Dark Matter as a Portal to New Physics

February 1(Mon.) ~ 5(Fri.), 2021
Online

apctp
아시아태평양이론물리센터
asia pacific center for theoretical physics

Recent progress in cosmological collider physics

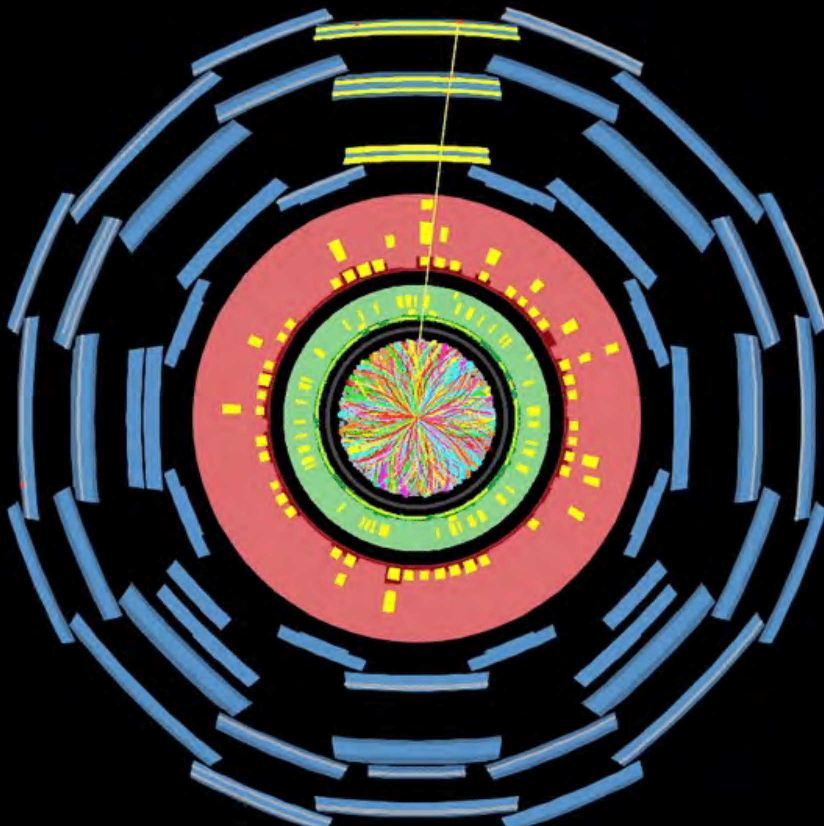
Zhong-Zhi Xianyu (Tsinghua University)

Feb 5, 2021

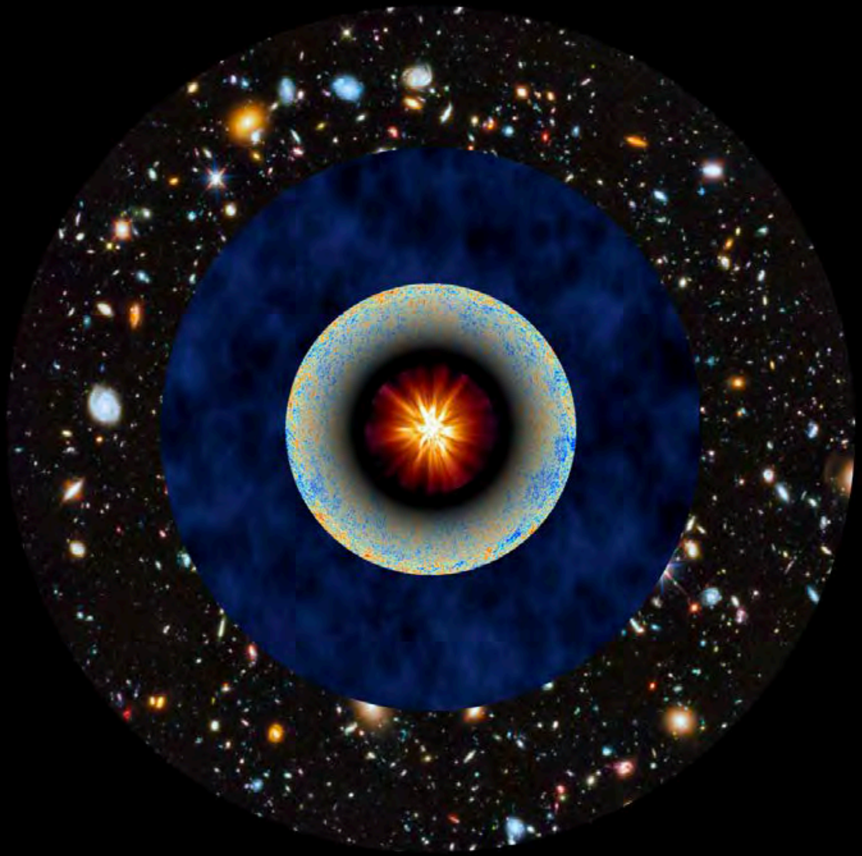
w/ Xingang Chen, Tao Liu, Shiyun Lu,
Xi Tong, Yi Wang, Liantao Wang

JHEP 08 (2016) 051; PRL 118 (2017) 261302; JHEP 04 (2017) 058; JCAP 12 (2017) 006; JCAP 05 (2018) 049; JHEP 09 (2018) 022; JHEP 02 (2020) 011; JHEP 04 (2020) 189; JHEP 02 (2020) 044; JHEP 11 (2020) 082

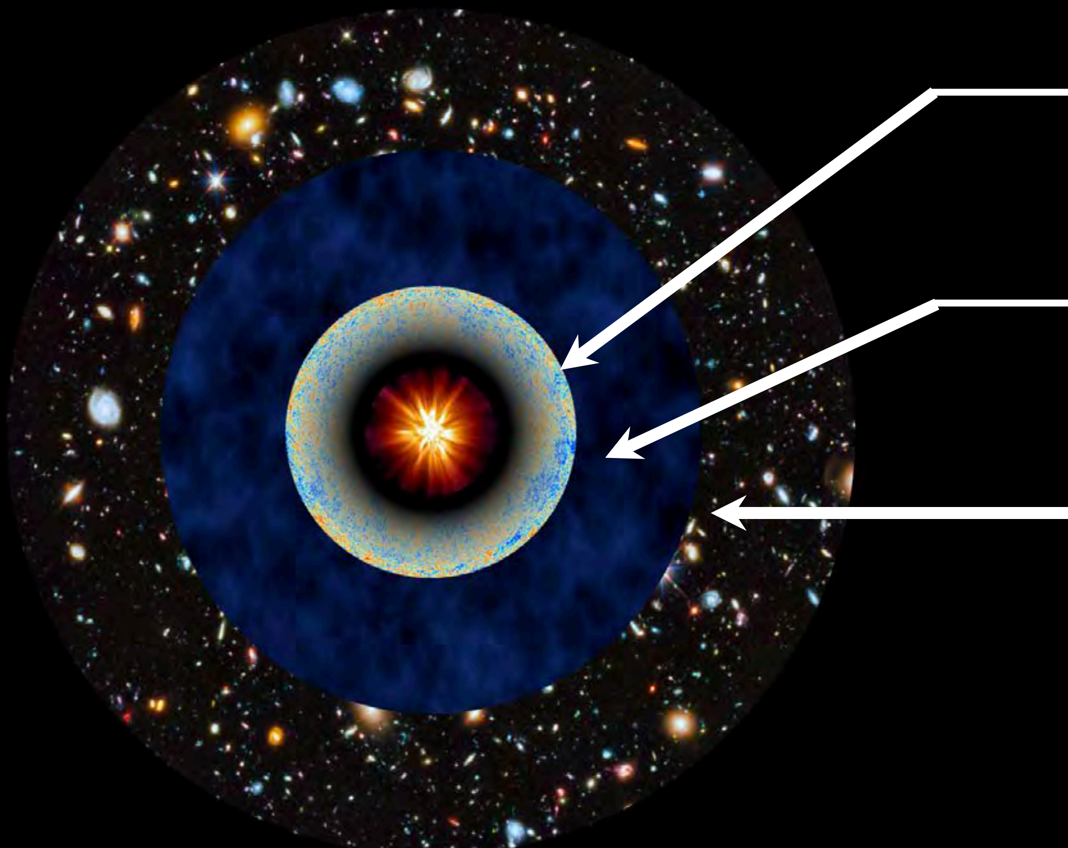
The APCTP is supported by the Korean Government through the Science and Technology Promotion Fund and Lottery Fund and strives to maximise social value through its various activities.
아시아태평양이론물리센터는 정부의 과학기술진흥기금 및 복권기금 지원으로 사회적 가치 제고에 힘쓰고 있습니다.



Large Hadron Collider
ATLAS detector



Cosmological Collider
The universe



photon decoupling

CMB

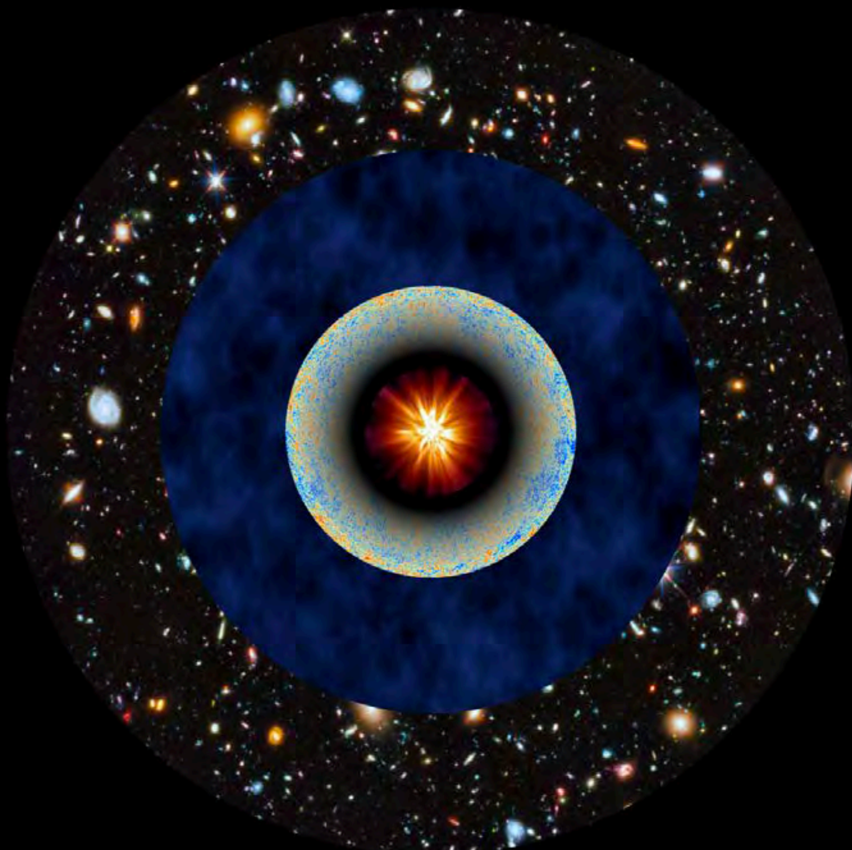
dark ages

21cm tomography

galaxies formed

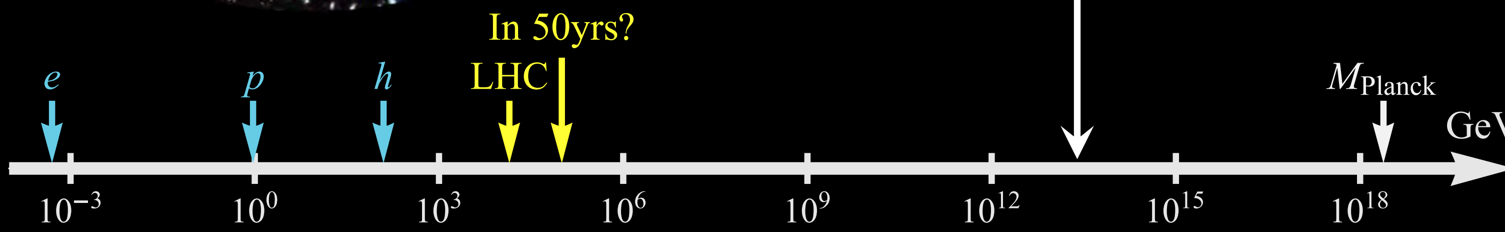
LSS survey

Gravitational waves

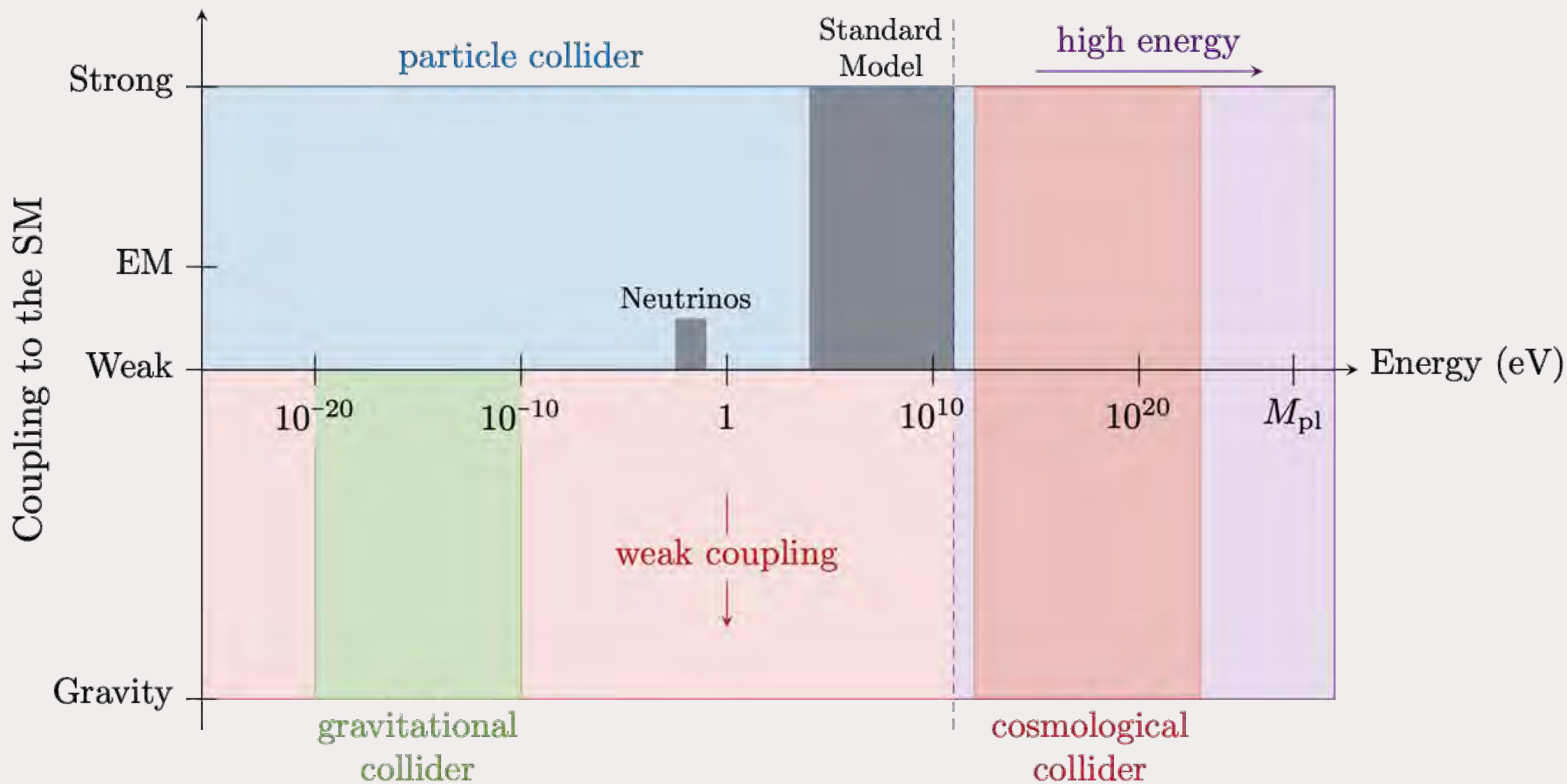


Cosmological Collider

The universe



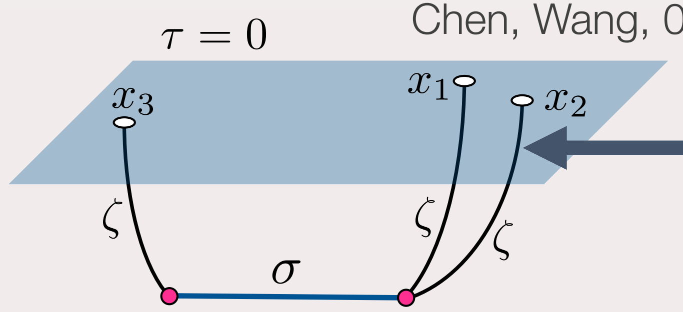
In connection with DM



Baumann, Chia, Porto, Stout, 1912.04932

Basic picture

Chen, Wang, 0911.3380; Arkani-Hamed, Maldacena, 1503.08043



massive mode

long-lived mode ζ

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

$$\langle\zeta^2\rangle' \equiv \frac{2\pi^2}{k^3}P_\zeta(k)$$

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

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

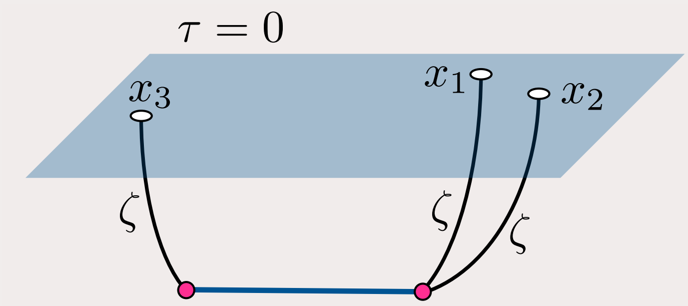
$$\sim \frac{H^2}{4\pi k^3}\left[\Gamma^2(-\nu)\left(\frac{k^2\tau_1\tau_2}{4}\right)^{3/2+\nu} + (\nu\to-\nu)\right] + \text{local} \qquad \nu = \sqrt{\frac{9}{4}-\frac{m^2}{H^2}}$$

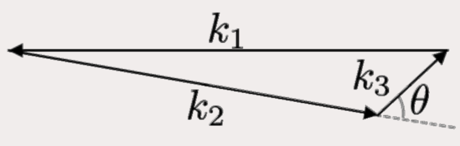
Boltzmann factor $\propto e^{-\pi m/H}$

comoving dilution

EFT $\propto 1/m$

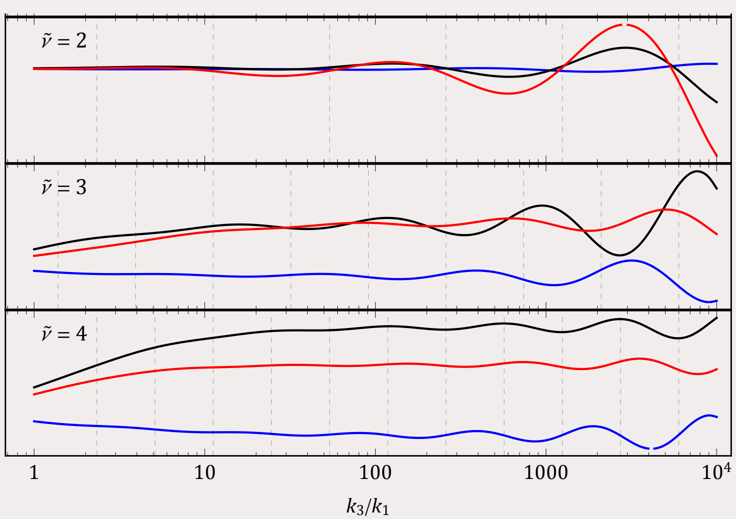
Basic picture



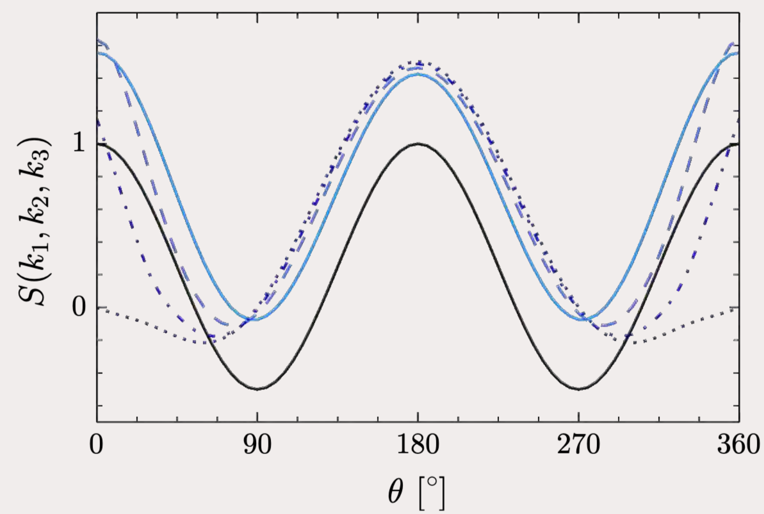


$$S(\mathbf{k}_1, \mathbf{k}_3) = A(\lambda, m)\left(\frac{k_3}{k_1}\right)^{1/2\pm\nu} P_s(\cos\theta)$$

$$\nu = \begin{cases} \sqrt{\dfrac{9}{4} - \dfrac{m^2}{H^2}} & s = 0 \\ \sqrt{\left(s - \dfrac{1}{2}\right)^2 - \dfrac{m^2}{H^2}} & s \neq 0 \end{cases}$$



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

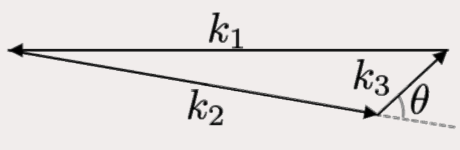


Lee, Baumann, Pimentel, 1607.03735

Confront with observation

"non-Gaussianity"

$$f_{\rm NL} \simeq |S(\mathbf{k}_1, \mathbf{k}_3)|$$



$$S(\mathbf{k}_1, \mathbf{k}_3) = A(\lambda, m)\left(\frac{k_3}{k_1}\right)^{1/2\pm\nu} P_s(\cos\theta)$$

$$\nu = \begin{cases} \sqrt{\dfrac{9}{4} - \dfrac{m^2}{H^2}} & s = 0 \\ \sqrt{\left(s - \dfrac{1}{2}\right)^2 - \dfrac{m^2}{H^2}} & s \neq 0 \end{cases}$$

Planck 2018

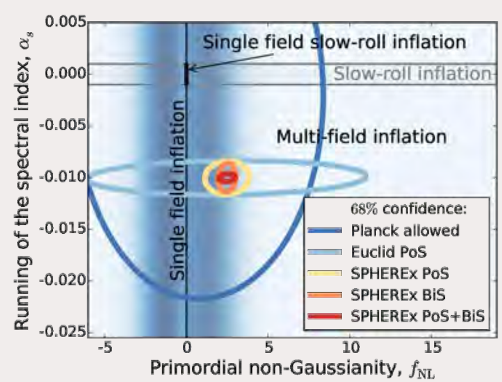
1905.05697

$$f_{\rm NL}^{\rm (local)} = -0.9 \pm 5.1$$

$$f_{\rm NL}^{\rm (equil)} = -26 \pm 47$$

$$f_{\rm NL}^{\rm (ortho)} = -38 \pm 24$$

O(1) in ~10yrs?



SPHEREx, 1412.4872

O(0.01) ultimately

21cm tomography

Meerburg, Muñoz, Ali-Haïmoud, Kamionkowski, 1506.04152; Münchmeyer, Muñoz, Chen, 1610.06559; Dizgah, Lee, Muñoz, Dvorkin 1801.07265;

Caveats

$$S(\mathbf{k}_1, \mathbf{k}_3) = A(\lambda, m)\left(\frac{k_3}{k_1}\right)^{1/2\pm\nu} P_s(\cos\theta)$$

Oscillations do not necessarily tell the mass

mass corrections: thermal, susy, background, many free parameters!

Angular dependence does not necessarily tell the spin

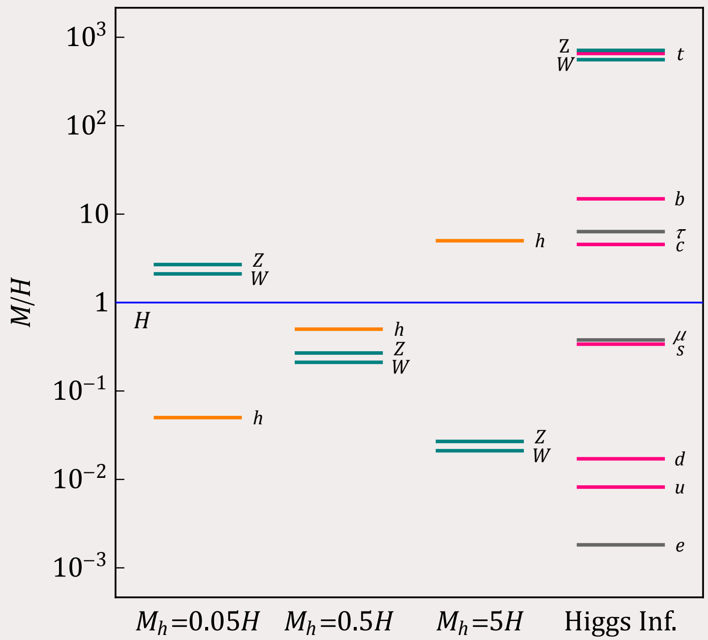
Loop, derivative couplings

The signal size is usually too small to be visible

and very model dependent

Caveats

$$S(\mathbf{k}_1, \mathbf{k}_3) = A(\lambda, m)\left(\frac{k_3}{k_1}\right)^{1/2\pm\nu} P_s(\cos\theta)$$



Example: "SM background"

"Thermal" mass ~ Hubble

All in loops: spin info lost

Signal size: tiny unless tuned

Xingang Chen, Yi Wang, ZZX, 1604.07841, 1610.06597, 1612.08122

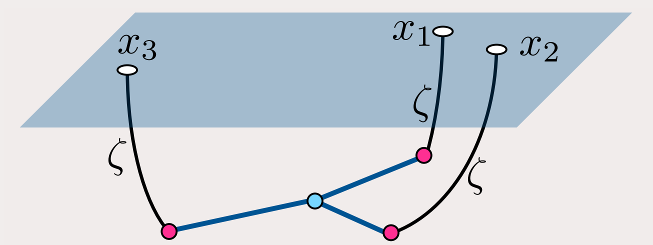
Signal size

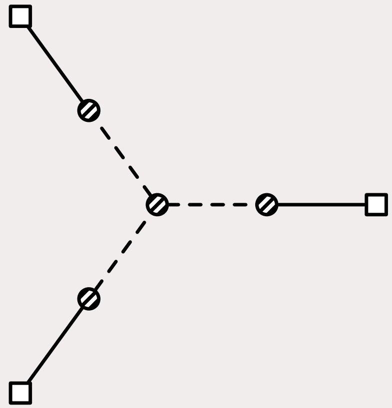
L. Wang, ZZX, 1910.12876

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

In the unit of Hubble: $\zeta = -\frac{H}{\dot\phi_0}\delta\phi = -2\pi P_\zeta^{1/2}\delta\phi$

$$f_{\rm NL} \sim (2\pi P_\zeta^{1/2})^{-1}\langle\delta\phi^3\rangle$$
$$\sim 3.6\times 10^3 \cdot \text{(vertices)} \cdot \text{(propagators)}$$





Signal size

Almost no-go in generic "minimal" scenarios

L. Wang, ZZX, 1910.12876

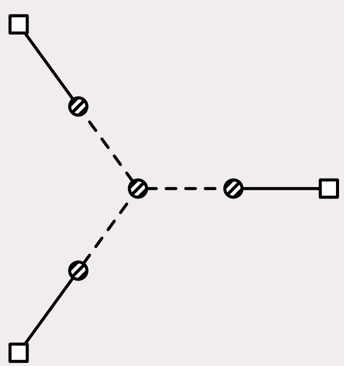
1. Standard slow-roll inflation
2. Scale invariance (up to slow-roll correction)
3. No further spacetime symmetry breaking
4. Dimensionless parameter being O(1)
5. No tree-level tuning

Signal size

$$\frac{1}{\Lambda^2}(\partial_\mu\phi)^2\sigma^2 \longrightarrow \frac{\dot\phi_0^2}{\Lambda^2}\sim H^2 \longrightarrow \Lambda\simeq 3600H$$

No Boltzmann supression $\qquad \dot\phi_0 \simeq (60H)^2$

$$\mathscr{L} = \frac{1}{2}(\partial_\mu\sigma)^2 - \frac{1}{2}m^2\sigma^2 - \lambda\sigma^4 + \frac{1}{\Lambda^2}(\partial_\mu\phi)^2\sigma^2$$



$$f_{\rm NL}\sim 3600\cdot\left(\frac{\dot\phi_0}{\Lambda^2}\langle\sigma\rangle\right)^3\cdot\lambda\langle\sigma\rangle\sim 10^{-7}\cdot\lambda\langle\sigma\rangle^4$$

QSFI: a very shallow potential is needed

$$\langle\sigma\rangle^2\sim H^2/\lambda \longrightarrow \lambda\langle\sigma\rangle^4\sim 1/\lambda \longrightarrow \lambda\lesssim 10^{-7}$$

$f_{\rm NL}\gtrsim 1$

dim-5 operators: the only exception

$$\frac{1}{\Lambda}(\partial_\mu\phi)\mathcal{J}^\mu \longrightarrow \frac{1}{\Lambda}\dot{\phi}_0\mathcal{N}$$

A new source of particle production

Not all chemical potentials work

$$(\omega \pm \mu)^2 = k^2 + m^2 \qquad (\partial_\mu\phi)\Phi^*\partial^\mu\Phi \qquad (\partial_\mu\phi)\bar{\Psi}\gamma^\mu\Psi$$

$$\omega^2 = (k \pm \mu)^2 + m^2 + \cdots \qquad (\partial_\mu\phi)\bar{\Psi}\gamma^\mu\gamma^5\Psi \qquad \phi F\widetilde{F}$$

$$\omega^2 = a^{-2}k_{\text{com}}^2 + \left[m^2 \pm 2\mu k_{\text{com}} a^{-1}(t) + \cdots\right]$$

Only parity-odd charge works

without breaking more symmetries

L. Wang, ZZX, 1910.12876

dim-5 operators: chemical potential

Fermion $(\partial_\mu\phi)\bar{\Psi}\gamma^\mu\gamma^5\Psi$

$$\omega^2 = (k\pm\mu)^2 + m^2 \longrightarrow e^{\mu/H}e^{-\sqrt{m^2+\mu^2}/H} \sim e^{-m^2/(\mu H)}$$

Probing heavy neutrinos Chen, Wang, ZZX, 1805.02656

New Higgs vacua Hook, Huang, Racco, 1907.10624, 1908.00019

Gauge boson $\phi F\widetilde{F}$

$$\omega^2 = k(k\pm 2\mu) + m^2 \longrightarrow e^{\mu/H}e^{-m/H}$$

Does not work by itself

Can see the effect w/ additional couplings L. Wang, ZZX, 2004.02887

CP-breaking in trispectrum Liu, Tong, Wang, ZZX, 1909.01819

Graviton: circularly polarized tensor mode

(e.g. in TB and EB)

Lue, Wang, Kamionkowski, astro-ph/9812088

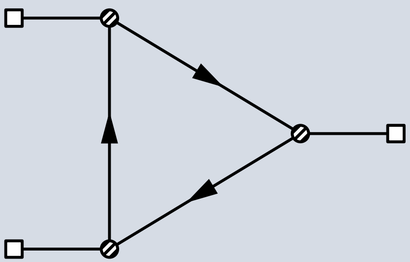
Probing heavy neutrinos

A rare chance to see right-handed neutrinos

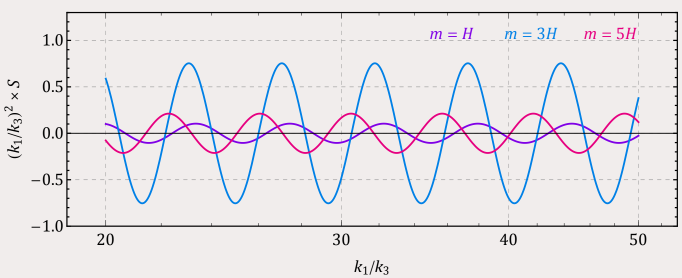
$$m \sim 10^{13}\text{GeV} \sim H$$

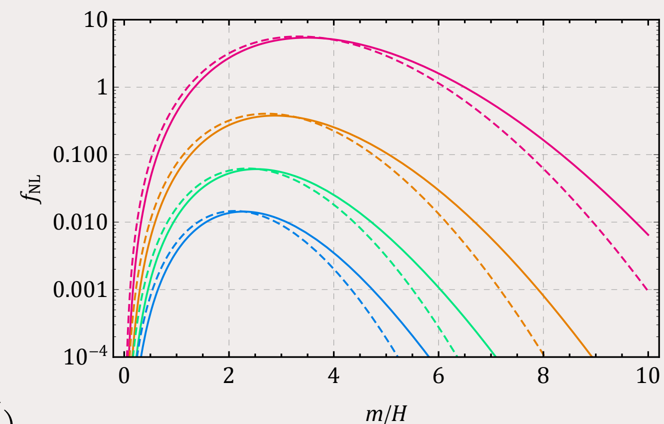
Inflaton background as a neutrino source

$$\frac{1}{\Lambda}(\partial_\mu \phi) N^\dagger \bar{\sigma}^\mu N \longrightarrow \frac{\dot{\phi}}{\Lambda} N^\dagger \bar{\sigma}^0 N$$



$$\lambda = \frac{\dot{\phi}_0}{\Lambda} \qquad \mu = \sqrt{m^2 + \lambda^2}$$

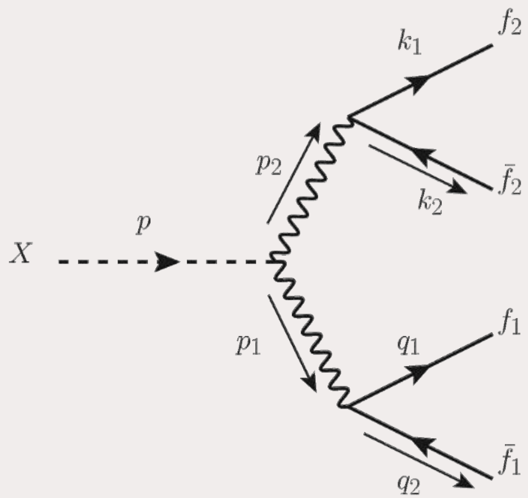




$$f_{NL}(\text{clock}) \simeq \frac{3\pi^2}{2} P_\zeta \widetilde{\lambda}^5 \widetilde{m}^3 e^{-5\pi \widetilde{m}^2/(4\widetilde{\lambda})}$$

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

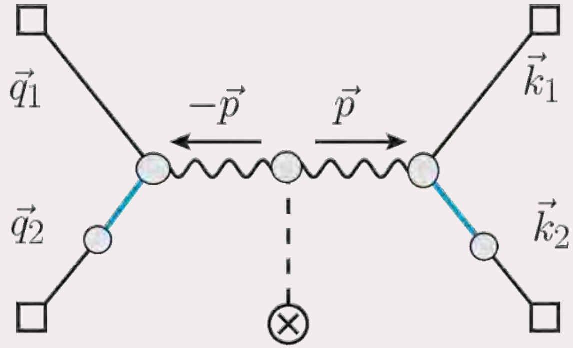
CP violation

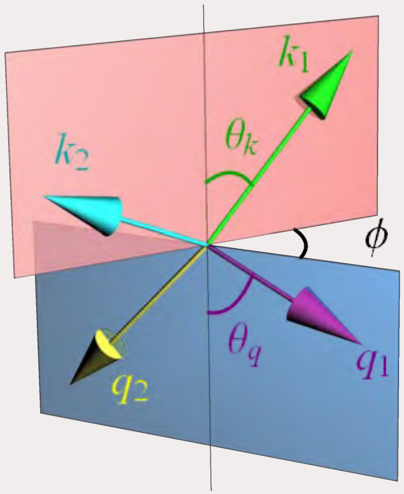


$$\mathcal{A}(X \to VV) = \mathcal{F}_1 \epsilon_1^* \cdot \epsilon_2^* + \frac{\mathcal{F}_2}{m_X^2}(\epsilon_1^* \cdot p)(\epsilon_2^* \cdot p) + i\frac{\mathcal{F}_3}{m_X^2}\epsilon^{\mu\nu\rho\sigma}p_\mu P_\nu \epsilon_{1\rho}^* \epsilon_{2\sigma}^*$$

Four-particle final state needed

Trispectrum





Liu, Tong, Wang, ZZX, 1909.01819

CP violation

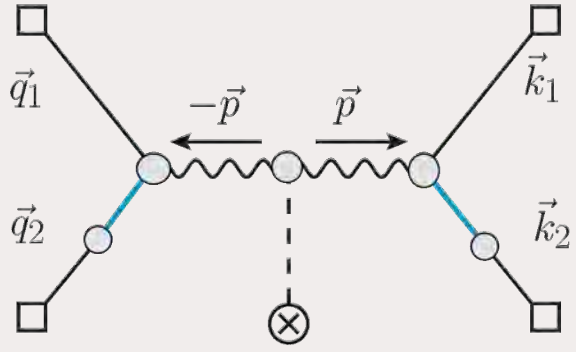
$$\Delta\mathscr{L} = \frac{c_1}{\Lambda}\partial_\mu\phi(\mathcal{H}^\dagger D^\mu \mathcal{H}) + \frac{c_2}{\Lambda^2}(\partial\phi)^2\mathcal{H}^\dagger\mathcal{H} - \frac{c_0}{4}\theta(t) Z_{\mu\nu}Z_{\rho\sigma}\mathcal{E}^{\mu\nu\rho\sigma}$$

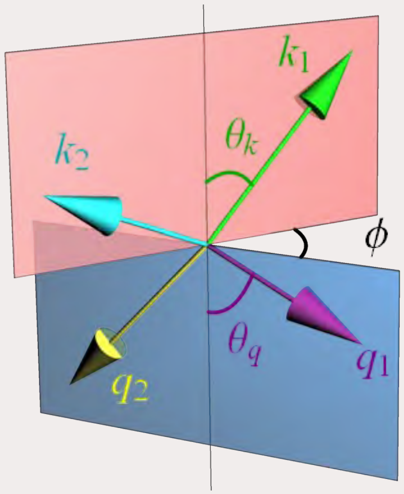
Two types of external legs needed

Odd-angular dependence in imaginary part

No local CP-odd correlations in dS limit

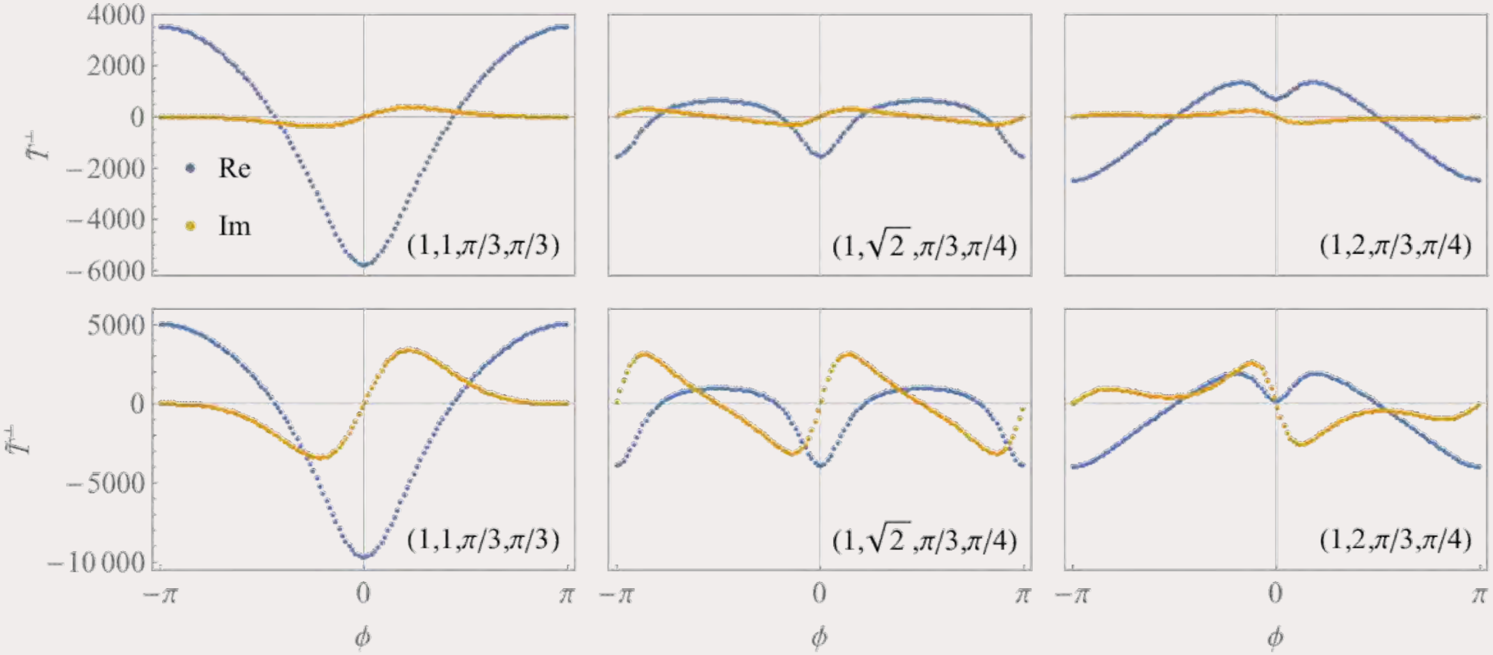
Chemical potential helps

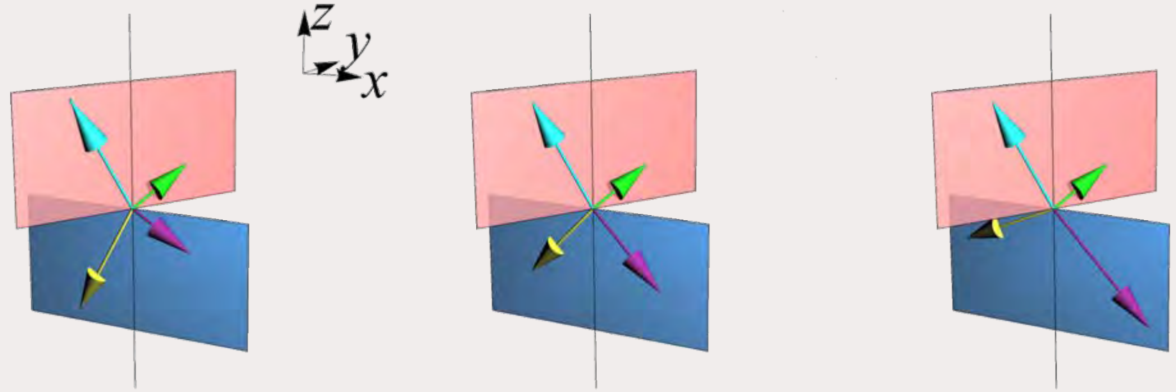




Liu, Tong, Wang, ZZX, 1909.01819

CP violation





Liu, Tong, Wang, ZZX, 1909.01819

Signal size

Beyond the “minimal” scenario

1. Standard slow-roll inflation
2. Scale invariance (up to slow-roll correction)
3. No further spacetime symmetry breaking
4. Dimensionless parameter being O(1)
5. No (tree-level) tuning

Signal size

Beyond the “minimal” scenario

~~1. Standard slow-roll inflation~~

Providing vacuum energy to expand; Generating inhomogeneities

Can separate

Vacuum energy from inflaton / fluctuations from a different source

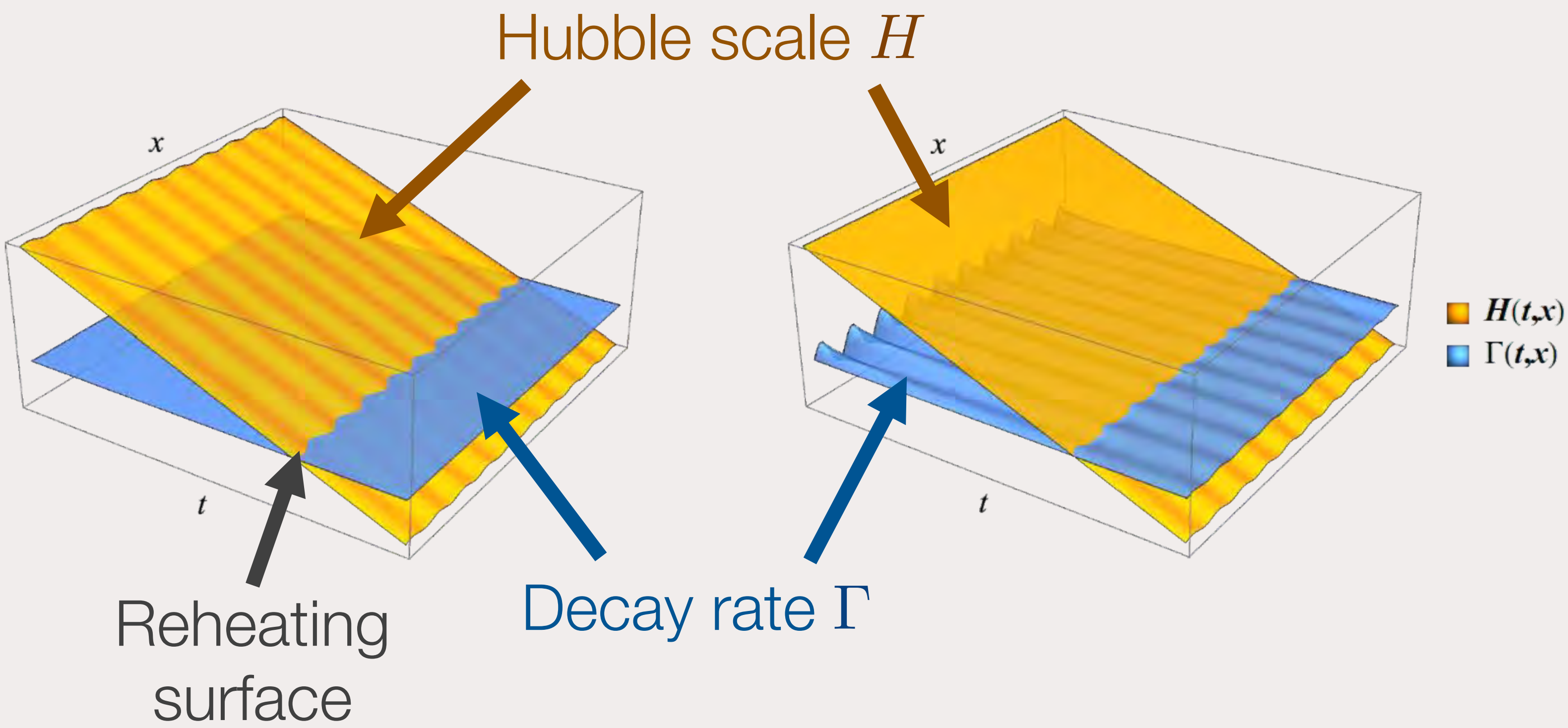
Modulated reheating (Dvali, Gruzinov, Zaldarriaga, astro-ph/0303591)

CHC: A cosmological Higgs collider Lu, Wang, ZZX, 1907.07390

Curvaton Kumar, Sundrum, 1908.11378

Modulated reheating

Standard inflation | Modulated reheating



Lu, Wang, ZZX, 1907.07390

Modulated reheating

$$\zeta(t_2,\mathbf{x}) = \zeta(t_1,\mathbf{x}) + \delta N(t_1,t_2,\mathbf{x})$$

$$\delta N(t_1,t_2,\mathbf{x}) \equiv N(t_1,t_2,\mathbf{x}) - \overline{N}(t_1,t_2,\mathbf{x})$$

Standard inflation

Modulated reheating

$$N(t_1,t_2;\mathbf{x}) = \int_{t_1}^{t_{\rm reh}} \mathrm{d}t\overline{H}(t) + \int_{t_{\rm reh}}^{t_2} \mathrm{d}t\overline{H}(t) = \frac{2}{3}\log\frac{t_{\rm reh}}{t_1} + \frac{1}{2}\log\frac{t_2}{t_{\rm reh}}$$

$H(t_{\rm reh}) = \Gamma$

matter

radiation

$$\delta N = \frac{1}{6}\frac{\delta t_{\rm reh}}{t_{\rm reh}} = -\frac{1}{6}\frac{\delta\Gamma}{\Gamma}$$

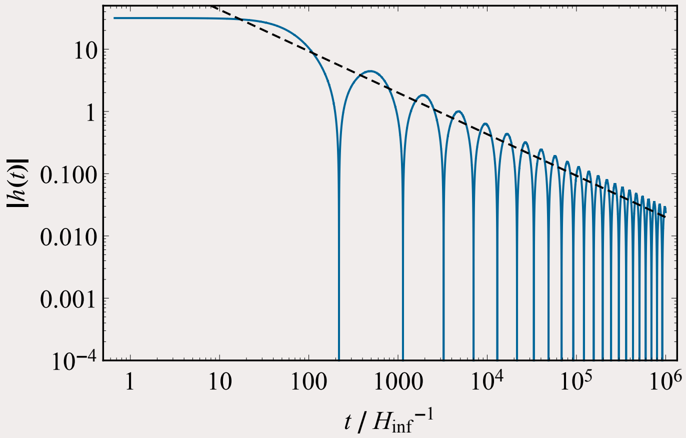
Can SM Higgs modulate the reheating?

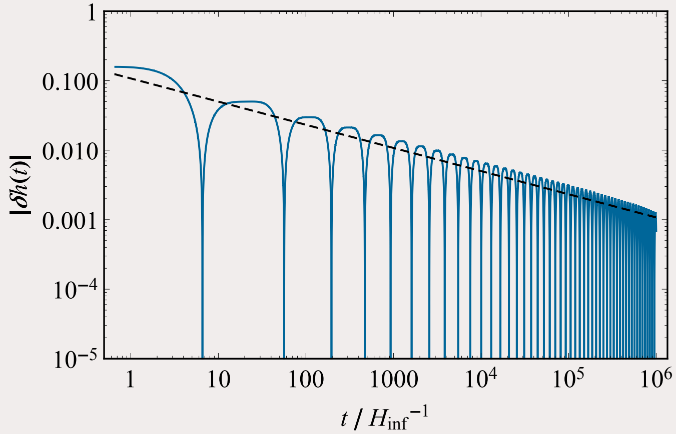
$$\Gamma(\phi \to \text{something}) \propto h^n \quad \rightarrow \quad \delta N \propto \delta\Gamma/\Gamma \propto \delta h/h$$

$$\mathcal{O} = \phi h \cdot \text{something}$$

$$\rho_h \sim \lambda h^4 \sim a^{-4} \sim t^{-8/3}$$

$$\Gamma(\phi \to \text{somthing}) \propto h^2 \propto t^{-4/3}$$





$$h_0(t) \sim \lambda^{-1/3} H_{\text{inf}} (H_{\text{inf}} t)^{-2/3}$$

$$\delta h(t) \sim \lambda^{-1/6} (H_{\text{inf}} t)^{-1/3} \delta h_{\text{ini}}$$

Can SM Higgs modulate the reheating?

The reheating should be faster than Higgs decay

Power-law dependence does not work; kinetic dependence

A solution: inflaton decays to Higgs-portal scalars

$$\Delta\mathscr{L} = -\frac{1}{2}(\partial_\mu S_i)^2 - \frac{1}{2}m_{S0}^2 S_i^2 - \alpha S_i^2 |\mathbf{H}|^2 + \frac{1}{\Lambda_S}(\partial_\mu \phi) S_i \partial^\mu S_i$$

$$\Gamma(\phi \to SS) = \frac{m_\phi^3}{16\pi\Lambda_S^2}\left(1 - \frac{4m_S^2}{m_\phi^2}\right)^{1/2} \qquad m_S^2(h_0) = m_{S0}^2 + \alpha h_0^2$$

$$\zeta = -\frac{1}{6}\frac{\delta\Gamma}{\Gamma} \simeq \frac{2\alpha h_0 \delta h}{3m_\phi^2}\bigg|_{t=t_{\rm reh}}$$

$$\Lambda_S \simeq \sqrt{\frac{N\alpha}{32\pi^2\lambda^{1/2}}P_\zeta^{-1/4}}\sqrt{m_\phi H_{\rm inf}}$$

S can be a DM candidate; thermally produced when α~1 and m_{S0}~10TeV

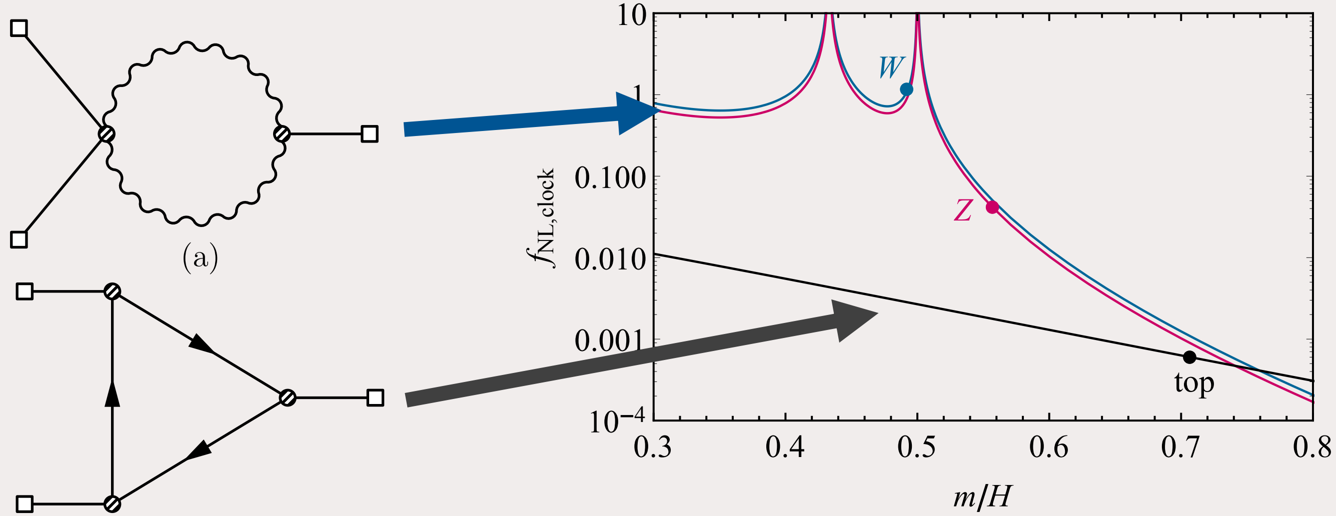
$$\alpha = 1,\ N = 10,\ m_\phi = 10 H_{\rm inf},\ \lambda \simeq 0.01 \qquad \Lambda_S \geq 266 H_{\rm inf}$$

A Cosmological Higgs Collider

Constraint from local non-G

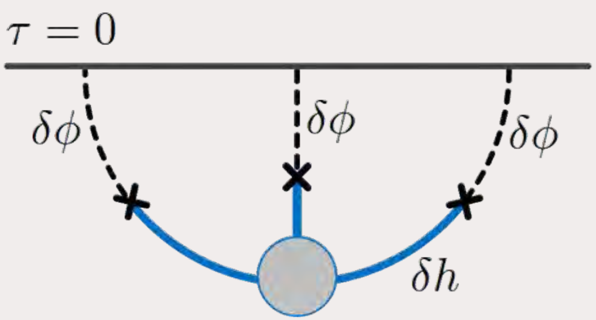
$$f_{\rm NL}(\text{local}) \sim -\mathcal{O}(1)\frac{R_h^3}{2\pi P_\zeta^{1/2}}\lambda N_e + \mathcal{O}(1)\frac{R_h^3}{(2\pi)^6 P_\zeta}\frac{2\alpha N}{(m_\phi/H_{\rm inf})^2}$$

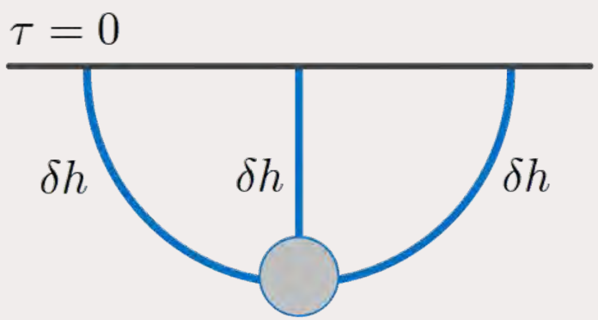
$$R_h \lesssim 0.14\left(\frac{\lambda}{0.01}\right)^{-1/3}\left(\frac{N_e}{50}\right)^{-1/3}$$



Lu, Wang, ZZX, 1907.07390

Inflaton collider vs. CHC





Inflaton collider

Inflaton-matter couplings
suppressed by cutoff Λ~60H
many free parameters

"CHC"

Higgs couplings
unsuppressed signals
less free parameters

Can be generalized to any isocurvature modes
a new playground of cosmological collider physics

More alternatives

Relieve the Boltzmann suppression by production mechanism at a higher scale

Breaking scale invariance

Resonance production of heavy particles /
Flauger, Mirbabayi, Senatore, Silverstein, 1606.00513

Breaking spacetime symmetry

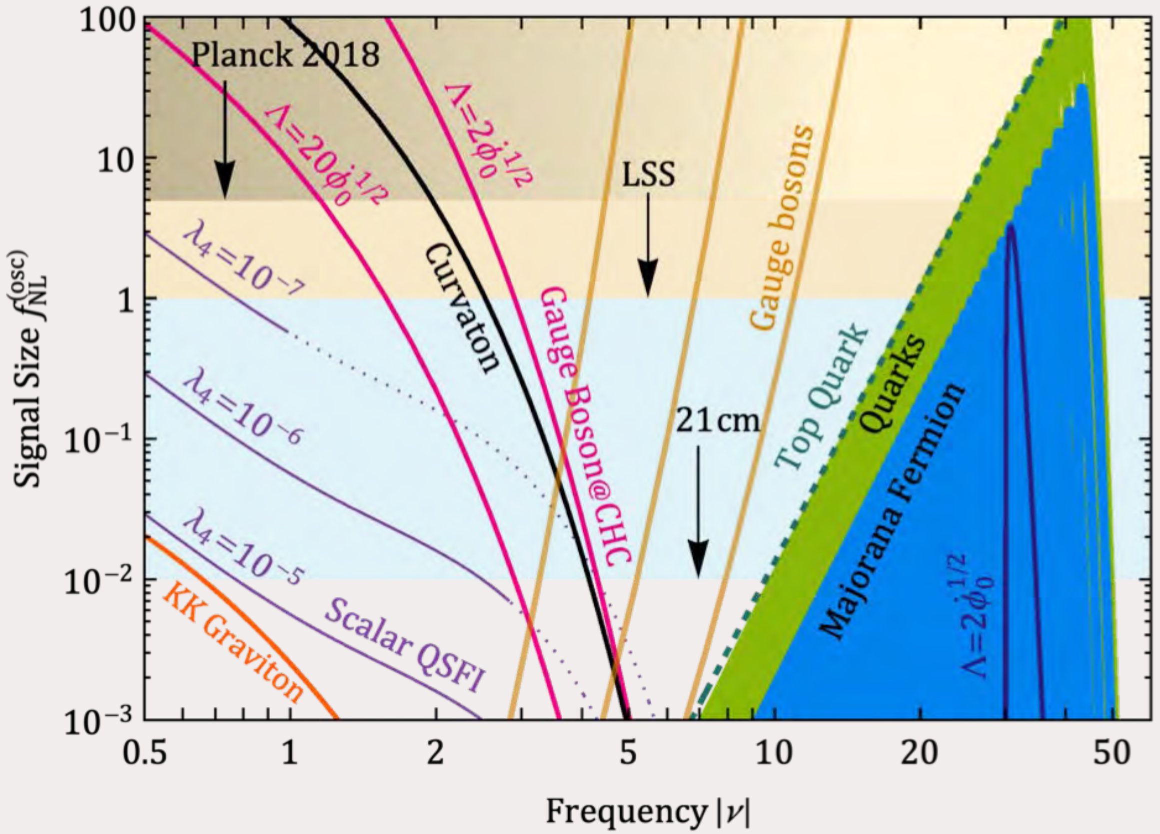
Schwinger production

Chua, Ding, Wang, Zhou 1810.09815

Warm inflation
Tong, Wang, Zhou, 1801.05688

DM isocurvature as a new channel of cosmological collider
Lingfeng Li, Tomohiro Nakama, Chon Man Sou, Yi Wang, Siyi Zhou,
1903.08842, 2002.01131

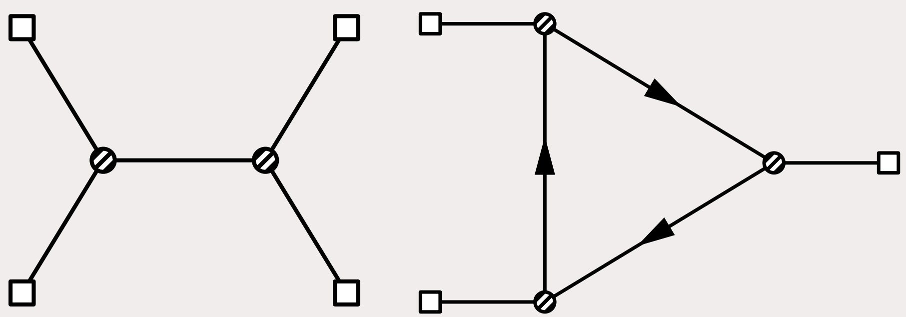
A status summary

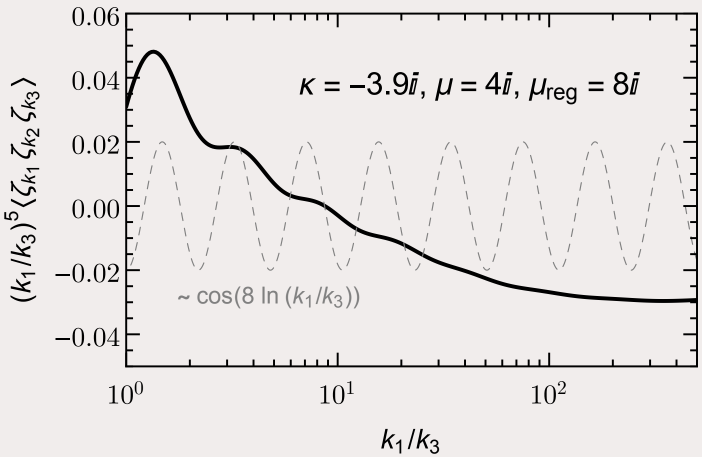


L. Wang, ZZX, 1910.12876, 2004.02887

Theory challenges

Calculating Feynman graphs in dS is difficult





Recent development in formal techniques

Conformal Bootstrap

Arkani-Hamed, Baumann, Joyce, Lee, Pimentel, 1811.00024, 1910.14051, 2005.04234

Mellin-Barnes representation

Sleight, Taronna, 1906.12302, 1907.01143

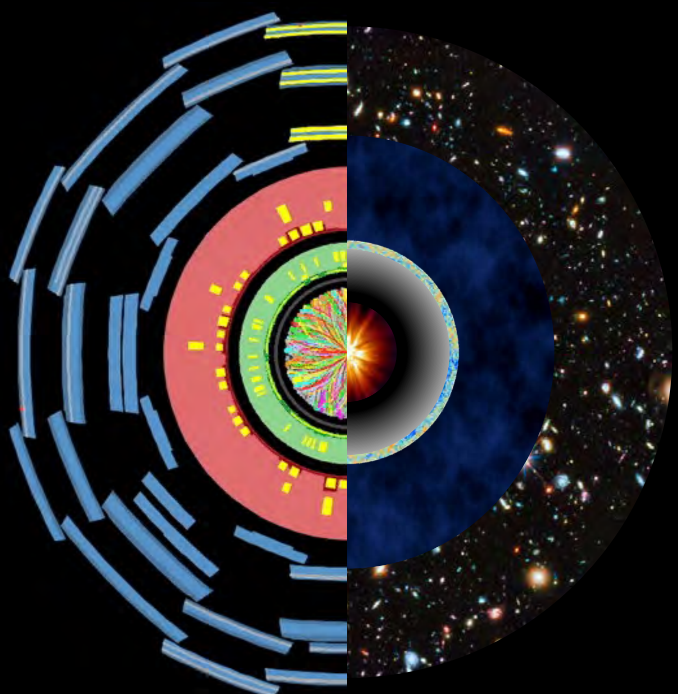
More pragmatic approaches

Schwinger-Keldysh diagrammatics

Chen, Wang, ZZX, 1703.10166

“brute force” computation

Wang, ZZX, Zhong, in progress



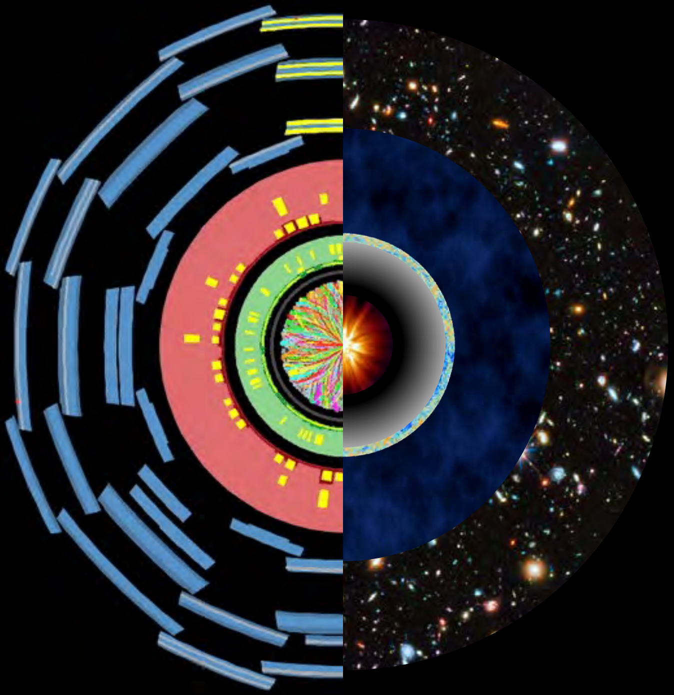
Take-home

Observational progress ahead

1 order of magnitude improvement in next decade / Can already test some interesting scenarios / another 1-2 orders ultimately, can reach gravity floor

Chance to do some real particle physics

More theoretical efforts called for / Not the sort of “1000 inflation models to fit 2 parameters n_s and r” thing



Thank you