12th Iberian Gravitational Waves Meeting
June 2022, 8th, from Braga

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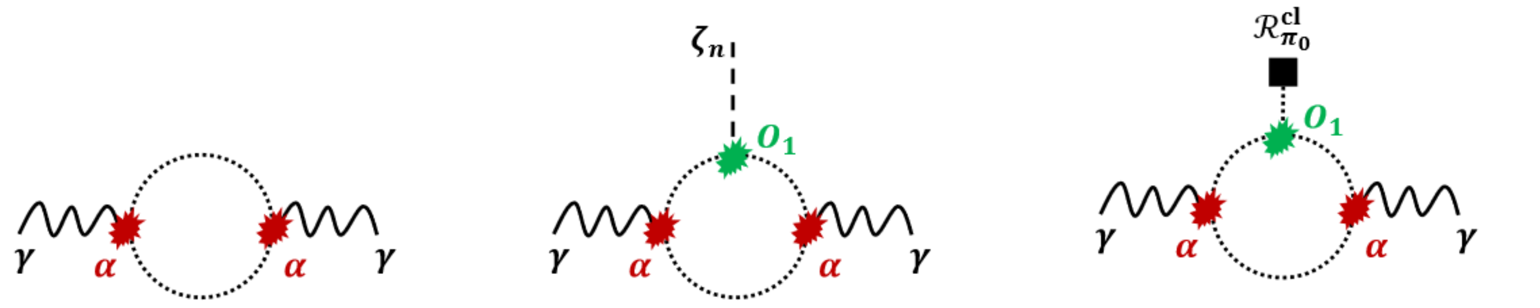
Based on:
[Dimastrogiovanni, Fasiello, LP 2022]
ArXiv:2203.17192

TENSOR PRIMORDIAL NON-GAUSSIANITIES
AND INDUCED ANISOTROPIES IN THE SGWB

Stochastic Gravitational Wave Background



(a) One-loop tensor power spectrum

(b) One-loop scalar-tensor-tensor bispectrum

(c) One-loop tensor two-point function in the presence of a classical scalar source.

I will try to connect to other talks of the conference in blue

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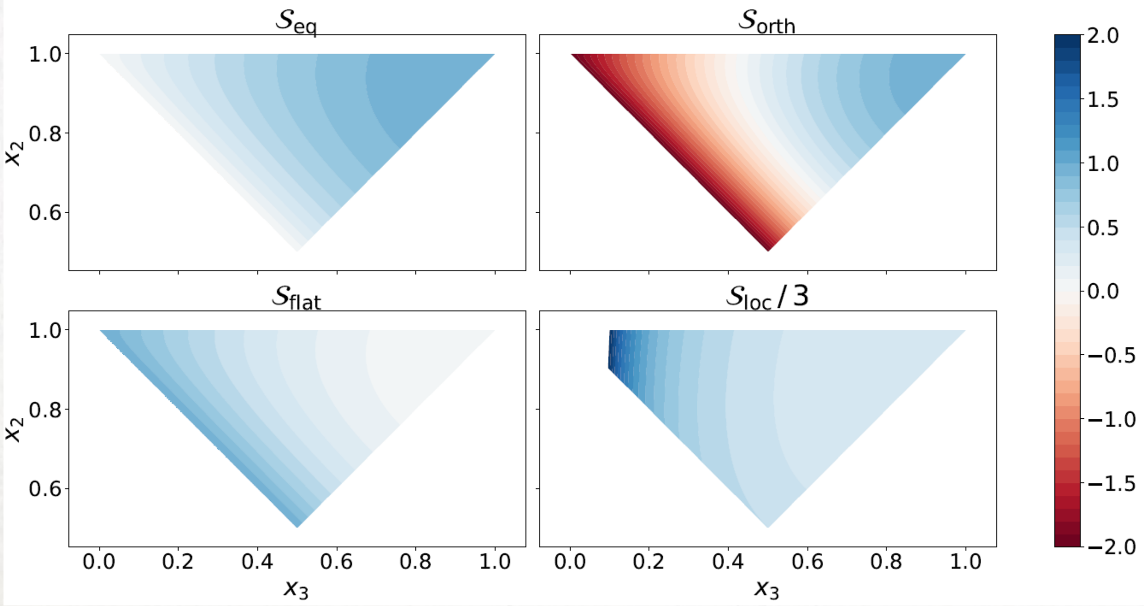
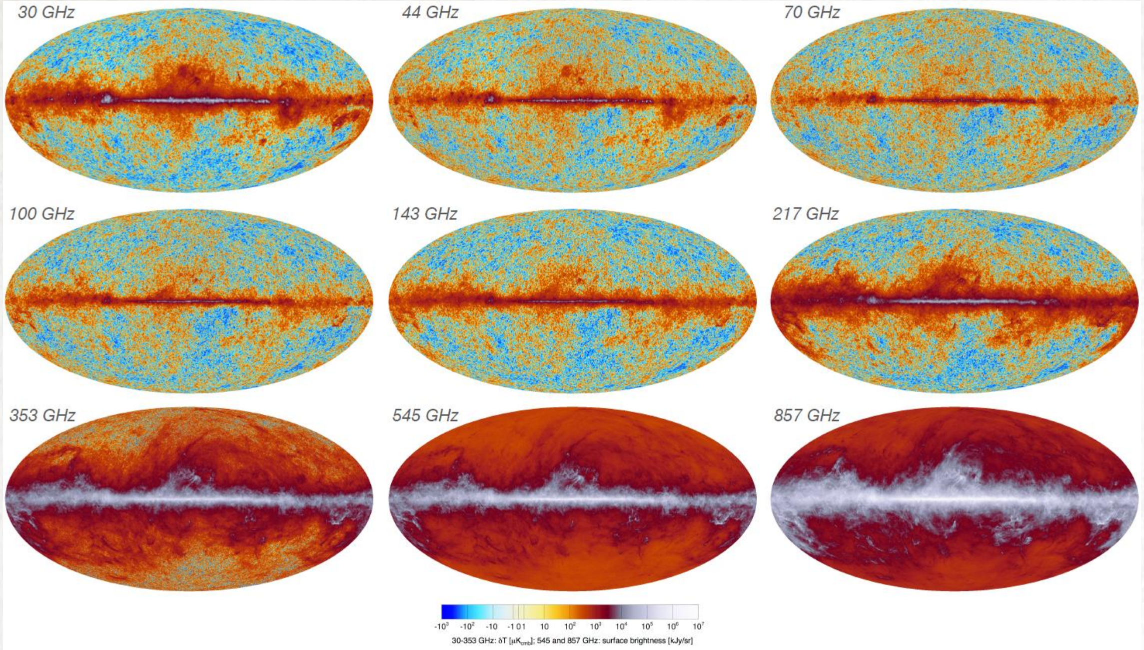
I. Primordial Non-Gaussianities (PNGs)

Quick introduction and definitions



Non-linearities in the sky



Planck CMB intensity maps

Reviews: **[Bartolo, Komatsu, Matarrese, Riotto 2004]**
[Chen 2010]

Sources of non-Gaussianity:

- Foreground
- Late-time evolution: lensing, etc.
- Early-time evolution: gravity, interactions, etc.
- **Initial conditions:**

Primordial non-Gaussianities from inflation

$$\boldsymbol{T_{\mathrm{ini}}(\theta,\varphi) = T^{G}_{\mathrm{ini}}(\theta,\varphi) + f^{\mathrm{local}}_{\mathrm{NL}} \times \left[T^{G}_{\mathrm{ini}}(\theta,\varphi)\right]^2}$$

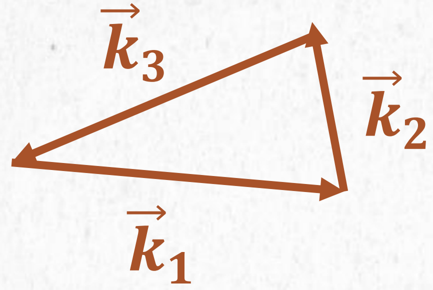
Gaussian *Non-Gaussian if* $f^{\mathrm{local}}_{\mathrm{NL}} \neq 0$

PRIMORDIAL BISPECTRUM

Power spectrum $= 2.10 \times 10^{-9}$

ζ the primordial curvature perturbation

$$< \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} >= (2\pi)^7 \, \delta^{(3)}(\overrightarrow{k_1} + \overrightarrow{k_2} + \overrightarrow{k_3}) \frac{A_s^2}{(k_1 k_2 k_3)^2} \times S(k_1, k_2, k_3)$$



Shape function

Similar definitions for tensor and mixed NGs: $< \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \gamma_{\vec{k}_3} >$, $< \zeta_{\vec{k}_1} \gamma_{\vec{k}_2} \gamma_{\vec{k}_3} >$, $< \gamma_{\vec{k}_1} \gamma_{\vec{k}_2} \gamma_{\vec{k}_3} >$

SST STT TTT

γ the primordial tensor perturbation

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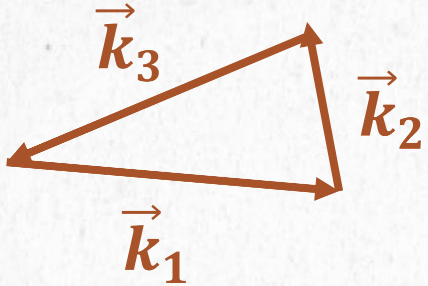

Shape function

[Acquaviva, Bartolo, Matarrese, Riotto 2002]

$< \mathbf{0.0035}$ (from $r < 0.056$)

[Maldacena 2003]

<u>Ex</u>: Single-field inflation (attractor)

$$S = \frac{5}{12}(1 - n_s) S_{\text{loc}} + \frac{\epsilon}{8} S_{\text{eq}} + \cdots = \textbf{VERY SMALL}$$

0.0351

PRIMORDIAL BISPECTRUM

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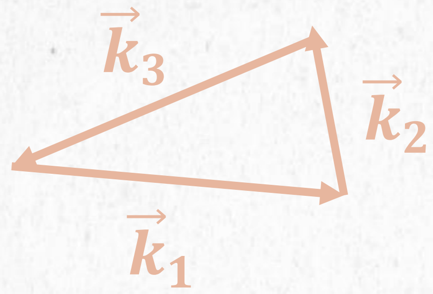

Shape function

Shape templates

Ex: Single-field inflation (attractor)

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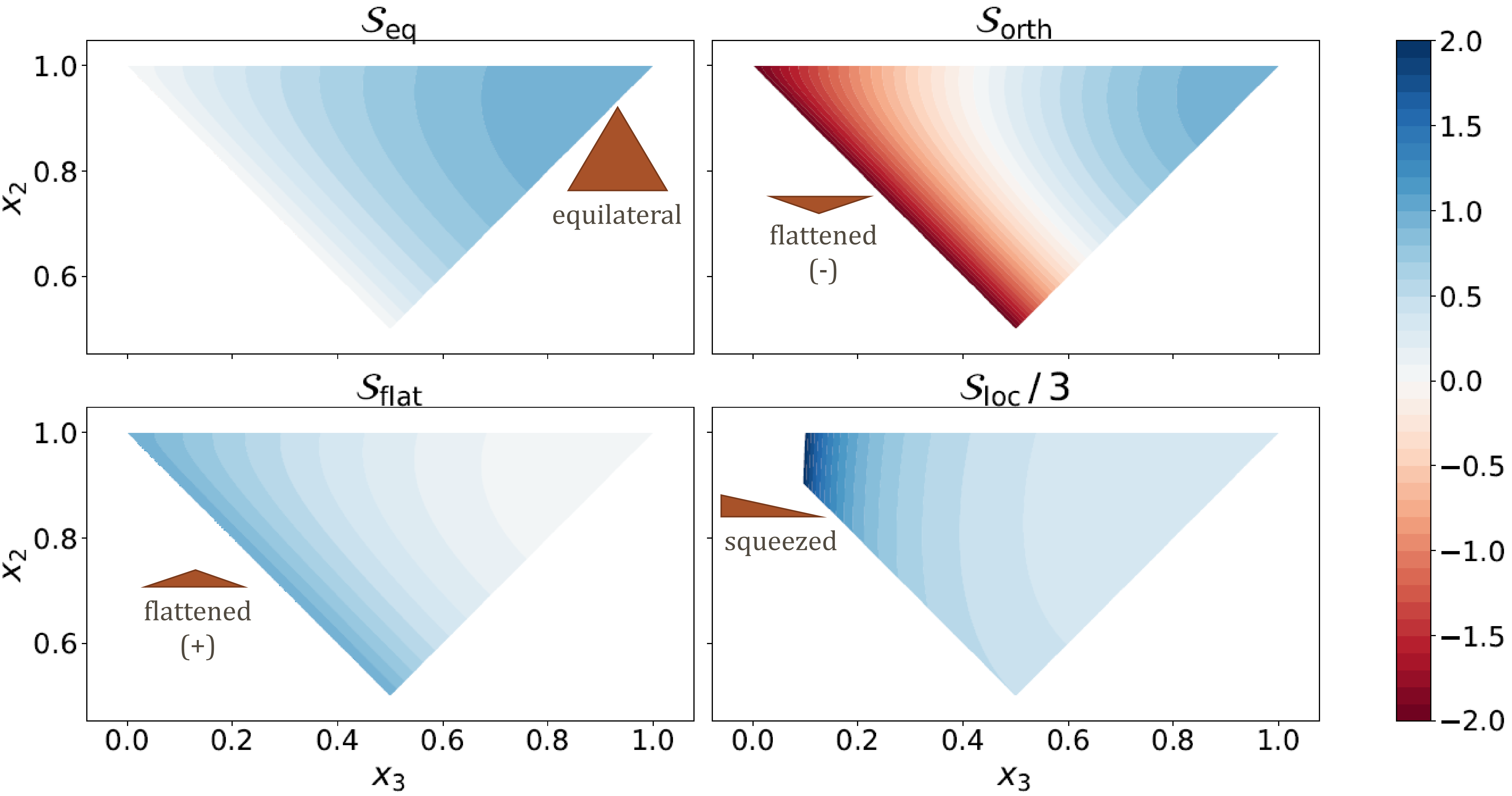
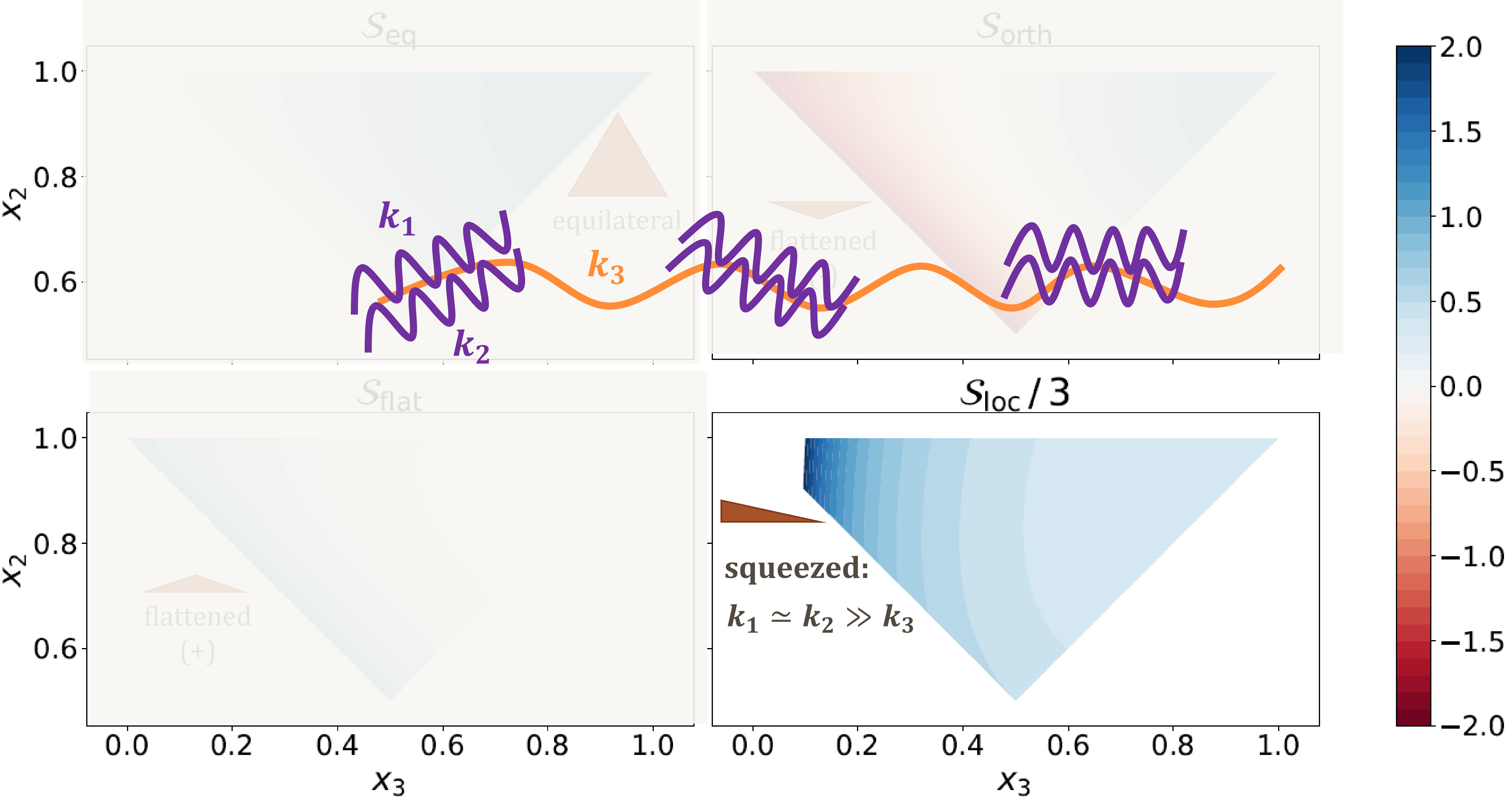
$f_{\rm NL}^{\rm loc}$ $f_{\rm NL}^{\rm eq}$


$S_{\rm eq}$
$S_{\rm orth}$
$S_{\rm flat}$
$S_{\rm loc}/3$
equilateral
flattened
(-)
flattened
(+)
squeezed
x_2
x_3
1.0
0.8
0.6
0.0
0.2
0.4
0.6
0.8
1.0
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0



S_{eq}
S_{orth}
S_{flat}
$S_{loc}/3$
equilateral
flattened
flattened
(+)
k_1
k_2
k_3
squeezed:
$k_1 \simeq k_2 \gg k_3$
x_2
x_3

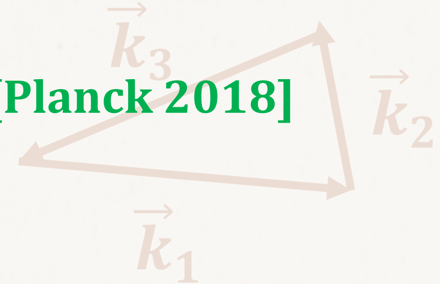
OBSERVATIONAL CONSTRAINTS

ζ the primordial curvature perturbation, γ the primordial tensor perturbation

$$< \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} >= (2\pi)^7 \, \delta^{(3)}(\overrightarrow{k_1} + \overrightarrow{k_2} + \overrightarrow{k_3}) \frac{A_s^2}{(k_1 k_2 k_3)^2} \times S(k_1, k_2, k_3)$$

Shape function

$\rightarrow f_{\mathrm{NL}}^{\mathrm{sq}} = -0.9 \pm 5.1$ **[Planck 2018]**



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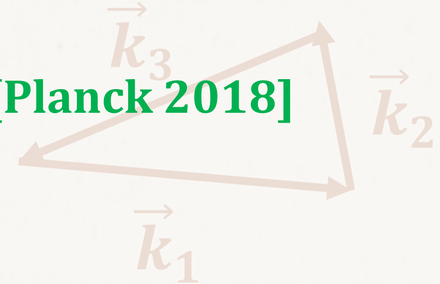

for tensor and mixed NGs: $< \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \gamma_{\vec{k}_3} >$, $< \zeta_{\vec{k}_1} \gamma_{\vec{k}_2} \gamma_{\vec{k}_3} >$, $< \gamma_{\vec{k}_1} \gamma_{\vec{k}_2} \gamma_{\vec{k}_3} >$

SST	STT	TTT
$f_{\rm NL}^{\rm sq} = 84 \pm 49$ **[WMAP]**	$f_{\rm NL}^{\rm sq} = ???$	$f_{\rm NL}^{\rm sq} = 290 \pm 170$ **[WMAP]**

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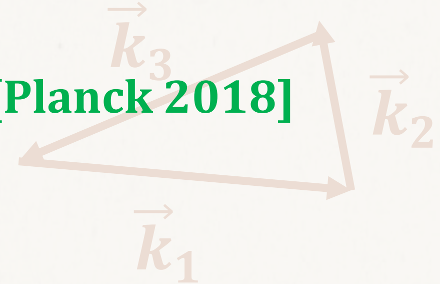

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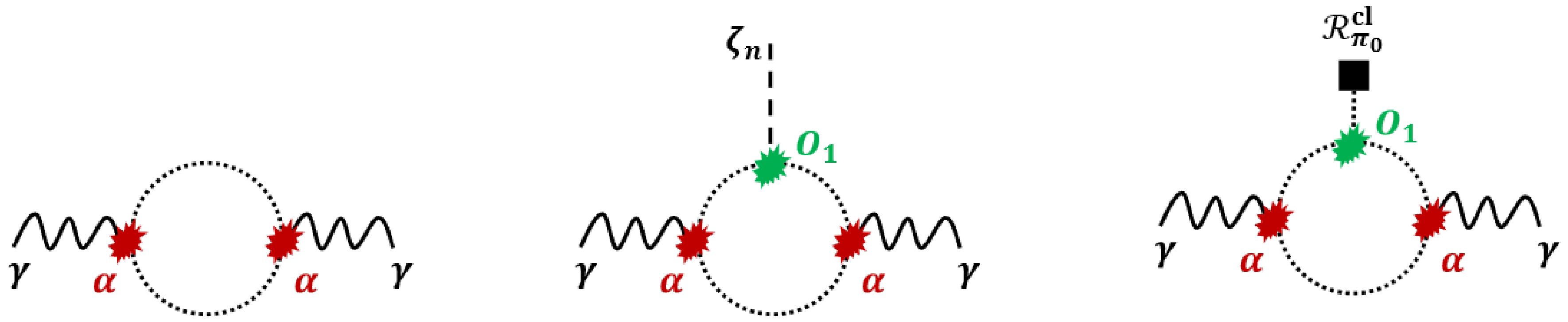
Stochastic Gravitational Wave Background

II. Tensor PNGs

And induced anisotropies in the SGWB



(a) One-loop tensor power spectrum

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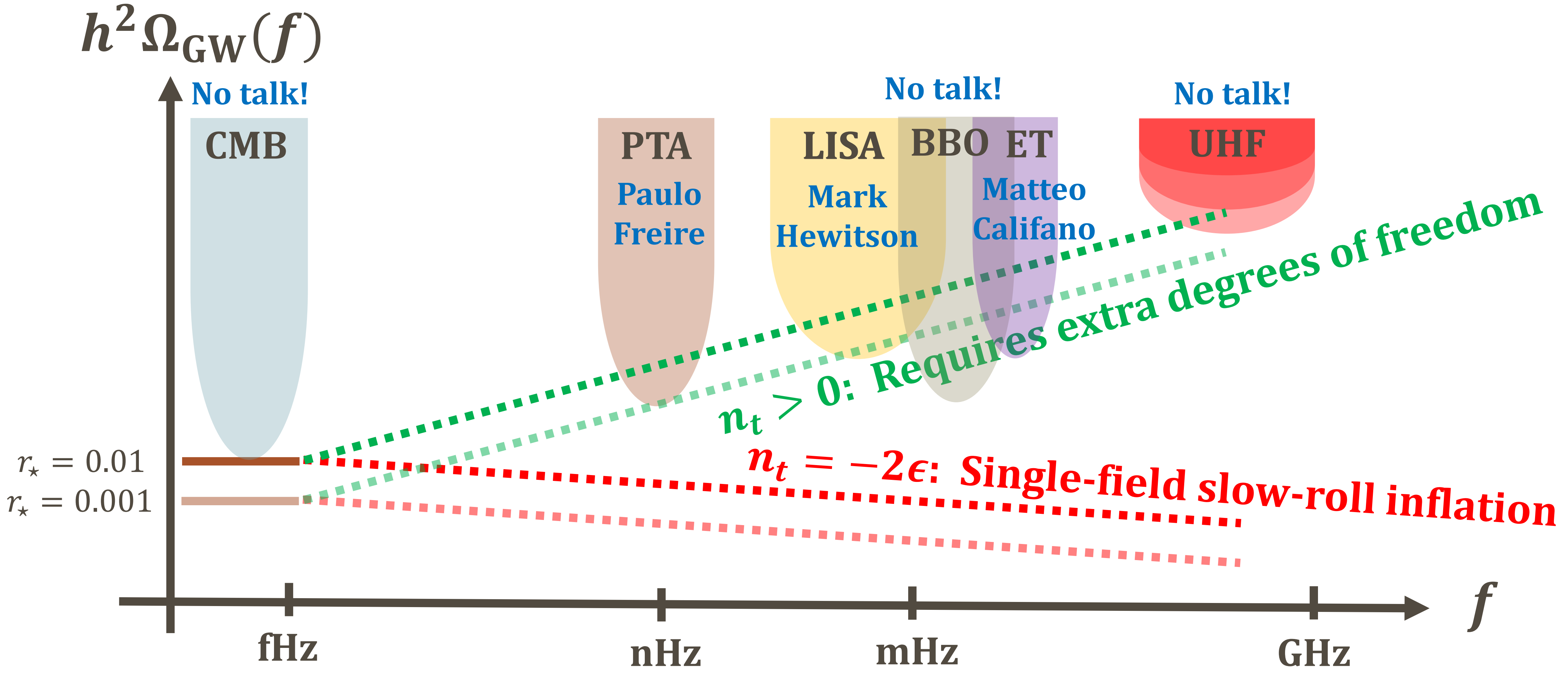
(c) One-loop tensor two-point function in the presence of a classical scalar source.

THE SGWB: ~30 DECADES OF SCALES

At CMB scales, we have the strong constraint $A_t = r_\star\, A_s < 10^{-11}$

But much more freedom at smaller scales (higher frequencies)



THE STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

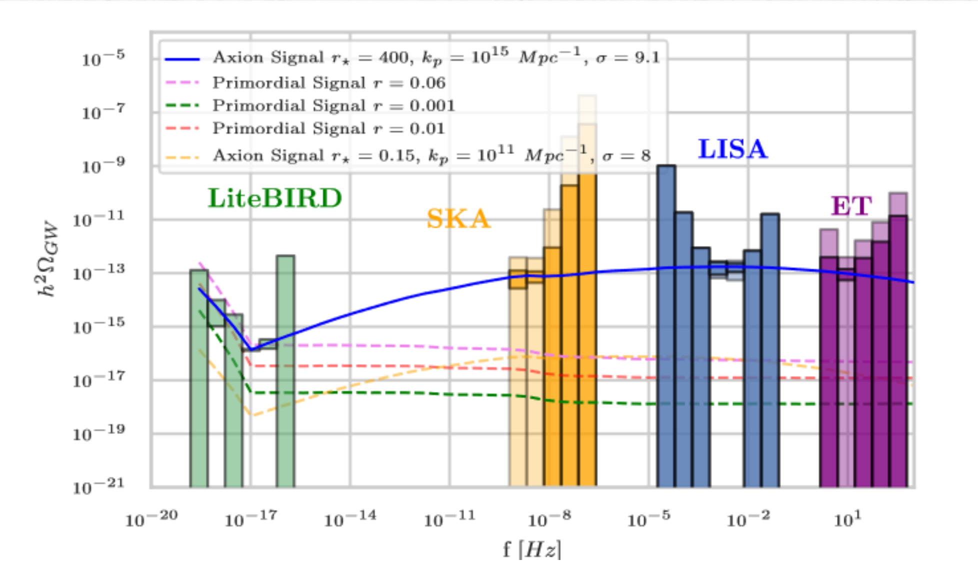
Many sources! Astrophysical, cosmological… How to disentangle them?

Ivan Martin Vilchez

DISTINCTIVE FEATURES OF THE SGWB

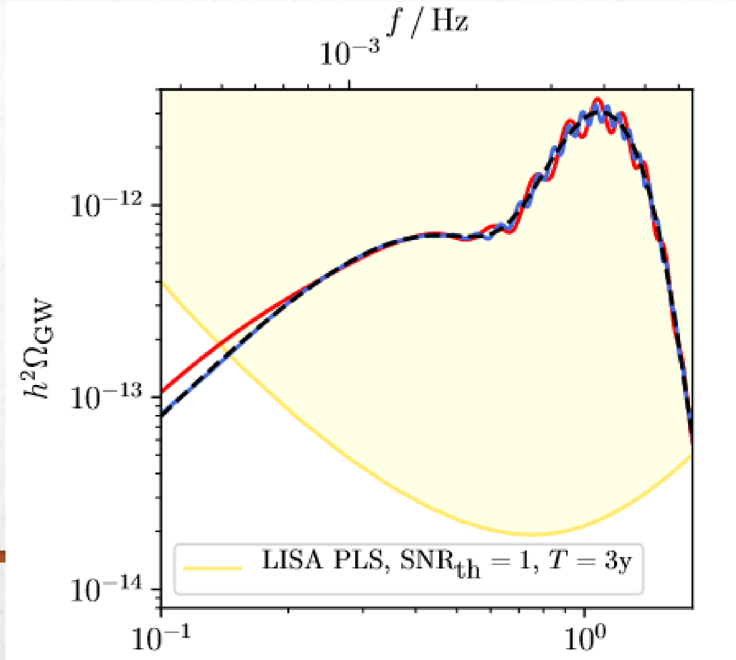
Frequency profile

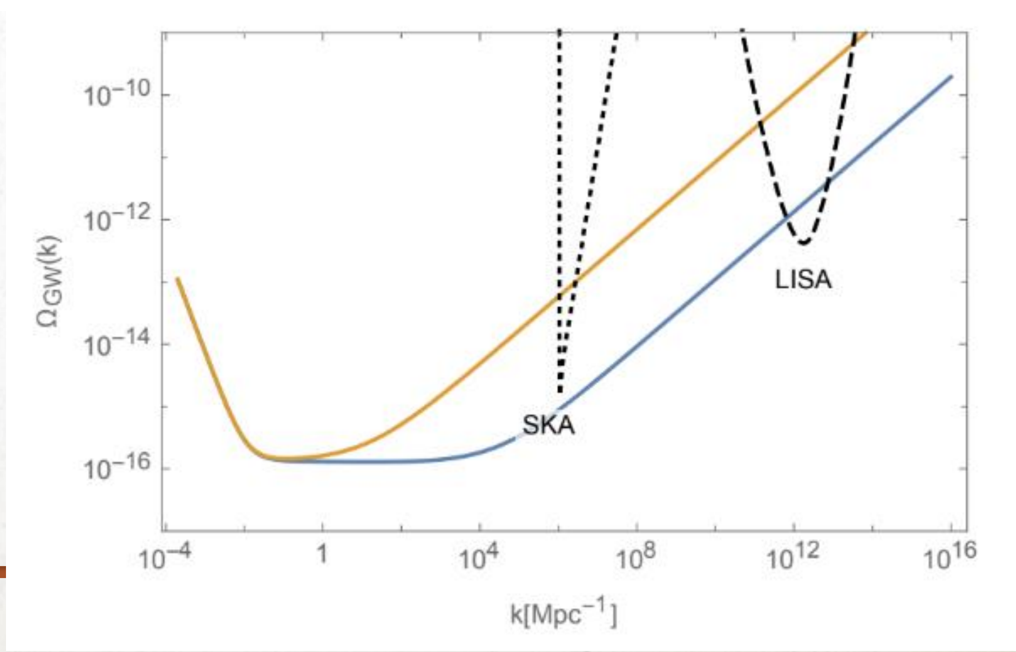
$$\bar{\Omega}_{GW}(f) = \Omega_0 \left(\frac{f}{f_*}\right)^{n_{GW}(f)}$$



Having access to several orders of magnitude in frequency can help

[Auclair *et al.*, LISA CWG 2022]





[Many many works, sorry for not showing yours]

DISTINCTIVE FEATURES OF THE SGWB

Chirality

Antonio Manso

Often in the context of a Cherns-Simon term

- Gauge fields: $g(\chi)F^{a\mu\nu}\,\tilde{F}^{a}_{\mu\nu} \in \mathcal{L}$

[Anber, Sorbo 2010, 2011]
[Barnaby, Peloso 2011]
[Dimastrogiovanni, Peloso 2013]
[Adshead, Martinec, Wyman 2013]
[Dimastrogiovanni, Fasiello, Fujita 2016]
[Watanabe, Komatsu 2020]

- Beyond GR: $g(\chi)R^{\mu\nu}\,\tilde{R}_{\mu\nu} \in \mathcal{L}$

[Bartolo, Orlando 2017, 2018]

Unstable polarisation that sources **chiral** GWs:

$$\gamma_L \gg \gamma_R$$

Chirality $\chi = \frac{|P^L_\gamma - P^R_\gamma|}{P^{\mathrm{tot}}_\gamma}$ can be measured

Also the possibility of other modes in the GWs: **Josu Aurrekoetxea**

DISTINCTIVE FEATURES OF THE SGWB

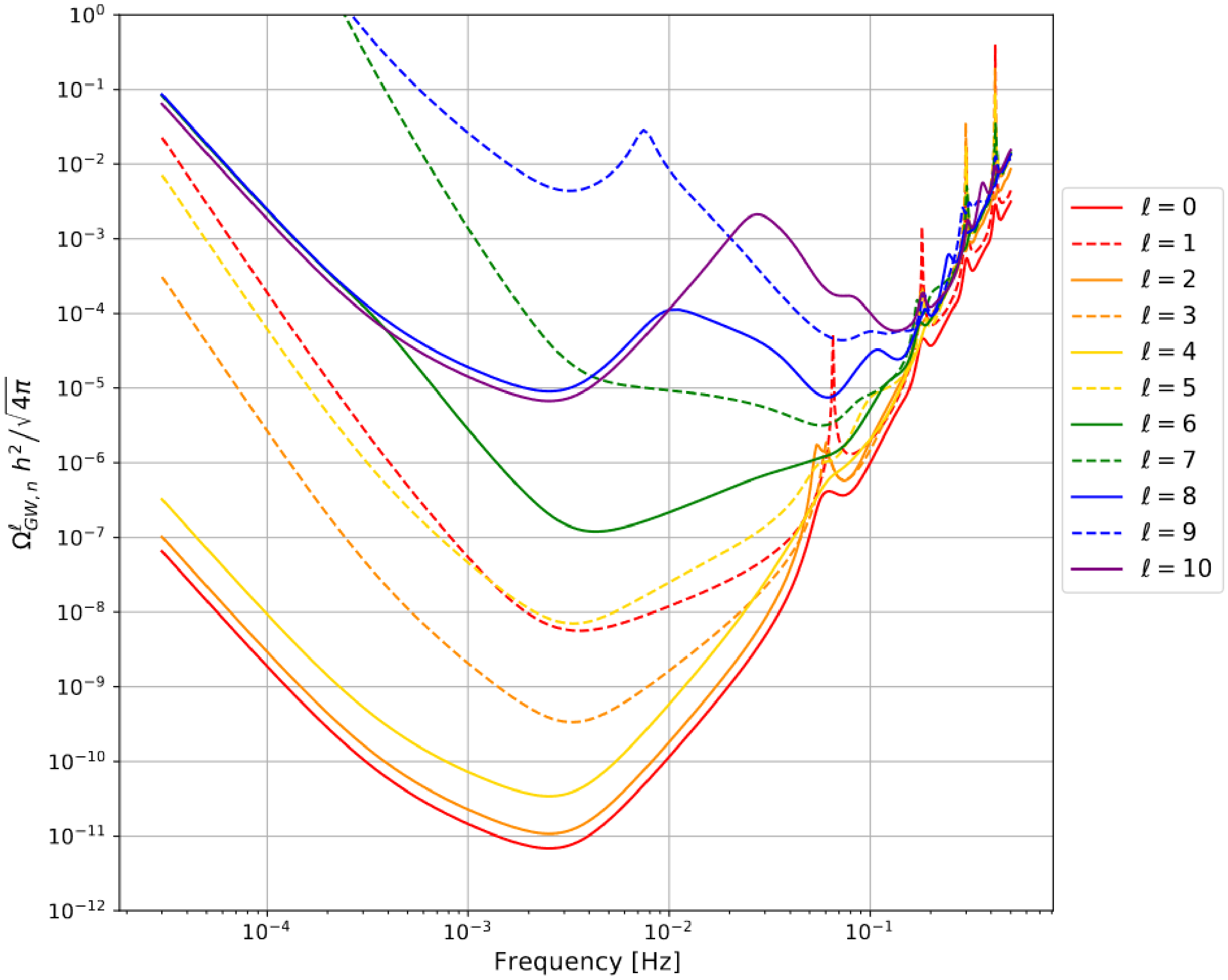
Anisotropies:

$$\Omega_{GW}(f,\hat{n}) = \bar{\Omega}_{GW}(f)\big(1+\boldsymbol{\delta_{GW}(f,\hat{n})}\big)$$

$$\boldsymbol{a_{\ell,m}} = \int \mathrm{d}\Omega \; Y_{\ell,m}(\hat{n})\boldsymbol{\delta_{GW}(\hat{n})}$$

$$\boldsymbol{C_\ell} = \frac{1}{2\ell+1}\sum_m \boldsymbol{a^*_{\ell,m}a_{\ell,m}}$$

Different sources give different anisotropies



[Bartolo *et al.*, LISA Cosmology Working Group 2022]

SEVERAL SOURCES OF ANISOTROPIES

- GWs signal from astrophysical sources expected to be anisotropic

[Cusin *et al*. 2017, 2018, 2019]

[Bertacca *et al*. 2019]

[Bellomo *et al*. 2021]

- Cosmological background propagates through structures → anisotropic

[Alba, Maldacena 2015]

[Contaldi *et al*. 2016]

[Bartolo *et al*. 2018, 2019] *These anisotropies inherit a non-Gaussian statistics from propagation*

[Domcke, Jinno, Rubira 2020]

- Primordial NGs also induce anisotropies:

[Jeong, Kamionkowski 2012] *Anisotropies of the LSS from the same effect*

[Brahma, Nelson, Chandera 2013]

[Dimastrogiovanni *et al*. 2014, 2015, 2021]

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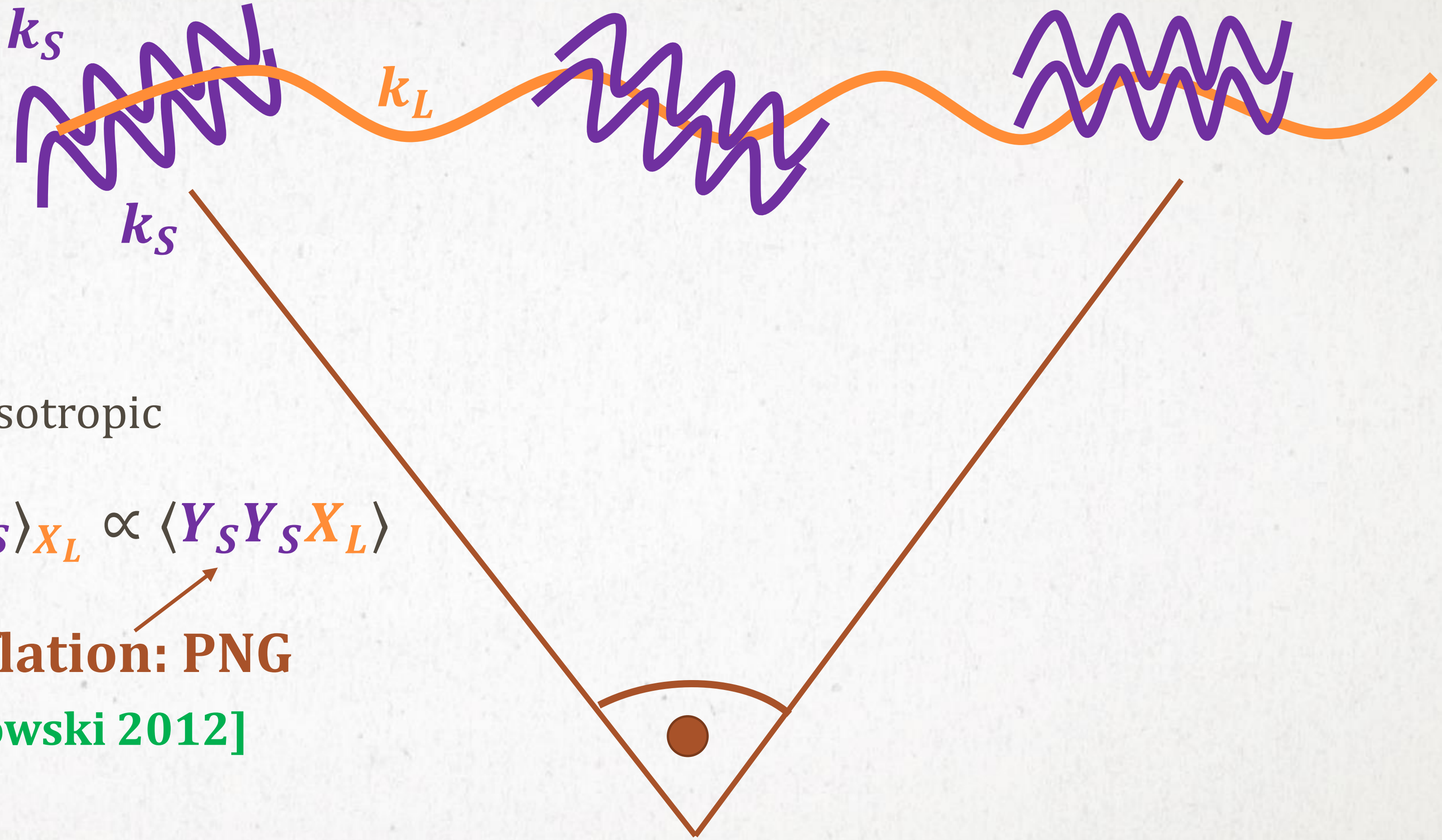
  [Dimastrogiovanni *et al*. 2014, 2015, 2021]

Squeezed: $k_S \gg k_L$

PNG-INDUCED ANISOTROPIES

- The idea:



Consider the modulation of
two short modes by a **long one**:

Seen from far away the signal is anisotropic

$$\delta_{LSS}(\boldsymbol{k}_S,\hat{n});\,\delta_{GW}(\boldsymbol{f}_S,\hat{n}) \;\propto \langle Y_S Y_S\rangle_{X_L} \;\propto \langle Y_S Y_S X_L\rangle$$

$f_{\rm NL,sq}^{YYX}$ from inflation: PNG

[Jeong, Kamionkowski 2012]

Here Y can be a scalar (anisotropies of the LSS) or a tensor (anisotropies of the SGWB)

Also X can be a scalar (modulation by a scalar mode) or a tensor (modulation by a tensor mode)

PNG-INDUCED ANISOTROPIES

[Dimastrogiovanni, Fasiello, LP 2022]
ArXiv:2203.17192

- Formal derivations with the **in-in formalism**:

$$\boxed{\left\langle \hat{\mathcal{O}}(t) \right\rangle = \left\langle 0 \right| \bar{T}\left(e^{i\int_{-\infty^+}^{t} \mathrm{d}t' \hat{H}^I_{\mathrm{int}}(t')} \right) \hat{\mathcal{O}}^I(t) T\left(e^{-i\int_{-\infty^-}^{t} \mathrm{d}t'' \hat{H}^I_{\mathrm{int}}(t'')} \right) \left| 0 \right\rangle ,}$$

Rigorous quantum computation of correlation functions in cosmology

$\neq$

Scattering amplitudes in particle physics

PNG-INDUCED ANISOTROPIES

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- Formal derivations with the in-in formalism:
  - We look for interactions between small and large scales → $f^{\mathrm{sq}}_{\mathrm{NL},\gamma\gamma\gamma}$ and $f^{\mathrm{sq}}_{\mathrm{NL},\gamma\gamma\zeta}$ → $\langle \gamma_S \gamma_S X_L \rangle$

    with $X_L \in \{\gamma_L, \zeta_L\}$

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- Formal derivations with the in-in formalism:
  - We look for interactions between small and large scales → $f^{\mathrm{sq}}_{\mathrm{NL},\gamma\gamma\gamma}$ and $f^{\mathrm{sq}}_{\mathrm{NL},\gamma\gamma\zeta}$
  - A long-wavelength source J_L can be treated classicaly and has negligible derivatives:

$$\hat{J}_L = J_L(\tau)\hat{a}_{\vec{k}} + J_L^*(\tau)\hat{a}^\dagger_{-\vec{k}} \underset{-k\tau \to 0}{\to} J_L^{\mathrm{cl}}(\tau)\underbrace{\left(\hat{a}_{\vec{k}} + \hat{a}^\dagger_{-\vec{k}}\right)}_{\boldsymbol{b_{\vec{k}}}} \quad ; \quad \left(\partial_i J_L^{\mathrm{cl}}, \partial_t J_L^{\mathrm{cl}}\right) \text{ are negligible}$$

$$\left[\hat{a}_{\vec{k}}, \hat{a}^\dagger_{\vec{k}'}\right] = (2\pi)^3\delta^{(3)}(\vec{k} - \vec{k}') \qquad \left[b_{\vec{k}}, b^\dagger_{\vec{k}'}\right] = 0$$

J can be X or not, here we keep it generic to treat multifield scenarios, e.g. $X = \zeta$ and $J = \sigma$

PNG-INDUCED ANISOTROPIES

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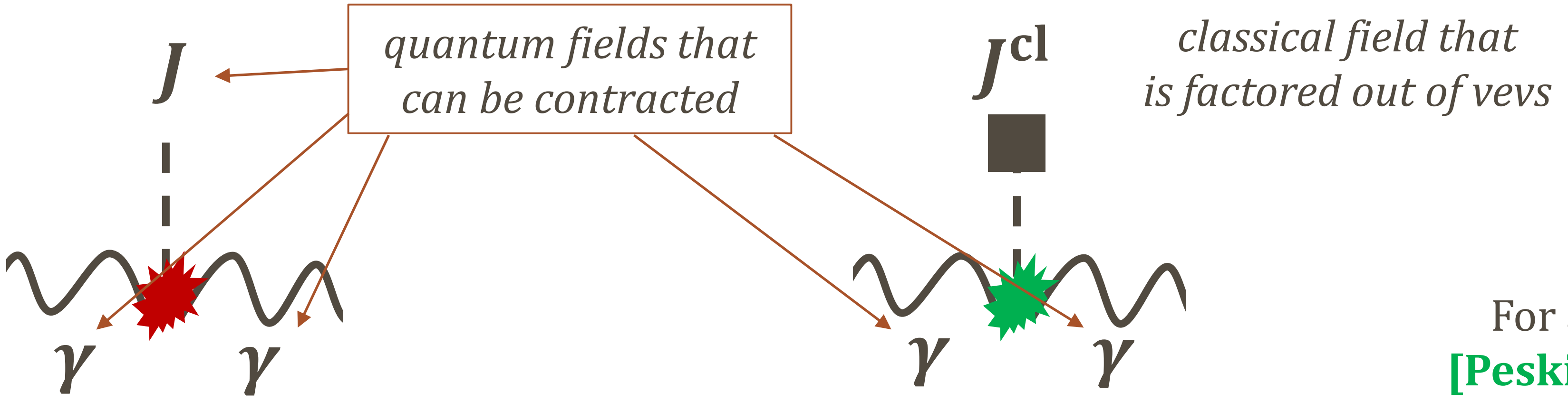
  - A **3-pt interaction** involving J_L becomes a **2-pt interaction** times a classical source J_L^{cl}



For a QED example see [Peskin, Schroeder 1995]

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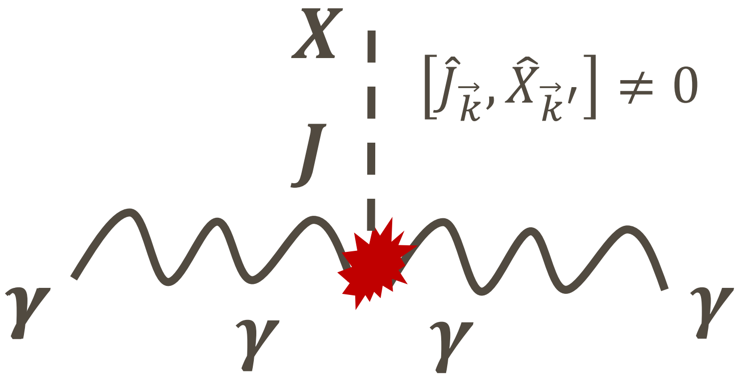
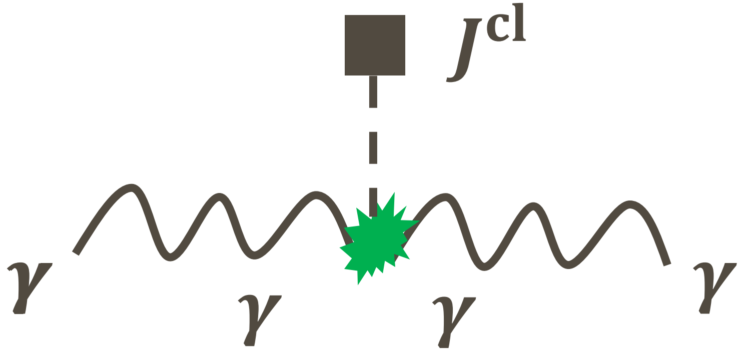
  - ❖ A **3-pt interaction** involving J_L becomes a **2-pt interaction** times a classical source J_L^{cl}
  - ❖ 2-pt functions in the presence of a classical source are now defined:

$$\langle \gamma_{\vec{k}_1}\gamma_{\vec{k}_2}X_{\vec{k}_3}\rangle = (2\pi)^3\ \delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3)B^{\gamma\gamma X}$$



$$< \gamma_{\vec{k}_1}\gamma_{\vec{k}_2} >_{J^{\mathrm{cl}}}$$



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  - 2-pt functions in the presence of a classical source are now defined
  - We compute both diagrams with the in-in formalism and are therefore able to relate them:

$$\boxed{\langle \gamma_{\vec{k}_1} \gamma_{\vec{k}_2} \rangle_{J^{\mathrm{cl}}} \underset{|\vec{k}_1+\vec{k}_2| \ll k_{1,2}}{=} \int \mathrm{d}^3\vec{q}\;\, \delta^{(3)}(\vec{q}+\vec{k}_1+\vec{k}_2)\, \frac{B_{\mathrm{sq}}^{\gamma\gamma X}(\vec{k}_1,\vec{k}_2,\vec{q})}{P_{JX}(q)} J^{\mathrm{cl}}(\vec{q})}$$

Non-diagonal part, $\vec{k}_1+\vec{k}_2 \neq \vec{0}$, of the 2-pt function does not vanish → anisotropies

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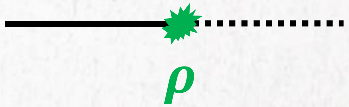
$\boldsymbol{J}^{\mathrm{cl}}(\vec{\boldsymbol{q}})$ is a statistical quantity → so is $\langle \gamma_{\vec{k}_1}\gamma_{\vec{k}_2}\rangle_{J^{\mathrm{cl}}}$ → $\langle \delta(\hat{n}_1)\delta(\hat{n}_2)\rangle \propto \langle J^{\mathrm{cl}}(\vec{q})J^{\mathrm{cl}}(\vec{q}\,')\rangle \neq 0$

MULTIFIELD MODELS WITH LARGE ANISOTROPIES

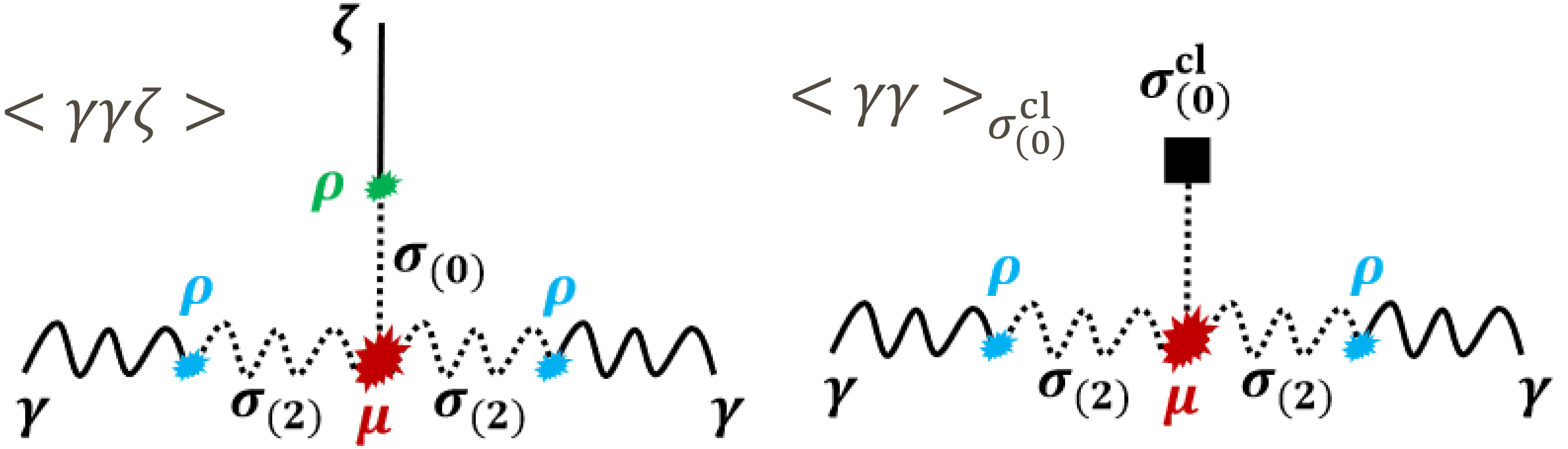
- Spin-2 EFT of inflation: $\sigma_{ij} = \partial_i \partial_j \sigma^{(0)} + \sigma_{ij}^{(2)}$ **[Bordin *et al.* 2018]**

$\rightarrow$ $\sigma^{(2)}$ couples linearly to γ and can make the tilt blue: $n_t > 0$ for half of parameter space $(\dot{c}_2 < 0)$

We compute anisotropies explicitly and find: $\sqrt{< \delta_{GW}^2(k_S, \hat{n}) >} \sim \dfrac{< \gamma\gamma\zeta > (k_S, k_S, k_L)}{P_\gamma(k_S) P_{\zeta\sigma^{(0)}}(k_L)} \sqrt{\mathcal{P}_{\sigma^{(0)}}(k_L)}$



$< \gamma\gamma\zeta >$ $< \gamma\gamma >_{\sigma^{cl}_{(0)}}$



(a) Mixed scalar-tensor-tensor bispectrum.

(b) Tensor two-point function in the presence of a classical scalar source.

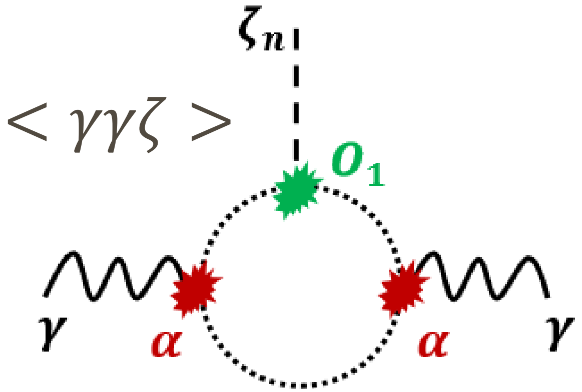
[Dimastrogiovanni, Fasiello, LP 2022]
ArXiv:2203.17192

MULTIFIELD MODELS WITH LARGE ANISOTROPIES

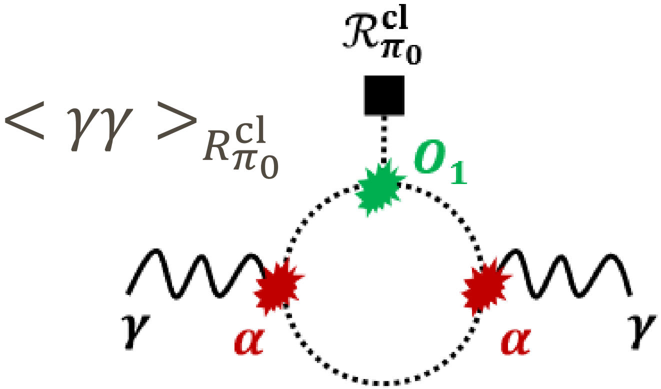
- Supersolid inflation: two fundamental scalar fluctuations $(\overset{\text{adiabatic}}{\zeta_n}, \overset{\text{entropic}}{R_{\pi_0}})$ **[Celoria *et al.* 2021]**

→ R_{π_0} couples **quadratically** to γ and can make the tilt blue: $n_t = 2(n_s^{\rm en} - 1) > 0$

We compute anisotropies explicitly and find: $$\sqrt{< \delta^2_{GW}(k_S, \hat{n}) >} \sim \underbrace{f^{\gamma\gamma\zeta}_{\rm NL,sq}(k_S, k_S, k_L)}_{\gg 1} \underbrace{\left(\sqrt{\frac{\mathcal{P}_{\zeta_n}\mathcal{P}_{R_{\pi_0}}}{\mathcal{P}_{\zeta_n R_{\pi_0}}}}\right)_{k_L}}_{\mathcal{O}(1)} \underbrace{A_s^{1/2}}_{4\times 10^{-5}}$$



(b) One-loop scalar-tensor-tensor bispectrum



(c) One-loop tensor two-point function in the presence of a classical scalar source.

[Dimastrogiovanni, Fasiello, LP 2022]
ArXiv:2203.17192

CONCLUSION

- Primordial NGs contain much more information than a single number $f_{\mathrm{NL}}^{\mathrm{local}}$
- We do not know much about tensor primordial NGs
- Squeezed tensor primordial NGs survive in the form of induced anisotropies in the SGWB, allowing for a new probe of the inflationary field content and interactions

Formidable opportunity to use the non-linear Universe as a particle detector

$$\boxed{\delta_{\mathrm{GW}}(\hat{n}) \propto \langle \gamma_{\vec{k}_1} \gamma_{\vec{k}_2} \rangle_{\zeta^{\mathrm{cl}}} \underset{|\vec{k}_1+\vec{k}_2| \ll k_{1,2}}{=} \int \mathrm{d}^3\vec{q}\ \delta^{(3)}(\vec{q}+\vec{k}_1+\vec{k}_2) P_\gamma(k_1) f_{\mathrm{NL,sq}}^{\gamma\gamma\zeta}(\vec{k}_1,\vec{k}_2,\vec{q}) \boldsymbol{\zeta}^{\mathbf{cl}}(\vec{\boldsymbol{q}})}$$

Note: $\boldsymbol{\zeta}^{\mathbf{cl}}(\vec{\boldsymbol{q}})$ is the seed of anisotropies in the CMB! Cross-correlations, *e.g.*, $\langle \delta_{\mathrm{GW}} \delta T \rangle \neq 0$

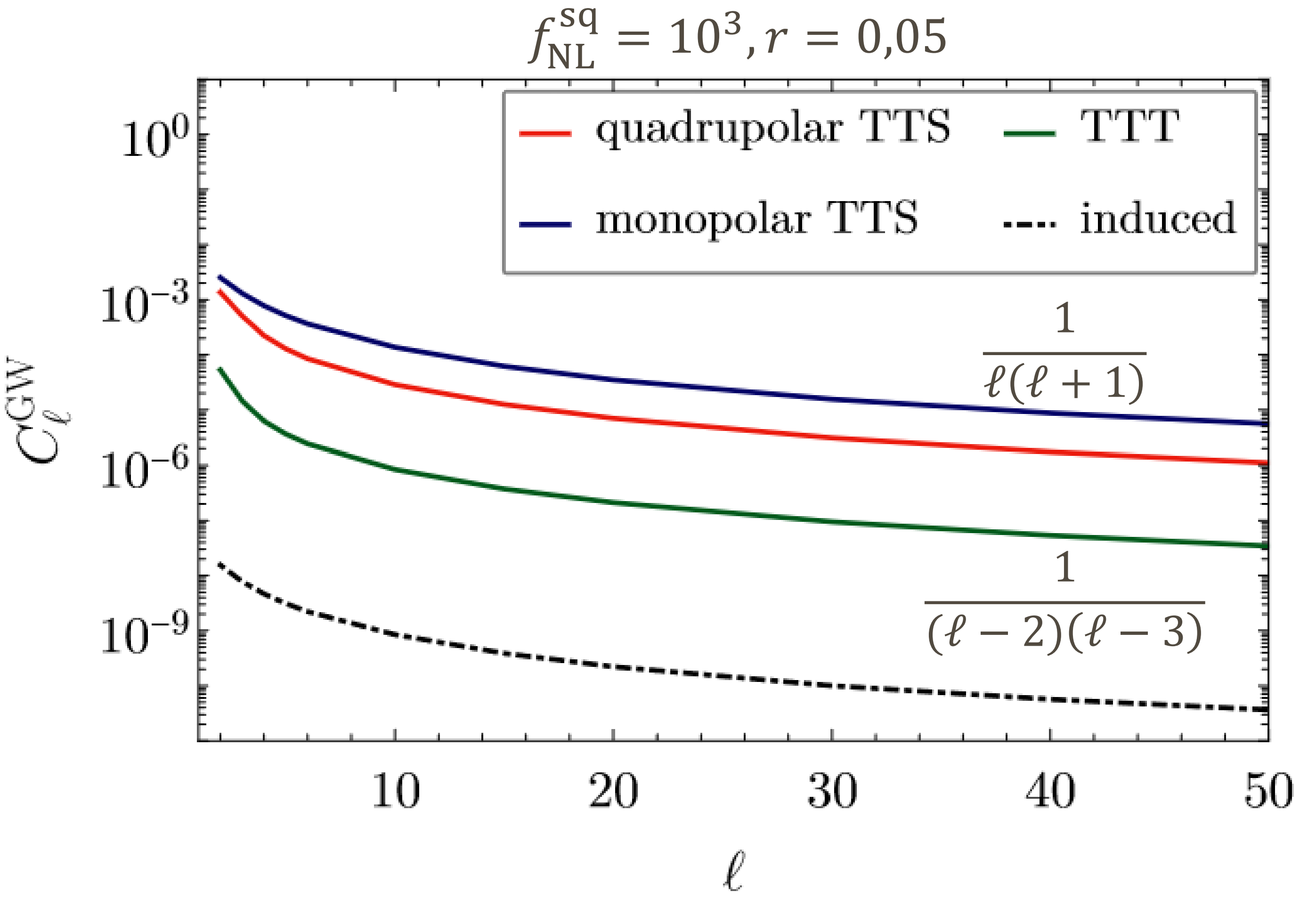
ℓ-DEPENDENCE

Anisotropies:

$$\Omega_{GW}(f,\hat{n}) = \bar{\Omega}_{GW}(f)\left(1 + \boldsymbol{\delta_{GW}(f,\hat{n})}\right)$$

$$\boldsymbol{a_{\ell,m}} = \int \mathrm{d}\Omega\ Y_{\ell,m}(\hat{n})\boldsymbol{\delta_{GW}(\hat{n})}$$

$$\boldsymbol{C_\ell} = \frac{1}{2\ell+1}\sum_m \boldsymbol{a^*_{\ell,m} a_{\ell,m}}$$



[Dimastrogiovanni *et al.* 2021]

Scalar PNGs

The rich multifield phenomenology