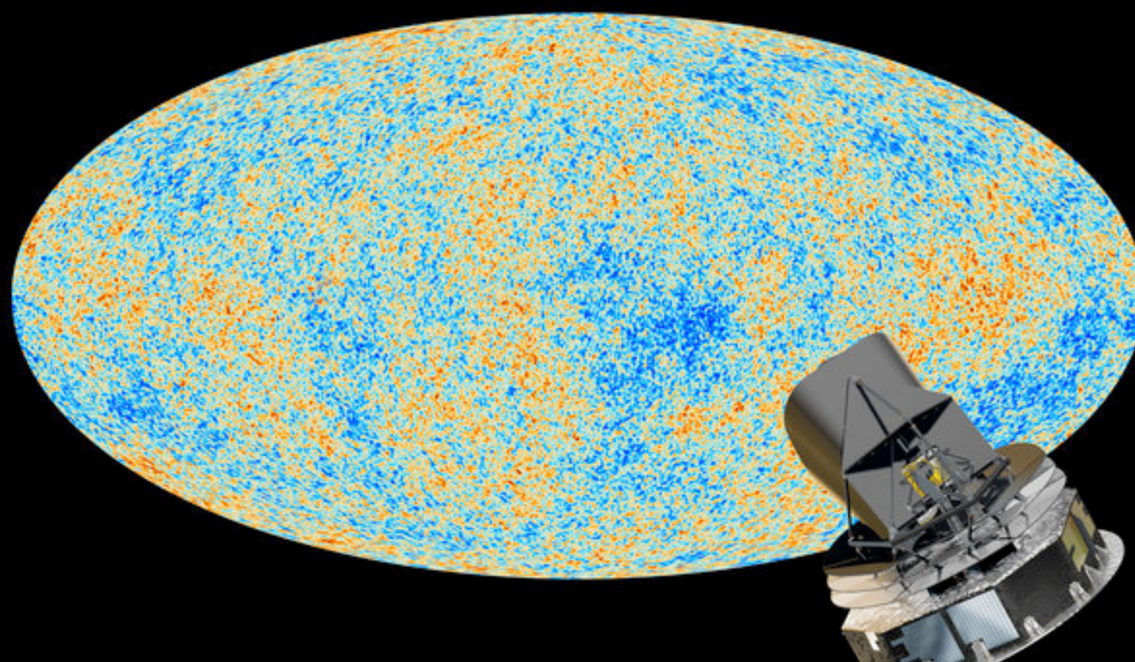
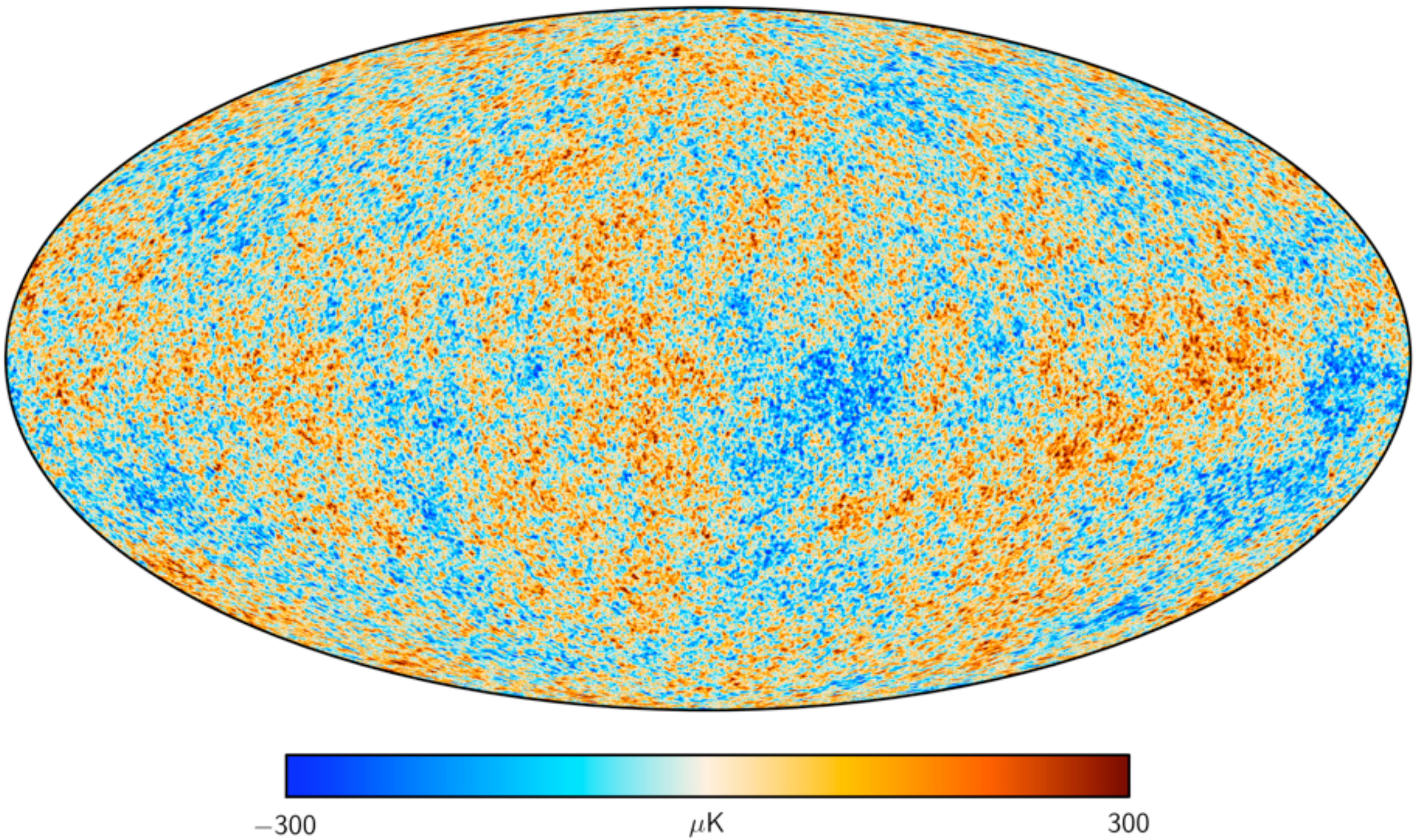
CMB probes of cosmological inflation: current status and future prospects



Anthony Challinor

KICC/IoA/DAMTP
Cambridge UK

Our window to the early universe

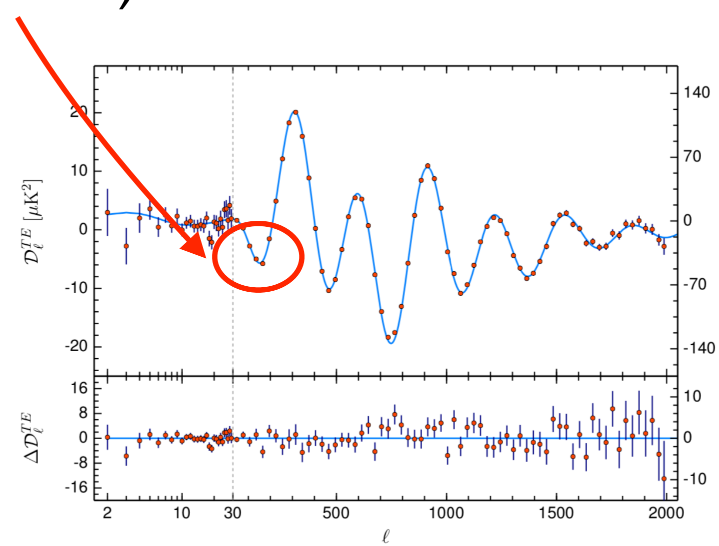


ESA/Planck

A simple early universe

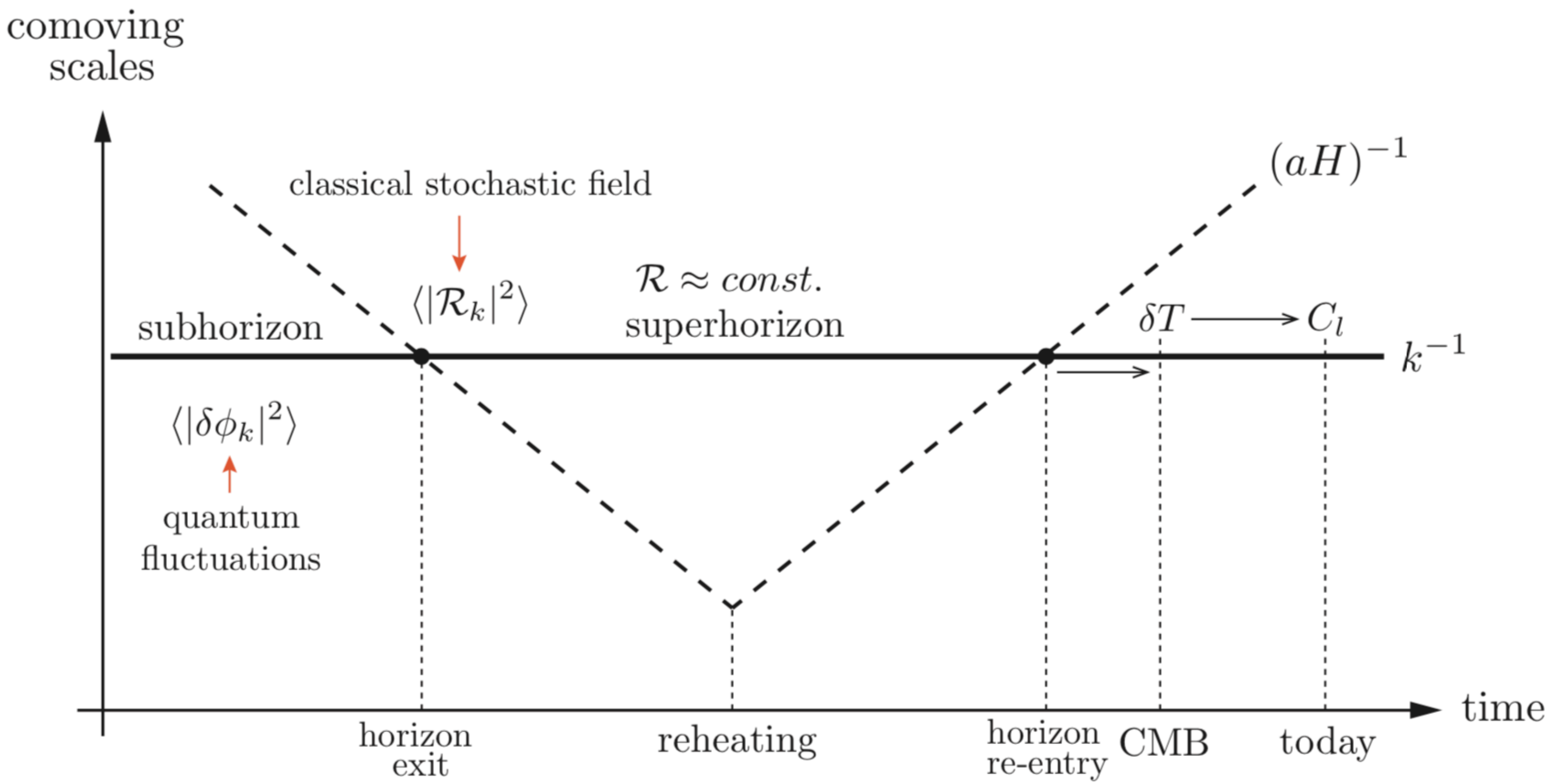
Fluctuations:

- Evolved passively from very early times
- Gaussian, adiabatic and nearly scale-invariant
- No evidence (yet) for non-scalar modes
- Super-Hubble (apparently acausal) correlations



Planck Collaboration 2018

Cosmic inflation: origin of structure



Credit: Baumann

Inflation theory – single-field, slow-roll

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

Two massless fields in unitary gauge ($\delta\phi = 0$):

$$d\ell^2 = a^2 e^{2\zeta} \left(e^{\gamma}\right)_{ij} dx^i dx^j$$

Curvature (→ ζ) Tensors/GWs (→ γ)

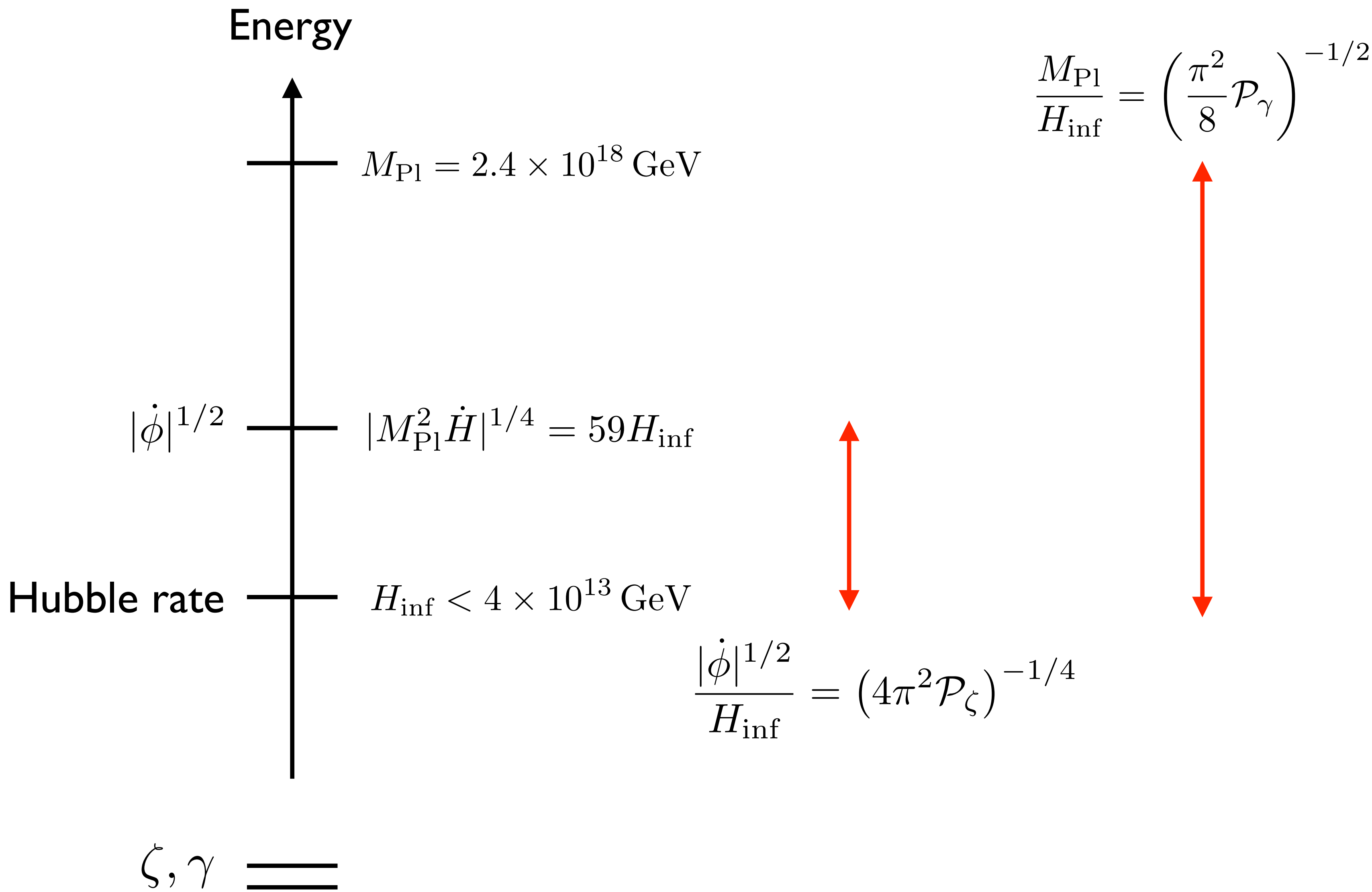
$$\mathcal{P}_\zeta(k) = \left(\frac{H}{2\pi}\right)^2 \left(\frac{H}{\dot\phi}\right)^2 = \frac{1}{8\pi^2} \frac{H^4}{M_{\rm Pl}^2 |\dot H|}$$

$$\mathcal{P}_h(k) = \frac{8}{M_{\rm Pl}^2} \left(\frac{H}{2\pi}\right)^2$$

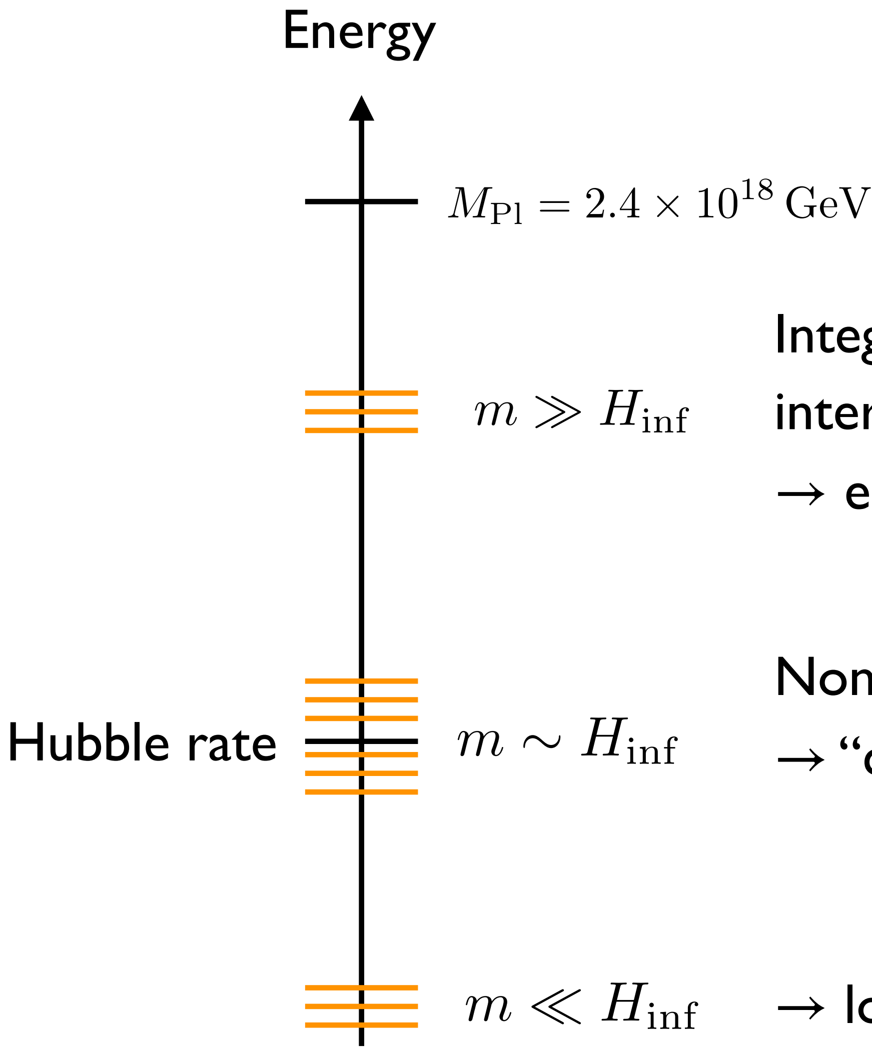
Observed:
- Gaussian
- Adiabatic
- Nearly scale-invariant

Not yet observed

Energy scales involved



More complete picture …



Integrate out to give local self interactions (EFT)

→ equilateral and orthogonal NG

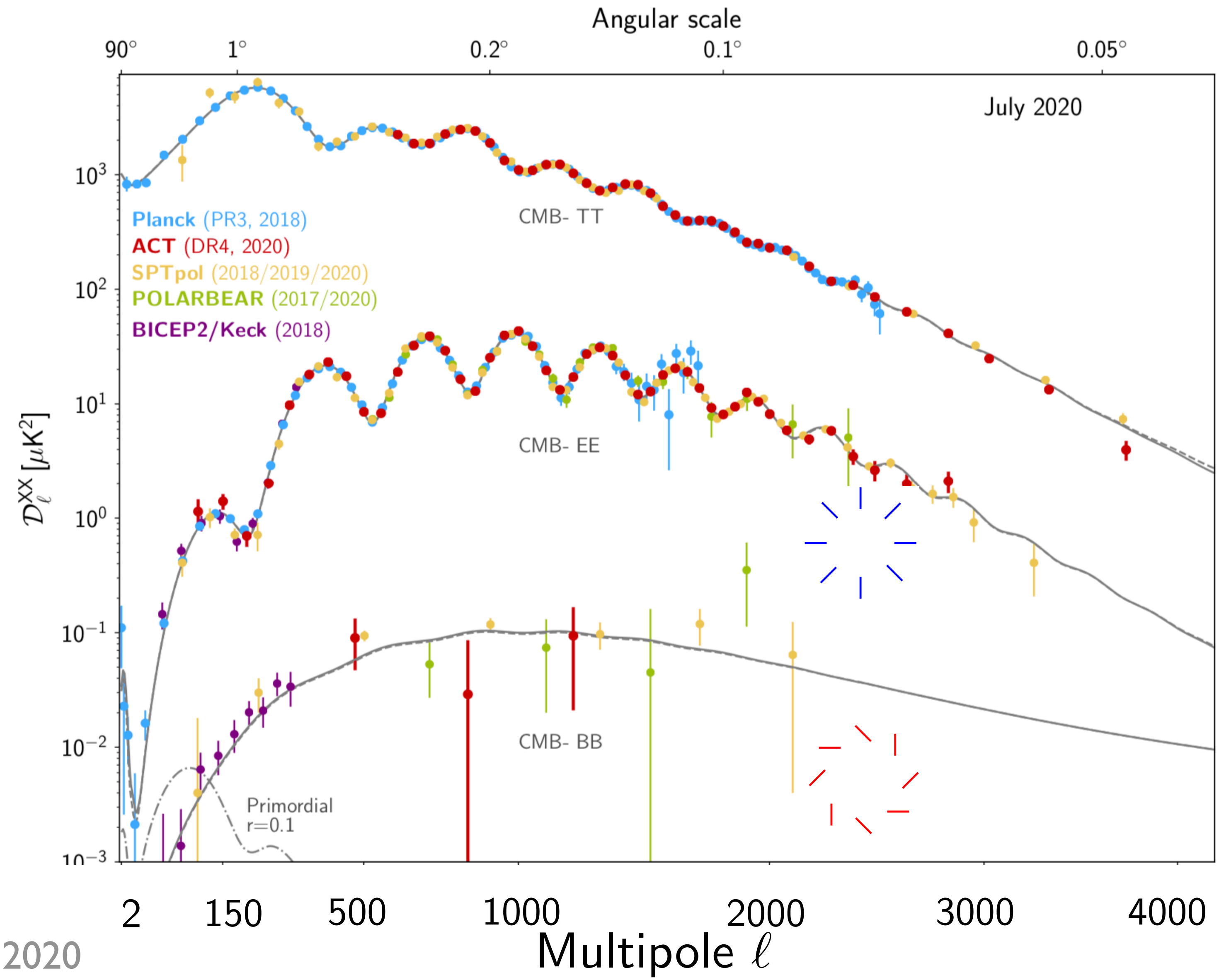
Non-local interactions

→ "cosmological collider physics"

→ local-model NG

Primordial scalar power spectrum

CMB power measurements



Choi+ 2020

Scalar spectral index

- Single-field inflation:

Expect $n_s \lesssim 1$

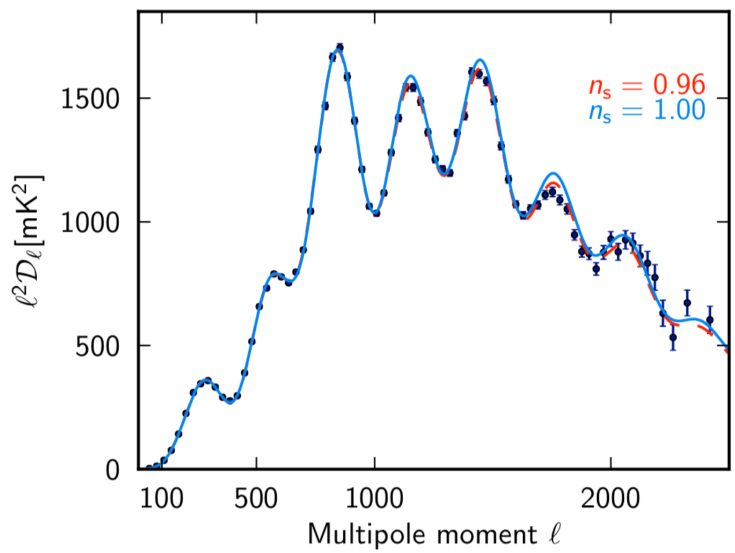
$$\mathcal{P}_\zeta(k) = \left(\frac{H}{2\pi}\right)^2 \left(\frac{H}{\dot\phi}\right)^2 \Bigg|_{k=aH} = \frac{1}{8\pi^2}\frac{H^4}{M_{\rm Pl}^2|\dot H|}\Bigg|_{k=aH} \approx A_s\left(\frac{k}{k_*}\right)^{n_s-1}$$

Planck TT,TE,EE+lowE:

$$n_{\rm s} = 0.9649 \pm 0.0044 \quad (68\,\%\,{\rm CL})$$

Scale-invariance strongly ruled out:

$$\Delta\chi^2 \approx 70$$

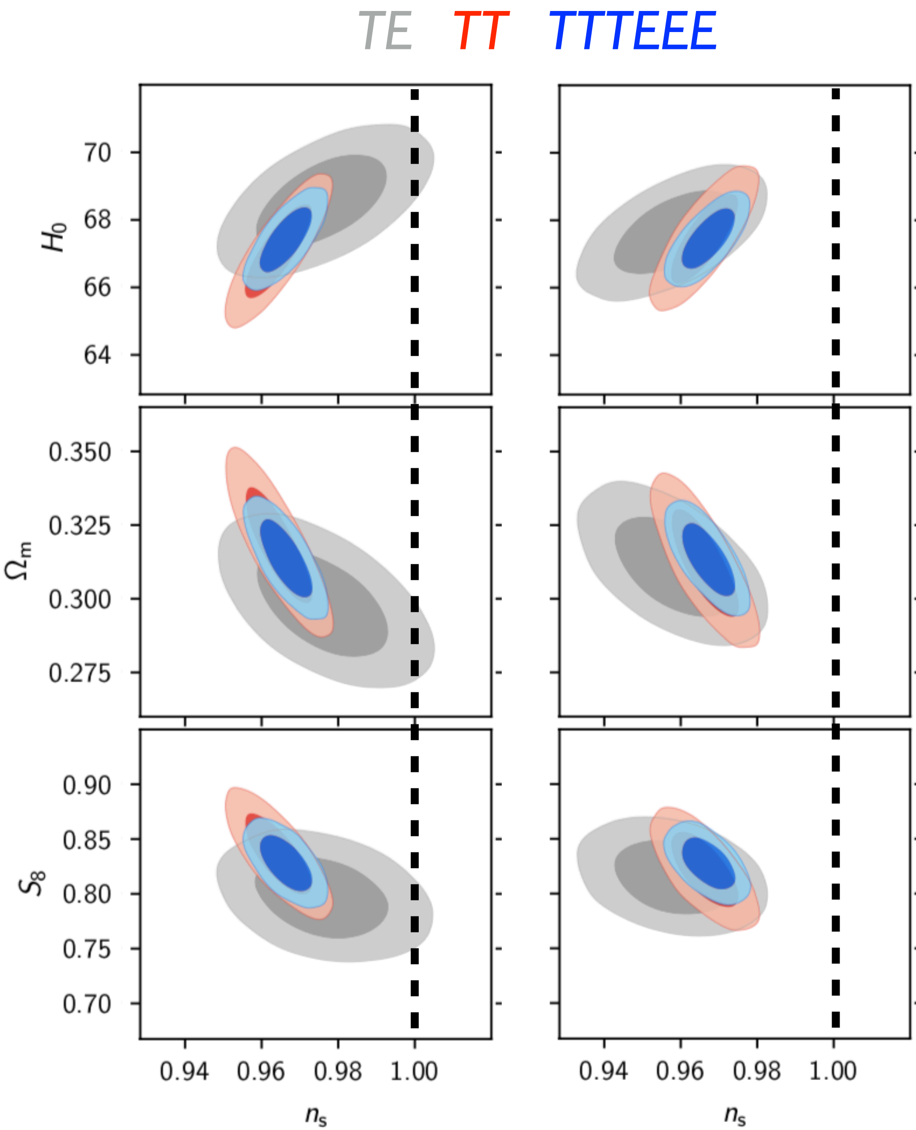


- Robust to most model assumptions (e.g., $N_{\rm eff}$, curvature, etc.)

Planck Collaboration 2013, 2018

Consistent picture from polarization

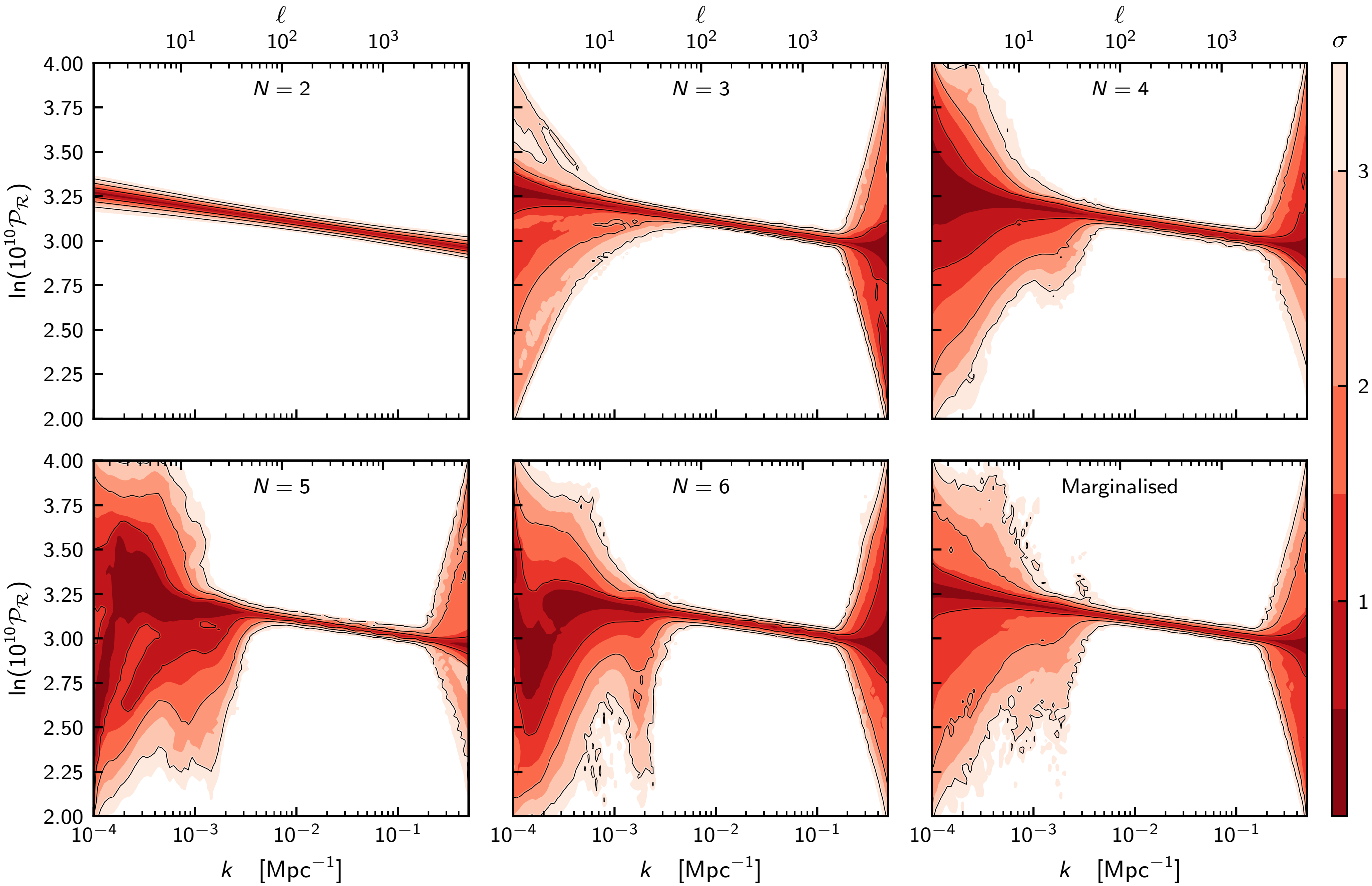
Similar to Planck 2018

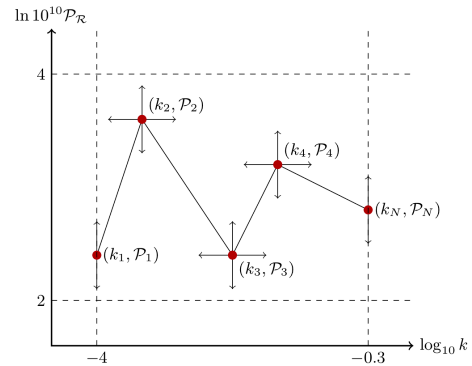


80% of sky with 545 GHz cleaning

Efstathiou & Gratton 2019

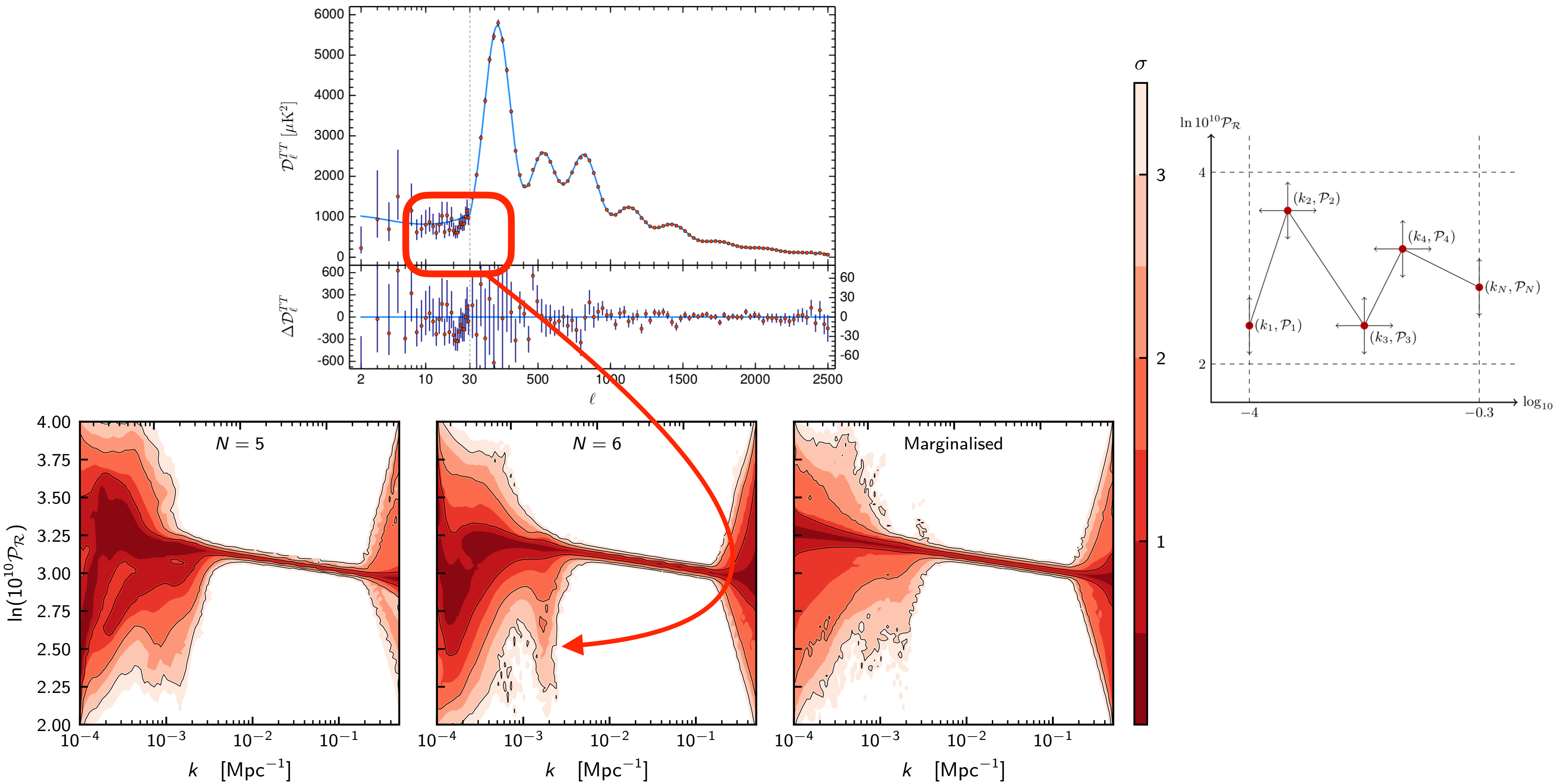
Primordial power spectrum reconstruction





Planck Collaboration 2018
Handley+ 2019

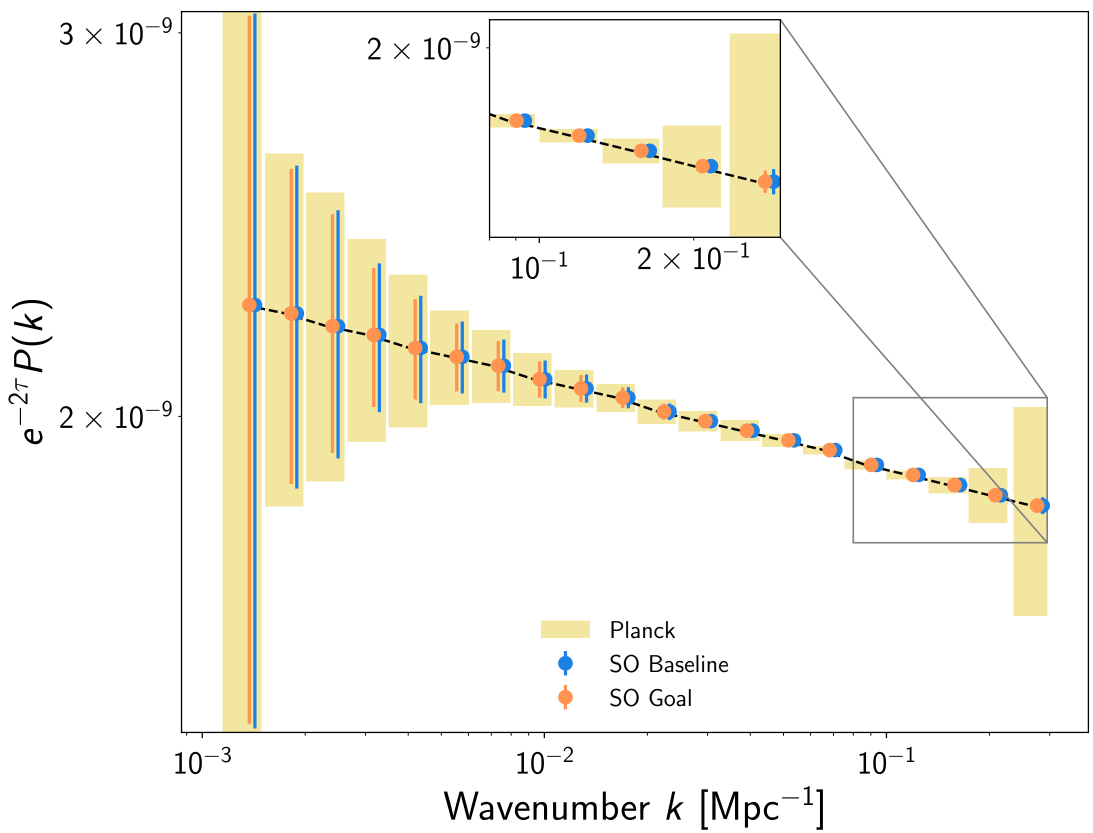
Primordial power spectrum reconstruction



Planck Collaboration 2018
Handley+ 2019

Pushing to smaller scales

10-fold improvement over Planck at 0.2 Mpc^{-1} from high-*l* polarization



Better *E*-mode data will also help with primordial feature searches

Simons Observatory Collaboration 2018

Primordial tensor power spectrum

Primordial gravitational waves

$$n_t \approx 2\dot{H}/H^2 \leq 0$$

$$\mathcal{P}_h(k) = \frac{8}{M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2_{k=aH} \approx A_t\left(\frac{k}{k_*}\right)^{n_t}$$

- Direct probe of energy scale associated with inflation:

$$H^2 = \frac{E_{\rm inf}^4}{3M_{\rm Pl}^2}$$

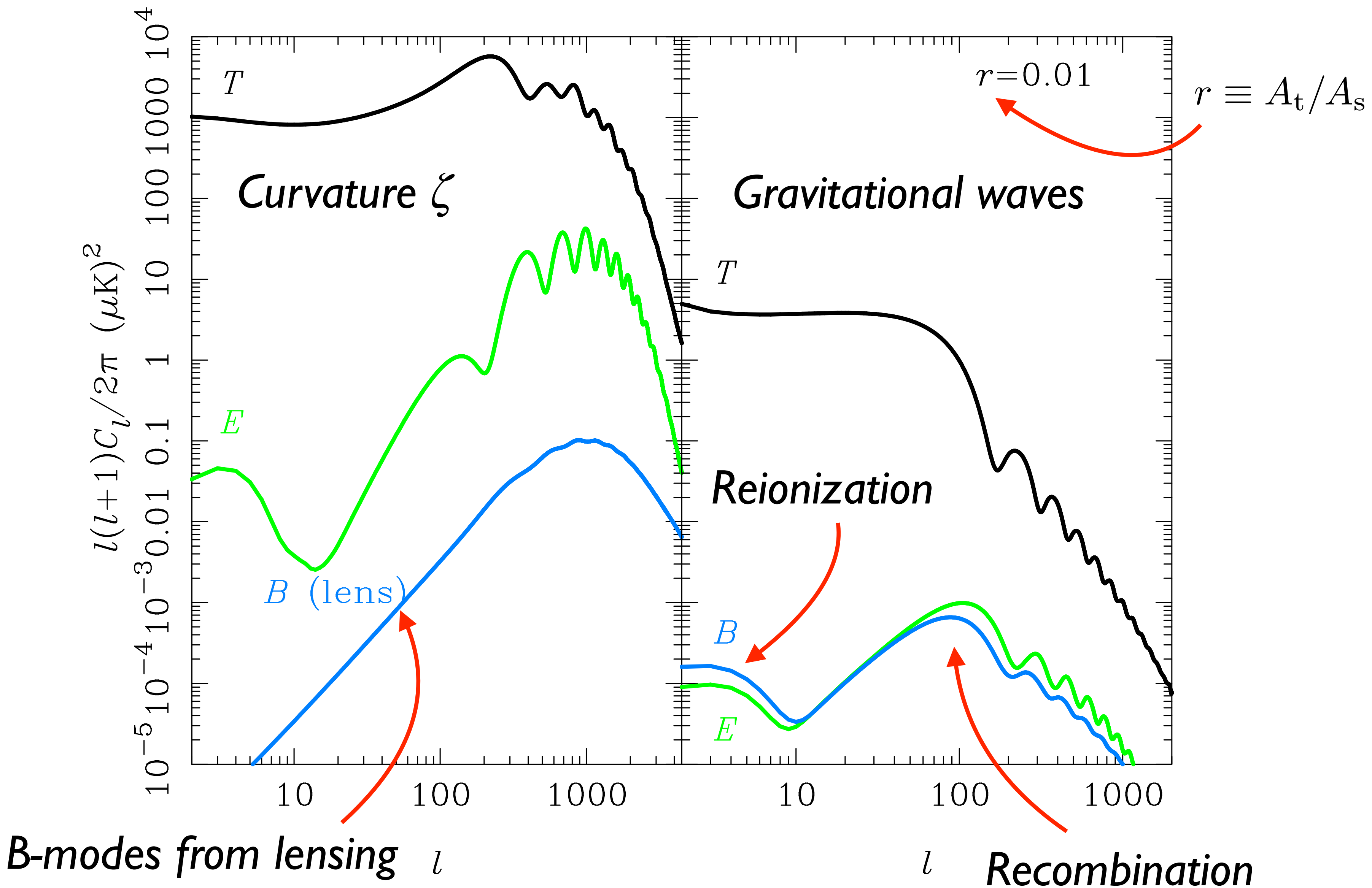
$$\Rightarrow \quad \mathcal{P}_h(k) \approx 1.93 \times 10^{-11}\left(\frac{E_{\rm inf}}{10^{16}\,{\rm GeV}}\right)^4$$

- Tensor-to-scalar ratio:

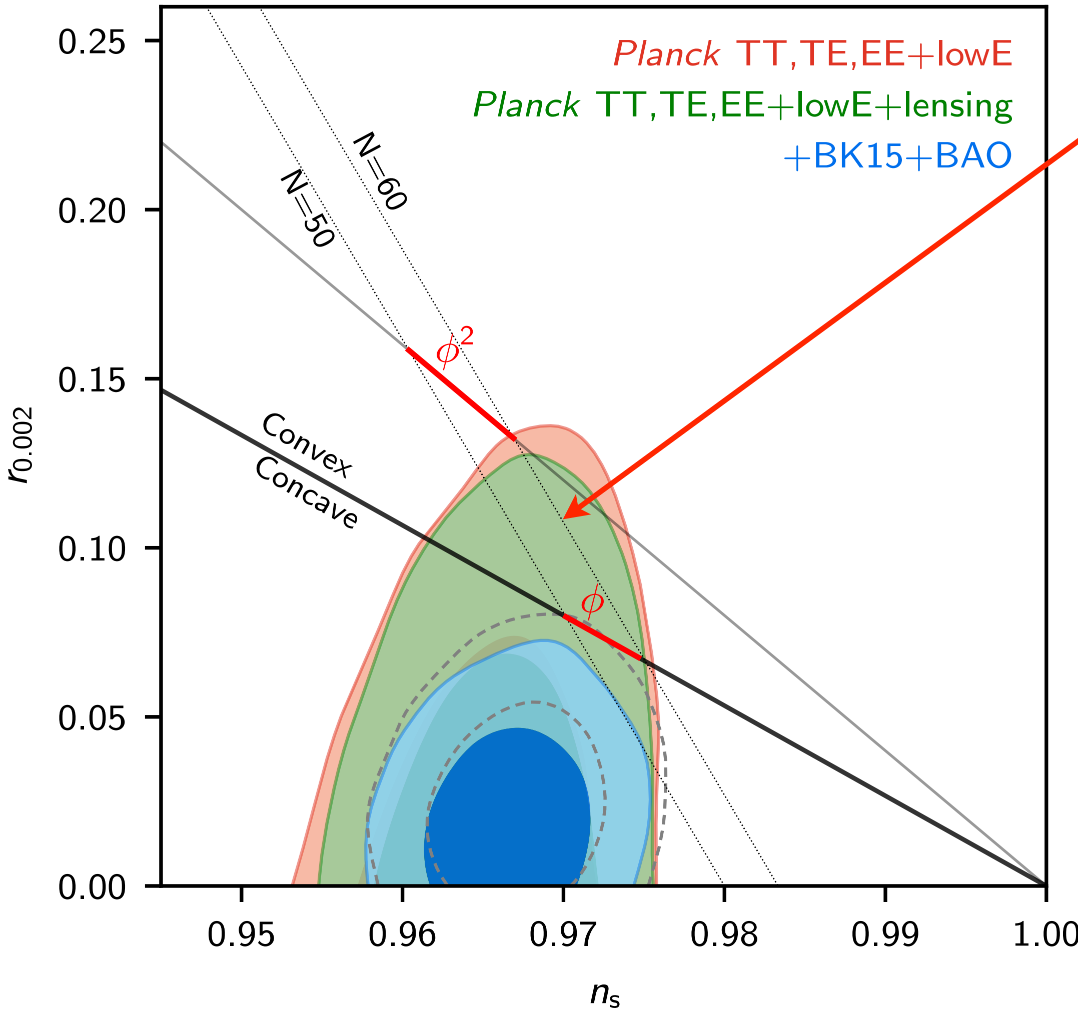
$$r = \frac{A_t}{A_s} = 16\frac{|\dot{H}|}{H^2}$$

Canonical, single-field

Primordial gravitational waves in CMB



Constraints from Planck T and E



$r_{0.002} < 0.1 \quad (95\,\%\ \mathrm{CL})$

- Weakens for extended models (e.g., running):

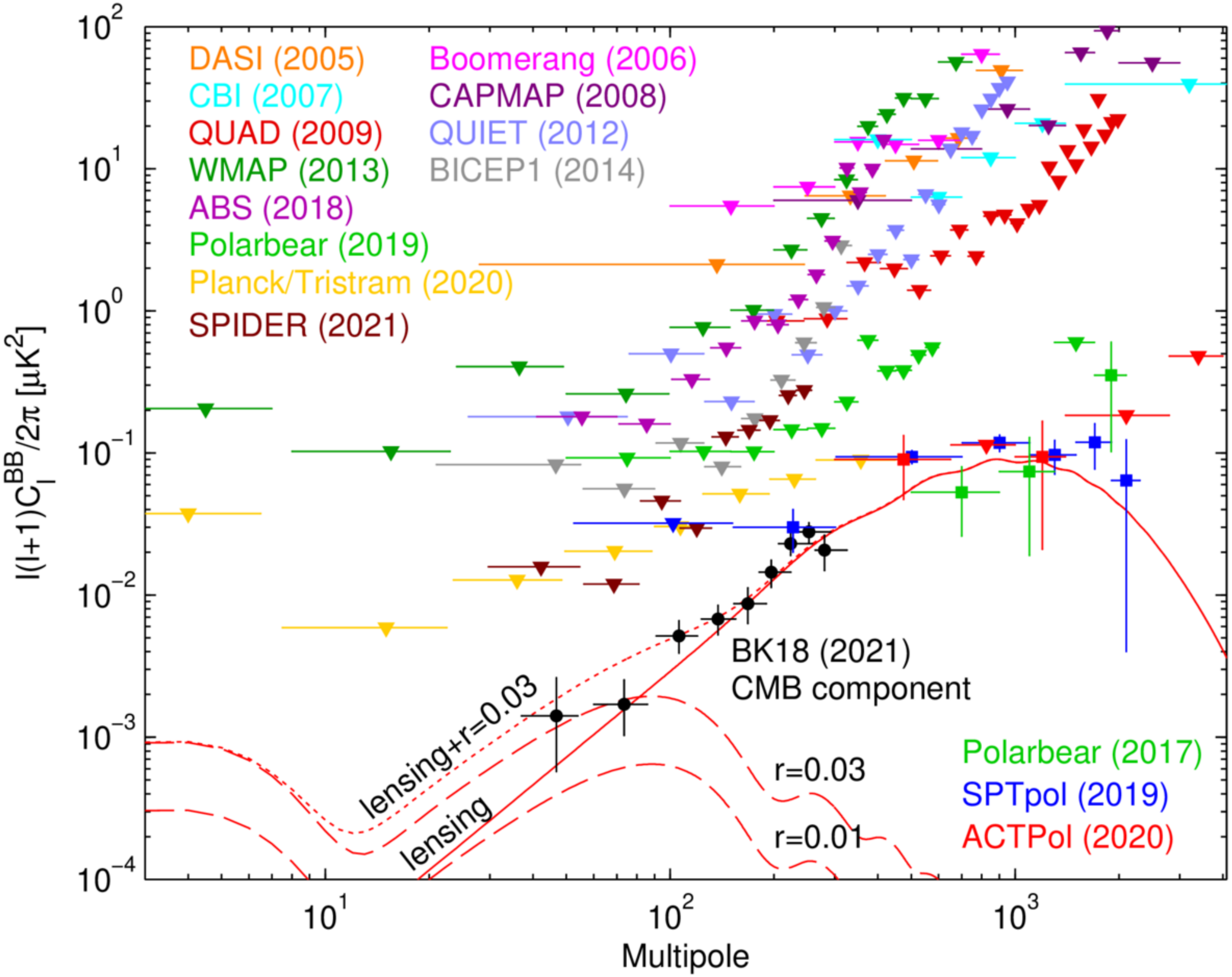
$$r_{0.002} < 0.16 \quad (95\,\%\ \mathrm{CL})$$

- Weakens if remove low-l TT (anomalously low):

$$r_{0.002} < 0.16 \quad (95\,\%\ \mathrm{CL})$$

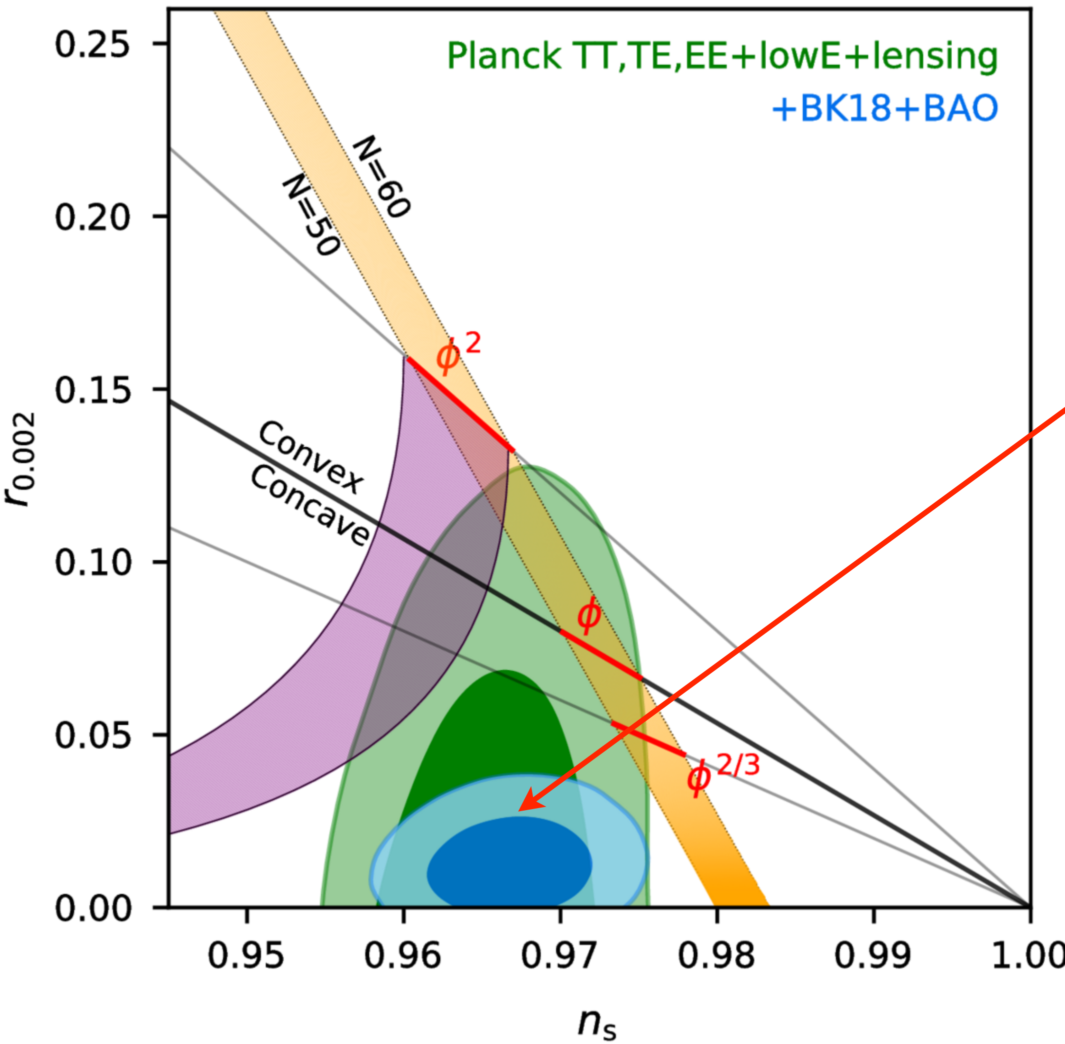
Planck Collaboration 2018

B-mode power measurements



BICEP/Keck Collaboration 2021

B-mode constraints



BICEP/Keck *BB* to 2018

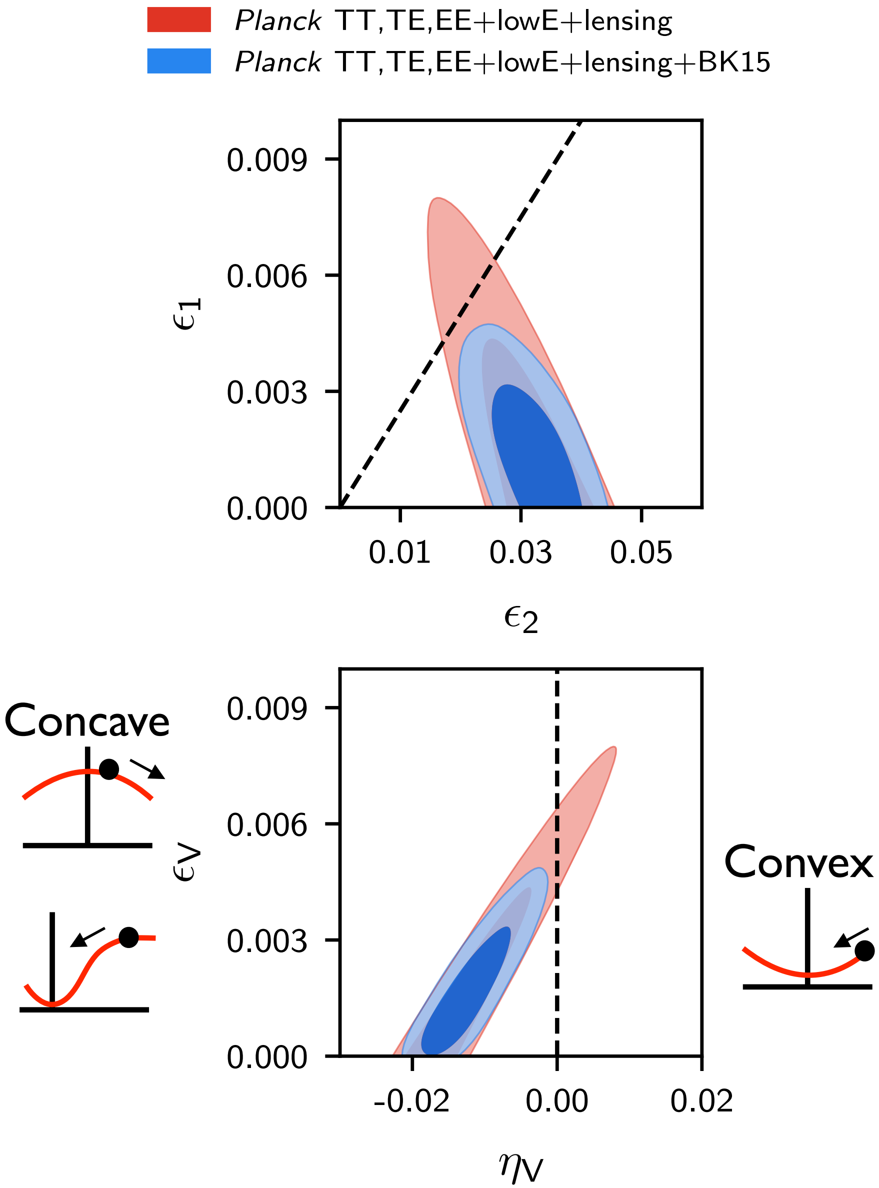
$$r_{0.002} < 0.032 \ (95\,\% \ \mathrm{CL})$$

$$E_{\rm inf} < 1.4 \times 10^{16}\,\mathrm{GeV}$$

$$H_{\rm inf} < 1.8 \times 10^{-5}\,M_{\rm Pl}$$

Planck Collaboration 2018; BICEP/Keck Collaboration 2021

Implications for dynamics of inflation



$$\epsilon_1 \equiv -\frac{\dot{H}}{H^2}\,, \qquad \epsilon_2 \equiv \frac{\dot{\epsilon}_1}{H\epsilon_1}$$

$$n_{\rm s} - 1 \approx -2\epsilon_1 - \epsilon_2$$

$$r \approx 16\epsilon_1 \quad \text{and} \quad n_{\rm t} \approx -2\epsilon_1$$

Non-detection of GWs:

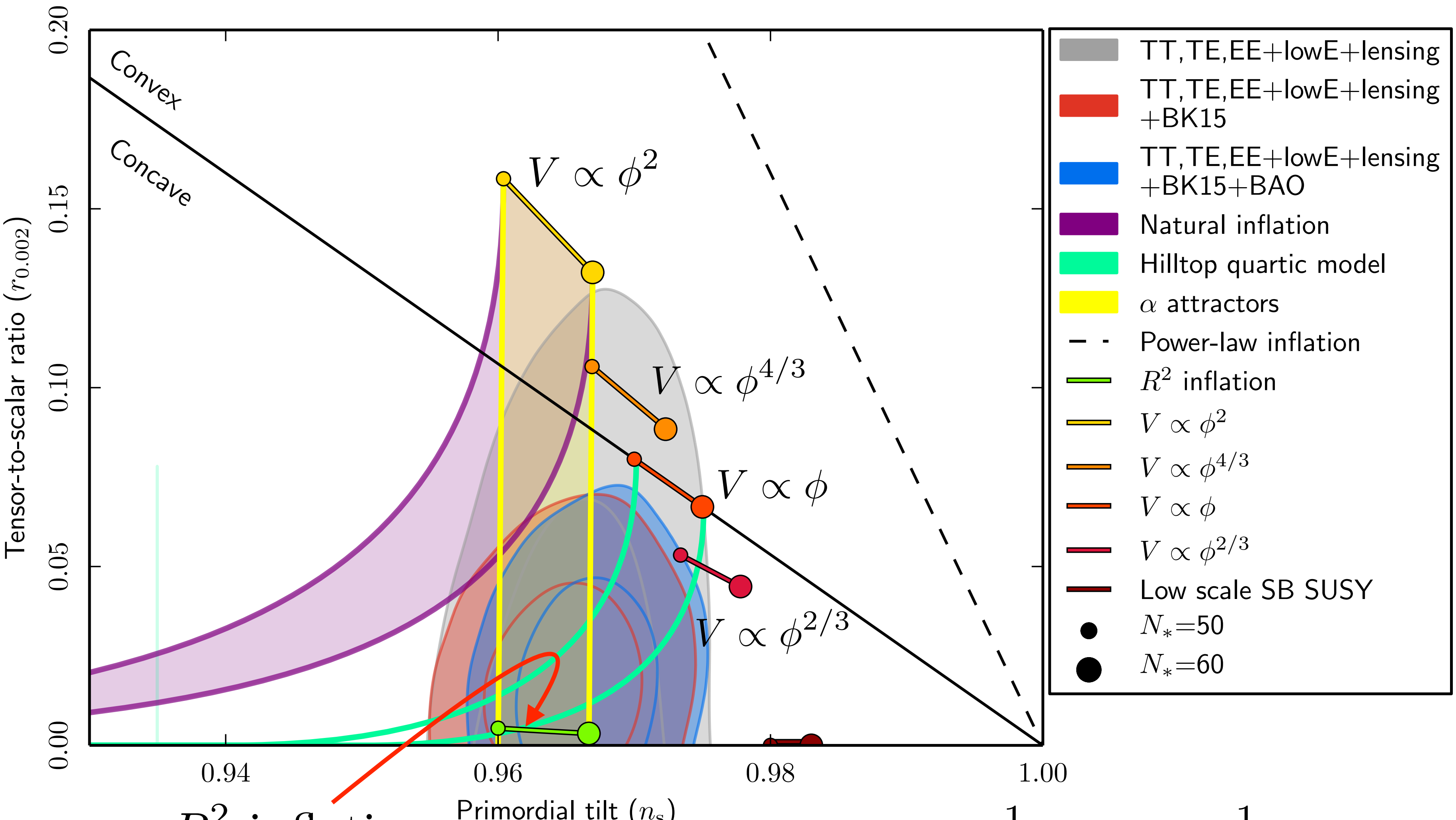
$$\epsilon_1 \ll |\epsilon_2|$$

$$\epsilon_V \equiv \frac{1}{2M_{\rm Pl^2}}\left(\frac{V'}{V}\right)^2 \approx \epsilon_1$$

$$\eta_V \equiv M_{\rm Pl}^2\frac{V''}{V} \approx 2\epsilon_1 - \frac{1}{2}\epsilon_2$$

Planck Collaboration 2018

Single-field model constraints

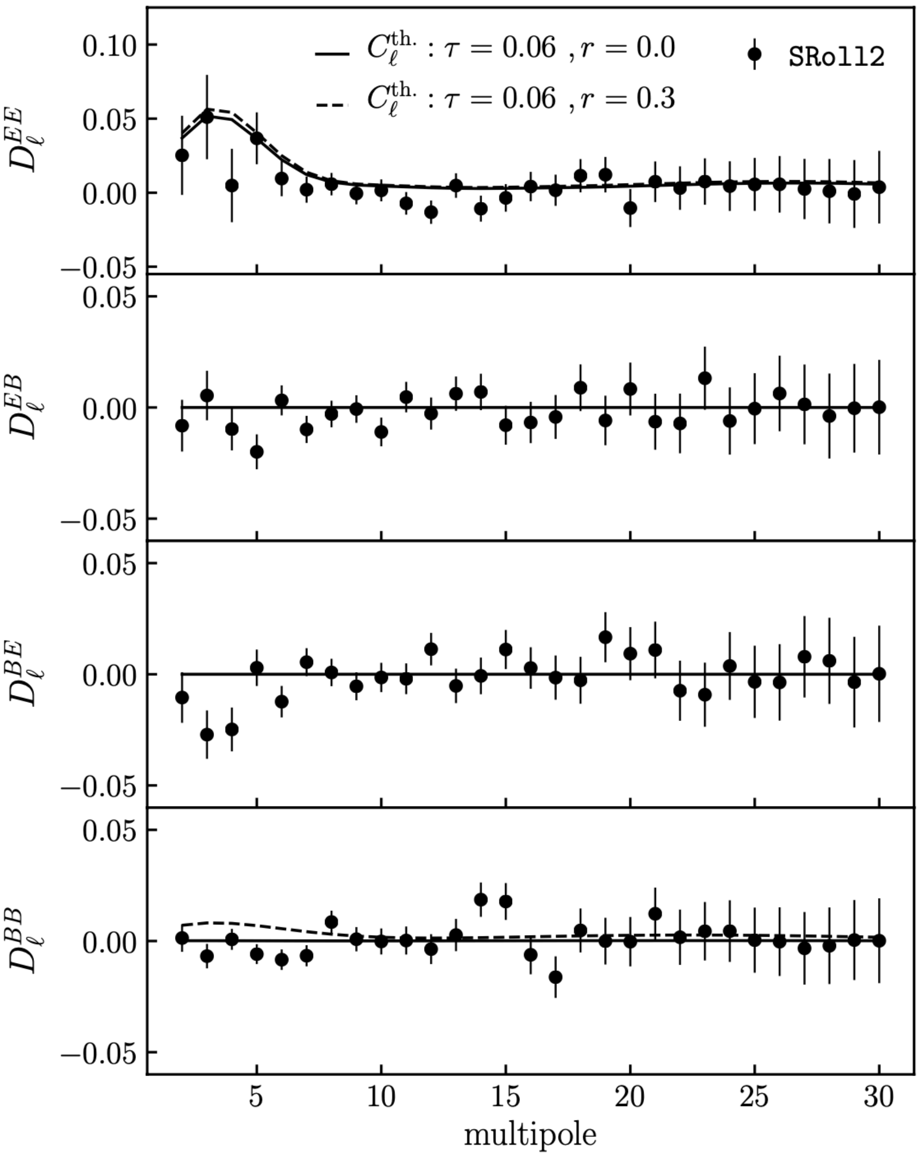


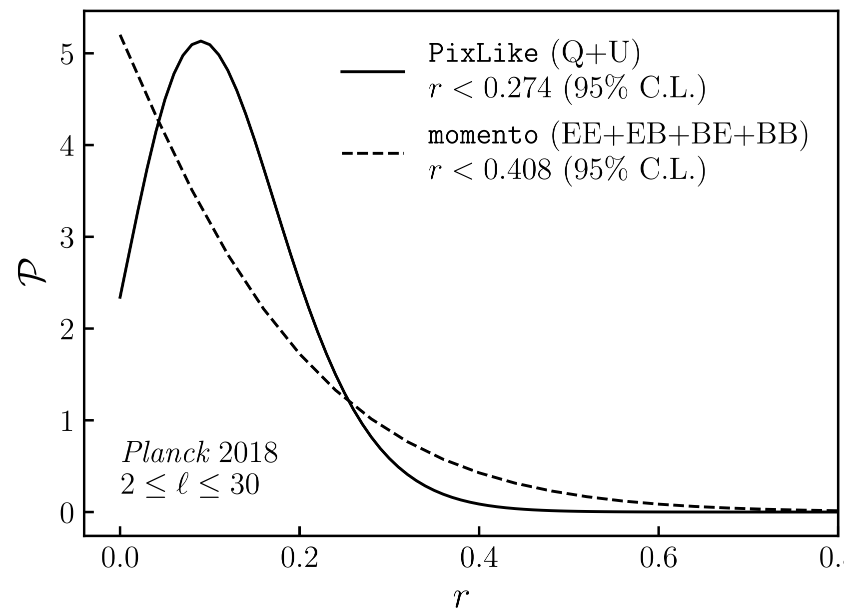
R^2 inflation

$$n_s - 1 \propto \frac{1}{N_*} \qquad r \propto \frac{1}{N_*^2}$$

Planck Collaboration 2018

Planck low-l constraints





Challenges:

- Instrumental systematics
- Foreground removal and propagation of uncertainties
- Likelihood approximations

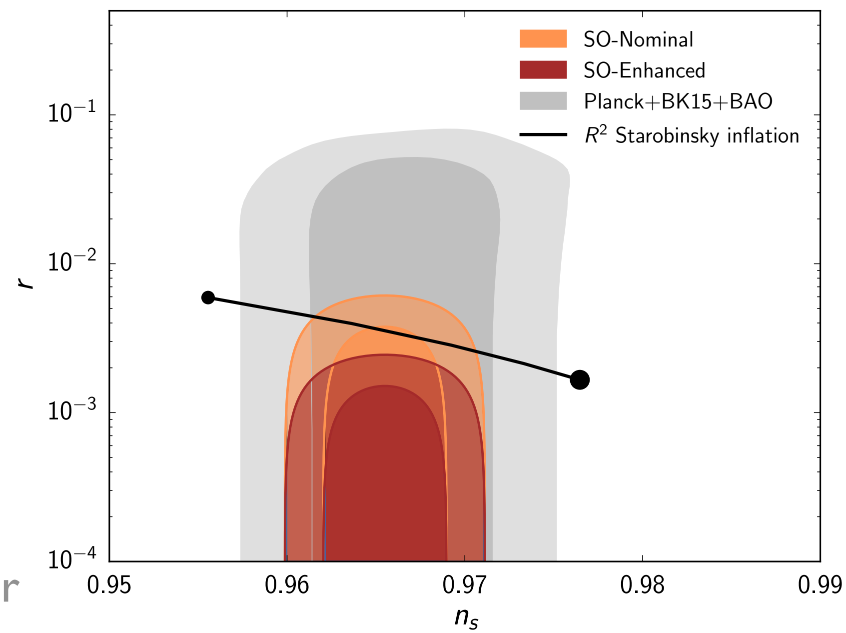
de Belsunce+ in prep.

Forthcoming ground-based constraints

- Stage-3 experiments (SPO and SO) targeting

$$\sigma(r) = 0.003$$

- Conclusive search for monomial potentials and start to reach into plateau models with $r \propto 1/N_*^2$



SO Collaboration
Astro2020 White Paper

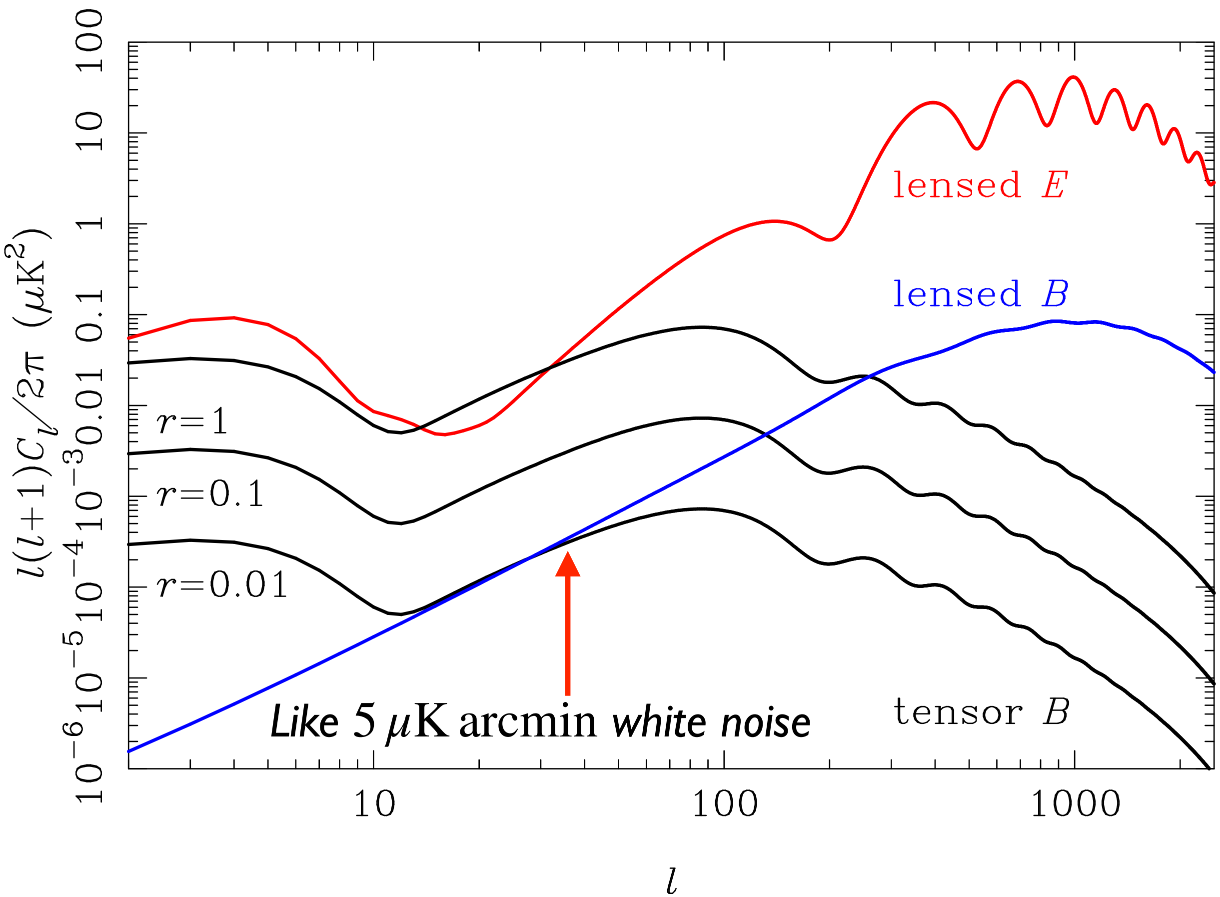
Main challenges

- Tiny signal:

$$\text{rms } B\text{-mode} = 10\,\text{nK}\left(r/10^{-3}\right)^{1/2}$$

  - Requires tens of thousands of detectors
  - Exquisite control of systematic effects
- Galactic foregrounds (mostly dust)
- Gravitational lensing-induced *B* modes

Lensing B-modes



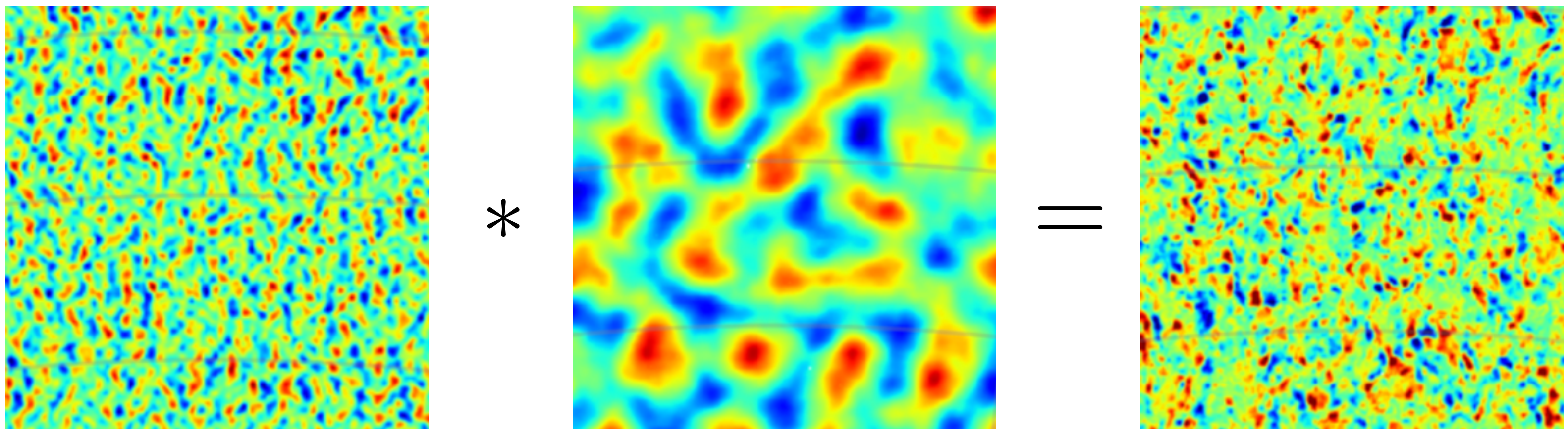
BK15	3 μK arcmin (150 GHz)
BICEP Array	1 μK arcmin (150 GHz)
SO (goal)	3 μK arcmin (150 GHz)

Note: post-component separation noise higher!

Delensing

$$B^{\mathrm{delens}} = B^{\mathrm{obs}} - E^{\mathrm{obs}} * \hat{\phi}$$

Some proxy for lensing potential

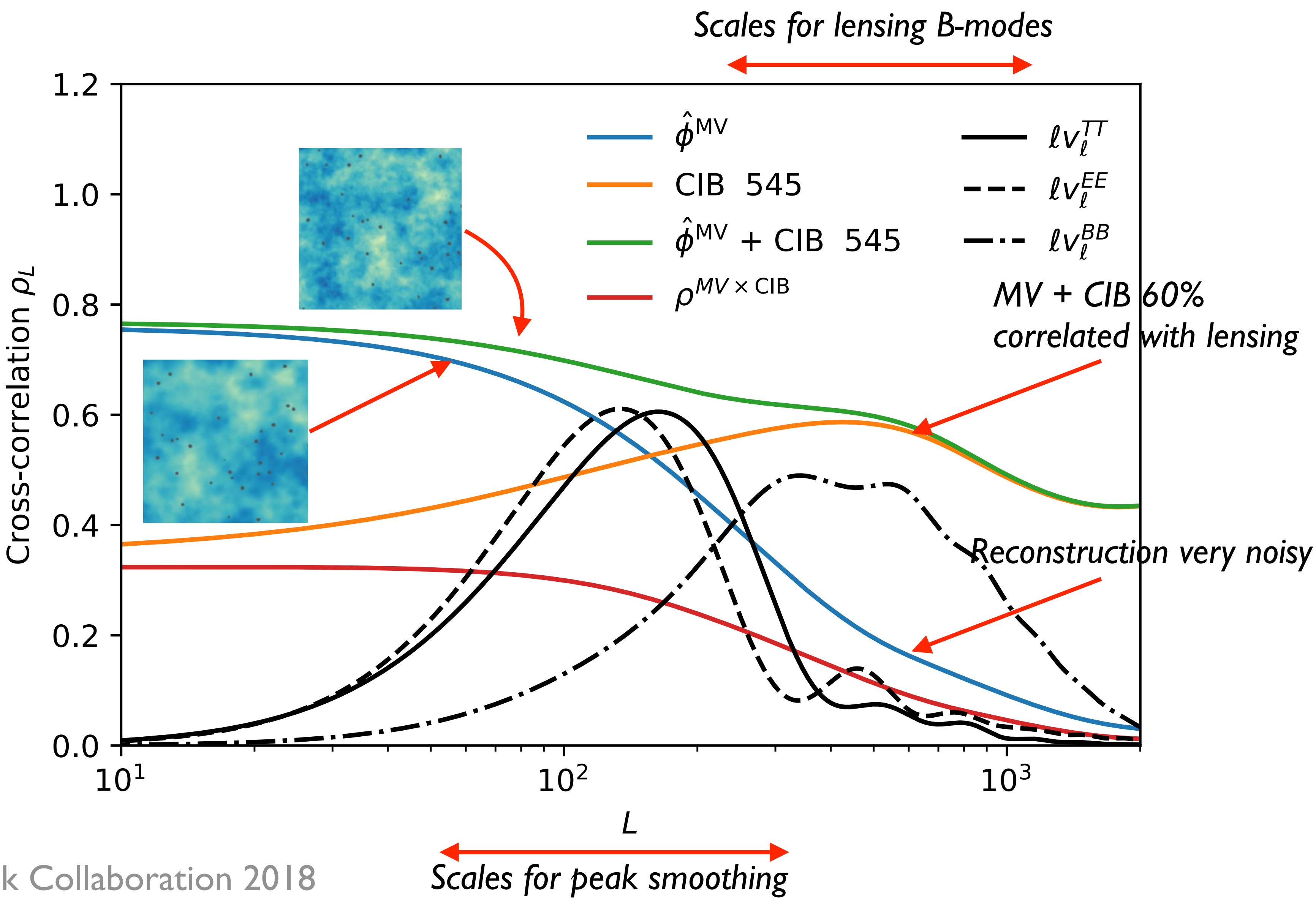


Filtered E modes $\quad * \quad$ $\hat{\phi}$ $\quad = \quad$ $\hat{B}^{\mathrm{lens}}$

- Want high S/N *E* modes and highly correlated tracer of lensing
- For SO, should be able to remove 60% of lensing power halving error on *r*; even more critical for BICEP Array and CMB-S4

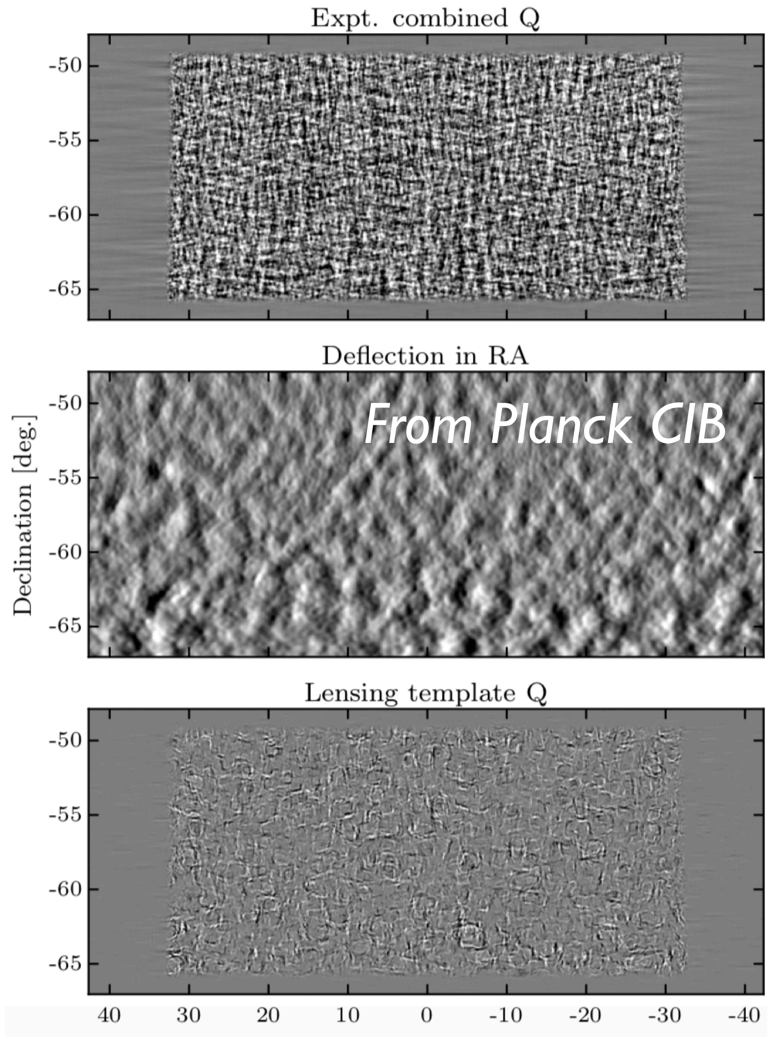
Hanson+ 2014

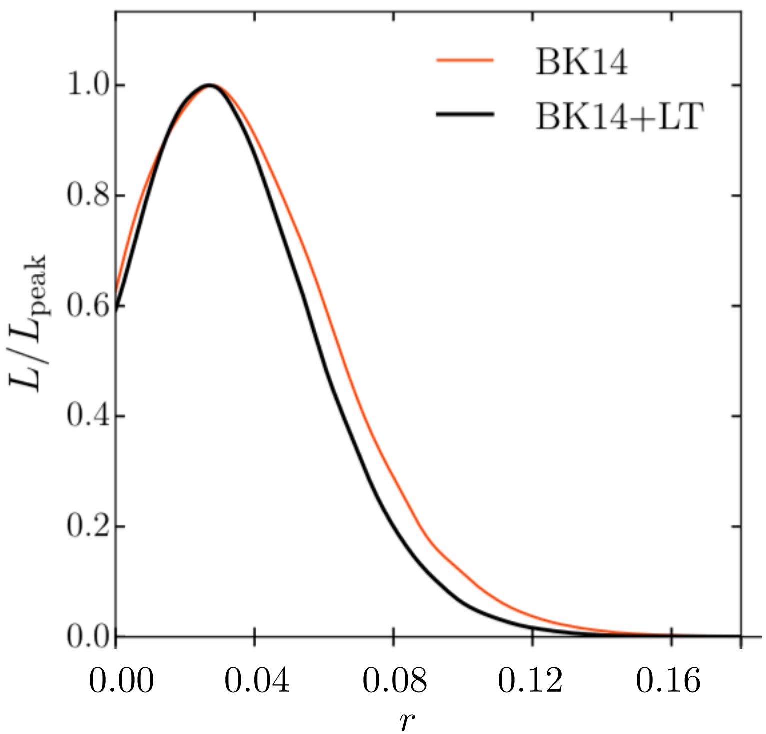
Multi-tracer delensing



Planck Collaboration 2018

Delensing now improving $\sigma(r)$





$\sigma(r) = 0.024 \rightarrow \sigma(r) = 0.022$

delensed

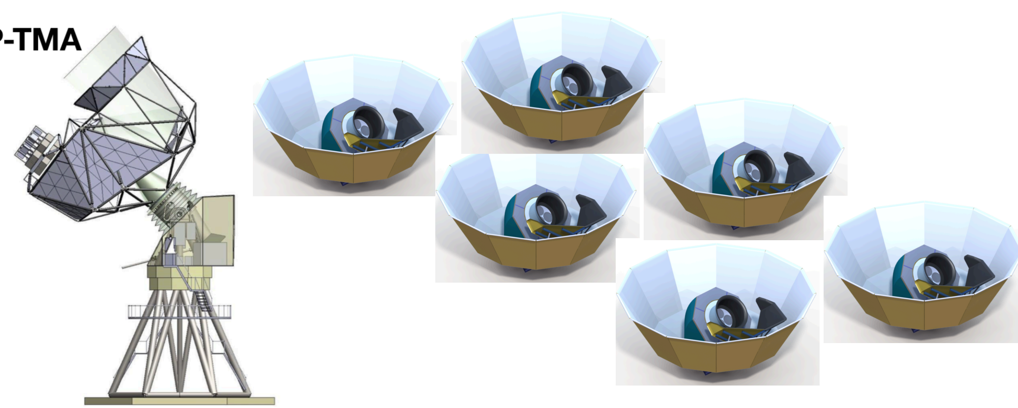
BICEP/Keck and SPT Collaborations 2021

CMB-S4 (reference design)

Deep "r" survey

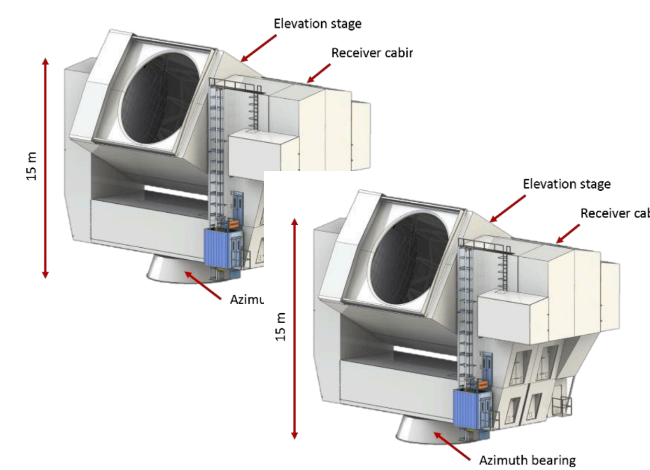
- 3% of sky to depth of $1\,\mu\mathrm{K\,arcmin}$ at 0.5 deg resolution from South Pole
- 20–270 GHz
- Dedicated delensing survey to depth of $1\,\mu\mathrm{K\,arcmin}$ at 1.5 arcmin resolution

$$\sigma(r) = 0.0005$$



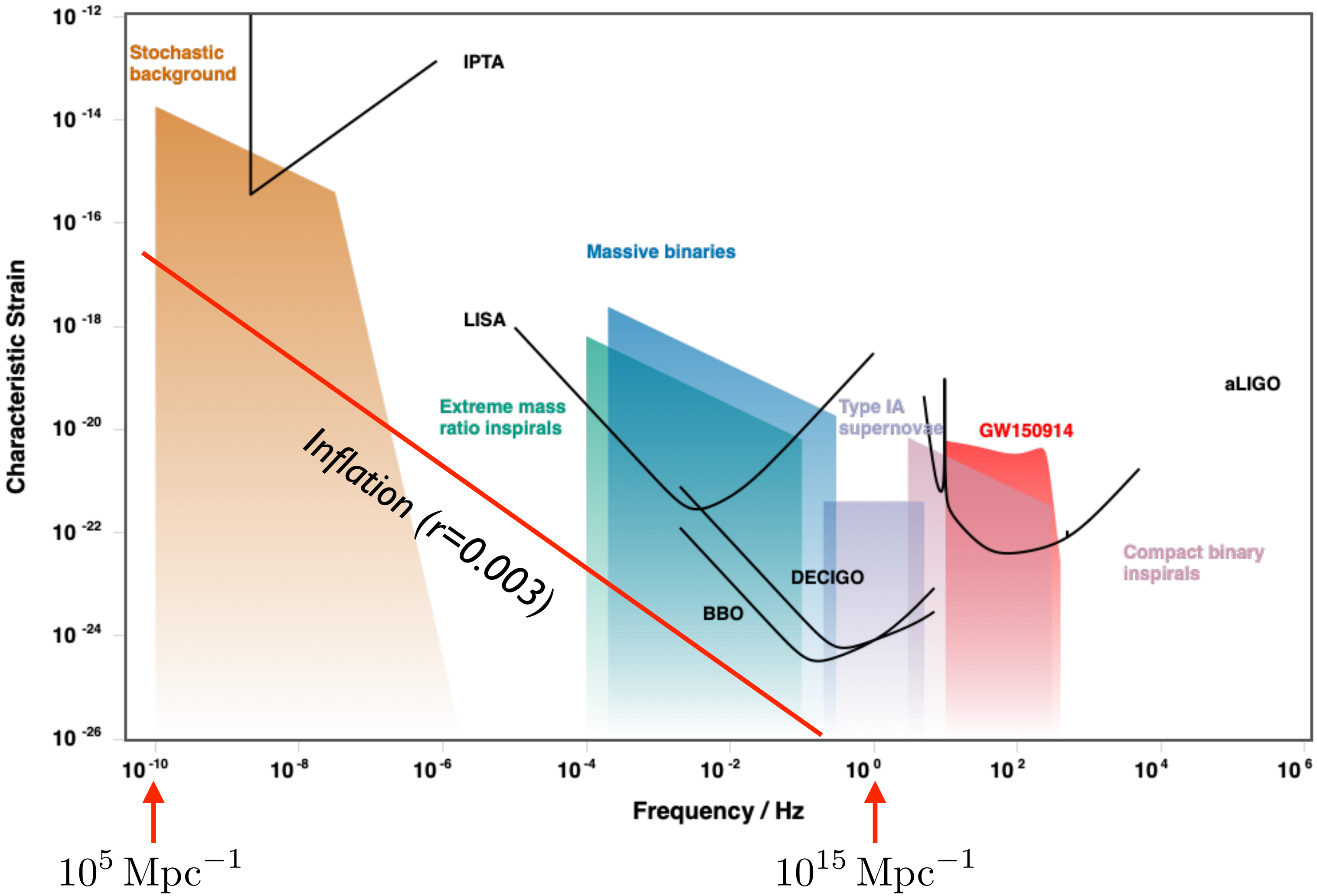
Deep-wide survey

- 70% of sky to depth of $1\,\mu\mathrm{K\,arcmin}$ from Chile
- 1.5 arcmin resolution



500,000 detectors in total

Direct detection?



Moore+ 2015

Primordial non-Gaussianity

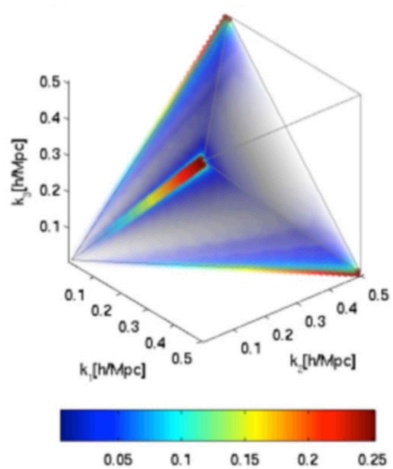
Primordial bispectrum

- Arises in models with non-linear interactions/dynamics

$$\langle \zeta(\boldsymbol{k}_1)\zeta(\boldsymbol{k}_2)\zeta(\boldsymbol{k}_3)\rangle \propto \delta^{(3)}(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3) B(k_1, k_2, k_3)$$

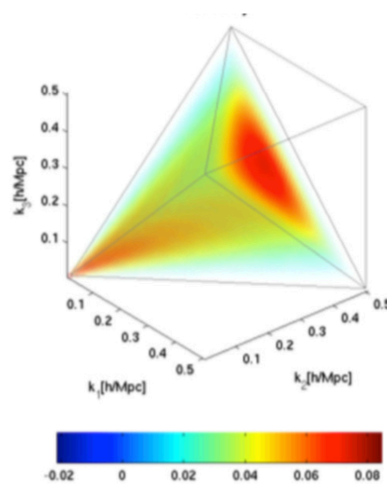
Bispectrum probing cubic interactions → $B(k_1, k_2, k_3)$

Local



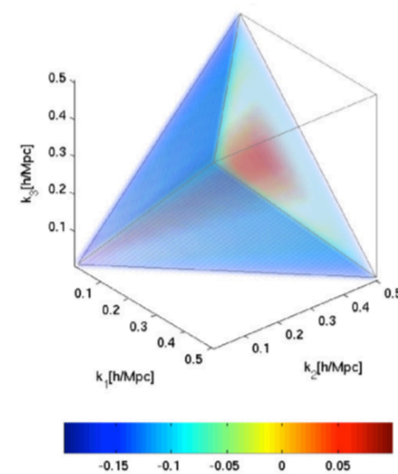
Multi-field inflation

Equilateral



Non-canonical kinetic terms
Higher-derivative terms

Orthogonal

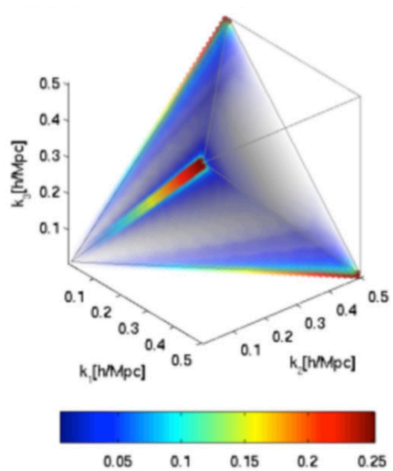


Schmittfull+ 2013

Primordial non-Gaussianity targets

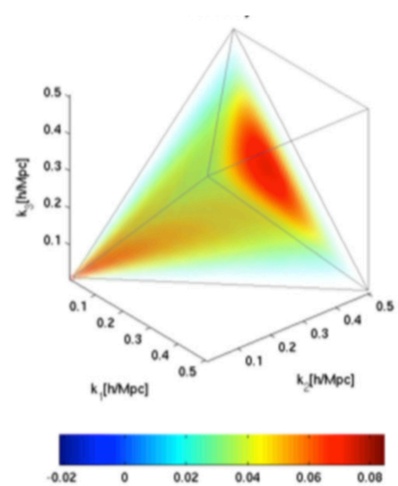
	$f_{\rm NL}^{\rm loc} \lesssim 1$	$f_{\rm NL}^{\rm loc} \gtrsim 1$
$f_{\rm NL}^{\rm eq,orth} \lesssim 1$	Single-field slow-roll	Multi-field
$f_{\rm NL}^{\rm eq,orth} \gtrsim 1$	Single-field non-slow-roll	Multi-field

Local



Multi-field inflation

Equilateral



Non-canonical kinetic terms
Higher-derivative terms

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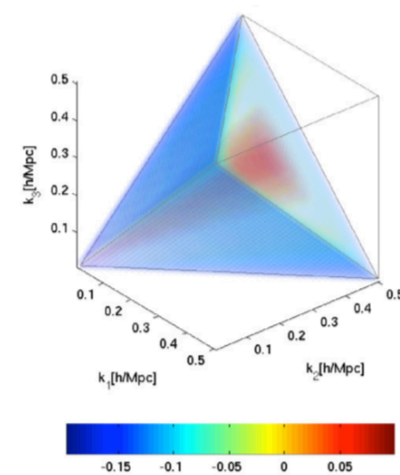
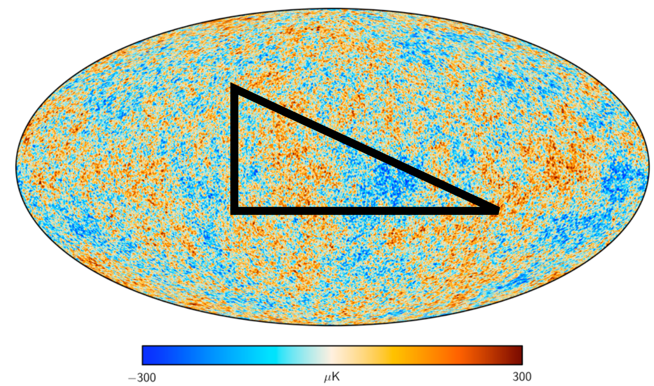
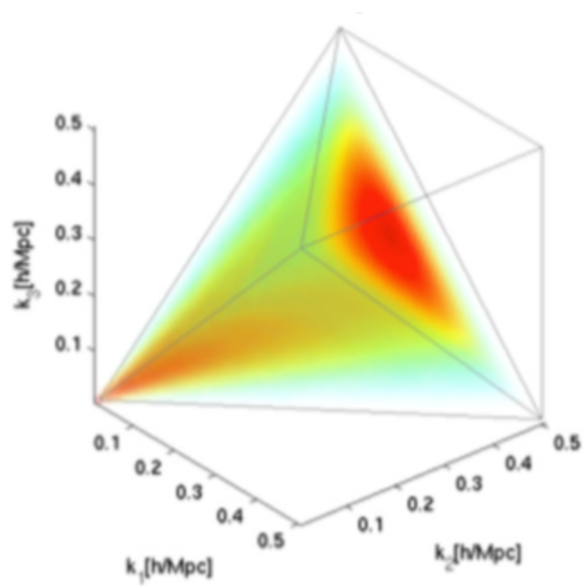


Alvarez+ 2014

Primordial non-Gaussianity: CMB

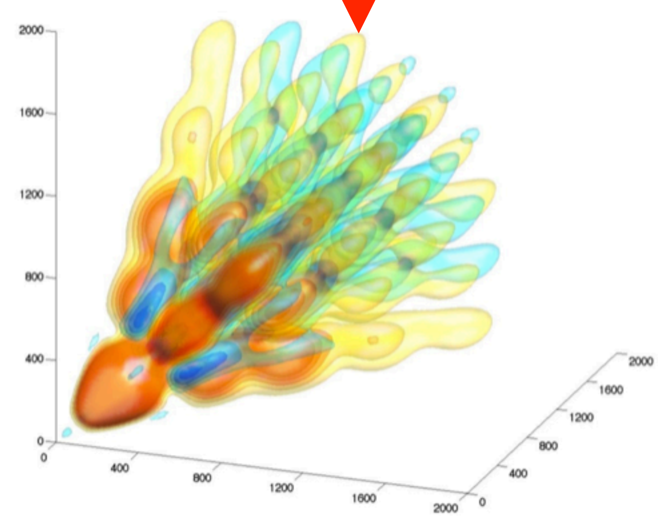
$$\hat{B}_{l_1 l_2 l_3} \sim \sum_{m_1 m_2 m_3} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3}$$





Primordial bispectrum

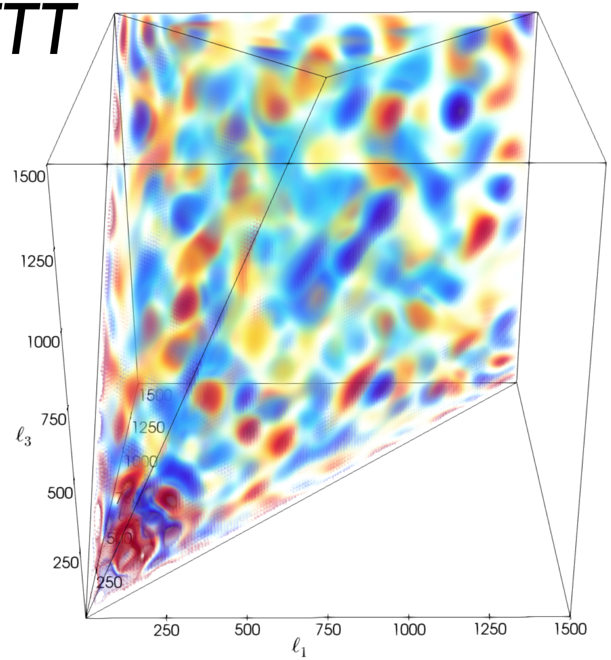
CMB transfer



CMB bispectrum

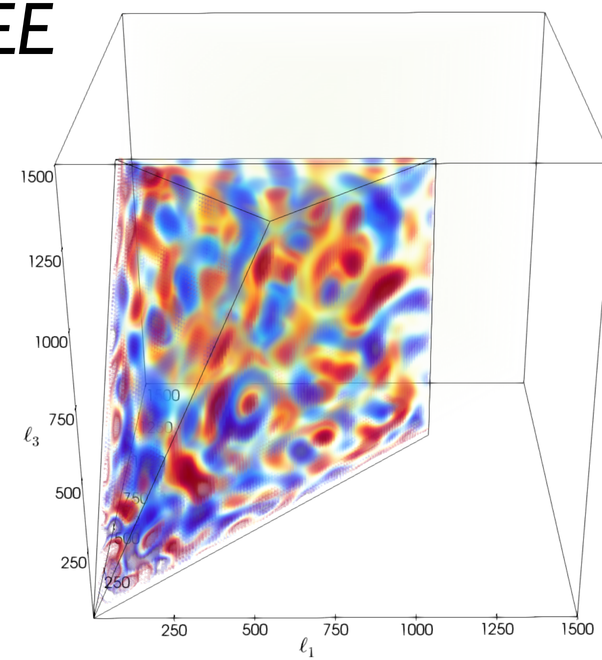
Planck bispectrum constraints

TTT



+

EEE



...

$$f_{\rm NL}^{\rm loc} = -0.5 \pm 5.6$$
$$f_{\rm NL}^{\rm eq} = 7 \pm 66$$
$$f_{\rm NL}^{\rm orth} = -15 \pm 36$$

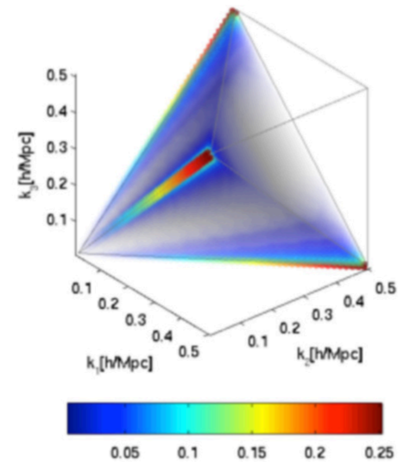
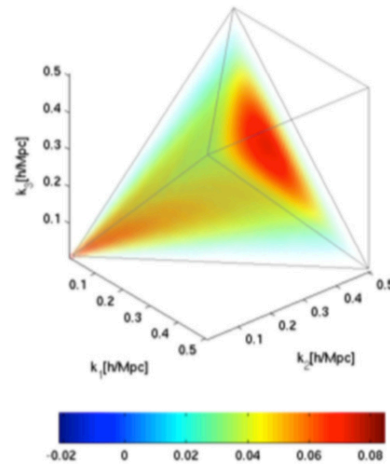
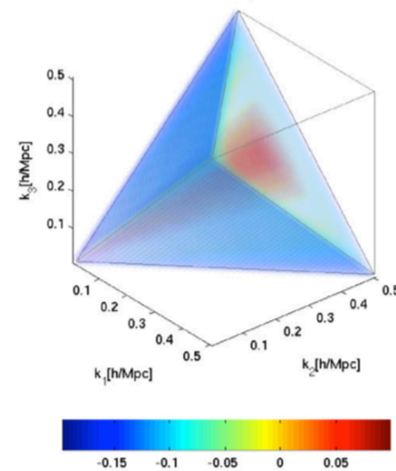
+ pol →

$$f_{\rm NL}^{\rm loc} = -0.9 \pm 5.1$$
$$f_{\rm NL}^{\rm eq} = -18 \pm 47$$
$$f_{\rm NL}^{\rm orth} = -37 \pm 23$$

Planck Collaboration 2019

Future CMB constraints

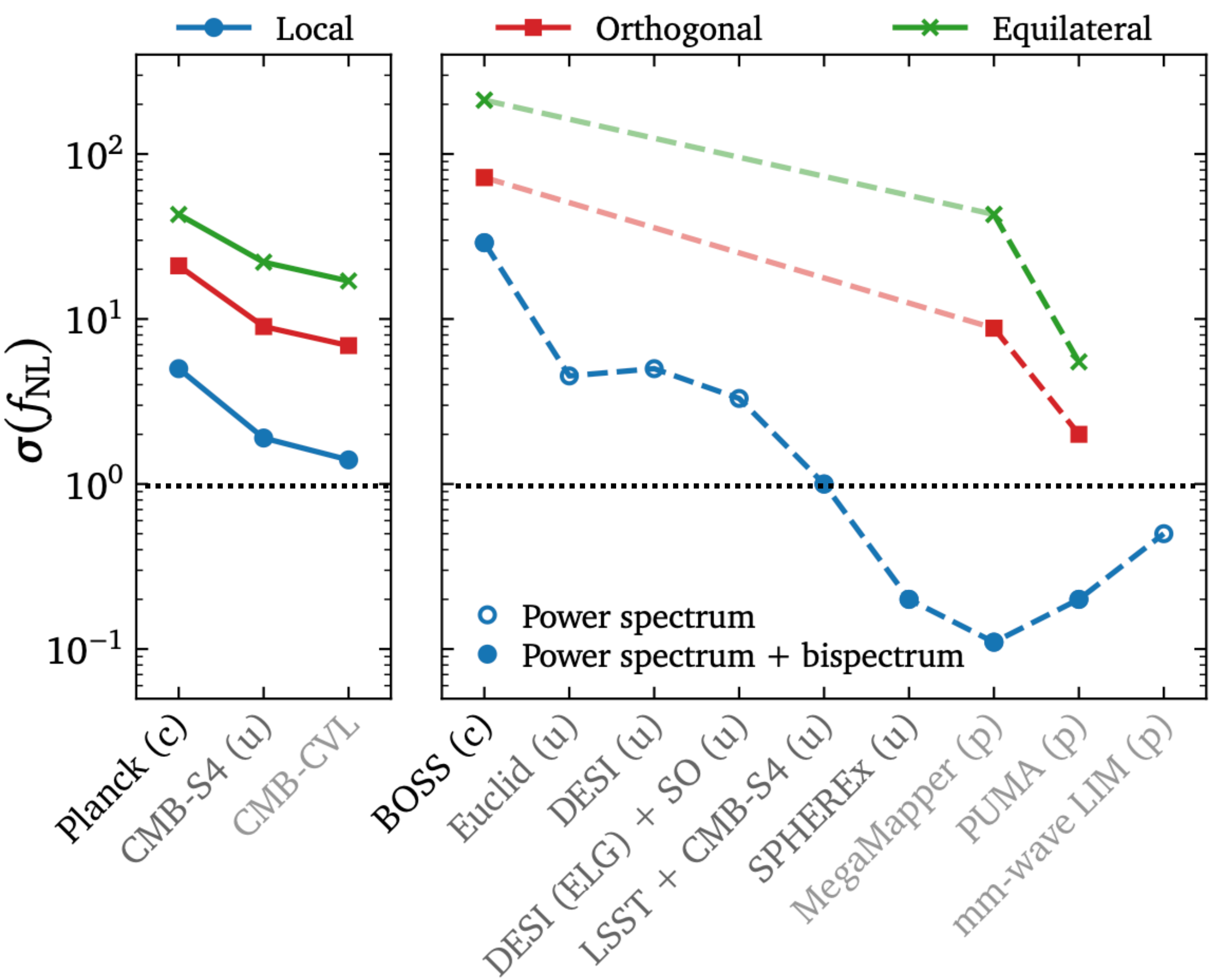
Threshold $\sigma(f_{\rm NL}) \sim 1$ will remain out of reach with CMB bispectrum

	Local	Equilateral	Orthogonal
			
Planck	$\sigma(f_{\rm NL}^{\rm loc}) = 5$	$\sigma(f_{\rm NL}^{\rm eq}) = 47$	$\sigma(f_{\rm NL}^{\rm orth}) = 23$
SO (goal)	$\sigma(f_{\rm NL}^{\rm loc}) = 3$	$\sigma(f_{\rm NL}^{\rm eq}) = 24$	$\sigma(f_{\rm NL}^{\rm orth}) = 13$

Significant improvements in tensor non-Gaussianity, e.g., $\langle \gamma\zeta\zeta \rangle$, from *B*-mode measurements

Simons Observatory Collaboration 2018

Reaching $\sigma\left(f_{\rm NL}^{\rm loc}\right) < 1$ *with LSS?*



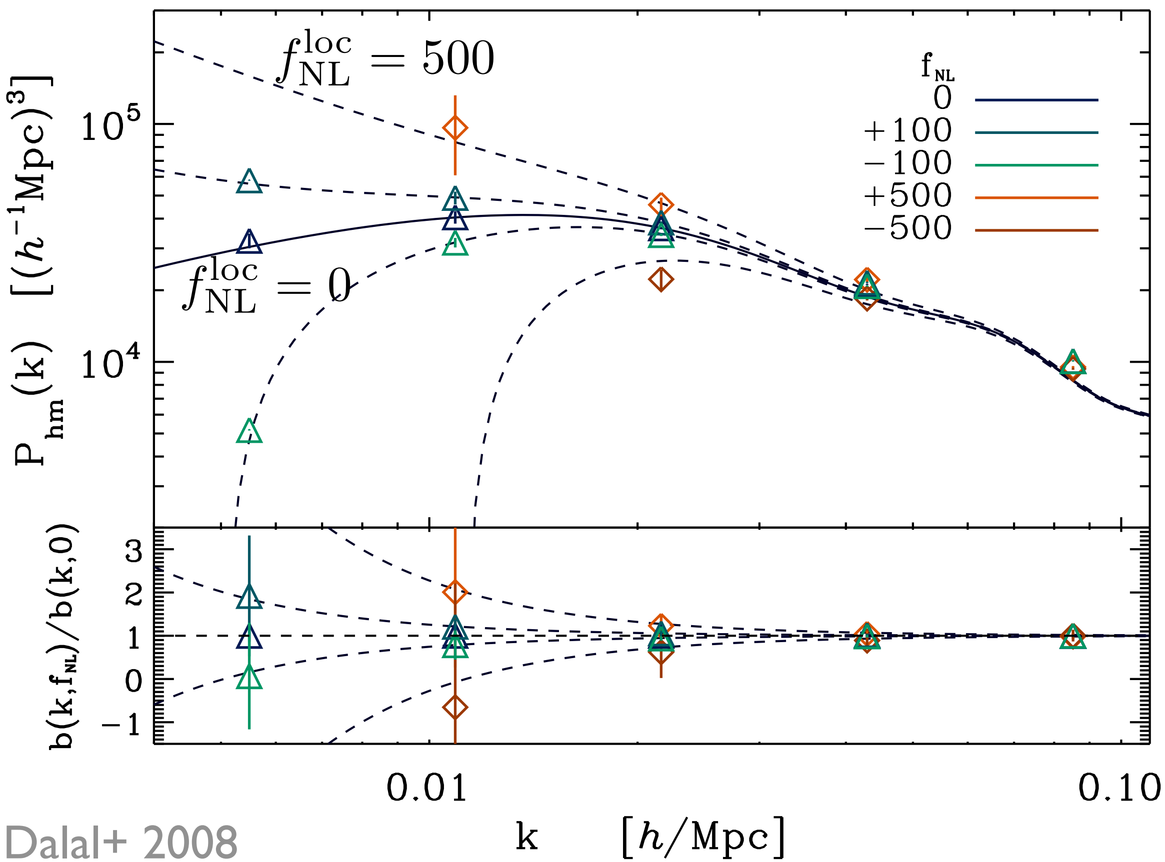
Pimentel+ 2022 [Snowmass 2021 – Inflation: theory and observations]

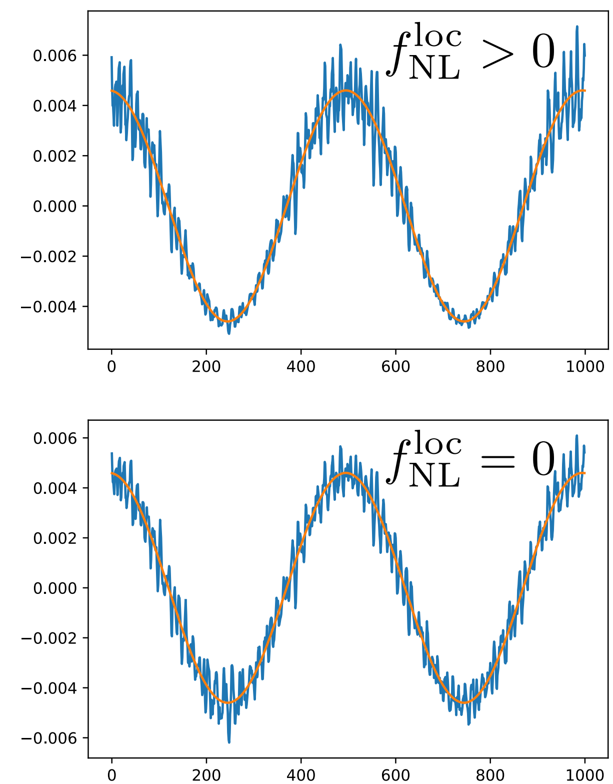
LSS: scale-dependent halo bias

$$\Phi = \phi_G + f_{\rm NL}^{\rm loc}\left(\phi_G^2 - \langle\phi_G^2\rangle\right) \qquad (\Phi = 3\zeta/5)$$

$$\Rightarrow \qquad \delta_s \approx \delta_{s,G}\left(1 + 2 f_{\rm NL}^{\rm loc}\phi_{l,G}\right)$$

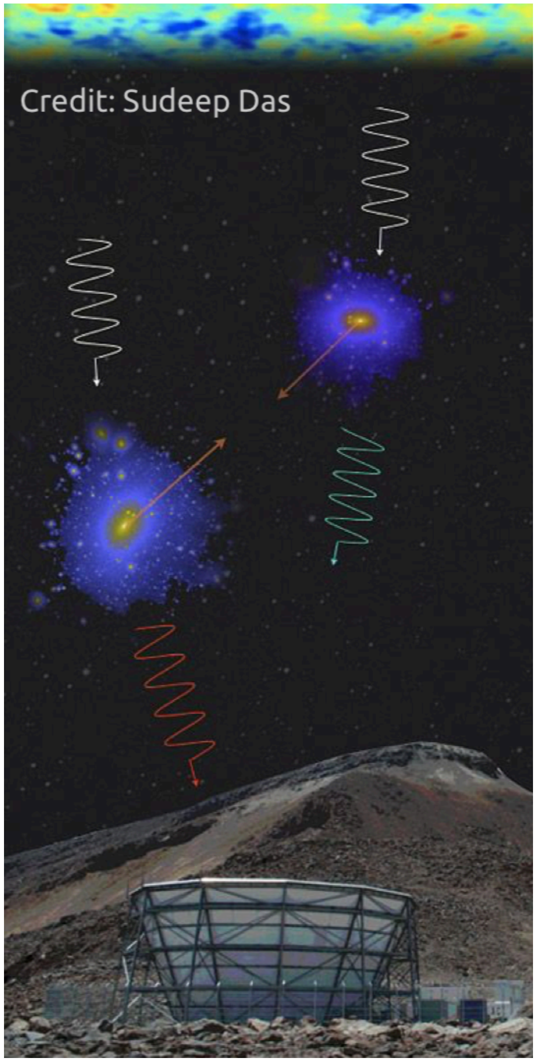
Modulation of small-scale power by long modes of primordial potential





Dalal+ 2008

Sample-variance cancellation



Galaxy overdensity

$$\delta_g(\boldsymbol{k}) = b(k, f_{\rm NL}^{\rm local})\delta_m(\boldsymbol{k}) + \text{shot noise}$$

Tracer of matter density

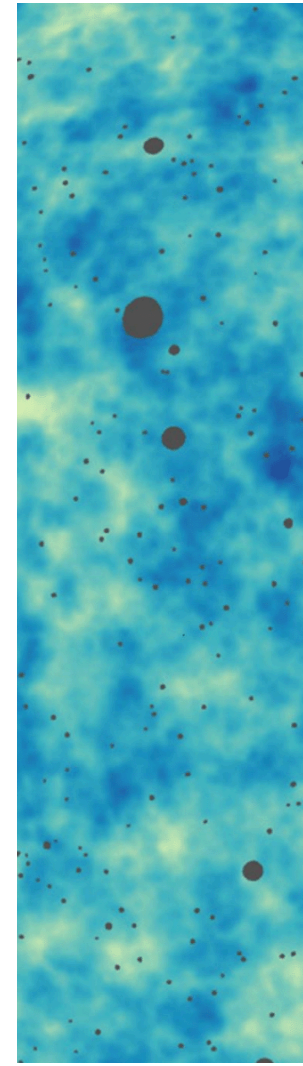
$$\hat{\delta}_m(\boldsymbol{k}) \sim \delta_m(\boldsymbol{k}) + \text{reconstruction noise}$$

Scale-dependent bias without cosmic variance from $\delta_g(\boldsymbol{k})/\hat{\delta}_m(\boldsymbol{k})$

Want highly correlated matter tracer

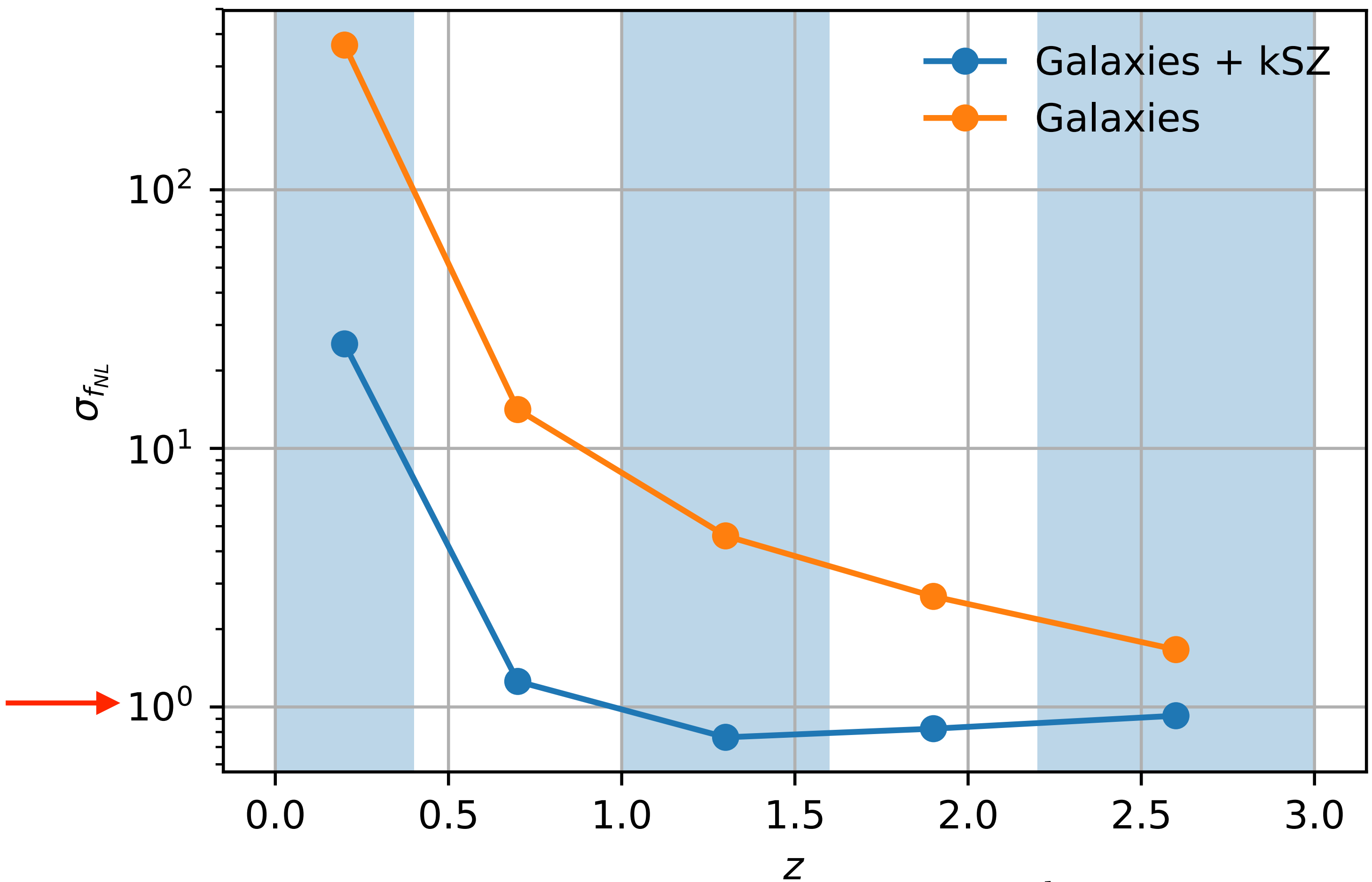
← From radial velocity from kSZ

or CMB lensing →



Munchmeyer+ 2019; Seljak 2008; Schmittfull & Seljak 2018

Sample-variance cancellation: kSZ



Galaxy overdensity (LSST) $\sigma(f_{\rm NL}^{\rm loc}) = 1.5$

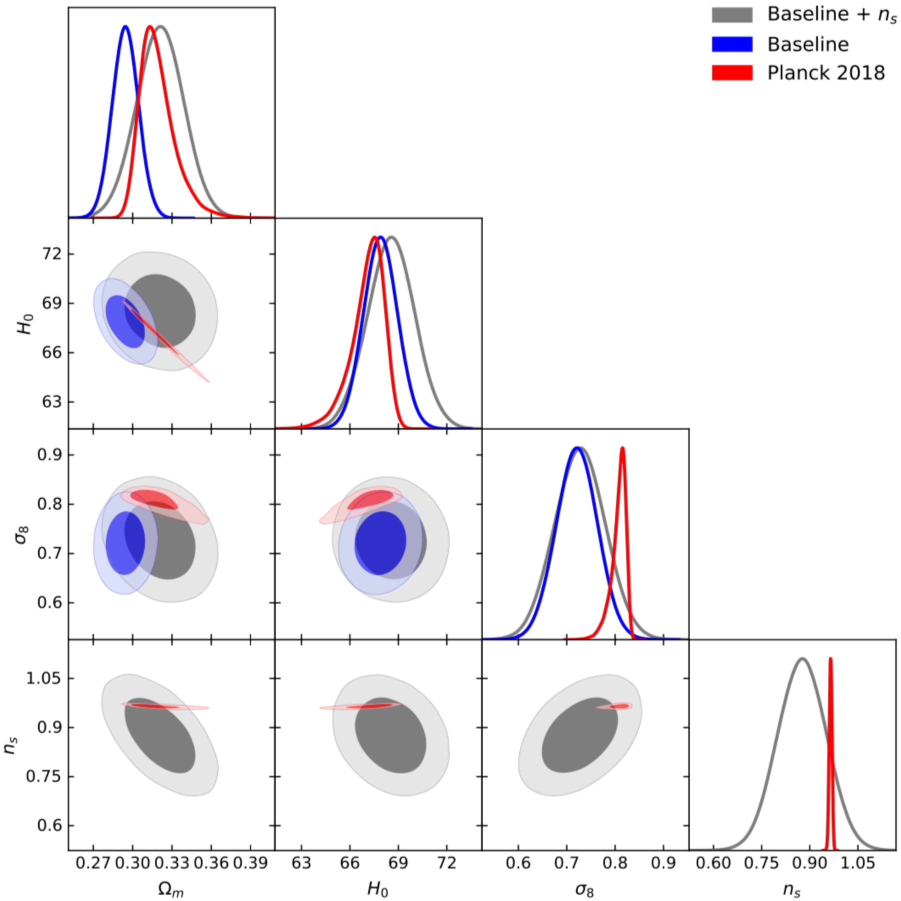
Galaxy overdensity + kSZ (CMB-S4) $\sigma(f_{\rm NL}^{\rm loc}) = 0.5$

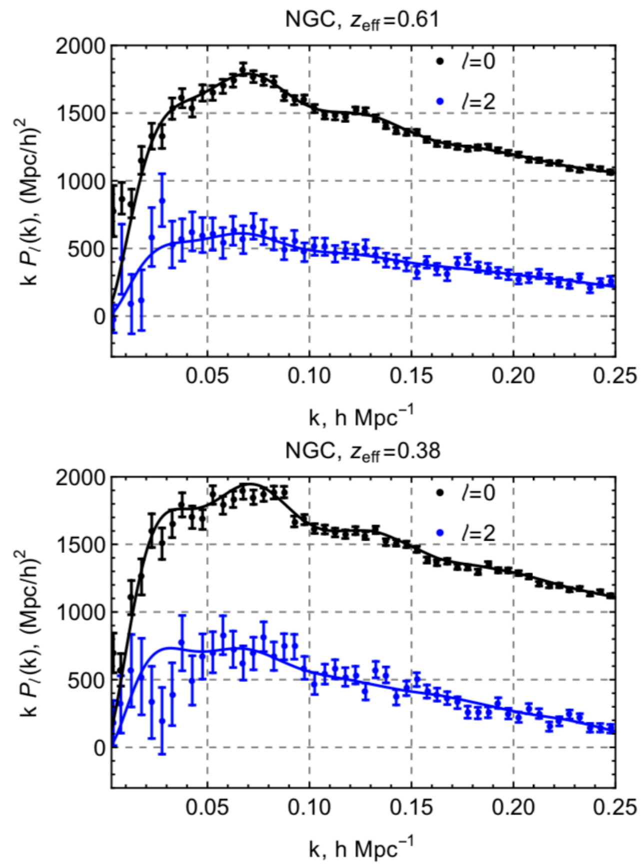
Munchmeyer+ 2019

Summary

- Single-field, slow-roll inflation is an excellent fit to current observations with no statistically-significant departures for CMB data
- Measured scalar spectral index and non-detection of primordial GWs imply $\epsilon_1 \ll |\epsilon_2|$ ruling out most monomial potentials
- Clear path forward to probe $r \propto 1/N_*^2$ models (e.g., R^2 inflation)
- Vacuum fluctuations from such models undetectable with future space-based GW interferometers
- Large-scale structure probes hold promise to reach $\sigma(f_{\rm NL}^{\rm loc}) < 1$

Constraints from BOSS galaxy P(k)





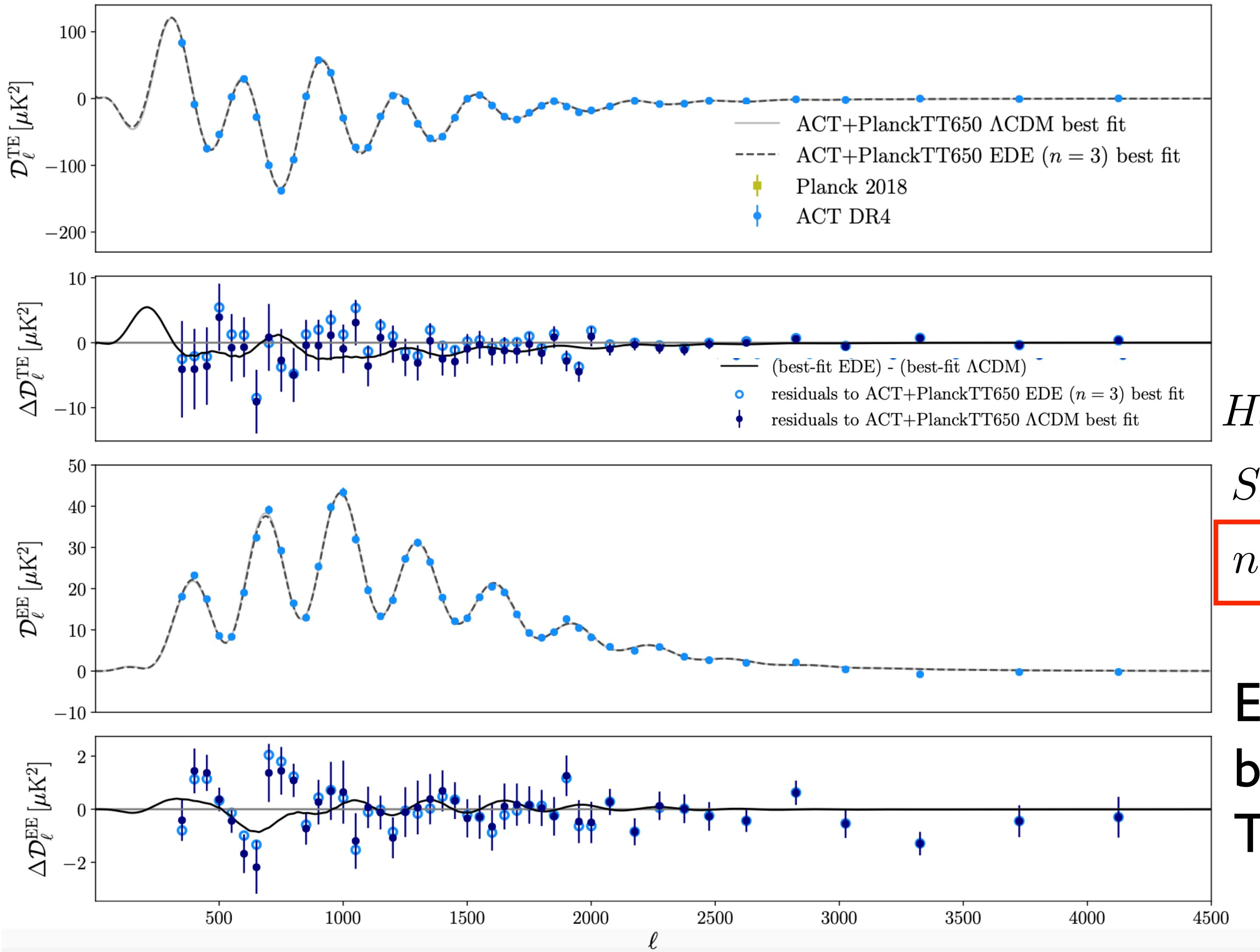
$$n_\mathrm{s} = 0.88 \pm 0.08$$

(BBN/Planck prior on baryon density)

Ivanov+ 2020

See also D'Amico+ 2020 & Philcox+ 2020

Pre-recombination dark energy?



$$H_0 = 74.4^{+2.2}_{-3.0}\,\mathrm{km\,s^{-1}}$$

$$S_8 = 0.791^{+0.040}_{0.046}$$

$$n_s = 0.985^{+0.011}_{-0.018}$$

EdE not favoured by Planck high-*l* TT

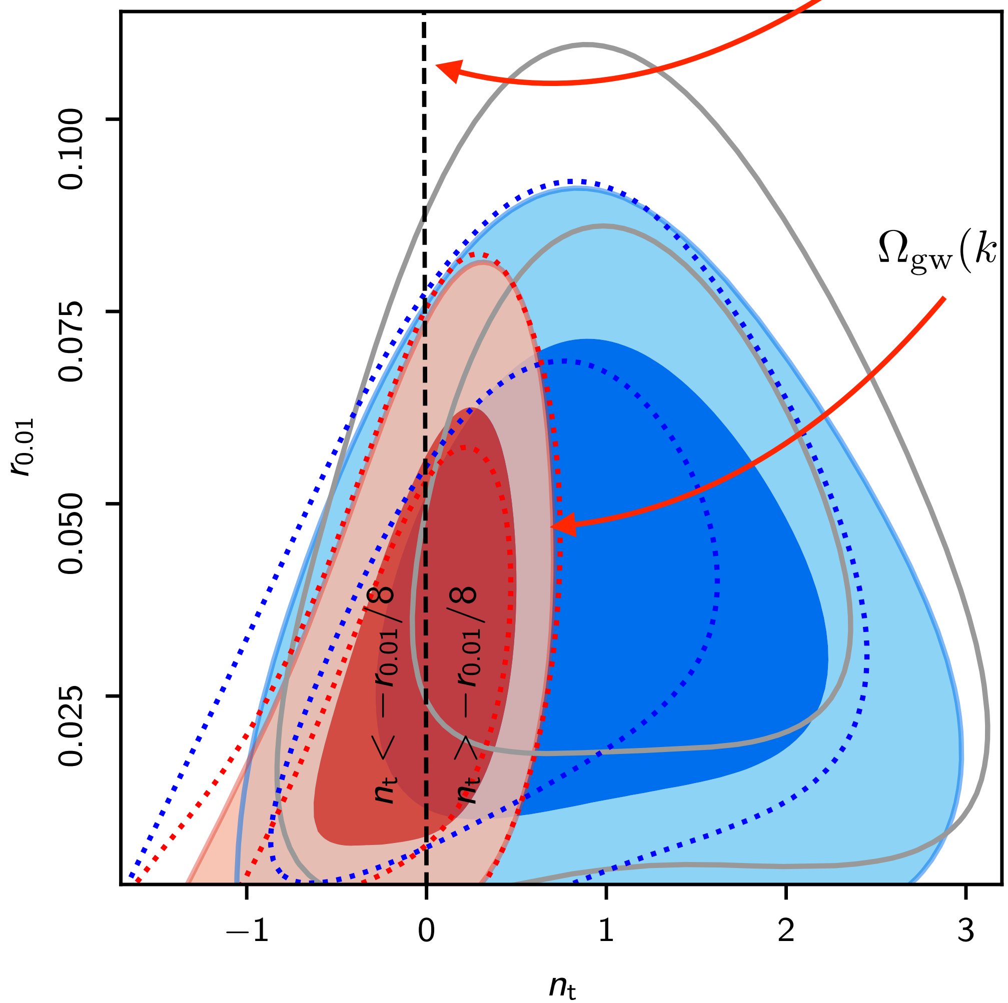
Hill+ 2021

BICEP/Keck (2006–)

- Small-aperture telescope(s) (deg. resolution) at South Pole
- Latest incarnation: BICEP Array
  - 6 frequencies (30–270 GHz)
  - 30,000 detectors when completed
  - Surveying 600 deg^2

Single-field, slow-roll consistency relation

$$r = -8n_t$$



$$\Omega_{gw}(k = 1.3 \times 10^{16}\,\mathrm{Mpc}^{-1}) < 1.7 \times 10^{-7}$$

20 Hz

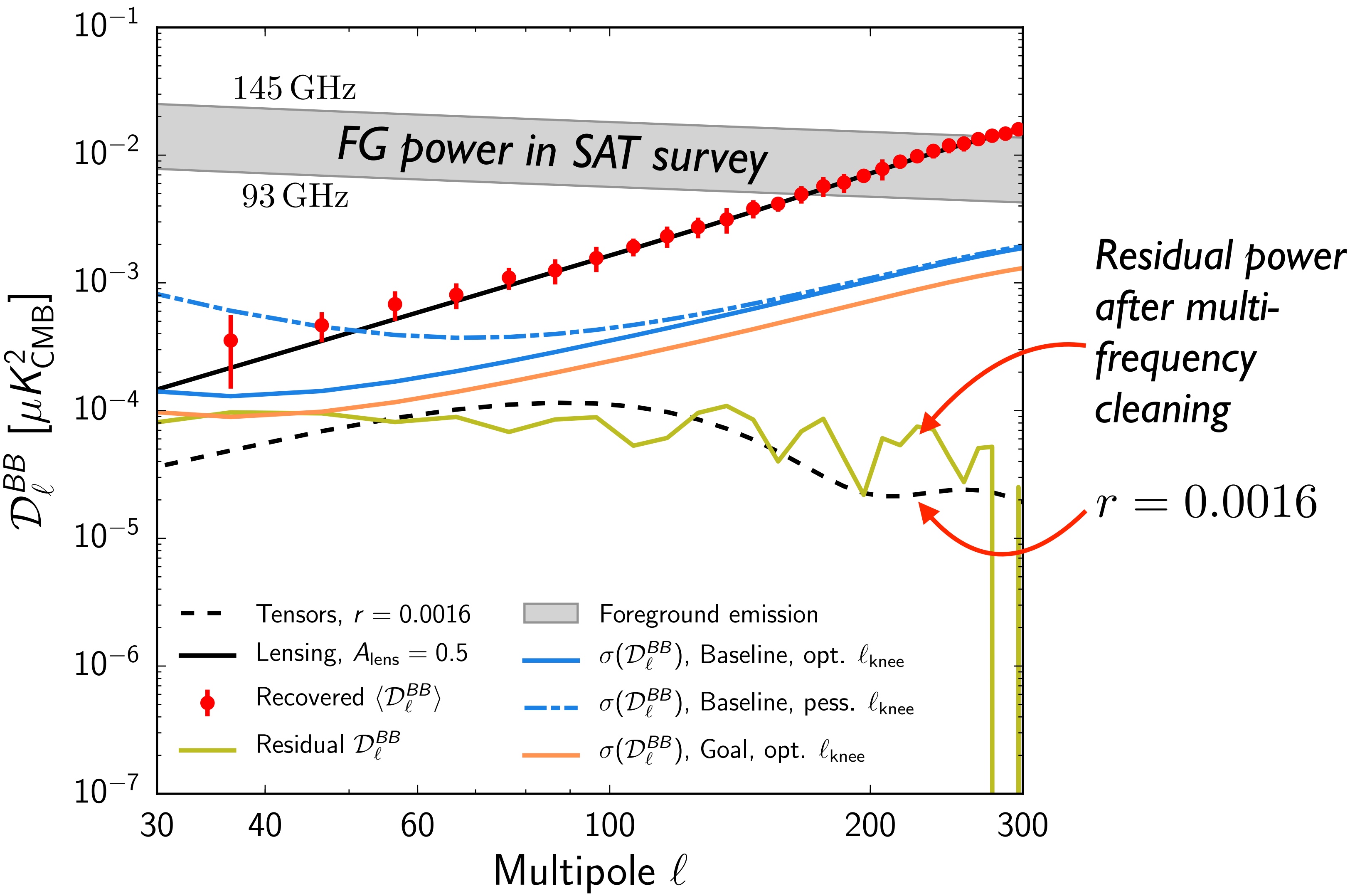
Extrapolating 18 orders of magnitude!

Planck TT,TE,EE+lowE+lensing+BK15

+LIGO & VIRGO 2016

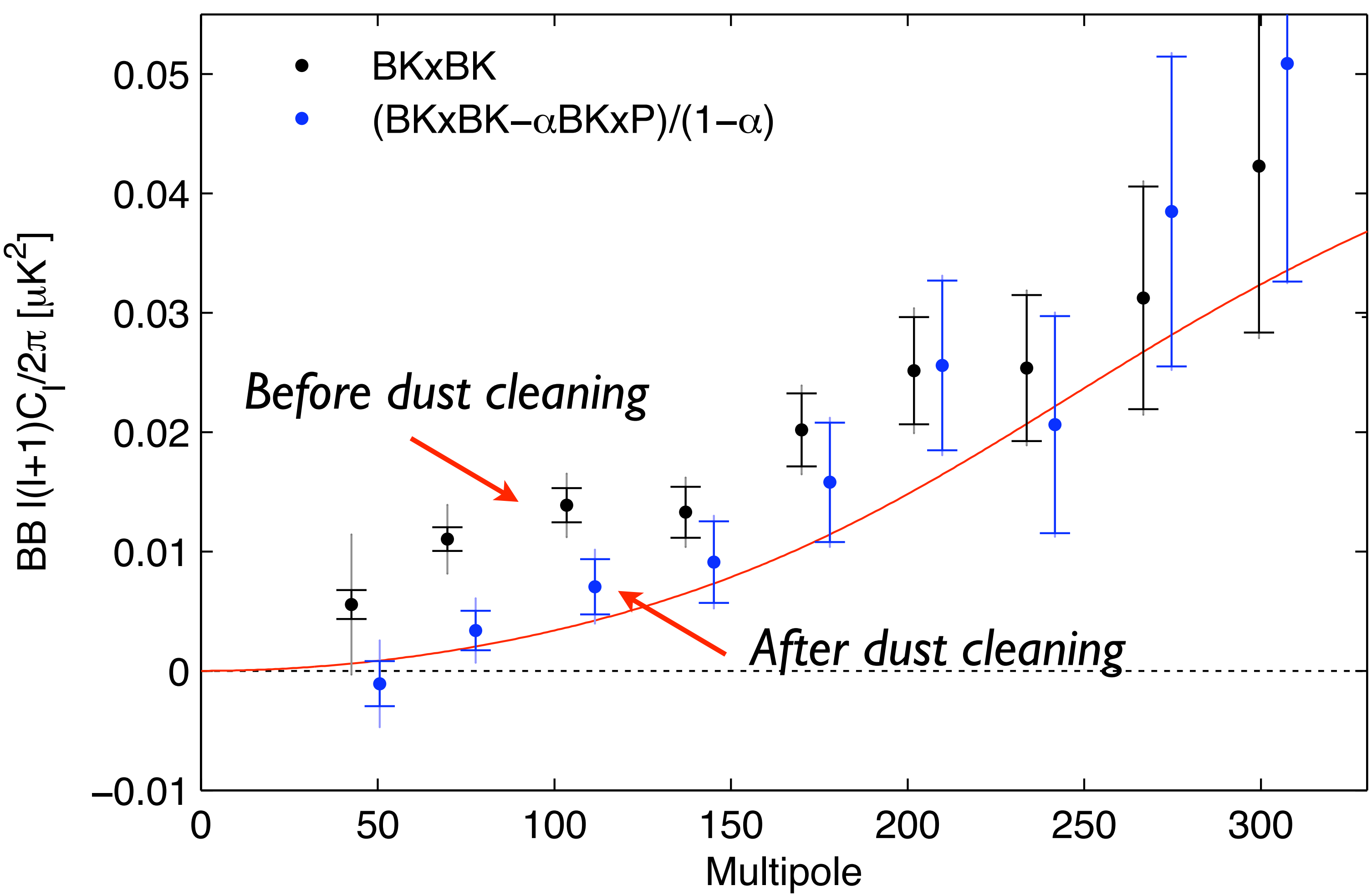
Planck Collaboration 2018

Galactic foregrounds



Simons Observatory Collaboration 2018

Dust-cleaned cross-power

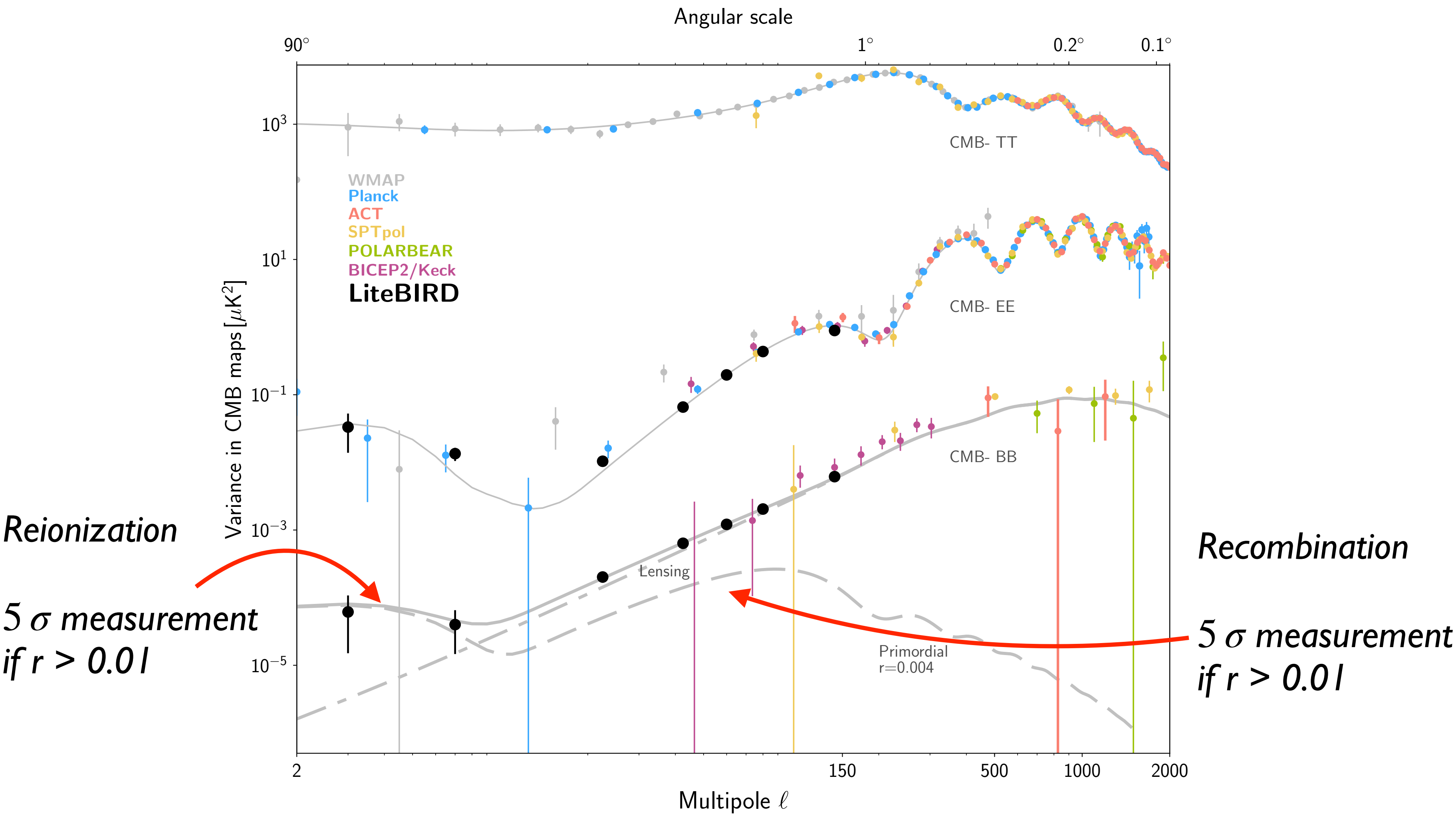


BICEP2/Keck + Planck Collaborations 2015

LiteBIRD

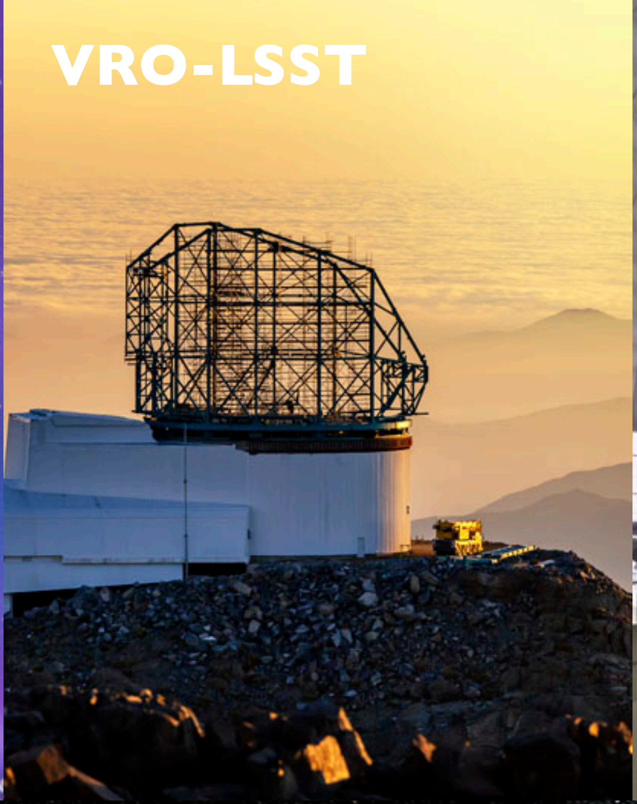
- JAXA-led mission with planned launch around 2027
  - Operate for 3 years
- Degree-scale resolution but 20x sensitivity of Planck
- 15 frequencies (40–400 GHz)
- Targeting primordial *B*-modes from recombination and reionization

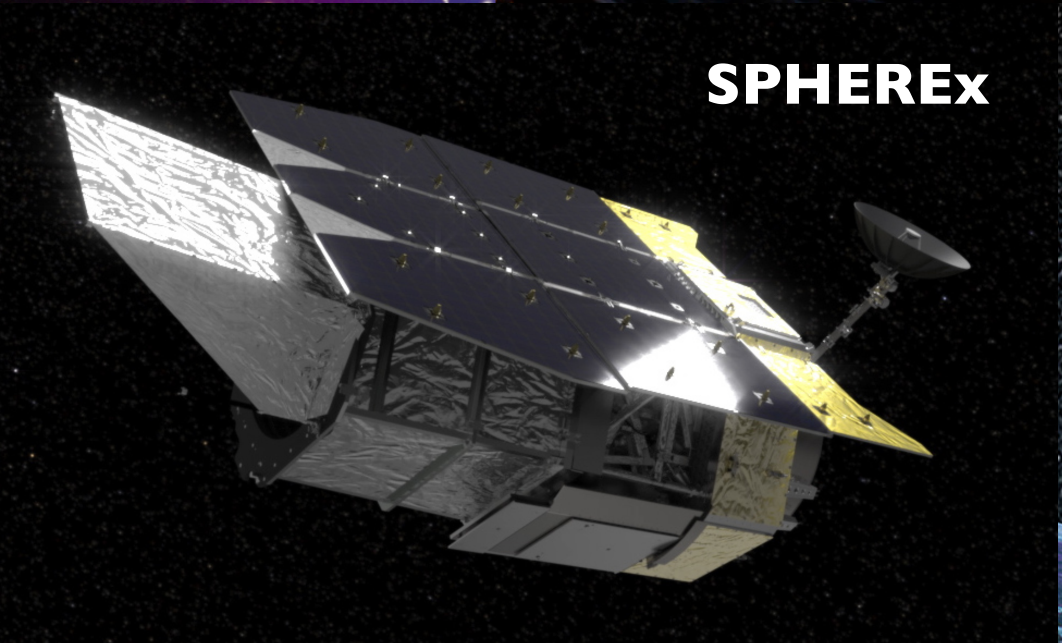
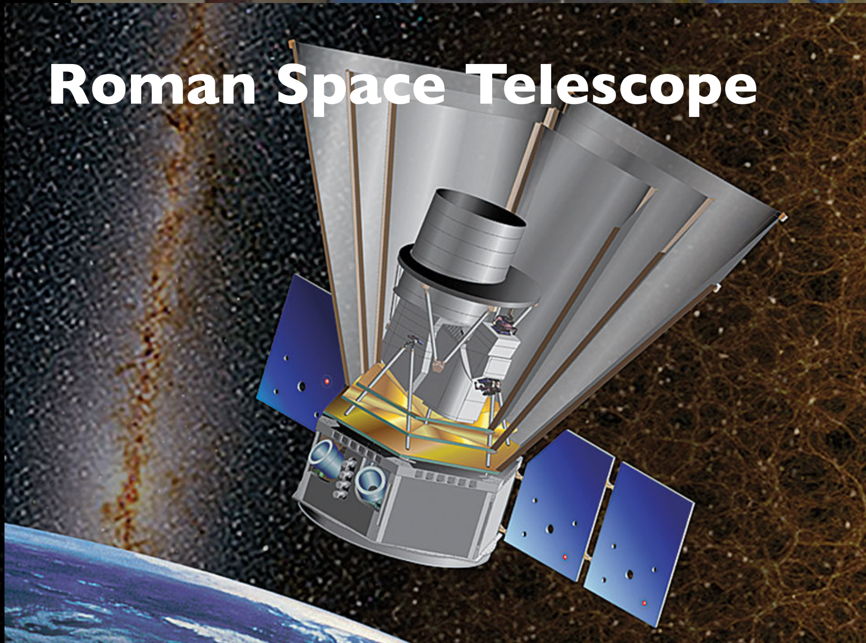
LiteBIRD spectra forecasts



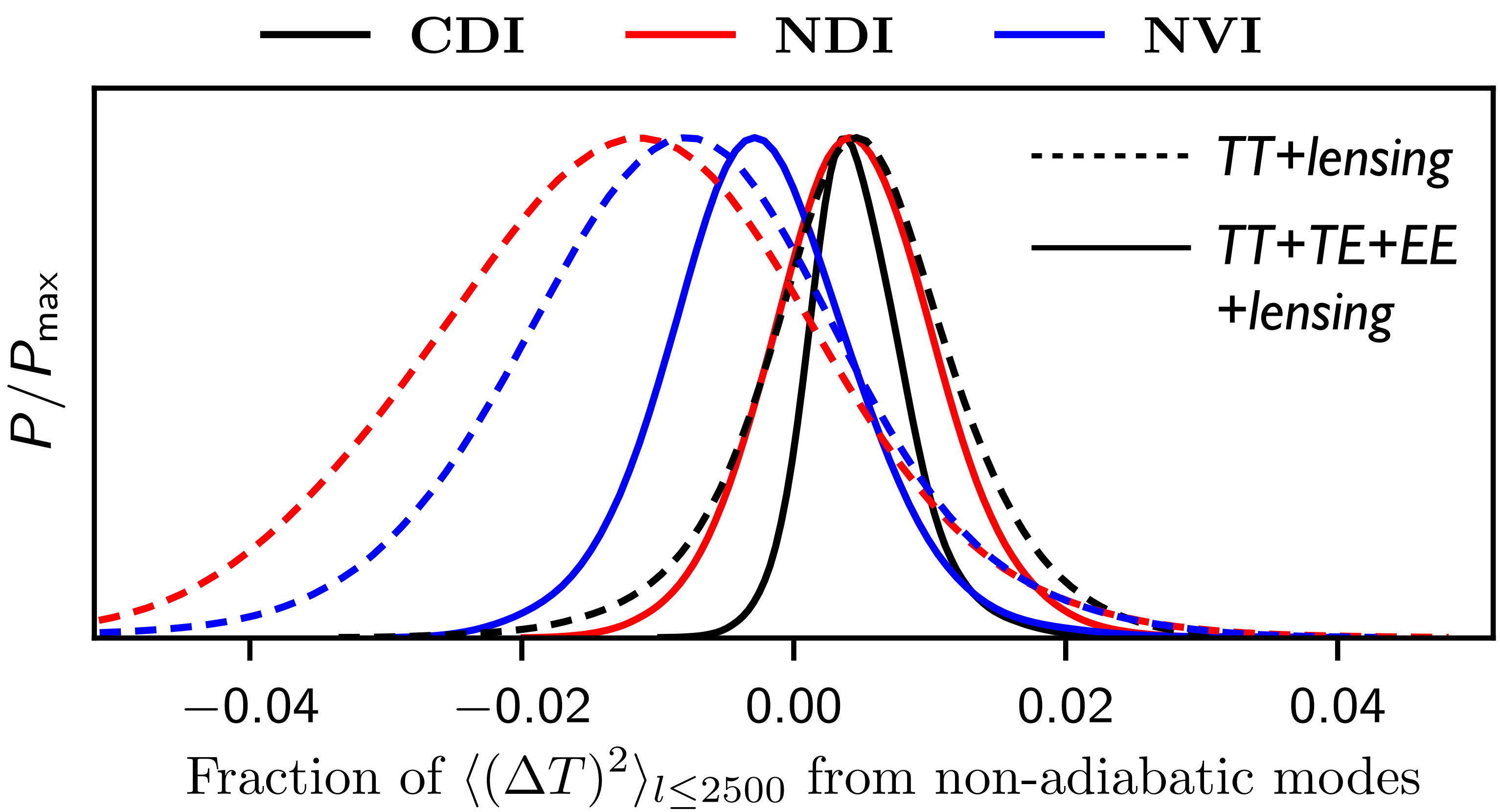
Total error budget for *r* = 0: $\sigma(r) < 0.001$

Hazumi+ 2021


Euclid

VRO-LSST

DESI

SPHEREx

Roman Space Telescope

No evidence for isocurvature modes

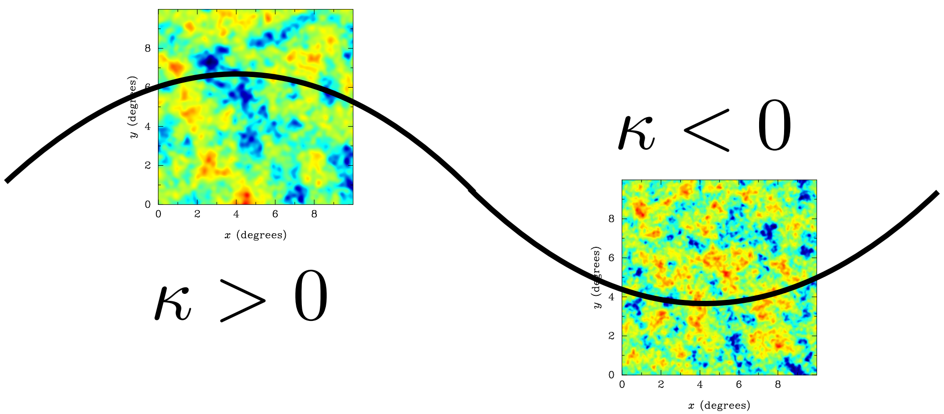


Less than 2% contribution to CMB (*T*) variance from generally correlated non-adiabatic modes

Planck Collaboration 2018

Bispectrum contaminants

- ISW-lensing has to be subtracted: $\Delta f_{\rm NL}^{\rm loc} = 7.3$
  $\Delta f_{\rm NL}^{\rm orth} = -23$



$$\Delta T^{\rm ISW} \longrightarrow f_{\rm NL}^{\rm loc} > 0$$

- Intrinsic bispectrum small correction: $|\Delta f_{\rm NL}^{\rm loc}| \approx 0.5$

Planck Collaboration 2019; Hill 2018; Pettinari+ 2013 etc.

Bispectrum contaminants: single frequency

Not including ISW-lensing

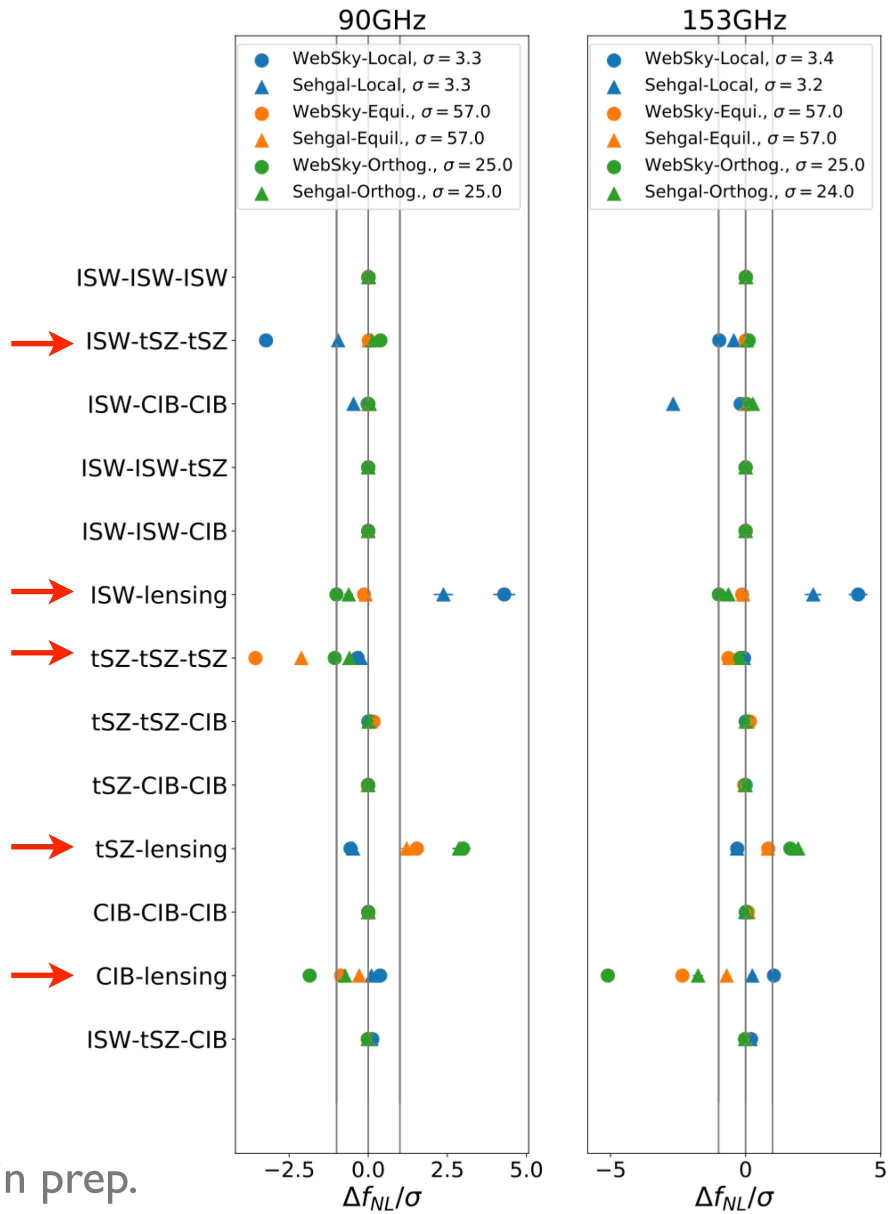
Experiment	Frequency (GHz)	$\Delta f_{\rm NL}^{\rm local}$ Total bias	$\sigma_{\rm Exp.}$	$\Delta f_{\rm NL}^{\rm equil}$ Total bias	$\sigma_{\rm Exp.}$	$\Delta f_{\rm NL}^{\rm orth}$ Total bias	$\sigma_{\rm Exp.}$
Planck	100	-0.8 ± 0.4	7.8	-16 ± 5.2	81	-2.4 ± 3.2	41
	143	0.3 ± 0.4	5.5	-21 ± 6.0	70	-30 ± 3.4	34
	217	4.7 ± 0.9	5.5	-37 ± 13	70	-140 ± 6.9	34
	353	11 ± 6.3	13	890 ± 51	110	43 ± 22	55
SO	90	-11 ± 0.7	3.3	-160 ± 13	57	7.2 ± 6.7	25
	145	-0.2 ± 0.9	3.4	-120 ± 14	57	-89 ± 7.4	25
	232	5.9 ± 1.6	4.6	-140 ± 21	66	-260 ± 12	30
	275	6.9 ± 2.3	6.1	62 ± 26	76	-270 ± 15	36

WebSky simulations

Hill 2018; Coulton, Miranthis & AC in prep.

Bispectrum contaminants: single frequency

Experiment	Frequency (GHz)
Planck	100
	143
	217
	353
SO	90
	145
	232
	275



Hill 2018; Coulton, Miranthis & AC in prep.

Bispectrum contaminants: ILC cleaning

Not including ISW-lensing

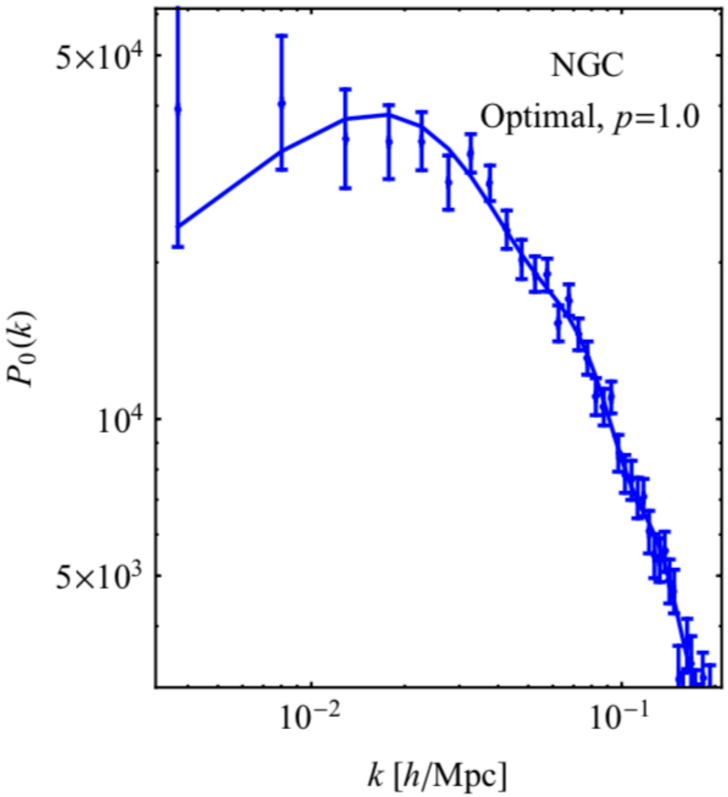
Experiment	Frequency (GHz)	$\Delta f_{\rm NL}^{\rm local}$ Total bias	$\sigma_{\rm Exp.}$	$\Delta f_{\rm NL}^{\rm equil}$ Total bias	$\sigma_{\rm Exp.}$	$\Delta f_{\rm NL}^{\rm orth}$ Total bias	$\sigma_{\rm Exp.}$
Planck	Base	0.1 ± 0.4	5.3	-6.6 ± 4.5	67	-13 ± 2.6	32
	tSZ deprojected	2.0 ± 0.4	5.6	-29 ± 6.2	69	-63 ± 3.6	33
	CIB deprojected	-2.15 ± 0.9	5.3	7.8 ± 4.3	67	17 ± 3.1	32
	tSZ & CIB deprojected	-0.4 ± 0.4	5.6	-5.8 ± 5.2	69	-6.7 ± 3.1	34
SO	Base	-2.5 ± 0.5	3.3	2.3 ± 8.6	57	-5.9 ± 4.5	25
	tSZ deprojected	1.6 ± 0.4	4.1	-55 ± 6.5	63	-75 ± 3.6	28
	CIB deprojected	-4.3 ± 0.4	3.4	44 ± 7.7	58	42 ± 4.1	25
	tSZ & CIB deprojected	-0.7 ± 0.3	4.2	-8.3 ± 5.6	63	-7.3 ± 3.2	28

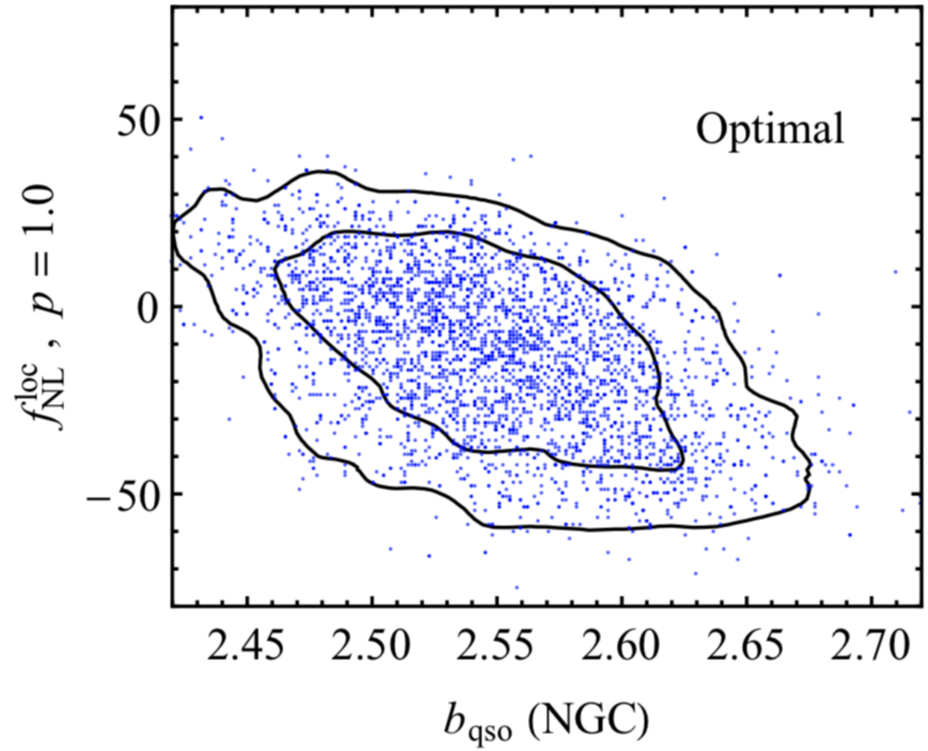
WebSky simulations

- Effectiveness of base ILC relies on cancellation between CIB- and tSZ-related biases
- Deprojecting **both** CIB and tSZ recommended for SO

Hill 2018; Coulton, Miranthis & AC in prep.

Scale-dependent halo bias: eBOSS QSOs





$$-51 < f_{\rm NL}^{\rm loc} < 21$$

- Quasars: highly biased and large volumes (eBOSS DR14: $0.8 < z < 2.2$)
- Prediction for full eBOSS: $\sigma\left(f_{\rm NL}^{\rm loc}\right) = 5\text{–}8$ (similar to current CMB)

Castorina+ 2019