Imprints of parity violation from gravitational waves V modes

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Outline

1. Importance of pnG to detect P-violation in the early-universe.

2. Current probes of P-violation.

3. Anisotropies in circular-polarized SGWB to probe P-violation.

Role of pnG, scalar sector

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

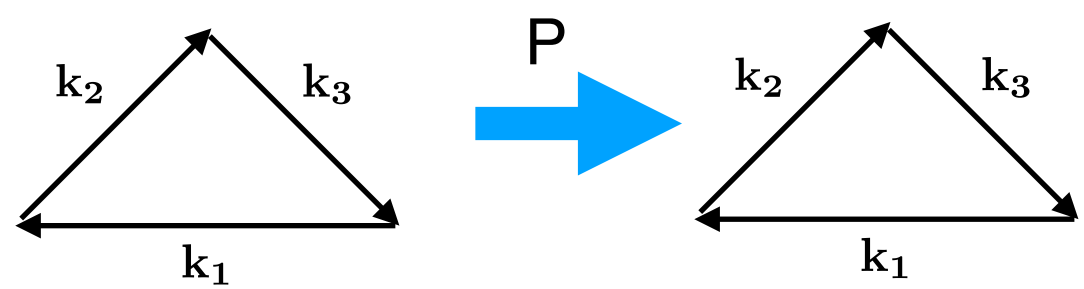
$$X = \zeta, \gamma^\lambda$$

- Assuming **homogeneity and isotropy,** not all primordial correlators matter.

\- POWER SPECTRUM AND BISPECTRUM:

- Need only **magnitude of momenta**.

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

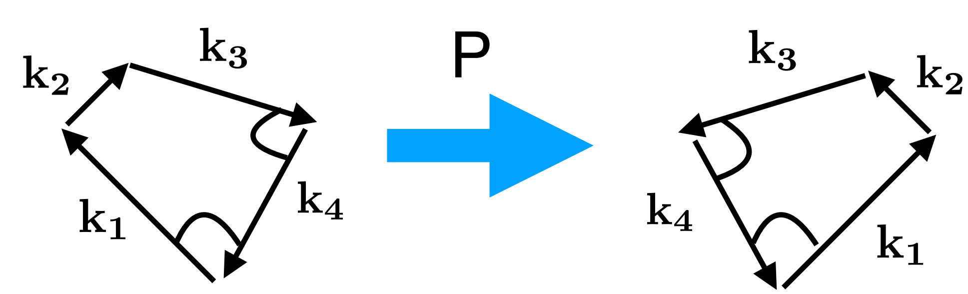


\- TRISPECTRUM:

- Need **magnitude of momenta + 2 angles**.

$$P(\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \zeta_{\mathbf{k}_4} \rangle) \neq \langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \zeta_{\mathbf{k}_4} \rangle$$

$$\langle \zeta\zeta\zeta\zeta \rangle_{\text{odd, NG}} \neq 0$$



Role of pnG, tensor sector

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

- POWER SPECTRUM:

$$P(\langle\gamma_k^R\gamma_k^R\rangle) = \langle\gamma_k^L\gamma_k^L\rangle$$

$$\langle\gamma_k\gamma_k\rangle|_{\mathrm{odd}} = \langle\gamma_k^R\gamma_k^R\rangle - \langle\gamma_k^L\gamma_k^L\rangle$$

- Issue: **tensor perturbations not detected yet**. (*$r < 0.032$, Tristram et. al. 2022)*
- **tensor perturbations detected —>** $\mathbf{S/N \sim r}$ (CMB)**:** *(e.g. Gerbino et. al. 2016)* **challenging** to observe.

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

e.g. $\langle\zeta\zeta\gamma\rangle|_{\mathrm{odd}} = \langle\zeta_{k_1}\zeta_{k_2}\gamma_{k_3}^R\rangle - \langle\zeta_{k_1}\zeta_{k_2}\gamma_{k_3}^L\rangle$

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

pnG PLAY A FUNDAMENTAL ROLE in detecting P-violation!

Current probes of P-violation

CMB (2D):

- POWER SPECTRUM: $\langle \gamma_k \gamma_k \rangle|_{\rm odd} \longrightarrow \langle TB \rangle, \langle EB \rangle$

  (e.g. Gerbino et. al. 2016)

Challenging:

$S/N \sim r$

No detection of B modes

- BISPECTRUM: $\langle \gamma_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle|_{\rm odd} \longrightarrow \langle BTT \rangle$

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

No detection of B modes

- TRISPECTRUM: $\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \zeta_{\mathbf{k_4}} \rangle|_{\rm odd} \longrightarrow \langle TTTT \rangle$

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Cosmic variance

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Cosmic variance

Large Scale Structures:

Galaxy shear (2D):

- POWER SPECTRUM: $\langle \gamma_k \gamma_k \rangle|_{\rm odd} \longrightarrow \langle EB \rangle$

  (e.g. Biagetti, **Orlando** 2020)

Challenging:

$S/N \sim r$

No detection of B modes

Large scale overdensity-field (3D):

- TRISPECTRUM: $\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \zeta_{\mathbf{k_4}} \rangle|_{\rm odd} \longrightarrow \langle \delta\delta\delta\delta \rangle$

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Recent OBSERVATION in BOSS!

Seen in Oliver Philcox's talk

First ever claimed detection

- The **cosmic birefringence** signal recently claimed *(e.g. 3.6σ in Eskilt, Komatsu 2022)* **cannot be explained by inflation!** The associated $r \sim 10^2$ is above the CMB constraint: **overproduction of B modes** *(e.g. Fujita et. al. 2022).*

- **First ever claimed detection of P-violation** that can be associated to inflation *(3σ in Philcox 2022; 7σ in Hou et. al. 2022)*.

- If confirmed, **smoking-gun** for **beyond single-field slow-roll models**!

Future: V modes from SGWB direct detection

Previous talks:

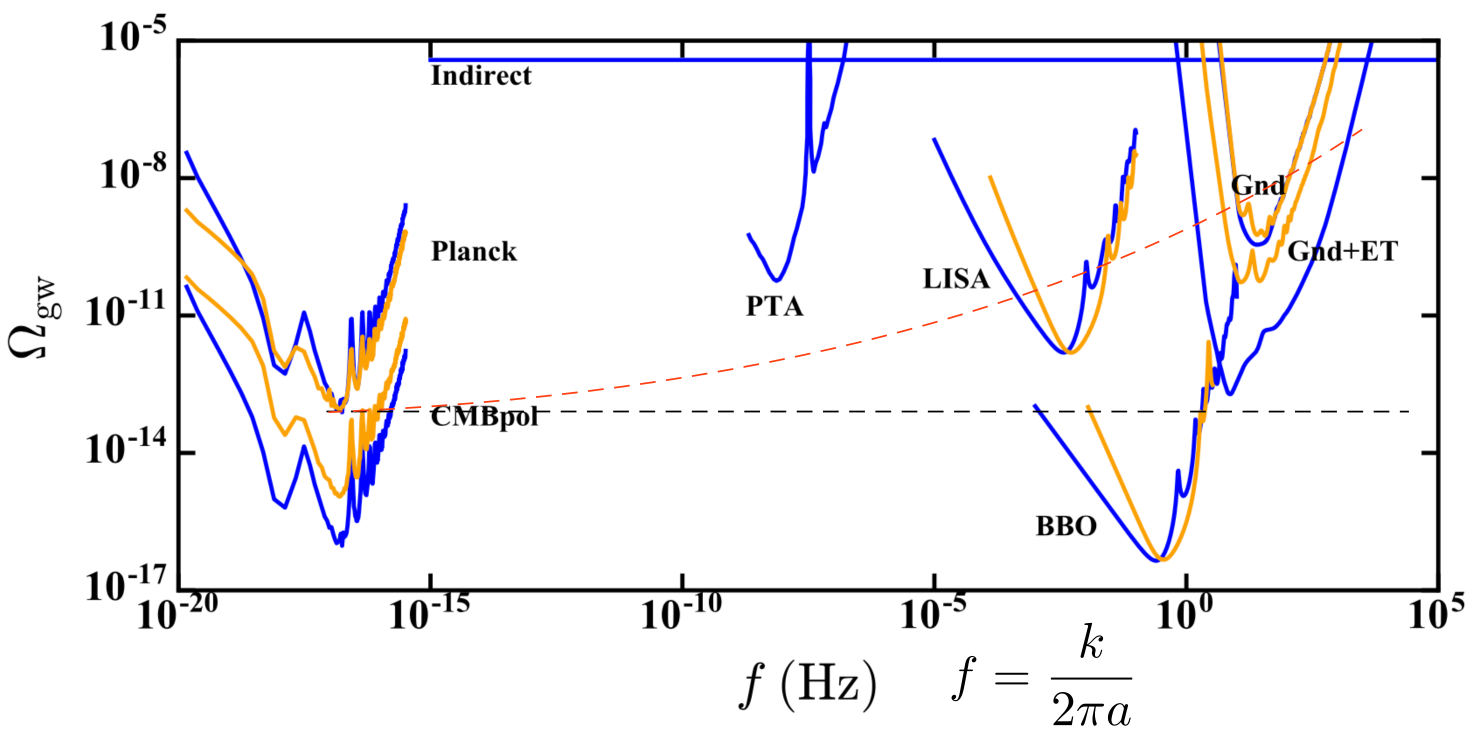
Unpolarised GWs (I modes):

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

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

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

(2040-2050):
BBO
DECIGO

SGWB V modes

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

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)*

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

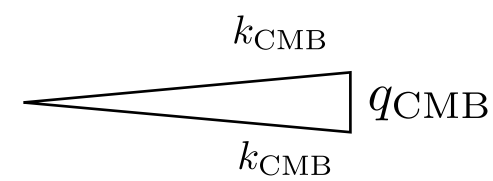
$k_{\rm GW} \gg k_{\rm CMB}$ ⟶ $r_{\rm GW}$ evades CMB constraint ⟶ Hope to measure the parity-odd tensor power spectrum

Recent: SGWB V modes anisotropies

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

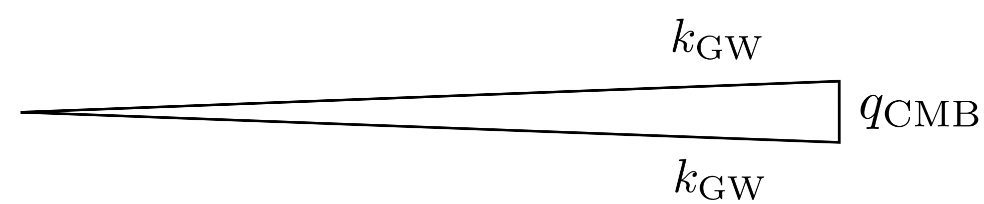
- New: study **V modes intrinsic anisotropies** (**G. Orlando** 2022, arXiv:2206.14173)

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



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

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



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

- I modes —> V modes:

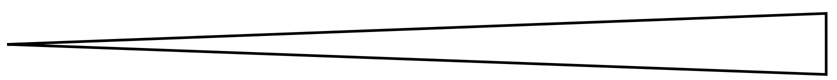
$$\boxed{\begin{aligned}\delta^V_{\rm GW}(\hat{n}) &\sim f_{\rm NL}^{RRR,sq} - f_{\rm NL}^{LLL,sq} \\ &\sim f_{\rm NL}^{RRs,sq} - f_{\rm NL}^{LLs,sq}\end{aligned}}$$

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

A non-linear probe of parity violation

- V modes angular power-spectrum:

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



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

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

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

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

- V modes anisotropies sourced by:

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

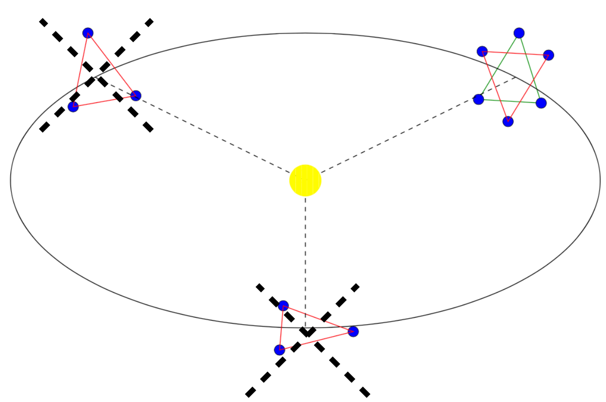
  - $\langle tts\rangle_{\rm odd}$ and $\langle ttt\rangle_{\rm odd}$ + $\langle tt\rangle_{\rm even}$ (**V modes monopole** $= 0$)

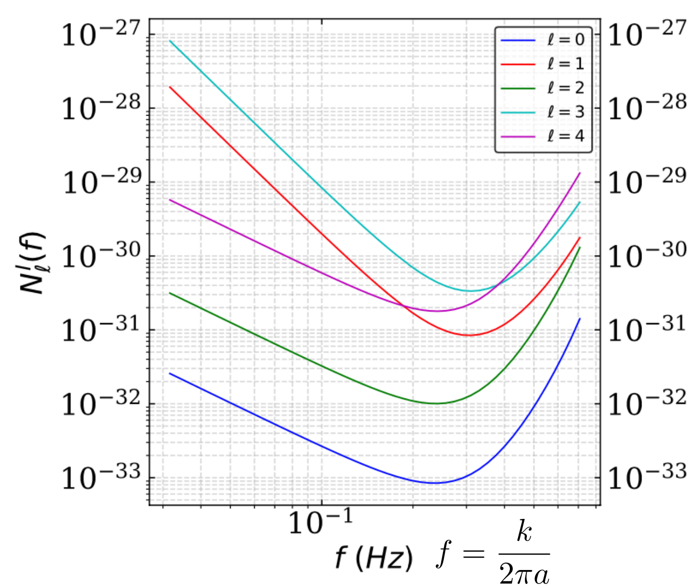
Detection prospects

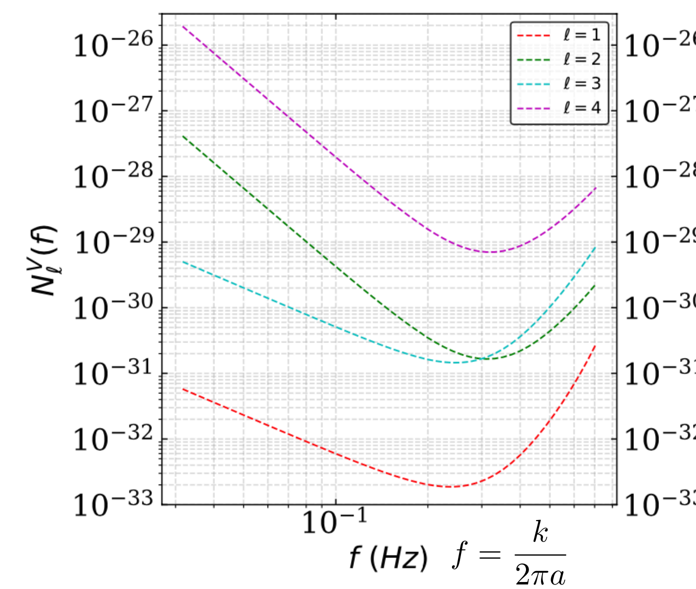
- Main difference with I modes case: in **V modes** channel there is **no contamination** from **astrophysical** GW backgrounds and **negligible** from **induced** anisotropies.

- Noise curves obtained with well-established pipeline *(Alonso et. al. 2020).*

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







- Fisher-forecast on **parity-odd** $\langle \mathbf{tts} \rangle$:

*(from **G. Orlando** 2022)*

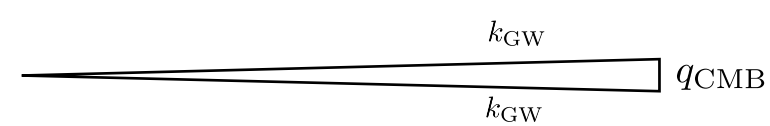
$$f_{\rm NL}^{\rm tts,odd}\Big|_{\rm 5yrs}^{\rm GW} \sim 10^3 \times \left(\frac{0.01}{r_{\rm GW}}\right)$$

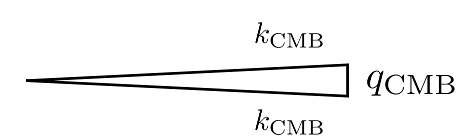
(Orlando 2022)

VS

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

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





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

Take home message

- **PnG important** to detect **P-violation** in the early-universe (scalar and tensor sectors).

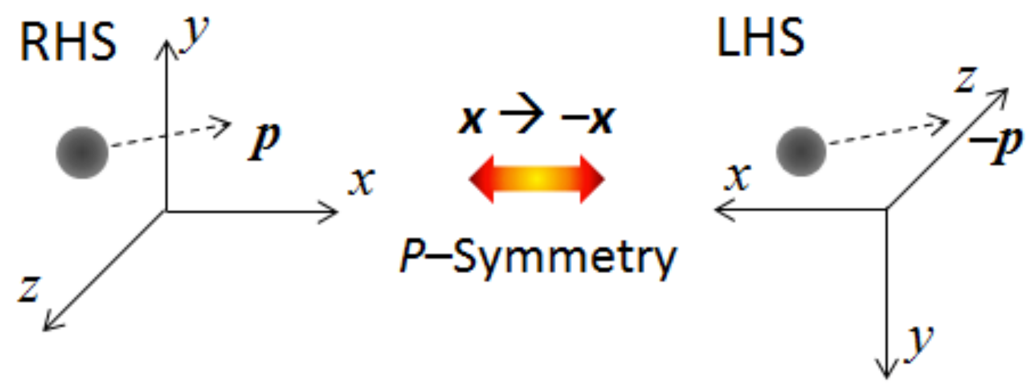
- **Anisotropies in SGWB circular polarization** can probe **P-violation** in tensor and tensor-scalar **pnG** on **configurations inaccessible to large-scale experiments**.

- In the future, **gravitational-wave experiments** will **probe** parity-odd $\langle tts \rangle$ with a **sensitivity competitive** with **CMB experiments**.

THANK YOU!

BACK-UP SLIDES

Motivation for studying P-violation in early-universe



- **Standard** modelling (slow-roll): inflation is **P-invariant**

THEORETICAL:

- P-violating early-universe processes **explain the baryonic asymmetry**
  (see e.g. Carroll 1998;   Alexander et. al. 2004)

OBSERVATIONAL:

- **Recent evidence for primordial P-violation** in LSS from BOSS galaxy survey
  (3σ in Philcox 2022;   7σ in Hou et. al. 2022)

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)*

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

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

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

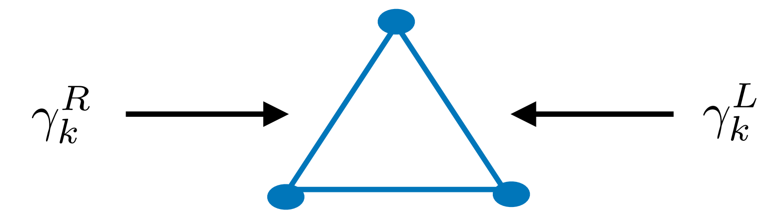
- Write all the operators that break P and are compatible with certain assumed symmetries
(e.g. Bordin, Cabass 2020; Cabass, Pajer, Stefanyszyn, Supel 2021)

SGWB V modes monopole

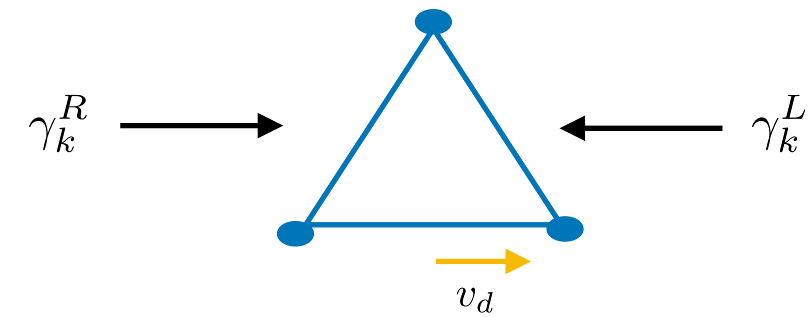
$$\Omega^V_{\rm GW}(k,\hat{n}) = \boxed{\overline{\Omega}^V_{\rm GW}(k)} + \delta^V_{\rm GW}(k,\hat{n})$$

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

- Coplanar detectors insensitive to V-mode monopole



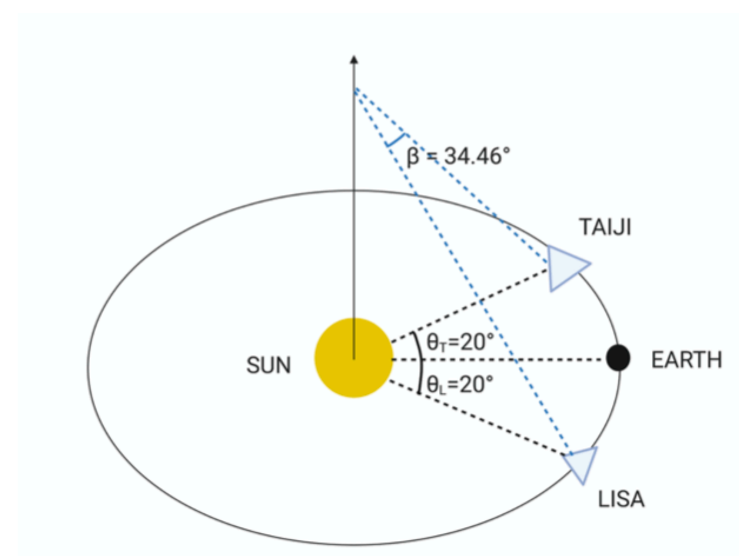
1. **Dipolar anisotropy** in the GW background **induced** by the detector-SGWB relative motion *(Domcke et. al. 2019)*



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