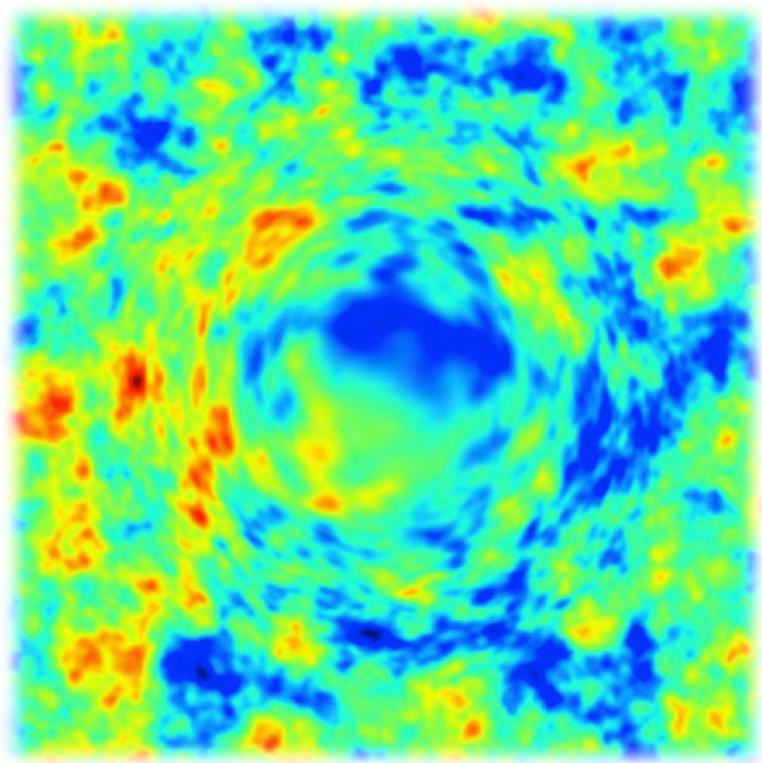
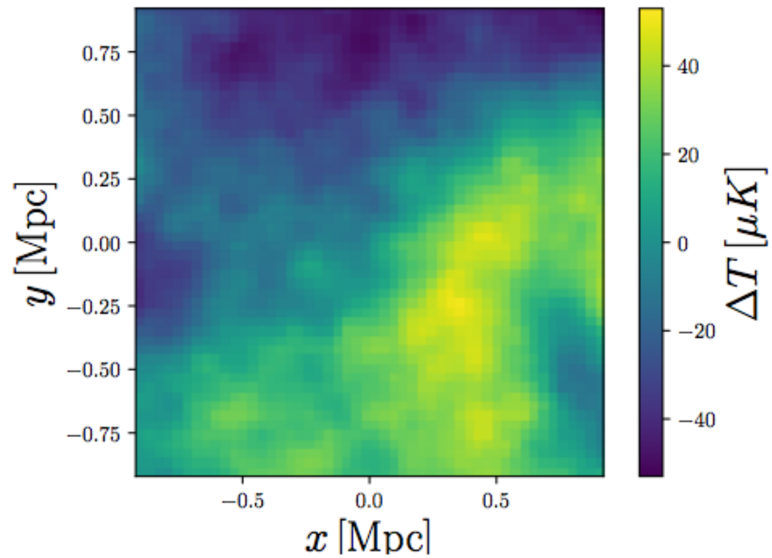
CMB (De-)Lensing: New Data and New Approaches



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

Other topics: find me for discussion!

- First measurement (?) of kSZ from cluster rotation: Baxter, Sherwin, Raghunathan 2019



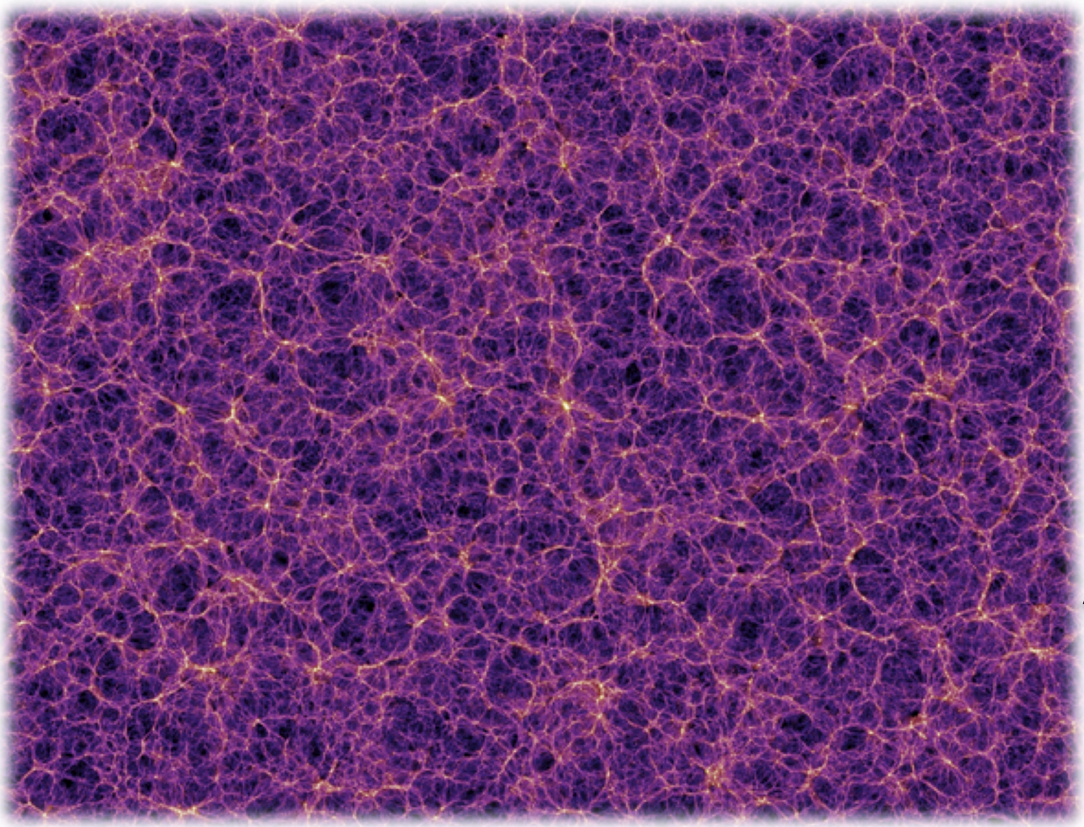
- What happens if I assume the wrong cosmology in BAO reconstruction? Sherwin & White 2019
- How well can I reconstruct low-k LSS modes with quadratic estimators? In prep. w. Darwish / Baldauf / Foreman / Meerburg

Large Scale Dark Matter Structure

- Want to probe distribution in detail, as contains clean information (no gal. bias) on open questions in cosmology:

What is the physics of inflation?

Is dark energy dynamical?

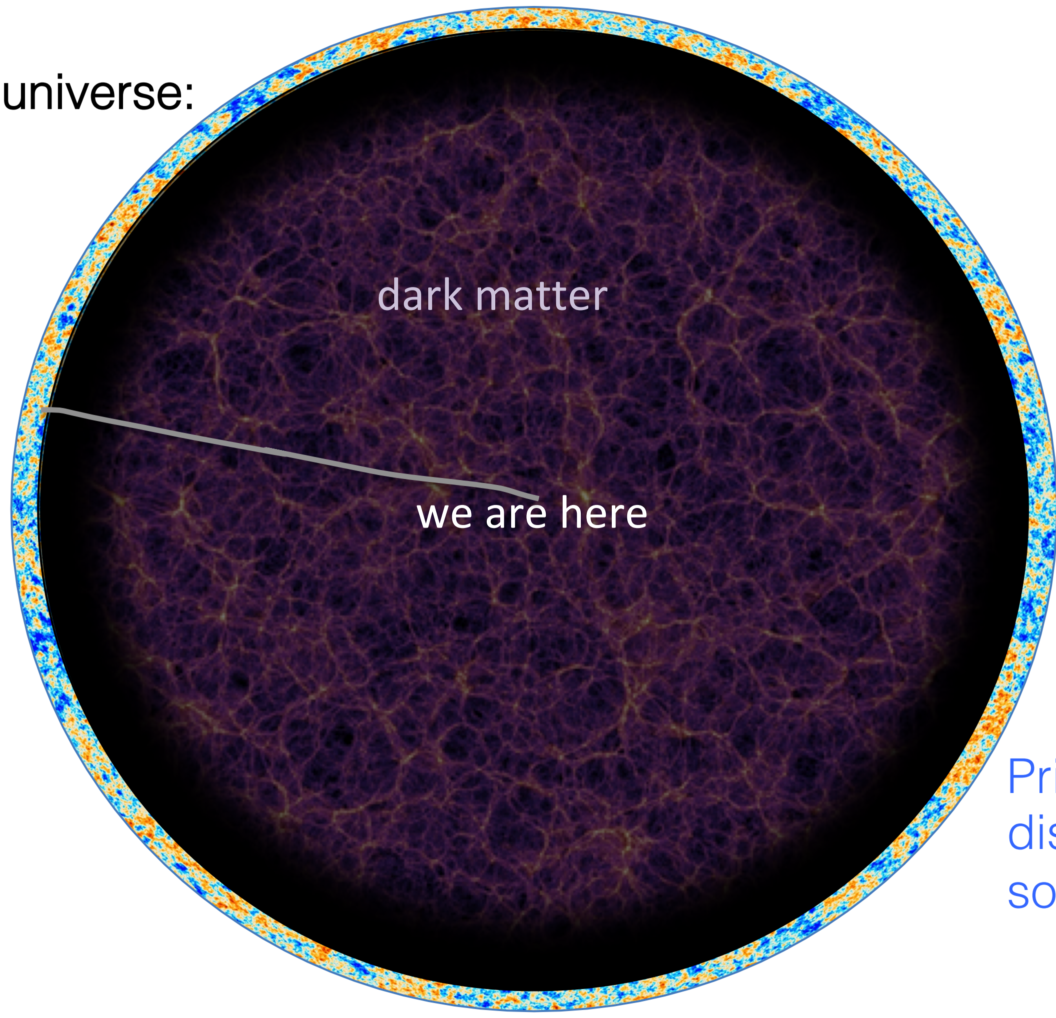


Is standard cosmology correct? (Is S8 consistent?)

What are the properties / masses of neutrinos?

- Access directly with gravitational lensing.

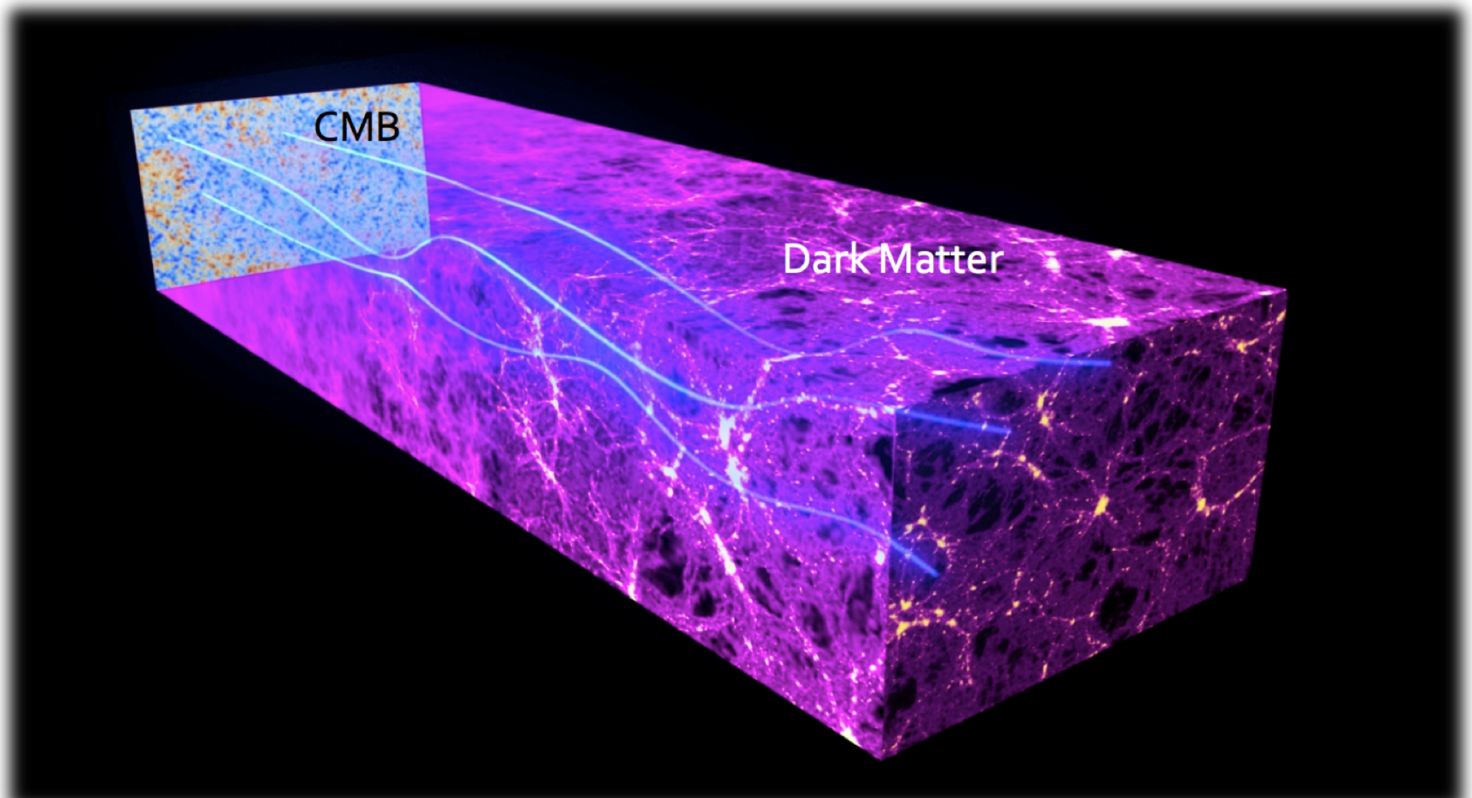
CMB: A Unique Source for Gravitational Lensing



- Advantages: CMB has perfectly known z, source physics linear/known, lens scales appear ~immune to baryons for now (OWLS)

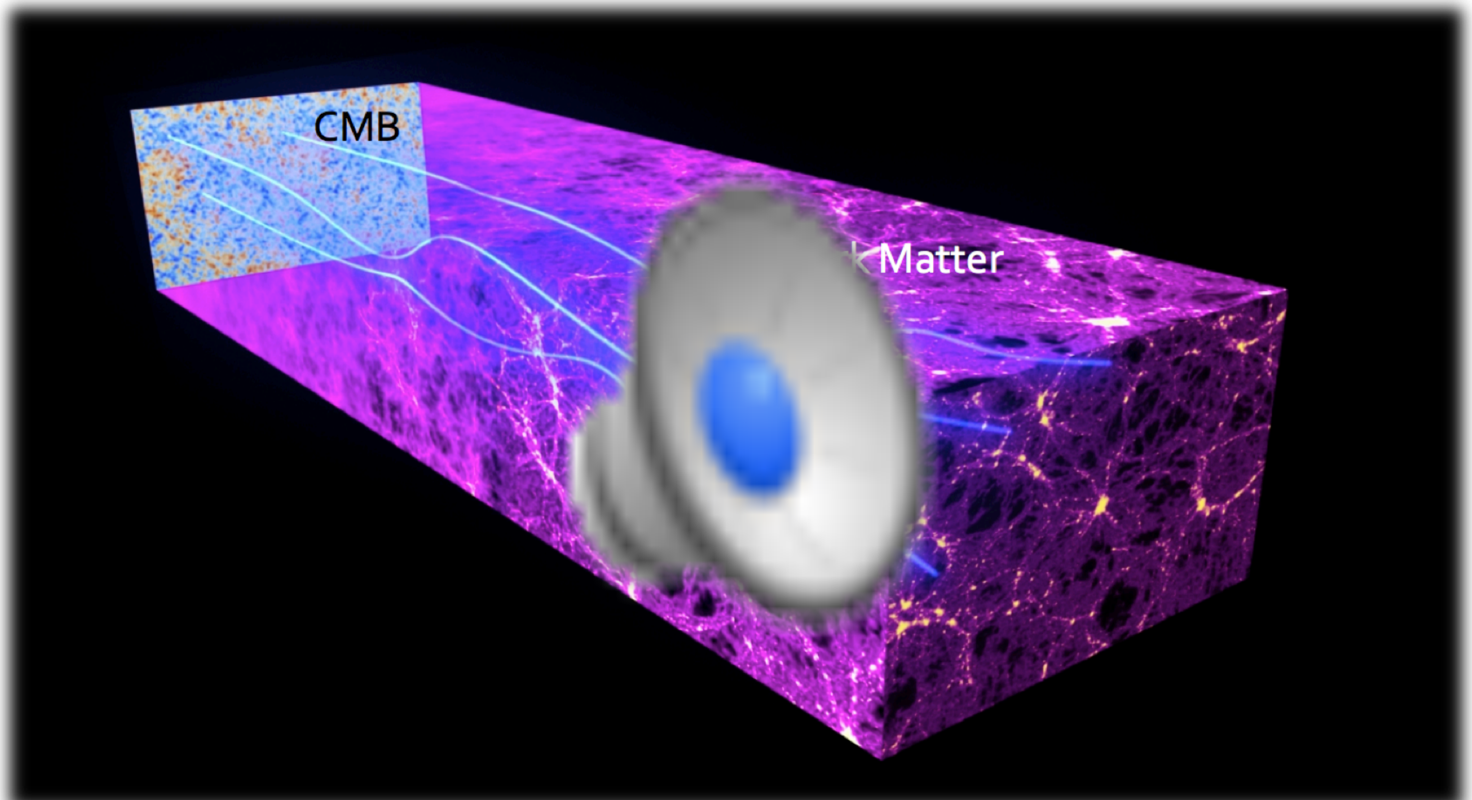
CMB Gravitational Lensing

- Distribution of dark matter deflects CMB light that passes through

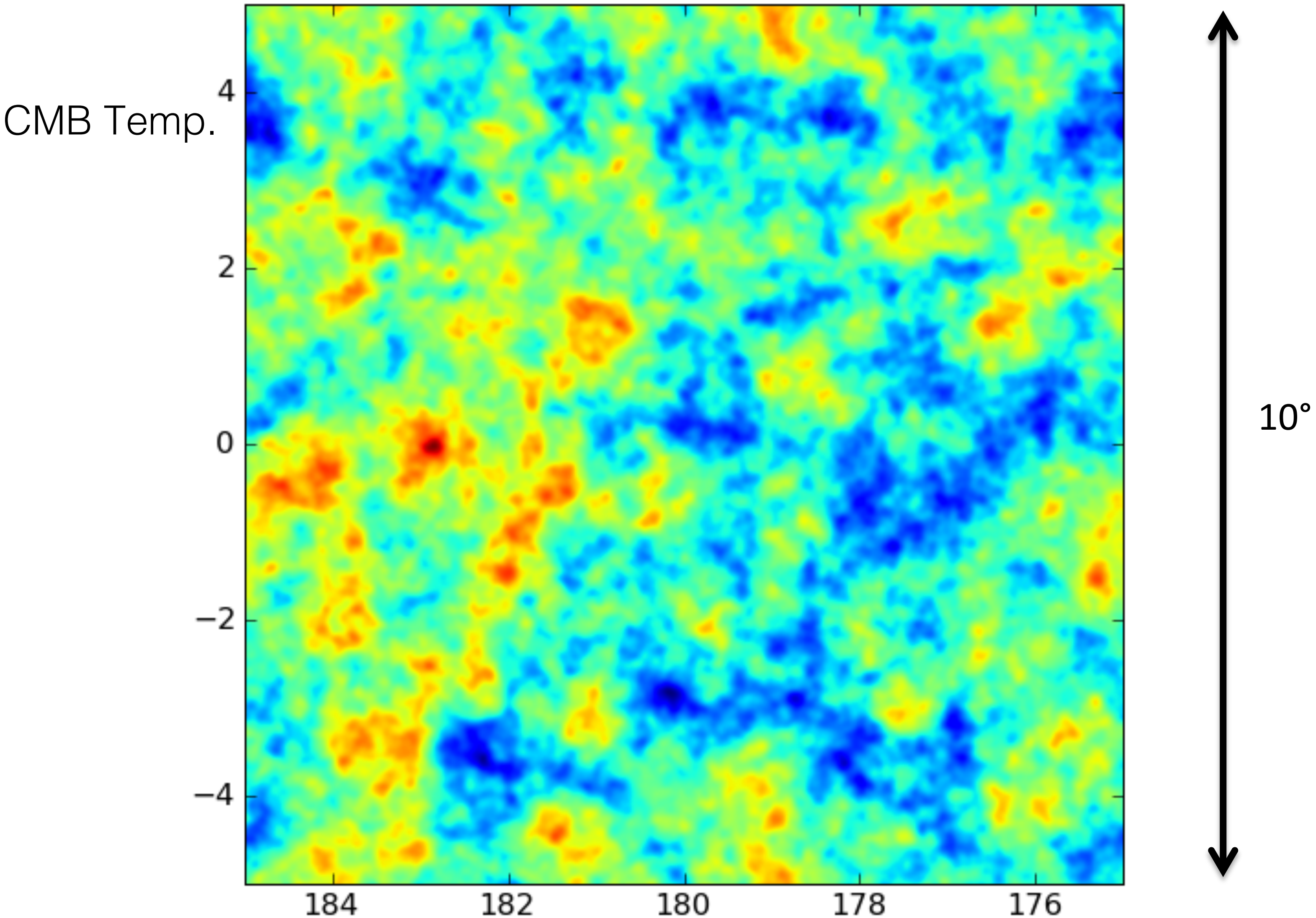


"Light" Source for Lensing: The Cosmic Microwave Background (CMB)

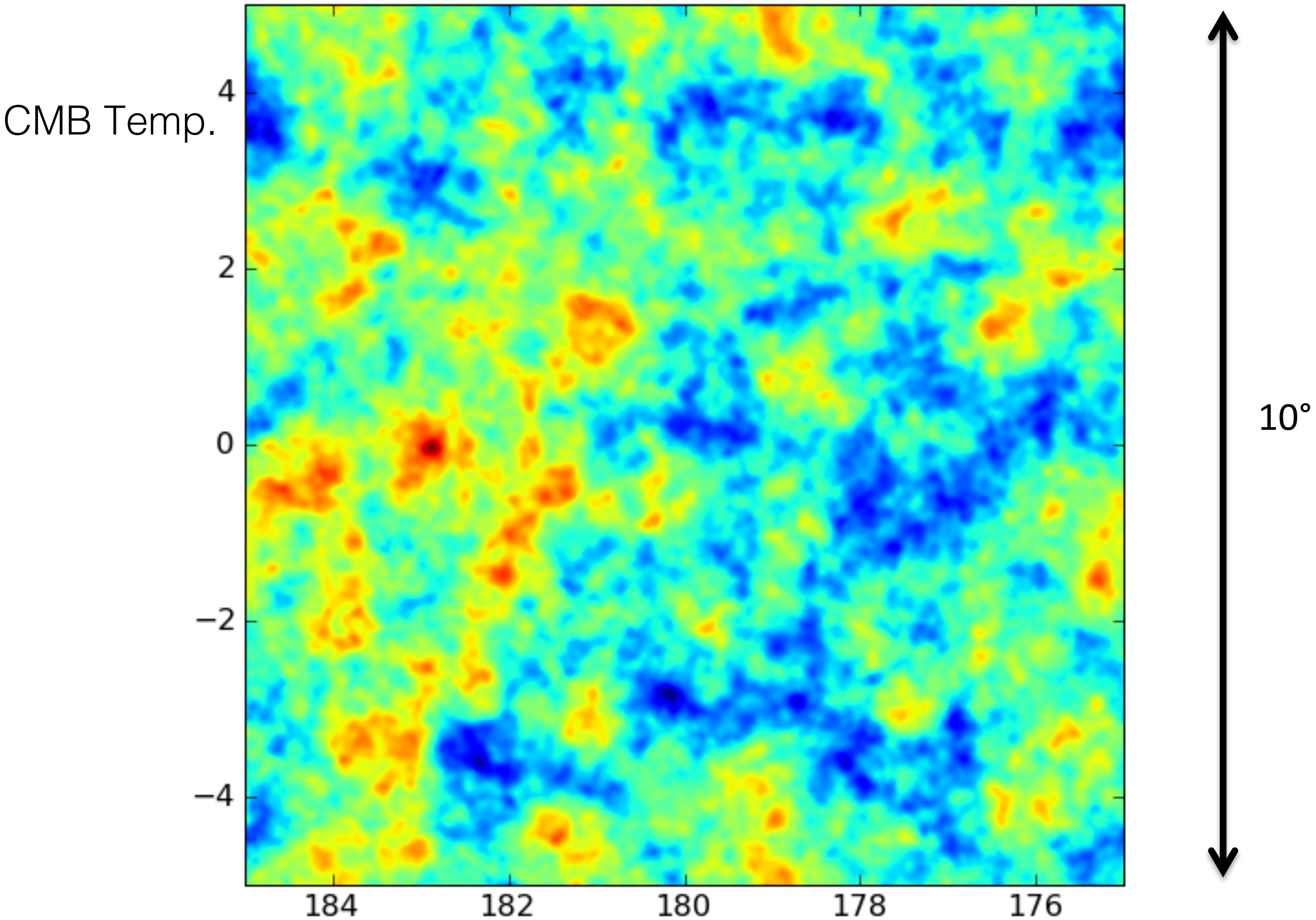
- CMB: leftover radiation from the hot primordial plasma – most distant observable source of light
- Distribution of dark matter deflects light that passes through



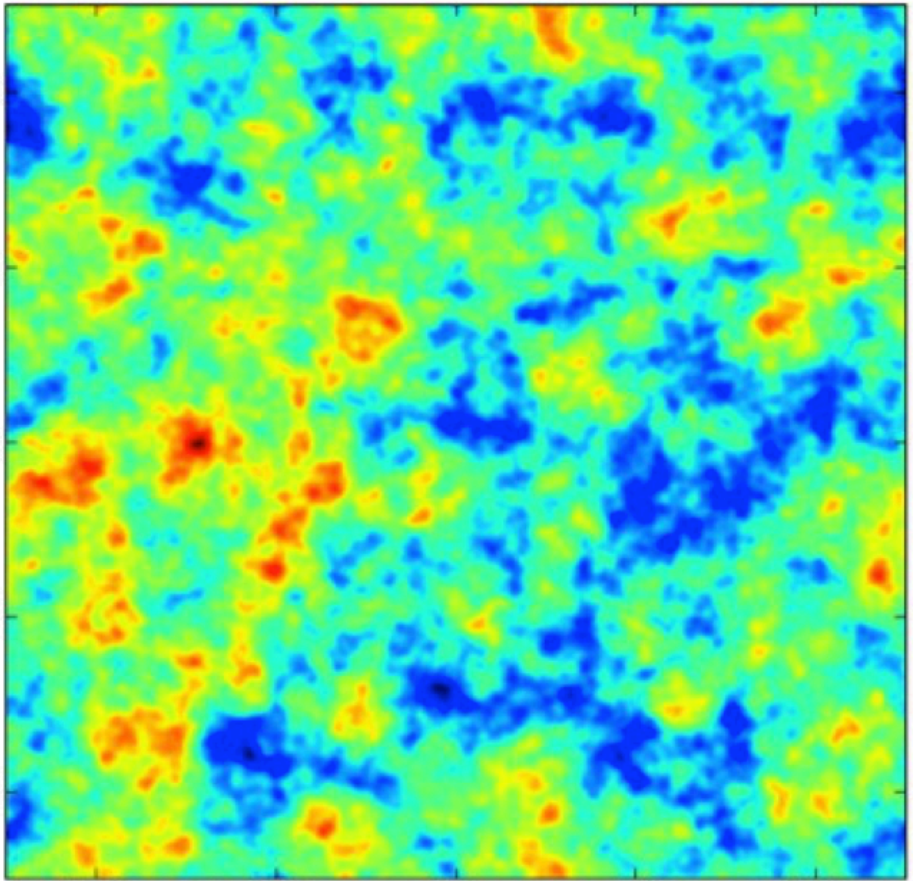
Unlensed CMB



Lensed CMB



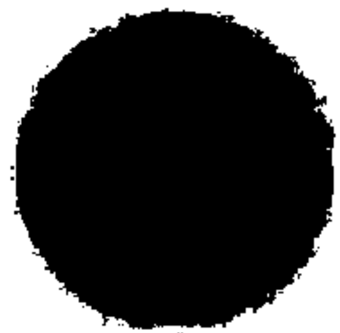
CMB Lensing: An Approximate Picture



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

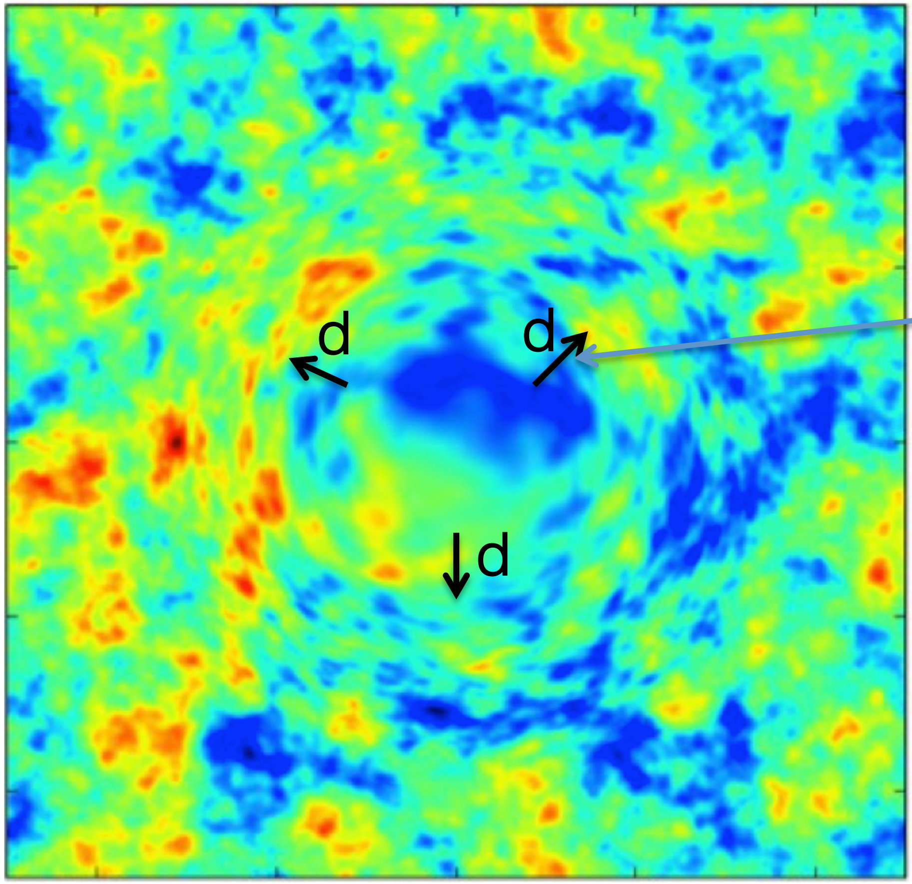
CMB Lensing: An Approximate Picture

- Clump of dark matter in front…



CMB Lensing: An Approximate Picture

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

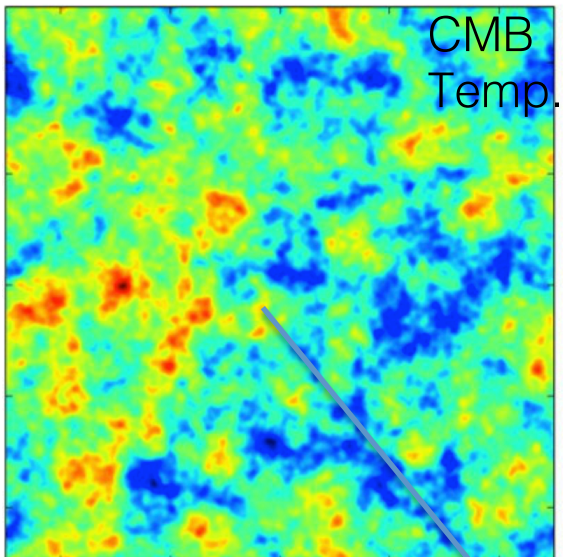


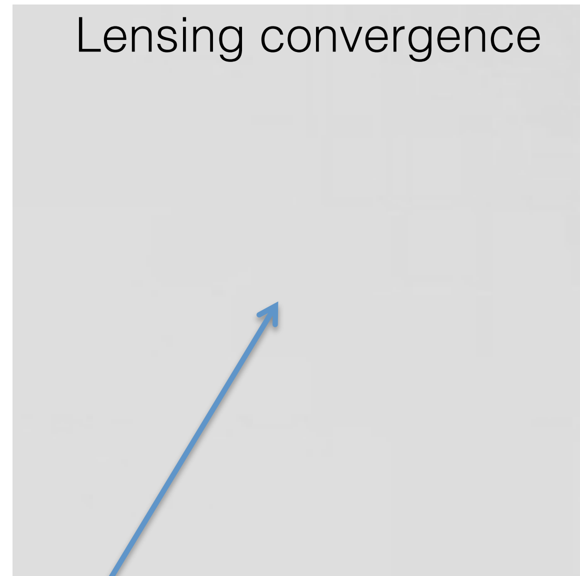
described by **lensing deflection field:** $\mathbf{d} = \nabla\phi$

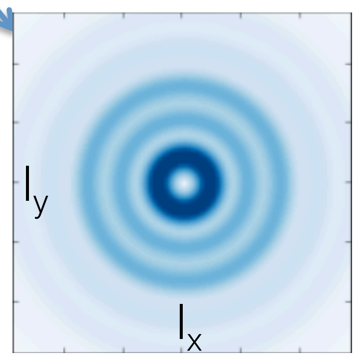
(very small: here exaggerated by x ~100, actually a few arcmins)

- Dark matter causes lensing magnification feature in the CMB

CMB Lensing Measurement: An Approximate Picture



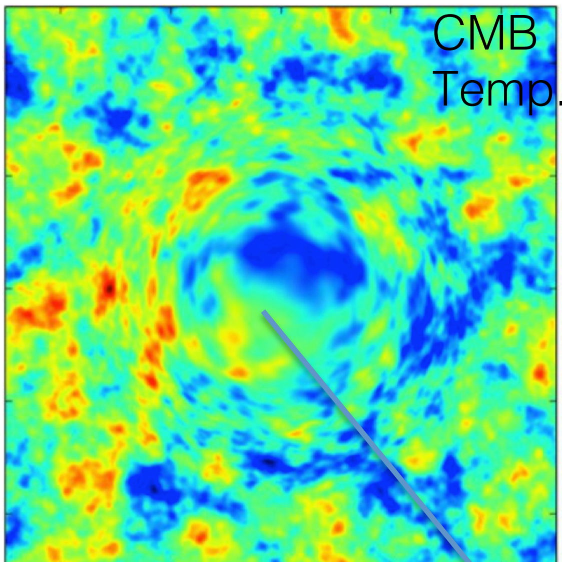


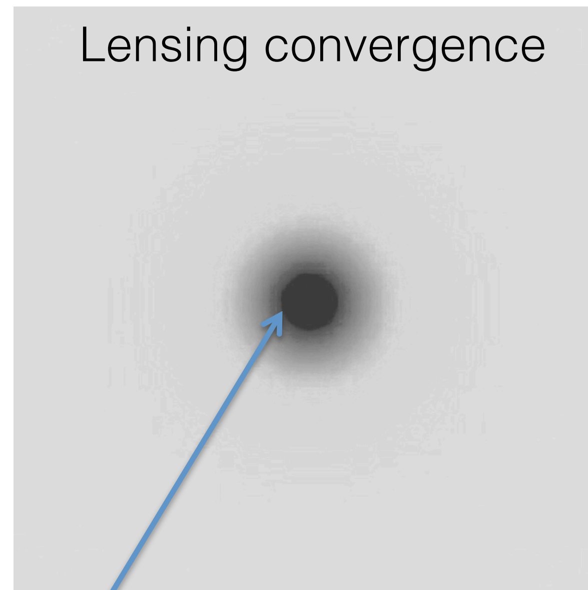


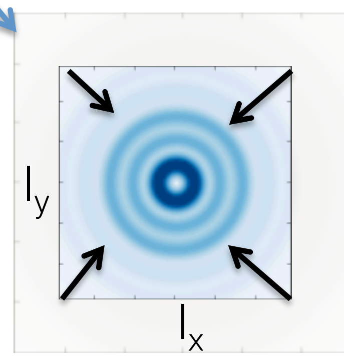
local 2D power spectrum

[Bucher++ 2012]

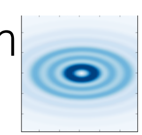
CMB Lensing Measurement: An Approximate Picture







local 2D power spectrum

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

N.B. better in polarization

[Bucher++ 2012]

Lensing Reconstruction Details

- From translation invariance (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 translation invariance**: introduces new correlations $T^{lensed}(\hat{\mathbf{n}}) = T^0(\hat{\mathbf{n}} + \mathbf{d}) \approx T^0 + \mathbf{d} \cdot \nabla T^0 + \cdots$

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

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

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

Quadratic estimator

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

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

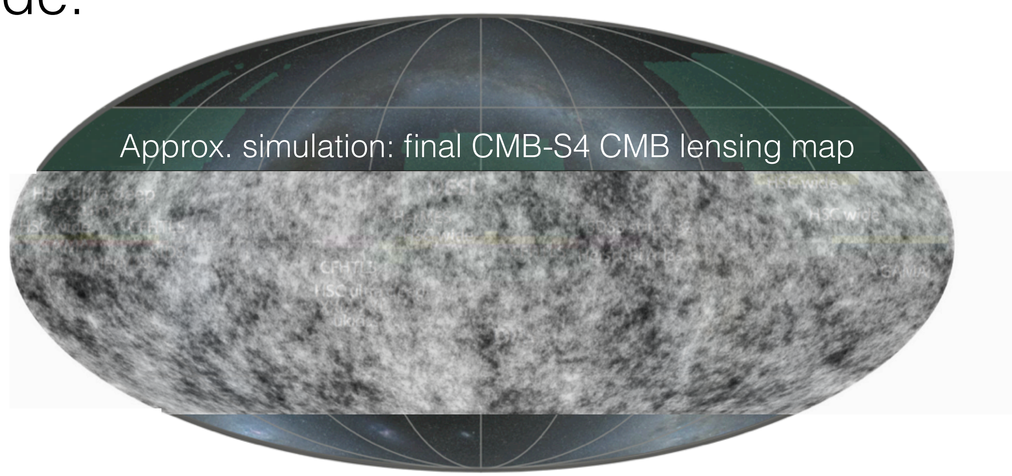
lensing deflection

radial distance

δ : fractional mass overdensity

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

- Next decade:

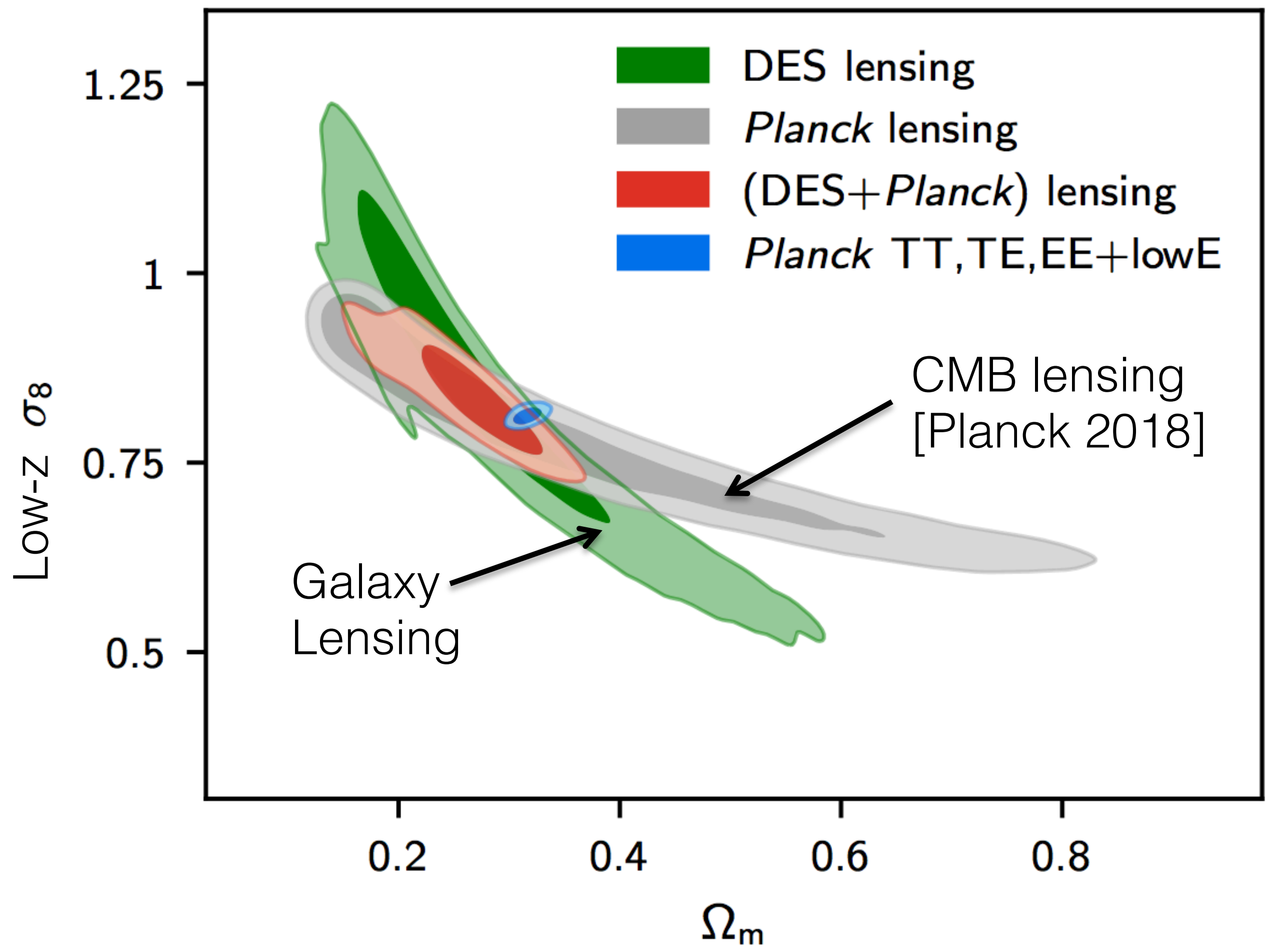


Outline

- Part 1: Lensing science (neutrinos++) from new CMB data
- Part 2: New approaches to small-scale CMB lensing - are our current estimators good enough?
- Part 3: Delensing Simons Observatory: new methods for revealing inflationary signals

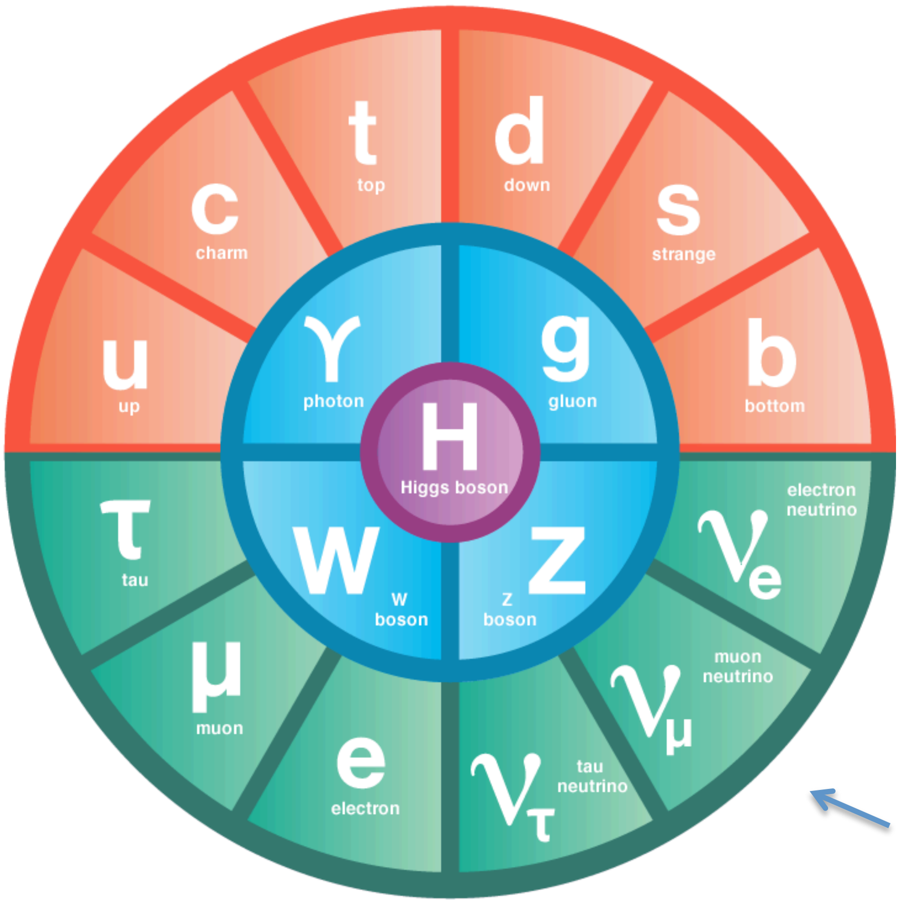
With Omar Darwish, Toshiya Namikawa et al.

Example Physics Lensing Can Tell Us:
General Test of Growth of Structure (Tensions?)



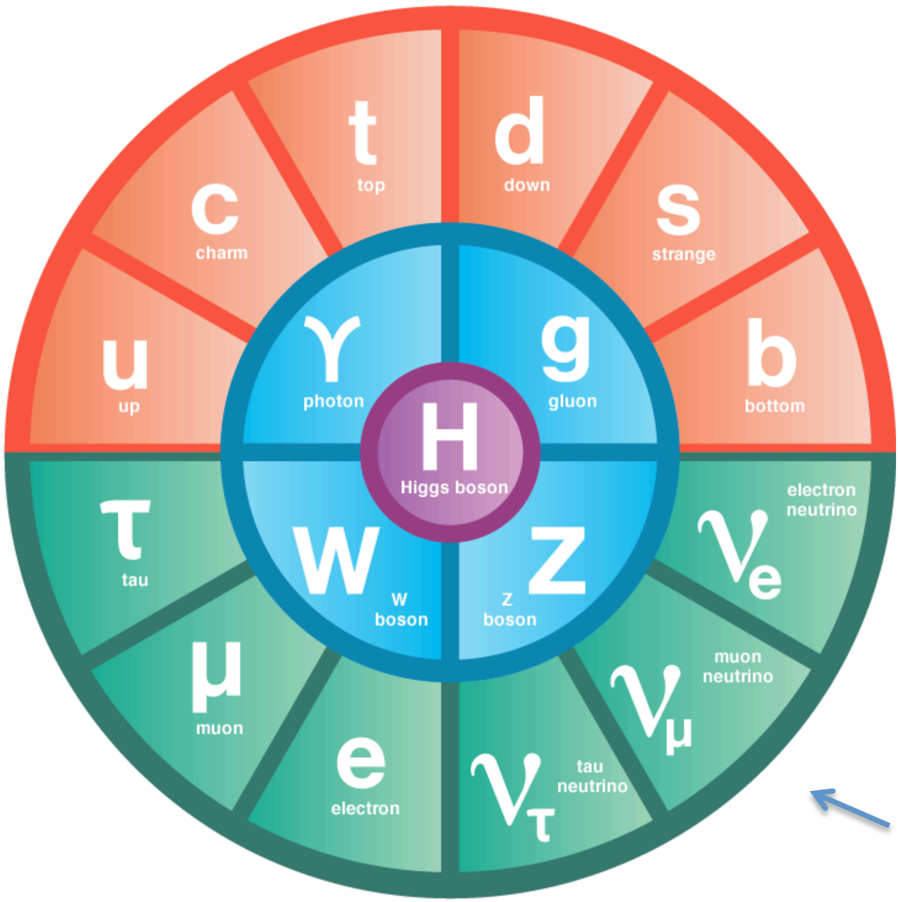
- Different degeneracy direction due to different z-dependence

Example Physics Lensing Can Tell Us: Neutrino Mass



- Neutrinos have mass – associated physics not well understood
- we don't know:
  - absolute scale
  - mass ordering
  - their own antiparticle?
  - what gives neutrinos mass? +…
- Cosmology: measurement of mass sum $\sum m_\nu$ >60meV will give insights

Example Physics Lensing Can Tell Us: Neutrino Mass



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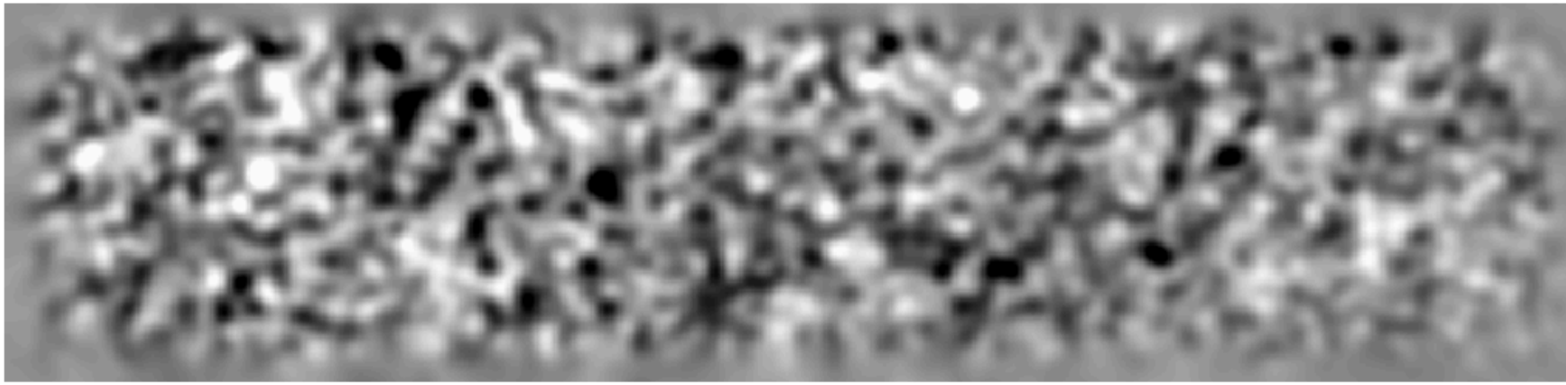
How to measure with lensing: neutrino mass suppresses small-scale structure growth and hence small-scales in a lensing map.

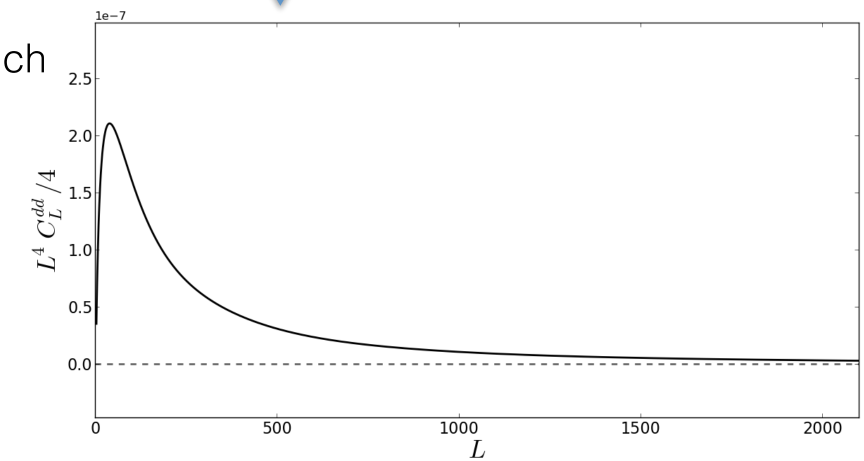
Key Observable: CMB Lensing Power Spectrum C_ℓ^{dd}

ACTPol CMB Lensing Dark Matter Map (small scales noise)



brightness = density

Y axis: “How much lensing ….”

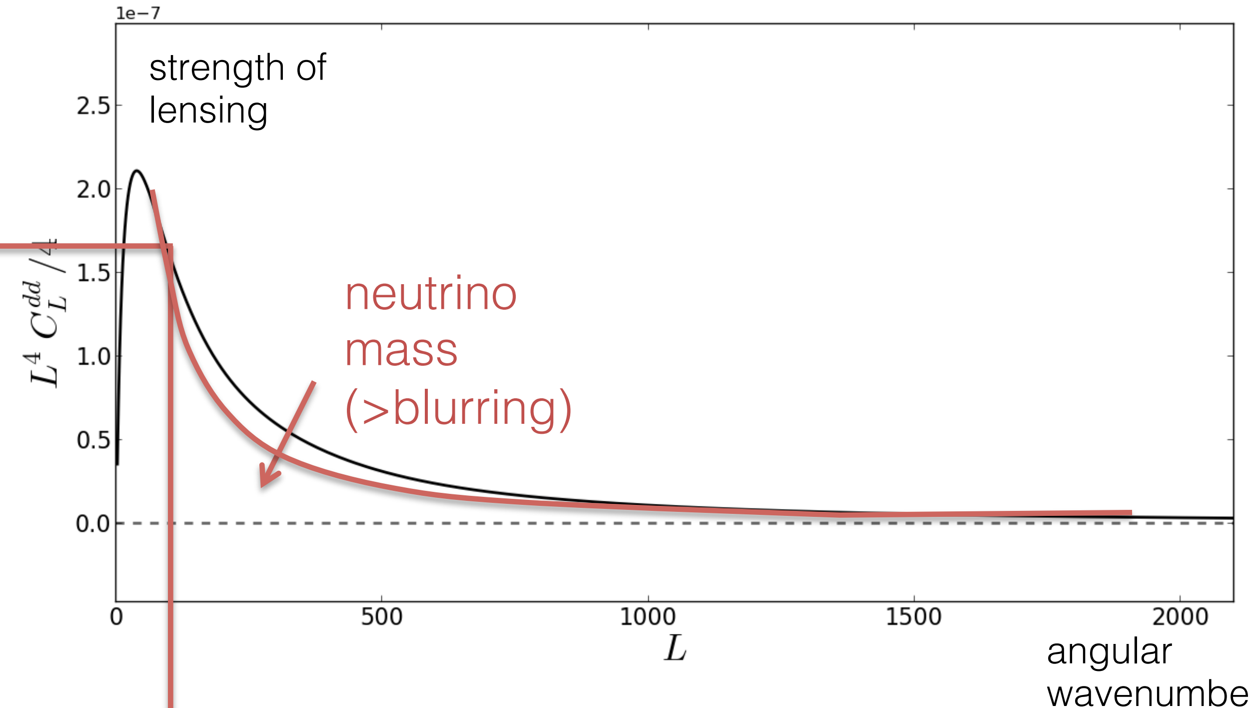


X axis: “for a lens of this angular scale?”

Describe lensing maps statistically with lensing power spectrum:

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

Y axis: “How much lensing[2] ….”

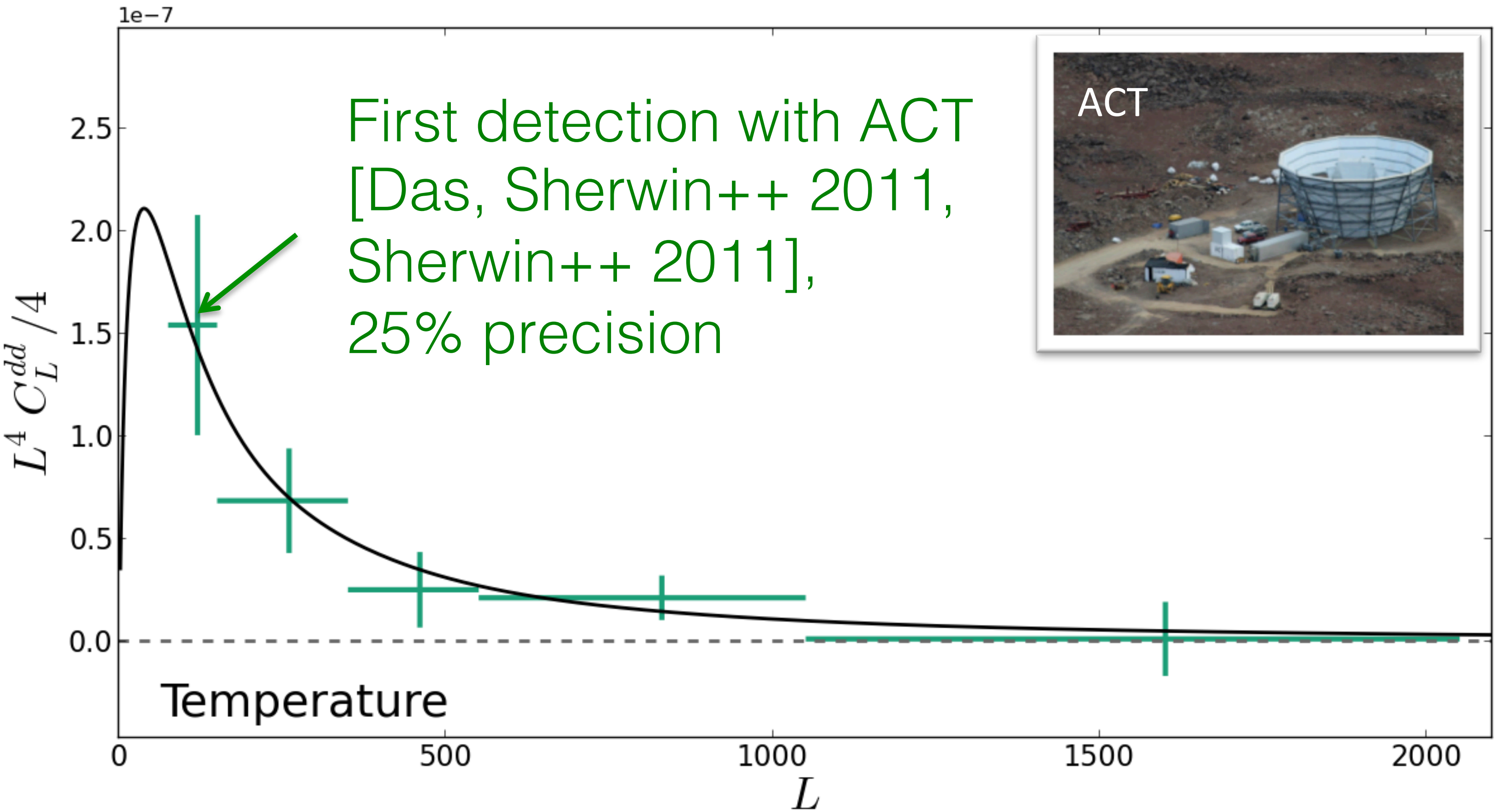


X axis: “for a lens of this angular scale?

Measurement: non-Gaussianity in four-point function

$$C_L^{dd} \sim \langle d^2 \rangle_{\text{NG}} \sim \langle TTTT \rangle_{\text{NG}}$$

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



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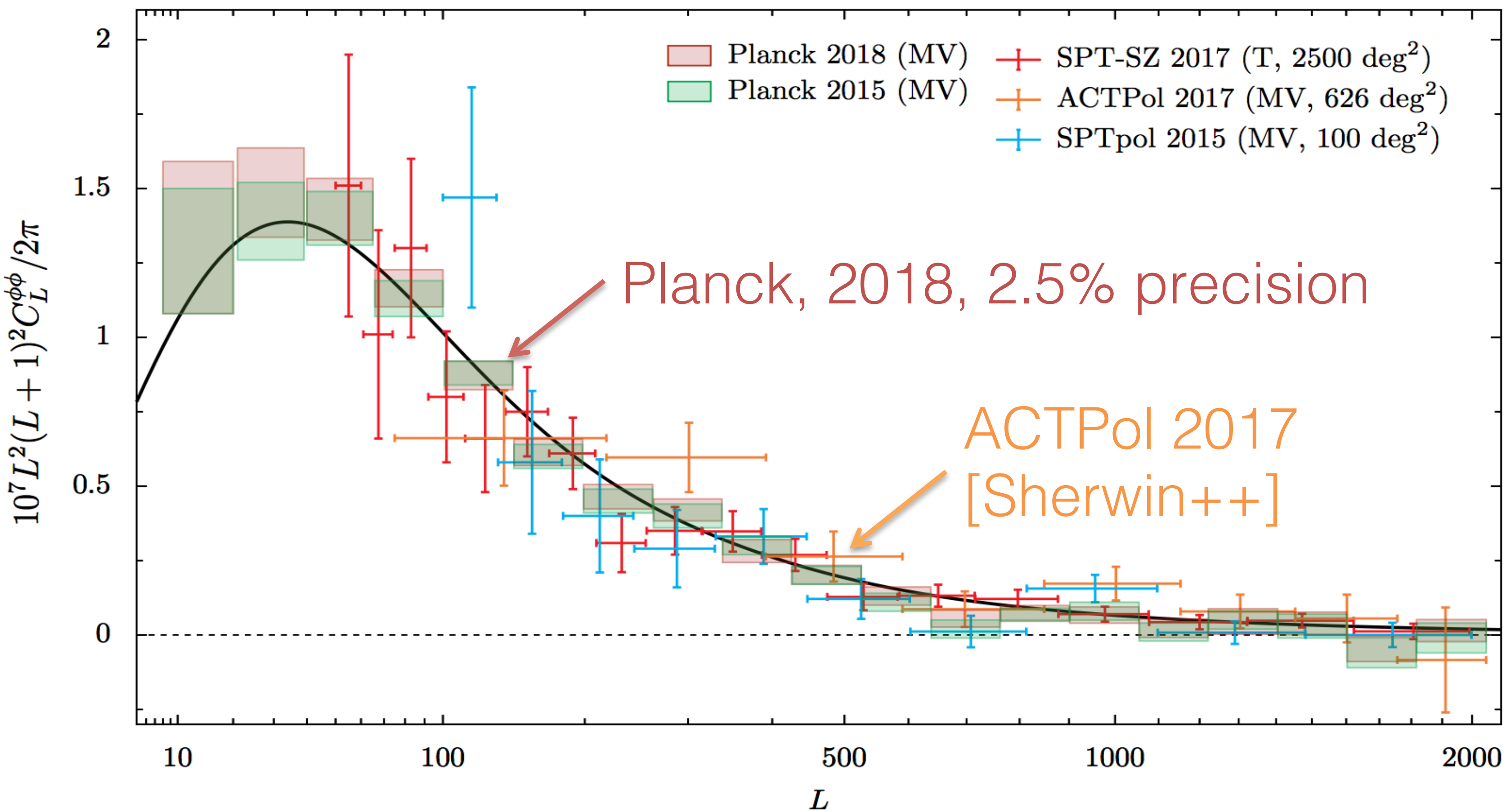
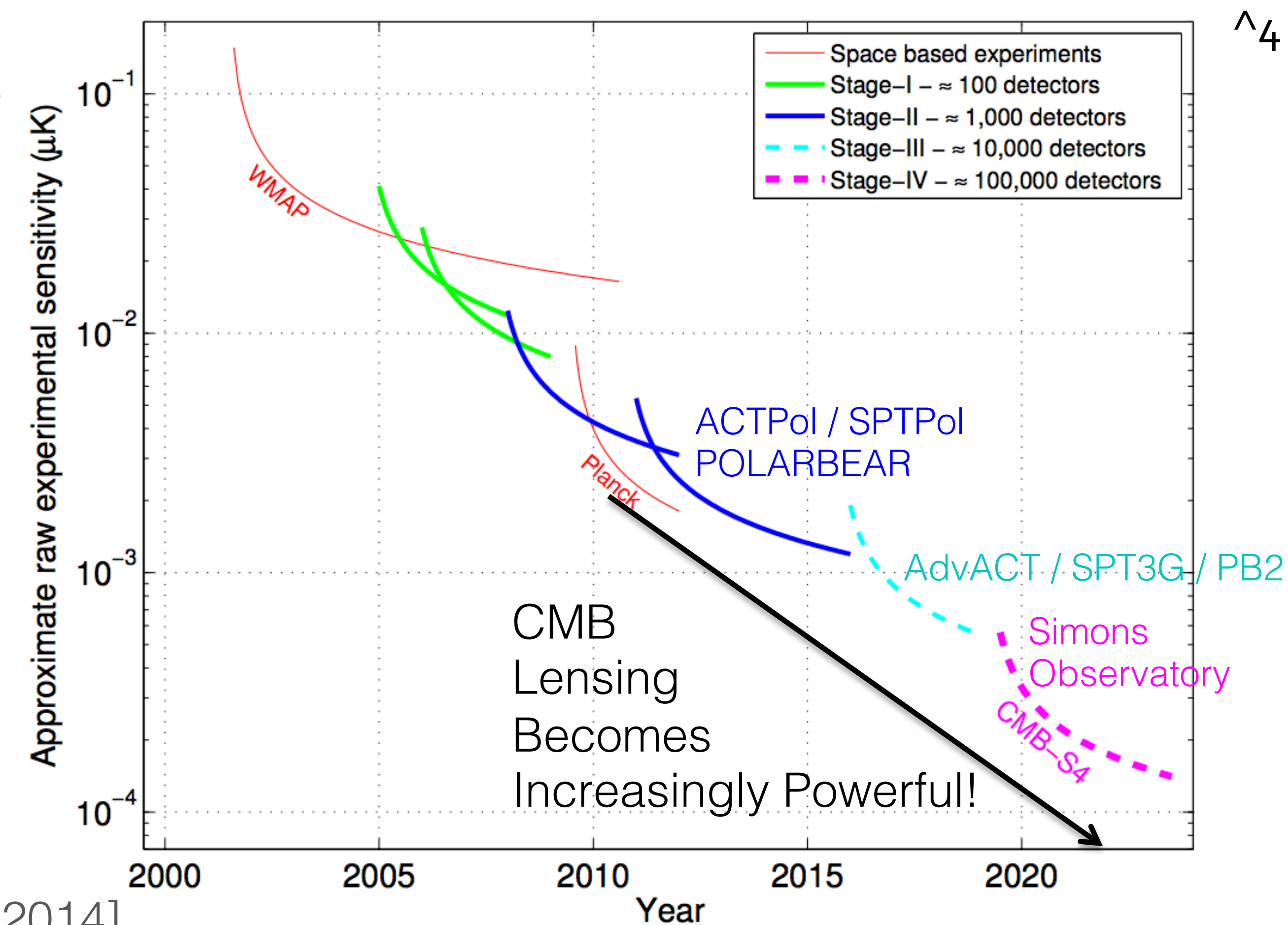


- Rapid progress – but only just beginning!

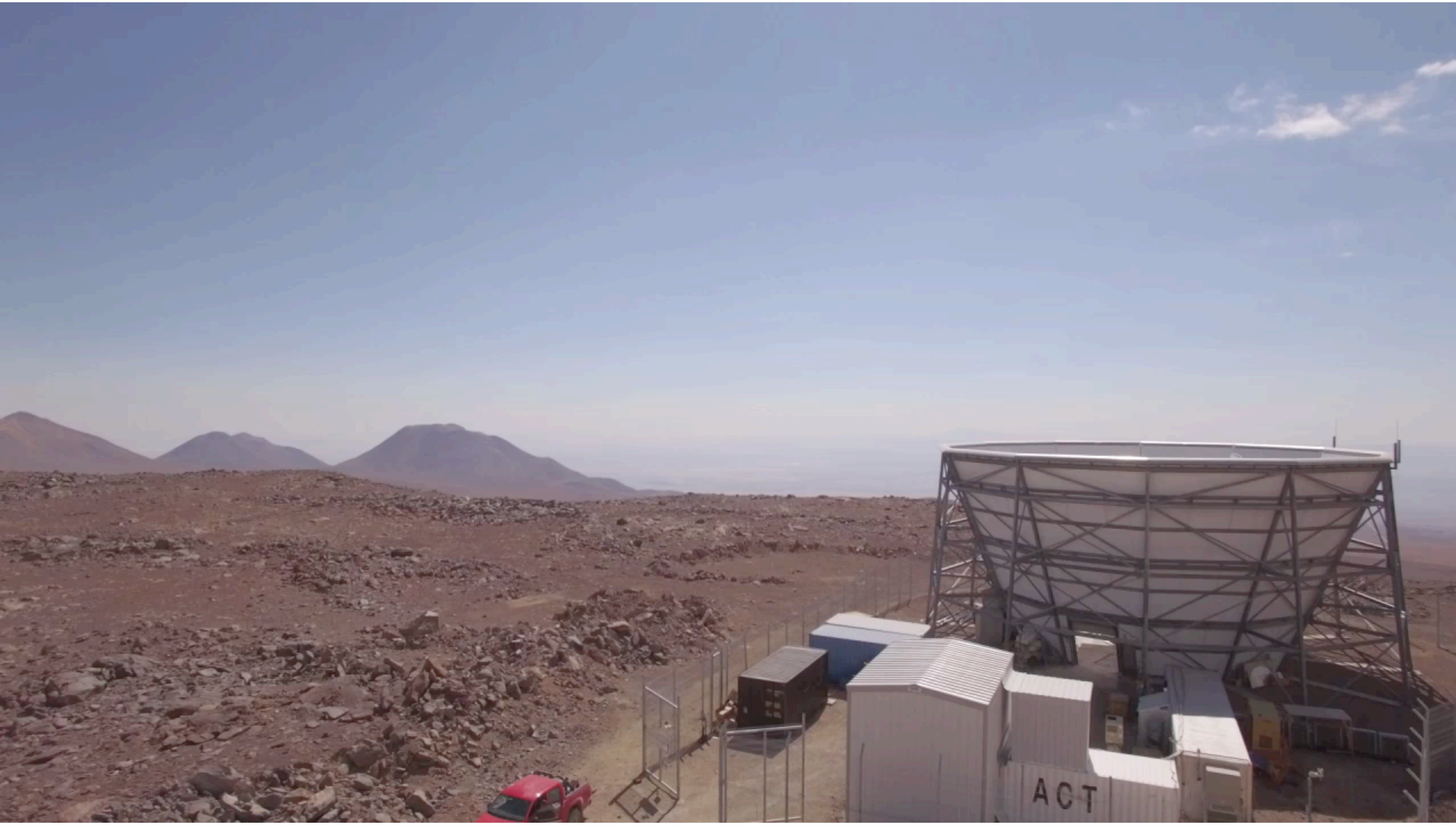
Rapid Progress: Upcoming Ground-Based CMB Experiments

CMB Experiment Noise Level



[Abazajian++ 2014]

Atacama Cosmology Telescope (ACT)



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

Now: ACTPol S13-S16

S13
PA1 @ 150 GHz
Patches: D1, D2, D5, D6

S14
PA1/PA2 @ 150 GHz
Patches: D56, BOSS-N

S15
PA1/PA2 @ 150 GHz
PA3 @ 90/150 GHz
Patches: D56, D8, BOSS-N

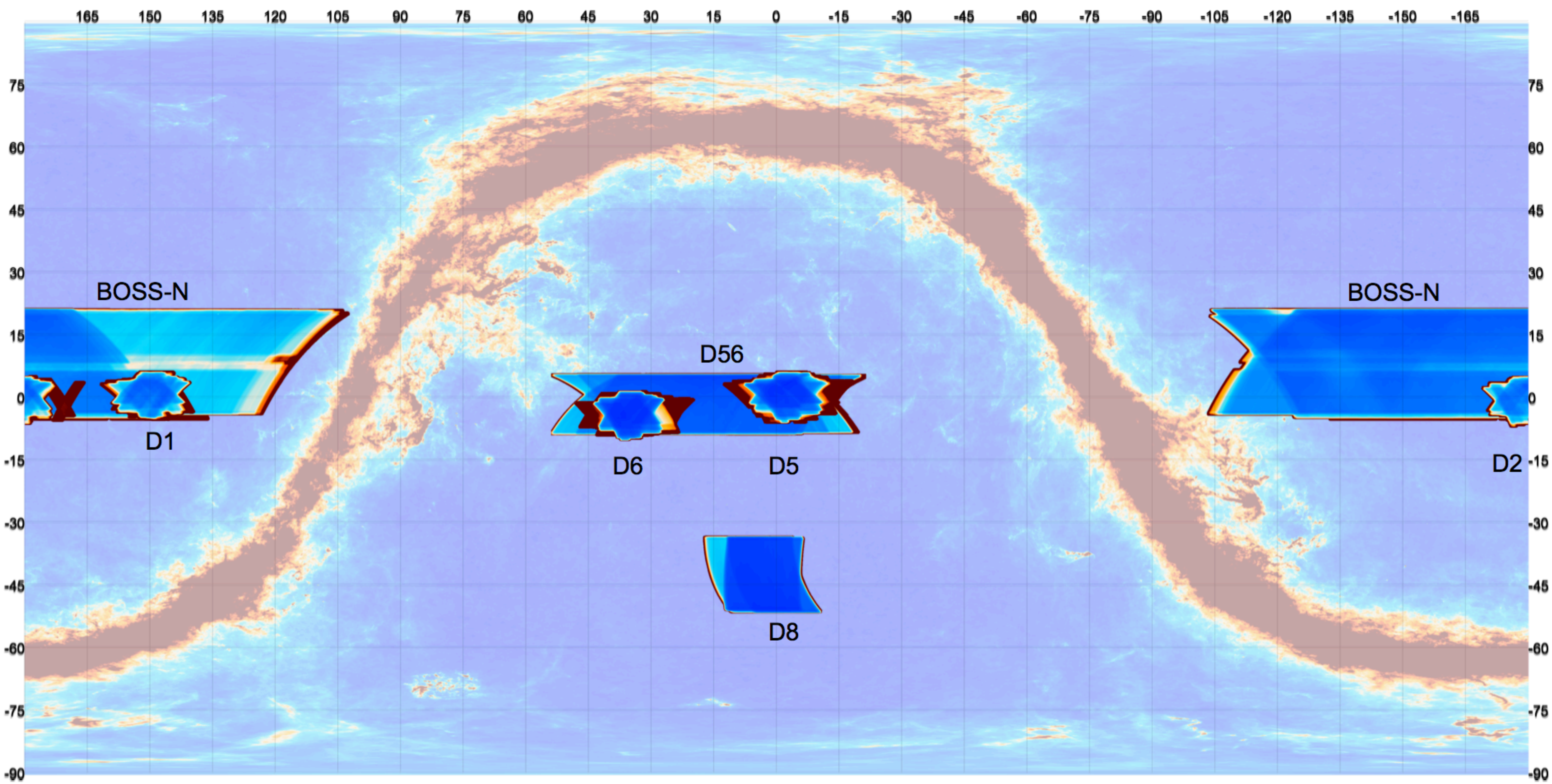


Figure: S. Aiola

- > 10x more data than used in Sherwin++ 2017 lensing

Polarization Comparison

Q

U

ACT

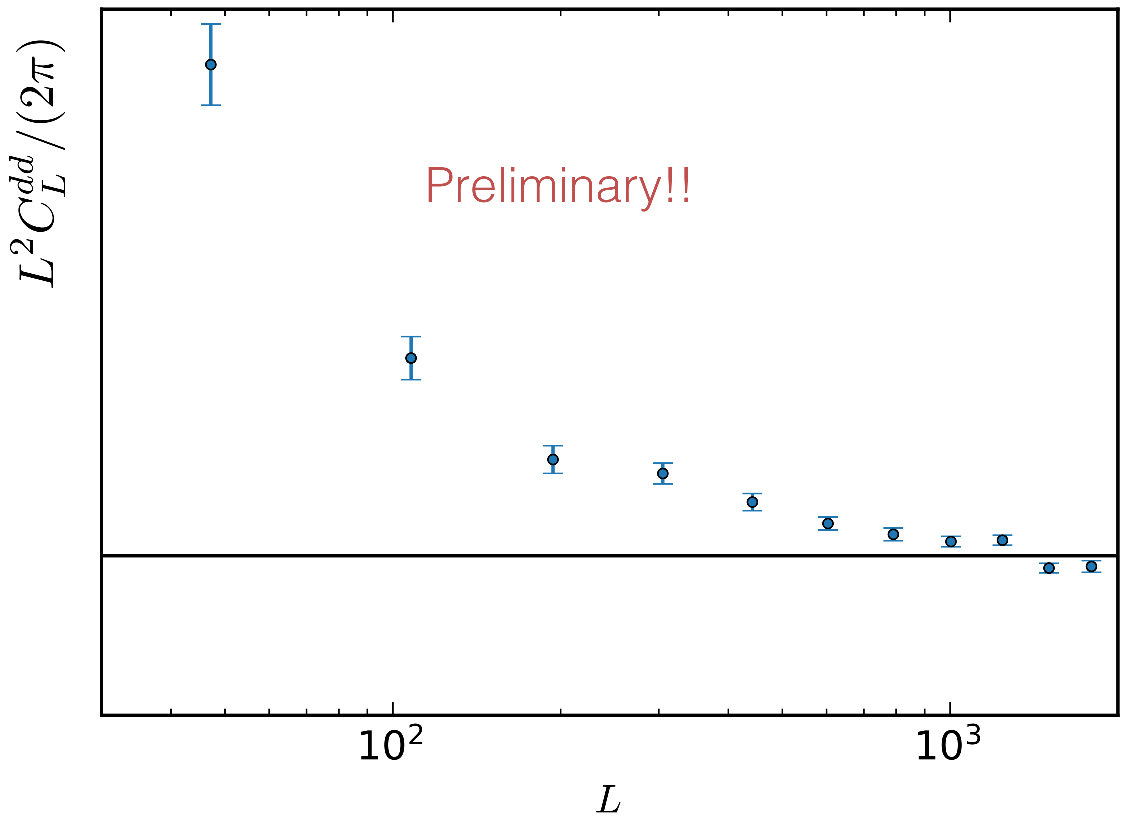
Planck

ACTPol – next lensing paper (2019): Expect around 4% precision (preliminary results)

- Potential to independently test Planck – e.g. M_ν, tensions (?) in high vs. low z structure,…

$$\sigma(\sum m_\nu) \sim 100 \text{ meV}$$

c.f. lower limit, >60meV



[Van Engelen, Sherwin++ in prep.]
[Namikawa++ in prep.]

Much more to come: AdvancedACT, +…

S16
PA2 @ 150 GHz
PA3 @ 90 / 150 GHz
HF @ 150 / 220 GHz

S17
MF @ 90 / 150 GHz
MF @ 90 / 150 GHz
HF @ 150 / 220 GHz

S18
LF @ 28 / 41 GHz
MF @ 90 / 150 GHz
HF @ 150 / 220 GHz

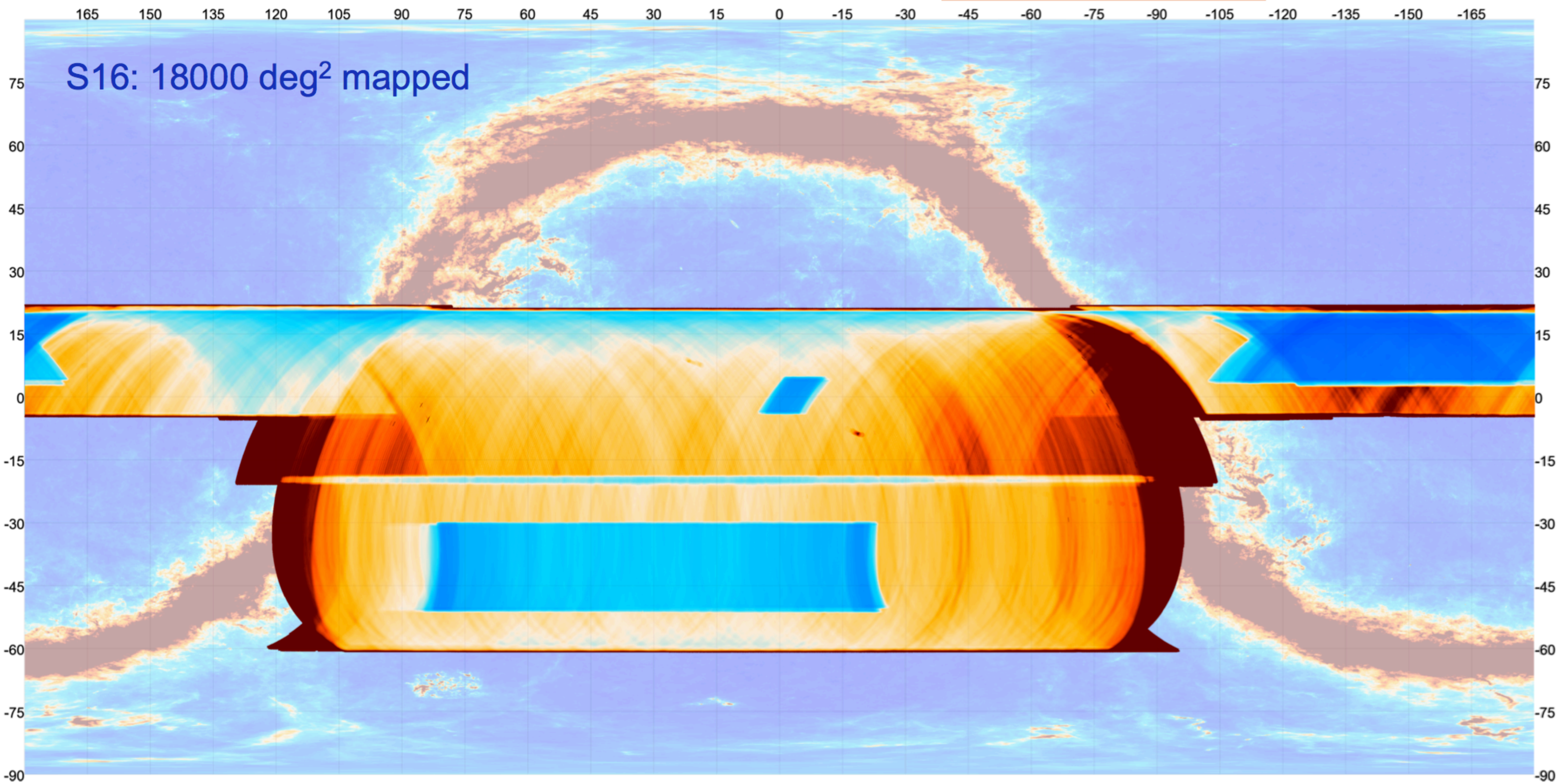
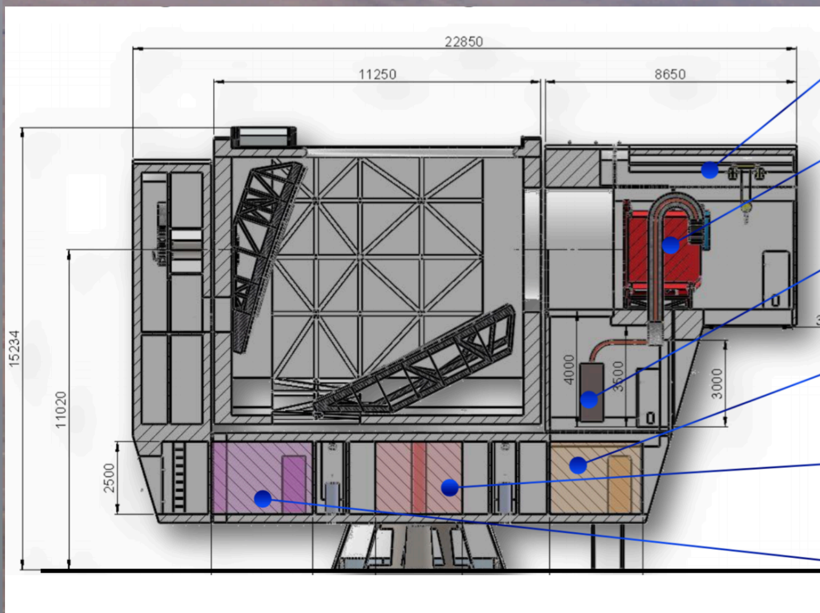
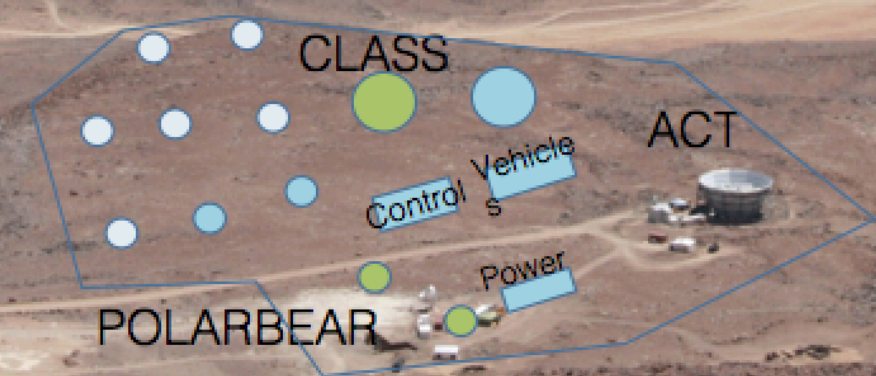


Figure: S. Aiola   Map: S. Naess

Simons Observatory



- Next generation, funded CMB experiment, 2020-
- Combines ACT, POLARBEAR collaborations



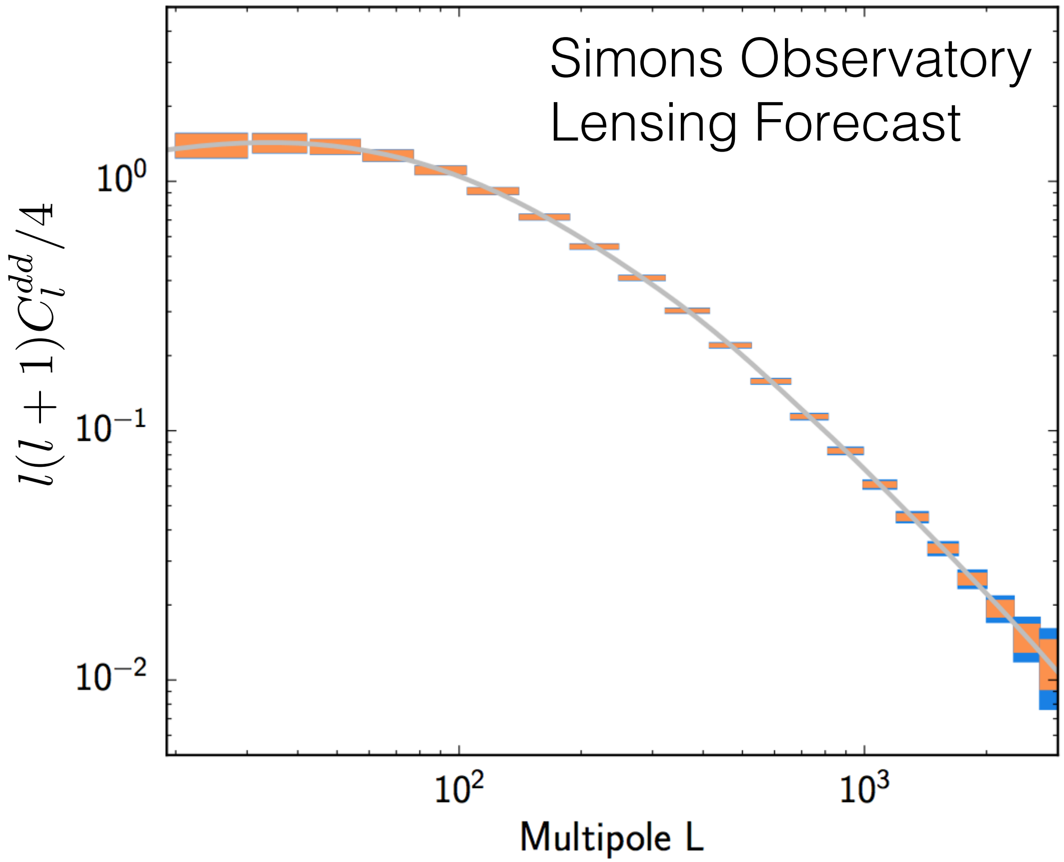
Existing

Notional Simons Observatory Phase 1

Notional Pads for Simons Observatory Phase 2 and CMB S4

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 + generally test structure growth

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

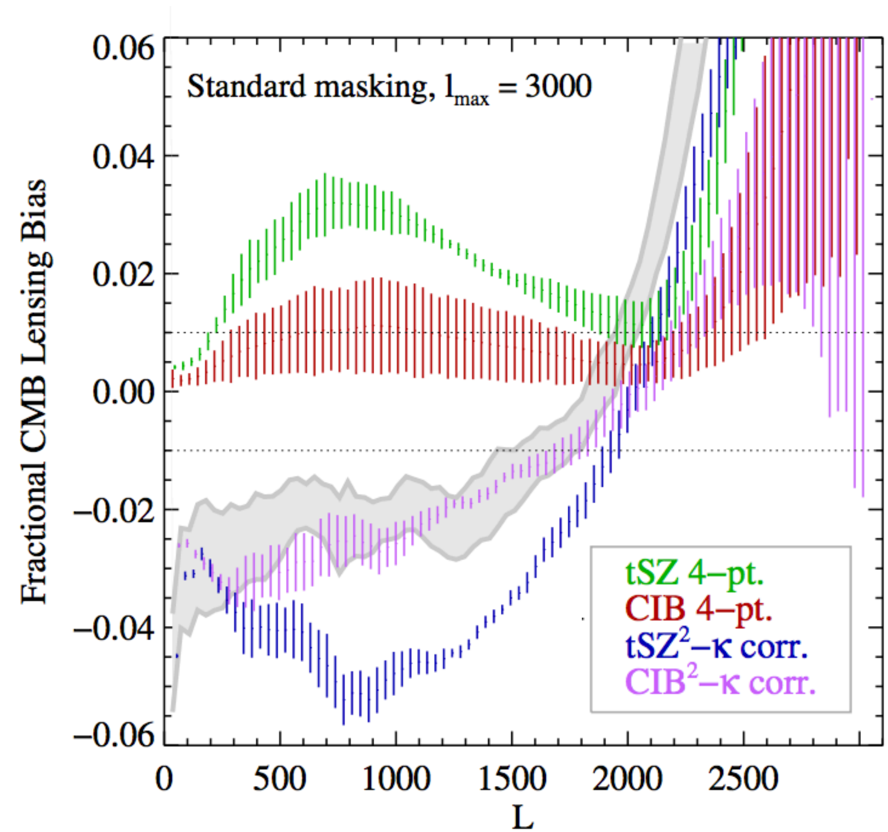
c.f. limit, >60meV

CMB Lensing Systematics: Main Concern

- Foreground biases from SZ, CIB, kSZ… contamination e.g. <SZ SZ SZ SZ>

- When nothing is done, ~few % effect. Multifrequency or geometric cleaning can reduce further – but work still required!

- Polarization: small (?) Unknown unknowns



[Sherwin++ in prep. 2016b]
[Liu, Hill, Sherwin++ 2016]
[van Engelen++ 2013, Osborne++2013]

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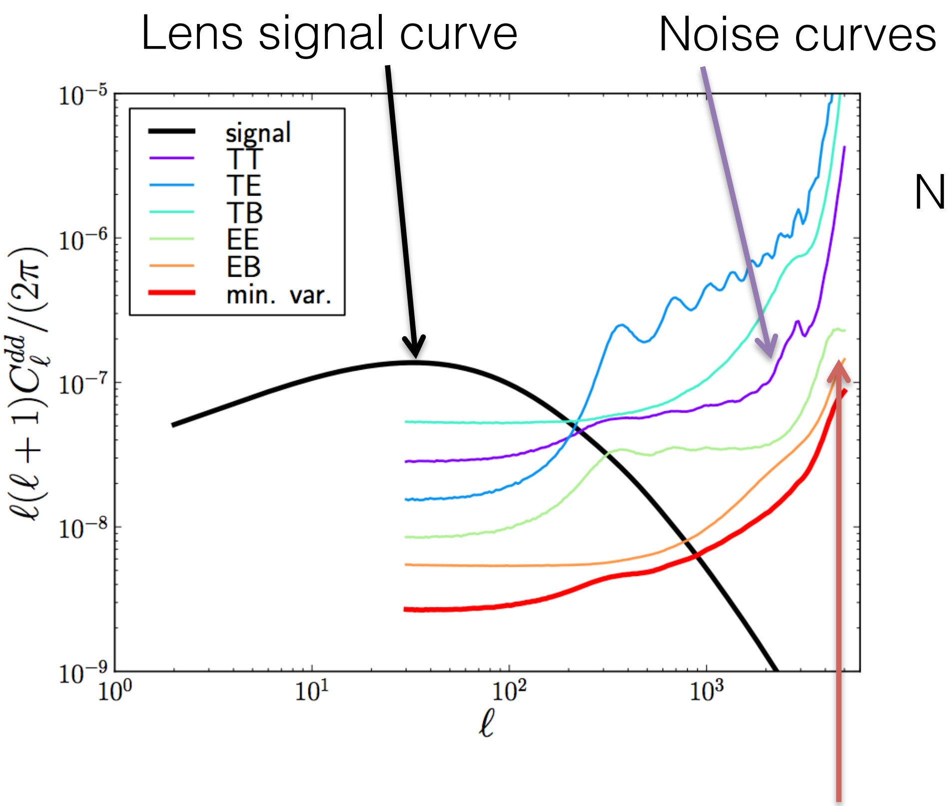
with Boryana Hadzhiyska, Simone Ferraro,
Mat Madhavacheril

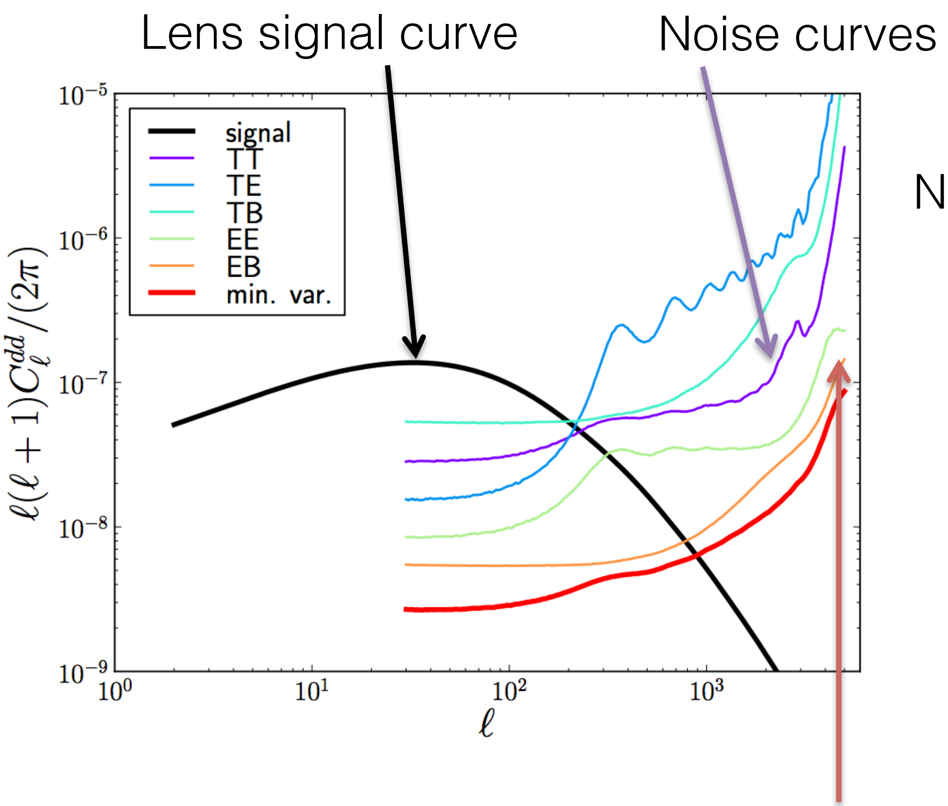
Hints at possible improvements on small scales



Noise for CMB-S4 [from Schaan++]

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

Hints at possible improvements on small scales



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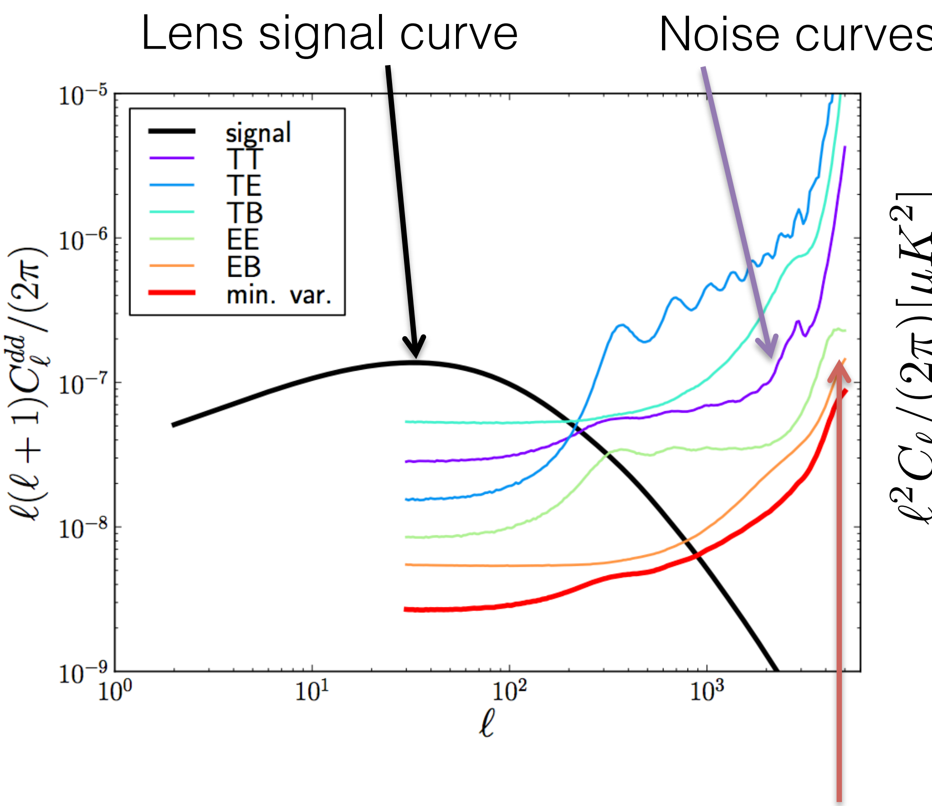
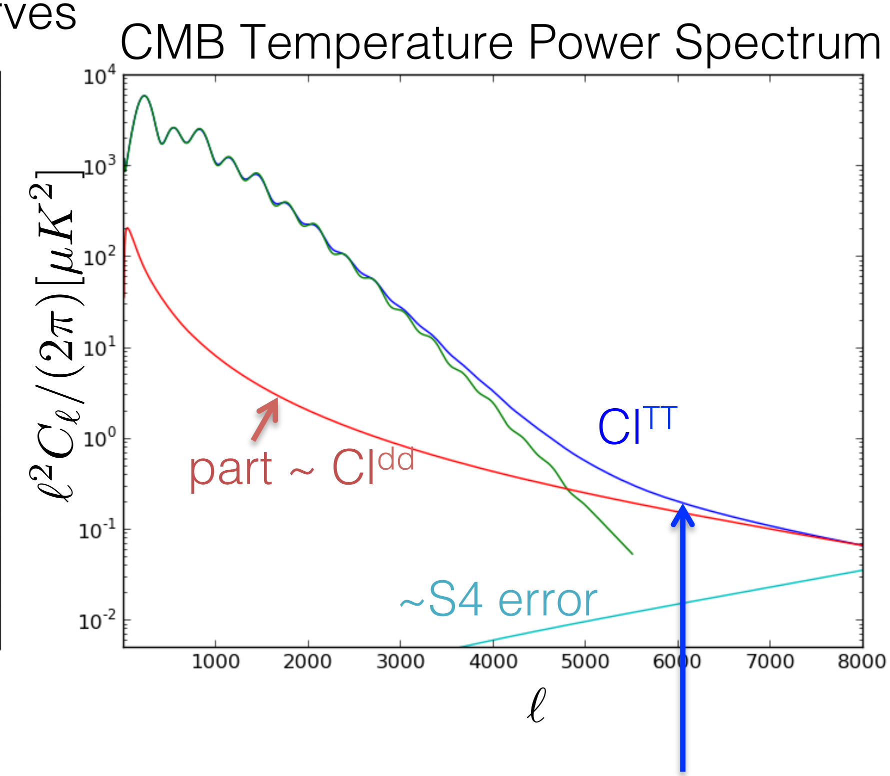
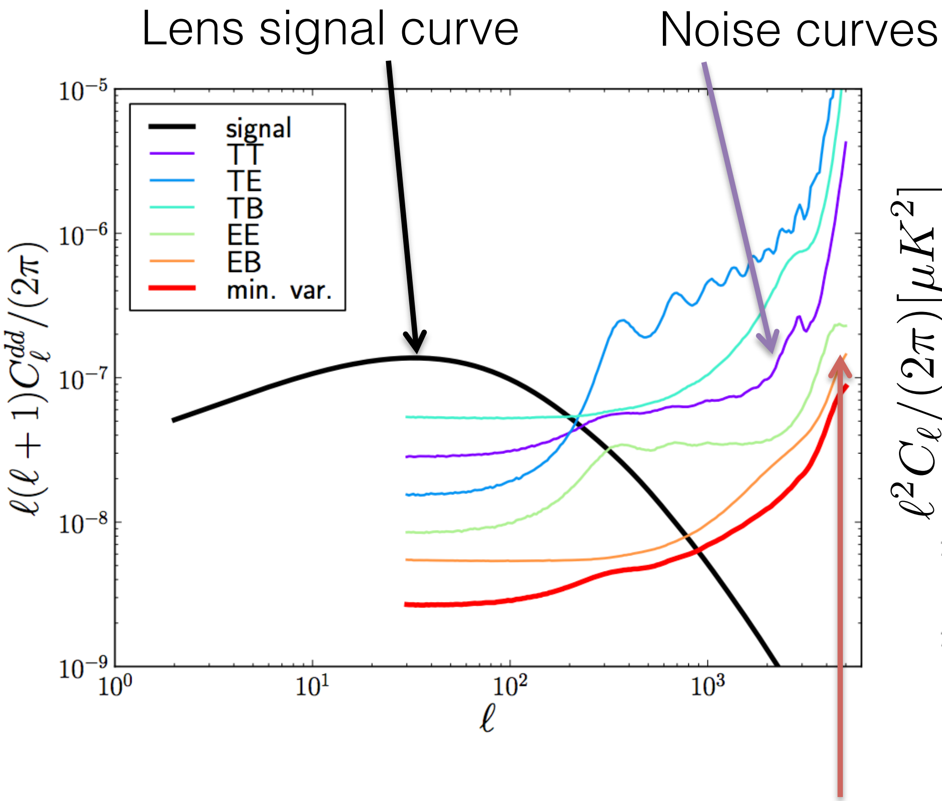
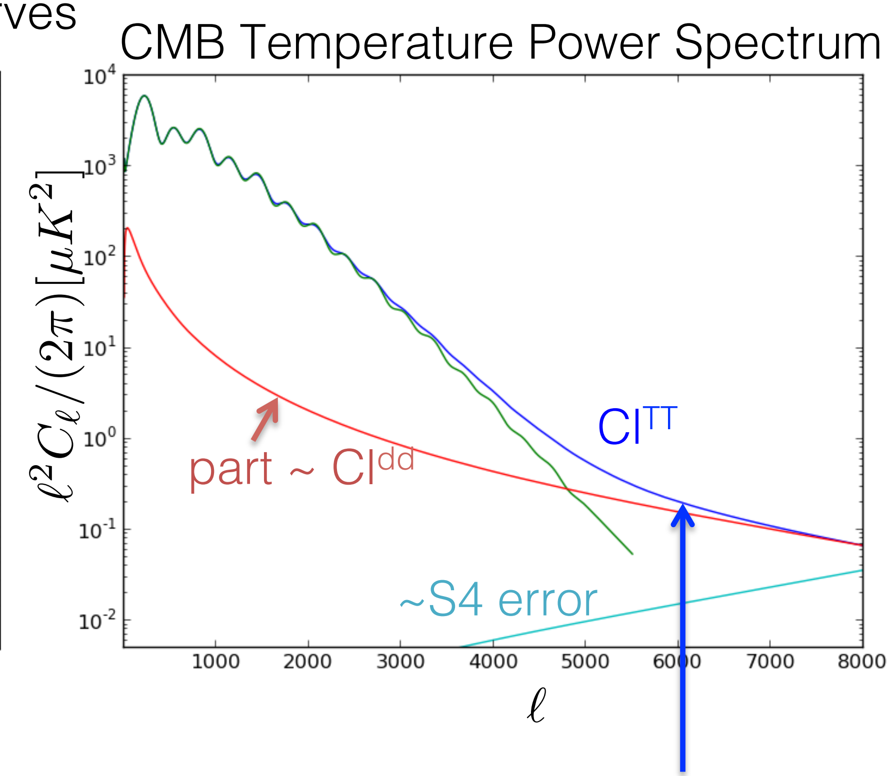




- A puzzle: quadratic estimator noise gets large – seemingly cannot probe tiny CMB lenses / scales (interesting for e.g. axions, WDM, cross-corrs…)
- But with low enough noise, can read off tiny lenses from small-scale power spectrum.

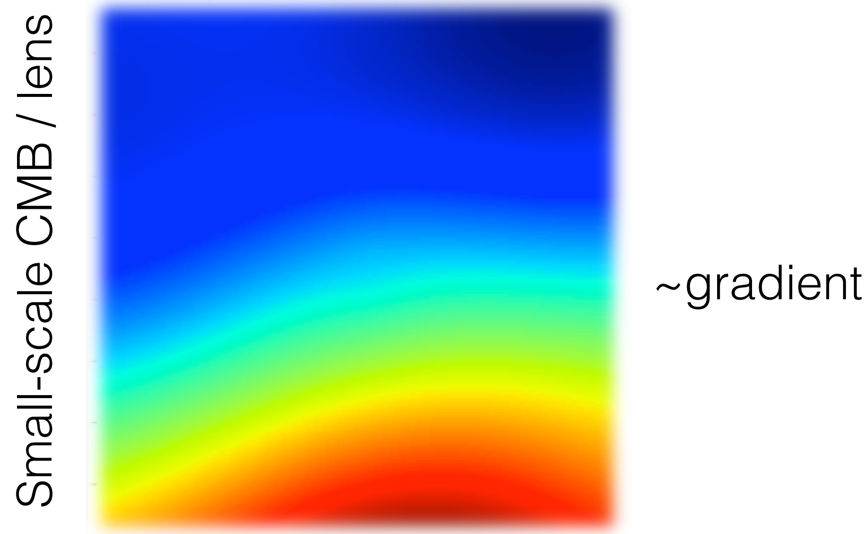
Hints at possible improvements on small scales





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

The simplicity of small-scale CMB



- On small scales, CMB gradient ∇T is effectively constant. Lensing expansion:

$$T(\mathbf{x}) = T^u(\mathbf{x}+\mathbf{d}) \approx T^u(\mathbf{x}) + \mathbf{d}(\mathbf{x}) \cdot \nabla T^u + \cdots$$

Noise
Foregrounds

$$\mathbf{d} = \nabla\phi$$

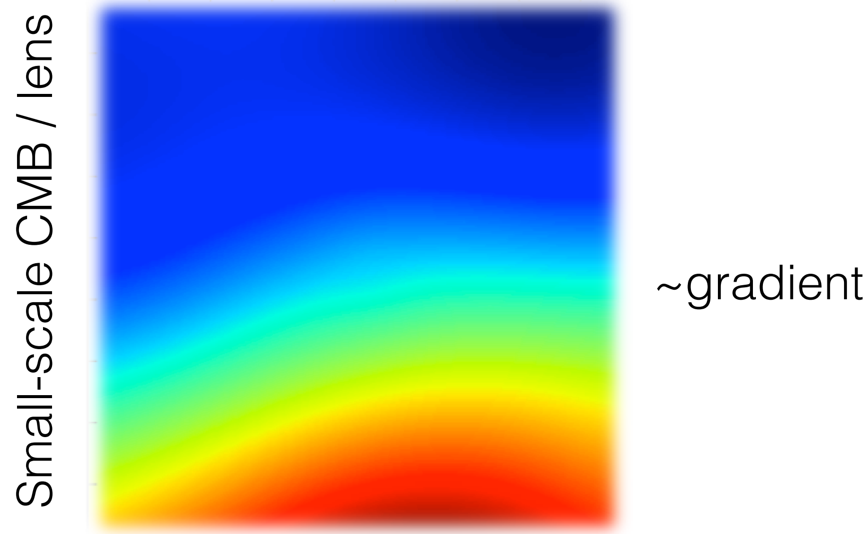
- Fourier transform with constant gradient:

$$T(\mathbf{L}) = d(\mathbf{L}) \times \hat{\mathbf{n}}_{\mathbf{L}} \cdot \nabla T^u$$

measured CMB

can measure this gradient (projected on L direction) from data easily

Gradient Inversion lensing estimation



- Suggests simple "gradient inversion" estimator:

$$\hat{d}^{GI}(\mathbf{L}) = \frac{T(\mathbf{L})}{\hat{\mathbf{n}}_{\mathbf{L}} \cdot \nabla T^u}$$

- c.f. quadratic estimator: only divides out <grad^2> – extra error!

$$\hat{d}^{QE}(\mathbf{L}) = \hat{d}^{GI}(\mathbf{L}) \frac{(\hat{\mathbf{n}}_{\mathbf{L}} \cdot \nabla T^u)^2}{\langle (\hat{\mathbf{n}}_{\mathbf{L}} \cdot \nabla T^u)^2 \rangle}$$

[Horowitz, Ferraro, Sherwin 2017, Zaldarriaga, Seljak 1997]

Continuous Small-scale Lensing Reconstruction

- Make continuous assuming slowly varying gradient, introduce anisotropic, gradient-dependent weighting:

$$\hat{d}^{GI}(\mathbf{L}) = \frac{T(\mathbf{L})}{\hat{\mathbf{n}}_{\mathbf{L}} \cdot \nabla T^{u}}$$

$$\downarrow$$

$$\hat{d}^{GI}(\mathbf{L}) \sim FT\left[\frac{T(\mathbf{x}) - T^{<2000}(\mathbf{x})}{\hat{\mathbf{n}}_{\mathbf{L}} \cdot \nabla T^{<2000}(\mathbf{x})} \times W(\mathbf{x}, \mathbf{L})\right]$$

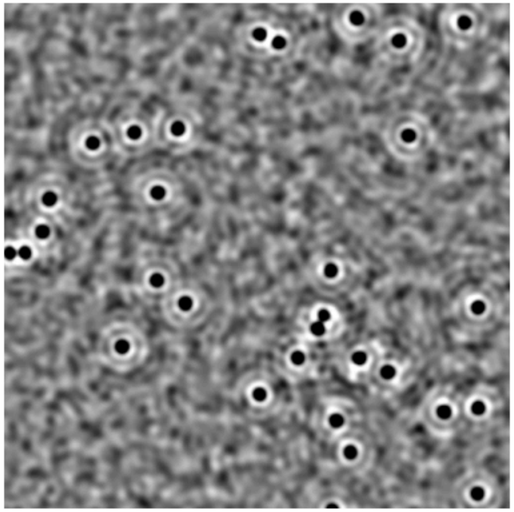
"Gradient inversion" estimator

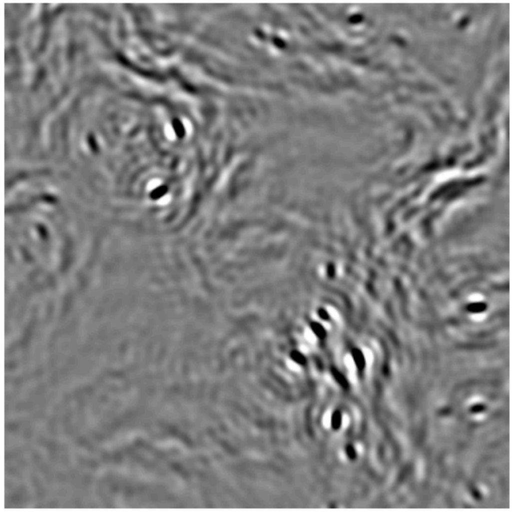
[Hadzhiyska, Sherwin, Madhavacheril, Ferraro 2019]

Simulation: GI lensing maps and spectra

- Simulated lensing reconstruction with new method (L>4000):

Input small-scale lens map (with artificial "halos")





Reconstructed lens map (weighted)

- GI reconstruction appears to do well, especially on large gradients

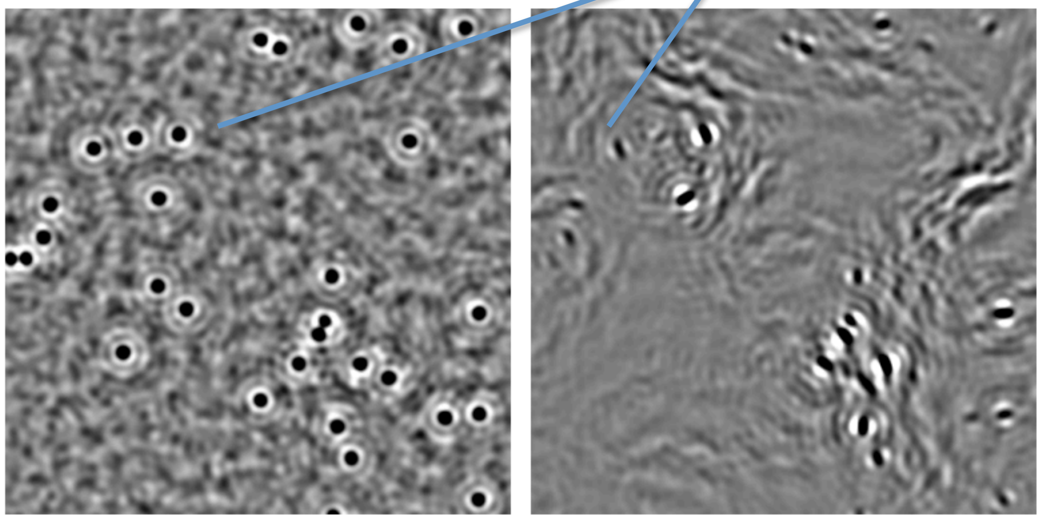
[Hadzhiyska, Sherwin, Madhavacheril, Ferraro 2019]

Simulation: GI lensing maps and spectra

- Simulated lensing reconstructi >4000):

Validate: cross-correlate reconstruction with input lensing

Input small-scale lens map (with artificial “halos”)

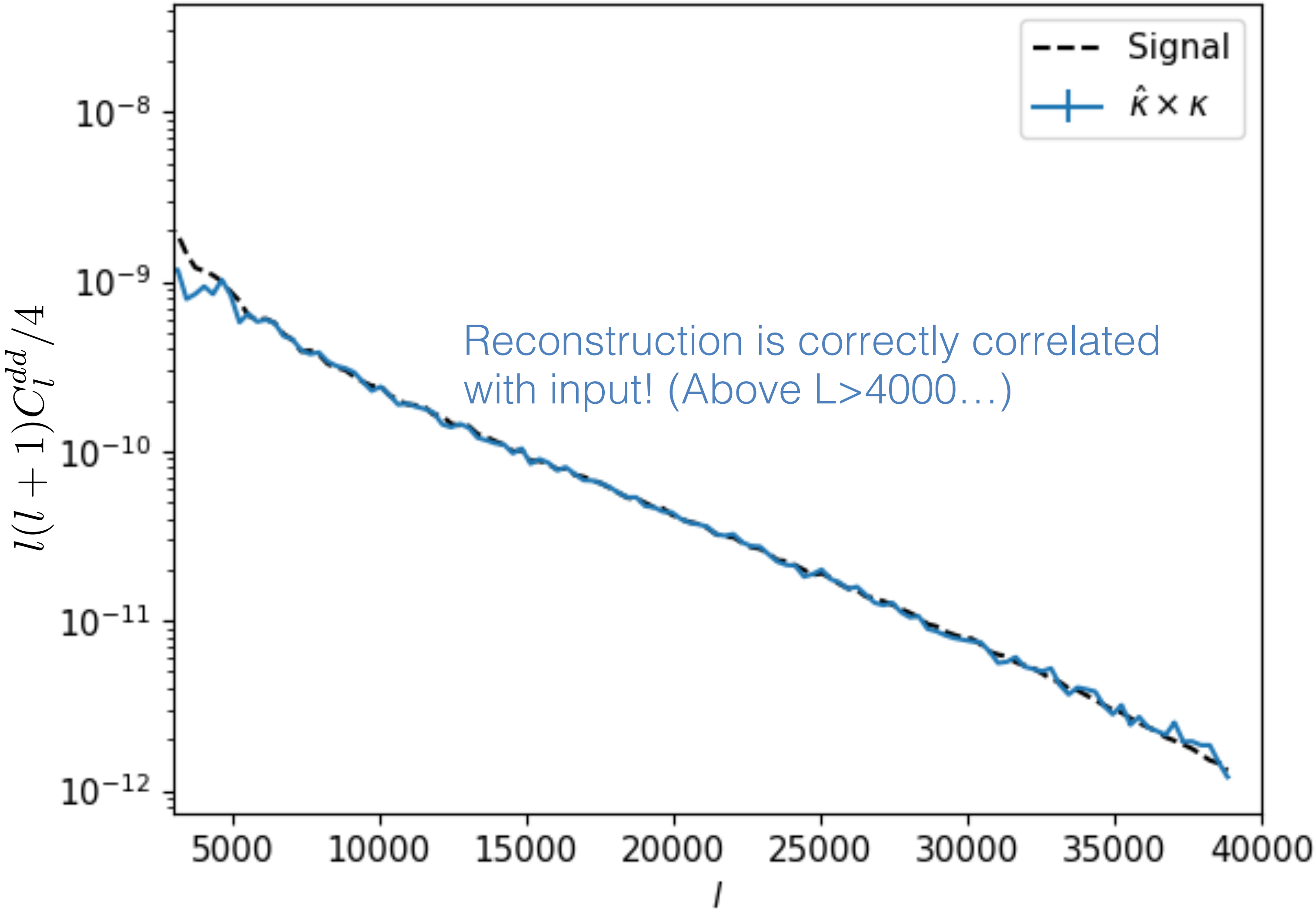


Reconstructed lens map (weighted)

- GI reconstruction appears to do well, especially on large gradients

[Hadzhiyska, Sherwin, Madhavacheril, Ferraro 2019]

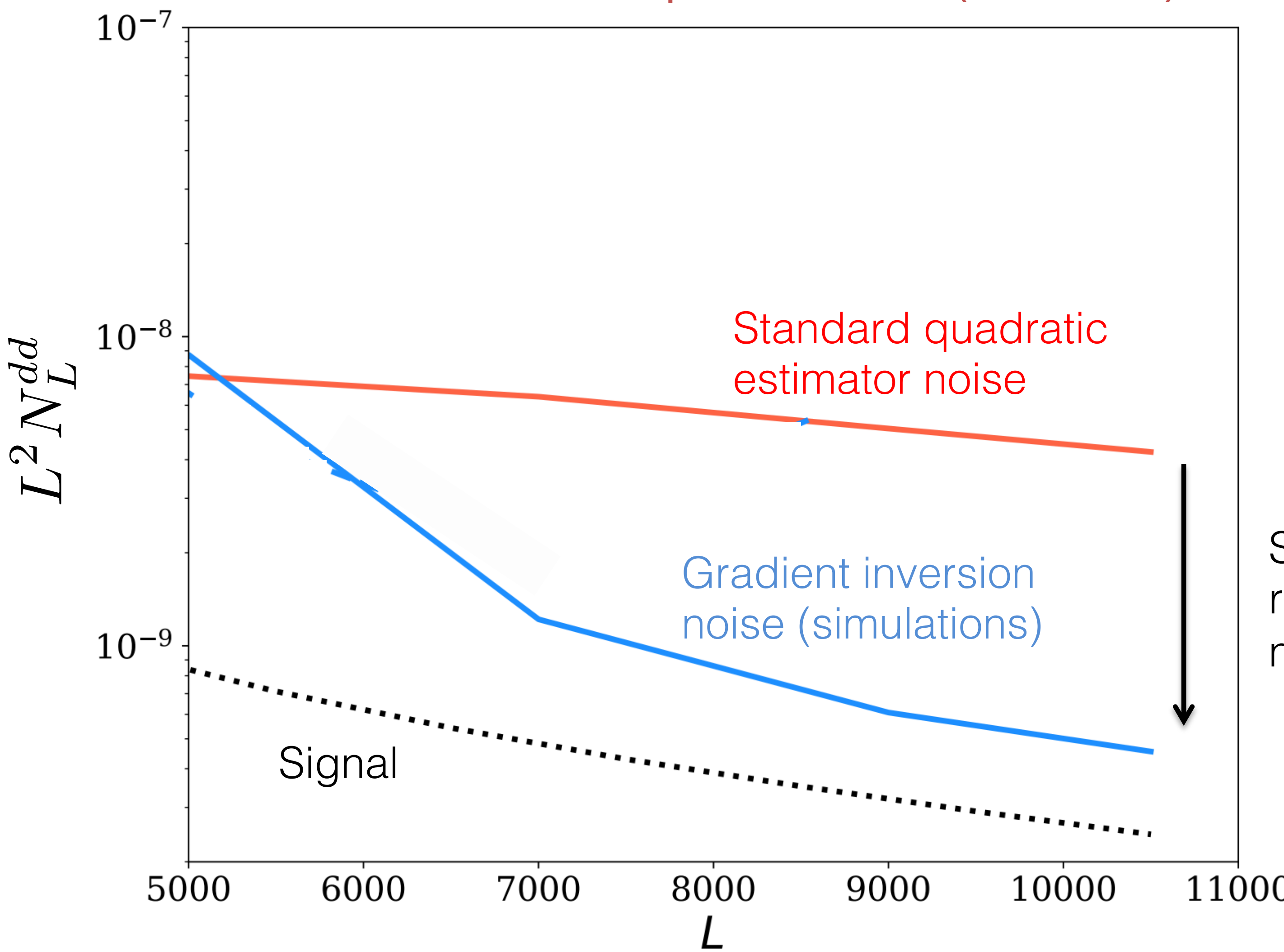
Validation: Reconstruction x input cross-correlation



Reconstruction is correctly correlated with input! (Above L>4000…)

[Hadzhiyska, Sherwin, Madhavacheril, Ferraro 2019]

Lensing noise improvements possible? Future CMB experiment (0.1uK')



Significant reduction of noise

[Hadzhiyska, Sherwin, Madhavacheril, Ferraro 2019]

Noise improvements possible? SO and CMB-S4

- Significant improvements possible on signal-noise ratio at L>4000

SNR	UL	S4-like	SO-like
Auto QE	205	100	7
Auto GI	1515	360	30

C_L^{dd} → Auto GI

Lensing power spectrum SNR

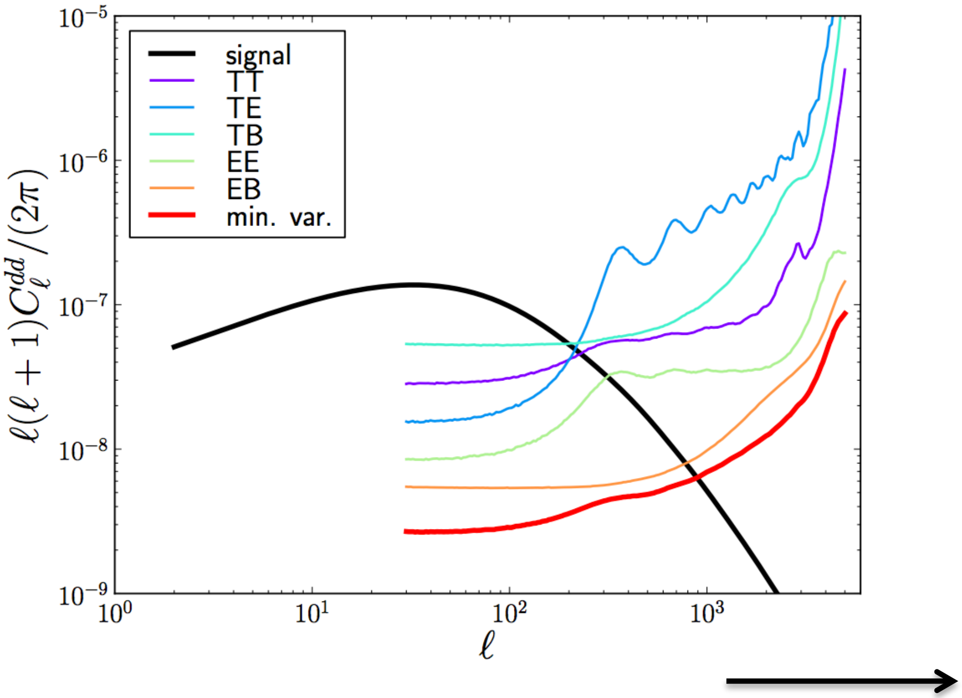
New method: factor ~four improvement in small scale SNR

- Major caveat: scatter from foregrounds. But not bias; signal, unlike foregrounds, is correlated with gradients.

[Hadzhiyska, Sherwin, Madhavacheril, Ferraro 2019,
Horowitz, Ferraro, Sherwin 2019]

Next steps and future work

- Detailed foreground and polarization analysis
- Same physics in maximum likelihood derivations, but need to fix algorithms for convergence (?)
- Can this improve constraints on e.g., cross-correlations, WDM, axion physics?

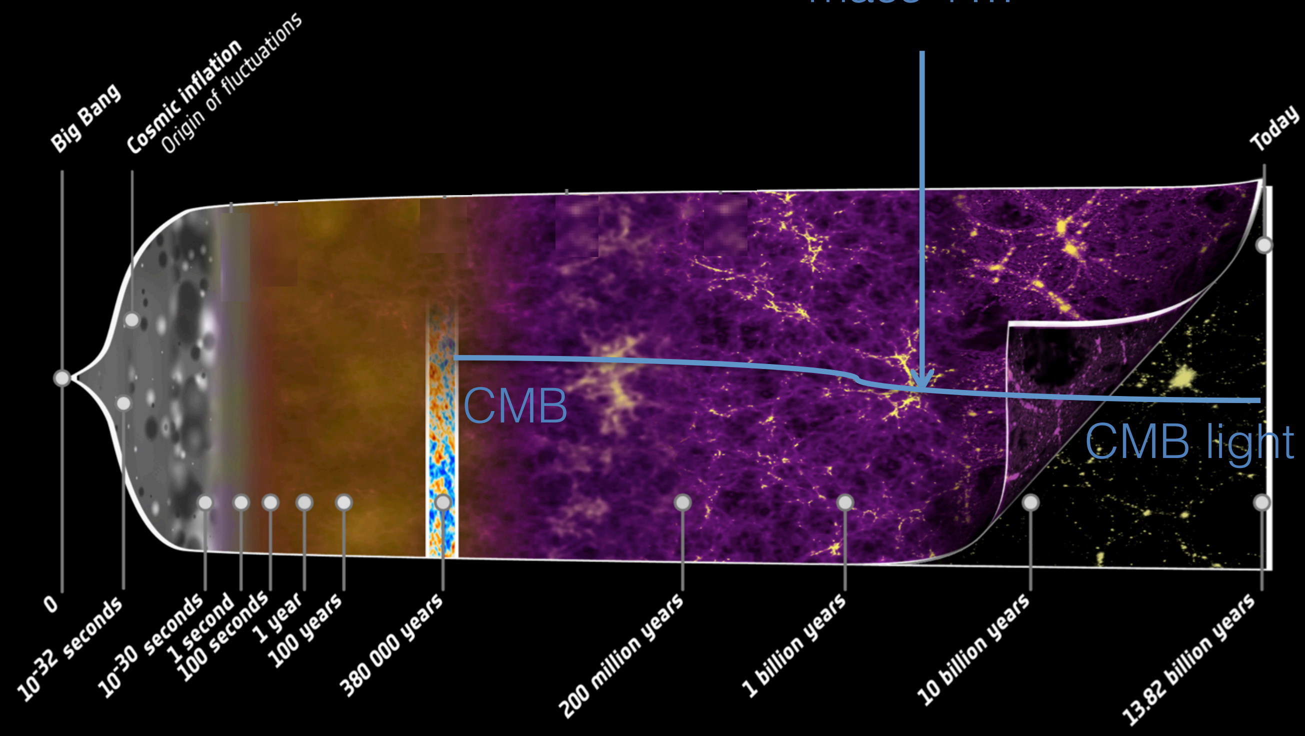


Measure lens power on much smaller scales

In progress!

Recap
CMB Lensing dark matter map: a signal to study neutrinos, +…

Lensing of CMB lets us map dark matter to study neutrino mass +…

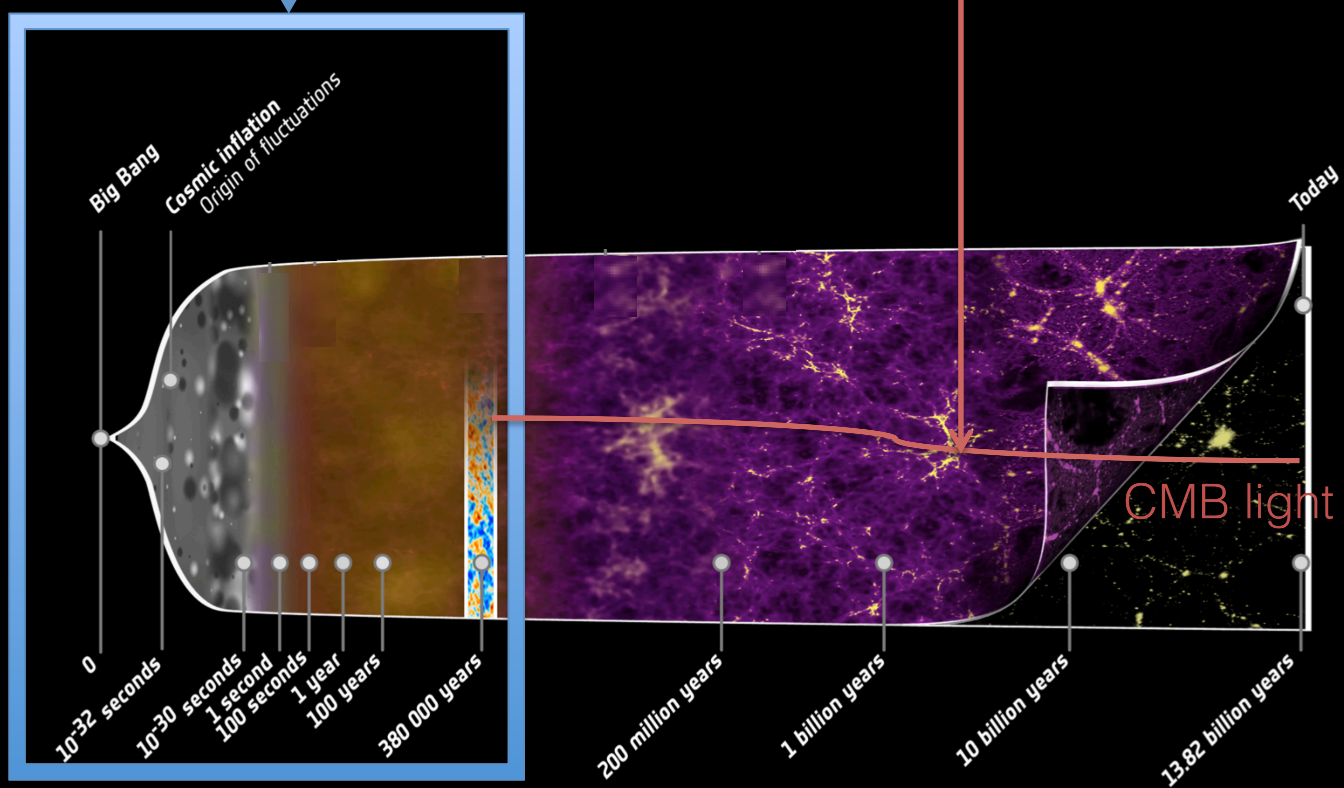


time (+ distance light travels!)

CMB Lensing as Noise for Early Universe Cosmology

But if we are interested in the early universe

Now lensing is a problem!

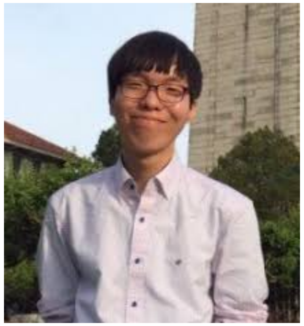


time (+ distance light travels!)

Outline

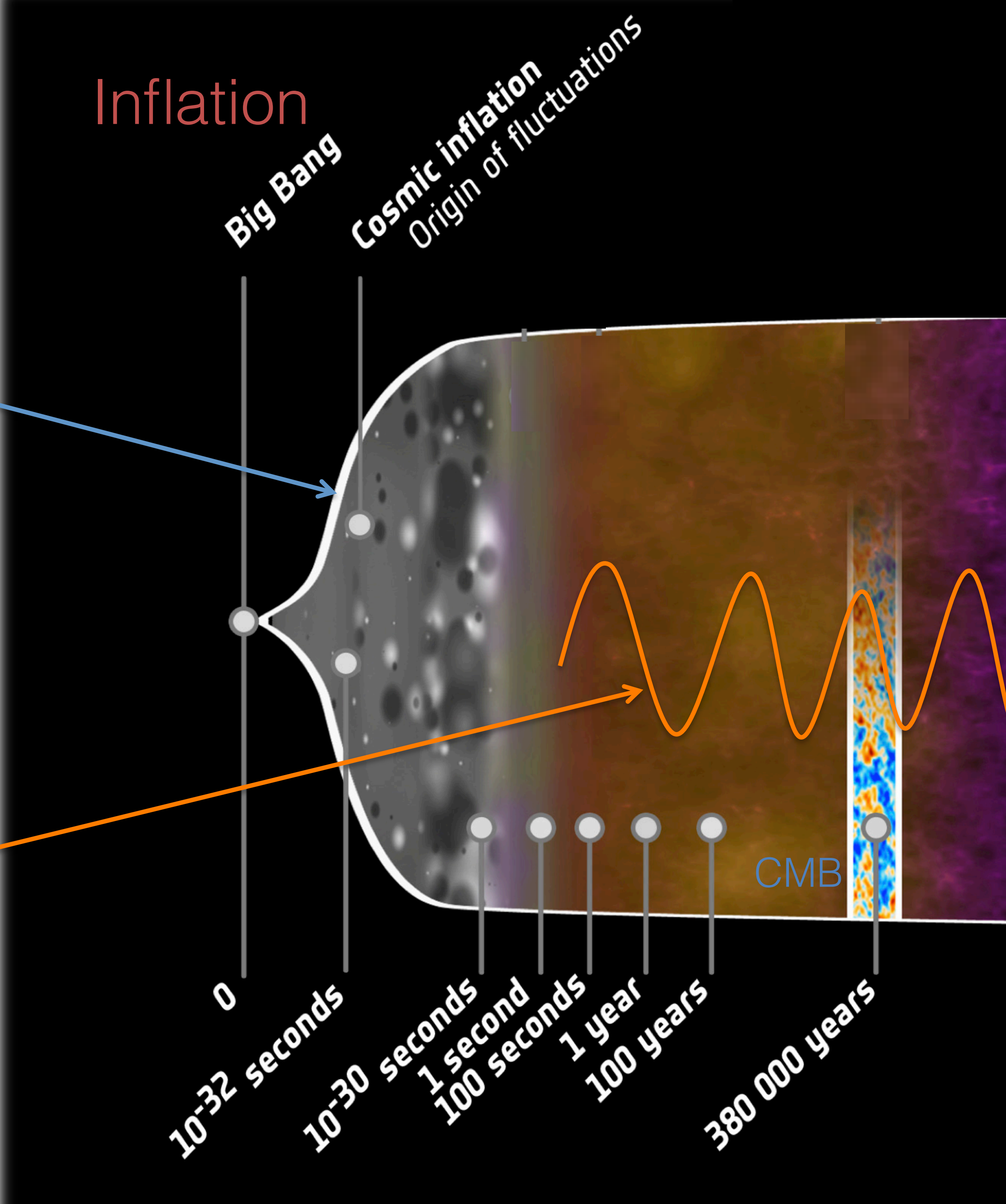
- Part 1: ACT and Simons Observatory: lensing and neutrino mass constraints
- Part 2: New approaches to small-scale CMB lensing - are our current estimators good enough?
- Part 3: Delensing Simons Observatory: new methods for revealing inflationary signals





With Toshiya Namikawa, Anton Baleato, Byeonghee Yu, et al.

- Inflation: initial accelerated cosmic expansion.
- Good evidence for idea – but we don't know for sure
- Many (simple) models make inflationary gravity waves*



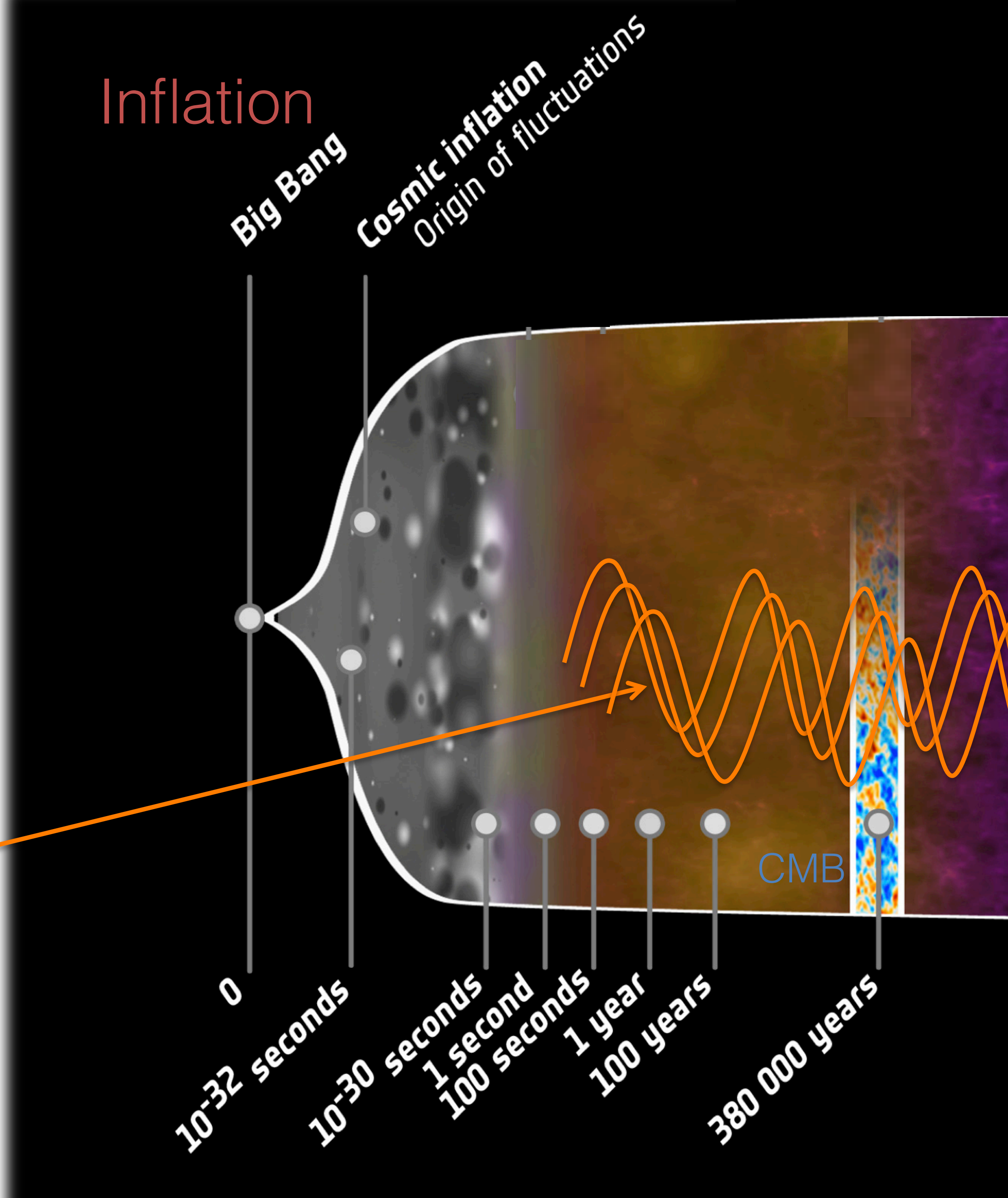
*N.B. Some other models also produce GWs

- Probe physics at ultra-high energy (at the doorstep of the Planck scale)

$$V^{1/4} = 1.04 \times 10^{16}\text{GeV} \left(\frac{r_*}{0.01}\right)^{1/4}$$

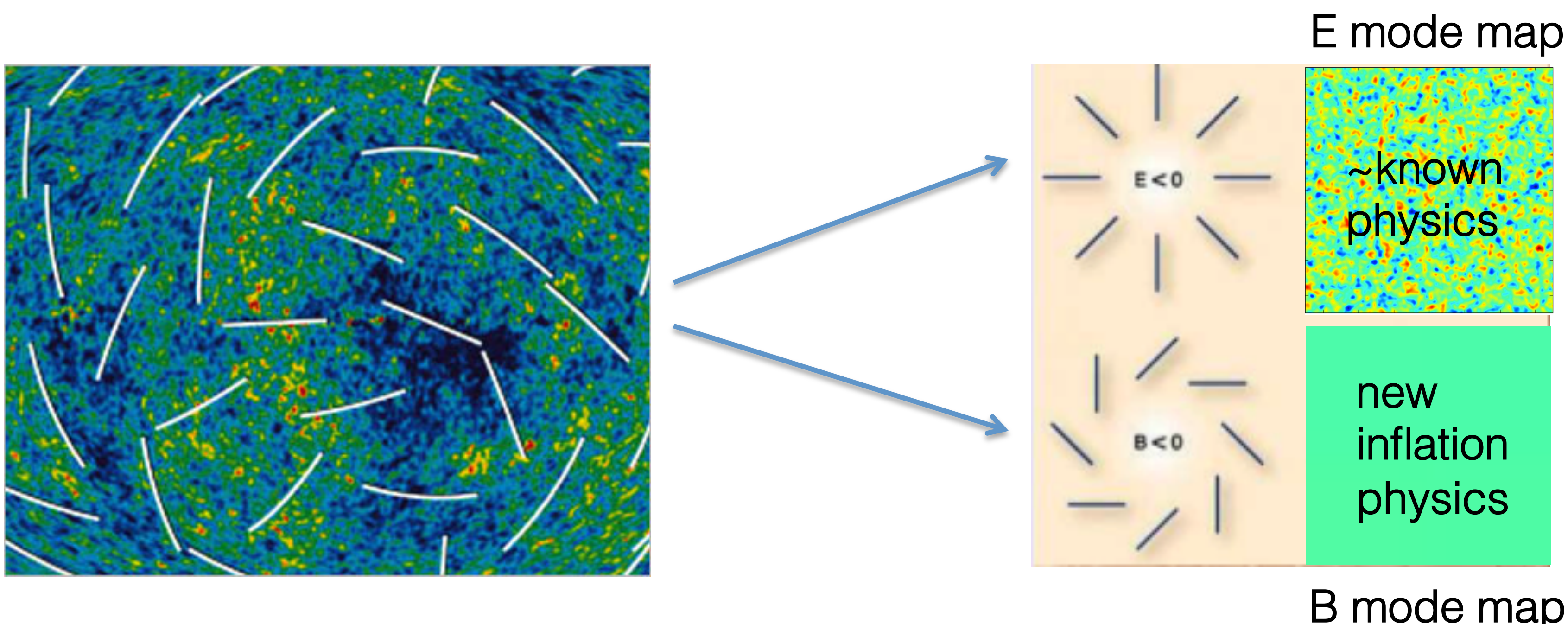
- The strength of the waves - tensor-to-scalar ratio r - tells us about the inflation energy scale, …

- Leaves a characteristic polarization pattern in CMB polarization



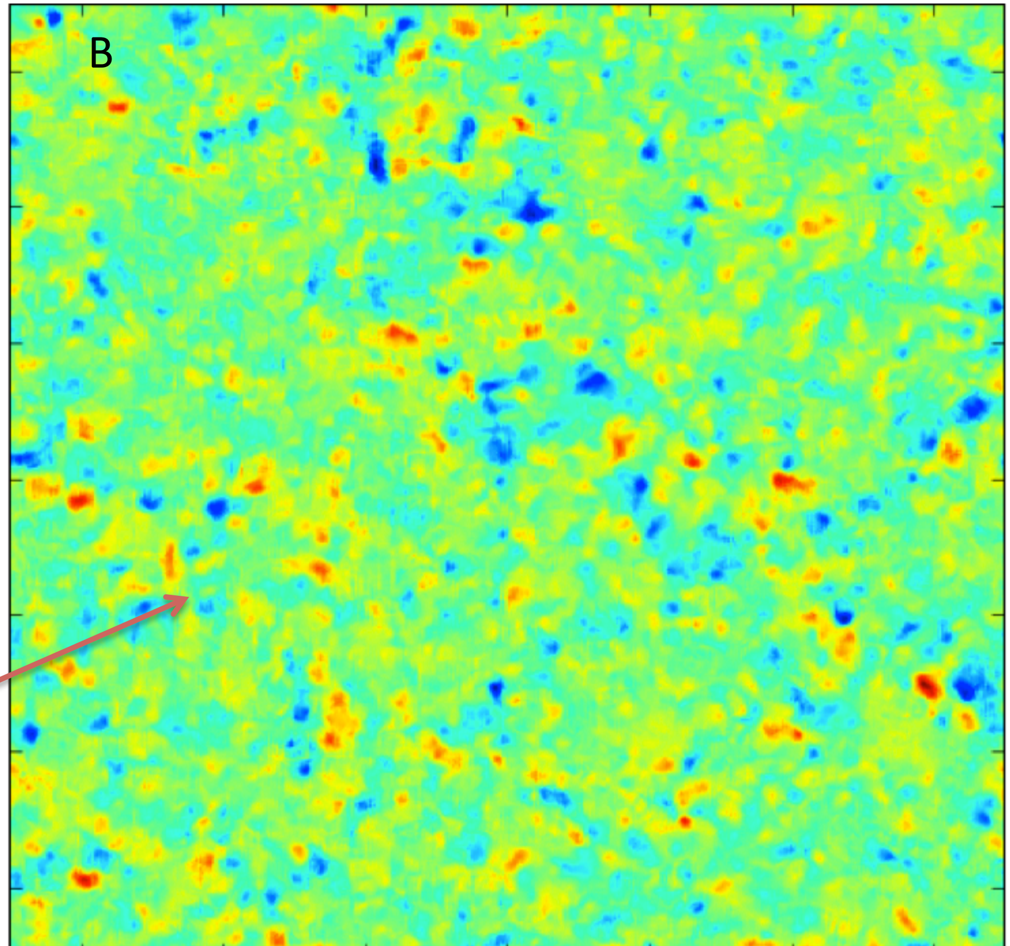
CMB B-mode Polarization: Reminder

- Any polarization map can be decomposed into E and B mode fields
- <u>B-mode: contains signals from inflation, if there</u>



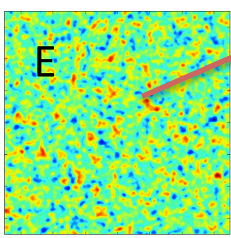
[Image credit: CMBPol]

Problem for CMB B-mode Searches: Lensing B-Mode Polarization



10°

Gravitational lensing converts E- to B- polarization

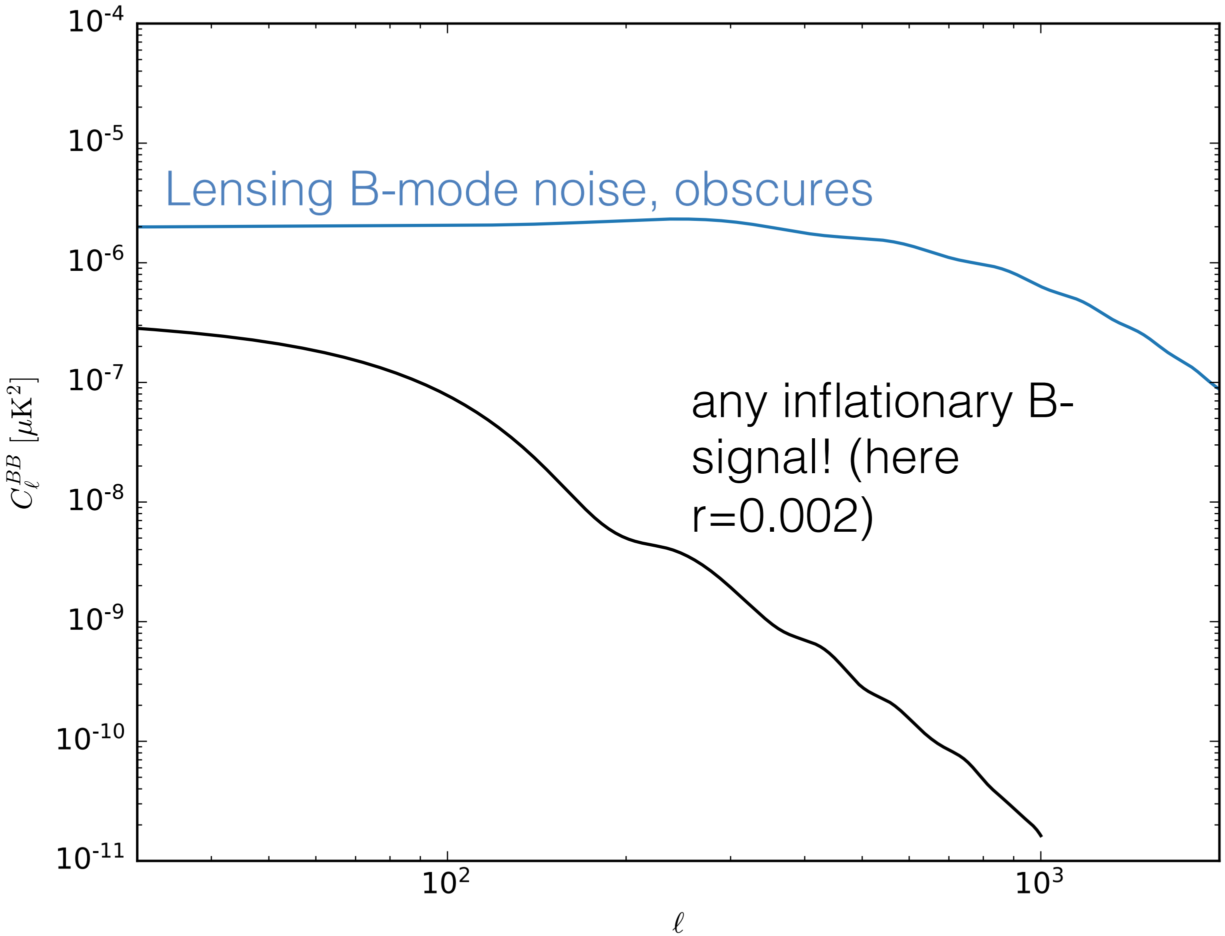


$$B^{lens}(\mathbf{L}) \sim \int d\mathbf{l}\; W(\mathbf{l},\mathbf{L}) E(\mathbf{l}) d(\mathbf{L}-\mathbf{l})$$

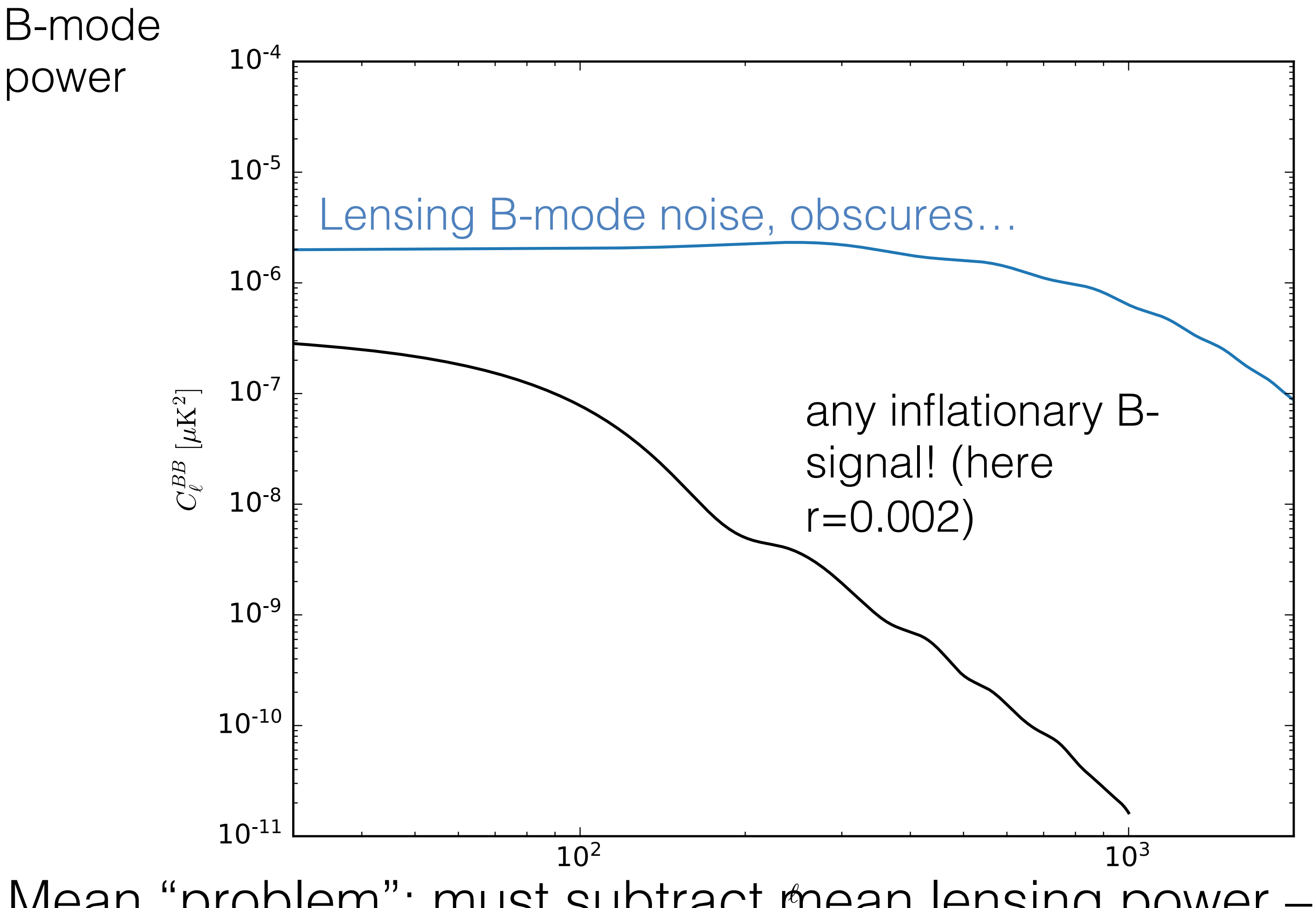
W: geometric kernel

Lensed CMB B-Polarization: Noise for Inflation-B

B-mode
power



Lensed CMB B-Polarization: Noise for Inflation-B

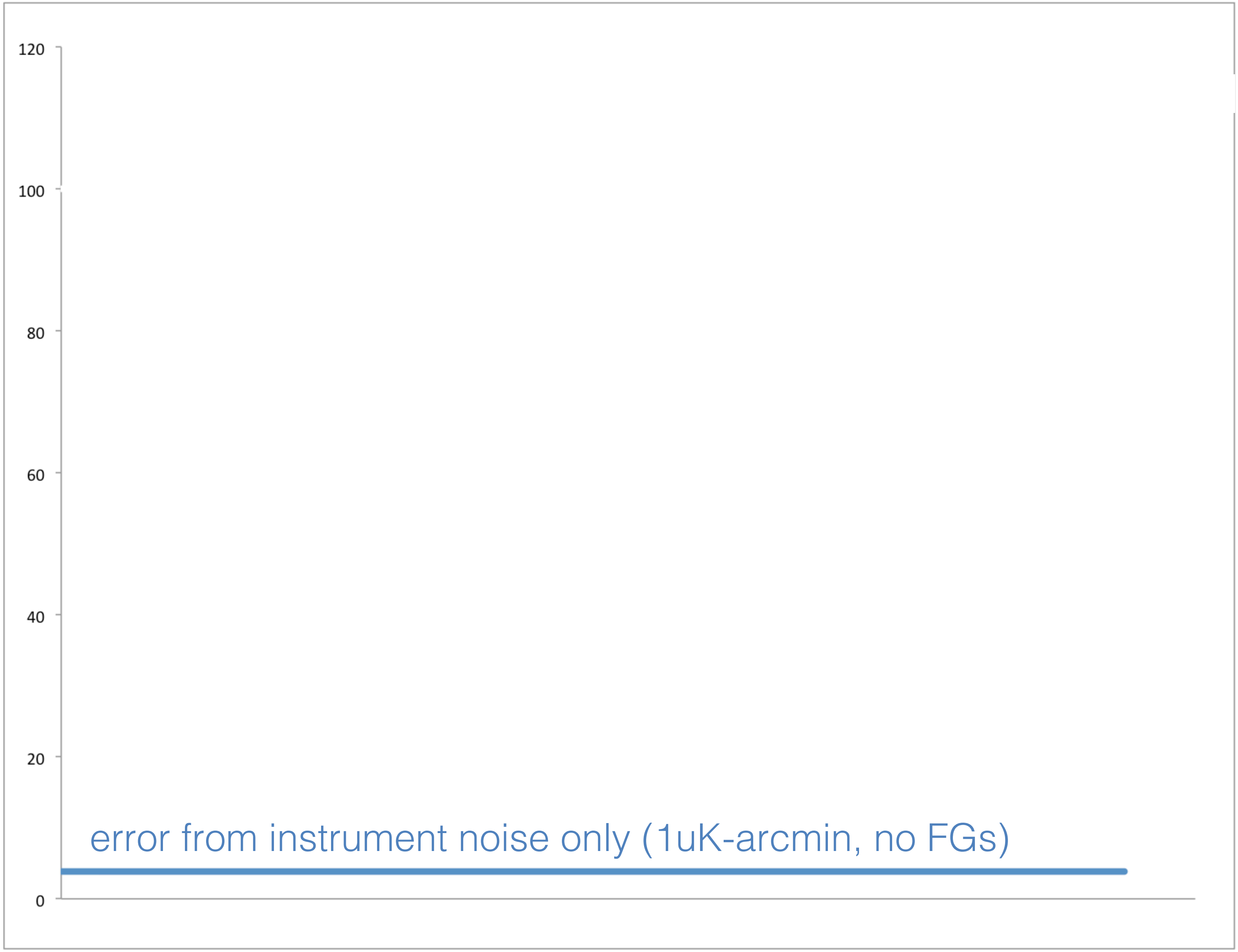


- Mean “problem”: must subtract mean lensing power – unimportant!
- Error problem: lensing adds additional cosmic variance

  $\sigma(r) \sim (N_l^{BB} + C_l^{BB,lens})$

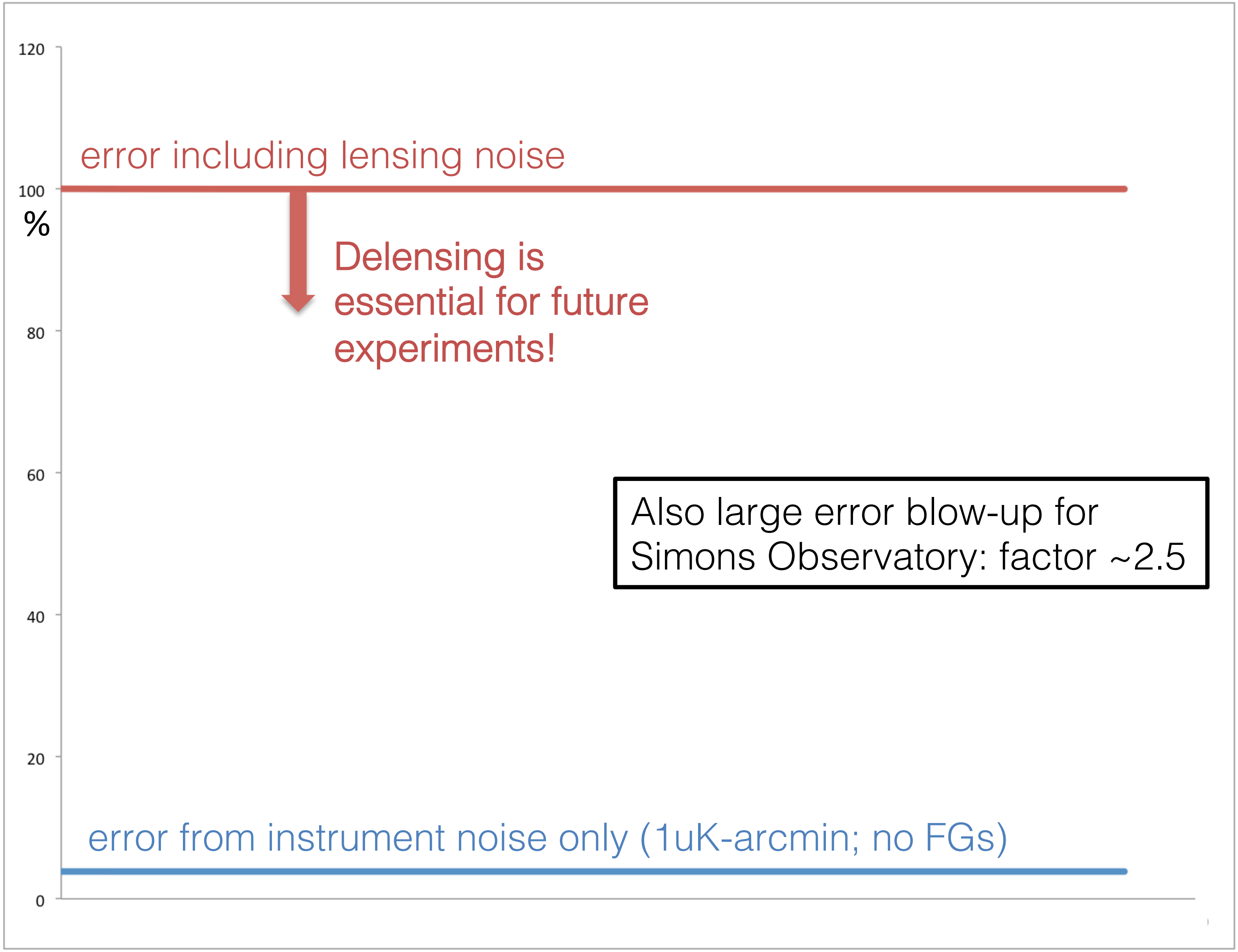
Error Inflation from Lensing Noise (Example: CMB-S4)

1-sigma Error On Strength Of Inflation Signal [i.e. σ(r)]

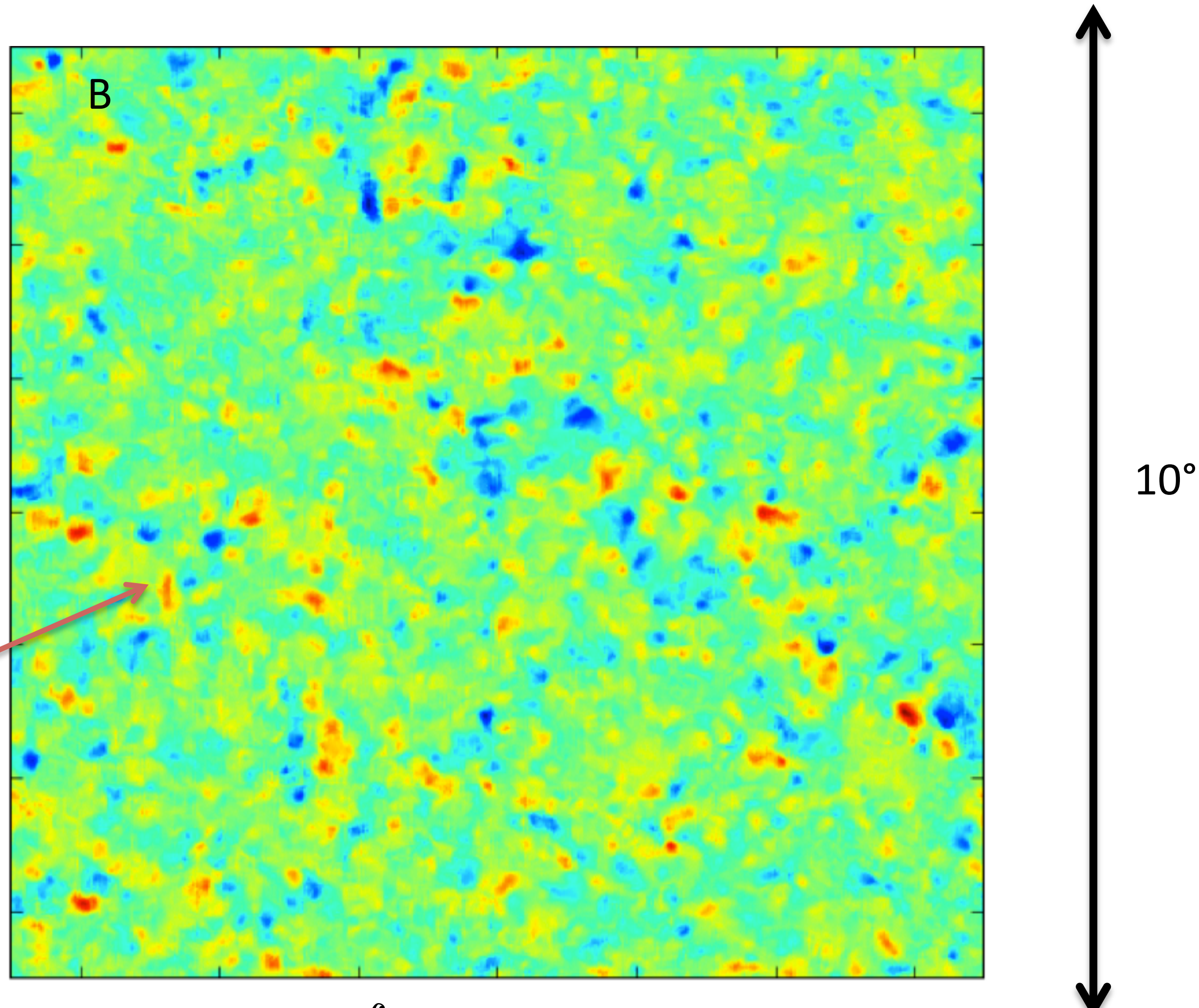


Error Inflation from Lensing Noise (Example: CMB-S4)

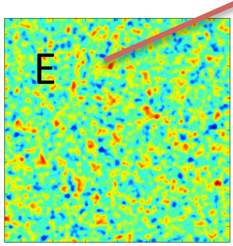
1-sigma Error On Strength Of Inflation Signal [i.e. σ(r)]



Delensing the CMB: Lensing Removal

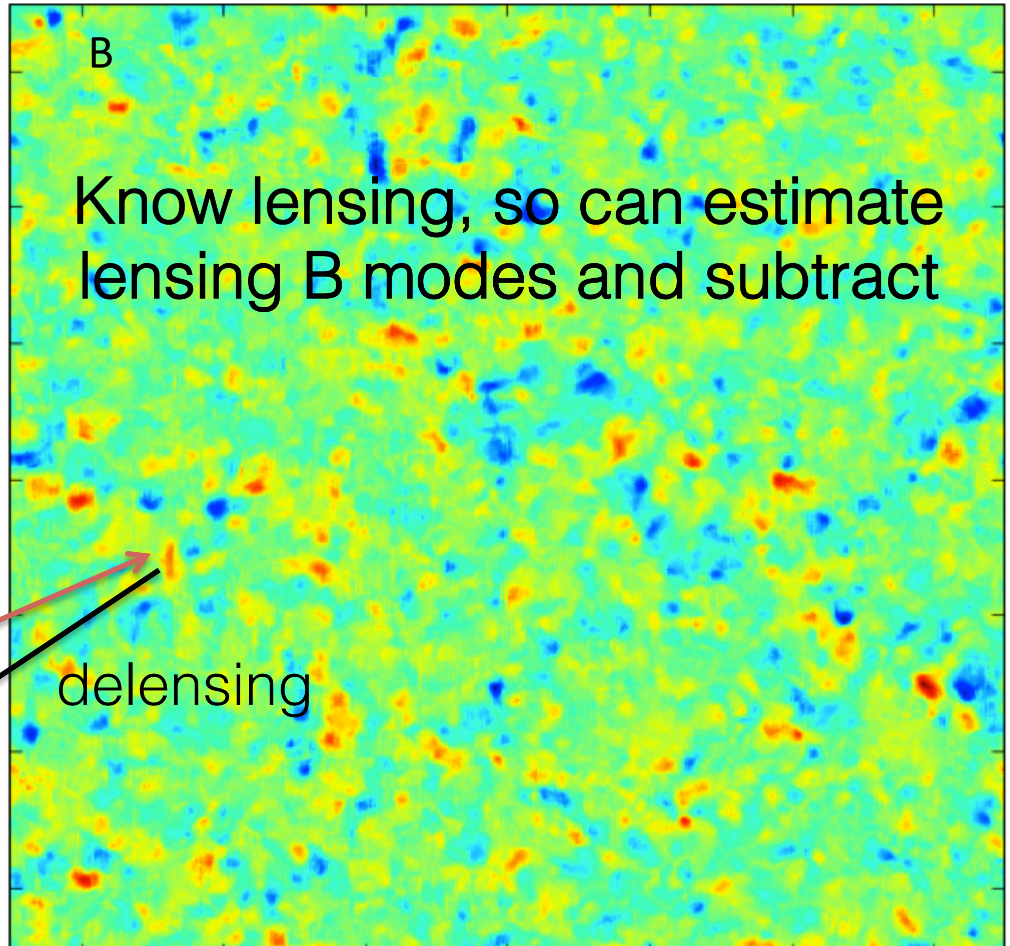


Gravitational lensing converts E- to B-polarization

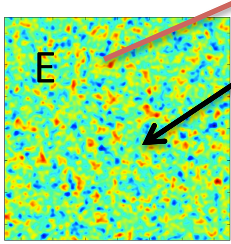


$$B^{lens}(\mathbf{L}) \sim \int d\mathbf{l}\; W(\mathbf{l},\mathbf{L})E(\mathbf{l})d(\mathbf{L}-\mathbf{l})$$

Delensing the CMB: Lensing Removal



Gravitational lensing converts E- to B- polarization

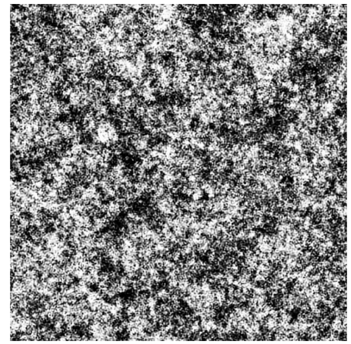


S/N weighted estimate of lensing d

Linearized version:

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

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



CMB lensing is a probe of the projected mass distribution

$$\nabla \cdot \mathbf{d} \sim \int dz W(z) \delta(z)$$

Standard "Internal" case:

1) Reconstruct lensing $\hat{d}$ from changes in background CMB

Delensing: Forecasting Performance

- Error reduction depends on residual lensing B-mode

$$\sigma(r) \sim \langle C_l^{BB,\mathrm{lens}} + N_l^{BB} \rangle_{l<100}$$

$C_l^{BB,res}$

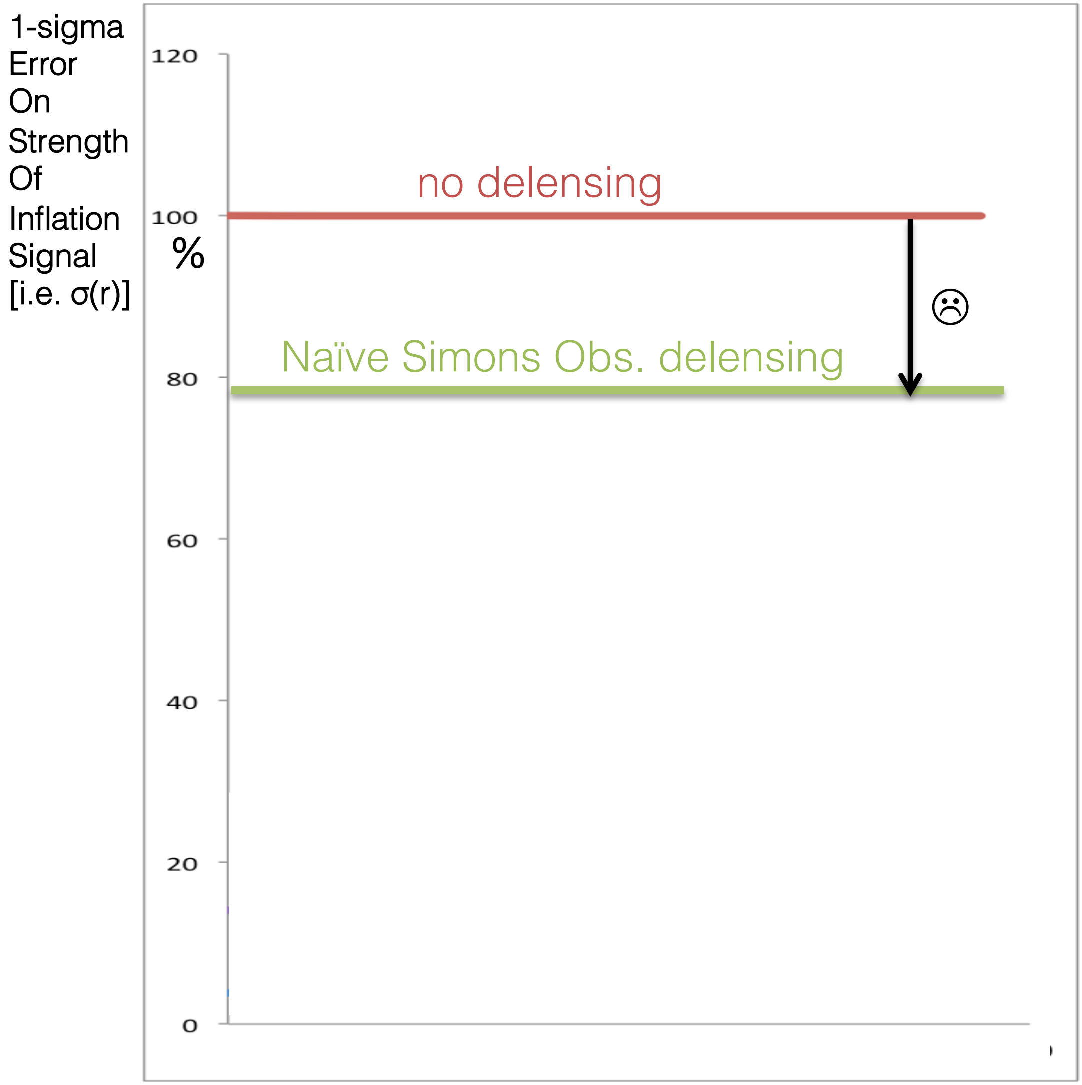
- Find that delensing reduces B-mode power by a factor ~ $(1-\rho^2)$

$$\rho_l^2 = \frac{(C_l^{\hat{d}d})^2}{C_l^{dd} C_l^{\hat{d}\hat{d}}}$$

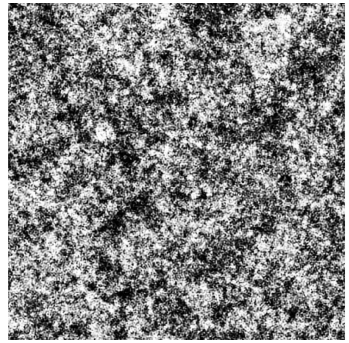
[ρ : correlation coefficient of lensing estimate $\hat{d}$ with true lensing d]

Delensing for Simons Observatory (SO)

- SO is significantly limited by lensing B-modes
- Problem: SO lensing reconstruction, while powerful, is still too noisy to allow large improvements from internal delensing
- Only ~20 % improvement expected internally



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



CMB lensing is a probe of the projected mass distribution

$$\nabla \cdot \mathbf{d} \sim \int dz W(z) \delta(z)$$

1) Reconstruct lensing from changes in background CMB

2) Estimate lensing from Large Scale Structure tracers of lensing, e.g. **CIB, galaxies.** Can show:

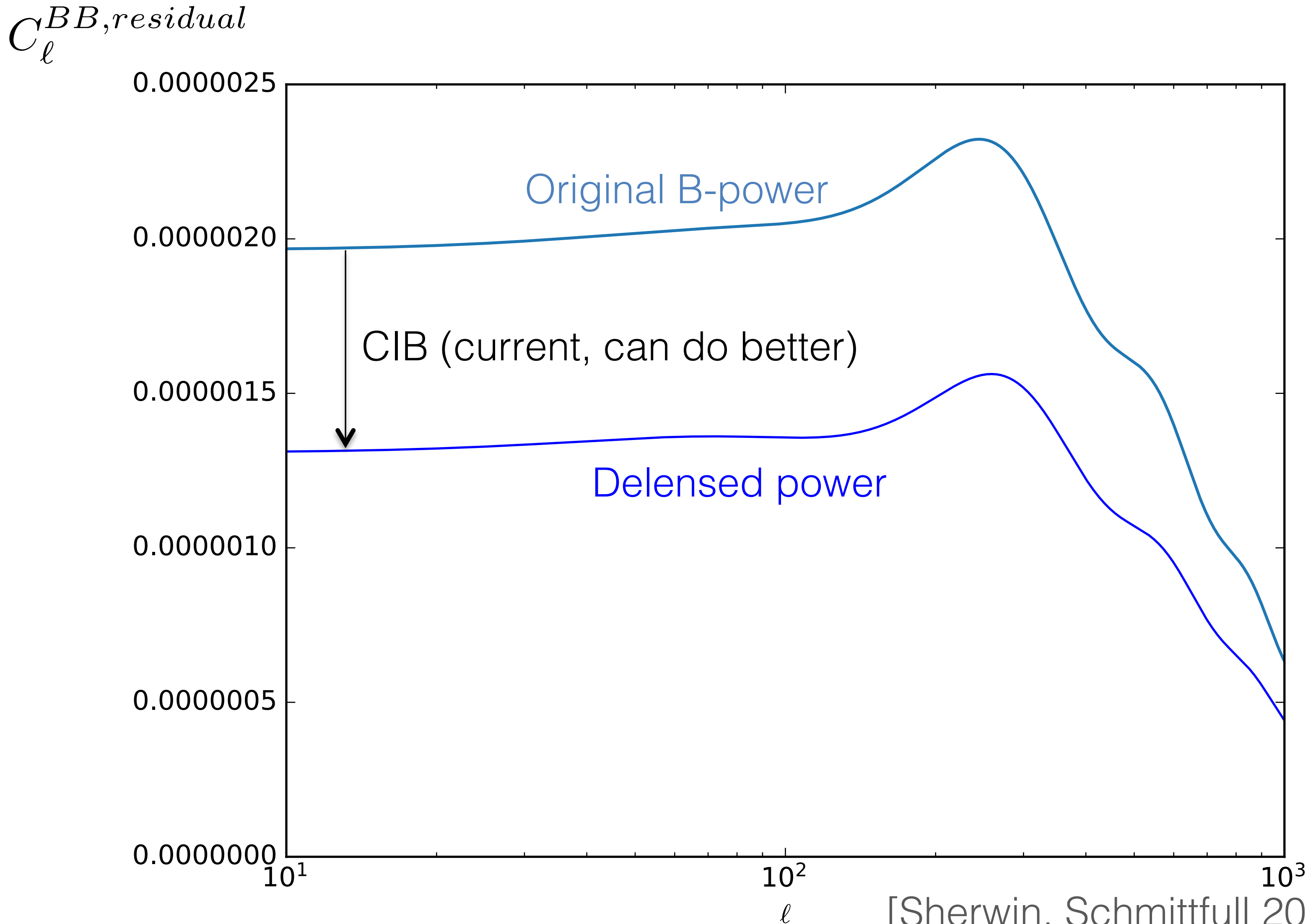
CIB-lensing cross

$$\hat{d}^I(\mathbf{l}) = \frac{C_l^{dI}}{C_l^{dd}} \times I(\mathbf{l})$$

Lensing power   CIB map

[Sherwin, Schmittfull 2015]

CIB Delensing for Simons Observatory



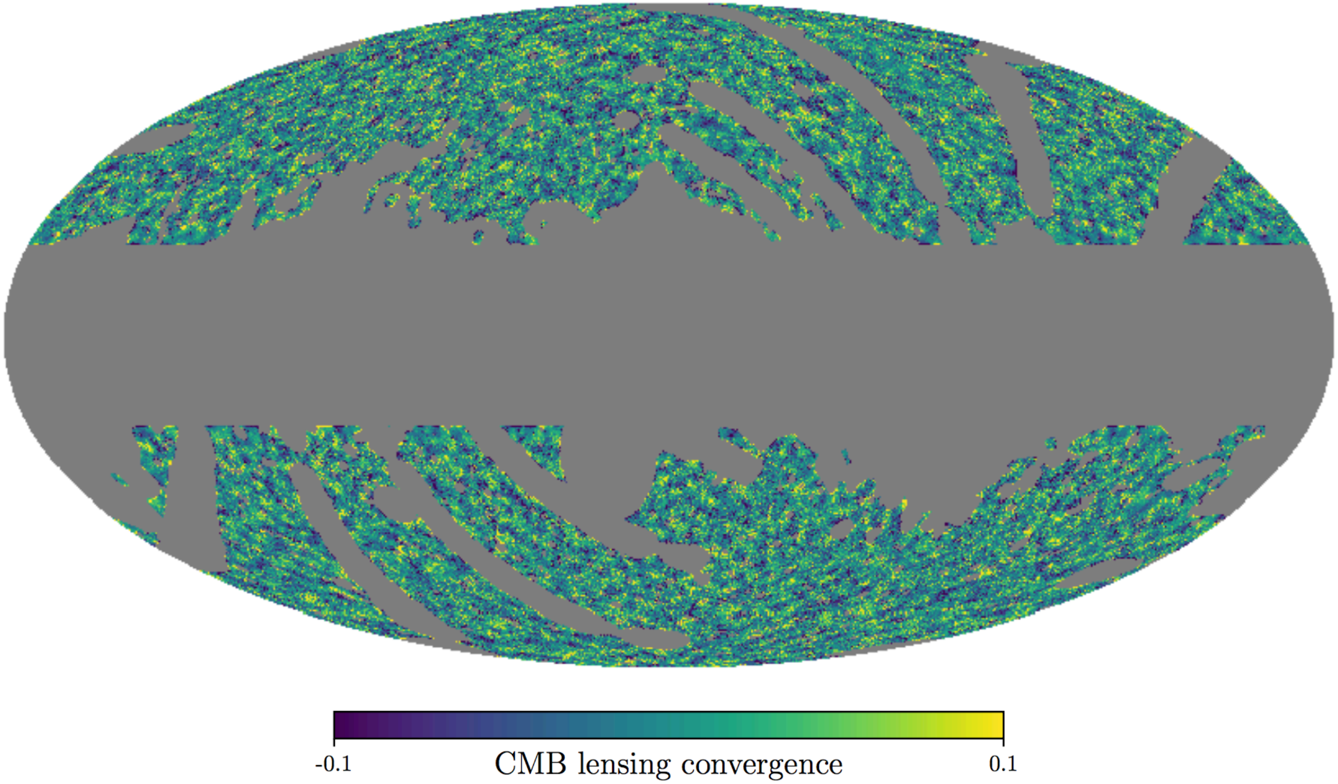
[Sherwin, Schmittfull 2015]

Use maps of cosmic infrared background (CIB), scaled by C_l^{dI}/C_l^{dd} , to infer and remove the lensing (used by SPT/BICEP now)

Multi-tracer Delensing for Simons Observatory

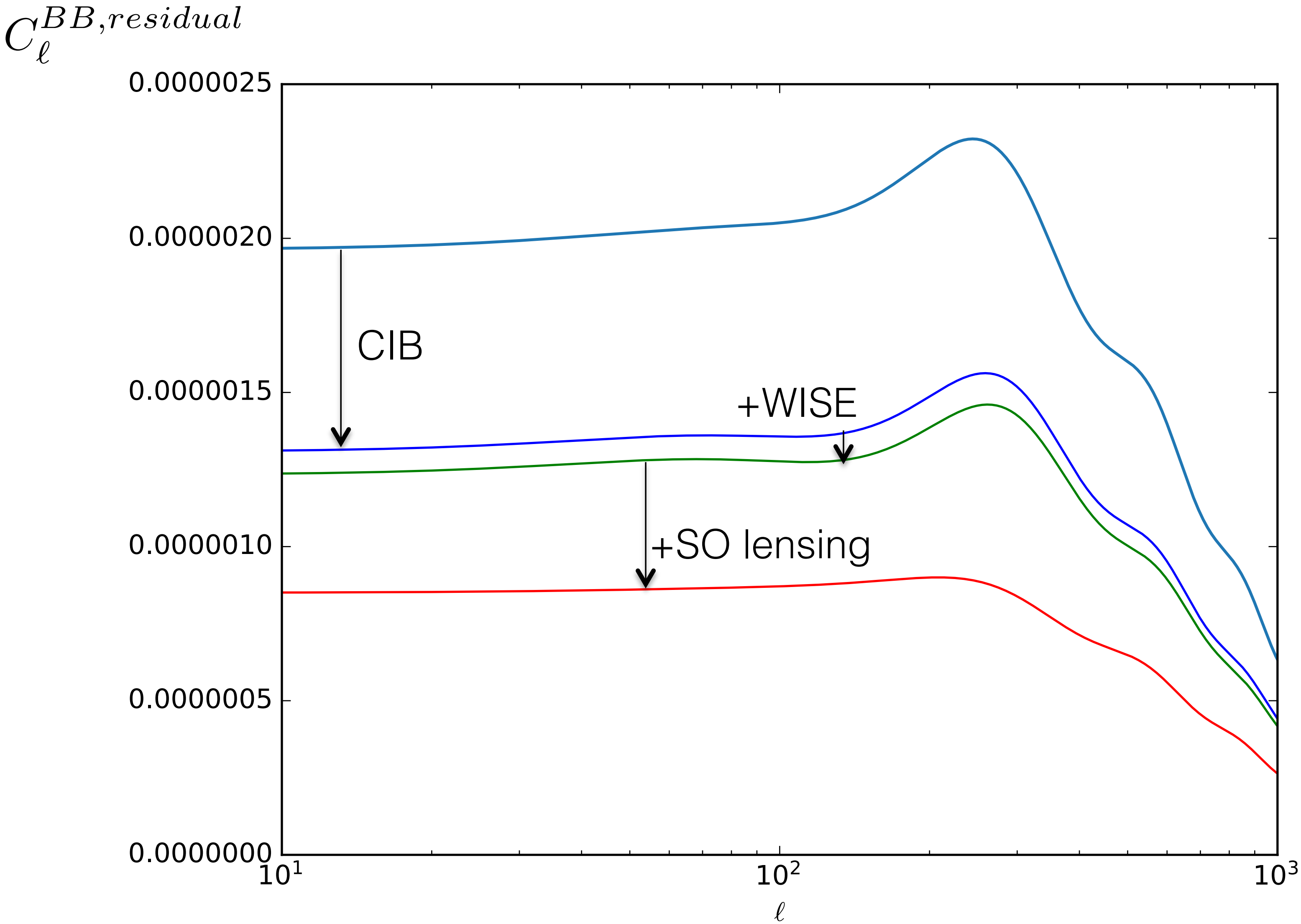
- Can co-add SO lensing map with different large scale structure tracers to delens [Yu, Hill, Sherwin 2017]

Example delensing map made from coadd of Planck lensing + CIB + WISE galaxies



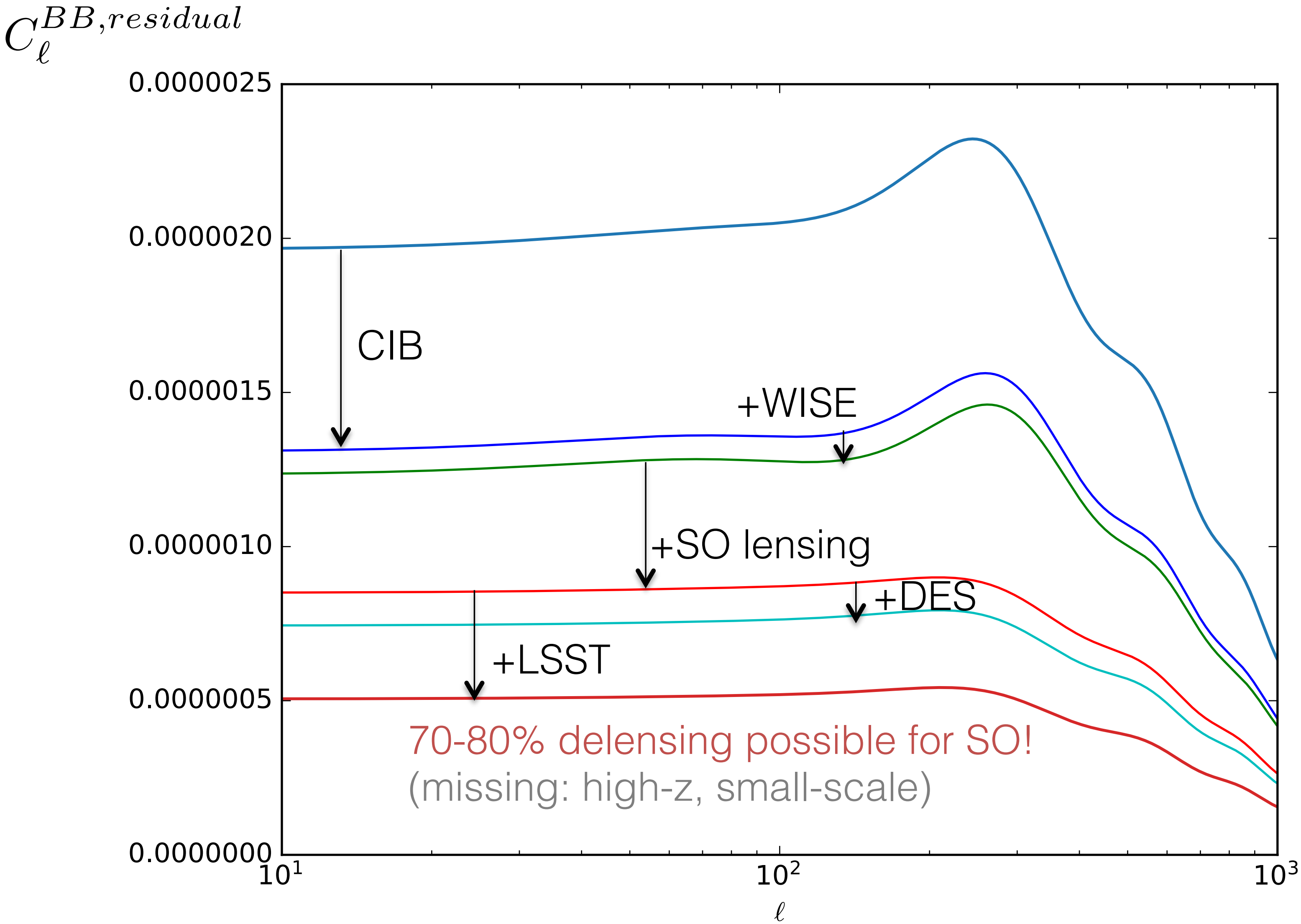
- “Multitracer” delensing can greatly improve delensing performance: now coadd SO lensing + DES/LSST + CIB + …

Multi-tracer Delensing for Simons Observatory



$$I(\mathbf{l}) = \sum c_i(\mathbf{l}) I_i(\mathbf{l}) \qquad c_i = (C_l^{I_i I_j})^{-1} C_l^{dI_j}$$

Multi-tracer Delensing for Simons Observatory

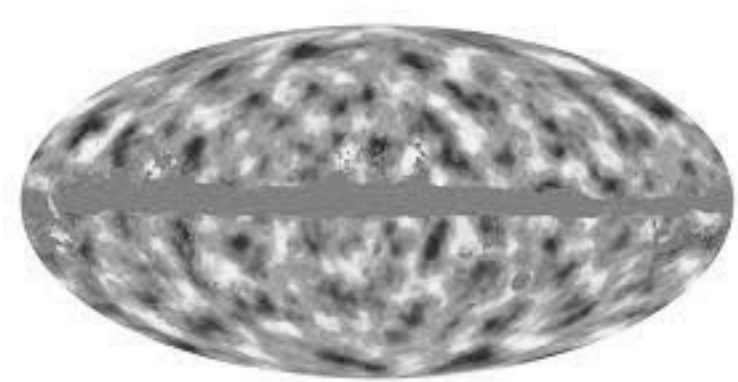


$$I(\mathbf{l}) = \sum c_i(\mathbf{l}) I_i(\mathbf{l}) \qquad c_i = (C_l^{I_i I_j})^{-1} C_l^{dI_j}$$

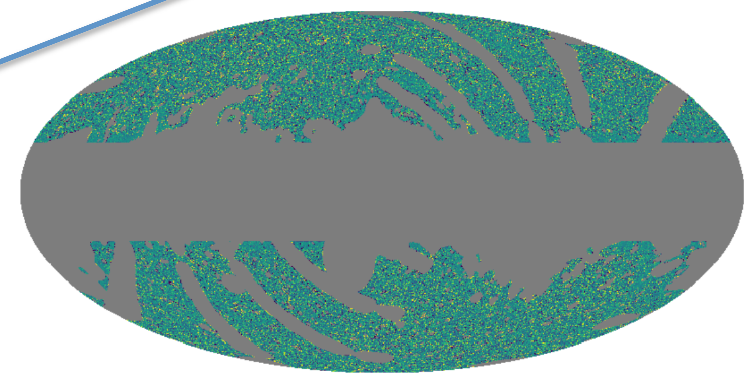
Why I think this will work I: LSS modeling required?

- Tracer calibration and delensing residual depend only on measurable spectra

$$I(\mathbf{l}) = \sum c_i(\mathbf{l}) I_i(\mathbf{l}) \qquad c_i = (C_l^{I_i I_j})^{-1} C_l^{dI_j}$$



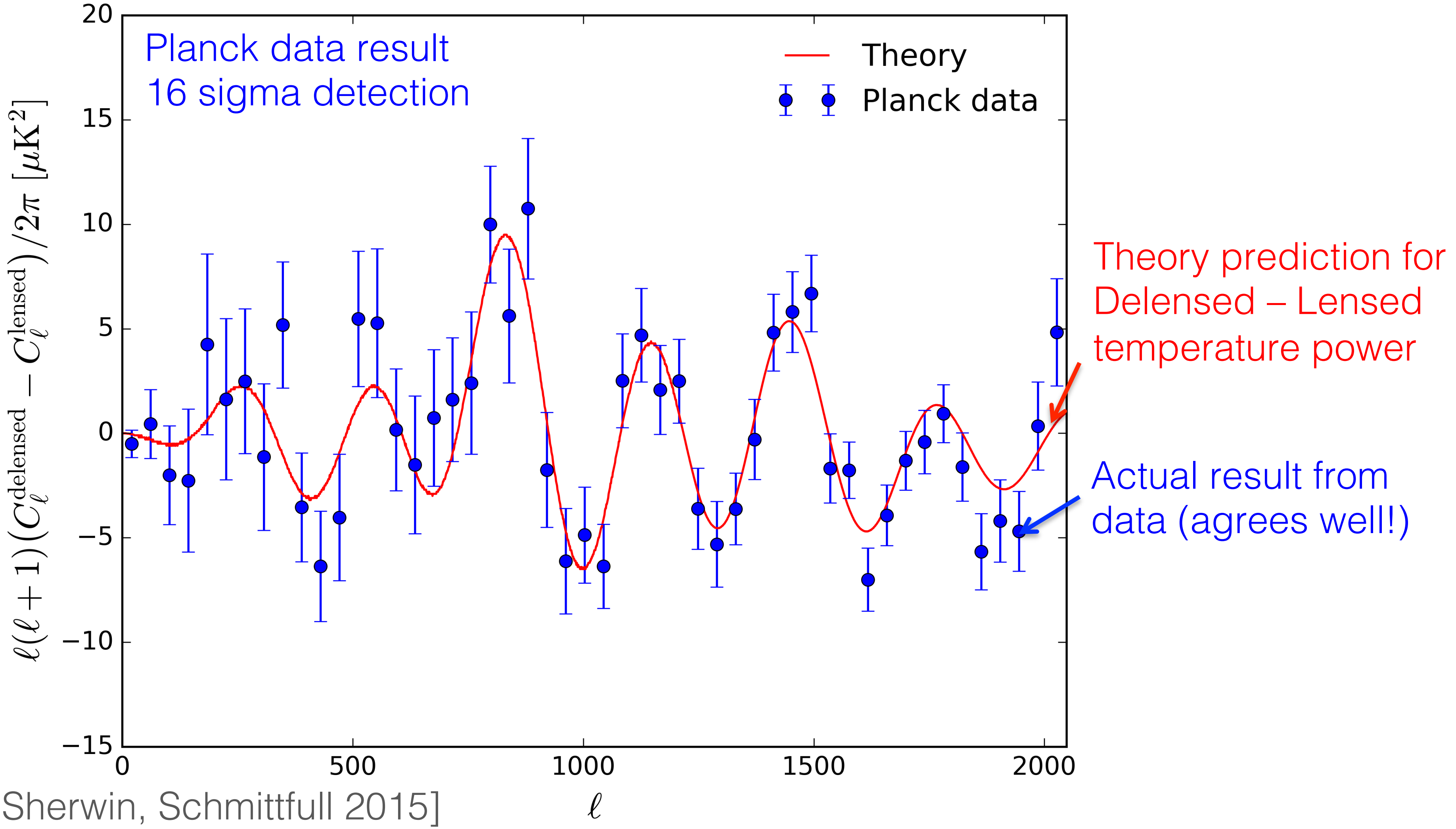
Noisy-ish lensing map (low S/N per mode)



High S/N but mis-scaled LSS map

- Cross-spectra (assuming isotropy) can have high S/N -> can calibrate low noise LSS map, modeling often not needed!

Why I think this will work II: Data demonstration of CIB delensing (of Temp.)

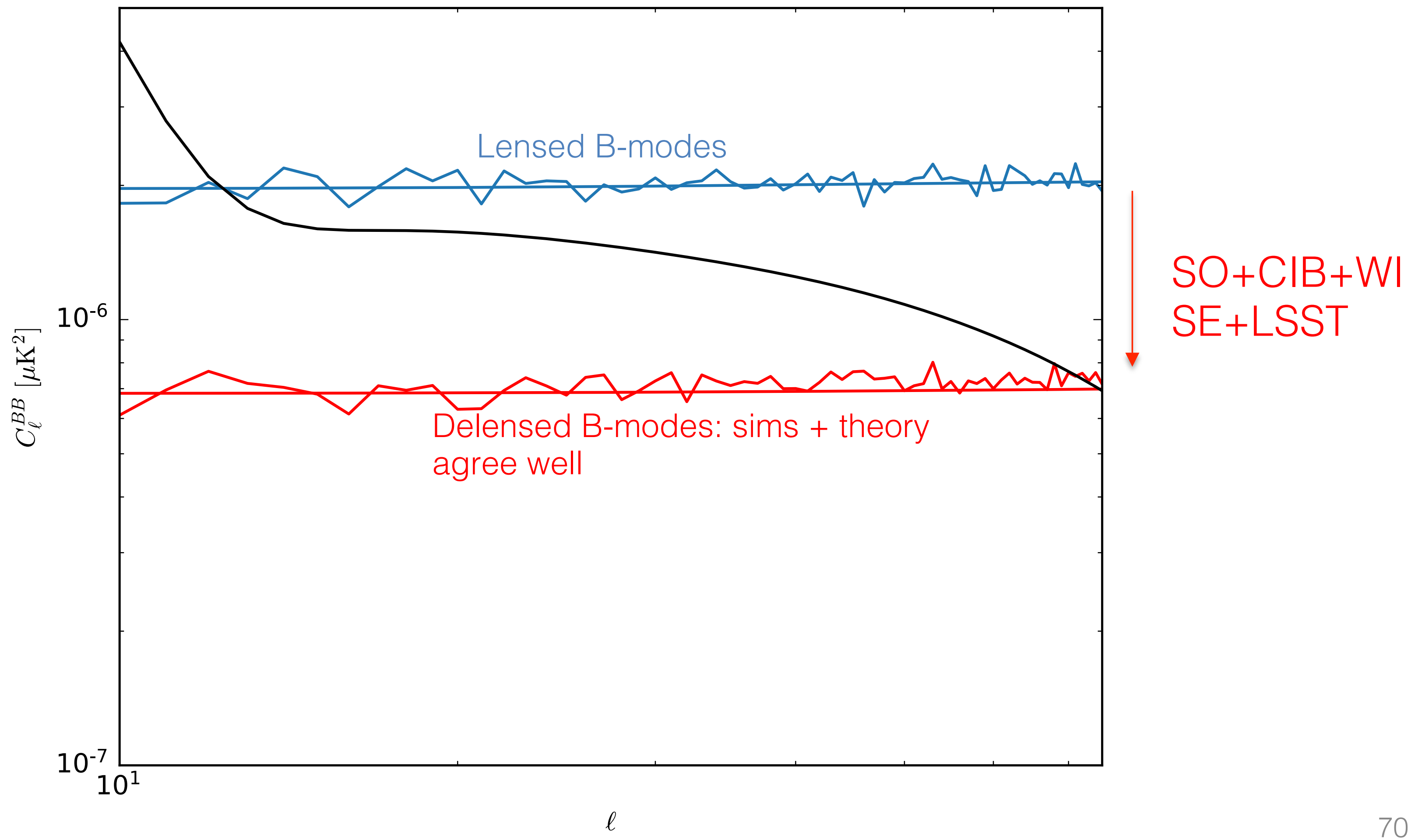


[Sherwin, Schmittfull 2015]

[Larsen, Challinor, Sherwin, Mak 2016] [Planck 2018, Manzotti++2017, Carron++ 2017…]

Why I think this will work III: New SO delensing pipeline applied to simulations

- Polarization simulation: multitracer delensing demonstration with SO (preliminary)



Why this might not work:
Correlated foreground propagation,…

- Lensing foregrounds correlated with B foregrounds can give biases, e.g., <(B-Ed) x (B-Ed)>, cross terms involving <BEd>

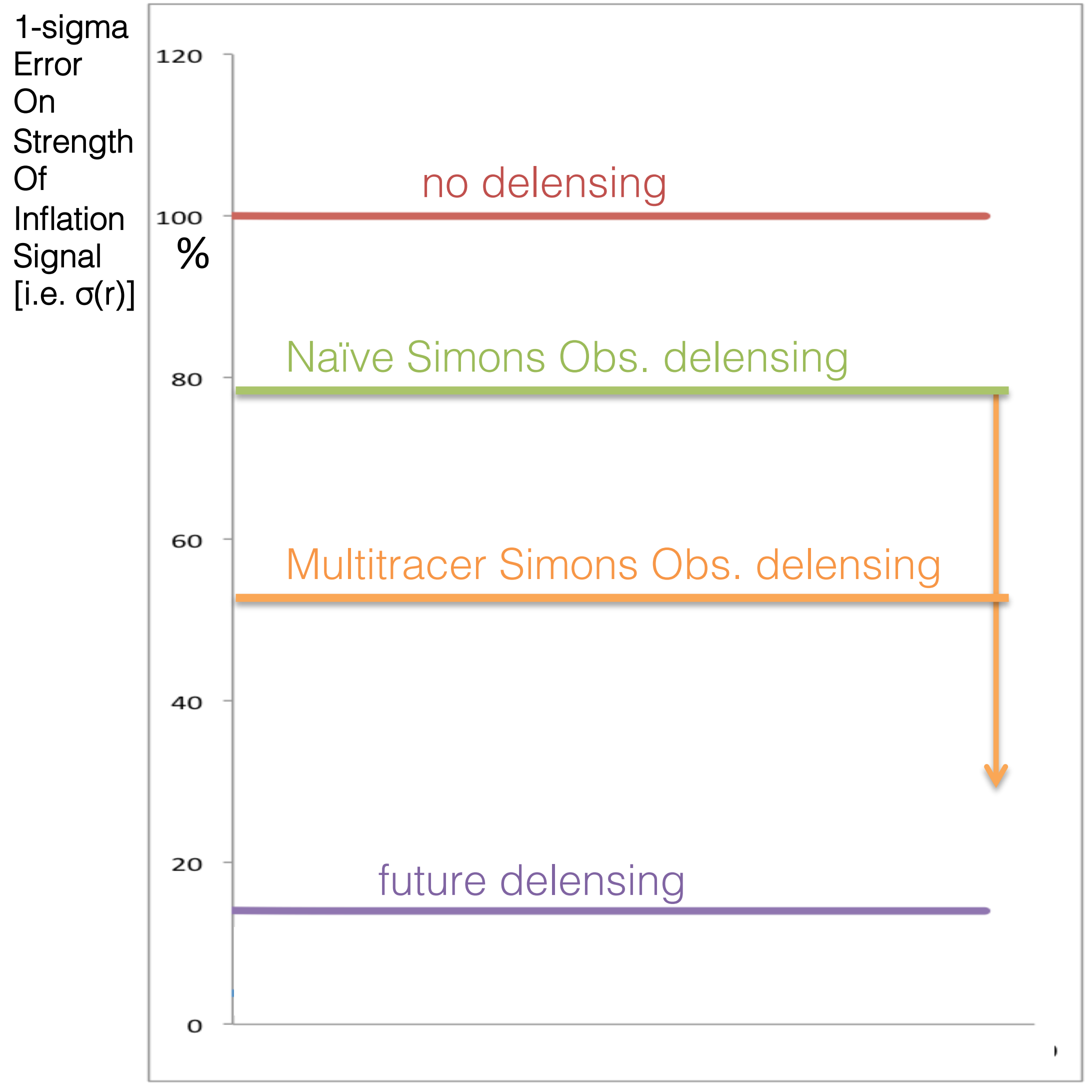
fgs.??? fgs.??? fgs.???

- Foregrounds in B, E, and d all could matter. Investigation in progress (with A. Baleato, A. Challinor)

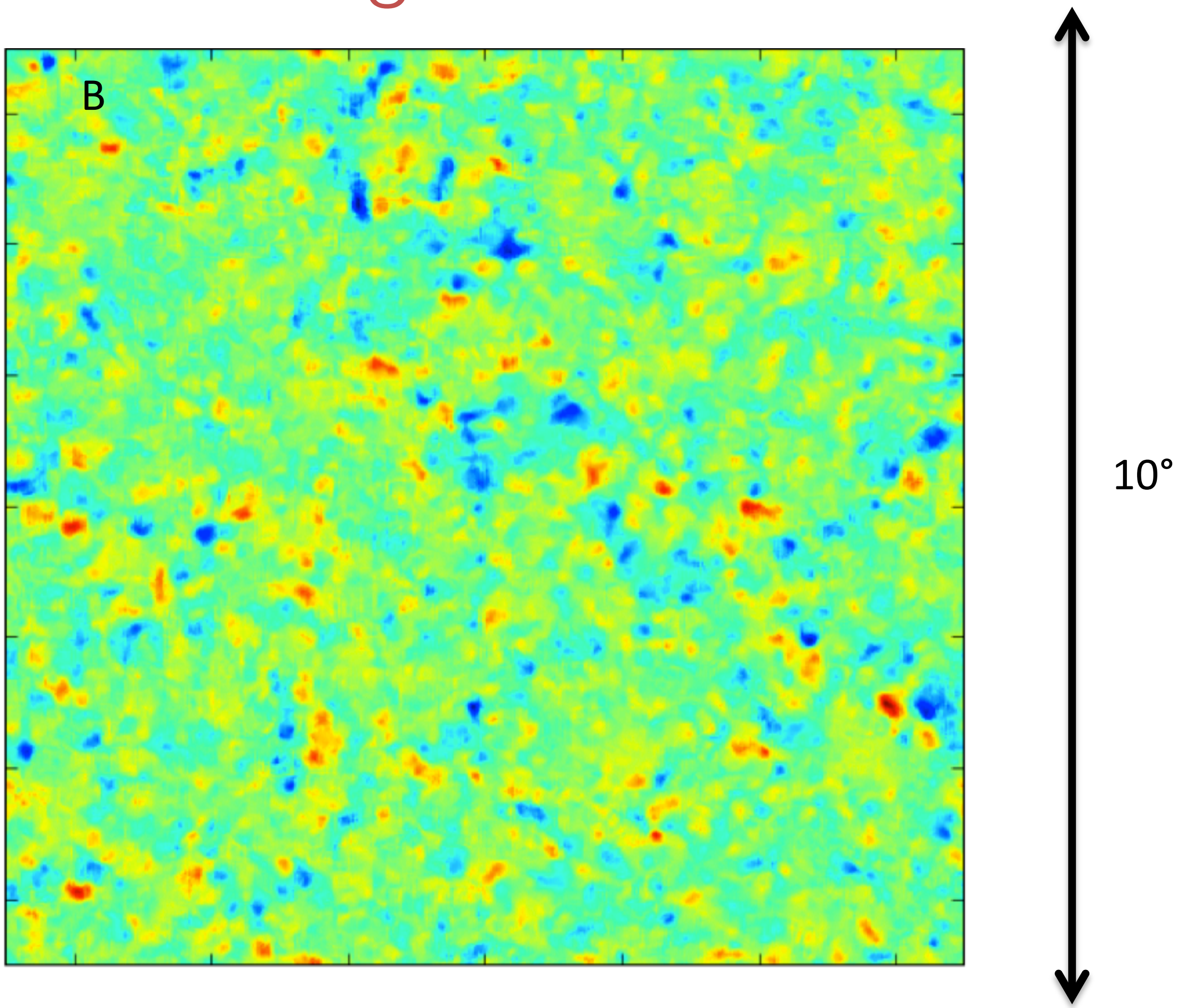
- Other challenges: likelihood, integration with foreground cleaning,…

Significant improvements possible for SO!

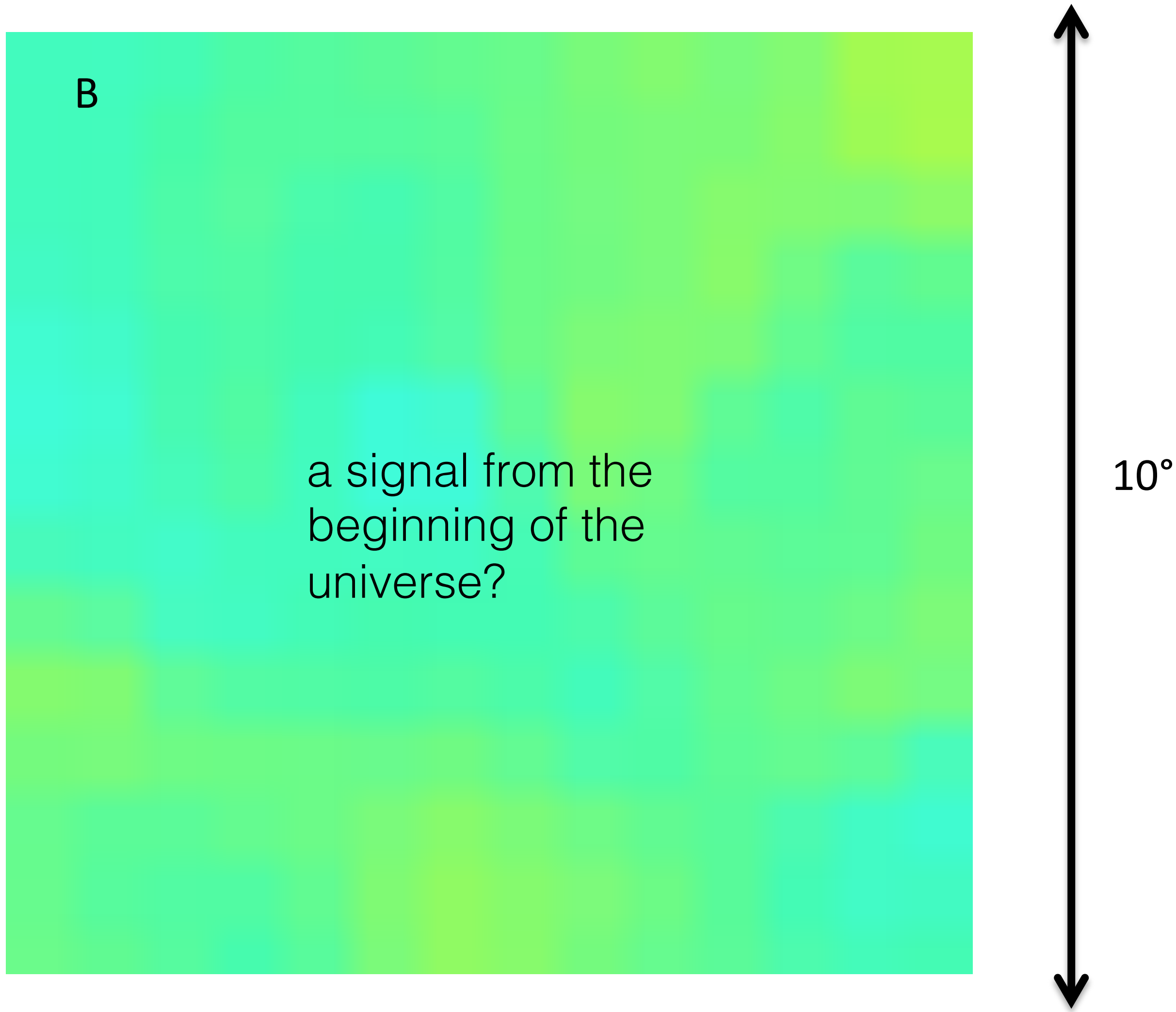
- Although lots to figure out:
- Significant improvements appear possible with multitracer delensing methods, ~2x improvement in SO r constraints [preliminary]
- Expected final results σ(r)~0.002 instead of 0.004 with delensing



Future B Mode Map – Lensing-Dominated



Delensed B Map – Inflation Signal?



Summary

- CMB lensing has rapidly progressed. With AdvACT / Simons Observatory / CMB-S4 we will have lots more data and lensing science: neutrino masses, S8,...
- New opportunities with new data: novel small scale gradient inversion reconstruction
- +new multi-tracer delensing methods that could nearly double SO performance