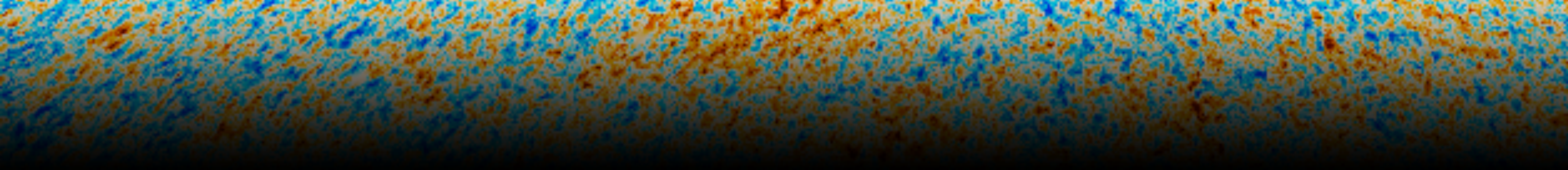
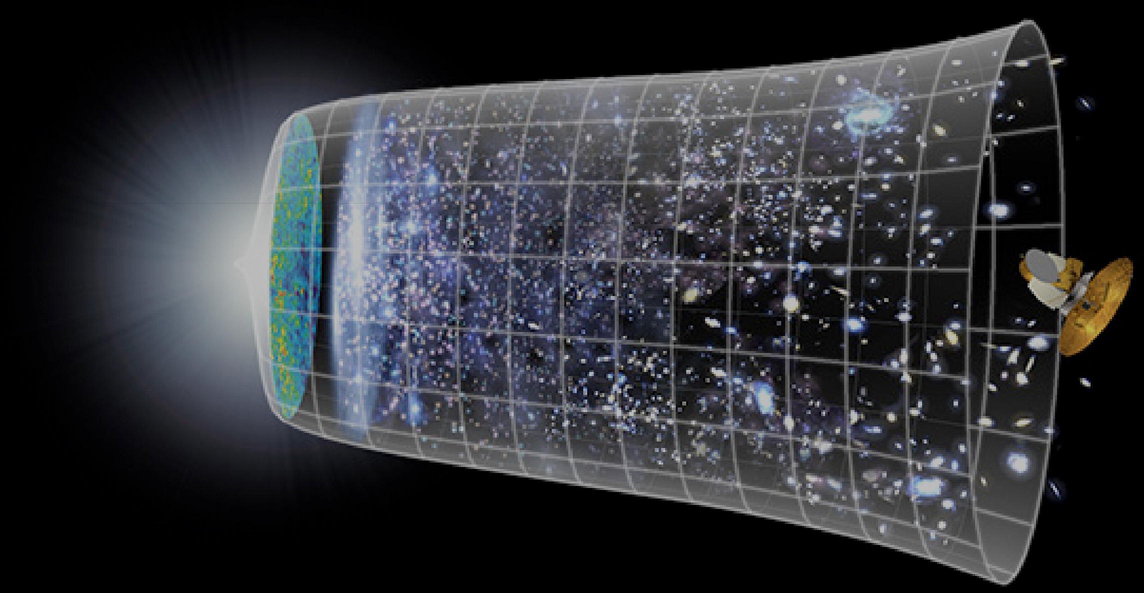


Deciphering the Beginning

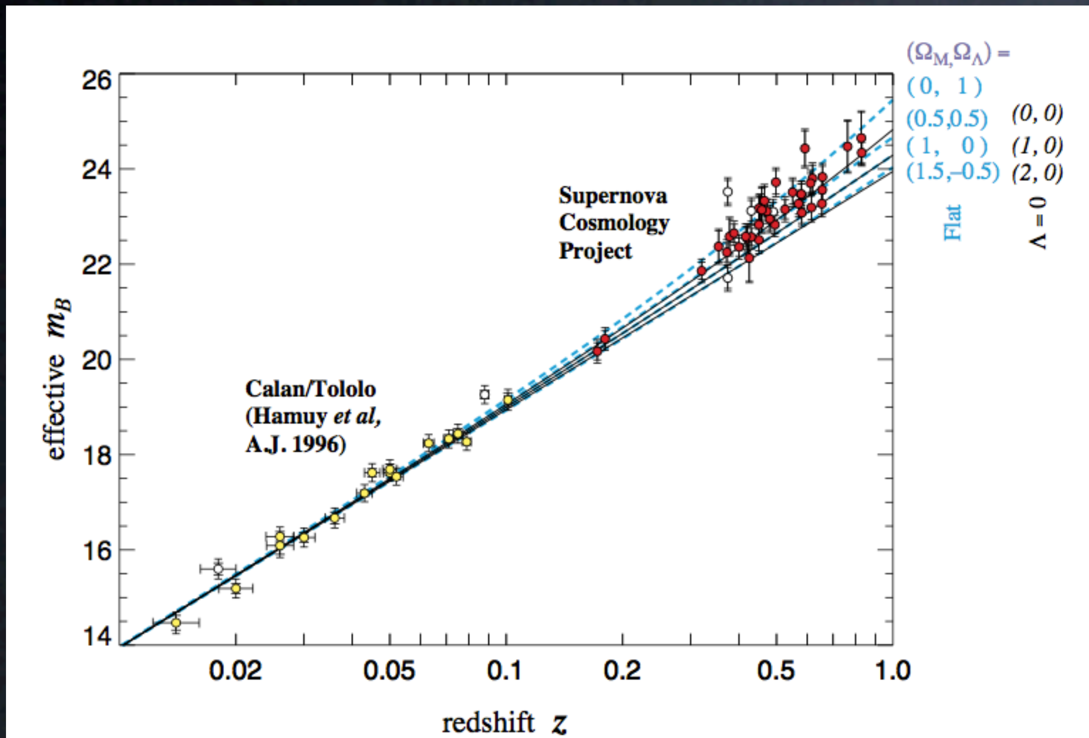
Raphael Flauger

RPM Seminar, Lawrence Berkeley Lab, March 26, 2024

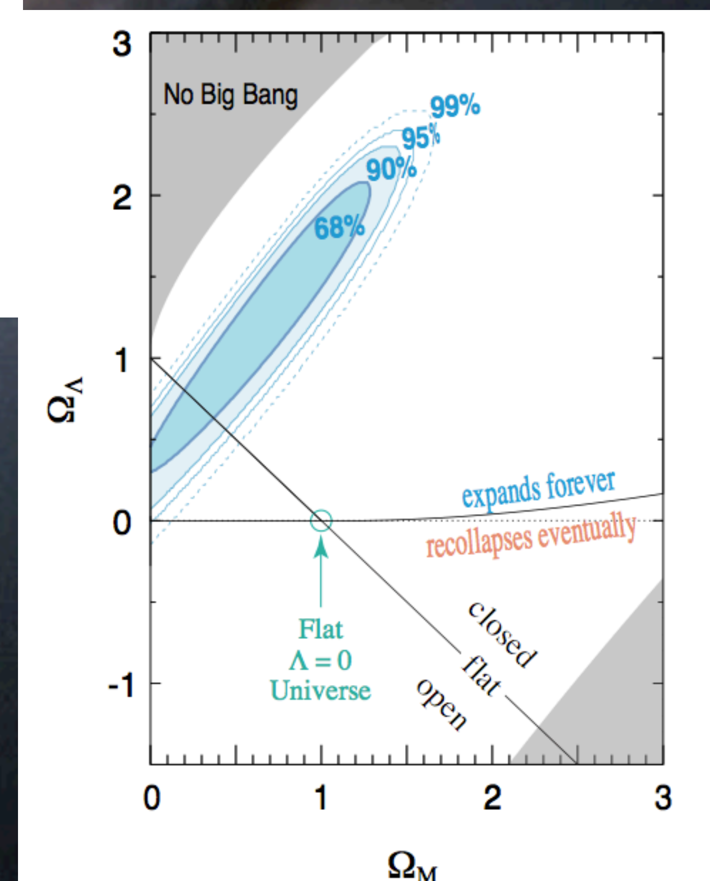
Cosmic history



Cosmic history

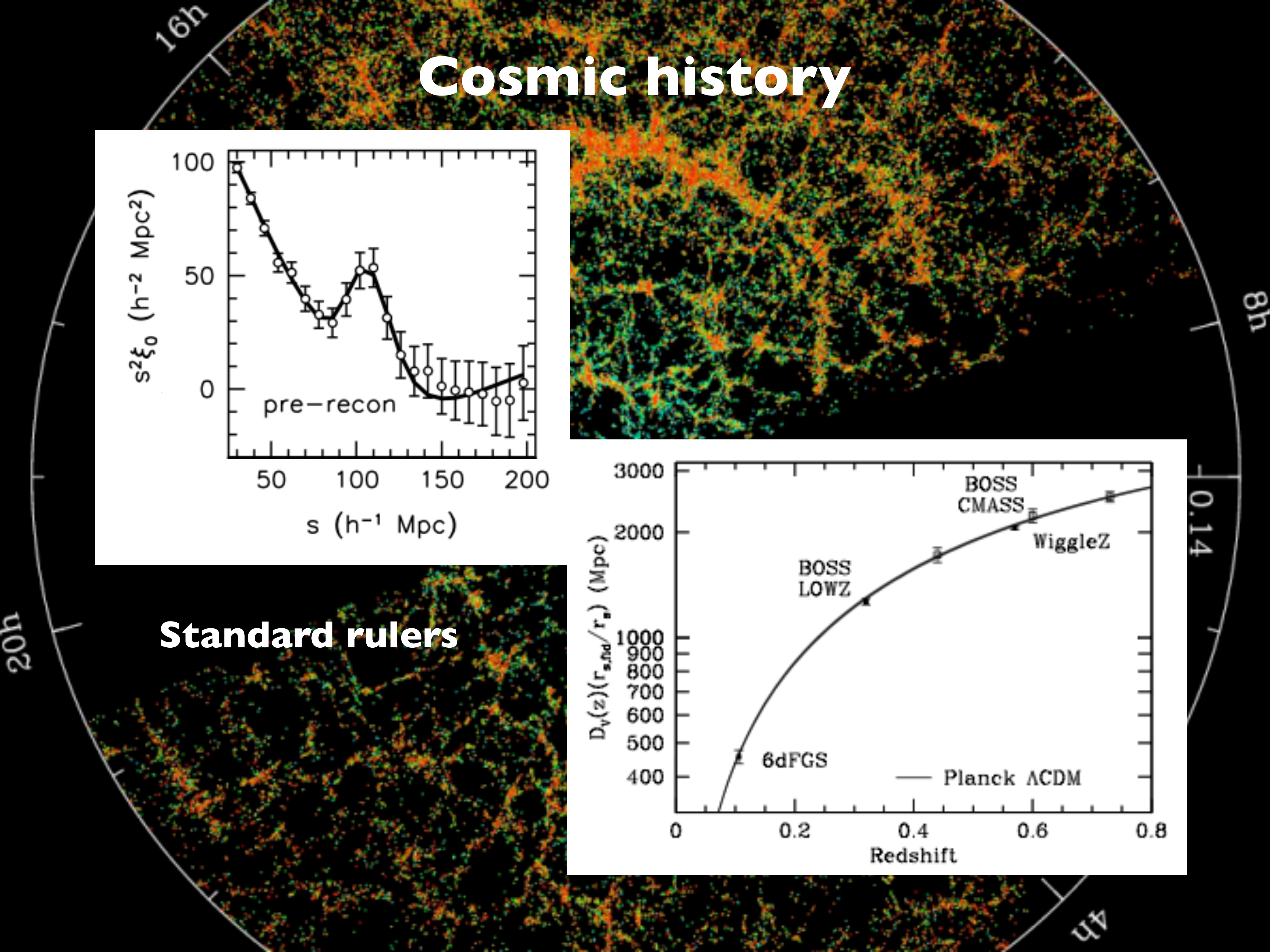


Standard candles

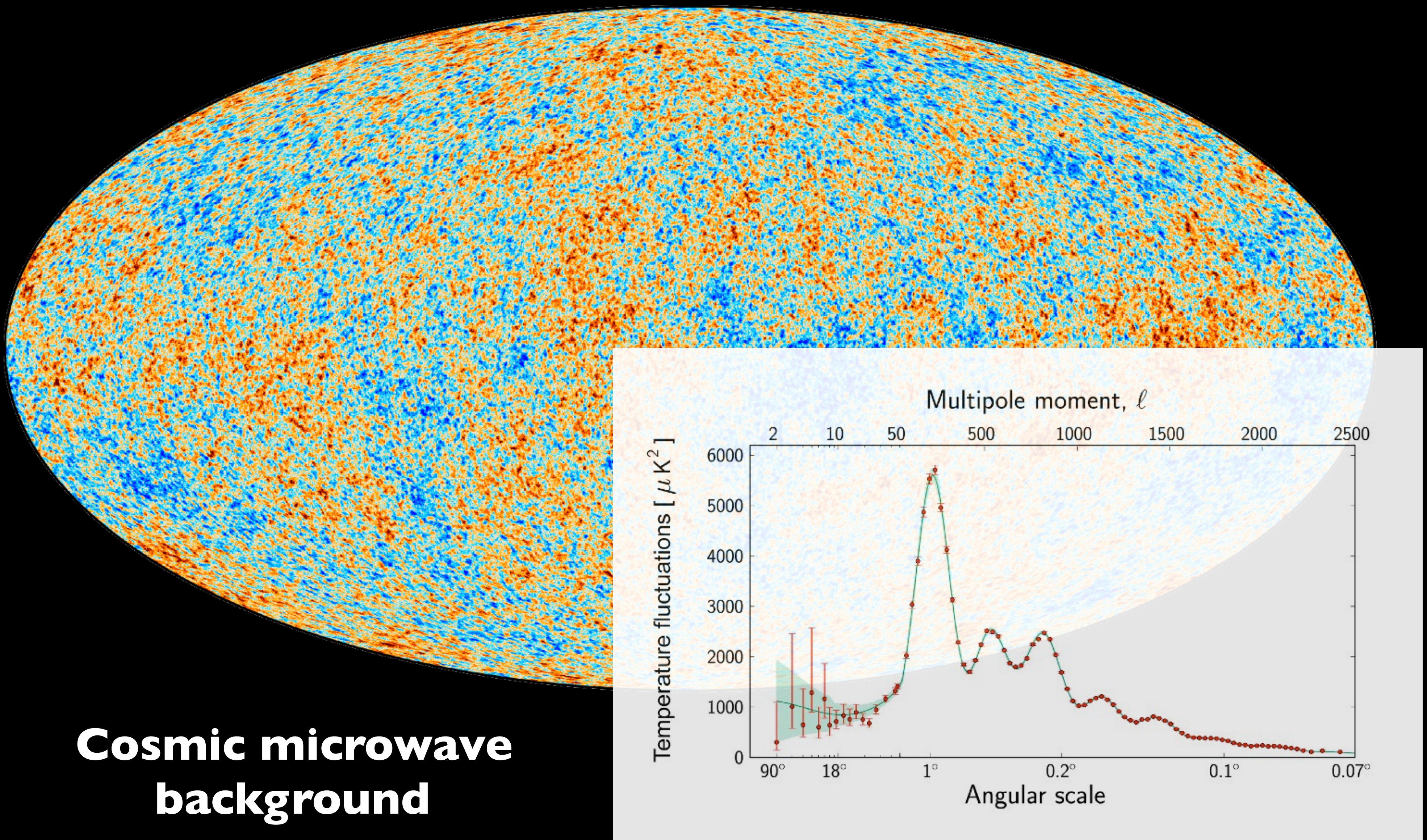


Cosmic history

Standard rulers

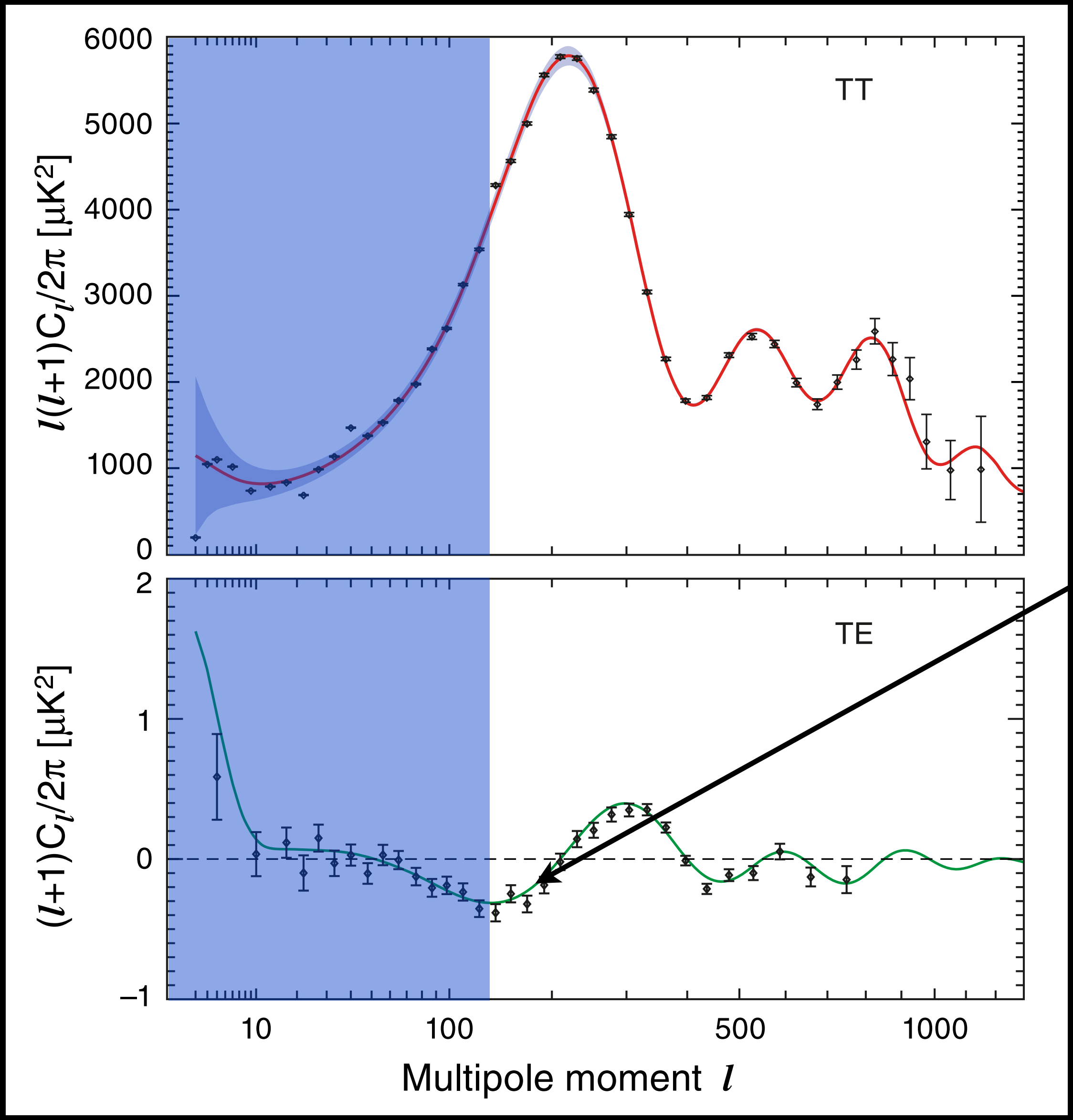


Cosmic history



Cosmic microwave background

Cosmic history



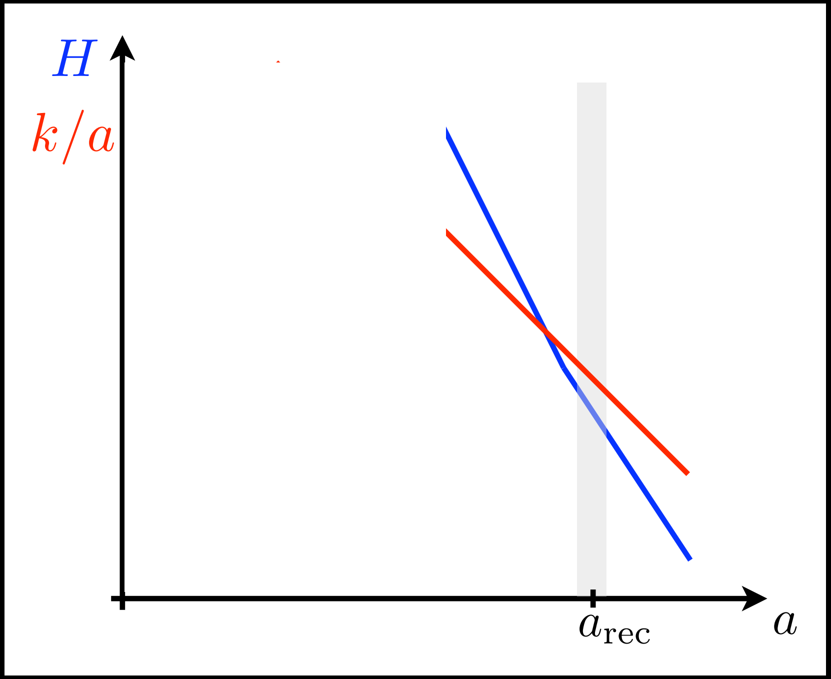
Perturbations exist on scales larger than the Hubble radius at recombination.

Implies these perturbations already existed at recombination

Together with General Relativity it means they existed before the hot big bang!

Cosmic history

The system of equations describing the early universe contains two important scales k/a and H.



To generate the perturbations causally, they cannot have been outside the horizon very early on, requiring a phase with

$$\frac{d}{dt}\left(\frac{k}{a|H|}\right) < 0$$

(inflation or bounce)

Inflation

The simplest system leading to a sufficiently long phase of accelerated expansion (that ends) is

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} R$$
$$- \int d^4x \sqrt{-g} \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi + V(\varphi) \right)$$

with $M_P^2 \left(\frac{V'}{V} \right)^2 \ll 1$ and $M_P^2 \left| \frac{V''}{V} \right| \ll 1$ somewhere

This leads to nearly exponential expansion if the scalar field is nearly homogeneous, and at a position in field space such that the potential energy dominates its energy density.

Inflation

The simplest models of inflation predict

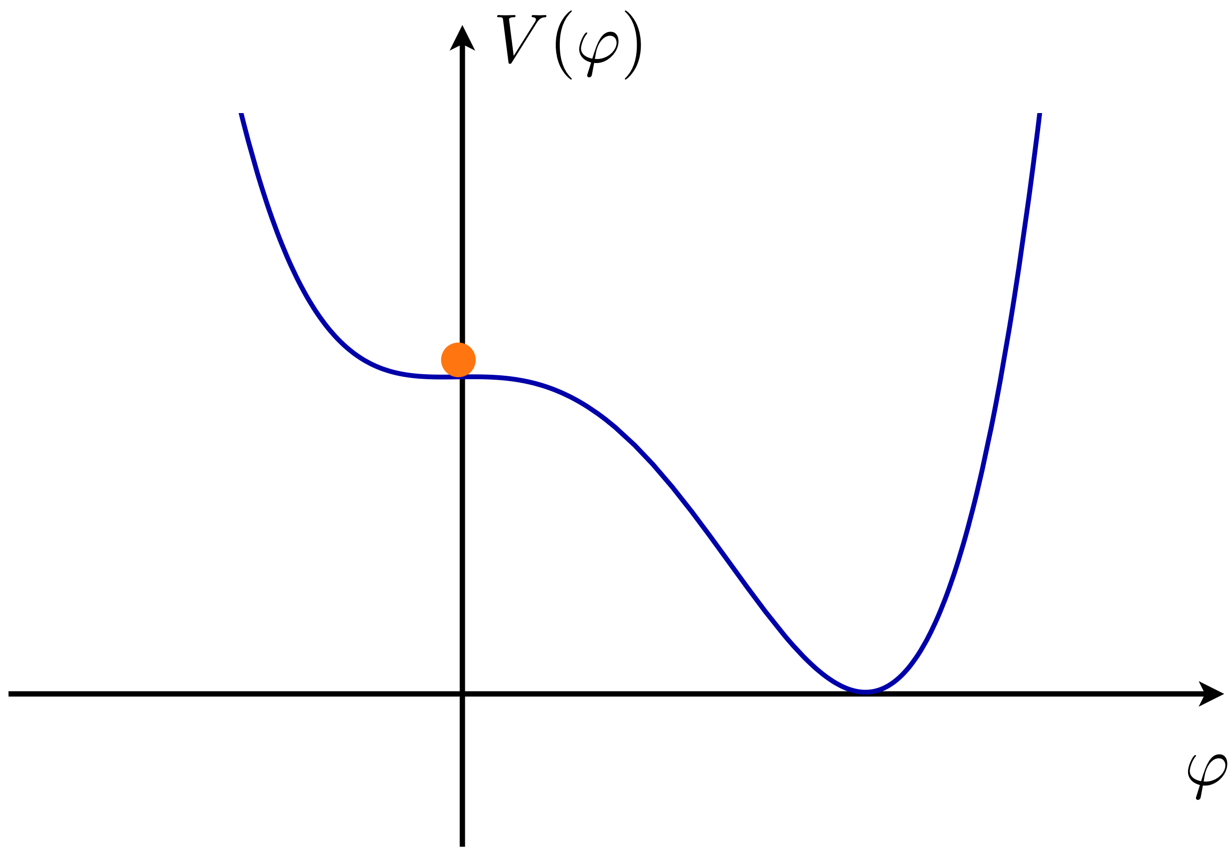
- primordial fluctuations that are
  - nearly scale invariant
  - well approximated by a power law
  - dominated by density fluctuations with subdominant contribution from gravitational waves
  - close to Gaussian
  - adiabatic
- a spatially flat universe

in excellent agreement with observations

Expectations

Inflation could be accidental

$$V(\varphi) = V_0 \left(1 + c_1\varphi + \frac{c_2}{2}\varphi^2 - \varphi^3 + \ldots\right) \quad \textbf{with} \quad c_1, c_2 \ll 1$$



Expectations

Inflation could be accidental

$$V(\varphi) = V_0 \left(1 + c_1\varphi + \frac{c_2}{2}\varphi^2 - \varphi^3 + \ldots\right) \text{ with } c_1, c_2 \ll 1$$

Sufficiently long inflation only for $|c_1| \lesssim 10^{-3}$

Then the tensor-to-scalar ratio is

$$r \approx 8c_1^2 \lesssim 10^{-5}$$

and gravitational waves are unobservably small

No prediction for the spectral index.

$$n_{\rm s} \approx 1 + 2c_2$$

Requires tuning and the observed value of spectral index is an accident.

Expectations

Taking the observed value of the spectral index seriously, we might expect

$$n_s(\mathcal{N}) - 1 = -\frac{p+1}{\mathcal{N}}$$

In general (provided $\epsilon \ll 1$)

$$\frac{d\ln r}{d\mathcal{N}} - (n_{\rm s}(\mathcal{N}) - 1) - \frac{r}{8} = 0$$

The solution is given by

$$r(\mathcal{N}) = \frac{8p}{\mathcal{N}} \frac{1}{1 \pm (\mathcal{N}/\mathcal{N}_{\rm eq})^p}$$

Expectations

Away from special period $\mathcal{N} \approx \mathcal{N}_{\rm eq}$, one of the terms dominates

Monomial models

$$r(\mathcal{N}) = \frac{8p}{\mathcal{N}}$$

or (during inflation) $V(\phi) = \mu^{4-2p}\phi^{2p}$

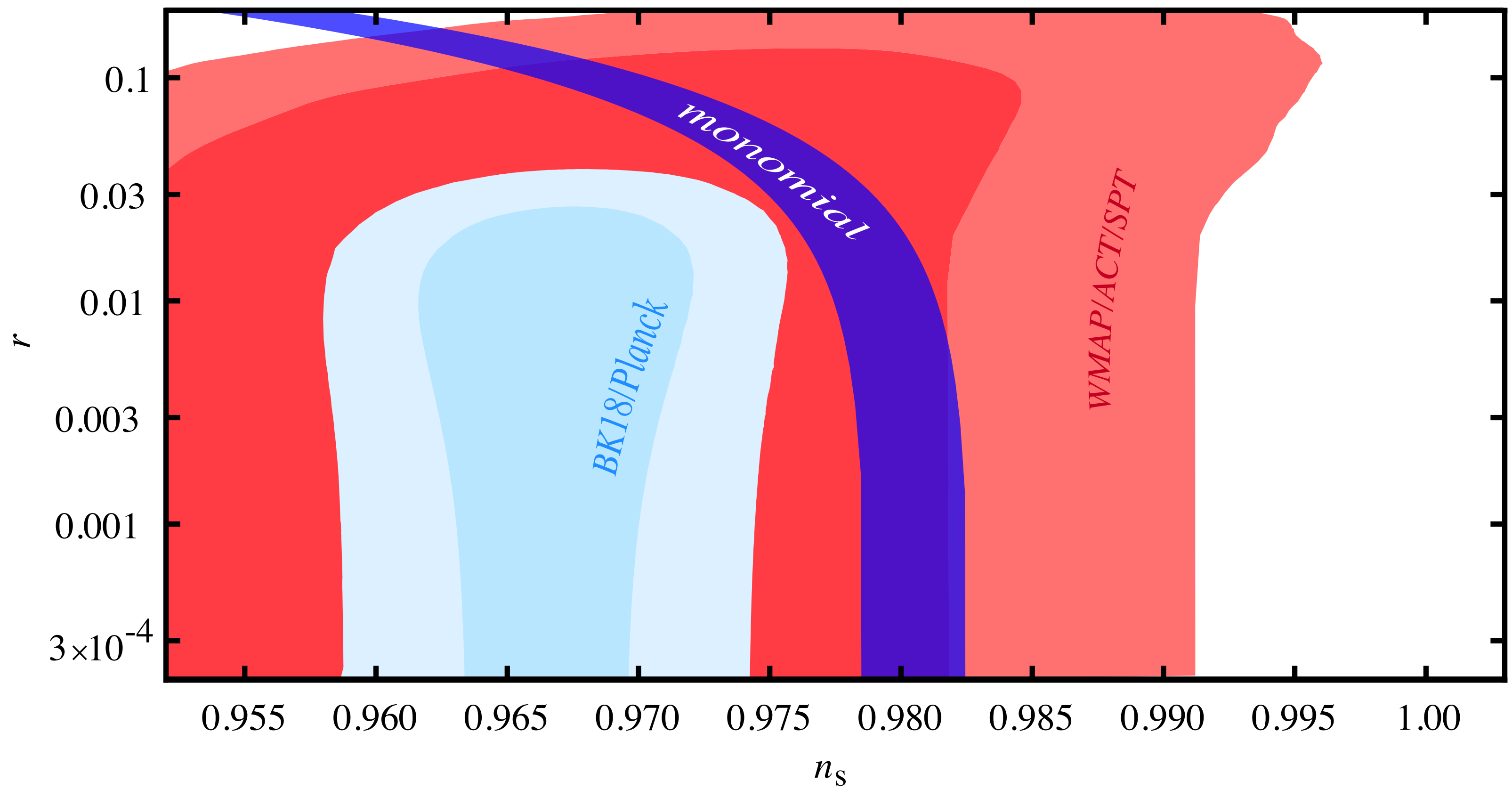
Hilltop and plateau models

$$r(\mathcal{N}) = \frac{8p}{\mathcal{N}}\left(\frac{\mathcal{N}_{\rm eq}}{\mathcal{N}}\right)^p$$

or (during inflation) $V(\phi) \approx V_0\left[1 - \left(\frac{\phi}{\Lambda}\right)^{\frac{2p}{p-1}}\right]$

Expectations

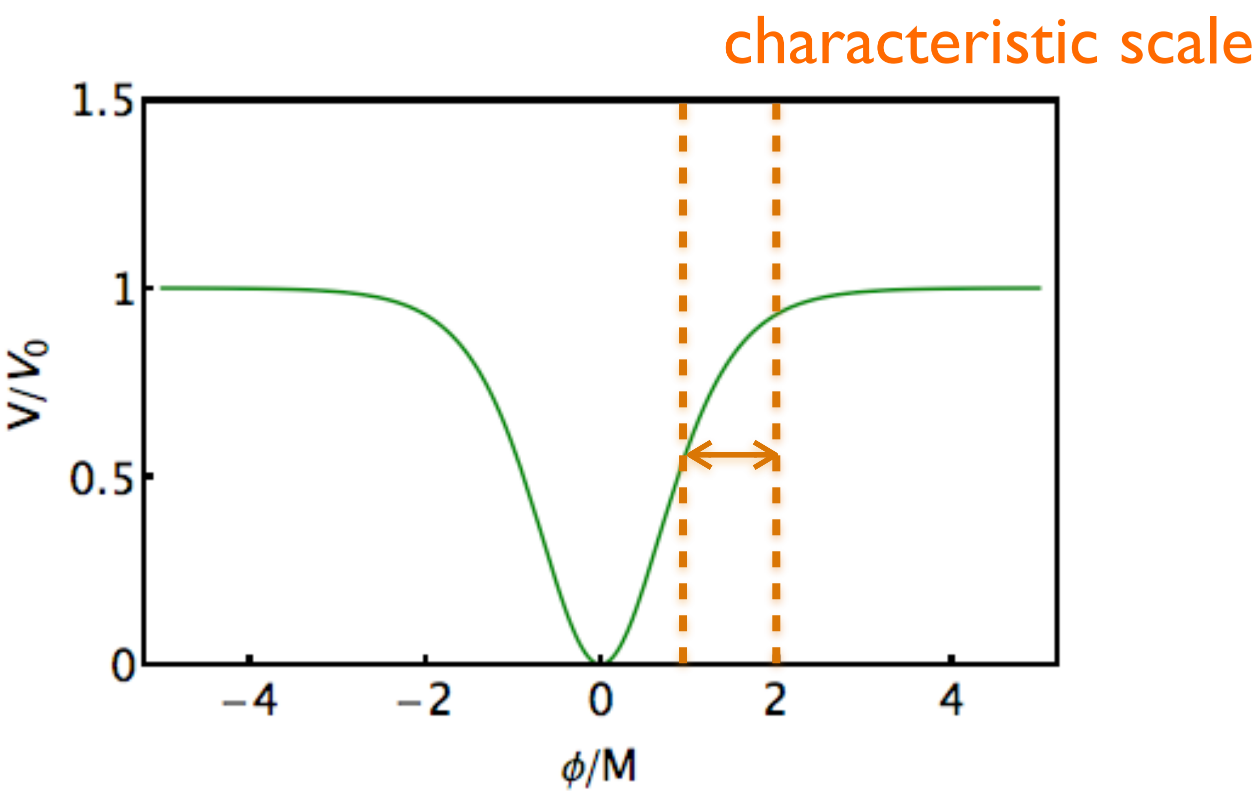
Monomial models



in their simplest form are essentially excluded by current data

Expectations

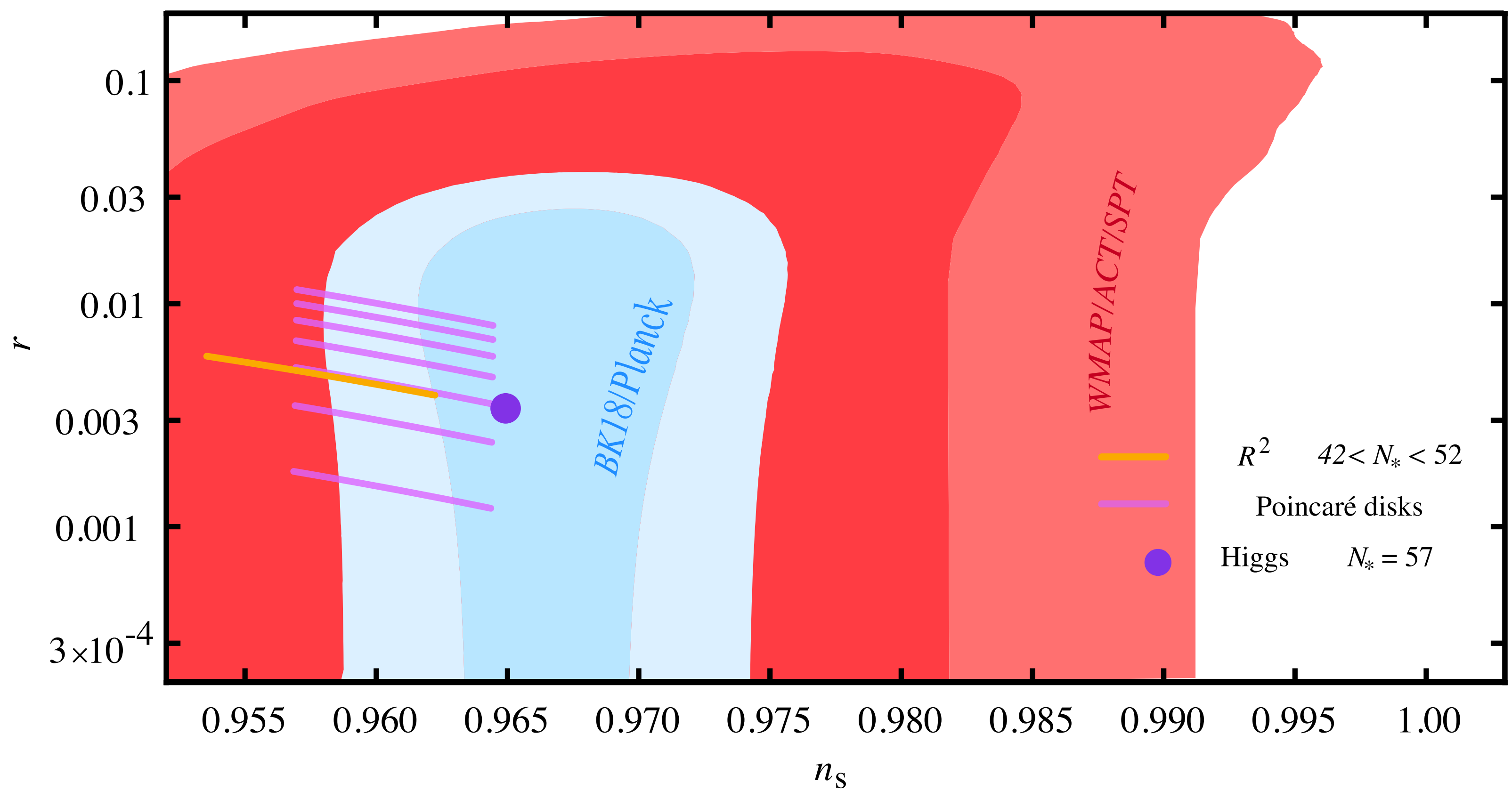
The hilltop and plateau models come with a characteristic scale over which the potential departs from a constant



The integration constant is given by $\mathcal{N}_{\rm eq} = \frac{p}{4}\left(\frac{M}{M_P}\right)^2$

Expectations

Plateau models for $M \approx M_P$



all within reach of future experiments

Expectations for M - Part I

In many models, $M \approx M_P$ because they have common origin

As an example consider Starobinsky model

$$S = \frac{M_P^2}{2} \int d^4x \sqrt{-g} \left[R + \frac{1}{\mu^2} R^2 \right]$$

After Weyl rescaling

$$S = \frac{M_P^2}{2} \int d^4x \sqrt{-g} \left[R - \frac{3}{2} g^{\mu\nu} \partial_\mu \sigma \partial_\nu \sigma - \tilde{V}(\sigma) \right]$$

with $\tilde{V}(\sigma) = \frac{\mu^2}{4} (1 - e^{-\sigma})^2$

Expectations for M - Part I

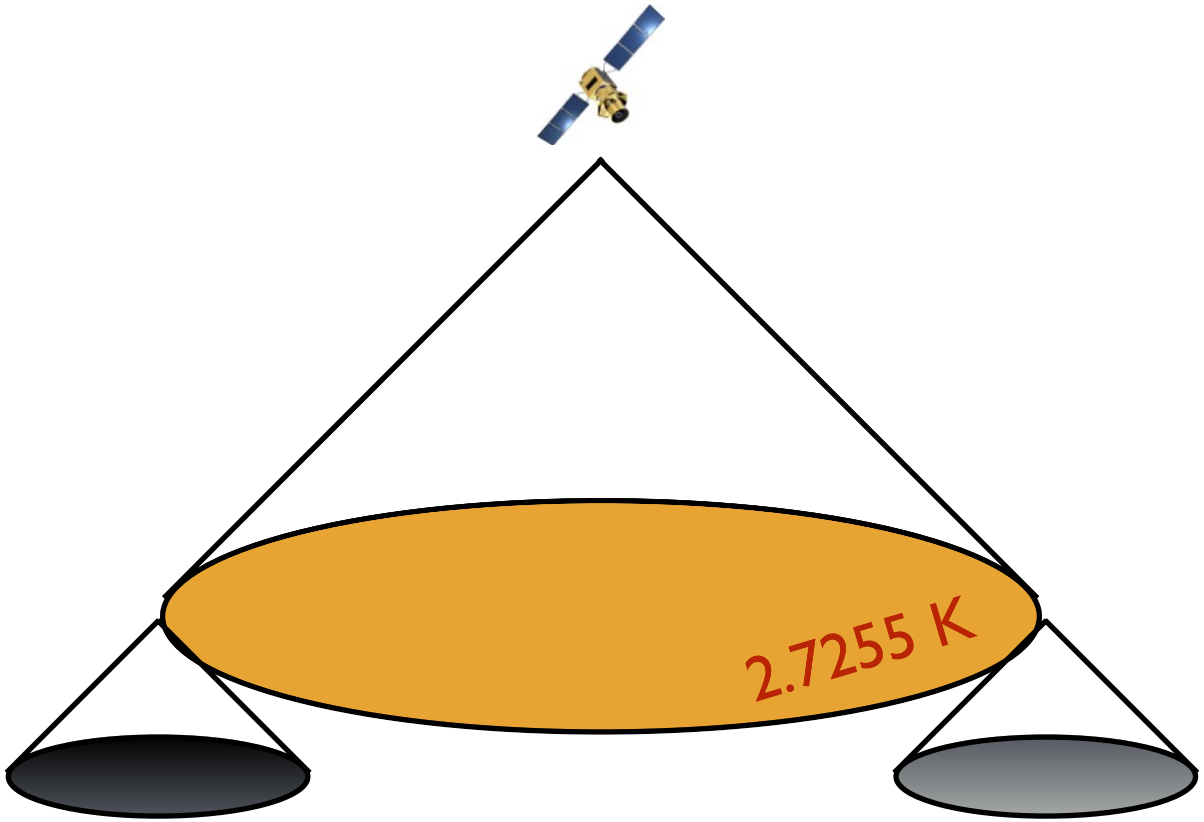
or in terms of the canonically normalized field $\phi = M_P\sqrt{\frac{3}{2}}\sigma$

$$S = \frac{M_P^2}{2}\int d^4x\sqrt{-g}R + \int d^4x\sqrt{-g}\left[-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

with $$V(\phi) = \frac{\mu^2 M_P^2}{8}\left(1 - e^{-\sqrt{2/3}\phi/M_P}\right)^2$$

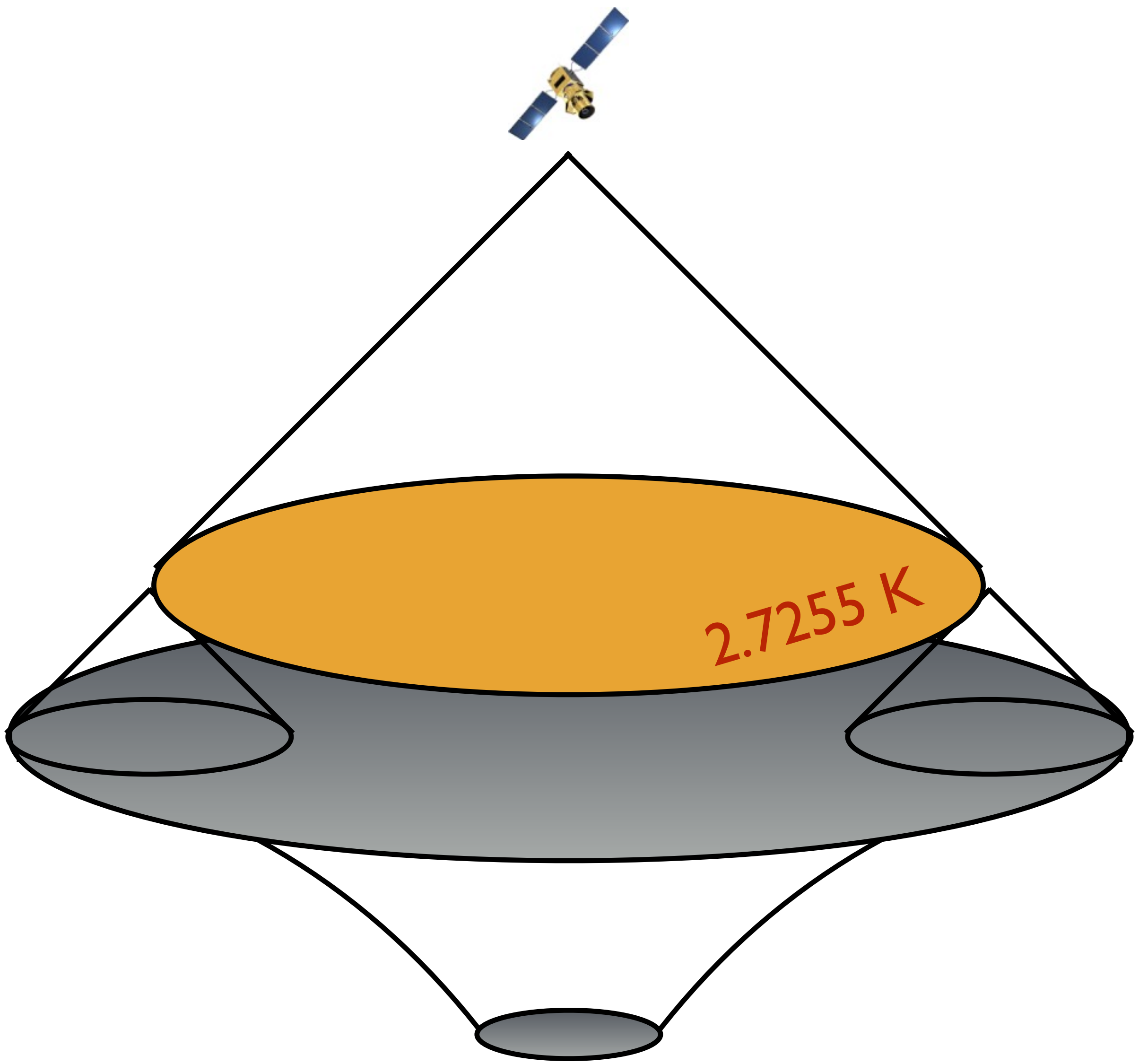
Similarly for Higgs inflation, and many others the characteristic scale is set by the 4d gravitational scale.

Expectations for M - Part II



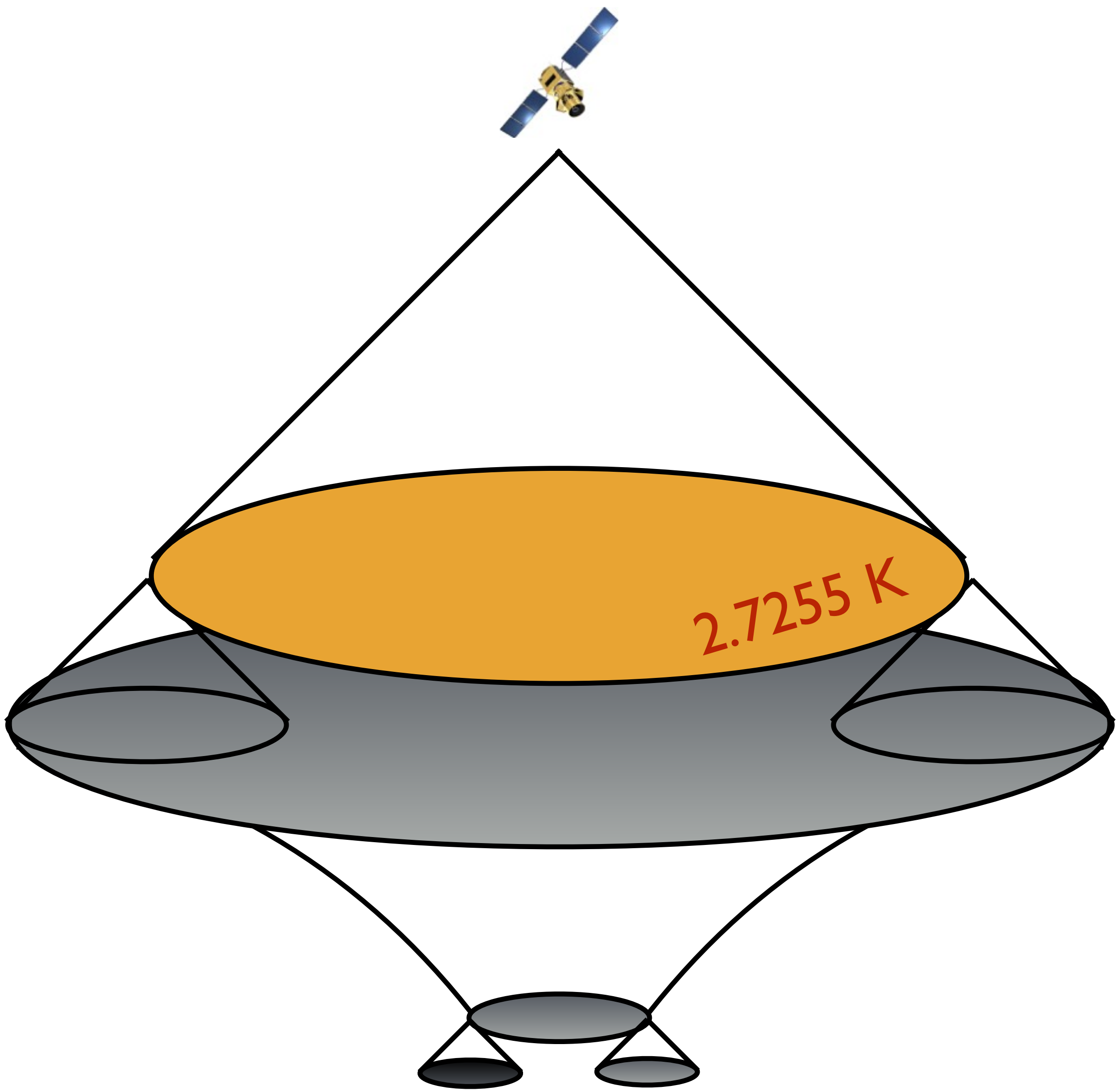
According to the standard big bang, points separated by more than a degree were never in causal contact.

Expectations for M - Part II



According to inflation the early universe underwent a period of nearly exponential expansion.

Expectations for M - Part II



Inflation is not a solution to the horizon problem if it comes with its own horizon problem

Expectations for M - Part II

Inflation can readily start if we assume that the description of the universe by one or several scalar fields coupled to GR is valid up to the Planck scale and

$$\rho \sim \rho_{\rm grad} \sim V \sim M_{\rm P}^4$$

Some regions will collapse rapidly, but some will be dominated by potential energy density and inflate.

For models with $V \ll M_{\rm P}^4$, as is the case for the plateau and hilltop models, we should understand if inflation naturally arises if $\rho_{\rm grad} \gg V$.

Cosmology with $\Lambda > 0$

For plateau models, results for positive Λ should apply provided the field is initially confined to the plateau.

Homogeneous anisotropic cosmologies with $\Lambda > 0$

- Except for Bianchi IX, all homogeneous anisotropic cosmologies with positive cosmological constant asymptote to de Sitter space.

Wald (1983)

Inhomogeneous anisotropic cosmologies with $\Lambda > 0$

- Provided the weak energy condition holds, global recollapse is only possible if ${}^{(3)}R > 0$ everywhere. For most 3-manifolds this is topologically impossible.

Barrow, Tipler (1985)

Kleban, Senatore (2016)

Beyond Λ

Confirmed for torus topology and a simple class of initial conditions through numerical GR simulations in

East, Kleban, Linde, Senatore (2016)

Clough, DiNunno, Fischler, Flauger, Lim, Paban (2017)

More general initial conditions were studied in

Clough, Flauger, Lim (2018)

Conclusions remain unchanged (as expected)

Beyond Λ

More systematic exploration of behavior if the field is not confined to the plateau and explores the minimum.

Aurrekoetxea, Clough, Flauger, Lim (2019)

and with general initial conditions for large field models

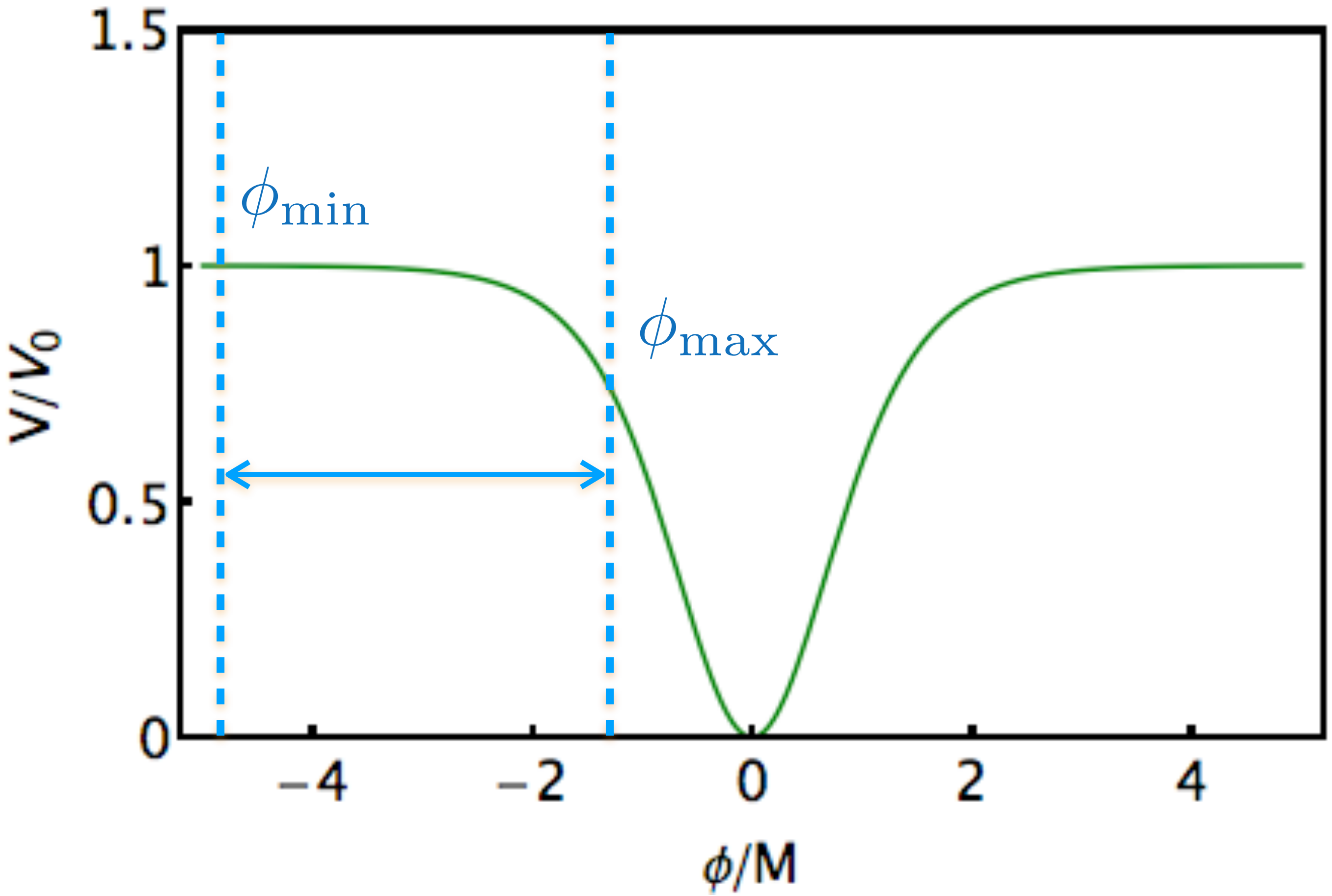
Corman, East (2023)

and general initial conditions for both large and small field models

Elley, Aurrekoetxea, Clough, Flauger, Giannadakis, Lim (to appear 2024)

Robustness against inhomogeneities

Consider field configurations that explore the minimum



Robustness against inhomogeneities

Evolution of the point closes to the minimum near initial slice determined by

$$\ddot{\phi}_{\rm max} = -k^2 \Delta\phi - \frac{dV(\phi_{\rm max})}{d\phi}$$

Defining

$$f(\phi_0, \Delta\phi) = k^2 \Delta\phi + \frac{dV(\phi_0 + \Delta\phi)}{d\phi}$$

For the field to fall toward the minimum, we need

$$\frac{\partial f}{\partial \Delta\phi} = k^2 + V''(\phi_0 + \Delta\phi) < 0$$

Positive definite for convex potentials so that the field is always pulled back.

Robustness against inhomogeneities

For concave potentials crudely

$$\frac{\partial f}{\partial \Delta\phi} \approx k^2 - H^2 \left(\frac{M_P}{M}\right)^2$$

We expect the field to be pulled back into the plateau for super-Planckian characteristic scales and off the plateau for sub-Planckian characteristic scales.

Characteristic Scale and Robustness to Inhomogeneities

Results

Monomial models are robust against inhomogeneities and inflation eventually begins even if initially $\rho_{\rm grad} \simeq 10^3 V$

Hilltop and plateau models are robust against $\rho_{\rm grad} \simeq 10^3 V$ if the field is initially confined to the plateau.

Hilltop and plateau models are robust even if the field explores the minimum provided the characteristic scale of the potential is super-Planckian $M \gtrsim M_{\rm P}$.

Inflection point models are susceptible to inhomogeneities and tuning or some mechanism is needed to set up appropriate initial conditions.

Targets

Science goals for CMB-S4

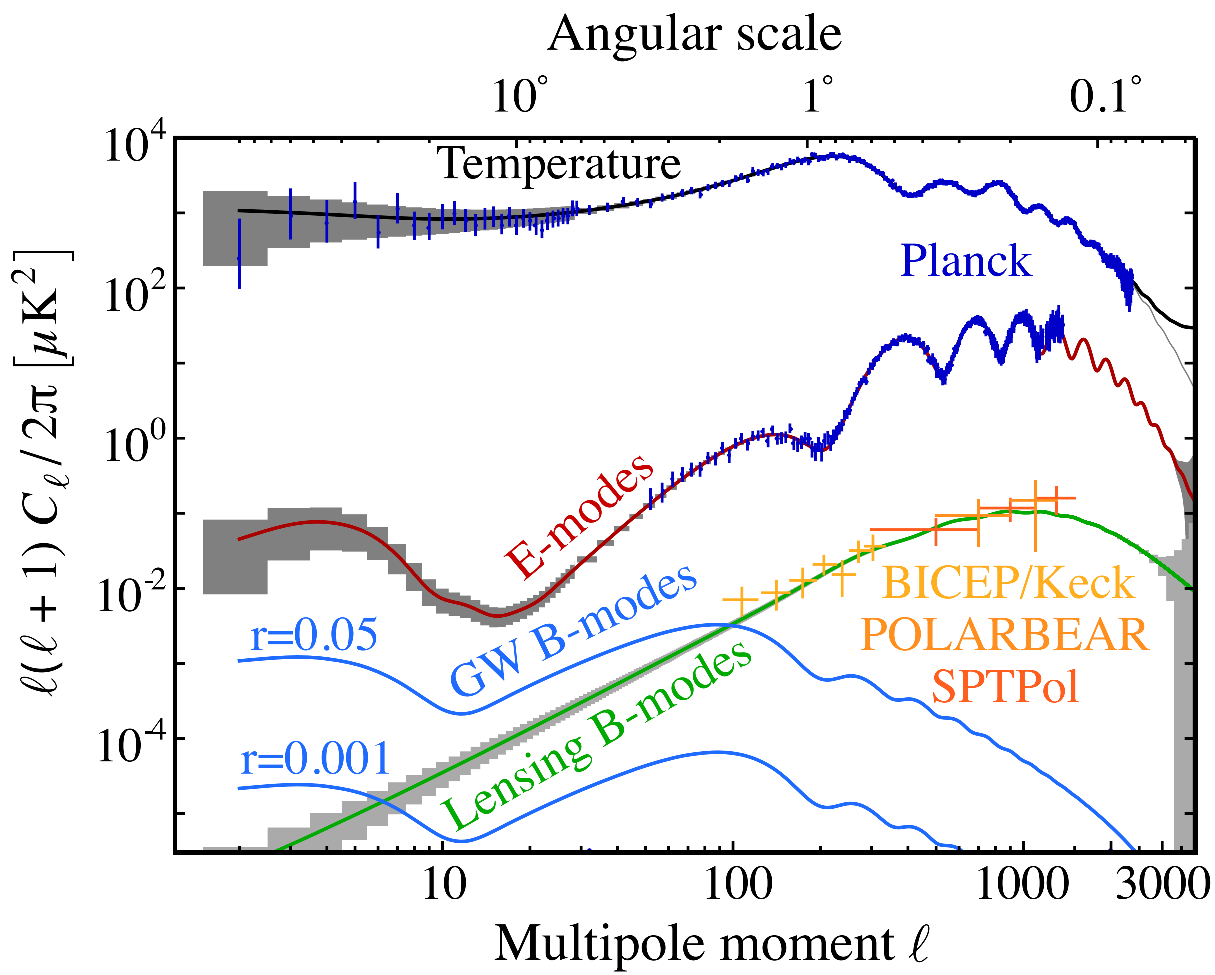
- Detect gravitational waves provided $r > 3 \times 10^{-3}$

Since $M = M_P$ is an important scale and $M > M_P$
leads to $r > 10^{-3}$ for the currently preferred value of $n_{\rm s}$

- provide an upper limit of $r < 10^{-3}$ at 95% CL
  for $r = 0$

Such an upper limit would exclude all models of inflation that naturally explain the observed value of the spectral index and have a super-Planckian characteristic scale.

Era of CMB Polarization

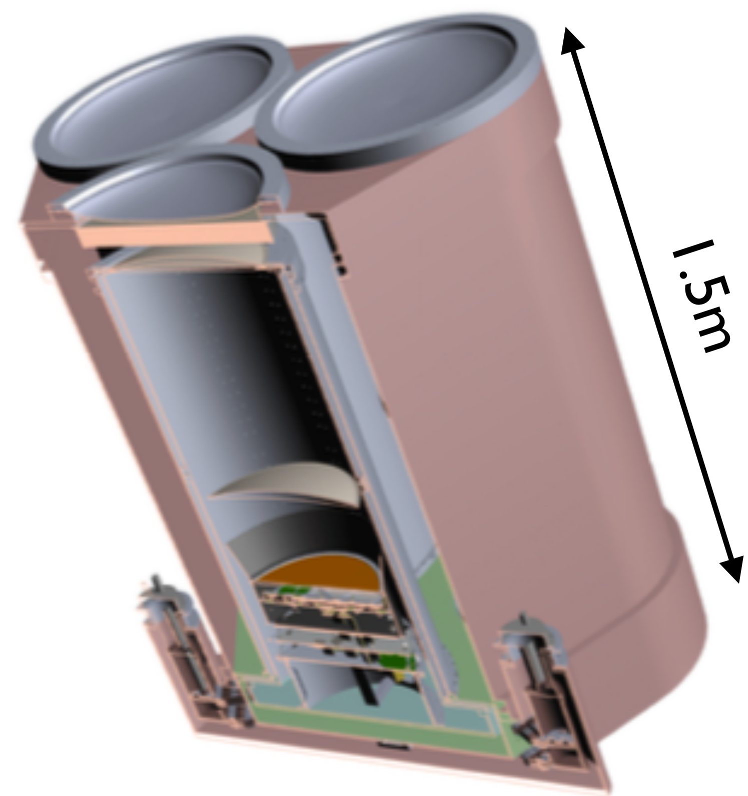


Invaluable information about both astro- and particle physics remains to be extracted from CMB polarization.

Large scale polarization

is a sensitive probe of any gravitational waves present at recombination

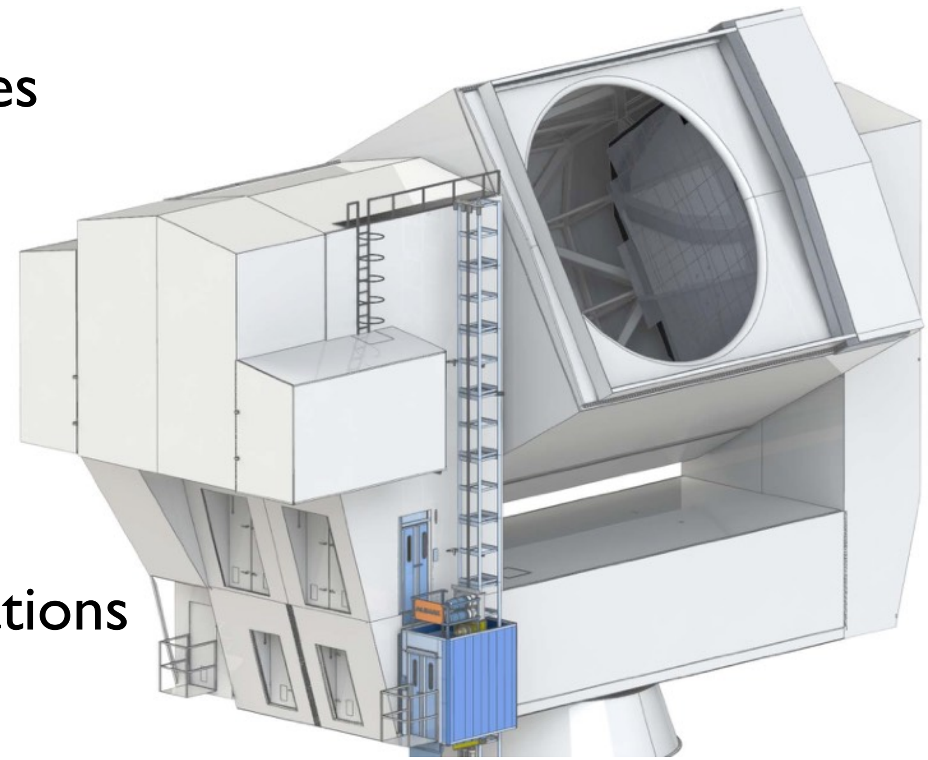
- These gravitational waves are a pristine relic of the primordial universe.
- In the foreseeable future, their imprint on the polarization of the CMB is our only way to detect them.
- These gravitational waves are statistically independent from density perturbations and a detection would provide a new window onto the early universe.



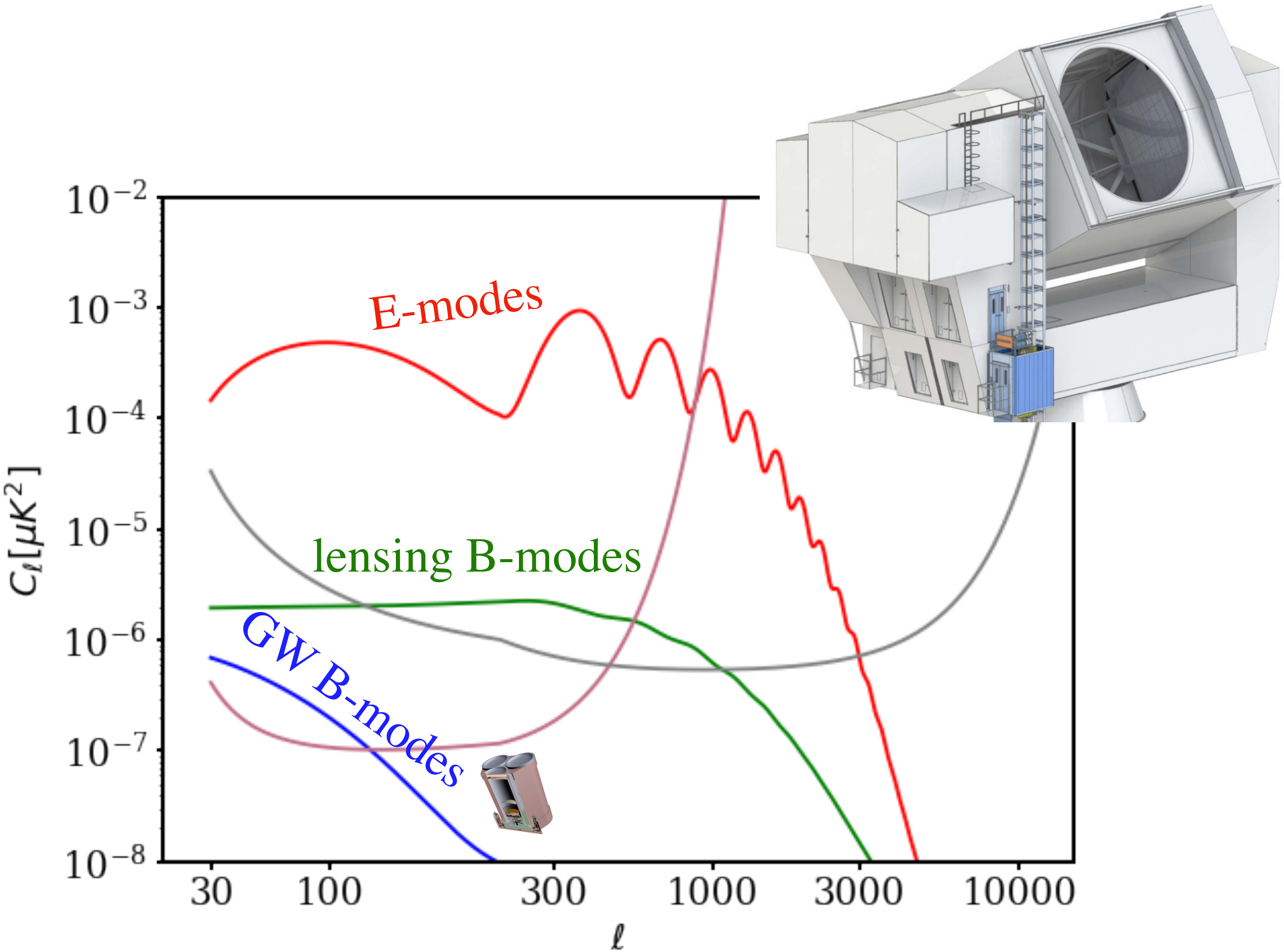
Small scale polarization

constrains

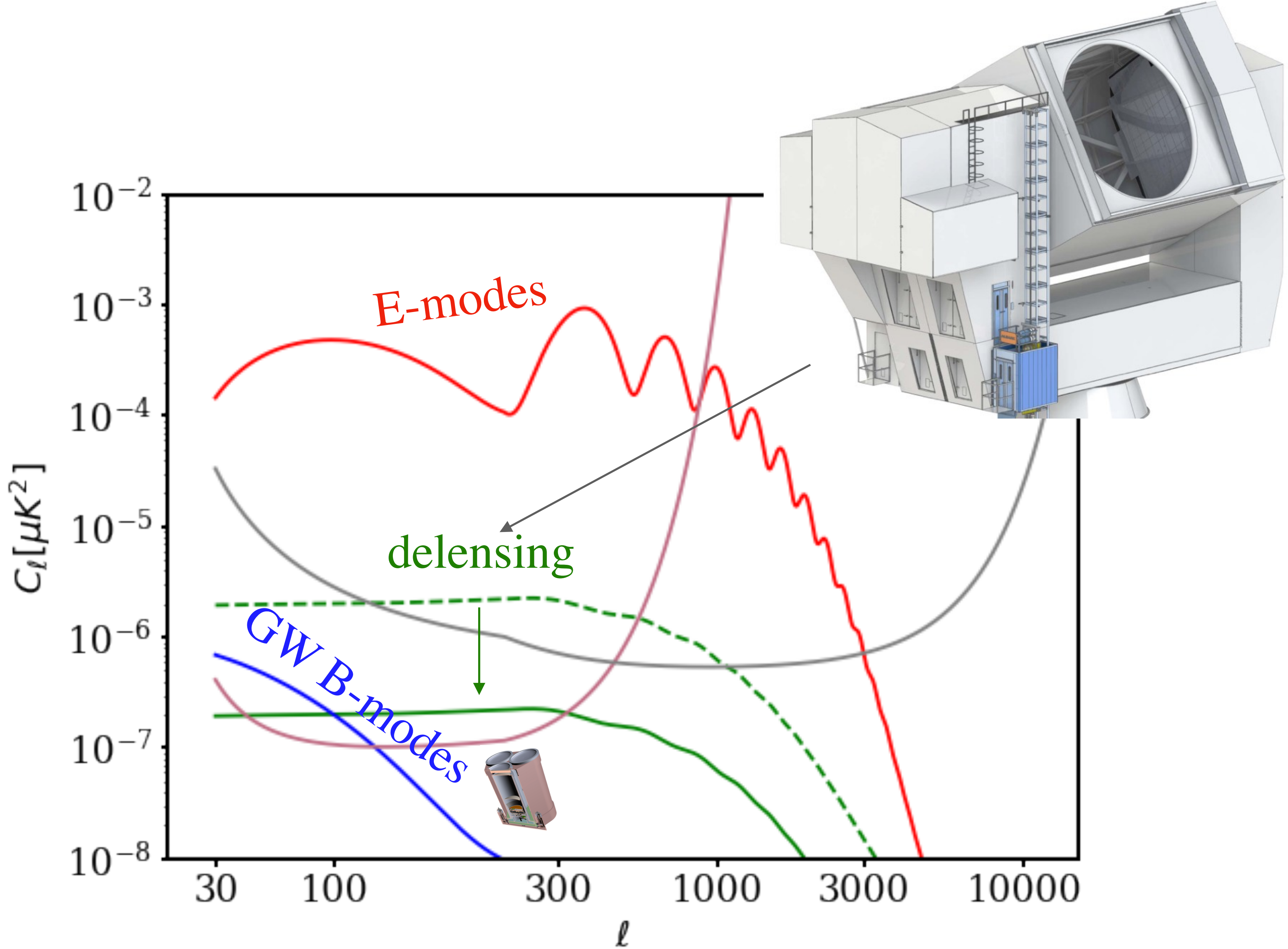
- number of relativistic species
- sum of neutrino masses
- dark matter properties
- dark energy properties
- statistical properties of primordial density perturbations
- …



Degree and small scale polarization



Degree and small scale polarization



Future CMB Experiments

Stage III.5

South Pole Observatory

Future CMB Experiments

Stage III.5

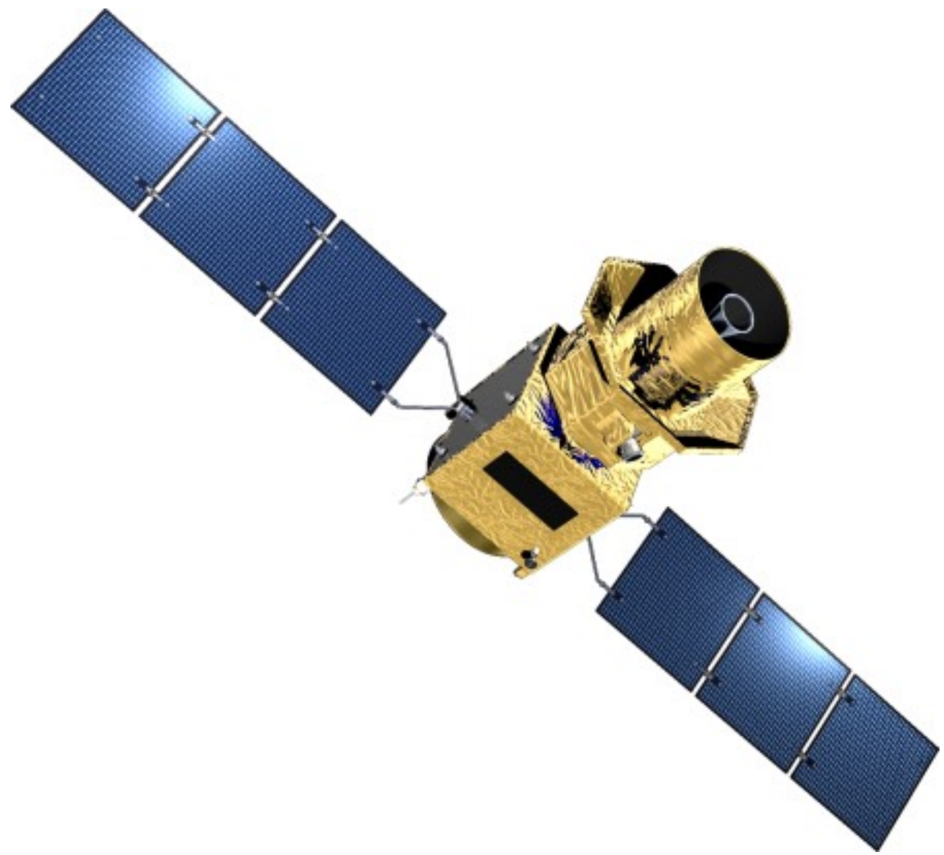
Simons Observatory

Future CMB Experiments

CMB-S4: 2032-2042

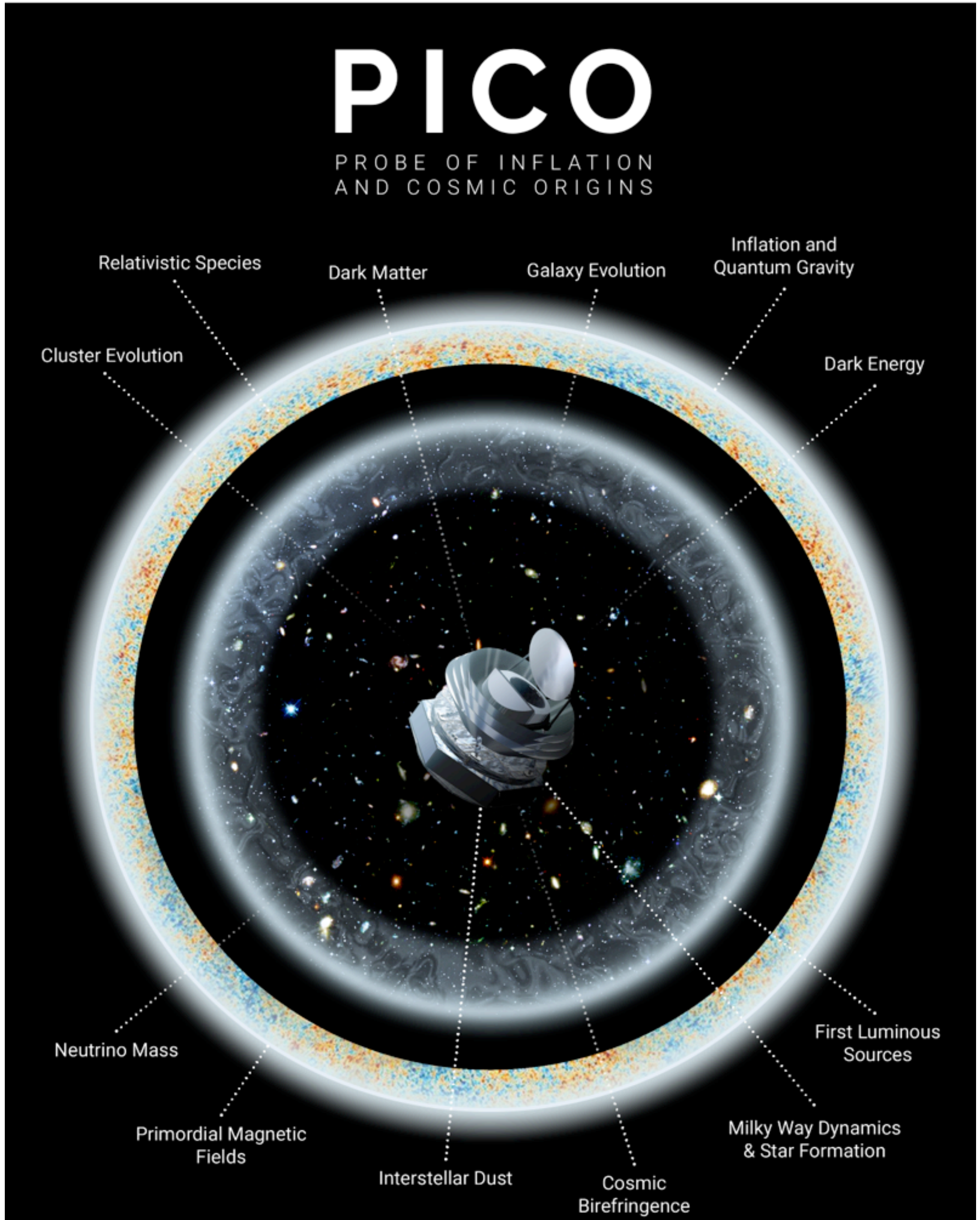
Future CMB Experiments

LiteBIRD



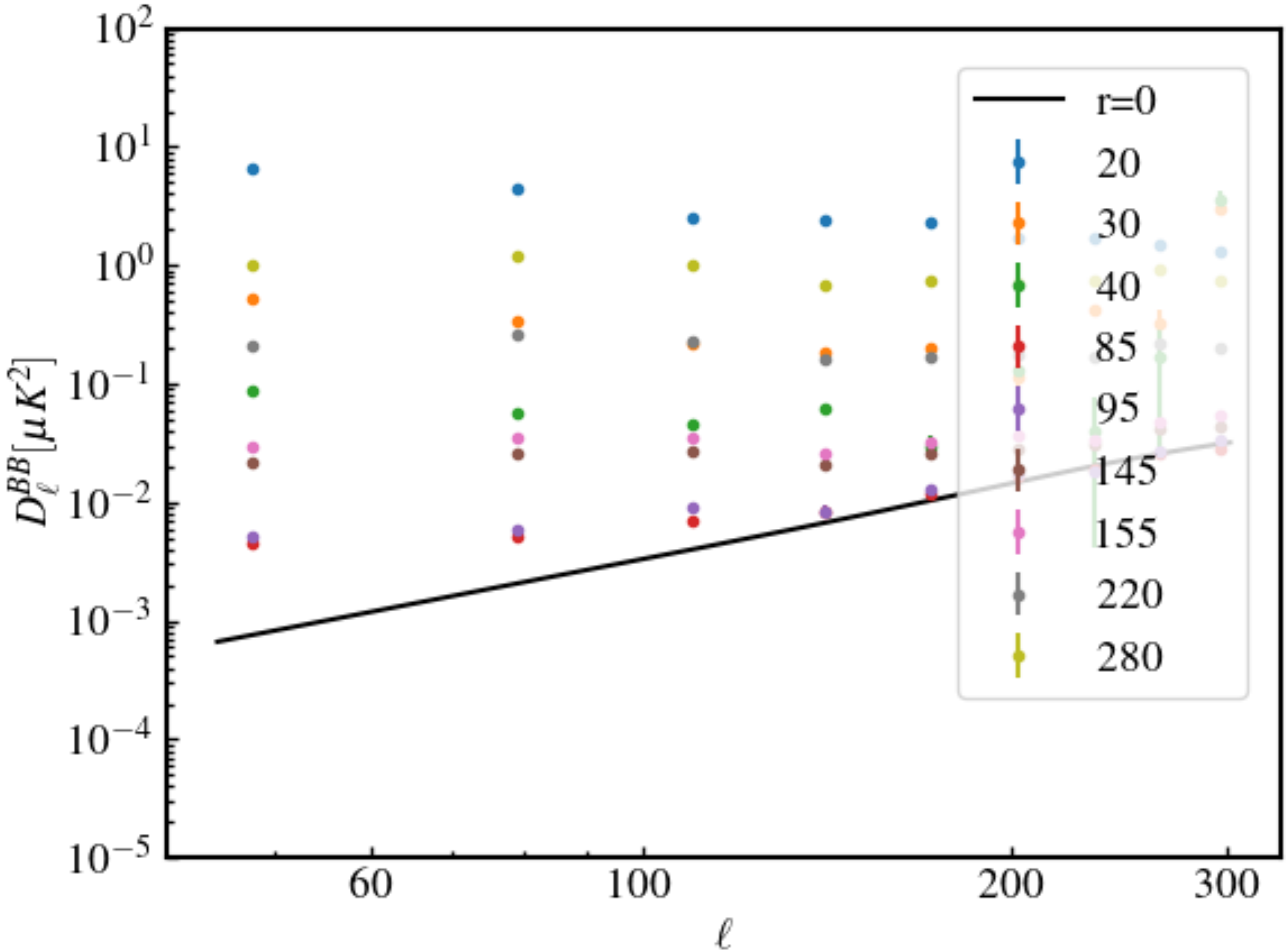
Selected by JAXA

Future CMB Experiments



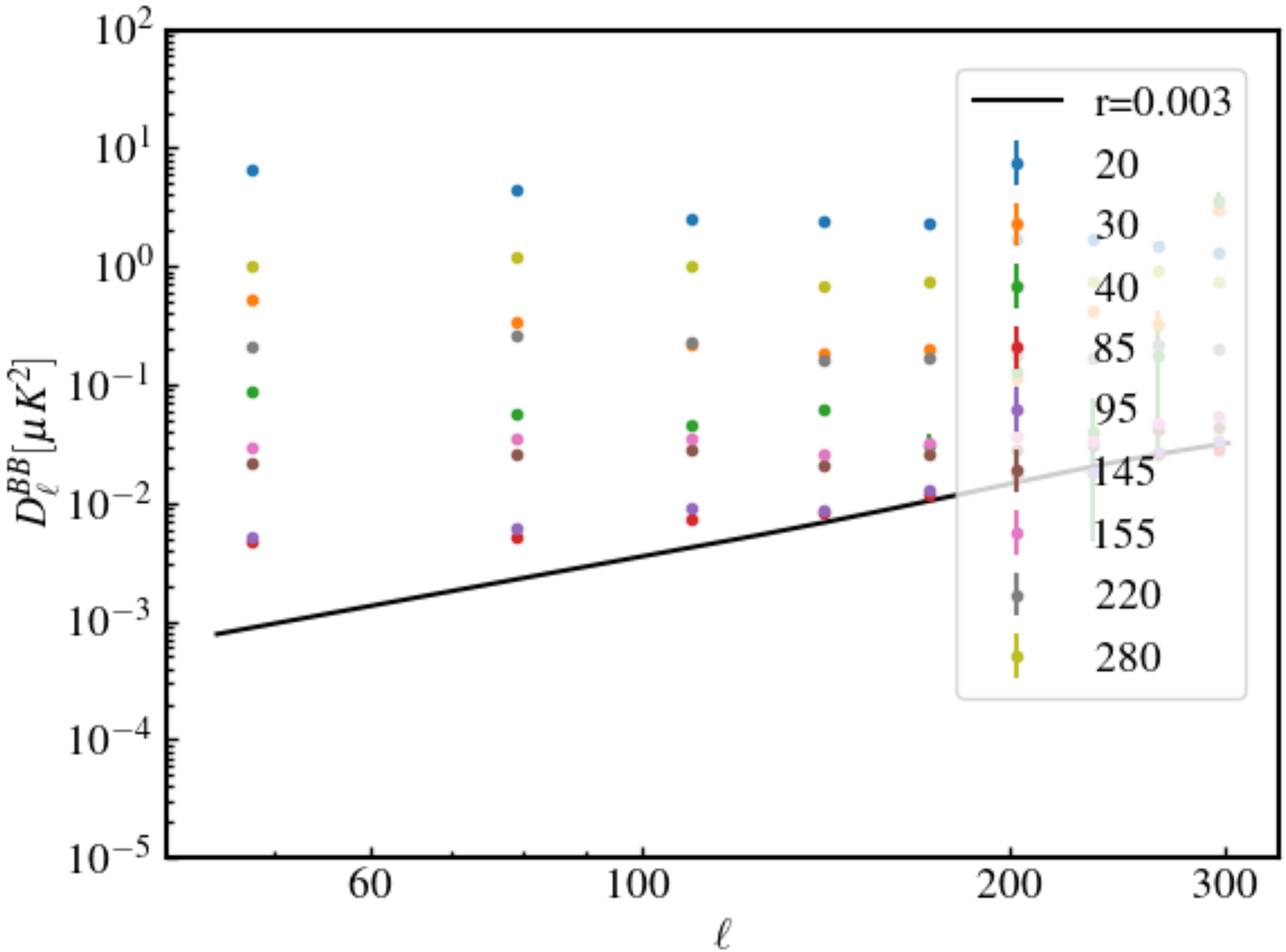
Large scale B-modes

The challenge is to use maps with auto-spectra shown below to tell the difference between…



Large scale B-modes

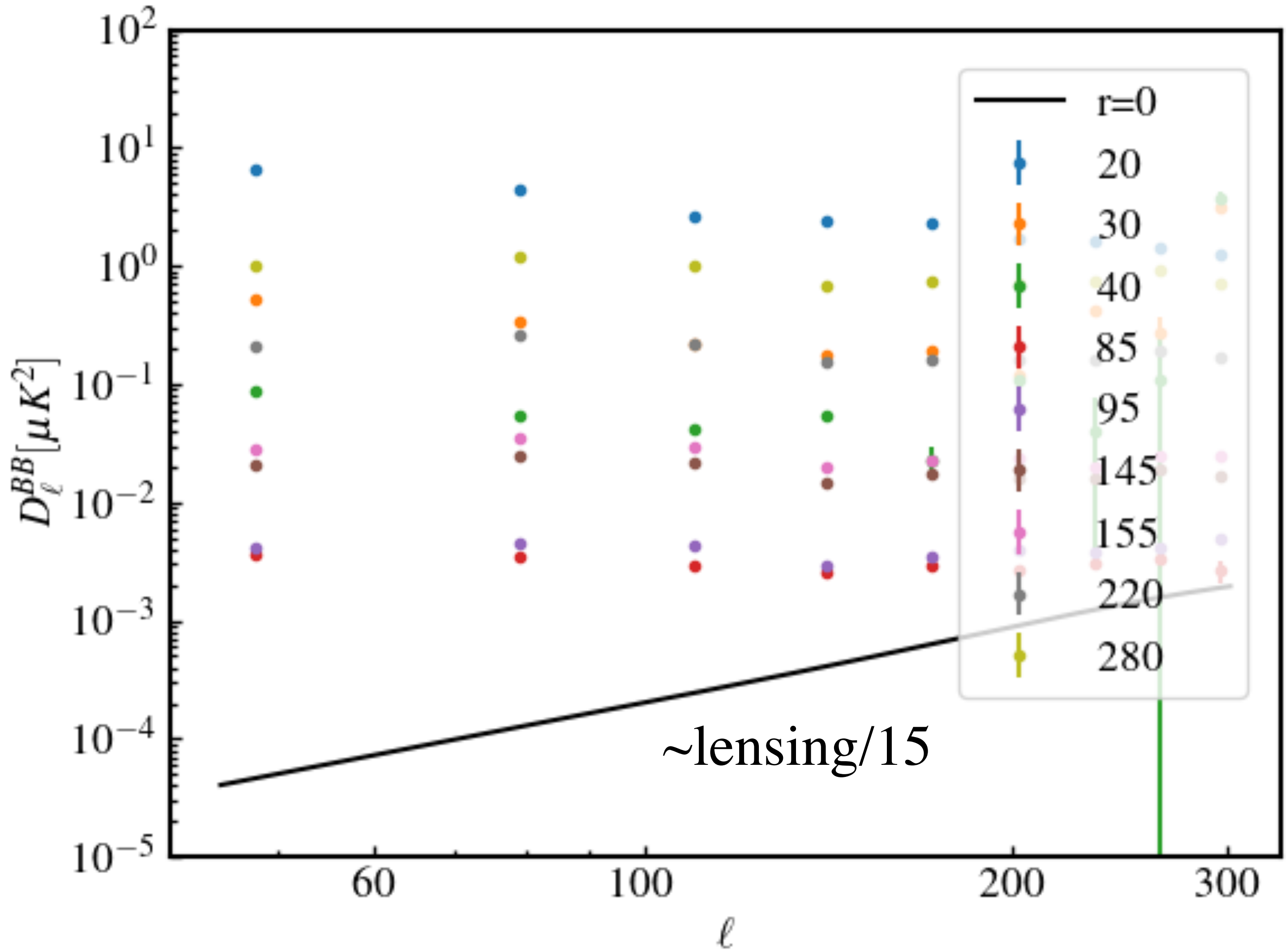
and...



at 5σ

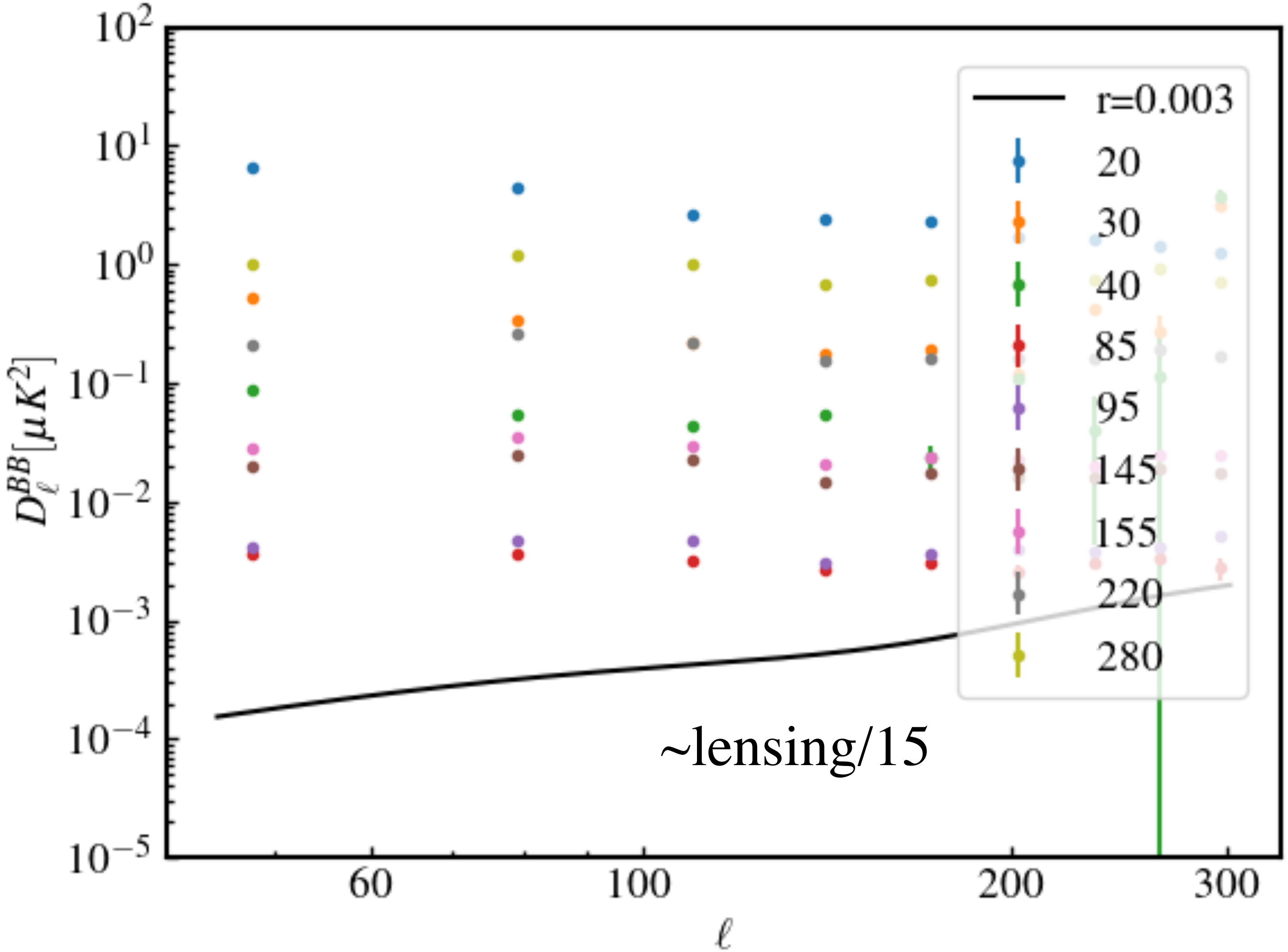
Large scale B-modes

Lensing B-modes can be partially removed through precise measurements of the lensing potential and E-modes



Large scale B-modes

r=0.003



Foregrounds

The biggest caveat to any forecast is our limited understanding of foregrounds.

We know polarized foreground emission is dominated by

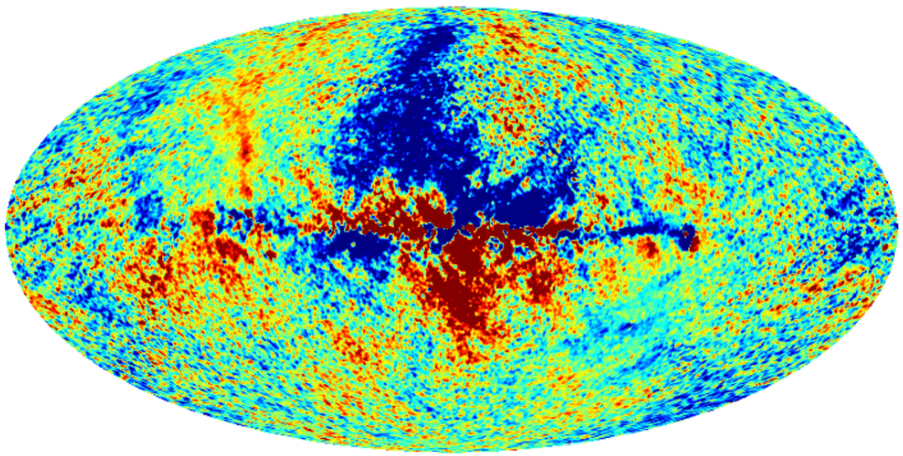
- Dust
- Synchrotron

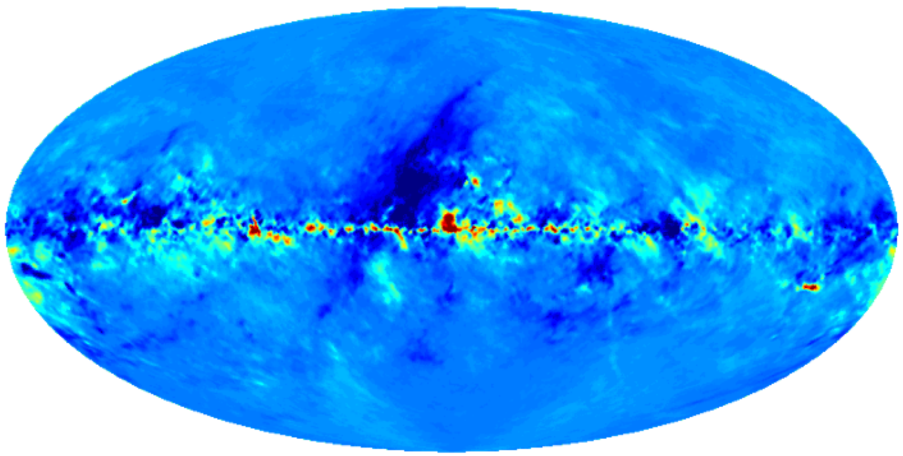
How do we model them?

- based on templates from WMAP and Planck
- based on HI data
- based on MHD simulations

Foregrounds

Template based models

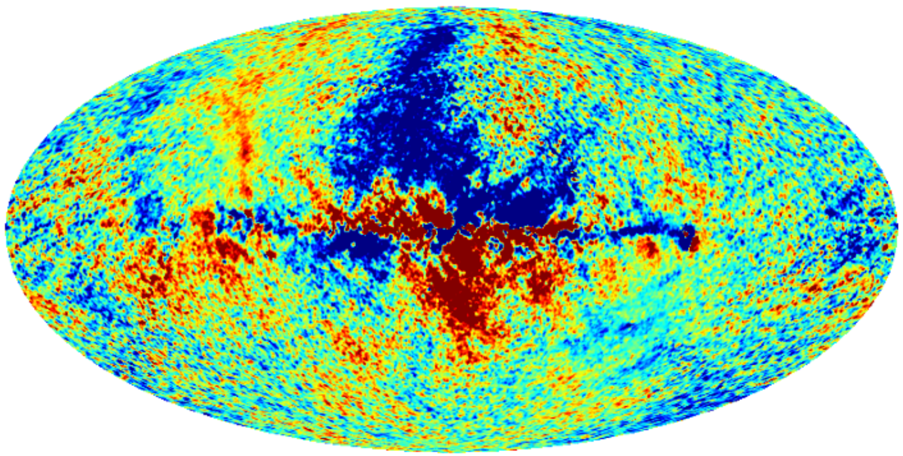


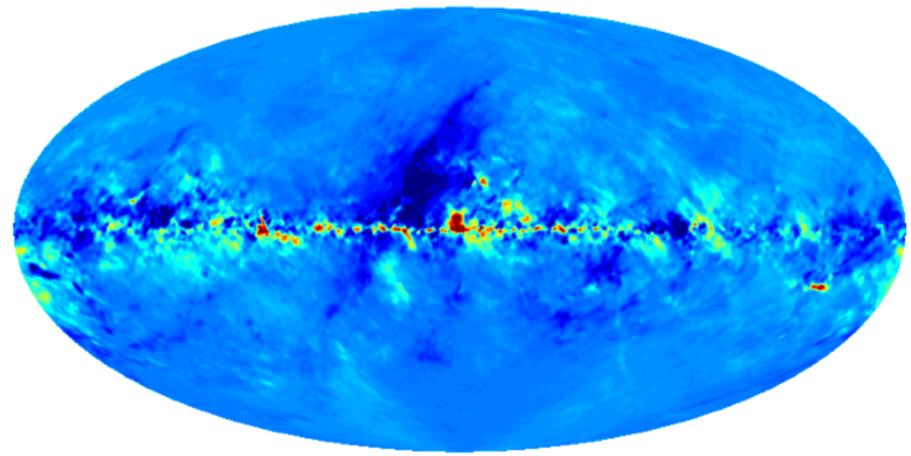


- synchrotron template from WMAP 23 GHz or LFI 30 GHz
- dust template from Planck 353 GHz
- assumed spectral dependence

Foregrounds

Template based models



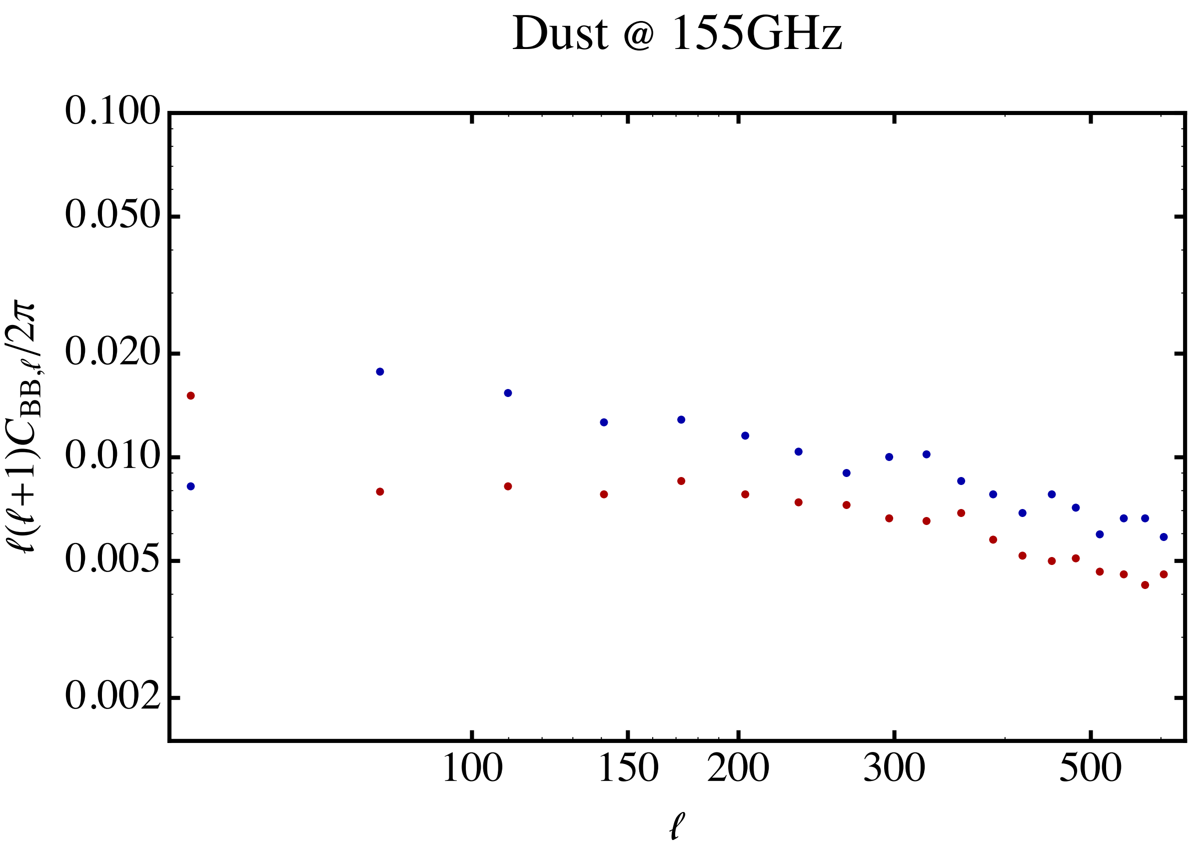


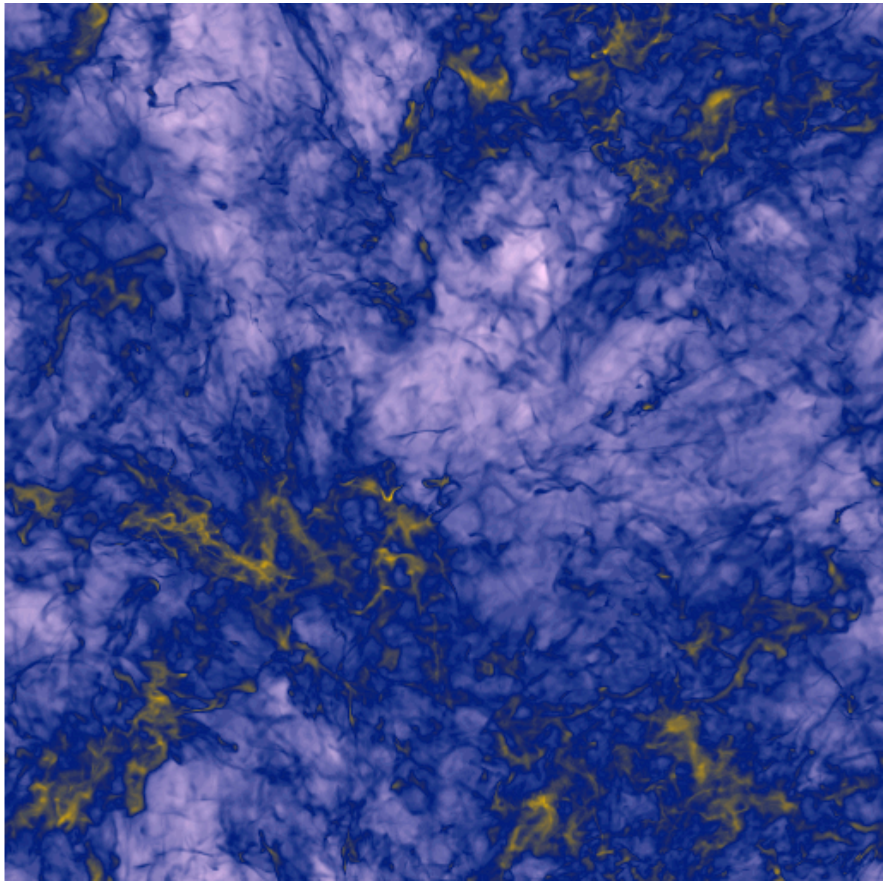
- contain instrumental noise
- small scales typically populated with Gaussian random fluctuations

As a consequence, template based models don't "look" like the real sky on the relevant scales

Foregrounds

Models based on MHD simulations

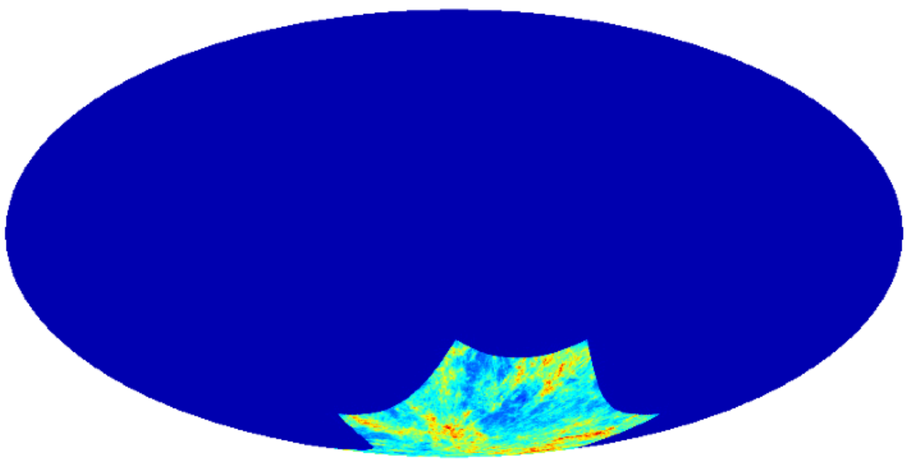




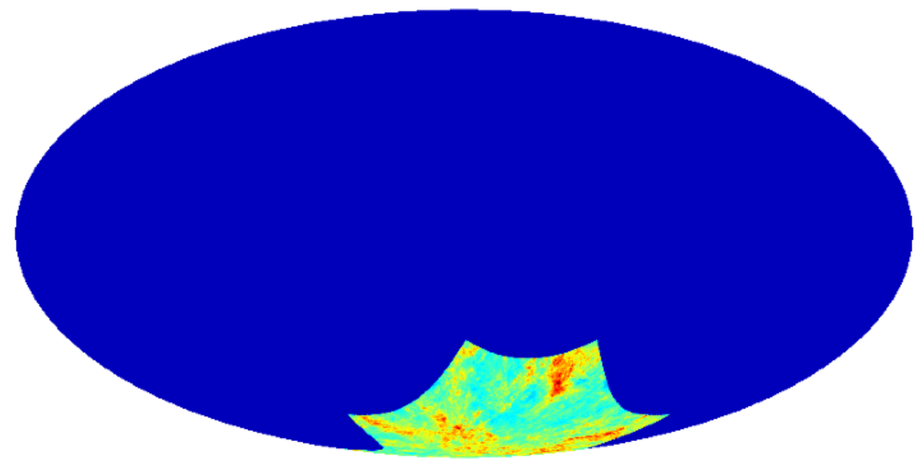
- Correctly reproduce E/B ratio, TE correlations, scale dependence

Forecasts for CMB-S4

Models based on MHD simulations



155 GHz

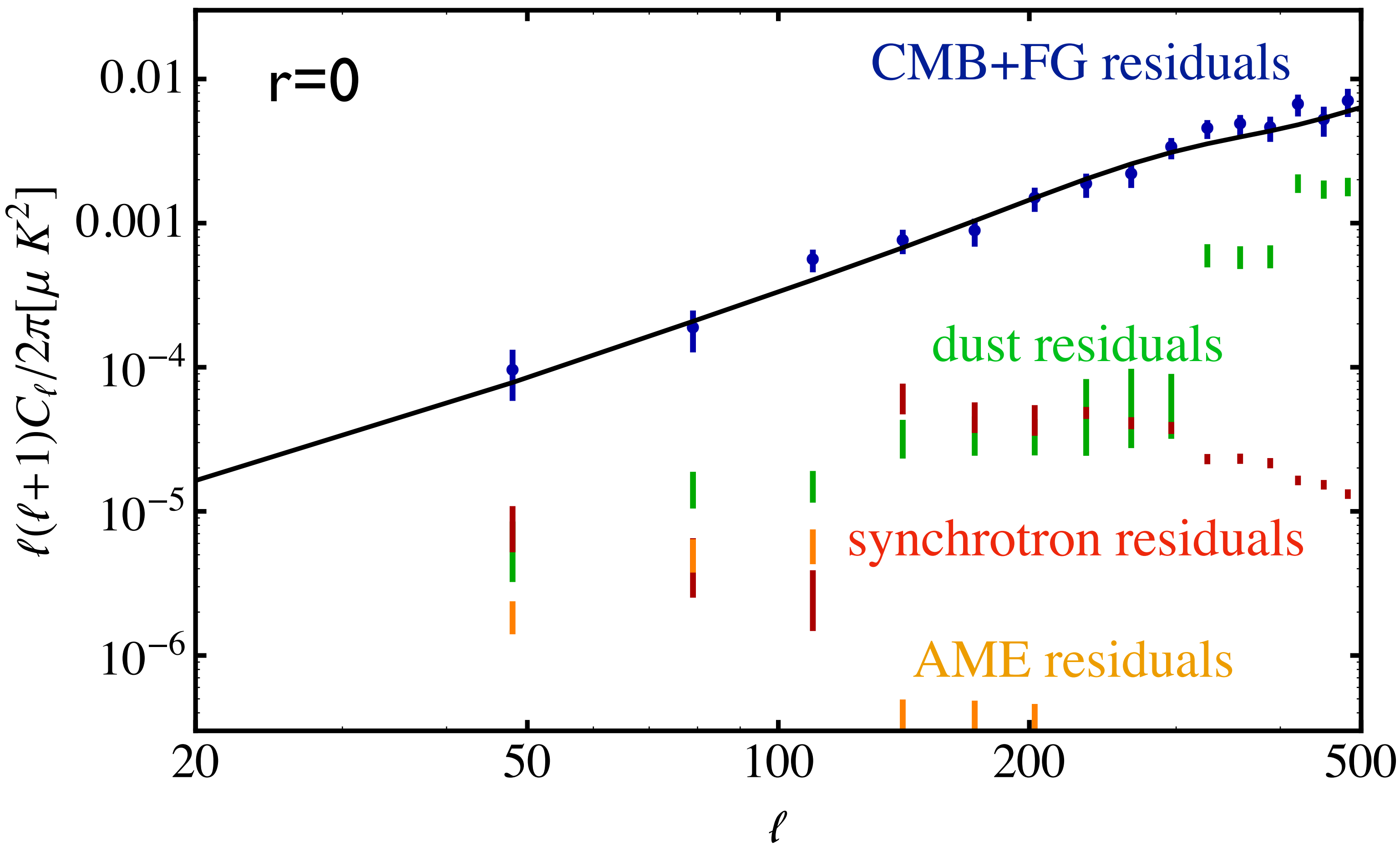


95 GHz

- At “high” resolution currently limited to small patches

Forecasts for CMB-S4

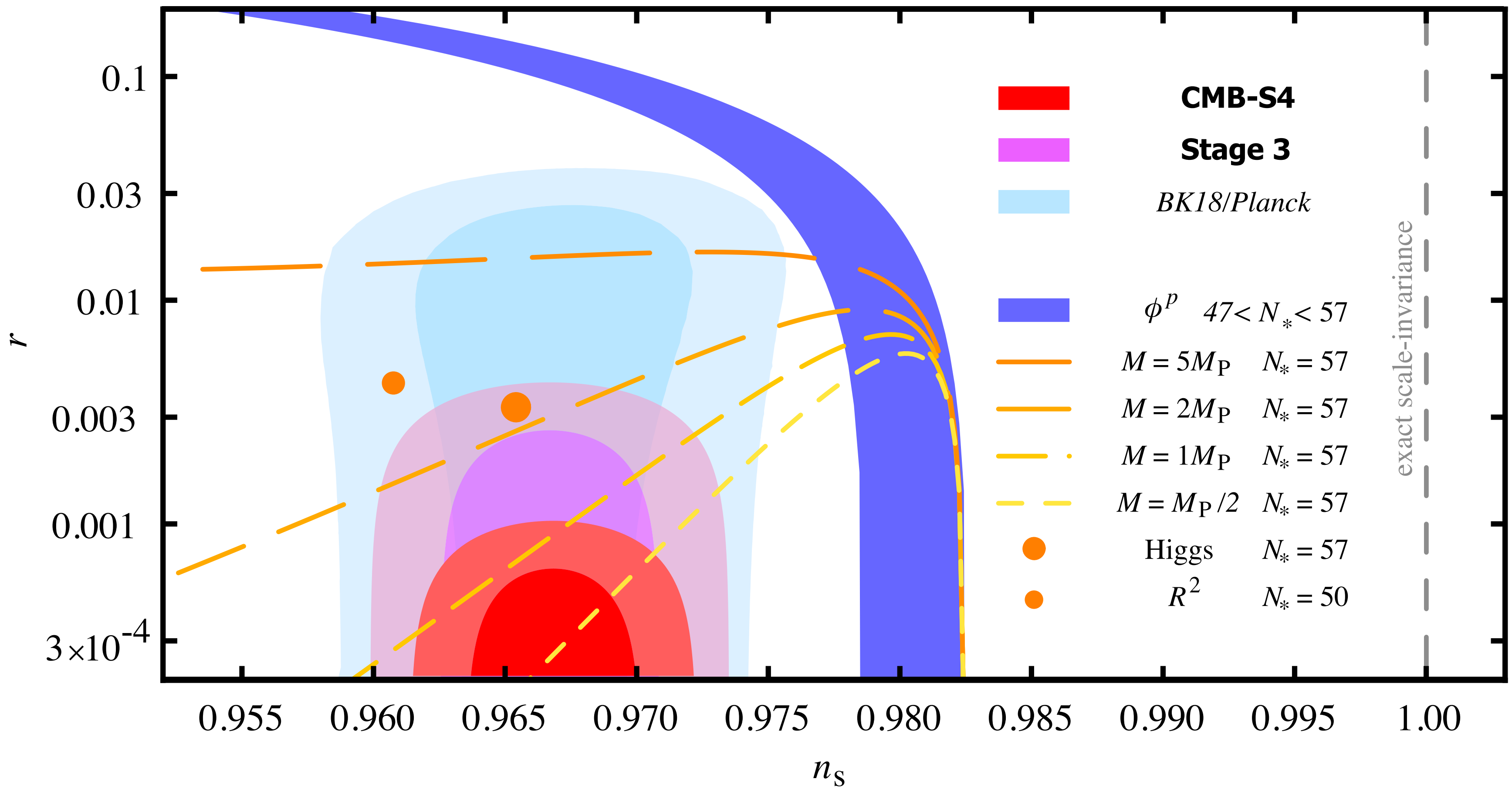
Foreground cleaned spectrum and foreground residuals



Synchrotron residuals early on led to biases and motivated the 20 GHz channel on the delensing telescope

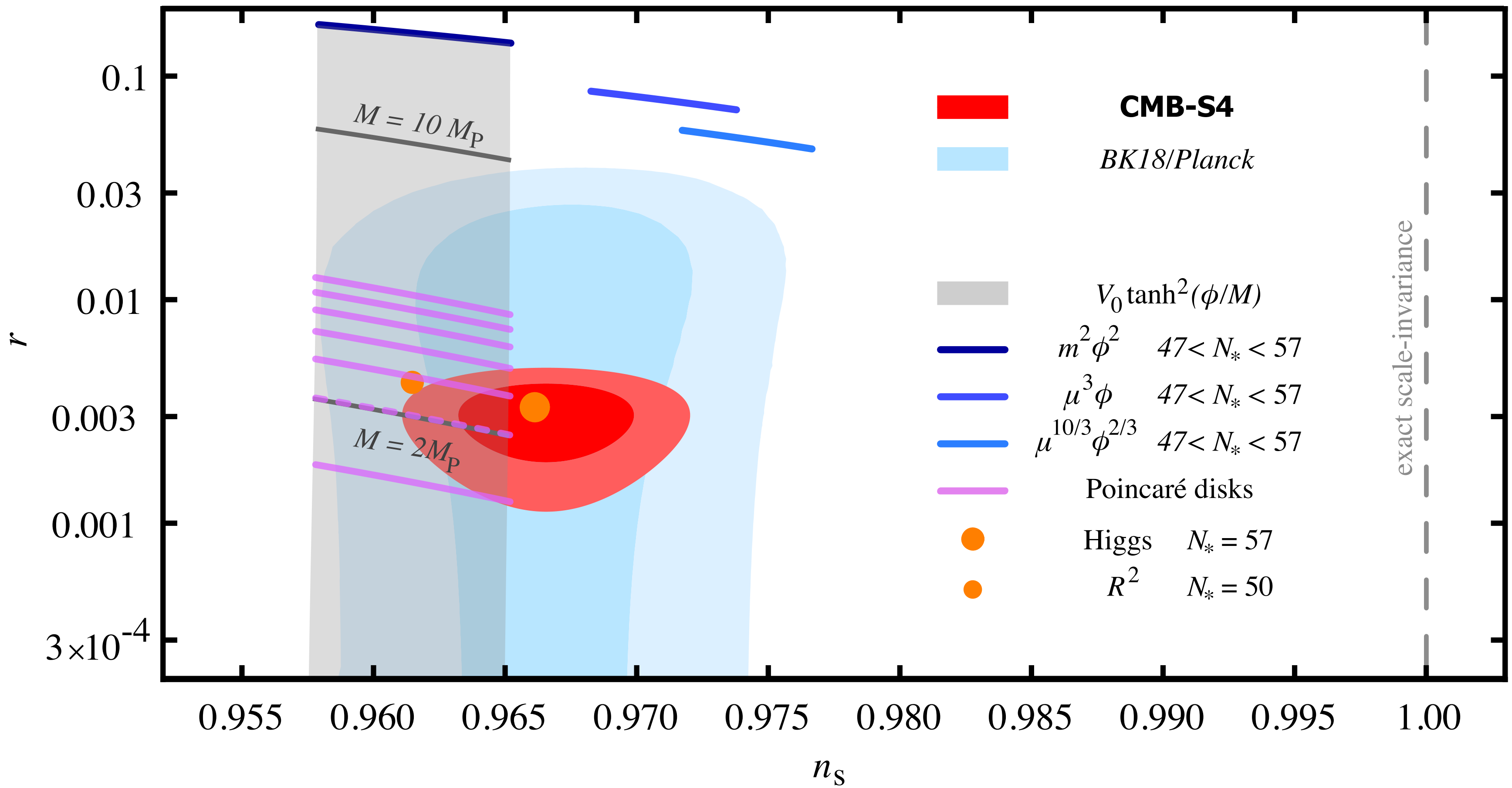
Targets

Forecast for upper limit with CMB-S4

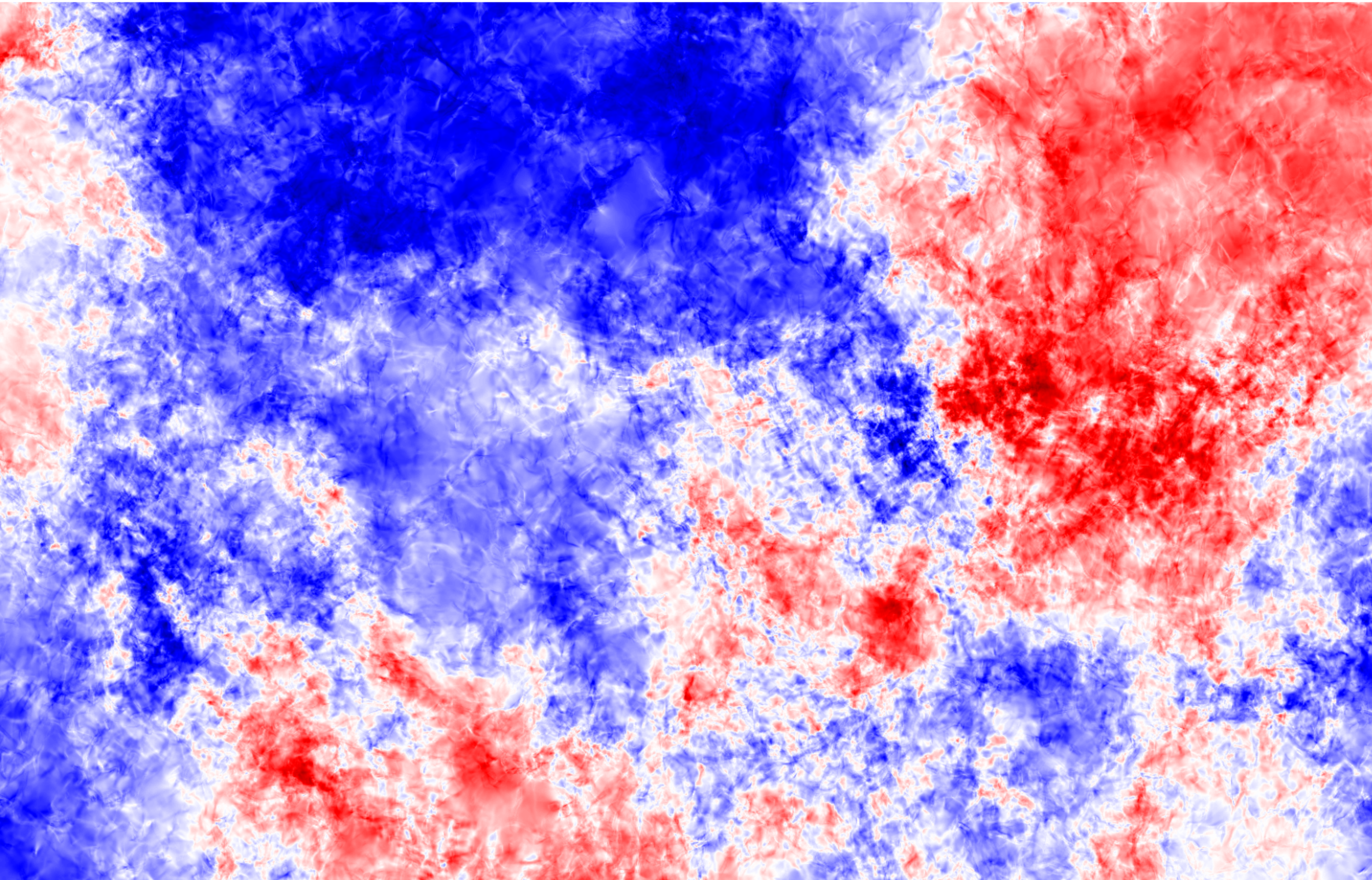


Targets

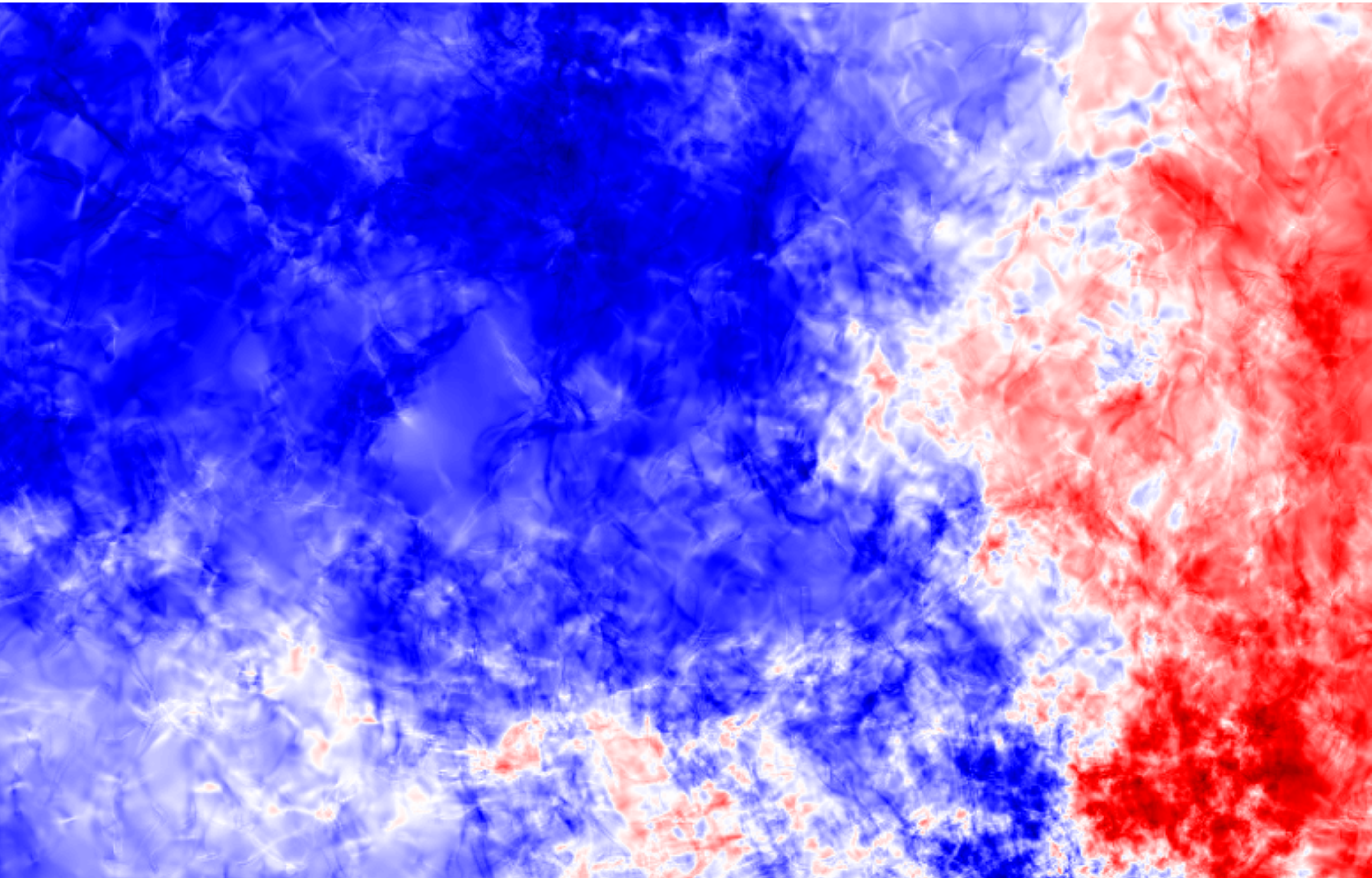
and for the more exciting detection



Dust emission

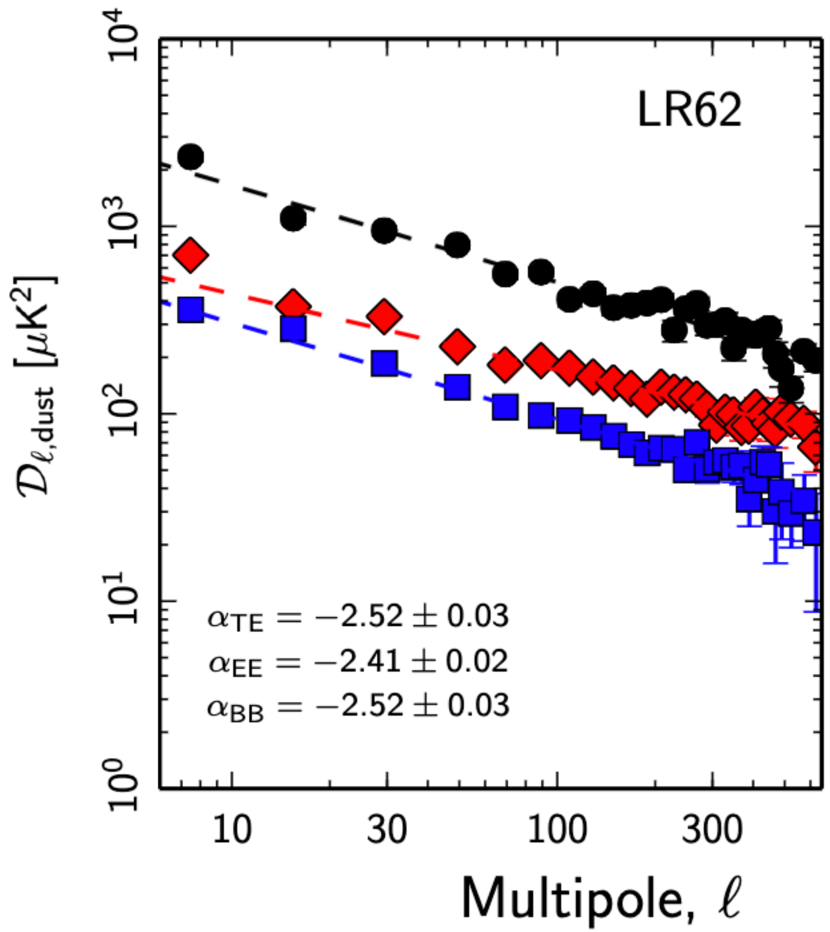


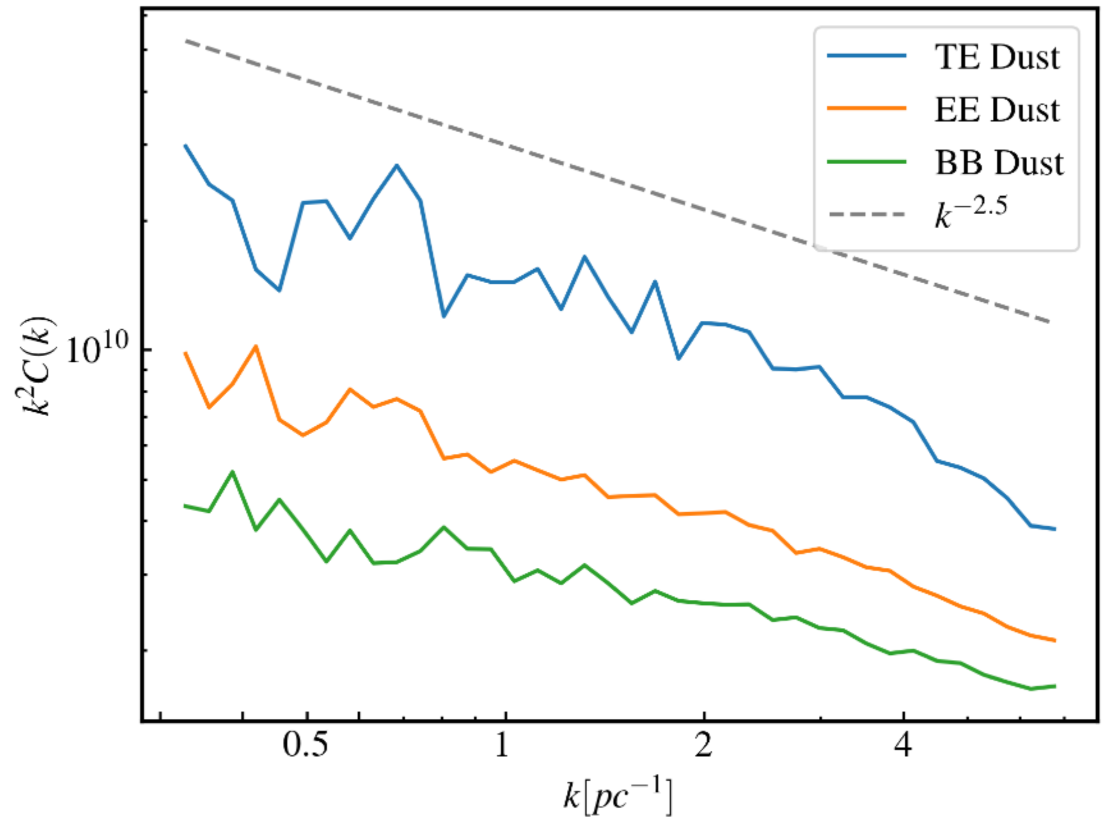
Dust emission



Dust emission

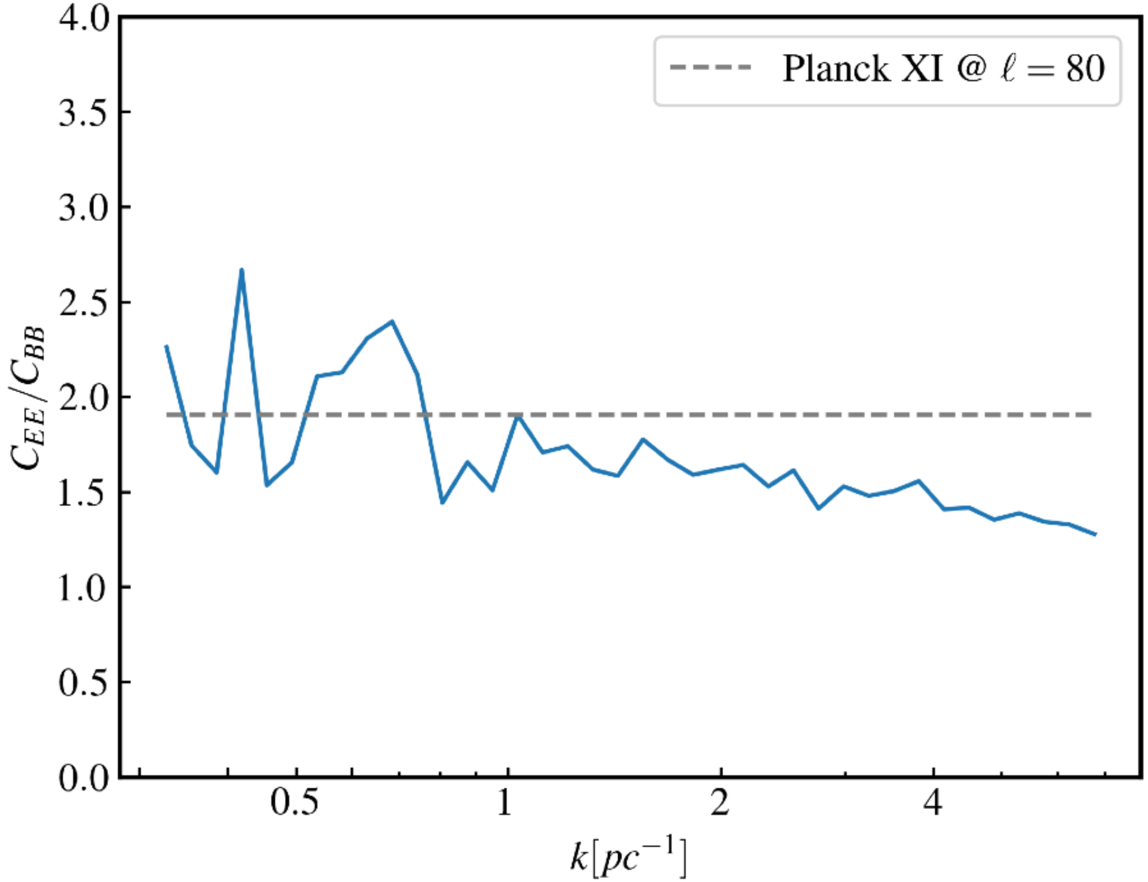
Comparison with Planck 353 GHz data



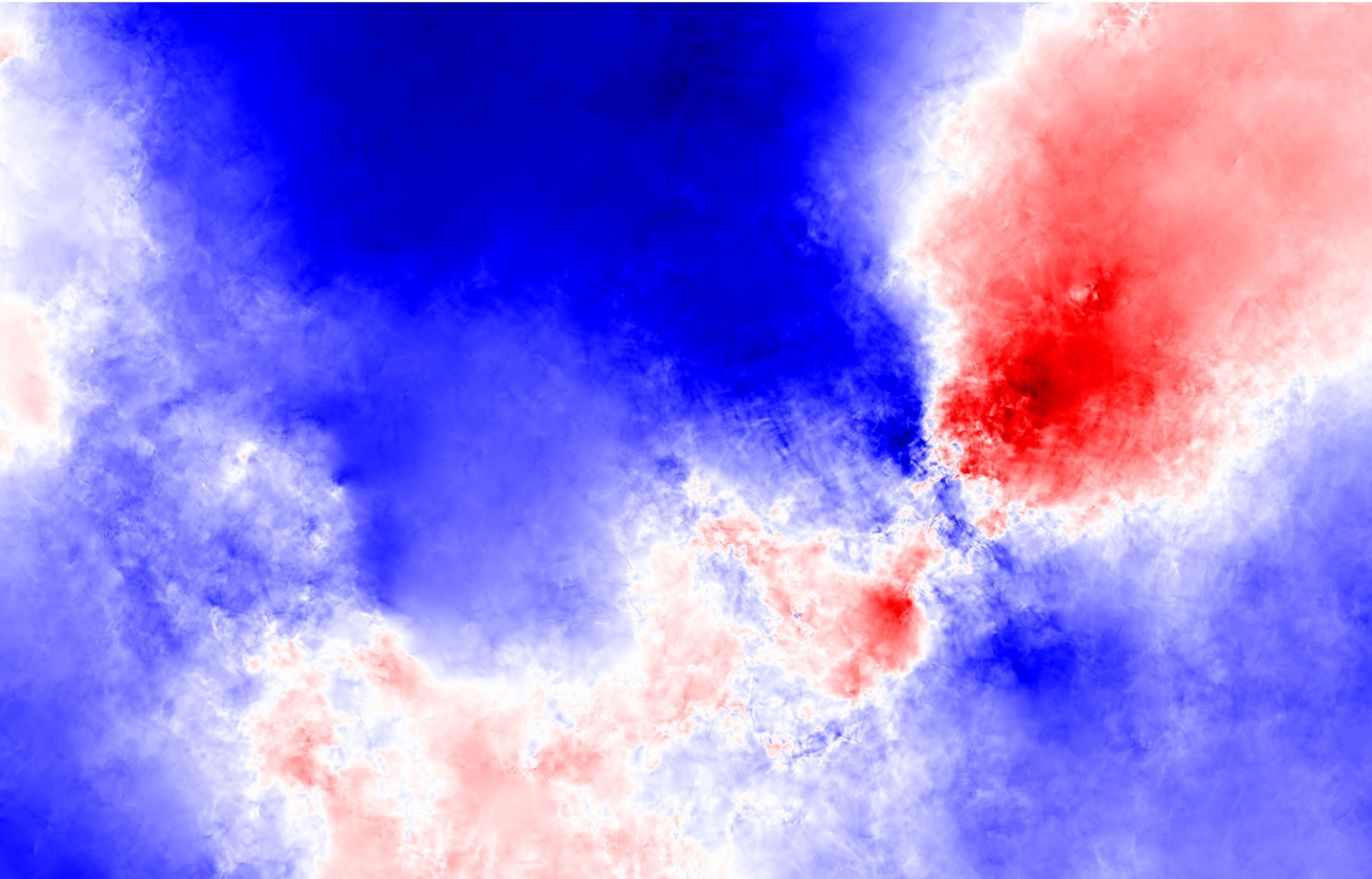


Dust emission

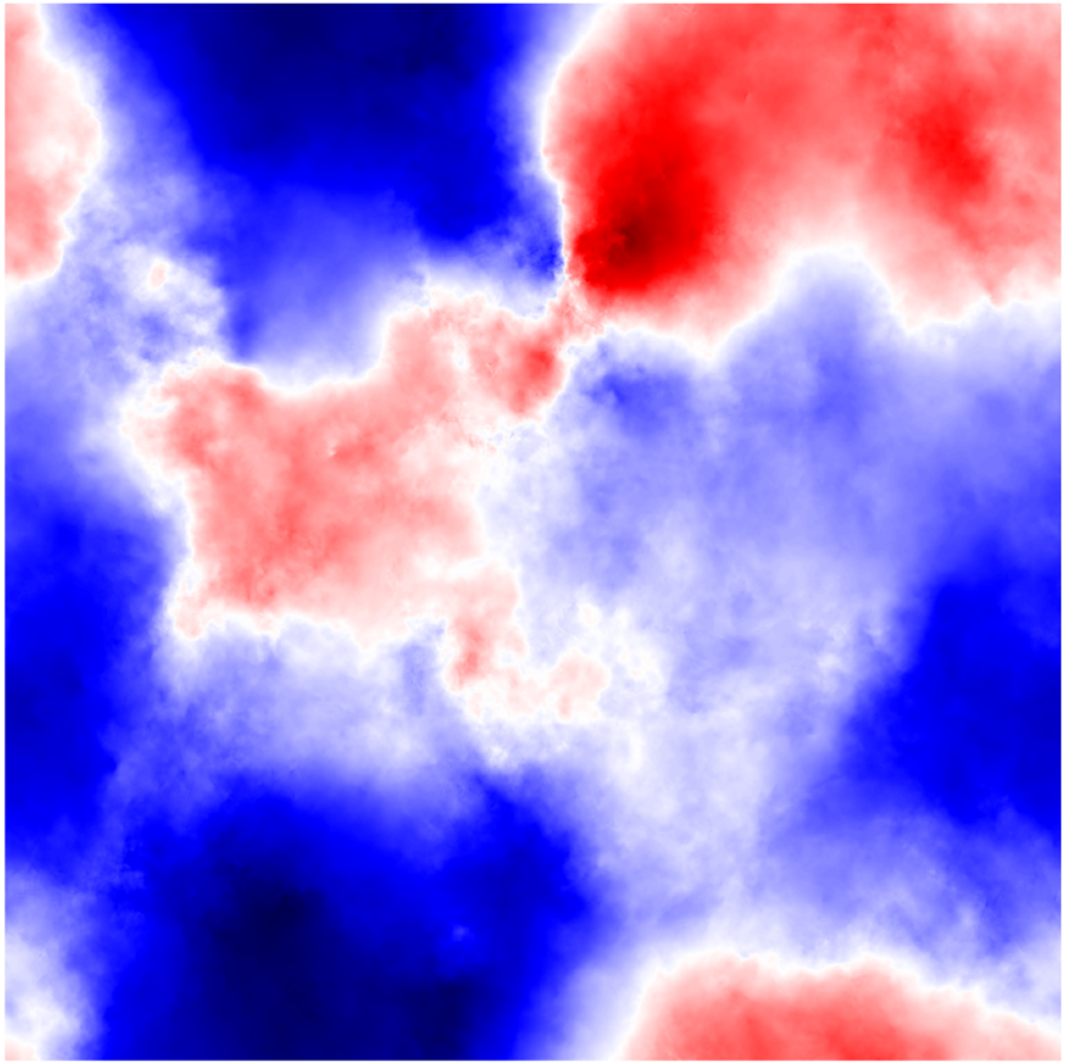
E-to-B ratio for dust



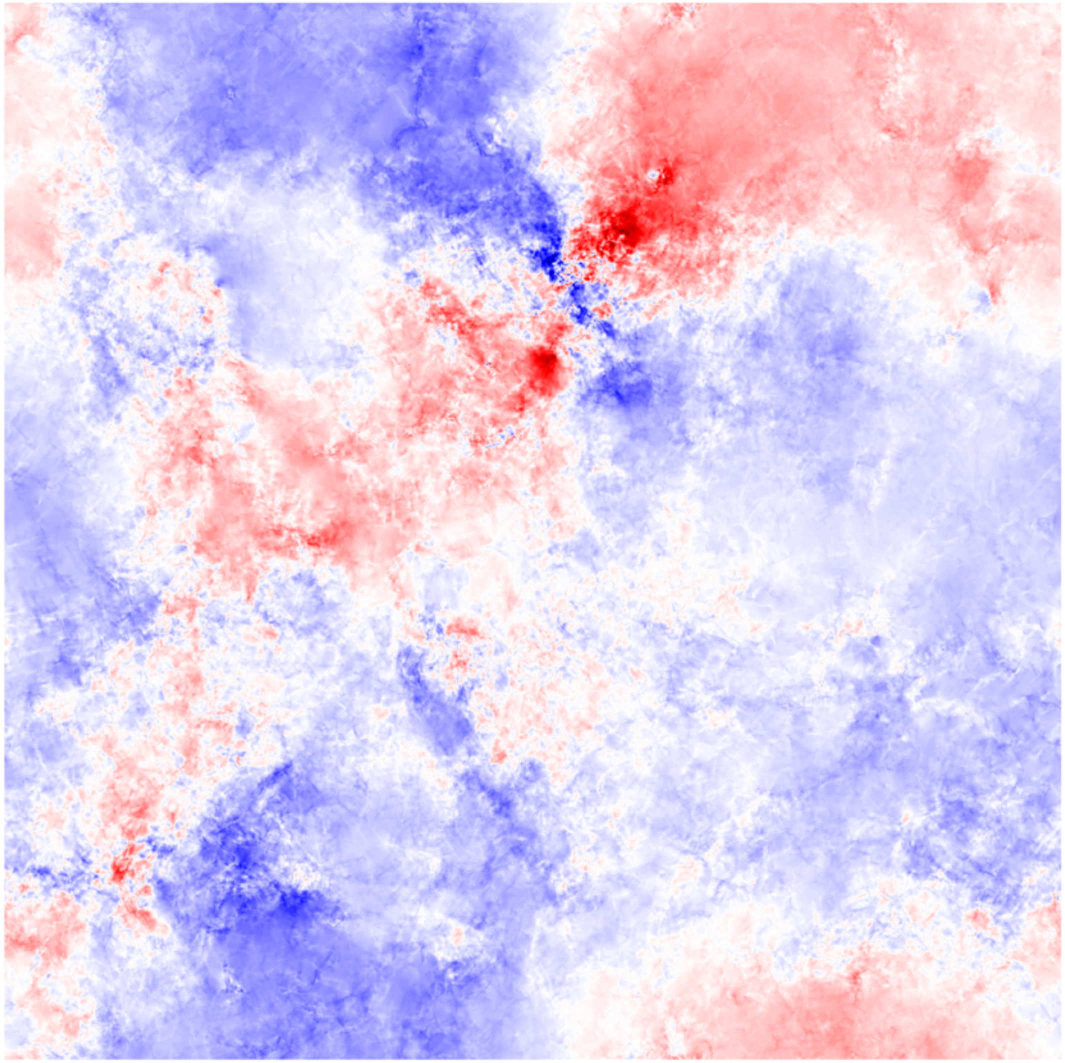
Synchroton emission



Synchrotron model



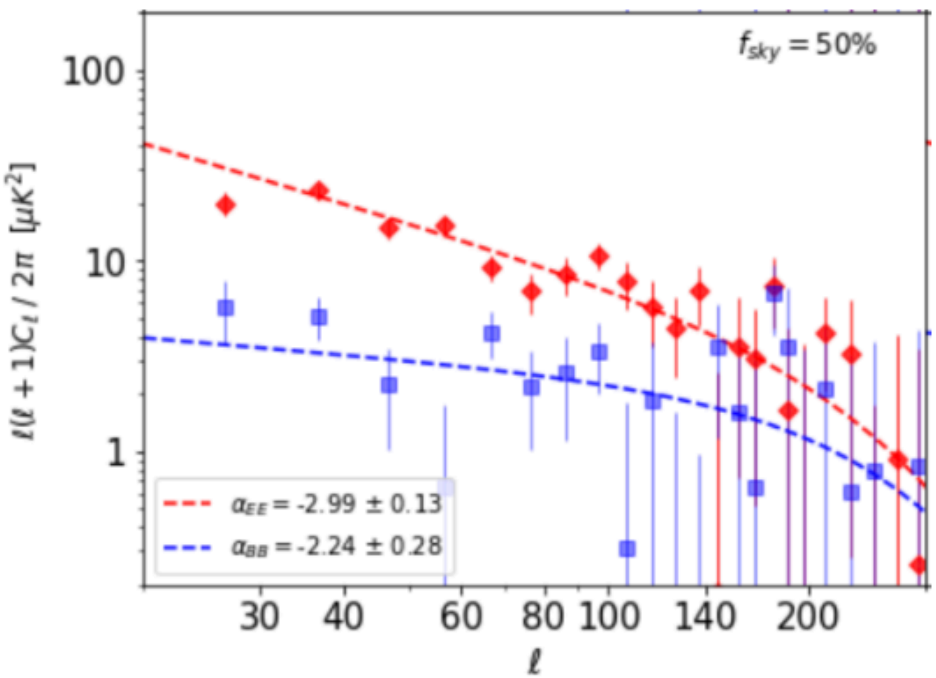
Primary cosmic ray electrons

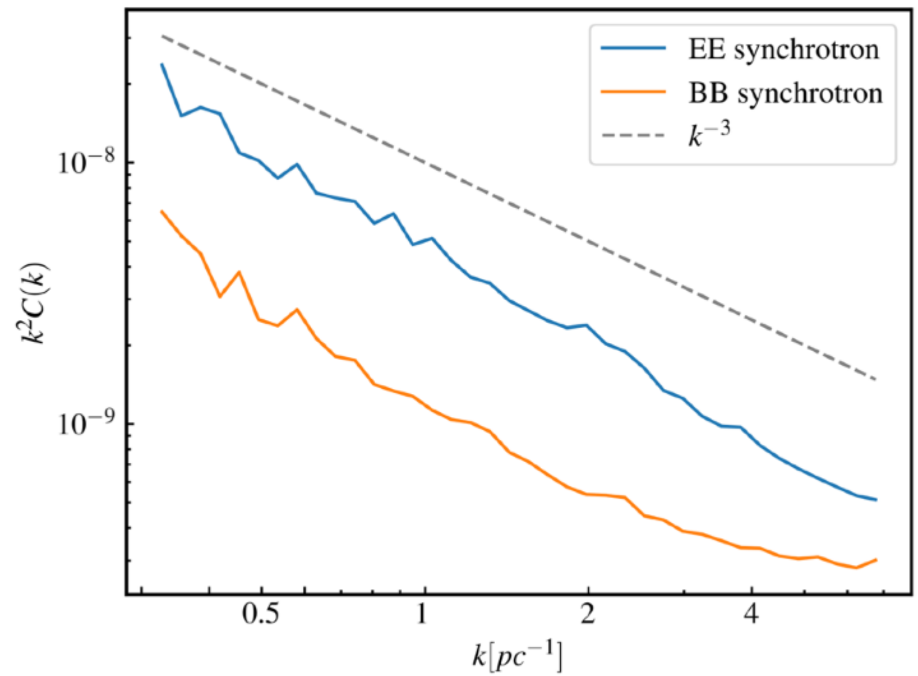


Secondary cosmic ray leptons

Synchroton spectrum

Comparison with Planck 30 GHz data

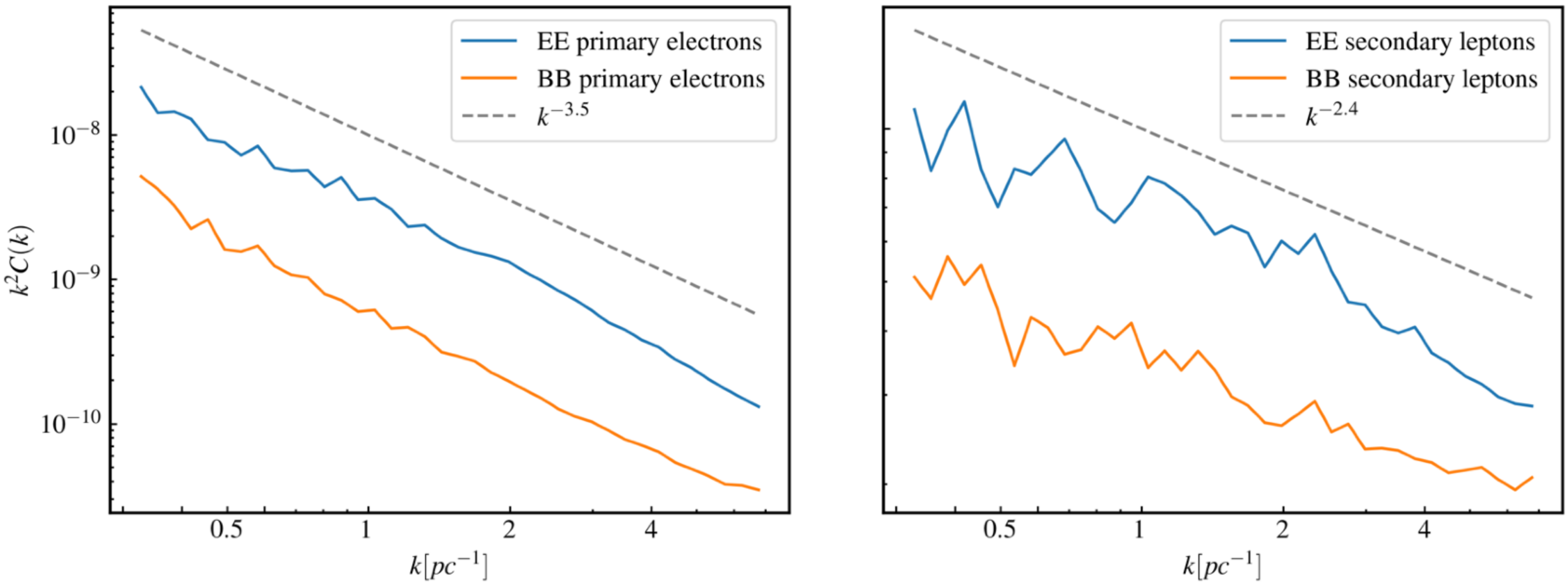




(Martire et al. 2021)

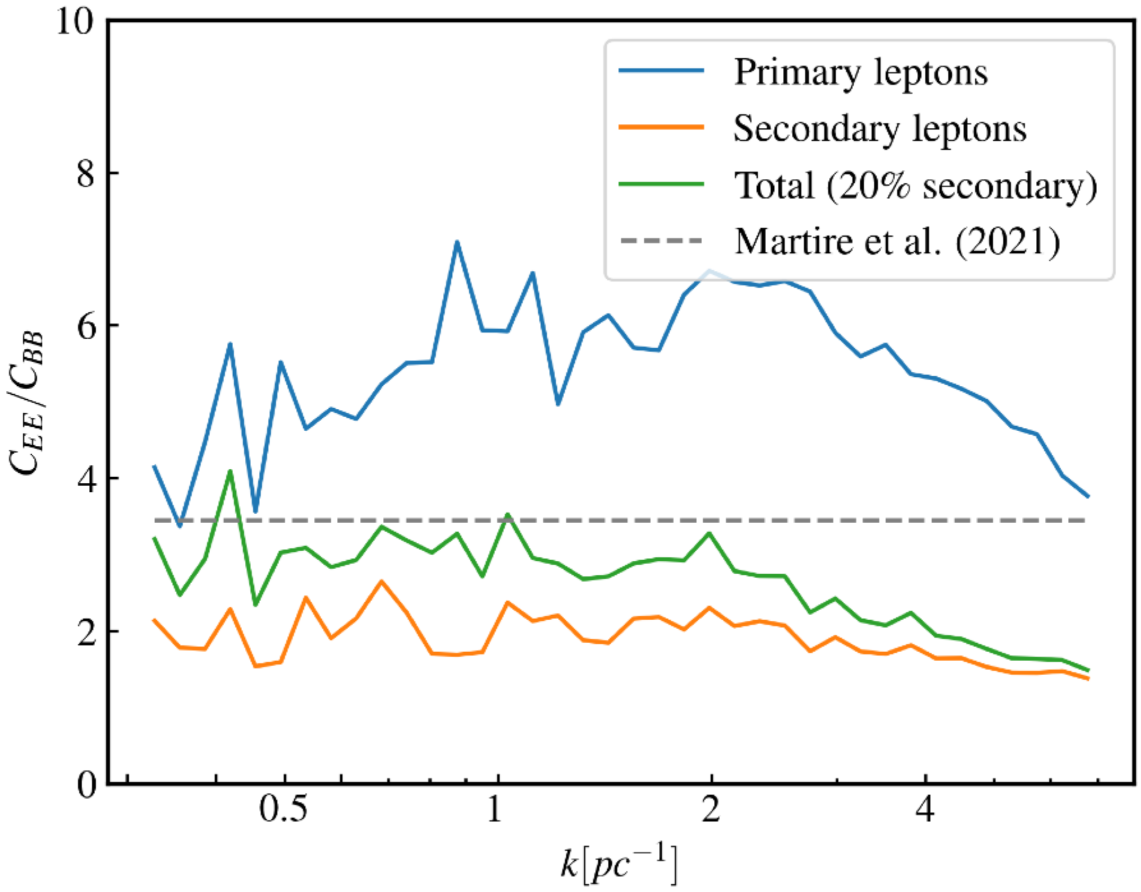
Synchroton spectrum

Primary vs secondary spectra

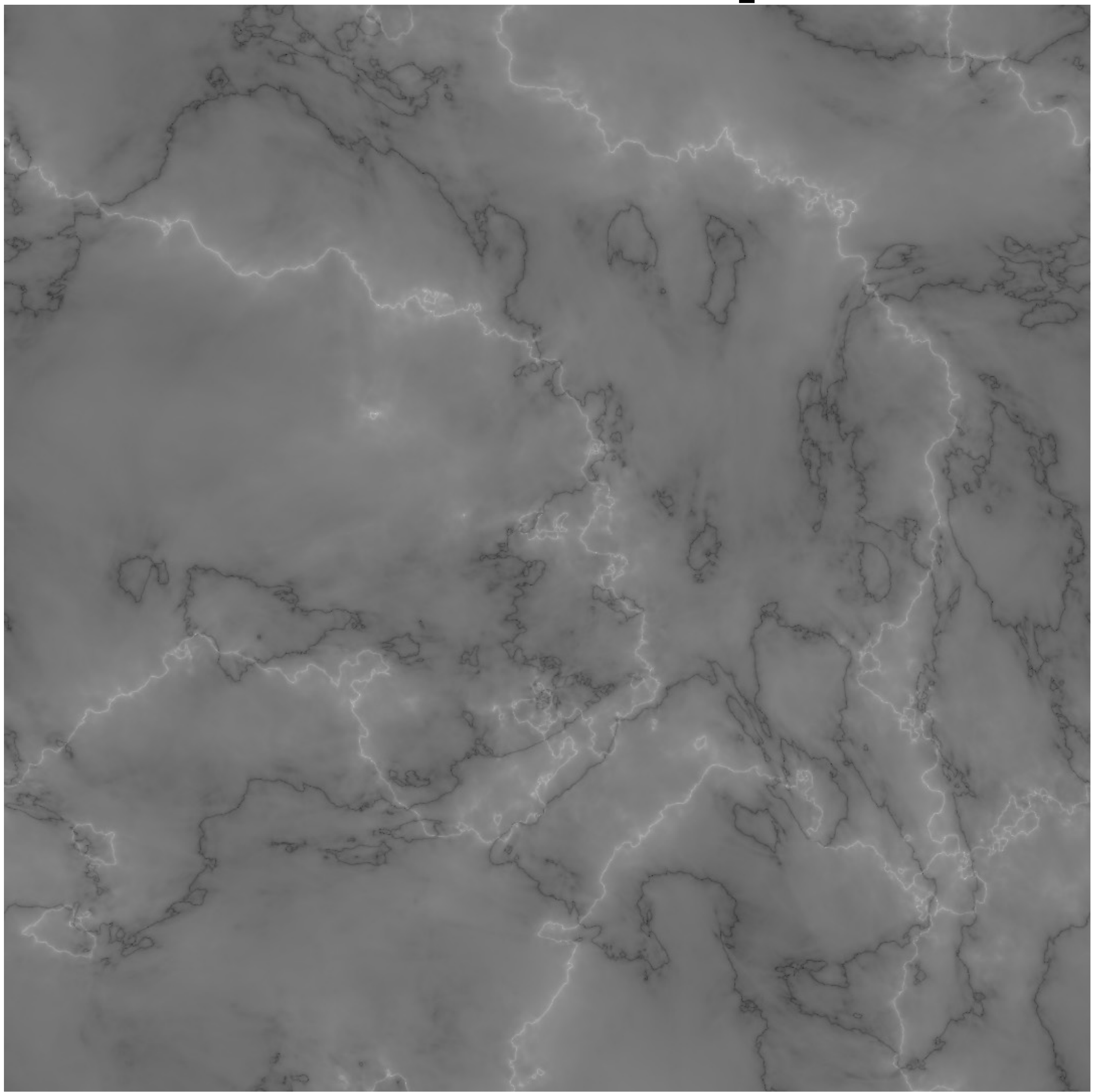


Synchroton spectrum

E-to-B ratio for synchrotron

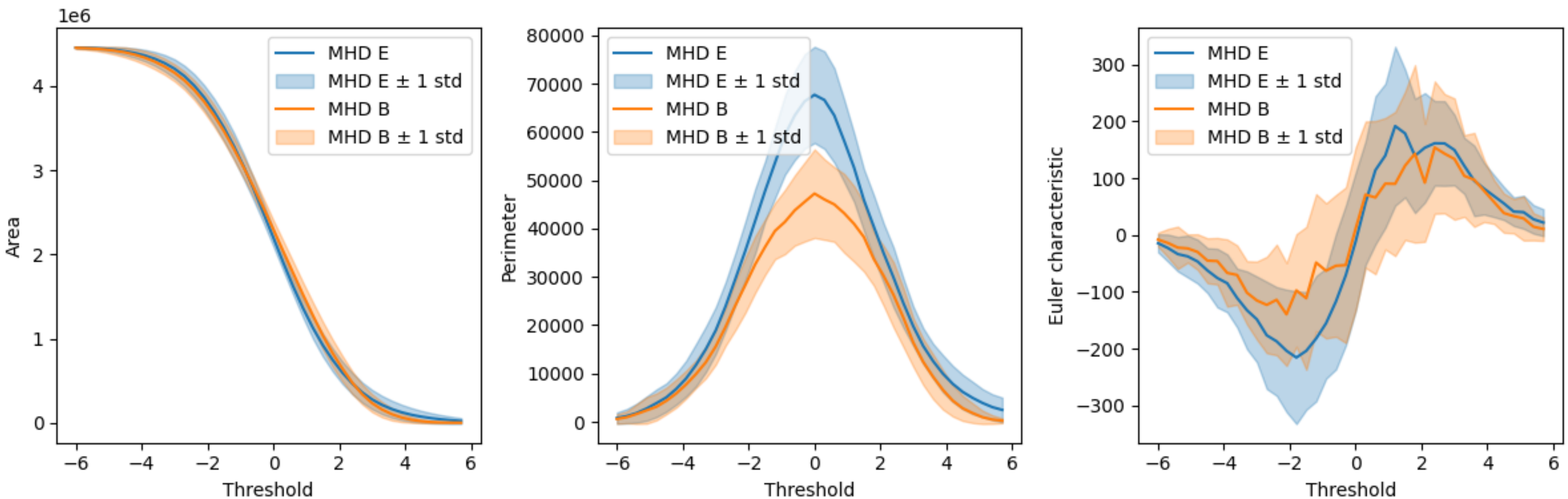


E-to-B maps



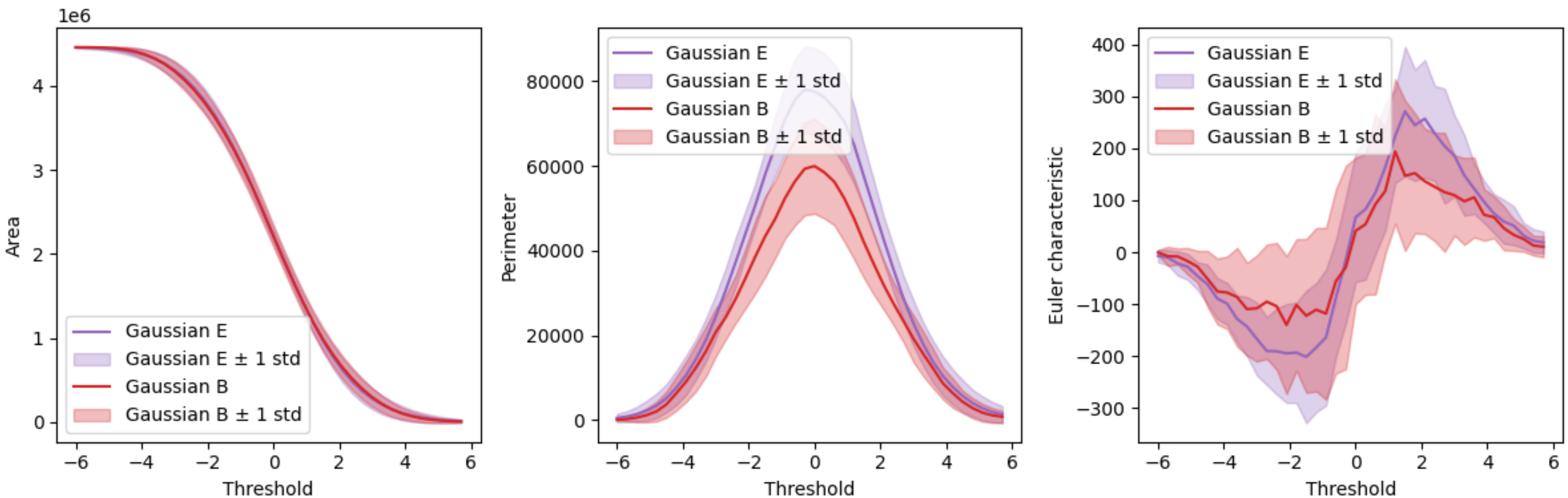
E/B asymmetry

Minkowski functionals for E and B maps



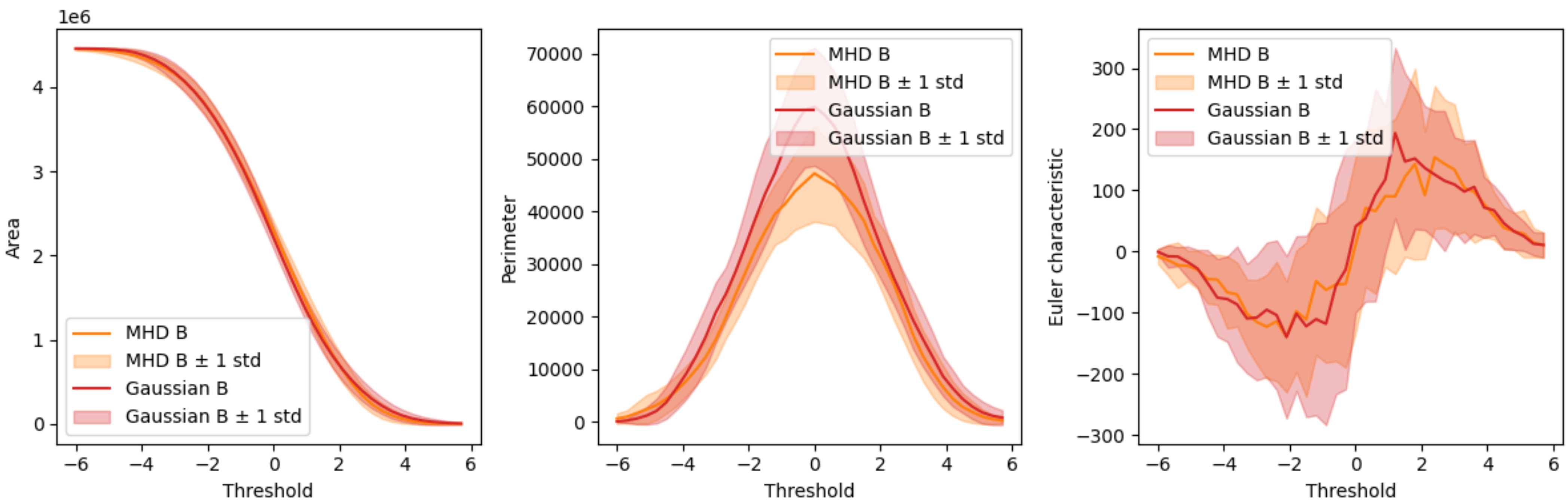
E/B asymmetry

Minkowski functionals for Gaussian maps with identical power spectra



E/B asymmetry

Gaussian vs MHD



It is natural to attempt to use this as a diagnostic tool for residuals in our maps and perhaps for foreground removal.

Conclusions

- The CMB has provided us with invaluable information about the early universe for 58 years and will continue to do so for at least another decade.
- Degree scale polarization is uniquely sensitive to gravitational waves present at recombination.
- With upcoming experiments like CMB-S4, we hope to detect cosmological gravitational waves present at recombination.
- Either a detection of, or an upper limit on, the amount of gravitational waves will provide invaluable information about the mechanism responsible for the generation of primordial perturbations.
- To detect this signal requires exquisite control over foregrounds and instrumental systematics.
- MHD simulations provide a promising route towards more realistic foreground models and hopefully better ways of dealing with them.

Thank you