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

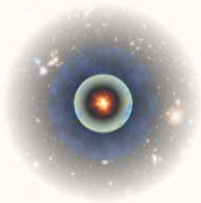
Abstract: The n-point correlation functions (n>2) of primordial fluctuations, known as primordial non-Gaussianities, encode rich information about the physical degrees of freedom and their interactions at inflation scale, and can be viewed as signals from a cosmological collider with huge energy. In 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

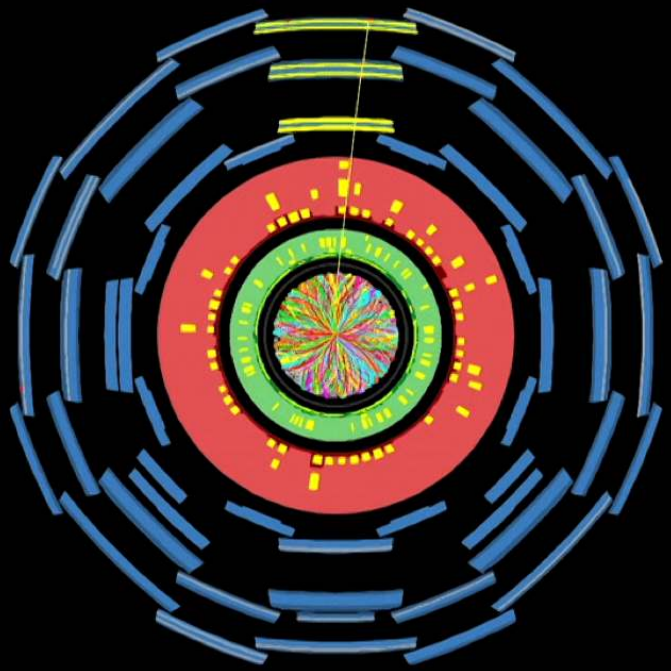


Cosmological Collider Phenomenology: SM & Beyond

Zhong-Zhi Xianyu (Harvard)

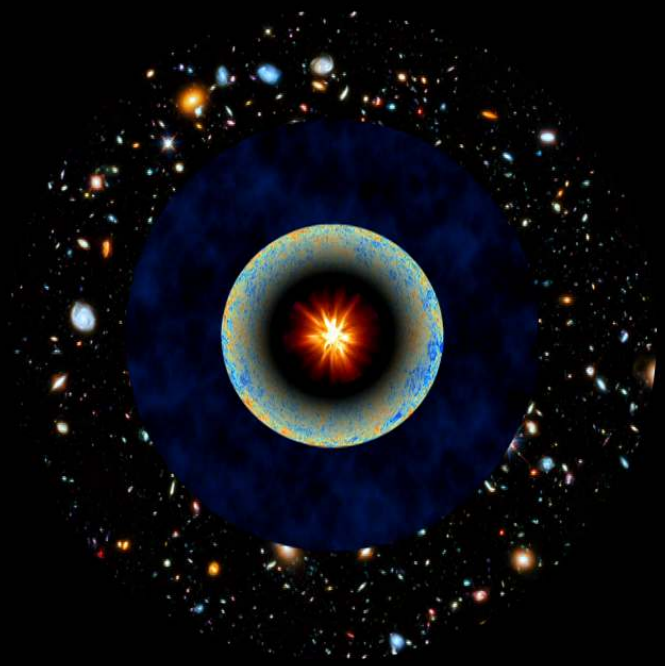
Perimeter Institute | May 21, 2019

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



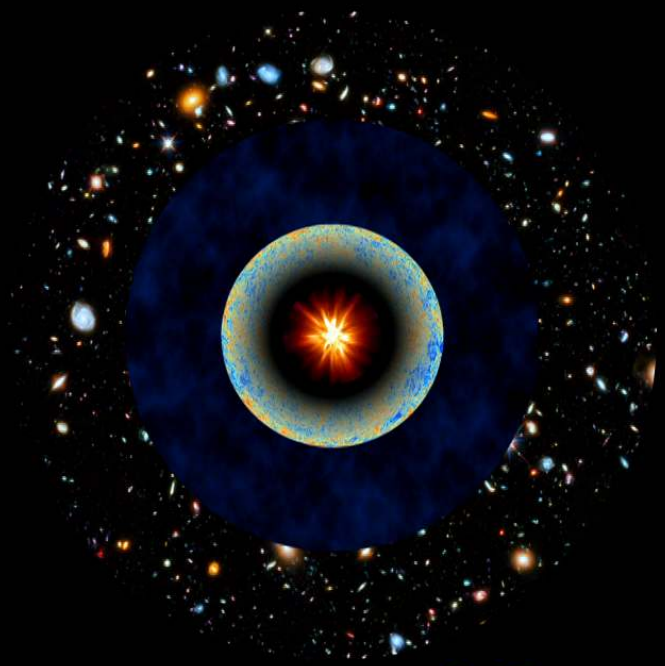
Large Hadron Collider

ATLAS detector



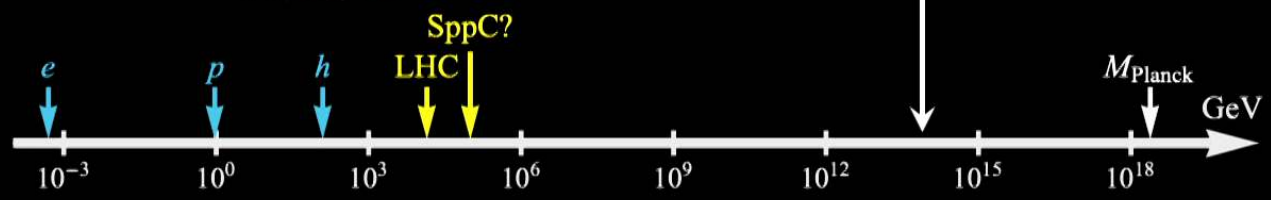
Cosmological Collider

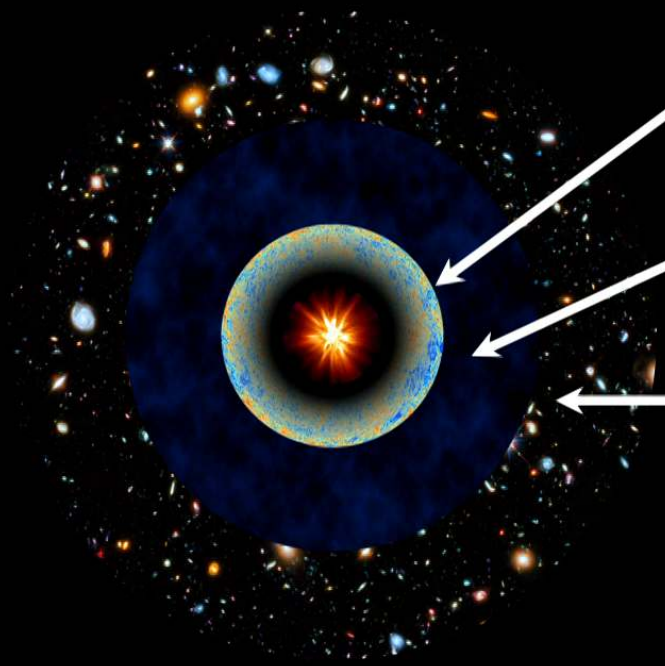
The universe



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

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

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

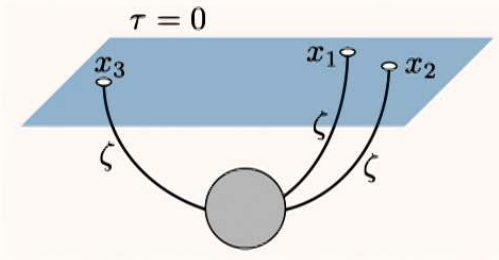
a long-lived scalar mode ζ

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

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

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

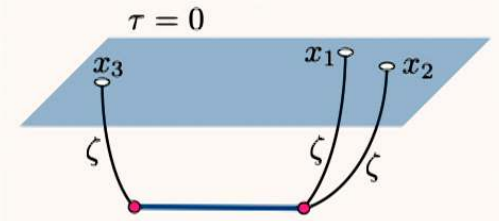
$$f_{\rm NL}^{\rm local} = 0.9 \pm 5.1; \quad f_{\rm NL}^{\rm equil} = -26 \pm 47; \quad f_{\rm NL}^{\rm ortho} = -38 \pm 24$$

Planck 2019, 68% CL

non-Gaussianity: the collision

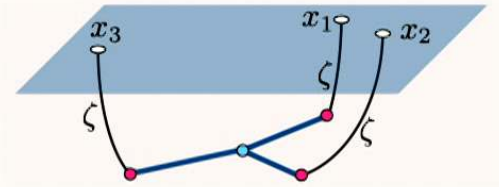
Future probe down to O(0.01): What can be seen?

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



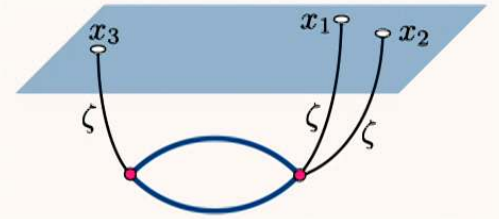
heavy particles?

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

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

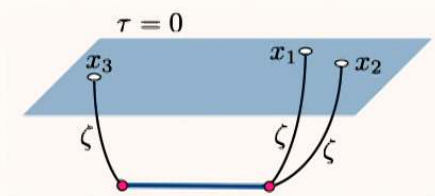
$$\nu = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

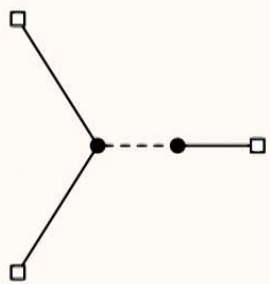
Late-time behavior

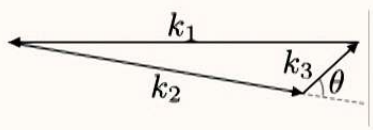
$$\langle \sigma_k(\tau_1)\sigma_{-k}(\tau_2)\rangle' \sim \frac{H^2}{4\pi k^3}\left[\Gamma^2(-\nu)\left(\frac{k^2\tau_1\tau_2}{4}\right)^{3/2+\nu} + (\nu \to -\nu)\right] + \text{local}$$

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







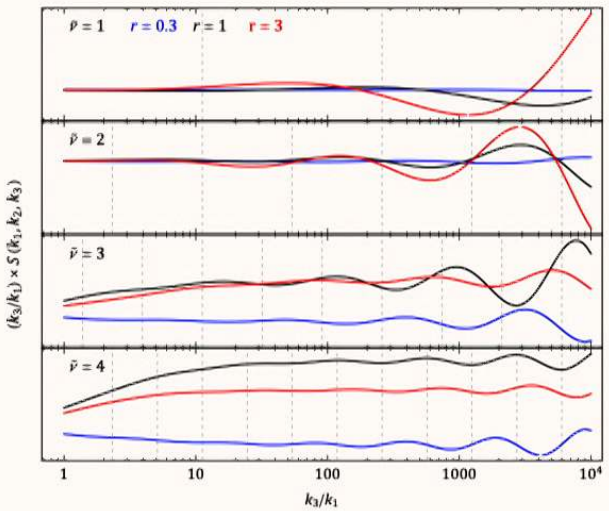
$$\langle \sigma_k^2 \rangle \sim \frac{1}{k^3}\left(\frac{k^2\tau_1\tau_2}{4}\right)^{3/2\pm\nu}$$

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

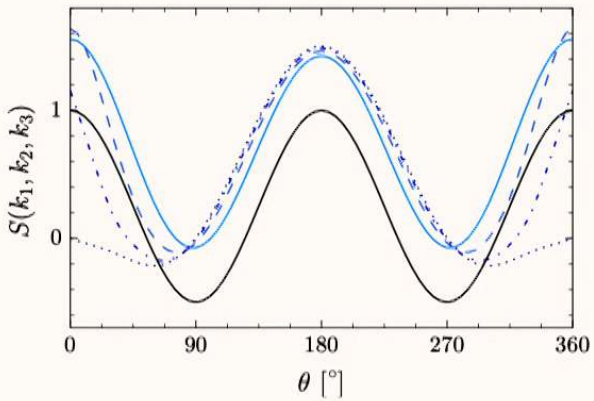
$$\longrightarrow \left(\frac{k_3}{k_1}\right)^{\pm\nu} P_s(\cos\theta)$$

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

squeezed bispectrum: a discovery channel



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



Lee, Baumann, Pimentel, 1607.03735

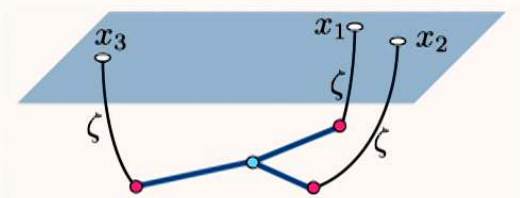
how to estimate

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

From ζ gauge to $\delta\phi$ gauge

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

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

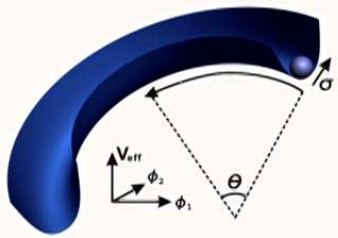


how to estimate

An example of QSFI

Chen, Wang, 0911.3380

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

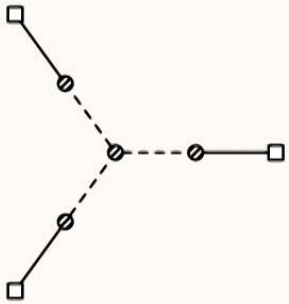


$$\frac{a^2}{2}\Big[(\delta\phi')^2 - (\partial_i\delta\phi)^2 + (\delta\sigma')^2 - (\partial_i\delta\sigma)^2\Big] - \tfrac{1}{2}a^4m^2\delta\sigma^2 + a^3\kappa_1\delta\sigma\delta\phi' - \tfrac{1}{6}a^4\lambda_3\delta\sigma^3$$

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

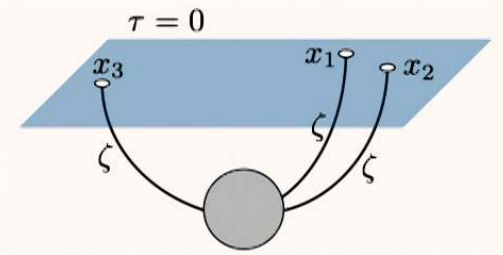
$\cdot$ (propagators)

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



"in-in formalism"

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



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

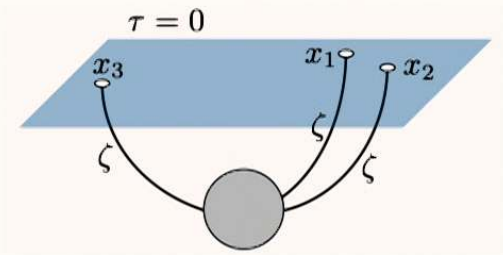
$$\int \mathcal{D}\phi_+ \mathcal{D}\phi_- e^{\mathrm{i}S[\phi_+]-\mathrm{i}S[\phi_-]}\delta\left[\phi_+(\tau=0)-\phi_-(\tau=0)\right]$$

Still Feynman diagrams, but with 2 sets of fields

2 types of vertices & 4 types of propagators

"in-in formalism"

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



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

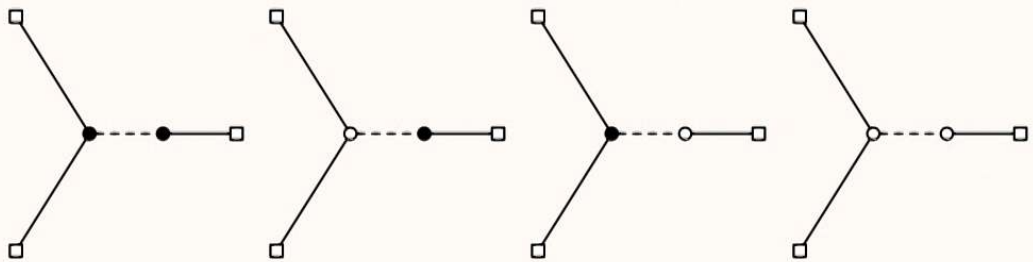
$$\int \mathcal{D}\phi_+ \mathcal{D}\phi_- e^{\mathrm{i}S[\phi_+]-\mathrm{i}S[\phi_-]}\delta\left[\phi_+(\tau=0)-\phi_-(\tau=0)\right]$$

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”

$$(1) = -12u^*_{p_1}u_{p_2}u_{p_3}(0) \times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde{\tau}_1\, a^3 c_2 v^*_{p_1} u'_{p_1}(\tilde{\tau}_1) \int_{-\infty}^{\tilde{\tau}_1} d\tilde{\tau}_2\, a^4 c_3 v_{p_1} v_{p_2} v_{p_3}(\tilde{\tau}_2) \times \int_{-\infty}^{0} d\tau_1\, a^3 c_2 v^*_{p_2} u'^*_{p_2}(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2\, a^3 c_2 v^*_{p_3} u'^*_{p_3}(\tau_2)\right] \times (2\pi)^3 \delta^3(\sum_i \mathbf{p}_i) + 5 \text{ perm.} \tag{B.2}$$

$$(2) = -12u^*_{p_1}u_{p_2}u_{p_3}(0) \times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde{\tau}_1\, a^4 c_3 v^*_{p_1} v_{p_2} v_{p_3}(\tilde{\tau}_1) \int_{-\infty}^{\tilde{\tau}_1} d\tilde{\tau}_2\, a^3 c_2 v_{p_1} u'_{p_1}(\tilde{\tau}_2) \times \int_{-\infty}^{0} d\tau_1\, a^3 c_2 v^*_{p_2} u'^*_{p_2}(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2\, a^3 c_2 v^*_{p_3} u'^*_{p_3}(\tau_2)\right] \times (2\pi)^3 \delta^3(\sum_i \mathbf{p}_i) + 5 \text{ perm.} \tag{B.3}$$

$$(3) = 12u_{p_1}u_{p_2}u_{p_3}(0) \times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde{\tau}_1\, a^4 c_3 v_{p_1} v_{p_2} v_{p_3}(\tilde{\tau}_1) \times \int_{-\infty}^{0} d\tau_1\, a^3 c_2 v^*_{p_1} u'^*_{p_1}(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2\, a^3 c_2 v^*_{p_2} u'^*_{p_2}(\tau_2) \int_{-\infty}^{\tau_2} d\tau_3\, a^3 c_2 v^*_{p_3} u'^*_{p_3}(\tau_3)\right] \times (2\pi)^3 \delta^3(\sum_i \mathbf{p}_i) + 5 \text{ perm.} \tag{B.4}$$

$$(4) = 12u^*_{p_1}u_{p_2}u_{p_3}(0) \times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde{\tau}_1\, a^3 c_2 v_{p_1} u'_{p_1}(\tilde{\tau}_1) \times \int_{-\infty}^{0} d\tau_1\, a^4 c_3 v^*_{p_1} v_{p_2} v_{p_3}(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2\, a^3 c_2 v^*_{p_2} u'^*_{p_2}(\tau_2) \int_{-\infty}^{\tau_2} d\tau_3\, a^3 c_2 v^*_{p_3} u'^*_{p_3}(\tau_3)\right] \times (2\pi)^3 \delta^3(\sum_i \mathbf{p}_i) + 5 \text{ perm.} \tag{B.5}$$

$$(5) = 12u^*_{p_1}u_{p_2}u_{p_3}(0) \times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde{\tau}_1\, a^3 c_2 v_{p_1} u'_{p_1}(\tilde{\tau}_1) \times \int_{-\infty}^{0} d\tau_1\, a^3 c_2 v_{p_2} u'^*_{p_2}(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2\, a^4 c_3 v^*_{p_1} v^*_{p_2} v_{p_3}(\tau_2) \int_{-\infty}^{\tau_2} d\tau_3\, a^3 c_2 v^*_{p_3} u'^*_{p_3}(\tau_3)\right] \times (2\pi)^3 \delta^3(\sum_i \mathbf{p}_i) + 5 \text{ perm.} \tag{B.6}$$

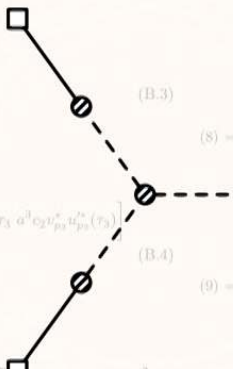
$$(6) = 12u^*_{p_1}u_{p_2}u_{p_3}(0) \times \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde{\tau}_1\, a^3 c_2 v_{p_1} u'_{p_1}(\tilde{\tau}_1) \times \int_{-\infty}^{0} d\tau_1\, a^3 c_2 v_{p_2} u'^*_{p_2}(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2\, a^3 c_2 v_{p_3} u'^*_{p_3}(\tau_2) \int_{-\infty}^{\tau_2} d\tau_3\, a^4 c_3 v^*_{p_1} v^*_{p_2} v^*_{p_3}(\tau_3)\right] \times (2\pi)^3 \delta^3(\sum_i \mathbf{p}_i) + 5 \text{ perm.} \tag{B.7}$$

$$(7) = -12u_{p_1}u_{p_2}u_{p_3}(0) \times \mathrm{Re}\left[\int_{-\infty}^{0} d\tau_1\, a^4 c_3 v_{p_1} v_{p_2} v_{p_3}(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2\, a^3 c_2 v^*_{p_1} u'^*_{p_1}(\tau_2) \int_{-\infty}^{\tau_2} d\tau_3\, a^3 c_2 v^*_{p_2} u'^*_{p_2}(\tau_3) \int_{-\infty}^{\tau_3} d\tau_4\, a^3 c_2 v^*_{p_3} u'^*_{p_3}(\tau_4)\right] \times (2\pi)^3 \delta^3(\sum_i \mathbf{p}_i) + 5 \text{ perm.} \tag{B.8}$$

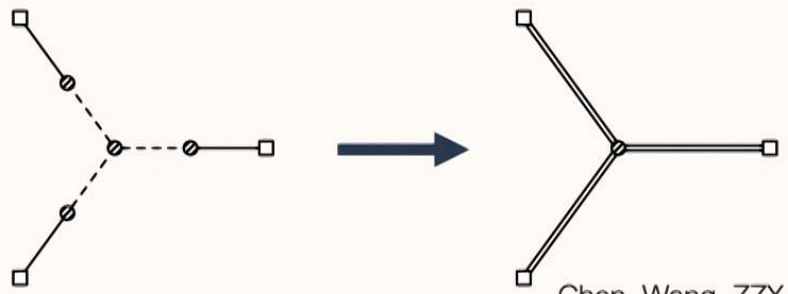
$$(8) = -12u_{p_1}u_{p_2}u_{p_3}(0) \times \mathrm{Re}\left[\int_{-\infty}^{0} d\tau_1\, a^3 c_2 v_{p_1} u'^*_{p_1}(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2\, a^4 c_3 v^*_{p_1} v_{p_2} v_{p_3}(\tau_2) \int_{-\infty}^{\tau_2} d\tau_3\, a^3 c_2 v^*_{p_2} u'^*_{p_2}(\tau_3) \int_{-\infty}^{\tau_3} d\tau_4\, a^3 c_2 v^*_{p_3} u'^*_{p_3}(\tau_4)\right] \times (2\pi)^3 \delta^3(\sum_i \mathbf{p}_i) + 5 \text{ perm.} \tag{B.9}$$

$$(9) = -12u_{p_1}u_{p_2}u_{p_3}(0) \times \mathrm{Re}\left[\int_{-\infty}^{0} d\tau_1\, a^3 c_2 v_{p_1} u'^*_{p_1}(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2\, a^3 c_2 v_{p_2} u'^*_{p_2}(\tau_2) \int_{-\infty}^{\tau_2} d\tau_3\, a^4 c_3 v^*_{p_1} v^*_{p_2} v_{p_3}(\tau_3) \int_{-\infty}^{\tau_3} d\tau_4\, a^3 c_2 v^*_{p_3} u'^*_{p_3}(\tau_4)\right] \times (2\pi)^3 \delta^3(\sum_i \mathbf{p}_i) + 5 \text{ perm.} \tag{B.10}$$

$$(10) = -12u_{p_1}u_{p_2}u_{p_3}(0) \times \mathrm{Re}\left[\int_{-\infty}^{0} d\tau_1\, a^3 c_2 v_{p_1} u'^*_{p_1}(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2\, a^3 c_2 v_{p_2} u'^*_{p_2}(\tau_2) \int_{-\infty}^{\tau_2} d\tau_3\, a^3 c_2 v_{p_3} u'^*_{p_3}(\tau_3) \int_{-\infty}^{\tau_3} d\tau_4\, a^4 c_3 v^*_{p_1} v^*_{p_2} v^*_{p_3}(\tau_4)\right] \times (2\pi)^3 \delta^3(\sum_i \mathbf{p}_i) + 5 \text{ perm.} \tag{B.11}$$

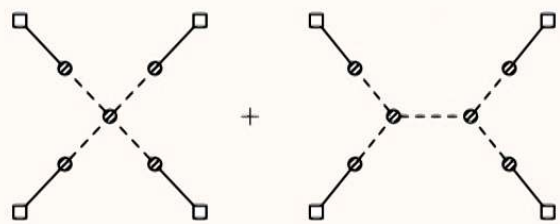


“in-in formalism”



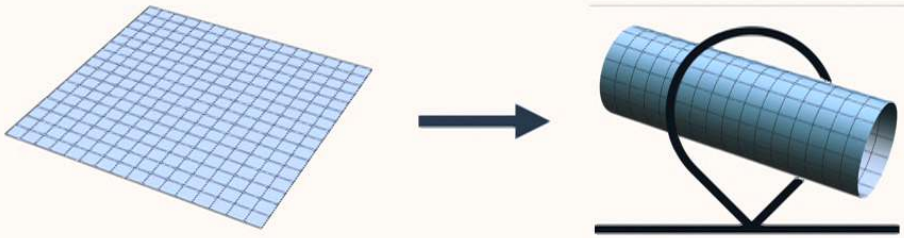
Chen, Wang, ZZX, 1703.10166

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



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

“thermal” background



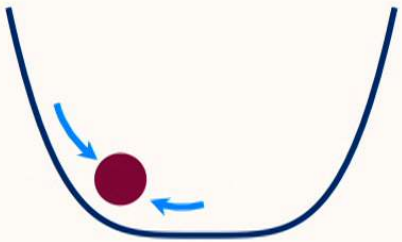
$$m_{\rm th}^2 \propto \lambda T^2$$

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

IR-enhanced loop mass

Classical rolling-down

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

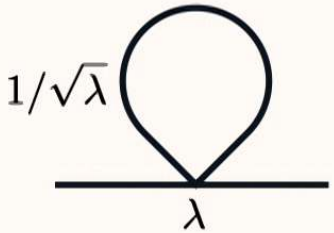


Quantum fluctuation $\langle\phi^2\rangle \sim H^3 t$

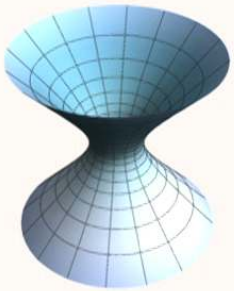
Equilibrium reached at $t \sim (\sqrt{\lambda}H)^{-1}$

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

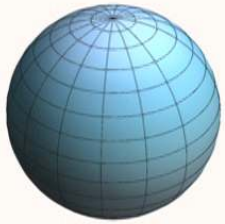
$\rightarrow$ $m^2 \sim \lambda\langle\phi^2\rangle \sim \sqrt{\lambda}H^2$



fun with spherical harmonics



Wick rotation



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

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

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

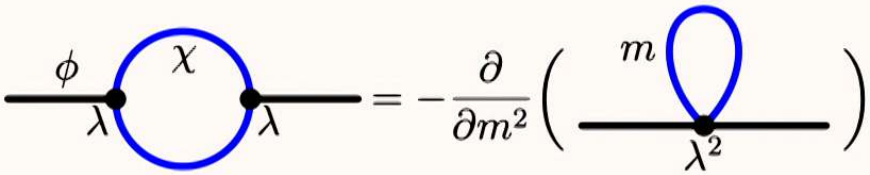
$$\lambda_L = L(L+d) + (m/H)^2$$

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

fun with spherical harmonics

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

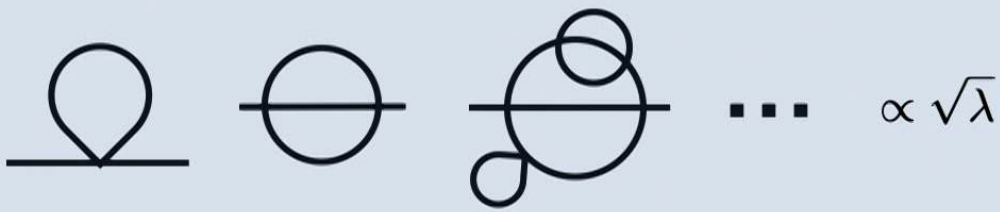
$$= \sum_{L} \int_{x} \frac{1}{\lambda_L^2} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x) = -\frac{\partial}{\partial m^2} \int_{x} G(x,x)$$



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

Higgs mass

Loop expansion breaks down



The zero-mode path integral to all orders

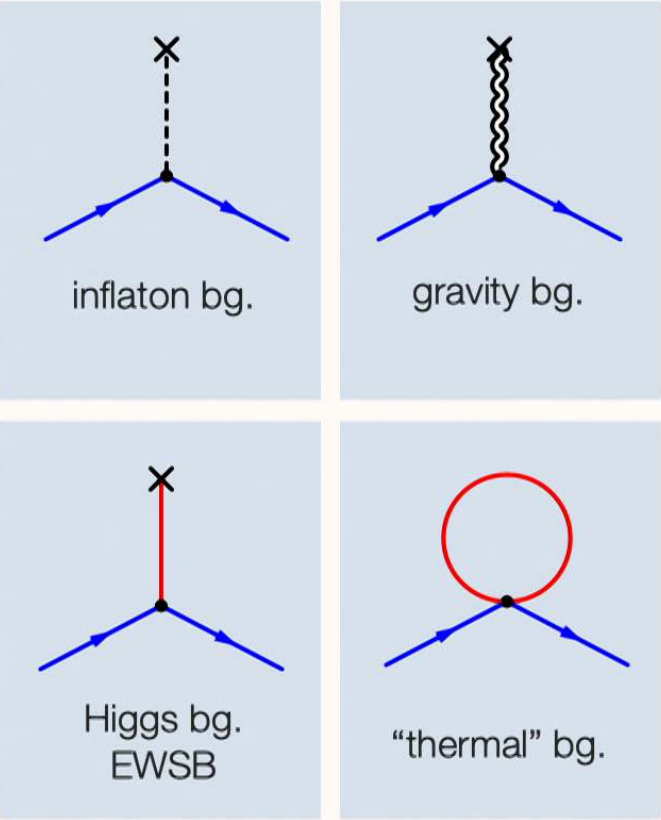
non-vanishing in the classically massless limit

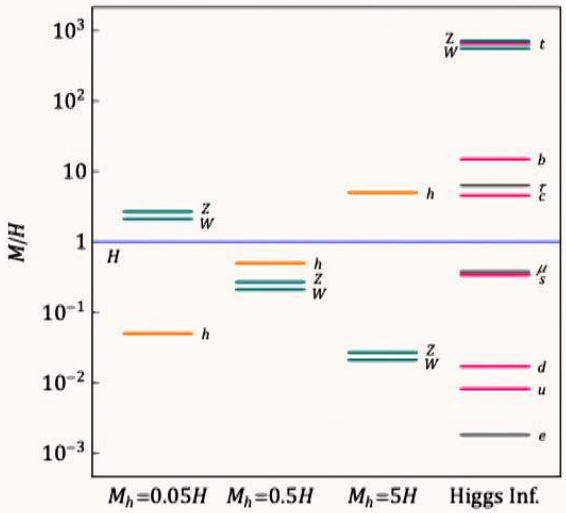
$$M_H^2 = \sqrt{\frac{6\lambda}{\pi^3}} H^2$$

Rajaraman, 1008.1271

Chen, Wang, ZZX, 1612.08122

SM spectrum





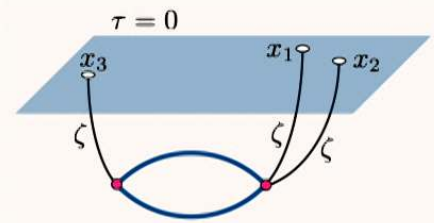
Chen, Wang, ZZX,
PRL **118** (2017) 261302

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

SM signatures

Without EWSB, always from loops

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



$$S_H = \left[\frac{f_H'(X_0)}{1+f_{DH}(X_0)}\right]^2 \frac{\dot{\phi}_0^2}{2\pi^4}\left[C_H(\mu_h)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_h} + (\mu_h \to -\mu_h)\right]$$

$$S_{DH} = \left[\frac{f_{DH}'(X_0)}{1+f_{DH}(X_0)}\right]^2 \frac{H^4\dot{\phi}_0^2}{8\pi^4}\left[C_{DH}(\mu_h)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_h} + (\mu_h \to -\mu_h)\right]$$

$$S_\Psi = \left[\frac{f_\Psi'(X_0)}{1+f_\Psi(X_0)}\right]^2 \frac{H^4\dot{\phi}_0^2\mu_{1/2}^2}{2\pi^4}\left[C_\Psi(\mu_{1/2})\left(\frac{k_L}{k_S}\right)^{1+2\mathrm{i}\mu_{1/2}} + \mathrm{c.c.}\right]$$

$$S_A = \left[\frac{f_A'(X_0)}{1+f_A(X_0)}\right]^2 \frac{27H^8\dot{\phi}_0^2}{16\pi^4 M_A^4}\left[C_A(\mu_1)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_1} + (\mu_1 \to -\mu_1)\right]$$

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

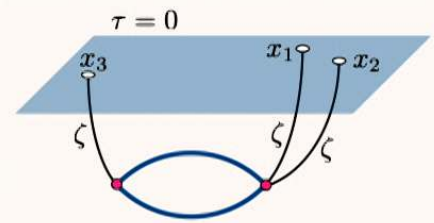
At most O(1), but technically unnatural

need to tune Boltzmann factor away

SM signatures

Without EWSB, always from loops

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



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

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

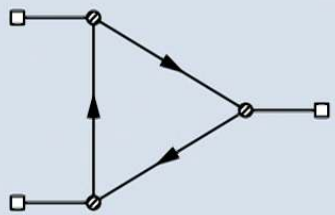
Probing heavy neutrinos

A rare chance to see right-handed neutrinos

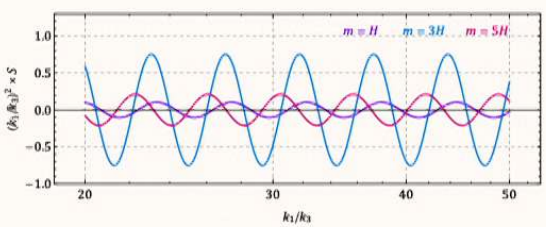
$$m \sim 10^{13}\mathrm{GeV} \sim H$$

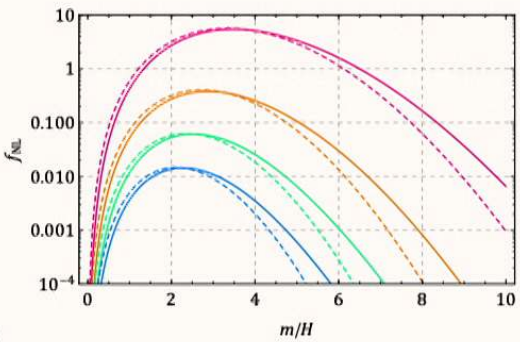
Inflaton background as a neutrino source

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



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

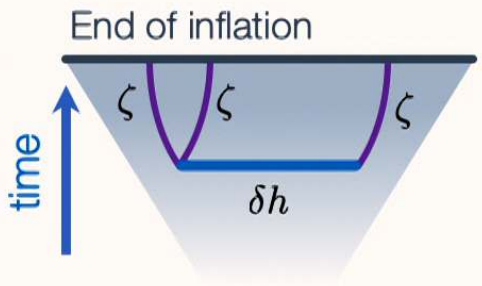




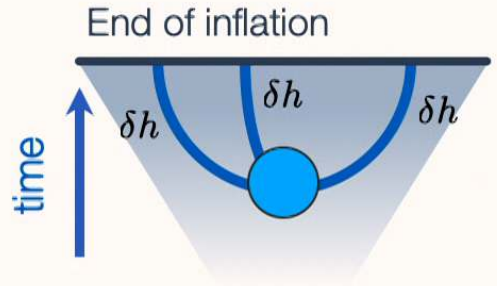
$$f_{NL}(\mathrm{clock}) \simeq \frac{3\pi^2}{2} P_\zeta \tilde{\lambda}^5 \tilde{m}^3 e^{-5\pi\tilde{m}^2/(4\tilde{\lambda})}$$

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

A Cosmological Higgs Collider



"inflaton collider"



"CHC"

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

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

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

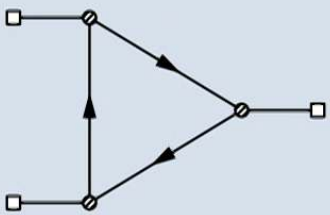
Probing heavy neutrinos

A rare chance to see right-handed neutrinos

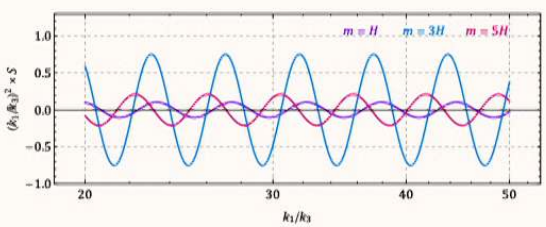
$$m \sim 10^{13}\mathrm{GeV} \sim H$$

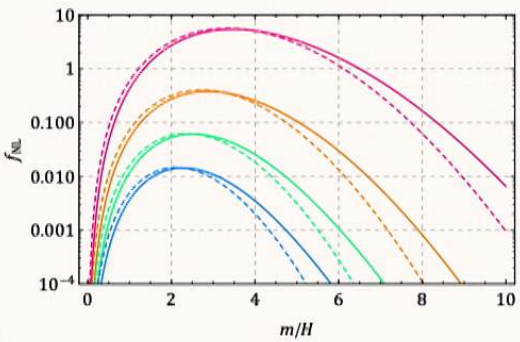
Inflaton background as a neutrino source

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



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





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

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