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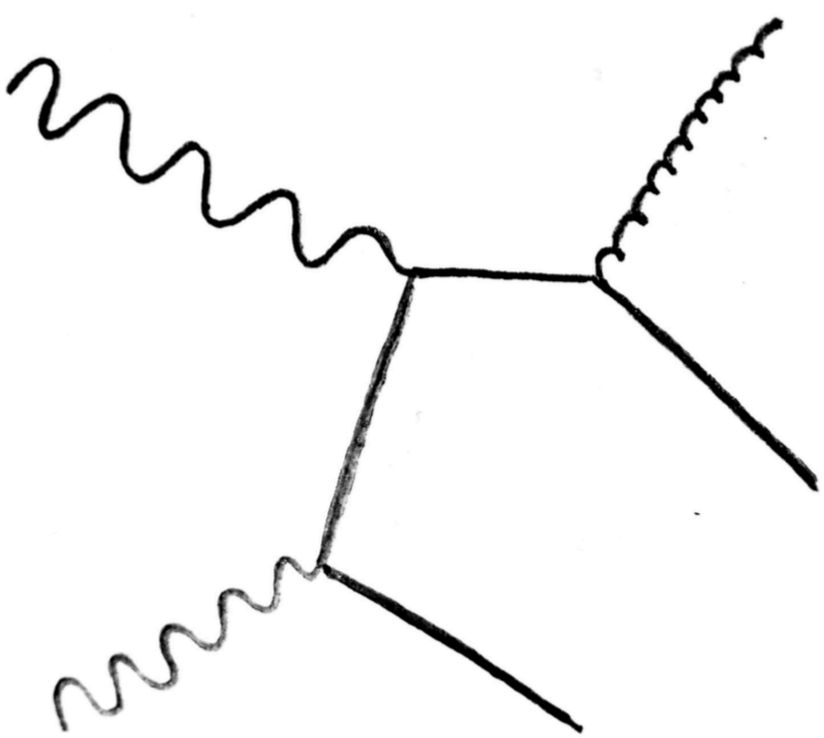
Lorenzo Bordin

Light Particles with Spin in Inflation

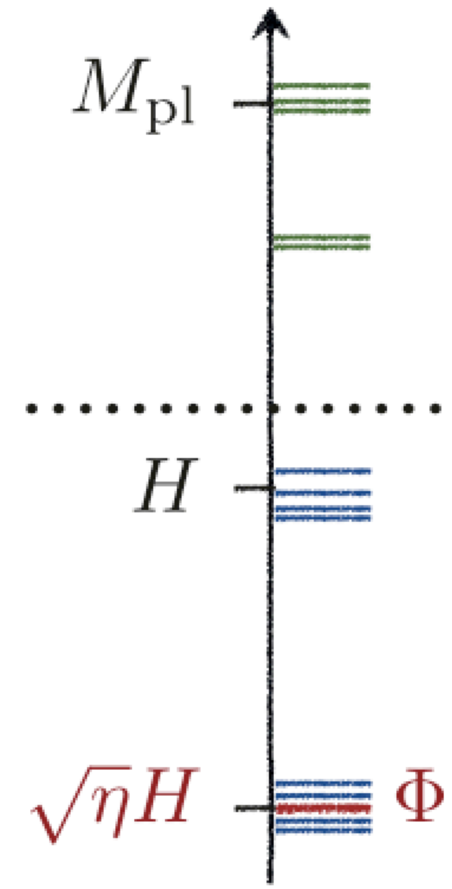


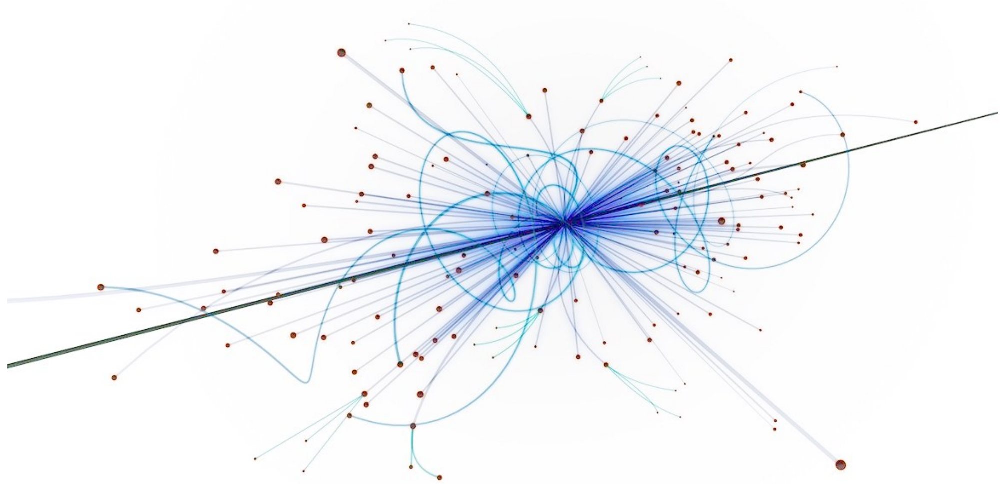
with Creminelli, Khmelnitski, Senatore, 1806.10587 (JCAP)
Warsaw, January 21st 2019

Inflation: highest energy observable natural process.

$$H \sim 10^{14}\ Gev$$

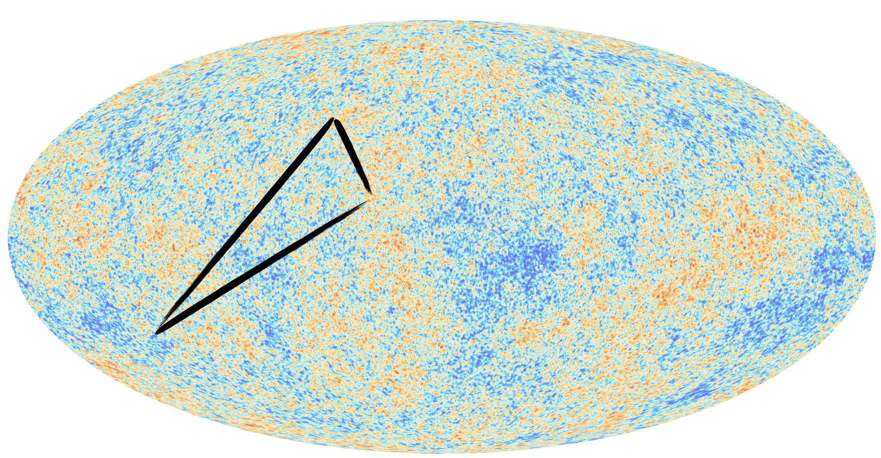
All light states ($m \lesssim H$) get excited.





Scattering amplitudes

Correlation Functions



Parametrise the most general dynamics compatible with symmetries

- Single clock: $\phi(t)$ → ~~Time Diff.s~~

  + 2 graviton helicities γ_{ij}

Cheung et al., 07

CCWZ approach:

classify fields in terms of representations of the unbroken group

Unitary Gauge: perturbations are eaten by the metric.

$$\to \left(t\,;\; g^{00}\,,\delta K\,,{}^{(3)}R\,\ldots\,;R,\,\delta R_{\mu\nu}\delta R^{\mu\nu}\,,\ldots\right)$$

Consistency relations

$$\mathcal{L} = \frac{M_{\rm Pl}^2}{2}\left[R + 2\dot{H} g^{00} - 2\left(3H^2 + \dot{H}\right) + \dots\right]$$

… 7 operators!

2nd order in a derivative expansion
up to cubic order in perturbations

LB, Cabass, Creminelli, Vernizzi 16

$\langle\zeta\zeta\zeta\rangle$ $\langle\zeta\gamma\gamma\rangle$ $\langle\gamma\zeta\zeta\rangle$ $\langle\gamma\gamma\gamma\rangle$

Fixed in the standard scenario

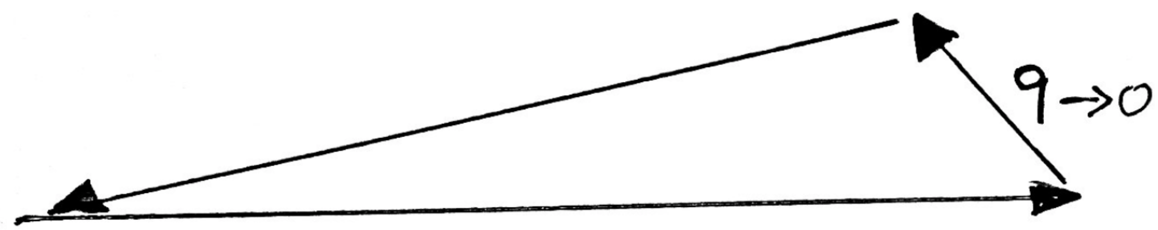
e.g. EFT of Inflation

~~CR~~ → Additional light particles

Squeezed configuration of NG correlates very sensible to the presence of additional degrees of freedom.

Single field consistency relation for 3-pt function

Squeezed limit



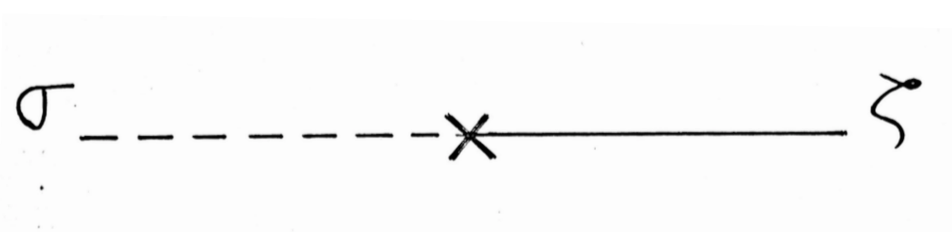
Maldacena 03
Creminelli, Zaldarriaga 04

$$\phi(t,\vec{x}) = \phi_0(t) \qquad\qquad h_{ij} = e^{2\zeta(t,\vec{x})}\left(e^{\gamma(t,\vec{x})}\right)_{ij}$$

The long mode is already classical when the other freeze and acts simply as a rescaling of the coordinates

$$\lim_{\vec{q}\to 0}\langle\zeta_{\vec{q}}\zeta_{\vec{k}}\zeta_{-\vec{k}-\vec{q}}\rangle' = -\langle\zeta_{\vec{q}}\zeta_{-\vec{q}}\rangle'\langle\zeta_{\vec{k}}\zeta_{-\vec{k}}\rangle'\,\frac{d\log k^3\langle\zeta_{\vec{k}}\zeta_{-\vec{k}}\rangle'}{d\log k}$$

Violated in multifield:



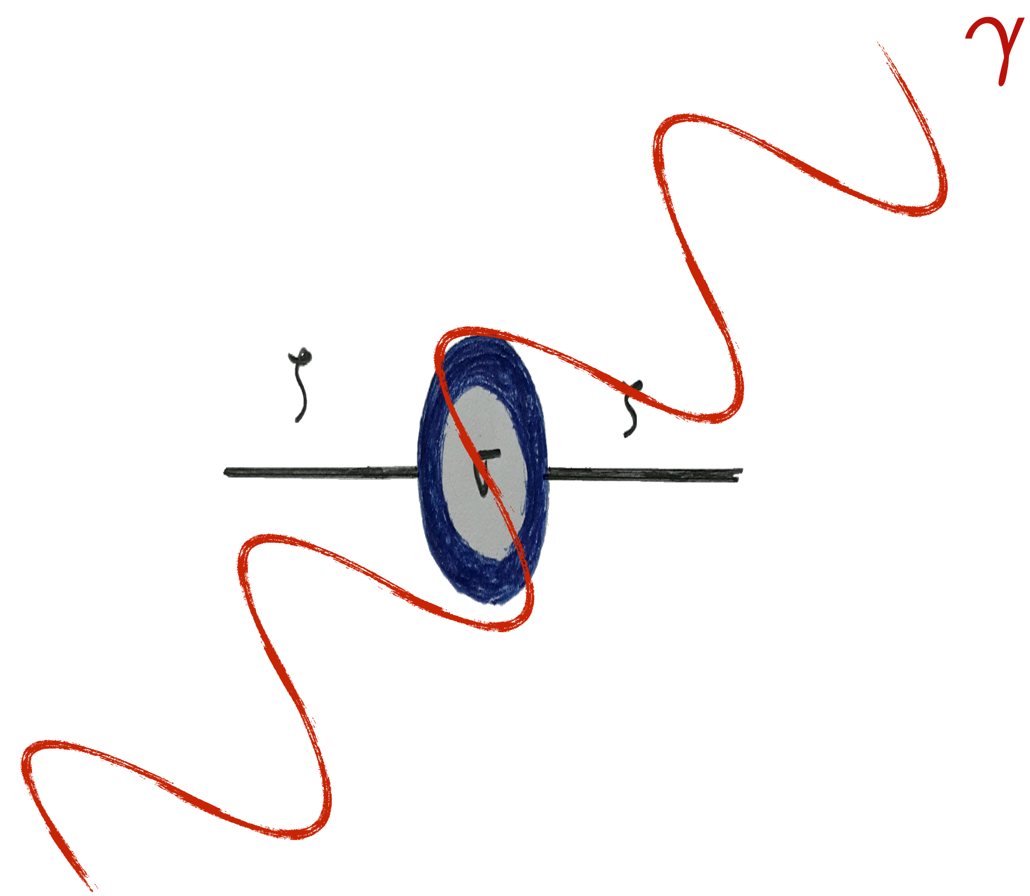
f_{NL}^{local} as smoking gun for multifield models

Tensor consistency relation for 3pf

Same logic leads to

$$\lim_{\vec{q}\to 0}\langle \gamma^s_{\vec{q}}\zeta_{\vec{k}}\zeta_{-\vec{k}-\vec{q}}\rangle' = -\langle \gamma^s_{\vec{q}}\gamma^s_{-\vec{q}}\rangle' \epsilon^s_{ij} k^i k^j \, \frac{d}{dk^2}\langle \zeta_{\vec{k}}\zeta_{-\vec{k}}\rangle'$$

But this is valid also for multi-field models of inflation



see e.g. LB, Creminelli, Mirbabayi, Noreña, 16

Violated if there are extra tensors

Higher spin fields and the Higuchi Bound

Sticking on a Lorentz invariant formulation we end up with very massive particles.

Lee, Baumann and Pimentel, 16

Massive states decay very quickly outside the horizon

$$\mathcal{O}_{i_1,\dots,i_s}(\eta,\vec{k}) \sim \eta^{\Delta}\, S_{i_1,\dots,i_s}(\vec{k}) \qquad \Delta_\pm = 3/2 \pm \sqrt{9/4-(m/H)^2}$$

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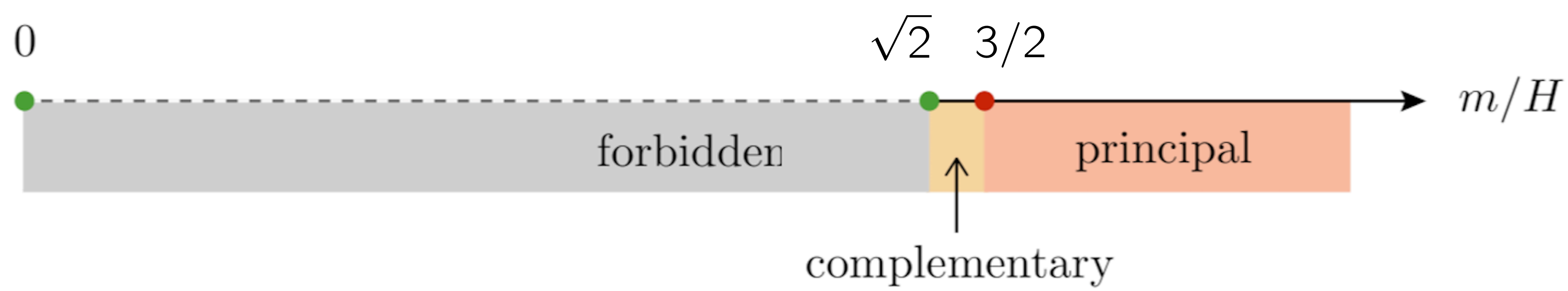
e.g.: spin 2 field



$$\langle \epsilon^2.S_{\vec{k}}\tilde{\epsilon}^2.S_{-\vec{k}}\rangle' \propto k^{2\Delta-3}\left[e^{-2ix}+\frac{4(3-\Delta)}{\Delta}e^{-ix}+\frac{6(3-\Delta)(2-\Delta)}{\Delta(\Delta-1)}+\frac{4(3-\Delta)}{\Delta}e^{ix}+e^{2ix}\right]$$

Becomes negative for Δ <1

e.g. KK gravitons with a small mass are forbidden!

Use ϕ as source of Lorentz Violation

Couplings with the foliation could make light spin-s healthy!

e.g.: spin 1 field

$$
\begin{aligned}
\mathcal{L}^{(2)} = & \frac{1}{2}\alpha\,\partial_\mu A^\mu \partial_\nu A^\nu + \frac{1}{2}\beta\,\partial_\mu A^\nu \partial^\mu A_\nu \\
& + \frac{1}{2}\gamma\,\partial^0 A^\mu \partial^0 A_\mu + \frac{1}{2}\delta\,\partial_\mu A^0 \partial^\mu A^0 + \frac{1}{2}\eta\,\partial_\mu A^\mu \partial^0 A^0 + \frac{1}{2}\epsilon\,\partial^0 A^0 \partial^0 A^0 \\
& + \mu\, A^0 \partial_\mu A^\mu - \frac{1}{2} m^2 A^\mu A_\mu - \frac{1}{2}(M^2 + m^2)\, A^0 A^0 \,.
\end{aligned}
$$

Not the correct procedure! Many theories have pathologies

Higher-Spins in the EFTI

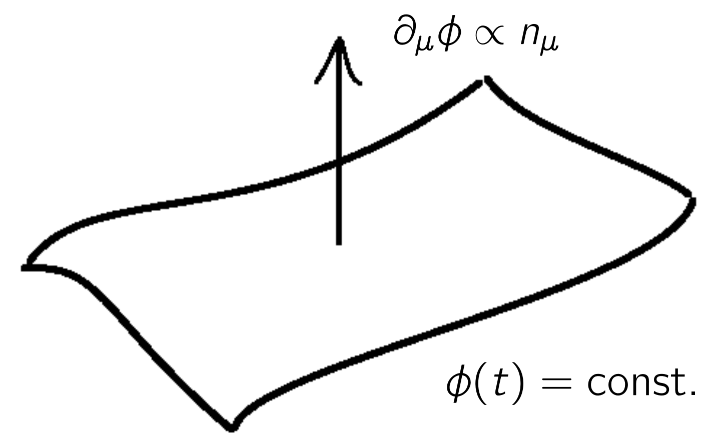
e.g.: spin 1 field

$$\mathcal{L}^{(2)} = \frac{1}{2}\alpha\,\partial_\mu A^\mu \partial_\nu A^\nu + \frac{1}{2}\beta\,\partial_\mu A^\nu \partial^\mu A_\nu \\ + \frac{1}{2}\gamma\,\partial^0 A^\mu \partial^0 A_\mu + \frac{1}{2}\delta\,\partial_\mu A^0 \partial^\mu A^0 + \frac{1}{2}\eta\,\partial_\mu A^\mu \partial^0 A^0 + \frac{1}{2}\epsilon\,\partial^0 A^0 \partial^0 A^0 \\ + \mu\,A^0 \partial_\mu A^\mu - \frac{1}{2}m^2 A^\mu A_\mu - \frac{1}{2}(M^2 + m^2)\,A^0 A^0\,.$$

Not the correct procedure! Many theories have pathologies

CCWZ approach

- ϕ foliates the spacetime → SO(3) Invariance
- $A^i \dfrac{\partial}{\partial x^i}$ lives on the 3-dim hyper-surfaces
- Embed in a 4-dim spacetime $A^\mu(A^i, \pi) = A^i \left.\dfrac{\partial x^\mu}{\partial x^i}\right|_\psi$



$$\mathcal{L} = \mathcal{L}(A^\mu, \nabla_\mu, n_\mu, \delta K_{\mu\nu}, \dots)$$

Spin 2 excitation: $\sigma^{\mu\nu}(\sigma^{IJ},\pi) = \sigma^{IJ} \left.\frac{\partial x^\mu}{\partial x^I}\right|_\psi \left.\frac{\partial x^\nu}{\partial x^J}\right|_\psi$

$$\mathcal{L} = \frac{1}{4}\left[\left(1-c_2^2\right)\left(n^\mu\nabla_\mu\sigma_{\alpha\beta}\right)^2 - c_2^2(\nabla_\mu\sigma_{\alpha\beta})^2 - \frac{3}{2}\left(c_0^2-c_2^2\right)\left(\nabla_\mu\sigma^{\mu\alpha}\right)^2 - \left(m^2+2c_2^2H^2\right)\sigma_{\alpha\beta}^2\right]$$

~~Lorentz Invariance~~ → different propagation velocities c_h, $h=0,1,2$

parametrically small mass m

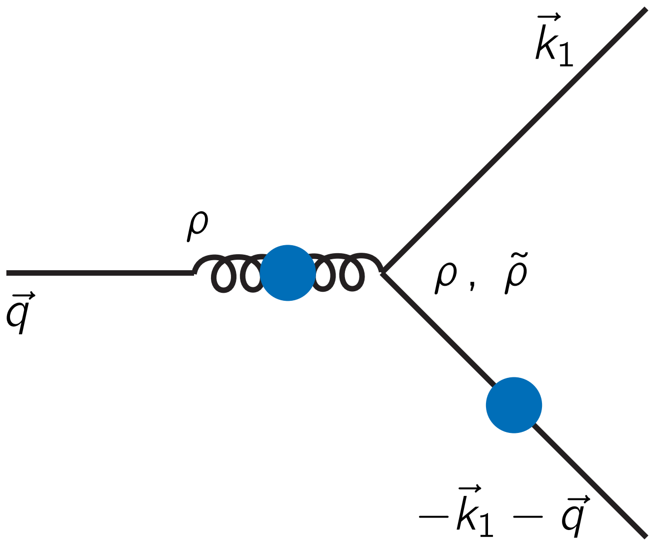
Interactions: $\mathcal{L}_{\rm int} \supset \left[M_{\rm Pl}\,\rho\,\delta K_{\alpha\beta}\,\sigma^{\alpha\beta} + M_{\rm Pl}\,\rho\,\delta g^{00}\,\delta K_{\alpha\beta}\,\sigma^{\alpha\beta} - \mu\,\sigma^{\alpha\beta}\sigma_\alpha{}^\gamma\sigma_{\gamma_\beta}\right]$

new sector could be highly Non-Gaussian

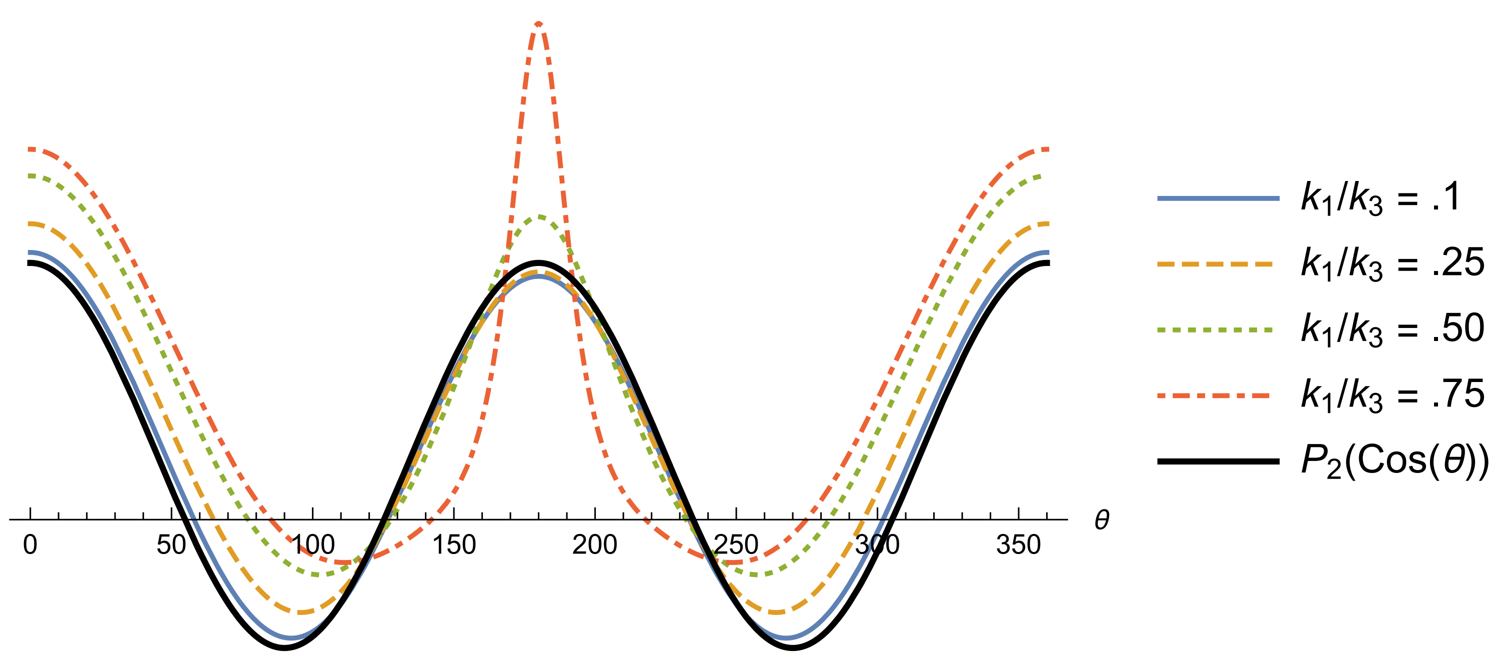
Scalar Non-Gaussianity

$$\left\langle \zeta_{\vec{q}\to 0}\zeta_{\vec{k}}\zeta_{-\vec{k}} \right\rangle' = B_\zeta \left(\frac{q}{k}\right)^{\frac{3}{2}-\nu} P_\zeta(q)\, P_\zeta(k)\, \mathrm{P}_2(\hat{q}\cdot\hat{k})$$

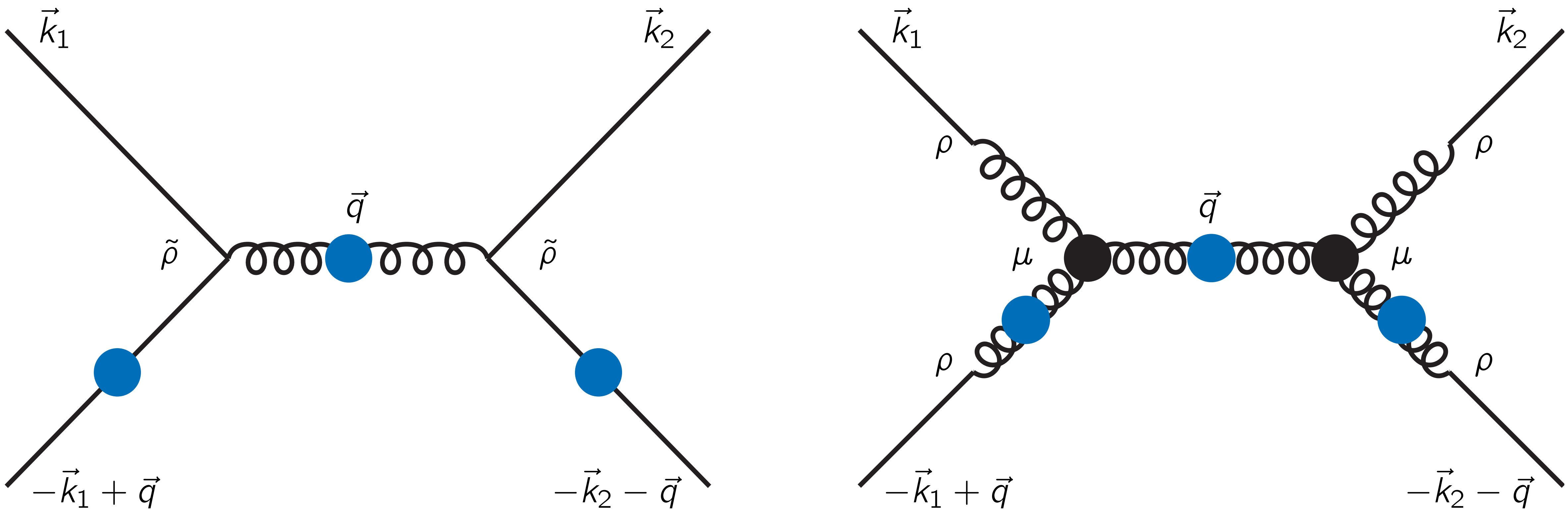
$$\nu = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$



$$B_\zeta = \frac{\mathcal{O}(1)}{c_0^{2\nu}} \frac{\rho\,\tilde{\rho}}{\epsilon\, H^2}$$

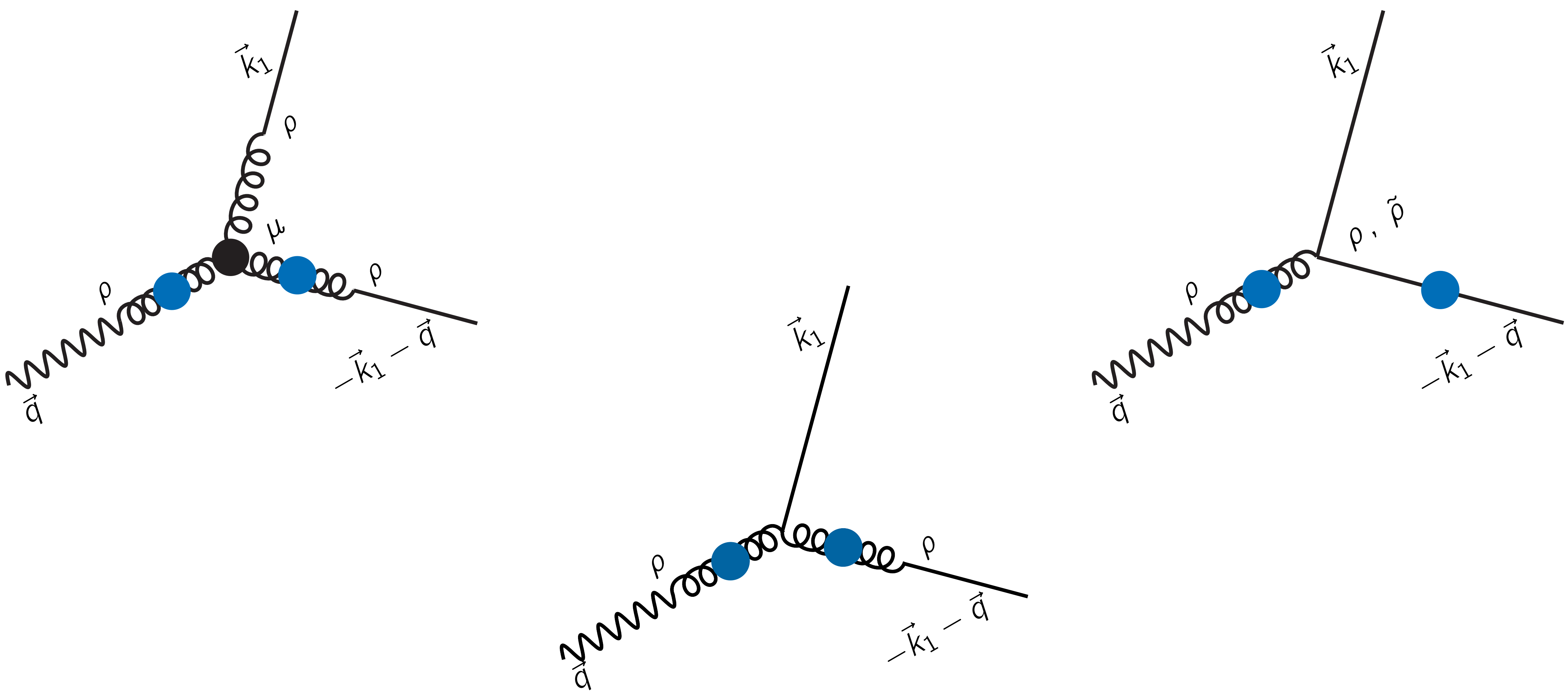


Scalar Non-Gaussianity



$$\left\langle \zeta_{\vec{k}_1}\zeta_{-\vec{k}_1+\vec{q}}\zeta_{\vec{k}_3}\zeta_{-\vec{k}_3-\vec{q}}\right\rangle' \propto (q^2/k_1k_3)^{\Delta}\; P_\zeta(q)P_\zeta(k_1)P_\zeta(k_3)\sum_s \mathrm{P}_2^{(s)}(\hat{q}\cdot\hat{k}_1)\,\mathrm{P}_2^{(s)}(\hat{q}\cdot\hat{k}_3)$$

~~Tensor~~ CR


$\vec{k}_1$
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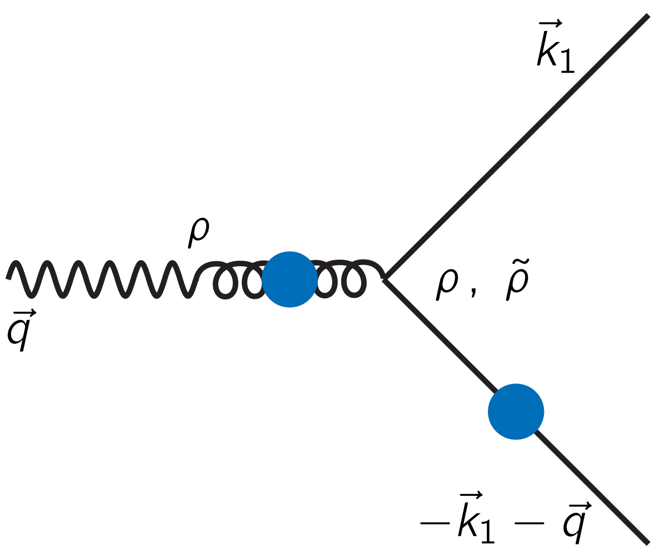
$-\vec{k}_1 - \vec{q}$
$\vec{k}_1$
$\rho\ ,\ \tilde{\rho}$
ρ
$\vec{q}$
$-\vec{k}_1 - \vec{q}$

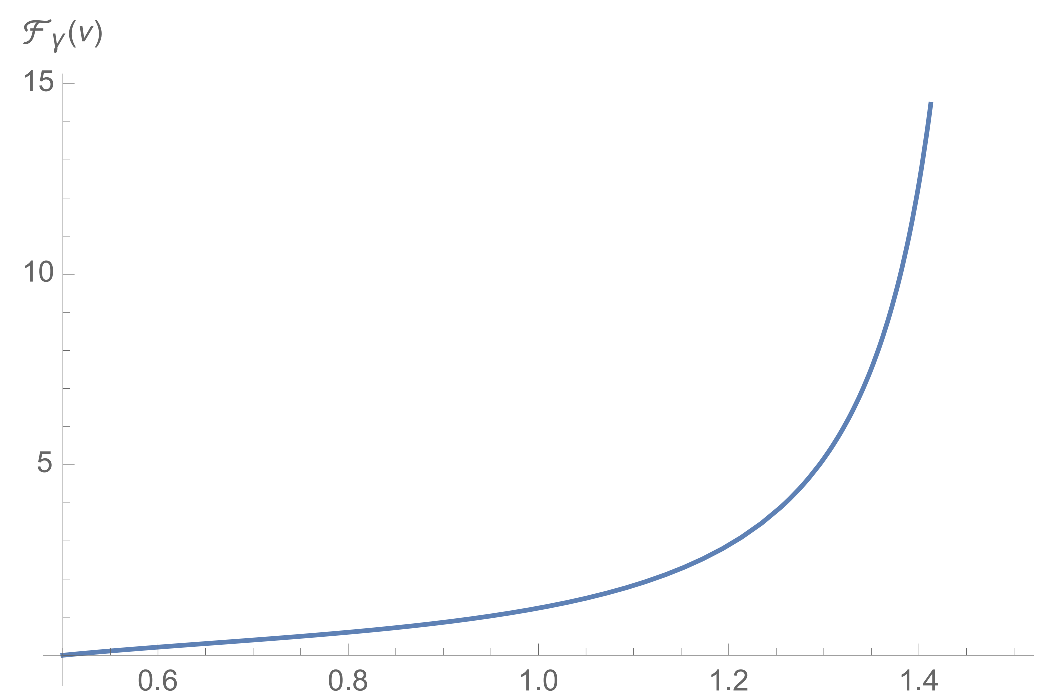
Tensor Non-Gaussianity

$$\left\langle \gamma^{(s)}_{\vec{q}\to 0}\,\zeta_{\vec{k}}\,\zeta_{-\vec{k}}\right\rangle' = B_\gamma \left(\frac{q}{k}\right)^{\frac{3}{2}-\nu} P_\gamma(q)\, P_\zeta(k)\; \epsilon^{(s)}_{ij}\,\hat{k}_i \hat{k}_j$$

$$\nu = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$



$$B_\gamma = \frac{\mathcal{F}_\gamma(\nu)}{c_2^{2\nu}}\;\frac{\rho\,\tilde{\rho}}{\epsilon\, H^2}$$



New templates for PNG

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle' \simeq \mathcal{F}_s \left(\frac{k_1}{k_2} \right)^{\Delta} P_\zeta(k_1)\, P_\zeta(k_2)\, \mathrm{P}_s(\hat{k}_1 \cdot \hat{k}_2) + (2 \text{ perms})$$

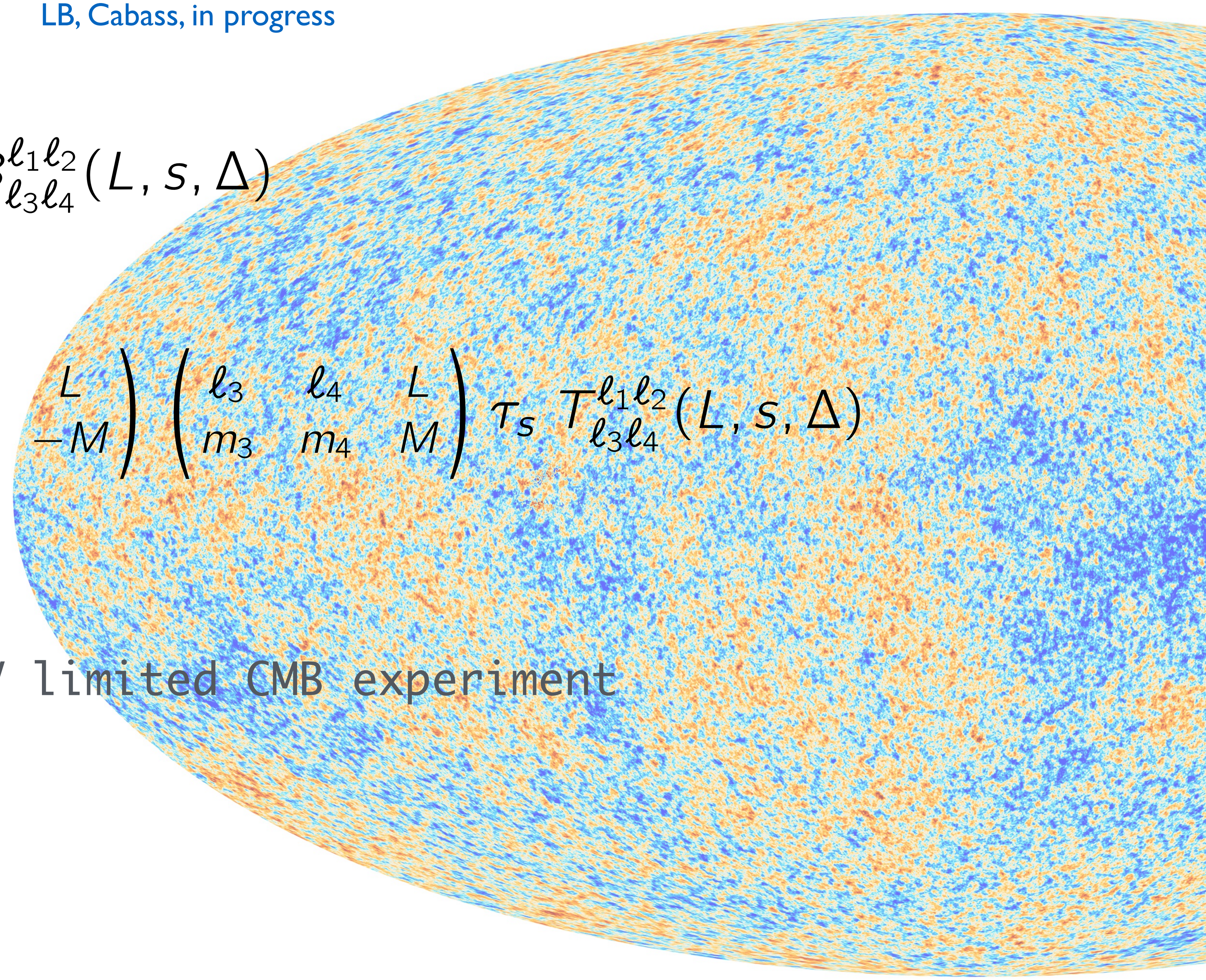
$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \zeta_{\vec{k}_4} \rangle' \simeq \tau_s \left(\frac{k_{12}^2}{k_1\, k_3} \right)^{\Delta} P_\zeta(k_{12})\, P_\zeta(k_1)\, P_\zeta(k_2)\, \mathrm{P}_s(\hat{k}_1 \cdot \hat{k}_3) + (2 \text{ perms})$$

$$\Delta_\pm = 3/2 \pm \sqrt{9/4 - (m/H)^2}$$

- Non-analytical scaling behaviour.
- Spin dependent angular modulation.
- Amplitude enhanced by speed of propagation c_λ.

Signal in multipole space

LB, Cabass, in progress



$$\langle \prod_{i=1}^{3} a_{l_i m_i} \rangle = \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \mathcal{F}_s \; B^{\ell_1 \ell_2}_{\ell_3 \ell_4}(L, s, \Delta)$$

$$\langle \prod_{i=1}^{4} a_{l_i m_i} \rangle = \sum_{LM} (-1)^M \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \begin{pmatrix} \ell_3 & \ell_4 & L \\ m_3 & m_4 & M \end{pmatrix} \tau_s \; T^{\ell_1 \ell_2}_{\ell_3 \ell_4}(L, s, \Delta)$$

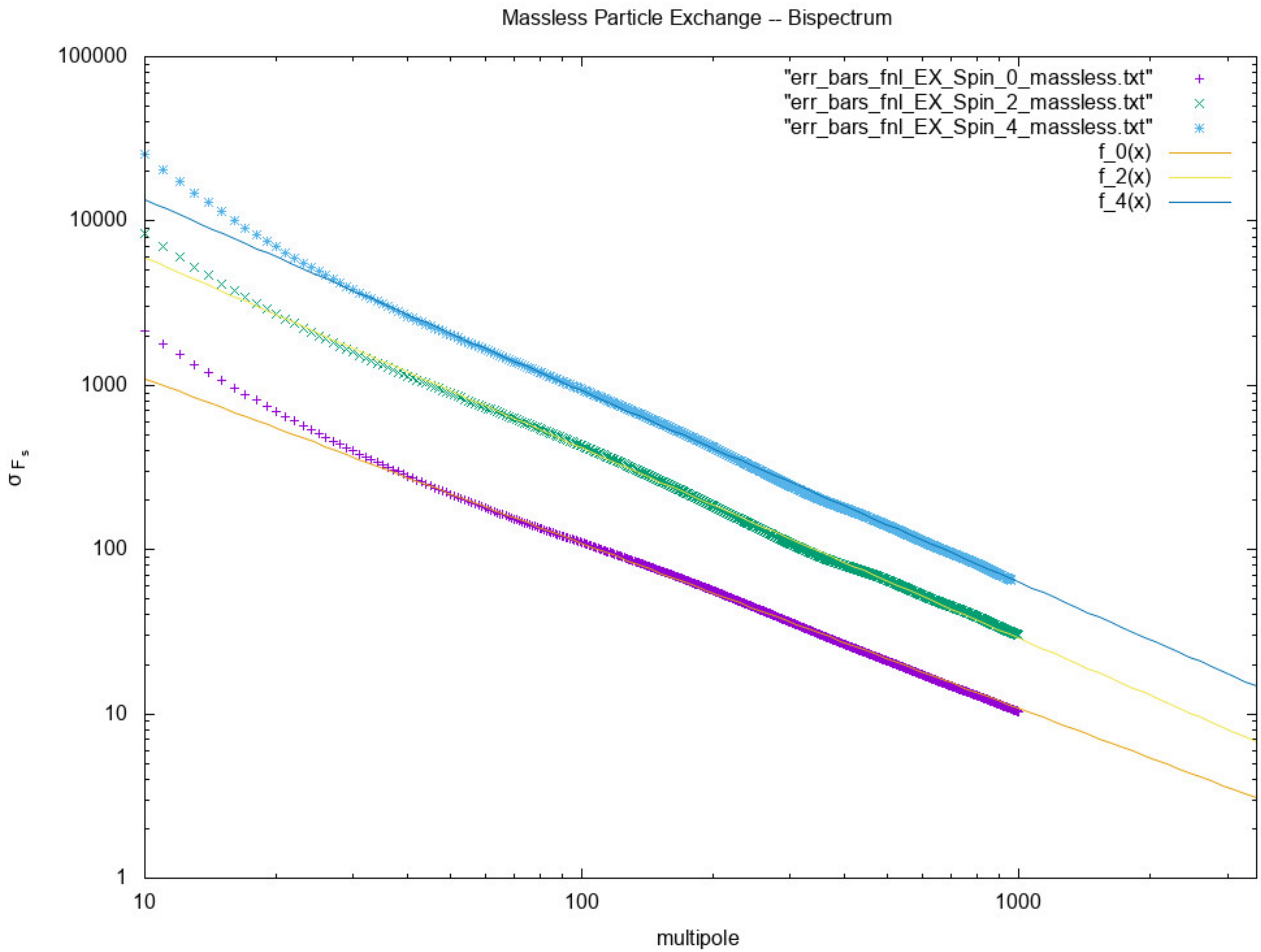
Assume weak NG signal and CV limited CMB experiment

$$\left(\frac{S}{N}\right)^2 \simeq \sum_{\ell_1 > \ell_2 > \ell_3} \frac{|B_{\ell_1 \ell_2 \ell_3}(s, \Delta)|^2}{C_{\ell_1} C_{\ell_2} C_{\ell_3}}$$

$$\left(\frac{S}{N}\right)^2 \simeq \sum_{L} \sum_{\ell_1 > \ell_2 > \ell_3 > \ell_4} \frac{|T_{\ell_1 \ell_2 \ell_3 \ell_4}(L, s, \Delta)|^2}{(2L+1) C_{\ell_1} C_{\ell_2} C_{\ell_3} C_{\ell_4}}$$

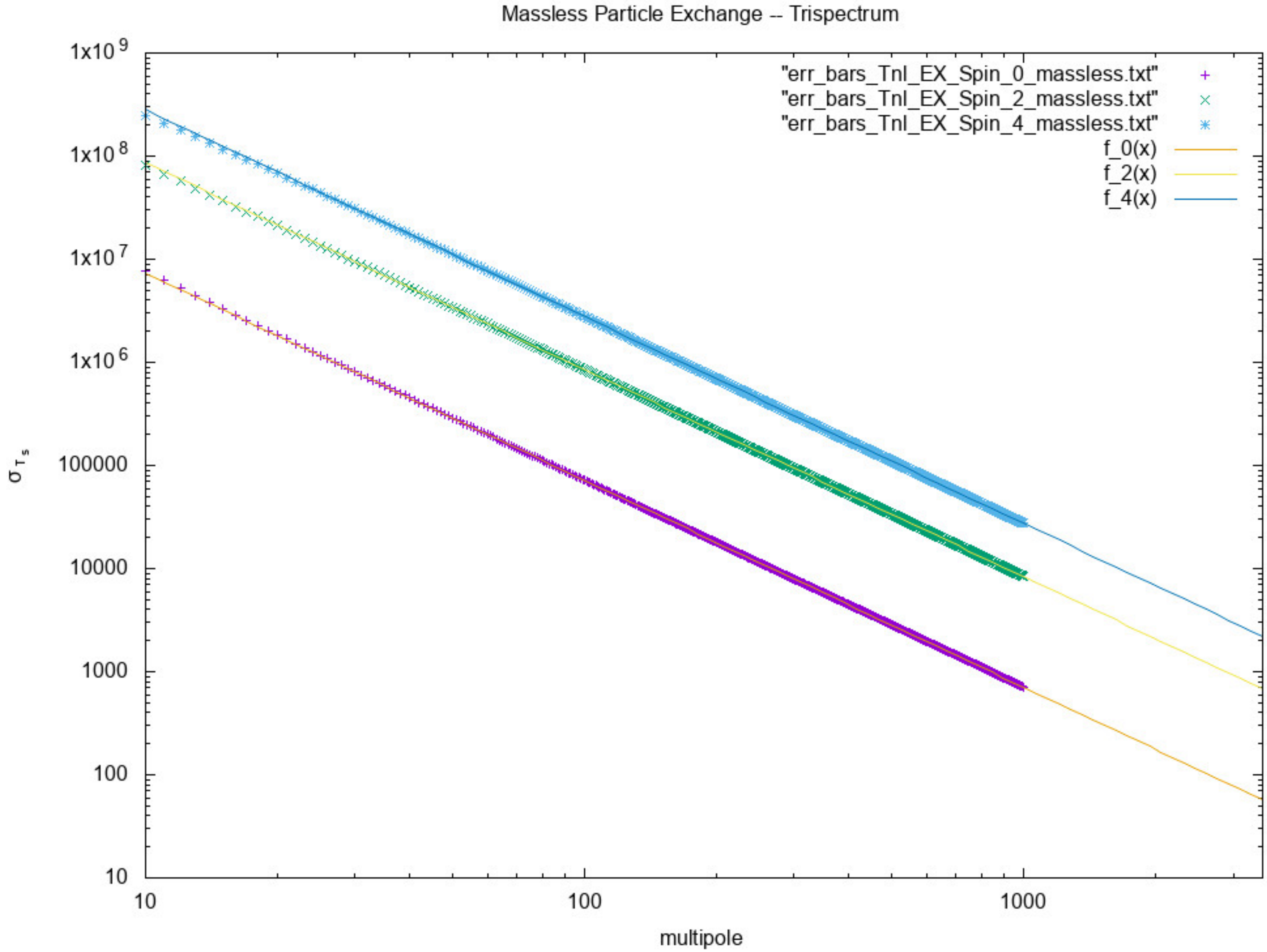
expected error bars

LB, Cabass, in progress



see also Franciolini, Kehagias, Riotto and Shiraishi, 18 expected error bars

LB, Cabass, in progress



Conclusions and future directions

- Coupling with the inflaton foliation allows to violate the Higuchi bound

- Light particles with spin can be present while preserving the approximate shift symmetry of the inflaton

- New shapes of Non-Gaussianity
  - CMB could already put strong constraints on the new shapes

- Use the LSS to constrain these new shapes primordial NG
  - New templates for the galaxy Bispectrum, galaxy bias,…
  - Forecasts for the new surveys (Euclid, DESI, …)
  - Fossil effect for spin 2 fields

- Gravitational Waves?

Backup slides

Does the Higuchi Bound apply for composite operators?

$$\partial_i\phi\partial_j\phi - \frac{1}{3}(\partial\phi)^2\delta_{ij}$$

No!

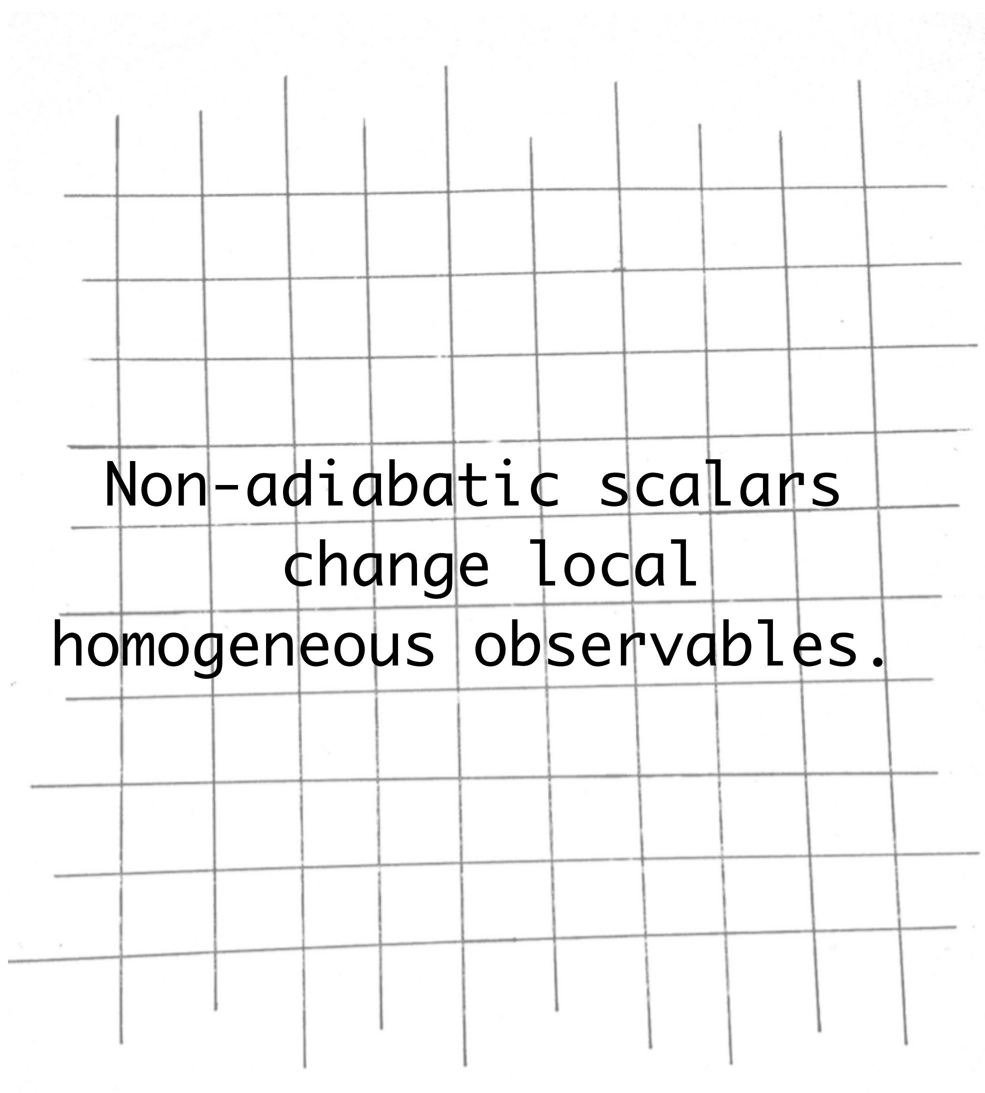
The Higuchi Bound applies only for conformal primaries: $\mathcal{O}_{\mu\nu} \sim \eta^{\Delta}$

$$(2\Delta+1)(\partial_i\partial_j\phi - \frac{1}{3}\delta_{ij}(\partial\phi)^2) - \Delta\left[\partial_i(\phi\partial_j\phi)) - \frac{1}{3}\delta_{ij}\partial_k(\phi\partial_k\phi)\right]$$

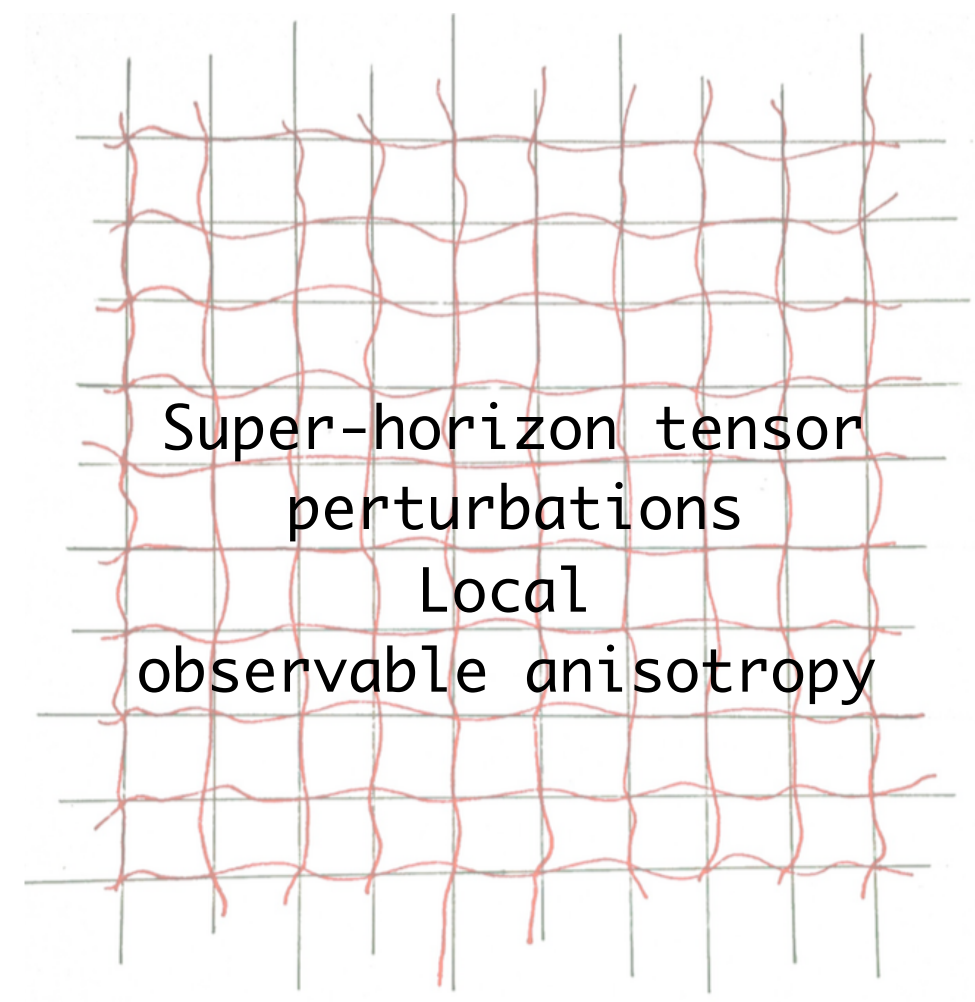
However one has to face tachyons.

Observational signatures

Non-abiabatic modes ⟷ ~~CR~~



vs



Anisotropies are not redshifted away exponentially fast during the inflationary epoch.