On the origin of primordial gravitational waves

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(Spectator) axion-U(1) inflation

Barnaby + '12, Namba + '15, Mukohyama + '14

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{pl}^2 R}{2} - \underbrace{\frac{1}{2}(\partial\phi)^2 - V(\phi)}_{\text{Standard inflaton sector}} - \underbrace{\frac{1}{2}(\partial\chi)^2 - U(\chi)}_{\text{Axion}} - \underbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Gauge field}} - \underbrace{\lambda\frac{\chi}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\text{Chern-Simons coupling}}\right]$$

- Axion and gauge field are spectators
- Inflation realised by standard inflaton
- Time-dependent axion + Chern-Simons coupling → breaks conformal invariance of gauge field → amplification of only one helicity → **parity-violating GWs!**
- Amplitude of gauge field fluctuations controlled by axion's velocity:
  $A_- \propto e^{\pi\xi} = e^{\frac{\pi\lambda|\dot{\chi}|}{2Hf}}$

Vacuum vs sourced fluctuations

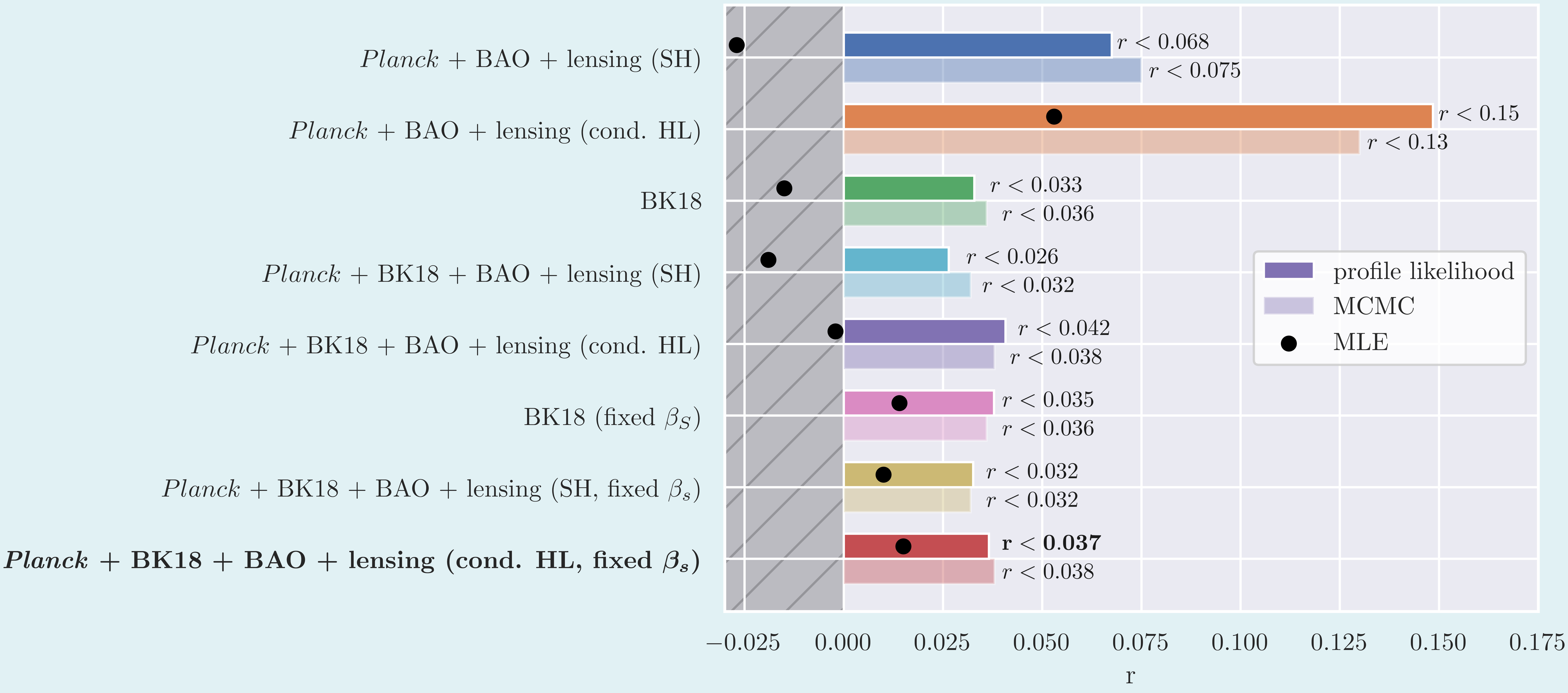
MODES	VACUUM	SOURCED	OBSERVATIONS
SCALARS	Slightly red-tilted, ∼Gaussian	Large and non-Gaussian or negligible depending on model	Remarkably consistent with vacuum
TENSORS	∼Scale-invariant, ∼Gaussian, non-chiral	Scale-dependent, non-Gaussian, chiral	? (To be checked)

Constraint on vacuum fluctuations

PC & E. Komatsu 2022 arXiv:2205.05617

Current CMB constraints on vacuum fluctuations

The CMB is the most promising way to detect vacuum fluctuations

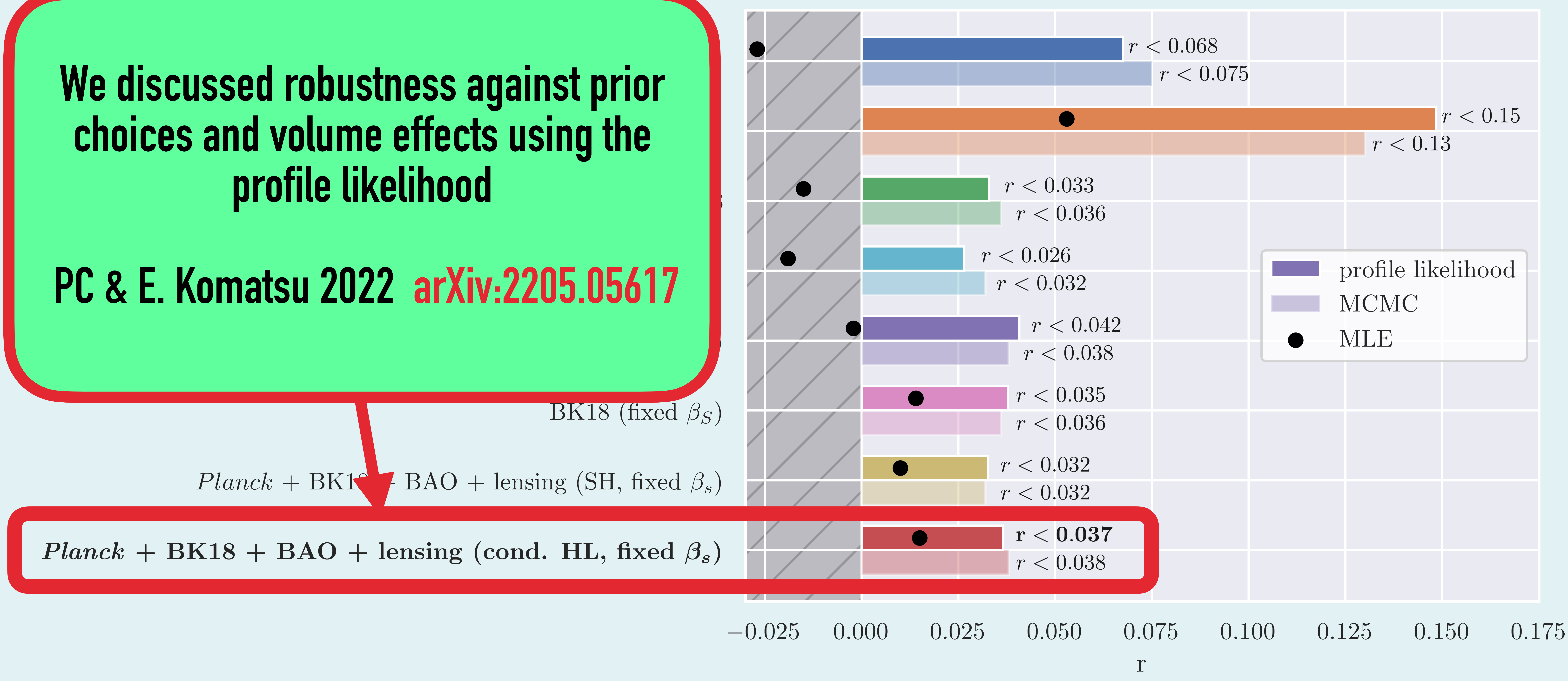


Current CMB constraints on vacuum fluctuations

The CMB is the most promising way to detect vacuum fluctuations

We discussed robustness against prior choices and volume effects using the profile likelihood

PC & E. Komatsu 2022 arXiv:2205.05617



Constraint on gravitational waves sourced by matter fields

PC & O. Özsoy, I. Obata, M. Shiraishi 2022 arXiv:2203.03401, accepted in JCAP

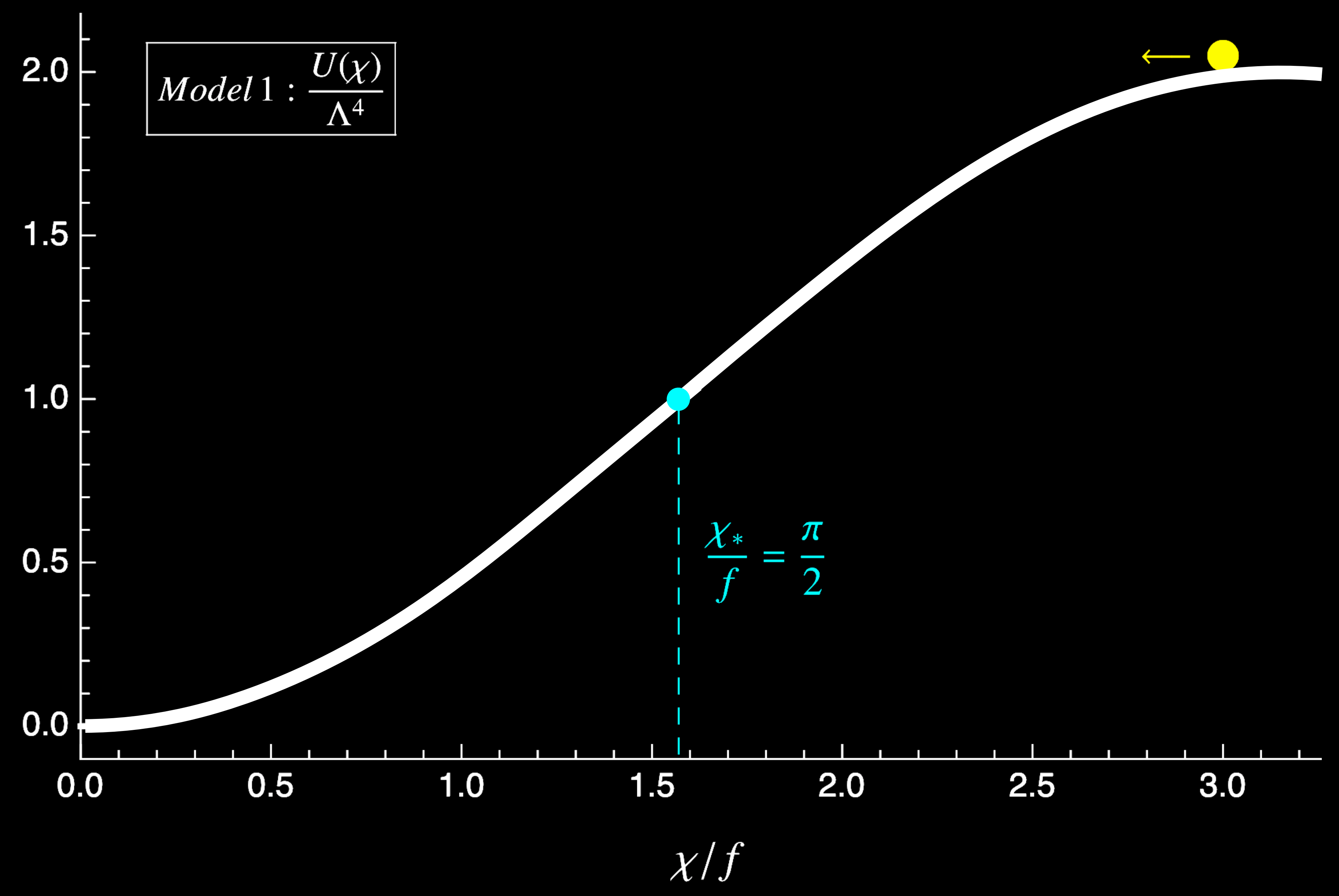
Axion potential and sourced scalar modes

- Sourced **non-Gaussian scalar modes** from inverse decay of gauge fields $A_i + A_i \to \delta\chi \to \delta\phi \propto \mathcal{R}$
- **Localized profile for axion velocity** → amplify only large scales modes where CMB constraints are weaker ($\ell \lesssim 100$)
- 2 choices of axion potential (**M1, M2**):

$$\begin{cases} U_{M1}(\chi) = \Lambda^4 \left[1 - \cos\left(\frac{\chi}{f}\right)\right] \\ U_{M2}(\chi) = \mu^3 \chi + \Lambda^4 \left[1 - \cos\left(\frac{\chi}{f}\right)\right] \quad \& \ \Lambda^4 \lesssim \mu^3 f \end{cases}$$

Freese + '90, Namba + '15

Özsoy + '20



- Axion's velocity peaks at time τ_*
- Effective coupling strength $\xi = -\frac{\lambda\dot{\chi}}{2Hf}$ peaks at $\xi_* = \xi(\tau_*)$

Sourced modes

- Strongly **scale-dependent** sourced tensor spectrum

- Gaussian bump feature:

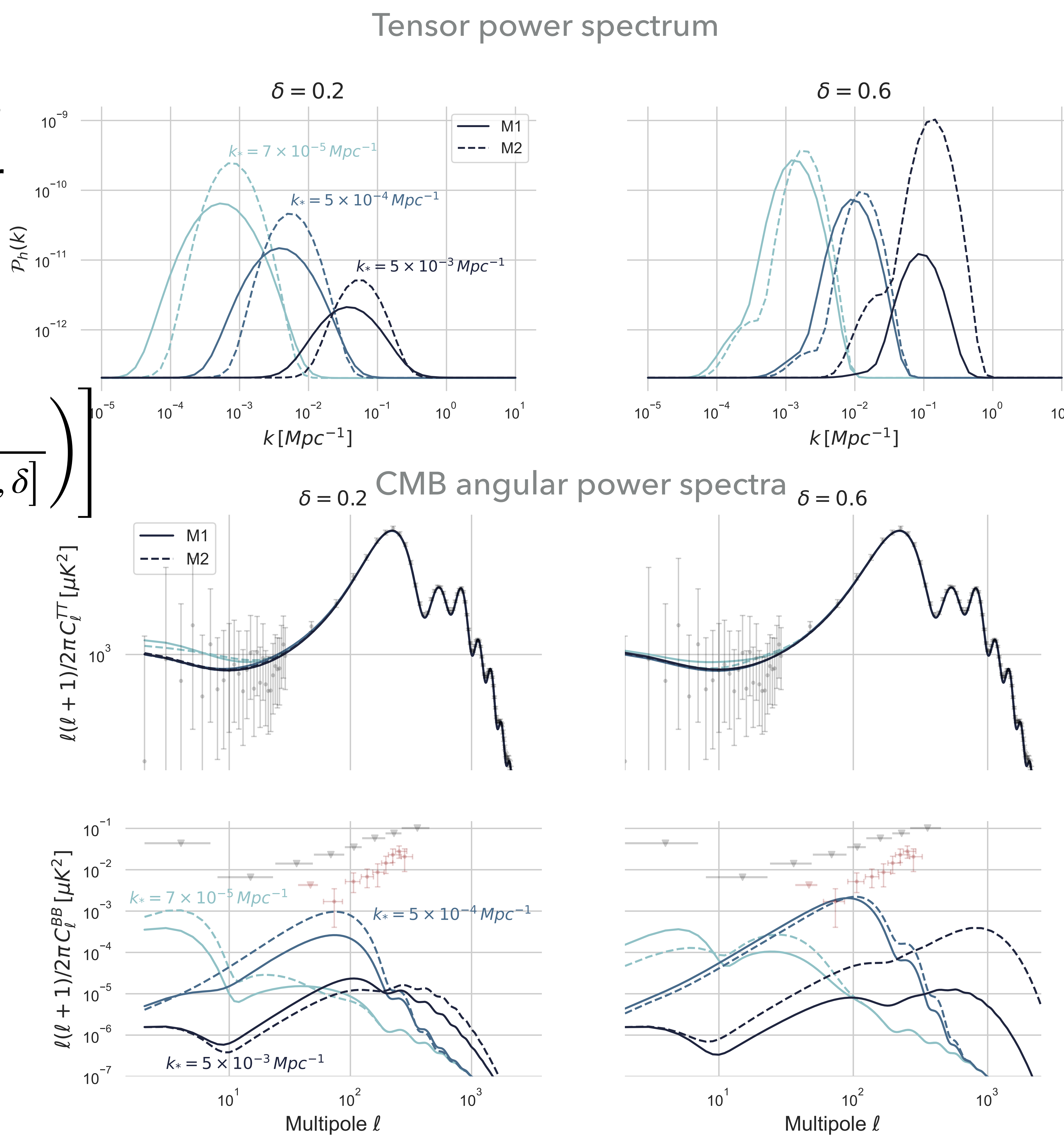
$$\mathscr{P}_j^{(\mathrm{s})}(k) = \left[\epsilon_\phi \mathscr{P}_{\mathscr{R}}^{(\mathrm{v})}(k)\right]^2 f_{2,j}^c\left[\xi_*, \delta\right] \exp\left[-\frac{1}{2\sigma_{2,j}^2\left[\xi_*, \delta\right]} \ln^2\left(\frac{k}{k_* \, x_{2,j}^c\left[\xi_*, \delta\right]}\right)\right]$$

$j = \{\mathscr{R}, \pm\}$

$\xi_* \rightarrow$ amplitude of the peak

$\delta \rightarrow$ ($\propto$ axion's acceleration) width of the peak

$k_* \rightarrow$ position of the peak (scale exiting the horizon when axion's velocity is max)



Method: data and likelihood

GOAL:
Determine the extent to which axion-U(1) can amplify tensor modes while staying consistent with CMB constraints

- We use ***Planck* + BICEP/Keck** latest data → state-of-the-art for constraining large cosmological scales
- Parity-violating correlations TB, EB give only very weak constraints *(Gerbino + '16)*
- Tensor bispectrum is complementary but expected to have lower SNR w.r.t. power spectrum *(Shiraishi + '19)*
- We exploit the scale-dependence of the **2-point function** (most constraining at the current state)

Method: profile likelihood

- Frequentist
- Profile likelihood for a parameter of interest θ:

1. fix θ to multiple values
2. Minimize $\chi^2(\theta) = -2\log\mathscr{L}(\theta)$
3. By construction minimum χ^2_{min} coincides with global MLE ("best-fit")

METHOD	MCMC	PROFILE LIKELIHOOD
PRIORS	Yes	No
INVARIANT UNDER REPARAMETRIZATION	Yes with Jeffreys prior	Yes
VOLUME EFFECTS	Maybe	No

Method: profile likelihood

- Frequentist
- Profile likelihood for a
parameter of interest

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2. Minimize $\chi^2(\theta) = -$
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("best-fit")

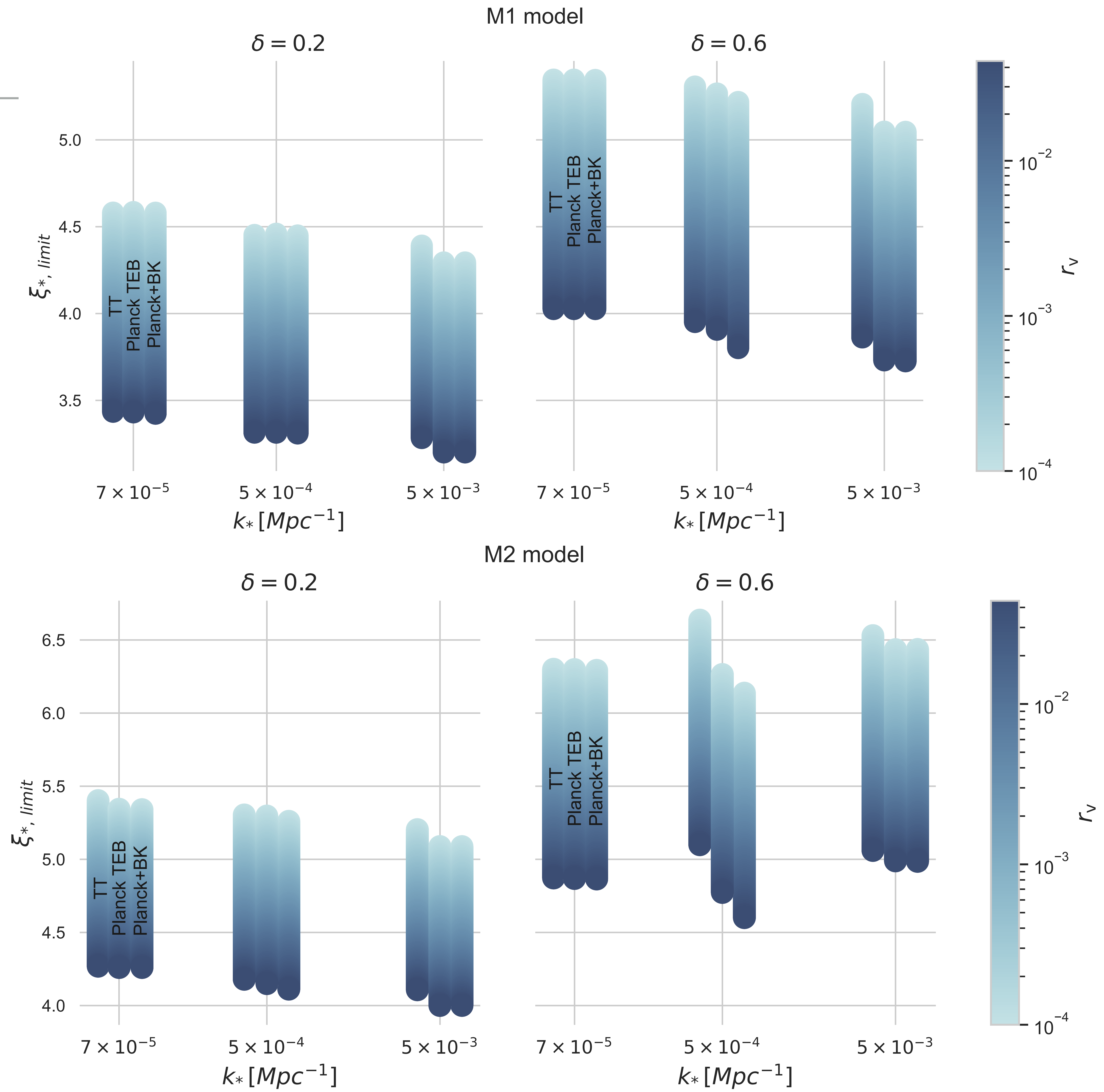
PROFILE LIKELIHOOD
No
Yes
No

We applied the profile likelihood to vacuum Planck +BICEP constraints and compared to MCMC

PC & E.Komatsu 2022
arXiv:2205.05617

Temperature vs polarization

- Observational constraints driven by *Planck* temperature (i.e. by sourced scalars!)
- *B*-modes data weakly constrained → minor effect on the bounds
- Large scale temperature data are already **cosmic-variance limited** in *Planck* data → improve polarization!

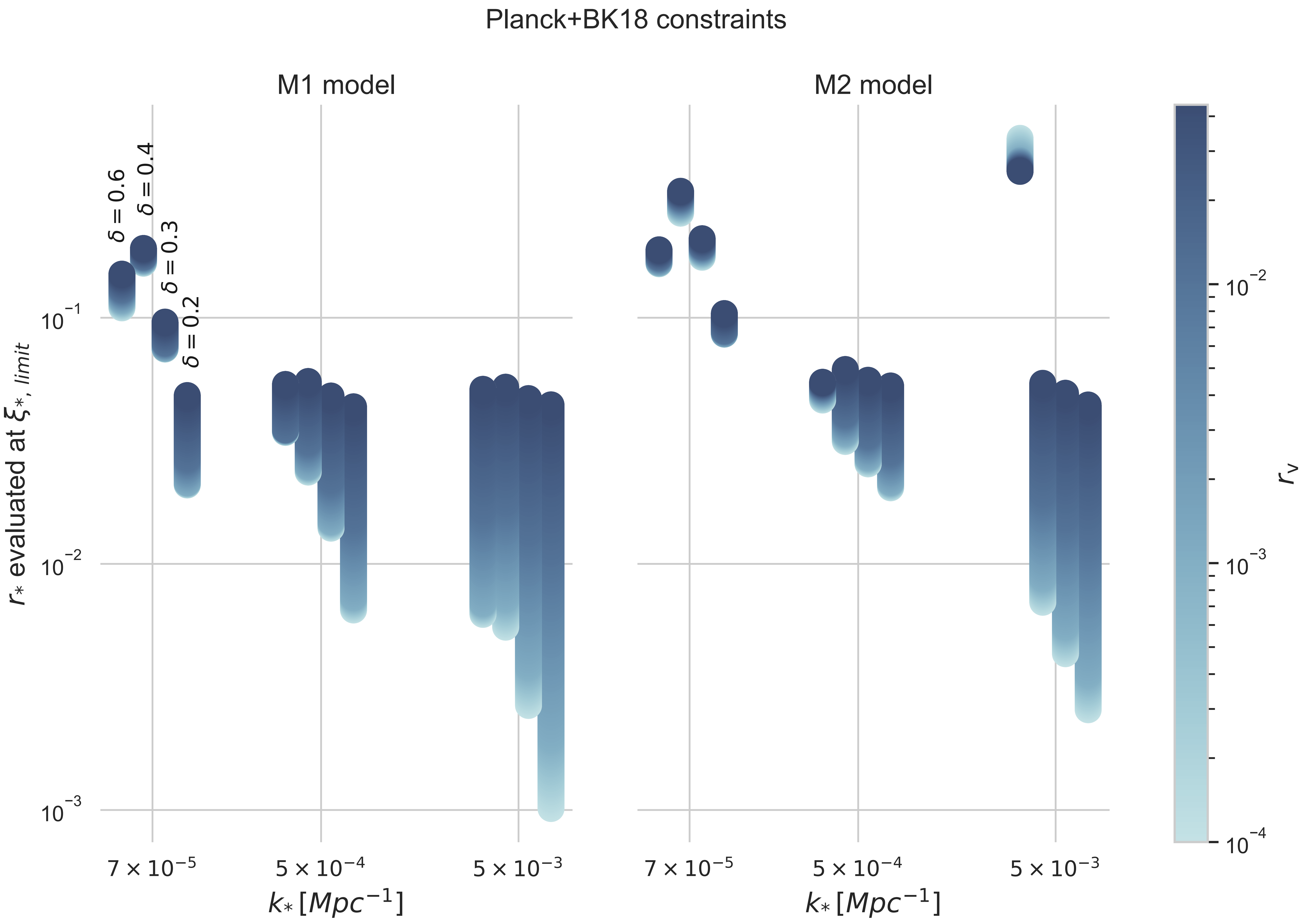


Total tensor-to-scalar ratio

- Total (vacuum + sourced) tensor-to-scalar ratio:

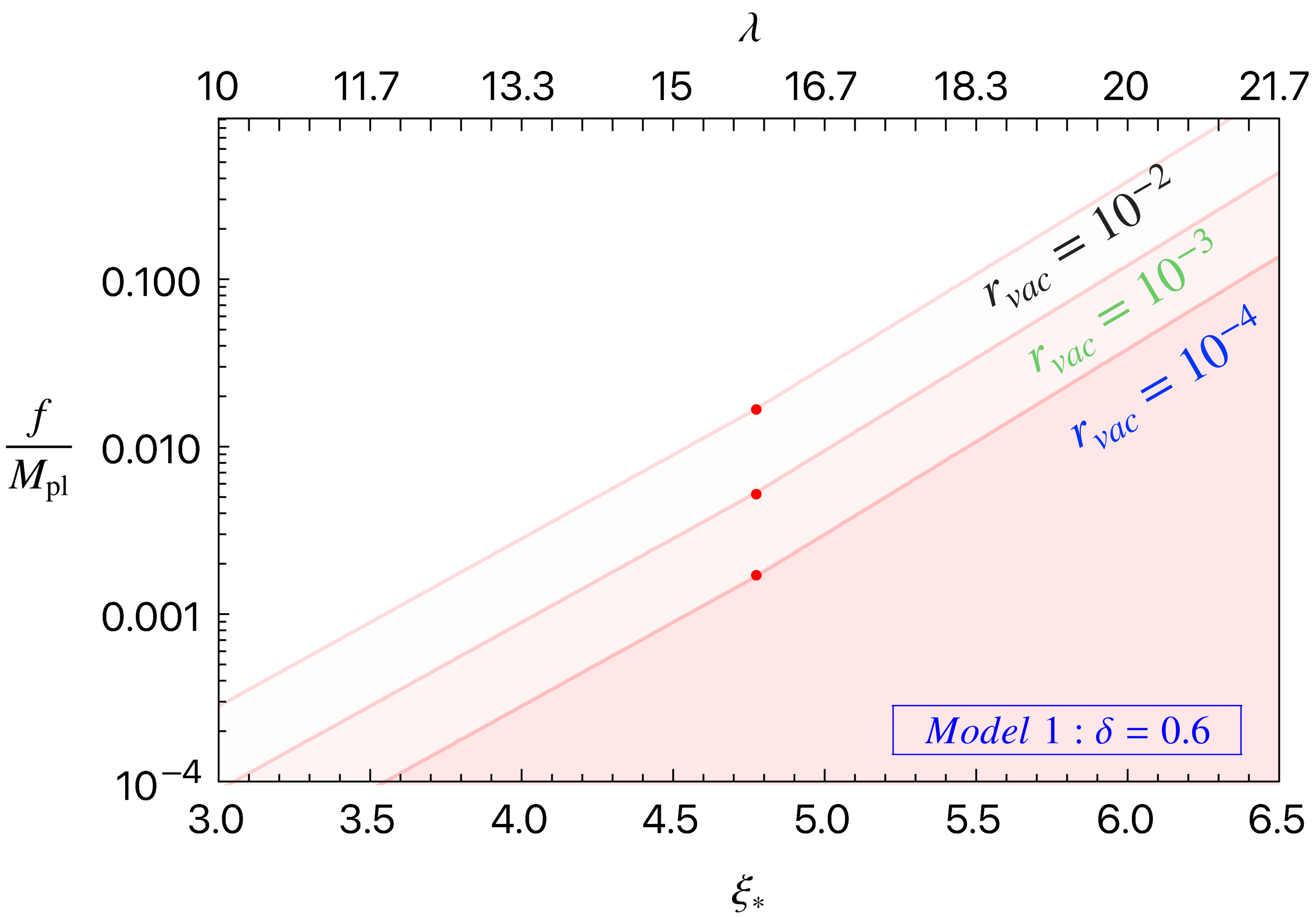
$$r_*(k) = \frac{\sum_{\lambda=\pm}\left[\mathscr{P}_\lambda^{(\mathrm{vac})}(k) + \mathscr{P}_\lambda^{(\mathrm{sourced})}(k)\right]}{\mathscr{P}_\mathscr{R}^{(\mathrm{vac})}(k) + \mathscr{P}_\mathscr{R}^{(\mathrm{sourced})}(k)}$$

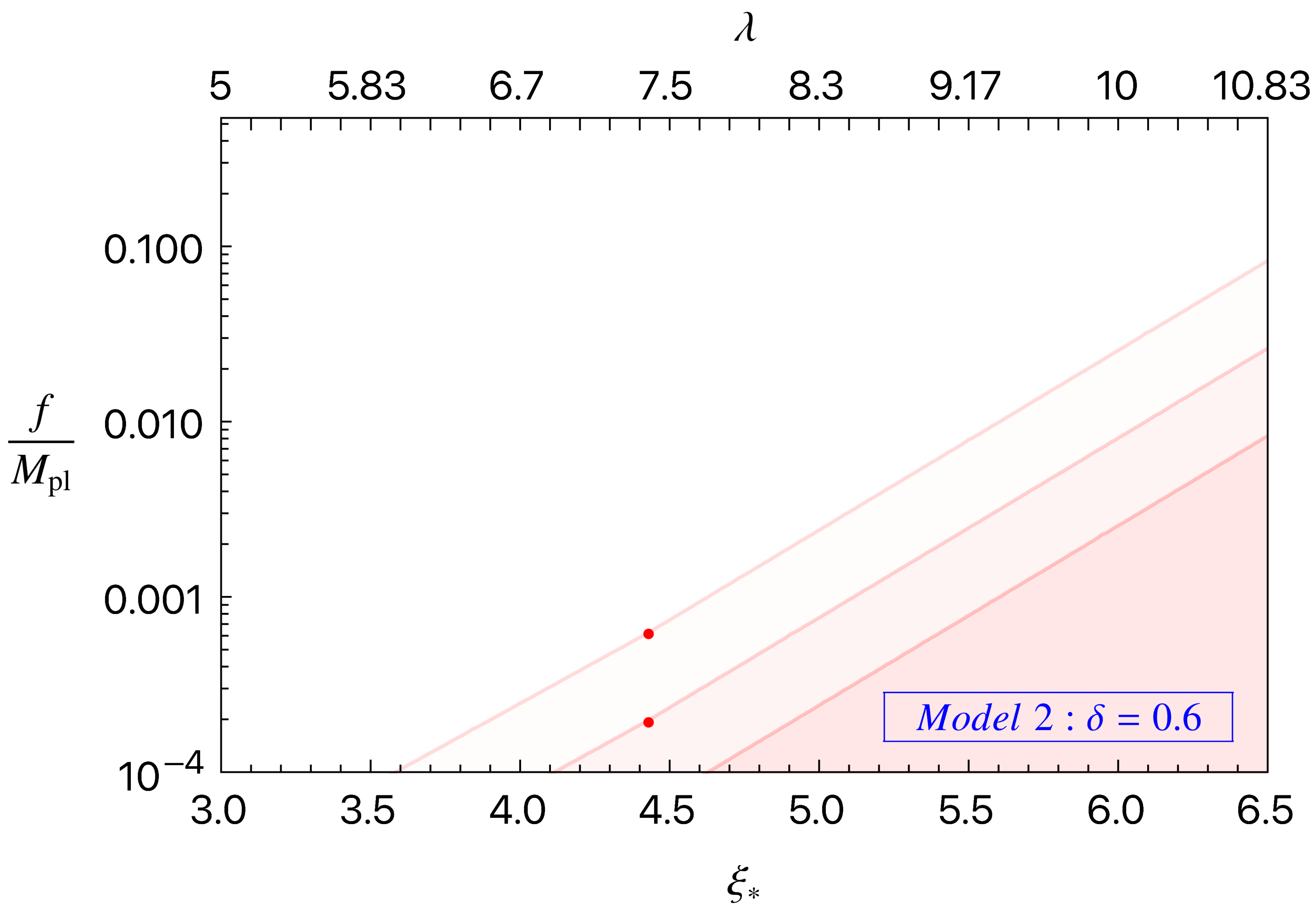
- Larger sourced signal allowed at larger scales
- Still possible to get significant sourced contribution to r_* even with small r_{vac}



Theoretical self-consistency bounds

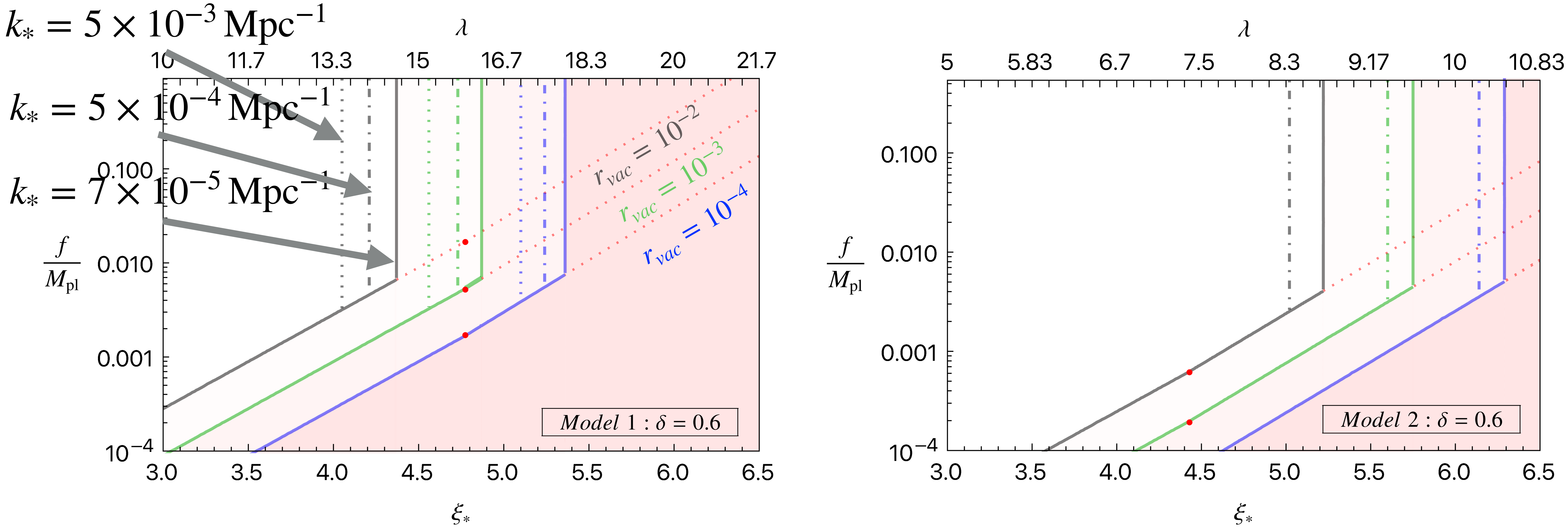
- **Backreaction** upper/lower bounds on f/M_{pl} (axion must be a spectator / gauge filed production should not influence background evolution of axion)
- **Perturbativity** (exponentially large gauge field amplitudes can driven the system out of perturbative regime) → lower bound on f/M_{pl}





Theoretical self-consistency + observations bounds

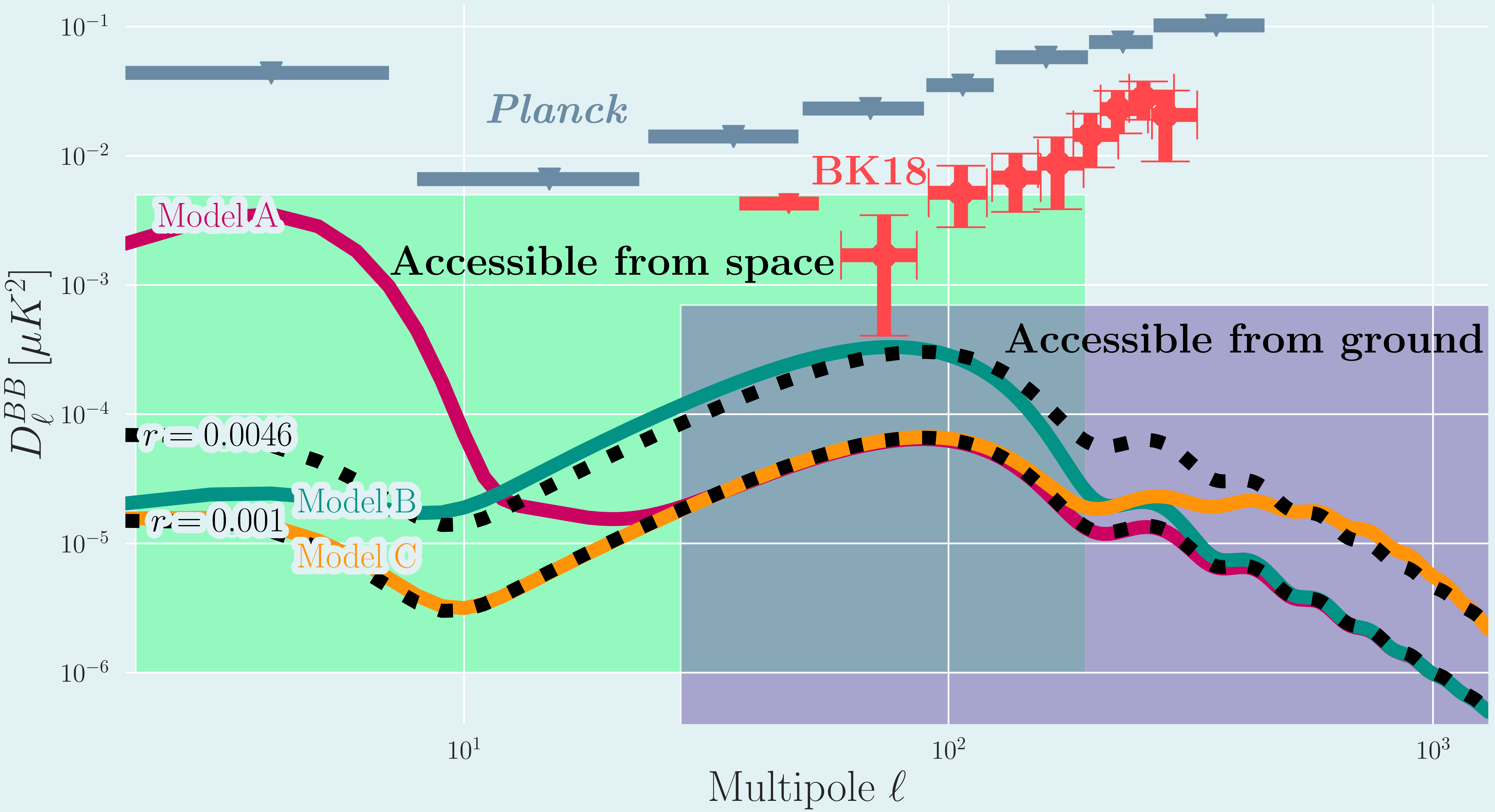
- Observational constraints are competitive with theoretical bounds
- Parameter space shrinks but still remains large and interesting for future B-mode experiments



Conclusions: axion-U(1) is still interesting for future experiments

- Future space and ground-based B-mode experiments will be necessary to **distinguish vacuum from sourced** (Models A, B, C) primordial gravitational waves

- Full-sky space mission will improve also EB, TB measurements and detect $\mathcal{O}(1)$ tensor non-Gaussianity



(Spectator) axion-SU(2) inflation

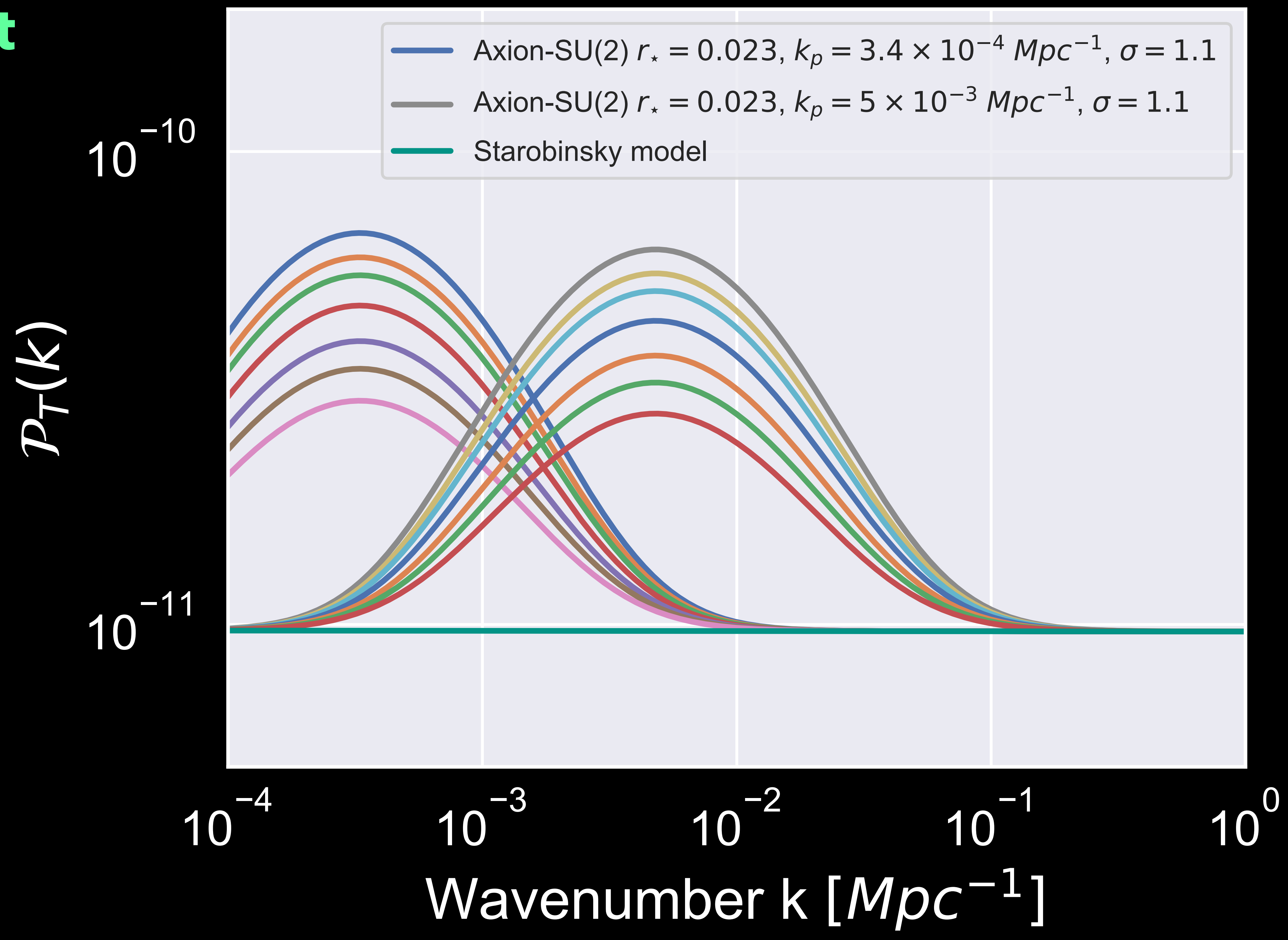
Dimastrogiovanni + '17

$$\mathscr{L} = \underbrace{\mathscr{L}_{inflaton}}_{\text{Standard inflaton sector}} + \underbrace{\frac{1}{2}\left(\partial_\mu \chi\right)^2 - \mu^4\left[1 + \cos\left(\frac{\chi}{f}\right)\right]}_{\text{Axion with cosine-type potential}} - \underbrace{\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}}_{\text{Gauge field}} + \underbrace{\frac{\lambda}{4f}\chi F^a_{\mu\nu}\tilde{F}^{a\mu\nu}}_{\text{Chern-Simons coupling}}$$

- **Chiral**, **non-Gaussian** sourced tensors with **scale-dependent** spectrum

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

Thorne + '17



- **U(1)** source tensors at 2^{nd} order → source scalars and scalar non-Gaussianity
- **SU(2)** source tensors at linear order! → negligible sourced scalars and scalar non-Gaussianity!

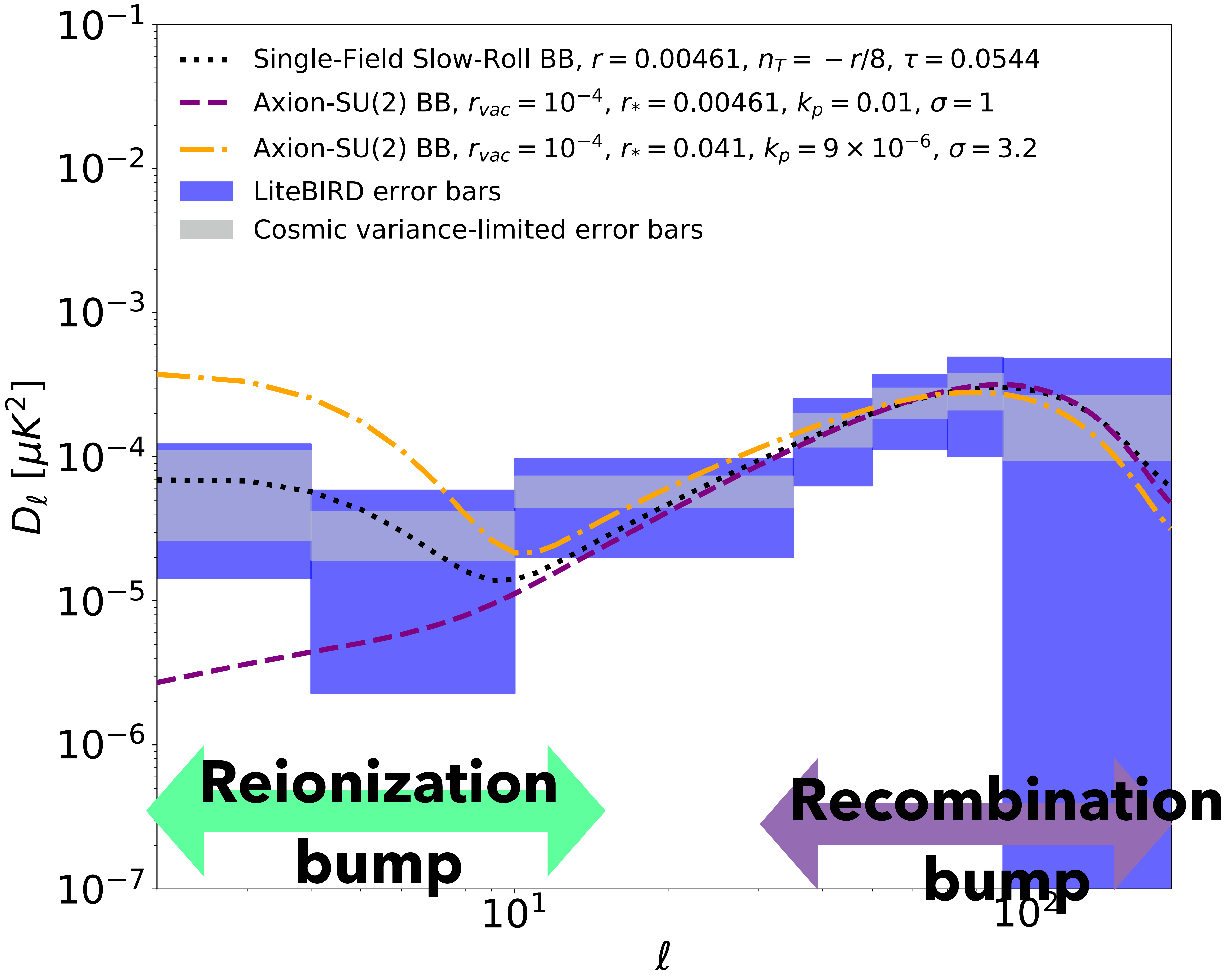
LiteBIRD constraints on axion-SU(2) inflation

PC & E. Komatsu and the LiteBIRD Collaboration in preparation

Constraining axion-SU(2) with LiteBIRD

PC, E. Komatsu + LiteBIRD collaboration (in preparation)

- SU(2) can source GWs the exceed vacuum contribution at reionization bump scales by factor ~ 5 (Ishiwata + '21)
- **Goal:** show that full-sky survey with access to **reionization bump** is necessary to understand origin of primordial GWs
- **Method:** Realistic simulations, profile likelihood

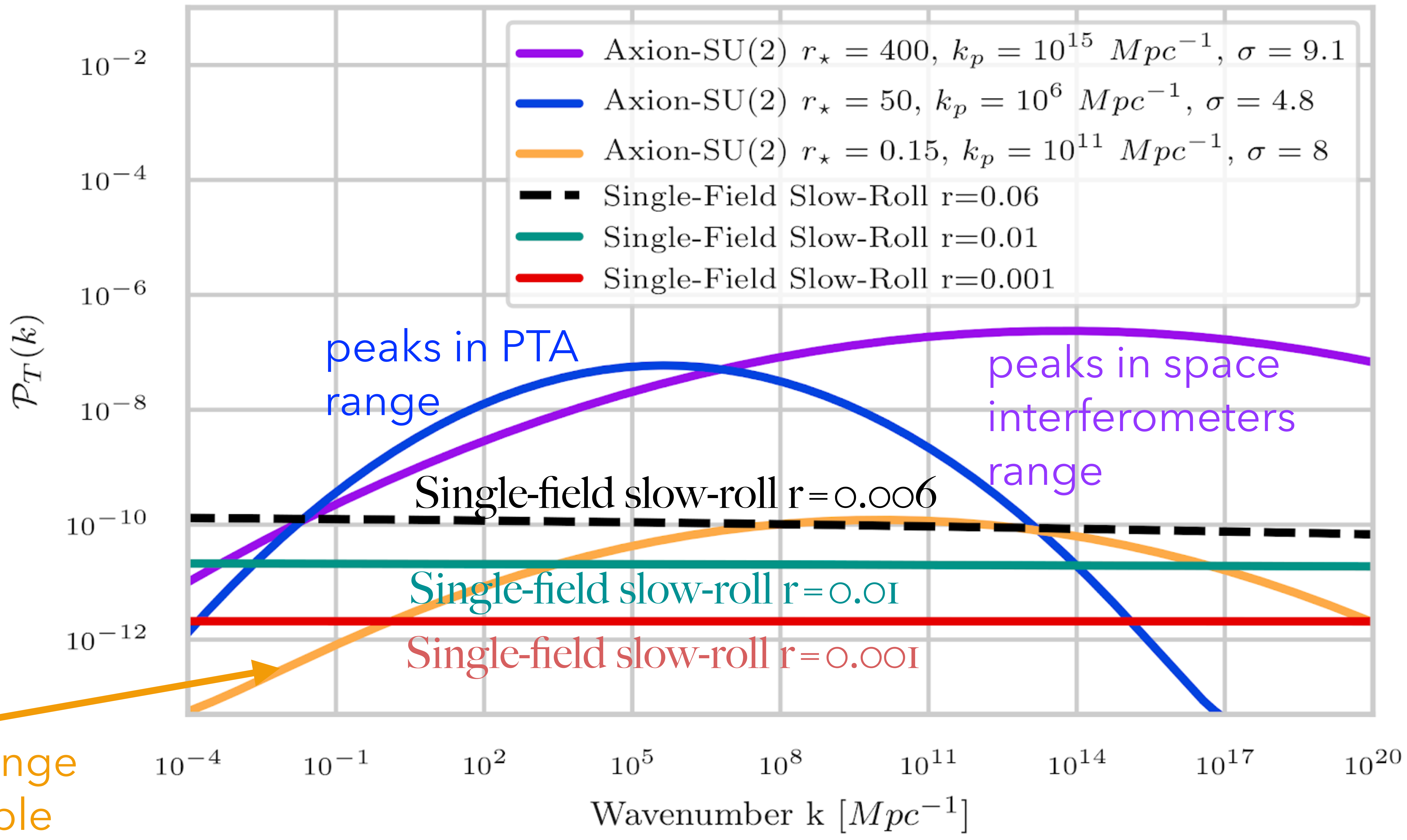


Constraints on axion-SU(2) from CMB, PTA and interferometers

PC & E. Komatsu, D. Poletti, C. Baccigalupi 2021 arXiv:2007.04241, JCAP 2021, 01,012

Testing SU(2) with interferometers

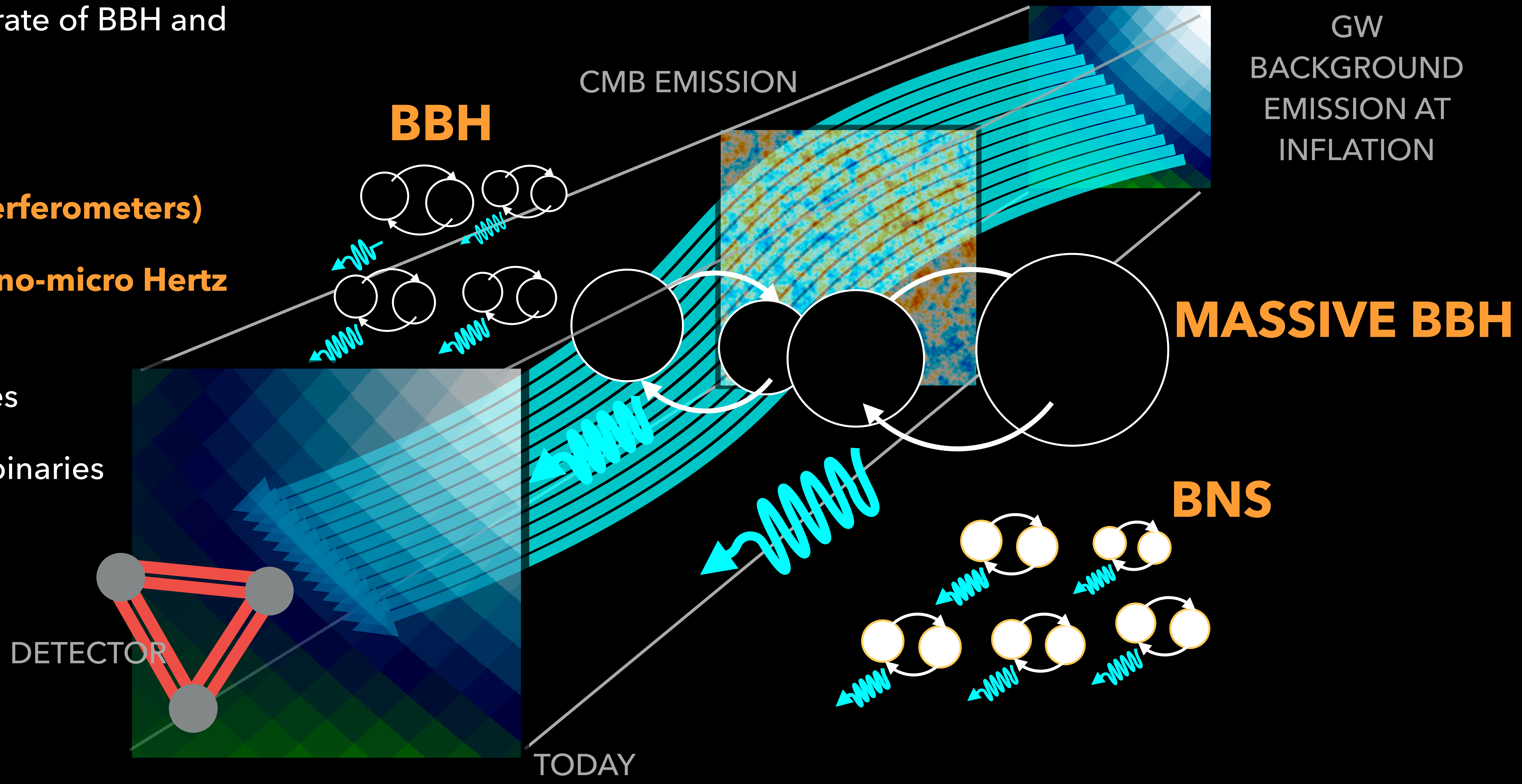
- Gauge fields (e.g. SU(2)) can generate a signal detectable in many decades in frequency while staying consistent with CMB bounds
- Testable at PTA and space interferometers!



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

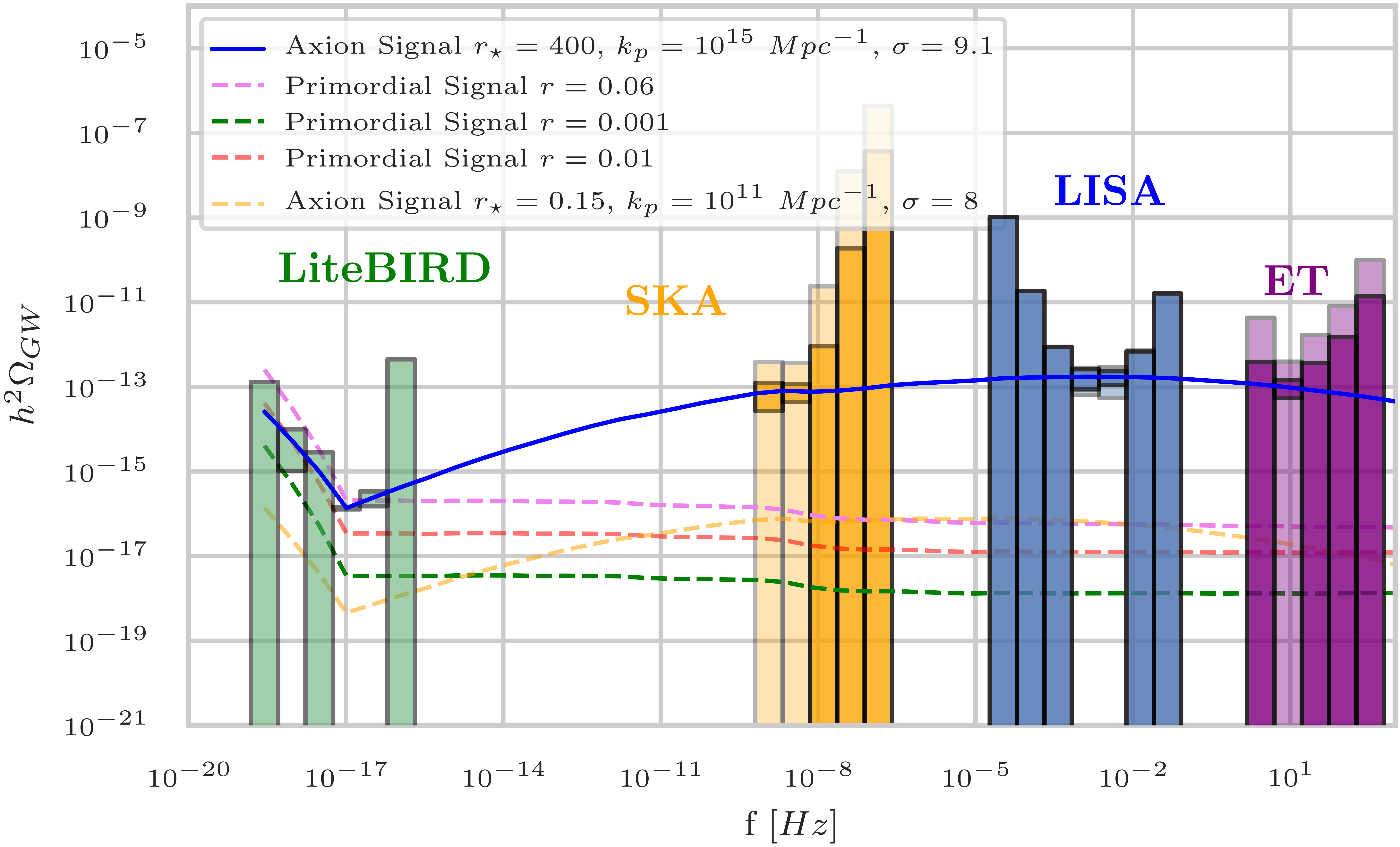
Astrophysical foregrounds for direct detection experiments

- Superposition of many astrophysical sources integrated over time
- LIGO/Virgo measured rate of BBH and BNS mergers
- Main sources:
  - **BBH + BNS (all interferometers)**
  - **Massive BBH in nano-micro Hertz range**
  - Galactic WD binaries
  - Extra-Galactic WD binaries



axion-SU(2) at interferometers scales

- We derived **new filter** for cross-correlation and foreground marginalisation for interferometers (including multi-band foreground cleaning)
- We take into account **foregrounds** for every experiment (lighter shade error bars) .
- Coherent assumptions and realism for every experiment



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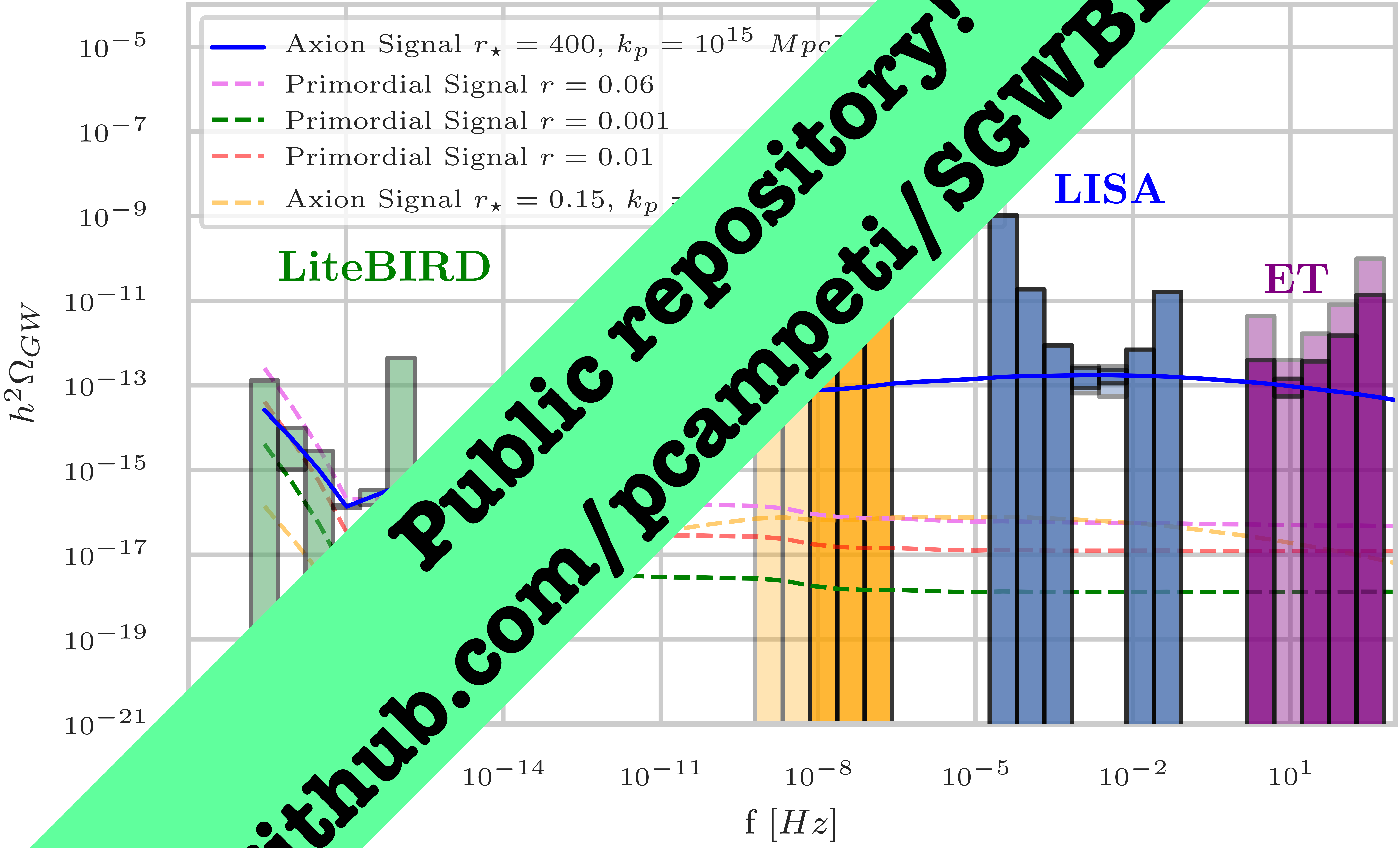
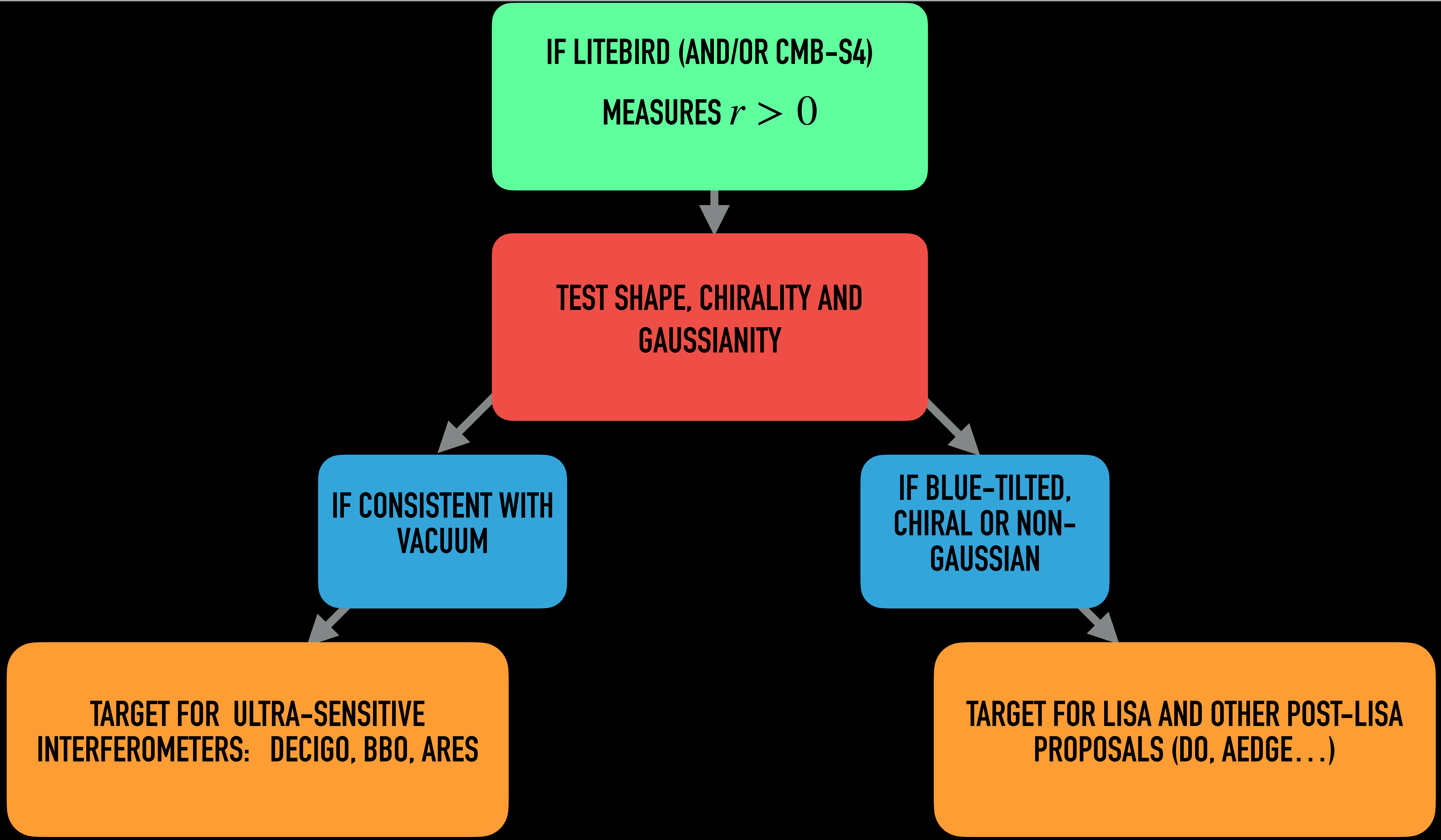


Public repository!

github.com/pcampeti/SGWBProbe

Future roadmap



Conclusions

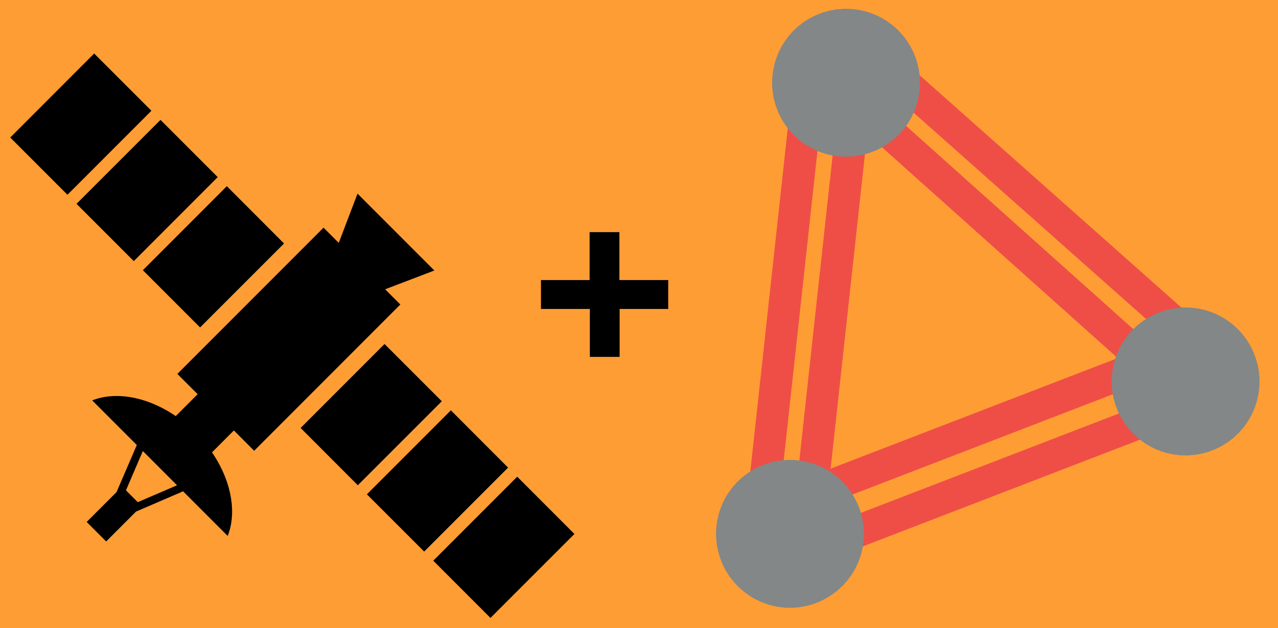
1.

In light of Planck and BICEP/Keck data the parameter space of axion-U(1) models remains large and interesting for future B-mode experiments.

2.

Axion-SU(2) can produce sourced GWs exceeding vacuum contribution especially at reionization bump scales, which are accessible only with a full-sky space mission like LiteBIRD.

3.



- Measuring the shape of the GW spectrum along many decades in frequency is needed to understand its origin.
- Control of foregrounds is fundamental for all probes.
- B-mode experiments are the most sensitive and closest in time.
- Results suggest a future roadmap.