Discovering New Particles with Cosmic Microwave Background: Cosmological Collider Primordial Non-Gausisanity

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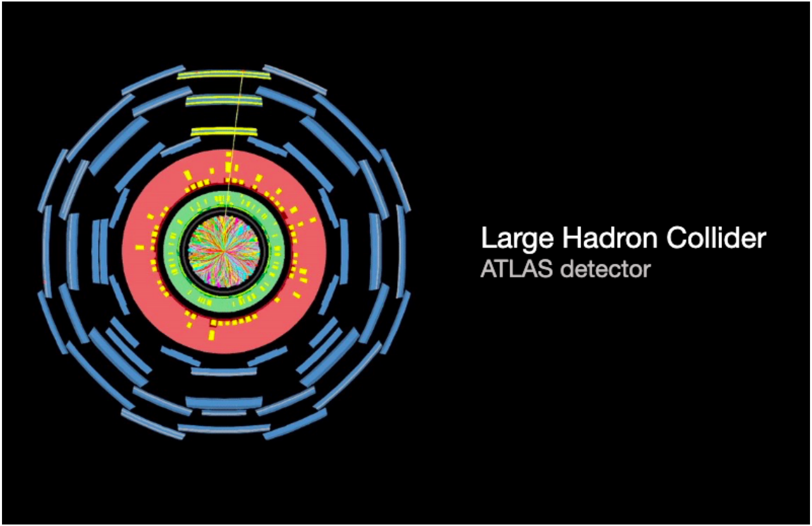
Based on JHEP 11 (2024) 009 (2408.07069) & 2606.XXXXX

Outline of the talk:

- Inflation & Primordial Non-gaussianities: cosmological collider.
- Imprints of SM and BSM Particles in cosmological collider
- Cosmological Collider in generic multi-field inflationary framework
- Cosmological Collider in Higgs-$\mathcal{R}^2$ Framework

Cosmological Collider: Introduction and Standard Model



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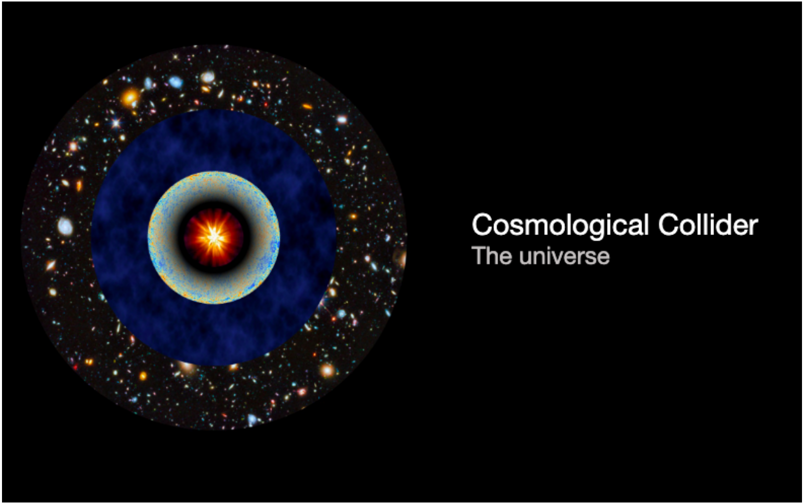

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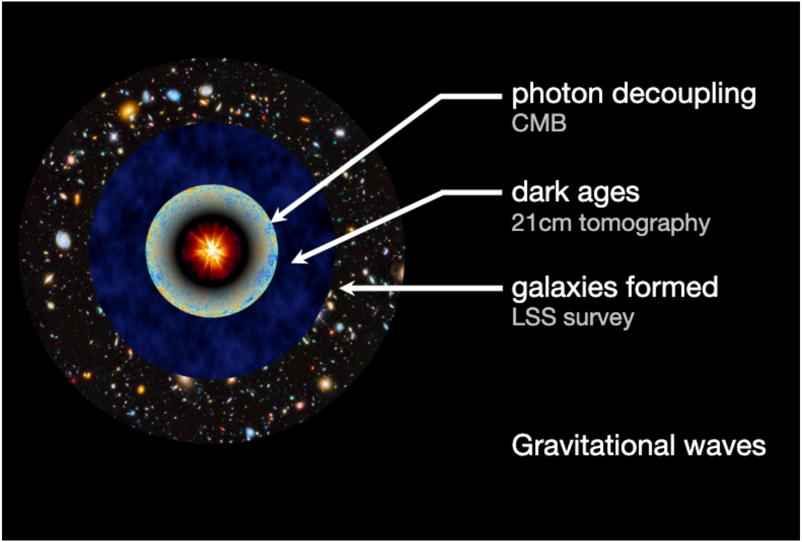

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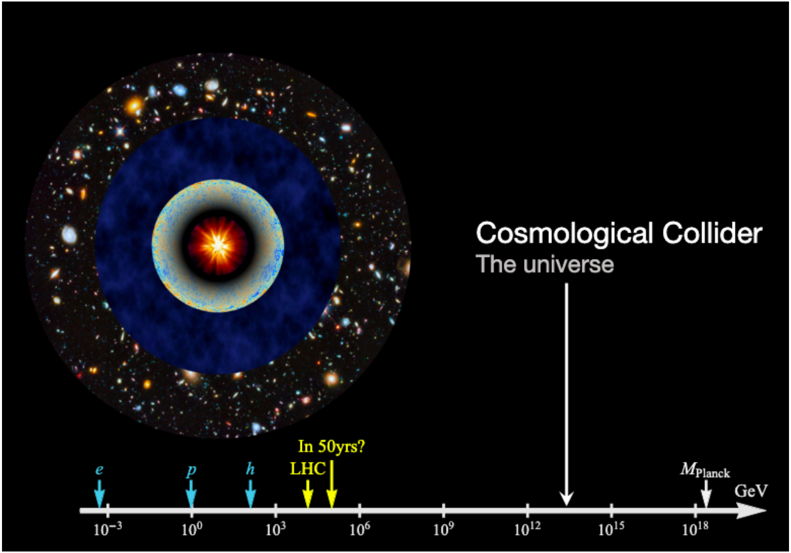
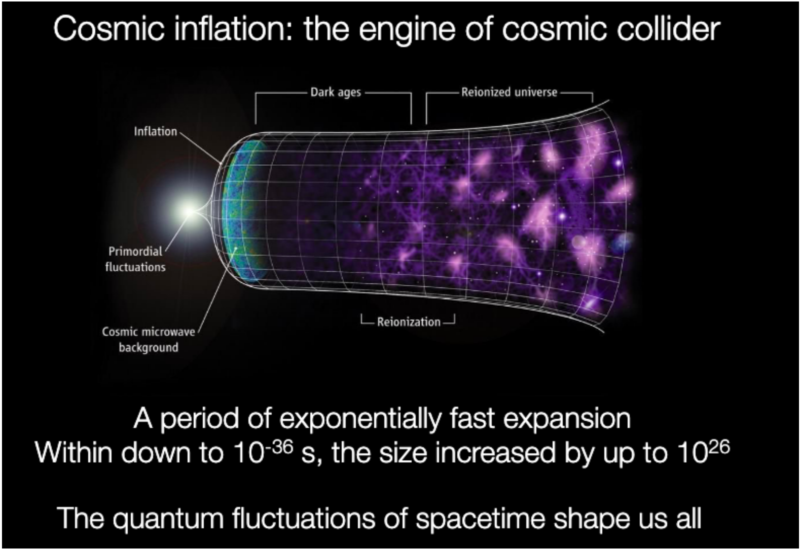


Cosmological Collider: Introduction and Standard Model

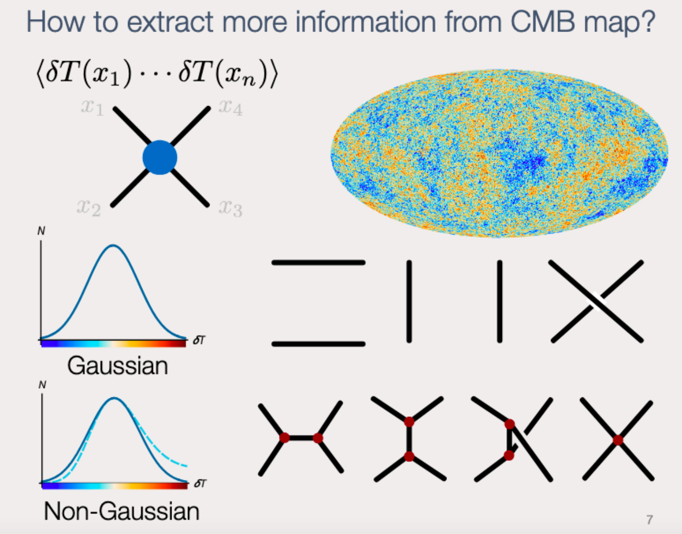


Cosmic inflation: the engine of cosmic collider

A period of exponentially fast expansion
Within down to 10^{-36} s, the size increased by up to 10^{26}

The quantum fluctuations of spacetime shape us all

Cosmological Collider: Introduction and Standard Model



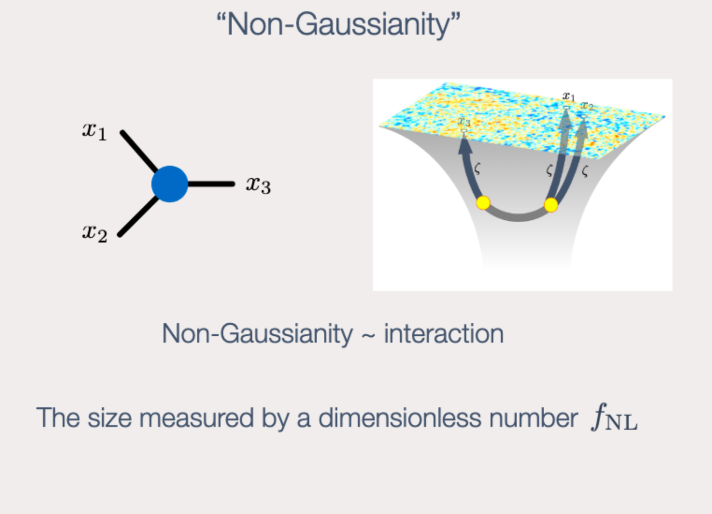
How to extract more information from CMB map?

$\langle \delta T(x_1) \cdots \delta T(x_n) \rangle$

Gaussian

Non-Gaussian

Cosmological Collider: Introduction and Standard Model

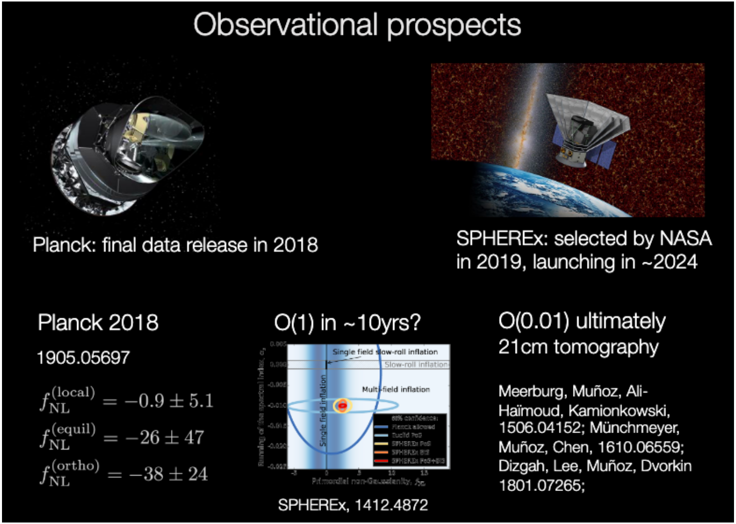


“Non-Gaussianity”

Non-Gaussianity ~ interaction

The size measured by a dimensionless number $f_{\rm NL}$

Cosmological Collider: Introduction and Standard Model



Observational prospects

Planck: final data release in 2018

SPHEREx: selected by NASA
in 2019, launching in ~2024

Planck 2018

1905.05697

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

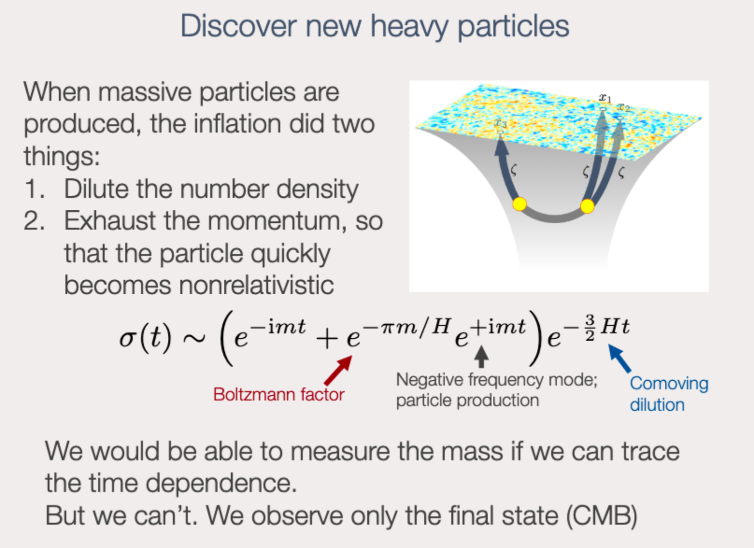
O(1) in ~10yrs?

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;

Cosmological Collider: Introduction and Standard Model



Discover new heavy particles

When massive particles are produced, the inflation did two things:

1. Dilute the number density
2. Exhaust the momentum, so that the particle quickly becomes nonrelativistic

$$\sigma(t) \sim \left(e^{-imt} + e^{-\pi m/H} e^{+imt}\right) e^{-\frac{3}{2}Ht}$$

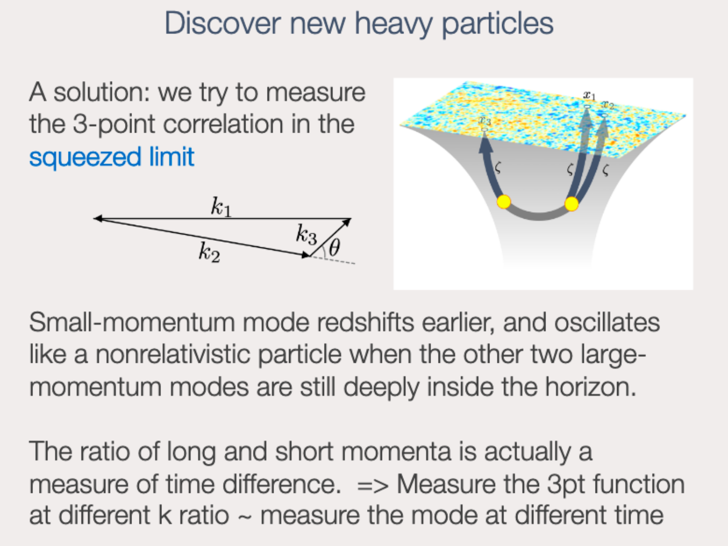
Boltzmann factor

Negative frequency mode; particle production

Comoving dilution

We would be able to measure the mass if we can trace the time dependence.
But we can't. We observe only the final state (CMB)

Cosmological Collider: Introduction and Standard Model



Discover new heavy particles

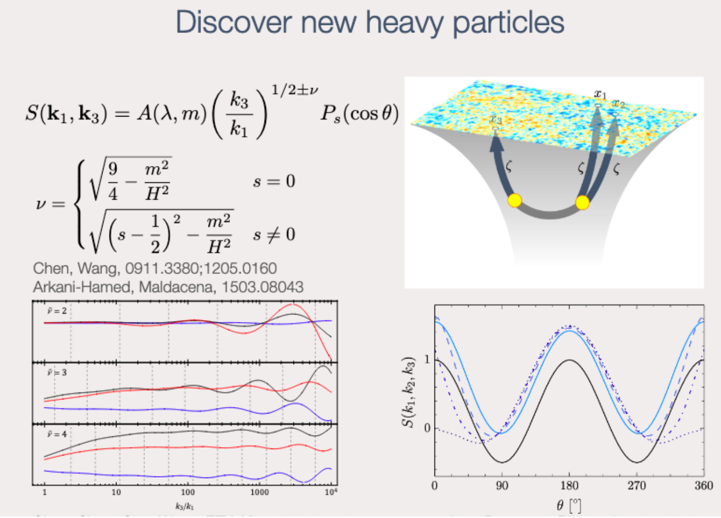
A solution: we try to measure the 3-point correlation in the squeezed limit

Small-momentum mode redshifts earlier, and oscillates like a nonrelativistic particle when the other two large-momentum modes are still deeply inside the horizon.

The ratio of long and short momenta is actually a measure of time difference. => Measure the 3pt function at different k ratio ~ measure the mode at different time

Cosmological Collider: Introduction and Standard Model

Point to appreciate: probe of masses and energy scales in early universe.



Discover new heavy particles

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

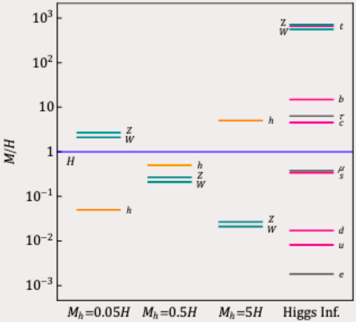
$$\nu = \begin{cases} \sqrt{\frac{9}{4} - \frac{m^2}{H^2}} & s = 0 \\ \sqrt{\left(s - \frac{1}{2}\right)^2 - \frac{m^2}{H^2}} & s \neq 0 \end{cases}$$

Chen, Wang, 0911.3380;1205.0160

Arkani-Hamed, Maldacena, 1503.08043

Cosmological Collider: Introduction and Standard Model

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



Example: "SM background"

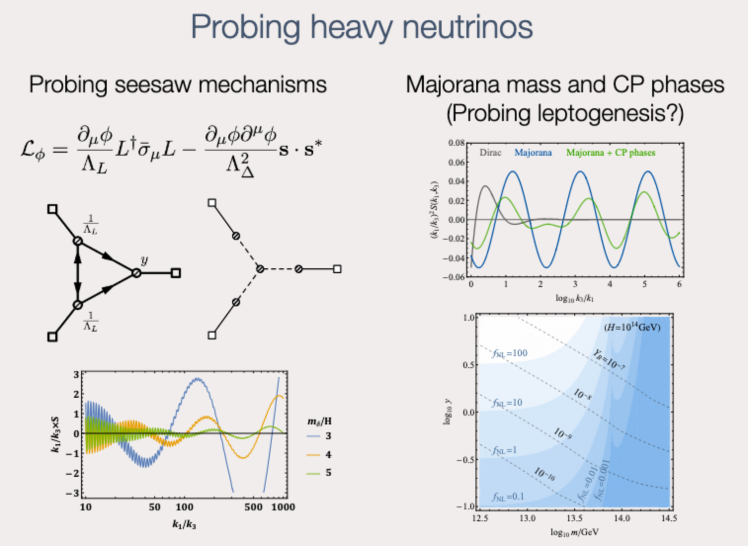
"Thermal" mass ~ Hubble

All in loops: spin info lost

Signal size: tiny unless tuned

Chen et. al. PRL 118 (2017) 26, 261302

Cosmological Collider: Introduction and Standard Model



Probing heavy neutrinos

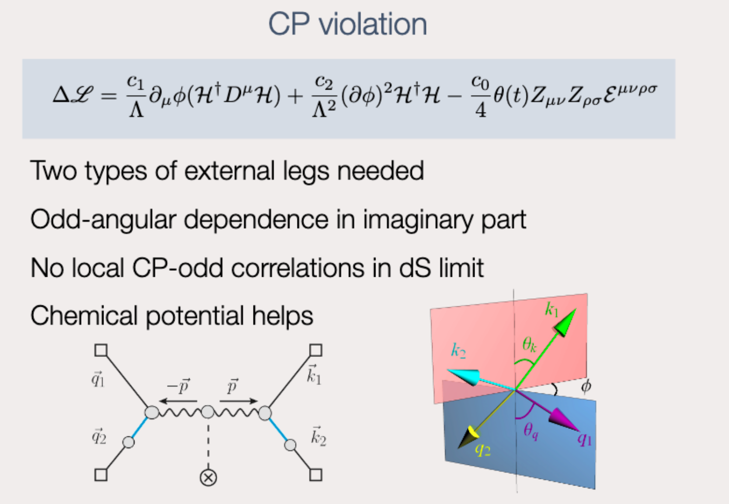
Probing seesaw mechanisms

$$\mathcal{L}_\phi = \frac{\partial_\mu \phi}{\Lambda_L} L^\dagger \bar{\sigma}_\mu L - \frac{\partial_\mu \phi \partial^\mu \phi}{\Lambda_\Delta^2} \mathbf{s} \cdot \mathbf{s}^*$$

Majorana mass and CP phases (Probing leptogenesis?)

Chen et; al. JHEP 09 (2018) 022

Cosmological Collider: Introduction and Standard Model



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

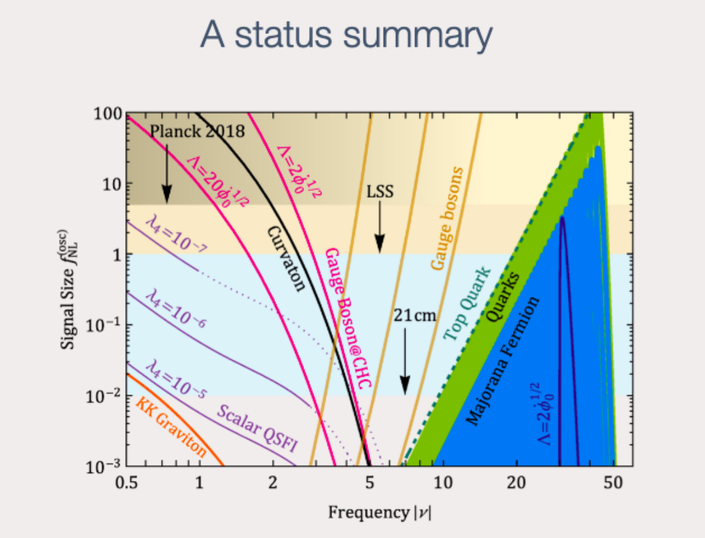
No local CP-odd correlations in dS limit

Chemical potential helps

Liu etl. al. JHEP 04 (2020) 189

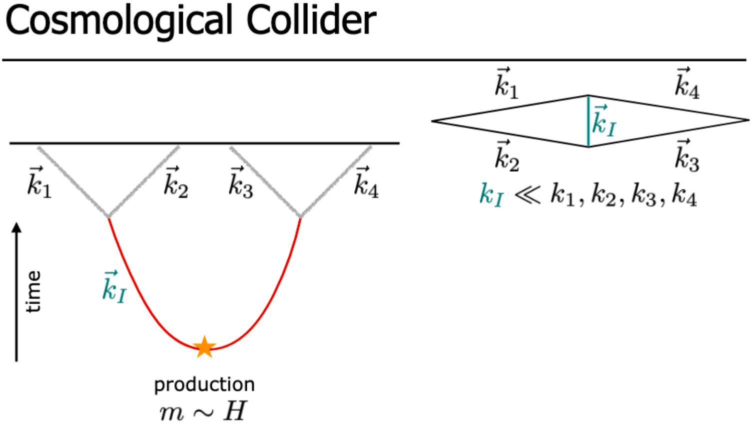
Slides (Xianyu (IHEP talk 2023))

Cosmological Collider: Introduction and Standard Model



Wang et. al. JHEP 02 (2020) 044

Cosmological Collider: Key Ideas & Probe of New Physics BSM



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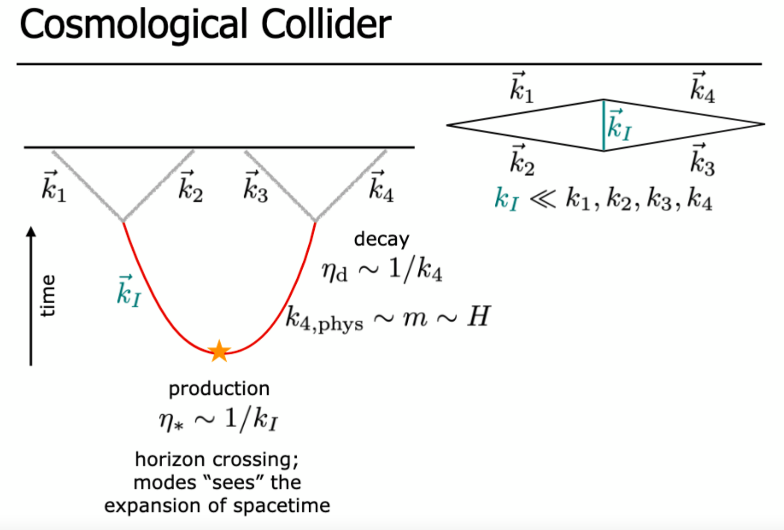

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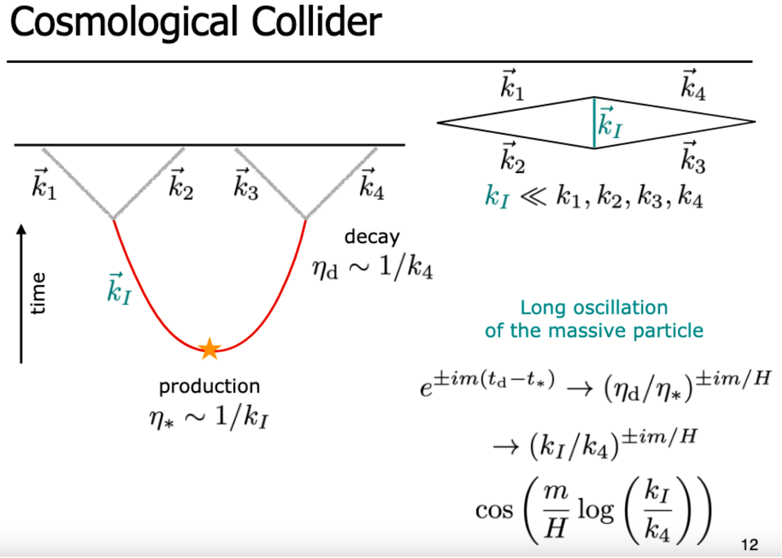


Cosmological Collider

$\eta_{\rm d} \sim 1/k_4$

$\eta_* \sim 1/k_I$

$k_I \ll k_1, k_2, k_3, k_4$

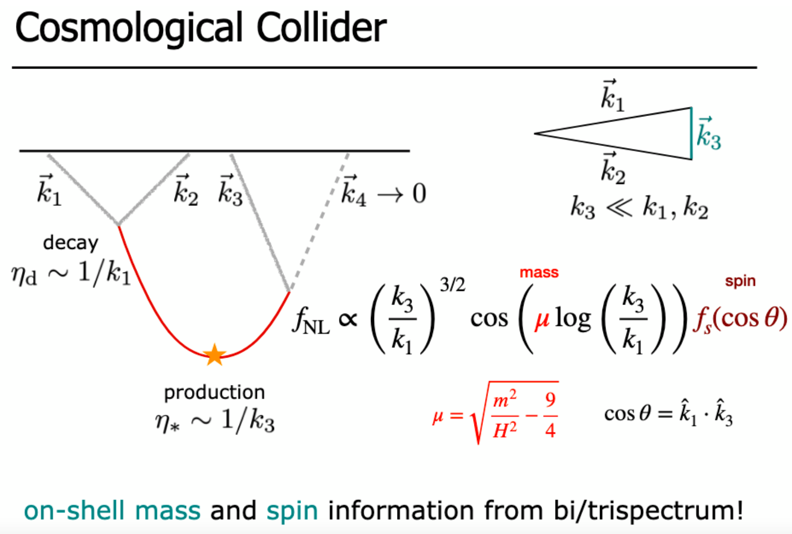
Long oscillation of the massive particle

$$e^{\pm im(t_{\rm d}-t_*)} \rightarrow (\eta_{\rm d}/\eta_*)^{\pm im/H}$$

$$\rightarrow (k_I/k_4)^{\pm im/H}$$

$$\cos\left(\frac{m}{H}\log\left(\frac{k_I}{k_4}\right)\right)$$

Cosmological Collider: Key Ideas & Probe of New Physics BSM



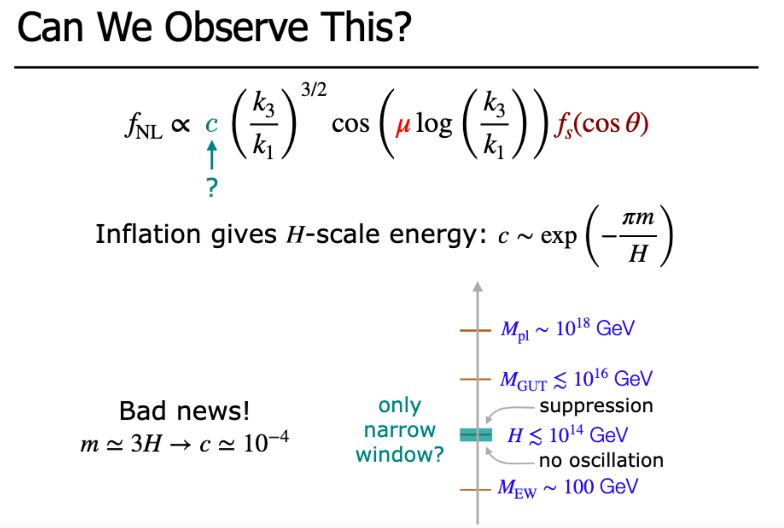
Cosmological Collider

$$f_{\rm NL} \propto \left(\frac{k_3}{k_1}\right)^{3/2} \cos\left(\mu \log\left(\frac{k_3}{k_1}\right)\right) f_s(\cos\theta)$$

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}} \qquad \cos\theta = \hat{k}_1 \cdot \hat{k}_3$$

on-shell mass and spin information from bi/trispectrum!

Cosmological Collider: Key Ideas & Probe of New Physics BSM



Can We Observe This?

$$f_{\rm NL} \propto \underset{\overset{\uparrow}{?}}{c} \left(\frac{k_3}{k_1}\right)^{3/2} \cos\left(\mu \log\left(\frac{k_3}{k_1}\right)\right) f_s(\cos\theta)$$

Inflation gives H-scale energy: $c \sim \exp\left(-\frac{\pi m}{H}\right)$

Bad news!

$m \simeq 3H \to c \simeq 10^{-4}$

only narrow window?

$M_{\rm pl} \sim 10^{18}$ GeV

$M_{\rm GUT} \lesssim 10^{16}$ GeV

suppression

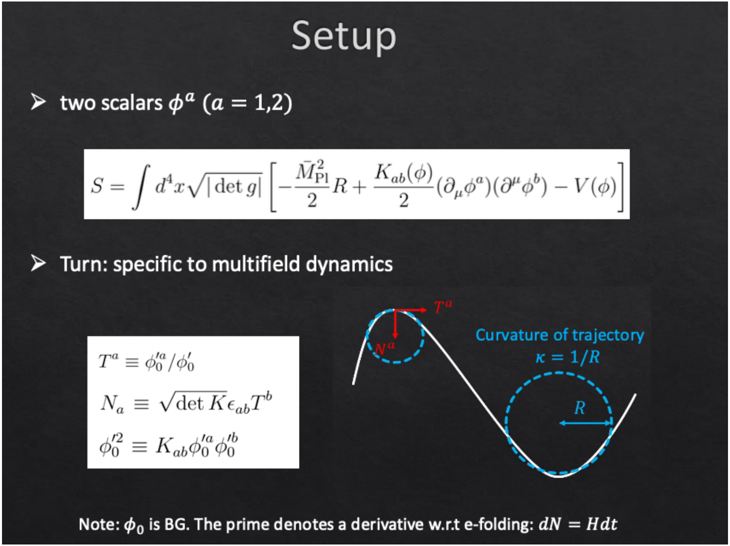
$H \lesssim 10^{14}$ GeV

no oscillation

$M_{\rm EW} \sim 100$ GeV

Slide (Kumar (2022))

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



Setup

- two scalars ϕ^a ($a = 1{,}2$)

$$S = \int d^4x \sqrt{|\det g|} \left[-\frac{\bar{M}_{\rm Pl}^2}{2} R + \frac{K_{ab}(\phi)}{2} (\partial_\mu \phi^a)(\partial^\mu \phi^b) - V(\phi) \right]$$

- Turn: specific to multifield dynamics

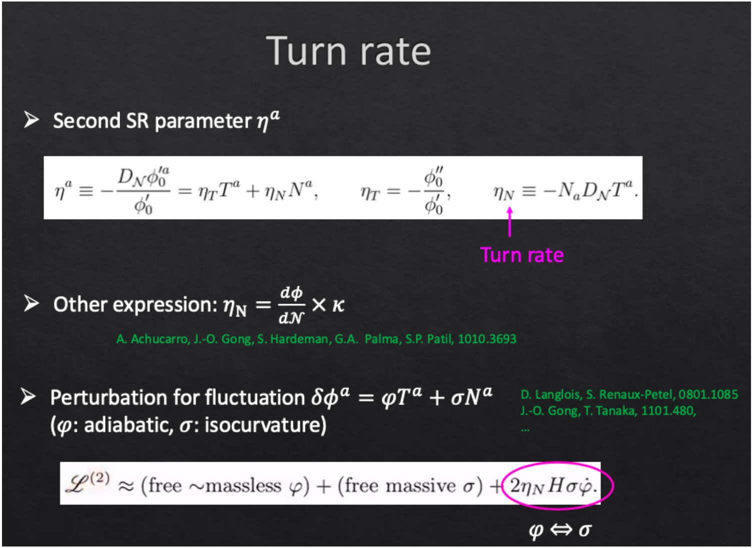
$$T^a \equiv \phi_0'^a / \phi_0'$$

$$N_a \equiv \sqrt{\det K} \epsilon_{ab} T^b$$

$$\phi_0'^2 \equiv K_{ab} \phi_0'^a \phi_0'^b$$

Note: ϕ_0 is BG. The prime denotes a derivative w.r.t e-folding: $dN = Hdt$

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



Turn rate

- Second SR parameter η^a

$$\eta^a \equiv -\frac{D_N \phi_0'^a}{\phi_0'} = \eta_T T^a + \eta_N N^a, \qquad \eta_T = -\frac{\phi_0''}{\phi_0'}, \qquad \eta_N \equiv -N_a D_N T^a.$$

Turn rate

- Other expression: $\eta_N = \frac{d\phi}{dN} \times \kappa$

A. Achucarro, J.-O. Gong, S. Hardeman, G.A. Palma, S.P. Patil, 1010.3693

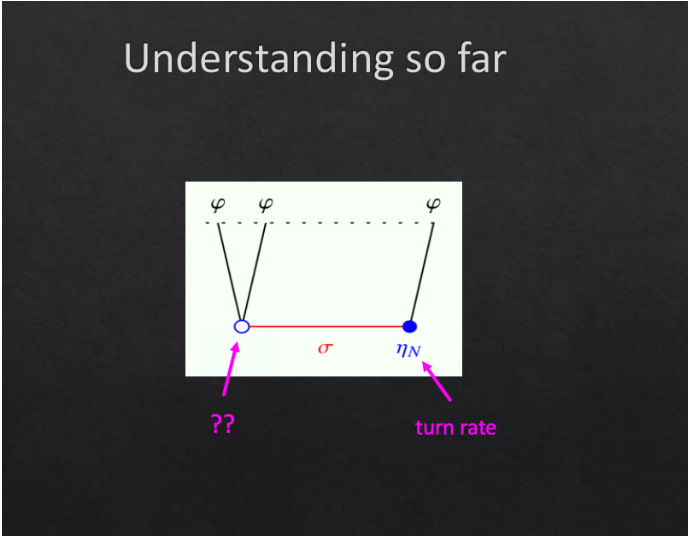
- Perturbation for fluctuation $\delta\phi^a = \varphi T^a + \sigma N^a$ (φ: adiabatic, σ: isocurvature)

D. Langlois, S. Renaux-Petel, 0801.1085
J.-O. Gong, T. Tanaka, 1101.480,
...

$$\mathscr{L}^{(2)} \approx (\text{free} \sim\!\text{massless } \varphi) + (\text{free massive } \sigma) + \boxed{2\eta_N H \sigma \dot{\varphi}.}$$

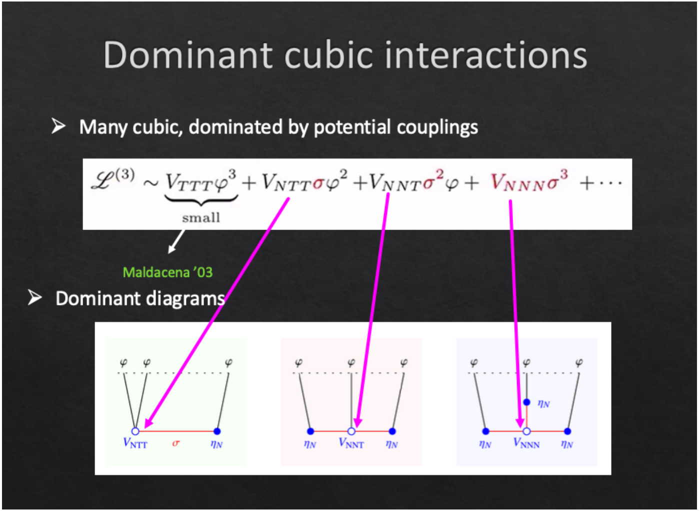
$$\varphi \Leftrightarrow \sigma$$

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



Understanding so far

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



Dominant cubic interactions

- Many cubic, dominated by potential couplings

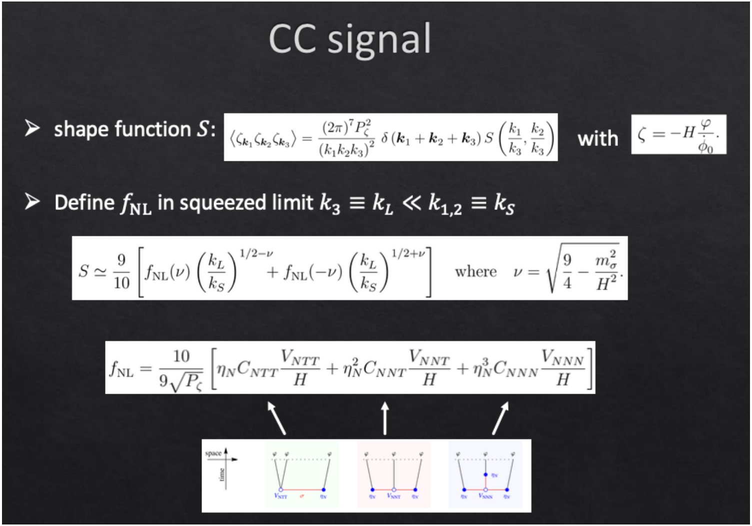
$$\mathscr{L}^{(3)} \sim \underbrace{V_{TTT}\varphi^3}_{\text{small}} + V_{NTT}\sigma\varphi^2 + V_{NNT}\sigma^2\varphi + V_{NNN}\sigma^3 + \cdots$$

Maldacena '03

- Dominant diagrams

Aoki, **Ghoshal**, Strumia, JHEP 11 (2024) 009

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



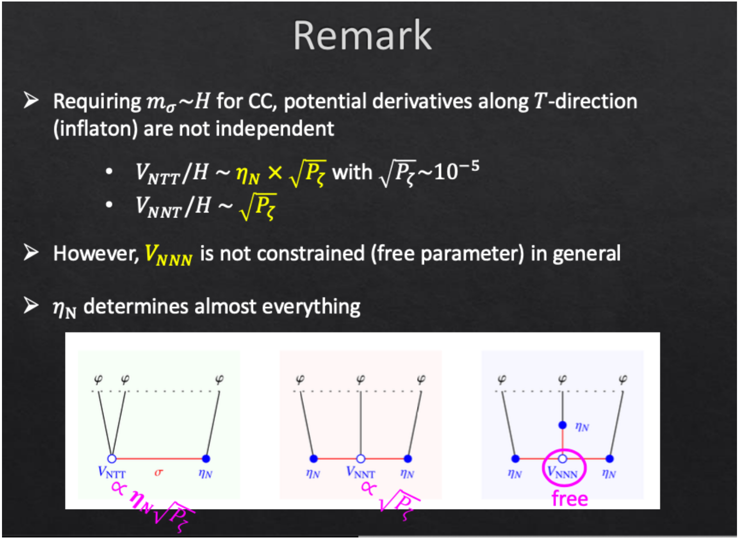
CC signal

- shape function S: $\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \zeta_{\boldsymbol{k}_3} \rangle = \frac{(2\pi)^7 P_\zeta^2}{(k_1 k_2 k_3)^2} \, \delta\left(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3\right) S\left(\frac{k_1}{k_3}, \frac{k_2}{k_3}\right)$ with $\zeta = -H \frac{\varphi}{\dot{\phi}_0}.$
- Define f_{NL} in squeezed limit $k_3 \equiv k_L \ll k_{1,2} \equiv k_S$

$$S \simeq \frac{9}{10} \left[f_{\mathrm{NL}}(\nu) \left(\frac{k_L}{k_S}\right)^{1/2-\nu} + f_{\mathrm{NL}}(-\nu) \left(\frac{k_L}{k_S}\right)^{1/2+\nu} \right] \quad \text{where} \quad \nu = \sqrt{\frac{9}{4} - \frac{m_\sigma^2}{H^2}}.$$

$$f_{\mathrm{NL}} = \frac{10}{9\sqrt{P_\zeta}} \left[\eta_N C_{NTT} \frac{V_{NTT}}{H} + \eta_N^2 C_{NNT} \frac{V_{NNT}}{H} + \eta_N^3 C_{NNN} \frac{V_{NNN}}{H} \right]$$

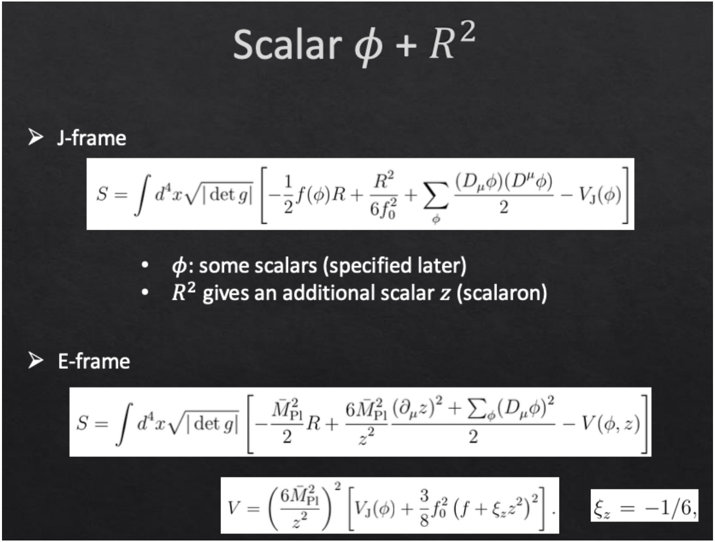
Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



Remark

- Requiring $m_\sigma \sim H$ for CC, potential derivatives along T-direction (inflaton) are not independent
  - $V_{NTT}/H \sim \eta_N \times \sqrt{P_\zeta}$ with $\sqrt{P_\zeta} \sim 10^{-5}$
  - $V_{NNT}/H \sim \sqrt{P_\zeta}$
- However, V_{NNN} is not constrained (free parameter) in general
- η_N determines almost everything

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



Scalar ϕ + R^2

- **J-frame**

$$S = \int d^4x \sqrt{|\det g|} \left[-\frac{1}{2} f(\phi) R + \frac{R^2}{6 f_0^2} + \sum_{\phi} \frac{(D_\mu \phi)(D^\mu \phi)}{2} - V_J(\phi) \right]$$

  - ϕ: some scalars (specified later)
  - R^2 gives an additional scalar z (scalaron)

- **E-frame**

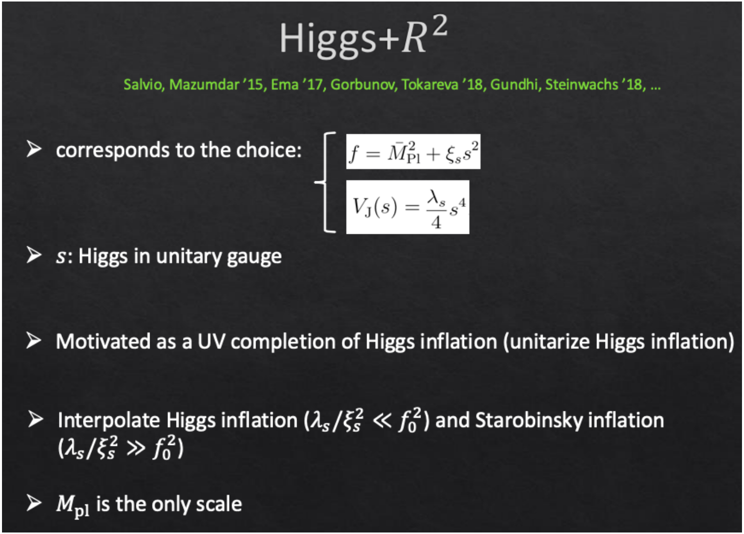
$$S = \int d^4x \sqrt{|\det g|} \left[-\frac{\bar{M}_{\rm Pl}^2}{2} R + \frac{6 \bar{M}_{\rm Pl}^2}{z^2} \frac{(\partial_\mu z)^2 + \sum_\phi (D_\mu \phi)^2}{2} - V(\phi, z) \right]$$

$$V = \left(\frac{6 \bar{M}_{\rm Pl}^2}{z^2} \right)^2 \left[V_J(\phi) + \frac{3}{8} f_0^2 \left(f + \xi_z z^2 \right)^2 \right].$$

$$\xi_z = -1/6,$$

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework

Imagine the Higgs being responsible for generating the Electroweak scale dynamically.

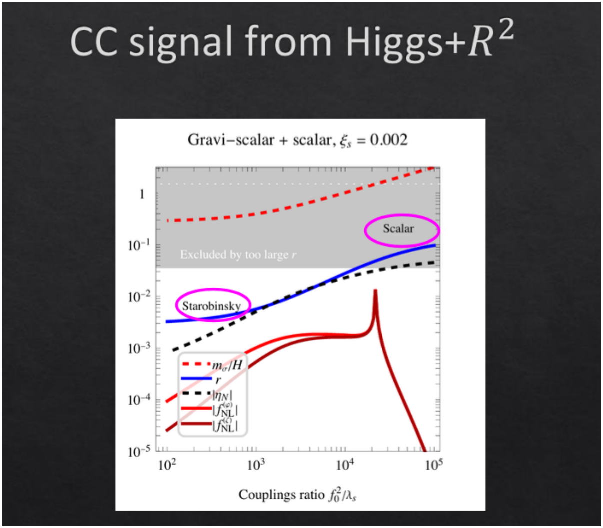


Higgs+R^2

Salvio, Mazumdar ’15, Ema ’17, Gorbunov, Tokareva ’18, Gundhi, Steinwachs ’18, ...

- corresponds to the choice: $\left\{ \begin{array}{l} \boxed{f = \bar{M}_{\rm Pl}^2 + \xi_s s^2} \\ \boxed{V_{\rm J}(s) = \frac{\lambda_s}{4} s^4} \end{array} \right.$
- s: Higgs in unitary gauge
- Motivated as a UV completion of Higgs inflation (unitarize Higgs inflation)
- Interpolate Higgs inflation ($\lambda_s/\xi_s^2 \ll f_0^2$) and Starobinsky inflation ($\lambda_s/\xi_s^2 \gg f_0^2$)
- $M_{\rm pl}$ is the only scale

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework

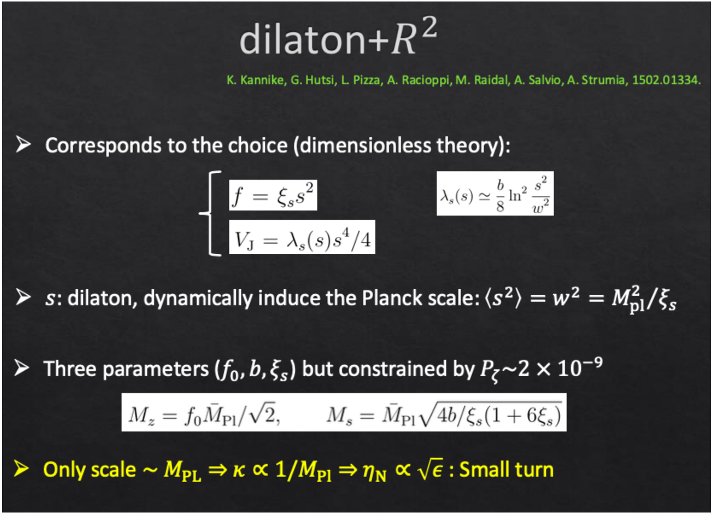


CC signal from Higgs+R^2

Aoki, **Ghoshal**, Strumia, JHEP 11 (2024) 009

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework

Imagine the Higgs being responsible for generating the Planck scale dynamically.



dilaton+R^2

K. Kannike, G. Hutsi, L. Pizza, A. Racioppi, M. Raidal, A. Salvio, A. Strumia, 1502.01334.

- Corresponds to the choice (dimensionless theory):

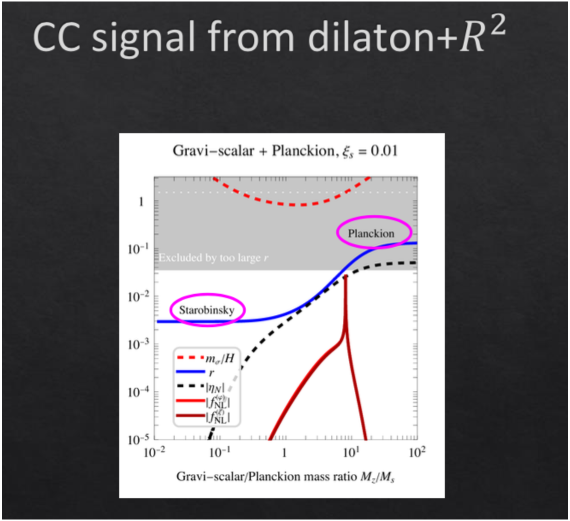
$$\begin{cases} f = \xi_s s^2 \\ V_J = \lambda_s(s) s^4/4 \end{cases} \qquad \lambda_s(s) \simeq \frac{b}{8}\ln^2\frac{s^2}{w^2}$$

- s: dilaton, dynamically induce the Planck scale: $\langle s^2\rangle = w^2 = M_{\rm pl}^2/\xi_s$
- Three parameters (f_0, b, ξ_s) but constrained by $P_\zeta \sim 2\times 10^{-9}$

$$M_z = f_0 \bar{M}_{\rm Pl}/\sqrt{2}, \qquad M_s = \bar{M}_{\rm Pl}\sqrt{4b/\xi_s(1+6\xi_s)}$$

- Only scale $\sim M_{\rm PL} \Rightarrow \kappa \propto 1/M_{\rm Pl} \Rightarrow \eta_{\rm N} \propto \sqrt{\epsilon}$: Small turn

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



CC signal from dilaton+R^2

Aoki, **Ghoshal**, Strumia, JHEP 11 (2024) 009

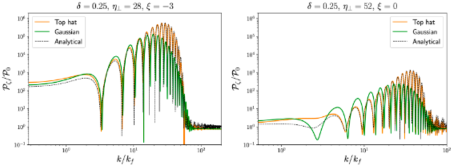
Primordial Gravitational Wave Signals

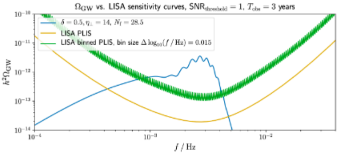
SGWB

- Primordial scalar perturbations induce a gravitational wave spectrum.

Baumann, Steinhardt, Takahashi, Ichiki, hep-th/0703290

$$\Omega_{\mathrm{GW}} \sim 10^{-5} P_\zeta^2$$





Fumagalli, Renaux-Petel, Witkowski: ArXiv:2012.02761

Summary:

- With current Planck data, and upcoming CMB missions like LiteBRD, & 21-cm, LSS experiments, one will measure primordial non-gaussianities and its shape dependence.
- During inflation, in early universe, there is enough energy to produce all SM particles as well as heavy BSM states like right-handed neutrinos. Any such interactions leave inevitable signal in primordial non-gaussianities. Particularly in the limit of cosmological collider ($m \sim \mathcal{O}(H)$), they leave a unique oscillatory scale-dependent bi-spectrum in $< \zeta\zeta\zeta >$ correlator in the squeezed limit that can be dug out from observational data.
- Higgs Inflation and Starobinsky inflation in the framework of EFT of Higgs-$\mathcal{R}^2$, having any interactions between the two fields along with matter sector (fermions and gauge bosons) can lead to such detectable oscillatory signals.
- At much smaller scales of the universe ($k \gg k_{\rm CMB}$) such Higgs-$\mathcal{R}^2$ framework also give rise to large scalar-induced Gravitational Waves (can be tested in LISA) and lead to formation of Primordial Blackholes as the entire DM candidate.

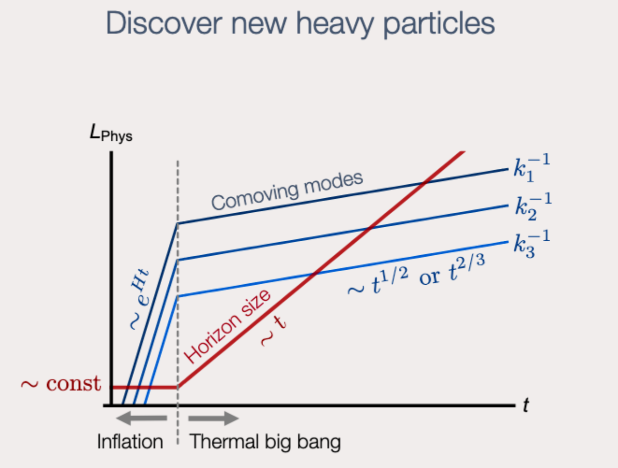
Future:

- Tests of your favorite BSM heavy particle models, CP Violation, mixed bi-spectrum, cross-correlation between scalars and tensors (ζhh) with CMB μ-distortions, 21-cm and GW..

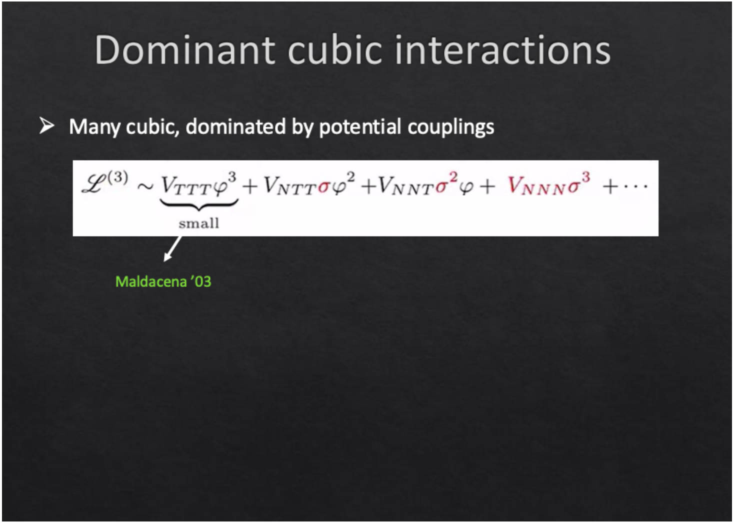
Thank You

Backup begins

Cosmological Collider: Introduction and Standard Model



Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



Dominant cubic interactions

- Many cubic, dominated by potential couplings

$$\mathscr{L}^{(3)} \sim \underbrace{V_{TTT}\varphi^3}_{\text{small}} + V_{NTT}\sigma\varphi^2 + V_{NNT}\sigma^2\varphi + V_{NNN}\sigma^3 + \cdots$$

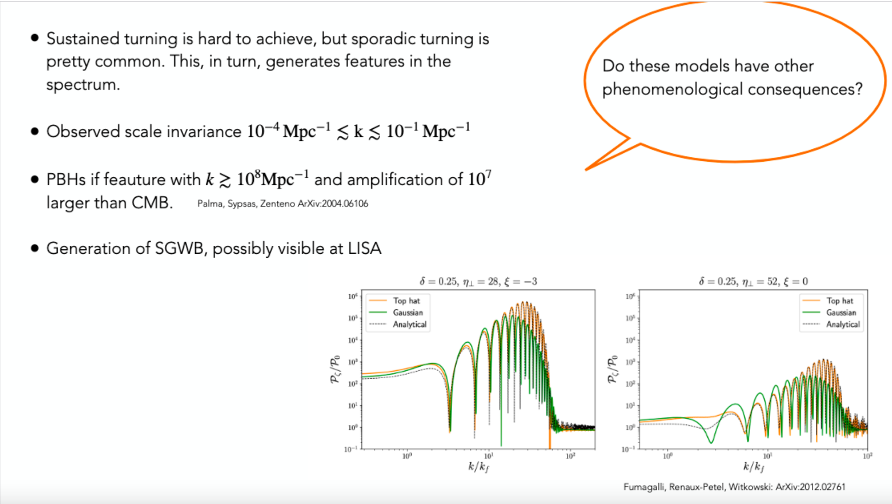
Maldacena '03

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework

Application to concrete models

Primordial Gravitational Wave Signals

So far only CMB, now we go to smaller scales of the universe, typically $k \gg k_{\rm CMB}$.

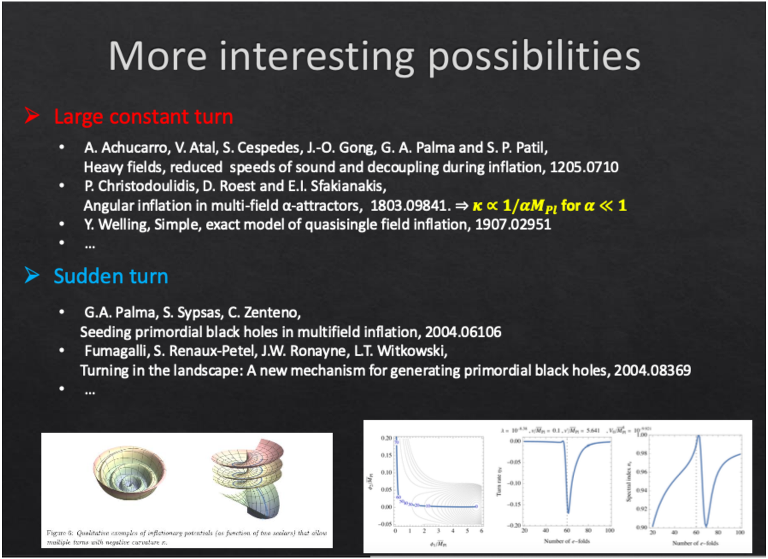


- Sustained turning is hard to achieve, but sporadic turning is pretty common. This, in turn, generates features in the spectrum.
- Observed scale invariance $10^{-4}\,\mathrm{Mpc}^{-1} \lesssim \mathrm{k} \lesssim 10^{-1}\,\mathrm{Mpc}^{-1}$
- PBHs if feauture with $k \gtrsim 10^{8}\mathrm{Mpc}^{-1}$ and amplification of 10^{7} larger than CMB. Palma, Sypsas, Zenteno ArXiv:2004.06106
- Generation of SGWB, possibly visible at LISA

Do these models have other phenomenological consequences?

Fumagalli, Renaux-Petel, Witkowski: ArXiv:2012.02761

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



More interesting possibilities

Large constant turn

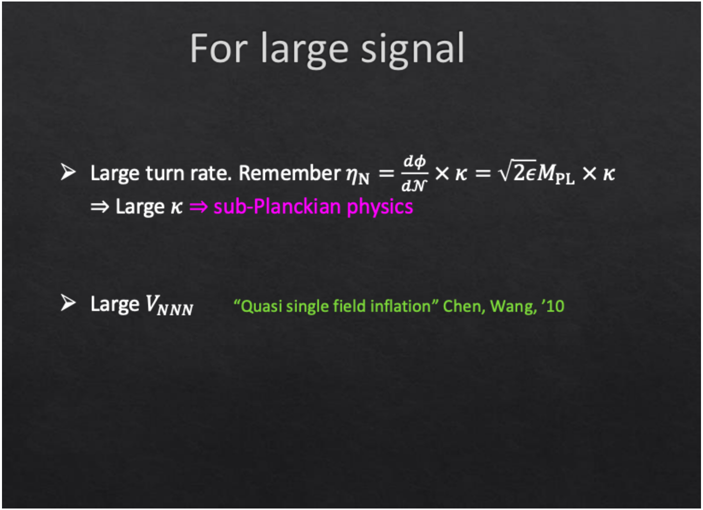
- A. Achucarro, V. Atal, S. Cespedes, J.-O. Gong, G. A. Palma and S. P. Patil, Heavy fields, reduced speeds of sound and decoupling during inflation, 1205.0710
- P. Christodoulidis, D. Roest and E.I. Sfakianakis, Angular inflation in multi-field α-attractors, 1803.09841. ⇒ $\kappa \propto 1/\alpha M_{Pl}$ **for** $\alpha \ll 1$
- Y. Welling, Simple, exact model of quasisingle field inflation, 1907.02951
- …

Sudden turn

- G.A. Palma, S. Sypsas, C. Zenteno, Seeding primordial black holes in multifield inflation, 2004.06106
- Fumagalli, S. Renaux-Petel, J.W. Ronayne, L.T. Witkowski, Turning in the landscape: A new mechanism for generating primordial black holes, 2004.08369
- …

Figure 6: *Qualitative examples of inflationary potentials (as function of two scalars) that allow multiple turns with negative curvature κ.*

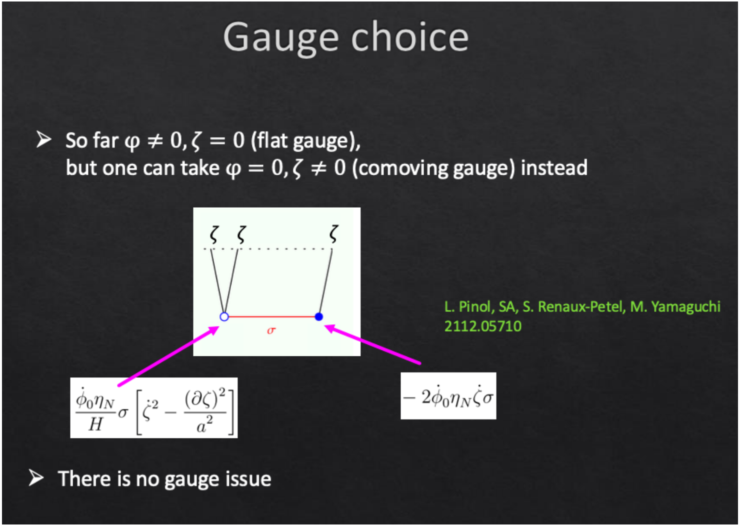
Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



For large signal

- Large turn rate. Remember $\eta_{\rm N} = \frac{d\phi}{d\mathcal{N}} \times \kappa = \sqrt{2\epsilon} M_{\rm PL} \times \kappa$
  $\Rightarrow$ Large κ $\Rightarrow$ sub-Planckian physics
- Large V_{NNN} “Quasi single field inflation” Chen, Wang, ’10

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



Gauge choice

- So far $\varphi \neq 0, \zeta = 0$ (flat gauge), but one can take $\varphi = 0, \zeta \neq 0$ (comoving gauge) instead

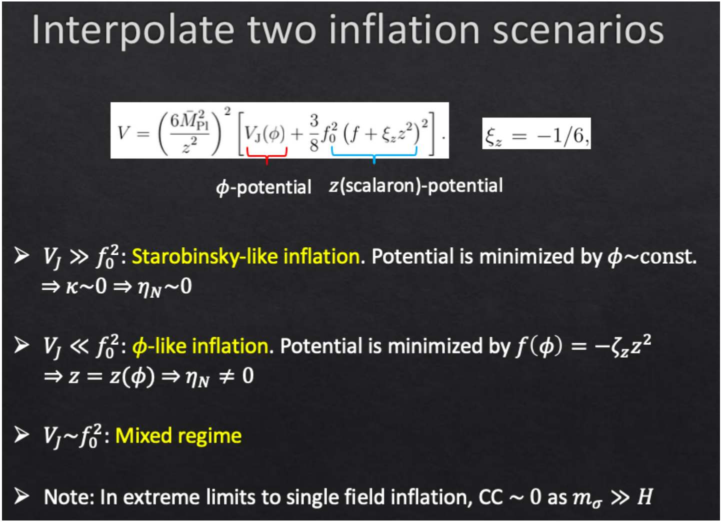
L. Pinol, SA, S. Renaux-Petel, M. Yamaguchi
2112.05710

$$\frac{\dot{\phi}_0 \eta_N}{H}\sigma\left[\dot{\zeta}^2 - \frac{(\partial\zeta)^2}{a^2}\right]$$

$$-2\dot{\phi}_0 \eta_N \dot{\zeta}\sigma$$

- There is no gauge issue

Cosmological Collider: Higgs-$\mathcal{R}^2$ Framework



Interpolate two inflation scenarios

$$V=\left(\frac{6\bar{M}_{\rm Pl}^2}{z^2}\right)^2\left[\underbrace{V_{\rm J}(\phi)}_{\phi\text{-potential}}+\frac{3}{8}\underbrace{f_0^2\left(f+\xi_z z^2\right)^2}_{z\text{(scalaron)-potential}}\right].\qquad \xi_z=-1/6,$$

- $V_J \gg f_0^2$: **Starobinsky-like inflation**. Potential is minimized by $\phi\sim$const. $\Rightarrow \kappa\sim 0 \Rightarrow \eta_N \sim 0$
- $V_J \ll f_0^2$: **ϕ-like inflation**. Potential is minimized by $f(\phi)=-\zeta_z z^2$ $\Rightarrow z=z(\phi)\Rightarrow \eta_N\neq 0$
- $V_J \sim f_0^2$: **Mixed regime**
- Note: In extreme limits to single field inflation, CC ~ 0 as $m_\sigma \gg H$

Primordial Gravitational Wave Signals

How generic are the potentials and field-space metrics in SUGRA?

Aragam, Chiovoloni, SP, Rosati, Zavala: ArXiv:2110.05516

- Rapid-turn inflation in supergravity is rare and tachyonic
- Large turning rates can be generated in a wide class of models, at the cost of high field space curvature.

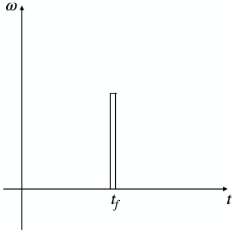
$$S = \int d^4x\sqrt{-g}\left[M_P^2\frac{R}{2} - K_{i\bar{j}}\partial_\mu\Phi^i\partial^\mu\bar{\Phi}^{\bar{j}} - V(\Phi^k, \bar{\Phi}^k)\right]$$

$$K = -3\,\alpha\,M_P^2\log[(\Phi+\bar{\Phi})/M_P] + S\bar{S}\,, \qquad V = \frac{M_P^{3\alpha}\,|F|^2}{(\Phi+\bar{\Phi})^{3\alpha}} \qquad \mathscr{R} = -4/(3\alpha)$$

$$\boxed{\frac{\omega}{H} \simeq \frac{2\sqrt{\epsilon}}{\sqrt{3\,\alpha}}}$$

In the ‘large” regime (large volume, large complex structure, weak coupling) this coefficient is certainly $\alpha \sim O(1)$, but its value is unclear away from this limit
—A. Lukas

Primordial Gravitational Wave Signals



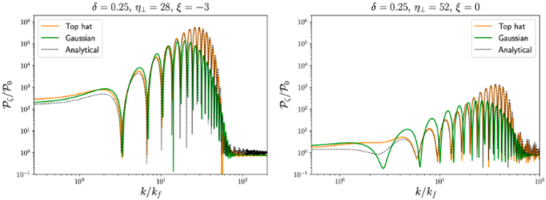
For a specific choice of masses,

$$D_t\dot{\zeta}_c + 3HD_t\zeta_c + \frac{k^2}{a^2}\zeta_c = 0$$
$$D_t\dot{Q}_s + 3HD_tQ_s + \frac{k^2}{a^2}Q_s = -2\omega D_t\zeta_c$$

During a top-hat feature:

$$\frac{q_\pm}{H} = \sqrt{\frac{k^2}{k_f^2} \pm 2\frac{\omega}{H}\frac{k}{k_f}}$$

$$k_f = Ha(t_f)$$



Fumagalli, Renaux-Petel, Witkowski: ArXiv:2012.02761