Broken spatial isometries during inflation: $n_T > 0$ and consequences for interferometers

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Supersolid inflation

$$\cancel{t \to t + \xi(t,x)}\,, \qquad \cancel{x^i \to x^i + \xi(t,x)}$$

Model 1 [Extension of **Solid inflation** [Endlich, Nicolis, Wang]]

`Einstein gravity + set of scalar fields (also vectors can work)`

- A quartet of scalar fields, $\phi(t)$, $\sigma^I(x^j)$ spontaneously breaking space-time diffeos.

$$\boxed{\phi(t) \quad , \quad \sigma^I = \alpha\, x^I}$$

- Interactions: most general self-interactions for ϕ, derivative interactions for σ^I preserving internal symmetries:

$$B^{IJ} = \partial_\mu \sigma^I\, \partial^\mu \sigma^J \qquad \Rightarrow \qquad \mathrm{tr}\, B, \;\; \mathrm{tr}\, B^2, \;\; \mathrm{tr}\, B^3$$

$$\boxed{f(\phi)\, G^{\mu\nu}\, \partial_\mu \sigma^I\, \partial_\nu\, \sigma_I}$$

Supersolid inflation

$$\cancel{t \to t + \xi(t,x)}\,, \qquad \cancel{x^i \to x^i + \xi(t,x)}$$

Model 2

`Bigravity + single scalar field`

$$S = \int \mathrm{d}^4x \left[M_P^2 \sqrt{-g}\, R[g] + \sqrt{-g}\, P_g(X,\varphi) + 2\sqrt{-g}\, m^2 M^2 V + M_f^2 \sqrt{-f}\, R[f] \right]$$

$$\boxed{V = \sum_{n=0}^{4} \beta_n\, \mathcal{E}_n(\sqrt{g^{-1}f})}$$

$$\mathcal{E}_0(\mathbb{X}) = 1, \quad \mathcal{E}_1(\mathbb{X}) = \mathrm{Tr}(\mathbb{X}) \equiv [\mathbb{X}], \quad \mathcal{E}_2(\mathbb{X}) = \frac{1}{2}\left([\mathbb{X}]^2 - [\mathbb{X}^2]\right),$$

$$\mathcal{E}_3(\mathbb{X}) = \frac{1}{3!}\left([\mathbb{X}]^3 - 3[\mathbb{X}^2][\mathbb{X}] + 2[\mathbb{X}^3]\right),$$

$$\mathcal{E}_4(\mathbb{X}) = \frac{1}{4!}\left([\mathbb{X}]^4 - 6[\mathbb{X}^2][\mathbb{X}]^2 + 8[\mathbb{X}^3][\mathbb{X}] + 3[\mathbb{X}^2]^2 - 6[\mathbb{X}^4]\right).$$

Quadratic tensor action acquires a mass term

$$S^T = \frac{1}{4}\int dt\, d^3x\, a^3\, M_{Pl}^2 \left[\frac{1}{2}\,\dot{h}_{ij}^2 - \frac{1}{2\,a^2}\,(\partial_k\, h_{ij})^2 - \frac{m^2}{2}\,h_{ij}^2\right]$$

The tensor spectral tilt acquires a positive contribution

$$n_T = -2\,\epsilon + \frac{2\,m^2}{3\,H^2}\left(1 + \frac{4}{3}\,\epsilon\right)$$

$$\boxed{n_T > 0}$$

Important feature: It's possible to avoid the **Higuchi bound** thanks to large couplings of tensors with fields breaking space-time symmetries

enough parameter freedom to tune preferred value for n_T

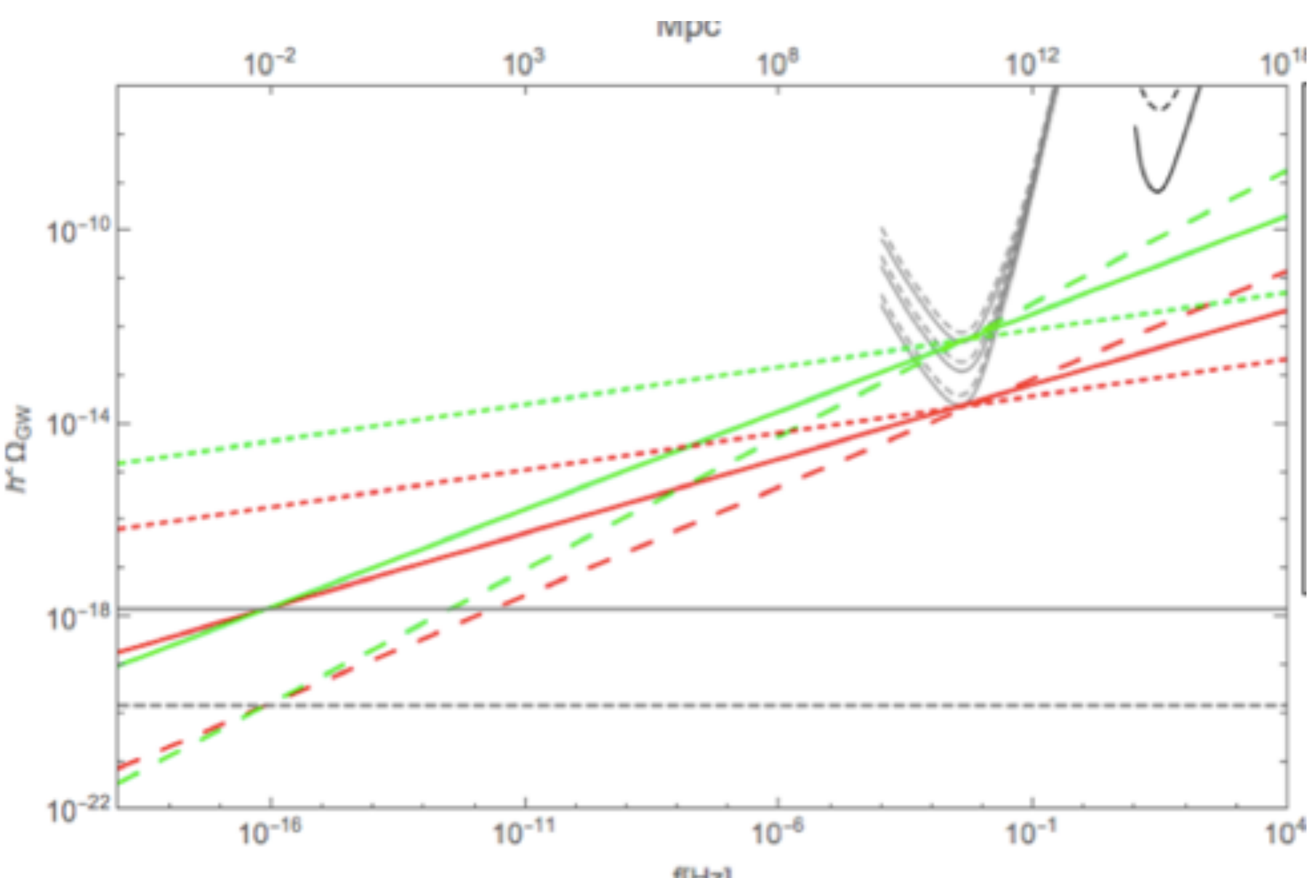
Schematic difference among two possibilities

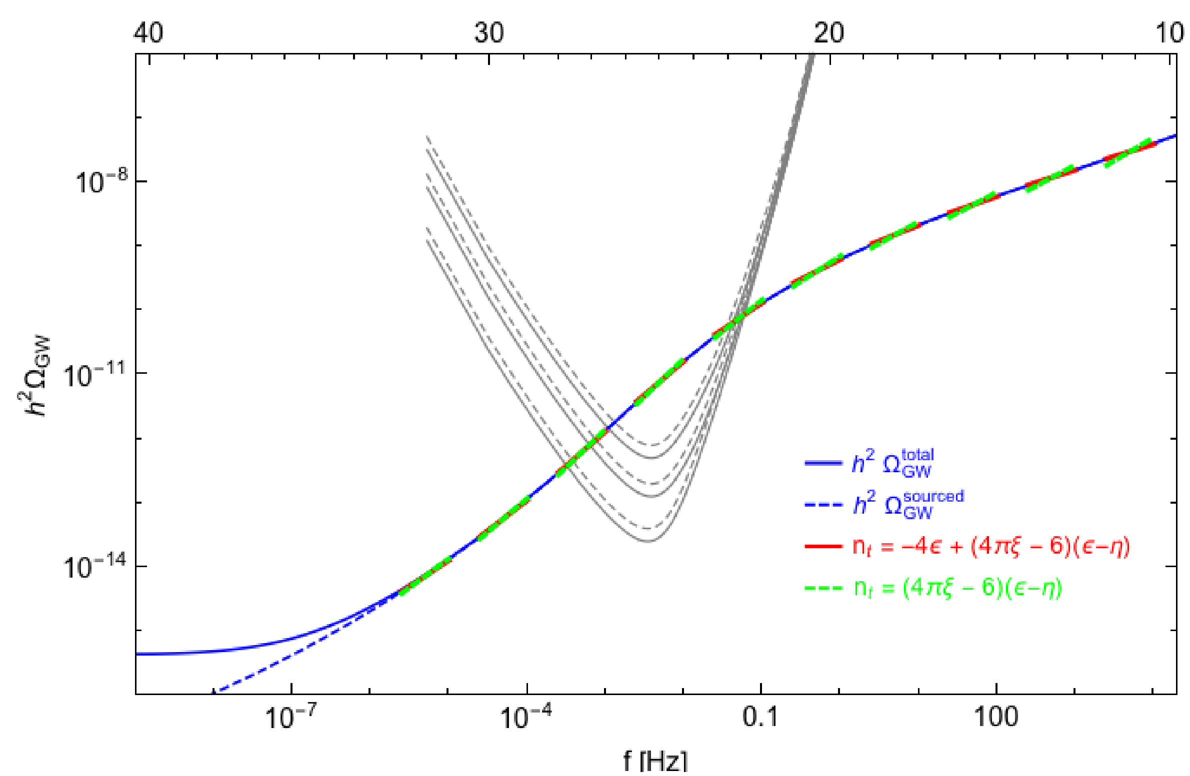
Evolution eq for linear fluctuations

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} + k^2\, h_{ij} + \boxed{m^2\, h_{ij}} = \boxed{\frac{2}{M_{Pl}^2}\, \Pi_{ij}^{TT}}$$

Broken
space reparameterizations

Interactions
with additional fields





Schematic difference among two possibilities

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Broken
space reparameterizations

- **Anisotropic** tensor power spectrum

$\Updownarrow$

Large tensor nonG
in the squeezed limit

Interactions
with additional fields

- Chiral spectrum
  L/R modes have different amplitude

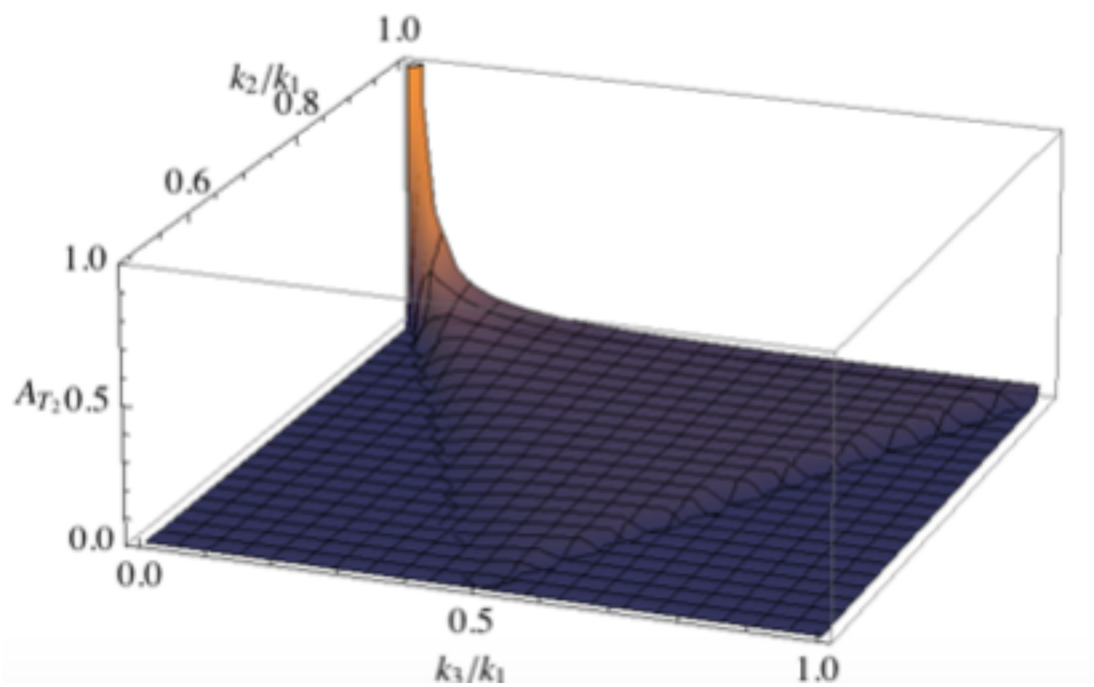
Schematic difference among two possibilities

<u>Tensor non-Gaussianity</u> $\langle h^{(s_1)}_{i_1 j_1} \, h^{(s_2)}_{i_2 j_2} \, h^{(s_3)}_{i_3 j_3} \rangle$

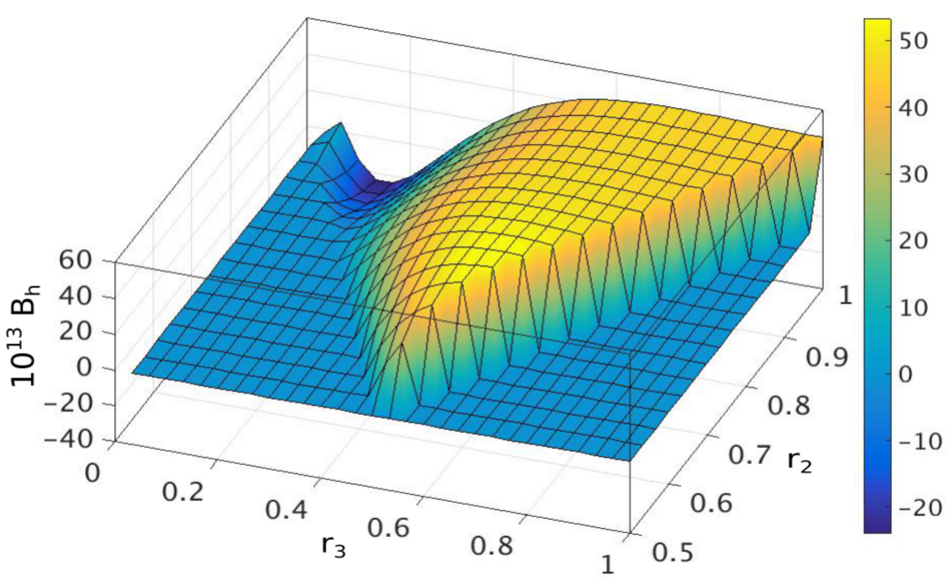
Broken
space reparameterizations

Interactions
with additional fields

Tensors are
not adiabatic
''LOCAL non-G''



Production of
gauge flucts
''EQUILATERAL non-G''



tensor 3pt function

What do we know today?

Little, but non-zero:

Planck and WMAP constrain the following quantity **in equilateral configuration** (dedicated template for axion models: [Shiraishi et al])

$$f_{\rm NL}^{tens} = \frac{5}{18}\,\frac{B_h^{++\pm}(k,\,k,\,k)}{P_\zeta^2(k)}$$

$$\left.\begin{aligned} 10^{-2}\times f_{\rm NL}^{tens}(\texttt{parity even}) &= 4\pm 16 \\ 10^{-2}\times f_{\rm NL}^{tens}(\texttt{parity odd}) &= 80\pm 110 \end{aligned}\right\}$$

`from bounds on T and E bispectra`

Very specific of equilateral-like shape

[Komatsu et al]

Large tensor nonG in the squeezed limit

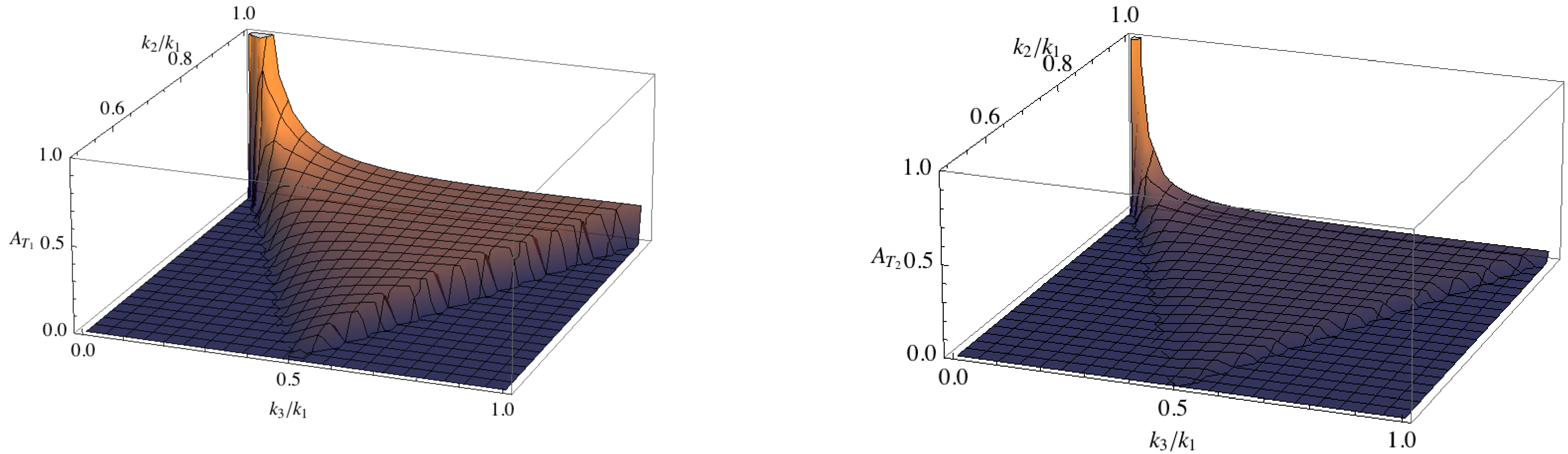
- Primordial tensor modes are **not adiabatic**. [Bordin et al]

Supersolid inflation:

$\boxed{\text{evade Maldacena consistency relation for squeezed tensor bispectrum}}$

$$\langle h^{s_1}_{k_1}\, h^{s_2}_{k_2}\, h^{s_3}_{k_3}\rangle'_{k_1 \ll k_{2,3}} = \delta^{s_2 s_3} \left(\frac{3}{2} + f^T_{NL}\right) P_h(k_1)\, P_h(k_2)\, \epsilon^{s_1}_{ij}\, \frac{k_2^i k_2^j}{k_2^2}$$

can be large

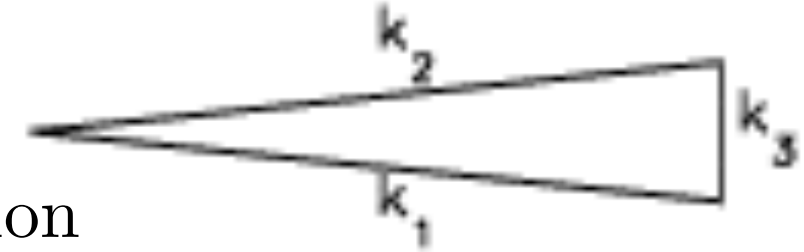


Large tensor nonG in the squeezed limit

- Primordial tensor modes are **not adiabatic**.

Enhanced

Squeezed limit of tensor 3pt function



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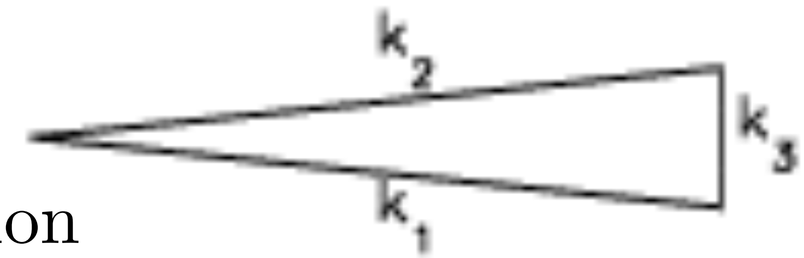

- **Physical consequence**: **anisotropic** amplitude of **tensor power spectrum**

[Shandera et al, Giddings and Sloth, Nurmi, Byrnes, GT]

$$\mathcal{P}_h(k) = \mathcal{P}_h^{(0)}(k)\left(1 + \mathcal{Q}_{ij}\,\frac{k^i\,k^j}{k^2}\right)$$

Couple short to long modes

`quadrupolar anisotropy`

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Background is isotropic:
this implies that all Stokes parameters, besides I, vanish
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Enhanced
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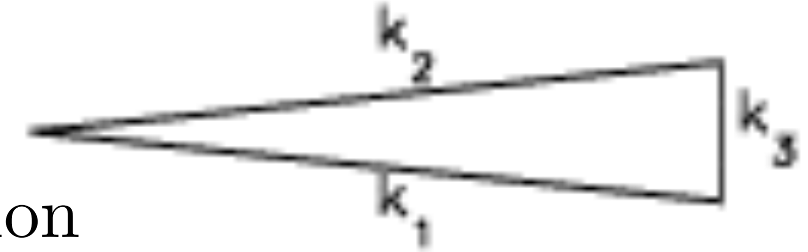

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$$\mathcal{P}_h(k) \,=\, \mathcal{P}_h^{(0)}(k)\left(1+\mathcal{Q}_{ij}\,\frac{k^i\,k^j}{k^2}\right)$$

$$\boxed{\mathcal{Q}_{ij}(\vec{x}) \,=\, \frac{f_{NL}^T}{V_L}\int_{|\vec{q}|<q_L} d^3q\, e^{i\vec{q}\vec{x}}\sum_s e_{ij}^{(s)}(\vec{q})\gamma_q^{(s)}}$$

Consequences for interferometers

Characteristic features for phase shift of light travelling through interferometers arms

[Cornish, Allen et al., Smith and Caldwell, Thorne et al]

$$\boxed{\phi_{12}(t)} = \phi_0 \left[1 + \int_{-\infty}^{+\infty} df \int d^2\vec{n} \sum_s \boxed{\gamma^{(s)}} e_{ab}^{(s)}\, e^{i\,2\pi\, f(t-\vec{n}\cdot\vec{x}_1)} \boxed{\mathcal{D}_{ab}\left(f,\, \vec{\ell}_{12}\cdot\vec{n}\right)} \right]$$

$\downarrow$ Phase change of light while travelling along arm

$\downarrow$ Tensor mode function in Fourier space

$\downarrow$ Arm transfer function

$\downarrow$

Depends on PS anisotropies

- **Signal** $$s_1(t) = \Delta\phi_{12}(t-2L) + \Delta\phi_{21}(t-L) + n_1(t)$$

- **Phase 2pt function (in Fourier space)**

$$\langle \Delta\tilde{\phi}_{ij}(f)\Delta\tilde{\phi}^*_{kl}(f')\rangle = \frac{1}{2}\,\delta(f-f')\,\delta^{pp'}\,S_h(f)\,\mathcal{R}^{ij,\,kl}_{p\,p'}(f)$$

Depends on tensor PS

Info about interferometer response

$$\begin{pmatrix} \langle h_+^*(f,\hat{n})h_+(f',\hat{n}')\rangle & \langle h_+^*(f,\hat{n})h_\times(f',\hat{n}')\rangle \\ \langle h_\times^*(f,\hat{n})h_+(f',\hat{n}')\rangle & \langle h_\times^*(f,\hat{n})h_\times(f',\hat{n}')\rangle \end{pmatrix} = \frac{1}{2}\delta(f-f')\frac{\delta^{(2)}(\hat{n}-\hat{n}')}{4\pi}\begin{pmatrix} I+\xcancel{Q} & \xcancel{U}+i\xcancel{V} \\ \xcancel{U}-i\xcancel{V} & I-\xcancel{Q} \end{pmatrix},$$

- **Signal** $$s_1(t) \;=\; \Delta\phi_{12}(t-2L) + \Delta\phi_{21}(t-L) + n_1(t)$$

- **Phase 2pt function (in Fourier space)**

$$\langle \Delta\tilde{\phi}_{ij}(f)\Delta\tilde{\phi}^*_{kl}(f')\rangle \;=\; \frac{1}{2}\,\delta(f-f')\,\delta^{pp'}\,S_h(f)\,\mathcal{R}^{ij,\,kl}_{p\,p'}(f)$$

- **Response function R contains info about PS quadrupolar anisotropy**

$$\begin{aligned}\mathcal{R}^{ij,\,kl}_{p\,p'}(f) \;\;&\equiv\;\; \int \frac{d^2\vec{n}}{4\pi}\,e^{i\,2\pi\,f\,\vec{n}(\vec{x}_i-\vec{x}_k)}\,\mathcal{D}_{ab}(\vec{\ell}_{ij}\cdot\vec{n},\;f)e^{(p)}_{ab}(\vec{n})\,\mathcal{D}^*_{cd}(\vec{\ell}_{kl}\cdot\vec{n},\;f)e^{(p')}_{cd}(\vec{n}')\\ &+\;\boxed{\mathcal{Q}_{mn}}\int\frac{d^2\vec{n}}{4\pi}\,n_m n_n\;e^{i\,2\pi\,f\,\vec{n}(\vec{x}_i-\vec{x}_k)}\,\mathcal{D}_{ab}(\vec{\ell}_{ij}\cdot\vec{n},\;f)e^{(p)}_{ab}(\vec{n})\,\mathcal{D}^*_{cd}(\vec{\ell}_{kl}\cdot\vec{n},\;f)e^{(p')}_{cd}(\vec{n})\end{aligned}$$

Time-dependent (annual?) modulation of phase 2pt function