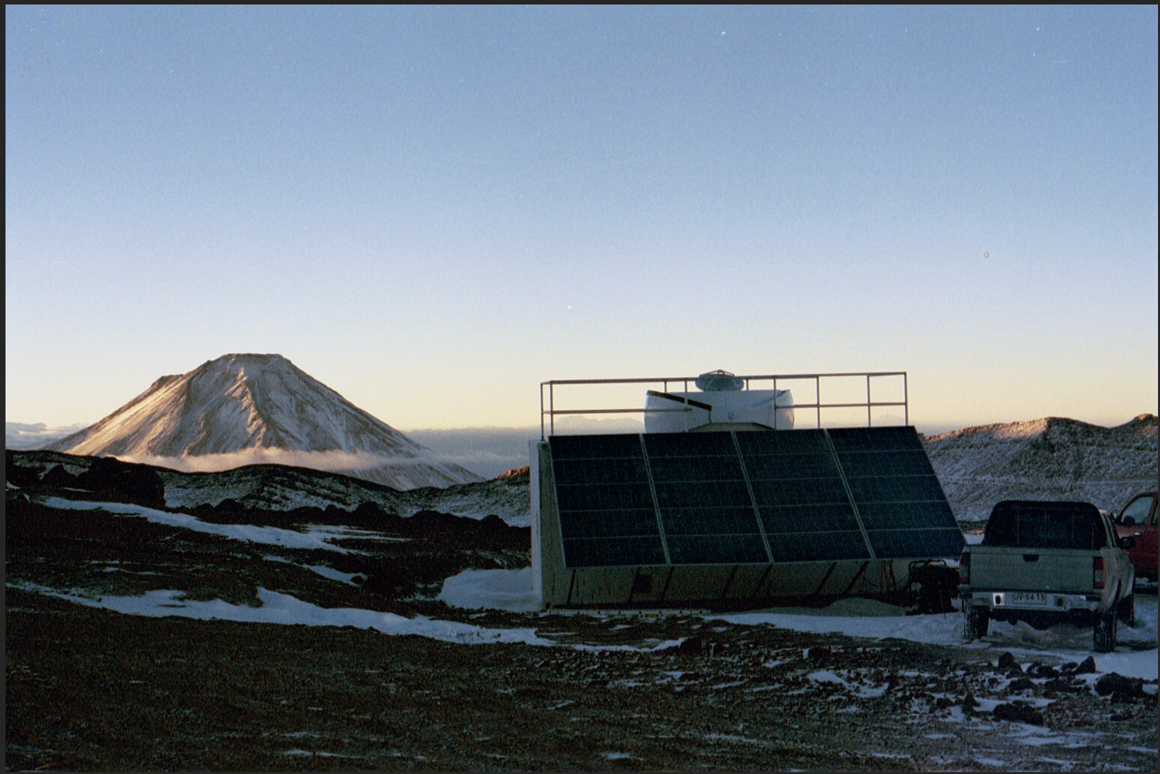
The SAO Receiver Lab Telescope: THz Spectroscopy from Northern Chile



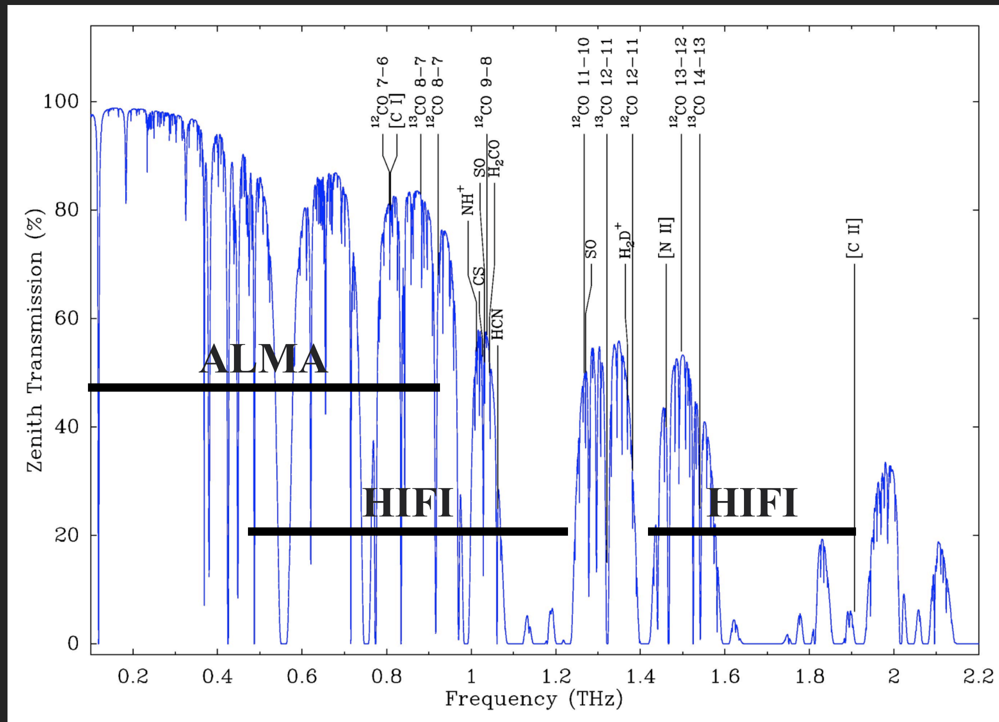
Dan Marrone

Jansky/KICP Fellow
University of Chicago

THz Spectroscopy in Context

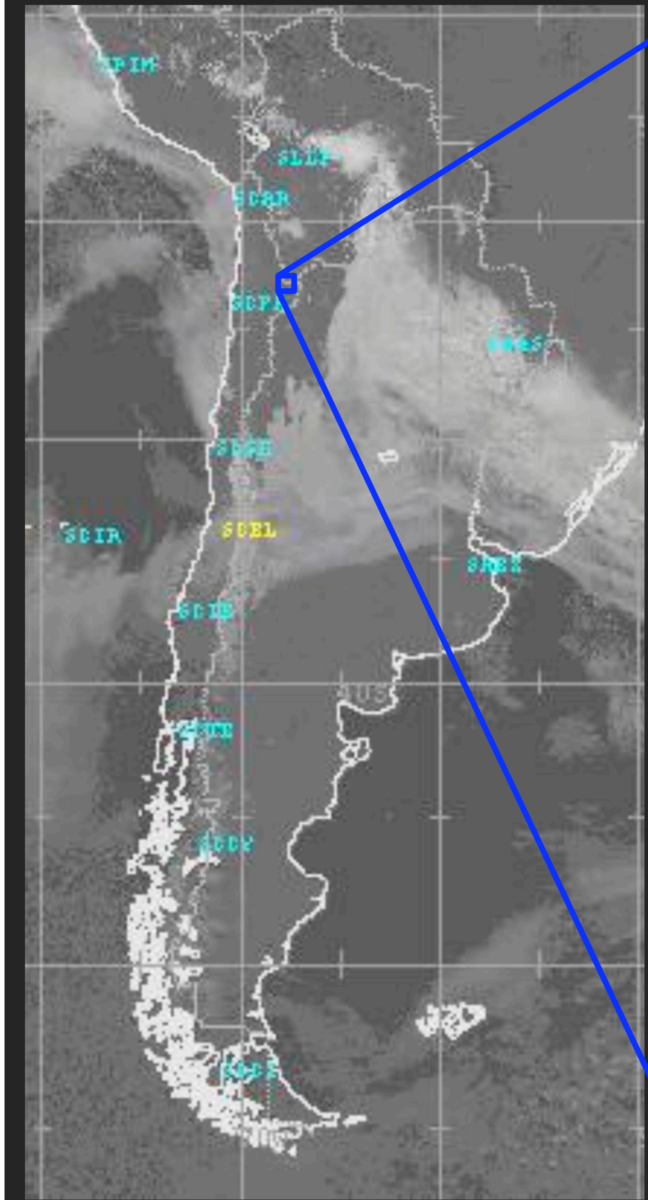
- Submillimeter/THz atmospheric windows remain under-explored
  - Heterodyne technology mature below 1THz, rapidly improving >1THz
- Major instruments for these frequencies (ALMA, Herschel-HIFI, SOFIA) are still in preparation, will not cover all available frequencies
- Many science topics available from the ground (see also Kramer talk):
  - High-J CO lines (high n_{crit}) in warm molecular material
  - [N II] emission in WIM of MW and other galaxies

    Large area mapping is ideal!
  - New species, unique transitions (NH^+, H_2D^+/D_2H^+)
  - Molecular probes: CH_3OH, H_2CO, HCO^+, SO, CS, HCN …

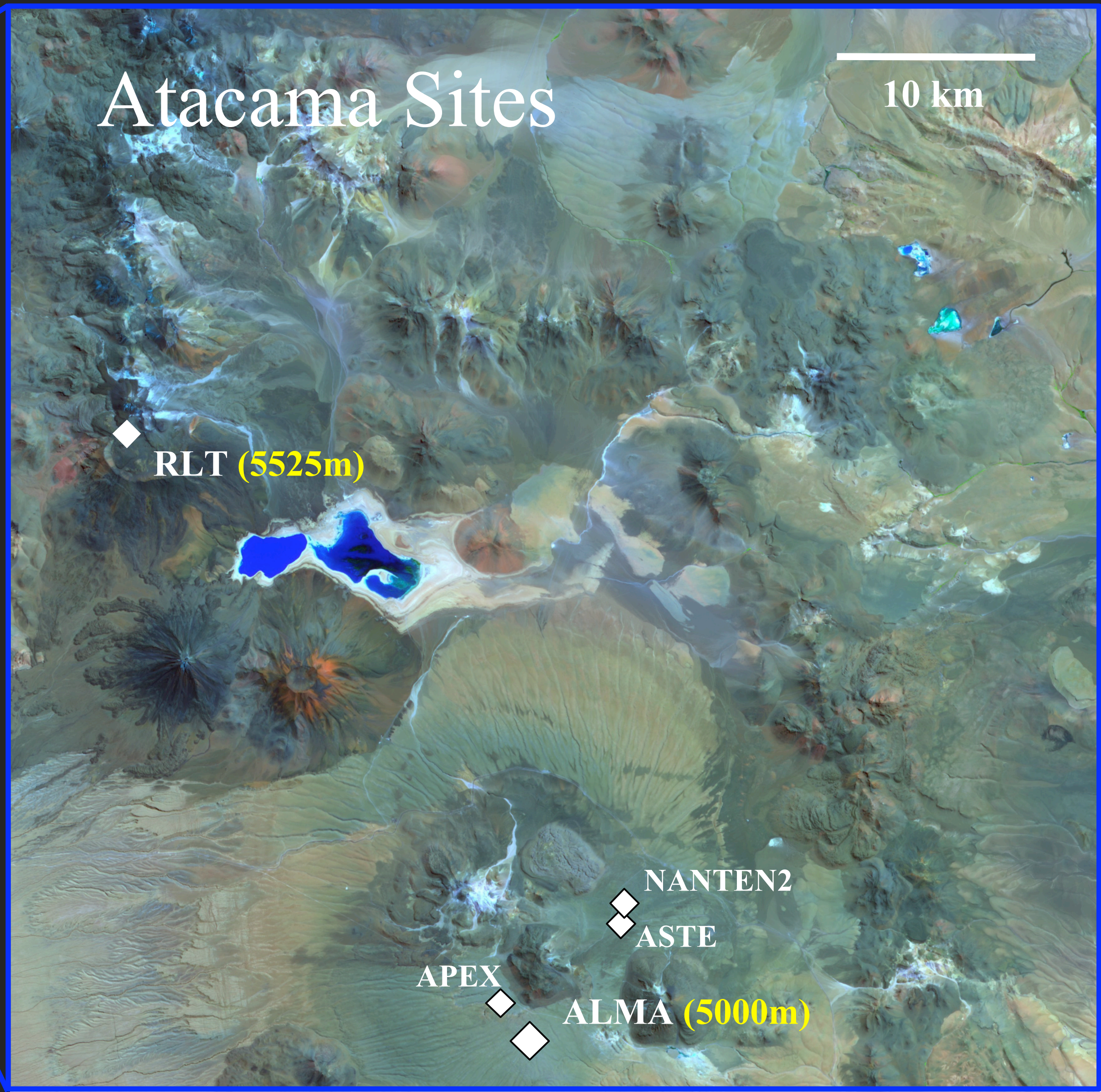


Scientific Goals of SAO THz program

- Initially focused on atmospheric characterization through FTS
- Small telescope designed as pathfinder instrument
  - Test bed for THz receivers using HEB mixers
  - Spectroscopy – CO and isotopologues, N+
  - Demonstration of THz observing techniques
  - Continued atmospheric studies



NOAA GOES-12 / Direccion Meteorologica de Chile



NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team

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2007 June 27

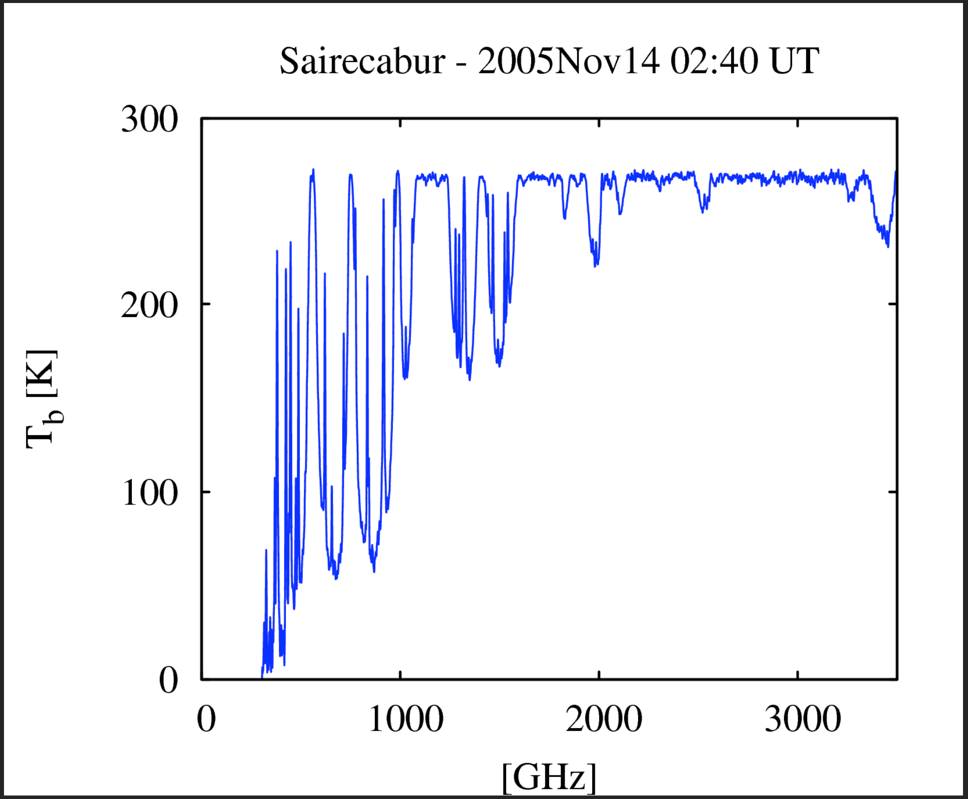
SAO THz Astronomy Site Testing

- Relies on Receiver Lab FTS (Paine et al. 2002)
  - Atmospheric spectra from 300 GHz to 3.5 THz
  - 3 GHz instrumental resolution
  - 10min sampling interval
- *am* atmospheric model developed to match spectra
  - S. Paine, SMA memo 152
  - Open source, fully configurable
  - Download: http://cfarx6.cfa.harvard.edu/am

- Chajnantor (ALMA site)
  - Hosted by NRAO, ESO for site studies
    - 10/97-12/99 (SAO FTS)
    - 4/95-present (Tipping radiometers, phase monitor)
  - Data available online: http://cfarx6.cfa.harvard.edu
- Sairecabur
  - ~7 years of atmospheric measurements
    - 9/00-present (SAO FTS, tipping 350μm radiometer)

FTS Spectra

Calibrated data product is T_b



(S. Paine)

FTS Spectra

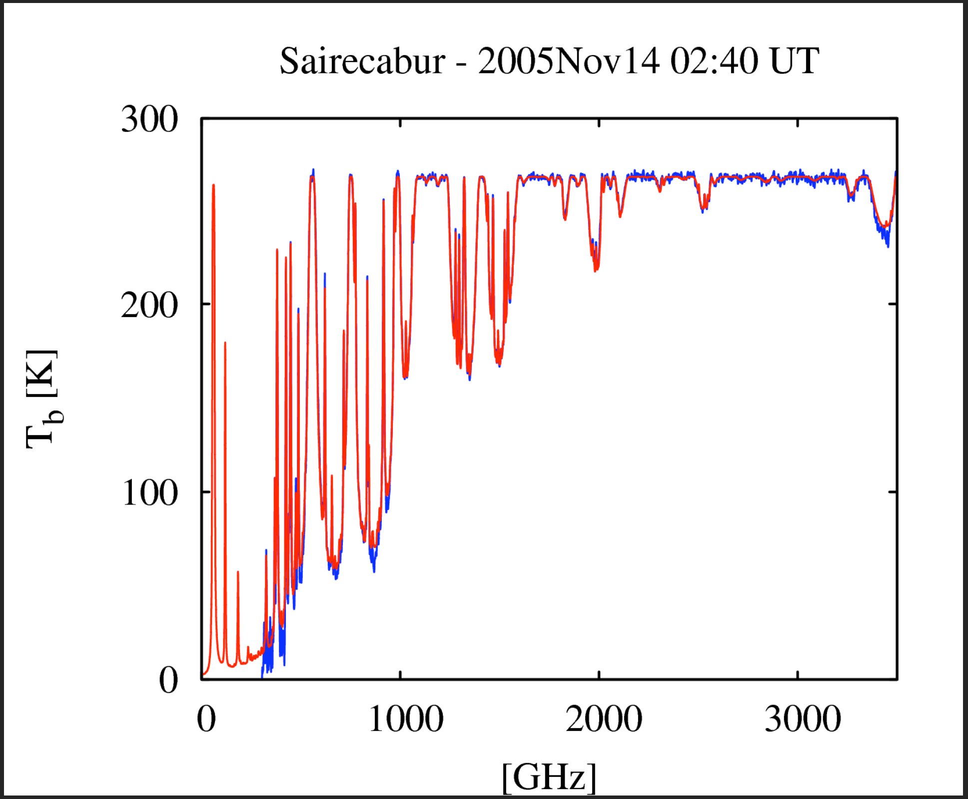
Calibrated data product is T_b

Simple transmittance

- Effective T_{atm} from baseline
- Isothermal transmittance

Model transmittance

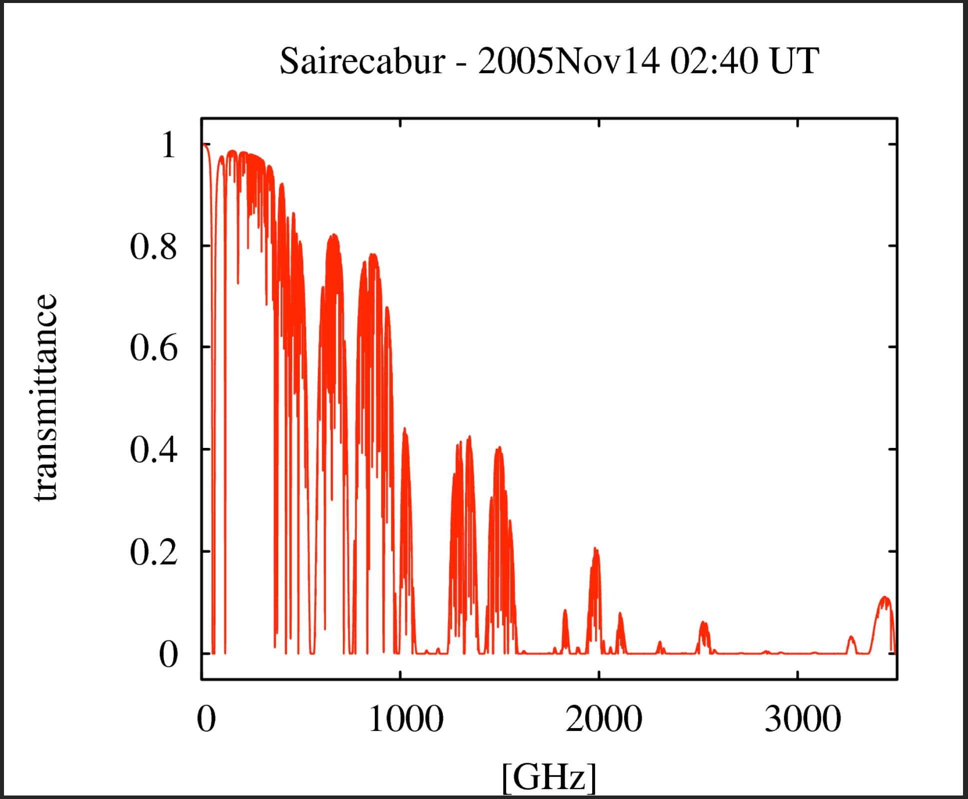
- *am* fit to T_b



(S. Paine)

FTS Spectra

- Calibrated data product is T_b
- Simple transmittance
  - Effective T_{atm} from baseline
  - Isothermal transmittance
- Model transmittance
  - *am* fit to T_b
  - Fully-resolved model transmittance
  - Very important for THz calibration



(S. Paine)

Llano de Chajnantor vs. Sairecabur

Only one FTS, so comparison is indirect

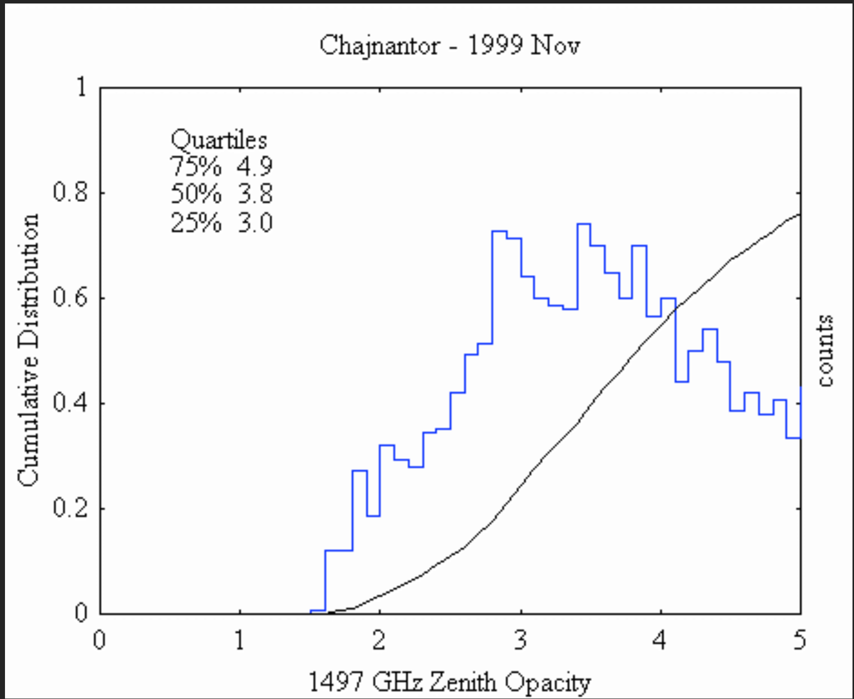
Use 1999 Nov and 2000 Nov, which had similar τ_{225} quartiles at Chajnantor

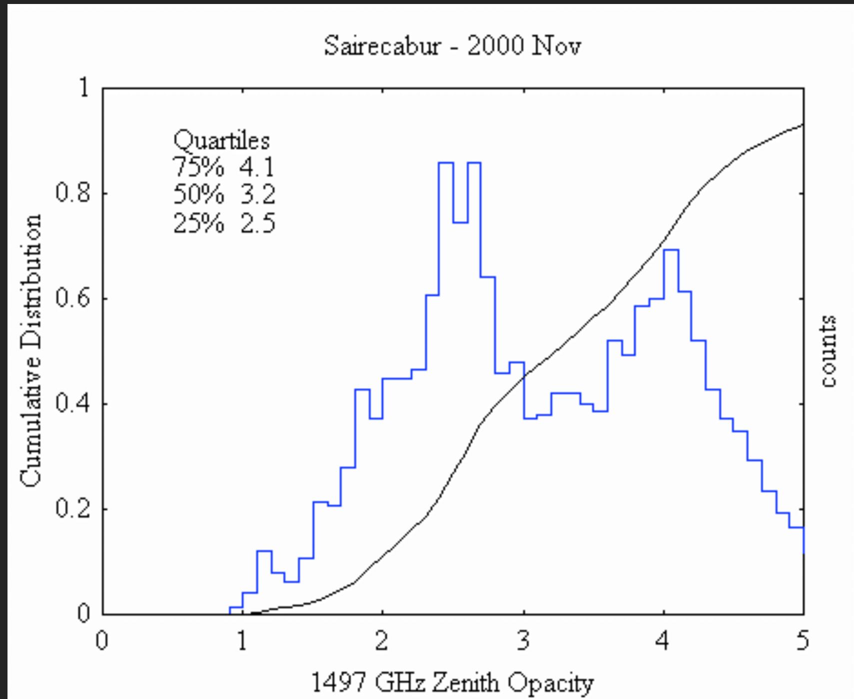
1999 Nov: 0.026 / 0.035 / 0.049	(FTS at Chajnantor)
2000 Nov: 0.027 / 0.037 / 0.054	(FTS at Sairecabur)

2000 Nov was slightly worse

(S. Paine)

Llano de Chajnantor vs. Sairecabur





200 μm opacity lower by about 0.6, down to endpoint

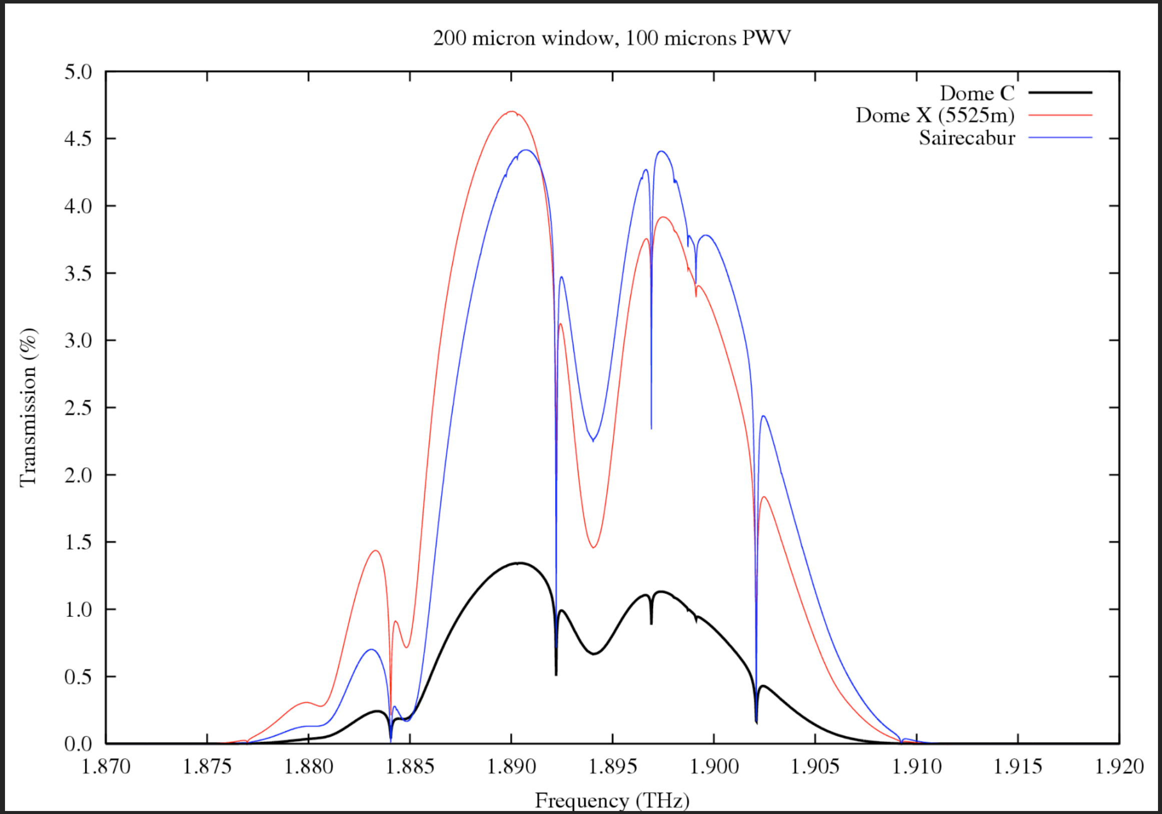
Consistent with H_2O profiles from radiosondes

Chilean sites under consideration for CCAT are superior to “Chajnantor” (ALMA)

(S. Paine)

Comment on Dome C

- Weak atmospheric windows at Dome C are adversely impacted by two effects
  - Low temperature biases H_2O partition function to strengthen THz absorption lines
  - Higher atmospheric pressure broadens very strong lines that bound THz windows
- Example: 158µm [C II] line



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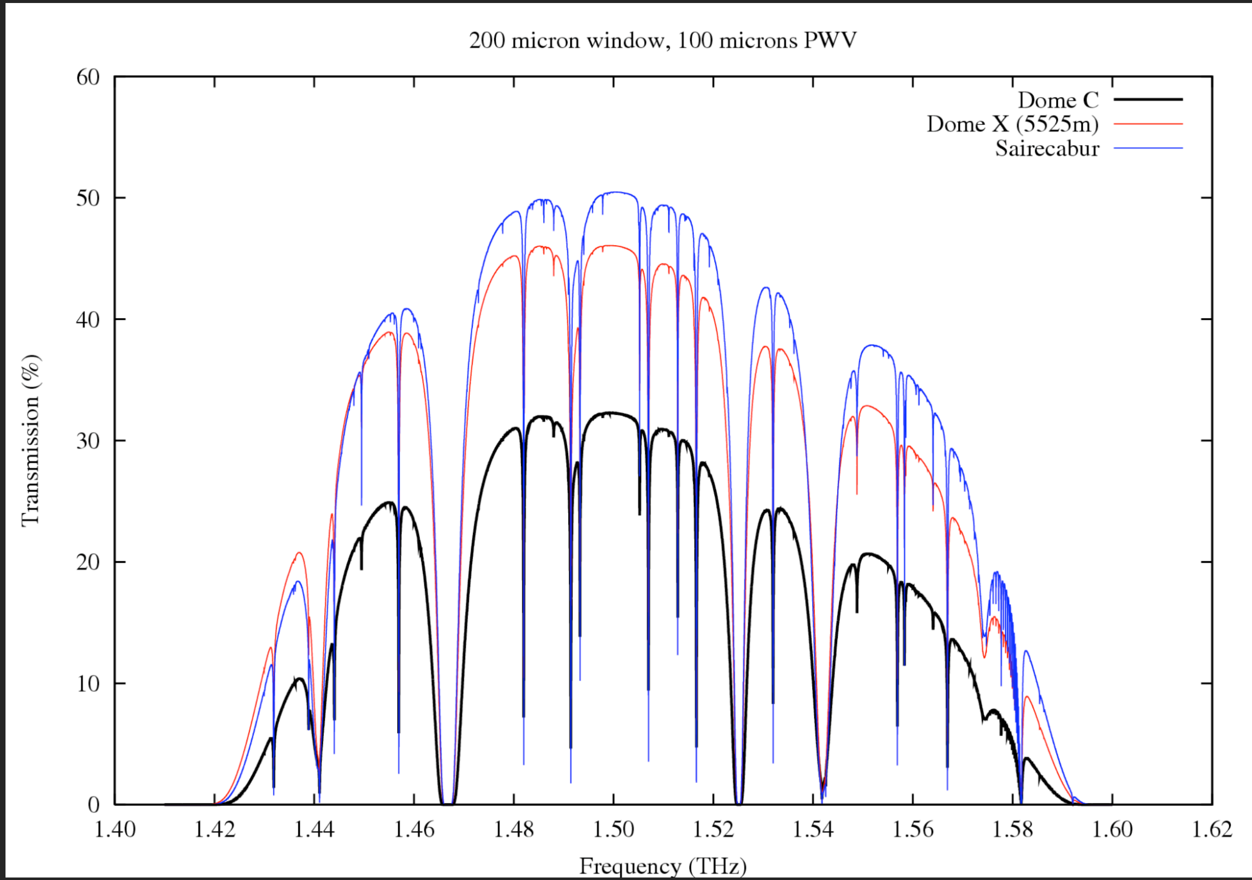
Comment on Dome C

- 200µm window



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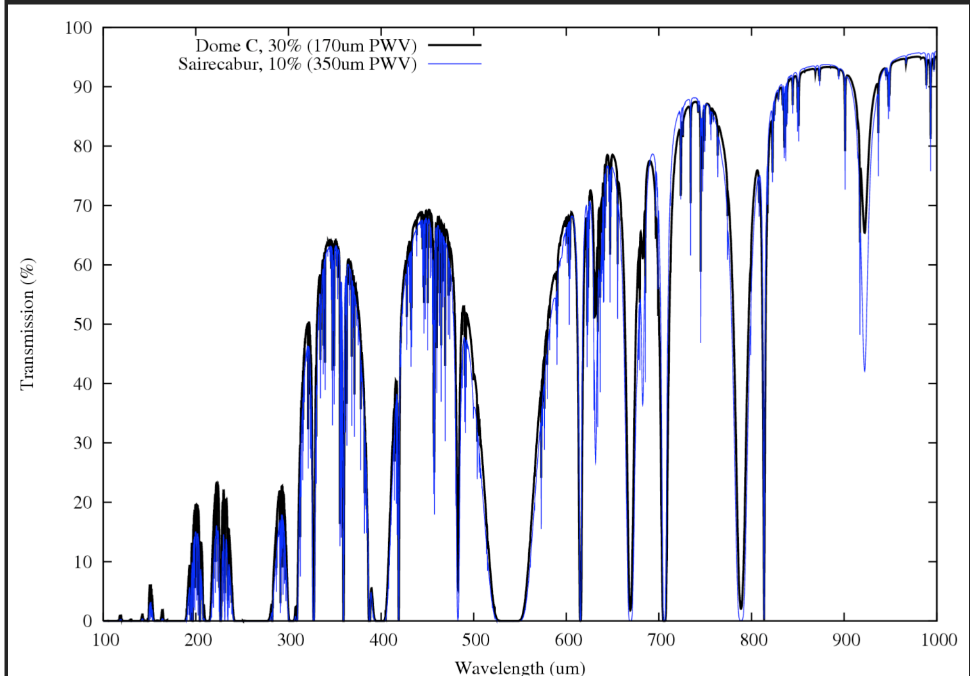
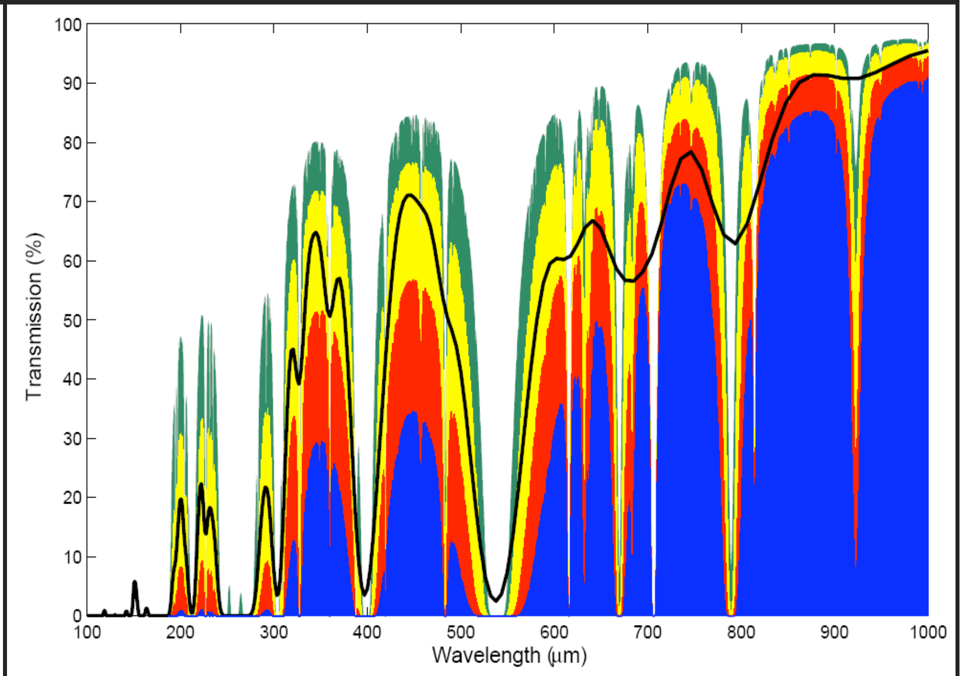
Comment on Dome C

Overall:

170µm at Dome C (30th percentile) =
350µm at 5500m in Chile (10-15th percentile)



am Dome C model



Lawrence (2004)

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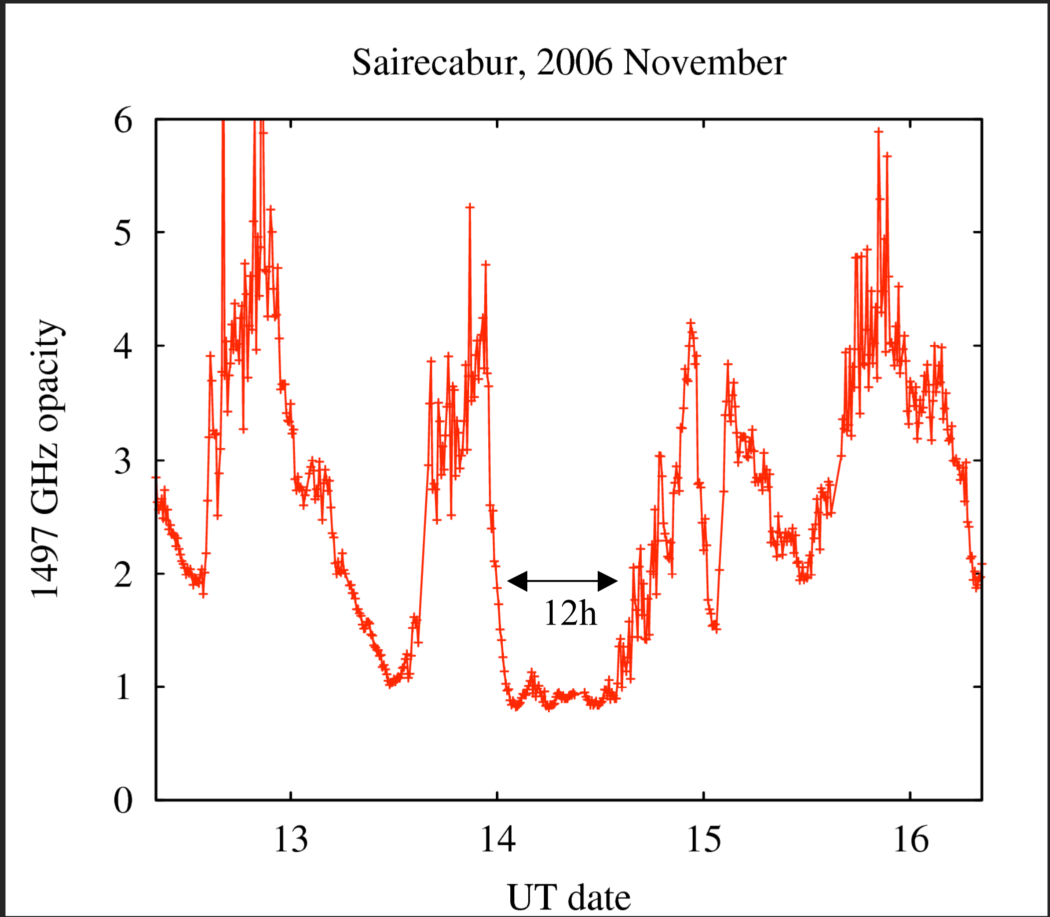
Typical Diurnal Variability (good weather)



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The Receiver Lab Telescope

R. Blundell, S. Paine, D. Marrone, E. Tong, D. C. Papa, T. Hunter, M. Smith, R. Plante, J. Battat, S. Leiker, T.K. Sridharan (CfA); J. Kawamura, J. Pearson, J. Stern, H. Yorke, I. Mehdi, J. Ward, S. Lord (JPL/Caltech), J. May, L. Bronfman, D. Luhr, C. Barrientos, W. Moerback (U. Chile); H. Gibson (RPG); B. Voronov, G. Goltsman (MSPU); M. Diaz (BU); D. Loudkov (Delft), D.Meledin (Chalmers), F. Bensch (Bonn); C. Groppi (NRAO); S. Radford (Caltech); A. Otarola, R. Rivera (ESO)

RLT specifications

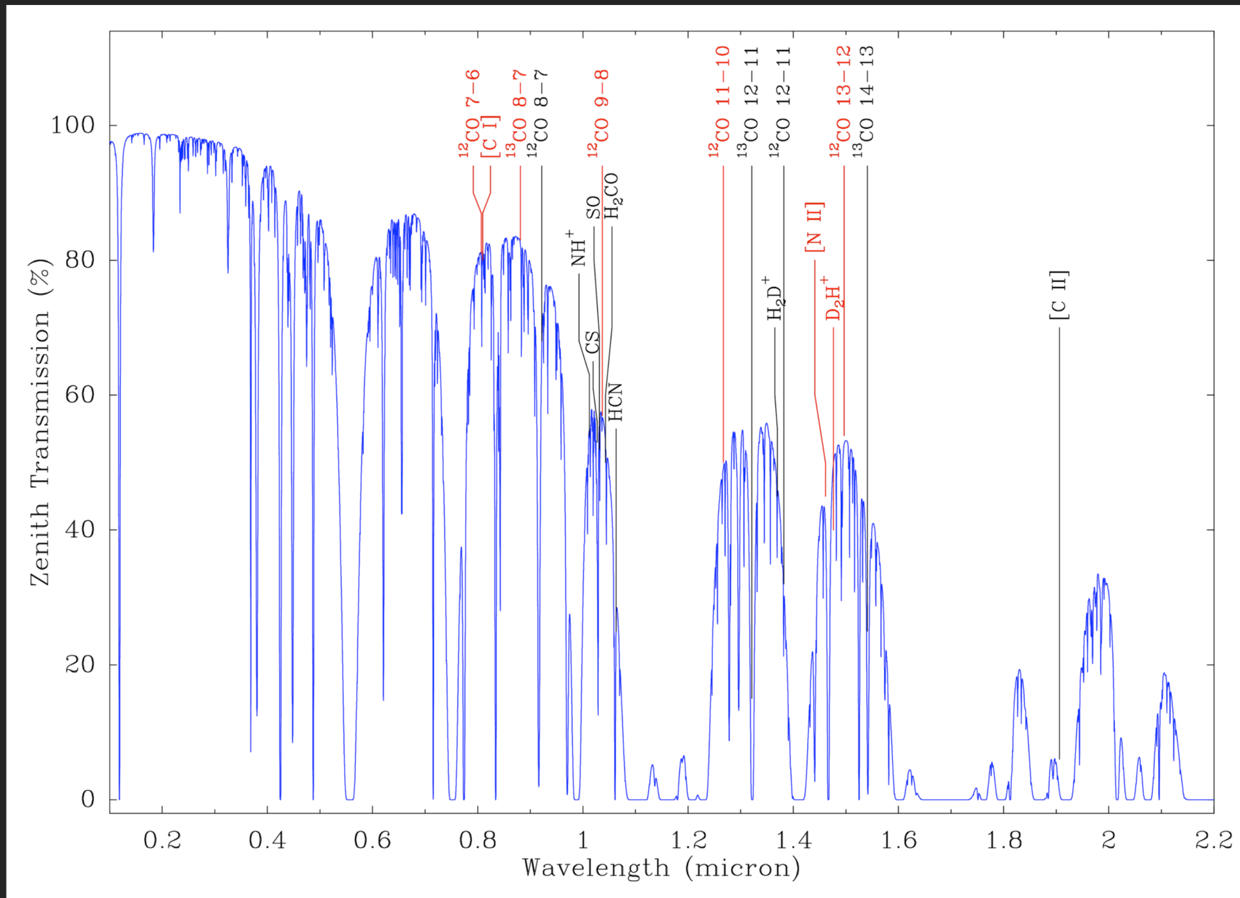
- 800 mm primary (1' at 1.5 THz)
  - Same as IRAIT (= Fr: "*Furieux*" / It: "*Irait*" ?) telescope
- HEB mixer receivers
  - 850 GHz, T_{rx} ~ 900 K
  - 1.03 THz
  - 1.3 THz
  - 1.5 THz, T_{rx} ~ 1600 K
- Autocorrelating spectrometer, 1 GHz BW

- Milestones

Deployed	Oct 2002
First spectrum above 1 THz	Nov 2002
First 1.3 THz observations	May 2004
First 1.5 THz observations	Dec 2004

A Few Science Results

- Spectral lines of interest can be divided into two groups
  - Easy: CO, [C I]
  - Hard: nearly everything else



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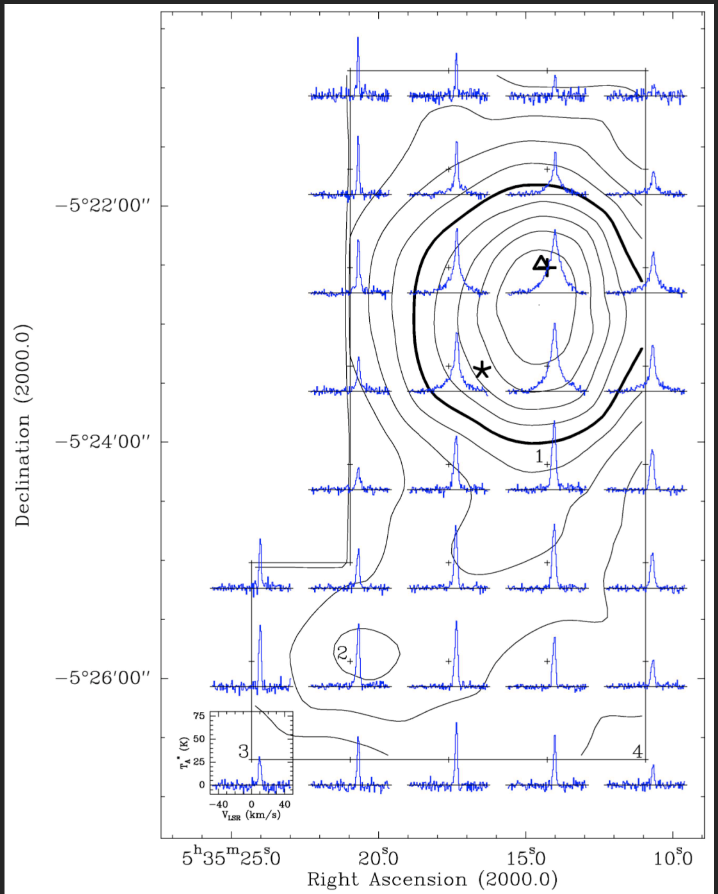
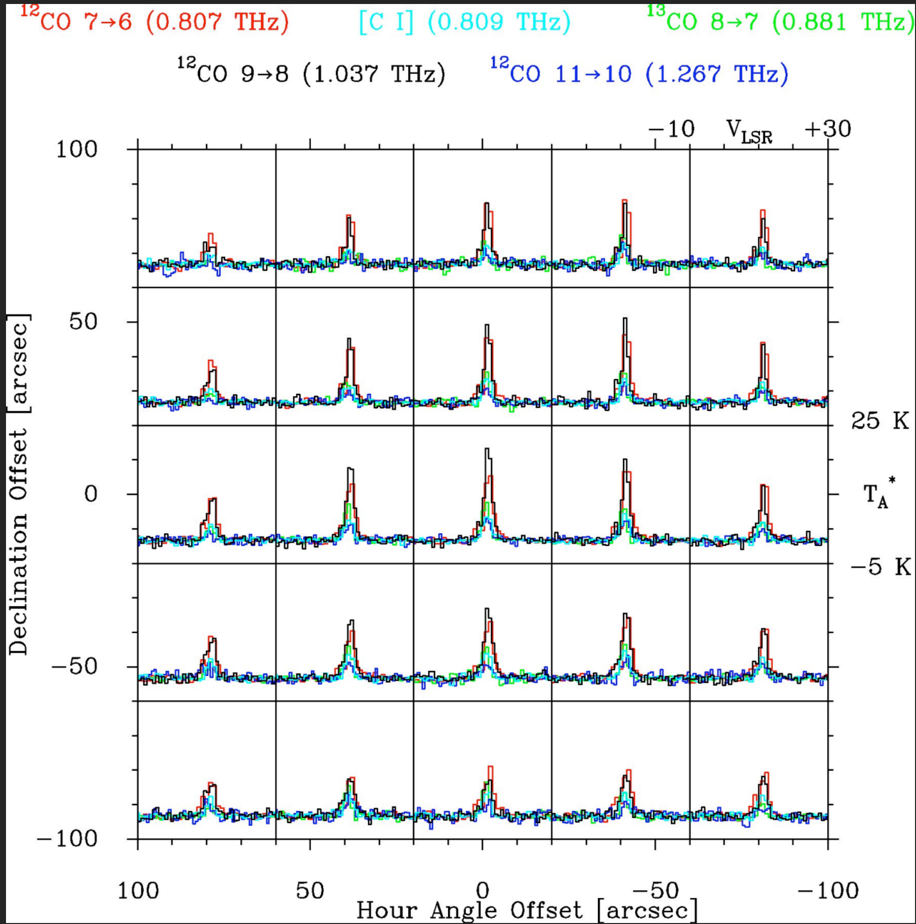
A Few Science Results

Easy: CO 7-6 (0.81), 9-8 (1.04), 11-10 (1.27), 13-12 (1.5 THz)

^{13}CO 8-7 (0.89), [C I] (0.81 THz)



First results: OMC-1 CO 9-8
(Marrone et al. 2004)



Subregion of 70+ point, 5 transition map of NGC 2024 (Orion B)

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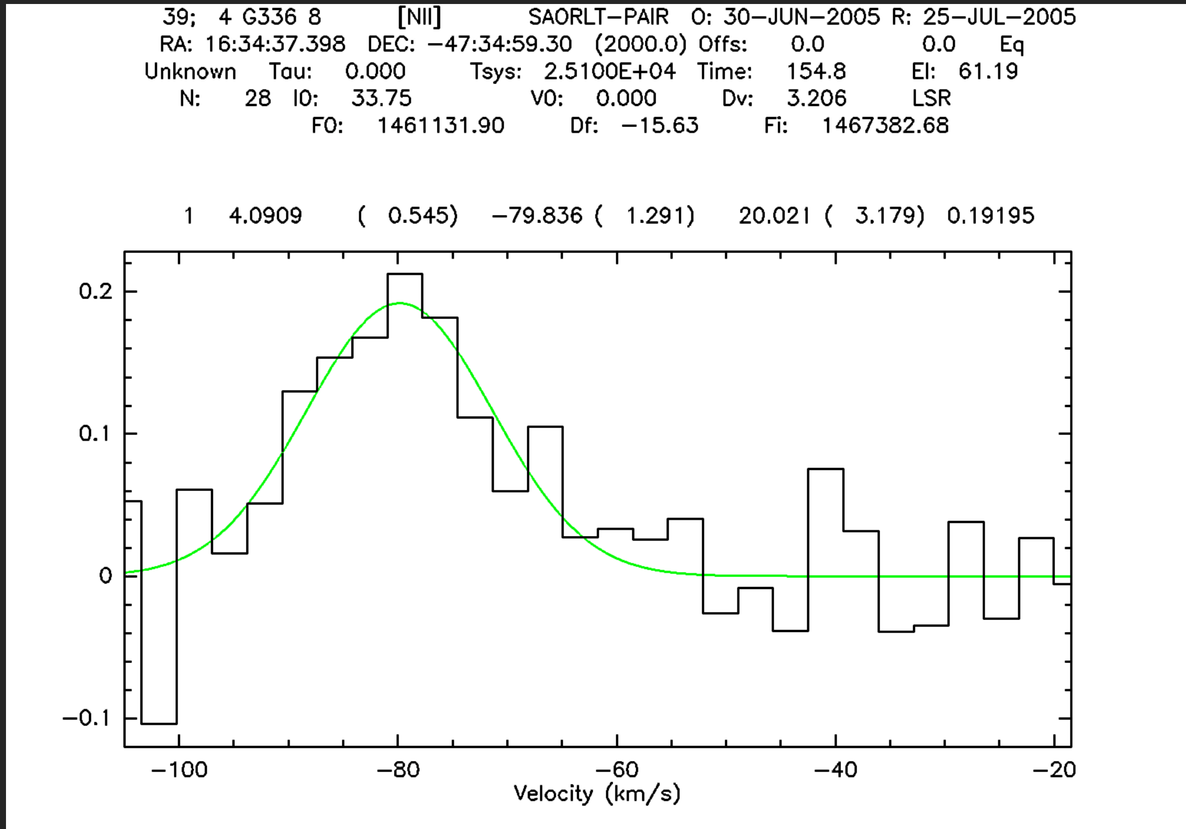
A Few Science Results

Hard: [N II] 1.46 THz

For localized emission sources (high *n*), $F_{205\mu m} / F_{122\mu m} = 1/10$

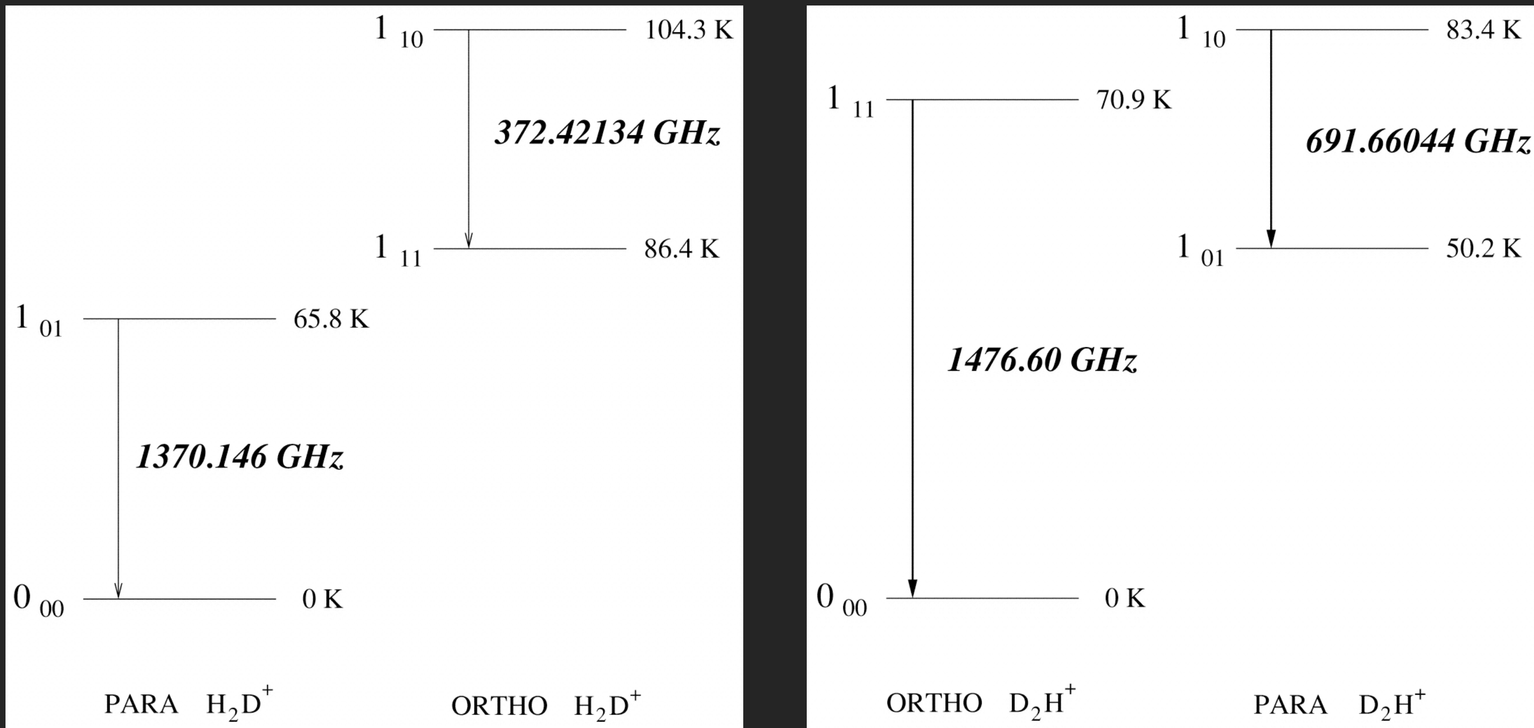


G336.84+0.05 Jun-Jul 2005
(Kawamura et al., submitted)

A Few Science Results

Hard: H_2D^+/ D_2H^+

- Ground-state transition desired as probe of cold regions
  - Superior to higher-energy submilllimeter transmission
- Expected to be enhanced at high A_V through fractionation

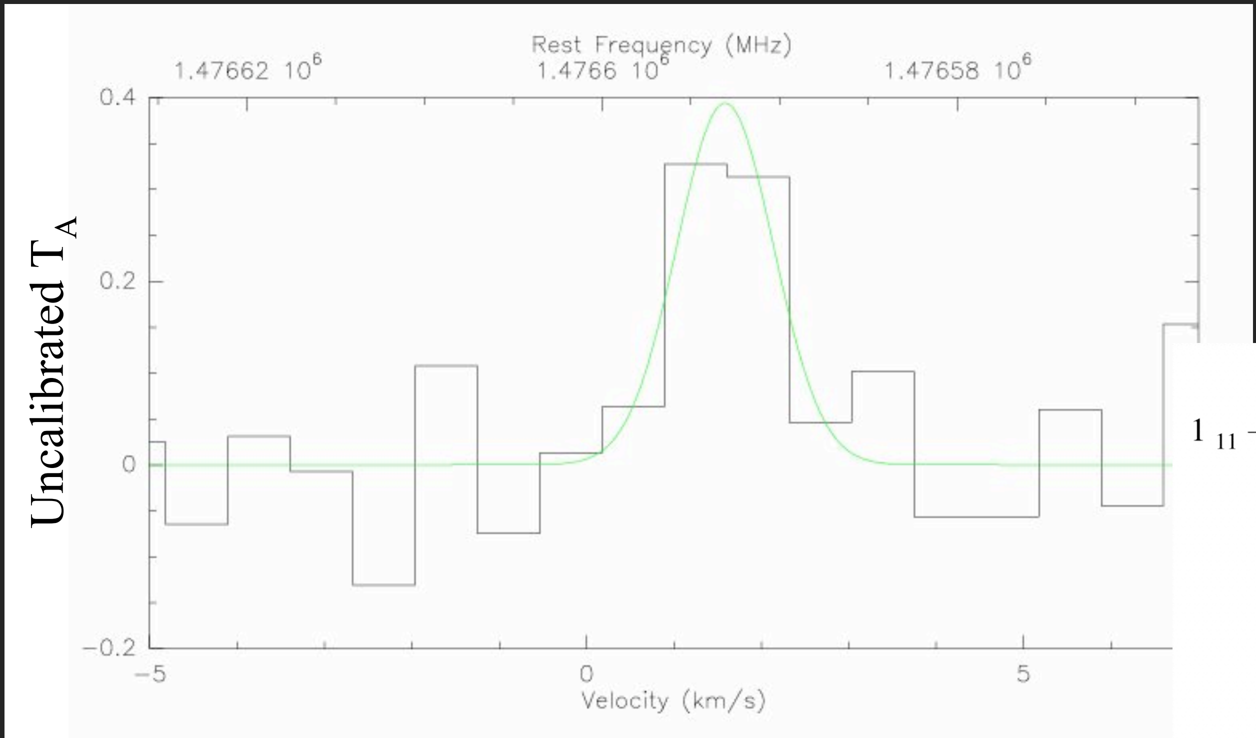


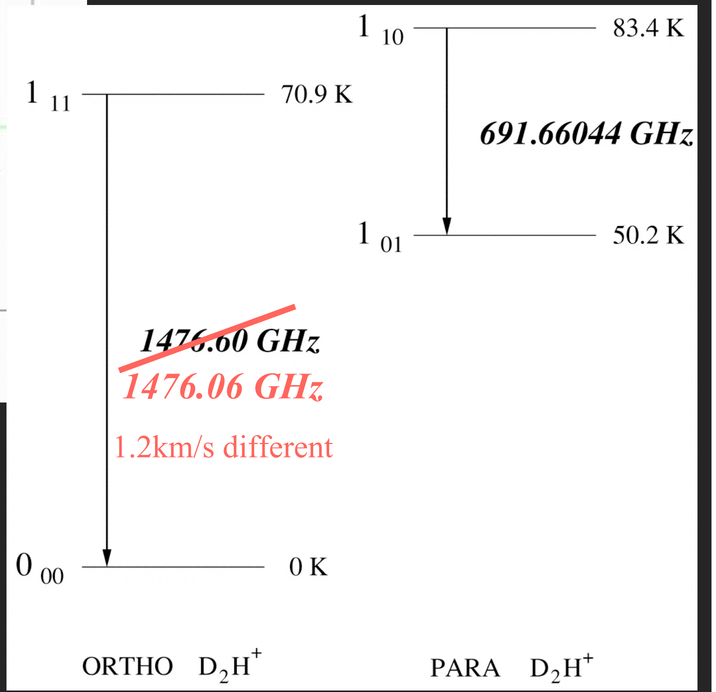
Energy-level diagrams (Vastel et al., 2004)

A Few Science Results

Hard: H_2D^+/ D_2H^+

692 GHz line detected in IRAS 16293-2422 with CSO





RLT Future

- Continuation of [N II] and H_2D^+/ D_2H^+
  – New, larger BW correlator for broad [N II]
- New SIS/HEB receiver
  – Access 850 GHz and 1.5 THz windows with single receiver
  – Allows good and bad weather time to be used easily (good idea!)

Observational Lessons

- Sky noise not a limiting factor for RLT, needn't be for IRAIT
  - Short integrations help
  - Even state of the art THz detectors have $T_{rx} >> T_{sky}$

- Calibration difficult with low atmospheric transmission
  - Variability not yet known at Dome C
    - System temperature changes are large when $\tau \sim 1$
    - $\Delta T_{sys} \sim e^{\tau} \Delta \tau$
  - Co-located atmospheric monitor very useful
    - FTS
    - High-frequency tipping radiometer