Imprints of parity violation from gravitational waves V modes

Based on arXiv: 2206.14173 + other

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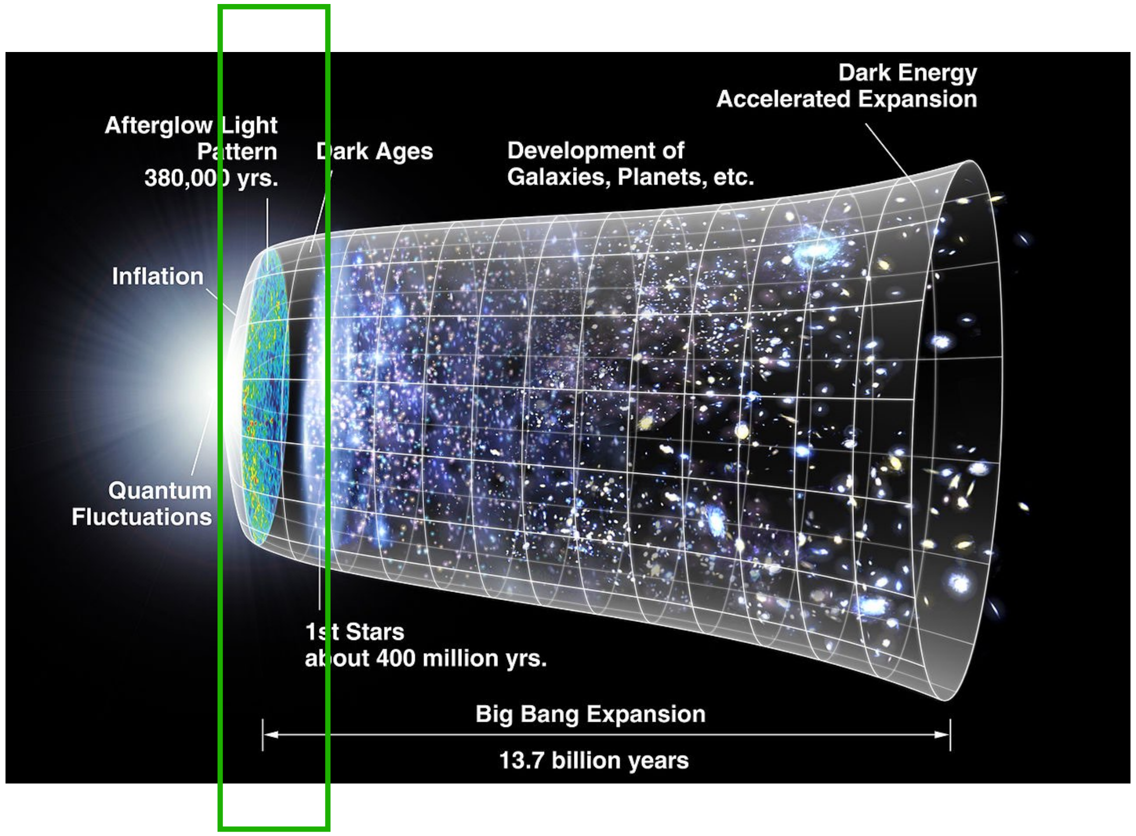
Outline



inflation: accelerated expansion

↓

cosmological perturbations (scalar and tensor)

- P-violation **can be introduced during inflation** in the context of known theories (Chern-Simons) or relying on symmetry principles.
- **No need** P-violation in **late times**.
- Might be unique probe of **new physics**.

1. Tensor sector and pnG to detect P-violation.
2. Large scale probes of P-violation.
3. SGWB V-mode to probe P-violation on small scales.

Scalar sector

- PARITY-ODD CORRELATORS:

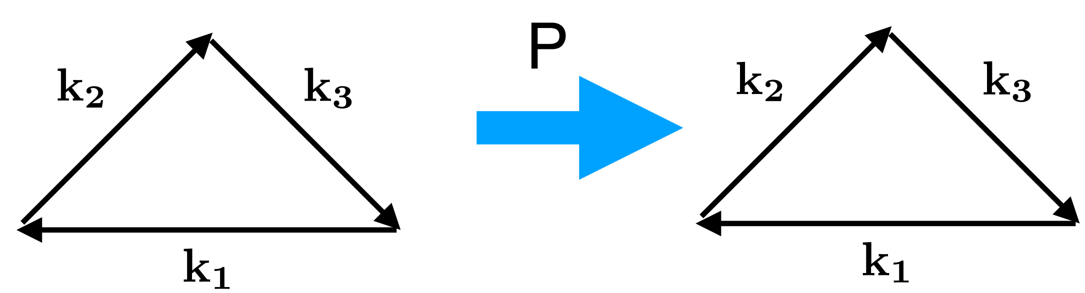
$$\langle X_{\mathbf{k}_1} ... X_{\mathbf{k}_n} \rangle_{\rm odd} = \langle X_{\mathbf{k}_1} ... X_{\mathbf{k}_n} \rangle - P(\langle X_{\mathbf{k}_1} ... X_{\mathbf{k}_n} \rangle)$$

$X = \zeta, \gamma^{\lambda}$ — ζ → scalar (s); γ^{λ} → tensor (t); $\lambda = R, L$

- POWER SPECTRUM AND BISPECTRUM:

- Depend on **magnitude of momenta**.

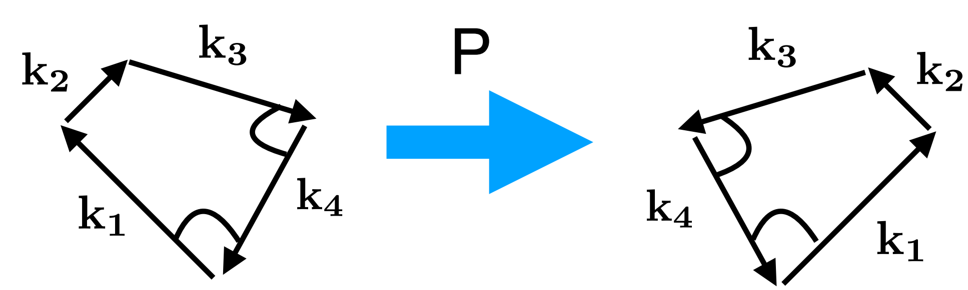
$$P(\langle \zeta_{k_1} \, \zeta_{k_2} \rangle) = \langle \zeta_{k_1} \, \zeta_{k_2} \rangle$$
$$P(\langle \zeta_{k_1} \, \zeta_{k_2} \, \zeta_{k_3} \rangle) = \langle \zeta_{k_1} \, \zeta_{k_2} \, \zeta_{k_3} \rangle$$
$$\langle \zeta\zeta \rangle_{\rm odd} = \langle \zeta\zeta\zeta \rangle_{\rm odd} = 0$$



- TRISPECTRUM:

- Depend on **magnitude of momenta + 2 angles**.

$$P(\langle \zeta_{\mathbf{k}_1} \, \zeta_{\mathbf{k}_2} \, \zeta_{\mathbf{k}_3} \, \zeta_{\mathbf{k}_4} \rangle) \neq \langle \zeta_{\mathbf{k}_1} \, \zeta_{\mathbf{k}_2} \, \zeta_{\mathbf{k}_3} \, \zeta_{\mathbf{k}_4} \rangle$$
$$\langle \zeta\zeta\zeta\zeta \rangle_{\rm odd, \, NG} \neq 0$$



Tensor sector

- Tensor perturbations possess 2 polarization states, **R- and L-handed**: $P(\gamma^R_{\mathbf{k}}) = \gamma^L_{-\mathbf{k}}$

- POWER SPECTRUM:

$$P(\langle \gamma^R_k \gamma^R_k \rangle) = \langle \gamma^L_k \gamma^L_k \rangle$$

$$\langle \gamma_k \gamma_k \rangle|_{\rm odd} = \langle \gamma^R_k \gamma^R_k \rangle - \langle \gamma^L_k \gamma^L_k \rangle$$

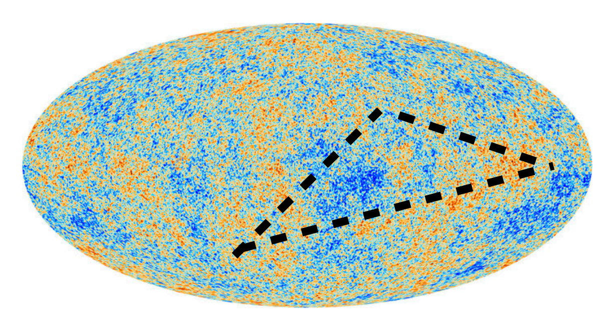
- Issue: **tensor perturbations not detected yet**.
(*r < 0.032, Tristram et. al. 2022)* $r = \frac{\langle \gamma\, \gamma \rangle}{\langle \zeta\, \zeta \rangle}$

- Tensor perturbations **Detected —>** $\mathbf{S/N} \sim \mathbf{r}$ (CMB)**:**
(e.g. Gerbino et. al. 2016) **challenging** to observe.

- TENSOR AND SCALAR-TENSOR BISPECTRA: $\langle \zeta\zeta\gamma \rangle_{\rm odd},\ \langle \zeta\gamma\gamma \rangle_{\rm odd},\ \langle \gamma\gamma\gamma \rangle_{\rm odd}$

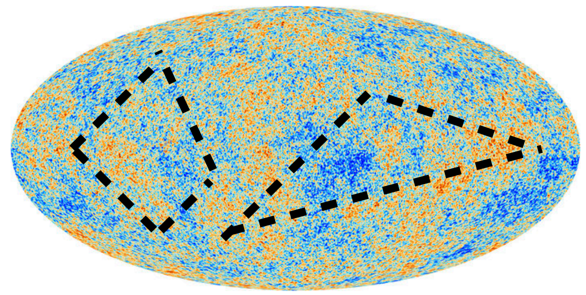
e.g. $\langle \zeta\zeta\gamma \rangle|_{\rm odd} = \langle \zeta_{k_1} \zeta_{k_2} \gamma^R_{k_3} \rangle - \langle \zeta_{k_1} \zeta_{k_2} \gamma^L_{k_3} \rangle$

- **Tensor perturbations detected —>** $\mathbf{S/N} \not\sim \mathbf{r}$ (CMB).
(e.g. Shiraishi 2019)



Large-scale probes of P-violation

CMB:



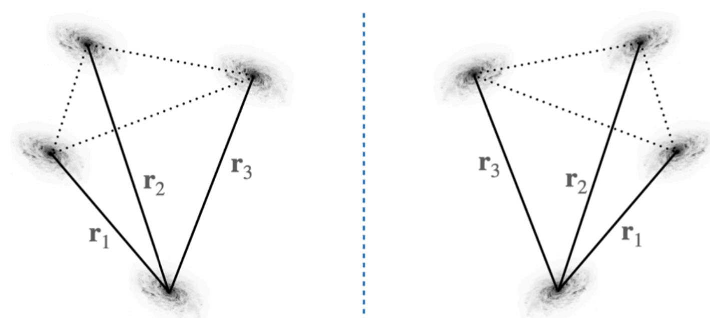
- BISPECTRUM: $\langle \gamma_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle|_{\mathrm{odd}} \longrightarrow \langle BTT \rangle$ **No detection of B modes**

*(e.g. Shiraishi, Liguori, Fergusson 2015; Bartolo, **Orlando**, Shiraishi 2017; Shiraishi 2019)*

- TRISPECTRUM: $\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \zeta_{\mathbf{k_4}} \rangle|_{\mathrm{odd}} \longrightarrow \langle TTTT \rangle$ **No evidence in Planck** *(Philcox 2023)*

(e.g. Shiraishi 2016)

Large Scale Structures:



Large scale overdensity-field:

- TRISPECTRUM: $\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \zeta_{\mathbf{k_4}} \rangle|_{\mathrm{odd}} \longrightarrow \langle \delta\delta\delta\delta \rangle$ **Observation in BOSS** *(e.g. Philcox 2022)*

Recap

no evidence of P-violation in $\langle\zeta\zeta\zeta\zeta\rangle_{\rm odd}$

→ Hidden in the cosmic variance (like $f_{\rm NL}\ldots$)

→ **P-violation** is there, but only in the **tensor and scalar-tensor sectors**

Future: SGWB

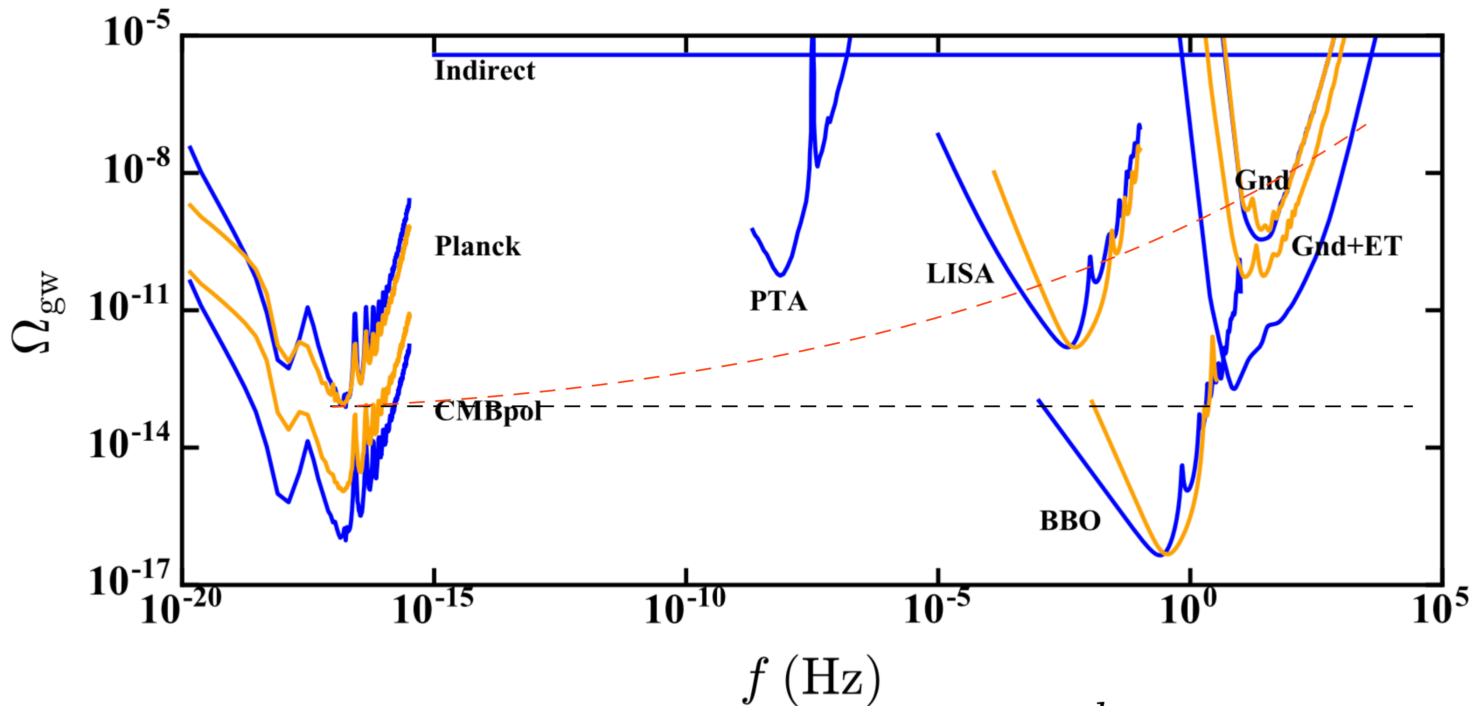
Unpolarised GWs (I modes):

$$\Omega^{I}_{\rm GW}(k) \propto \langle \gamma^R_k \gamma^R_k \rangle + \langle \gamma^L_k \gamma^L_k \rangle$$

Circular polarised GWs (V modes):

$$\Omega^{V}_{\rm GW}(k) \propto \langle \gamma^R_k \gamma^R_k \rangle - \langle \gamma^L_k \gamma^L_k \rangle$$

P-violation!



Courtesy of Smith, Caldwell 2016

$$f = \frac{k}{2\pi a}$$

- - - - - Growth-mechanism
(2030-2040):
LISA
Taiji
Einstein Telescope
Cosmic Explorer

- - - - - - (2040-2050):
BBO
DECIGO

SGWB V modes

$$\Omega^{V}_{\rm GW}(k,\hat{n}) = \overline{\Omega}^{V}_{\rm GW}(k) + \delta^{V}_{\rm GW}(k,\hat{n})$$

Monopole

Anisotropies

SGWB V modes monopole

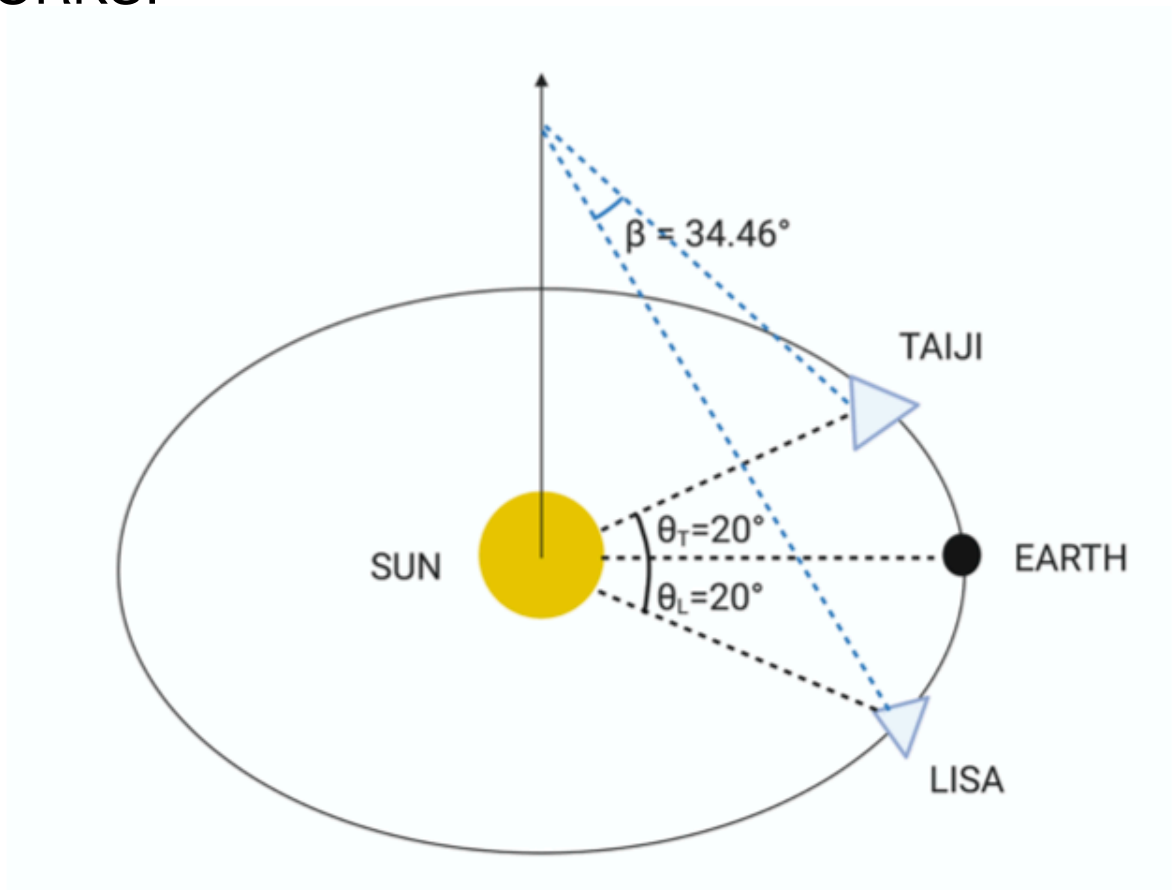
$$\Omega^V_{\rm GW}(k,\hat{n}) = \boxed{\overline{\Omega}^V_{\rm GW}(k)} + \delta^V_{\rm GW}(k,\hat{n})$$

(e. g. Seto, Taruya 2008; Smith, Caldwell 2016; Domcke et. al. 2019; ***Orlando****, Pieroni, Ricciardone 2020; Seto 2020, Cai et. al. 2023)*

$$\overline{\Omega}^V_{\rm GW}(k) \propto \langle \gamma^R_k \gamma^R_k \rangle - \langle \gamma^L_k \gamma^L_k \rangle$$

$$k_{\rm GW} \gg k_{\rm CMB} \longrightarrow \overline{\Omega}^{\rm V}_{\rm GW}(k) \propto \left(\frac{k_{\rm GW}}{k_{\rm CMB}}\right)^{n_t} \qquad n_t > 0$$

NETWORKS:



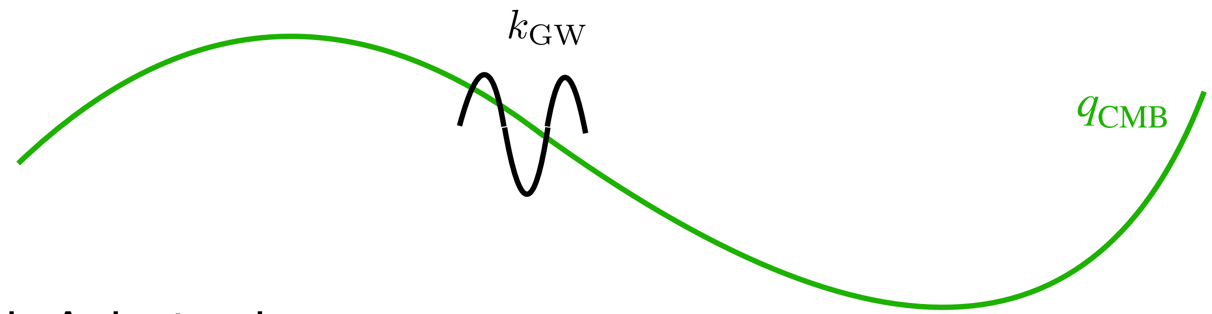
$$\overline{\Omega}^V_{\rm GW,\, LISA-TAIJI} \gtrsim 10^{-12}\chi$$

$$\chi = \frac{P_R - P_L}{P_R + P_L}$$

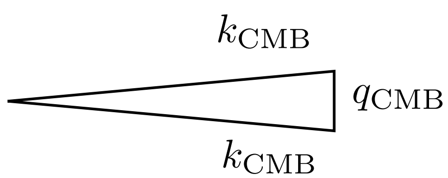
SGWB V modes anisotropies

$$\Omega^V_{\rm GW}(k,\hat{n}) = \overline{\Omega}^V_{\rm GW}(k) + \delta^V_{\rm GW}(k,\hat{n})$$

Intrinsic Anisotropies

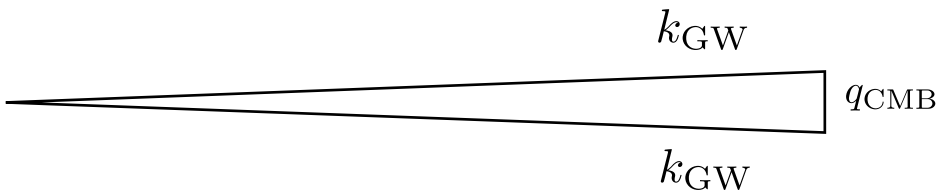


- Previous works: $\Omega^I_{\rm GW}(k,\hat{n}) = \overline{\Omega}^I_{\rm GW}(k) + \delta^I_{\rm GW}(k,\hat{n})$



$$\delta^I_{\rm GW}(\hat{n}) \sim f^{ttt,{\rm sq}}_{\rm NL}, f^{tts,{\rm sq}}_{\rm NL}$$

$$f^{tts,sq}_{\rm NL} = f^{RRs,sq}_{\rm NL} + f^{LLs,sq}_{\rm NL}$$



(e.g. Adshead et. al. 2021; Malhotra et. al. 2021; Dimastrogiovanni et. al. 2021-2022)

- I modes —> V modes: (**G. Orlando** 2022, arXiv:2206.14173)

$$\delta^V_{\rm GW}(\hat{n}) \sim f^{RRR,sq}_{\rm NL} - f^{LLL,sq}_{\rm NL}$$
$$\sim f^{RRs,sq}_{\rm NL} - f^{LLs,sq}_{\rm NL}$$

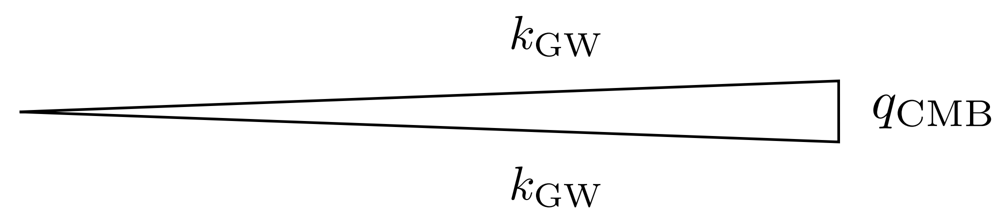
Sourced by $\langle tts \rangle_{\rm odd}$ and $\langle ttt \rangle_{\rm odd}$ ultra-squeezed bispectra

Sizeable signals are compatible with inflation *(Cabass et. al. 2021)*

A non-linear probe of P-violation

- V modes angular power-spectrum:

$\mathcal{A}$:= power-spectra amplitudes



$$C_\ell^{VV} = \frac{1}{2\ell+1}\sum_m \langle \delta^V_{{\rm GW},\ell {\rm m}}\, \delta^{*V}_{{\rm GW},\ell {\rm m}}\rangle$$

$$C_0^{VV}(k) \sim \left[\mathcal{A}_t^R(k) - \mathcal{A}_t^L(k)\right]^2$$

$$C_\ell^{VV}(k)|_{\langle tts\rangle} \sim \int dq \ldots \mathcal{A}_s(q)\, \left[\mathcal{A}_t^R(k)\, f_{\rm NL}^{\rm RRs}(k,q) - \mathcal{A}_t^L(k)\, f_{\rm NL}^{\rm LLs}(k,q)\right]^2 \qquad \ell \geq 1$$

$$C_\ell^{VV}(k)|_{\langle ttt\rangle} \sim \int dq\, \left\{\mathcal{A}_t^R(q)\left[\mathcal{A}_t^R(k)\, f_{\rm NL}^{RRR,{\rm ttt}}(k,q) - \mathcal{A}_t^L(k)\, f_{\rm NL}^{LRR,{\rm ttt}}(k,q)\right]^2 + \right.$$
$$\left. + \mathcal{A}_t^L(q)\left[\mathcal{A}_t^L(k)\, f_{\rm NL}^{LLL,{\rm ttt}}(k,q) - \mathcal{A}_t^R(k)\, f_{\rm NL}^{RLL,{\rm ttt}}(k,q)\right]^2\right\}$$

- V modes anisotropies sourced by:

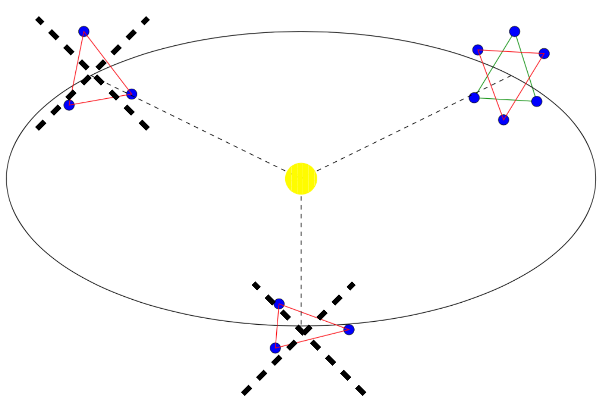
- $\langle tts\rangle_{\rm even}$ and $\langle ttt\rangle_{\rm even}$ + $\langle tt\rangle_{\rm odd}$ (**V modes monopole** $\neq 0$) ⟶ Linear

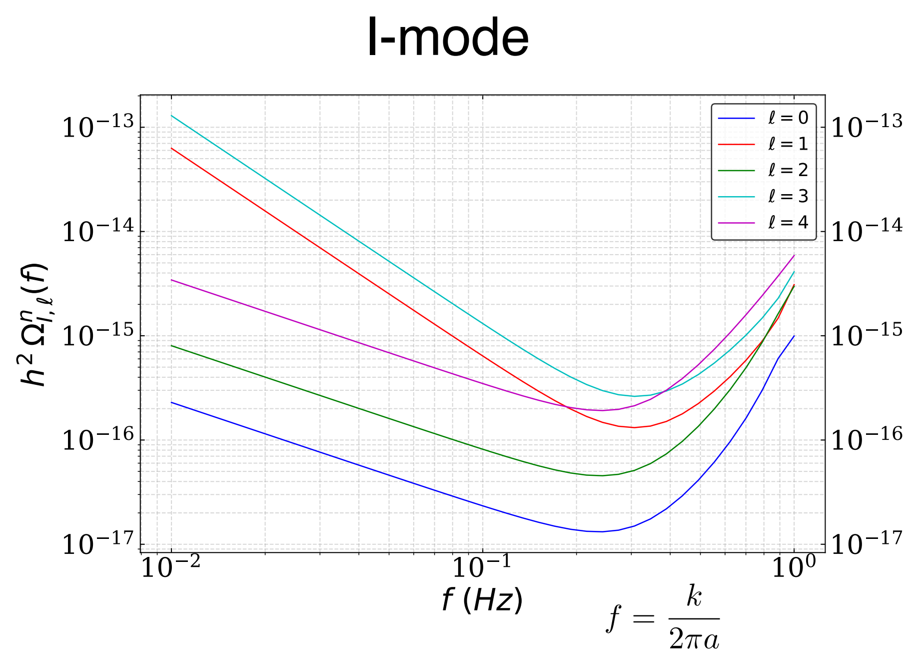
- $\langle tts\rangle_{\rm odd}$ and $\langle ttt\rangle_{\rm odd}$ + $\langle tt\rangle_{\rm even}$ (**V modes monopole** $= 0$) ⟶ Non-linear

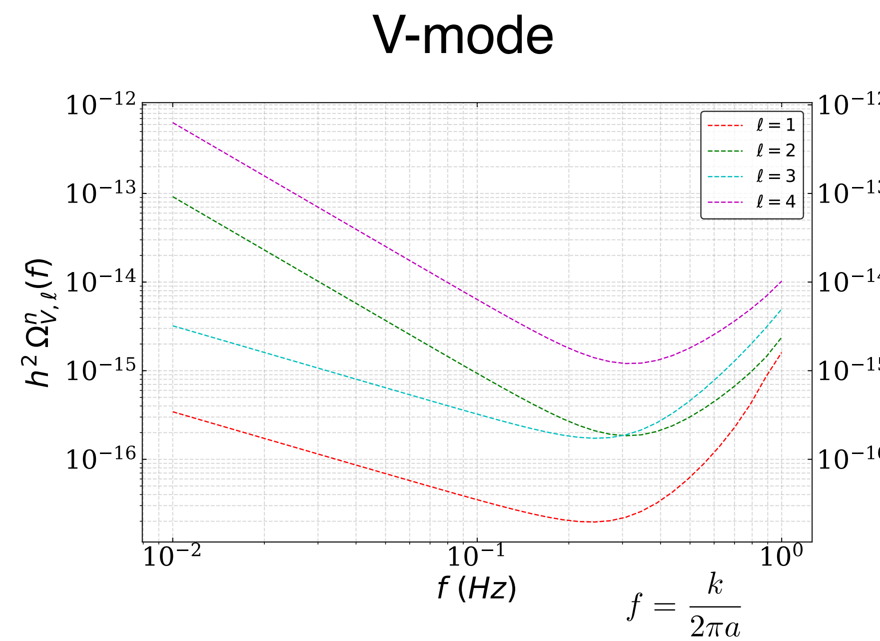
Forecast on parity-odd $\langle \mathrm{tts} \rangle$

- Noise curves obtained following *Alonso et. al. 2020, Bartolo et. al. 2022.*

- **BBO/DECIGO**-like experiment, early-stage.







- Fisher-forecast on **parity-odd** $\langle \mathbf{tts} \rangle$: (SNR higher than $\langle \mathrm{ttt} \rangle$)

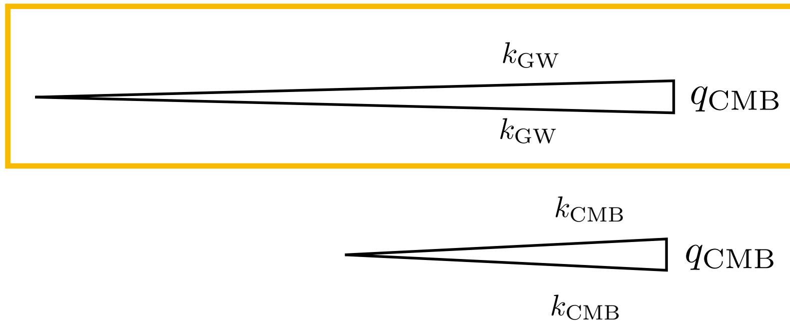
$$f_{\rm NL}^{\rm tts,odd}\Big|^{\rm GW}_{\rm 5yrs} \sim 10^3 \times \left(\frac{0.01}{r_{\rm GW}}\right)$$

(Orlando 2022)

vs

$$f_{\rm NL}^{\rm tts,odd}\Big|^{\rm CMB}_{\rm B-mode,\,\ell_{max}=100} \sim 10^4$$

(*Bartolo*, ***Orlando***, *Shiraishi 2017*)



Message: $\mathbf{r_{GW} \gtrsim 10^{-3}}$ **competitive** (not only complementary) with **CMB experiments!**

Take home message

- **Tensor** sector+**PnG crucial** to detect **P-violation** in the early-universe.
  Unique probe of **new physics**.

- **SGWB V modes** allow to probe **P-violation** in tensor sector and scalar-tensor pnG on **scales inaccessible** to **large-scale** experiments (CMB).

- SGWB V-mode monopole:
  - parity-odd tensor PS

- SGWB V-mode anisotropies**:**
  - parity-odd tensor PS + parity-even squeezed pnG
  - parity-even tensor PS + **parity-odd squeezed pnG**.

BACK-UP SLIDES

P-violation modelling

- **Modified gravity models (higher derivatives):**

- Hořava–Lifshitz gravity, 3 deriv. *(e.g. Wang 2017)*
- Chern-Simons gravitational term coupled to a scalar field, 4 deriv. *(e.g. Bartolo, **Orlando** 2017)*
- Higher-order chiral scalar-tensor theories, > 4 deriv. *(e.g. Bartolo, Caloni, **Orlando**, Ricciardone 2020)*

$$\Delta\mathcal{L}_{\rm CS}^{\rm gravit} = f(\phi)\,\epsilon^{\mu\nu\rho\sigma}\,R_{\mu\nu}{}^{\kappa\lambda}\,R_{\rho\sigma\kappa\lambda}$$

- **Gauge field-axion Chern-Simons couplings** *(e.g. Dimastrogiovanni, Fasiello, Fujita 2016)*

$$\Delta\mathcal{L}_{\rm CS}^{\rm gauge} \propto \phi\,\epsilon^{\mu\nu\rho\sigma}\,F^a_{\mu\nu}\,F_{\rho\sigma,a} \qquad a \in \mathcal{G} = U(1), SU(2), \ldots$$

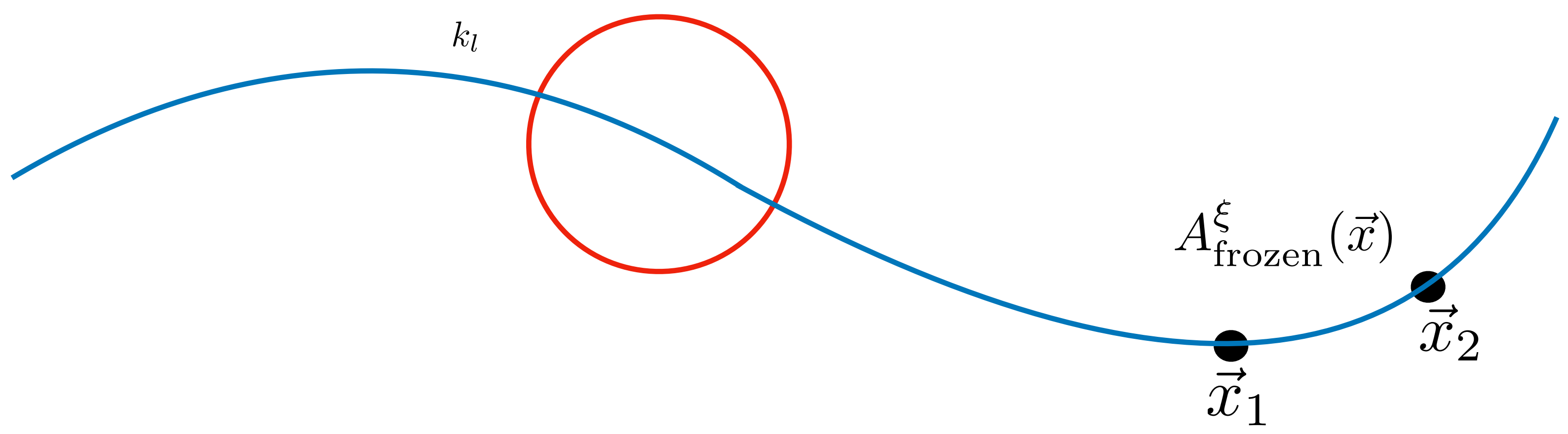
- **Modified gravity + Gauge-field coupling** *(e.g. Mirzagholi, Komatsu, Lozanov, Watanabe 2020)*

- **Effective field theory, cosmological bootstrap**:

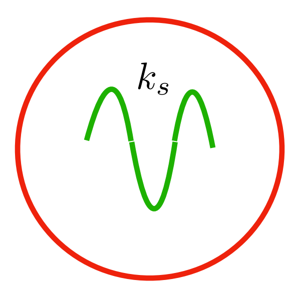
- Write all the operators that break P and are compatible with certain **symmetries**
  (e.g. Bordin, Cabass 2020; Cabass, Pajer, Stefanyszyn, Supel 2021)

Inhomogeneities from squeezed bispectra

- The amplitude of scalar and tensor perturbations leaving the horizon **freeze-out.**



Local modulations of the background space,
affect time evolution of short-scales still within the horizon



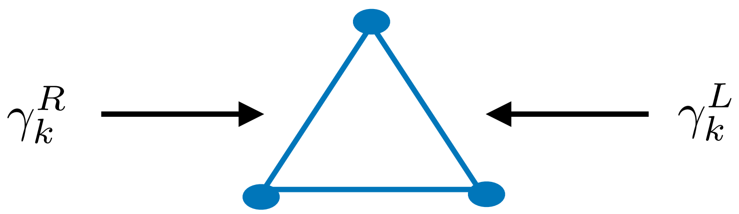
$$P_{\Delta\Delta}(k_s, \vec{x}) \leftrightarrow B^{\text{squeez}}_{\Delta\Delta\xi}(k_s, k_s, k_l)$$

SGWB V modes monopole

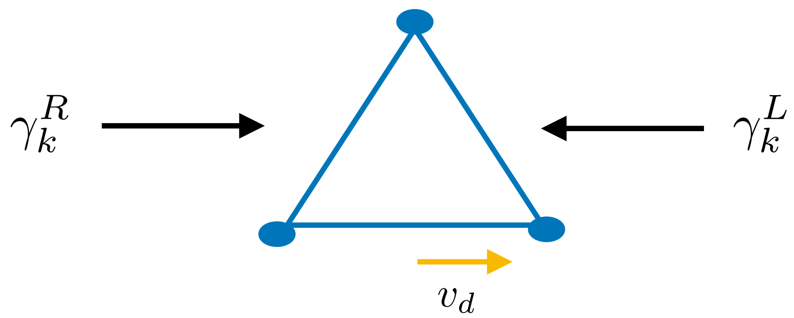
$$\Omega^V_{\rm GW}(k,\hat{n}) = \boxed{\overline{\Omega}^V_{\rm GW}(k)} + \delta^V_{\rm GW}(k,\hat{n})$$

$$\overline{\Omega}^V_{\rm GW}(k) \propto \langle \gamma^R_k \gamma^R_k \rangle - \langle \gamma^L_k \gamma^L_k \rangle$$

- Coplanar detectors insensitive to V-mode monopole



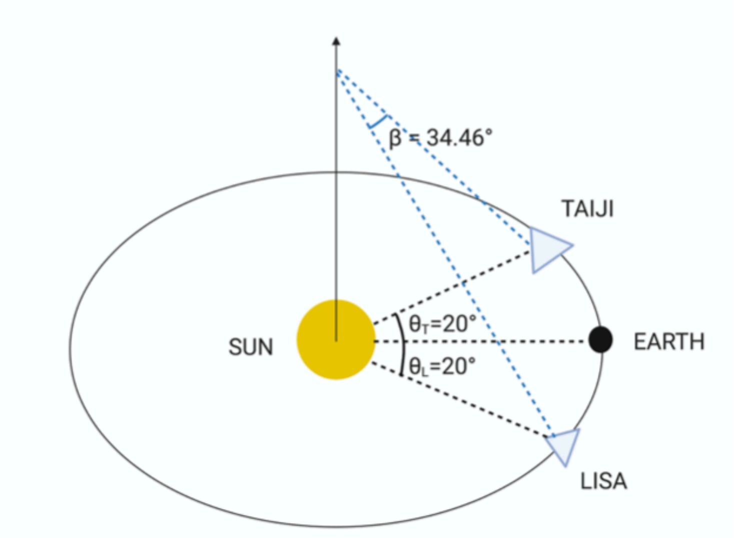
1. **Dipolar anisotropy** in the GW background **induced** by the detector-SGWB relative motion *(Domcke et. al. 2019)*



2. **Network of detectors**:

   - network of ground-based interferometers
     (e.g. Seto, Taruya 2008; Smith, Caldwell 2016)

   - network of space-based interferometers
     (e. g. **Orlando**, Pieroni, Ricciardone, 2020; Seto 2020)



S/N : **space-net $\gg$ dipolar $\gg$ ground-net**

Next steps?

- Role of **advanced state of BBO/DECIGO** missions and their network
- Role of f**orthcoming experiments** (LISA, Taiji, ET, CE, PTA)
- Role of **cross-correlations**:

$$\langle V_{\rm GW} - T_{\rm CMB}\rangle, \langle V_{\rm GW} - E_{\rm CMB}\rangle, \langle V_{\rm GW} - B_{\rm CMB}\rangle, \langle {\rm V}_{\rm GW} - \mu_{\rm CMB}\rangle, \ldots$$

- Role of **different polarisation states**: $Q_{\rm GW}$, $U_{\rm GW}$ modes