The path to precision measurements of the primordial SGWB spectrum

The role of CMB and direct-detection experiments

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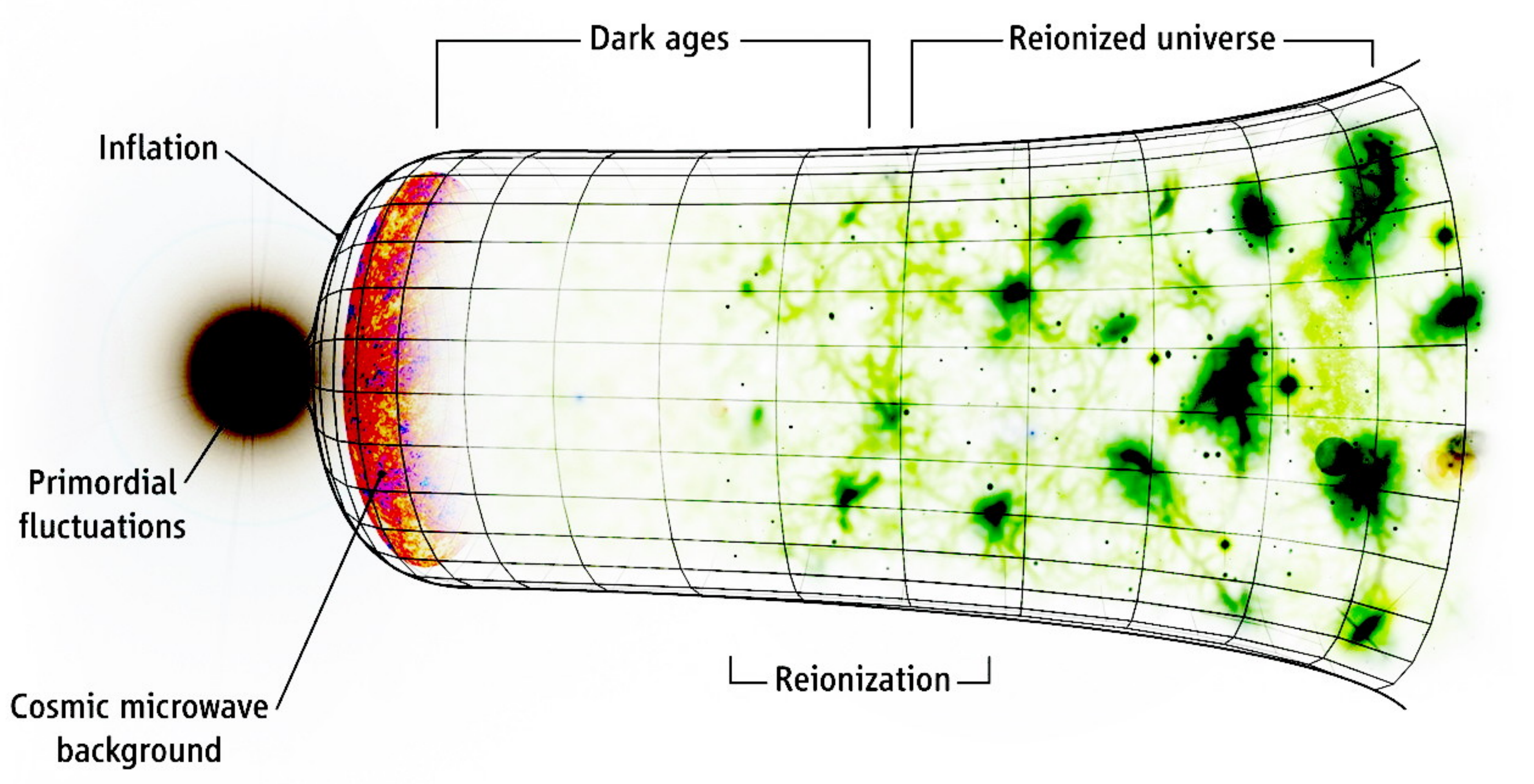
The inflationary paradigm

- Period of accelerated expansion
- Simplest model Single-Field Slow-Roll (SFSR)
- Solves several Big Bang Theory problems
- Predictions:
  - Flat universe ✓
  - Density perturbations with ~ scale-invariant red-tilted power-law spectrum ✓
  - Gaussian/adiabatic scalar perturbations ✓
  - Tensor (and scalar) perturbations from quantum vacuum fluctuations



Why hunting for the primordial SGWB?

- Super-horizon tensor modes (with power spectrum $P_T(k)$) encode the initial conditions of the Universe

- Standard power-law parametrisation

$$P_T(k) = A_T \left(\frac{k}{k_0}\right)^{n_T}$$

- Tensor-to-scalar ratio $r = \dfrac{A_T}{A_S}$

- r directly connected to the energy scale of inflation in SFSR:

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

→

- Window on new physics
- Unique information on the early universe
- Probe energy scales unreachable by particle colliders
- Definitive evidence for inflation

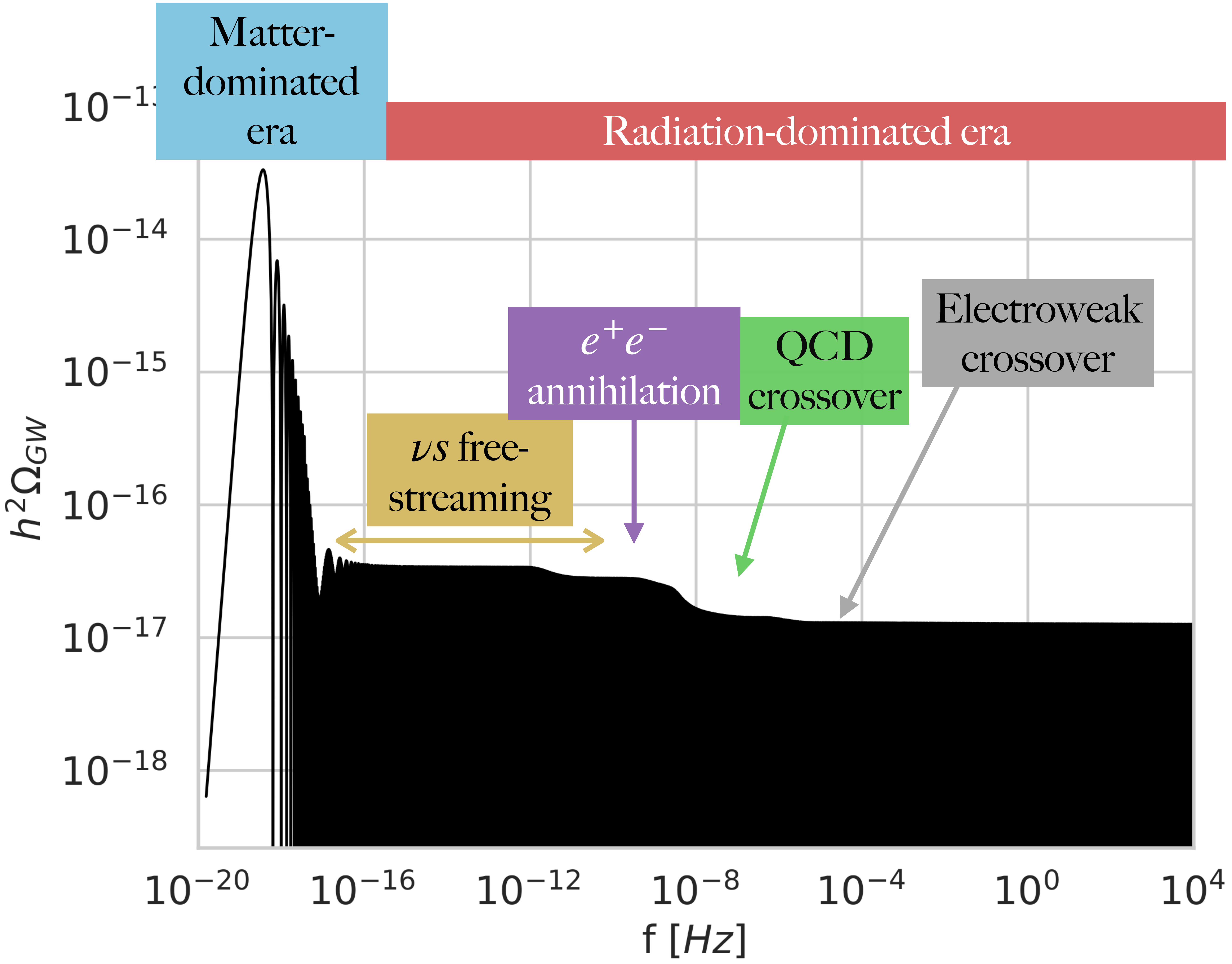
The spectrum of primordial GWs today

- Time evolution of tensor amplitude encoded in GW transfer function: $h_P(\mathbf{k},\tau) = h_P^{prim}(k)T(\tau,\mathbf{k})$

- Energy density in GWs today:

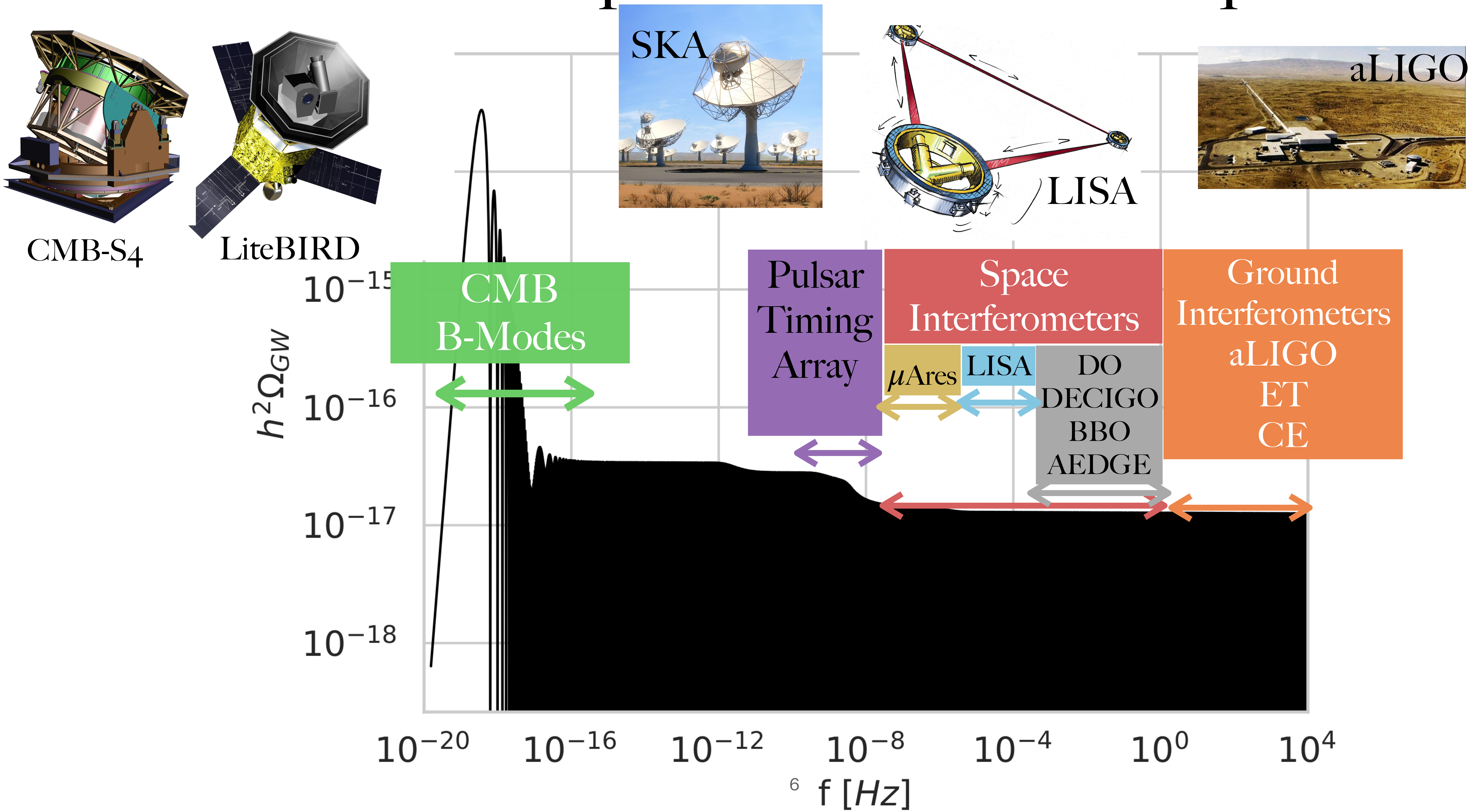
$$\Omega_{GW}(k,\tau_0) = \frac{1}{\rho_c(\tau_0)}\frac{\partial\rho_{GW}(k,\tau_0)}{\partial \ln k} = \frac{P_T(k)}{12H_0^2}\cdot\left[T'(k,\tau_0)\right]^2$$

- Spectrum extends across $\sim$ 21 decades in frequency!



Observational probes and challenges

Observational probes at different frequencies



Polarisation B-modes in the CMB

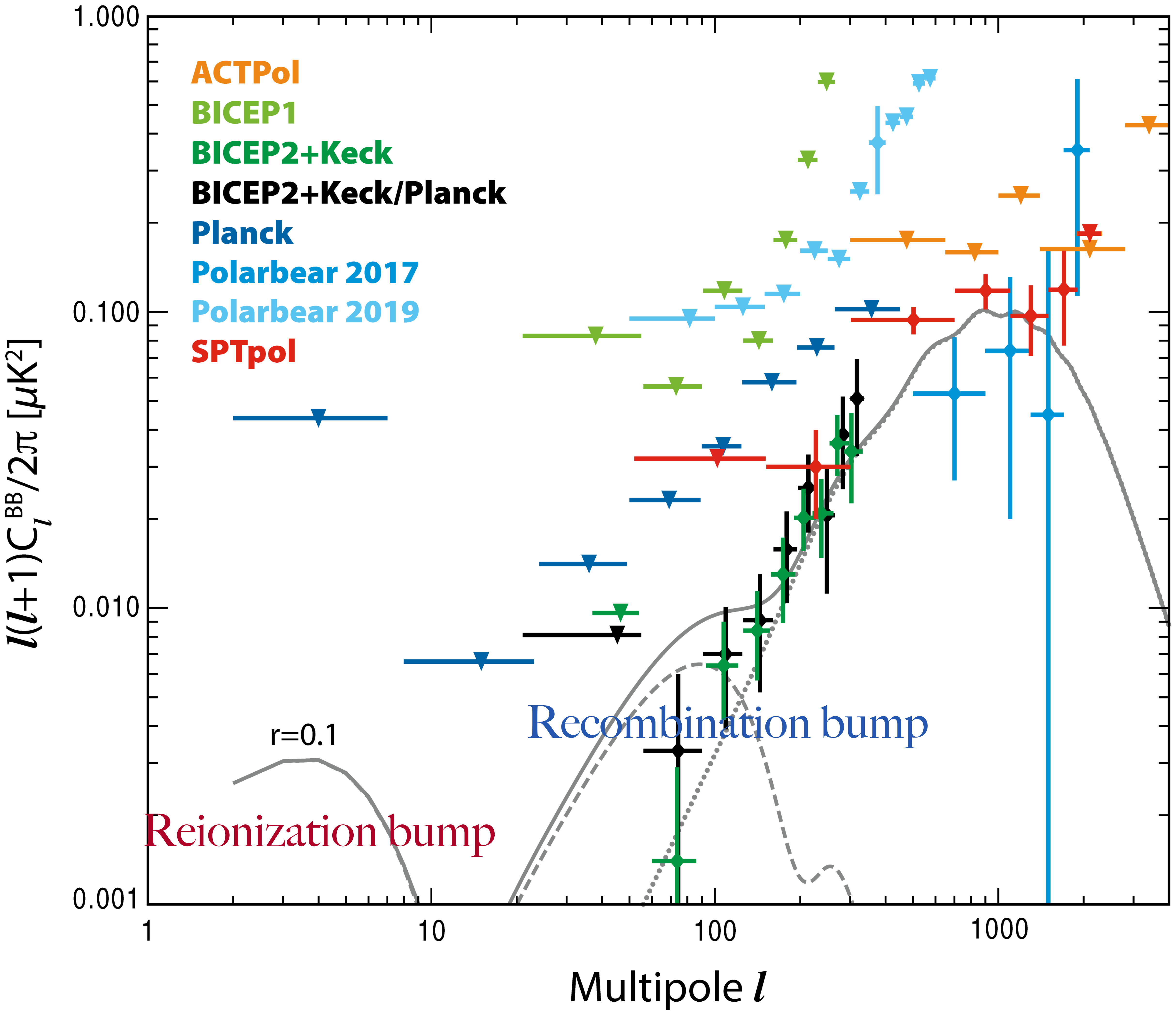
- Produced by Thomson scattering at recombination and reionization times

- Observables angular power spectra $C_\ell^{XX'}$
  $X, X' = \{T, E, B\}$

  - Total intensity T
  - Gradient mode of polarisation E
  - Curl mode of polarisation B

- Primordial B produced only by tensor perturbations, not by scalar!

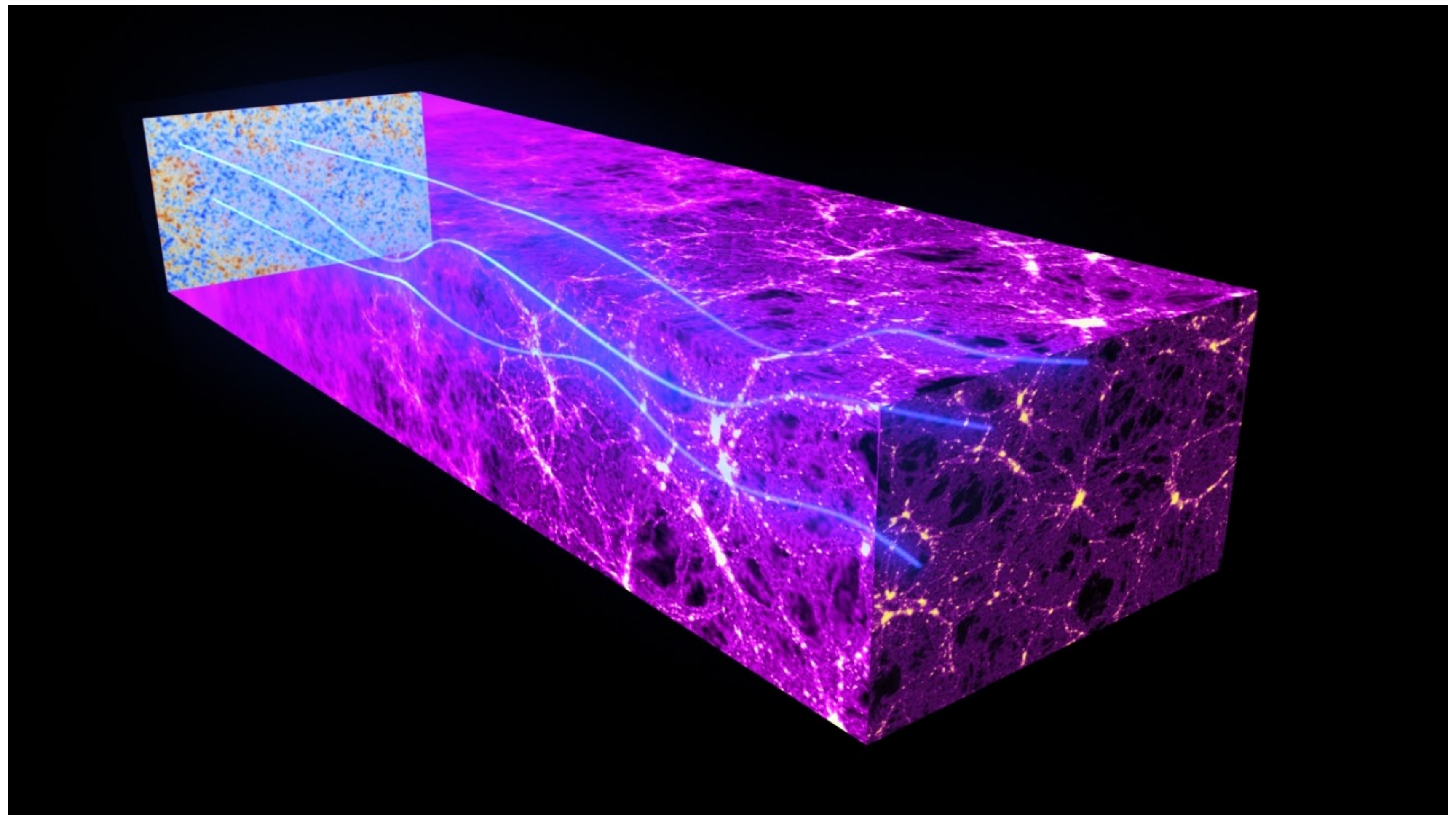
- No detection yet of primordial B, only upper limits $r < 0.044$ at $95\,\%\,C.L.$

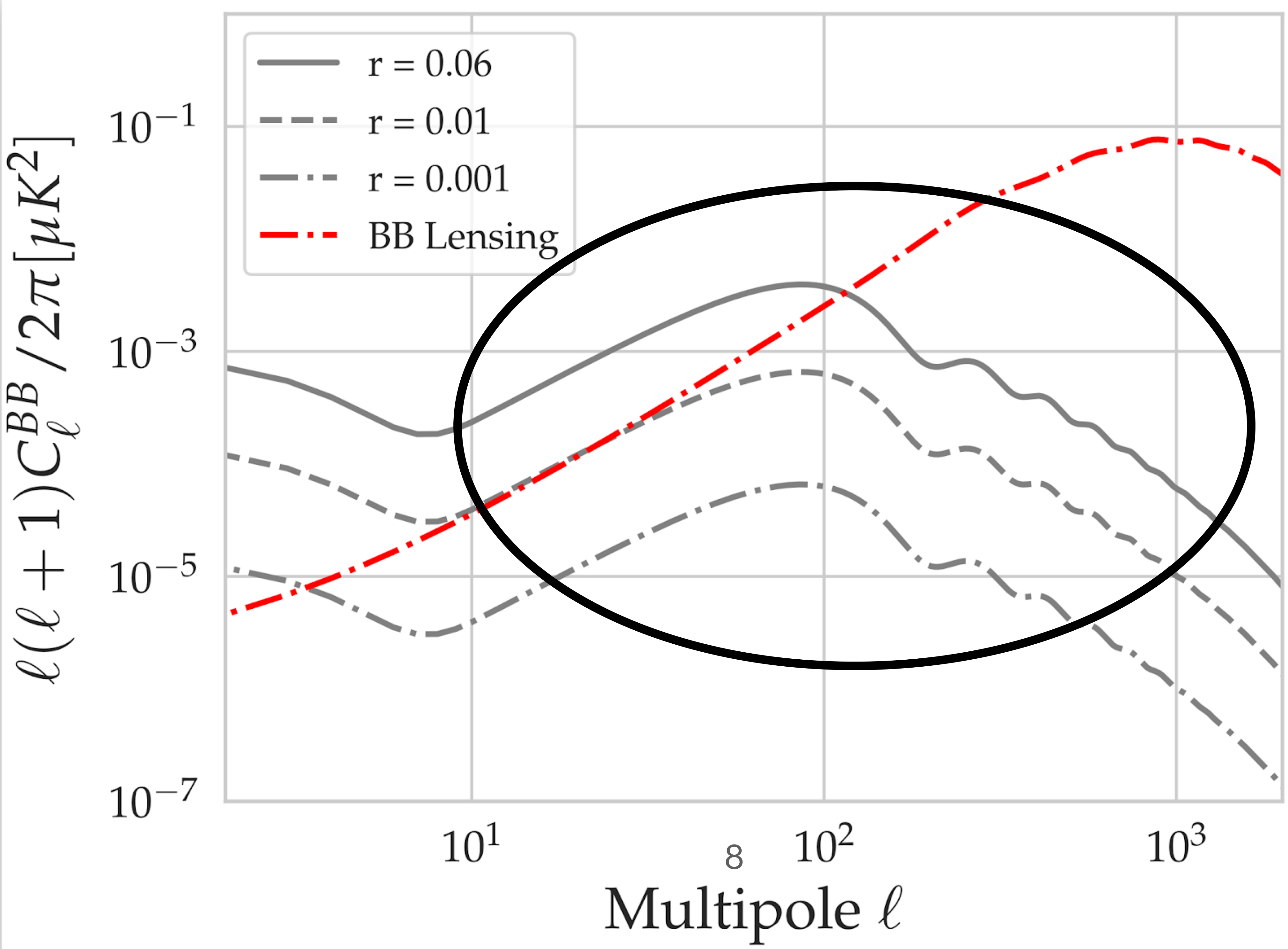


LAMBDA - April 2021

B-modes contaminant: weak gravitational lensing

- Remaps CMB T and polarisation due to intervening cosmological LSS
- Convert E-modes into secondary B-modes
- Dominates intermediate/small-scales





B-modes contaminant: Galactic foregrounds

- Thermal dust emission

$$\mathrm{A}_{dust}(\nu) = \left(\frac{\nu}{\nu_d}\right)^{\beta_d+1} \frac{e^{\frac{h\nu_d}{kT_d}} - 1}{e^{\frac{h\nu}{kT_d}} - 1}$$

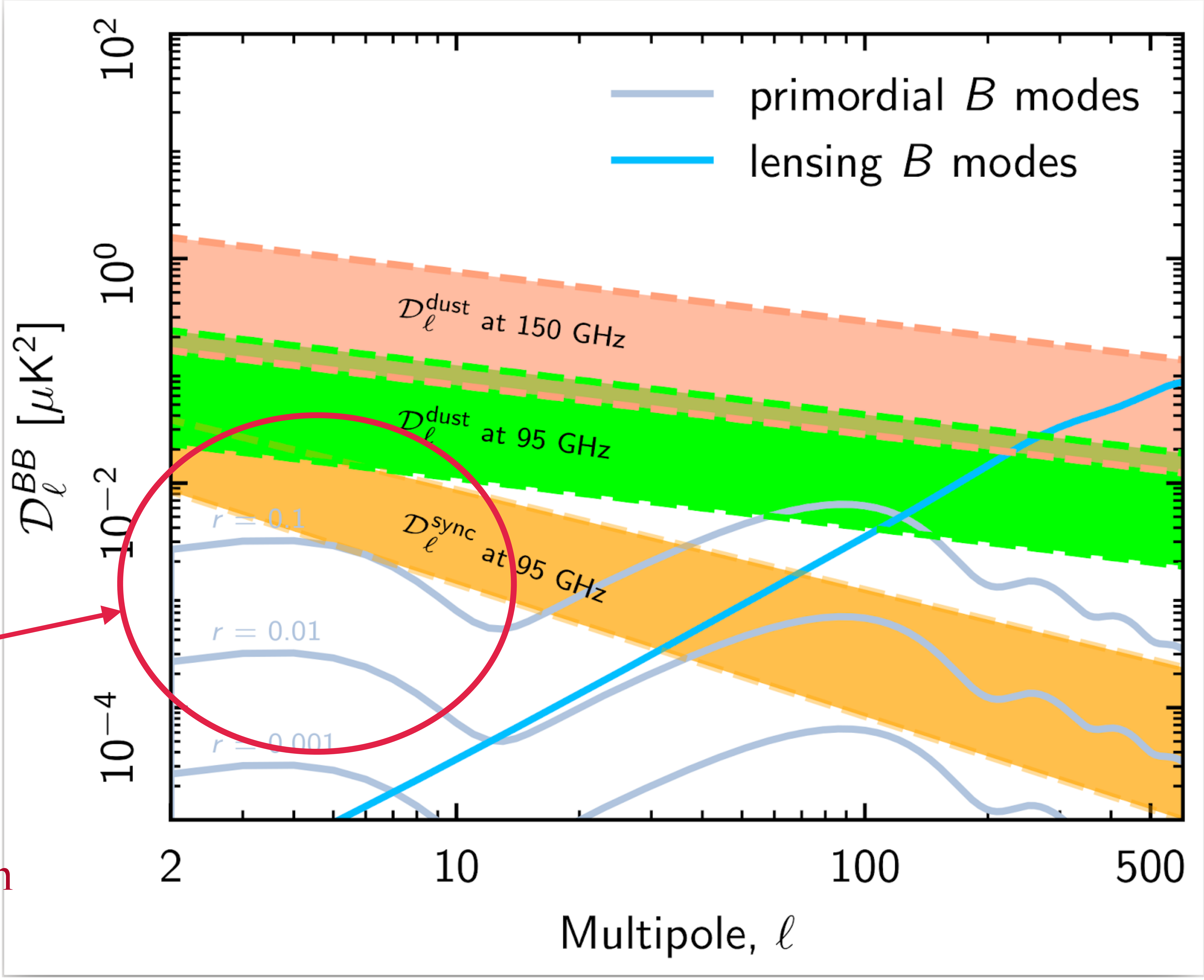
- Synchrotron emission

$$\mathrm{A}_{sync}(\nu) = \left(\frac{\nu}{\nu_s}\right)^{\beta_s + C_s \ln(\nu/\nu_s)}$$

- Dominates large-scale B-modes

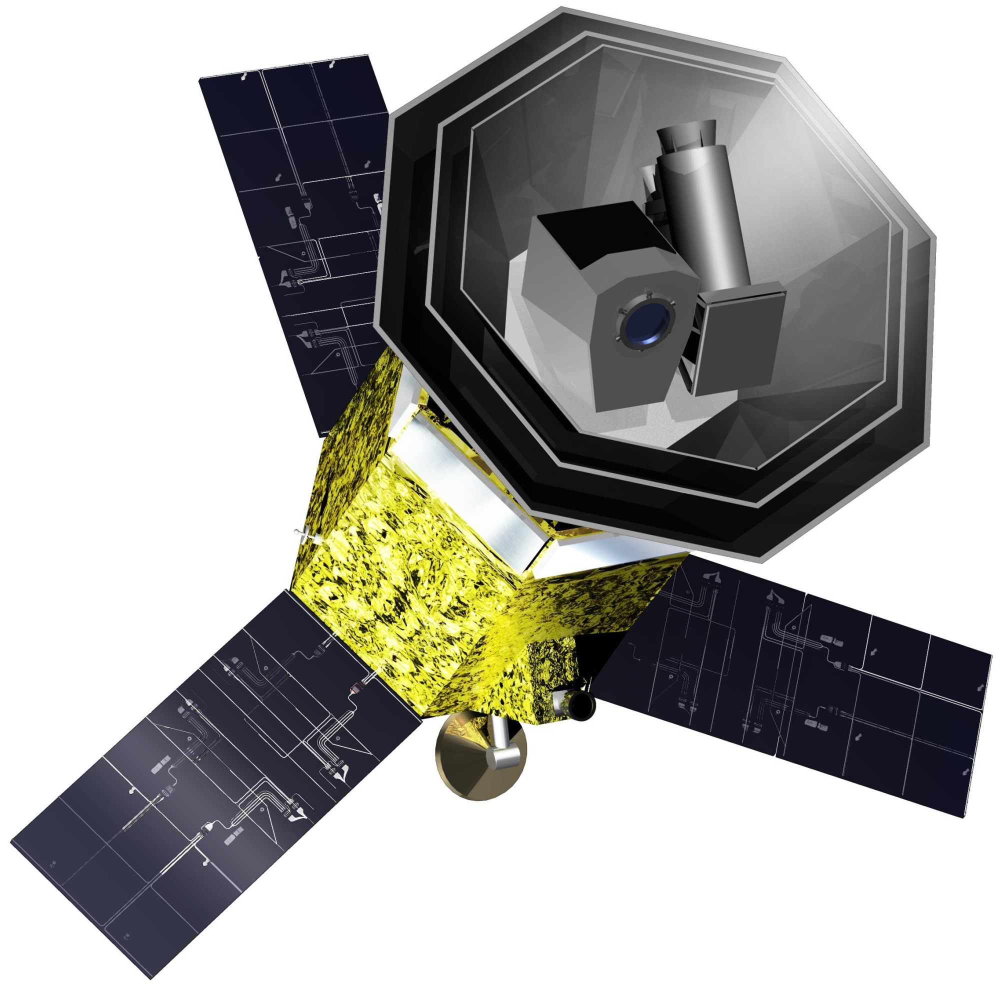
- No point in the sky at any frequency totally free from contamination!

- Parametric max likelihood component separation (`FGBuster` code *Errard & Poletti in preparation*)

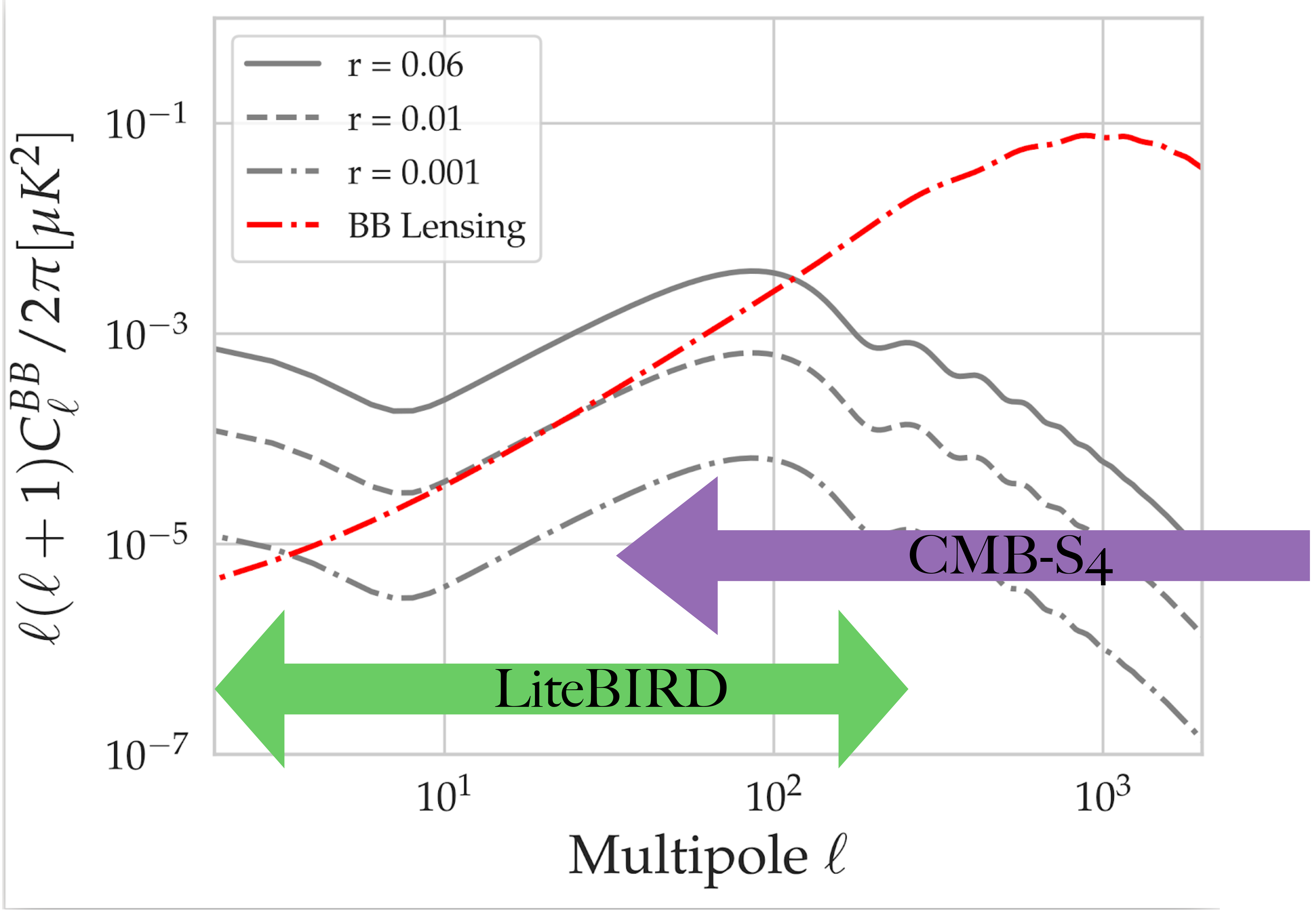


B-modes state-of-the-art (2028-2029)

LiteBIRD

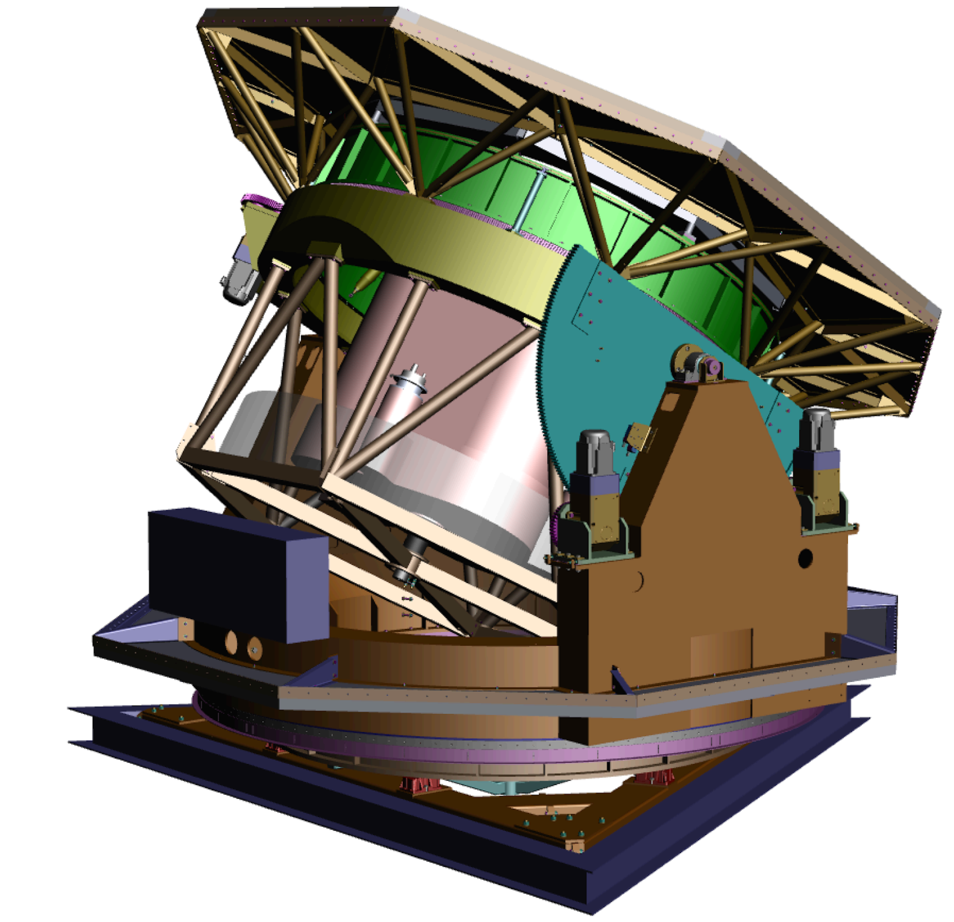


- Satellite mission
- ~ 2028
- Full sky (60%)
- $\ell \sim 2 - 200$
- Access to reionization bump
- 15 freq bands [34 - 448 GHz] (powerful foreground cleaning)
- No atmospheric contamination/ground pickup
- Lower resolution



➡ Highly complementary experiments!

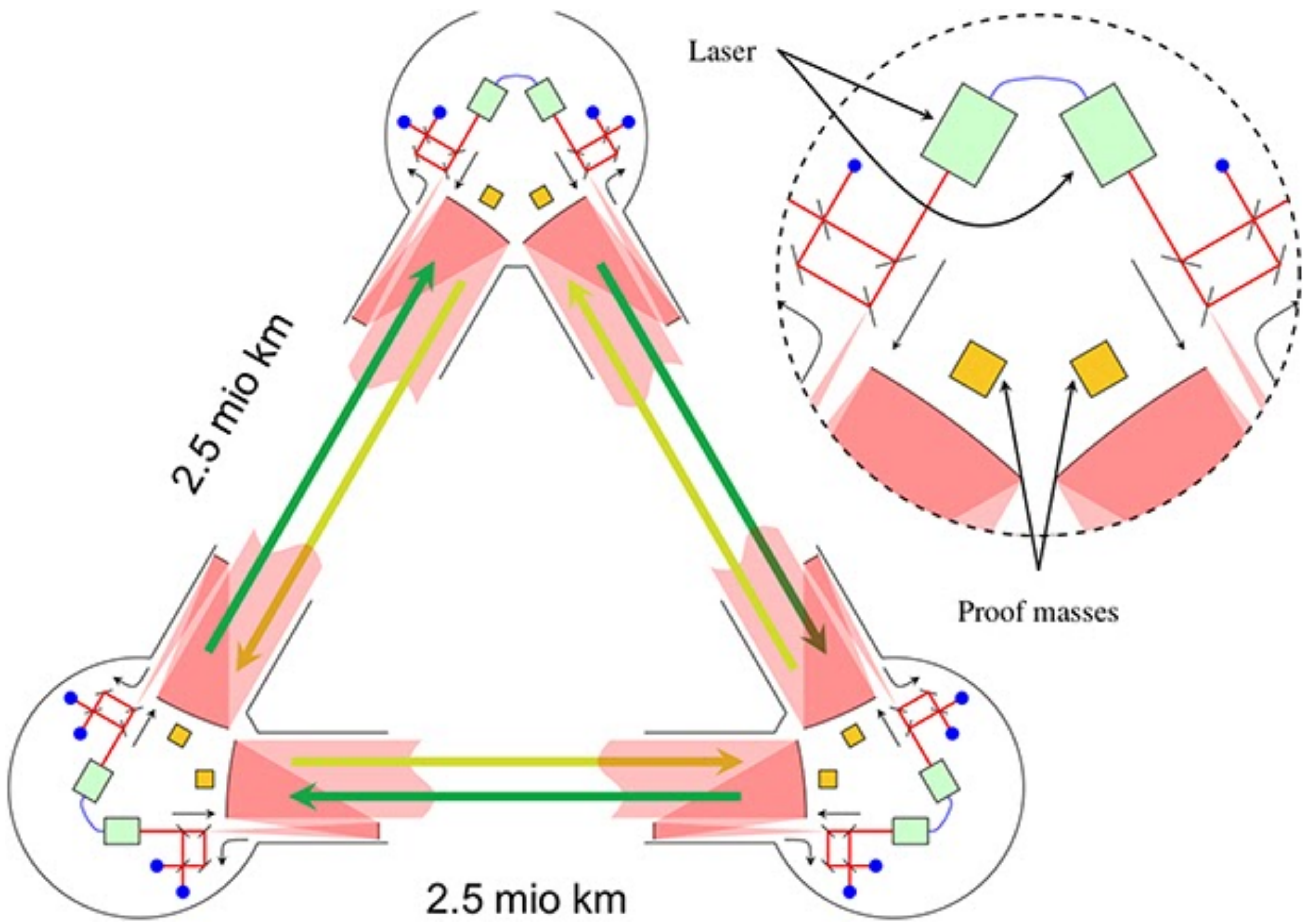
CMB-S4



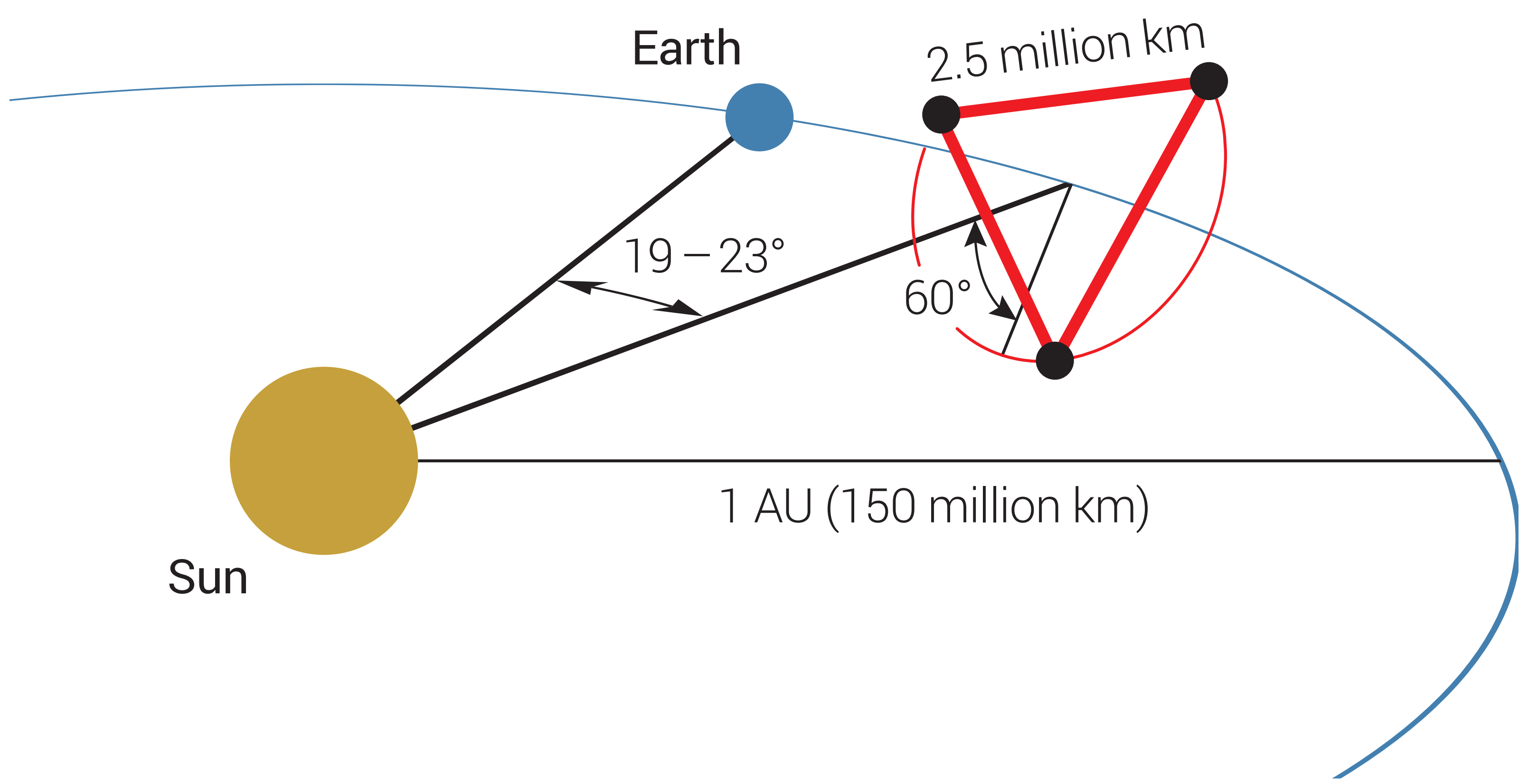
- Ground-based
- ~ 2029
- Sky fraction 3%
- $\ell \sim 30 - 4000$
- Access to very small scales
- 9 freq bands [20 - 270 GHz]
- Atmospheric contamination/ ground pickup
- Higher resolution (powerful delensing)

Space-borne laser interferometers: LISA

- GW changes proper distance between two test-masses, producing phase-shifts in laser beams
- Can access low frequencies in Space
- LISA in mHz range
- 3 spacecraft in equilateral triangle constellation
- Launch early/mid 2030s

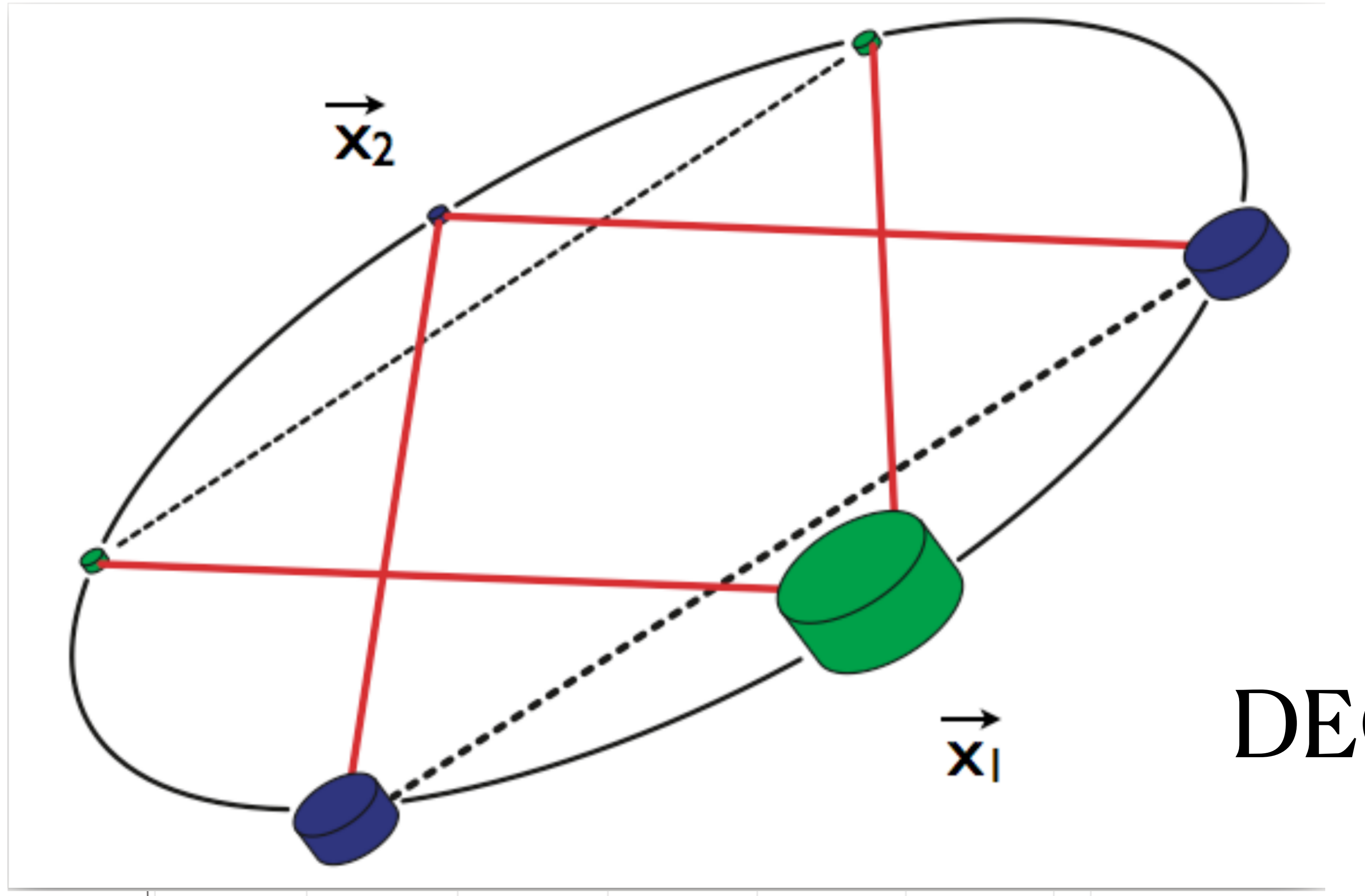


LISA

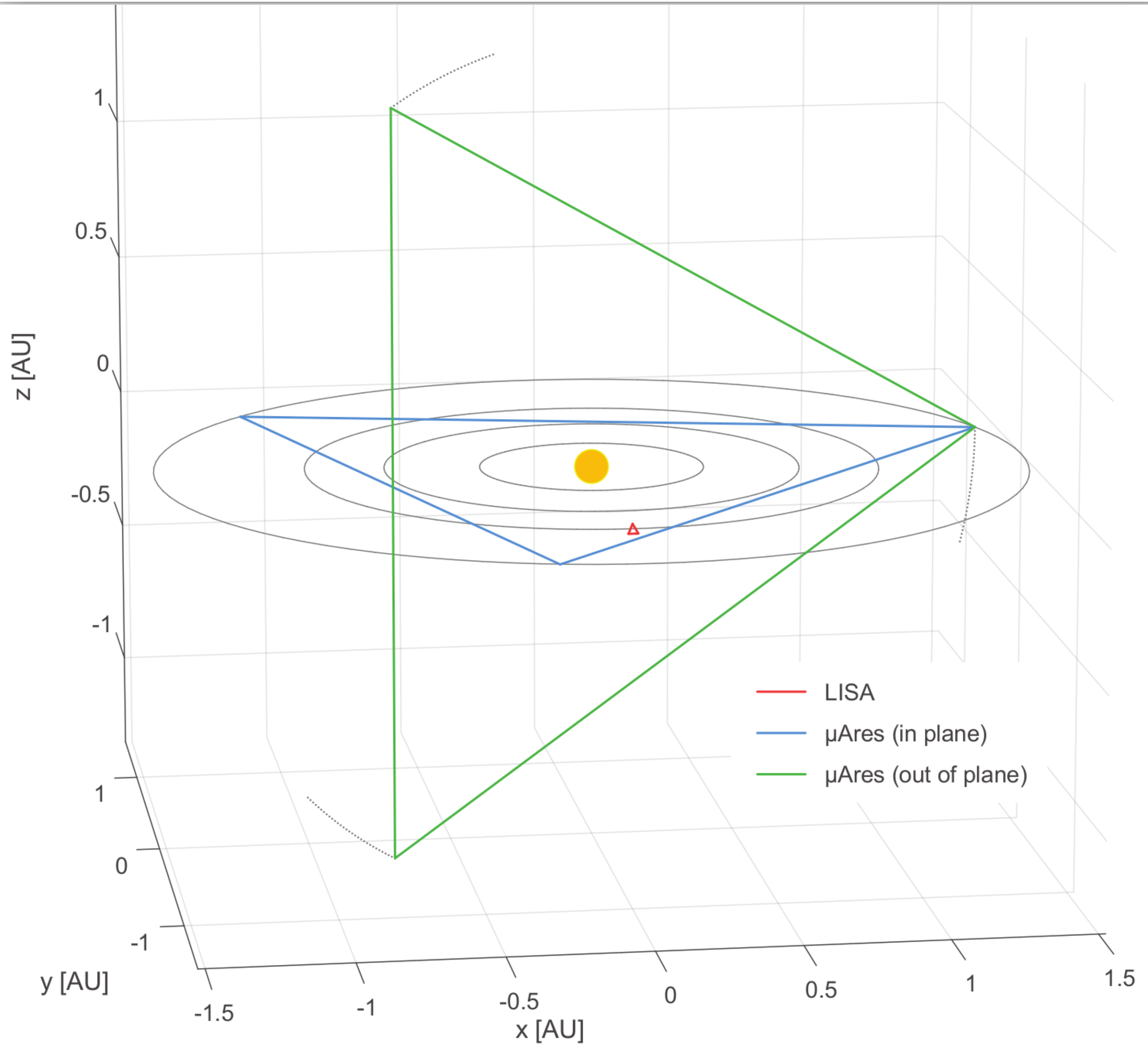


Post-LISA space missions (2035-2050)

- DO in deciHz range
- DECIGO/BBO:
    - Ultra-sensitive in deciHz range
    - Hexagram configuration
    - 4 independent constellations
- μAres in μHz range: perpendicular triangular configuration, Mars orbit
- AEDGE atomic interferometer in deciHz range



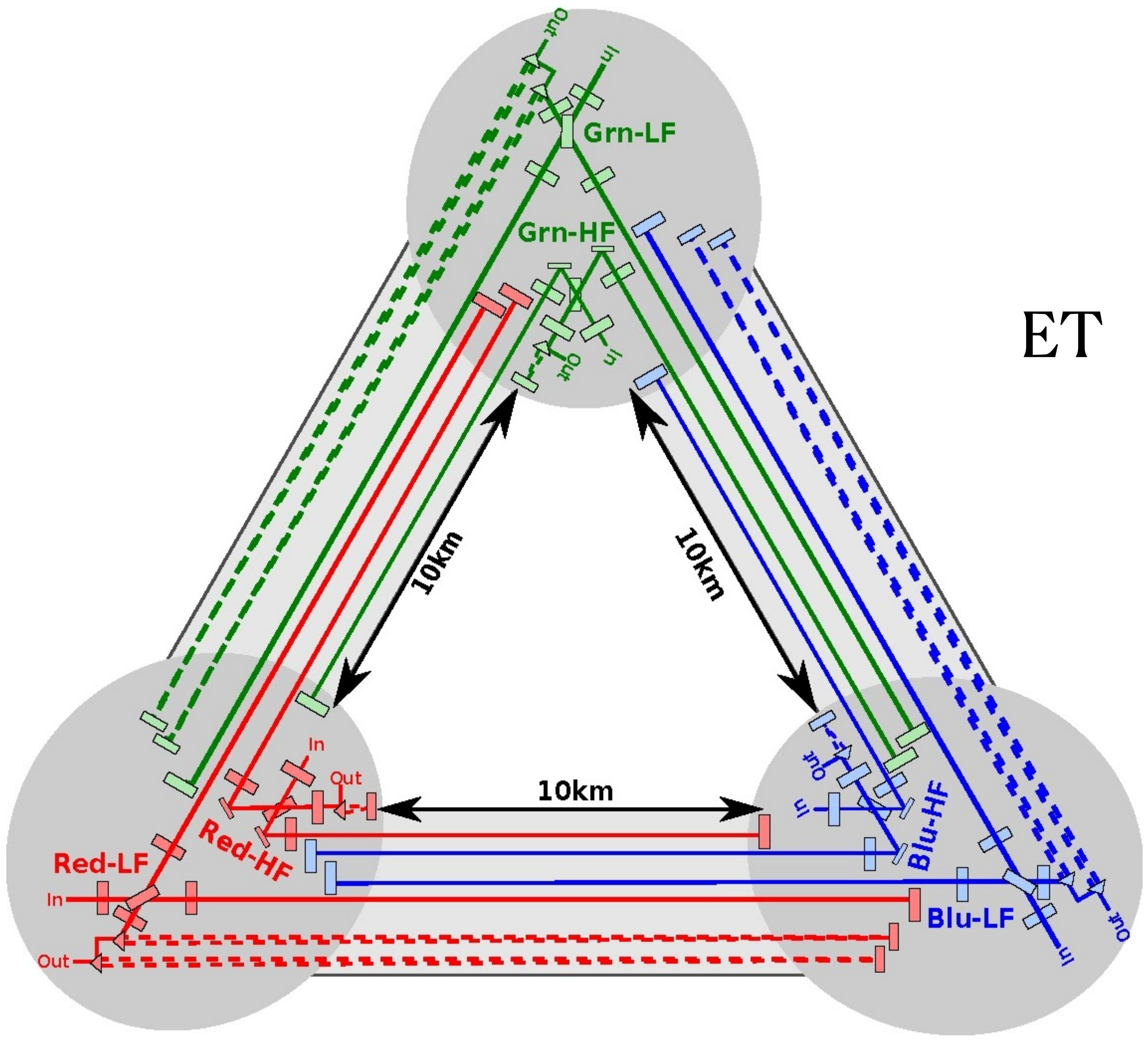
DECIGO/BBO



μAres

Ground-based interferometers

- Higher frequencies ($1 - 10^4$ Hz)
- Einstein Telescope ($\sim$ 2035) in "xylophone" configuration
- 3 independent detectors in equilateral triangle
- each detector made by 2 interferometers (optimized for Low Freq or High Freq)

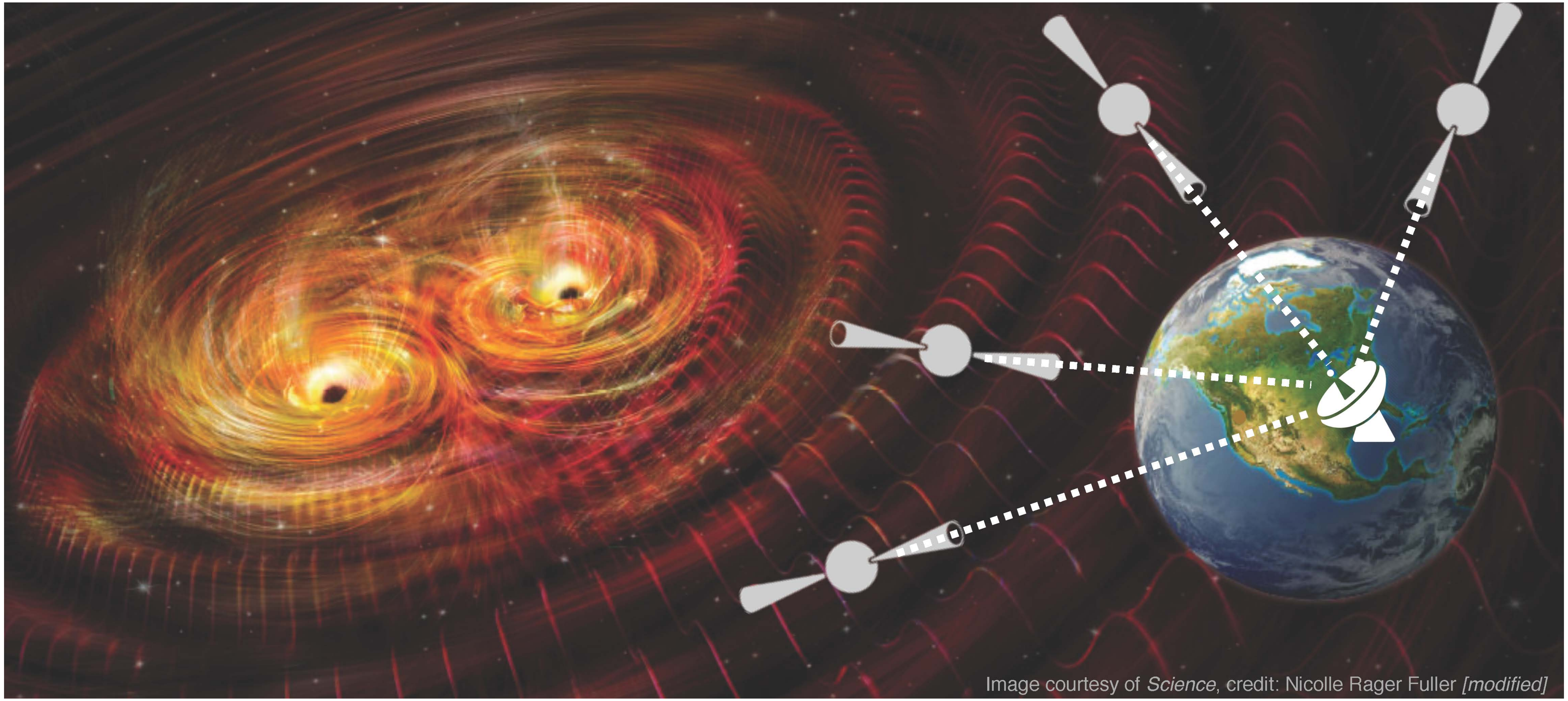


ET

From Hild +2011

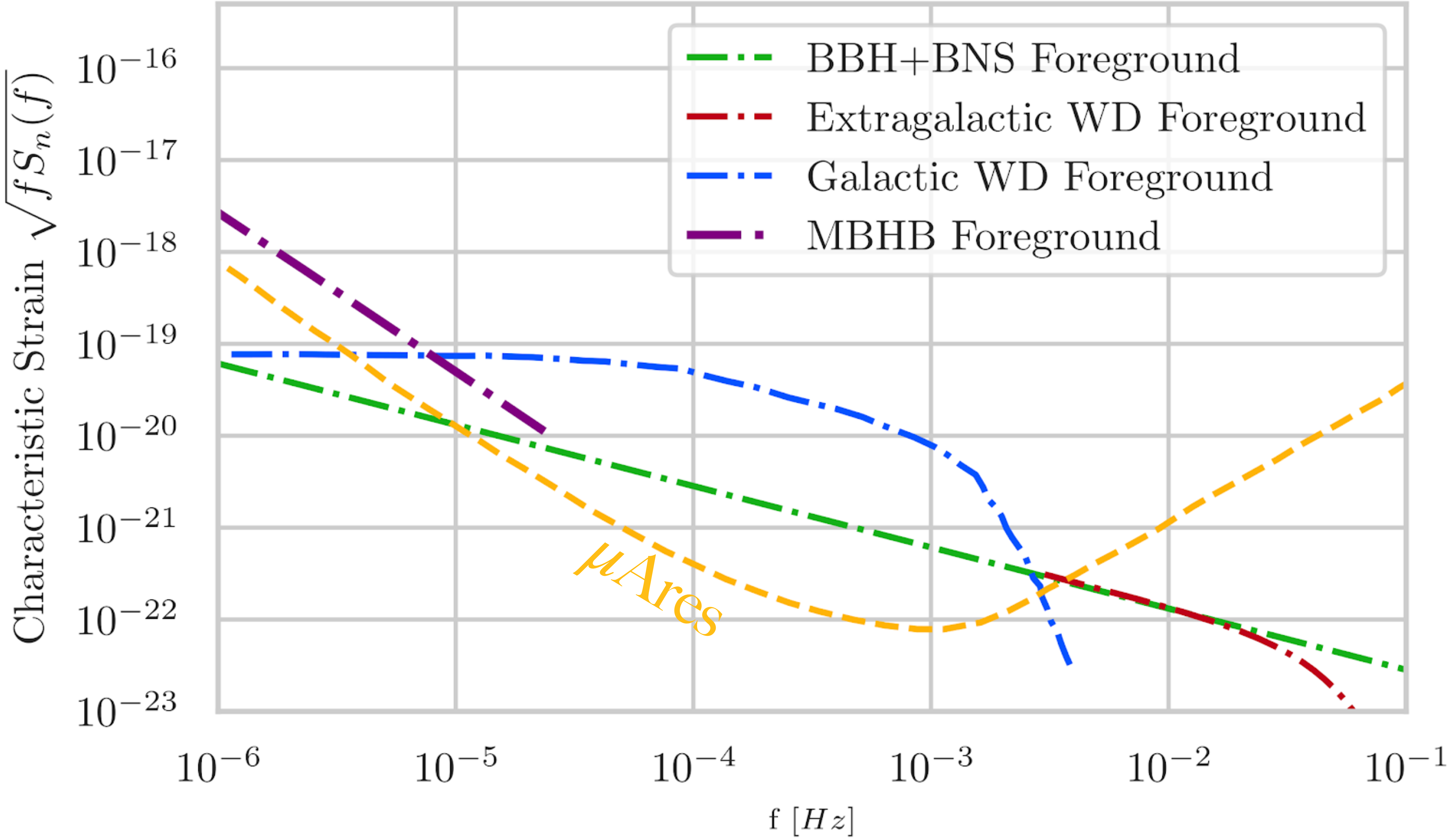
Pulsar Timing Array (PTA)

- Passage of GW induces correlated modulation in the arrival times of radio pulses from array of Galactic millisecond pulsars
- Freq range $10^{-9} - 10^{-7}$ Hz
- SKA (~ 2040s) 200 pulsars observed for 10 yr



Astrophysical foregrounds for direct experiments

- GW superposition from many astrophysical sources integrated over time produces an Astrophysical SGWB
- LIGO/Virgo measured rate of BBH and BNS mergers
- Main sources:
  - BBH + BNS (all interferometers)
  - Massive Black Hole Binaries (MBHB) in nano-micro Hertz range
  - Galactic WD binaries
  - Extra-Galactic WD binaries
  - ...



An exciting era for cosmological SGWB

LIGO/Virgo
BBH and BNS detections

NANOGrav
SGWB detection (2020):
next 5-7 yrs? *Pol+2021*
15 yrs dataset?

CMB probes
LiteBIRD, CMB-S4
first to take data
~ 2028/2029

LISA ESA Phase A mission
(early/mid 2030s)

Many Post-LISA mission proposals
ESA Voyage 2050
2035 - 2050

- Need for realistic and accurate forecasts (often too simplified in existing literature)
- Comprehensive picture of status and future of SGWB observations
- Consider a variety of possible theoretical scenarios

Forecast for CMB, PTA and laser interferometers

Tensor spectra: vacuum & sourced

Single-field Slow-roll

- SGWB produced by quantum vacuum fluctuations

$$P_T^{vac}(k) = A_T \left(\frac{k}{k_0}\right)^{n_T + \frac{1}{2}\alpha_T \ln(k/k_0)}$$

- Consistency relations:

$$n_T = -r/8$$

$$\alpha_T = (r/8)\left[(n_S - 1) + r/8\right]$$

- Gaussian
- Parity even ($C_\ell^{TB,EB}$ CMB spectra vanishing)
- No circular polarisation

Spectator axion-SU(2) inflation

- Chiral SGWB production from SU(2) gauge field (*Dimastrogiovanni, Fasiello & Fujita 2017*)

$$\mathscr{L} = \mathscr{L}_{inflaton} + \frac{1}{2}\left(\partial_\mu \chi\right)^2 - \mu^4 \left[1 + \cos\left(\frac{\chi}{f}\right)\right] - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{\lambda}{4f}\chi F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$$

- Left or right circular polarisation with strongly scale-dependent spectrum:

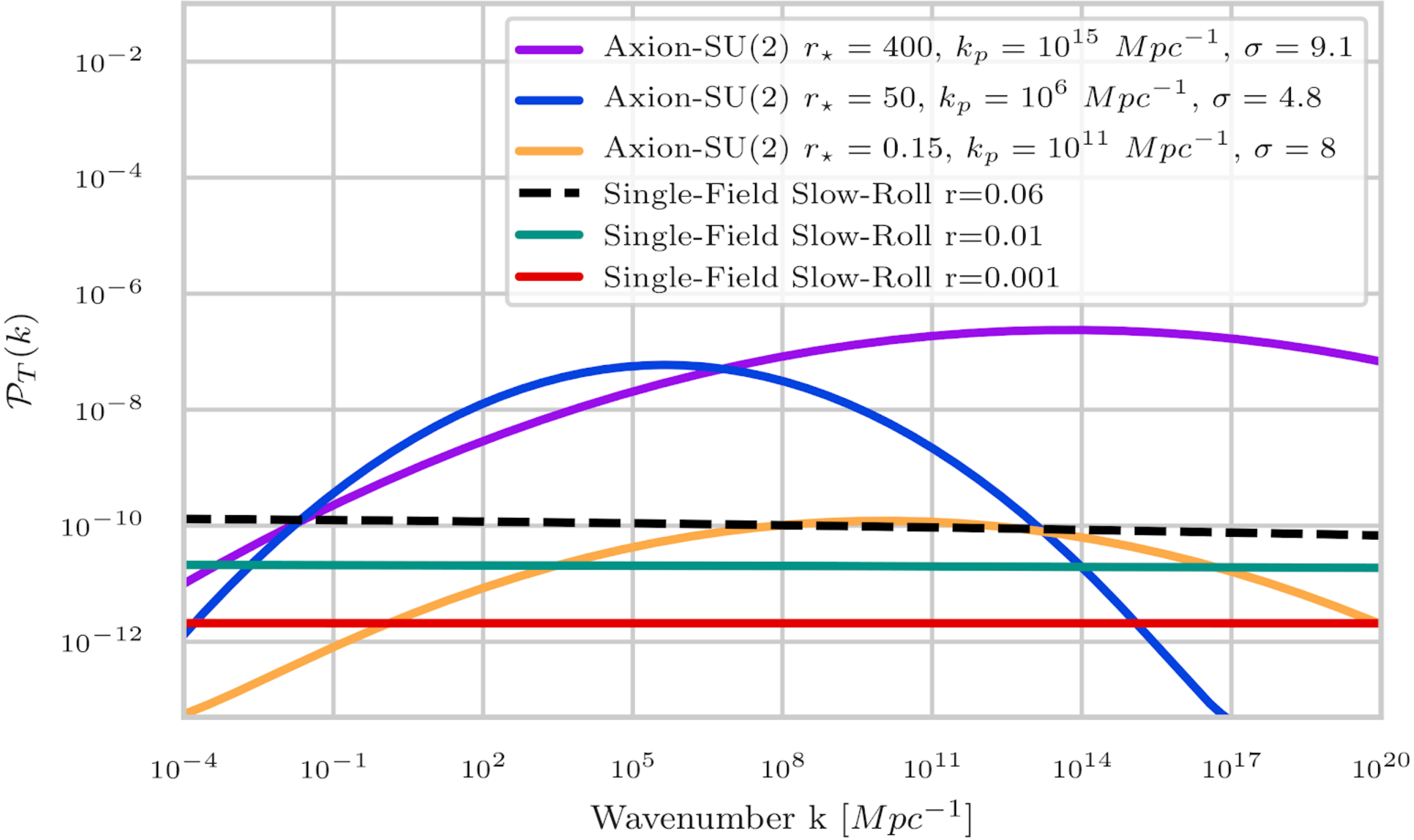
$$P_T^{L,Sourced}(k) = r_* P_R(k) \exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{k}{k_p}\right)\right]$$

$$P_T^{R,Sourced}(k) \simeq 0$$

- Strongly non-Gaussian
- $C_\ell^{TB,EB}$ CMB spectra non-vanishing

Benchmark models

satisfying BICEP2/Planck upper bound on r



Benchmark models

satisfying BICEP2/Planck upper bound on r

AX3 model

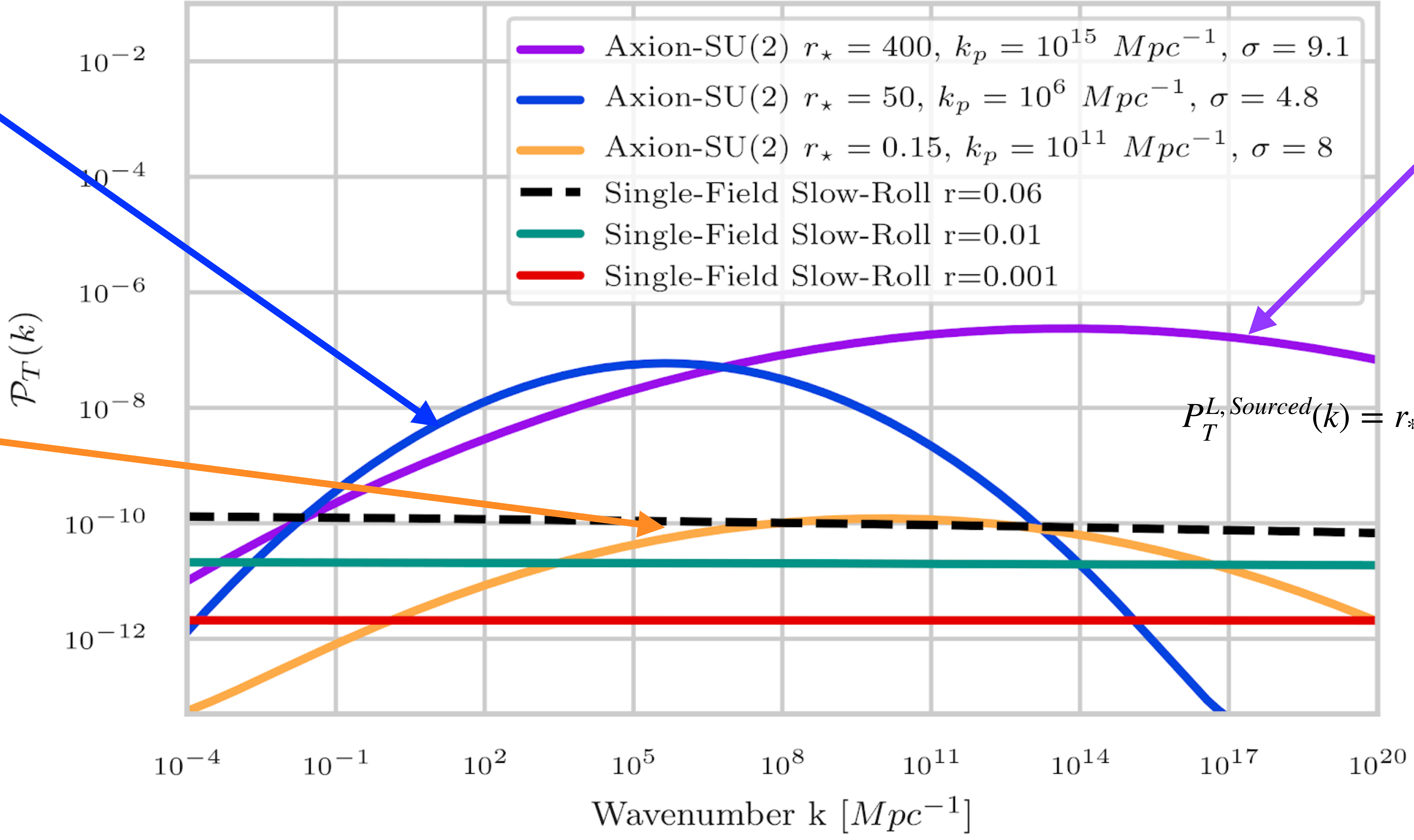
peaks in PTA range

AX2 model

peaks in space interferometers range but is not detectable at CMB scales

AX1 model

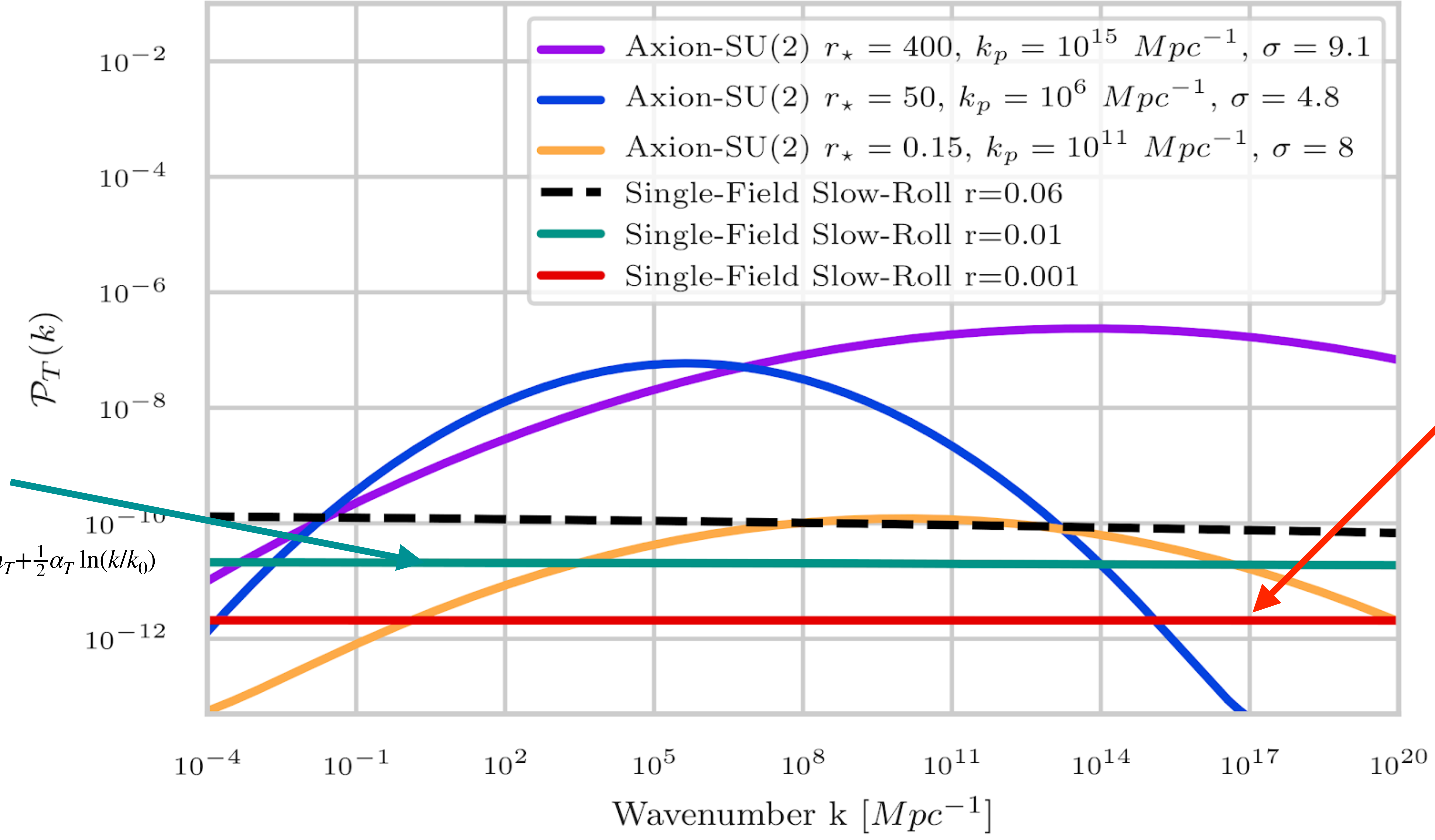
peaks in space interferometers range



$$P_T^{L,Sourced}(k) = r_* P_R(k) \exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{k}{k_p}\right)\right]$$

Benchmark models

satisfying BICEP2/Planck upper bound on r



Standard SFSR r=0.001

Standard SFSR r=0.01

$$P_T^{vac}(k) = A_T\left(\frac{k}{k_0}\right)^{n_T+\frac{1}{2}\alpha_T\ln(k/k_0)}$$

SGWB search: cross-correlation of 2 detectors

- Output of detector = signal + noise

$$d_I(t) = s_I(t) + n_I(t)$$

- Cross-correlation of output of 2 detectors I and J:

$$\hat{X} = \int_{-\infty}^{+\infty} df \int_{-\infty}^{+\infty} df' \delta_T(f - f')\, d_I^*(f)\, d_J(f')\, Q(f)$$

- Filter function $Q(f)$ can be chosen to maximise the SNR of the cross-correlation

- Standard expression for $Q(f)$ available in the literature does not account for foregrounds: overestimates SNR!

New filter for cross-correlation and foreground marginalisation

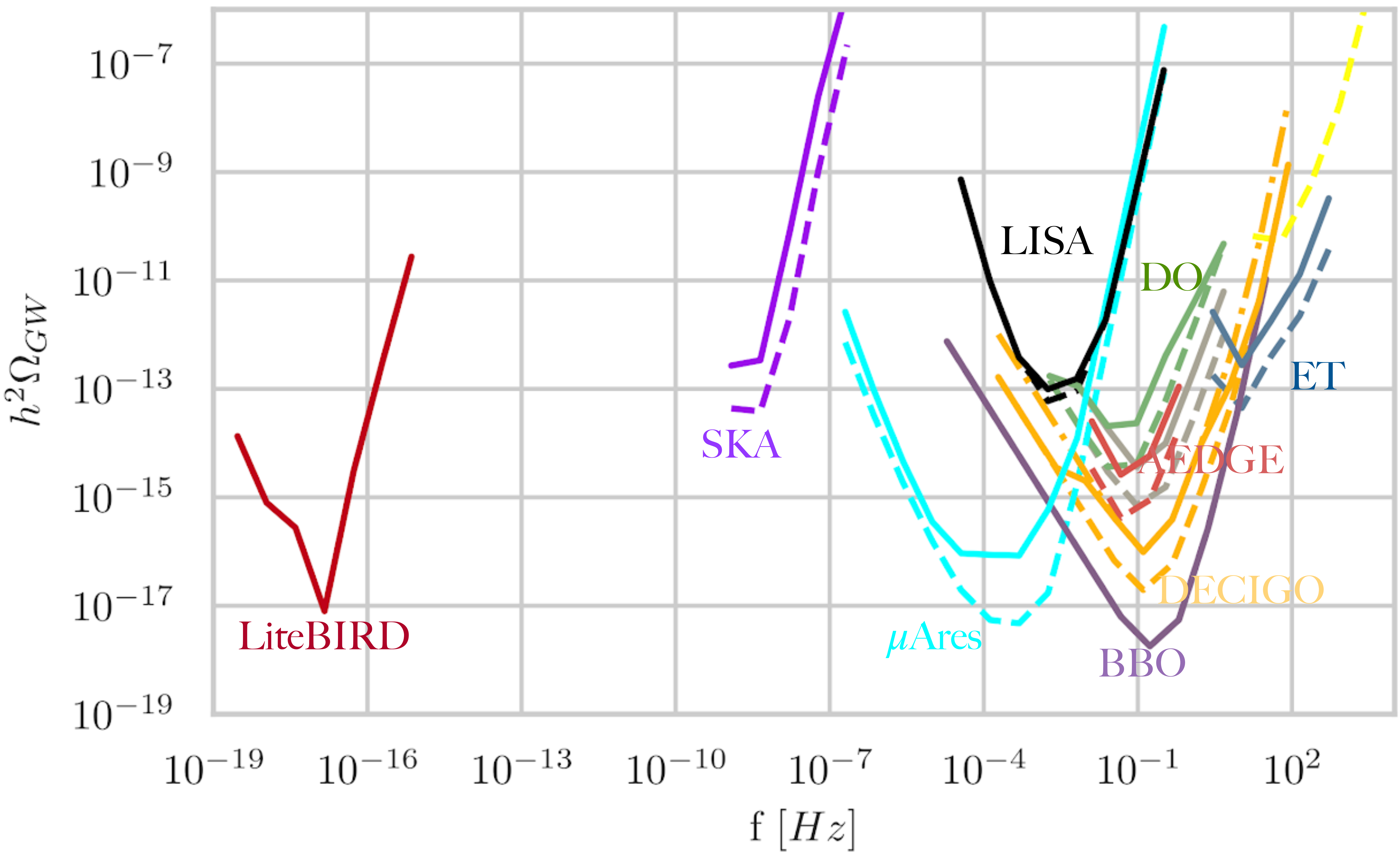
- Known foreground spectral shape S_{fg} up to uncertainty σ_{fg} on its amplitude (e.g. information from external experiments, theoretical priors...)
- Find filter $Q(f)$ maximising SNR in presence of foregrounds (*D. Poletti 2021 arXiv 2101.02713*)

$$Q(f) = \frac{S_s R_{IJ}^*}{S_n^I S_n^J} - 2T \frac{I_{s\times fg}}{\sigma_{fg}^{-2} + 2T\, I_{fg\times fg}} \frac{S_{fg} R_{IJ}^*}{S_n^I S_n^J}$$

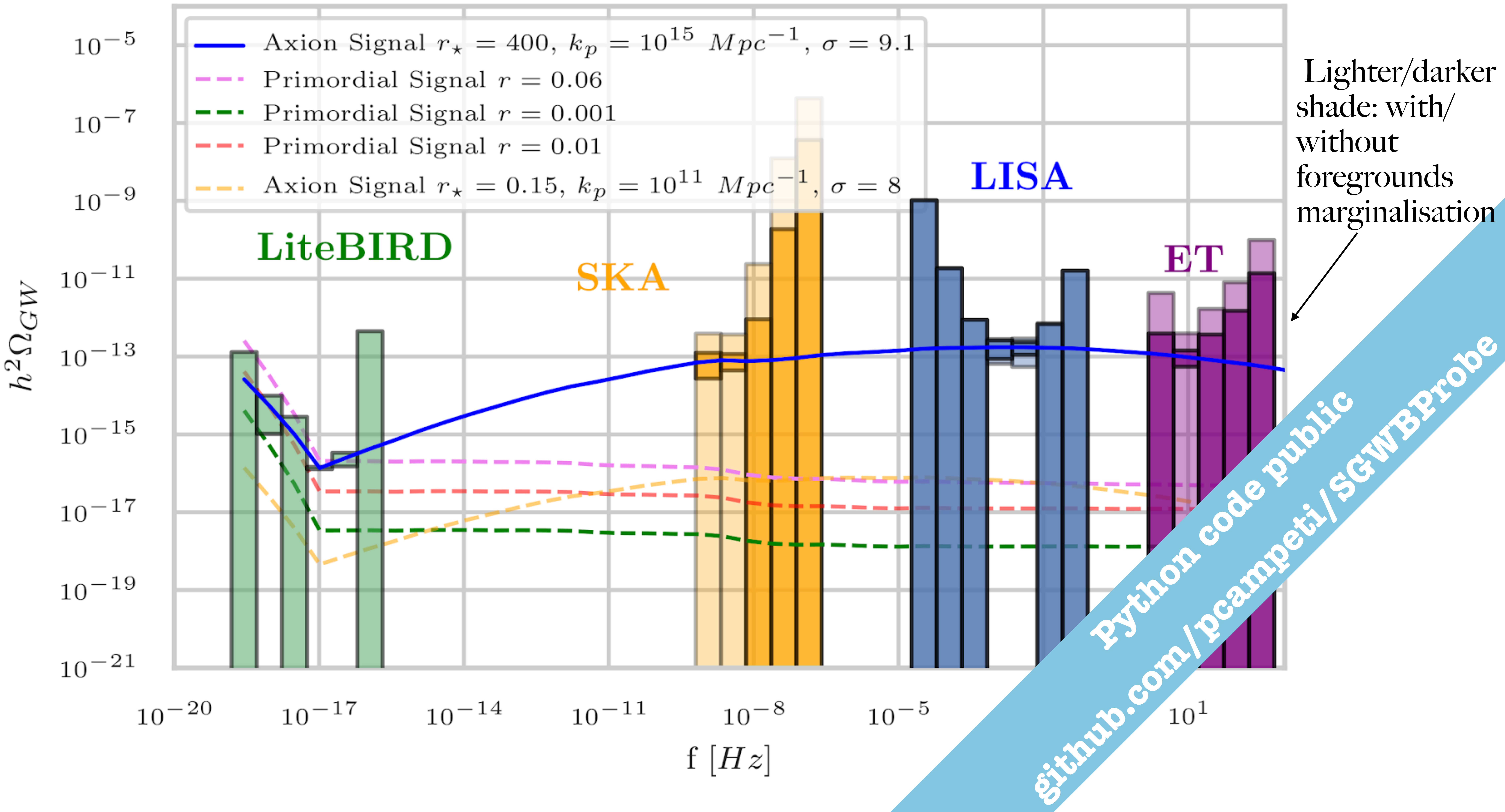
$$I_{s\times fg} = \int \frac{S_s S_{fg}}{S_n^I S_n^J} |R_{IJ}|^2 df \qquad I_{fg\times fg} = \int \frac{S_{fg}^2}{S_n^I S_n^J} |R_{IJ}|^2 df$$

Binned Ω_{GW} sensitivity curves

- Most comprehensive picture of all main SGWB experiments of next decade and beyond
- Coherent assumptions and realism (dashed: no foregrounds marginalization)



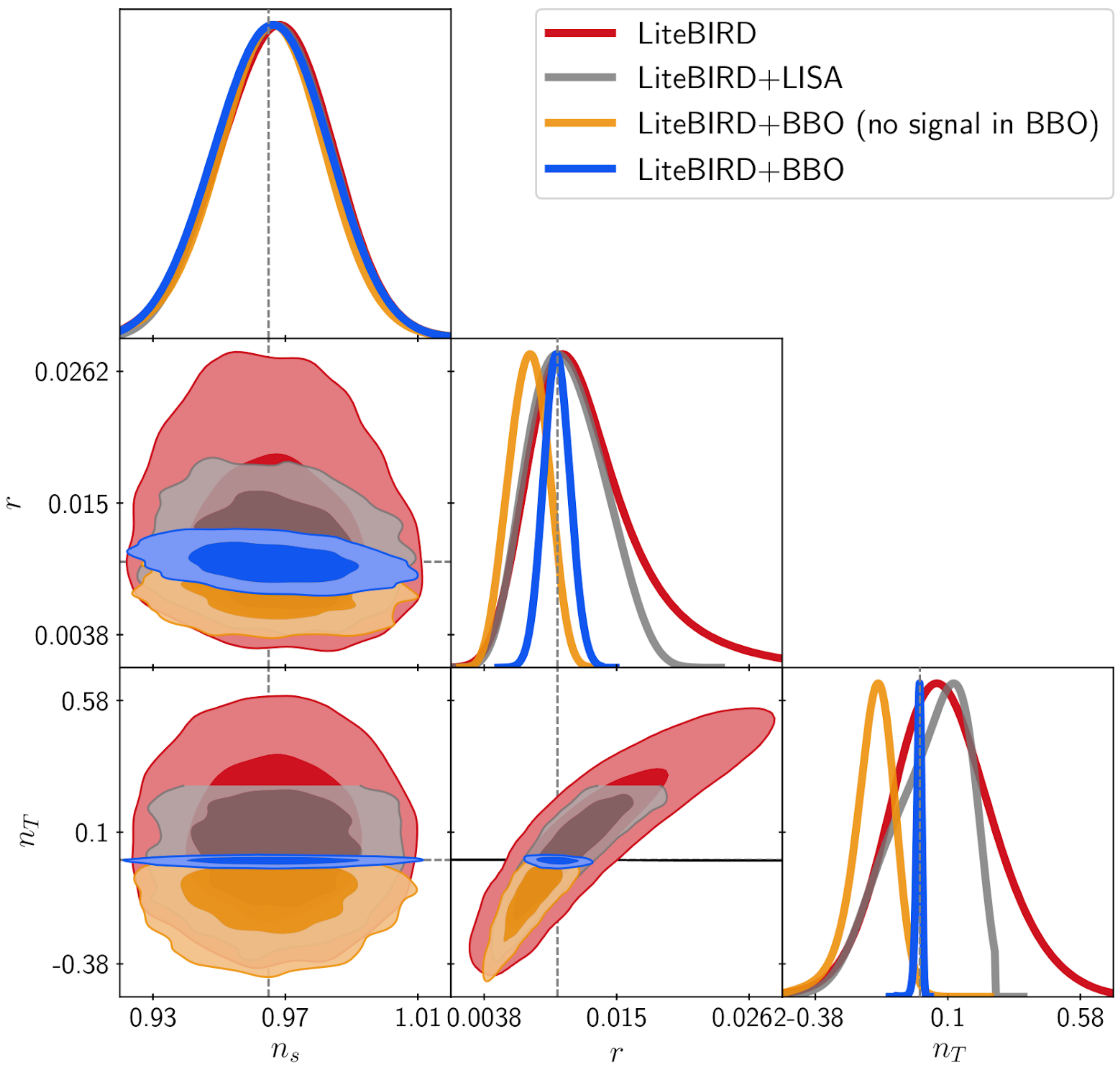
Error-bars for axion-SU(2) model



Lighter/darker shade: with/ without foregrounds marginalisation

Inflationary consistency relation $n_T = -r/8$

- Large lever-arm CMB/interferometers
- Case r=0.01
- LiteBIRD alone
- LiteBIRD + LISA
- LiteBIRD + BBO
- Not even LiteBIRD + BBO can distinguish scale-invariance from consistency relation
- 5σ detection in LiteBIRD but no detection in BBO: bias on r, we can detect departure from scale-invariance at CMB scales due to large red-tilt



Conclusions and path ahead

- New filter: control of foregrounds is fundamental
- B-modes experiments most sensitive and closest in time: only ones to reach $r \sim 10^{-3}$
- CMB in detail: model-independent spectrum reconstruction in *Campeti, Poletti & Baccigalupi (2019)*
- Results suggest a future roadmap (see right panel)
- Future work: increase realism of foreground treatment for direct experiments