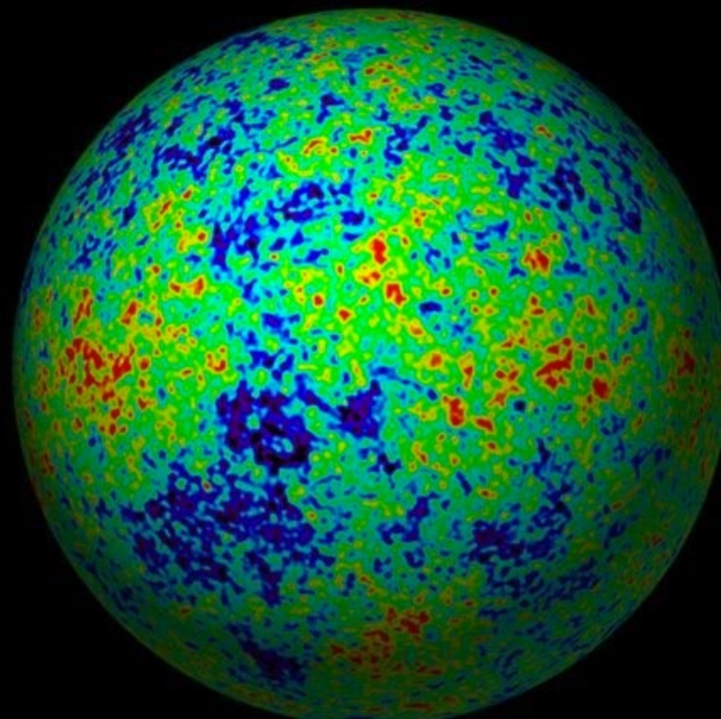
The Cosmic Microwave Background
Lecture 5: CMB Lensing



Blake Sherwin
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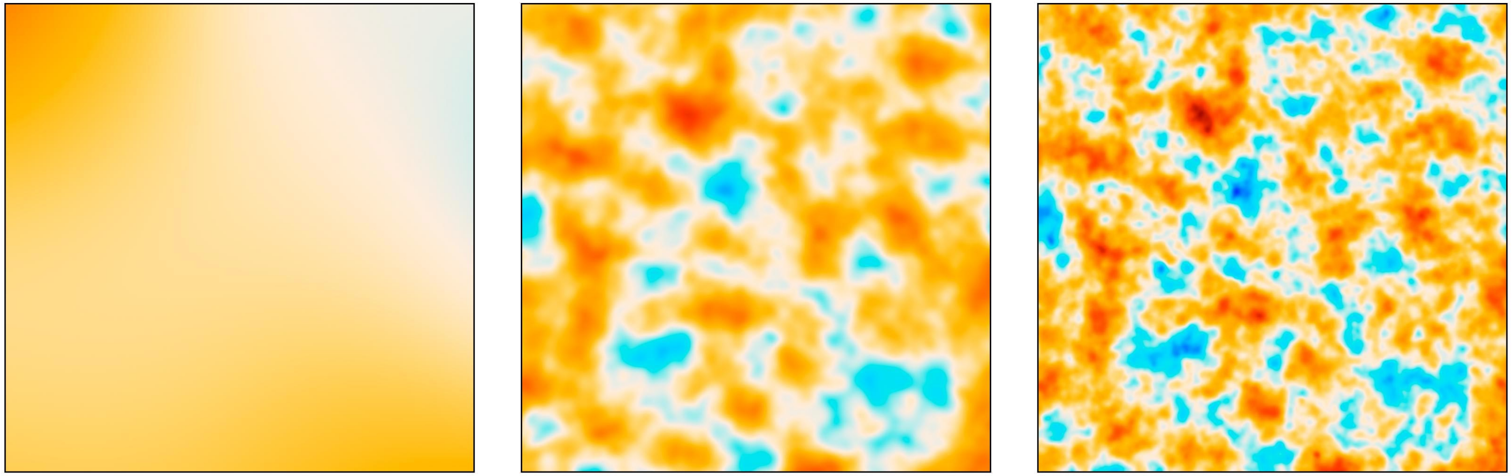
University of Cambridge

Outline

- CMB lensing basics
- Cosmology dependence
- CMB lensing measurement
- Effect on power spectra
- Delensing

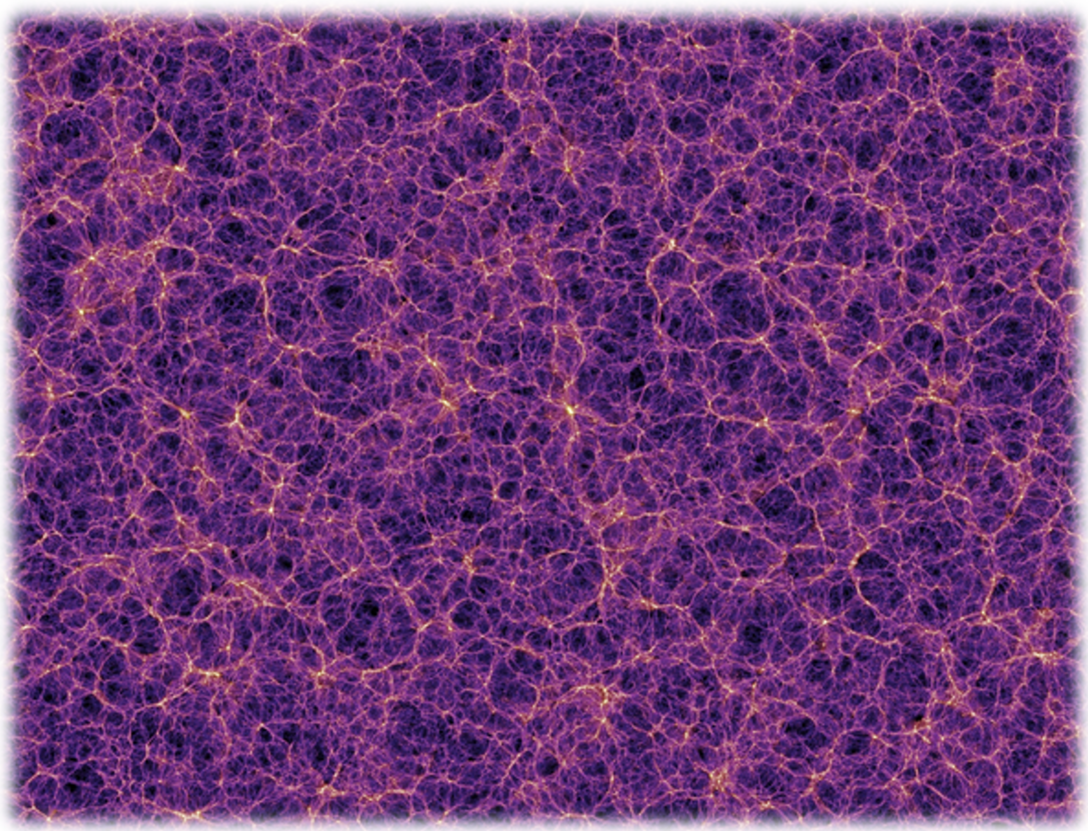


Large Scale Dark Matter Structure

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

What is the physics of inflation and the early universe?

What is dark energy?



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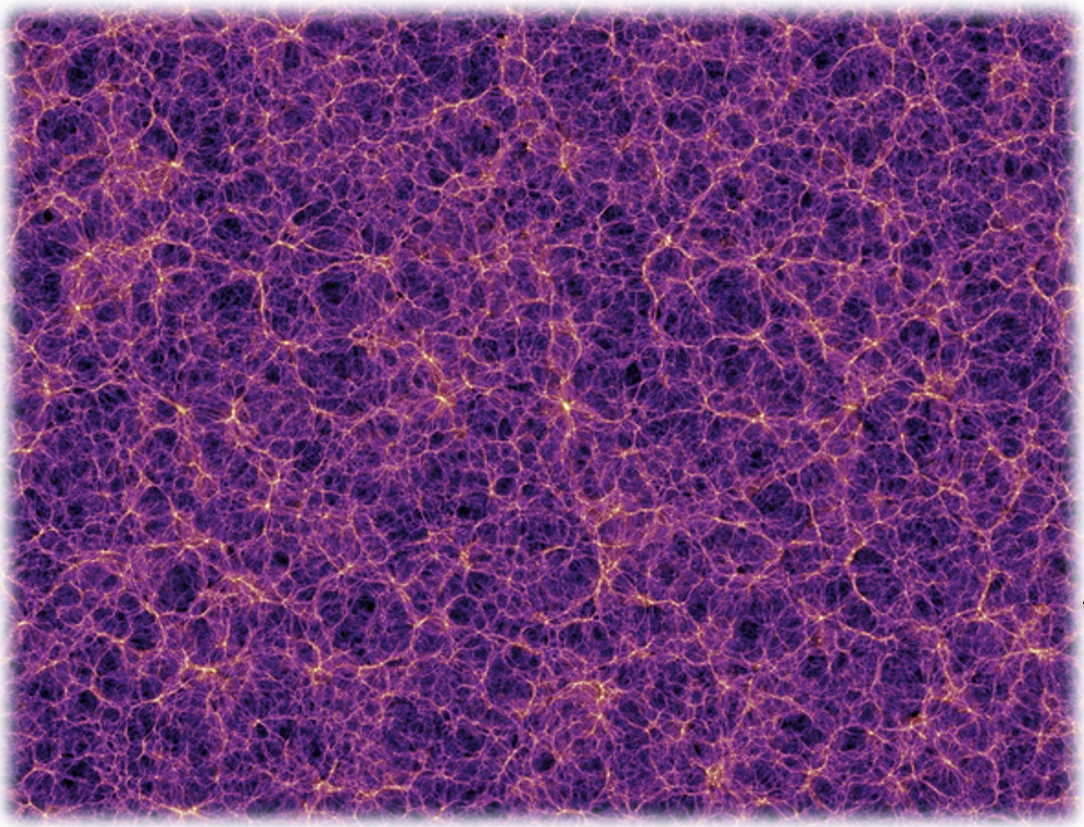
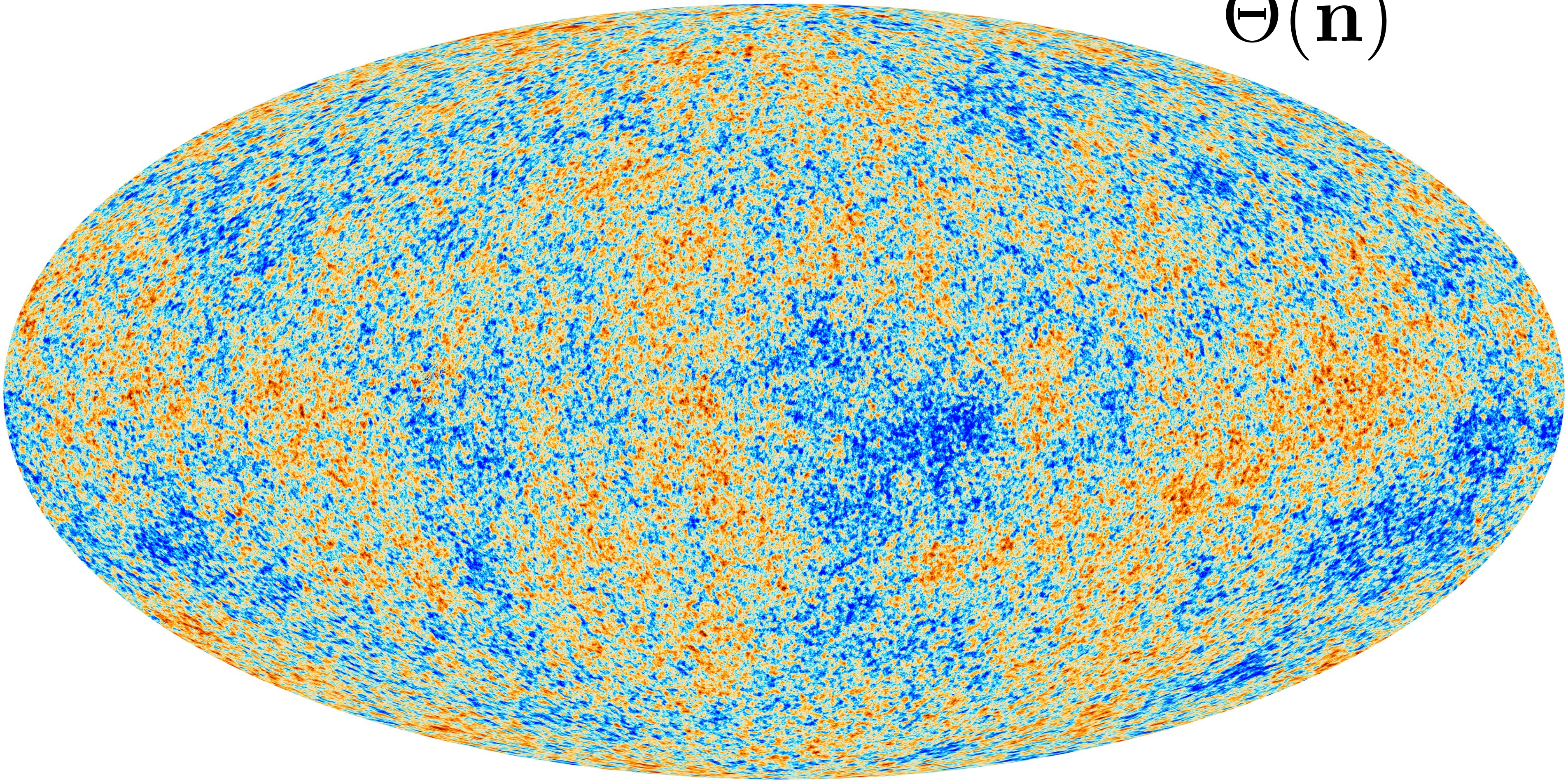


Is standard cosmology correct?

What are the properties / masses of neutrinos?

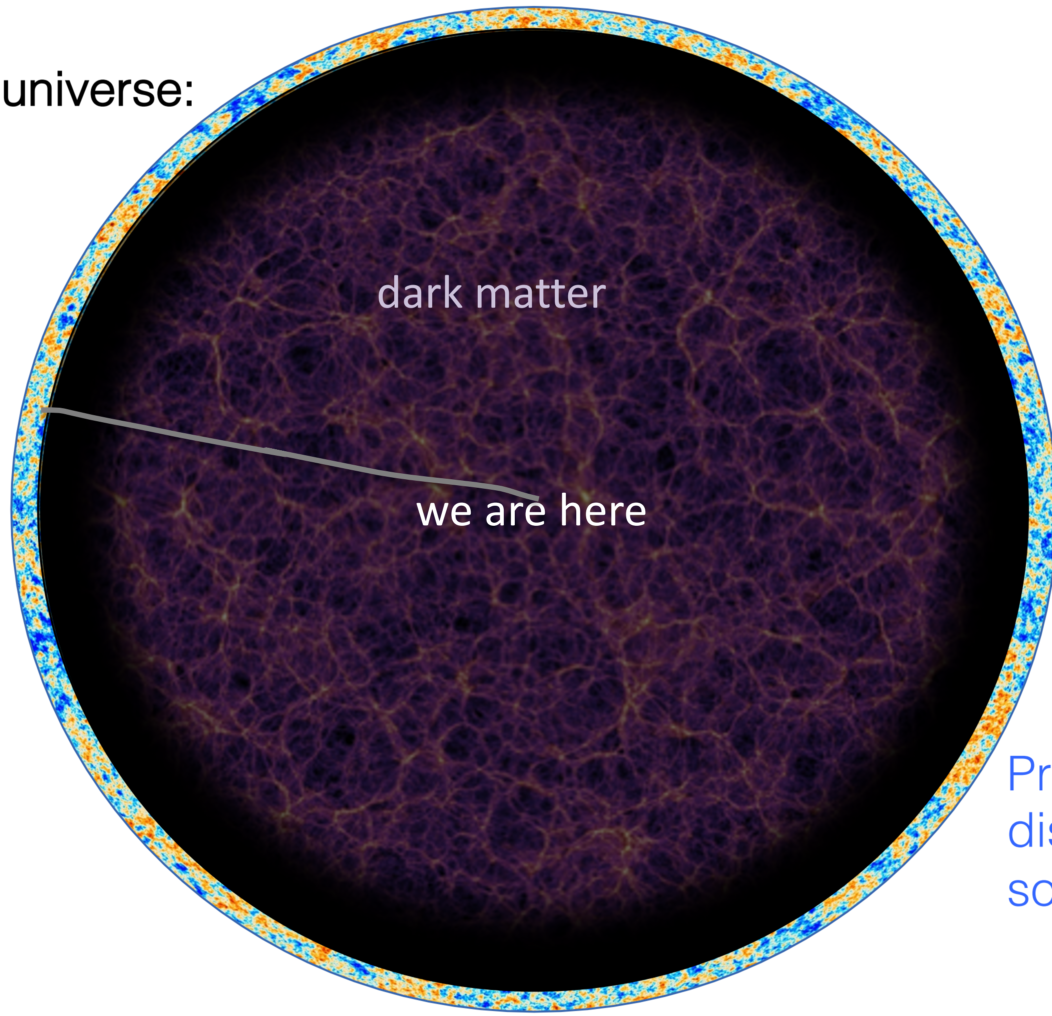
Source for Gravitational Lensing:
The Cosmic Microwave Background (CMB) Radiation

$\Theta(\hat{\mathbf{n}})$



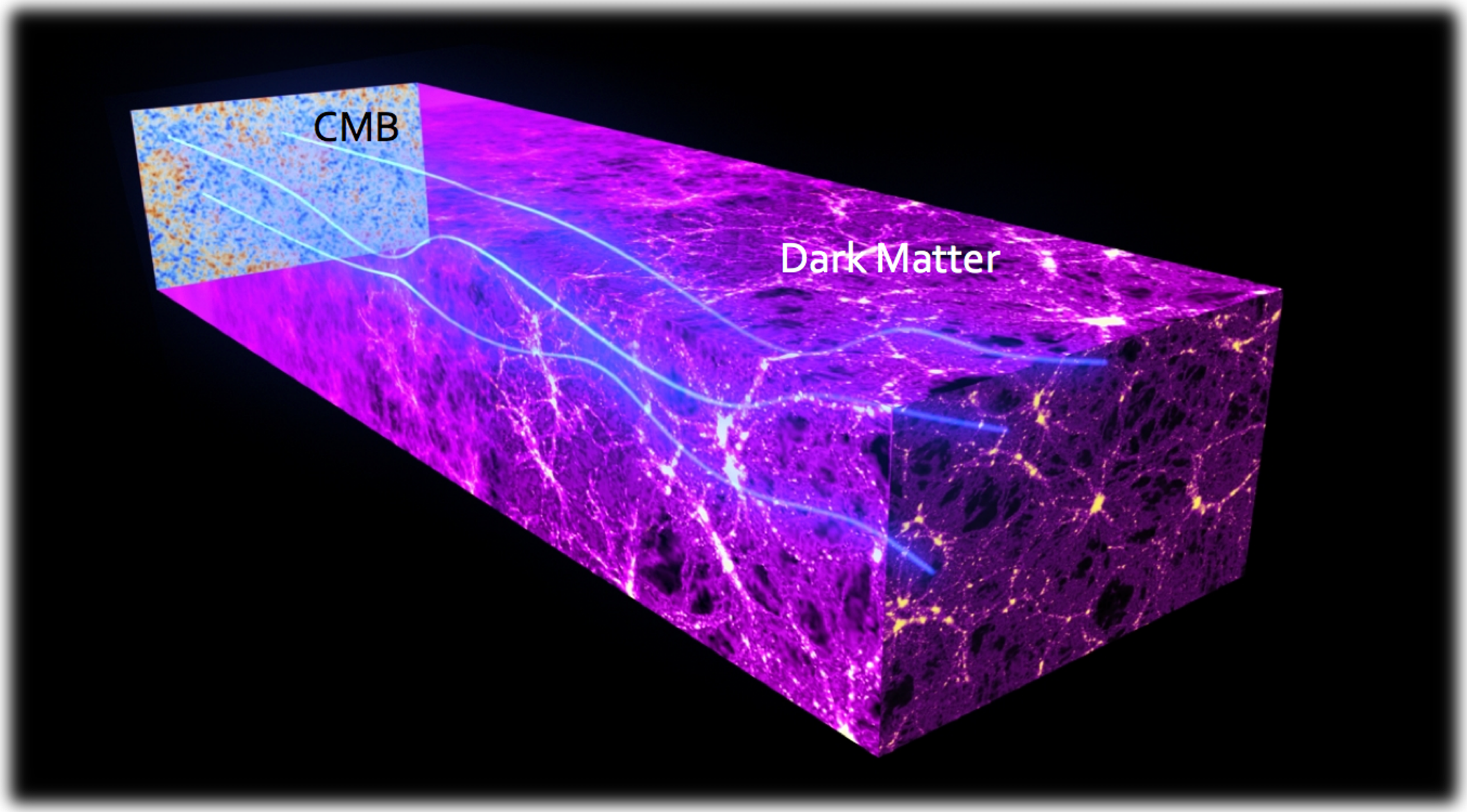
CMB: A Unique Source for Gravitational Lensing

The observable universe:



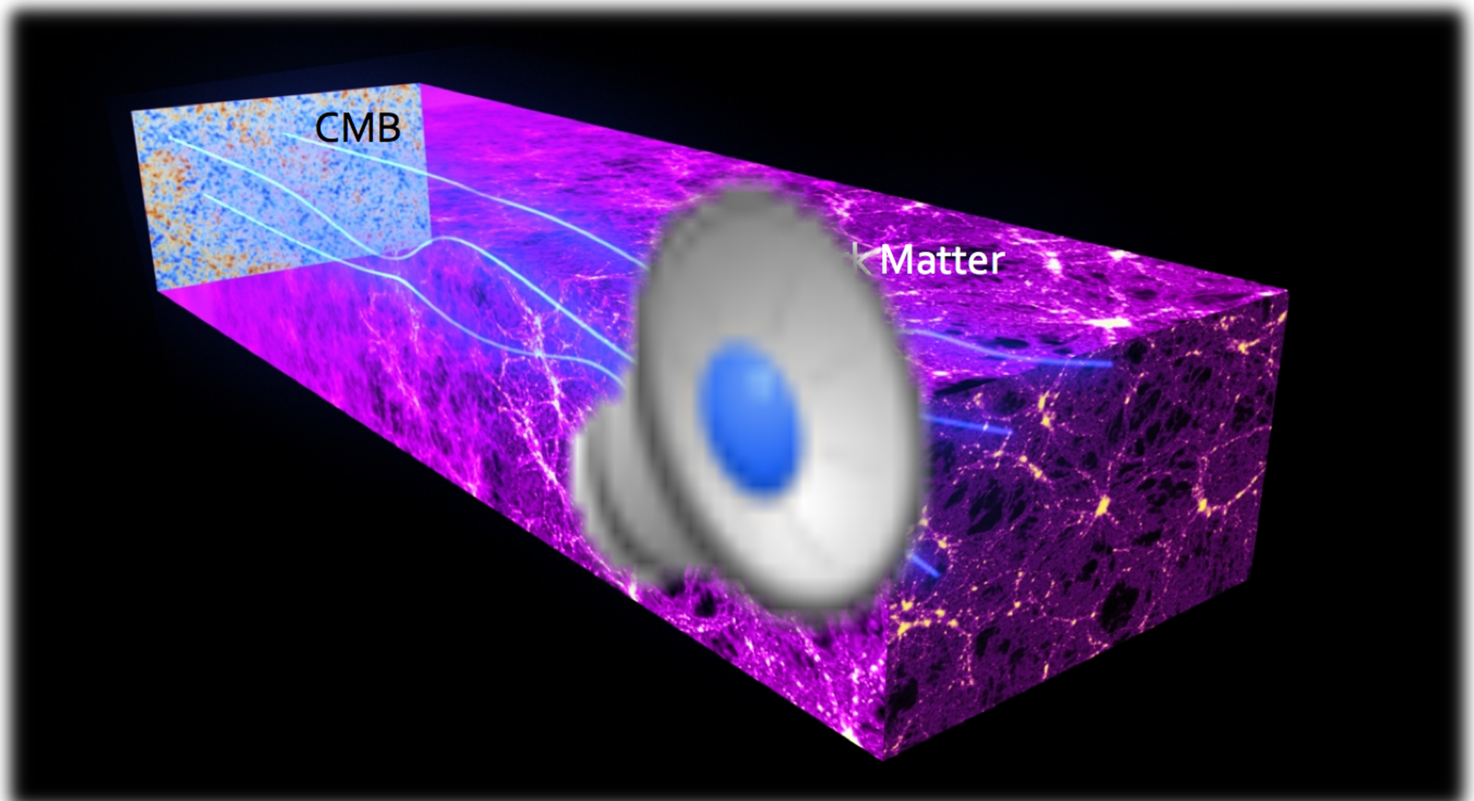
CMB Gravitational Lensing

- Distribution of dark matter deflects CMB light that passes through. (Preserves surface brightness so no effect on uniform CMB.)

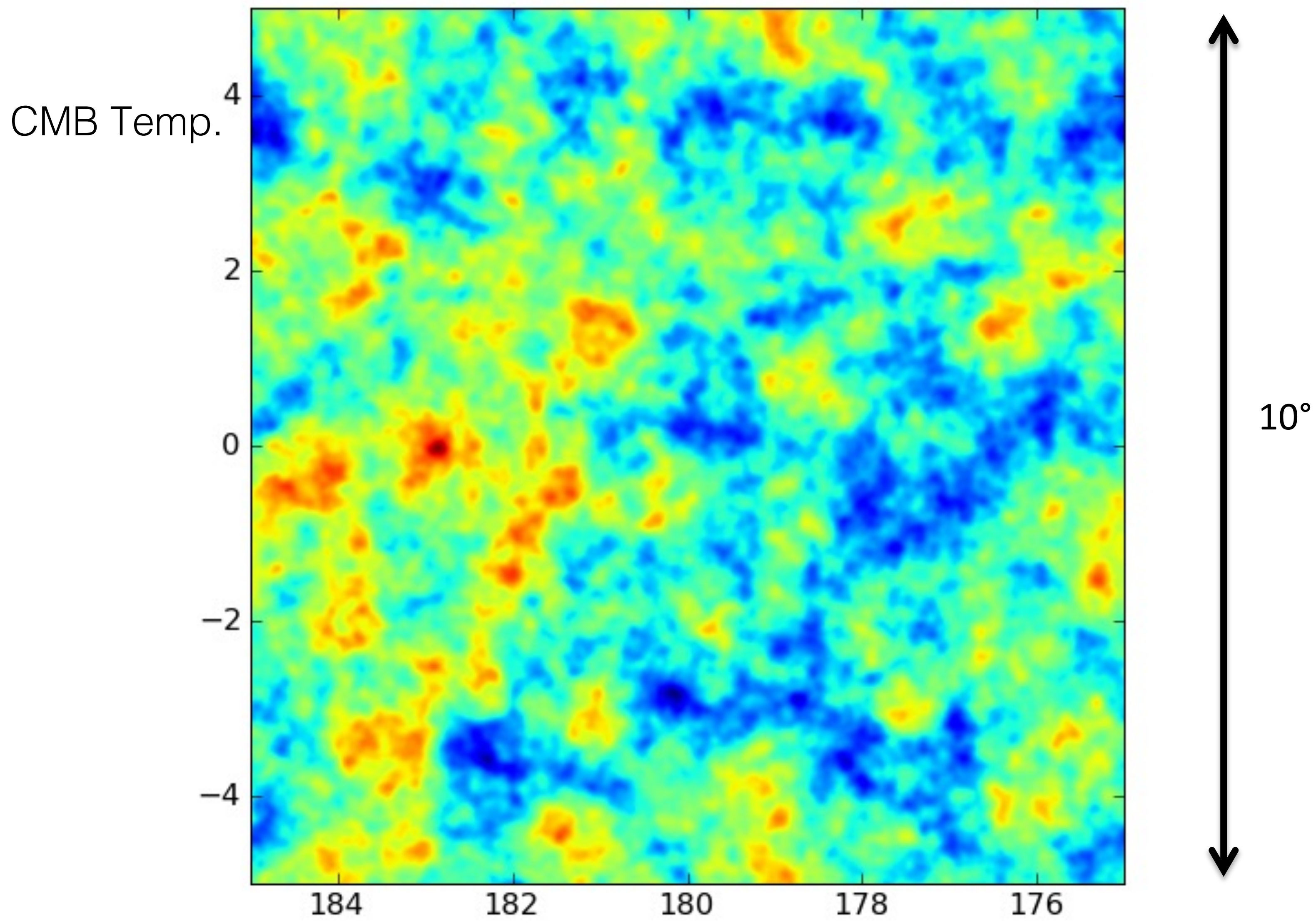


“Light” Source for Lensing: The Cosmic Microwave Background (CMB)

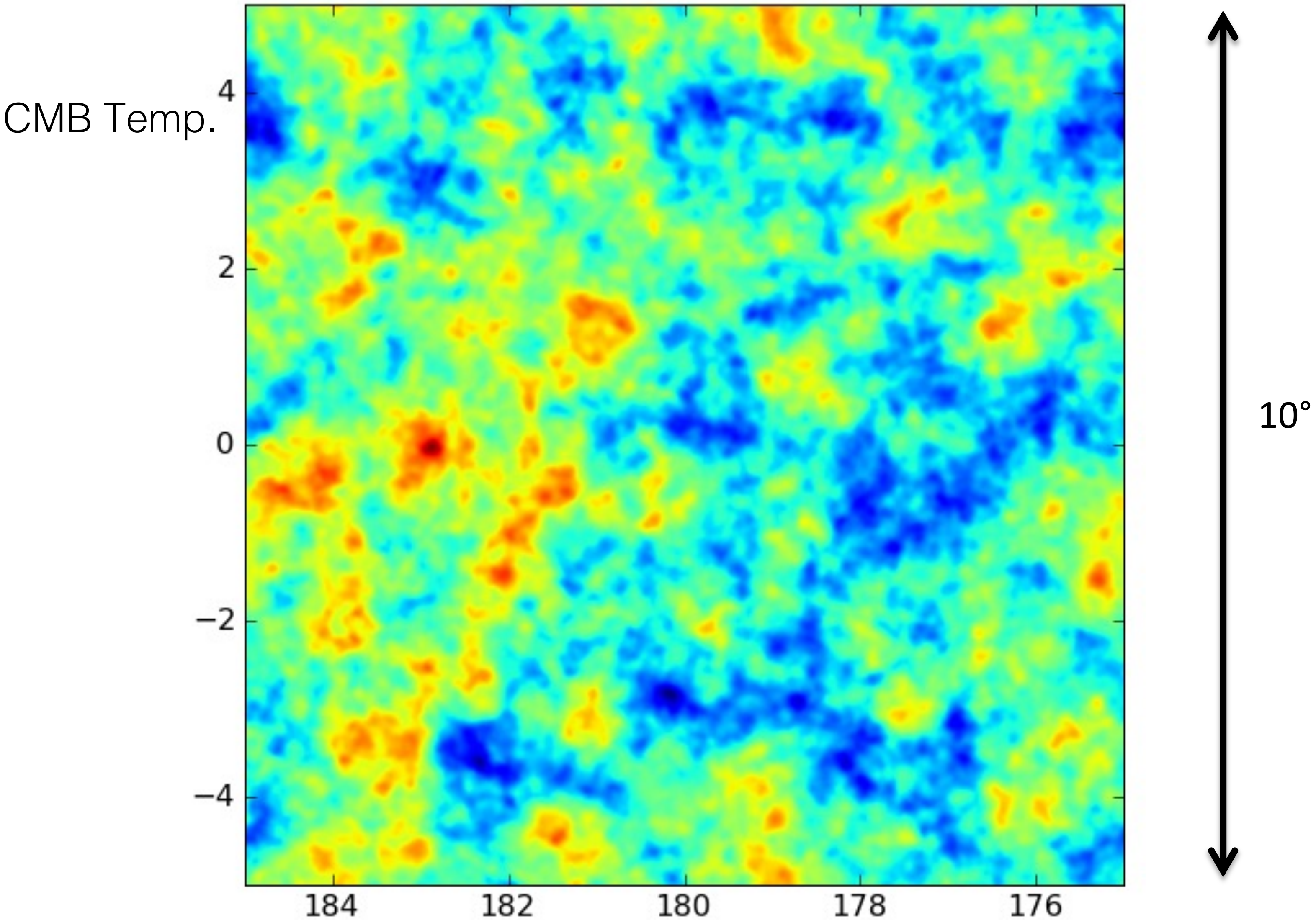
- CMB: leftover radiation from the hot primordial plasma – most distant observable source of light
- Distribution of dark matter deflects light that passes through



Unlensed CMB



Lensed CMB

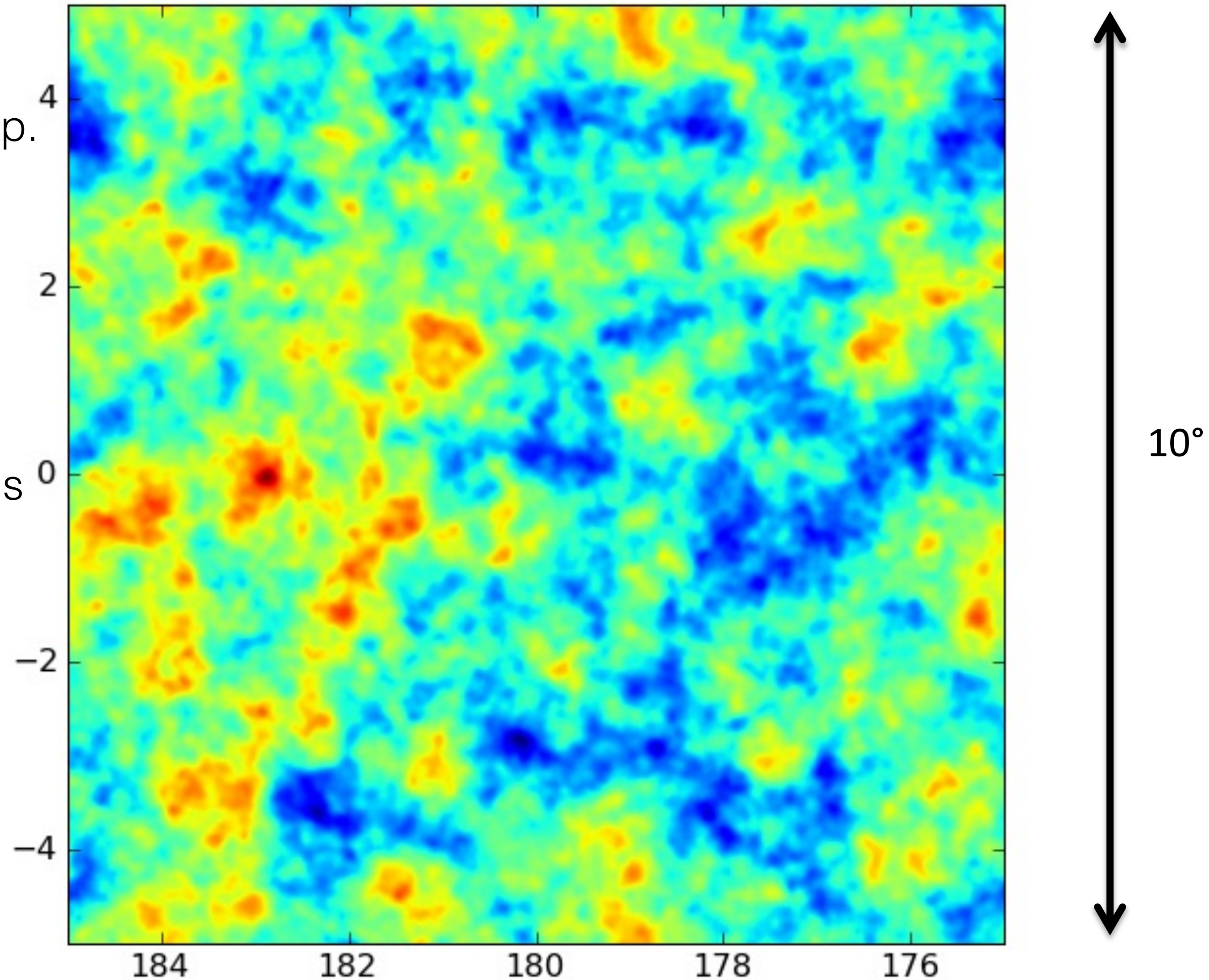


Lensed CMB

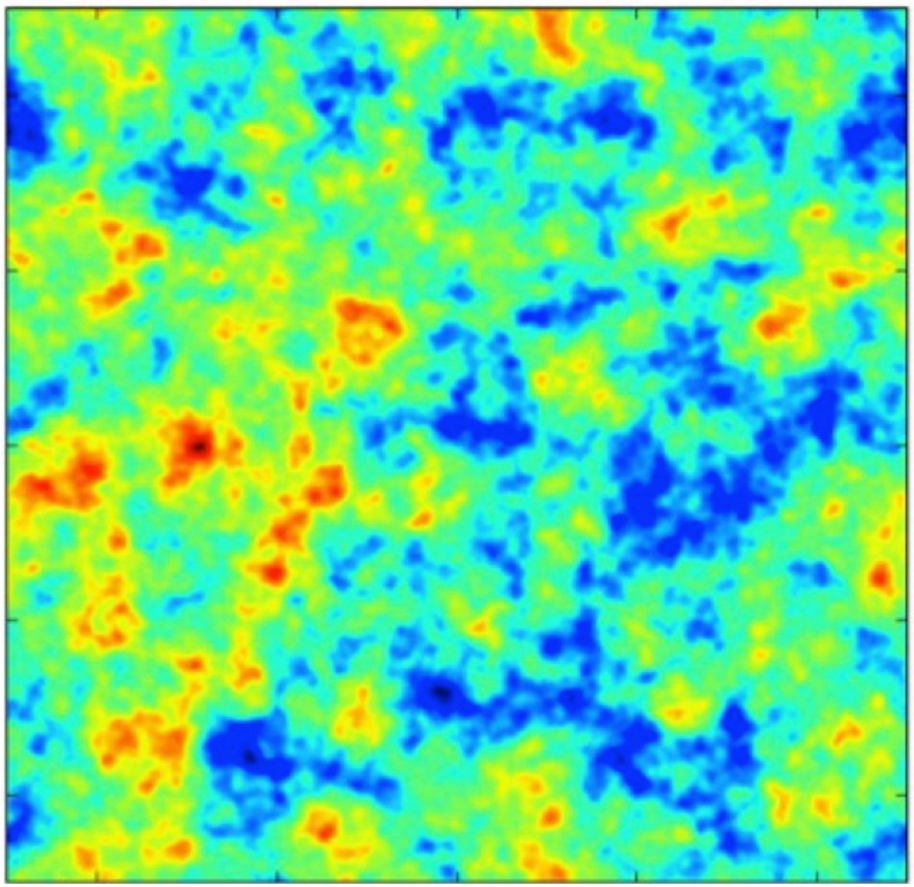
CMB Temp.

Typical deflection of few arcmins

Coherent deflection ~ over degree scales



CMB Lensing: An Approximate Picture

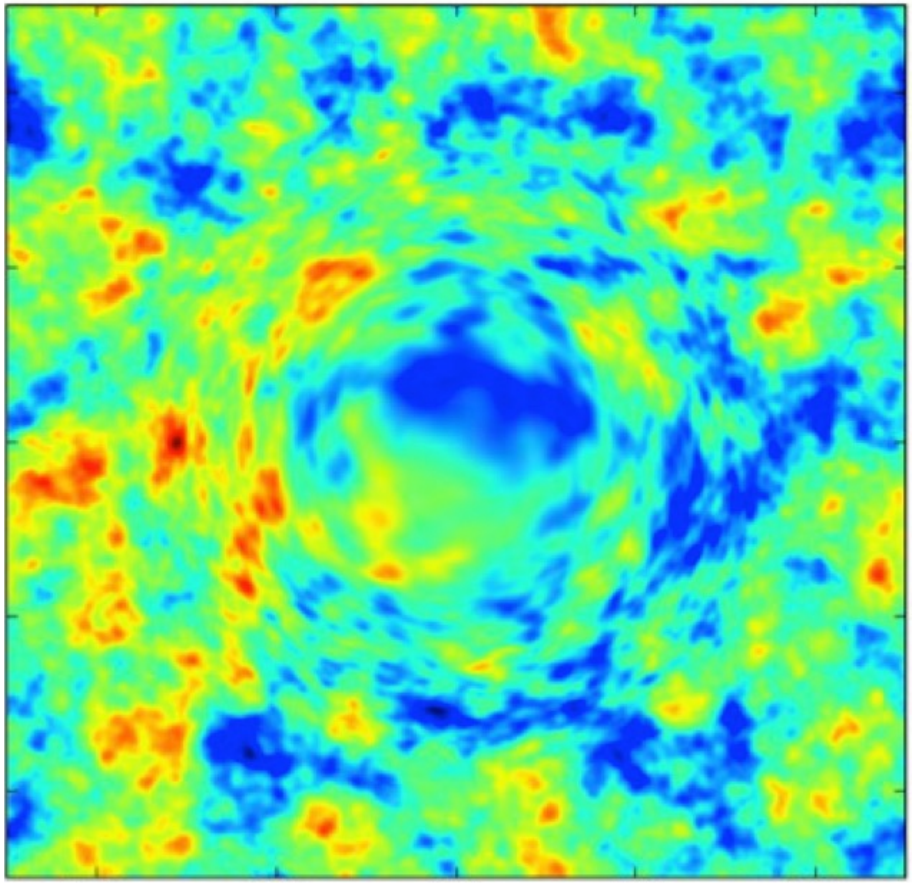


- Original, un-lensed, CMB fluctuations. Very well understood statistical properties, e.g., isotropy.

CMB Lensing: An Approximate Picture

- Clump of dark matter / mass in front…

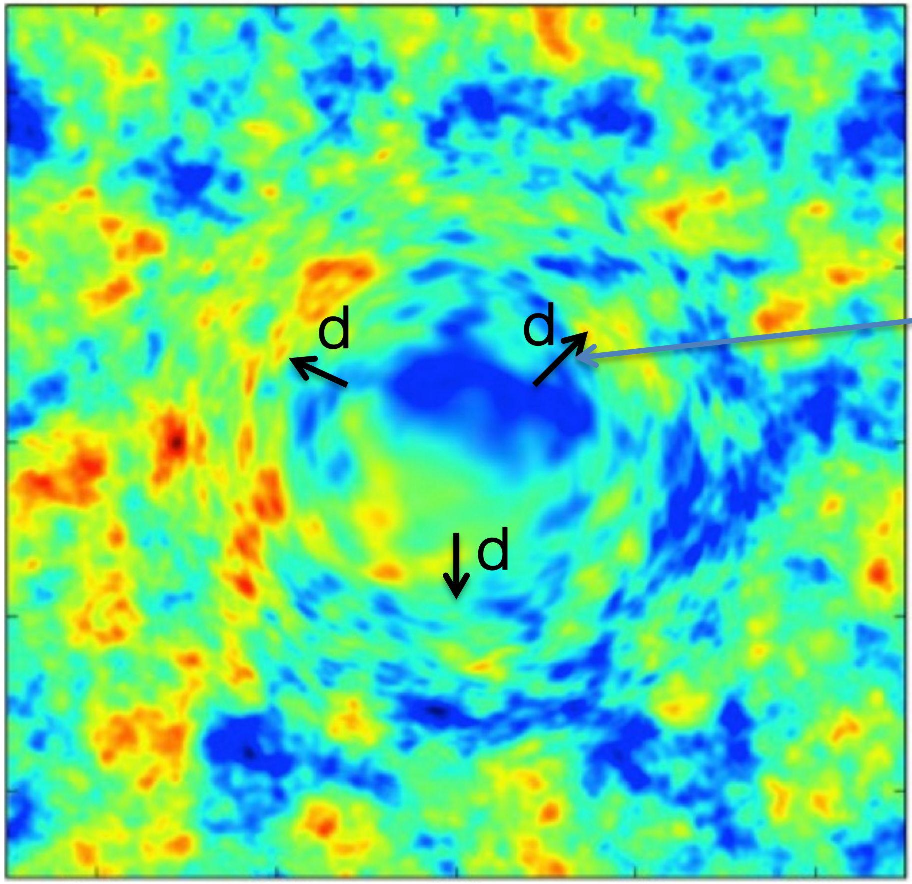
CMB Lensing: An Approximate Picture



- Dark matter / mass causes magnification and shearing feature in the CMB

CMB Lensing: An Approximate Picture

$$\tilde{\Theta}(\hat{\mathbf{n}}) = \Theta(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))$$

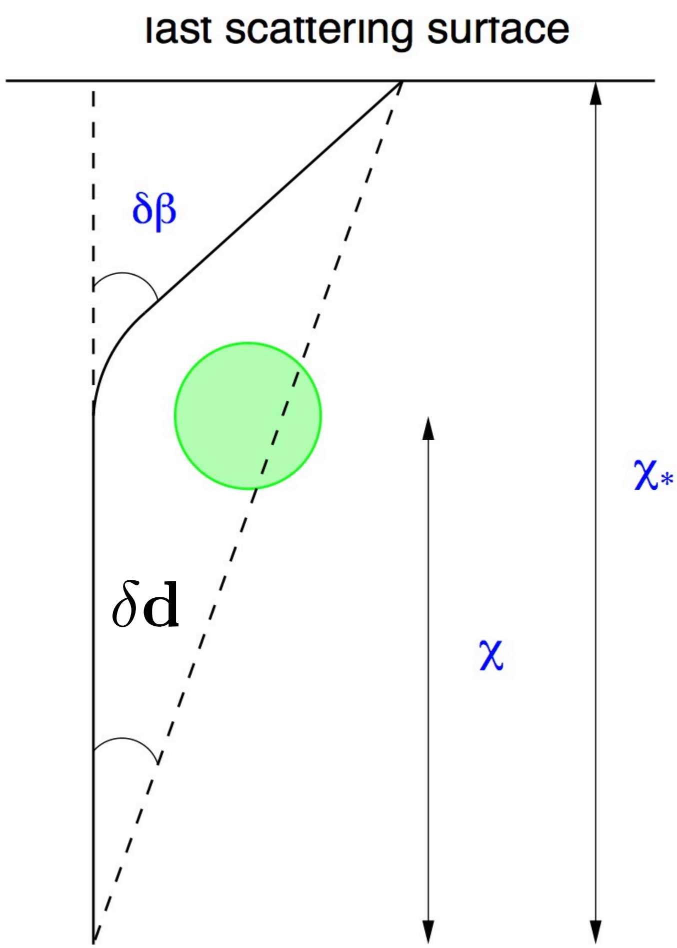


described by **lensing deflection field: d**

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

- Dark matter causes lensing feature in the CMB

Details: Lensing Geometry



- CMB is deflected by mass it passes by. Described by i component of geodesic equation

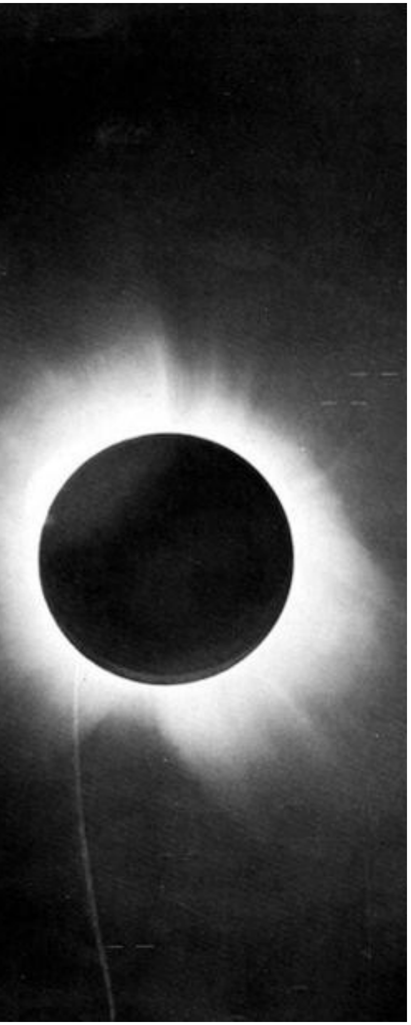
$$\frac{dp^\mu}{d\lambda} + \Gamma^\mu_{\nu\rho} p^\nu p^\rho = 0$$

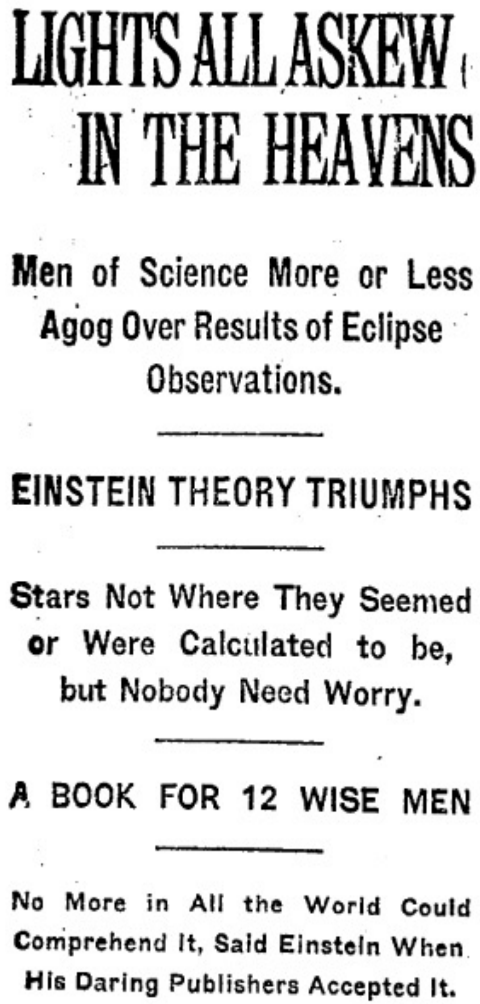
- Derive $\delta\beta = -2\delta\chi\nabla_\perp\Phi$

- And hence

$$\delta\mathbf{d} = -2\frac{\chi_* - \chi}{\chi_*}\delta\chi\nabla_\perp\Phi$$

Details: Lensing Geometry





LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

CMB is deflected by mass it passes by. Described by i component of geodesic equation

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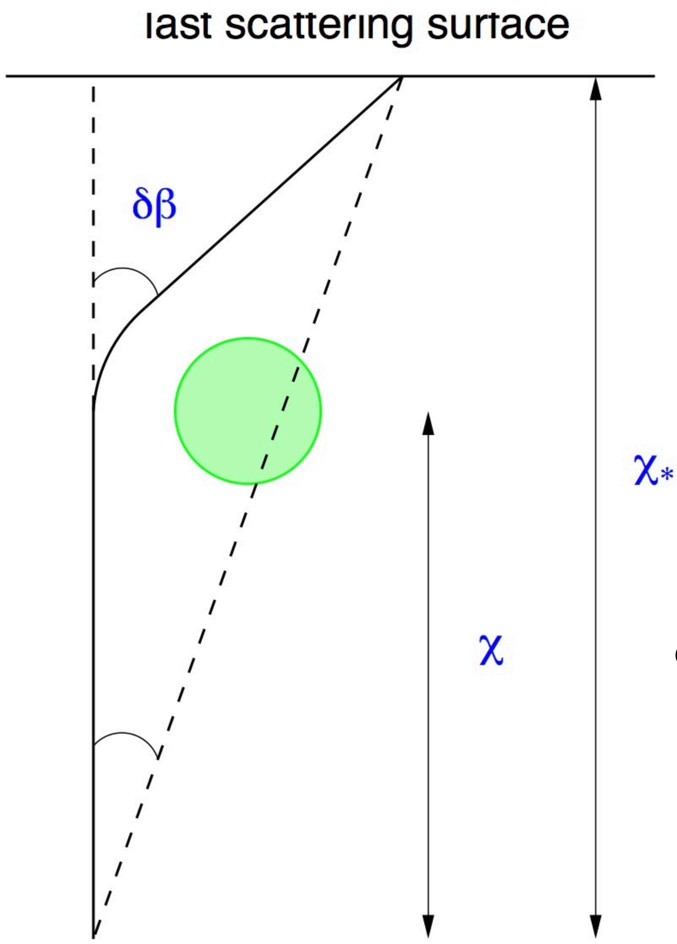
Details: Lensing Geometry



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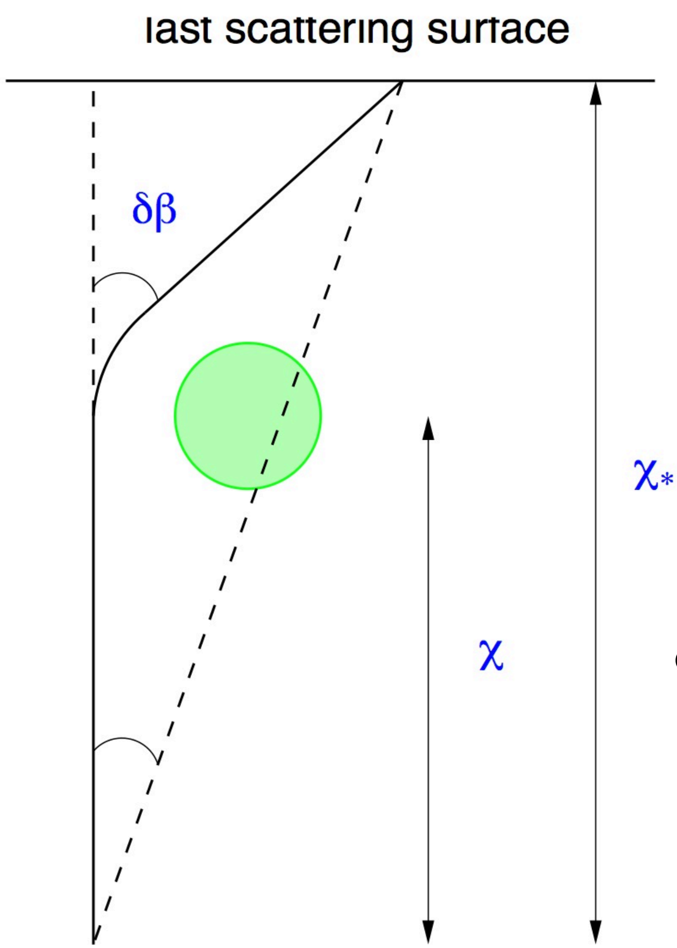
$$\delta \mathbf{d} = -2\frac{\chi_* - \chi}{\chi_*}\delta\chi\nabla_\perp\Phi$$

- Therefore, the lensing is related to an integral of the potential

$$\mathbf{d}(\hat{\mathbf{n}}) = -\int_0^{\chi_*} 2d\chi\frac{\chi_* - \chi}{\chi_*}\delta\chi\nabla_\perp\Phi(\chi\hat{\mathbf{n}}, \eta_0 - \chi)$$

Image: A. Challinor

Details: Lensing Geometry



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$$\mathbf{d}(\hat{\mathbf{n}}) = -\int_0^{\chi_*} 2d\chi\frac{\chi_* - \chi}{\chi_*}\delta\chi\nabla_\perp\Phi(\chi\hat{\mathbf{n}}, \eta_0 - \chi)$$

- We can hence introduce a 2D lensing potential $\mathbf{d}(\hat{\mathbf{n}}) = \nabla\phi$

$$\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_*} d\chi\left(\frac{\chi_* - \chi}{\chi_*\chi}\right)\Phi(\chi\hat{\mathbf{n}}, \eta_0 - \chi)$$

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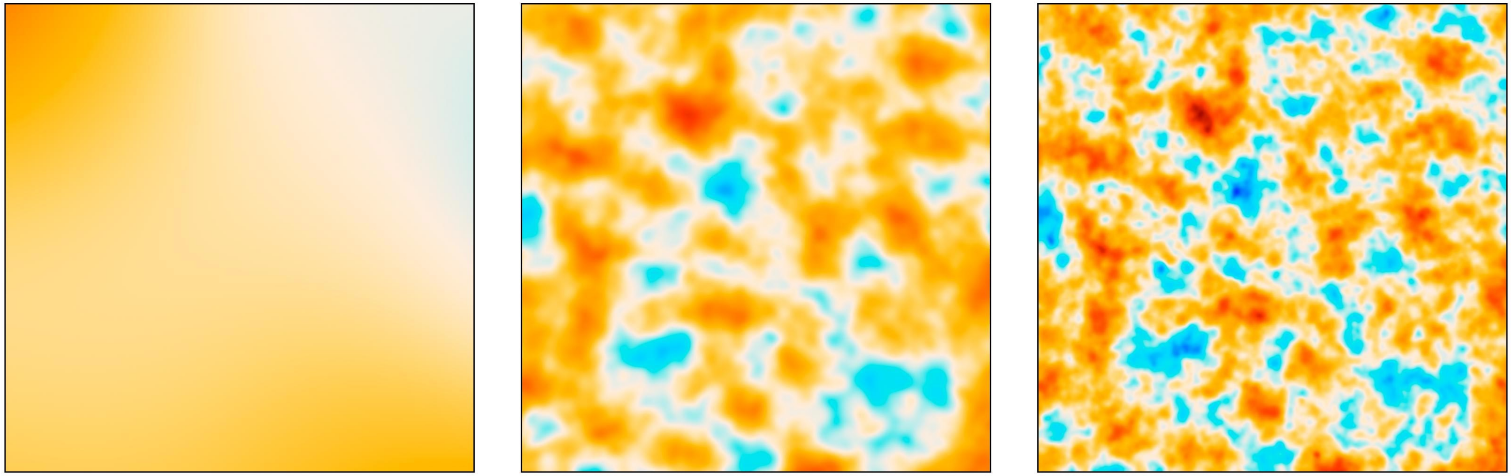


What Does CMB Lensing Tell Us?

- Lensing probes the projected total mass density in each direction (of which most is dark matter) from z~0.5-5, peak at z~2

geometric projection kernel

$$\nabla^2 \phi \sim \int_0^{\chi_*} d\chi W(\chi) \delta(\hat{\mathbf{n}}, \chi)$$

lensing potential (poisson gives convergence)

radial distance

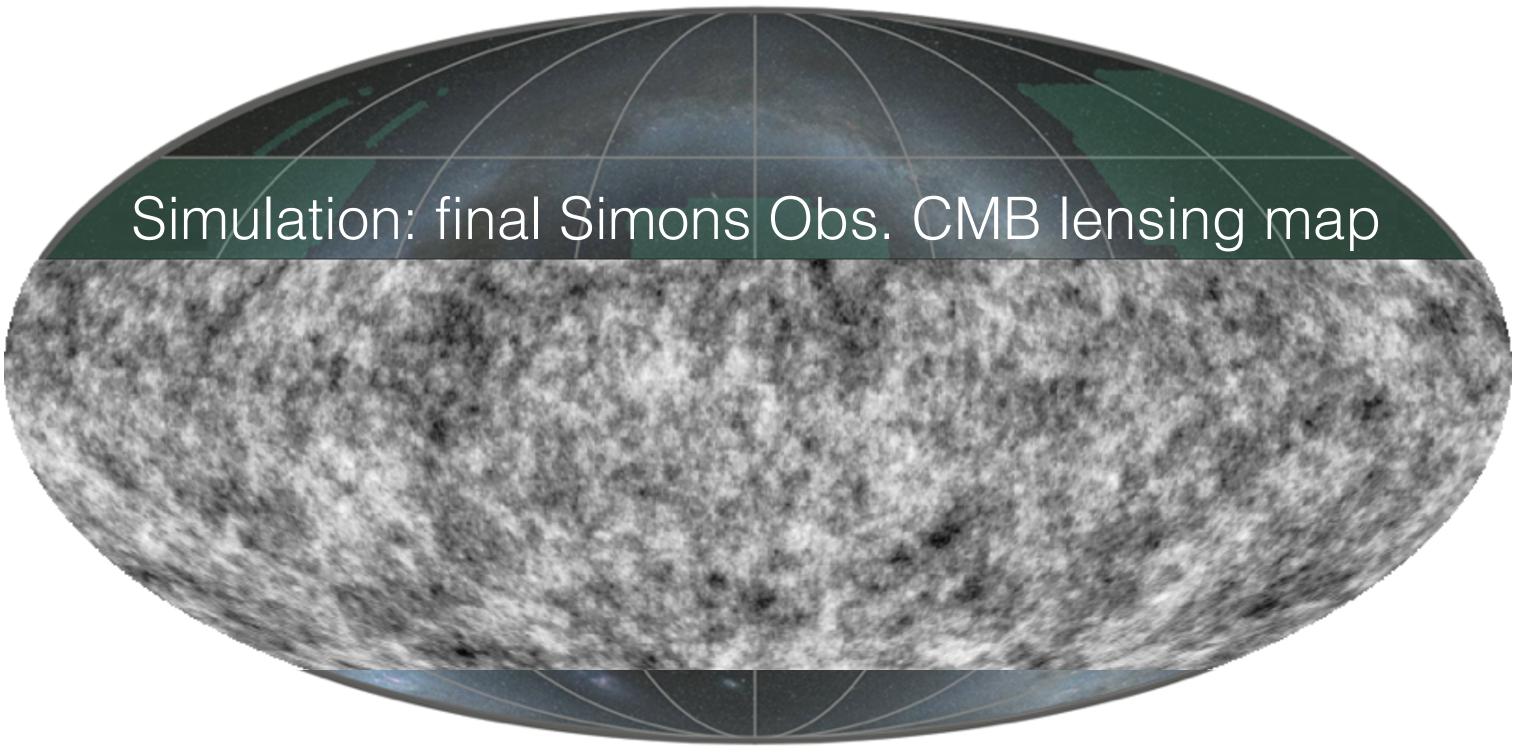
δ : fractional mass overdensity

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

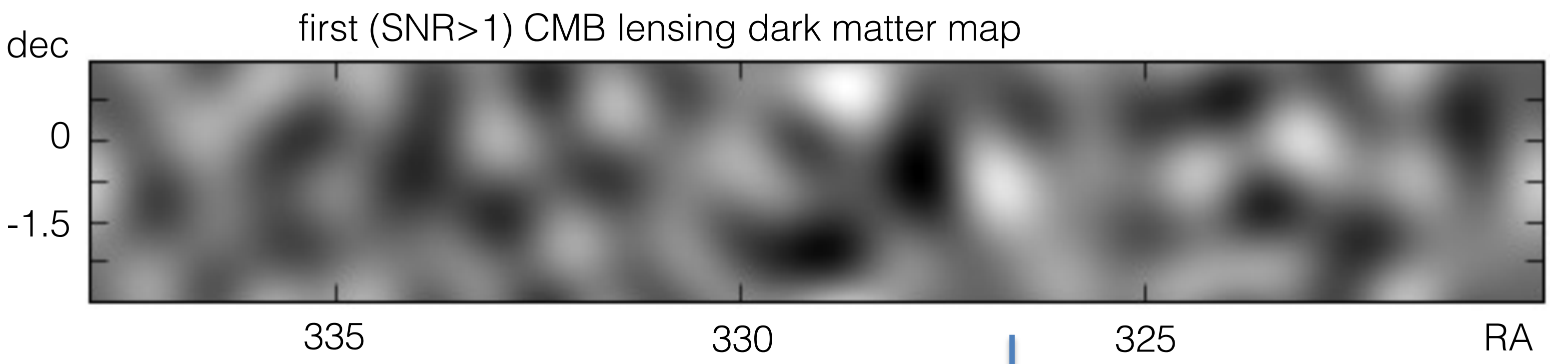
- Sensitive to amount of matter and how clumpy it is; constrains $\sigma_8 \, \Omega_m^{0.25}$

A Powerful Probe of Physics

- Next decade: precise mass maps over half or full sky

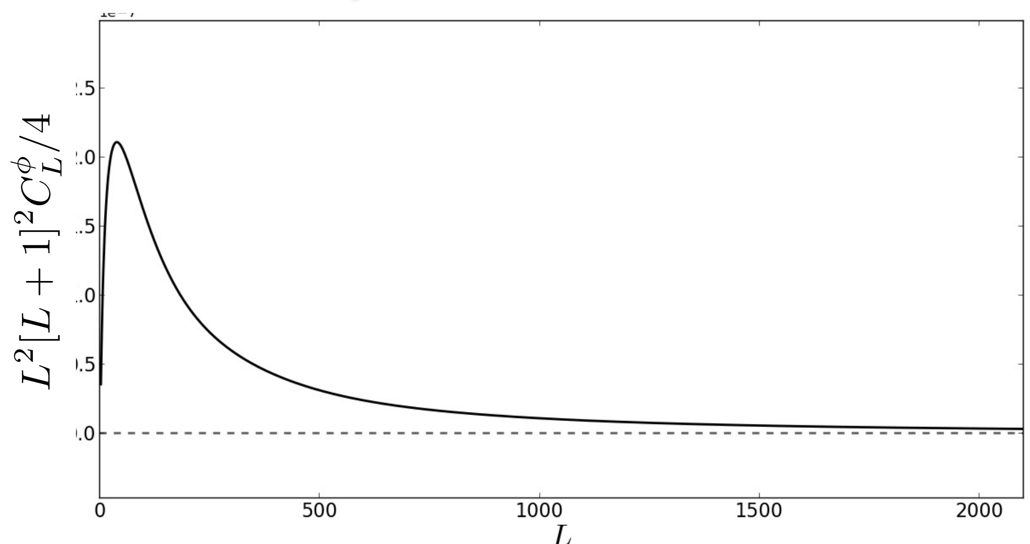


Key Observable: CMB Lensing Power Spectrum C_l^{ϕ}



white = higher density

Y axis: "How much lensing …."

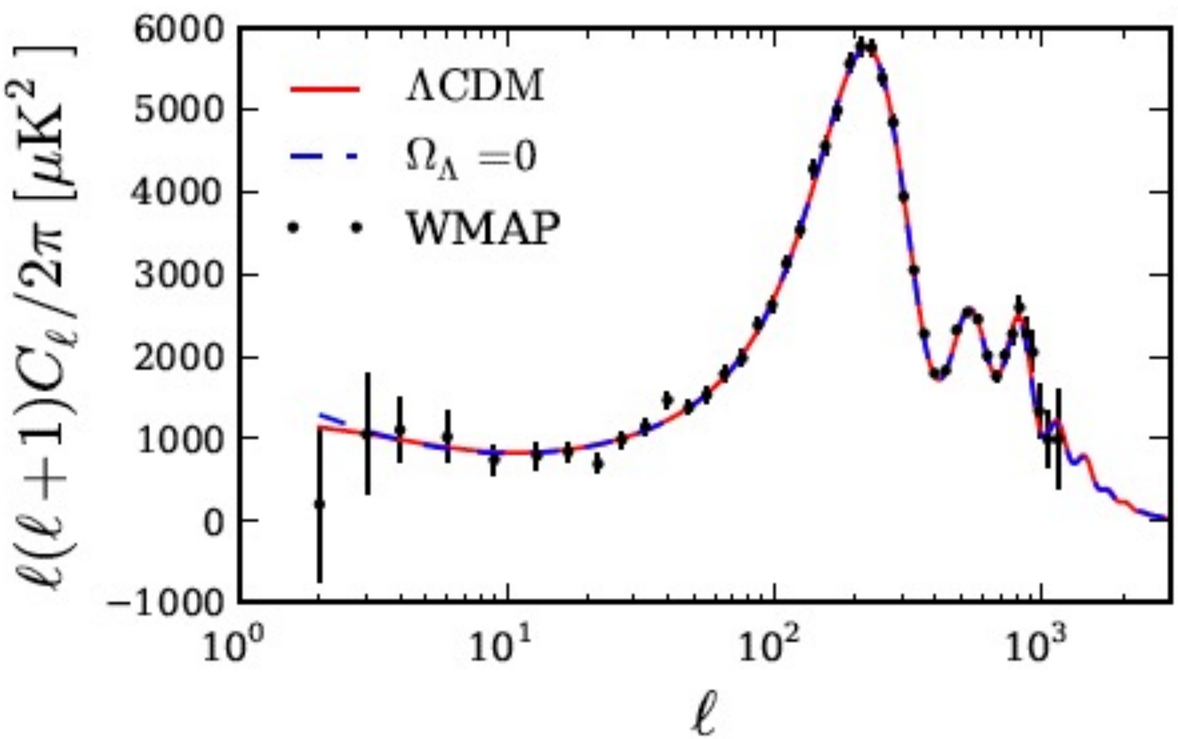


X axis: "for a lens of this angular scale?"

Describe lensing maps statistically with lensing power spectrum:

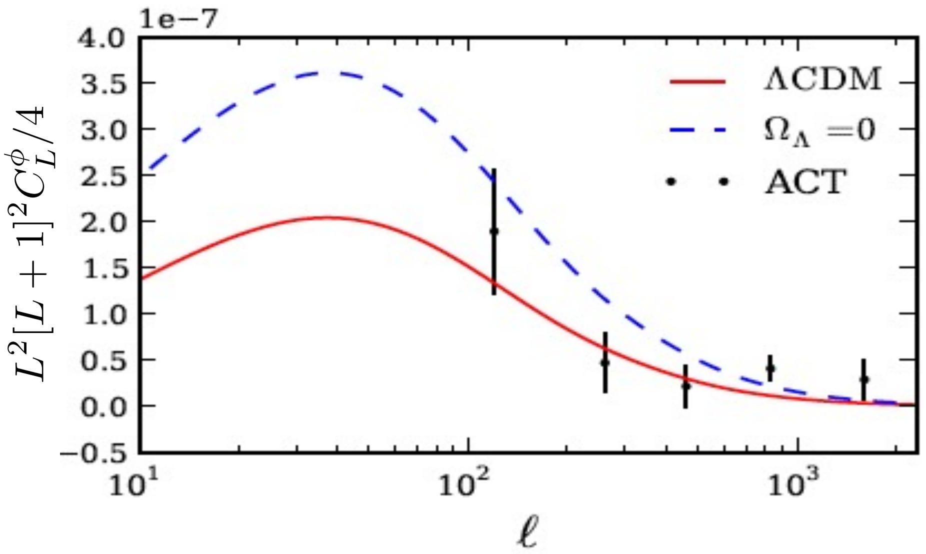
Example Physics Lensing Can Tell Us I: Dark Energy

- Geometric degeneracy of universe with and without Lambda clearly visible in power spectrum (same d_A!)

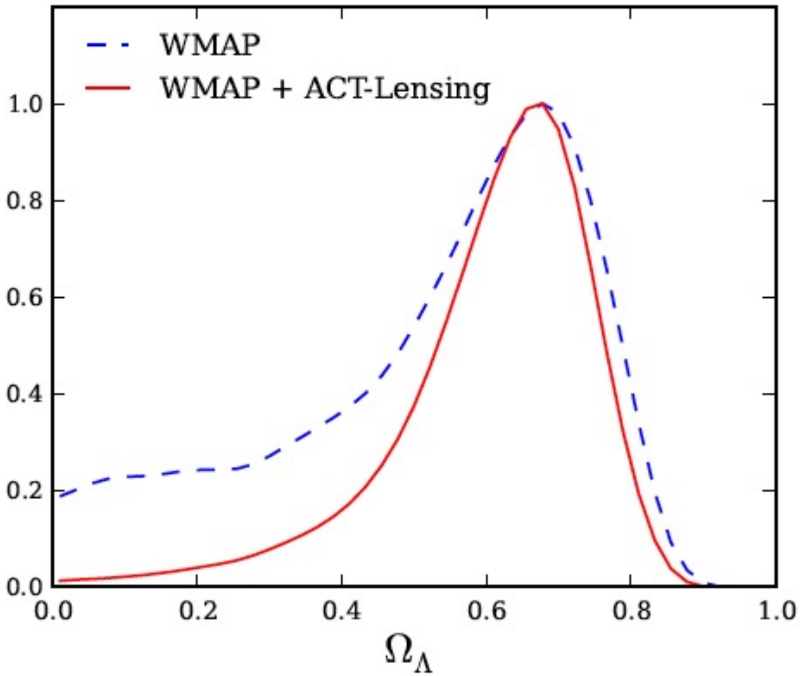


Lensing: CMB-only Evidence for Ω_Λ

Lensing breaks degeneracy:



1-D Posterior distribution for Ω_Λ:

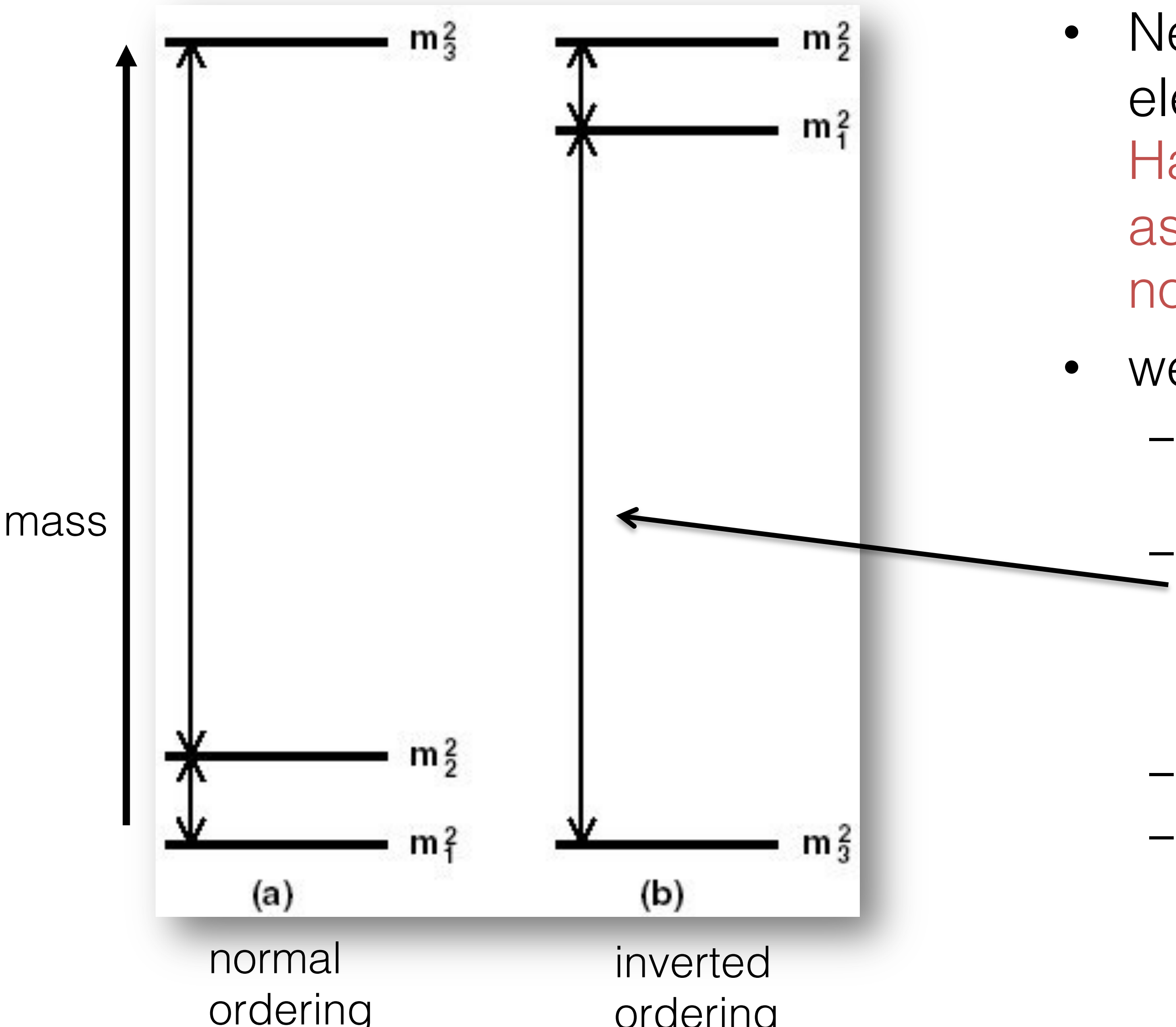


Peak at $\Omega_\Lambda = 0.67$

[Sherwin, Dunkley, Das et al. 2011]

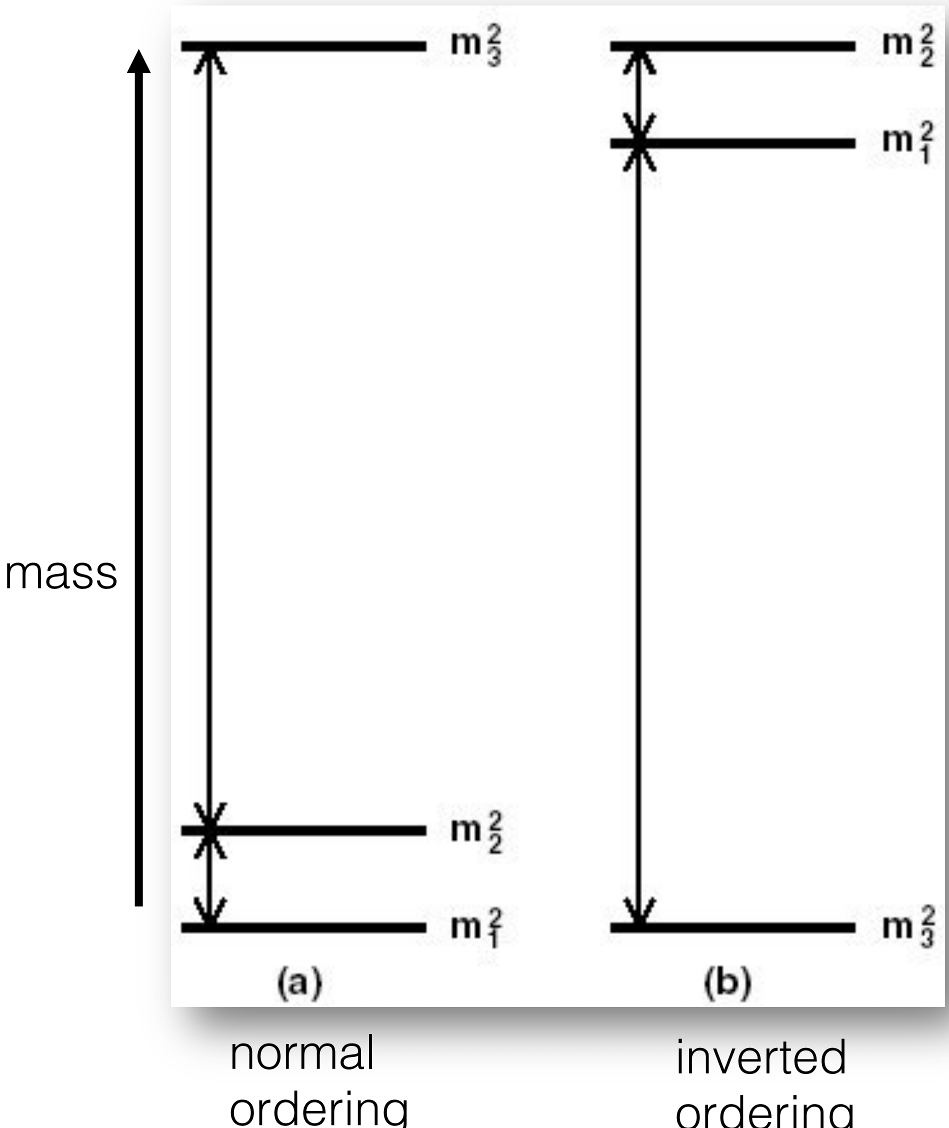
Lensing breaks geometric degeneracy, allows constraints on Lambda/curvature

Example Physics Lensing Can Tell Us II: Neutrinos!



- Neutrinos: 3/12 elementary Fermions. Have mass – associated physics not well understood
- we don't know:
  - absolute mass = new scale
  - order of neutrino masses (2 light, 1 heavy? 2 heavy 1 light?)
  - Dirac / Majorana?
  - what new physics gives neutrinos mass?
  - +…

Example Physics Lensing Can Tell Us II: Neutrinos!



- If we measure mass sum, $\sum m_\nu$ can get insight to some of the questions (scale, mass ordering, type)

  Target: mass at least >60meV

- Part of a big program to understand this new physics!

N.B. +look for extra neutrinos!

Neutrinos Affect How Cosmic Structure Grows

- Matter perturbations growth…

- is affected by neutrino streaming: gravitational driving “force” from neutrinos is missing on small scales

ρ: energy density

$$\ddot{\delta}_m + 2H(\rho_m)\dot{\delta}_m - 4\pi G(1 - f_\nu)\rho_m\delta_m = 0$$

δ: density

H: hubble rate (friction term)

f: fraction of energy density in neutrinos, ~ mass

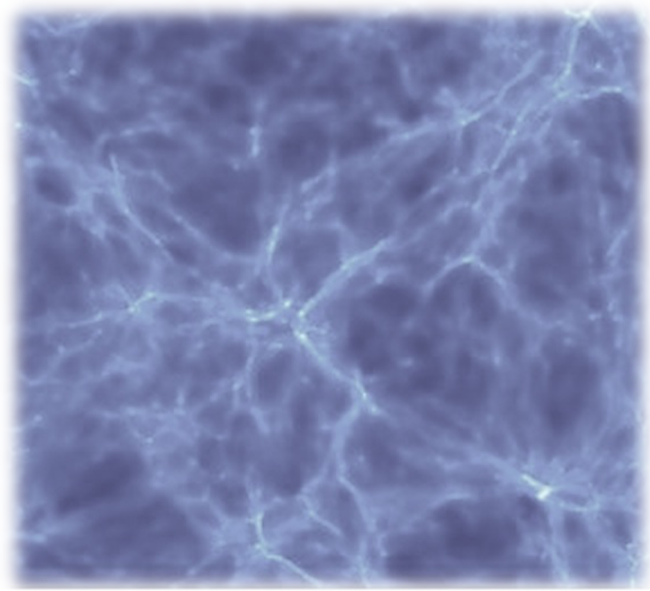
[Video: A. Kravtsov++]

Neutrinos Affect How Cosmic Structure Grows

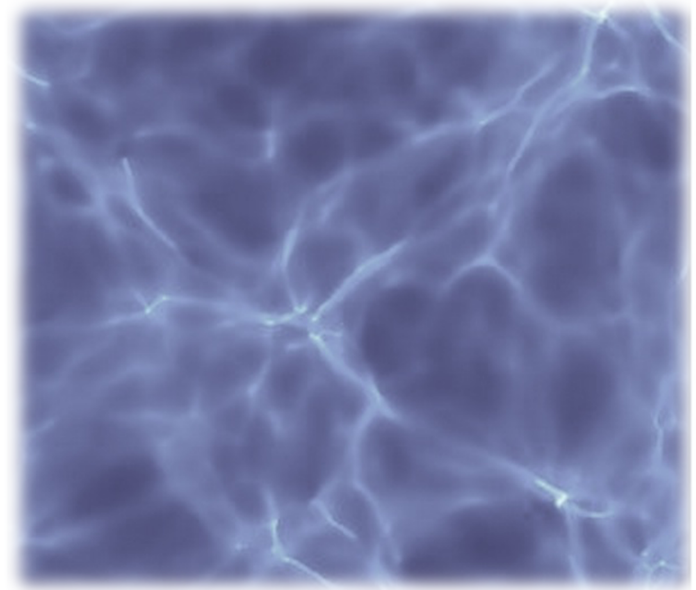
- The more massive neutrinos are, the more small scale dark matter structure is suppressed.

Large-scale mass distribution:

Image: Viel++ 2013



Neutrino Mass Negligible



Neutrino Mass Really Large (qualitative)

- Suppression also visible in lensing map – want to measure (and compare with primordial CMB amplitude)!

Neutrinos Affect How Cosmic Structure Grows

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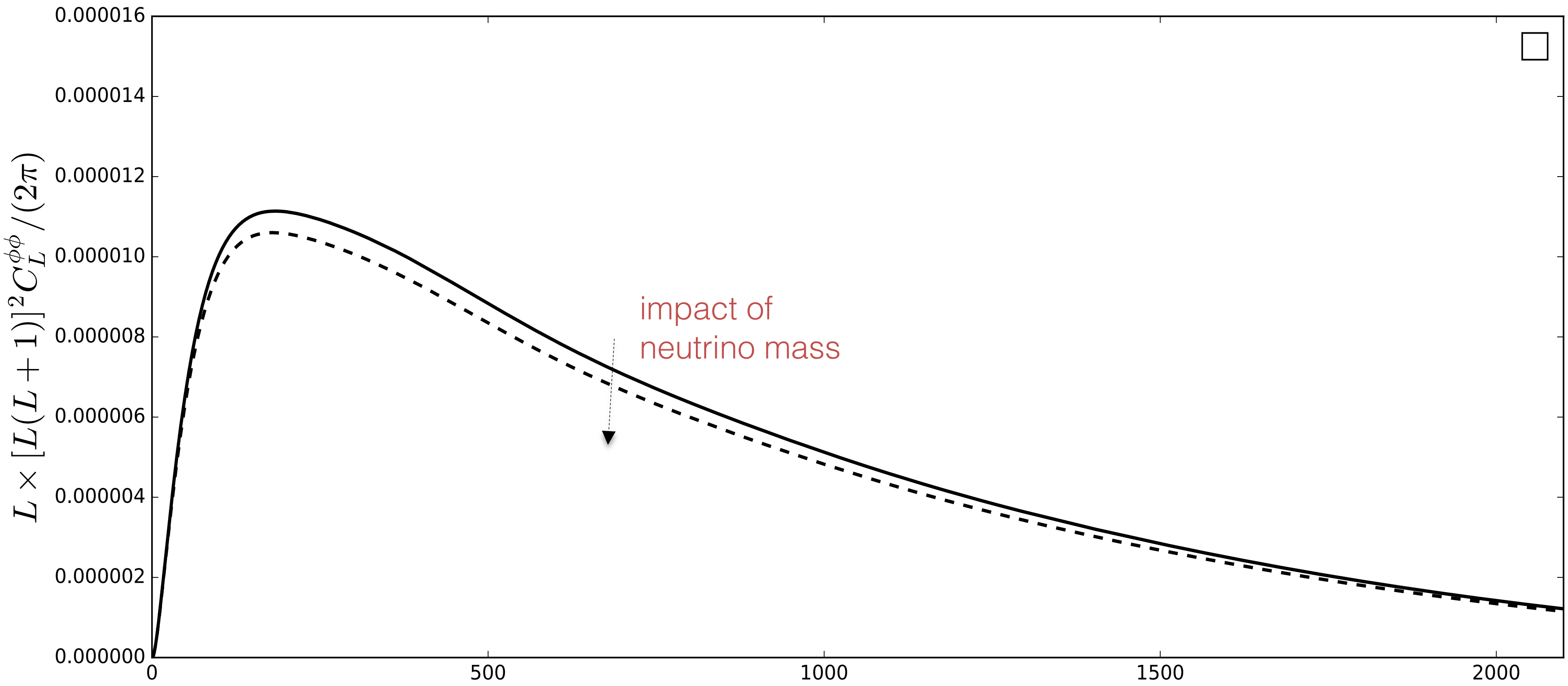


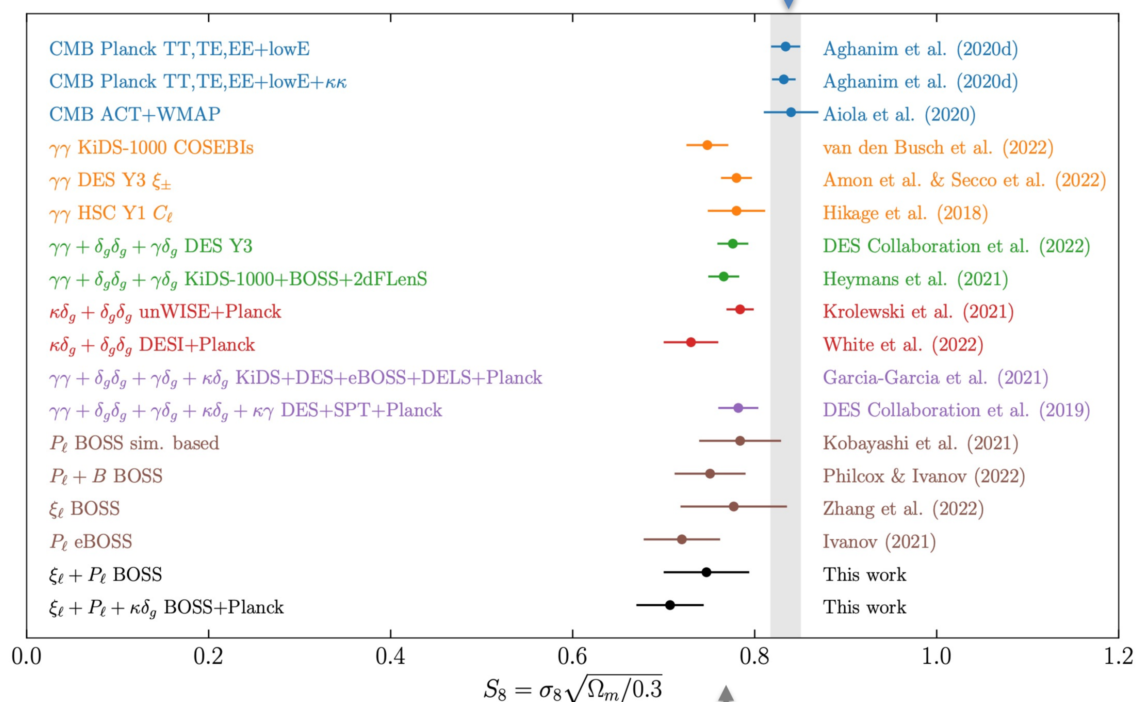
- Suppression also visible in lensing map – want to measure (and compare with primordial CMB amplitude)!

Example Physics Lensing Can Tell Us III: S8 Tension?

- S8~ $\sigma_8\ \Omega_m^{0.5}$ measured by several probes is ~2-3 sigma low compared to prediction from early-time CMB

- New CMB lensing measurements of mass distribution with different systematics crucial: Do we also find a low S8?

CMB extrapolation



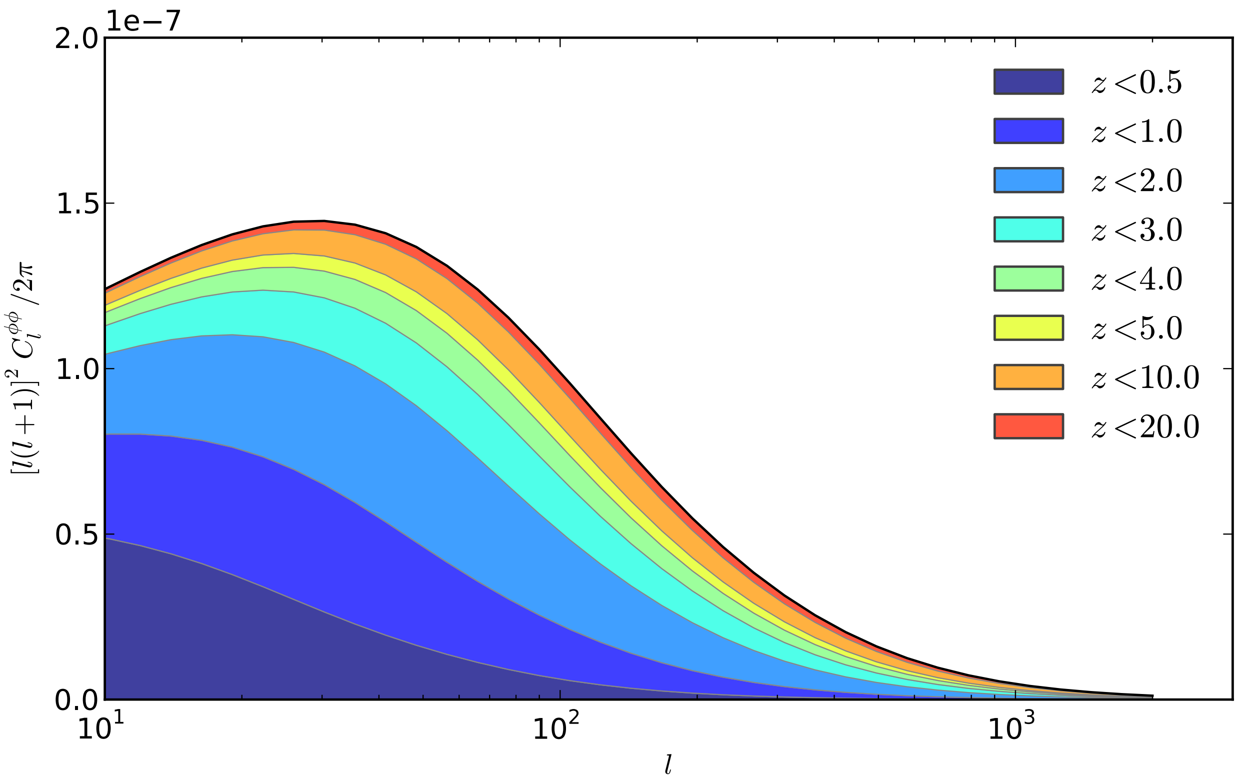
[Chen++ 2022]

~σ_8

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

Example Physics Lensing Can Tell Us III: S8 Tension?

- Lensing maps probe matter density, projected over a wide redshift range peaking at z~2. Great probe for testing if growth of structure is LCDM out to high z.



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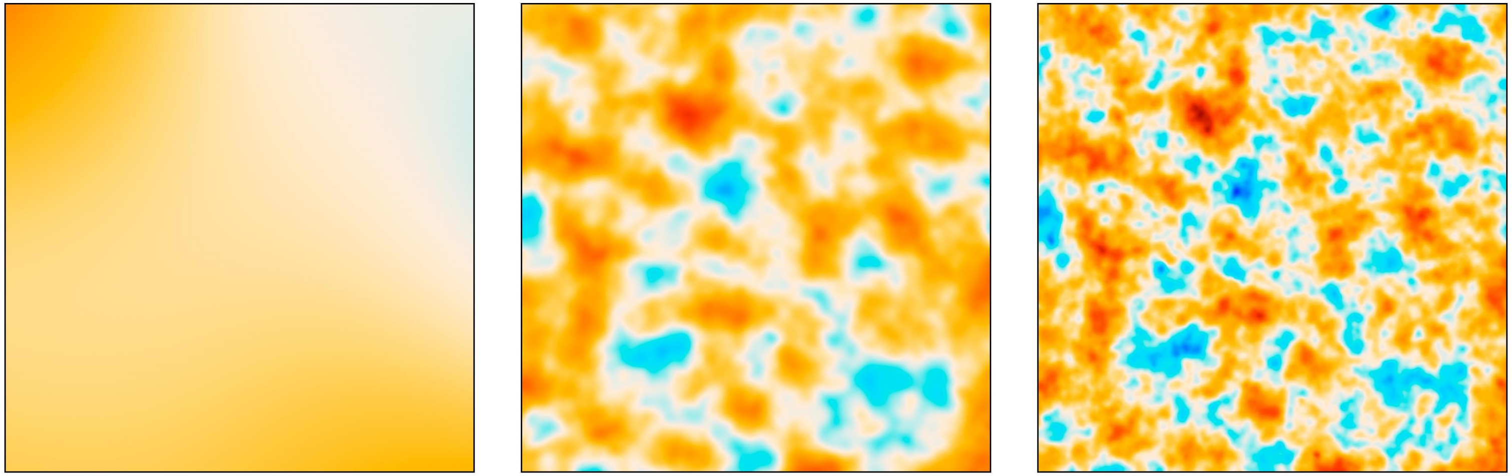
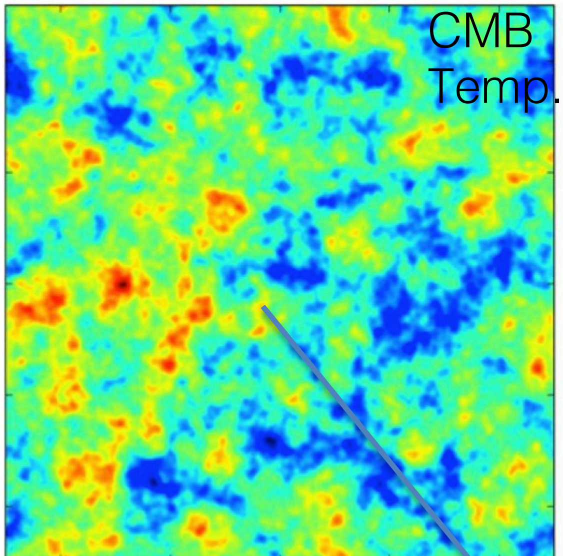
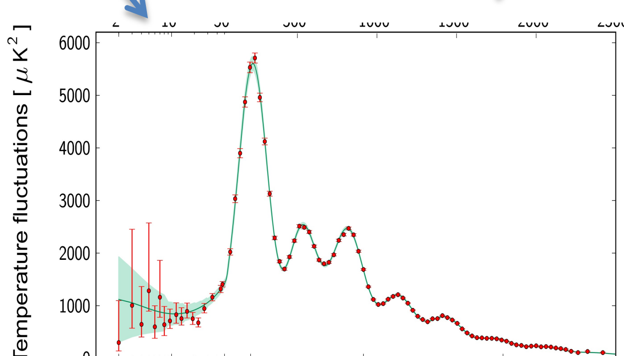
- Cosmology dependence
- CMB lensing measurement: methods and some new results
- Effect on power spectra
- Delensing



CMB Lensing Measurement: An Approximate Picture

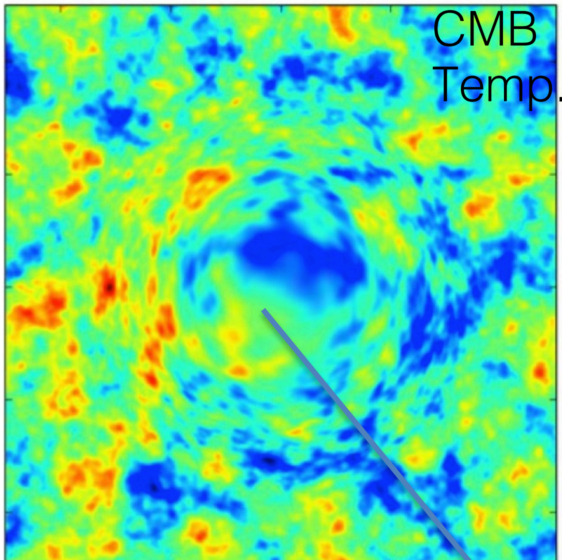


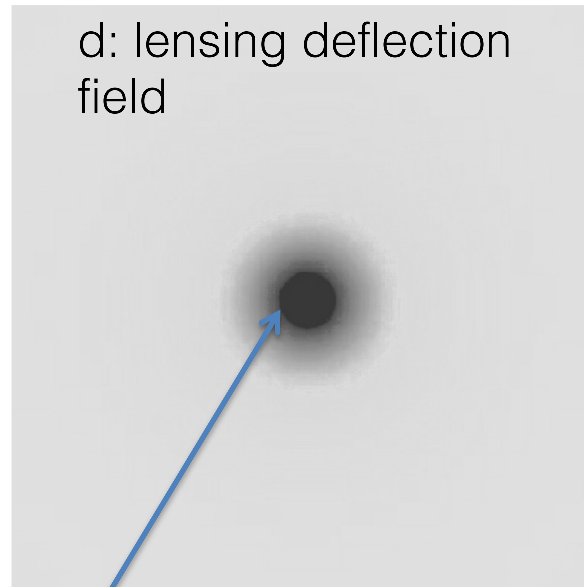
d: lensing deflection field

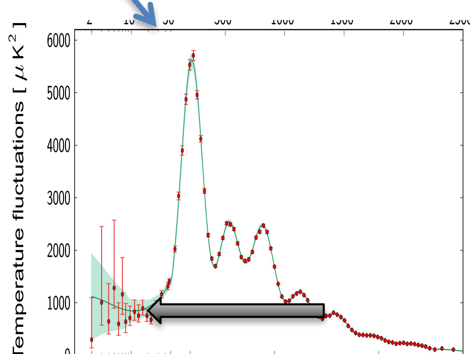


Local CMB power spectrum

CMB Lensing Measurement: An Approximate Picture







shift to larger angular scales

Infer magnification and lensing from "stretching" of the local CMB power spectrum

Lensing Reconstruction Details - Overview

- From translation invariance (of 2-point correlation function),

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

T: temperature (Fourier mode)
l: wavenumber

- **Lensing breaks translation invariance**: introduces new correlations $\tilde{\Theta}(\mathbf{x}) = \tilde{\Theta}(\mathbf{x} + \mathbf{d}) = \Theta(\mathbf{x}) + \nabla\phi \cdot \nabla\Theta + \cdots$

$$\langle \tilde{\Theta}(\mathbf{l}) \tilde{\Theta}^*(\mathbf{l} - \mathbf{L}) \rangle \sim \phi(\mathbf{L})$$

- So: measure lensing by looking for these new correlations in the CMB two-point functions. Let's work this out more carefully.

Lensing Reconstruction Technical Details

- Showed earlier that

$$\tilde{\Theta}(\mathbf{x}) = \Theta(\mathbf{x} + \mathbf{d}) = \Theta(\mathbf{x}) + \nabla\phi \cdot \nabla\Theta + \cdots$$

$$\tilde{\Theta}(\mathbf{l}) = \Theta(\mathbf{l}) + \int \frac{d^2 L}{(2\pi)^2} [\mathbf{L}\phi(\mathbf{L})] \cdot [(\mathbf{l} - \mathbf{L})\Theta(\mathbf{l} - \mathbf{L})]$$

- This implies that to leading order

$$\langle \tilde{\Theta}(\mathbf{l}) \tilde{\Theta}(\mathbf{L} - \mathbf{l}) \rangle_{\mathrm{CMB}} = \left[(\mathbf{L} - \mathbf{l}) \cdot \mathbf{L}\ \tilde{C}_{\mathbf{l}-\mathbf{L}} + \mathbf{l} \cdot \mathbf{L}\ \tilde{C}_l \right] \phi(\mathbf{L}) \equiv K(\mathbf{l}, \mathbf{L}) \phi(\mathbf{L})$$

response function

Lensing Reconstruction Technical Details

- This motivates us to derive a quadratic lensing estimator

$$\hat{\phi}(\mathbf{L}) = \int \frac{d^2\mathbf{l}}{(2\pi)^2} f(\mathbf{l},\mathbf{L})\tilde{\Theta}(\mathbf{l})\tilde{\Theta}(\mathbf{L}-\mathbf{l})$$

where we must suitably choose the weight function f.

- Our first condition for choosing f is unbiasedness, i.e. $\phi(\mathbf{L}) = \left\langle \hat{\phi}(\mathbf{L}) \right\rangle_{\mathrm{CMB}}$ which implies a constraint

$$I[f] \equiv \int \frac{d^2\mathbf{l}}{(2\pi)^2} f(\mathbf{l},\mathbf{L}) K(\mathbf{l},\mathbf{L}) = 1$$

Lensing Reconstruction Technical Details

- Our second condition for choosing f is minimum variance V:

$$\left\langle \hat{\phi}^*(\mathbf{L})\hat{\phi}(\mathbf{L}')\right\rangle_{\rm CMB} - \phi^*(\mathbf{L})\phi(\mathbf{L}') = (2\pi)^2\ V[f](\mathbf{L})\ \delta(\mathbf{L}-\mathbf{L}')$$

$$= (2\pi)^2 \int \frac{d^2\mathbf{l}}{(2\pi)^2} \left[|f(\mathbf{l},\mathbf{L})|^2 \overset{n}{C_l} \overset{n}{C}_{|\mathbf{L}-\mathbf{l}|} + f^*(\mathbf{l},\mathbf{L}) f(\mathbf{L}-\mathbf{l},\mathbf{L}) \overset{n}{C_l} \overset{n}{C}_{|\mathbf{L}-\mathbf{l}|} \right] \delta(\mathbf{L}-\mathbf{L}')$$

- So, minimize V[f] subject to constraint I[f]=1 with Lagrange multipliers. Exercise!

- Guess f~(S/N)^2: $\hat{\phi}(\mathbf{L}) \sim \int d\mathbf{l} \frac{K(\mathbf{l},\mathbf{L})}{\mathrm{var}[\Theta(\mathbf{l})\Theta(\mathbf{L}-\mathbf{l})]} \tilde{\Theta}(\mathbf{l})\tilde{\Theta}(\mathbf{L}-\mathbf{l})$

Lensing Reconstruction Technical Details

- Agrees with full calculation, "Optimal" Quadratic Estimator:

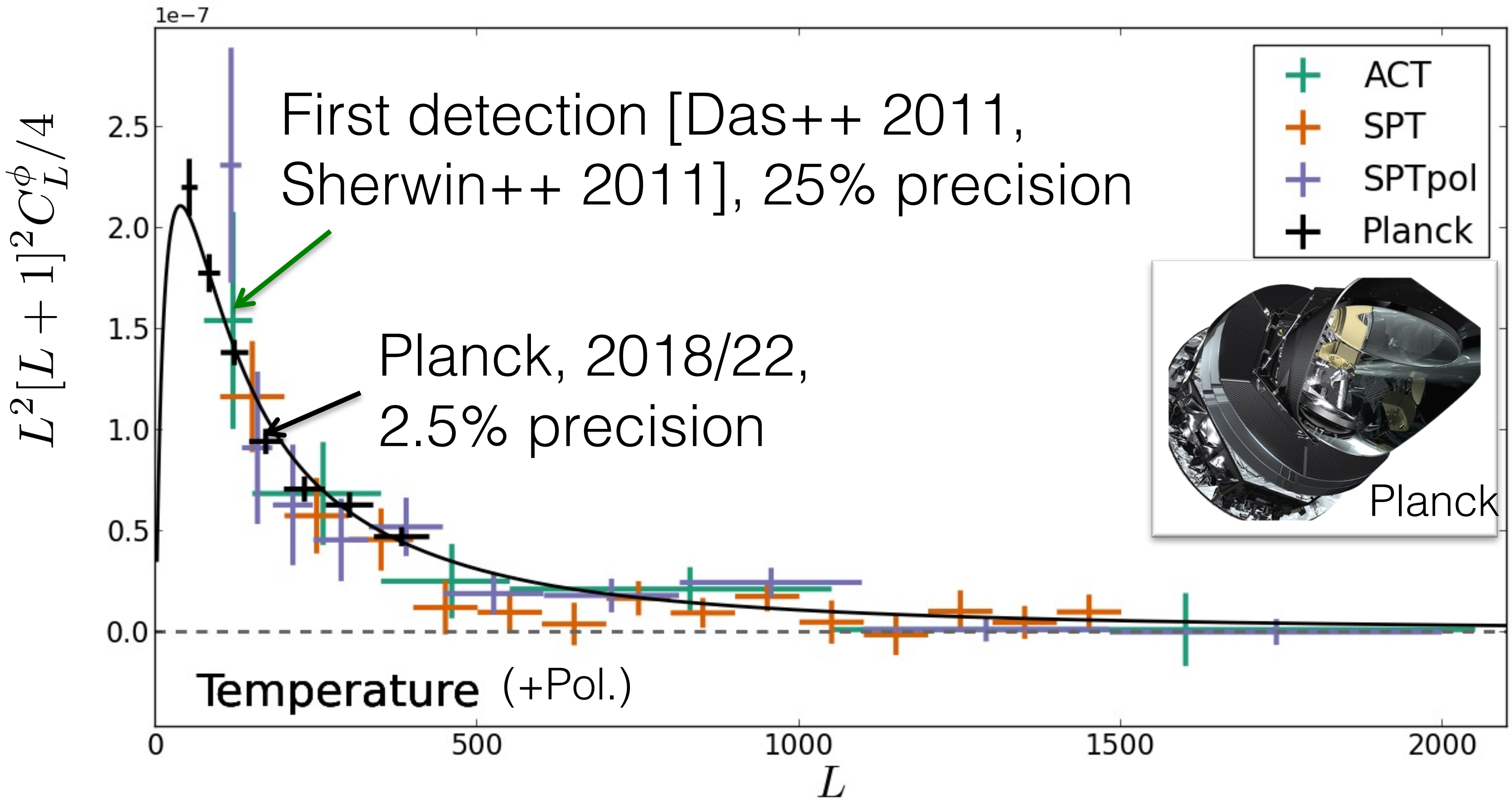
$$\hat{\phi}(\mathbf{L}) = N(\mathbf{L})\mathbf{L} \cdot \int \frac{d^2l}{(2\pi)^2} \frac{\mathbf{l}C_l}{C_l^{noisy}} \Theta(\mathbf{l}) \frac{C_{|L-l|}}{C_{|L-l|}^{noisy}} \Theta^*(\mathbf{l} - \mathbf{L})$$

where N is normalization function of Cls.

- Similar estimators can be derived for polarization (and better ones).

- We can measure lensing power spectrum from this reconstruction (with some complications!)

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

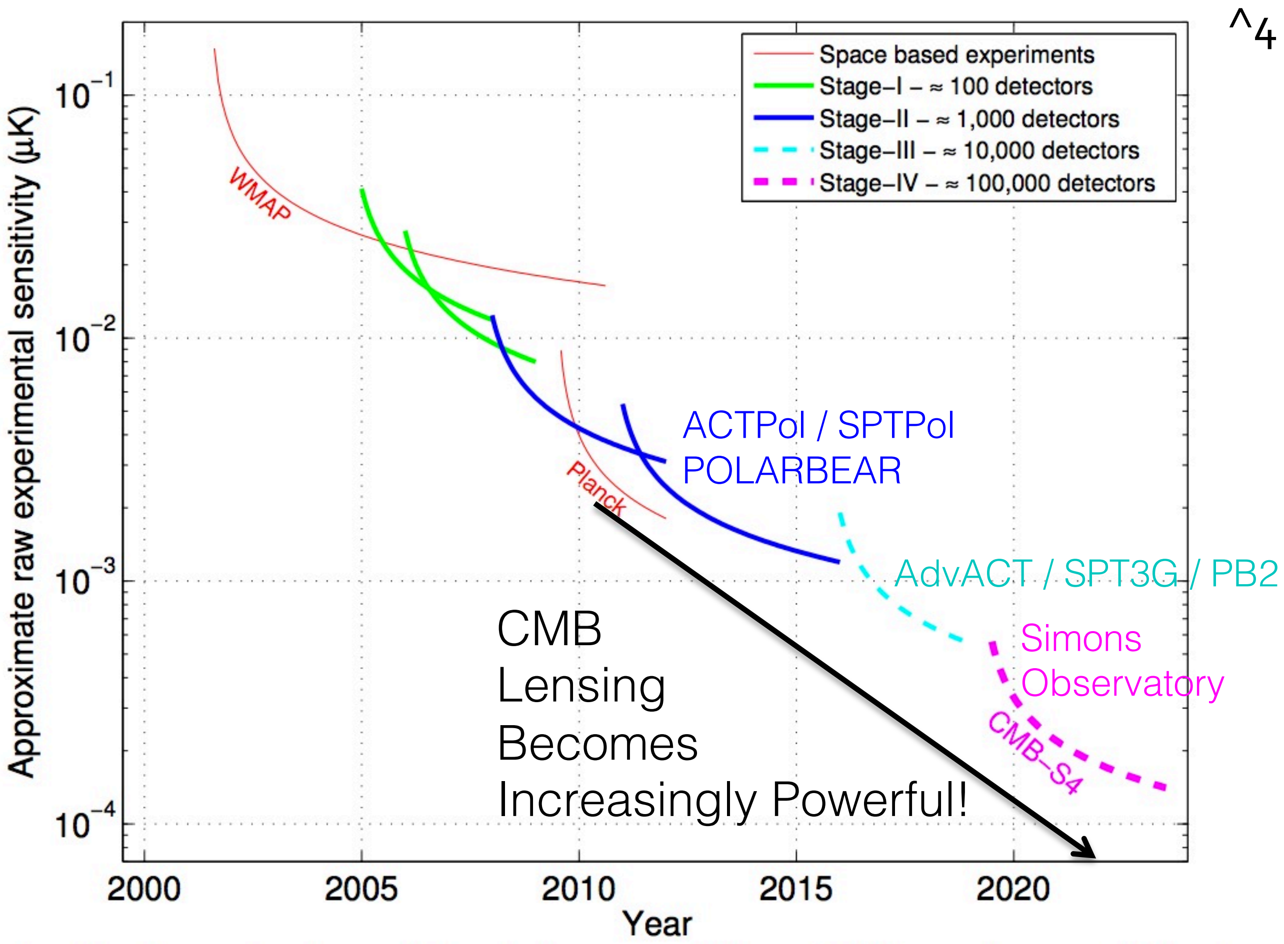


[Planck 2013/15/18]

- Rapid progress – but only just beginning!

Rapid Progress:
Upcoming Ground-Based CMB Experiments

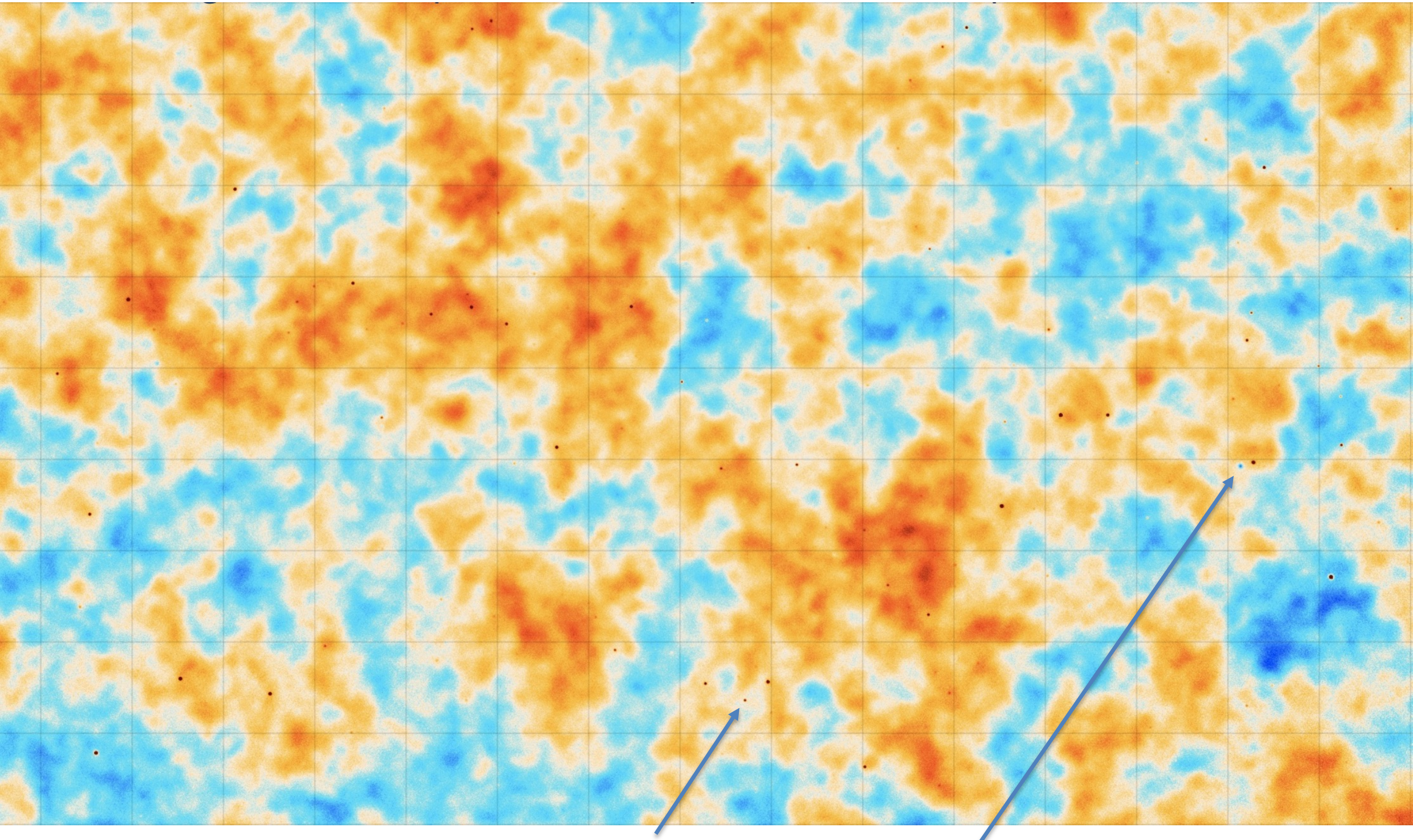
CMB
Experiment
Noise
Level



Atacama Cosmology Telescope (ACT)

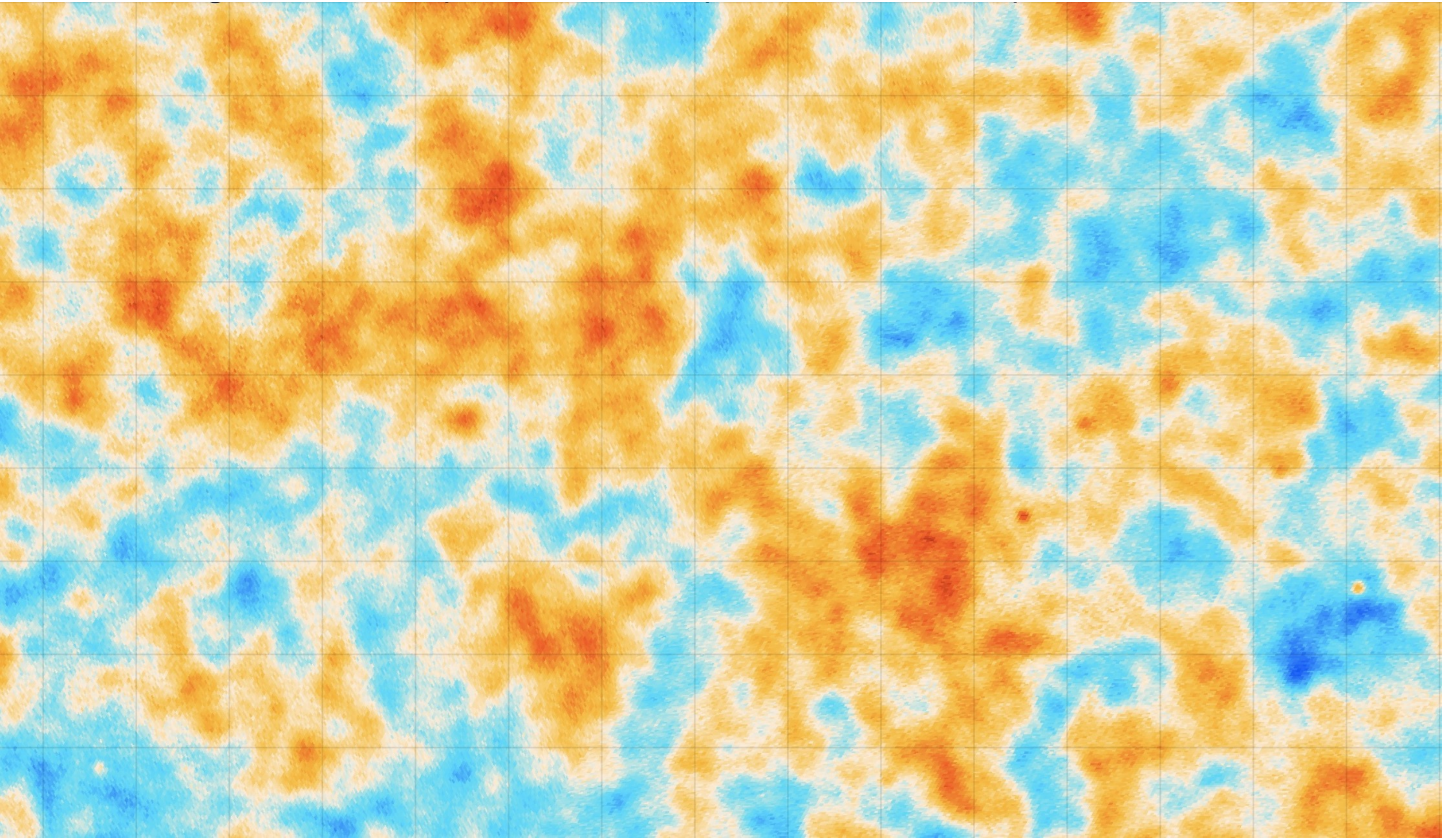
- Arcminute resolution CMB telescope high in the Chilean Atacama desert, with arrays of sensitive (TES bolometer) detectors

High-resolution ACT maps



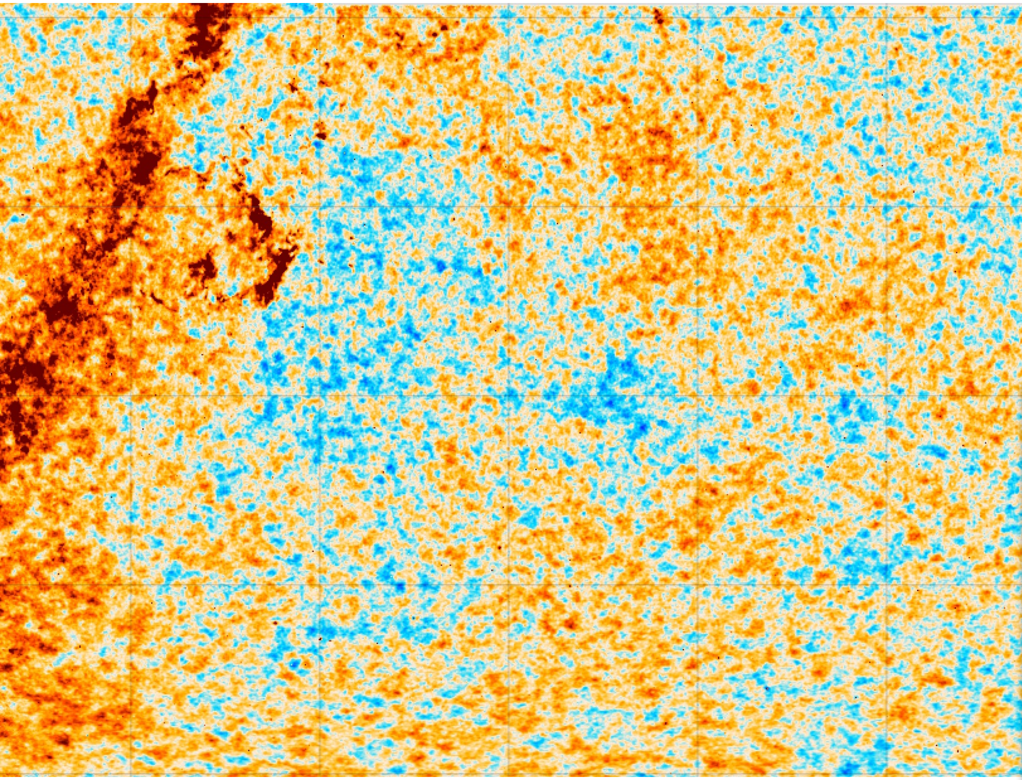
- High resolution, low noise (Radio/IR sources and SZ clusters visible by eye)

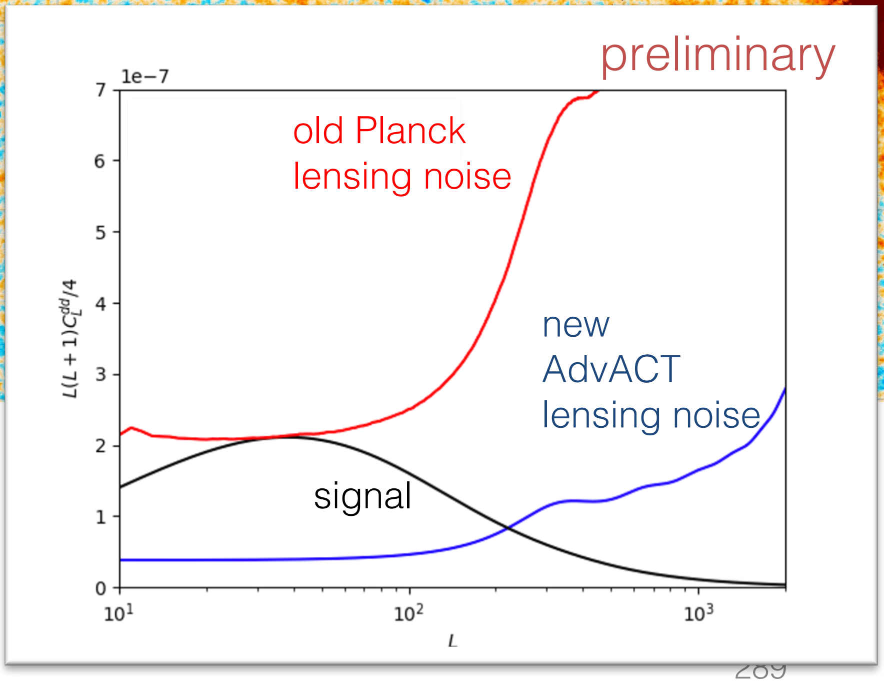
Planck maps



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

AdvACT CMB map

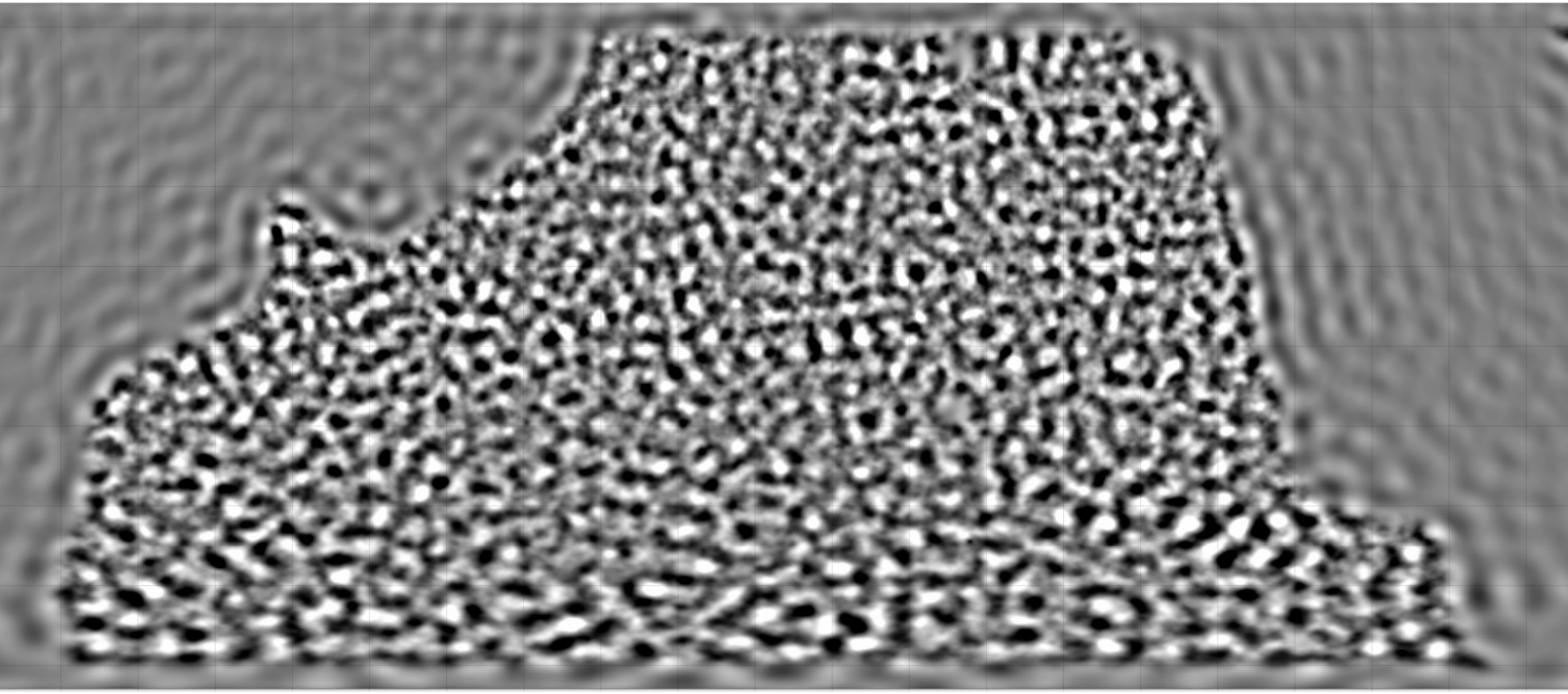




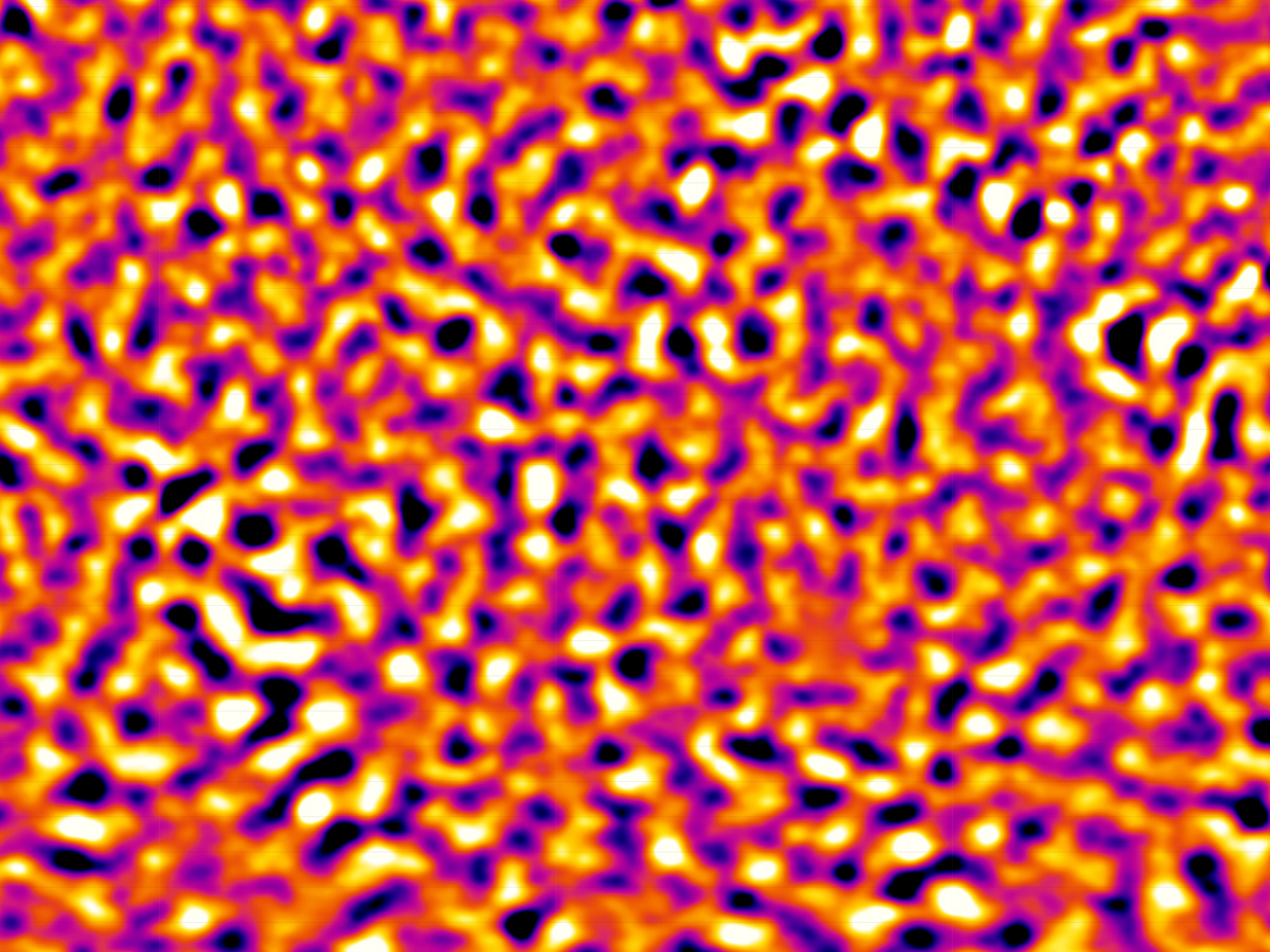
- Gives powerful lensing map! (link)

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

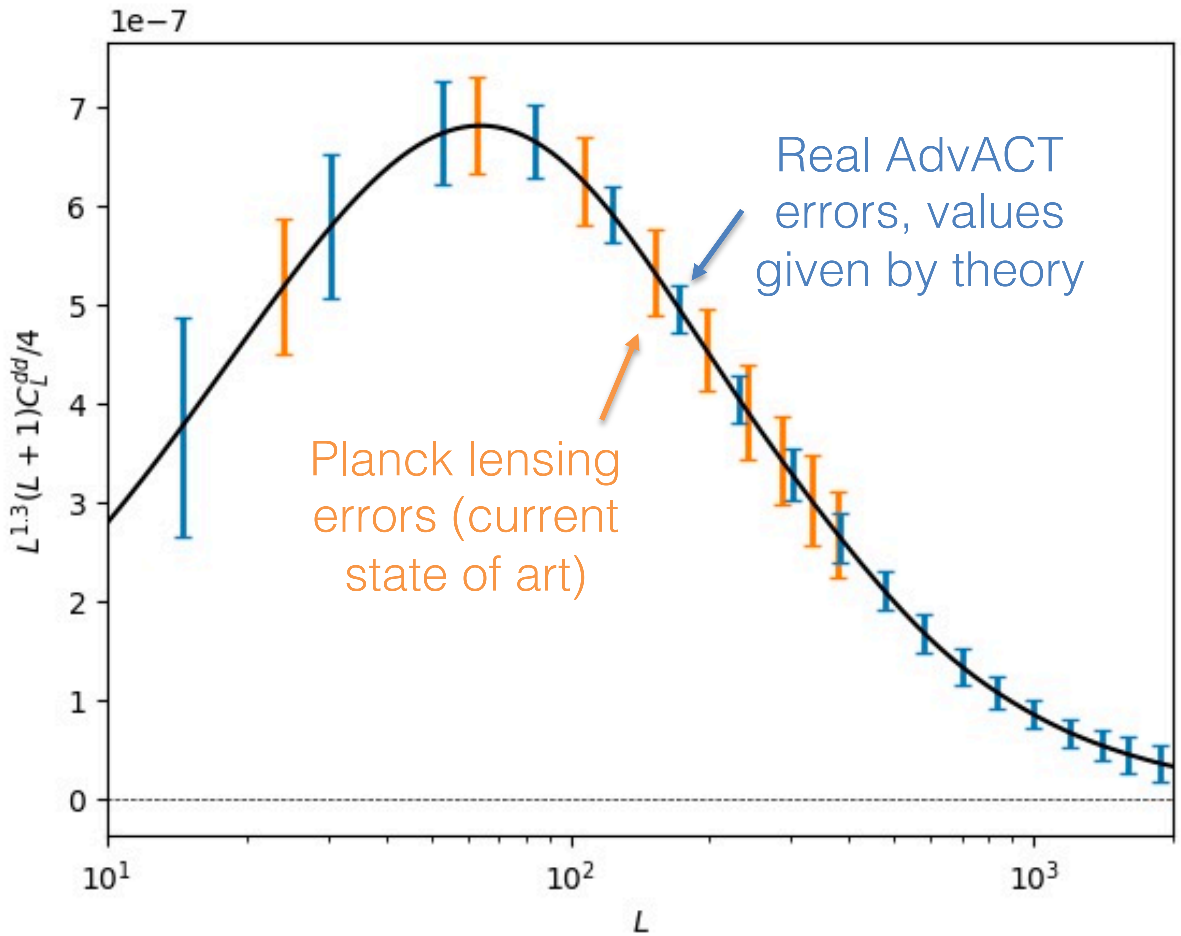
AdvACT CMB lensing map



- Gives powerful lensing map! (link)

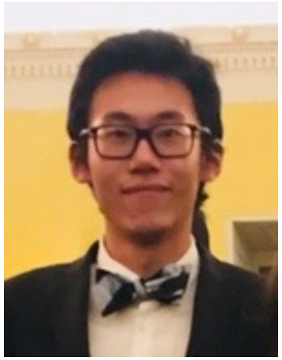


New AdvACT lensing power spectrum errors



preliminary

Frank Qu



+ Mat Madhavacheril, Niall MacCrann

- Expect SNR ~50 (state of the art)

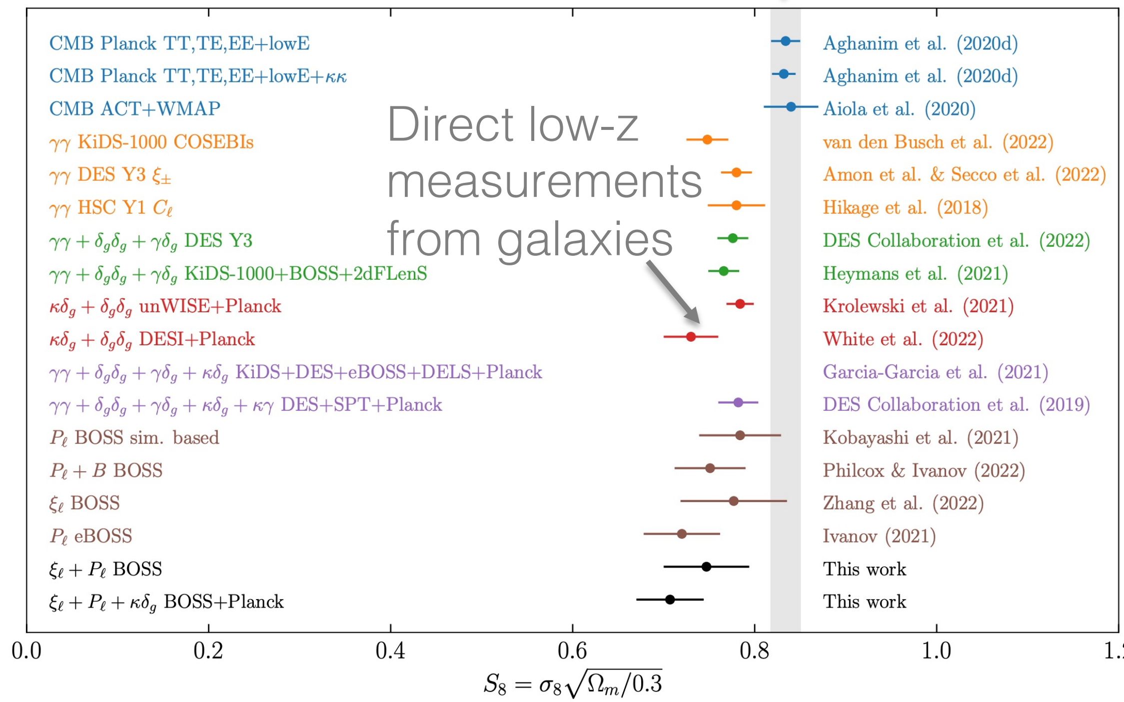
[Qu++ in prep.]

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]



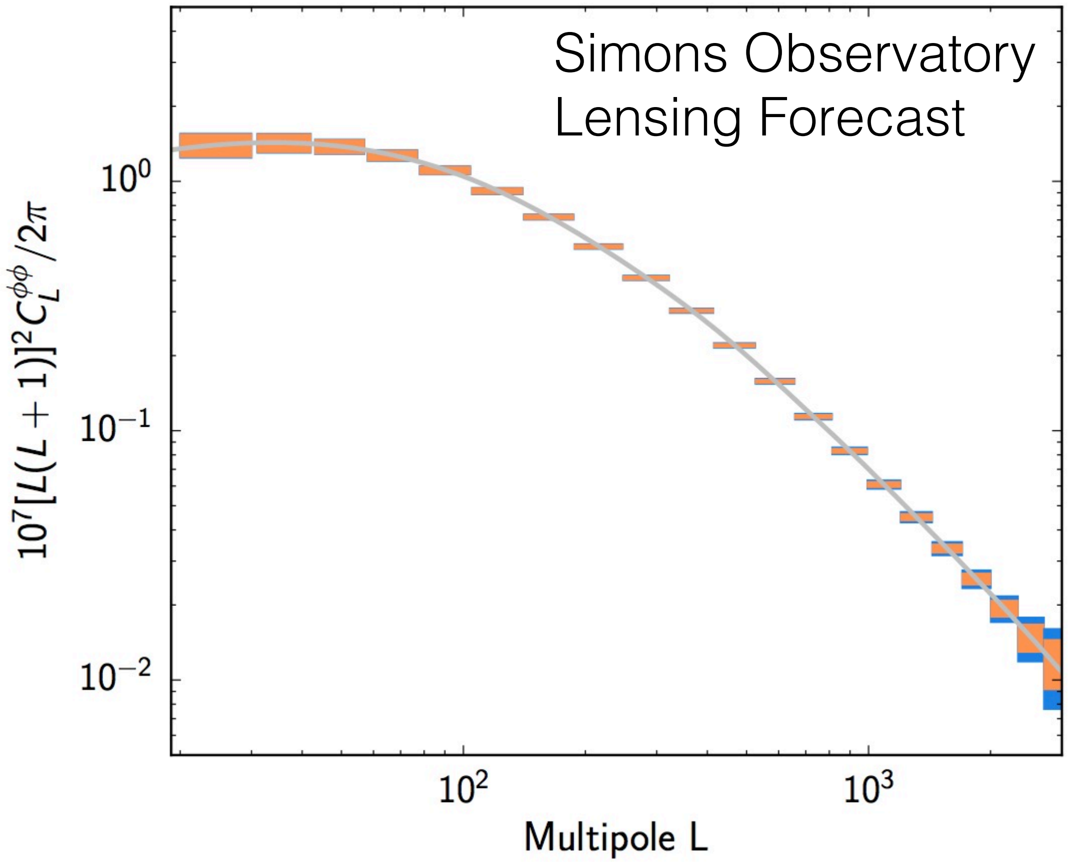
Our error bar size

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

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

Simons Observatory: ~**0.6% precise** lensing, half sky (2020-2025); CMB-S4: ~0.3% precise

- Will determine (to >few sigma) unknown neutrino mass in any scenario

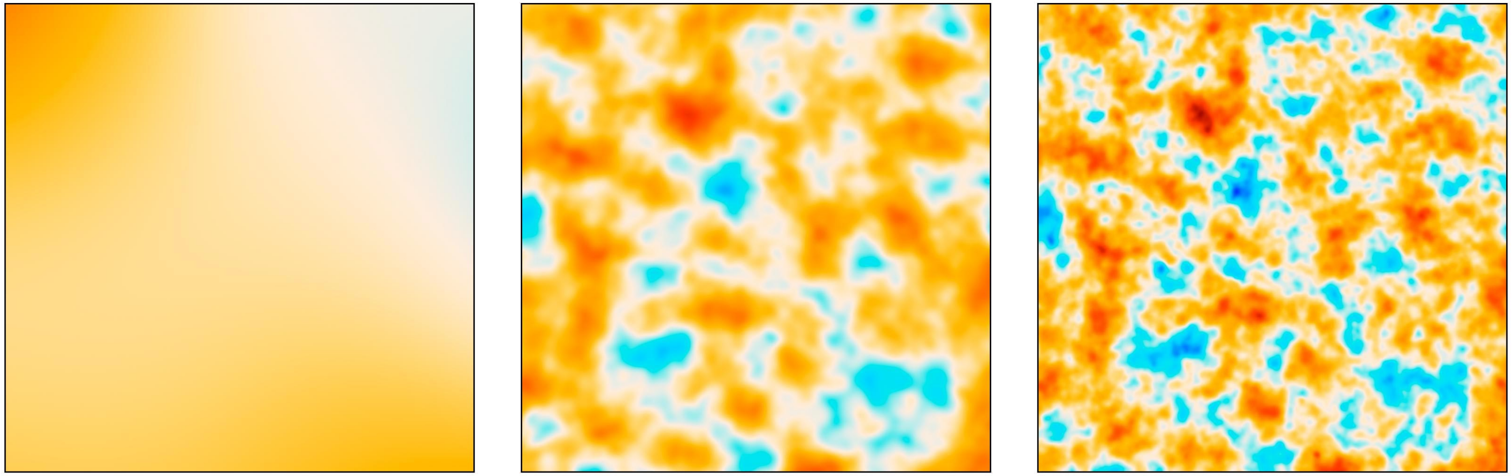


$$\sigma(\sum m_\nu) \approx 20 - 30\mathrm{meV}$$ (Simons Obs. / CMB-S4)

c.f. limit, >60meV

Outline

- CMB lensing basics
- Cosmology dependence
- CMB lensing measurement: methods and some new results
- Effect on power spectra
- Delensing



Effect On Power Spectra

$$\langle\Theta(\mathbf{l})\Theta^*(\mathbf{l}')\rangle = (2\pi)^2 C_{\mathbf{l}}\delta(\mathbf{l}-\mathbf{l}')$$

- Expand temperature in Fourier modes

$$\Theta(\mathbf{x}) = \int \frac{d^2l}{(2\pi)^2}\Theta(\mathbf{l})e^{i\mathbf{l}\cdot\mathbf{x}}$$

- Therefore

$$\tilde{\Theta}(\mathbf{x}) = \Theta(\mathbf{x}+\mathbf{d}) = \Theta(\mathbf{x}) + \nabla\phi\cdot\nabla\Theta + \cdots$$

$$\tilde{\Theta}(\mathbf{l}) = \Theta(\mathbf{l}) + \int \frac{d^2L}{(2\pi)^2}[\mathbf{L}\phi(\mathbf{L})]\cdot[(\mathbf{l}-\mathbf{L})\Theta(\mathbf{l}-\mathbf{L})] + \cdots$$

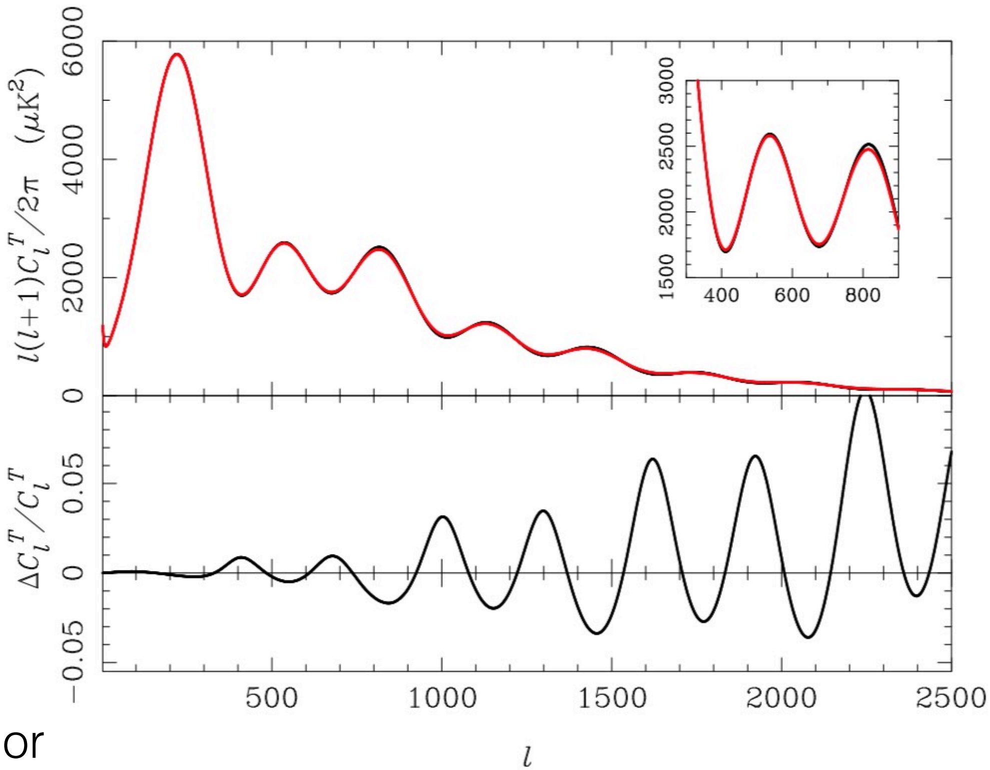
- And the lensed power spectrum follows from

$$\langle\tilde{\Theta}(\mathbf{l})\tilde{\Theta}^*(\mathbf{l}')\rangle = (2\pi)^2 C_{\mathbf{l}}\delta(\mathbf{l}-\mathbf{l}') + \langle\delta^{(1)}\Theta(\mathbf{l})\delta^{(1)}\Theta(\mathbf{l}')\rangle + \langle\Theta(\mathbf{l})\delta^{(2)}\Theta(\mathbf{l}')\rangle$$
$$+\langle\Theta(\mathbf{l}')\delta^{(2)}\Theta(\mathbf{l})\rangle + \cdots$$

Effect On Power Spectra

$$\tilde{C}_{\mathbf{l}} = \left[1 - \frac{1}{2} l^2 \langle d^2 \rangle\right] C_{\mathbf{l}} + \int \frac{d^2 L}{(2\pi)^2} C_{|\mathbf{l}-\mathbf{L}|} C^{\phi}_{\mathbf{L}} [\mathbf{L} \cdot (\mathbf{l} - \mathbf{L})]^2$$

- Second term is a convolution. Interpretation: some regions magnified, some demagnified



Result: Peak Smoothing

Image: A. Challinor

Effect On Power Spectra

- Similar calculation and similar peak-smoothing effect for other polarized spectra

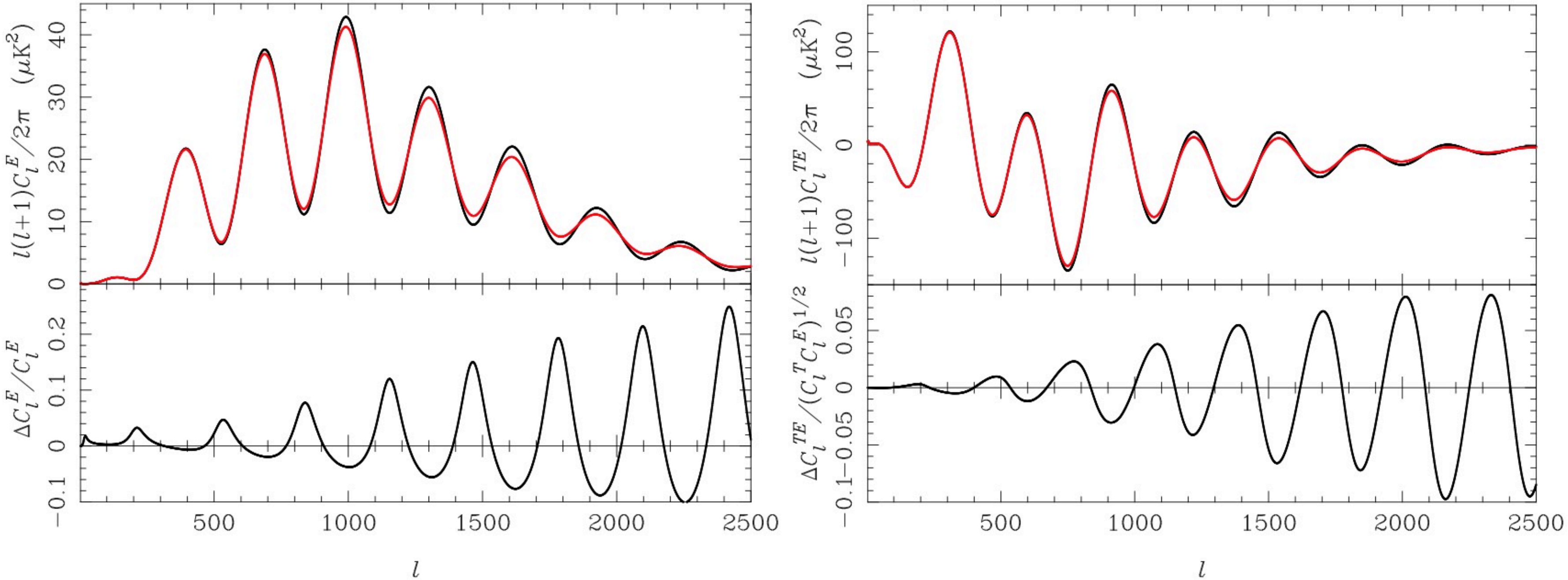
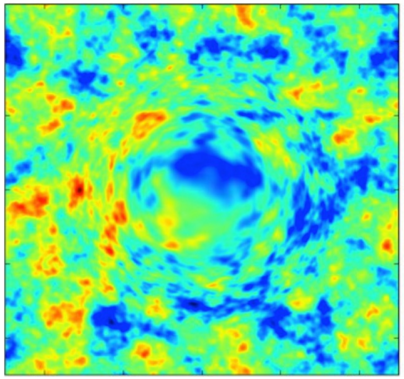
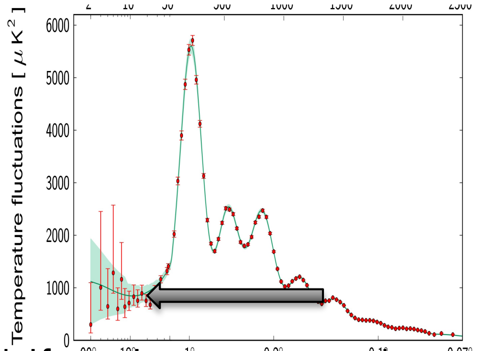


Image: A. Challinor

Interpretation:
Some Regions Magnified, Some Demagnified

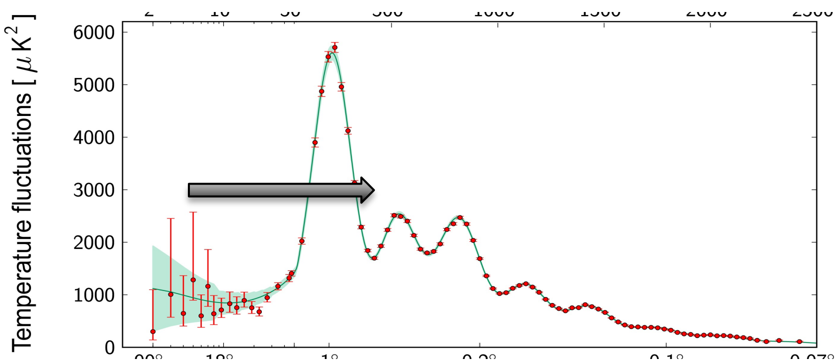


Magnified region:



shift to larger angular scales

Demagnified region:



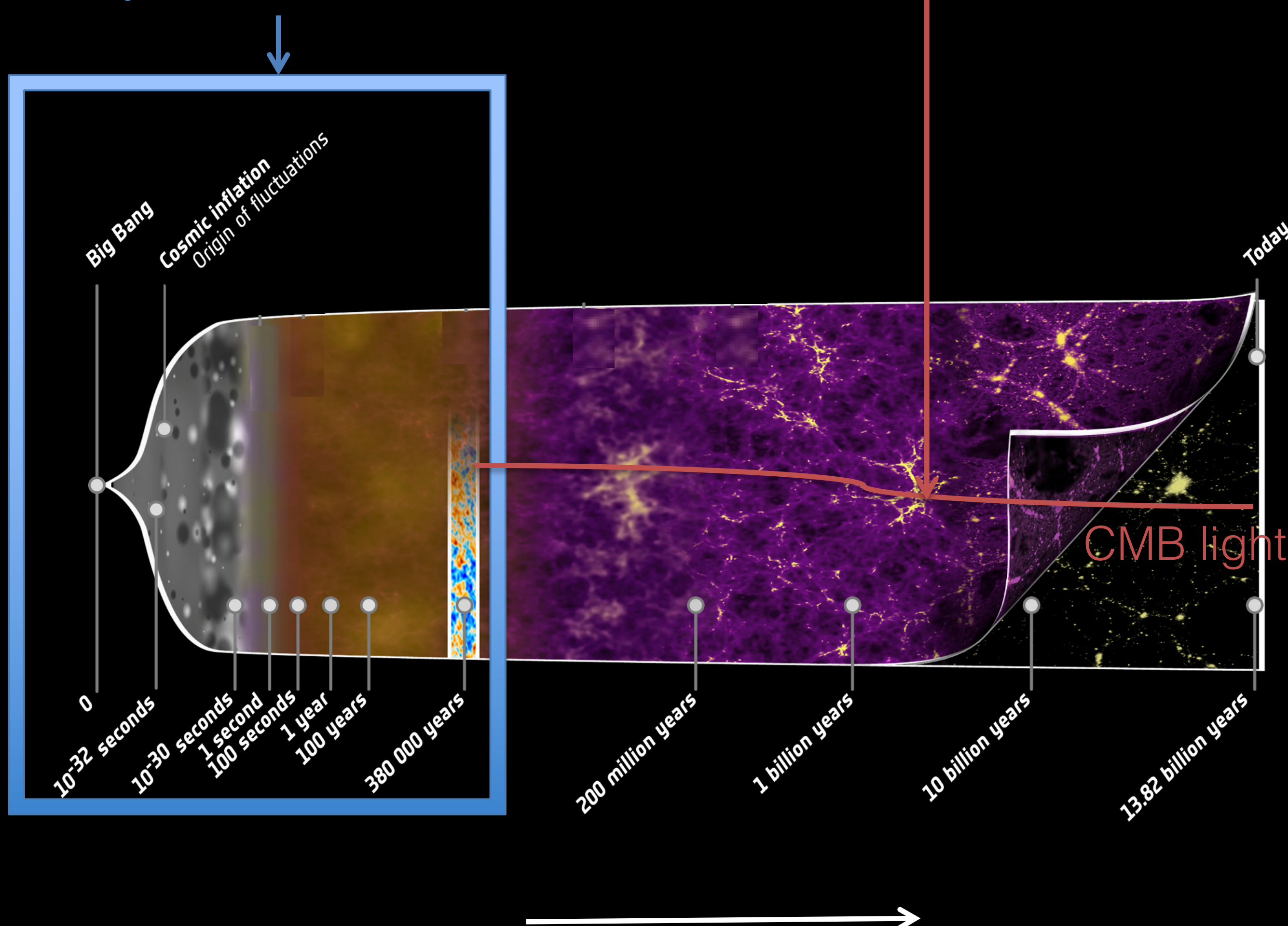
shift to smaller angular scales

- Some spectra shifted to high ell, some to low. Net effect is blurring / smoothing.

CMB Lensing as Noise for Early Universe Cosmology

If we are interested in the early universe

Now lensing is a problem!



time (+ distance light travels!)

Outline

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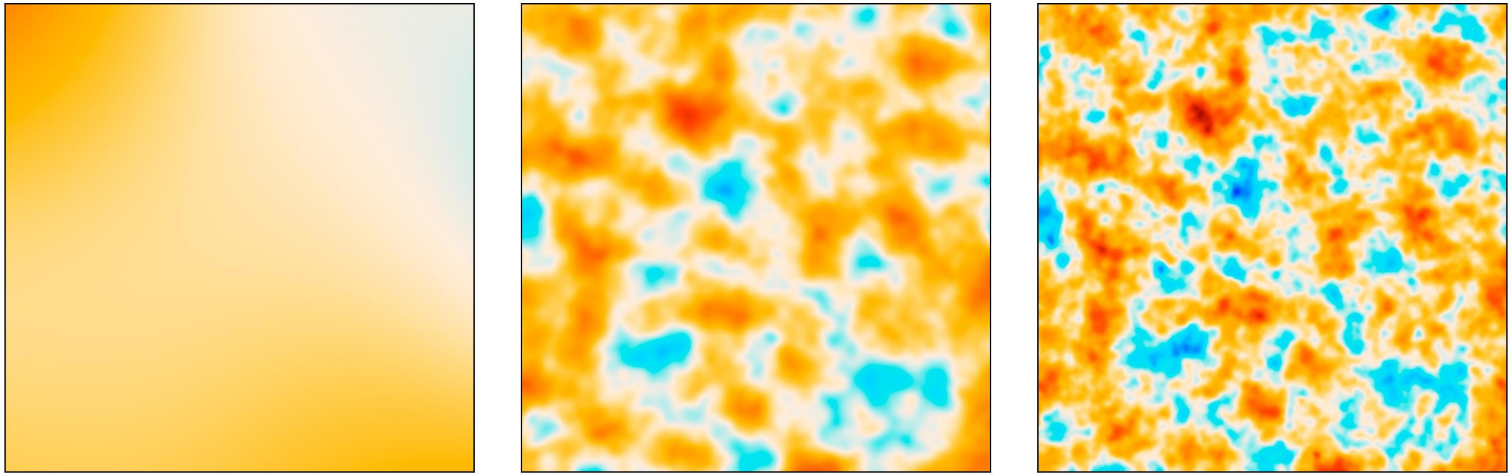
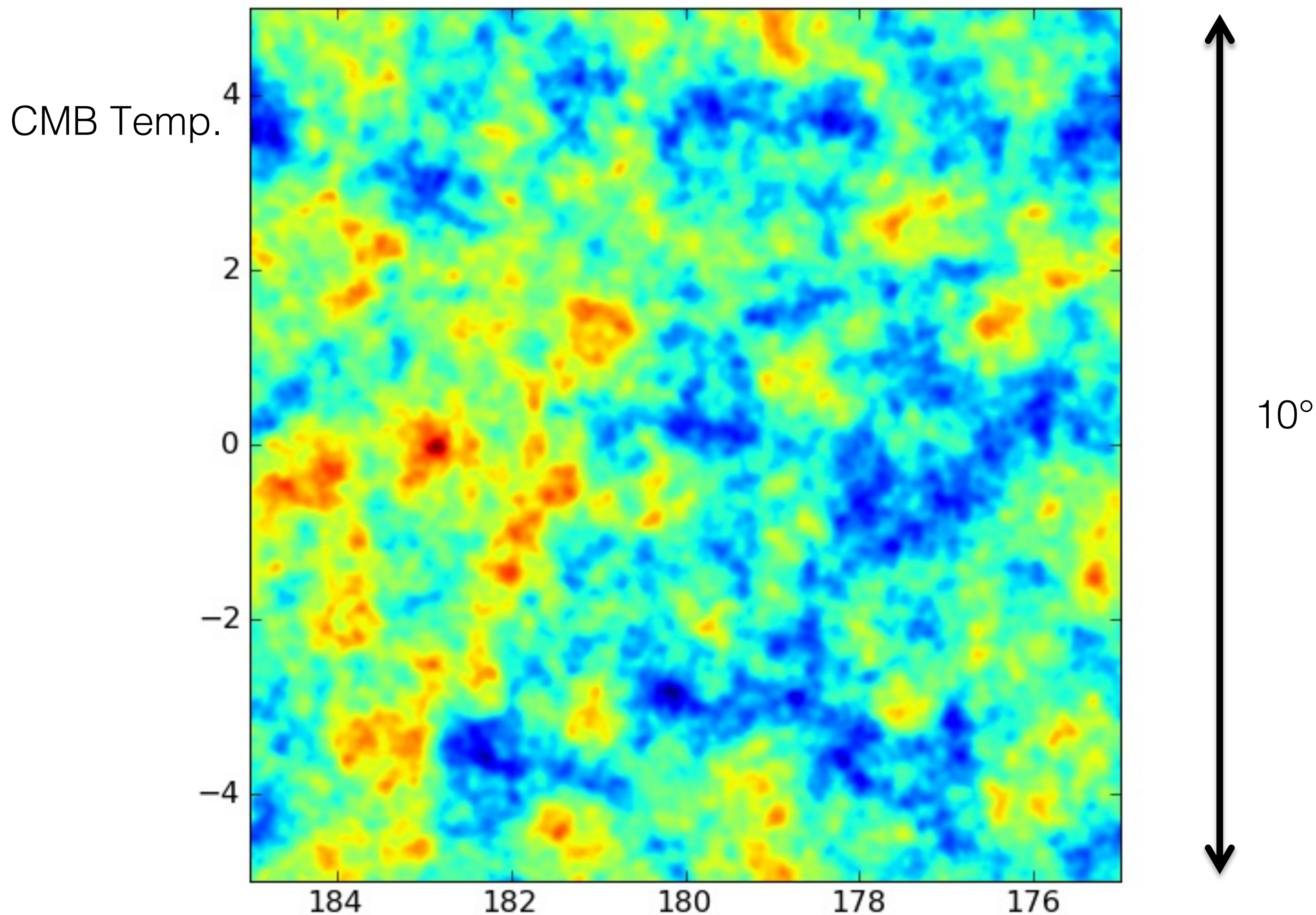
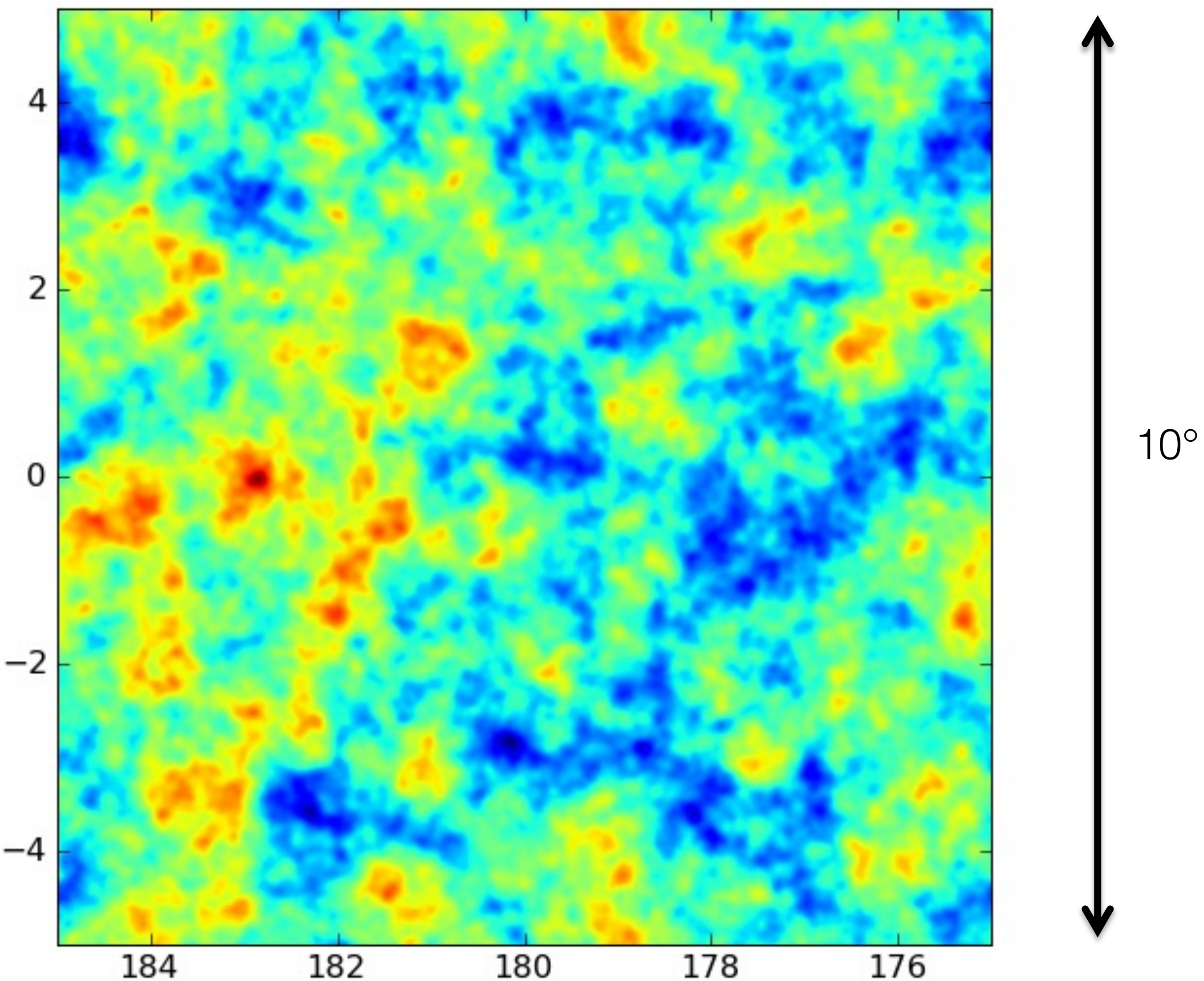


CMB temperature with no r



CMB temperature with very small r

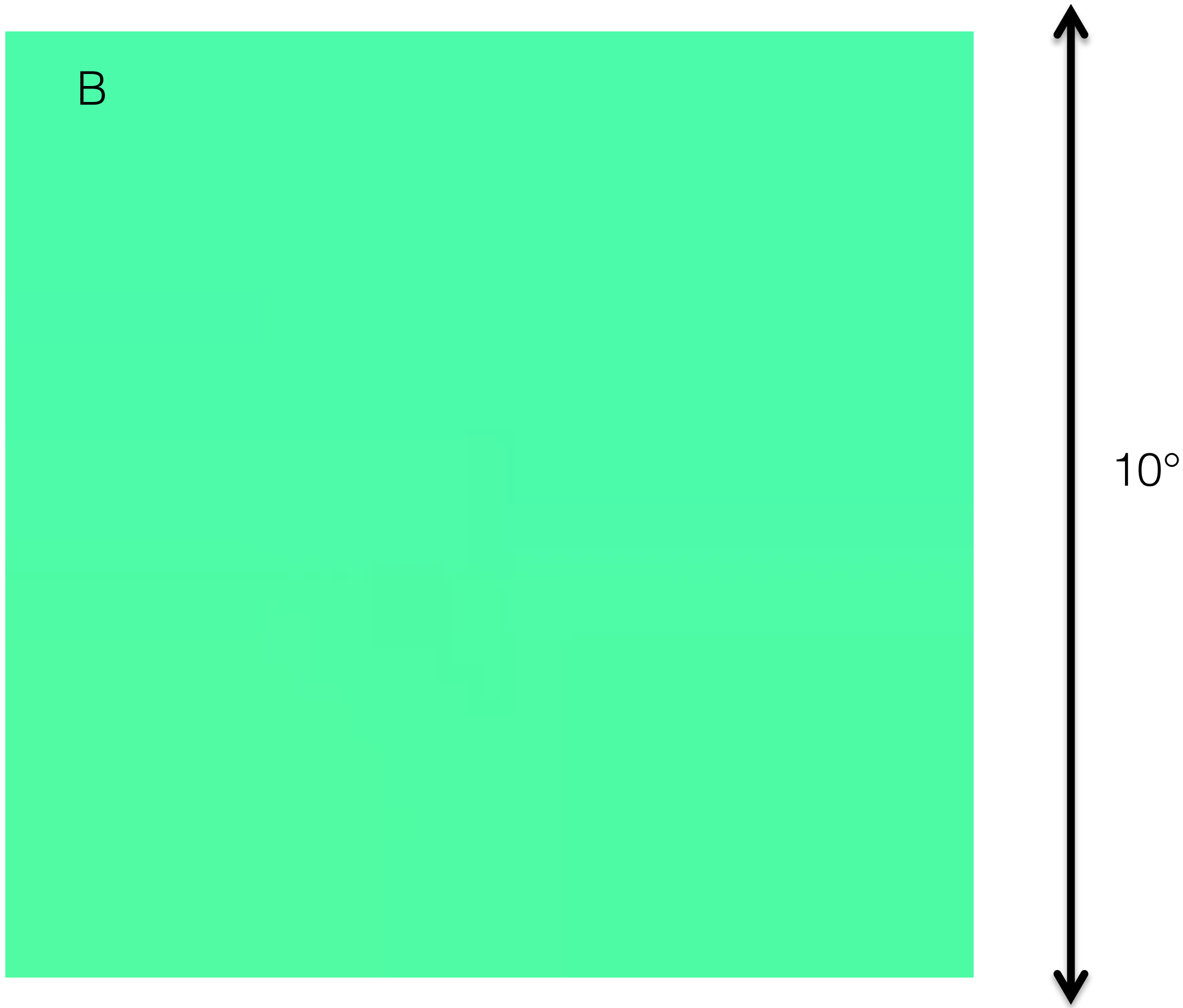
CMB Temp. (cartoon picture)

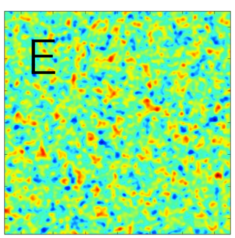


difficult to find r due to cosmic variance and confusion from scalar density perturbations

CMB B polarization* with r = 0

No leading order signal from scalar density perturbations!



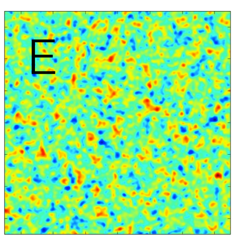


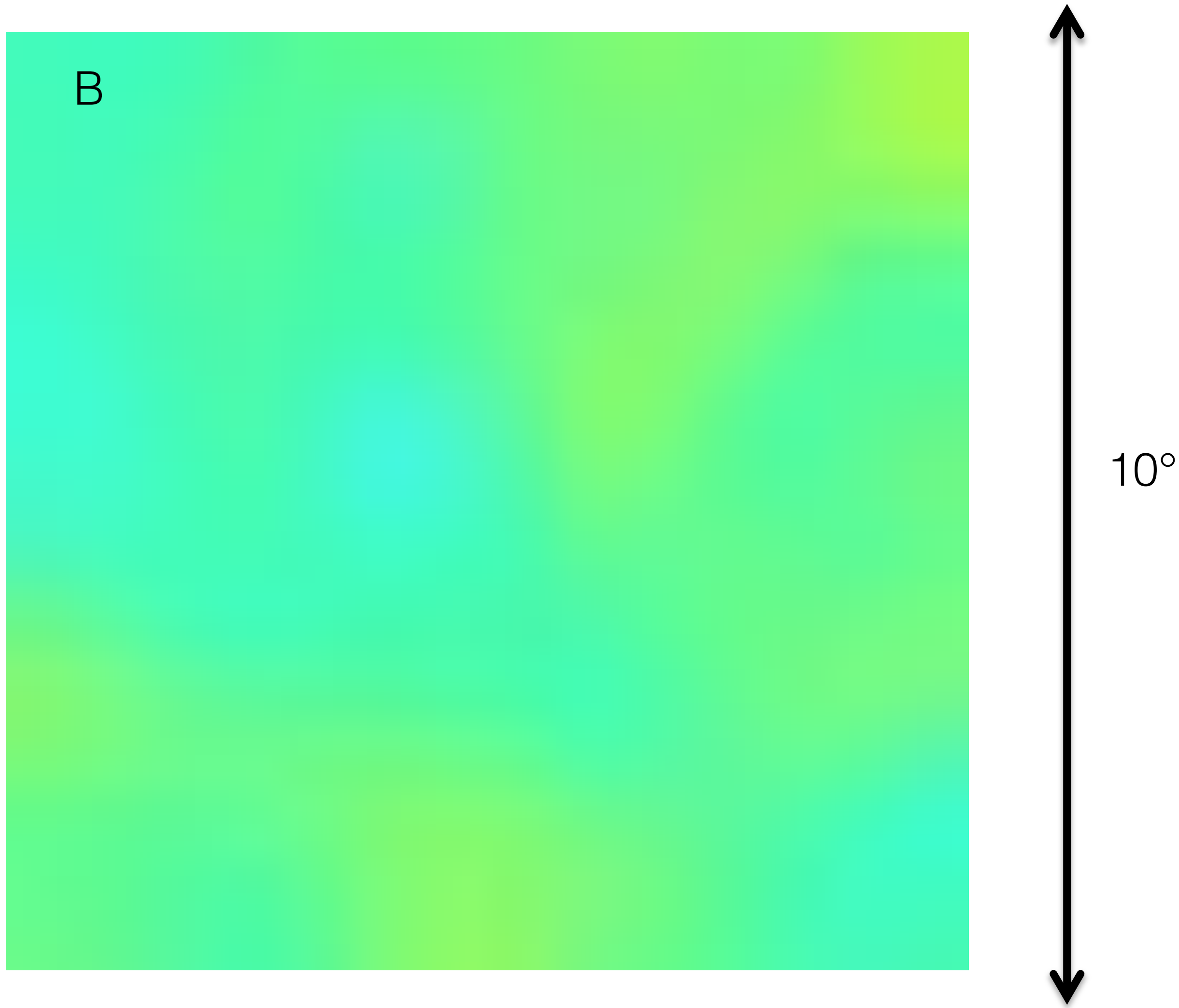
*ignoring foregrounds, lensing for now

CMB B polarization* with small r

See r clearly as there is no background variance from scalar density perturbations

B-modes are a "null channel"

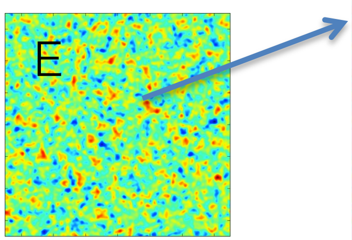


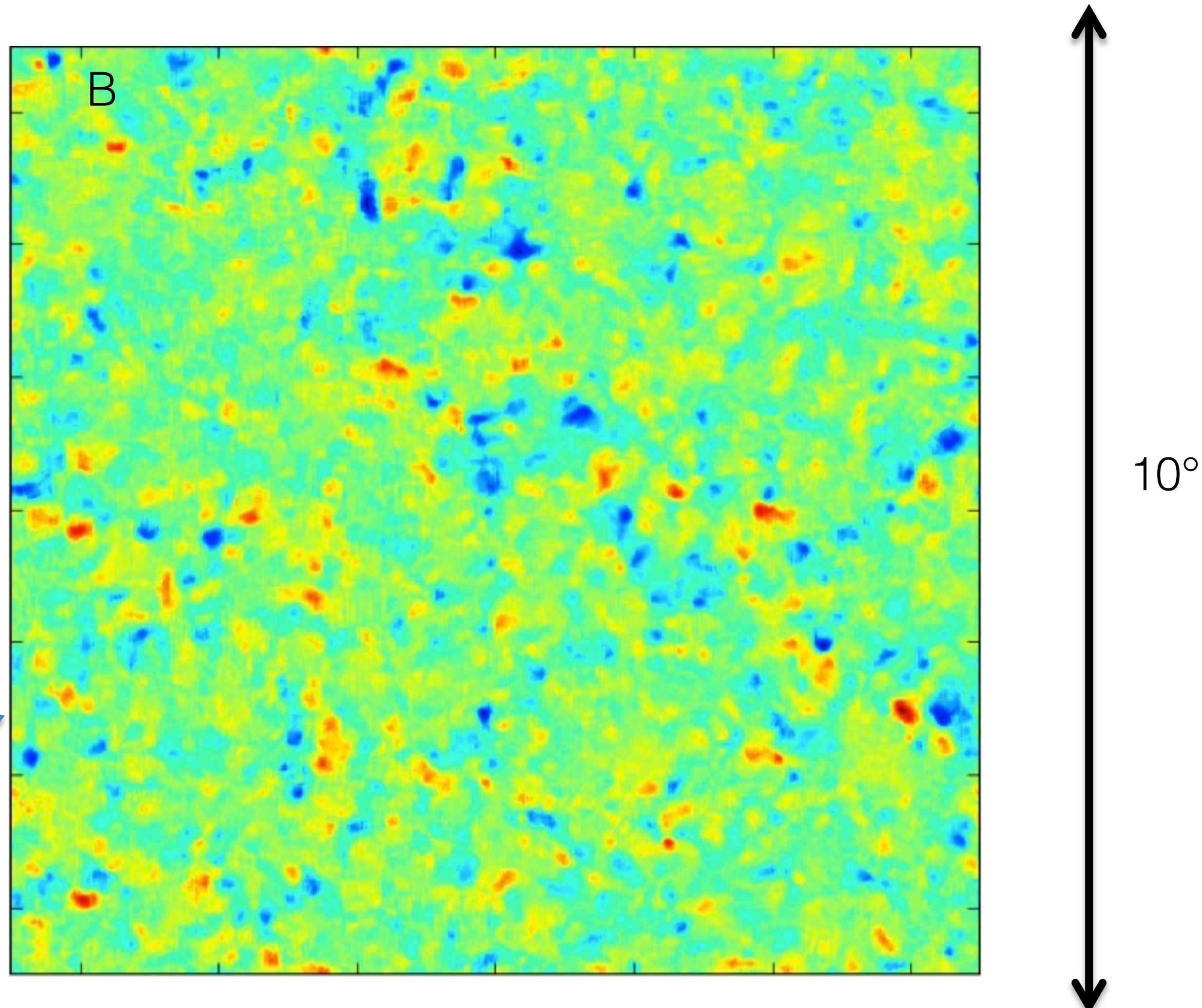


*ignoring foregrounds, lensing for now

Lensed CMB B-Polarization

Gravitational lensing converts E- to B-polarization:

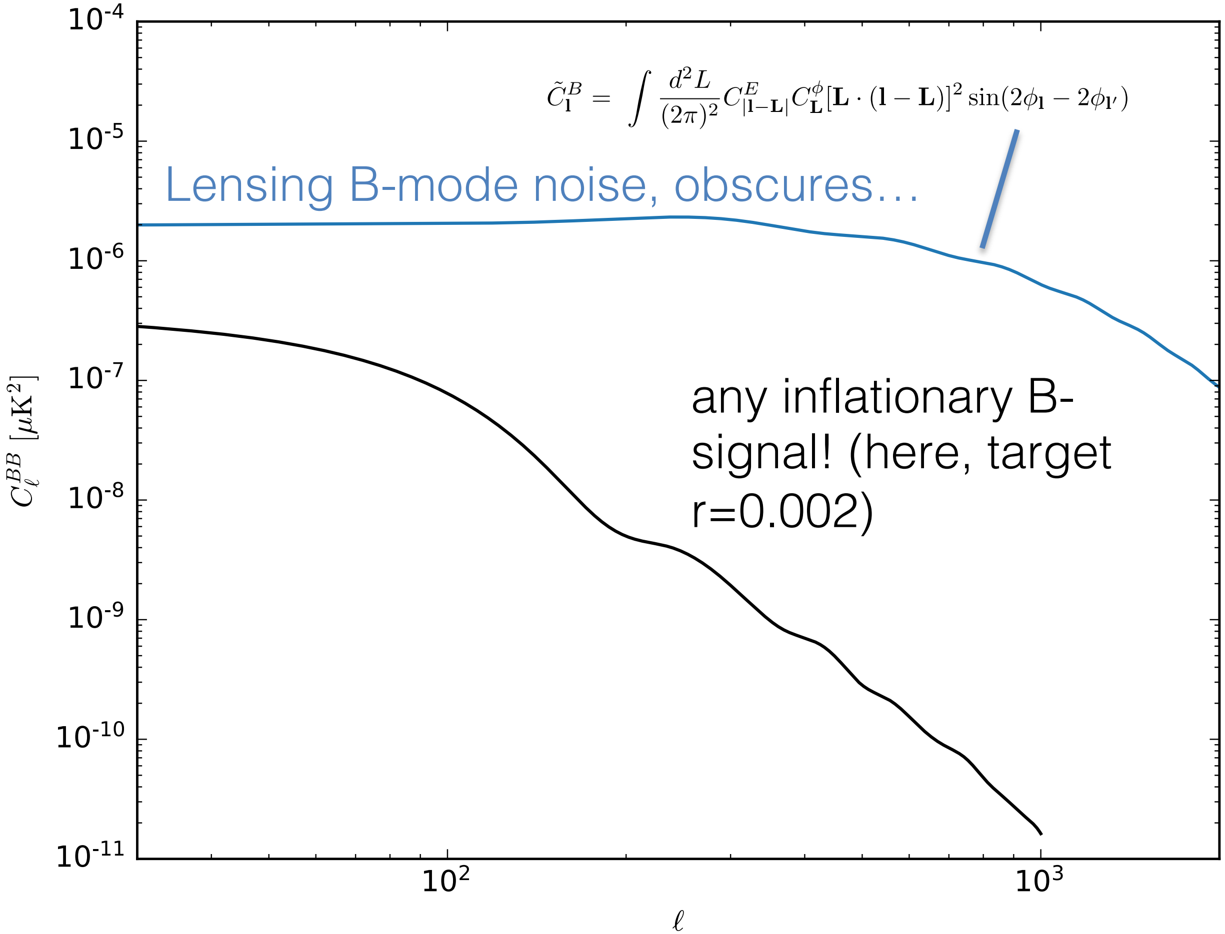




$$B^{lens}(\mathbf{l}) \sim \int d\mathbf{l}' \; W(\mathbf{l},\mathbf{l}')E(\mathbf{l}')\phi(\mathbf{l}-\mathbf{l}')$$

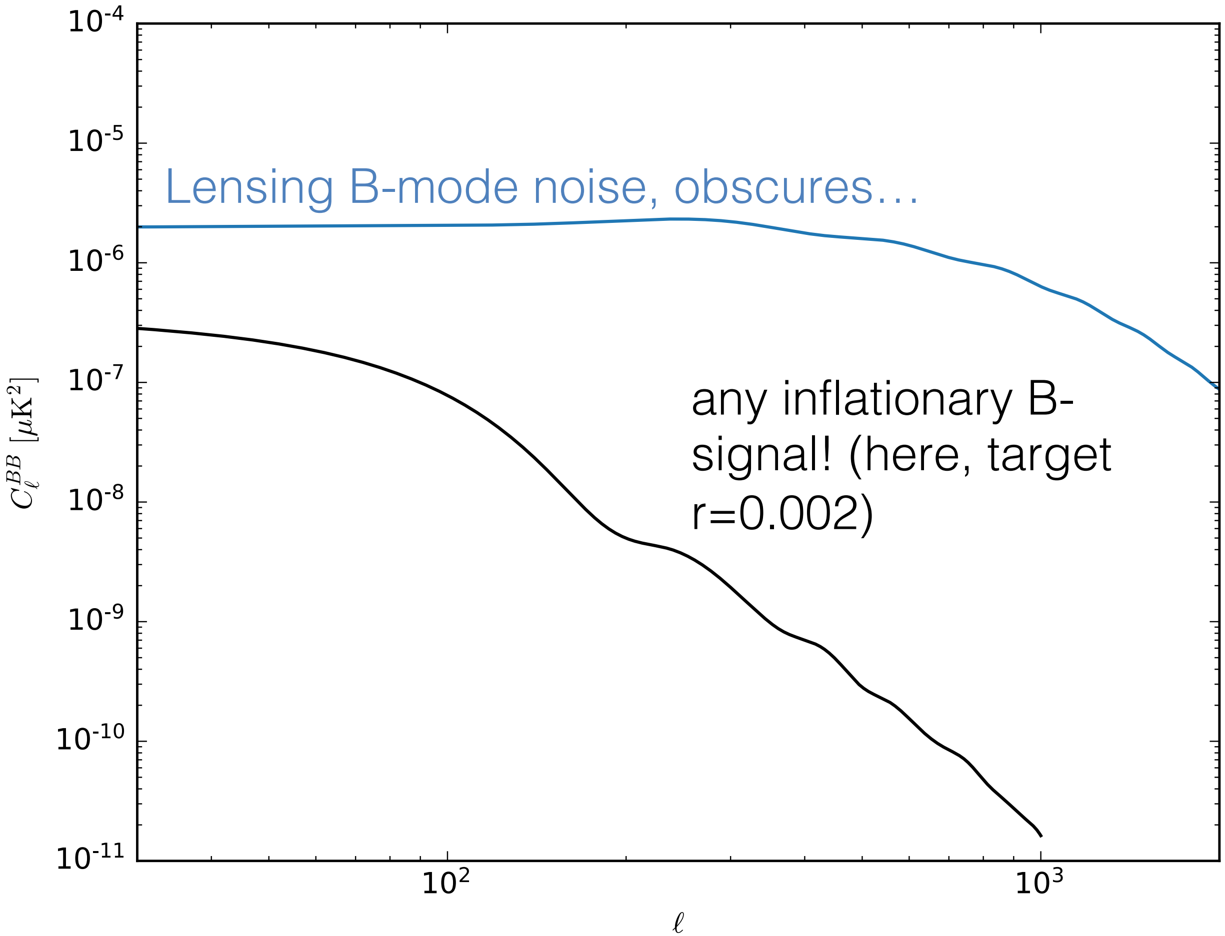
Lensed CMB B-Polarization: Noise for Inflation-B

B-mode power



Lensed CMB B-Polarization: Noise for Inflation-B

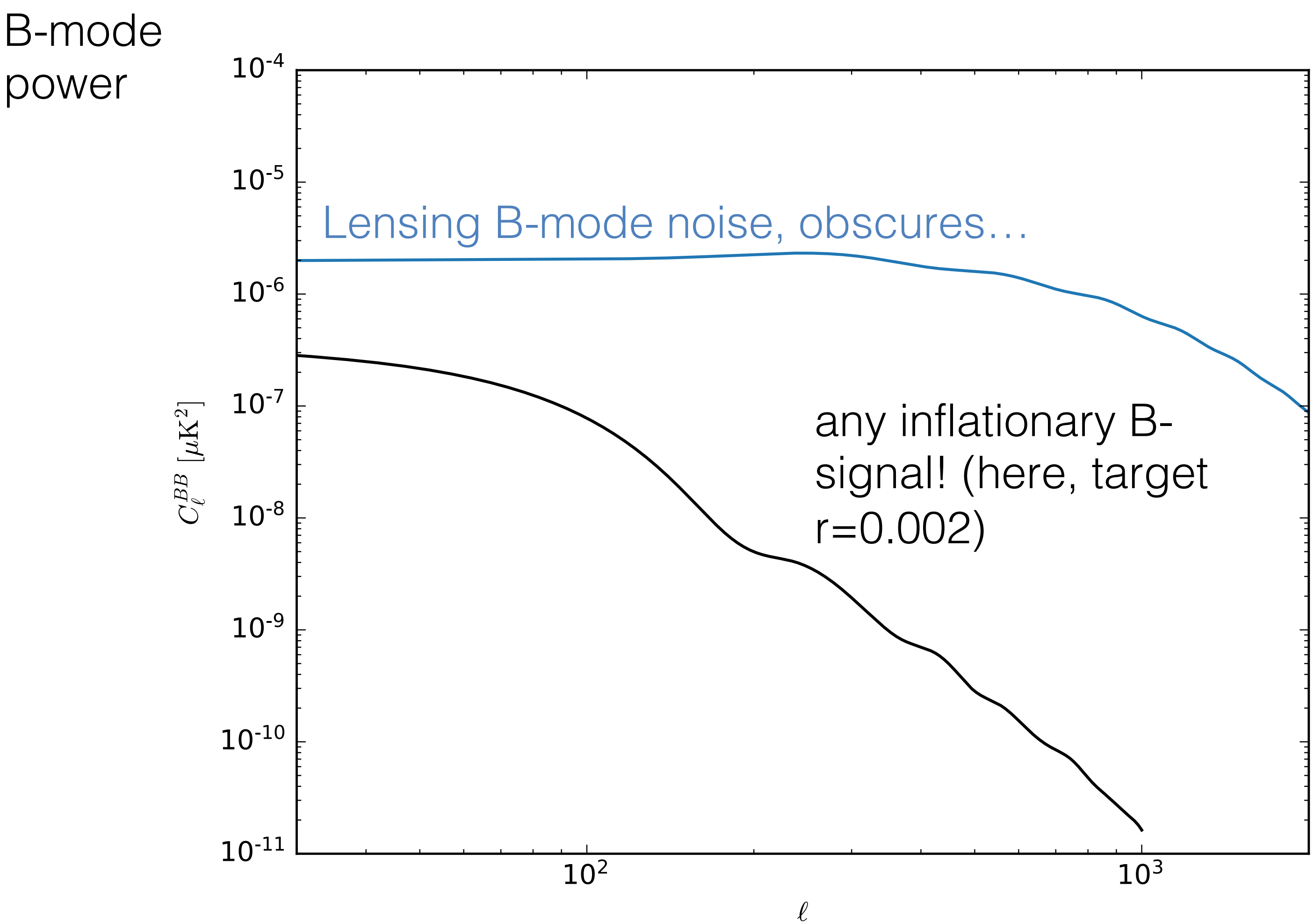
B-mode
power



- Problem: lensing B-modes add additional noise (cosmic variance)

$\sigma(r) \sim (N_l^{BB} + C_l^{BB,lens})$. When $N_l^{BB} < C_l^{BB}$ ~5uK', lensing B is limiting noise

Lensed CMB B-Polarization: Noise for Inflation-B



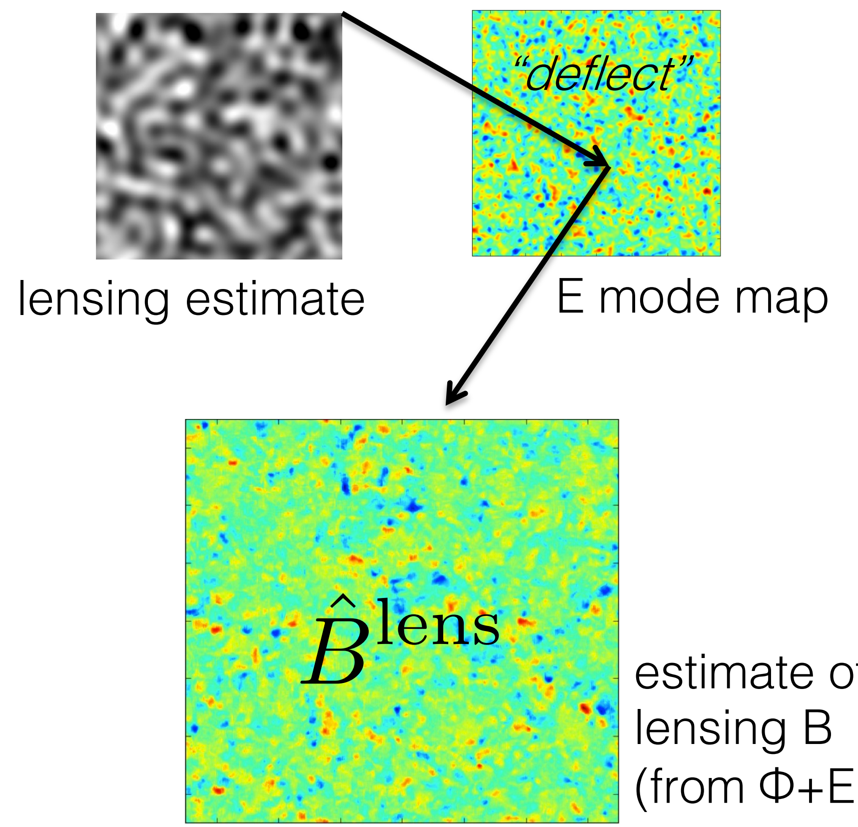
- Problem: lensing B-modes add additional noise (cosmic variance) $\sigma(r) \sim (N_l^{BB} + C_l^{BB,lens})$. ~x 2 error for Simons Observatory, ~10 for CMB-S4

Delensing The CMB

- How to reduce lensing noise?

- Delensing: construct $B_{lensing}$~EΦ map from measured Φ and E and subtract: B - $B_{lensing}$

$$B^{lens}(\mathbf{l}) \sim \int d\mathbf{l}' \; W(\mathbf{l},\mathbf{l}')E(\mathbf{l}')\phi(\mathbf{l}-\mathbf{l}')$$



Delensing The CMB

- How to reduce lensing noise?

$$B^{lens}(\mathbf{l}) \sim \int d\mathbf{l}' \; W(\mathbf{l},\mathbf{l}')E(\mathbf{l}')\phi(\mathbf{l}-\mathbf{l}')$$

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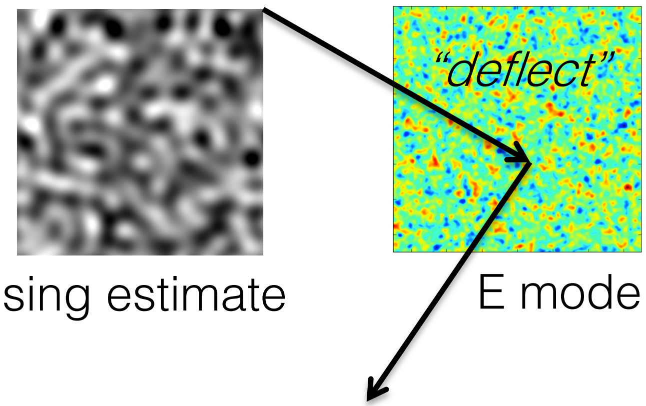
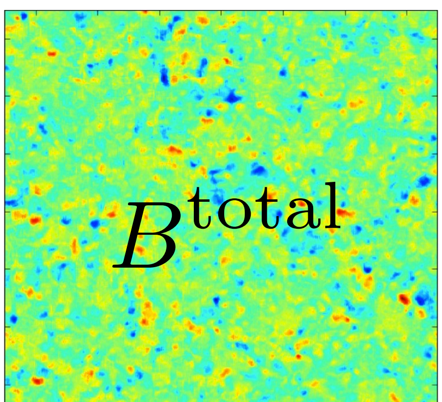


lensing estimate

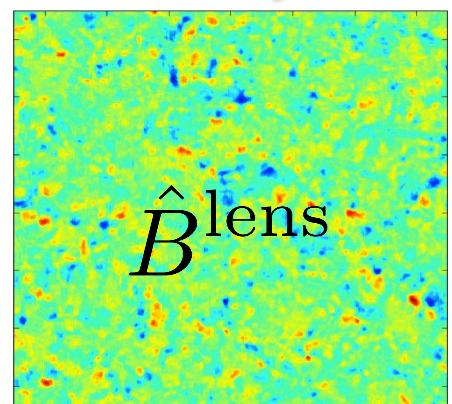
E mode map



measured B map – tensors + lensing

subtract

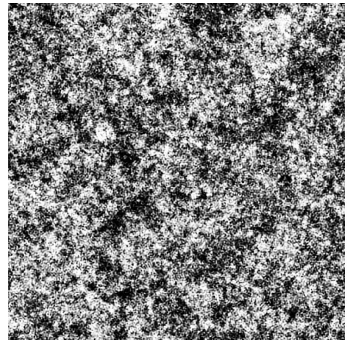
—



estimate of lensing B (from Φ+E)

$$B^{data} - \hat{B}^{lens} \sim B^{data} - \int d\mathbf{l}' W(\mathbf{l},\mathbf{l}')E(\mathbf{l}')\phi(\mathbf{l}-\mathbf{l}')$$

To Delens, Need To Measure Good Maps of CMB Lensing - How?



CMB lensing is a probe of the projected mass distribution

$$\nabla^2 \phi \sim \kappa = \int dz W(z) \delta(z)$$

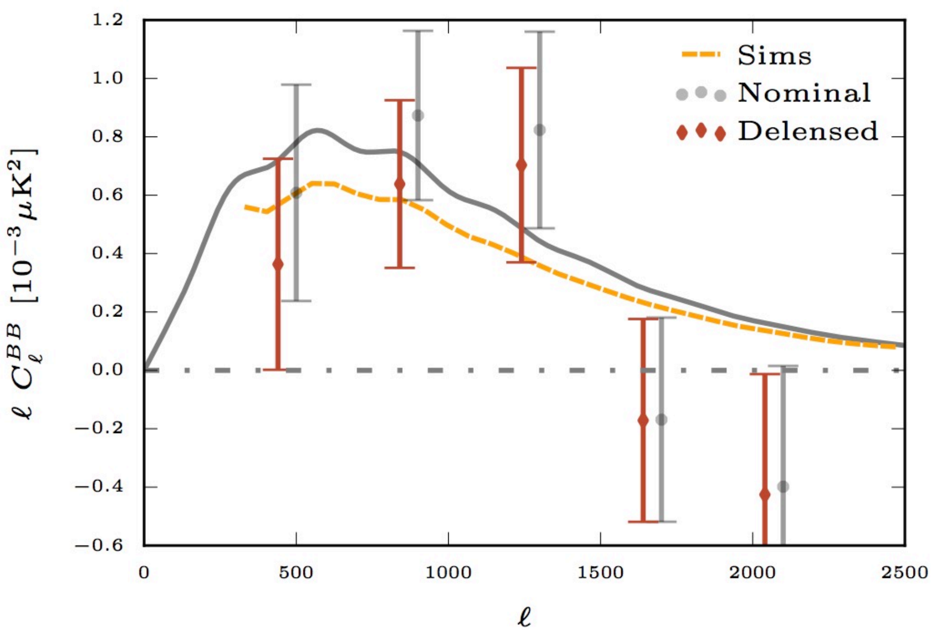
1) Reconstruct lensing from changes in high-res background CMB, e.g., **CMB-S4**. Usually optimal methods needed.

2) Estimate lensing from Large Scale Structure tracers of lensing, e.g. **CIB, Galaxies** [Sherwin/Schmittfull 2015]

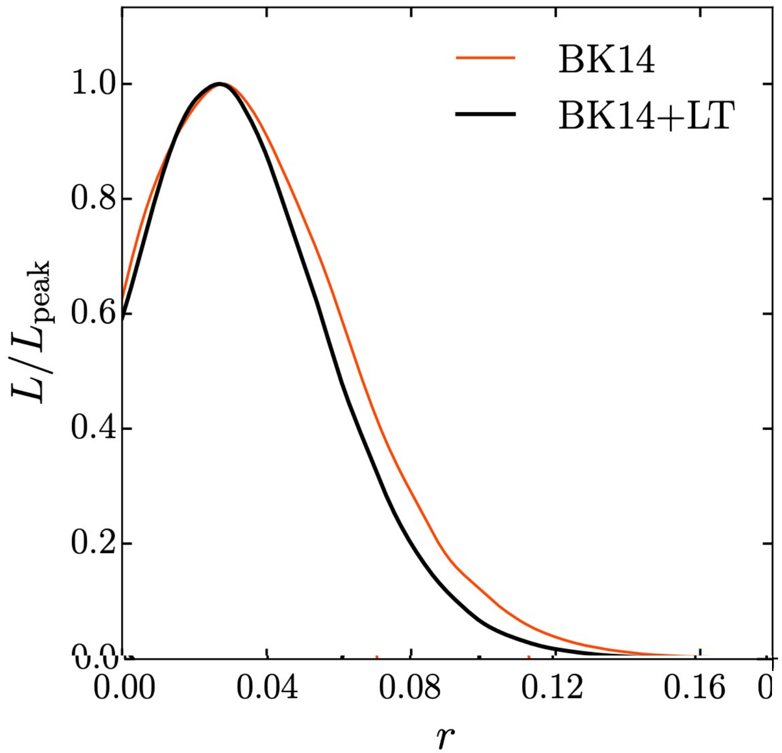
First Delensing Demonstrations

[2016: first demo in CMB temperature]

2017: first reduction in B-mode power



2021: first improved r constraints

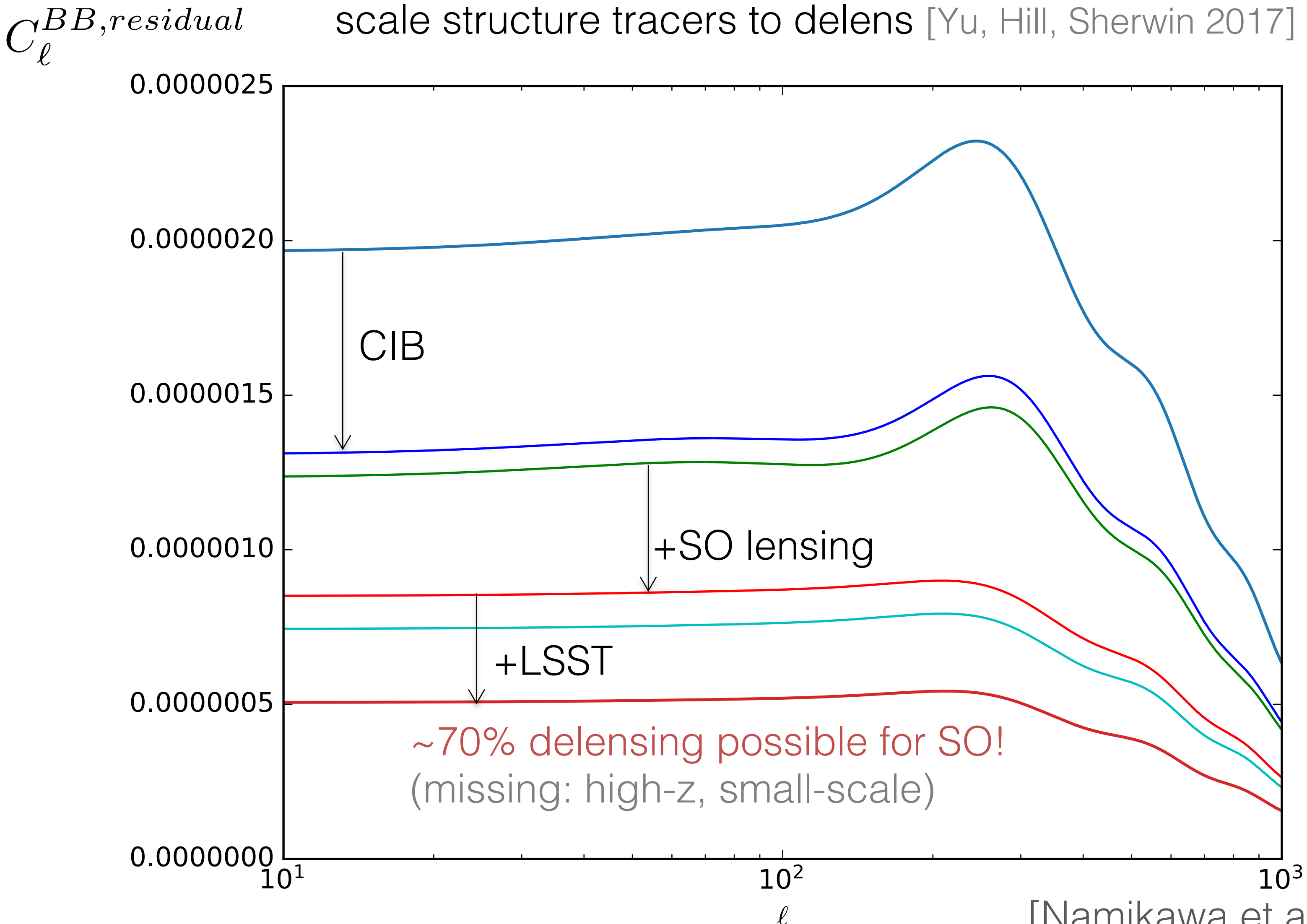


[Larsen, Challinor, Sherwin, Mak 2016, Manzotti++ 2017, Carron++ 2018, BK 2021]

- First demonstrations give us confidence that methods work!

Example: Multi-tracer Delensing for Simons Observatory

Can linearly co-add SO lensing map with different large scale structure tracers to delens [Yu, Hill, Sherwin 2017]



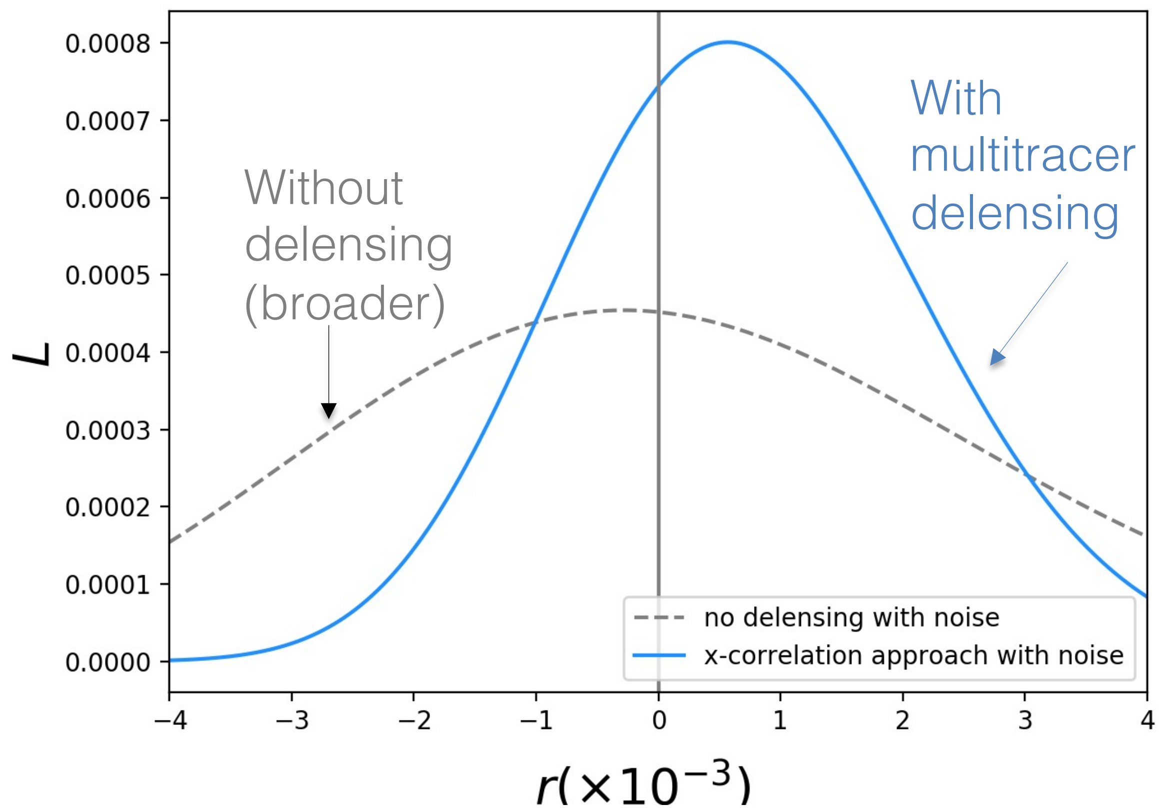
[Namikawa et al. 2021]

Example: Simulations of future SO delensing

- Significant improvements appear possible with multitracer delensing methods, ~2x improvement in SO r constraints

- Important, as near thresholds from interesting models

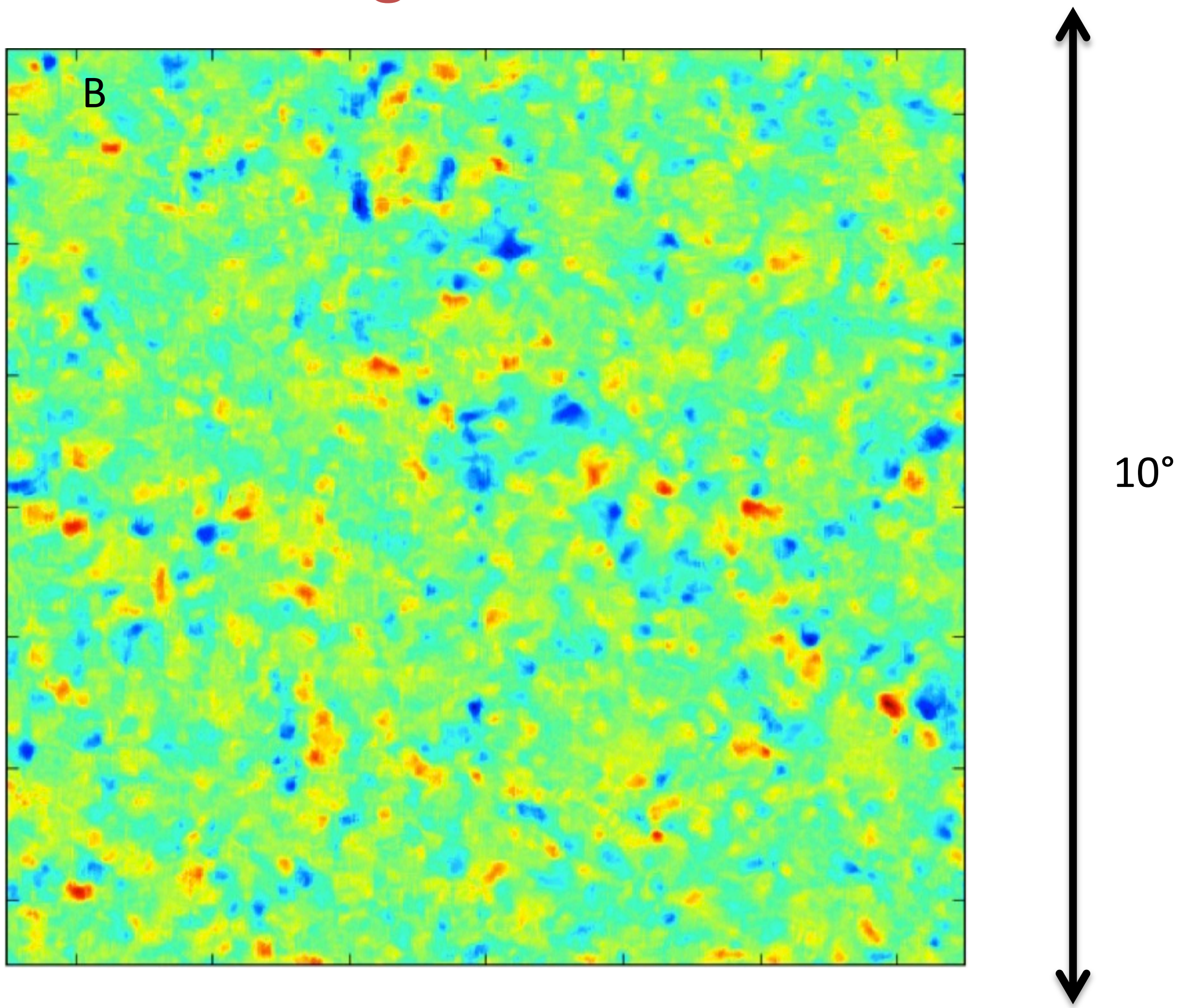
Preliminary



[Simons Observatory Collaboration]

[Namikawa et al. 2021]

Future B Mode Map – Lensing-Dominated



Delensed B Map – Inflation Signal?