Probing Particle Physics with the Cosmological Collider

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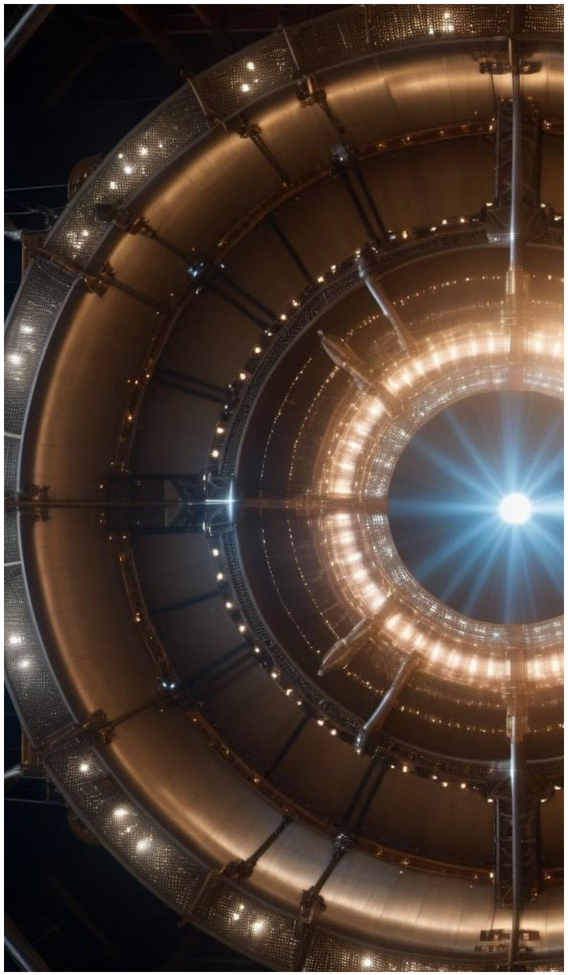
5 Dec 2024

Why the name "Cosmological Collider"?



Looks Similar

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

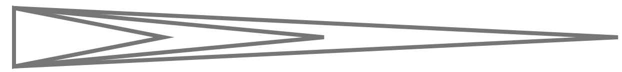
Conserved quantities: $\zeta, h_{ij}, \ldots$

Detectors: CMB, LSS

and more

How to determine particle mass?

Through "how squeezed"



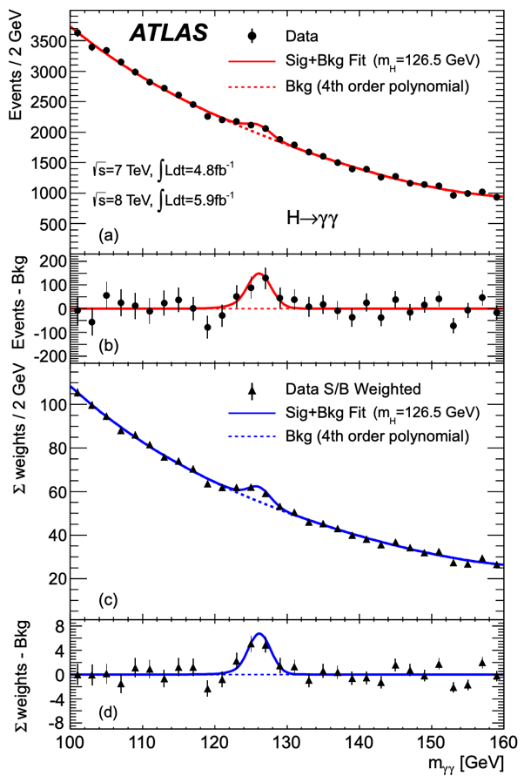
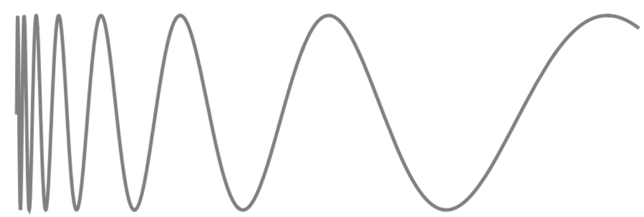


Figure: ATLAS

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

$\Longleftrightarrow$



How to determine particle mass?

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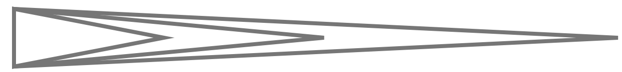

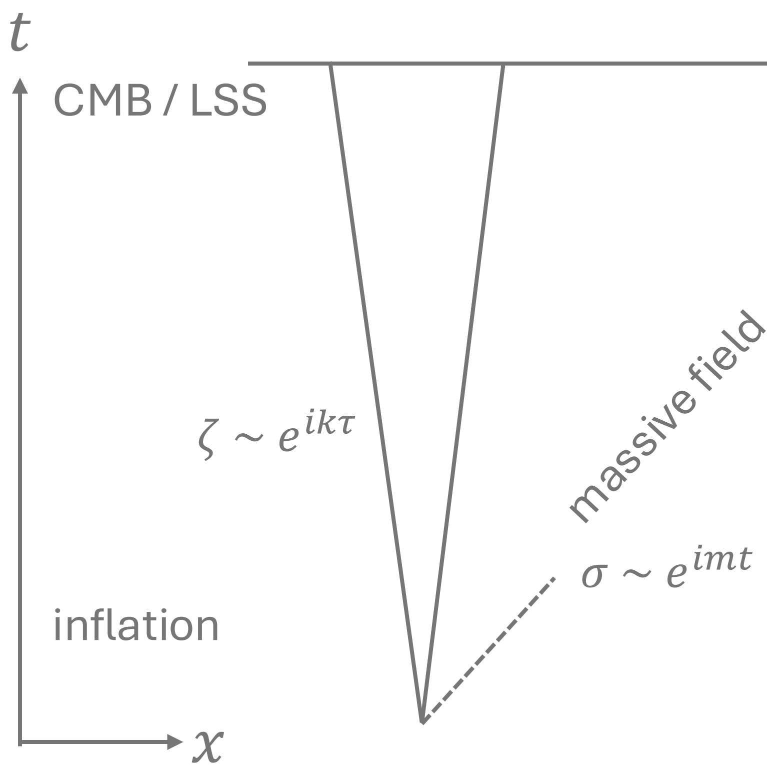

$$ds^2 = -dt^2 + a^2 d\mathbf{x}^2 = a^2\left(-d\tau^2 + d\mathbf{x}^2\right)$$

Chen, YW, 0909.0496, 0911.3380

Baumann, Green, 1109.0292

Noumi, Yamaguchi, Yokoyama, 1211.1624

Arkani-Hamed, Maldacena, 1503.08043

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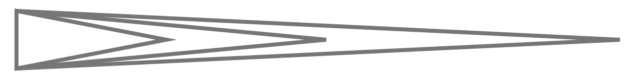
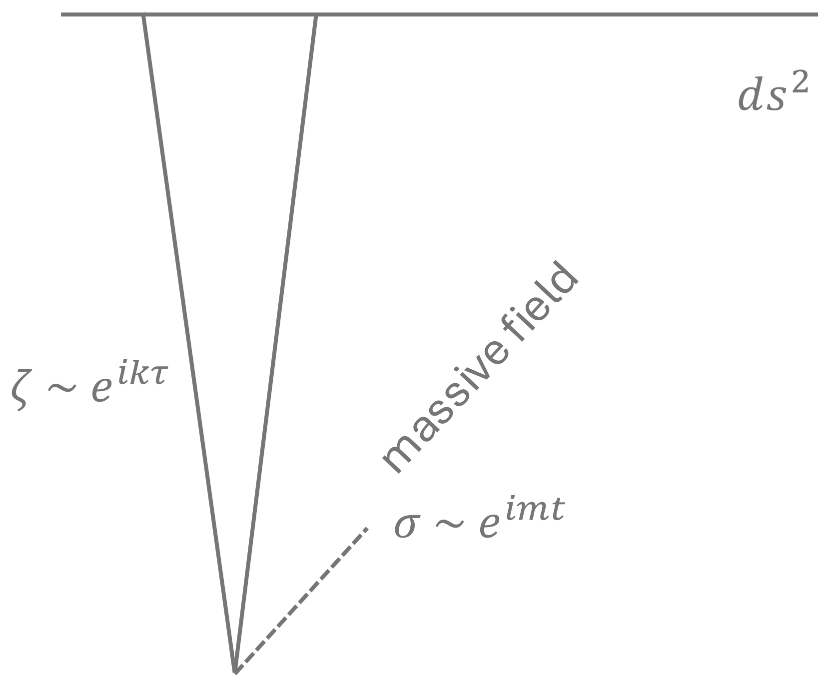


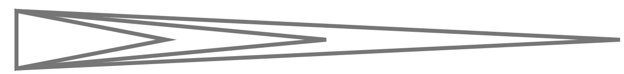


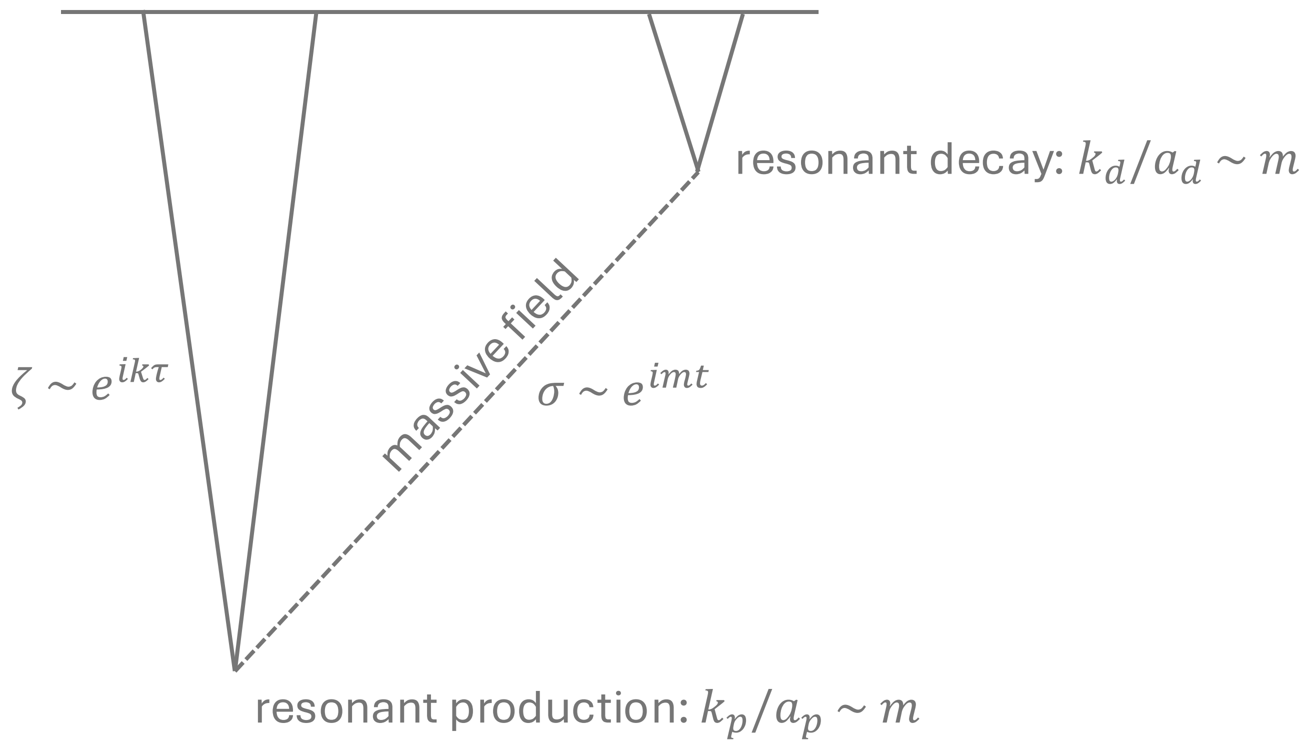
$$ds^2 = -dt^2 + a^2 d\mathbf{x}^2 = a^2 \left(-d\tau^2 + d\mathbf{x}^2\right)$$

resonant production: $k_p/a_p \sim m$

How to determine particle mass?

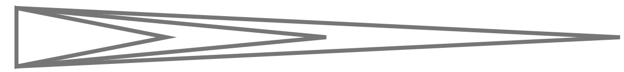
Through "how squeezed"

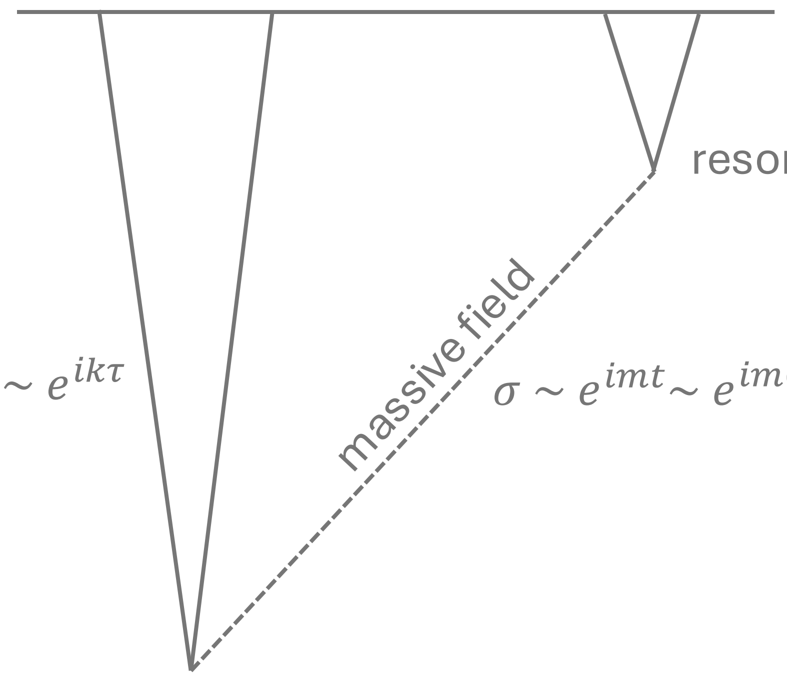




How to determine particle mass?

Through "how squeezed"





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

resonant decay: $k_d/a_d \sim m$

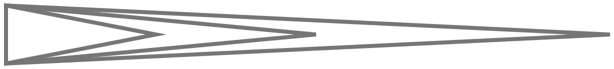
$$\sigma \sim e^{imt} \sim e^{im(t_d - t_p)} \sim e^{i\mu(\ln a_d - \ln a_p)} \sim \left(\frac{a_d}{a_p}\right)^{i\mu} \sim \left(\frac{k_d}{k_p}\right)^{i\mu}$$

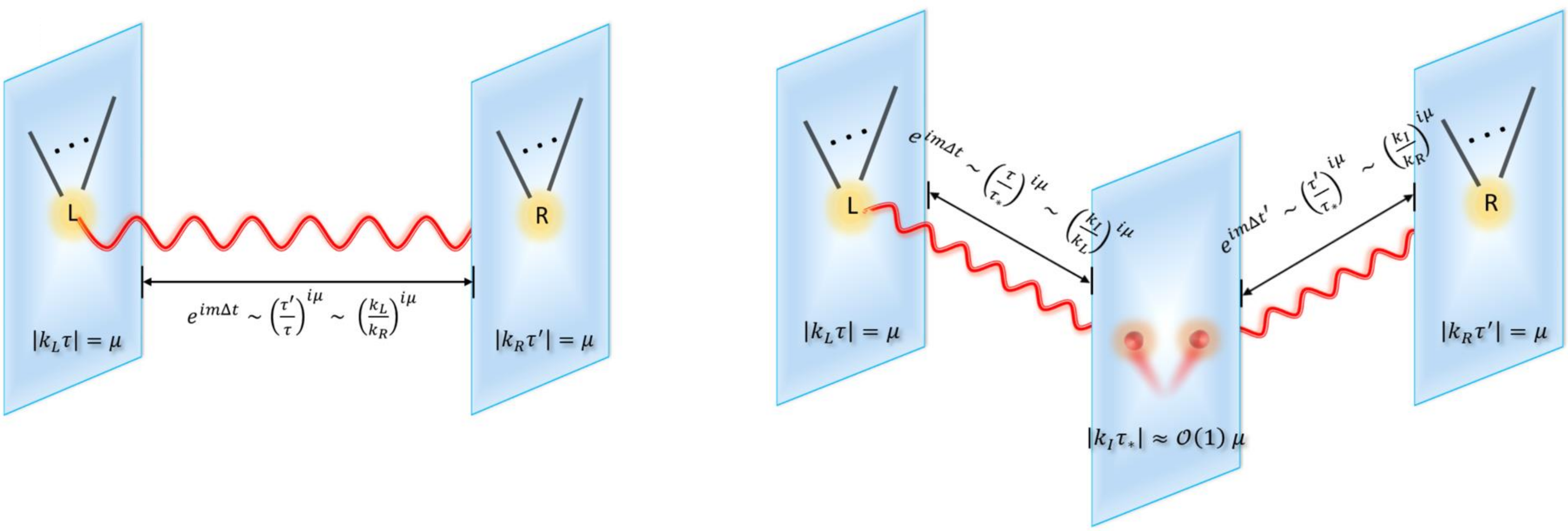
$$\mu \sim \frac{m}{H} = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

resonant production: $k_p/a_p \sim m$

How to determine particle mass?

Through "how squeezed"

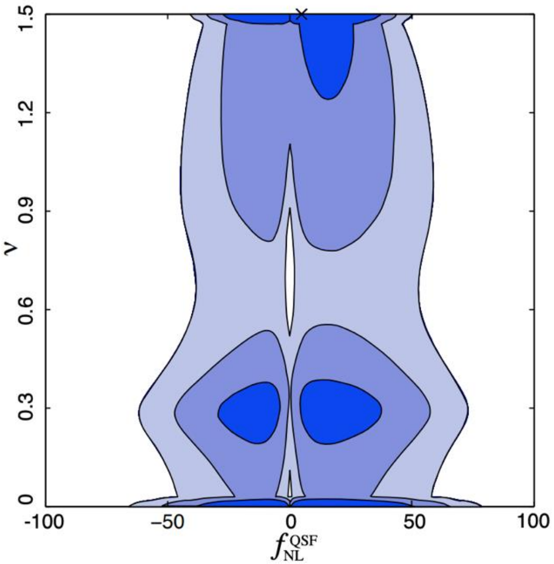


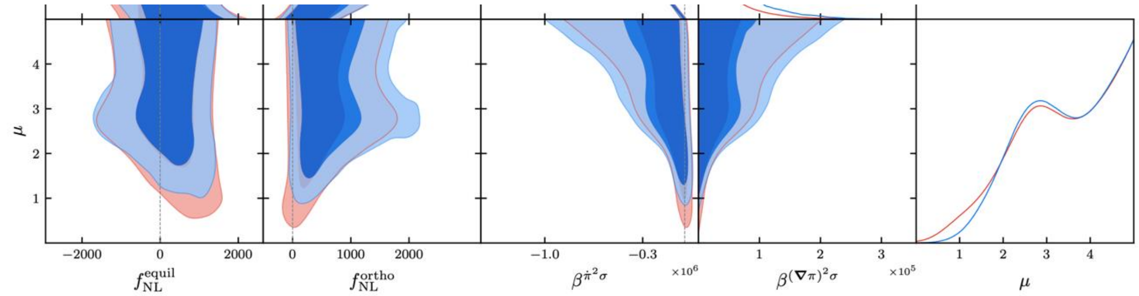


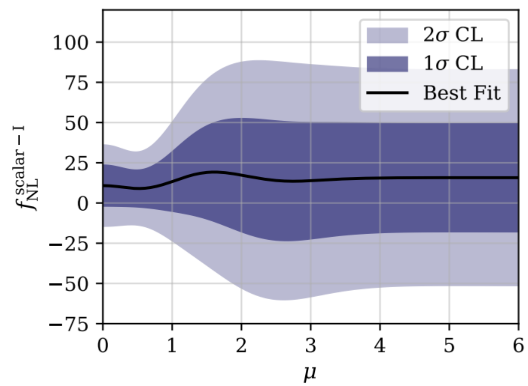
Local vs non-local particle productions

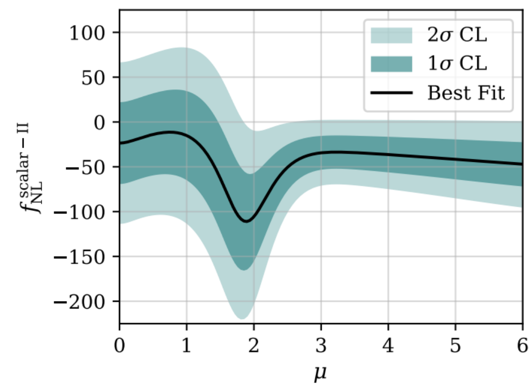
Figure: Tong, Zhu, YW, 2112.03448

Observational searches









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

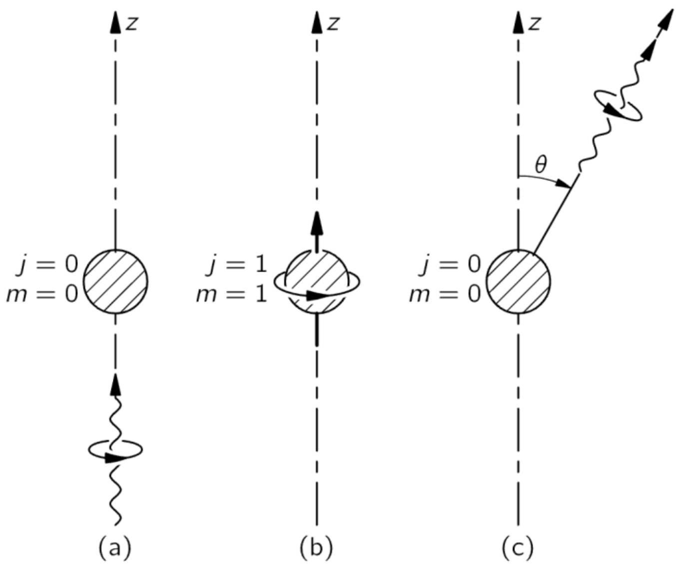
Planck Team, 1303.5084

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

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: $P_j\ (\cos\theta)$

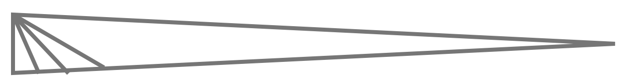


Figure from
https://www.feynmanlectures.caltech.edu/III_18.html

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

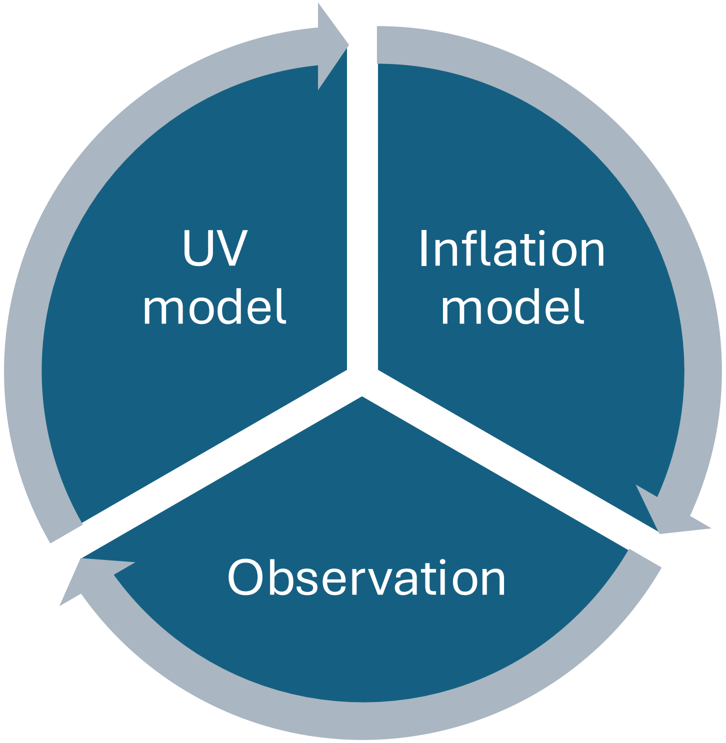
Extract parity: $\mathrm{Im}\,\langle \cdots \rangle$ Liu, Tong, YW, Xianyu, 1909.01819

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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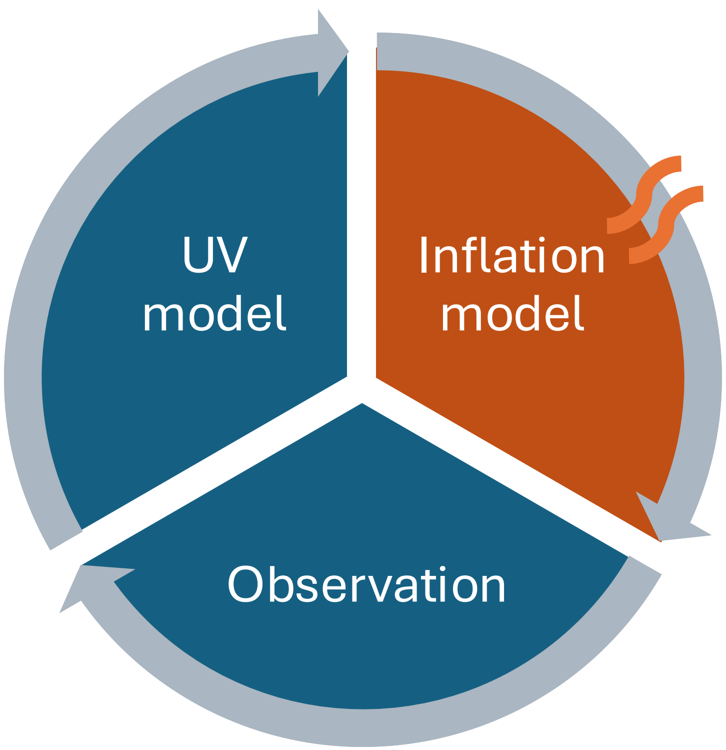

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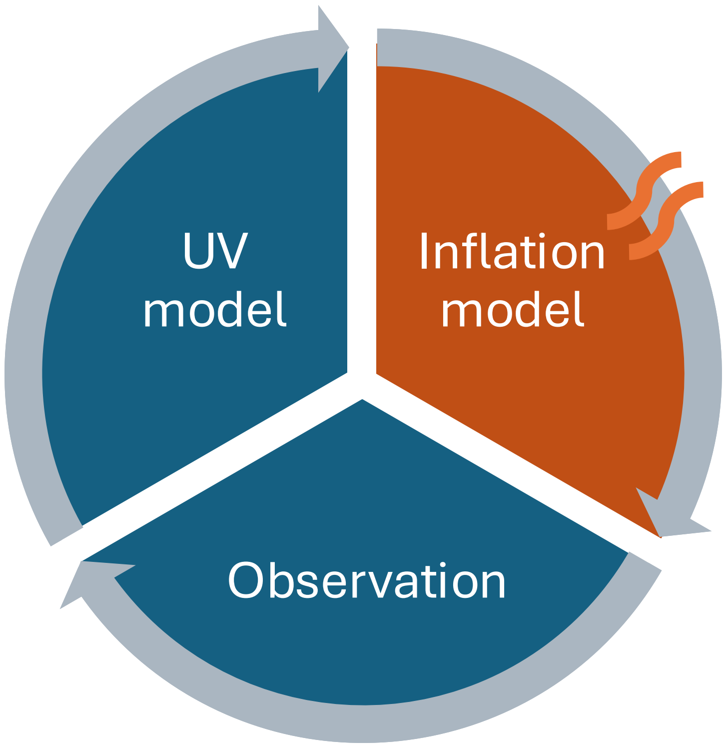
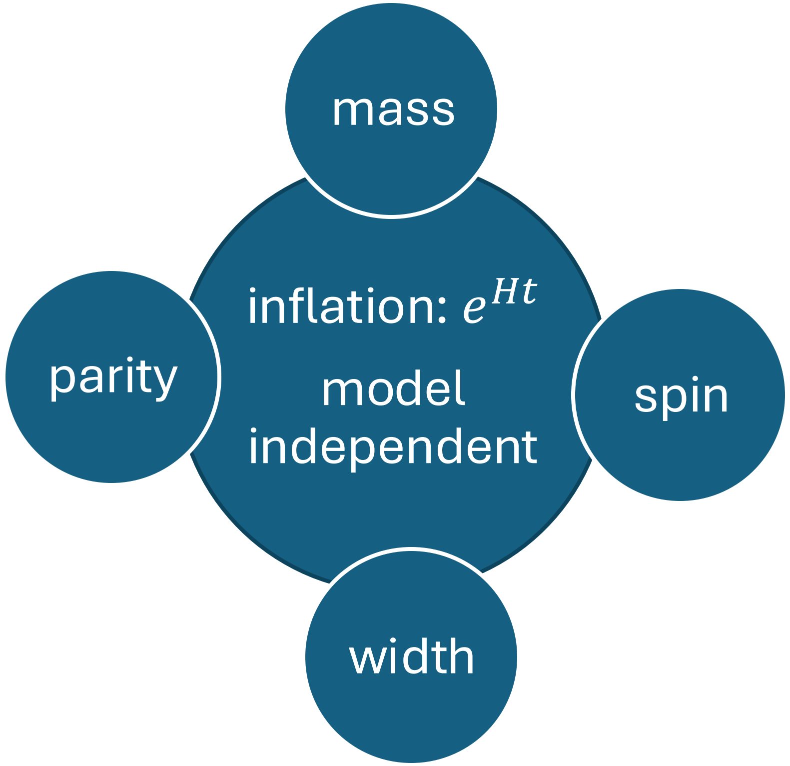


Cosmological Collider



Plan

- Introduction
- Why $m \sim H$? $\Longrightarrow$ related particle physics
- Towards $m \gg H$?
- Parity violation?

$\Big\}\Longrightarrow$ chemical potential

- Did inflation happen? (Or alternatives to inflation?)

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

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

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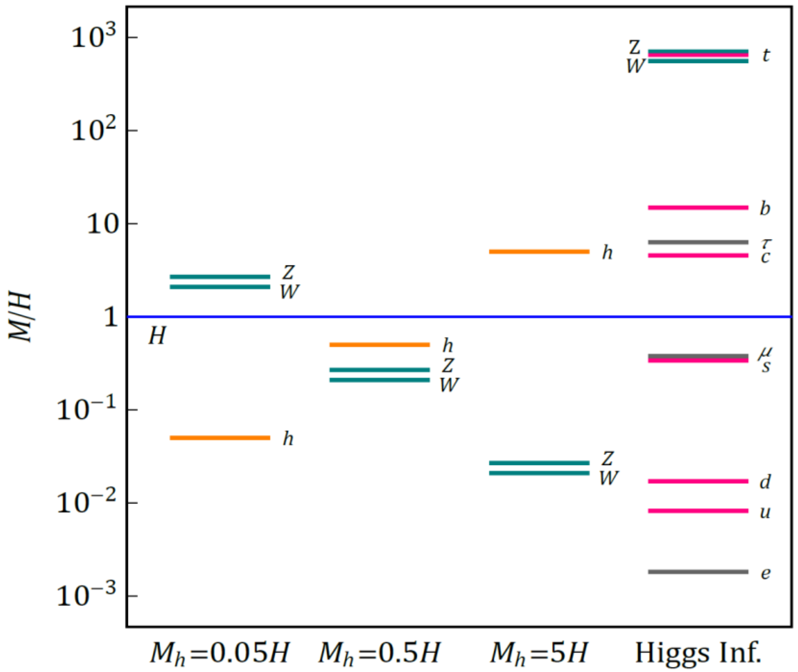
Example: Standard Model

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? ...

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

$\frac{1}{\Lambda}\left(\partial_\mu \phi\right) \bar{\psi}\gamma^5\gamma^\mu\psi,\ \frac{1}{\Lambda}\ \phi\ F\tilde{F}$, (& a few more for 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:

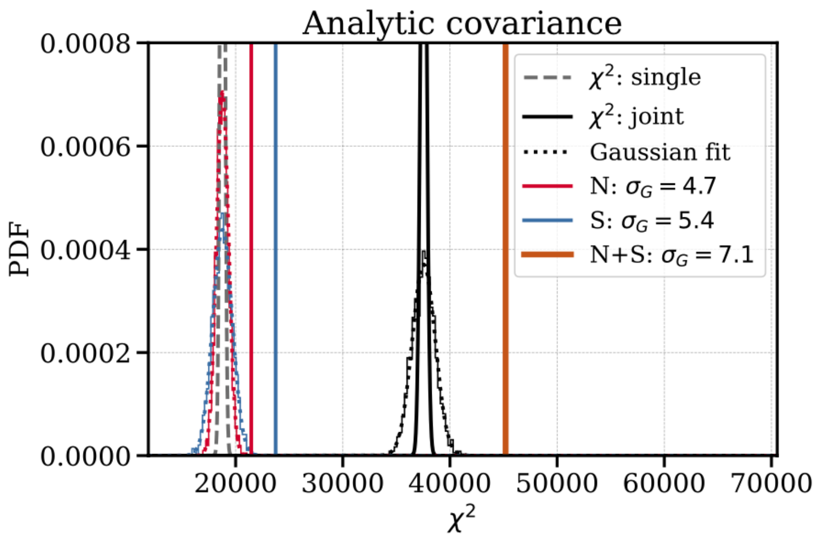
- Scalar $\mathcal{L} = [(\partial_t + \mathrm{i}\mu)\Phi^*][(\partial_t - \mathrm{i}\mu)\Phi] - |\partial_i \Phi|^2 - m^2|\Phi|^2$

  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

Parity violation in the LSS trispectrum?



7.1σ: Hou, Slepian, Cahn, 2206.03625

⇓

2.9σ: evidence Philcox, 2206.04227

⇓

1.4σ: Philcox, Ereza, 2401.09523

Evidence gone, but the idea & technology stays

project to robust observables

efficient data analysis

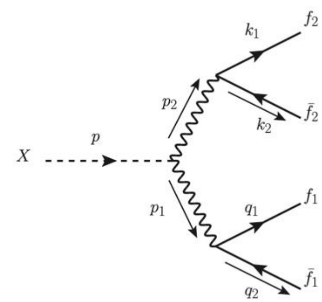
What's needed to produce parity violation?

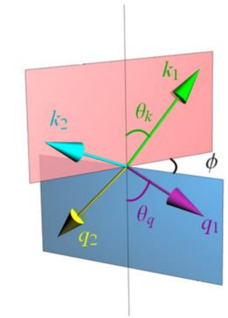
(1) Source of CP violation

(2) Four-point correlation needed

(if observing momenta only)

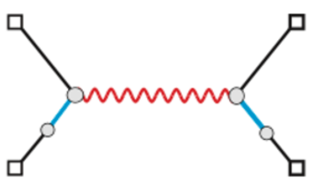
- Decay-plane correlation





- 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 satisfied

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

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

Liu, Tong, YW, Xianyu, 1909.01819

More elegant proof from unitarity, etc., see

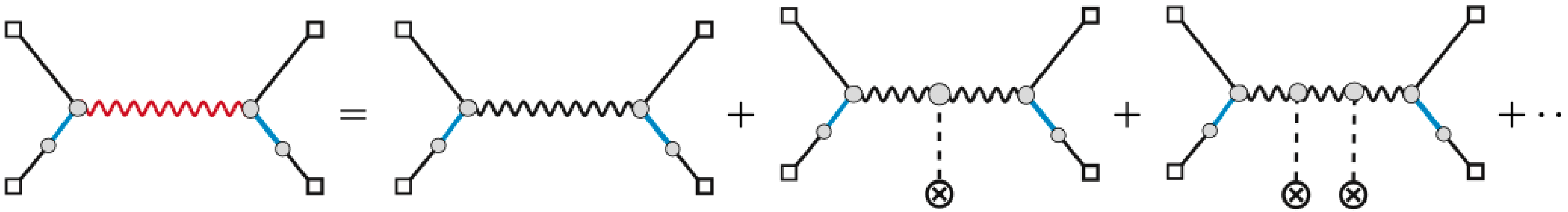
Cabass, Jazayeri, Pajer, Stefanyszyn, 2210.02907

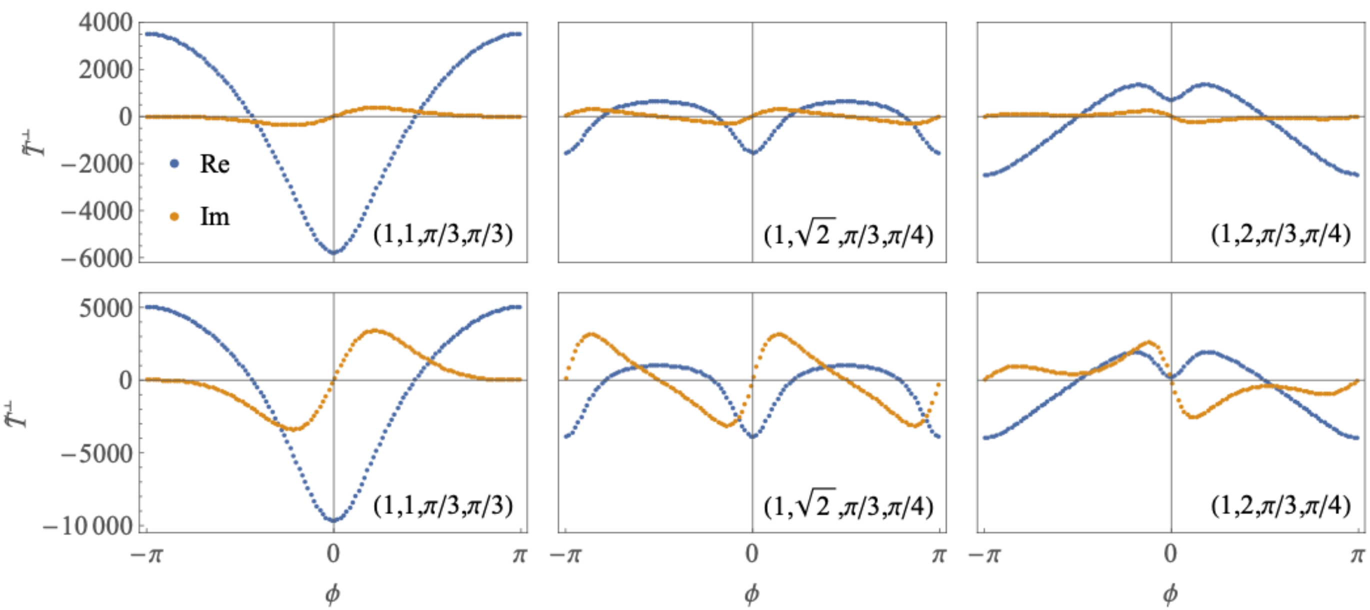
See also Jazayeri, Renaux-Petel, Tong, Werth, Zhu, 2308.11315

Stefanyszyn, Tong, Zhu, 2309.07769

Parity violation: example model

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





Liu, Tong, YW, Xianyu

1909.01819

Inflation or not?

SCIENTIFIC AMERICAN FEBRUARY 2017

Cosmic Inflation Theory Faces Challenges

The latest astrophysical measurements, combined with theoretical problems, cast doubt on the long-cherished inflationary theory of the early cosmos and suggest we need new ideas

By Anna Ijjas, Paul J. Steinhardt, Abraham Loeb

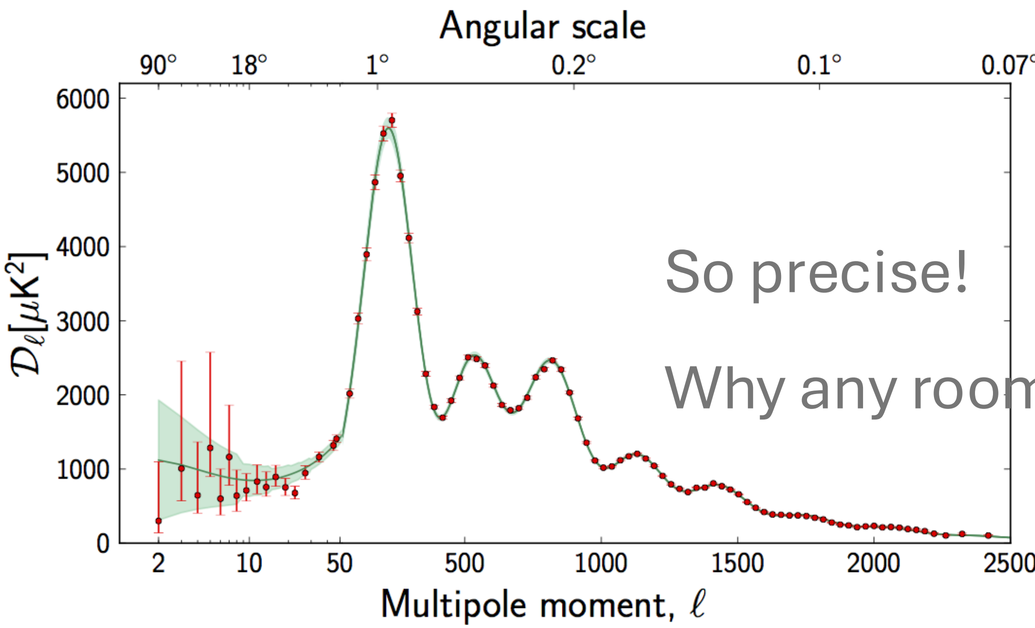
VS

Observations

A Cosmic Controversy

A *Scientific American* article about the theory of inflation prompted a reply from a group of 33 physicists, along with a response from the article's authors

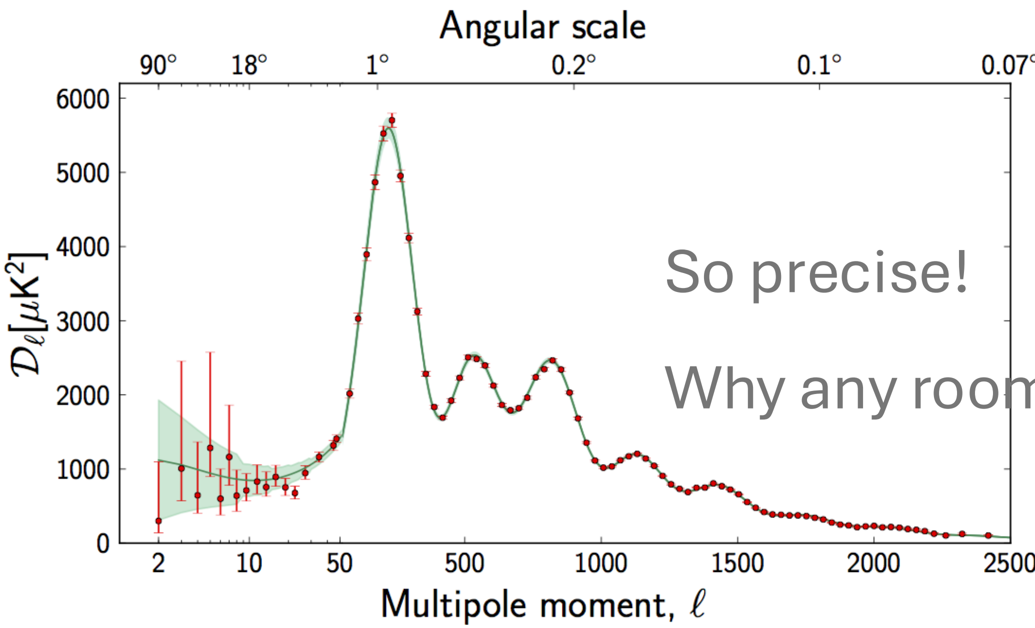
Haven't we measured inflation very well?



So precise!

Why any room for alternatives?

Haven't we measured inflation very well?



So precise!

Why any room for alternatives?

What we know well of:

$\delta\rho_k$ via horizon crossing $|k\tau| \sim 1 \Rightarrow \quad \delta\rho$(conformal time τ)

But what's $\tau(t)$? $\quad ds^2 = -dt^2 + a^2 d\mathbf{x}^2 = a^2 \left(-d\tau^2 + d\mathbf{x}^2\right)$

Haven't we measured inflation very well?

What we know well of:

$\delta\rho_k$ via horizon crossing $|k\tau|\sim 1 \Rightarrow \quad \delta\rho(\text{conformal time } \tau)$

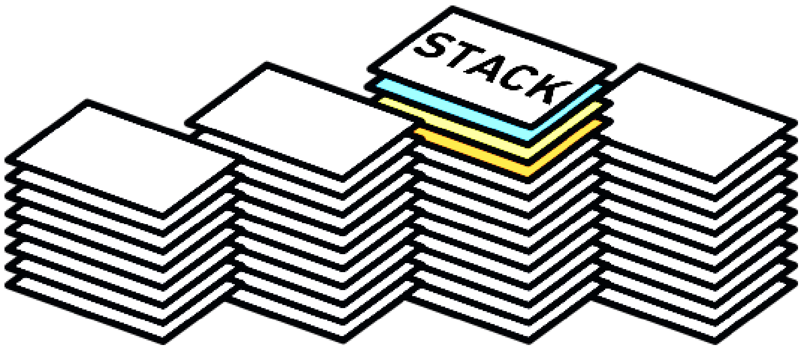
But what's $\tau(t)$?

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

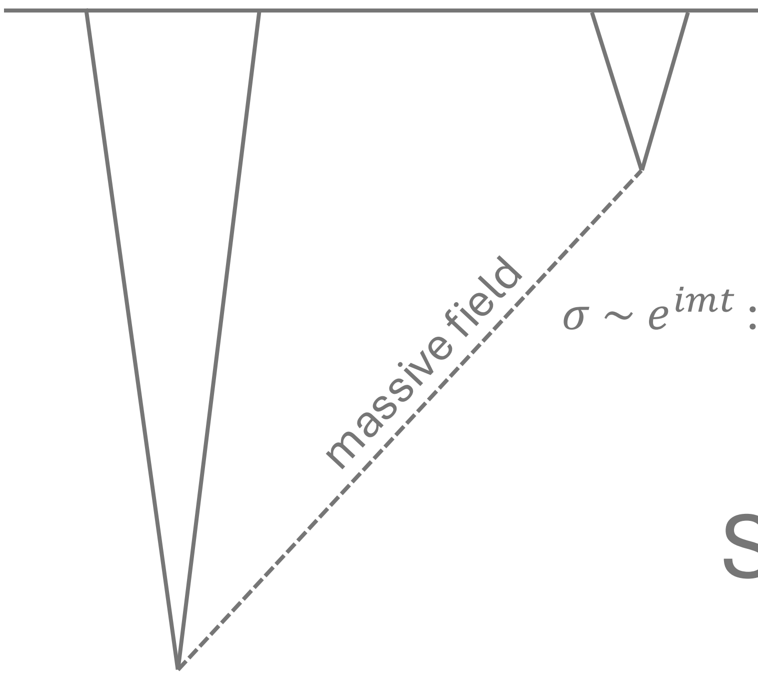
If we don't know $\tau(t)$:

like a stack of films

without timestamps



Inflation or not? Cosmological collider measures $\tau(t)$



$\sigma \sim e^{imt}$: the heavy mode "knows" physical time

Standard Clock

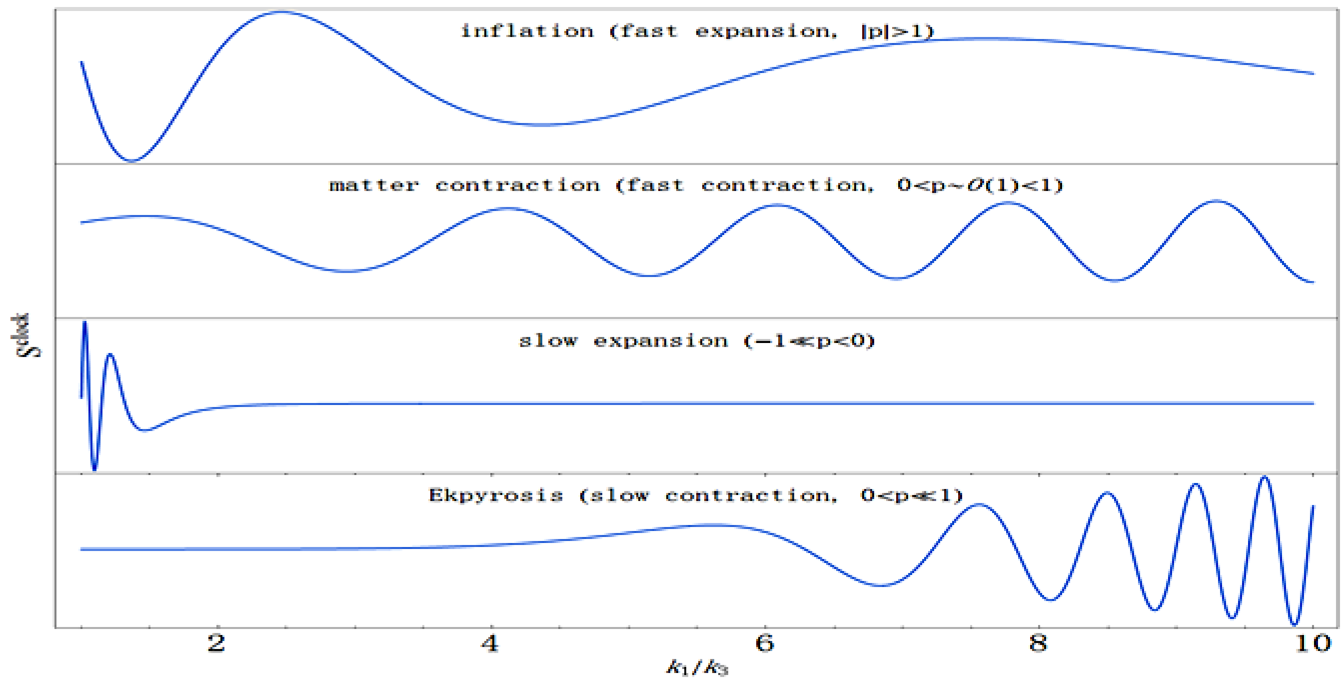
Classical standard clocks: Chen, 1104.1323, 1106.1635
Quantum standard clocks: Chen, Namjoo, YW, 1509.03930

Inflation or not? Cosmological collider measures $\tau(t)$

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

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

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



Inflation or not?

Known existing results with unknown amplitudes --

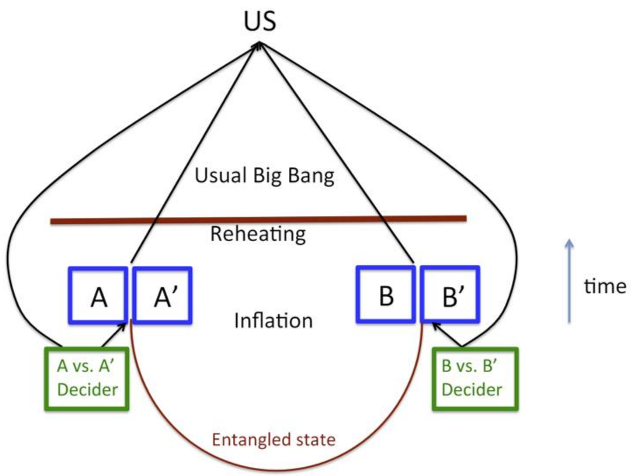
Tensor-to-scalar ratio r

Standard clock signal $\tau(t)$

Which comes first to "prove" inflation?

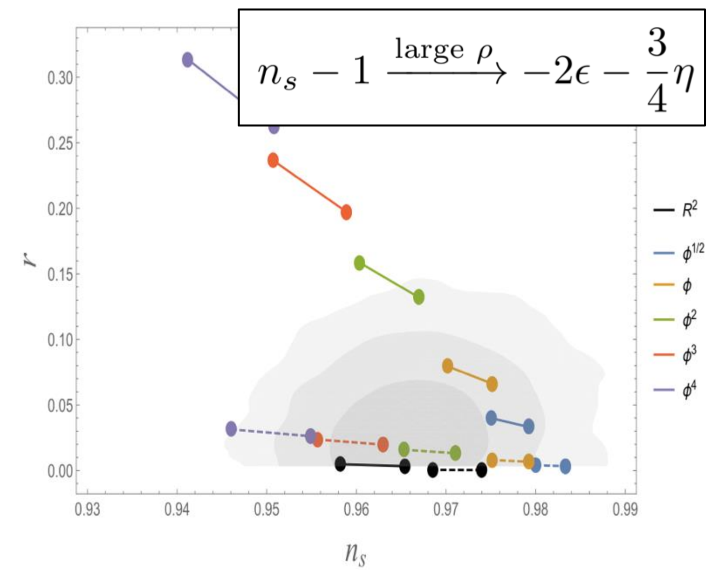
Other aspects of heavy fields:

Keep quantum nature against decoherence



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

Shift the n_s - r diagram



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

Modified gravity?

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

Summary

- Cosmological collider

  mass, angular momentum, width

  $m \sim H$: standard model & beyond

- Chemical potential

  $m \gg H$, enhanced rate & parity

- Inflation or not?

  standard clock to measure $\tau(t)$

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