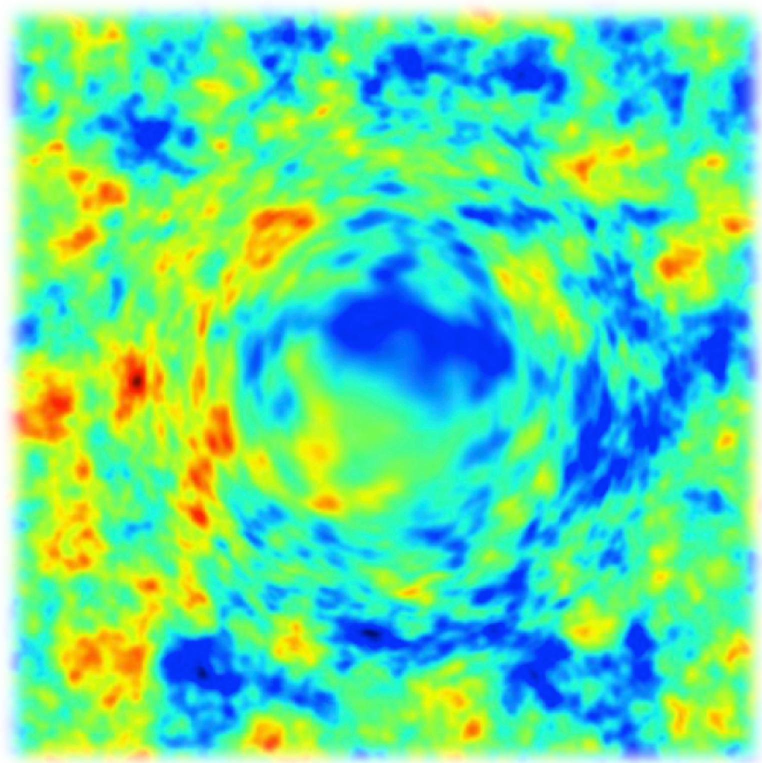
CMB Lensing:
On The Path Towards Ultra-High Precision



Blake Sherwin

DAMTP, University of Cambridge

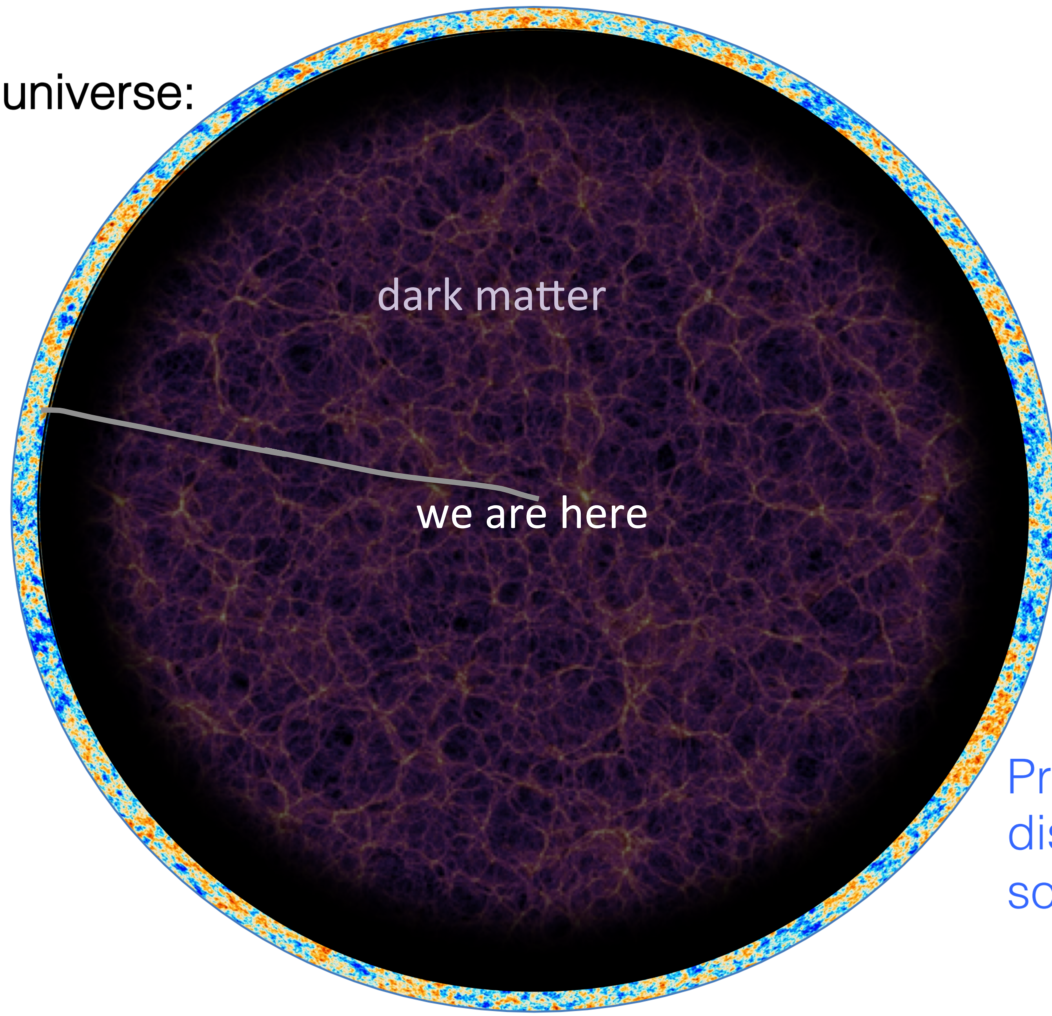
with ACT/Simons Observatory/CMB-S4 collaborations, Ben Horowitz, Simone Ferraro

Outline

- Ongoing / upcoming advances in CMB lensing measurements
  - AdvACT + Simons Observatory lensing: testing Planck, and beyond
- CMB lensing theory: new science in the low noise regime
  - Lots of room for improvement on small scales?

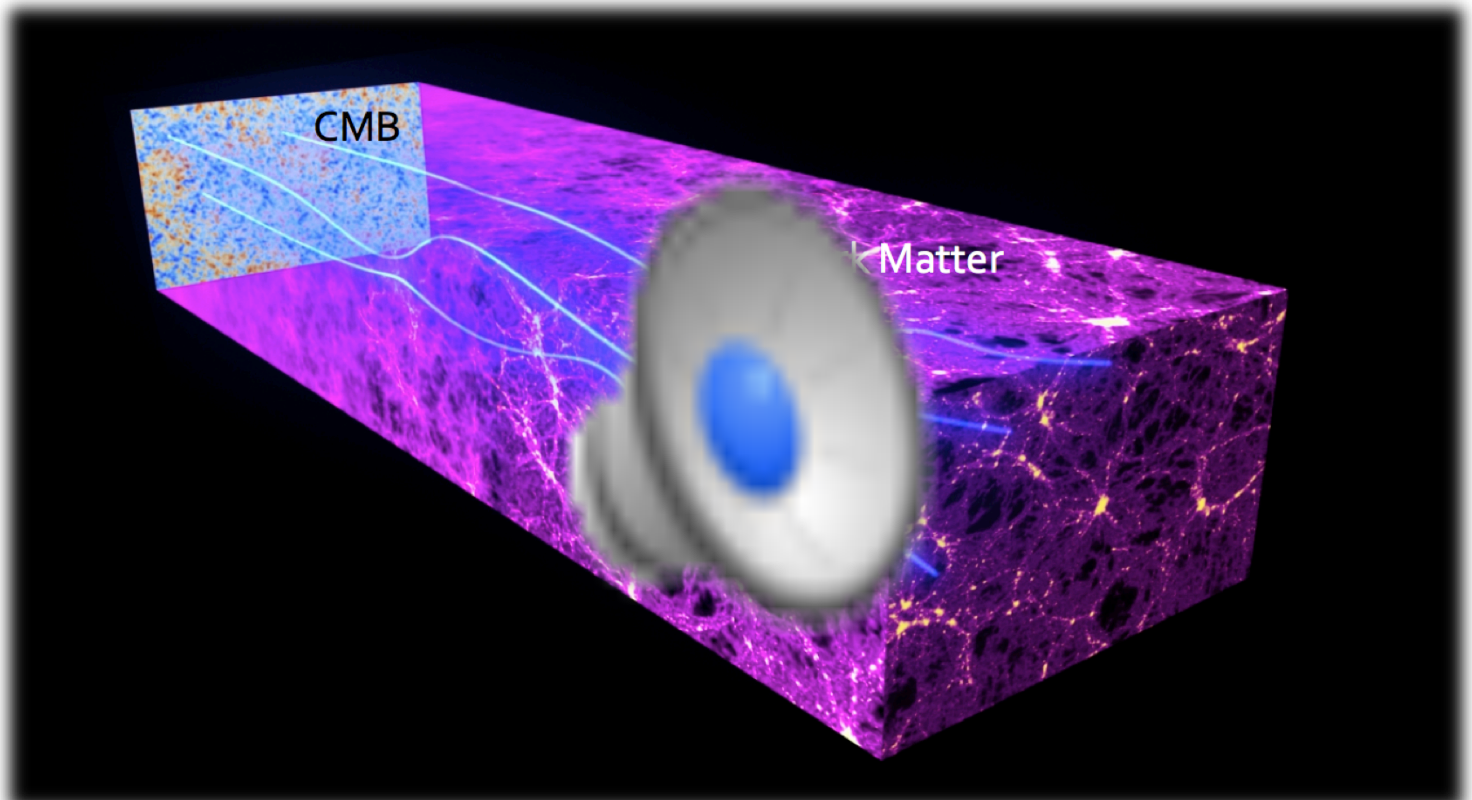
CMB: A Distant Backlight On the Matter Distribution

The observable universe:



“Light” Source for Lensing: The Cosmic Microwave Background (CMB)

- CMB: leftover radiation from the hot primordial plasma – most distant observable source of light
- Distribution of dark matter deflects light that passes through



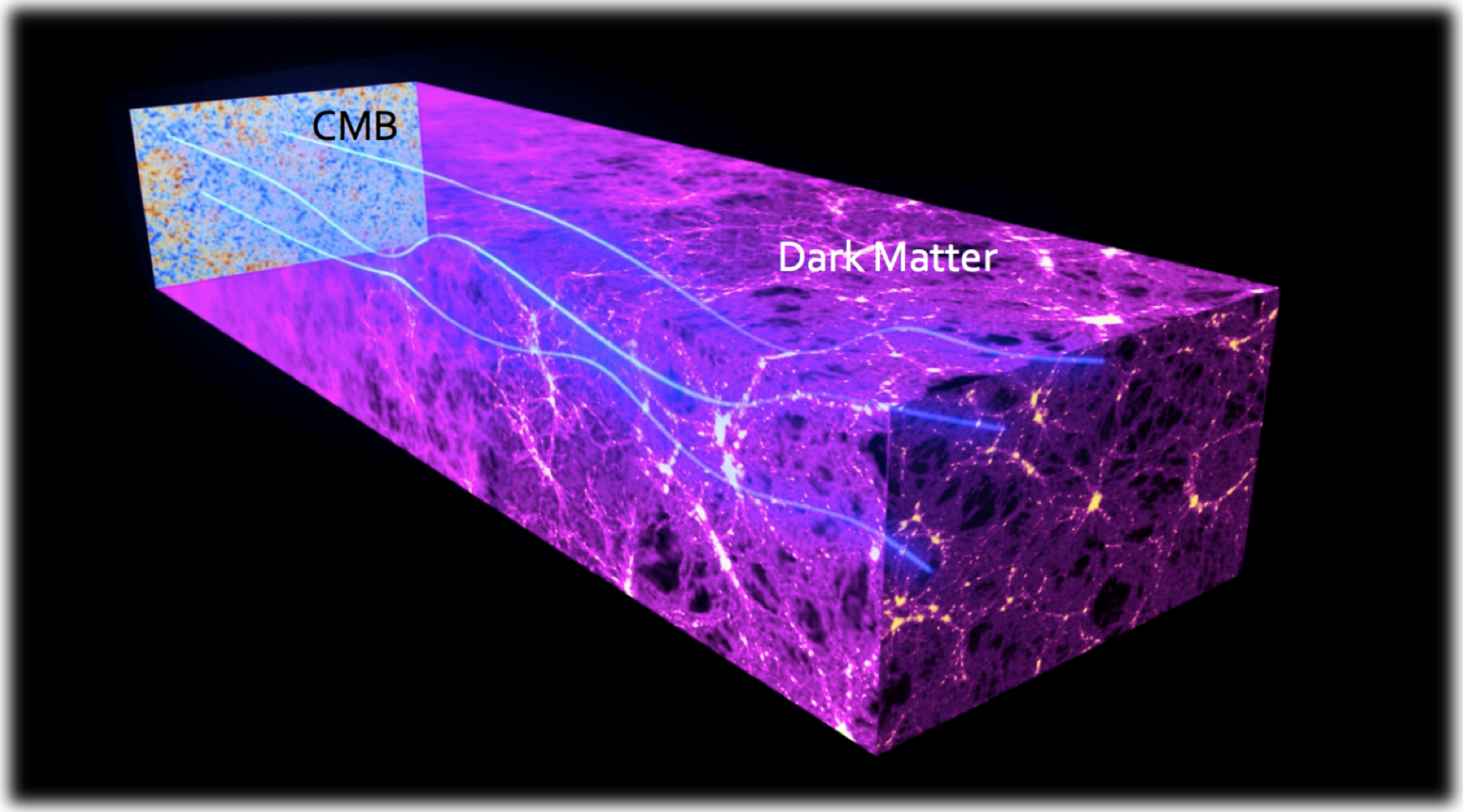
CMB Gravitational Lensing

- Distribution of dark matter deflects CMB photons that pass through; remapping described by lensing deflection field d

$$T(\hat{\mathbf{n}})_{\mathrm{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\mathrm{unlensed}}$$

d: lensing deflection;
T: CMB temperature

5



Key Observable Over Next Decade: High Precision Lensing Maps

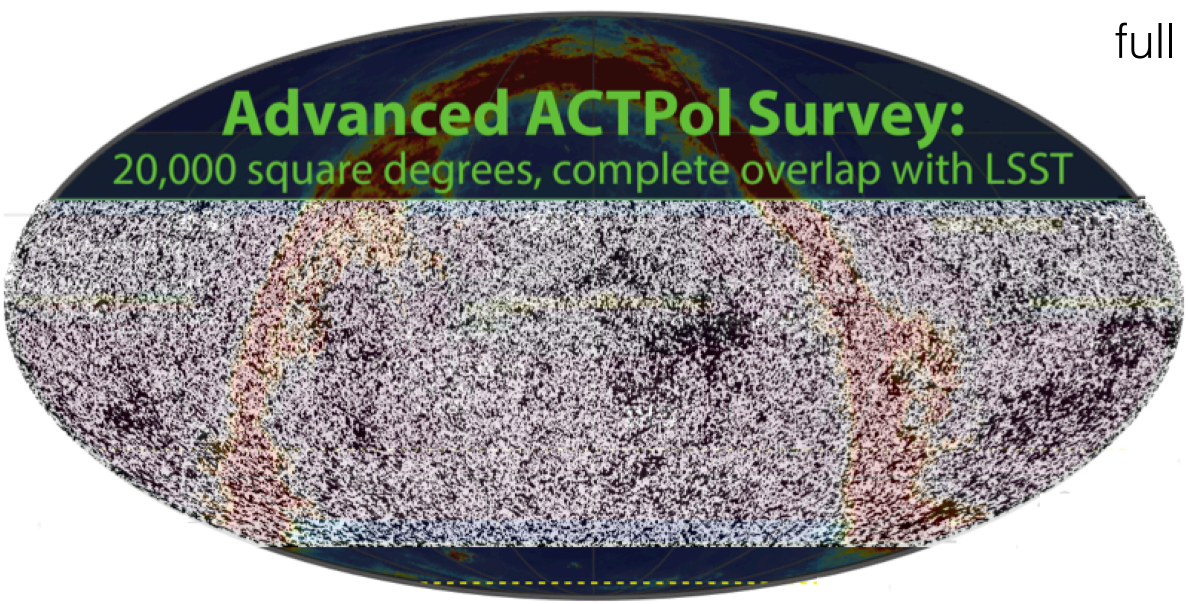
- Lensing field **d** probes projected mass distribution to CMB

geometric projection kernel, z~0.5-5

$$d(\hat{\mathbf{n}}) = \int_0^{r_{\rm CMB}} dr W(r) \delta(\hat{\mathbf{n}}, r)$$

lensing deflection

- Working towards high precision lensing maps over ½ sky - essential for key science of future CMB…

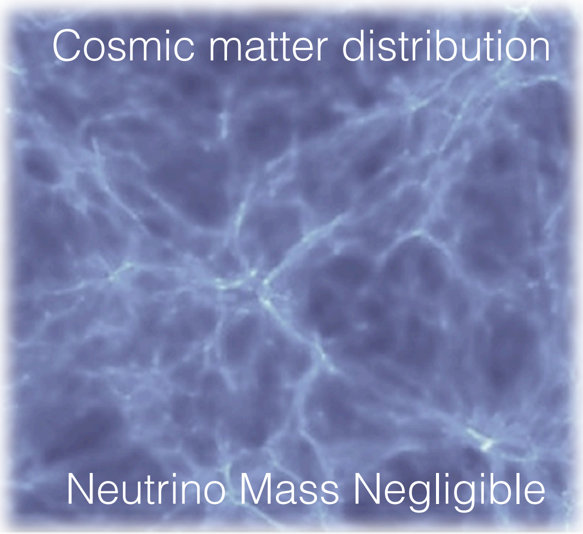


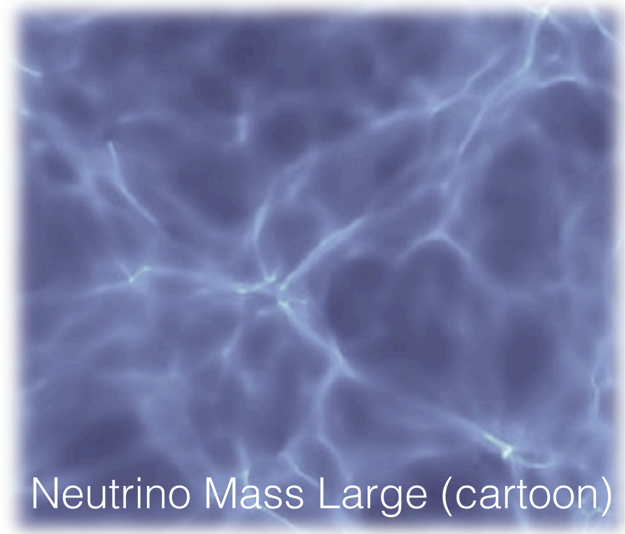
full sky sphere

lensing map covering half the sky (illustration)

I. Measure the Sum of the Neutrino Masses

- The more massive neutrinos are, the more they reduce growth of small-scale structure; gives “blurring” in lensing.

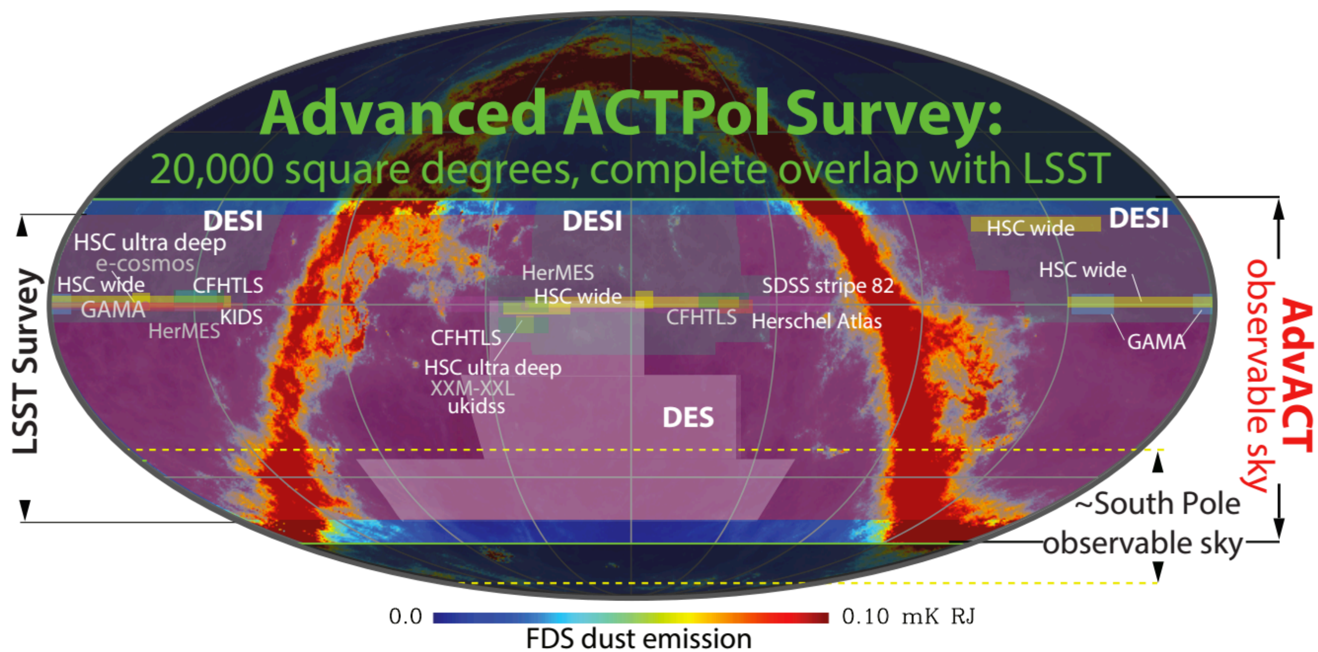




- Measure in AdvACT / Simons Observatory / CMB-S4 lens maps – constraints approaching known lower limit: >60 meV

II. Probe Astrophysics and Dark Energy with CMB Lensing Cross-correlations

- By correlating with lensing maps
  - probe relation of galaxies, quasars.. to dark matter
  - check/calibrate optical lensing systematics to help improve dark energy constraints (e.g., LSST/Euclid)

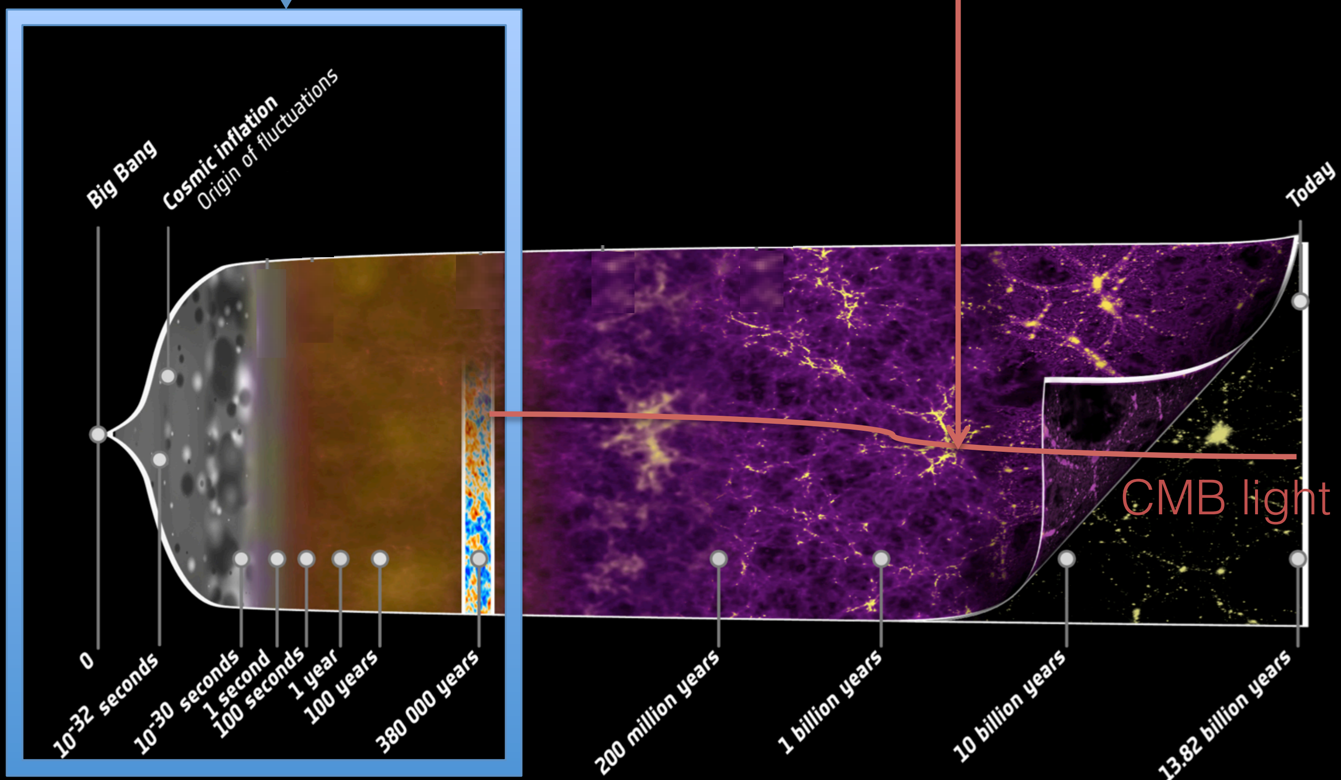


[e.g. Sherwin++ 2012; POLARBEAR, Sherwin corr. author., 2015; Ferraro, Sherwin, Spergel 2015; v. Engelen, Sherwin++ 2015]

CMB Lensing: Noise for Early Universe Cosmology

Lensing not just signal: if we are interested in the early universe

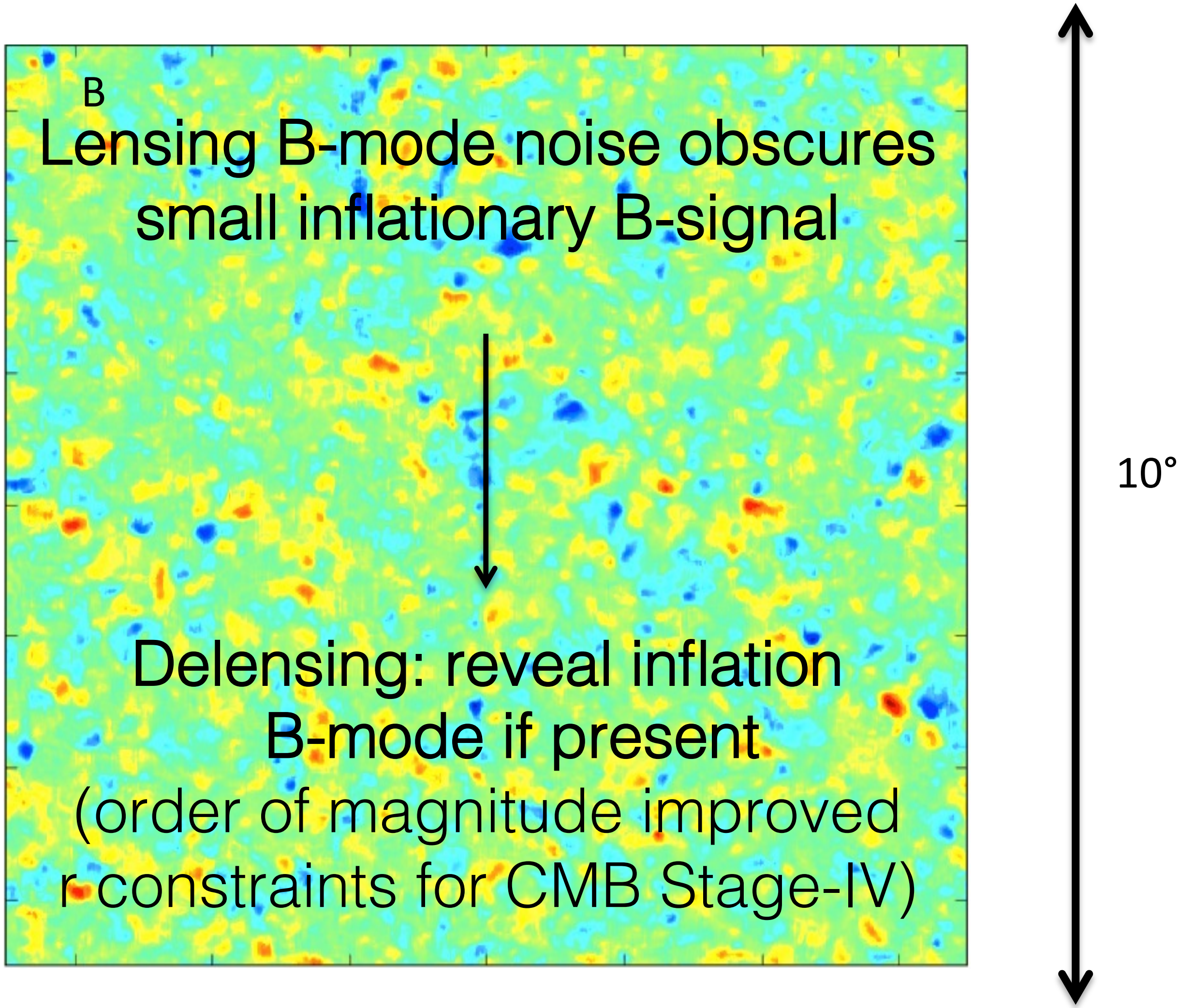
Now lensing is a problem!



time (+ distance light travels!)

III. Reveal Inflationary Signals by Delensing (Removing Lensing Noise)

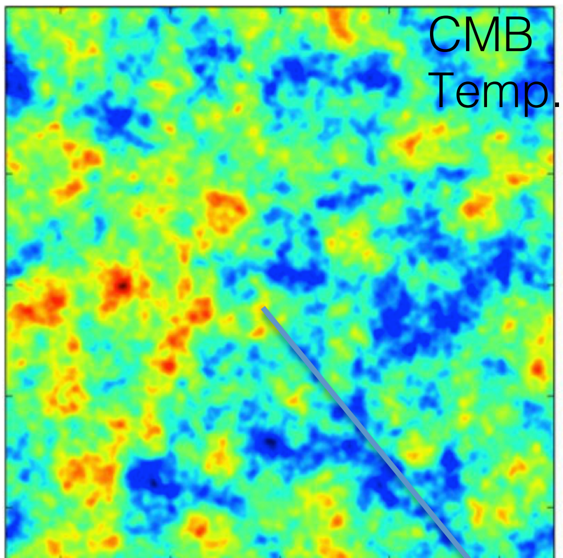
B mode
Polarization

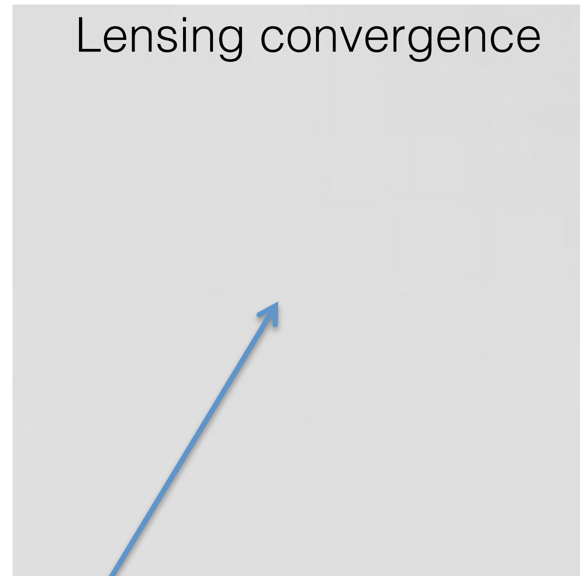


[see Anthony's talk (and Larsen, Challinor, Sherwin, Mak 2016)]

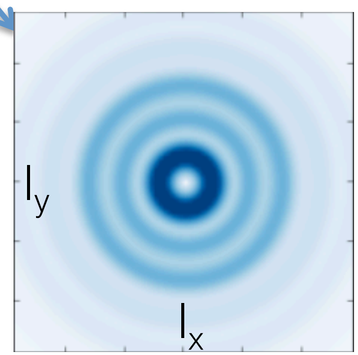
CMB Lensing Measurement: An Approximate Picture

- Quadratic estimator: measures mode correlations $d \sim \int dl\ T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})$





- Physical picture:



local 2D power spectrum

[Bucher++ 2012]

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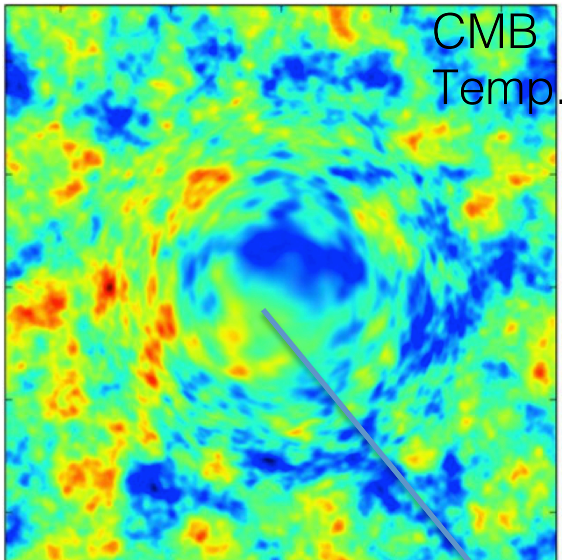
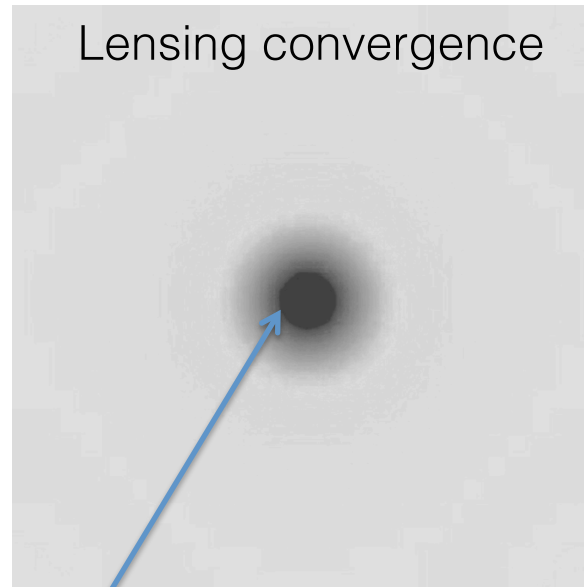
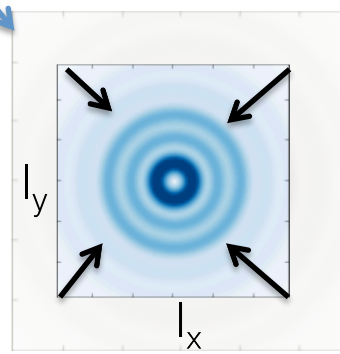
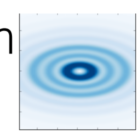




- Physical picture:



local 2D power spectrum

Infer lensing from "stretching" of the local CMB power spectrum  shearing)

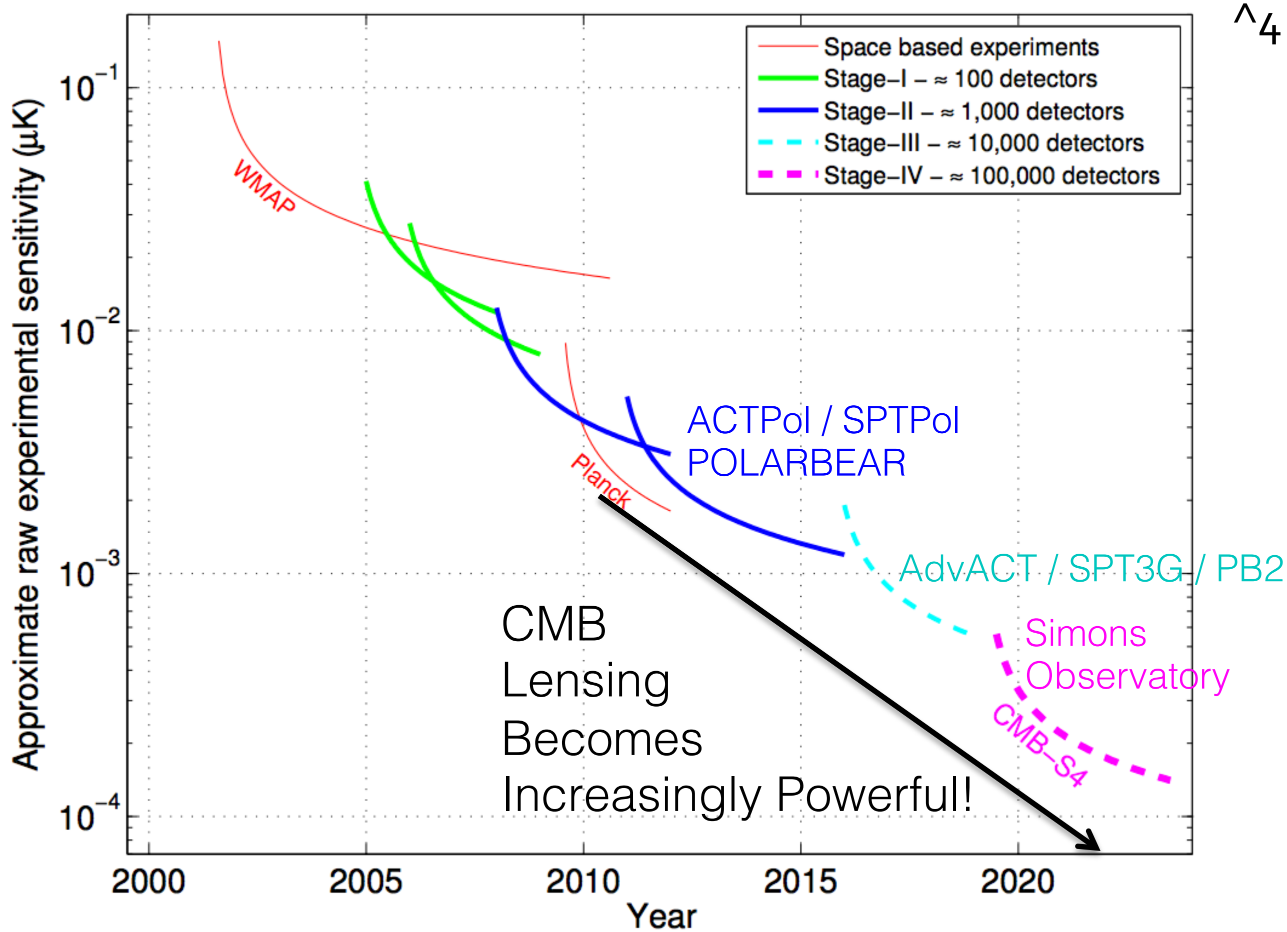
N.B. better in polarization

[Bucher++ 2012]

Rapid Progress:
Ongoing/Upcoming Ground-Based CMB Experiments

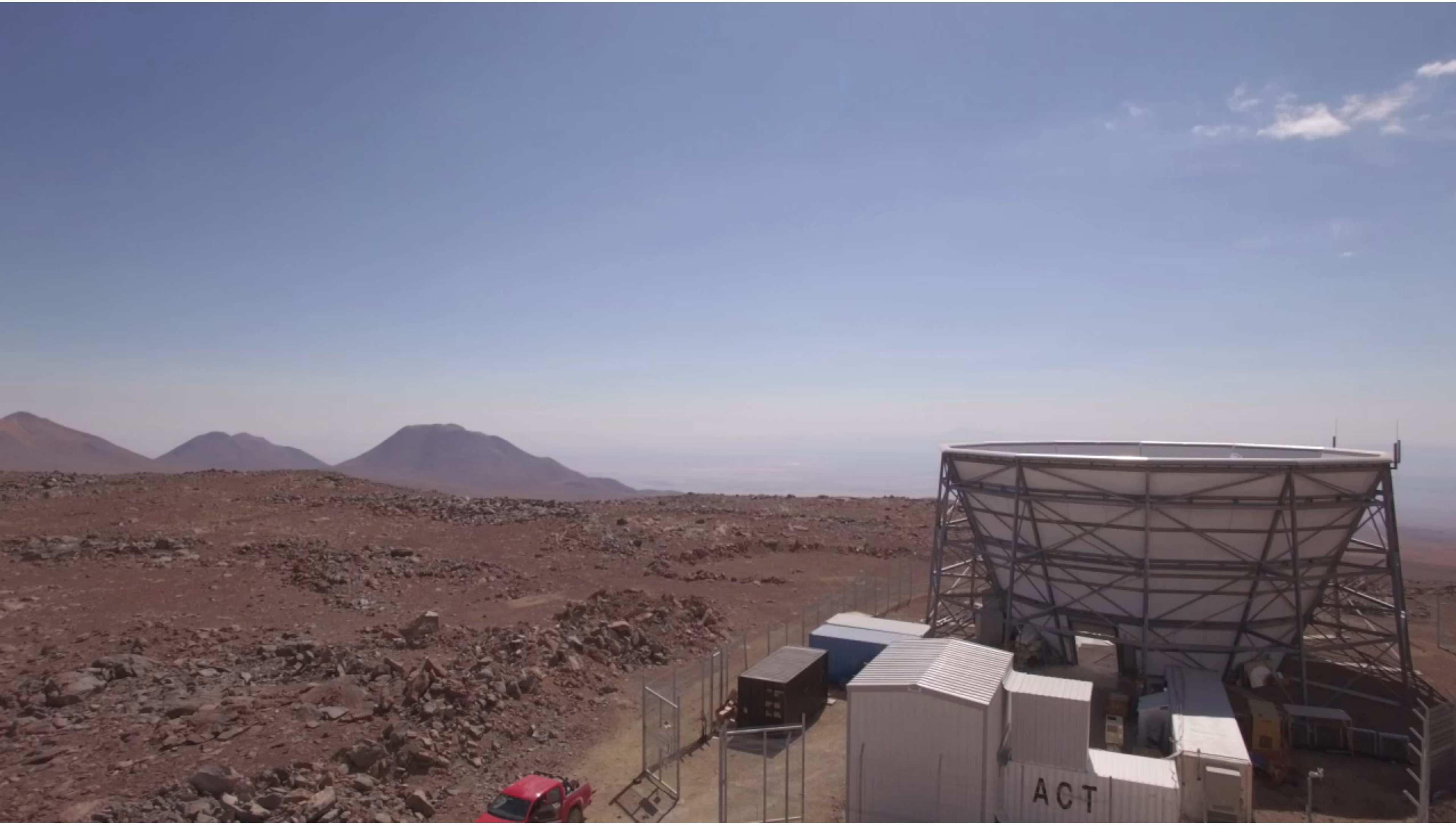
CMB Experiment Noise Level

^4



[Abazajian++ 2014]

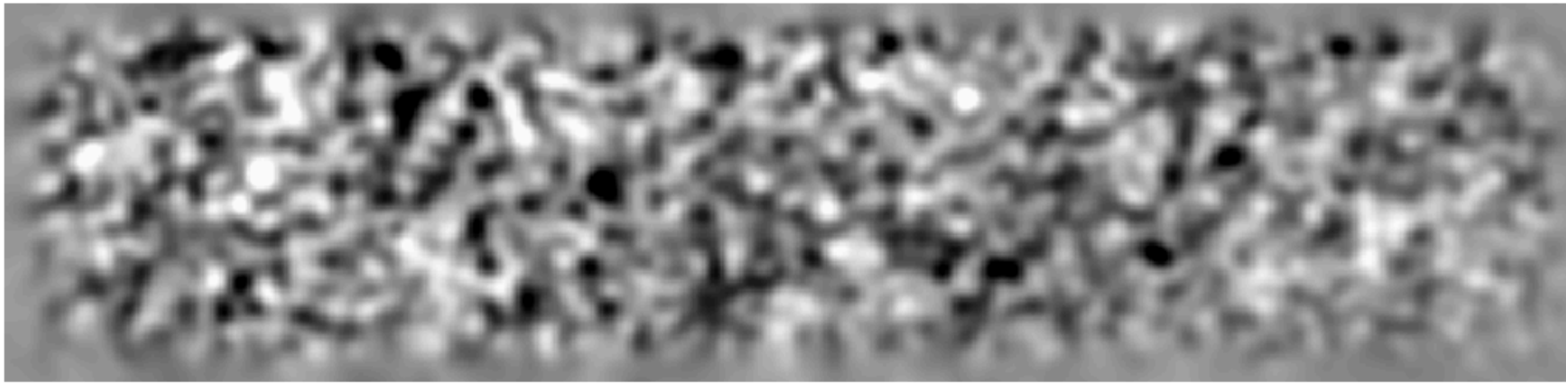
Atacama Cosmology Telescope (ACT)



- Arcminute resolution CMB telescope high in the Chilean Atacama desert, with arrays of sensitive (TES bolometer) detectors

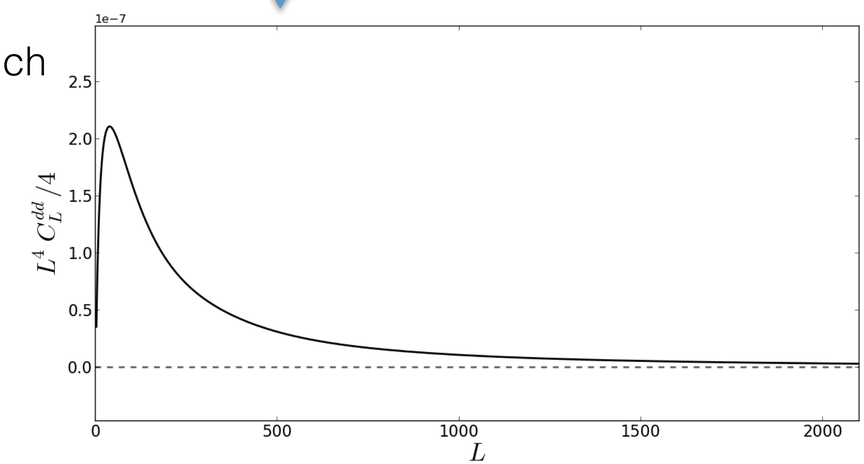
Key Observable: CMB Lensing Power Spectrum C_ℓ^{dd}

ACTPol CMB Lensing Dark Matter Map (small scales noise)



brightness = density

Y axis: “How much lensing ….”

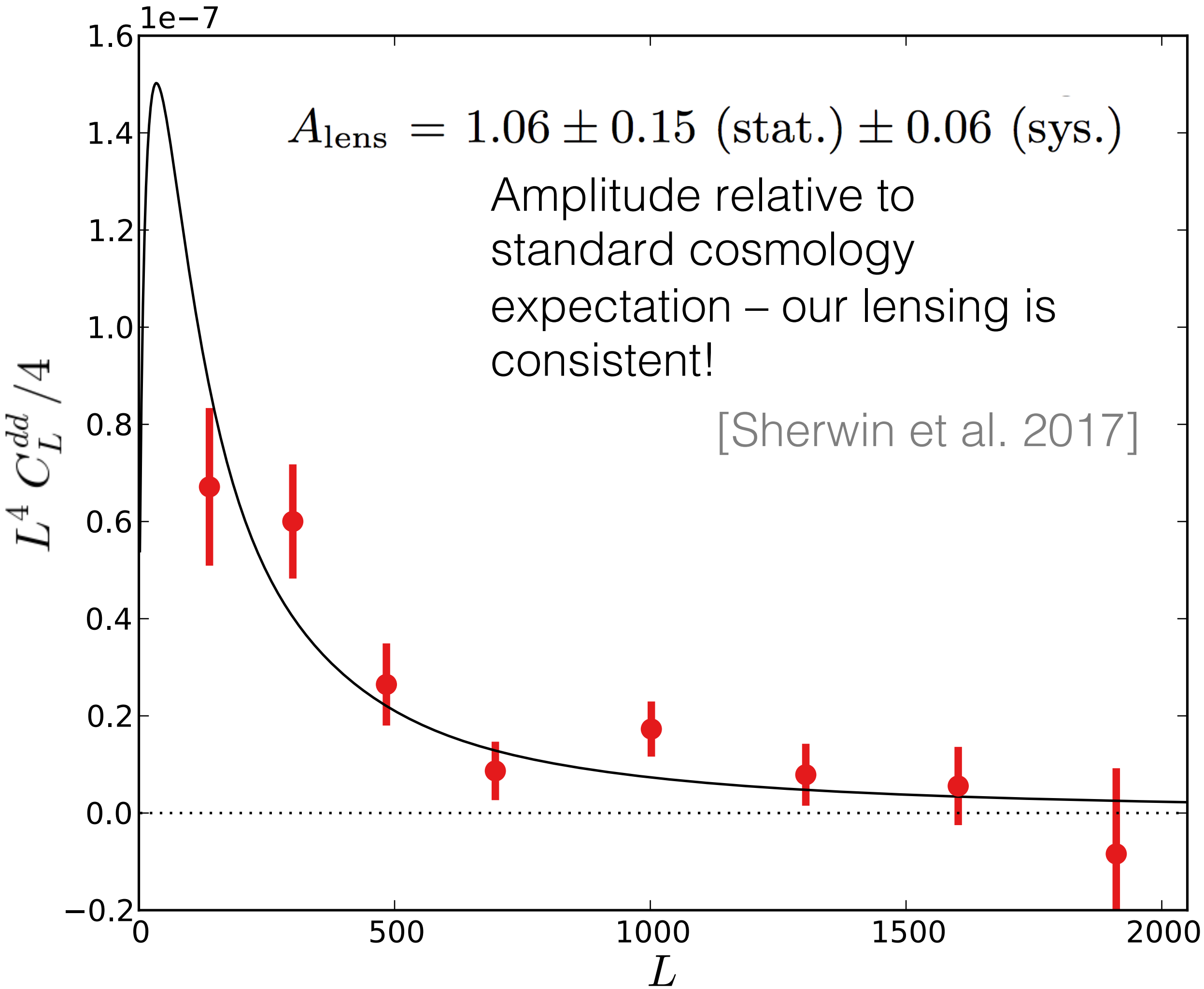


X axis: “for a lens of this angular scale?”

Describe maps statistically with lensing power spectrum:

[First detection: Das, Sherwin++2011, Sherwin, Dunkley, Das++2011]

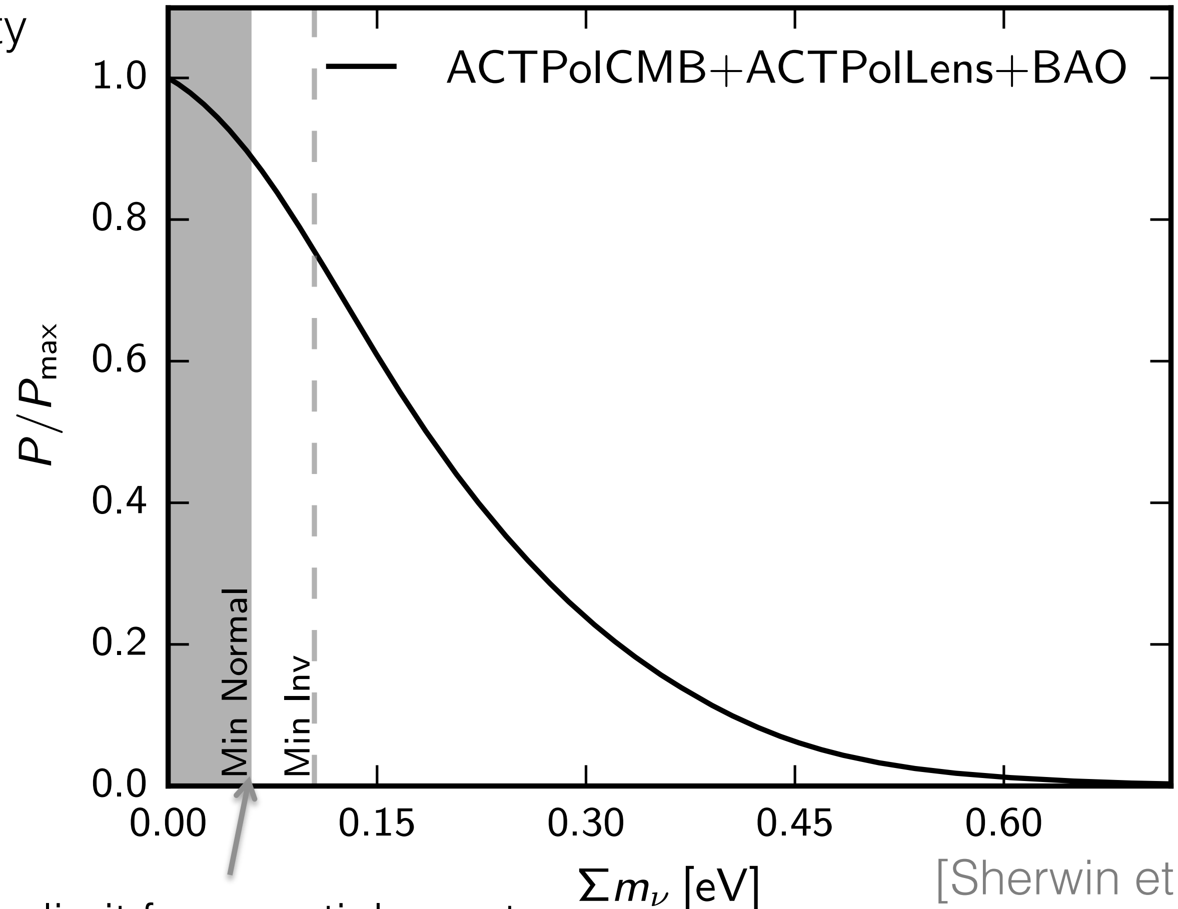
ACTPol – Early Lensing Power Spectrum Results (~10% of our data)



- Main systematic: few %-level biases from foregrounds (solvable w. new frequencies/estimators)

ACTPol Early Lensing Power Spectrum: Constraints On Neutrino Mass (~10% of our data)

Probability

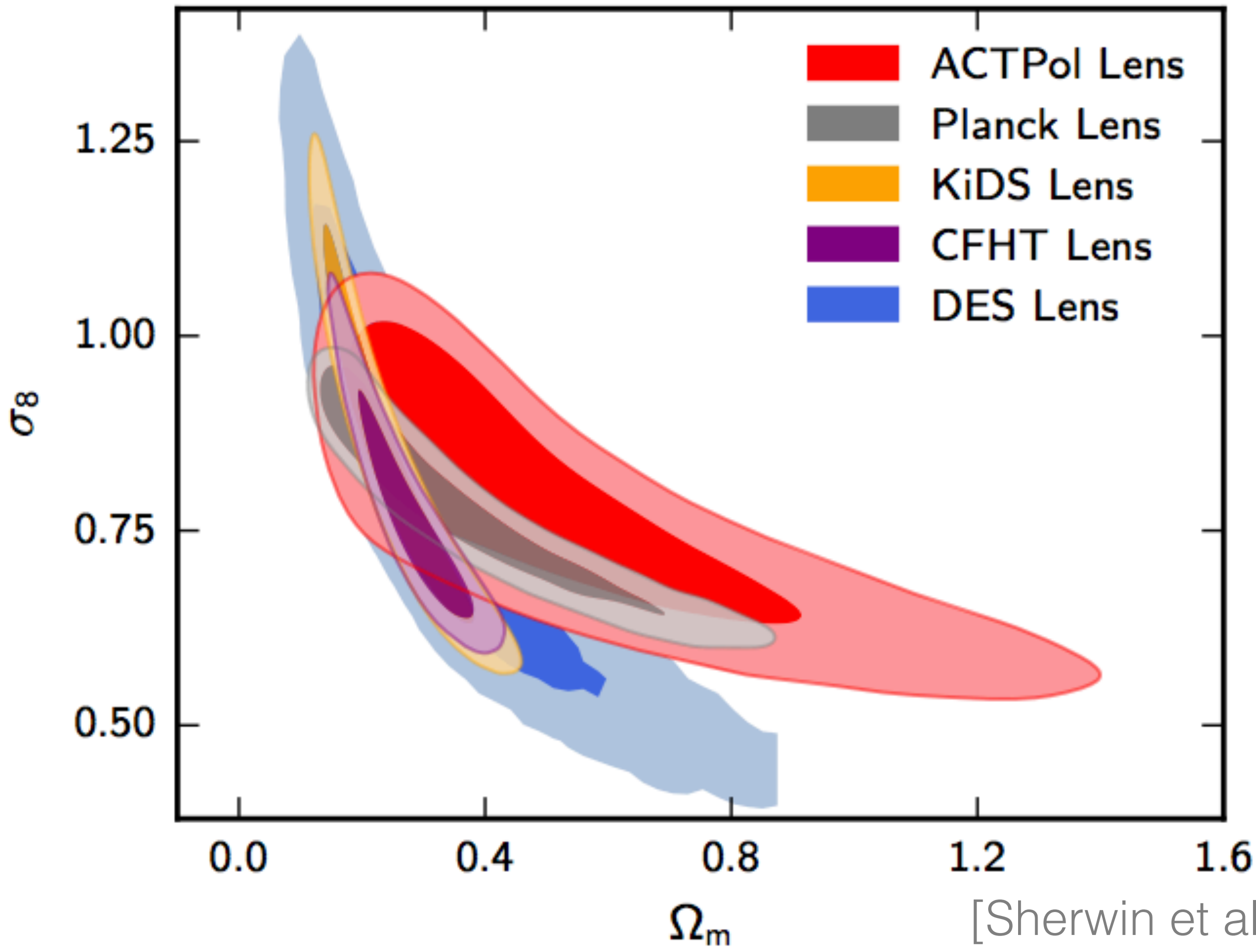


[Sherwin et al. 2017]

60 meV lower limit from particle expts.

- Constraint: $\sum m_\nu < 396\mathrm{meV} \quad (95\%\mathrm{C.L.})$

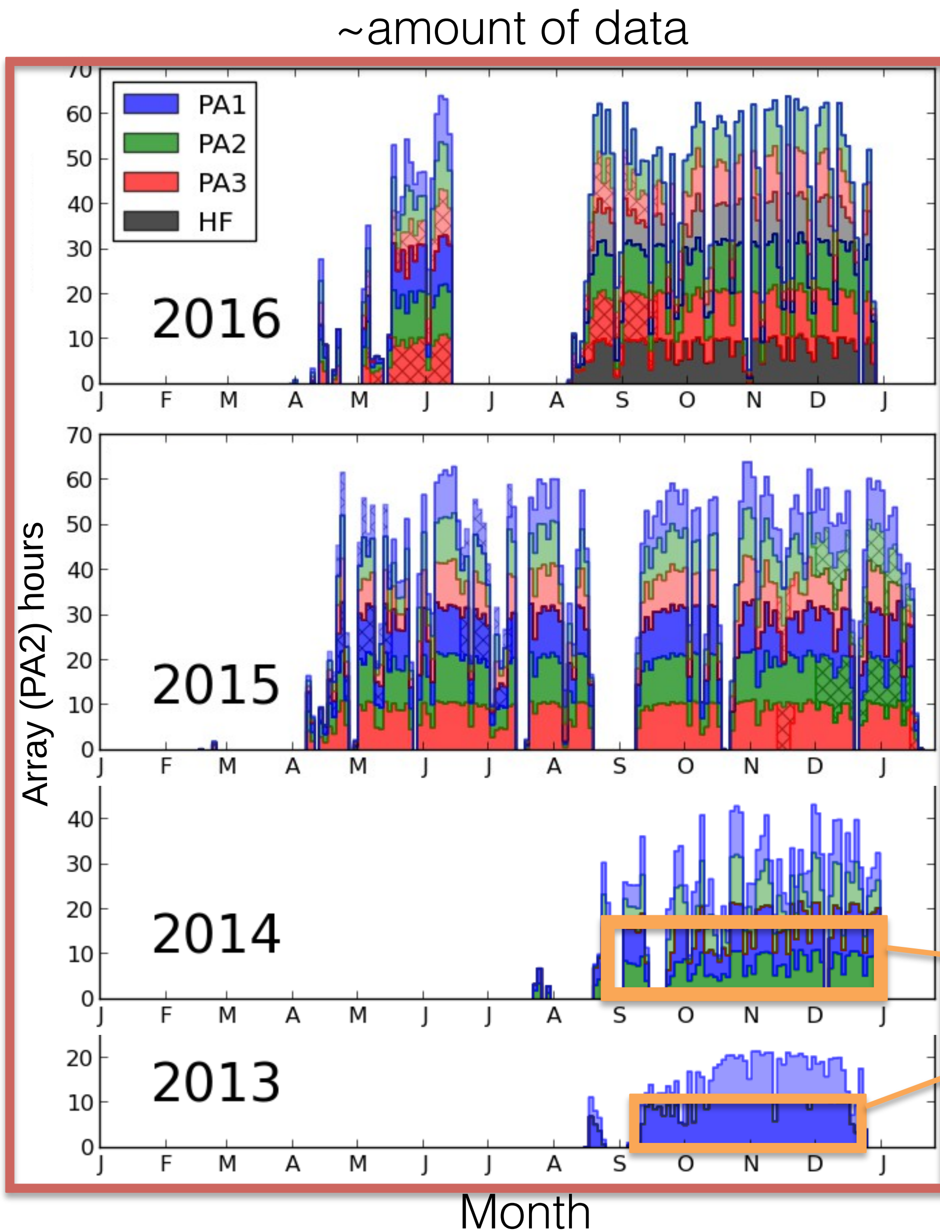
ACTPol Early Lensing Power Spectrum: Constraints (with ~10% of current data)



[Sherwin et al. 2017]

- Constrains combination of amplitude of structure x matter density ~ $\sigma_8 \Omega_m^{0.25}$

ACTPol Lensing Spectrum – Data in Early Paper

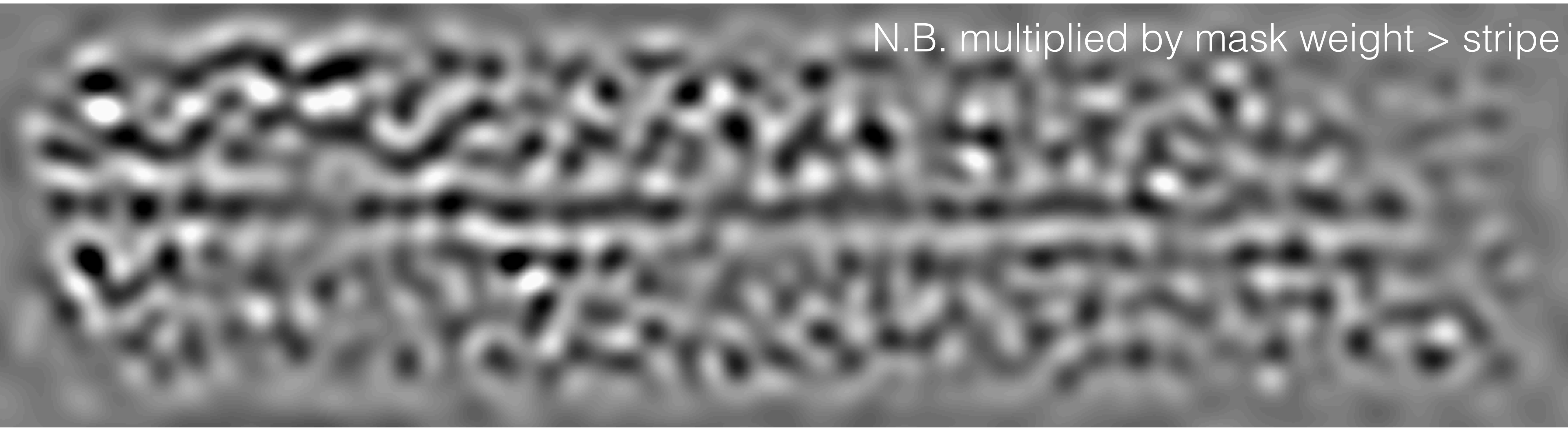


Data in prep. (2017)

data for Sherwin+ 2016
< 10% of data already taken!

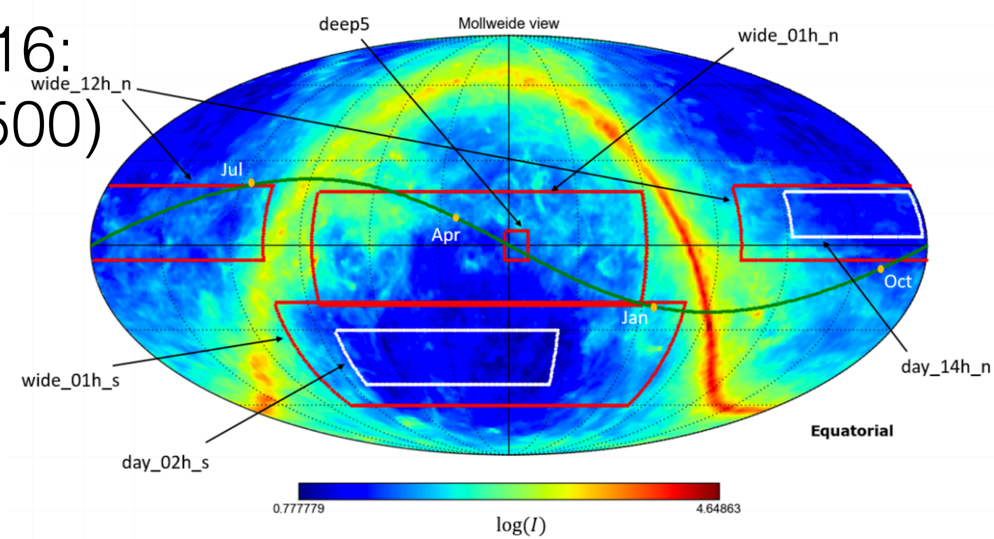
Now: Very Large ACTPol/AdvACT Lensing Maps

- BOSS-N (~3000 sq. deg.) lens map (noisy) - preliminary!

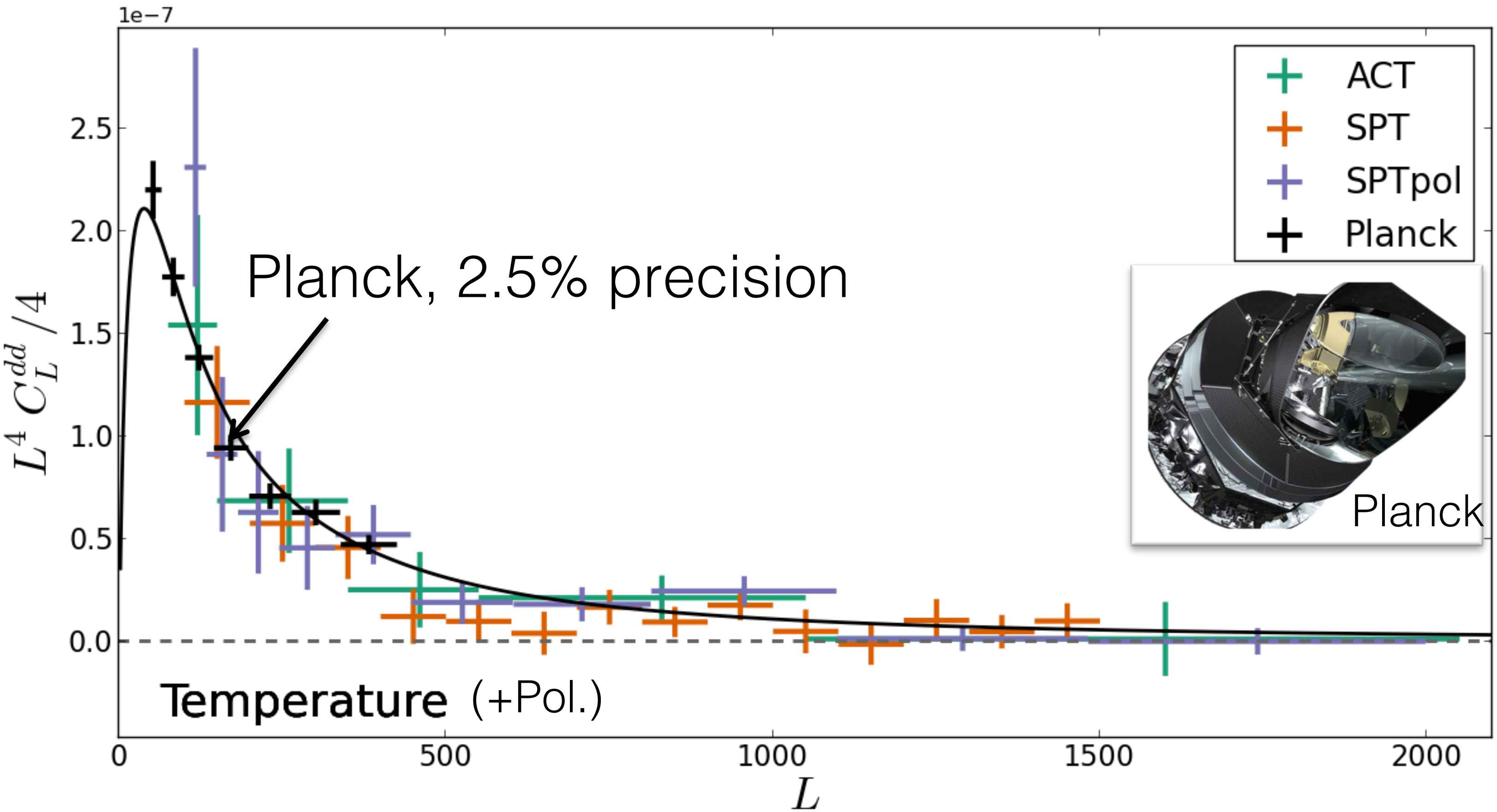


- Total observed through 2016:

12000 sq. deg. (1st release 500)
35 to <10uK-arcmin
– being analyzed now!



Current CMB lensing Measurements



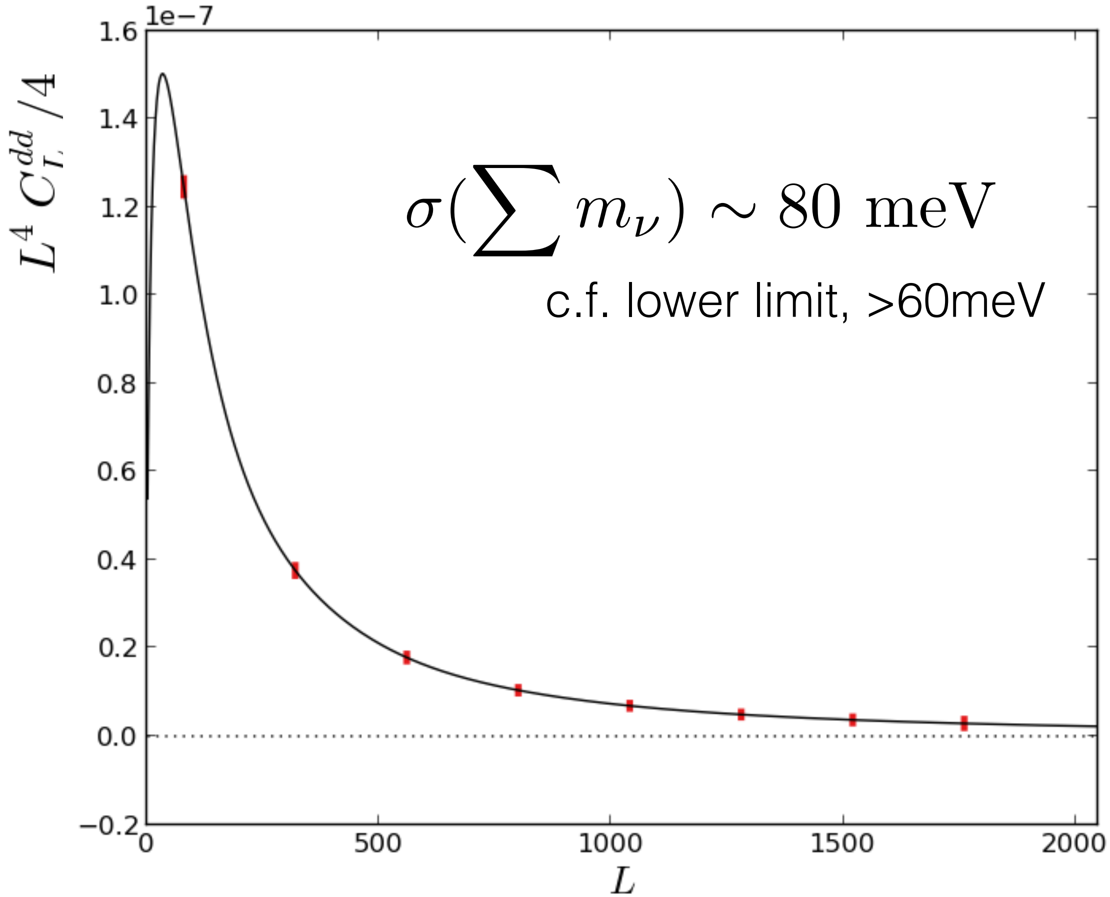
- Planck is still state of the art, but rapid progress only just beginning

ACTPol/AdvACT – Next Paper Expectation (≥2018)
2-3% Precision!

- 12000 square degrees, 170 million pixels, temperature and polarization – lensing analysis is a challenge

- Potential to independently test Planck

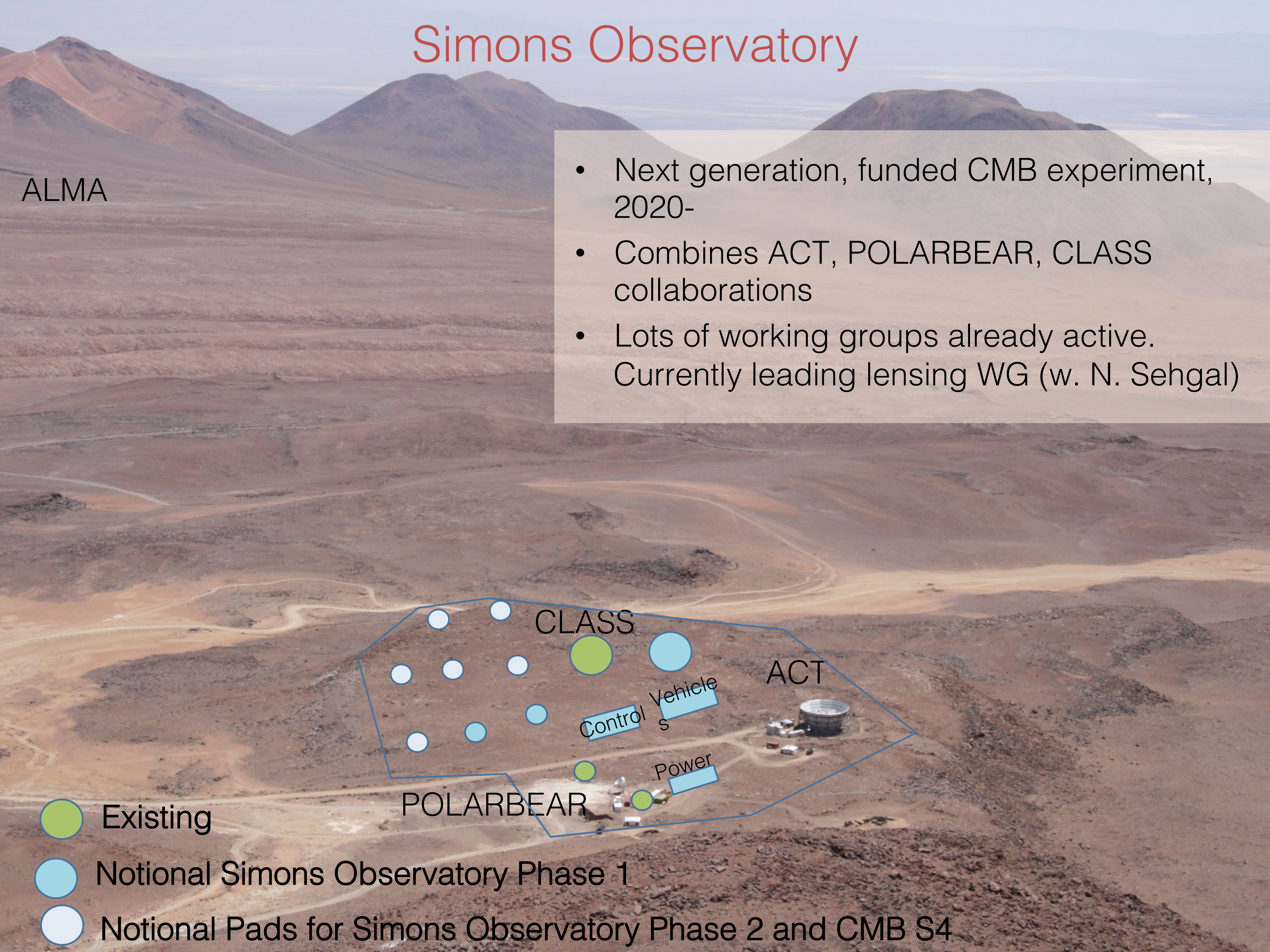
- + push to higher precision with ACT/Planck coadd maps



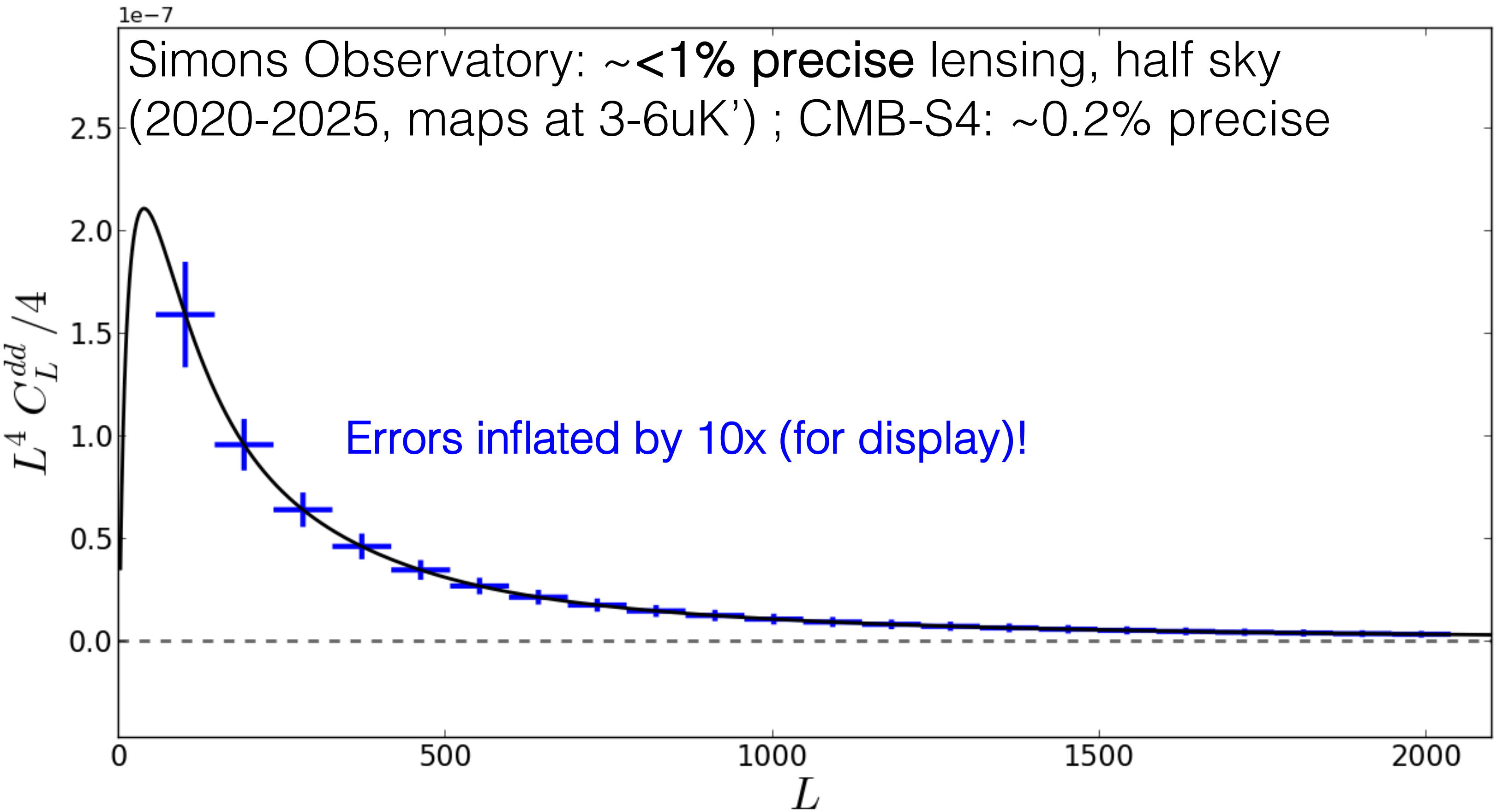
[Sherwin++ in prep.]
[van Engelen++ in prep.]

Simons Observatory

- Next generation, funded CMB experiment, 2020-
- Combines ACT, POLARBEAR, CLASS collaborations
- Lots of working groups already active. Currently leading lensing WG (w. N. Sehgal)



The Future: **Simons Observatory** and CMB Stage-IV
Precision Lensing Power Spectra



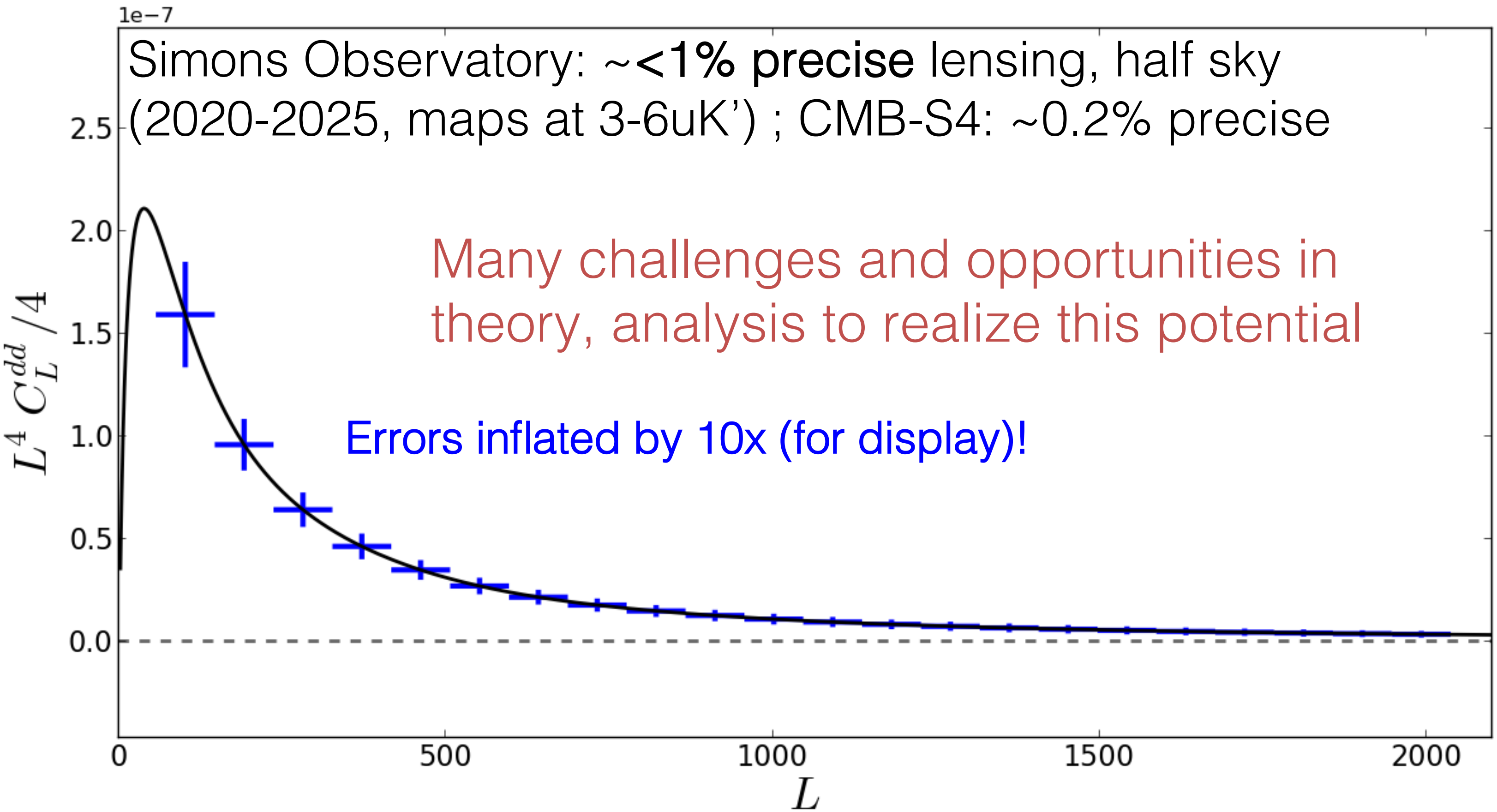
- Will determine unknown neutrino mass at moderate significance in any scenario.

$$\sigma\left(\sum m_\nu\right) \sim \begin{array}{c} 20\mathrm{meV} \\ -30\mathrm{meV} \end{array}$$

(Simons Obs. / CMB-S4)

c.f. limit, >60meV

The Future: **Simons Observatory** and CMB Stage-IV Precision Lensing Power Spectra



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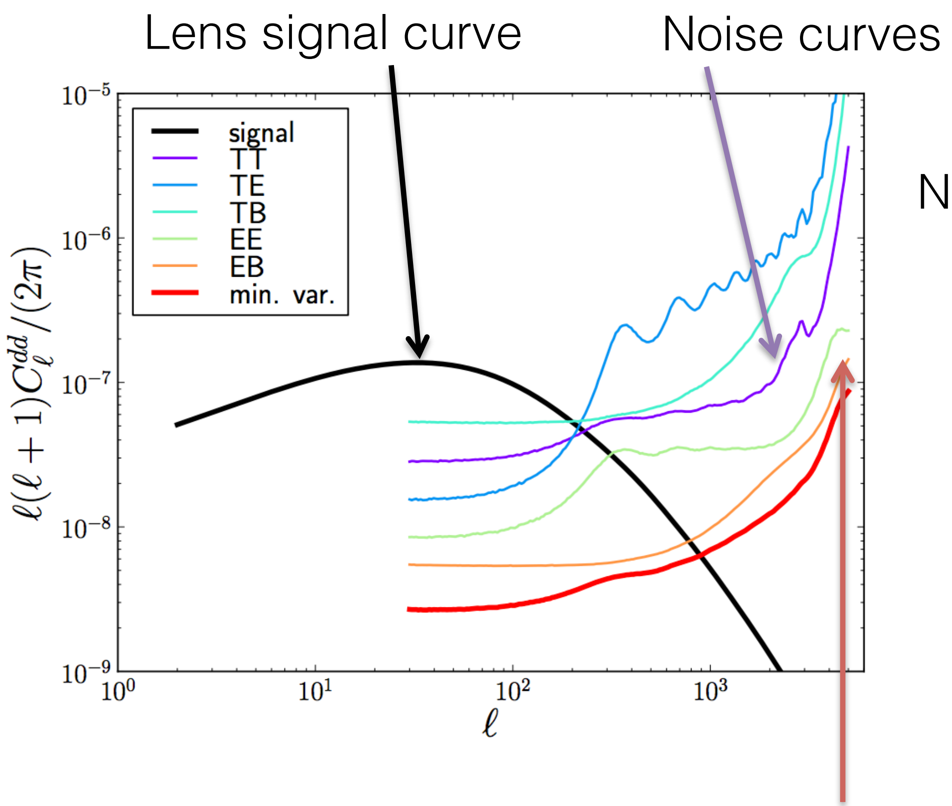
Outline

- Ongoing / upcoming advances in CMB lensing measurements
  - AdvACT + Simons Observatory lensing: testing Planck, and beyond
- CMB lensing theory: new science in the low noise regime
  - Lots of room for improvement on small scales (preliminary)?

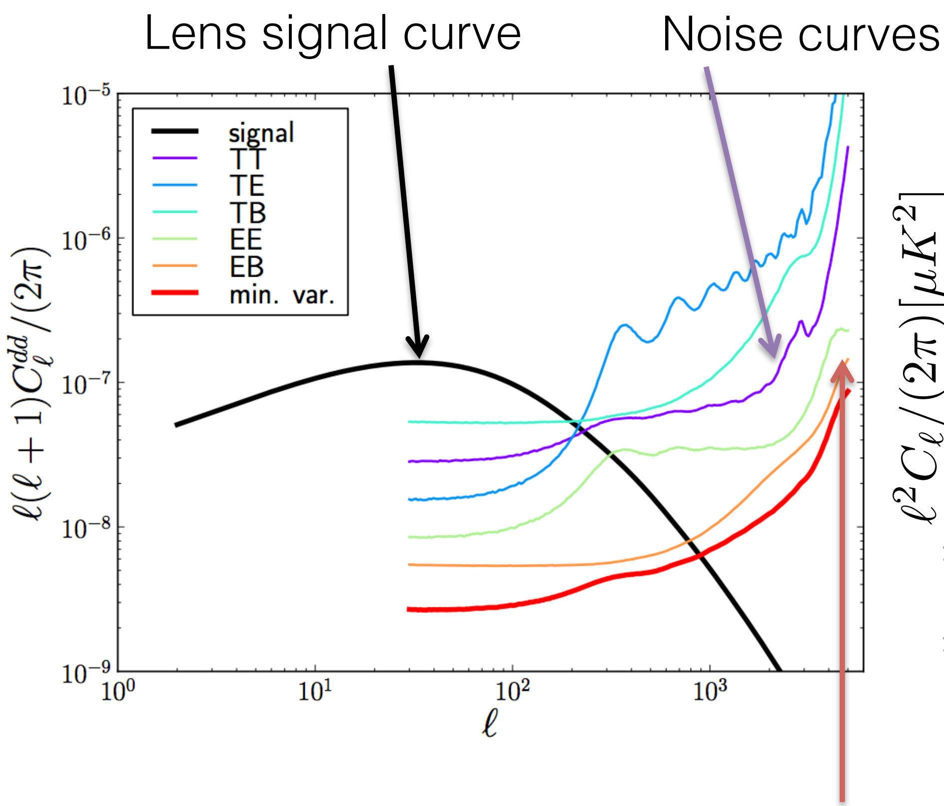
Hints at possible improvements on small scales

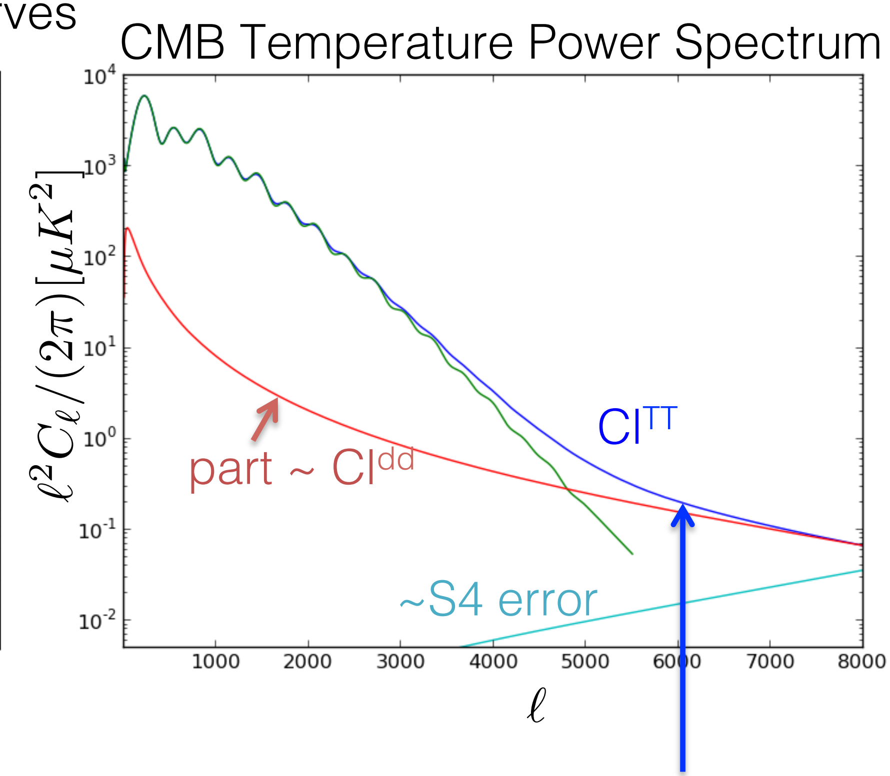


Noise for CMB-S4 [from Schaan++]

- A puzzle: quadratic estimator noise gets large – seemingly cannot probe tiny CMB lenses / scales (interesting for e.g. WDM, axions)

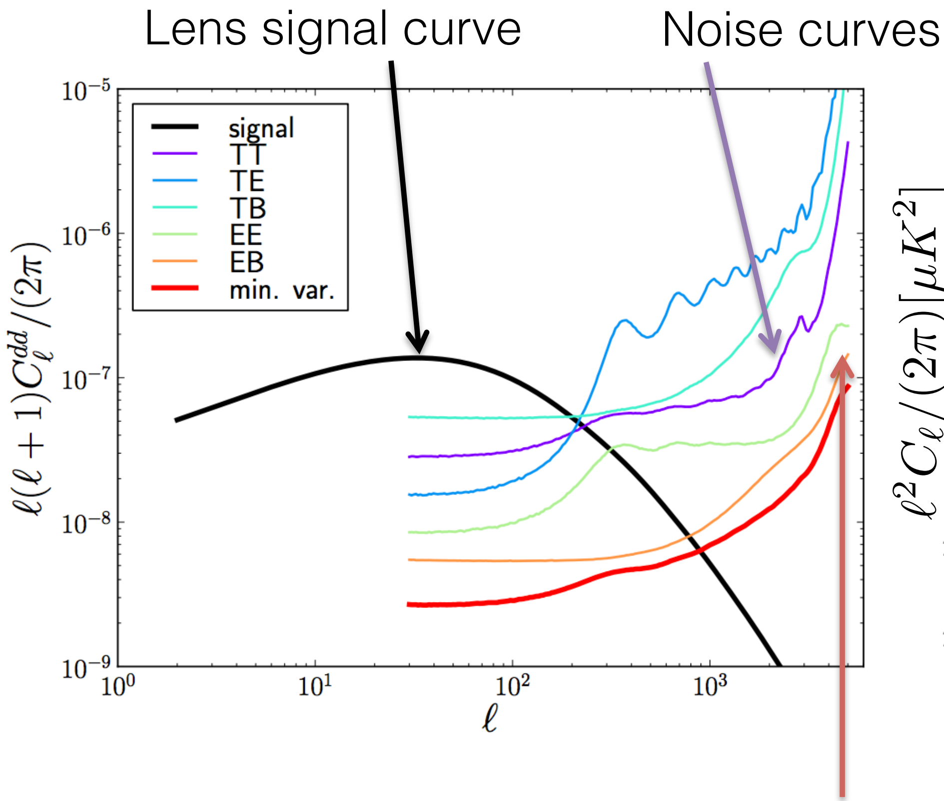
Hints at possible improvements on small scales

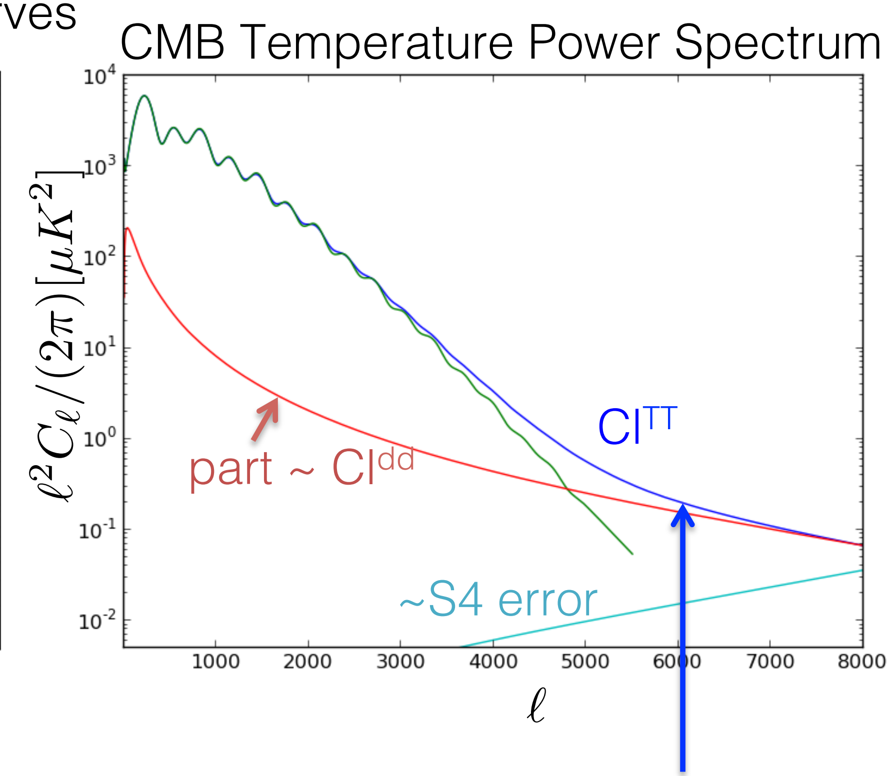




- A puzzle: quadratic estimator noise gets large – seemingly cannot probe tiny CMB lenses / scales (interesting for e.g. WDM, axions)
- But with low enough noise, can read off tiny lenses from small-scale power spectrum.

Hints at possible improvements on small scales





- A puzzle: quadratic estimator noise gets large – seemingly cannot probe tiny CMB lenses / scales (interesting for e.g. WDM, axions)
- But with low enough noise, can read off tiny lenses from small-scale power spectrum. Is there a better estimator out there?

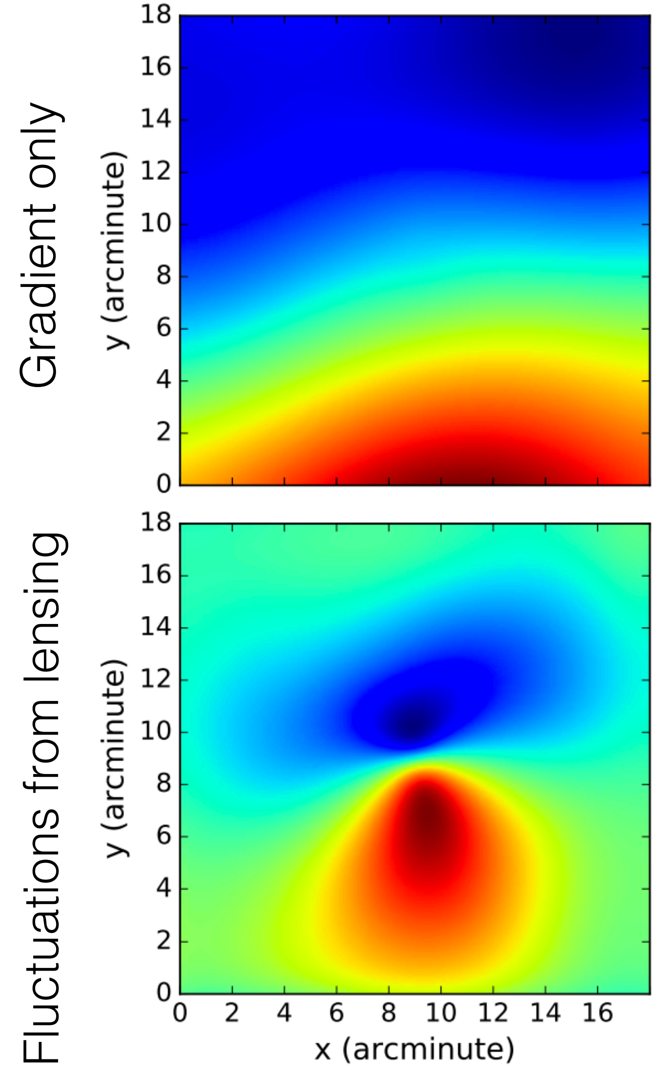
Limitations of Normal Approach (Quadratic Estimator)

- Lens d on small scale temperature T^S ~ dipole “wiggle” on long CMB gradient T^L

$$T^S(\mathbf{x}+\mathbf{d}) \approx \mathbf{d}\cdot\nabla T^L(\mathbf{x})$$

- Quadratic estimator multiplies this by grad(T^L); ~$(T^L)^2$ gradient cosmic variance limits S/N

- But: know gradient, so can “divide” to get d!

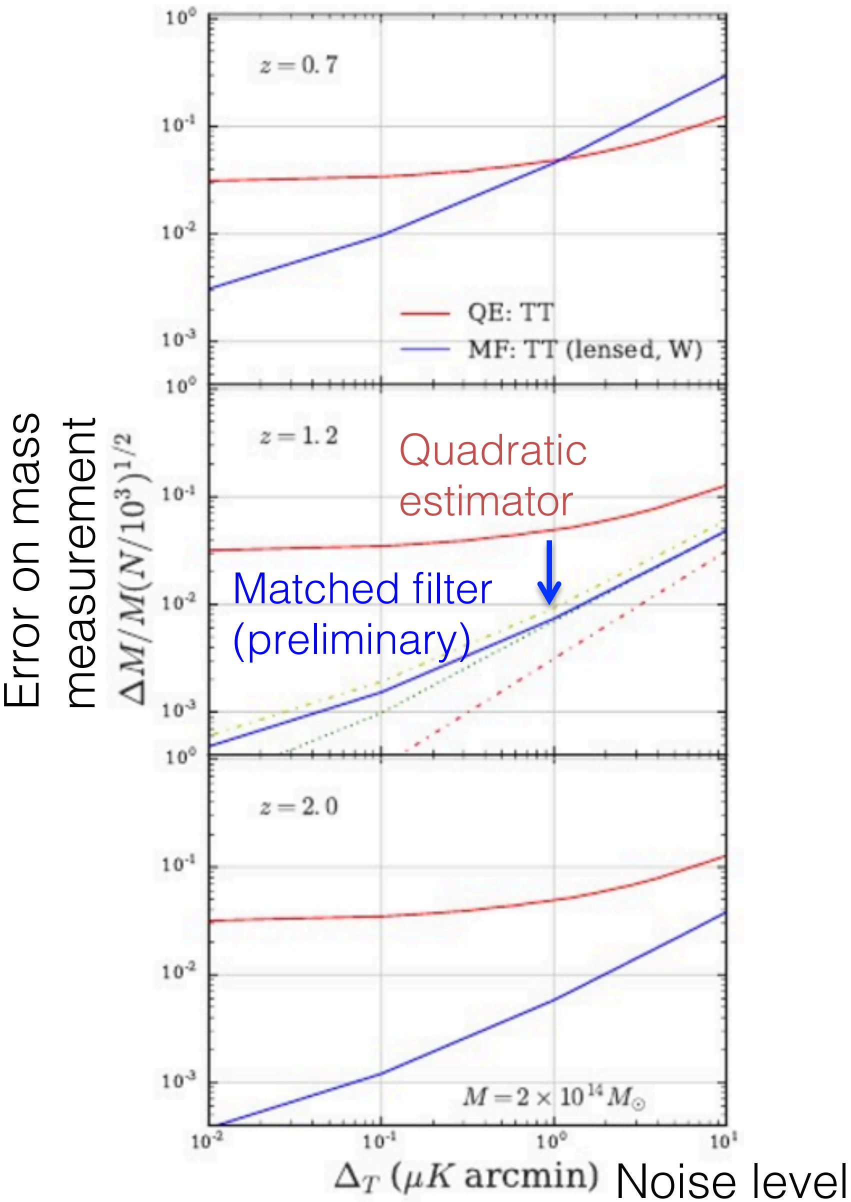


Improved small-scale CMB halo lensing

- Apply to clusters by matched-filtering result [Seljak/Zaldarriaga 2000]. How does this perform for CMB-S4 clusters?

- We find significant improvement for small clusters (caveat: kSZ…) See Ben's fireslides!

[Horowitz, Ferraro, Sherwin in prep.]



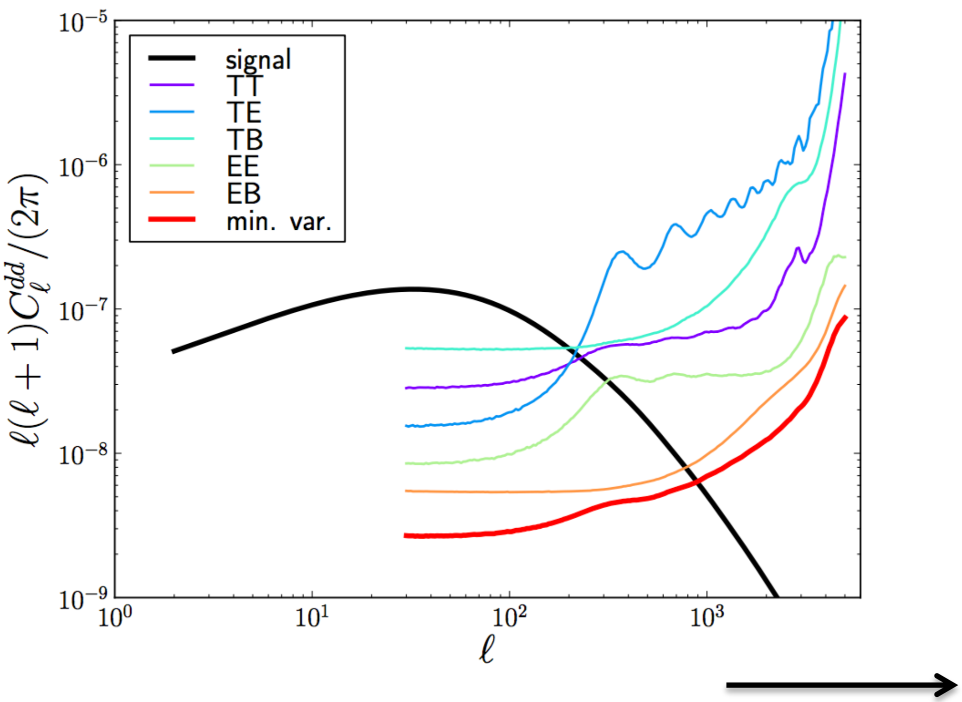
Towards better small scale CMB lensing power?

- Generalize, or use maximum likelihood, for not just clusters, but small scale power spectrum

- Can we better measure small-scale, high-redshift structure?

- Can this improve constraints on e.g., WDM, axion physics?

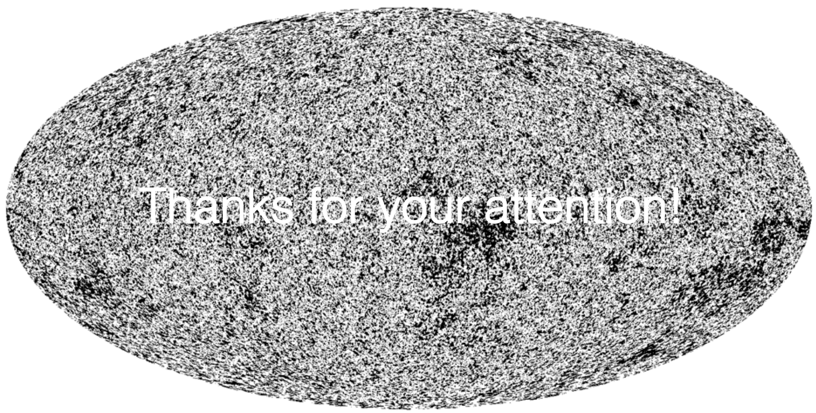
In progress!



Measure lens power on much smaller scales?

Summary

- CMB lensing is a powerful and clean probe of neutrino masses, inflation (via delensing), and dark energy (via cross-correlations.)
- Rapid progress from ground based CMB: current AdvACT data will allow us to check and surpass Planck, Simons Observatory will allow ultra-high precision lensing.
- Work in progress: how much can we improve small scale lensing theory?



- + happy to discuss work on BAO (can errors in fiducial cosmology for reconstruction cause problems?) and delensing!