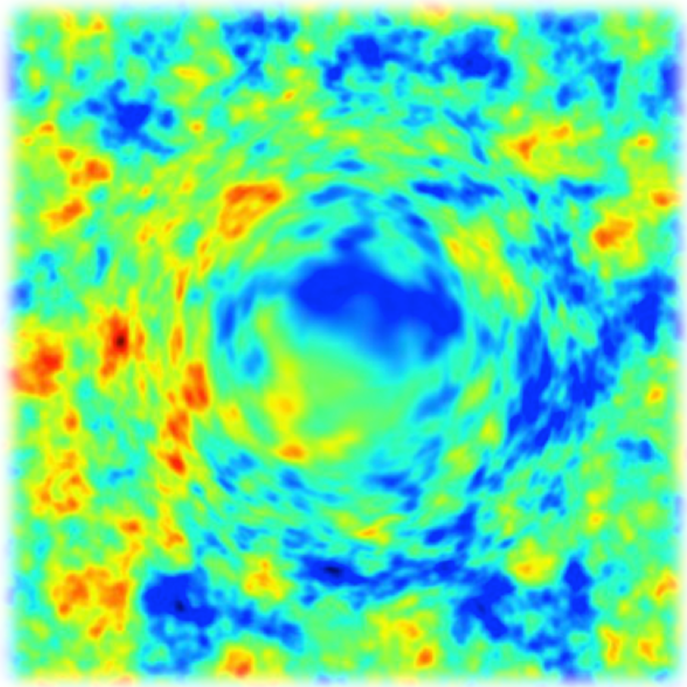
Cosmology and Fundamental Physics from Atacama Cosmology Telescope CMB Lensing



Blake D. Sherwin for the ACT Collaboration
Department of Applied Mathematics and Theoretical Physics / Kavli Institute for Cosmology
University of Cambridge

Science & Technology Facilities Council
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European Research Council
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Galaxies Trace
Large Amounts of Underlying Dark Matter
Galaxies, Gas: <20% of the mass

Galaxies Trace
Large Amounts of Underlying Dark Matter

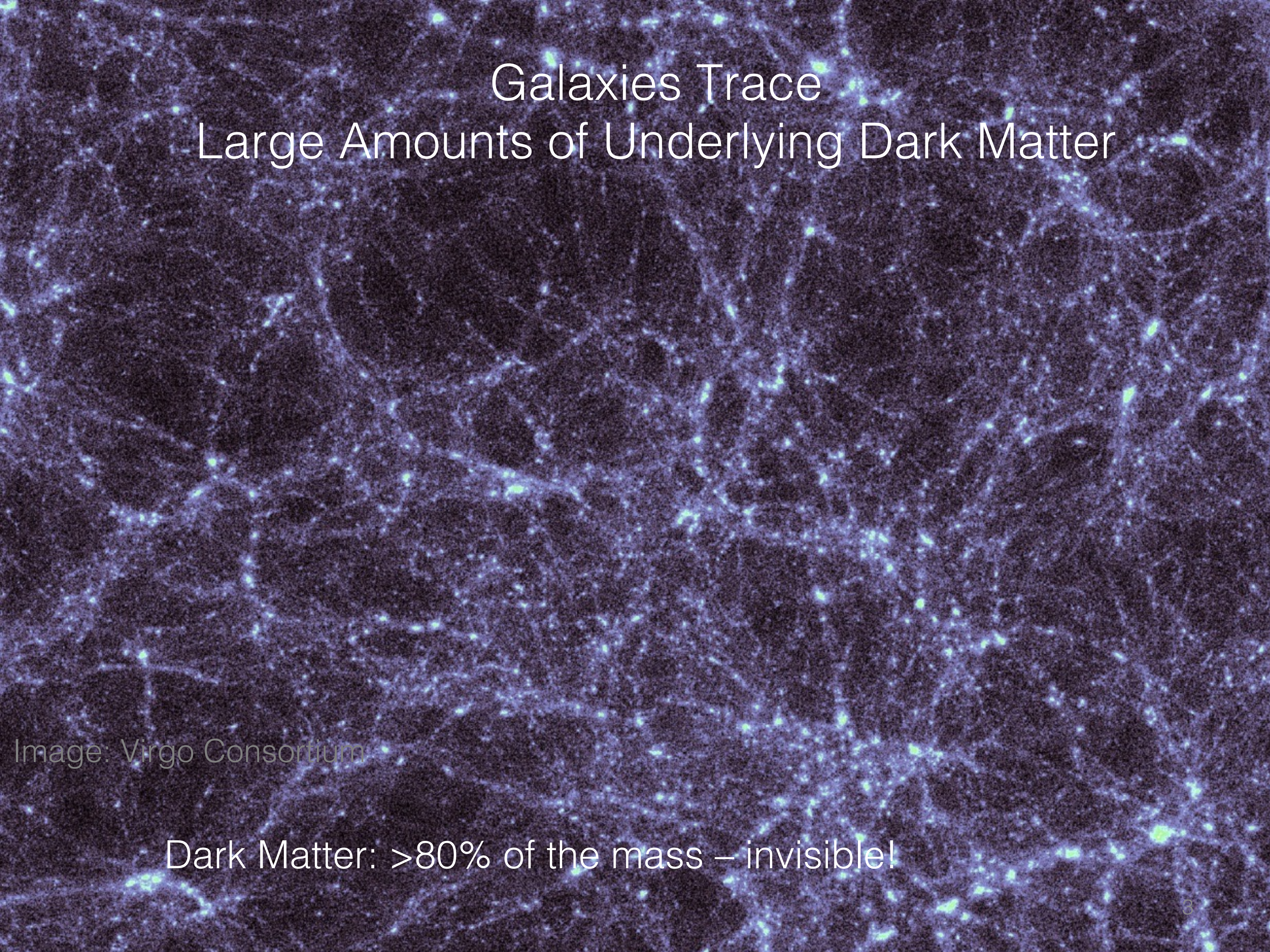
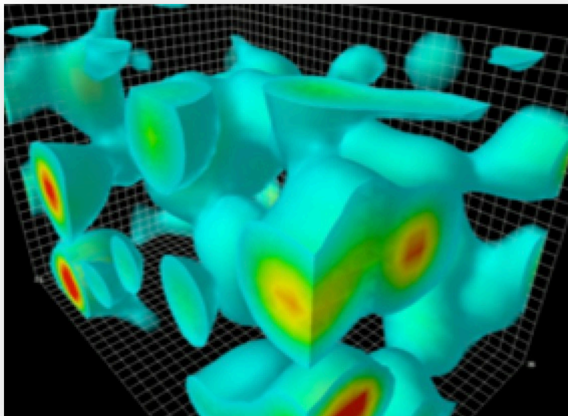


Image: Virgo Consortium

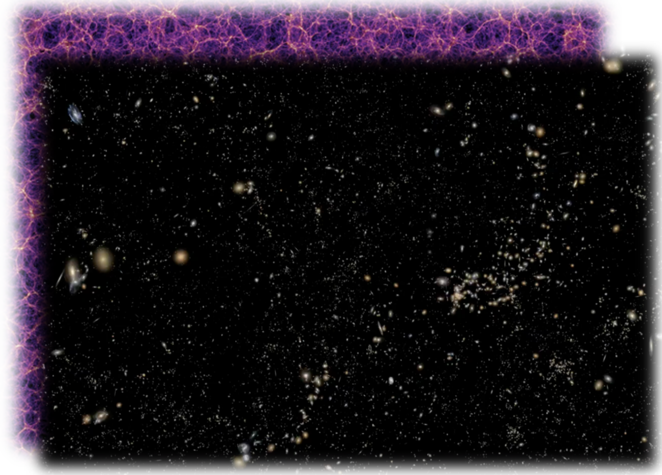
Dark Matter: >80% of the mass – invisible!

Formation of structure well-understood (?) in our standard cosmological model

Primordial fluctuations from inflation



Growth due to gravity



Cosmic structure today (affected by composition, physics, initial conditions of the universe!)

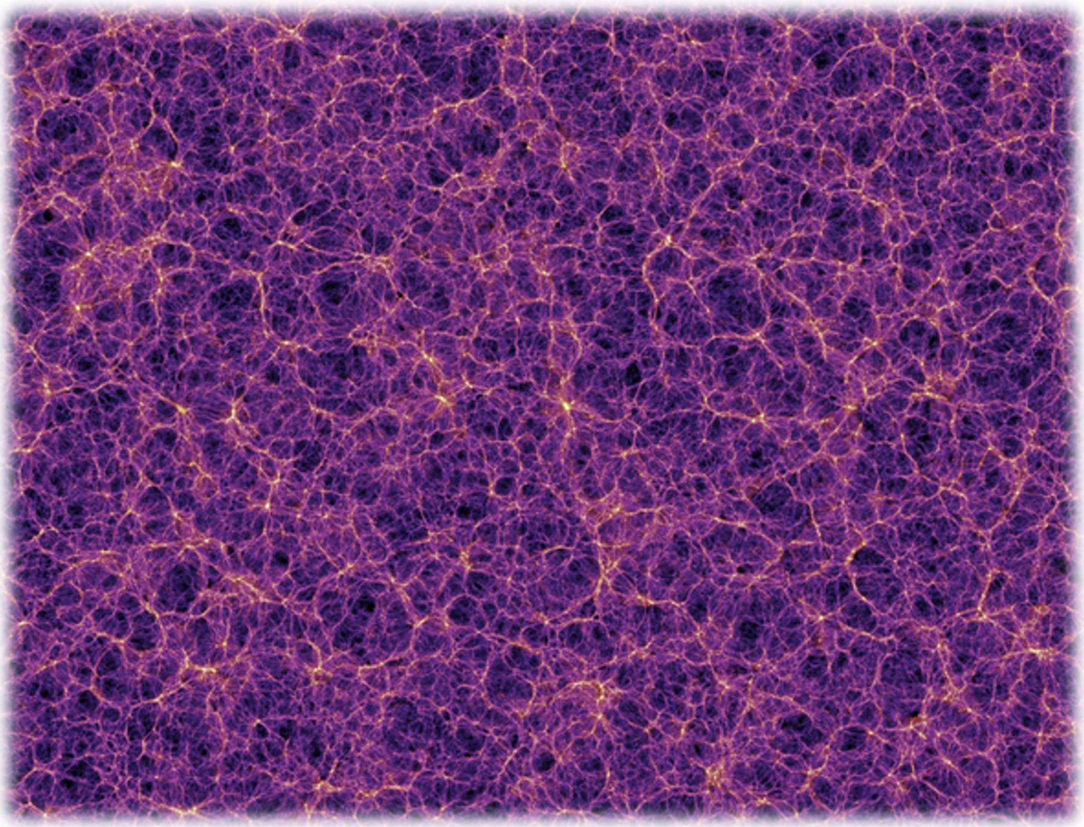
[Video: A. Kravtsov++]

Cosmic mass maps: a powerful observable

- Want to probe mass distribution in detail, as contains clean information on open questions in cosmology and physics:

1. Is standard cosmology correct?

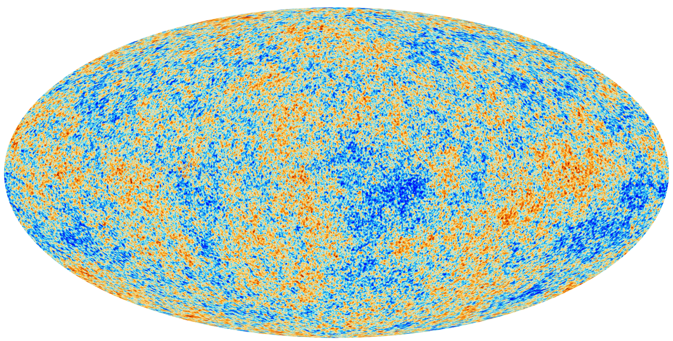
E.g., dark matter, dark energy = cosmological constant, GR

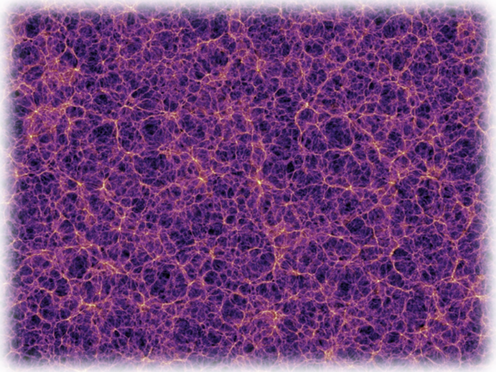


2. What are the properties of particles in the universe: masses of neutrinos?

1. Mass maps: a strong test of our cosmological model

- Do observations match predictions of standard model structure growth (dark matter, w=-1 dark energy, GR)?
- E.g., powerful consistency test:





Fit standard cosmological model to CMB at early times, t=0.004 Gyr

Predict size of structure formed at late times (t>1 Gyr) + compare with observations

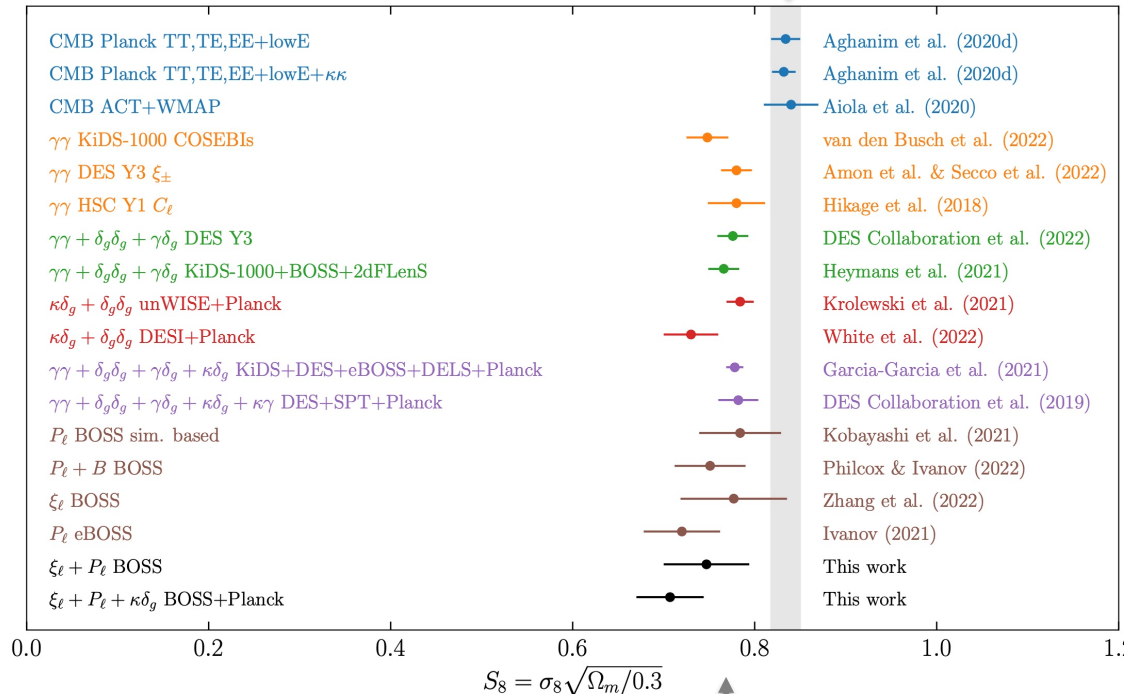
- Parametrize structure size today with σ_8 , RMS matter density fluctuation smoothed on scale of 8 Mpc/h

Motivation for further testing: σ_8* tension claims

CMB extrapolation

- σ_8* measured by several galaxy probes is ~2-3 sigma low compared to prediction from early-time CMB

- New, robust measurements of mass distribution crucial: Do we also find a low σ_8?



[Chen++ 2022]

~σ_8

Direct low-z measurements (from lensing and/or galaxies)

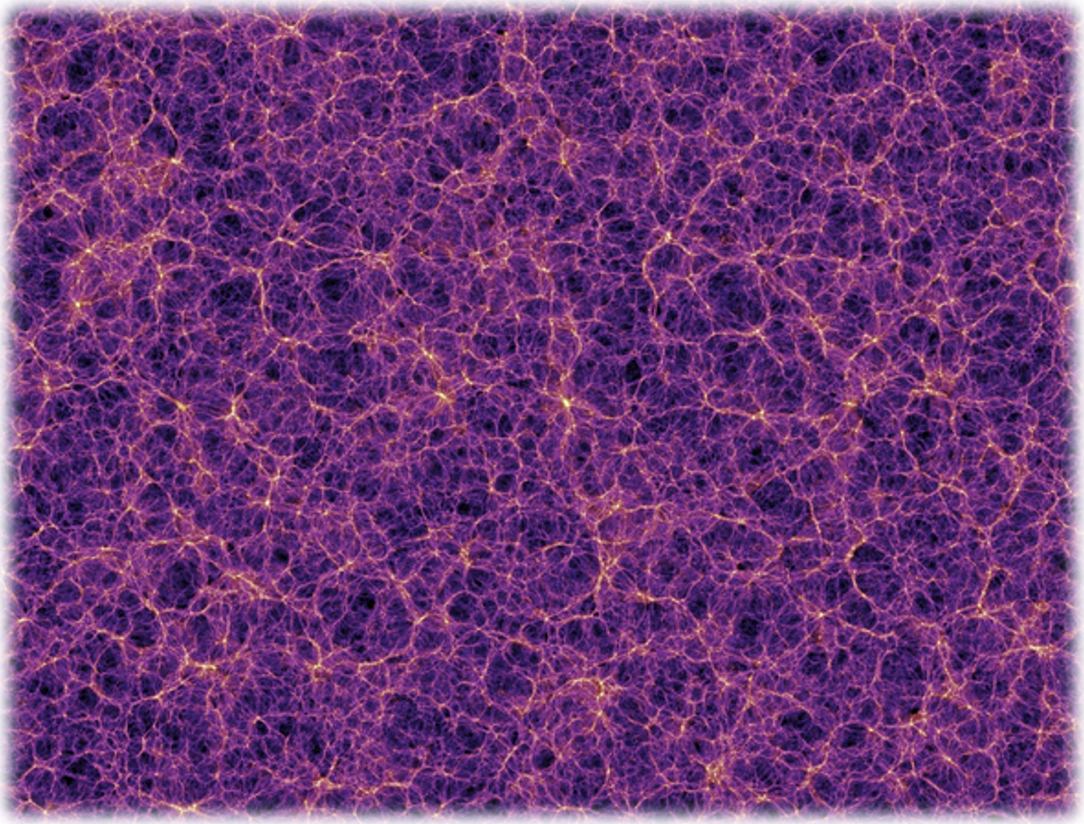
* actually $\sigma_8\,\Omega_m^{0.5}$

Cosmic mass maps: a powerful observable

- Want to probe mass distribution in detail, as contains clean information on open questions in cosmology and physics:

1. Is standard cosmology correct?

E.g., dark energy = cosmological constant, GR



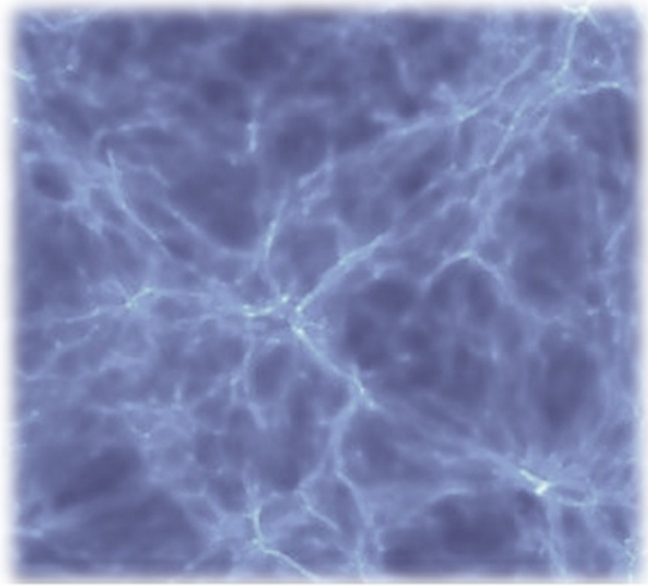
2. What are the properties / masses of neutrinos?

2. Mass maps: a powerful probe of neutrino mass

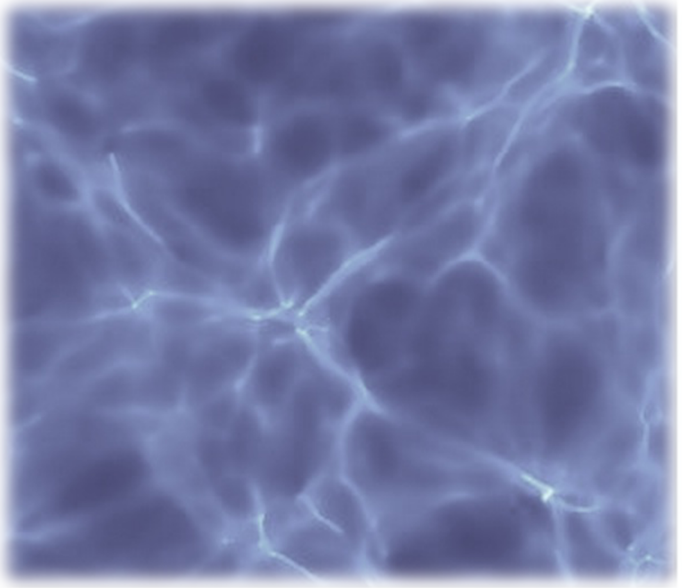
- Neutrino mass affects structure growth: the more massive neutrinos are, the more small-scale growth is suppressed.

Large-scale mass distribution:

Image: Viel++ 2013

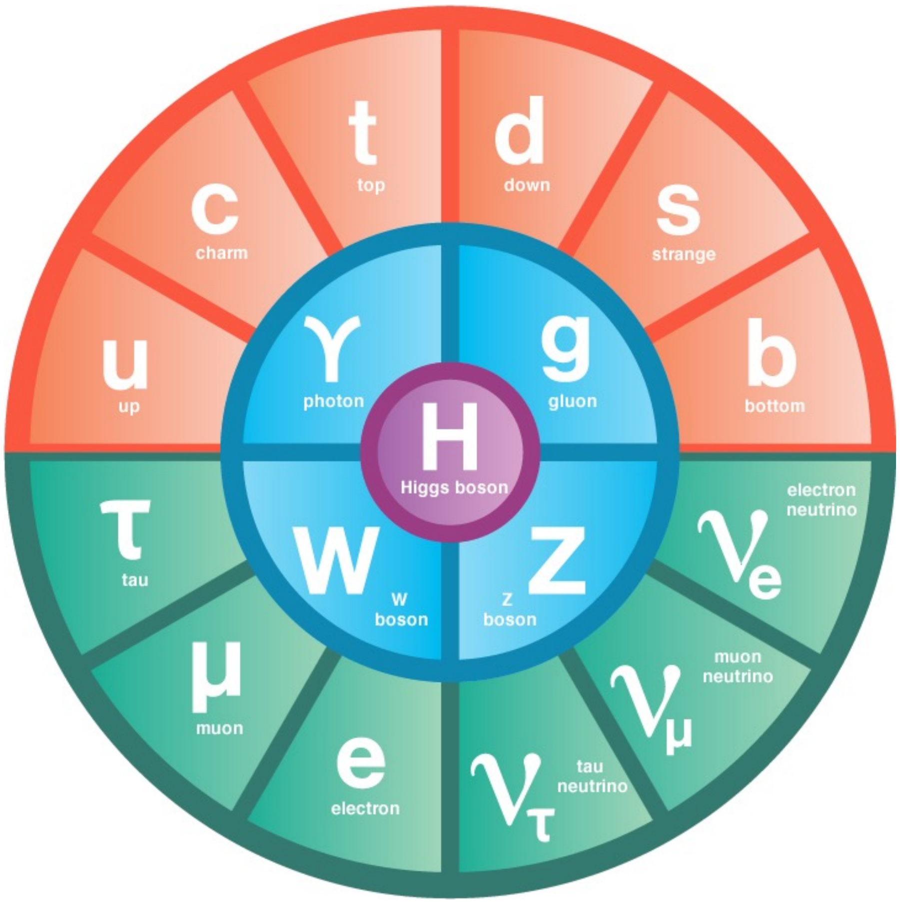


Neutrino Mass Negligible



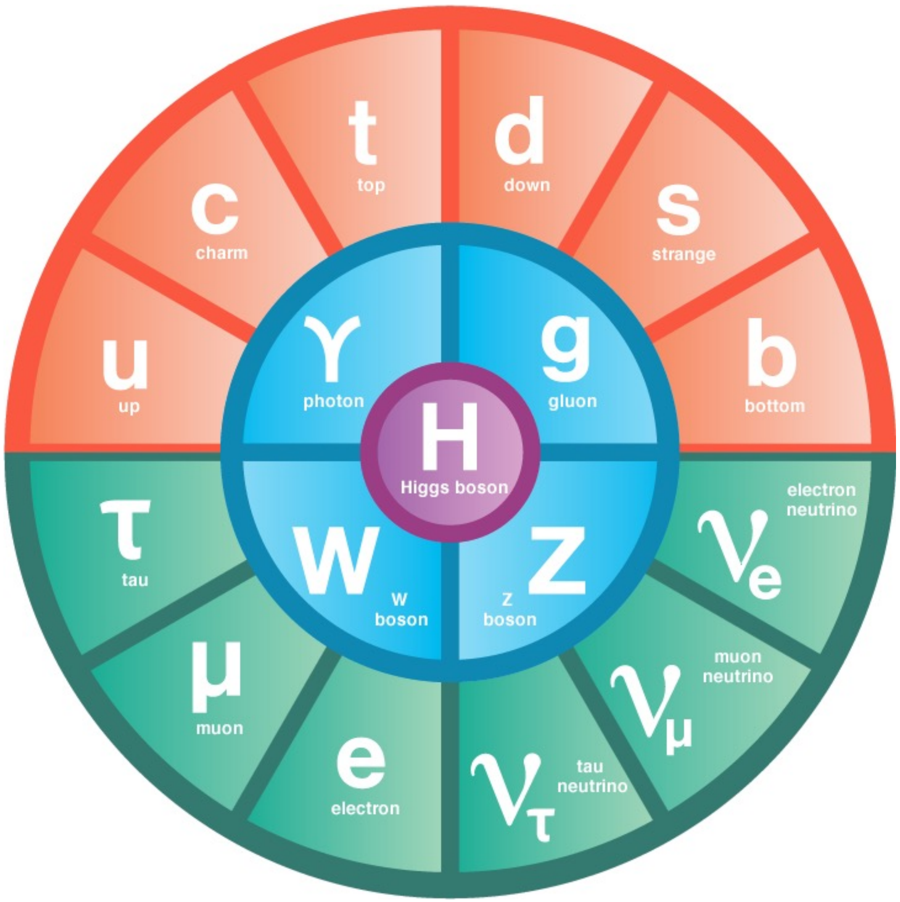
Neutrino Mass Really Large (qualitative)

2. Mass maps: a powerful probe of neutrino mass



- Measurements of mass sum $\sum m_\nu$ can give insight to key questions:
  - What is unknown neutrino mass?
  - Ordering?
  - Dirac / Majorana?
  - What new physics?
- Possibility soon of detection: nearing lower limit, 60meV

2. Mass maps: a powerful probe of neutrino mass



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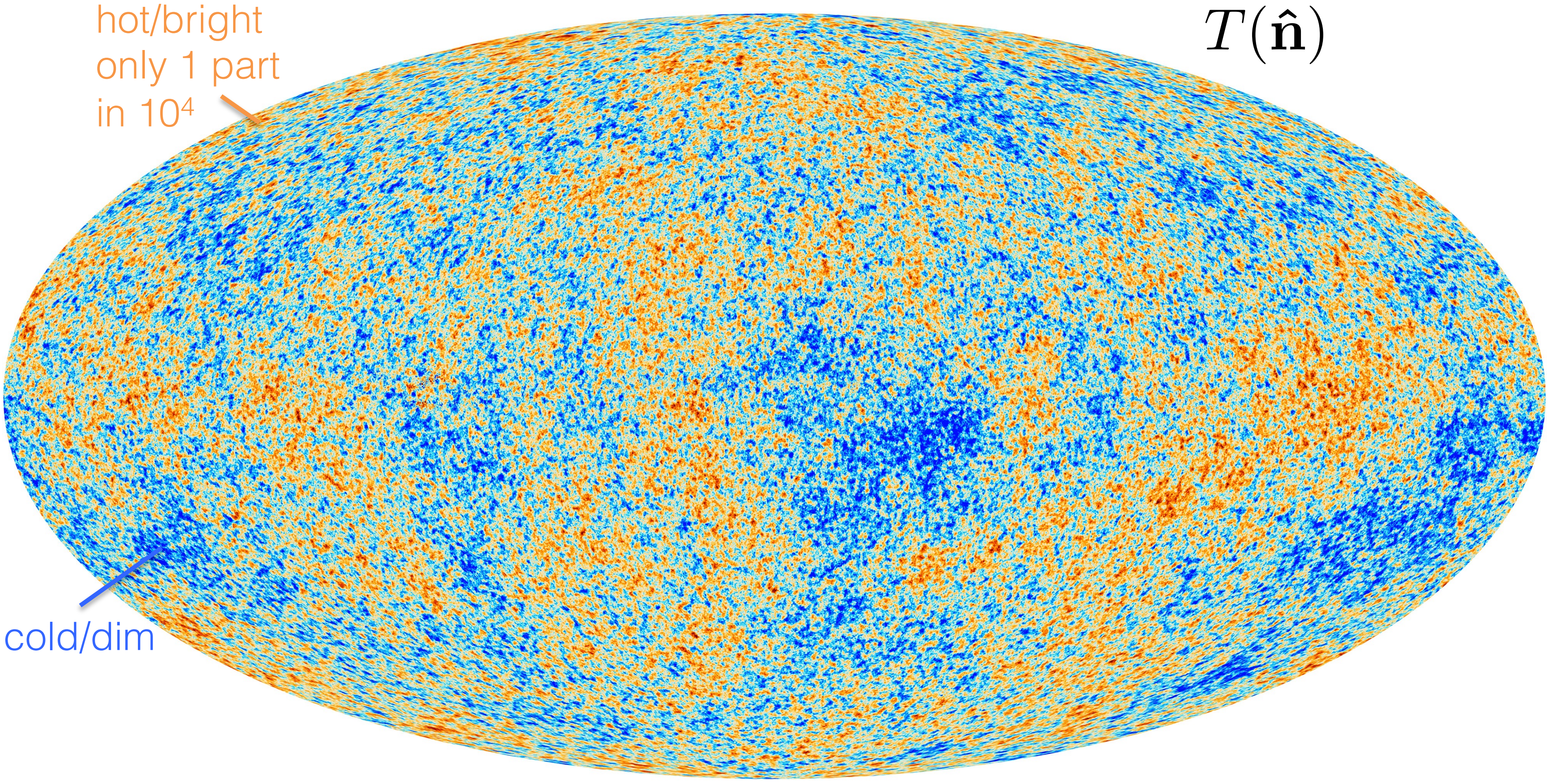
Want to map mass – best method: gravitational lensing!

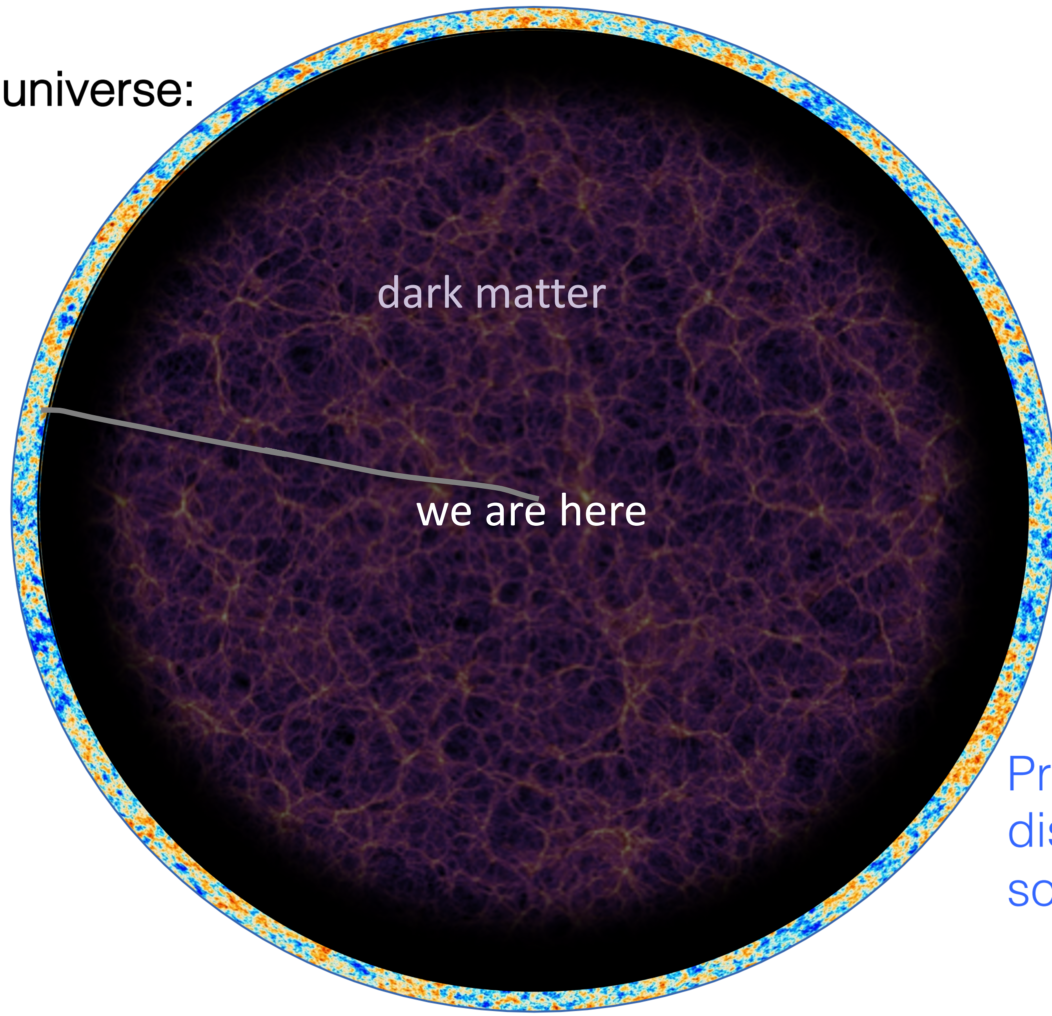
Source for Studying Gravitational Lensing: The Cosmic Microwave Background (CMB) Radiation



CMB temperature fluctuations T (picture of primordial plasma from the Planck Satellite)

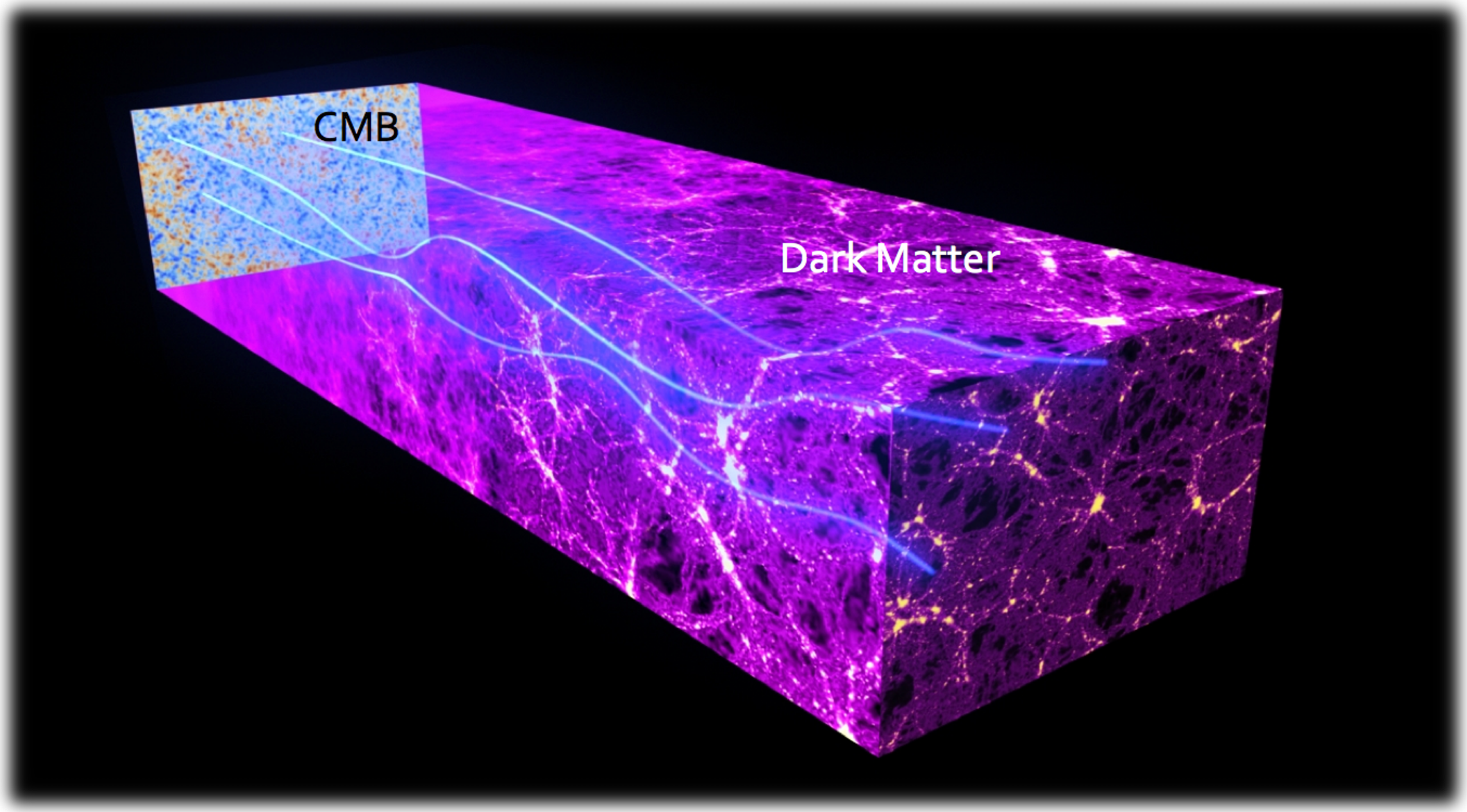
CMB: A Unique Source for Gravitational Lensing

The observable universe:



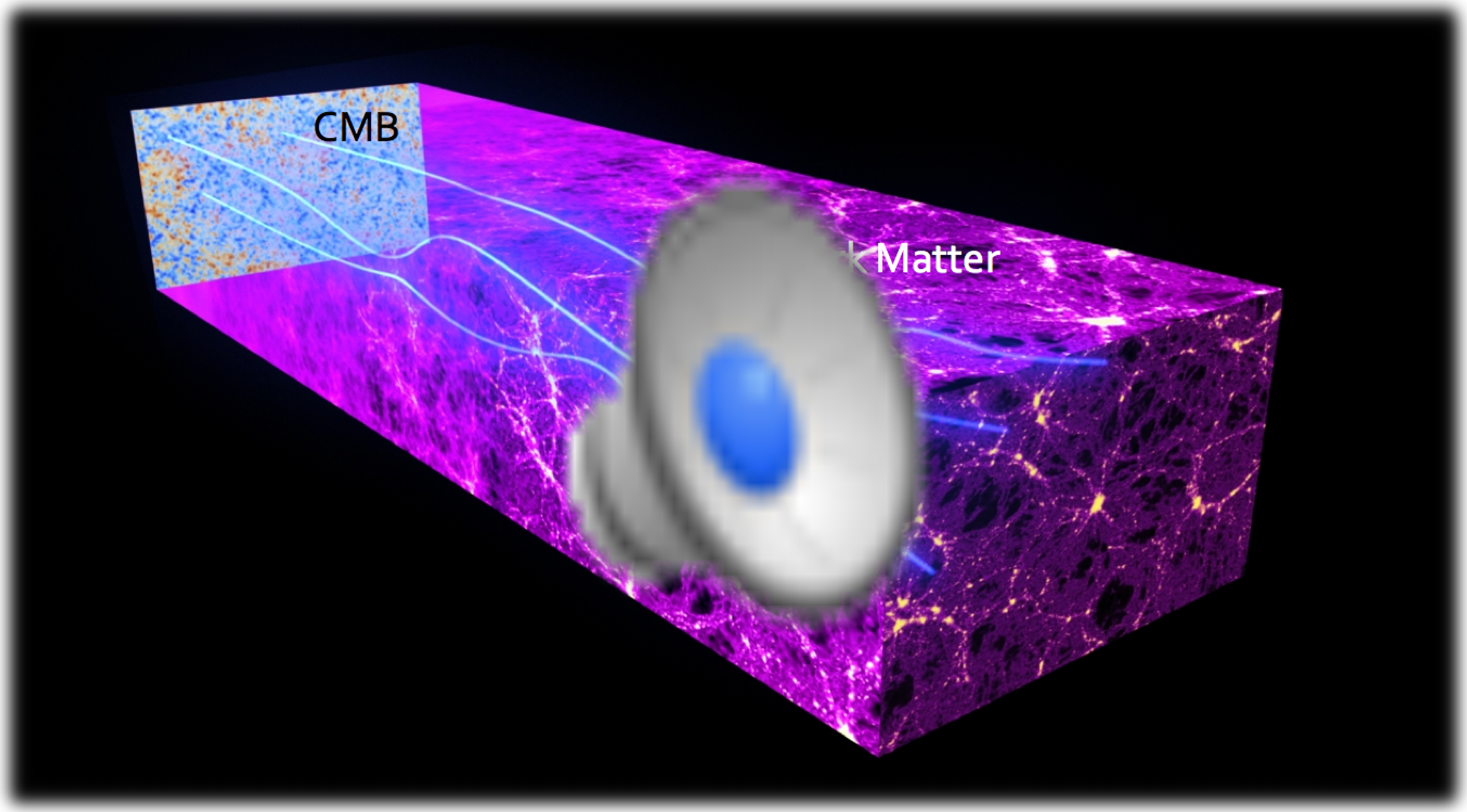
CMB Gravitational Lensing

- Distribution of dark matter deflects CMB light that passes through

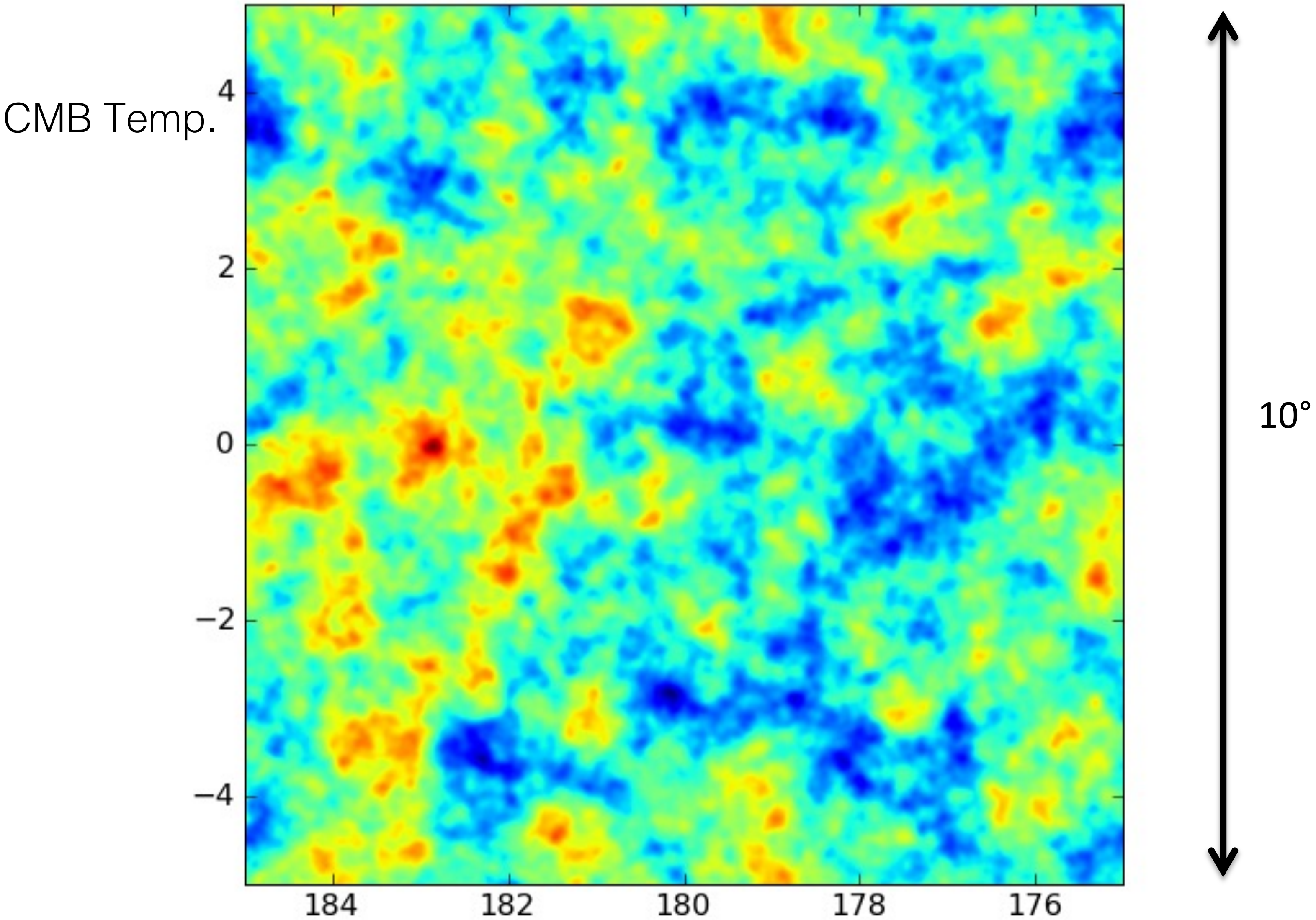


"Light" Source for Lensing: The Cosmic Microwave Background (CMB)

- Distribution of dark matter deflects light that passes through

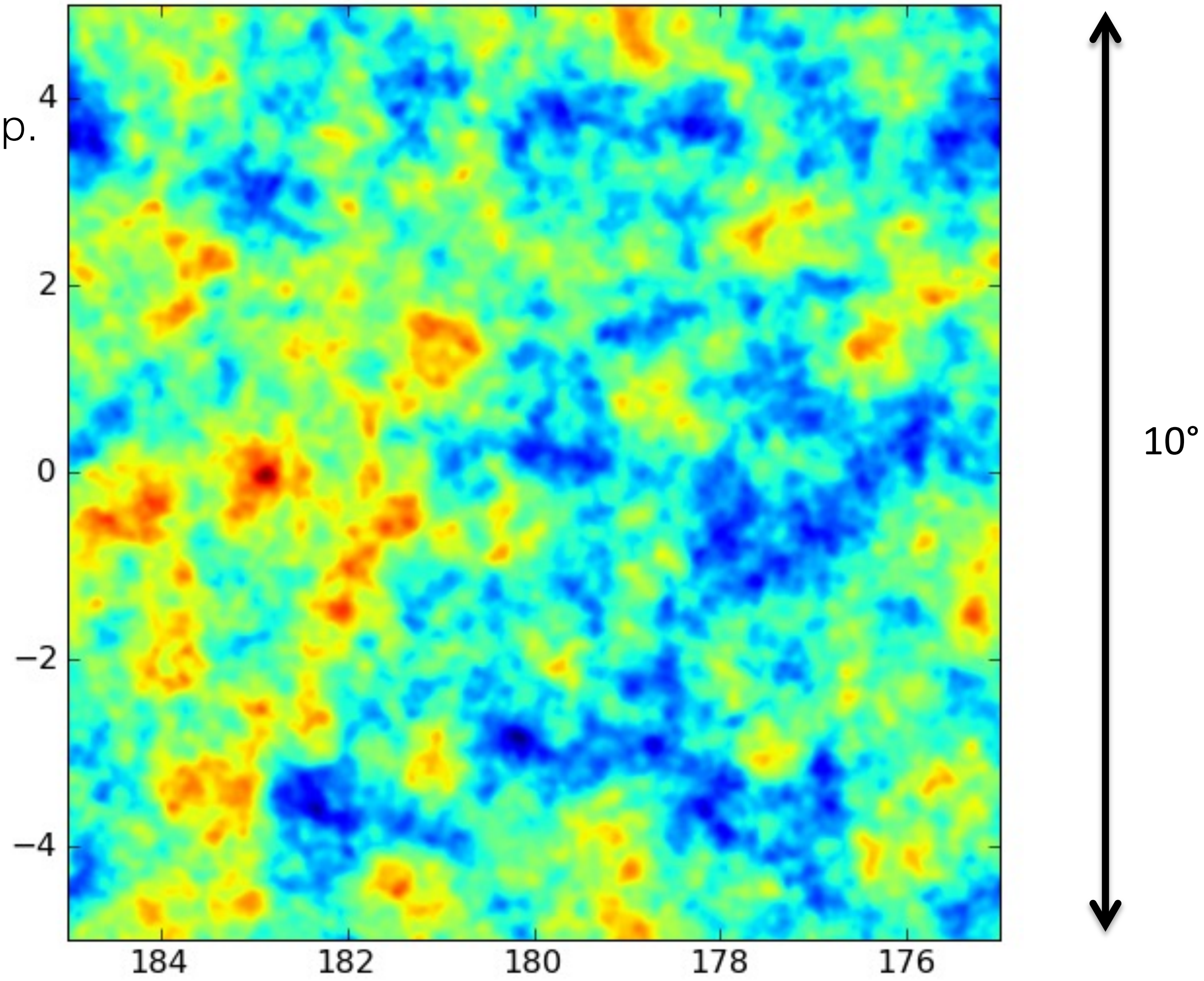


Unlensed CMB

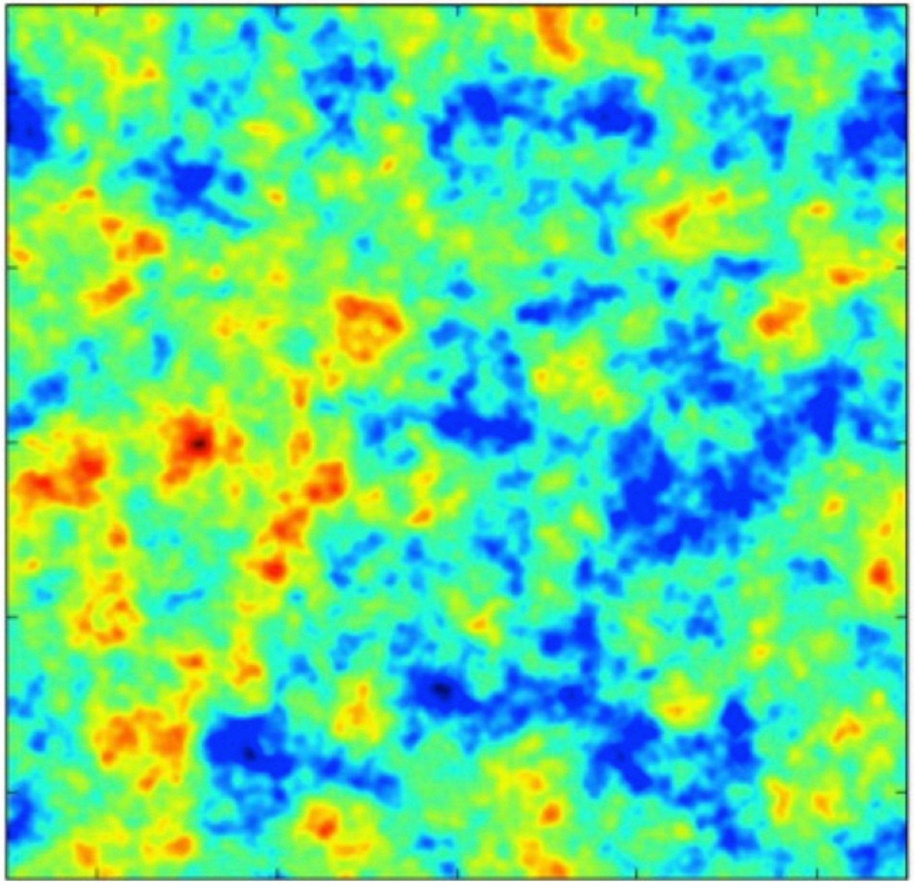


Lensed CMB

CMB Temp.



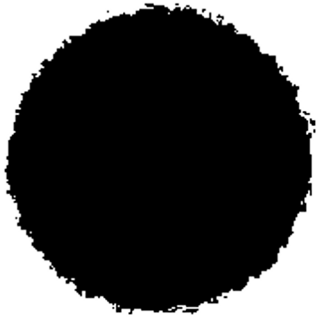
CMB Lensing: An Approximate Picture



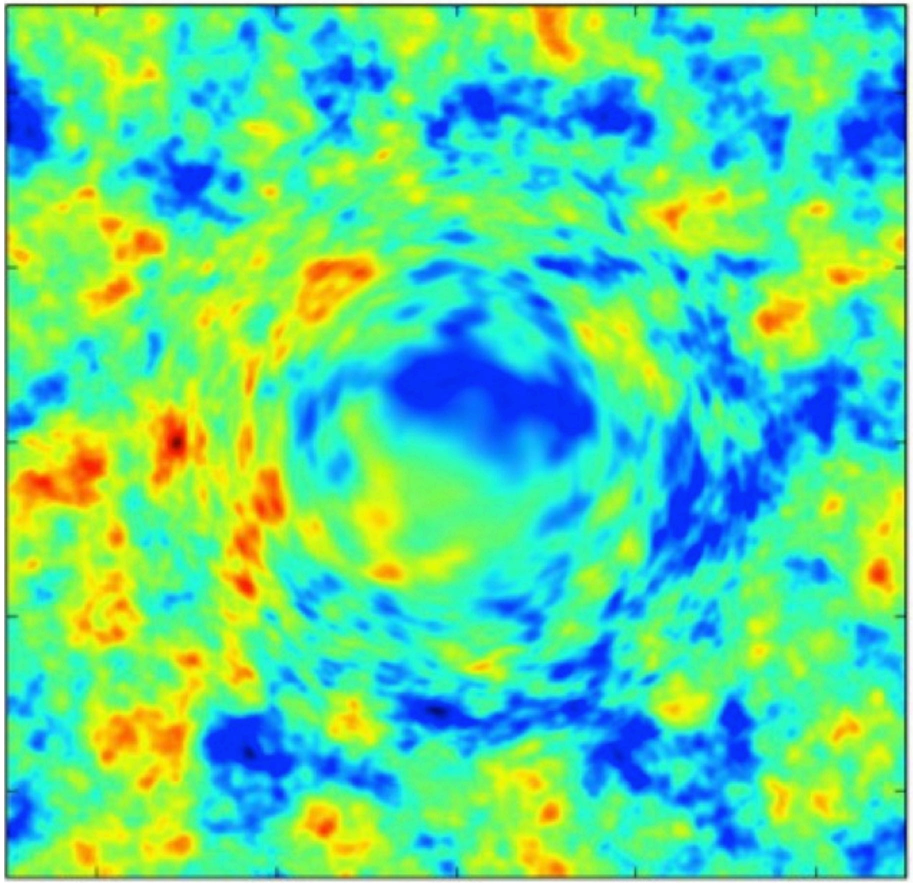
- Original, un-lensed, CMB fluctuations. Very well understood; fluctuations have same stats in all directions (stat. isotropic)

CMB Lensing: An Approximate Picture

- Clump of dark matter in front…



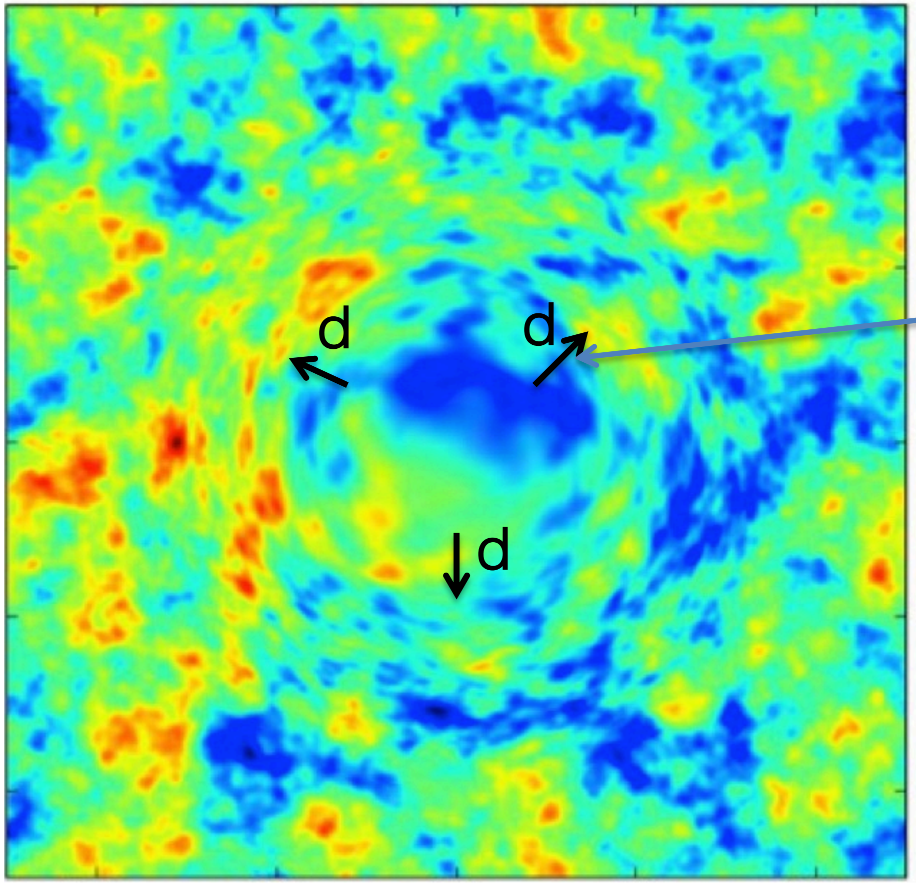
CMB Lensing: An Approximate Picture



- Dark matter causes local lensing magnification of CMB fluctuations

CMB Lensing: An Approximate Picture

$$T^{lensed}(\hat{\mathbf{n}}) = T^0(\hat{\mathbf{n}} + \mathbf{d})$$

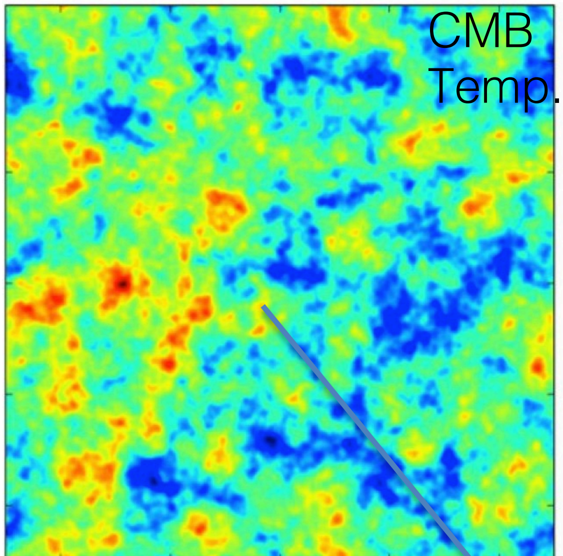


described by **lensing deflection field: d**

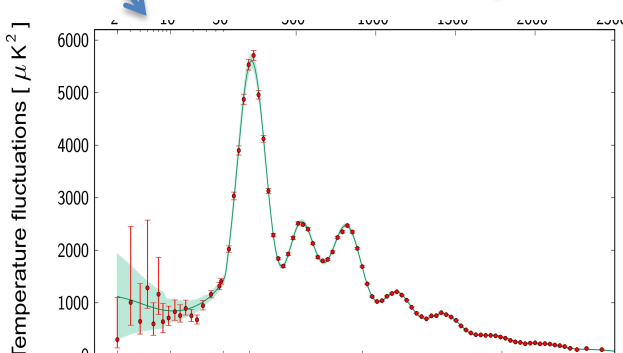
(very small: here exaggerated by x ~100, actually a few arcmins)

- Dark matter causes local lensing magnification of CMB fluctuations

CMB Lensing Measurement: An Approximate Picture

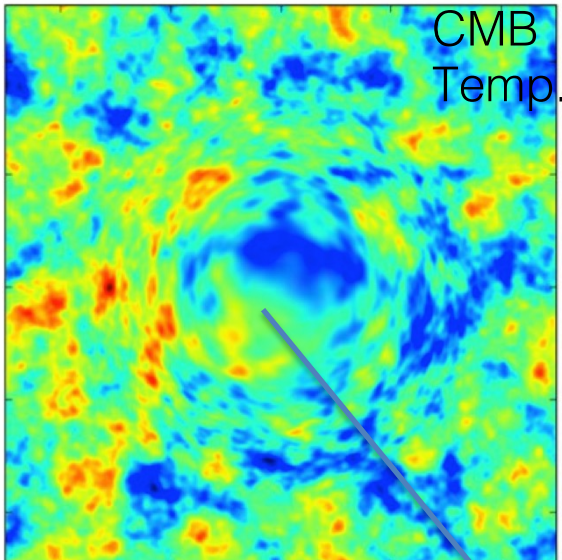


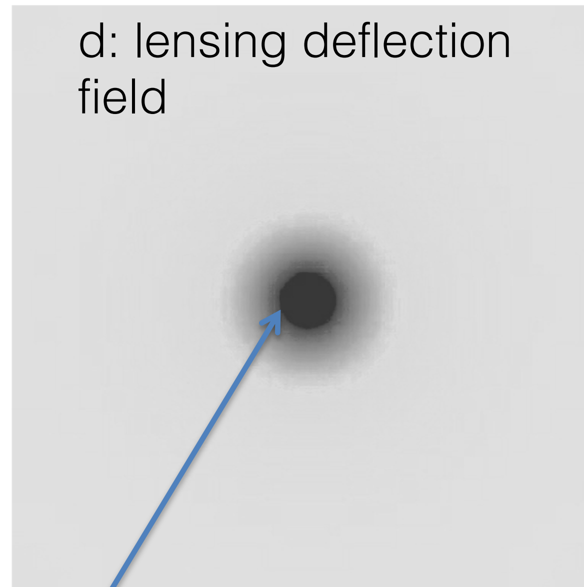
d: lensing deflection field

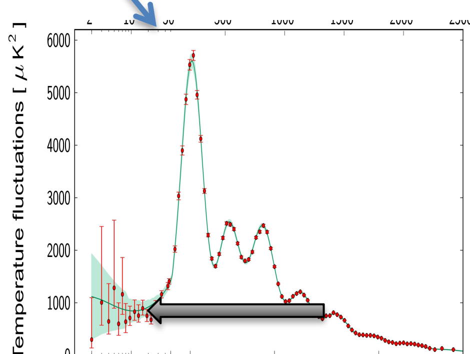


Average CMB power spectrum

CMB Lensing Measurement: An Approximate Picture







shift to larger angular scales

Local CMB power spectrum: Infer magnification and lensing from its "shifting"

Aside: Lensing Reconstruction Details

- From statistical isotropy (of 2-point correlation function),

$$\langle T^0(\mathbf{l}) T^{0*}(\mathbf{l} - \mathbf{L}) \rangle = 0$$

T: temperature (Fourier mode)
l: wavenumber

- **Lensing breaks isotropy** => new correlations

$$\langle T(\mathbf{l}) T^{*}(\mathbf{l} - \mathbf{L}) \rangle \sim d(\mathbf{L})$$

- So: measure lensing by looking for these new lensing correlations in the CMB two-point function

$$\hat{d}(\mathbf{L}) \sim \int d^2\mathbf{l}\, T(\mathbf{l}) T^{*}(\mathbf{l} - \mathbf{L})$$

What Does CMB Lensing Tell Us?

- Lensing probes the projected total mass density in each direction (of which most is dark matter) from z~0.5-5

geometric projection kernel

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

lensing deflection

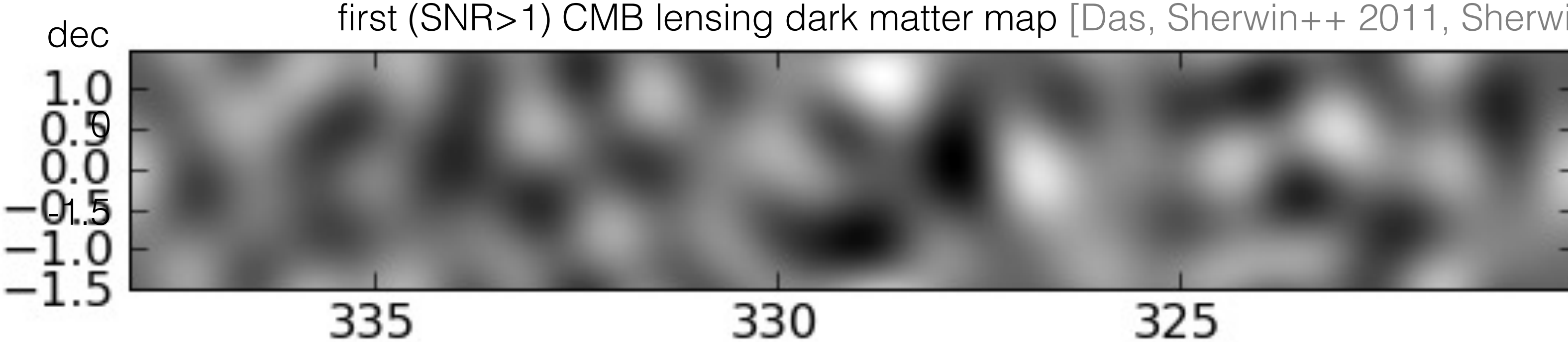
radial distance

δ : fractional mass overdensity

$$\delta = (\rho - \bar{\rho})/\bar{\rho}$$

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

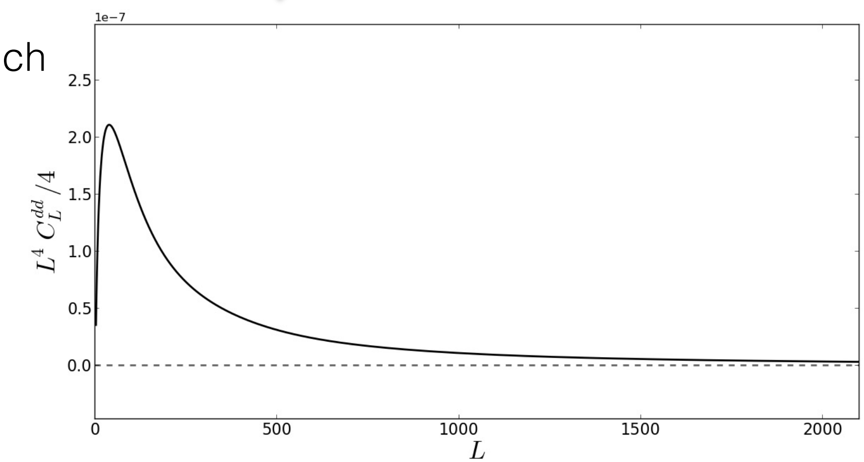
first (SNR>1) CMB lensing dark matter map [Das, Sherwin++ 2011, Sherwin++ 2011]



white = higher density

↓

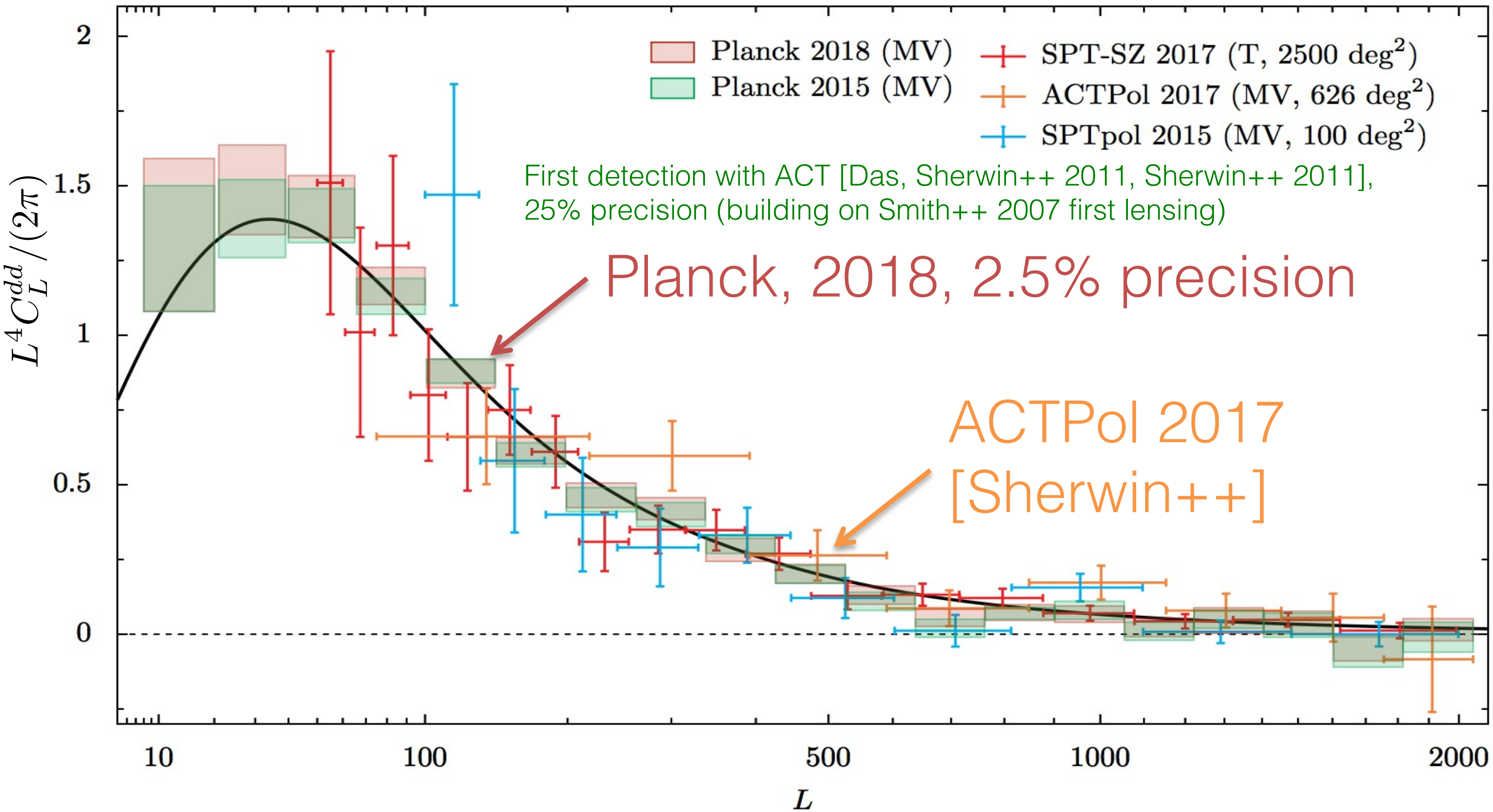
Y axis: "How much lensing …."



X axis: "for a lens of this angular scale?"

Describe lensing maps statistically with lensing power spectrum

CMB Lensing Power Spectra: From First Measurements…to a Precise Probe

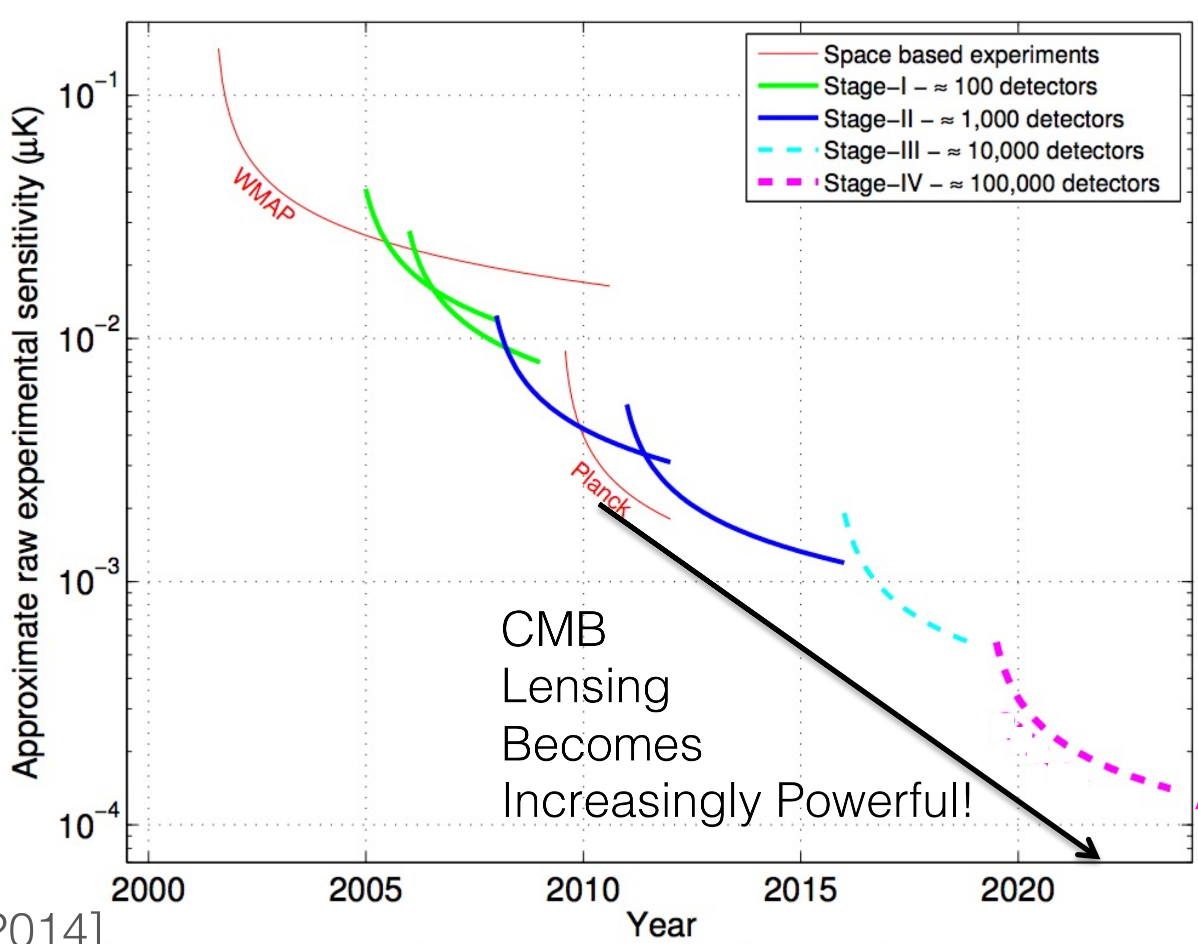


- Rapid progress – but only just beginning!

Rapid Progress:
New Ground-Based CMB Experiments

CMB
Experiment
Noise
Level

^4



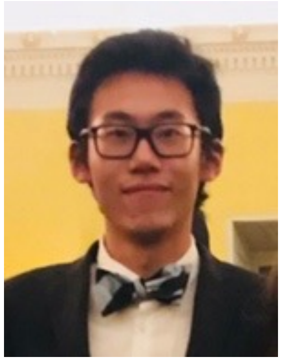
AdvACT

+ Simons
Observatory…

[Abazajian++ 2014]

Outline

- Introduction: CMB lensing, a powerful probe of σ_8 (tension?) and neutrino mass
- AdvACT CMB lensing maps and spectra: progress and expected constraints



With:

Frank Qu

Mat Madhavacheril

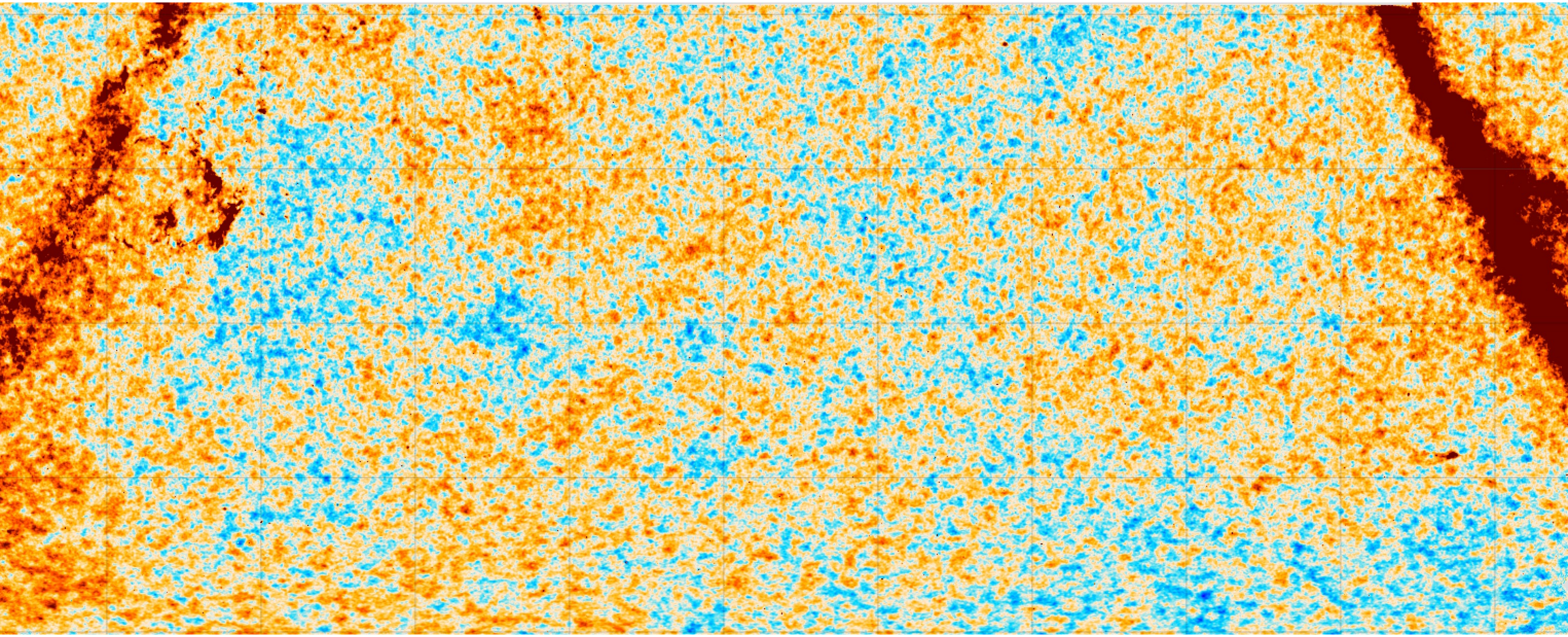
Niall MacCrann

Advanced Atacama Cosmology Telescope (AdvACT)

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

AdvACT: new, state of the art CMB and lensing maps!

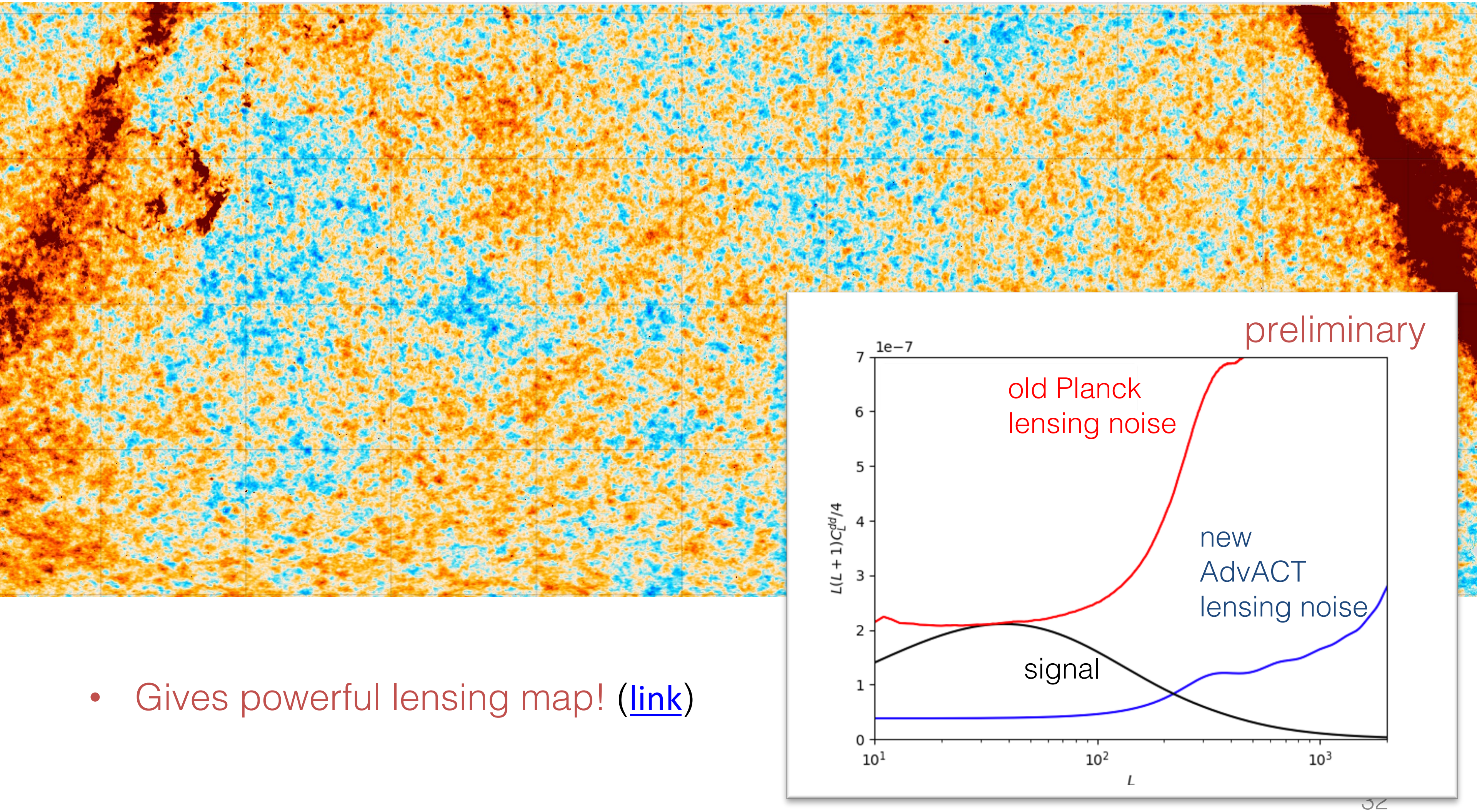
AdvACT CMB map



- New AdvACT polarized data through 2020: low noise (15uK’) CMB maps (link) on 20000 deg^2 at high resolution.

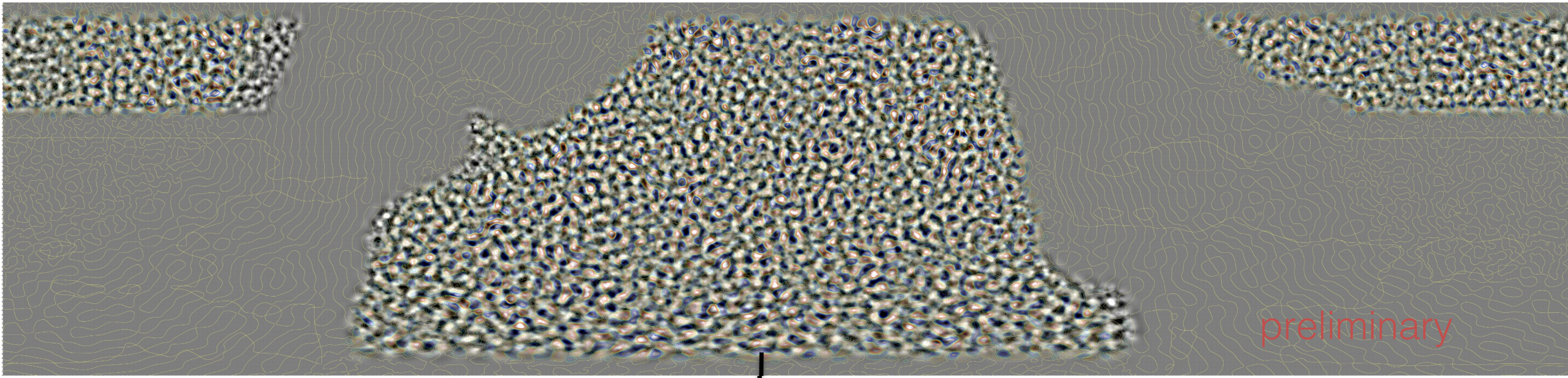
AdvACT: new, state of the art CMB and lensing maps!

AdvACT CMB map



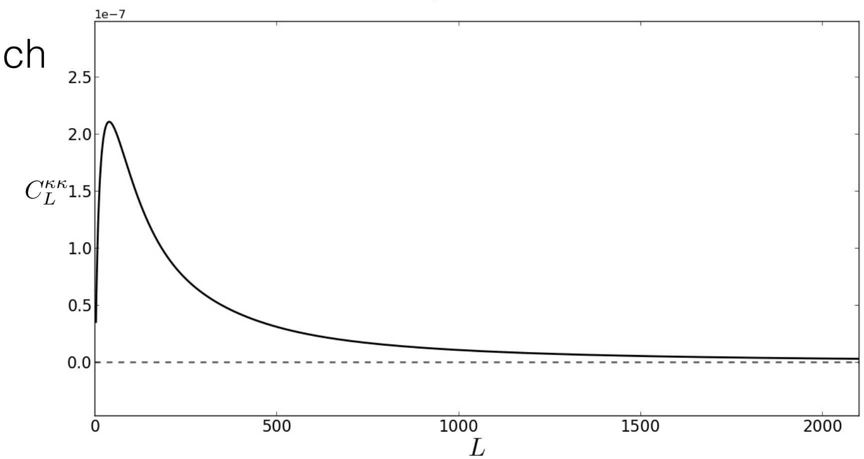
- Gives powerful lensing map! ([link]())

New Measurements of the CMB Lensing Power Spectrum C_L^{dd}



$$C_L^{dd} \sim \langle \hat{d}_L^* \hat{d}_L \rangle - \text{biases} \sim \langle TTTT \rangle - \langle TT \rangle \langle TT \rangle_{gauss} - \cdots$$

Y axis: "How much lensing ...."



X axis: "for a lens of this angular scale?"

[Qu++ in prep.]

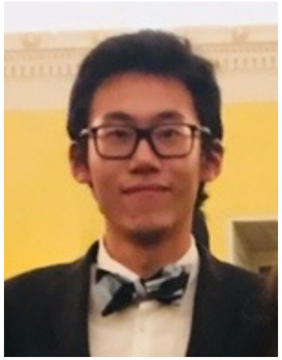
Null and systematic test suite

Expecting high precision so need to be careful. Although clean, null tests and systematics checks needed!

Main worries: noise sim issues, foregrounds.

Frequencies consistent?	Temp./Polarization consistent?
Sky regions consistent?	Scales consistent?
Arrays consistent?	Curl deflection null?

… (~100 tests)

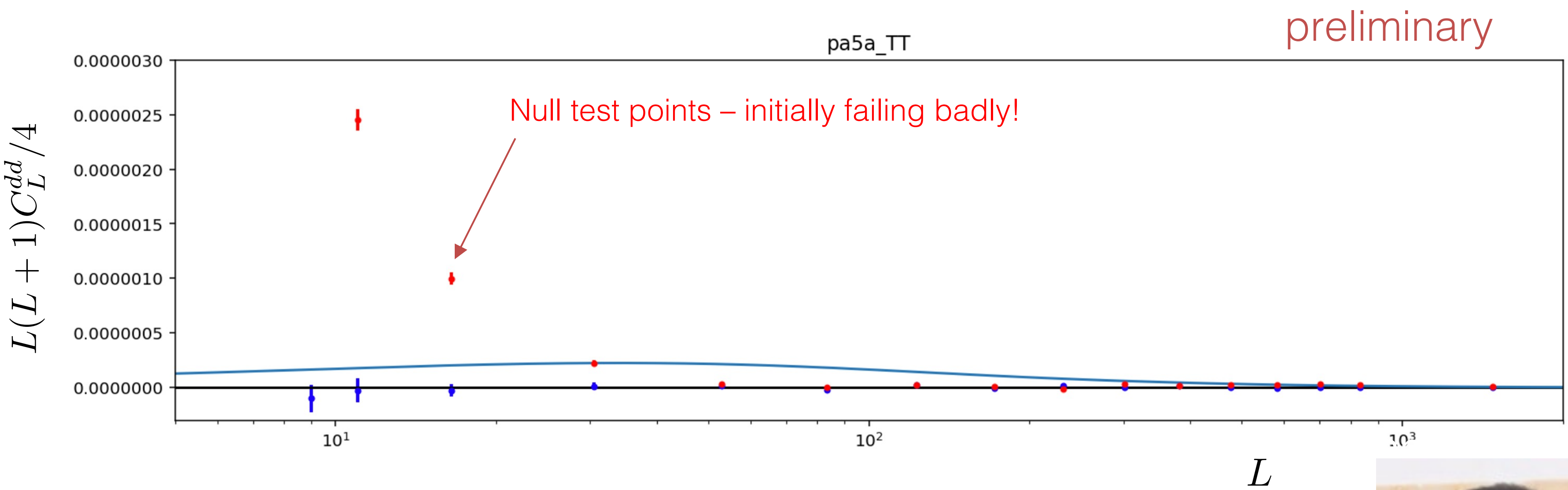


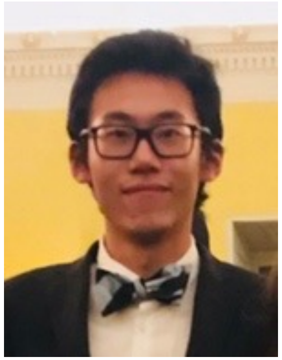
Frank Qu

[Qu++ in prep.]

Null test problems…

- Problem: getting biased results from even basic null with data noise, despite advanced methods.





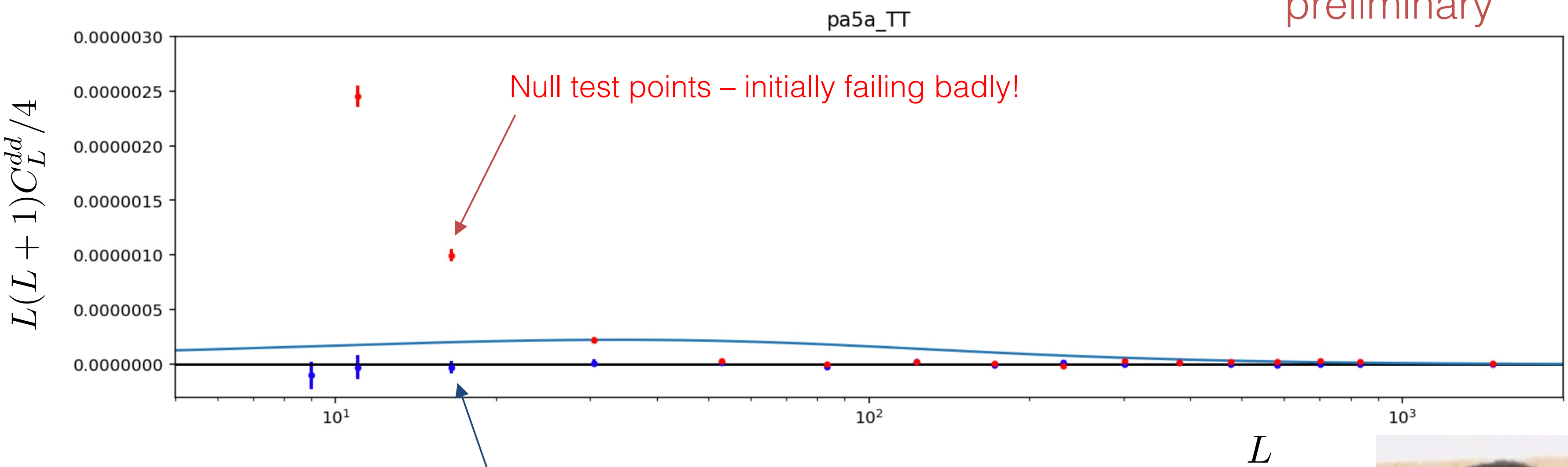
Frank
Qu

[Qu++ in prep.]

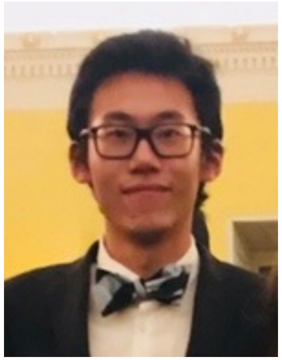
…and solutions

- Solution: new cross-estimator method. Divide data into independent splits, use only different crosses (combinatorics non-trivial). $C_L^{dd} \sim \langle T_1 T_2 T_3 T_4 \rangle$

preliminary



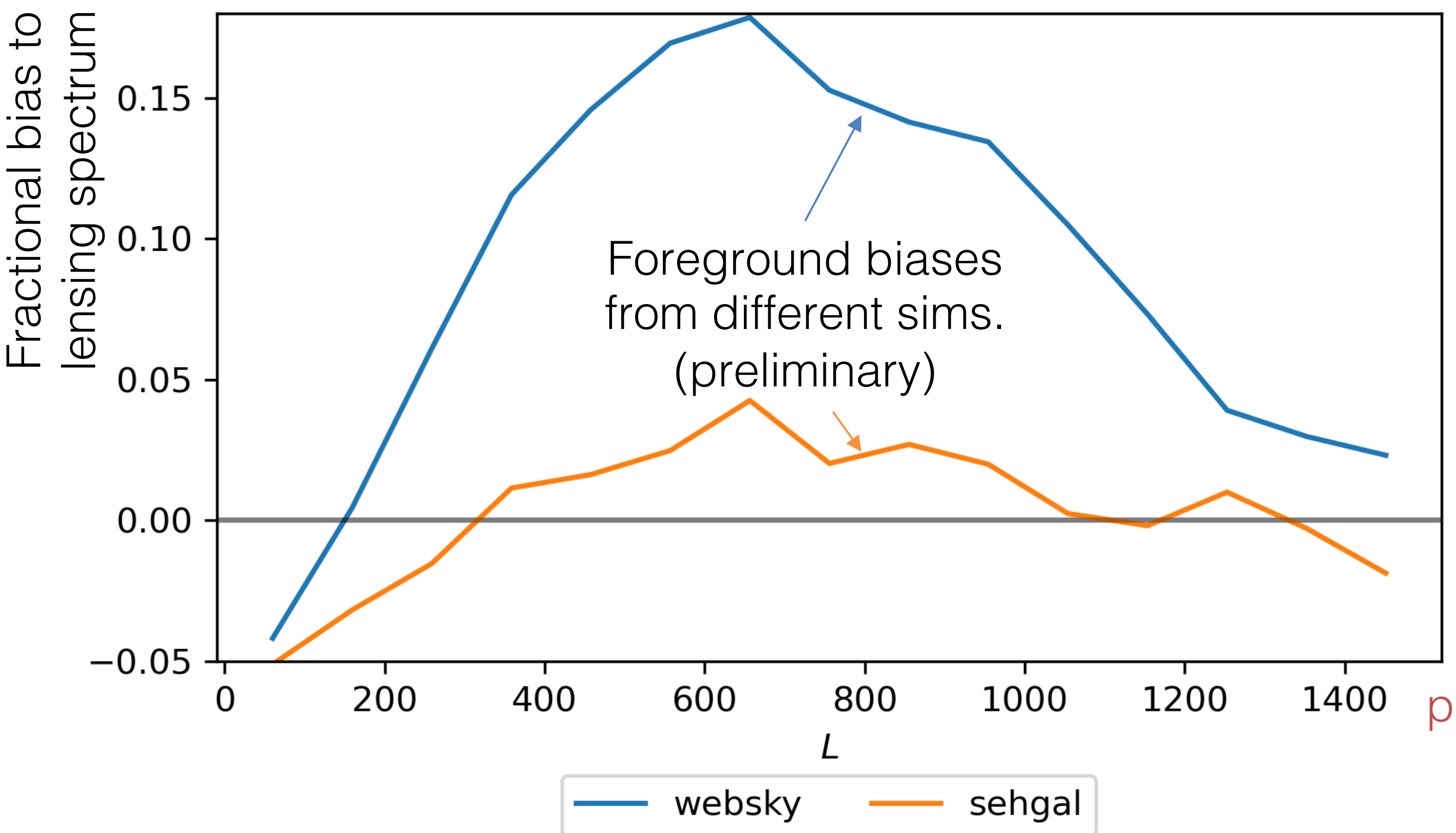
[Madhavacheril, Smith, Sherwin, Naess 20]



Frank Qu

- Tests now all looking good!

Key challenge: foreground mitigation

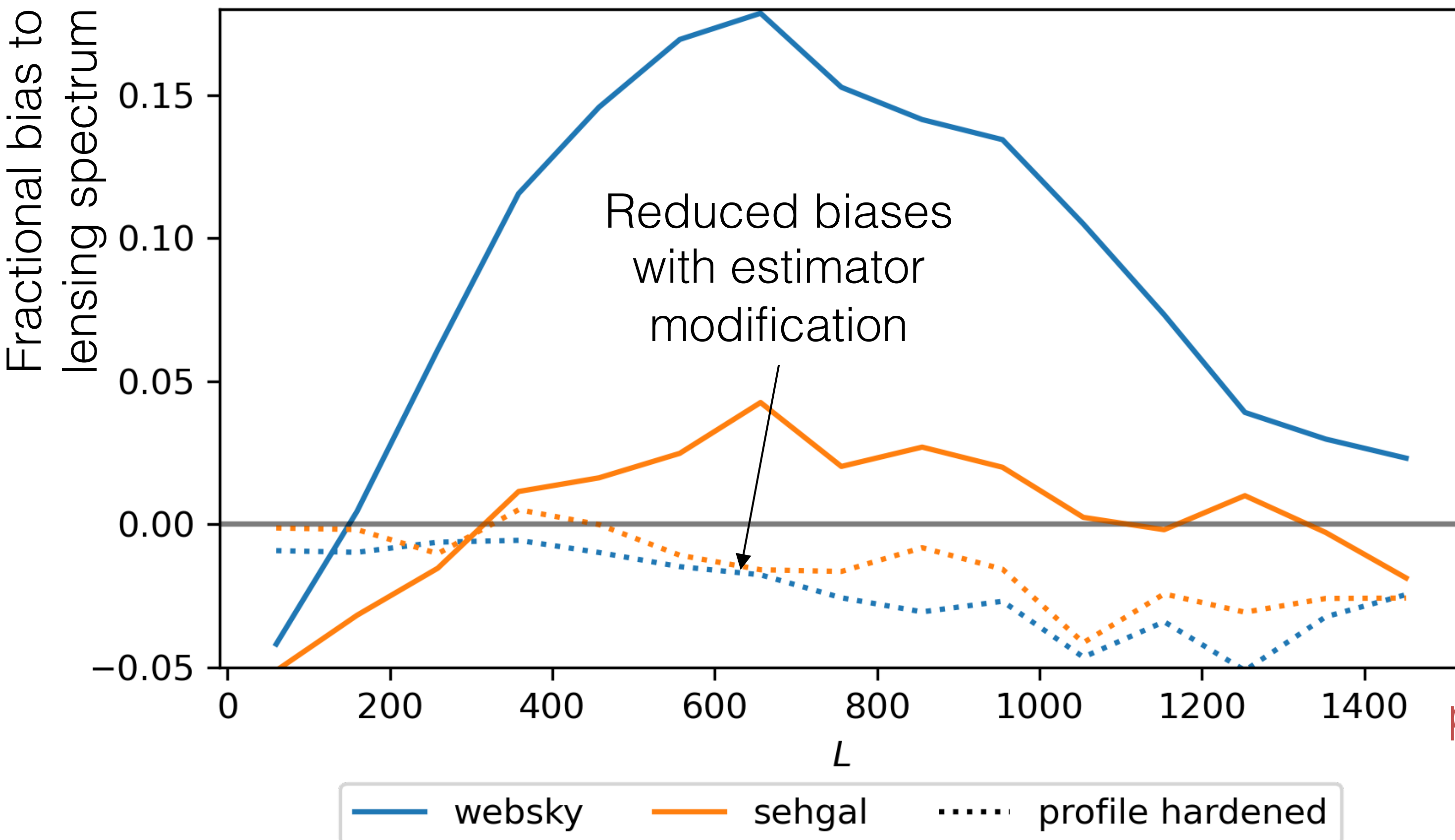


Niall MacCrann

preliminary

- Foreground biases from galaxy emission and cluster signals potential issues.

Key challenge: foreground mitigation

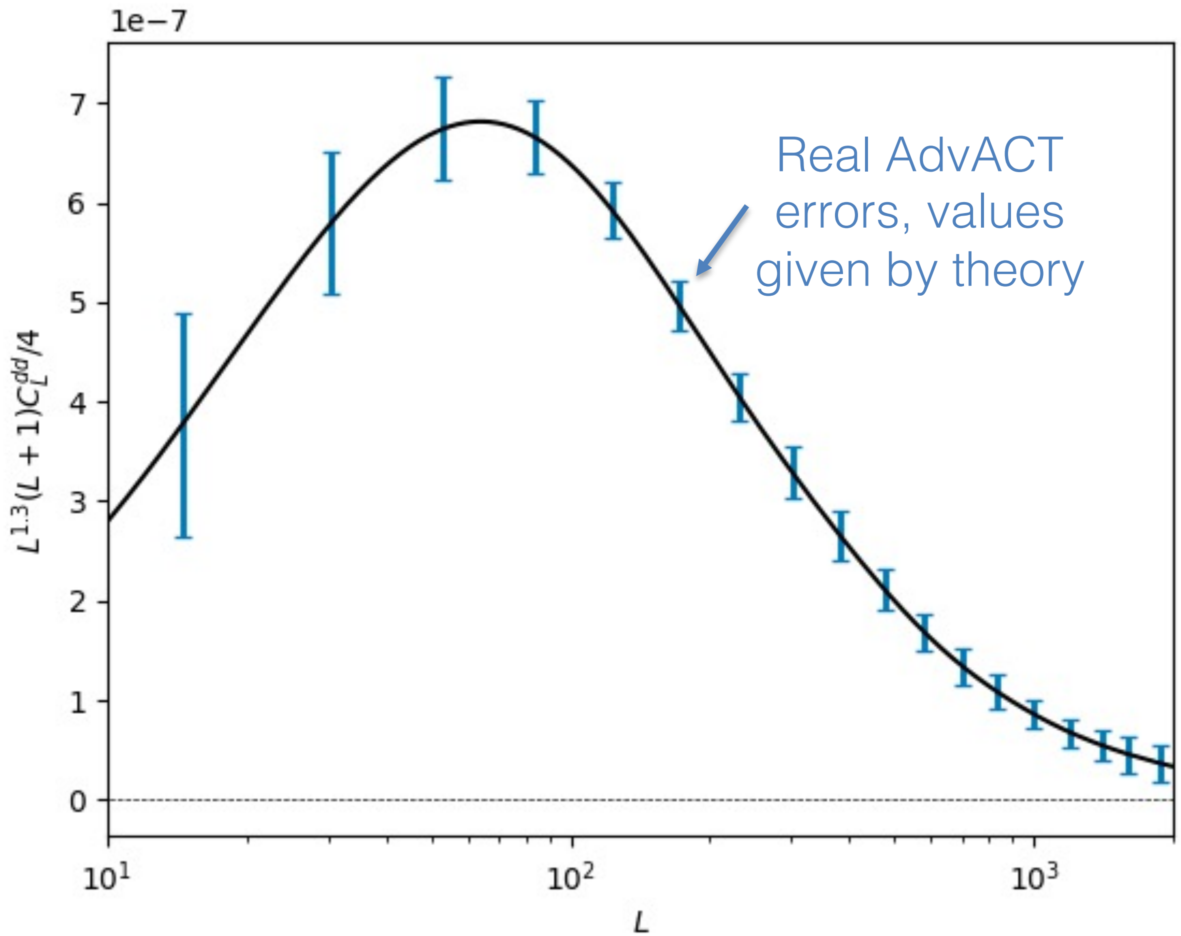


preliminary

Niall MacCrann

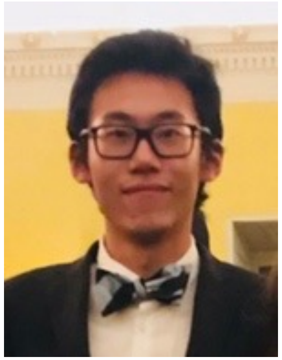
- Mitigating these with two different methods (estimator modification and multifrequency cleaning) – now negligible! [Darwish++21]

New AdvACT lensing power spectrum errors



preliminary

Frank
Qu

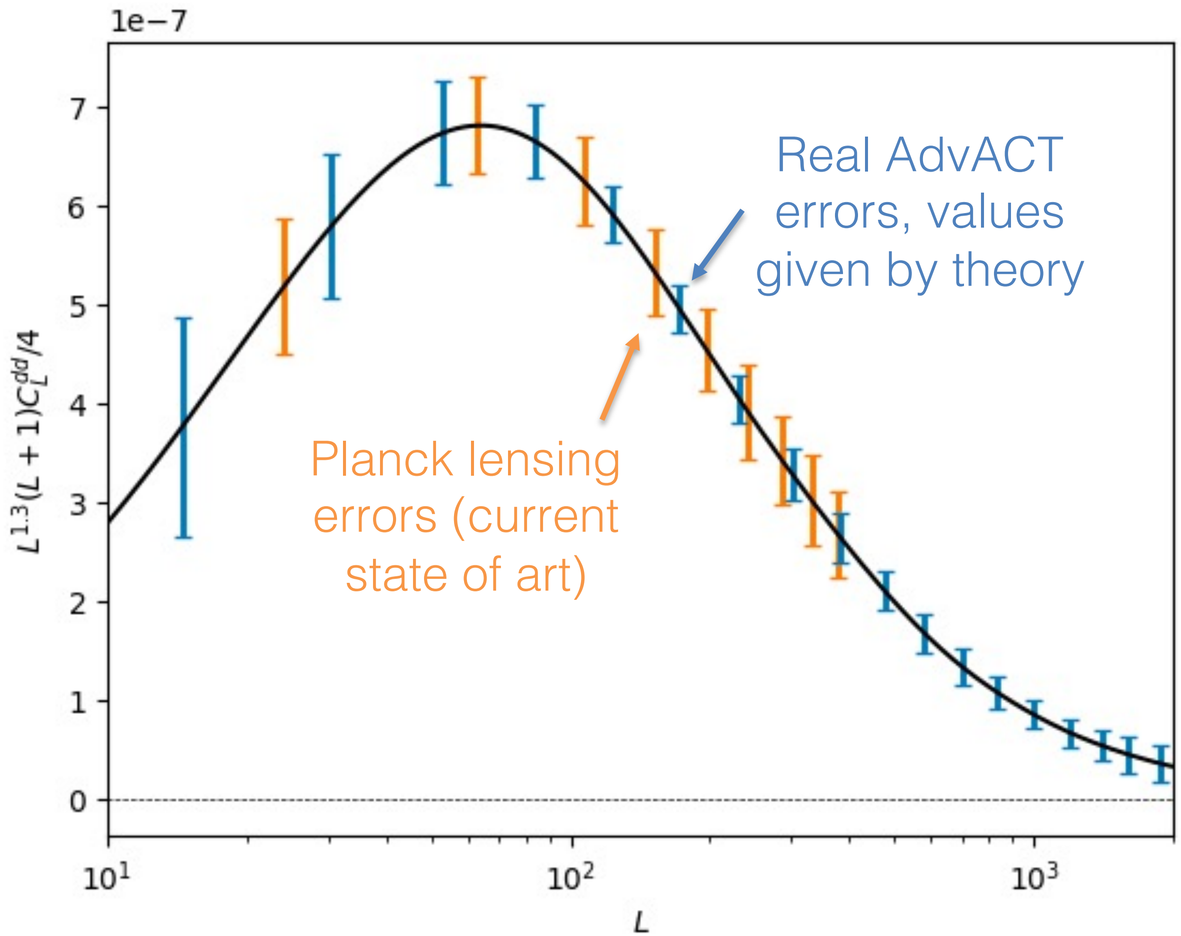


+ Mat Madhavacheril,
Niall MacCrann

- Expect SNR ~50 (state of the art)

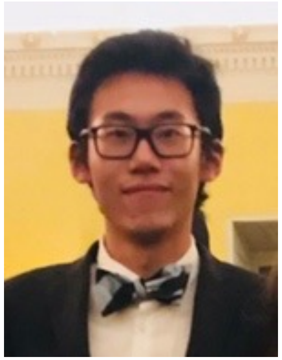
[Qu++ in prep.]

New AdvACT lensing power spectrum errors



preliminary

Frank Qu

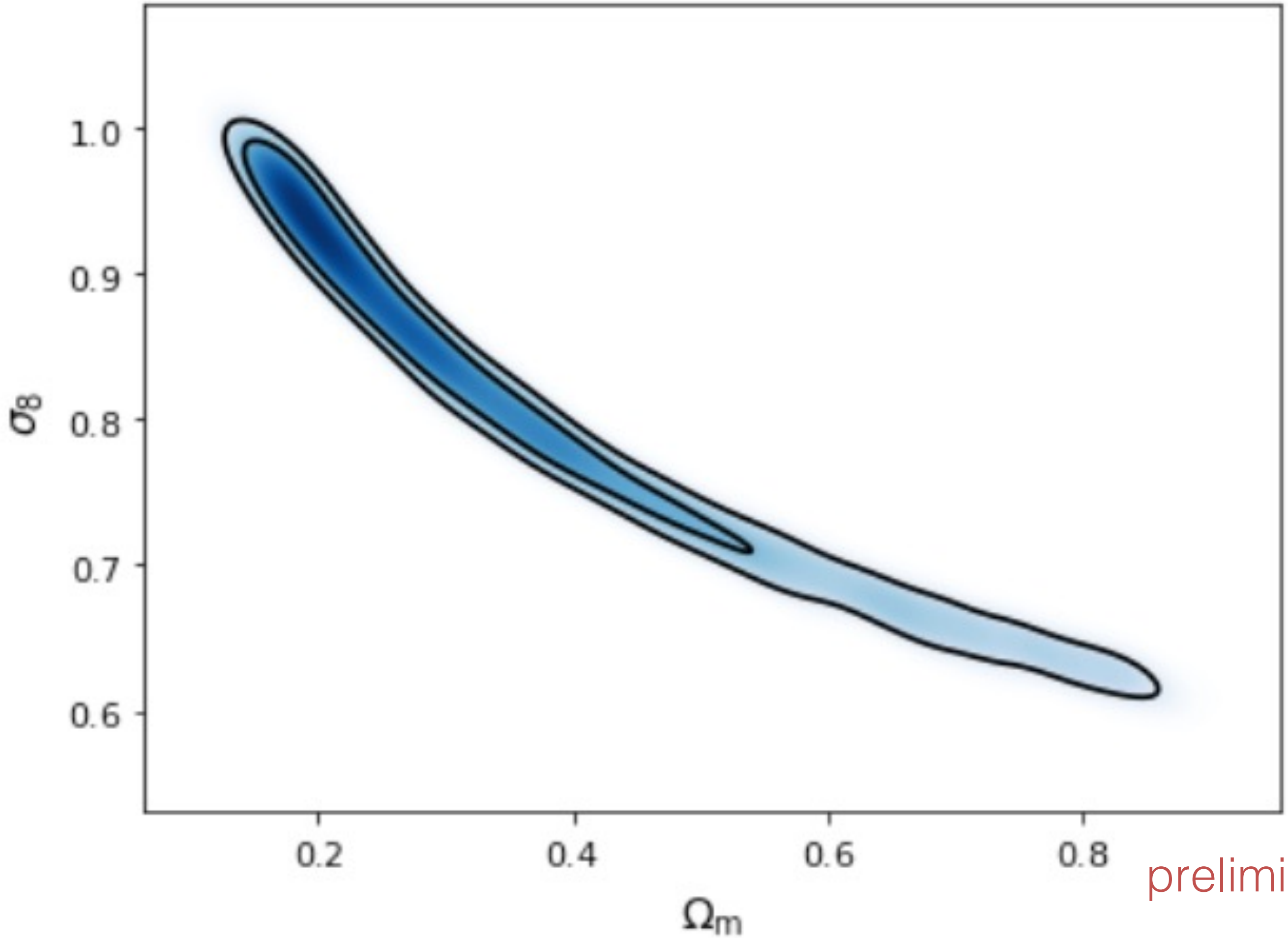


+ Mat Madhavacheril, Niall MacCrann

- Expect SNR ~50 (state of the art)

[Qu++ in prep.]

AdvACT lensing power spectra: Expected parameter constraints



preliminary

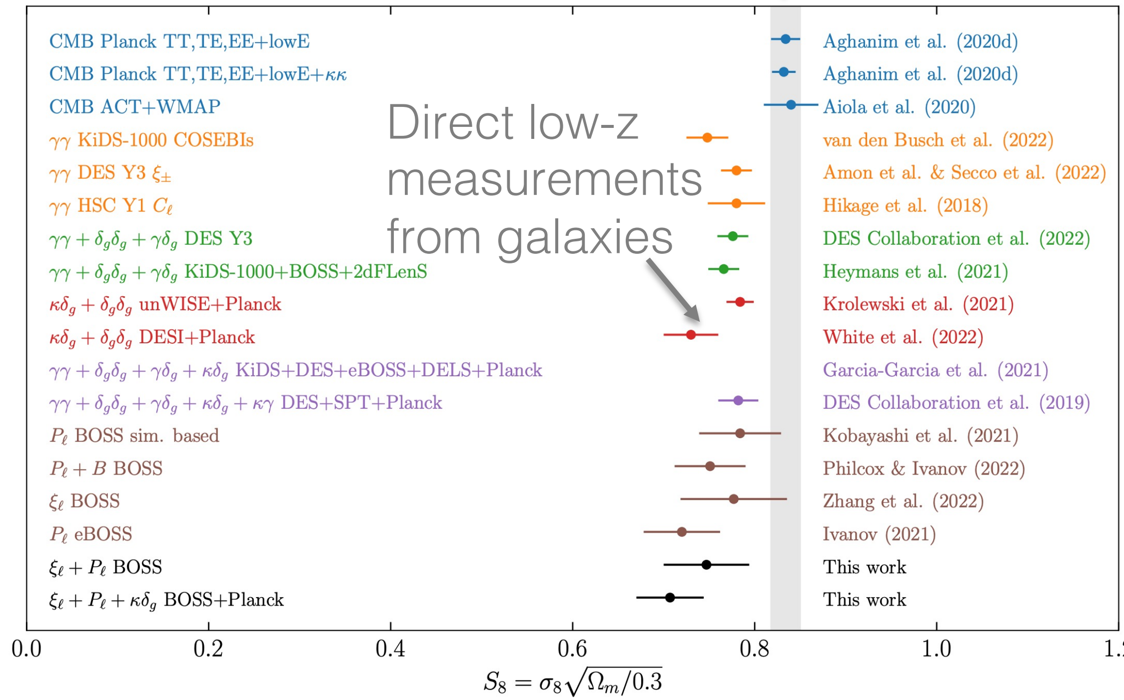
- Expected constraints: $\sim\sigma_8\,\Omega_m^{0.25}$ to $\pm$ 0.013
  [1.5 x beyond CMB lensing state of art]

Exciting applications: test claims of σ_8 tension, neutrino mass…

- Expected constraints: $\sigma_8\ \Omega_m^{0.25}$ to ± 0.013 [1.5 x beyond CMB lensing state of art]

CMB extrapolation

[Chen++ 2022]



Our error bar size

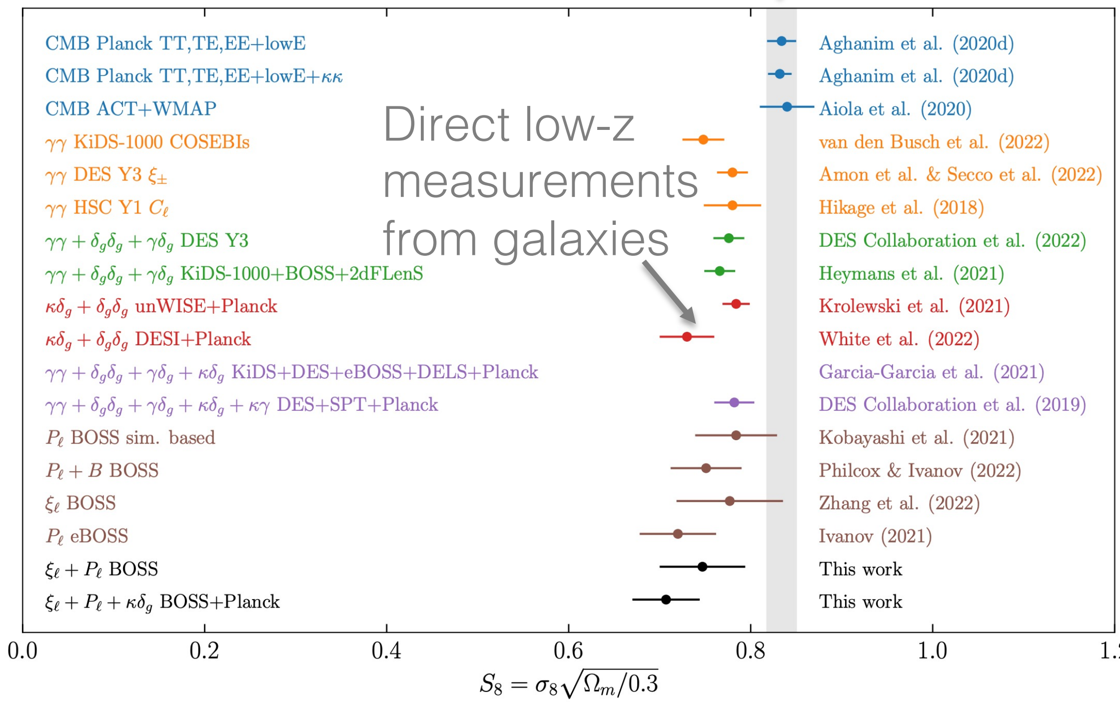
- Possible clarification of σ_8 tension very soon with new ACT lensing results!

Exciting applications: test claims of σ_8 tension, neutrino mass…

- Expected constraints: $\sigma_8 \, \Omega_m^{0.25}$ to ± 0.013
  [1.5 x beyond CMB lensing state of art]

CMB extrapolation

[Chen++ 2022]

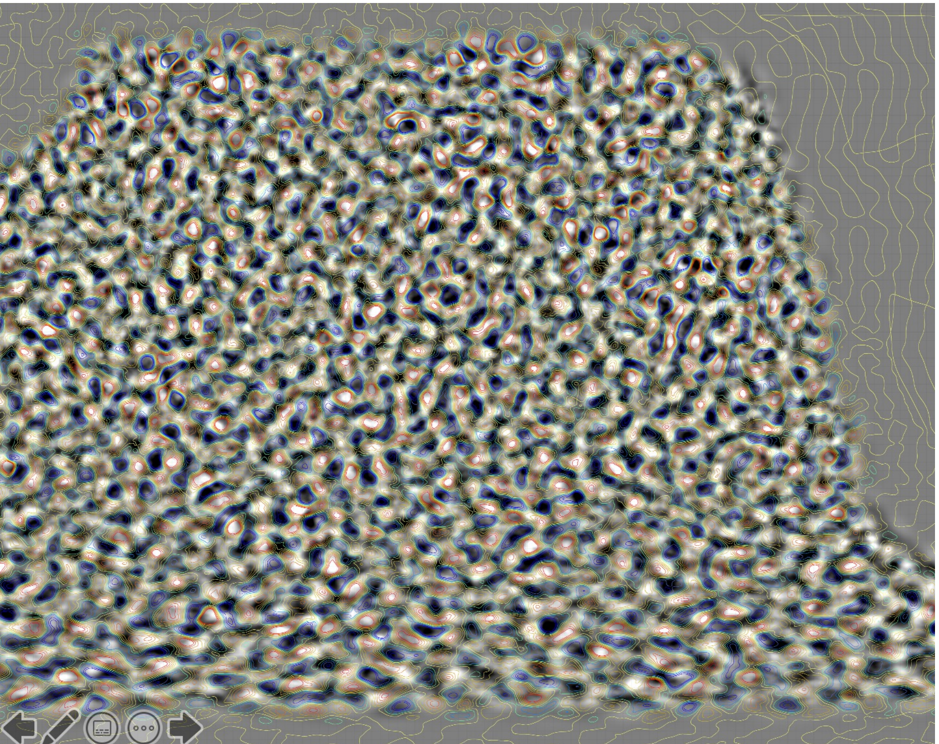


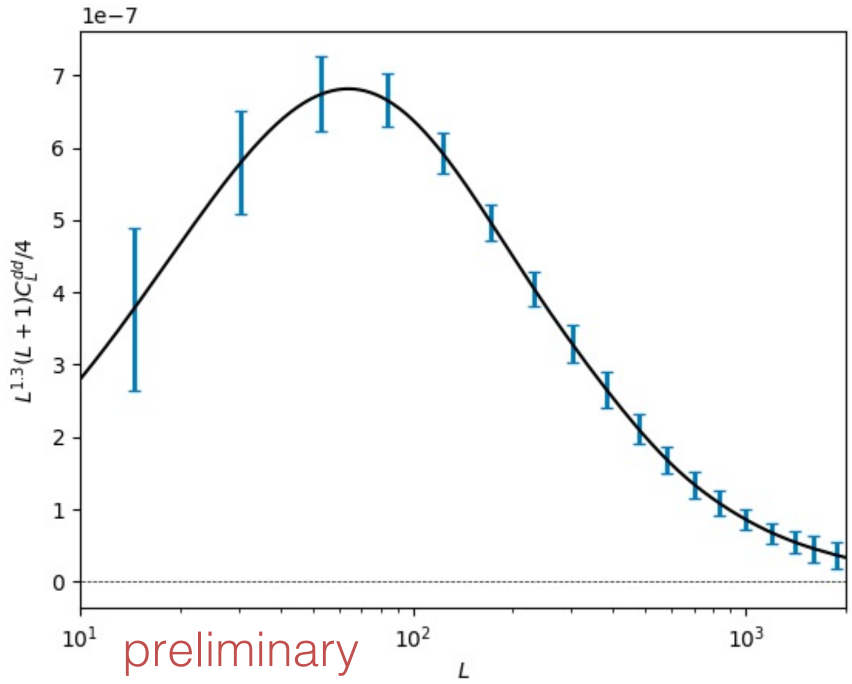
Our error bar size

- And: new, tightest (?) constraints on neutrino mass of 70 meV (with BOSS BAO) or 40 meV (with DESI BAO.) C.f. minimum 60 meV!

Summary: AdvACT Lensing

- Amazing CMB data from AdvACT:
- Largest signal-dominated lensing mass map + lensing power spectrum with highest SNR to date…
- with potential to confirm (or not!) the S8 tension and place some of the best constraints on neutrino mass!





Backup Slides

Properties of Future / S4 CMB Lensing Maps

- Lensing maps probe matter density, projected over a wide redshift range peaking at z~2: