Updates on the Cosmological Collider Physics

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, to appear

Isocurvature: Lu, YW, Xianyu, to appear

Quantum Primordial Standard Clocks: Chen, Namjoo, YW 1509.03930
Why is inflation a cosmological “collider”? 
What’s needed as a “collider”?

HEP process:
Create heavy particles
Let them interact

Detectors

Long-lived signals
HEP process:
Create heavy particles
Let them interact

Detectors

Man-made colliders

e.g. LHC

leptons, photons, jets

e.g. ATLAS, CMS

Long-lived signals
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
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
\[ a(t) \propto \exp(Ht) \]
\[ T_{GH} \sim H \text{ is up to } 10^{13}\text{GeV} \]

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

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

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

Formalism: QFT in curved spacetime

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

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

PGW & remaining isocurvature fluctuation (if any): similarly

Inflation of the very early universe

$\alpha(t) \propto \exp(\lambda t)$

$T_{GH} \sim H$ is up to $10^{13}$ 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"?

e.g. LHC
leptons, photons, jets
e.g. ATLAS, CMS

Man-made colliders

HEP process:
Create heavy particles
Let them interact

Detectors

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

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

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

The cosmological collider
Observations: Correlation functions of

- 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
- PGW: 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"?

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 perturbation \( \zeta \)
- PGW \( \gamma_{ij} \), isocurvature

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

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

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

Traditional Way
Inflation model

Observation

UV model

Traditional Way

Cosmological Collider

mass

inflation: $e^{Ht}$

model independent

CP

spin
Mass: from resonance

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

$\sqrt{s}=8\text{ TeV}, \int L dt=5.9\text{fb}^{-1}$

$H \rightarrow \gamma \gamma$
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

$$\int d\tau \, f(\tau) \, e^{-i\kappa\tau} e^{imt}$$
Heavy particle:
mass $m$

$k_{\text{prod}} : \frac{k_{\text{prod}}}{a_{\text{prod}}} \sim m$

(resonant production)
Heavy particle: mass $m$

$k_{\text{prod}} : \frac{k_{\text{prod}}}{a_{\text{prod}}} \sim m$ (resonant production)

$k_{\text{decay}} : \frac{k_{\text{decay}}}{a_{\text{decay}}} \sim m$ (resonant decay)
Heavy particle: mass \( m \)

Resonant production:

\[ k_{\text{prod}} : \frac{k_{\text{prod}}}{a_{\text{prod}}} \sim m \]

Phase changed by \( e^{imt} \)

Resonant decay:

\[ k_{\text{decay}} : \frac{k_{\text{decay}}}{a_{\text{decay}}} \sim m \]

(resonant decay)
interference:
\[ \text{corr} \sim \exp[im(t_{\text{decay}} - t_{\text{prod}})] \]
\[ \sim \left( \frac{k_{\text{decay}}}{k_{\text{prod}}} \right)^{im/H} \]

\[ k_{\text{decay}} : \frac{k_{\text{decay}}}{a_{\text{decay}}} \sim m \]
(resonant decay)

phase changed by \( e^{imt} \)

\[ k_{\text{prod}} : \frac{k_{\text{prod}}}{a_{\text{prod}}} \sim m \]
interference:
\[
\text{corr} \sim \exp\left[im(t_{\text{decay}} - t_{\text{prod}})\right]
\]
\[
 \sim \left(\frac{k_{\text{decay}}}{k_{\text{prod}}}\right)^{im/H}
\]
actually \( \mu = \sqrt{\left(\frac{m}{H}\right)^2 - \frac{9}{4}} \)

Model-independent
All based on known principles.
Spin

Figure from Feynman Lecture Notes for spin 1/2
Spin

Figure from Feynman Lecture Notes for spin 1/2
Spin: angular distribution

For integer spin: $P_s (\cos \theta)$ angular distribution
CP: decay plane correlation

CP arises from the plane correlation of the red and the blue

Liu, Tong, YW, Xianyu, to appear
CP: decay plane correlation

CP arises from the plane correlation of the red and the blue
Recap so far

Cosmological collider:
model-independently read off particle mass (resonance),
spin (2D angle), CP (3D angle), ... from inflation
Recap so far

Cosmological collider:

model-independently read off particle mass (resonance), spin (2D angle), CP (3D angle), ... 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
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

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

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

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

  Chen & YW, 0911.3380

  Chen, YW & Xianyu, 1610.06597

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

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

- SUSY breaking
  Baumann & Green, 1109.0292
  Delacretaz, Gorbenko
  & Senatore 1610.04227

Uplifted to $H$ scale:
- Standard Model
  $\langle h^2 \rangle \sim H^2$
  $\lambda h^4 \supset \lambda \langle h^2 \rangle h^2 \sim m_{\text{eff}} h^2$
  also: possible $h^2 R \sim H^2 h^2$
  Chen & YW, 0911.3380
  Chen, YW & Xianyu, 1610.06597
  Kumar & Sundrum, 1711.03988
Beyond, beyond and beyond
Beyond $m \sim H$? Usually $e^{-\pi m/H}$ suppressed. However:

- **Bumpier inflaton potential**
  
  Flauger, Mirbabayi, Senatore, Silverstein 1606.00513

- **Non-minimal temperature**  Tong, YW, Zhou 1801.05688

- **Chemical potential**  Chen, YW & Xianyu, 1805.02656
Beyond curvature perturbation:

- PGW Collider
- Cosmological Isocurvature Colliders  Lu, YW, Xianyu, to appear
  e.g. Cosmological Higgs Collider with modulated reheating
Beyond cosmological collider:

- Quantum primordial standard clocks Chen, Namjoo, YW 1509.03930
- Quantum nature of fluctuation Maldacena 1508.01082; Liu, Sou, YW 1608.07909
- Hubble tension Adhikari, Huterer 1905.02278
- Impacts on inflation models Jiang, YW 1703.04477

Consider dim-5 operator \((\partial \phi)^2 \sigma / \Lambda, \mathcal{L}_2 \supset \frac{2\dot{\phi}}{\Lambda} \delta \dot{\phi} \delta \sigma\)

Note: \(\dot{\phi} \sim 3600H^2\).

Even \(\Lambda = M_p\), if \(m \sim H\) for \(\sigma\), still \(\mathcal{L}_2 \sim \sqrt{\epsilon}H \times \delta \dot{\phi} \delta \sigma\)

For \(r \geq 10^{-3}\) (i.e. \(\epsilon \geq 10^{-4}\))

Potentially observable change of
\[
\frac{\Delta r}{r} \text{ and } \frac{\Delta (n_s - 1)}{(n_s - 1)}
\]

Observable \(M_p\) effect!
Beyond cosmological collider:

- **Quantum primordial standard clocks** Chen, Namjoo, YW 1509.03930
- **Quantum nature of fluctuation** Maldacena 1508.01082; Liu, Sou, YW 1608.07909
- **Hubble tension** Adhikari, Huterer 1905.02278
- **Impacts on inflation models** Jiang, YW 1703.04477

Consider dim-5 operator \((\partial \phi)^2 \sigma / \Lambda, \mathcal{L}_2 \supset \frac{2\dot{\phi}}{\Lambda} \delta \dot{\phi} \delta \sigma\)

Note: \(\dot{\phi} \sim 3600H^2\).

Even \(\Lambda = M_p\), if \(m \sim H\) for \(\sigma\), still \(\mathcal{L}_2 \sim \sqrt{\frac{2\dot{\phi}}{\Lambda} \delta \dot{\phi} \delta \sigma}\)

For \(r \geq 10^{-3}\) (i.e. \(\epsilon \geq 10^{-4}\))

Potentially observable change of \(\Delta r/r\) and \(\Delta(n_s - 1)/(n_s - 1)\)

Observable \(M_p\) effect!

And many possible enhancement factors:

1. Larger \(r\)
2. Multi-field (all positive \(\Delta P_\zeta\))
3. IR growth if \(m \lesssim H\)
4. If \(M_{\text{string}} < M_p\)
5. If \(M_{\text{extra}} < M_p\)
Beyond cosmological collider:

- **Quantum primordial standard clocks** Chen, Namjoo, YW 1509.03930
- **Quantum nature of fluctuation** Maldacena 1508.01082; Liu, Sou, YW 1608.07909
- **Hubble tension** Adhikari, Huterer 1905.02278
- **Impacts on inflation models** Jiang, YW 1703.04477

![Graph showing the relationship between $n_s$ and $r^*$ with different lines for $R^2$, $\phi$, $\phi^2$, $\phi^3$, and $\phi^4$.](image)

Tong, YW, Zhou 1708.01709, see also An, McAneny, Ridgway, Wise 1706.09971
Summary:

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

Standard model and beyond, and beyond and beyond

Acknowledgment

This talk is supported in part by Grants ECS 26300316 and GRF 16301917, 16304418 from Research Grants Council (RGC) of Hong Kong