Exploring New Physics in the Cosmological Collider

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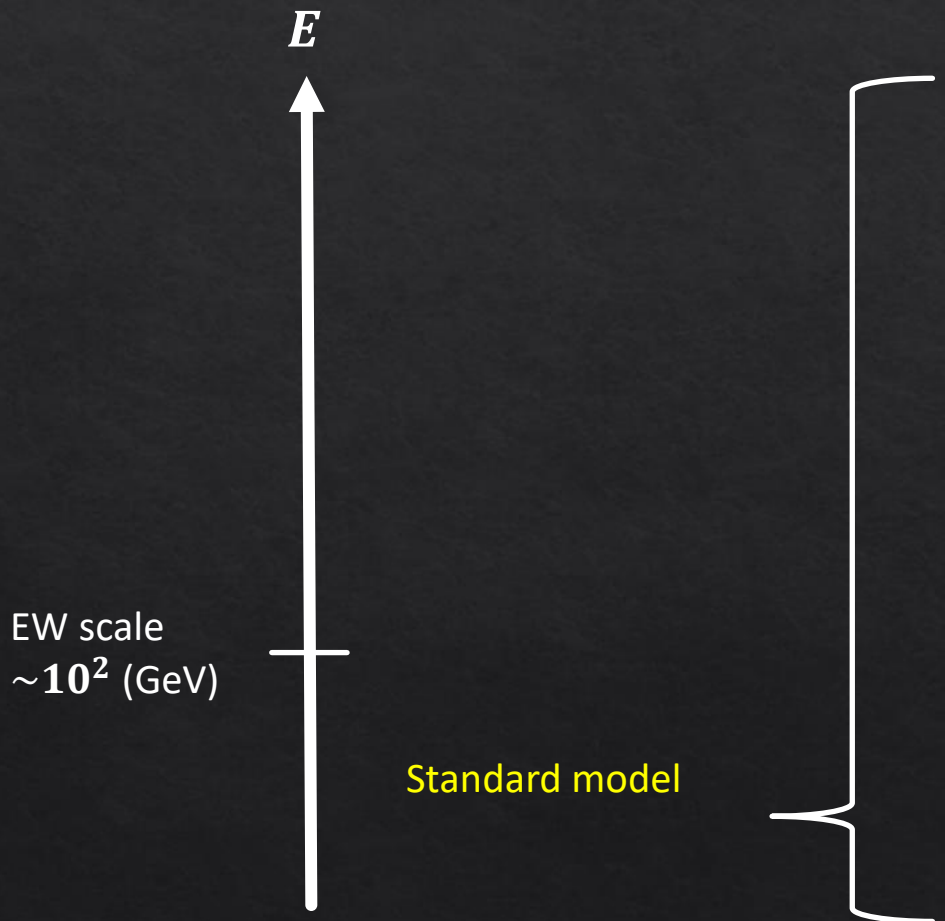
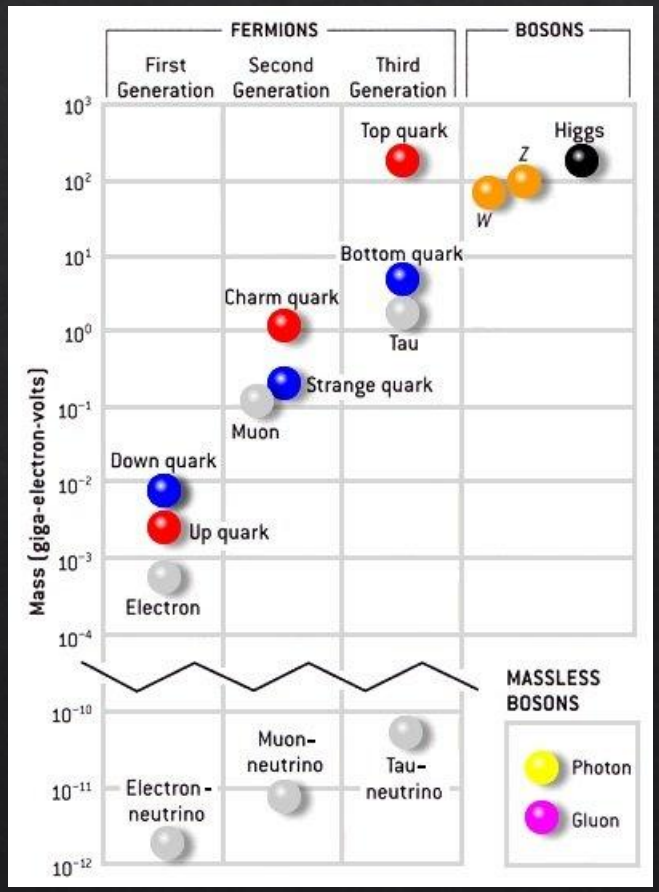
N3AS annual meeting
6/8/2025

Standard model of particle physics and beyond





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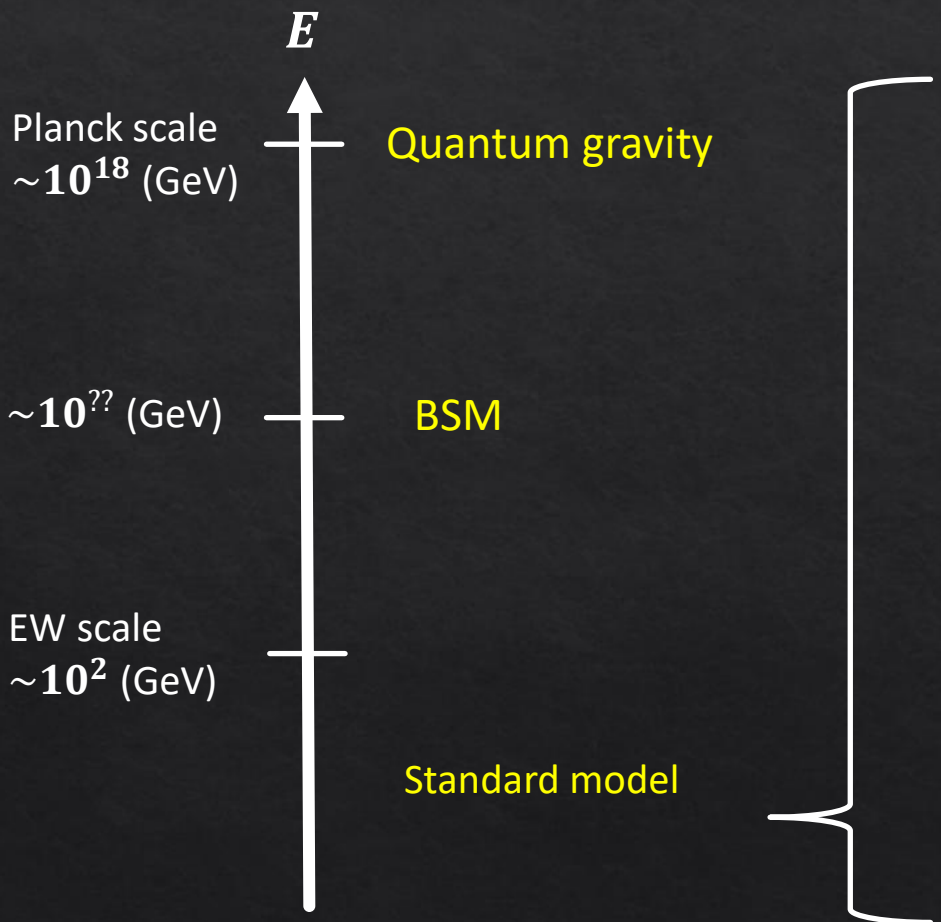
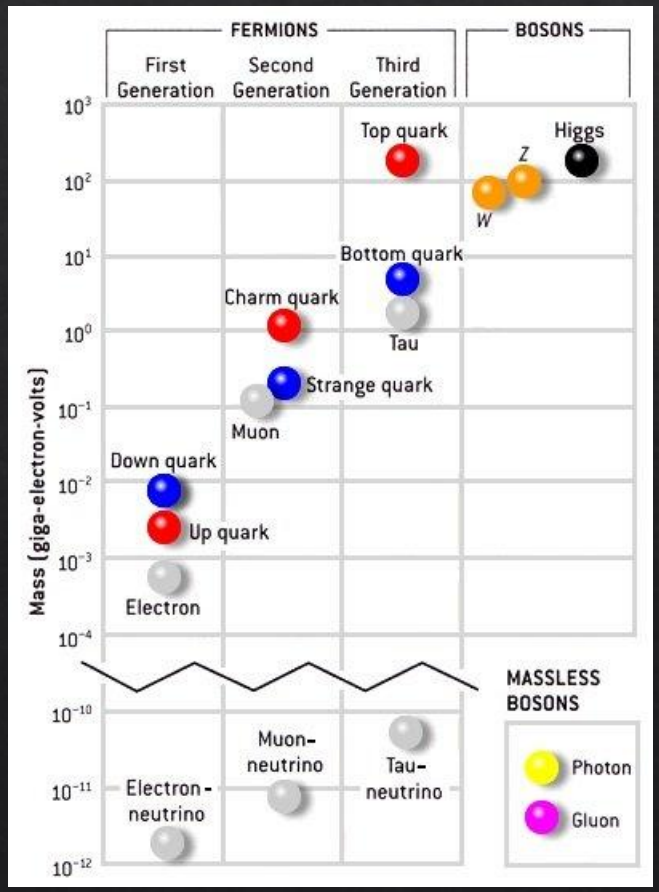
Standard model of particle physics and beyond





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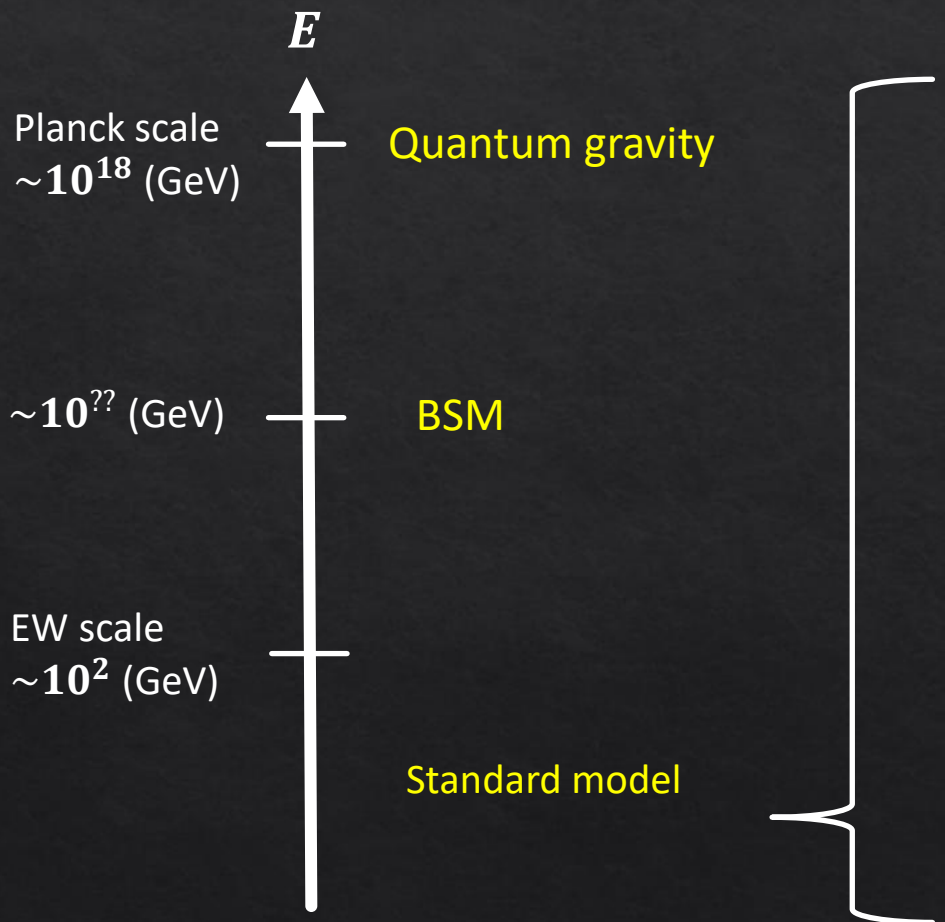
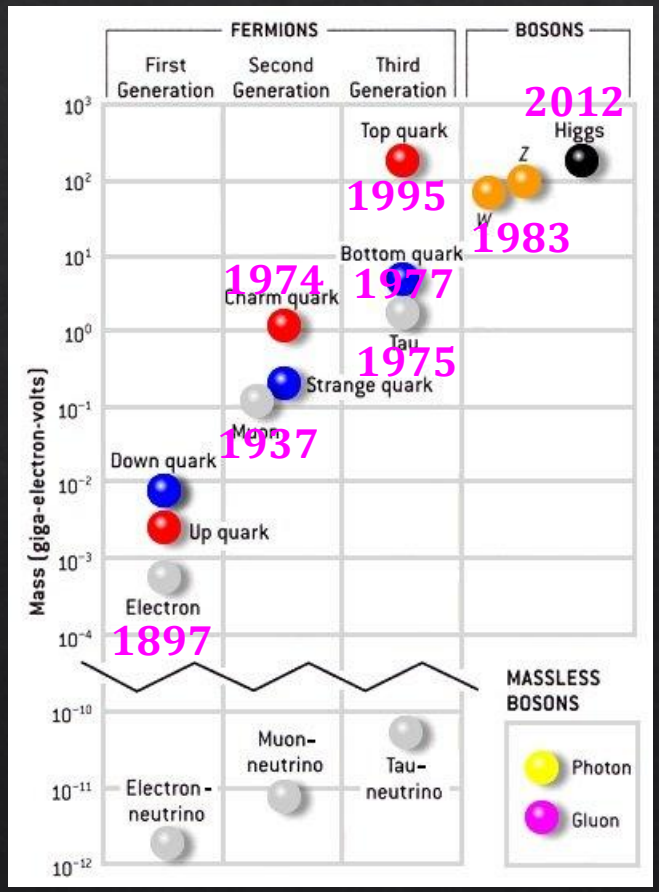
Standard model of particle physics and beyond





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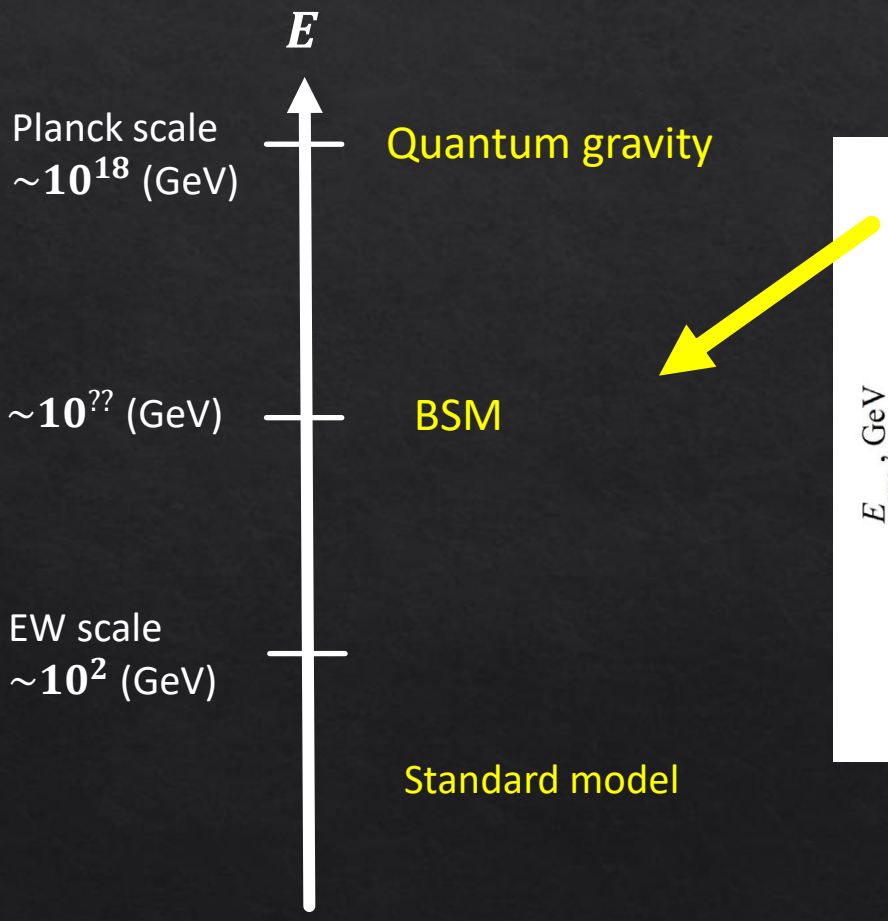
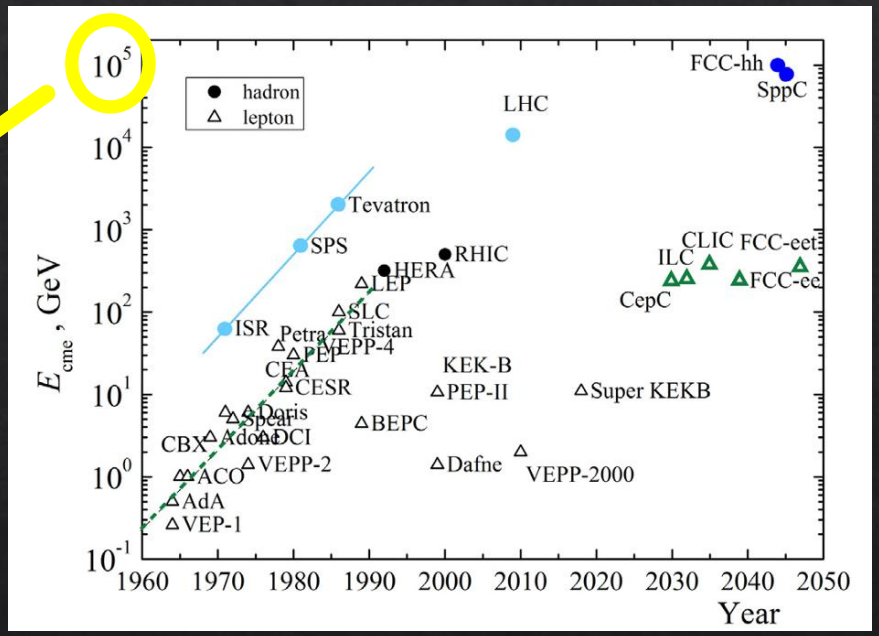
Future colliders

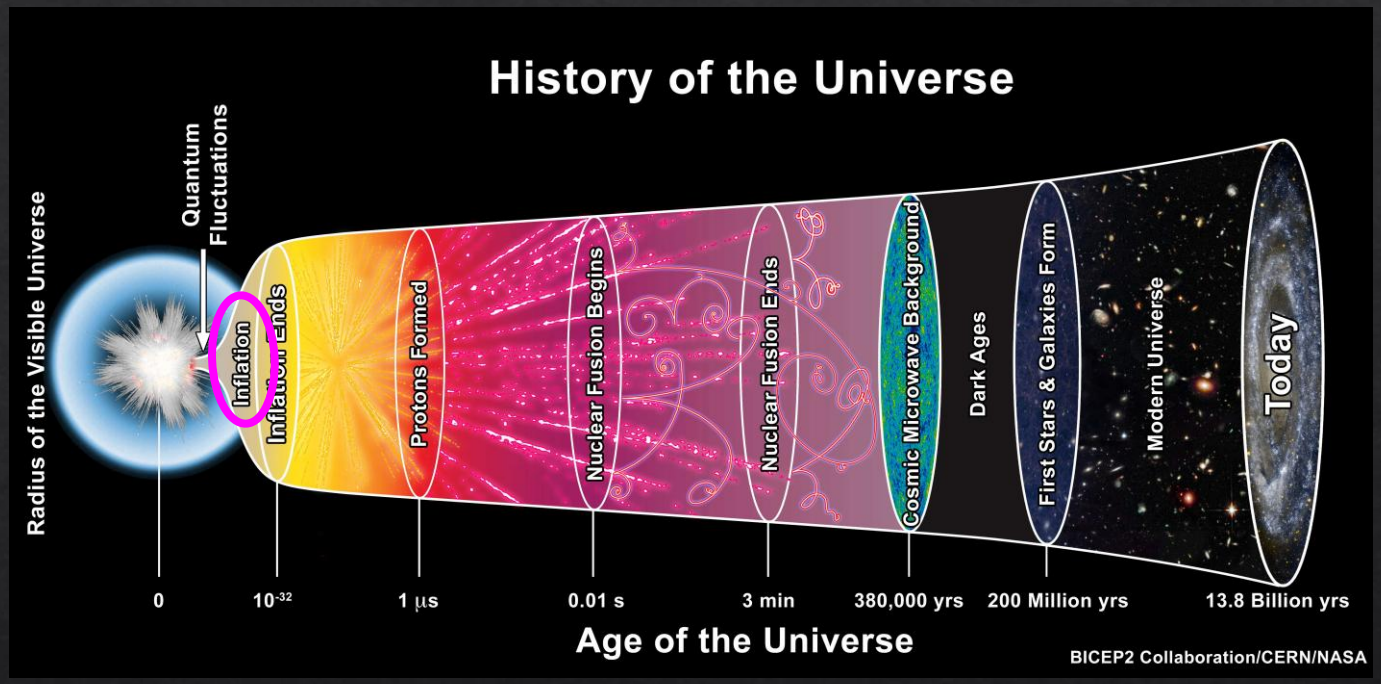


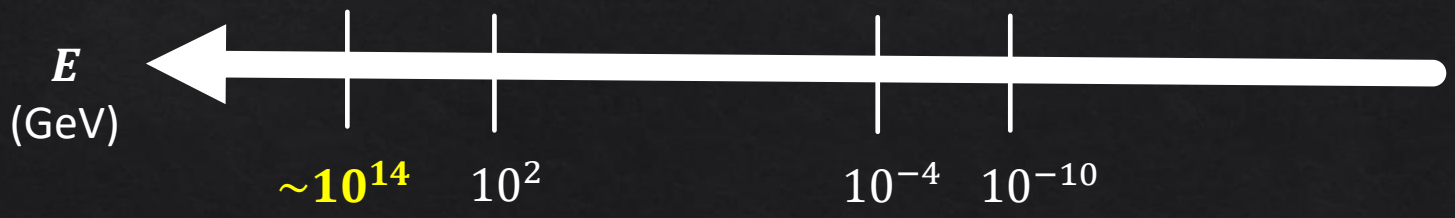


Gray, Future colliders for the high-energy frontier

Very important, but BSM might appear at higher scale ⇒ Another approach?

Universe as a gigantic accelerator





Idea: probing new physics with inflation energy

Inflation

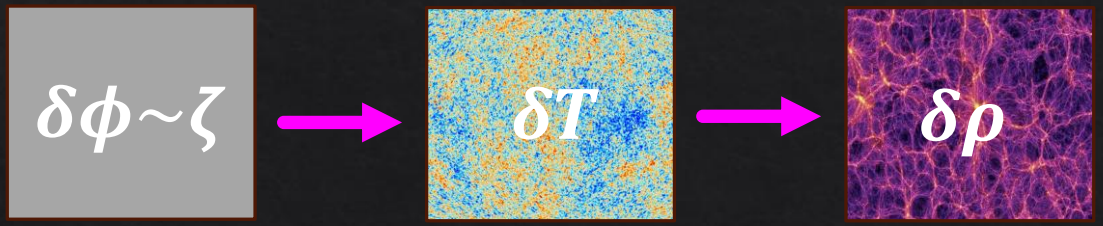
- Inflation = rapid expansion of early universe

  Guth, Sato, Starobinsky, Linde,…

- Solve initial condition problems in standard cosmology

- Caused by a scalar ϕ: "inflaton"

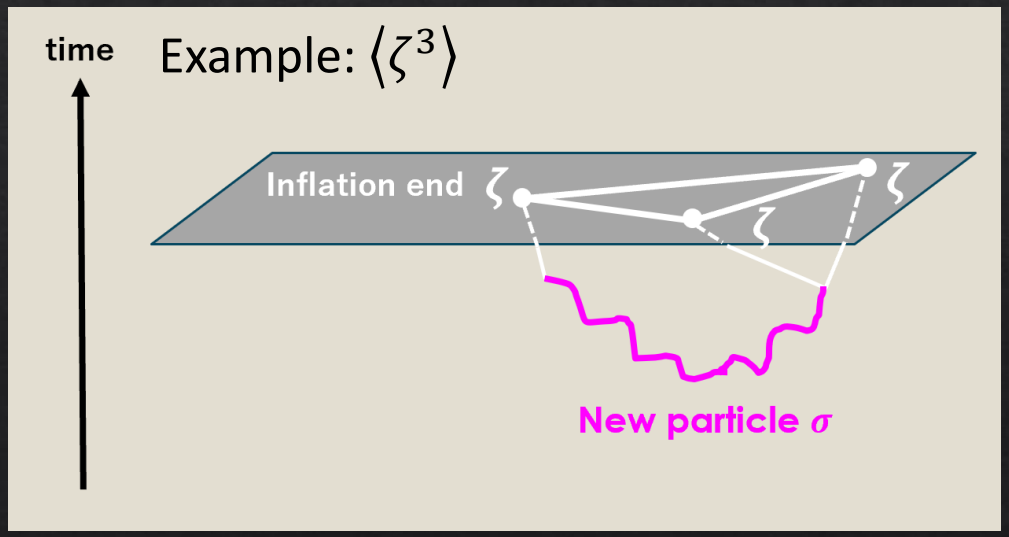
- Quantum inflaton fluctuation $\delta\phi \rightarrow$ curvature ζ



Cosmological Collider

Chen, Wang, '10
Baumann, Green, '12
Noumi, Yamaguchi, Yokoyama, '13
Arkani-Hamed, Maldacena, '15

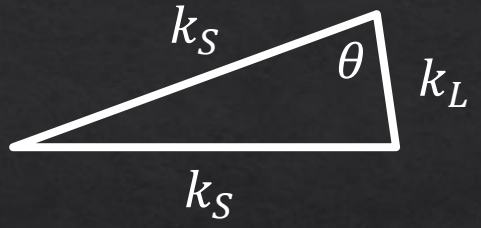
- $\langle \zeta^n \rangle$ may contain information of heavy (new) particle σ



Cosmic expansion creates σ with mass $\sim H$

Cosmological Collider

- Clear signal in squeezed limit of triangle $k_S \gg k_L$



- σ leaves specific imprint on $\langle \zeta^3 \rangle$

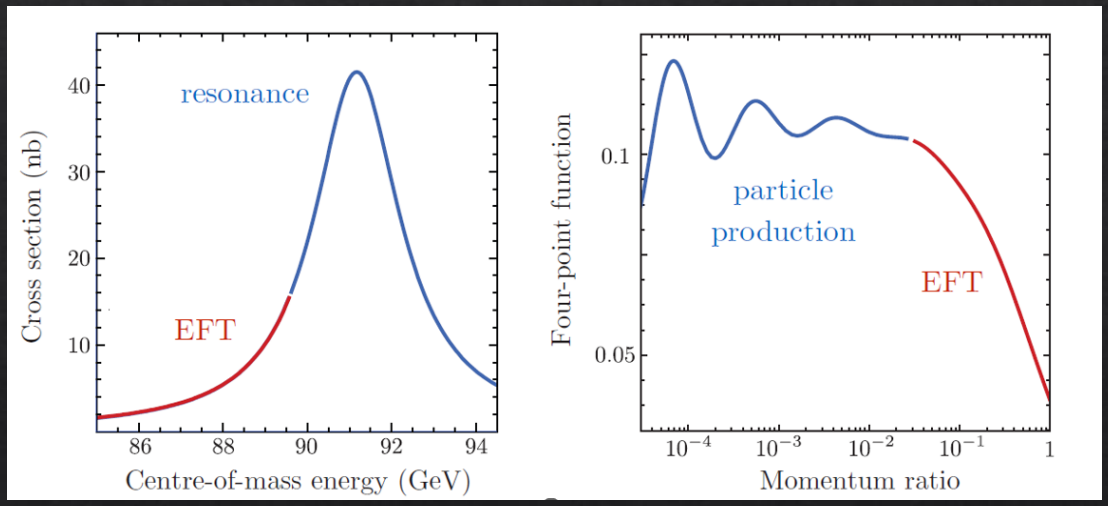
$$\langle \zeta^3 \rangle|_{k_L \ll k_S} \sim e^{-\pi\mu} \left(\frac{k_L}{k_s}\right)^{\frac{3}{2}} \cos\left[\mu \log\left(\frac{k_L}{k_s}\right) + \delta(\mu)\right] P_s(\cos\theta)$$

$\mu \sim m_\sigma / H$: mass

spin

Cosmological Collider

- Particle physics analogy

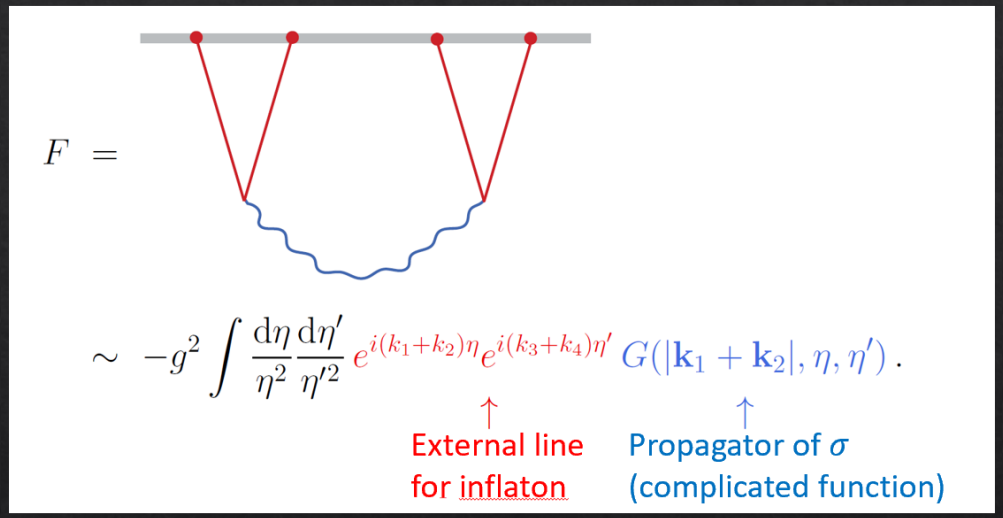


Baumann, Lectures on The Cosmological Bootstrap

- $m_\sigma \sim H_{\rm inf} \sim 10^{14}$(GeV) $\gg\gg\gg\gg$ $10^{4,5}$(GeV) ~ collider on earth

Structure of correlators & Challenges

- Structure of correlators
  e.g., $\langle \zeta^4 \rangle$ with tree level single exchange

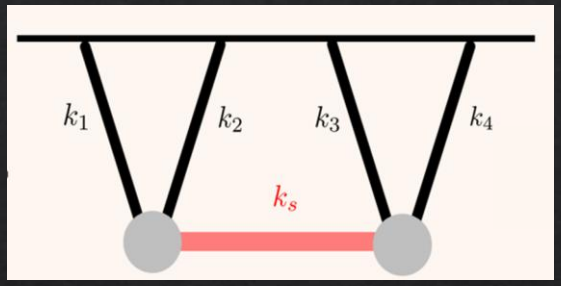


- Challenges:
  - Mode functions (Hankel, Whittacker, …)
  - Nested time integral

Recent development

Arkani-Hamed, Baumann, Lee, Pimentel, 1811.00024

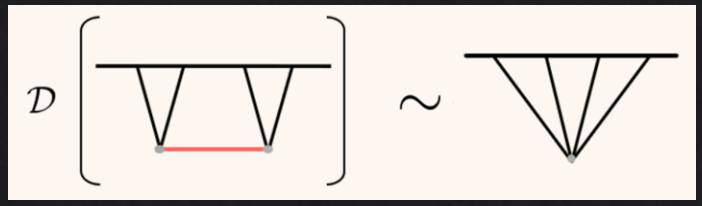
- Correlators satisfy differential equations w.r.t momentum
  $u \equiv k_s/(k_1+k_2)$ & $v \equiv k_s/(k_3+k_4)$



$$\left(\Delta_u + M^2\right) F = uv/(u+v)$$
$$\left(\Delta_v + M^2\right) F = uv/(u+v)$$

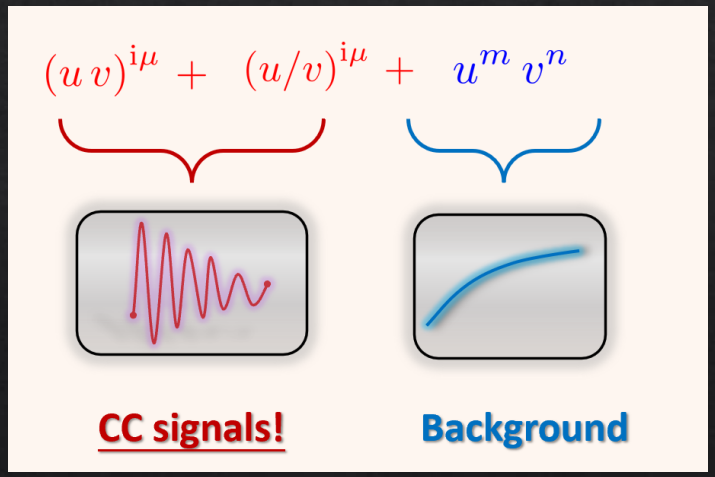
$$\Delta_u \equiv u^2(1-u^2)\partial_u^2 - 2u^3\partial_u \,,$$

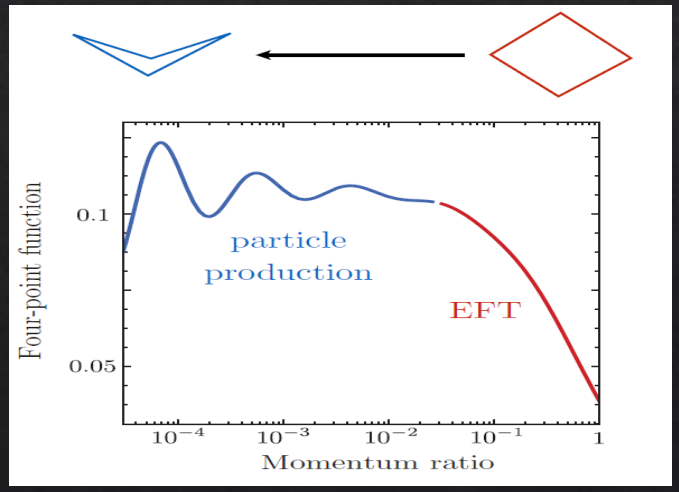
- Schematical expression:



Solutions

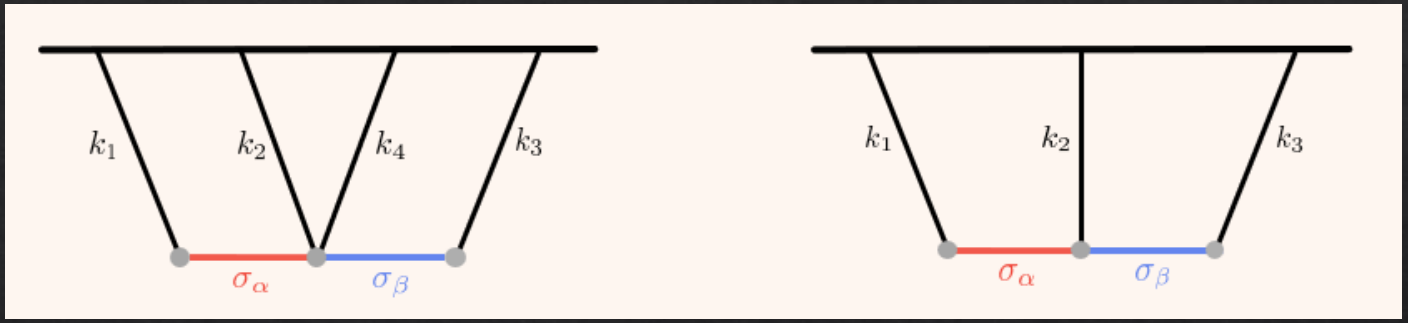
$$\left(\Delta_u + M^2\right) F = uv/(u+v)$$ + B.C.





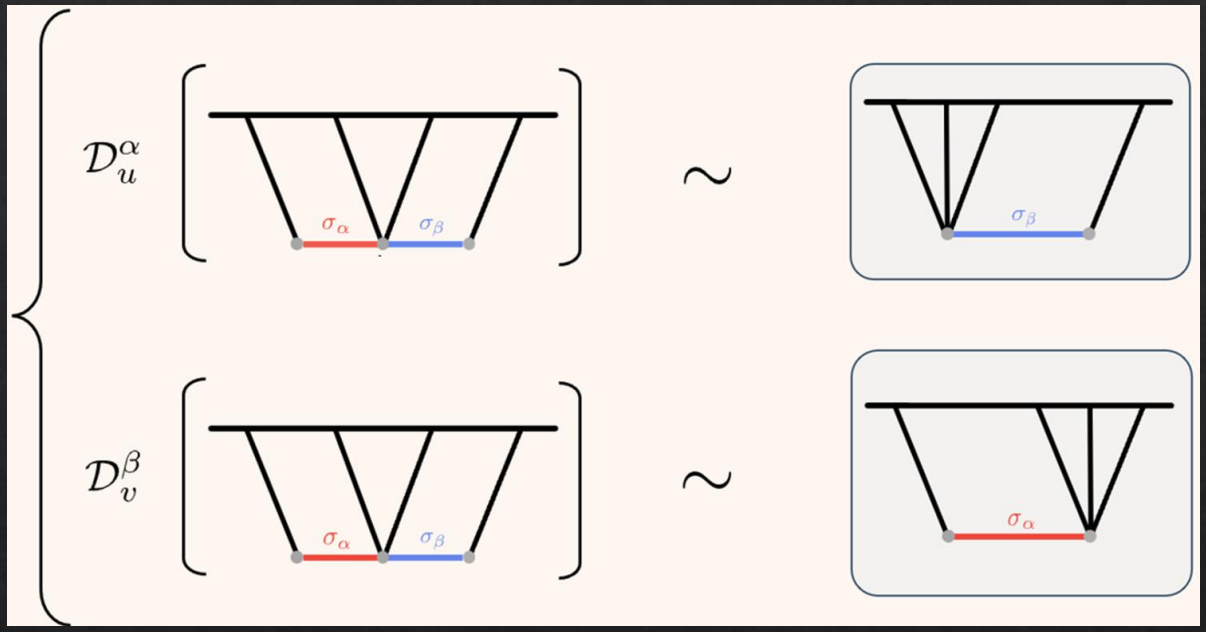
Double exchange

SA, L. Pinol, F. Sano, M. Yamaguchi, Y. Zhu, 2404.09547



$$F = F(u,v) \text{ with } u \equiv \frac{k_1}{k_2+k_4}\,,\; v \equiv \frac{k_3}{k_2+k_4}$$

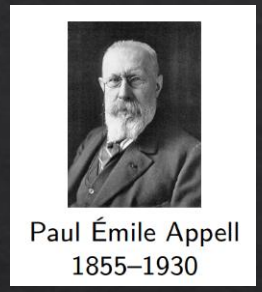
Differential equations



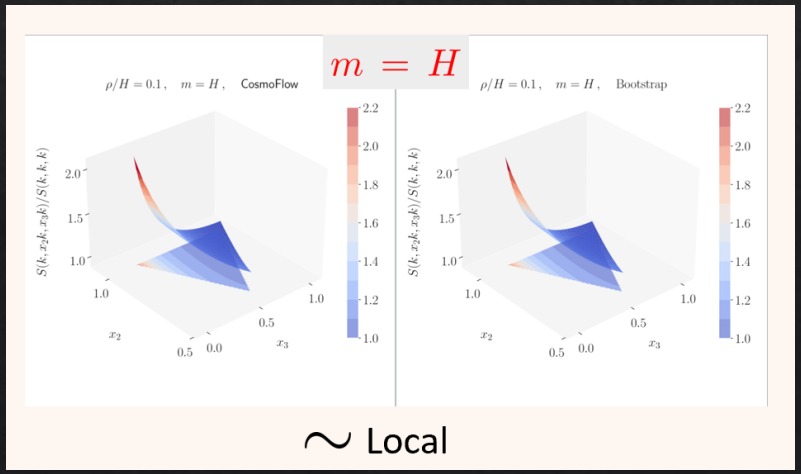
$$\mathcal{D}_u^\alpha \equiv u^2\partial_u^2 - 2u\partial_u + \mu_\alpha^2 + \frac{9}{4} - u^2\left(u\partial_u + v\partial_v\right)\left(u\partial_u + v\partial_v - 1\right)$$

Result

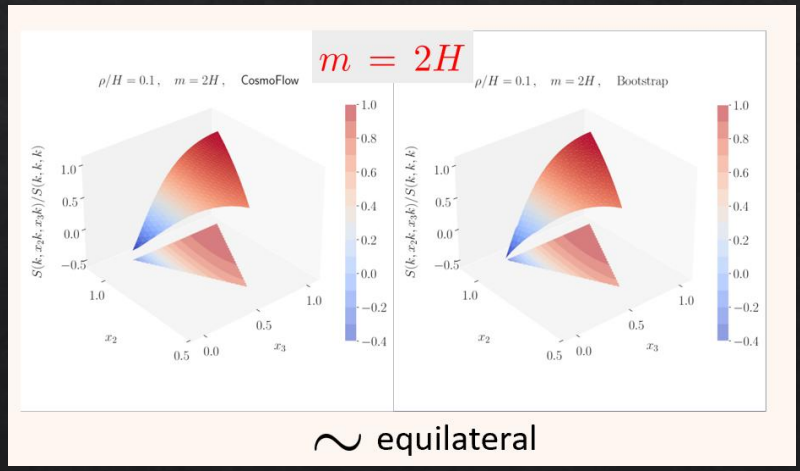
- Analytic solutions (based on Appell series $F_4(u^2, v^2)$)
- valid in any kinematic configuration
- vs Numeric



Paul Émile Appell
1855–1930



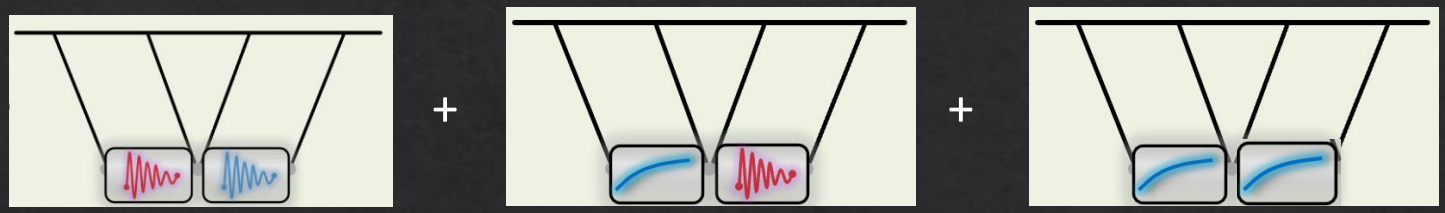
$\sim$ Local



$\sim$ equilateral

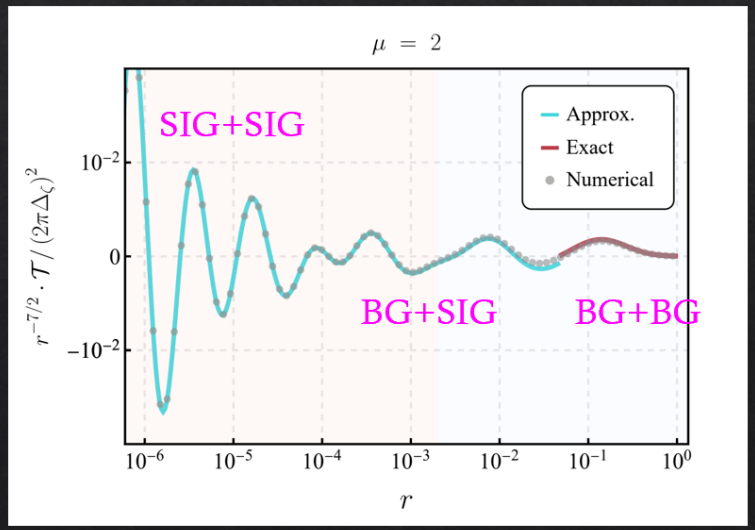
Phenomenological implication

F =



SIG+SIG BG+SIG BG+BG

Specific oscillation signal (change of frequency $\mu \to 2\mu$) which cannot be mimicked by single exchange



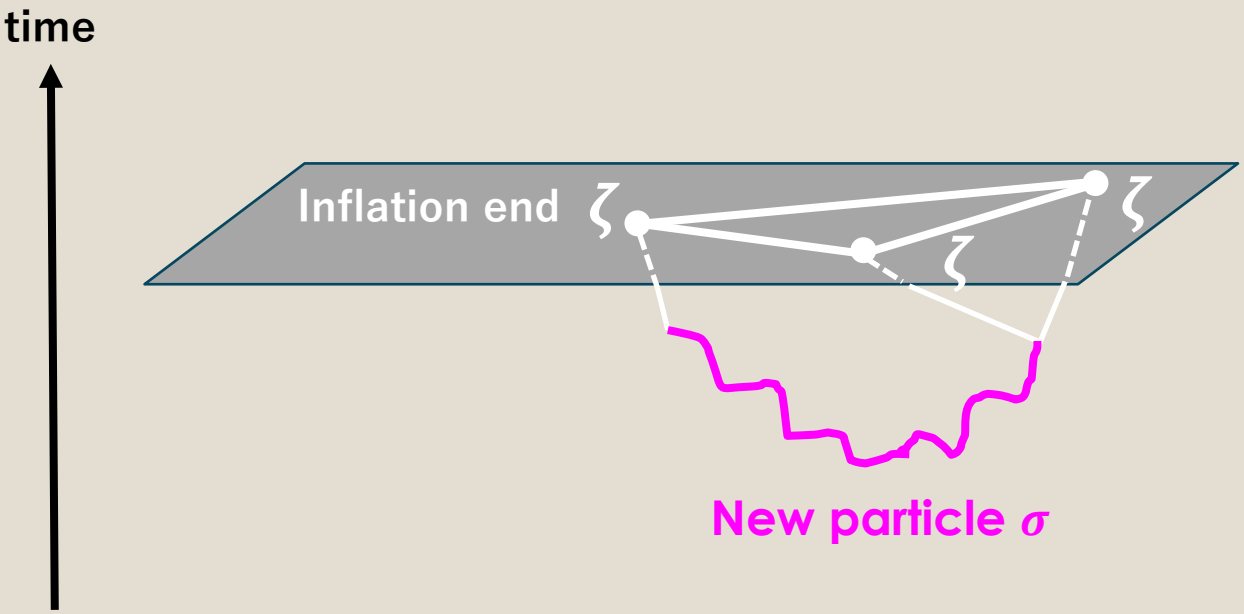
Summary

- Cosmological collider can probe high-energy physics (mass, spin, couplings of heavy fields)

- Full analytic expressions of correlators
  - Differential equation technique
  - Double exchange ⇒ Specific signal which cannot be mimicked by single exchange

- Many things to do:
  - Precision
  - Application to BSM
  - Observation

Thank you!!


time
Inflation end
ζ
ζ
ζ
New particle σ