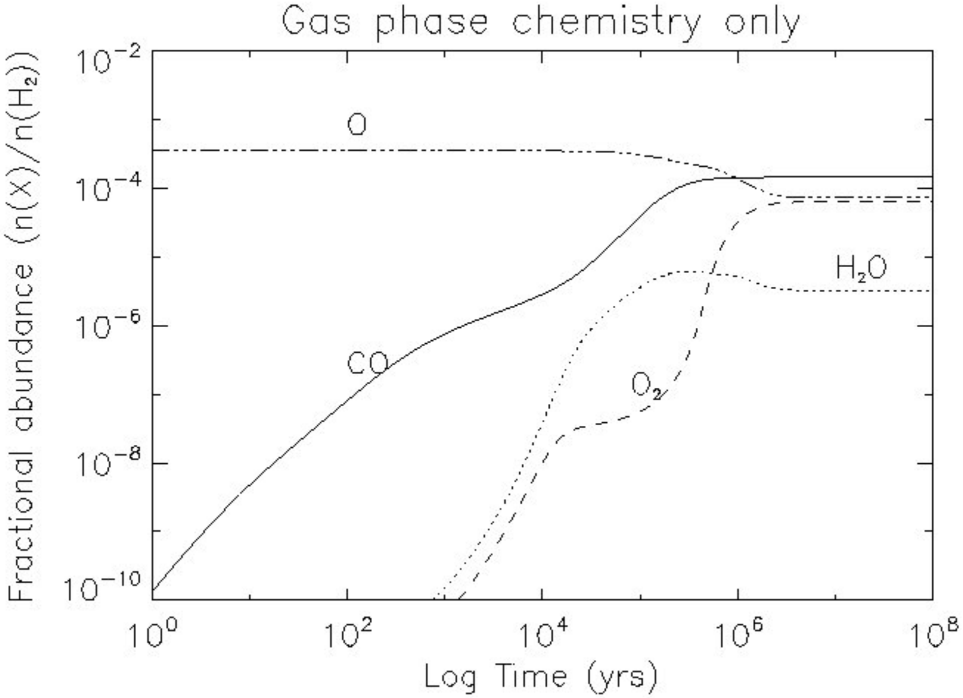
L1689N



W49N

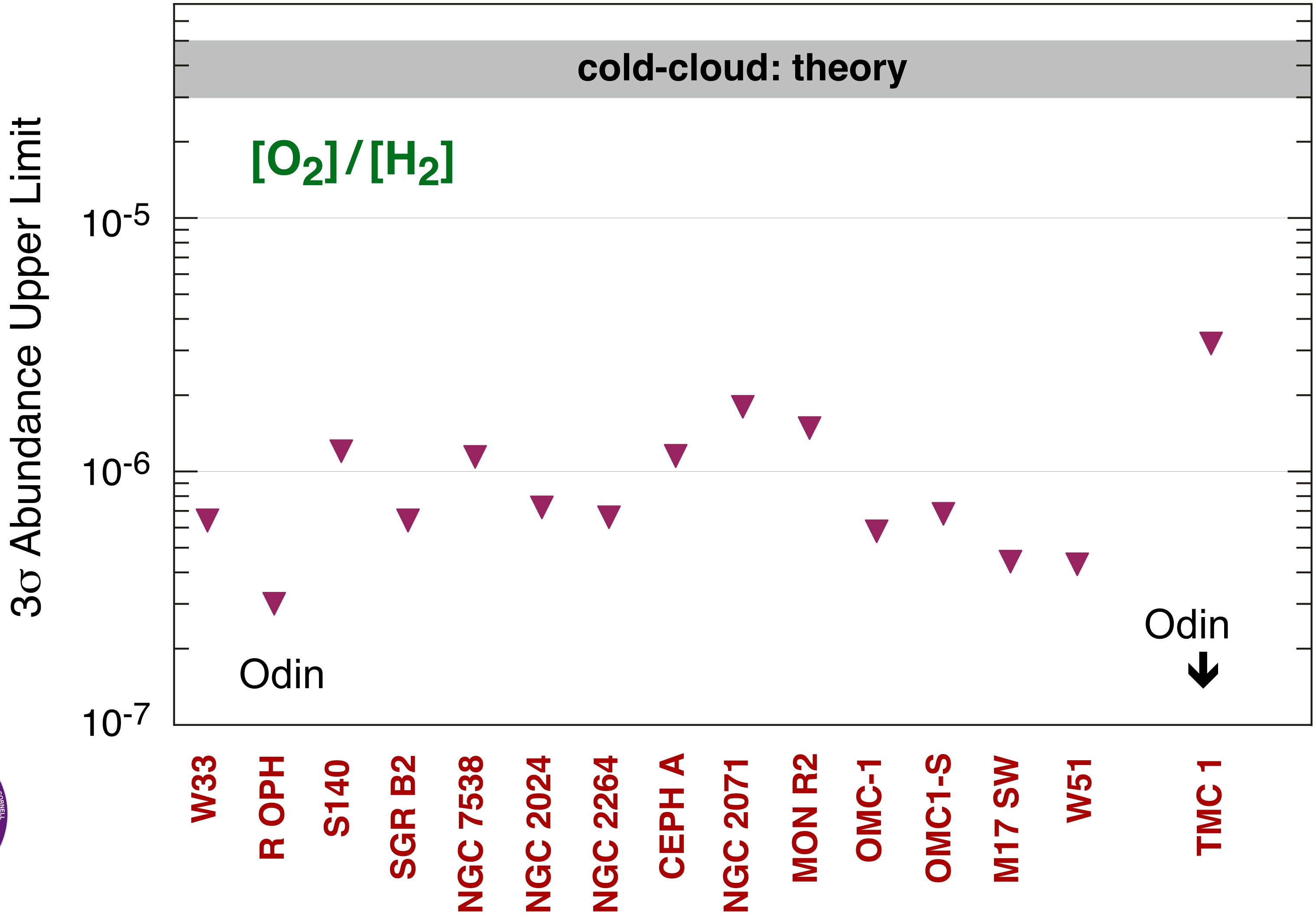
Vastel et al. (2002) Sgr B2: [OI]/[CO] = 2.5

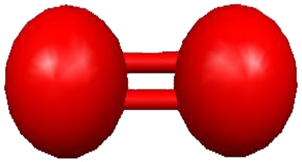
Standard Gas-Phase Chemistry Models Predict Lots of O_2



The time dependent evolution of a gas phase chemistry model. The physical conditions are $n(H_2) = 10^4$ cm^{-3}, T = 10 K, and A_v = 10 mag. The oxygen is initially atomic (K. Willacy).

$X(O_2)$ in IS Clouds from Odin & SWAS is ≥ 100X less than Predicted by Gas-phase Chemistry





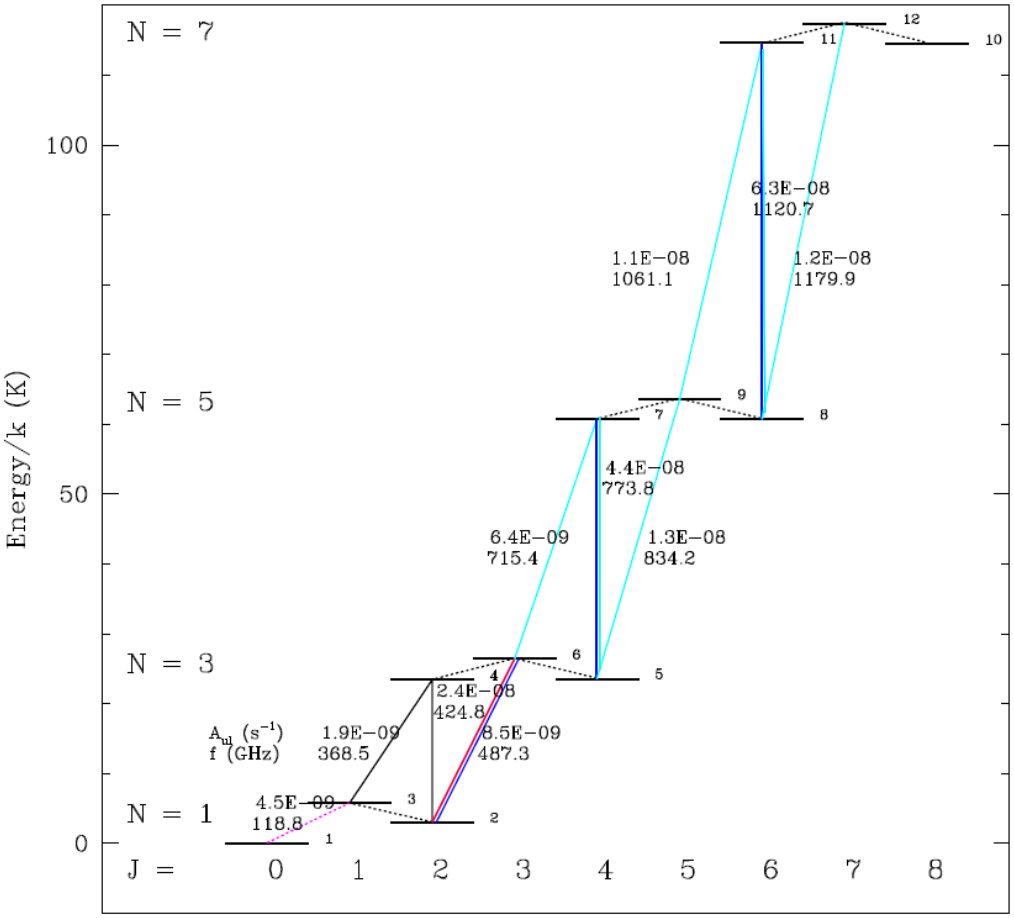
Lower Rotational Levels and Transitions of O_2

O_2 Rotational Levels are Connected by Weak Magnetic Dipole Transitions

Quantum calculations of He-O_2 collisions carried out by Lique (2010) Deex. rate coeffs ≅ $5 \times 10^{-11} cm^3 s^{-1}$

- Critical densities 200 – 1000 cm^{-3}
- Level populations will be in LTE

- Emission will be Optically Thin



Observed by SWAS

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Observed by Odin

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Observable with Herschel

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Most favorable transitions for Herschel

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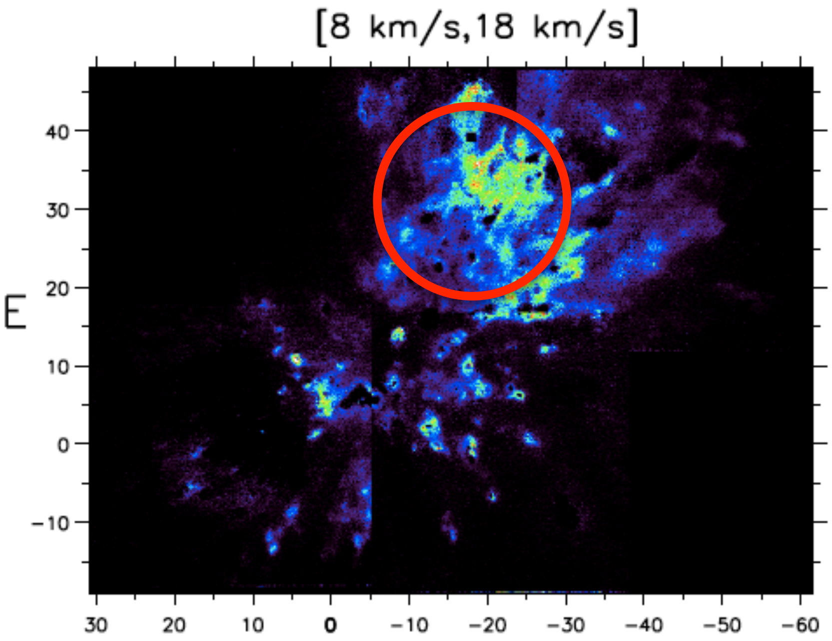
HOP Initial Results

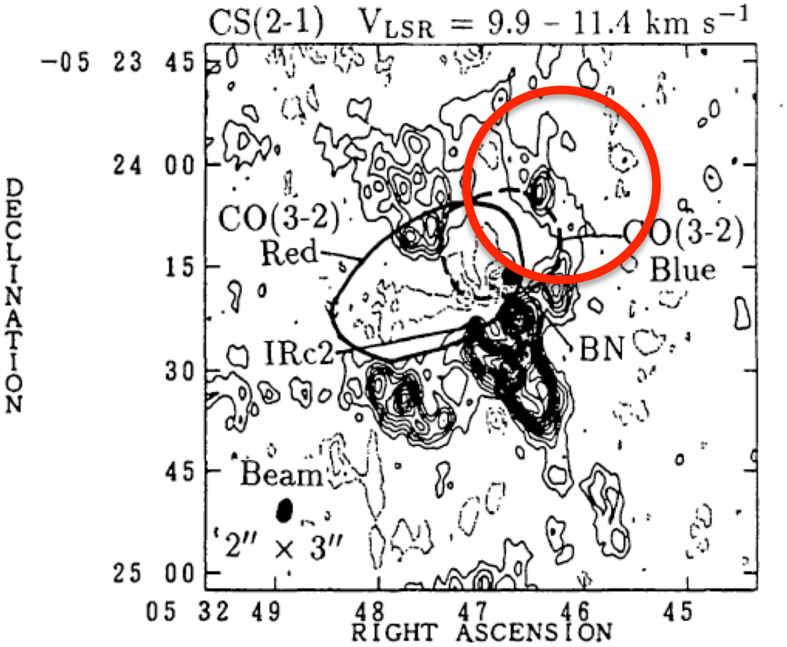
- **Orion Bar** – classic PDR G ~ 10^5 [Melnick, Tolls]
  - 487 and 774 GHz O_2 transitions observed. Based on parameters for CS J = 10-9 line, upper limits for O_2 correspond to $X(O_2) \leq 5 \times 10^{-8}$ if O_2 traces full H_2 column
- **ρ Oph** – intermediate mass YSO region possibly PDR [Liseau, Larsson]
  - No detection at 487 GHz that would confirm Odin result, but this may be due to extended PDR type structure with $N(O_2)$ limited between photodestruction and freeze-out
- **Orion(S)** – embedded protostar L ~10^4 L_{sun} [Nagy, van der Tak]
  - 3 O_2 transitions observed; $N(O_2) < 1 \times 10^{16}$ cm^{-2}; total $N(H_2) \sim 5 \times 10^{24}$ cm^{-2} (McMullin et al. 1993]. If this is relevant #, $X(O_2) < 2 \times 10^{-9}$
- **AFGL2591** - XDR [Benz, Bruderer]
  - No detections at few mK level; X-ray dominated region severely beam diluted; overall $X(O_2) < 5 \times 10^{-8}$; awaiting data on high frequency transitions.
- **NGC1333 IRAS4A –** low-mass YSO region [van Dishoeck, Yildiz]
  - $X(O_2) <$ few x 10^{-9}; further data analysis and source modeling in progress
- **Sgr A 50 km s^{-1}** - Galactic Center foreground cloud
  - Detection of 487 GHz line in very recent observations, but not 774 GHz line -> low temperature

HOP Results in Orion at H_2 Peak 1 Position

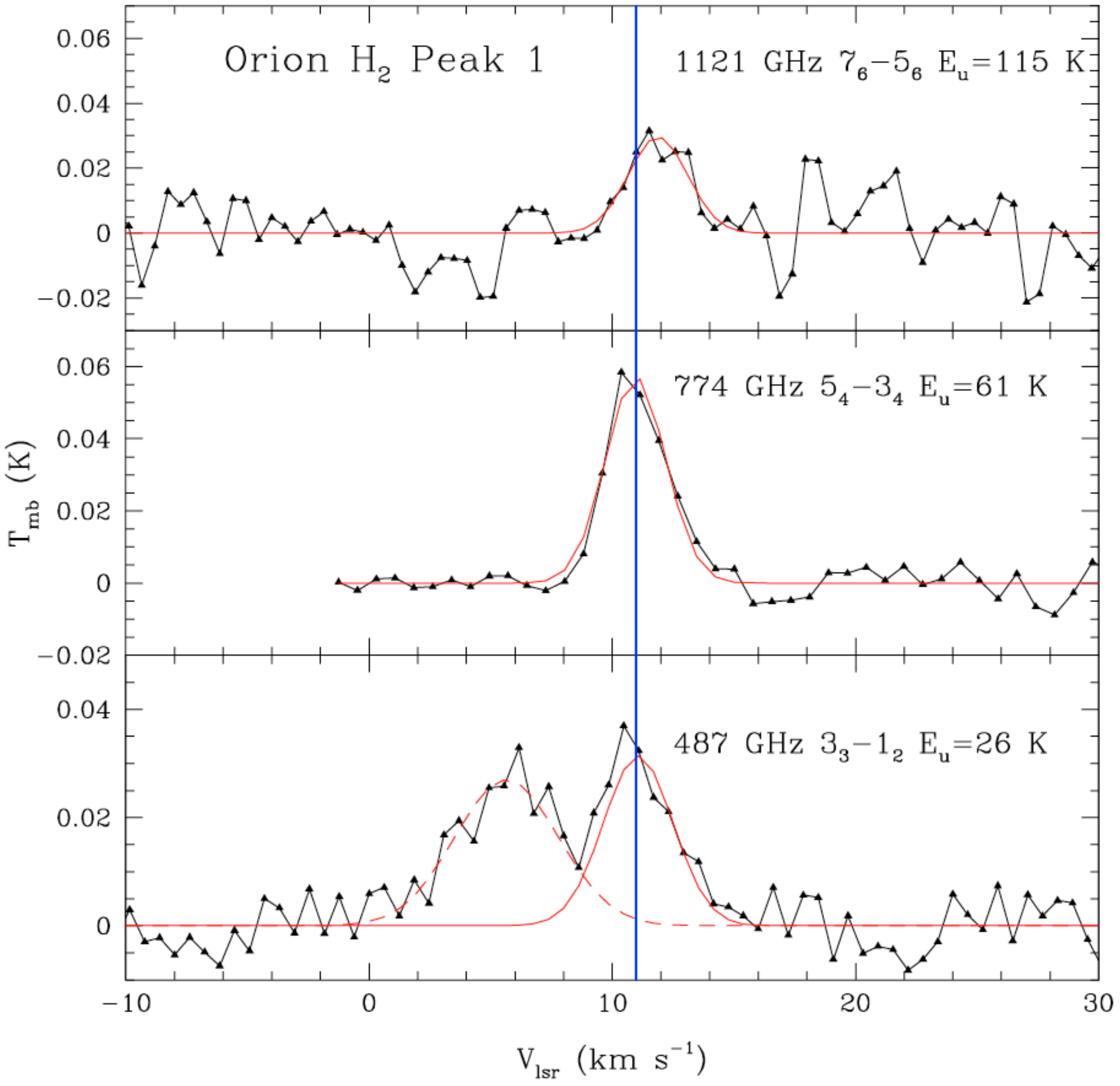
In Low-v H_2 Outflow, at Edge of Blue Lobe of CO Outflow, and near Clump in CS(2-1)



H_2 v = 1-0 S(1) from Gustafsson et al. (2003)
Relative to (J2000) 05 35 14.9; -05 22 39



Murata et al. (1991)
B1950 coordinates



Herschel HIFI Data

- Beam Sizes:

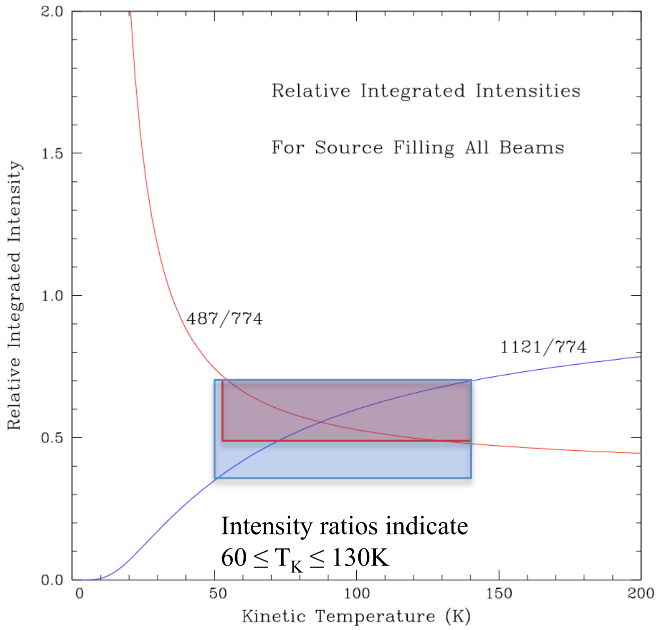
487 GHz 44”
774 GHz 30”
1121 GHz 20”

- Integration times up to 8 hr
- 3 transitions observed consistent with v_{lsr} = 11 km s^{-1} δv = 2.9 km s^{-1}

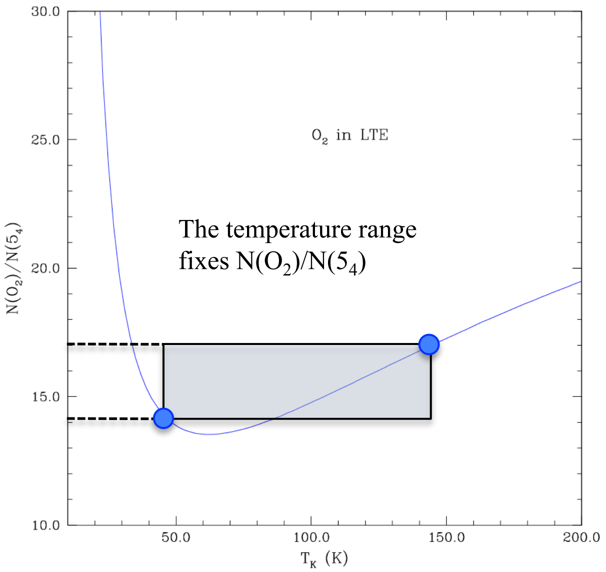
First multitransition detection of molecular oxygen in the ISM

Work analyzing possible “interlopers” continuing…

Line Intensity Ratios Determine Kinetic Temperature and Total O_2 Column Density



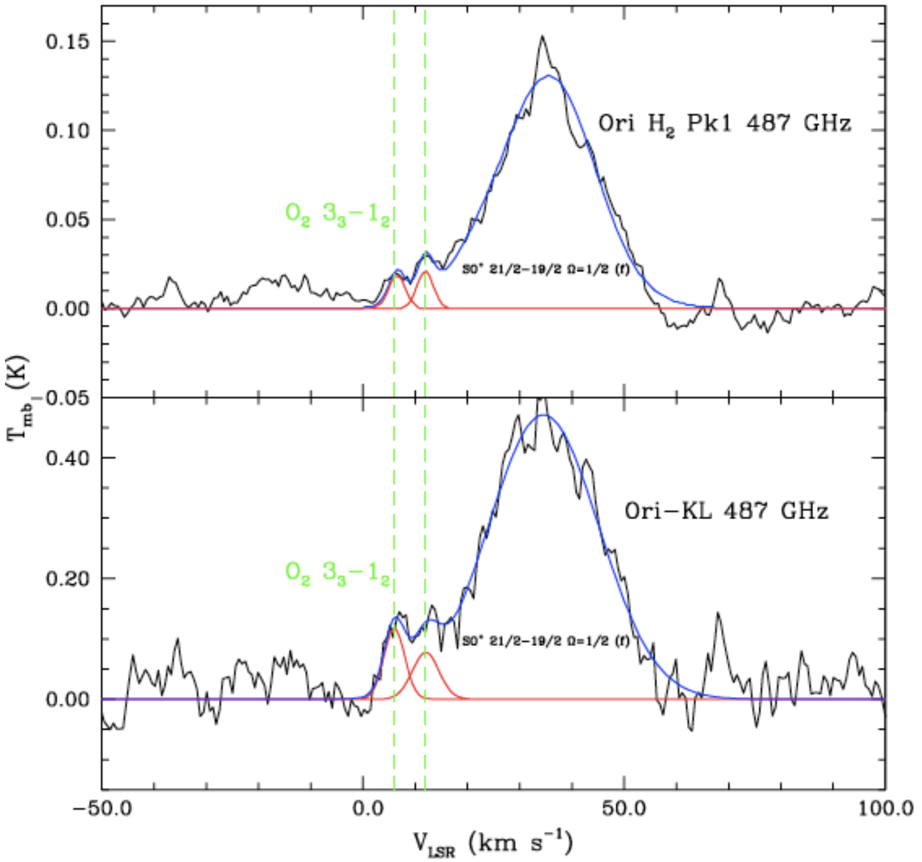
Intensity ratios indicate
$60 \le T_K \le 130K$



The temperature range
fixes $N(O_2)/N(5_4)$

$N(O_2)$ = 6.8(+0.7 -1.0) x 10^{16} cm^{-2} (statistical + kinetic temperature uncertainties)
$N(H_2) > 1 \times 10^{22}$ cm^{-2} (warm gas; Boonman et al. 2003) indicating $X(O_2) < 7 \times 10^{-6}$
Low velocity shock optimum for producing O_2; not a problem to get this $N(O_2)$
Location, preshock conditions, and relevant $N(H_2)$ all highly uncertain
Postshock velocity and line widths challenging **– M. Kaufman talk after coffee break**

487 GHz Data from HEXOS Project Towards KL also Show O_2 Features



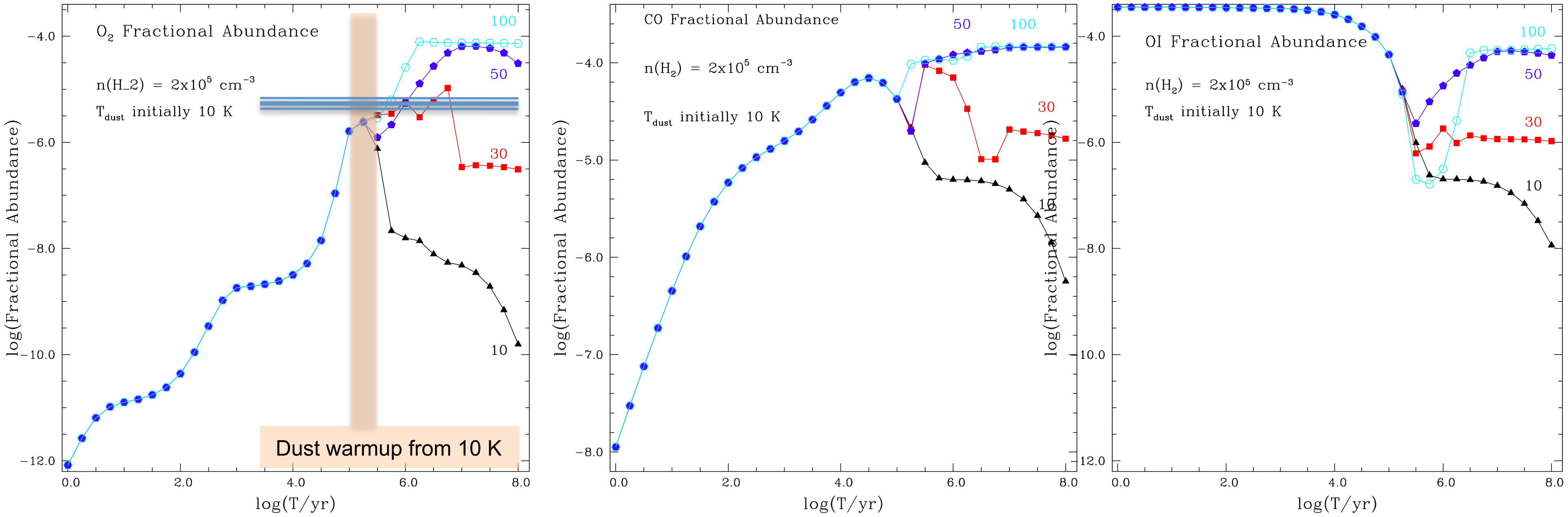
- 5 km s^{-1} feature particularly stronger at KL
- Plausibly emission from "hot core"
- 5 km s^{-1} feature not seen at H_2 Peak 1 in higher transitions due to smaller beam size. 11 km s^{-1} also present at KL
- Relatively large (44") 487 GHz beam allows pickup of both sources (25" separation) simultaneously
- Multitransition deeper observations of KL planned

Modeling of centrally heated "hot core like" source with T = 100 K indicates **$N(O_2)$ = 4.3x10^{16} cm^{-2}** and $X(O_2)$ = 5.5x10^{-6}
(Beam-averaged values; source is significantly beam diluted)

Warm Dust Surrounding Embedded Source ⇒ Large Gas Phase X(O_2)

- O_2 binding weak compared to that of H_2O (Acharyya et al. 2007) O_2 on grains likely to be converted to H_2O (Ioppolo et al. 2008; Miyauchi et al. 2008)
- Atomic O will start desorbing for $T_d > 25$ K (Hasegawa & Herbst 1993)
- When $T_d \geq 100$ K, H_2O will start desorbing (Fraser et al. 2001)
- With gas phase H_2O present, “normal” gas-phase chemistry will reassert itself in few x 10^5 yr. There may not have yet been time to reach asymptotic value

Quan, Herbst, & Goldsmith (2010)



Conclusions

•With limited data available, mostly in lowest frequency transition, most sources show no detectable O_2 emission with Herschel HIFI.

•The broad-brush interpretation is that in regions of modest temperature, the O_2 abundance is extremely low, with limits between few $x10^{-9}$ and few $x10^{-8}$.

•O_2 in Sgr A 50 kms^{-1} has been detected and other sources are still to be observed.

•These results confirm and extend SWAS and Odin results: O2 is not a significant coolant or major contributor to Unidentified Depleted Oxygen (UDO).

•HOP data are testing models of PDR photodestruction – freeze-out, shock chemistry, and dust grain surface chemistry.

•We have statistically significant detections of three O_2 transitions in Orion. Modeling in terms of of shocks and warm dust chemistry is encouraging, but not yet fully satisfactory.

•Complete HOP data set will provide important tests of various aspects of astrochemistry and models of cloud and protostar evolution.