Title: The next decade of CMB cosmology: gravitational waves, neutrinos and non-Gaussianities

Date: Feb 21, 2017 11:00 AM

URL: http://pirsa.org/17020124

Abstract: <p>We are currently entering the era of precision CMB polarization observations. The most exciting scientific targets are a possible detection of primordial gravitational waves and a measurement of the sum of the neutrino masses. The former depends on the extensive landscape of early Universe models, while the latter has been forecasted to present a clear, and reachable, scientific target. First, if large angular B modes are detected, we should firmly establish that these are sourced by primordial gravitational waves. I will discuss that cross correlating the B-mode signal with the curl-lensing field could help establish the nature of the detected B-modes. Second, I will propose to look beyond Gaussianity in the tensor sector. Scalar non-Gaussianities are tightly constrained by Planck, but couplings between tensors and scalars are currently not constrained and future CMB polarization surveys could open a new window into the early Universe, by searching for tensor non-Gaussianites. Finally, a detection of the normal hierarchy of the neutrino mass requires an excellent measurement of the amplitude of primordial fluctuations. The required measurement can only be achieved if we are able to measure the large angle E-mode polarization spectrum, which currently lies beyond reach, at least within the foreseeable future. I will present a possible solution and show how this simple methodology can be used to constrain exotic primordial physics at the same time.</p>

The next Decade of CMB cosmology

Based on work in collaboration with Alex van Engelen, Joel Meyers, Yacine Ali-Haïmoud, Kendrick Smith, Adri Duivenvoorden and Connor Sheere: 1603.02243, 1701.06992, 1610.09365, 1702.xxxxx and CMB-S4 collaboration

Outline

Introduction

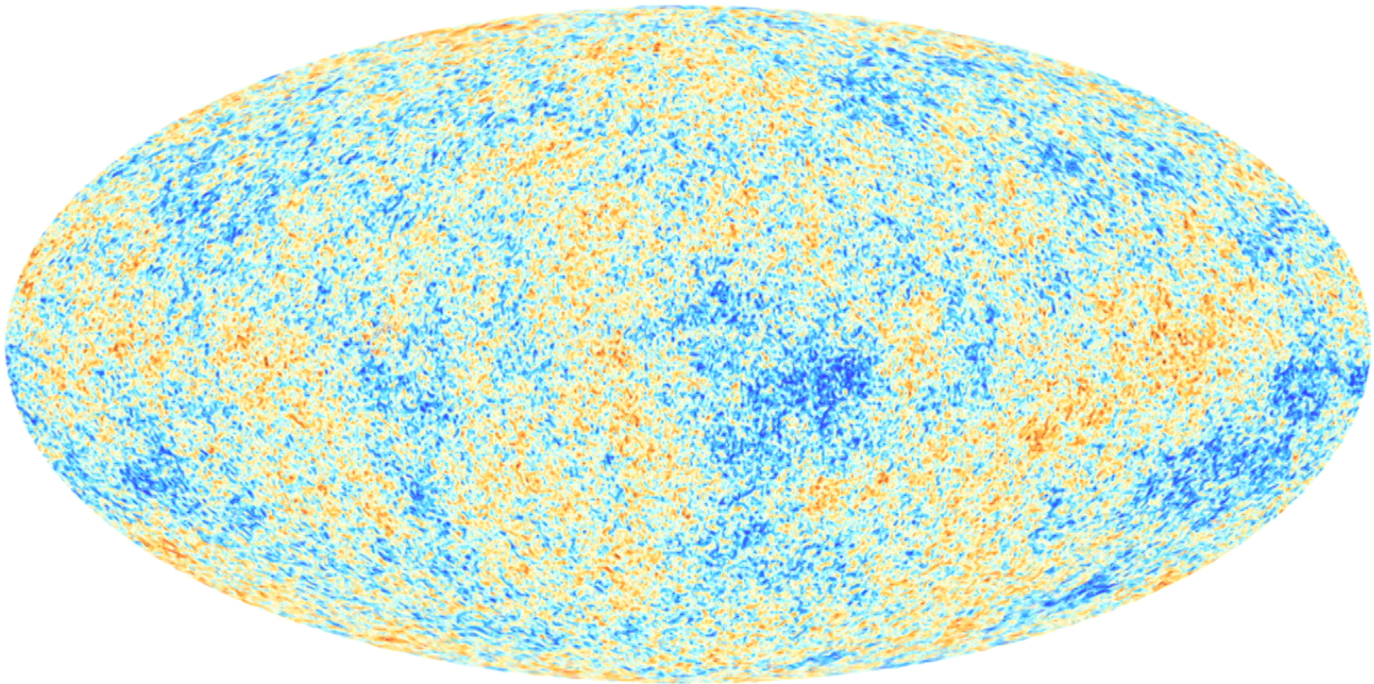
-Establishing the Origin of B-modes

-Tensors and Non-Gaussianities

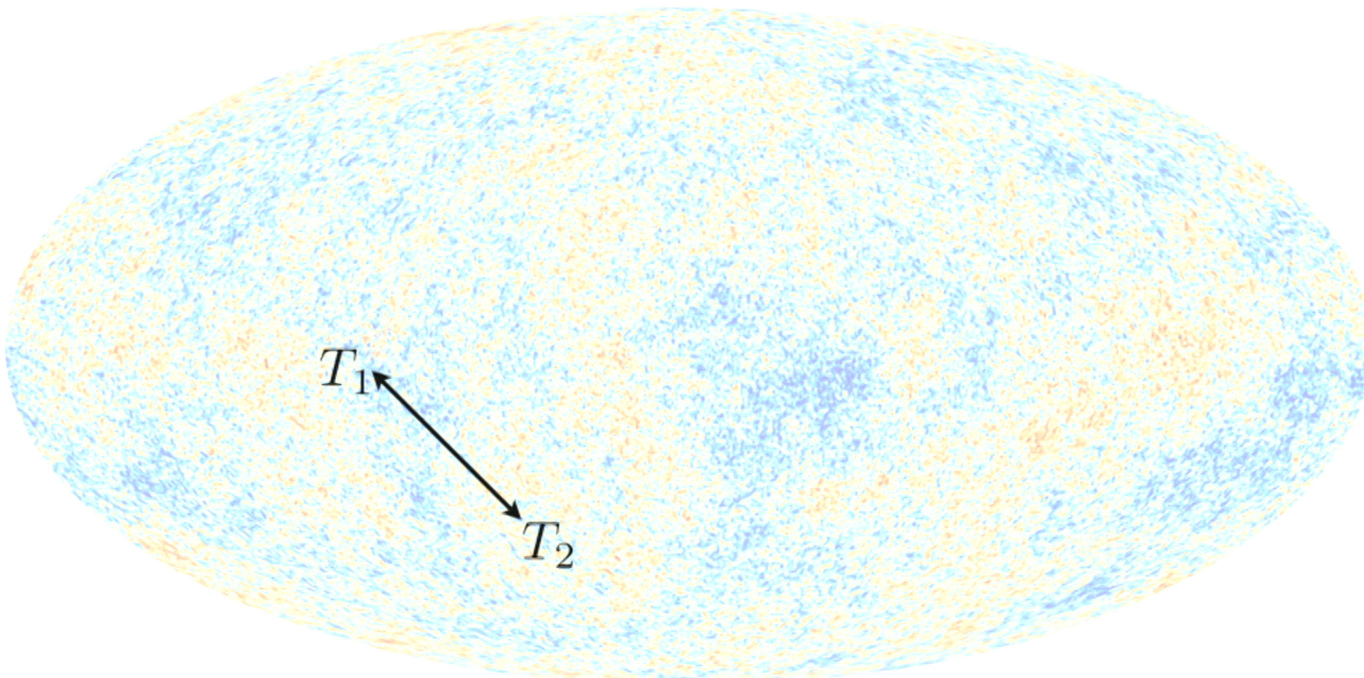
-Neutrinos and the ‘tau’ problem

Conclusions

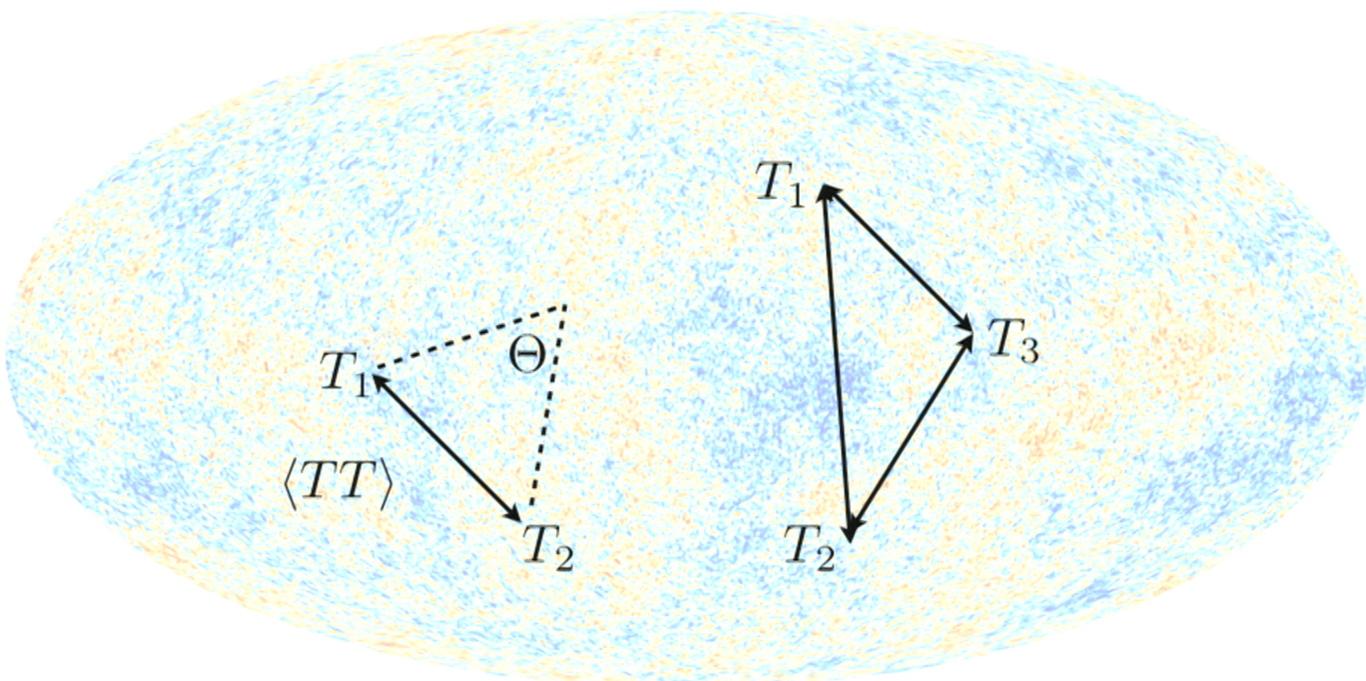
Introduction



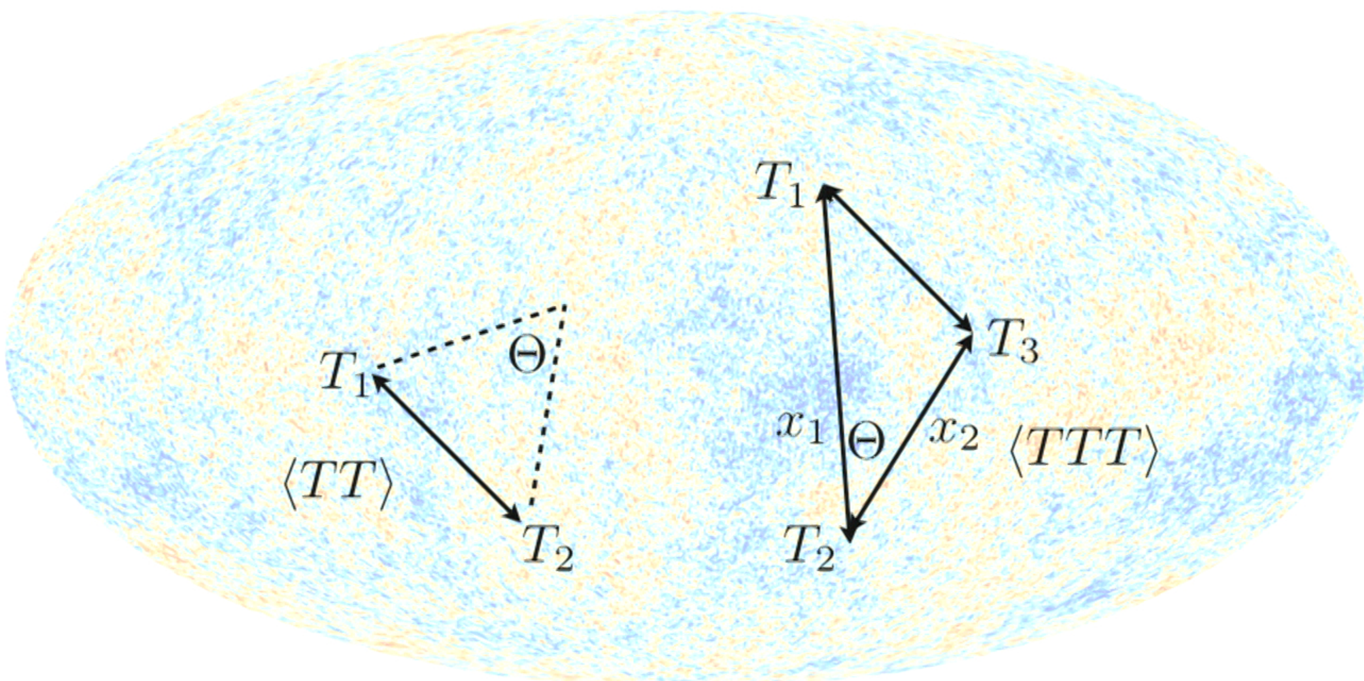
Introduction



Introduction



Introduction



Introduction

Schematically:

$$\Delta T/T = \sum a_{\ell m} Y_{\ell m} \rightarrow \langle a_{\ell_1 m_1} a_{\ell_2 m_2} \ldots a_{\ell_n m_n} \rangle$$

Introduction

Schematically:

$$\Delta T/T = \sum a_{\ell m} Y_{\ell m} \rightarrow \langle a_{\ell_1 m_1} a_{\ell_2 m_2} \ldots a_{\ell_n m_n} \rangle$$

Can be done for intensity (T), but also for E and B mode polarization e.g.

$$\langle a^X_{\ell m} a^{X*}_{\ell' m'} \rangle \rightarrow C^{XX}_\ell$$

and

$$\langle a^X_{\ell m} a^X_{\ell' m'} a^X_{\ell'' m''} \rangle \rightarrow B^{XXX}_{\ell \ell' \ell''}$$

$$X = \{T, E, B\}$$

Introduction

Schematically:

$$\Delta T/T = \sum a_{\ell m} Y_{\ell m} \rightarrow \langle a_{\ell_1 m_1} a_{\ell_2 m_2} \ldots a_{\ell_n m_n} \rangle$$

Can be done for intensity (T), but also for E and B mode polarization e.g.

$$\langle a^X_{\ell m} a^{X*}_{\ell' m'} \rangle \rightarrow C^{XX}_\ell \qquad \text{(powerspectra)}$$

and

$$\langle a^X_{\ell m} a^X_{\ell' m'} a^X_{\ell'' m''} \rangle \rightarrow B^{XXX}_{\ell \ell' \ell''} \qquad \text{(bispectra)}$$

$$X = \{T, E, B\}$$

Throughout this talk I will refer to these as 'TT', 'EE' etc powerspectra and 'TTT', 'EEE' etc. bispectra

Introduction

Paradigm

E.g. LCDM

Initial Cond.

Scalar, vector, tensor

$P_\zeta(k)$ $P_h(k)$ $P_s(k)$

$B_{\zeta\zeta\zeta}(k_1, k_2, k_3)$

.....

Projection

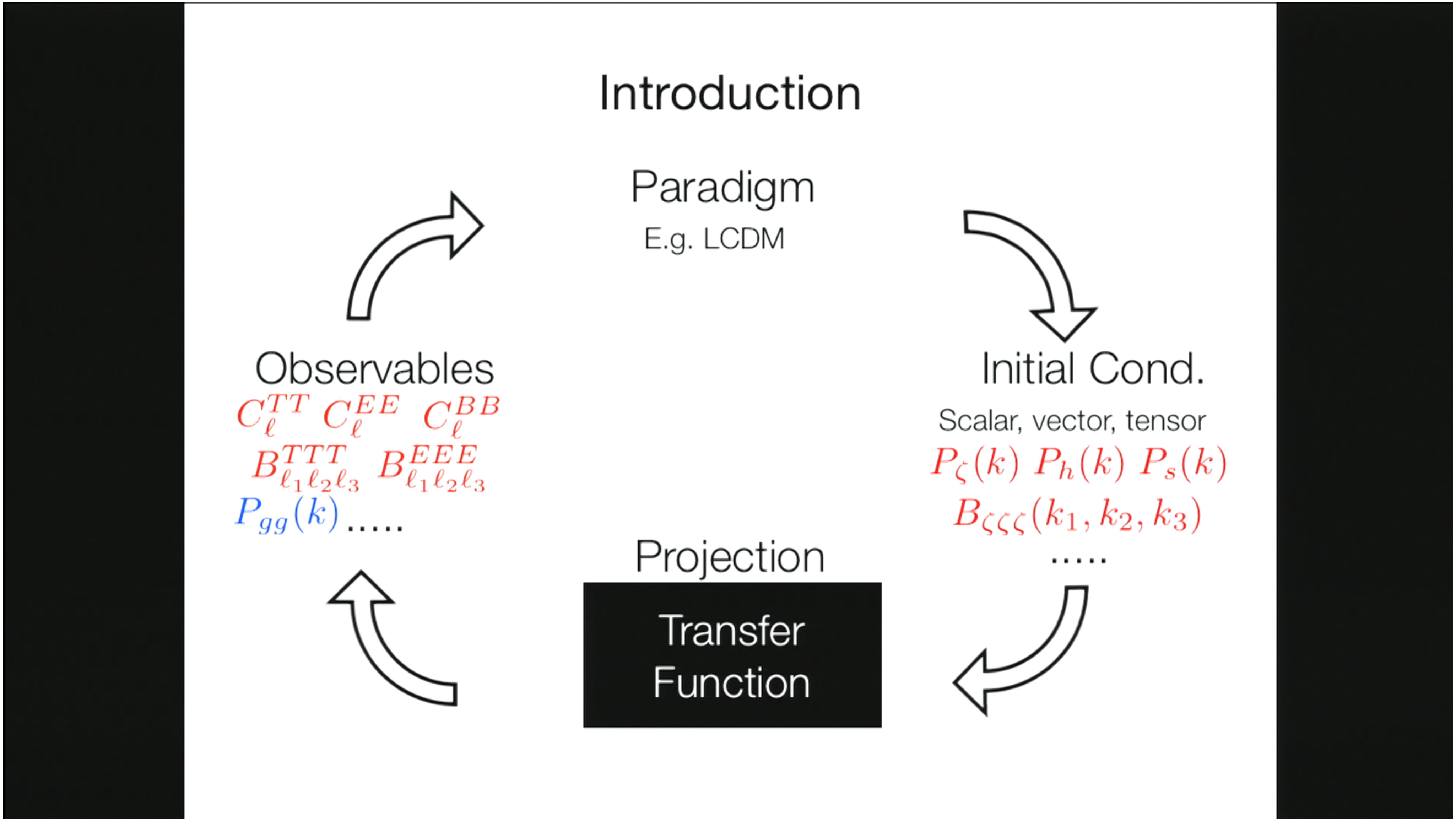
Reheating ($\delta\zeta \rightarrow \delta\rho$), 'physics': gravity, interactions (e.g. scatterings) etc.

Observables

C_ℓ^{TT} C_ℓ^{EE} C_ℓ^{BB}

$B_{\ell_1\ell_2\ell_3}^{TTT}$ $B_{\ell_1\ell_2\ell_3}^{EEE}$

$P_{gg}(k)$ .....


Introduction
Paradigm
E.g. LCDM
Initial Cond.
Scalar, vector, tensor
$P_\zeta(k)$ $P_h(k)$ $P_s(k)$
$B_{\zeta\zeta\zeta}(k_1, k_2, k_3)$
.....
Projection
Transfer Function
Observables
C_ℓ^{TT} C_ℓ^{EE} C_ℓ^{BB}
$B_{\ell_1\ell_2\ell_3}^{TTT}$ $B_{\ell_1\ell_2\ell_3}^{EEE}$
$P_{gg}(k)$.....

Introduction

Transfer Function

E.g.:

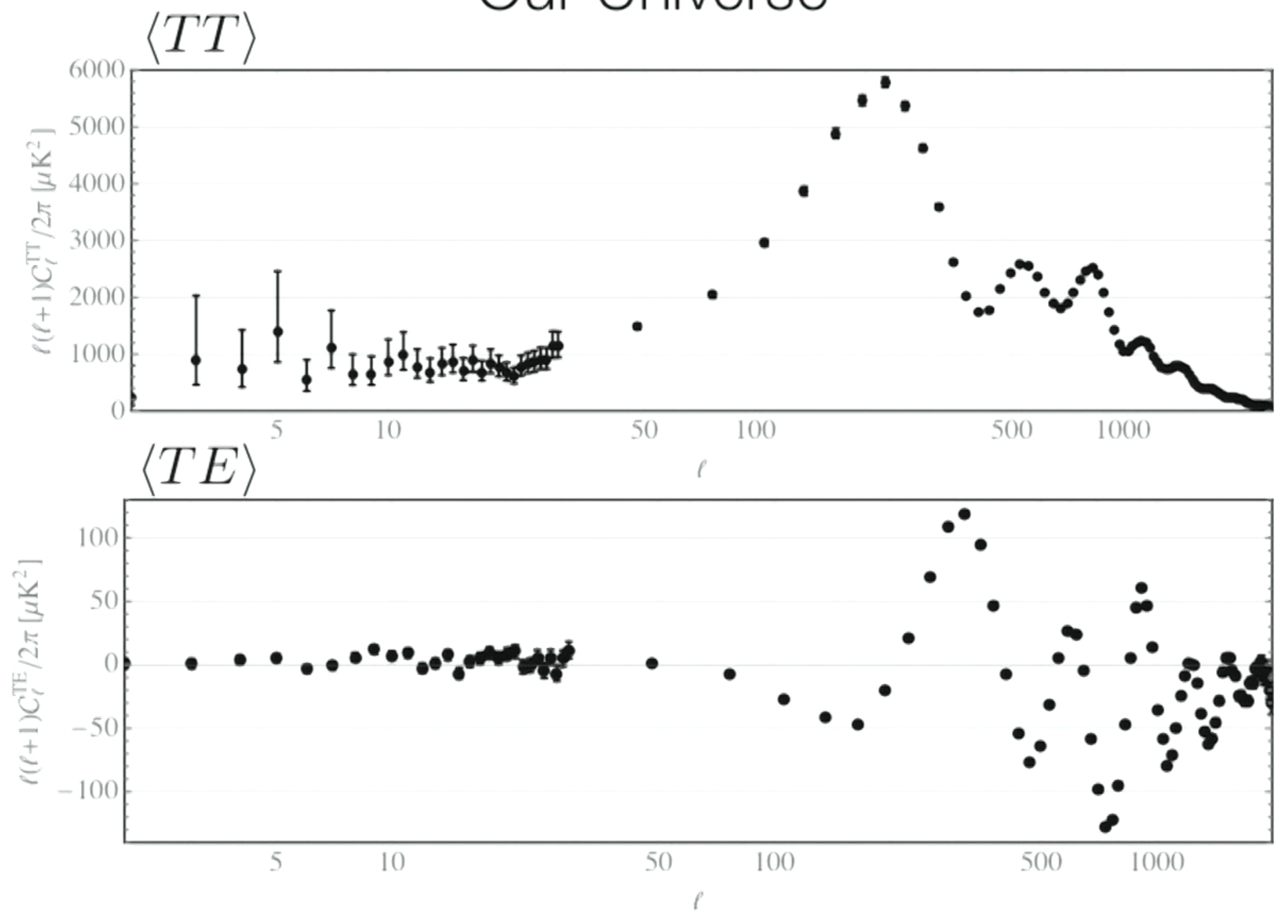
$$C_\ell^{XX'} \propto \int dkk \sum \left[P_{\zeta,h.s}(k)\right] \Delta_\ell^X(k)\Delta_\ell^{X'}$$

and

$$B_{\ell_1\ell_2\ell_3}^{XX'X''} \propto \int dx x^2 \prod_i \left[\int dk_i k_i^2 j_{\ell_i}(k_i x)\Delta_{\ell_i}^{X,X',X''}(k_i)\right] \sum B_{\zeta,h,s}(k_1,k_2,k_3)$$

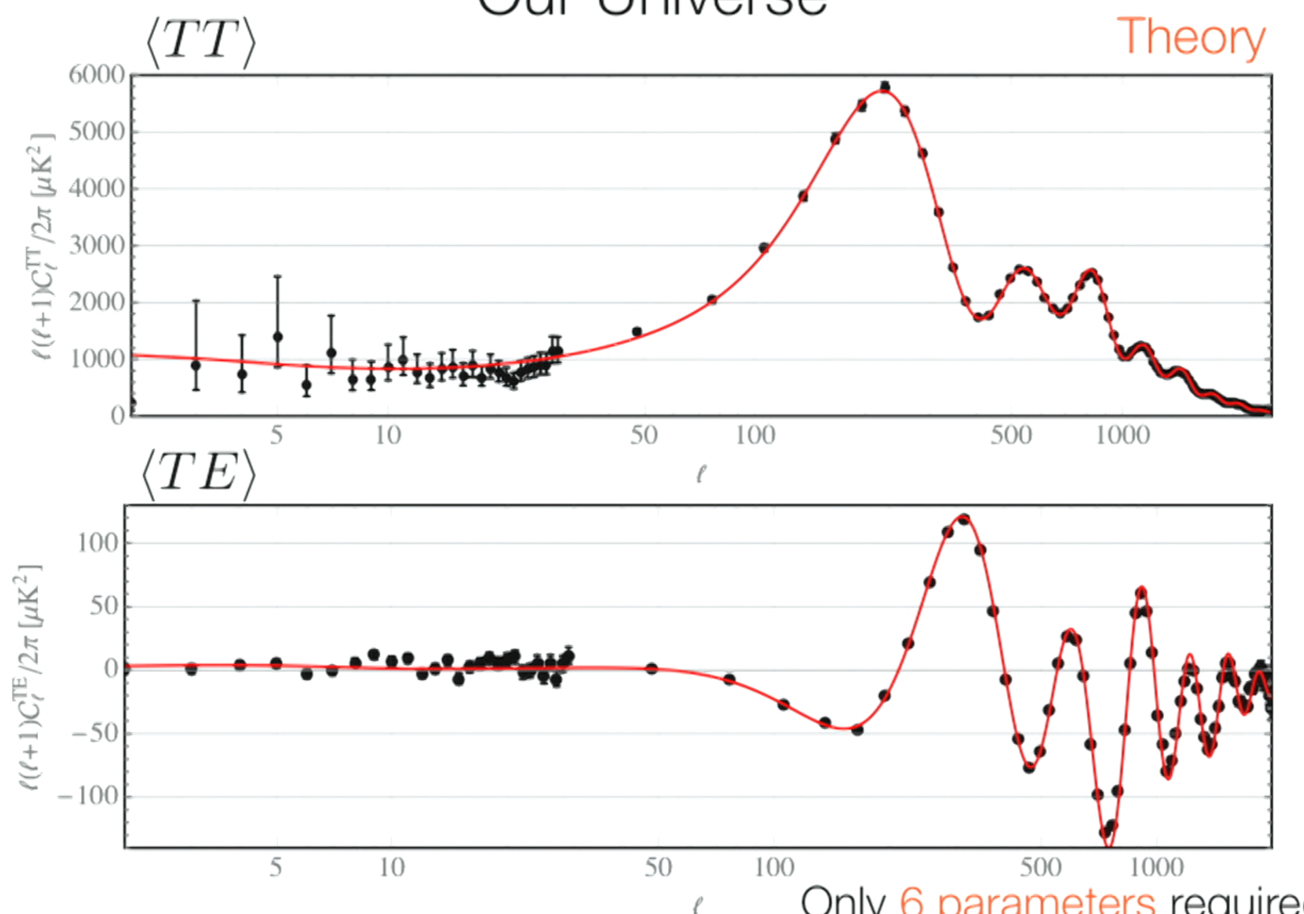
Introduction

Our Universe



Introduction

Our Universe



Only 6 parameters required

Introduction

Our Universe

Only 6 parameters required

4 late time: $\Omega_b,\ \Omega_c,\ \tau,\ H_0 \rightarrow \Delta_\ell^X(k)$

2 primordial time: $n_s,\ A_s \rightarrow P_\zeta \propto \frac{A_s}{k^3}\left(\frac{k}{k_*}\right)^{n_s-1}$

Introduction

Our Universe

Only 6 parameters required

4 late time: $\Omega_b,\ \Omega_c,\ \tau,\ H_0 \to \Delta_\ell^X(k)$

2 primordial time: $n_s,\ A_s \to P_\zeta \propto \frac{A_s}{k^3}\left(\frac{k}{k_*}\right)^{n_s-1}$

Caveat: Many more params e.g. k, Yp, G, recomb etc

Introduction

Our Universe

Only 6 parameters required

4 late time: $\Omega_b,\ \Omega_c,\ \tau,\ H_0 \rightarrow \Delta_\ell^X(k)$

2 primordial time: $n_s,\ A_s \rightarrow P_\zeta \propto \frac{A_s}{k^3}\left(\frac{k}{k_*}\right)^{n_s-1}$

Caveat: Many more params e.g. k, Yp, G, recomb etc

Initial conditions: adiabatic, scalar-like, scale invariant and Gaussian.

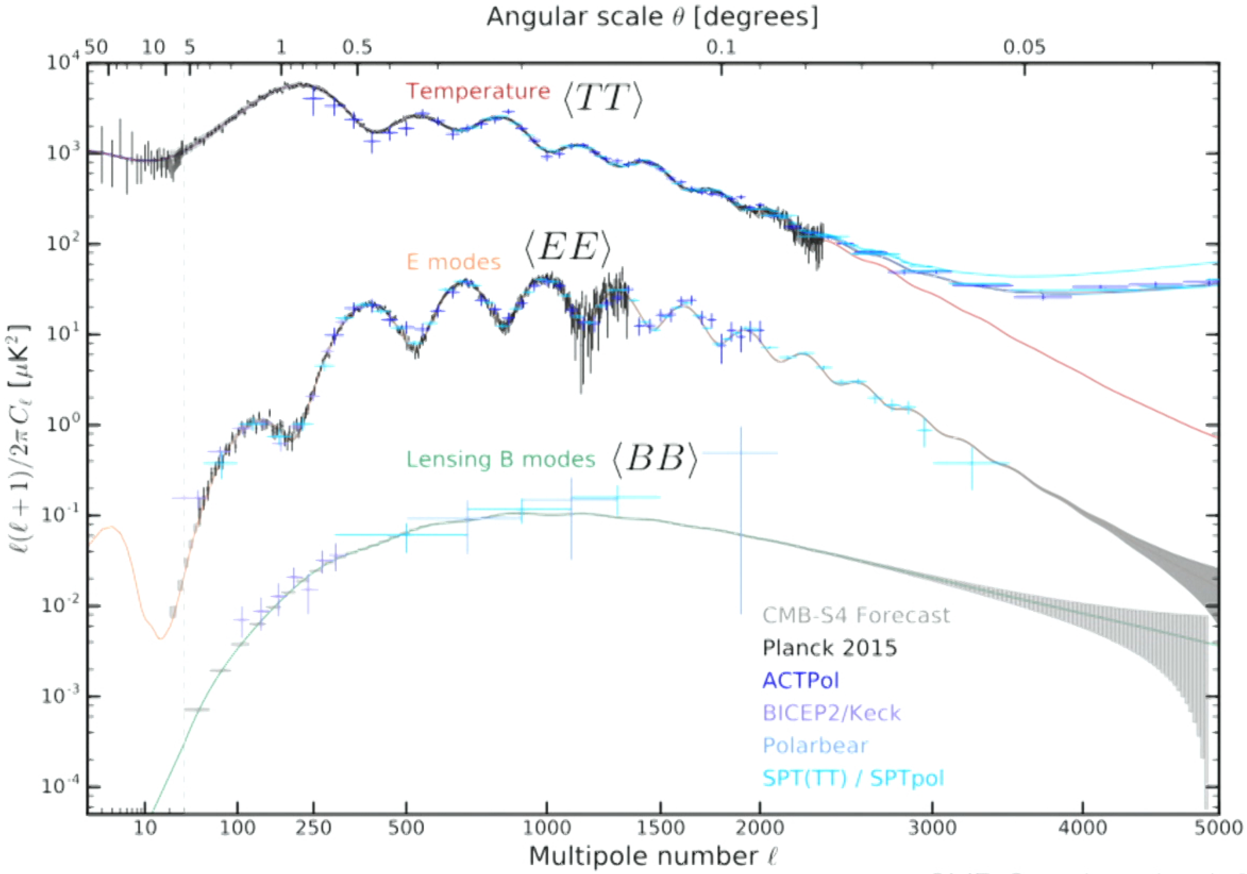
Search for deviations from this simple picture: e.g. primordial tensors and neutrinos

Introduction

Search for deviations from this simple picture:
e.g. primordial tensors and neutrinos

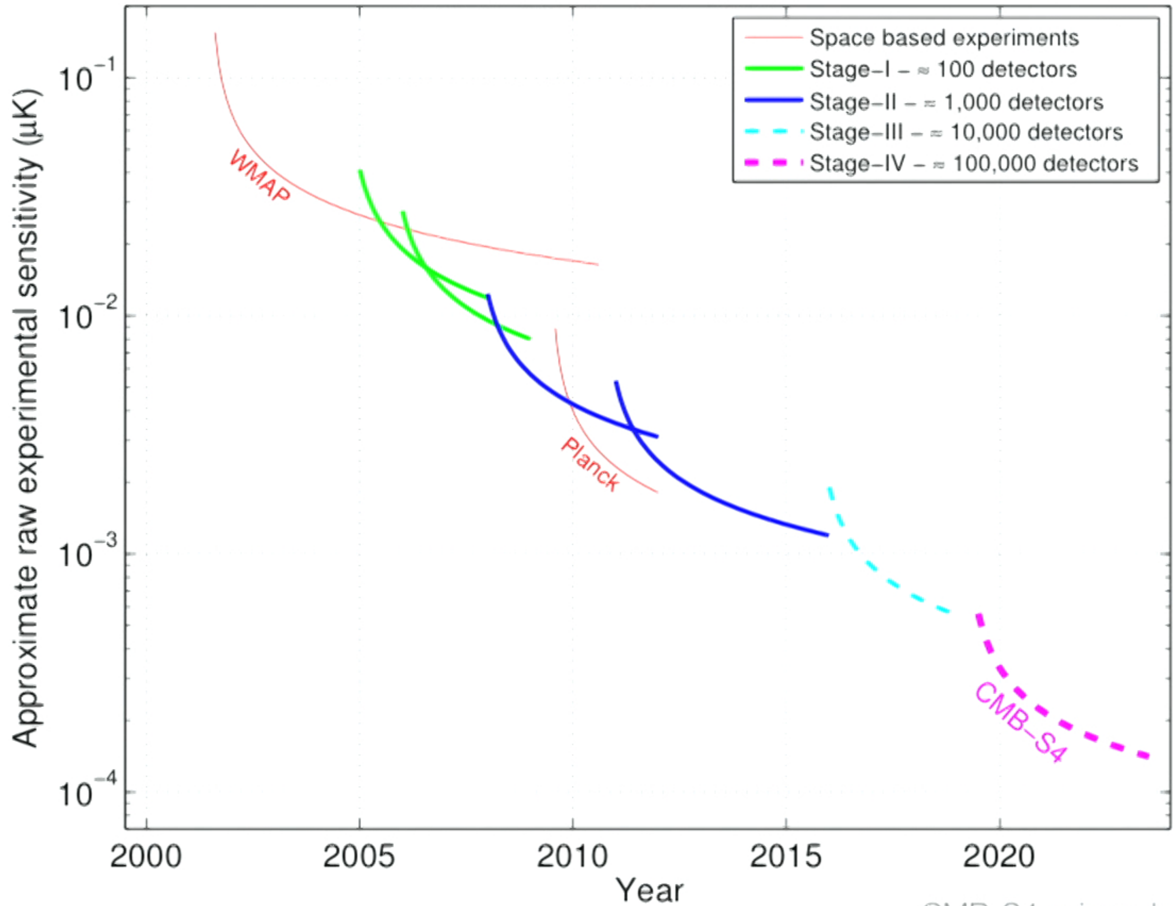
$$\Lambda\text{CDM}+$$

State of the Art



CMB-S4 sciencebook 2016

Moore's Law



CMB-S4 sciencebook 2016

		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	Stage 4 CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO $+\tau_e$ prior	DESI +LSST S4 Clusters
Target		$\mathbf{10^{-8}}$	**0.0005**	**0.027**	**0.015eV**	**1250**

CMB-S4 sciencebook 2016

Next decade of CMB cosmology

Clear targets for future CMB missions:

*Tensor to scalar ratio r

*Sum of mass of neutrinos $\sum m_\nu$

*Number of relativistic species $N_{\rm eff}$

Establishing the Origin of B-modes

Inflation and gravitational waves: LCDM + r

>Inflation naturally produces scalar and tensors degrees of freedom

Establishing the Origin of B-modes

Inflation and gravitational waves: LCDM + r

>Inflation naturally produces scalar and tensors degrees of freedom

>How much? Depends on energy scale of inflation (energy + => tensors +)

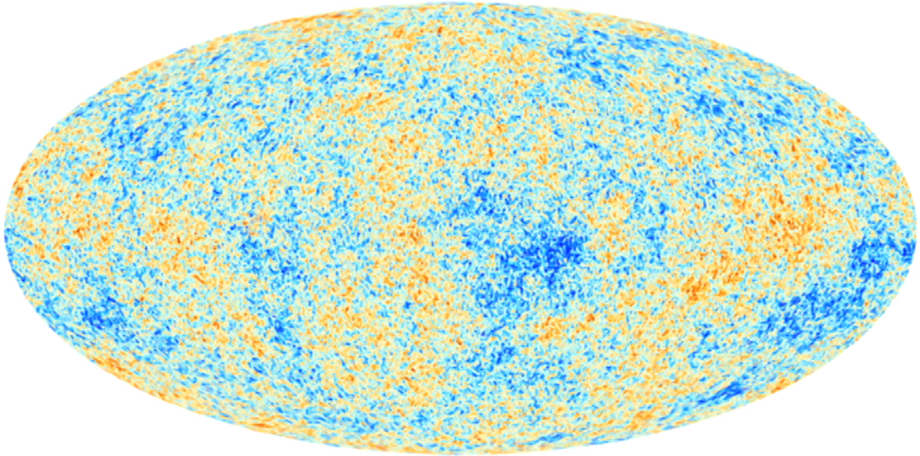
>Can compute distribution:

$$\left\langle h^{\lambda}(\vec{k}_1)h^{\lambda'}(\vec{k}_2)\right\rangle = \frac{(2\pi)^3}{2}\delta(\vec{k}_1+\vec{k}_2)P_h(k)\delta^{\lambda\lambda'}$$

>with:

$$P_h(k) = rA_S k^{-3}\left(\frac{k}{k_0}\right)^{n_T}$$

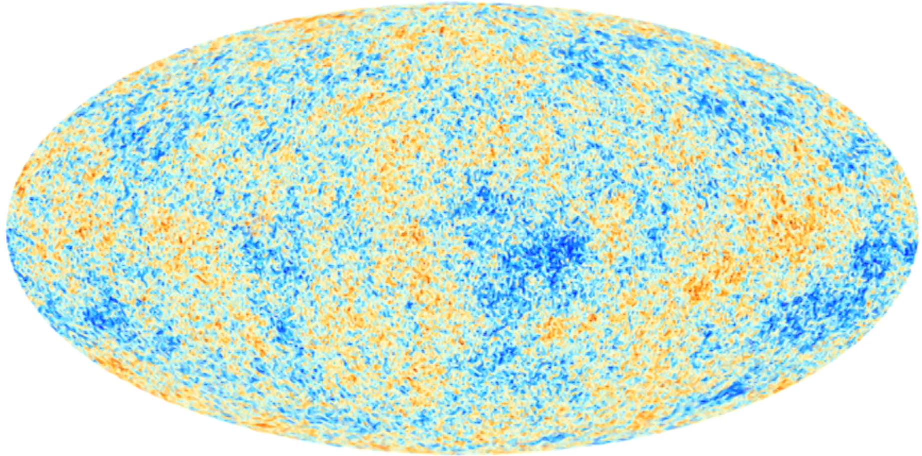
Establishing the Origin of B-modes



Scalars --> {T,E}

Tensors --> {T,E,B}

Establishing the Origin of B-modes

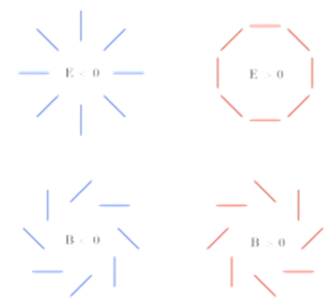


Scalars --> {T,E}

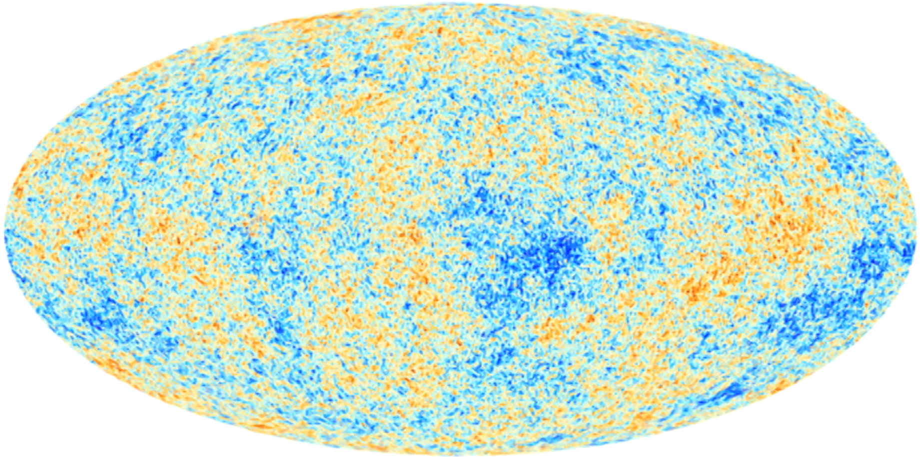
Tensors --> {T,E,B}

B = Divergence Free

E = Curl Free



Establishing the Origin of B-modes

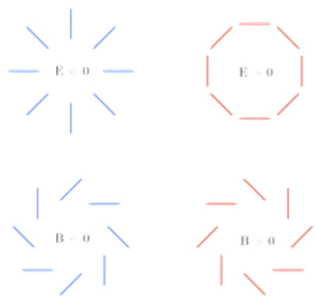


Scalars --> {T,E}

Tensors --> {T,E,B}

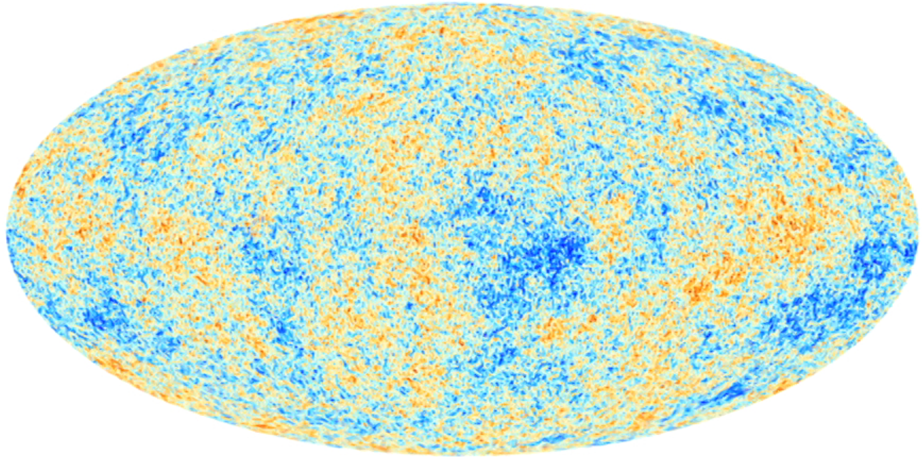
B = Divergence Free

E = Curl Free



B is cleanest channel for tensors

Establishing the Origin of B-modes

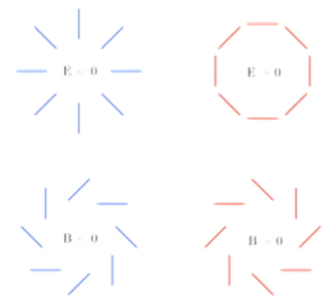


Scalars --> {T,E}

Tensors --> {T,E,B}

B = Divergence Free

E = Curl Free



B is <u>cleanest</u> channel for tensors

However, once measured it is extremely important to establish that these are truly of primordial origin!

Establishing the Origin of B-modes

>Consider another tracer of tensors: Curl lensing modes:

$$X(\hat{\mathbf{n}}) = \tilde{X}(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}) + \nabla \times \Omega(\hat{\mathbf{n}}))$$

Establishing the Origin of B-modes

>Consider another tracer of tensors: Curl lensing modes:

$$X(\hat{\mathbf{n}}) = \tilde{X}(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}) + \nabla \times \Omega(\hat{\mathbf{n}}))$$

>And:

$$\omega(\hat{\mathbf{n}}) = -\frac{1}{2}\nabla^2\Omega(\hat{\mathbf{n}})$$

>Cross-correlate fields:

$$C_\ell^{B\omega} = \frac{2}{\pi}\int dk k^2 P_h(k) T_l^B(k) T_l^{\omega *}(k)$$

Establishing the Origin of B-modes

>Consider another tracer of tensors: Curl lensing modes:

$$X(\hat{\mathbf{n}}) = \tilde{X}(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}) + \nabla \times \Omega(\hat{\mathbf{n}}))$$

>And:

$$\omega(\hat{\mathbf{n}}) = -\frac{1}{2}\nabla^2\Omega(\hat{\mathbf{n}})$$

>Cross-correlate fields:

$$C_\ell^{B\omega} = \frac{2}{\pi}\int dk k^2 P_h(k) T_l^B(k) T_l^{\omega *}(k)$$

>Directly proportional to r

Establishing the Origin of B-modes

>Consider another tracer of tensors: Curl lensing modes:

$$X(\hat{\mathbf{n}}) = \tilde{X}(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}) + \nabla \times \Omega(\hat{\mathbf{n}}))$$

>And:

$$\omega(\hat{\mathbf{n}}) = -\frac{1}{2}\nabla^2\Omega(\hat{\mathbf{n}})$$

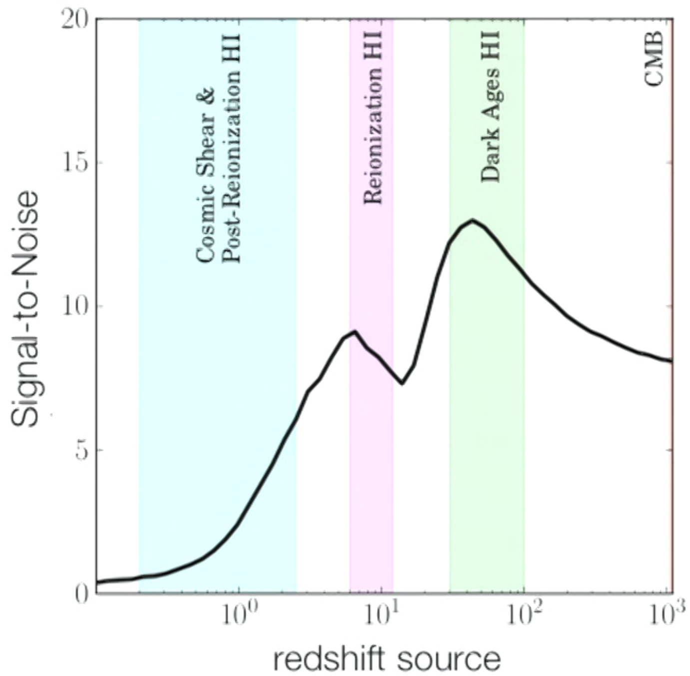
>Cross-correlate fields:

$$C_\ell^{B\omega} = \frac{2}{\pi}\int dk k^2 P_h(k) T_l^B(k) T_l^{\omega *}(k)$$

>Directly proportional to r

>Redshift dependent

Establishing the Origin of B-modes



Sheere, van Engelen, **Meerburg** and Meyers 2016

>Best detectable at high z

>Post-SKA experiment with 100 km baseline (for r = 0.01)

>Would establish the primordial nature of B-modes

>Evidence for LCDM+

Tensors and Non-Gaussianities

Inflation, gravitational waves and NGs: LCDM + r + fNL

Consider 2 additional primordial parameters:

Tensors and Non-Gaussianities

Inflation, gravitational waves and NGs: LCDM + r + fNL

Consider 2 additional primordial parameters:

Tensor to scalar ratio: $r \equiv P_h(k_*)/P_\zeta(k_*)$

Non-Gaussianity: $f_{\rm NL} \propto \langle\zeta\zeta\zeta\rangle/P_\zeta^2(k)$

Tensors and Non-Gaussianities

Inflation, gravitational waves and NGs: LCDM + r + fNL

Consider 2 additional primordial parameters:

Tensor to scalar ratio: $r \equiv P_h(k_*)/P_\zeta(k_*)$

Non-Gaussianity: $f_{\rm NL} \propto \langle\zeta\zeta\zeta\rangle/P_\zeta^2(k)$

This talk: Non-Gaussianity from tensors

$$f_{\rm NL}^{h\zeta\zeta} \equiv \langle h\zeta\zeta\rangle/(P_\zeta^{3/2}P_h^{1/2})$$

Should be sensitive to the tensor to scalar ratio as well as NGs!

Tensors and Non-Gaussianities

-Tensors affect T, E and B modes

Tensors and Non-Gaussianities

-Tensors affect T, E and B modes

-We can constrain tensors using TT (WMAP/Planck)

-Similarly TTT can be used to constrain tensors as well

Tensors and Non-Gaussianities

-Tensors affect T, E and B modes

-We can constrain tensors using TT (WMAP/Planck)

-Similarly TTT can be used to constrain tensors as well

-However, just as TT, it suffers from large cosmic variance

-Hence we choose BB over TT

-Likewise, we should consider BTT (or BEE, BTE) over TTT

Tensors and Non-Gaussianities

Does BTT vanish? No!

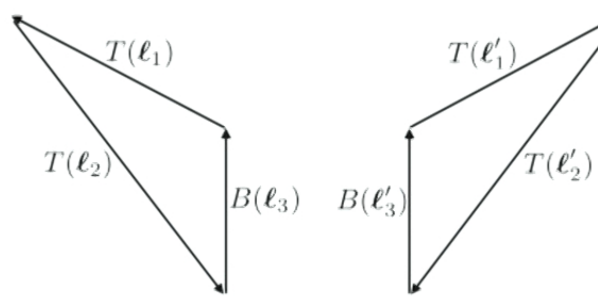
Tensors and Non-Gaussianities

Does BTT vanish? No!

BT is a special case (only non-zero in a parity violating Universe)

All higher order correlation functions containing B/T/E in any combination will have non-zero contributions

In flat-sky:



Motivation

Theoretical

-Non-Gaussianities predicted by a scalar tensor coupling are relatively large (Maldacena 2002)

-Could possibly be used as consistency test (Bordin (2016))

Observational

Motivation

Theoretical

-Non-Gaussianities predicted by a scalar tensor coupling are relatively large (Maldacena 2002)

-Could possibly be used as consistency test (Bordin (2016))

-Would be a smoking gun for new physics (e.g. Hayden, Baumann & Pimentel (2016))

Observational

Motivation

Theoretical

-Non-Gaussianities predicted by a scalar tensor coupling are relatively large (Maldacena 2002)

-Could possibly be used as consistency test (Bordin (2016))

-Would be a smoking gun for new physics (e.g. Hayden, Baumann & Pimentel (2016))

Observational

-Right time: Constraints on B-modes are not yet cosmic variance limited

Motivation

Theoretical

-Non-Gaussianities predicted by a scalar tensor coupling are relatively large (Maldacena 2002)

-Could possibly be used as consistency test (Bordin (2016))

-Would be a smoking gun for new physics (e.g. Hayden, Baumann & Pimentel (2016))

Observational

-Right time: Constraints on B-modes are not yet cosmic variance limited

Less systematics if you cross correlate

Distinguish from non-primordial sources?

Motivation

Theoretical

-Non-Gaussianities predicted by a scalar tensor coupling are relatively large (Maldacena 2002)

-Could possibly be used as consistency test (Bordin (2016))

-Would be a smoking gun for new physics (e.g. Hayden, Baumann & Pimentel (2016))

Observational

-Right time: Constraints on B-modes are not yet cosmic variance limited

Less systematics if you cross correlate

Distinguish from non-primordial sources?

Have total of 10 tracers (as opposed to just 4 for scalars)

Graviton-Scalar-Scalar interaction

What does it look like (generally)?

Schematically:

$$\langle h\zeta\zeta\rangle \propto \sqrt{r}\, f_{\rm NL}^{h\zeta\zeta}\, \delta(\sum \vec{k}_i)\, \mathcal{I}(k_1, k_2, k_3)\, \epsilon_{ij}(k_3)\, \hat{k}_1^i \hat{k}_2^j$$

With

$$\mathcal{I}(k,k,k) \propto k^{-6}$$

And ϵ_{ij} the transverse traceless polarization tensor

Graviton-Scalar-Scalar interaction

What does it look like (generally)?

Schematically:

$$\langle h\zeta\zeta\rangle \propto \sqrt{r}\, f_{\rm NL}^{h\zeta\zeta}\, \delta(\sum \vec{k}_i)\, \mathcal{I}(k_1, k_2, k_3)\, \epsilon_{ij}(k_3)\, \hat{k}_1^i \hat{k}_2^j$$

With

$$\mathcal{I}(k,k,k) \propto k^{-6}$$

And ϵ_{ij} the transverse traceless polarization tensor

Vanishes if scalar mode is aligned with tensor

Signal to Noise

Compute observable bispectrum $B_{\ell_1 \ell_2 \ell_3}$ for different shapes $\mathcal{I}(k_1, k_2, k_3)$

Compute $F_{ii} = \sum_{\text{all modes}} \frac{(B^{BTT})^2}{\text{variance}}$ for 3 experiments:

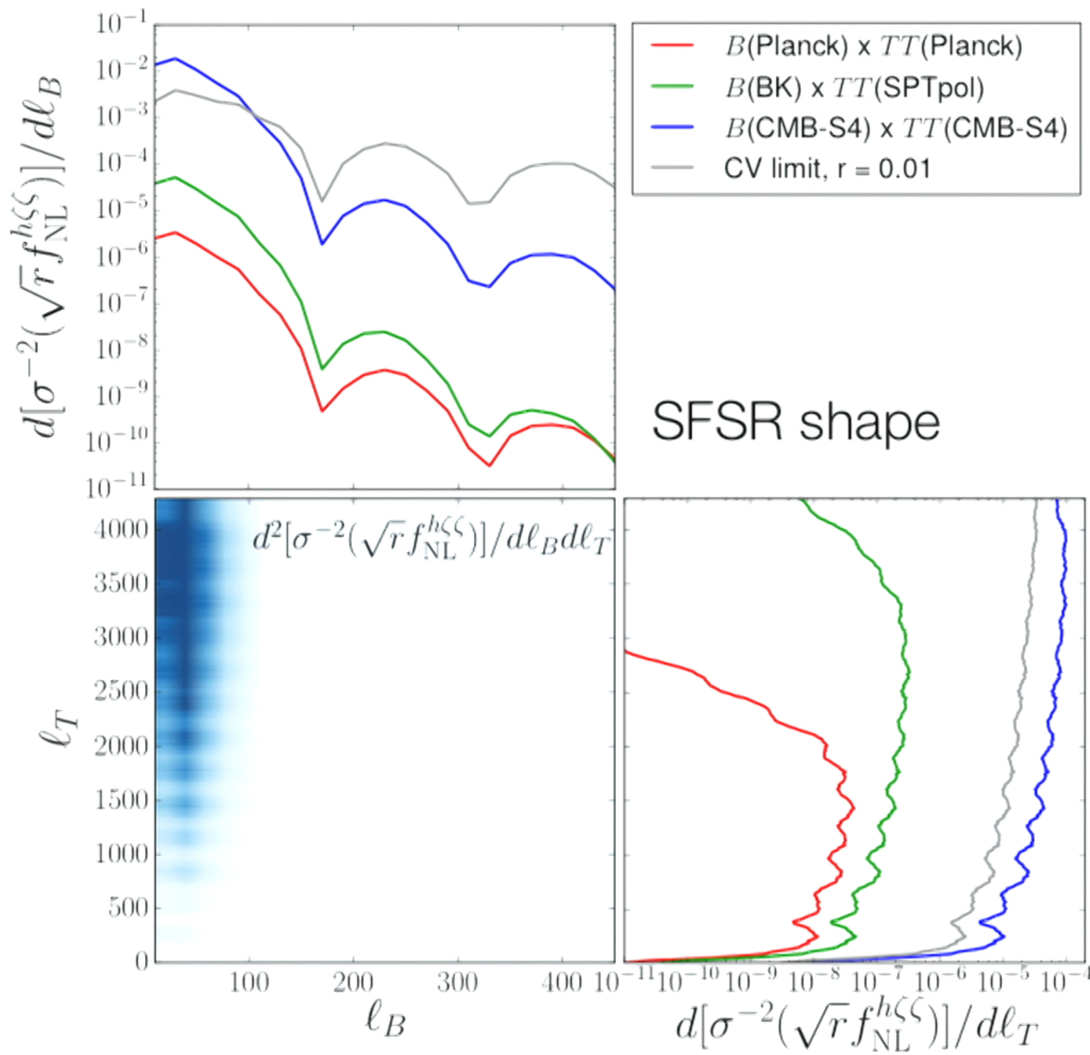
-Planck(B) x Planck (TT)

-BICEP/Keck(B) x SPTpol (TT)

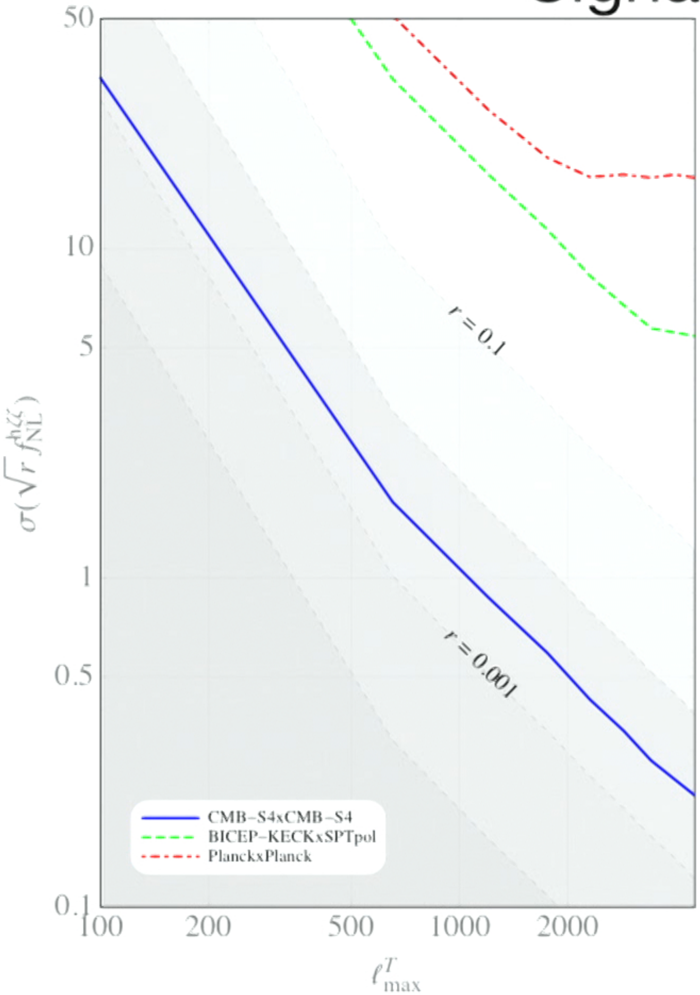
-CMBS4(B) x CMBS4(TT)

1) Noise limited in B

2) And cosmic variance limited (B and T)

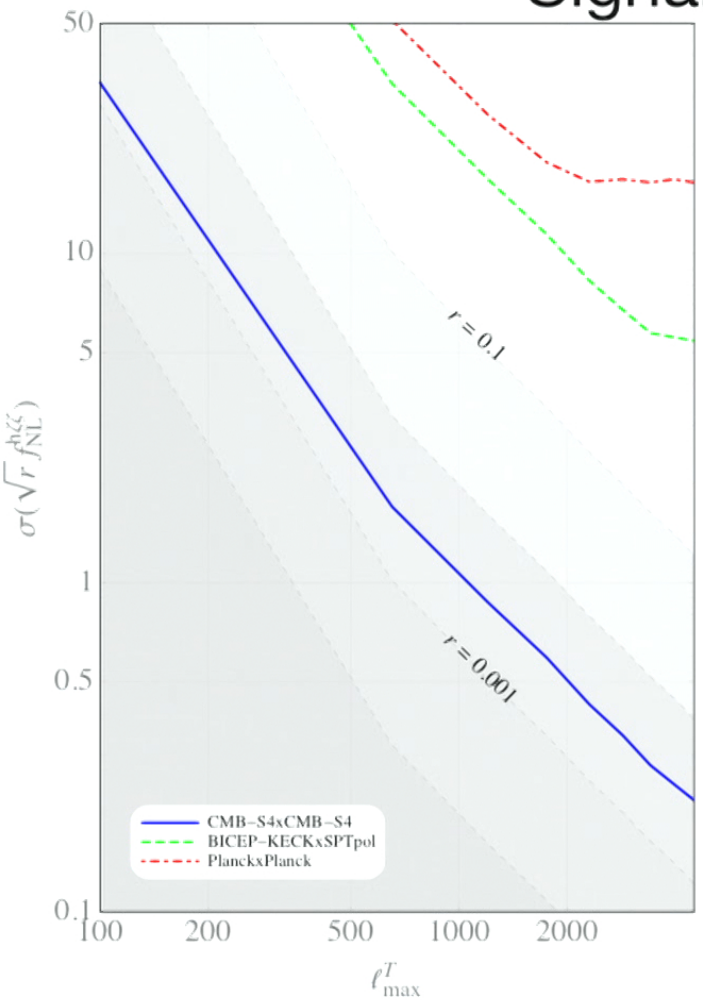

B(Planck) x TT(Planck)
B(BK) x TT(SPTpol)
B(CMB-S4) x TT(CMB-S4)
CV limit, r = 0.01
SFSR shape
$d[\sigma^{-2}(\sqrt{r} f_{\rm NL}^{h\zeta\zeta})]/d\ell_B$
$d^2[\sigma^{-2}(\sqrt{r} f_{\rm NL}^{h\zeta\zeta})]/d\ell_B d\ell_T$
ℓ_T
ℓ_B
$d[\sigma^{-2}(\sqrt{r} f_{\rm NL}^{h\zeta\zeta})]/d\ell_T$

Signal to Noise



PDM, Meyers, van Engelen and Ali-Haïmoud (2016)

Signal to Noise

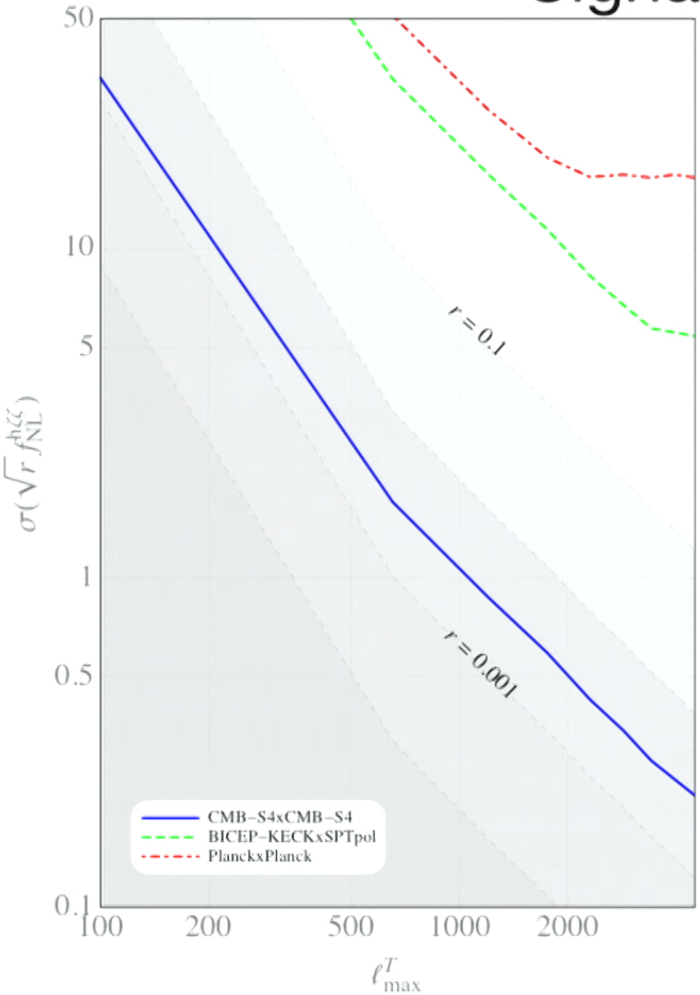


For noise dominated B-modes:

$$\sigma(\sqrt{r} f_{\rm NL}^{h\zeta\zeta}) \sim \mathcal{O}(0.1)$$

PDM, Meyers, van Engelen and Ali-Haïmoud (2016)

Signal to Noise



For noise dominated B-modes:

$$\sigma(\sqrt{r}f_{\rm NL}^{h\zeta\zeta}) \sim \mathcal{O}(0.1)$$

For cosmic variance limited B-modes gray contours e.g. for *r* = 0.01

$$\sigma(\sqrt{r}f_{\rm NL}^{h\zeta\zeta}) \sim \mathcal{O}(0.3)$$

Will get more difficult to measure as *r* gets smaller

PDM, Meyers, van Engelen and Ali-Haïmoud (2016)

Forecast CMB-S4

Future constraints on scalar NGs (TTT,TTE,TEE,EEE)

Type	*Planck* actual (forecast)	CMB-S4	CMB-S4 + low-ℓ *Planck*	Rel. improvement
Local	$\sigma(f_{\rm NL}) = 5\,(4.5)$	$\sigma(f_{\rm NL}) = 2.6$	$\sigma(f_{\rm NL}) = 1.8$	2.5
Equilateral	$\sigma(f_{\rm NL}) = 43\,(45.2)$	$\sigma(f_{\rm NL}) = 21.2$	$\sigma(f_{\rm NL}) = 21.2$	2.1
Orthogonal	$\sigma(f_{\rm NL}) = 21\,(21.9)$	$\sigma(f_{\rm NL}) = 9.2$	$\sigma(f_{\rm NL}) = 9.1$	2.4

Future constraints on tensor NGs (BTT only)

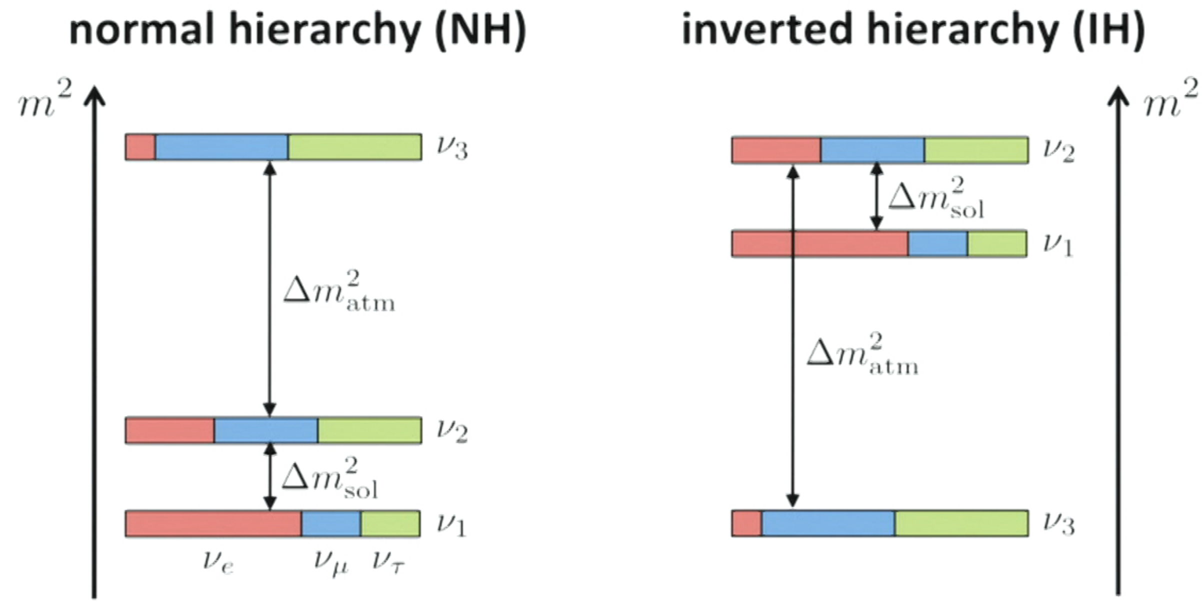
Type	Planck	CMB-S4	rel. improvement
local	$\sigma(\sqrt{r}\,f_{\rm NL}) = 15.2$	$\sigma(\sqrt{r}\,f_{\rm NL}) = 0.3$	50.7
equilateral	$\sigma(\sqrt{r}\,f_{\rm NL}) = 200.5$	$\sigma(\sqrt{r}\,f_{\rm NL}) = 7.4$	27.1
local ($r = 0.01$)	$\sigma(\sqrt{r}\,f_{\rm NL}) = 15.2$	$\sigma(\sqrt{r}\,f_{\rm NL}) = 0.7$	25.3
equilateral ($r = 0.01$)	$\sigma(\sqrt{r}\,f_{\rm NL}) = 200.8$	$\sigma(\sqrt{r}\,f_{\rm NL}) = 14.7$	13.7

CMB-S4 Science book.

Relative improvement compared to 'current' best constraints is almost 2 orders of magnitude

Neutrinos

Neutrinos: LCDM + mnu



Normal Hierarchy:

$$\sum m_\nu \geq 58 \text{ meV}$$

$\sigma_{m_\nu} = 20$ meV for 3σ detection

Inverted Hierarchy:

$$\sum m_\nu \geq 105 \text{ meV}$$

$\sigma_{m_\nu} = 35$ meV for 3σ detection

Neutrinos

The effect of massive Neutrinos:

Suppress formation on small scales

Add to matter density

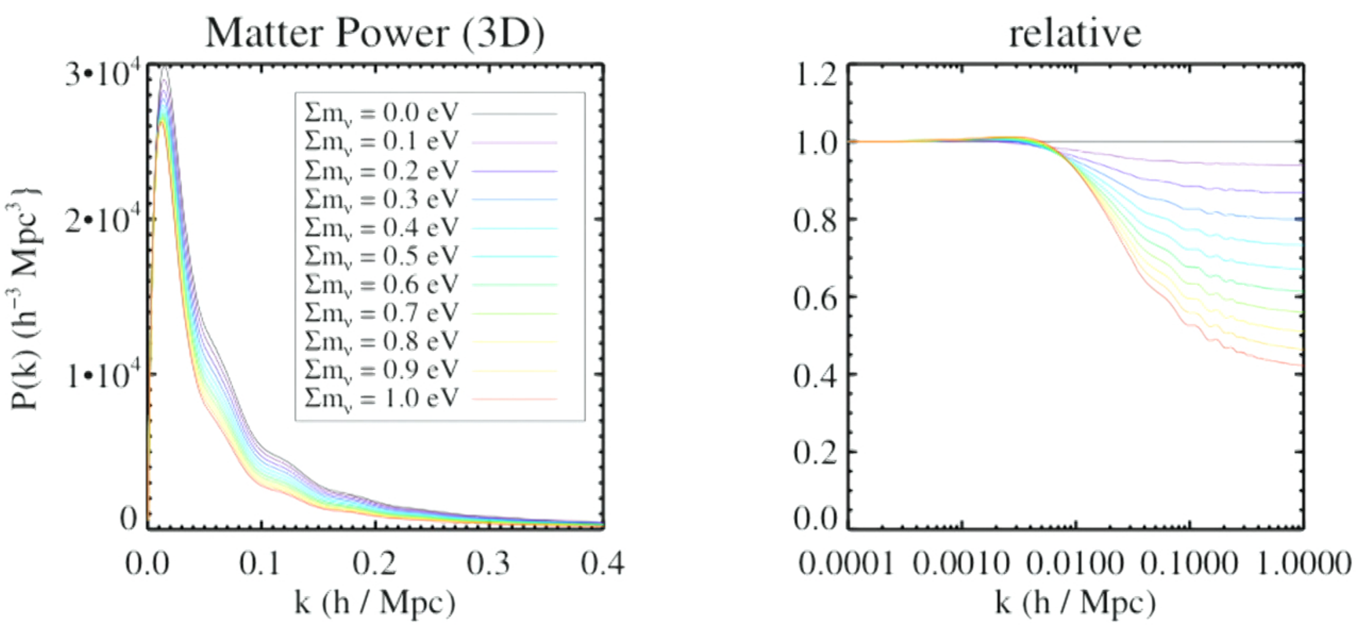
CMB-S4 sciencebook 2016

Neutrinos

The effect of massive Neutrinos:

Suppress formation on small scales

Add to matter density



CMB-S4 sciencebook 2016

Neutrinos and the optical depth τ

Measuring the mass of the neutrinos requires an exquisite measure of overall power A_s

Neutrinos and the optical depth τ

Measuring the mass of the neutrinos requires an exquisite measure of overall power A_s

However power is measured as $A_s e^{-2\tau}$

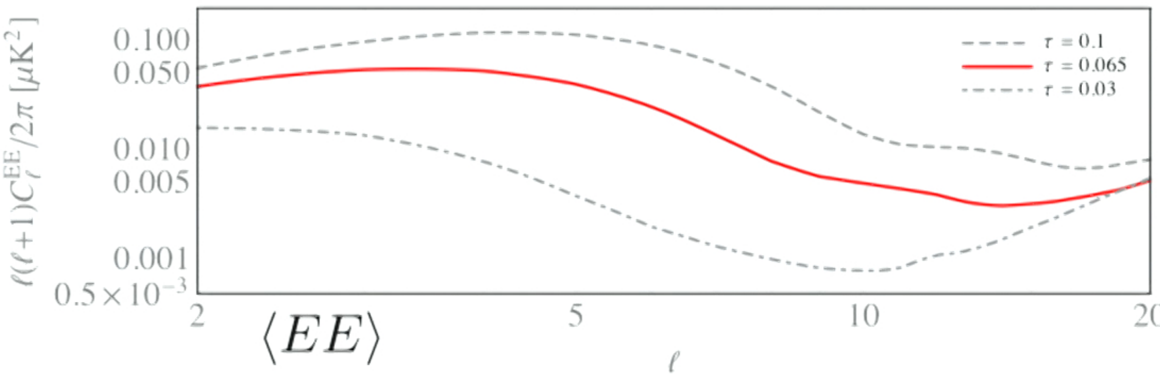
Neutrinos and the optical depth τ

Measuring the mass of the neutrinos requires an exquisite measure of overall power A_s

However power is measured as $A_s e^{-2\tau}$

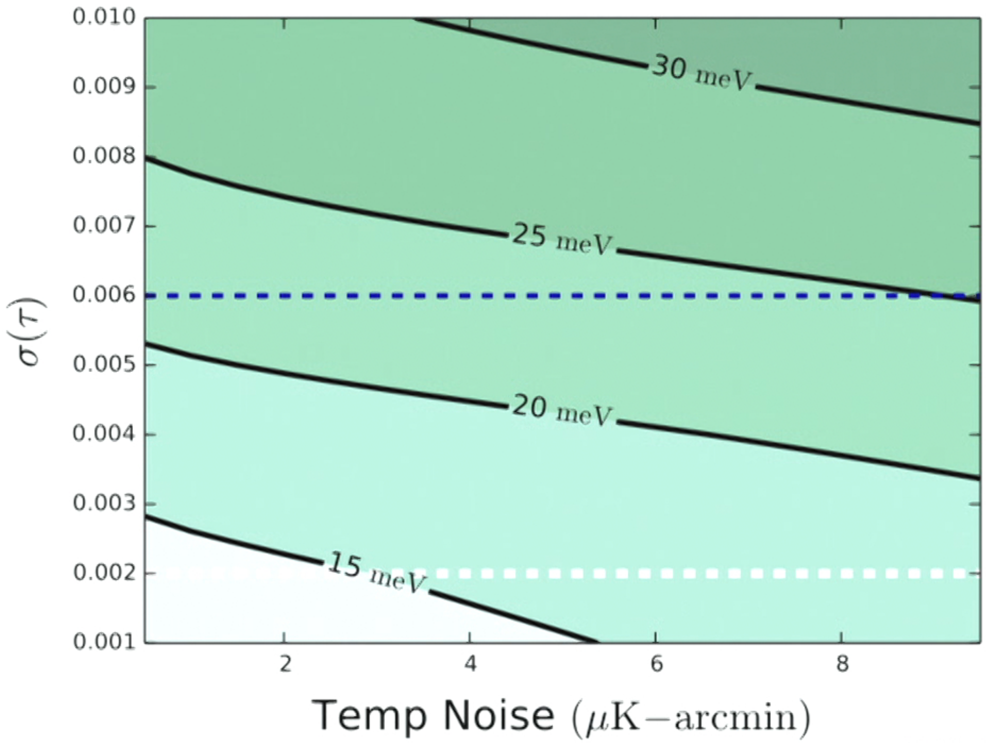
This is a degeneracy

Can only be broken using large scale E-mode polarization; $E \propto \tau$ reionization bump



Neutrinos and the optical depth τ

The problem at hand:



CMB-S4 sciencebook 2016

Neutrinos and the optical depth τ

What to do?

1) Measure directly from the ground

Neutrinos and the optical depth τ

What to do?

1) Measure directly from the ground

2) Build a new satellite

3) Find alternative measures

Neutrinos and the optical depth τ

What to do?

1) Measure directly from the ground

*Large foregrounds in T, T to E leakage
*Rotating Half-wave plates E.g. BICEP/KECK (lmin = 50)
*Need lmin = 2-5. CLASS

2) Build a new satellite

3) Find alternative measures

Neutrinos and the optical depth τ

What to do?

1) Measure directly from the ground

*Large foregrounds in T, T to E leakage
*Rotating Half-wave plates E.g. BICEP/KECK (lmin = 50)
*Need lmin = 2-5. CLASS

2) Build a new satellite

*CORE (no funds)
*Litebird (no funds yet?)
*PIXIE (no funds yet?)

3) Find alternative measures

Neutrinos and the optical depth τ

What to do?

1) Measure directly from the ground

*Large foregrounds in T, T to E leakage
*Rotating Half-wave plates E.g. BICEP/KECK (lmin = 50)
*Need lmin = 2-5. CLASS

2) Build a new satellite

*CORE (no funds)
*Litebird (no funds yet?)
*PIXIE (no funds yet?)

3) Find alternative measures

*21cm? Will depend on modeling of the signal
*Using small scale CMB?

Reconstructing CMB fluctuations

Idea:

>E-modes are be ‘converted’ into B-modes

Reconstructing CMB fluctuations

Idea:

>E-modes are be ‘converted’ into B-modes

>This happens on all scales in E to all scales in B

Reconstructing CMB fluctuations

Idea:

>E-modes are be ‘converted’ into B-modes

>This happens on all scales in E to all scales in B

>Most well-known example is lensing B-modes

Reconstructing CMB fluctuations

Idea:

>E-modes are be 'converted' into B-modes

>This happens on all scales in E to all scales in B

>Most well-known example is lensing B-modes

>In a no-tensor Universe, there are only lensing B-modes

Reconstructing CMB fluctuations

Idea:

>E-modes are be 'converted' into B-modes

>This happens on all scales in E to all scales in B

>Most well-known example is lensing B-modes

>In a no-tensor Universe, there are only lensing B-modes

>Specifically, there is a non-zero 3p function

$$\langle EB\phi \rangle \neq 0$$

first detected by the SPT collaboration in 2013

Reconstructing CMB fluctuations

Idea:

>E-modes are be 'converted' into B-modes

>This happens on all scales in E to all scales in B

>Most well-known example is lensing B-modes

>In a no-tensor Universe, there are only lensing B-modes

>Specifically, there is a non-zero 3p function

$$\langle EB\phi \rangle \neq 0$$

first detected by the SPT collaboration in 2013

>We will use this non-zero 3p function to 'reconstruct' E modes on large scales using only small scale B modes.

Reconstructing CMB fluctuations

Idea:

>E-modes are be ‘converted’ into B-modes

>This happens on all scales in E to all scales in B

>Most well-known example is lensing B-modes

>In a no-tensor Universe, there are only lensing B-modes

>Specifically, there is a non-zero 3p function

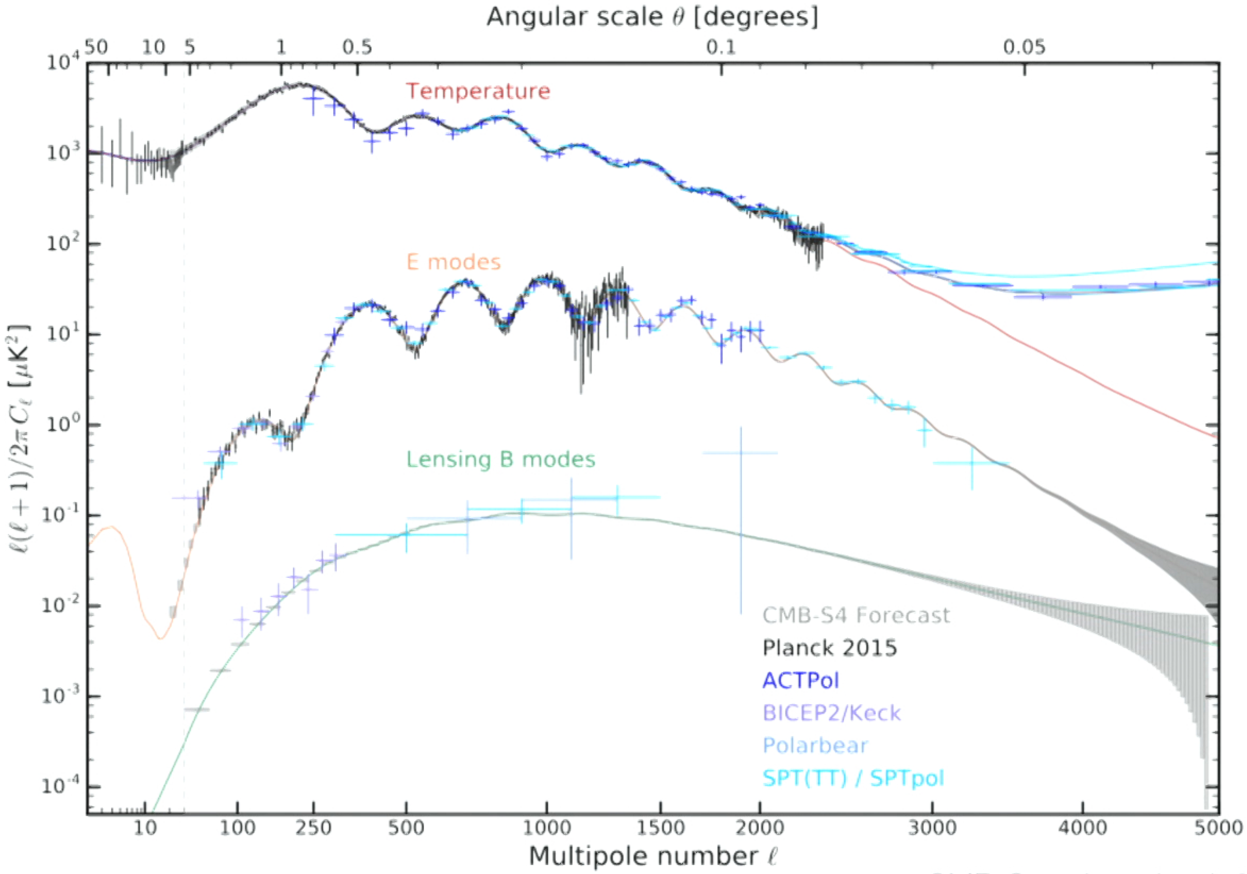
$$\langle EB\phi \rangle \neq 0$$

first detected by the SPT collaboration in 2013

>We will use this non-zero 3p function to ‘reconstruct’ E modes on large scales using only small scale B modes.

>>Also works for screened B-modes and Birefringence.

Reconstructing CMB fluctuations



CMB-S4 sciencebook 2016

Reconstructing CMB fluctuations

Can derive minimum variance quadratic estimator for E and reconstruction Noise:

$$N_\ell^{\hat{E}\hat{E}} \propto \left[\sum_{\ell_1 \ell_2} o_{\ell_1 \ell_2 \ell} \frac{(2\ell_1+1)(2\ell_2+1)}{4\pi} (J_{\ell_1 \ell_2 \ell})^2 \left(\frac{1}{C_{\ell_1}^{BB} + N_{\ell_1}^{BB}} \right) \left(\frac{(C_{\ell_2}^{\phi\phi})^2}{C_{\ell_2}^{\phi\phi} + N_{\ell_2}^{\phi\phi}} \right) \right]^{-1}$$

Reconstructing CMB fluctuations

Can derive minimum variance quadratic estimator for E and reconstruction Noise:

$$N_\ell^{\hat{E}\hat{E}} \propto \left[\sum_{\ell_1 \ell_2} o_{\ell_1 \ell_2 \ell} \frac{(2\ell_1+1)(2\ell_2+1)}{4\pi}(J_{\ell_1 \ell_2 \ell})^2 \left(\frac{1}{C_{\ell_1}^{BB}+N_{\ell_1}^{BB}}\right)\left(\frac{(C_{\ell_2}^{\phi\phi})^2}{C_{\ell_2}^{\phi\phi}+N_{\ell_2}^{\phi\phi}}\right)\right]^{-1}$$

-Depends on B noise

-Depends on lensing noise

-Strong function of cosmic variance

Reconstructing CMB fluctuations

Can derive minimum variance quadratic estimator for E and reconstruction Noise:

$$N_\ell^{\hat{E}\hat{E}} \propto \left[\sum_{\ell_1 \ell_2} o_{\ell_1 \ell_2 \ell} \frac{(2\ell_1+1)(2\ell_2+1)}{4\pi} (J_{\ell_1 \ell_2 \ell})^2 \left(\frac{1}{C_{\ell_1}^{BB} + N_{\ell_1}^{BB}}\right) \left(\frac{(C_{\ell_2}^{\phi\phi})^2}{C_{\ell_2}^{\phi\phi} + N_{\ell_2}^{\phi\phi}}\right)\right]^{-1}$$

-Depends on B noise

-Depends on lensing noise

-Strong function of cosmic variance

-Can 'delens' as much as possible (using all information including T), i.e. $C_\ell^{BB} \rightarrow C_\ell^{\mathrm{res},BB}$

Reconstructing CMB fluctuations

Can derive minimum variance quadratic estimator for E and reconstruction Noise:

$$N_\ell^{\hat{E}\hat{E}} \propto \left[\sum_{\ell_1 \ell_2} o_{\ell_1 \ell_2 \ell} \frac{(2\ell_1+1)(2\ell_2+1)}{4\pi} (J_{\ell_1 \ell_2 \ell})^2 \left(\frac{1}{C_{\ell_1}^{BB} + N_{\ell_1}^{BB}} \right) \left(\frac{(C_{\ell_2}^{\phi\phi})^2}{C_{\ell_2}^{\phi\phi} + N_{\ell_2}^{\phi\phi}} \right) \right]^{-1}$$

-Depends on B noise

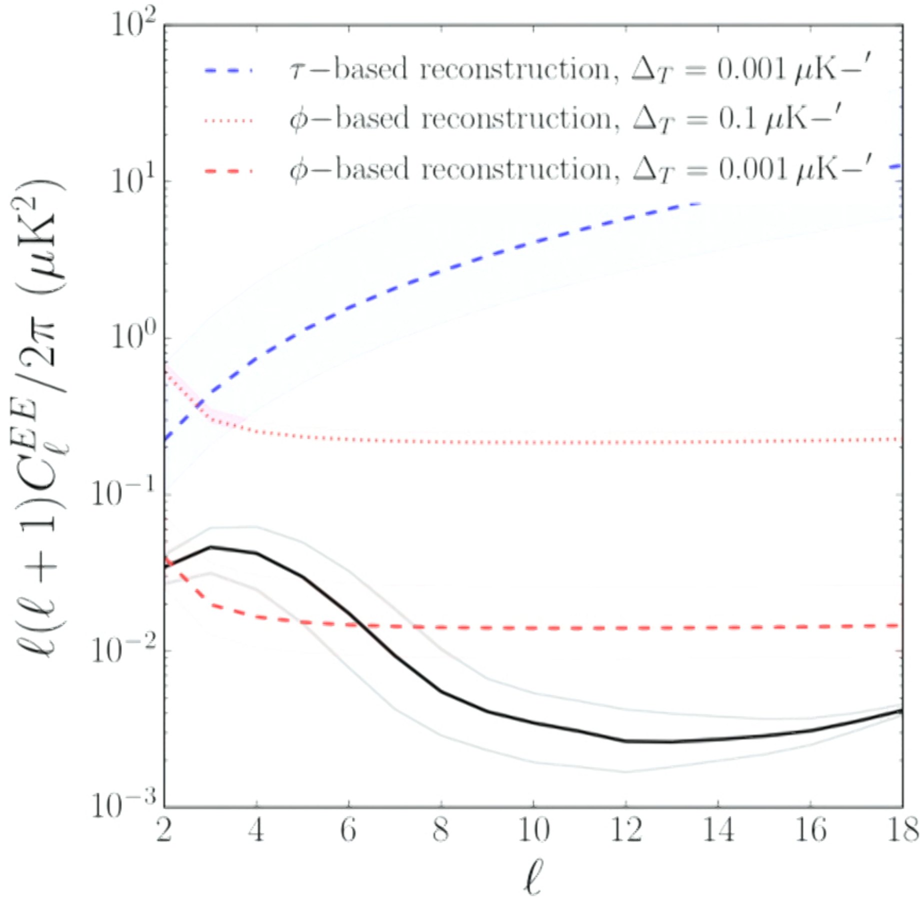
-Depends on lensing noise

-Strong function of cosmic variance

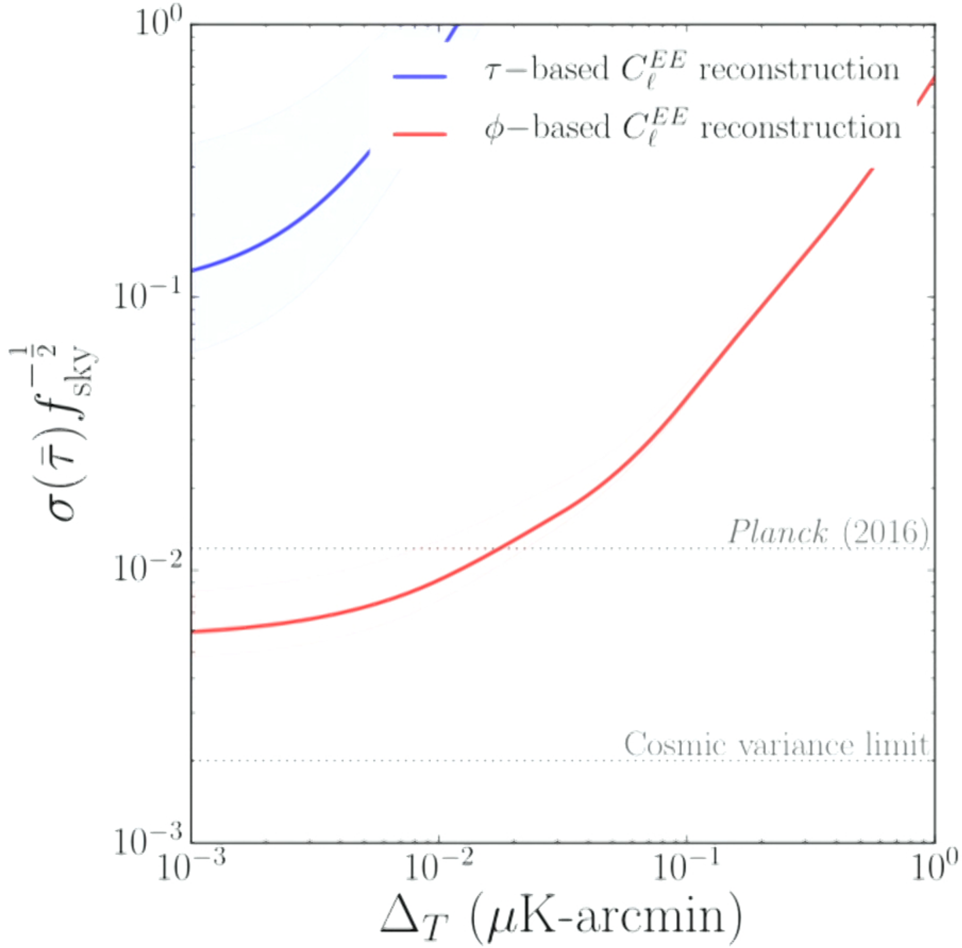
-Can ‘delens’ as much as possible (using all information including T), i.e. $C_\ell^{BB} \to C_\ell^{\mathrm{res},BB}$

-caveat: reionization bump is created at z ~ 10. Can not use lensing potential from CMB directly (z ~ 1100), use cross correlation coefficient (see paper)

Reconstructing CMB fluctuations



Reconstructing CMB fluctuations



Reconstructing CMB fluctuations

Reconstruction could work!

-mitigates need for a satellite or possible foreground leakage (T to E) or detailed modeling (21cm)

Reconstructing CMB fluctuations

Reconstruction could work!

-mitigates need for a satellite or possible foreground leakage (T to E) or detailed modeling (21cm)

Need very low noise (beyond CMB-S4)

Possible improvements can be achieved:

Reconstructing CMB fluctuations

Reconstruction could work!

-mitigates need for a satellite or possible foreground leakage (T to E) or detailed modeling (21cm)

Need very low noise (beyond CMB-S4)

Possible improvements can be achieved:

>Having a map of the lensing potential at low z (e.g. using 21cm lensing)

>Having a direct measurement of the low z patchy screening signal (e.g. using direct measurement of dusty galaxies)

>Could improve this by a factor 2 for very low noise if also using E (lensed into E)

Reconstructing CMB fluctuations

Reconstruction could work!

-mitigates need for a satellite or possible foreground leakage (T to E) or detailed modeling (21cm)

Need very low noise (beyond CMB-S4)

Possible improvements can be achieved:

>Having a map of the lensing potential at low z (e.g. using 21cm lensing)

>Having a direct measurement of the low z patchy screening signal (e.g. using direct measurement of dusty galaxies)

>Could improve this by a factor 2 for very low noise if also using E (lensed into E)

Other applications??

Reconstructing CMB fluctuations

Yes: primordial dipole.

TT dipole now completely swamped by kinematic dipole from our movement through the galaxy (relative to the CMB rest frame)

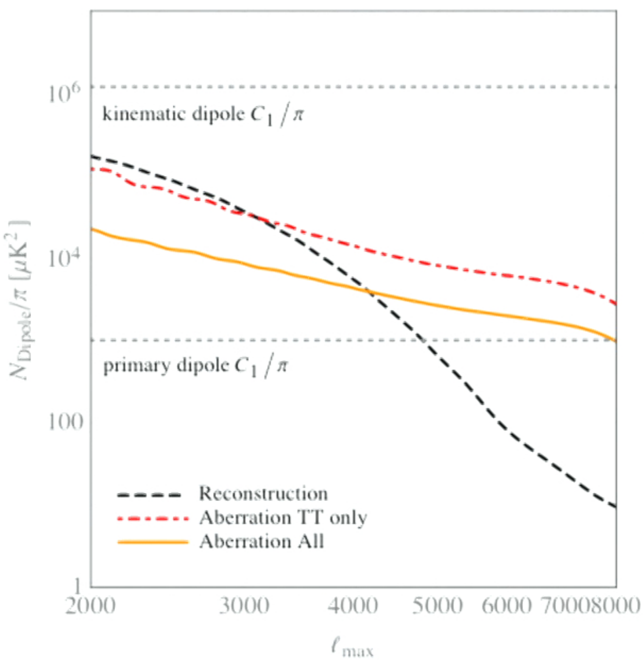
Not the case for lensed TT into small TT. Not as clear as lensing B modes since there is large cosmic variance from the scalar mode

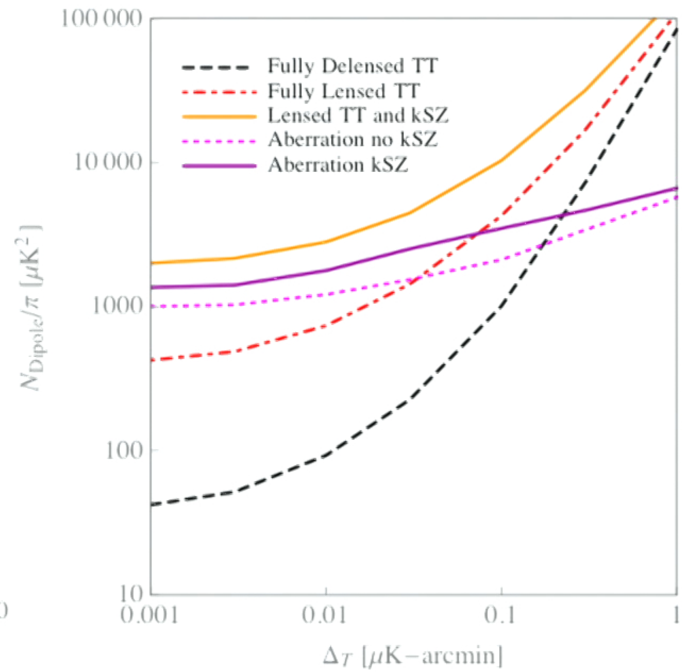
Still, can use all modes measured above l = 1, i.e. l = 2 and up

Write down estimator, very similar (even bispectrum instead of odd): $\langle TT\phi \rangle$

Reconstructing CMB fluctuations

Preliminary





Meerburg, Meyers, van Engelen, in prep 2017

Reconstructing CMB fluctuations

What could you do with this?

>map out the earliest times when the largest modes left the horizon during inflation

Meerburg, Meyers, van Engelen, in prep 2017

Reconstructing CMB fluctuations

What could you do with this?

>map out the earliest times when the largest modes left the horizon during inflation

>test early universe models that predict specific dipole (e.g. bubble Universe)

Meerburg, Meyers, van Engelen, in prep 2017

Reconstructing CMB fluctuations

What could you do with this?

>map out the earliest times when the largest modes left the horizon during inflation

>test early universe models that predict specific dipole (e.g. bubble Universe)

>measure local NG with a 10% improvement (just having this single mode to cosmic variance)

Meerburg, Meyers, van Engelen, in prep 2017

Reconstructing CMB fluctuations

What could you do with this?

>map out the earliest times when the largest modes left the horizon during inflation

>test early universe models that predict specific dipole (e.g. bubble Universe)

>measure local NG with a 10% improvement (just having this single mode to cosmic variance)

>constraining super horizon isocurvature modes

Meerburg, Meyers, van Engelen, in prep 2017

Conclusions

>Next decade of CMB cosmology will aim for a detection of

Conclusions

>Next decade of CMB cosmology will aim for a detection of

the tensor-to-scalar ratio

sum of the neutrino masses

Conclusions

>Next decade of CMB cosmology will aim for a detection of

the tensor-to-scalar ratio

sum of the neutrino masses

deviations from the standard number of relativistic species

Conclusions

>Next decade of CMB cosmology will aim for a detection of

the tensor-to-scalar ratio

sum of the neutrino masses

deviations from the standard number of relativistic species

>Once detected, cross-correlating B-modes with curl lensing field could confirm primordial origin

Conclusions

>Next decade of CMB cosmology will aim for a detection of

the tensor-to-scalar ratio

sum of the neutrino masses

deviations from the standard number of relativistic species

>Once detected, cross-correlating B-modes with curl lensing field could confirm primordial origin

>Looking beyond the power spectrum, couplings between tensors and scalars present a new window into the early Universe

>Sum of the neutrino masses depends on our constraint of the optical depth

>We proposed a new method to obtain constraints on large angle E-modes

Conclusions

>Next decade of CMB cosmology will aim for a detection of

the tensor-to-scalar ratio

sum of the neutrino masses

deviations from the standard number of relativistic species

>Once detected, cross-correlating B-modes with curl lensing field could confirm primordial origin

>Looking beyond the power spectrum, couplings between tensors and scalars present a new window into the early Universe

>Sum of the neutrino masses depends on our constraint of the optical depth

>We proposed a new method to obtain constraints on large angle E-modes

>Could have other practical applications (features, dipole)