Probing Particle Physics with the Cosmological Collider

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TAUP 28 Aug 2025

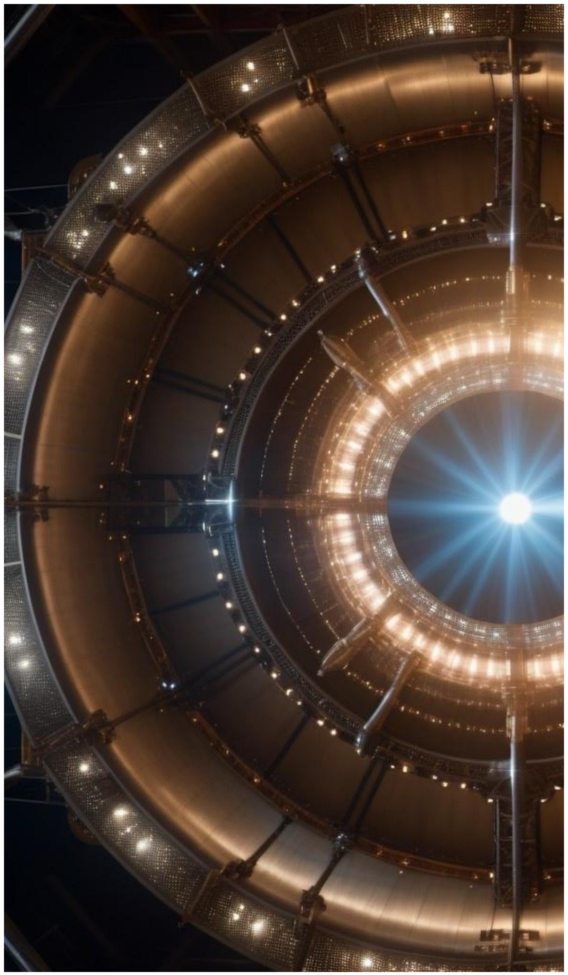
Cosmological Collider (Roughly) --

Given galaxy distributions / CMB correlations,

to infer what particles existed during inflation

Why called "Cosmological Collider"?

Why the name "Cosmological Collider"?



Looks Similar

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

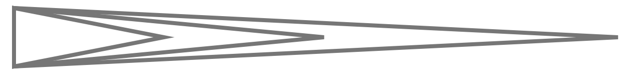
Conserved quantities: $\zeta, h_{ij}, \ldots$

Detectors: CMB, LSS

and more

How to determine particle mass?

Through "how squeezed"



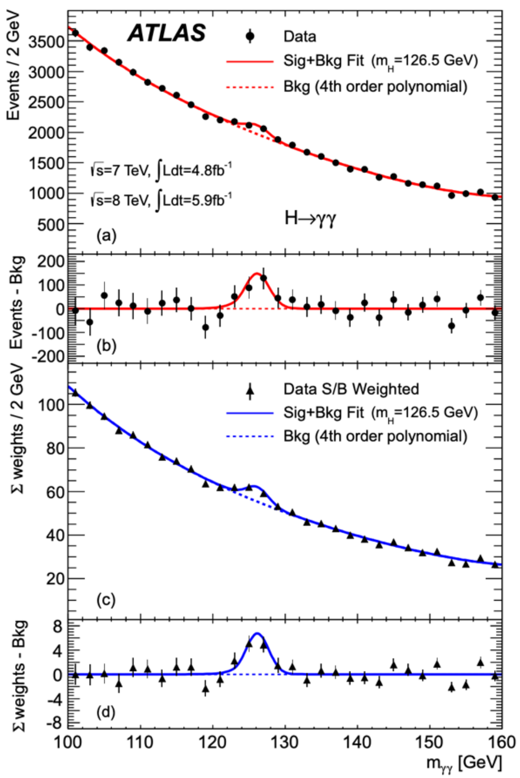
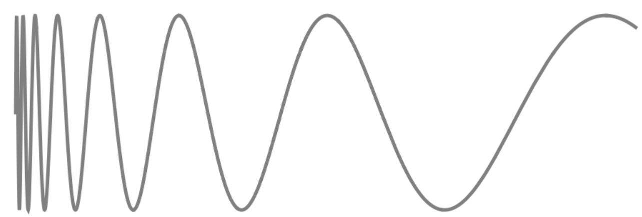


Figure: ATLAS

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

$\Longleftrightarrow$



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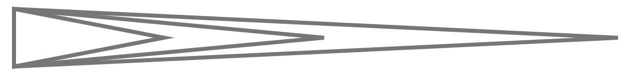

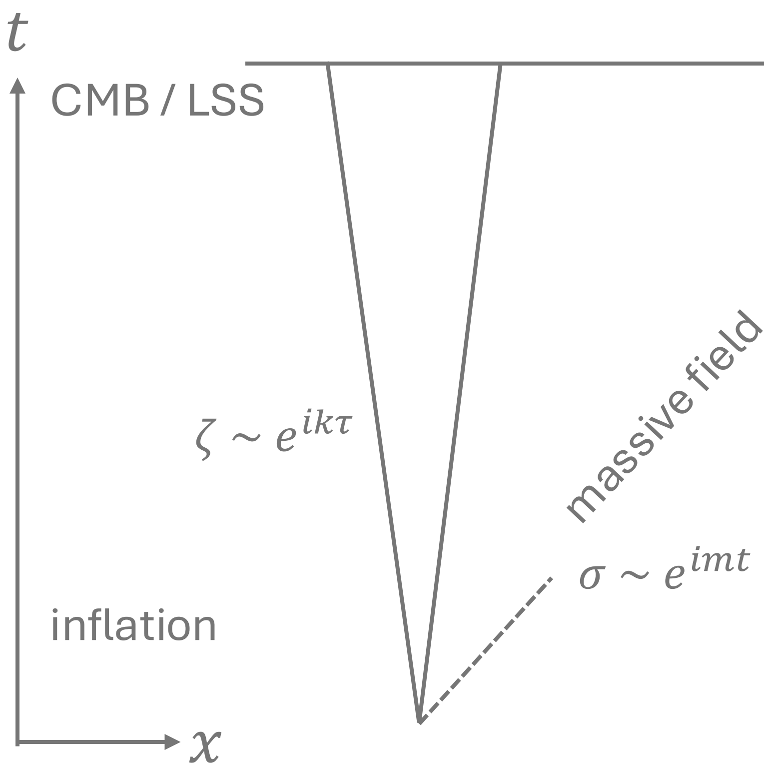

$$ds^2 = -dt^2 + a^2 d\mathbf{x}^2 = a^2\left(-d\tau^2 + d\mathbf{x}^2\right)$$

Chen, YW, 0909.0496, 0911.3380

Baumann, Green, 1109.0292

Noumi, Yamaguchi, Yokoyama, 1211.1624

Arkani-Hamed, Maldacena, 1503.08043

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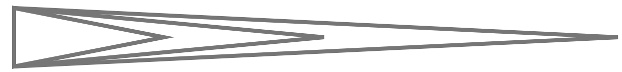
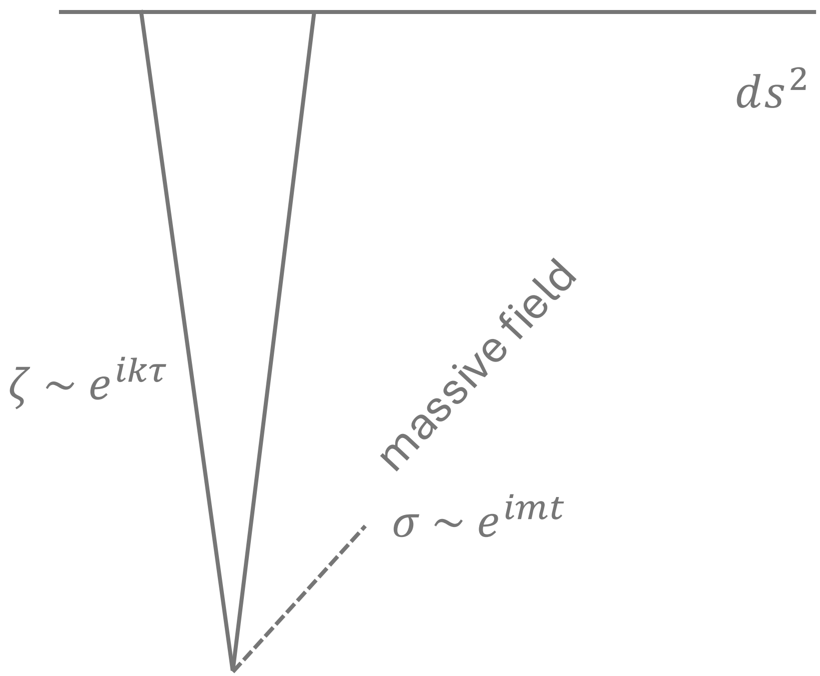
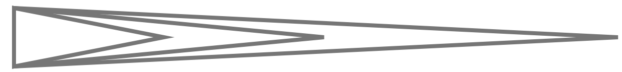


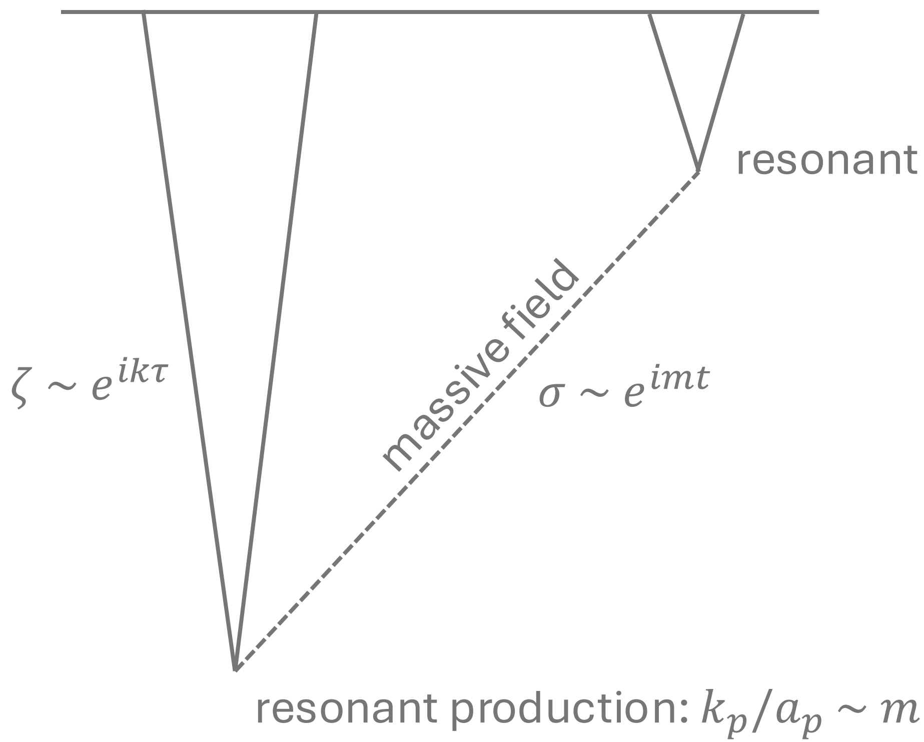


$$ds^2 = -dt^2 + a^2 d\mathbf{x}^2 = a^2\left(-d\tau^2 + d\mathbf{x}^2\right)$$

resonant production: $k_p/a_p \sim m$

How to determine particle mass?

Through "how squeezed" 



How to determine particle mass?

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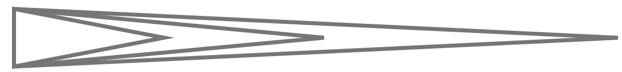
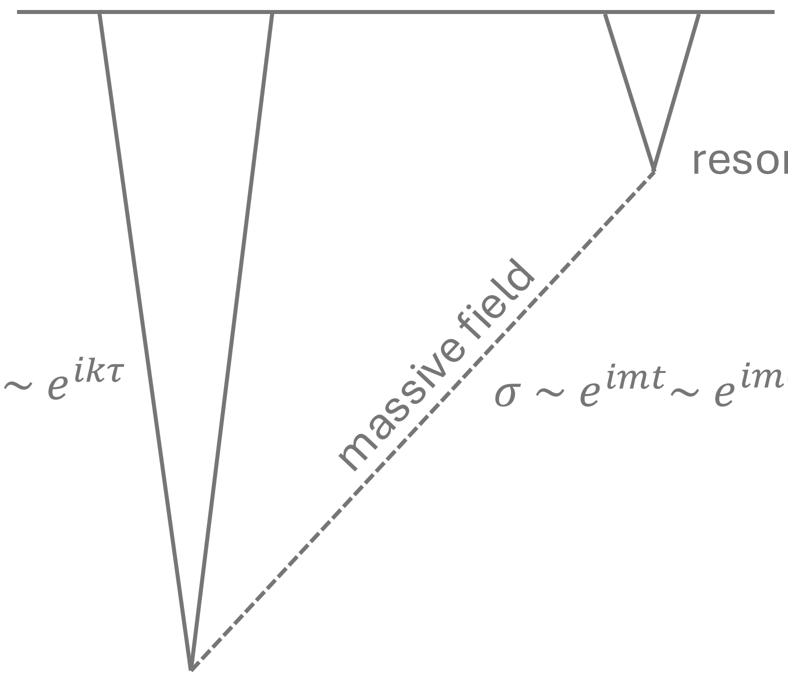




resonant decay: $k_d/a_d \sim m$

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

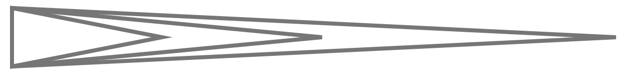
$$\sigma \sim e^{imt} \sim e^{im(t_d - t_p)} \sim e^{i\mu(\ln a_d - \ln a_p)} \sim \left(\frac{a_d}{a_p}\right)^{i\mu} \sim \left(\frac{k_d}{k_p}\right)^{i\mu}$$

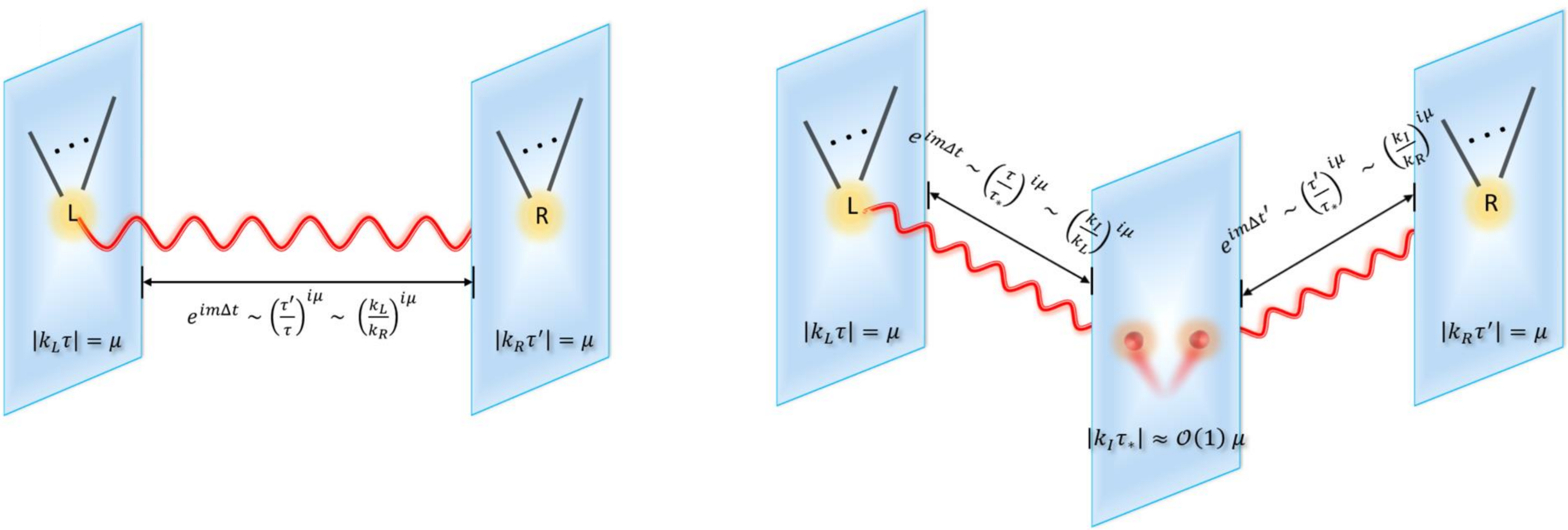
$$\mu \sim \frac{m}{H} = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

resonant production: $k_p/a_p \sim m$

How to determine particle mass?

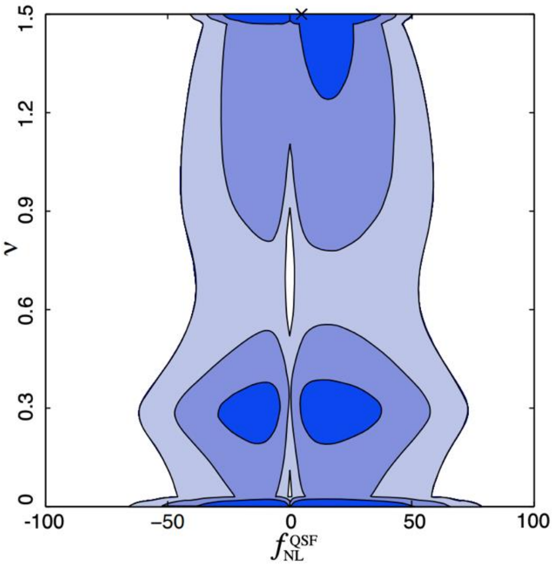
Through "how squeezed"

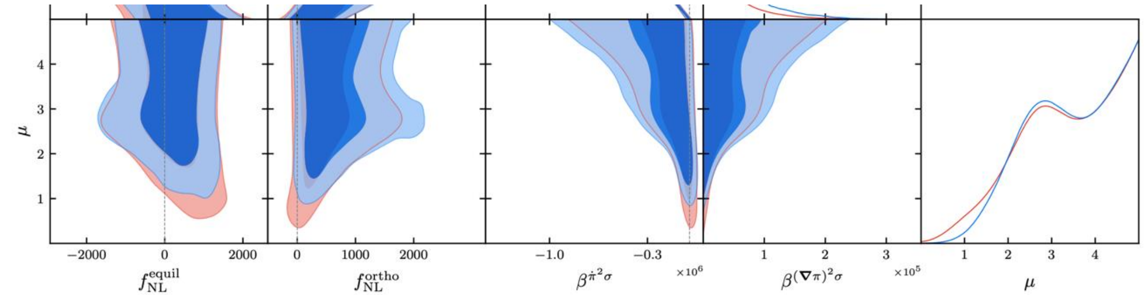


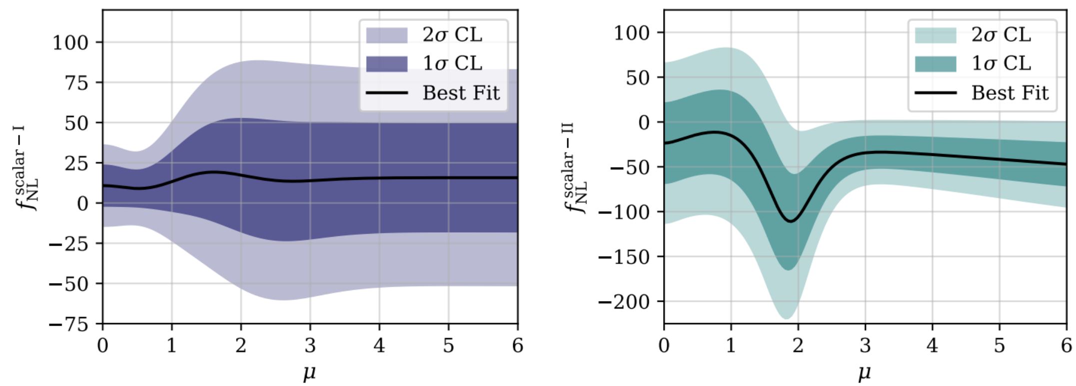


Local vs non-local particle productions Figure: Tong, Zhu, YW, 2112.03448

Observational searches







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

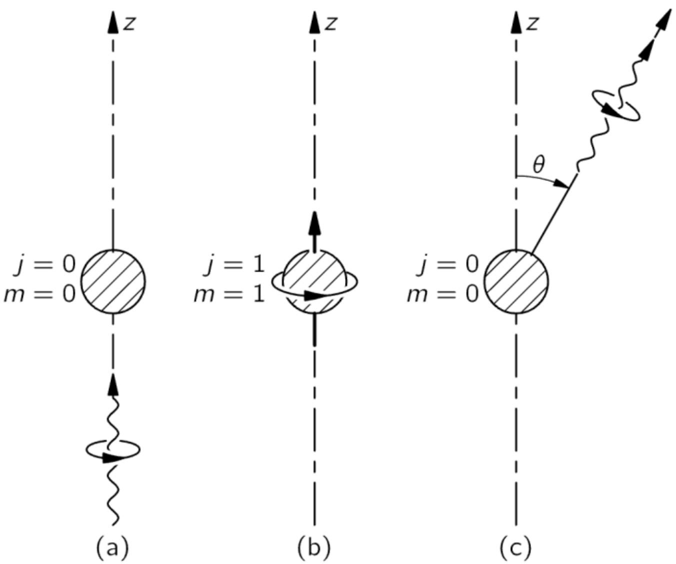
Planck Team, 1303.5084

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: $P_j\ (\cos\theta)$

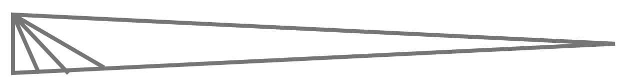


Figure from https://www.feynmanlectures.caltech.edu/III_18.html

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

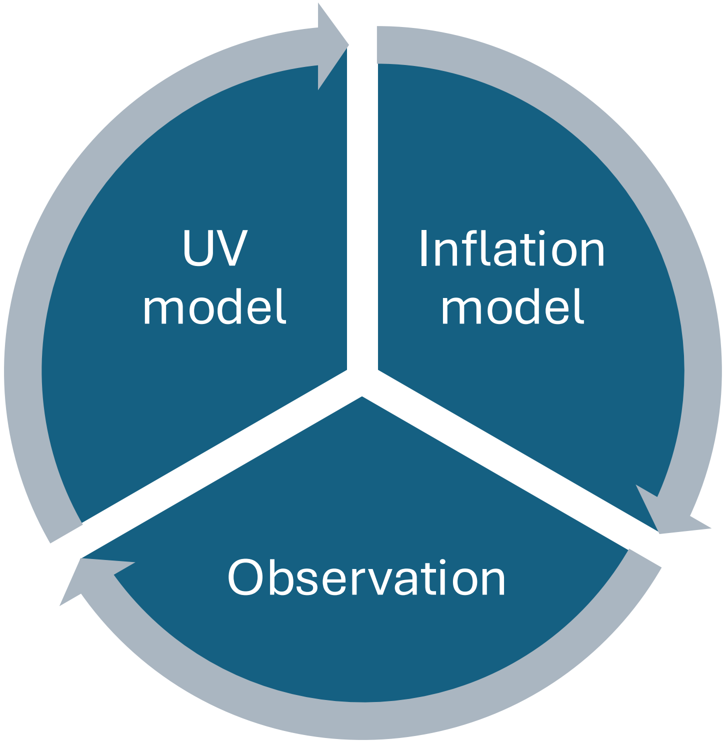
Extract parity: $\mathrm{Im}\,\langle\cdots\rangle$ Liu, Tong, YW, Xianyu, 1909.01819

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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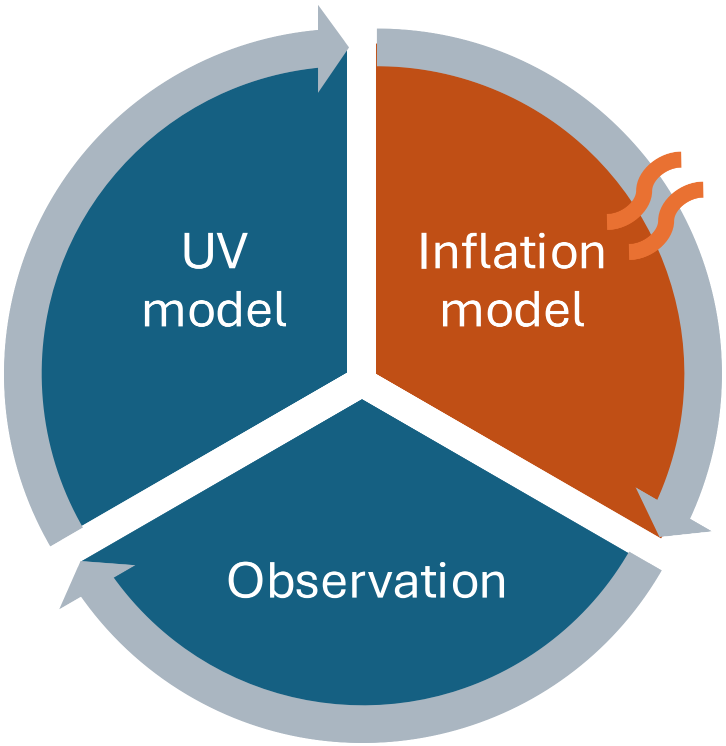

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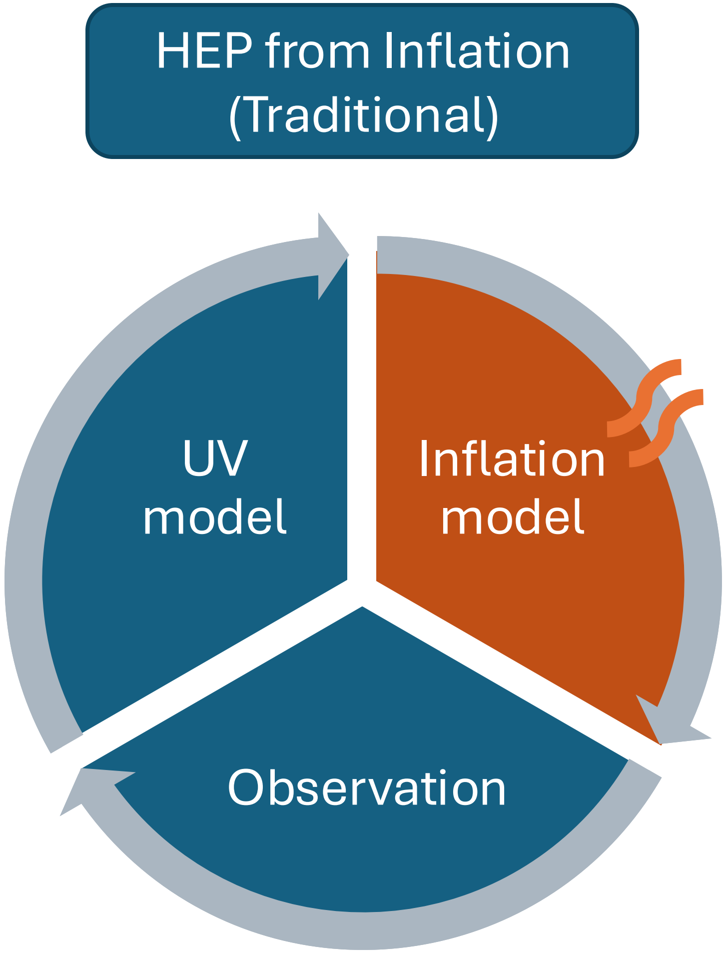

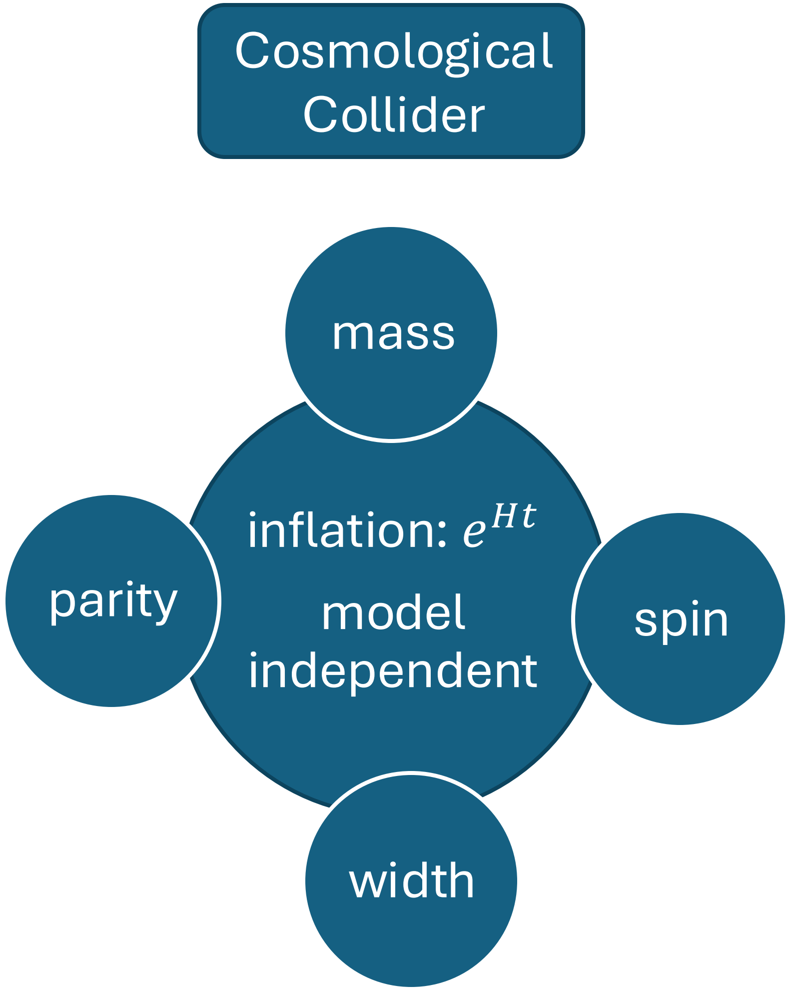

Plan

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

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

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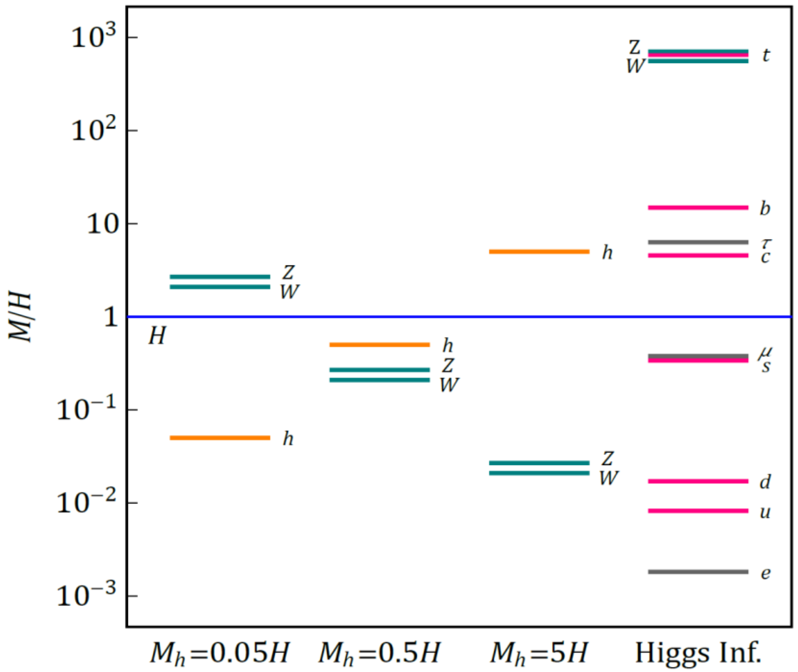

Example: Standard Model

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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(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? ...

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

How should the Higgs couple to the inflaton?

We don't know – but likely:

(1) Shift symmetry of the inflaton: $\partial\phi$

(2) EW charge of the Higgs: h^2

What's the lowest dimension to put them together?

Previously studied: $h^2\partial\phi\partial\phi$ (dim 6)

This talk: $h\ \partial h\ \partial\phi$ (dim 5) (Wang, Wang, YW, Yu, 2508.12856)

Dim 5 operators of the scalar sector?

Hope to keep shift symmetry of ϕ

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, 2508.12856)

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 $\partial\,(\frac{\sqrt{-g}}{2\Lambda}\, h^2\, \partial\phi) - \frac{\sqrt{-g}}{2\Lambda}\, h^2 \Box\phi$

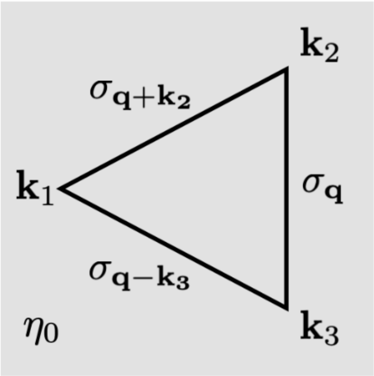
Field redefinition: $\phi = \tilde{\phi} + \frac{1}{2\Lambda} h^2 \rightarrow$ free $-\frac{1}{2}(\partial\tilde{\phi})^2$

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

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

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



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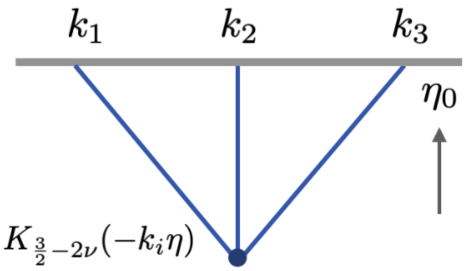


"Dual" to a tree diagram,

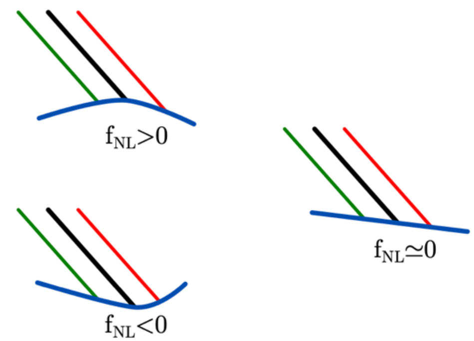
composite conform dim

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

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, $\Box\phi \approx 0$

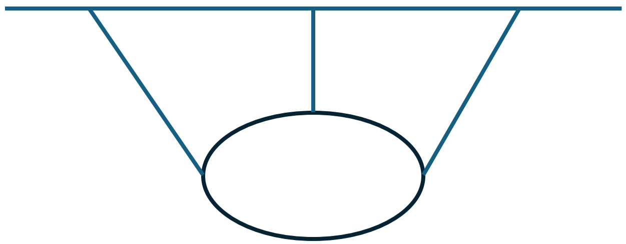
(if not on-shell: □ on Green's function $\rightarrow \delta$-function)

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

Wang, Wang, YW, Yu, 2508.12856

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

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



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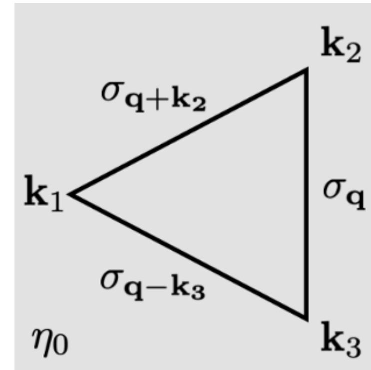
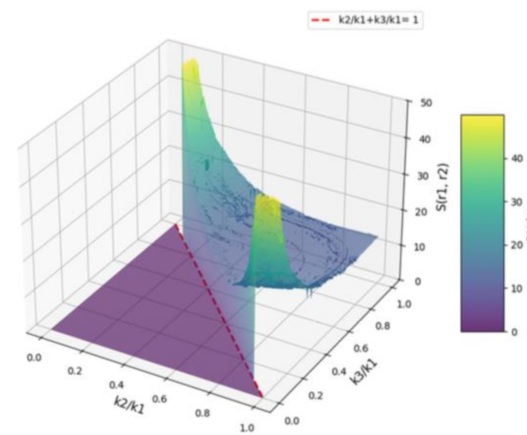


Squeezed limit:

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



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

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

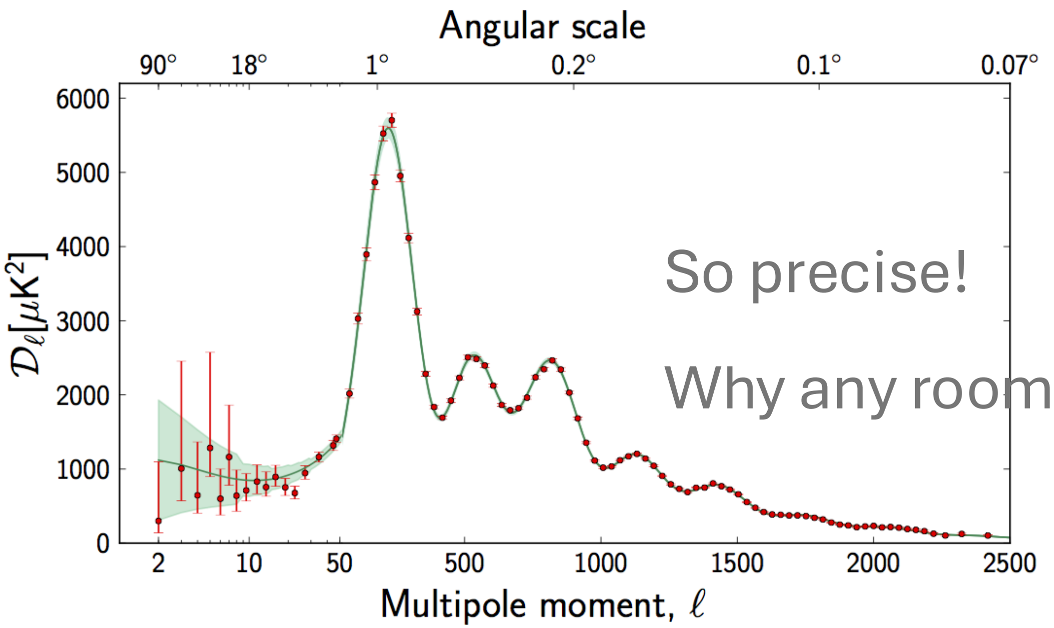
VS

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

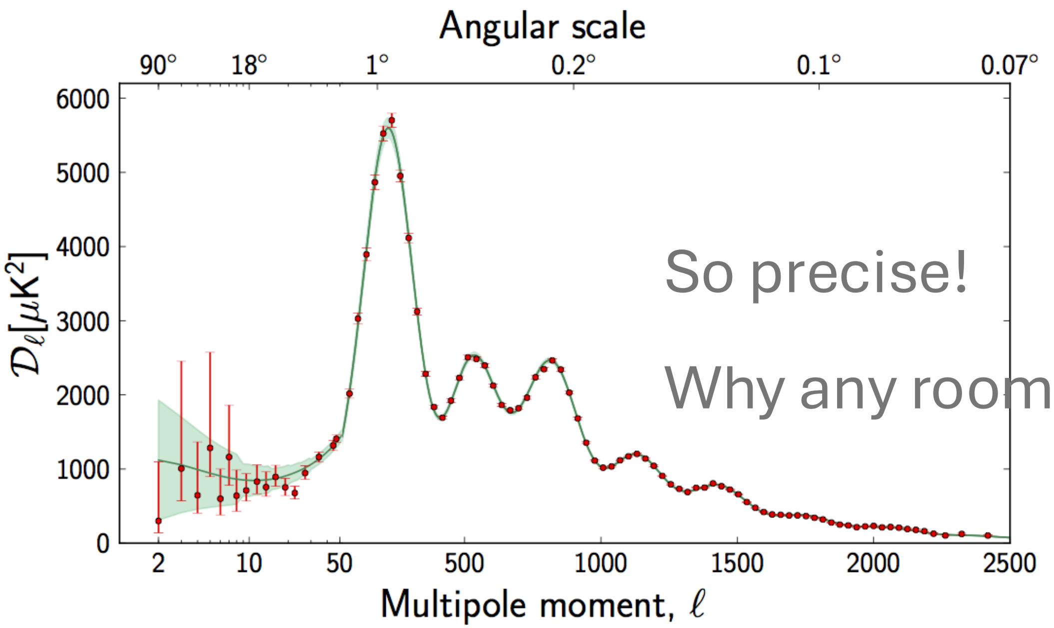
Haven't we measured inflation very well?



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 $\tau(t)$?

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

Haven't we measured inflation very well?

What we know well of:

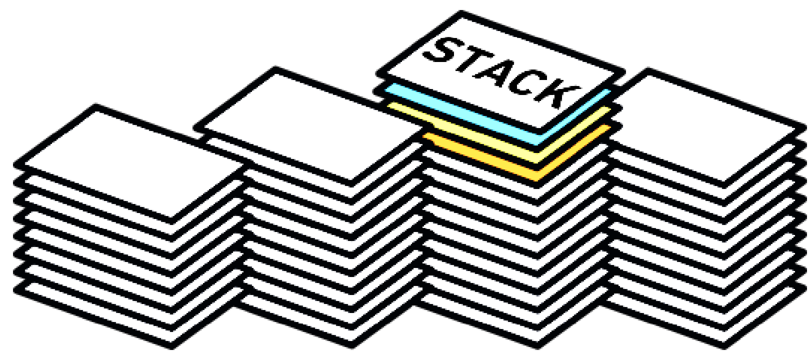
$\delta\rho_k$ via horizon crossing $|k\tau|\sim 1 \Rightarrow \quad \delta\rho(\text{conformal time } \tau)$

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

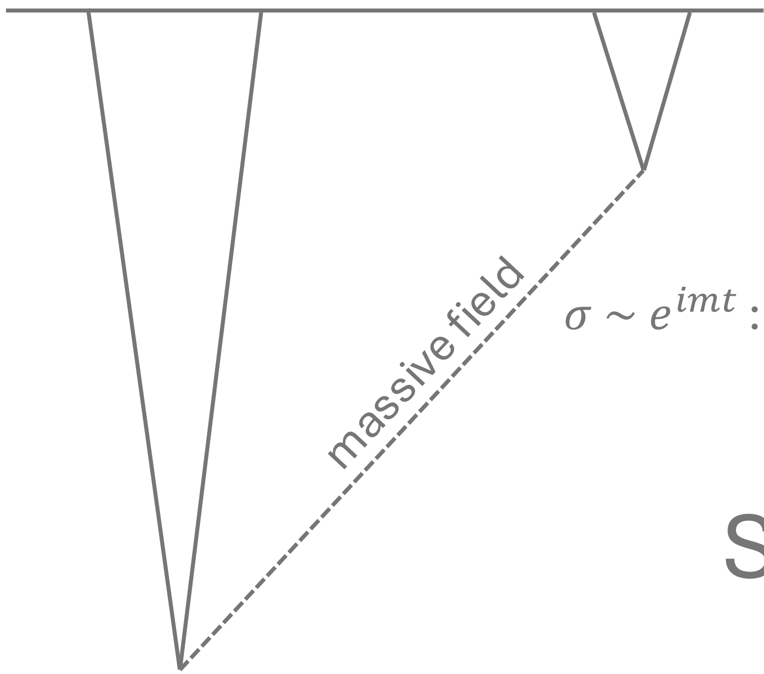
If we don't know $\tau(t)$:

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

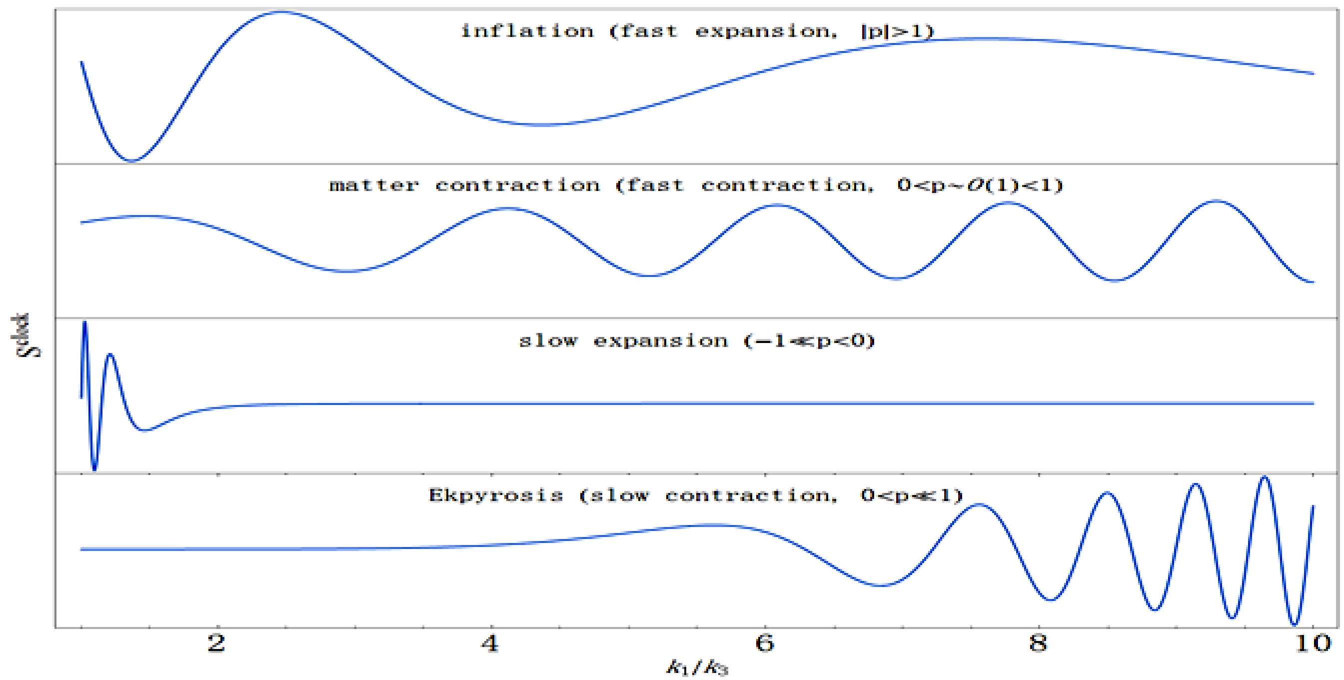
Classical standard clocks: Chen, 1104.1323, 1106.1635
Quantum standard clocks: Chen, Namjoo, YW, 1509.03930

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

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

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

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



Inflation or not?

Known existing results with unknown amplitudes --

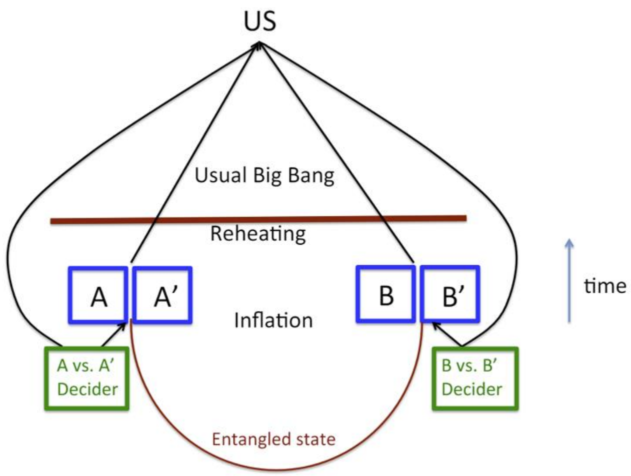
Tensor-to-scalar ratio r

Standard clock signal $\tau(t)$

Which comes first to "prove" inflation?

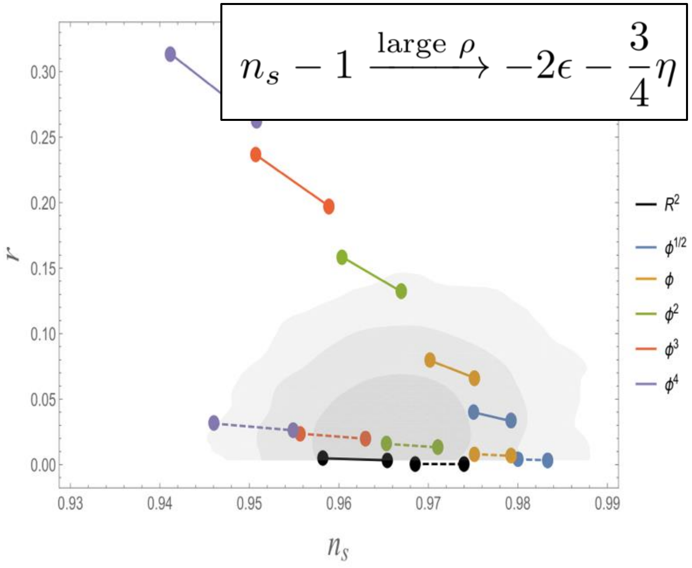
Other aspects of heavy fields:

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?

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