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

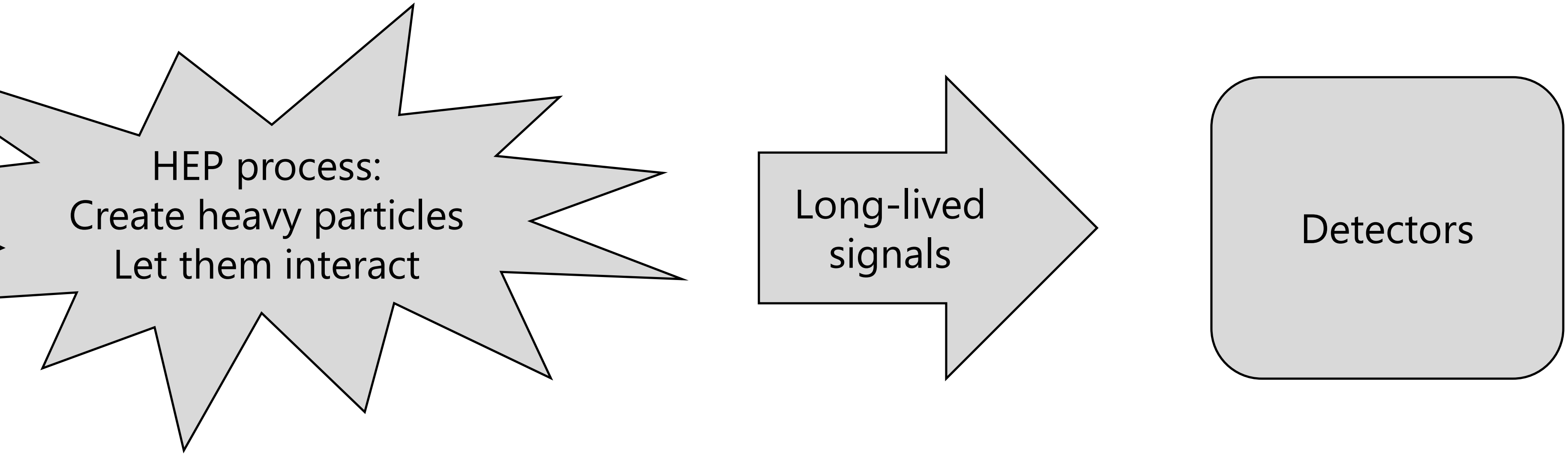
Parity and CP: Liu, Tong, YW, Xianyu, to appear

Isocurvature: Lu, YW, Xianyu, to appear

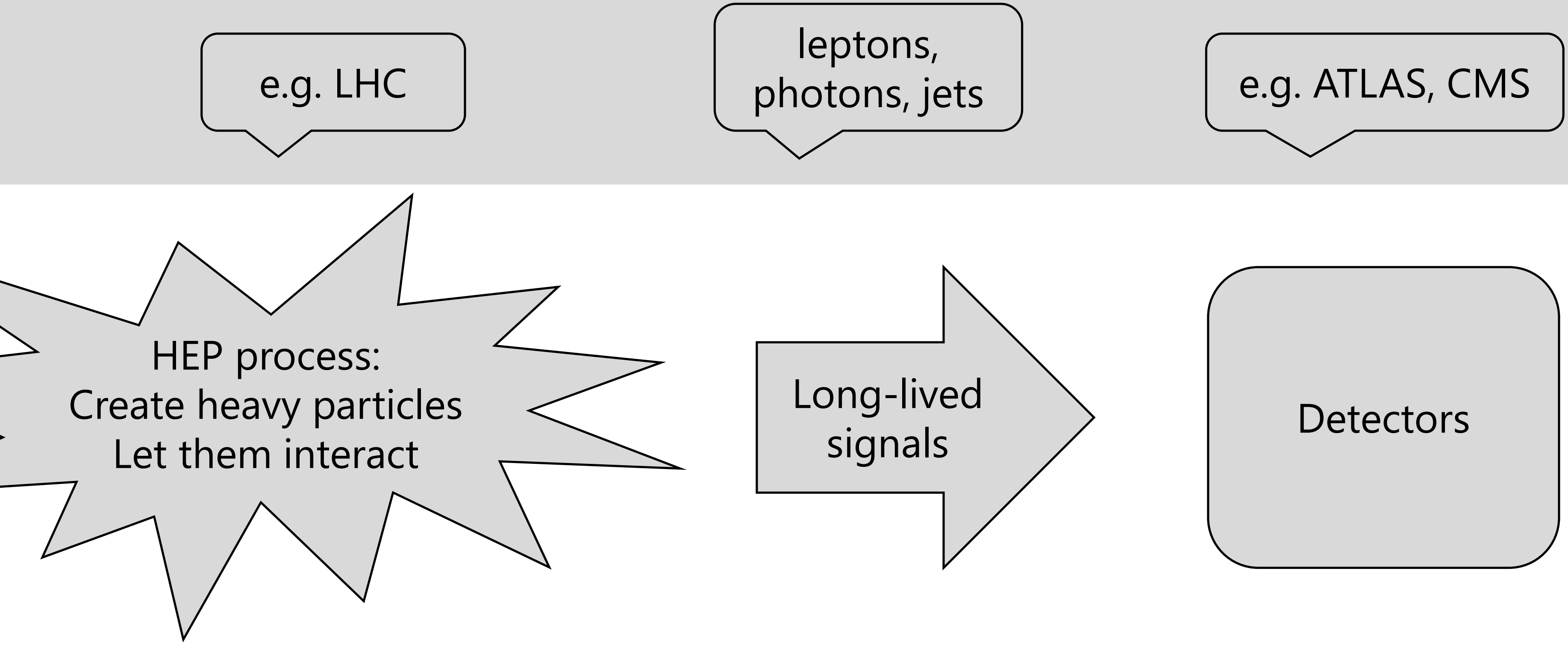
Quantum Primordial Standard Clocks: Chen, Namjoo, YW 1509.03930

Why is inflation a cosmological “collider”?

What’s needed as a “collider”?



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

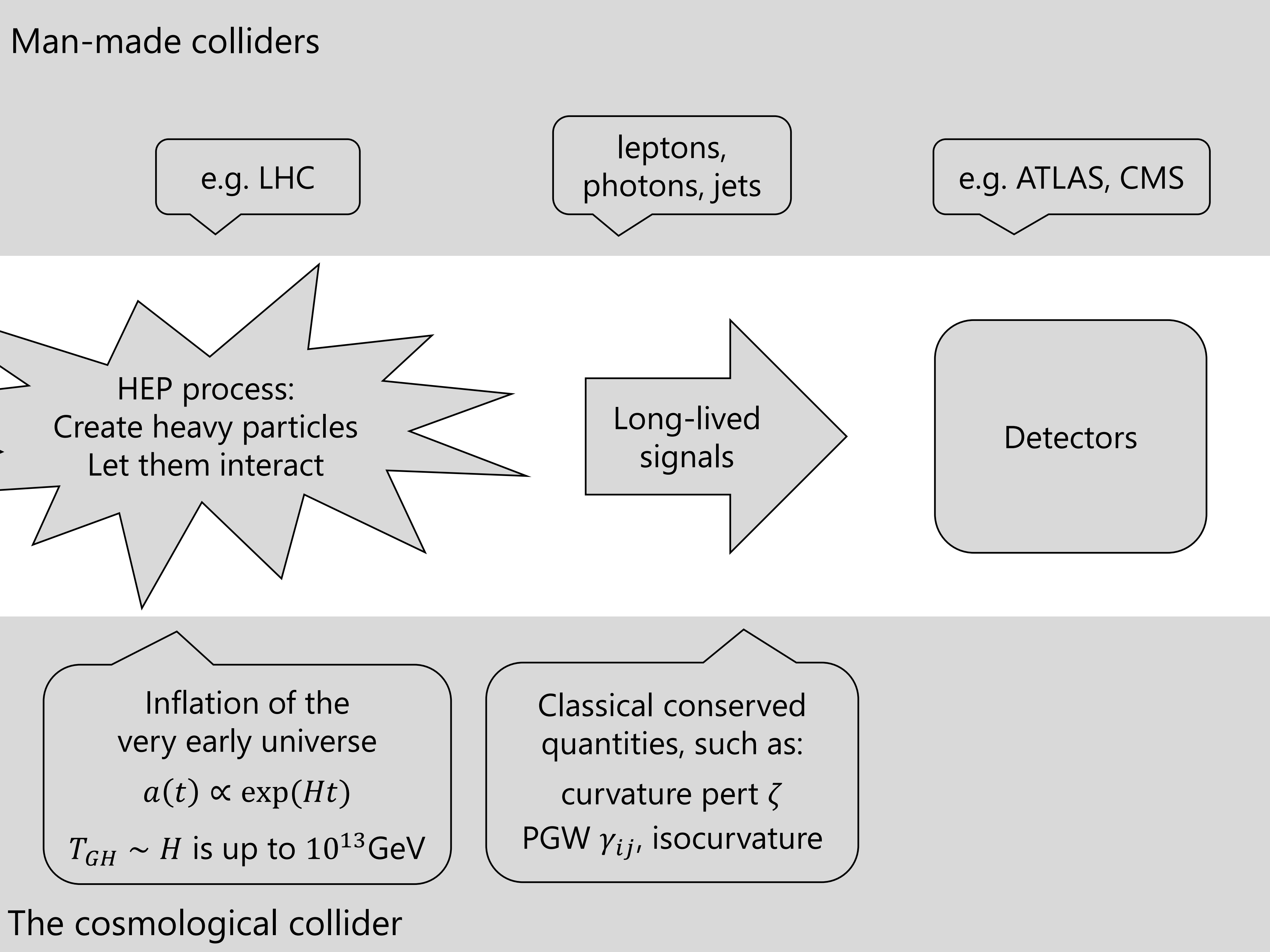
Detectors

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 in curved spacetime

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

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

PGW & remaining isocurvature fluctuation (if any): similarly

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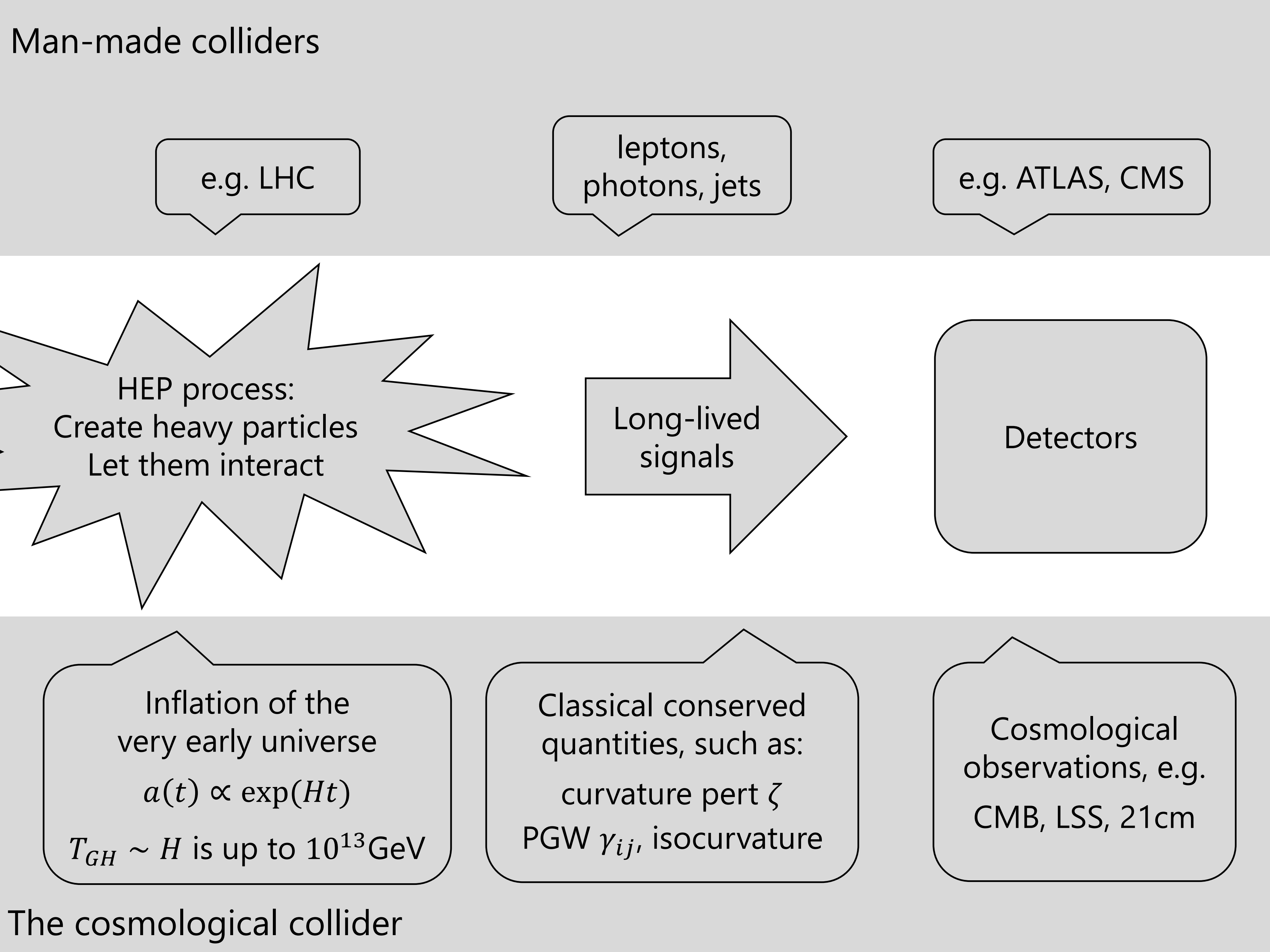

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Cosmological observations, e.g.
CMB, LSS, 21cm
The cosmological collider

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. SphereX: 10X
- PGW: From CMB B-mode, not yet observed
- Isocurvature: From details of CMB/LSS, not yet observed

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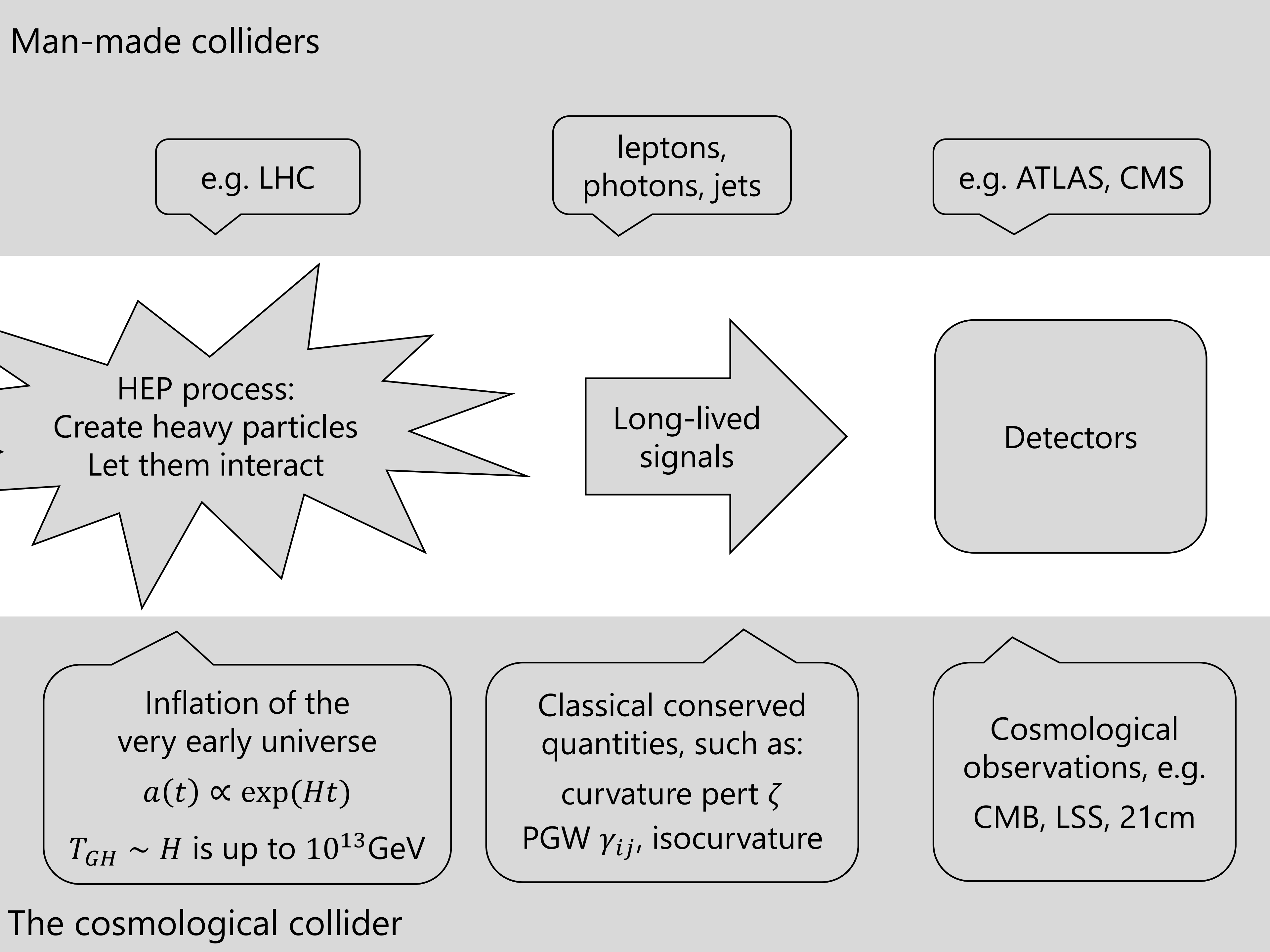
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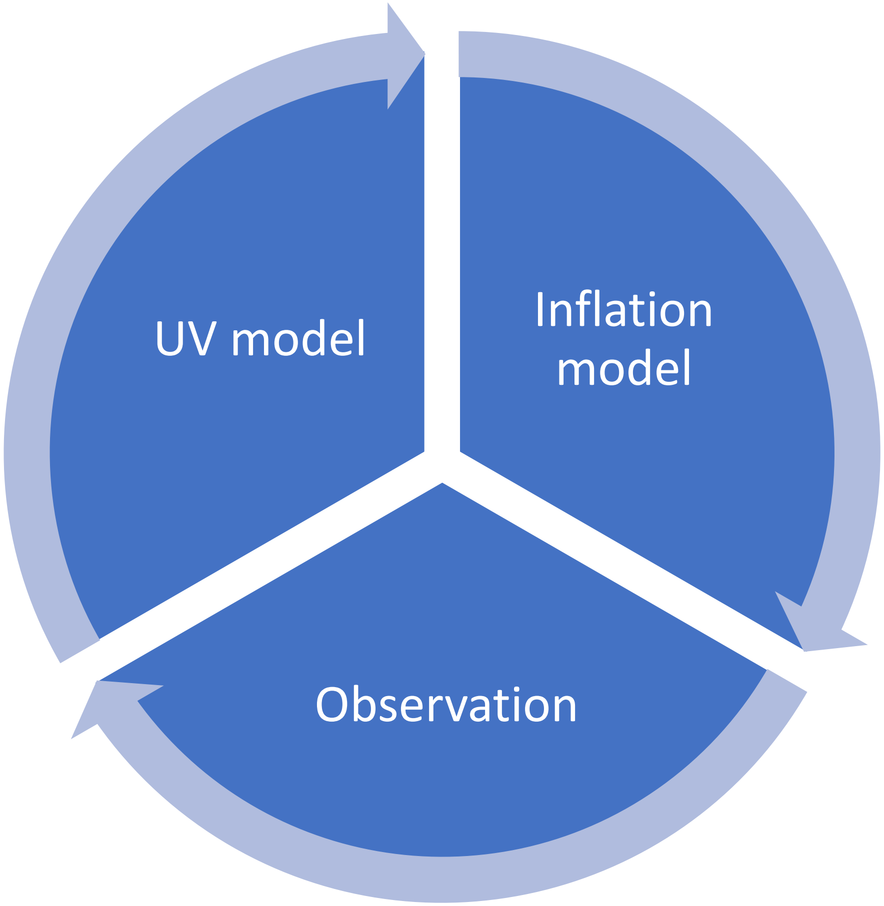
Ever since inflation was proposed,

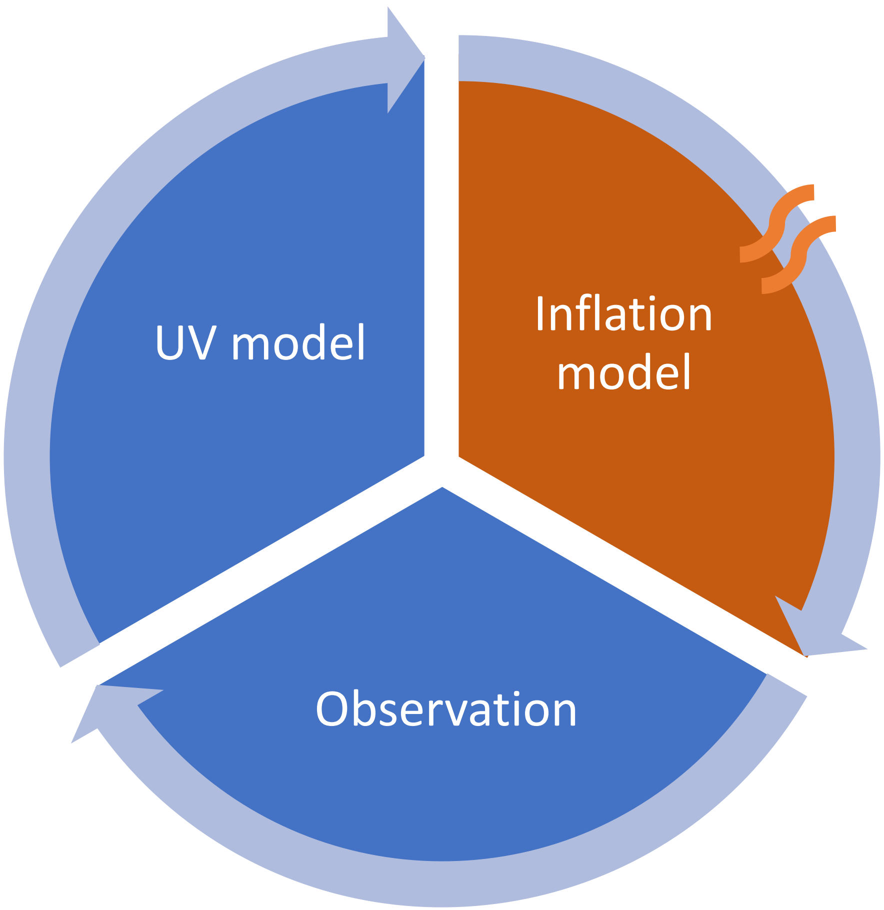
people use inflation to study HEP.

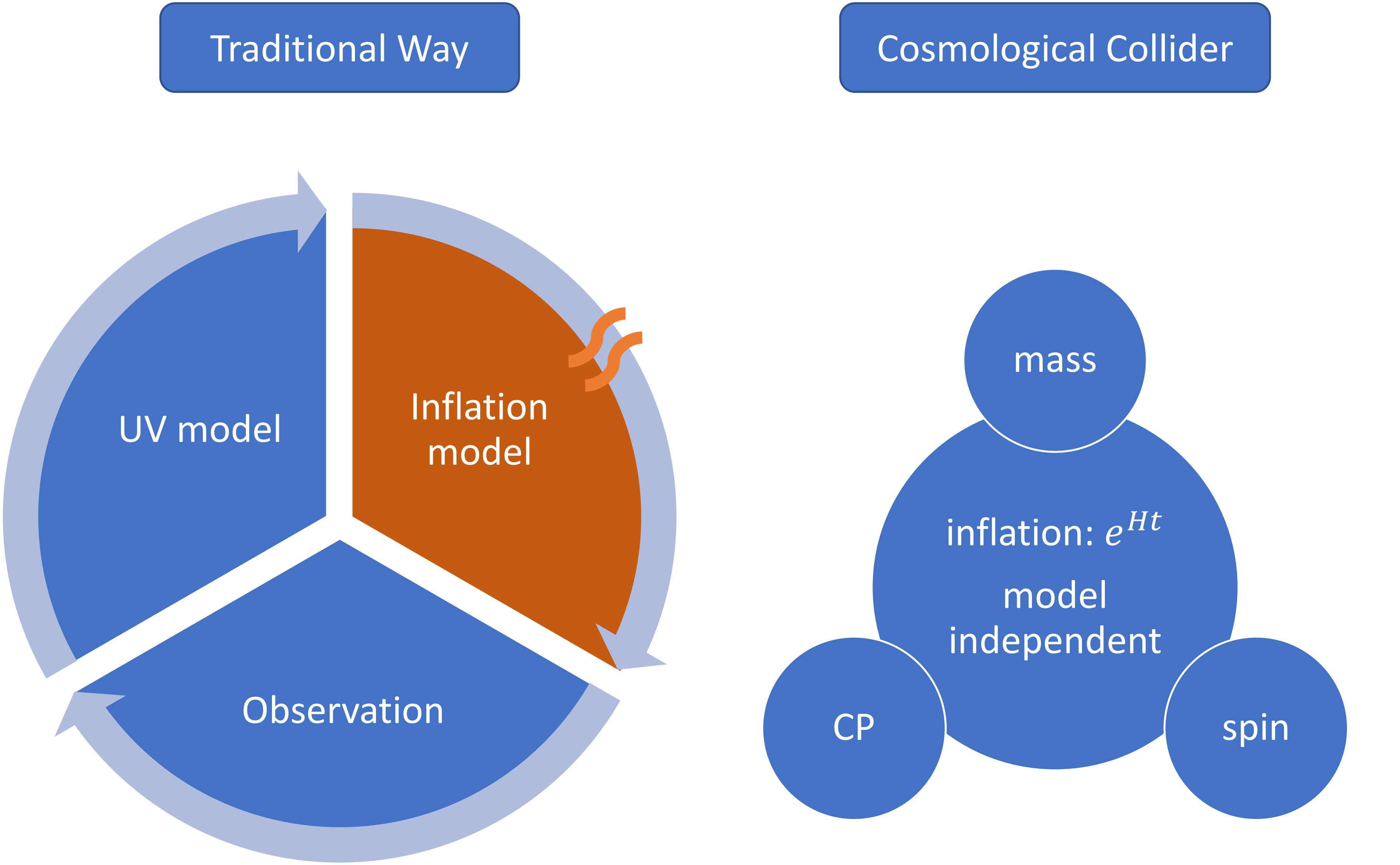
What's new about the "cosmological collider"?

Traditional Way



Traditional Way




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

Mass: from resonance

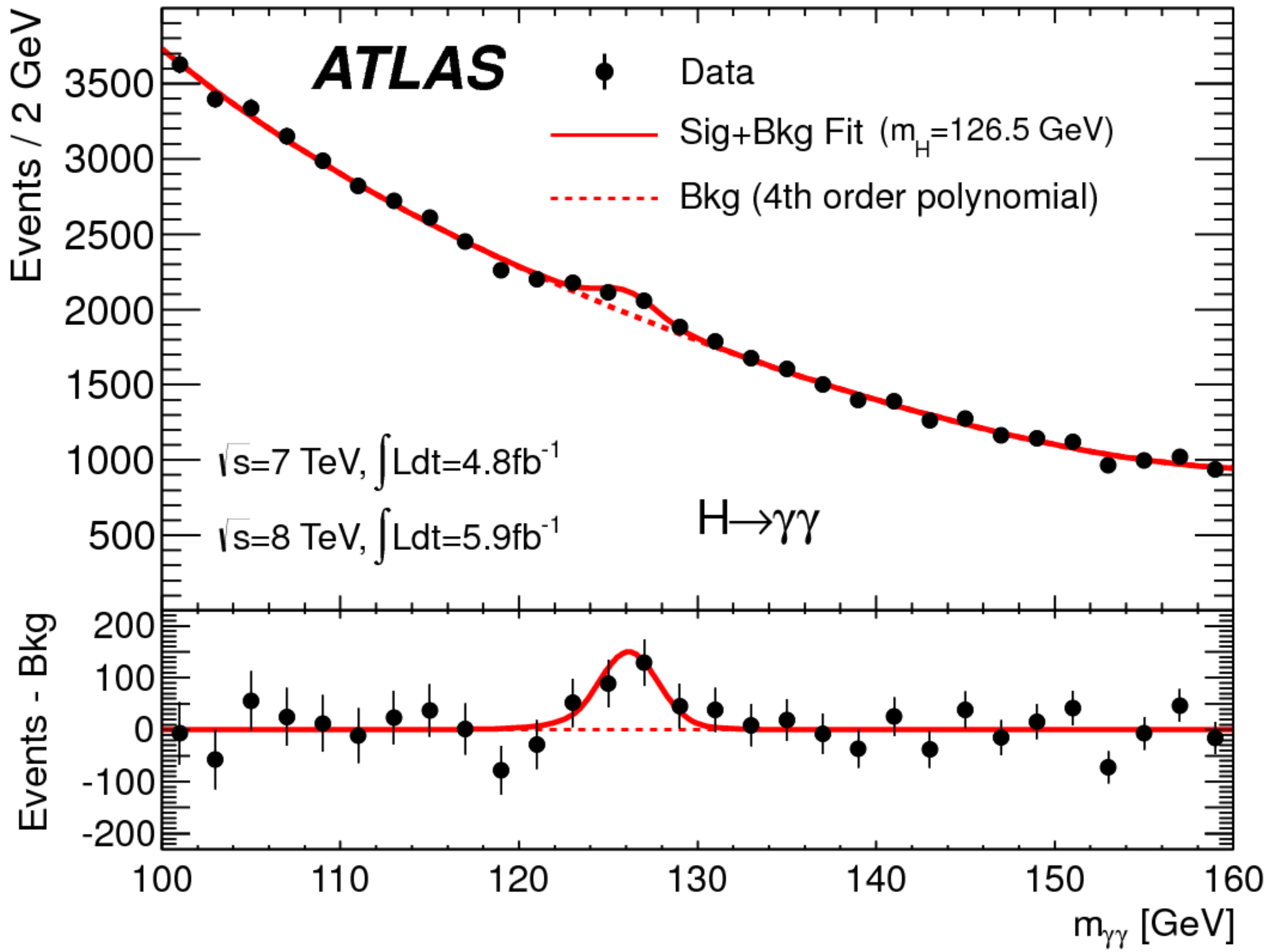


Image: ATLAS

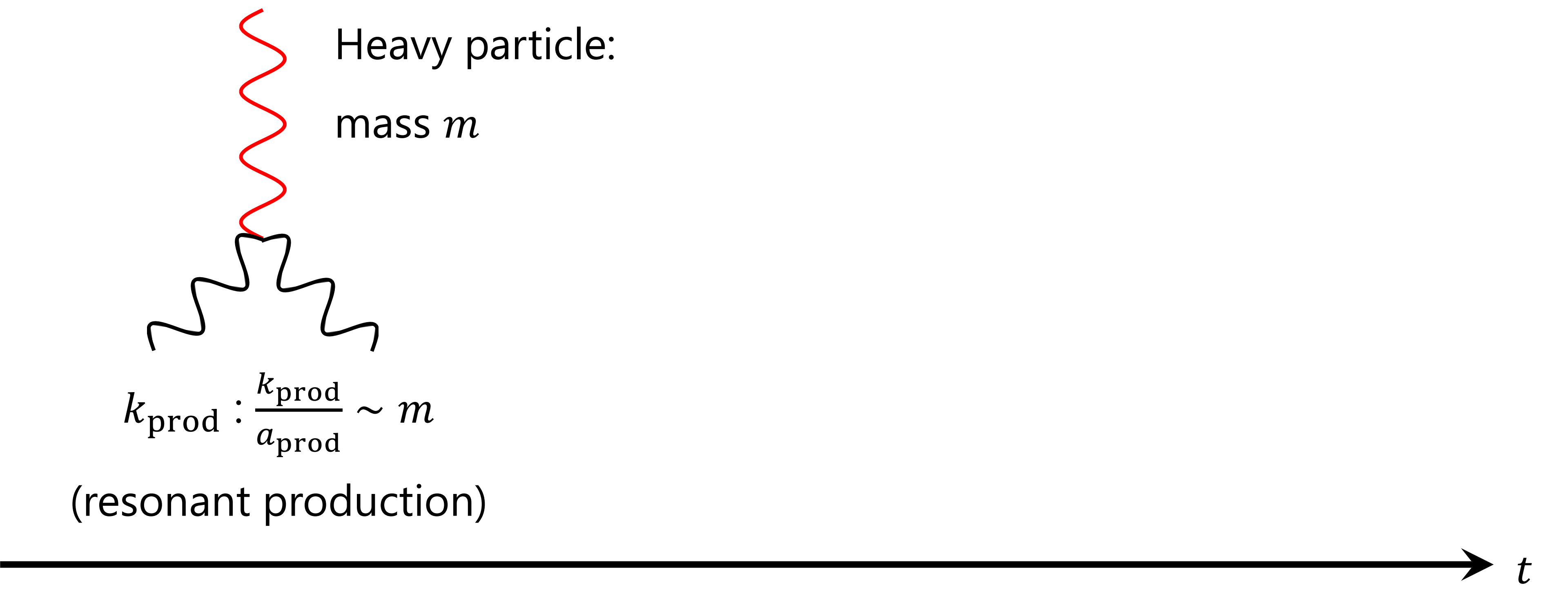
Dispersion relation for light and heavy particles during inflation

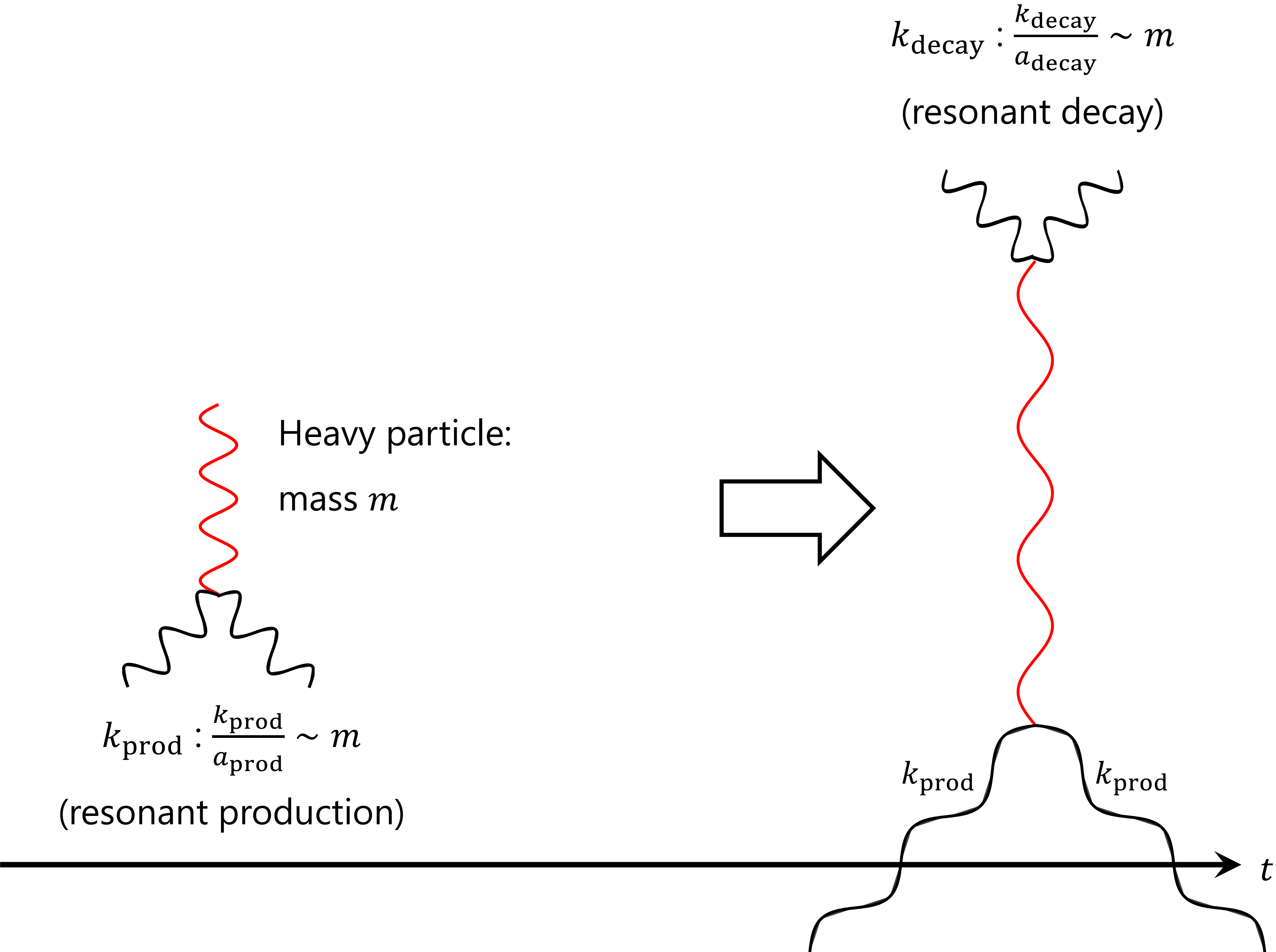
Light: $m \ll H$: $\omega = k/a$ (time dependent)

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

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


Heavy particle:
mass m
$k_{\rm prod}: \frac{k_{\rm prod}}{a_{\rm prod}} \sim m$
(resonant production)
t


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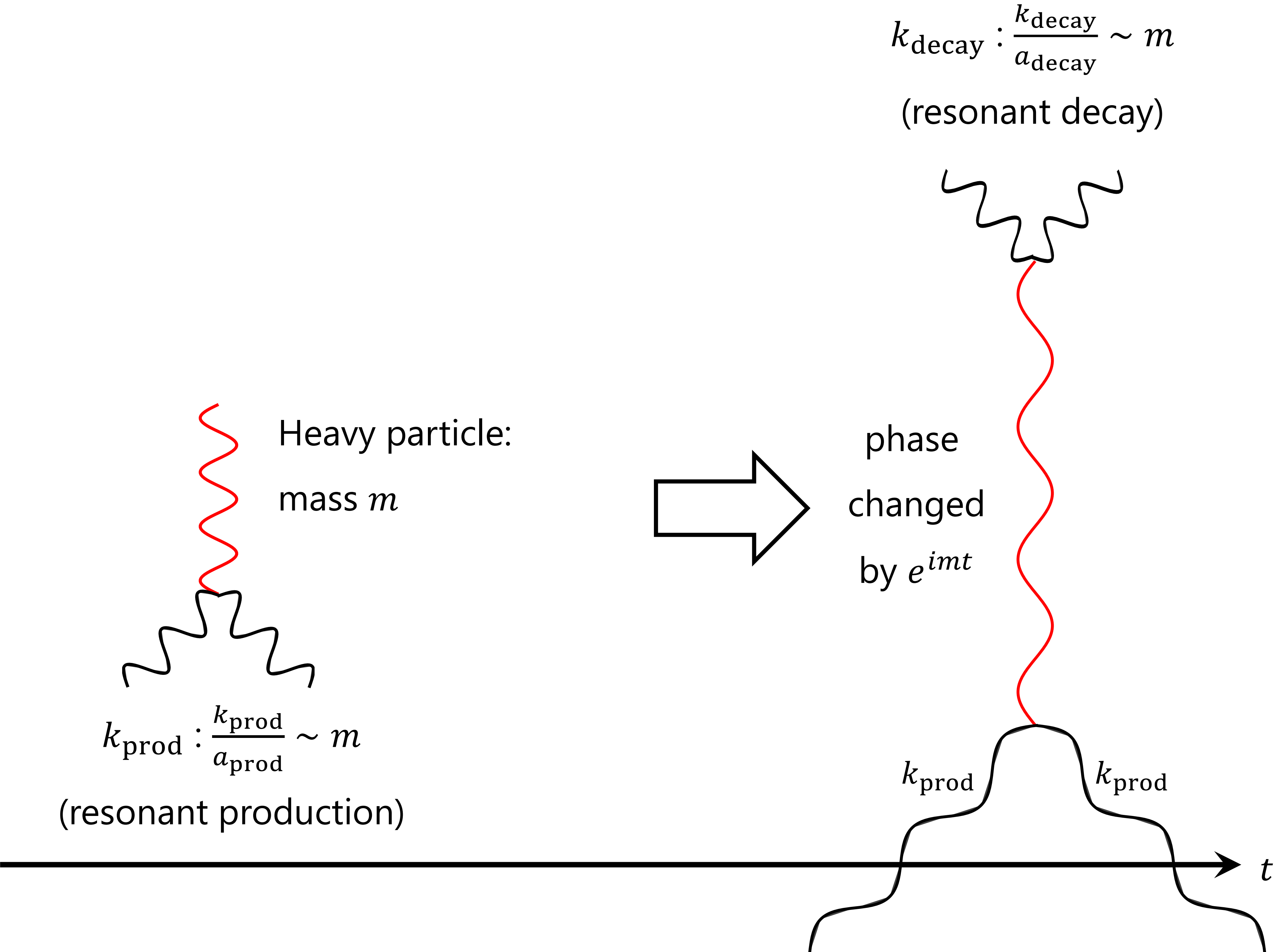
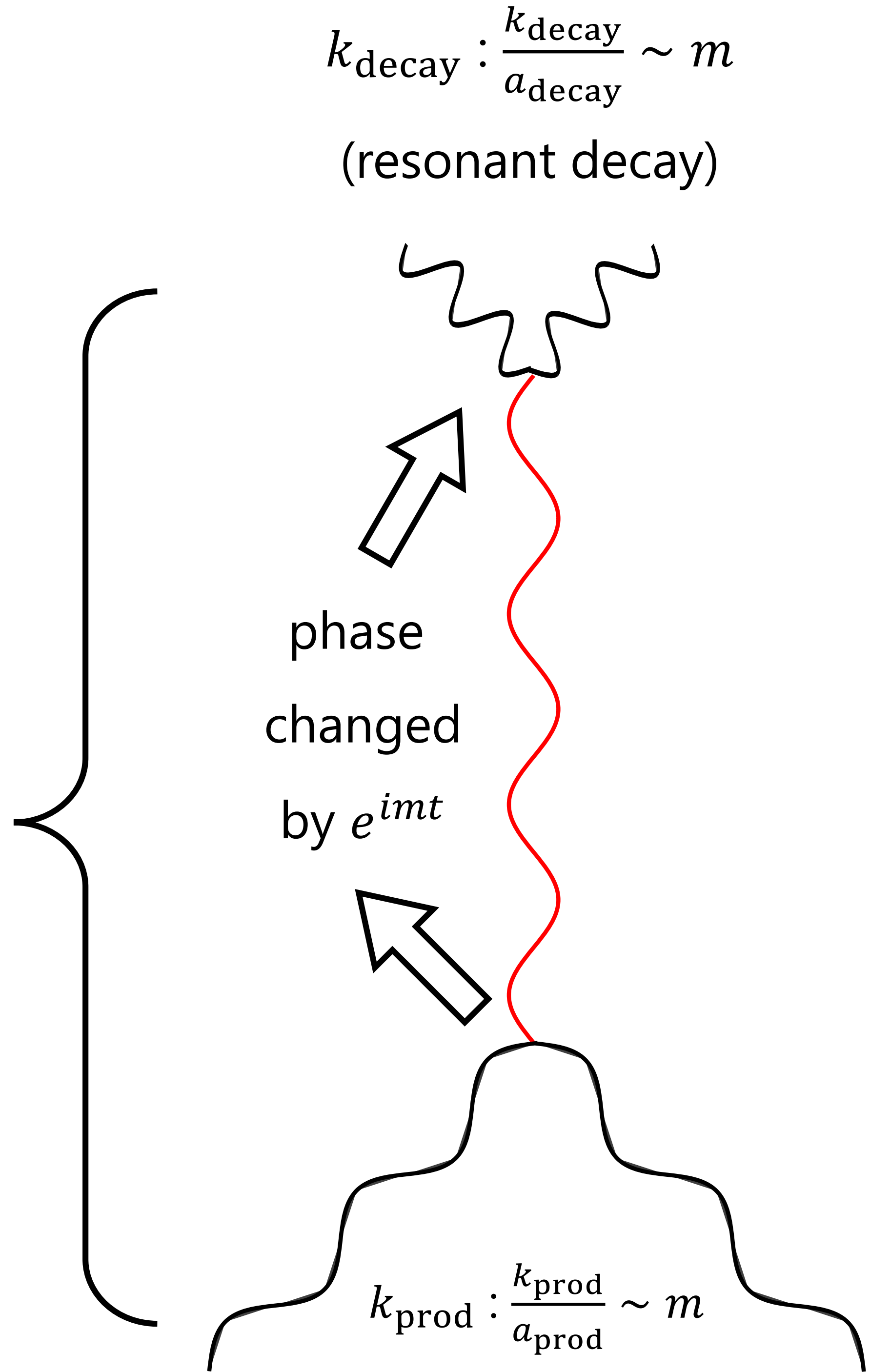


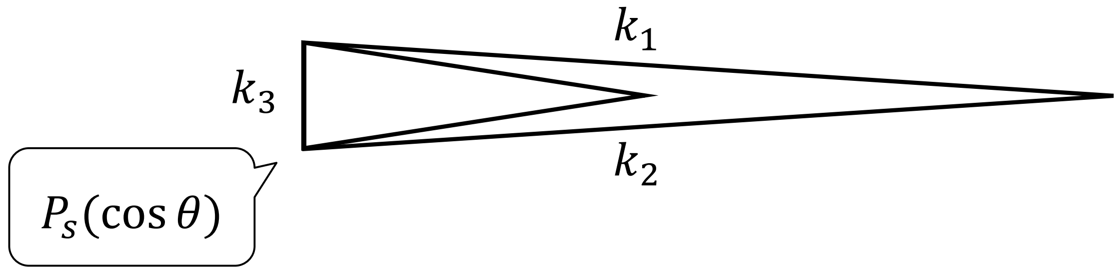
$k_{\text{decay}} : \frac{k_{\text{decay}}}{a_{\text{decay}}} \sim m$
(resonant decay)
Heavy particle:
mass m
phase
changed
by e^{imt}
$k_{\text{prod}} : \frac{k_{\text{prod}}}{a_{\text{prod}}} \sim m$
(resonant production)
k_{prod}
k_{prod}
t

interference:

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

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





Model-independent

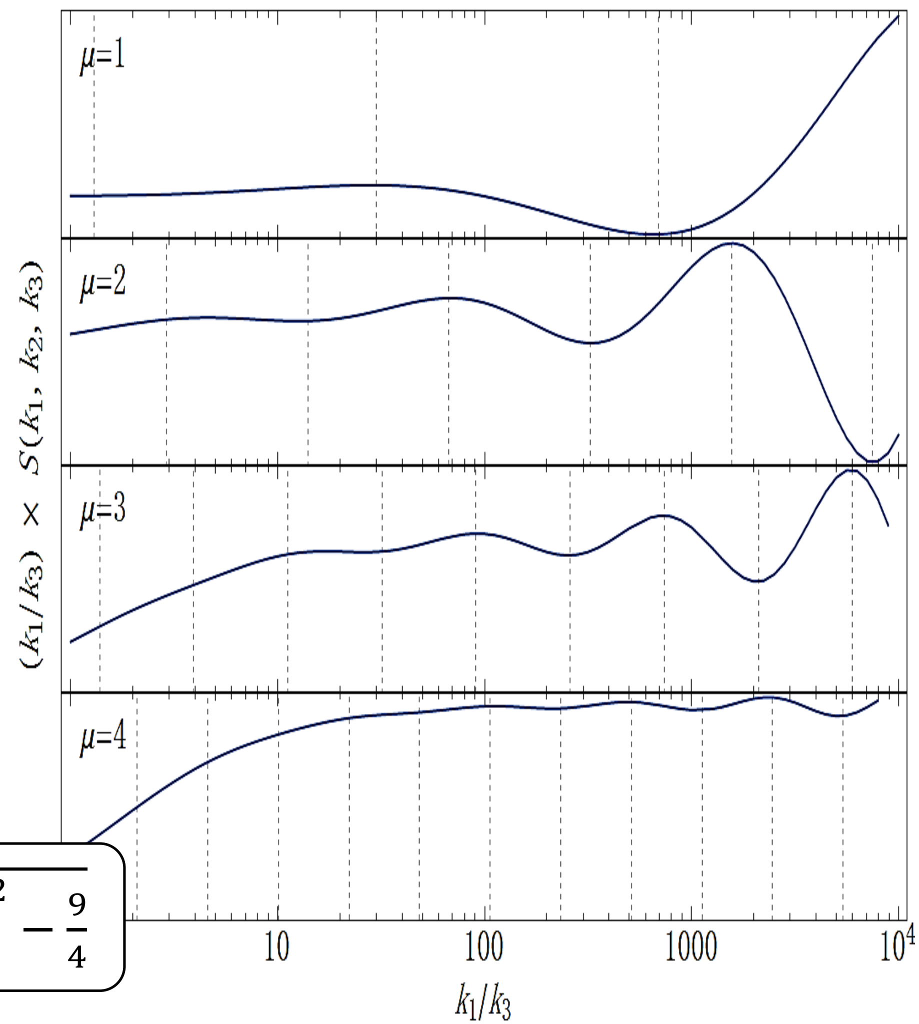
All based on known principles.

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



Spin

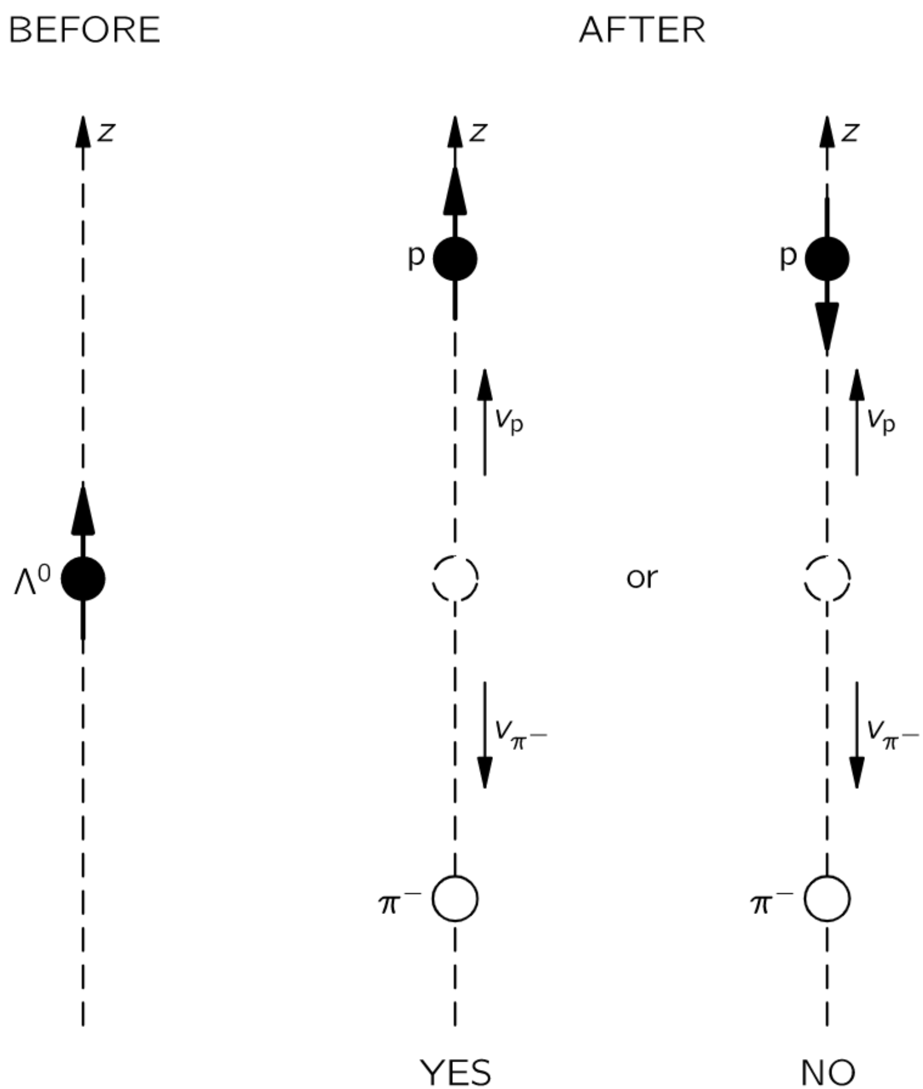


Figure from
Feynman
Lecture Notes
for spin 1/2

Spin

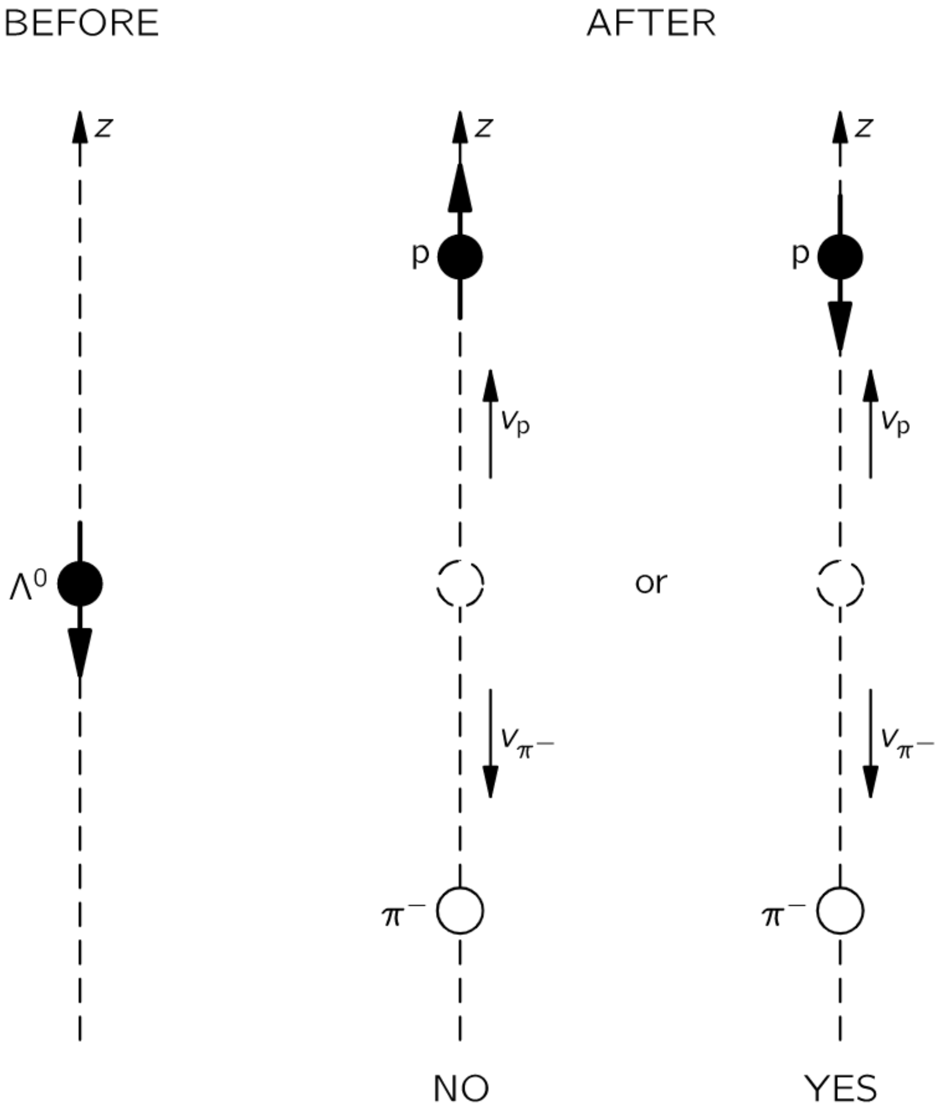


Figure from Feynman Lecture Notes for spin 1/2

Spin: angular distribution

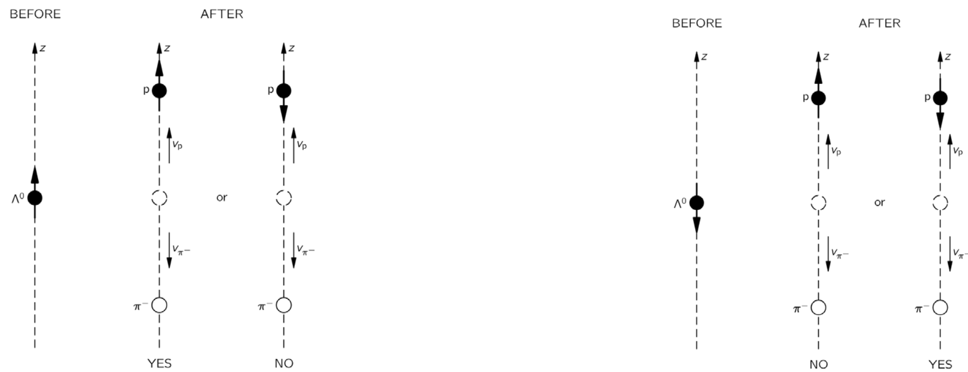
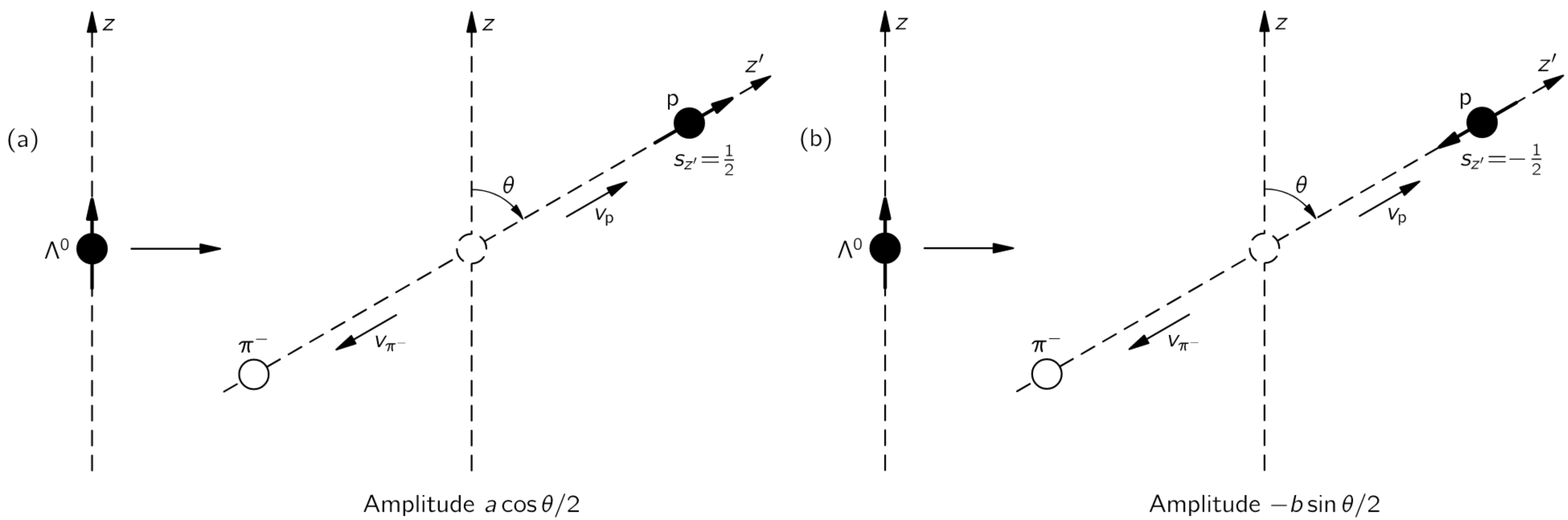
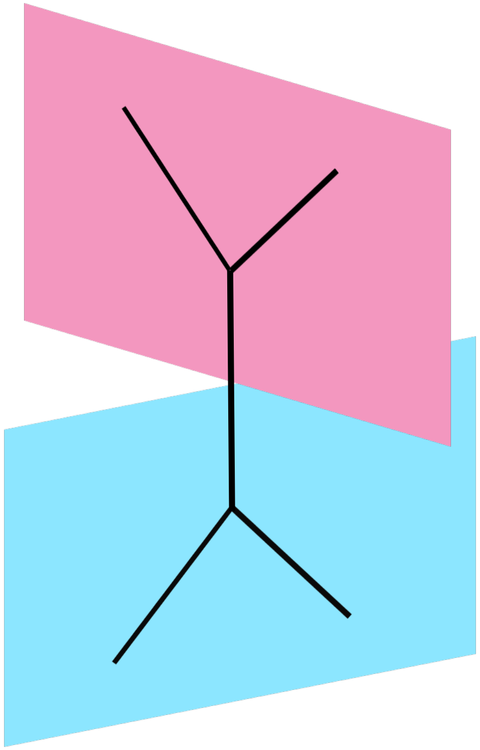


Figure from Feynman Lecture Notes for spin 1/2



For integer spin: $P_s(\cos\theta)$ angular distribution

CP: decay plane correlation

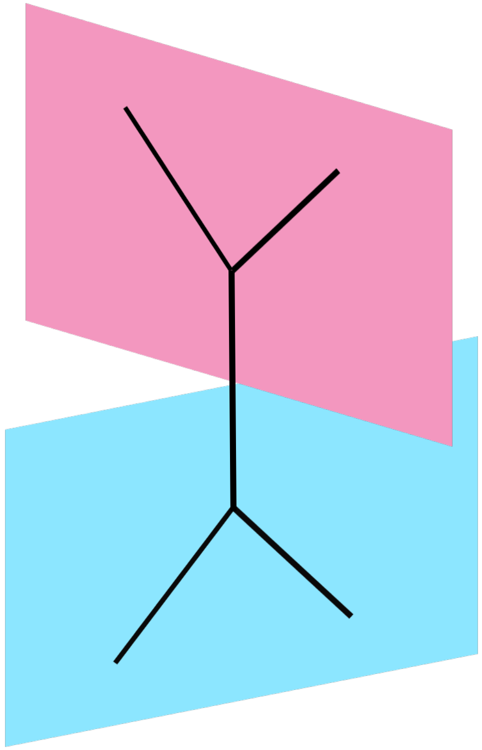


CP arises from the plane correlation

of the red and the blue

Liu, Tong, YW, Xianyu, to appear

CP: decay plane correlation



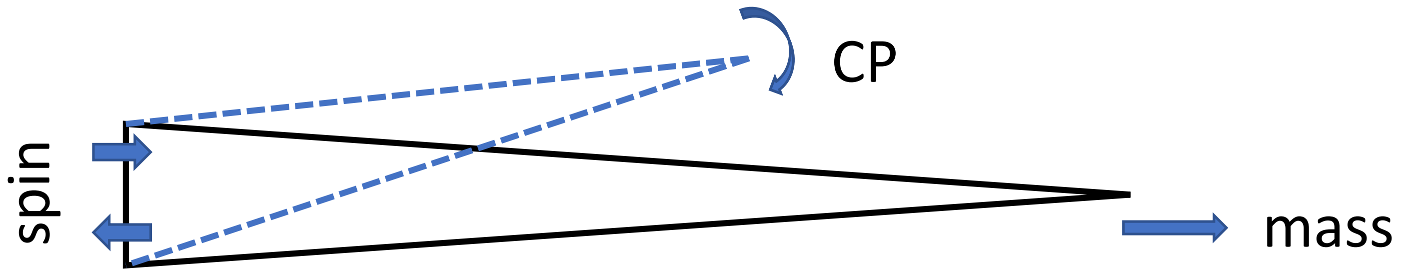
CP arises from the plane correlation of the red and the blue

自古红蓝出CP

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:

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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 $h^2 R \sim H^2 h^2$

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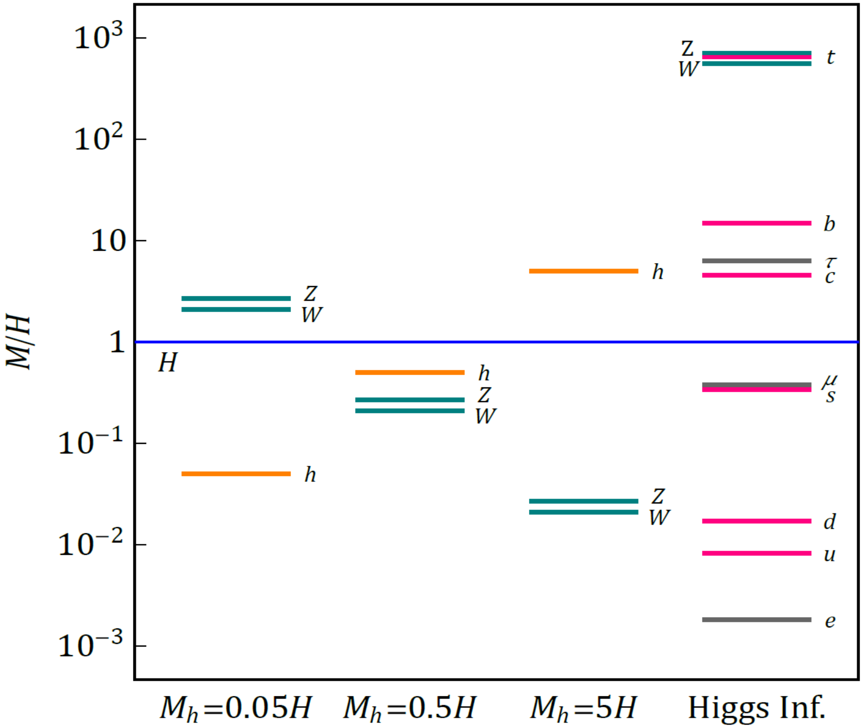

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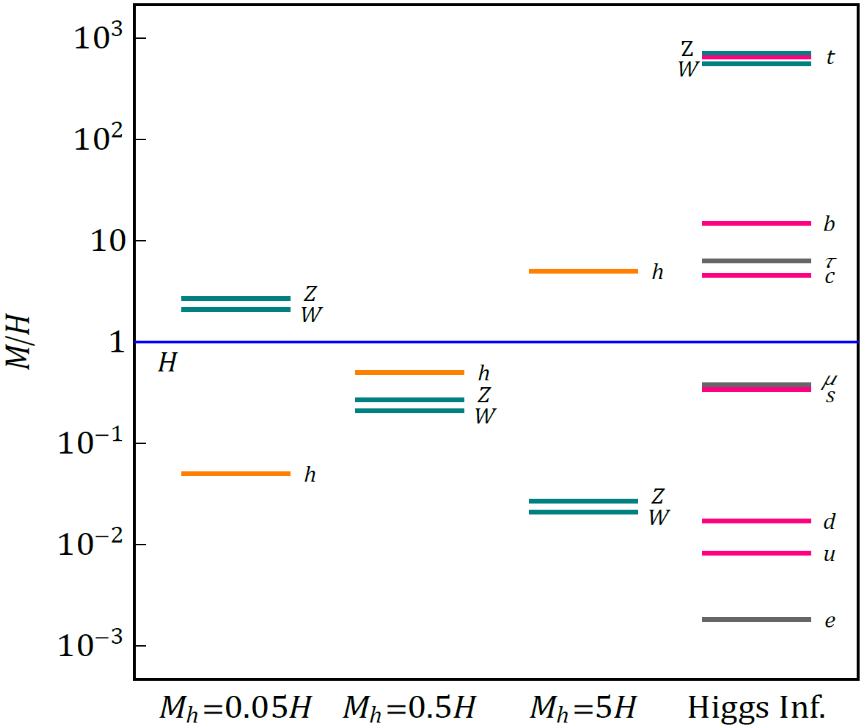

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Chen, YW & Xianyu, 1610.06597

Kumar & Sundrum, 1711.03988

- SUSY breaking

Baumann & Green, 1109.0292

Delacretaz, Gorbenko & Senatore 1610.04227

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

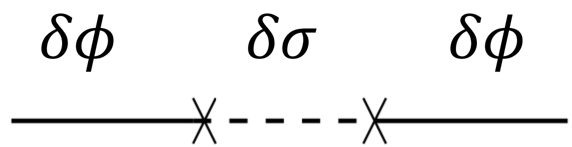
Consider dim-5 operator $(\partial\phi)^2\sigma/\Lambda$, $\mathcal{L}_2 \supset \frac{2\dot{\phi}}{\Lambda}\delta\dot{\phi}\delta\sigma$

Note: $\dot{\phi} \sim 3600H^2$.
Even $\Lambda = M_p$, if $m{\sim}H$ for σ, 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

$\Delta r/r$ and $\Delta(n_s-1)/(n_s-1)$



Observable M_p effect!

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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 ΔP_ζ)
3. IR growth if $m \lesssim H$
4. If $M_{\text{string}} < M_p$
5. If $M_{\text{extra}\,D} < M_p$

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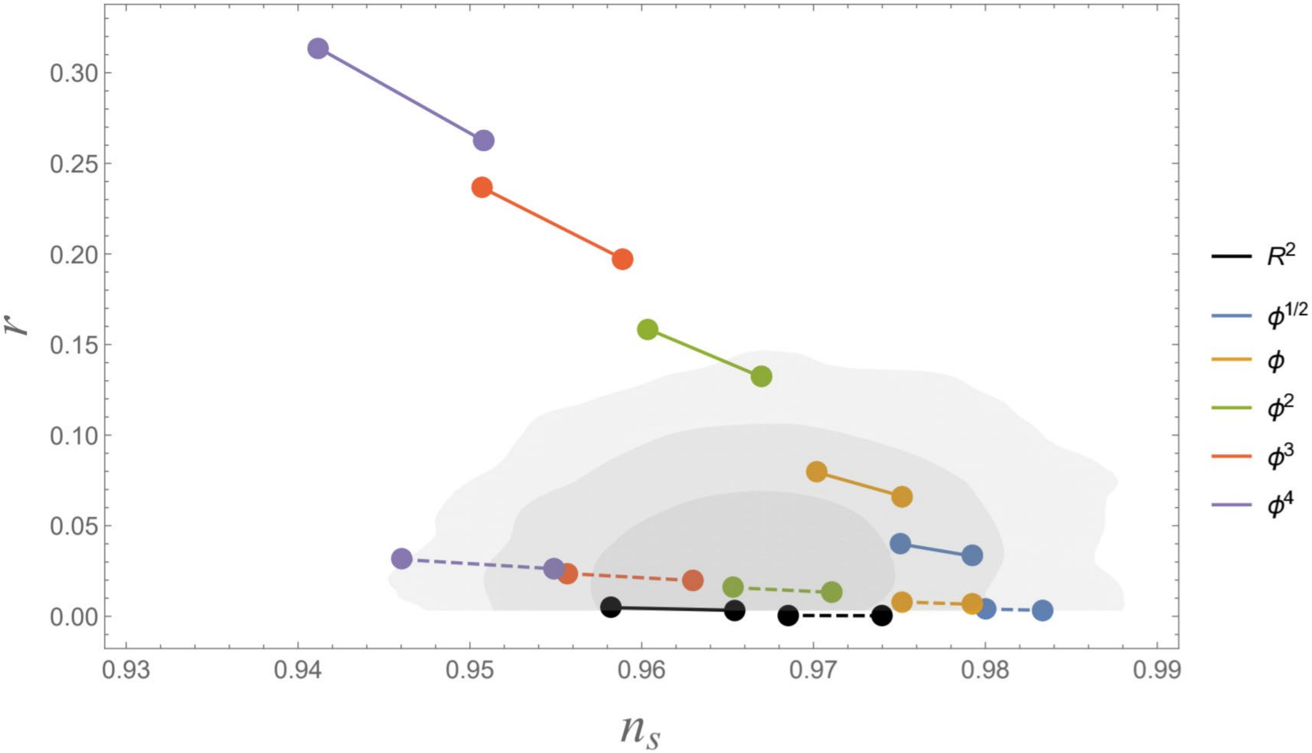

Tong, YW, Zhou 1708.01709, see also An, McAneny, Ridgway, Wise 1706.09971

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

Thank you!