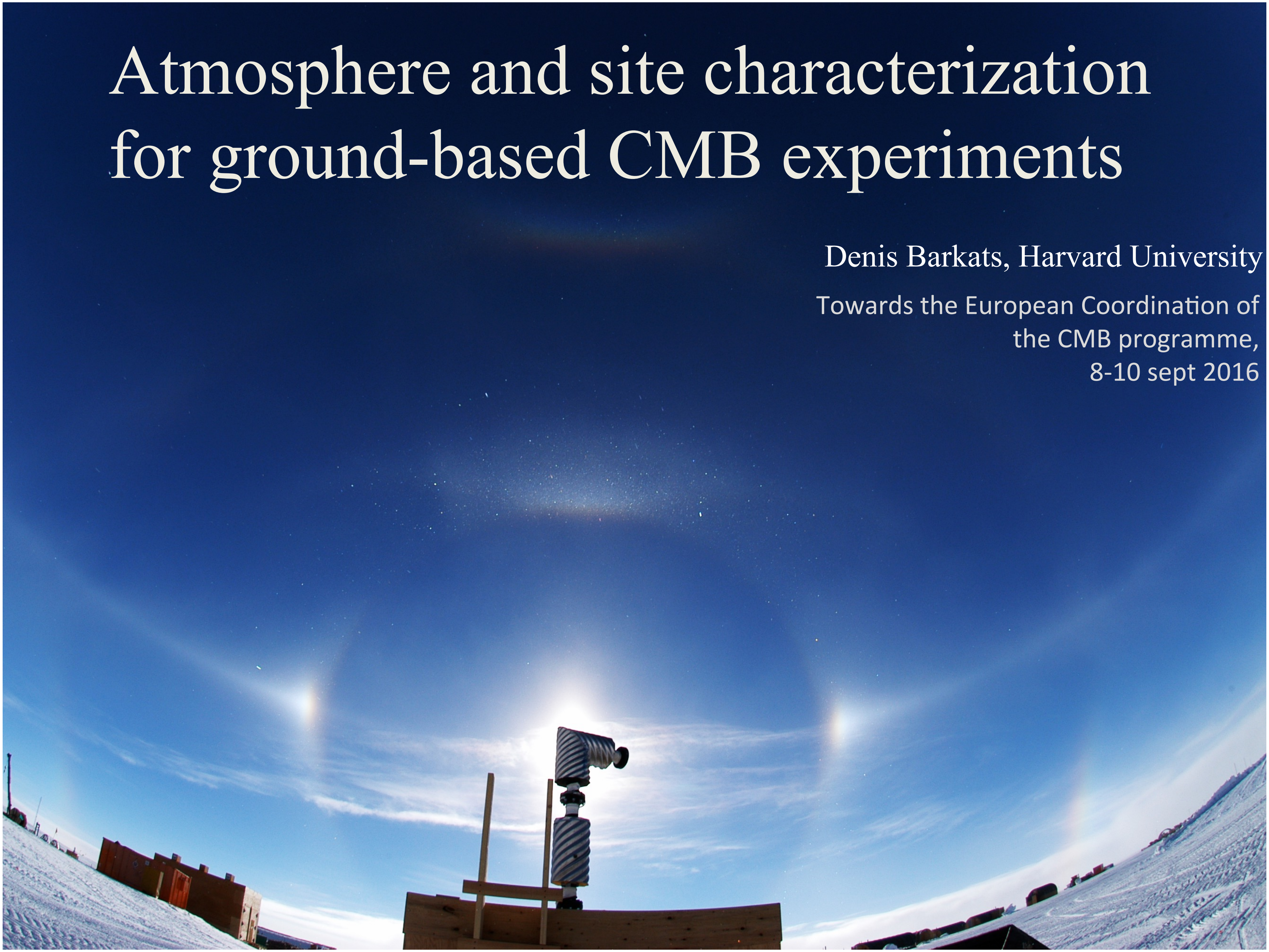
Atmosphere and site characterization for ground-based CMB experiments

Denis Barkats, Harvard University

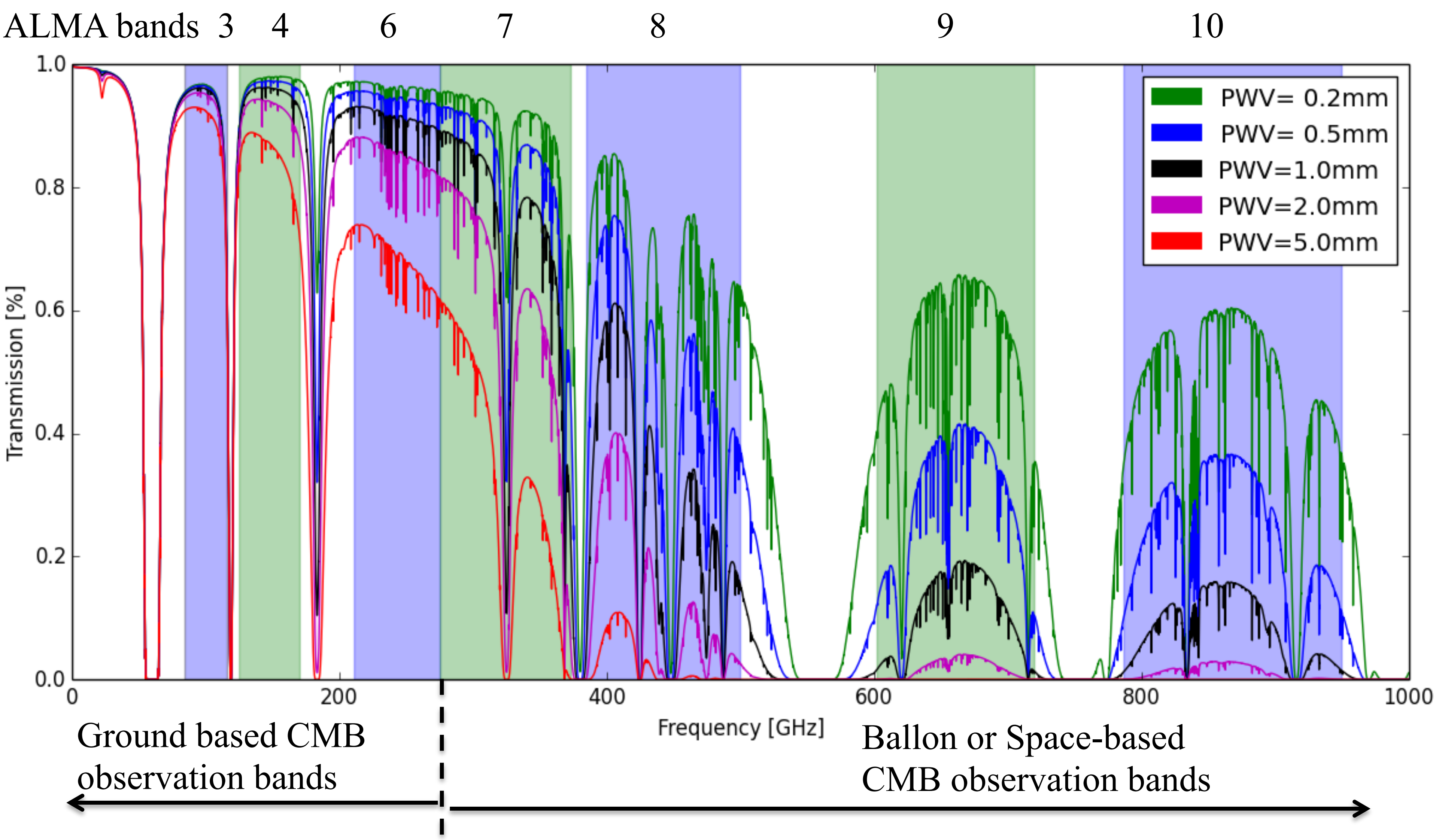
Towards the European Coordination of the CMB programme, 8-10 sept 2016



Mm/submm atmosphere basics

- In the mm and submm, Earth's atmosphere only partially transparent.
- Water vapor is the primary cause of atmospheric opacity.
- So we can only observe in discrete spectral windows bracketed by strong water vapor transition lines.
- Within these windows, the water vapor absorb incoming light and emit thermally contributing to the background noise.

Mm/submm atmosphere basics



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- Within these windows, the water vapor absorb incoming light and emit thermally contributing to the background noise.
- Best sites on the ground are the ones with exceptionally dry air: top of mountains or very cold conditions.
- Water vapor is poorly mixed gas. Main source of atmospheric brightness fluctuation (for total power telescopes) and phase noise / decoherence (for interferometers)
- Ideal sites for CMB telescopes: Dry AND stable

Site exploration/testing for future CMB instruments

GOAL: Come up with a metric which encompass all the criteria which affect the bottom line sensitivity of your experiment.

Map noise at angular scales of interest ~ One detector sensitivity x Number of functional detectors x Duration of observation x real-world efficiency

- Sky transmission (PWV, opacity..)
- Short time-scale stability (PWV fluctuations, wind, turbulence, diurnal cycles)
- Weather patterns (wind, snow, rain, cloud cover, snow accumulation)
- Accessibility (scientists, equipment, cryogenics)
- Connectivity (and reliability)
- Power (and reliabiliy)
- Cost
- Safety
- Sky coverage
- …

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Atmospheric qualities

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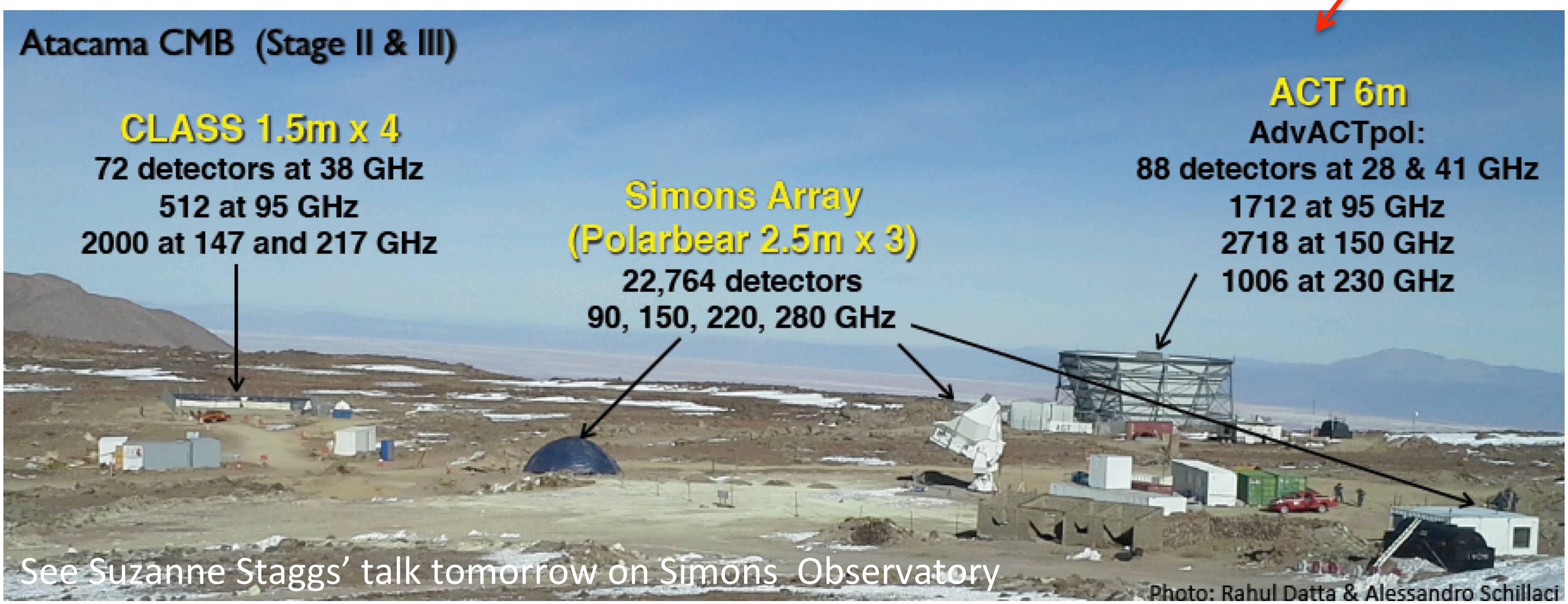
Operational challenges

Ex: Early days CMB observations in Chile

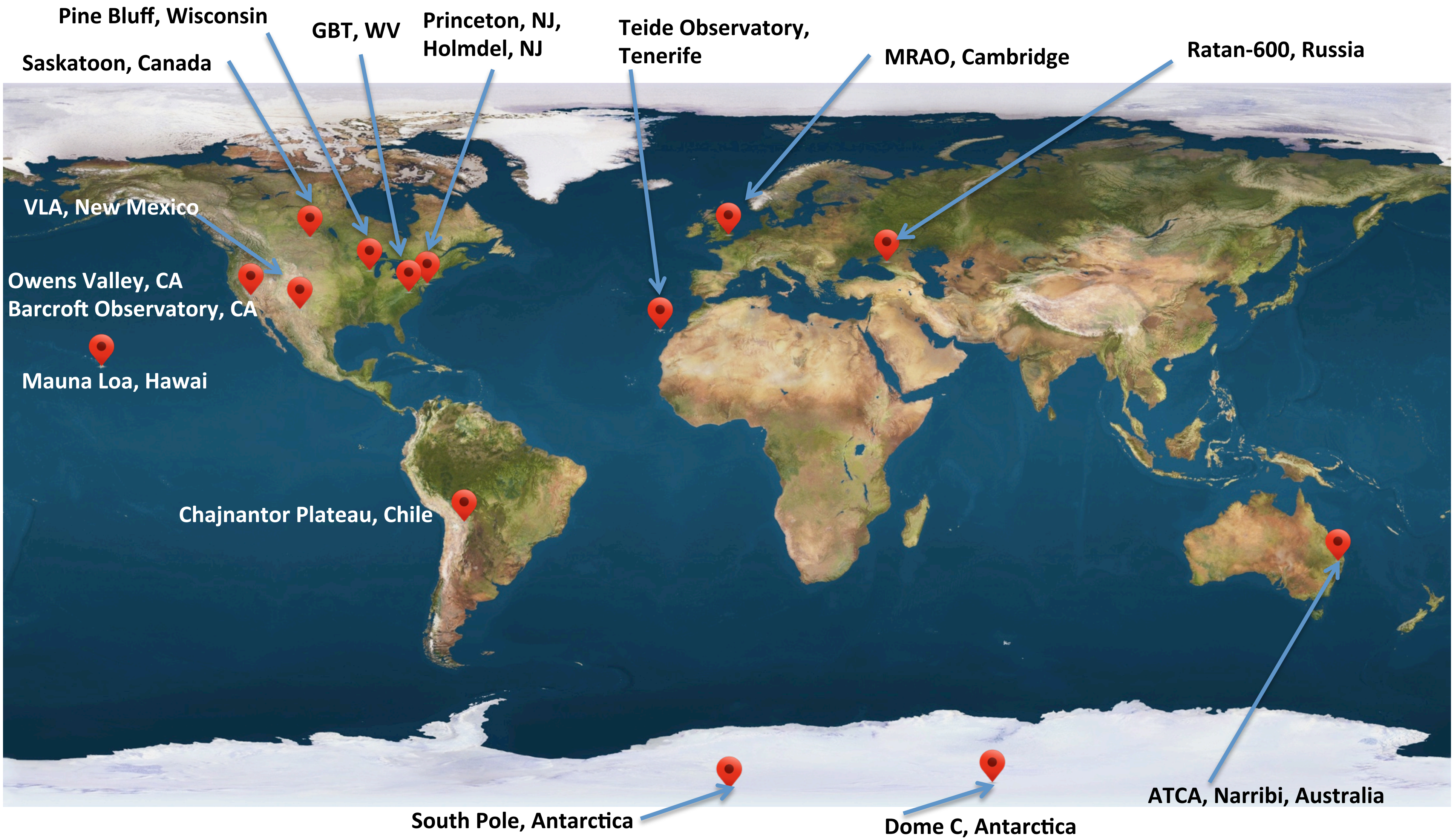
CMB site below Cerro Toco in 2001, MINT deployment

Same location in 2016



CMB telescopes sites: 1960-2016

from CMB expt list on http://lambda.gsfc.nasa.gov/



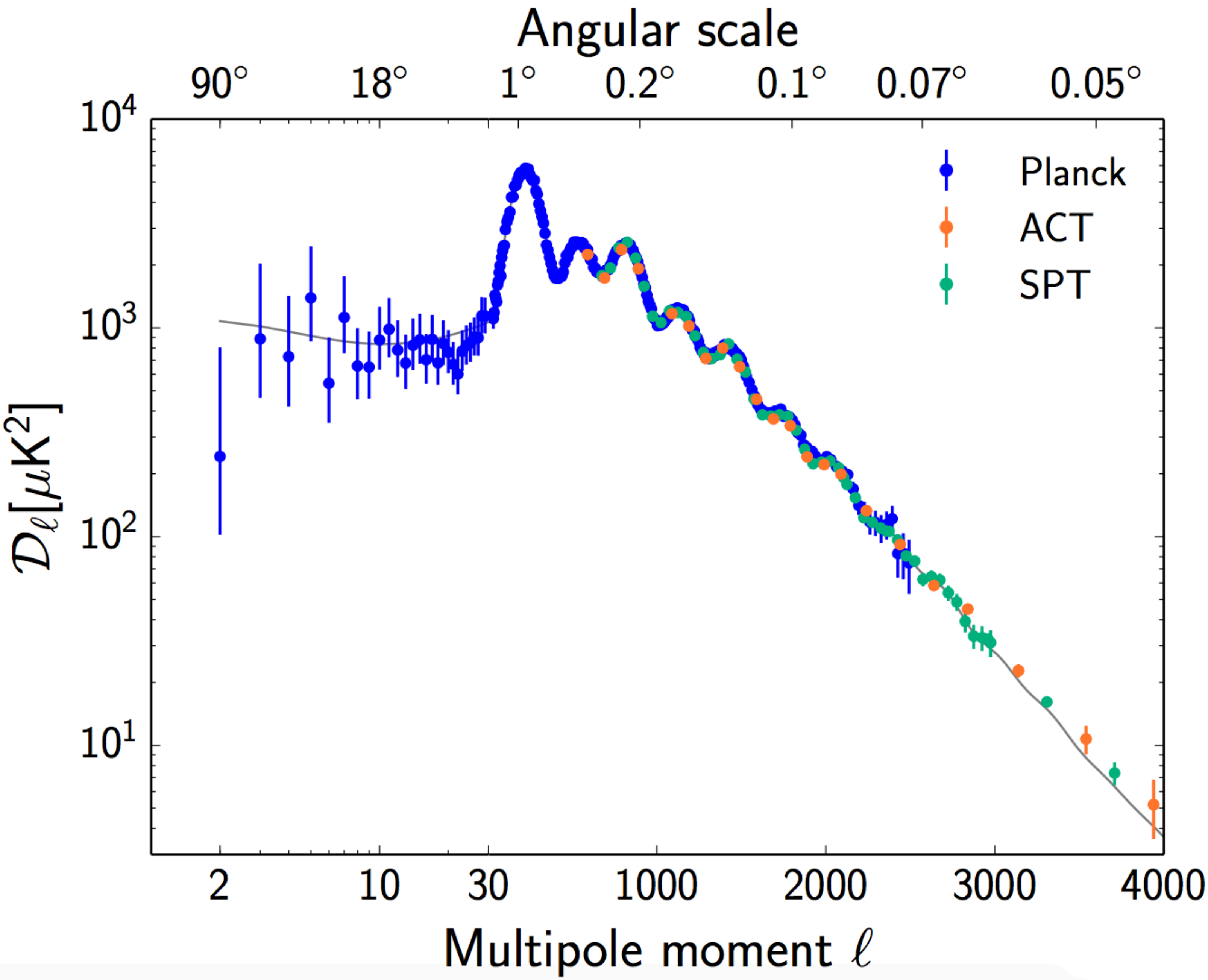
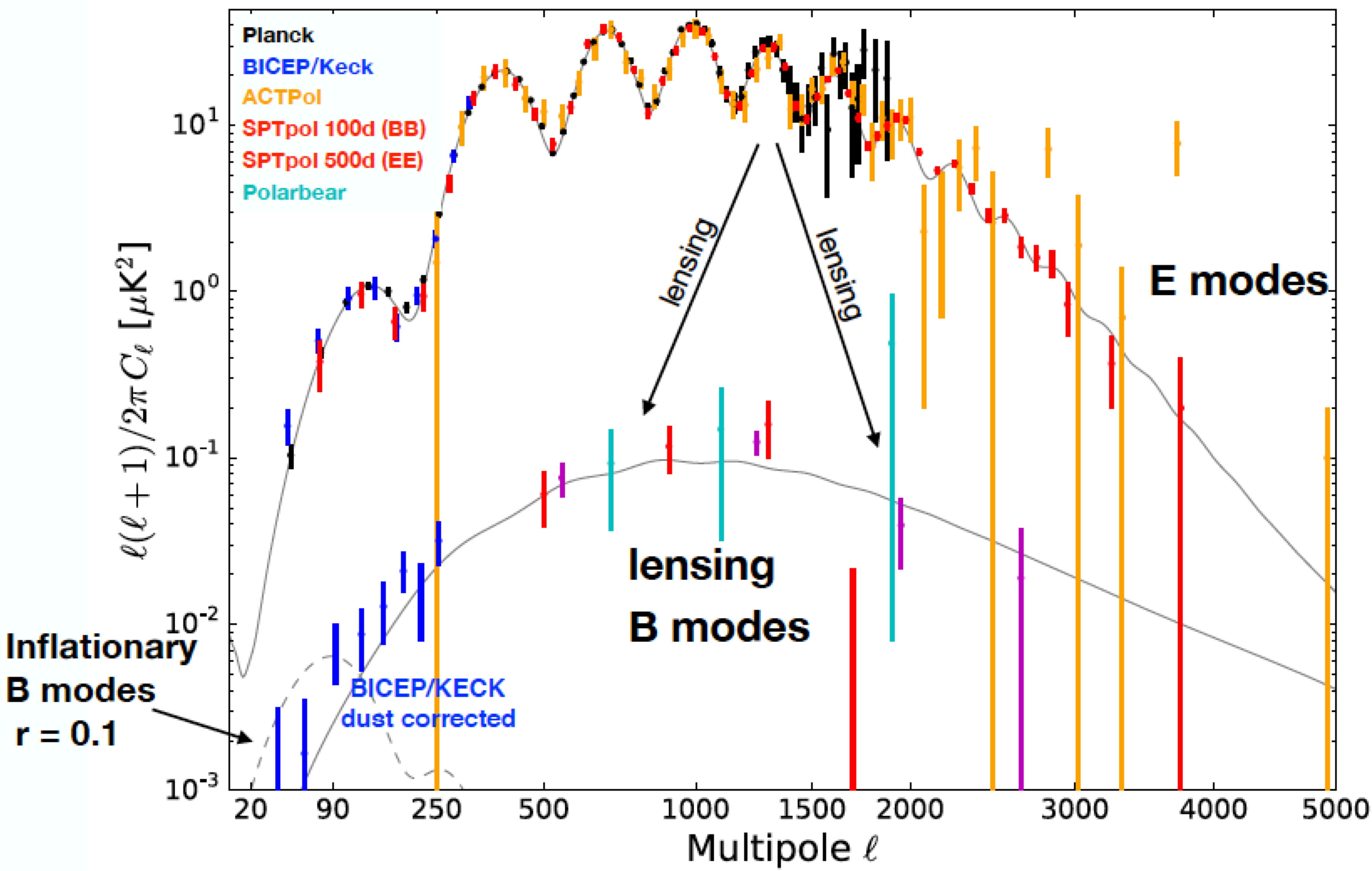


Figure from Planck 2015 results XI

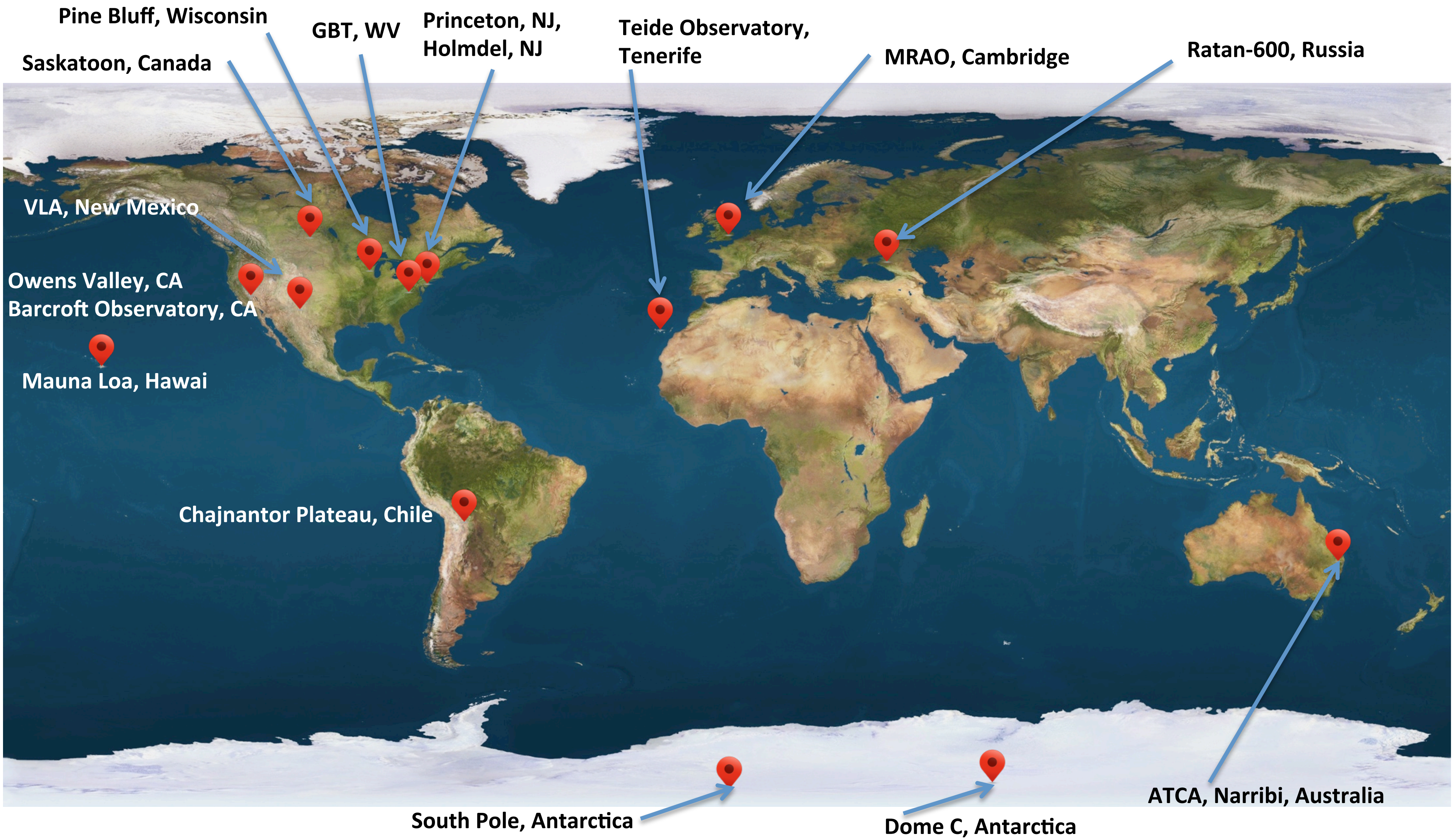
Current status CMB polarization



Rapid progress. All within last 3 years.

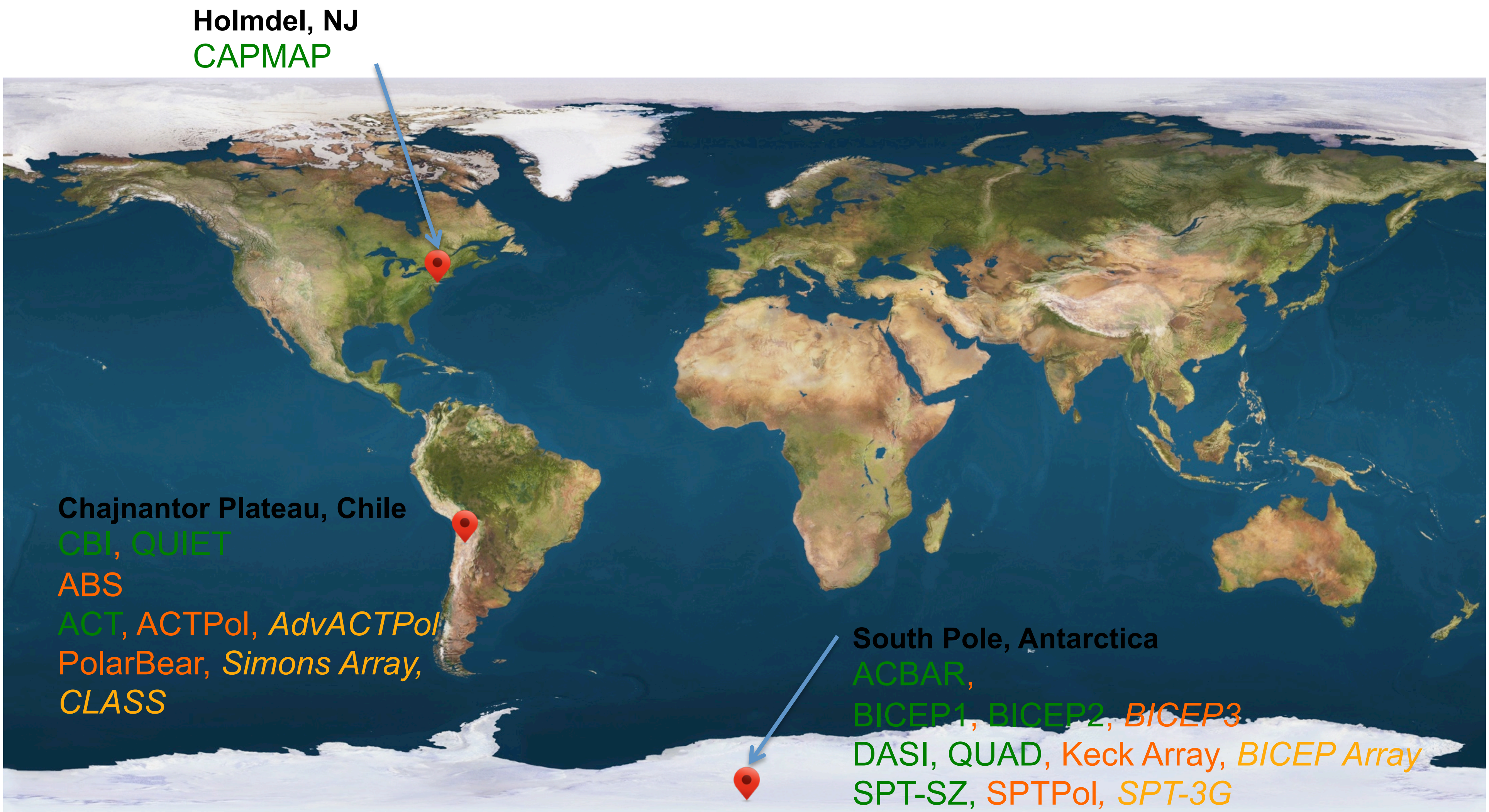
CMB telescopes sites: 1960-2016

from CMB expt list on http://lambda.gsfc.nasa.gov/



CMB telescope sites: Last decade

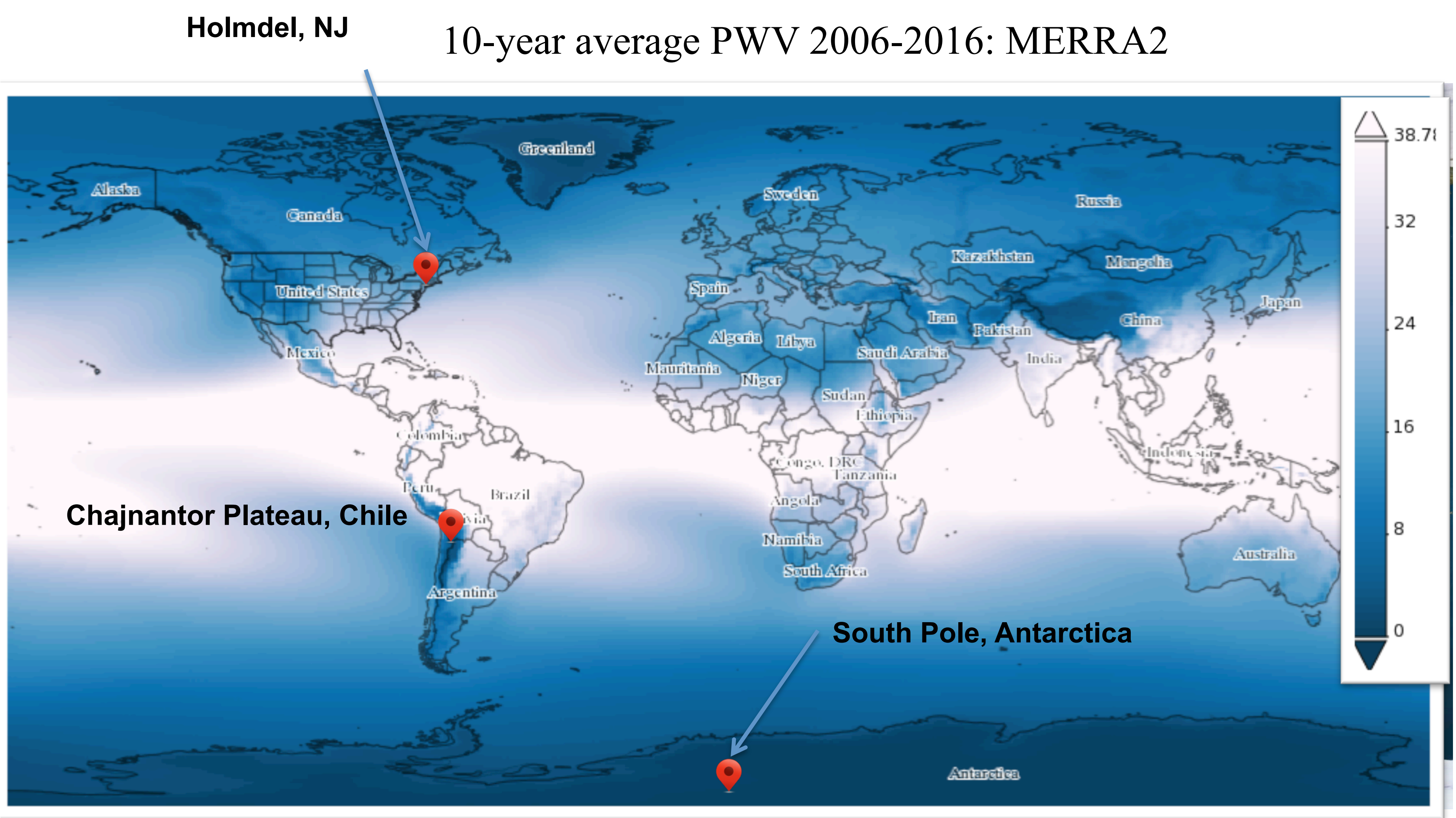
high precision/accuracy CMB temperature and polarization measurements



Also: *QUBIC, QUIJOTE, GroundBird*

Past, **Current**, *Future*

CMB sites and atmospheric transmission



MERRA reference: M. M. Rienecker, et al. 2011 “MERRA, NASA's Modern-Era Retrospective Analysis for Research and Applications.” J. Climate 24:3624.

What is a re-analysis?

- A re-analysis estimates the past history of the atmosphere using a numerical model to assimilate historic measurements (like weather forecast)

- Measurements are "truth", but sparse in space or time.
  - Satellites: full spatial coverage at low resolution; typical twice daily visit on sun synchronous orbit results in biased sampling.
  - Radiosondes: excellent vertical resolution; most sites launch twice daily
  - Surface weather stations: fixed point; high time resolution

- A general circulation model (GCM) has high spatial and temporal resolution.

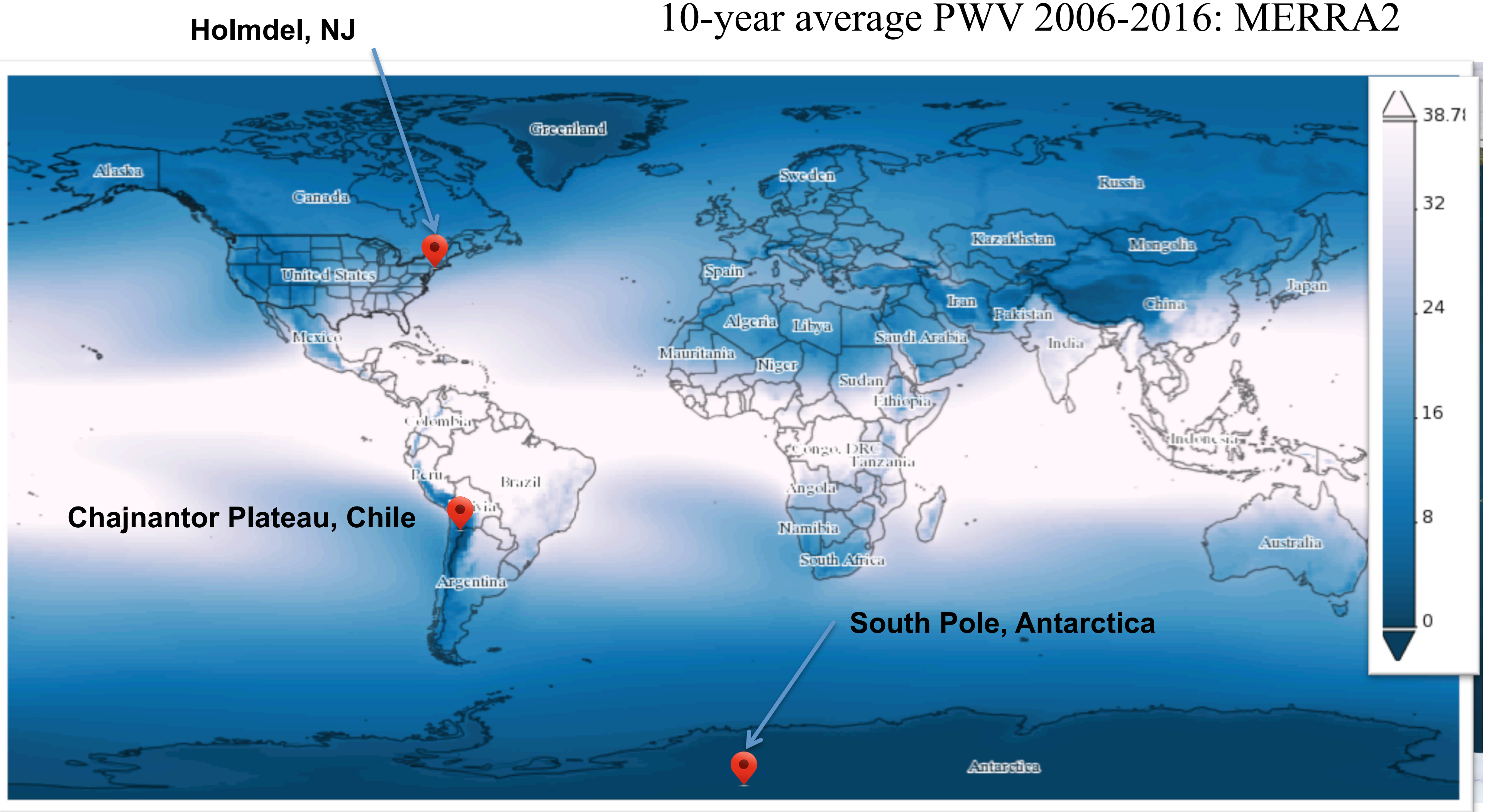
- In a reanalysis, measurements are used to add extra forcing terms to the GCM to make the state of the model tend towards the measured state.

The NASA MERRA-2 reanalysis (successor to MERRA)

- Atmosphere grid has ~50 km horizontal resolution × 72 vertical layers
- 1980 – present; 3-hour time step for many meteorological fields such as temperature, water vapor, ozone, wind, vorticity...
- Data access provided by the NASA Goddard Earth Sciences Data and Information Services Center:
  http://disc.sci.gsfc.nasa.gov/daac-bin/DataHoldings.pl
- Giovanni online visualization tools developed and maintained by the NASA GES DISC (used to produce the previous two slides):
  http://disc.sci.gsfc.nasa.gov/giovanni
- MERRA general reference:
  M. M. Rienecker, et al. 2011 "MERRA, NASA's Modern-Era Retrospective Analysis for Research and Applications." J. Climate 24:3624.
- MERRA2 + atmospheric radiative transfer modeling (am, atm) —> very powerful site survey and characterization tool.

CMB sites and atmospheric transmission

10-year average PWV 2006-2016: MERRA2



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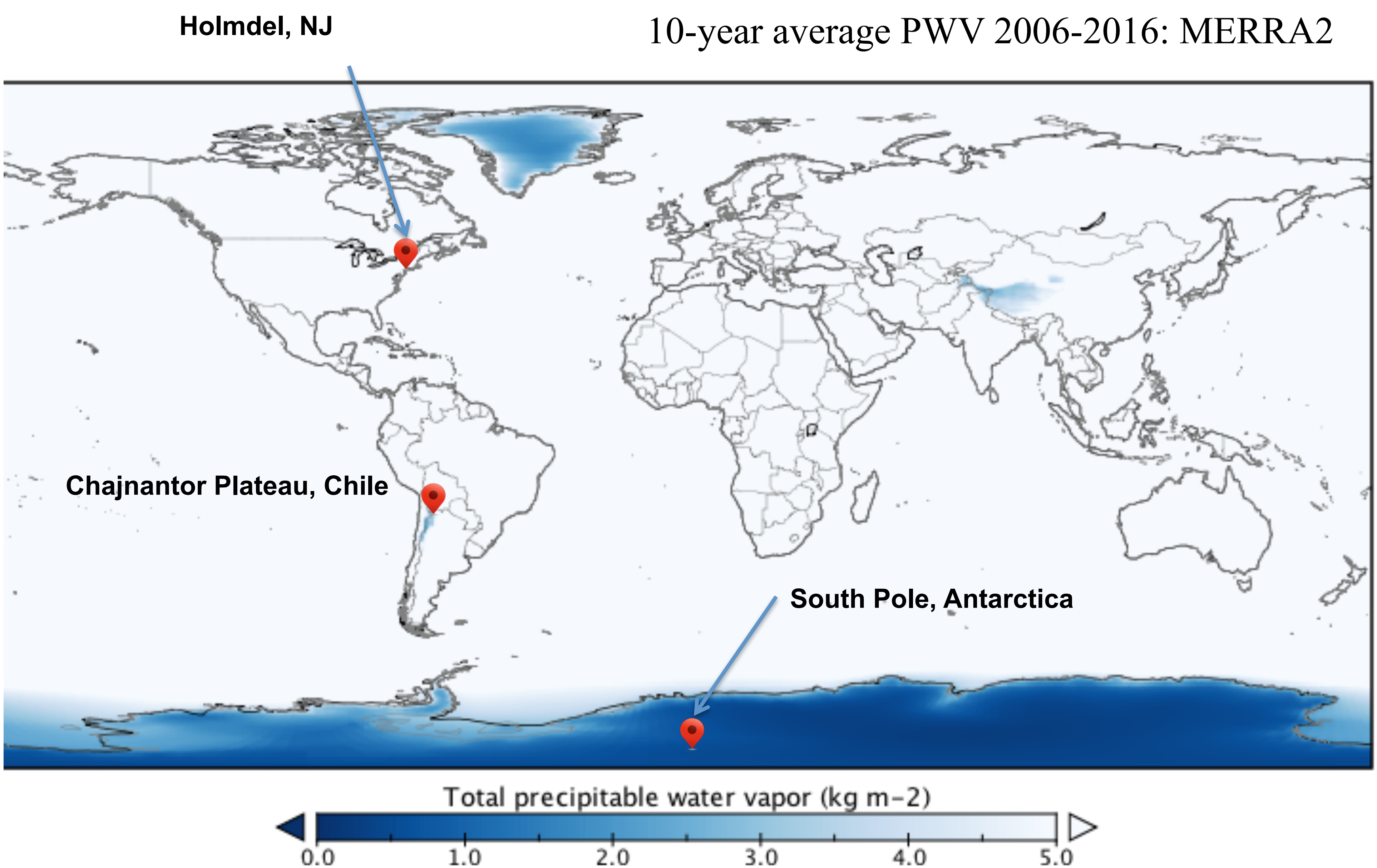
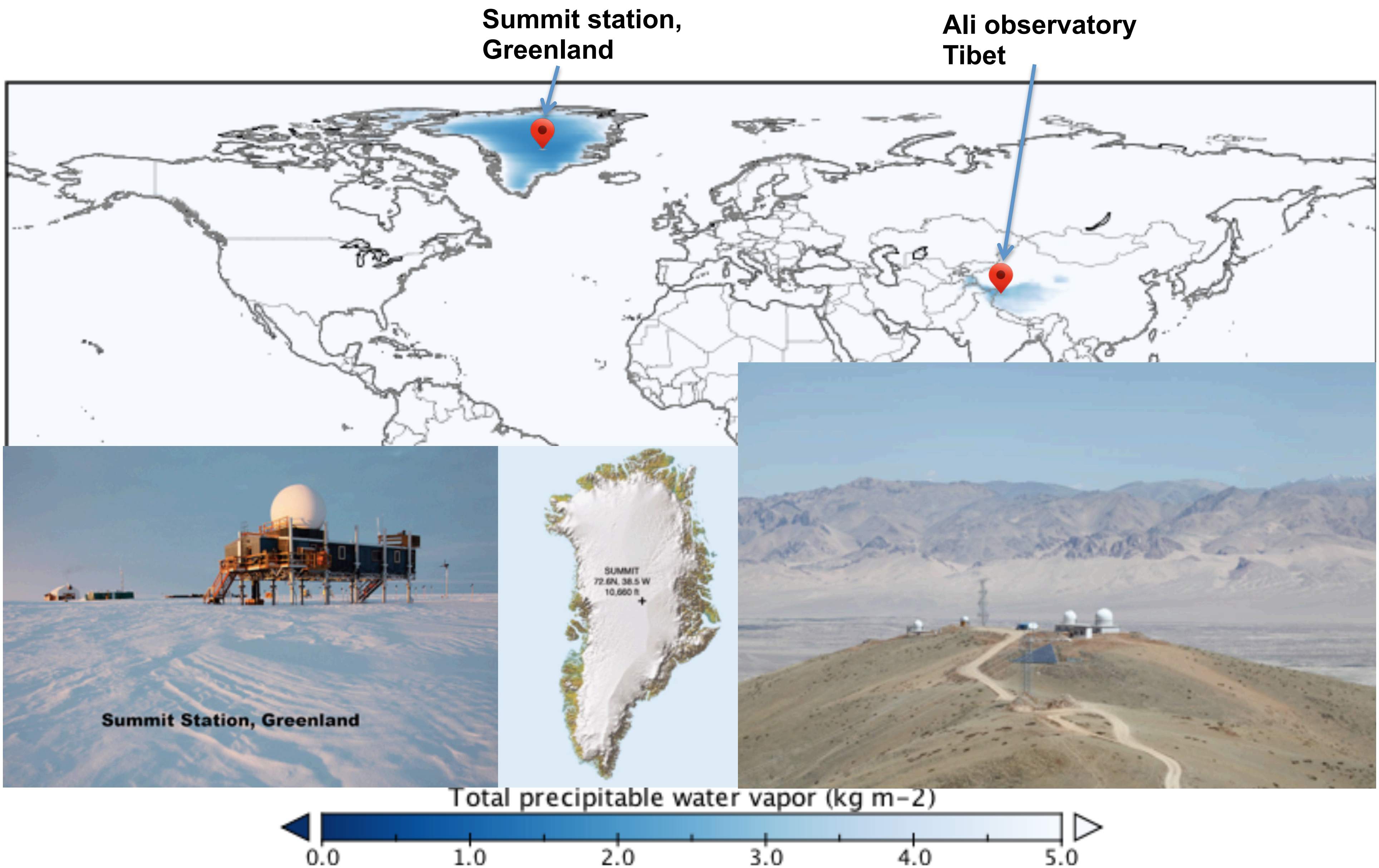
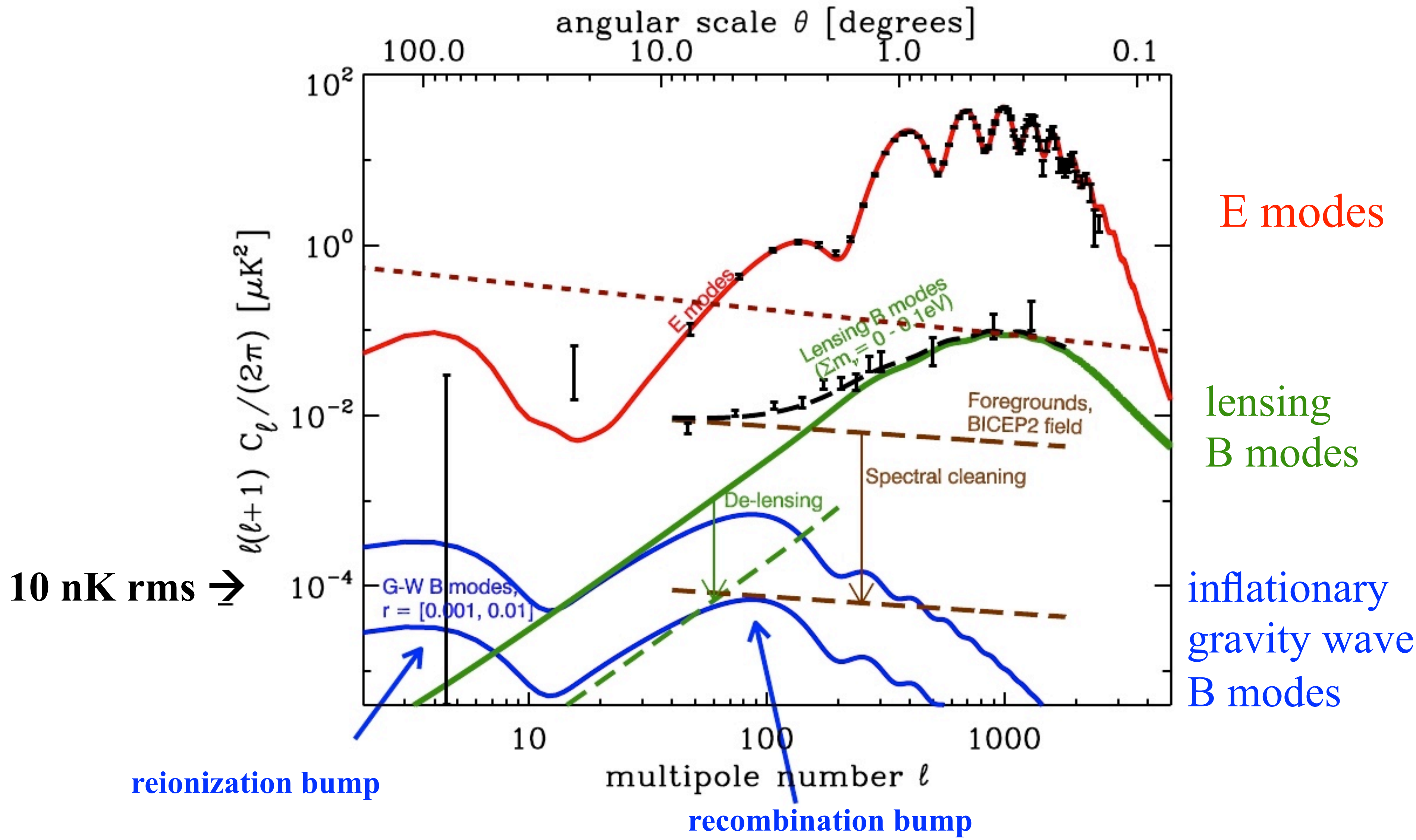
CMB sites and atmospheric transmission



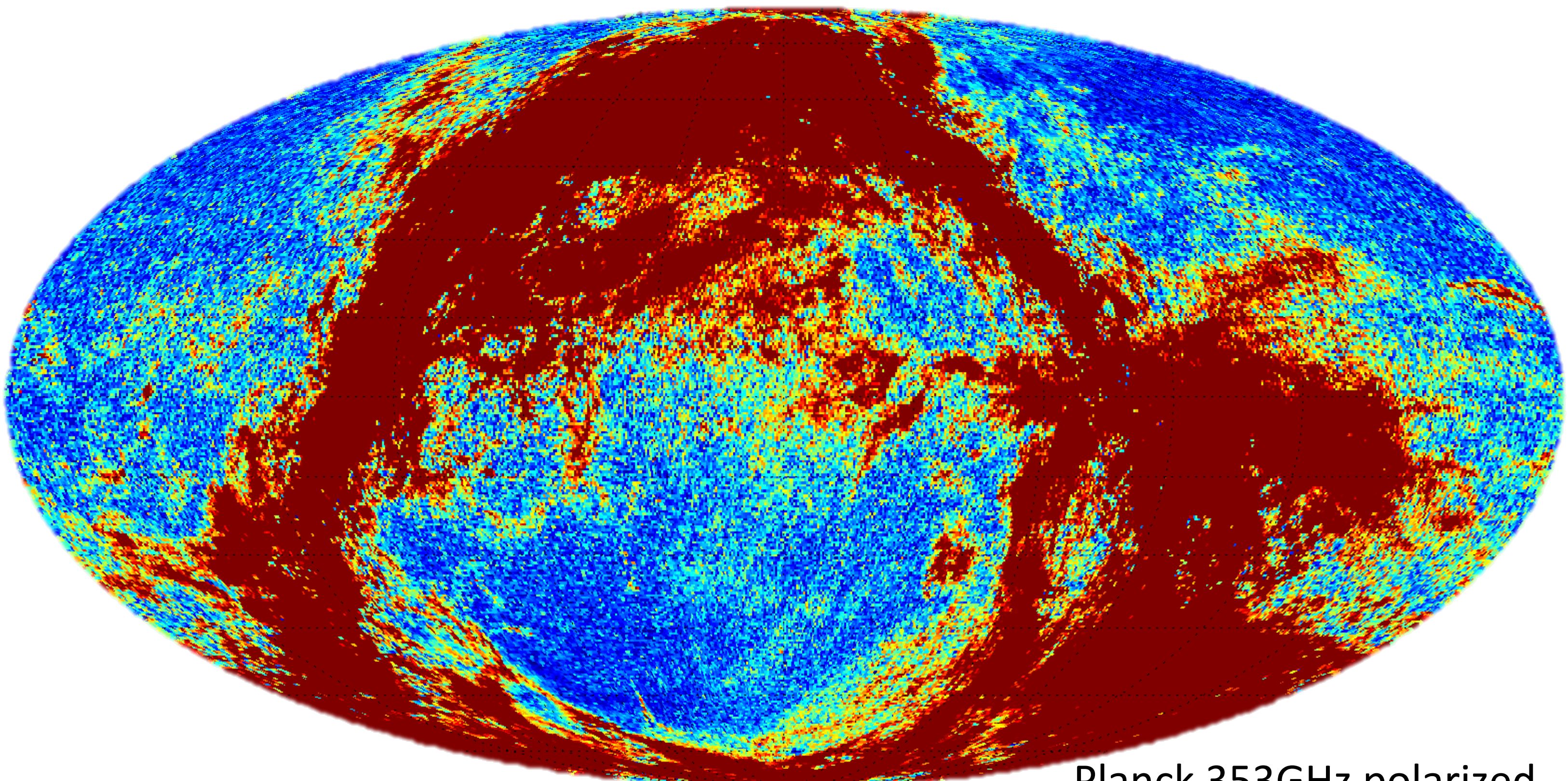
CMB sites and atmospheric transmission



Polarization status and future challenges



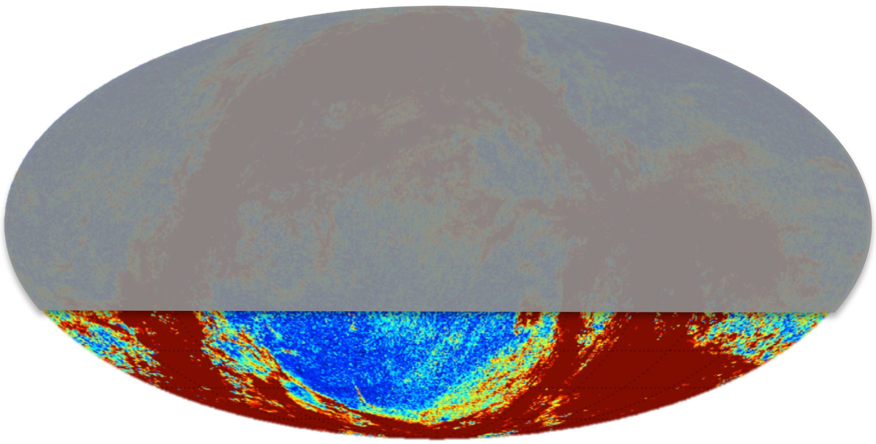
Sky Availability from :



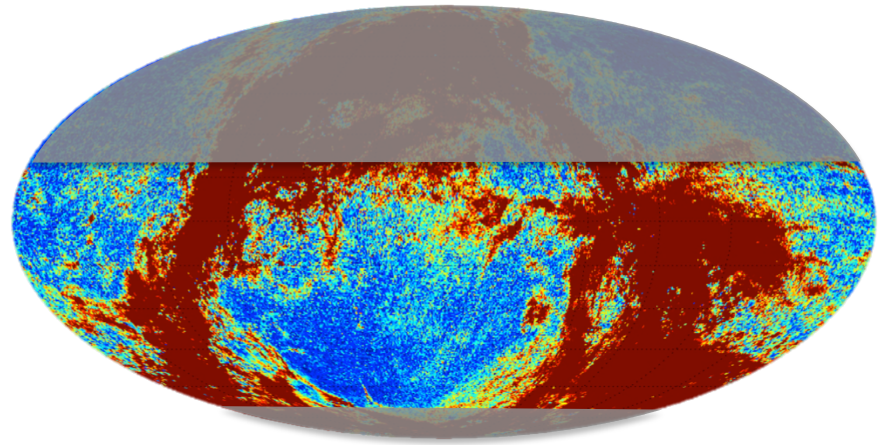
Planck 353GHz polarized intensity map in celestial coordinates
(color scale 0-100uK)

Sky Availability from Chile, South Pole, Greenland & Tibet

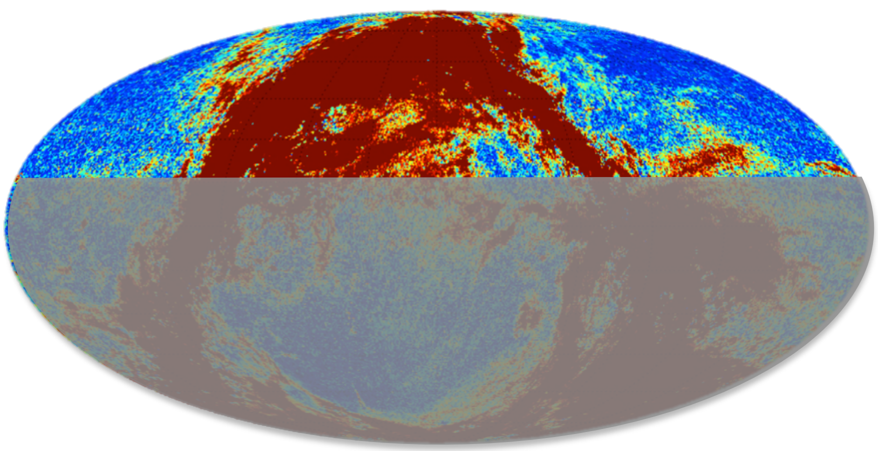
For zenith angle < 50



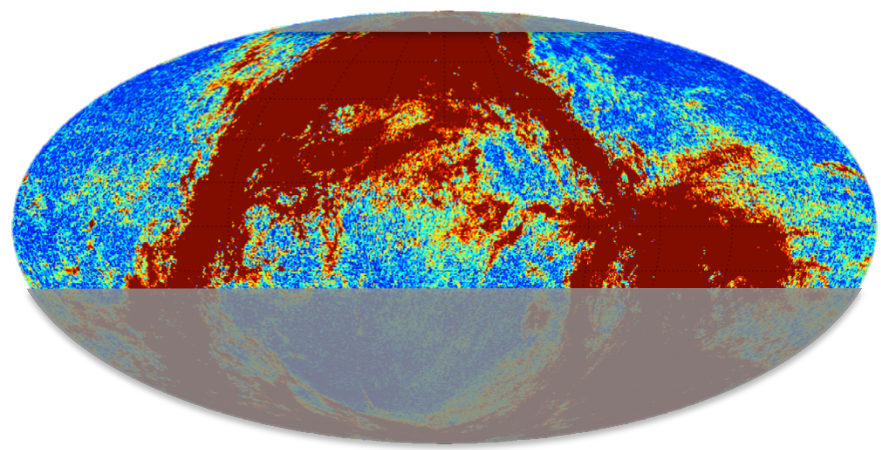
South Pole



Chile



Summit, Greenland



Ali, Tibet

Tools for site characterization

- Radiosondes
  - Full vertical profile of T, RH, and wind
  - Moderate RH accuracy thus PWV (~20%)
  - biased sampling

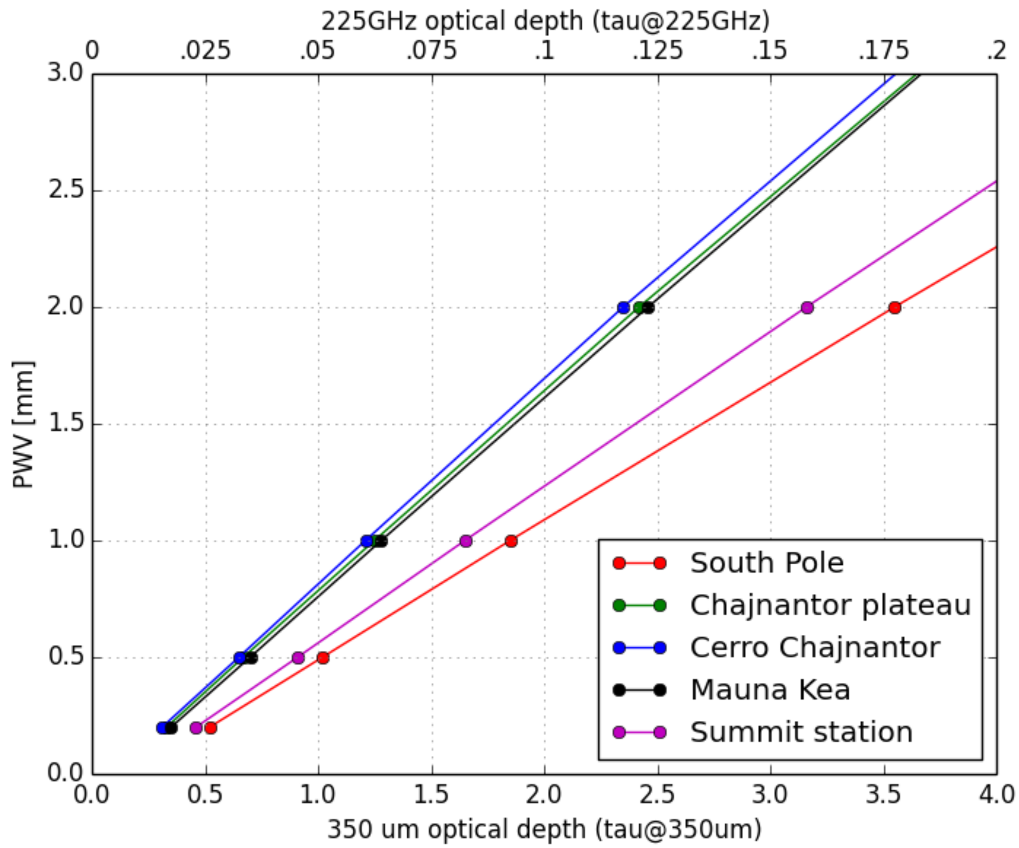
- Dedicated radiometers
  - Direct measurement of zenith opacity through skydip (tipping measurements)
  - Unbiased and dense sampling
  - can yield accurate PWV using radiative transfer model (atm, am..)
  - Many 225GHz, 350um (857GHz) radiometers @ South Pole, Chajnantor plateau, Cerro Chajnantor, Mauna Kea, Summit station (Greenland)
  - None sample the temporal AND spatial structure of the atmosphere.

- Global Climatological data (modern re-analyses)

- Radiative Transfer Modeling (am, atm, moliere..)

Mm and Sub-mm site comparison:

Reminder: In comparing atmospheric qualities at multiple site, use of PWV only can be misleading, as the opacity of the atmosphere depends on also on the pressure and temperature of air column.



am models (Paine, 2016) https://www.cfa.harvard.edu/sma/memos/152.pdf

Site characterization w/ dedicated radiometers

- Mauna Kea, Hawai, 350um tipper: 1997-2016,
- Chajnantor plateau, Chile, 225GHz/350um tipper: 1997-2016
- Cerro Chajnantor, Chile, 350um tipper: 2006-2013

- South Pole station, Antarctica 225GHz/350um tipper, 1998-2016
- Summit station, Greenland, 225GHz tipper, 2011-2014
- Dome C station, Antarctica, 200um/350um tipper, 2007-2010

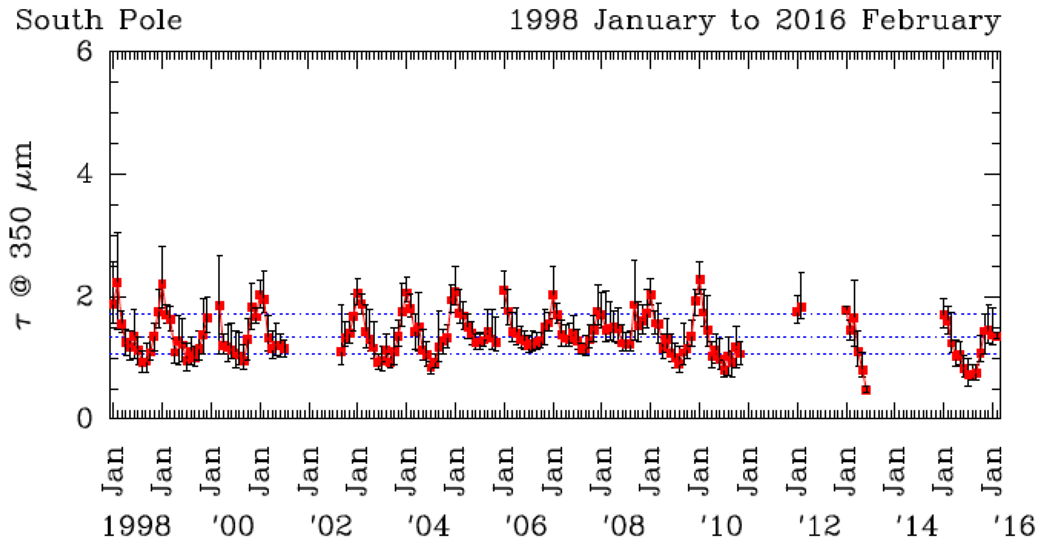
- Ali Observatory, Tibet, MERRA2 10yr model.

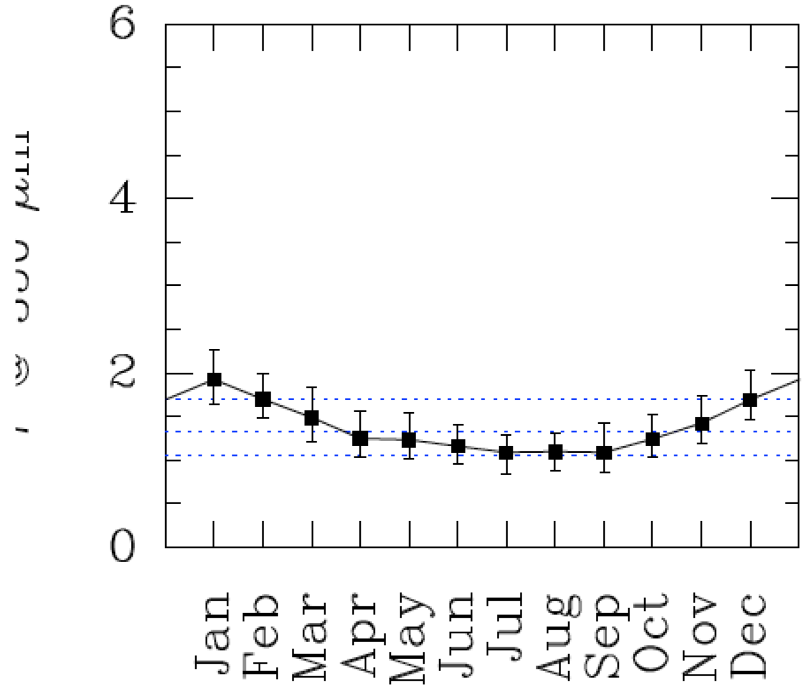
References:

- **Radford & Peterson, 2016, arXiv:1602.08795**
- **Radford, 2011, arXiv:1107.5633**
- **Martin-Cocher et al, SPIE 9147, 2014**
- **Tremblin et al. A&A 2014, arXiv:1110.4311**
- **Calisse et al., PASA 2004, 21 256**

Site characterization: South Pole, Antarctica

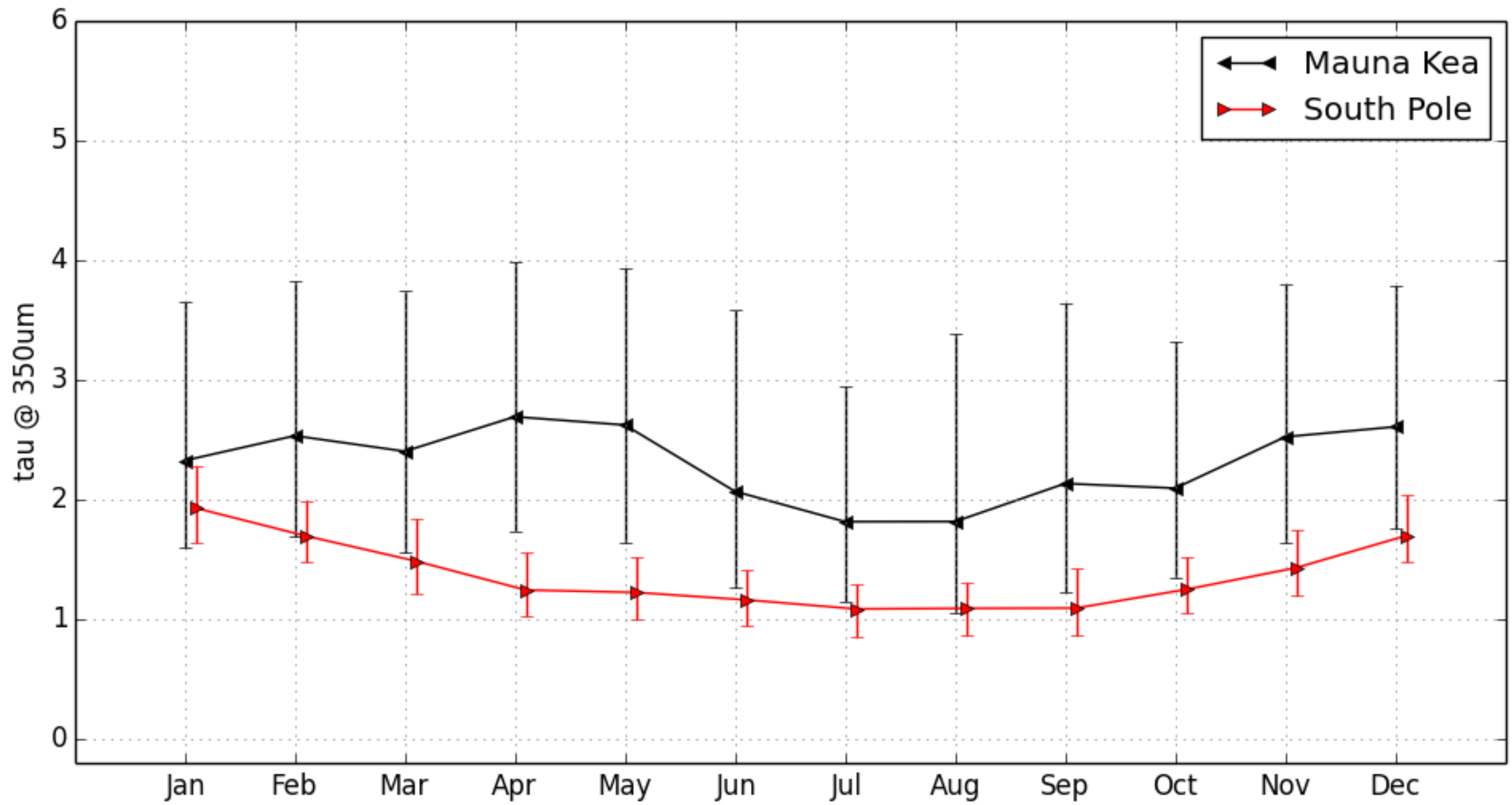
Lat: -90°
Alt: 2835m
Temp: -50 °C
Home to ACBAR, DASI, BICEP, Keck Array, SPT…
τ @ 350um: 1.1, 1.3, 1.7
Median PWV: 0.25mm





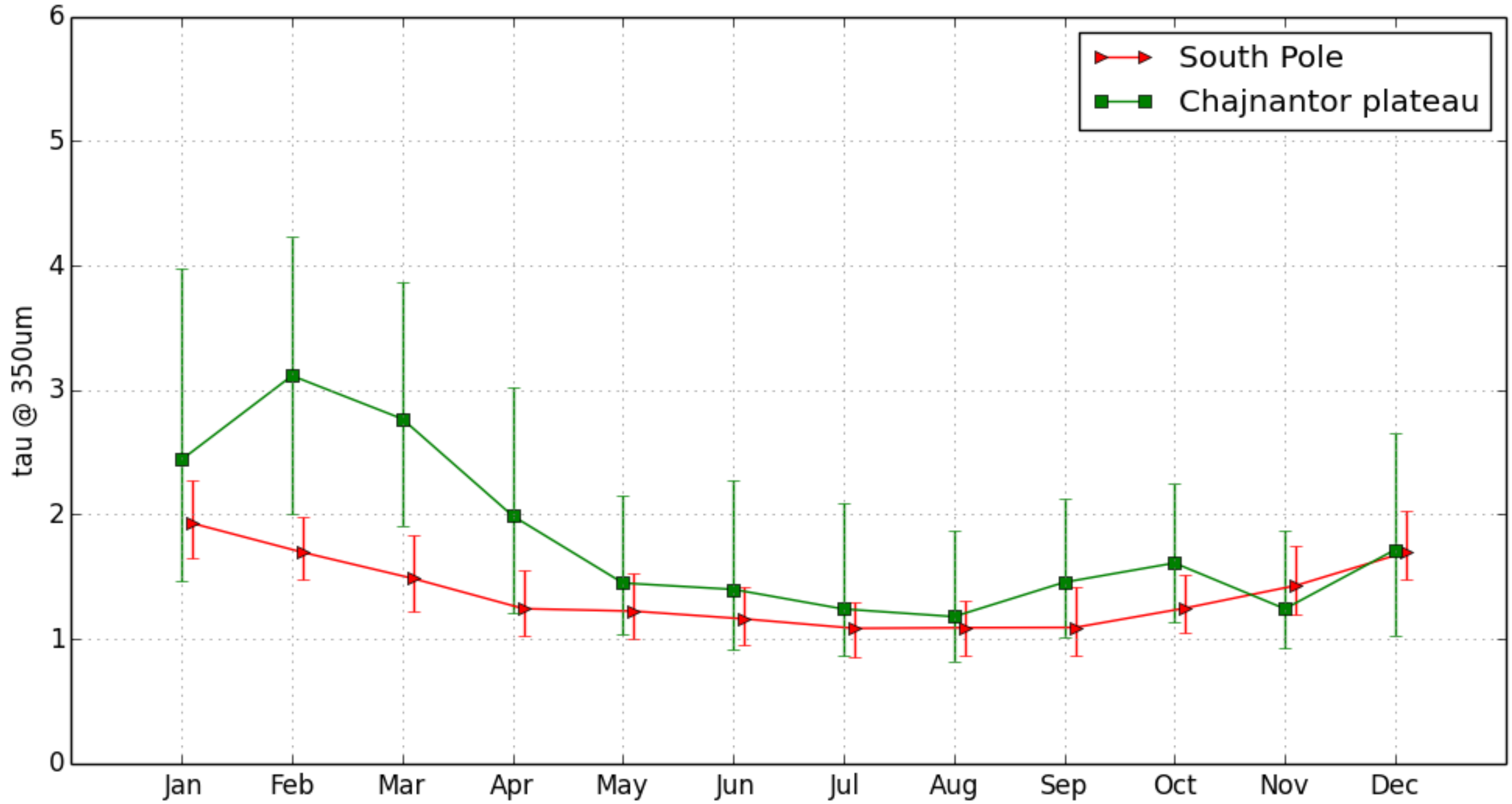
Plots from Radford & Peterson, 2016, arXiv:1602.08795

Site characterization: South Pole vs Mauna Kea



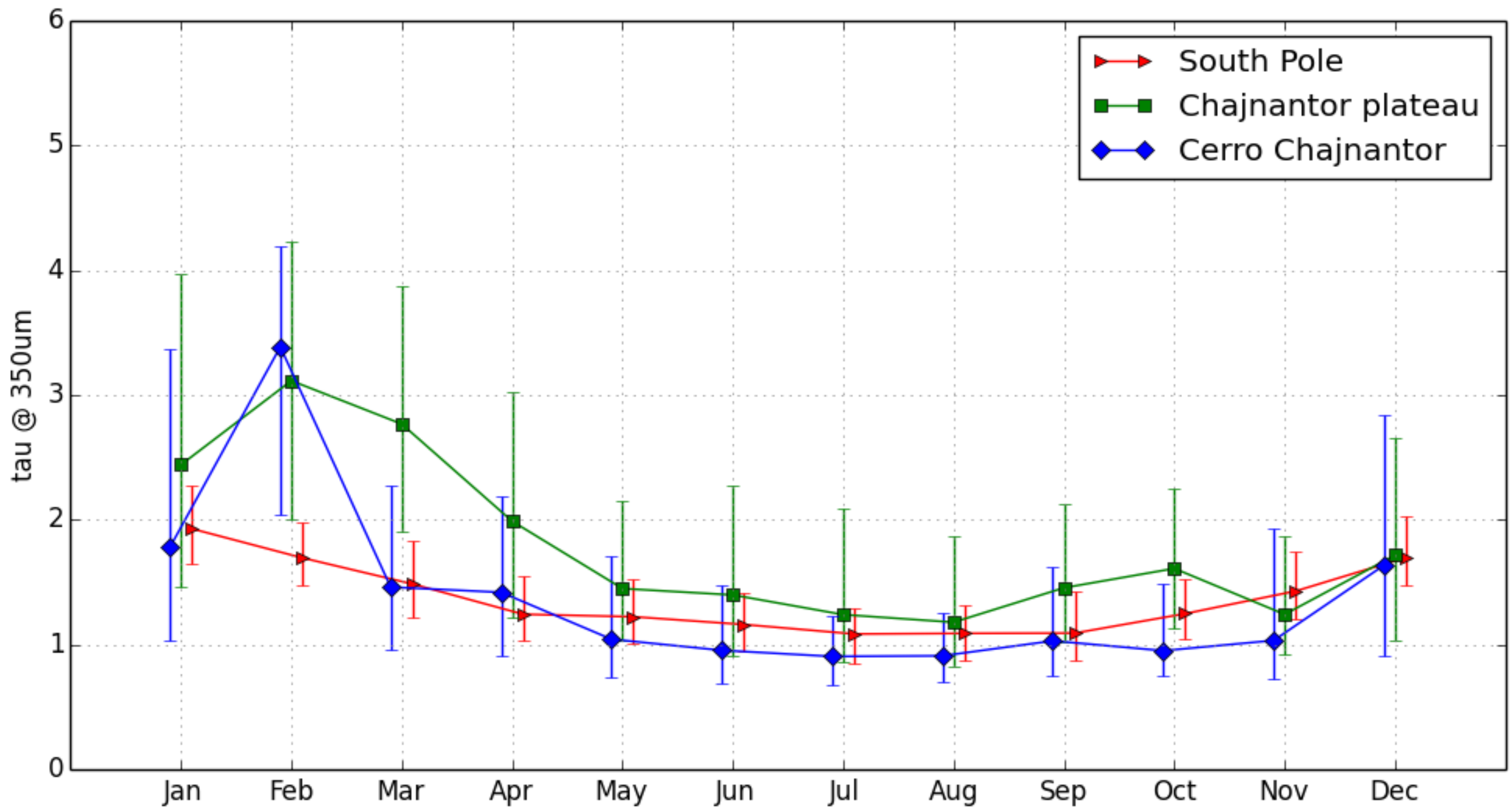
Data from Radford & Peterson,2016, arXiv 1602.08795

Site characterization: South Pole vs Chajnantor



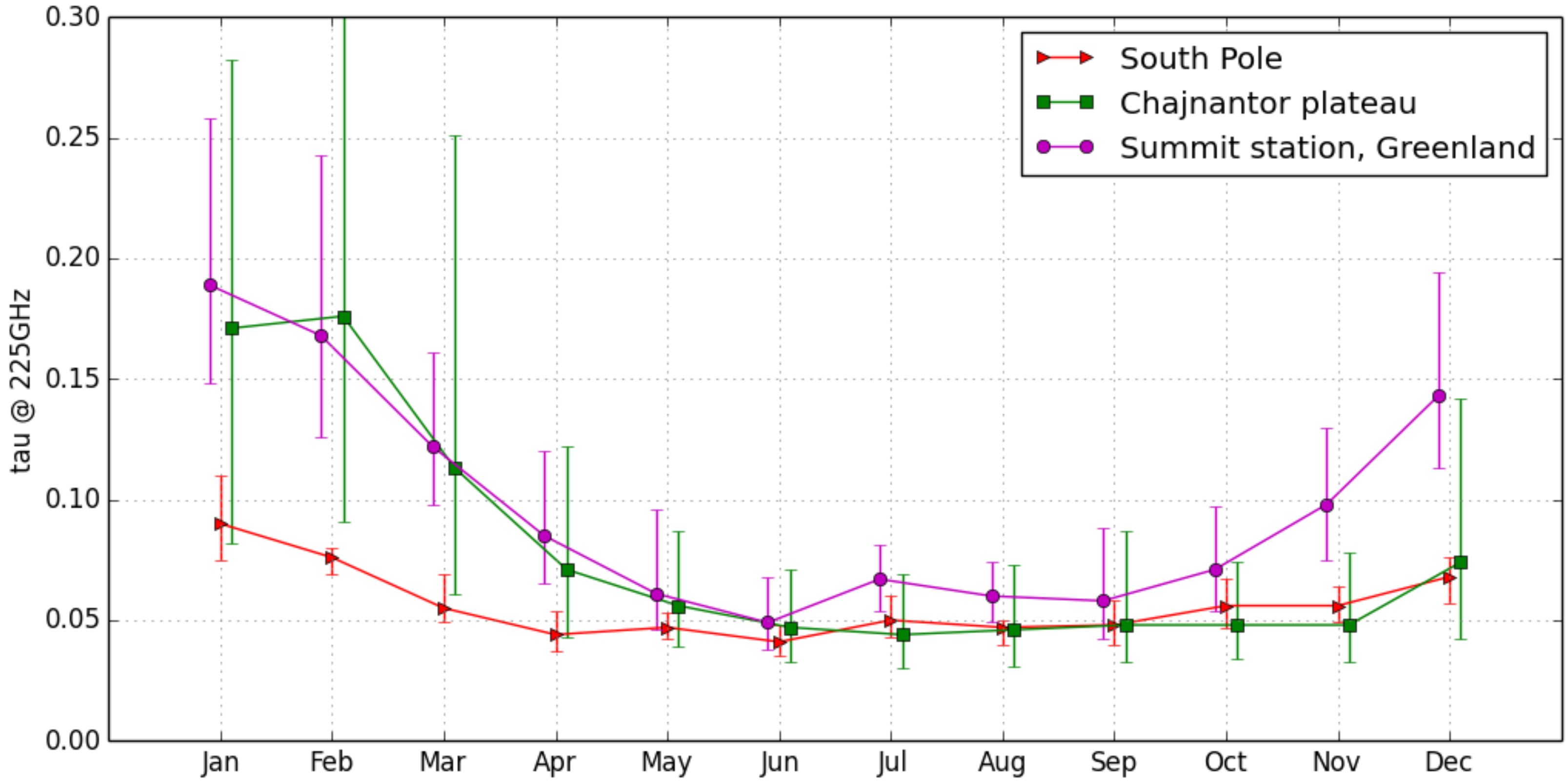
Data from Radford & Peterson,2016, arXiv:1602.08795

Site characterization: South Pole vs Chajnantor



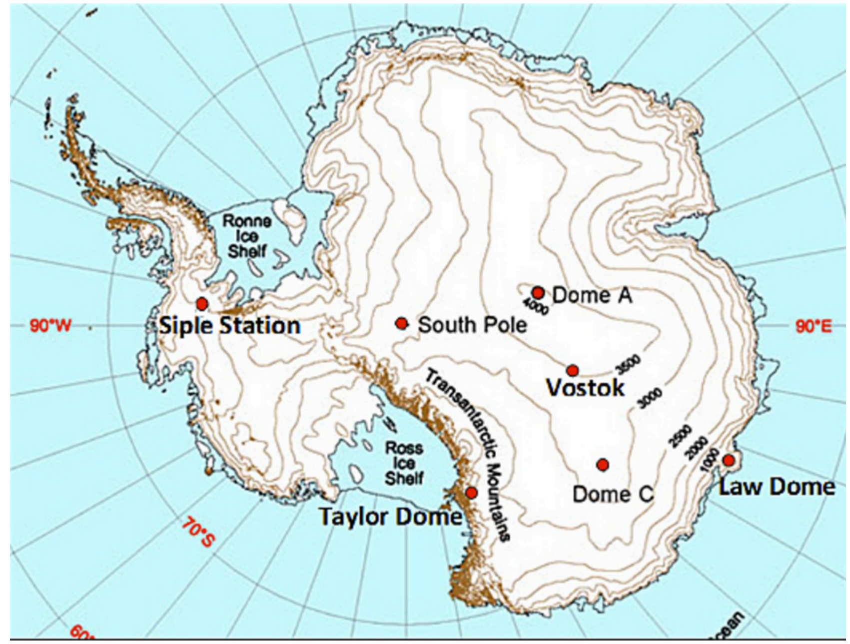
Data from Radford & Peterson,2016, arXiv 1602.08795

Site characterization: South Pole vs Summit station, Greenland

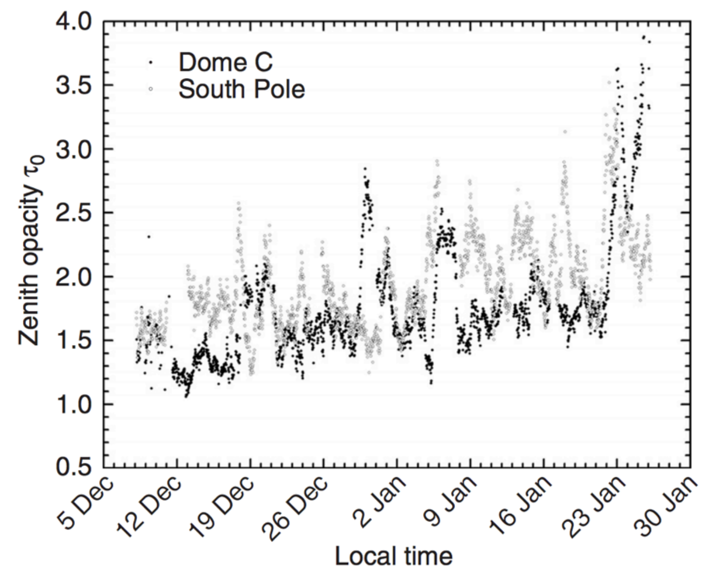


Site characterization: Dome C

Lat: -75 °
Alt: 3230 m
Temp: -51 °C
Lower wind speed than Pole.



PWV quartiles in mm		
	South Pole	Dome C
25%:	0.21	0.21
50%:	0.30	0.27
75%:	0.49	0.35

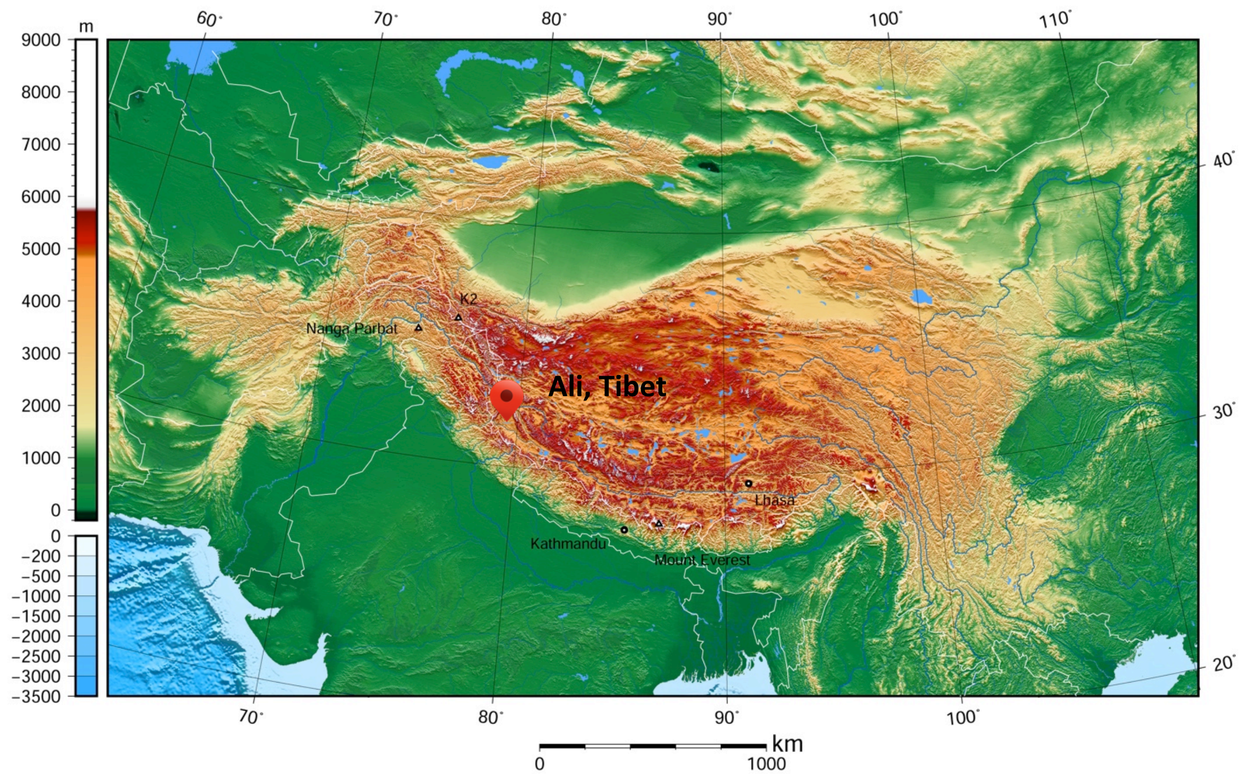


Tremblin et al. A&A 2014, arXiv:1110.4311

Calisse et al., PASA 2004, 21 256

Site characterization: Ali, Tibet

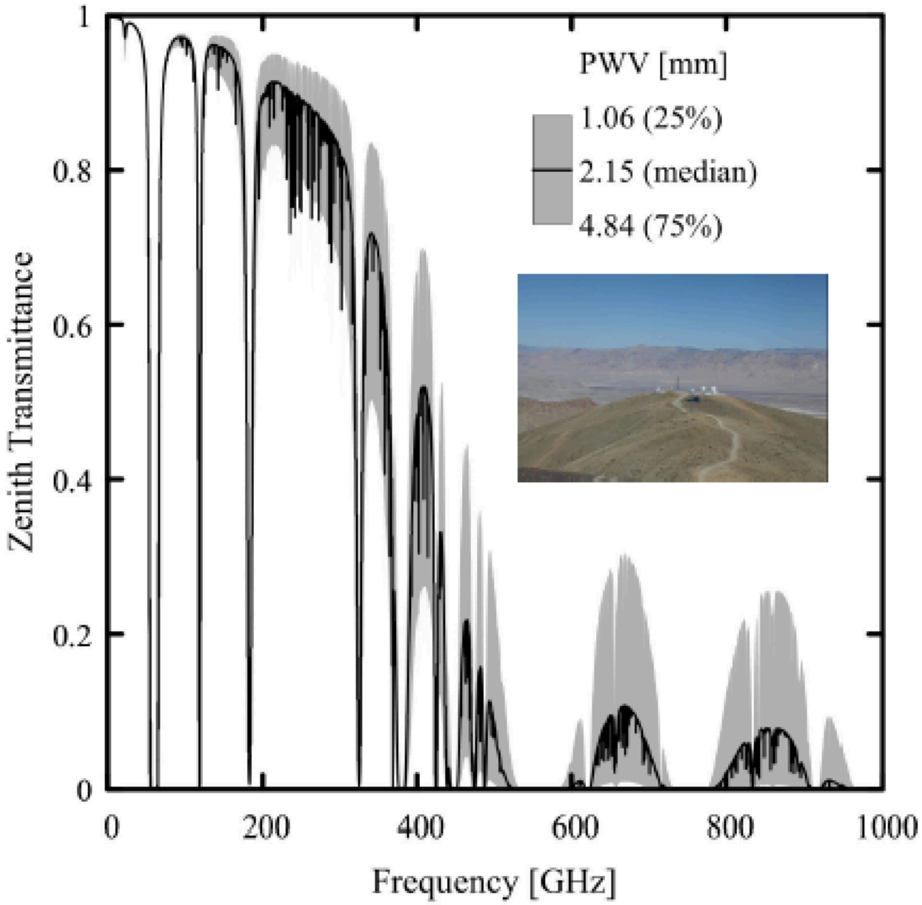
Lat: +32 °
Alt: > 5100 m
Temp: -5 °C
No CMB telescope yet.
PWV quartiles:
Winter: 0.5, 1.0, 1.5
Summer: 4.7, 7.8, 10.8



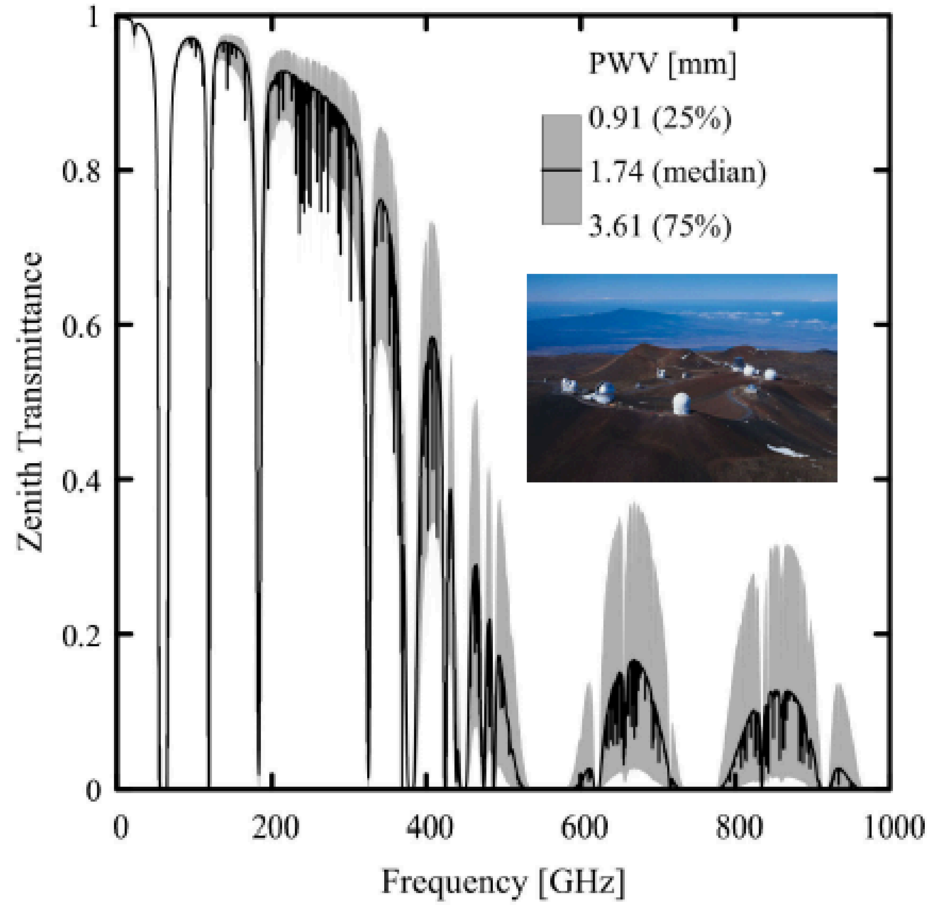
- Existing site infrastructure
- Preliminary atmospheric site monitoring (with PWV monitors and radiometers)
- Strong interest from Chinese scientific community to develop Ali as CMB site.

Ali compared with Mauna Kea – 10 year annual statistics

Ali (阿里) (80.0 E, 32.3 N) • annual Transmittance Quartiles



MaunaKea (155.5 W, 19.8 N) • annual Transmittance Quartiles



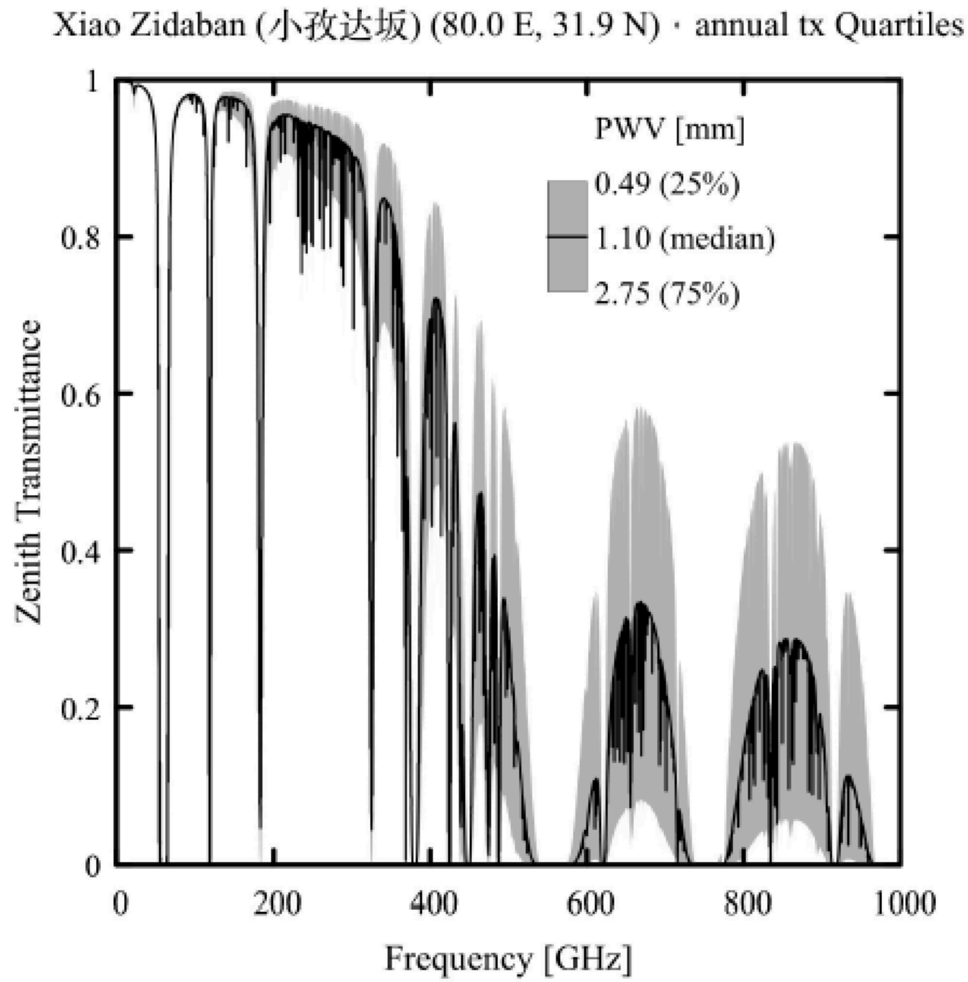
Similar in annual statistics, but Ali is much more seasonally variable.

Plots by Scott Paine

Going higher

Xiao Zidaban (6040 m altitude)

Comparable to ALMA site on annual average basis



Plots by Scott Paine

Beyond absolute transparency

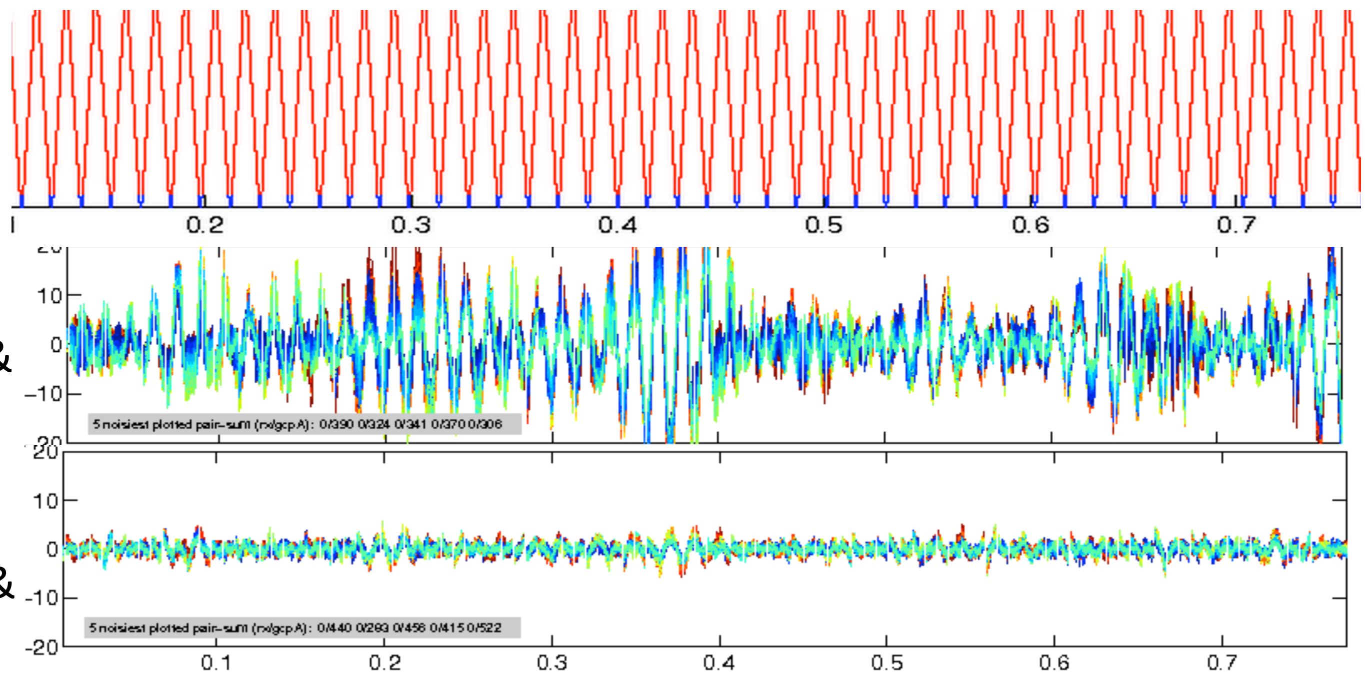
- In our CMB telescopes, degree scale sky noise originates from PWV fluctuations
- At South Pole, years of observation has honed our expertise in assessing sky noise quality.
- Long-term measurements of sky stability to directly compare the relative qualities of leading CMB sites does not exist ... yet.

Azimuth of telescope

Pair-sum timestreams

Poor
sky noise: large temporal &
spatial pwv fluctuations

Reduced
sky noise: lower temporal &
spatial pwv changes



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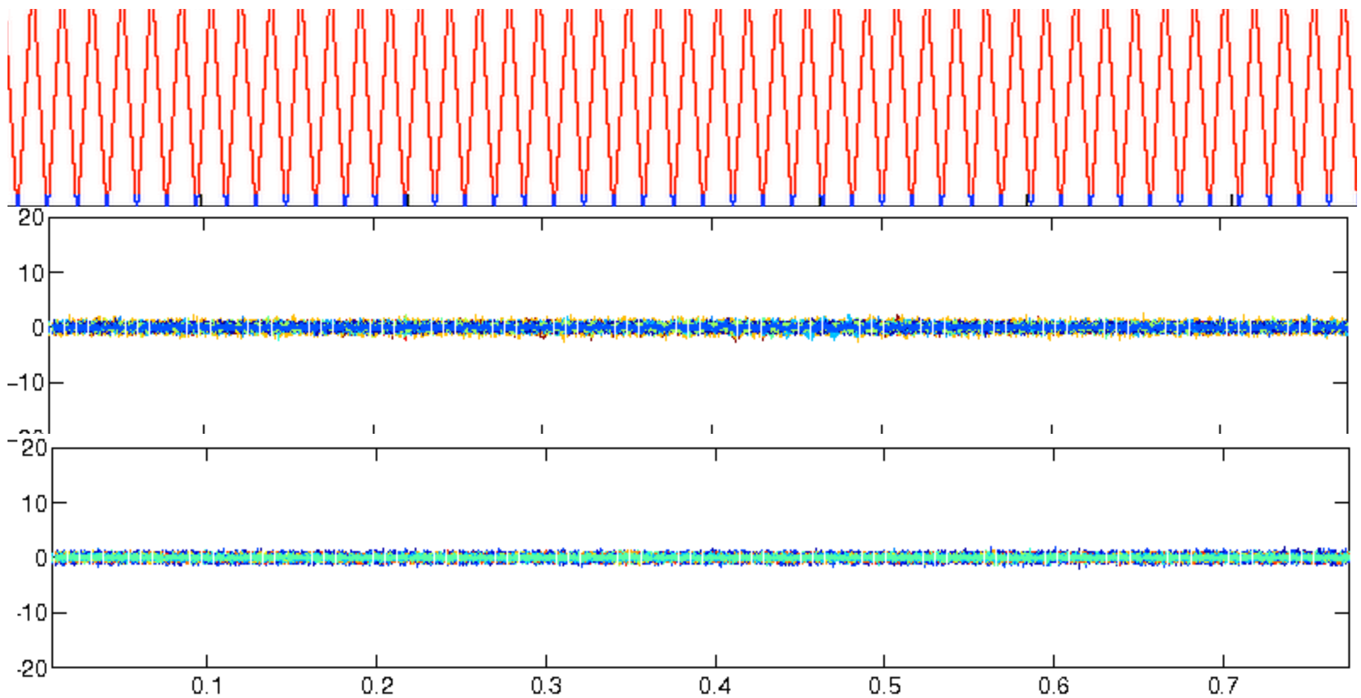


Scanning Water Vapor Radiometer Project

- GOAL: Collect quantitative and directly-comparable atmospheric noise and stability measurements to compare established sites (Pole, Atacama) and potential Northern sites (Summit station, Tibet).
- 183GHz warm Dicke-switched radiometer
- Uncooled mixer, double-sideband, Trx ~1000K
- Total bandwidth ~18GHz split into 4 DSB channels
- Dicke-switches at ~5Hz with a chopper wheel against 2 loads (hot/cold) allowing continuous calibration to < 2K absolute.
- Specifications:
    - Sensitivity: 0.08-0.1K RMS per channel
    - Sensitivity to water: σ pwv ~ (1 +w [mm]) μm in 1s integration
- Sensitive to measure typical PWV fluctuations on best South Pole days
- Partner with Omnisys, leverage R&D of ~60 units built for ALMA
- New Azimuth/Elevation fast scanning platform, environmental package for extreme environment, and data acquisition system.

Scanning Water Vapor Radiometer Campaign

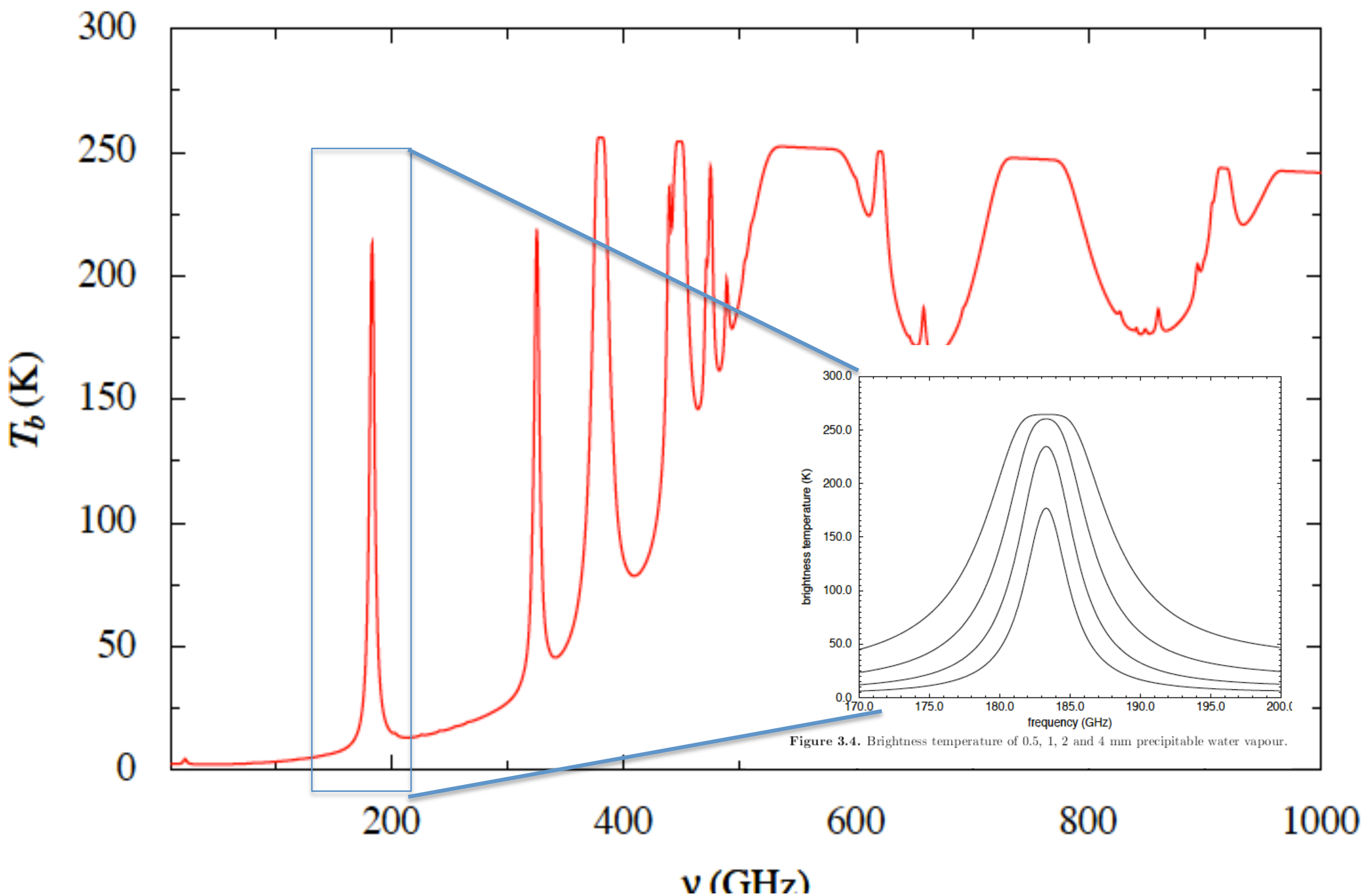
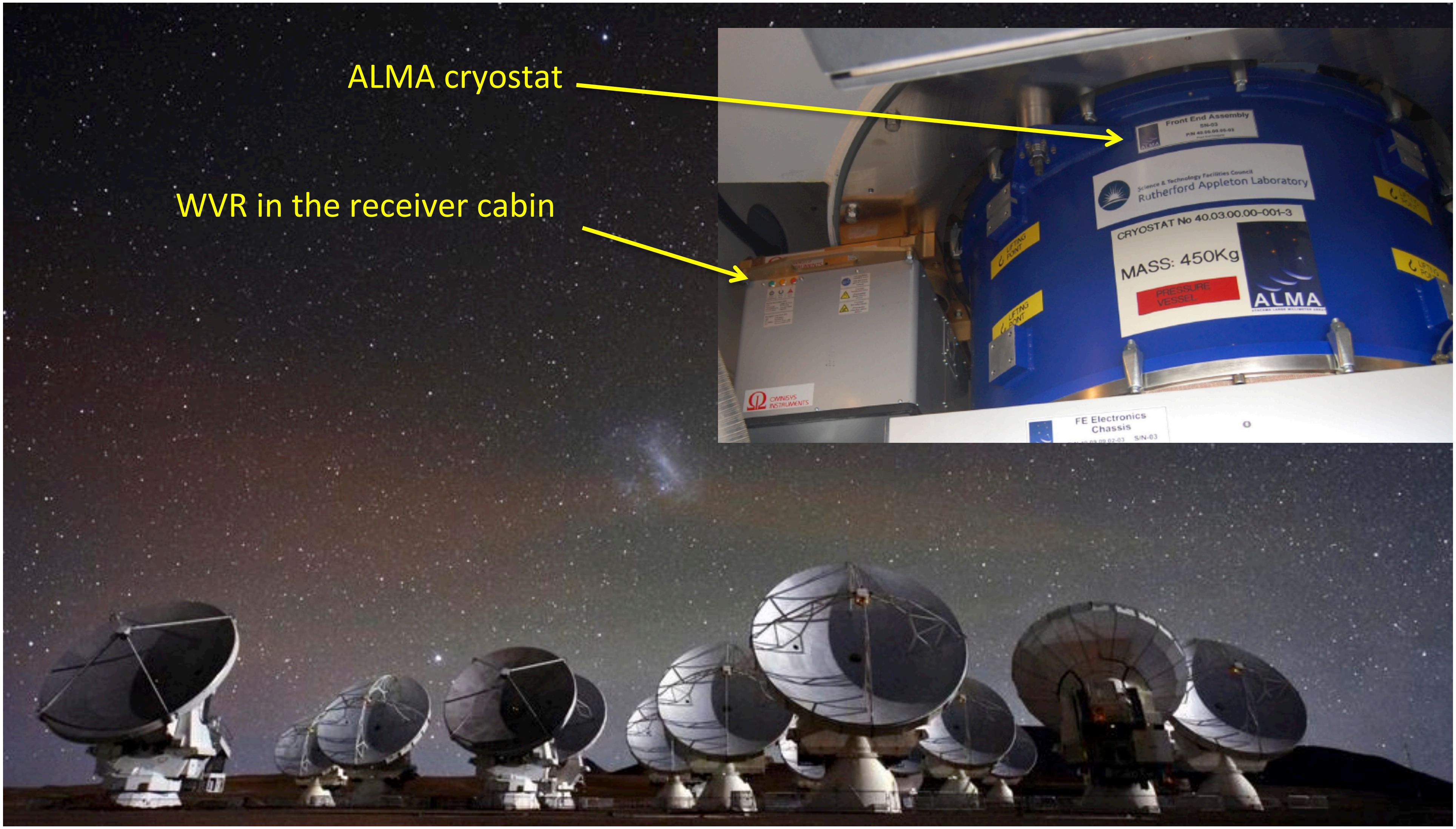


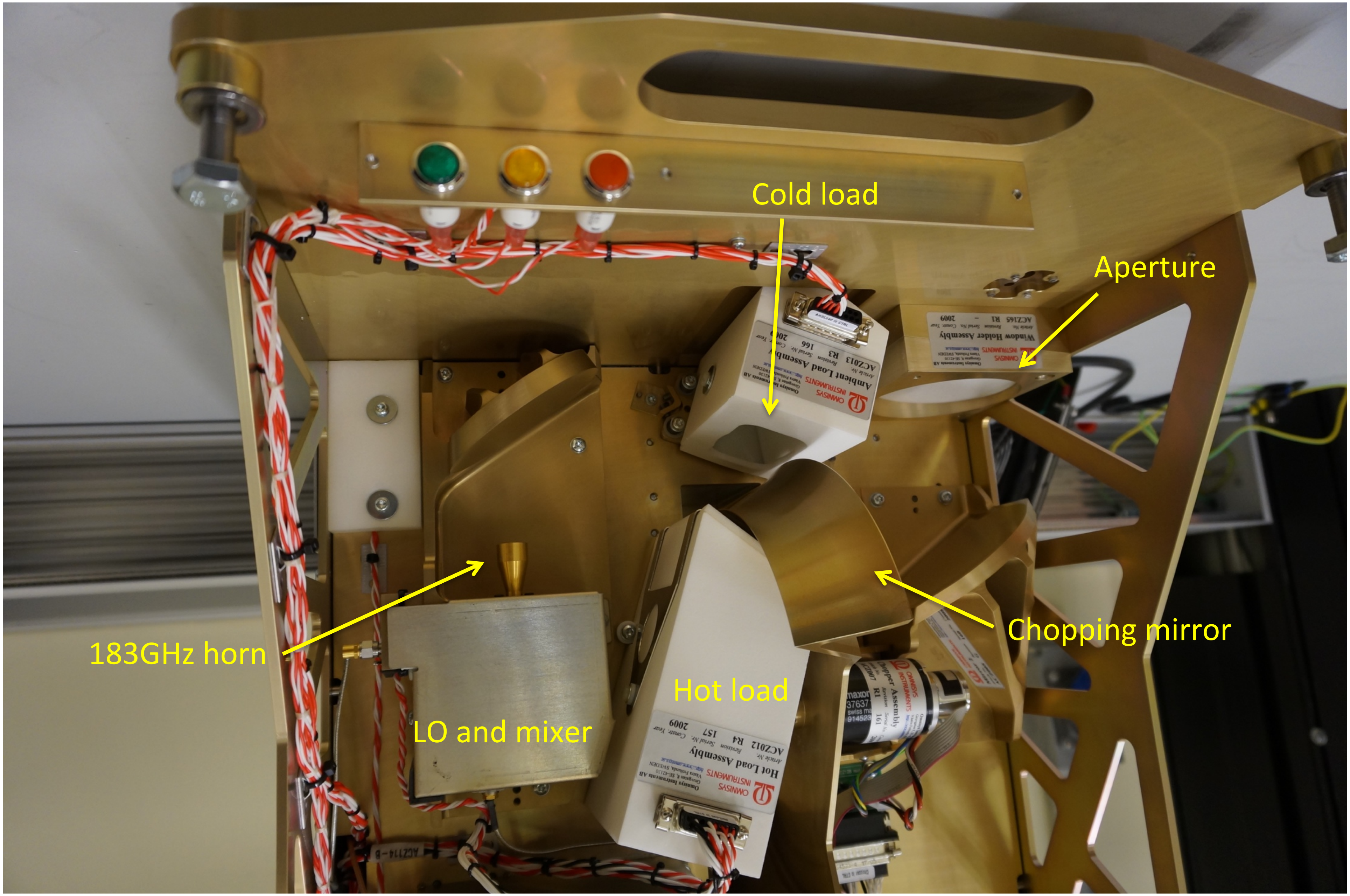
Figure 3.4. Brightness temperature of 0.5, 1, 2 and 4 mm precipitable water vapour.

A WVR with a strong experience

Each of the 50 ALMA 12m antennas uses one of these Omnisys WVR to measure the line-of-sight water column and correct in real time for the differential phase induced on the signal.



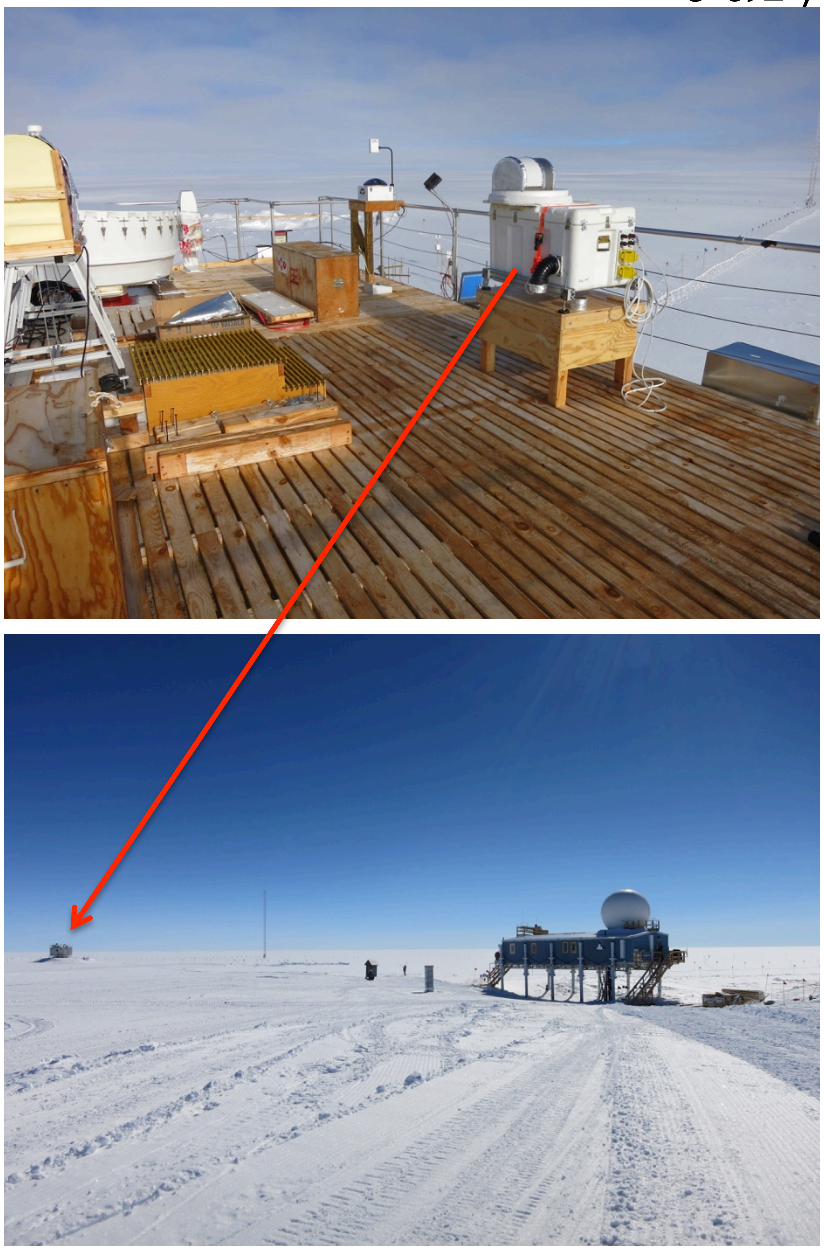
Front end of Omnisys WVR



WVR Unit 1: installed at Pole Jan 2016

- Weight 200lbs
- Draws < 600W.
- Operates from -20 to -80C.
- Sensitivity: 0.08-0.1K RMS per channel (~1s integration)
- Sensitivity to water: σ pwv ~ (1 +w [mm]) μm in 1s integration.

WVR Unit 2: installed at Summit station, Greenland July 2016



- Weight 200lbs
- Draws < 600W.
- Operates from -20 to -80C.
- Sensitivity: 0.08-0.1K RMS per channel
- Sensitivity to water: σ pwv ~ (1 +w [mm]) μm in 1s integration.

- PWV timestreams and reduced data will be publically posted (service to CMB S4 community)

- Considering additional units in 2017 to Atacama and Tibet. Open to collaboration.

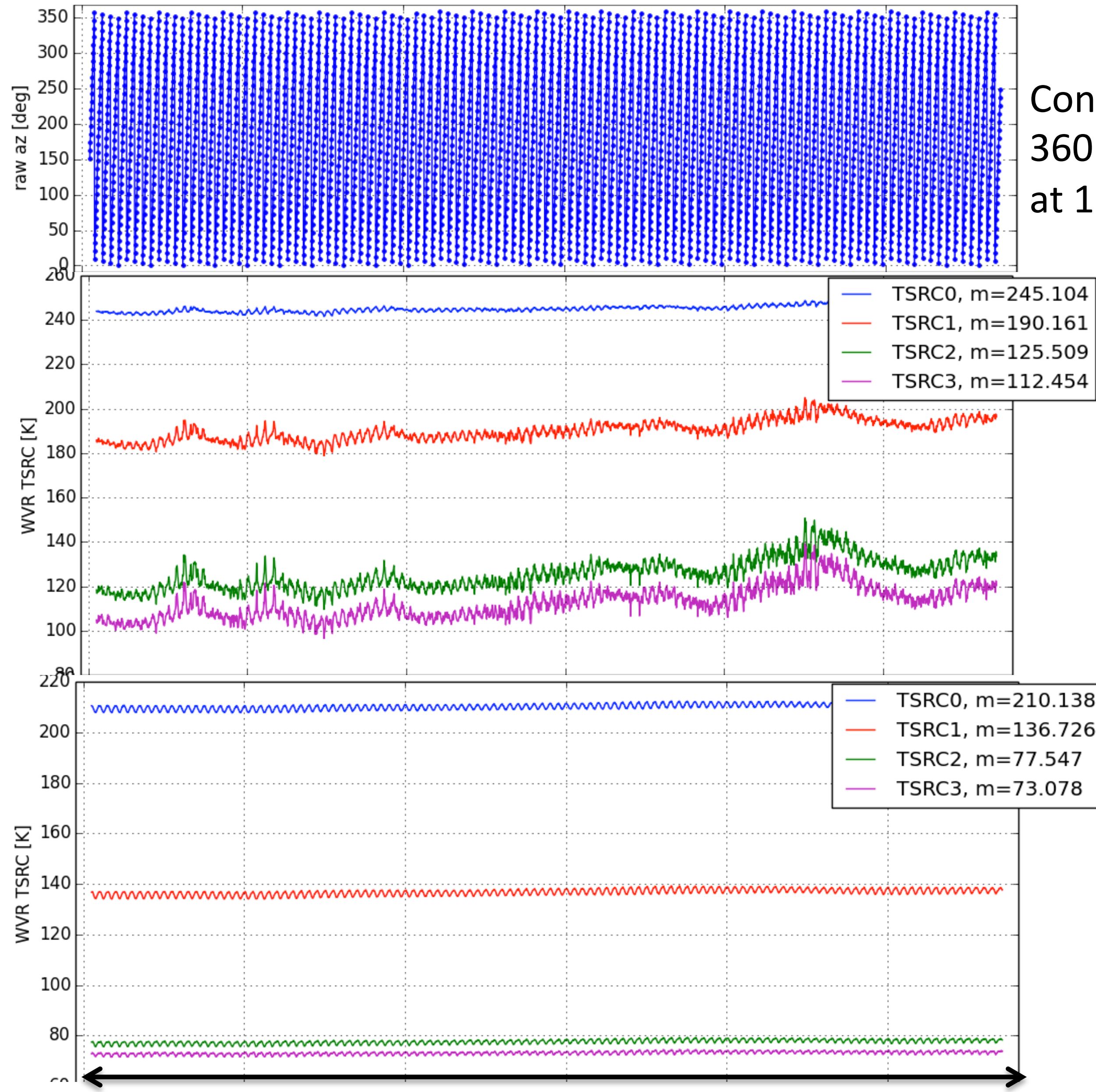
WVR2 raw timestreams from Sept 5 2016

Azimuth

Continuous 360 rotation at 12deg/s

Sep 5th 2016 13-14UT
Poor sky noise and stability

Sep 4th 2016 01-02 UT
Lower PWV and much better stability.



1hr time span

Concluding remarks:

- South Pole, and Chajnantor vincinity and currently leading sites for CMB observations.

- Other locations could provide better transparency (Cerro Chajnantor, Dome C!!!) and/or additional sky coverage (Tibet, Greenland) …

- … but may require significant logistical spin-up period before being able to host current-generation type CMB instruments.

- Modern reanalysis offers a means of assessing long-term radiative properties of an observing site. Accuracy for a particular site can be improved with a relatively short (~1 year) test campaign.

- We’ve started a campaign to compare South Pole, Greenland, Chile and Tibet degree-scale PWV fluctuations.

END