CMB:

part one on the

South Pole Telescope

Now open in 2014!

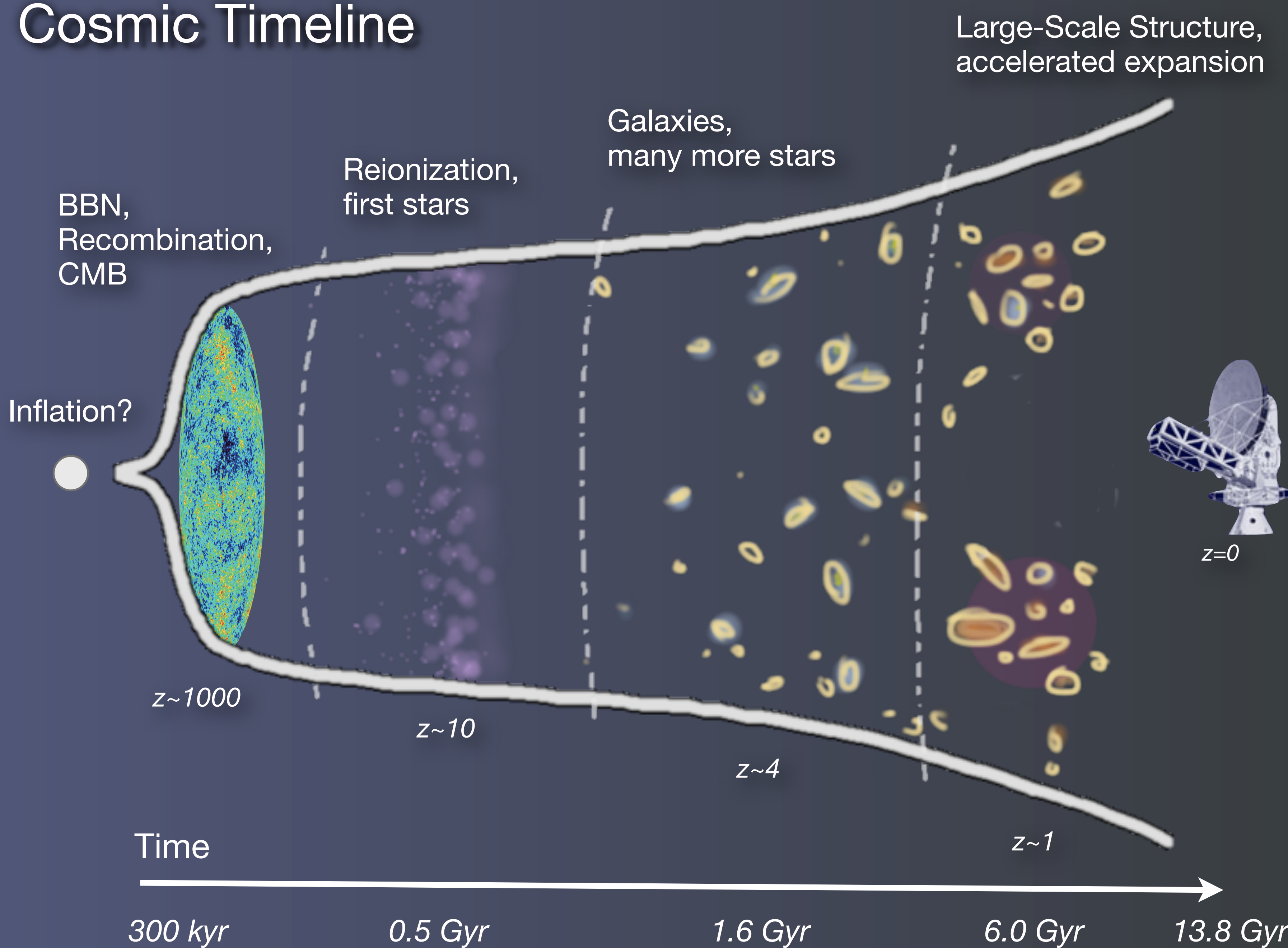
Christian Reichardt

UC Berkeley

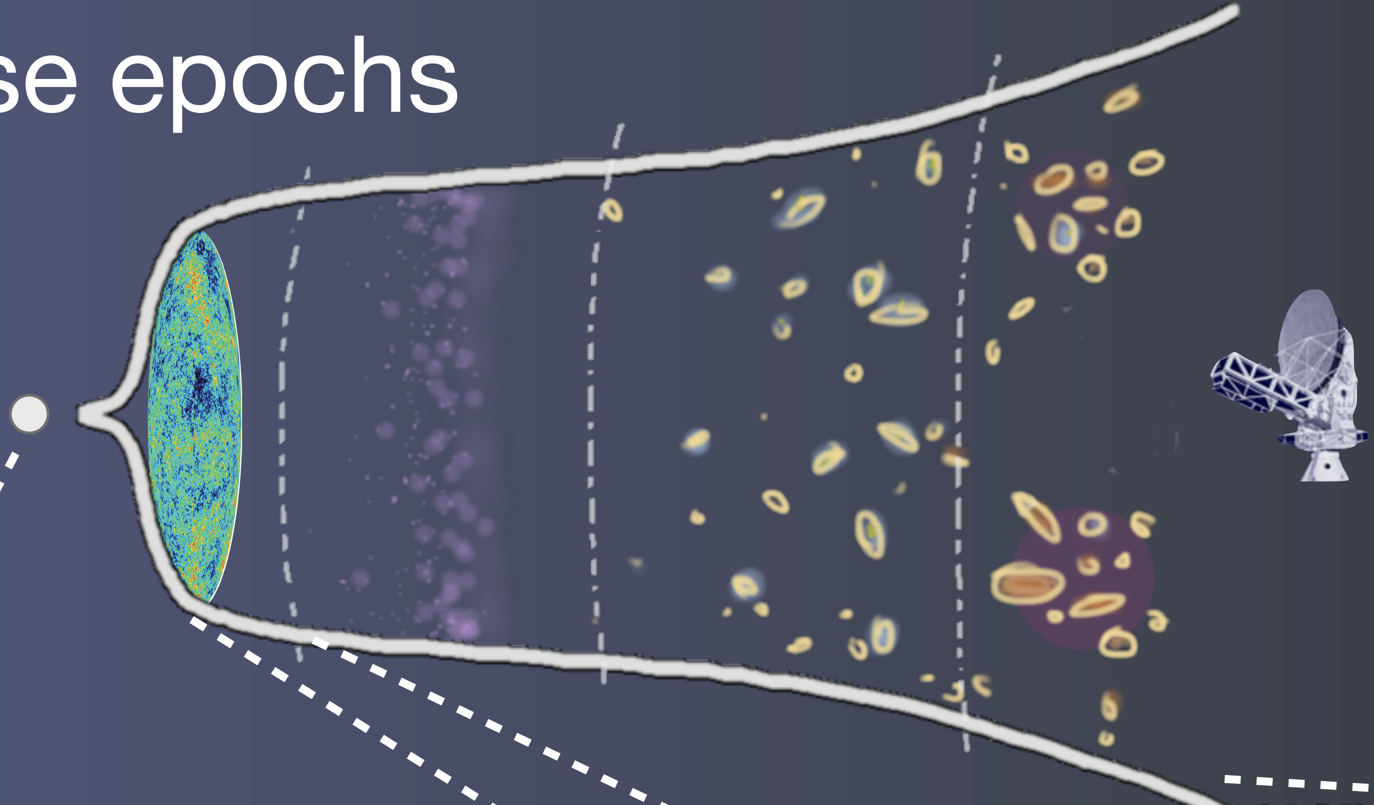
Outline

- The three cameras of the South Pole Telescope
  - SPT-SZ, SPTpol, SPT-3G
- CMB power spectrum
  - What caused Inflation?
- CMB lensing
  - 1st B-mode detection from SPTpol
  - What are the neutrino masses?

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

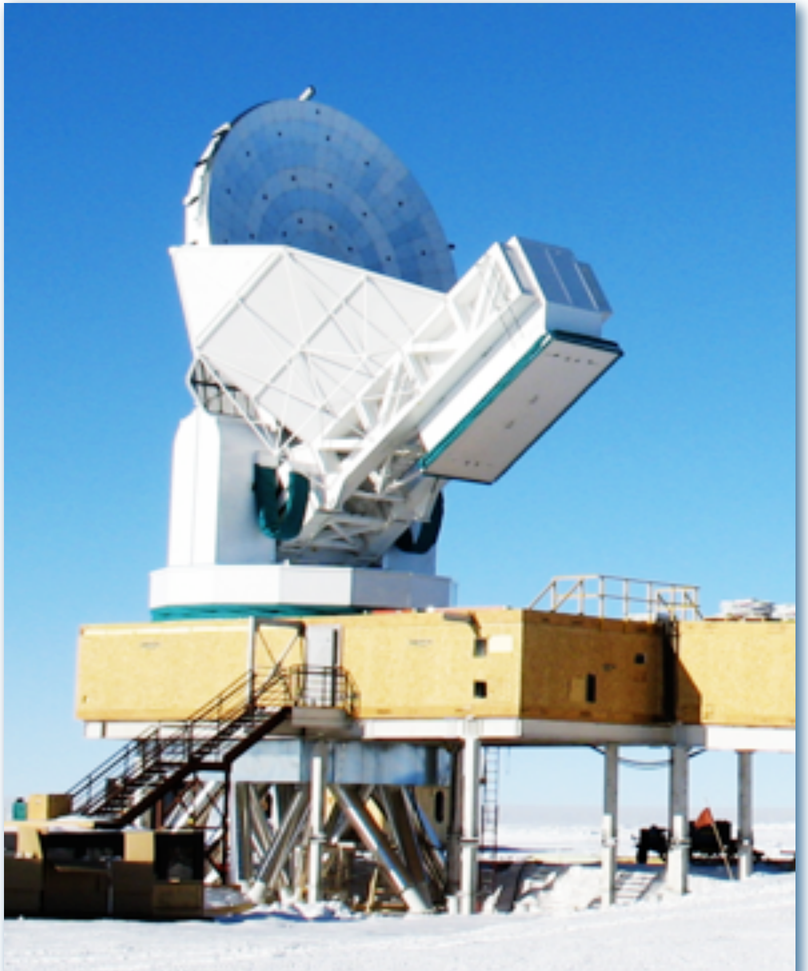
(next talk)

Gravitational lensing:

- **What are the neutrino masses?**

etc.

The South Pole Telescope (SPT)



Site:

- Best known mm-wavelength observing conditions

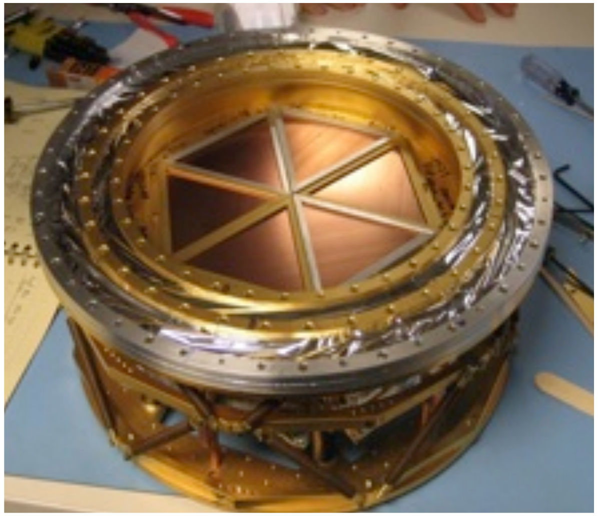
Telescope:

- 10 meter telescope (1.1’ FWHM beam)
- Fast scanning (up to 2 deg/sec in az)
- 2” pointing accuracy

Funded by NSF

Receivers

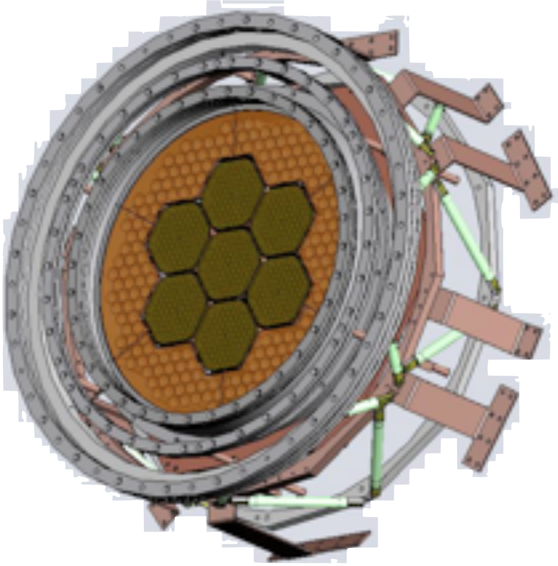
SPT-SZ (2007-2011)



- 960 bolometers
- Surveyed 2500 deg^2
- Final map depths of

40 μK-arcmin @ 95 GHz
18 μK-arcmin @ 150 GHz
70 μK-arcmin @ 220 GHz

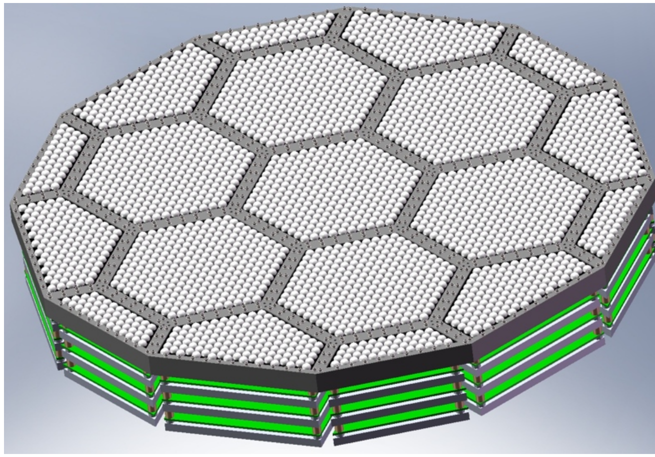
SPTpol (2012-2015)



- 1536 polarization-sensitive bolometers
- Conducting 600 deg^2 survey
- Exp. map depths of

8 μK-arcmin @ 95 GHz
5 μK-arcmin @ 150 GHz

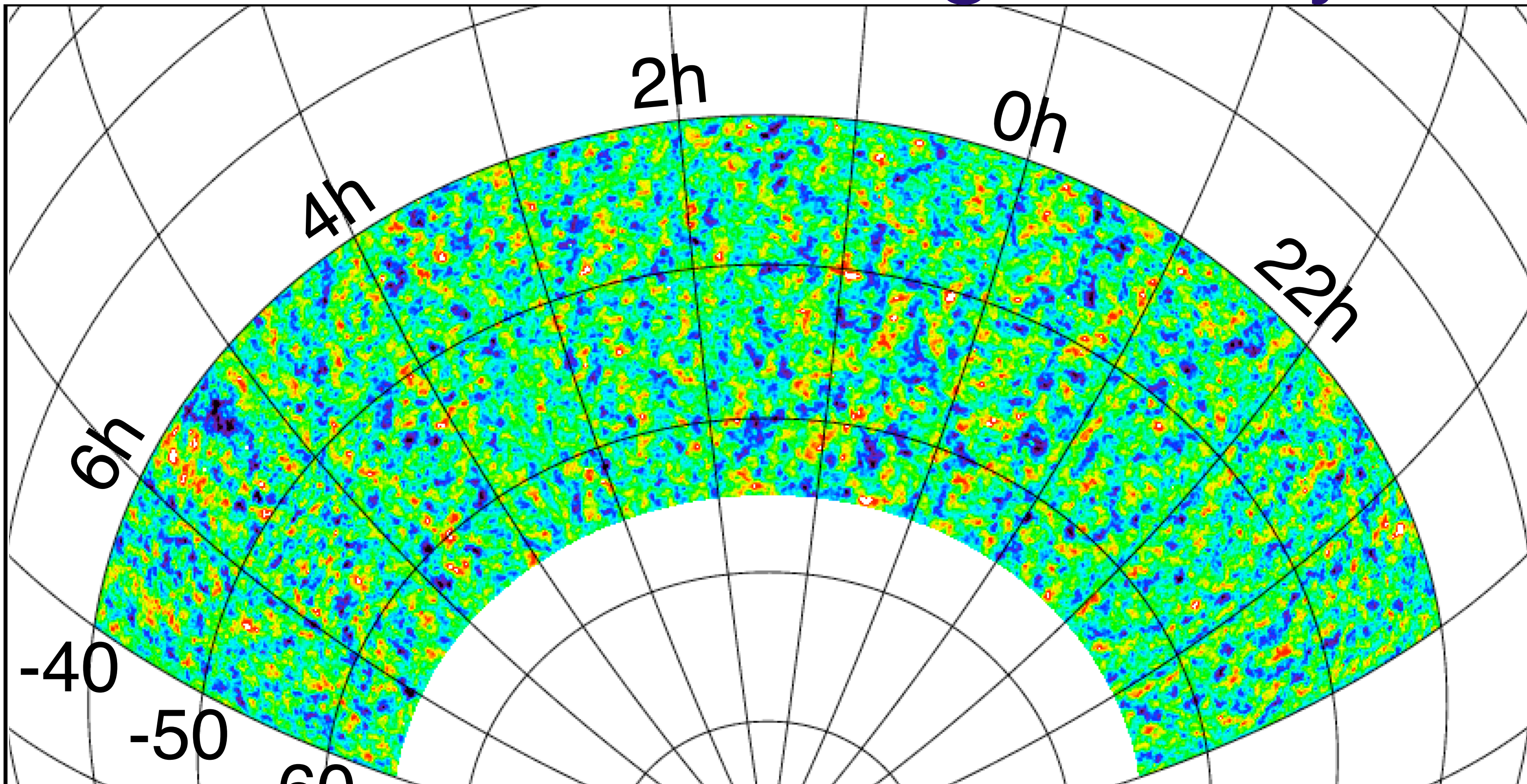
SPT-3G (2016-)



- 15,234 polarization-sensitive bolometers
- Plan 2500 deg^2 survey
- Exp. map depths of

4.2 μK-arcmin @ 95 GHz
2.5 μK-arcmin @ 150 GHz
4.0 μK-arcmin @ 220 GHz

SPT-SZ 2500 deg^2 survey



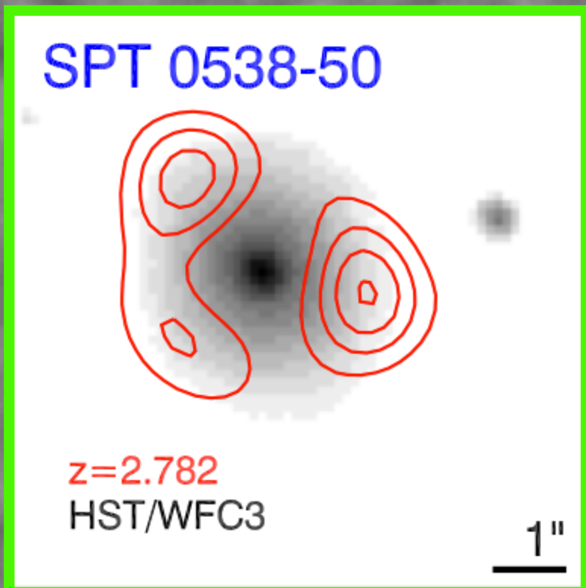
Status: finished in *Nov. 2011*.

18 μK-arcmin at 150 GHz

Deepest large-area CMB map

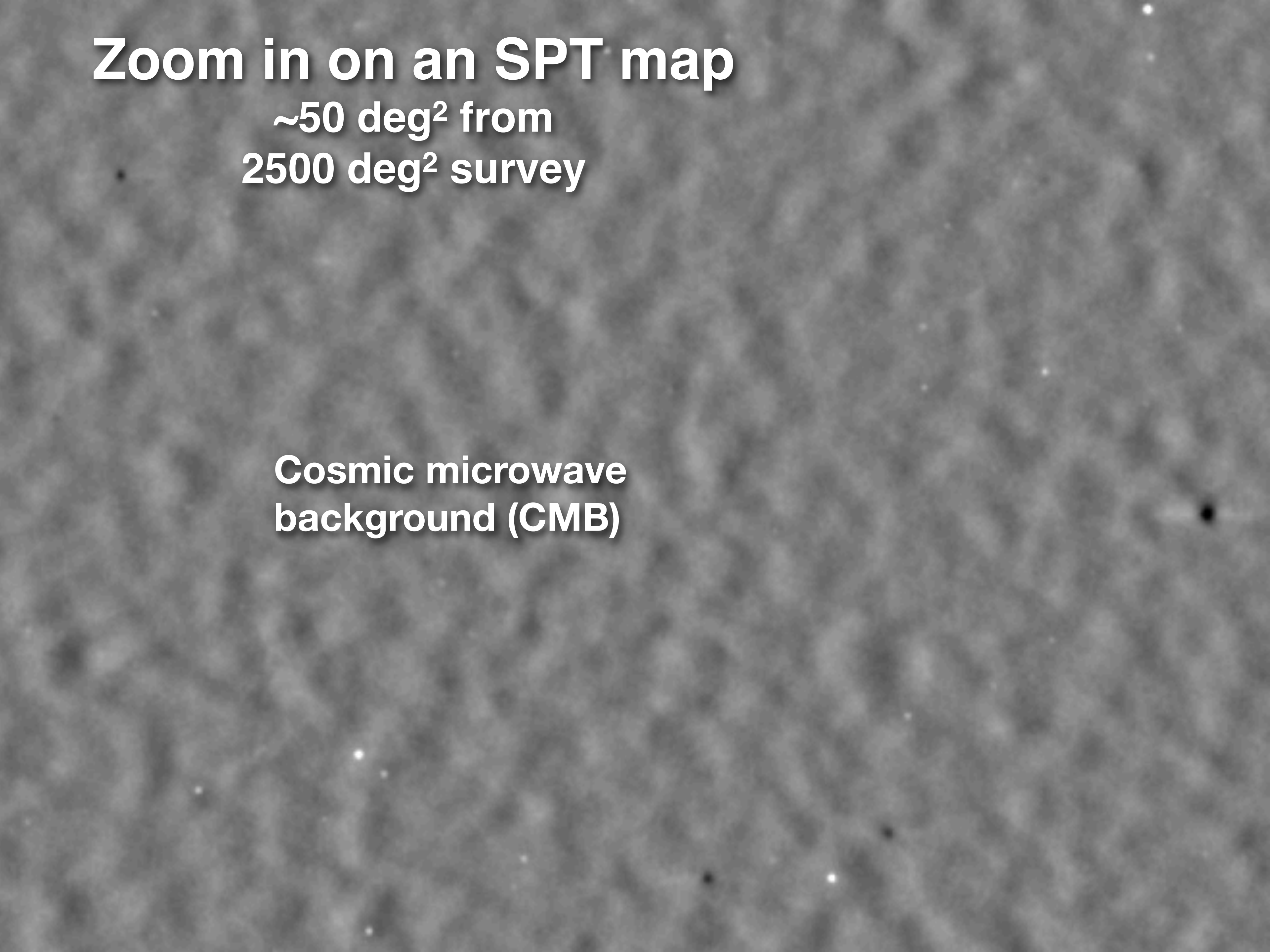
Zoom in on an SPT map

~50 deg² from 2500 deg² survey



Galaxy cluster show up as “shadows” against the CMB!

Radio and dusty galaxies show up as bright spots


Zoom in on an SPT map
~50 deg^2 from
2500 deg^2 survey
Cosmic microwave
background (CMB)

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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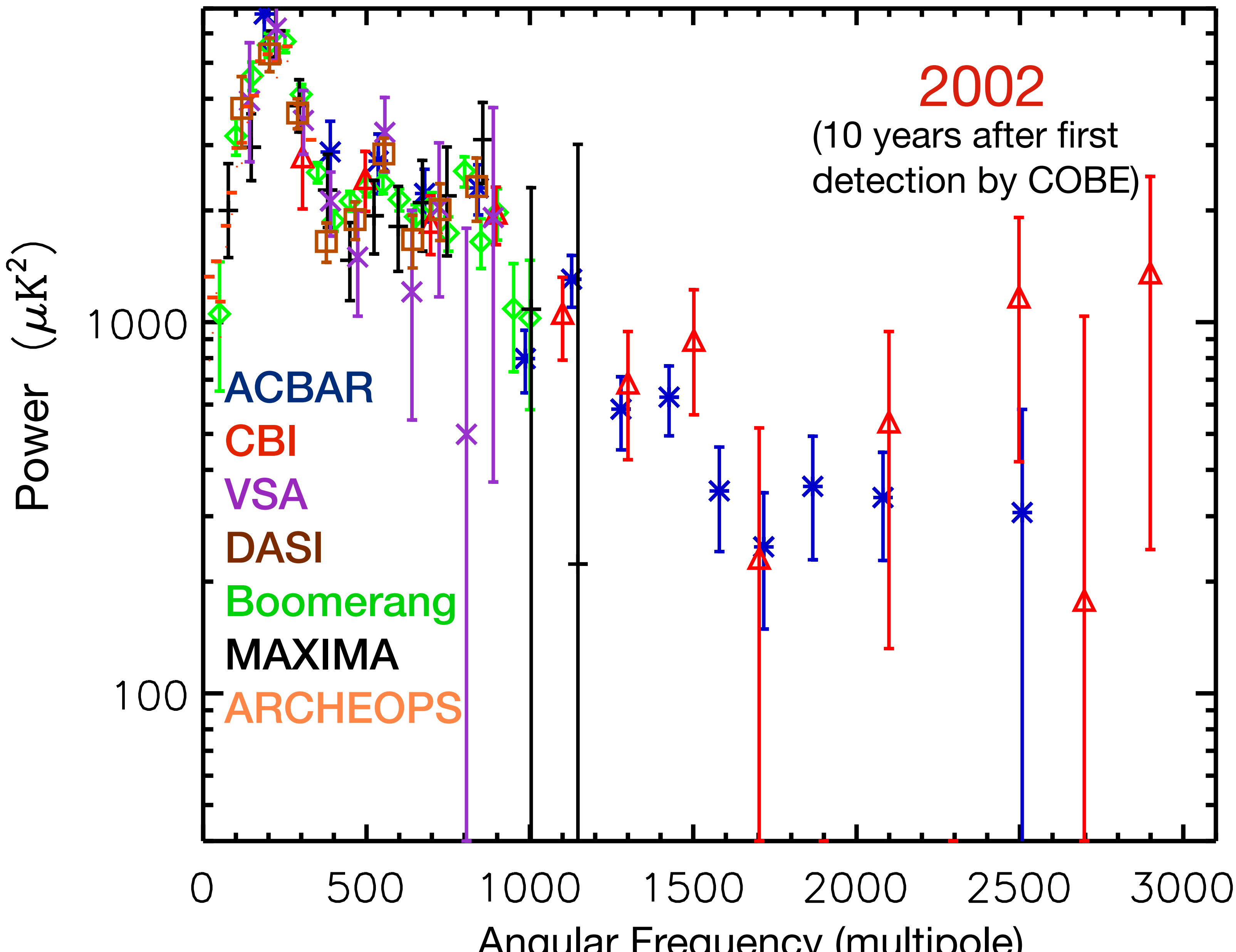
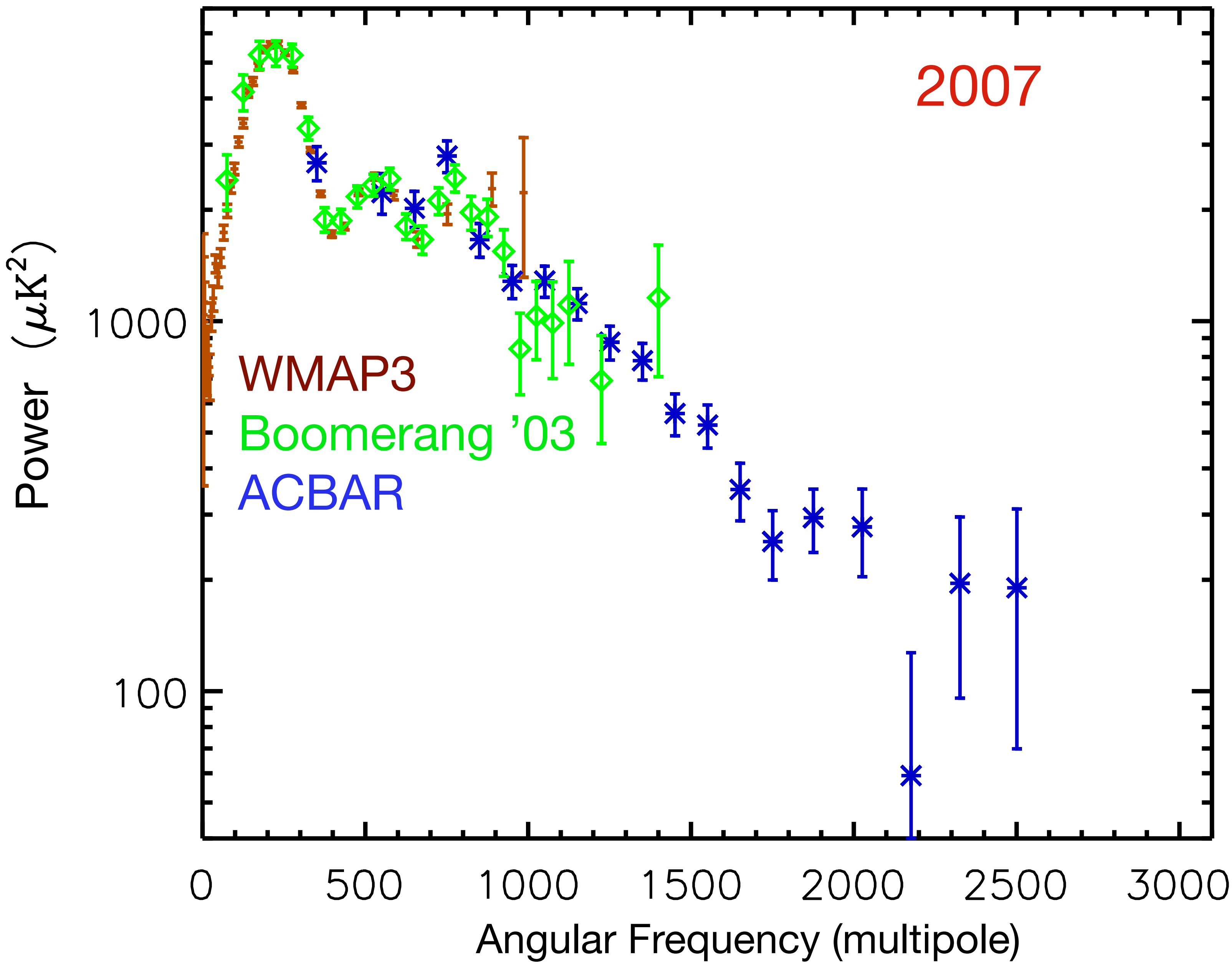
  - **What caused Inflation?**
- CMB lensing
  - 1^{st} B-mode detection from SPTpol
  - What are the neutrino masses?

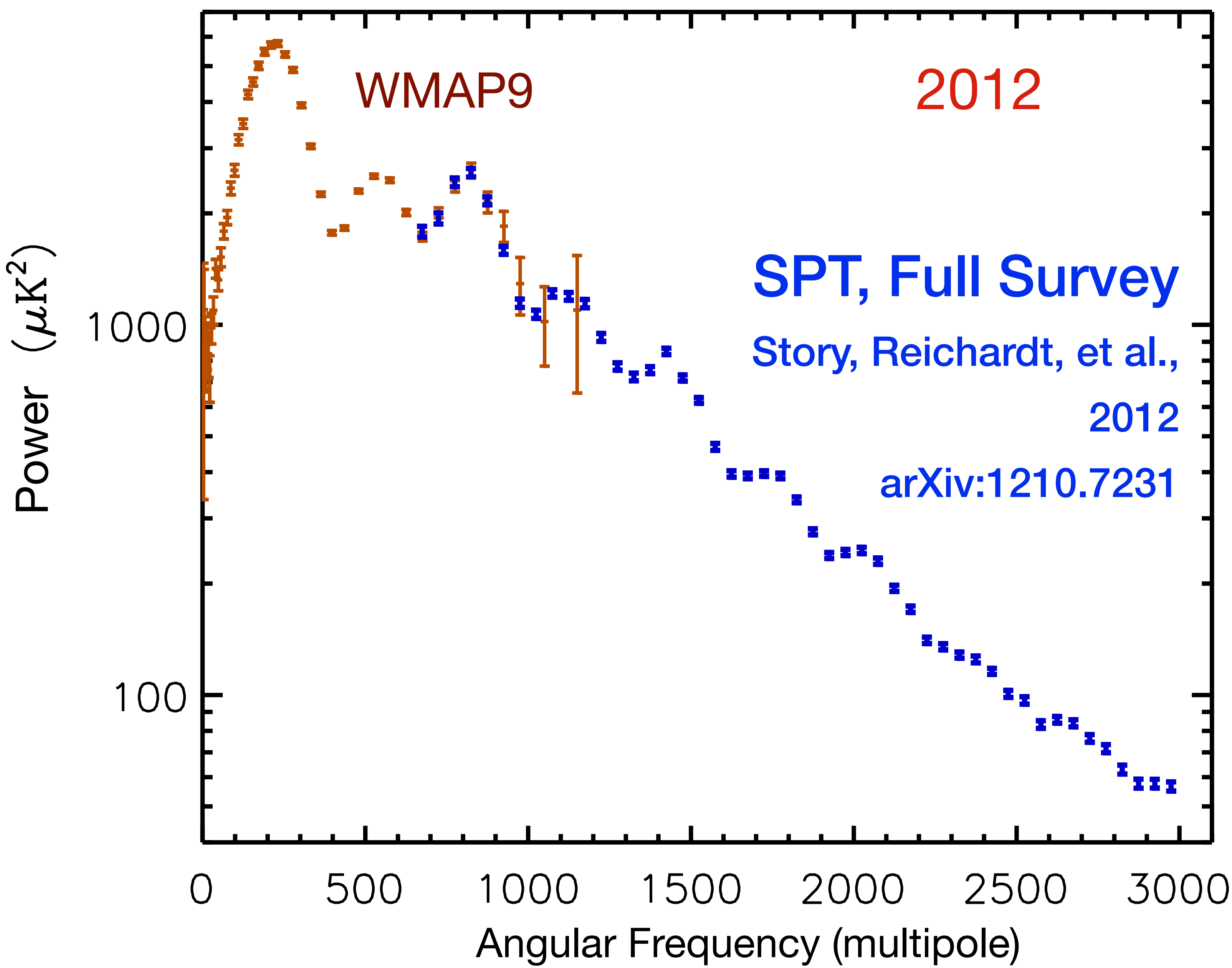
Strong experimental progress



Strong experimental progress



First results from full survey!



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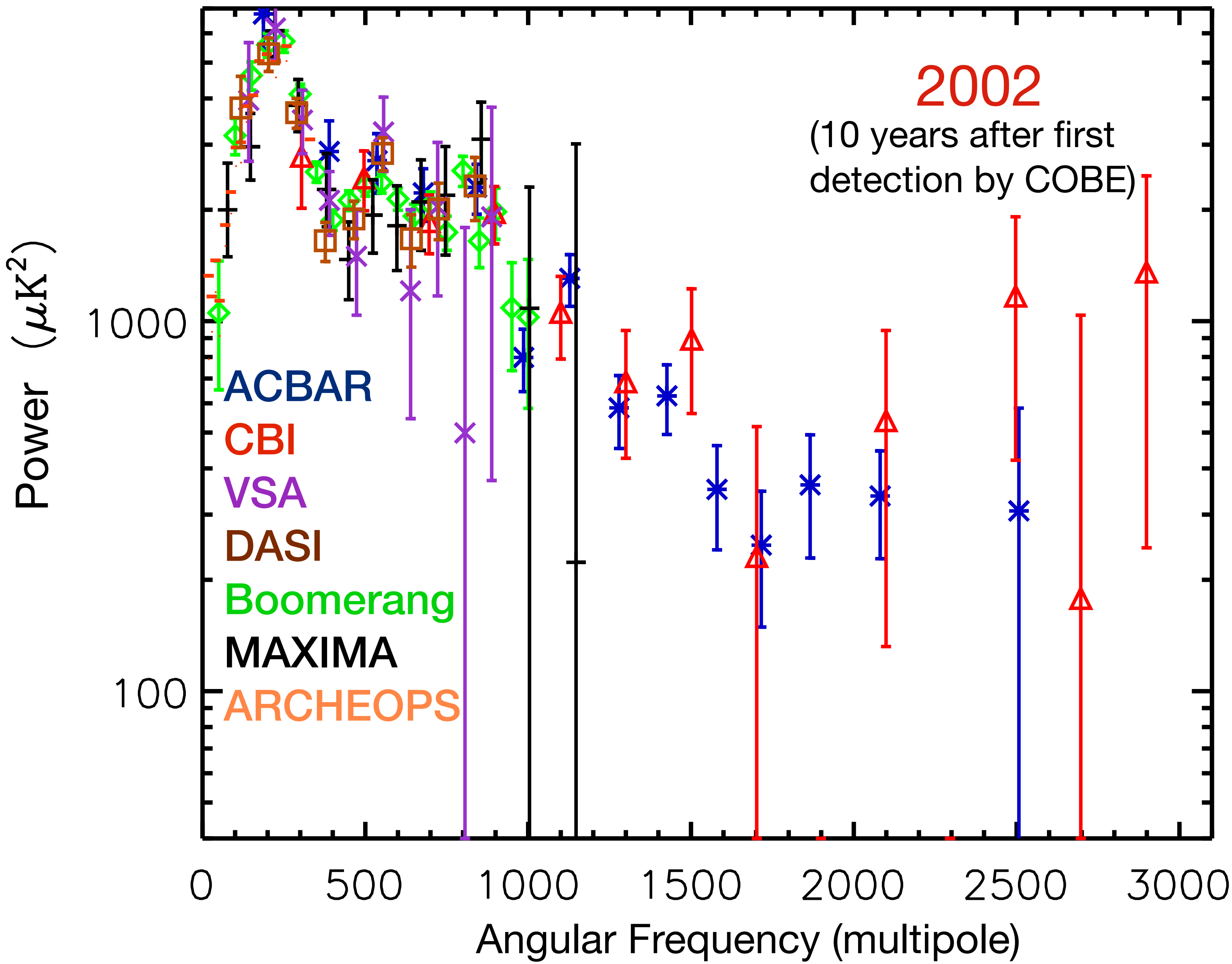
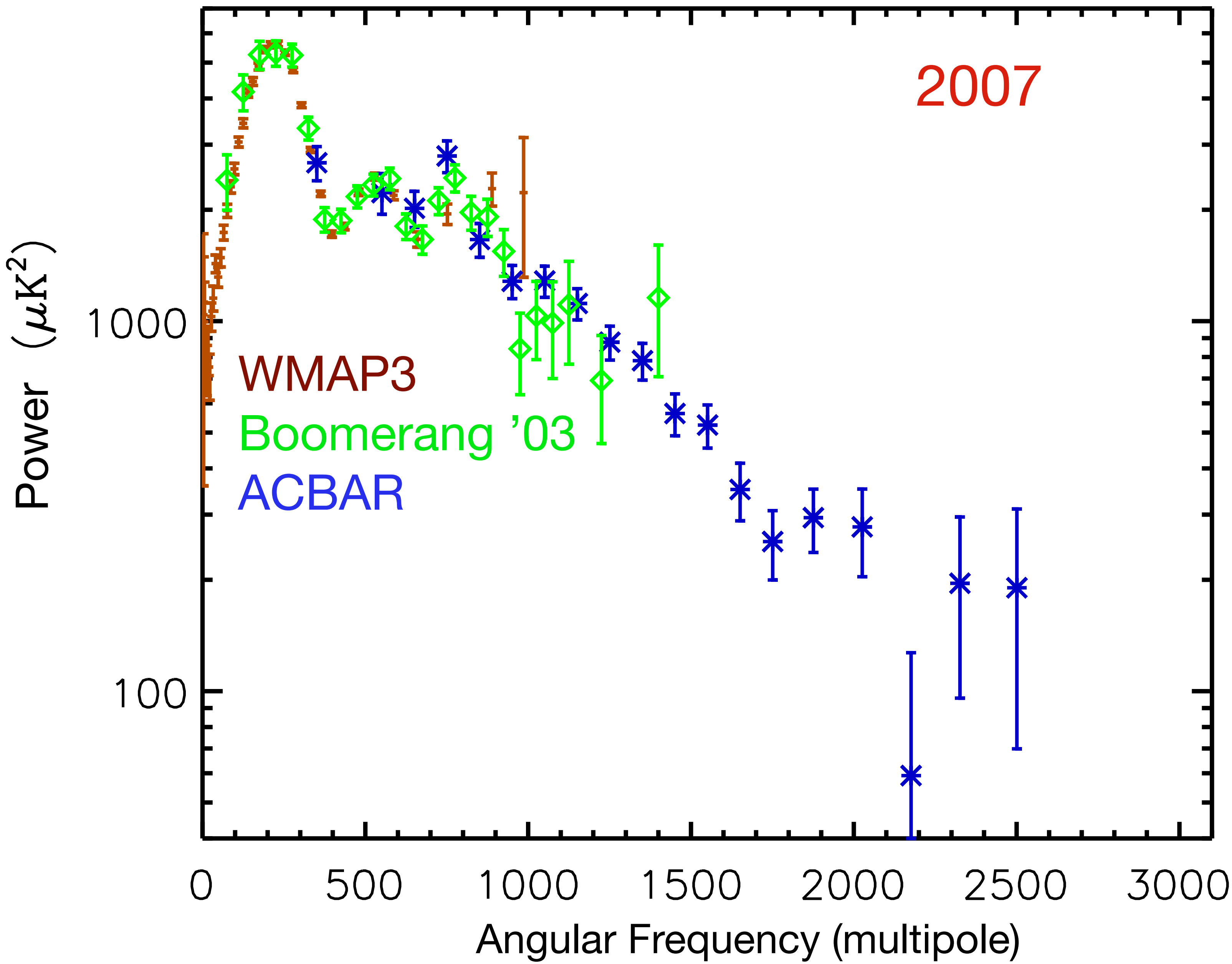


Strong experimental progress



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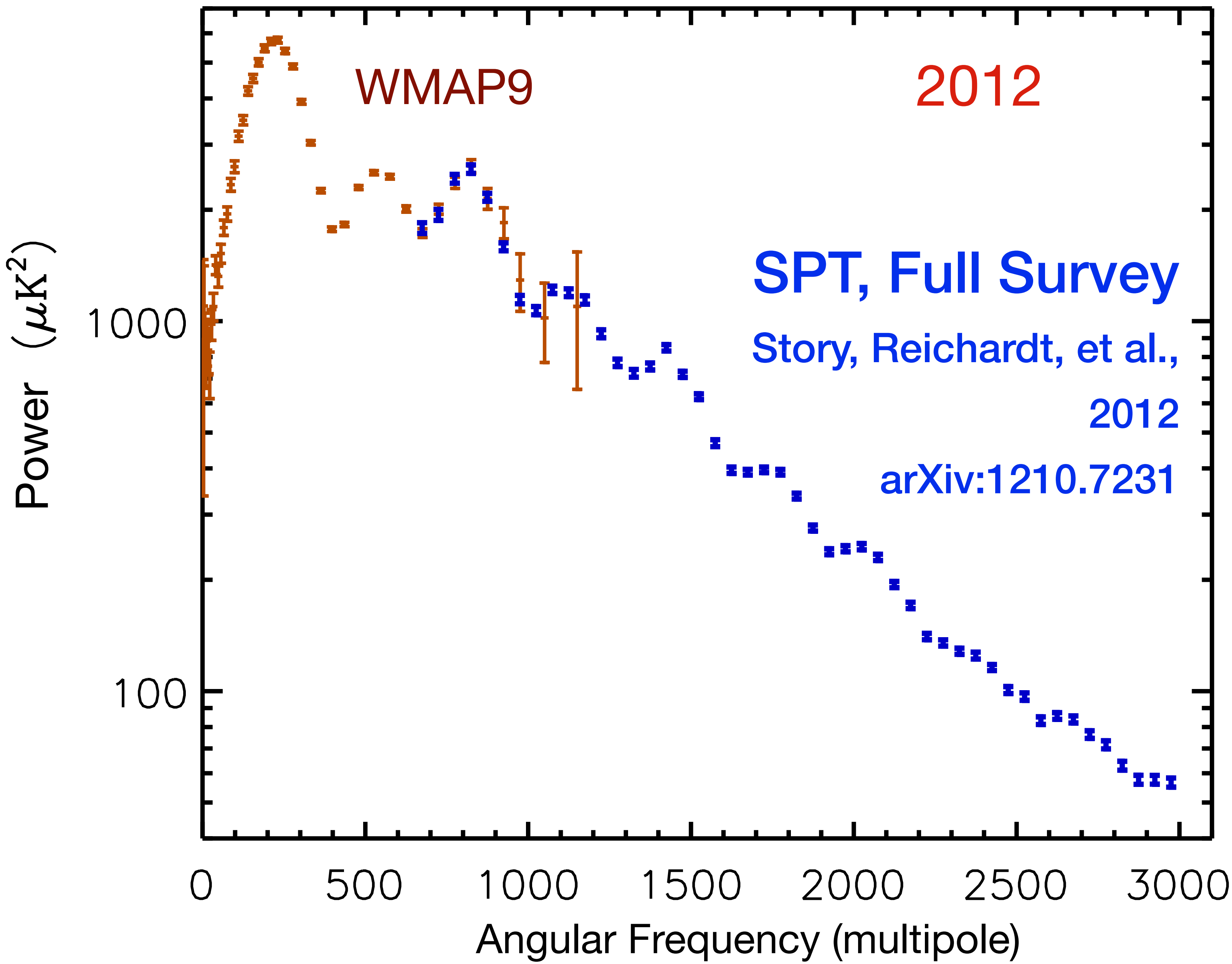
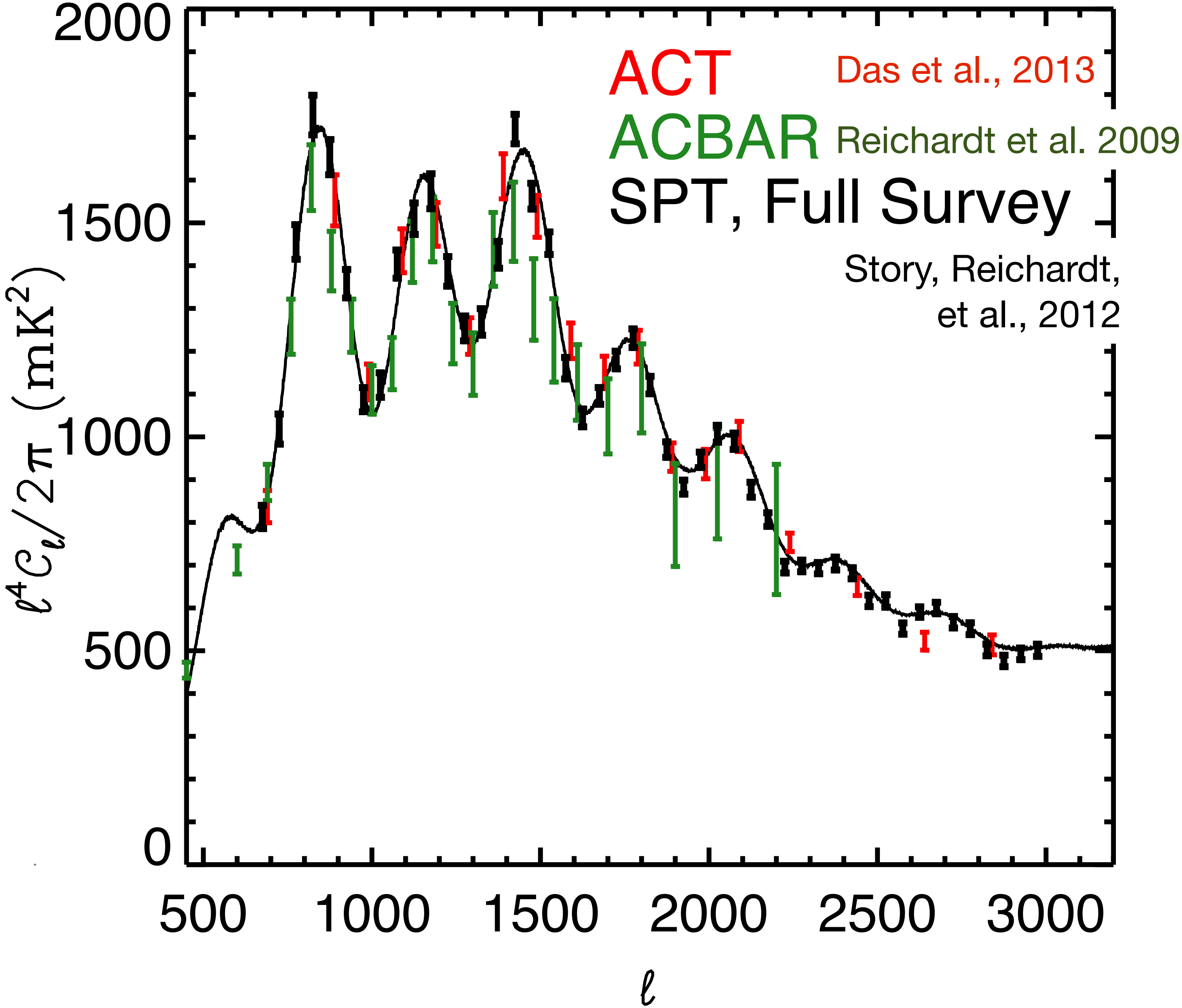


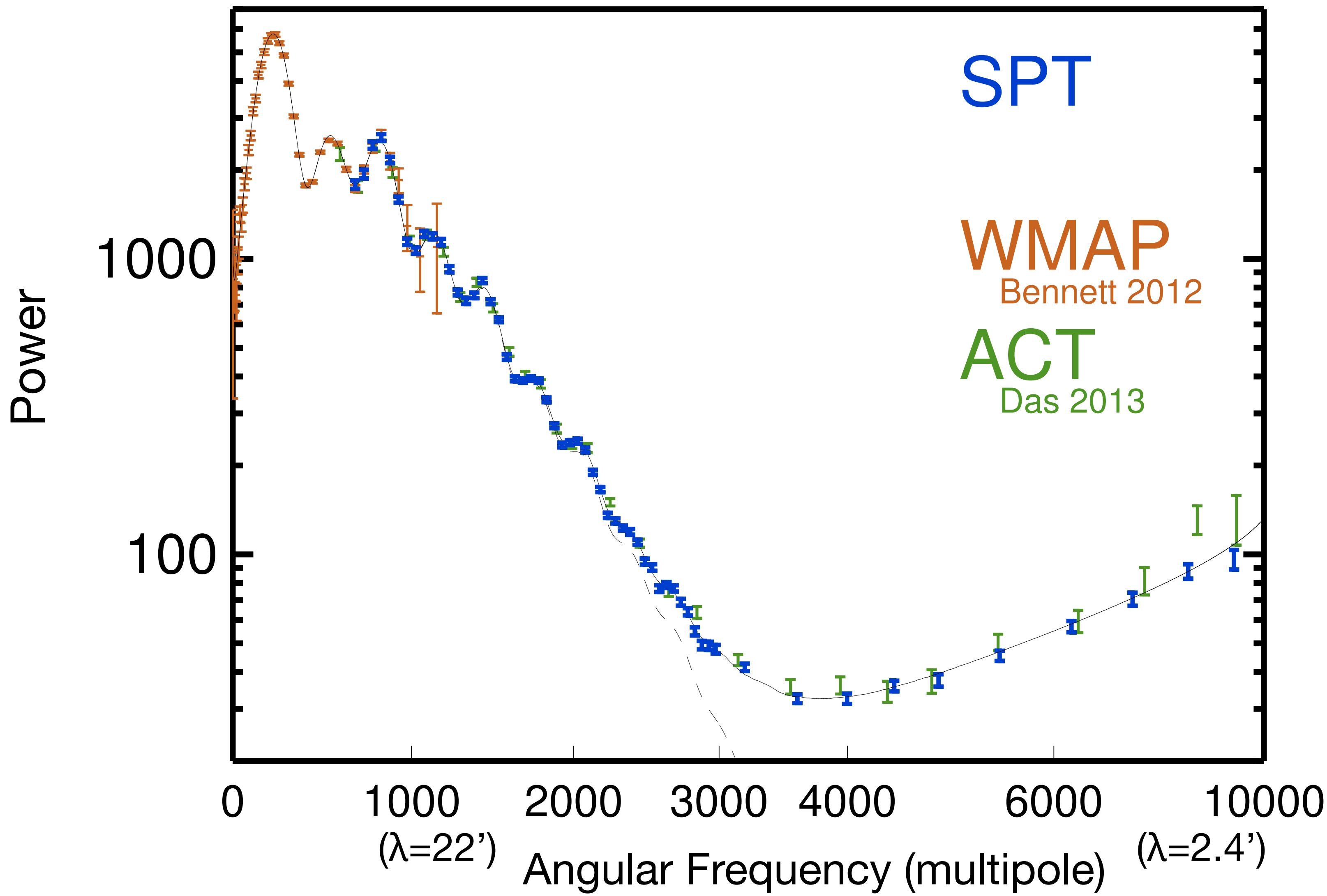
x3 improvement from SPT



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

State before Planck

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



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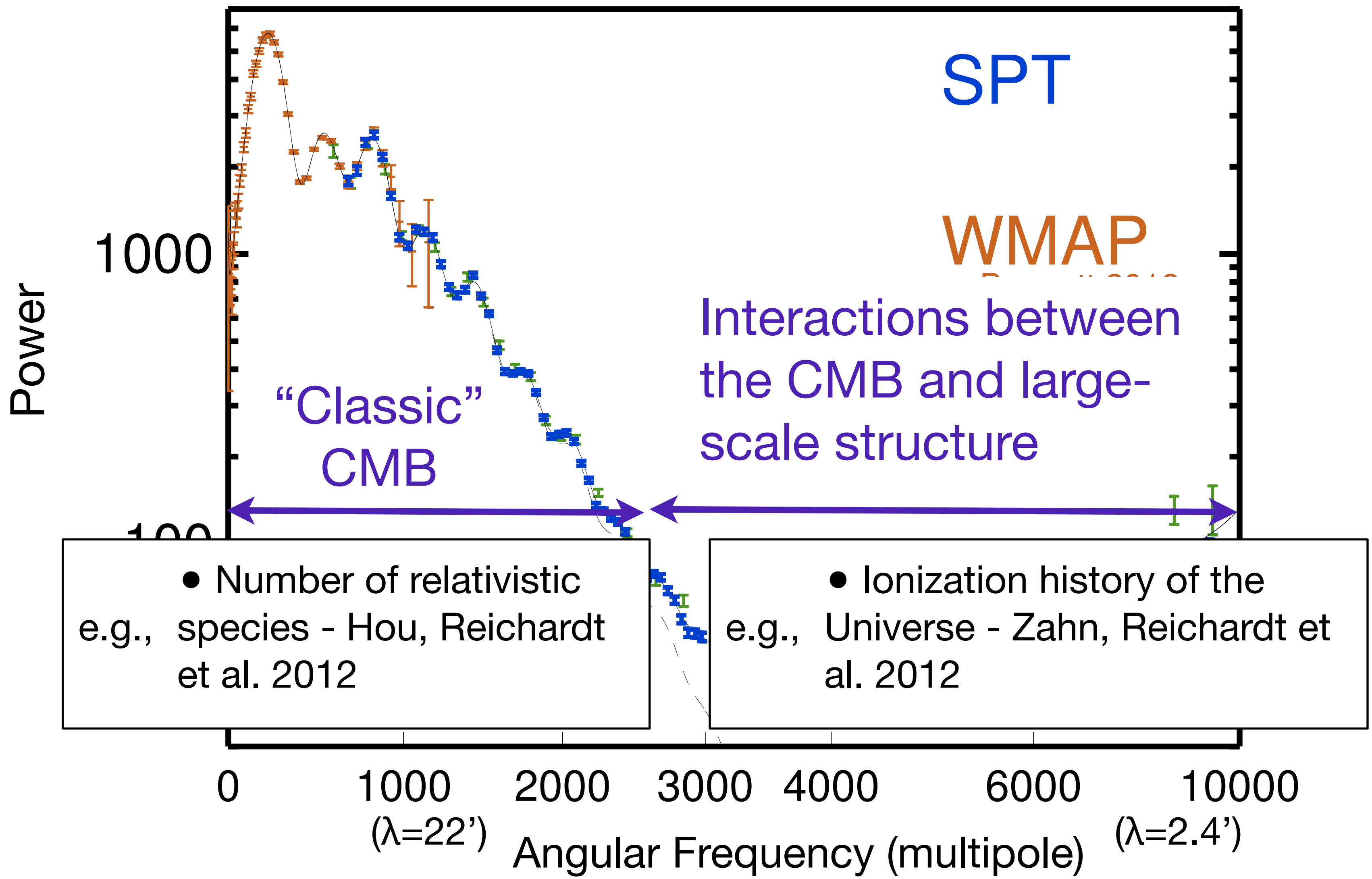
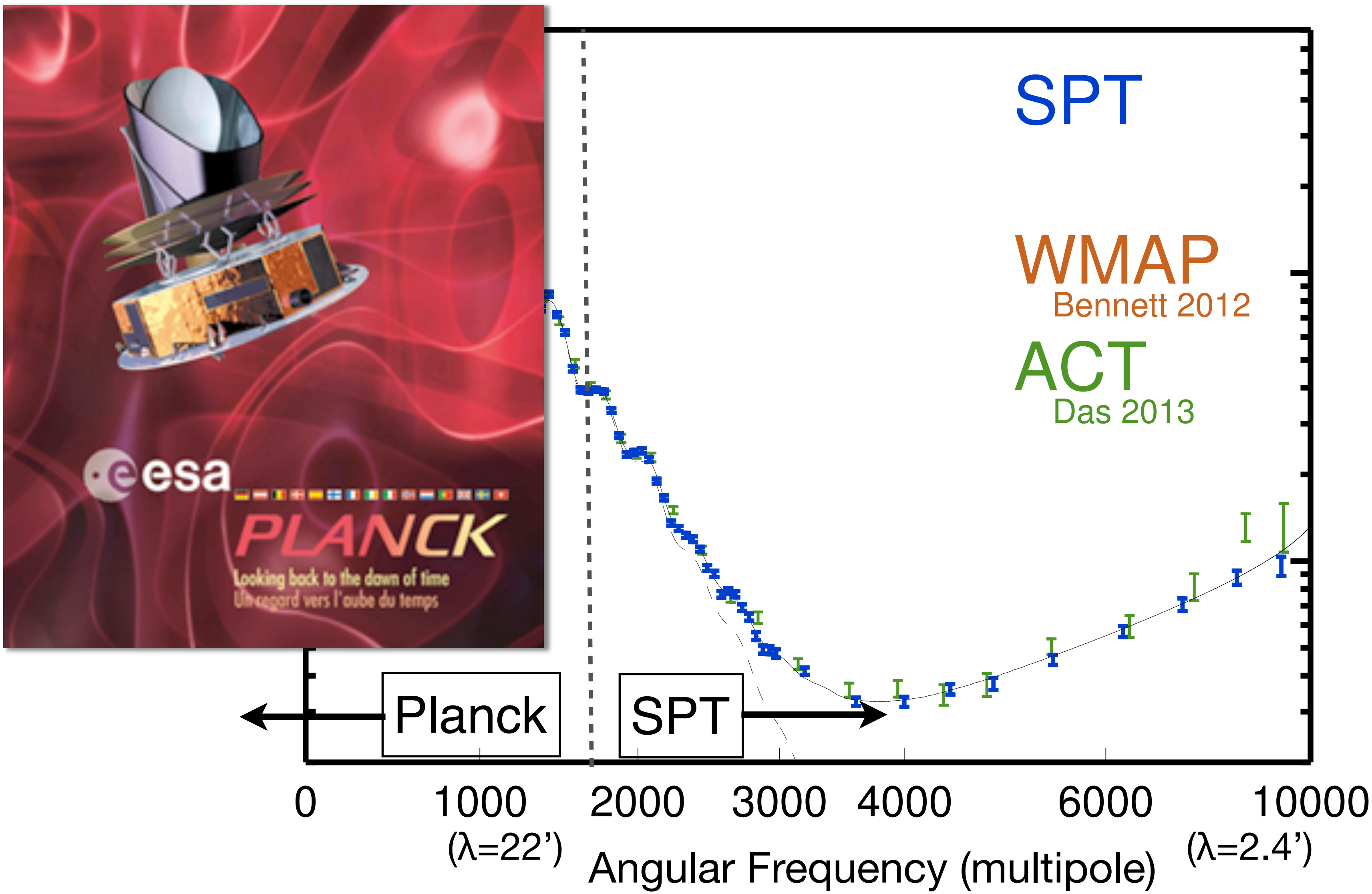
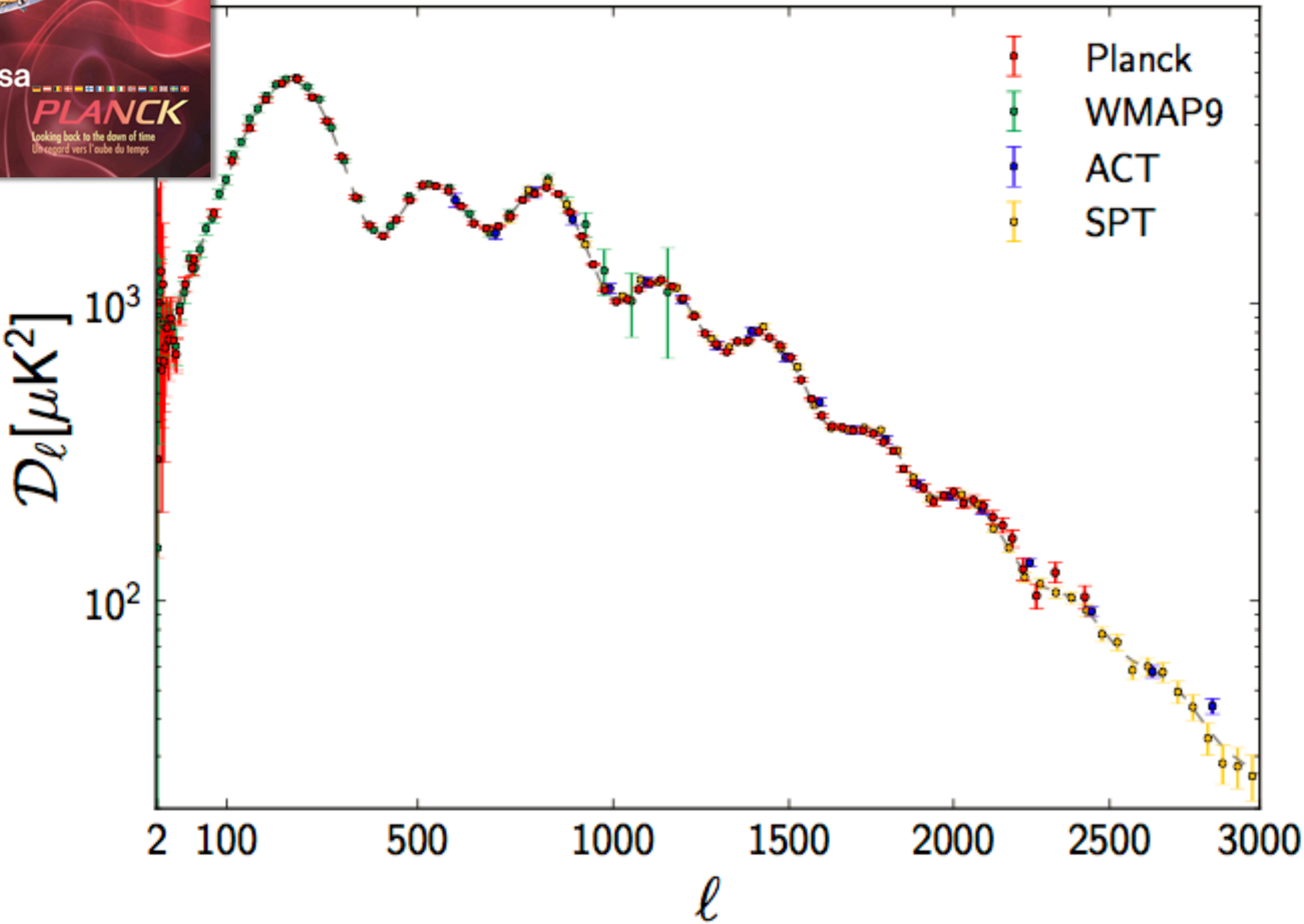


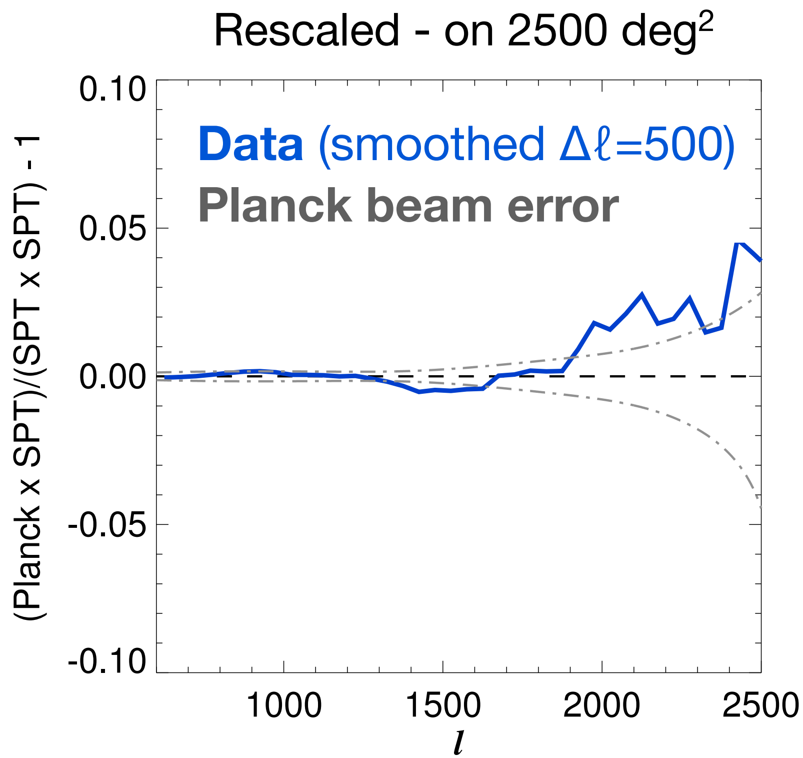
with Planck

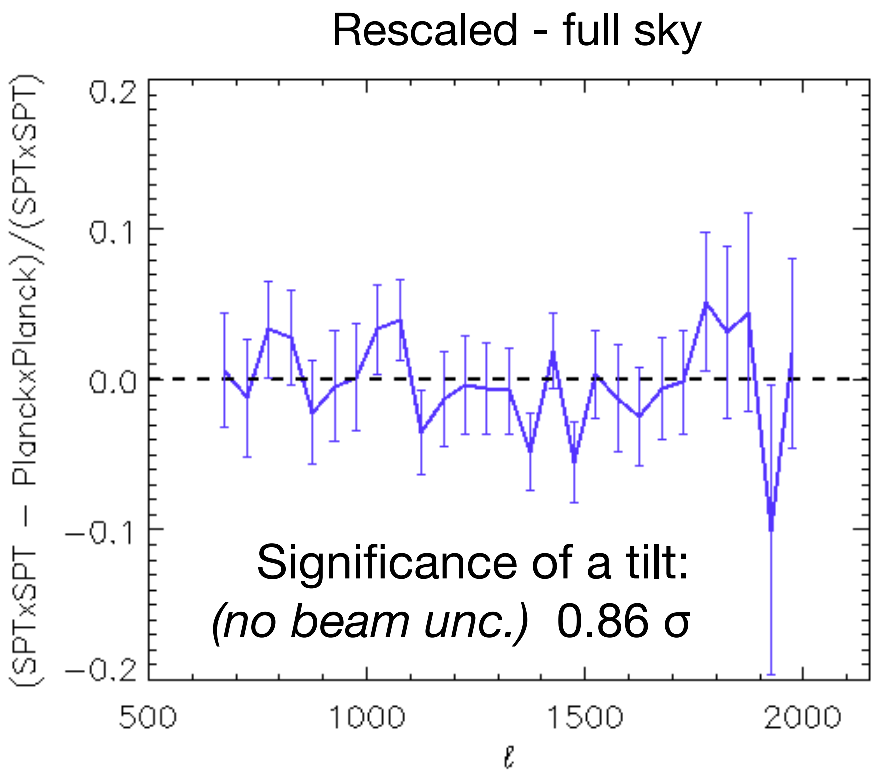

esa
PLANCK
Looking back to the dawn of time
Un regard vers l'aube du temps
SPT
WMAP
Bennett 2012
ACT
Das 2013
Planck
SPT
0
1000
(λ=22’)
2000
3000
4000
6000
10000
(λ=2.4’)
Angular Frequency (multipole)

Stunning agreement



Comparing SPT & Planck





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

Re-scale: **1.8%**
SPT cal uncertainty: **2.6%**

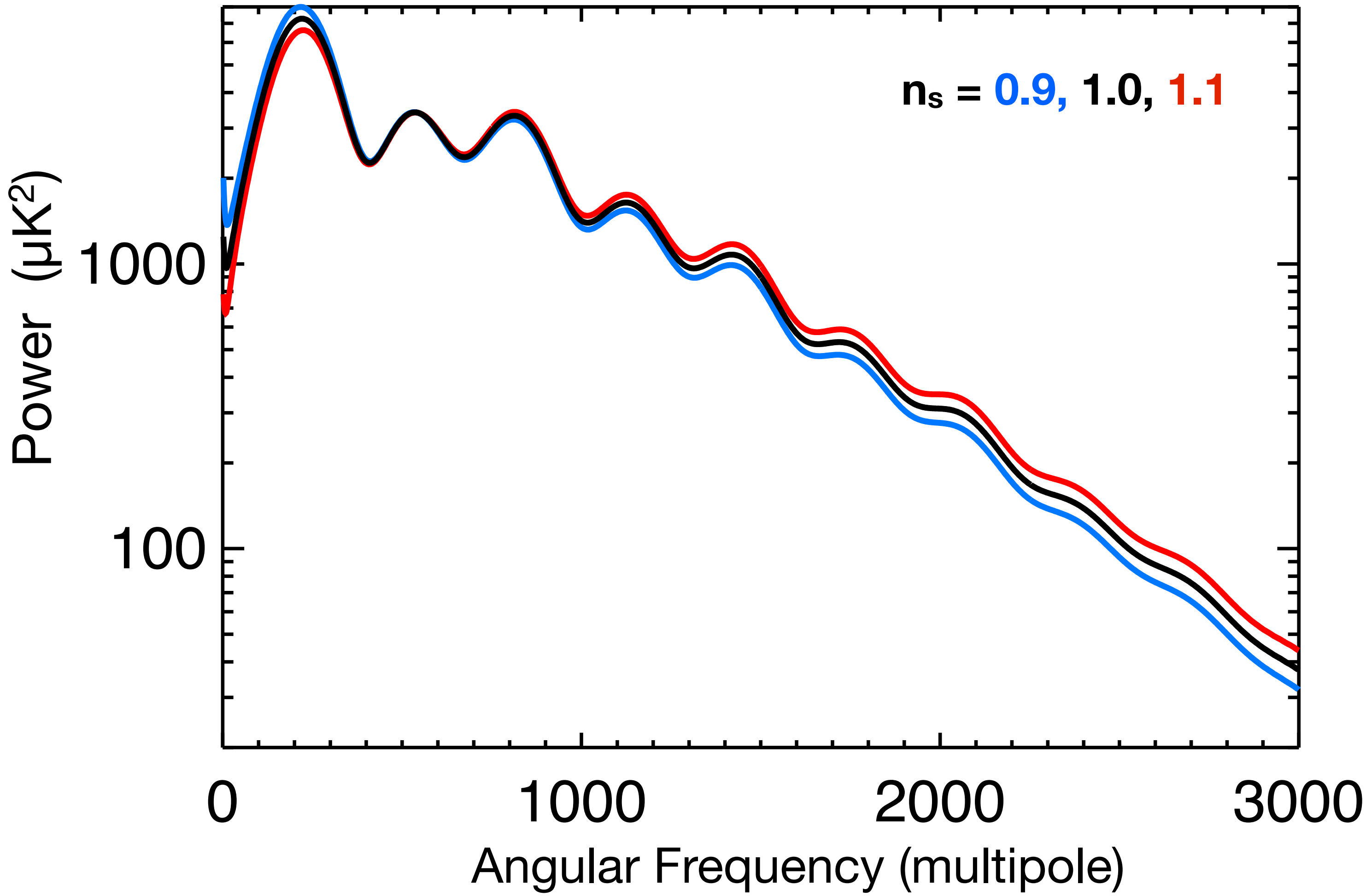
[units of Power]

What caused inflation?

What were the initial conditions of the Universe?

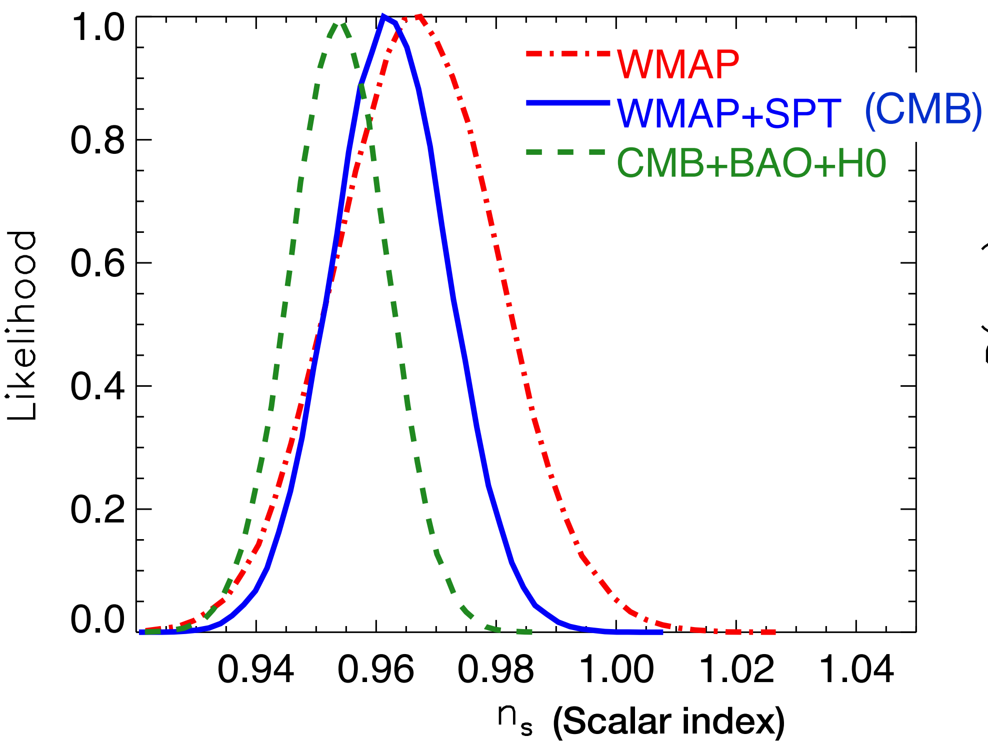
Inflation predicts nearly scale invariant spectrum

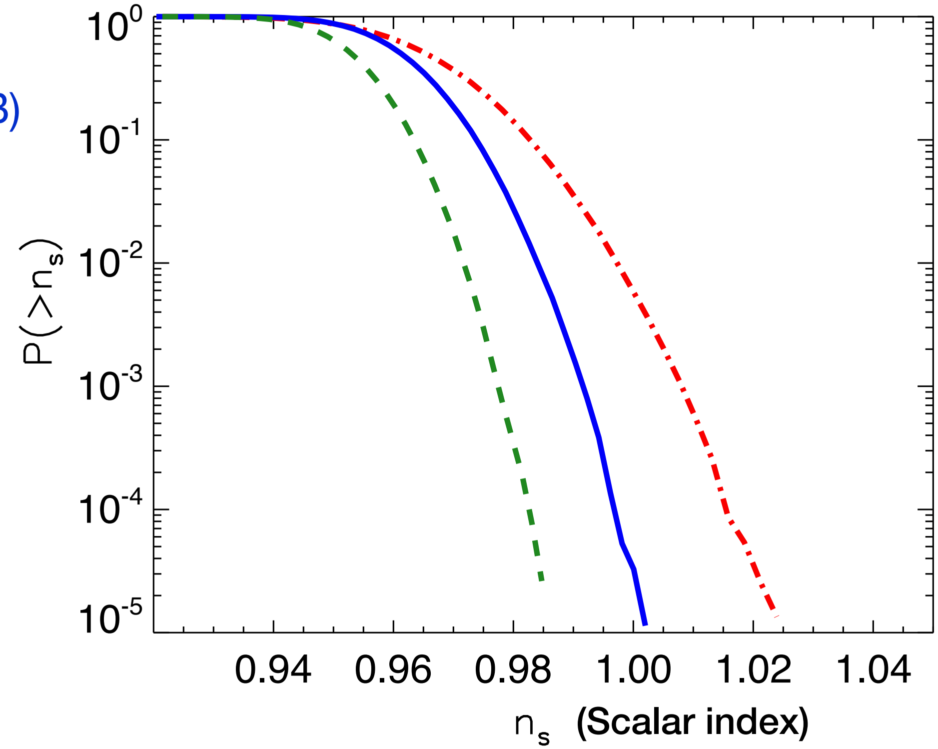
Primordial spectrum: $\Delta^2_R(k) = \Delta^2_R(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$ $\longleftrightarrow$ $n_s \sim 1$ for scale invariance



Story, Reichardt et al., arXiv:1210.7231

Data:



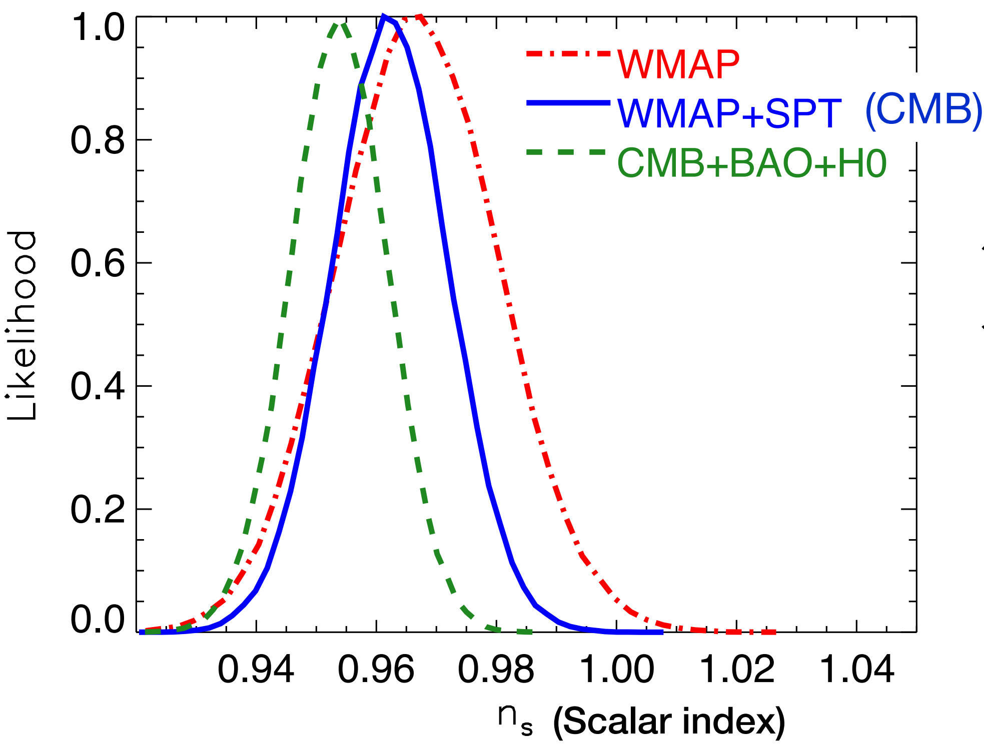


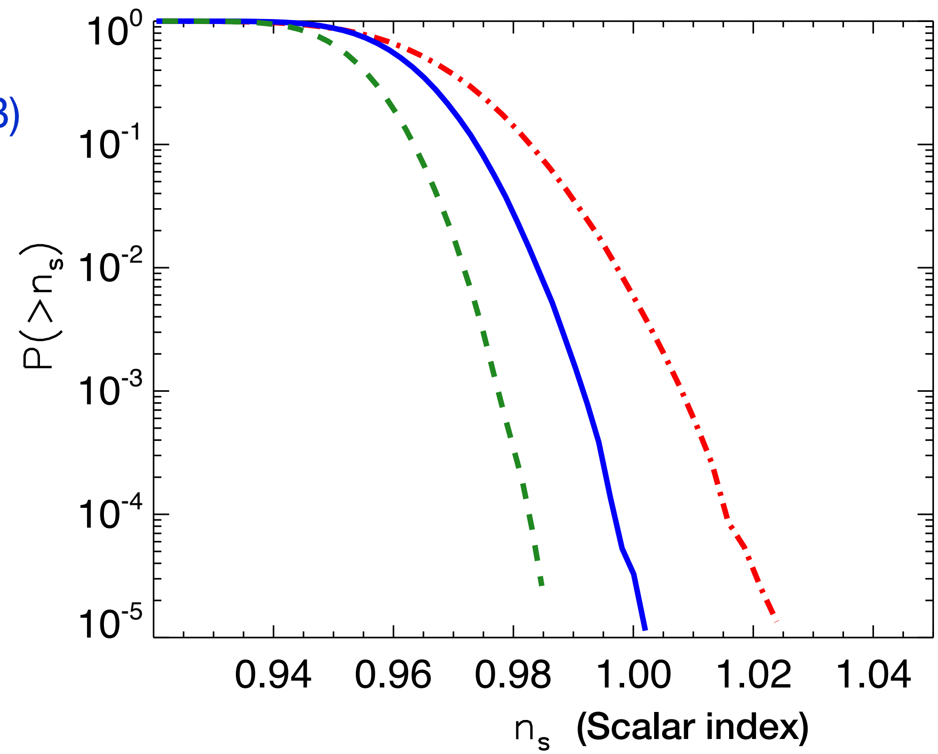
n_s: **WMAP7 = 0.969 ± 0.014**
WMAP7+SPT (CMB) = 0.962 ± 0.010
CMB+BAO+H_0 = 0.954 ± 0.008

$P(n_s > 1)$: 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)

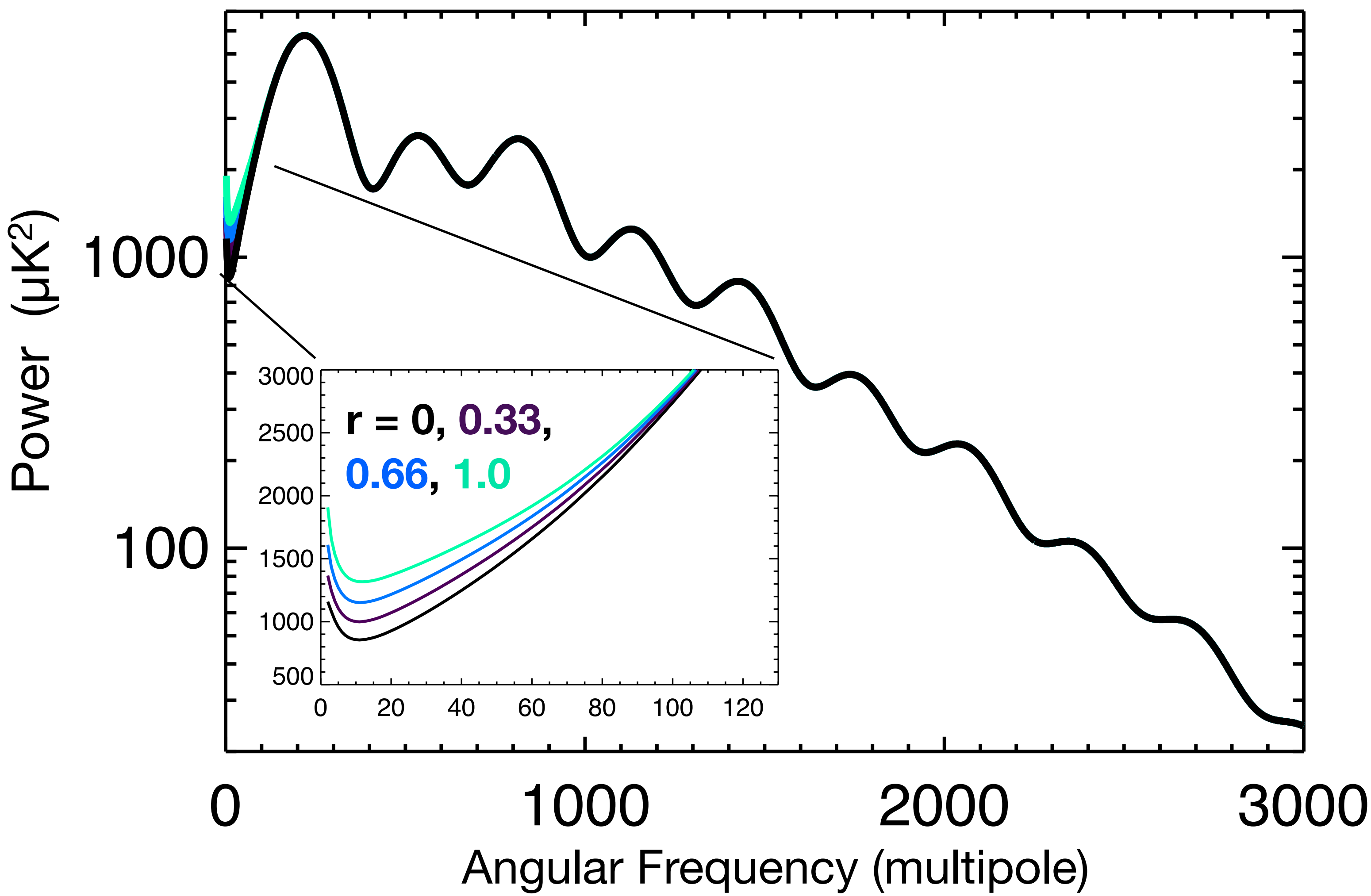
+SPT = 3.9e-4 (3.9 σ)

+BAO+H_0=1.4e-9 (5.9 σ)

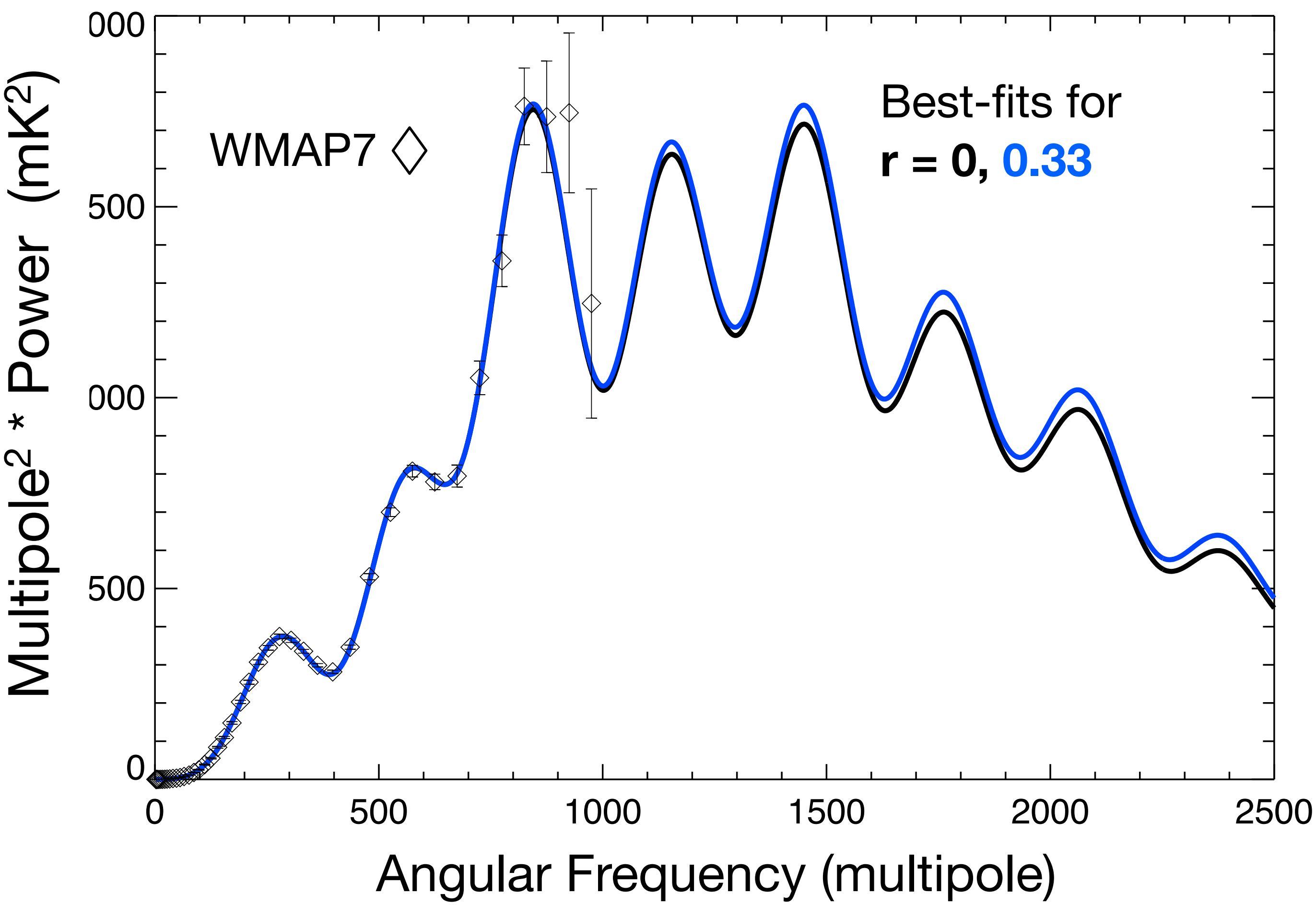
Planck improves by ~ x1.5

Same CMB value (shift <0.2 σ)

Tensor perturbations and temperature anisotropy



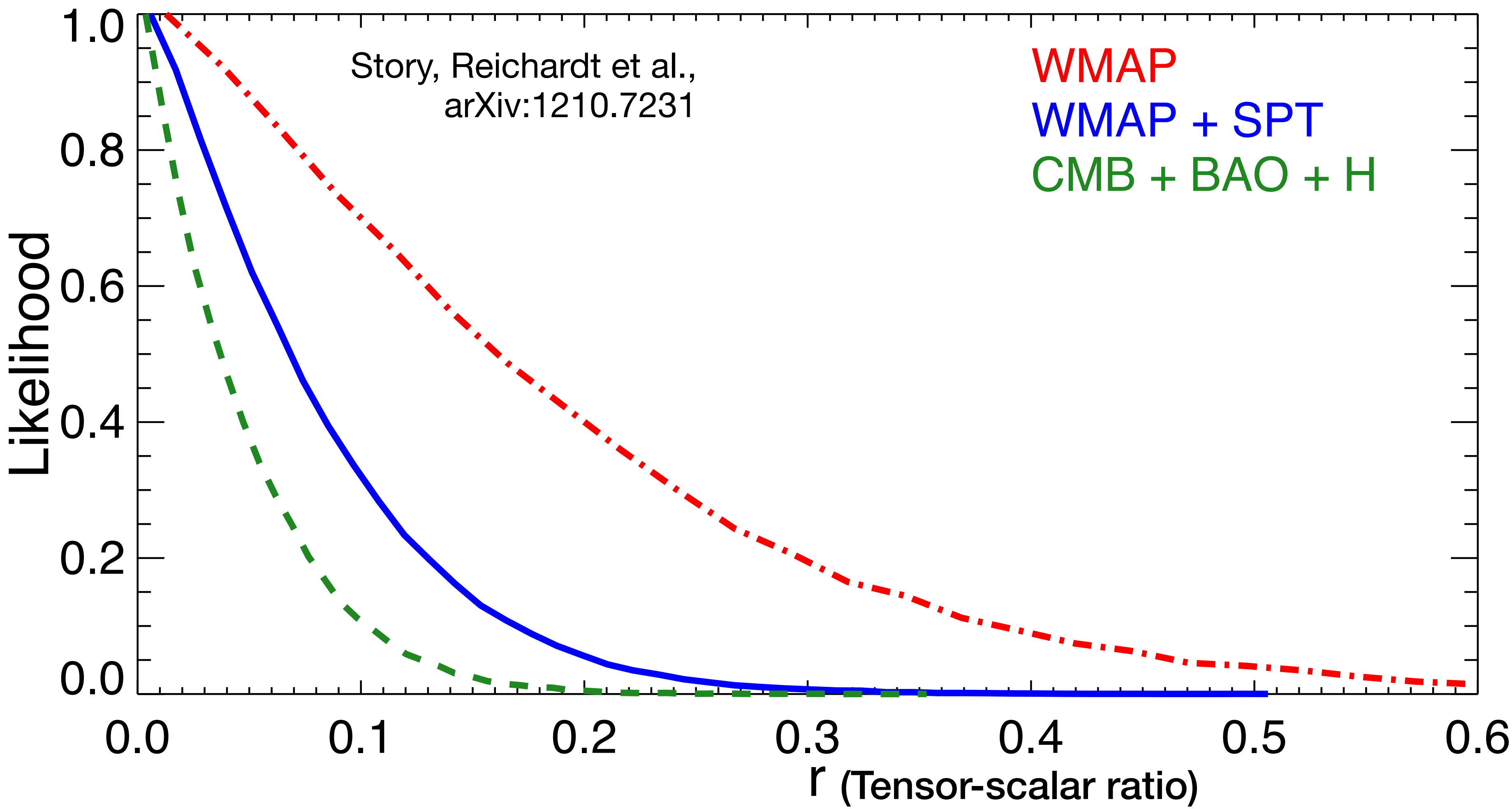
Role of small-scale data



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.

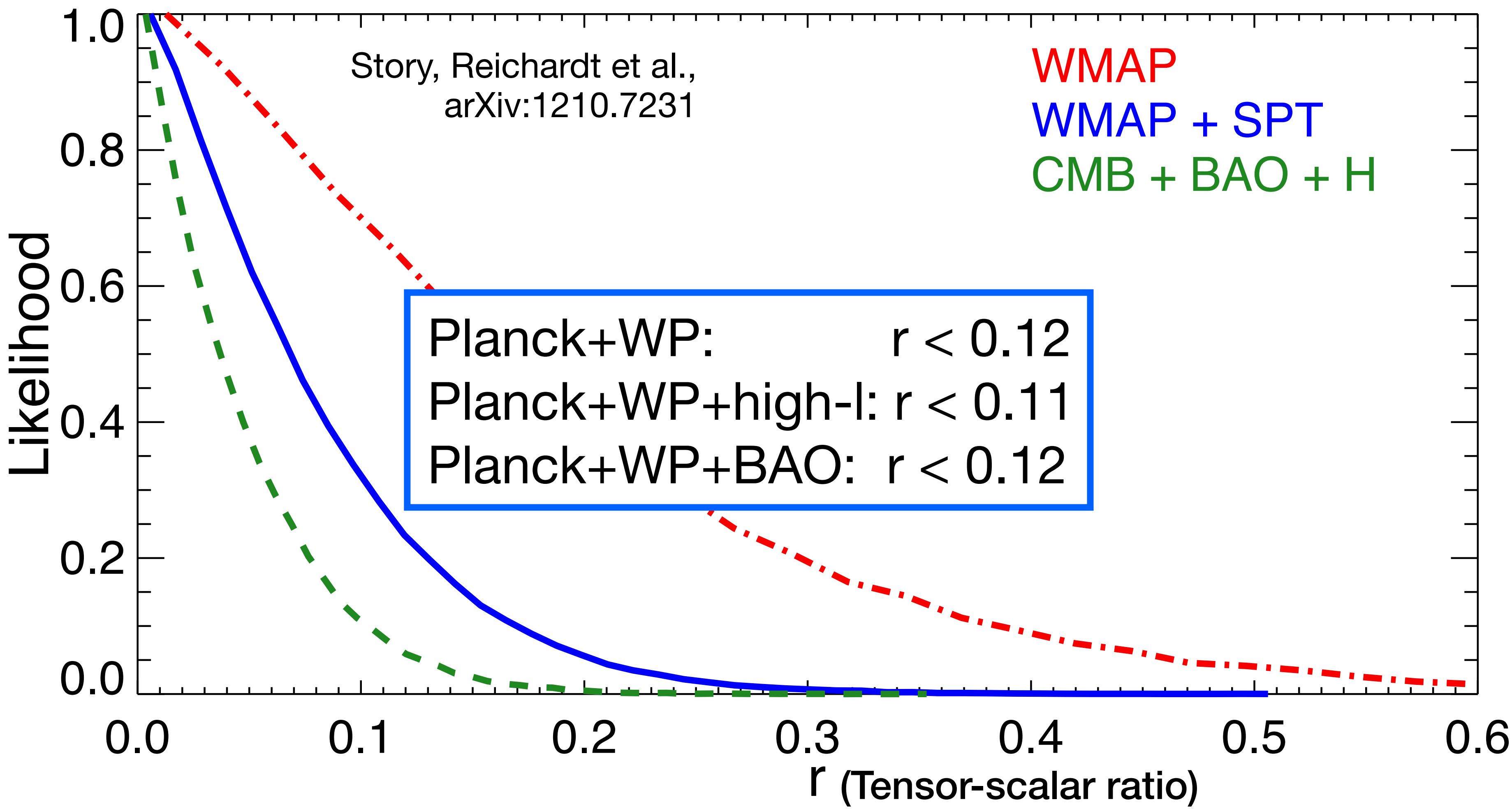
Hitting TT sample variance limit



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



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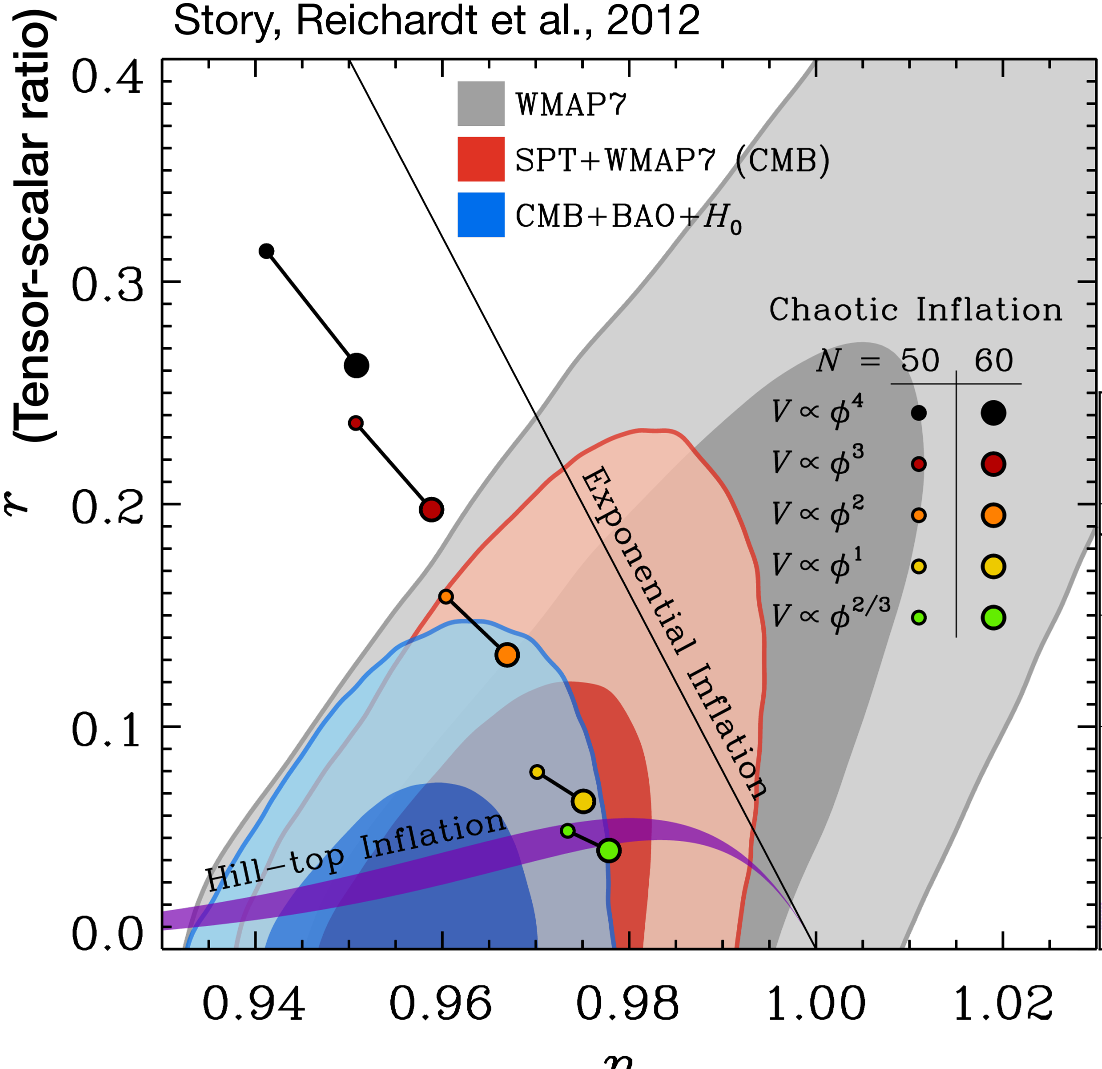
Implications for inflation

(variations on n_s vs. r)

As seen in Jerome and Cliff's talks

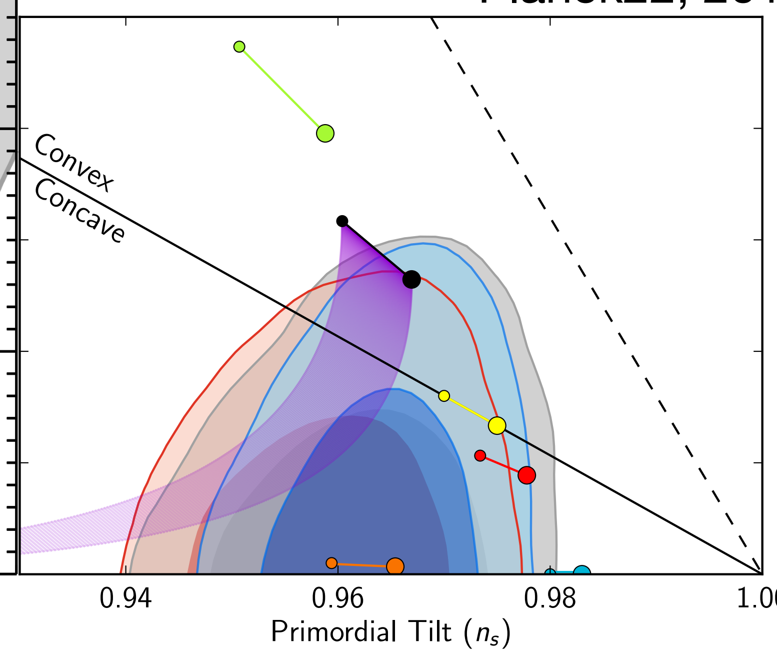
Story, Reichardt et al., 2012



(Scalar index)

Consistent allowed region!

Planck22, 2013



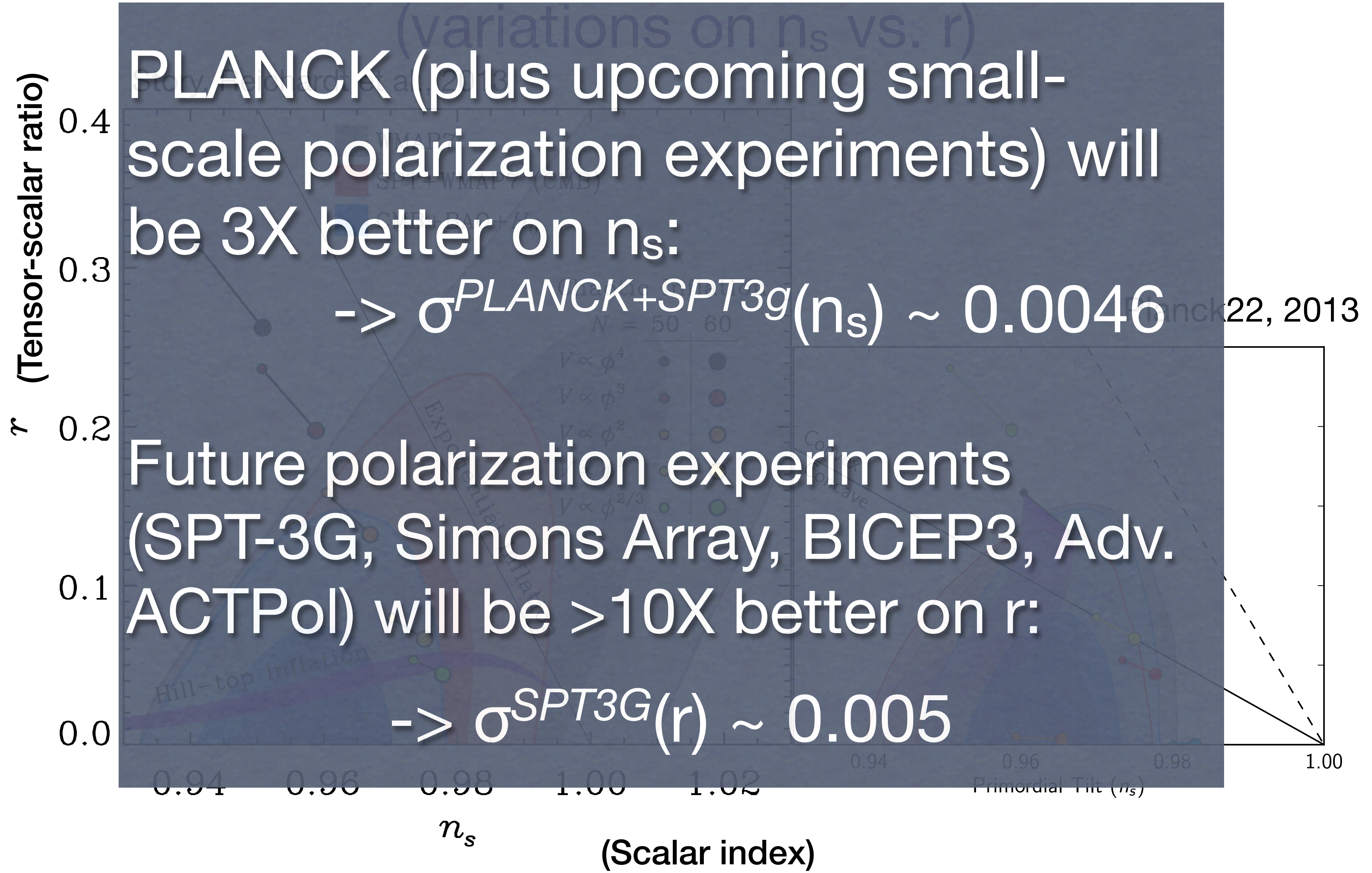
Implications for inflation

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, BICEP3, Adv. ACTPol) will be >10X better on r:

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



Outline

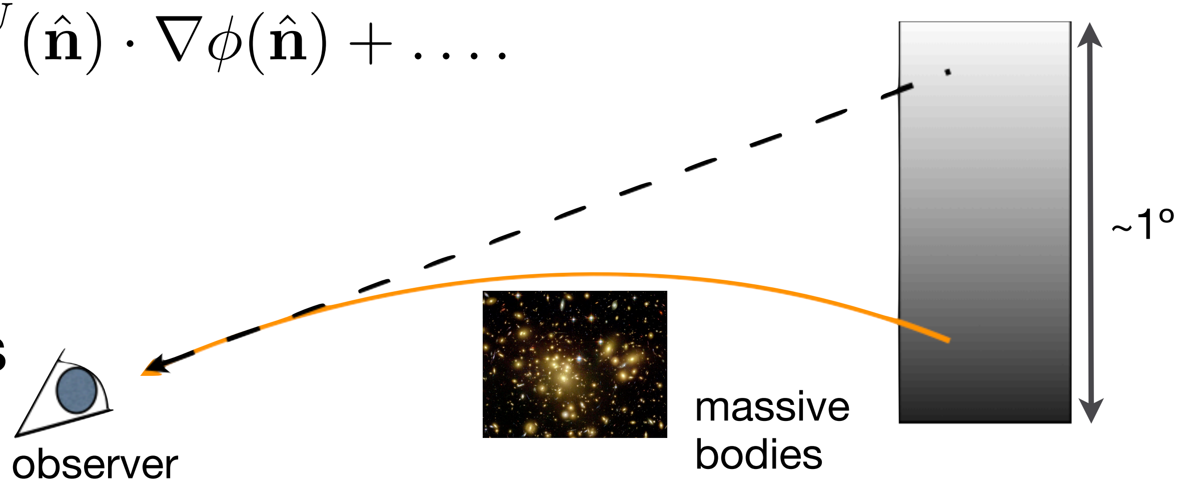
- ☑ The three cameras of the South Pole Telescope
  - SPT-SZ; SPTpol; SPT-3G
- ☑ CMB power spectrum
  - What caused Inflation?
- **CMB lensing**
  - **1st B-mode detection from SPTpol**
  - **What are the neutrino masses?**

CMB Lensing

Photons get shifted

$$
\begin{aligned}
T^L(\hat{\mathbf{n}}) &= T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})) \\
&= T^U(\hat{\mathbf{n}}) + \nabla T^U(\hat{\mathbf{n}}) \cdot \nabla\phi(\hat{\mathbf{n}}) + \ldots .
\end{aligned}
$$

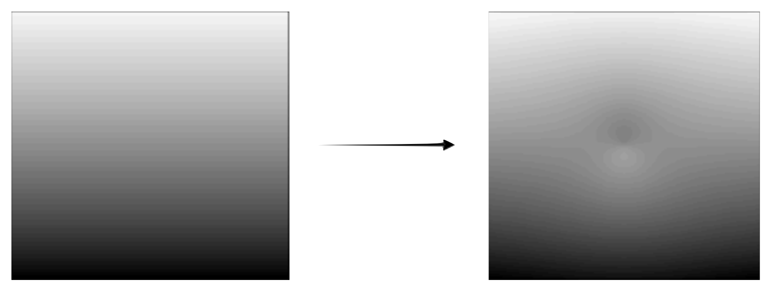
Unlensed
CMB looks like
a
pure gradient.



CMB Lensing estimators look at:

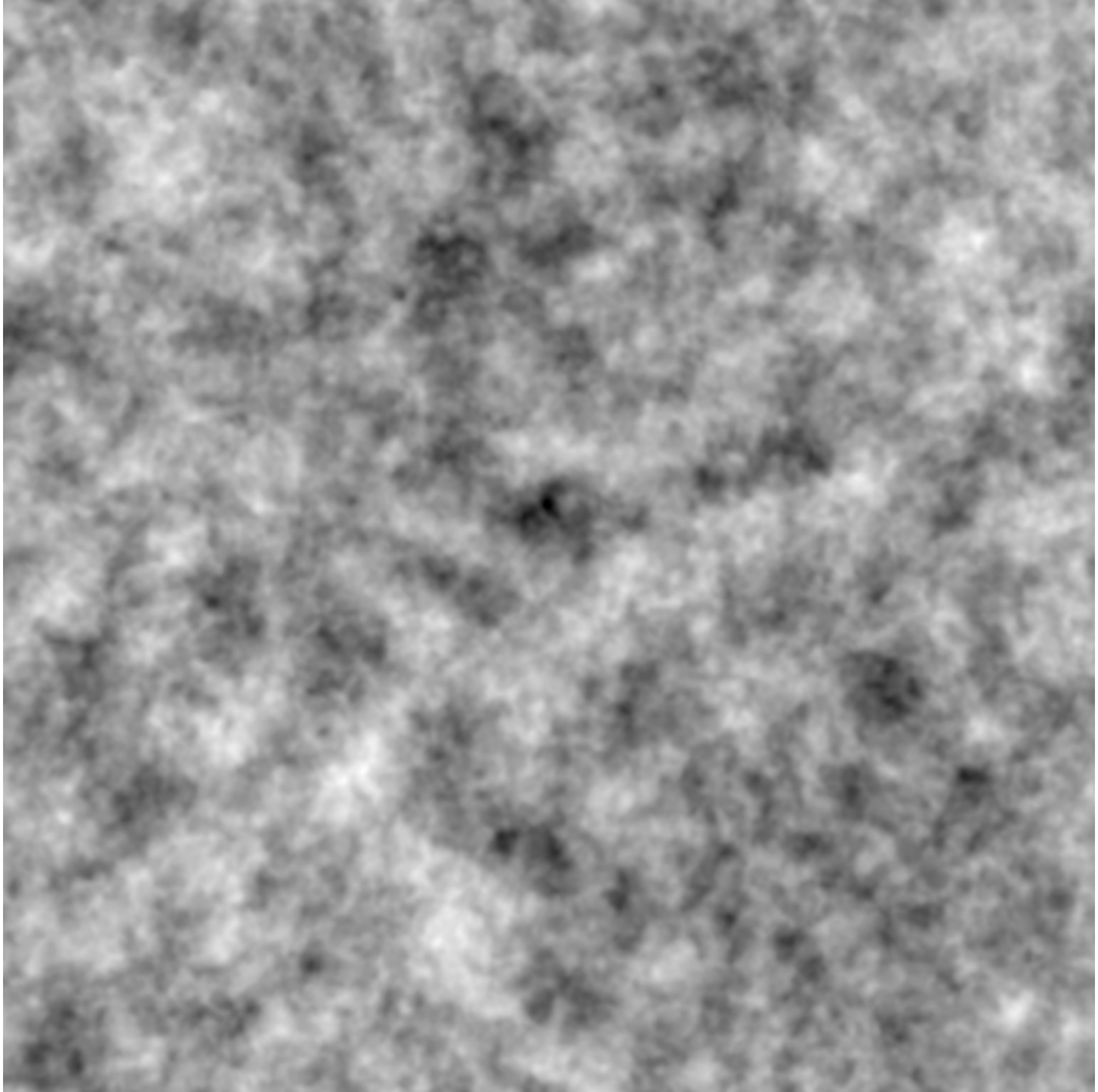
$\langle T\nabla T\rangle = 0$ (unlensed - no preferred direction)

$\sim d$ (lensed)



Small-scale wiggles are correlated with large-scale gradient.

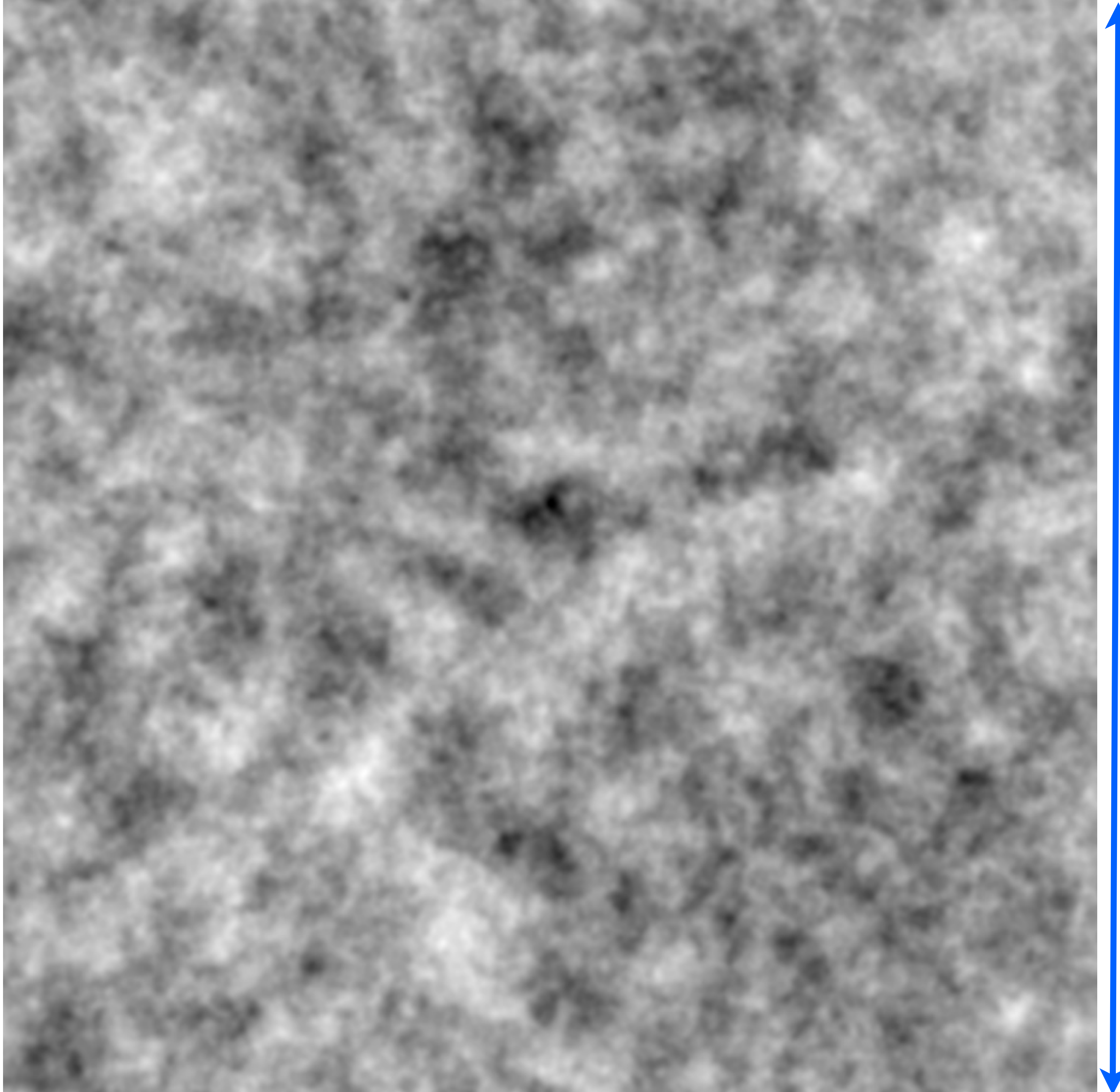
Unlensed



15°

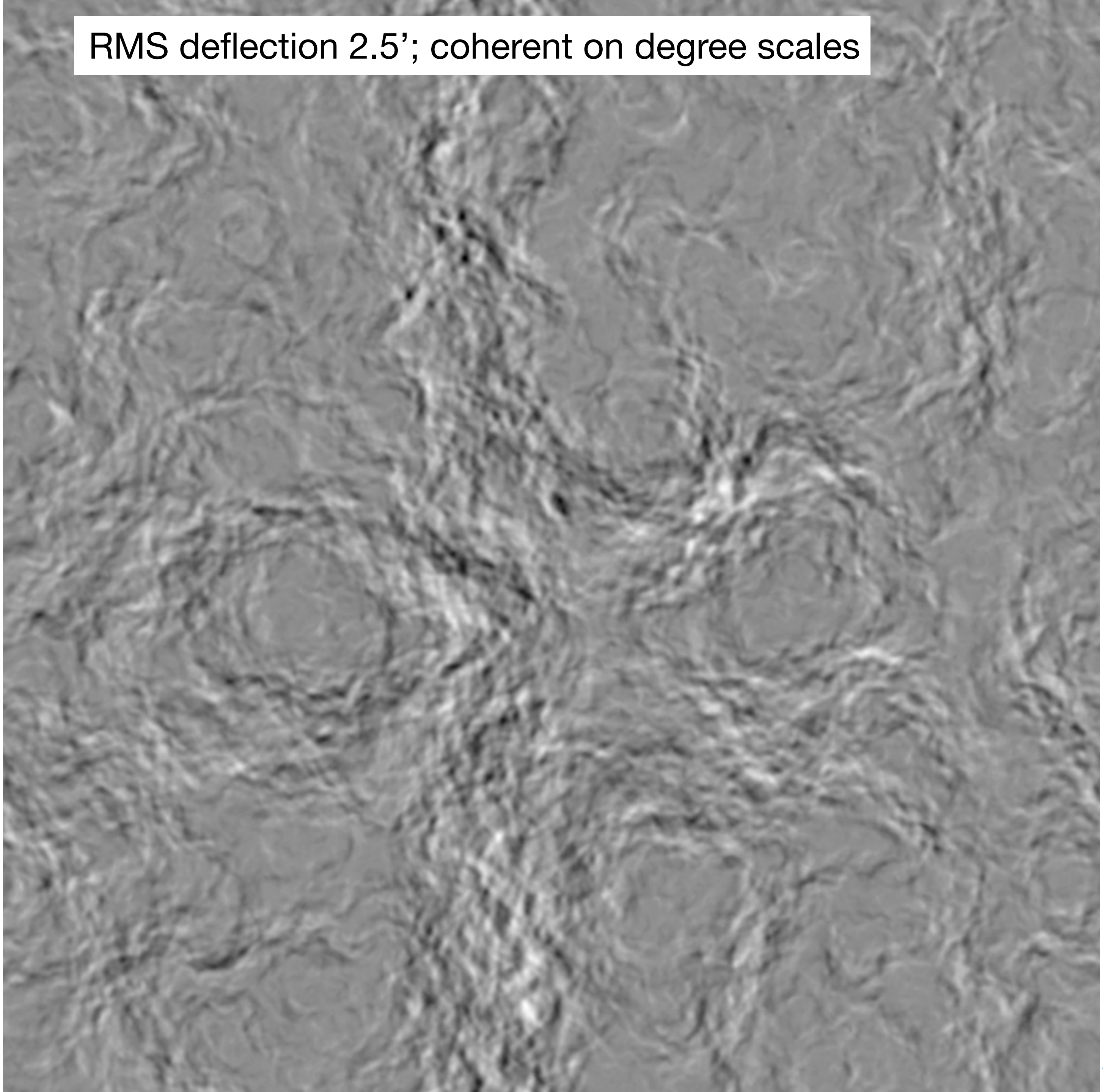
from Oliver Zahn

Lensed



from Oliver Zahn

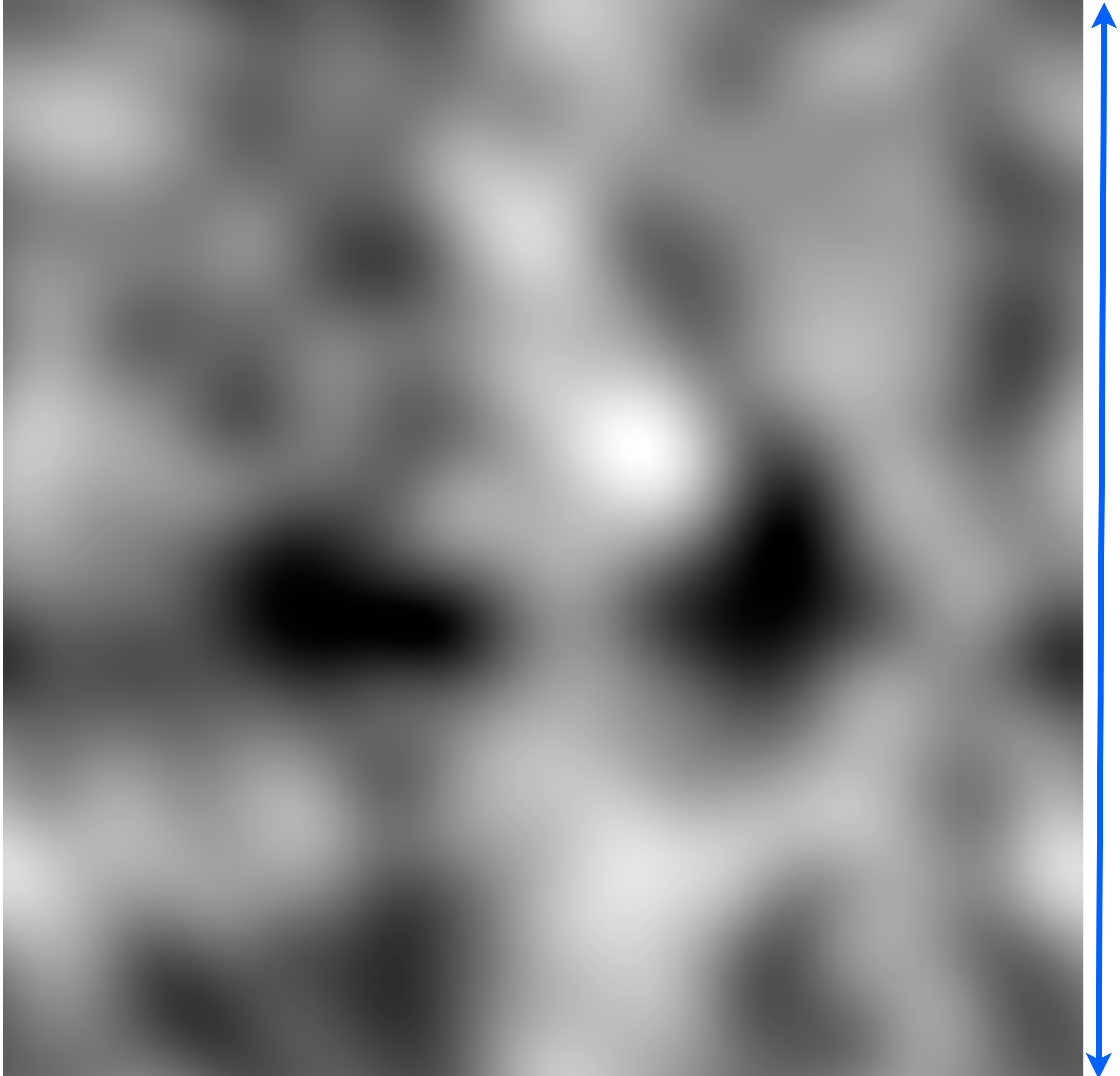
Difference



15°

from Oliver Zahn

Potential



from Oliver Zahn

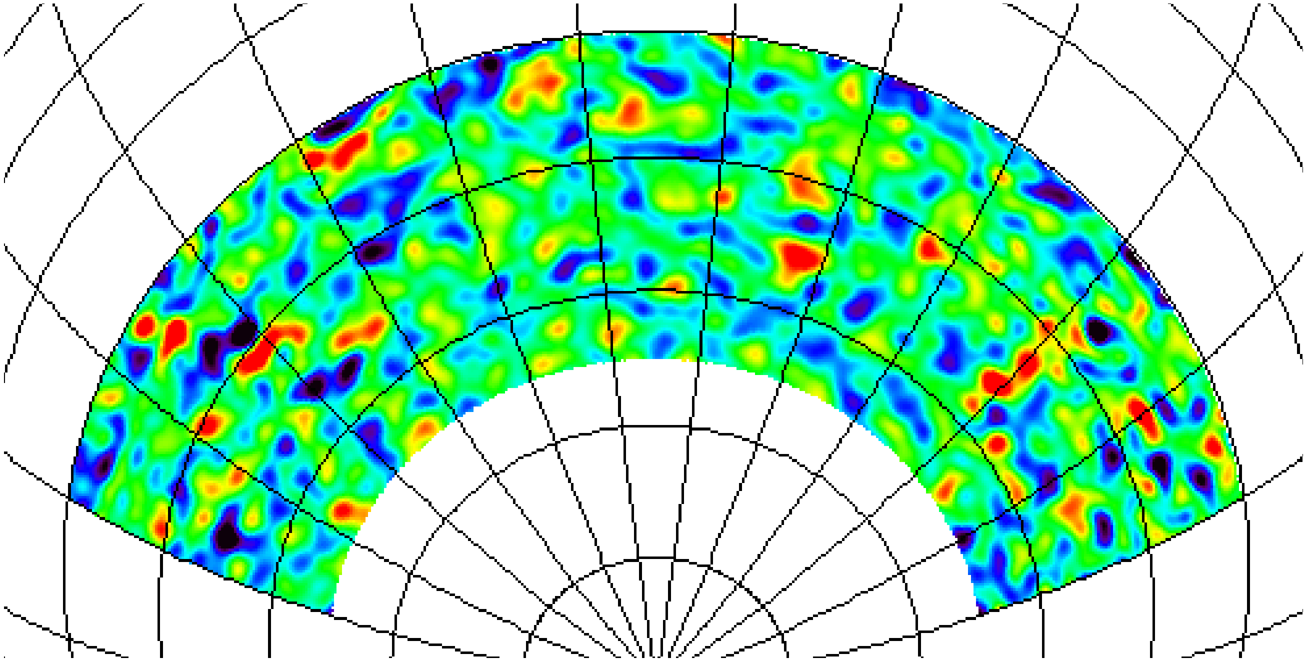
CMB is a unique lensing source

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

2. High redshift
   - No higher-z source

Weighing the Hubble Volume

work being led by O. Zahn



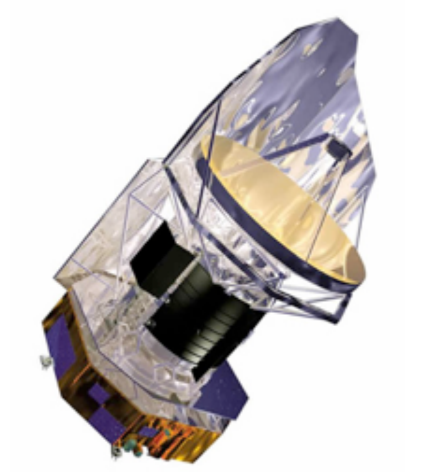
SPT map of 6% of matter in observable Universe

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

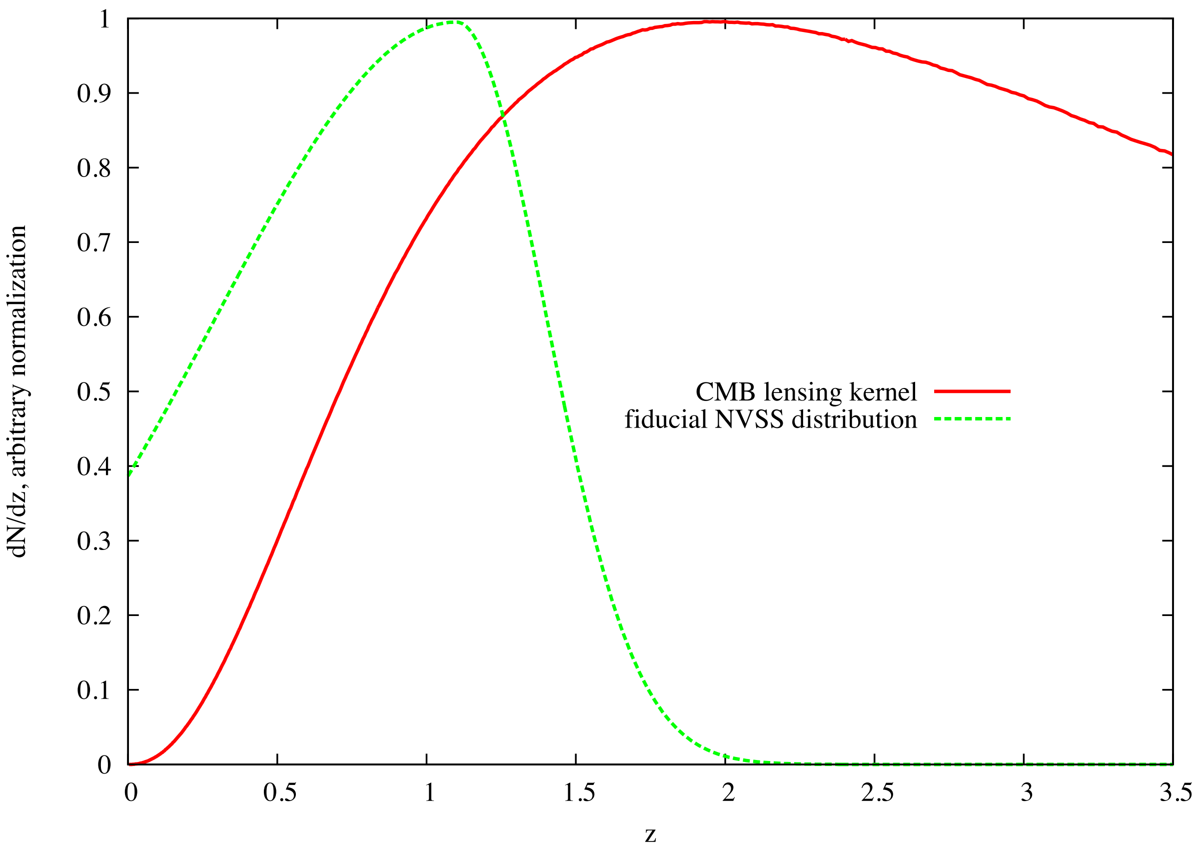
Lensing detection: ~20 σ in SPT
~30 σ in Planck

Correlation with the Cosmic Infrared Background (CIB)

Smith+, 2007

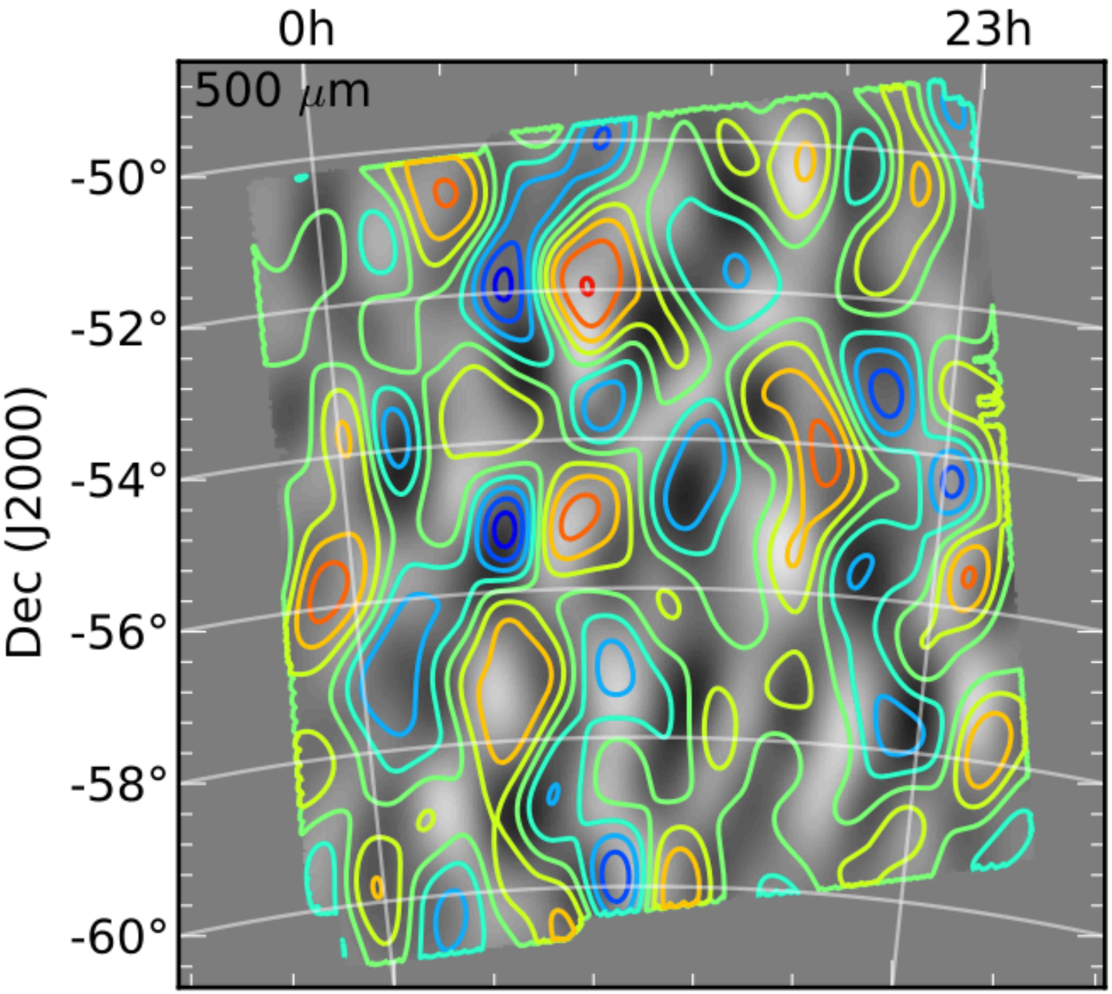


May 2012: Map deepest 100 deg^2 of SPT survey to the confusion limit.



- Redshift kernel of lensing peaks z~2
- Well-matched to CIB (80% correlation)

Correlation between lensing and CIB

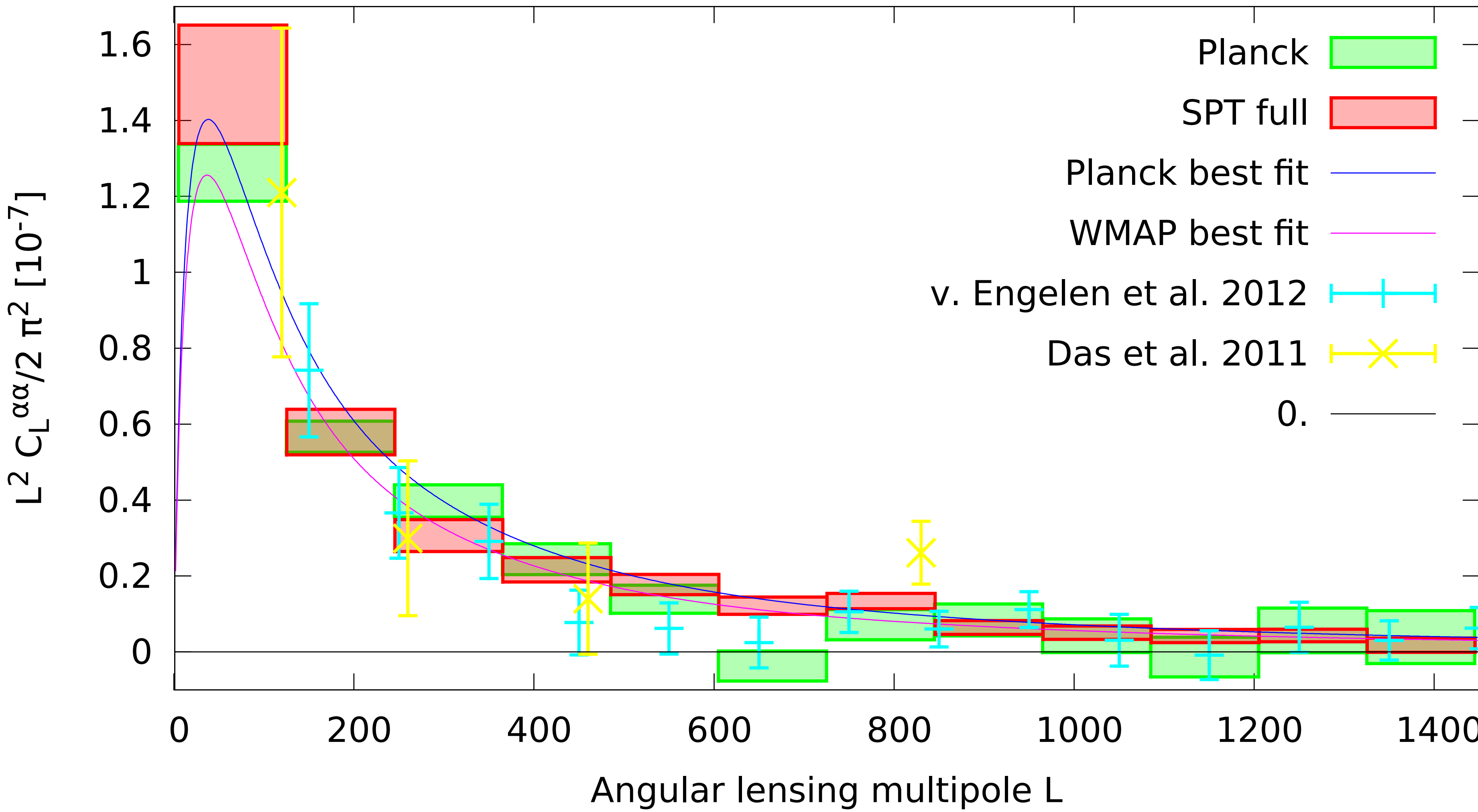


- Colors: SPT's CMB lensing map
- Greys: Herschel 500 μm map, smoothed to 100 Mpc scales
- Correlation detected at ~10 σ
- Galaxy bias: 1.3 < b < 1.8, model dependent
- CMB lensing is **well-calibrated in mass** and probes how CIB traces dark matter

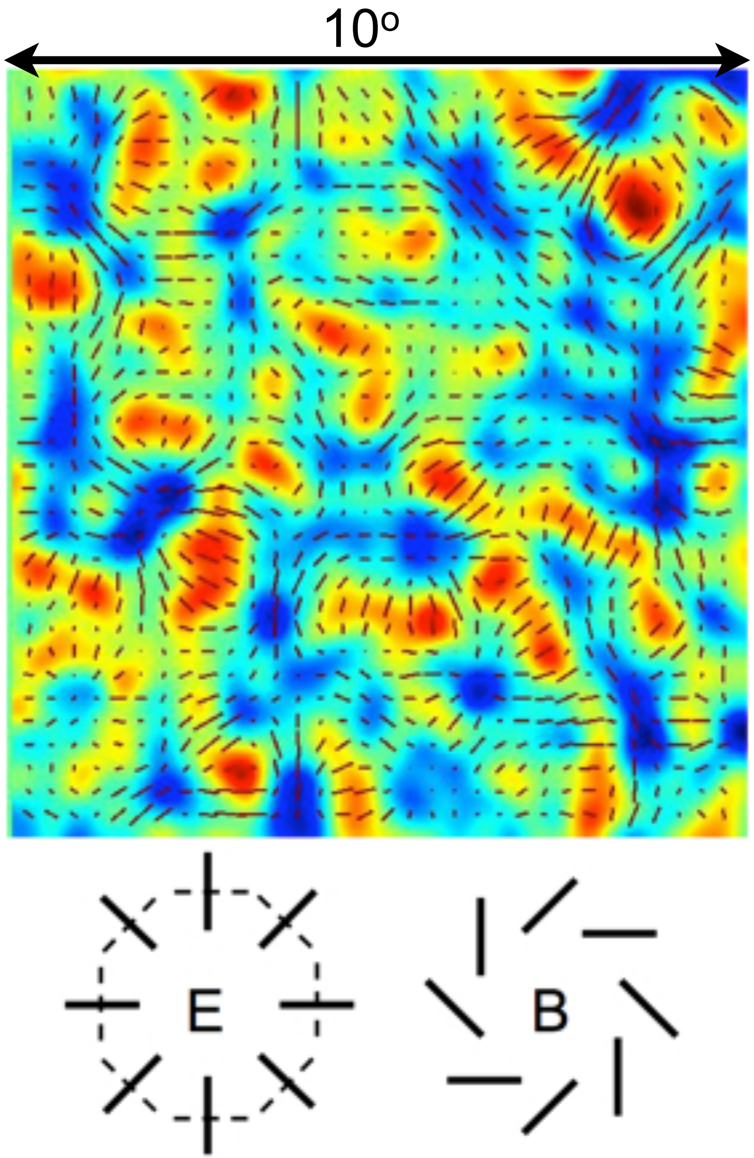
Holder et al., arXiv:1112:5435

Lensing Power Spectrum

Zahn et al., In prep.



The Next Frontier:
Polarization

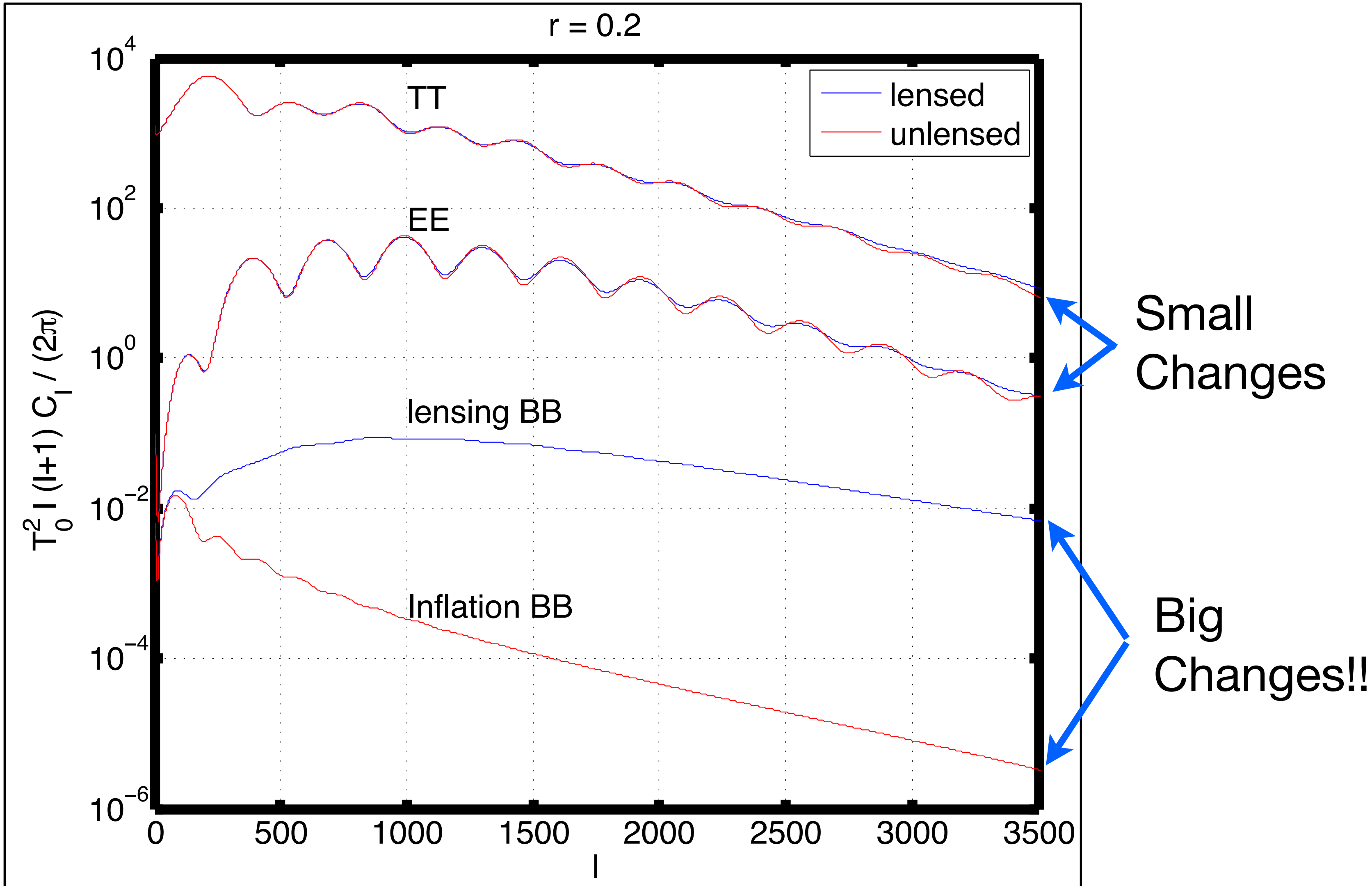


Smith et al 2008

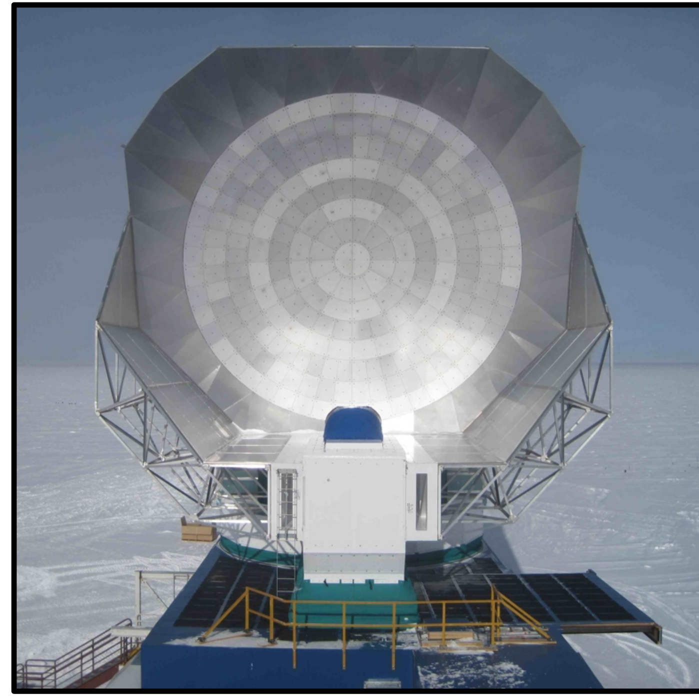
- Any polarization pattern can be decomposed into "E" (grad) and "B" (curl) modes
- Quadrupole anisotropy introduces polarization at surface of last scattering
- Density fluctuations do not produce "B" modes!
- "B" modes are created by:
  - On large scales: primordial gravity waves from Inflation
  -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

Effect of Lensing on the CMB Power Spectrum:

B-modes from Lensing



SPTpol:
a new ***polarization***-sensitive camera for SPT
First light Jan. 2012

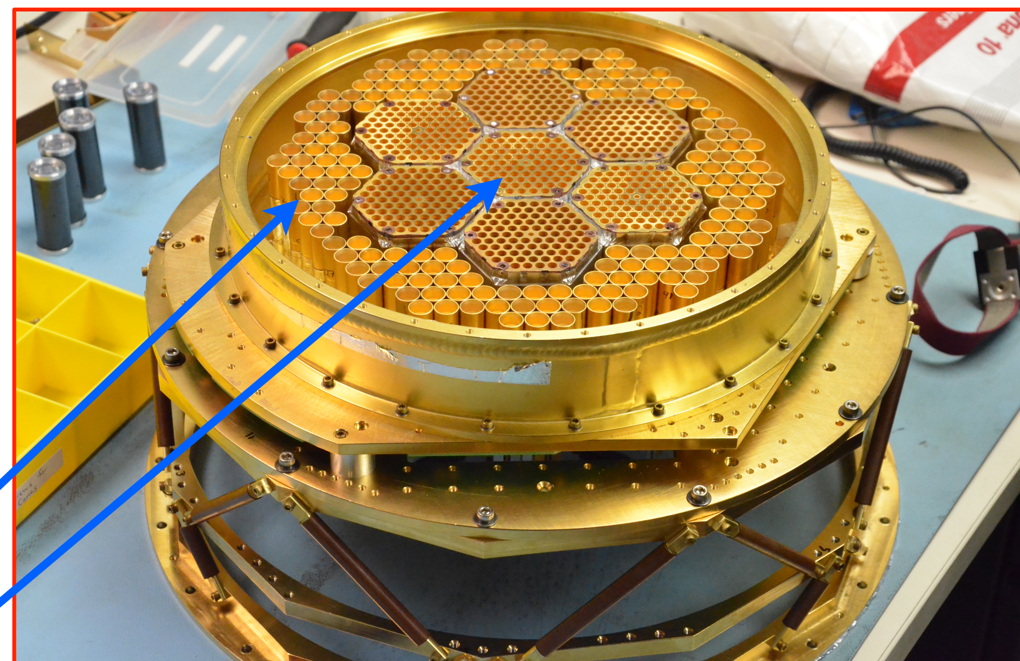


Measure “B-mode” polarization to constrain **neutrino mass** and **energy scale of inflation**.

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

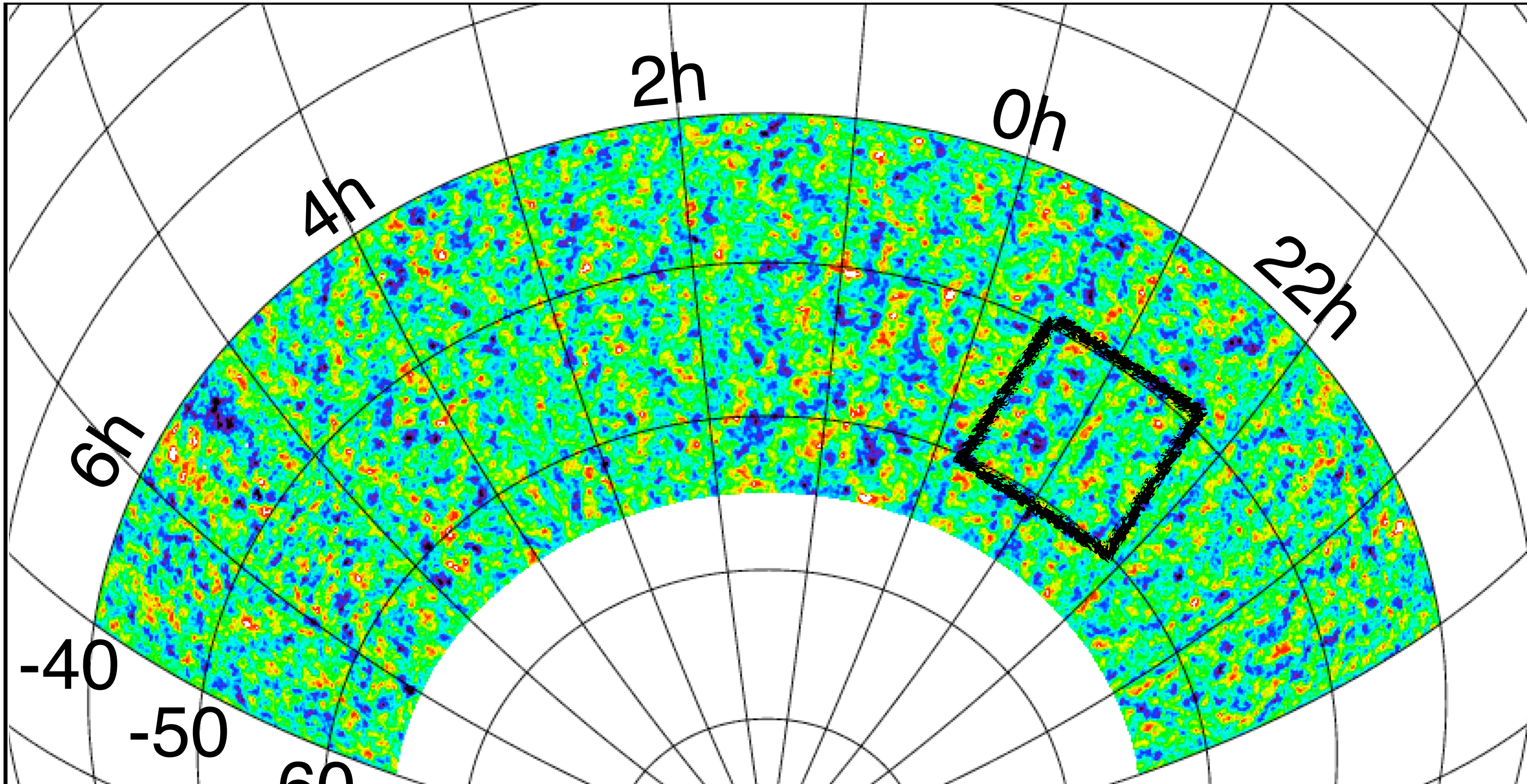
$r \lesssim 0.04$ (95%)

Investigate dark energy using **galaxy cluster abundances** - deeper cluster survey



360 - 100 GHz
1176 - 150 GHz

1st year: SPTpol survey



Status: finished first 100 deg^2 in 2012

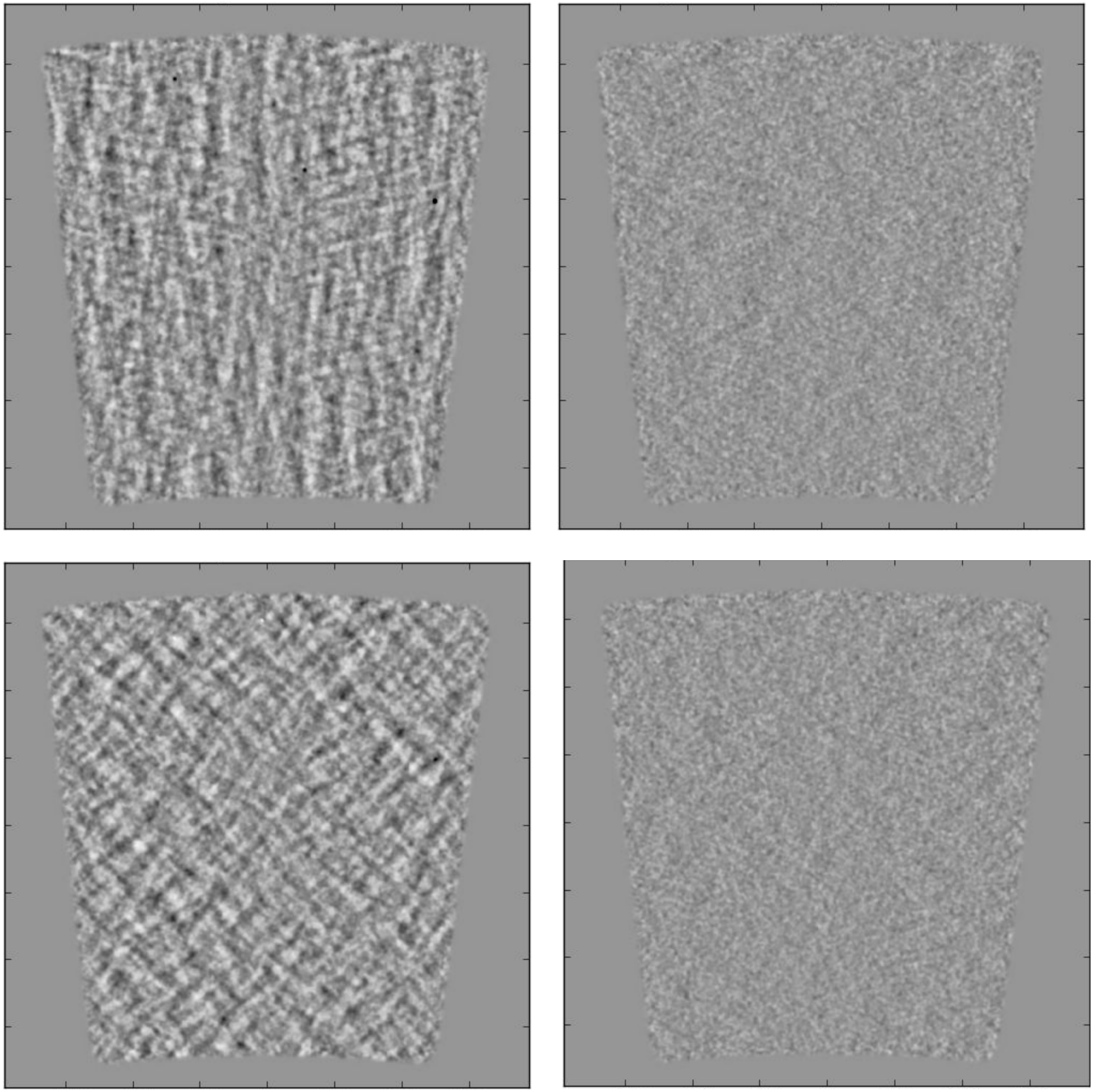
Currently observing ~600 deg^2

Q sum

Q diff

U sum

U diff

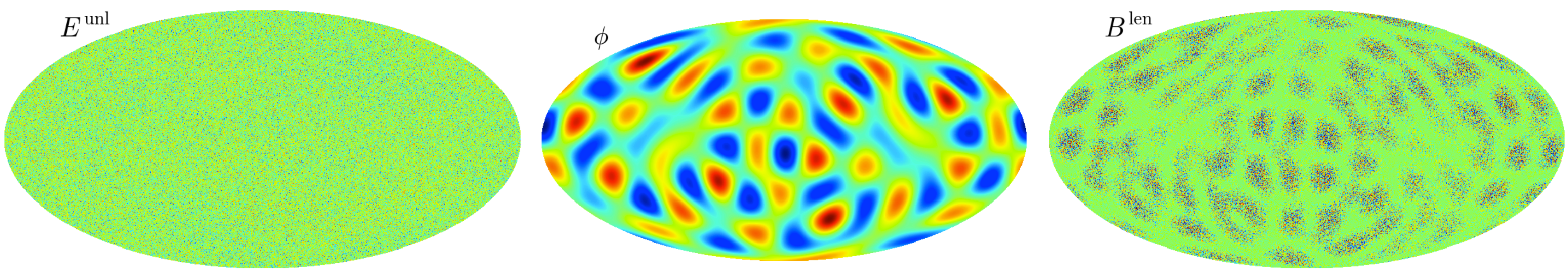


SPTpol 1-year Q/U maps

Map noise
10 μK-arcmin

- Lens reconstruction in polarization can be thought of as a process of template fitting.

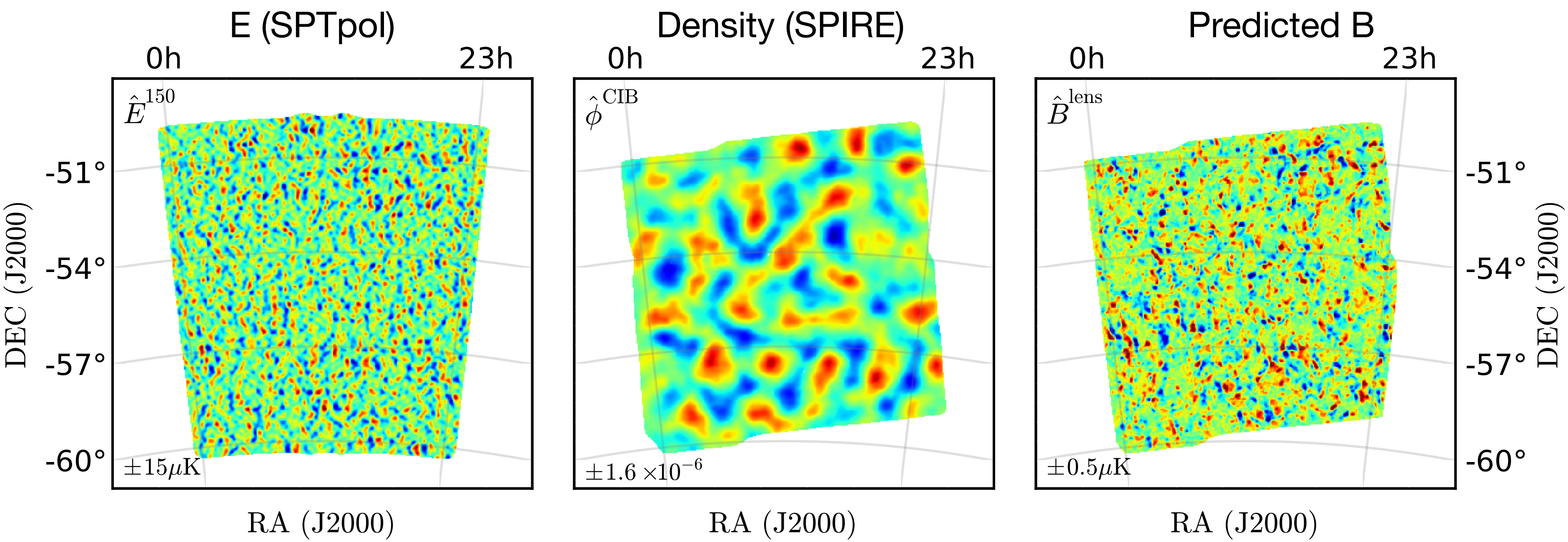
$$B^{\mathrm{lens}}(\vec{l}_B) = \int d^2\vec{l_E} \int d^2\vec{l_\phi} W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi) E(\vec{l}_E)\phi(\vec{l}_\phi)$$



$$E \qquad \phi \qquad B^{\mathrm{lens}}$$

Detection of B-mode Polarization in the Cosmic Microwave Background with Data from the South Pole Telescope

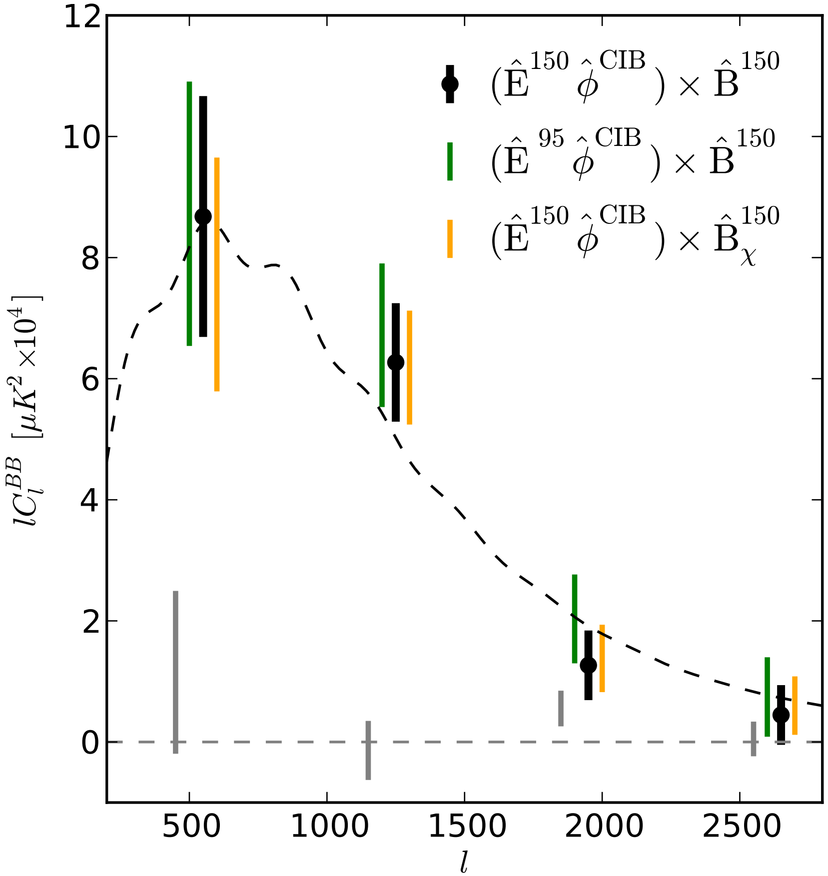
Duncan Hanson et al. arXiv:1307:5830



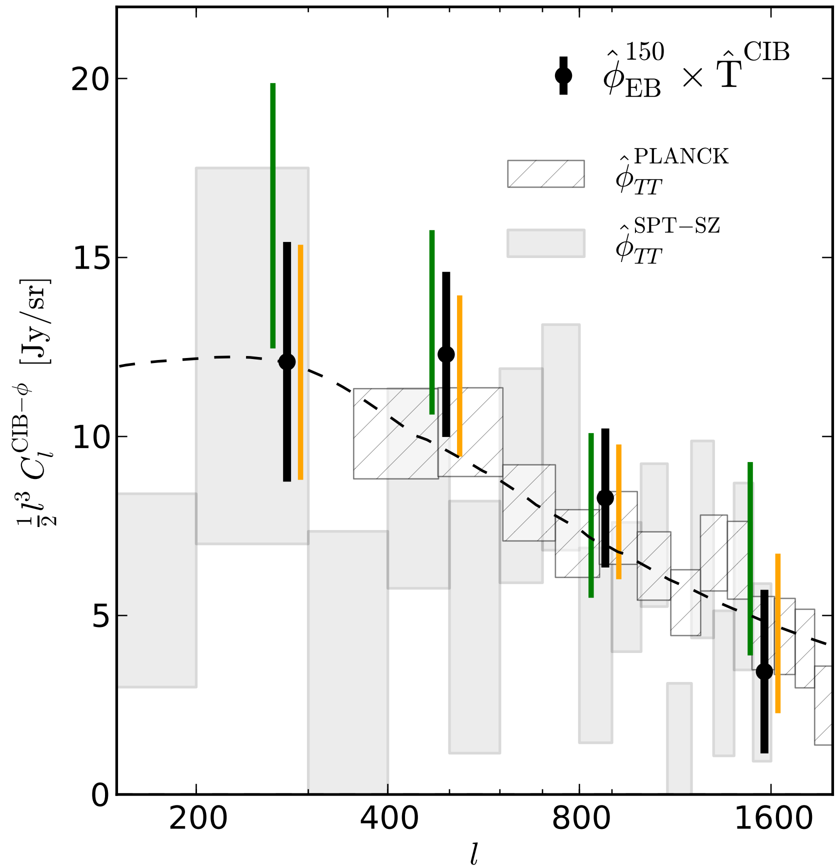
First detection of lensing B modes (7.7 σ)

Uses three-point EBϕ from SPTpol + Herschel-SPIRE maps of the cosmic infrared background.

Lensing amplitude: A_L=1.092 ± 0.141



«B mode view»



«Lensing view»

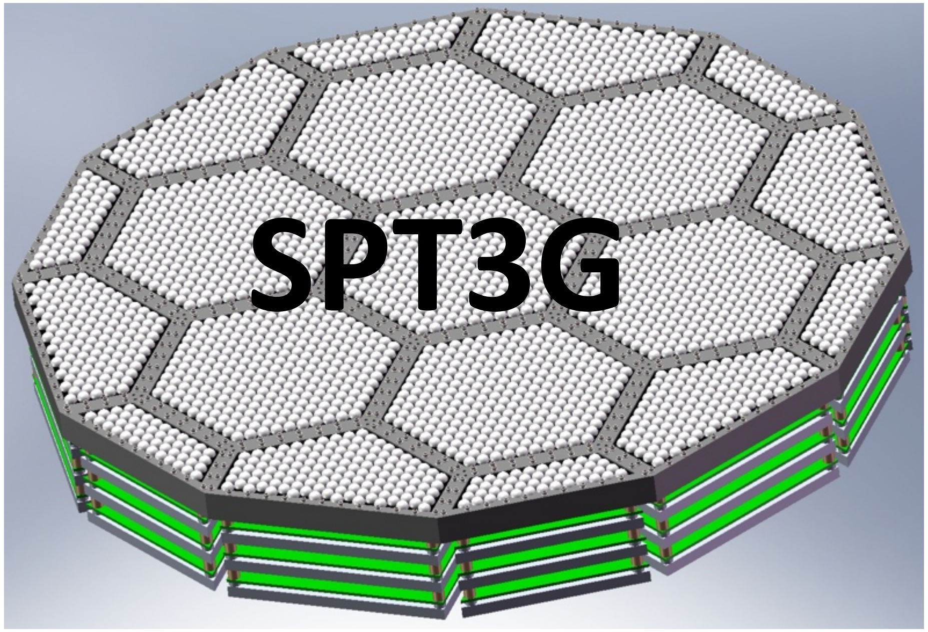
<u>Consistent results using:</u>

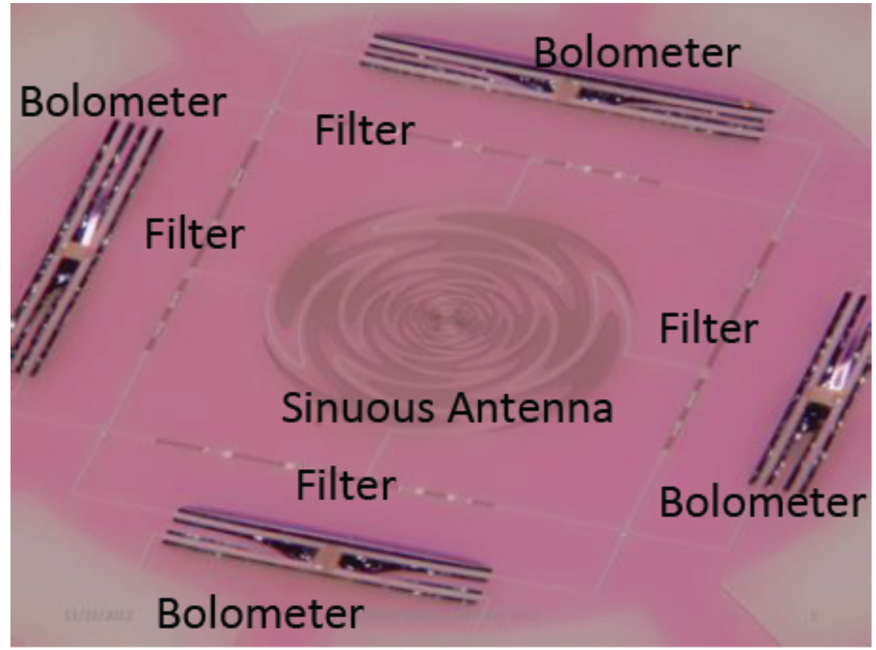
- 90GHz E-modes.
- Temperature-derived E-modes.
- TT, TE, EE, EB lensing estimators.

<u>No signal seen using:</u>

- Curl-mode null test.
- E-modes from diff. map.
- B-modes from diff. map.

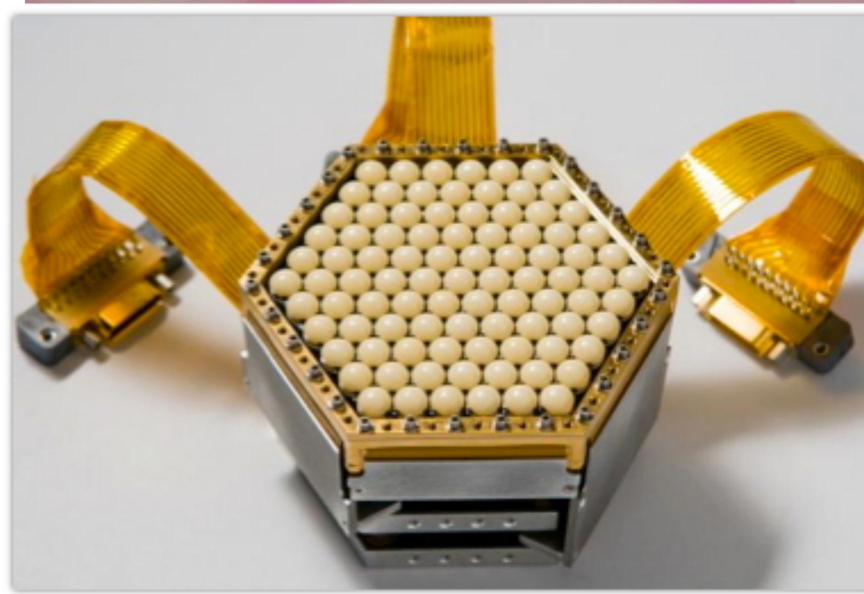
Cover x4 the area to twice the depth as SPTpol



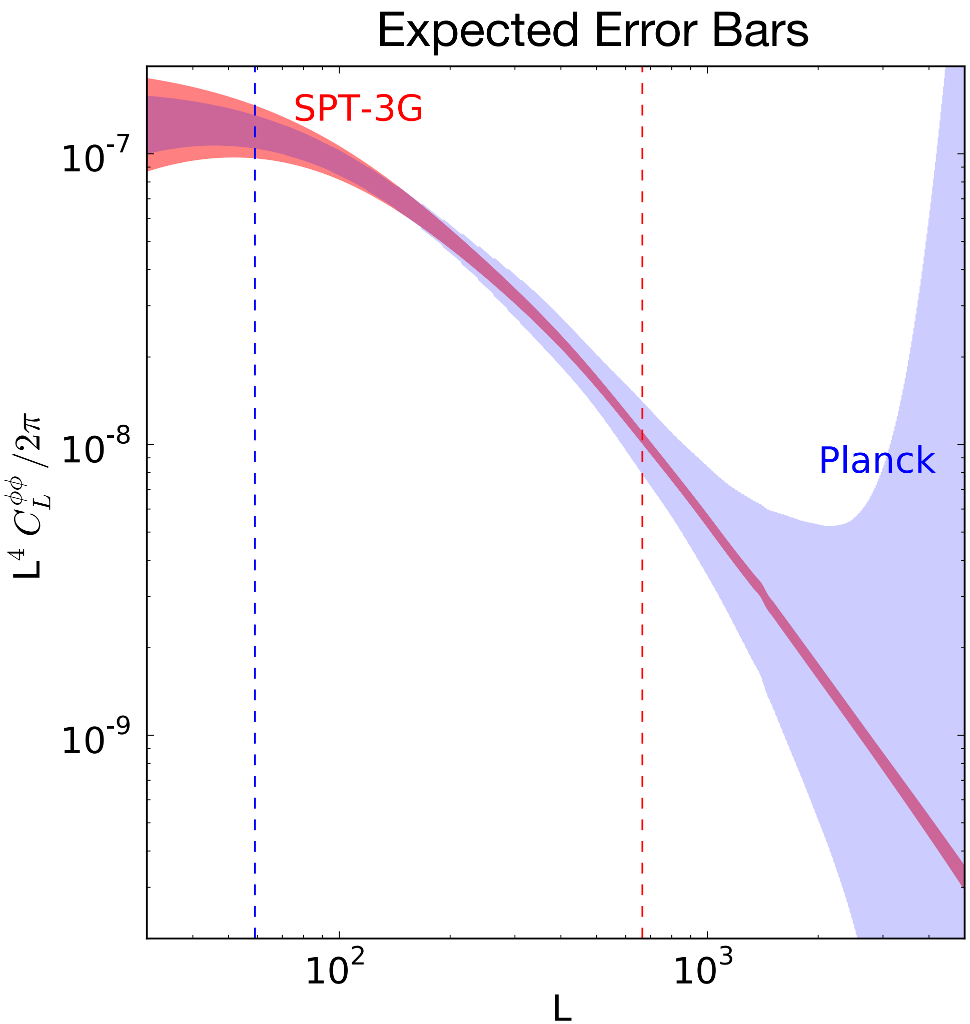


- 15,234 polarization-sensitive bolometers
- Plan **2500** deg^2 survey
- Exp. map depths of

4.2 μK-arcmin @ 95 GHz
2.5 μK-arcmin @ 150 GHz
4.0 μK-arcmin @ 220 GHz



SPT-3G: Lensing power spectrum



- CMB Lensing Detection Significance
  - SPT-SZ = 20 σ
  - Planck = 30 σ
  - SPTpol = 45 σ
  - **SPT-3G = 150 σ**

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

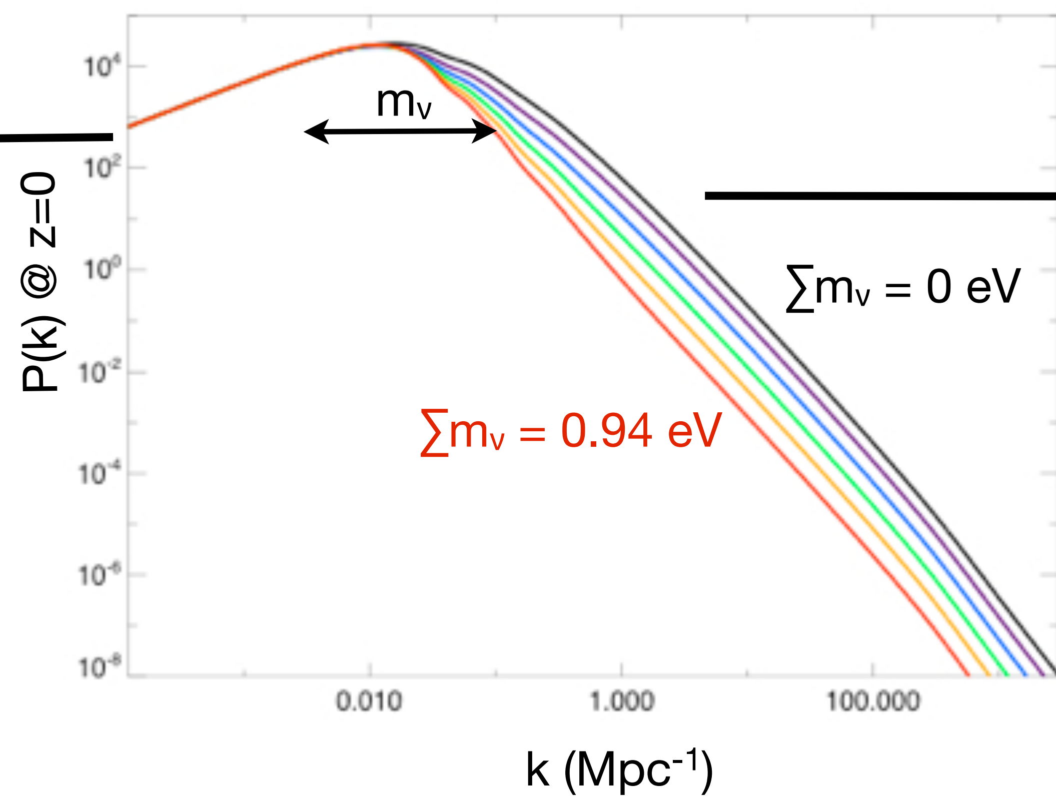
- Cross-correlating with DES will measure galaxy bias to <1%

Credit: G. Holder

Neutrinos as seen by LSS

Long scales: Faster expansion & clustering cancel (no net change)

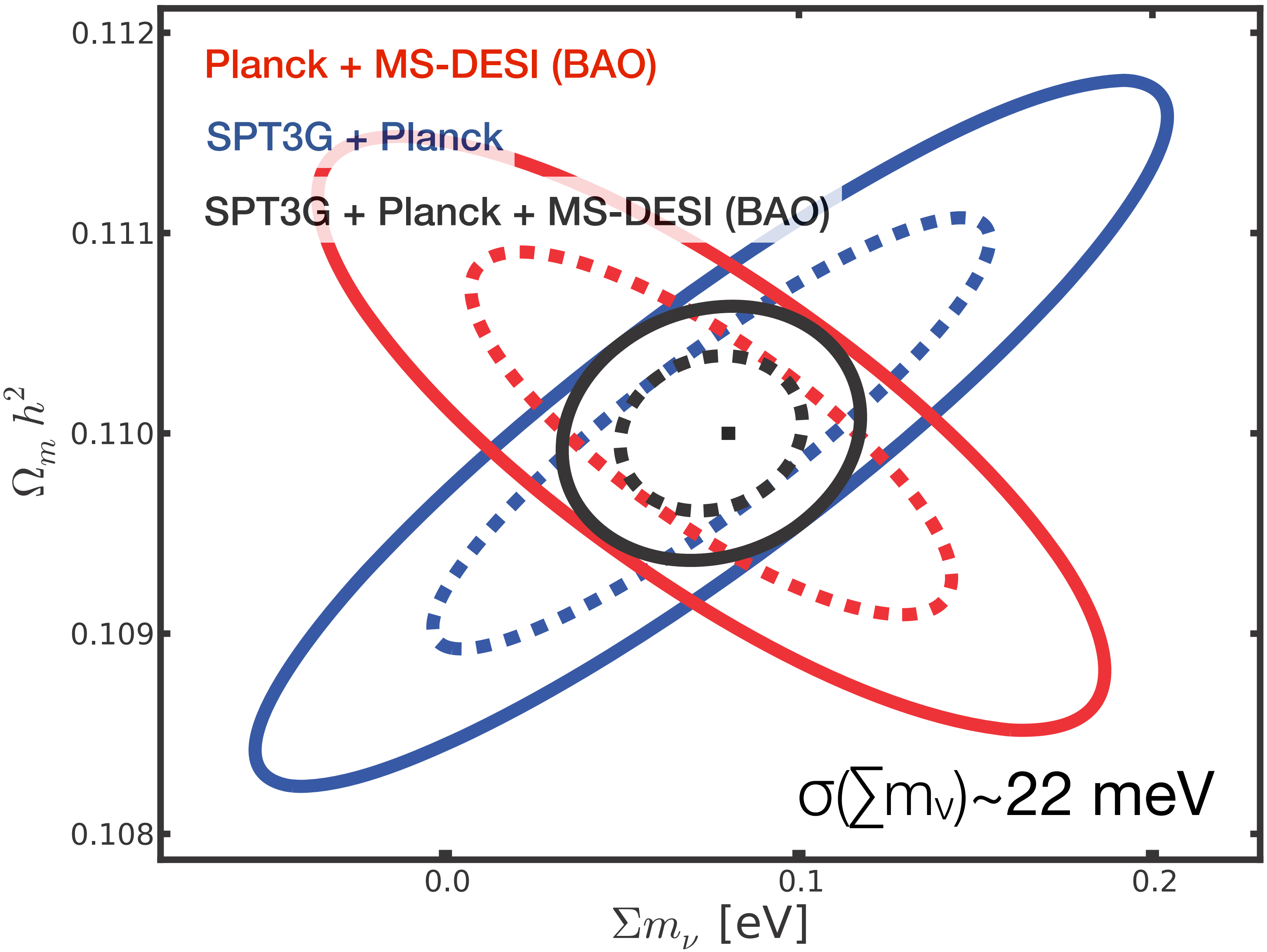
Matter power spectrum today



Short scales: Faster expansion suppresses structure

0.1 eV changes BB power by 5%

Predictions for neutrino masses



In conclusion

- **SPT-SZ survey complete with broad science impact:**
  - **High-redshift galaxies:** Early star and galaxy formation
  - **Distant, massive clusters:** Dark energy, neutrinos, cluster evolution
  - **Primordial CMB anisotropy:** Inflation, early universe physics
  - **CMB lensing:** "weighing" the universe, neutrinos
- **SPTpol: 1.4 years into 4 year survey**
  - **First detection of Lensing "B"-modes:** Improve neutrino constraints
  - **Inflationary "B"-modes:** Improve constraints on inflation's energy scale
- **SPT-3G: Development underway**
  - Observations begin in 2016
  - Inflation, Lensing (neutrino masses), Clusters (see next talk), kSZ/tSZ

- **Initial polarized power spectra coming soon!**

Other extensions similar, e.g., N_{eff}

	SPT+WMAP7	Planck+WP
CMB only	3.62 ± 0.48	3.51 ± 0.38
CMB+BAO	3.50 ± 0.47	3.40 ± 0.29
CMB+BAO+H_0	3.71 ± 0.35	-

Tighter, but no shift

(Note, Planck errors quoted here as half the 95% confidence interval, symmetrized)