Probing Particle Physics with the Cosmological Collider

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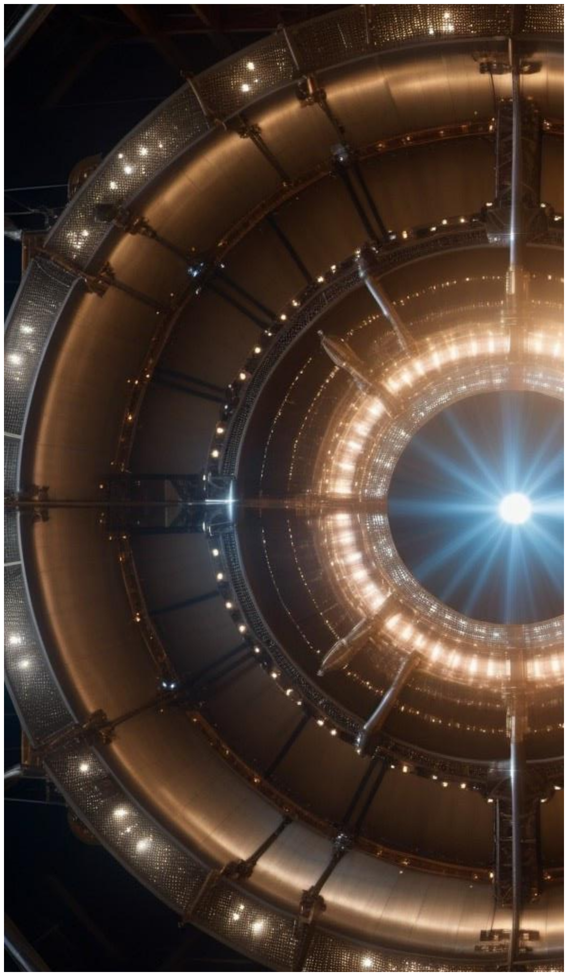
Why the name "Cosmological Collider"?



Looks Similar

High energy particles: $E \sim H \sim 10^{13}$ GeV (?)

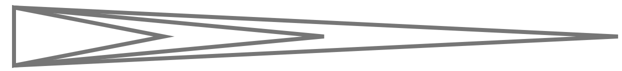
Conserved quantities: $\zeta, h_{ij}, \ldots$

Detectors: CMB, LSS

and more

How to determine particle mass?

Through "how squeezed"



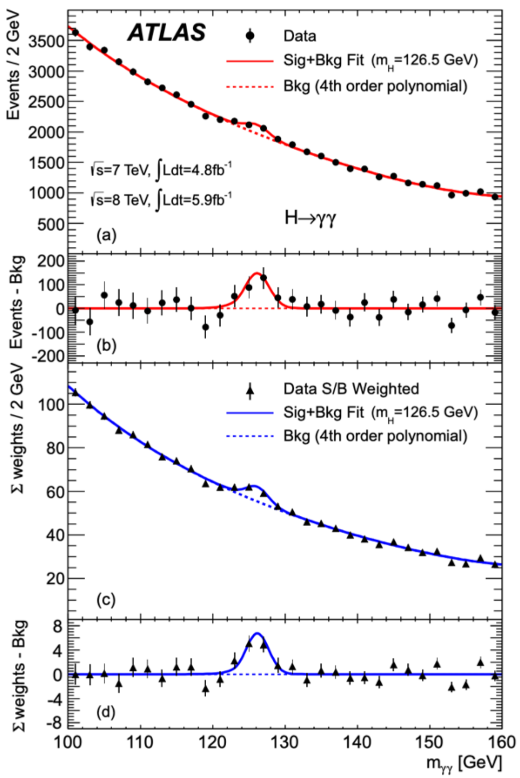
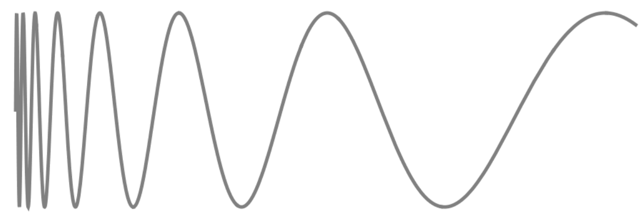


Figure: ATLAS

$$\left(\frac{k_d}{k_p}\right)^{i\mu}$$

$\Longleftrightarrow$



How to determine particle mass?

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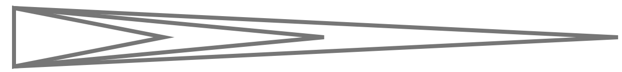

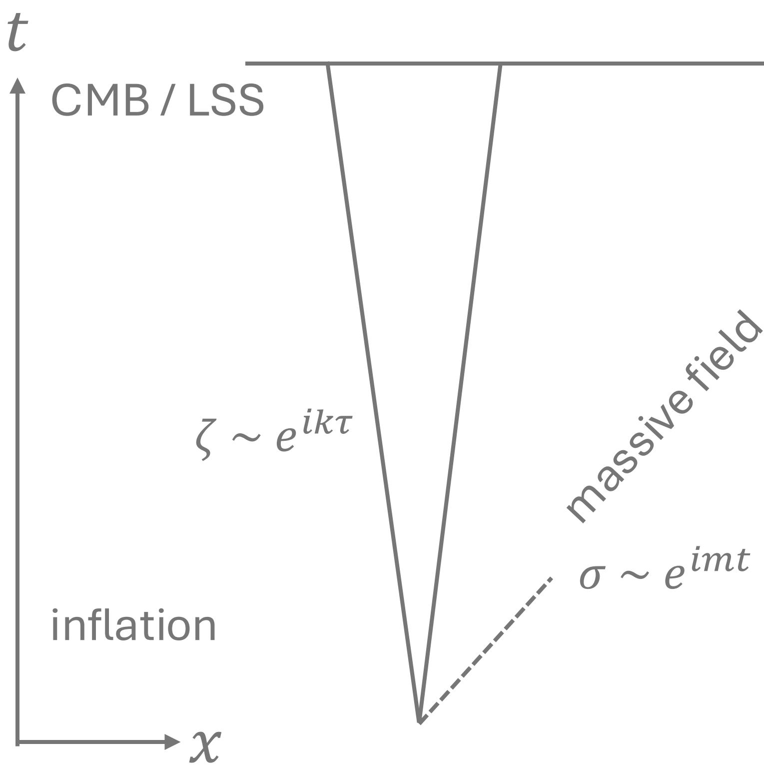

$$ds^2 = -dt^2 + a^2 d\mathbf{x}^2 = a^2\left(-d\tau^2 + d\mathbf{x}^2\right)$$

Chen, YW, 0909.0496, 0911.3380

Baumann, Green, 1109.0292

Noumi, Yamaguchi, Yokoyama, 1211.1624

Arkani-Hamed, Maldacena, 1503.08043

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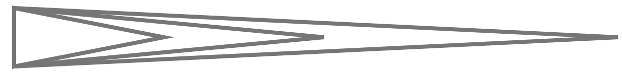
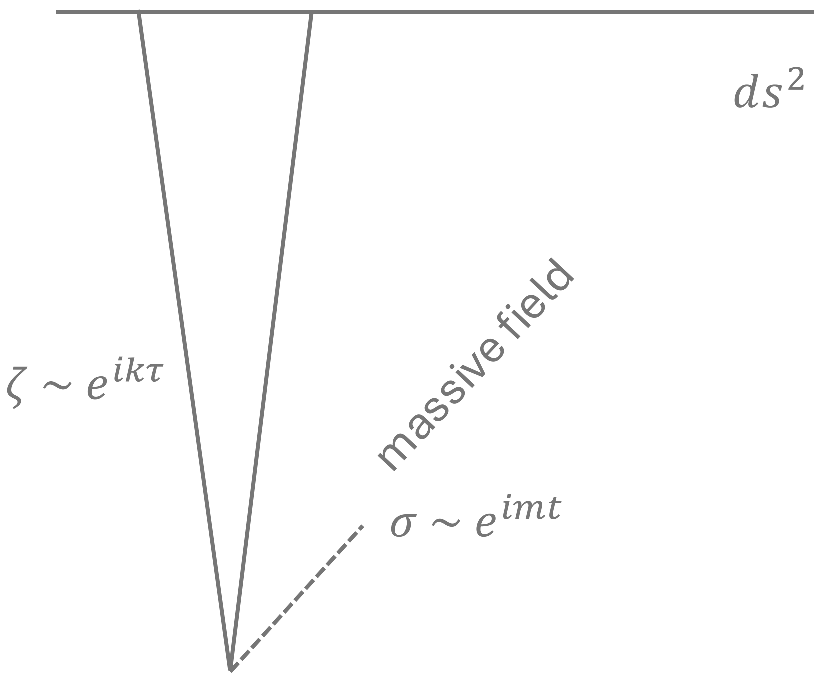
Through "how squeezed" 

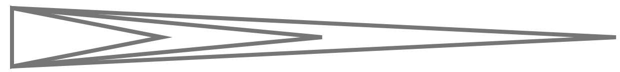


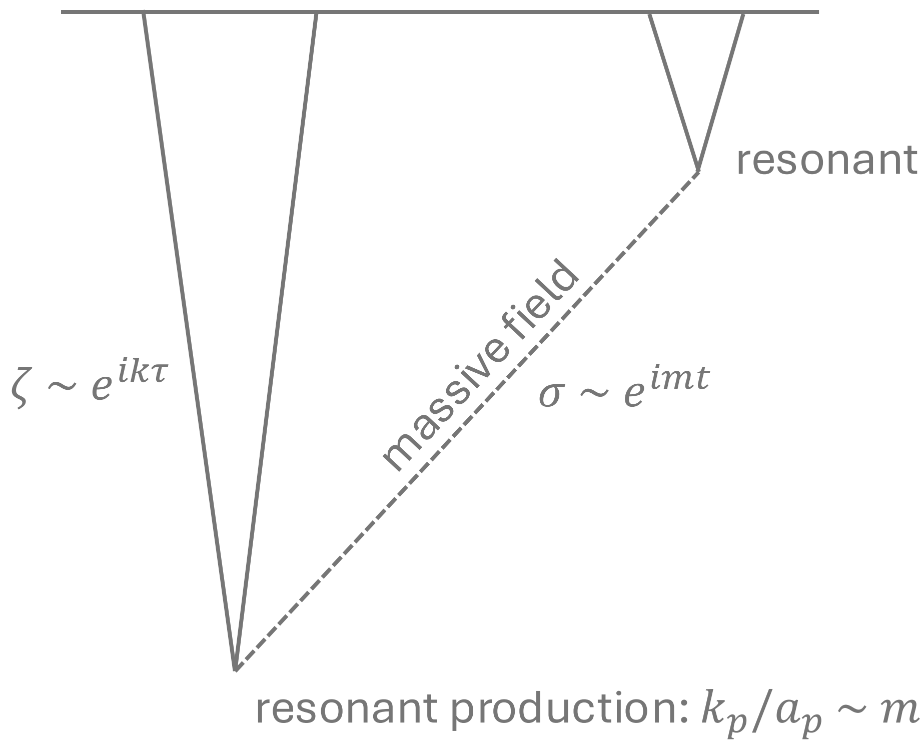
$$ds^2 = -dt^2 + a^2 d\mathbf{x}^2 = a^2\left(-d\tau^2 + d\mathbf{x}^2\right)$$

resonant production: $k_p/a_p \sim m$

How to determine particle mass?

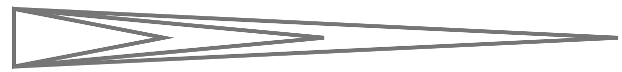
Through "how squeezed"

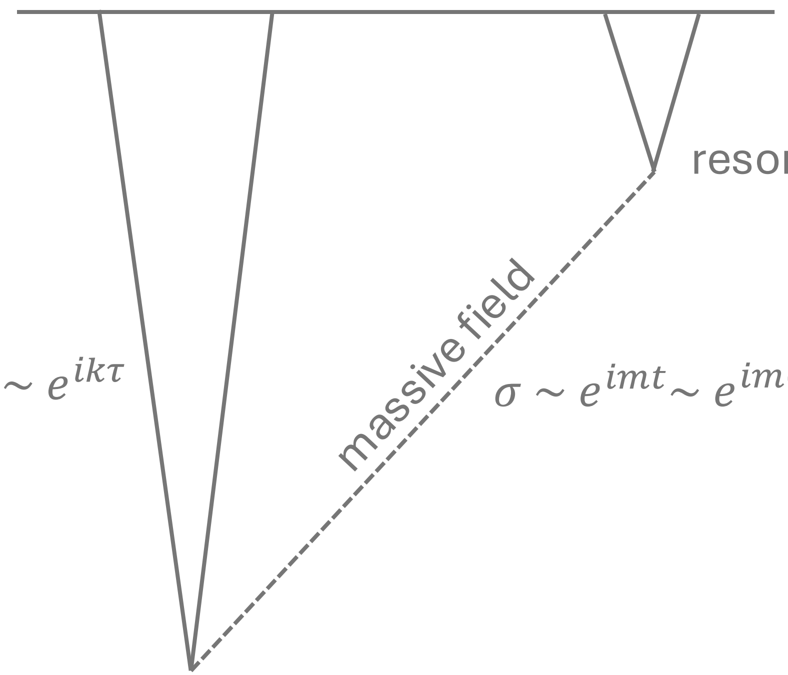




How to determine particle mass?

Through "how squeezed"





resonant decay: $k_d/a_d \sim m$

$\zeta \sim e^{ik\tau}$

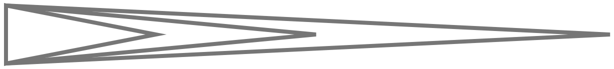
$$\sigma \sim e^{imt} \sim e^{im(t_d - t_p)} \sim e^{i\mu(\ln a_d - \ln a_p)} \sim \left(\frac{a_d}{a_p}\right)^{i\mu} \sim \left(\frac{k_d}{k_p}\right)^{i\mu}$$

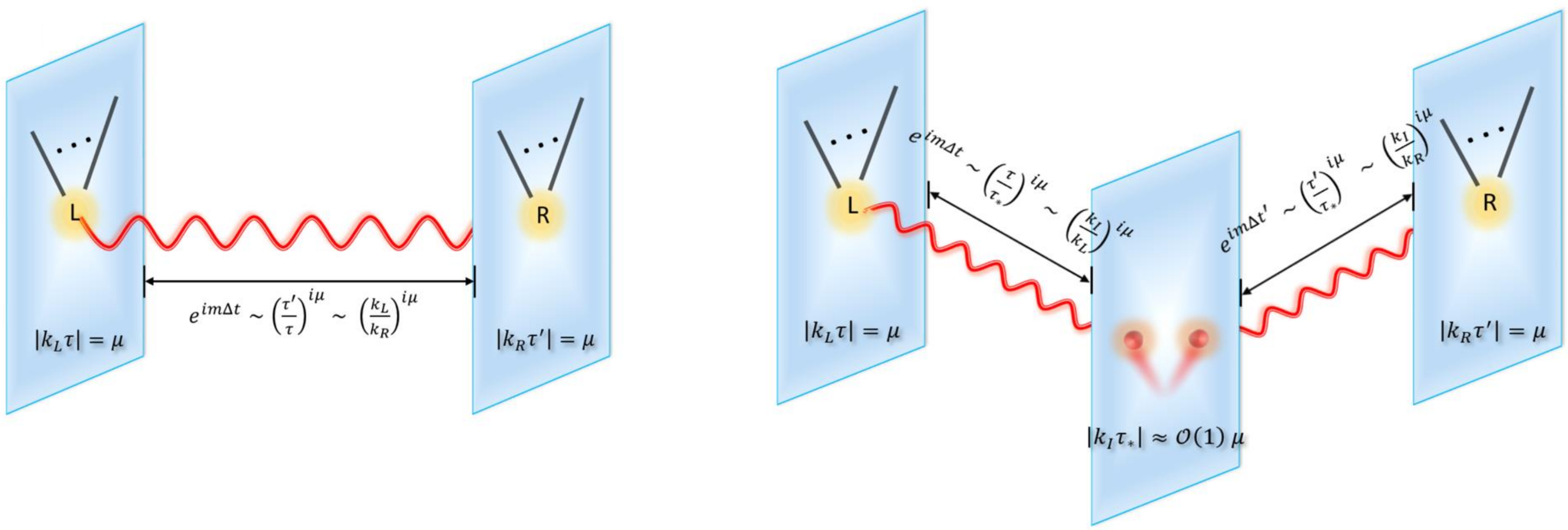
$$\mu \sim \frac{m}{H} = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

resonant production: $k_p/a_p \sim m$

How to determine particle mass?

Through "how squeezed"

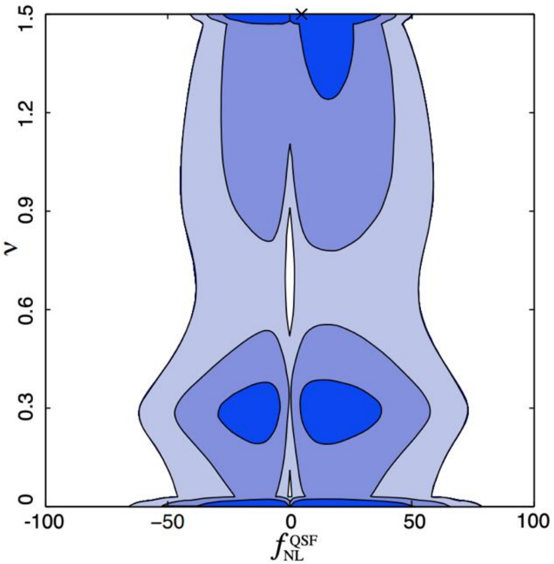


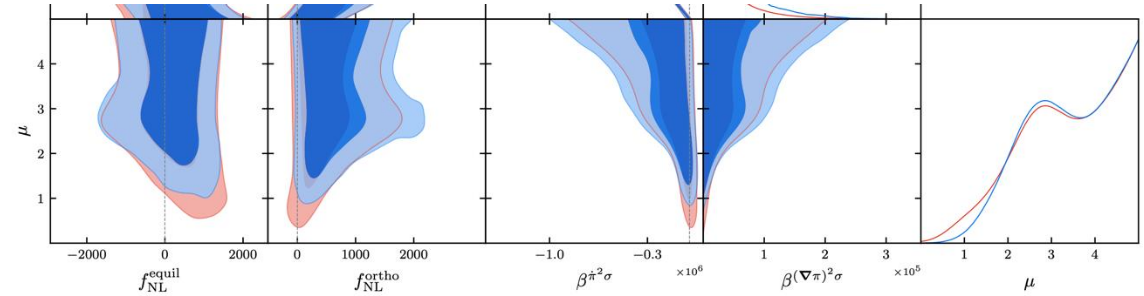


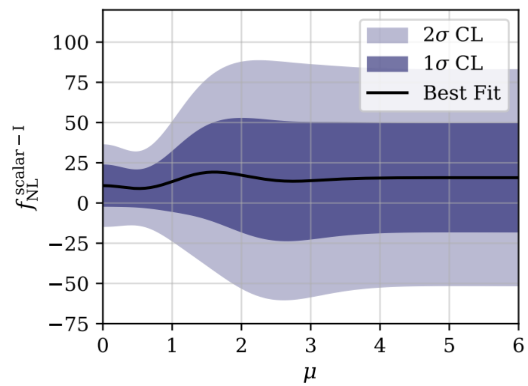
Local vs non-local particle productions

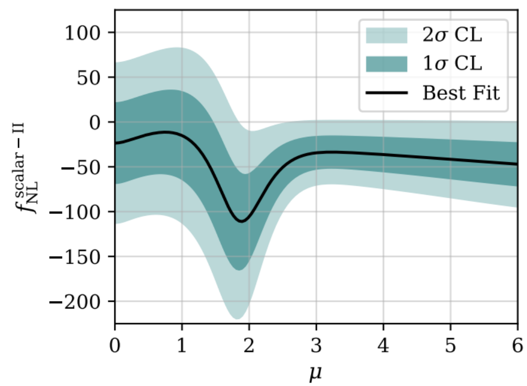
Figure: Tong, Zhu, YW, 2112.03448

Observational searches









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

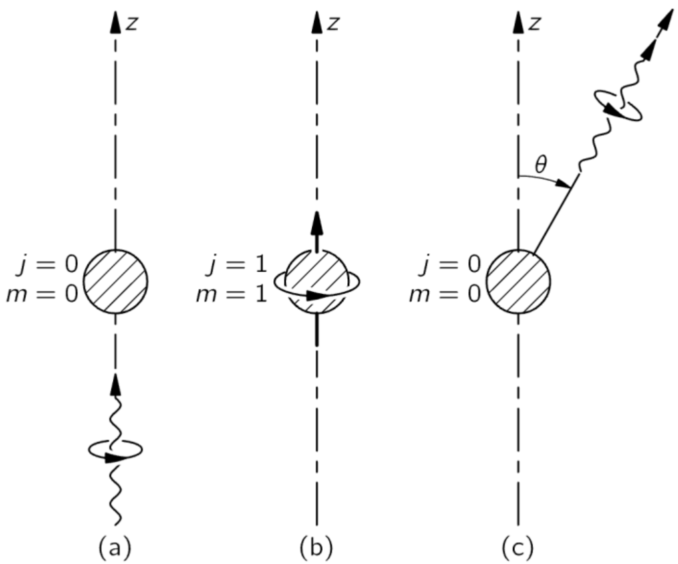
Heavy exchange $\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$, $\dot{\varphi}^2\sigma$ and "ortho"

Planck Team, 1303.5084

LSS: Cabass, Philcox, Ivanov, Akitsu, Chen, Simonovic, Zaldarriaga, 2404.01894

CMB: Sohn, Wang, Fergusson, Shellard, 2404.07203

How to determine angular momentum?



$$a\langle + \,|\, R_y(\theta) \,|\, + \rangle = \frac{a}{2}\,(1+\cos\theta)$$

Combinations of RHC, LHC,

convert to linear polarizations: $P_j\ (\cos\theta)$

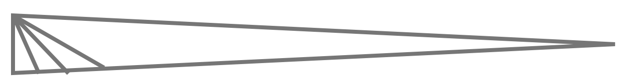


Figure from https://www.feynmanlectures.caltech.edu/III_18.html

Extracting the particle physics data

From correlation $\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \cdots \rangle$:

Extract mass: $(\mathrm{k\ ratios})^{\pm i\mu}$ Chen, YW, 0911.3380

Extract spin: $P_J(\cos\theta)$ Arkani-Hamed, Maldacena, 1503.08043

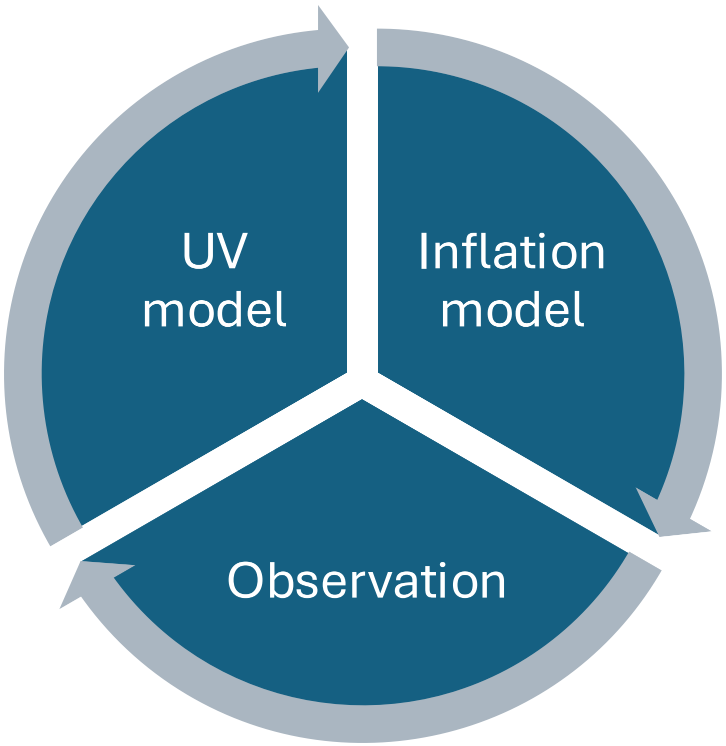
Extract parity: $\mathrm{Im}\,\langle \cdots \rangle$ Liu, Tong, YW, Xianyu, 1909.01819

Extract width: $(\mathrm{k\ ratios})^{-\frac{3}{2}-\alpha}$ Lu, Reece, Xianyu, 2108.11385

Empowered by bootstraps Arkani-Hamed, Baumann, Lee, Pimentel, 1811.00024, ...

How it compares to traditional methods?

HEP from Inflation (Traditional)



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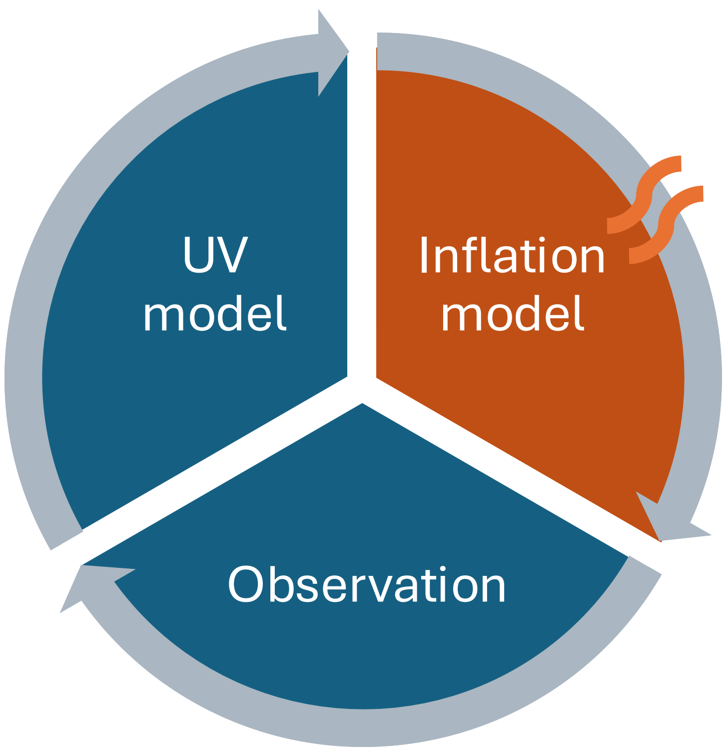

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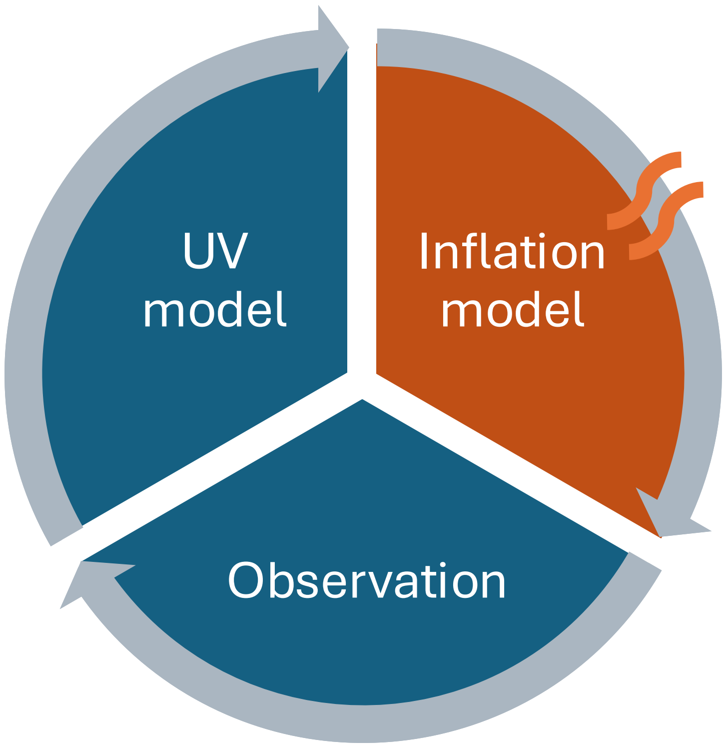
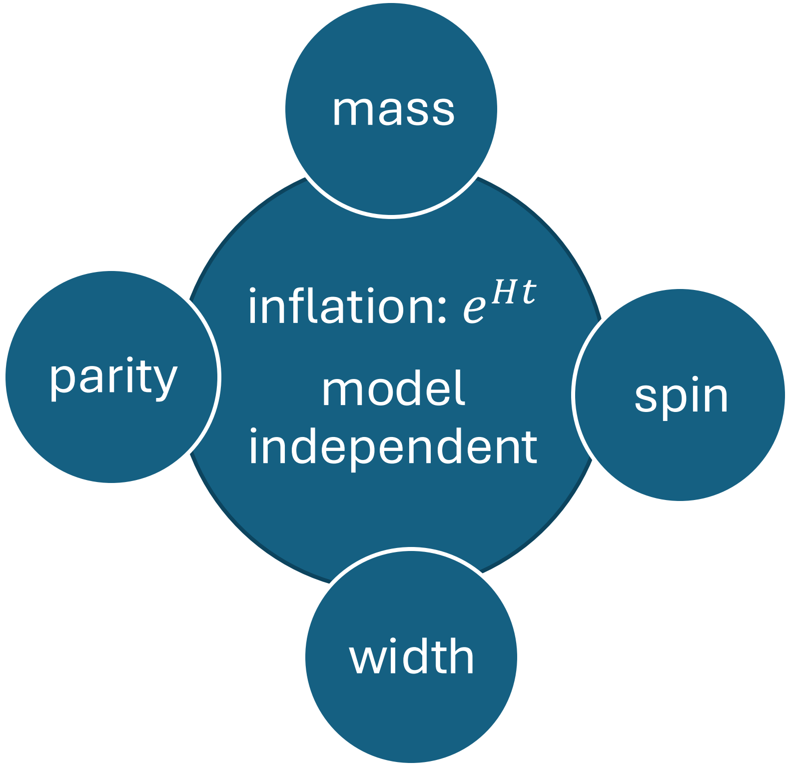


Cosmological Collider



Plan

- Introduction
- Why $m \sim H$? $\Longrightarrow$ related particle physics
- Towards $m \gg H$? $\Longrightarrow$ chemical potential
- Field redefinition / boundary interactions

Why $m \sim H$?

(1) Dynamical: $\mathcal{L} \sim -(\partial\varphi)^2 - \lambda\varphi^4$

massless $\Rightarrow \langle\varphi^2\rangle \sim H^2$

Note: $\varphi^4 \supset \langle\varphi^2\rangle\, \varphi^2$

$\Rightarrow \quad m_{\text{eff}}^2 \sim \langle\varphi^2\rangle \sim H^2$

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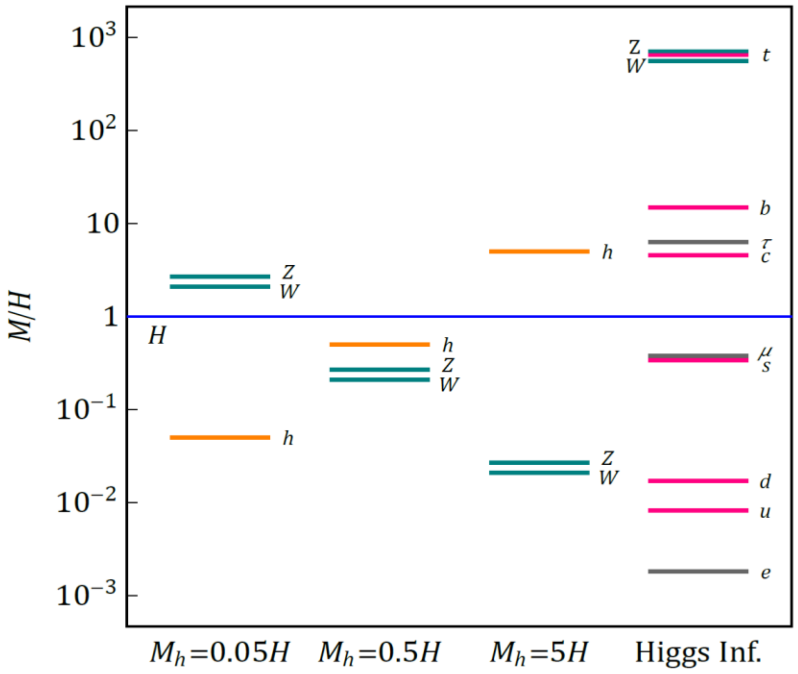
Example: Standard Model

Chen, YW, Xianyu,

1604.07841; 1610.06597; 1612.08122;

Kumar, Sundrum, 1711.03988



Why $m \sim H$?

(1) Dynamical: $\langle \varphi^2 \rangle \sim H^2$

(2) Non-minimal: $\varphi^2 R \sim H^2 \varphi^2$

Thus, Higgs may be in unbroken/broken phases

Chen, YW, Xianyu,

1604.07841; 1610.06597; 1612.08122;

Kumar, Sundrum, 1711.03988

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(3) Supersymmetry: broken at least at $M \sim H$

Baumann, Green, 1109.0292

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(2) Non-minimal: $\varphi^2 R \sim H^2 \varphi^2$

(3) Supersymmetry: broken at least at $M \sim H$

(4) Coincidental

Neutrino seesaw: Chen, YW, Xianyu, 1805.02656

Grand unification: Kumar, Sundrum, 1811.11200

… …

Beyond $m \sim H$?

Strings? Quantum gravity? …

$$\text{Prob} \sim e^{-\frac{m}{H/2\pi}}, \quad \langle \ldots \rangle \sim \sqrt{\text{Prob}} \sim e^{-\pi\, m/H} \text{ suppressed}$$

Making use of more than "temperature"?

Kinetic energy of inflaton:

$$P_\zeta = \left(\frac{H^2}{2\pi\,\dot{\varphi}}\right)^2 \sim 2 \times 10^{-9} \quad \Longrightarrow \quad \sqrt{\dot{\varphi}} \sim 60\, H$$

How to use $\sqrt{\dot{\varphi}}$?

Beyond $m \sim H$?

How to use $\sqrt{\dot{\varphi}} \sim 60\ H$?

- Classical oscillation or periodic potential?

  Chen 1104.1323; Chen, Namjoo, Wang: 1411.2349;

  Flauger et al, 1606.00513; Chen, Ebadi, Kumar, 2205.01107

- Warm inflation? Tong, YW, Zhou, 1801.05688
- Distorted signals with varying mass?
- Chemical potential Chen, YW, Xianyu 1805.02656
  Wang, Xianyu 1910.12876
  Sou, Tong, YW, 2104.08772

Beyond $m \sim H$?

Chemical Potential: Three questions converge to one answer

(1) Theoretical dreaming: How to use $\sqrt{\dot{\varphi}} \sim 60\ H$?

(2) Theoretical reasoning: How to couple to inflaton?

(a) Shift symmetry: couples to $\partial\varphi$

(b) EFT: lowest dimension operators: dim-5

$\frac{1}{\Lambda}\left(\partial_\mu \phi\right) \bar{\psi}\gamma^5\gamma^\mu\psi,\ \frac{1}{\Lambda}\ \phi\ F\tilde{F}$, (scalars?)

Note: c_s is higher dimensional, though historically studied more

Beyond $m \sim H$?

Chemical Potential: Three questions converge to one answer

(1) Theoretical dreaming: How to use $\sqrt{\dot{\varphi}} \sim 60\,H$?

(2) Theoretical reasoning: dim-5 $\frac{1}{\Lambda}(\partial_\mu \phi)\,\bar{\psi}\gamma^5\gamma^\mu\psi,\ \frac{1}{\Lambda}\,\phi F\tilde{F}$

(3) Parity odd operators

Chemical potentials $\mu N \to \partial_\mu \phi \ J^\mu$

Long history in cosmology, e.g., Spontaneous Baryogenesis, Cohen, Kaplan, 1988

$e^{-\pi m/H}$ $\to$ subsidy by N $\to$ $e^{-\pi(m-\mu)/H}$

Chen, YW, Xianyu, 1805.02656
Wang, Xianyu, 1910.12876

Various spins:

- Scalar $\mathcal{L} = [(\partial_t + \mathrm{i}\mu)\Phi^*][(\partial_t - \mathrm{i}\mu)\Phi] - |\partial_i \Phi|^2 - m^2|\Phi|^2$

  Can be rotated away by $\Phi \to e^{i\mu t}\,\Phi$ (Wang, Xianyu, 1910.12876)

  Symmetry breaking (Bodas, Kumar, Sundrum, 2010.04727)

- Spinor $\frac{1}{\Lambda}(\partial_\mu\phi)\bar{\Psi}\gamma^5\gamma^\mu\Psi$ Chen, YW, Xianyu, 1805.02656; Wang, Xianyu, 1910.12876
- Vector $-\phi F\widetilde{F}/(4\Lambda)$ Lu, YW, Xianyu, 1907.07390; Wang, Xianyu, 1910.12876
- Tensor $\frac{1}{4\Lambda^3}\phi W_{\mu\nu\rho\sigma}\widetilde{W}^{\mu\nu\rho\sigma}$ Wang, Xianyu, 1910.12876; Tong, Xianyu, 2203.06349

Dim 5 operators of the scalar sector?

Hope to keep shift symmetry of ϕ (plenty otherwise)

Studied already: $\frac{\sqrt{-g}}{\Lambda}\, h\, \partial\phi\, \partial\phi$ (the first operator studied)

Other dim 5 scalar operators? $\rightarrow \frac{\sqrt{-g}}{\Lambda}\, h\, \partial h\, \partial\phi$

(Wang, Wang, YW, Yu, to appear)

Question: is it trivial? Viewpoints:

(1) Field redefinition: $\phi = \tilde{\phi} + \frac{1}{2\Lambda} h^2 \rightarrow$ free $-\frac{1}{2}(\partial\tilde{\phi})^2$

(2) Using IBP: reduced to $\partial\,(\frac{\sqrt{-g}}{2\Lambda}\, h^2\, \partial\phi) - \frac{\sqrt{-g}}{2\Lambda}\, h^2 \Box\phi$

Field redefinition: $\phi = \tilde{\phi} + \frac{1}{2\Lambda} h^2 \to$ free $-\frac{1}{2}(\partial\tilde{\phi})^2$

$$\Delta_\sigma = \tfrac{3}{2} - \nu, \quad x_{ij} = |\mathbf{x_i} - \mathbf{x_j}|$$

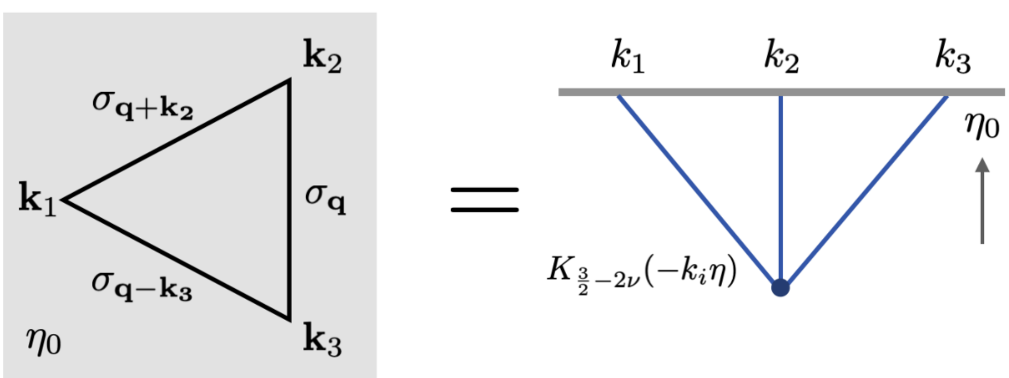
Then in x-space:

$$\langle \phi(\mathbf{x}_1)\phi(\mathbf{x}_2)\phi(\mathbf{x}_3)\rangle = \frac{1}{8\Lambda^3}\langle \sigma(\mathbf{x}_1)^2\sigma(\mathbf{x}_2)^2\sigma(\mathbf{x}_3)^2\rangle = \frac{C_\sigma^3 \eta_0^{6\Delta_\sigma}/8\Lambda^3}{x_{12}^{2\Delta_\sigma} x_{23}^{2\Delta_\sigma} x_{31}^{2\Delta_\sigma}}$$

in p-space:

$$\langle \phi_{\mathbf{k}_1}\phi_{\mathbf{k}_2}\phi_{\mathbf{k}_3}\rangle' = \left(-\frac{\eta_0}{2}\right)^{9-6\nu} \frac{H^6}{\pi^3\Lambda^3}\Gamma(\nu)^6 I_\nu(k_1,k_2,k_3),$$

$$I_\nu = \frac{\pi^{-\frac{3}{2}}2^{-\frac{1}{2}}}{\Gamma\left(\frac{3\Delta-3}{2}\right)\Gamma\left(\frac{3-\Delta}{2}\right)^3}(k_1k_2k_3)^{\Delta-\frac{3}{2}}\int_{-\infty}^{0} d\eta(-\eta)^{1/2}$$
$$\times K_{\Delta-3/2}(-k_1\eta)K_{\Delta-3/2}(-k_2\eta)K_{\Delta-3/2}(-k_3\eta),$$

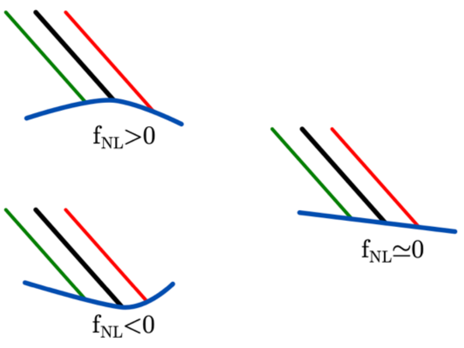


"Dual" to a tree diagram,

composite conform dim

Field redefinition: $\phi = \tilde{\phi} + \frac{1}{2\Lambda} h^2 \rightarrow \text{free} -\frac{1}{2}(\partial\tilde{\phi})^2$

Alternative view: modulated reheating



The ϕ theory: trivial reheating surface

The $\tilde{\phi}$ theory: non-trivial reheating surface

Thus "field redefinition" can be considered as

a particle-physics-realization of modulated reheating

Using IBP: reduced to $\partial\,(\frac{\sqrt{-g}}{2\Lambda}\;h^2\;\partial\phi) - \frac{\sqrt{-g}}{2\Lambda}\;h^2\Box\phi$

(1) $\frac{\sqrt{-g}}{2\Lambda}\;h^2\Box\phi$: since ϕ is on-shell, $\Box\phi\approx 0$

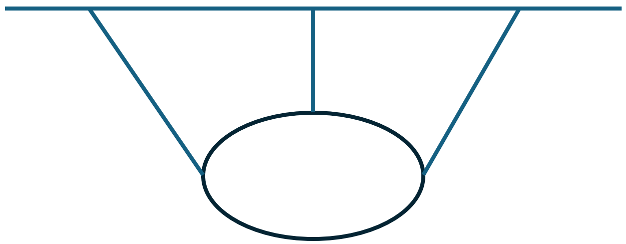
(if not on-shell: $\Box$ on Green's function $\rightarrow\delta$-function)

(2) $\partial\,(\frac{\sqrt{-g}}{2\Lambda}\;h^2\;\partial\phi)$: agrees with field redefinition

Wang, Wang, YW, Yu, to appear

A systematic study: Ma, Wang, Wang, YW, Yu, in prep.

Non-Gaussianities of $h\,\partial h\,\partial\phi$



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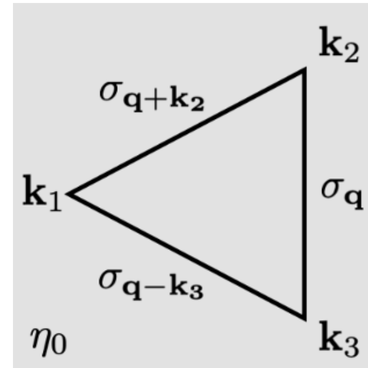
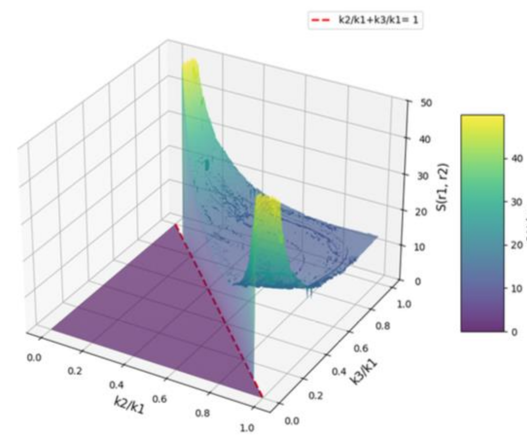


Squeezed limit:

$$I_{\text{signal}} \sim \frac{(H\eta_0)^6\,(k_1\eta_0)^{3-6\nu}\,(-2)^{6\nu-11}\sin\nu\pi}{\Lambda^3(\pi)^{9/2}}\Gamma(\nu)^4\,\Gamma\left(\begin{matrix}2\nu-2,\,2\nu-\frac{3}{2},\,-\nu+\frac{3}{2}\\ \nu-\frac{1}{2}\end{matrix}\right)\left(\frac{k_3}{k_1}\right)^{3-4\nu}.$$



See also a tree diagram when h has VEV

Summary

- Cosmological collider

    mass, angular momentum, width

    $m \sim H$: standard model & beyond

- Chemical potential

    $m \gg H$, enhanced rate & parity

- Boundary interactions

    New terms overlooked in the literature

Acknowledgement: supported in part by the RGC of Hong Kong, Projects 16303621, 16306422 and RFS2425-6S02