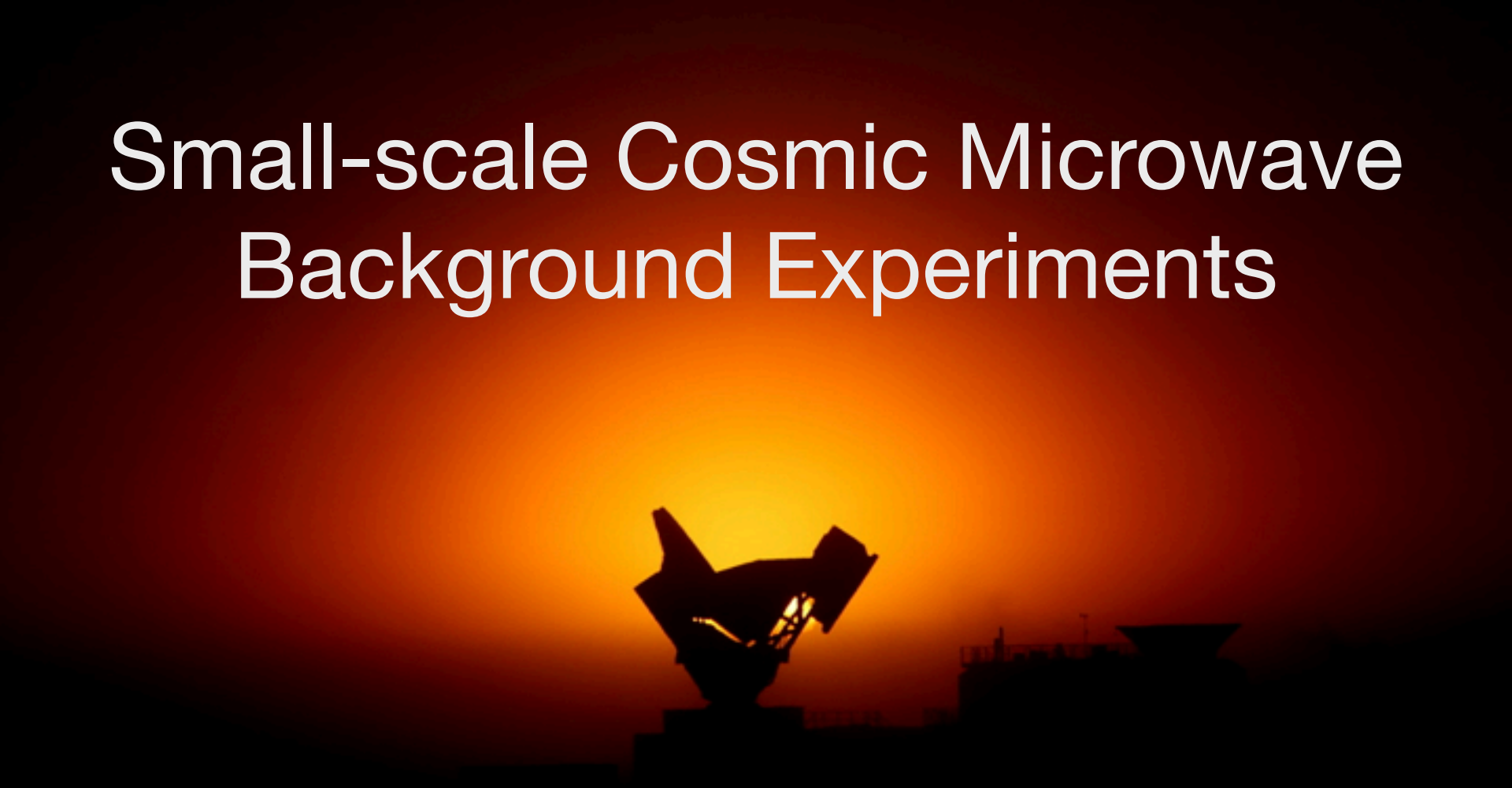
Small-scale Cosmic Microwave Background Experiments

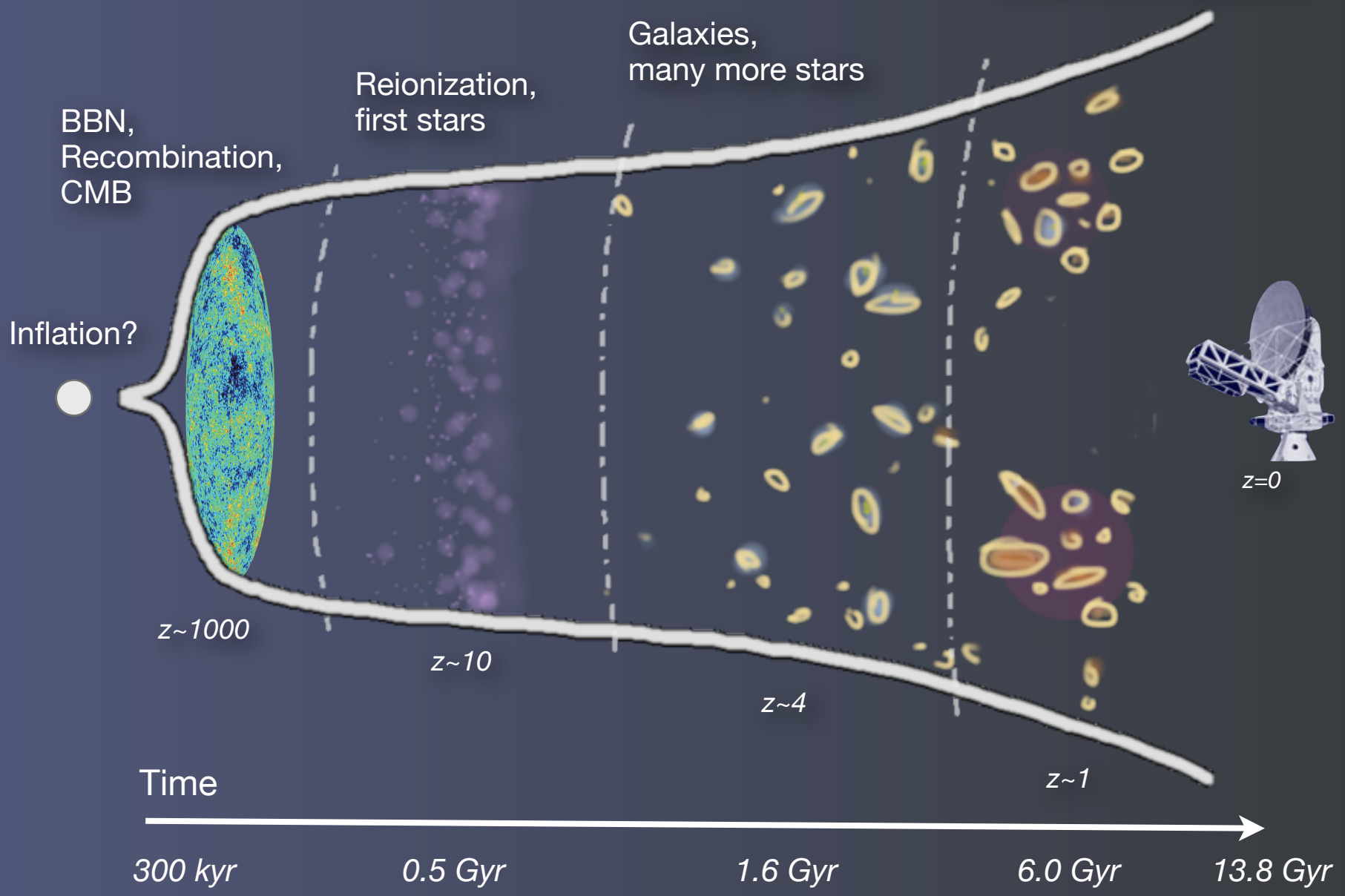


Christian Reichardt
UC Berkeley

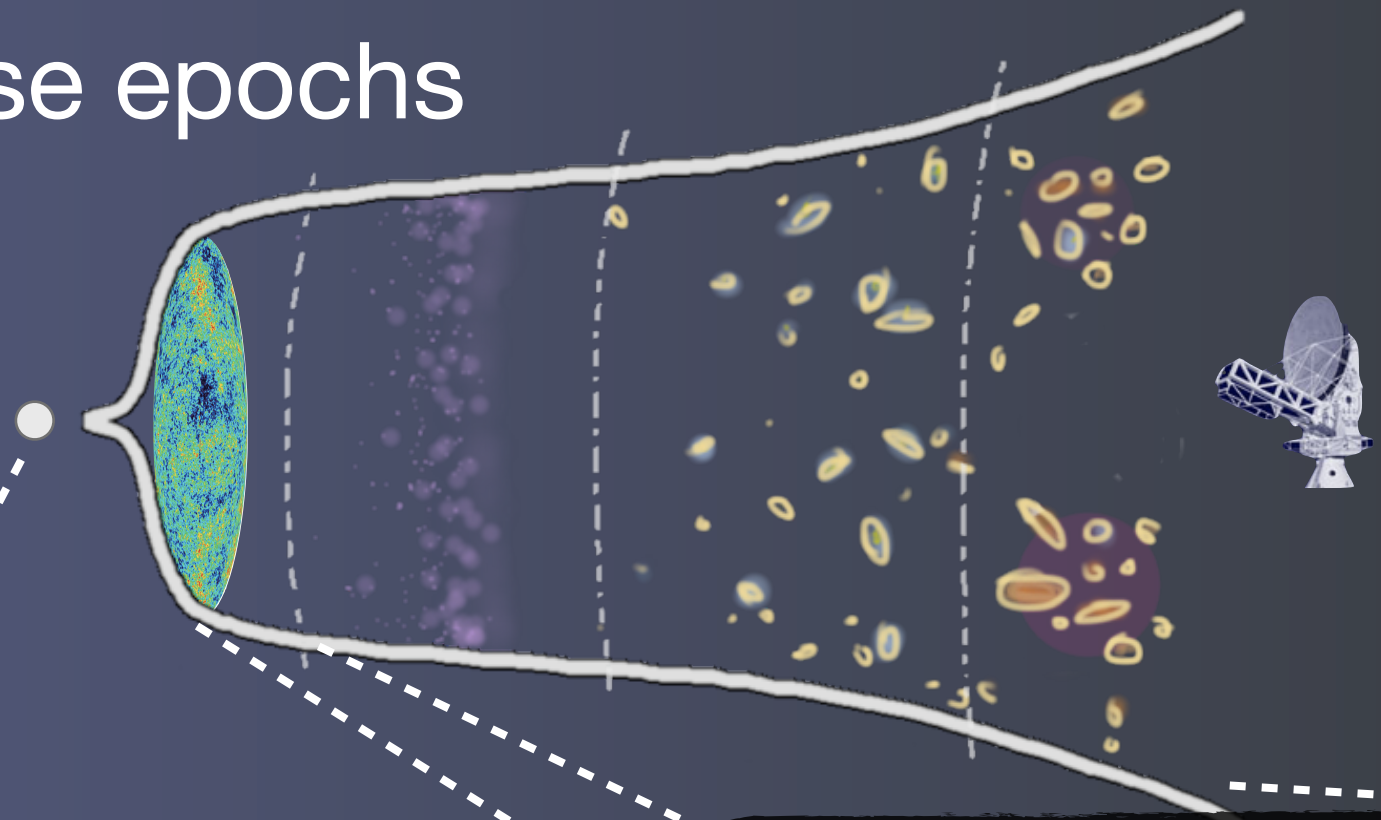
Outline

- Why study small scales? What do you see?
- Cosmic microwave background (CMB) power spectrum & interpretation
  - What caused inflation?
- Future directions with CMB lensing
  - SPT-Pol, PolarBear & ACTPol + their successors

Cosmic Timeline



Small-scale CMB touches all these epochs



CMB power spectrum:

- **What caused inflation?**
- How many neutrino species are there?

etc.

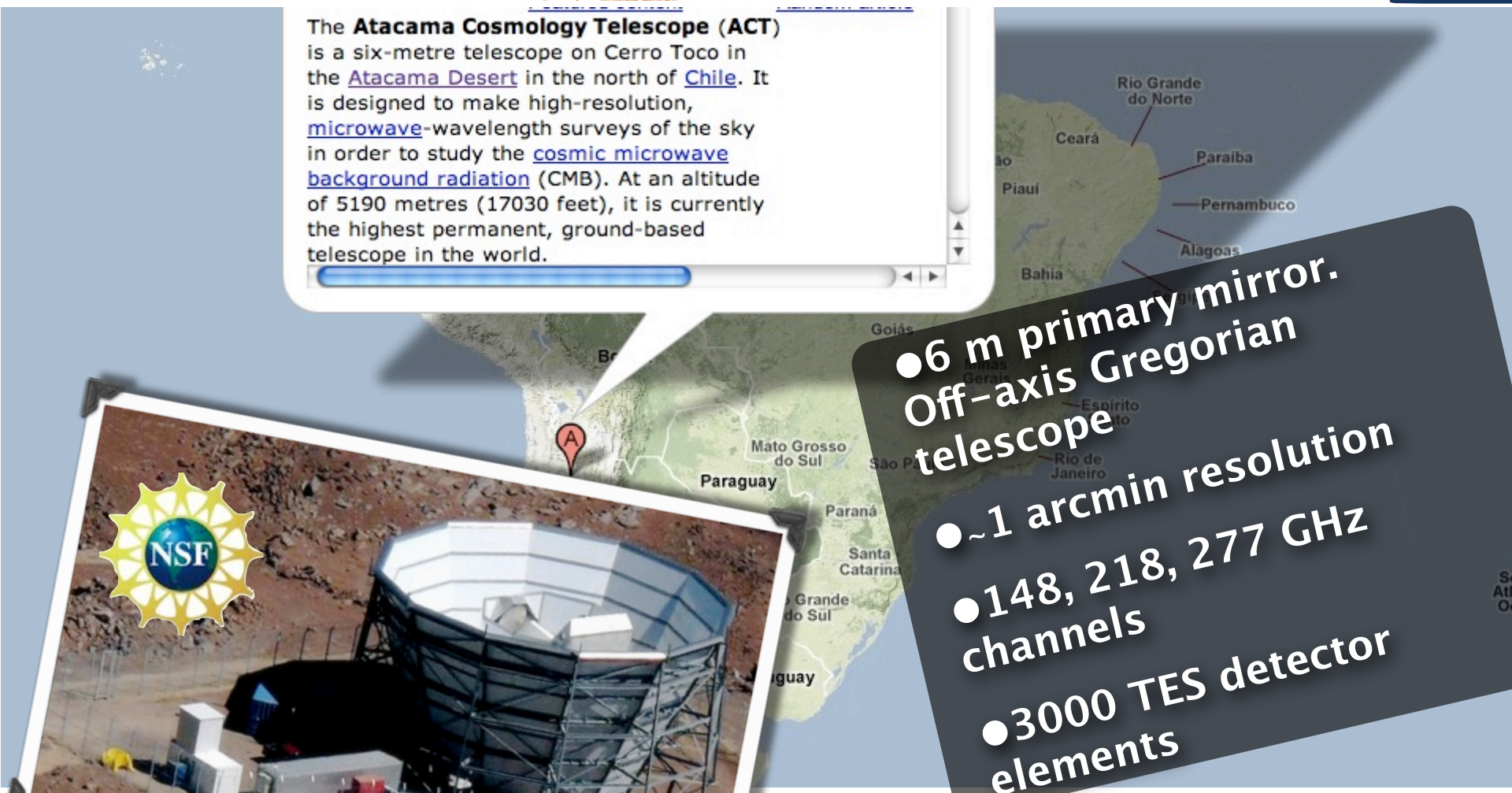
Sunyaev-Zel'dovich (SZ) signal & gravitational lensing:

- What are the neutrino masses?
- How long did the epoch of reionization last?

etc.

THE ATACAMA COSMOLOGY TELESCOPE

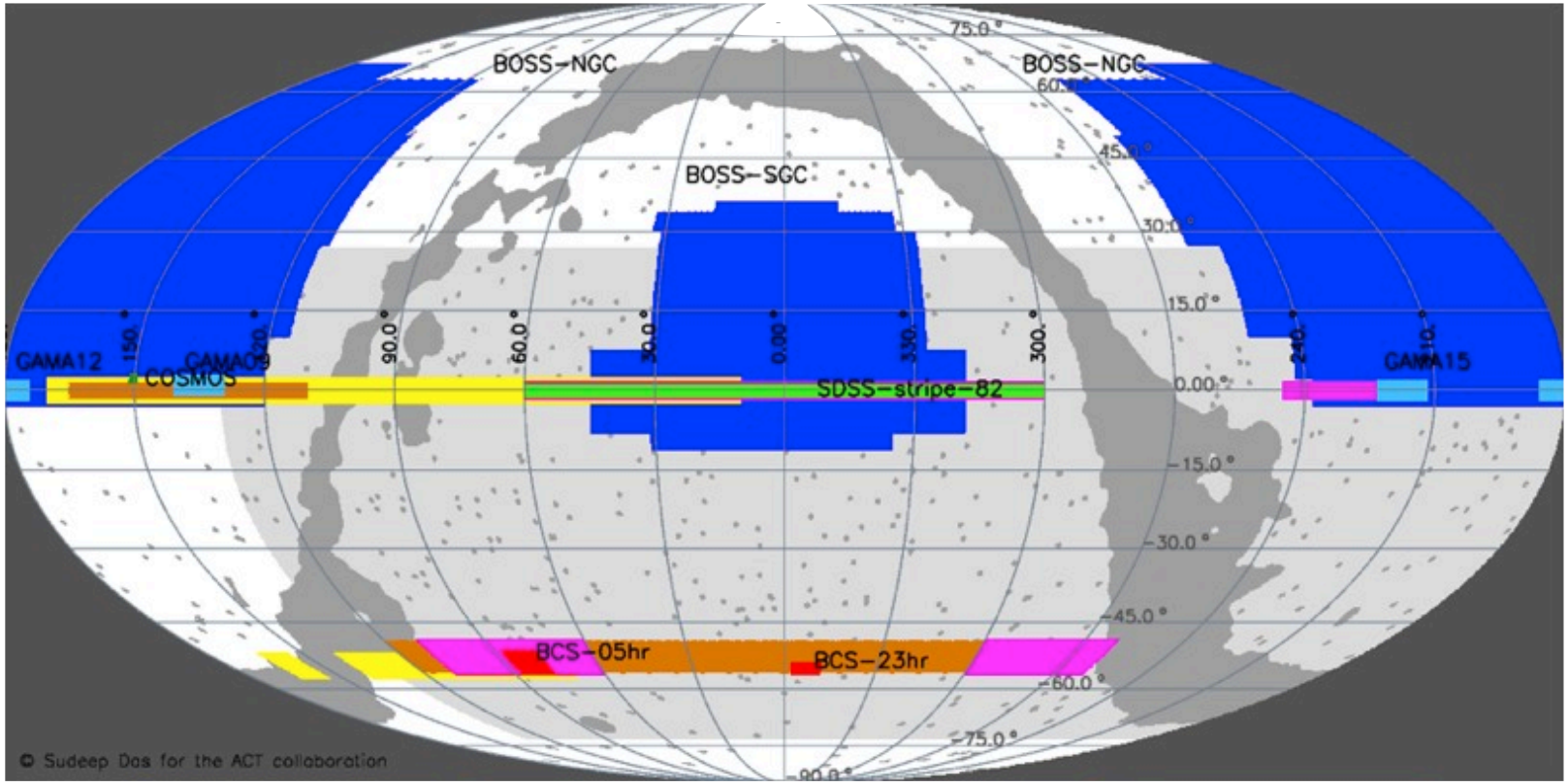
The **Atacama Cosmology Telescope** (**ACT**) is a six-metre telescope on Cerro Toco in the Atacama Desert in the north of Chile. It is designed to make high-resolution, microwave-wavelength surveys of the sky in order to study the cosmic microwave background radiation (CMB). At an altitude of 5190 metres (17030 feet), it is currently the highest permanent, ground-based telescope in the world.



- 6 m primary mirror. Off-axis Gregorian telescope
- ~1 arcmin resolution
- 148, 218, 277 GHz channels
- 3000 TES detector elements

Swetz et al. (2010)

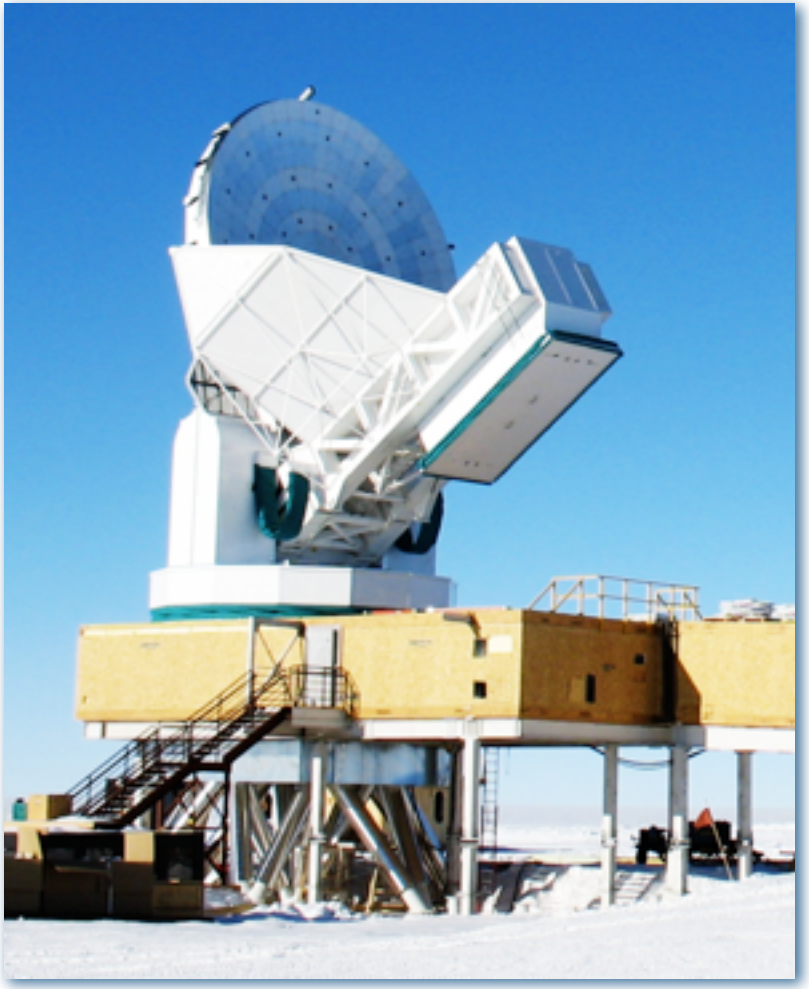
ACT has observed about 1800 sq. Degrees at arcminute resolution!



2007 | 2008 | 2009+10 | Stripe 82

BCS | BOSS | GAMA | ACT Range | Mask

The South Pole Telescope (SPT)

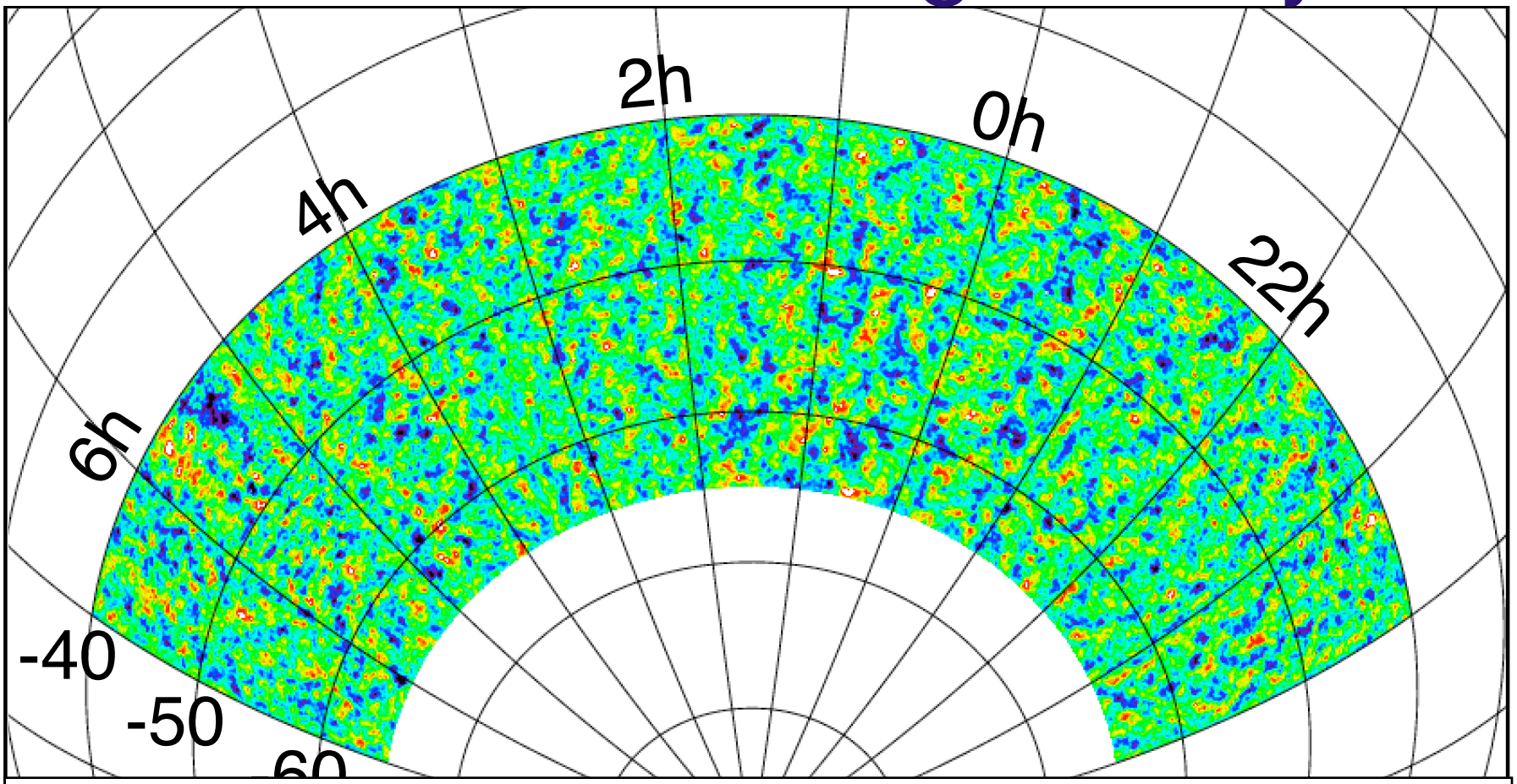


Sub-millimeter Wavelength Telescope:

- 10 meter telescope (1.1’ FWHM beam)
- Three frequencies: 95, 150, 220 GHz
- Fast scanning (up to 2 deg/sec in azimuth)
- 2” pointing accuracy

Funded by NSF

SPT-SZ 2500 deg^2 survey



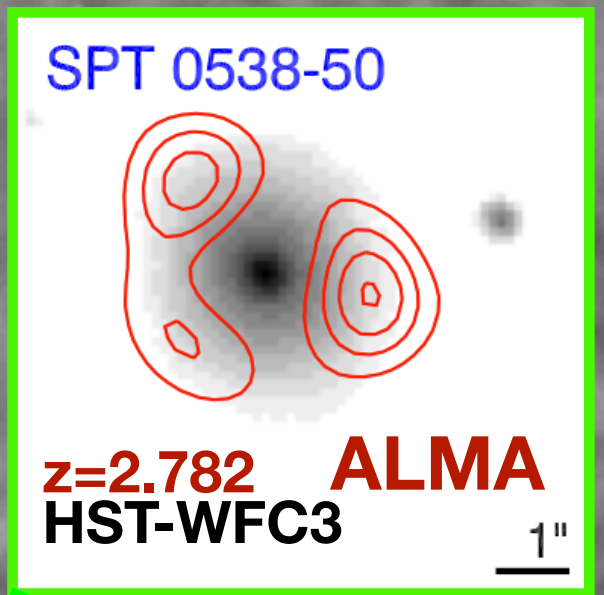
Status: finished in *Nov. 2011*.

18 μK-arcmin at 150 GHz

Deepest large-area CMB map

Zoom in on an SPT map

~50 deg^2 from
2500 deg^2 survey



Radio and dusty galaxies
show up as bright spots

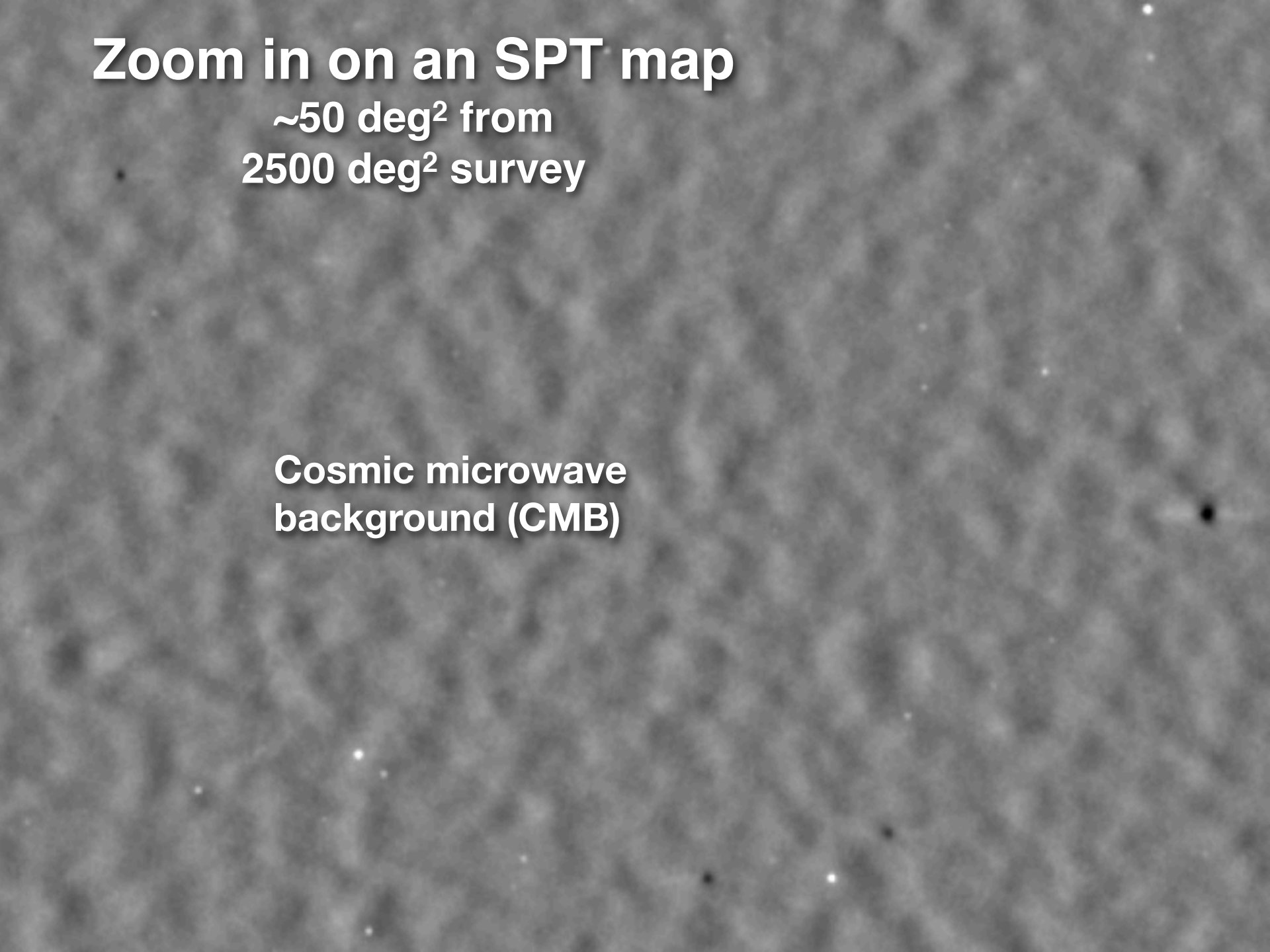
Zoom in on an SPT map

~50 deg^2 from
2500 deg^2 survey

High signal to noise Sunyaev-Zel'dovich (SZ) galaxy cluster detections as "shadows" against the CMB!

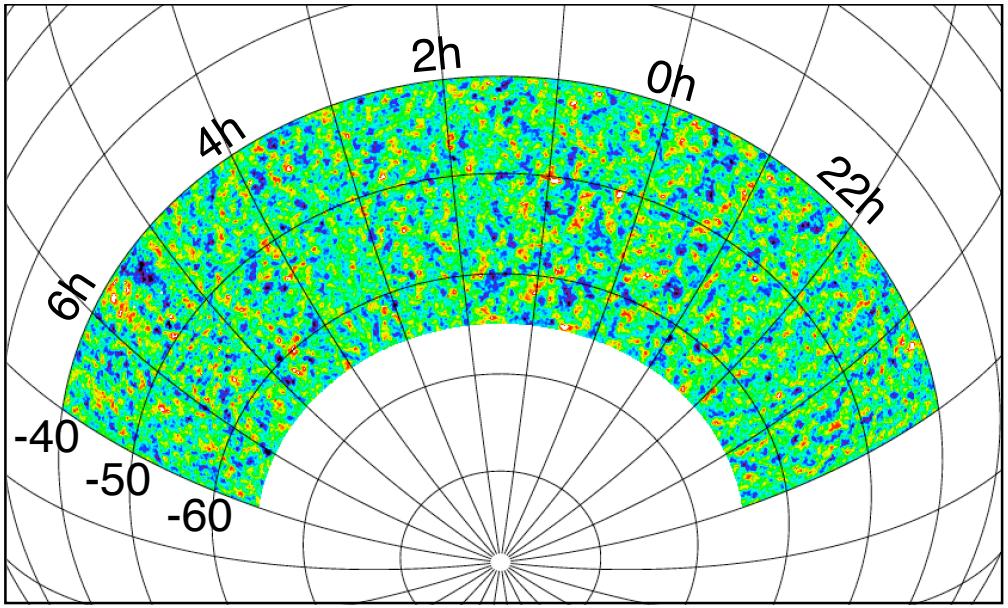
Zoom in on an SPT map

~50 deg^2 from
2500 deg^2 survey



Small scale surveys

SPT-SZ 2500 deg^2 survey



Two main types of analyses:

(1) Find objects in the map

- Sunyaev-Zel'dovich (SZ) clusters, high-redshift galaxies

(2) Calculate the N-point function of the map

- usually power spectrum, but also higher orders

SPT-SZ 2500 deg^2 survey

Non-exhaustive list of awesomeness:

Objects

- SZ-selected galaxy cluster catalog (~600 clusters, 85% new discoveries) out to high redshift (for Dark Energy)
- Discovery of a population of strongly lensed, high-redshift, star-forming galaxies.

2-point

- Most sensitive pre-Planck measurement of CMB power spectrum at ell>~600 (and still most sensitive at ell>~1850).
- Constraints on duration of epoch of reionization from kinetic SZ.

3-point

- >30 σ detection of bispectrum due to SZ & galaxies

4-point

- 2500 deg^2 CMB-lensing-derived map of projected mass between z=0 and z=1100.

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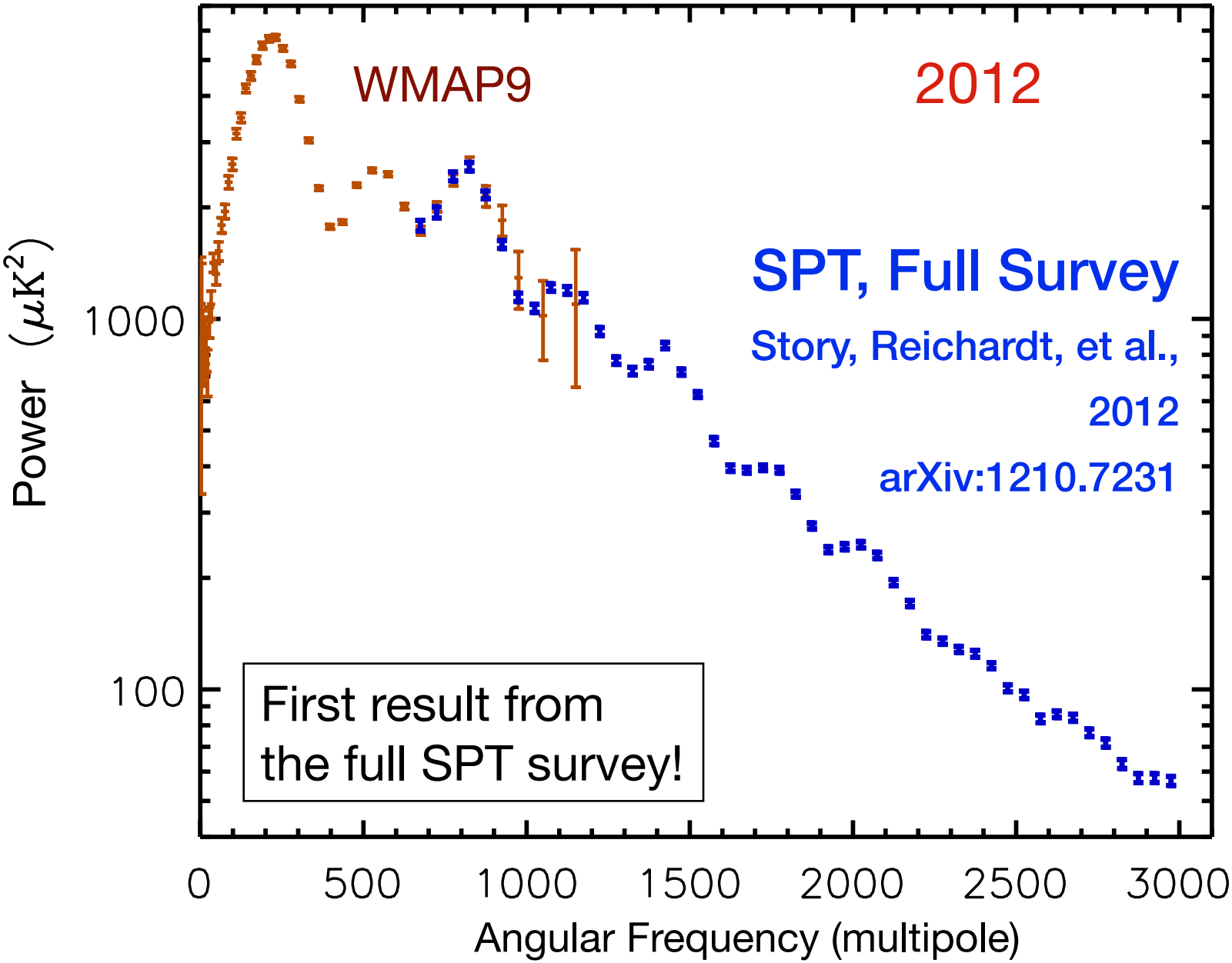
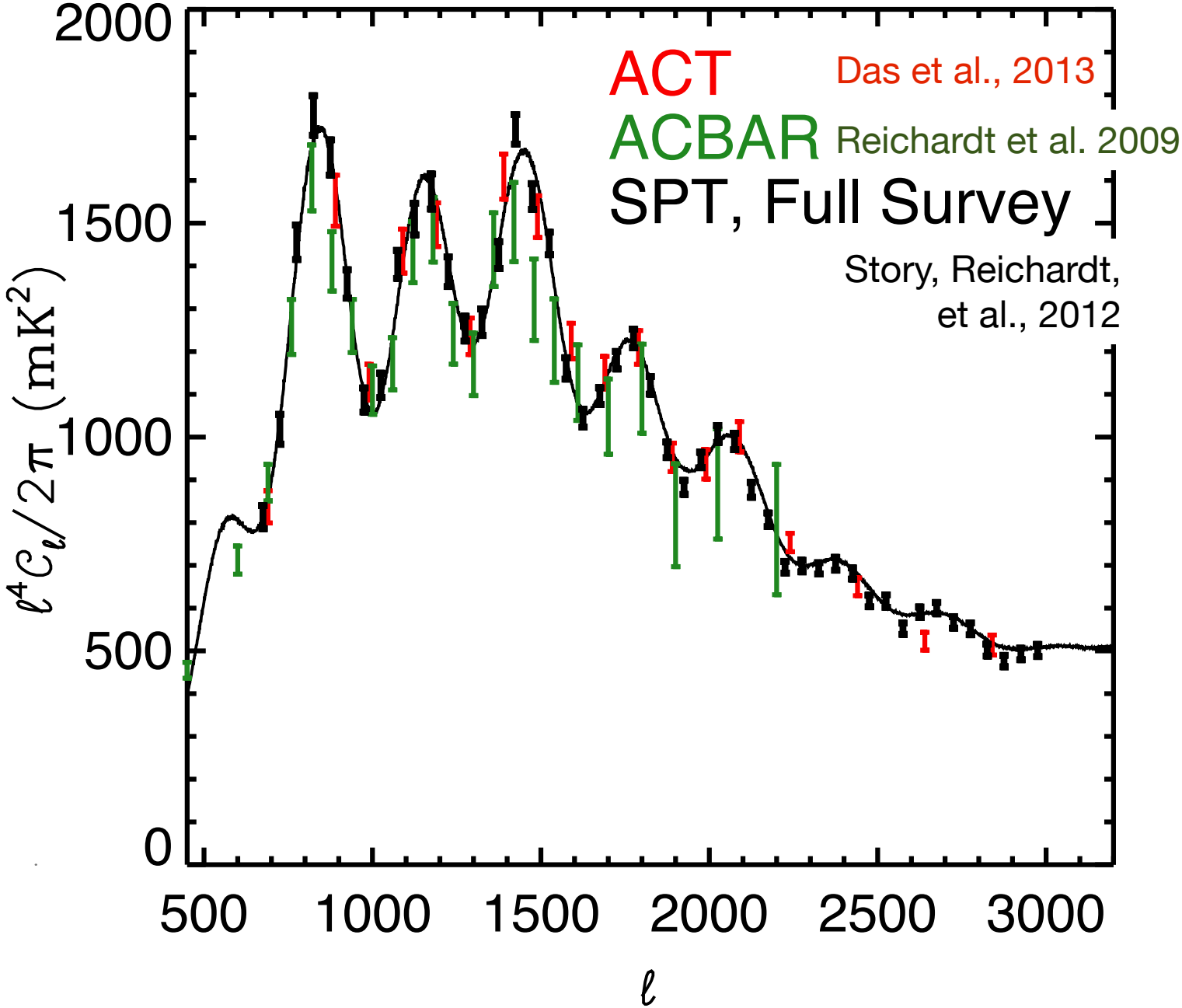
Cosmic microwave power spectrum



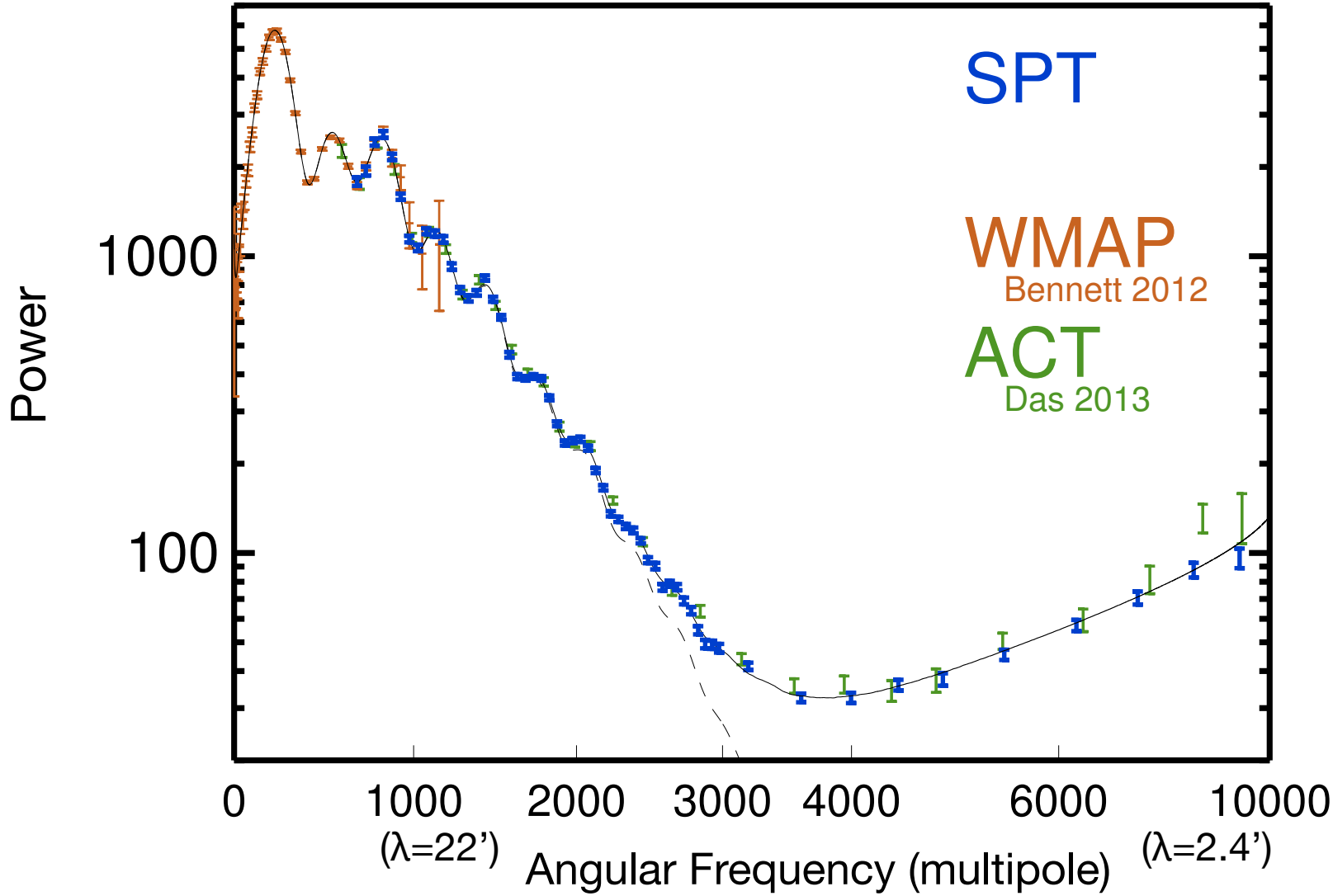
x3 improvement from SPT



Story, Reichardt, *et al.*, 2012
arXiv:1210.7231

State before Planck

Reichardt *et al.* 2012
arXiv:1111:0932



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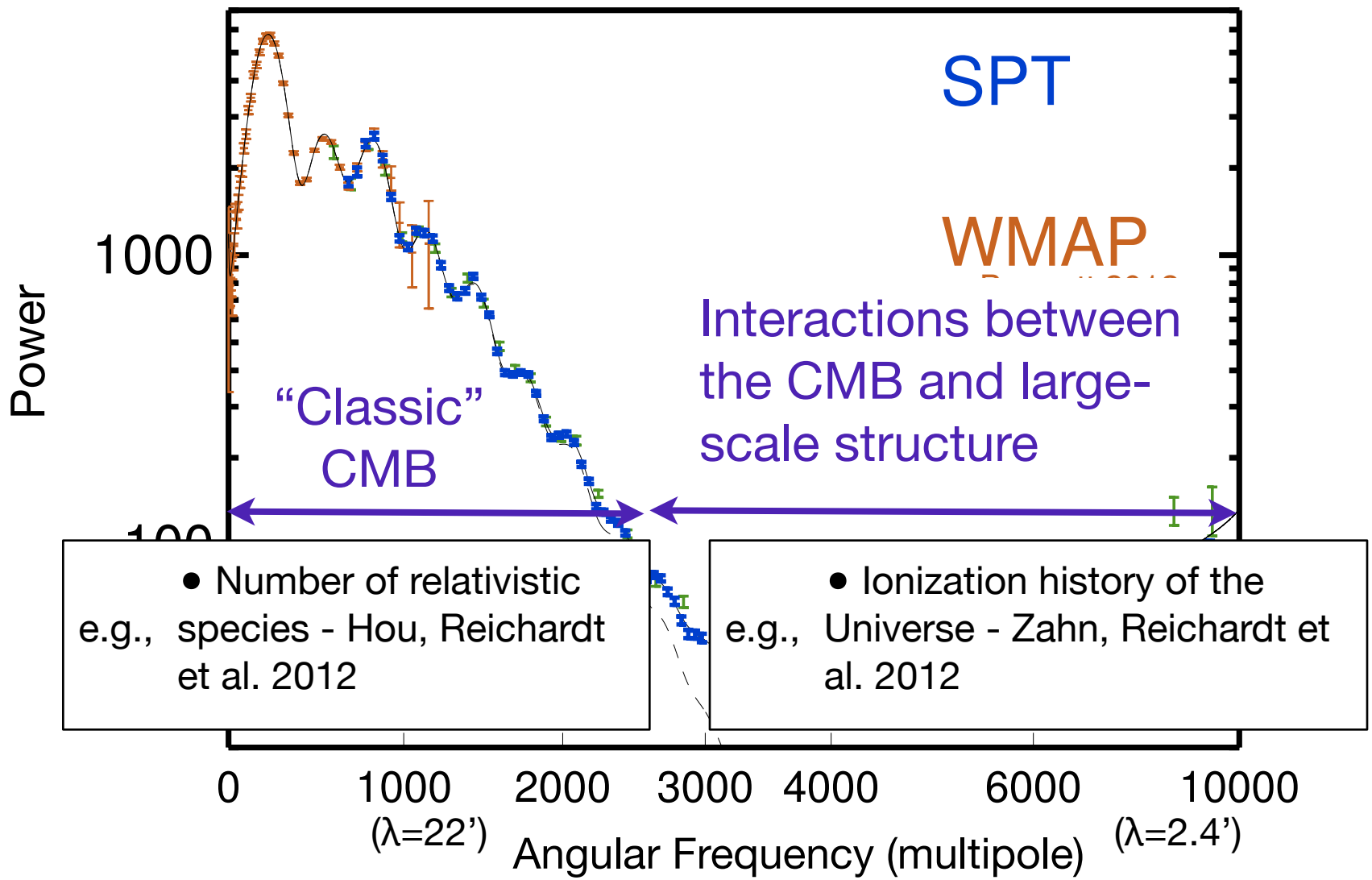


- Number of relativistic species - Hou, Reichardt et al. 2012

e.g.,

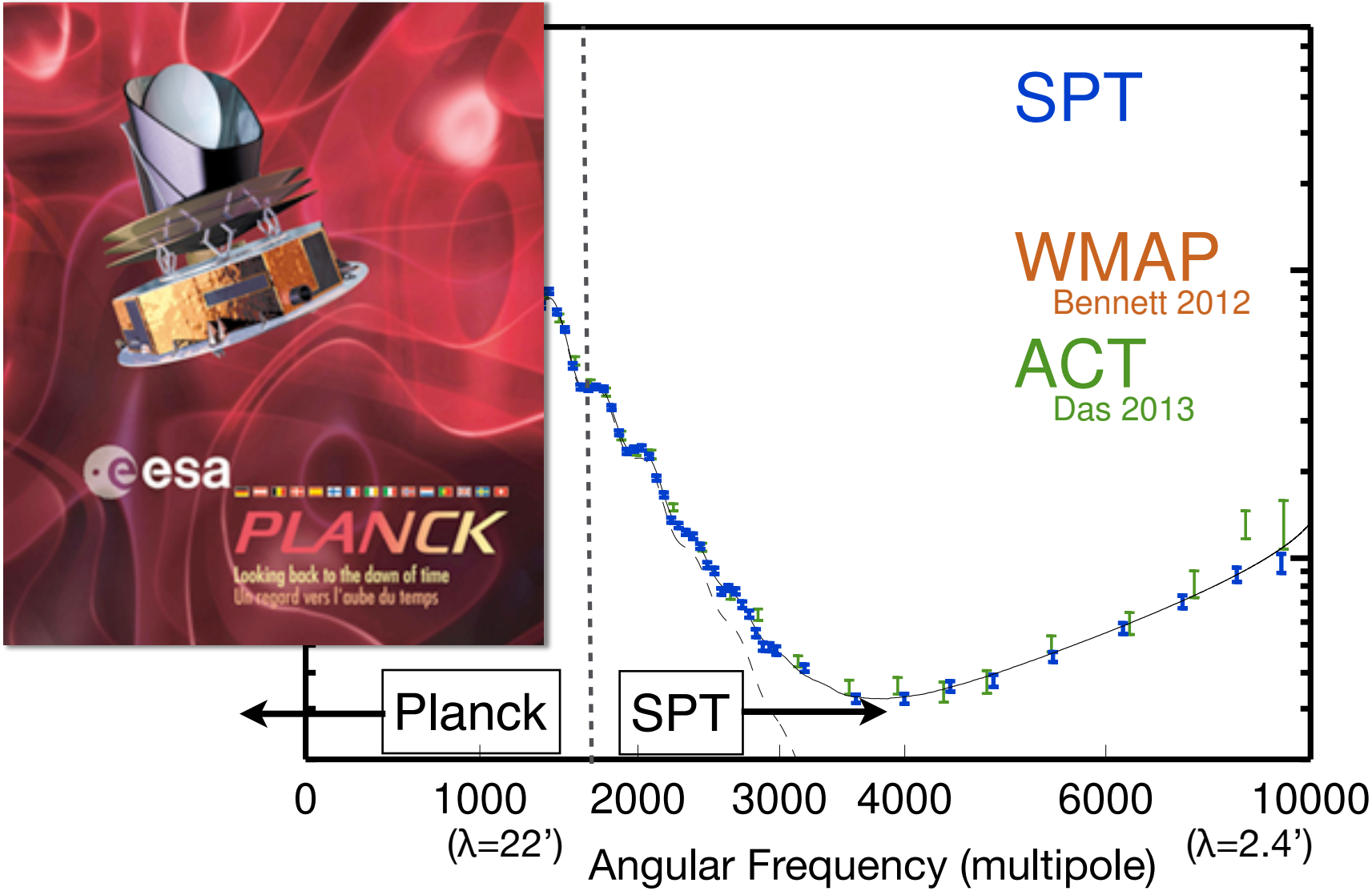
- Ionization history of the Universe - Zahn, Reichardt et al. 2012

e.g.,

Story, Reichardt, *et al.*, 2012
arXiv:1210.7231

with Planck

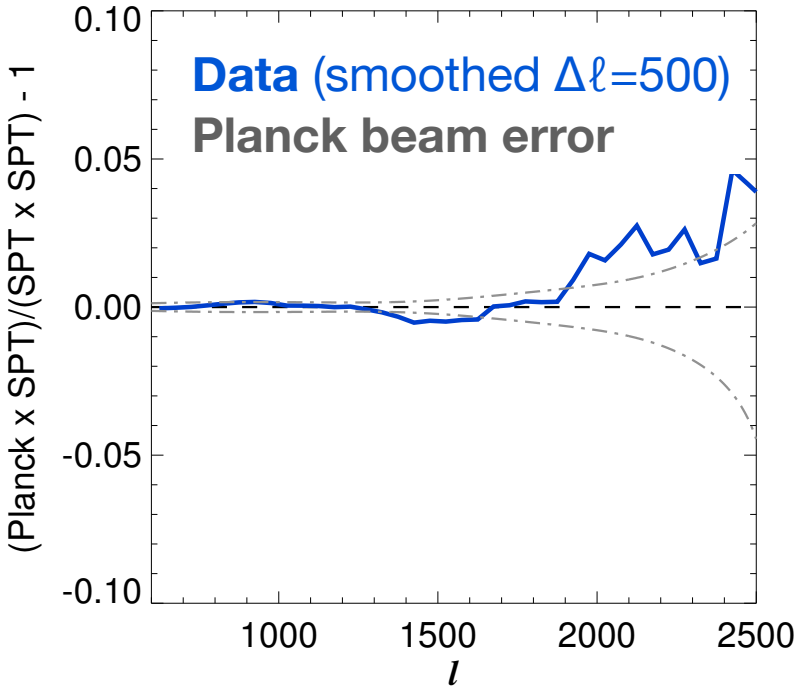
Reichardt *et al.* 2012
arXiv:1111:0932



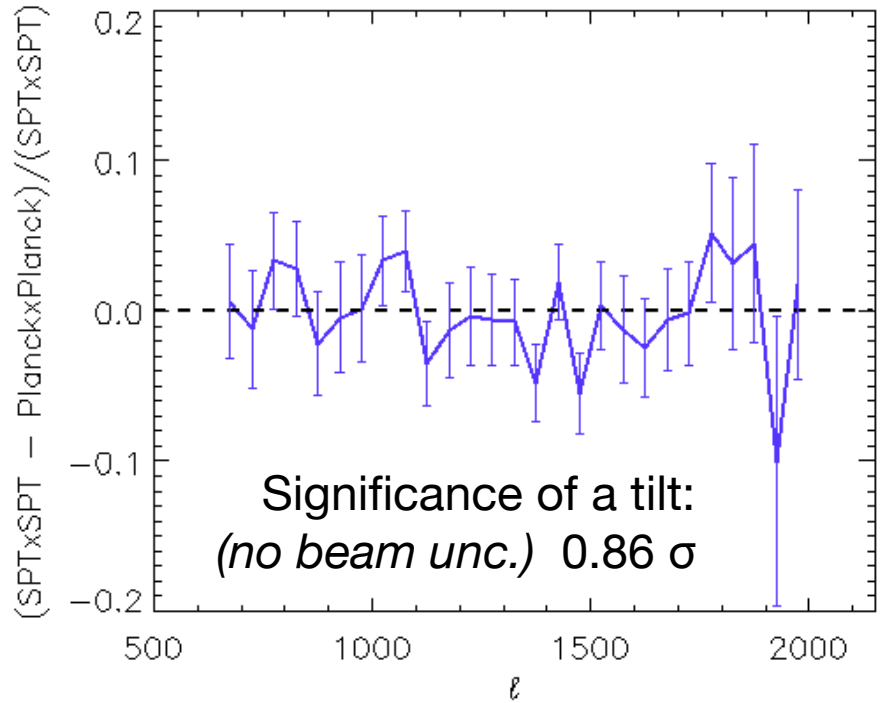
(as seen in John Ruhl's talk)

Comparing SPT & Planck

Rescaled - on 2500 deg^2



Rescaled - full sky



- Cross-spectrum is **consistent** within calibration and beam errors.
- No evidence for scale-dependent differences.

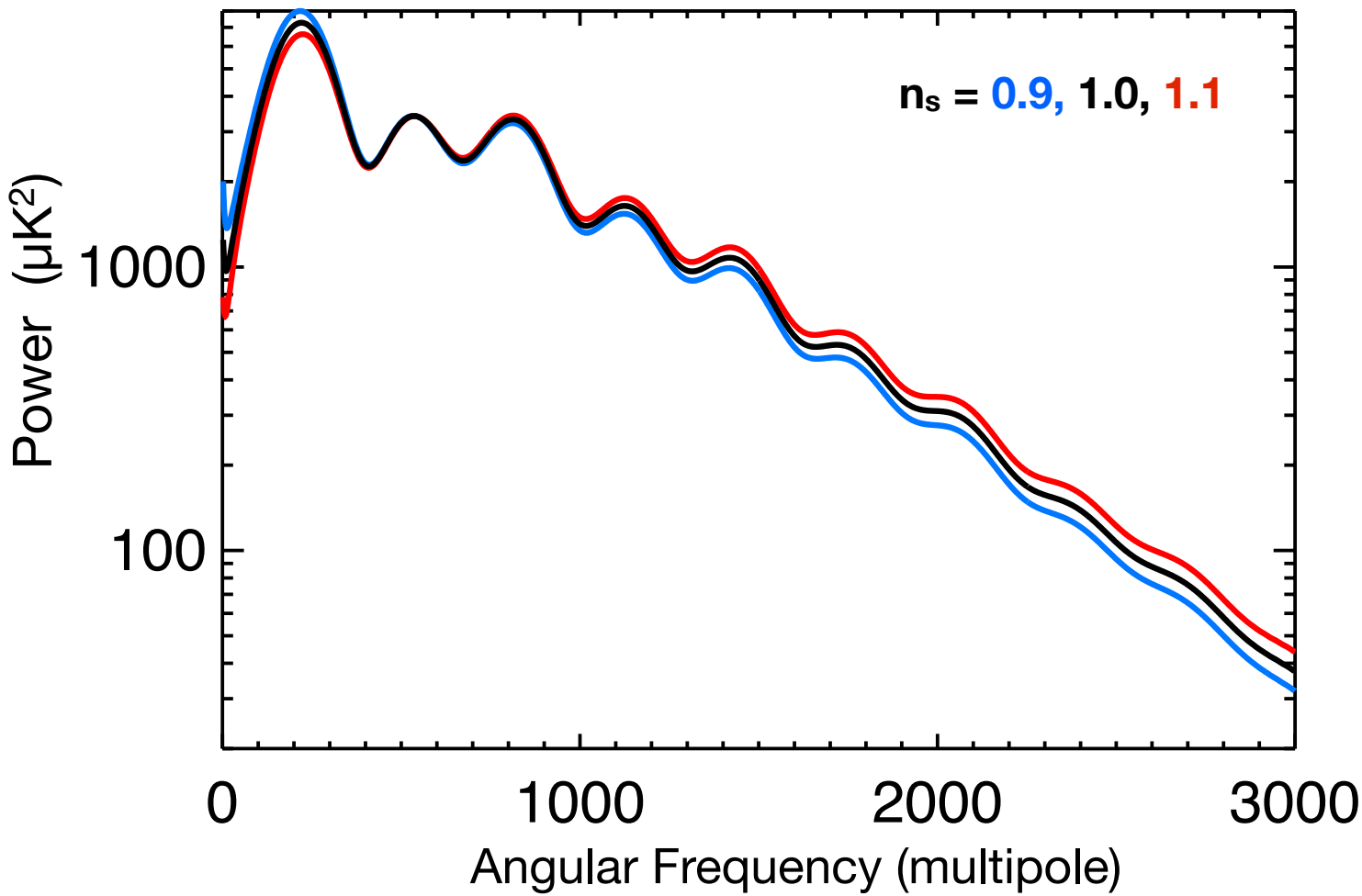
Re-scale: **1.8%**

SPT cal uncertainty: **2.6%**

[units of Power]

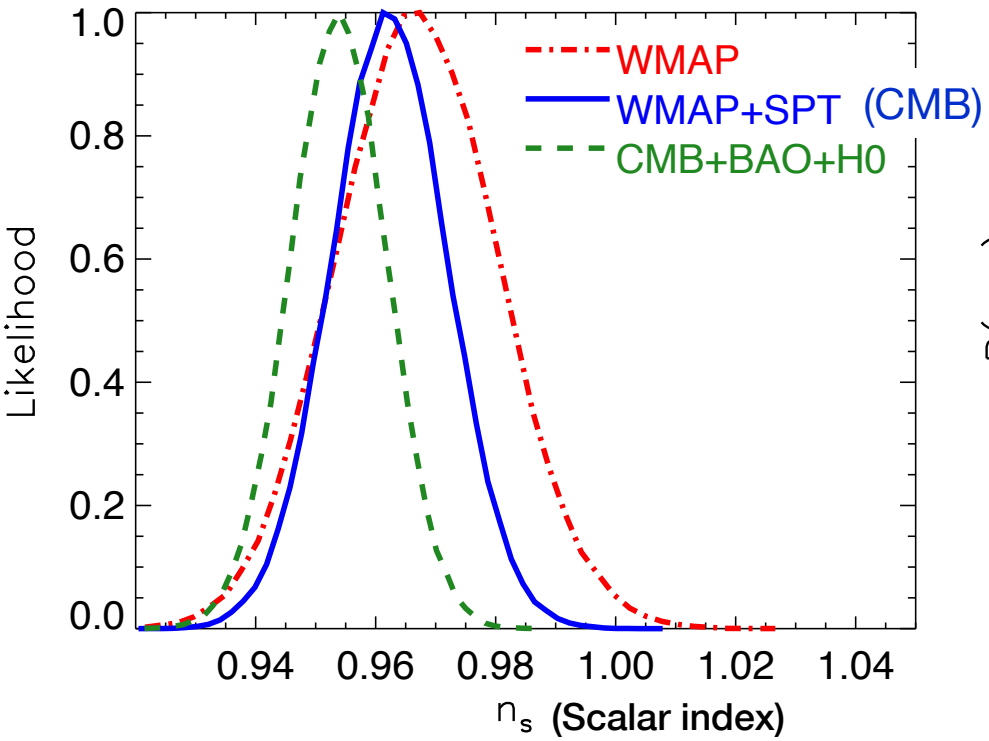
Inflation predicts nearly scale invariant spectrum

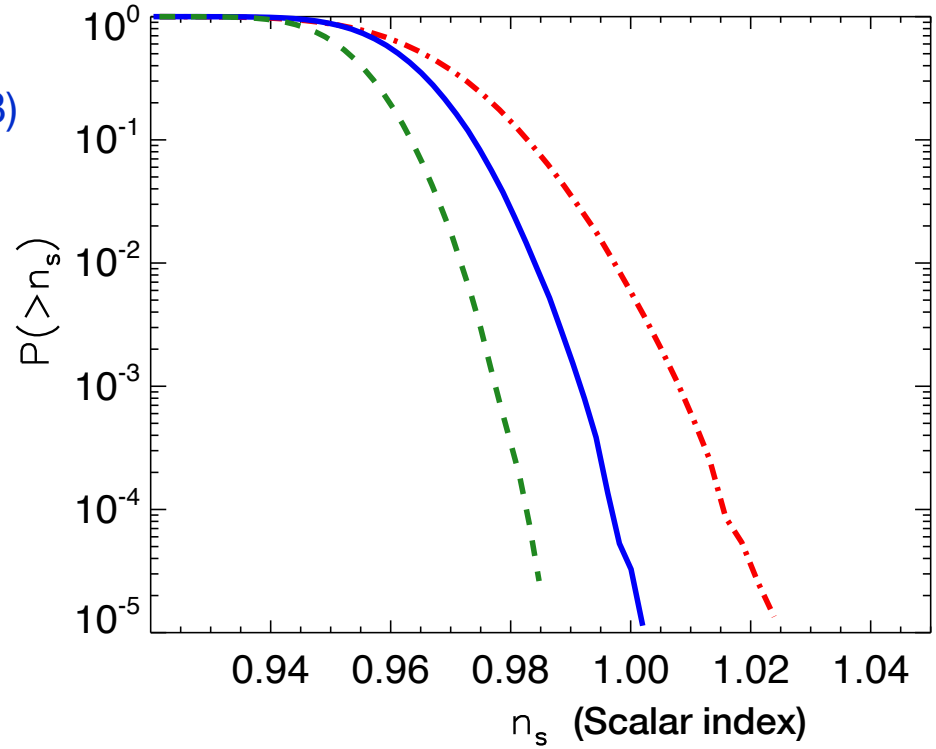
Primordial spectrum: $\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$ ⟷ $n_s \sim 1$ for scale invariance



Story, Reichardt et al., arXiv:1210.7231

Data:



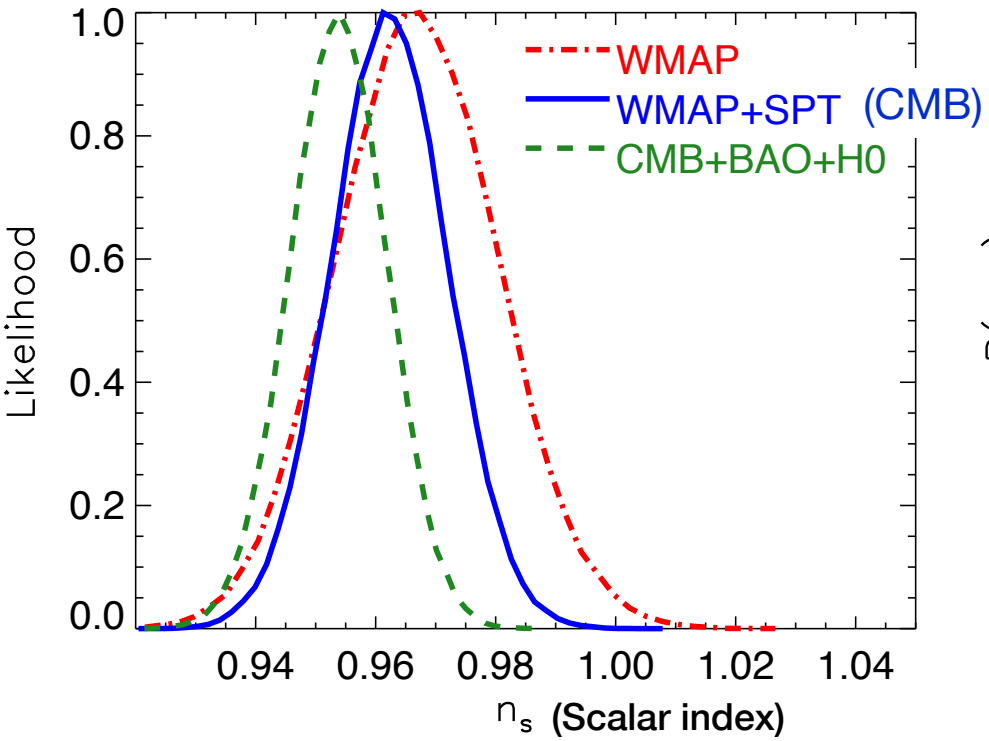


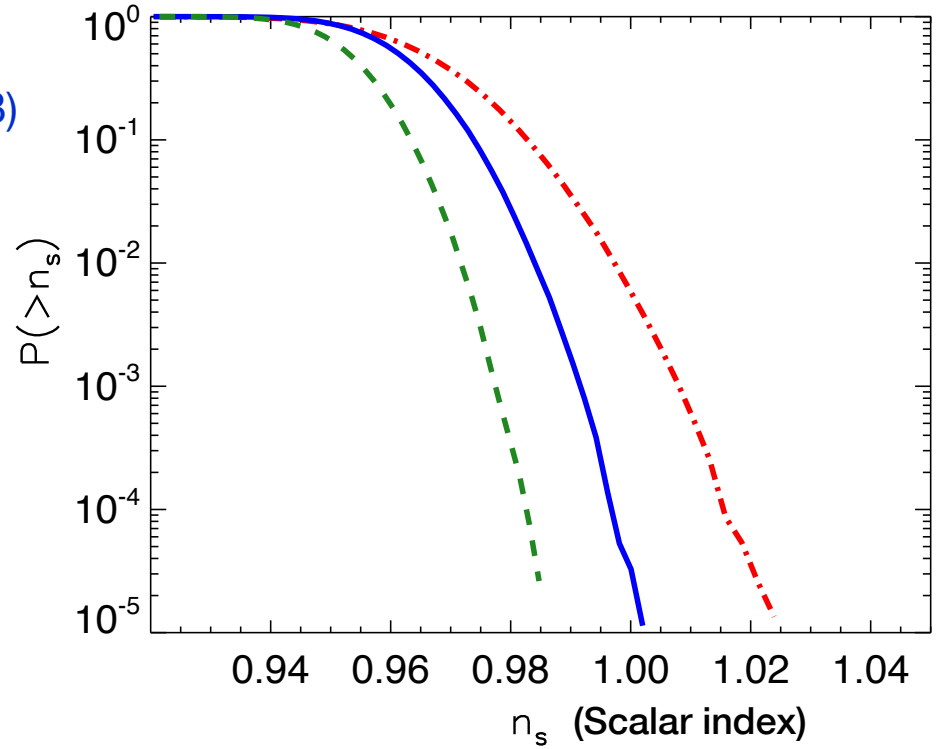
n_s: WMAP7 = 0.969 ± 0.014
WMAP7+SPT (CMB) = 0.962 ± 0.010
CMB+BAO+H_0 = 0.954 ± 0.008

$P(n_s > 1)$: WMAP7 = 1.4e-2 (2.2 σ)
+SPT = 3.9e-4 (3.9 σ)
+BAO+H_0=1.4e-9 (5.9 σ)

Story, Reichardt et al., arXiv:1210.7231

Data:





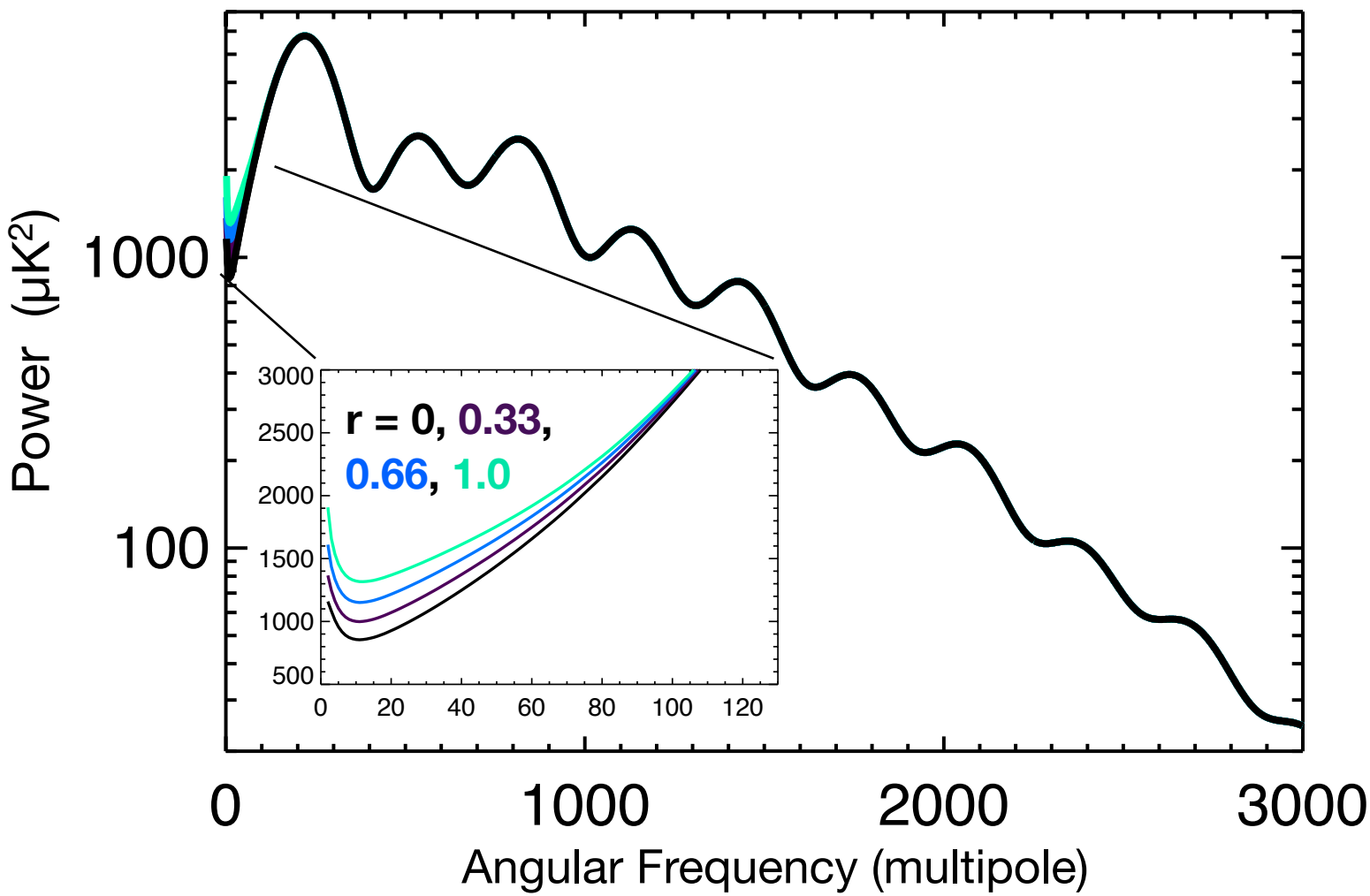
n_s: WMAP7 = 0.969 ± 0.014
WMAP7+SPT (CMB) = **0.962 ± 0.010**
CMB+BAO+H_0 = 0.954 ± 0.008

Planck+WMAP-Pol = **0.9603 ± 0.0073**
+SPT/ACT+BAO = 0.961 ± 0.0054

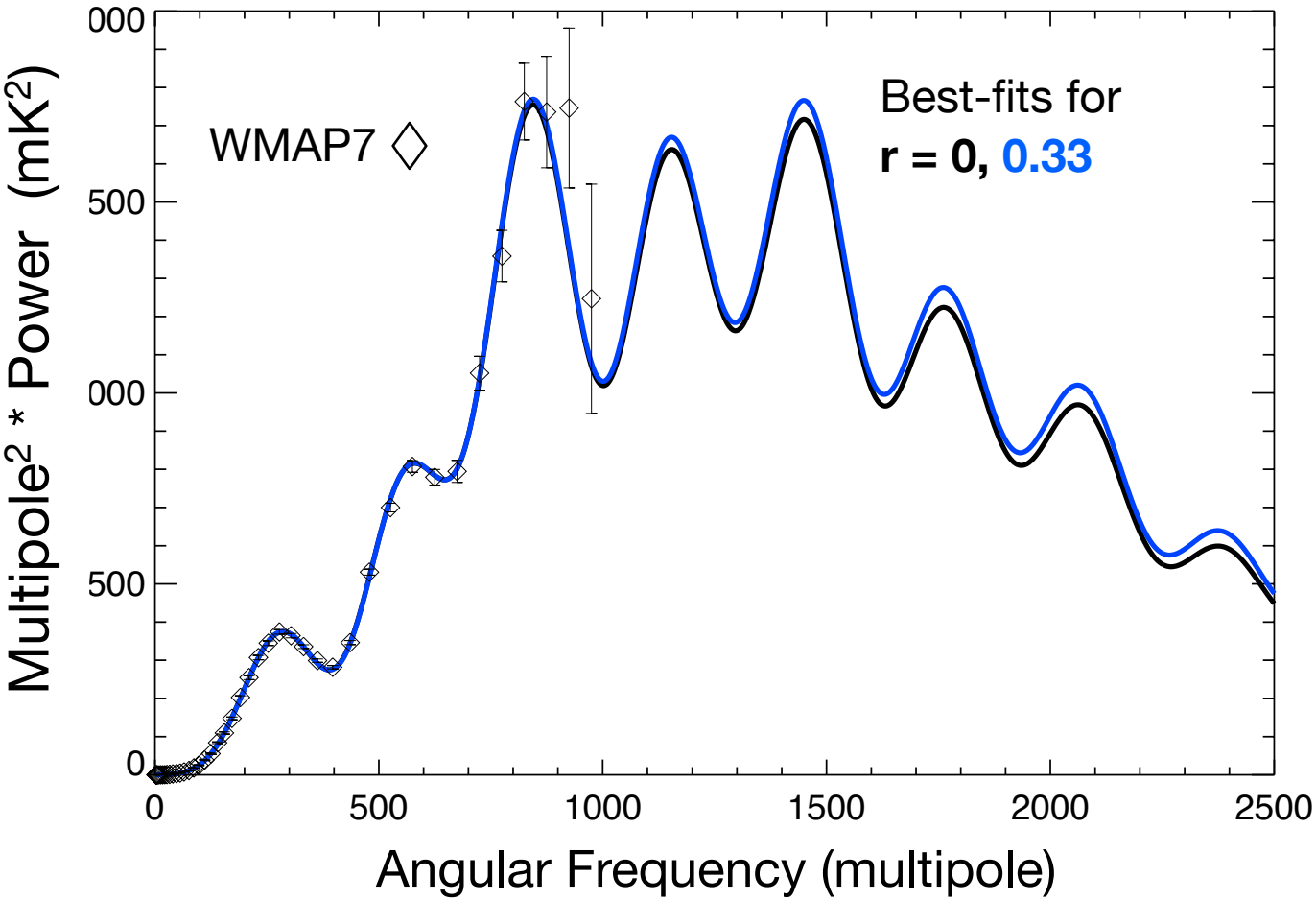
$P(n_s > 1)$: WMAP7 = 1.4e-2 (2.2 σ)
+SPT = 3.9e-4 (3.9 σ)
+BAO+H_0=1.4e-9 (5.9 σ)

Planck improves by ~ x1.5
Same CMB value (shift <0.2 σ)

Tensor perturbations and temperature anisotropy



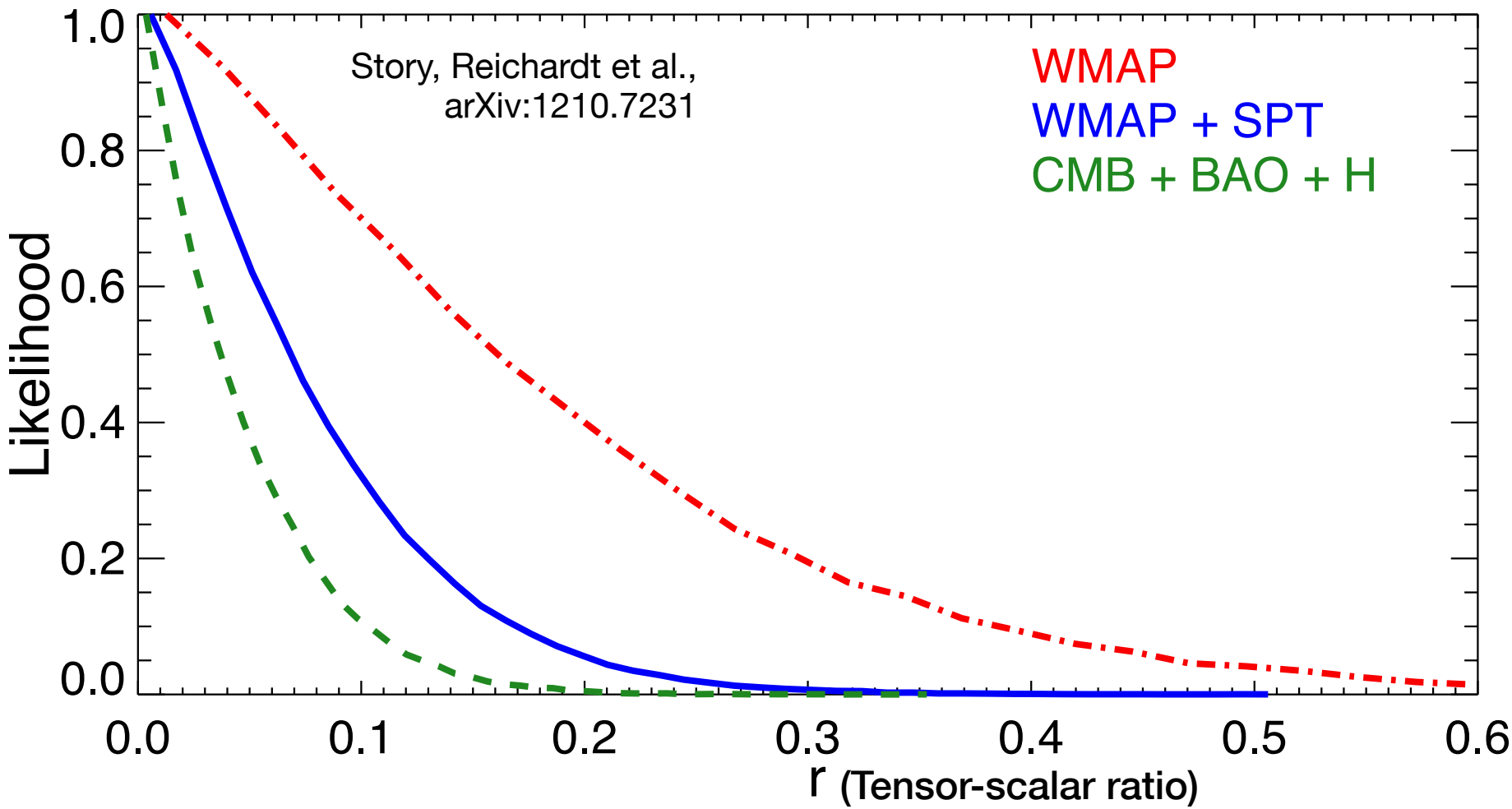
Role of small-scale data



Tensors only affect large scales, but their impact is partially degenerate with the scalar power law slope (n_s) and other parameters.

Small-scale data help disentangle the two.

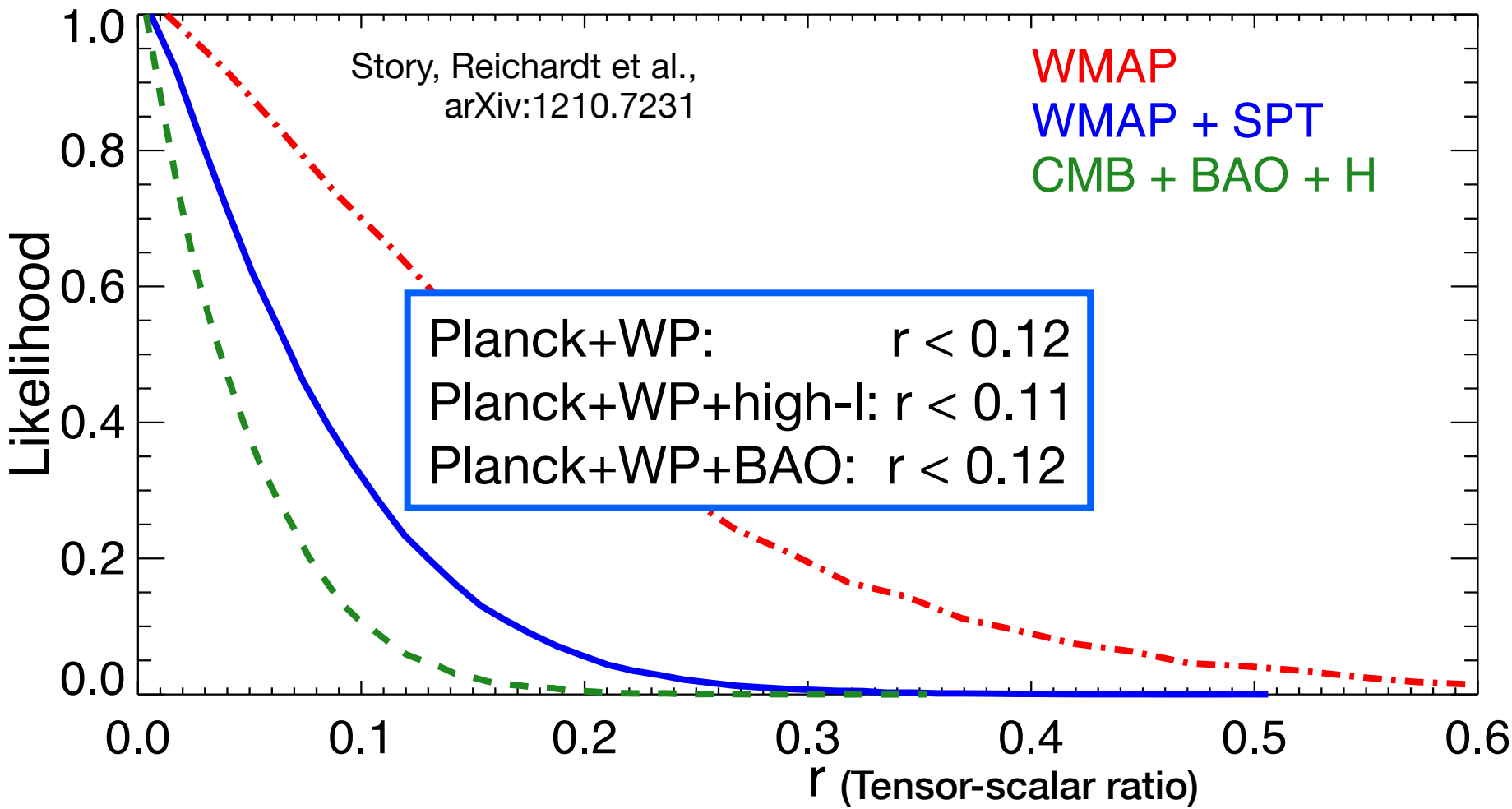
Hitting TT sample variance limit



No evidence for tensors yet; 95% upper limits are:

WMAP: r < 0.36 **WMAP+SPT: r < 0.18** **CMB+BAO+H0: r < 0.11**

Planck - same limits internally



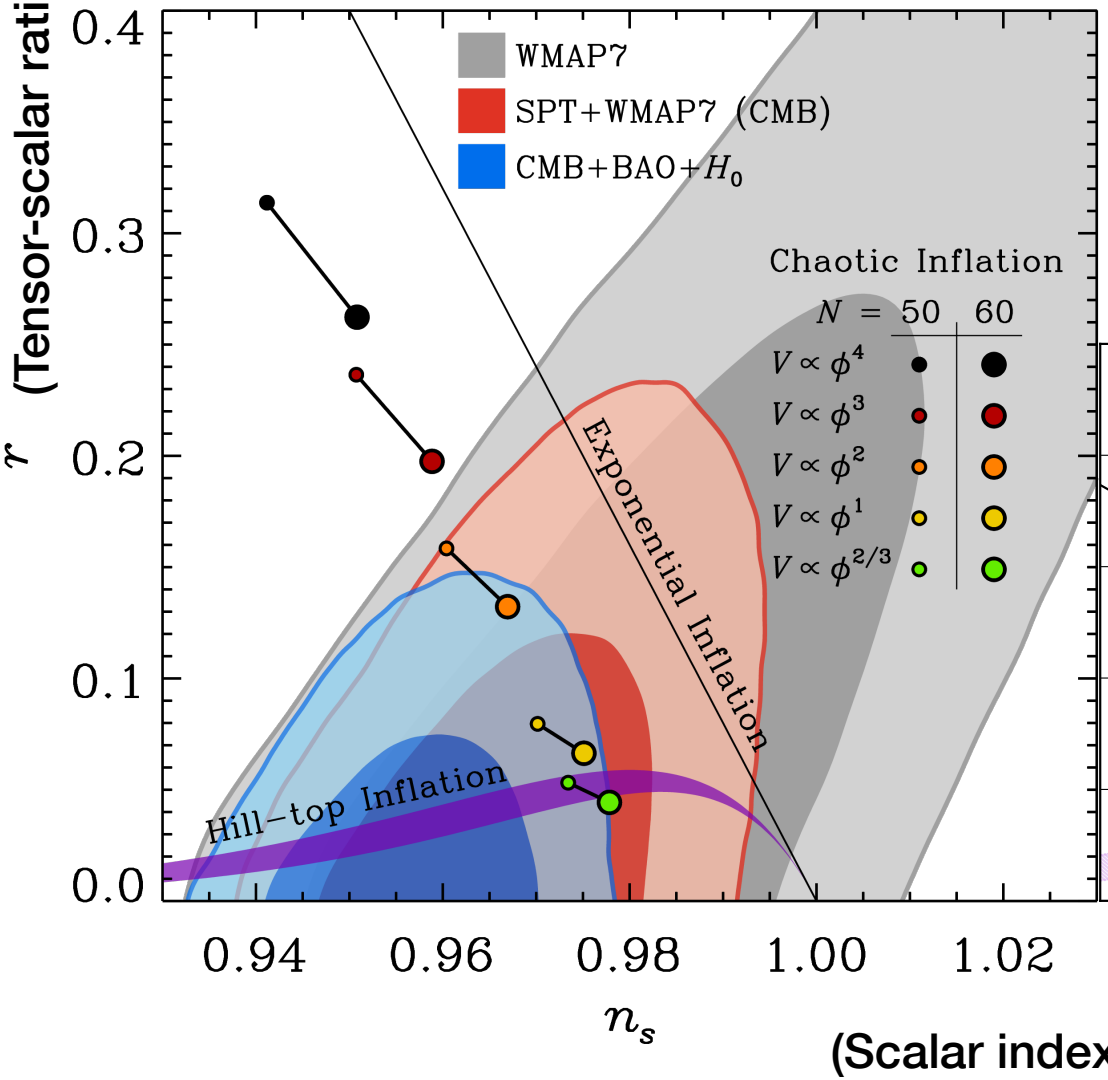
No evidence for tensors yet; 95% upper limits are:

WMAP: r < 0.36 WMAP+SPT: r < 0.18 CMB+BAO+H0: r < 0.11

Implications for inflation

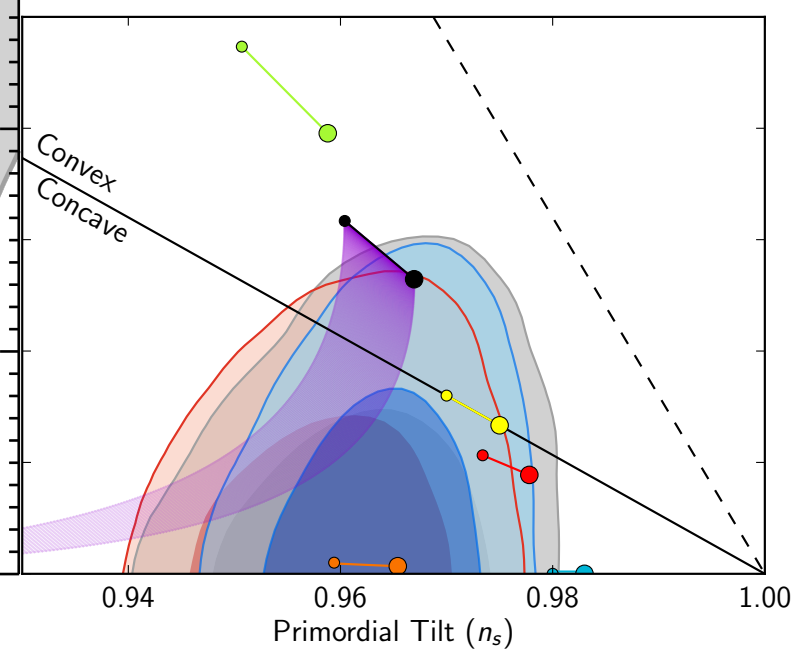
(variations on n_s vs. r)

Story, Reichardt et al., 2012

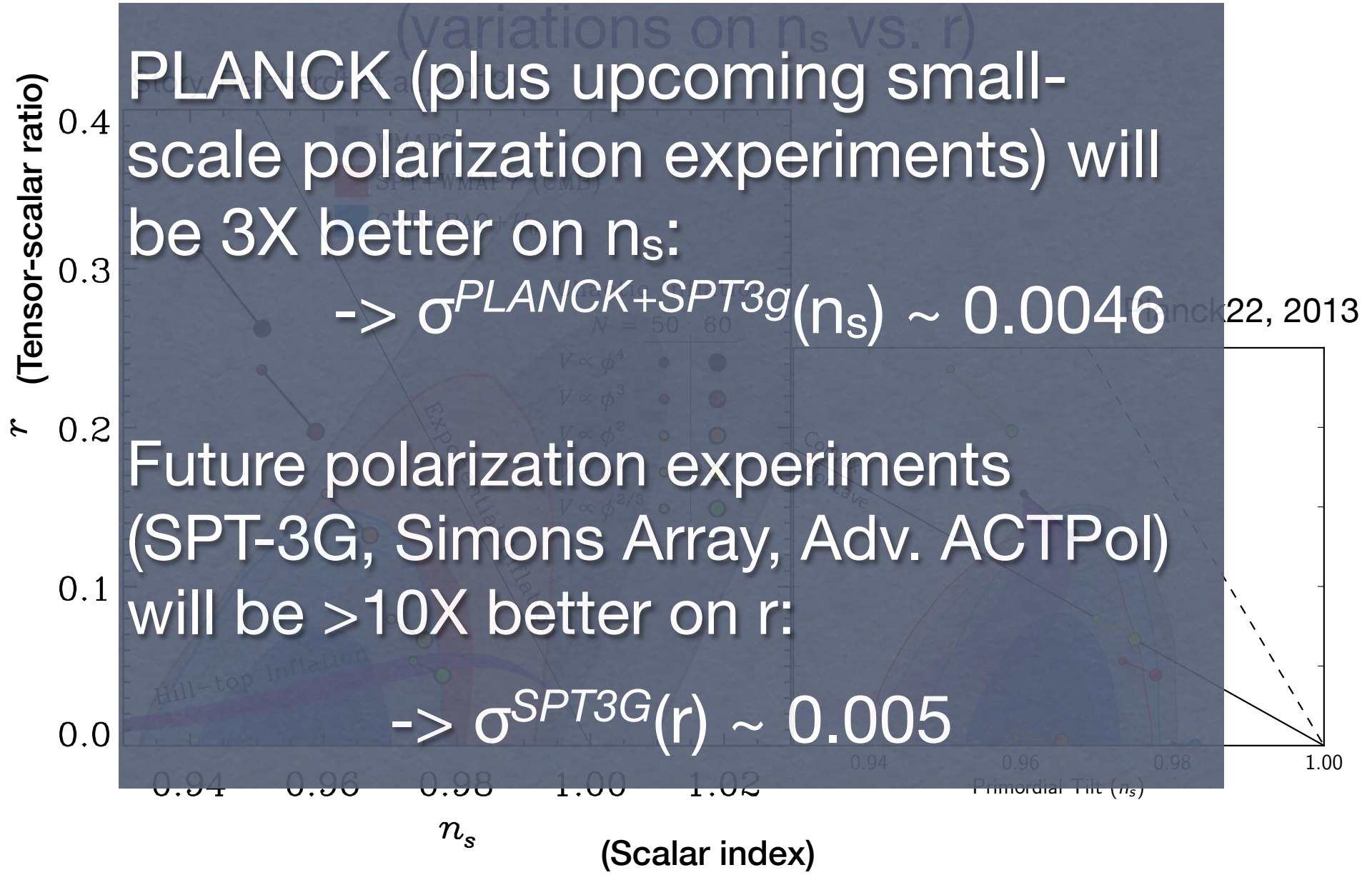


Consistent allowed region!

Planck22, 2013



Implications for inflation



PLANCK (plus upcoming small-scale polarization experiments) will be 3X better on n_s:

-> $\sigma^{PLANCK+SPT3g}(n_s) \sim 0.0046$

Future polarization experiments (SPT-3G, Simons Array, Adv. ACTPol) will be >10X better on r:

-> $\sigma^{SPT3G}(r) \sim 0.005$

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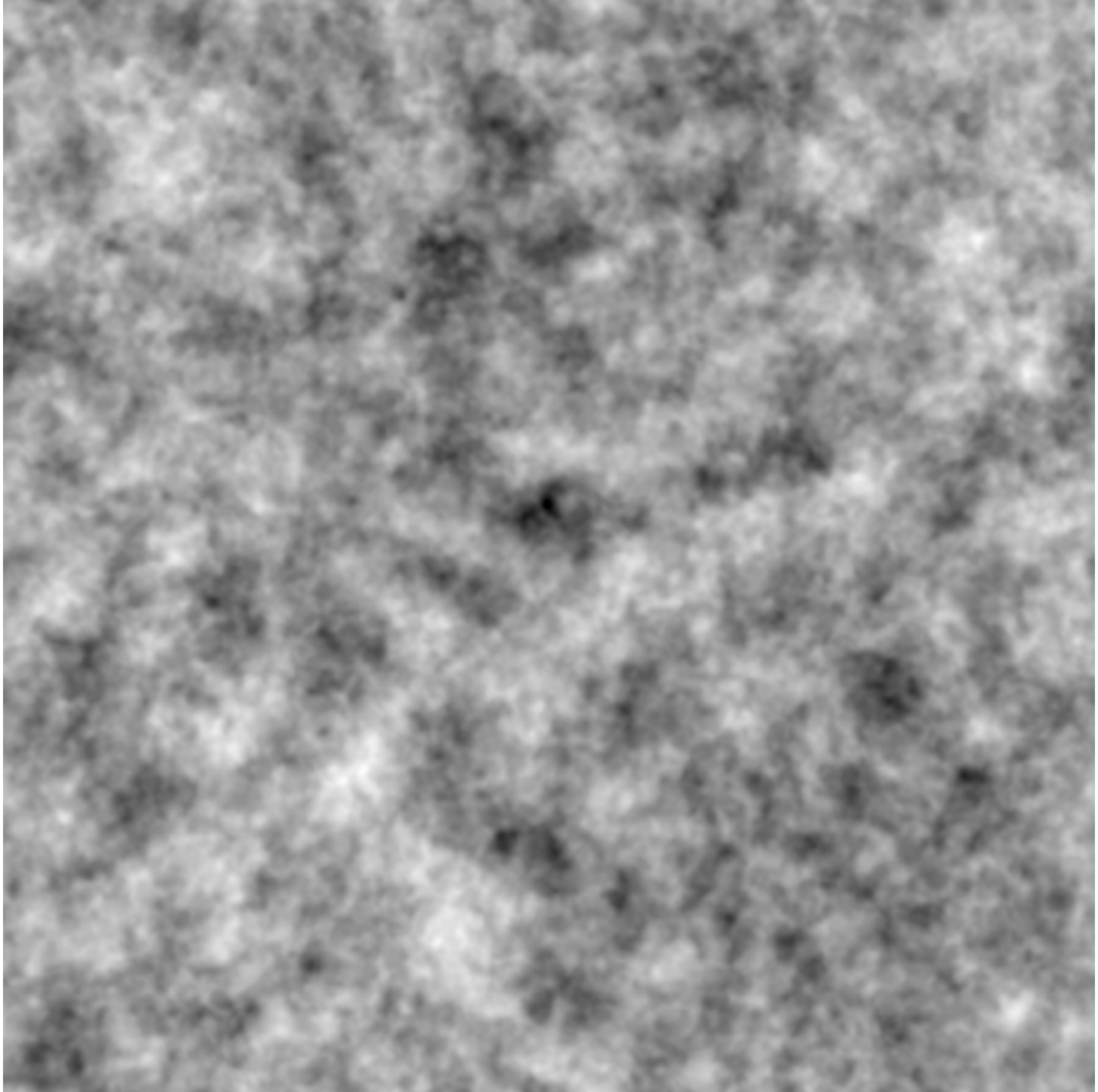
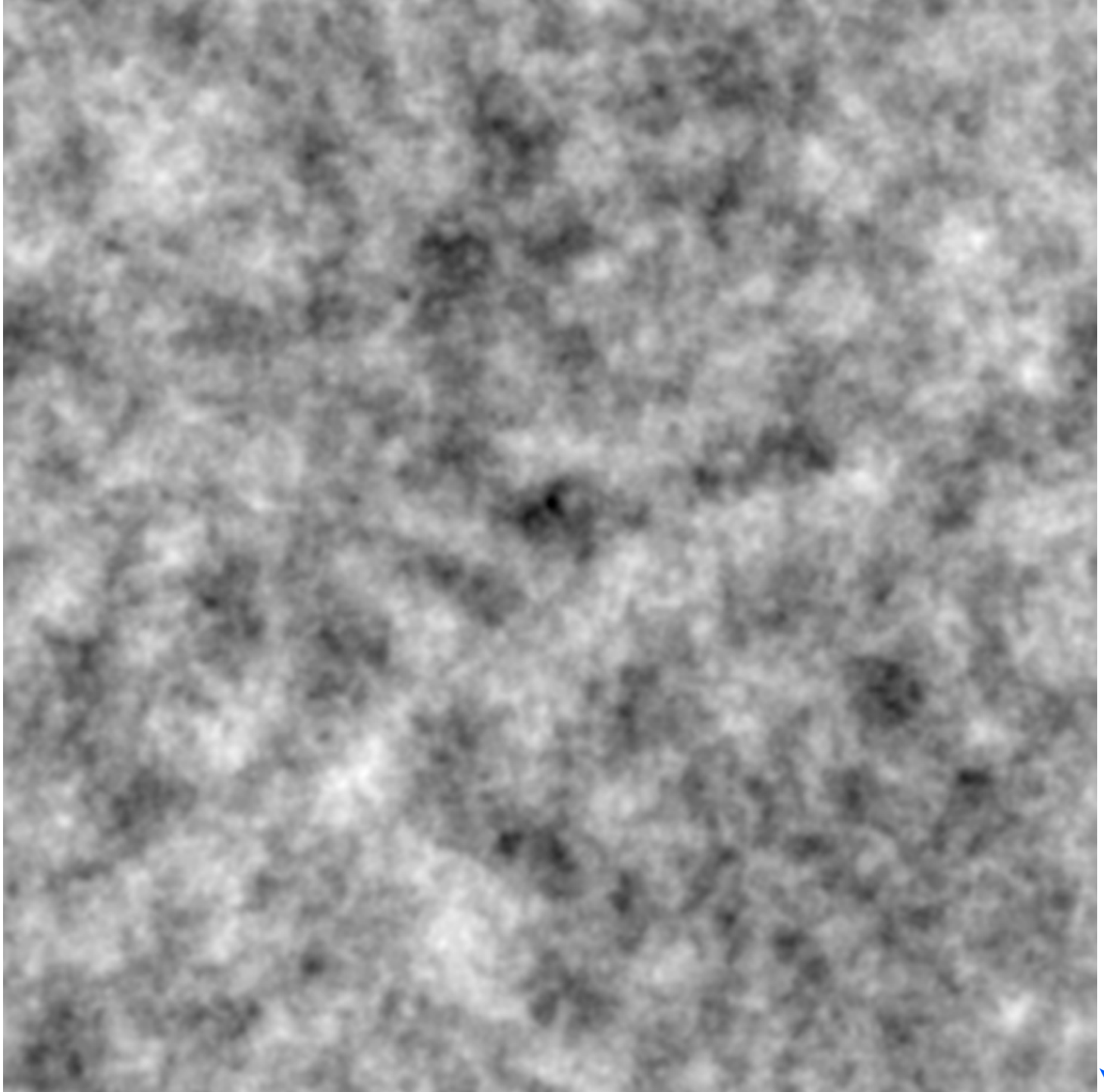


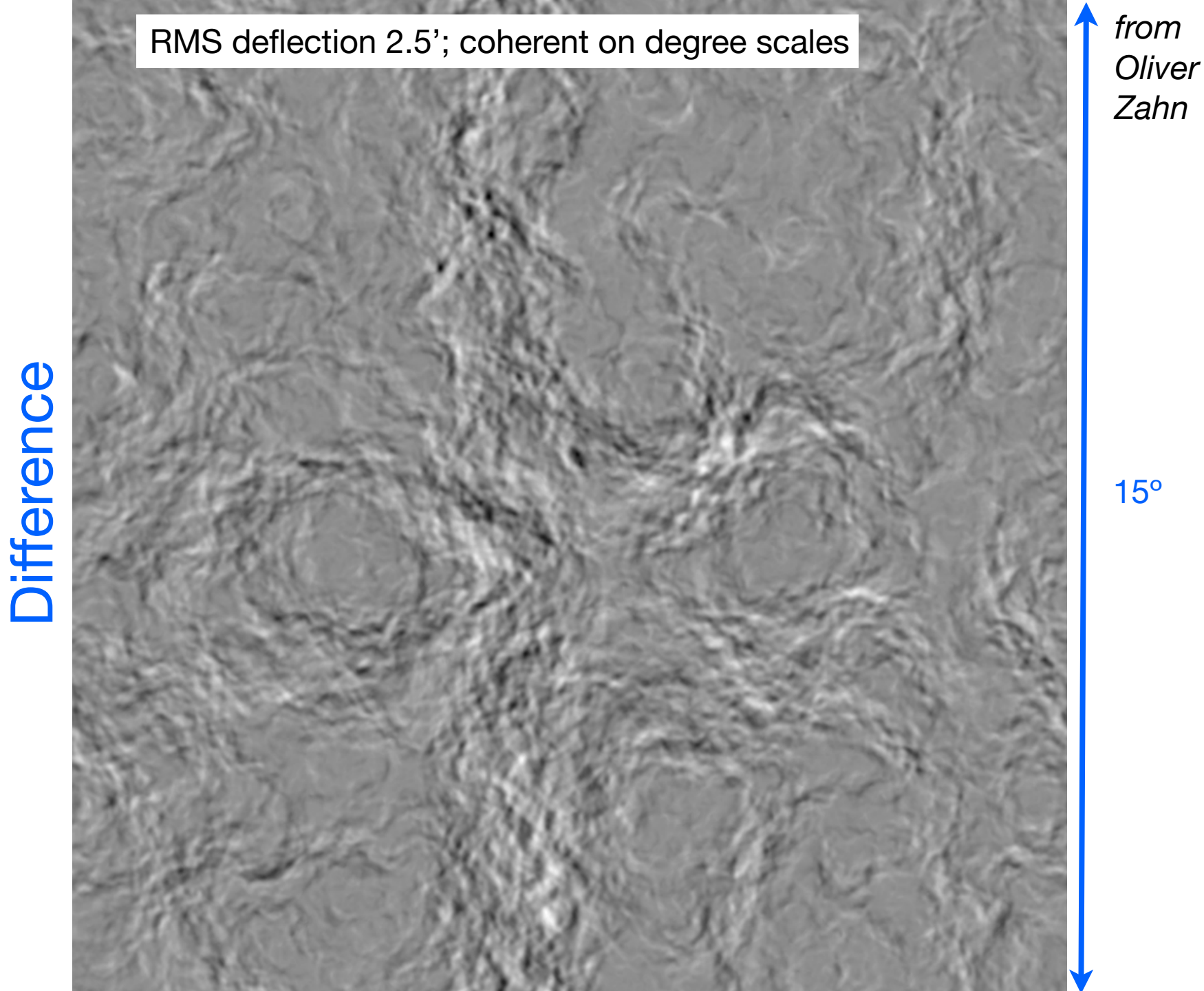
Unlensed

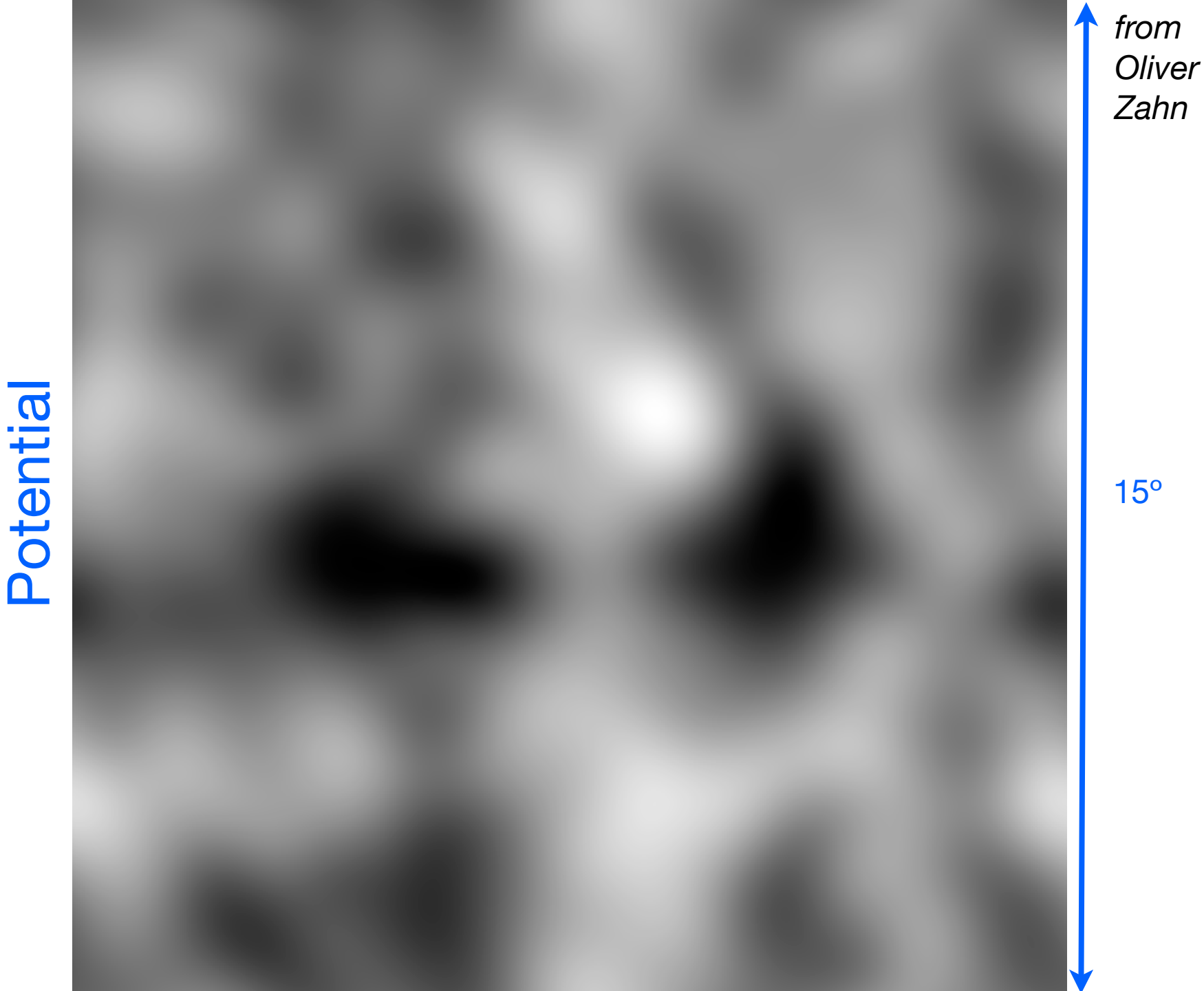
15°

from Oliver Zahn



from Oliver Zahn


RMS deflection 2.5'; coherent on degree scales
Difference
from Oliver Zahn
15°



from Oliver Zahn

CMB is a unique lensing source

1. Low systematic uncertainties:
   - Gaussian, well-understood power spectrum
   - Known, unique redshift

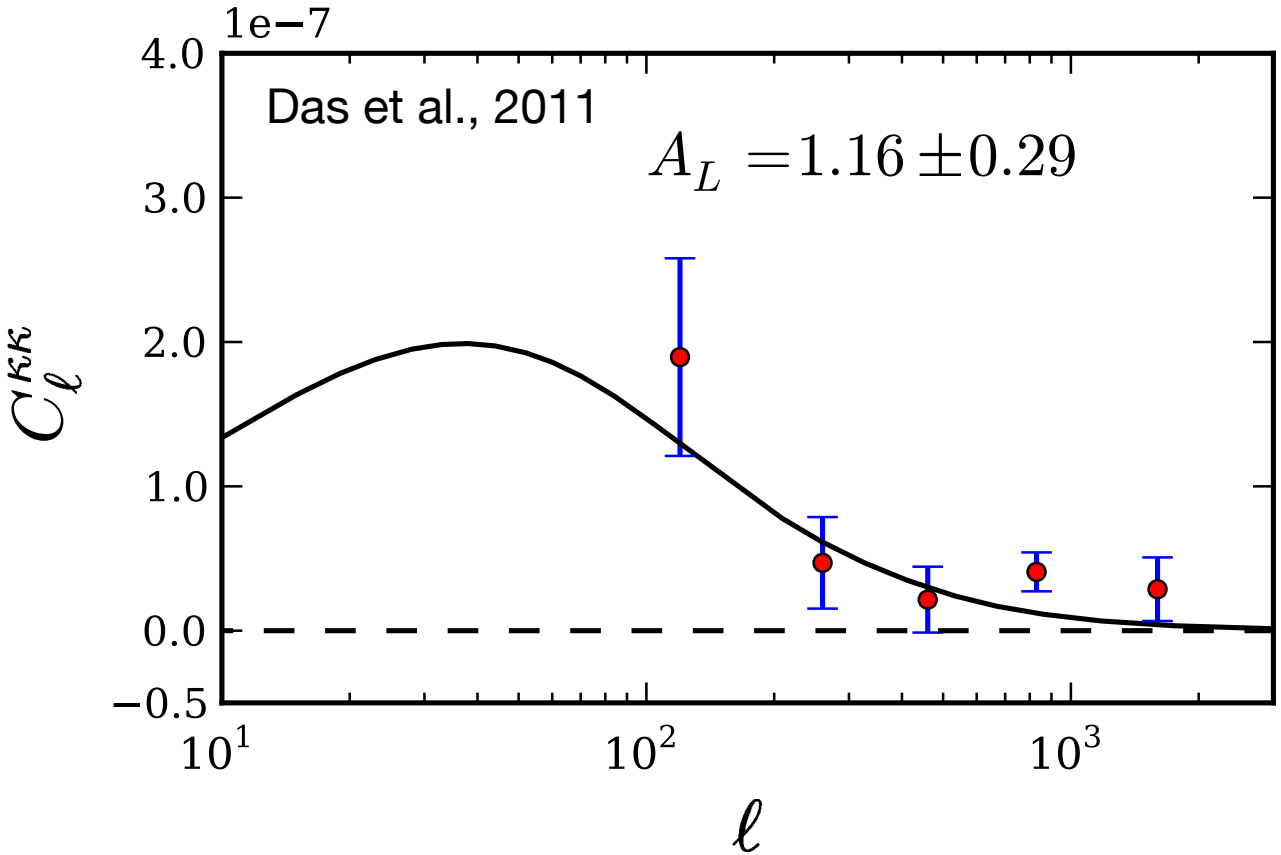
2. High redshift
   - No higher-z source

CMB Lensing Milestones
(firsts @ >3 σ)

1) 3 σ; **CMB x LSS** (WMAP+) Smith et al **2007**

2) 4 σ; **CMB TTTT** (WMAP+ACT) Das et al **2011**

3) 5 σ; **CMB TT** (WMAP+SPT) Keisler, Reichardt et al **2011**

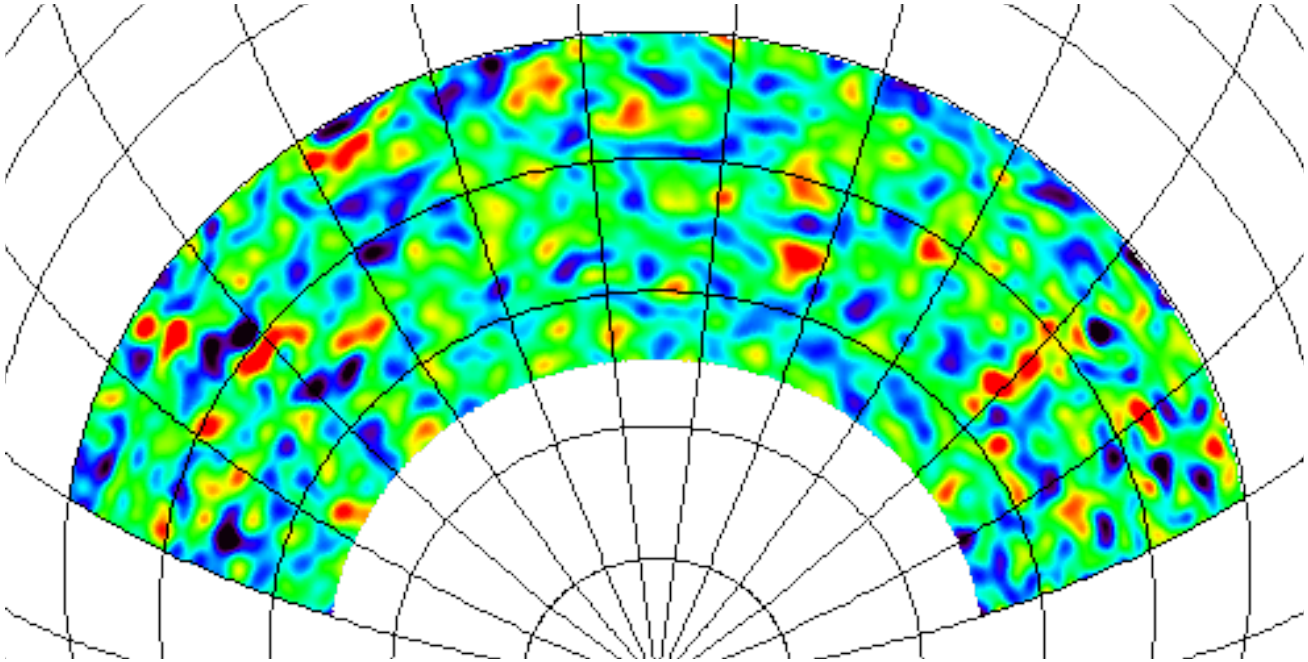


- Lensing detected at 4 σ with 300 deg^2 of ACT data

2013 - Big jump from Planck (8 -> 30 σ)

Weighing the Hubble Volume

work being led by O. Zahn

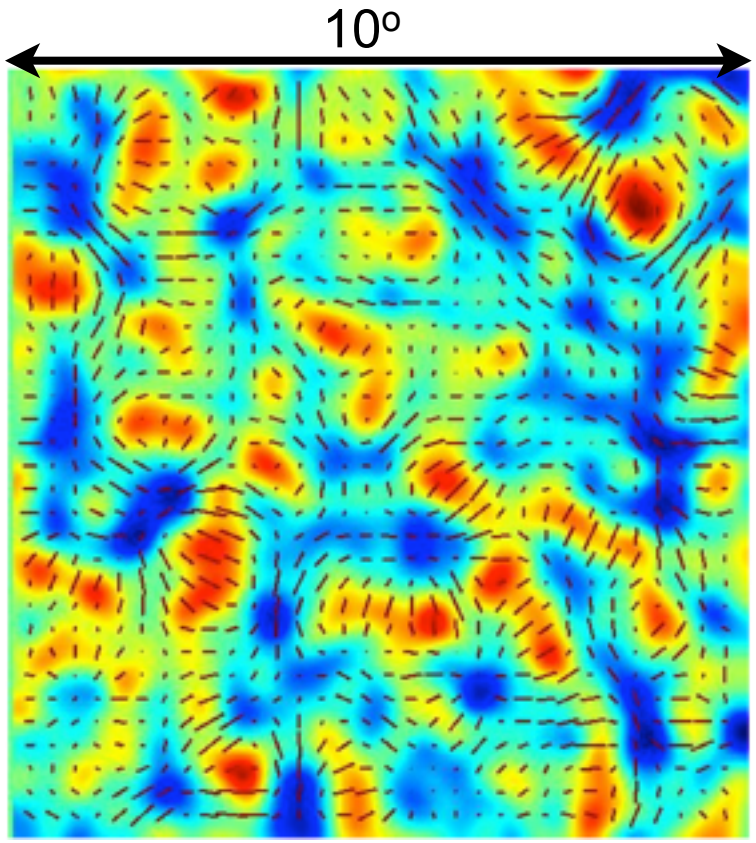


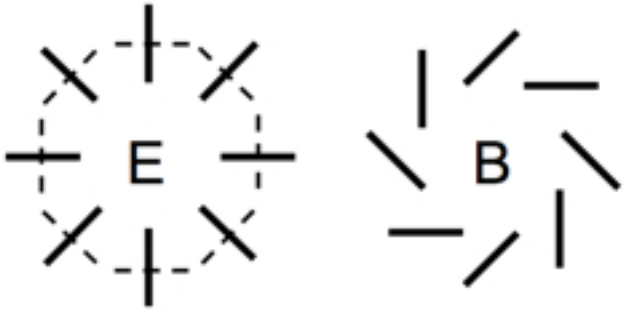
SPT map of 6% of matter in observable Universe

- S/N > 1 per mode on large scales
- Less sky than Planck

Lensing detection: ~20 σ in SPT
~30 σ in Planck

The Next Frontier:
Polarization

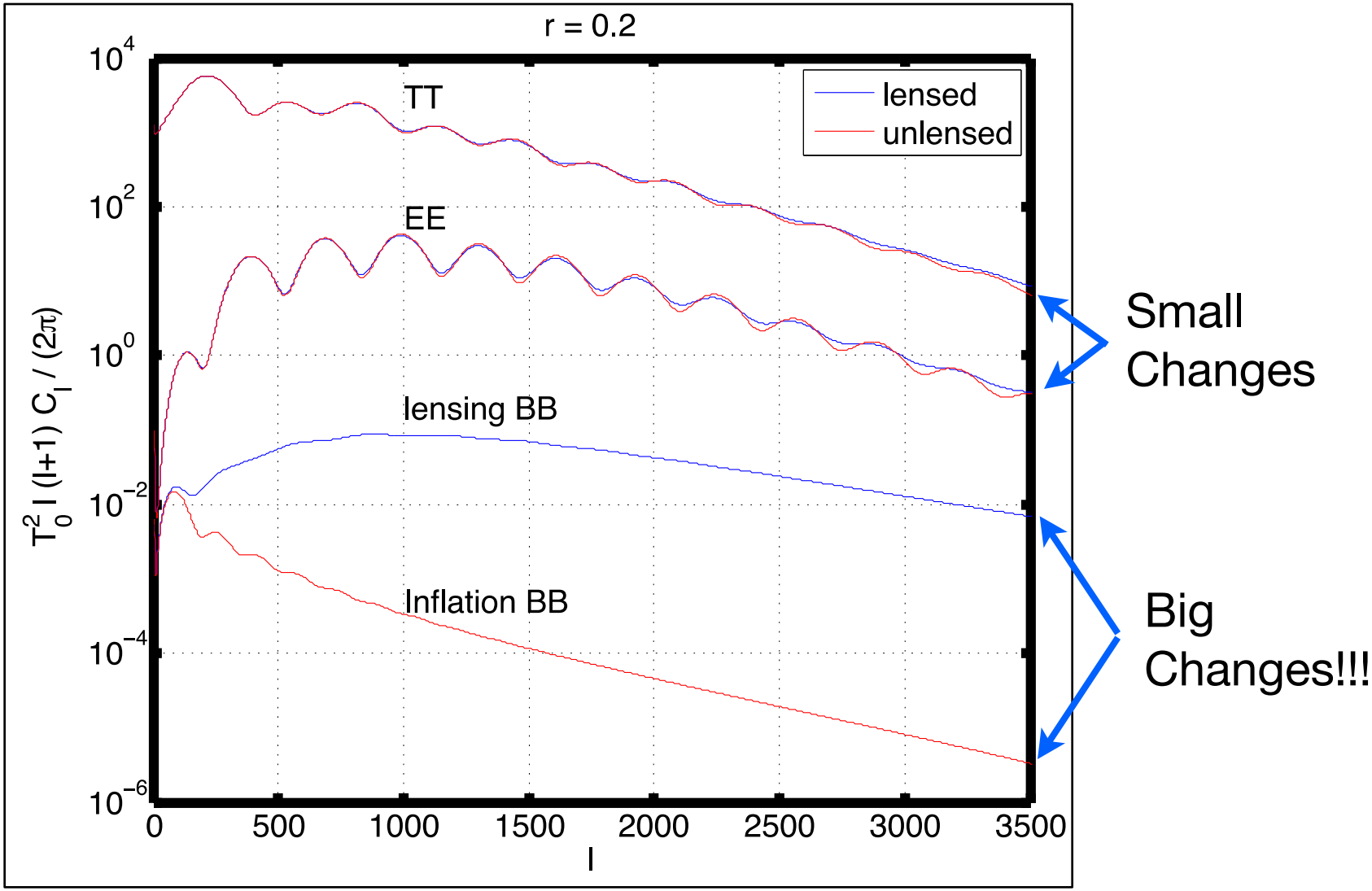




Smith et al 2008

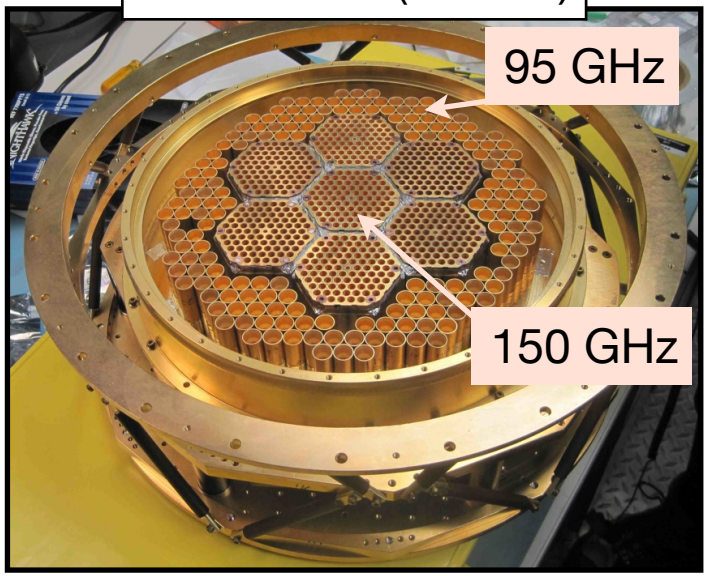
- Any polarization pattern can be decomposed into “E” (grad) and “B” (curl) modes
- Quadrupole anisotropy introduces polarization at surface of last scattering
- Density fluctuations do not produce “B” modes!
- “B” modes are created by:
  - On large scales: primordial gravity waves from Inflation
  - On small scales: lensing of the CMB from large scale structure

Effect of Lensing on the CMB Power Spectrum:
B-modes from Lensing

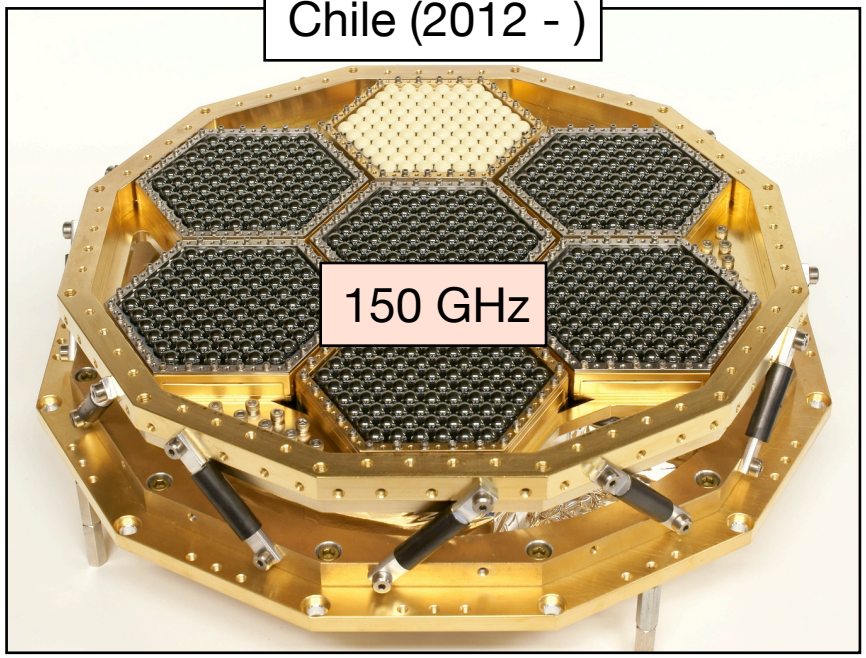


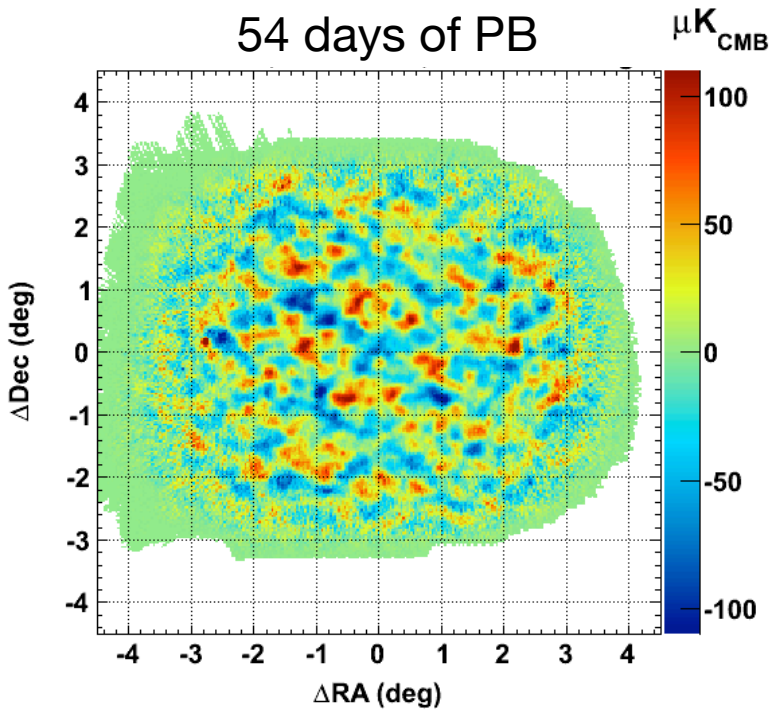
Current Small-Scale Polarization Experiments

SPT-Pol
South Pole (2012 -)



PolarBear
Chile (2012 -)



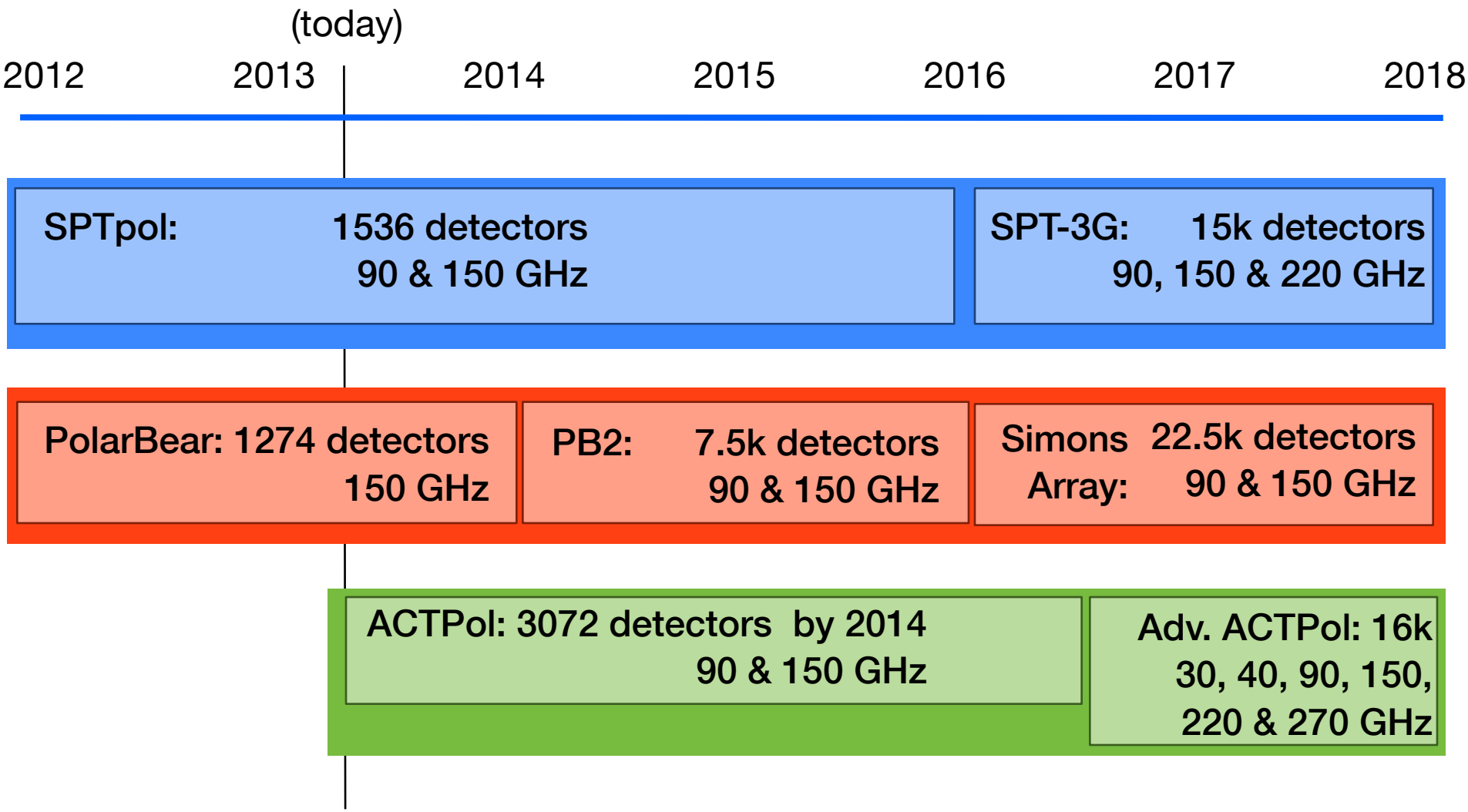


First light for both experiments Jan. 2012!

Site:
SPT: South Pole
PB: Chile
ACT: Chile

Next 5 years

150 GHz beams:
SPT: 1.2'
PB: 3.5'
ACT: 1.7'



Science

SPT/ACT: Investigate dark energy using **galaxy cluster abundances:**

i.e. SPT-Pol:

4x deeper maps than SPT

lower mass threshold and find ~1000 clusters

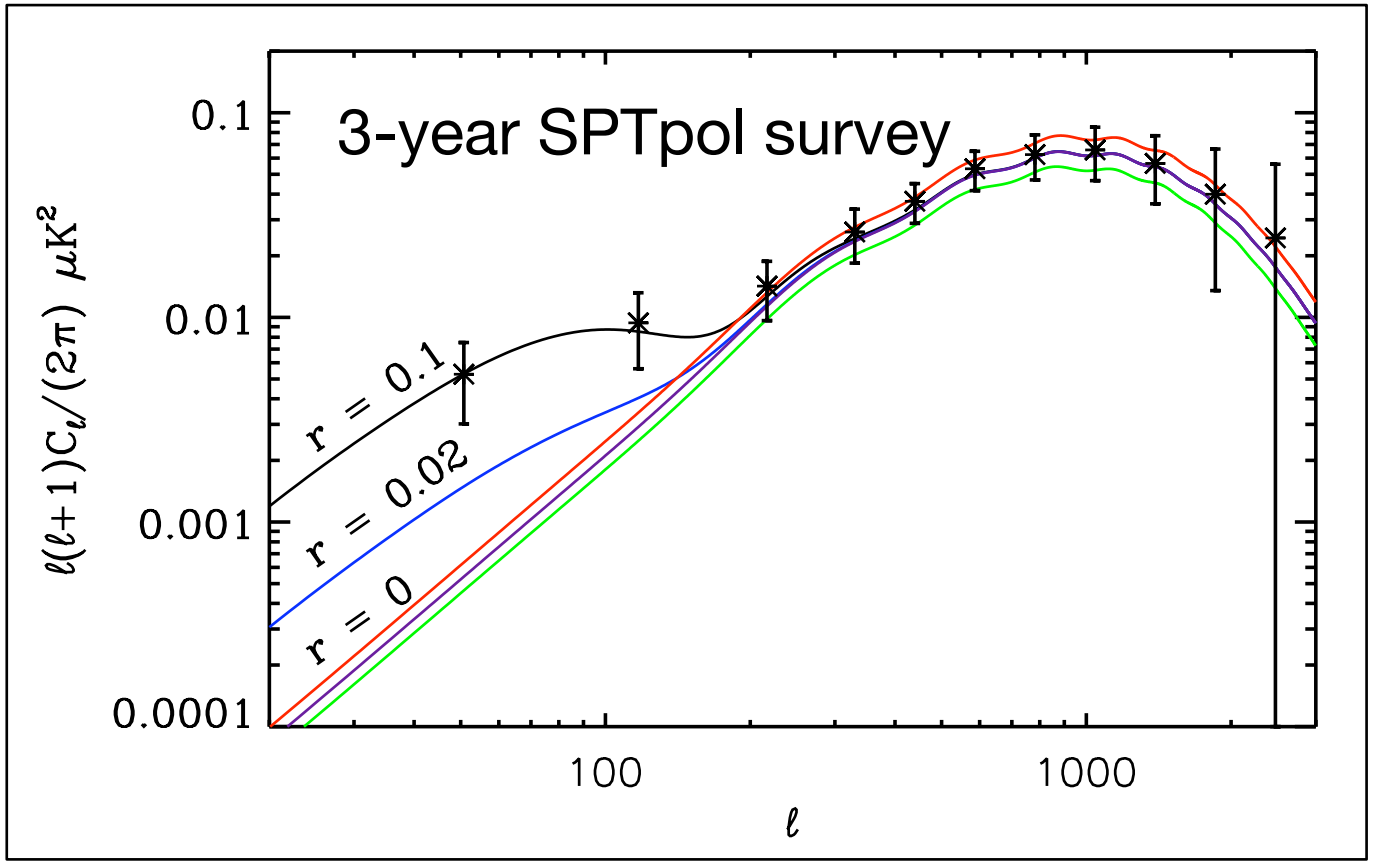
All:

Measure "B-mode" polarization to constrain **neutrino mass** and **energy scale of inflation**.

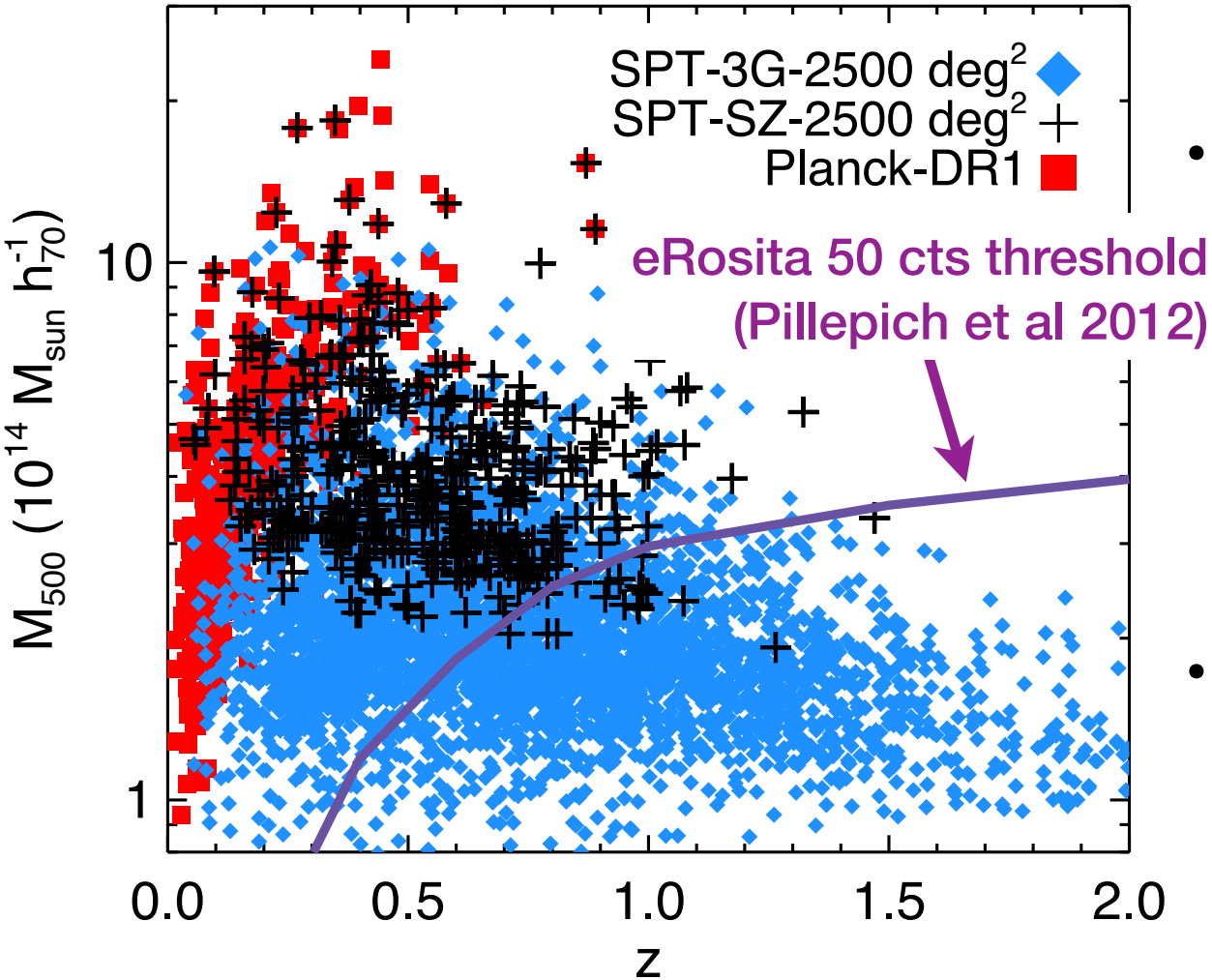
i.e. SPT-Pol or PolarBear:

$\sigma(\sum m_\nu) \sim 0.1$ eV

$r \lesssim 0.04$ (95%)



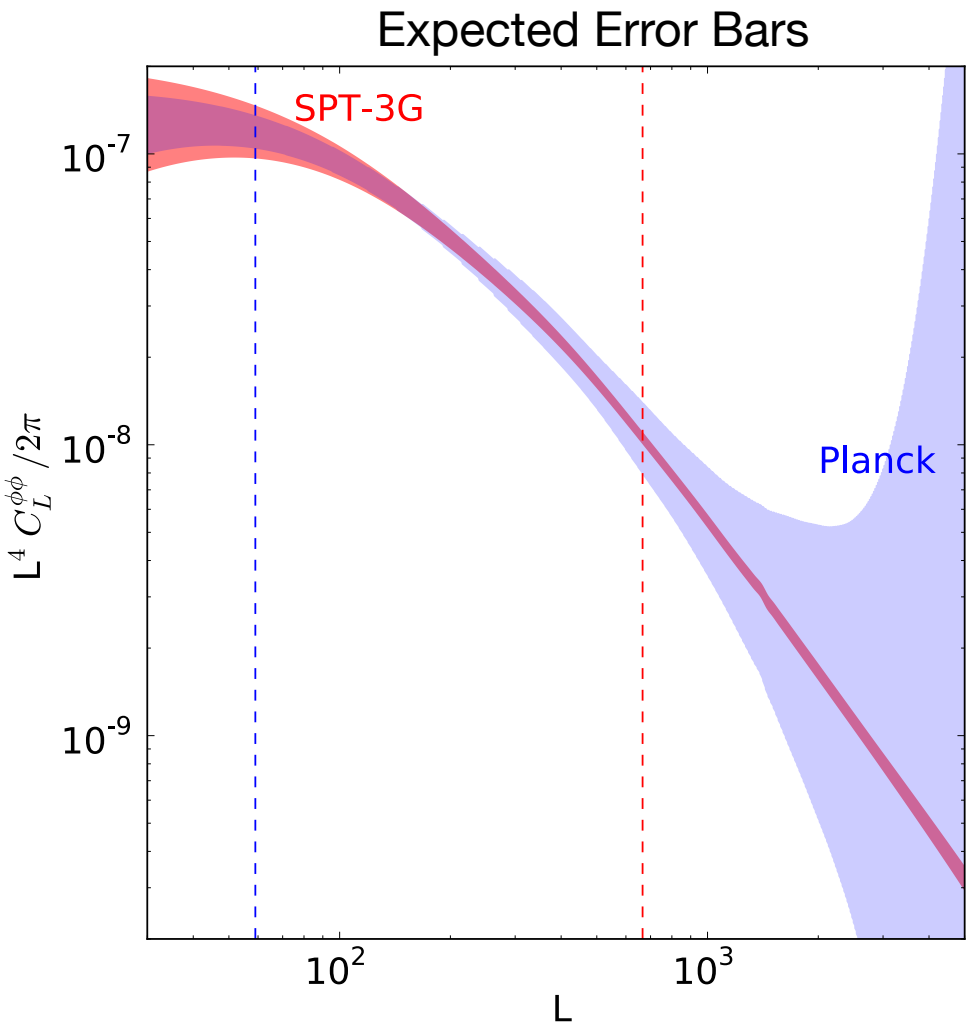
SPT-3G will have 10x more clusters



- 8000 clusters
- Improves DES dark energy figure of merit by x4 (Wu et al. 2010)
- 2% mass calibration from CMB-cluster lensing

Credit: B. Benson

SPT-3G: Lensing power spectrum



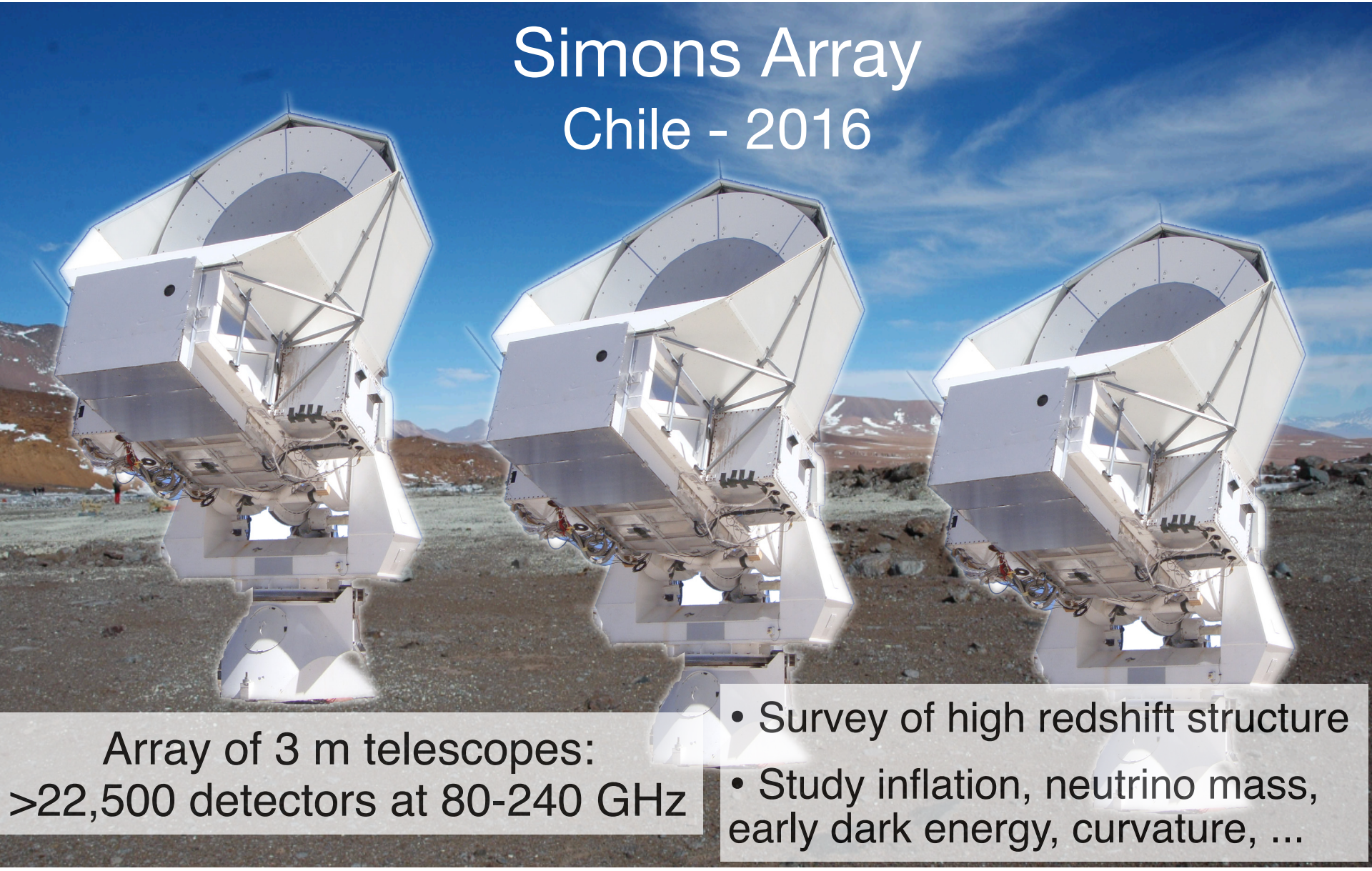
- CMB Lensing Detection Significance
  - SPT-SZ=20-σ
  - Planck=30-σ
  - **SPT-3G=150-σ**

- SPT-3G will measure individual lensing modes out to ell~800 (Planck will go ell~60)

- Cross-correlating with DES will measure galaxy bias to <1%

Credit: G. Holder

To 50% of the sky



Array of 3 m telescopes:
>22,500 detectors at 80-240 GHz

- Survey of high redshift structure
- Study inflation, neutrino mass, early dark energy, curvature, ...

In conclusion

- Small-scale CMB measurements are consistent with Planck.
- Small-scale CMB allows:
  - Constraints on inflation
  - as well as investigations of dark energy, neutrino mass, number of neutrino species, ...
  - High S/N lensing maps
- Expect first B-mode results from CMB polarization experiments this year!
  - New window into inflation and structure growth at z~2