Inflation as a Cosmological Collider

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Collider Built by Nature?

High energies in nature

- HEP at Higher Energies?
- Collider Built by Nature?

High energies in nature:

- Black holes



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- The early universe



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Probably the highest energy in our universe

Is it a "collider"?



Collider Built by Nature?

What's needed as a "collider"?

High energies in nature:

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Is it a "collider"?



Image: WMAP

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









The cosmological collider



The cosmological collider



The cosmological collider

What can be studied?

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- What's needed as a "collider"?
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Information in correlation functions: Mass: resonance in energy dependence Spin: angular dependence Interactions: size & energy envelop

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Detections New particle Mass of Higgs

Information in correlation functions: Mass: resonance in energy dependence Chen & YW, 0909.0496, 0911.3380 Arkani-Hamed & Maldacena, 1503.08043 **Spin:** angular dependence Arkani-Hamed & Maldacena, 1503.08043 Baumann, Goon, Lee, Pimentel, 1712.06624 **Interactions:** size & energy envelop Model dependent, lots of studies

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- What's needed as a "collider"?
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Recent: Cosmology → particle Model-independent Information in correlation functions:

Mass: resonance in energy dependence

Chen & YW, 0909.0496, 0911.3380

Arkani-Hamed & Maldacena, 1503.08043

Spin: angular dependence

Arkani-Hamed & Maldacena, 1503.08043

Baumann, Goon, Lee, Pimentel, 1712.06624

Traditional: Particle \rightarrow cosmology \rightarrow particle Model-dependent

Interactions: size & energy envelop

Model dependent, lots of studies

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Accidentally near *H* ?

- Grand unification
- Neutrino seesaw

Chen, Wang & Xianyu, 1805.02656

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Uplifted to *H* scale: - Standard Model $\langle h^2 \rangle \sim H^2$ $\lambda h^4 \supset \lambda \langle h^2 \rangle h^2 \sim m_{eff}^2 h^2$ also: possible $h^2 R \sim H^2 h^2$ Chen & YW, 0911.3380 Chen, YW & Xianyu, 1610.06597 Kumar & Sundrum, 1711.03988



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Chen & YW, 0911.3380

Chen, YW & Xianyu, 1610.06597

Kumar & Sundrum, 1711.03988

- SUSY breaking

Baumann & Green, 1109.0292 Delacretaz, Gorbenko & Senatore 1610.04227

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- Mass: what's the resonance?
- From resonance to interference
- What's at the energy scale *H*?
- How is the collider "built"?

Expansion history Chen, Namjoo & YW, 1509.03930

Maldacena, 1508.01082

Correction to 2pt Jiang & YW, 1703.04477

Testing QM

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By Anna Ijjas, Paul J. Steinhardt, Abraham Loeb



🖞 Observations

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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

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Image: Planck Team



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?



We know fluctuations as
functions of scales (k) very well.
k ~ −1/τ (conformal time)
Thus we know
fluctuation ↔ conformal time τ
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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?



X. Chen, Namjoo & YW, 1509.03930



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Observation?

 $f_{NL} \sim (\text{coupling}) \times (\text{Boltzmann})$

(coupling) Don't actually know

- Worst case is gravitational (order ϵ) Arkani-Hamed, Maldacena 1503.08043
- Efficient reheating indicates stronger couplings (?)
- Naturally large in EFT with $\Lambda \leq 10^{2\sim 5} H$

Assassi, Baumann, Green, McAllister 1304.5226

 $f_{NL} \sim (\text{coupling}) \times (\text{Boltzmann})$

(coupling) Don't actually know (Boltzmann) Naturally $m \sim H$

If $m \leq \frac{3}{2}H$: no Boltzmann suppression (and $\exists IR \text{ growth}$)

If
$$m > \frac{3}{2}H$$
: let $\mu = \sqrt{m^2 - \frac{9}{4}H^2}$

- Usually (Boltzmann) ~ $e^{-\pi\mu/H}$
- May be enhanced by

 $\dot{\phi}$ Flauger, Mirbabayi, Senatore, Silverstein 1606.00513 Temperature Tong, YW, Zhou 1801.05688 Chemical potential Chen, YW, Xianyu 1805.02656



For example: SphereX http://spherex.caltech.edu/ $\Delta f_{NL} \sim 0.5 \ ?$

 $\Delta f_{NL} \sim 10^{-3}$? See e.g. 1610.06559 Meerburg, Münchmeyer, Muñoz and Chen



Very high energy

Meerburg,

Münchmeyer,

Muñoz and Chen

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- Mass: what's the resonance?
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- What's at the energy scale *H*?
- How is the collider "built"?
- Has inflation indeed happened?
- Challenges for observations ...

Thank you!

Main References:

X. Chen & YW, 0909.0496, 0911.3380, 1205.0160 D. Baumann & D. Green, 1109.0292 Noumi, Yamaguchi & D. Yokoyama 1211.1624 Gong, Sasaki & Pi 1306.3691 N. Arkani-Hamed & J. Maldacena, 1503.08043 X. Chen, Namjoo & YW, 1509.03930, 1601.06228 X. Chen, YW & Z. Z. Xianyu, 1610.06597, 1612.08122 An, McAneny, Ridgway & Wise, 1711.02667 S. Kumar & R. Sundrum, 1711.03988 and so on

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