CMB at Other Sites

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Outline

- Scientific advantages for including a site in the Northern Hemisphere
- Site comparisons (Dome A, South Pole, Atacama, Ali, Greenland)
- Plans and Status for Ali-CMB (Tibet)

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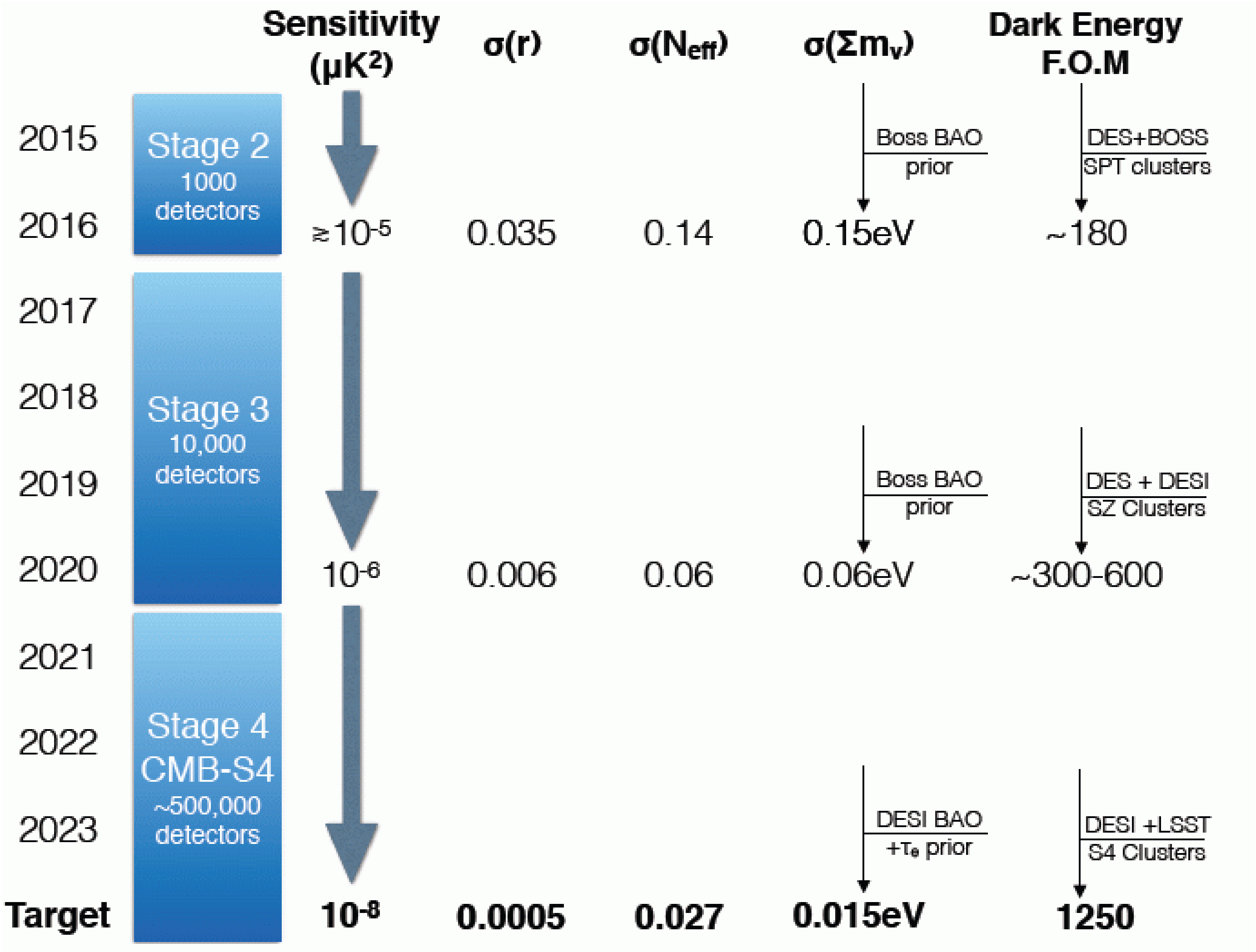
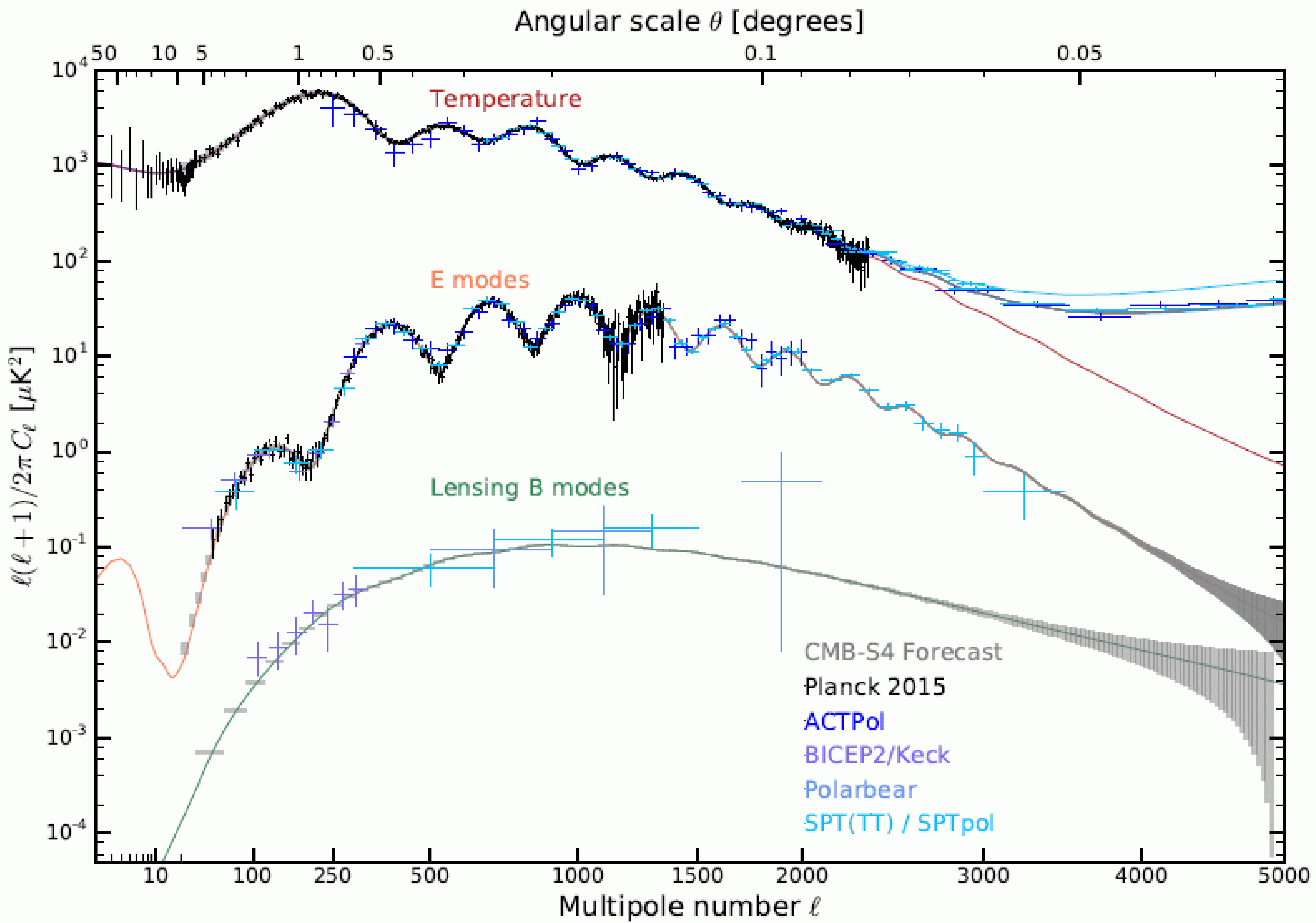


CMB-S4 Science Book, 2017



Angular scale θ [degrees]
50
10
5
1
0.5
0.1
0.05
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\ell(\ell+1)/2\pi\, C_\ell\ [\mu K^2]$
Temperature
E modes
Lensing B modes
CMB-S4 Forecast
Planck 2015
ACTPol
BICEP2/Keck
Polarbear
SPT(TT) / SPTpol
10
100
250
500
1000
1500
2000
3000
4000
5000
Multipole number ℓ

CMB-s4 Science

- **E-mode polarization**

- **Lensing B-modes**

- **Degree-scale B-modes**

CMB-s4 Science

- **E-mode polarization**
  - Light relics (N_{eff})
  - Scalar perturbations (n_s and running)
  - Dark Matter
  - Isocurvature perturbations
- **Lensing B-modes**
  - Dark energy
  - Neutrino mass
- **Degree-scale B-modes**
  - Tensor modes

Ref:
Wu et al., ApJ, 788, 138, 2014

E-mode science

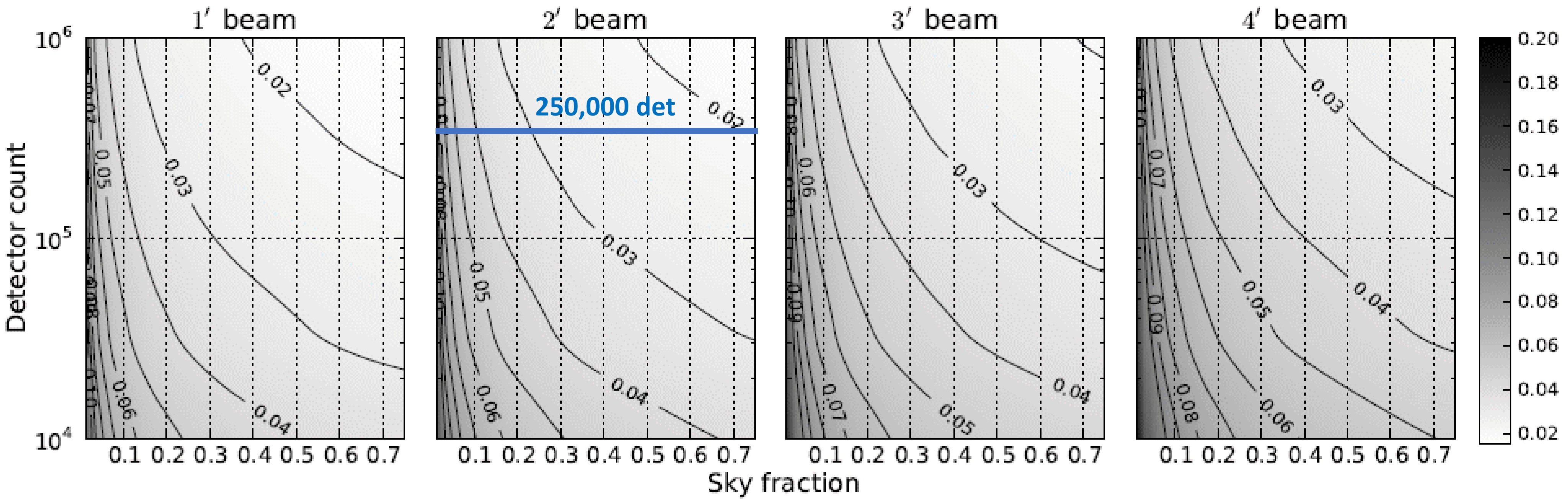


Figure 3: Constraints for $\sigma(N_{\rm eff})$ as a function of the number of detectors and observing sky fraction for 1′ to 4′ beam sizes.

Wu et al. 2014

E-mode science

	CMB				CMB+BAO			
	1′	2′	3′	4′	1′	2′	3′	4′
10^4 detectors								
$f_{sky} = 0.25$	2.91	2.94	2.98	3.04	2.19	2.23	2.29	2.36
$f_{sky} = 0.50$	2.11	2.13	2.16	2.21	1.64	1.67	1.71	1.75
$f_{sky} = 0.75$	1.76	1.77	1.80	1.83	1.39	1.42	1.45	1.48
10^5 detectors								
$f_{sky} = 0.25$	2.66	2.73	2.80	2.86	1.93	1.98	2.04	2.12
$f_{sky} = 0.50$	1.94	1.97	2.01	2.06	1.44	1.47	1.51	1.56
$f_{sky} = 0.75$	1.60	1.63	1.66	1.70	1.22	1.24	1.28	1.32
10^6 detectors								
$f_{sky} = 0.25$	2.38	2.48	2.62	2.73	1.70	1.76	1.83	1.92
$f_{sky} = 0.50$	1.75	1.81	1.90	1.96	1.28	1.32	1.37	1.43
$f_{sky} = 0.75$	1.45	1.51	1.57	1.61	1.10	1.12	1.16	1.20

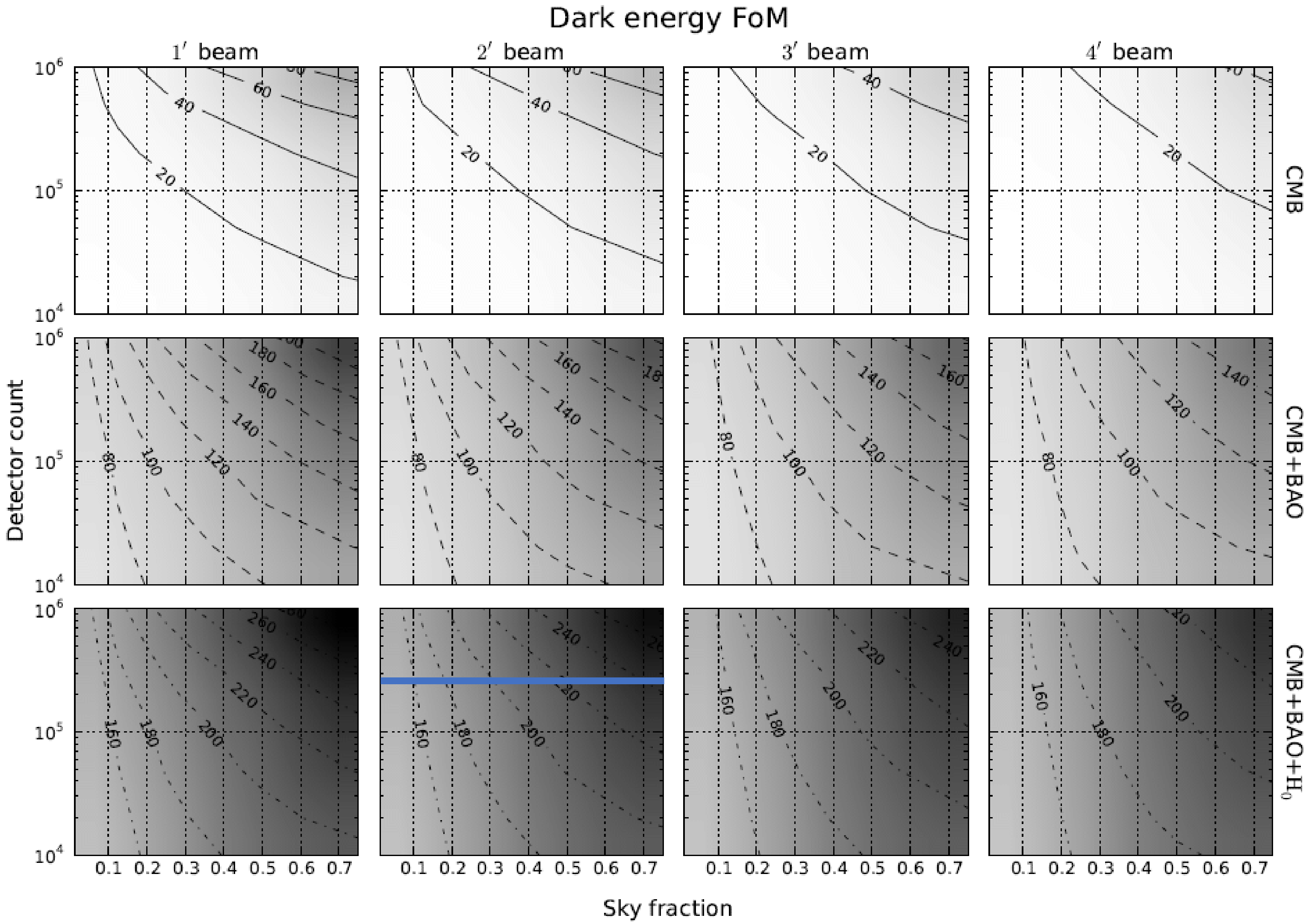
Table V: n_s 1-σ constraints in units of 10^{-3} from CMB and from CMB+BAO. "CMB" includes lensing.

	CMB				CMB+BAO			
	1′	2′	3′	4′	1′	2′	3′	4′
10^4 detectors								
$f_{sky} = 0.25$	3.40	3.51	3.69	3.92	3.40	3.51	3.68	3.91
$f_{sky} = 0.50$	2.58	2.66	2.79	2.96	2.58	2.66	2.78	2.95
$f_{sky} = 0.75$	2.20	2.26	2.37	2.51	2.20	2.26	2.37	2.51
10^5 detectors								
$f_{sky} = 0.25$	2.79	2.92	3.09	3.31	2.78	2.91	3.08	3.30
$f_{sky} = 0.50$	2.09	2.17	2.29	2.45	2.08	2.17	2.29	2.44
$f_{sky} = 0.75$	1.76	1.83	1.93	2.06	1.76	1.82	1.92	2.05
10^6 detectors								
$f_{sky} = 0.25$	2.32	2.46	2.65	2.87	2.27	2.42	2.63	2.86
$f_{sky} = 0.50$	1.75	1.83	1.96	2.12	1.72	1.82	1.96	2.11
$f_{sky} = 0.75$	1.47	1.54	1.65	1.77	1.45	1.53	1.64	1.77

Table VI: α_s 1-σ constraints in units of 10^{-3} from CMB and from CMB+BAO. "CMB" includes lensing. BAO measurements improve constraints in α by a few percent. The improvement is more significant for small sky fractions and small beam size scenarios.

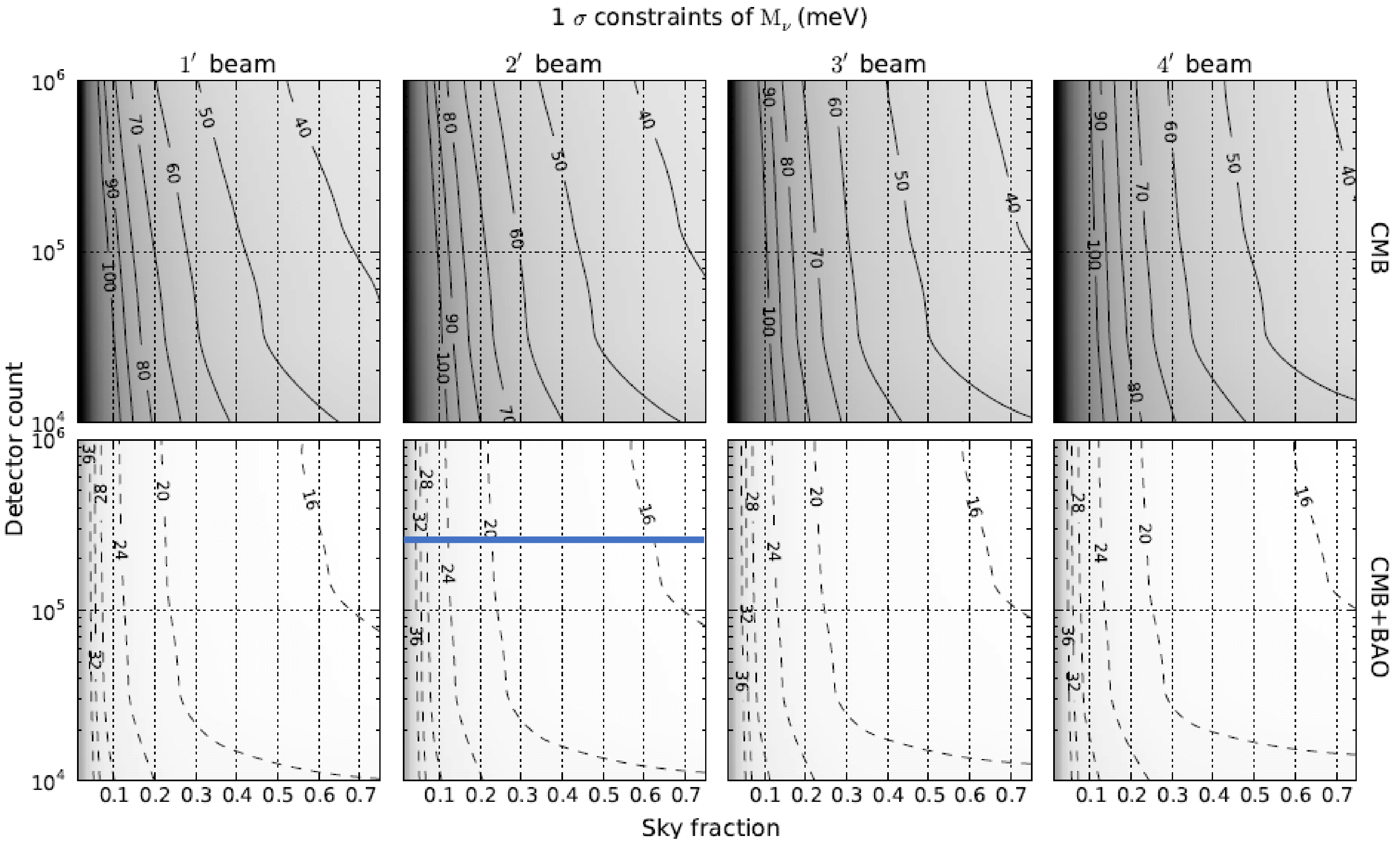
Wu et al. 2014

Lensing B-modes



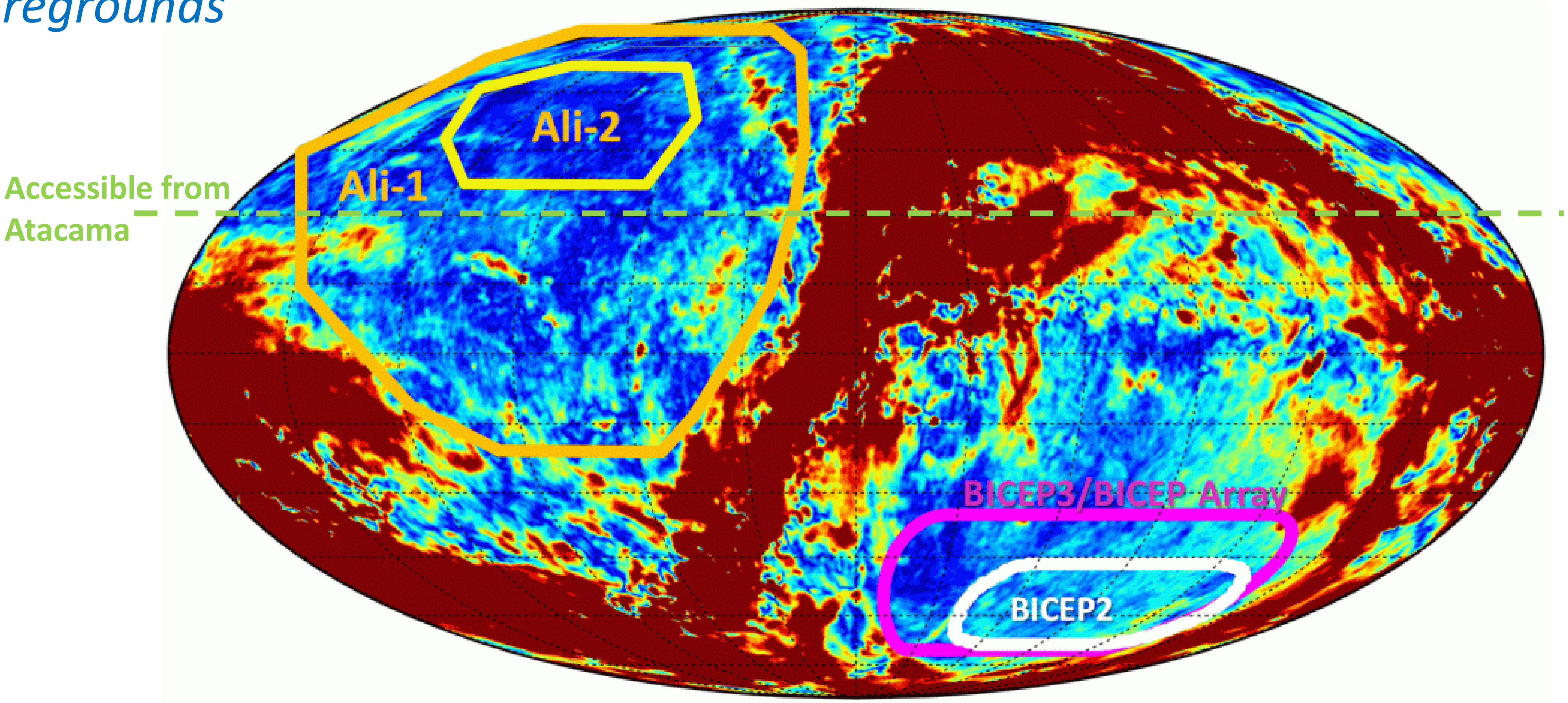
Wu et al. 2014

Lensing B-modes



Wu et al. 2014

Primordial B-modes:
foregrounds



1. There will be lots of lessons learned with better statistics
2. Staged wedding cake strategy may be advantageous (e.g. Kovetz & Kamionkowski PRD 91, 081303R,2015)

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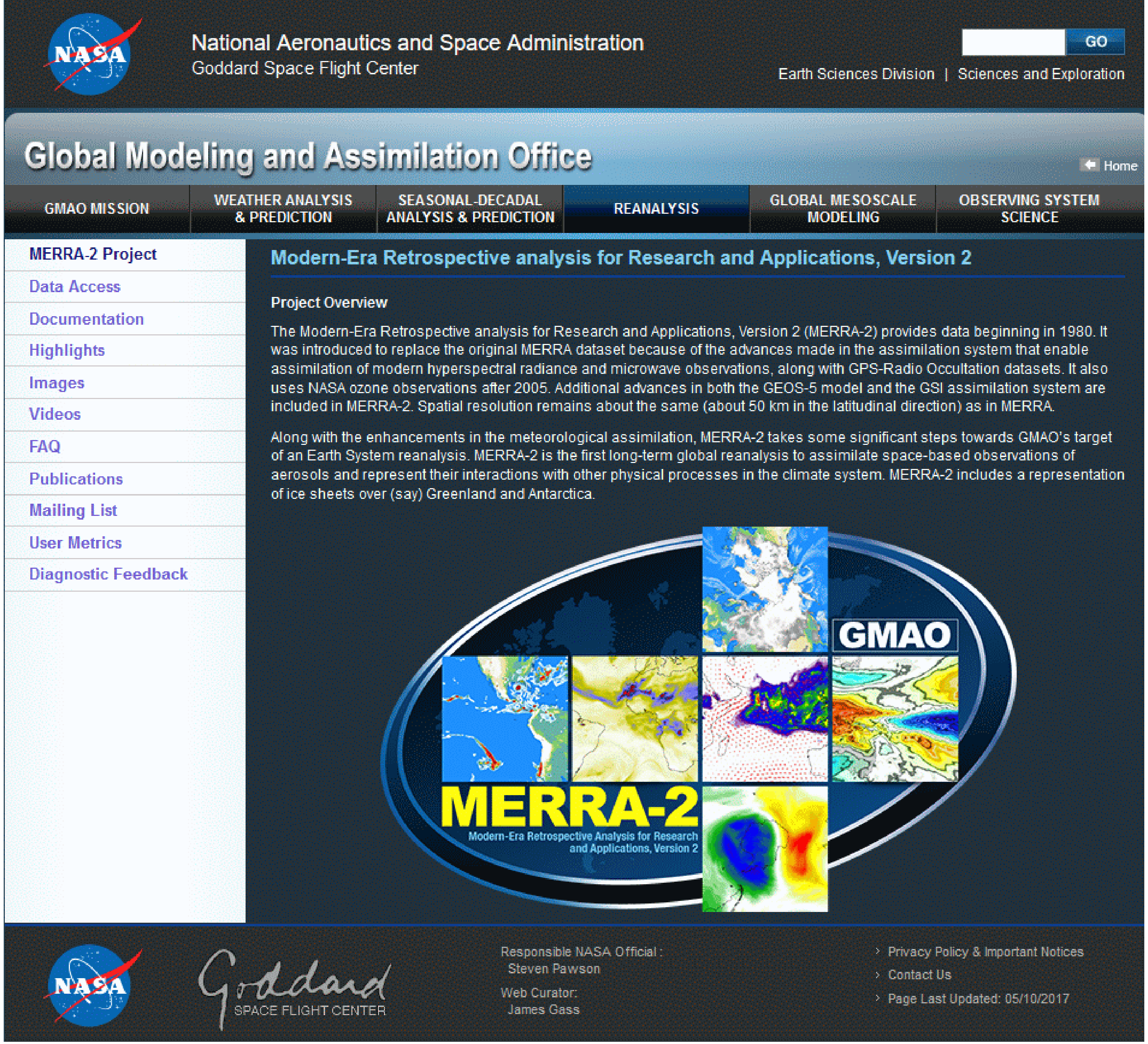
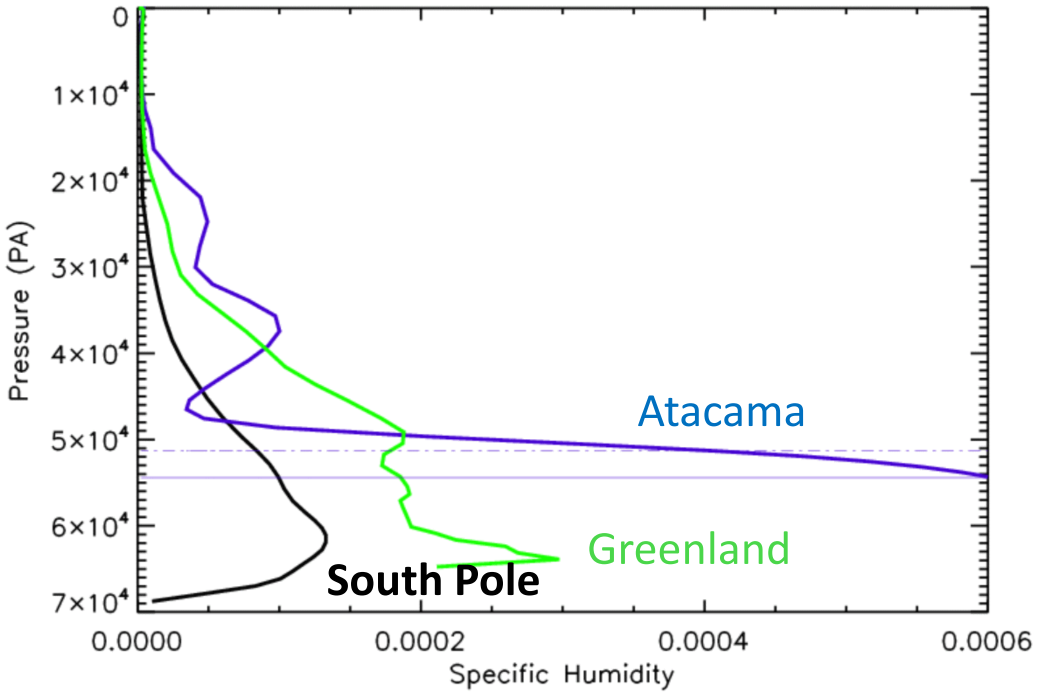


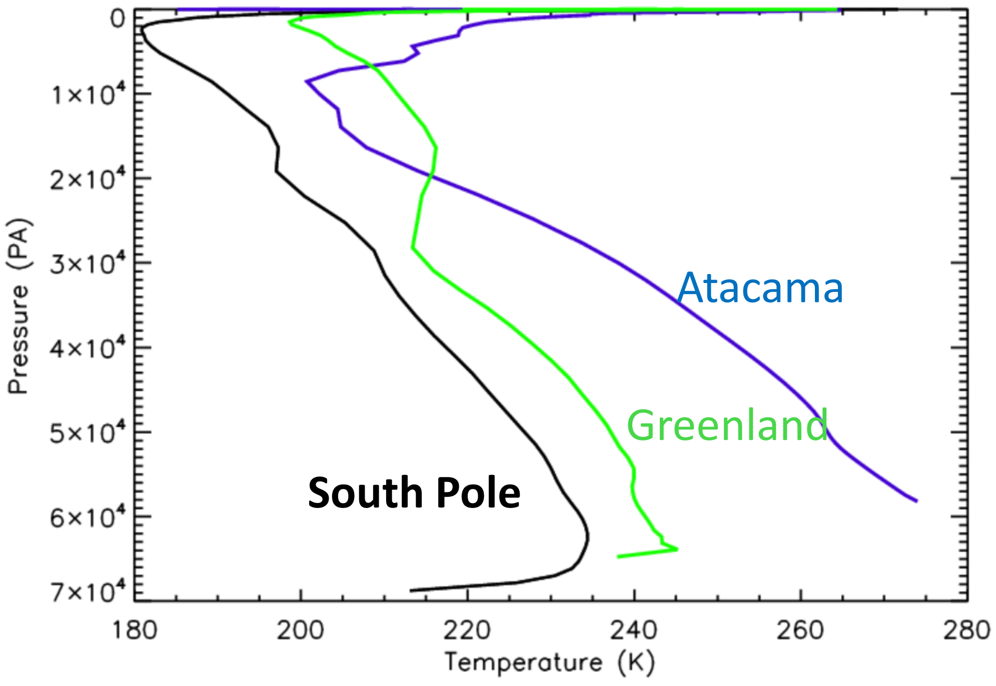
NASA's MERRA-2
T, *p*, humidity, wind, CO2, clouds…
Observed by a wide range of instr.
One profile every 3 hours
(0.65° x 0.5°) spatial resolution
72 vertical (pressure) layers
1980 – present, no gaps

Great for "armchair" evaluation
of the potential sites
(not a replacement of actual site testing)

arXiv:1707.08400 CK

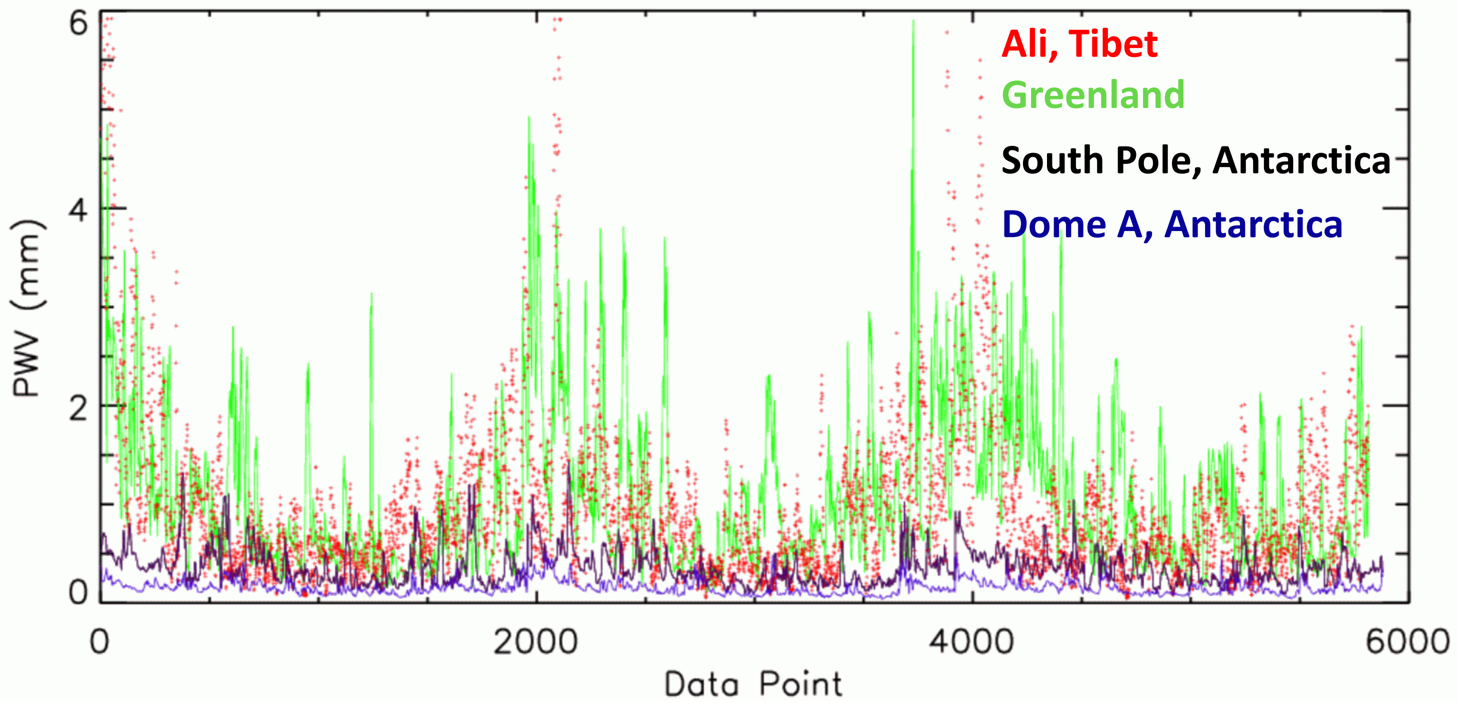
Representative MERRA-2 data

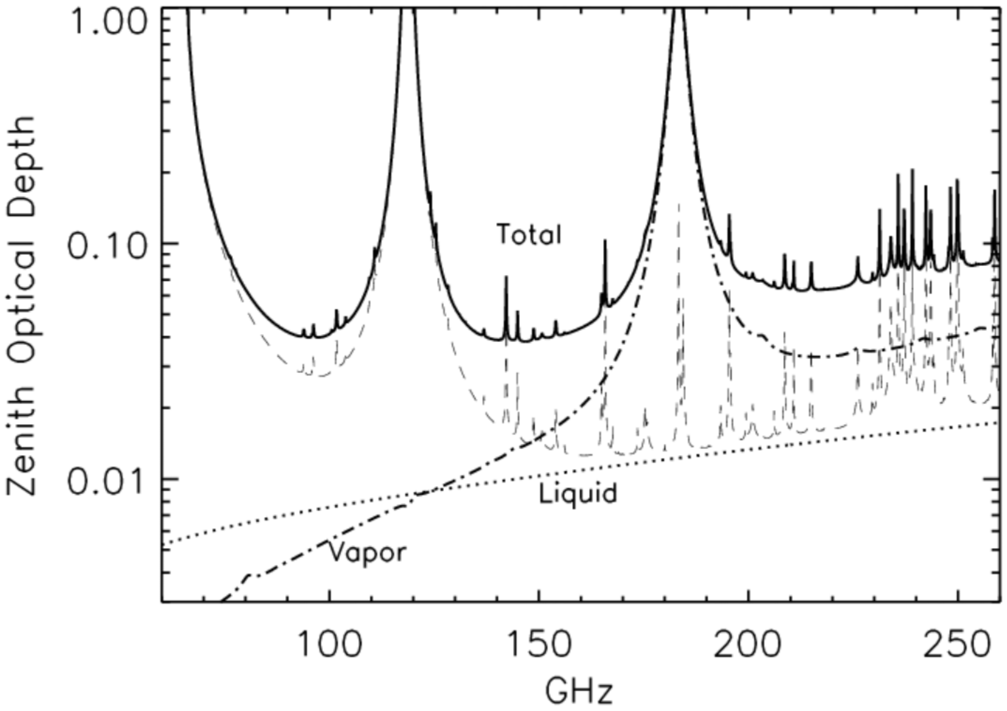




Integral gives you PWV

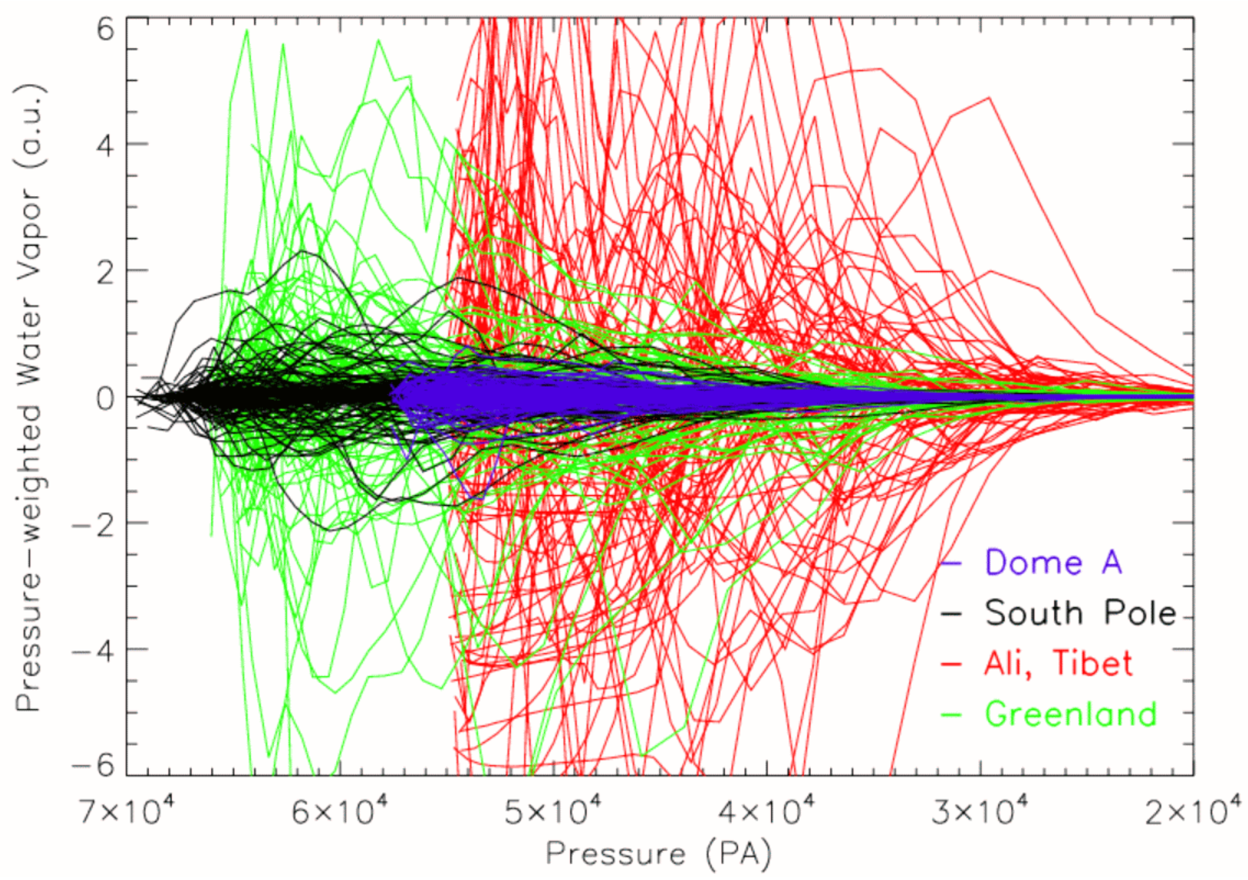
Effects of water in the atmosphere





am Scott Paine 2017

Representative MERRA-2 data



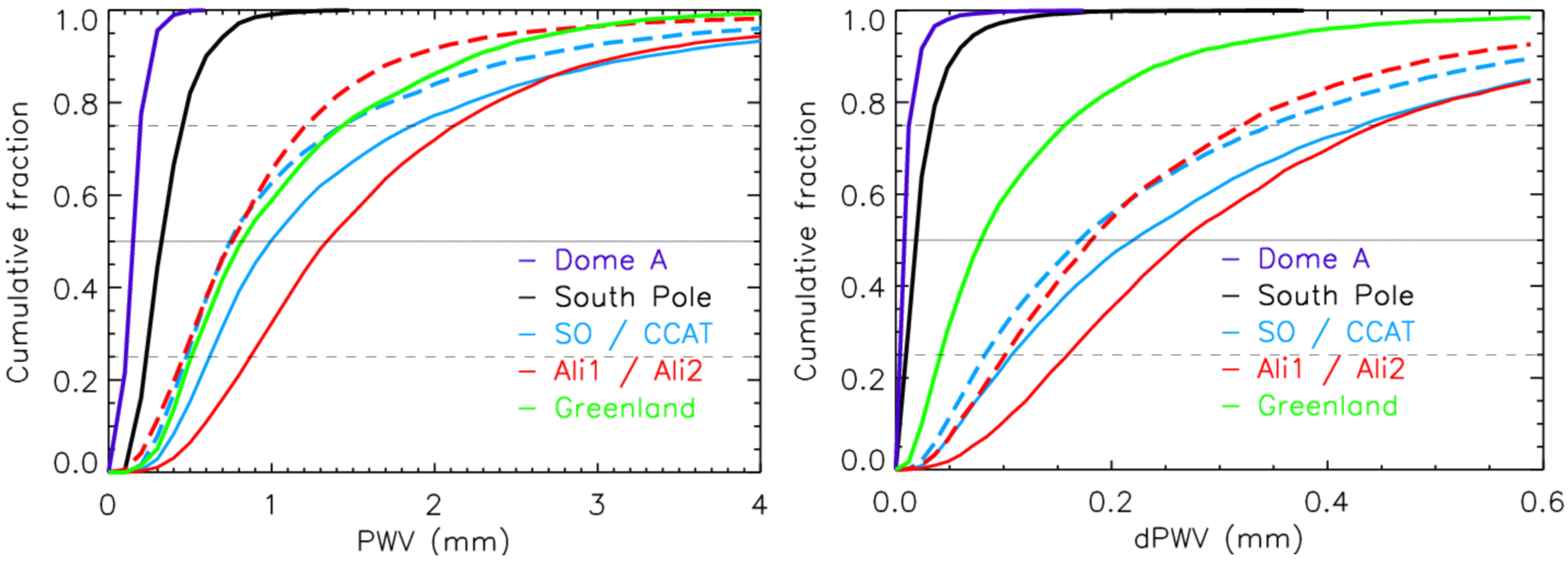
Instantaneous – time-averaged
Specific Humidity Profile
in the **vertical** direction

Turbulence seen should be
closely related to
angular fluctuations of
brightness temperature

Can be used to define "***d*PWV**"

which provides relative comparisons of
different sites using the **same** measure.

MERRA-2 Results

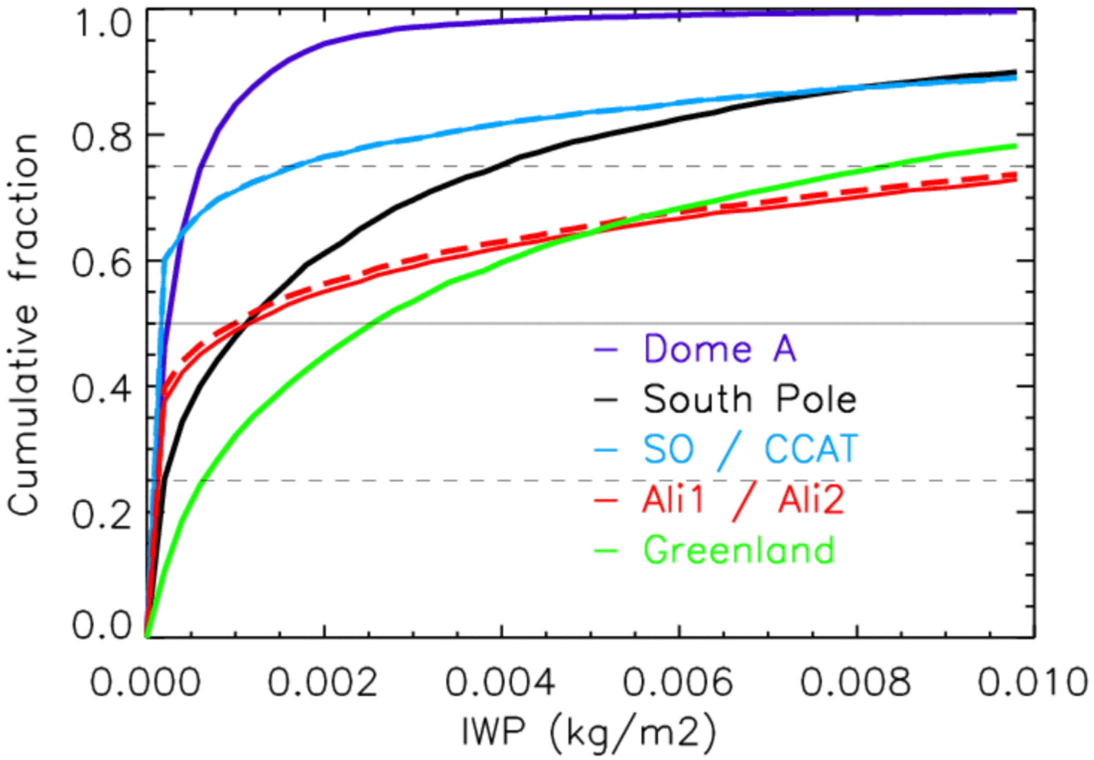


Main Results

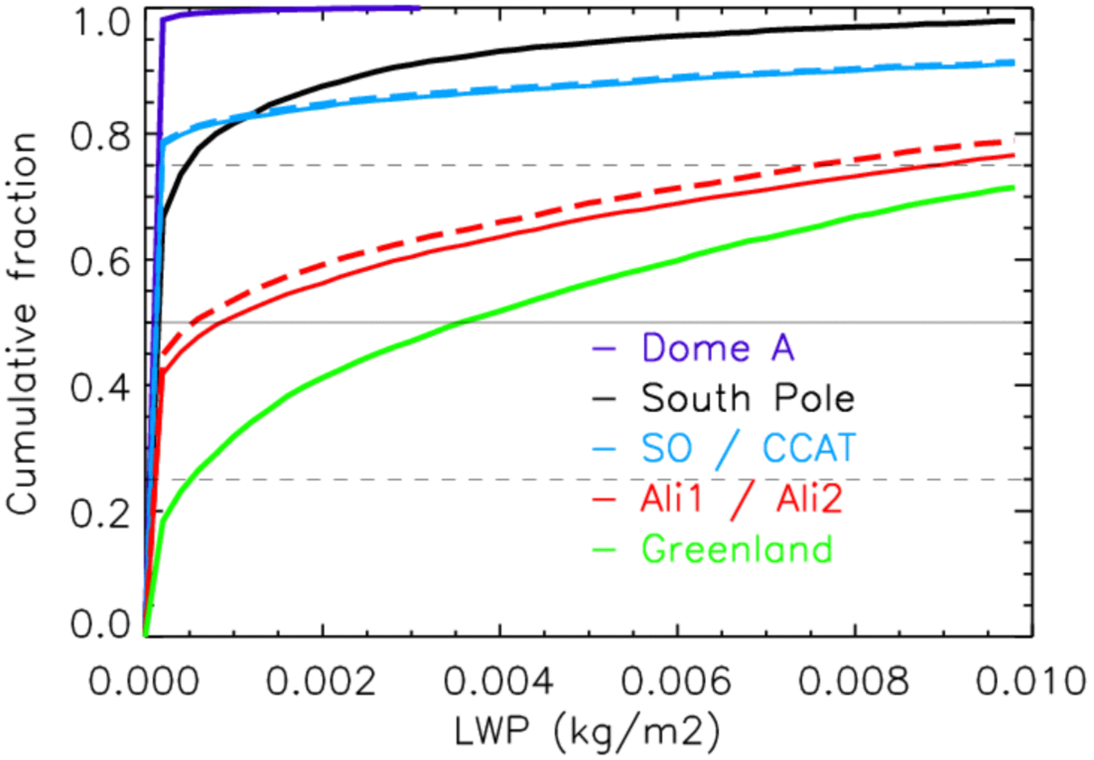
	elev. (m)	*PWV* (mm)			d*PWV* (mm)			*IWP* (kg.m^-2)			*LWP* (kg.m^-2)		
		25%	**50%**	75%	25%	**50%**	75%	25%	**50%**	75%	25%	**50%**	75%
Dome A	4,093	0.105	**0.141**	0.191	3.65E-03	**6.56E-03**	1.21E-02	8.09E-05	**2.30E-04**	6.11E-04	-	**-**	-
South Pole	2,835	0.231	**0.321**	0.448	1.04E-02	**1.77E-02**	3.17E-02	1.96E-04	**1.14E-03**	3.97E-03	-	**1.77E-05**	4.54E-04
Chajnantor (SO)	5,190	0.618	**0.993**	1.871	1.07E-01	**2.20E-01**	4.32E-01	-	**2.23E-05**	1.69E-03	-	**-**	4.33E-05
Cerro Chajnantor	5,612	0.48	**0.746**	1.439	8.28E-02	**1.71E-01**	3.47E-01	-	**2.15E-05**	1.69E-03	-	**-**	3.22E-05
Ali1	5,250	0.871	**1.343**	2.125	1.59E-01	**2.66E-01**	4.45E-01	7.62E-06	**1.16E-03**	1.14E-02	-	**8.70E-04**	8.91E-03
Ali2	6,100	0.459	**0.759**	1.207	1.01E-01	**1.81E-01**	3.21E-01	1.70E-06	**9.91E-04**	1.08E-02	-	**5.36E-04**	7.56E-03
Greenland	3,216	0.509	**0.817**	1.436	4.14E-02	**7.89E-02**	1.56E-01	6.34E-04	**2.54E-03**	8.34E-03	5.18E-04	**3.57E-03**	1.15E-02

1. In terms of PWV quartiles: **Dome A** < **South Pole** < **Ali2 ~ CC ~ GL** < **SO ~ Ali1**
2. We should also pay attention to dPWV (fluctuations) and LWP (liquid clouds)

MERRA-2 Results

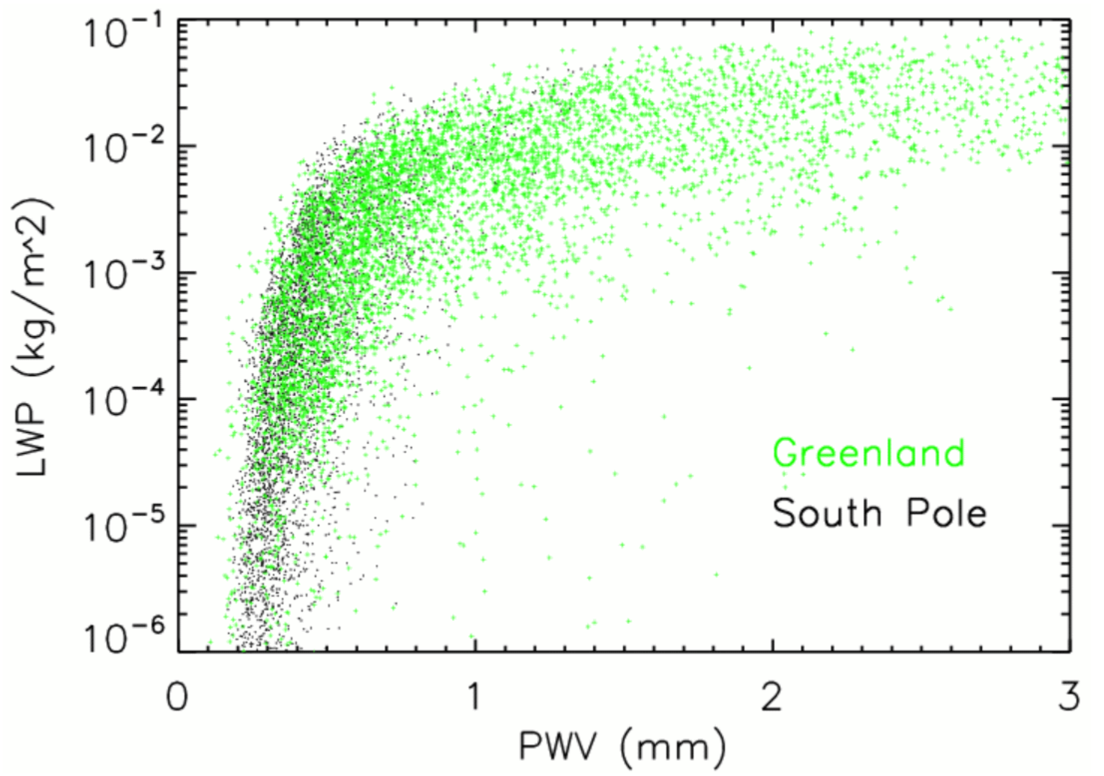


icy clouds

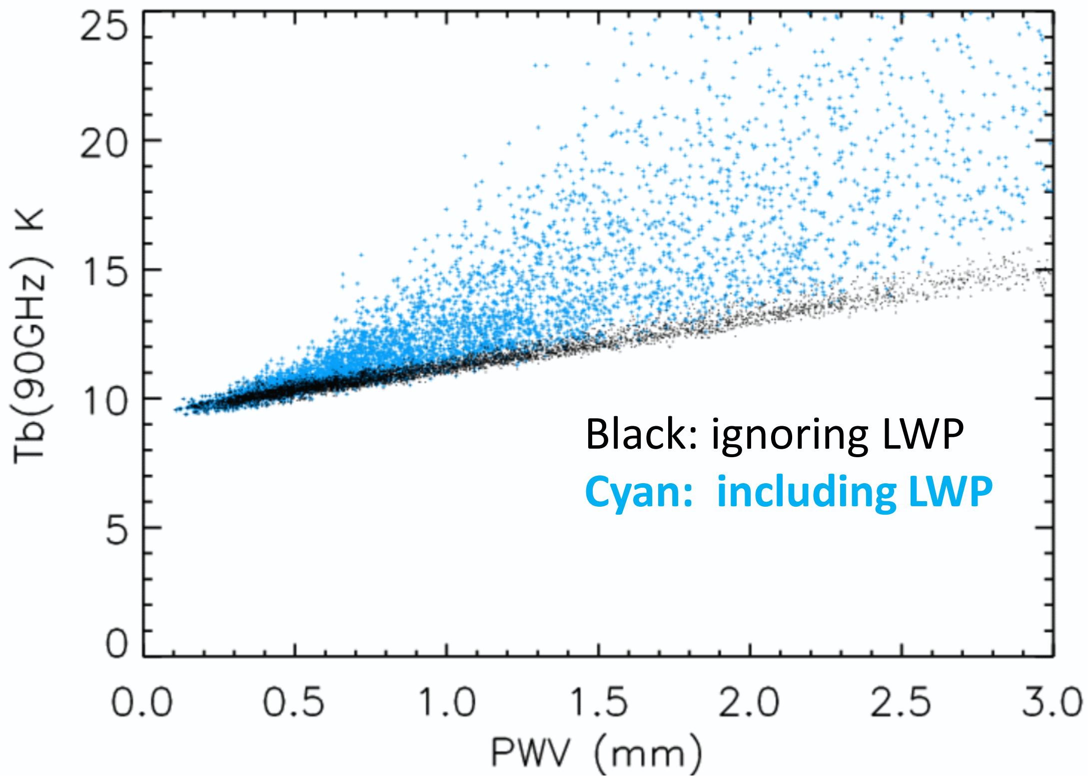


liquid clouds

Effects of liquid water clouds



Summit Camp, Greenland



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Brightness temperature fluctuations

			90GHz			150GHz			220GHz		
			25%	**50%**	**75%**	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**
Dome A	dT_{rj} (K)		5.6E-03	1.0E-02	1.9E-02	1.9E-02	3.5E-02	6.4E-02	4.2E-02	7.6E-02	0.14
South Pole	dT_{rj} (K)		1.6E-02	2.7E-02	4.9E-02	5.5E-02	9.3E-02	0.17	0.12	0.20	0.37
	ΔT_{rj} (K)	**vapor only**	2.24E-03	4.27E-03	8.18E-03	7.65E-03	1.46E-02	2.79E-02	1.67E-02	3.19E-02	6.11E-02
		v+liq. lnr	3.10E-03	7.08E-03	2.07E-02	9.55E-03	2.04E-02	5.08E-02	1.99E-02	4.21E-02	9.61E-02
		v+liq. quad	2.77E-03	6.18E-03	1.65E-02	8.73E-03	1.80E-02	4.13E-02	1.84E-02	3.65E-02	8.04E-02
Simons Obs.	dT_{rj} (K)		0.17	0.34	0.67	0.55	1.14	2.24	1.20	2.46	4.83
Cerro Chaj.	dT_{rj} (K)		0.13	0.26	0.54	0.43	0.89	1.80	0.93	1.91	3.89
Ali1	dT_{rj} (K)		0.25	0.41	0.69	0.82	1.38	2.31	1.78	2.98	4.98
Ali2	dT_{rj} (K)		0.16	0.28	0.50	0.52	0.94	1.66	1.13	2.03	3.59
Greenland	dT_{rj} (K)		6.39E-02	0.12	0.24	0.21	0.41	0.81	0.46	0.88	1.75
	ΔT_{rj} (K)	**vapor only**	9.35E-03	2.01E-02	4.28E-02	3.14E-02	6.75E-02	0.14	6.79E-02	0.15	0.31
		v+liq. lnr	3.40E-02	0.11	0.29	8.00E-02	0.21	0.50	0.14	0.36	0.81
		v+liq. quad	3.01E-02	9.41E-02	0.25	6.49E-02	0.17	0.40	0.11	0.27	0.64

“ When measured in the units of the South Pole *d*PWV median, the *d*PWV medians for Dome A, Greenland, Cerro Chajnantor, Simons Obs., Ali2, Ali1 are **0.37, 4.5, 9.7, 12.4, 10.2, 15.0**, respectively. ”

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Ali-CMB Program

- **Program:** one of the four major astro-cosmo projects supported by Chinese Academy of Sciences (the others being FAST, studies of space gravitational wave probes TianQin & TaiJi)
- **Goal:** search for primordial gravitational waves through *B*-mode polarization
- **Site:** Ali, Tibet
  - Near Ali airport/town; good transportation + electricity
- **Experimental Program:**
  - Focusing on tensor perturbations (*r*)
  - Phase I: at 5,250m (single receiver, 95/150GHz); wide survey
  - *Phase II+: ~6,000m (multiple multichroic receivers) + possible delensing telescope(s)* : this could be China's generation-4 CMB program


Summit station
Greenland
Latitude: N+32° 19'
Daily flight from Lhasa (Tibet capital)
Dry side of Himalayas
Ali, Tibet
US Dept of State Geographer
© 2016 Google
Image Landsat / Copernicus
© 2009 GeoBasis-DE/BKG
Google

IHEP / SLAC Collaboration on Ali-CMB

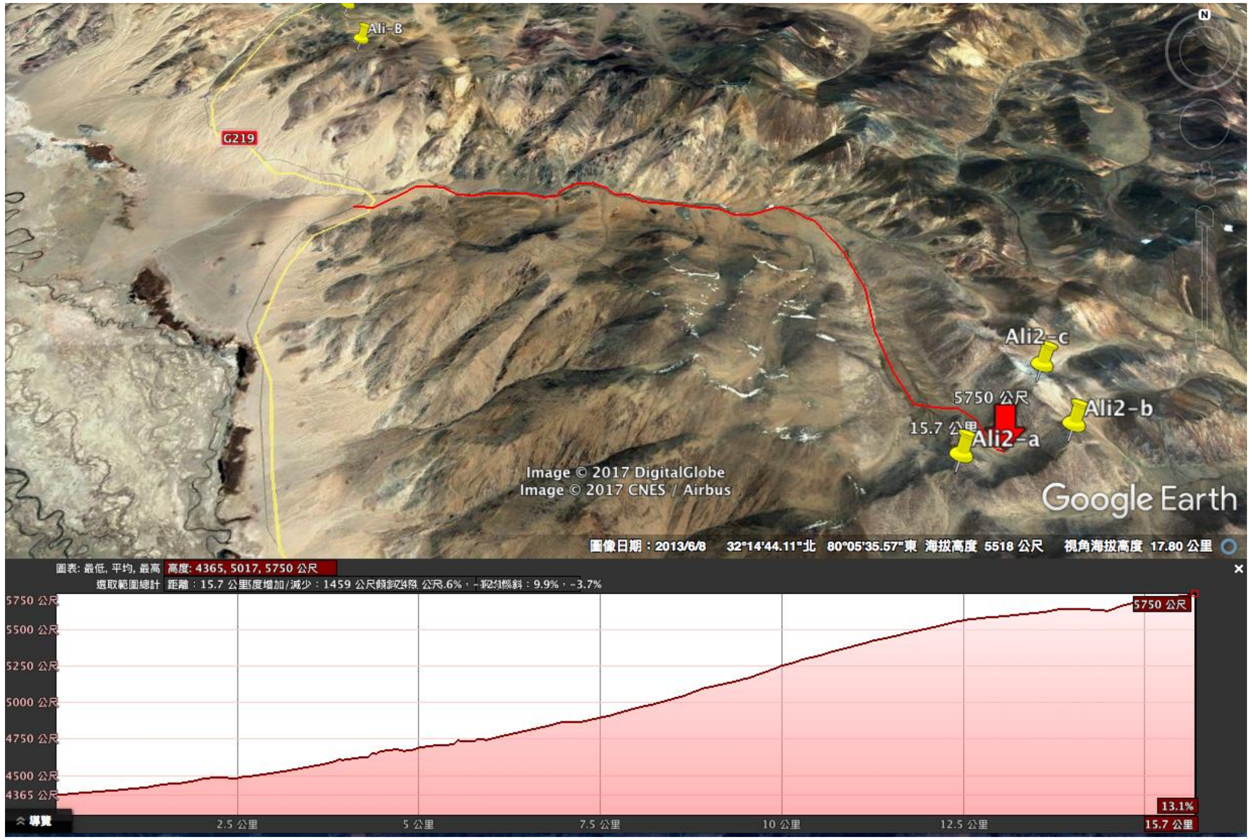
- Institute of High Energy Physics, Chinese Academy of Sciences
  - Leading the 100-TeV collider concept
  - Has a strong particle-astrophysics program, e.g., HXMT (successfully launched in June)
  - Past collaborating with DOE and NSF:
    - Daya Bay neutrino exp. made ground-breaking measurements on ϑ_{13}
    - Collider-based particle experiments
- SLAC/Stanford CMB group just led the development and deployment of BICEP3 receiver (running at 8 uK-rtS) ; does cold optics; starting a major program on microwave SQUIDs ; building a clean room for fabrication of superconducting detectors
- Discussions between IHEP and SLAC started in 2014. First agreement concerning Phase-I of the program (single receiver), carried out under the guidance of CAS, DOE using the ICRADA framework (International Cooperative Research Development Agreement)
- SLAC becomes a full science partner of Ali-CMB program ; China joins the R&D effort
- Responsibilities: SLAC (receiver/focal plane/readout) ; China (site/observatory/mount)

June 6

July 1

Collaboration Meeting @ Stanford Center in Peking U (July 11)

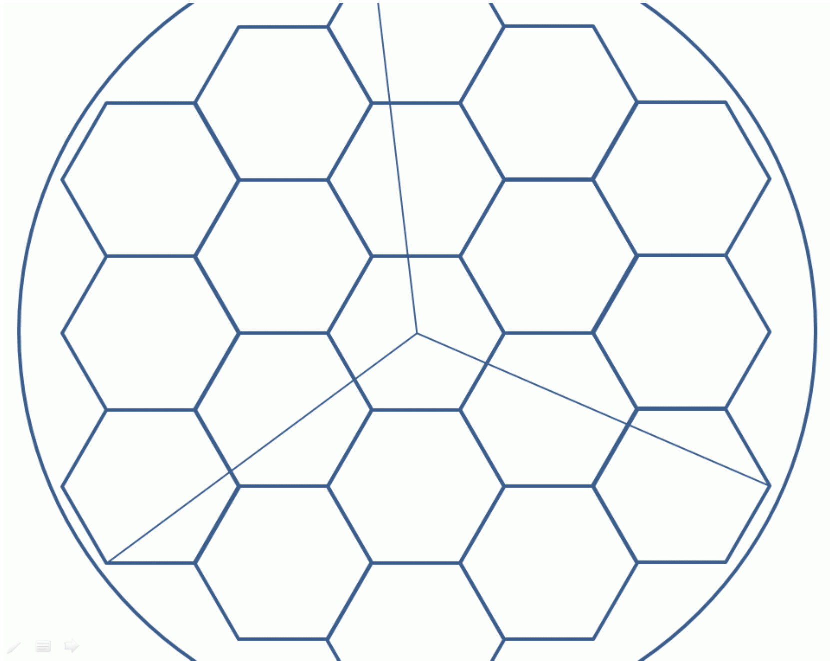
SLAC team visited Ali 5250m (July 16)

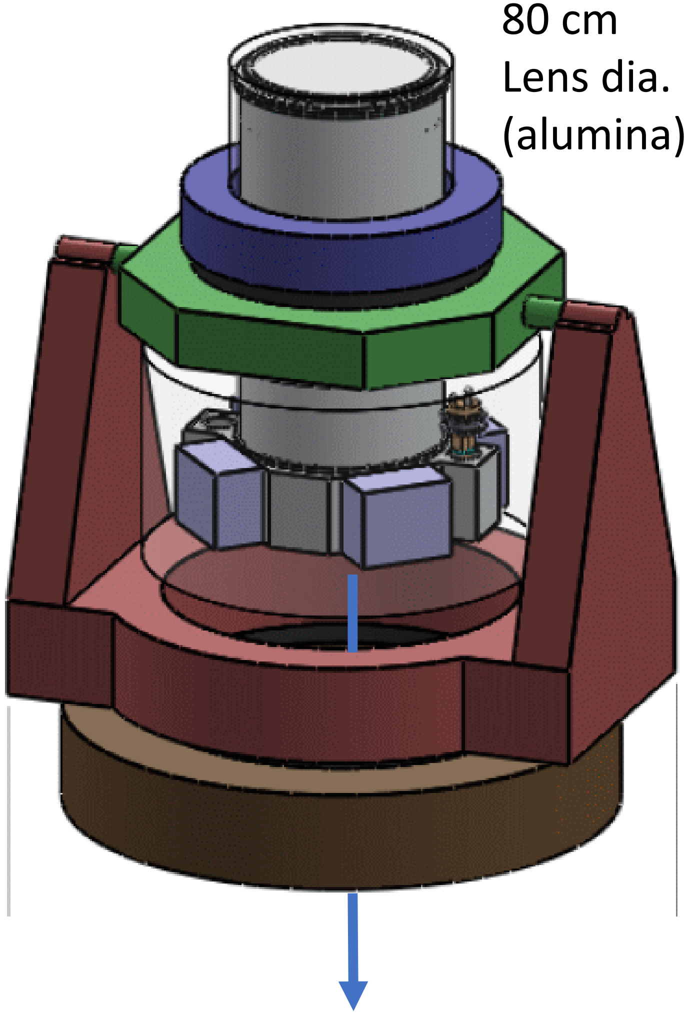


All three candidate sites at 6000 m+

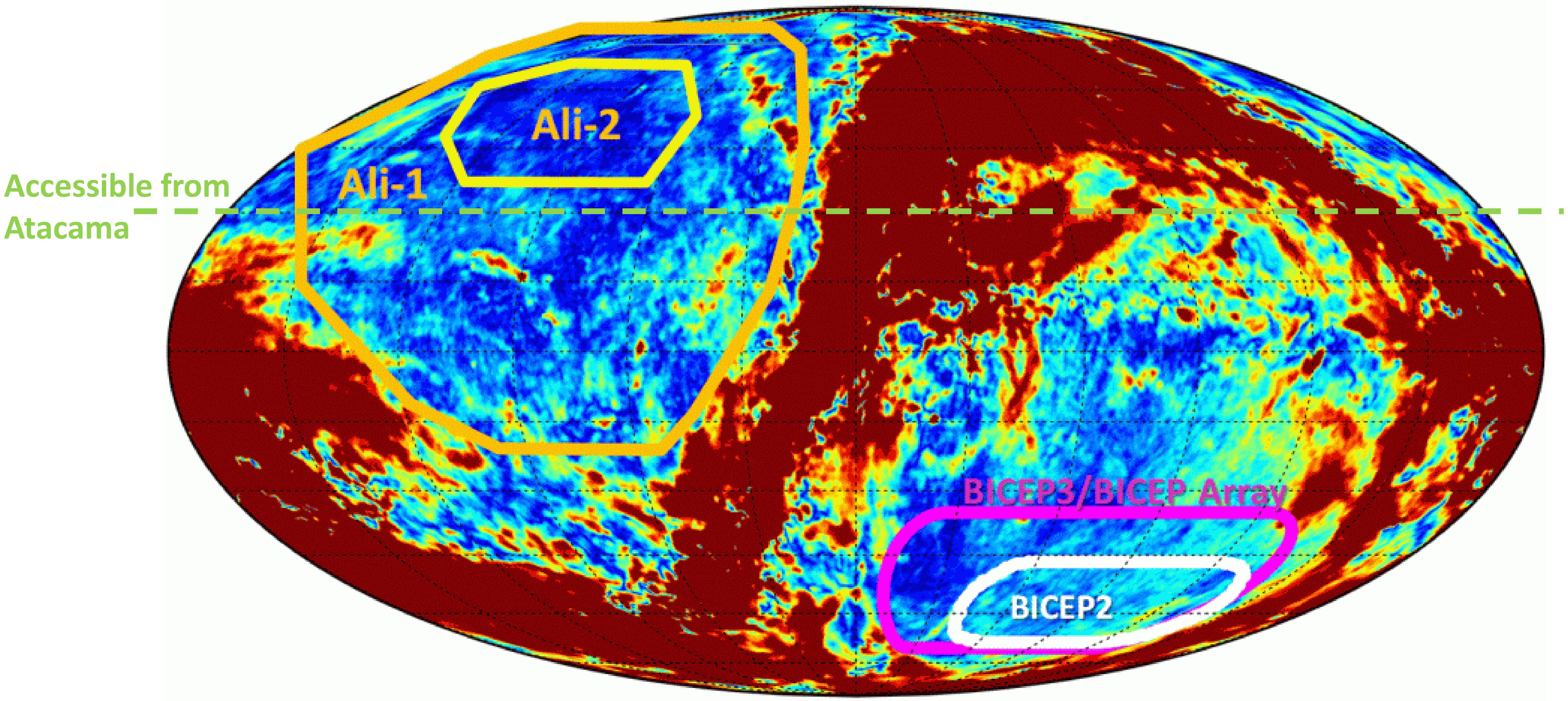
Basic features of the receiver

- We know how to build 80cm lenses (SPT3G) & ~90 cm windows/ IR filters (SPT3G & BICEP3)
- Easily accommodating **19** **six-inch** modules in a single compact telescope





Complementary to CMB-S4



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Thank you!