Title: Cosmological Collider Phenomenology: the Standard Model and Beyond

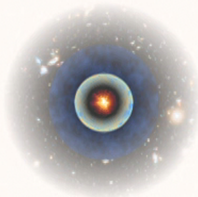
Speakers: Zhong-Zhi Xianyu

Series: Particle Physics

Date: May 21, 2019 - 1:00 PM

URL: http://pirsa.org/19050028

Abstract: The n-point correlation functions (n>2) of primordial fluctuations, known as primordial non-Gaussianities, encode rich information about the physical degrees of freedom and their interactions at inflation scale, and can be viewed as signals from a cosmological collider with huge energy. In this talk we introduce recent theoretical attempts to extract new physics at the inflation scale from primordial non-Gaussianities, including possible discovery channels, the background signals from the standard model, and signals from new physics such as heavy neutrinos, and a possible way to turn inflation into a Higgs collider.

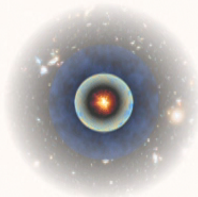


Cosmological Collider Phenomenology: SM & Beyond

Zhong-Zhi Xianyu (Harvard)

Perimeter Institute | May 21, 2019

Xingang Chen, Yi Wang, ZZX, JHEP 1608 (2016) 051
PRL 118 (2017) 261302
JHEP 1704 (2017) 058
JCAP 1712 (2017) 006
(w/ Wan Zhen Chua, Yuxun Guo, Tianyou Xie) JCAP 1805 (2018) 049
JHEP 1809 (2018) 022
Shiyun Lu, Yi Wang, ZZX, in progress



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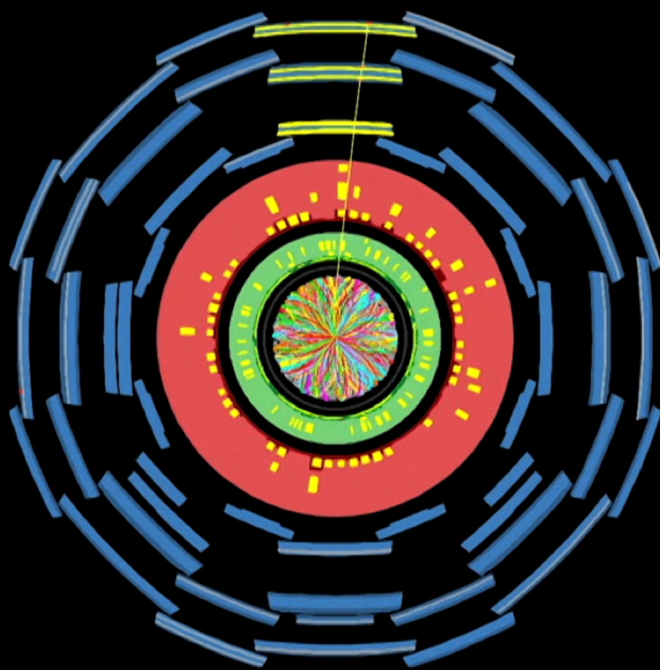


Large Hadron Collider

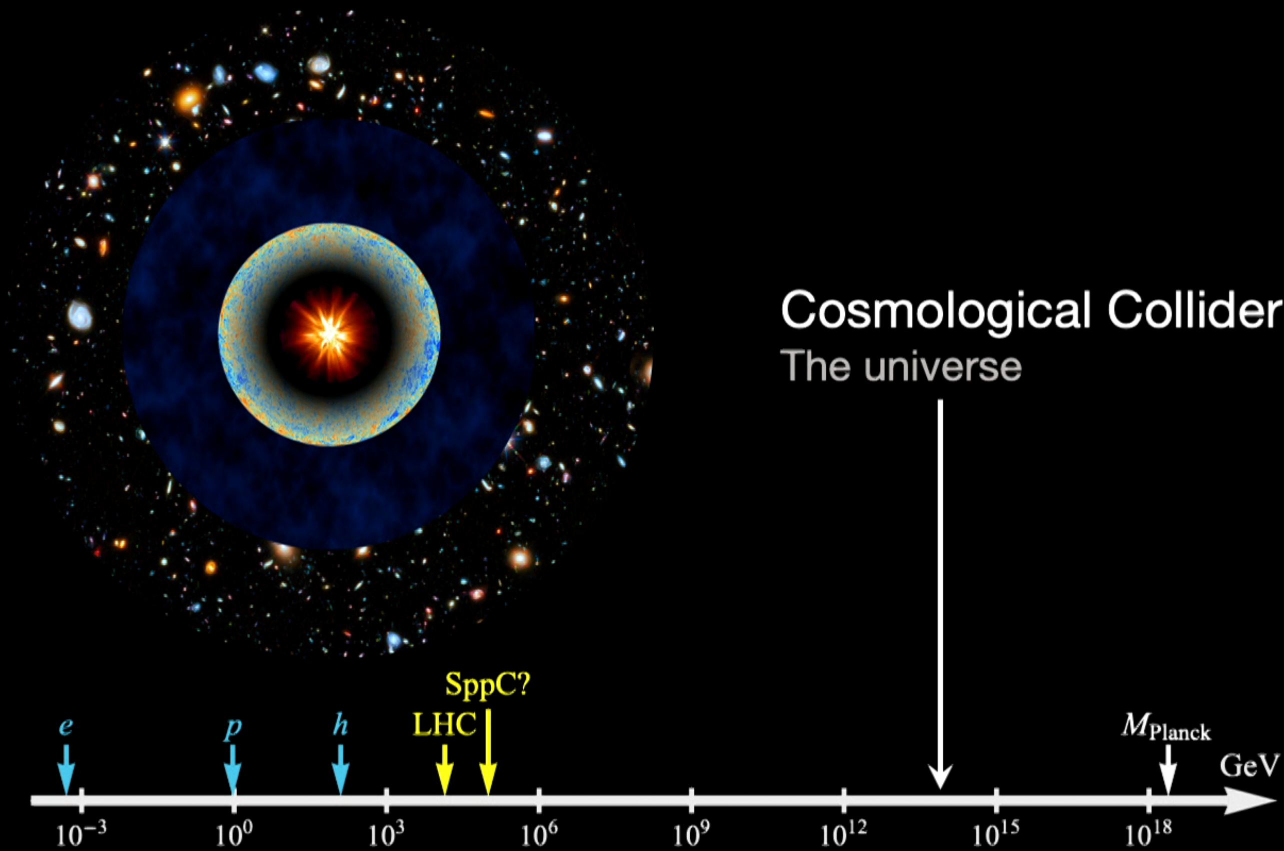
ATLAS detector

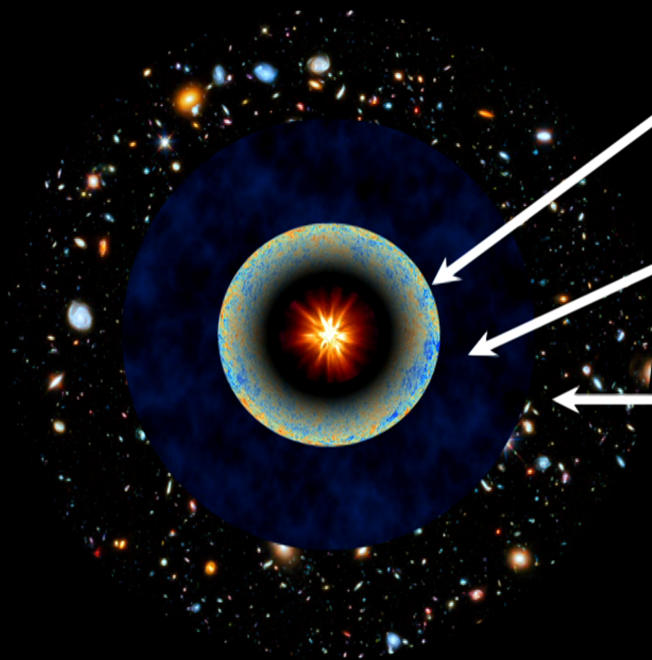
Cosmological Collider

The universe

Cosmological Collider

The universe





photon decoupling
CMB

dark ages
21cm tomography

galaxies formed
galaxy map /
lensing / Lyα /
cosmic rays …

Gravitational waves

cosmic Schwinger pair production

Origin of large-scale inhomogeneity and anisotropy

$$\mathscr{L} = \sqrt{-g}\Big[\tfrac{1}{2}M_{\rm Pl}R - \tfrac{1}{2}(\partial_\mu\phi)^2 - V(\phi)\Big]$$

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + e^{2Ht+2\zeta}\mathrm{d}x^2$$

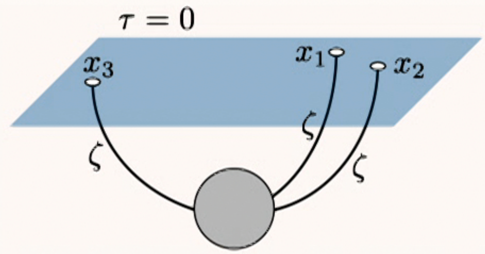
a long-lived scalar mode ζ

$$\zeta_k = \frac{H}{M_{\rm Pl}\sqrt{4\epsilon k^3}}(1+\mathrm{i}k\tau)e^{-\mathrm{i}k\tau} \longrightarrow \frac{H}{M_{\rm Pl}\sqrt{4\epsilon k^3}}$$

$$\langle\zeta^2\rangle' \equiv \frac{2\pi^2}{k^3}P_\zeta(k) \qquad P_\zeta(k) = \frac{H^2}{8\pi^2\epsilon M_{\rm Pl}^2} \simeq 2\times 10^{-9}$$

non-Gaussianity: the collision

Interactions of the scalar modes during inflation



$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle' \equiv (2\pi)^4 P_\zeta^2 \frac{1}{(k_1 k_2 k_3)^2} S(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$$

The long-lived scalar mode is weakly coupled

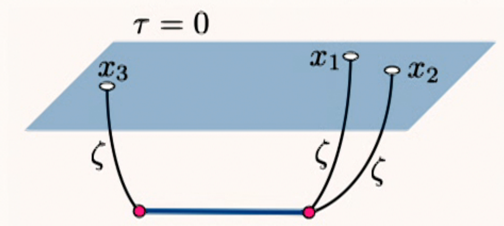
$$f_{\rm NL}^{\rm local} = 0.9 \pm 5.1; \quad f_{\rm NL}^{\rm equil} = -26 \pm 47; \quad f_{\rm NL}^{\rm ortho} = -38 \pm 24$$

Planck 2019, 68% CL

non-Gaussianity: the collision

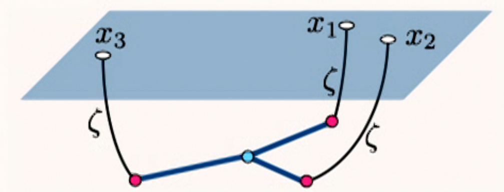
Future probe down to O(0.01): What can be seen?

Muñoz et al., 1506.04152; Meerburg et al., 1610.06559



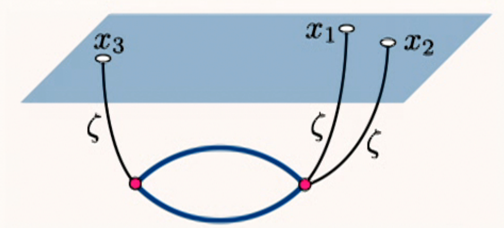
heavy particles?

Chen, Wang, 0911.3380;1205.0160
Pi, Sasaki, 1205.0161
Arkani-Hamed, Maldacena, 1503.08043
Chen, Namjoo, Wang, 1509.03930



new interactions?

Chen, Wang, 0911.3380
Chen, Wang, ZZX, 1703.10166



loop effects?

Arkani-Hamed, Maldacena, 1503.08043
Chen, Wang, ZZX, 1610.06597,1612.08122, 1805.02656

heavy particles in inflation

A massive scalar particle σ in inflation

$$\sigma_k(\tau) = -\frac{\mathrm{i}\sqrt{\pi}}{2} e^{\mathrm{i}\pi(\nu/2+1/4)} H(-\tau)^{3/2} \mathrm{H}_\nu^{(1)}(-k\tau)$$

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

Late-time behavior

$$\langle \sigma_k(\tau_1)\sigma_{-k}(\tau_2)\rangle'$$

$$\sim \frac{H^2}{4\pi k^3}\left[\Gamma^2(-\nu)\left(\frac{k^2\tau_1\tau_2}{4}\right)^{3/2+\nu} + (\nu \to -\nu)\right] + \text{local}$$

Boltzmann suppression $\propto e^{-\pi m/H}$

comoving dilution

EFT $\propto 1/m$

heavy particles in inflation

A massive scalar particle σ in inflation

$$\sigma_k(\tau) = -\frac{\mathrm{i}\sqrt{\pi}}{2} e^{\mathrm{i}\pi(\nu/2+1/4)} H(-\tau)^{3/2} \mathrm{H}_\nu^{(1)}(-k\tau)$$

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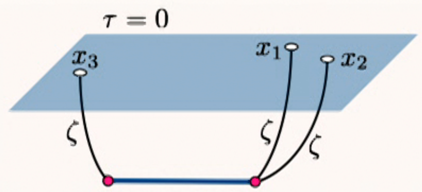
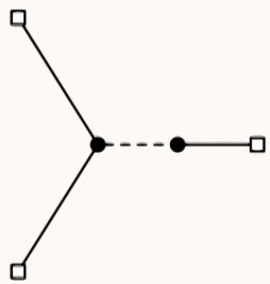
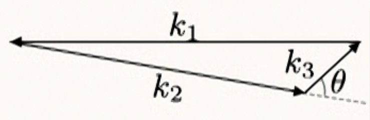
particles with spin: $\nu_s = \sqrt{\left(s - \frac{1}{2}\right)^2 - \frac{m^2}{H^2}} \quad (s \neq 0)$

squeezed bispectrum: a discovery channel







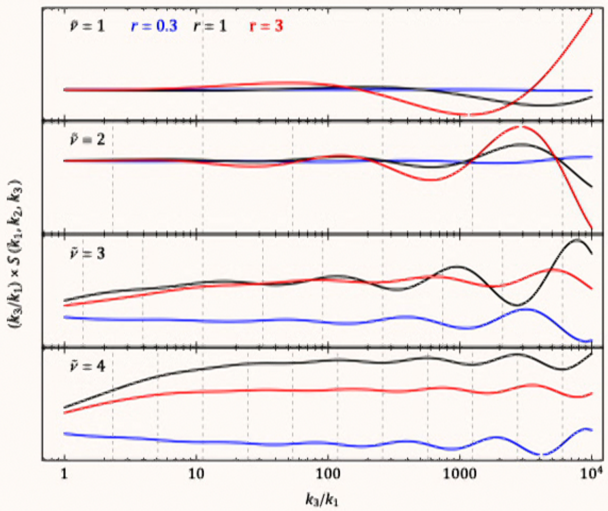
$$\langle \sigma_k^2 \rangle \sim \frac{1}{k^3}\left(\frac{k^2\tau_1\tau_2}{4}\right)^{3/2\pm\nu}$$

$$\int \mathrm{d}\tau_1 \mathrm{d}\tau_2\, \phi_{k_1}(\tau_1)\phi_{k_2}(\tau_1)\phi_{k_3}(\tau_2)$$
$$\times \langle \sigma_{k_3}(\tau_1)\sigma_{k_3}(\tau_2)\rangle$$

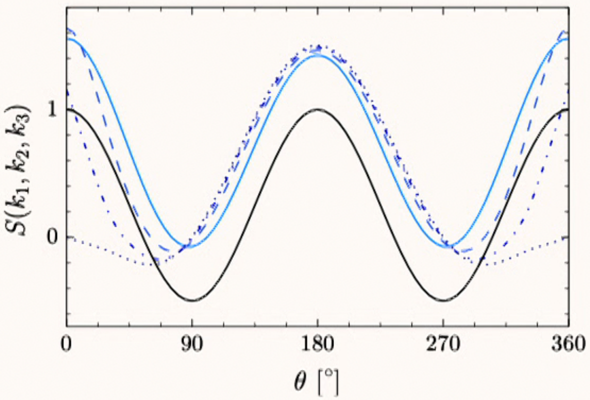
$$\longrightarrow \left(\frac{k_3}{k_1}\right)^{\pm\nu} P_s(\cos\theta)$$

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

squeezed bispectrum: a discovery channel



Chen, Chua, Guo, Wang, ZZX, Xie, 1803.04412



Lee, Baumann, Pimentel, 1607.03735

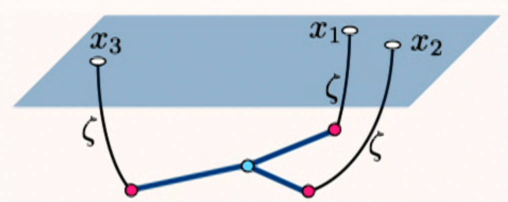
how to estimate

$$\langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle' \equiv (2\pi)^4 P_\zeta^2 \frac{1}{(k_1k_2k_3)^2} S(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

From ζ gauge to $\delta\phi$ gauge

$$\zeta = -(H/\dot{\phi}_0)\delta\phi \sim -P_\zeta^{1/2}\delta\phi$$

$f_{NL} \sim P_\zeta^{-1/2}\langle\delta\phi^3\rangle \sim P_\zeta^{-1/2}$ · (vertices) · (propagators)

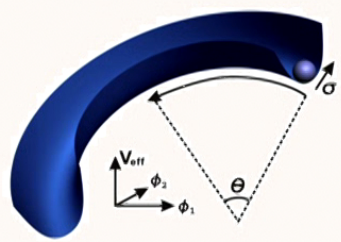


how to estimate

An example of QSFI

Chen, Wang, 0911.3380

$$\mathscr{L} = \sqrt{-g}\left[-\frac{1}{2}(\widetilde{R}+\sigma)^2(\partial_\mu\theta)^2 - \frac{1}{2}(\partial_\mu\sigma)^2 - V_{\rm sr}(\theta) - V(\sigma)\right]$$

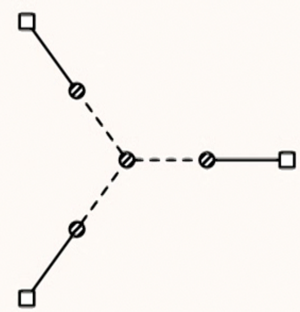


$$\frac{a^2}{2}\left[(\delta\phi')^2 - (\partial_i\delta\phi)^2 + (\delta\sigma')^2 - (\partial_i\delta\sigma)^2\right]$$
$$- \frac{1}{2}a^4 m^2\delta\sigma^2 + a^3\kappa_1\delta\sigma\delta\phi' - \frac{1}{6}a^4\lambda_3\delta\sigma^3$$

$$f_{NL} \sim P_\zeta^{-1/2}\cdot\left(\frac{\kappa_1}{H}\right)^3\cdot\left(\frac{\lambda_3}{H}\right)$$

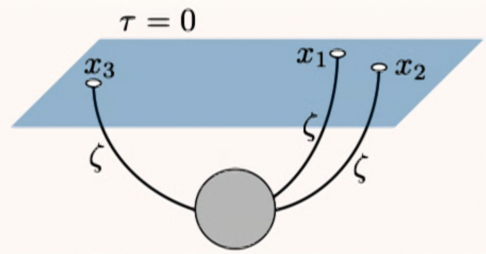
· (propagators)

$$\kappa_1 < m \qquad m \lesssim H$$



"in-in formalism"

S-matrix = $\langle \text{out} | \text{in} \rangle$ ⟶ Feynman diagrams



$$\langle \text{in} | \phi_1 \cdots \phi_n | \text{in} \rangle = \sum_{\text{out}} \langle \text{in} | \text{out} \rangle \langle \text{out} | \phi_1 \cdots \phi_n | \text{in} \rangle$$

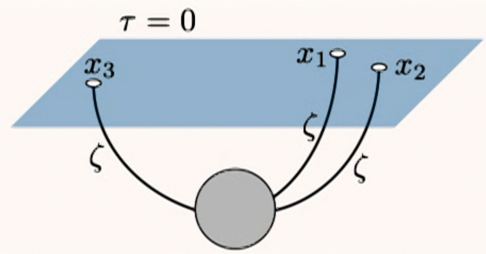
$$\int \mathcal{D}\phi_+ \mathcal{D}\phi_- e^{\mathrm{i}S[\phi_+] - \mathrm{i}S[\phi_-]} \delta\big[\phi_+(\tau = 0) - \phi_-(\tau = 0)\big]$$

Still Feynman diagrams, but with 2 sets of fields

2 types of vertices & 4 types of propagators

“in-in formalism”

S-matrix = $\langle \text{out} | \text{in} \rangle$ ⟶ Feynman diagrams



$$\langle \text{in} | \phi_1 \cdots \phi_n | \text{in} \rangle = \sum_{\text{out}} \langle \text{in} | \text{out} \rangle \langle \text{out} | \phi_1 \cdots \phi_n | \text{in} \rangle$$

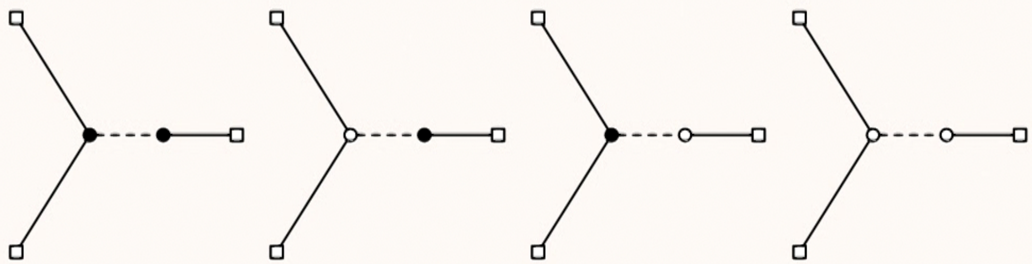
$$\int \mathcal{D}\phi_+ \mathcal{D}\phi_- e^{iS[\phi_+] - iS[\phi_-]} \delta\left[\phi_+(\tau = 0) - \phi_-(\tau = 0)\right]$$

Still Feynman diagrams, but with 2 sets of fields

2 types of vertices & 4 types of propagators

"in-in formalism"

Decorated Feynman diagrams



"Schwinger-Keldysh diagrammatics"

Chen, Wang, ZZX, arXiv:1703.10166

— A recipe for particle physicists

"in-in formalism"

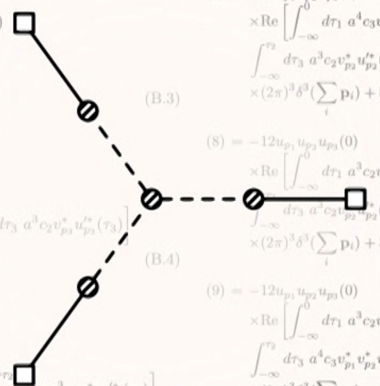
$$
\begin{aligned}
(1) =& -12u^*_{p_1}u_{p_2}u_{p_3}(0)\\
&\times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde\tau_1\ a^3c_2v^*_{p_1}u'_{p_1}(\tilde\tau_1)\int_{-\infty}^{\tilde\tau_1} d\tilde\tau_2\ a^4c_3v_{p_1}v_{p_2}v_{p_3}(\tilde\tau_2)\right.\\
&\left.\times\int_{-\infty}^{0} d\tau_1\ a^3c_2v^*_{p_2}u'^*_{p_2}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\ a^3c_2v^*_{p_3}u'^*_{p_3}(\tau_2)\right]\\
&\times(2\pi)^3\delta^3(\sum_i \mathbf{p}_i) + 5\ \text{perm.}
\end{aligned} \tag{B.2}
$$

$$
\begin{aligned}
(2) =& -12u^*_{p_1}u_{p_2}u_{p_3}(0)\\
&\times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde\tau_1\ a^4c_3v^*_{p_1}v_{p_2}v_{p_3}(\tilde\tau_1)\int_{-\infty}^{\tilde\tau_1} d\tilde\tau_2\ a^3c_2v_{p_1}u'_{p_1}(\tilde\tau_2)\right.\\
&\left.\times\int_{-\infty}^{0} d\tau_1\ a^3c_2v^*_{p_2}u'^*_{p_2}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\ a^3c_2v^*_{p_3}u'^*_{p_3}(\tau_2)\right]\\
&\times(2\pi)^3\delta^3(\sum_i \mathbf{p}_i) + 5\ \text{perm.}
\end{aligned} \tag{B.3}
$$

$$
\begin{aligned}
(3) =& \ 12u_{p_1}u_{p_2}u_{p_3}(0)\\
&\times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde\tau_1\ a^4c_3v_{p_1}v_{p_2}v_{p_3}(\tilde\tau_1)\right.\\
&\left.\times\int_{-\infty}^{0} d\tau_1\ a^3c_2v^*_{p_1}u'^*_{p_1}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\ a^3c_2v^*_{p_2}u'^*_{p_2}(\tau_2)\int_{-\infty}^{\tau_2} d\tau_3\ a^3c_2v^*_{p_3}u'^*_{p_3}(\tau_3)\right]\\
&\times(2\pi)^3\delta^3(\sum_i \mathbf{p}_i) + 5\ \text{perm.}
\end{aligned} \tag{B.4}
$$

$$
\begin{aligned}
(4) =& \ 12u^*_{p_1}u_{p_2}u_{p_3}(0)\\
&\times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde\tau_1\ a^3c_2v_{p_1}u'_{p_1}(\tilde\tau_1)\right.\\
&\left.\times\int_{-\infty}^{0} d\tau_1\ a^4c_3v^*_{p_1}v_{p_2}v_{p_3}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\ a^3c_2v^*_{p_2}u'^*_{p_2}(\tau_2)\int_{-\infty}^{\tau_2} d\tau_3\ a^3c_2v^*_{p_3}u'^*_{p_3}(\tau_3)\right]\\
&\times(2\pi)^3\delta^3(\sum_i \mathbf{p}_i) + 5\ \text{perm.}
\end{aligned} \tag{B.5}
$$

$$
\begin{aligned}
(5) =& \ 12u^*_{p_1}u_{p_2}u_{p_3}(0)\\
&\times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde\tau_1\ a^3c_2v_{p_1}u'_{p_1}(\tilde\tau_1)\right.\\
&\left.\times\int_{-\infty}^{0} d\tau_1\ a^3c_2v_{p_2}u'^*_{p_2}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\ a^4c_3v^*_{p_1}v^*_{p_2}v_{p_3}(\tau_2)\int_{-\infty}^{\tau_2} d\tau_3\ a^3c_2v^*_{p_3}u'^*_{p_3}(\tau_3)\right]\\
&\times(2\pi)^3\delta^3(\sum_i \mathbf{p}_i) + 5\ \text{perm.}
\end{aligned} \tag{B.6}
$$



$$
\begin{aligned}
(6) =& \ 12u^*_{p_1}u_{p_2}u_{p_3}(0)\\
&\times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde\tau_1\ a^3c_2v_{p_1}u'_{p_1}(\tilde\tau_1)\right.\\
&\left.\times\int_{-\infty}^{0} d\tau_1\ a^3c_2v_{p_2}u'^*_{p_2}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\ a^3c_2v_{p_3}u'^*_{p_3}(\tau_2)\int_{-\infty}^{\tau_2} d\tau_3\ a^4c_3v^*_{p_1}v^*_{p_2}v^*_{p_3}(\tau_3)\right]\\
&\times(2\pi)^3\delta^3(\sum_i \mathbf{p}_i) + 5\ \text{perm.}
\end{aligned} \tag{B.7}
$$

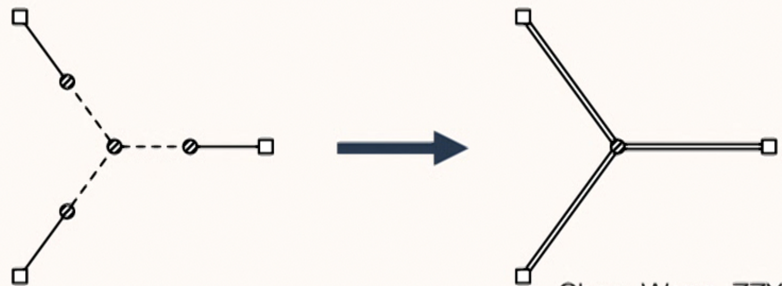
$$
\begin{aligned}
(7) =& -12u_{p_1}u_{p_2}u_{p_3}(0)\\
&\times \mathrm{Re}\left[\int_{-\infty}^{0} d\tau_1\ a^4c_3v_{p_1}v_{p_2}v_{p_3}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\ a^3c_2v^*_{p_1}u'^*_{p_1}(\tau_2)\right.\\
&\left.\int_{-\infty}^{\tau_2} d\tau_3\ a^3c_2v^*_{p_2}u'^*_{p_2}(\tau_3)\int_{-\infty}^{\tau_3} d\tau_4\ a^3c_2v^*_{p_3}u'^*_{p_3}(\tau_4)\right]\\
&\times(2\pi)^3\delta^3(\sum_i \mathbf{p}_i) + 5\ \text{perm.}
\end{aligned} \tag{B.8}
$$

$$
\begin{aligned}
(8) =& -12u_{p_1}u_{p_2}u_{p_3}(0)\\
&\times \mathrm{Re}\left[\int_{-\infty}^{0} d\tau_1\ a^3c_2v_{p_1}u'^*_{p_1}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\ a^4c_3v^*_{p_1}v_{p_2}v_{p_3}(\tau_2)\right.\\
&\left.\int_{-\infty}^{\tau_2} d\tau_3\ a^3c_2v^*_{p_2}u'^*_{p_2}(\tau_3)\int_{-\infty}^{\tau_3} d\tau_4\ a^3c_2v^*_{p_3}u'^*_{p_3}(\tau_4)\right]\\
&\times(2\pi)^3\delta^3(\sum_i \mathbf{p}_i) + 5\ \text{perm.}
\end{aligned} \tag{B.9}
$$

$$
\begin{aligned}
(9) =& -12u_{p_1}u_{p_2}u_{p_3}(0)\\
&\times \mathrm{Re}\left[\int_{-\infty}^{0} d\tau_1\ a^3c_2v_{p_1}u'^*_{p_1}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\ a^3c_2v_{p_2}u'^*_{p_2}(\tau_2)\right.\\
&\left.\int_{-\infty}^{\tau_2} d\tau_3\ a^4c_3v^*_{p_1}v^*_{p_2}v_{p_3}(\tau_3)\int_{-\infty}^{\tau_3} d\tau_4\ a^3c_2v^*_{p_3}u'^*_{p_3}(\tau_4)\right]\\
&\times(2\pi)^3\delta^3(\sum_i \mathbf{p}_i) + 5\ \text{perm.}
\end{aligned} \tag{B.10}
$$

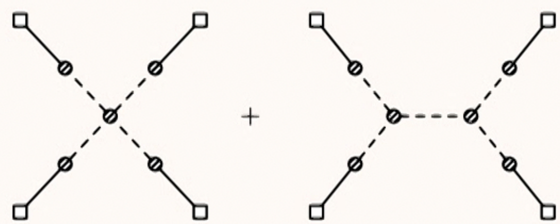
$$
\begin{aligned}
(10) =& -12u_{p_1}u_{p_2}u_{p_3}(0)\\
&\times \mathrm{Re}\left[\int_{-\infty}^{0} d\tau_1\ a^3c_2v_{p_1}u'^*_{p_1}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\ a^3c_2v_{p_2}u'^*_{p_2}(\tau_2)\right.\\
&\left.\int_{-\infty}^{\tau_2} d\tau_3\ a^3c_2v_{p_3}u'^*_{p_3}(\tau_3)\int_{-\infty}^{\tau_3} d\tau_4\ a^4c_3v^*_{p_1}v^*_{p_2}v^*_{p_3}(\tau_4)\right]\\
&\times(2\pi)^3\delta^3(\sum_i \mathbf{p}_i) + 5\ \text{perm.}
\end{aligned} \tag{B.11}
$$

"in-in formalism"



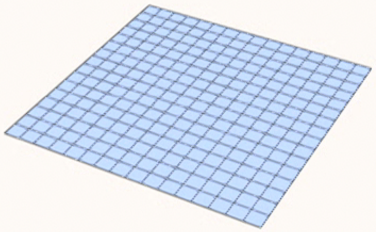
Chen, Wang, ZZX, 1703.10166

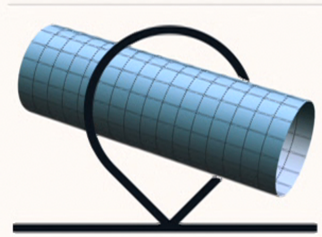
$$\langle \delta\phi^3 \rangle' = \frac{\pi^3 \lambda_2^3 \lambda_3}{256 H k_2^3 k_3^3} \,\mathrm{Im} \int_0^\infty \frac{\mathrm{d}z}{z^4} I_+(z) I_+(\frac{k_2}{k_1} z) I_+(\frac{k_3}{k_1} z)$$



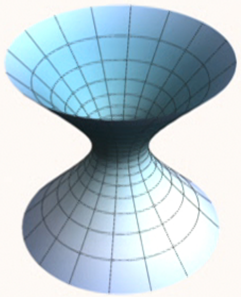
Chen, Chua, Guo, Wang, ZZX, Xie, 1803.04412

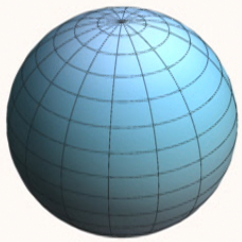
“thermal” background





$$m_{\text{th}}^2 \propto \lambda T^2$$



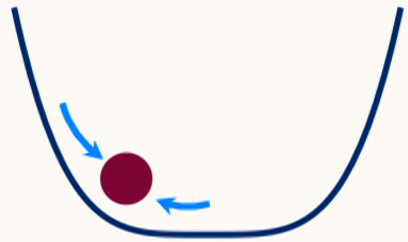


$$m^2 \propto \sqrt{\lambda} T^2$$

IR-enhanced loop mass

Classical rolling-down

$$H\dot{\phi} \simeq \lambda\phi^3 \qquad \phi^2 \sim H/(\lambda t)$$

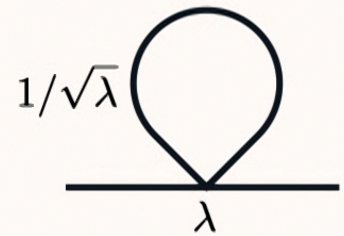


Quantum fluctuation $\langle\phi^2\rangle \sim H^3 t$

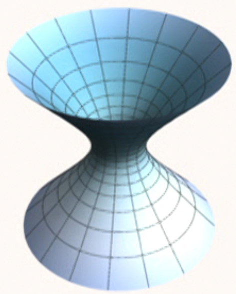
Equilibrium reached at $t \sim (\sqrt{\lambda}H)^{-1}$

$$\rightarrow \quad \langle\phi^2\rangle \sim H^2/\sqrt{\lambda}$$

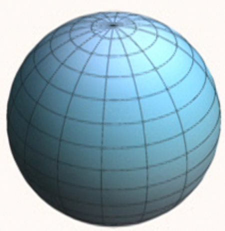
$$\rightarrow \quad m^2 \sim \lambda\langle\phi^2\rangle \sim \sqrt{\lambda}H^2$$



fun with spherical harmonics



Wick rotation



$$\Box Y_{\vec{L}}(x) = -H^2 L(L+d) Y_{\vec{L}}(x)$$

$$(\Box - m^2)\phi = 0$$

$$G(x, x') = \sum_{\vec{L}} \frac{H^{d+1}}{\lambda_L} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x')$$

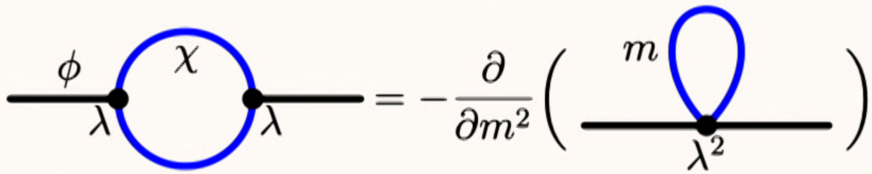
$$\lambda_L = L(L+d) + (m/H)^2$$

Zero mode $\frac{H^{d+3}}{m^2} Y_{\vec{0}}^2$

fun with spherical harmonics

$$\int_{x,x'} G(x,x')^2 = \sum_{L,M} \int_{x,x'} \frac{1}{\lambda_L \lambda_M} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x') Y_{\vec{M}}(x') Y^*_{\vec{M}}(x)$$

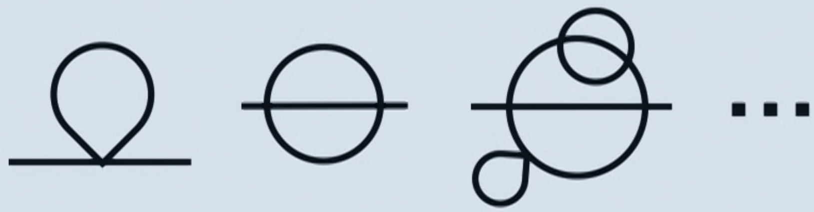
$$= \sum_{L} \int_x \frac{1}{\lambda_L^2} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x) = -\frac{\partial}{\partial m^2} \int_x G(x,x)$$



Small mass limit $m_\chi \ll H$ ➡ $\delta m_\phi^2 = \dfrac{3\lambda^2 H^4}{8\pi^2 m_\chi^2}$

Higgs mass

Loop expansion breaks down



$\propto \sqrt{\lambda}$

The zero-mode path integral to all orders

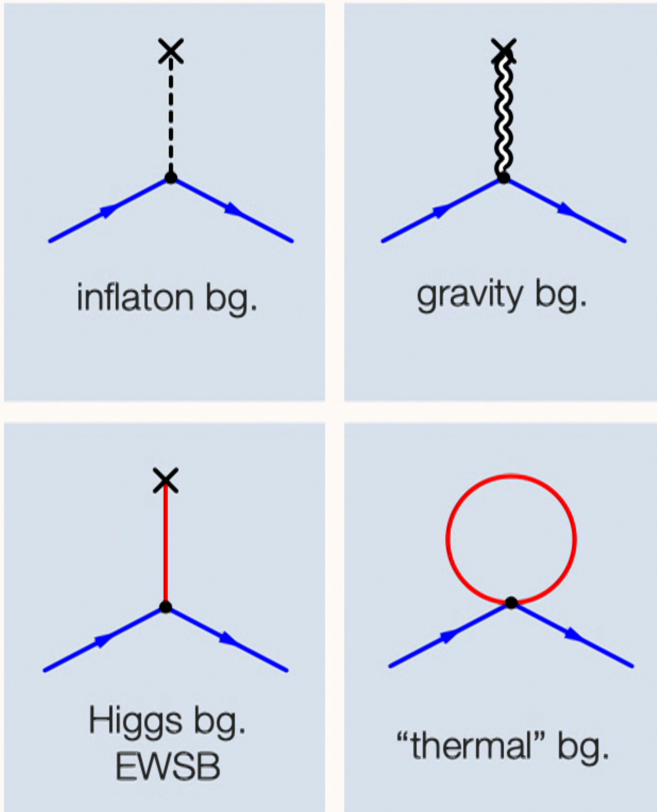
non-vanishing in the classically massless limit

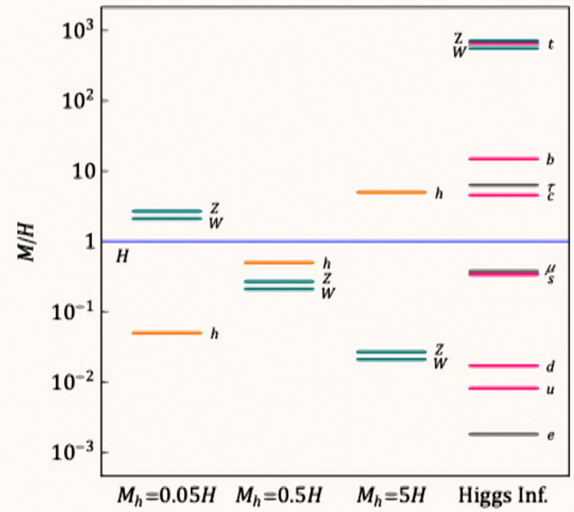
$$M_H^2 = \sqrt{\frac{6\lambda}{\pi^3}} H^2$$

Rajaraman, 1008.1271

Chen, Wang, ZZX, 1612.08122

SM spectrum





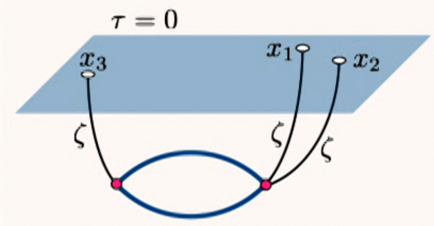
Chen, Wang, ZZX,
PRL **118** (2017) 261302

JHEP **1608** (2016) 051
JHEP **1704** (2017) 058

SM signatures

Without EWSB, always from loops

$$\mathscr{L} \supset -f_H(X)\mathbf{H}^\dagger\mathbf{H} - f_{DH}(X)|\mathrm{D}_\mu\mathbf{H}|^2$$
$$- f_{\Psi_i}(X)\bar{\Psi}_i \not{D}\Psi_i - \frac{1}{4}f_{A_a}(X)F_{a\mu\nu}F_a^{\mu\nu}$$



$$S_H = \left[\frac{f'_H(X_0)}{1+f_{DH}(X_0)}\right]^2 \frac{\dot{\phi}_0^2}{2\pi^4}\left[C_H(\mu_h)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_h} + (\mu_h \to -\mu_h)\right]$$
$$S_{DH} = \left[\frac{f'_{DH}(X_0)}{1+f_{DH}(X_0)}\right]^2 \frac{H^4\dot{\phi}_0^2}{8\pi^4}\left[C_{DH}(\mu_h)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_h} + (\mu_h \to -\mu_h)\right]$$
$$S_\Psi = \left[\frac{f'_\Psi(X_0)}{1+f_\Psi(X_0)}\right]^2 \frac{H^4\dot{\phi}_0^2\mu_{1/2}^2}{2\pi^4}\left[C_\Psi(\mu_{1/2})\left(\frac{k_L}{k_S}\right)^{1+2\mathrm{i}\mu_{1/2}} + \text{c.c.}\right]$$
$$S_A = \left[\frac{f'_A(X_0)}{1+f_A(X_0)}\right]^2 \frac{27H^8\dot{\phi}_0^2}{16\pi^4 M_A^4}\left[C_A(\mu_1)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_1} + (\mu_1 \to -\mu_1)\right]$$

SM signatures

How to identify SM? A consistency relation

$$\frac{d\ln\tan^2\theta_W}{d\ln k} = \frac{\pi(1-n_s-\frac{1}{4}r)}{3\sqrt{3P_\zeta}\sin^2\theta_W}\left[\frac{M_W^2}{H^2}\sqrt{\frac{f_{NL}^W}{N_W|C_A(\mu_W)|}} - \frac{M_Z^2}{H^2}\sqrt{\frac{f_{NL}^Z}{N_Z|C_A(\mu_Z)|}}\right]$$

Chen, Wang, ZZX, 1612.08122

Estimate signal strength

$$f_{NL}(\text{clock}) \sim \frac{1}{16\pi^2}\cdot P_\zeta^{-1/2}\cdot\frac{\dot\phi_0}{\Lambda^4}\cdot(\text{propagators})$$

Unitarity bound: $\Lambda \gtrsim \dot\phi_0^{1/2}$

At most O(1), but technically unnatural

need to tune Boltzmann factor away

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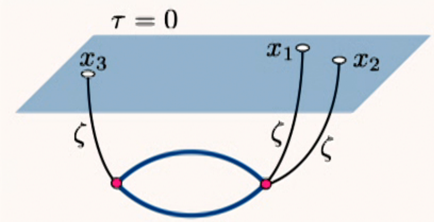

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Chen, Wang, ZZX, 1612.08122

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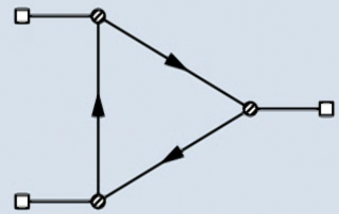
Probing heavy neutrinos

A rare chance to see right-handed neutrinos

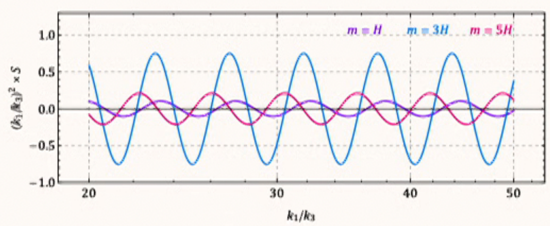
$$m \sim 10^{13}\text{GeV} \sim H$$

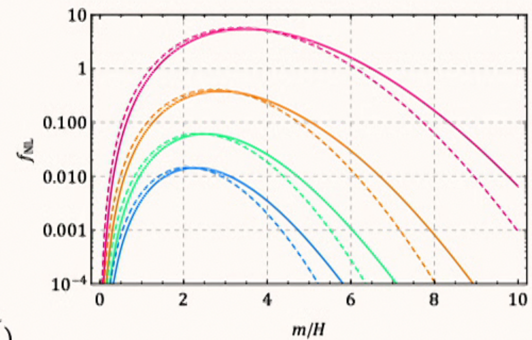
Inflaton background as a neutrino source

$$\frac{1}{\Lambda}(\partial_\mu \phi) N^\dagger \bar{\sigma}^\mu N \qquad \frac{\dot{\phi}}{\Lambda} N^\dagger \bar{\sigma}^0 N \qquad \lambda = \frac{\dot{\phi}_0}{\Lambda}$$



$$\mu = \sqrt{m^2 + \lambda^2}$$

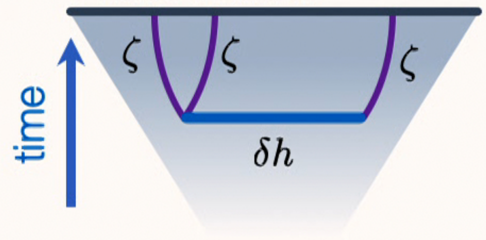




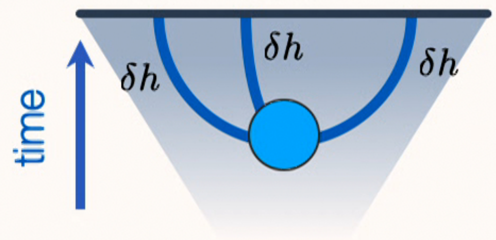
$$f_{NL}(\text{clock}) \simeq \frac{3\pi^2}{2} P_\zeta \widetilde{\lambda}^5 \widetilde{m}^3 e^{-5\pi\widetilde{m}^2/(4\widetilde{\lambda})}$$

Chen, Wang, ZZX, JHEP **1809** (2018) 022

A Cosmological Higgs Collider



"inflaton collider"



"CHC"

Modulated reheating $\quad \zeta \propto \delta\Gamma \propto \delta h$

$$\frac{1}{\Lambda}\bar{f}(\partial\!\!\!/\phi)\gamma^5 f \qquad \Gamma(\phi \to f\bar{f}) = \frac{1}{2\pi\Lambda^2} m_\phi m_f^2 \left(1 - \frac{4m_f^2}{m_\phi^2}\right)^{1/2} \qquad m_f \propto h$$

Studying Higgs interactions directly in non-G

Lu, Wang, ZZX, in preparation


more possibilities
CP violation?
SYMMETRY BREAKING
Very low scale inflation
EWSB
"Heavy-lifting senario"
Kumar, Sundrum, 1711.03988, 1811.11200
Delacretaz et al., 1610.04227
GUT?
Chen, Wang, ZZX, 1612.08122
Supersymmetry?
Lee et al., 1607.03735
Baumann et al., 1712.06624
HIGHER SPINS
scale-dependent features
Tensor mode / gravitational wave
Chen, Loeb, ZZX, 1809.02603
Maldacena, Pimentel, 1104.2846
& MANY MORE
String excitations?
Strongly coupled theory
An et al., 1706.09971, 1711.02667
Iyer et al., 1710.03054
May 21, 2019
Zhong-Zhi Xianyu
29

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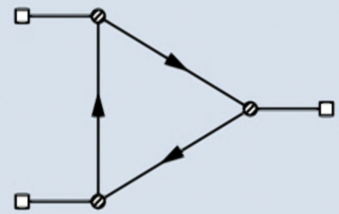

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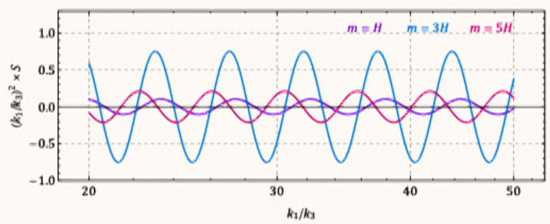

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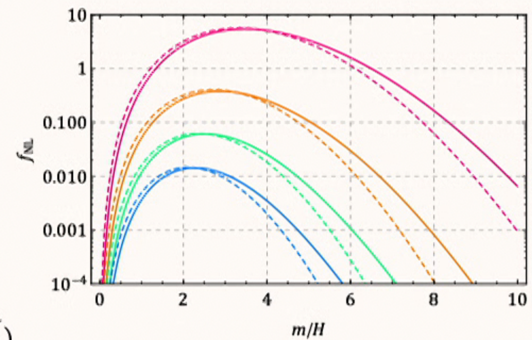

Chen, Wang, ZZX, JHEP **1809** (2018) 022