Title: CMB lensing and new constraints on the early universe

Speakers: Blake Sherwin

Series: Cosmology & Gravitation

Date: September 15, 2020 - 11:00 AM

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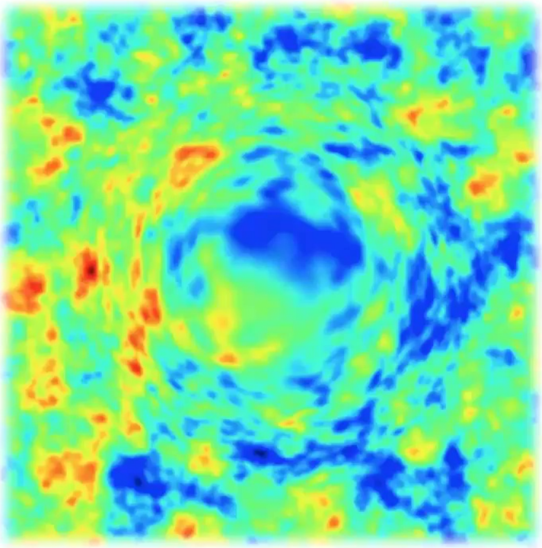
Abstract: Measurements of gravitational lensing in the cosmic microwave background (CMB) allow the dark matter distribution to be mapped out to uniquely high redshifts. After giving a brief overview of current and upcoming CMB lensing measurements, I will focus on two new ways of using CMB lensing, in combination with galaxy surveys, to constrain the early universe. First, I will explore how CMB lensing and galaxy surveys could provide insights into current discrepancies in measurements of the Hubble constant. Second, I will explain why new approaches to de-lensing â€“ removing the lensing effect to reveal the primordial polarization sky â€“ will be important for probing the early universe with the Simons Observatory CMB experiment.

CMB lensing, galaxy surveys and new constraints on the early universe



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UK Research and Innovation
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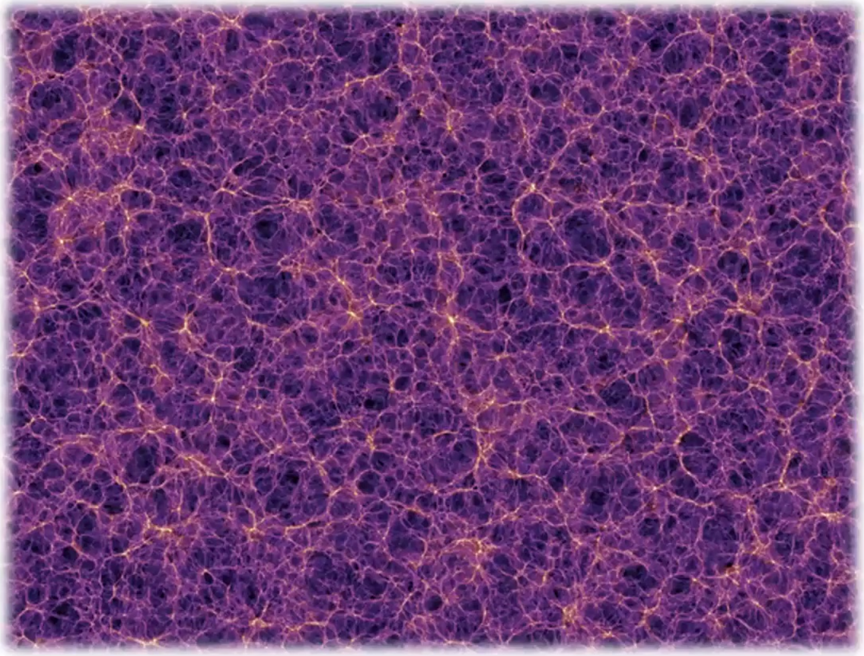
Large Scale Dark Matter Structure

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



Large Scale Dark Matter Structure

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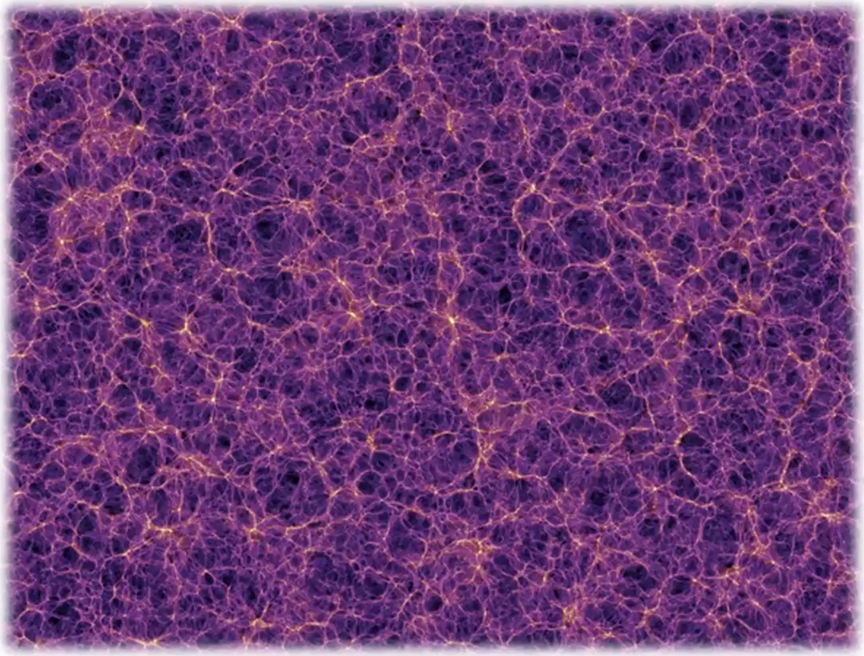


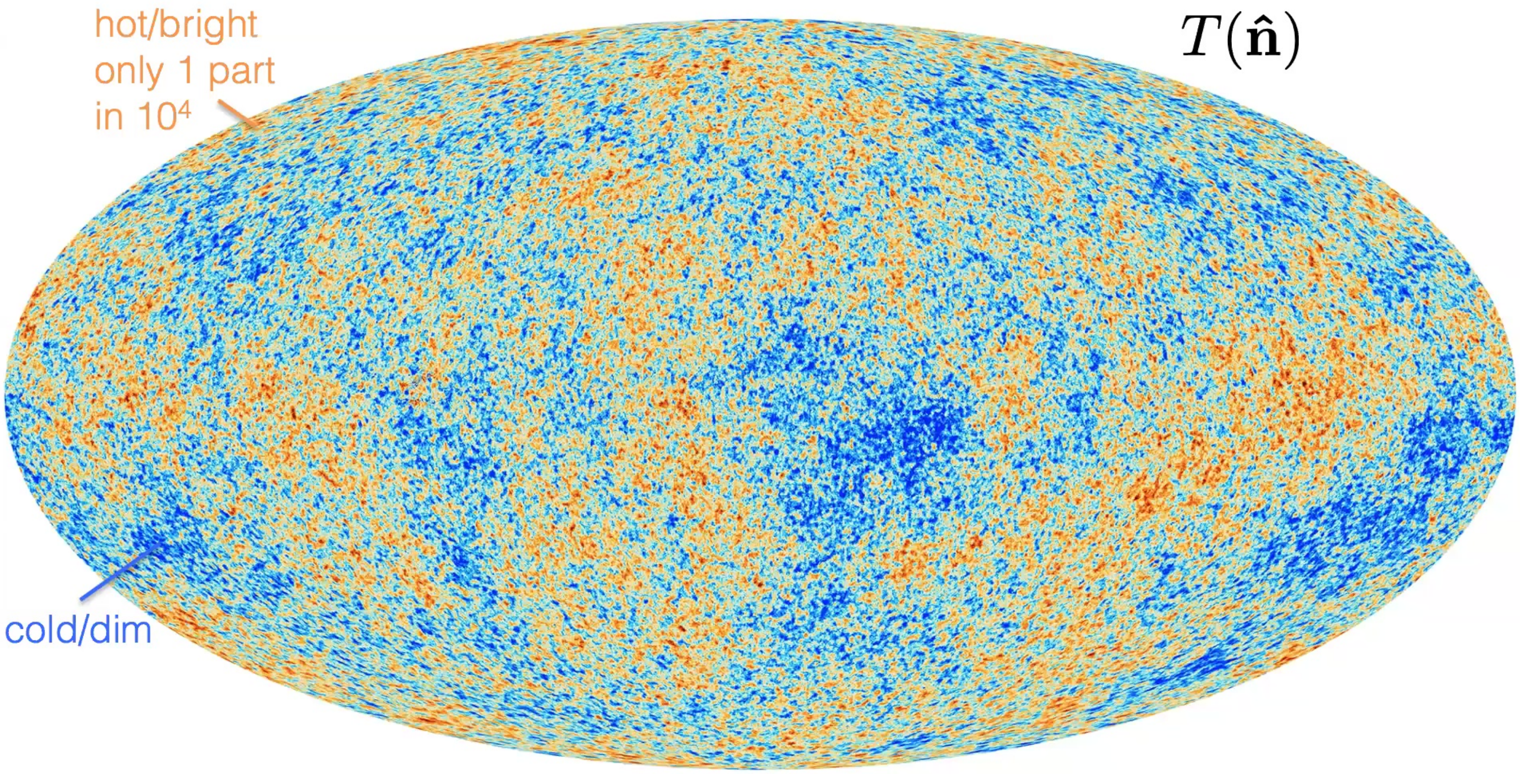
What is the physics of inflation and the early universe?

How quickly is the universe expanding?

Is standard cosmology correct?

What are the properties / masses of neutrinos?

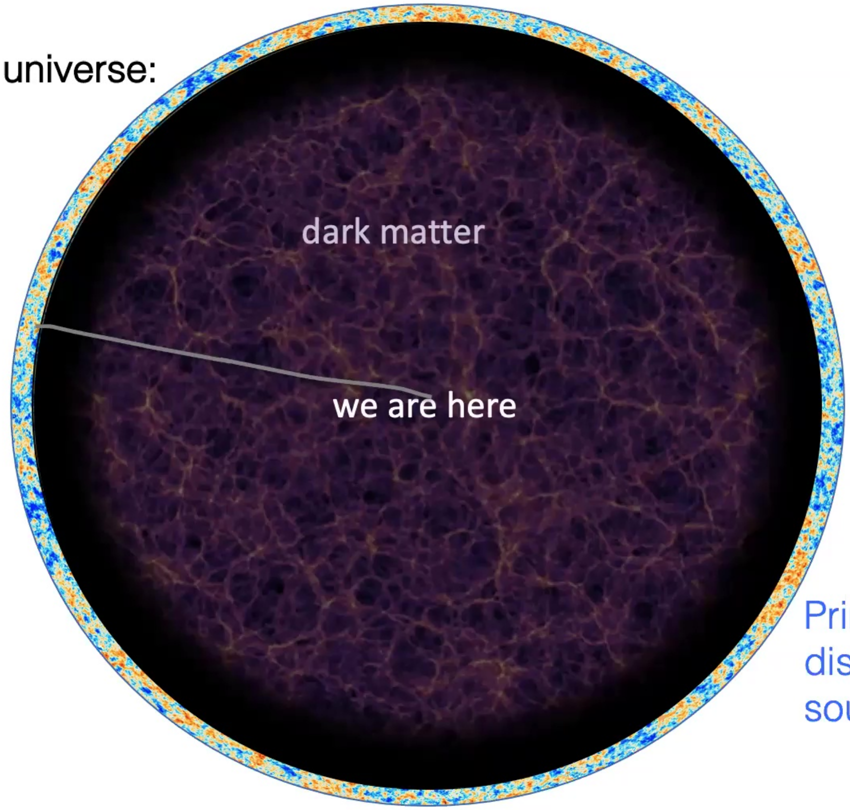
Source for Studying Gravitational Lensing: The Cosmic Microwave Background (CMB) Radiation



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

CMB: A Unique Source for Gravitational Lensing

The observable universe:

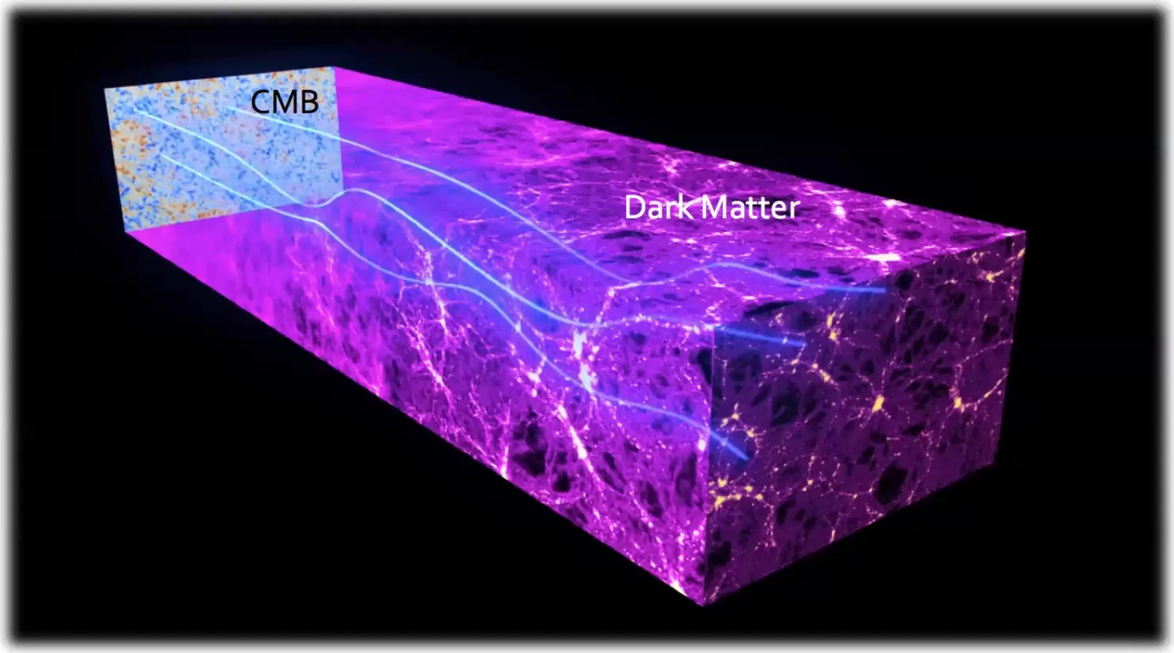


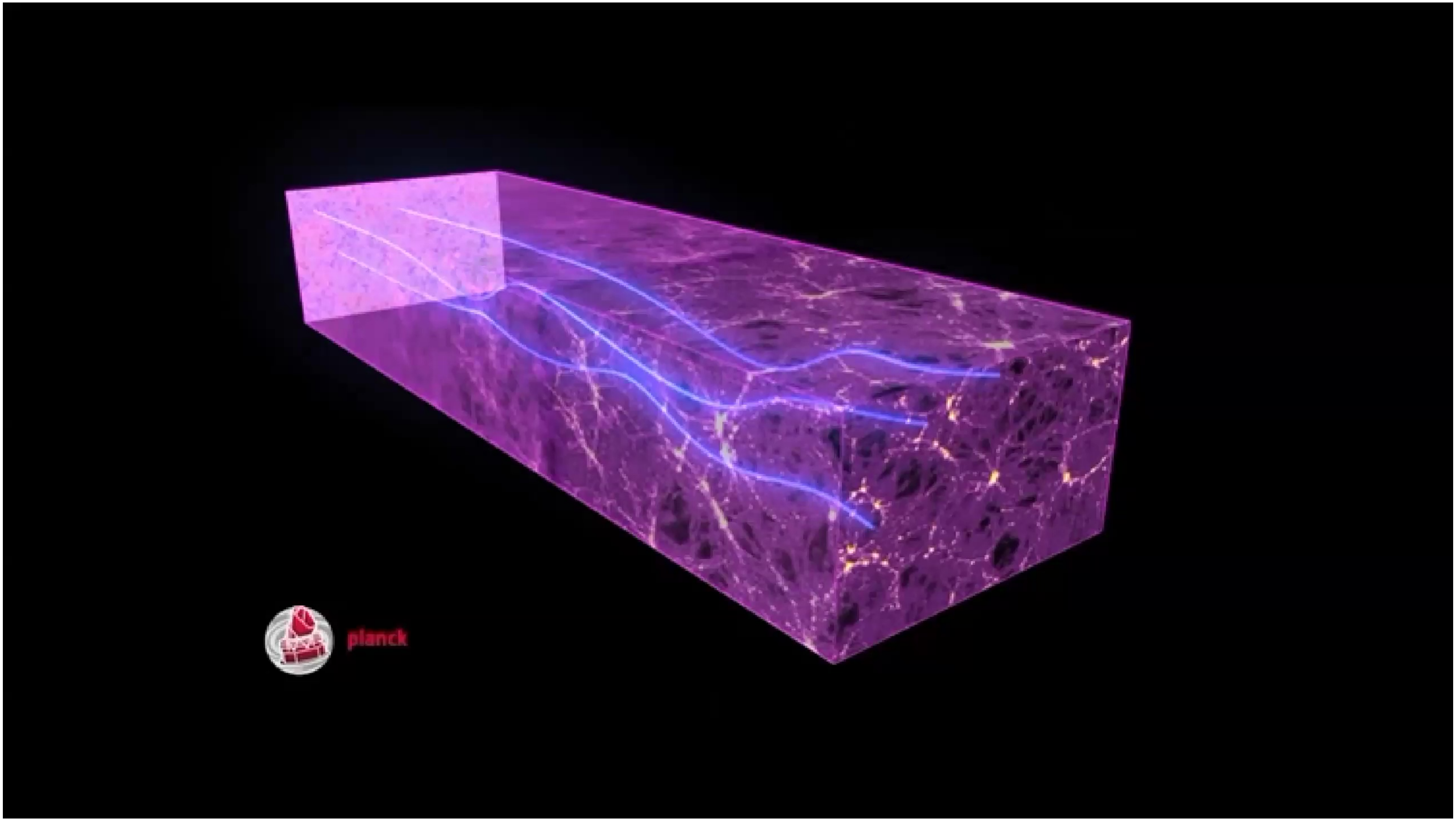
CMB photon path

Primordial CMB (most distant and oldest source of radiation)

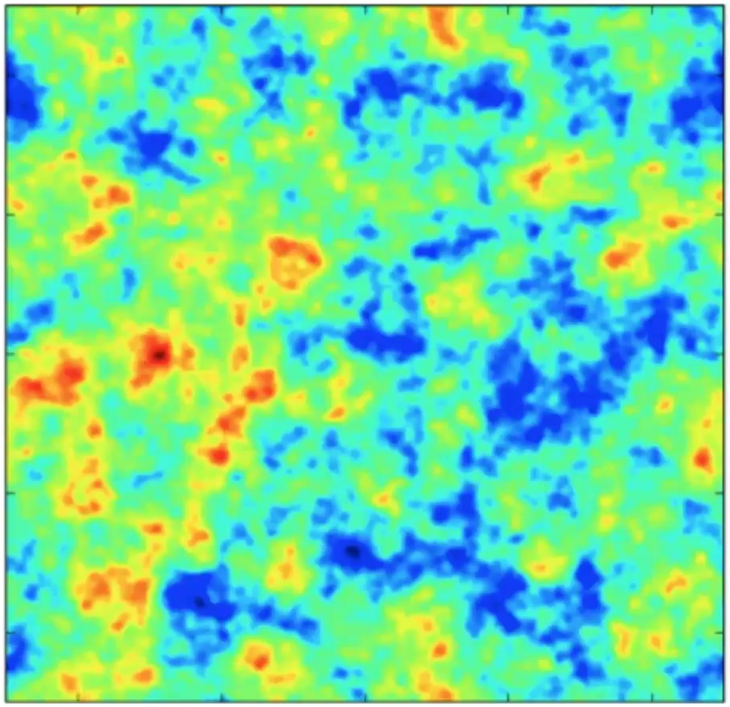
CMB Gravitational Lensing

- Distribution of dark matter deflects CMB light that passes through




planck

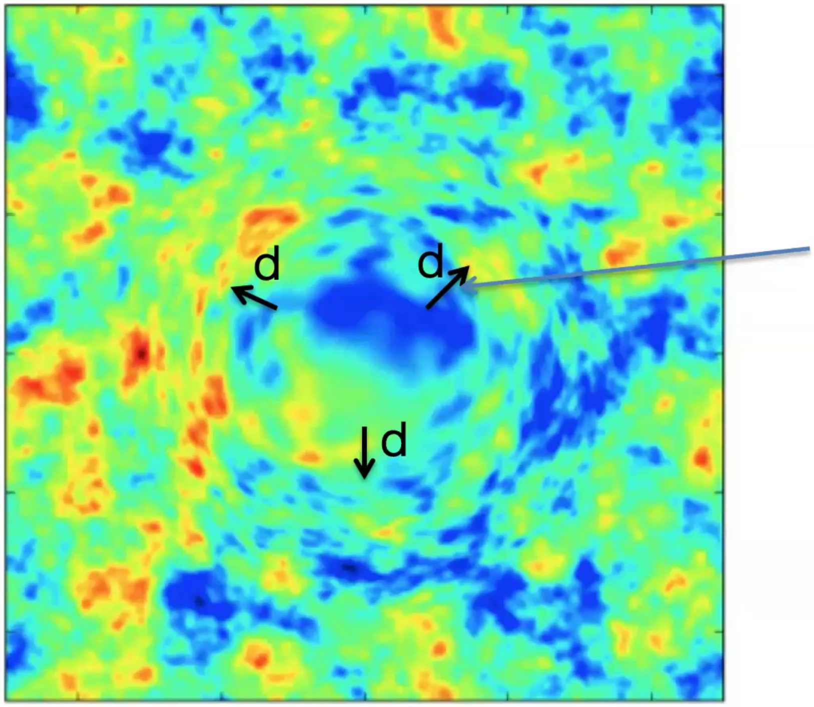
CMB Lensing: An Approximate Picture



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

CMB Lensing: An Approximate Picture

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

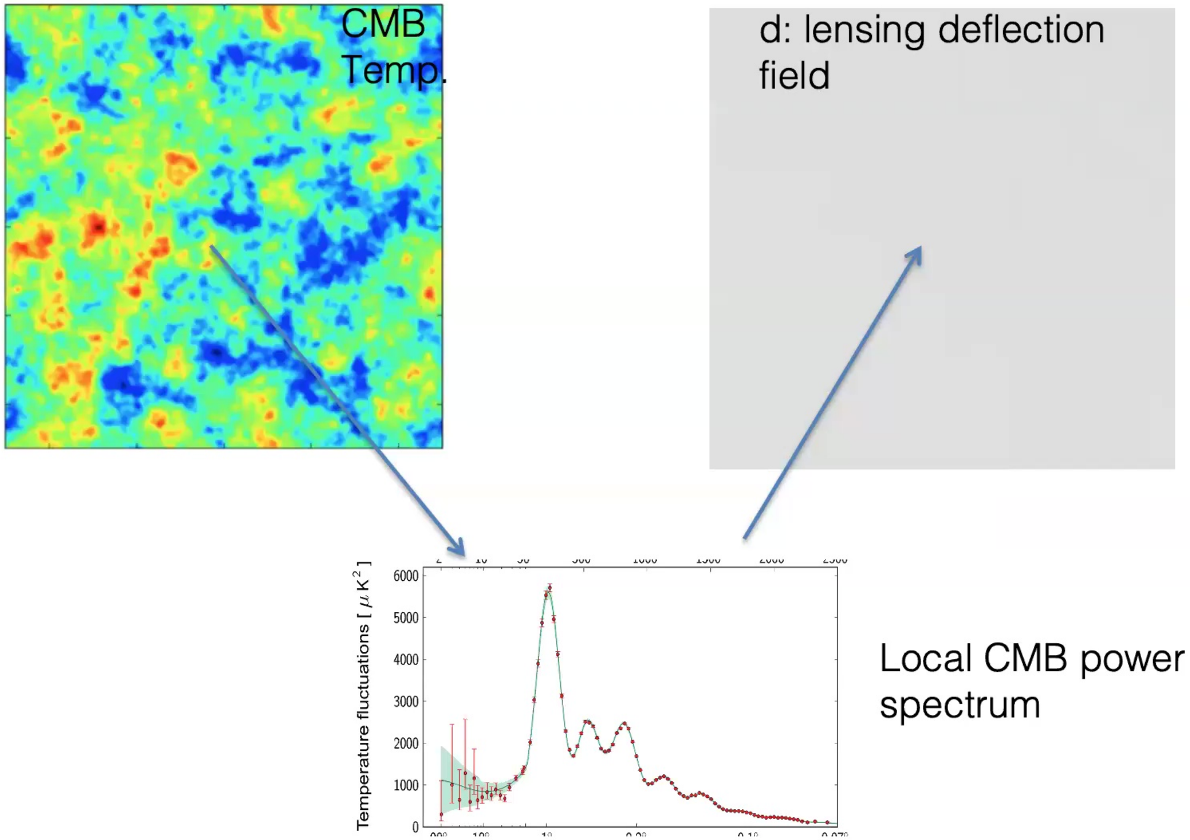


described by **lensing deflection field: d**

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

- Dark matter causes lensing magnification feature in the CMB

CMB Lensing Measurement: An Approximate Picture

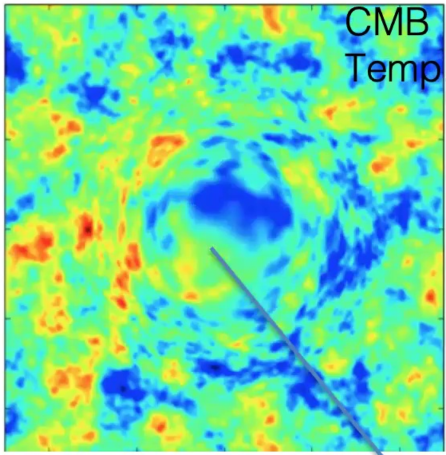


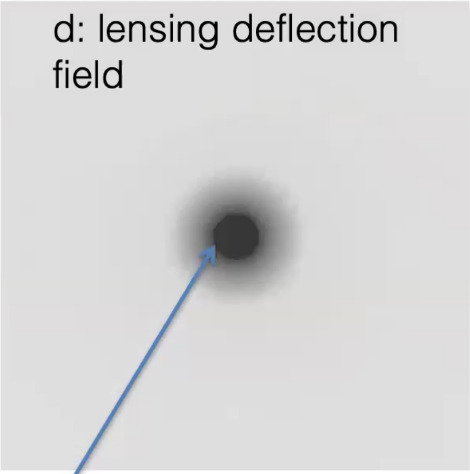
CMB Temp.

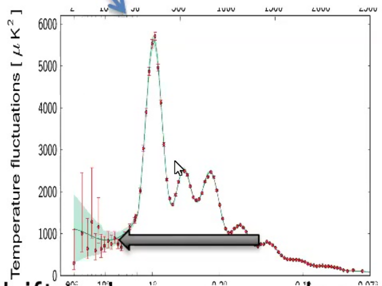
d: lensing deflection field

Local CMB power spectrum

CMB Lensing Measurement: An Approximate Picture




d: lensing deflection field



shift to larger angular scales

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

Aside: 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 => new correlations

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

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

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

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

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

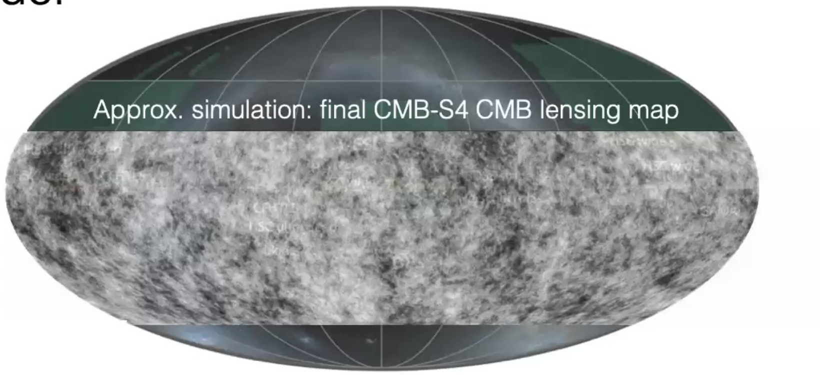
lensing deflection

radial distance

δ : fractional mass overdensity

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

- Next decade:



Approx. simulation: final CMB-S4 CMB lensing map

Outline

- Part 1: Lensing from ACT and Simons Observatory
- Part 2: Can CMB lensing and galaxies tell us something new about the Hubble tension?
- Part 3: Delensing Simons Observatory: new methods for revealing inflationary signals

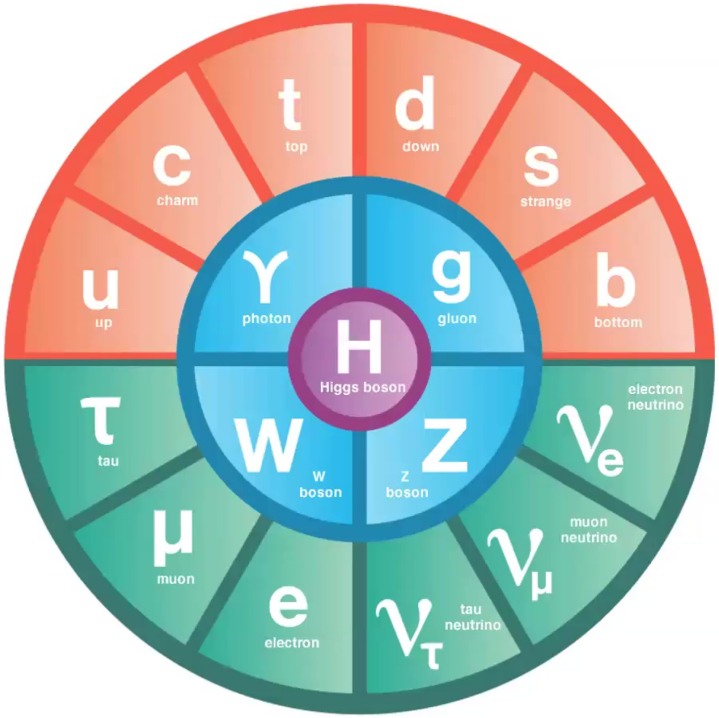
With Omar Darwish, et al.

Toshiya Namikawa,

Frank Qu,

Toshiya Namikawa

Example Physics Lensing Can Tell Us: Neutrinos!



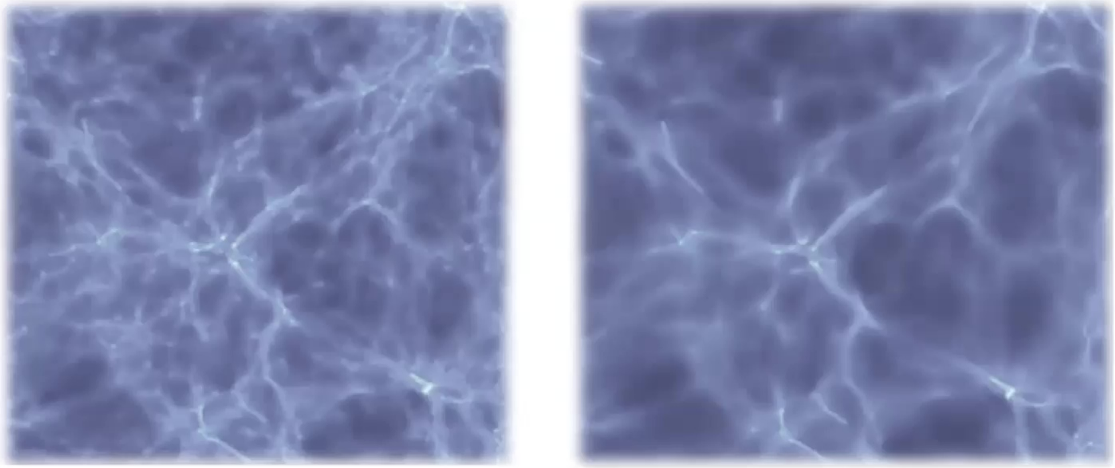
- If we measure mass sum $\sum m_\nu$ can get insight to key questions:
  - What is unknown neutrino mass?
  - Ordering?
  - Dirac / Majorana?
  - What new physics?
- Part of a big program to understand this new physics!

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



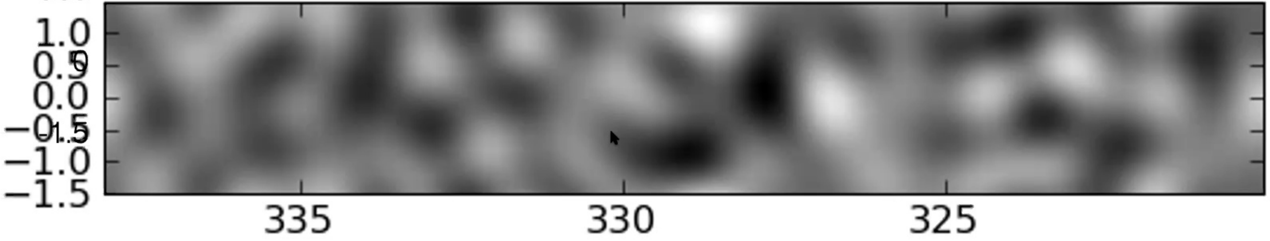
Neutrino Mass Negligible

Neutrino Mass Really Large (qualitative)

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

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

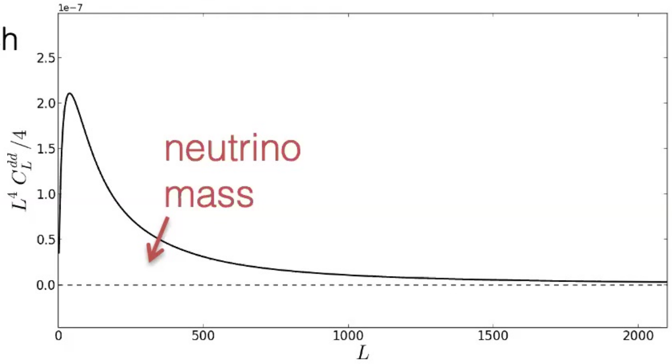
first (SNR>1) CMB lensing dark matter map



white = higher density

brightness = density

Y axis: “How much lensing ….”

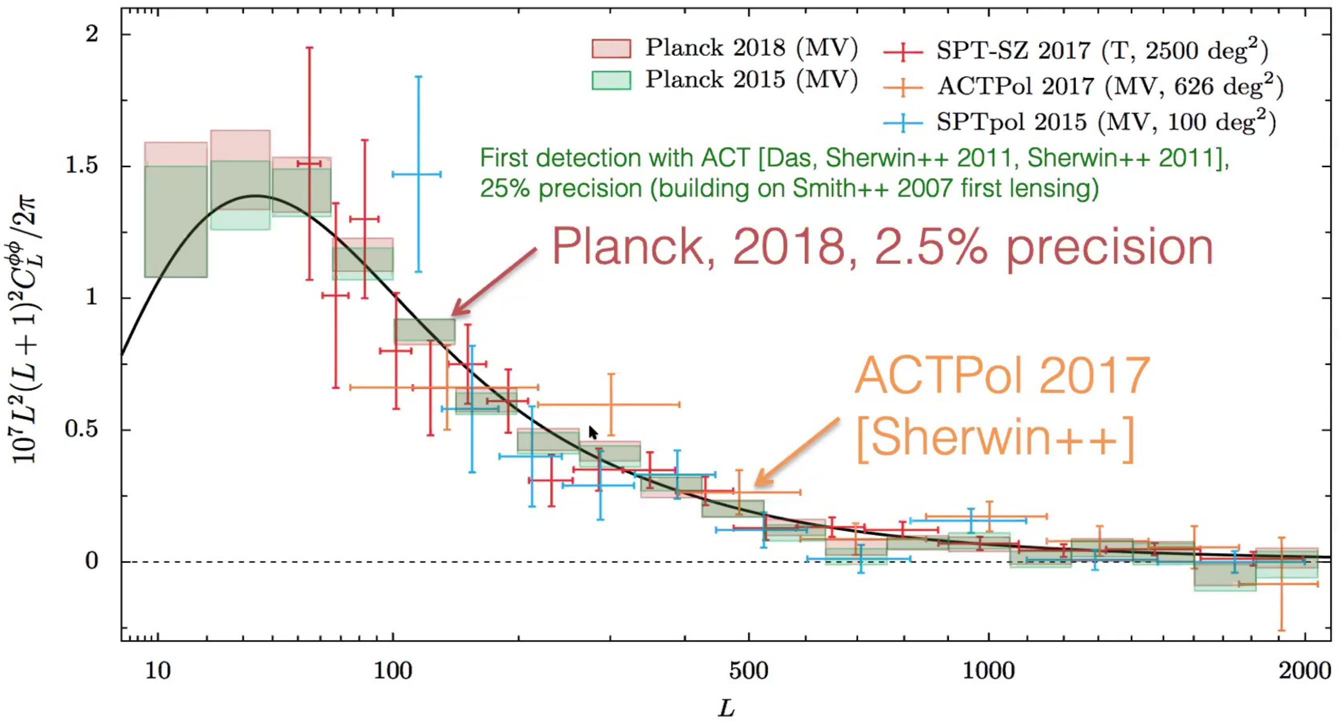


neutrino mass

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



First detection with ACT [Das, Sherwin++ 2011, Sherwin++ 2011], 25% precision (building on Smith++ 2007 first lensing)

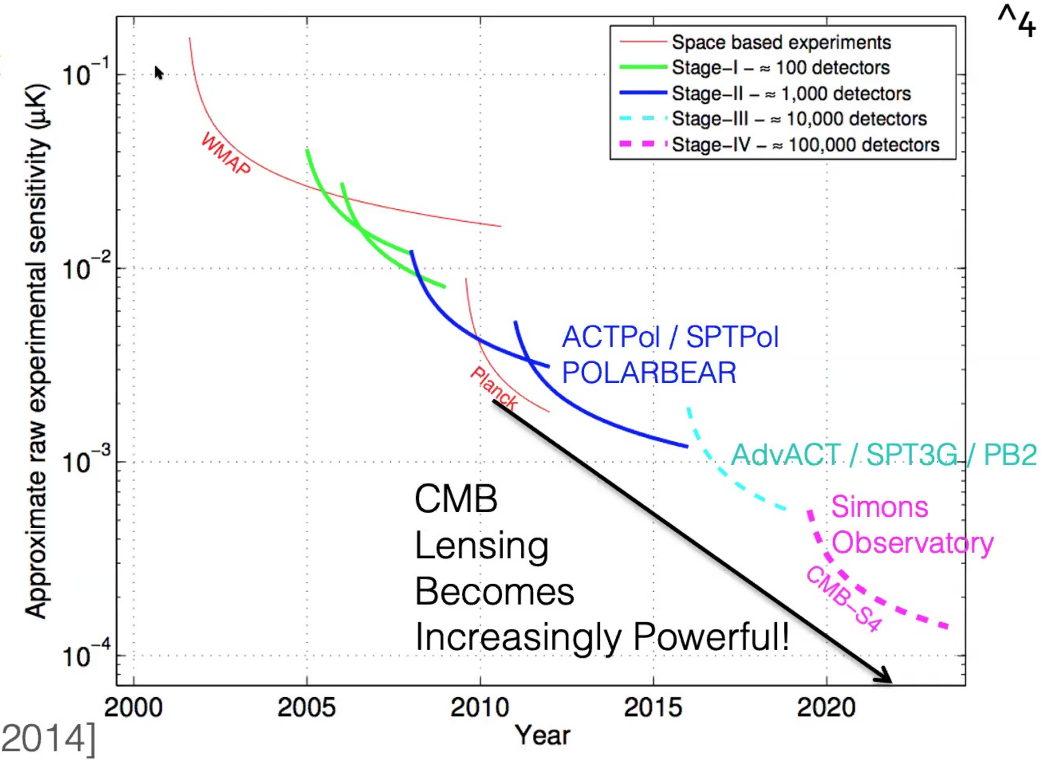
Planck, 2018, 2.5% precision

ACTPol 2017 [Sherwin++]

- Rapid progress – but only just beginning!

Rapid Progress:
Upcoming Ground-Based CMB Experiments

CMB Experiment Noise Level



CMB Lensing Becomes Increasingly Powerful!

^4

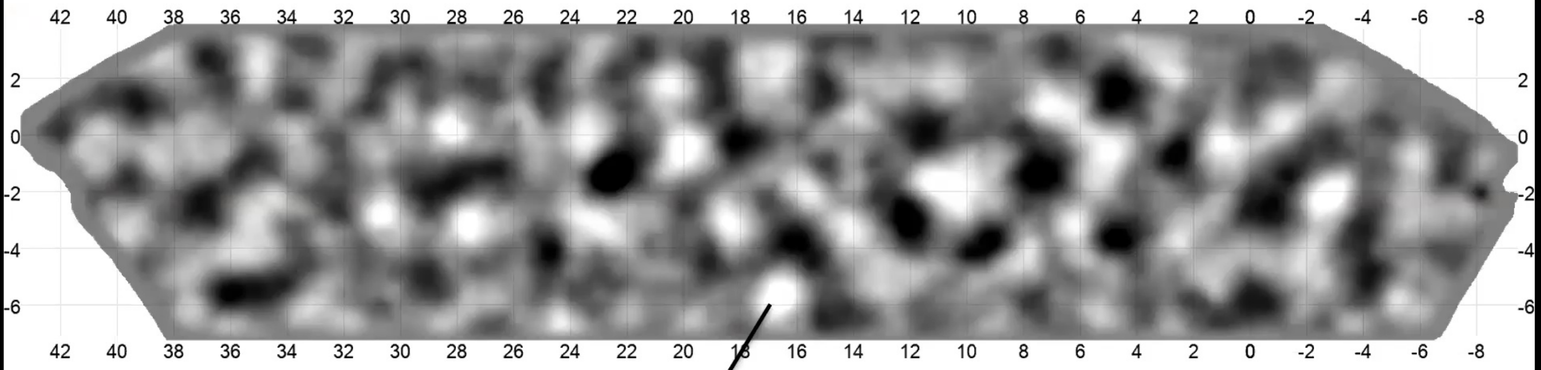
[Abazajian++ 2014]

Atacama Cosmology Telescope (ACT)

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

ACTPol (Darwish et al. 2020): High-resolution Lensing Map release

ACT lensing mass map (potential), one 500 deg^2 field (out of ~2100 in 2019 release)



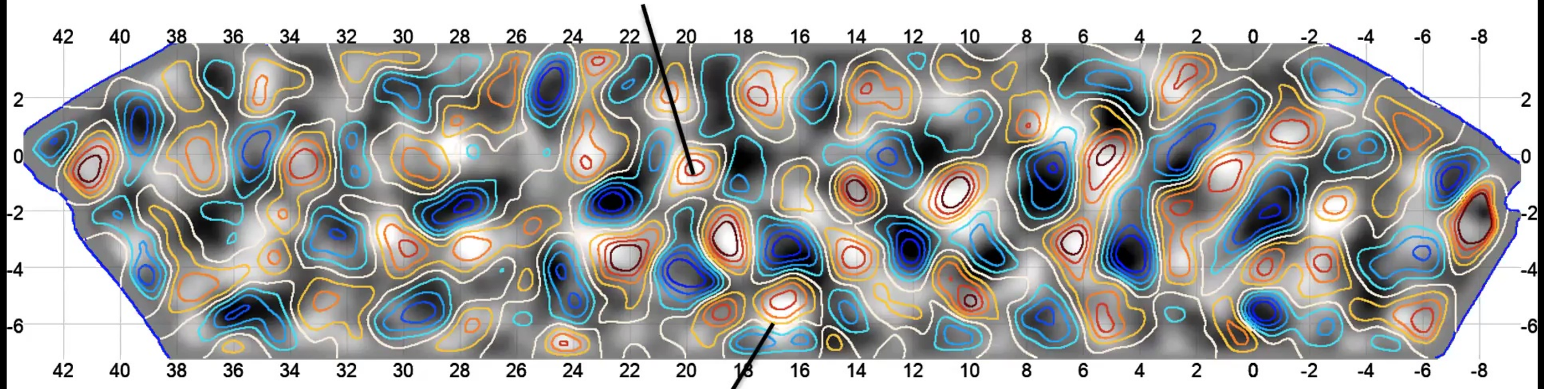
Color scale: strength of lensing
[light = more lensing / matter]

Map uses new foreground cleaning process


[Omar Darwish,
Madhavacheril,
Sherwin+ 2020.]

ACTPol (Darwish et al. 2020): High-resolution Lensing Map release

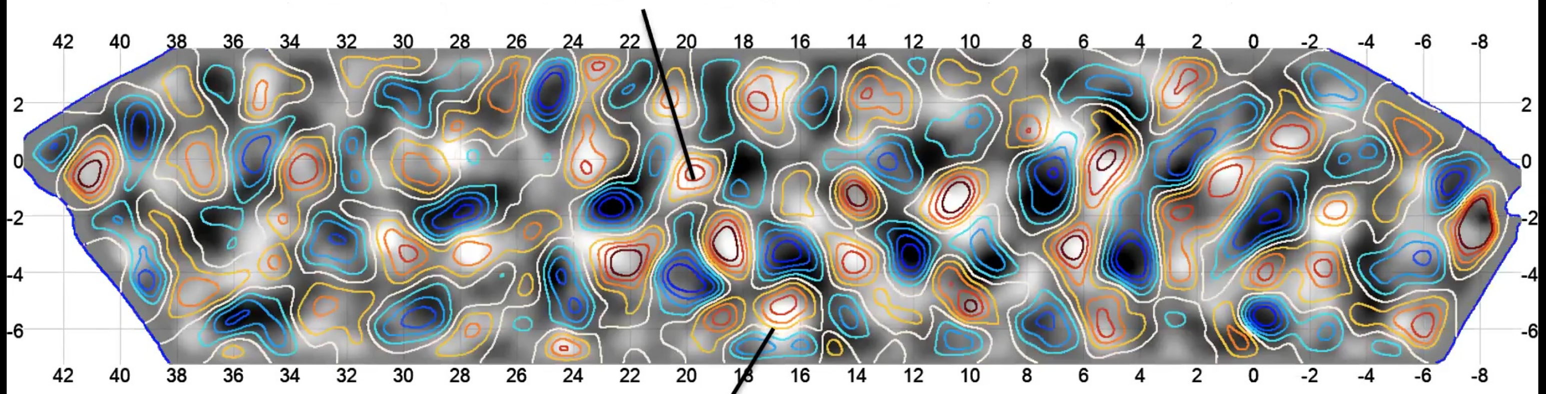
Orange/blue contours: cosmic infrared background (galaxy emission)
[orange = more galaxies]



Grey color scale: strength of lensing
[light = more lensing / matter]

[Omar Darwish,
Madhavacheril,
Sherwin+ 2020.]

ACTPol (Darwish et al. 2020): High-resolution Lensing Map release



Orange/blue contours: cosmic infrared background (galaxy emission)
[orange = more galaxies]

Grey color scale: strength of lensing
[light = more lensing / matter]

[Omar Darwish,
Madhavacheril,
Sherwin+ 2020.]

Much more to come: AdvancedACT lens. map and (SNR~70) spectrum

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

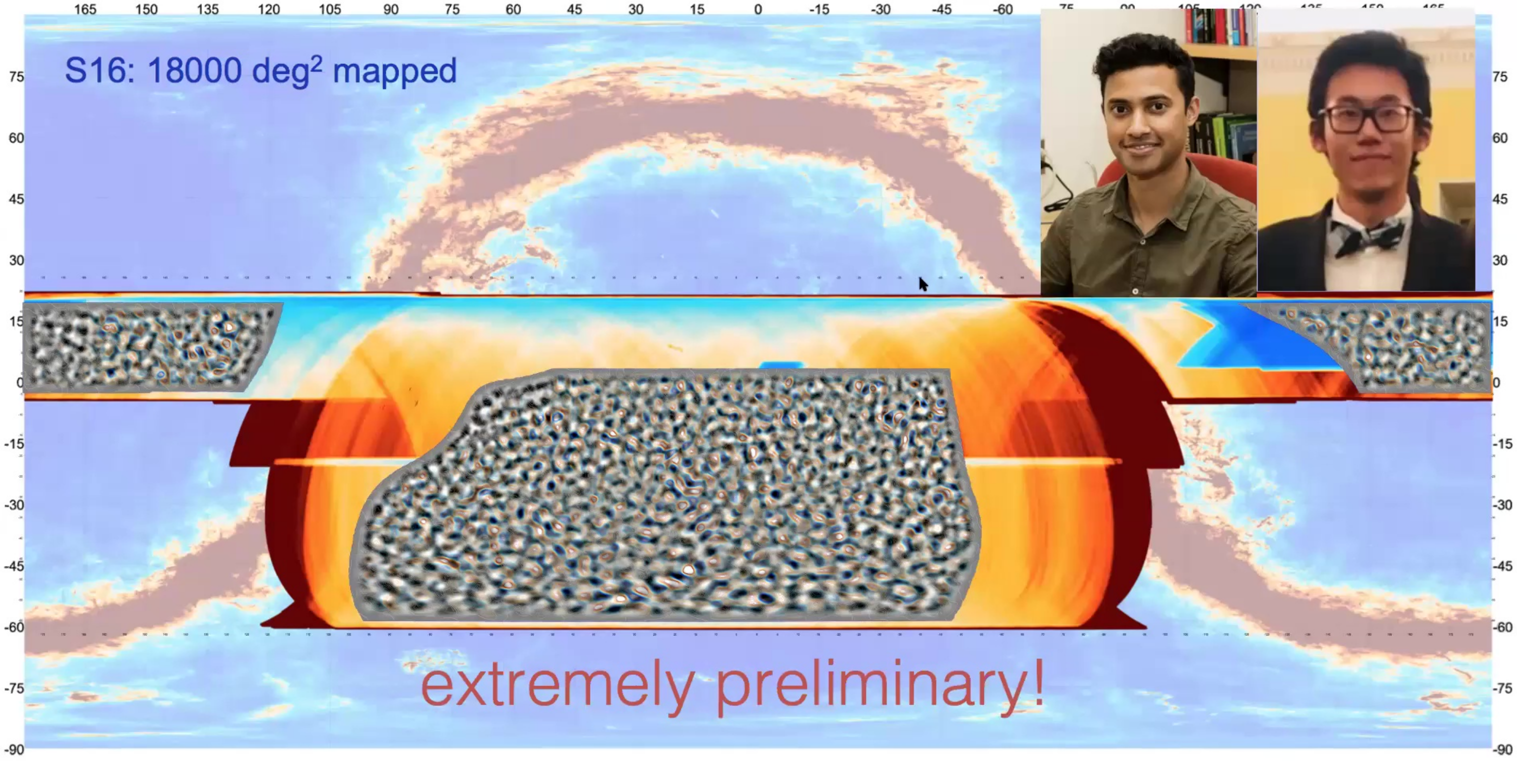
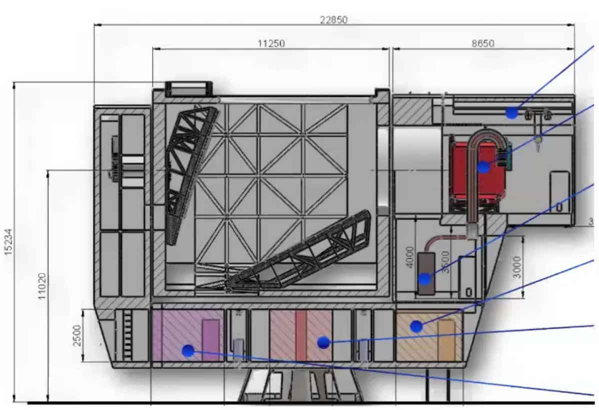


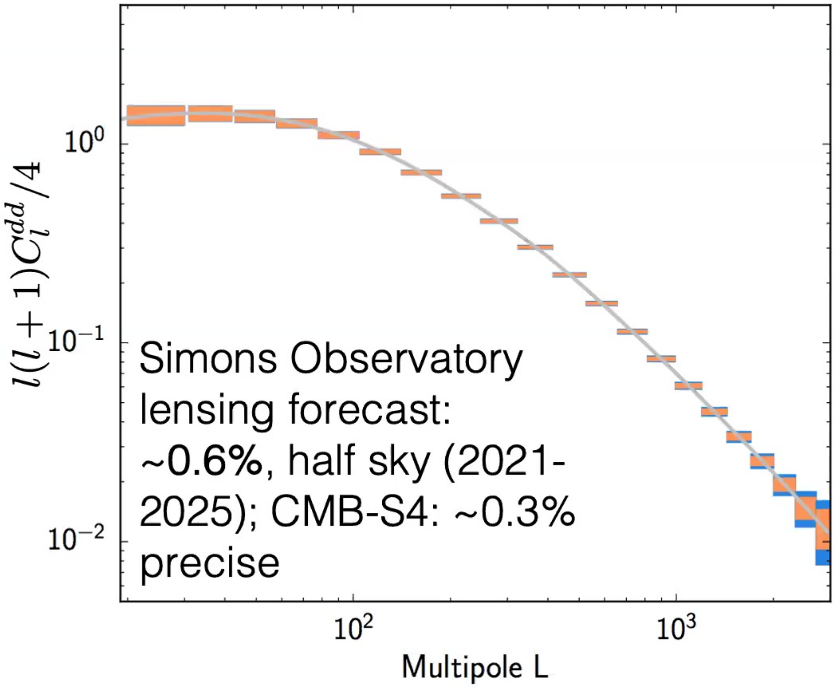
Figure: S. Aiola Map: S. Naess

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



Simons Observatory

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



Simons Observatory lensing forecast: ~**0.6%**, half sky (2021-2025); CMB-S4: ~0.3% precise

$$\sigma(\sum m_\nu) \approx 20 - 30\mathrm{meV}$$

(Simons Obs. / CMB-S4)

c.f. limit, >60meV

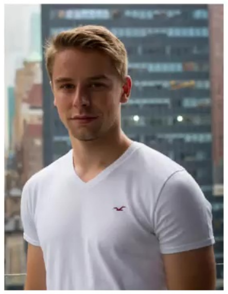
Outline

- Part 1: Lensing from ACT and Simons Observatory
- Part 2: New application: can CMB lensing and galaxies tell us something about the Hubble constant tension?
- Part 3: Delensing Simons Observatory: new methods for revealing inflationary signals

With Eric Baxter

Oliver Philcox

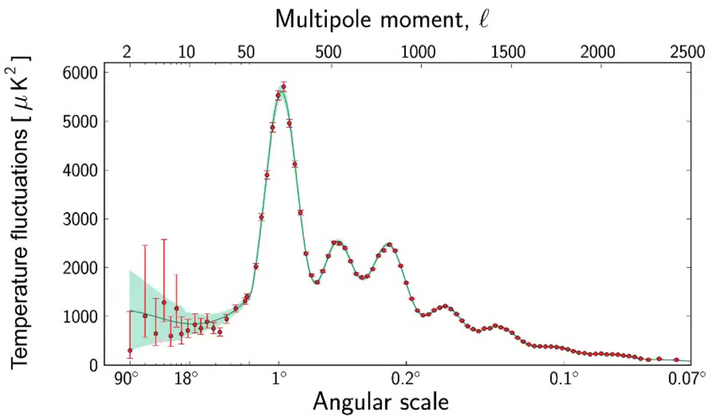
Gerrit Farren



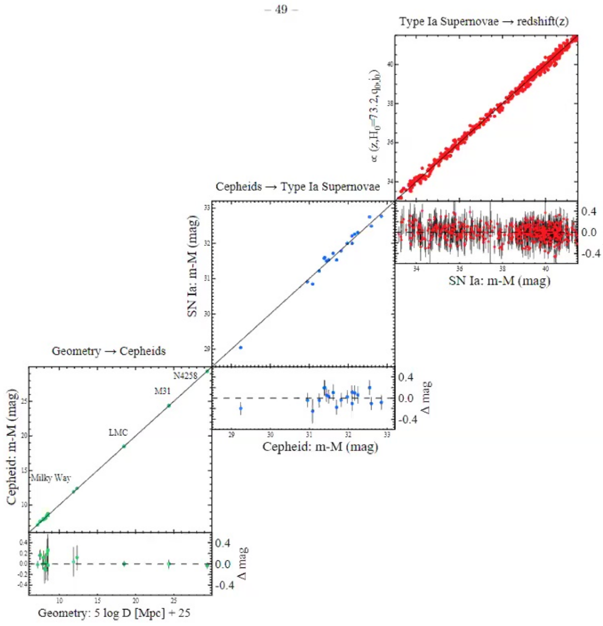
See: arXiv:2007.04007, 2008.08084

Ways to measure Hubble constant $H_0 = \frac{\dot{a}}{a}$ i.e. expansion rate of Universe

CMB power spectrum / early / indirect

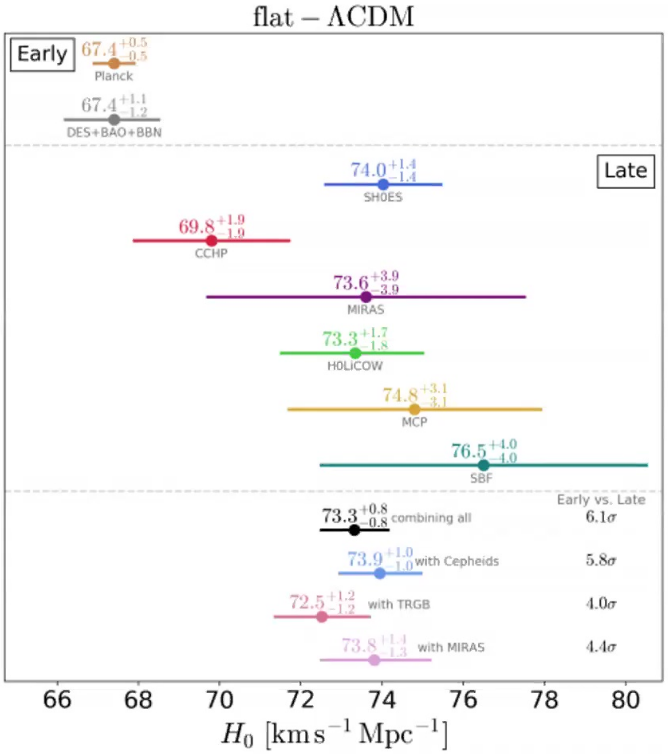


Cosmic distance ladder / late / direct



A big puzzle: the current Hubble constant tension

~67 km/s/Mpc ?   ~74 km/s/Mpc ?

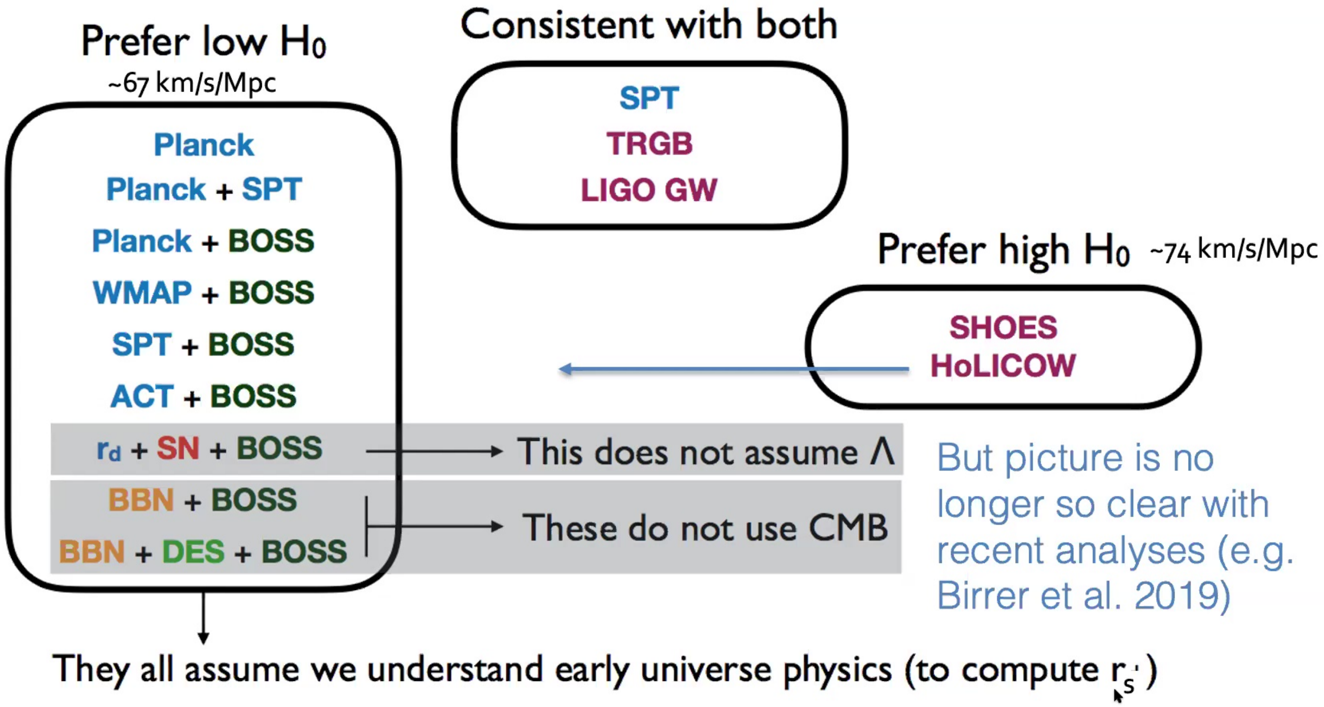


[Verde et al. '19]

~5 sigma tension between distance ladder and early-time/indirect measurements

Hubble tension: not just one probe (?)

Figure credit: A. Font-Ribera



Prefer low H_0

~67 km/s/Mpc

- Planck
- Planck + SPT
- Planck + BOSS
- WMAP + BOSS
- SPT + BOSS
- ACT + BOSS
- r_d + SN + BOSS
- BBN + BOSS
- BBN + DES + BOSS

Consistent with both

- SPT
- TRGB
- LIGO GW

Prefer high H_0 ~74 km/s/Mpc

- SHOES
- HoLICOW

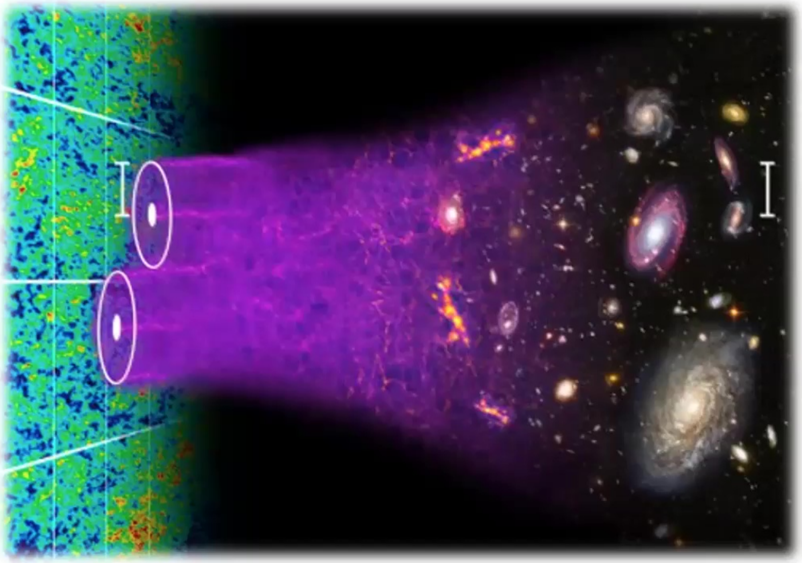
r_d + SN + BOSS → This does not assume Λ

BBN + BOSS, BBN + DES + BOSS → These do not use CMB

They all assume we understand early universe physics (to compute r_s)

But picture is no longer so clear with recent analyses (e.g. Birrer et al. 2019)

The sound horizon r_s and the CMB

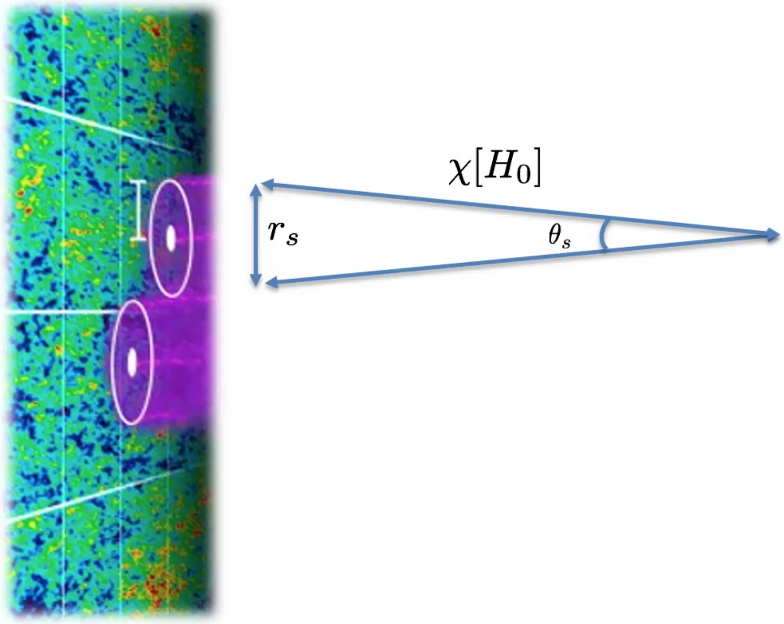


- Sound horizon: distance a sound wave travels

$$r_s = \int_{z_r}^{\infty} \frac{c}{H(z)} dz$$

- Characteristic scale imprinted in the CMB peaks and in LSS as BAO feature

Measuring Hubble using the CMB



- Compute sound horizon r_s

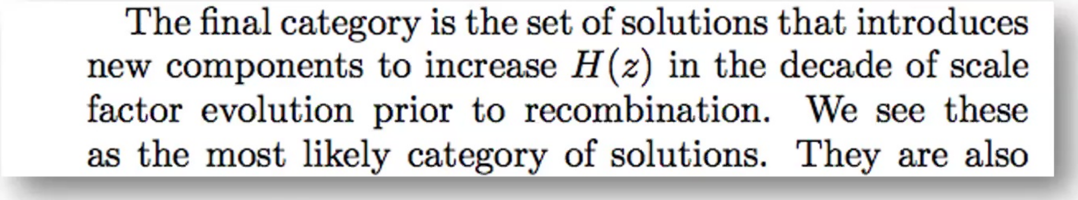
$$r_s = \int_{z_r}^{\infty} \frac{c}{H(z)} dz$$

- Measure angle θ_s and infer distance $\chi[H_0] \sim r_s/\theta_s$
- Distance[H_0]

  => H_0 !

Idea for resolving tension: is new physics changing r_s ?

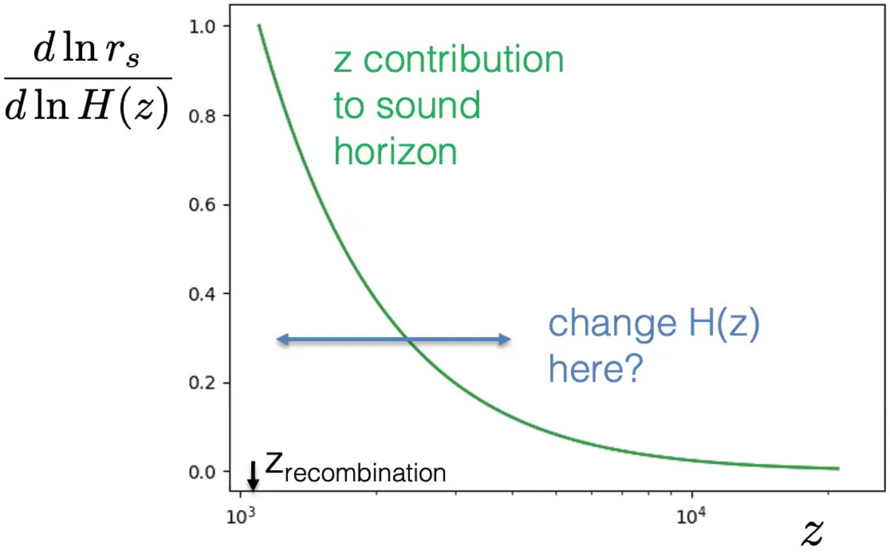
Possible explanation for tension:
Changing sound horizon via early expansion



The final category is the set of solutions that introduces new components to increase $H(z)$ in the decade of scale factor evolution prior to recombination. We see these as the most likely category of solutions. They are also

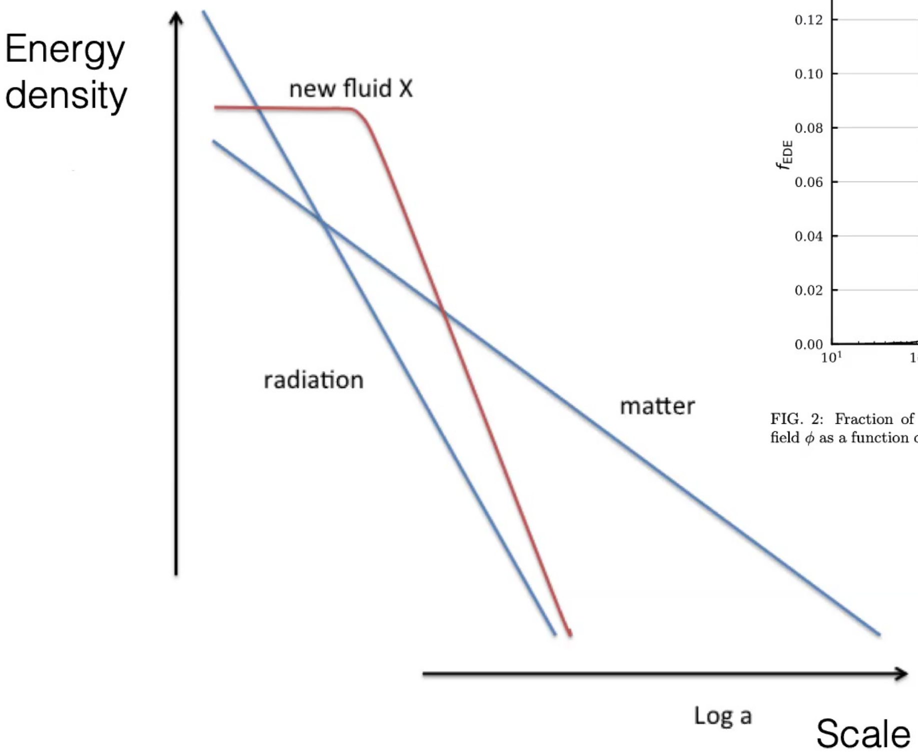
[Knox + Millea 2019]

$$r_s = \int_{z_r}^{\infty} \frac{c}{H(z)} dz$$



Example: Early Dark Energy

[Poulin et al. 2018, ...]



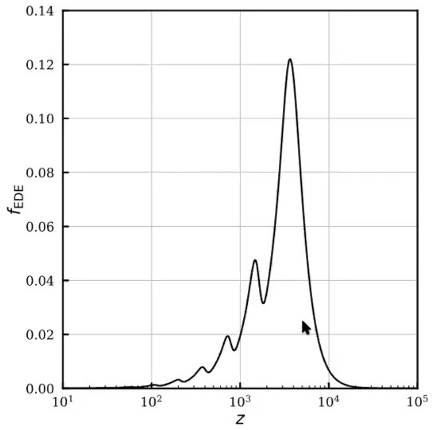


FIG. 2: Fraction of the cosmic energy density in the EDE field ϕ as a function of redshift, for the parameters in Eq. (7).

Example: Early Dark Energy

[Poulin et al. 2018, ...]

Constraining Early Dark Energy with Large-Scale Structure

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Michael W. Toomey,[7] Stephon Alexander,[7] and Matias Zaldarriaga[8]
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New York, NY 10003, USA
[2] *Institute for Nuclear Research of the Russian Academy of Sciences*
60th October Annive
[3] *Center for Theoretical*
Ca
[4] *Department of Physics,*
[5] *Center for Computational Astr*
[6] *Theoreti*
1 Esplanade des Pa
[7] *Brown Theoretical*
Brown Univ
[8] *School of Natura*
1 Einstein

An axion-like field comprising ∼ 10
equality is a candidate to resolve the
However, as shown in Hill et al. (20
tension and maintain a good fit to
structure (LSS) data. Here, we use re
the EDE model. We perform the first
from the Baryon Oscillation Spectrosc
of LSS. The inclusion of this likeliho
compared to primary CMB data alon
we constrain the maximum fractiona
(95% CL). We explicitly demonstrate t
on EDE than the standard BOSS lik
surveys,the constraints narrow by an a
and $f_{\rm EDE} < 0.053$ (95% CL). These b
which is in strong tension with the CM
MCMC analyses of EDE that omit S
Finally, we show that upcoming *Eucli*
the EDE constraints. We conclude th
Hubble tension, and that future LSS s

Early Dark Energy Does Not Restore Cosmological Concordance

J. Colin Hill,[1,2] Evan McDonough,[3,4] Michael W. Toomey,[3] and Stephon Alexander[3]
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[3] *Brown Theoretical Physics Center and Department of Physics, Brown University, Providence, RI, USA 02912*
[4] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

Current cosmological data exhibit a tension between inferences of the Hubble constant, H_0, derived from early- and late-universe measurements. One proposed solution is to introduce a new component in the early universe, which initially acts as "early dark energy" (EDE), thus decreasing the physical size of the sound horizon imprinted in the cosmic microwave background (CMB) and increasing the inferred H_0. Previous EDE analyses have shown this model can relax the H_0 tension, but the CMB-preferred value of the density fluctuation amplitude, σ_8, increases in EDE as compared to ΛCDM, increasing tension with large-scale structure (LSS) data. We show that the EDE model fit to CMB and SH0ES data yields scale-dependent changes in the matter power spectrum compared to ΛCDM, including 10% more power at $k = 1\,h/\mathrm{Mpc}$. Motivated by this observation, we reanalyze the EDE scenario, considering LSS data in detail. We also update previous analyses by including *Planck* 2018 CMB likelihoods, and perform the first search for EDE in *Planck* data alone, which yields no evidence for EDE. We consider several data set combinations involving the primary CMB, CMB lensing, supernovae, baryon acoustic oscillations, redshift-space distortions, weak lensing, galaxy clustering, and local distance-ladder data (SH0ES). While the EDE component is weakly detected (3σ) when including the SH0ES data and excluding most LSS data, this drops below 2σ when further LSS data are included. Further, this result is in tension with strong constraints imposed on EDE by CMB and LSS data without SH0ES, which show no evidence for this model. We also show that physical priors on the fundamental scalar field parameters further weaken evidence for EDE. We conclude that the EDE scenario is, at best, no more likely to be concordant with all current cosmological data sets than ΛCDM, and appears unlikely to resolve the H_0 tension.

I. INTRODUCTION

The value of the Hubble constant H_0, the present-day expansion rate of the Universe, is crucial to cosmology. All cosmological quantities are connected to H_0, which effectively sets the scale of the Universe. In recent years, the value of H_0 inferred from probes of the early universe has been in persistent disagreement with that measured from probes of the late universe, a discrepancy that has

(BAO) experiments.[1] Applied to Dark Energy Survey (DES) data combined with Baryon Oscillation Spectroscopic Survey (BOSS) BAO data, this methodology leads to $H_0 = 67.4^{+1.1}_{-1.2}\,\mathrm{km/s/Mpc}$ [10], in near-perfect agreement with the CMB constraints, albeit with error bars doubled in size. Recent analyses have further refined this cosmological approach to constrain H_0 using not only sound horizon information, but also information in the shape of the matter power spectrum, as measured from the redshift-space galaxy power spectrum [11–13]. The results are consistent with those from the *Planck* CMB

New Early Dark Energy is compatible with current LSS data

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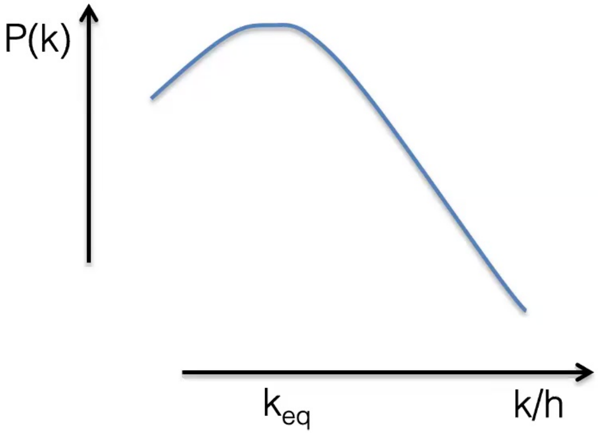
Recently a full-shape analysis of Large-Scale Structure (LSS) data was employed to provide
new constraints on a class of Early Dark Energy (EDE) models. In this note we derive
ts on New Early Dark Energy (NEDE) using the publicly available `PyBird`
the full-shape analysis of LSS together with measurements of the Cosmic
ground (CMB), Baryonic Acoustic Oscillations (BAO) and supernovae (SN)
$H_0 = 71.2 \pm 1.0\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (68% C.L.) together with a $\simeq 4\,\sigma$ evidence
ng fraction of NEDE. This is an insignificant change to the value previously
ll-shape LSS data, $H_0 = 71.4 \pm 1.0\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (68% C.L.). As a result,
ible with current constraints from LSS data.

8.80.Cq,98.80.-k,98.80.Es

Many models. How to test these kinds of modifications generically?

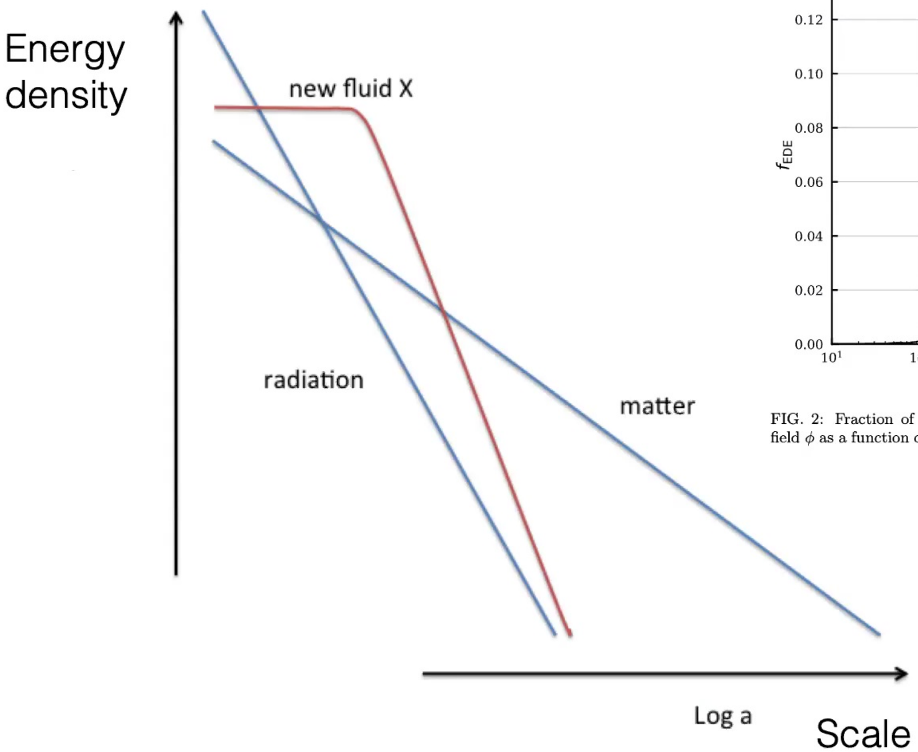
Idea:
Can I measure early H_0 without the sound horizon?

- H_0 from different ”standard ruler”: matter radiation equality scale k_{eq} in the matter power spectrum
- Details: get $k_{eq} \sim \Omega_m H_0^2$ [actually $\Omega_m H_0$ as probe k_{eq}/H_0]. Then just need a probe of Ω_m and solve for H_0!



Example: Early Dark Energy

[Poulin et al. 2018, ...]



Scale factor ~time

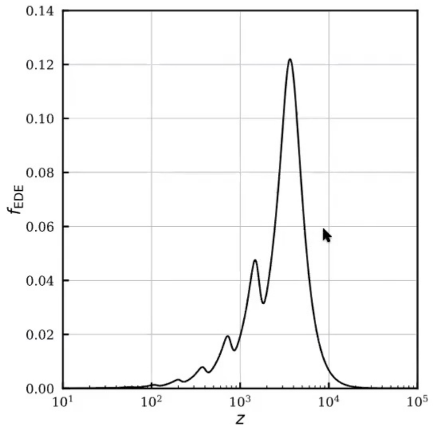
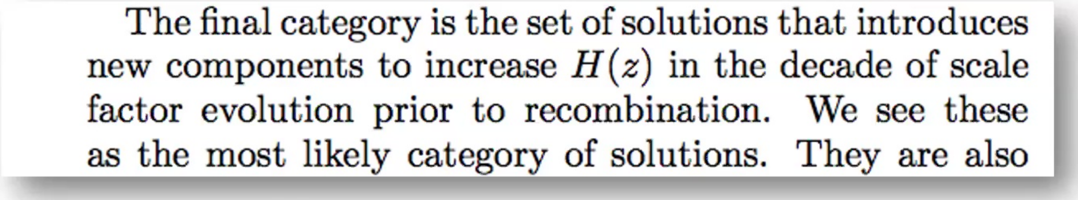


FIG. 2: Fraction of the cosmic energy density in the EDE field ϕ as a function of redshift, for the parameters in Eq. (7).

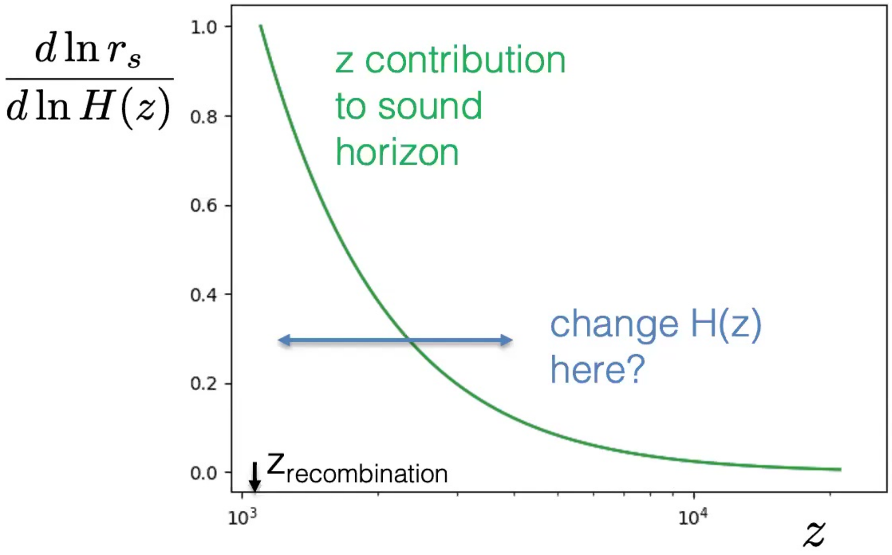
Possible explanation for tension: Changing sound horizon via early expansion



The final category is the set of solutions that introduces new components to increase $H(z)$ in the decade of scale factor evolution prior to recombination. We see these as the most likely category of solutions. They are also

[Knox + Millea 2019]

$$r_s = \int_{z_r}^{\infty} \frac{c}{H(z)} dz$$



H_0 via k_{eq} : different sensitivity to new physics

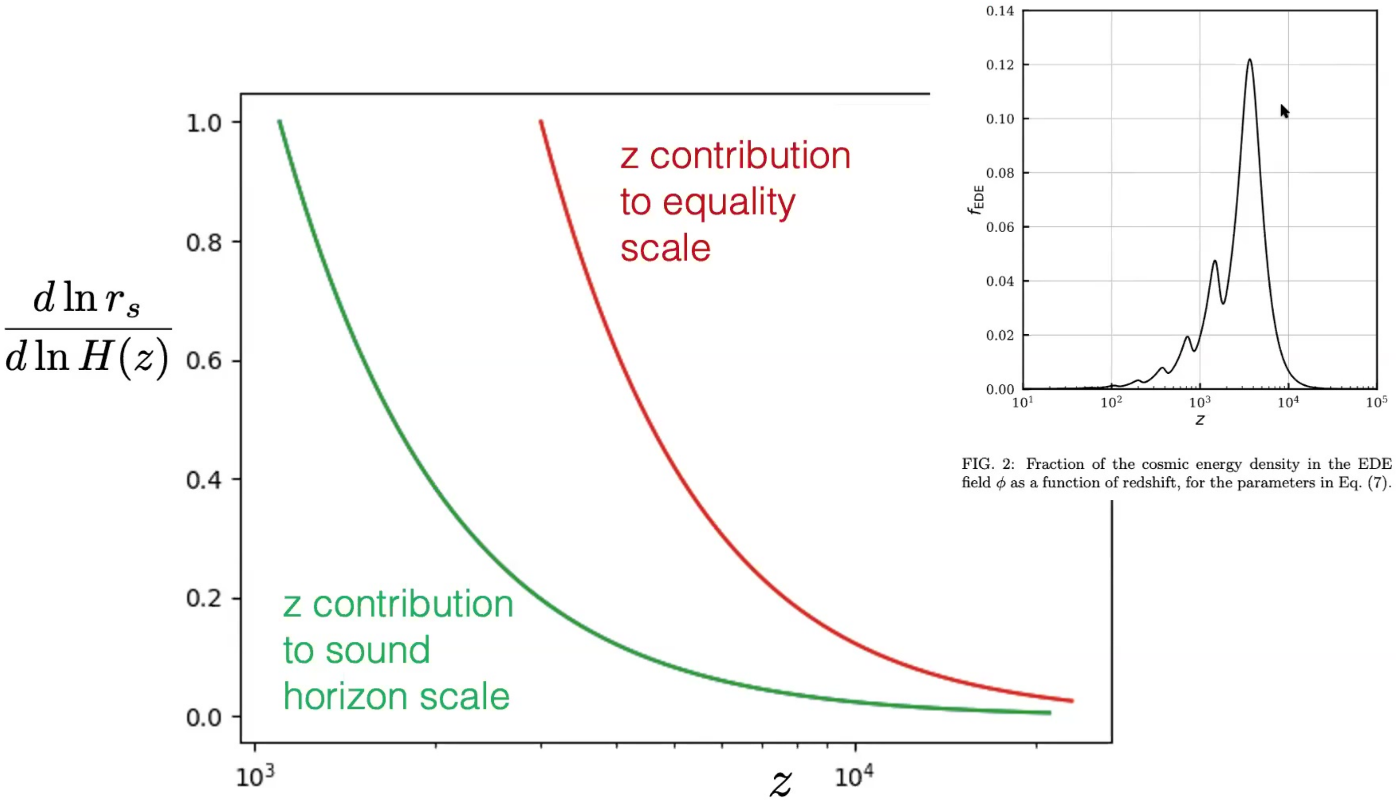
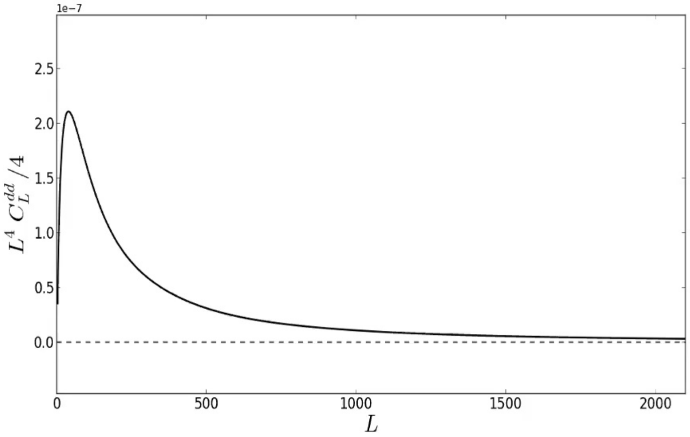


FIG. 2: Fraction of the cosmic energy density in the EDE field ϕ as a function of redshift, for the parameters in Eq. (7).

r_s and k_{eq} have somewhat different sensitivity to different redshifts

Problem for matter power spectrum analysis: still some dependence on sound horizon

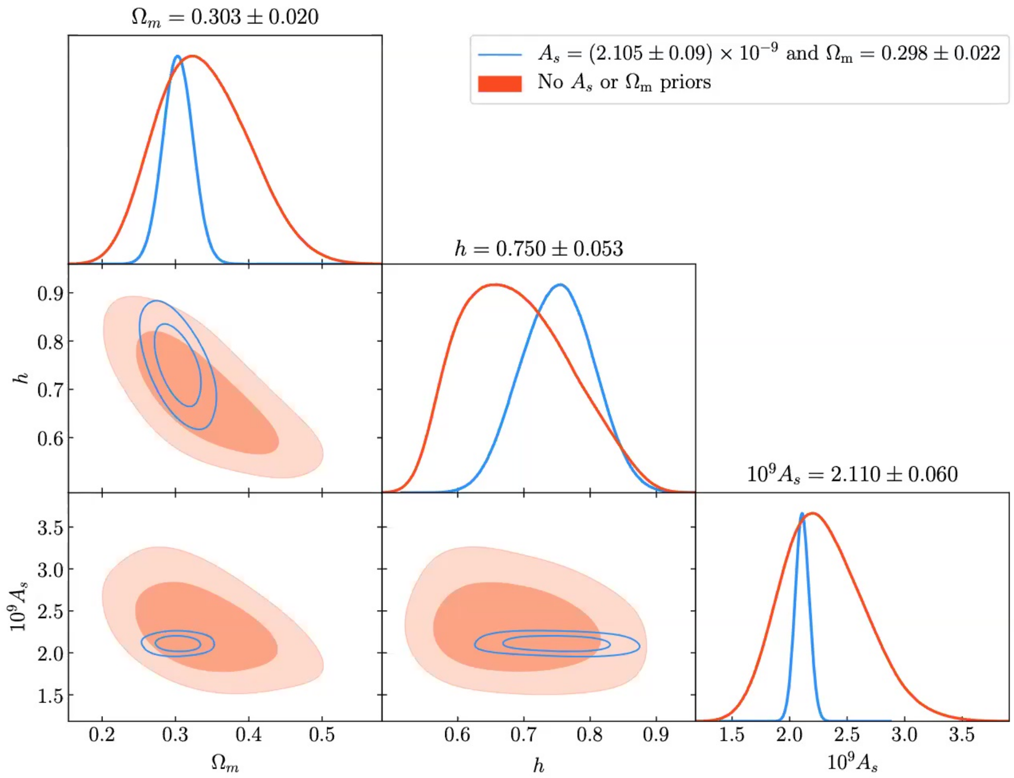
CMB lensing power spectrum ~ projected matter power



- First step: avoid BAO wiggles (and broadband baryon suppression) as these contain r_s information
- Projection washes these out…so use CMB lensing power to probe $L_{eq} \sim \Omega_m{}^a H_0$
- (+lots of work to show the information is r_s independent)
- Get H_0!

Hubble constraints from current data

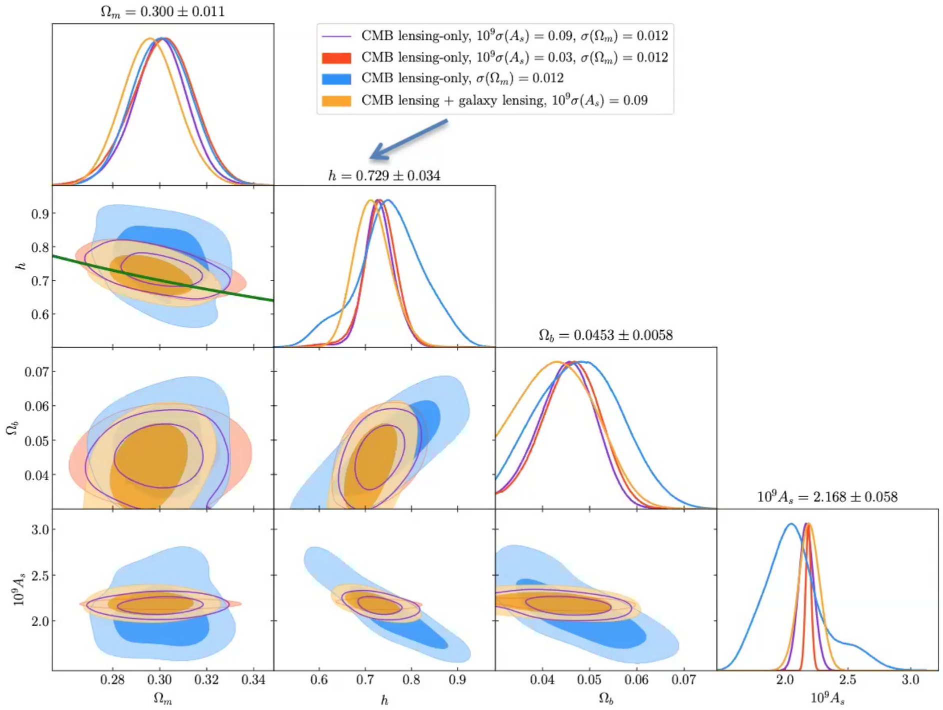
[Planck CMB lensing, SNae Ω_m, weak A_s prior]



- H_0 = 75 +/- 5 km/s/Mpc – constraint without the sound horizon!

Hubble constraints from future data

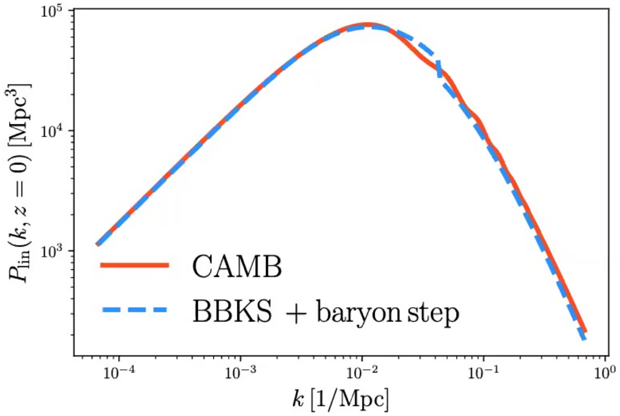
[CMB-S4 lensing + Pantheon supernovae + conservative priors]



- Future forecast: H_0 to within 3km/s/Mpc. Improvements quite slow.

Further Improvements:
3D galaxy power spectrum analysis

- 3D P(k) has more modes and potential for stronger sound-horizon free Hubble measurements. Again, get $k_{eq}/h \sim \Omega_m H_0$, combine with external Ω_m to derive $H_{0.}$

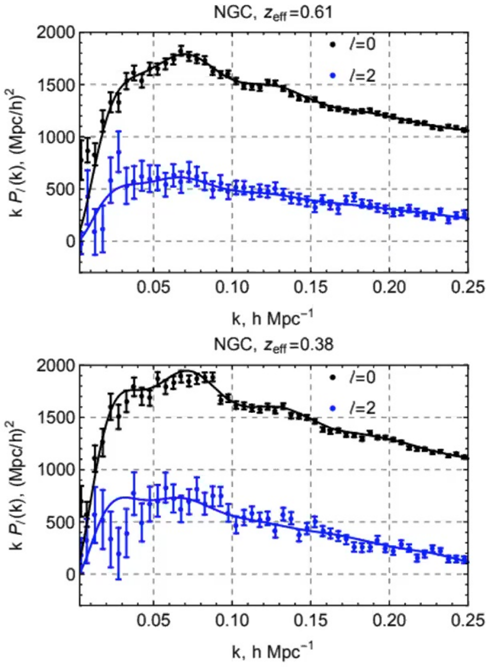


- But must ensure independence of sound horizon features (BAO, suppression)

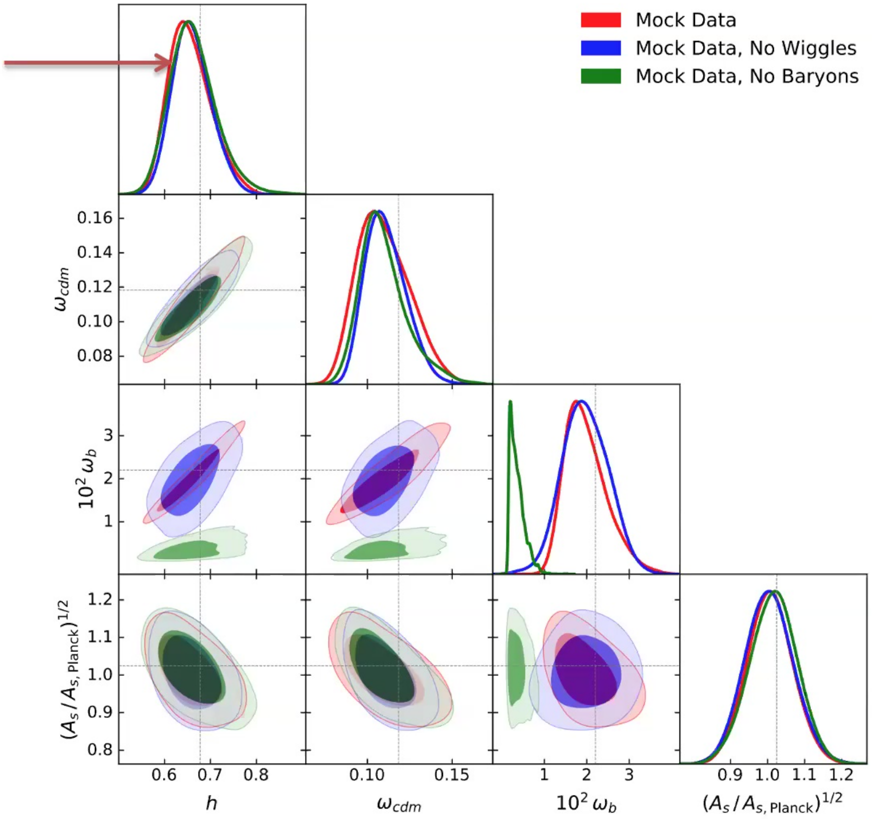
H_0 without the sound horizon from galaxy surveys

- For current data: use Ivanov et al. 2020 EFT full-shape analysis of BOSS galaxies, combined with matter probe from supernovae.
- Use ~ no baryon constraint so hope r_s is uncalibrated. But: worry of self-calibration…
- Challenge: how to show the constraints do not derive from $r_{s?}$

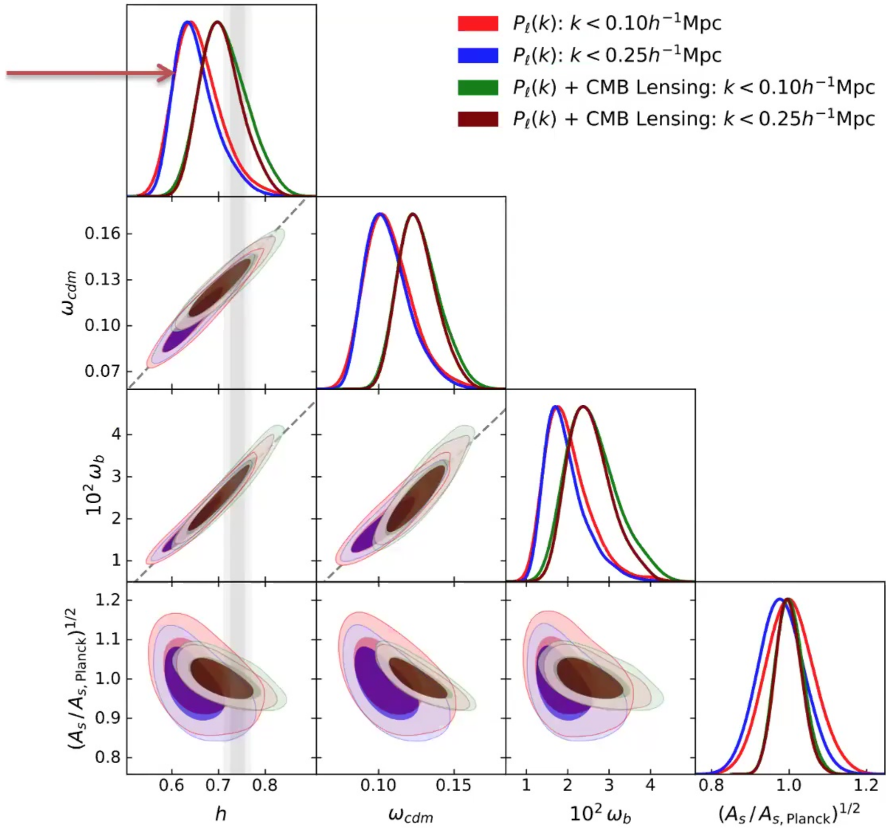
BOSS galaxy power spectra



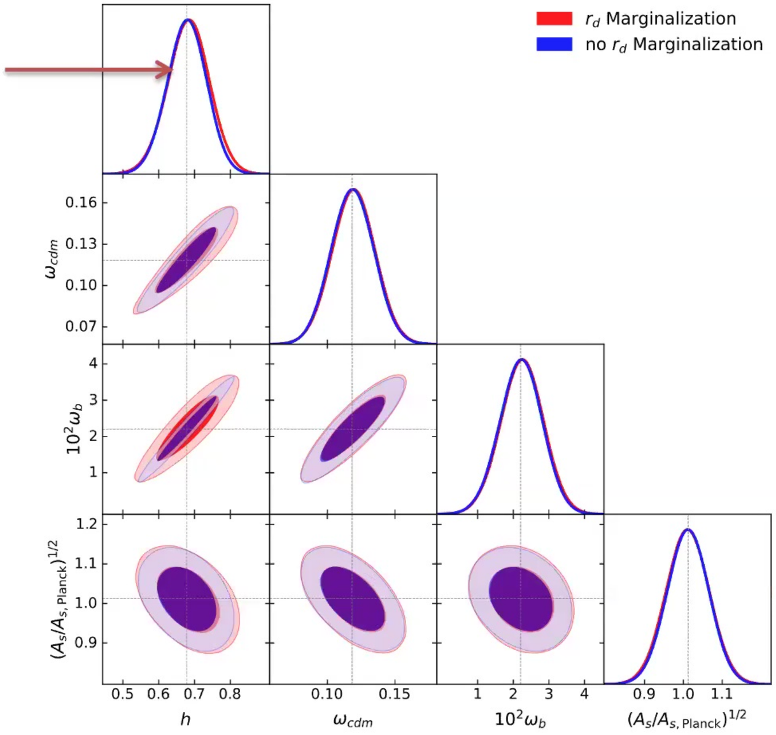
Showing that this is r_s independent I: Sims with no wiggles / baryons give same results



Showing that this is r_s independent II: Constraints derive only from large scales (unlike BAO)



Showing that this is r_s independent III: Can marginalize over r_s in forecasts with no change

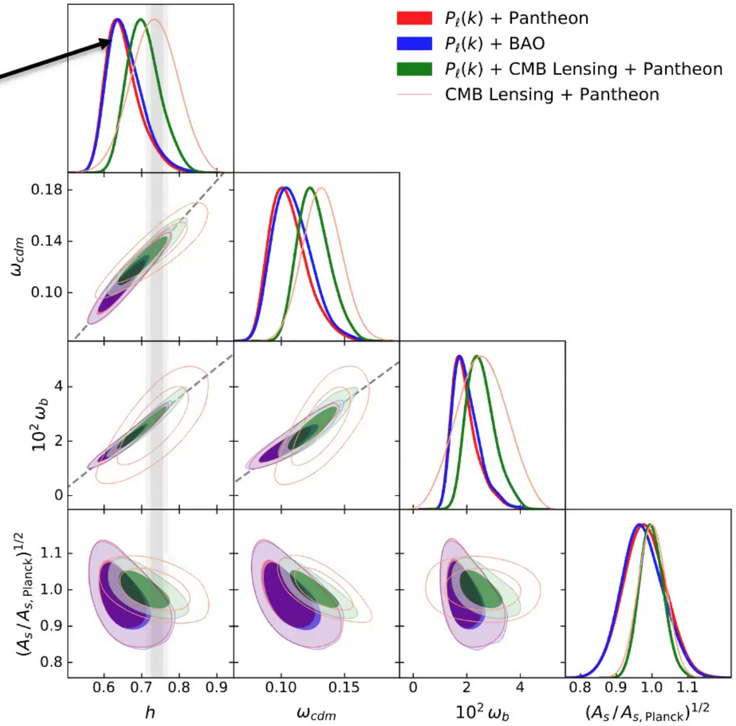


Results: galaxy power spectrum analysis

[BOSS full-shape galaxy power, SNae Ω_m]

- $H_0 = 65.1^{+3.0}_{-5.4}$ km/s/Mpc – constraint without the sound horizon! Note: consistent with 74 at 95%C.L.

[Constraint from galaxies]

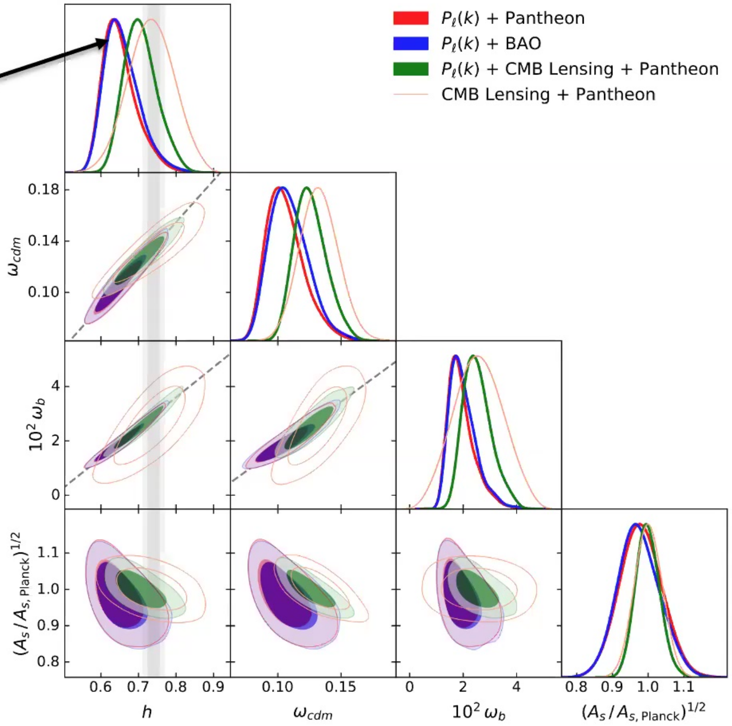


Results: galaxy power spectrum analysis

[BOSS full-shape galaxy power, SNae Ω_m]

- $H_0 = 65.1^{+3.0}_{-5.4}$ km/s/Mpc – constraint without the sound horizon! Note: similar result with matter from BAO

[Constraint from galaxies]

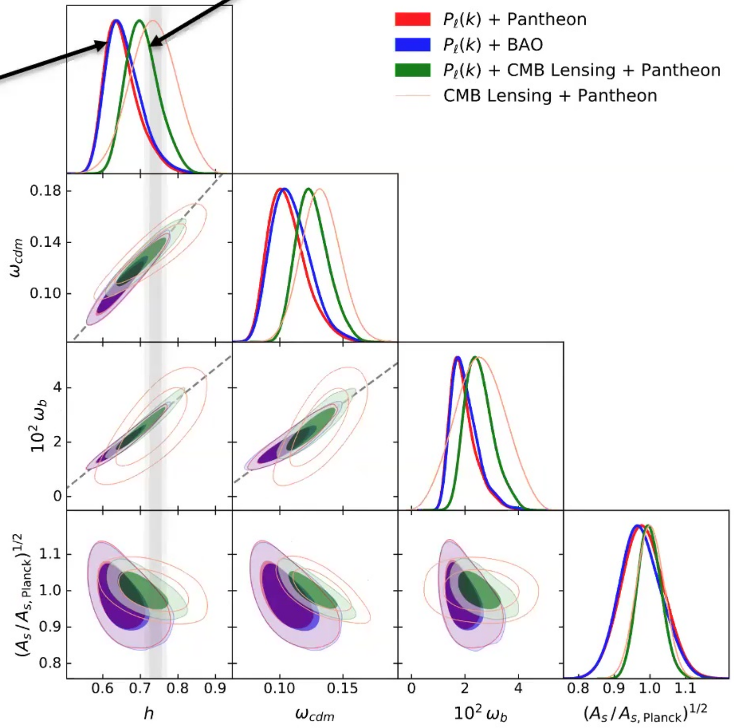


Results: CMB lensing + galaxy power

- $H_0 = 70.6^{+3.7}_{-5.0}$ – constraint without the sound horizon, in combination with CMB lensing.

[Combined with CMB lensing]

[Constraint from galaxies]



Outlook:
Can this method do better with future probes?

- Forecast H_0 to +/- 1.6 km/s/Mpc – for Euclid-like survey constraint without the sound horizon (here directly marginalized over sound horizon). + potential improvements?

- But: more complex analysis may be needed. May not get away with simply omitting baryon prior. Currently investigating.

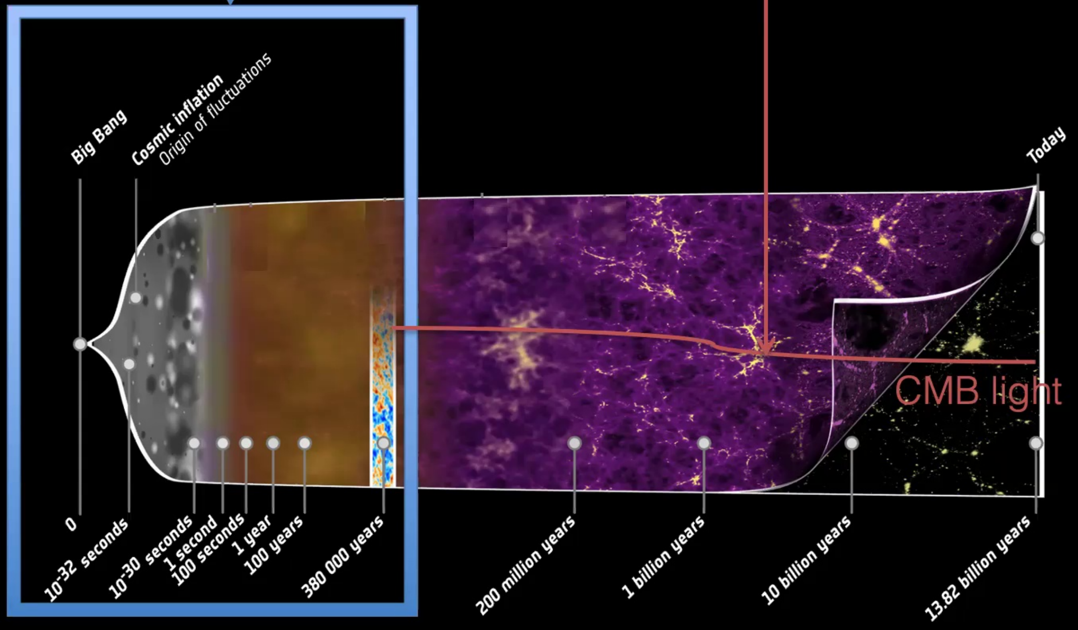
- Currently investigating predictions of different new physics models for the difference in H_0 via this method.

- Goal: if consistent to very high precision, great consistency test for LCDM; if inconsistent at high significance, confirmation / insight into new physics!

CMB Lensing as Noise for Early Universe Cosmology

But if we are interested in the early universe

Now lensing is a problem!

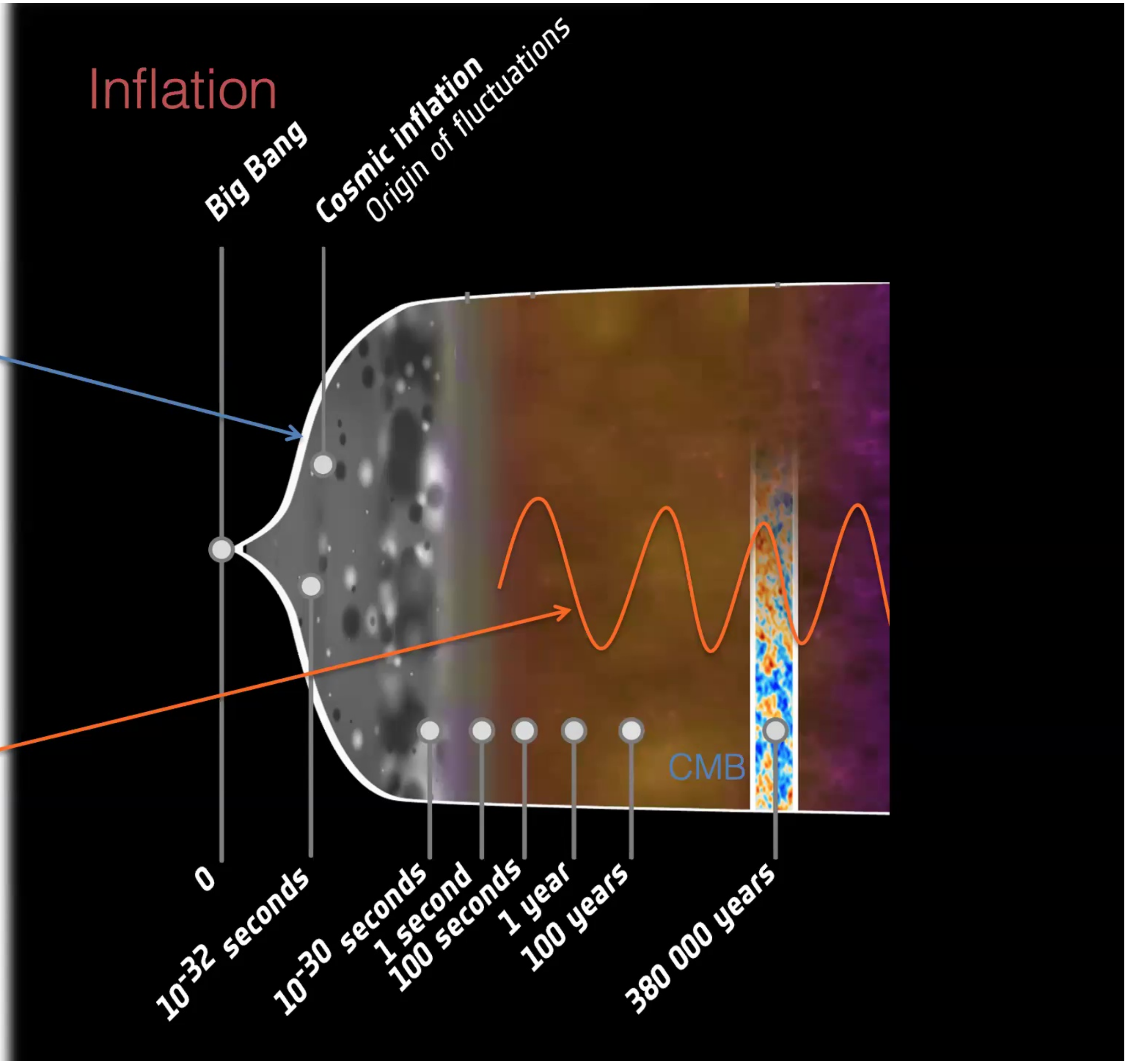


CMB light

time (+ distance light travels!)

Inflation

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



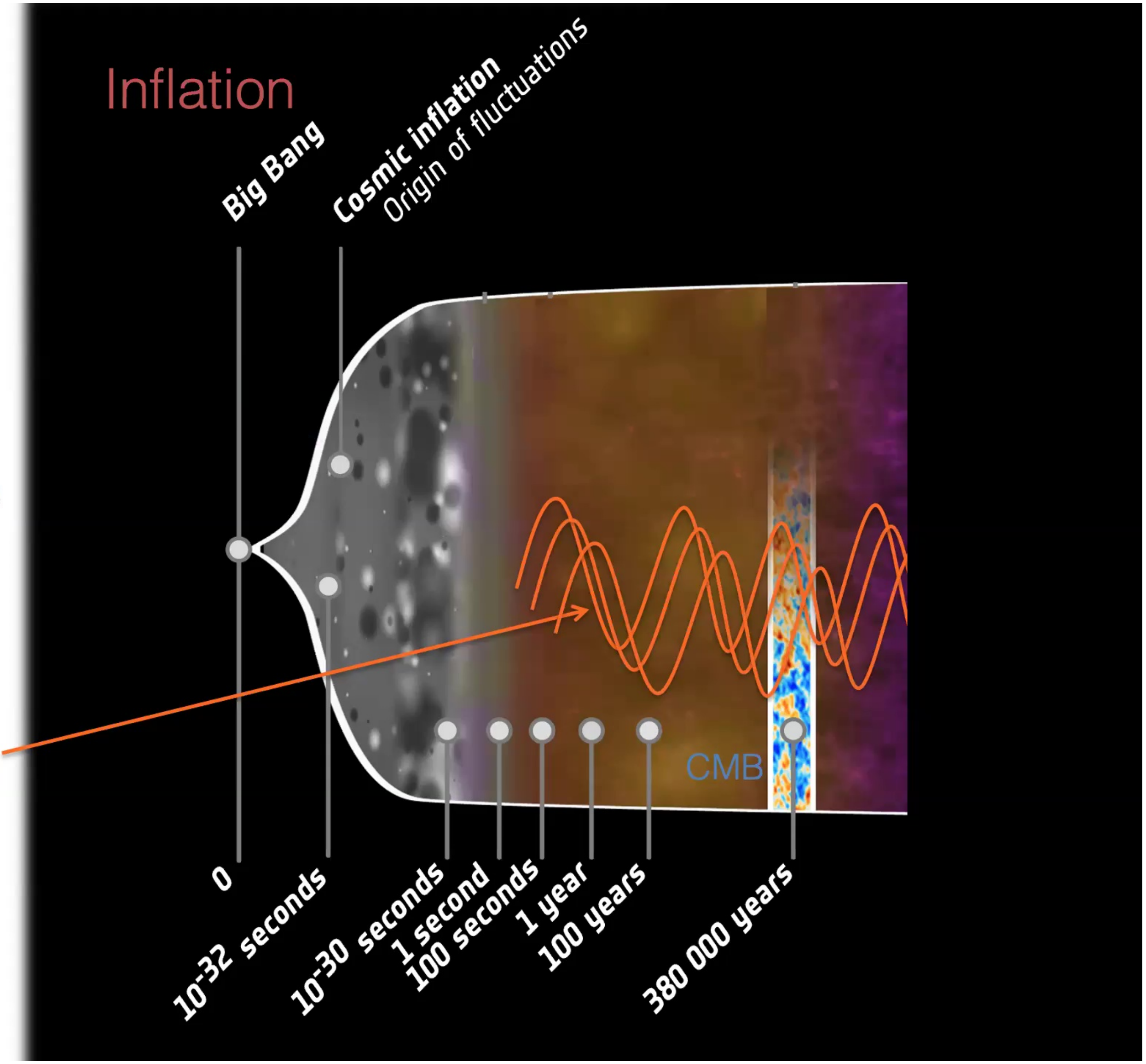
*N.B. Some other models also produce GWs

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

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

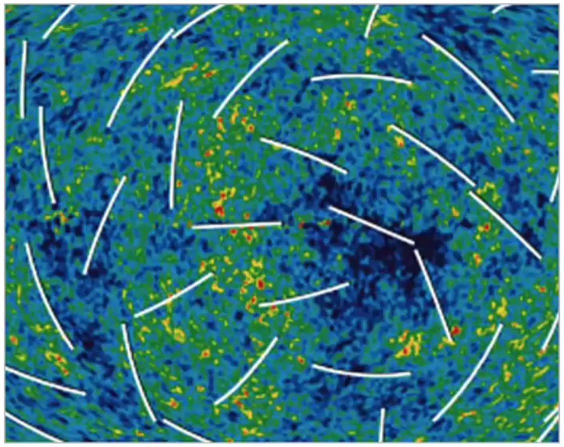
- Strength of the waves - tensor-to-scalar ratio r - tells us about the energy at which inflation happened!

N.B. Even improved upper limits interesting.

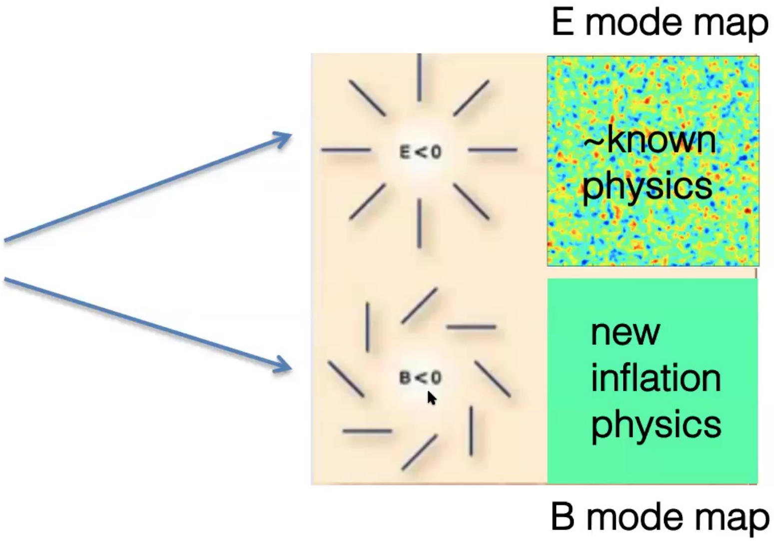


CMB Polarization Basics

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



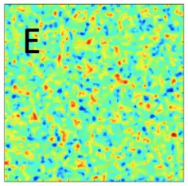
[Image credit: CMBPol]

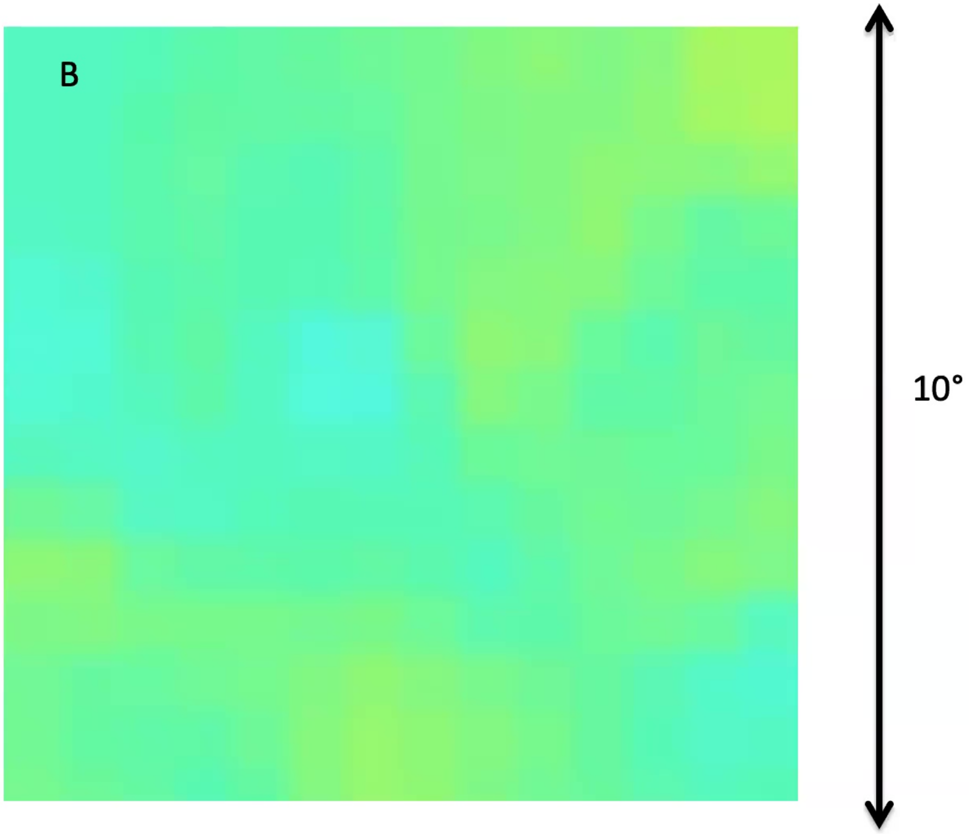


CMB B-polarization* with small inflationary signal

See signal clearly as there is no background

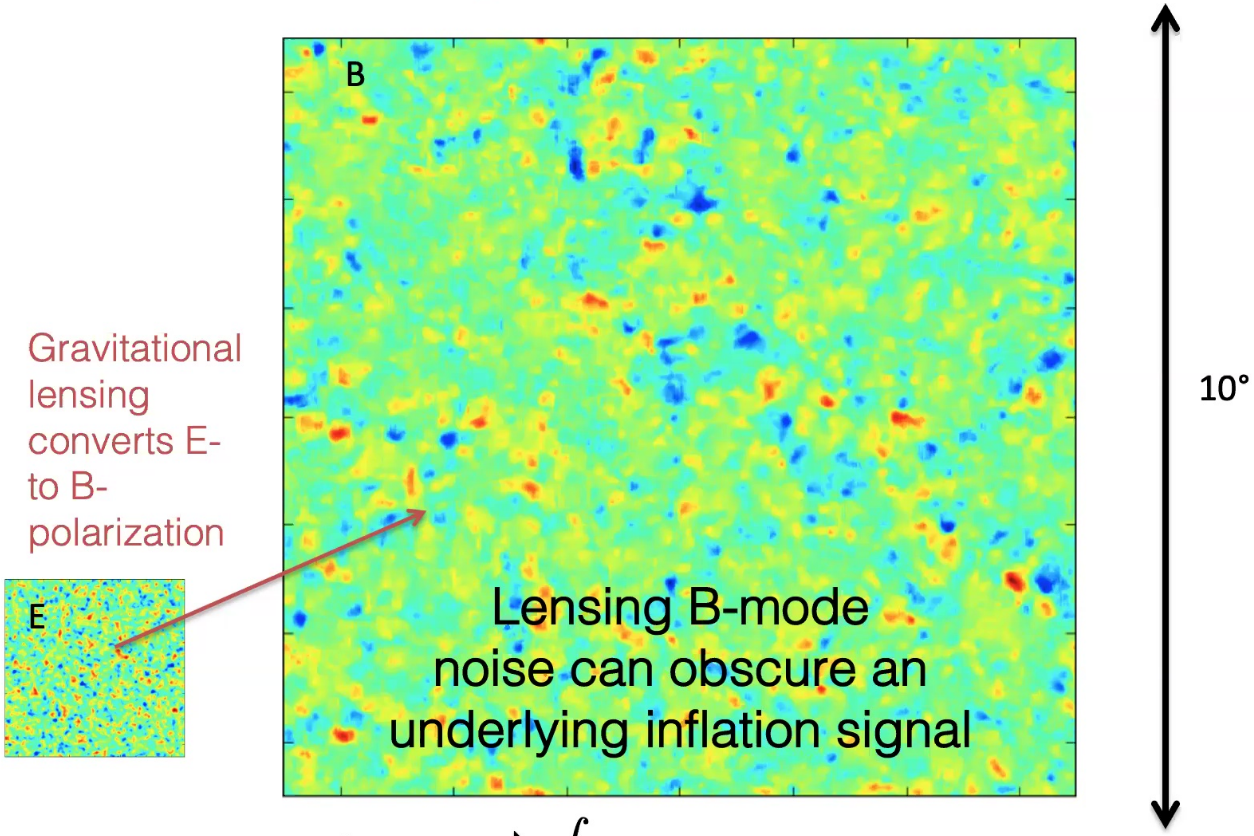
B-modes are a "null channel"





*ignoring lensing and dust for now

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



Gravitational lensing converts E- to B-polarization

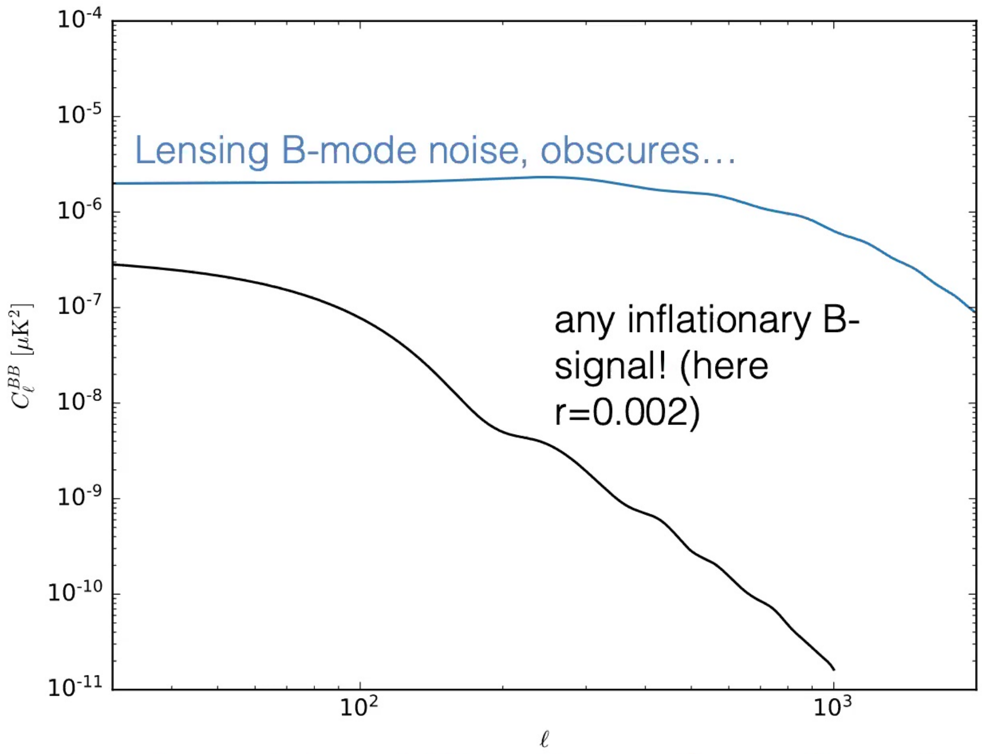
Lensing B-mode noise can obscure an underlying inflation signal

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

W: geometric kernel

Lensed CMB B-Polarization: Noise for Inflation-B

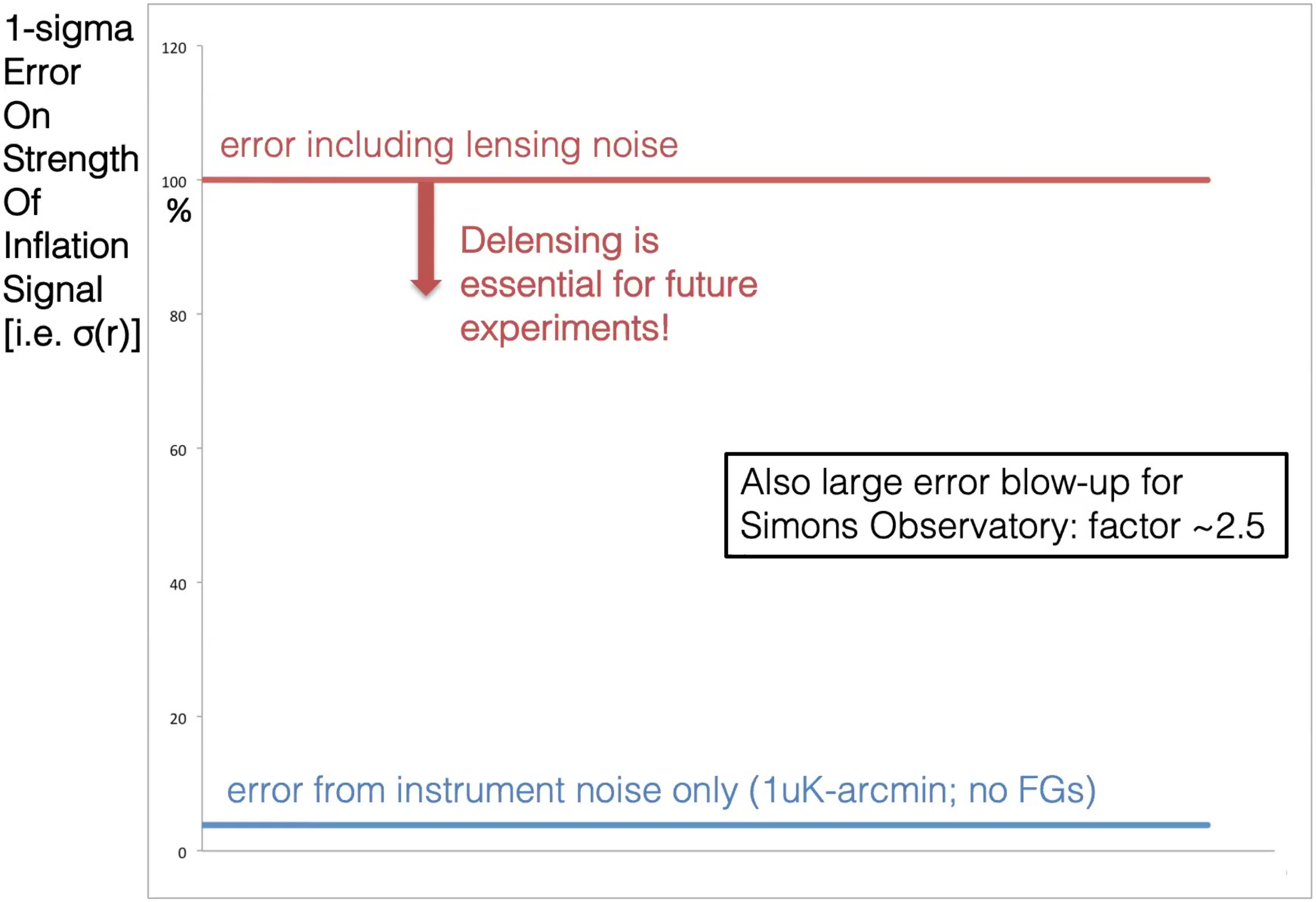
B-mode
power



- Problem: lensing adds additional error (cosmic variance) ~

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

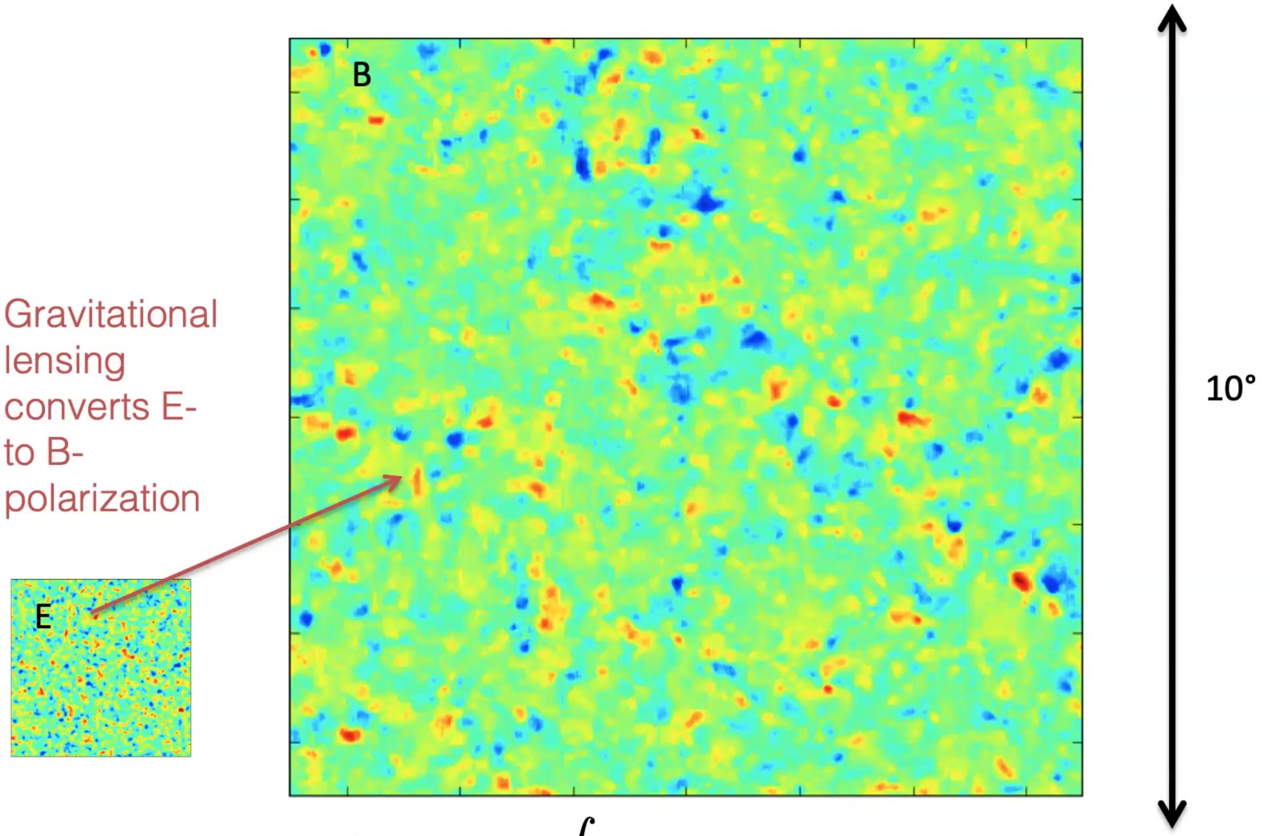
Error Inflation from Lensing Noise (Example: CMB-S4)



Delensing is essential for future experiments!

Also large error blow-up for Simons Observatory: factor ~2.5

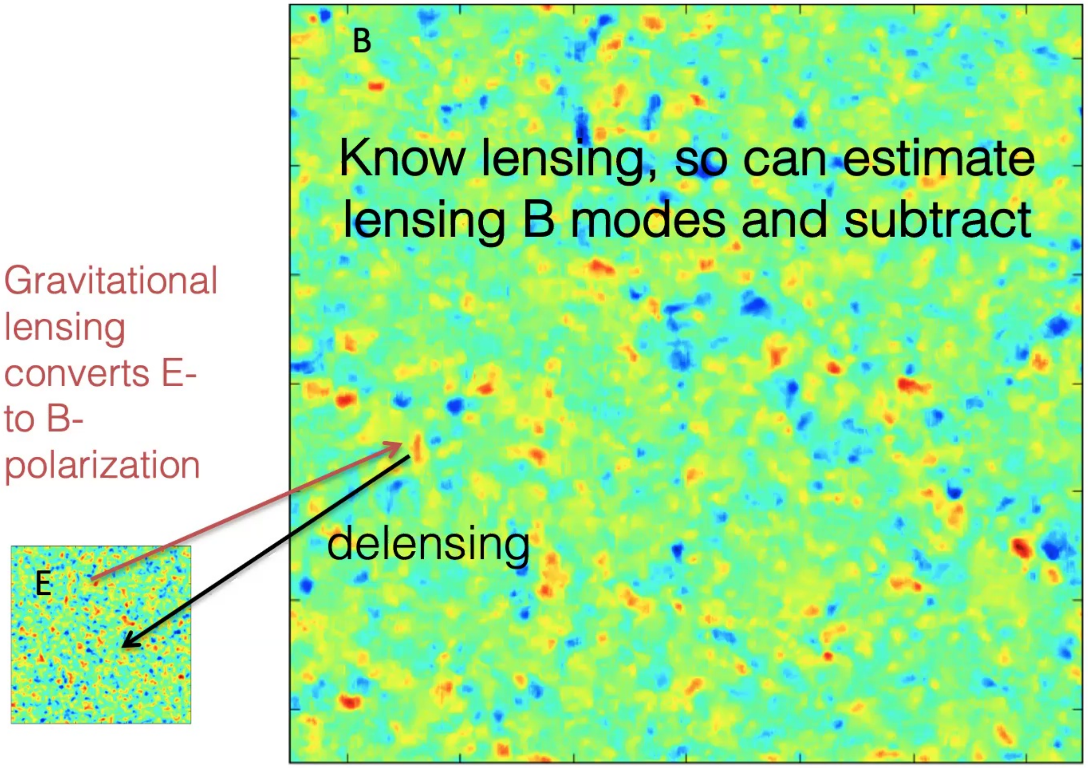
Delensing the CMB: Lensing Removal



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



Know lensing, so can estimate lensing B modes and subtract

Gravitational lensing converts E- to B-polarization

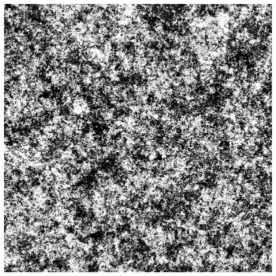
delensing

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 probes
projected
mass distribution

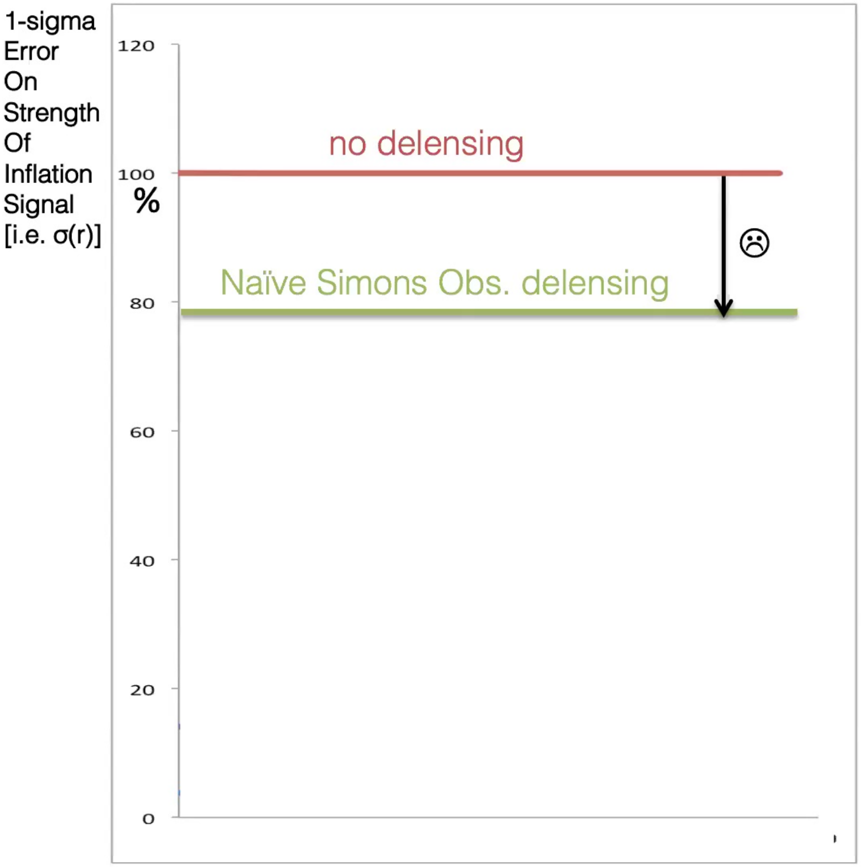
$$\mathbf{d} \sim \int dz W(z)\delta(z)$$

Standard “Internal” case:

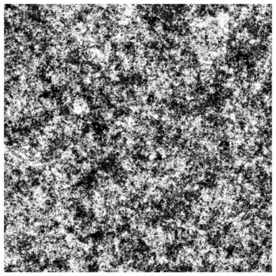
1) Reconstruct lensing $\hat{d}$ from changes in background CMB

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 probes
projected
mass distribution

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

CIB=Cosmic
Infrared
Background

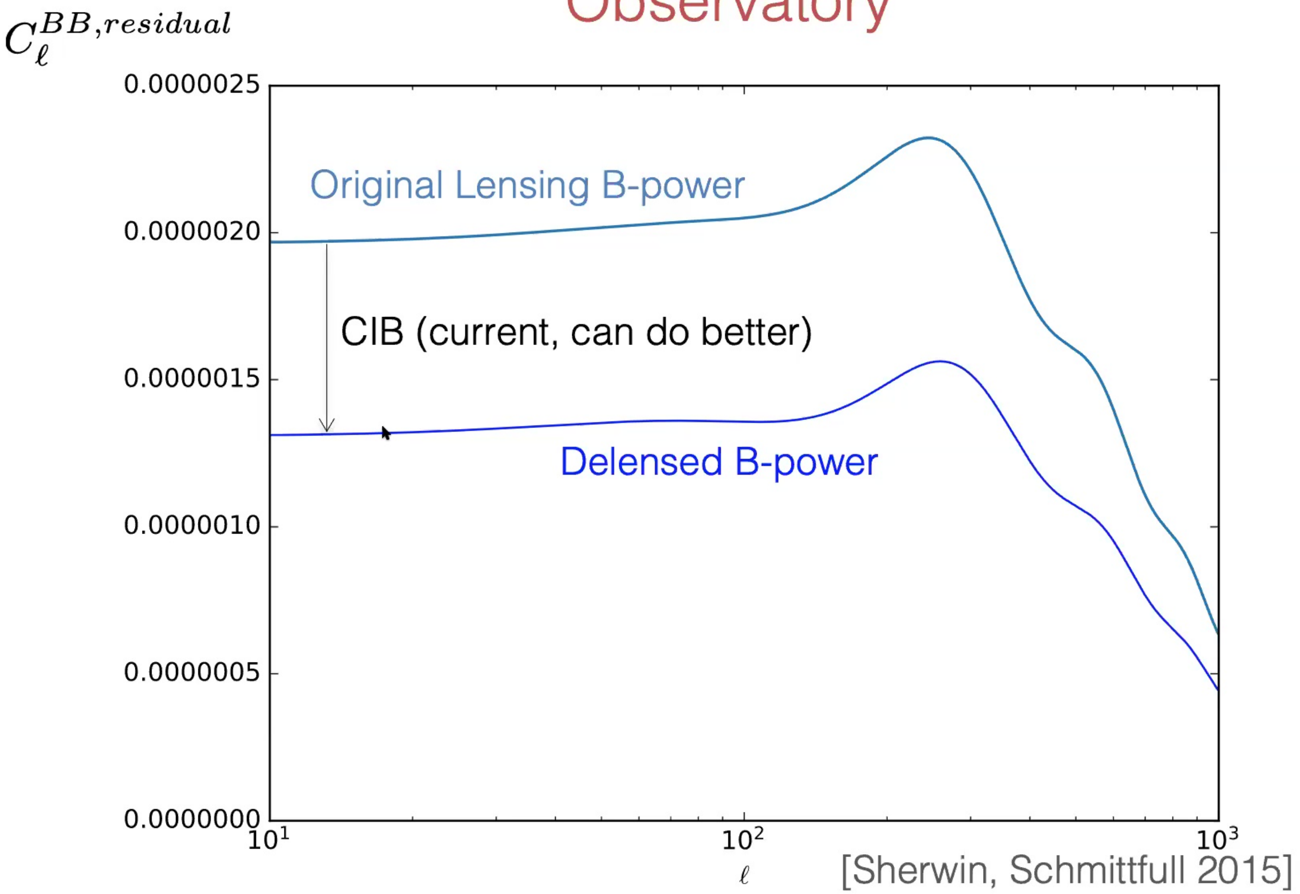
1) Reconstruct lensing from changes in background CMB

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

$$\hat{d}^I(\mathbf{l}) = \underbrace{f(l)}_{\text{filter function}} \times \underbrace{I(\mathbf{l})}_{\text{CIB map}}$$

[Sherwin, Schmittfull 2015]

CIB (Infrared Background) Delensing for Simons Observatory



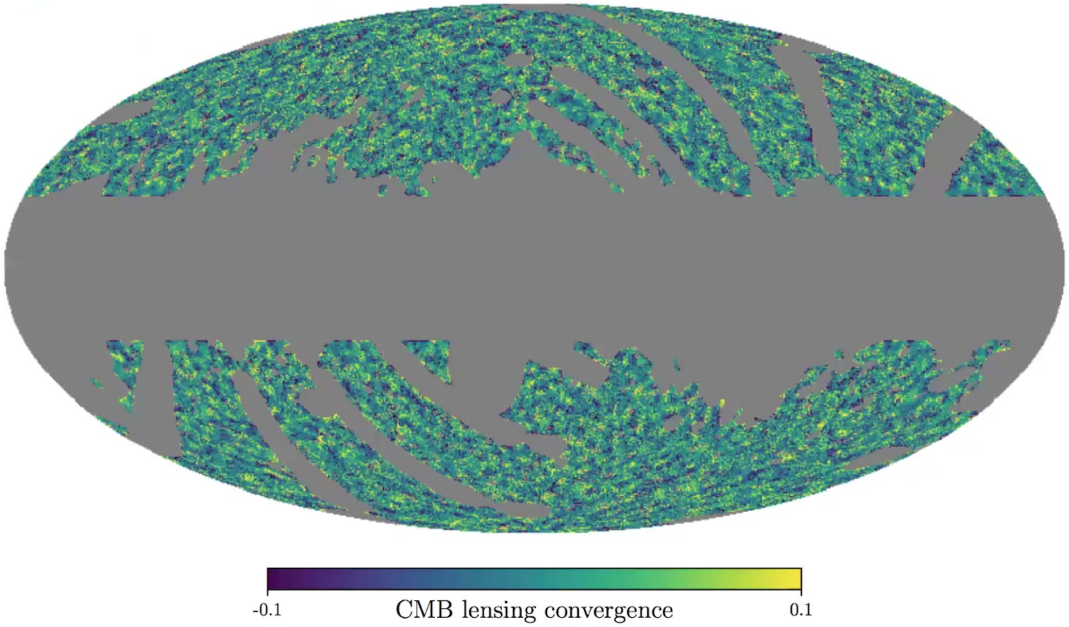
[Sherwin, Schmittfull 2015]

Use maps of cosmic infrared background (CIB) to delens

Multi-tracer Delensing for Simons Observatory

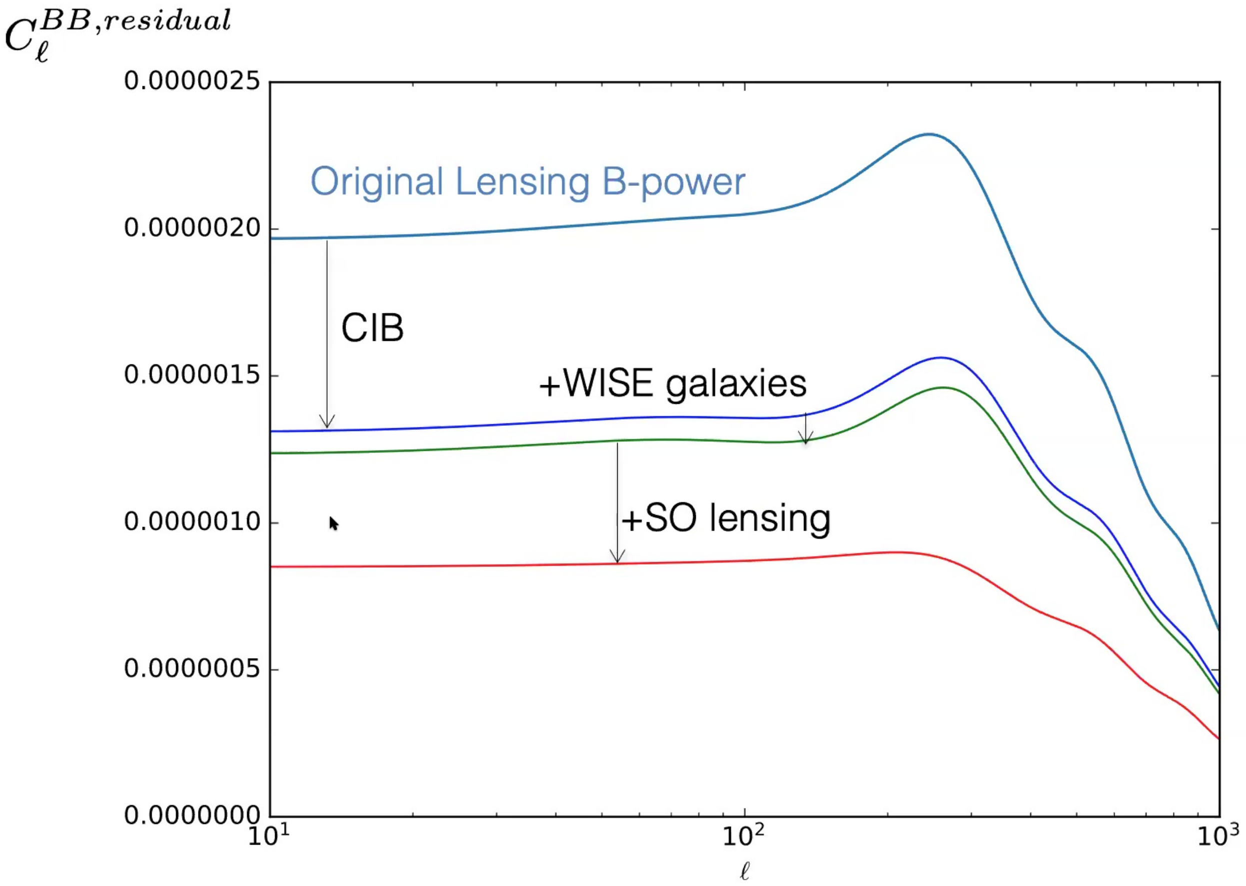
- Can co-add SO lensing map with different large scale structure tracers to delens [Yu, Hill, Sherwin 2017]

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

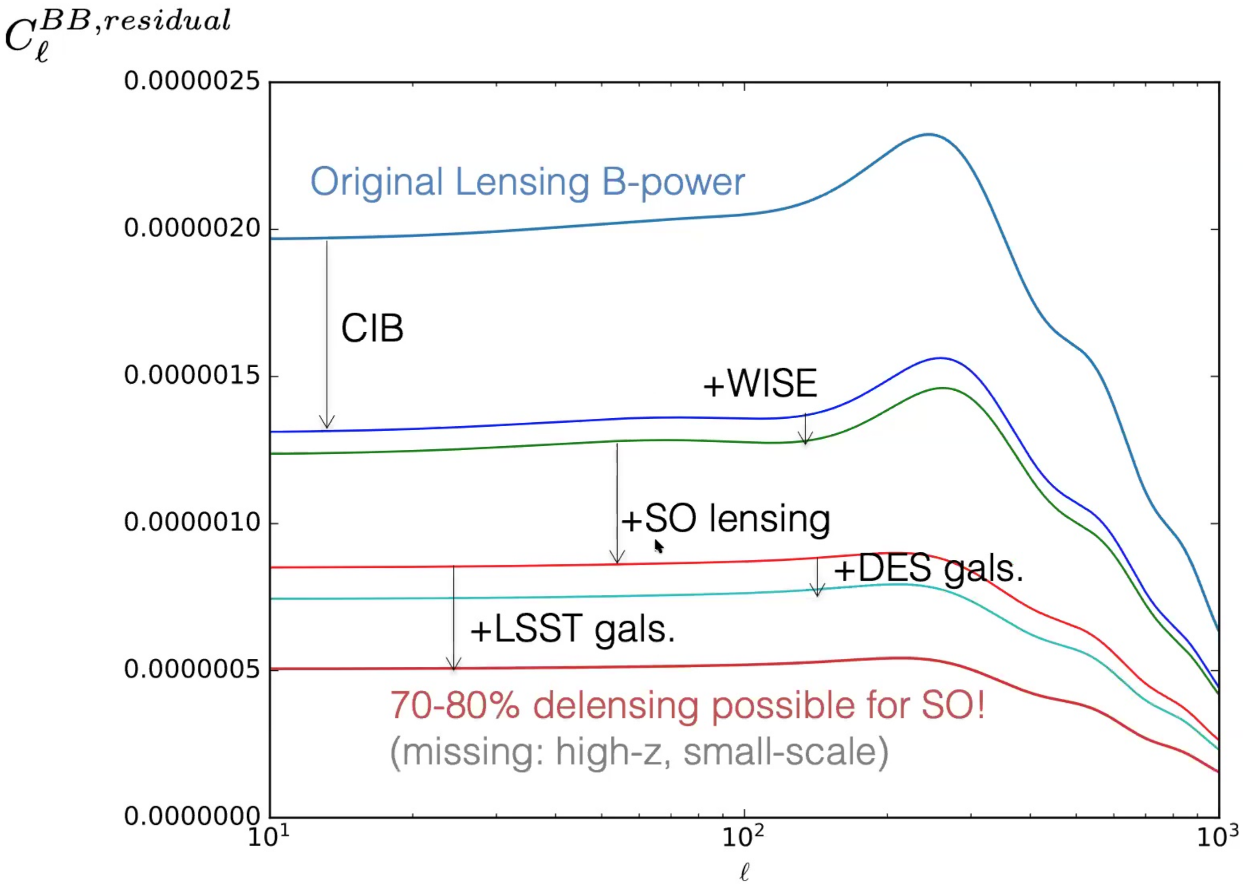


- “Multitracer” delensing can greatly improve delensing performance: now coadd SO lensing + DES/LSST + CIB +…

Multi-tracer Delensing for Simons Observatory



Multi-tracer Delensing for Simons Observatory



70-80% delensing possible for SO!

(missing: high-z, small-scale)

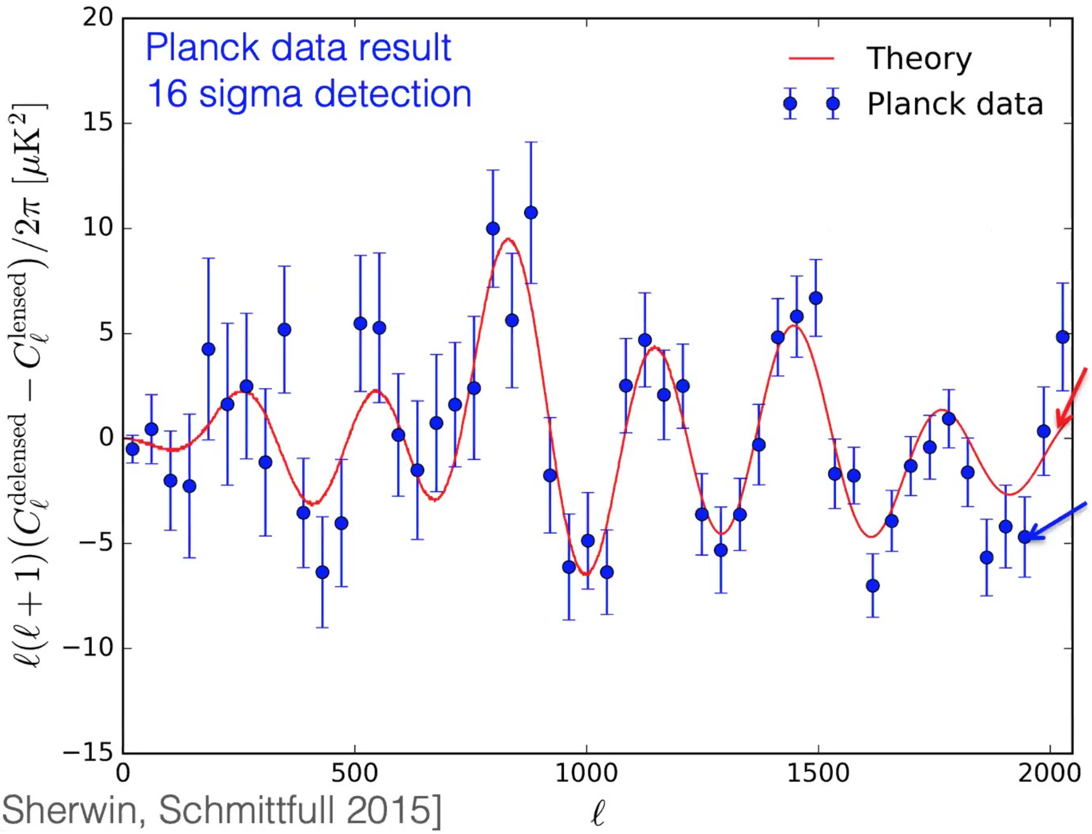
Why I think this will work I: LSS modeling required?

- All steps depend only on measurable spectra C_l

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

- Spectra typically have high S/N -> can self-calibrate, modeling often not needed!

Why I think this will work II:
Demonstrations of LSS delensing in data



Theory prediction for Delensed – Lensed temperature power

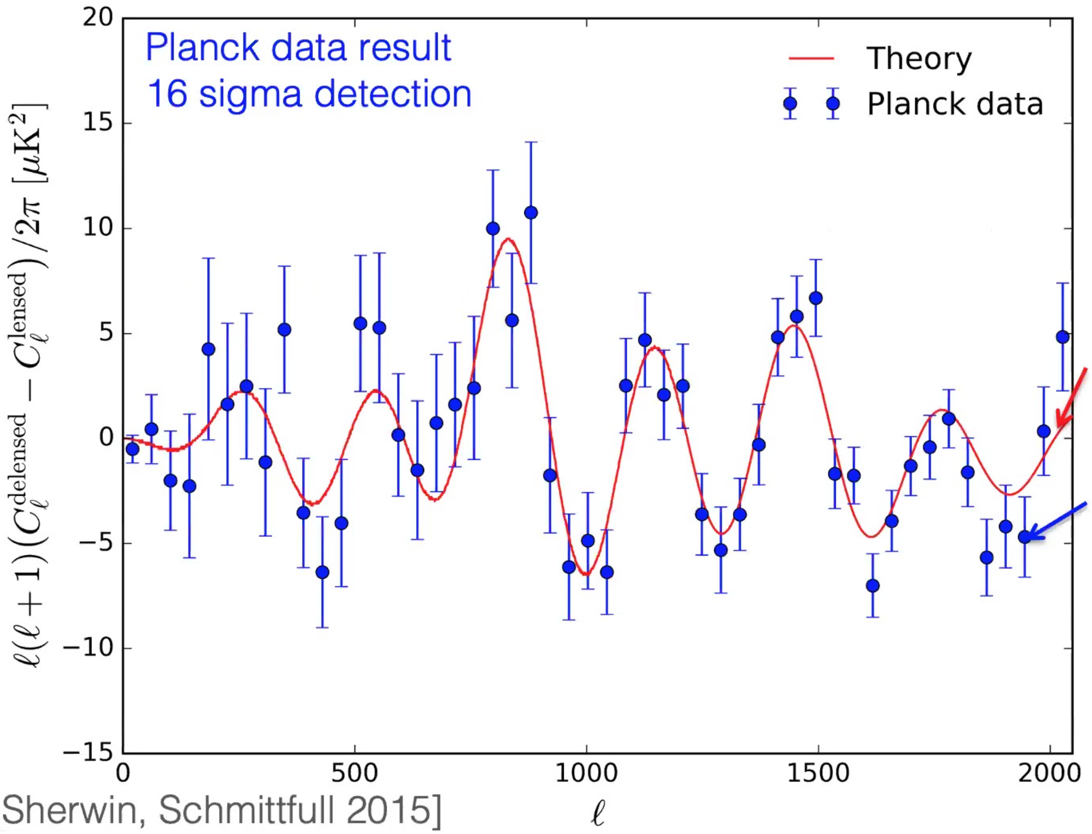
Actual result from data (agrees well!)

First demonstration of delensing in data!

[Sherwin, Schmittfull 2015]

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

Why I think this will work II: Demonstrations of LSS delensing in data



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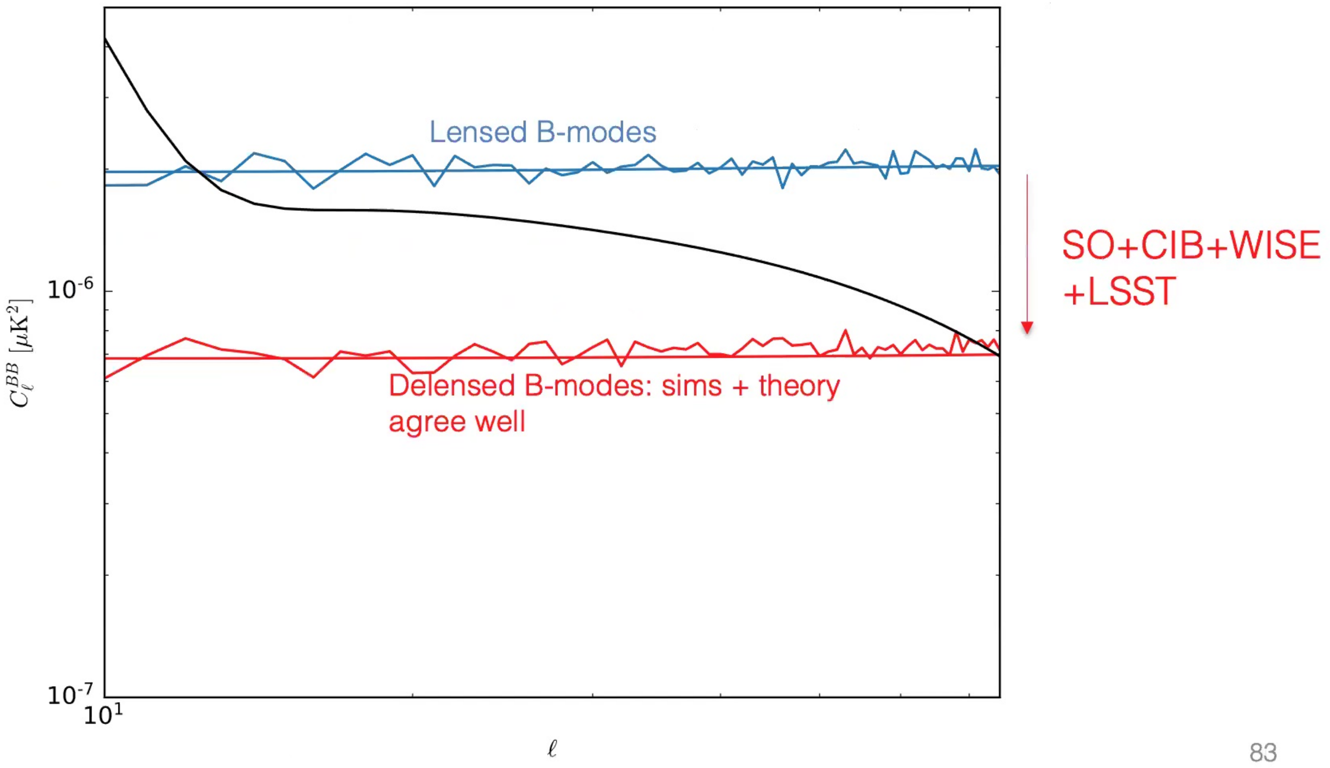
[Sherwin, Schmittfull 2015]

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

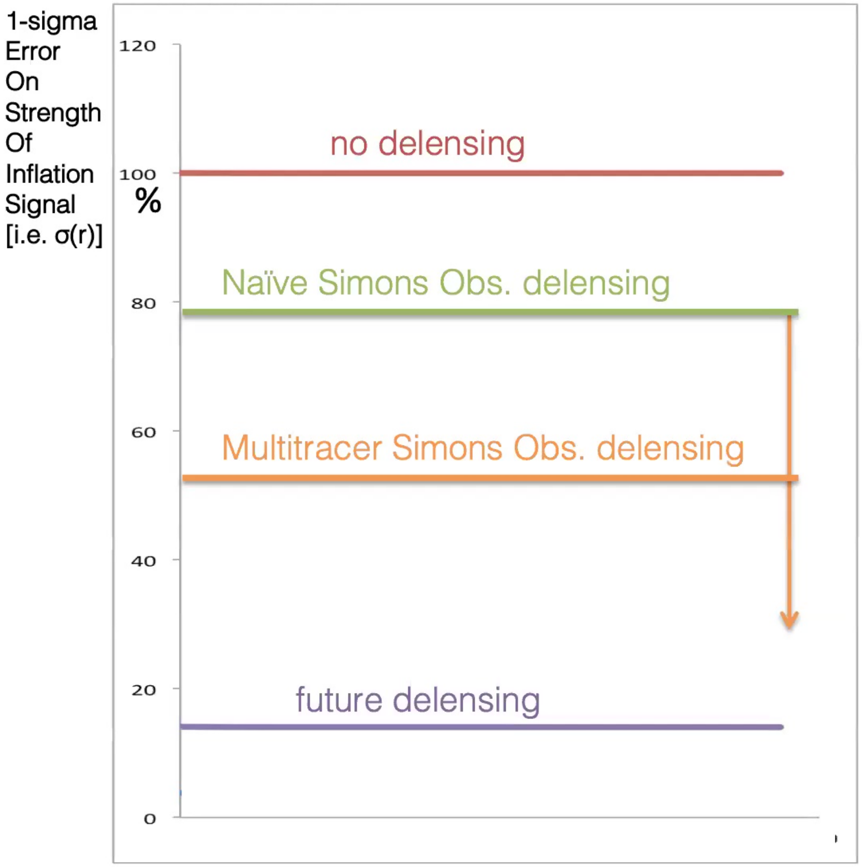
Why I think this will work III:
New SO delensing pipeline applied to simulations

- Simulation: multitracer delensing demonstration with SO (preliminary)

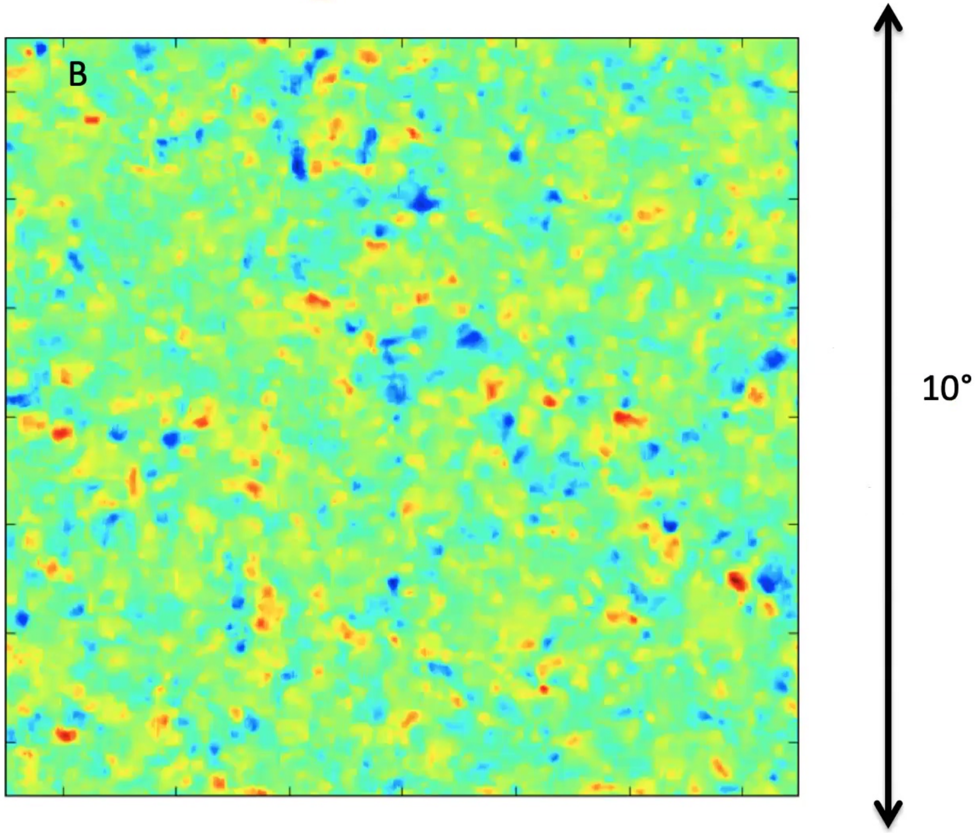


Significant improvements possible for SO!

- Although lots to figure out (foregrounds…):
- Significant improvements appear possible with multitracer delensing methods, ~2x improvement in SO r constraints [preliminary]
- Important, as near thresholds from interesting models

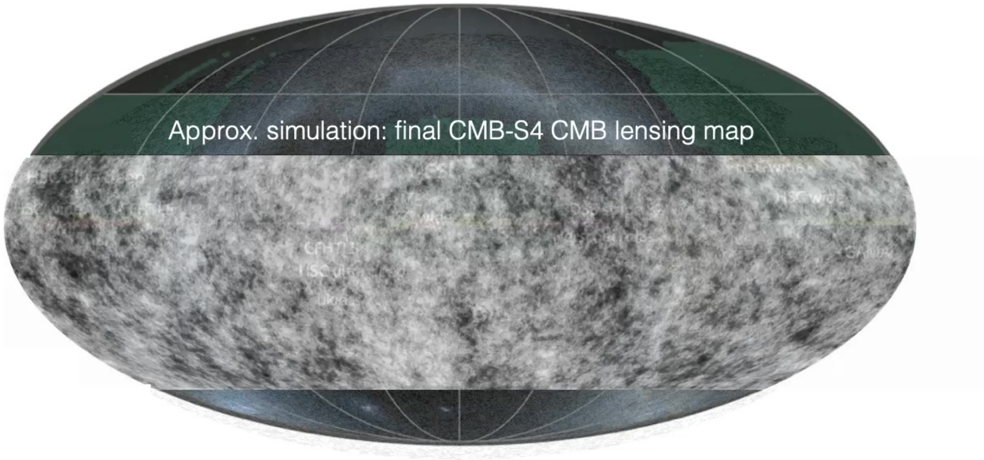


Future B Mode Map – Lensing-Dominated

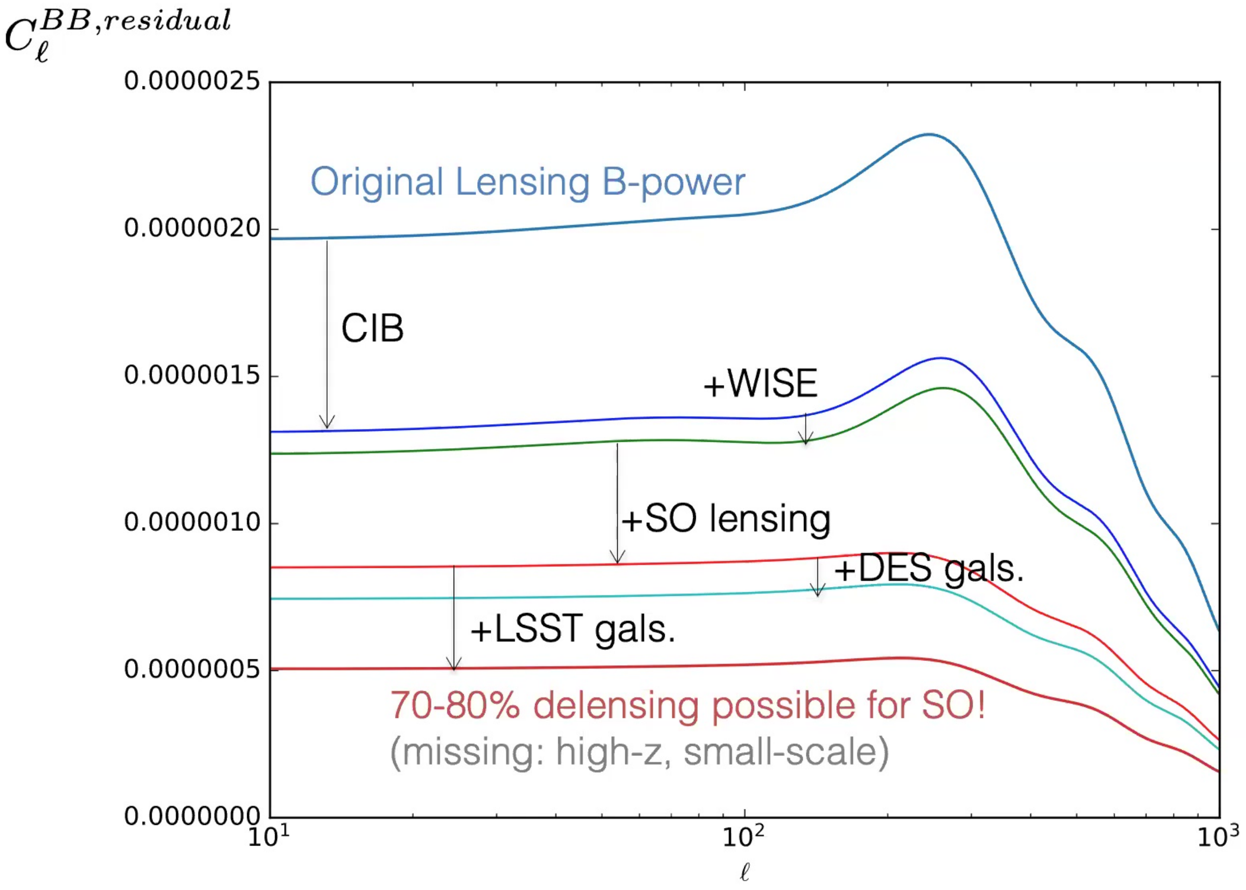


Summary

- CMB lensing has rapidly progressed. With AdvACT / Simons Observatory / CMB-S4 will have powerful new lensing maps, giving neutrino masses,…
- Lensing and galaxy surveys can measure Hubble constant without relying on sound horizon, a test of new physics
- New multi-tracer delensing methods will double power of inflation / early universe constraints



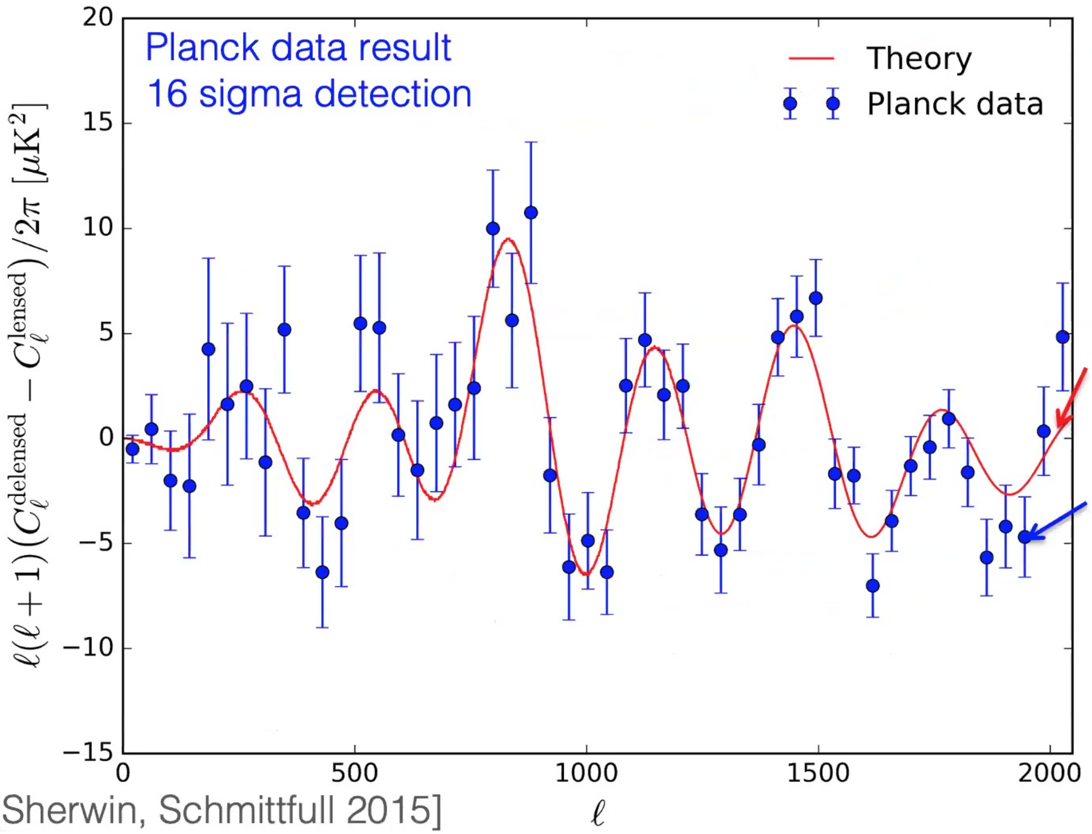
Multi-tracer Delensing for Simons Observatory



70-80% delensing possible for SO!

(missing: high-z, small-scale)

Why I think this will work II:
Demonstrations of LSS delensing in data



Planck data result
16 sigma detection

Theory prediction for Delensed – Lensed temperature power

Actual result from data (agrees well!)

First demonstration of delensing in data!

[Sherwin, Schmittfull 2015]

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

Aside: What structures are we missing?