Probing Particle Physics with the Cosmological Collider

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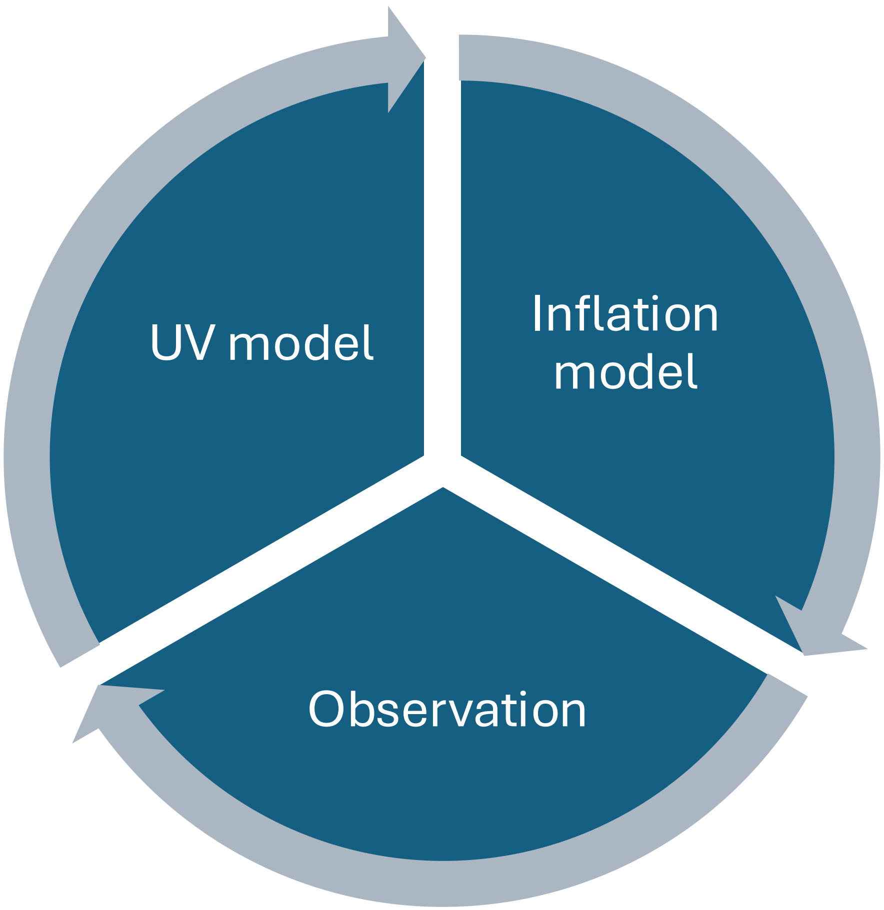
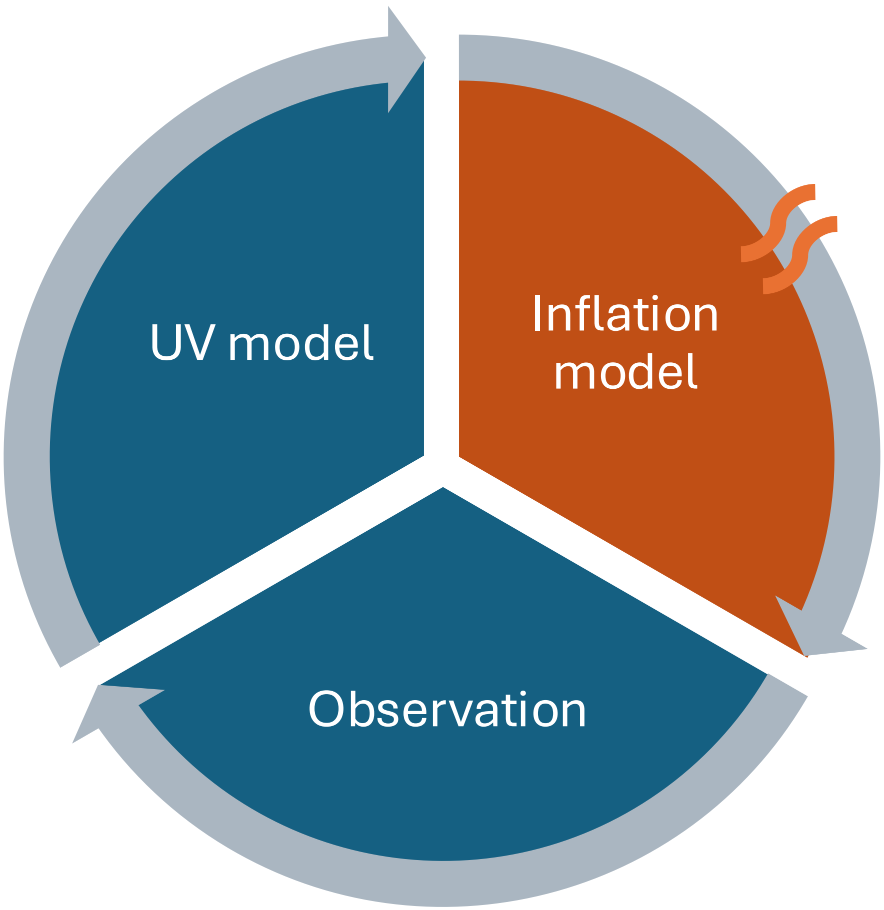
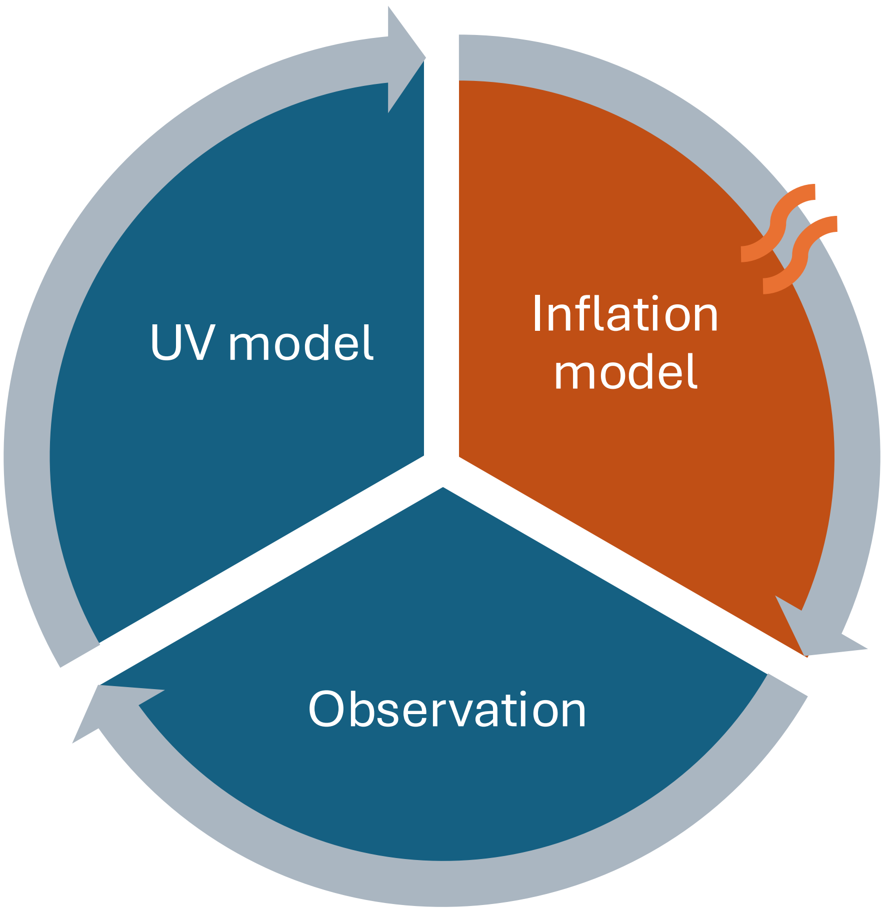
HEP from Inflation (Traditional)



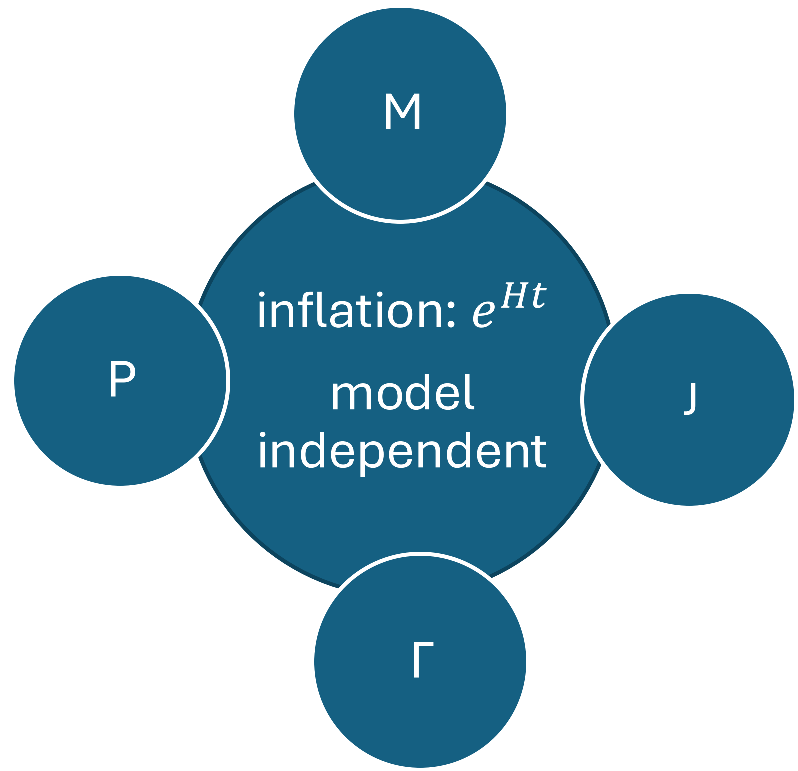
HEP from Inflation (Traditional)



HEP from Inflation (Traditional)



Cosmological Collider



Chen, YW, 0911.3380; Arkani-Hamed, Maldacena, 1503.08043
See also: Baumann, Green, 1109.0292; Noumi, Yamaguchi, Yokoyama, 1307.7110

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

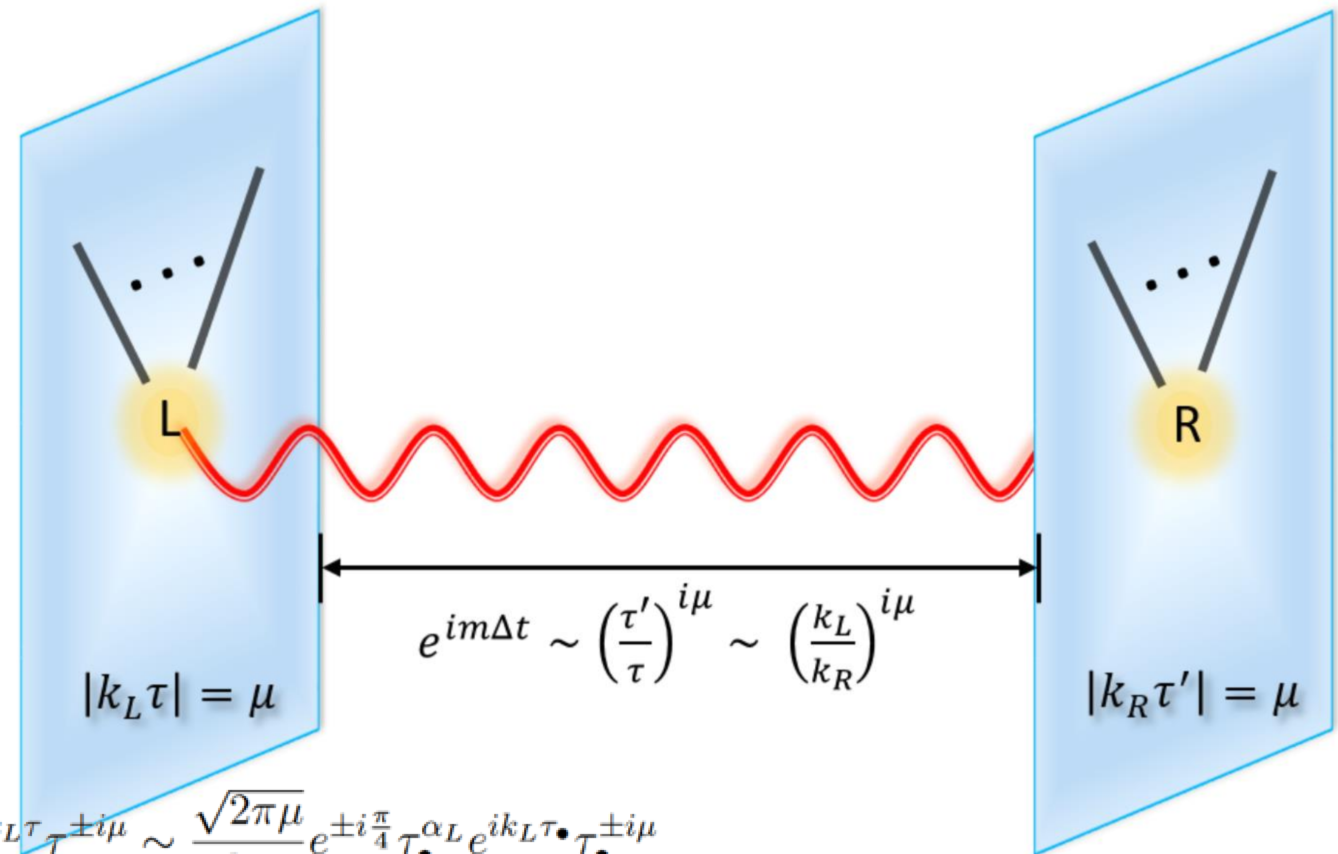
Extract angular momentum: $P_S(\cos\theta)$ Arkani-Hamed, Maldacena, 1503.08043

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

Example: How to extract mass?

Local Particle Production on Vertices



$$\int d\tau\, \tau^{\alpha_L} e^{ik_L\tau} \tau^{\pm i\mu} \sim \frac{\sqrt{2\pi\mu}}{k_L} e^{\pm i\frac{\pi}{4}} \tau_\bullet^{\alpha_L} e^{ik_L\tau_\bullet} \tau_\bullet^{\pm i\mu}$$

Figure: Tong, Zhu, YW, 2112.03448
See also Qin, Xianyu, 2208.13790

Non-local Particle Production on Propagators

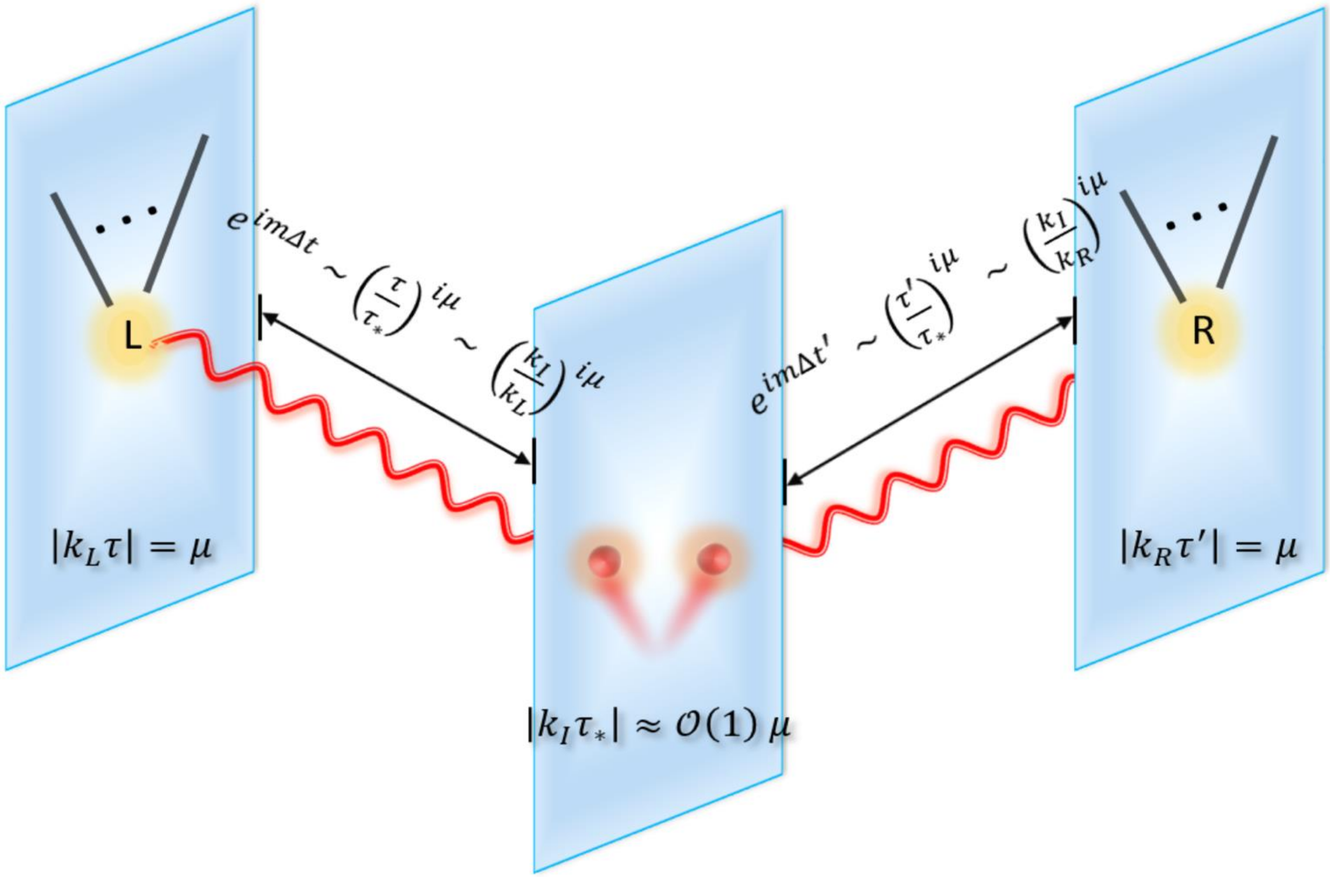


Figure: Tong, Zhu, YW, 2112.03448
See also Qin, Xianyu, 2208.13790

Imprints on observables:

- Curvature
- Isocurvature

Higgs: Lu, YW, Xianyu, 1907.07390
Curvaton: Kumar, Sundrum, 1908.11378
Axion: Lu, 2103.05958

- Primordial gravitational waves

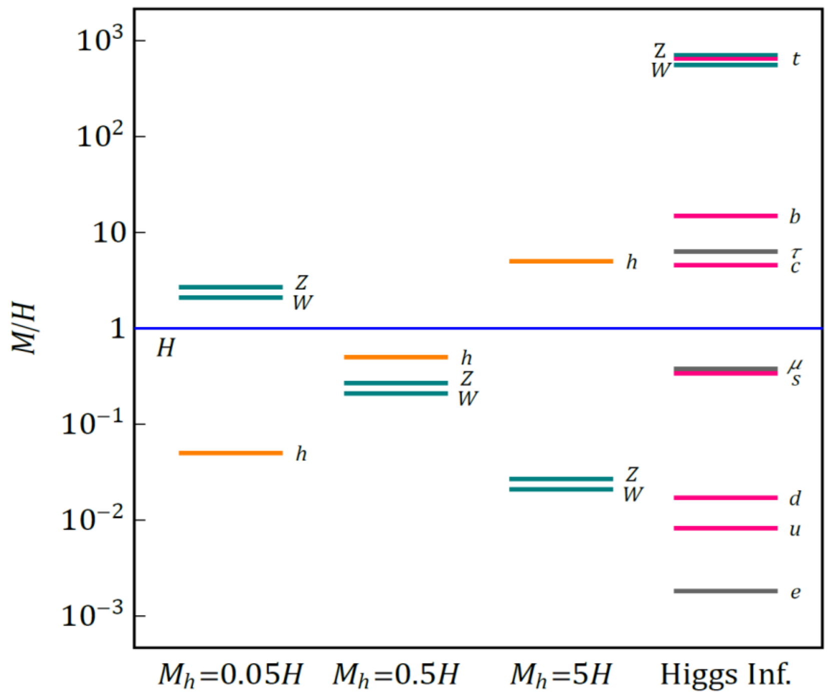
YW, Zhu, 2001.03879

Plan:

- Heavy particles (✓)
- What can we learn? (← _ ←)
- Chemical potential
- Party violation

What can we learn?

- Cosmological collider signals
  - Individual particles: mass, spin, lifetime, parity
  - Particle physics models: Standard Model



$\langle h^2 \rangle \sim H^2$

$\lambda h^4 \supset \lambda \langle h^2 \rangle h^2 \sim m_{\text{eff}}^2 h^2$

Also: possible $h^2 R \sim H^2 h^2$

Chen, YW, Xianyu, 1604.07841; 1610.06597; 1612.08122; Kumar, Sundrum, 1711.03988

What can we learn?

- Cosmological collider signals
  - Individual particles: mass, spin, lifetime, parity
  - Particle physics models: Standard Model
  - Particle physics models: BSM

SUSY: Baumann, Green, 1109.0292

Neutrino seesaw: Chen, YW, Xianyu, 1805.02656

Grand unification: Kumar, Sundrum, 1811.11200

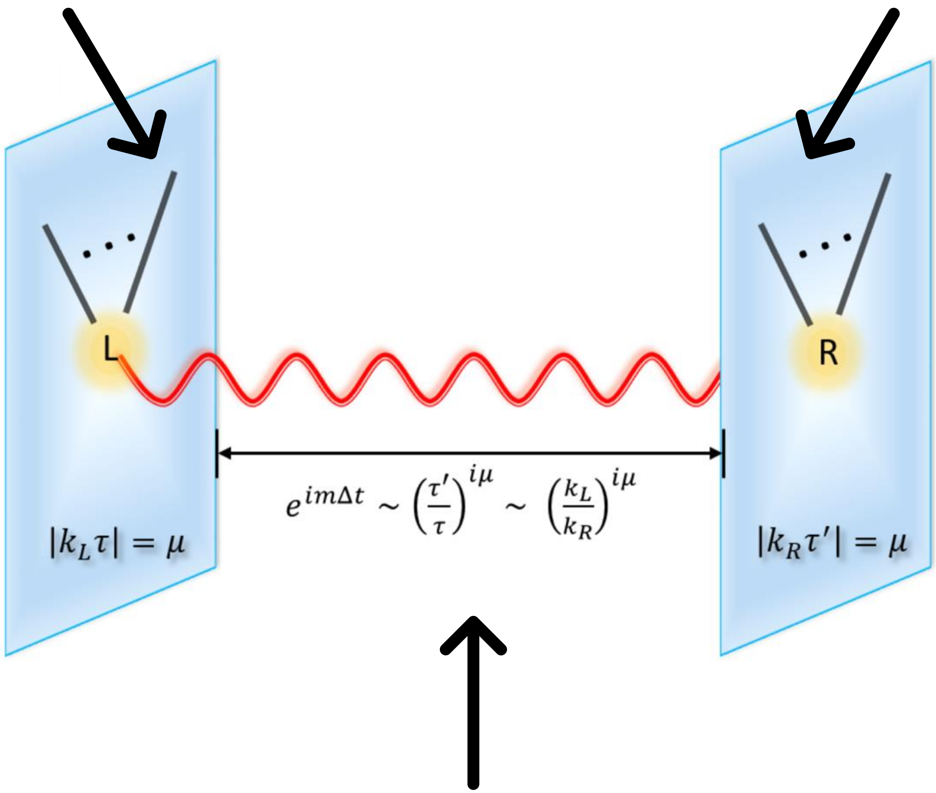
… …

What can we learn?

- Cosmological collider signals
  - Individual particles: mass, spin, lifetime, parity
  - Particle physics models: Standard Model
  - Particle physics models: BSM
  - A quantum "primordial standard clock"

Classical standard clocks: Chen, 1104.1323, 1106.1635
Quantum standard clocks: Chen, Namjoo, YW, 1509.03930

Light modes: tells conformal time τ



Heavy modes: tells physical time t

Correlation:

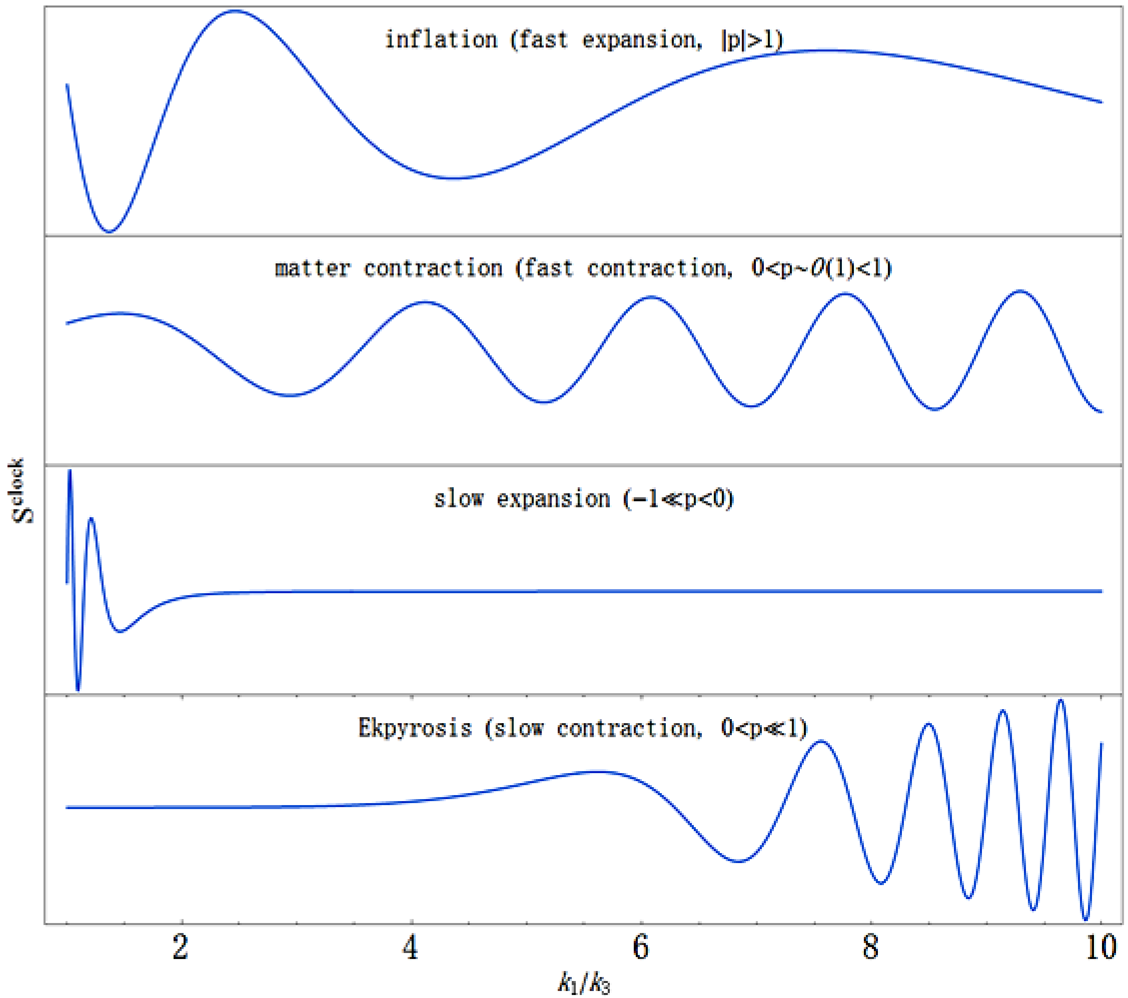
Can tell

$a(t) = dt/d\tau$

$$a(t) = a_0 \left(\frac{t}{t_0}\right)^p$$

$$\int_{\tau_{\rm begin}}^{\tau_{\rm end}} d\tau g(t) e^{imt} e^{-iK\tau}$$

$$\to \sqrt{2\pi} g(t_*) \left(\frac{m}{|H_{k_0}|}\right)^{1/2} K^{-1} \left(\frac{K}{k_0}\right)^{1/2p} \exp\left[-i\frac{p^2}{1-p}\frac{m}{H_{k_0}}\left(\frac{K}{k_0}\right)^{1/p} \mp i\frac{\pi}{4}\right]$$



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  - Individual particles: mass, spin, lifetime, parity
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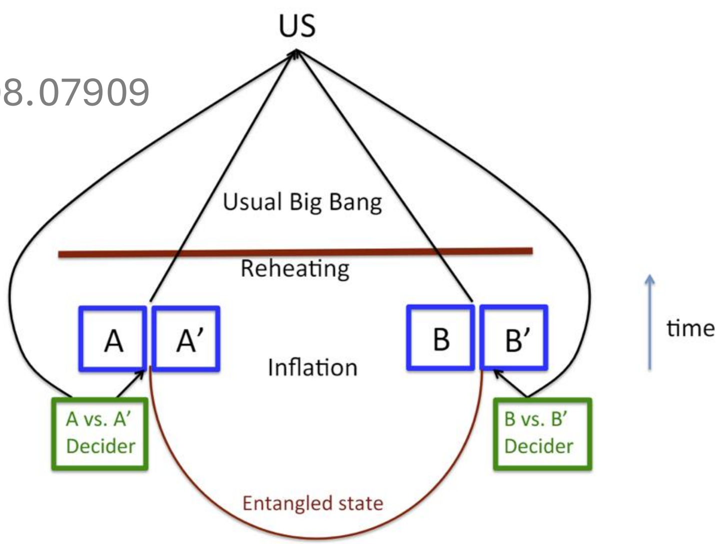
  - A quantum “primordial standard clock”
  - Probing quantum mechanics

Bell test: Maldacena, 1508.01082
Against decoherence: Liu, Sou, YW, 1608.07909



What can we learn?

- Cosmological collider signals
  - Individual particles: mass, spin, lifetime, parity
  - Particle physics models: Standard Model
  - Particle physics models: BSM
  - A quantum "primordial standard clock"
  - Probing quantum mechanics
  - Testing modified gravity (?)

$$ds^2 = -(1-2\Phi)dt^2 + (1-2\Psi)dx^2 + \cdots$$

  - Distorted cosmological colliders (?)

$$f(\varphi)\sigma^2$$

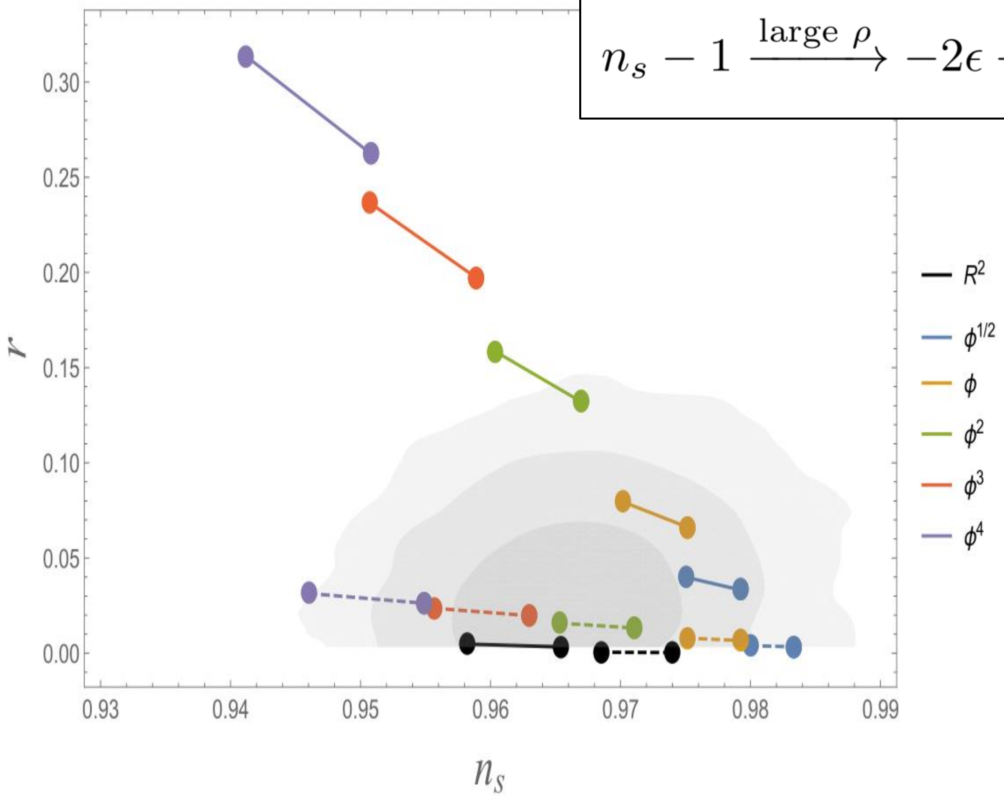
e.g., particle production: J, Γ, P are still valuable

For models like Romano, Sasaki, 0809.5142, Barnaby, Huang, 0909.0751

What can we learn?

- Cosmological collider signals
- By-products:
    - Corrections on the n_s-r diagram

$$n_s - 1 \xrightarrow{\text{large } \rho} -2\epsilon - \frac{3}{4}\eta$$



$\delta\sigma$ is additional source

→ Enhance P_ζ

→ Lower H

→ Lower r

→ Saves $m^2\varphi^2$

Jiang , YW, 1703.04477
Tong, YW, Zhou, 1708.01709
See also Achucarro, Atal, Welling 1503.07486
An, McAneny, Ridgway, Wise 1706.09971

What can we learn?

- Cosmological collider signals
- By-products:
  - Corrections on the n_s-r diagram
  - More careful abundance for WIMPZILLAs

Li, Nakama, Sou, YW, Zhou, 1903.08842
Li, Lu, YW, Zhou, 2002.01131
For WIMPZILLAs, see, e.g., Kolb, Chung, Riotto, hep-ph/9810361

What can we learn?

- Cosmological collider signals

  Individual particles, SM, BSM

  As a clock to measure the expansion (or even contraction?) history

  Quantum effects, free from decoherence

  Testing modified gravity (?)

  Cosmological colliders with distorted mass (?)

- By-products

  n_s-r diagram; WIMPZILLAs

- Assisted the advances of tools

  bootstrap, Mellin-Barnes, spectral decomposition, dispersion relation…

Larger signals? Especially removing $e^{-\pi m/H}$ for $m \gg H$?

- Classical oscillation or periodic potential? $\frac{H^2}{\dot{\phi}} \simeq \frac{1}{3600}$

  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

Plan:

- Heavy particles (✓)
- What can we learn? (✓)
- Chemical potential (← _ ←)
- Party violation

EFT power counting:

How to couple inflaton to other fields?

Nice to keep the inflaton shift symmetry: $\partial_\mu \phi$.

Leading: dim-5: $\frac{1}{\Lambda}\left(\partial_\mu \phi\right) \bar{\psi}\gamma^5\psi$, $\frac{1}{\Lambda}\ \phi\ F\tilde{F}$

(see also the scalar mixings & interactions $\partial\phi\partial\sigma$,$\sigma(\partial\phi)^2$)

Note: c_s is higher dimensional, though historically studied more

Chemical potential: $\mu N \to \partial_\mu \phi \ J^\mu$

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)

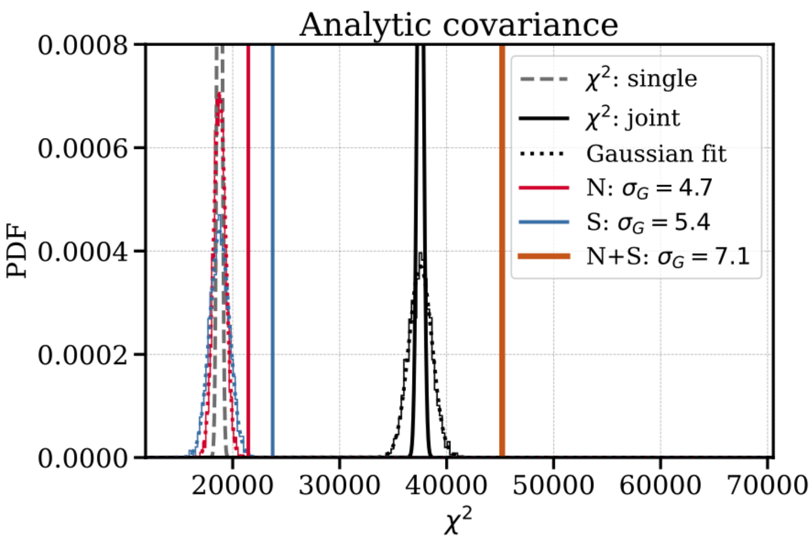
  Symmetry breaking (Bodas, Kumar, Sundrum, 2010.04727)

- 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

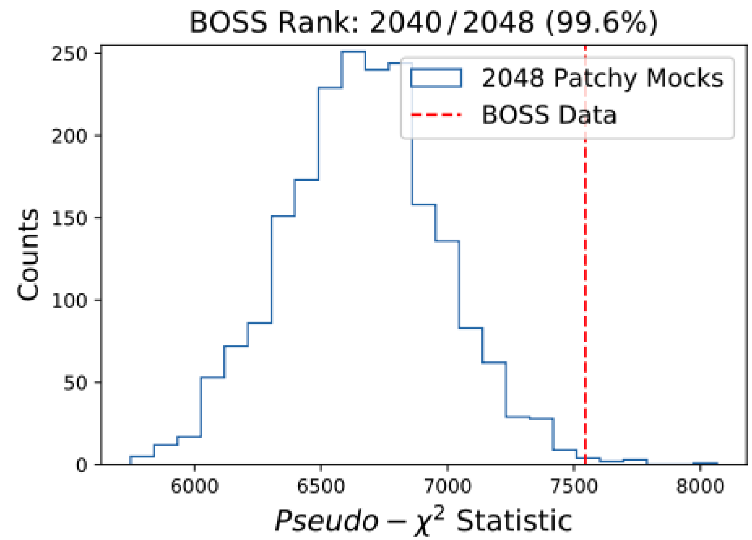
Plan:

- Heavy particles (✓)
- What can we learn? (✓)
- Chemical potential (✓)
- Party violation (← _ ←)

Parity violation in the trispectrum?



7.1σ: Hou, Slepian, Cahn, 2206.03625



2.9σ: evidence Philcox, 2206.04227

1.4σ: Philcox, Ereza, 2401.09523

(Improved estimation of covariance)

New method + attention = standard observable in new data?

The way of Parity —

Chiral fermions, such as only left-handed neutrinos:

Cosmological collider primordial bispectrum: Chen, YW, Xianyu 1805.02656 => trispectrum?

Wenqi Yu, YW, to appear

The way of CP —

CKM-like mixing matrices: Pinol, Aoki, Renaux-Petel, Yamaguchi 2112.05710 => trispectrum?

Axion-like couplings: Liu, Tong, YW, Xianyu, 1909.01819

How cosmological collider naturally violates parity?

Dimension counting of interactions,

preserving the shift symmetry of inflaton: starting from dim 5

- Scalar interaction: $\sigma(\partial\varphi)^2$
- Vector interaction: $\varphi F\tilde{F}$
- Spinor interaction: $(\partial\varphi)\bar{\psi}\,\gamma^5\gamma^\mu\,\psi$

For vector and spinor:

Large signal (chemical potential) + parity violating

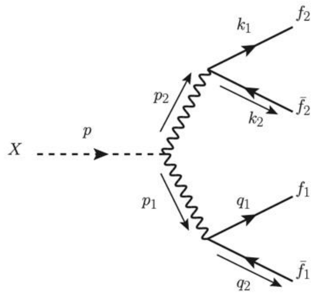
Requirements for parity violating trispectrum

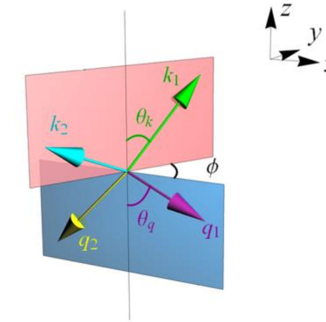
(1) Source of CP violation

(2) Four-point correlation needed

(if observing momenta only)

- Decay-plane correlation

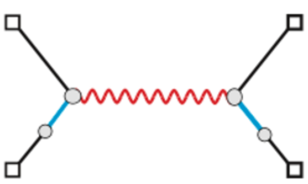




- 3 sets of independent momenta

$$\epsilon^{ijk}(q_1+q_2)_i(q_1-q_2)_j(k_1-k_2)_k$$

- For 3pt, 3D rot makes P trivial



(3) Difference between k_1 & k_2 needed

(4) Imaginary part in k-space

$$\langle\zeta(\vec{k}_1)\ldots\zeta(\vec{k}_4)\rangle - \langle\zeta(-\vec{k}_1)\ldots\zeta(-\vec{k}_4)\rangle$$

No-go theorem: No parity violation if all below

- Massless
- Scale invariant
- IR finite
- BD initial condition
- Local
- Tree level

$$
\begin{aligned}
\tilde{\psi}_4 &\propto i\epsilon^{(3)}(ik_i)^{3+2m}\int_{-\infty}^{0} d\tau a^{1-2m-n}\partial_\tau^n G_+^4 \\
&\propto \epsilon^{(3)}(k_i)^3 \times (k_j)^{2m}\int_{-\infty}^{0} d\tau\tau^{2m+n-1}\partial_\tau^n u^{*4} \\
&\propto \epsilon^{(3)}(k_i)^3 \times (k_j)^{2m}\int_{-\infty}^{0} d\tau\tau^{2m+n-1}\partial_\tau^n \left(1-k\frac{\partial}{\partial k}\right)^4 e^{iK\tau} \\
&\propto \epsilon^{(3)}(k_i)^3 \times (k_j)^{2m}\left(1-k\frac{\partial}{\partial k}\right)^4 \int_{-\infty}^{0} d\tau\tau^{2m+n-1}(iK)^n e^{iK\tau} \\
&\propto \epsilon^{(3)}(k_i)^3 \times (k_j)^{2m}\left(1-k\frac{\partial}{\partial k}\right)^4 (iK)^n(-1)^{n+1}(iK)^{-2m-n}\Gamma(2m+n) \\
&\propto \epsilon^{(3)}(k_i)^3 \times (k_j)^{2m}\left(1-k\frac{\partial}{\partial k}\right)^4 K^{-2m} \in \mathbb{R}\ .
\end{aligned}
$$

Liu, Tong, YW, Xianyu, 1909.01819

More elegant proof from unitarity, etc., see

Cabass, Jazayeri, Pajer, Stefanyszyn, 2210.02907

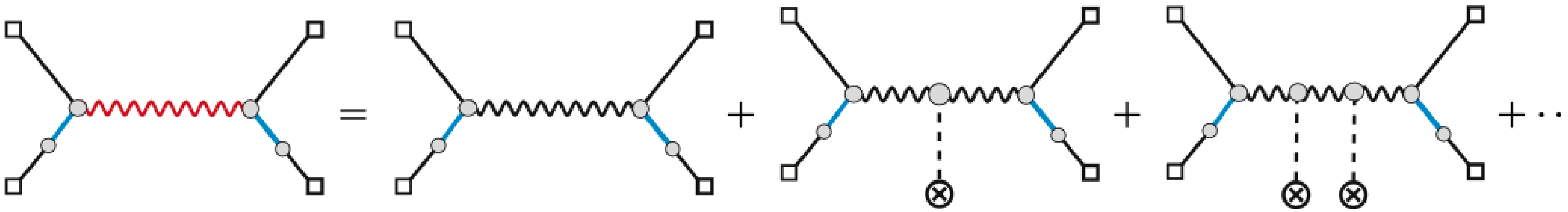
See also

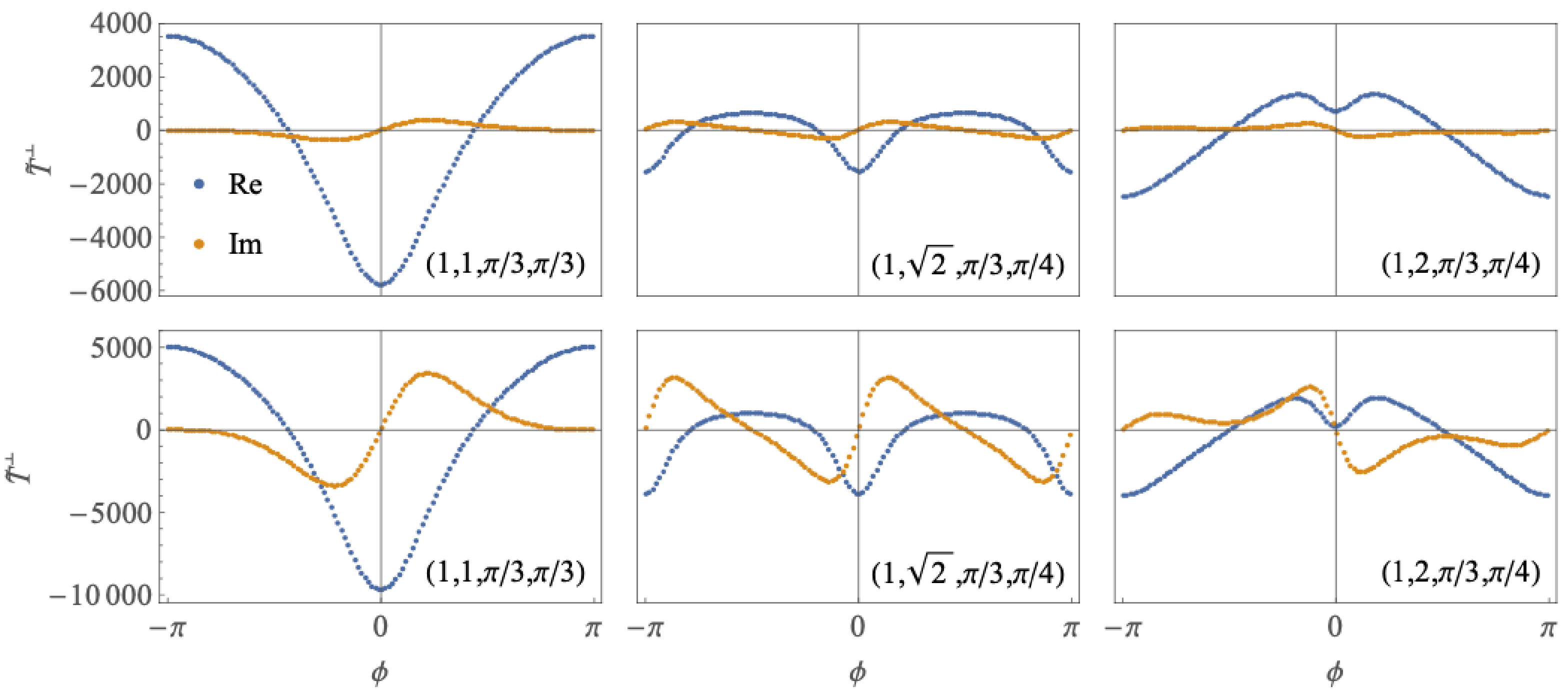
Jazayeri, Renaux-Petel, Tong, Werth, Zhu, 2308.11315

Stefanyszyn, Tong, Zhu, 2309.07769

Example: Z, Higgs and the inflaton

$$\Delta\mathcal{L}_1 = \frac{\rho_{1,Z}}{\dot\phi_0} h\partial_\mu\varphi Z^\mu, \qquad \Delta\mathcal{L}_2 = -\rho_2\dot\varphi h, \qquad \Delta\mathcal{L}_3 = -\frac{c_0}{4}\theta(t)Z_{\mu\nu}Z_{\rho\sigma}\mathcal{E}^{\mu\nu\rho\sigma}$$





Liu, Tong, YW, Xianyu, 1909.01819

Thank you!

Summary:

- Heavy particles

  mass, spin, lifetime, parity

- What can we learn?

  Signal: SM, BSM, dark matter, distorted (?)

  Test: standard clock, quantum mechanics, modified gravity (?)

  By-product: shift the $n_s - r$ diagram

- Chemical potential

  scalar (*), spinor, vector, tensor

- Party violation

  observation, requirement, no-go theorem, vector example