Constraining Inflation with BICEP/Keck Array and the South Pole Telescope

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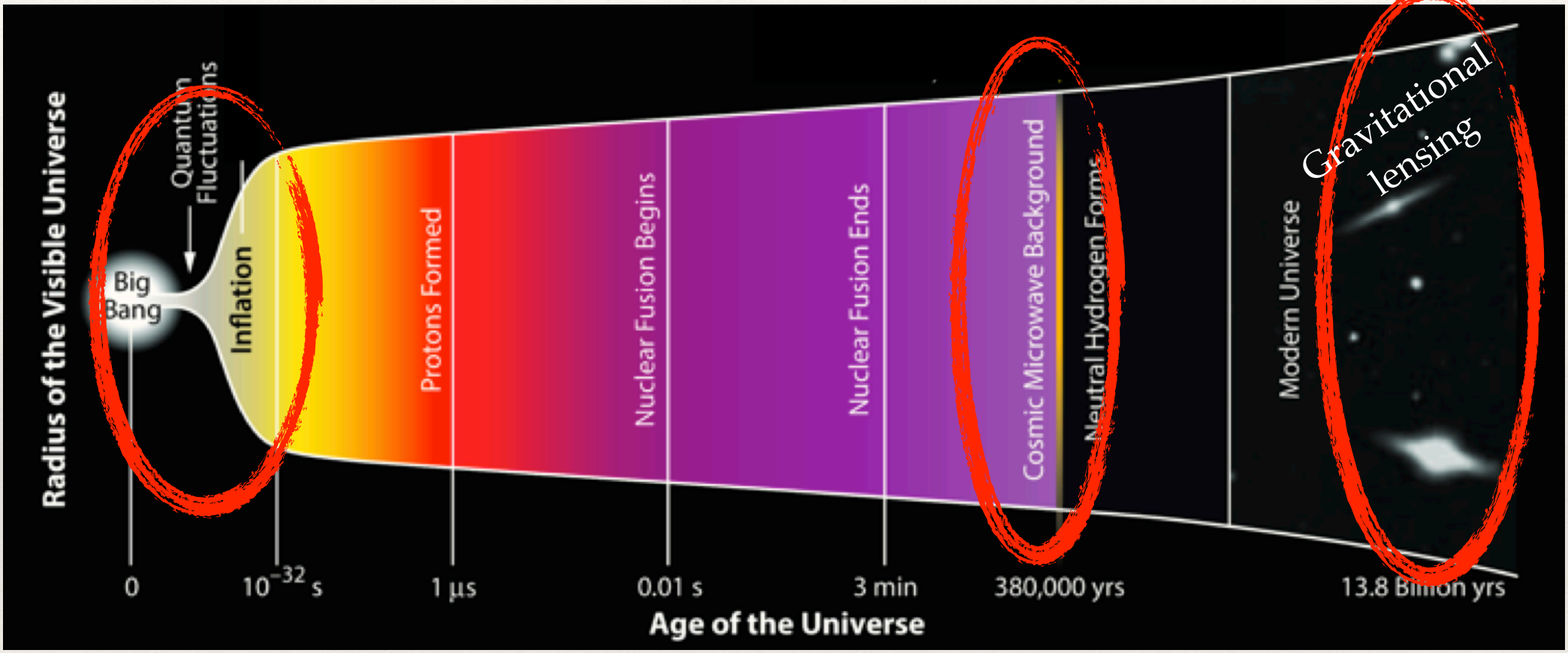
UC Berkeley
Croucher Fellow

LBL RPM Nov 30, 2016

Outline

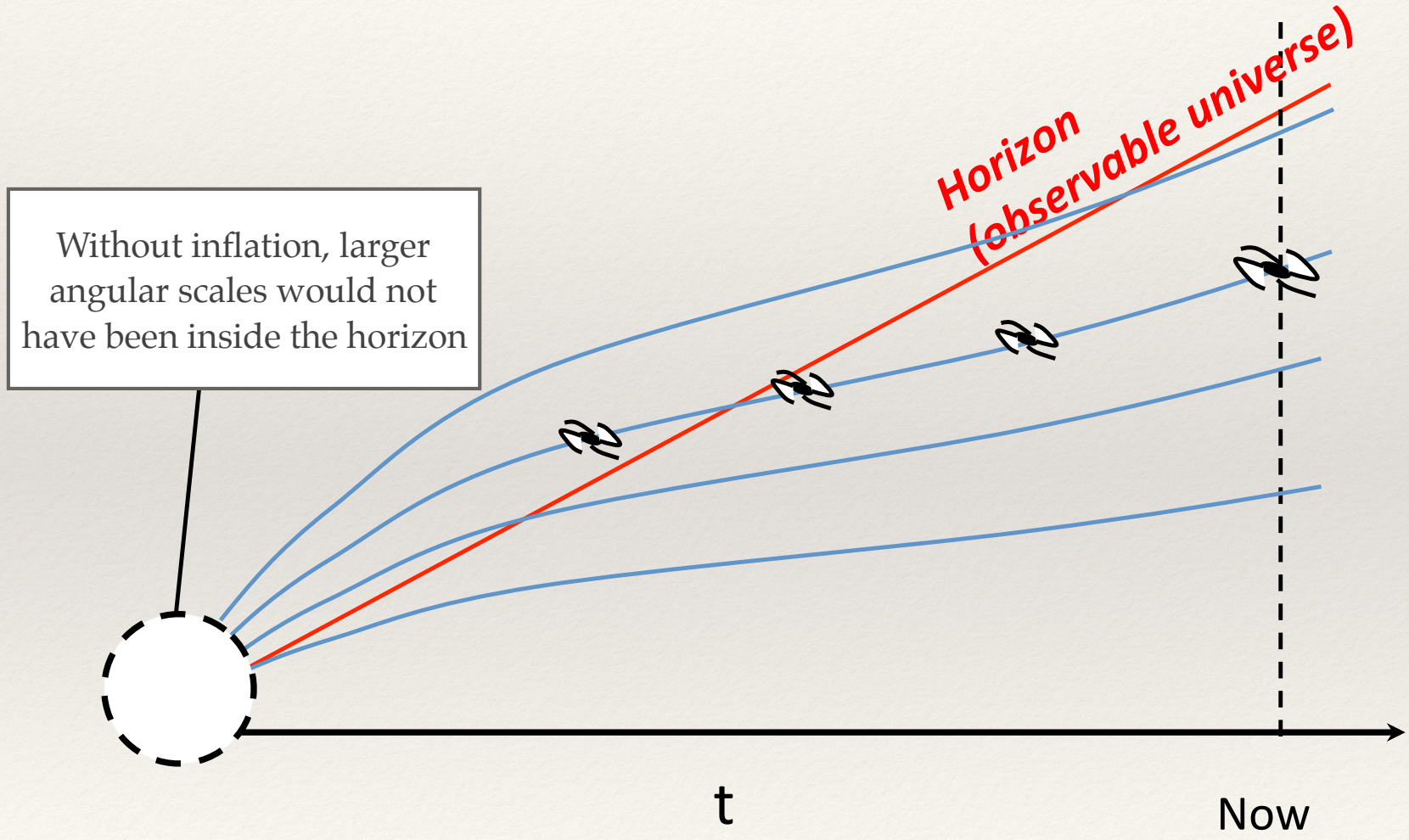
- Inflation and CMB polarization
- Delensing with SPTPol; Understanding Delensing Efficiency
- BICEP/Keck; BICEP3 noise improvements
- Future with CMB-S4

Inflation

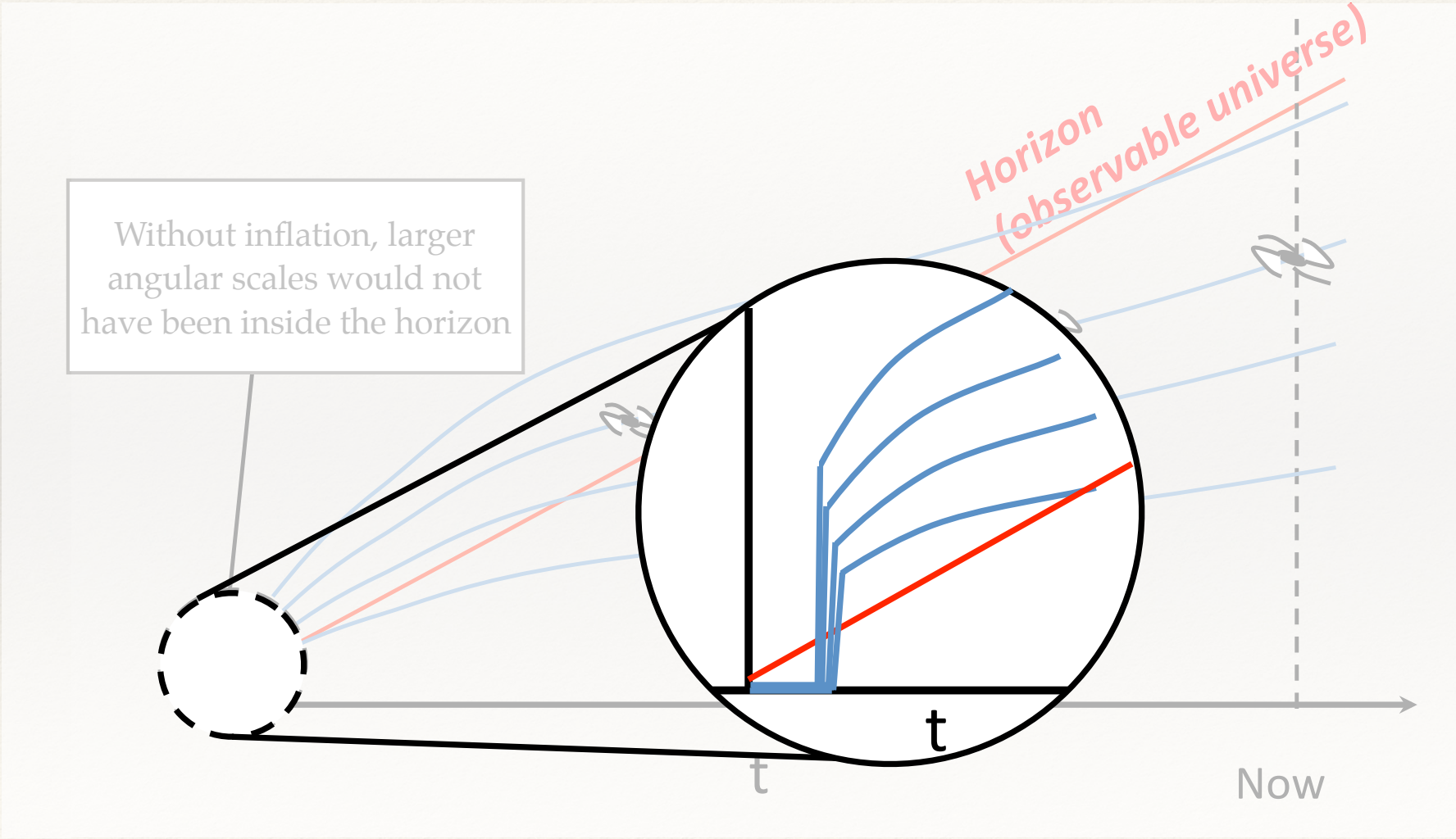


- near-exponential expansion within a fraction of a second
- solves conceptual problems with hot big bang

Horizon problem



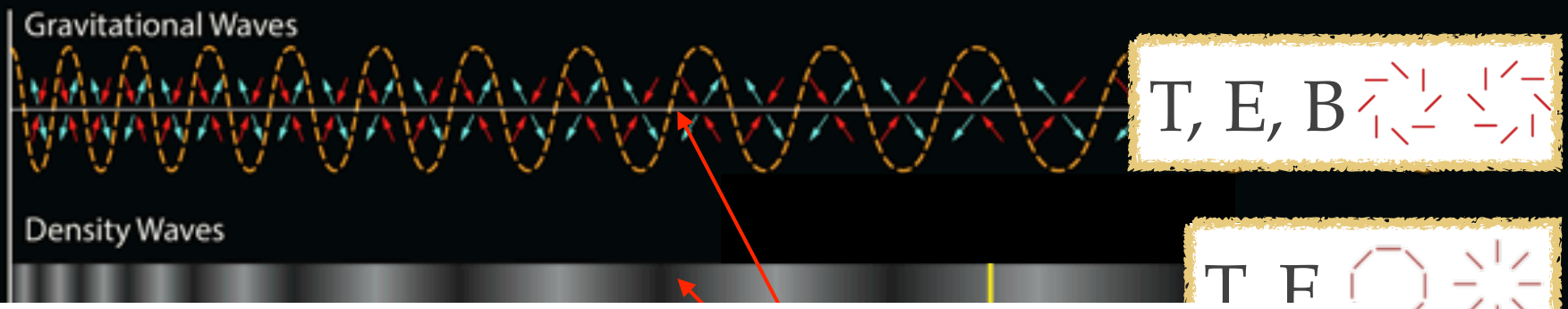
Inflation solves the Horizon problem



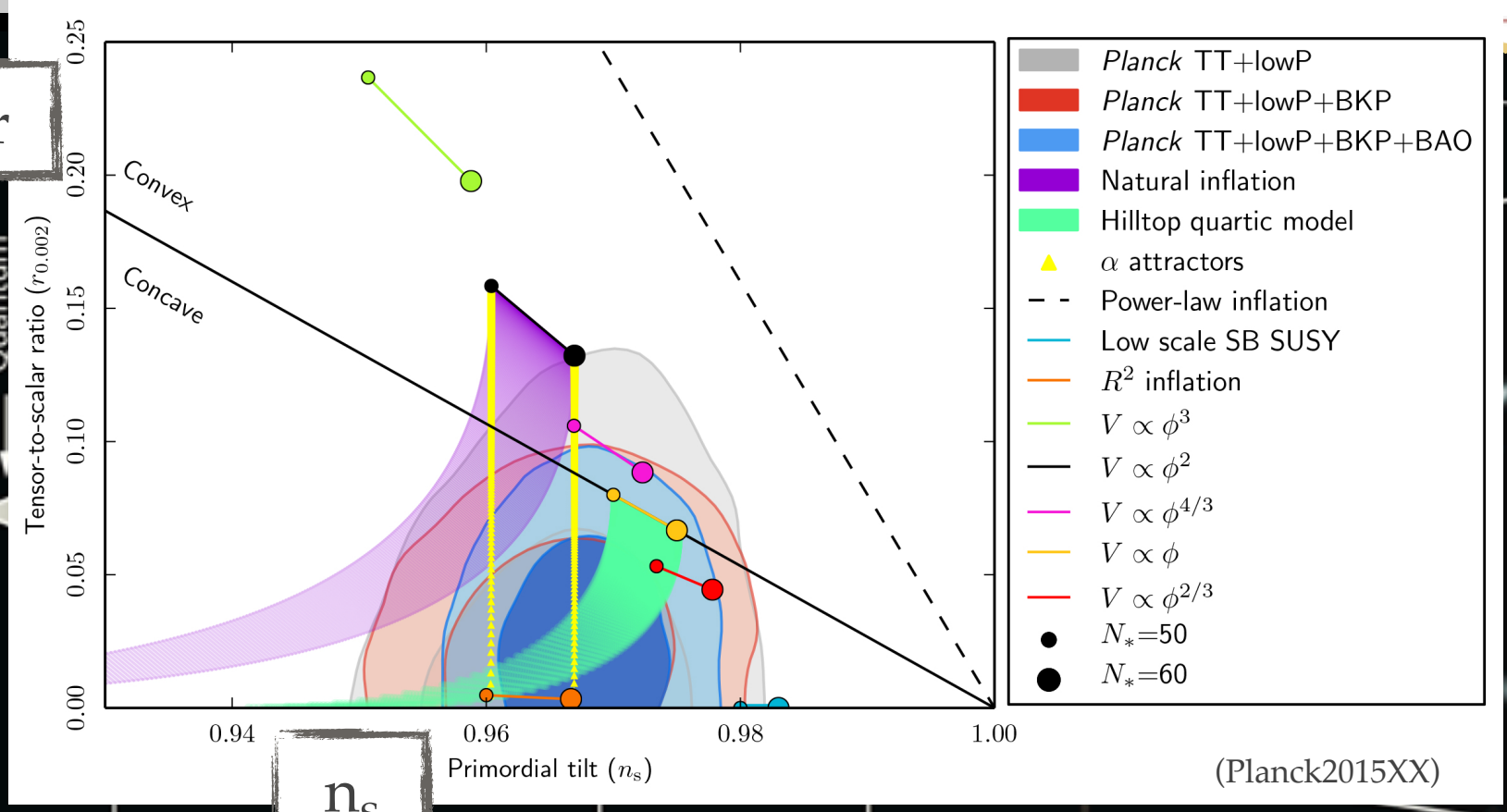
Observational Signatures of Inflation

tensor perturbations

scalar perturbations



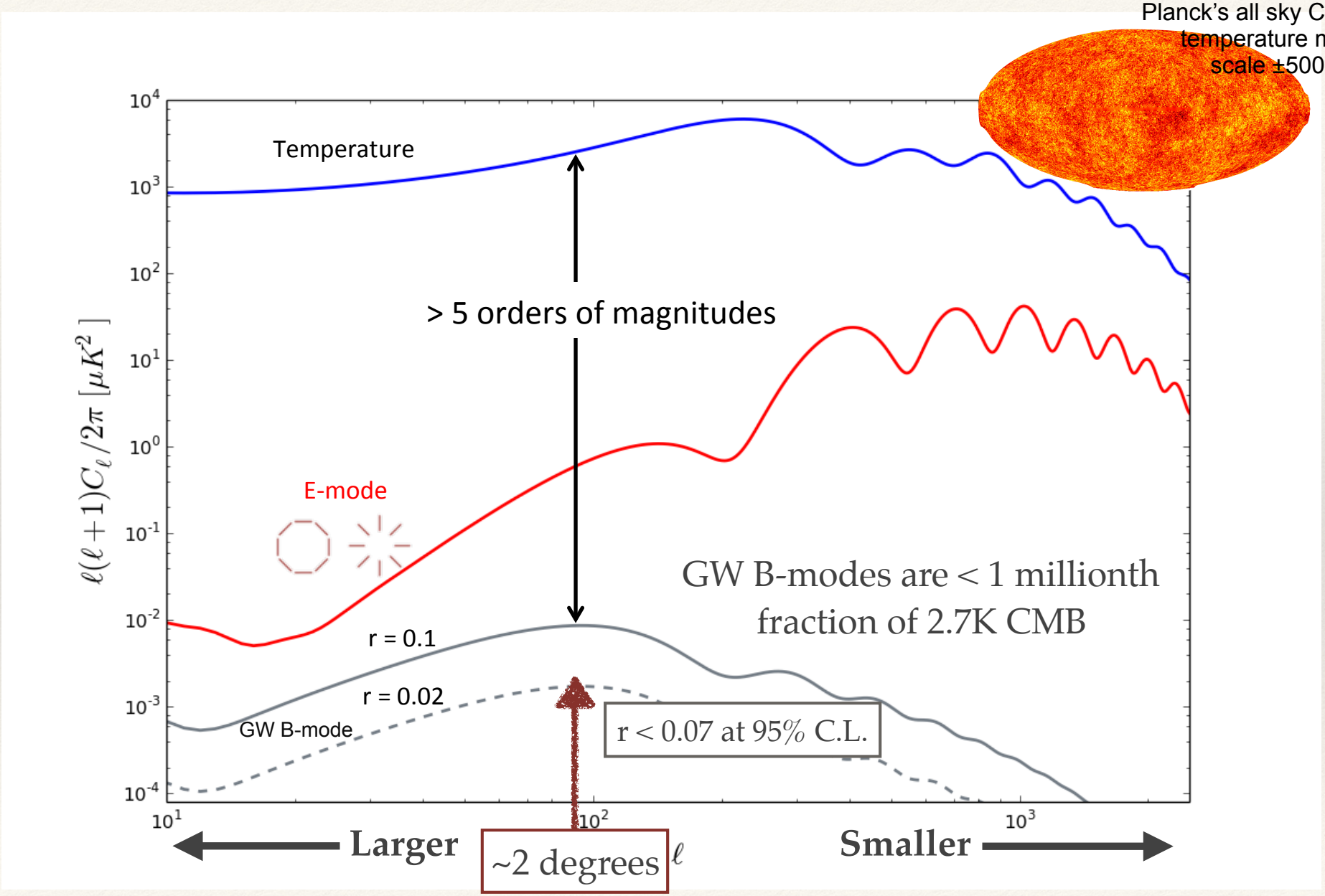
r



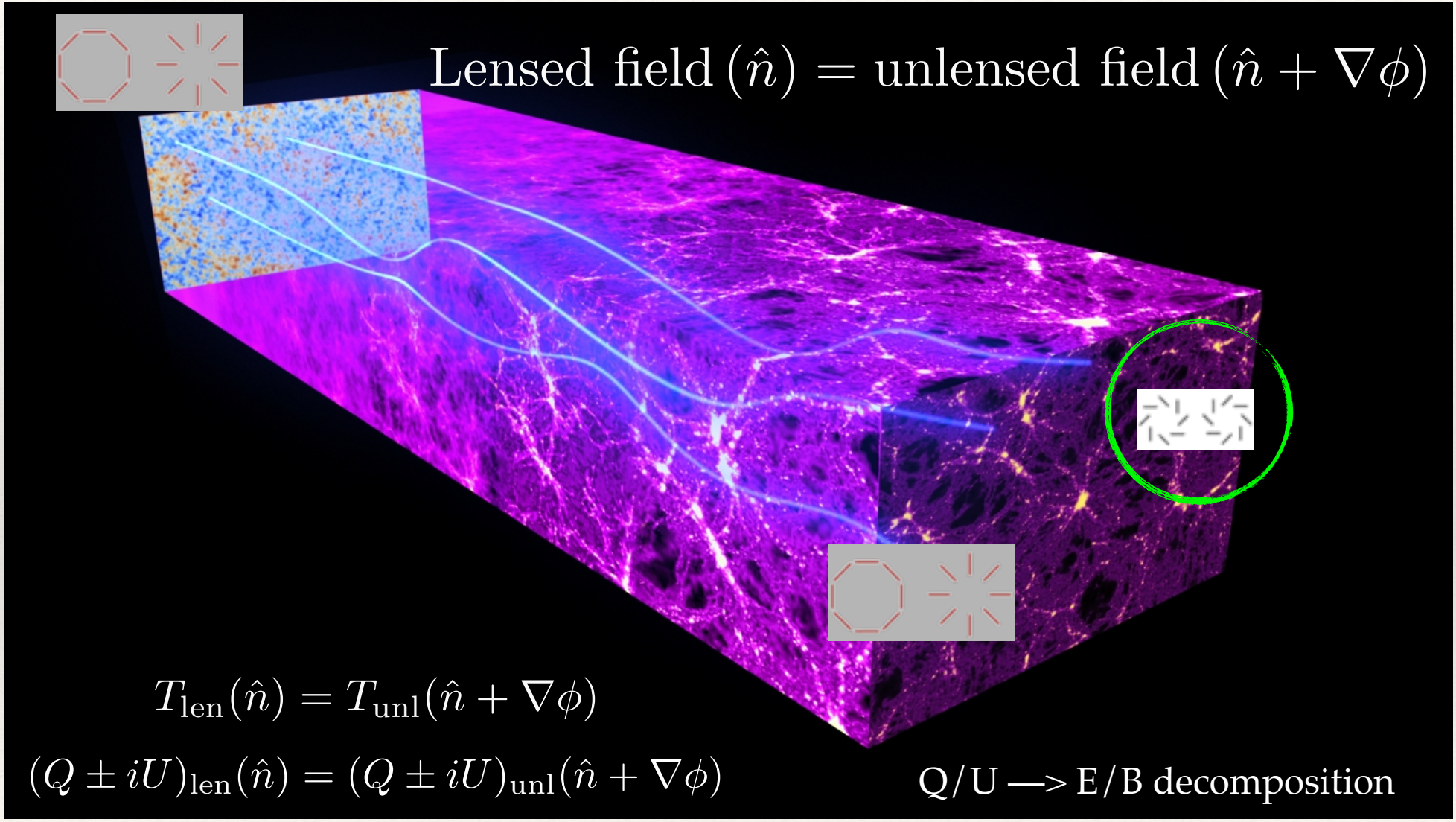
n_S

(Planck2015XX)

CMB spectra

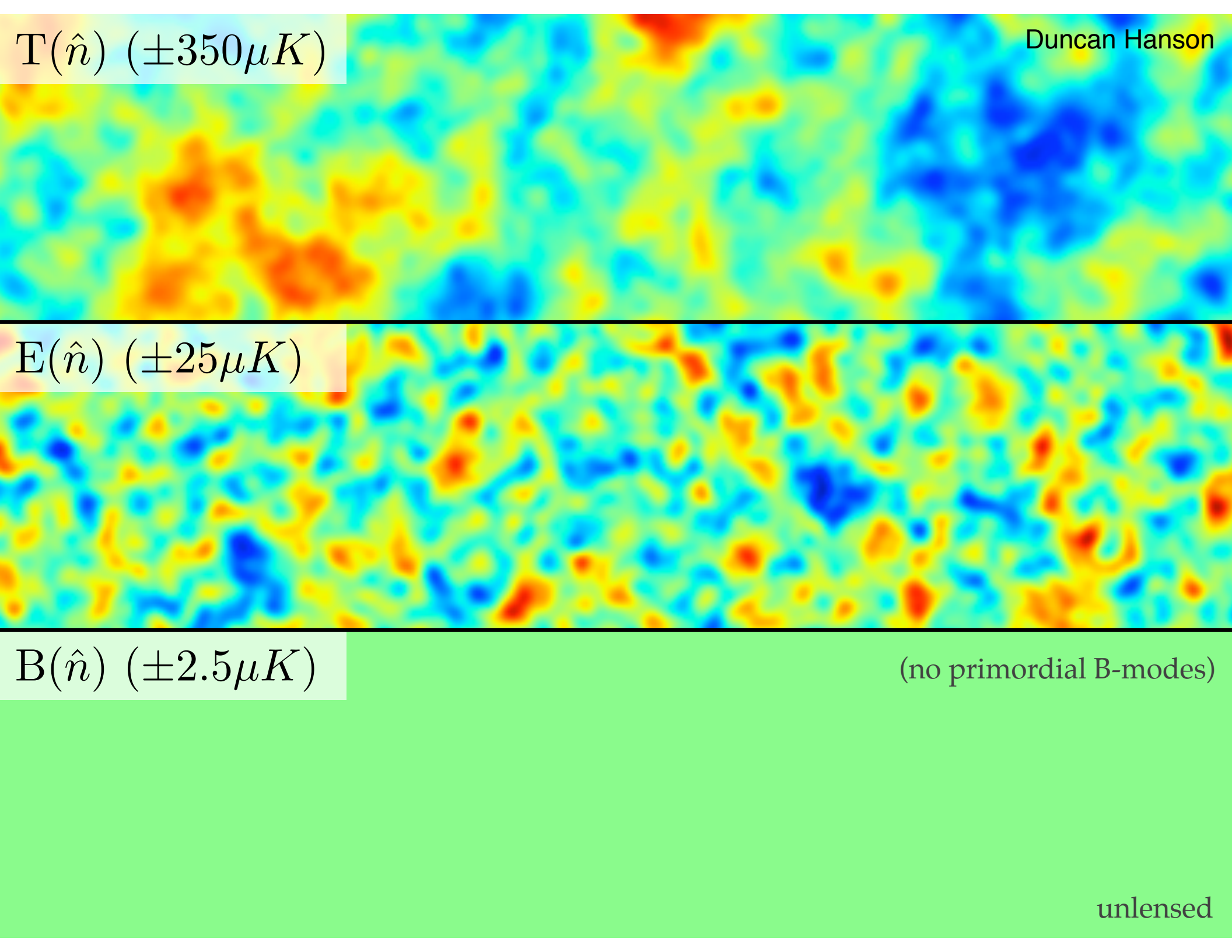

Planck's all sky CMB temperature map scale ±500 μK
Temperature
> 5 orders of magnitudes
E-mode
GW B-modes are < 1 millionth fraction of 2.7K CMB
r = 0.1
r = 0.02
GW B-mode
r < 0.07 at 95% C.L.
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3
Larger
~2 degrees
ℓ
Smaller

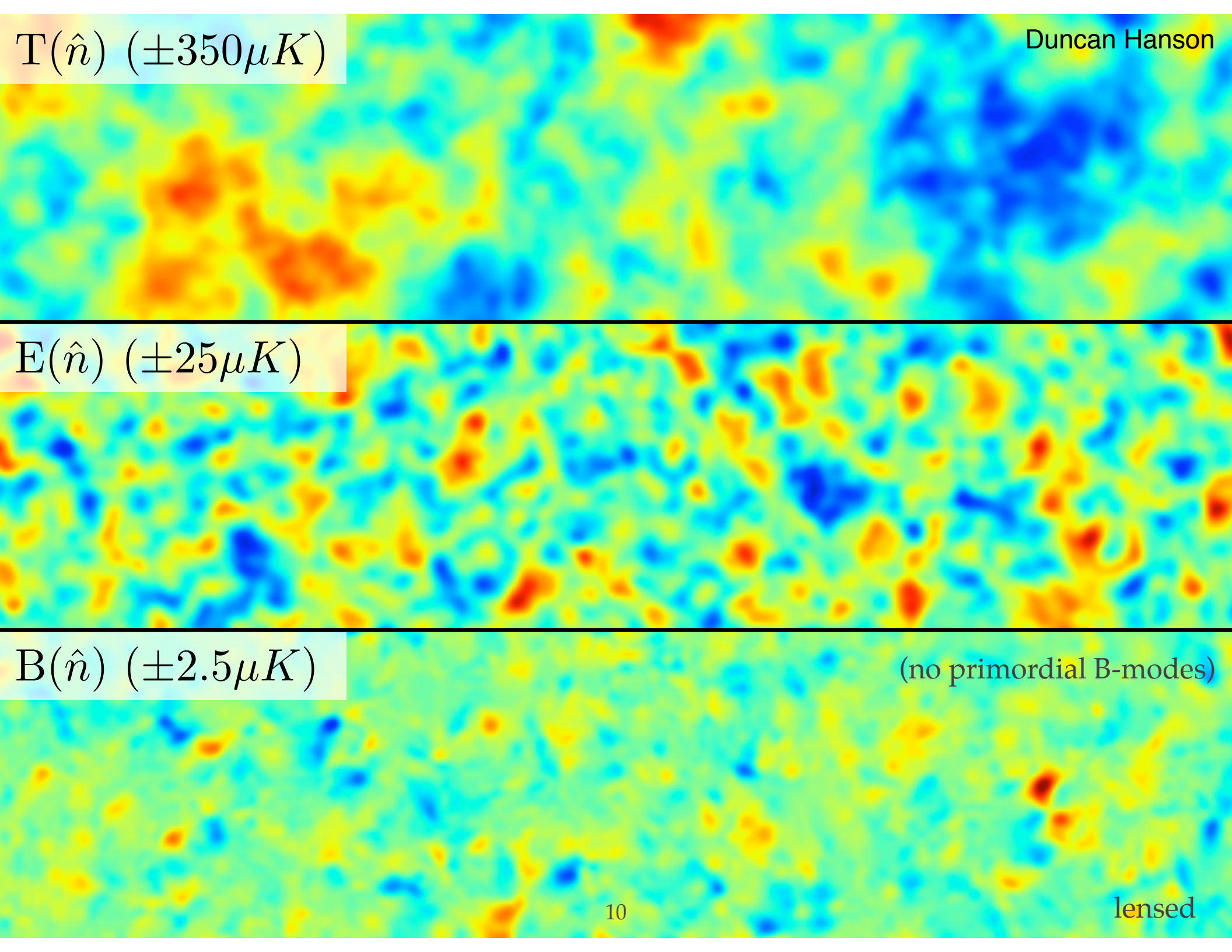
Gravitational lensing: "lensing" B modes



Background image credit: ESA

Zaldarriaga, Seljak astro-ph/9803150
Kamionkowski, Kosowsky, Stebbins, astro-ph/9609132


$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$
Duncan Hanson
$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$
$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$
(no primordial B-modes)
unlensed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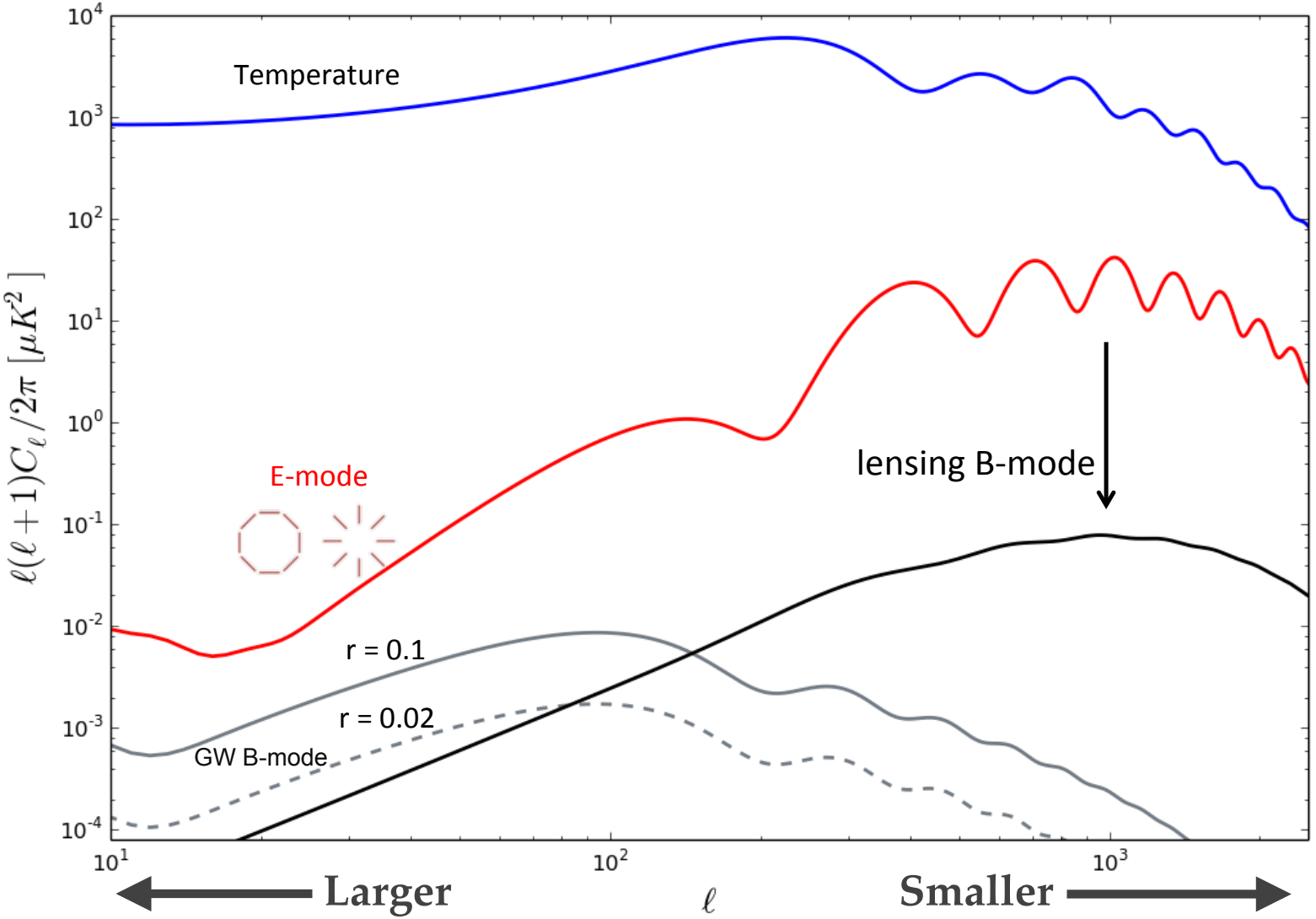
lensed

CMB spectra


Temperature
E-mode
lensing B-mode
r = 0.1
r = 0.02
GW B-mode
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^4
10^3
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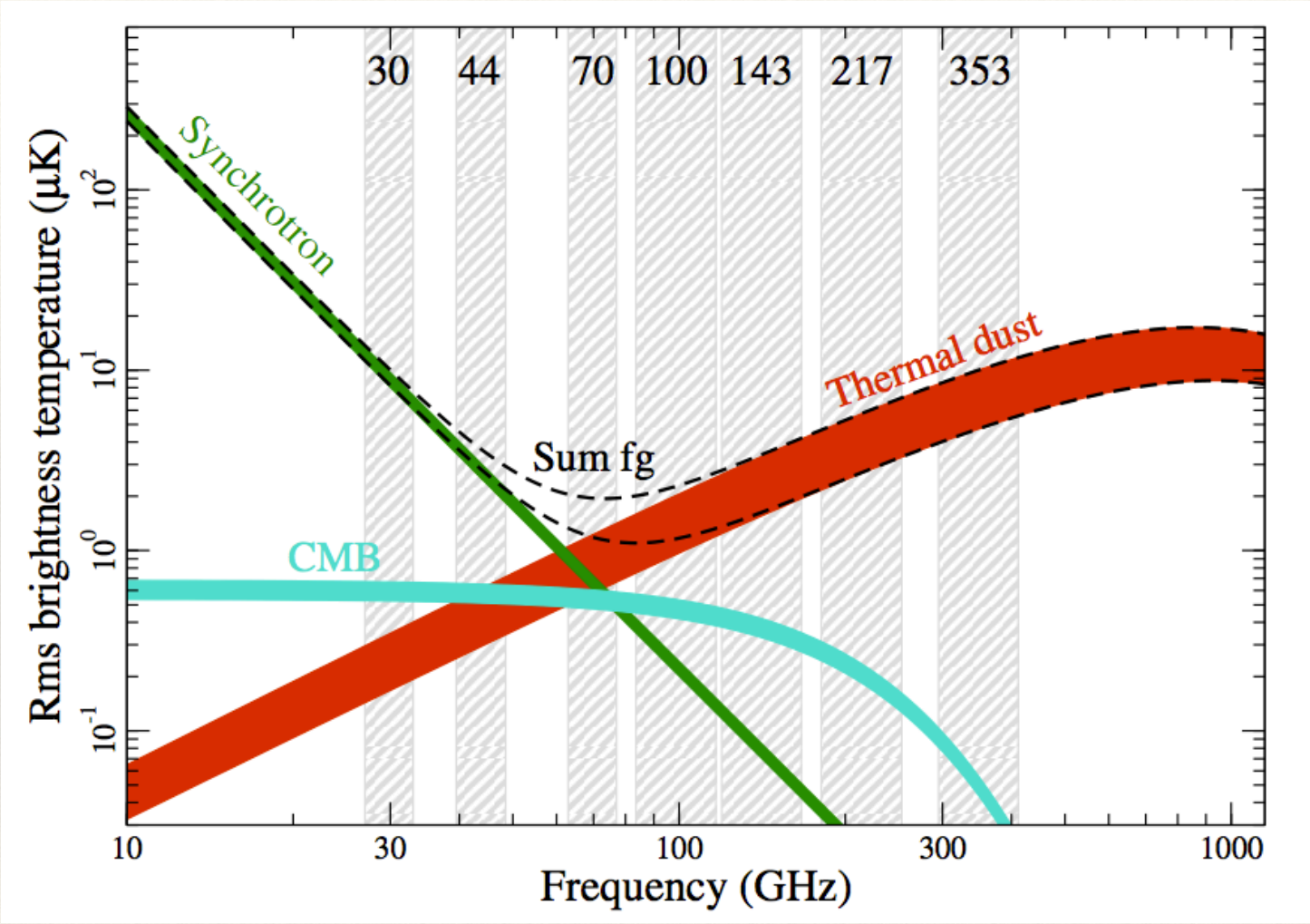
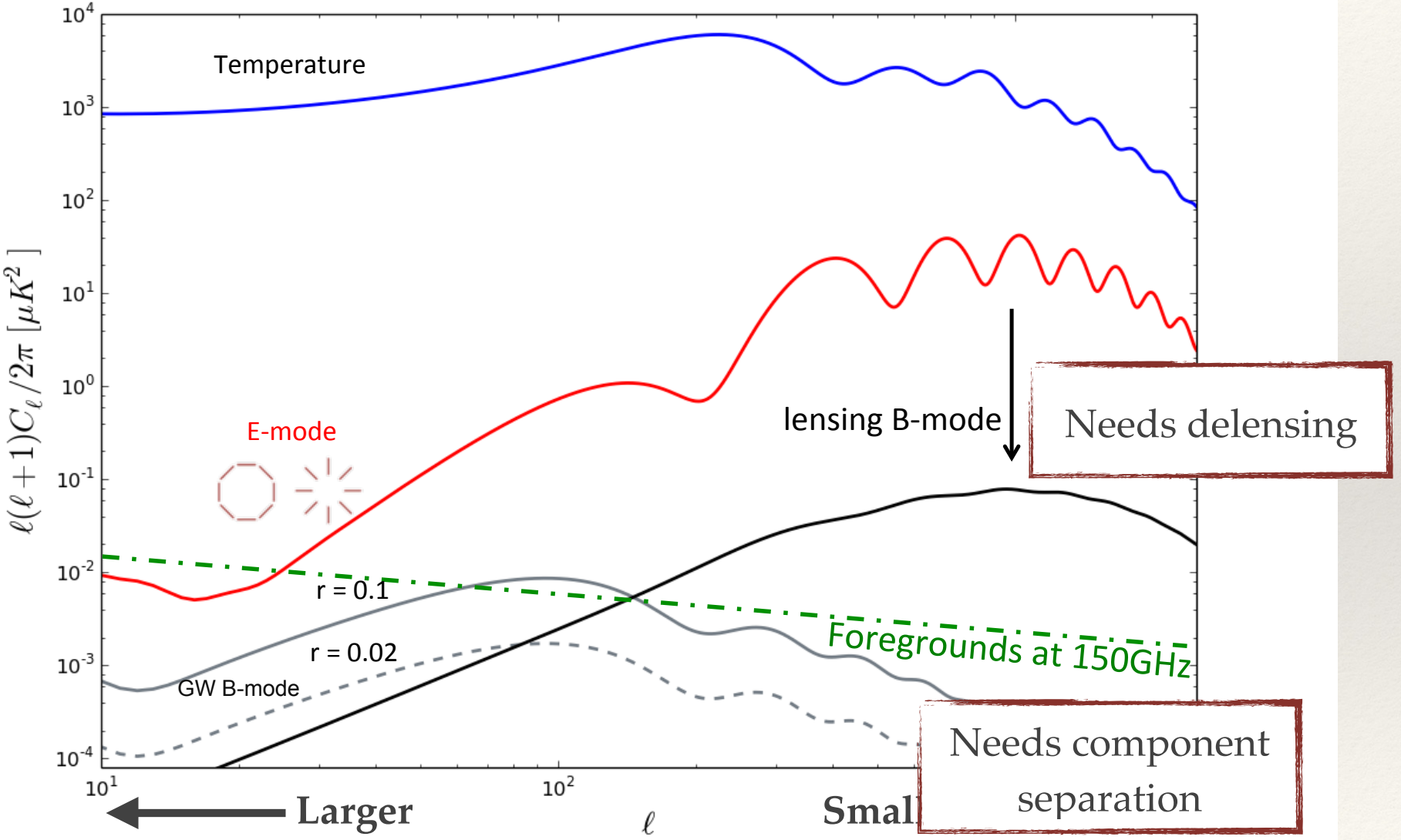
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3
Larger
ℓ
Smaller

Polarized foregrounds



73% - 93% of sky; Planck 2015 X

CMB spectra + foregrounds



Take away 1:

Lensing and component separation needed to constraint r, strong evidence for inflation

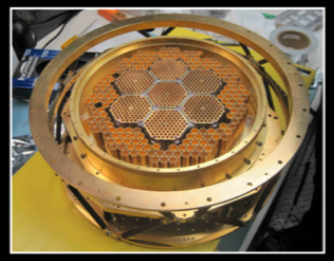
Outline

- Inflation and CMB polarization
- Delensing with SPTPol; Understanding Delensing Efficiency
- BICEP/Keck: BICEP3 noise improvements
- Future with CMB-S4

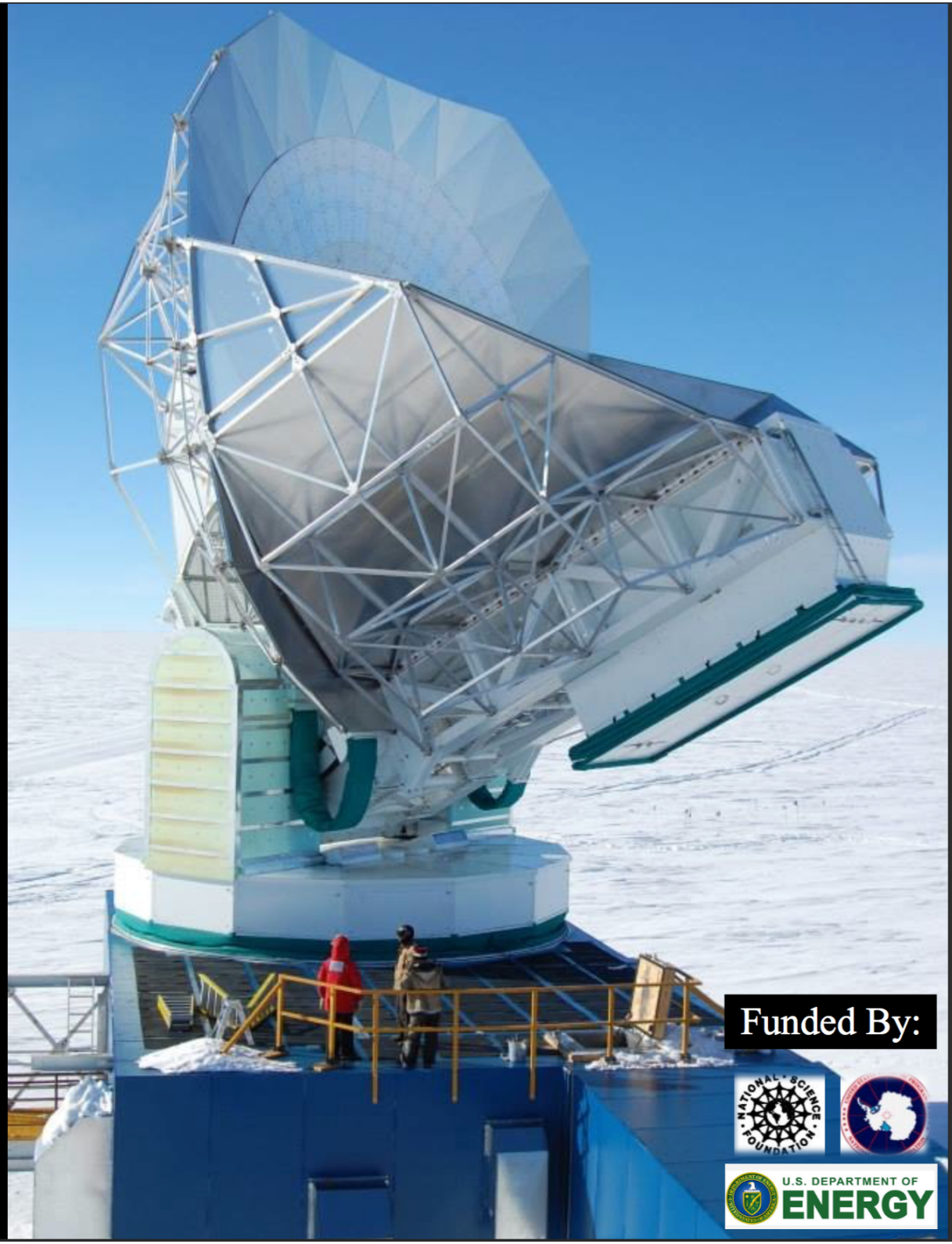
The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

2012: SPTpol
1600 detectors
95,150 GHz
+Polarization

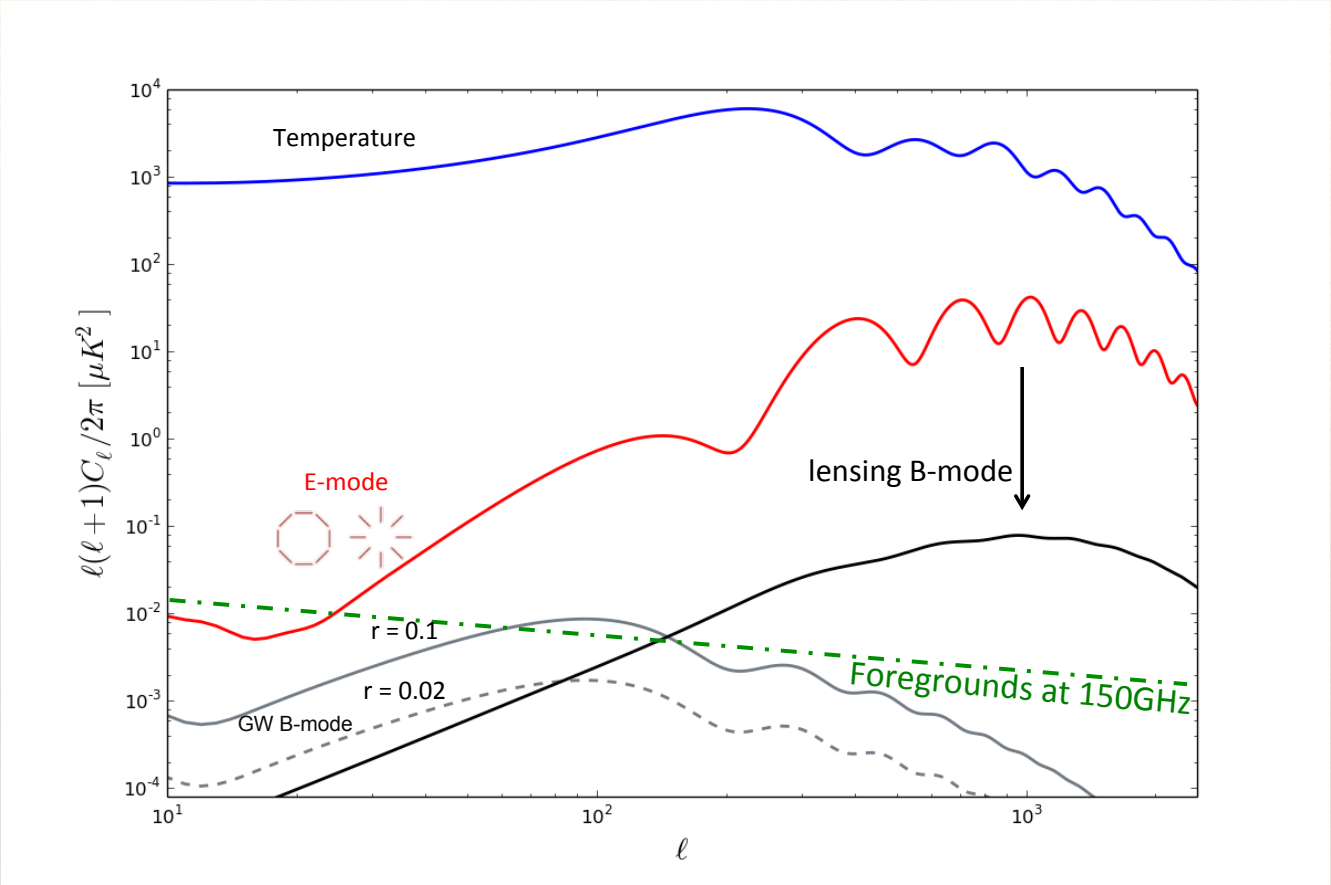


Collaborators:
Alessandro Manzotti, Kyle Story
+ SPTpol collaboration



Funded By:
NATIONAL SCIENCE FOUNDATION
U.S. DEPARTMENT OF ENERGY

Why delensing?



- Besides galactic foregrounds, lensing is a source of confusion for measuring r
- We can fit lensing model + *r* simultaneously, but limited by sample variance of lensing
- **Delensing** B-modes: subtracting the ***realization-specific*** lensing B-mode sky to reduce lensing sample variance

Delensing: the idea

1. Use Phi to lens E-mode map to get expected lensing B

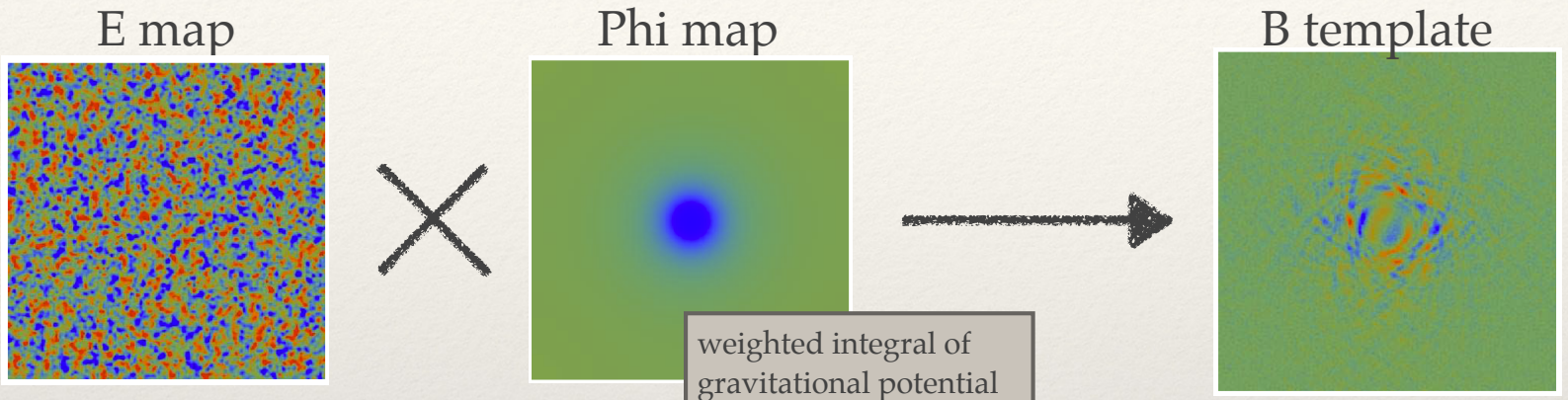
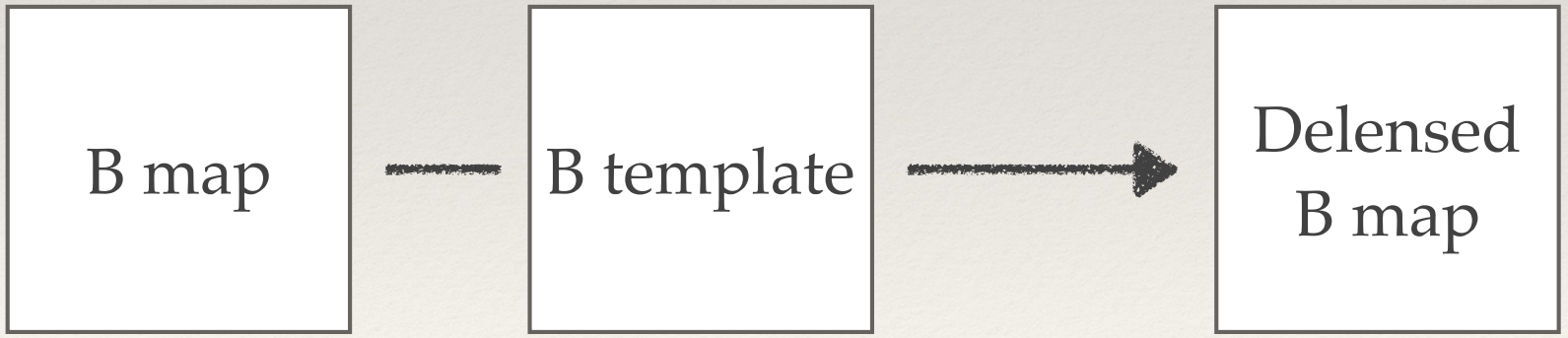


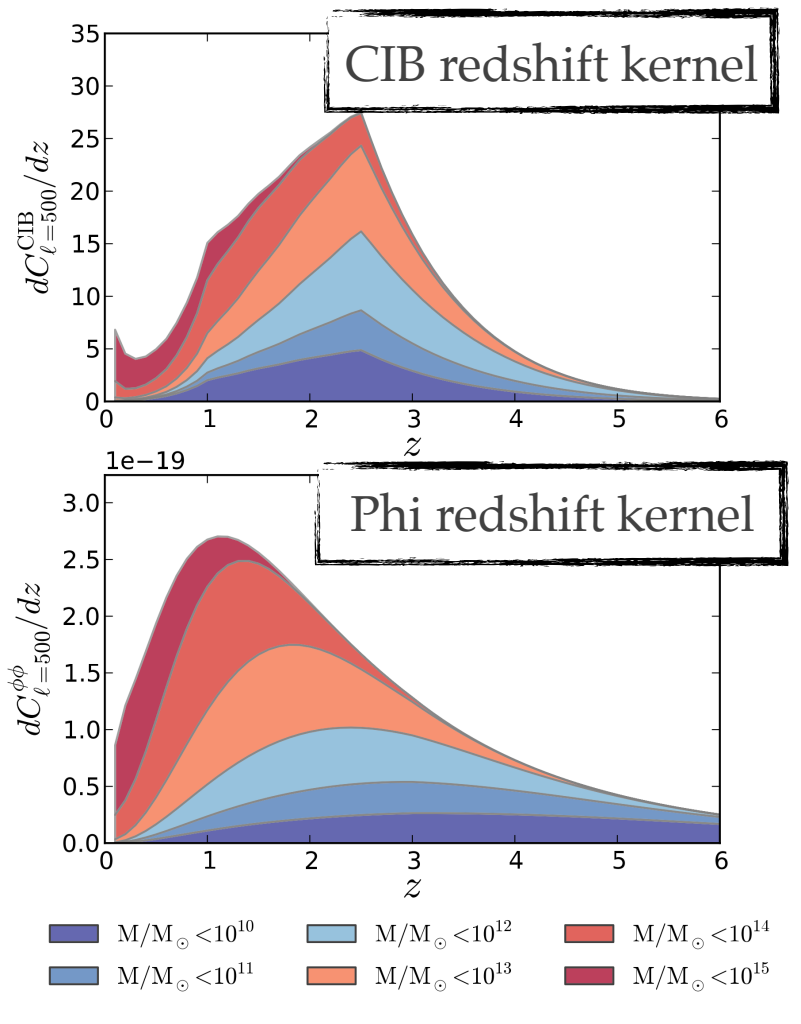
Image credit: Hu & Okamoto (2002)

2. Subtract B template from B map



CIB as a Phi tracer

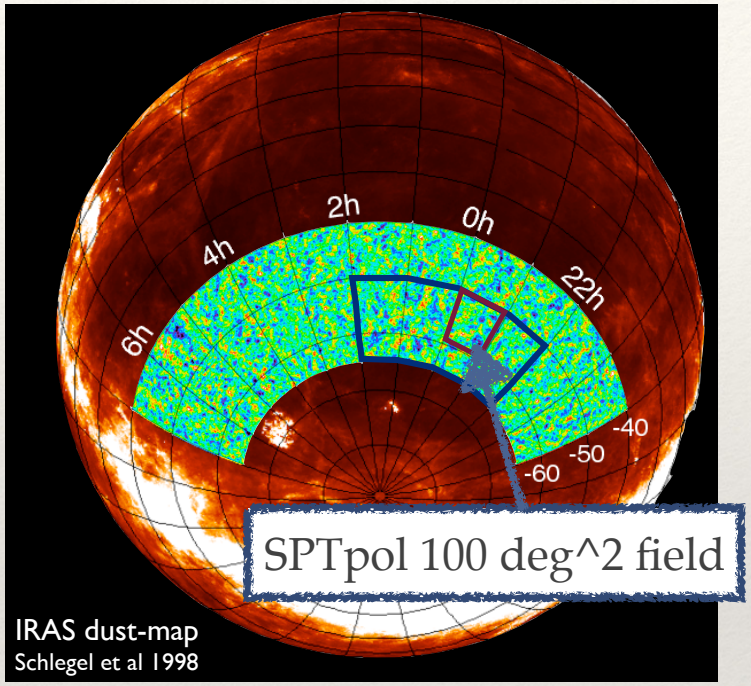
- Phi: can reconstruct from CMB, but S/N rather low currently (Future will be better!)
- Cosmic infrared background (CIB) from dusty star-forming dusty galaxies with redshift distribution peaked between z~1 and 2.
- CMB lensing potential's redshift kernel peaks between $1 < z < 3$
- Cross-correlation can be as high as ~80%
- Used for first detection of lensing B-modes through cross-correlations (Hanson et al. 2013); first delensing of CMB temperature anisotropies (Larson et al. 2016)



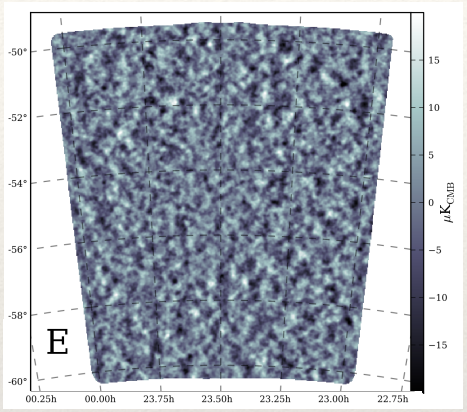
Planck 2013 XVIII

Lensing B template to delens SPTpol B modes

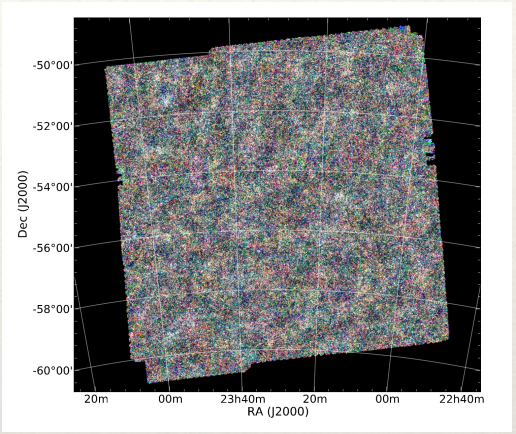
Inputs to form the B template



E-mode measurement
(Crites et al., SPT 2015)

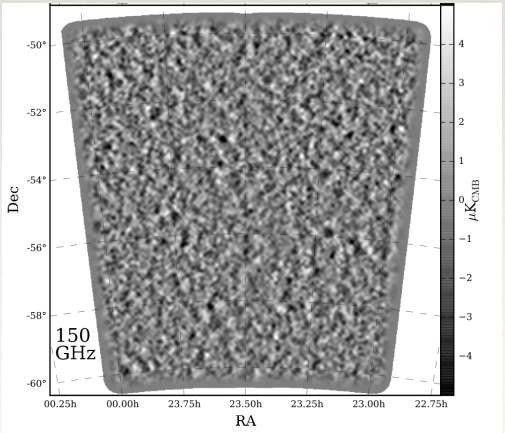


CIB map from Herschel 500μm map

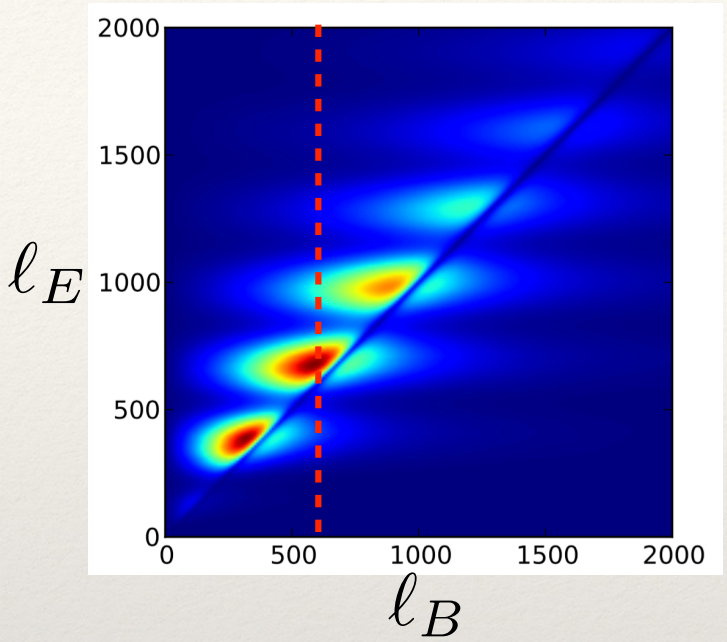


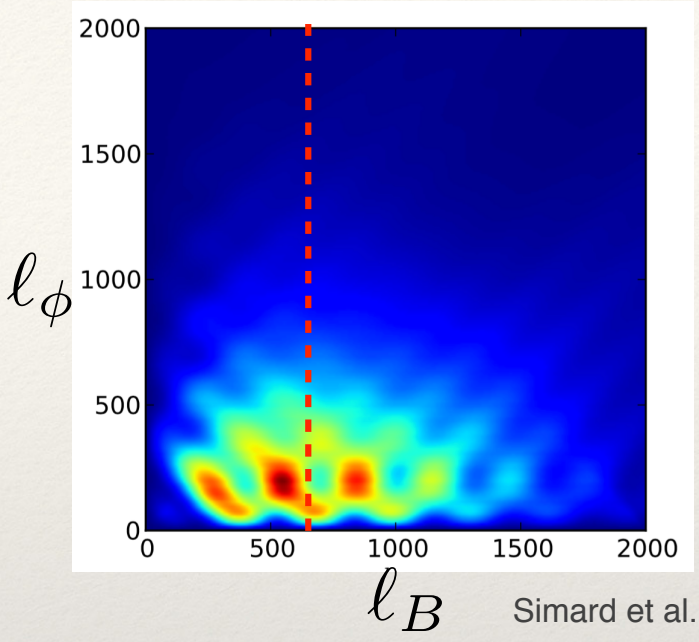
B-mode map to be delensed

(Keisler et al., SPT 2015)



Forming the B template: I



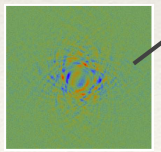


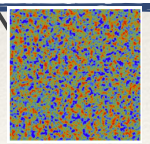
Simard et al. 2014 (1401.0691)

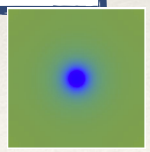
Lensing B modes to first order in Phi has the form*

$$B^{\rm lens}(\boldsymbol{\ell}) = \int \frac{d^2\boldsymbol{\ell}'}{(2\pi)^2} W(\boldsymbol{\ell},\boldsymbol{\ell}') E(\boldsymbol{\ell}') \phi(\boldsymbol{\ell}-\boldsymbol{\ell}')$$

theoretical unlensed E, phi







where weight function

$$W(\boldsymbol{\ell},\boldsymbol{\ell}') = \boldsymbol{\ell}' \cdot (\boldsymbol{\ell}-\boldsymbol{\ell}') \sin(2\varphi_{\boldsymbol{\ell},\boldsymbol{\ell}'}).$$

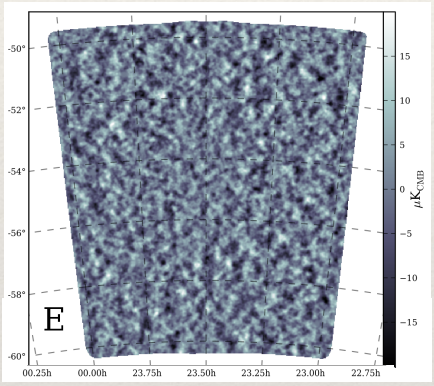
* flat-sky approx.: $\boldsymbol{\ell} = 2\pi|\boldsymbol{u}|$, u is Fourier mode.

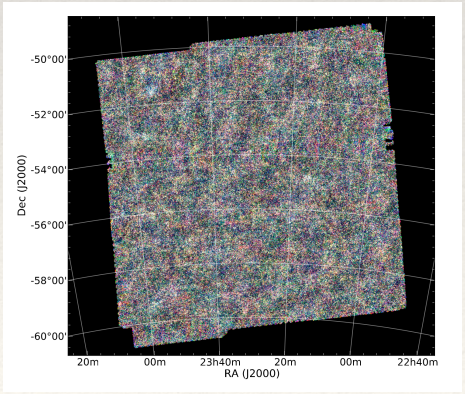
Forming the B template: II

So we can build a B template by replacing theory E/Phi with measured+filtered E/Phi

$$\hat{B}^{\rm lens}(\boldsymbol{\ell}) = \int \frac{d^2\boldsymbol{\ell}'}{(2\pi)^2} W(\boldsymbol{\ell},\boldsymbol{\ell}')\bar{E}(\boldsymbol{\ell}')\hat{\phi}(\boldsymbol{\ell}-\boldsymbol{\ell}')$$

Input maps





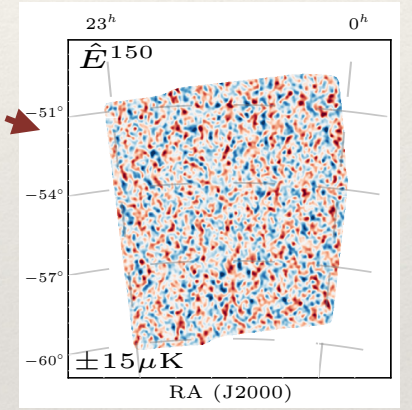
Filtering

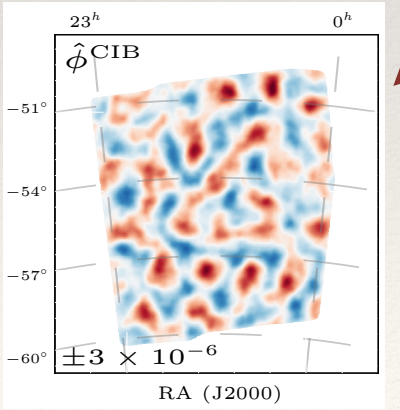
$$\bar{E}(\boldsymbol{\ell}) \approx \left(\frac{C_\ell^{EE}}{C_\ell^{EE}+N_\ell^{EE}}\right) E^N(\boldsymbol{\ell})$$

$$\hat{\phi}^{\rm CIB}_{\boldsymbol{\ell}} = \left(\frac{C_l^{\rm CIB\text{-}\phi}}{C_l^{\rm CIB\text{-}CIB}}\right) I^{\rm CIB}(\boldsymbol{\ell})$$

filters chosen to minimize residual variance

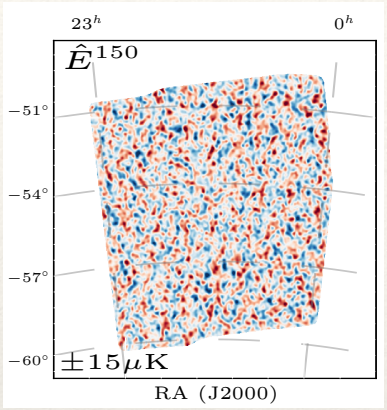
Filtered maps



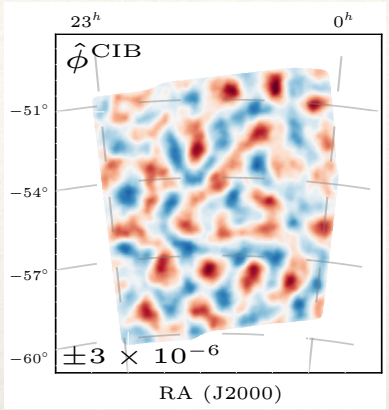


Delens

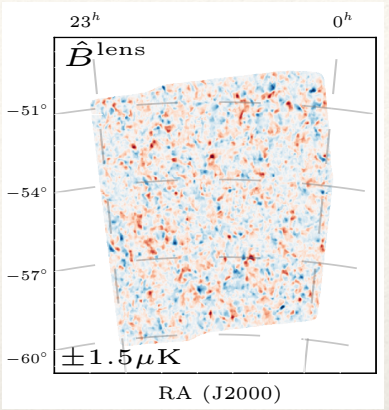
filtered E map



filtered Phi estimate

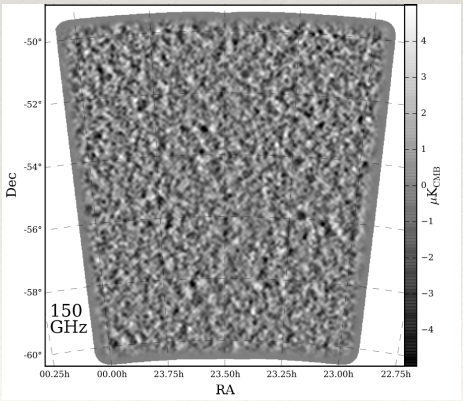


B template

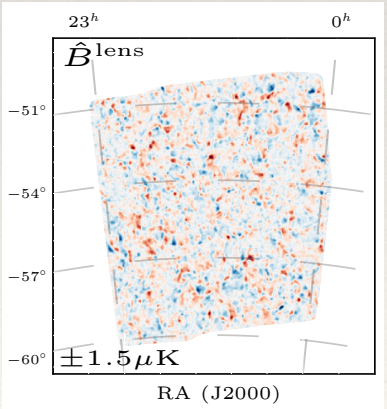


To ensure 'fair subtraction', apply 2D transfer function on the B template before subtracting from B mode map

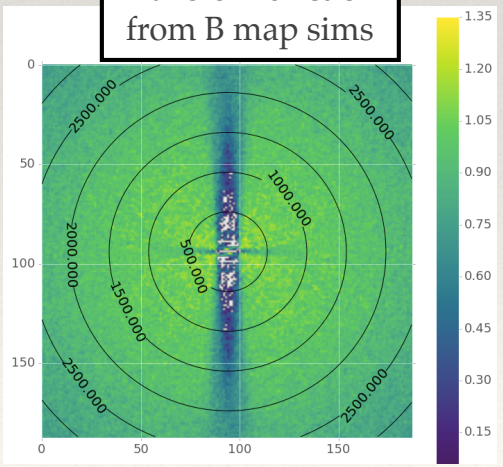
B map



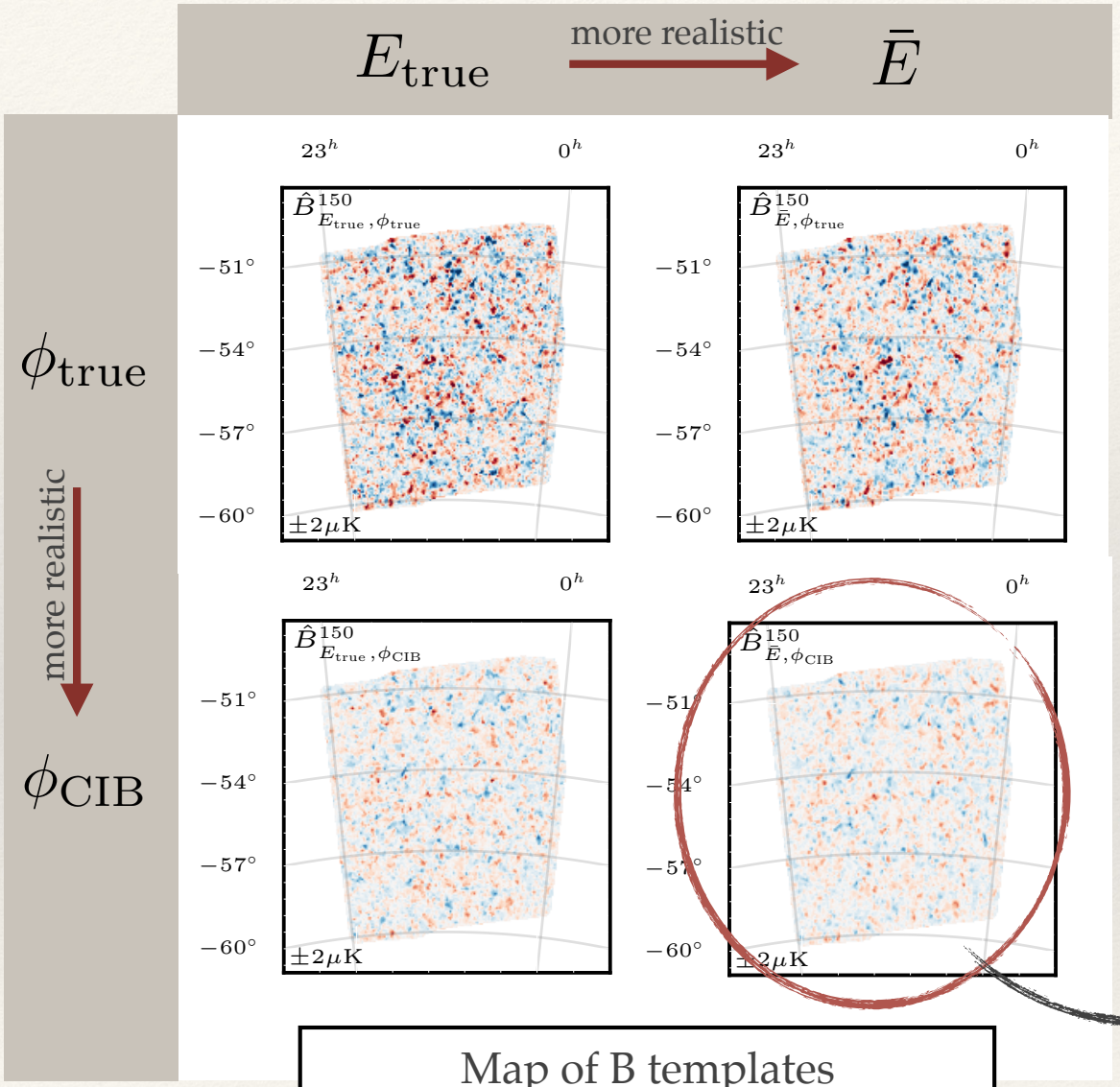
B template

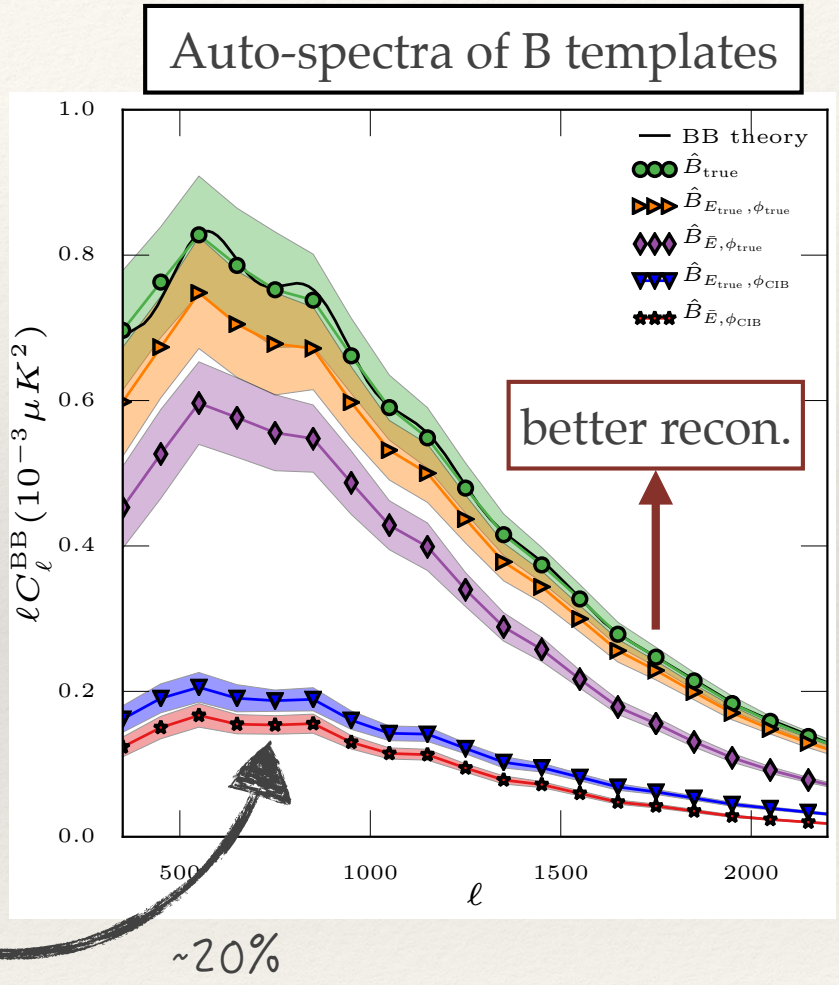


Transfer Function from B map sims

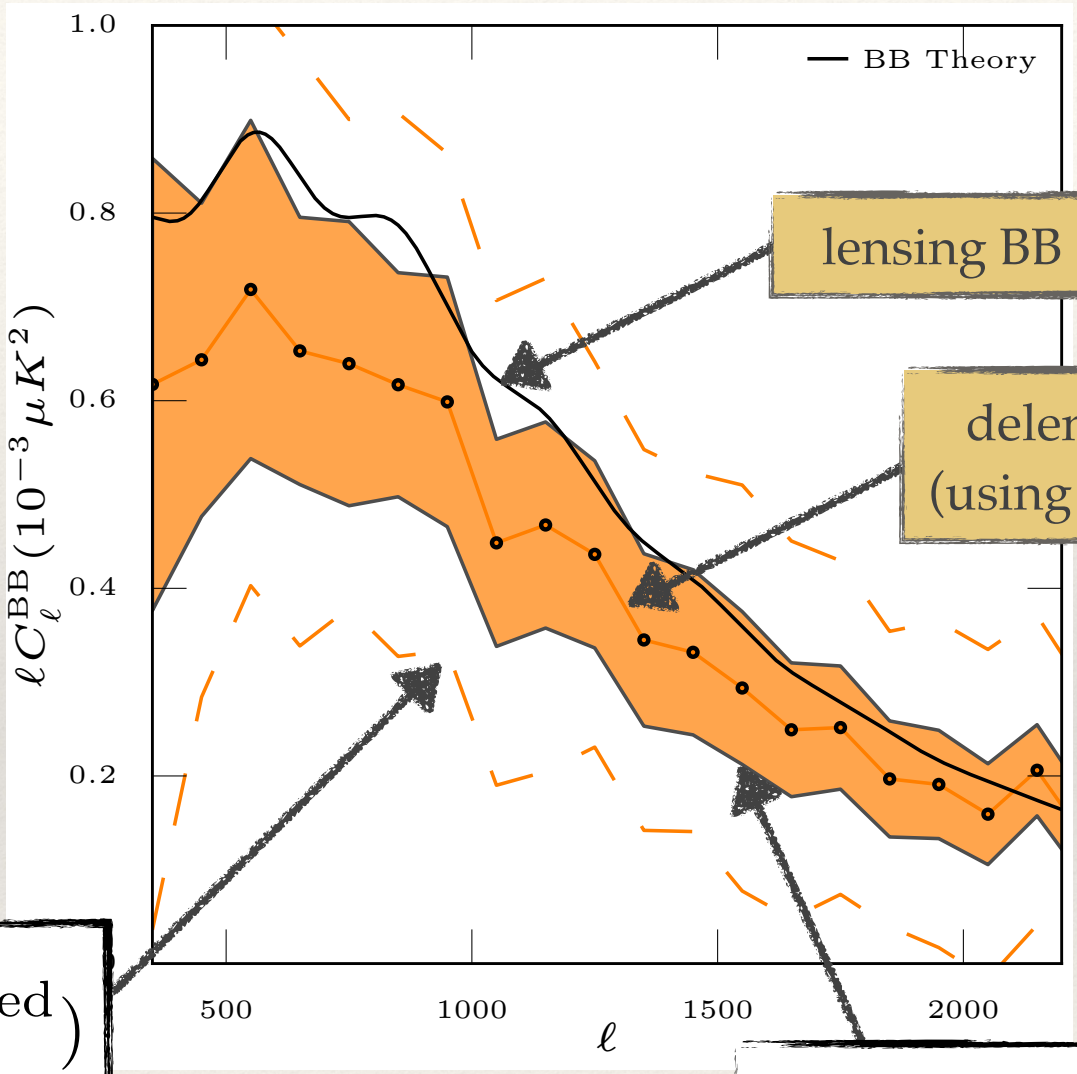


How well we reconstruct lensing B-modes → how well we delens





Now we subtract B template from B map in simulations



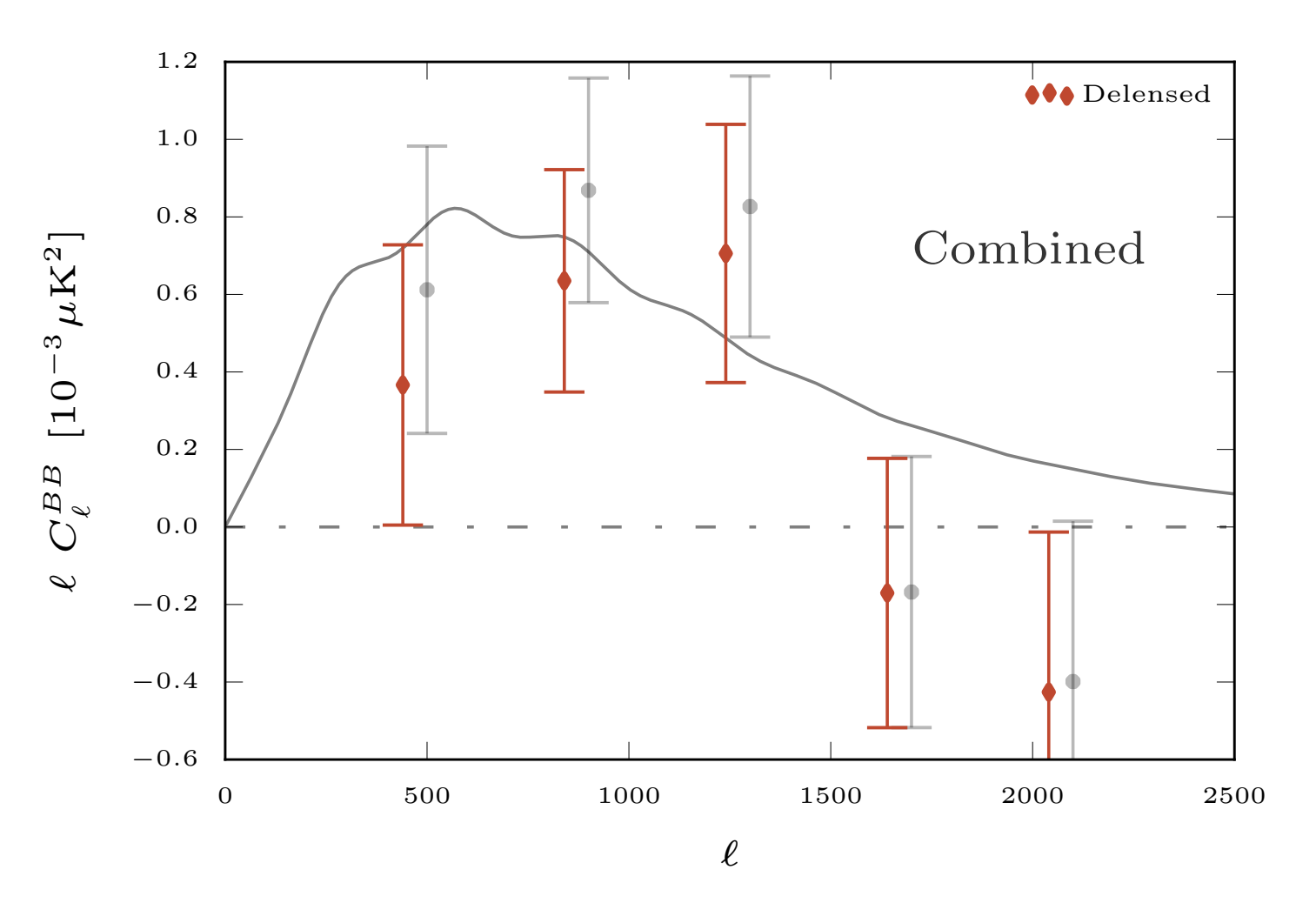
lensing BB

delensed BB (using $\bar{E}, \phi_{\rm CIB}$)

$\sigma(C_\ell^{\rm BB,delensed})$

$\sigma(C_\ell^{\rm BB} - C_\ell^{\rm BB,delensed})$

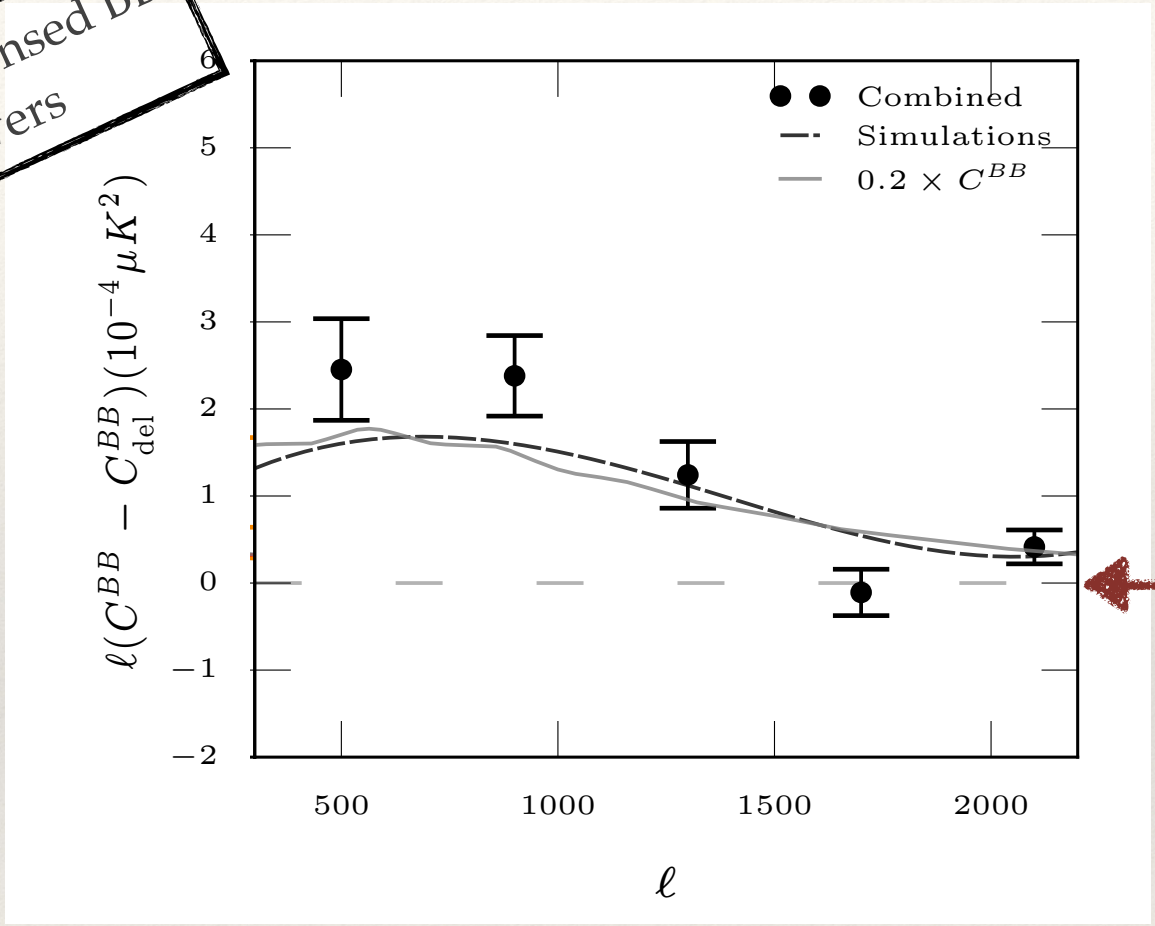
Delensed SPTpol BB spectrum



Remove ~28% of BB bandpowers
(consistent with expectations from simulations)

Difference spectrum: test no delensing

lensing BB - delensed BB bandpowers



zero,
if no delensing

Reject no delensing at 6.9 sigma

Take away 2:
delensing works on B-modes

Understanding delensing efficiency

Delensed BB spectrum:

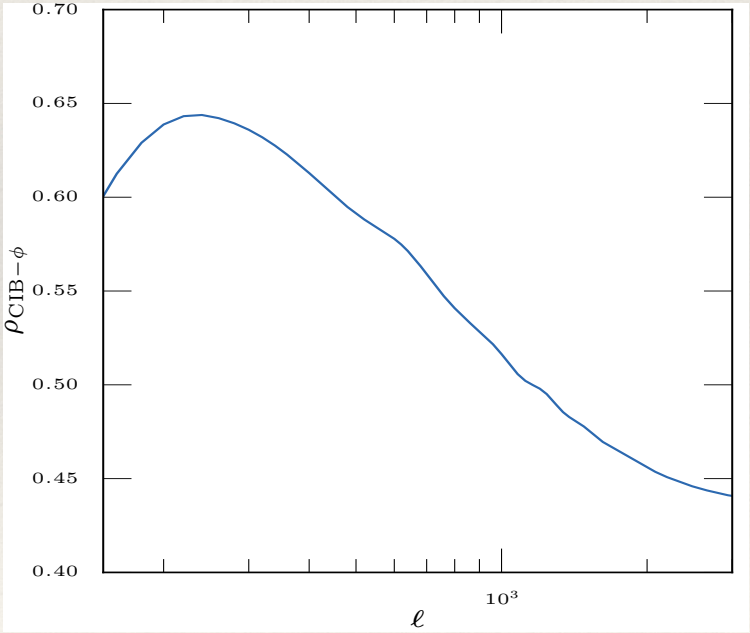
Nominal lensing B

B template part

$$C_\ell^{BB,\mathrm{res}} = \int \frac{d^2\boldsymbol{\ell'}}{(2\pi)^2} W^2(\boldsymbol{\ell},\boldsymbol{\ell'}) C_{\ell'}^{EE} C_{|\boldsymbol{\ell}-\boldsymbol{\ell'}|}^{\phi\phi} \left[1 - \left(\frac{C_{\ell'}^{EE}}{C_{\ell'}^{EE} + N_{\ell'}^{EE}}\right) \rho^2_{|\boldsymbol{\ell}-\boldsymbol{\ell'}|}\right]$$

CIB-phi cross-correlation

$$\rho_\ell = \frac{C_\ell^{\text{CIB-}\phi}}{\sqrt{C_\ell^{\text{CIB-CIB}} C_\ell^{\phi\phi}}}$$



Factors affecting delensing efficiency:

- E noise
- phi 'noise' (decorrelation)
- Non-idealities in E/phi signal

Non-idealities in E, phi signal

Nominal lensing B

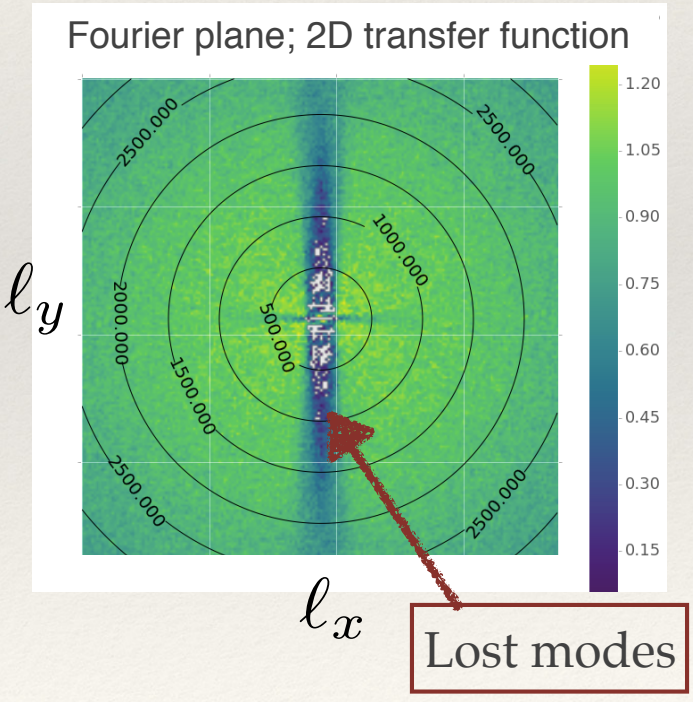
B template part

$$C_\ell^{BB,\mathrm{res}} = \int \frac{d^2\boldsymbol{\ell'}}{(2\pi)^2} W^2(\boldsymbol{\ell},\boldsymbol{\ell'}) C_{\ell'}^{EE} C_{|\boldsymbol{\ell}-\boldsymbol{\ell'}|}^{\phi\phi} \left[1 - \left(\frac{C_{\ell'}^{EE}}{C_{\ell'}^{EE} + N_{\ell'}^{EE}}\right) \rho^2_{|\boldsymbol{\ell}-\boldsymbol{\ell'}|}\right]$$

Not all the modes in E/phi are well-measured

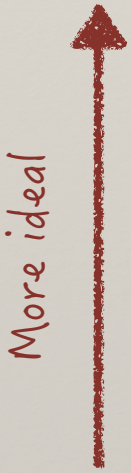
E: Loss of modes due to time-stream filtering; impose $|\ell_x| < 200$ cut on input E map

Phi: cut L < 150 due to galactic dust contamination



Case study: delensing efficiency from E non-idealities

Notations



$E_{\rm true}$ noiseless, unfiltered E map; (LCDM realizations projected)

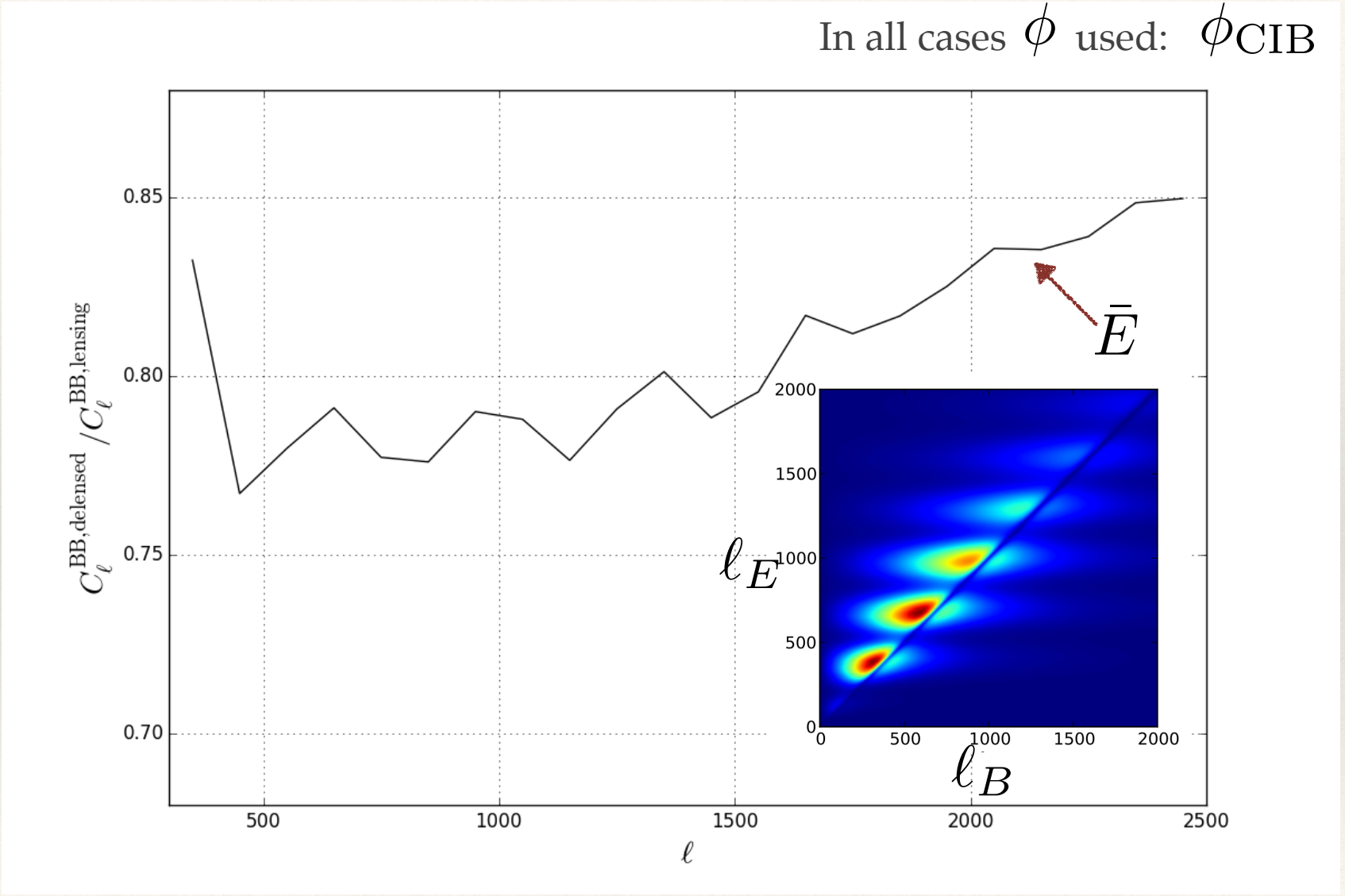
$\bar{E}_{\rm nf}$ noiseless, filtered E map; ($E_{\rm true}$ with mock-observing)

$\bar{E}$ noisy, filtered E map; ($\bar{E}_{\rm nf}$ with noise)

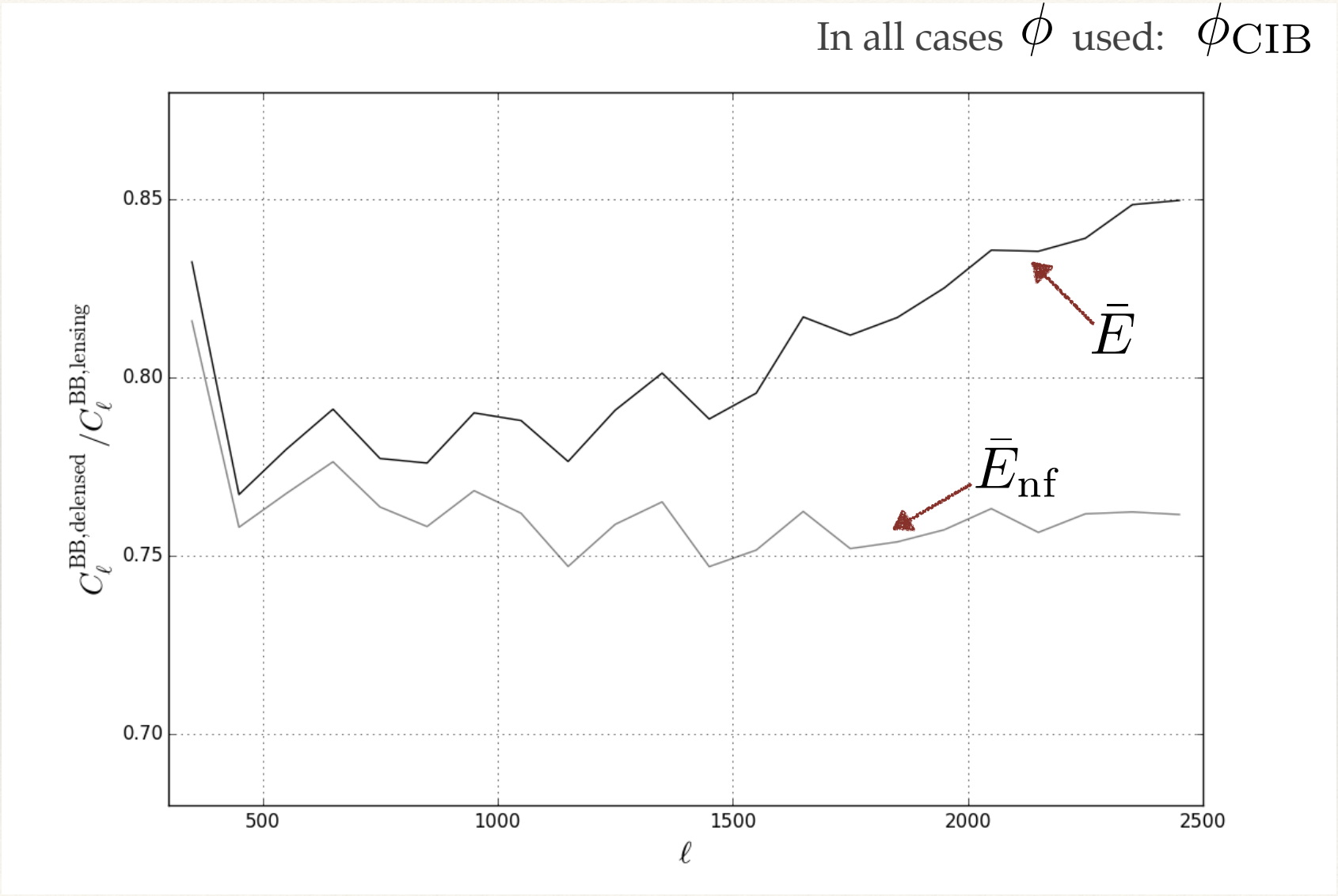
$\phi_{\rm true}$ noiseless phi

$\phi_{\rm CIB}$ CIB estimated phi

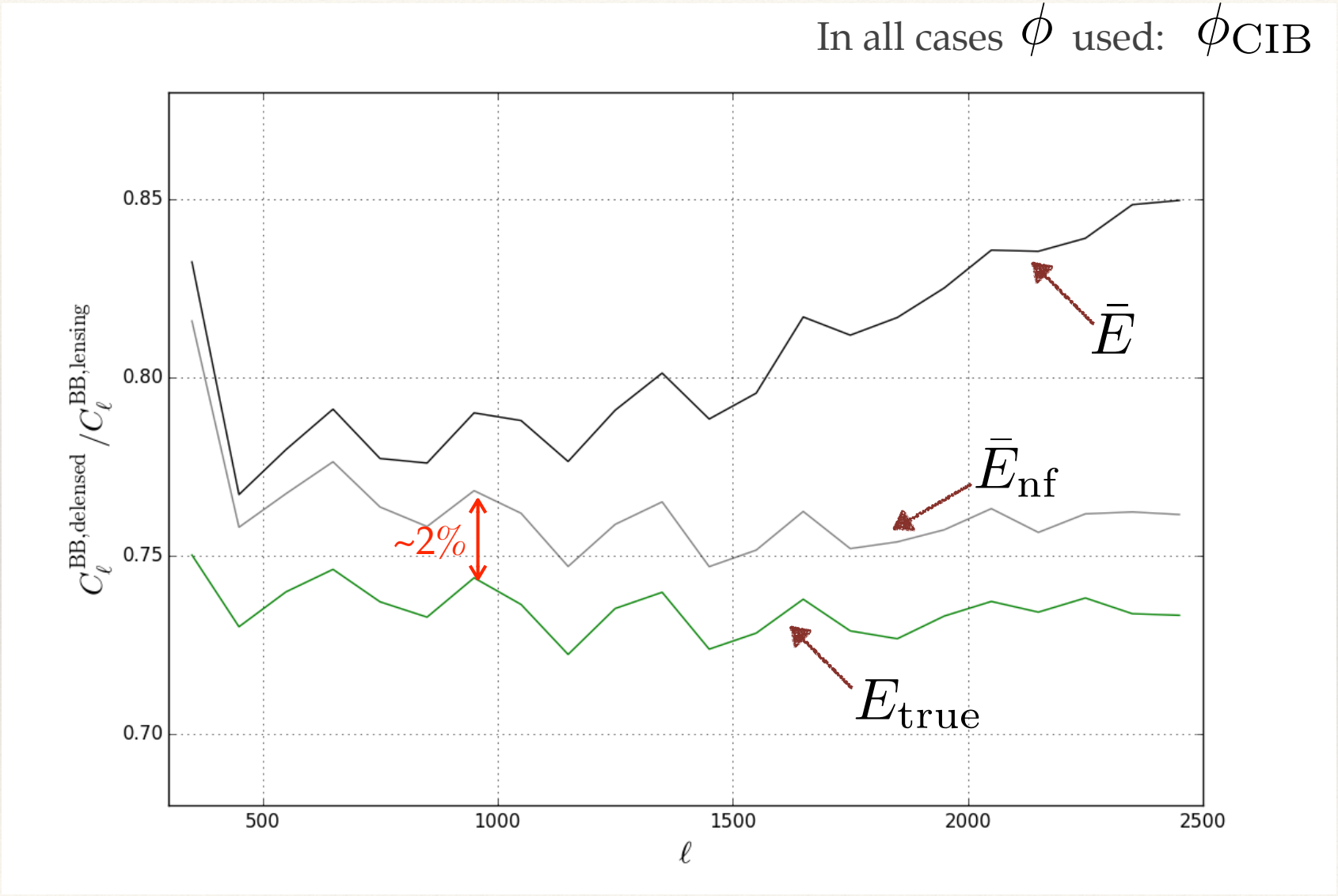
Case study: delensing efficiency from E non-idealities



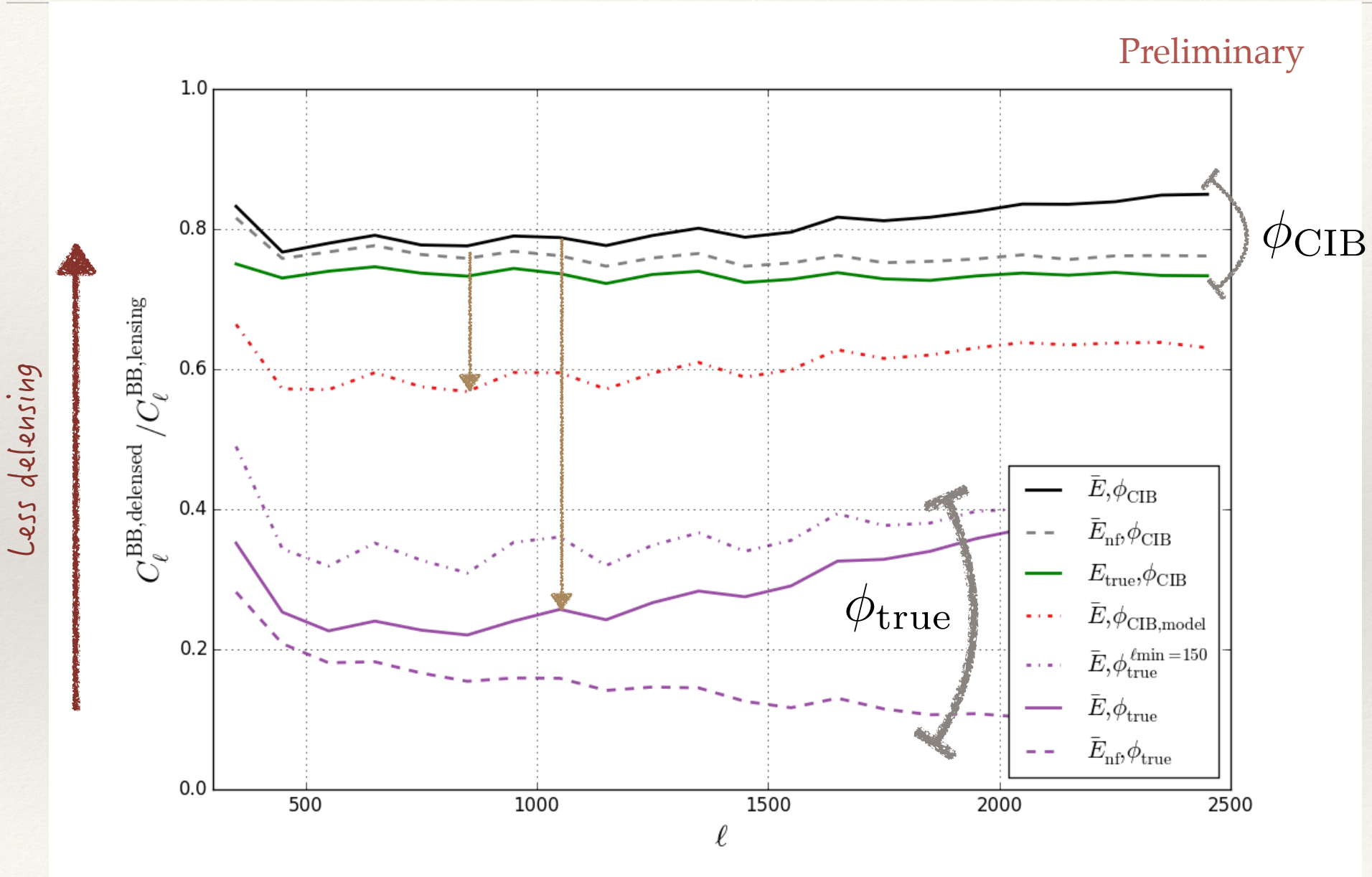
Case study: delensing efficiency from E non-idealities



Case study: delensing efficiency from E non-idealities



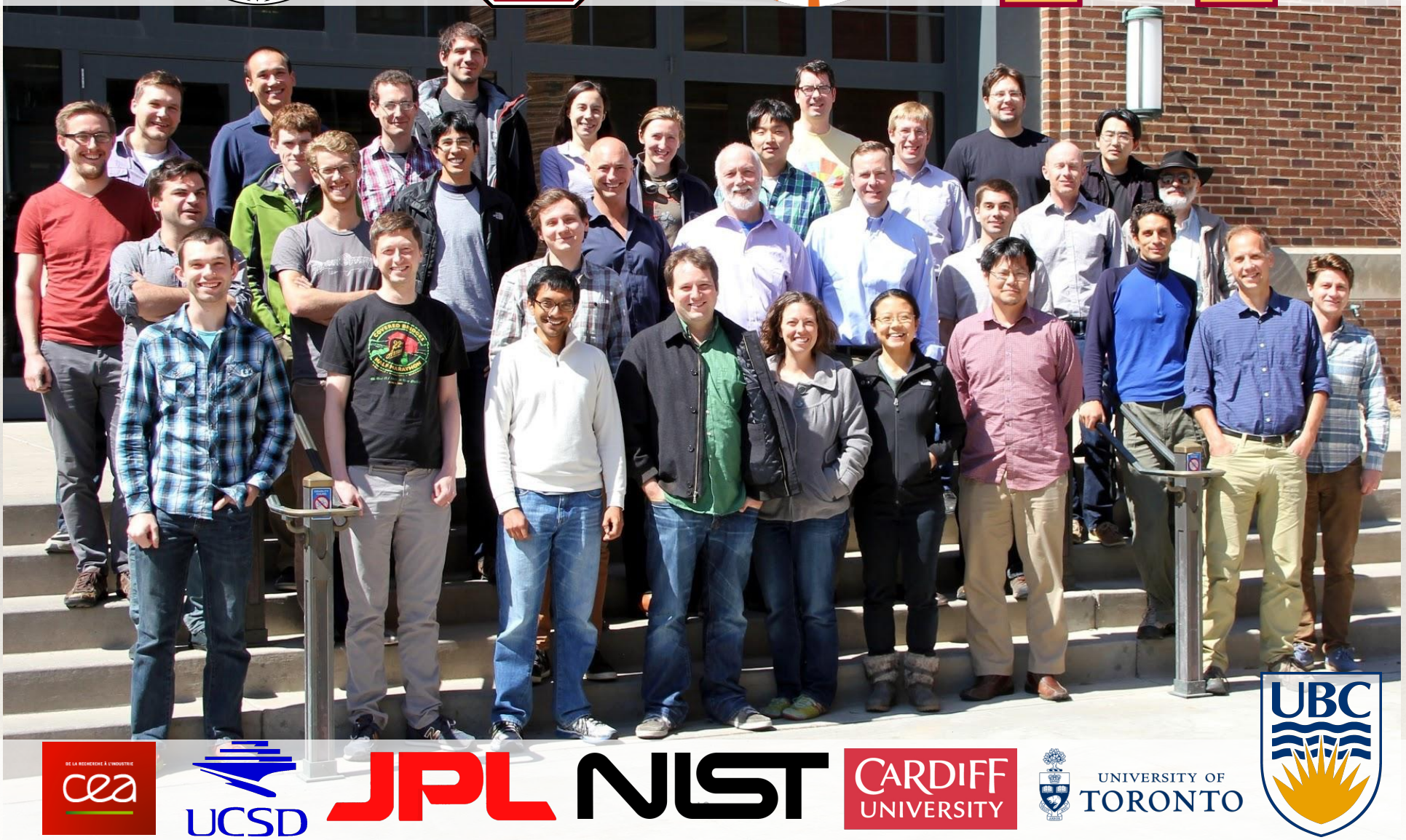
Delensing currently limited by Phi



Take away 3:
delensing currently limited by noise in Phi;
future forecasts should include non-idealities in E/Phi

Outline

- Inflation and CMB polarization
- Delensing with SPTPol; Understanding Delensing Efficiency
- BICEP/Keck; BICEP3 noise improvements
- Future with CMB-S4

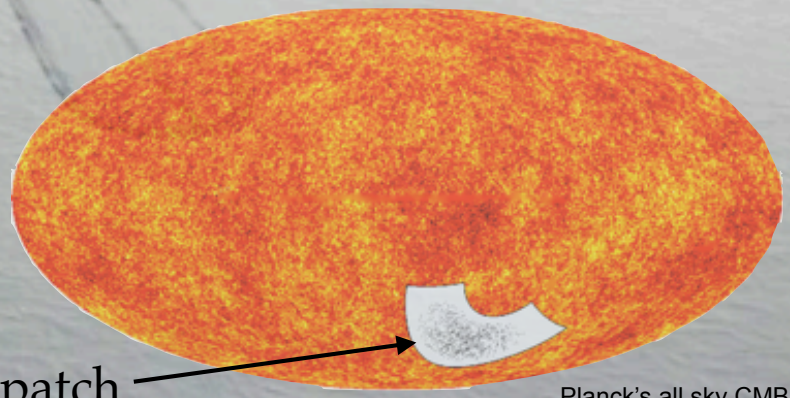

VE RI TAS
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
cea
UCSD
JPL
NIST
CARDIFF UNIVERSITY
UNIVERSITY OF TORONTO
UBC

BICEP/Keck: Targeted Inflationary B-mode search

- **Small aperture** telescopes: sufficient resolution to resolve the ~2 degree peak of the recombination bump from inflationary B-modes
- **Multifrequency observations** for component separation
- **Small patch** (~1% of sky) observations to beat down noise quickly; available 24/7
- South Pole: dry, high altitude, low PWV, stable atmosphere during its 6-month long night

BICEP3, SPT

Keck



BK patch

Planck's all sky CMB temperature map, scale ±500 μK

Stage 2

Stage 3

BICEP2 (2010-2012)

Keck Array (2012-2017)

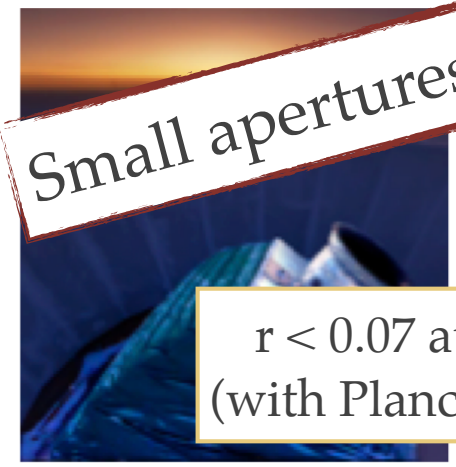
BICEP3 (2015-)

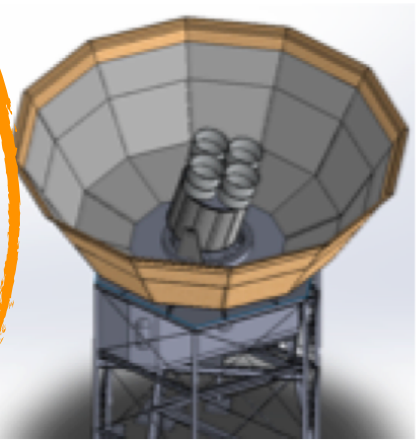
BICEP Array (2018-)

Telescope and Mount

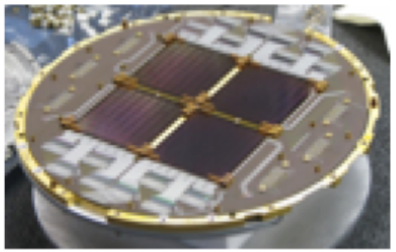
Small apertures

$r < 0.07$ at 95% C.L.
(with Planck + WMAP)



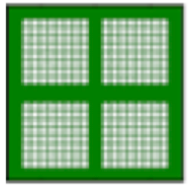


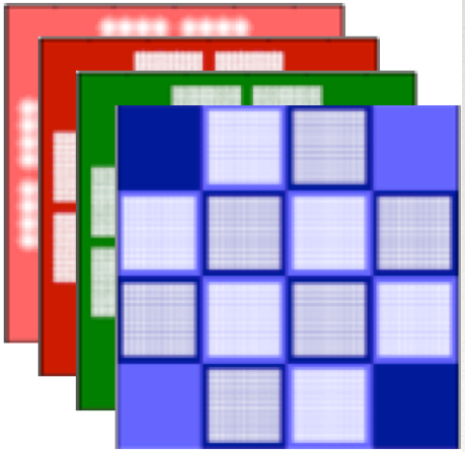
Focal Plane



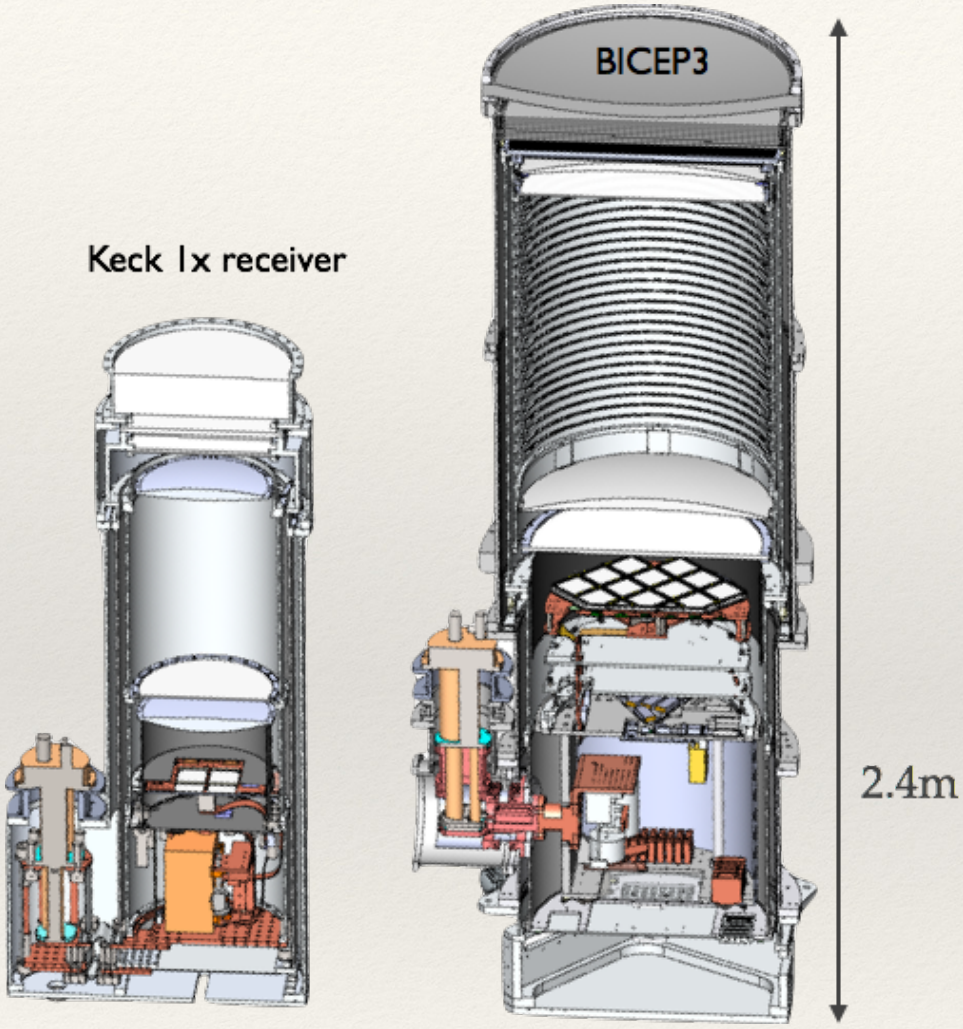
Beams on Sky

Multi-Frequency





BICEP3: path-finder for BK's Stage-3 program

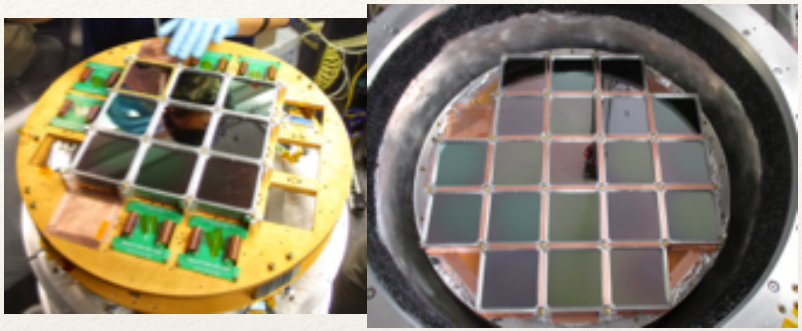


- Cold, compact, on-axis refractors with comoving absorptive forebaffle
- Aperture diameter **doubles**:
  26.4 cm —> 52 cm
- 8.8 x TES detector count
  Keck: 512 @ 150 GHz / **288 @ 95 GHz**
  BICEP3: **2560 @ 95 GHz**

e.g. Wu et al. J. Low Temp. Phys. 184 (2016) 765-771
arXiv: 1601.00125

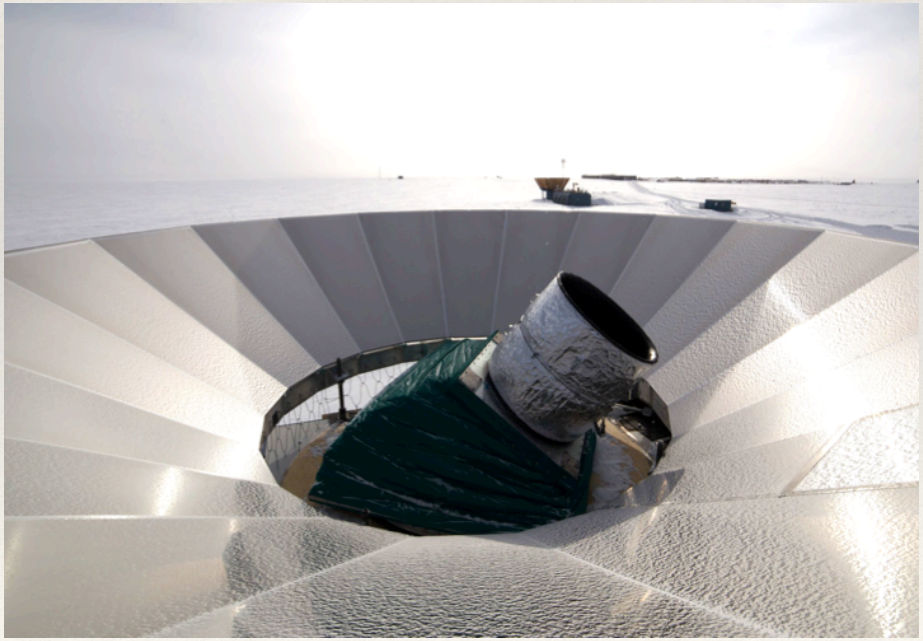
BICEP3 improvements in 2016

- Deployed austral summer 2014-2015; upgrades during austral summer 2015-2016 for 2016 season
- Focal plane fully populated from 9 to 20 detector modules



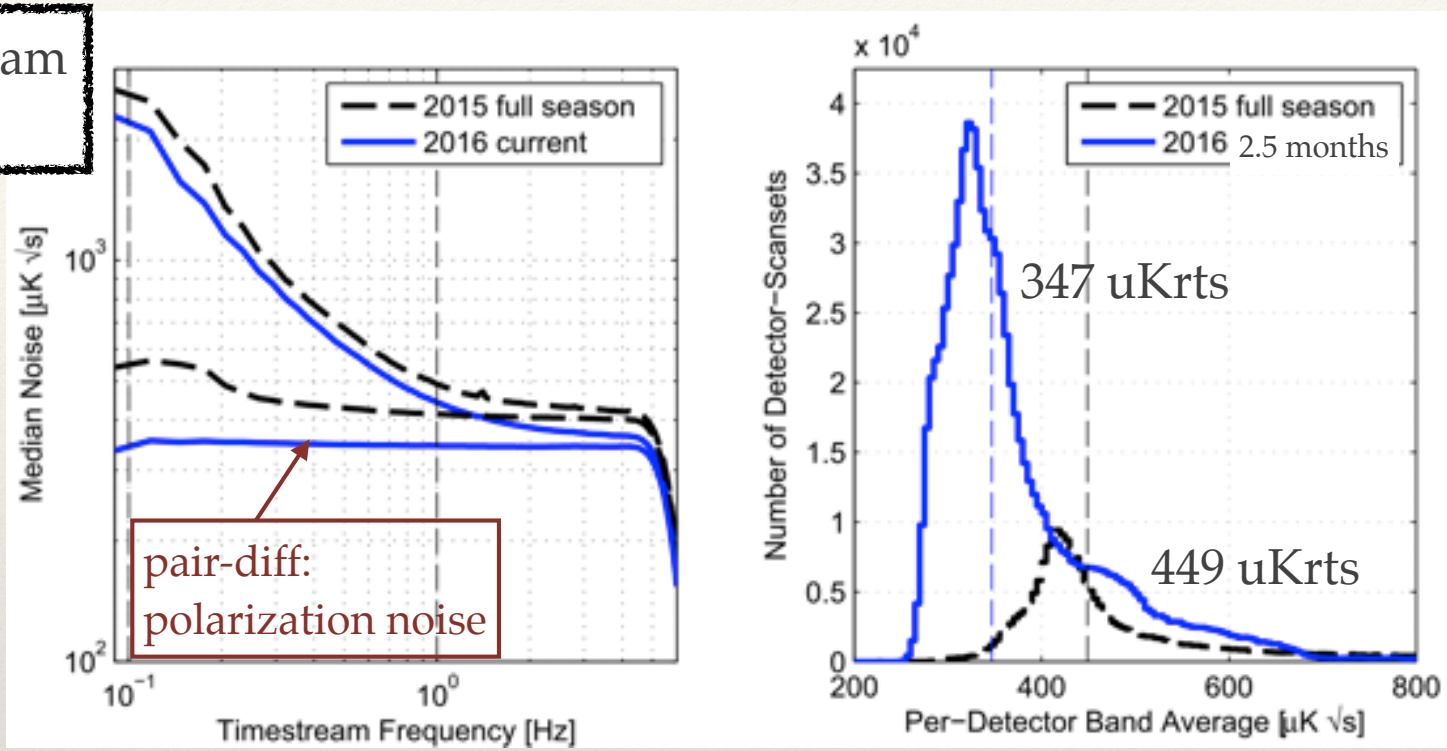
9 modules → 20 modules
1152 → 2560 TESs

- Resolved cryogenic issues and boosted duty cycle by > 20%, with > 48 hours hold time
- Replaced 2 faulty IR shaders that caused extra scattering onto forebaffle
- Reduced 450MHz hand-held radio band pick-up by a total of 45dB



BICEP3 2016 performance

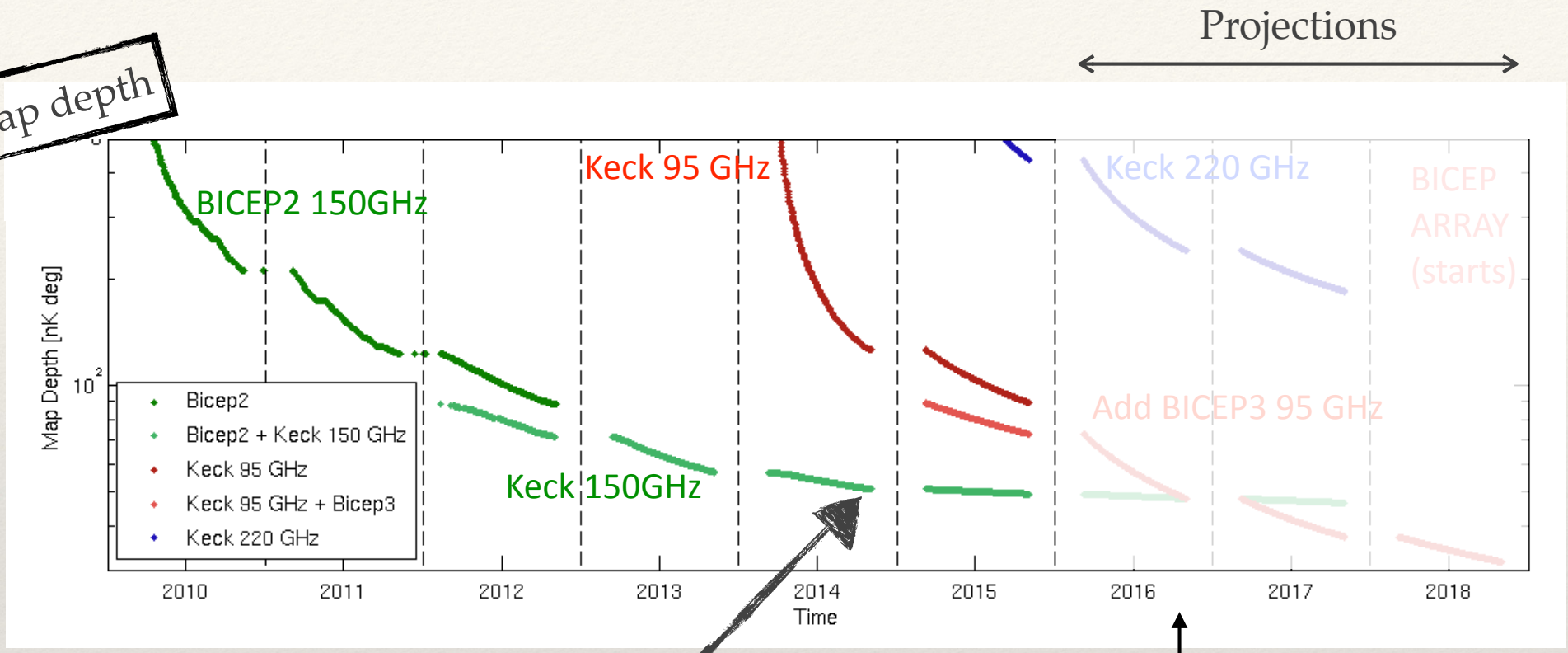
Time-stream PSD



- 3rd order poly filtered time pair-difference stream data, w/ prelim data cuts
- Median white noise level lowered: scattering/loading decrease and RF fixes
- Histogram amplitude difference due to full focal plane, duty cycle
- Whole receiver array NET median 2015 / 2016 = 24.6 / 9.91 uKrts

Grayson, …, WU et al. SPIE 2016
arXiv: 1607.04668

Projections of map depth from BICEP/Keck

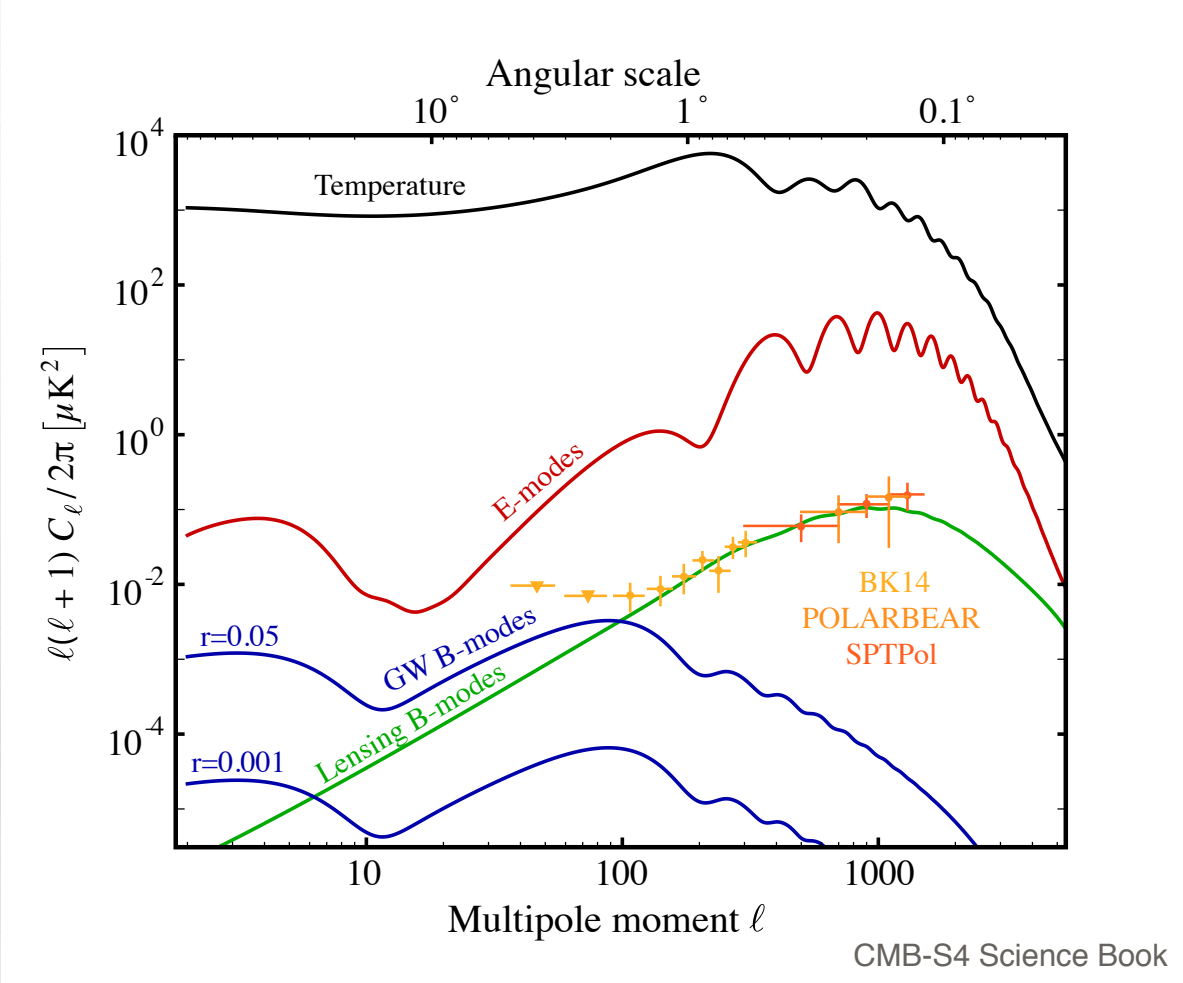


95GHz: 7.6 μK′
150GHz: 3 μK′
Deepest map of ~1% sky at 150GHz
best upper limit on r
$r < 0.07$ at 95% C.L. (with Planck + WMAP)

(BK14 PRL 116.031302)

BICEP/Keck constraints on r already limited by lensing

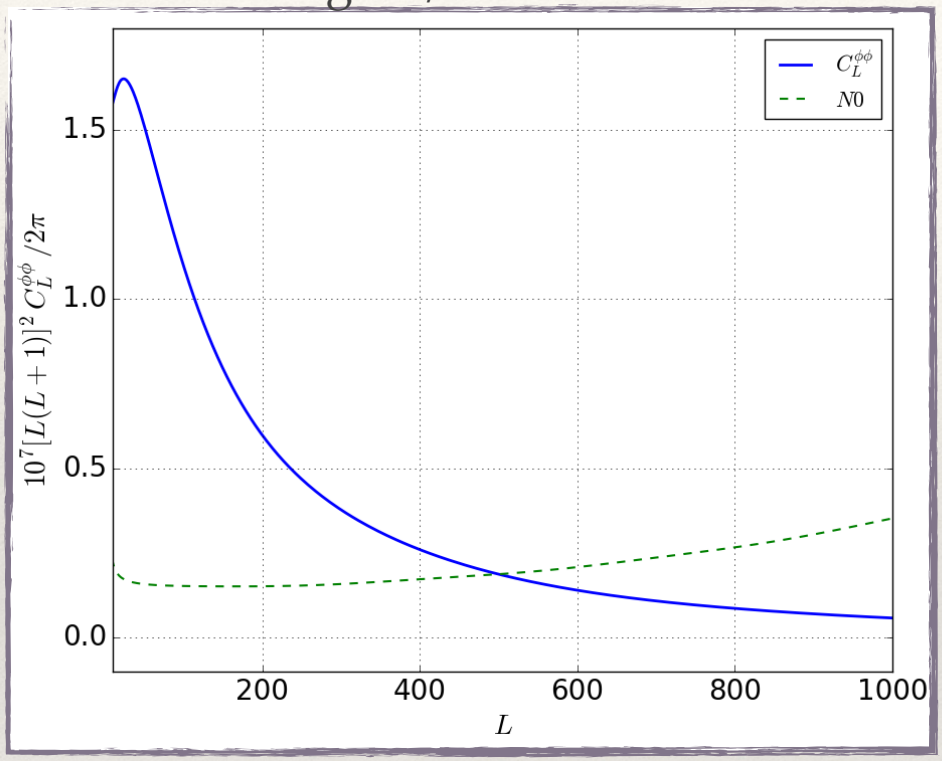
Resolution for Phi reconstruction from CMB

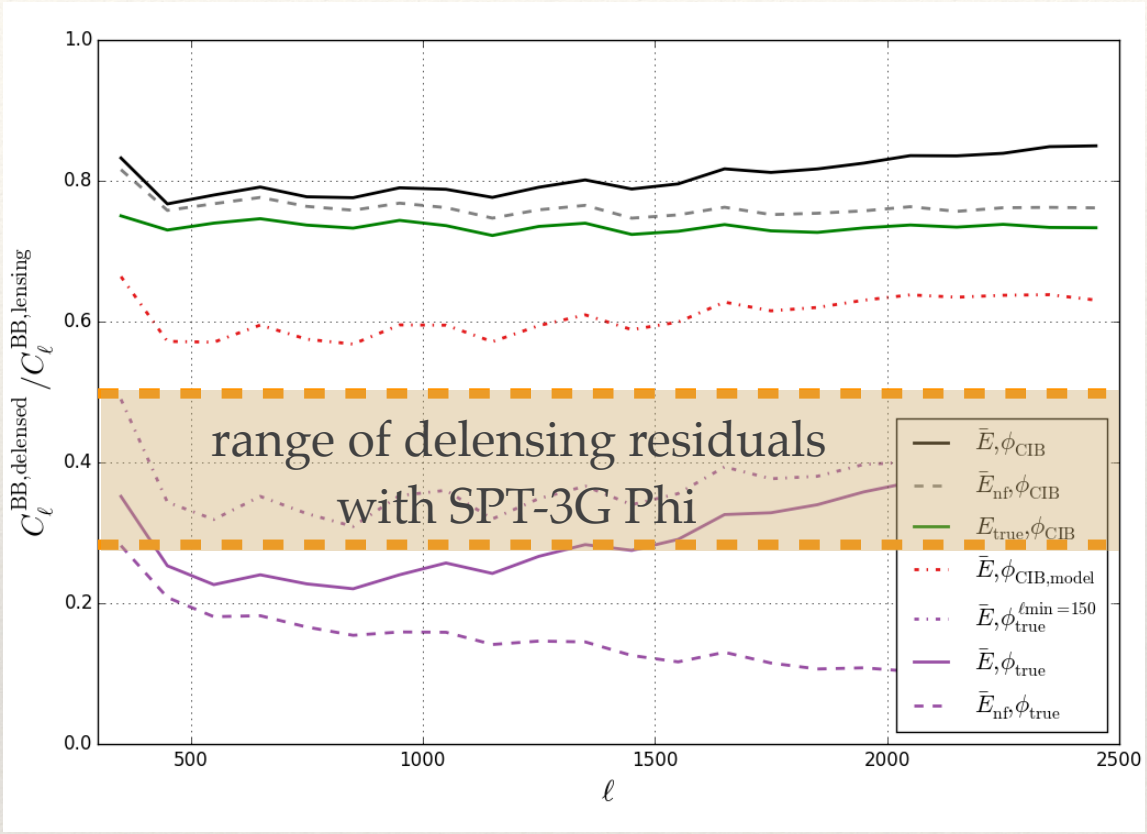


BICEP/Keck telescopes do not measure modes with fine enough resolution for high S/N Phi reconstruction

Delensing BICEP/Keck with SPT-3G Phi map

SPT-3G : high S/N Phi reconstruction





BICEP-Keck / Planck joint analysis — **σ(*r*) = 0.034** — arXiv:1502.00612

2014 BICEP/Keck analysis adds deep 95 GHz — **σ(*r*) = 0.025** — arXiv:1510.09217

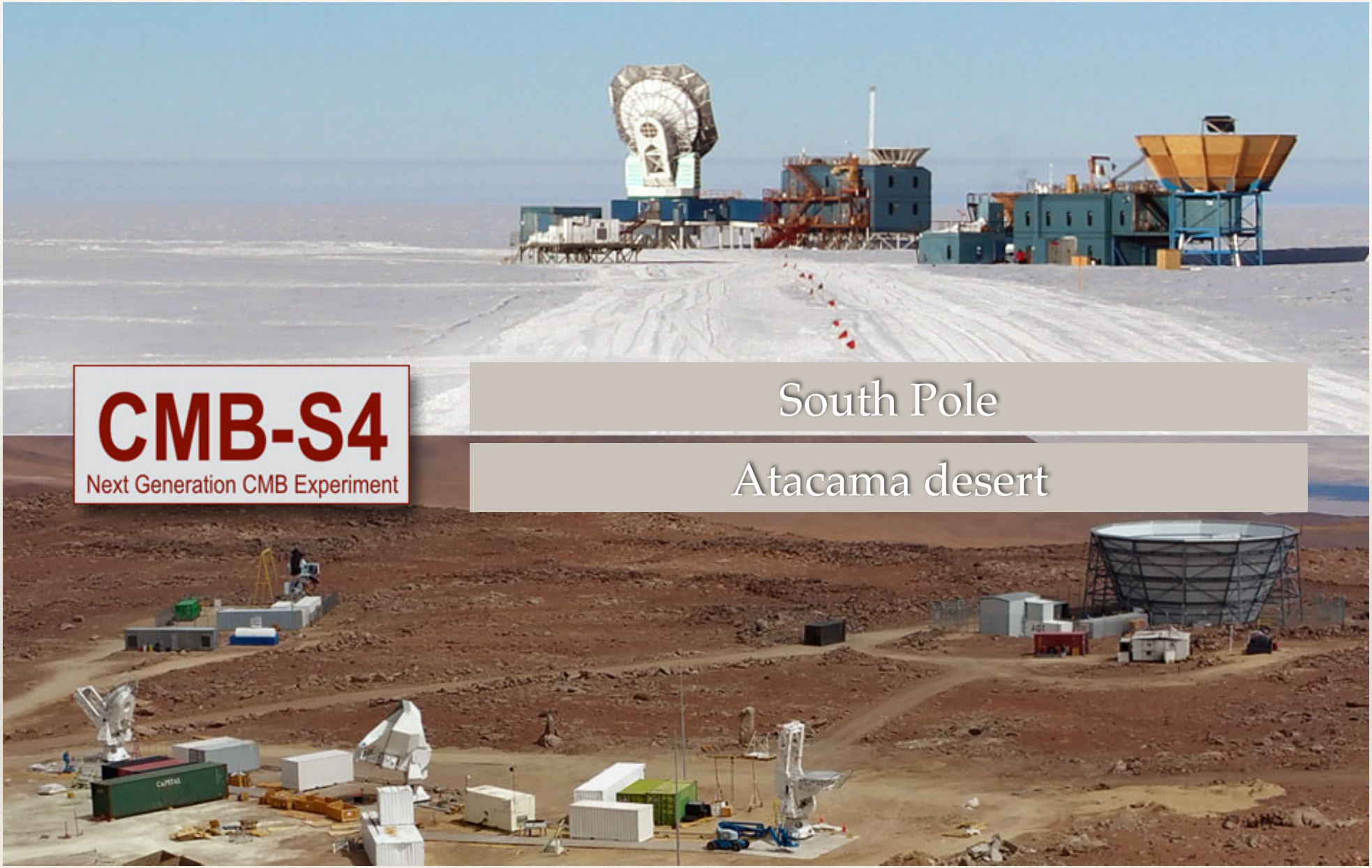
2018+ BICEP Array + SPT3G — forecast **σ(*r*) < 0.005**

Take Away 4:

BICEP/Keck Array will push the limits on r through component separation and delensing using Phi from SPT

Outline

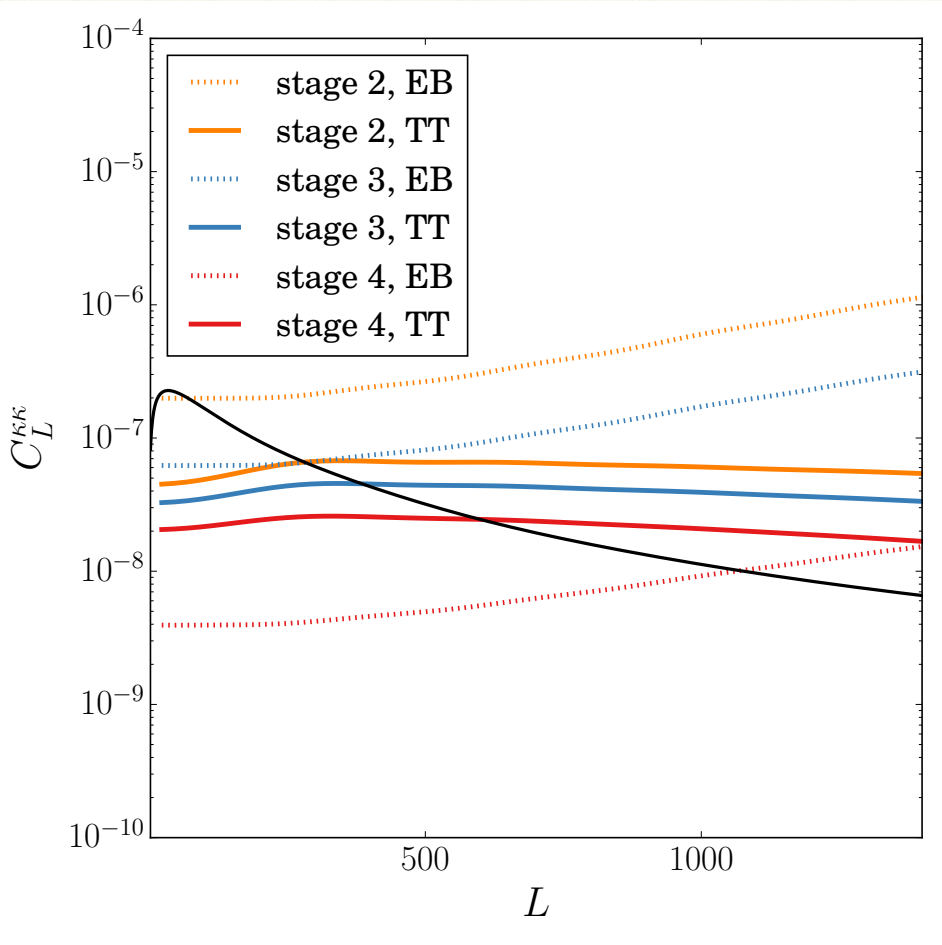
- Inflation and CMB polarization
- Delensing with SPTPol; Understanding Delensing Efficiency
- BICEP/Keck; BICEP3 noise improvements
- Future with CMB-S4



- ~500,000 detectors
- deep survey for *r;* wide survey (> 40% sky) for lensing science
- $\sigma(r) \sim 0.001$; $\sigma(\sum m\nu) < 20$ meV

CMB-S4 Science Book, Abazajian, …, WU, et al. (arXiv:1610.02743)

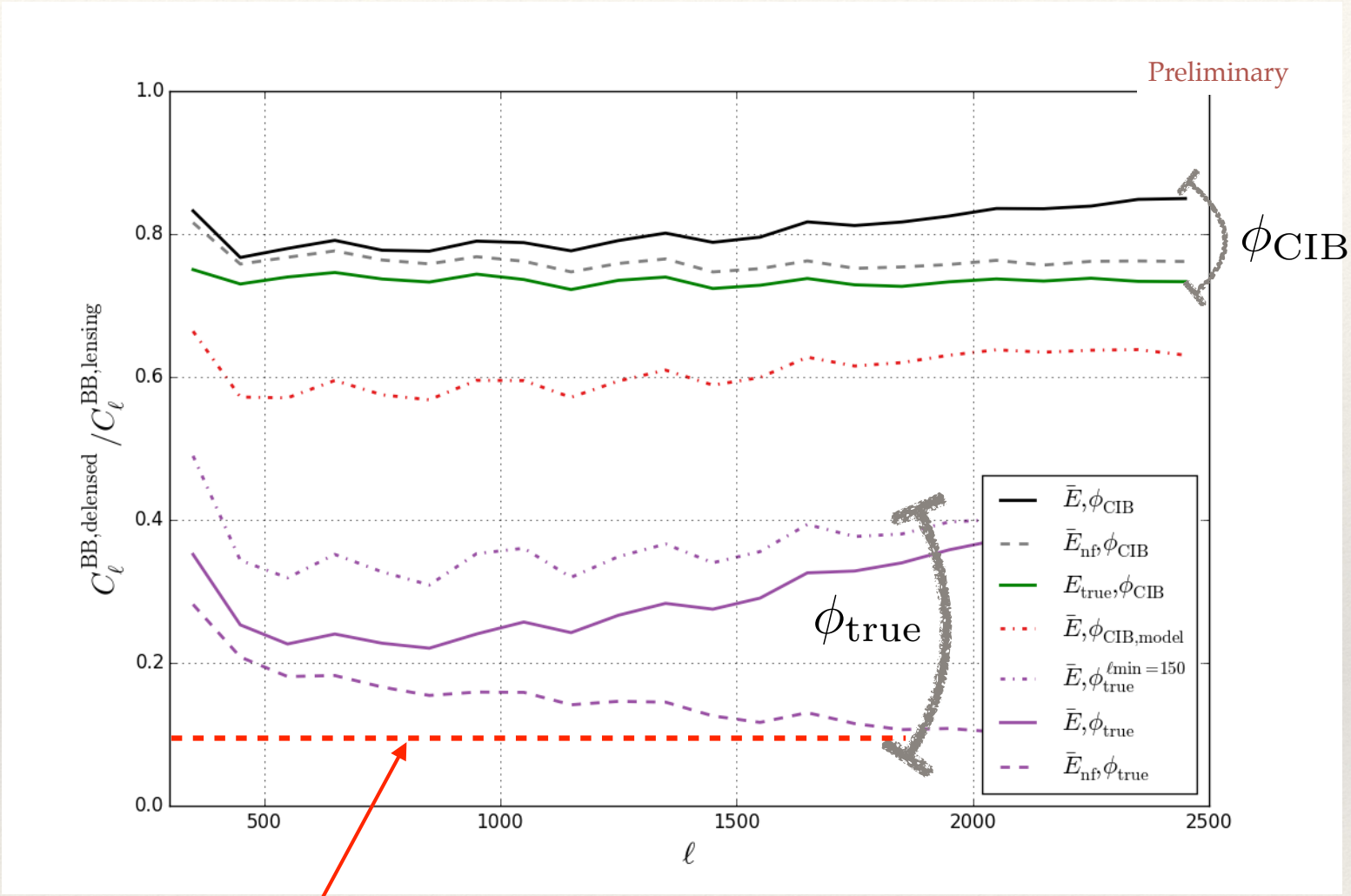
Phi reconstruction reach in CMB-S4



CMB-S4 Science Book

- Individual Phi modes below L ~ 1000 will be measured to S/N > 1 by stage-4

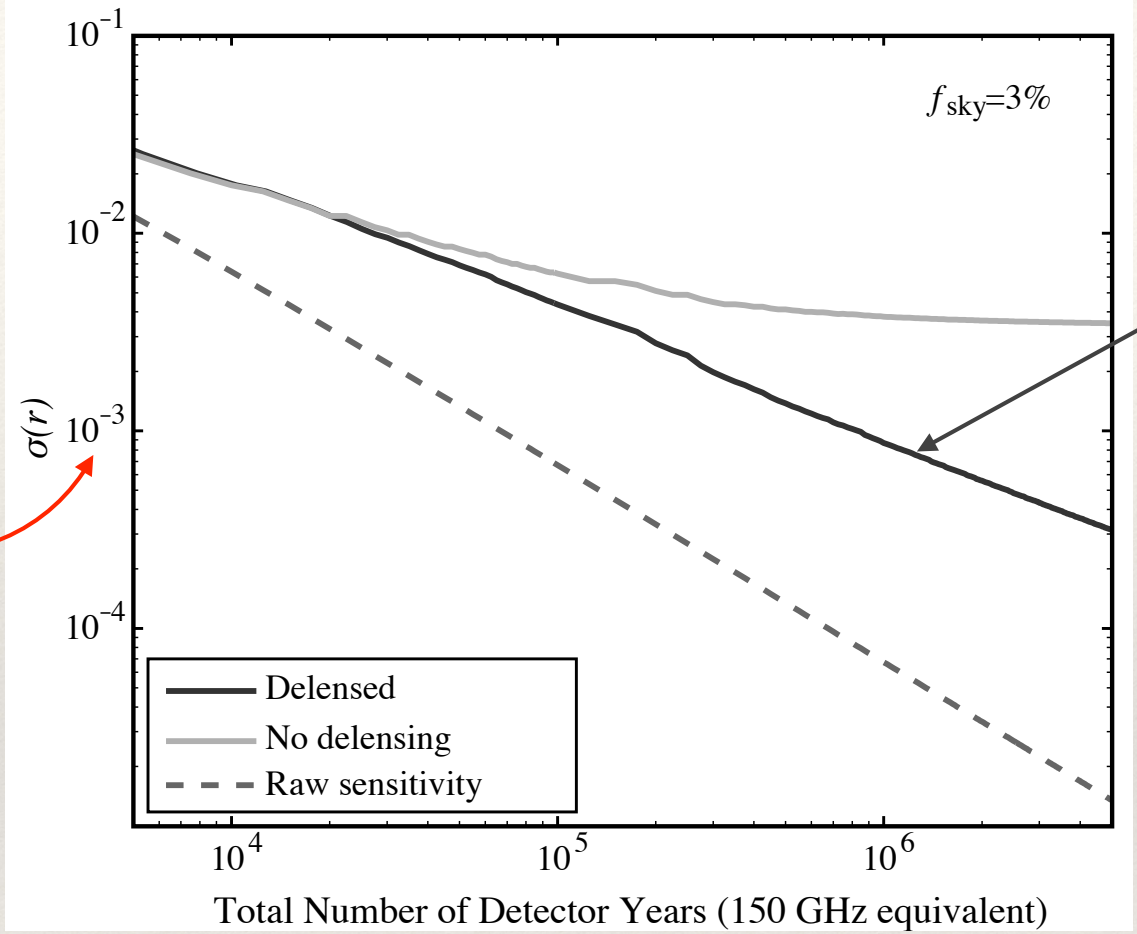
Level of delensing required



~ CMB-S4 analytic forecast level (3% sky for r)

r forecast with CMB-S4

σ(r) = 0.001 benchmark



CMB-S4 Science Book

- With Phi reconstructed with Stage-4 level noise, we expect ~10% lensing Cl^BB residuals
- Need realistic delensing forecast that include non-idealities

Summary

- B modes generated from primordial gravitational waves would provide strong evidence for inflation
- *r* is directly related to the energy scale of inflation: its upper limit or measurements will significantly limit allowable theory model parameter space
- Lensing B mode and galactic foregrounds contaminate primordial measurements
- Using SPTpol data, we have demonstrated for the first time delensing of B modes
- BICEP3 as the path-finder experiment of the Stage-3 effort of the BICEP/Keck program, will continue to tighten constraints on *r* through component separation and delensing with SPT
- Data from CMB-S4 will provide even tighter constraints on *r*

Thank you for your attention