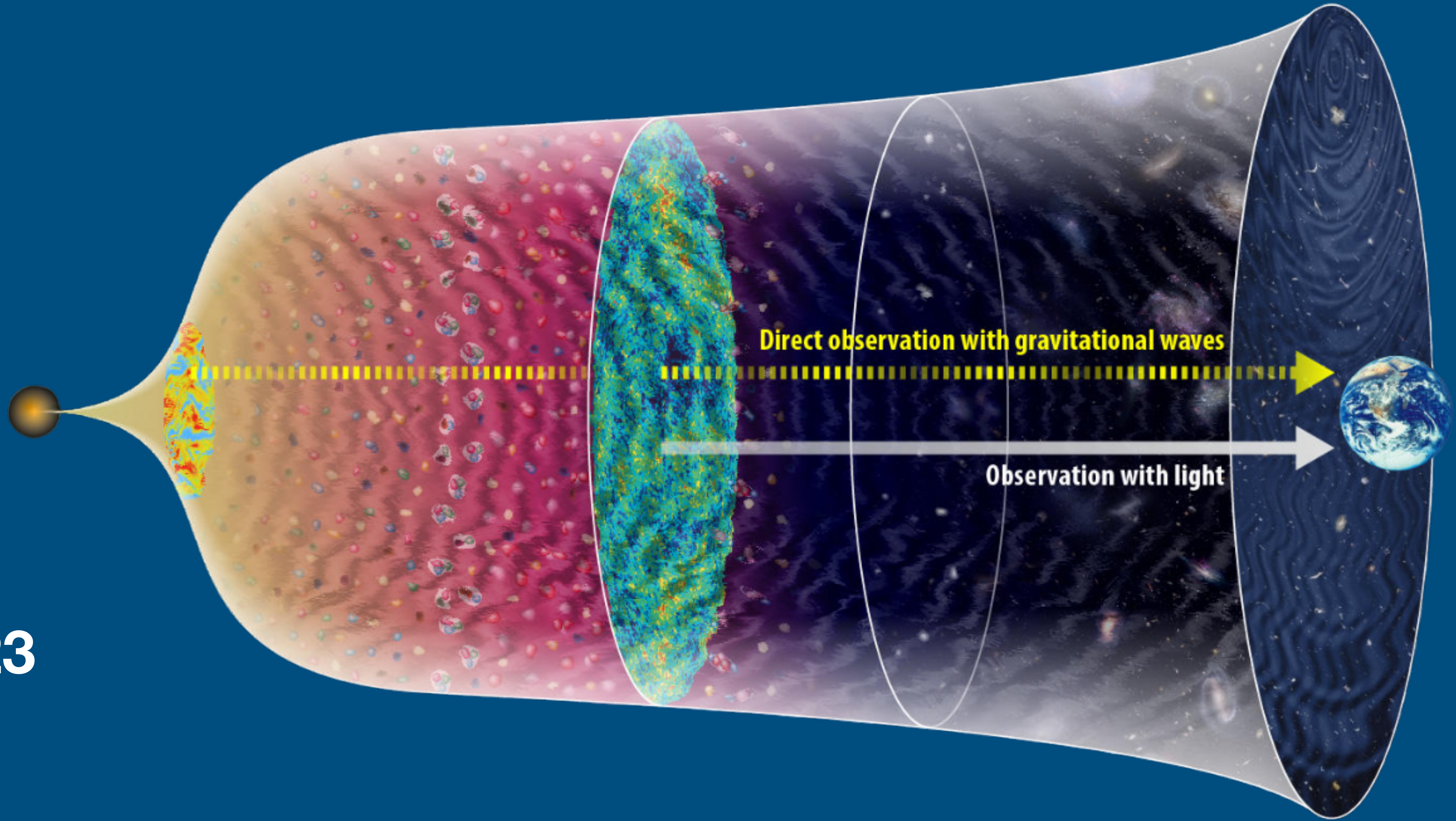
Probing the early universe with SGWB



Ameek Malhotra
UNSW Sydney

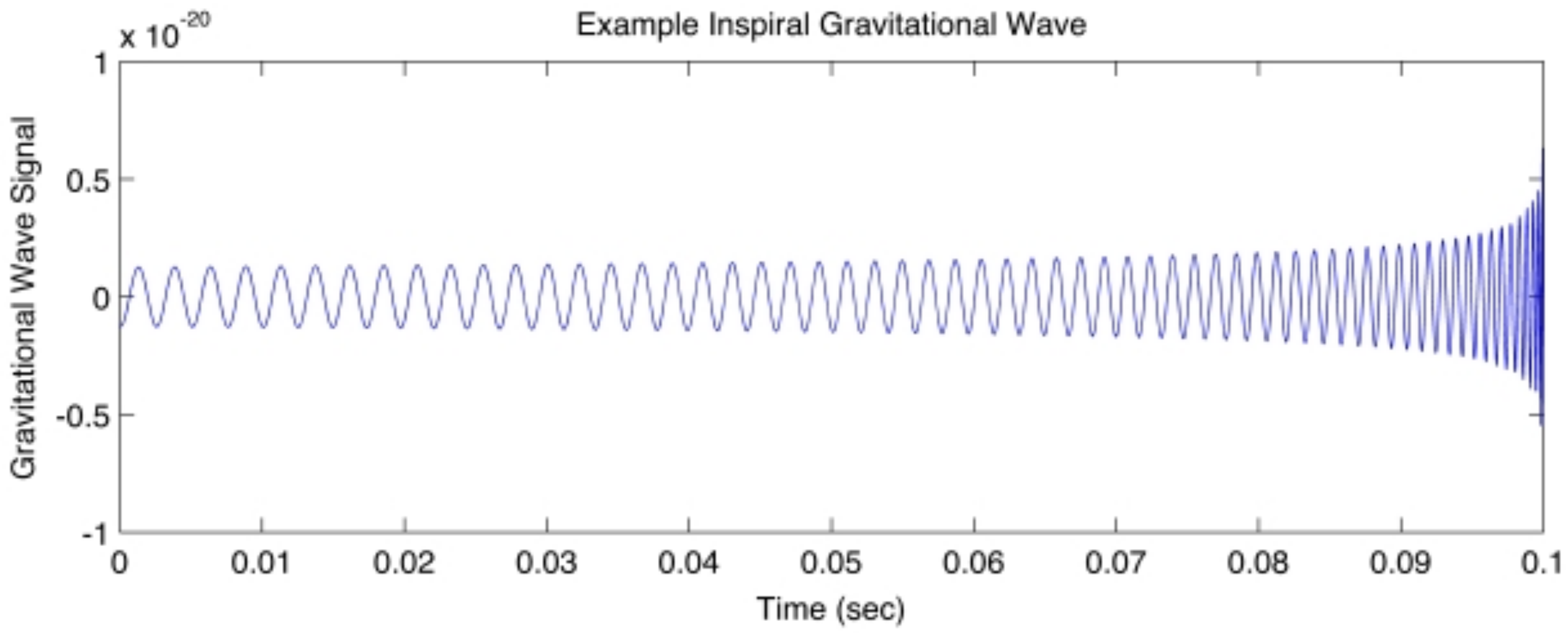
Sydney CPPC meeting 2023

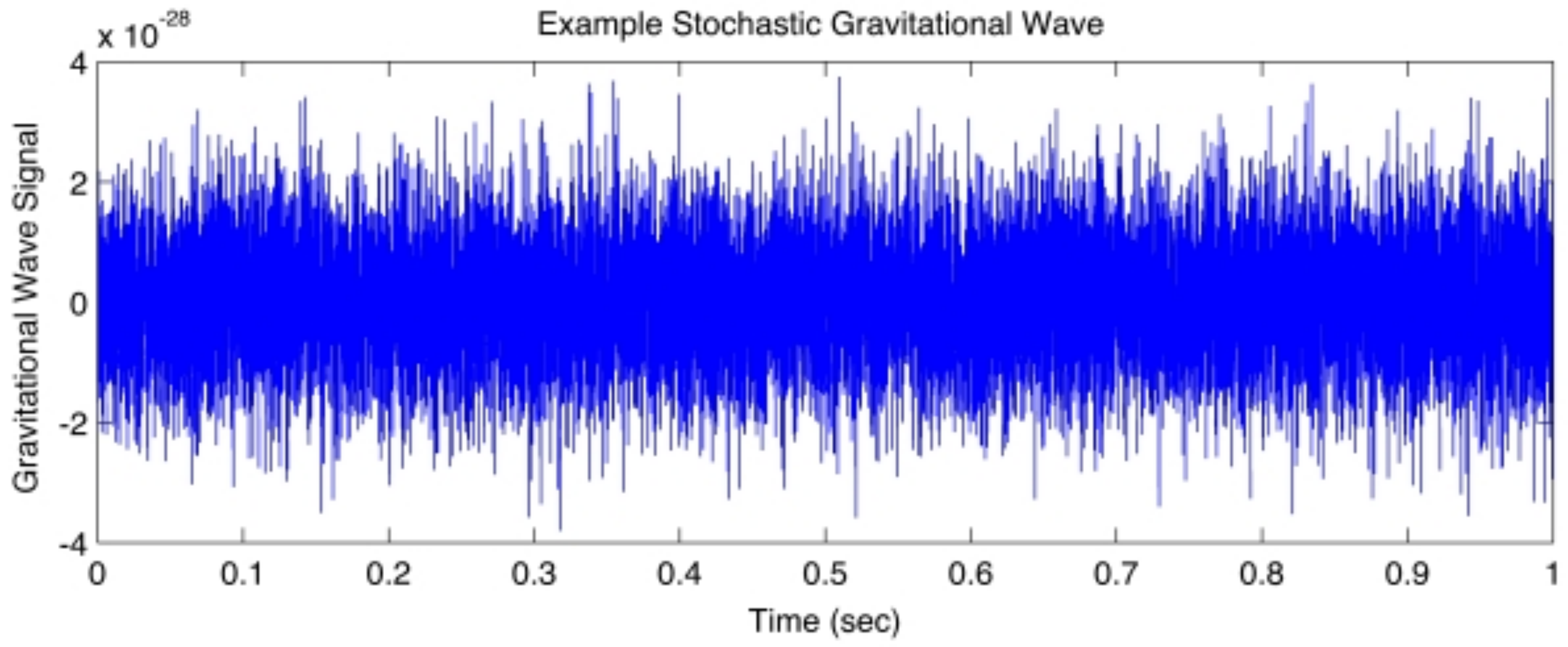
Outline

- SGWB overview
- SGWB properties
  - Anisotropies
  - Spectral Shape
  - Non-Gaussianity
- Summary

SGWB

Stochastic GW backgrounds appear similar to noise





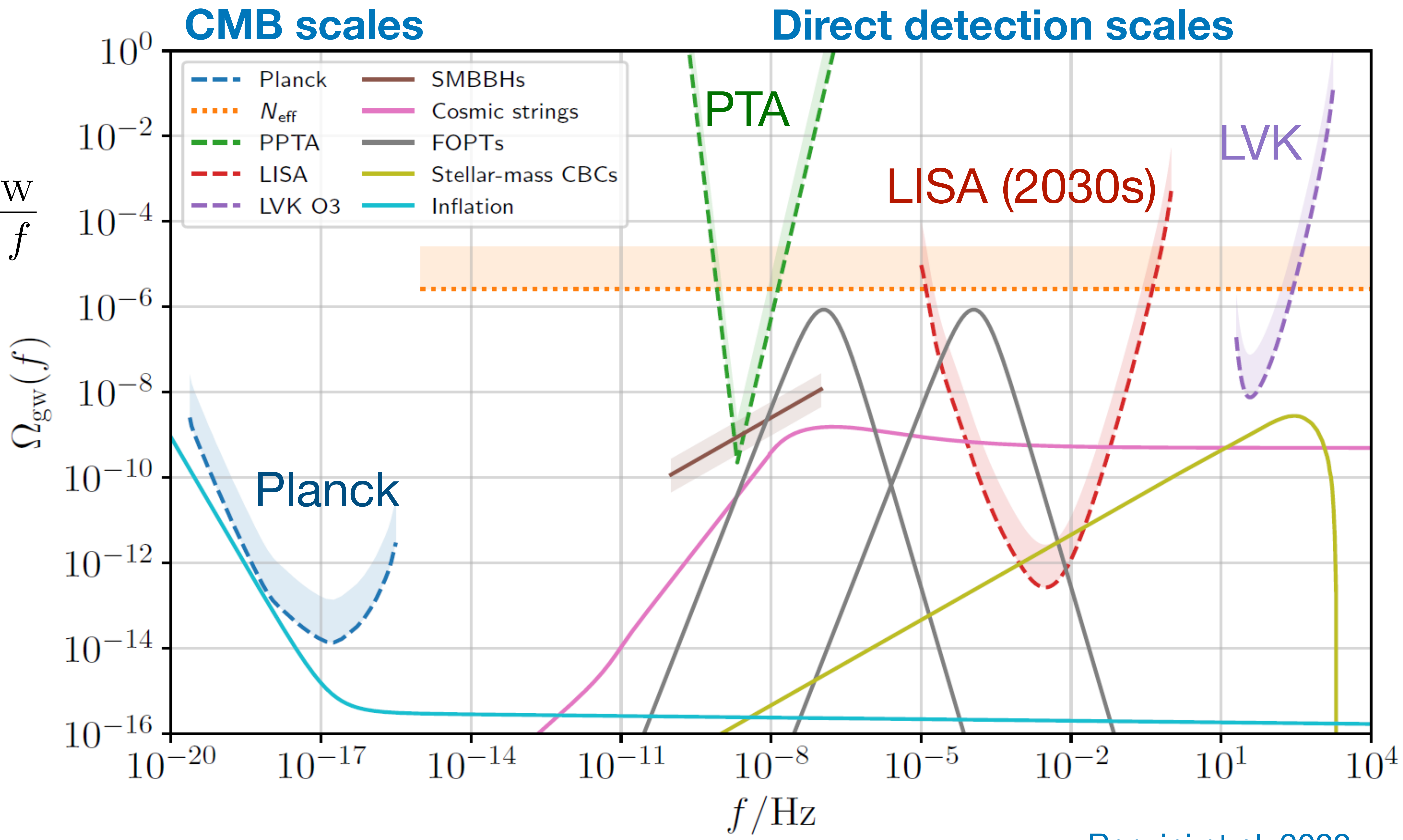
[Images: A. Stuver/LIGO]

SGWB detected by correlating outputs of multiple interferometers

$$\langle d_I d_J \rangle = \langle h_I h_J \rangle + \langle N_I N_J \rangle$$

SGWB Landscape

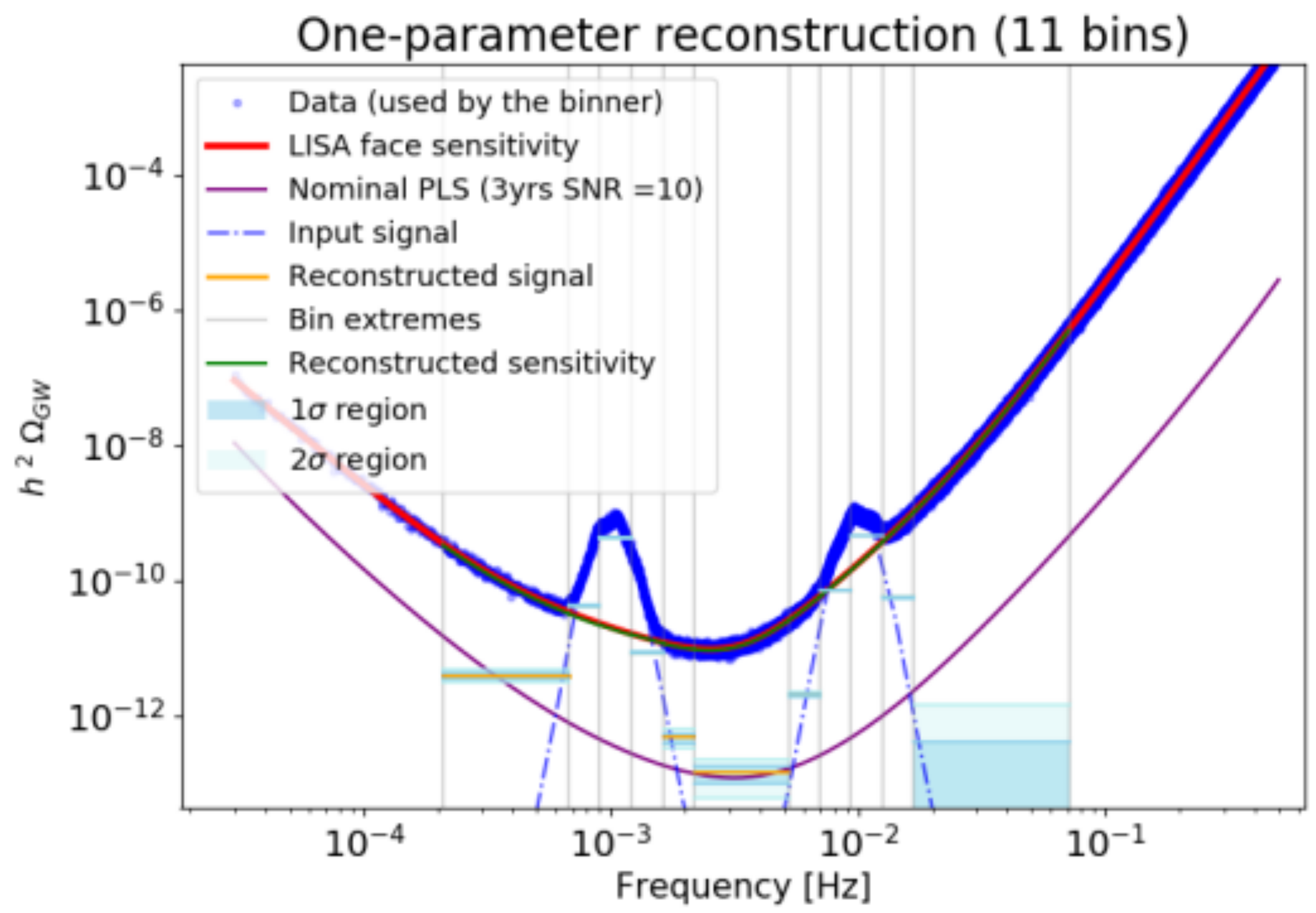
$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln f}$$

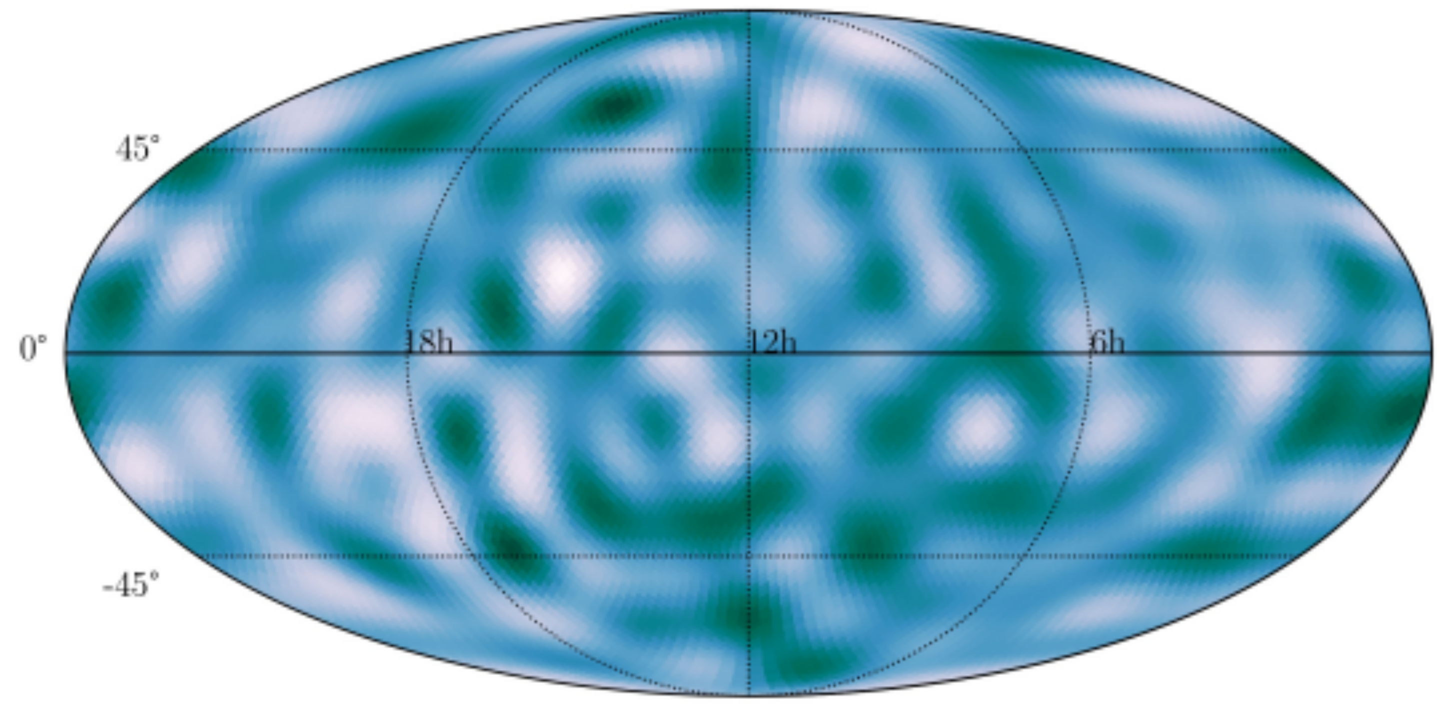


Renzini et al. 2022

SGWB Characterisation

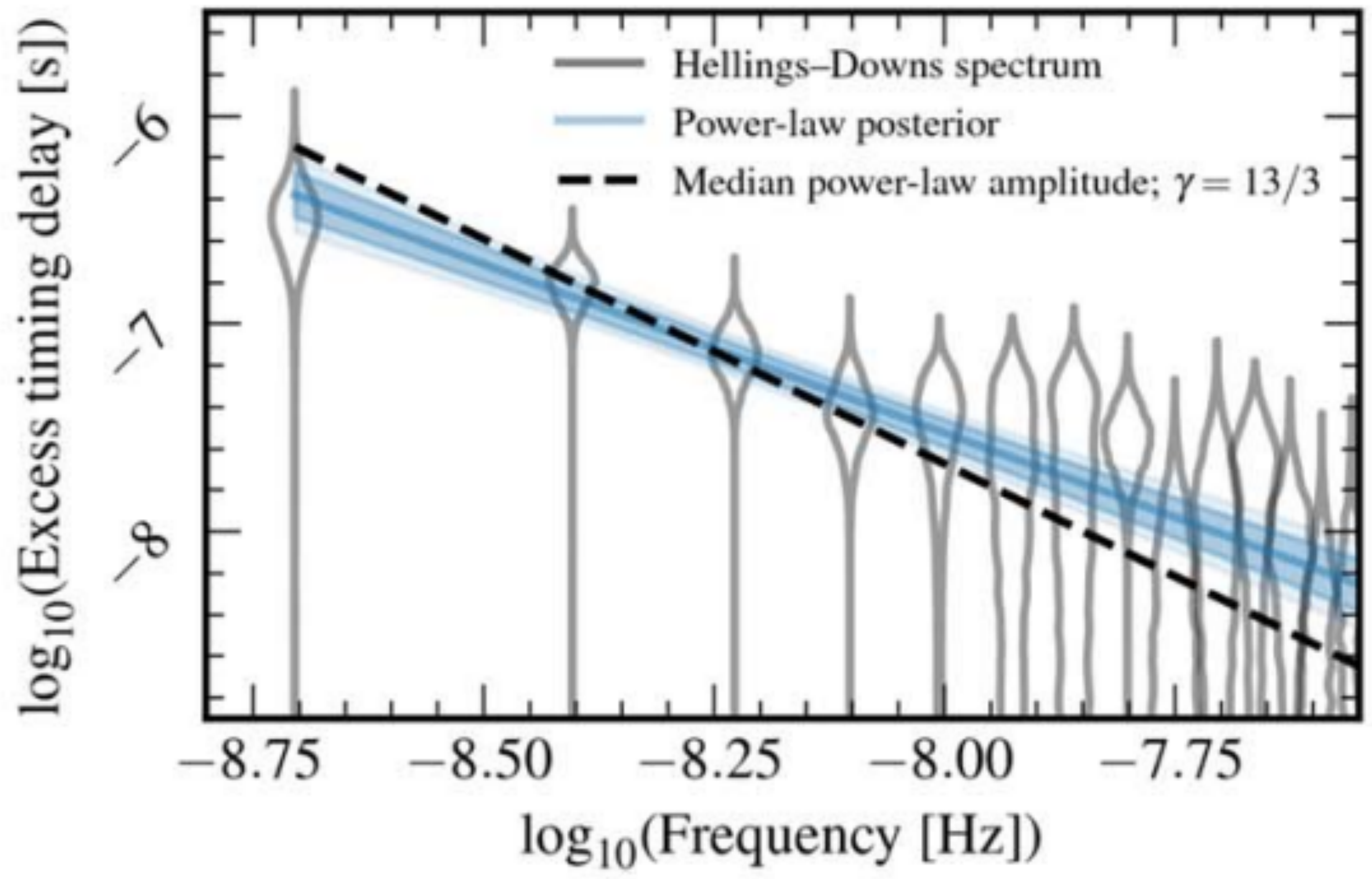
- SGWB characterised in terms of statistical properties:
  - Intensity/energy density $\Omega_{\mathrm{GW}} \propto h^2$
  - Spectral shape $\Omega_{\mathrm{GW}}(f)$
  - Anisotropies $\delta\Omega_{\mathrm{GW}}(f, \hat{n})$
  - non-Gaussianity $\langle hhh \rangle \ldots$
  - Polarisation (circular/linear)





SGWB Characterisation

- Understanding these properties important for identifying origin of SGWB
- This is relevant already, not just for 3G detectors!



The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background #1

NANOGrav Collaboration • Gabriella Agazie et al. (Jun 28, 2023)

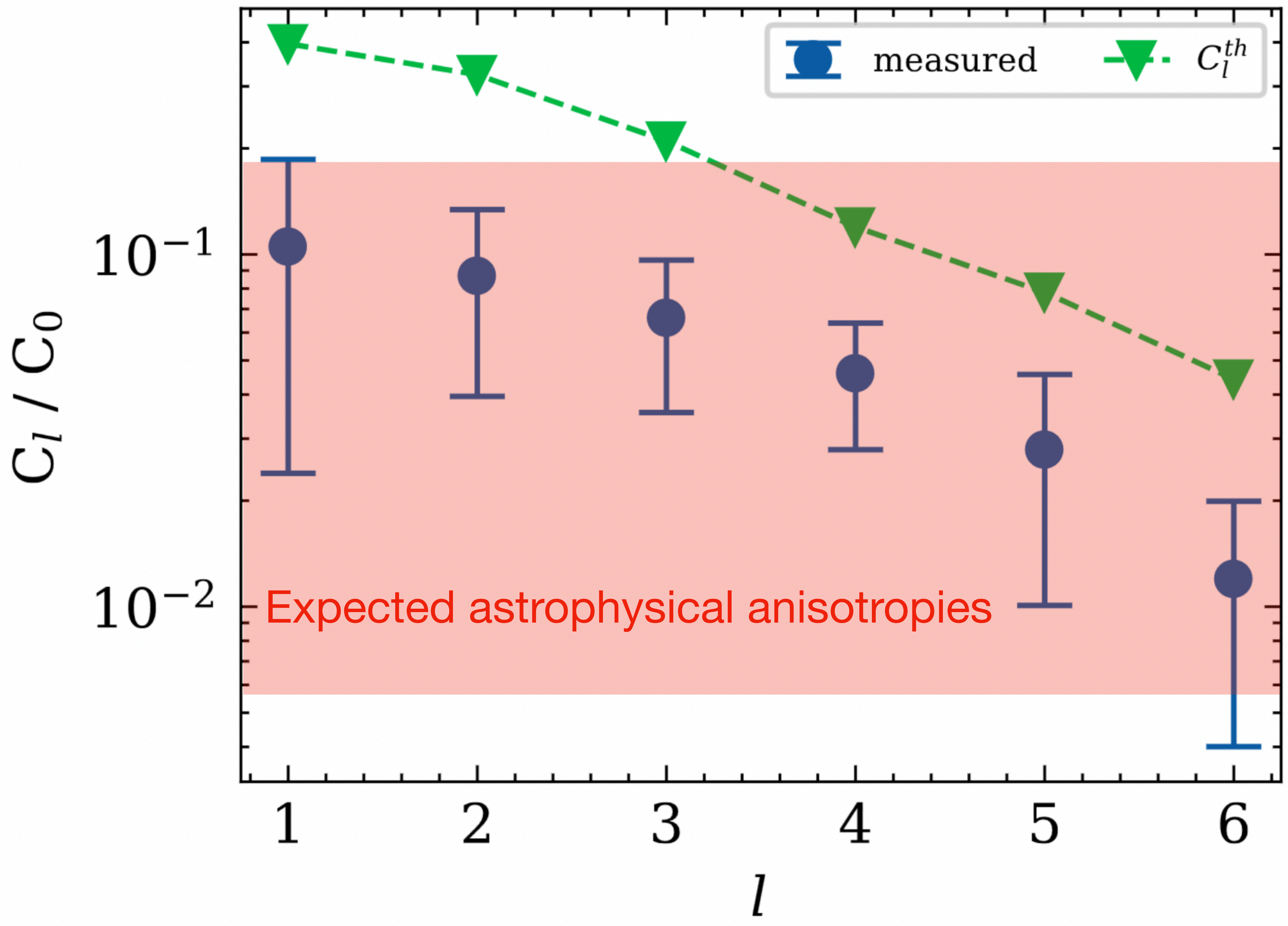
Published in: *Astrophys.J.Lett.* 951 (2023) 1, L8 • e-Print: 2306.16213 [astro-ph.HE]

pdf DOI cite claim reference search 108 citations

50+ cosmological scenarios explaining the PTA signal amplitude and slope

SGWB Characterisation

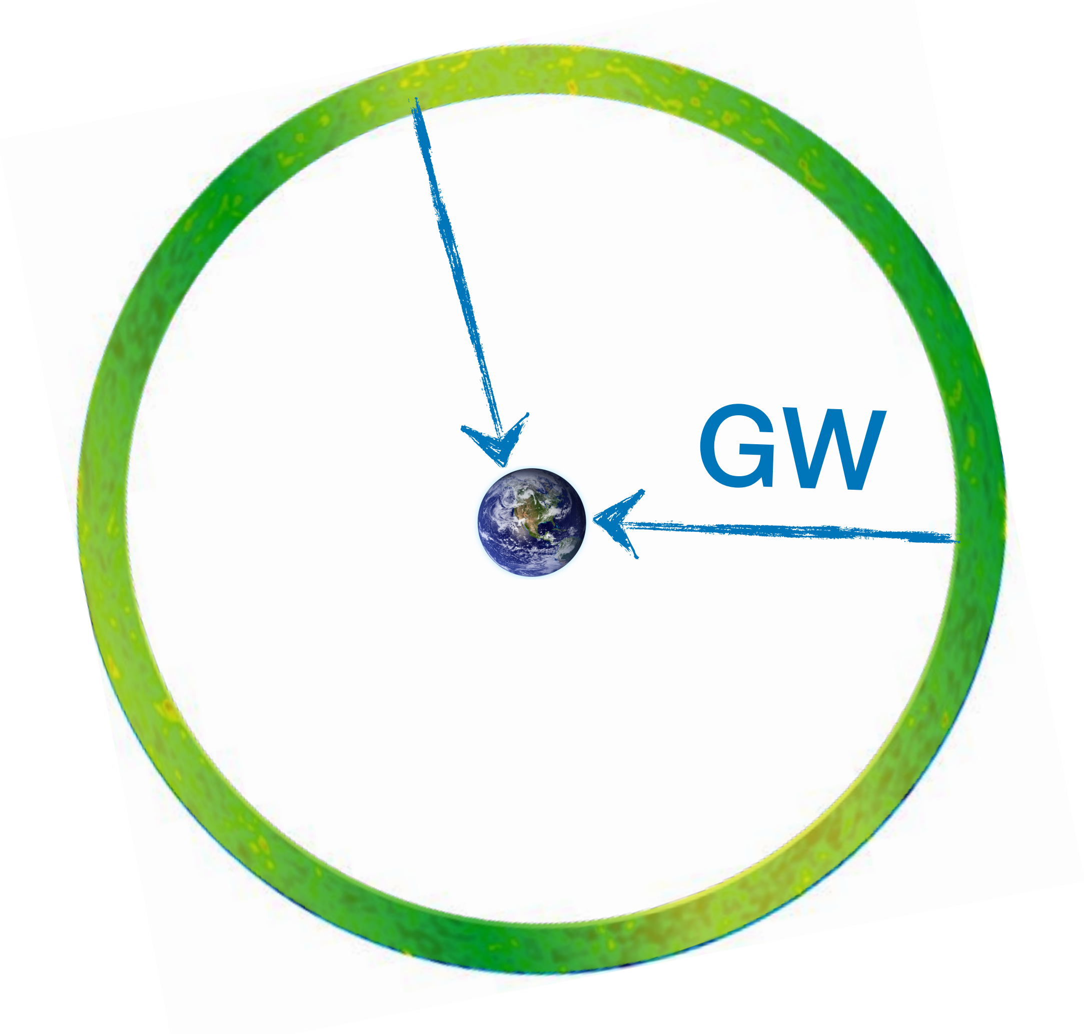
- Currently PTA data is consistent with isotropy
- Cosmological SGWB anisotropies much smaller than astrophysical
- Anisotropies may help distinguish cosmological vs astrophysical origin of signal



NANOGrav 15-year Anisotropic Gravitational-Wave Background

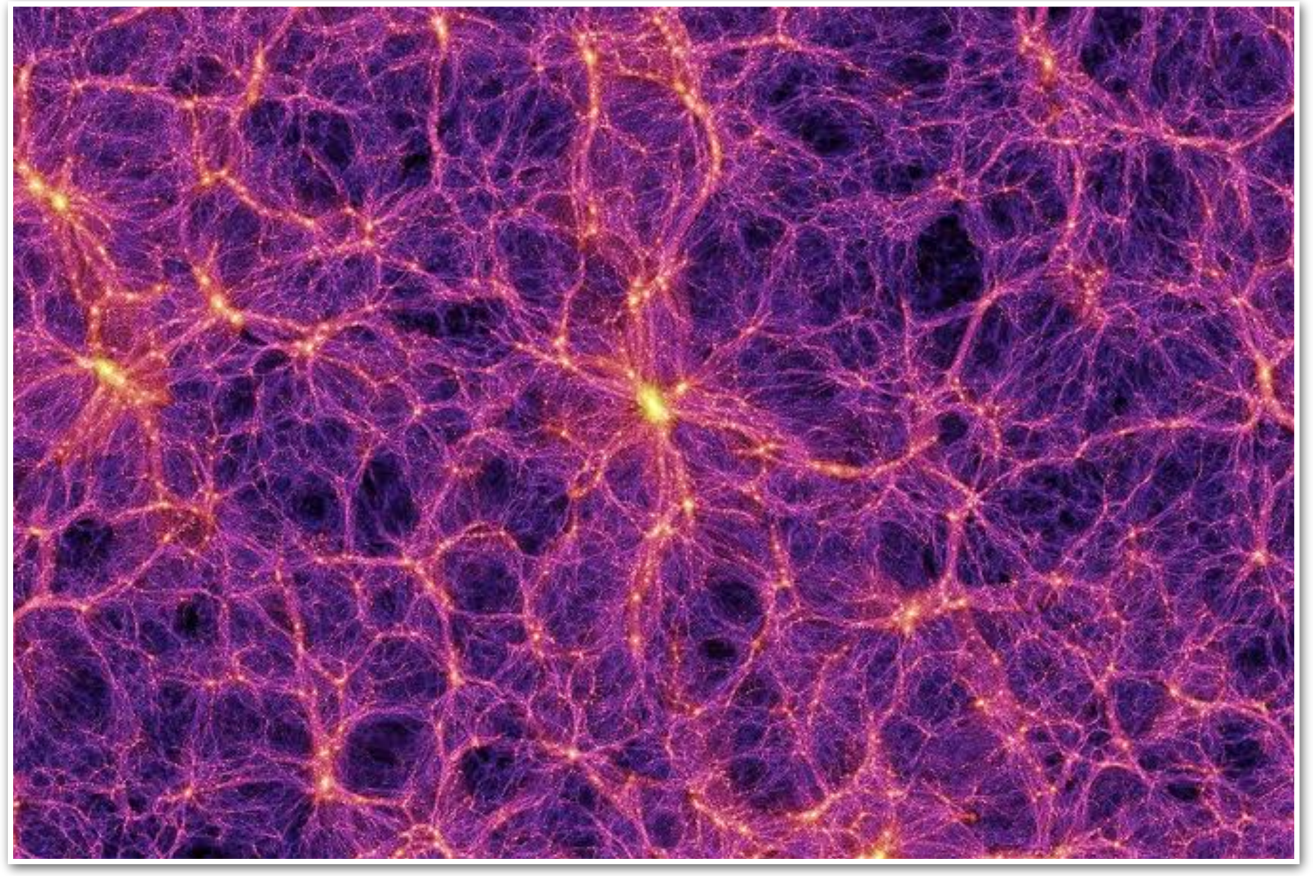
SGWB Anisotropies

GW Production



Primordial source properties imprinted on anisotropies (Inflation, PT, PBH…)

GW Propagation



Propagation through large scale density perturbations

$t \approx 0$ Today

See review by LISA CosWG (2022)

SGWB Anisotropies

Zeroth order term + perturbation

$$f(\eta, \vec{q}, \vec{x}) \equiv \bar{f}(\eta, q) - \Gamma(\eta, \vec{x}, q, \hat{n}) \frac{d\bar{f}}{d\ln q}$$

The isotropic and anisotropic parts of the energy density are

$$\bar{\Omega}_{\rm GW} = \frac{4\pi}{\rho_{\rm cr}} \left(\frac{q}{a_0}\right)^4 \bar{f}(\eta, q), \quad \delta_{\rm GW} = \left[4 - \frac{\partial \ln \bar{\Omega}_{\rm GW}(q)}{\partial \ln q}\right] \Gamma(\eta, \vec{x}, q, \hat{n})$$

[Alba & Maldacena 2015, Contaldi 2017; Bartolo et al. 2019a, 2019b]

SGWB line-of-sight formalism

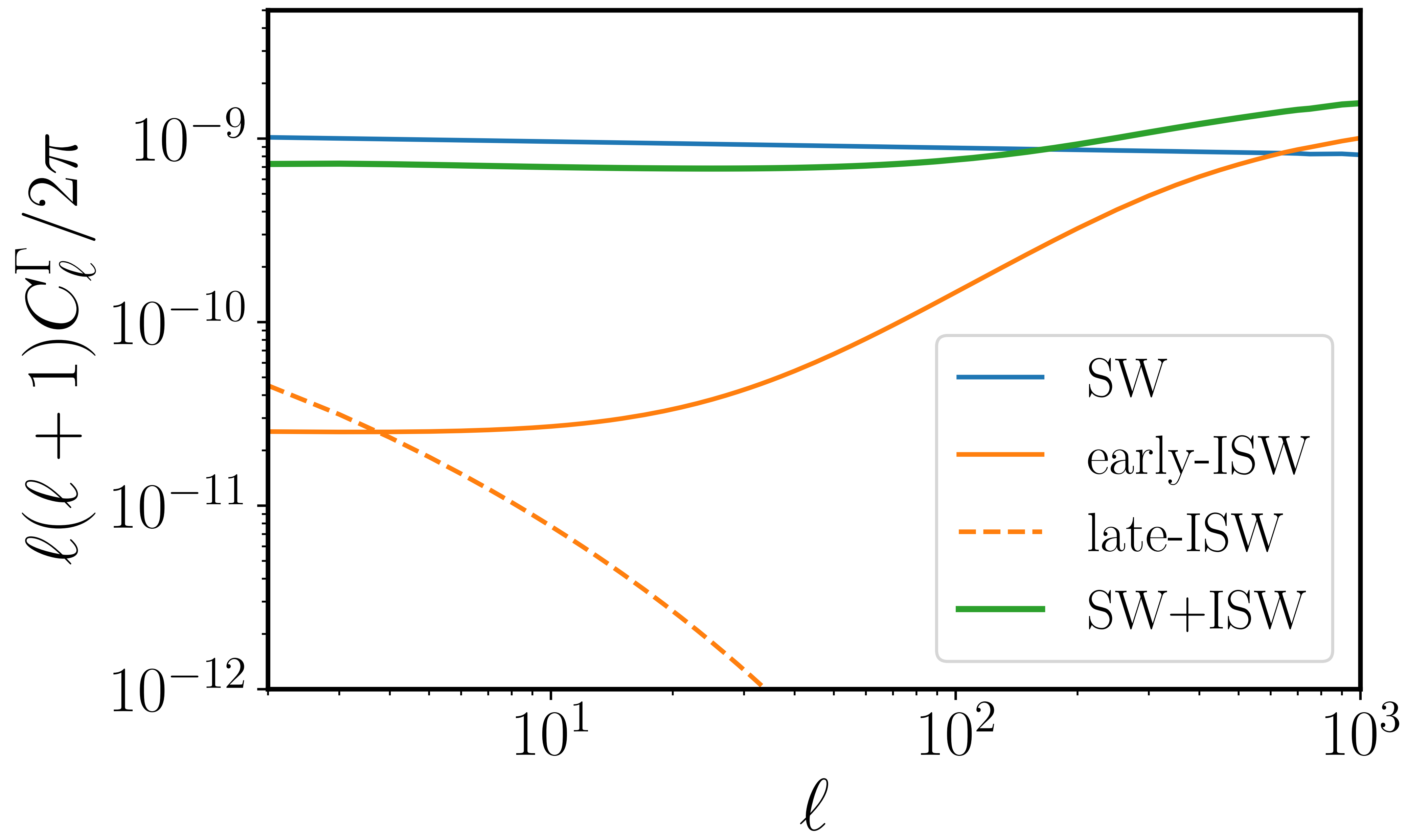
In terms of Newtonian gauge potentials

$$\underbrace{\Gamma(\eta_0, k, f, \hat{n})}_{\text{“}\Delta T/T\text{” for GW}} = \Gamma_I + \Phi_I + \int_{\eta_i}^{\eta_0} d\eta \, \{\Phi'(k,\eta) + \Psi'(k,\eta)\} \, e^{-i\hat{k}\cdot\hat{n}(\eta_0 - \eta)}$$

$$\Gamma_I \equiv \Gamma(\eta_i, k, f, \hat{n}) \rightarrow \text{initial perturbation}$$

$$\Phi_I \equiv \Phi(k, \eta_i) \rightarrow \text{SW}$$

$$\Phi'(k,\eta) + \Psi'(k,\eta) \rightarrow \text{ ISW}$$



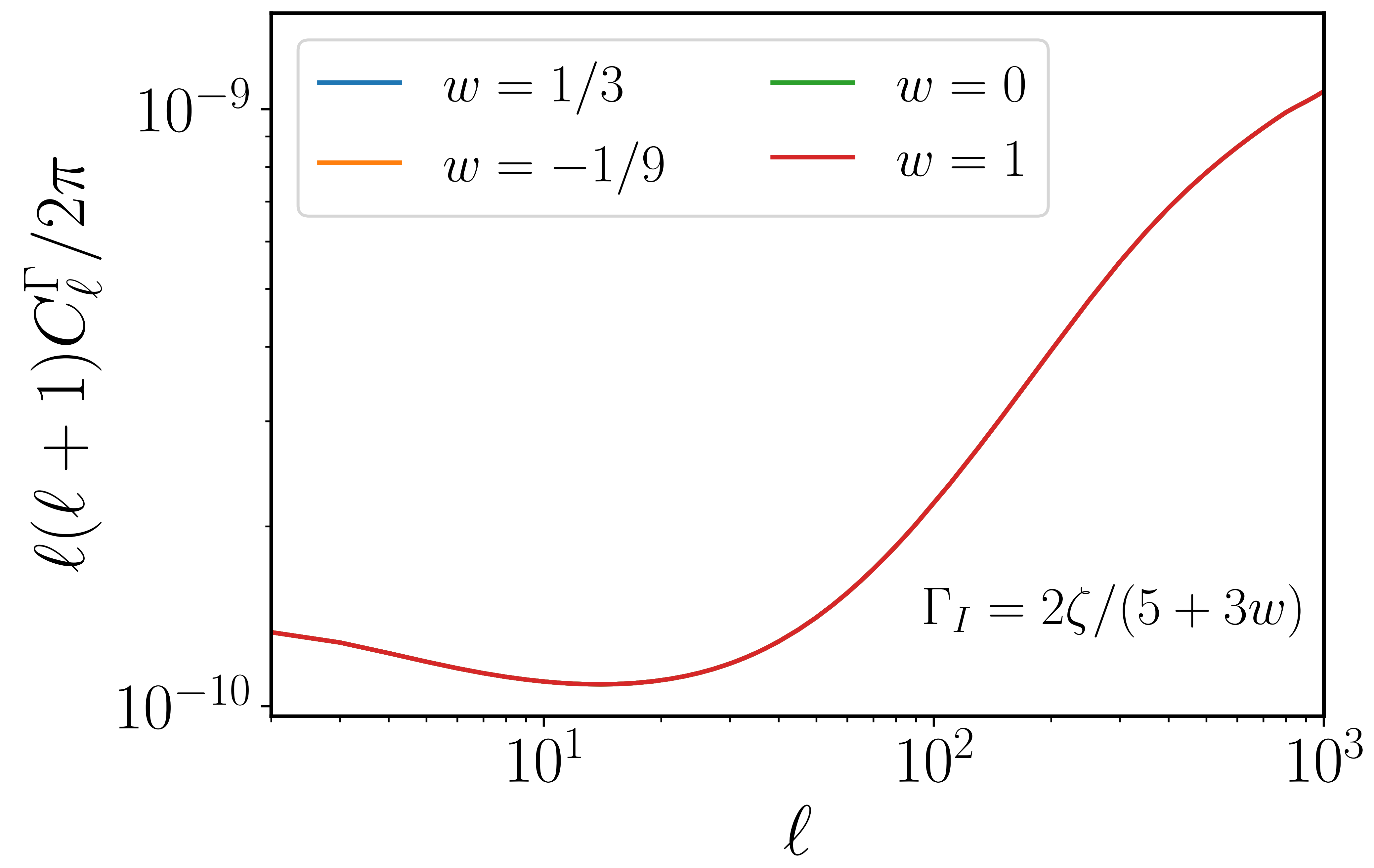
[Alba & Maldacena 2015, Contaldi 2017; Bartolo et al. 2019a, 2019b]

Adiabatic initial conditions

- Adiabaticity $\rightarrow$ $\left.\frac{\delta\rho_{\rm GW}}{\rho_{\rm GW}}\right|_I = \left.\frac{\delta\rho_{\rm r}}{\rho_{\rm r}}\right|_I$

- SGWB anisotropies independent of initial w for adiabatic I.C.

$$C_\ell^\Gamma \propto \left[-\frac{1}{3}\zeta j_\ell(k\eta_0) + {\rm ISW}\right]^2$$



[**AM**, Dimastrogiovanni, Doménech, Fasiello and Tasinato *PRD* 107 (2023) 10, 103502]

Isocurvature via curvaton mechanism

- Additional subdominant scalar field besides the inflaton [Enqvist & Sloth, Lyth & Wands, Moroi & Takahashi (2002)]

- Post-inflation, it behaves like dust and may dominate the energy density of the universe

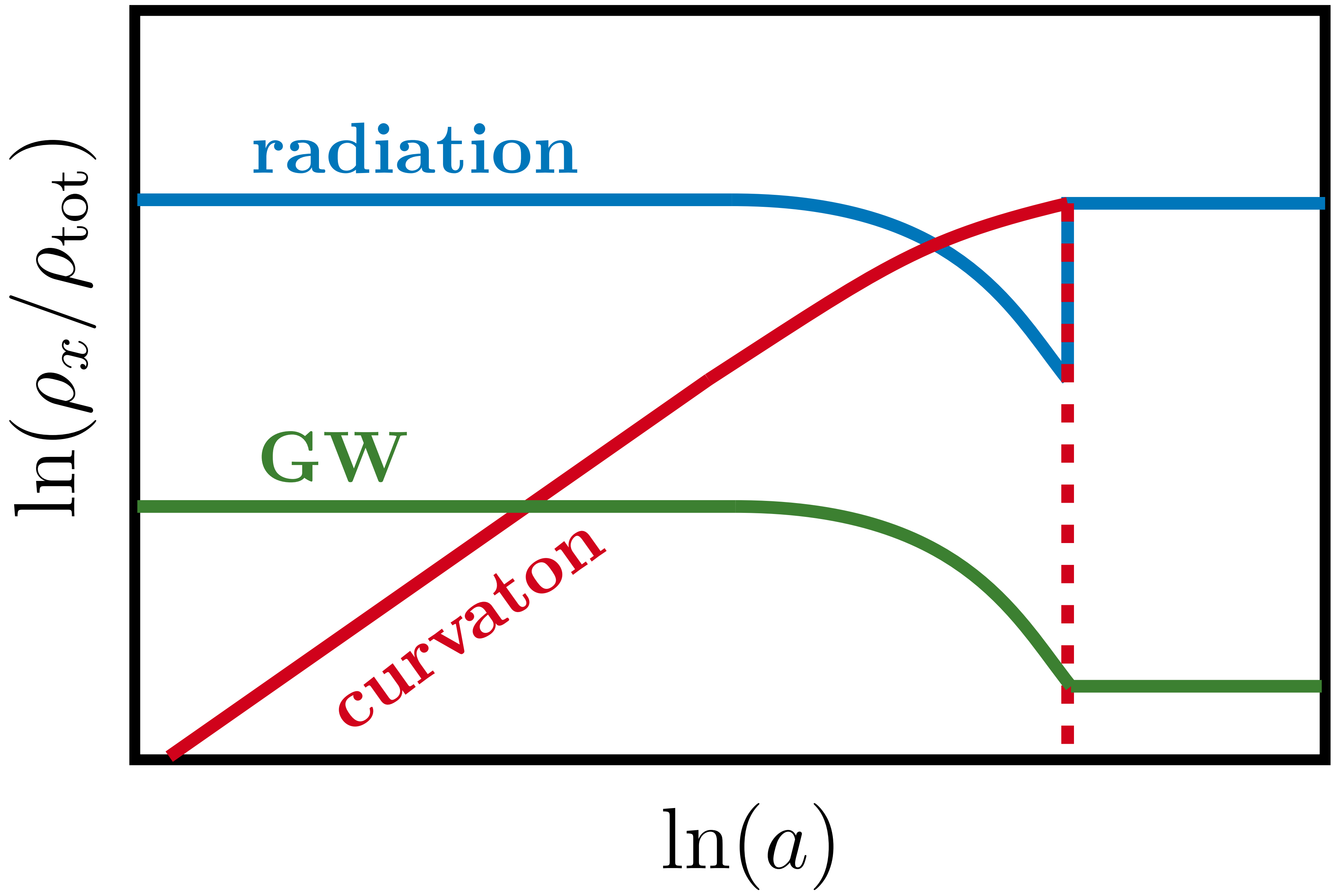
- Resulting isocurvature depends on the decay products of the curvaton

$$S_{\mathrm{GW,r}} \equiv \left(\frac{\delta\rho_{\mathrm{GW}}}{\rho_{\mathrm{GW}}} - \frac{\delta\rho_{\mathrm{r}}}{\rho_{\mathrm{r}}} \right) \neq 0$$

GW isocurvature w.r.t radiation

Curvaton scenario I

- Curvaton dominates $\rho_{\rm tot}$ then decays entirely into radiation
- Fluctuation amplitude fixed by CMB normalisation

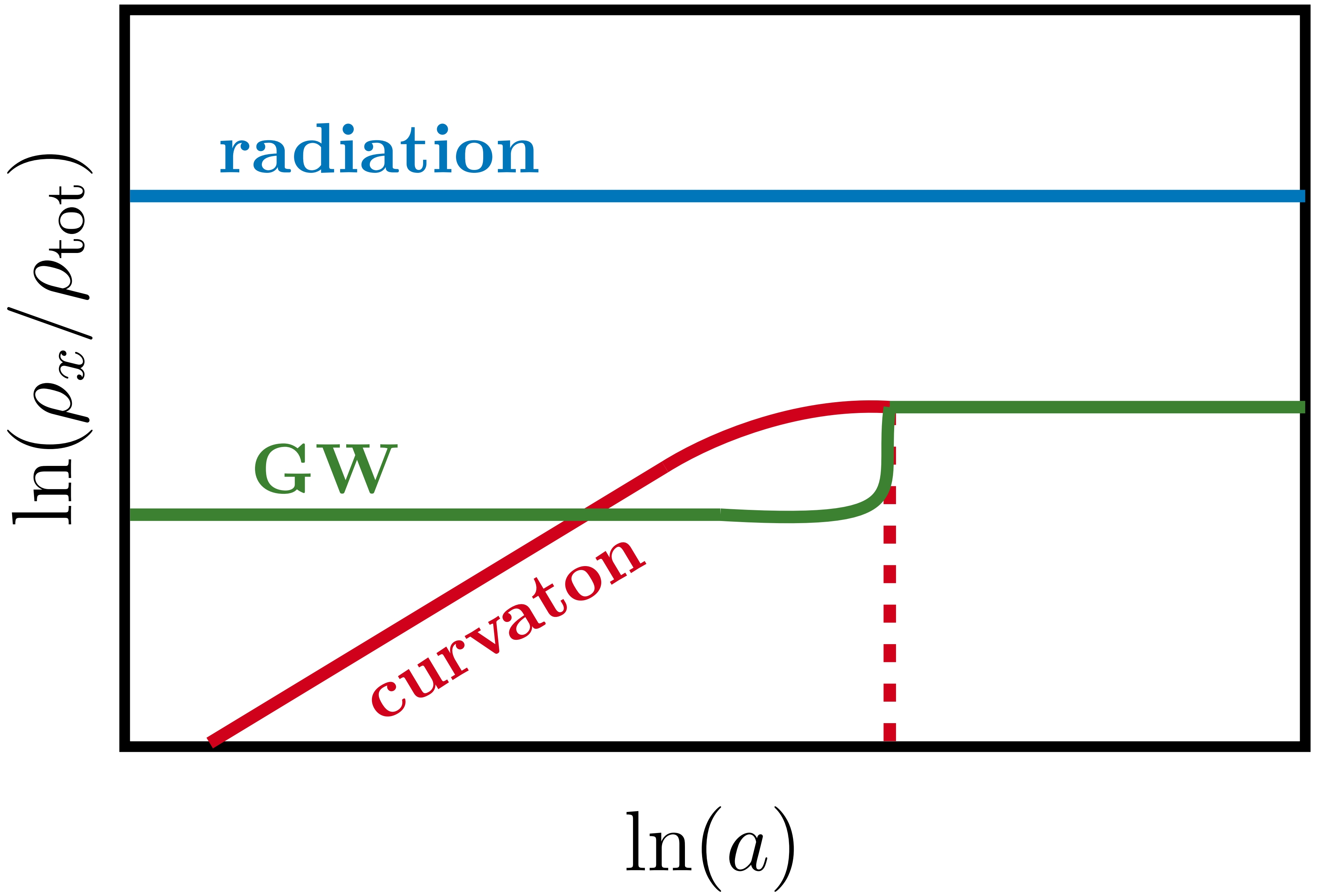


$$C_\ell^\Gamma \propto \left[-\frac{4}{3}\zeta_r\, j_\ell[k\eta_0] + \text{ISW} \right]^2$$

4x adiabatic term

Curvaton scenario II

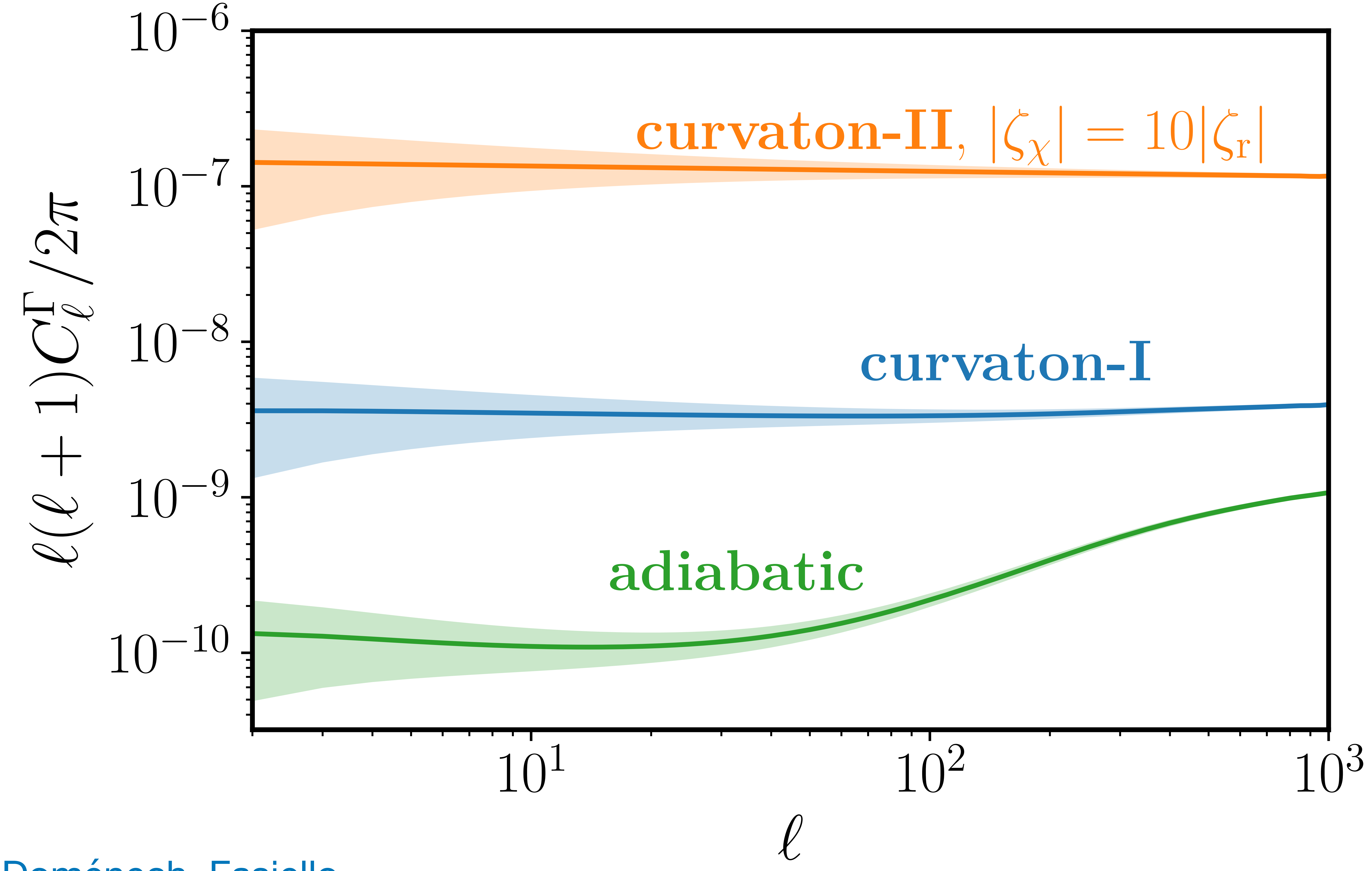
- Curvaton remains subdominant and decays entirely into GW
- Fluctuation amplitude not fixed



$$C_\ell^\Gamma \propto \left\{ \left[\frac{(1+w_\chi)}{(1+w_r)}\zeta_\chi - \frac{1}{3}\zeta_r \right] j_\ell[k\eta_0] + \mathrm{ISW} \right\}^2$$

independent curvaton fluctuations

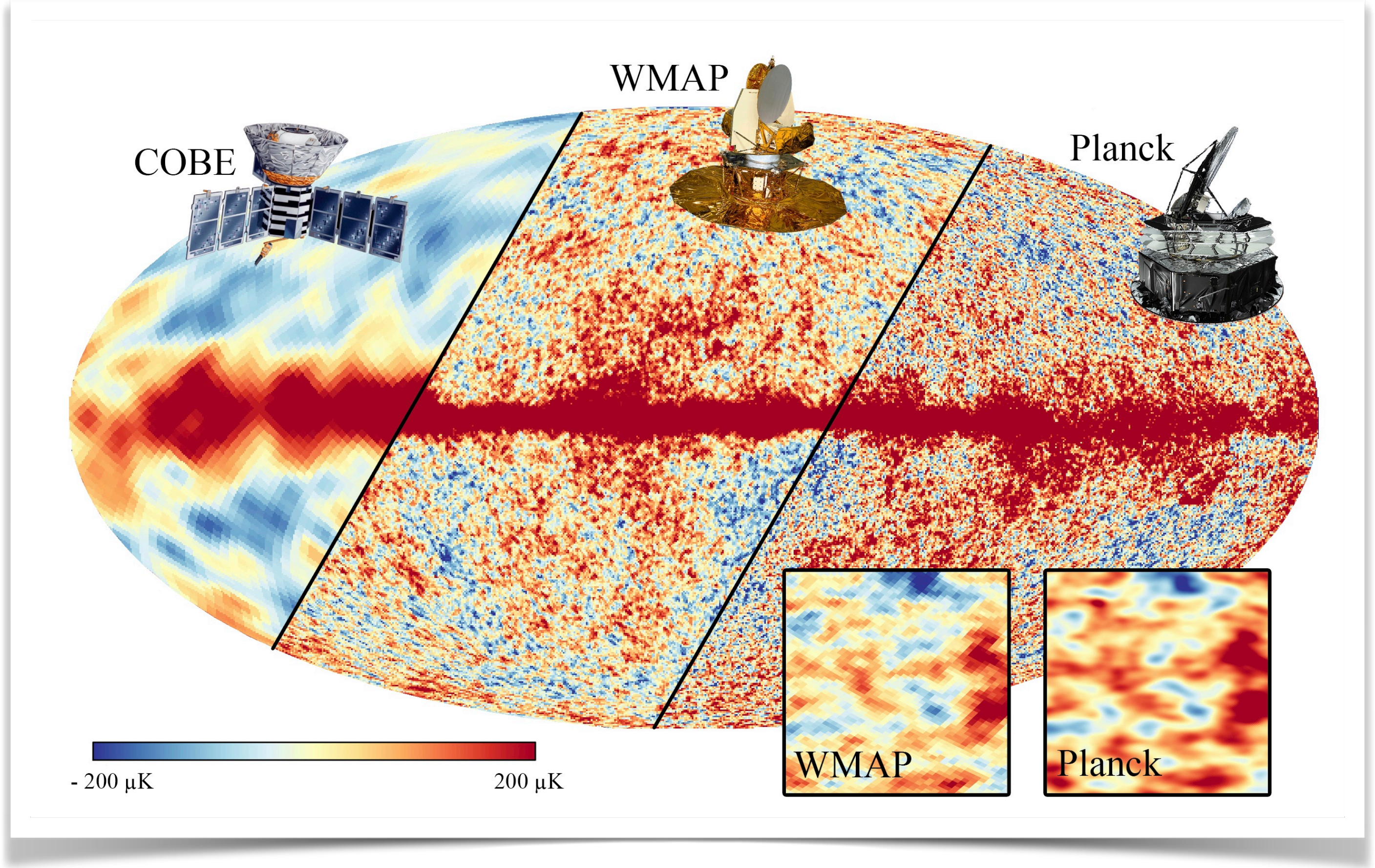
Curvaton anisotropies

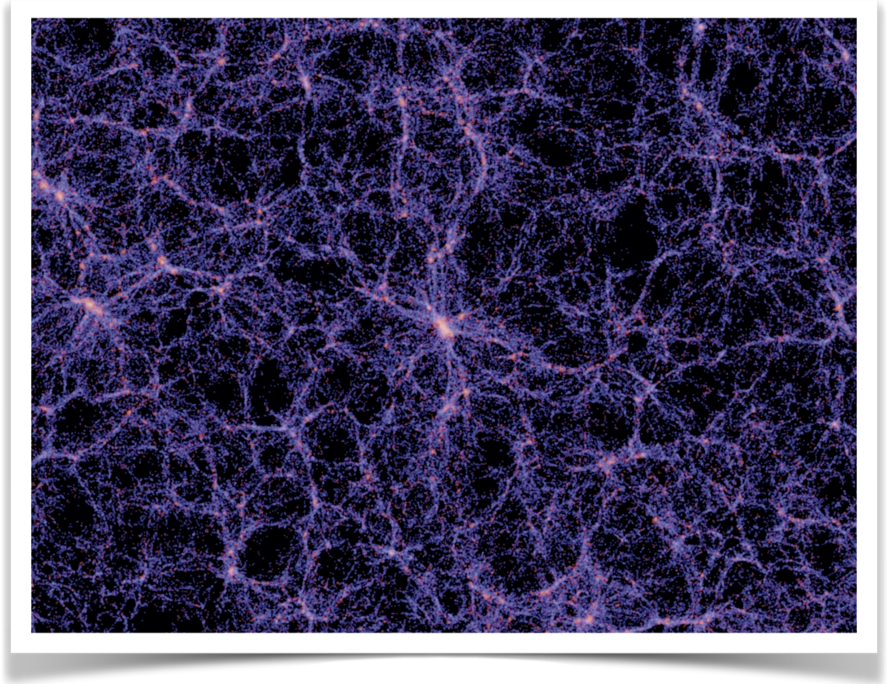


[**AM**, Dimastrogiovanni, Doménech, Fasiello and Tasinato *PRD* 107 (2023) 10, 103502]

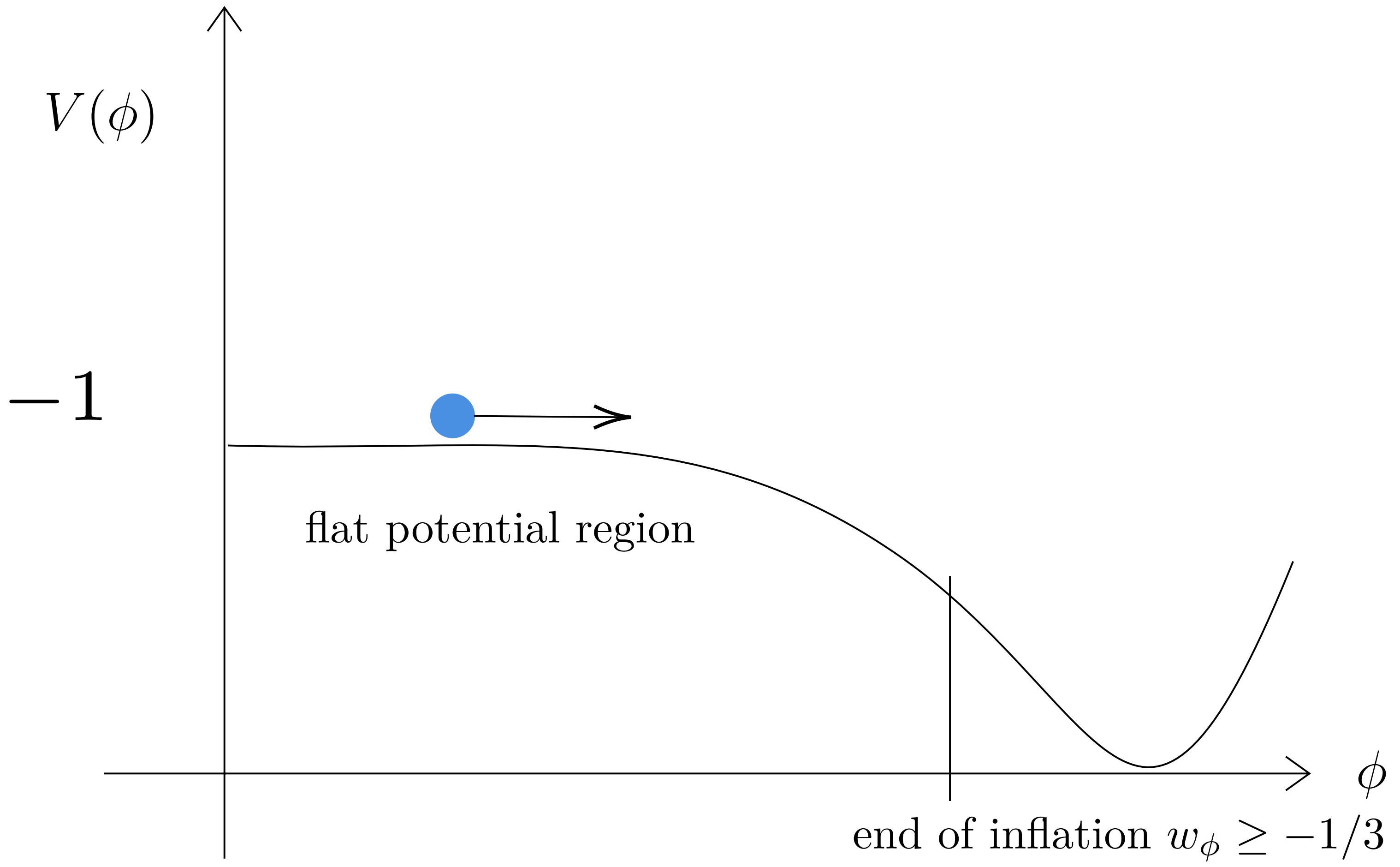
Inflationary Perturbations

$$ds^2 = a^2(\eta)\left[-d\eta^2 + \left(e^{2\zeta}\delta_{ij} + h_{ij}\right)dx^i dx^j\right]$$





$$\mathcal{P}_\zeta(k) = A_s\left(\frac{k}{k_\mathrm{p}}\right)^{n_\mathrm{s}-1}$$

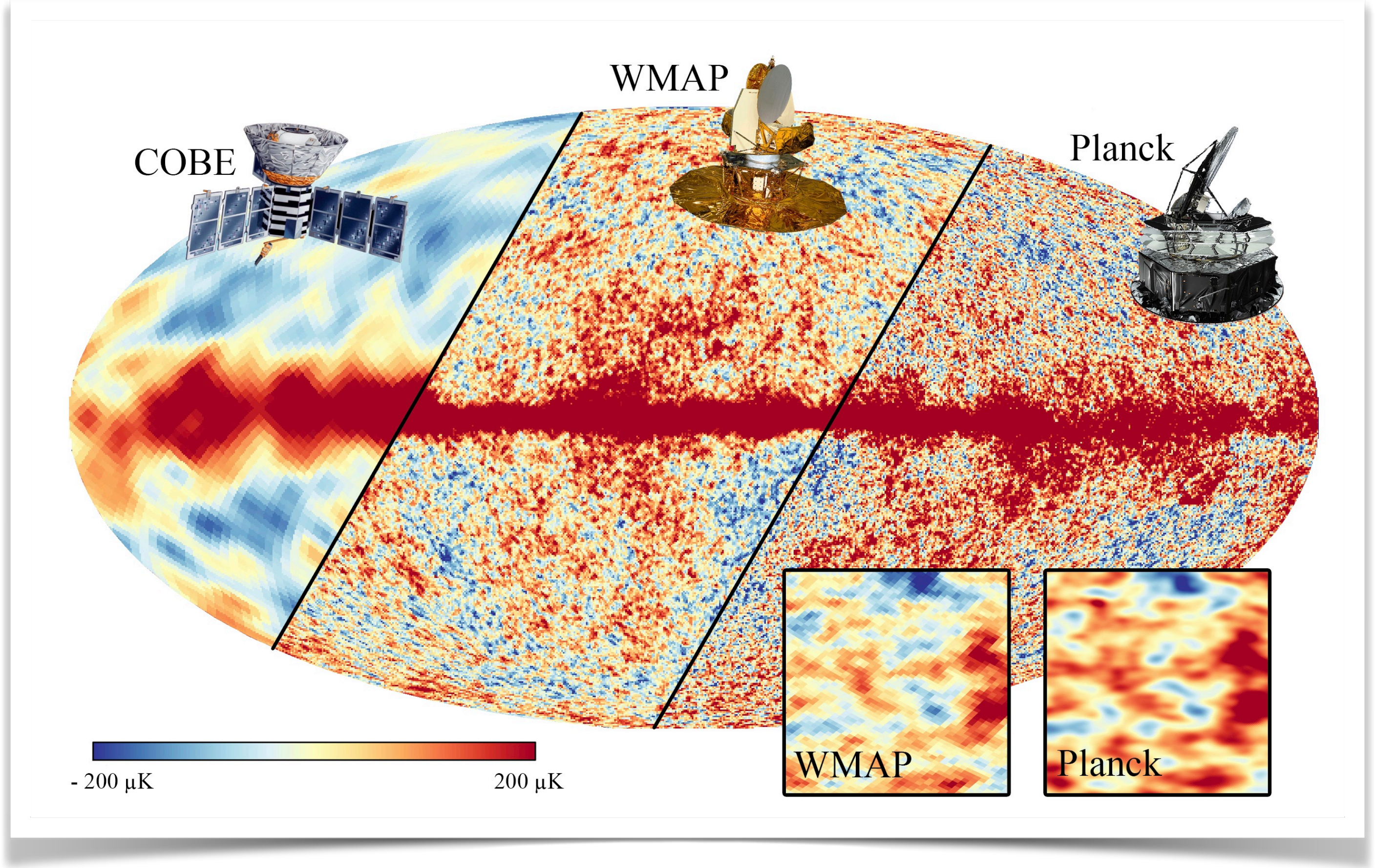


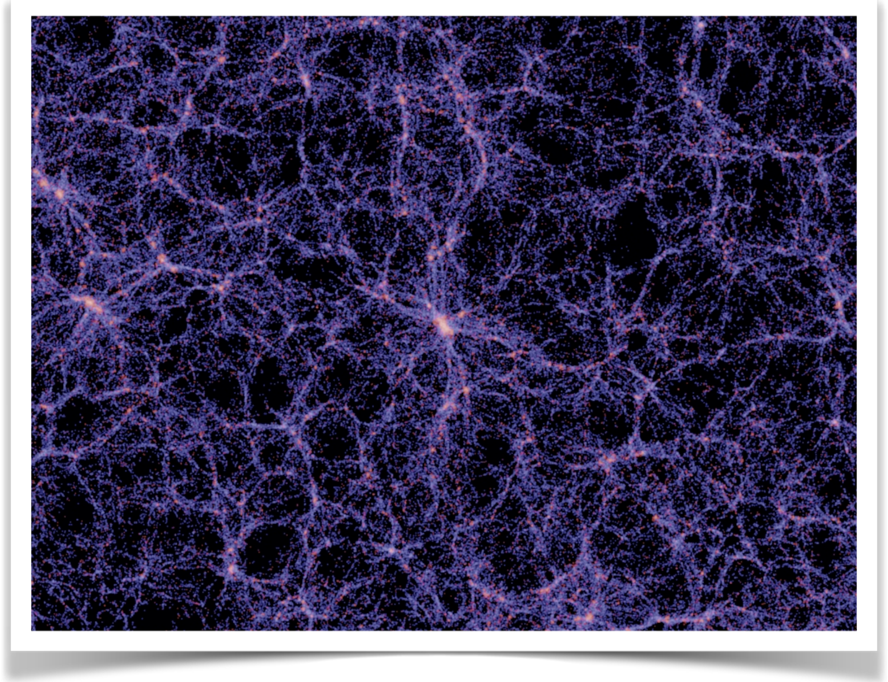
Scalar amplitude and tilt measured precisely on large scales, explained well by SFSR models

Inflationary Perturbations

$$ds^2 = a^2(\eta)\left[-d\eta^2 + \left(e^{2\zeta}\delta_{ij} + h_{ij}\right)dx^i dx^j\right]$$

Not detected so far





B-modes and GW

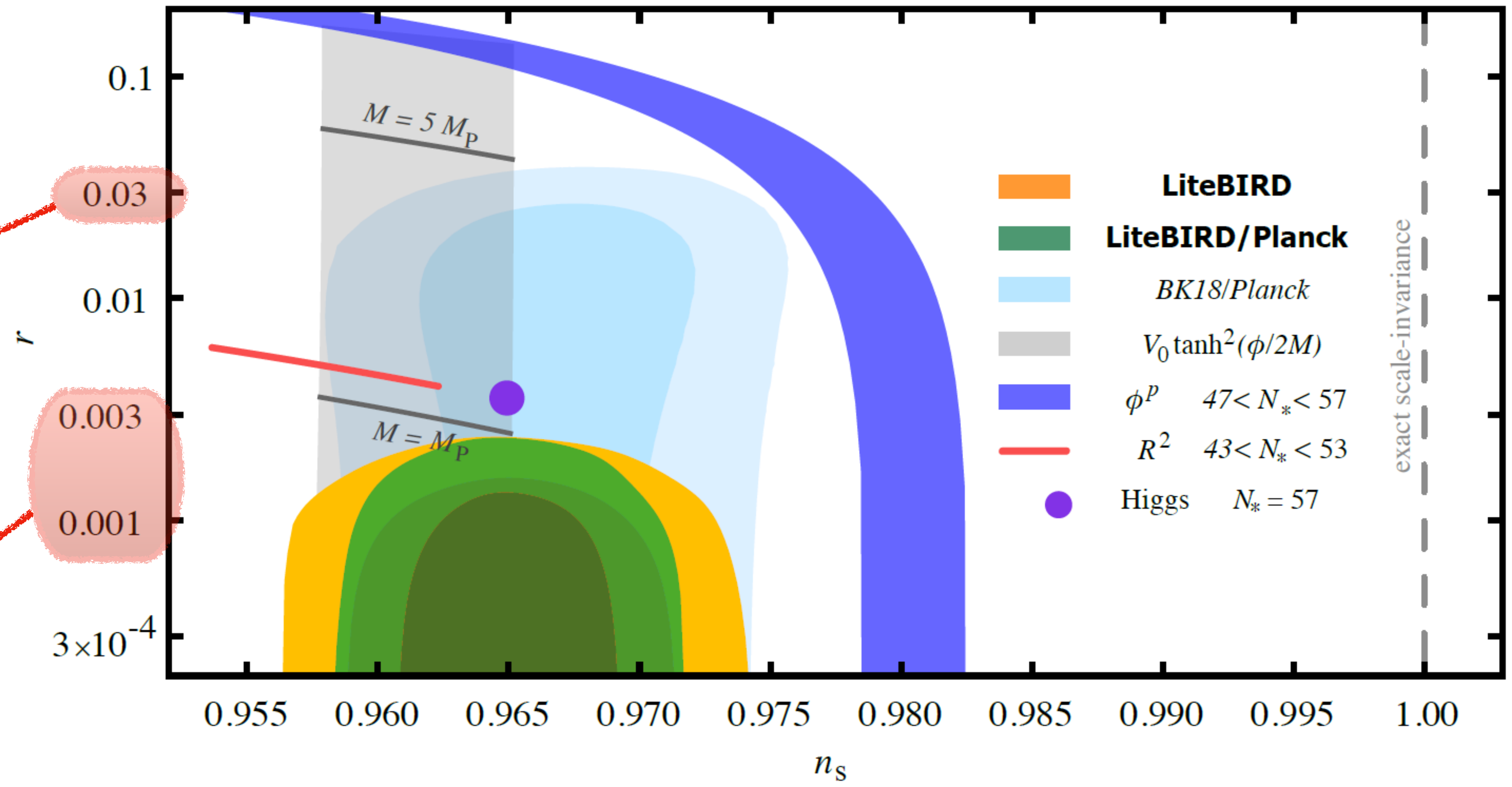
GW lead to ***B*-mode** polarisation of CMB

SFSR spectrum

$$\mathcal{P}_h(k) = r\, A_\mathrm{s} \left(\frac{k}{k_\mathrm{p}}\right)^{n_\mathrm{T}}$$

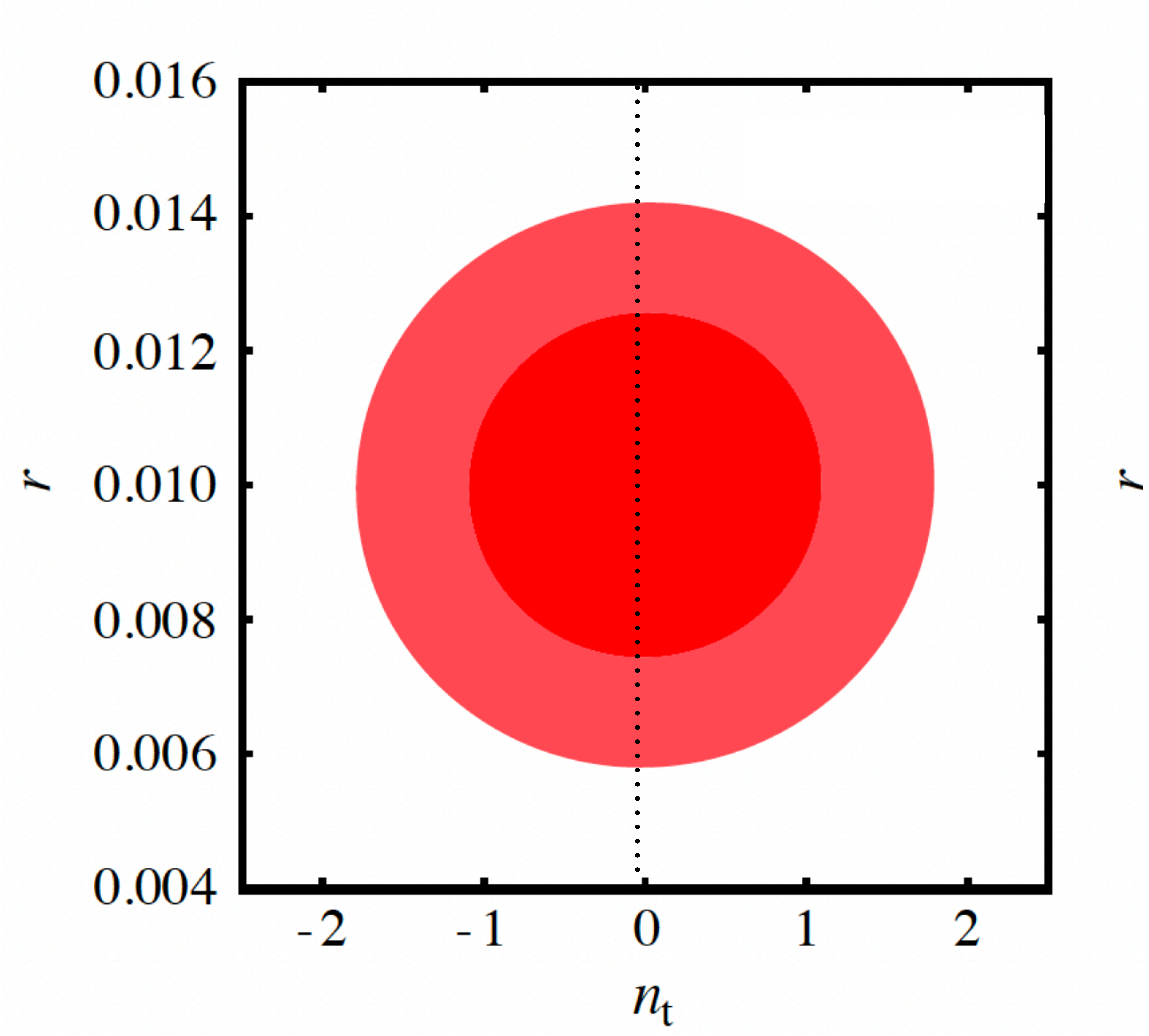
Current upper limit

Expected sensitivity of SO, CMB-S4, LiteBIRD etc.



Credit: LiteBIRD collaboration [arxiv:2202.02773]

SFSR consistency



CMB-S4 collaboration

SFSR also predicts $n_T = -r/8$, however, this will be hard to test.

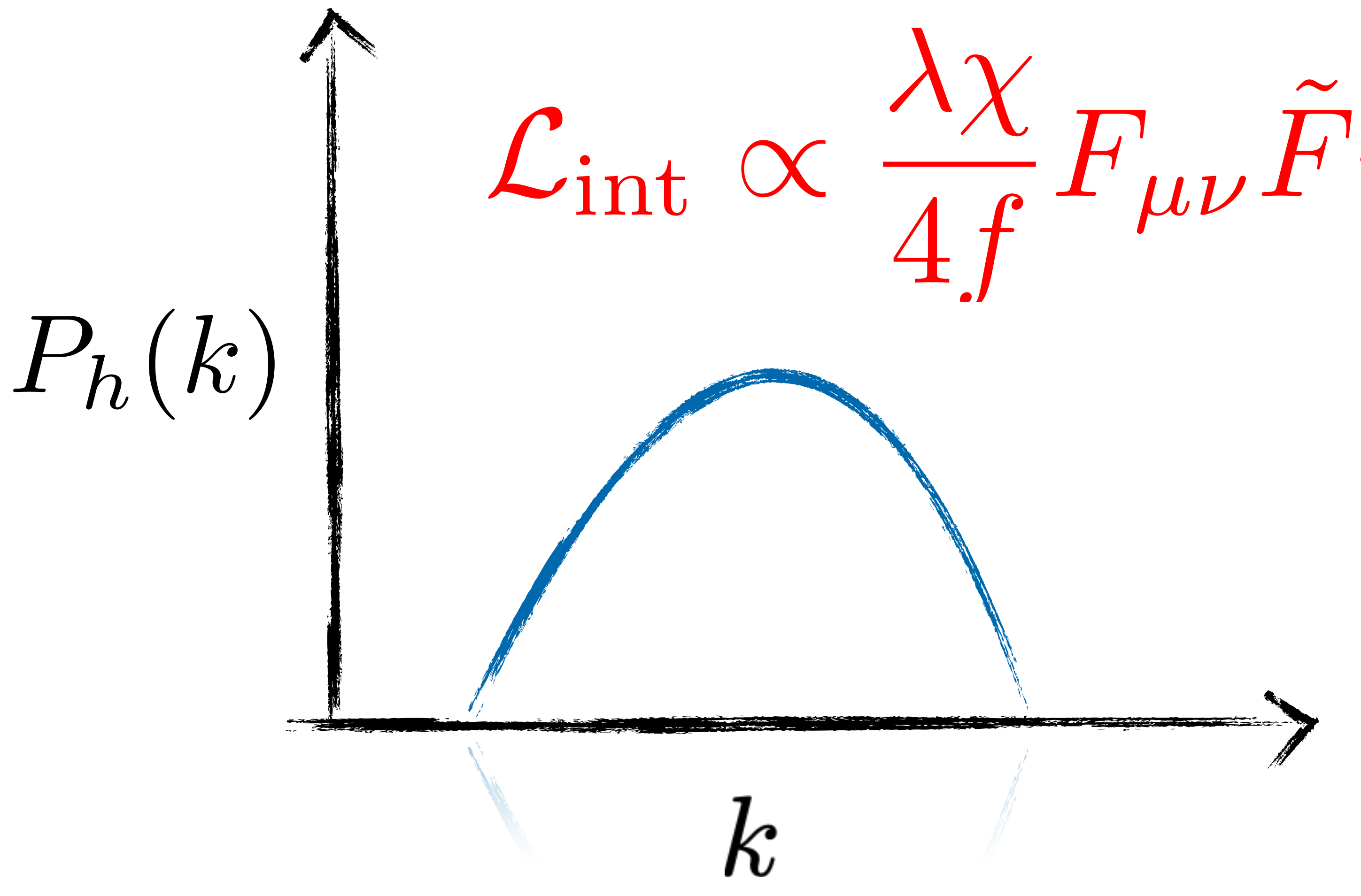
Deviations from SFSR consistency

- Possible to test for deviations
- e.g. Models involving axion + gauge fields may produce a bump like feature

[Dimastrogiovanni et al. 2016, Thorne et al. 2017 + more]

$$\mathcal{L}_{\rm int} \propto \frac{\lambda\chi}{4f} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\left[\partial_\eta^2 + k^2 \pm \frac{2k\xi}{\eta}\right] A_\pm(k,\eta) = 0, \quad \xi = \frac{\dot{\chi}}{2Hf}$$

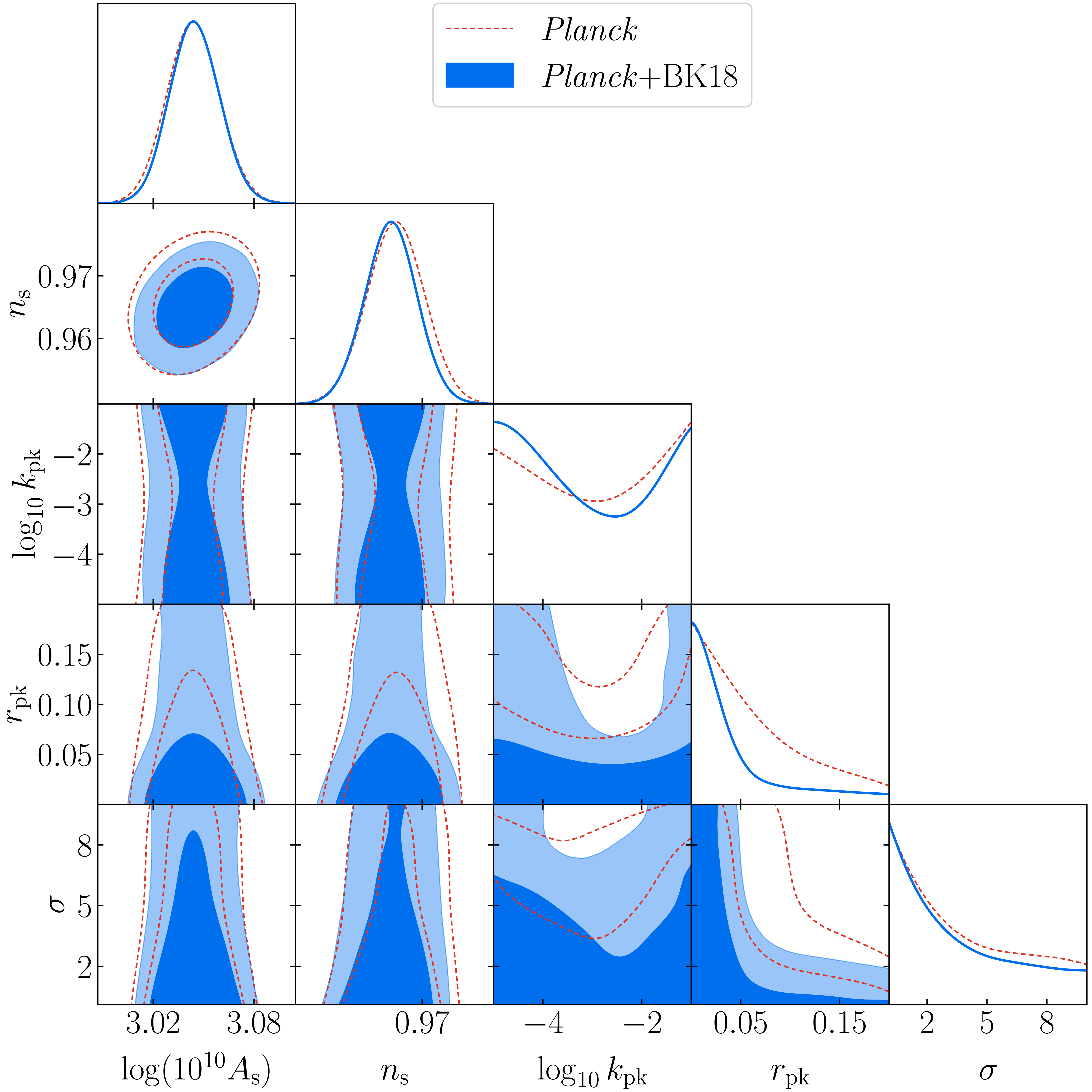


Current constraints

$$\mathcal{P}_h = r_{\rm pk} A_s \exp\left[-\frac{\ln(k/k_{\rm pk})^2}{2\sigma^2}\right]$$

Parameter	68% limit
$\boldsymbol{\sigma}$	< 4.83
$\boldsymbol{r}_{\bf pk}$	< 0.0460

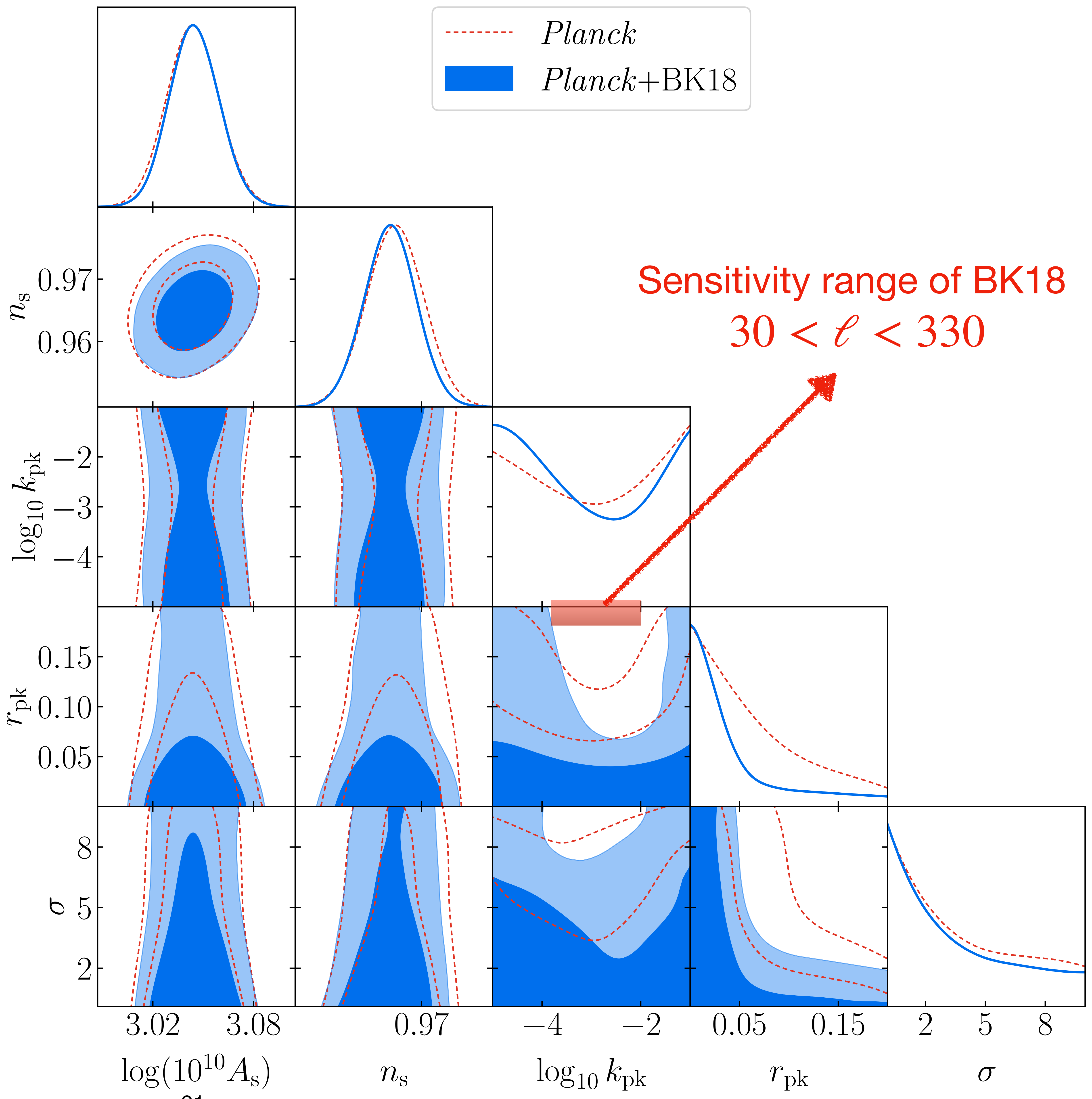
[Hamann and **AM**, *JCAP* 12 (2022) 015]



Current constraints

$$\mathcal{P}_h = r_{\rm pk} A_s \exp\left[-\frac{\ln(k/k_{\rm pk})^2}{2\sigma^2}\right]$$

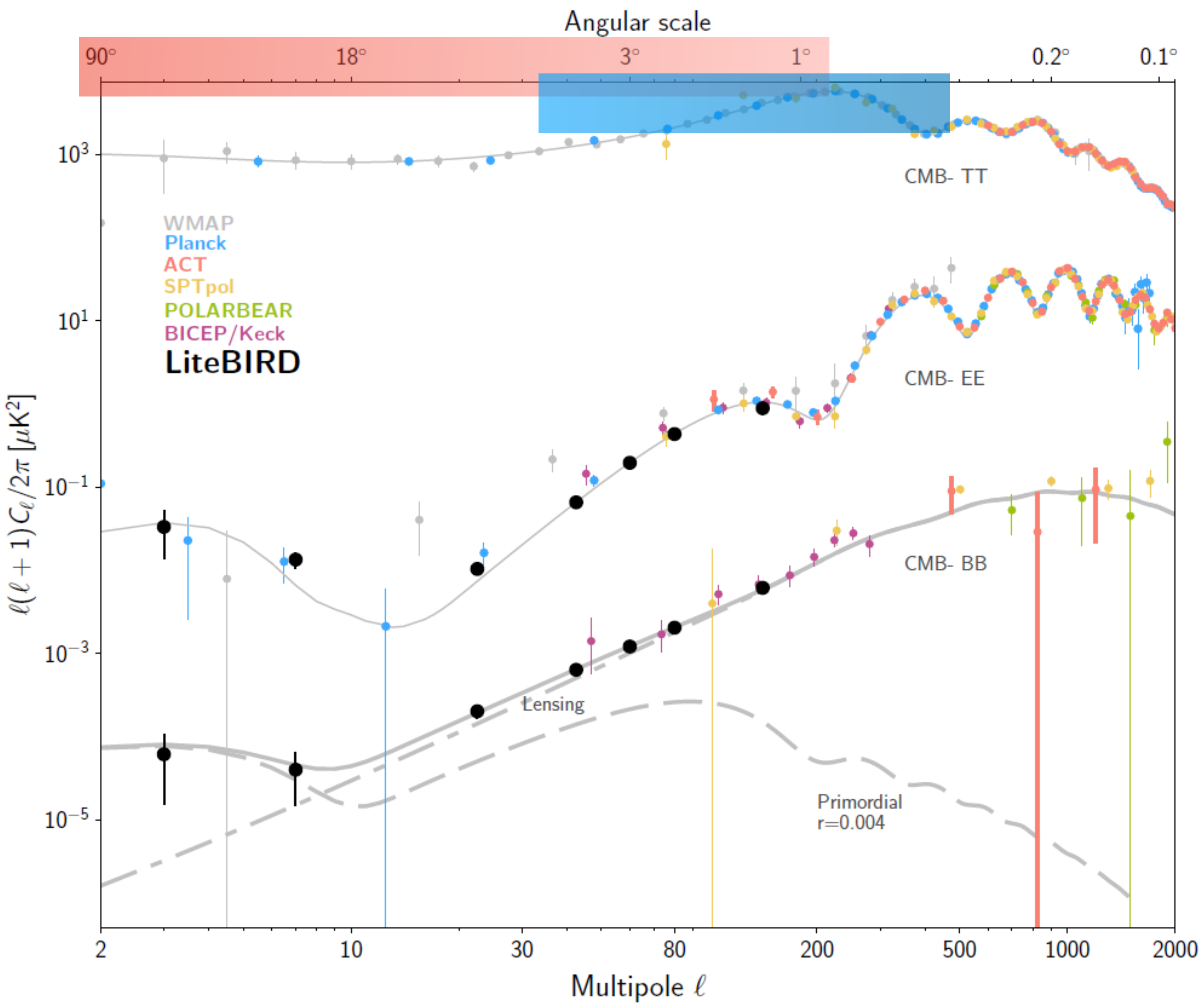
Parameter	68% limit
$\boldsymbol{\sigma}$	< 4.83
$\boldsymbol{r_{\rm pk}}$	< 0.0460



[Hamann and **AM**, *JCAP* 12 (2022) 015]

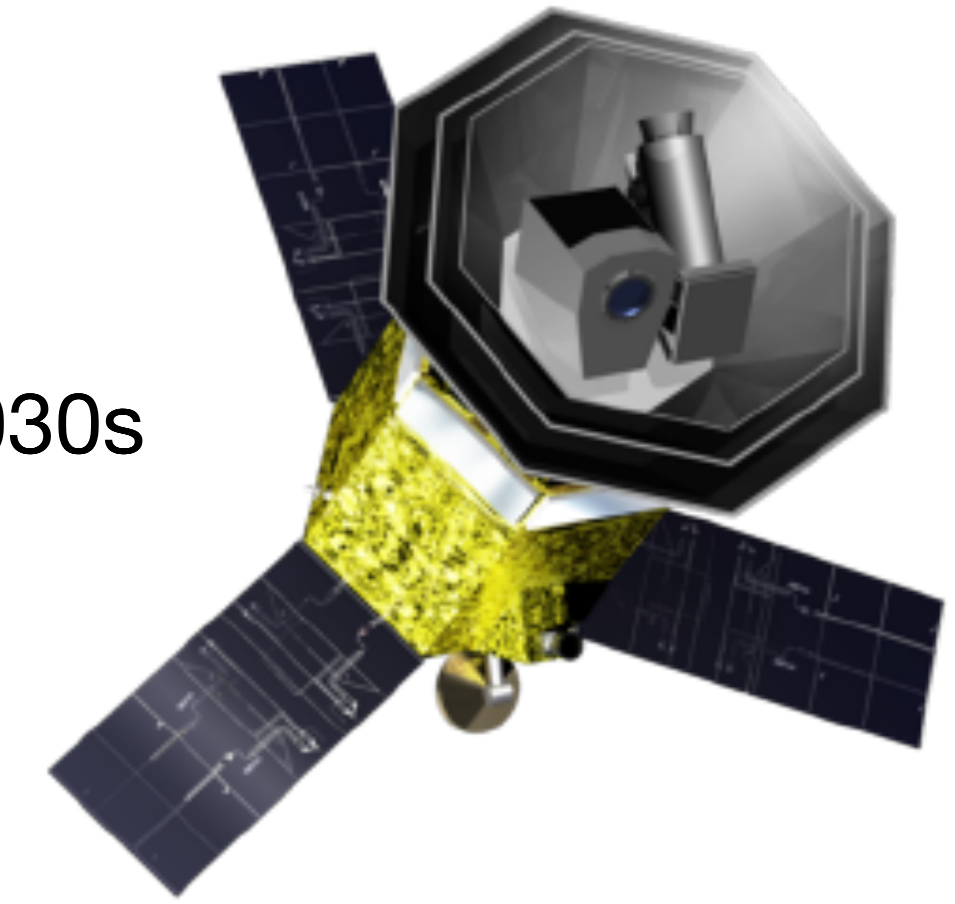
Forecasts with LiteBIRD + CMB-S4

$2 < \ell < 200$ $30 < \ell < 330$



Credit: LiteBIRD collaboration

2030s

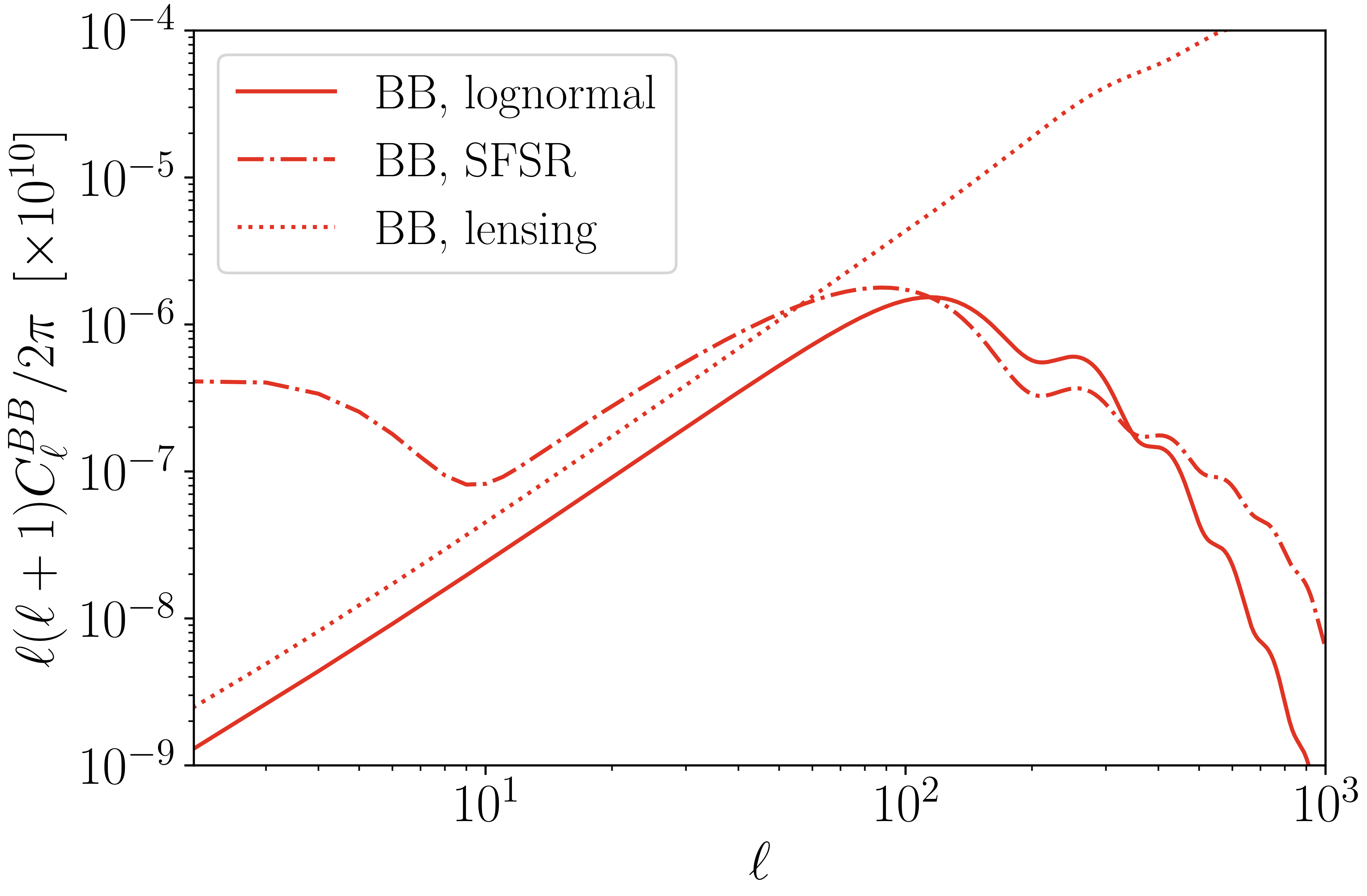


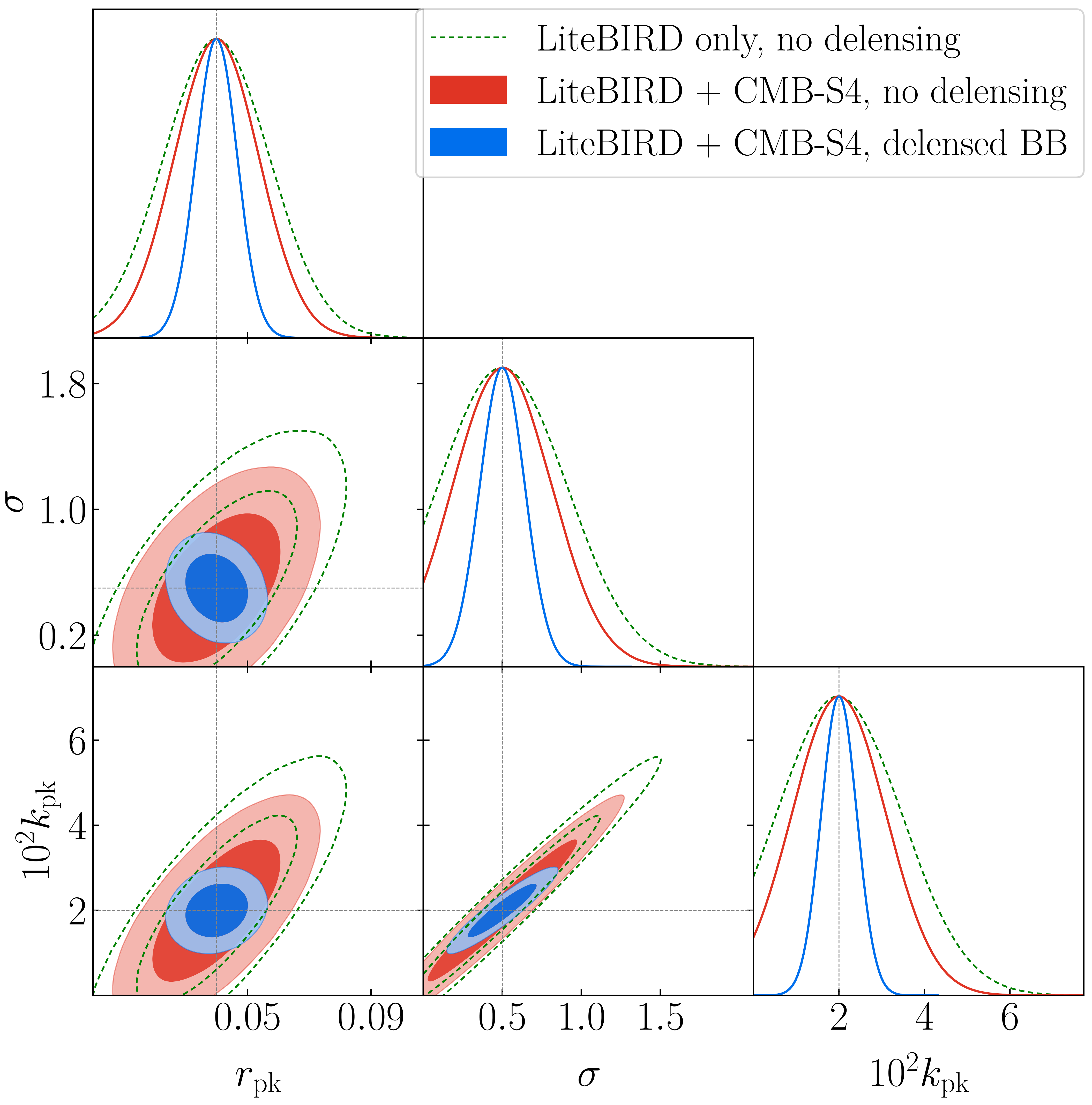
LiteBIRD

CMB-S4 (SPT+)

Small scale feature

$$r_{\rm pk} = 0.04,\ \sigma = 0.5,\ k_{\rm pk} = 2\times 10^{-2}\,{\rm Mpc}^{-1}$$





Delensing important for small scale features

Tensor NG

SFSR fluctuations are **Gaussian**.

GW may also be sourced by additional fields (or other non-standard dynamics)

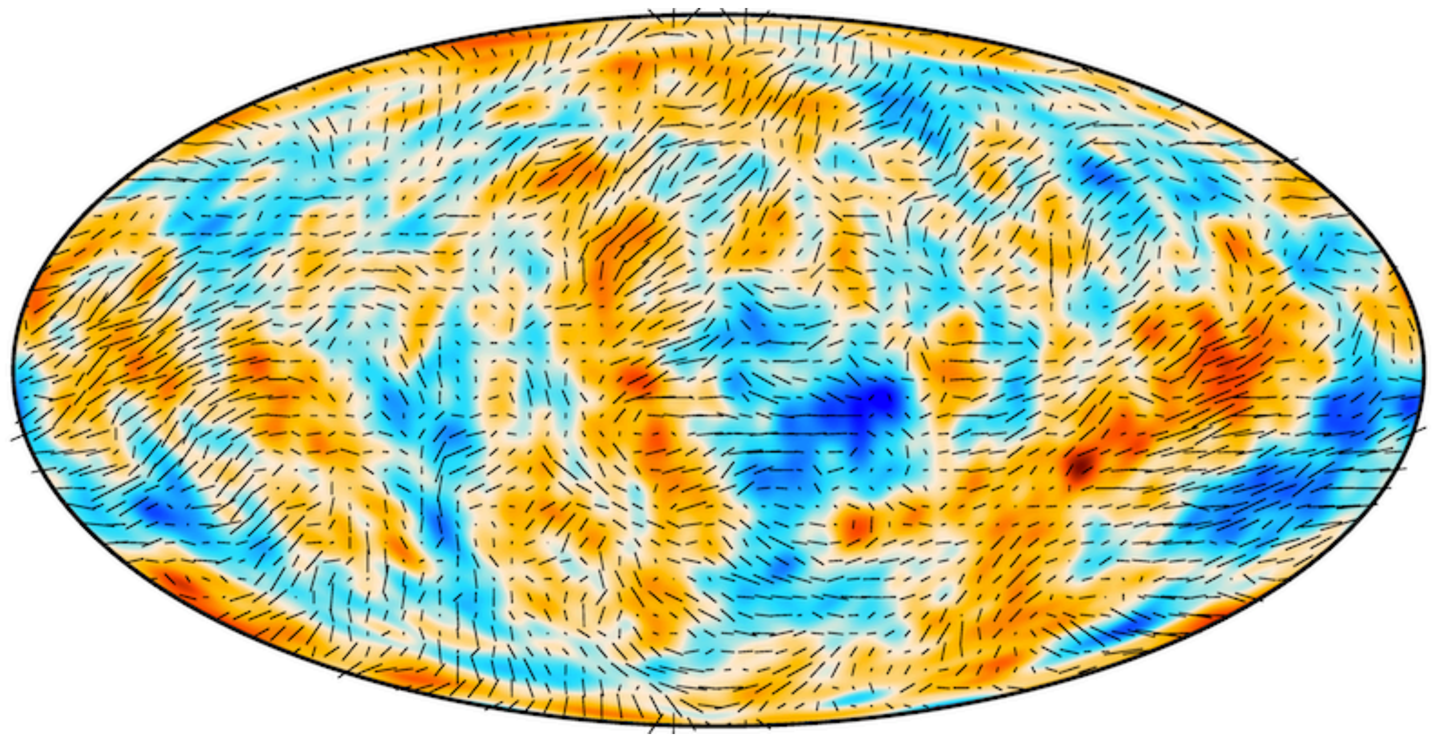
$$h''_{ij} + 2\mathcal{H}h'_{ij} + k^2 h_{ij} = 16\pi a^2 G \Pi_{ij}^{\rm TT}$$

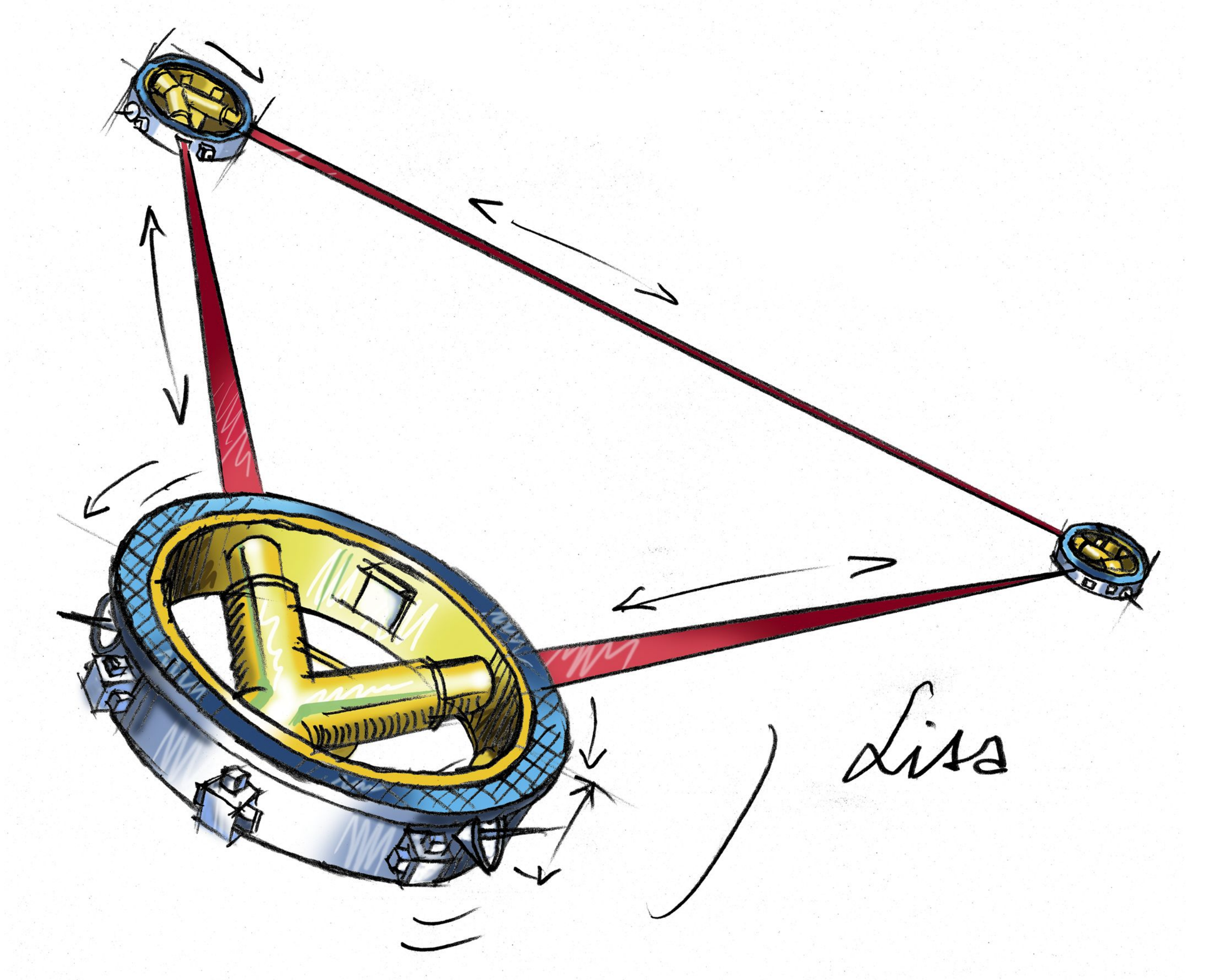
Non-Gaussianity provides additional information beyond power spectrum, hints to nature of interactions —"***cosmological collider physics***"

[Noumi et al. (2012); Arkani-Hamed, Maldacena (2015); Kehagias, Riotto (2015); Lee et al. (2016)+more!]

Tensor NG probes

$\langle BBB \rangle, \langle BBT \rangle \ldots$





$k_{\mathrm{CMB}} \sim 10^{-3}\mathrm{Mpc}^{-1}$

$k_{\mathrm{GW}} \sim 10^{12}\mathrm{Mpc}^{-1}$

$\Delta N \sim 30$

Direct detection of tensor NG

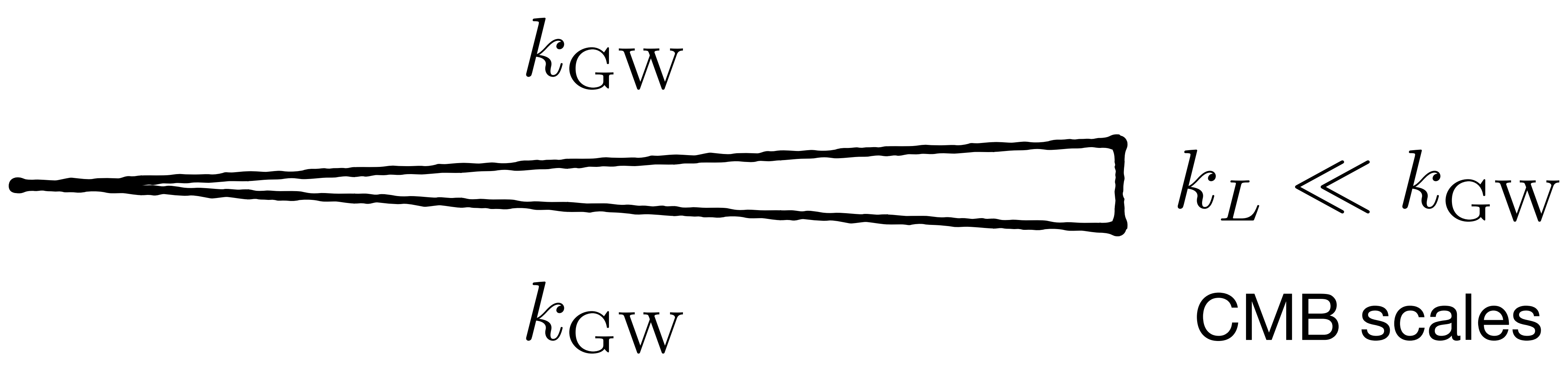
- Unfortunately, interferometers cannot directly measure NG of h
- Decorrelation due to propagation effects Gaussianizes the signal
- Observed $\langle h^{2n+1} \rangle$ vanishes for the SGWB [Bartolo et al. (2018), Margalit et al. (2020)]

Direct detection of tensor NG

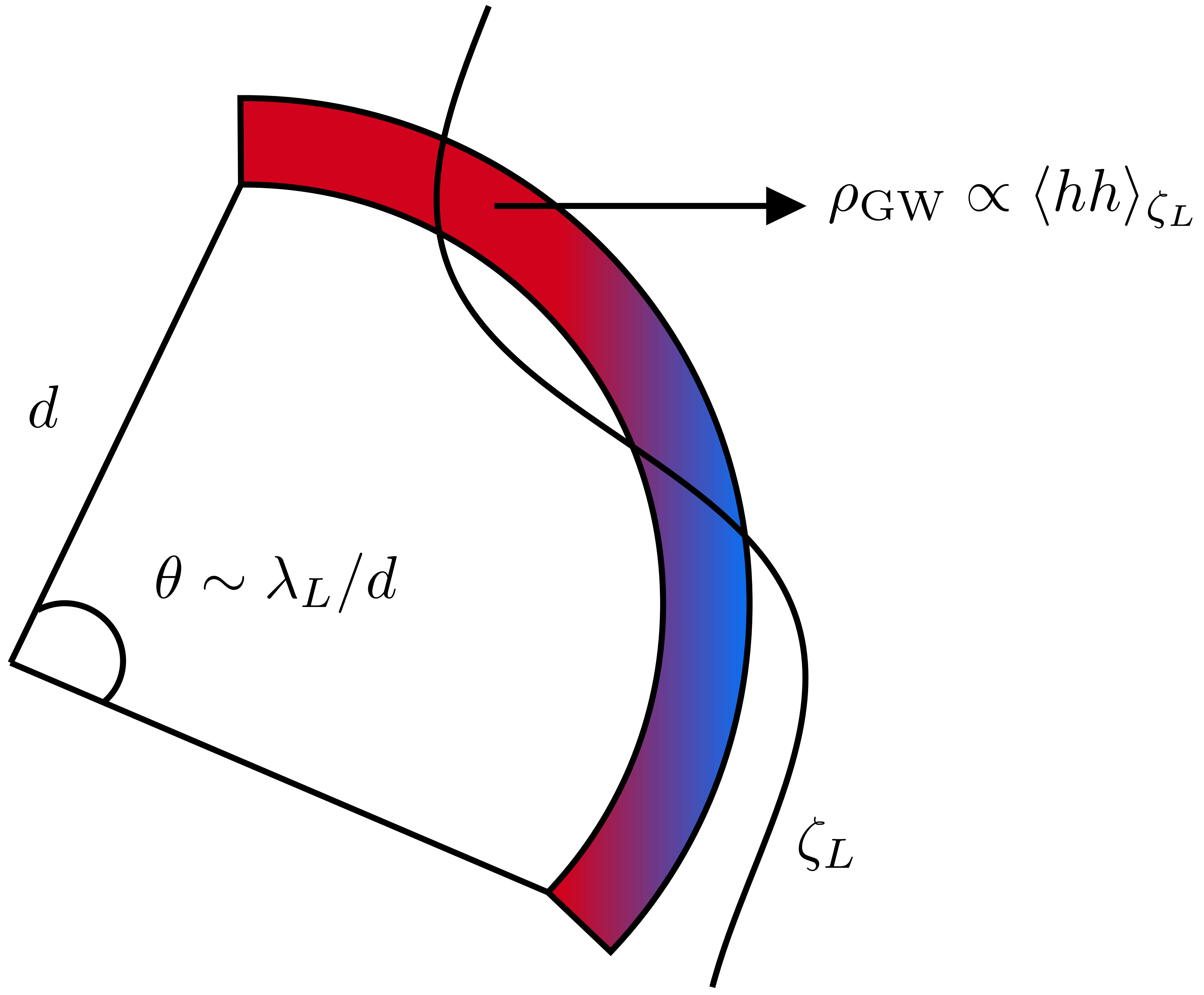
- Unfortunately, interferometers cannot directly measure NG of h
- Decorrelation due to propagation effects Gaussianizes the signal
- Observed $\langle h^{2n+1} \rangle$ vanishes for the SGWB [Bartolo et al. (2018), Margalit et al. (2020)]

How do we get around this?

NG via SGWB anisotropies



$$\delta_{\rm GW} \sim F_{\rm NL} X_L , \quad X = \zeta,\, h$$



Anisotropies may still be used to constrain $F_{\rm NL}$!

$$F_{\rm NL} = \frac{B_{Xhh}(k_L, k_{\rm GW})}{P_X(k_L) P_h(k_{\rm GW})}$$

[**AM**, Dimastrogiovanni, Fasiello, Shiraishi *JCAP* 03 (2021) 088]
[Dimastrogiovanni, Fasiello, **AM**, Orlando, Meerburg *JCAP* 02 (2022) 02, 040]

Summary

- SGWB a promising probe of primordial physics — missing piece of inflationary puzzle
- Spectral shape, non-Gaussianity, anisotropies and polarisation are key to characterising the SGWB
- Exciting results from PTAs and hopefully from CMB + interferometers in the near future