Cosmological Collider Physics: 基礎と最近の進展

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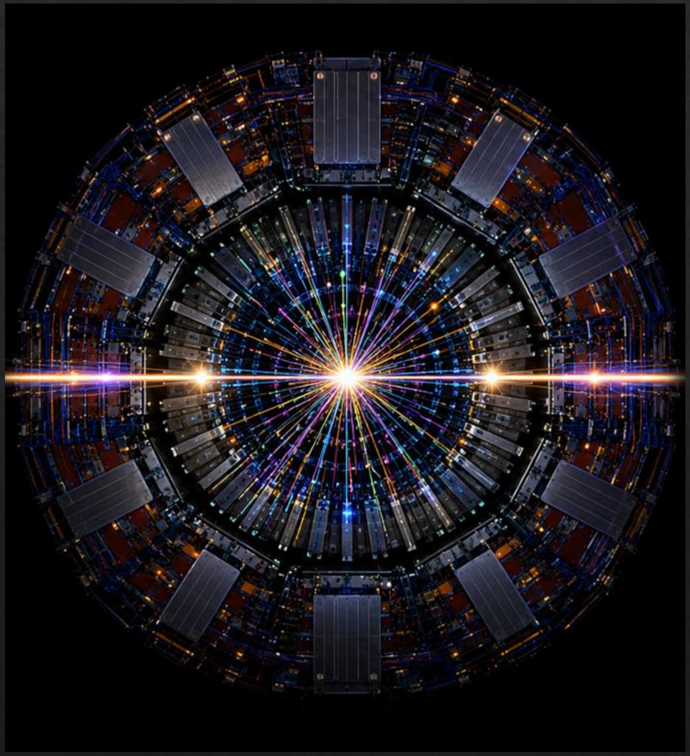
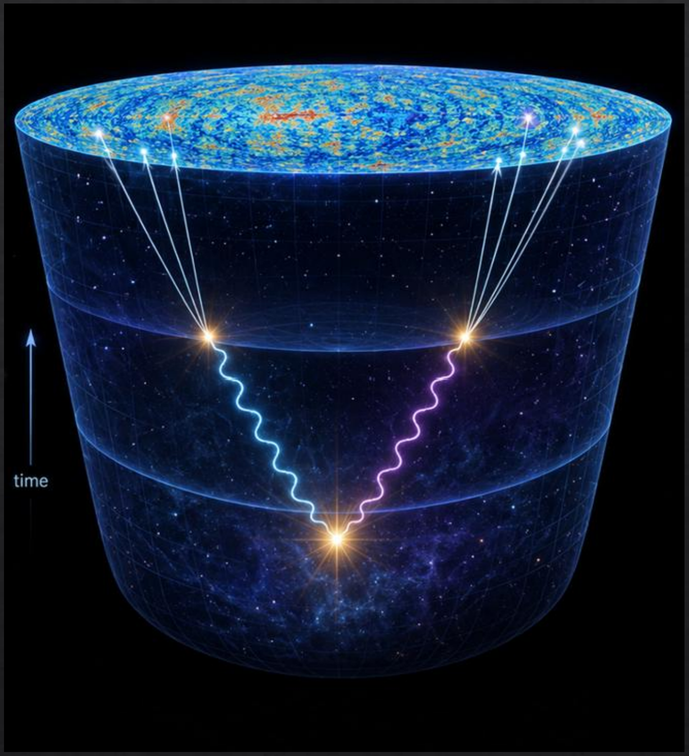
What is “Cosmological Collider”?

Particle collider

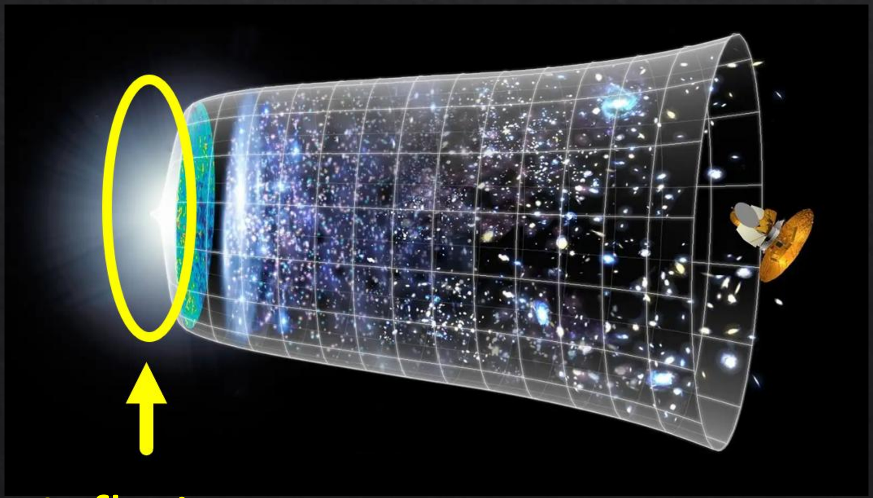


Cosmological collider

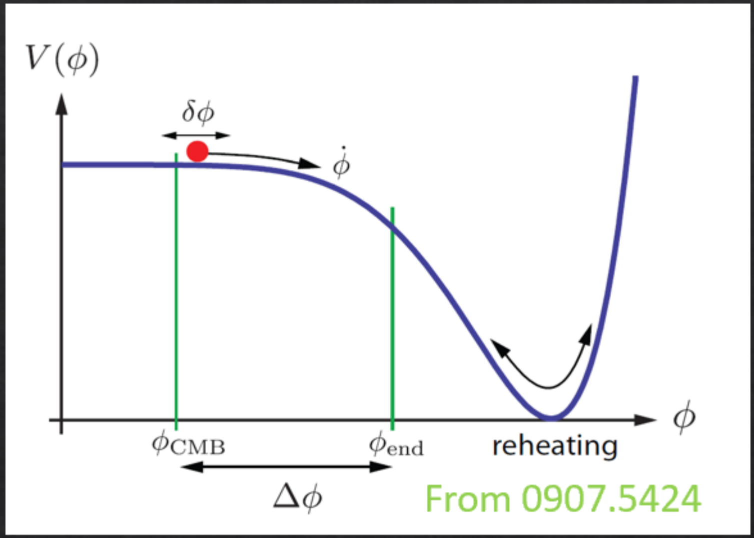


Inflation in One Slide

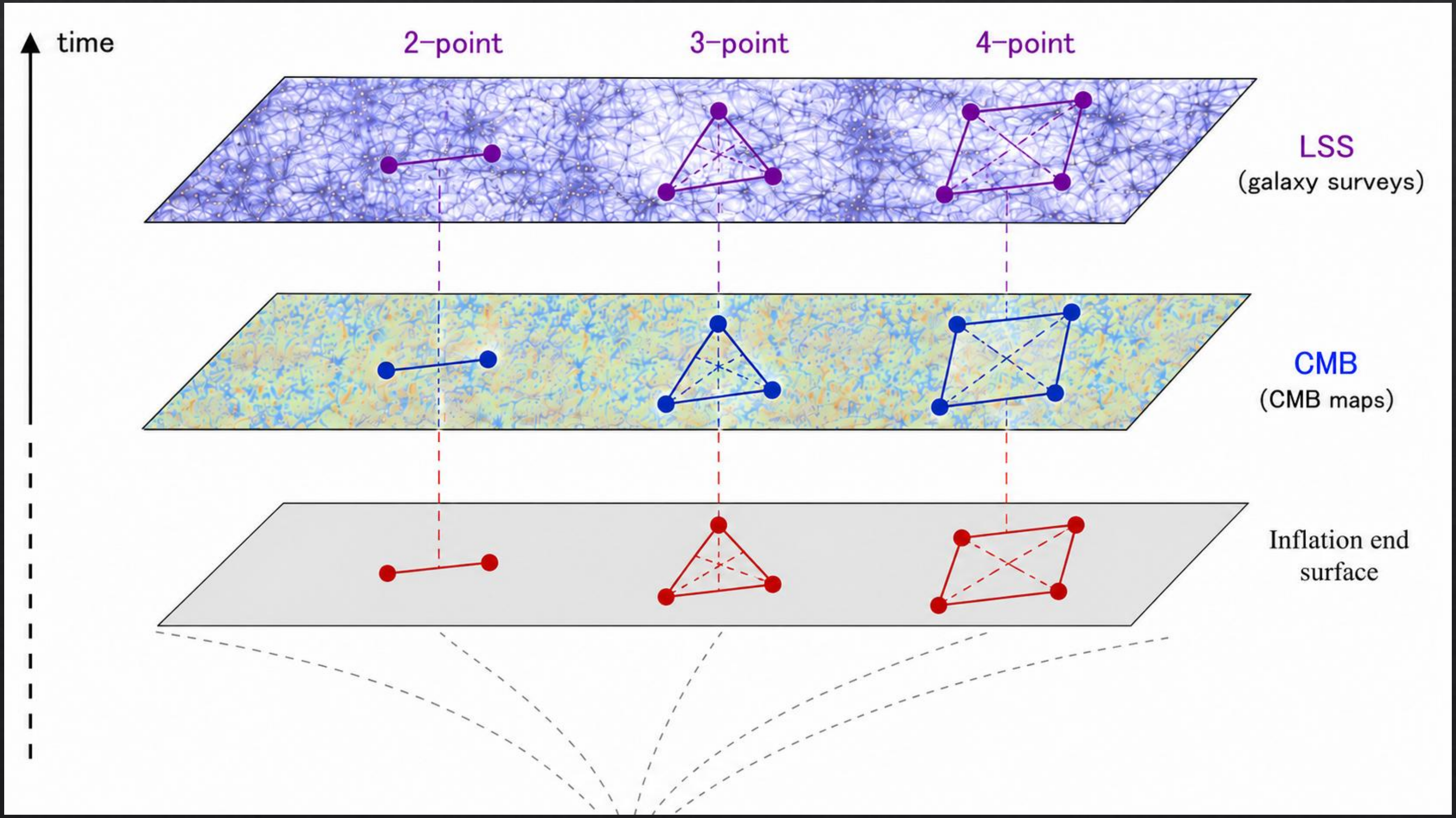
- Accelerated expansion driven by a slowly rolling scalar field ϕ
- Generates primordial fluctuations $\zeta \sim \delta\phi$ (scalar) & γ (tensor)



Inflation



Cosmological correlators as observables



$\delta\rho$

δT

$\delta\phi \sim \zeta$

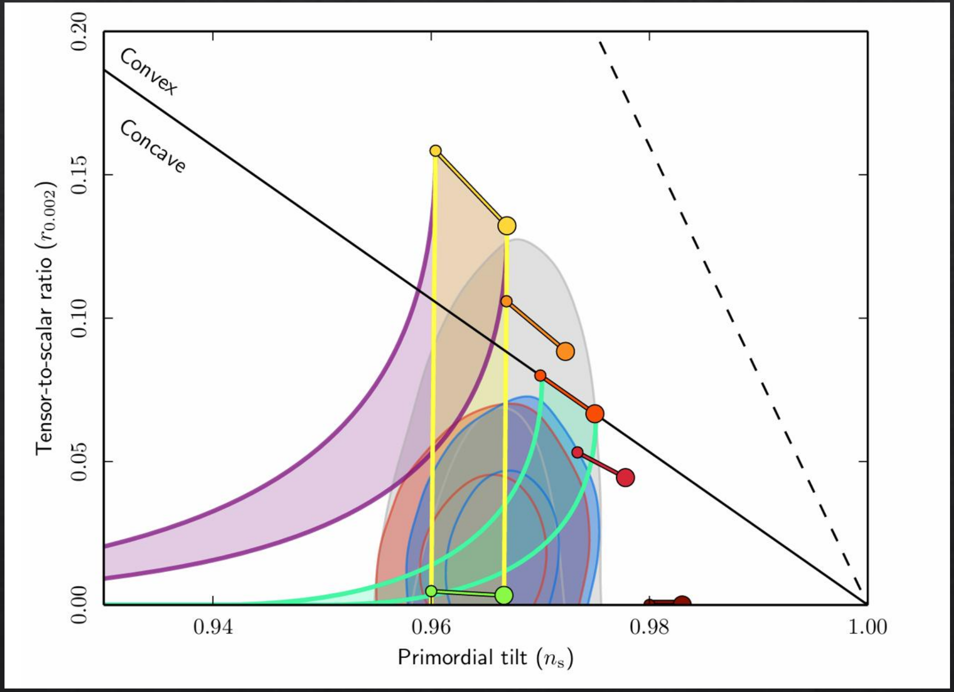
What Do Two-Point Functions Tell Us?

$$\langle \zeta\zeta \rangle \rightarrow A_s, n_s$$

scalar amplitude & tilt

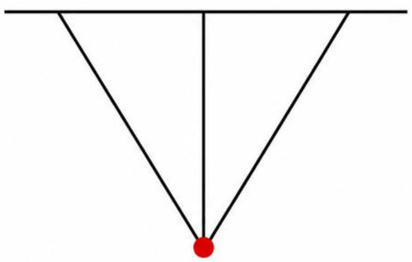
$$\langle \gamma\gamma \rangle \rightarrow r, H_{\text{inf}}$$

tensor amplitude & inflation scale



Higher point = non-Gaussianity

- inflaton self-interactions give only minimal NG



inflaton contact interaction

$$f_{\mathrm{NL}} \sim \mathcal{O}(\epsilon)$$

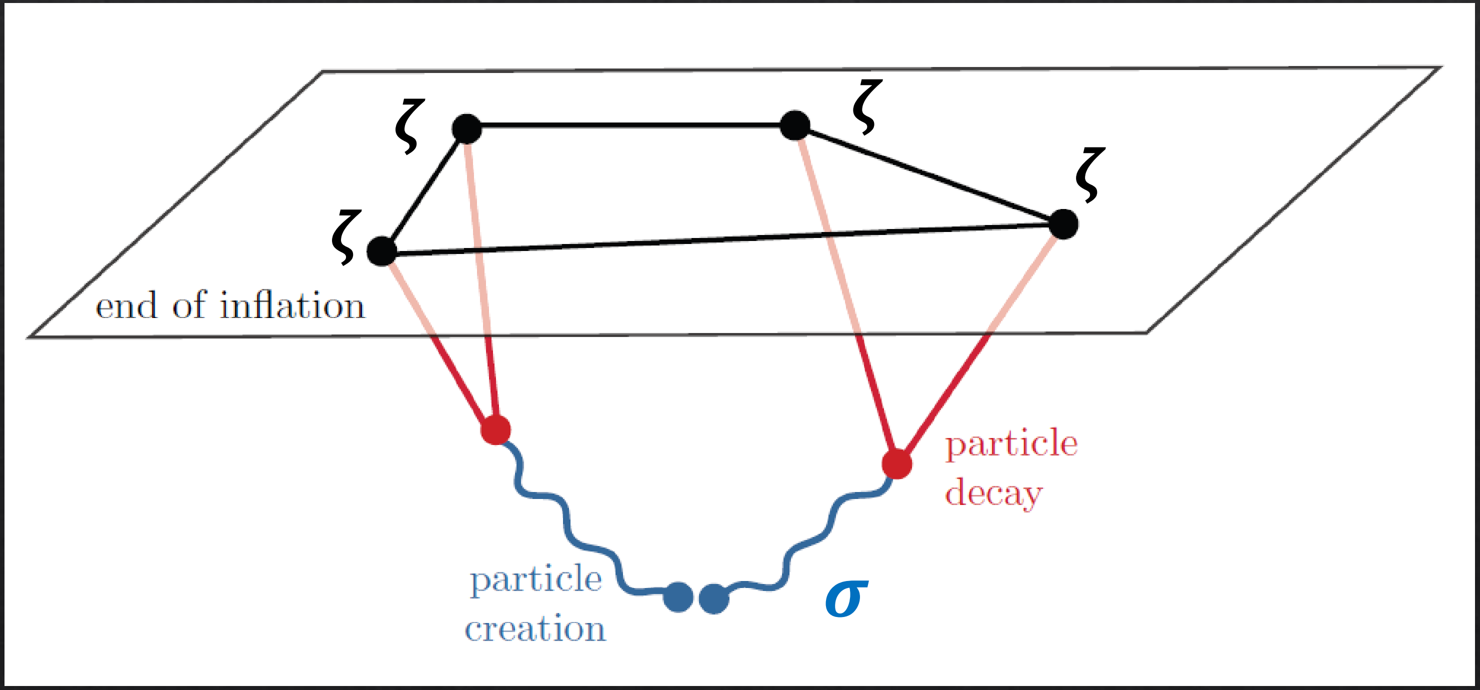
slow-roll suppressed

Maldacena'03

- Large NG is possible beyond the minimal setup
  - ➢ Higher-derivative interactions
  - ➢ Excited initial states
  - ➢ Additional fields

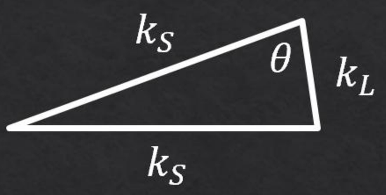
Correlators with massive particles

Cosmic expansion creates σ with mass $\sim H$



Characteristic feature in squeezed limit

Cosmological Collider Signal



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

Boltzmann factor

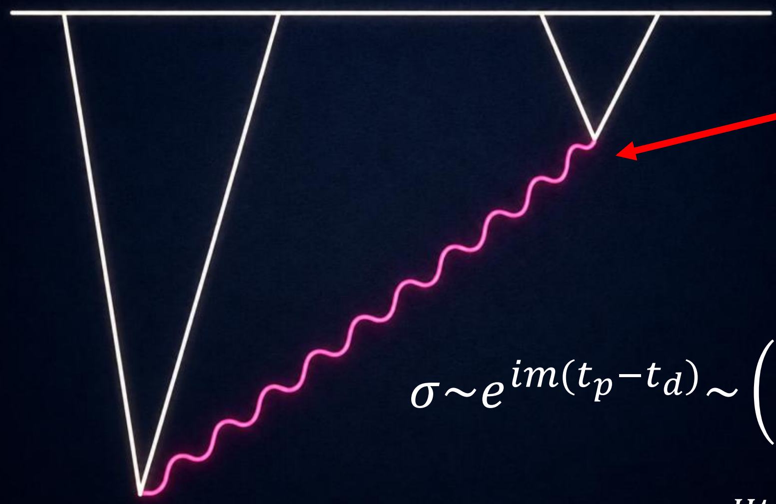
dilution

$\mu \sim \frac{m_\sigma}{H}$: **mass**

spin

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

Why oscillation??



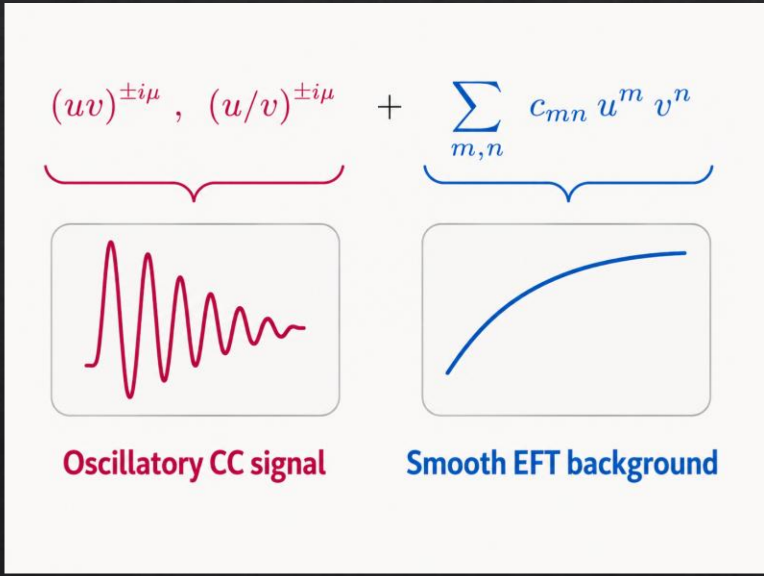
Resonant decay
$k_d/a_d \sim m$

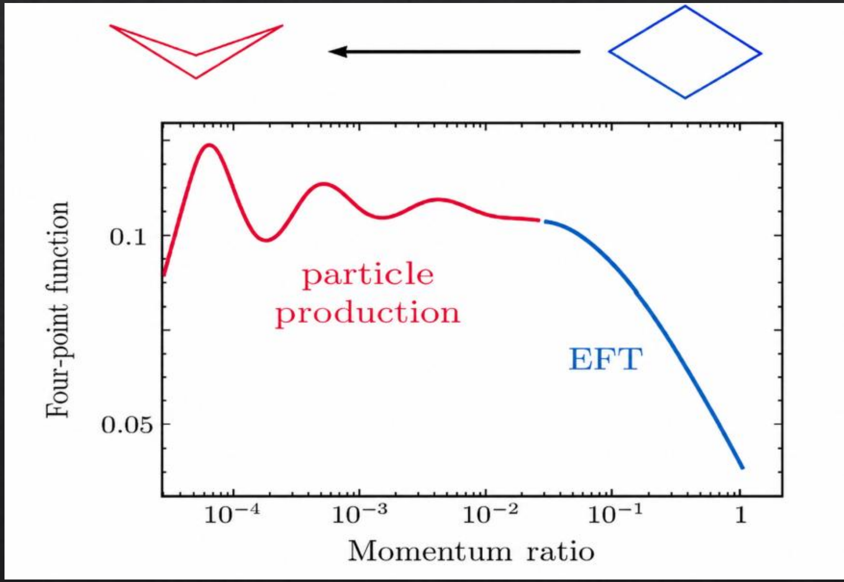
$$\sigma \sim e^{im(t_p - t_d)} \sim \left(\frac{a_d}{a_p}\right)^{im/H} \sim \left(\frac{k_d}{k_p}\right)^{im/H}$$

$a = e^{Ht}$ in dS

Resonant production
$k_p/a_p \sim m$

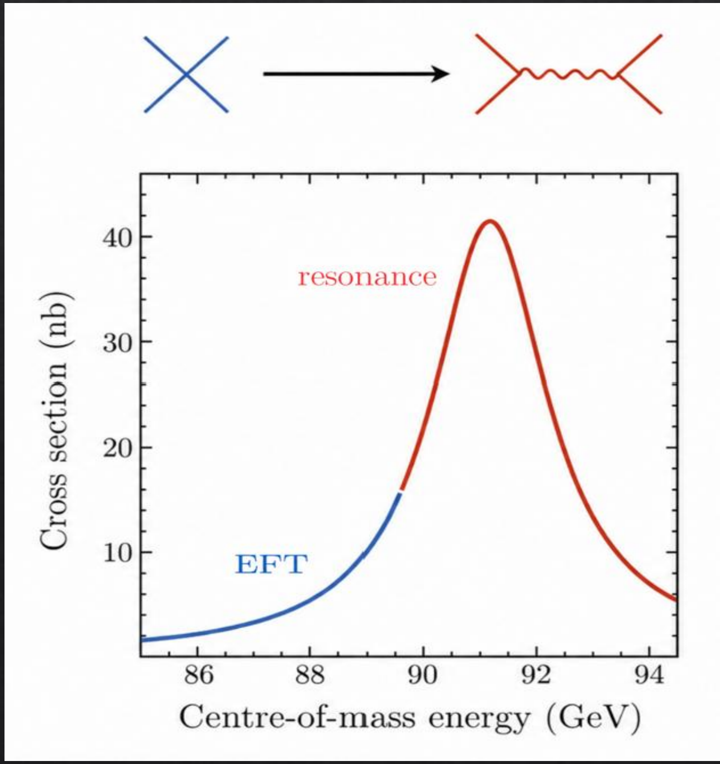
Non-analytic Signal vs Analytic Background



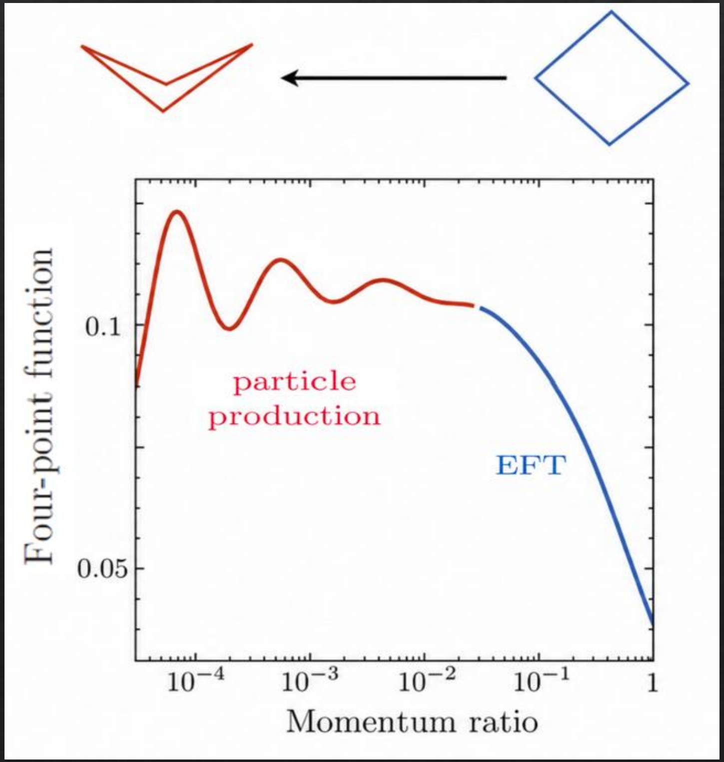


Particle Collider vs Cosmological Collider

Scattering cross section



Cosmological correlator



Same Physics, Different Observables

Similarities

- **Particle spectroscopy:** mass, spin, couplings
- **Intermediate particle propagation** beyond łocal EFT

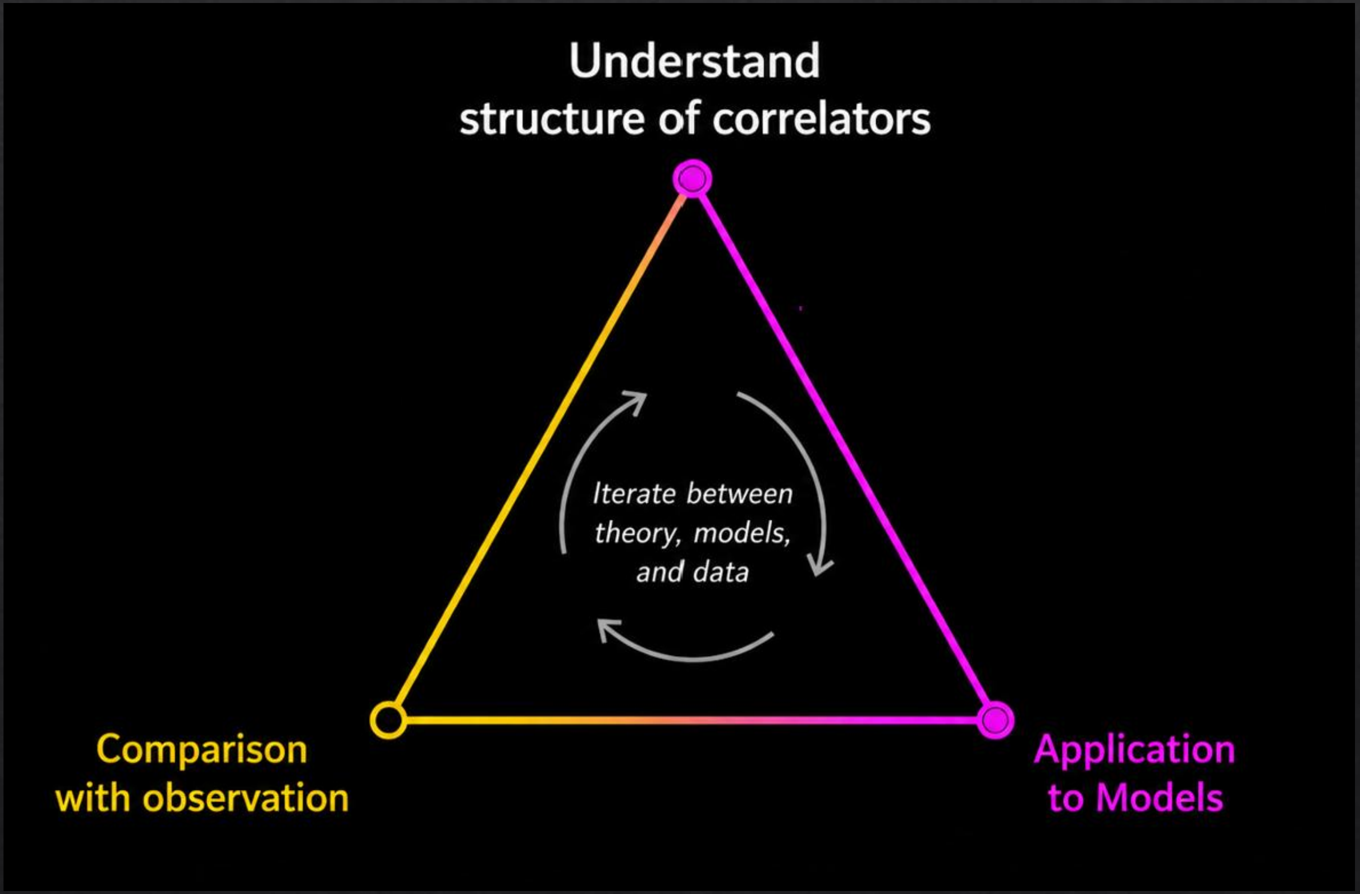
Differences

- **Observable:** cross sections vs primordial correlators
- **Signal:** poles / thresholds vs non-analytic momentum dependence

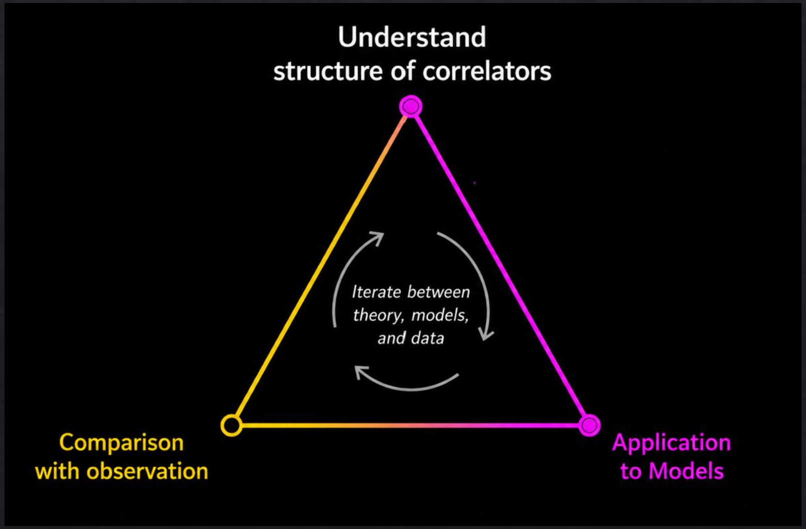
A unique energy frontier

Inflation may open a window to particle physics far beyond terrestrial collider energies

Three directions



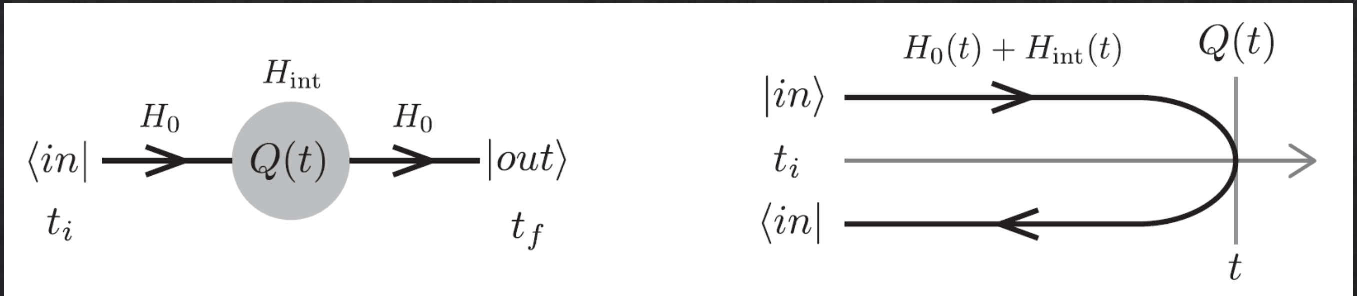
Structure of Correlators



Challenges

- No energy conservation → must perform (nested) time integral

in-out (S-matrix) in-in (Correlator)

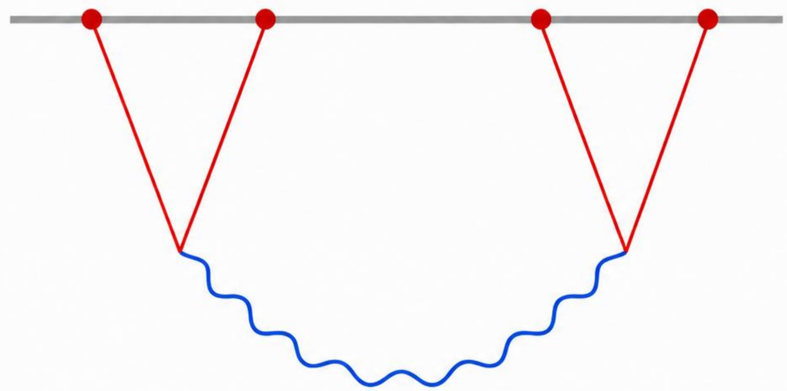


Baumann, Lectures on The Cosmological Bootstrap

- de Sitter makes mode functions complicated

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

$F =$



$$-g^2 \int_{-\infty}^{0} \frac{\mathrm{d}\eta}{\eta^2} \int_{-\infty}^{0} \frac{\mathrm{d}\eta'}{\eta'^2} \; e^{i(k_1+k_2)\eta} \; e^{i(k_3+k_4)\eta'} \; G(|\mathbf{k}_1 + \mathbf{k}_2|, \eta, \eta') \, .$$

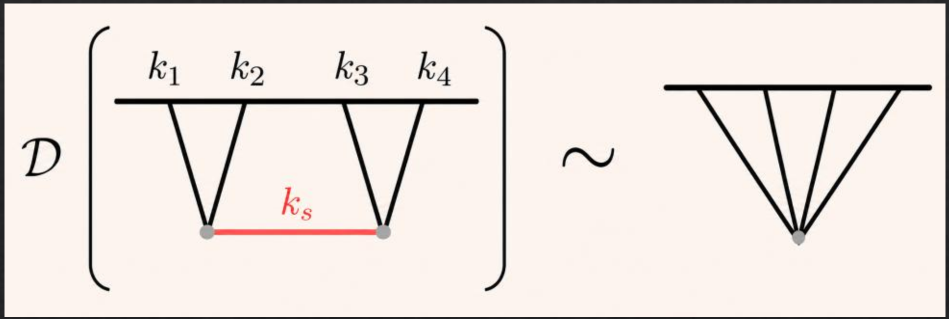
External line for inflaton

Propagator of σ (complicated function)

From Time Integrals to Differential Equations

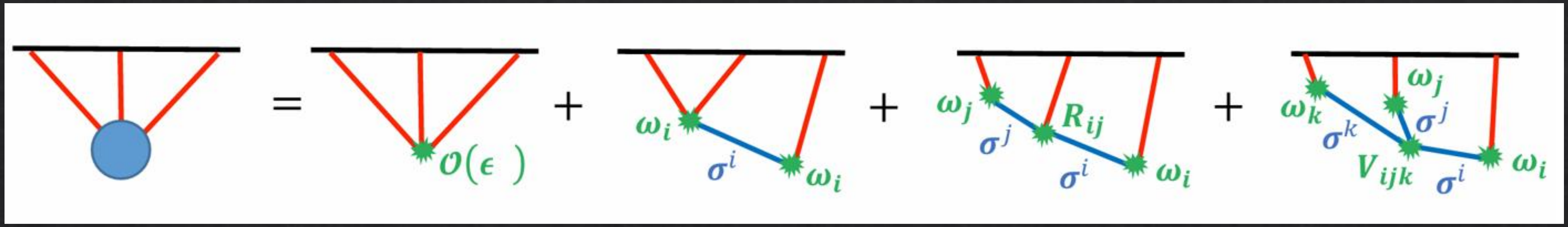
Arkani-Hamed, Maldacena, 1503.08043

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



$$\mathcal{D}_u \equiv u^2\left(1-u^2\right)\partial_u^2 - 2u^3\partial_u + \mu^2 + \frac{1}{4}$$

Beyond Single Exchange



contact — Maldacena '03

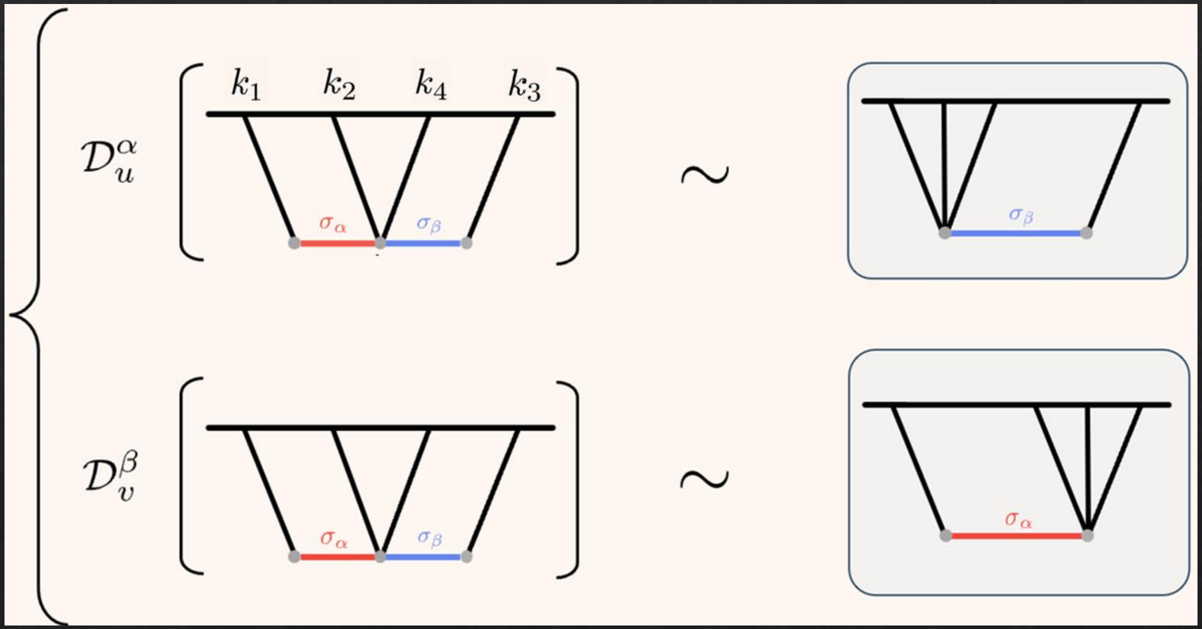
single exchange — Arkani-Hamed et al 1811.00024

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

triple

Double Exchange: Coupled Differential Equation

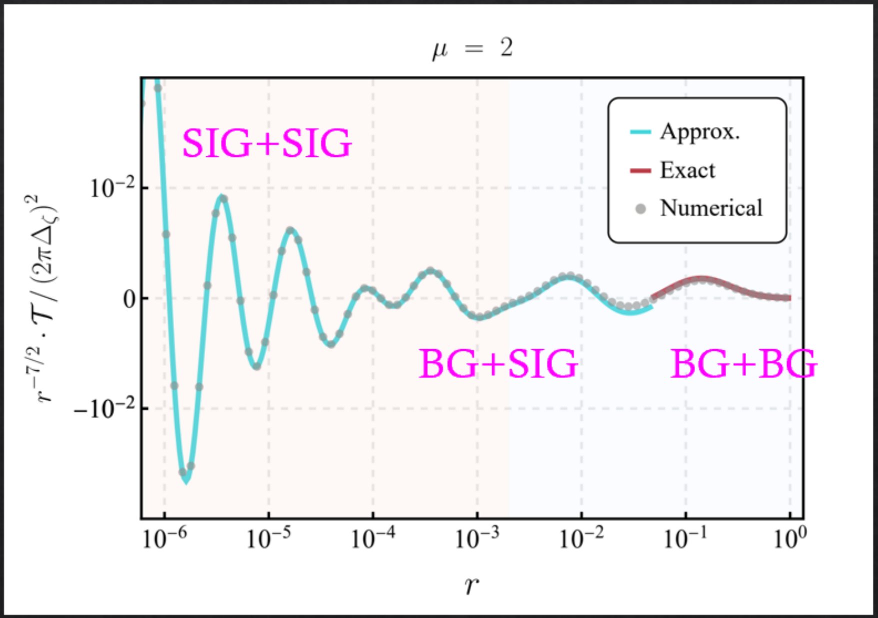
SA, L. Pinol, F. Sano, M. Yamaguchi, Y. Zhu, 2404.09547



- Result: Exact analytic solution based on Appell $F_4(u^2, v^2)$

$$u \equiv \frac{k_1}{k_2+k_4}, \; v \equiv \frac{k_3}{k_2+k_4}$$

Phenomenological Implications

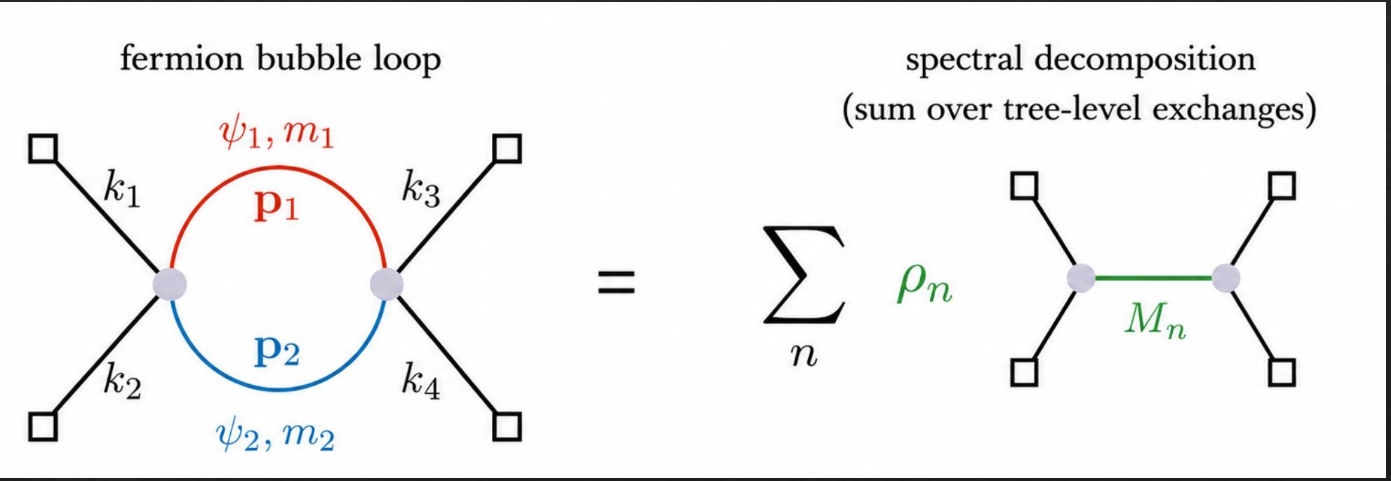


- Double-soft trispectrum: frequency transition: $\mu \to 2\mu$
- Cannot be mimicked by single exchange

Beyond Tree Level

- Exact analytic formula for fermion bubble loop signals

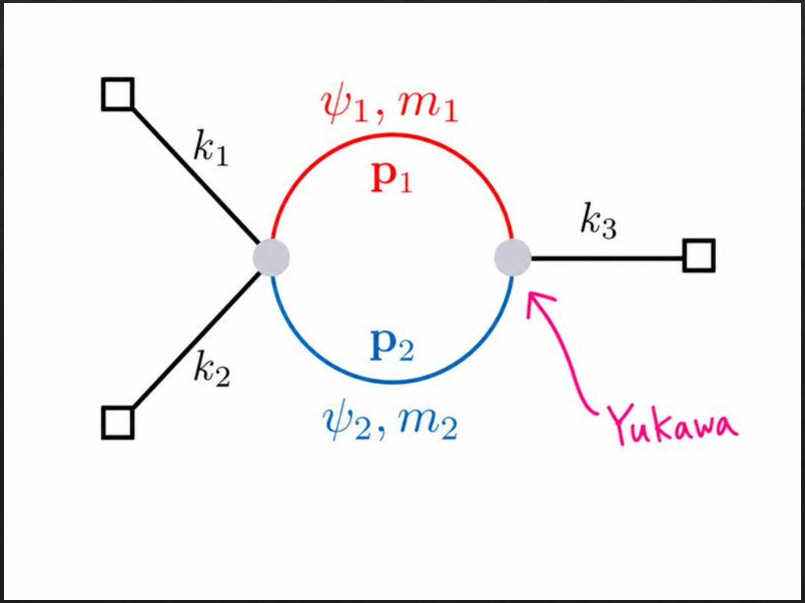
SA, Z. Qin, M. Yamaguchi, Y. Zhu, 2605.28054



Beyond Tree Level

- Surprising result: no oscillatory signal for the Yukawa bubble

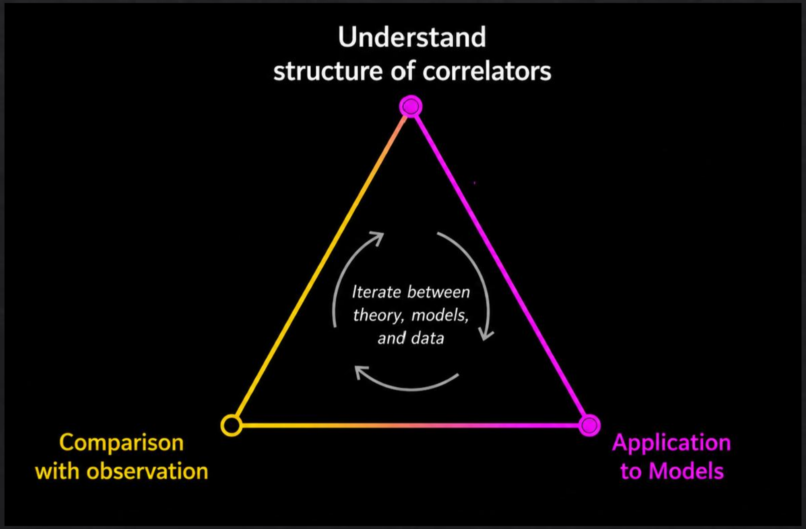
$$f_{\mathrm{NL}}^{\mathrm{osc}}\Big|_{\text{Yukawa bubble}} = 0$$



My Perspective

- Multiple exchanges and loops are becoming analytically tractable
- It is time to revisit earlier model predictions beyond rough estimates

Application to particle physics models



Main Obstacle: Boltzmann Suppression

$$e^{-\pi\mu} \text{ with } \mu = \sqrt{\frac{m_\sigma^2}{H^2} - \frac{9}{4}} \simeq \frac{m_\sigma}{H}$$

the oscillatory signal is exponentially suppressed

Question : How can we evade this suppression?

Chemical Potential

inflaton rolling background → chemical potential

$$\partial_\mu \phi \, J^\mu / \Lambda \;\rightarrow \kappa \, N \quad \text{where } \kappa \equiv \dot{\phi}/\Lambda$$

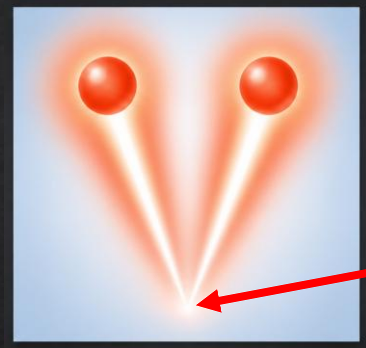
Sou, Tong, Wang, 2104.08772

Chemical Potential Enhancement

κ can exceed H (up to $\sim 60H$)→ enhanced particle production

Standard case

$\sim e^{-\pi m/H}$



$\kappa \sim \dot{\phi} > H$

with chemical potential

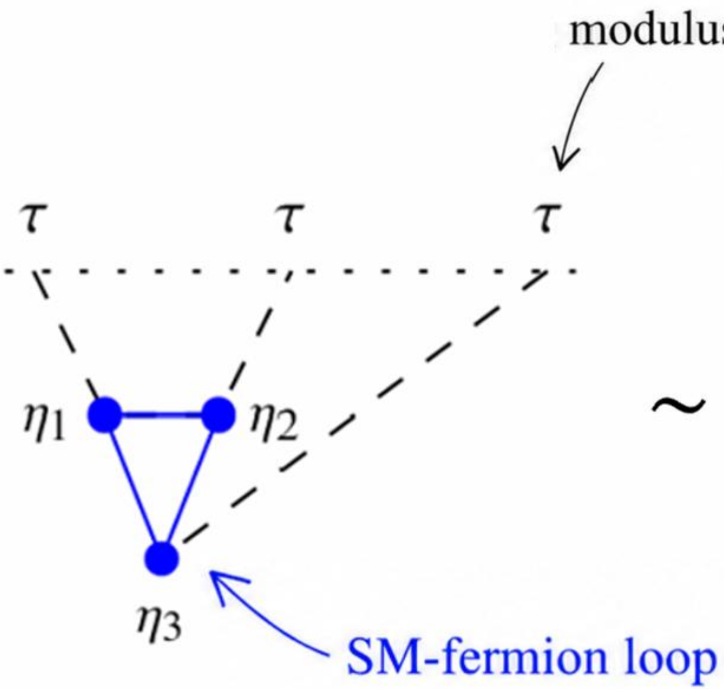
$$\sim \begin{cases} e^{-\pi(m-\kappa)/H} & \text{(boson)} \\ e^{-\pi m^2/\kappa H} & \text{(fermion)} \end{cases}$$

Examples with Chemical Potentials

• Gauge bosons	$-\phi F\widetilde{F}/(4\Lambda)$	Wang, Xianyu, 2004.02887
• Massive spin-2	$\frac{1}{4\Lambda^3}\,\phi\, W_{\mu\nu\rho\sigma}\widetilde{W}^{\mu\nu\rho\sigma}$	Tong, Xianyu, 2203.06349
• Neutrinos	$\frac{1}{\Lambda}\,(\partial_\mu\phi)\;\bar{\Psi}\;\gamma^5\gamma^\mu\Psi$	Chen, Wang, Xianyu, 1805.02656
• Our example: SM fermions + rolling modulus τ	$\frac{\partial_\mu\tau}{\Lambda}\;J^\mu_{\rm SM}$	SA, Strumia, 2604.05548

Cosmological collider signal from SM fermions

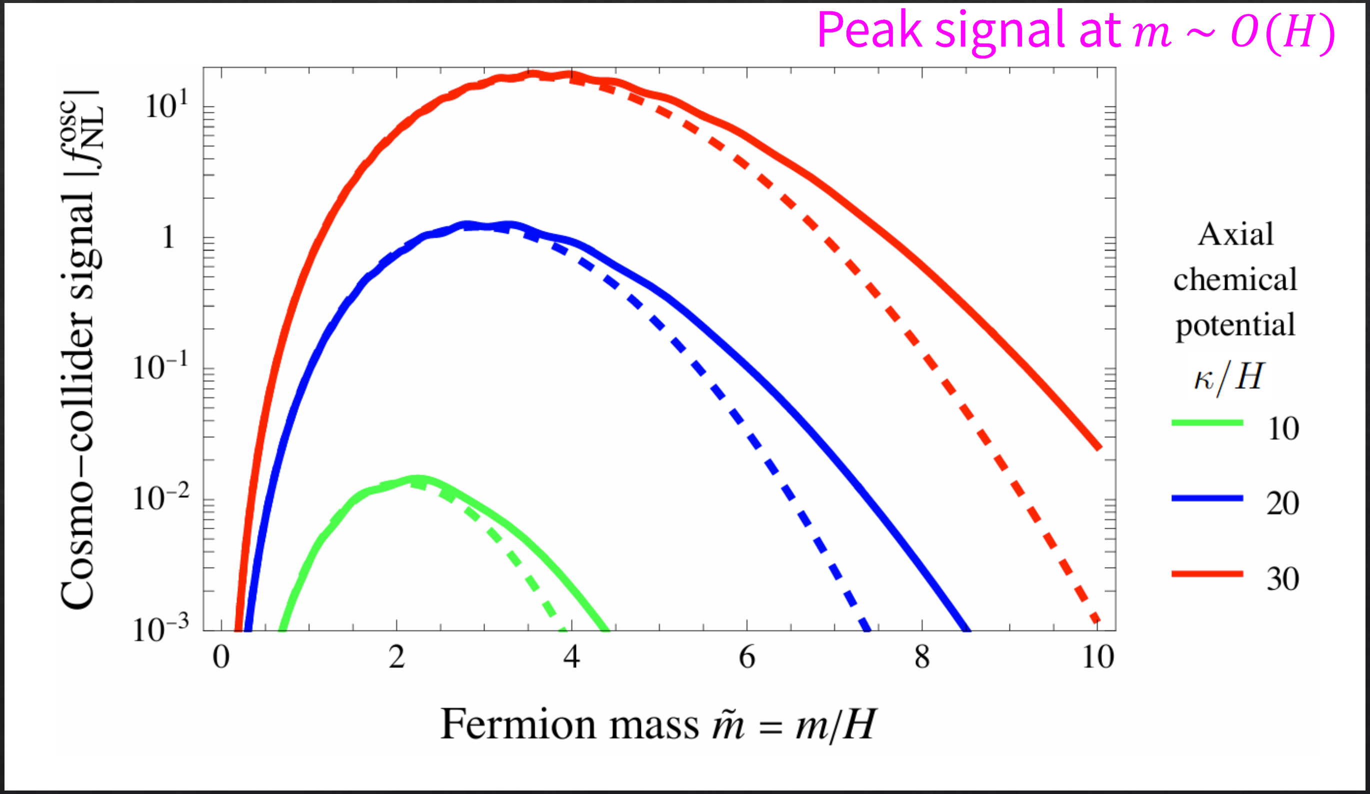
Modular symmetry ⇒ chemical potentials & Hubble-scale masses for SM fermions



$$\sim \quad f_{\rm NL}^{\rm osc}\left(\frac{k_L}{k_S}\right)^{2+2i\lambda} + \text{ h.c.}$$

$$\lambda \equiv \sqrt{\tilde{m}^2+\tilde{\kappa}^2}$$

Order-of-Magnitude Estimate

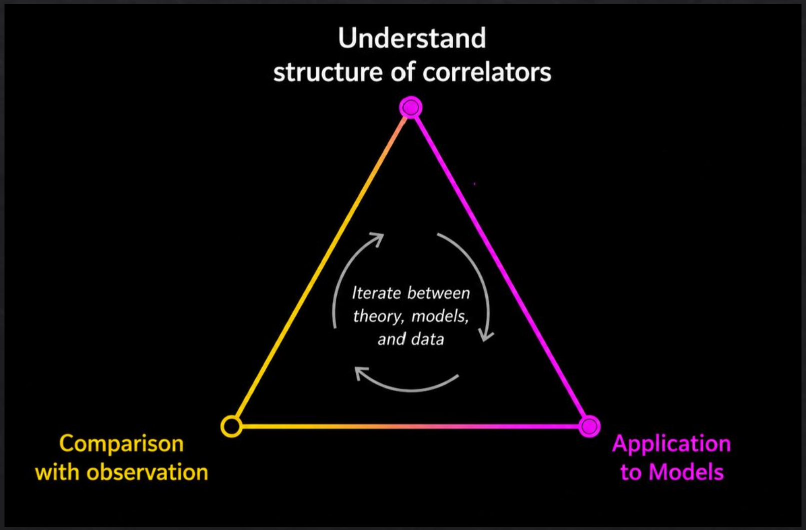


The final size is still under investigation …

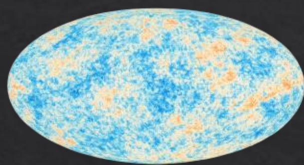
My Perspective

- It is too early to conclude that cosmological collider signals are necessarily unobservable: Chemical potentials offer a promising route

Comment on observation



Observational Searches for Cosmological Collider Signals



CMB (Planck)

- **2024** **arXiv:2404.07203** — first broad Planck bispectrum search
- **2025** **arXiv:2502.06931** — Planck trispectrum constraints
- **2025** **arXiv:2511.19179** — arbitrary / strong-mixing bispectra
- **2026** **arXiv:2603.15728** — beyond-Hubble-scale search
- **2026** **arXiv:2603.17004** — reconstructed-shape analysis
- **2026** **arXiv:2603.13486** — unparticle search
- **2026** **arXiv:2604.07434** — full scalar tree-level shapes
- **2026** **arXiv:2607.02651** — KK graviton / radion
- **2026** **arXiv:2607.18369** — full scalar collider likelihood

LSS (BOSS / DESI era)

- **2024** **arXiv:2404.01894** — dedicated cosmological-collider search with BOSS
- **2024** **arXiv:2401.09523** — reassessment of parity signal
- **2026** **arXiv:2602.12232** — new scaling regimes from BOSS
- **2026** **arXiv:2604.06021** — parity tests with BOSS + DESI

Dedicated searches for cosmological-collider signatures have rapidly developed since 2024!

Summary

Cosmological correlators offer a unique window into high-energy particle physics during inflation.

1. Structure: new analytic tools are advancing

Analytic control now extends to multiple exchanges and loops, making earlier model predictions worth revisiting.

2. Models: rich possibilities, still underexplored

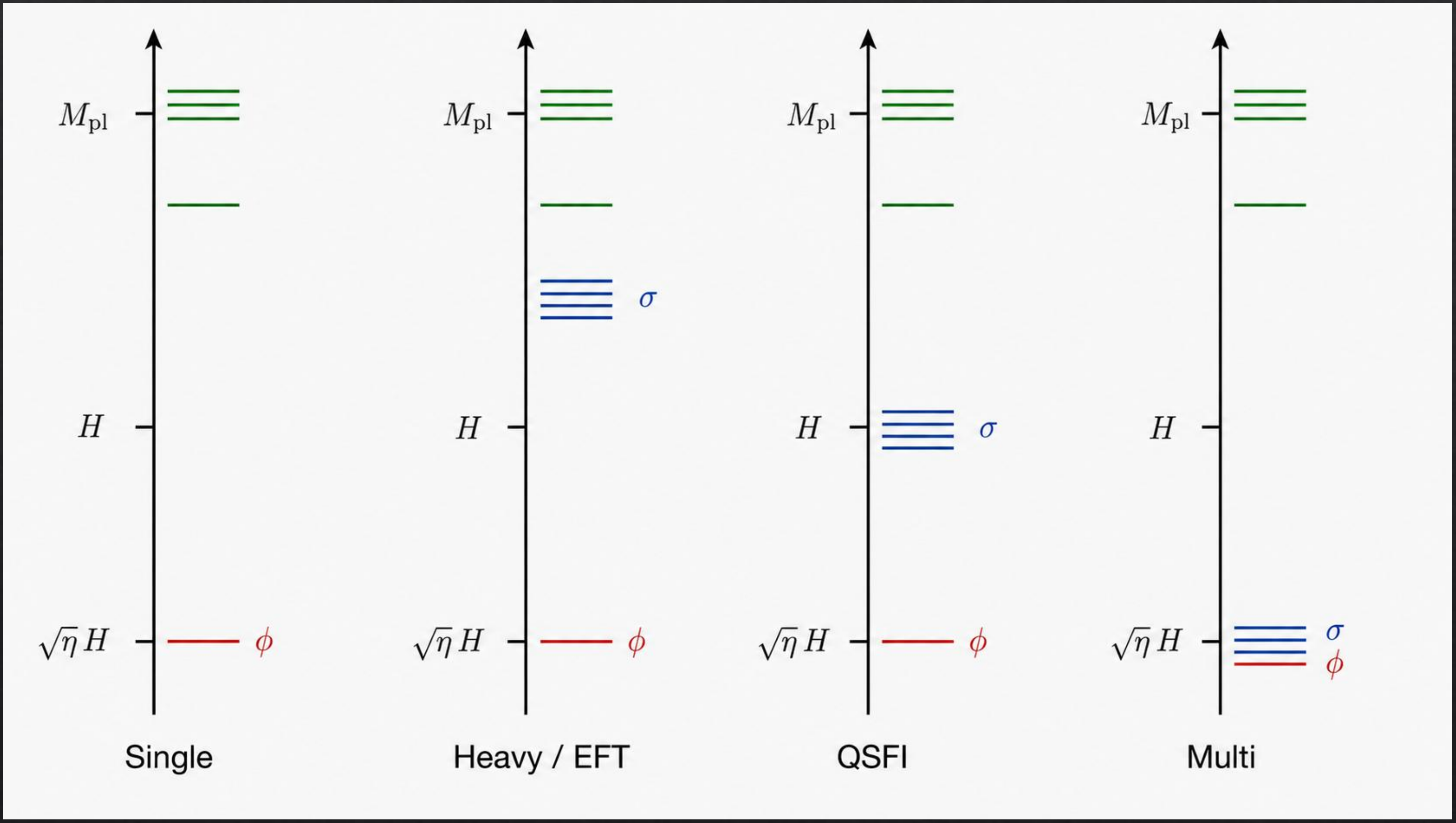
Chemical potentials are promising.
Many models remain to be explored.

3. Observation: dedicated searches have only recently begun

CMB (Planck) and LSS (BOSS/DESI) analyses using collider templates have started in 2024–2026.

Thank you!

Field Spectrum During Inflation



Maldacena

equilateral

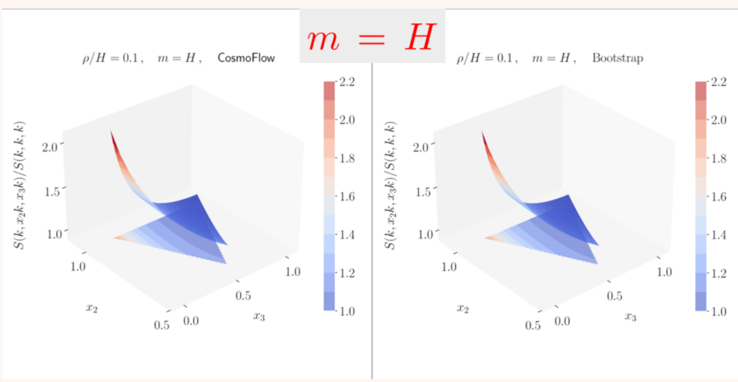
Intermediate
Cosmo-Collider

local

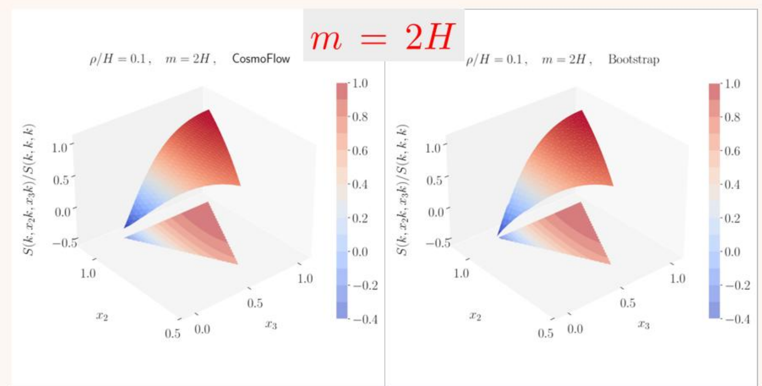
Bispectrum Shapes

Different mechanisms leave different momentum-space shapes

vs Numeric



∼ Local



∼ equilateral

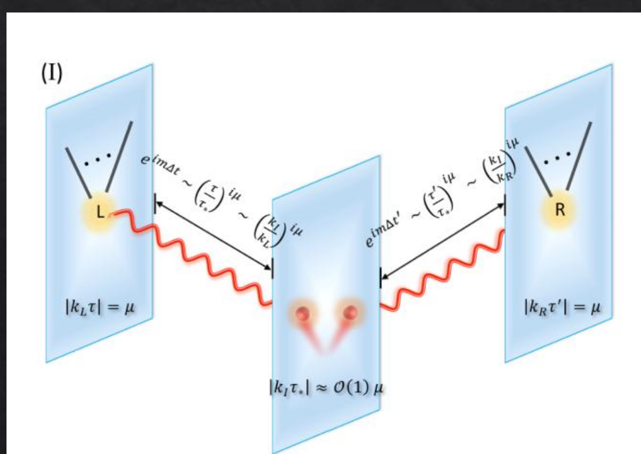
Local vs Non local signal

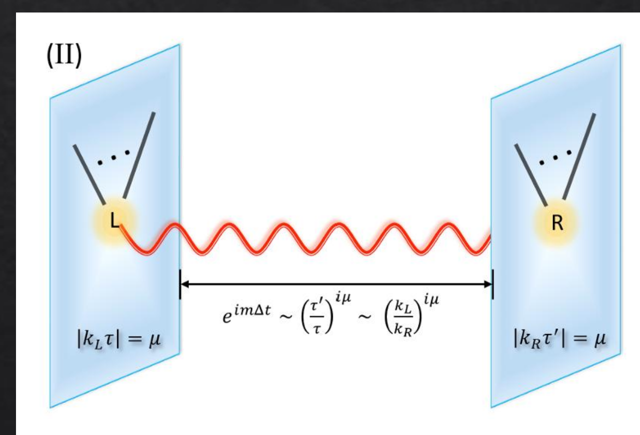
Non-local signal

- gravitational pair production
- $(uv)^{\,i\mu}$
- nonanalytic in k_s
- long-range in position space

local signal

- resonant production at a vertex
- $(u/v)^{\,i\mu}$
- analytic in k_s
- local in exchanged spatial separation





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