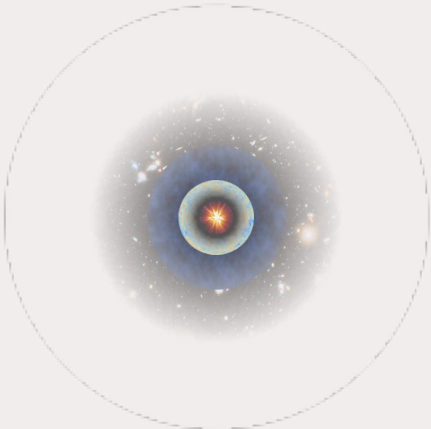
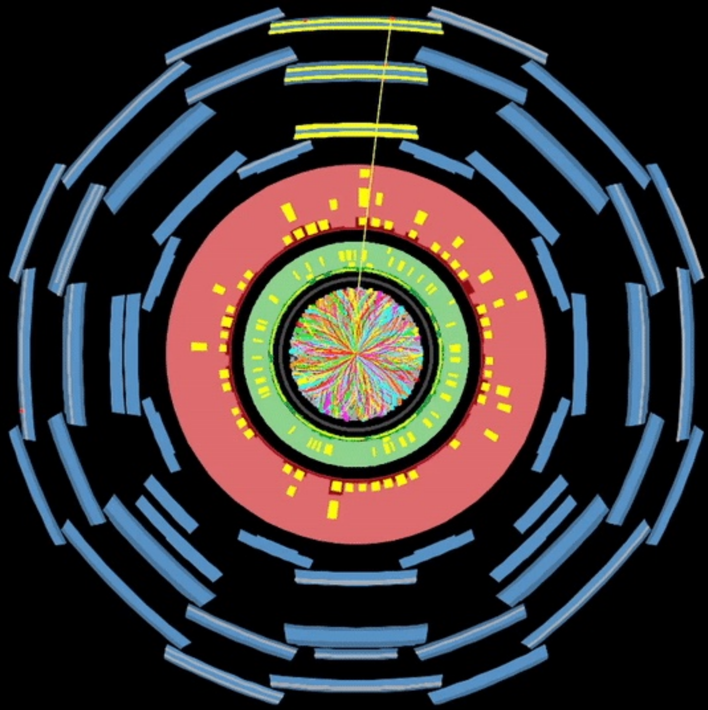


Cosmological Collider Phenomenology: SM & Beyond

Zhong-Zhi Xianyu (鲜于中之)

Harvard University | CHEP2018

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
1805.02656



Large Hadron Collider

ATLAS detector

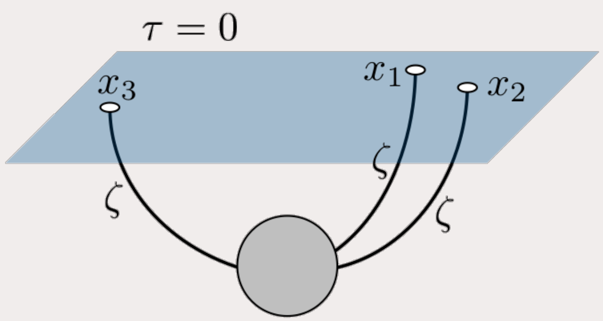
Cosmological Collider

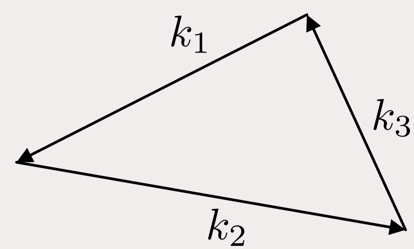
Universe the detector

Inflation the accelerator

non-Gaussianity: the collision

Interactions of the scalar/tensor modes during inflation





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

A long-lived, weakly-coupled scalar mode

$$f_{NL}^{\text{local}} = 2.5 \pm 5.7 \qquad f_{NL}^{\text{equil}} = -16 \pm 70 \qquad f_{NL}^{\text{ortho}} = -34 \pm 33$$

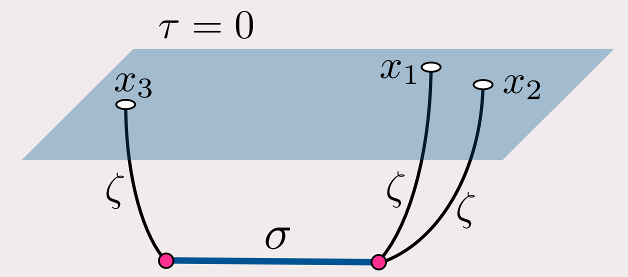
Planck 2015, 68% CL

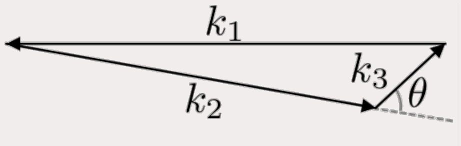
Future probe down to O(0.01): What can be seen?

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

squeezed bispectrum: a discovery channel

Heavy particles in inflation





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

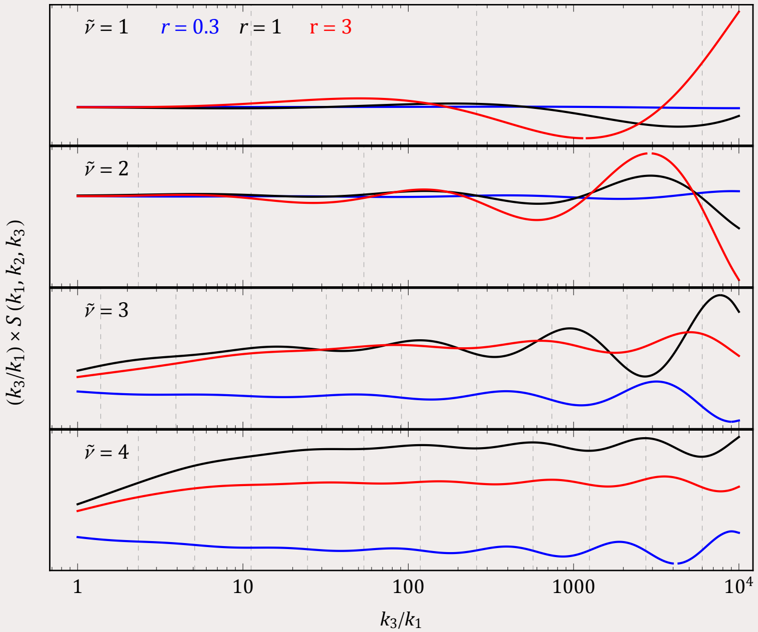
$$\sim \frac{H^2}{4\pi k^3}\left[\Gamma^2(-\nu)\left(\frac{k^2\tau_1\tau_2}{4}\right)^{3/2+\nu} + (\nu \to -\nu)\right]$$

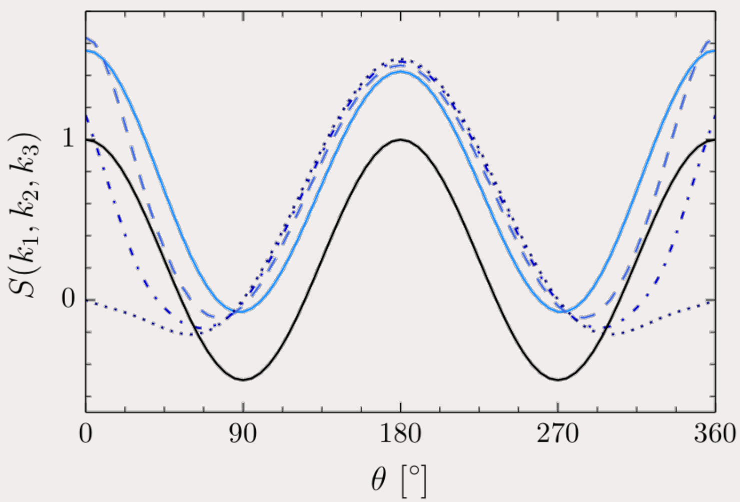
$$\nu = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

$$\int \mathrm{d}\tau_1 \mathrm{d}\tau_2\, \phi_{k_1}(\tau_1)\phi_{k_2}(\tau_1)\phi_{k_3}(\tau_2) \times \langle \sigma_{k_3}(\tau_1)\sigma_{k_3}(\tau_2)\rangle \longrightarrow \left(\frac{k_3}{k_1}\right)^{\pm\nu} P_s(\cos\theta)$$

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

squeezed bispectrum: a discovery channel





Chen, Chua, Guo, Wang, ZZX, Xie,
JCAP 1805 (2018) 049

Lee, Baumann, Pimentel,
JHEP 1612 (2016) 040

"in-in formalism"

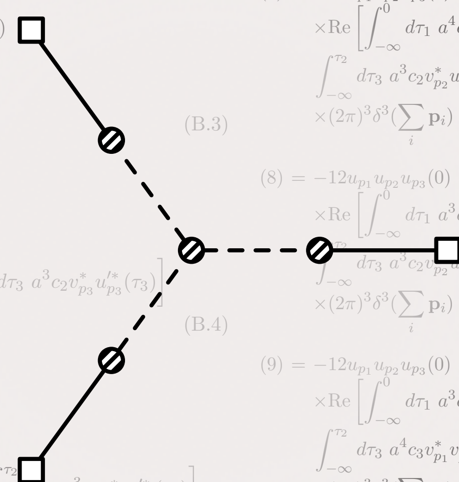
$$
\begin{aligned}
(1) =& -12u^*_{p_1}u_{p_2}u_{p_3}(0)\\
&\times\mathrm{Re}\Big[\int_{-\infty}^{0} d\tilde\tau_1\, a^3c_2v^*_{p_1}u'_{p_1}(\tilde\tau_1)\int_{-\infty}^{\tilde\tau_1} d\tilde\tau_2\, a^4c_3v_{p_1}v_{p_2}v_{p_3}(\tilde\tau_2)\\
&\times\int_{-\infty}^{0} d\tau_1\, a^3c_2v^*_{p_2}u'^*_{p_2}(\tau_1)\int_{-\infty}^{\tau_1}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

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

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

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

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



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

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

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

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

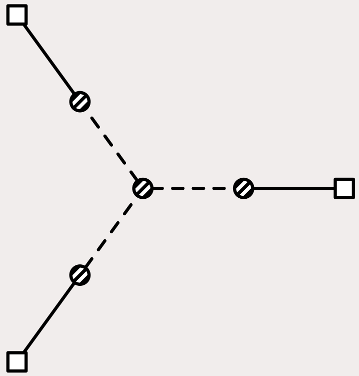
$$
\begin{aligned}
(10) =& -12u_{p_1}u_{p_2}u_{p_3}(0)\\
&\times\mathrm{Re}\Big[\int_{-\infty}^{0} d\tau_1\, a^3c_2v_{p_1}u'^*_{p_1}(\tau_1)\int_{-\infty}^{\tau_1} d\tau_2\, a^3c_2v_{p_2}u'^*_{p_2}(\tau_2)\\
&\int_{-\infty}^{\tau_2} d\tau_3\, a^3c_2v_{p_3}u'^*_{p_3}(\tau_3)\int_{-\infty}^{\tau_3} d\tau_4\,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

“in-in formalism”

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

“Decorated” Feynman diagrams

$$\frac{\pi^3\lambda_2^3\lambda_3}{256Hk_2^3k_3^3}\,\mathrm{Im}\int_0^\infty \frac{\mathrm{d}z}{z^4} I_+(z)I_+(\frac{k_2}{k_1}z)I_+(\frac{k_3}{k_1}z)$$

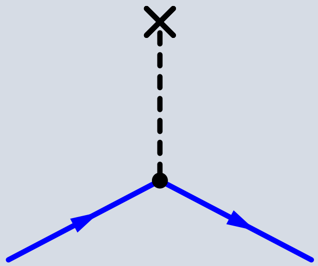


“Schwinger-Keldysh diagrammatics”

Chen, Wang, ZZX, JCAP 1712 (2017) 006 [arXiv:1703.10166]

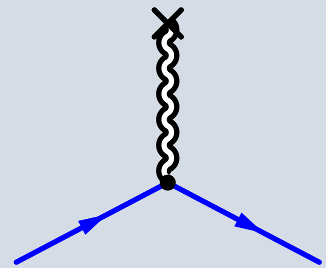
— A path-integral-based, particle-physicist-friendly review

SM spectrum



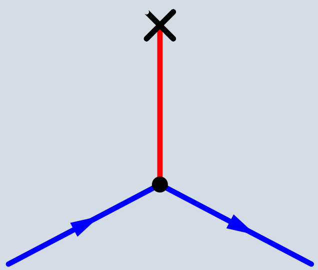
inflaton bg.

$(\partial_\mu \phi)^2 \mathbf{H}^\dagger \mathbf{H}$

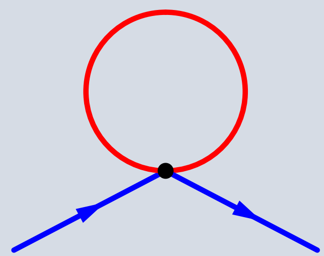


gravity bg.

$R\mathbf{H}^\dagger \mathbf{H}$



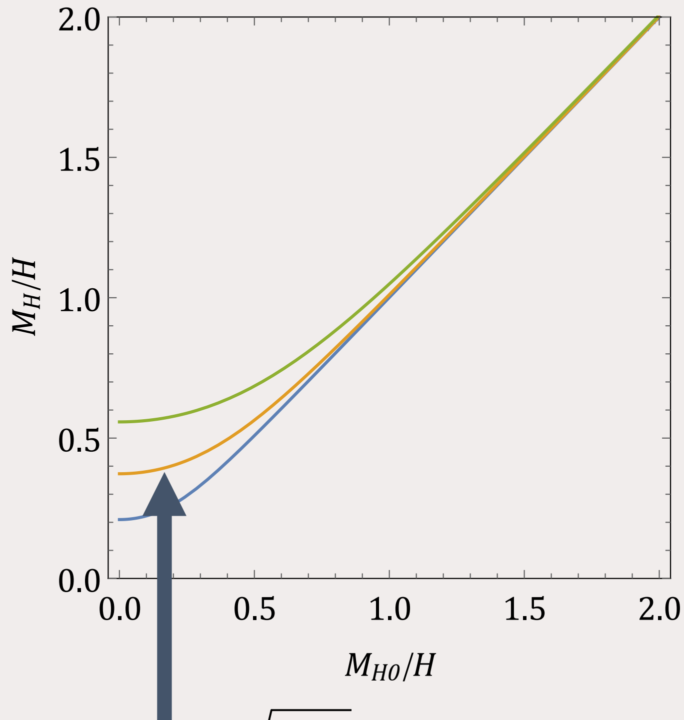
Higgs bg.
EWSB



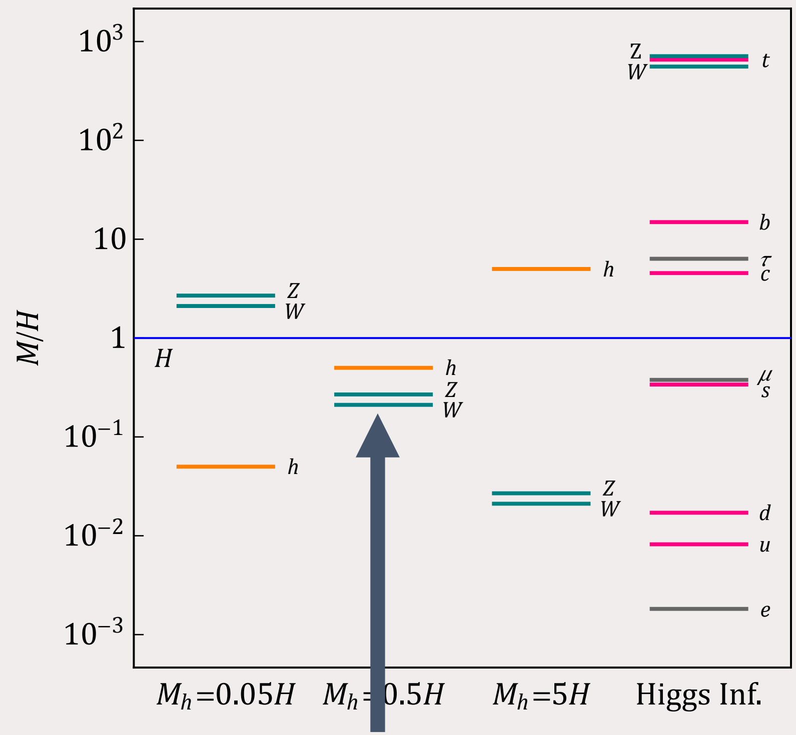
“thermal” bg.

Chen, Wang, ZZX, JHEP 1608 (2016) 051

SM spectrum



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



$$\delta m_A^2 = \frac{3e^2H^4}{4\pi^2m^2}$$

Chen, Wang, ZZX, JHEP 1704 (2017) 058

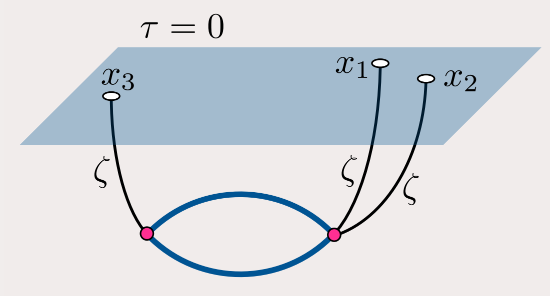
Chen, Wang, ZZX, PRL 118 (2017) 261302

SM signatures

Without EWSB, always from loops

$$\mathscr{L} \supset -f_H(X)\mathbf{H}^\dagger\mathbf{H} - f_{DH}(X)|\mathrm{D}_\mu\mathbf{H}|^2$$

$$X \equiv (\partial_\mu\phi)^2$$



$$S_H = \left[\frac{f'_H(X_0)}{1+f_{DH}(X_0)}\right]^2 \frac{\dot\phi_0^2}{2\pi^4}\left[C_H(\mu_h)\Big(\frac{k_L}{2k_S}\Big)^{2-2\mu_h} + (\mu_h \to -\mu_h)\right]$$

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

At most O(1), with tuning

Consistency relation

Chen, Wang, ZZX, PRL 118 (2017) 261302
Chen, Wang, ZZX, JHEP 1704 (2017) 058

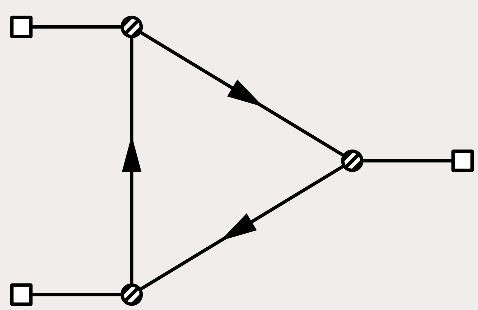
inflaton background as a chemical potential

Heavy neutrino

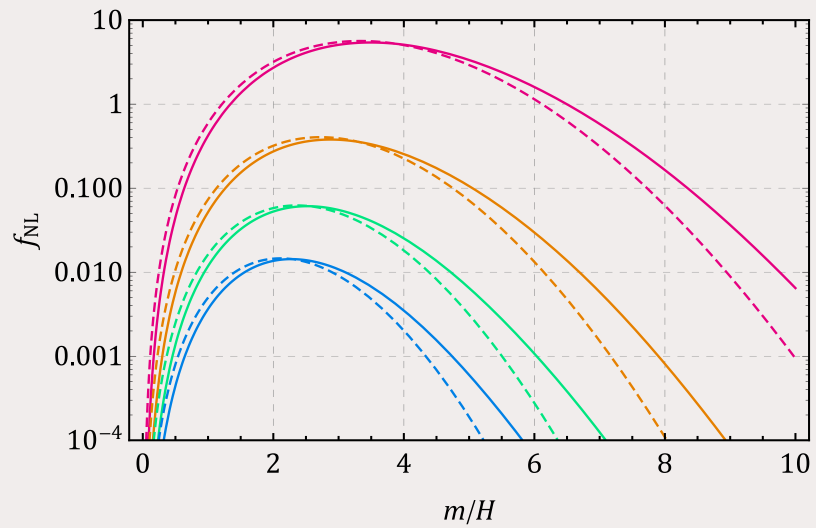
$$\sqrt{-g}\left[N^\dagger \mathrm{i}\bar\sigma^\mu \mathrm{D}_\mu N - \frac{1}{2}m\big(NN + \mathrm{h.c.}\big) - \frac{1}{\Lambda}(\partial_\mu\phi)N^\dagger\bar\sigma^\mu N\right]$$

$$\widetilde{N}^\dagger \mathrm{i}\bar{\not\partial}\widetilde{N} - \frac{1}{2}am(\widetilde{N}\widetilde{N} + \mathrm{c.c.}) - a\lambda\widetilde{N}^\dagger\bar\sigma^0\widetilde{N} \qquad \lambda = \frac{\dot\phi_0}{\Lambda}$$

enhanced loops from particle production



Chen, Wang, ZZX, 1805.02656



more possibilities

CP violation?

SYMMETRY BREAKING

Very low scale inflation

EWSB

"Heavy-lifting senario"

Higgs inflation

Kumar, Sundrum, 1711.03988

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

& MANY MORE

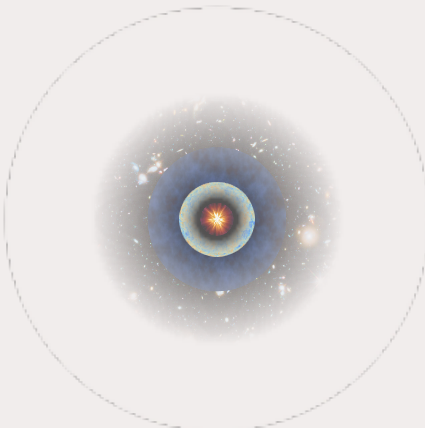
Maldacena, Pimentel, 1104.2846

String excitations?

Strongly coupled theory

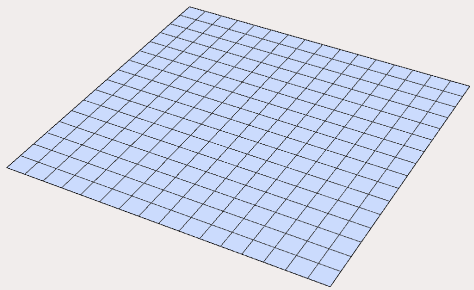
An et al., 1706.09971, 1711.02667

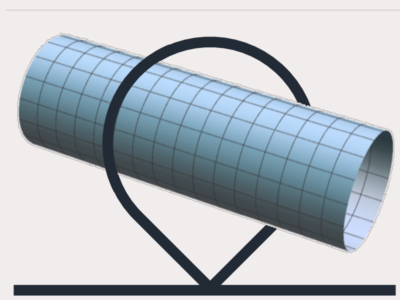
Iyer et al., 1710.03054



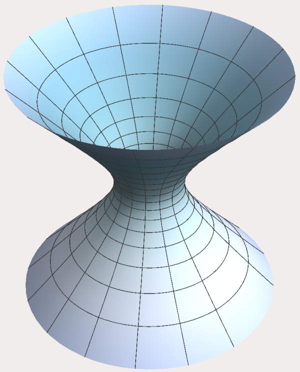
THANK YOU

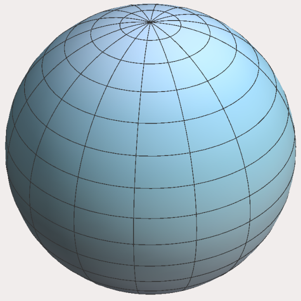
“thermal” background





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



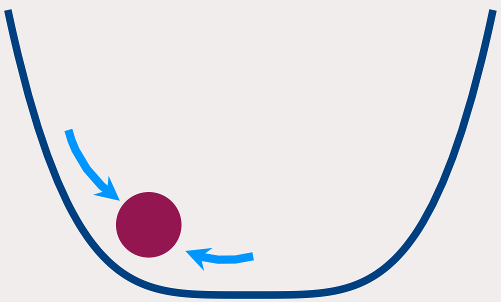


$$m^2 \propto \sqrt{\lambda} T^2$$

IR-enhanced loop mass

Classical rolling-down

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

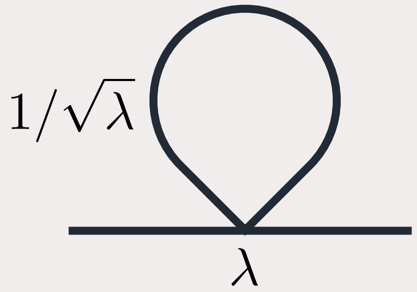


Quantum fluctuation $\langle\phi^2\rangle \sim H^3 t$

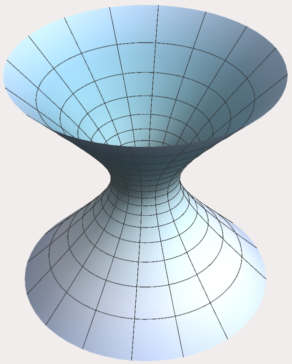
Equilibrium reached at $t \sim (\sqrt{\lambda}H)^{-1}$

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

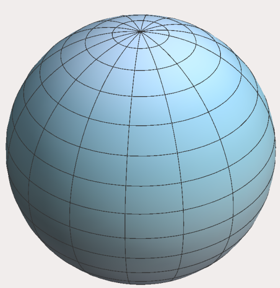
$$\Rightarrow \quad m^2 \sim \lambda\langle\phi^2\rangle \sim \sqrt{\lambda}H^2$$



fun with spherical harmonics



Wick rotation



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

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

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

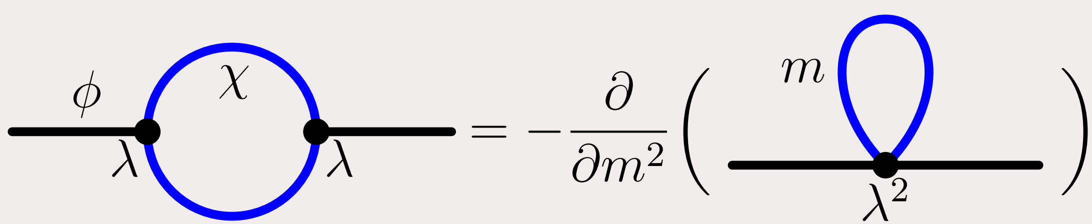
$$\lambda_L = L(L+d) + (m/H)^2$$

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

fun with spherical harmonics

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

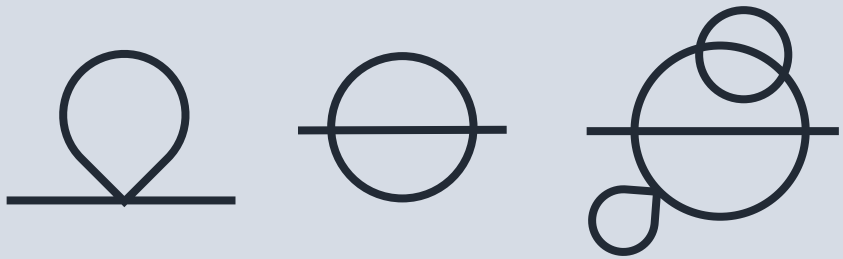
$$= \sum_{L} \int_{x} \frac{1}{\lambda_L^2} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x) = -\frac{\partial}{\partial m^2} \int_x G(x,x)$$



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



$$\cdots \quad \propto \sqrt{\lambda}$$

The zero-mode path integral to all orders

non-vanishing in the classically massless limit

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

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Chen, Wang, ZZX, 1612.08122