Gravitational wave anistropies as a probe of the inflationary particle content

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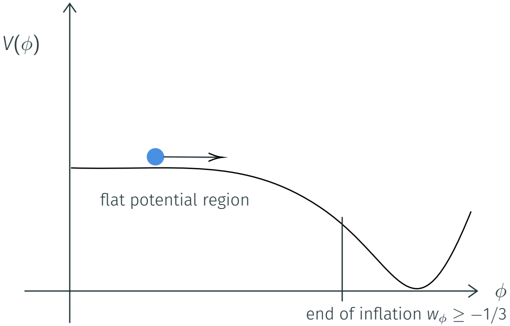
Cosmology from Home 2022

Inflation

Minimal scenario (SFSR)

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

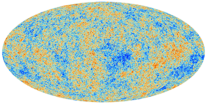


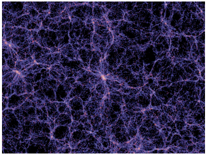
Inflationary perturbations

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

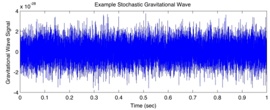
tensor perturbations (GW)

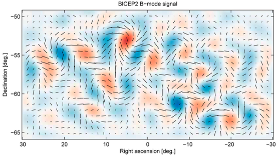
scalar perturbations - adiabatic, nearly scale invariant





[Images: ESA/Planck and V.Springel]





[Images: A. Stuver/LIGO and BICEP]

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)

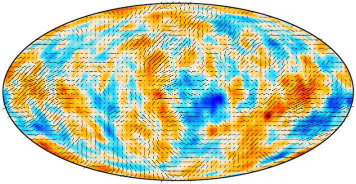
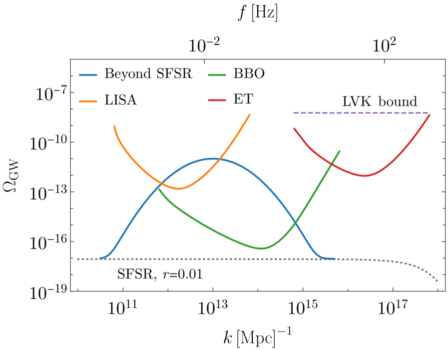


Image credit: ESA/Planck

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.



Beyond SFSR

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

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) + many more!]

Beyond SFSR

$$h_{ij}'' + 2\mathcal{H}h_{ij}' + k^2 h_{ij} + m_{\text{eff}}^2 h_{ij} = 0$$

Effective ‘mass’ term from alternative symmetry breaking patterns

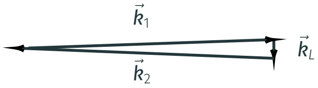
[Solid, Super-Solid Inflation - Endlich et al. (2012); Ricciardone, Tasinato (2016); Celoria et al. (2020) + more!]

Assuming the SGWB is detectable, what can we learn from observing primordial non-Gaussianity?

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

Consistency relation for squeezed nG in single field inflation,

$$\lim_{k_L \to 0} \langle \zeta_{\vec{k}_L} \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle' = P_\zeta(k_L) P_\zeta(k_2) \frac{d \ln k^3 P_\zeta(k_2)}{d \ln k_3}$$



[Maldacena (2003)]

[Creminelli & Zaladrriaga (2004)]

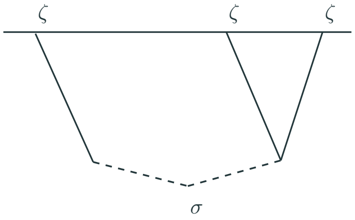
Single field nG is extremely small...

CRs violated if there are additional fields/alternative symmetry breaking patterns

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

$$\lim_{k_L \to 0} \langle \zeta_{\vec{k}_L} \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle' \propto \frac{1}{k_L^3 k_2^3} \left(\frac{k_L}{k_2} \right)^{3/2 - \nu_s} \mathcal{P}_s(\hat{k}_L \cdot \hat{k}_2)$$

$$\nu_s = \sqrt{(s - 1/2)^2 - m^2/H^2}, \quad \nu_s \in \mathbb{R}$$



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

non-Gaussianity

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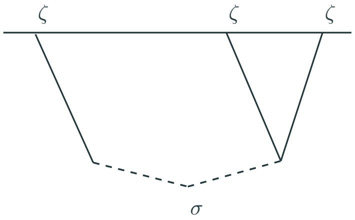
additional angular dependence



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

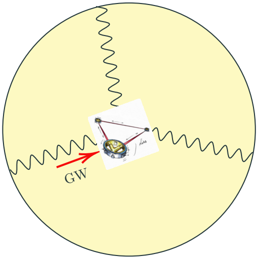
Observing tensor nG

Can we learn about primordial tensor interactions via direct detection? Not directly...

GW propagate through inhomegeneities $\implies$ directional phase shift

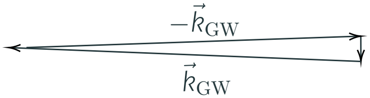
$\therefore$ **non-Gaussian information is lost** [Bartolo et al. (2019)]

Odd n-point functions of **h** cannot be reconstructed due to propagation effects [Margalit et al. (2020)]



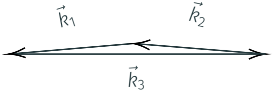
Observing tensor nG

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



$\vec{k}_L \sim k_{\rm CMB} \ll k_{\rm GW}$

Another possibility : folded bispectra - see Powell, Tasinato (2020)



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

Modulation of the short mode power spectrum leads to large scale variations in the energy density of GW produced in different regions.

Anisotropies from non-Gaussianity

e.g. for $\langle \zeta_{\vec{k}_L} h_{\vec{k}} h_{-\vec{k}} \rangle$ with $k_L \ll k$,

$$\mathcal{P}_h^{\rm mod}(\vec{k},\vec{x}) = \bar{\mathcal{P}}_h(k) \left[1 + \int_{k_L \ll k} \frac{d^3 k_L}{(2\pi)^3} \, e^{i\vec{k}_L\cdot\vec{x}} \, F_{\rm NL}(\vec{k},\vec{k}_L) \, \zeta(\vec{k}_L) \right]$$

[Adshead, Afshordi, Dimastrogiovanni, Fasiello, Lim, Tasinato (2020)]

$$F_{\rm NL} = \frac{B^{\rm sq}_{\zeta hh}(\vec{k}_L, \vec{k}, -\vec{k})}{\mathcal{P}_\zeta(k_L)\mathcal{P}_h(k)} \sim \textit{interaction strength}$$

Similarly for $\langle h^3 \rangle$ [Dimastrogiovanni, Fasiello, Tasinato (2019)]

Anisotropies from non-Gaussianity

Directional intensity flux of the SGWB,

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

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

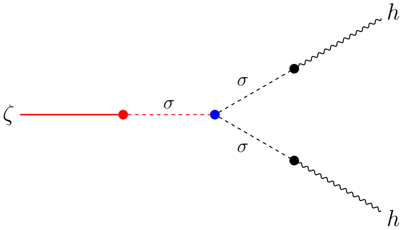
$$|\delta_{\rm GW}| \sim F_{\rm NL}\sqrt{A_S} \sim 10^{-4} F_{\rm NL}$$

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

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

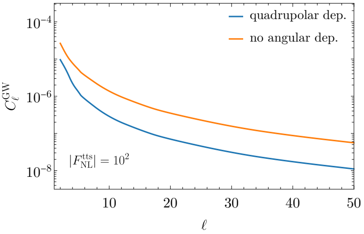


[Bordin et al. (2018); Iacconi et al. (2020a); Iacconi et al. (2020b)]

How does the angular dependence affect the anisotropies?

$$C_\ell^{\rm GW} \propto \frac{1}{\ell^2}$$

Scaling of auto-correlation with ℓ not significantly different



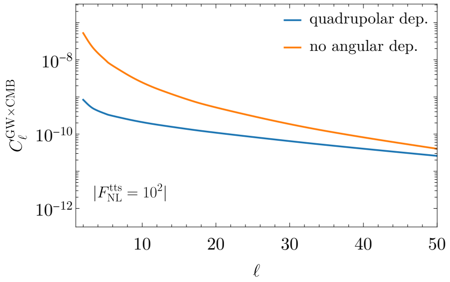
[Dimastrogiovanni, Fasiello, AM, Meerburg, Orlando (2022)]

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

Anisotropies from STT

How does the angular dependence affect the cross-correlation GW×CMB?

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



GW×CMB could also test primordial nature of signal

Scaling with ℓ quite different!

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

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

Recall,

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

Models + TTT analysis + forecasts for F_{NL} + more!

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

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

Summary

- Models with **small scale GW** can also have large **squeezed nG**
- Squeezed limit nG knows about **mass, spin** of additional fields during inflation
- Tensor nG can be detected at small scales via **SGWB anisotropies**
- Possible to **indirectly probe** both $\langle \zeta\, h\, h \rangle$ and $\langle h\, h\, h \rangle$ for large $\Omega_{\rm GW}$ and $|F_{\rm NL}| \gg 1$

Thank you!