



# SEARCHING FOR PRIMORDIAL TENSOR MODES ACROSS SMALL AND LARGE SCALES

In collaboration with E. Dimastrogiovanni, M. Fasiello, J. Hamann, P.D. Meerburg, G. Orlando, M. Shiraishi and G. Tasinato

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Ameek Malhotra

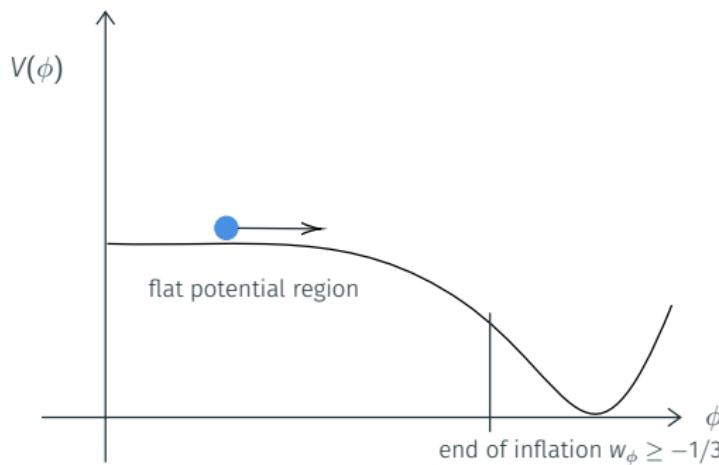
27 June, 2022

Sydney CPPC Meeting 2022

# Inflation

## Minimal scenario (SFSR)

- Single scalar field  $\phi$
- slowly rolling  $\dot{\phi}^2 \ll V$
- $p_\phi \simeq -\rho_\phi \implies w_\phi \simeq -1$  drives exponential expansion

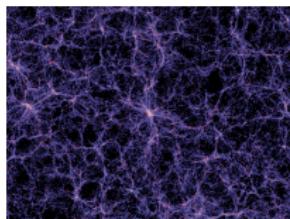
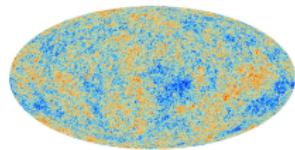


# Inflationary perturbations

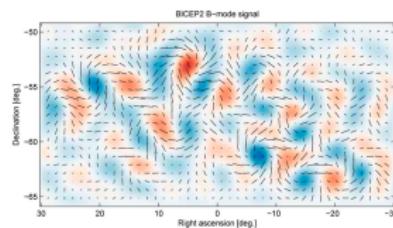
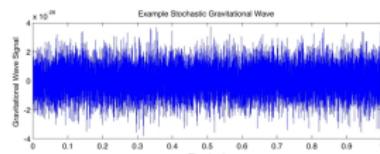
$$ds^2 = a^2(\eta) \left\{ -d\eta^2 + \left[ e^{2\zeta} \delta_{ij} + h_{ij} \right] dx^i dx^j \right\}$$

tensor perturbations (GW)

scalar perturbations - Gaussian, nearly scale invariant



[Images: ESA/Planck and V.Springel]



[Images: A. Stuver/LIGO and BICEP]

# GW from SFSR Inflation

Gaussian and unpolarised

$$\mathcal{P}_T(k) = A_T \left( \frac{k}{k_p} \right)^{n_t}$$

$n_t \simeq -2\epsilon < 0$

$A_T \propto H^2$ , Energy scale of Inflation

CMB bounds on  $r \equiv A_T/A_s$

- $r < 0.032$  [Tristam et al. (2021)]

Future sensitivity

- $r \sim 0.001$  [LiteBIRD/CMB-S4]

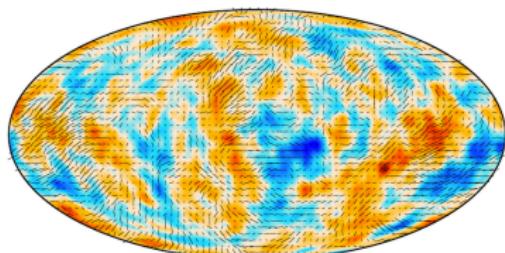
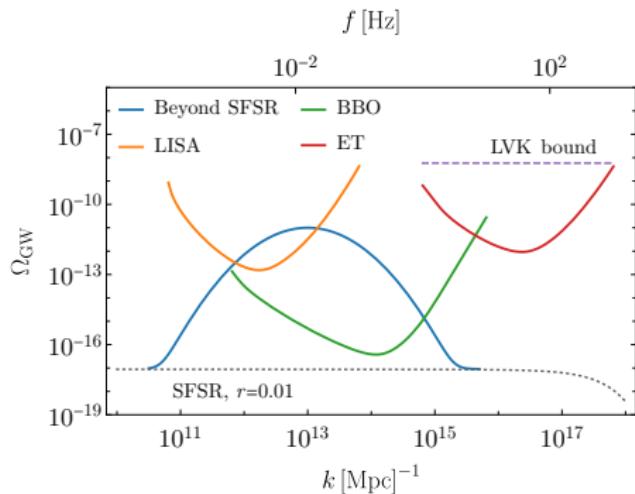


Image credit: ESA/Planck

# Beyond SFSR

With present and future planned detectors, interferometric observations of inflationary GW (and its polarisation and nG) requires ***small scale enhancement*** of the tensor power spectrum.



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

Sourced by additional fields

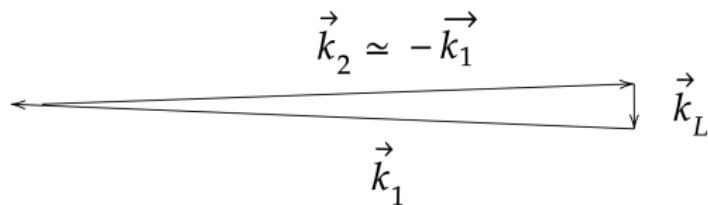
[Cook, Sorbo (2012); Barnaby et al. (2012); Biagetti et al. (2014); Fujita et al. (2012); Dimastrogiovanni et al. (2016); Bordin et al. (2018); Iacconi et al. (2020a); Iacconi et al. (2020b); Campeti et al. (2022) + many more!]

# non-Gaussianity

What can we learn from observing primordial non-Gaussianity?

Probe the action beyond the free field limit → *Interactions*

Focus on squeezed limit nG

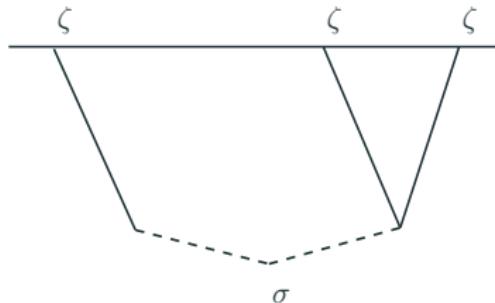


Large squeezed nG → clear signature of beyond SFSR dynamics

# non-Gaussianity

Signature of additional field with mass  $m$  and spin  $s$  in the squeezed bispectrum,

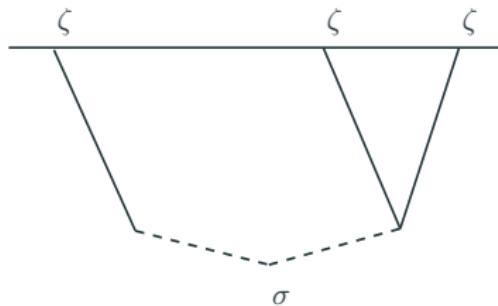
$$\lim_{k_L \rightarrow 0} \langle \zeta_{\vec{k}_L} \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle' \propto \frac{1}{k_L^3 k_2^3} \left( \frac{k_L}{k_2} \right)^{3/2 - \nu_s} \mathcal{P}_s(\hat{k}_L \cdot \hat{k}_2)$$
$$\nu_s = \sqrt{(s - 1/2)^2 - m^2/H^2}, \quad \nu_s \in \mathbb{R}$$



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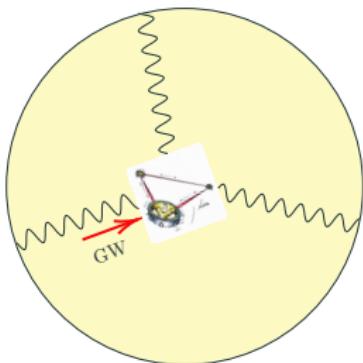


additional angular dependence

## Observing tensor nG

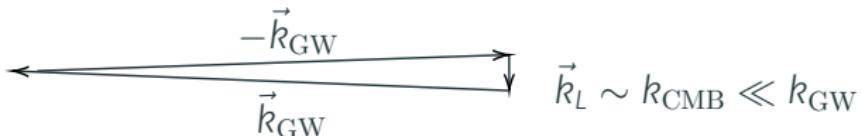
GW propagate through inhomogeneities  $\Rightarrow$  directional phase shift  
 $\therefore$  non-Gaussian information is lost [Bartolo et al. (2019)]

Odd n-point functions of  $\mathbf{h}$  cannot be reconstructed due to propagation effects  
[Margalit et al. (2020)]



## Observing tensor nG

Workaround : probe ultra-squeezed bispectrum via anisotropies of the energy density which is insensitive to the phase



Primordial squeezed non-Gaussianity  $\rightarrow$  long wavelength modes modulate power spectrum of short wavelength modes  
[Jeong, Kamionkowski (2012); Dai et al. (2013)]

# Anisotropies from non-Gaussianity

Directional intensity flux of the SGWB,

$$\Omega_{\text{GW}}(f, \hat{n}) = \bar{\Omega}_{\text{GW}}(f)[1 + \delta_{\text{GW}}(f, \hat{n})]$$

with monopole  $\bar{\Omega}_{\text{GW}} \propto \bar{\mathcal{P}}_h$  and anisotropy

$$|\delta_{\text{GW}}| \sim F_{\text{NL}} \sqrt{A_S} \sim 10^{-4} F_{\text{NL}}$$

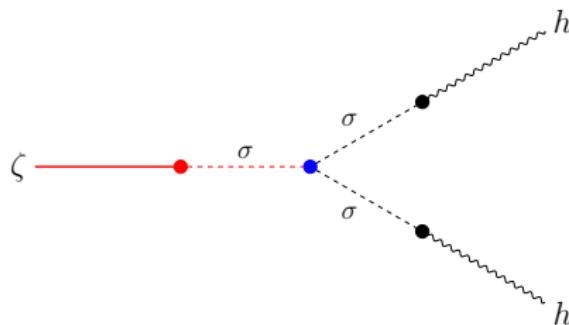
$$F_{\text{NL}} = \frac{B_{\zeta hh}^{\text{sq}}(\vec{k}_L, \vec{k}, -\vec{k})}{\mathcal{P}_\zeta(k_L)\mathcal{P}_h(k)}, \quad \text{similarly for } \langle hhh \rangle$$

Also correlated with the large scale CMB anisotropies  $|\Delta T/T| \sim \sqrt{A_S}$ , sourced by the same  $\zeta_{\vec{k}_L}$ !

# Anisotropies from STT

If  $\sigma$  is a spin-2 field,  $\langle \zeta_{\vec{R}_L \rightarrow 0} h_{\vec{k}} h_{-\vec{k}} \rangle$  has angular dependence s.t.,

$$B_{\zeta hh}^{\text{sq}}(\vec{k}_L, \vec{k}, -\vec{k}) = \tilde{B}_{\zeta hh}^{\text{sq}}(k_L, k) \times \underbrace{\mathcal{P}_2(\hat{k}_L \cdot \hat{k})}_{\text{quadrupolar dep.}}$$

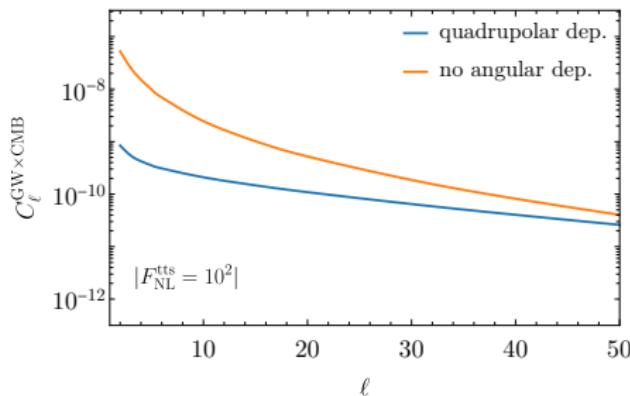


[Bordin et al. (2018); Iacconi et al. (2020a); Iacconi et al. (2020b)]

# Anisotropies from STT

How does the angular dependence affect the anisotropies?

$$|C_\ell^{\text{GW} \times \text{CMB}}| \propto \begin{cases} \frac{1}{\ell^2} & \text{no angular dep.} \\ \frac{1}{\ell^{1/2}} & \text{quadrupolar dep.} \end{cases}$$



GW  $\times$  CMB could also test primordial nature of signal

Scaling with  $\ell$  quite different!

# Anisotropies from NG

Possible to also see effects of scale dep. non-Gaussianity

$$C_\ell^{\text{GW}}(f) \simeq C_\ell^{\text{GW}}(f_{\text{ref}}) \times \left(\frac{f_{\text{ref}}}{f}\right)^{3 - 2\nu_s}$$

Recall,

$$\nu_s = \sqrt{(s - 1/2)^2 - m^2/H^2}$$

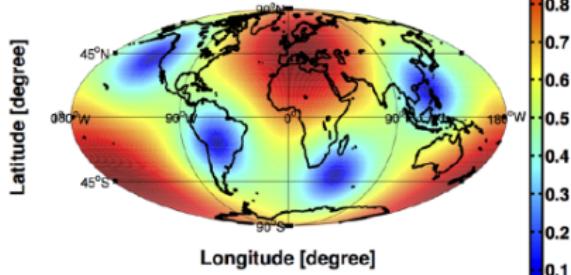
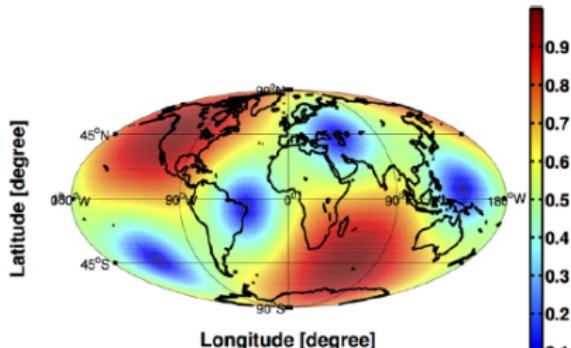
Models + TTT analysis + forecasts for  $F_{\text{NL}}$

[Dimastrogiovanni, Fasiello, AM, Meerburg, Orlando (2022)]

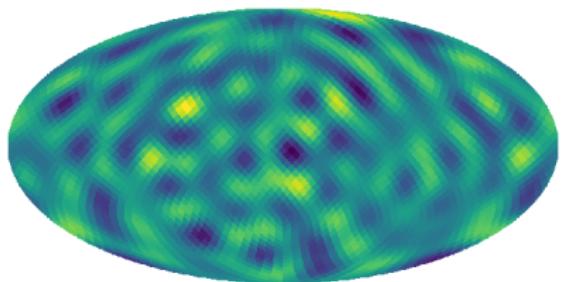
[AM, Dimastrogiovanni, Fasiello, Shiraishi (2021)]

# SGWB detection

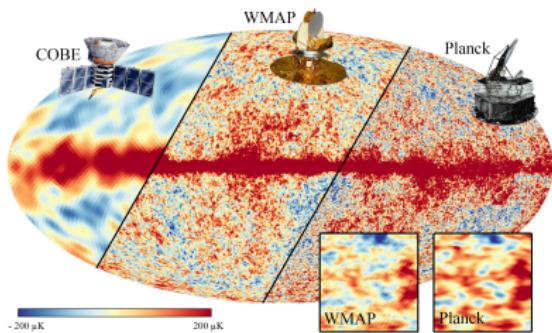
An interferometer is *not* a pointed instrument



# SGWB Angular resolution



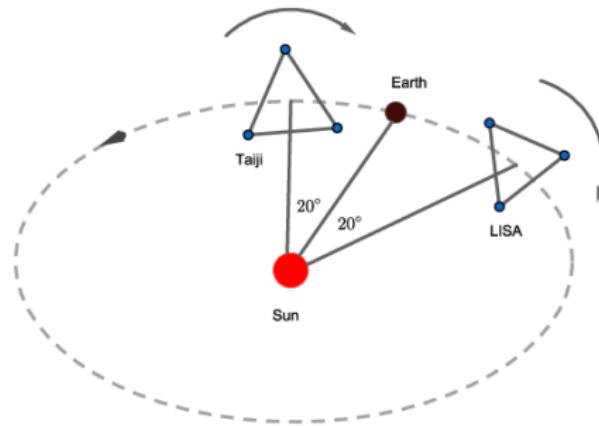
We are here



CMB for scale

# Optimal detector configurations

SGWB detected by cross-correlating signals across different detectors



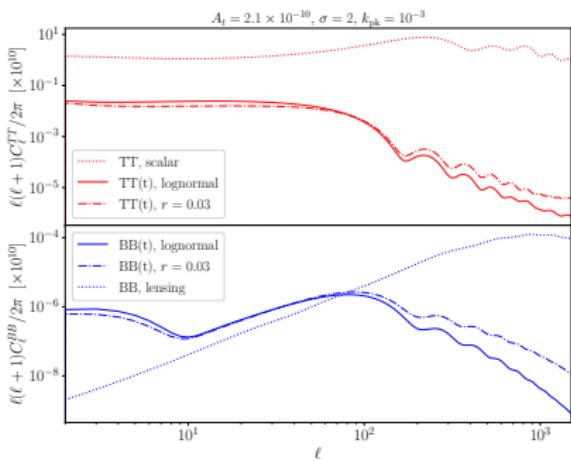
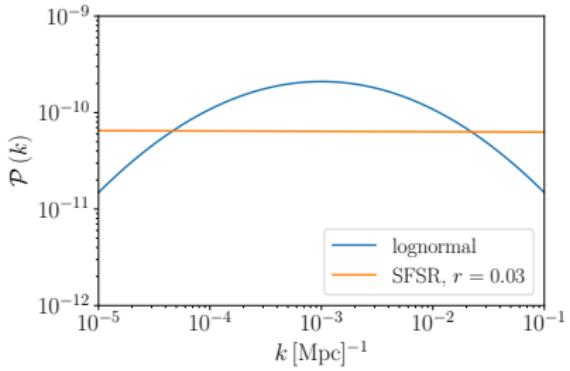
LISA-Taiji network [Ruan et al. (2020)]

How to maximise angular resolution for intensity + polarisation?  
[AM, Orlando - in progress]

# Tensor modes in the CMB

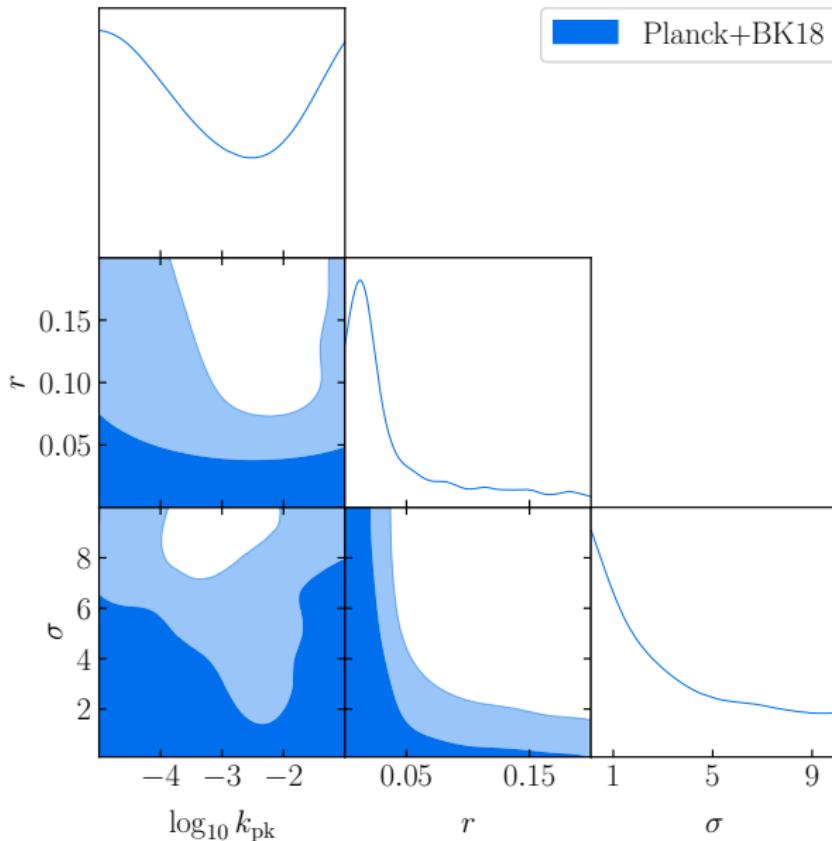
'Bump' feature in the tensor power spectrum

$$\mathcal{P}_T(k) = r A_S \exp \left[ -\frac{\ln^2(k/k_{\text{pk}})}{2\sigma^2} \right]$$

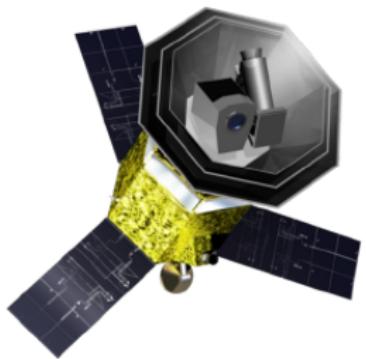


[AM, Hamann - in progress]

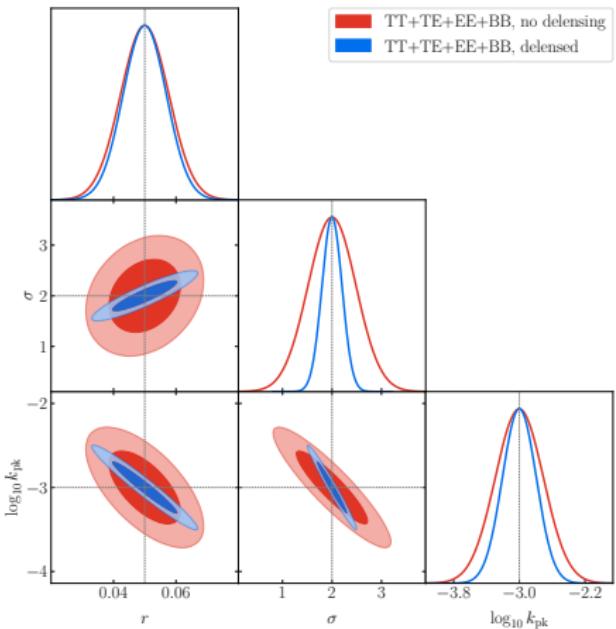
# Planck + BK18 constraints



# Forecast with LiteBIRD



parameter	value
$r$	0.05
$\sigma$	2
$k_{\text{pk}}$	$10^{-3}$



Thank you!