Inflation as a Cosmological Collider

Yi Wang 王一, 2019.01.10

The Hong Kong University of Science and Technology

References:

X. Chen & YW, 0909.0496, 0911.3380, 1205.0160

D. Baumann & D. Green, 1109.0292

Noumi, Yamaguchi & D. Yokoyama 1211.1624

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Arkani-Hamed & 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

Arkani-Hamed, Baumann, Lee, Pimentel 1811.00024

A black-box 1-sentence summary of cosmological collider:

If we knew the 3pt density correlation function of our universe precisely, we know the mass and spin of all massive fields during inflation.

HEP at Higher Energies?

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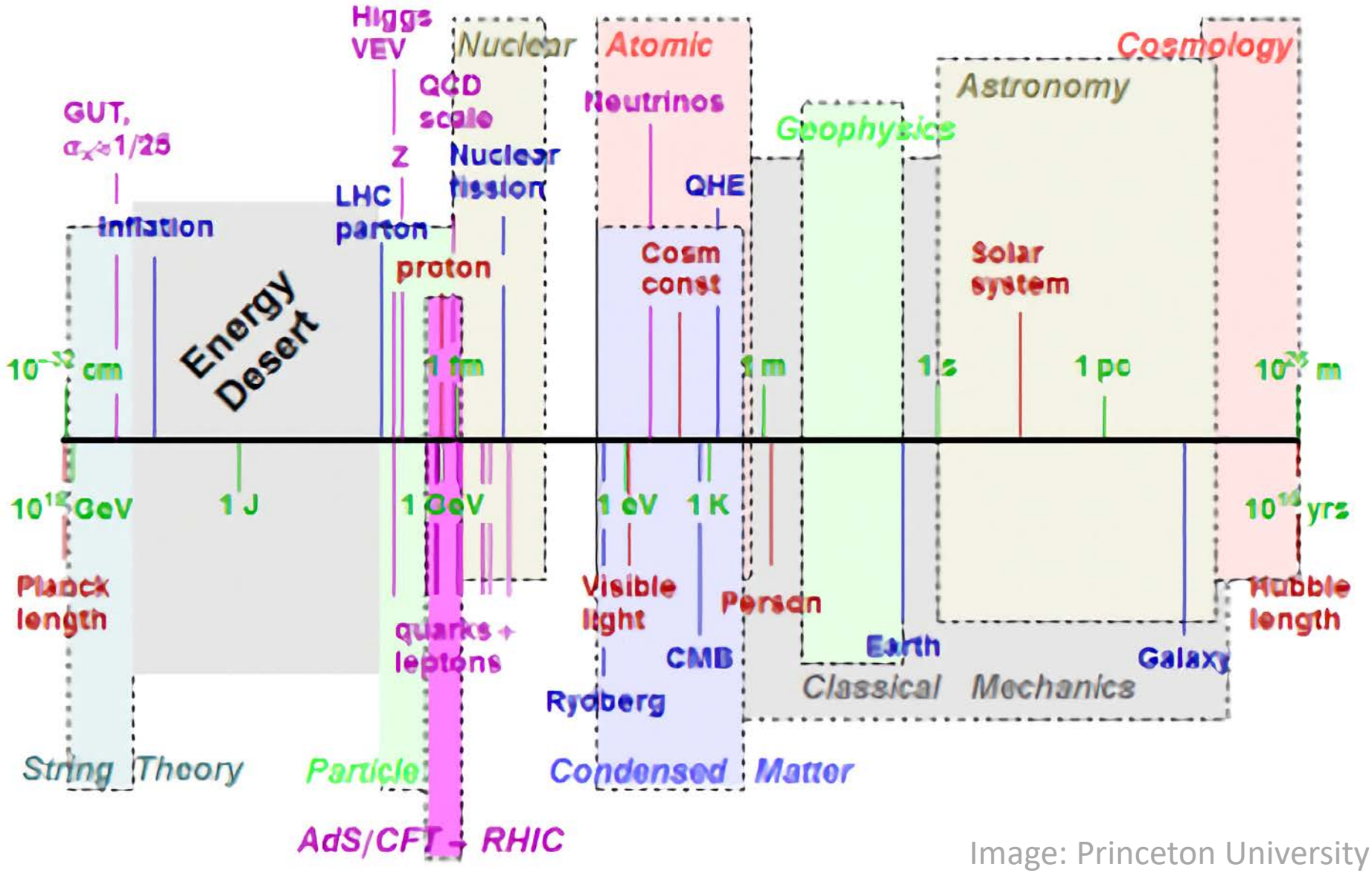
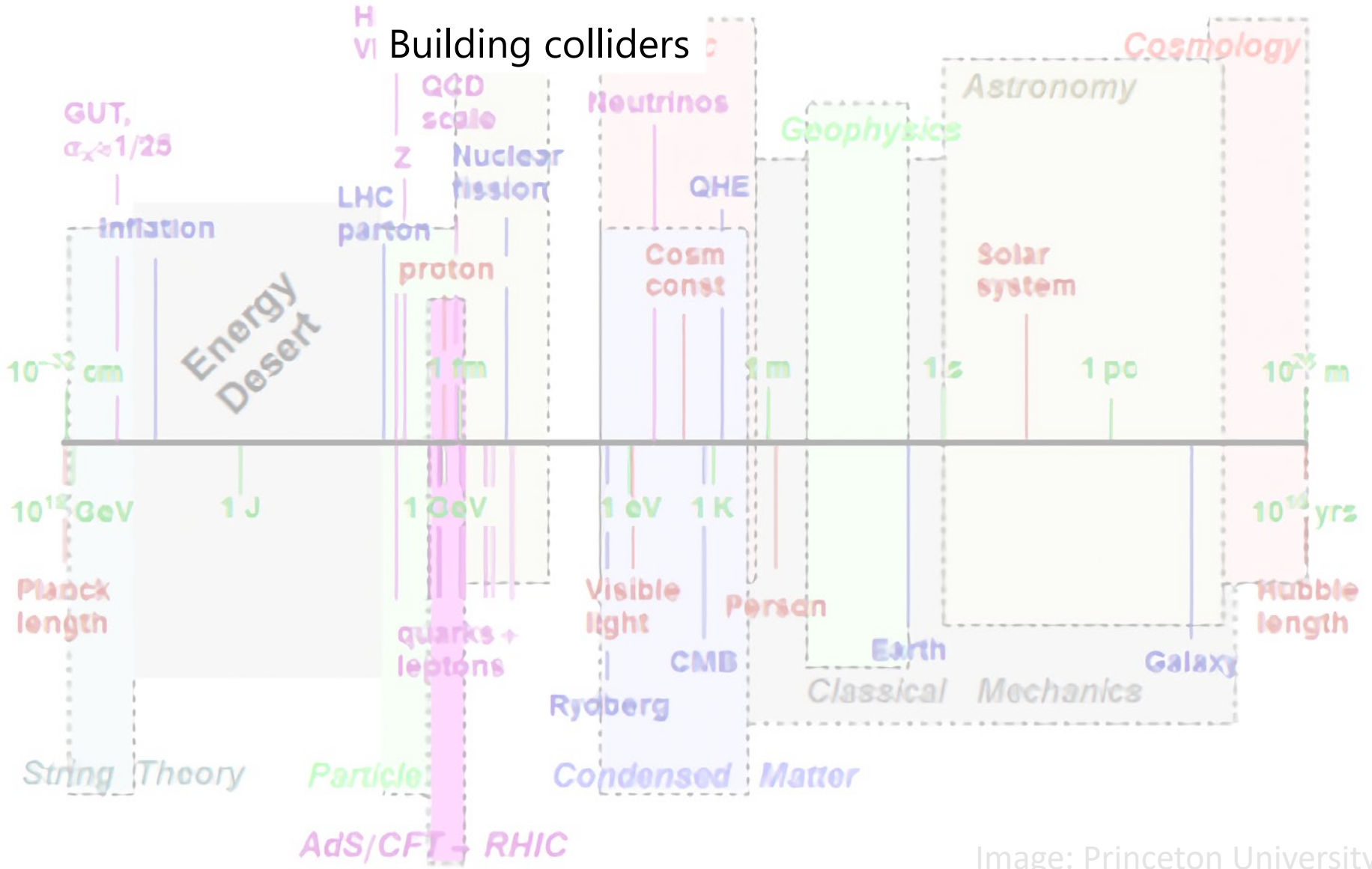


Image: Princeton University

HEP at Higher Energies?

Building colliders



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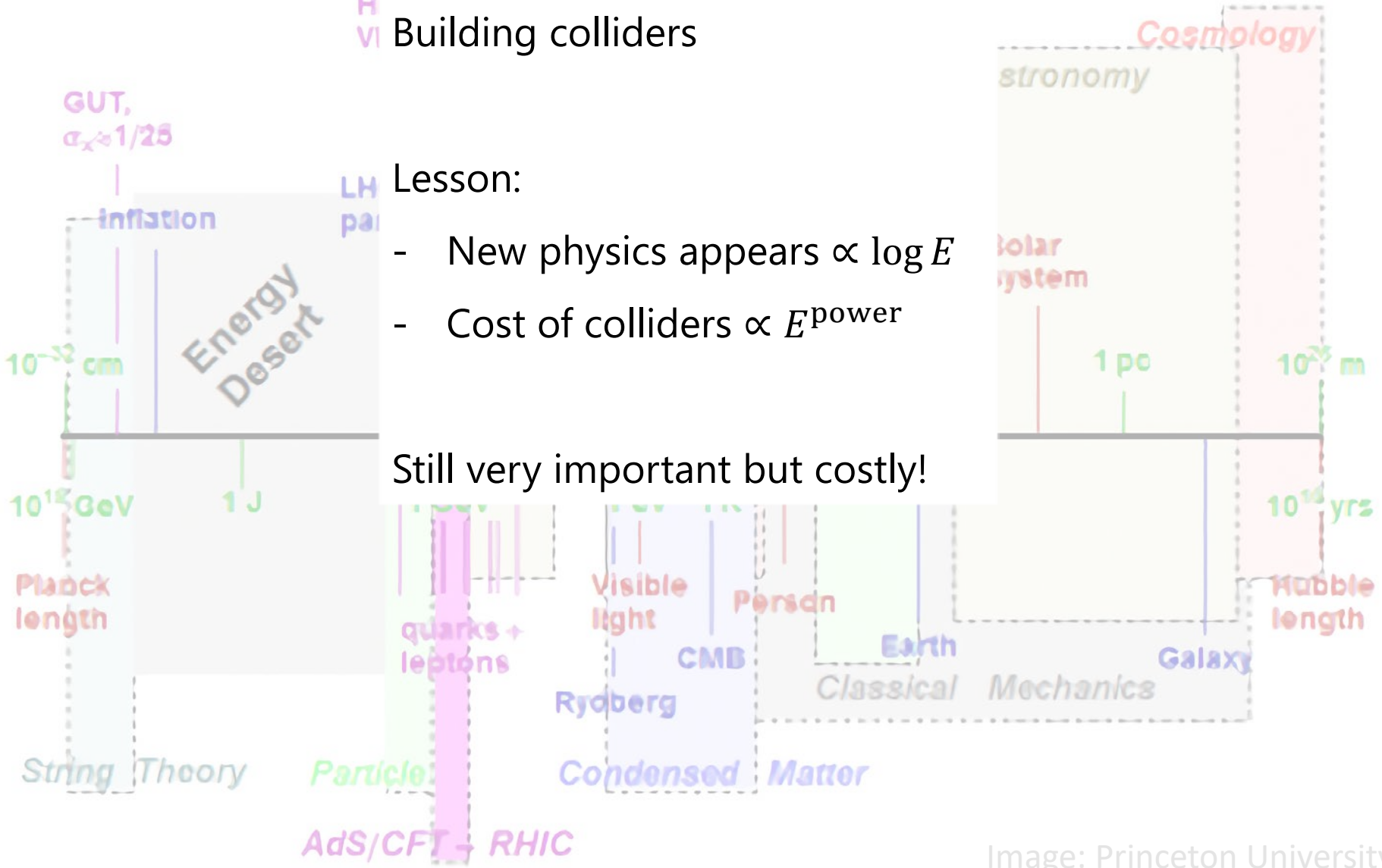
HEP at Higher Energies?

Building colliders

Lesson:

- New physics appears $\propto \log E$
- Cost of colliders $\propto E^{\text{power}}$

Still very important but costly!



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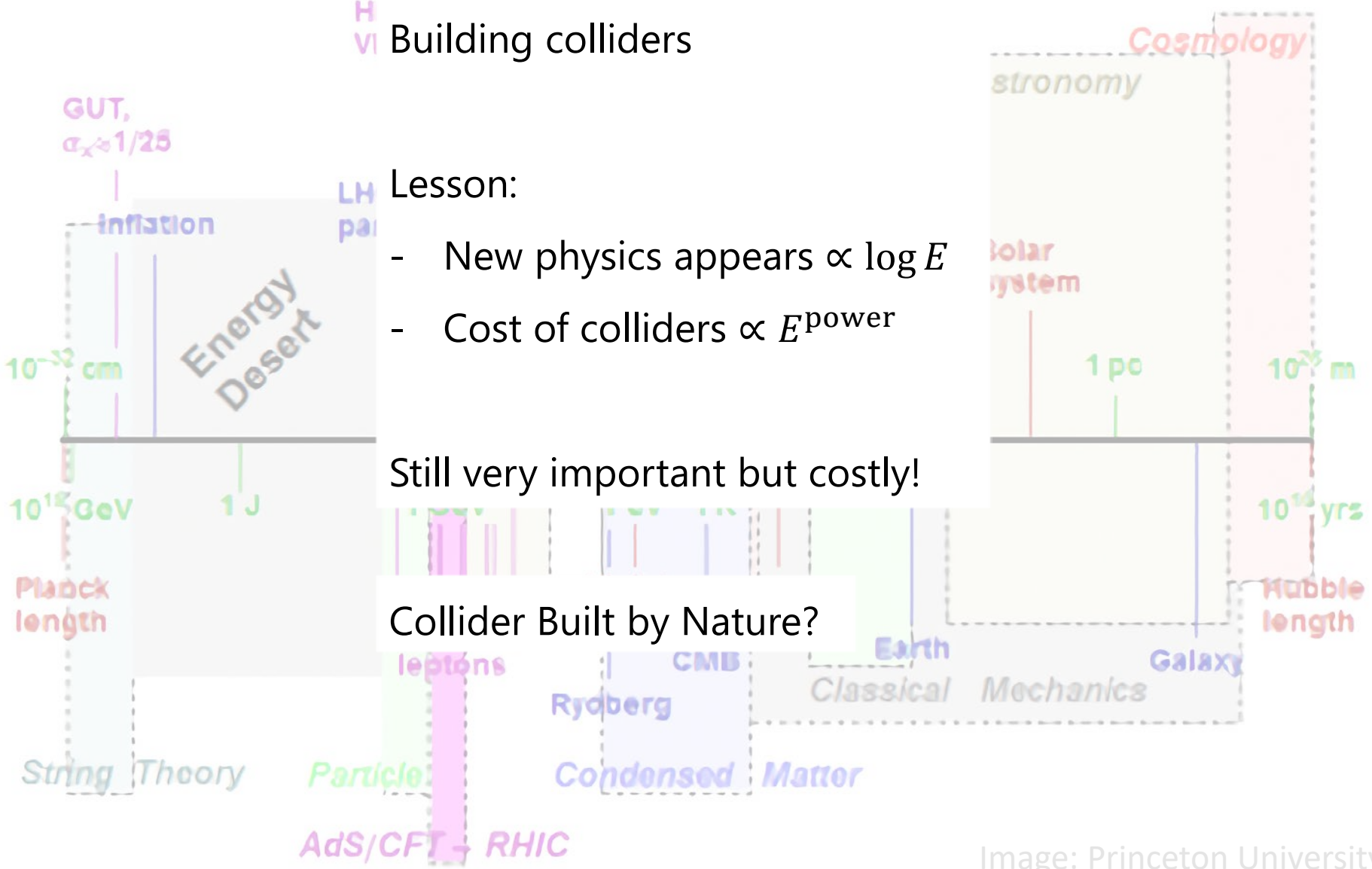
Collider Built by Nature?



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HEP at Higher Energies?

Collider Built by Nature?

High energies in nature

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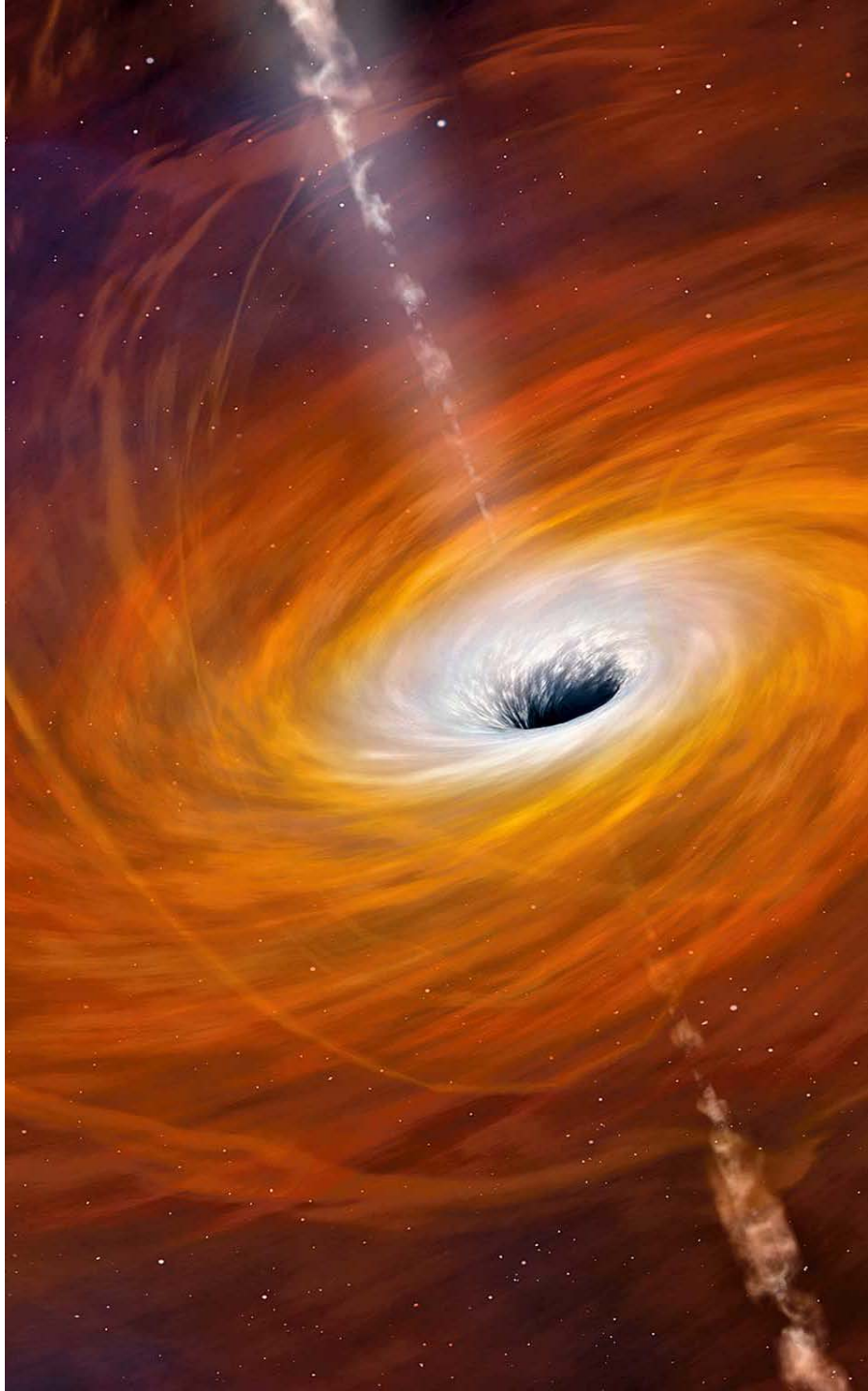
Collider Built by Nature?

High energies in nature:

- Black holes



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Collider Built by Nature?

High energies in nature:

- Black holes
- The early universe

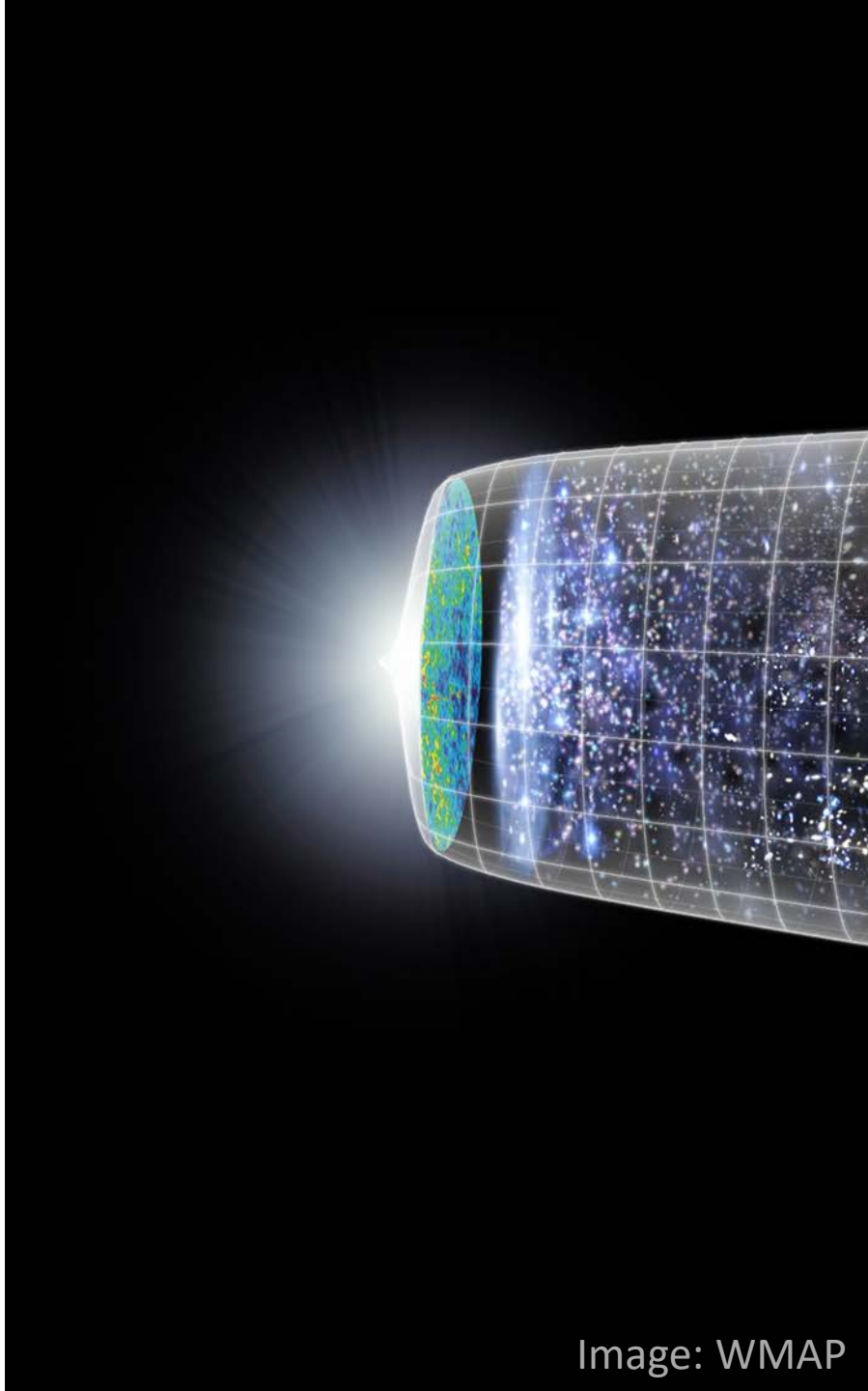

Image: WMAP

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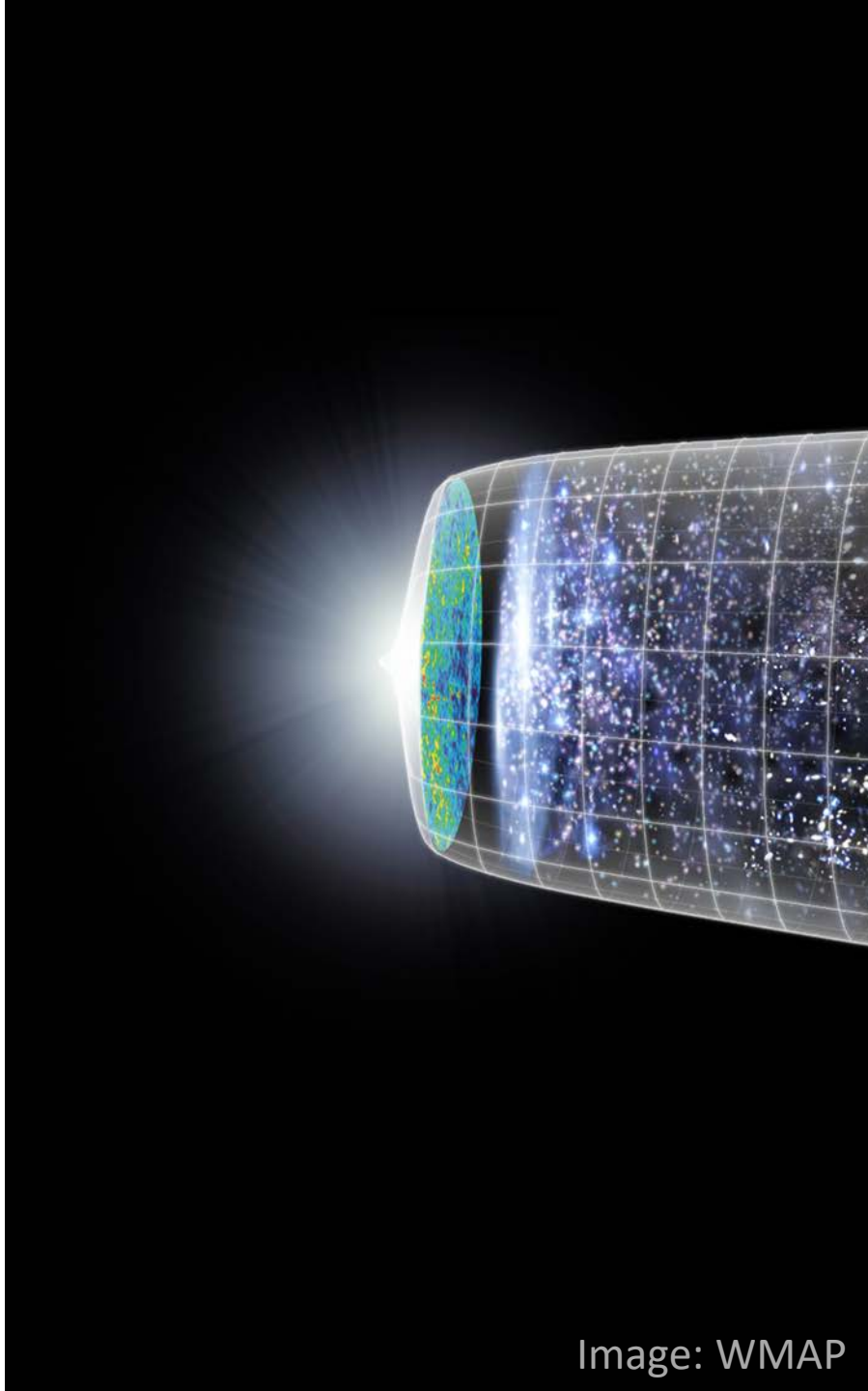
Probably
the highest energy
in our universe

Is it a “collider”?



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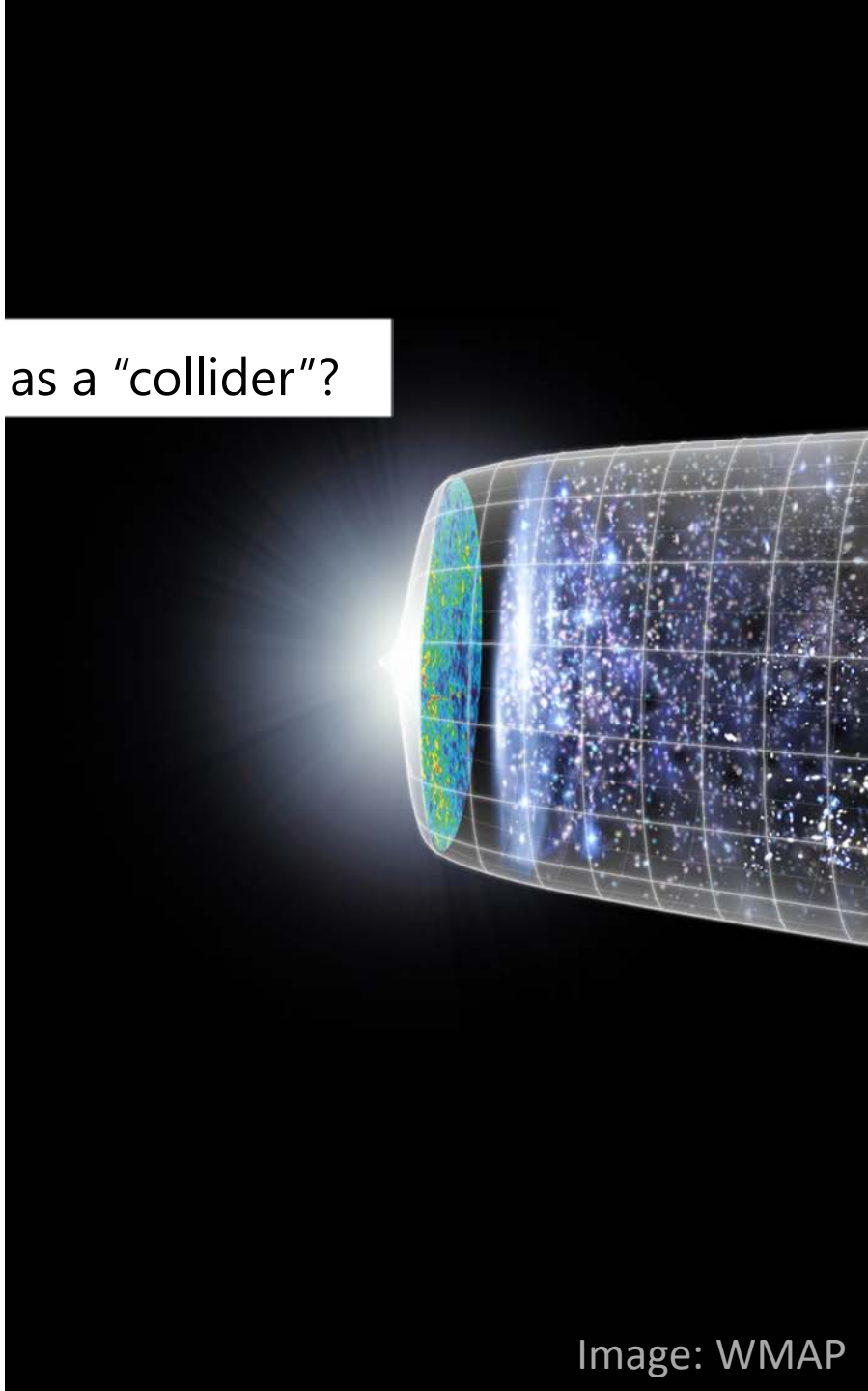

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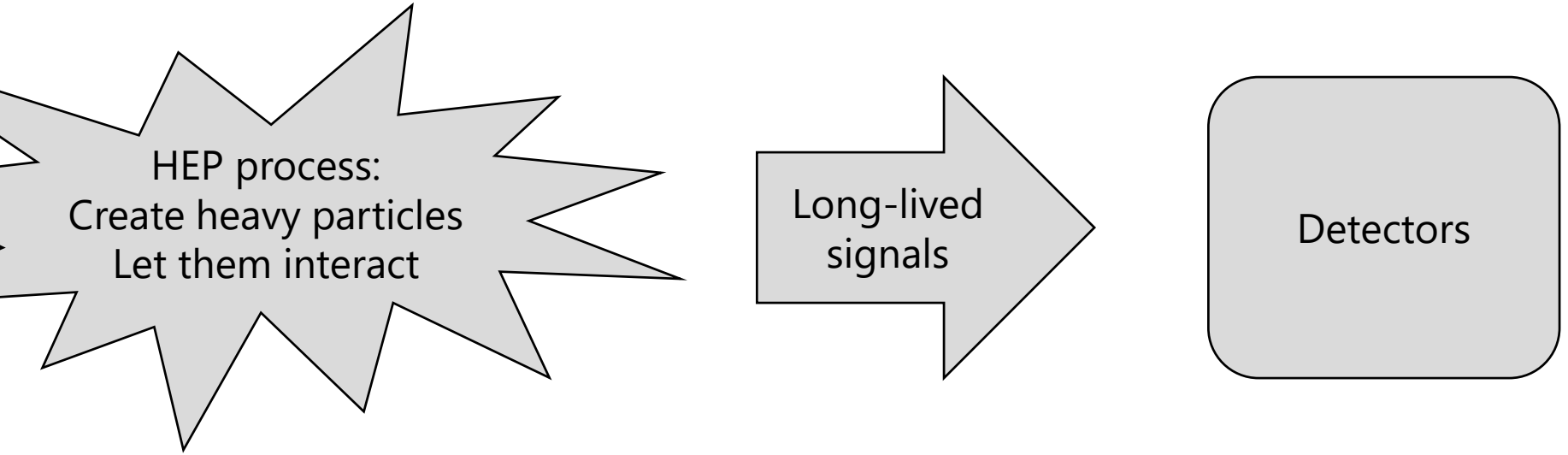
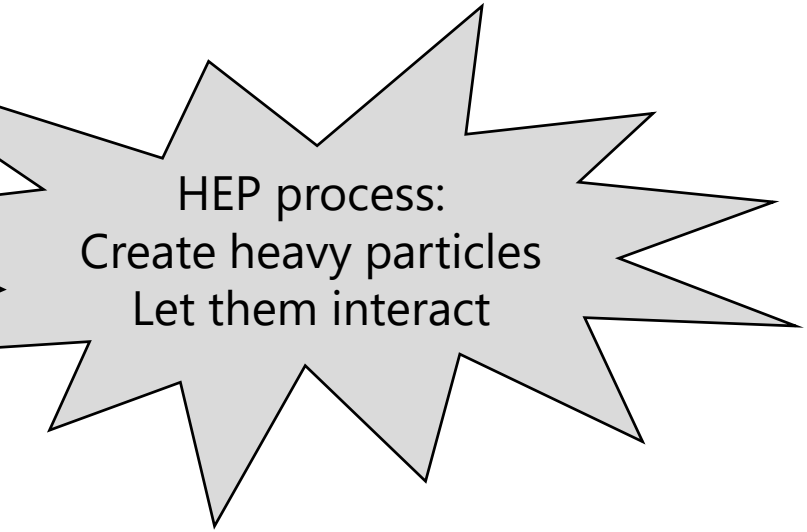


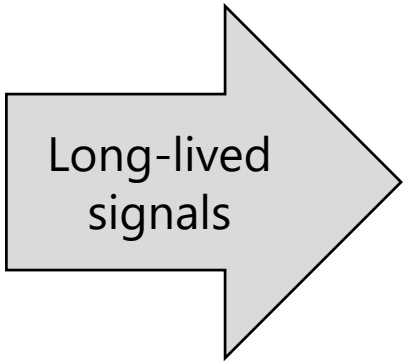
Man-made colliders

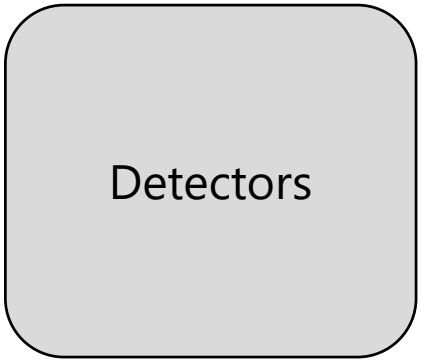
e.g. LHC

leptons,
photons, jets

e.g. ATLAS, CMS







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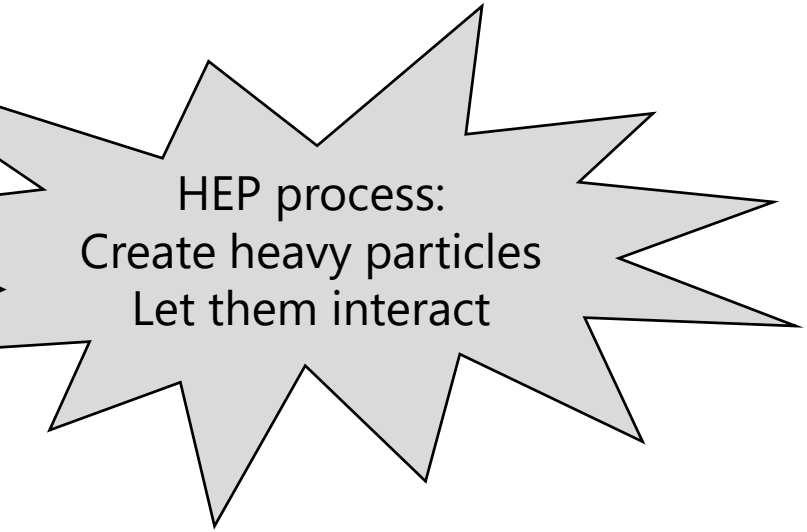

Long-lived
signals

Detectors

Inflation of the
very early universe

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

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

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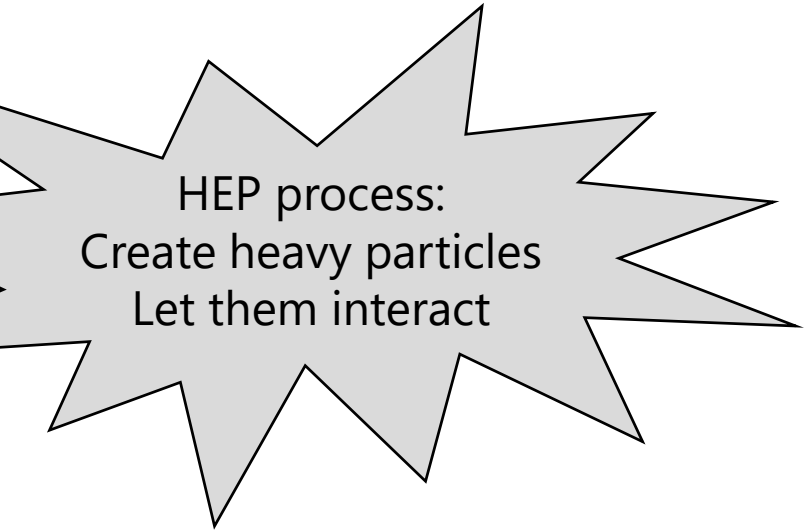

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Classical conserved
quantities, such as:

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 in curved spacetime

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

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

PGW & remaining isocurvature fluctuation (if any): similarly

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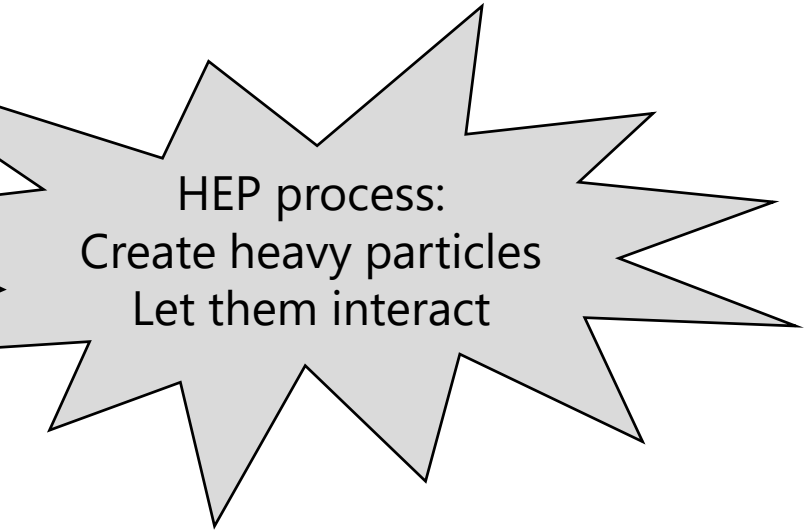

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Cosmological
observations, e.g.

CMB, LSS, 21cm

The cosmological collider

Observations: Correlation functions of

- 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
- PGW: From CMB B-mode, not yet observed
- Isocurvature: From details of CMB/LSS, not yet observed

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What can be studied?

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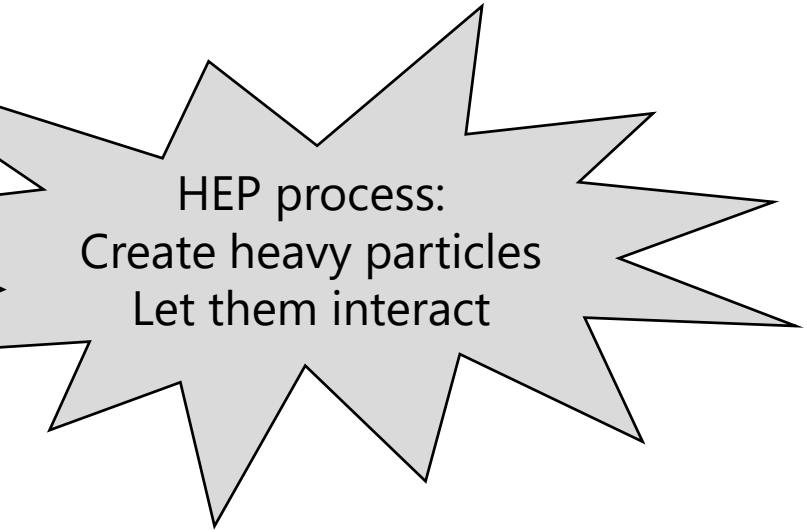

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Collider Built by Nature?

What's needed as a "collider"?

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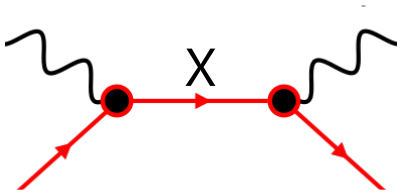

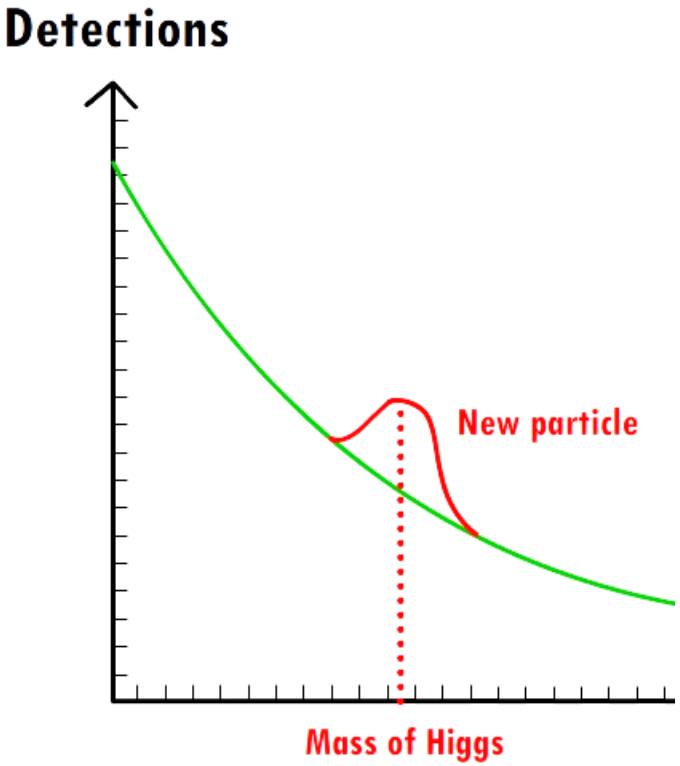

Information in correlation functions:

Mass: resonance in energy dependence

Spin: angular dependence

Interactions: size & details

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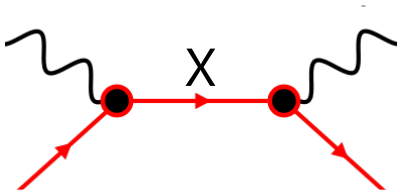

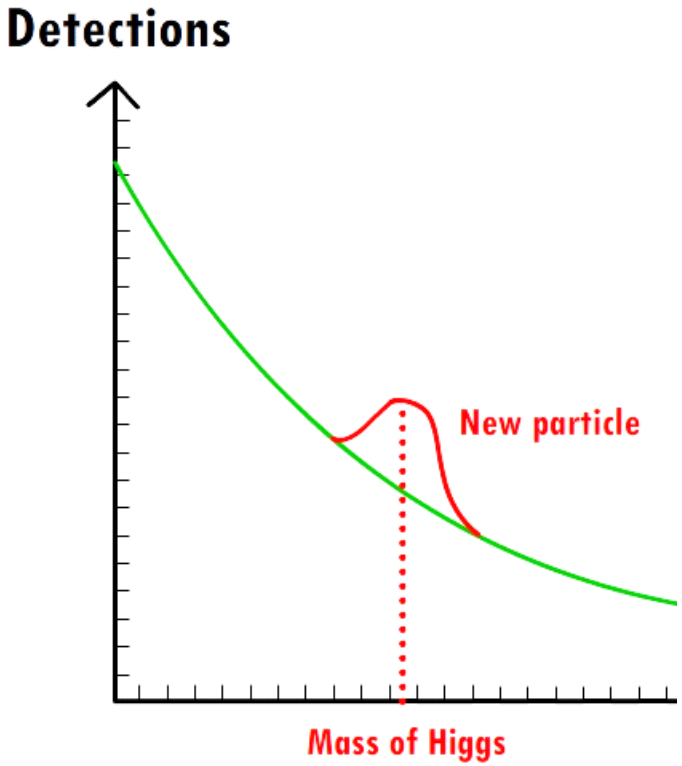

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Chen & YW, 0909.0496, 0911.3380

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Spin: angular dependence

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Baumann, Goon, Lee, Pimentel, 1712.06624

Interactions: size & details

Model dependent, lots of studies

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Recent:
Cosmology → particle
Model-independent

Traditional:
Particle → cosmology → particle
Model-dependent

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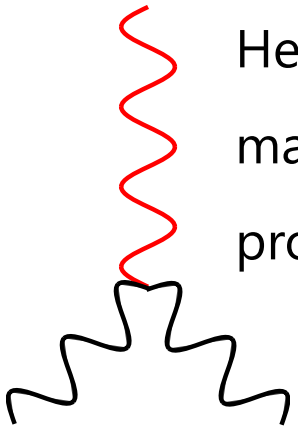

Heavy particle:

mass m

prob: $\exp(-m\,/\,T_{GH})$

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

(resonant production)

Here k is defined as: $ds^2 = -dt^2 + a^2(t)d\mathbf{x}^2$

$\mathbf{k}$ is the Fourier space of $\mathbf{x}$, and $k = |\mathbf{k}|$.

Thus $\omega \sim k/a(t)$ for massless (light) particles

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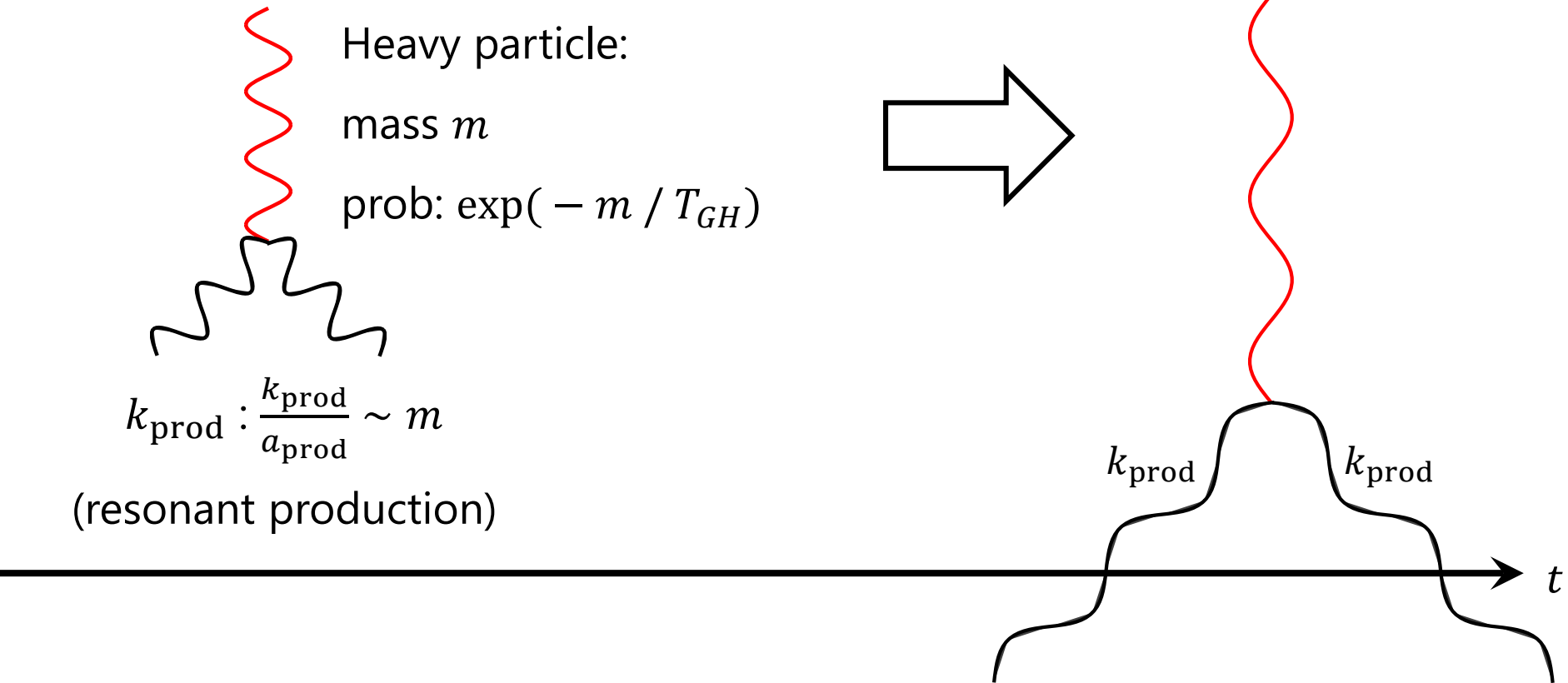

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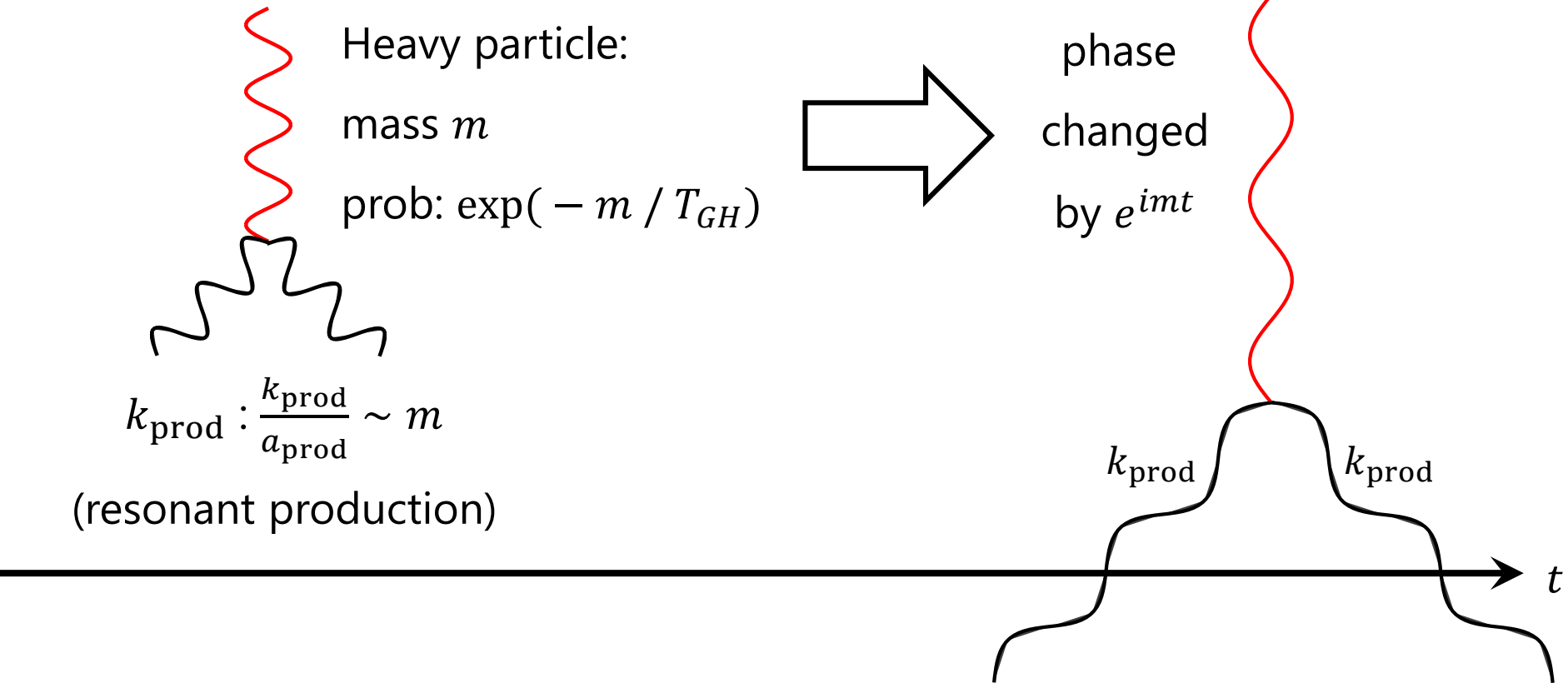

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Mass: what's the resonance?

From resonance to interference

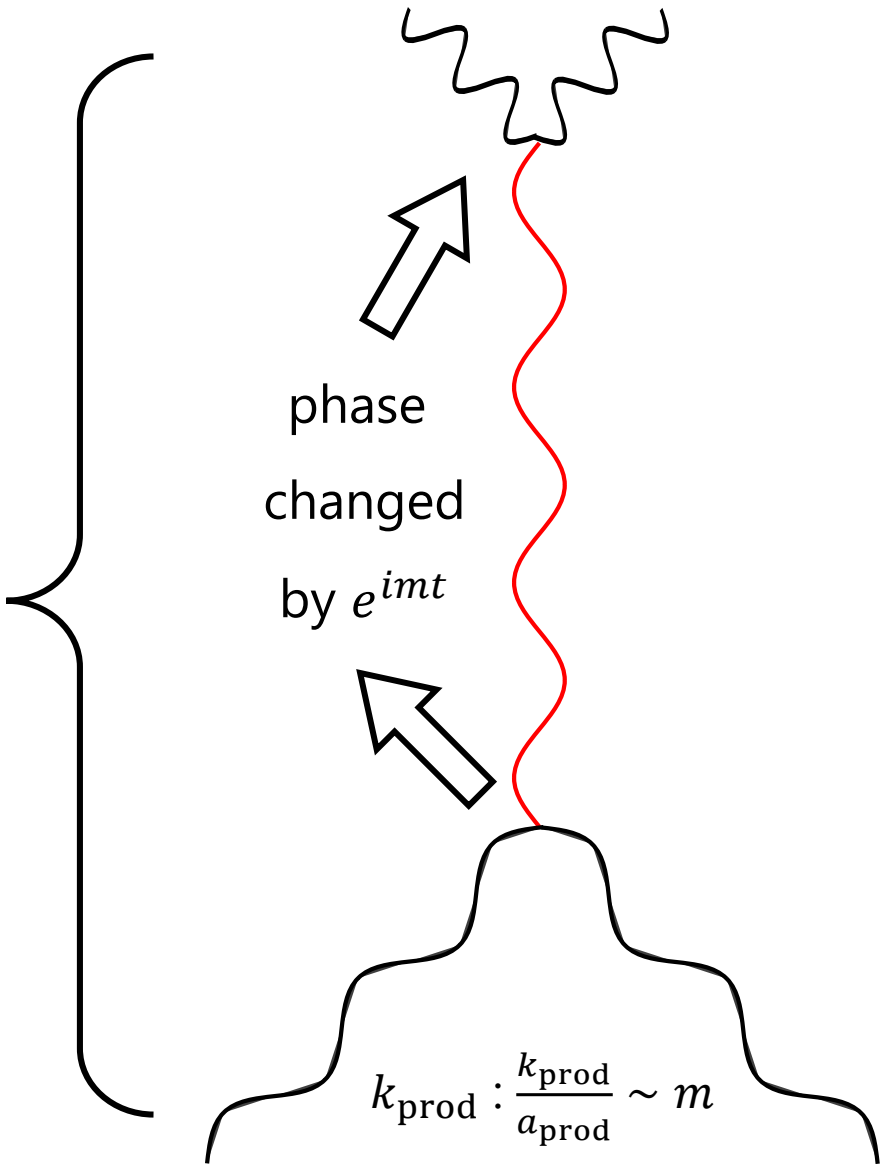
interference:

corr $\sim \exp\left[im(t_{\text{decay}} - t_{\text{prod}})\right]$

$$\sim \left(\frac{k_{\text{decay}}}{k_{\text{prod}}}\right)^{im/H}$$

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

(resonant decay)



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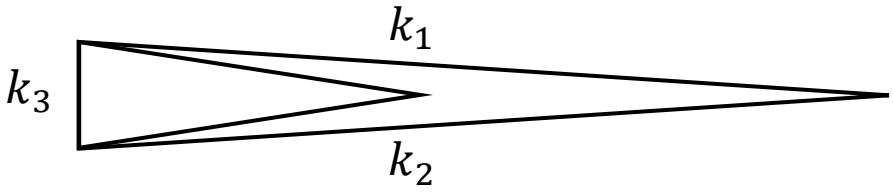

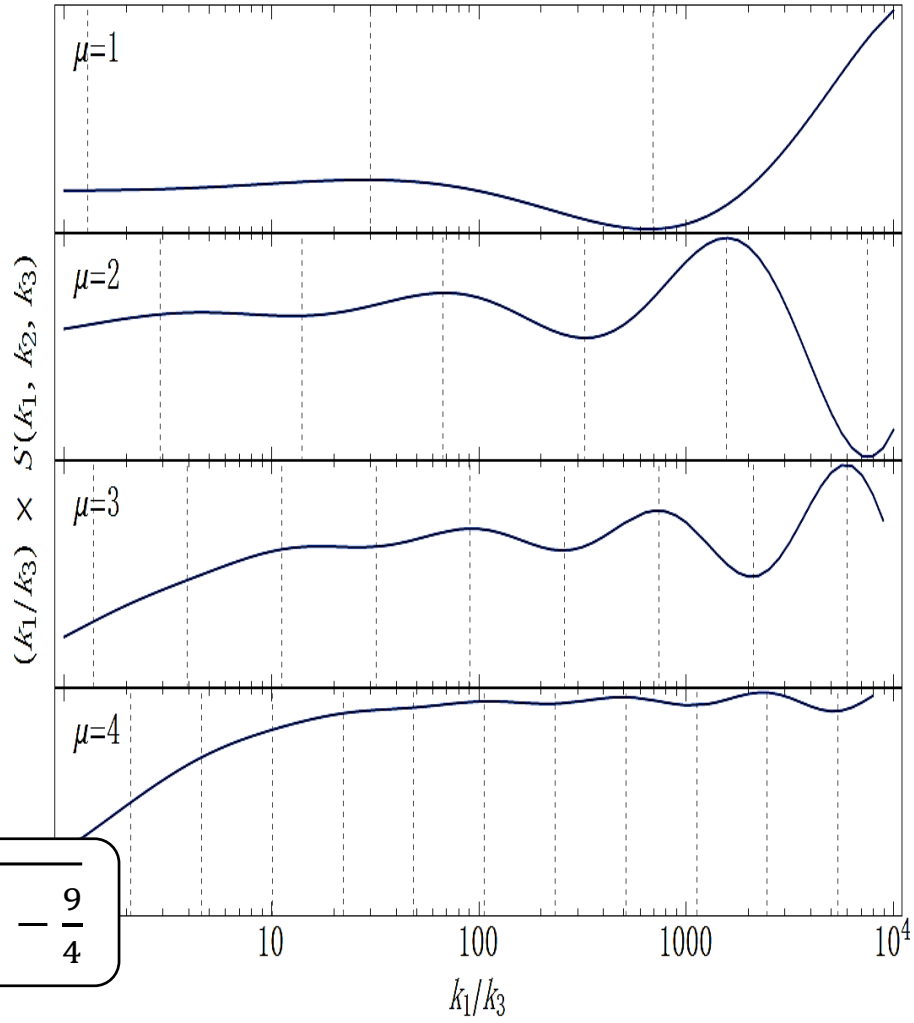

interference:

$$\text{corr} \sim \exp\left[im(t_{\text{decay}} - t_{\text{prod}})\right]$$

$$\sim \left(\frac{k_{\text{decay}}}{k_{\text{prod}}}\right)^{im/H}$$

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

What's at the energy scale H?

What's at the energy scale H?

Accidentally near H ?

- Grand unification
- Neutrino seesaw

Chen, Wang & 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 $h^2 R \sim H^2 h^2$

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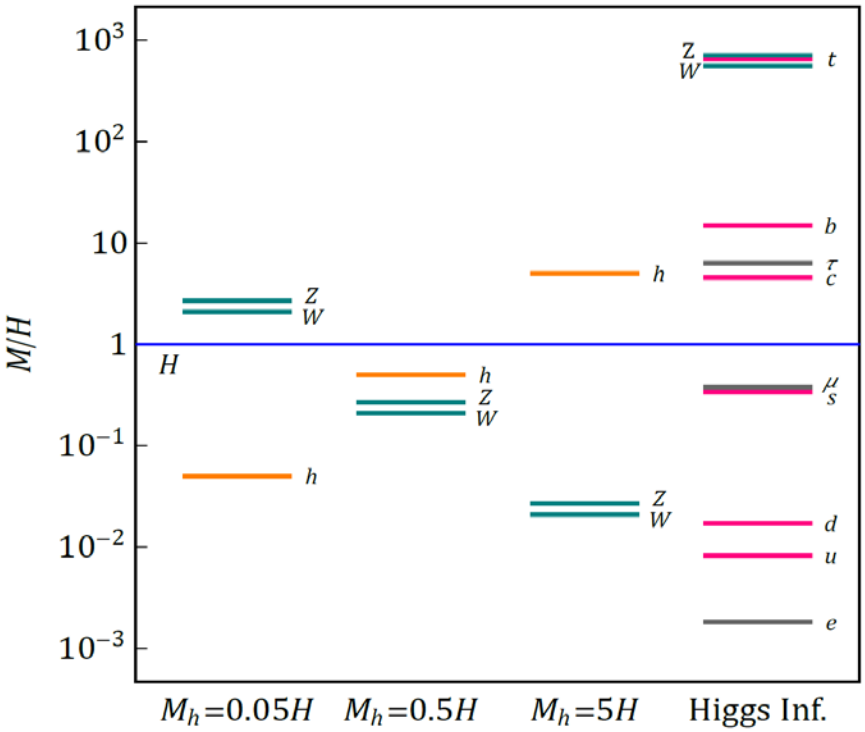

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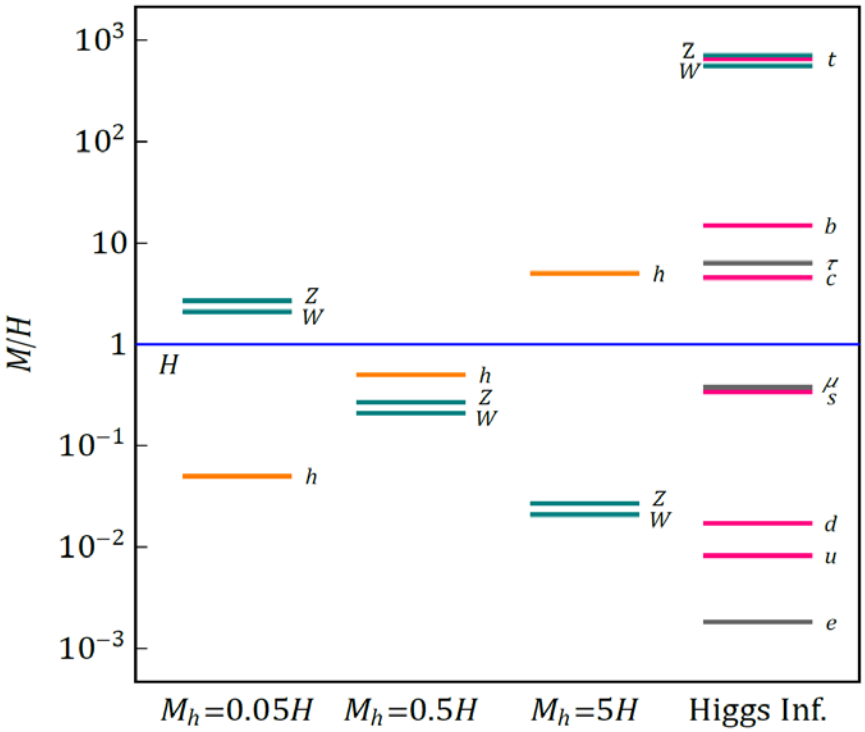

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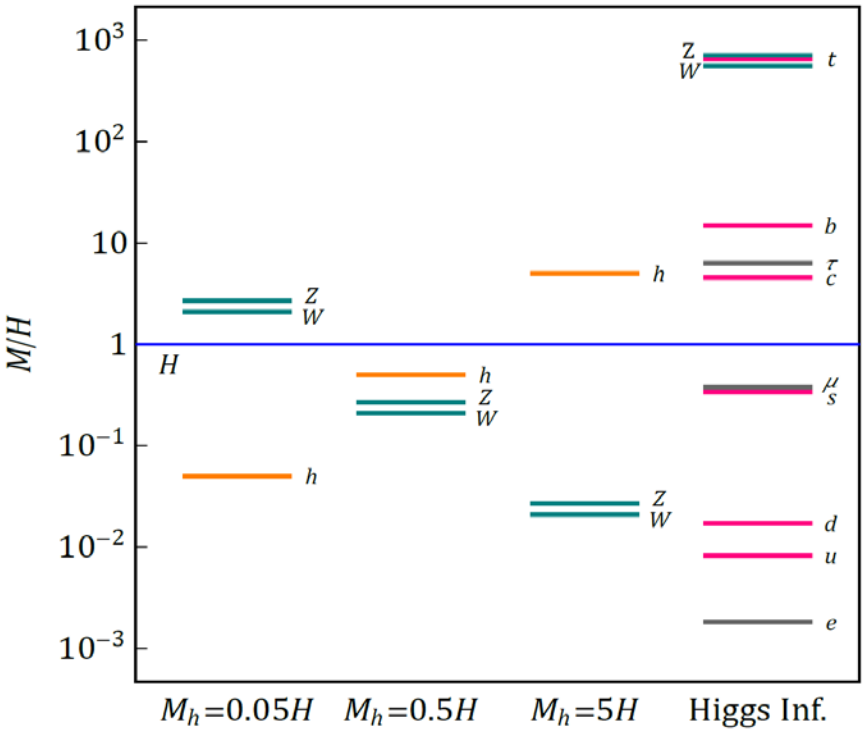

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- SUSY breaking

Baumann & Green, 1109.0292

Delacretaz, Gorbenko & Senatore 1610.04227

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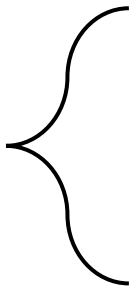

Expansion history — Chen, Namjoo & YW, 1509.03930

Testing QM — Maldacena, 1508.01082

Correction to 2pt — Jiang & YW, 1703.04477

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Has inflation indeed happened?

SCIENTIFIC AMERICAN FEBRUARY 2017

Cosmic Inflation Theory Faces Challenges

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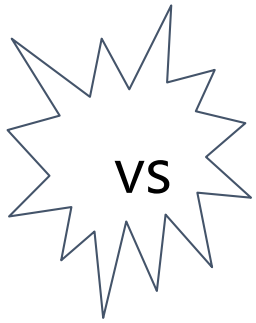
By Anna Ijjas, Paul J. Steinhardt, Abraham Loeb



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

Precision Era:

Haven't we known our universe very well?

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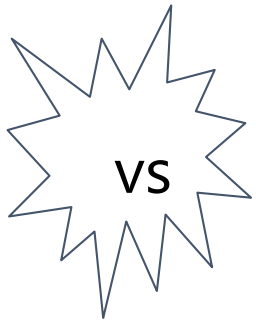

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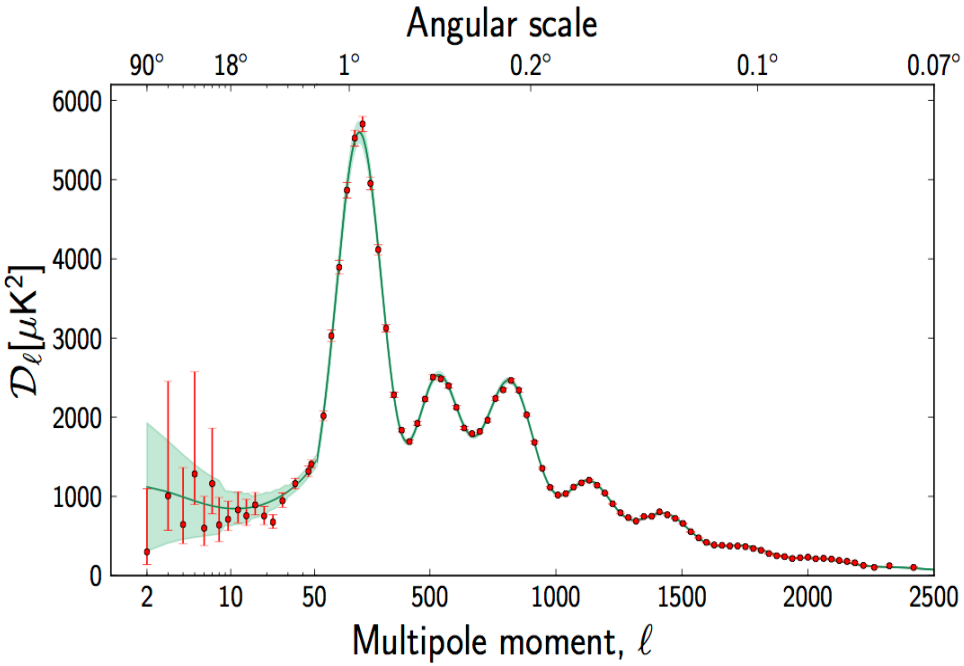

Image: Planck Team

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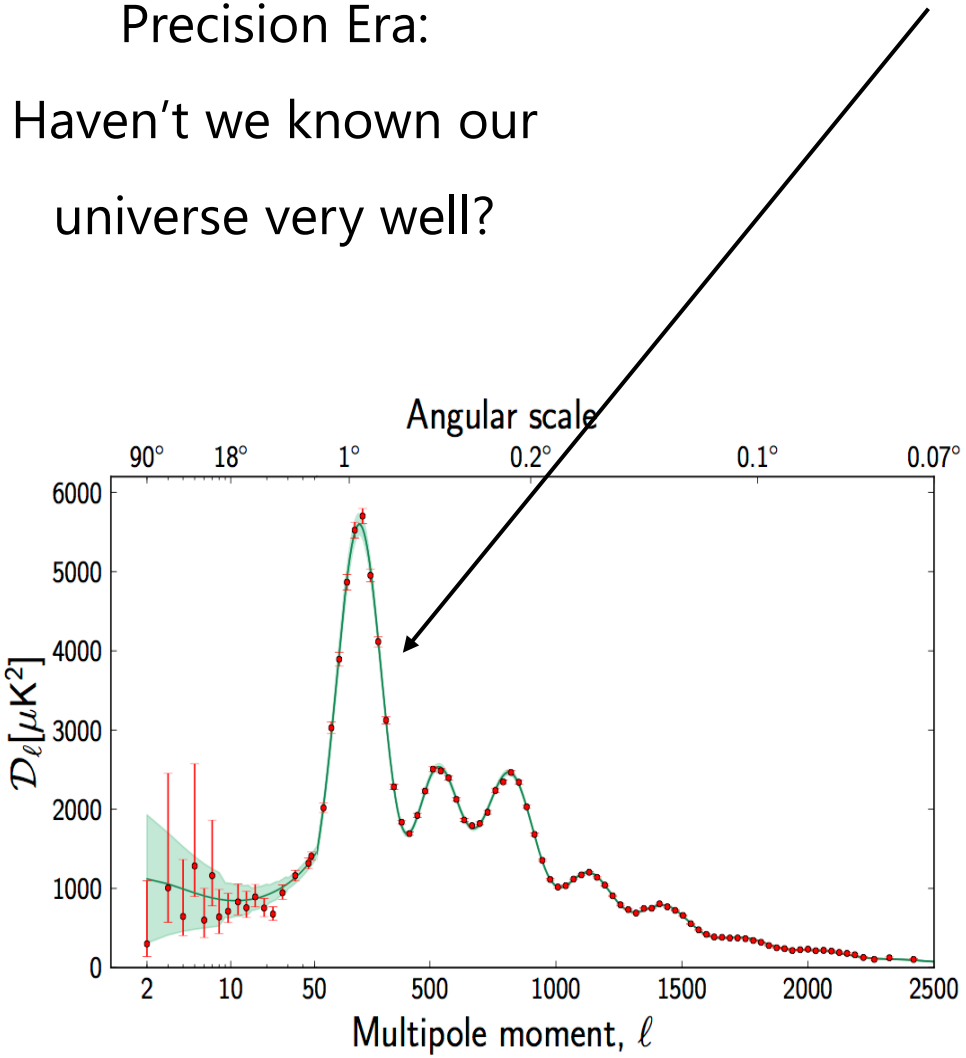

We know fluctuations as functions of scales (k) very well.

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

Thus we know

fluctuation ↔ conformal time τ

But what about

fluctuation ↔ physical time t?

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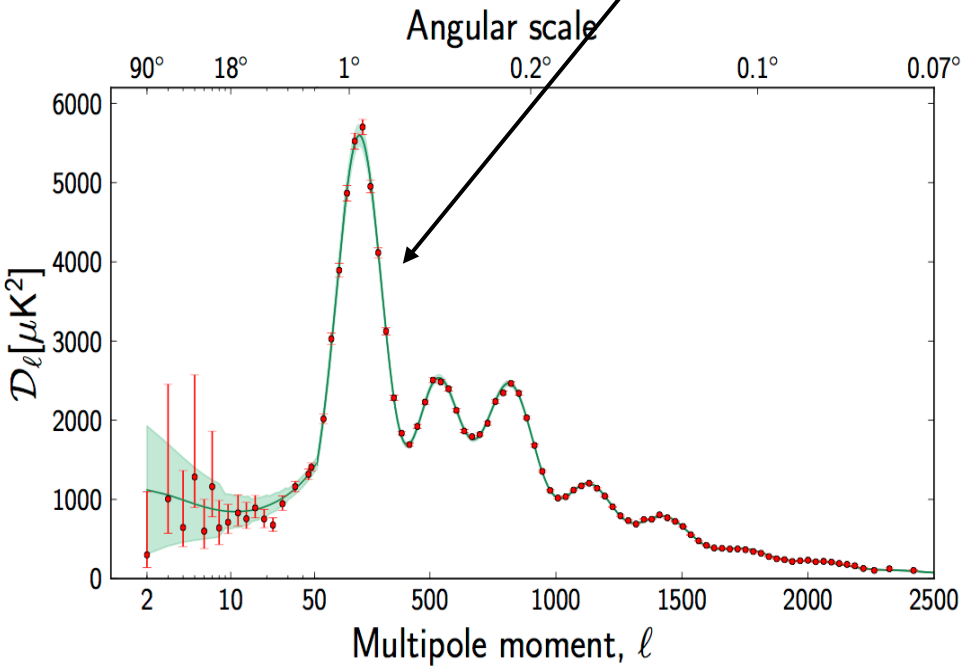

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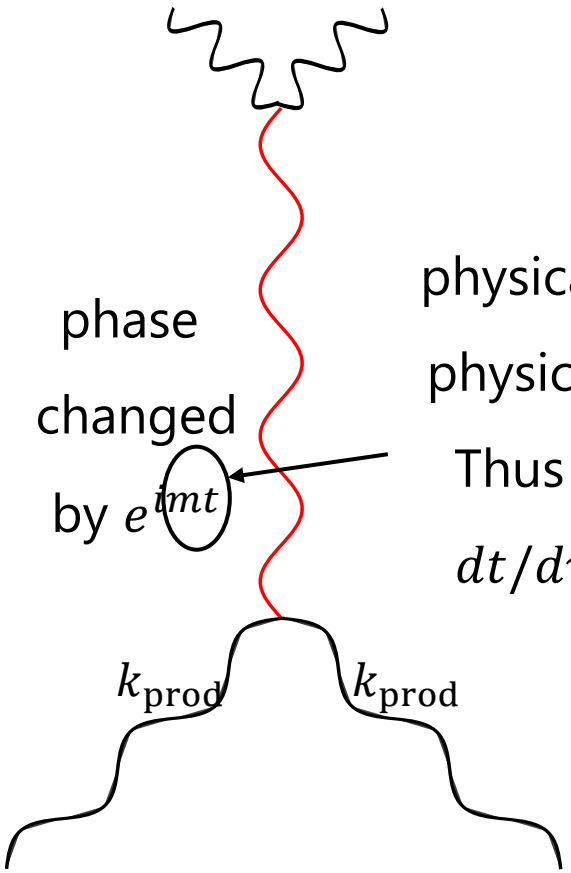

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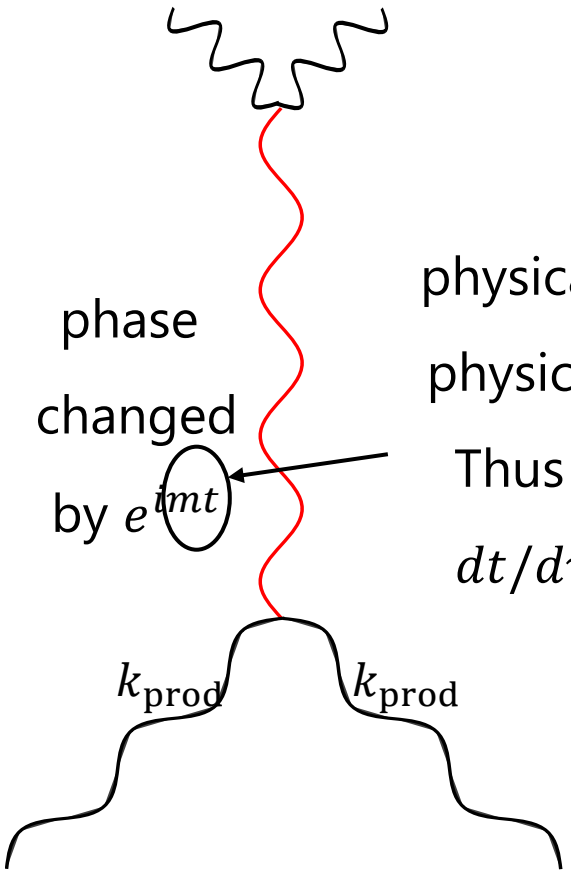
X. Chen, Namjoo & YW, 1509.03930



physical mass

physical time

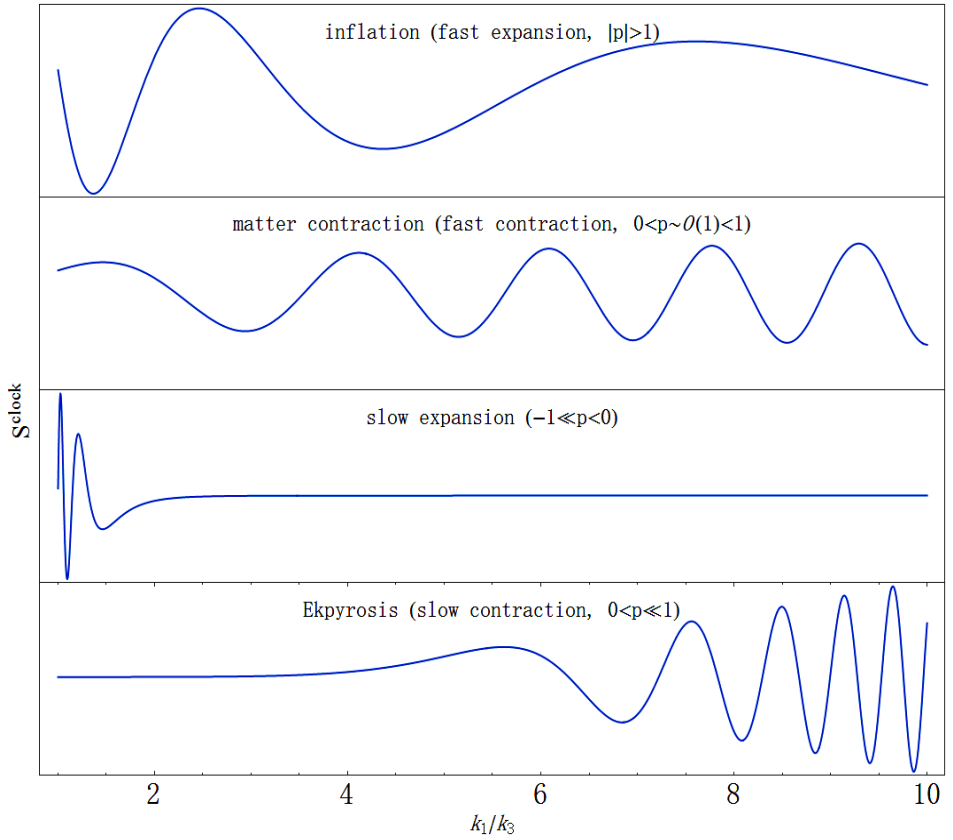
Thus $\tau \leftrightarrow t$

$dt/d\tau = a$

inverse functions

direct probe of expansion history

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



X. Chen, Namjoo & YW, 1509.03930

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

What's at the energy scale H?

How is the collider "built"?

Has inflation indeed happened?

Observation?

f_{NL} ~ (coupling) × (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 $\Lambda \leq 10^{2\sim5}\ H$

  Assassi, Baumann, Green, McAllister 1304.5226

f_{NL} ~ (coupling) × (Boltzmann)

(coupling) Don't actually know

(Boltzmann) Naturally $m \sim H$

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

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

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

  $\dot{\phi} \sim 3600H^2$ Flauger, Mirbabayi, Senatore, Silverstein 1606.00513

  Temperature Tong, YW, Zhou 1801.05688

  Chemical potential Chen, YW, Xianyu 1805.02656

COBE

(1990s)

$\Delta f_{NL} \sim 2000$

WMAP

1yr (2003)

$\Delta f_{NL} \sim 100$

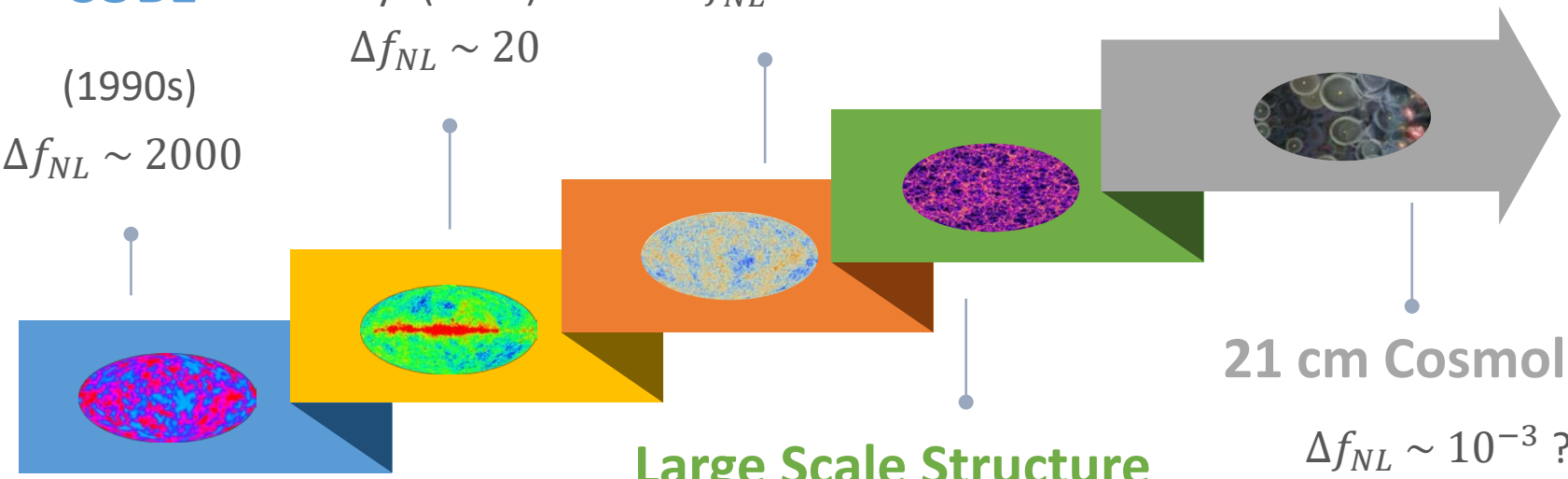
7yr (2010)

$\Delta f_{NL} \sim 20$

PLANCK

(2013)

$\Delta f_{NL} \sim 5$



Large Scale Structure

For example: SphereX

http://spherex.caltech.edu/

$\Delta f_{NL} \sim 0.5$?

21 cm Cosmology

$\Delta f_{NL} \sim 10^{-3}$?

See e.g. 1610.06559

Meerburg,

Münchmeyer,

Muñoz and Chen

Very high energy

Very low luminosity

Challenging observers!

COBE

(1990s)

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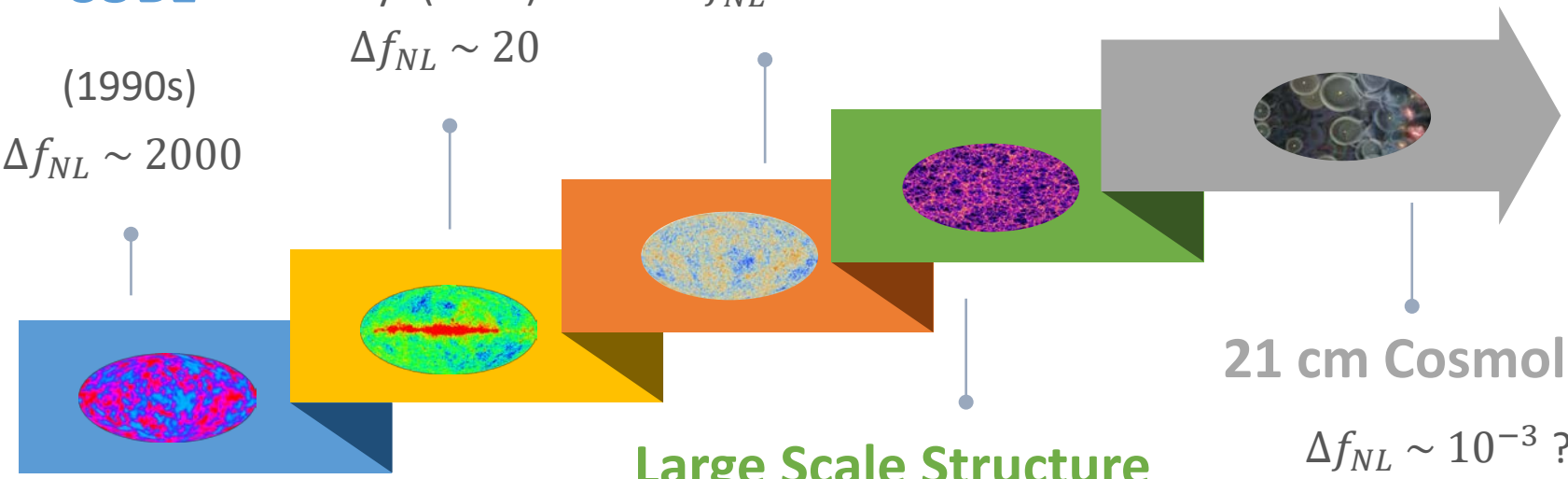

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Challenges for observations …

Thank you!

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… …

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