Scale-dependent Non-Gaussianity from massive gravity during inflation

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COSMO 17, August 28th

Based on: G.D., T.Hiramatsu, C.Lin, M.Sasaki, M.Shiraishi, Y.Wang (1701.05554)
JCAP 1705 (2017) no.05, 034

Introduction

- **What if gravity was massive during inflation?**
  - Gravity on cosmological scales?
    (inflation, dark energy…)
  - Perhaps tensor structure modified in early universe! Observational consequences?
- **If so, tensor modes could be responsible for scale dependent features in the CMB.**
  - Possible observable effects of tensor modes, not only in B-modes?

Inflation and the CMB

Power spectrum:

$$n_s = 0.9569 \pm 0.0077$$

(68 % CL, *Planck* TT,TE,EE+lowP)

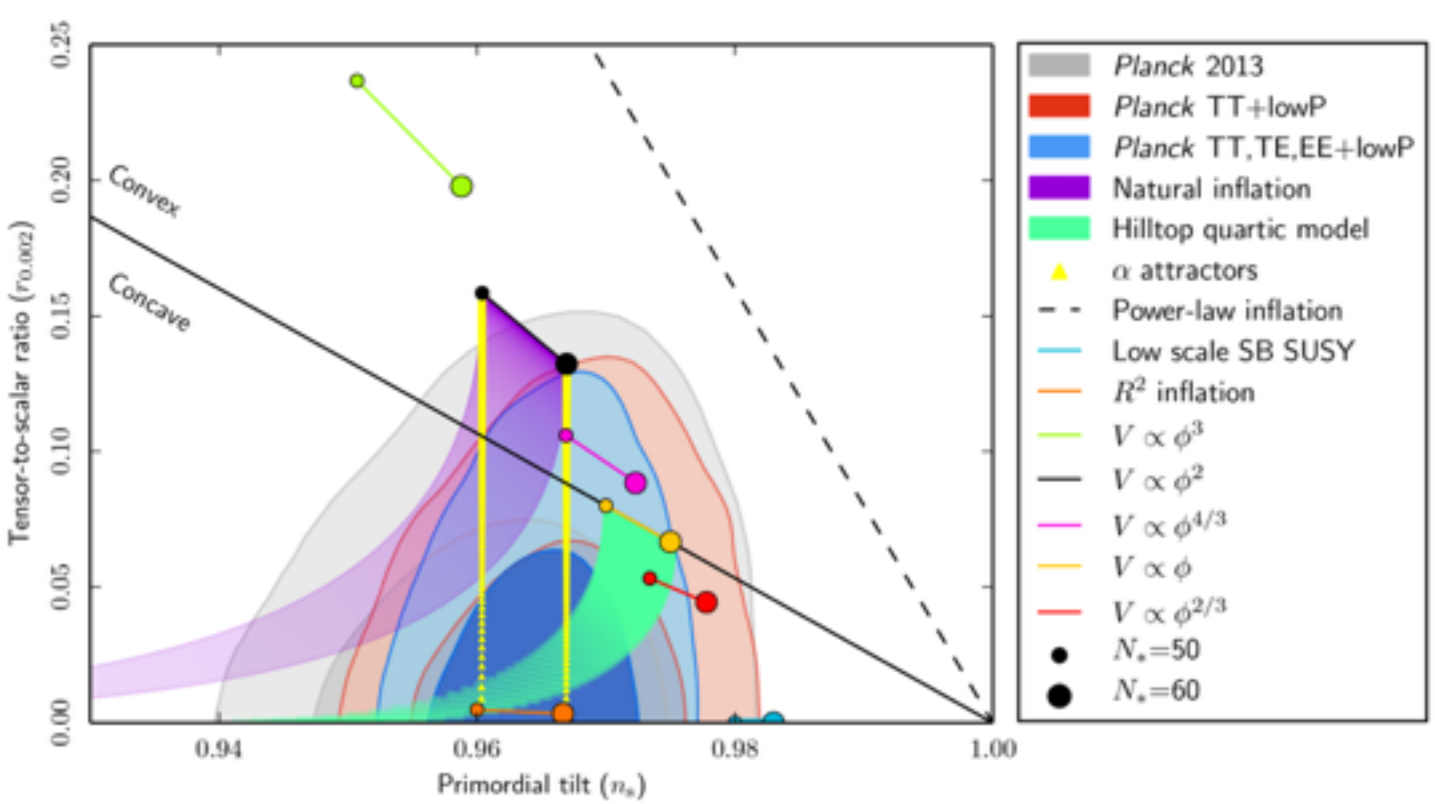
$$r_{0.002} < 0.10$$

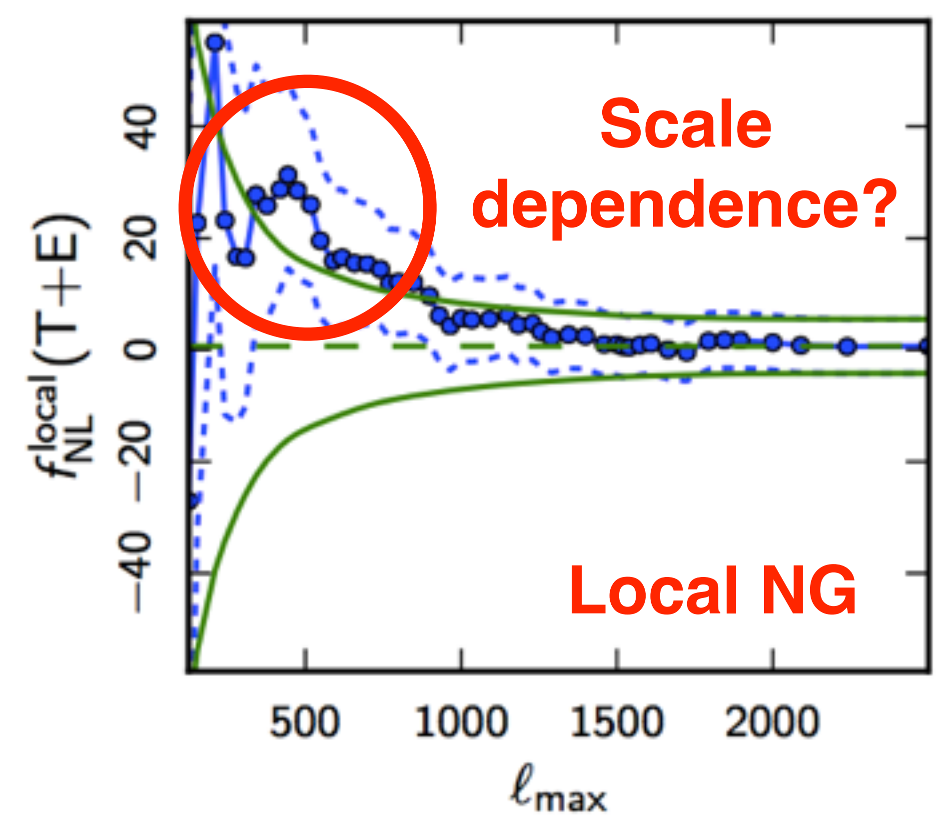
(95 % CL, *Planck* TT,TE,EE+lowP)

Non-Gaussianity:

$$f_{NL}^{\text{local}} = 0.8 \pm 5.0$$
$$f_{NL}^{\text{equil}} = -4 \pm 43$$
$$f_{NL}^{\text{ortho}} = -26 \pm 21$$

Planck 2015 68% *CL statistical*





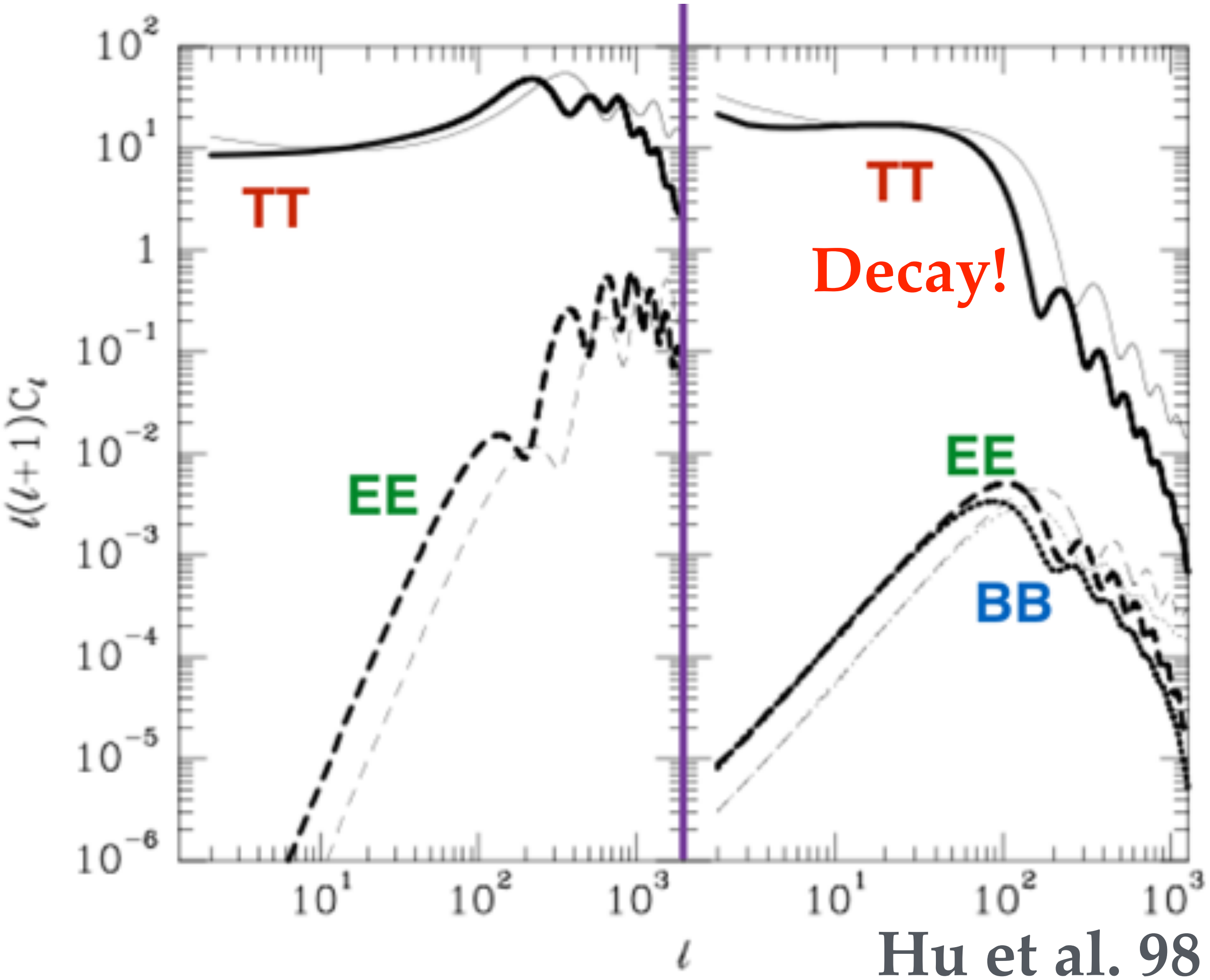
Tensor modes in the CMB

Power spectrum:

$$\langle\gamma\gamma\rangle \sim r\langle\zeta\zeta\rangle \sim \epsilon\langle\zeta\zeta\rangle$$

Slow roll suppressed!

Scalar contribution Tensor contribution



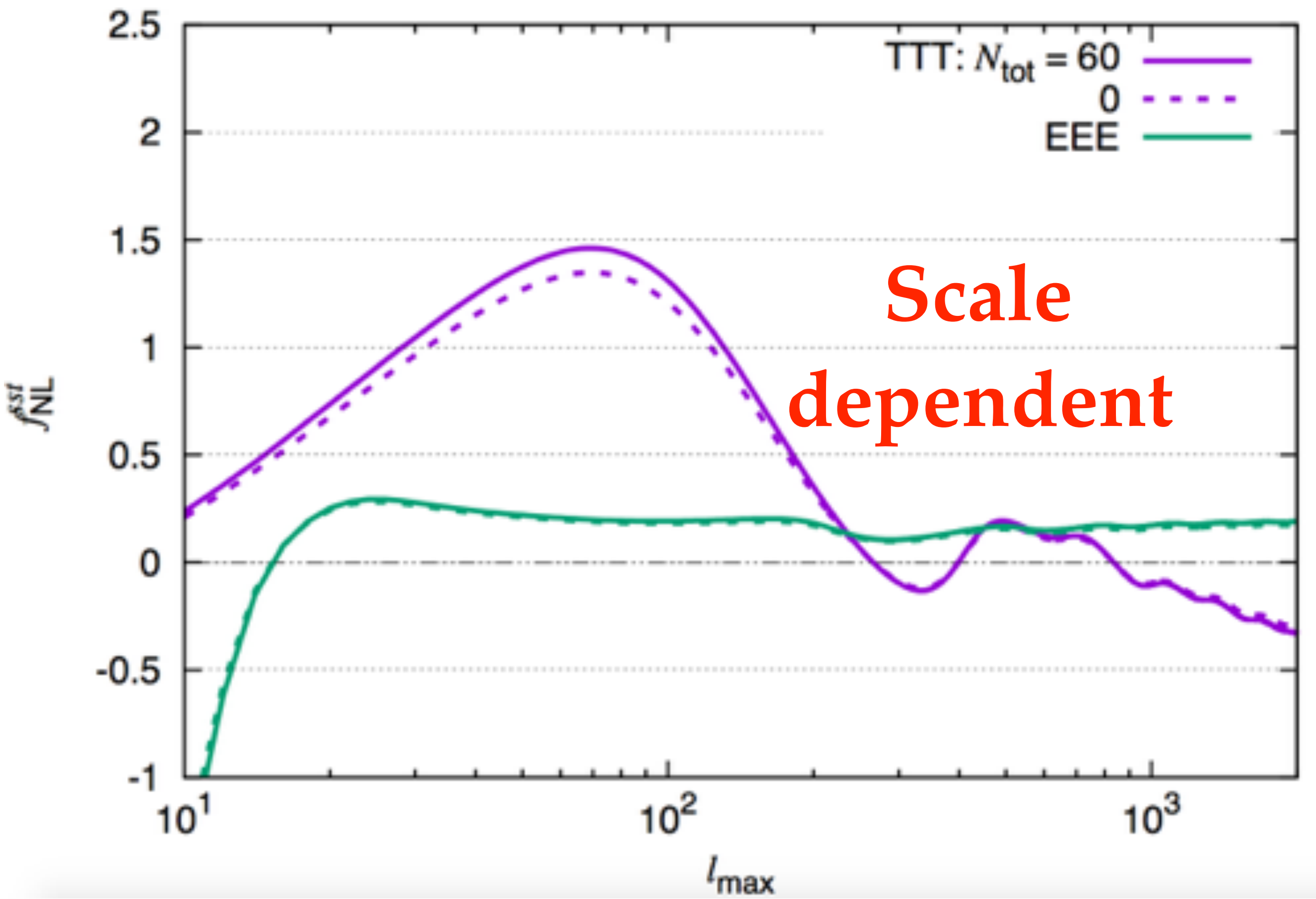
Hu et al. 98

Non-Gaussianity:

$$\langle\delta T\delta T\delta T\rangle \sim \langle\gamma_{ij}\partial_i\zeta\partial_j\zeta\rangle$$

$$\langle\gamma_{ij}\partial_i\zeta\partial_j\zeta\rangle \sim \epsilon\langle\zeta\zeta\zeta\rangle$$

Tensor modes decay as 1/a(t)



What if gravity was massive during inflation?

(Inflation plus preferred spatial frame)

The model

C.Lin: 1501.07160

- Inflation driven by $\phi(t)$ —> Preferred time slicing

- 3 space-like scalar fields —> Preferred spatial frame

$$\varphi^i \qquad i = 1, 2, 3$$

- Homogeneous & Isotropic expanding background
—> φ^i Fields configuration H & I in the background.

- Perturbations do not preserve the symmetries of the background $\varphi^i = x^i + \pi^i$ π=E=0

$$h_{ij} = a^2 e^{2\zeta} \exp\left(\gamma_{ij} + \partial_i \partial_j E\right) \qquad \phi = \phi(t) + \delta\phi(t, x^i)$$

$\delta\phi(t, x^i) = 0$ ϕ-cnt hypersurface

Recipe

- On top of inflation there is a non-trivial spatial frame.

  - Symmetries: $\varphi^i \to \Lambda^i_j \varphi^j , \qquad \varphi^i \to \lambda \varphi^i$

  - Ingredients: $Z^{ij} \equiv \partial^\mu \varphi^i \partial_\mu \varphi^j , \qquad \bar{\delta} Z^{ij} \equiv \frac{Z^{ij}}{Z} - 3\frac{Z^{ik}Z^{kj}}{Z^2}$

- The action:

$\gamma_{ij}\gamma^{ij}$ **Mass**

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_p^2\mathcal{R} - \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) - \frac{9}{8}M_p^2 m_g^2 \bar{\delta}Z^{ij}\bar{\delta}Z^{ij} \right.$$

$$\left. + \frac{1}{2}\lambda_{sst}\bar{\delta}Z^{ij}\cdot\partial^\mu\varphi^i\partial_\mu\phi\cdot\partial^\nu\varphi^j\partial_\nu\phi/Z + \ldots\right]$$

$$\varphi^i = x^i$$

Shift vector $N_i = \partial_i \beta ,$

$\gamma_{ij} N^i N^j$ **SST**

Linear perturbations

- Scalar modes (untouched)

$$S_{(2)} = M_p^2 \int d^4x a^3 \epsilon \left(\dot{\zeta}^2 - a^{-2} \partial_i \zeta \partial_i \zeta \right)$$

- Tensor modes (massive)

$$S_T^{(2)} \sim \frac{M_p^2}{8} \int dt d^3x a^3 \left[\dot{\gamma}_{ij} \dot{\gamma}^{ij} - \left(\frac{k^2}{a^2} + m_g^2 \right) \gamma_{ij} \gamma^{ij} \right]$$

$$P_\gamma = \frac{2H^2}{\pi^2 M_p^2} \left(\frac{k}{aH} \right)^{2m_g^2/3H^2} \qquad n_t \simeq -2\epsilon + \frac{2m_g^2}{3H_i^2}$$

Note: Tensor power spectrum could be blue!

or have a resonant amplification of GW! Lin & Sasaki: 1504.01373

Non-linear perturbations

- Interaction term:

$$H_{int} = -L_{int} \supset \lambda_{sst} M_p^2 H^2 \epsilon \int a^5 \gamma_{ij} N^i N^j \longrightarrow \gamma_{ij}\partial_i\zeta\partial_j\zeta$$

- After solving constraints $N_i = \partial_i \beta, \quad \beta = -\frac{\zeta}{H} - \frac{a^2\epsilon\dot{\zeta}}{k^2}$

- 3-point function: in-in formalism

Maldacena: astro-ph/0210603

$$\langle 0|\gamma\zeta\zeta|0\rangle \sim i\langle 0|\left[\gamma\zeta\zeta, H_{int}\right]|0\rangle \sim \lambda_{sst}\langle\gamma\gamma\rangle\langle\zeta\zeta\rangle \qquad \langle\zeta\zeta\zeta\rangle \sim \epsilon\langle\zeta\zeta\rangle^2$$

- A rough estimation tells us $\frac{\langle\gamma\zeta\zeta\rangle}{\langle\zeta\zeta\zeta\rangle} \sim \lambda_{sst}$

$$f_{NL}^{local} \sim 10 \longrightarrow \lambda_{sst} \sim 100$$

$$\langle\gamma\gamma\rangle \sim r\langle\zeta\zeta\rangle \sim \epsilon\langle\zeta\zeta\rangle$$

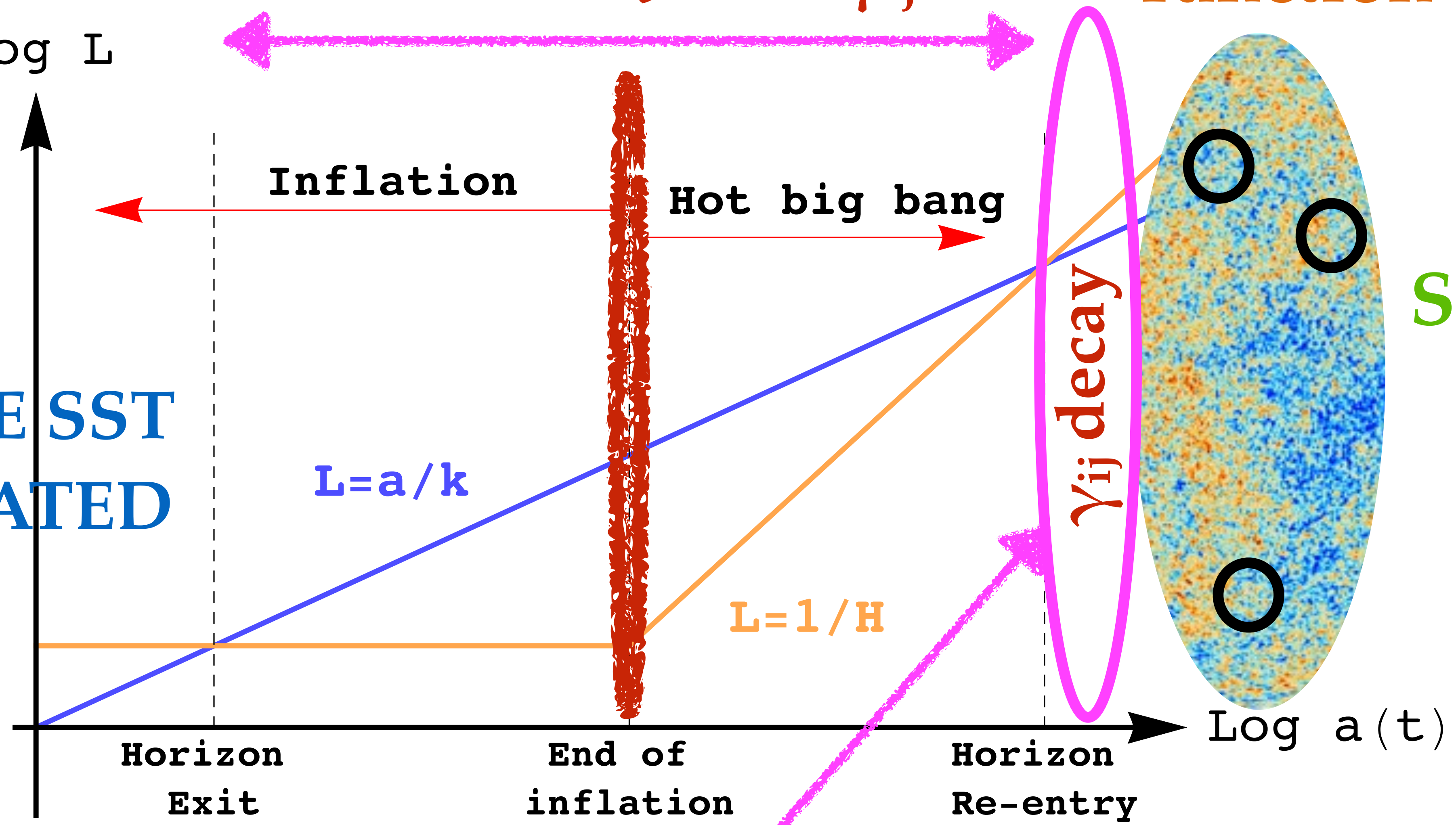
Tensor modes responsible for the scale dependent NG

(From inflation to CMB.
Numerical results)

From inflation to CMB

scalar 2-point function unaffected

constant ζ and γ_{ij}



SIZABLE SST GENERATED

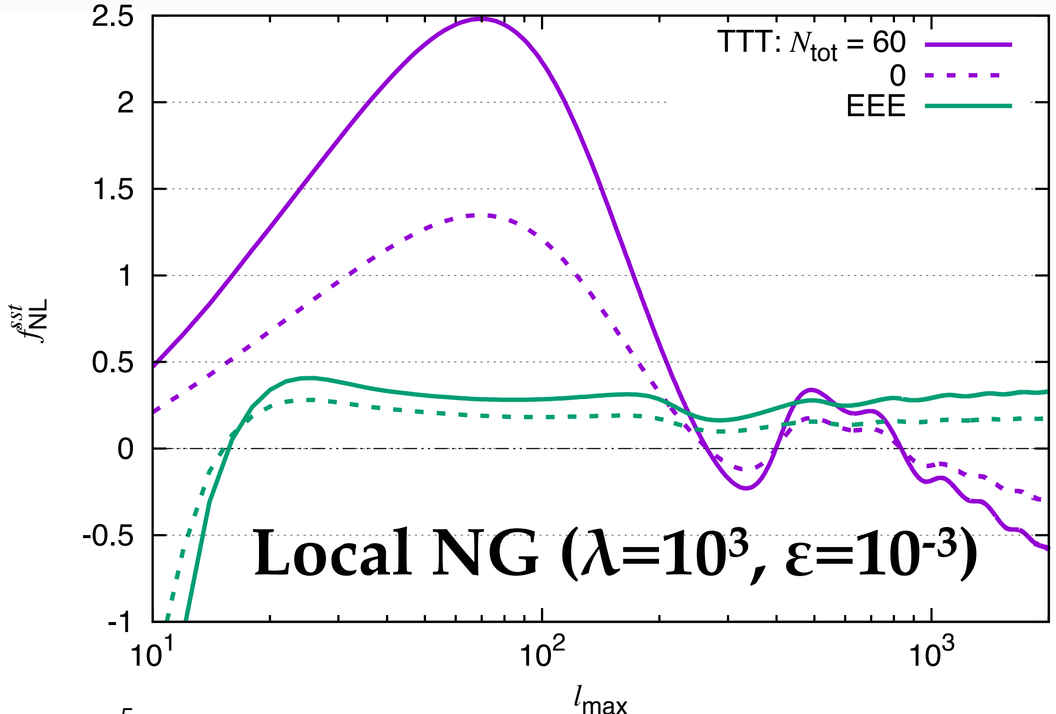
Last Scattering Surface CMB

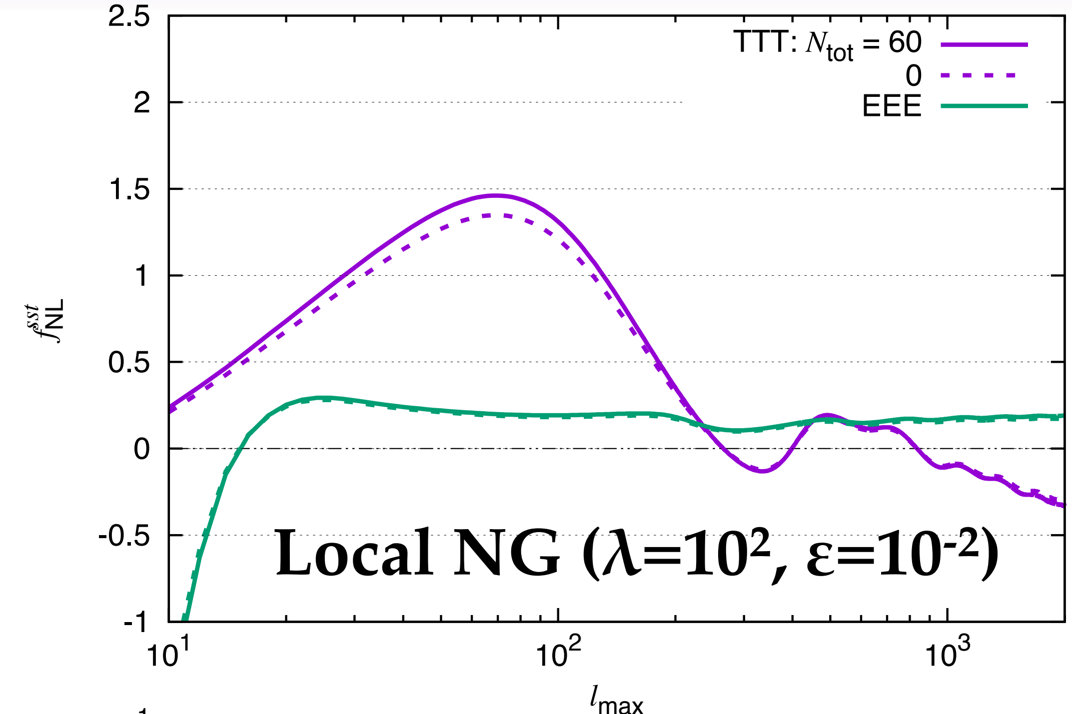
Tensor modes decay as 1/a(t)

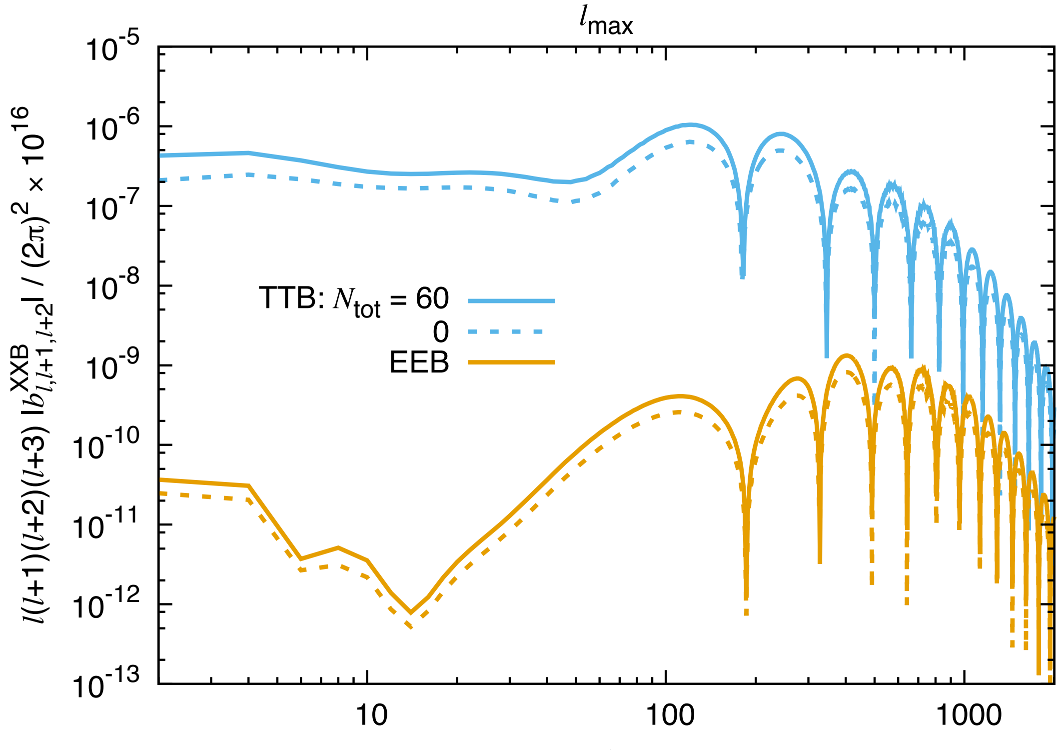
3-point function scale-dependent!

Numerical results

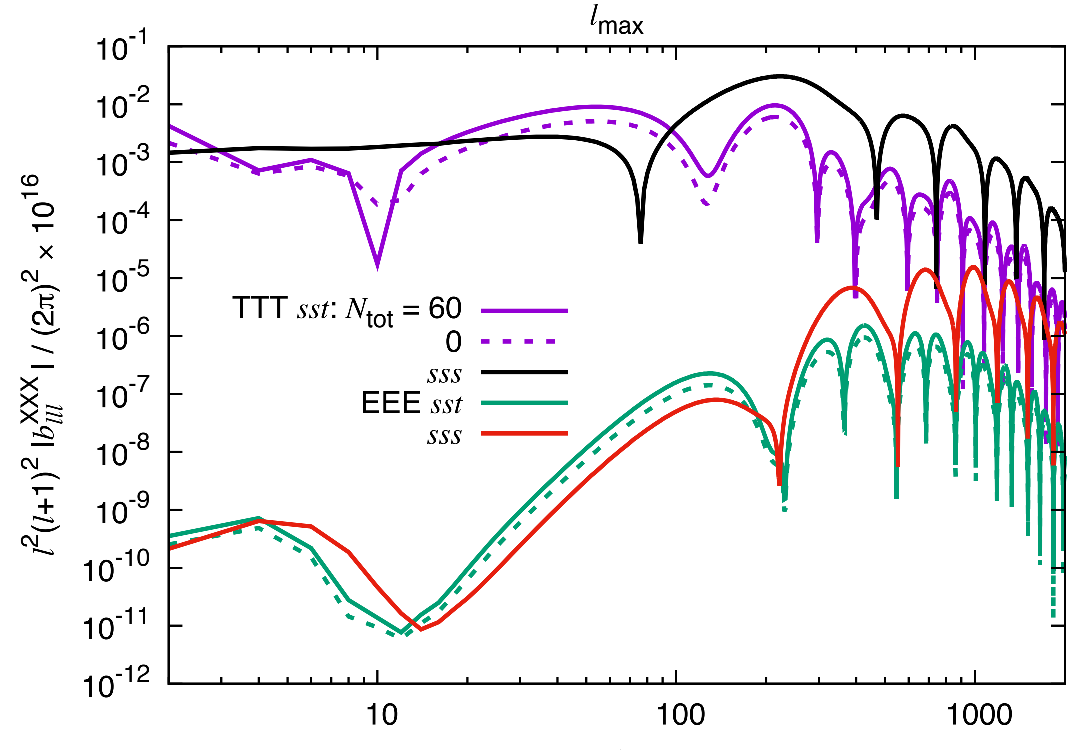
Numerical calculation by T. Hiramatsu and M.Shiraishi







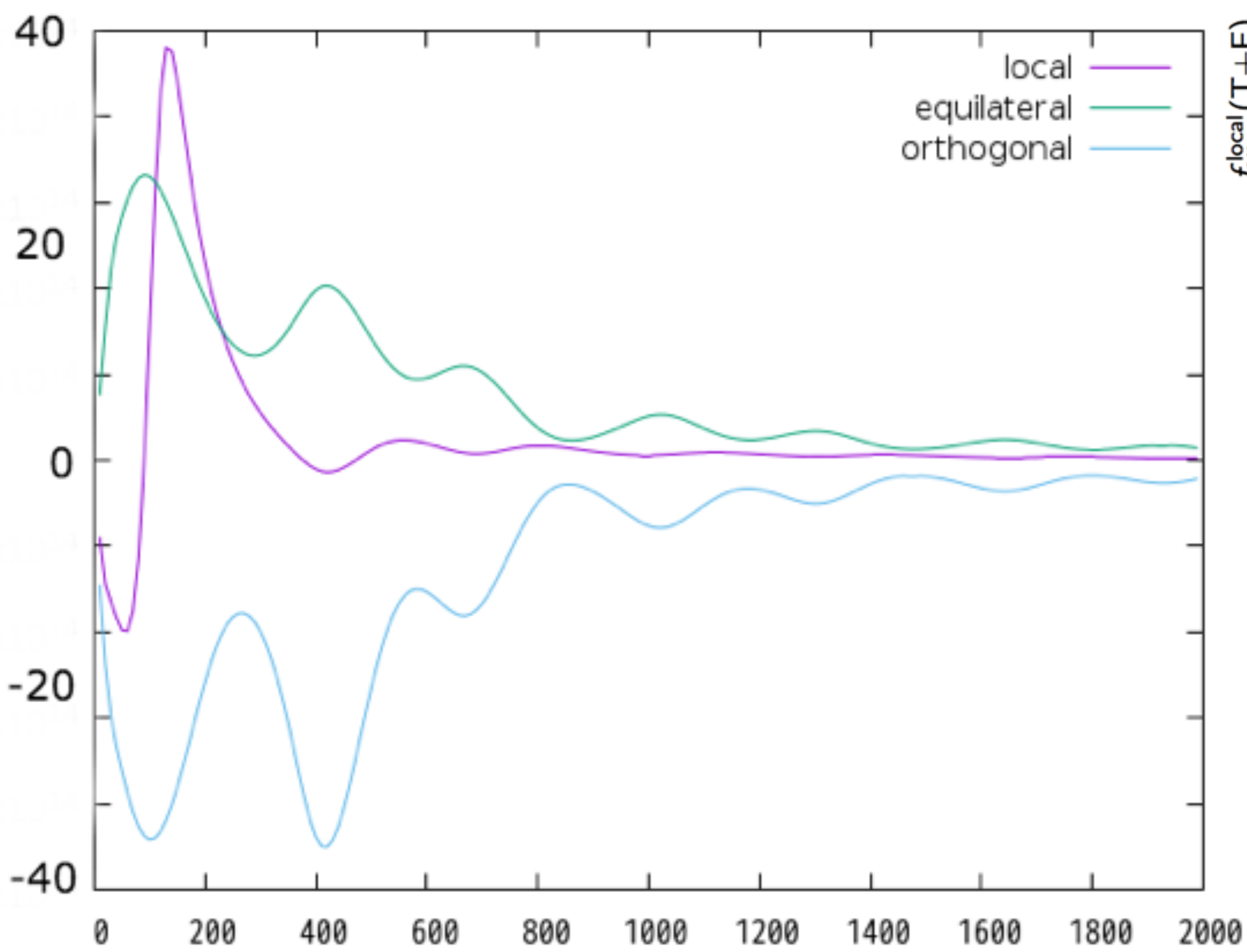
Equilateral NG (λ=10³, ε=10⁻³)



Equilateral NG (λ=10³, ε=10⁻³)

Scale dependent Non-Gaussanity

In a scale closer to Planck 2015…



Numerical calculation by
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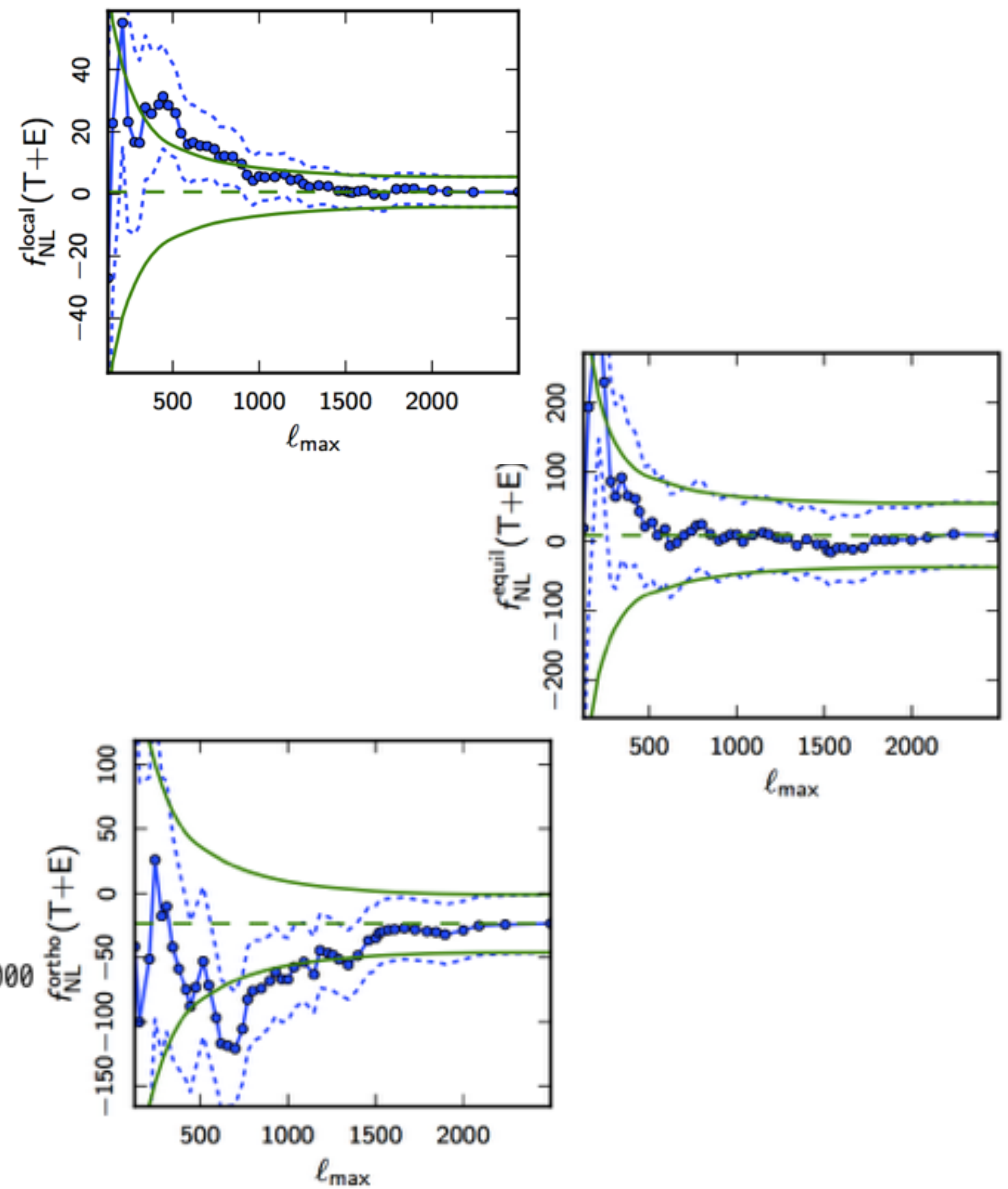

Summary

- There are several motivations to explore beyond GR+ single field (scale dependent non-gaussianity, tensor structure,…)
- Presence of **preferred spatial frame** leads to **massive tensor modes** and a **sizeable SST**.
- Sizeable SST = **scale dependent non-gaussianity**.
- Any other effect from the presence of preferred spatial frame?