Particle Physics on the Cosmological Collider

Yi Wang (王一), the Hong Kong University of Science and Technology

References:

Quasi-Single Field Inflation and the Cosmological Collider:

Chen, YW 0909.0496, 0911.3380; Arkani-Hamed, Maldacena 1503.08043

Standard Model on the Cosmological Collider:

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

BSM on the Cosmological Collider:

Chen, YW, Xianyu 1805.02656; Kumar, Sundrum 1811.11200

High-Spin: Arkani-Hamed, Maldacena 1503.08043, Lee, Baumann, Pimentel 1607.03735

Parity and CP: Liu, Tong, YW, Xianyu, 1909.01819

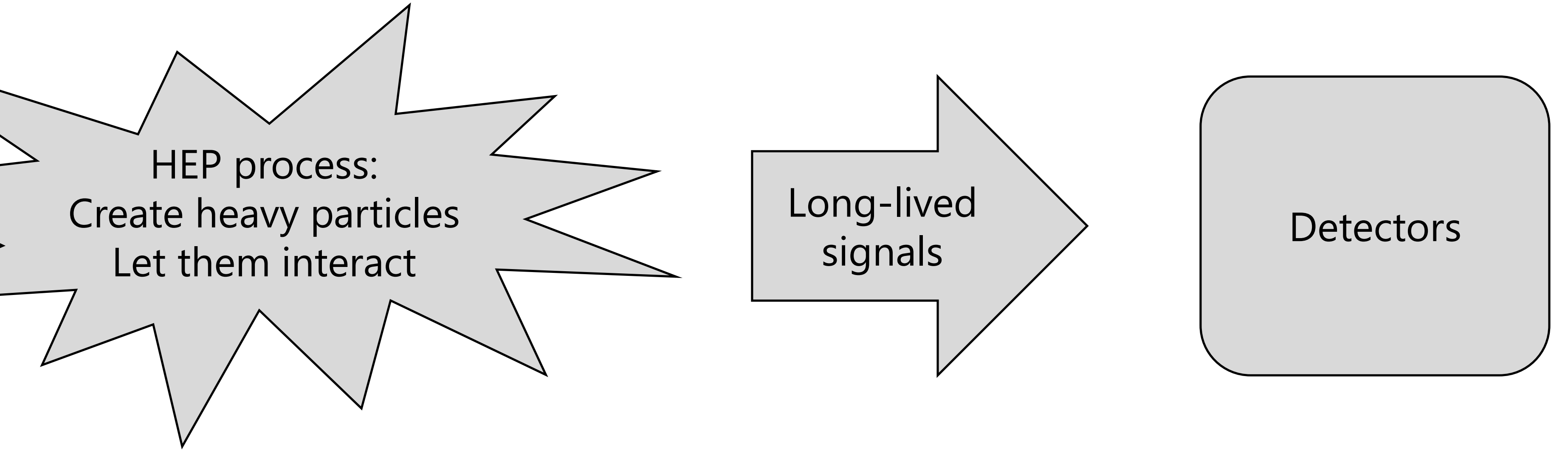
Isocurvature: Lu, YW, Xianyu, 1907.07390 & in progress, Kumar, Sundrum 1908.11378

Quantum Primordial Standard Clocks: Chen, Namjoo, YW 1509.03930

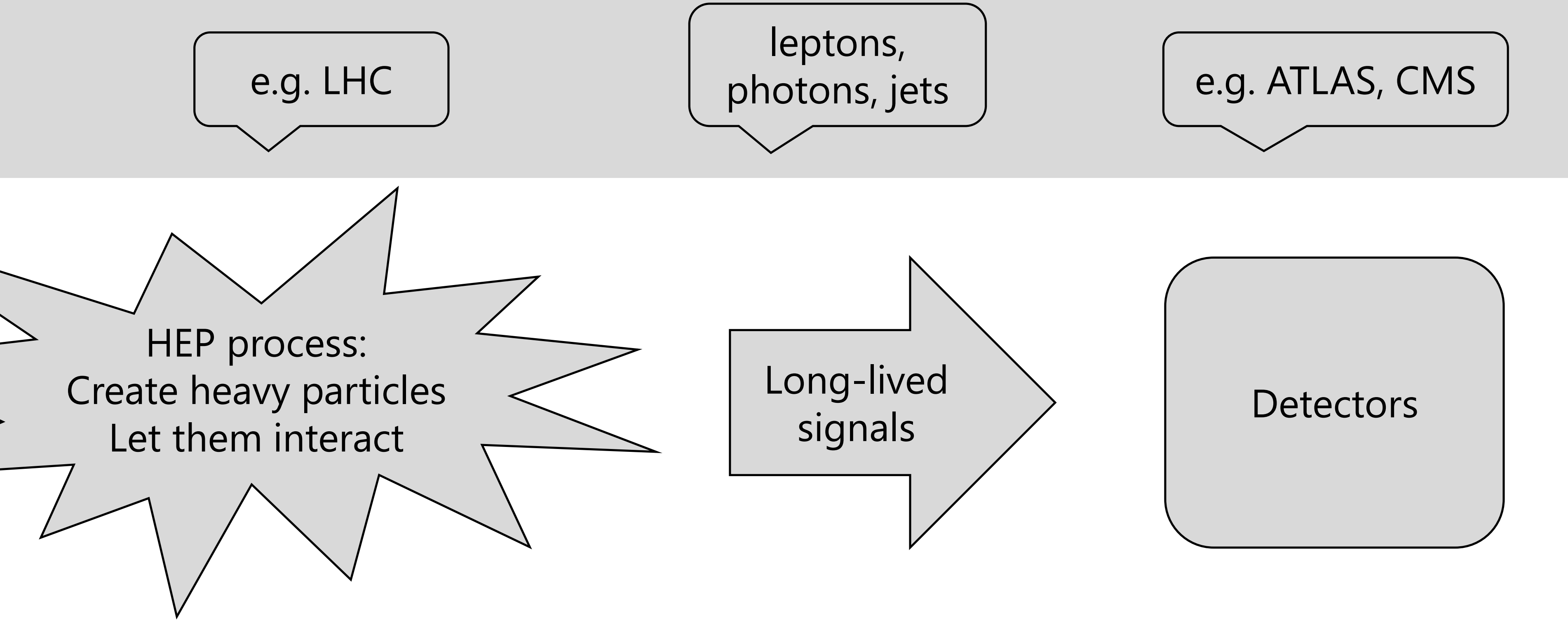
Impact on inflation models: An, McAneny, Ridgway, Wise 1706.09971, Tong, YW, Zhou 1708.01709

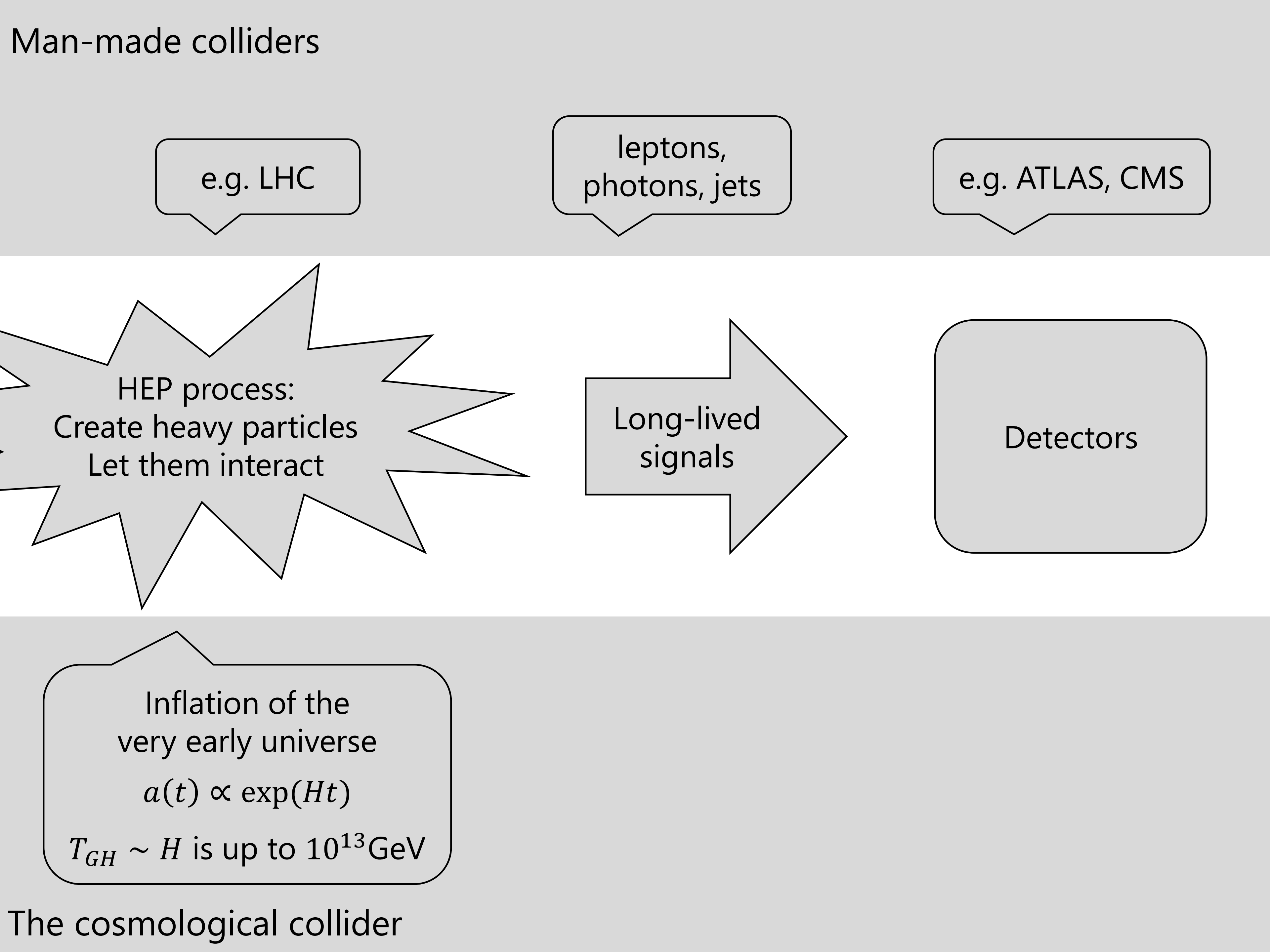
Why is inflation a cosmological “collider”?

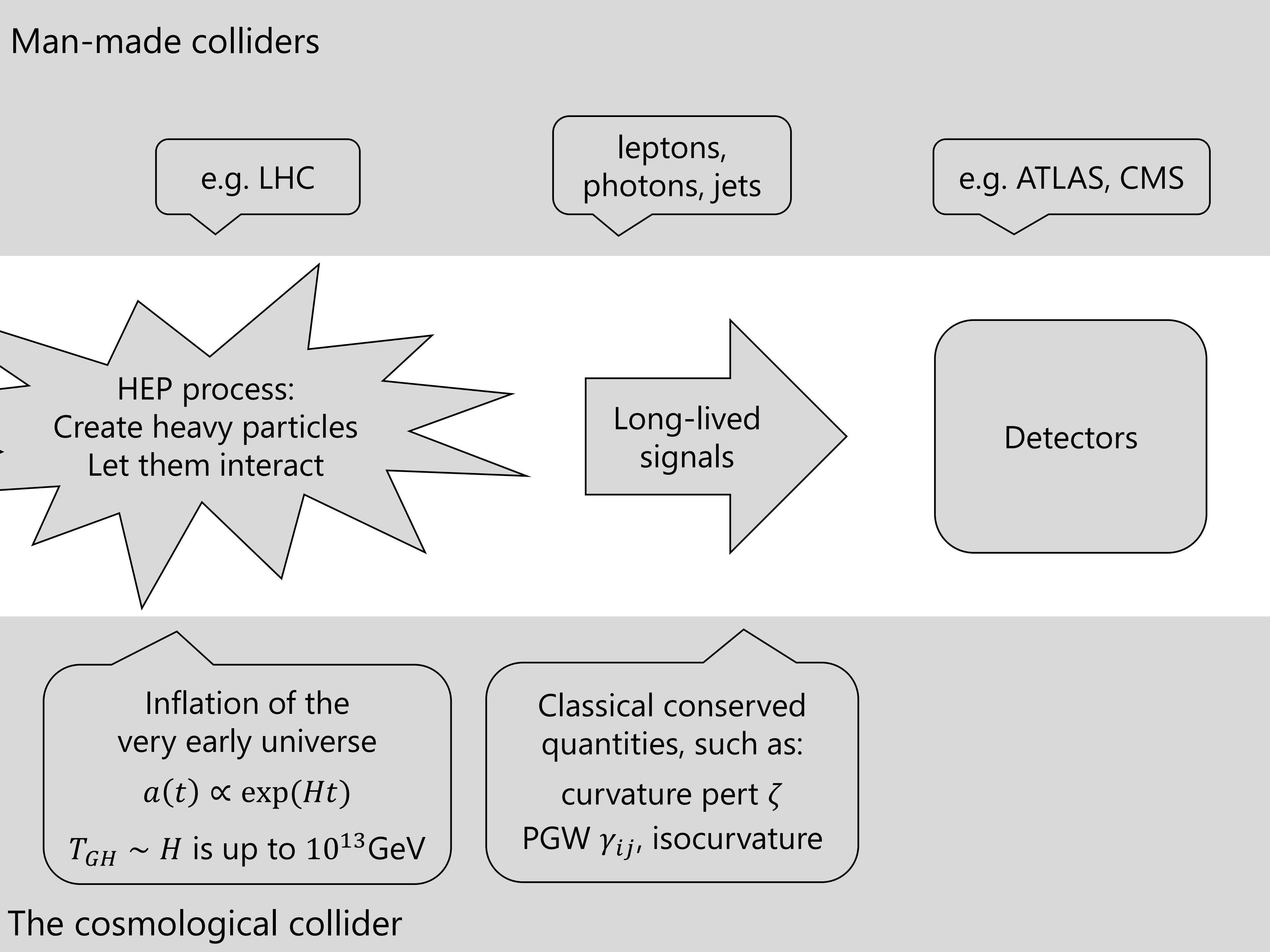
What’s needed as a “collider”?



Man-made colliders




Man-made colliders
e.g. LHC
leptons, photons, jets
e.g. ATLAS, CMS
HEP process: Create heavy particles Let them interact
Long-lived signals
Detectors
Inflation of the very early universe
$a(t) \propto \exp(Ht)$
$T_{GH} \sim H$ is up to 10^{13}GeV
The cosmological collider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Classical conserved quantities, such as:
curvature pert ζ
PGW γ_{ij}, isocurvature
The cosmological collider

The curvature perturbation $\zeta(\mathbf{x}) \sim \delta N(\mathbf{x}) \sim \frac{H}{\dot\phi}\delta\phi \quad \left(\phi = \phi_0(t) + \delta\phi(\mathbf{x}, t)\right)$

Intuitive (probably too rough) $\quad T_{GH} \sim H \quad \rightarrow \quad \delta\phi \sim H$

Formalism: QFT i

Recall Subodh's talk

$$S = \int d^3x\, dt\, a^3(t) \left(\frac{\varphi}{2} + \cdots\right),$$

$$\langle \delta\phi^n(\mathbf{x}, t)\rangle = \left\langle \left(\bar{T} e^{i\int^t dt\, H_I}\right) \delta\phi^n_{(I)} \left(T e^{-i\int^t dt\, H_I}\right) \right\rangle, \qquad \langle\delta\phi^2\rangle \sim H^2, \quad \langle\delta\phi^3\rangle \cdots$$

PGW & remaining isocurvature fluctuation (if any): similar

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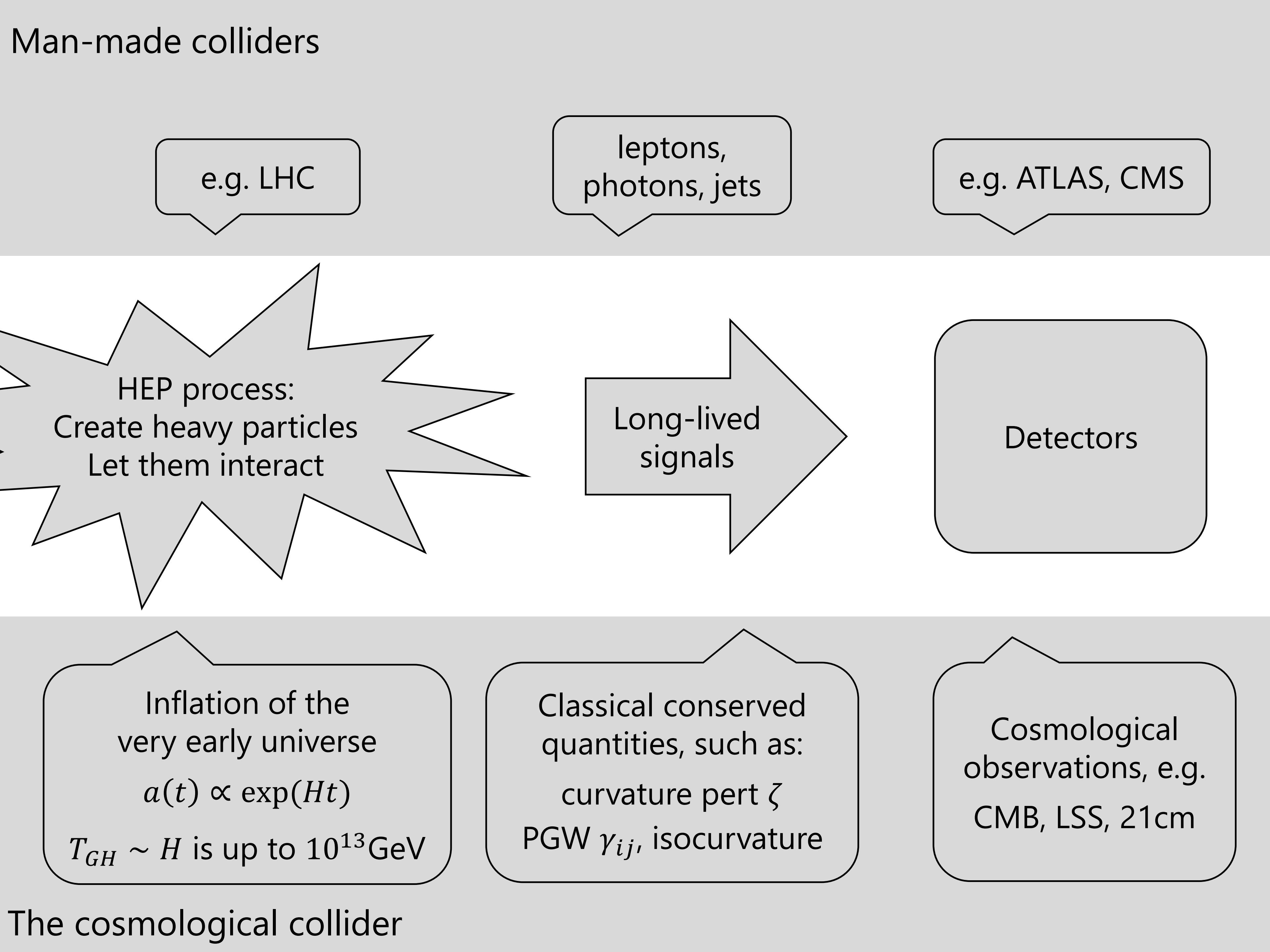

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Cosmological observations, e.g.
CMB, LSS, 21cm
The cosmological collider

Observations: Correlation functions of primordial --

- Curvature perturbation ζ
    - From CMB $\Delta T/T$, LSS & 21cm $\delta\rho/\rho$
    - Status: 2pt well measured (COBE DMR)
    - 3pt, … (non-Gaussianity) not yet observed. SphereX: 10X
- GW: From CMB B-mode, not yet observed
- Isocurvature: From details of CMB/LSS, not yet observed

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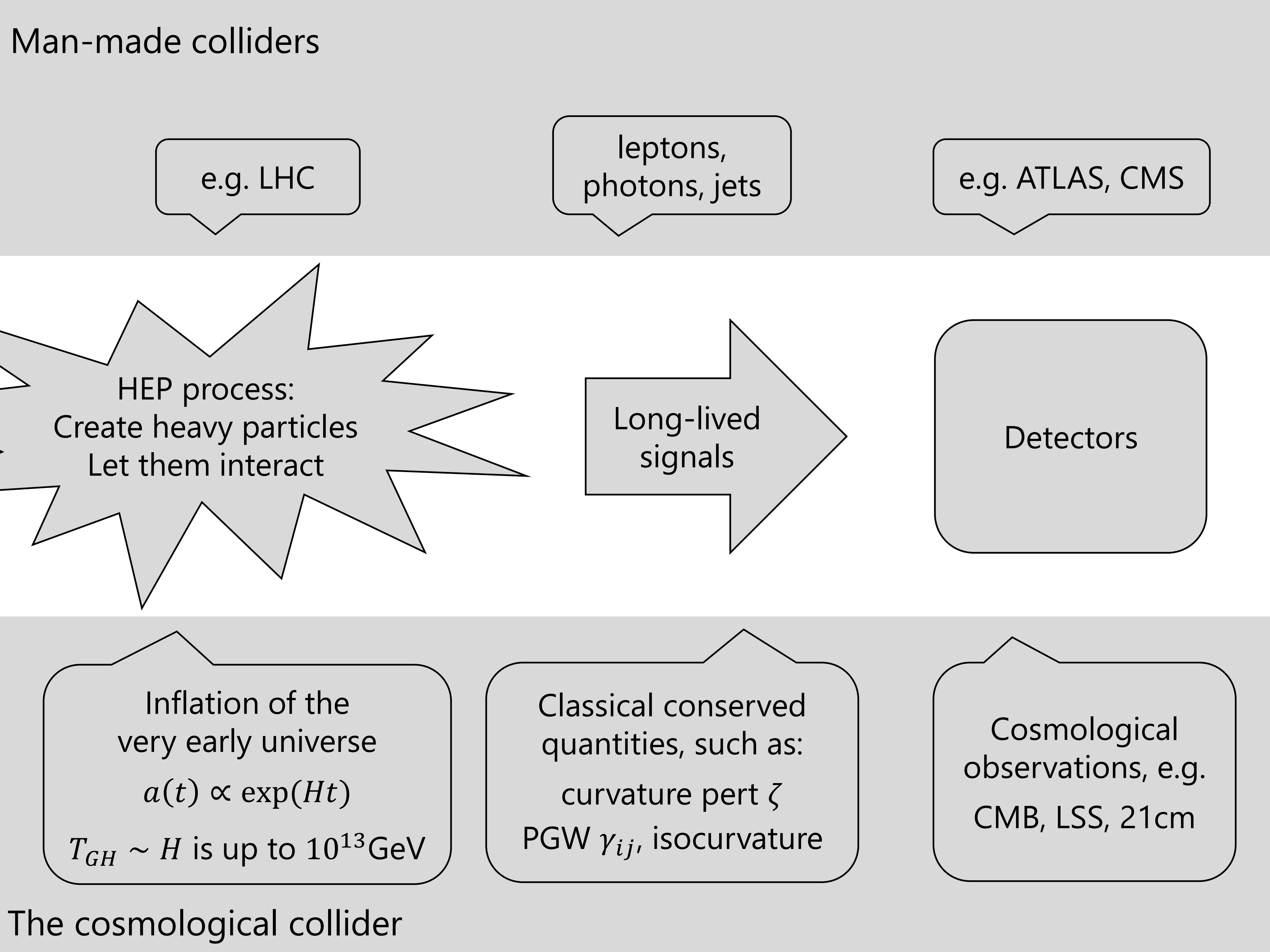
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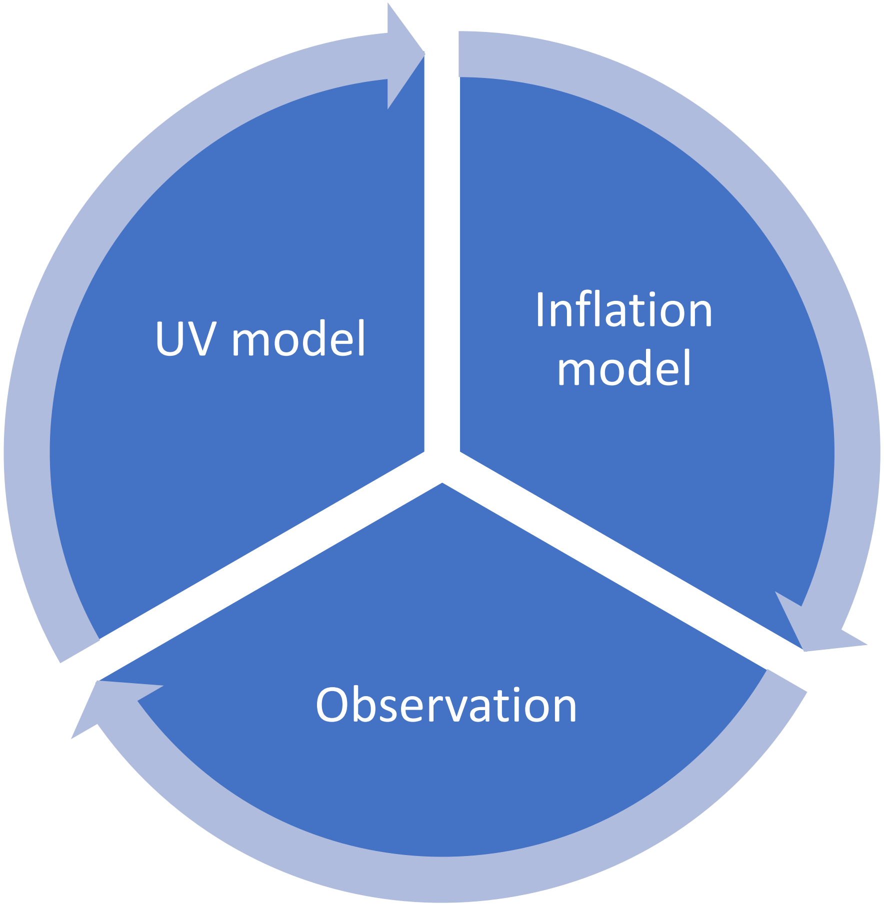
Ever since inflation was proposed,
people use inflation to study HEP.
What’s new about the “cosmological collider”?

Traditional Way



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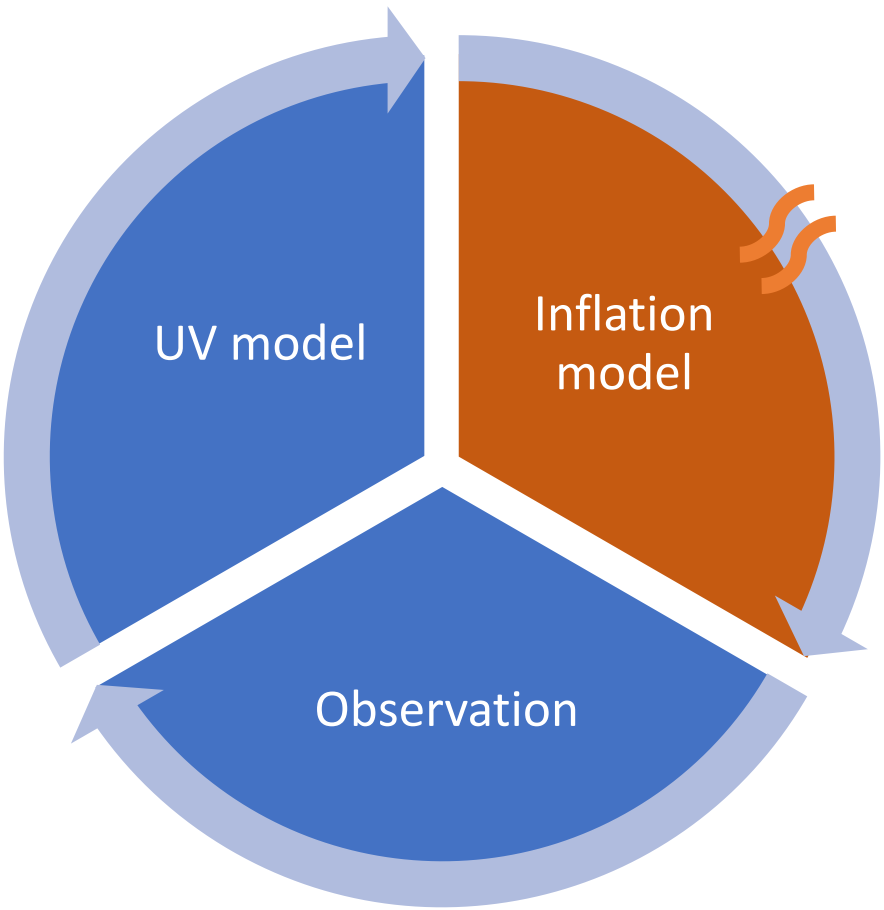
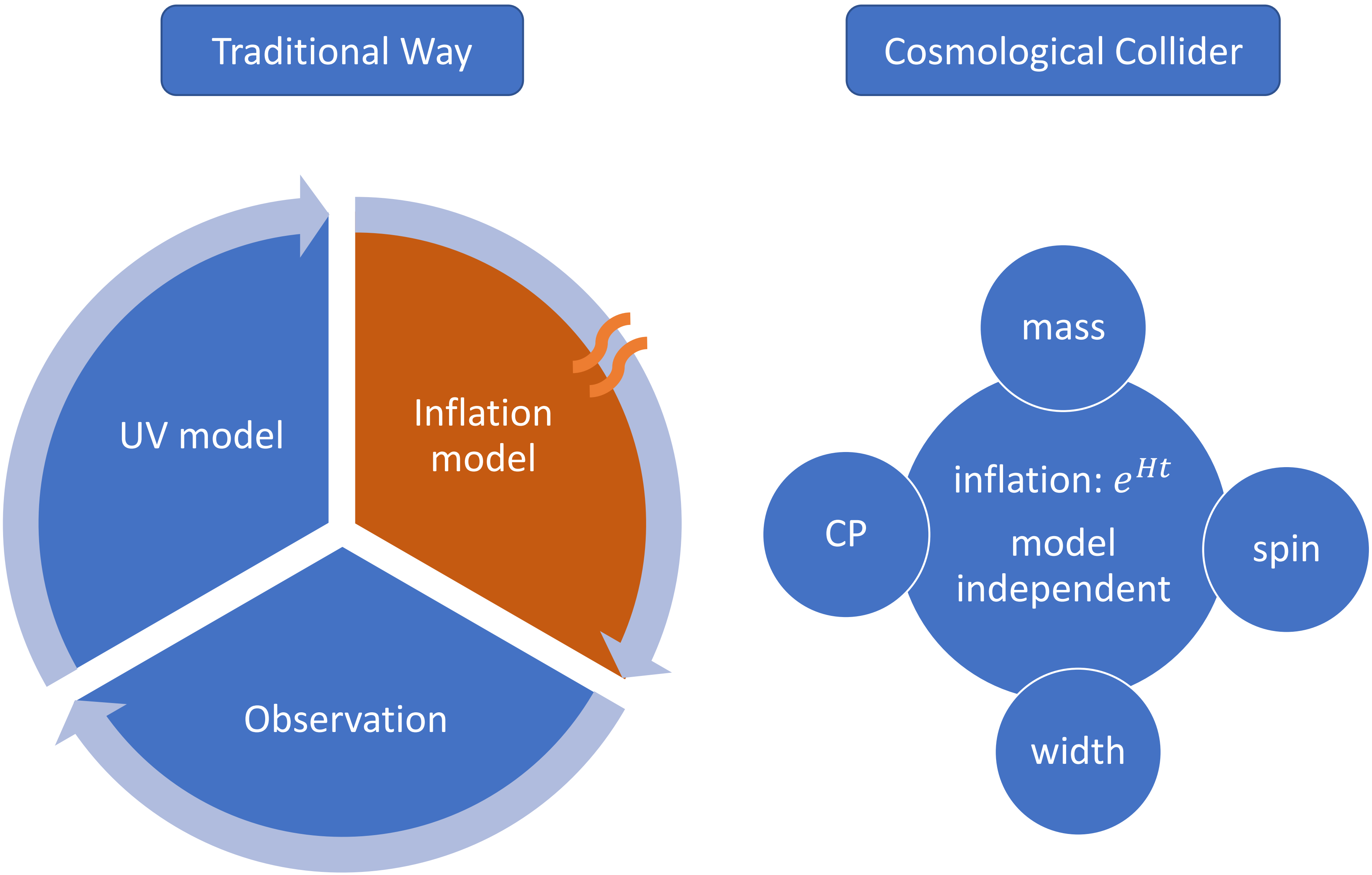




Traditional Way
Cosmological Collider
UV model
Inflation model
Observation
mass
inflation: e^{Ht}
model independent
CP
spin
width

Mass

Mass: from resonance

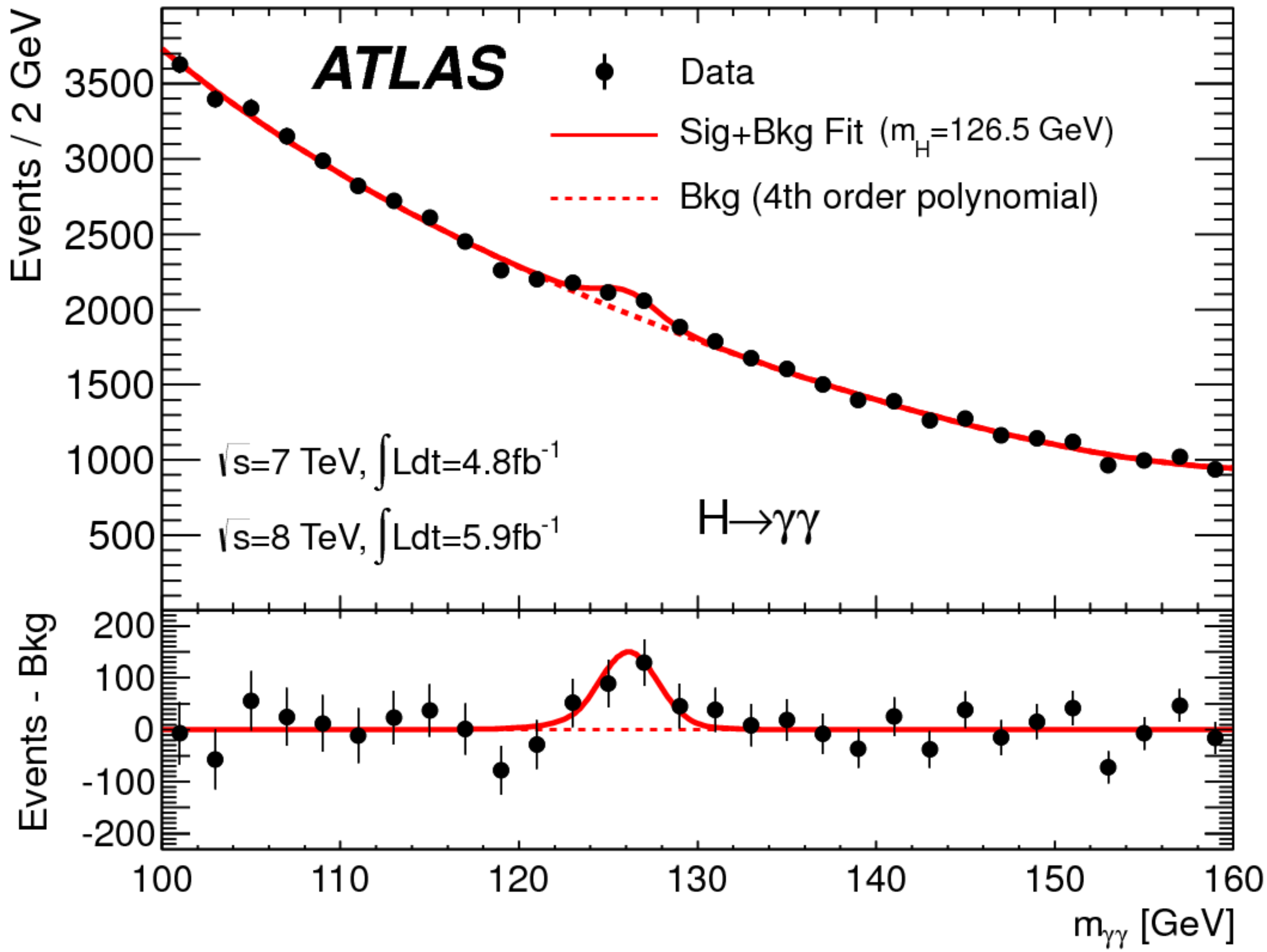


Image: ATLAS

Dispersion relation for light and heavy particles during inflation

Light: $m \ll H$: $\omega = k/a$ (time dependent)

Heavy: $m \sim H$ or larger: $\omega = \sqrt{\left(\frac{k}{a}\right)^2 + m^2} \sim m$ (time independent)

Thus can have a "resonant time" if these two coincide

$$\int d\tau\, f(\tau)\, e^{-ik\tau} e^{imt}$$

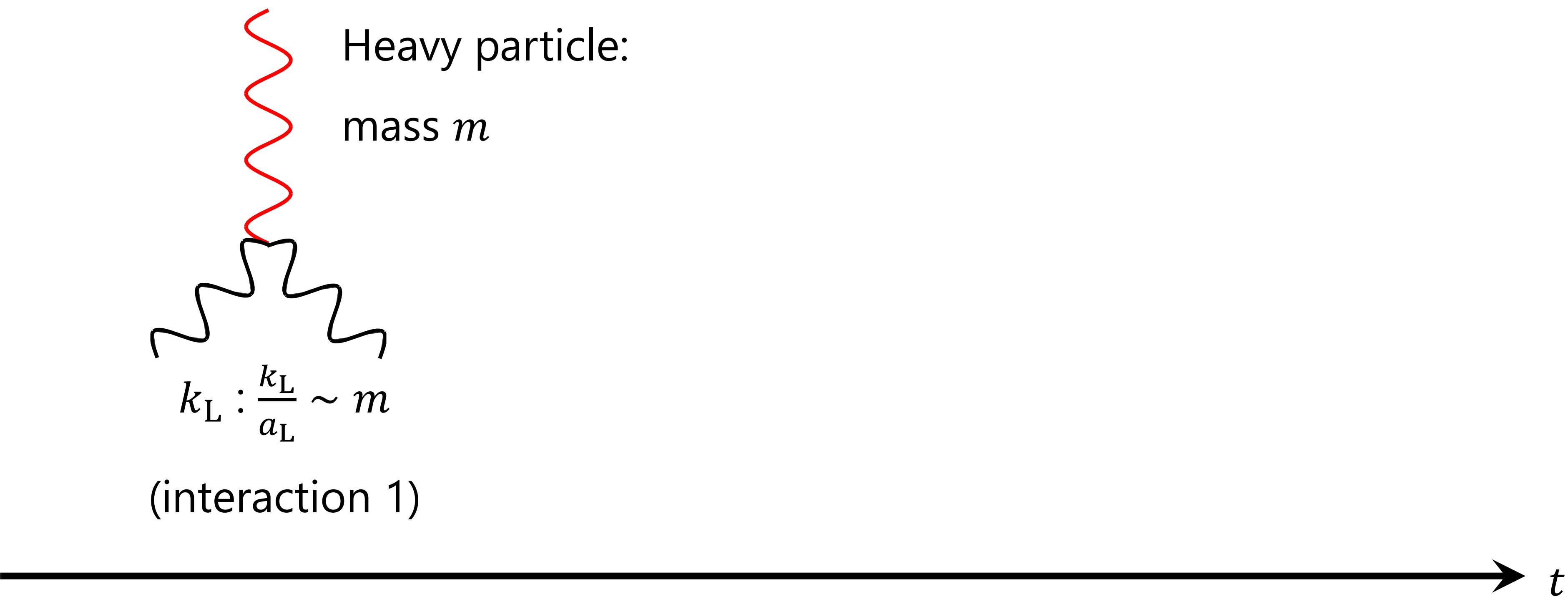
conformal time   proper time

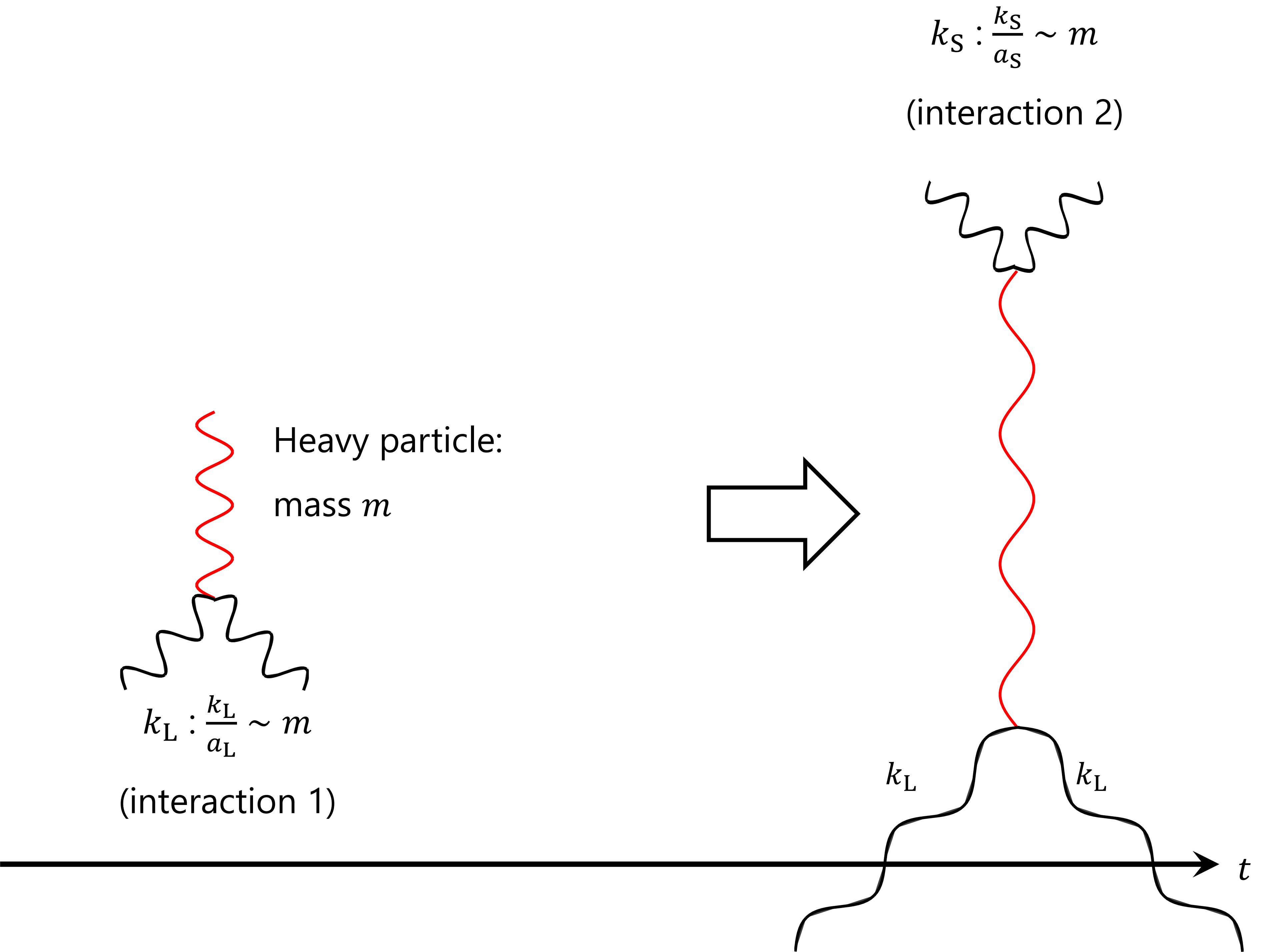
Suppose a heavy particle is produced in de Sitter

Let's study its interactions

Heavy particle:

mass m


Heavy particle:
mass m
$k_{\mathrm{L}} : \frac{k_{\mathrm{L}}}{a_{\mathrm{L}}} \sim m$
(interaction 1)
t



$k_S : \frac{k_S}{a_S} \sim m$
(interaction 2)
Heavy particle:
mass m
$k_L : \frac{k_L}{a_L} \sim m$
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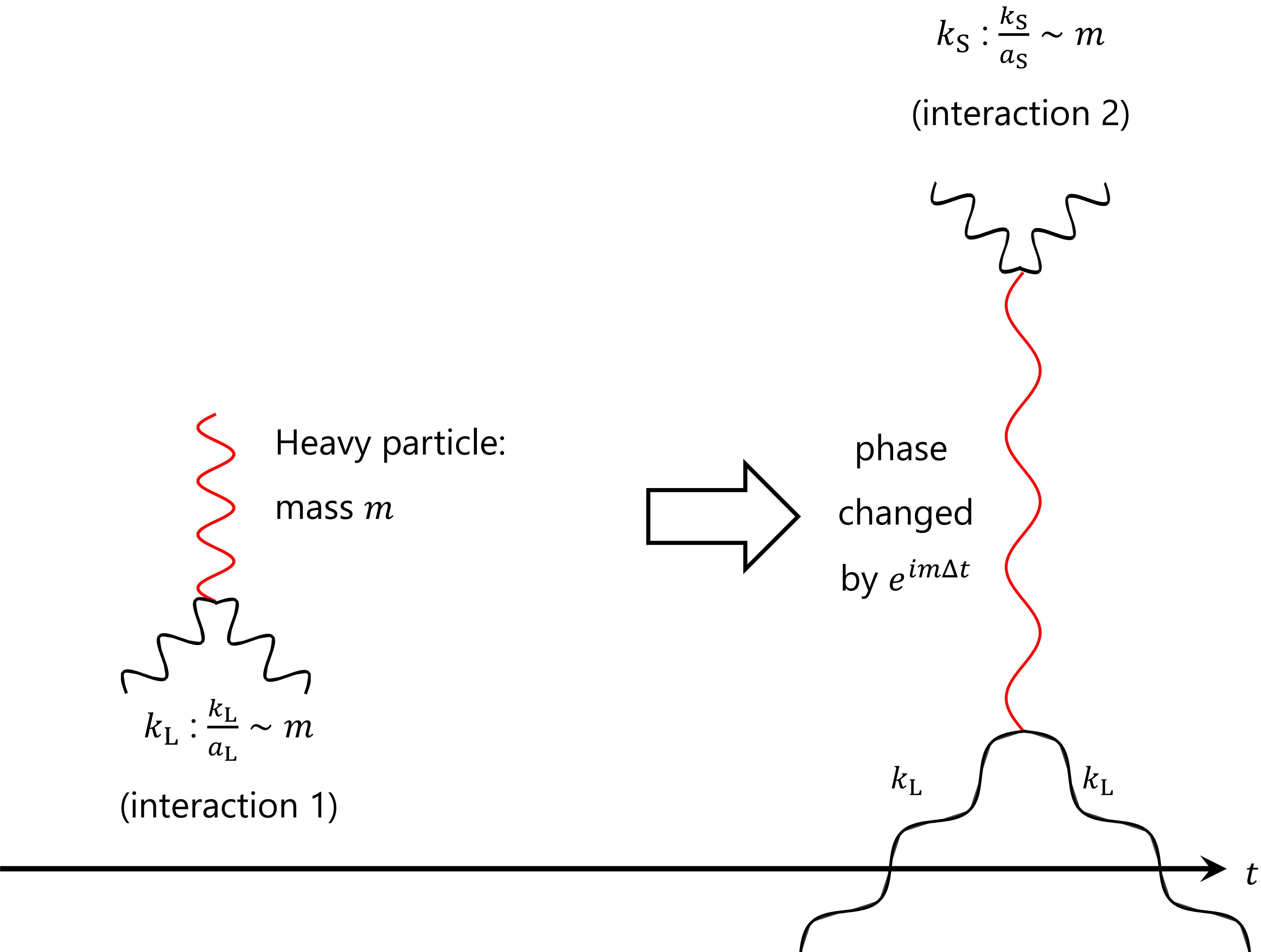
k_L
k_L
t



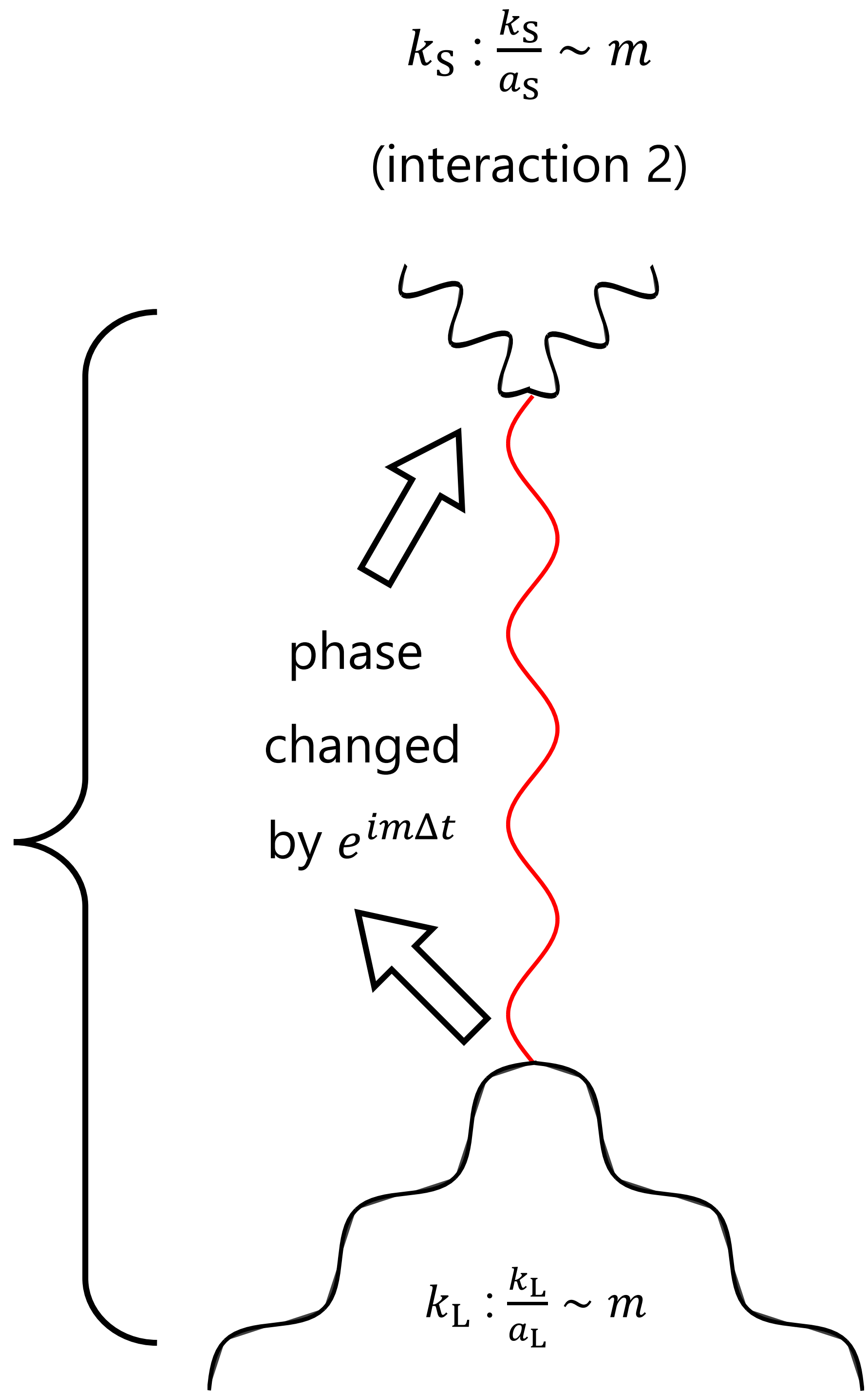
$k_S : \frac{k_S}{a_S} \sim m$
(interaction 2)
Heavy particle:
mass m
phase
changed
by $e^{im\Delta t}$
k_L
k_L
$k_L : \frac{k_L}{a_L} \sim m$
(interaction 1)
t

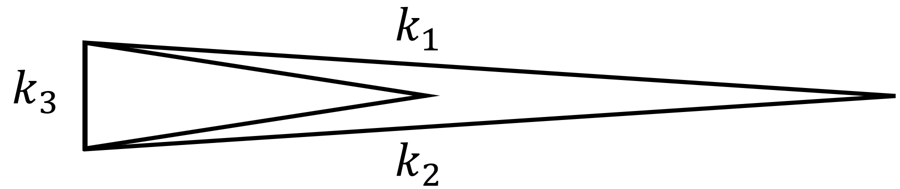
interference:

$$\mathrm{corr} \sim \exp[im(t_\mathrm{S} - t_\mathrm{L})]$$

$$\sim \exp\left[i\frac{m}{H}(\ln(k_S/m) - \ln(k_L/m))\right]$$

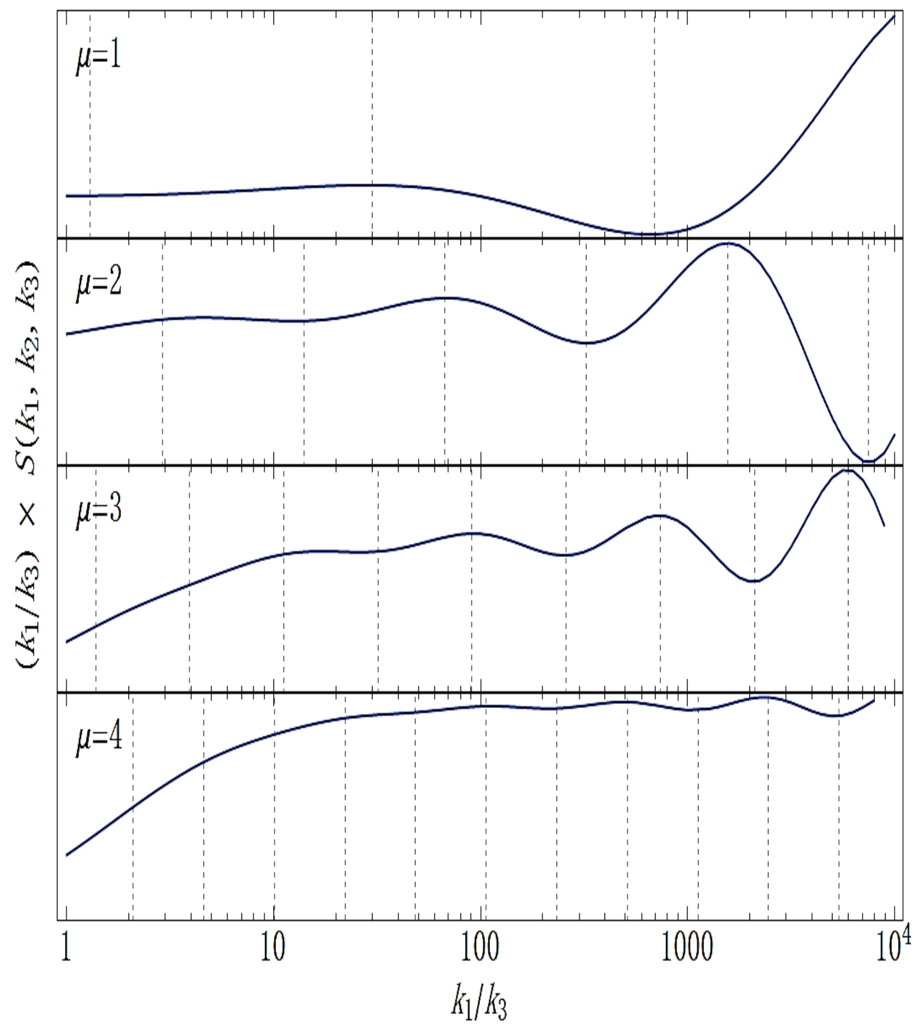
$$\sim \left(\frac{k_\mathrm{S}}{k_\mathrm{L}}\right)^{im/H}$$





Model-independent

All based on known principles.



interference:

corr $\sim \exp[im(t_\mathrm{S} - t_\mathrm{L})]$

$$\sim \exp\left[i\frac{m}{H}(\ln(k_S/m) - \ln(k_L/m))\right]$$

$$\sim \left(\frac{k_\mathrm{S}}{k_\mathrm{L}}\right)^{im/H}$$

actually $\mu = \sqrt{\left(\frac{m}{H}\right)^2 - \frac{9}{4}}$

Remark: Quantum nature

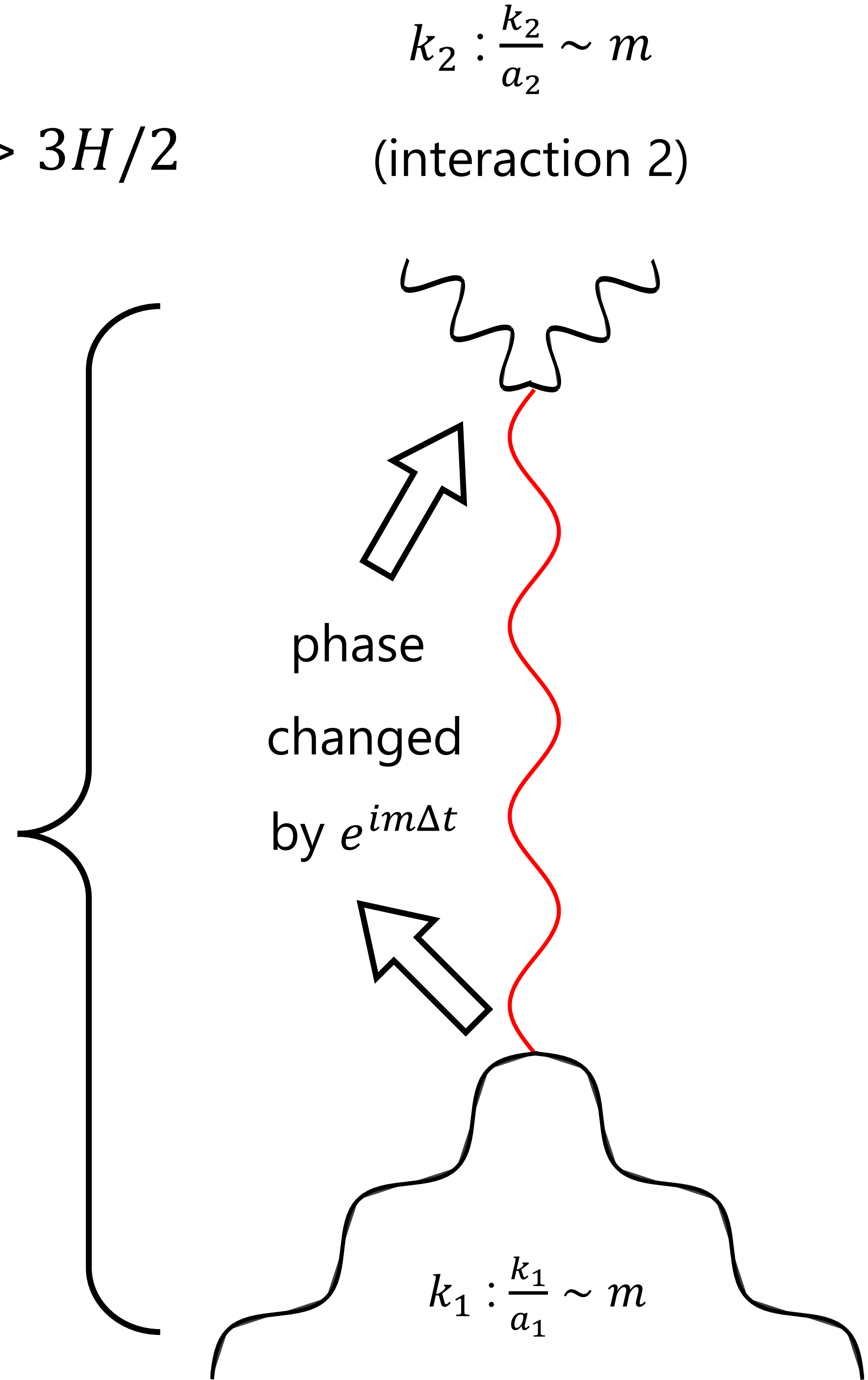
Heavy field: 1 particle state for $m > 3H/2$

Inflaton: 2p from resonance to H

Test of QM during inflation?

Maldacena 1508.01082

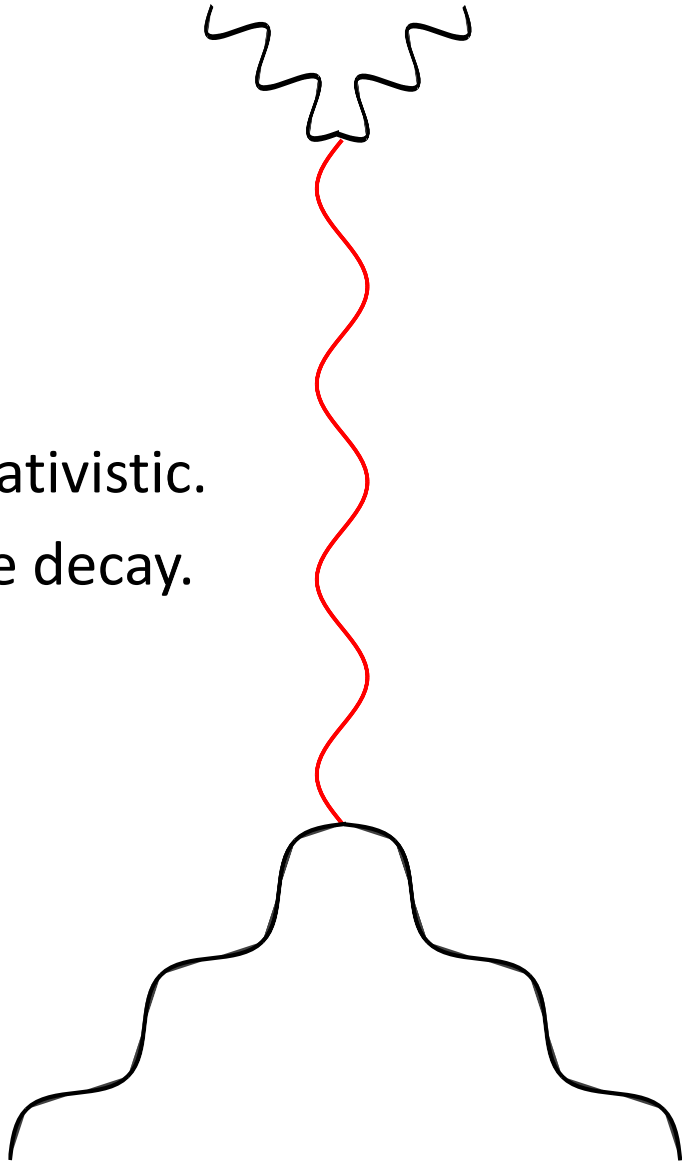
Liu, Sou, YW 1608.07909



Spin

The intermediate heavy particle is non-relativistic.

Angular distribution is the same as particle decay.



Spin 1

spin & motion parallel/anti-parallel for $m = \pm 1$. $m = 0$ is forbidden

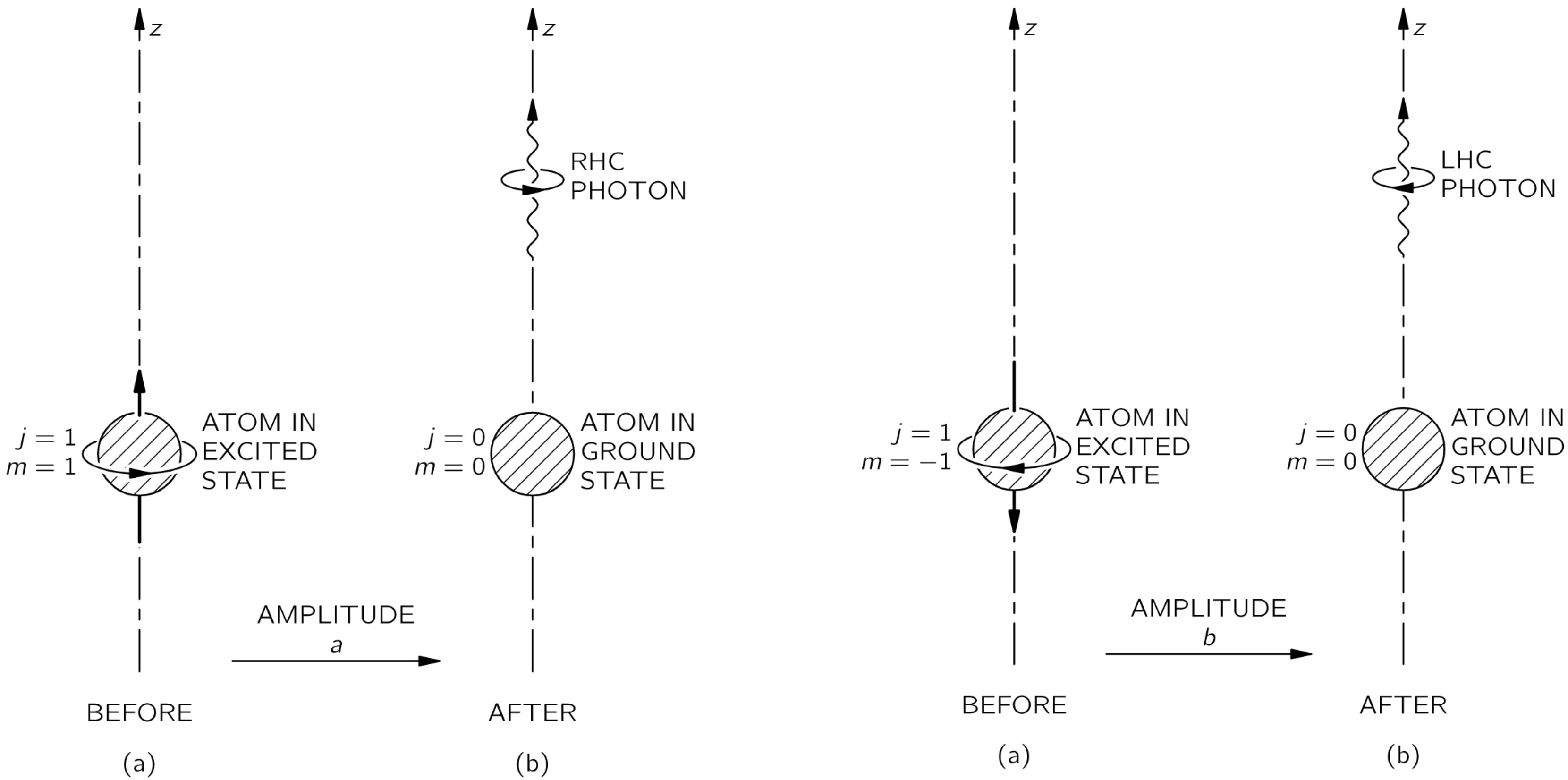
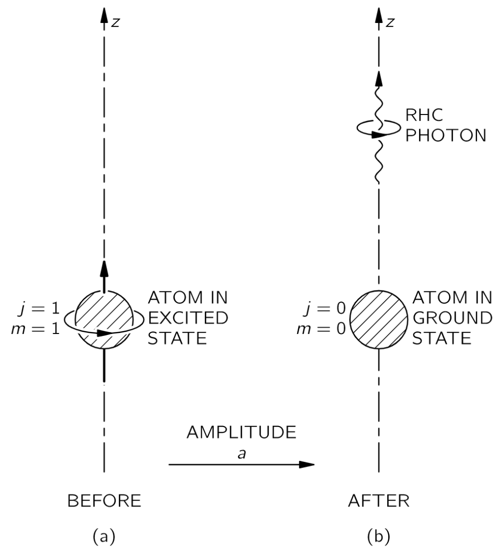


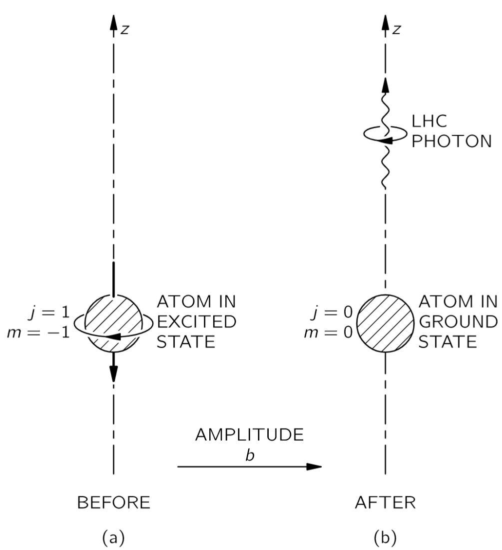
Figure from Feynman Lecture Notes

Spin 1

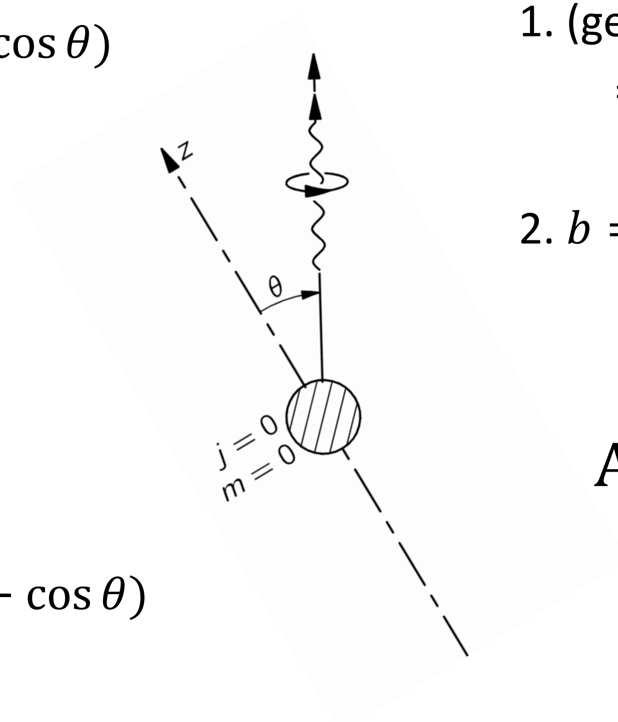
What about spin & motion has a general angle?



$a\,(1+\cos\theta)$



$-b\,(1-\cos\theta)$



Note:

1. (general direction)
   = superposition of
   m = -1, 0, 1 states
2. $b = a$ by parity + rotation

$\text{Amp} \propto \cos\theta$

Figure from Feynman Lecture Notes

In general, for integer spin s,
the angular distribution is $P_s(\cos\theta)$

Arkani-Hamed & Maldacena 2015

Parity and CP

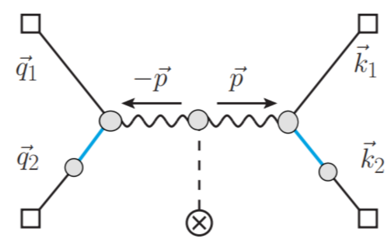
How to observe parity?

Compare “left” and “right” configurations

Beyond 2D. For scalar correlation: need 4pt.

Parity and CP:

- Since the inflaton is charge neutral, P = CP
- May probe CP for fermions
- No CPT invariance due to universe expansion

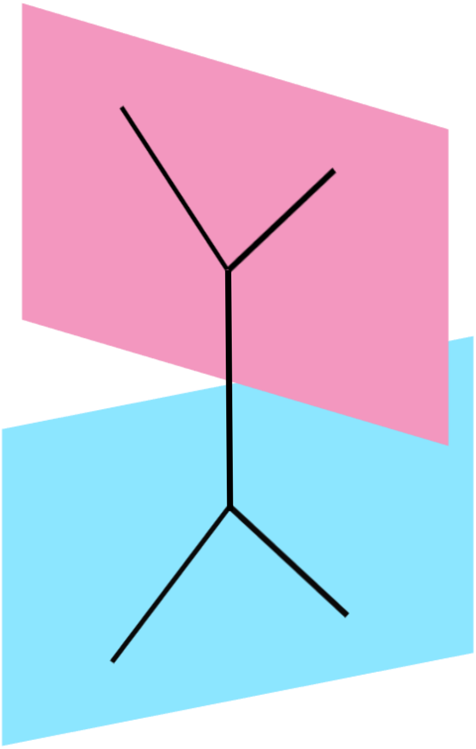


Interaction: $-\frac{c_0}{4}\theta(t)Z_{\mu\nu}Z_{\rho\sigma}\mathcal{E}^{\mu\nu\rho\sigma}$

Here θ is a rolling field (may or may not be the inflaton)

Liu, Tong, YW, Xianyu 1909.01819

CP: decay plane correlation



CP arises from the plane correlation

of the red and the blue in the early universe

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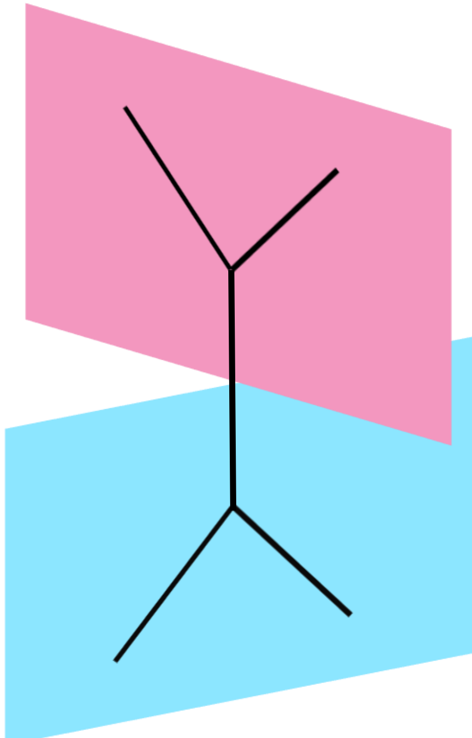


CP arises from the plane correlation of the red and the blue in the early universe

自古红蓝出CP

Width

Width of peak after Fourier transform:

contributions from

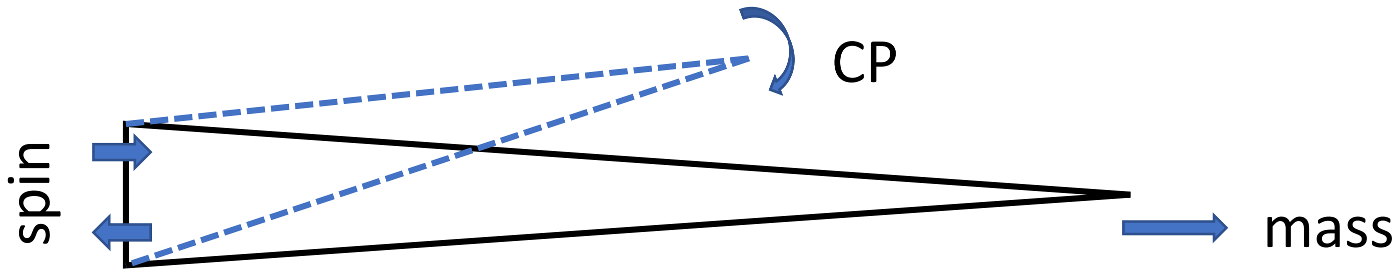
- Decay rate: $\left(\frac{k_L}{k_S}\right)^{\left(3+\frac{\Gamma}{H}\right)/2 \pm i\mu}$ (Arkani-Hamed, Maldacena)
- Thermal motion (non-Rel & redshifting, subdominant)
  (Chemical potential?)
- Higgs mechanism (Higgs fluctuation $\Rightarrow$ Fuzzy mass)

Recap so far

Cosmological collider:

model-independently read off particle mass (resonance), spin (2D angle), CP (3D angle), width (real power law)

… from inflation



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Any target physics on the cosmological collider?

What’s at the energy scale H?

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Accidentally near H ?

- Grand unification

Kumar, Sundrum 1811.11200

- Neutrino seesaw

Chen, YW & Xianyu, 1805.02656

Uplifted to H scale:

- Standard Model

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

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

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

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$h = h_{\rm long} + h_{\rm short}$

$\lambda h^4 \supset \lambda h_{\rm long}^2 h_{\rm short}^2 \sim \lambda \langle h^2 \rangle h^2$

Details:

1. One loop and match IR divergence
2. PI of Euclidean zero mode

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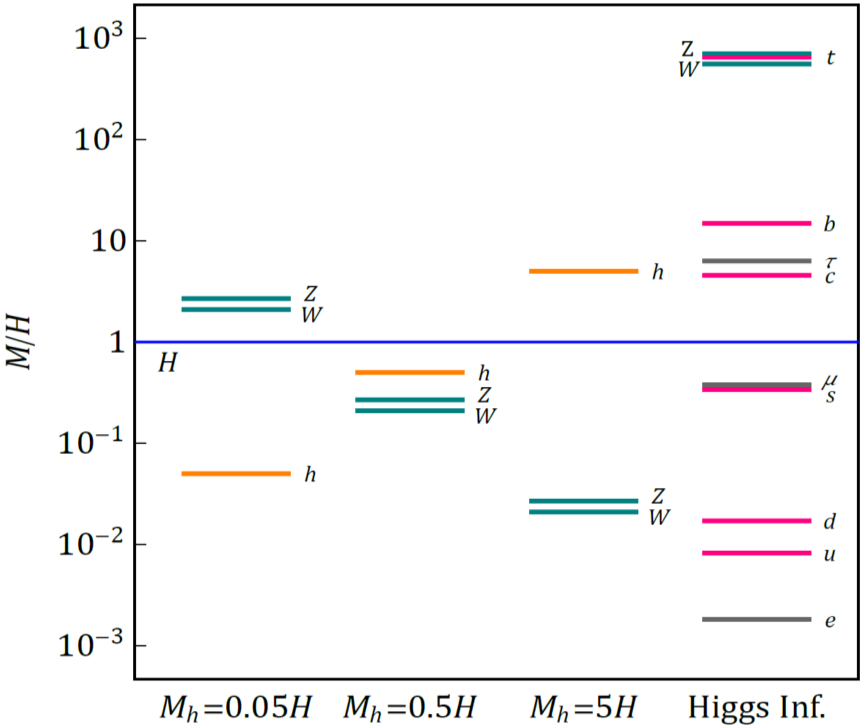

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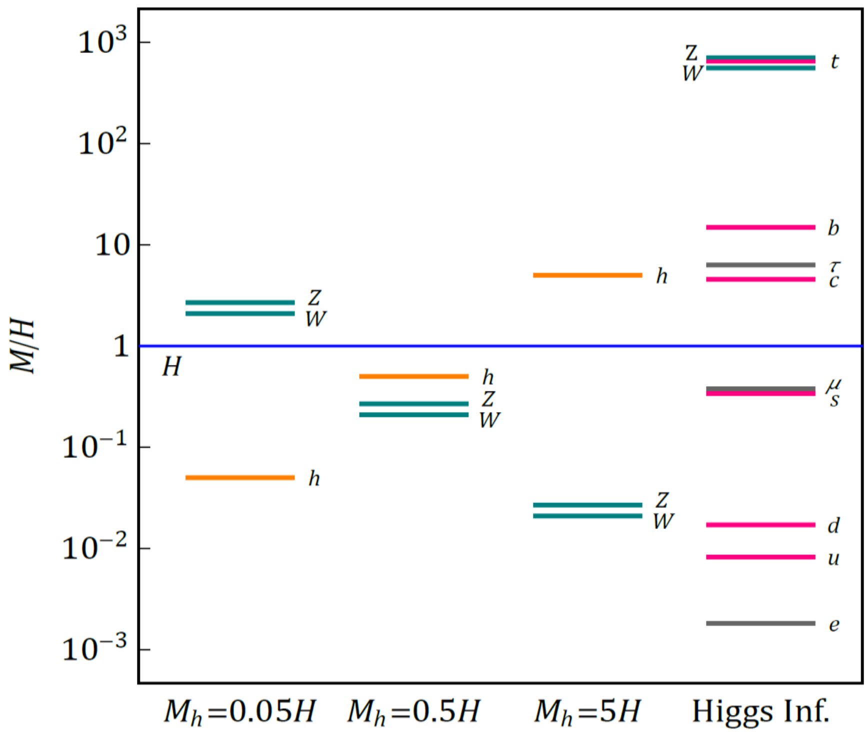

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Kumar & Sundrum, 1711.03988

- SUSY breaking

Baumann & Green, 1109.0292

Delacretaz, Gorbenko

& Senatore 1610.04227

So far so good? Difficulties?

1. Non-Gaussian f_{NL} too small to observe
2. Limited to $m \lesssim H$
3. Challenge for observing very squeezed limits
4. Pollution from coupling with inflaton

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Solutions:

a) Future experiments $\Rightarrow$ 1 (partially)
b) Periodic potential $\Rightarrow$ 2~4 Flauger, Mirbabayi, Senatore, Silverstein, 1606.00513
c) Higher temperature $\Rightarrow$ 2~4 Tong, YW, Zhou 1801.05688 (see also Gilles' talk)
d) Chemical potential $\Rightarrow$ 1~4 Chen, YW, Xianyu 1805.02656; LT Wang, Xianyu 1910.12876
e) Isocurvature collider $\Rightarrow$ 4 Lu, YW, Xianyu, 1907.07390; Kumar, Sundrum 1908.11378

Summary:

If we knew cosmological correlations infinitely precisely,
we know mass, spin, CP, width of all heavy fields during inflation.

SM & beyond, chemical potential, isocurvature

Acknowledgment

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GRF 16301917, 16303819, 16304418 from

Research Grants Council (RGC) of Hong Kong

Thank you!

The “cosmological collider” is also a “primordial standard clock”.

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By Anna Ijjas, Paul J. Steinhardt, Abraham Loeb

VS

Observations

A Cosmic Controversy

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Haven't we known our universe very well?

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vs

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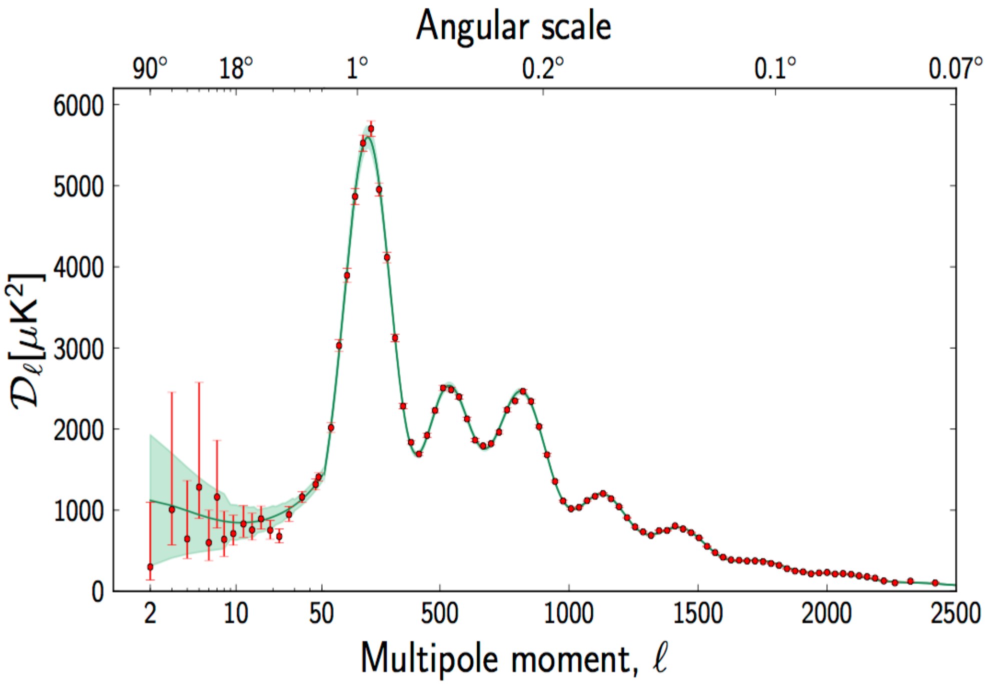

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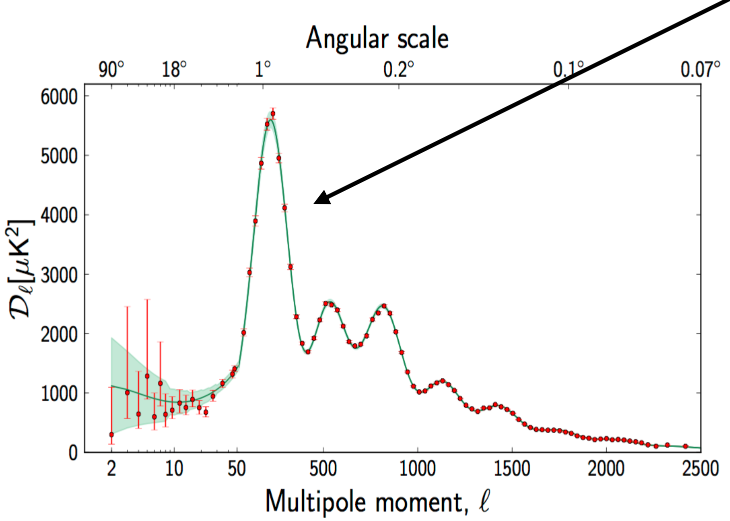

We know fluctuations as functions of scales (k) very well.

$k \sim -1/\tau$ (conformal time)

Thus we know

fluctuation $\leftrightarrow$ conformal time τ

But what about

fluctuation $\leftrightarrow$ physical time t?

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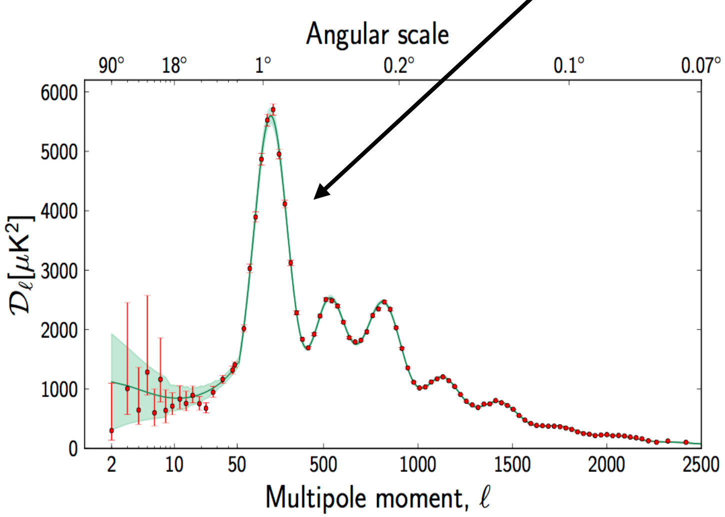

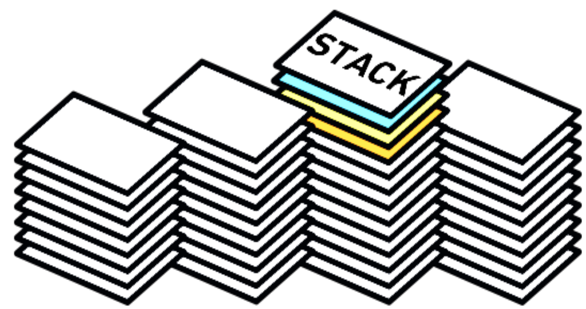

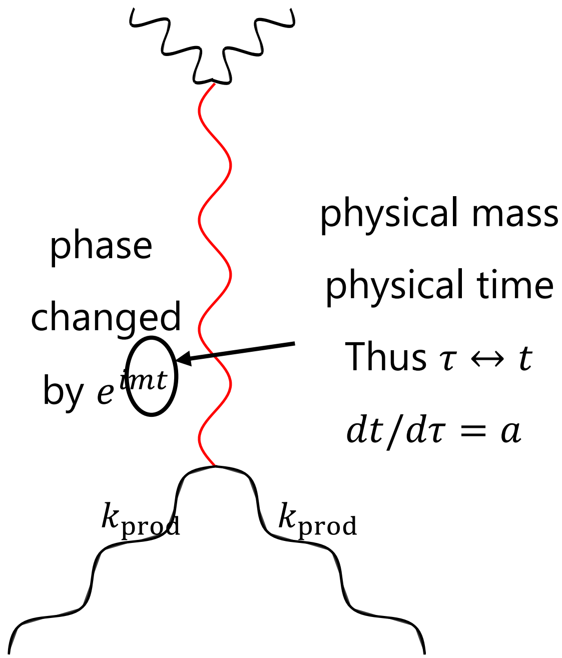

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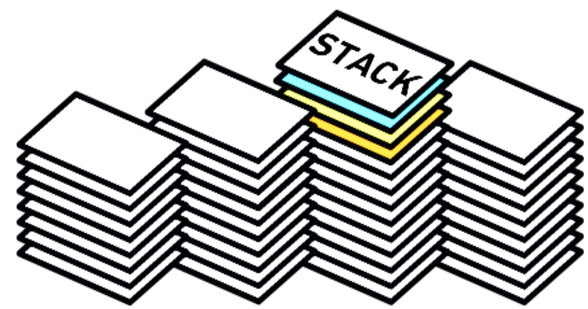
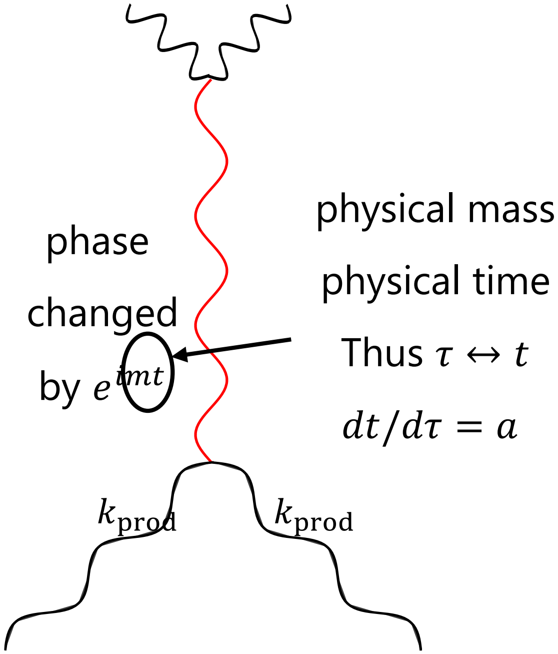
fluctuation $\leftrightarrow$ physical time t?



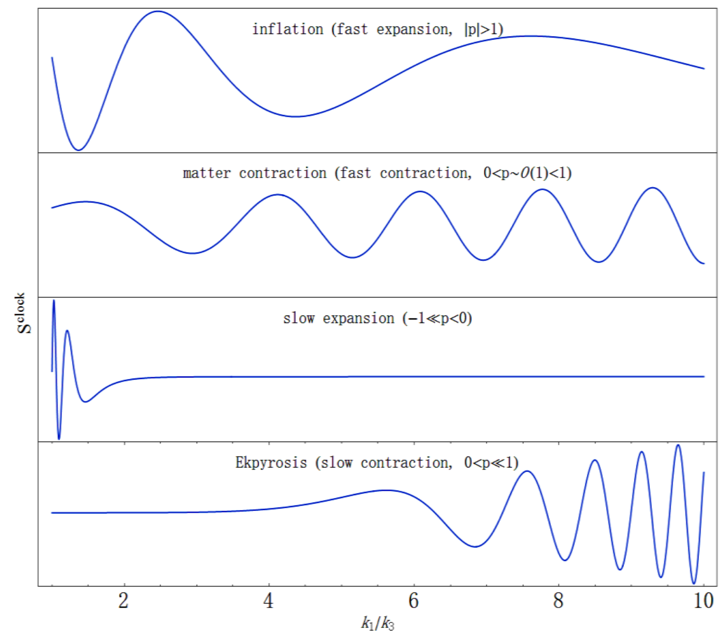
Classical Clock: Chen, 1104.1323
Quantum Clock: Chen, Namjoo & YW, 1509.03930
2pt: Chen, Loeb & Xianyu, 1809.02603



inverse functions

direct probe of expansion history

$$a \propto t^p \text{ then } \langle \phi_{\mathbf{k}_1}\phi_{\mathbf{k}_2}\phi_{\mathbf{k}_3}\rangle \sim \cos\left[\cdots\left(\frac{k_1}{k_3}\right)^{\frac{1}{p}}\right]$$



Classical Clock: Chen, 1104.1323
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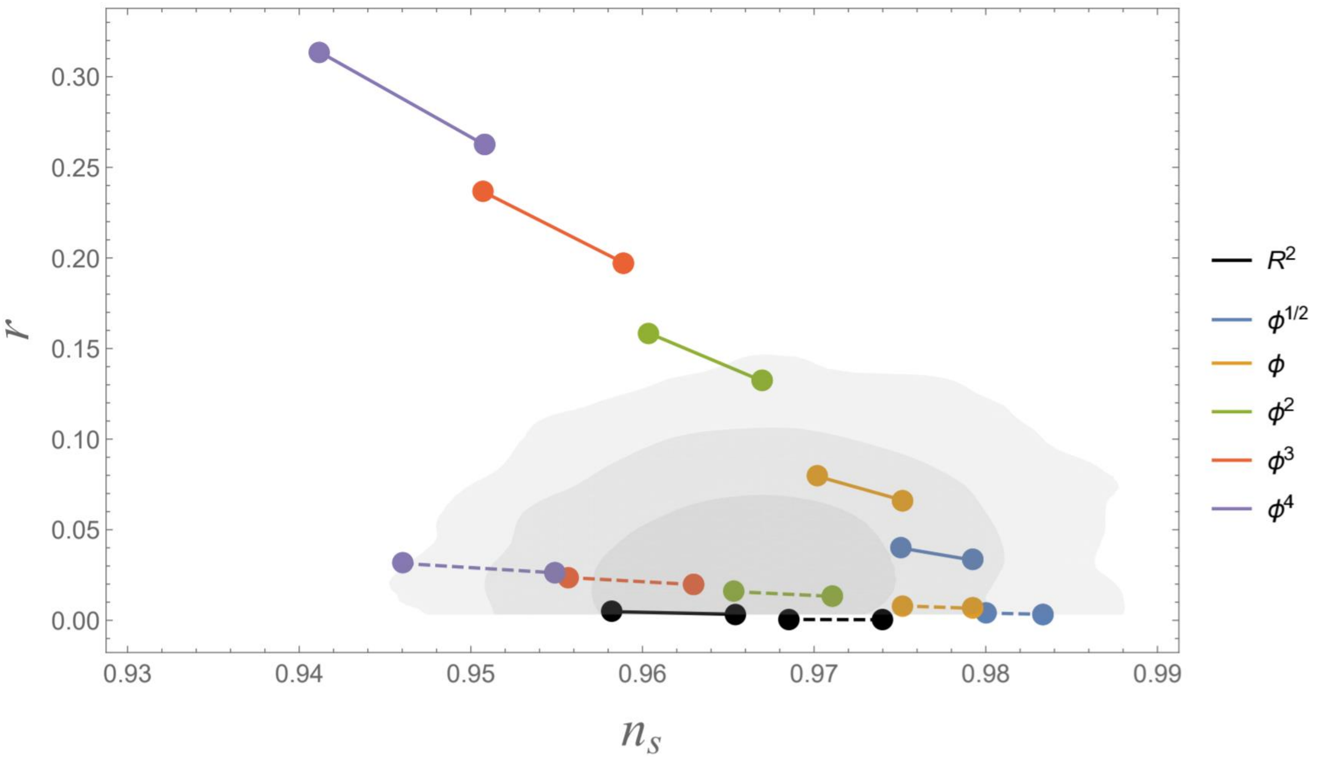
Impacts on inflation models



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An, McAneny, Ridgway, Wise 1706.09971
Tong, YW, Zhou 1708.01709