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”? 

HEP process: 
Create heavy particles 
Let them interact

Long-lived signals

Detectors
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
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

\[ a(t) \propto \exp(HT) \]

\[ T_{GH} \sim H \text{ is up to } 10^{13}\text{GeV} \]

The cosmological collider
HEP at Higher Energies?
Collider Built by Nature?
What's needed as a "collider"?

**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**
\[ a(t) \propto \exp(\frac{H}{t}) \]
\[ T_{GH} \sim H \text{ is up to } 10^{13}\text{GeV} \]

**Classical conserved quantities, such as:**
- curvature pert \( \zeta \)
- PGW \( \gamma_{ij} \), isocurvature

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

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

Formalism: QFT in curved spacetime

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

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

PGW & remaining isocurvature fluctuation (if any): similar

Inflation of the very early universe

$$a(t) \propto \exp(Ht)$$

$T_{GH} \sim H$ is up to $10^{13}\text{GeV}$

Classical conserved quantities, such as:

- curvature pert $\zeta$
- PGW $\gamma_{ij}$, isocurvature

The cosmological collider
HEP at Higher Energies?
Collider Built by Nature?
What's needed as a "collider"?

HEP process:
Create heavy particles
Let them interact

Long-lived signals

Detectors

Man-made colliders
e.g. LHC
e.g. ATLAS, CMS

Inflation of the very early universe
\[ a(t) \propto \exp(Ht) \]
\[ T_{GH} \sim H \text{ is up to } 10^{13}\text{GeV} \]

Classical conserved quantities, such as:
- curvature pert \( \zeta \)
- PGW \( \gamma_{ij} \), isocurvature

Cosmological observations, e.g.
- CMB, LSS, 21cm

The cosmological collider
Observations: Correlation functions of primordial --
- Curvature perturbation $\zeta$
  - 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

Inflation of the very early universe
\[ a(t) \propto \exp(Ht) \]
\[ T_{GH} \sim H \text{ is up to } 10^{13}\text{GeV} \]

Classical conserved quantities, such as:
- curvature pert $\zeta$
- PGW $\gamma_{ij}$, isocurvature

Cosmological observations, e.g.
- CMB, LSS, 21cm

The cosmological collider
HEP at Higher Energies?
Collider Built by Nature?
What's needed as a "collider"?

**HEP process:**
- Create heavy particles
- Let them interact

**Long-lived signals**

**Detectors**

**Man-made colliders**
- e.g. LHC
- leptons, photons, jets
- e.g. ATLAS, CMS

**Inflation of the very early universe**
- $a(t) \propto \exp(HT)$
- $T_{GH} \sim H$ is up to $10^{13} \text{GeV}$

**Classical conserved quantities, such as:**
- curvature pert $\zeta$
- PGW $\gamma_{ij}$, isocurvature

**Cosmological observations, e.g.**
- CMB, LSS, 21cm

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

Traditional Way

Cosmological Collider

UV model

Observation

Inflation model

inflation: $e^{Ht}$

CP

mass

spin

width

model independent
Mass
Mass: from resonance

ATLAS

Data

Sig+Bkg Fit ($m_H=126.5$ GeV)

Bkg (4th order polynomial)

H → γγ

$\sqrt{s}=7$ TeV, $\int L dt=4.8$ fb$^{-1}$

$\sqrt{s}=8$ TeV, $\int L dt=5.9$ fb$^{-1}$
Dispersion relation for light and heavy particles during inflation

Light: \( m \ll H \): \( \omega = \frac{k}{a} \) (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 $m$

$k_L : \frac{k_L}{a_L} \sim m$

(interaction 1)
Heavy particle: mass $m$

$k_L : \frac{k_L}{a_L} \sim m$ (interaction 1)

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

$k_L : \frac{k_L}{a_L} \sim m$

(interaction 1)

$k_S : \frac{k_S}{a_S} \sim m$

(interaction 2)

phase changed by $e^{im\Delta t}$

$t$
\[
\begin{align*}
  k_S : \frac{k_S}{a_S} & \sim m \\
  (\text{interaction 2}) \\
  \text{interference:} \\
  \text{corr} & \sim \exp[im(t_S - t_L)] \\
  & \sim \exp\left[i \frac{m}{H} (\ln(k_S/m) - \ln(k_L/m))\right] \\
  & \sim \left(\frac{k_S}{k_L}\right)^{im/H} \\
  k_L : \frac{k_L}{a_L} & \sim m
\end{align*}
\]
Model-independent
All based on known principles.

interference:
\[ \text{corr} \sim \exp[im(t_S - t_L)] \]

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

\[ \sim \left( \frac{k_S}{k_L} \right)^{im/H} \]

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?

$k_2 : \frac{k_2}{a_2} \sim m$

(interaction 2)

$k_1 : \frac{k_1}{a_1} \sim m$

phase changed by $e^{im\Delta t}$

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

---

(a) $j = 1$, $m = 1$ ATOM IN EXCITED STATE
(b) $j = 0$, $m = 0$ ATOM IN GROUND STATE

Figure from Feynman Lecture Notes
Spin 1

What about spin & motion has a general angle?

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

\[
\text{Amp } \propto \cos \theta
\]
In general, for integer spin $s$, the angular distribution is $P_s(\cos \theta)$
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 $\theta$ is a rolling field (may or may not be the inflaton)
CP: decay plane correlation

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

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:
contribution 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
Recap so far

Cosmological collider:
  model-independently read off particle mass (resonance),
  spin (2D angle), CP (3D angle), width (real power law)
  ... from inflation

Any target physics on the cosmological collider?
What’s at the energy scale $H$?
What’s at the energy scale $H$?

Accidentally near $H$?

- Grand unification
  Kumar, Sundrum 1811.11200
- Neutrino seesaw
  Chen, YW & Xianyu, 1805.02656
What’s at the energy scale $H$?

Accidentally near $H$?
- Grand unification
  
  Kumar, Sundrum 1811.11200

- Neutrino seesaw
  
  Chen, YW & Xianyu, 1805.02656

Uplifted to $H$ scale:
- Standard Model
  
  $\langle h^2 \rangle \sim H^2$

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

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

  Chen & YW, 0911.3380

  Chen, YW & Xianyu, 1610.06597

  Kumar & Sundrum, 1711.03988
What’s at the energy scale $H$?

Accidentally near $H$?
- Grand unification
  
  Kumar, Sundrum 1811.11200

- Neutrino seesaw
  
  Chen, YW & Xianyu, 1805.02656

Uplifted to $H$ scale:

- Standard Model

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

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

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

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

$\lambda h^4 \supset \lambda h_{\text{long}}^2 h_{\text{short}}^2 \sim \lambda \langle h^2 \rangle h^2$
What's at the energy scale $H$?

Accidentally near $H$?
- Grand unification
  Kumar, Sundrum 1811.11200
- Neutrino seesaw
  Chen, YW & Xianyu, 1805.02656

Uplifted to $H$ scale:
- Standard Model
  $$\langle h^2 \rangle \sim H^2$$
  $$\lambda h^4 \supset \lambda \langle h^2 \rangle h^2 \sim m_{\text{eff}}^2 h^2$$
  also: possible $h^2 R \sim H^2 h^2$
  Chen & YW, 0911.3380
  Chen, YW & Xianyu, 1610.06597
  Kumar & Sundrum, 1711.03988
HEP at Higher Energies?
Collider Built by Nature?

What’s needed as a “collider”?

What can be studied?

Mass: what’s the resonance?

From resonance to interference

Uplifted to $H$ scale:

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

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

  Chen & YW, 0911.3380
  Chen, YW & Xianyu, 1610.06597
  Kumar & Sundrum, 1711.03988

- SUSY breaking

  Baumann & Green, 1109.0292
  Delacretaz, Gorbenko
  & Senatore 1610.04227

What’s at the energy scale $H$?

Accidentally near $H$?

- Grand unification
  Kumar, Sundrum 1811.11200

- Neutrino seesaw
  Chen, YW & Xianyu, 1805.02656
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
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

Solutions:

a) Future experiments $\Rightarrow 1$ (partially)

b) Periodic potential $\Rightarrow 2 \sim 4$ Flauger, Mirbabayi, Senatore, Silverstein, 1606.00513

c) Higher temperature $\Rightarrow 2 \sim 4$ Tong, YW, Zhou 1801.05688 (see also Gilles’ talk)

d) Chemical potential $\Rightarrow 1 \sim 4$ 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

This talk is supported in part by

Grants ECS 26300316 and

GRF 16301917, 16303819, 16304418 from Research Grants Council (RGC) of Hong Kong
The “cosmological collider” is also a “primordial standard clock”.
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 Iijas, Paul J. Steinhardt, Abraham Loeb

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.
Precision Era:
Haven’t we known our universe very well?

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 Iijas, Paul J. Steinhardt, Abraham Loeb

VS

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.
Precision Era:
Haven’t we known our universe very well?
Precision Era:
Haven’t we known our universe very well?

We know fluctuations as functions of scales \( k \) very well. 
\( k \sim -1/\tau \) (conformal time) 
Thus we know 
fluctuation \( \leftrightarrow \) conformal time \( \tau \) 
But what about 
fluctuation \( \leftrightarrow \) physical time \( t \)?
Precision Era:
Haven’t we known our universe very well?

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

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

Thus we know fluctuation $\leftrightarrow$ conformal time $\tau$

But what about fluctuation $\leftrightarrow$ physical time $t$?
We know fluctuations as functions of scales (k) very well. \( k \sim -1/\tau \) (conformal time)

Thus we know

\[ \text{fluctuation} \leftrightarrow \text{conformal time} \ \tau \]

But what about

\[ \text{fluctuation} \leftrightarrow \text{physical time} \ t? \]

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

\[ a \propto t^p \text{ then } \left\langle \phi_k \phi_{k^2} \phi_{k^3} \right\rangle \sim \cos \left[ \cdots \left( \frac{k_1}{k_3} \right)^{\frac{1}{p}} \right] \]
Impacts on inflation models

Jiang, YW 1703.04477
An, McAneny, Ridgway, Wise 1706.09971
Tong, YW, Zhou 1708.01709