Extending the Reach of the Cosmological Collider

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New York University

Fundamental Physics from Future Spectroscopic Surveys
LBL, May 2024

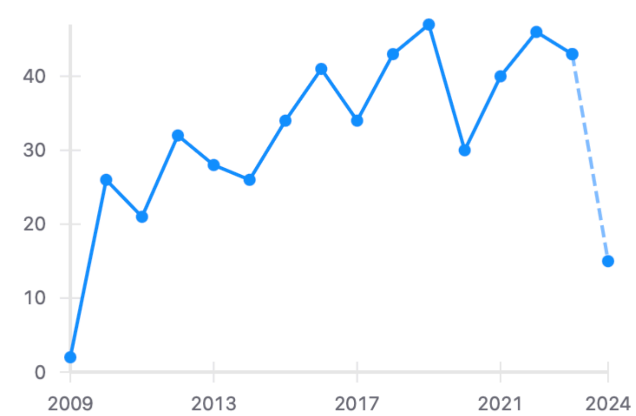
Cosmological Collider

Quasi-Single Field Inflation and Non-Gaussianities

Xingang Chen (Cambridge U., DAMTP and MIT), Yi Wang (McGill U. and Beijing, KITPC)

Nov, 2009

Citations per year



Cosmological Collider Physics

Nima Arkani-Hamed (Princeton, Inst. Advanced Study), Juan Maldacena (Princeton, Inst. Advanced Study)

Mar 27, 2015

Citations per year

A powerful on-shell probe of very high-energy physics

$$H \lesssim 5 \times 10^{13}\ \mathrm{GeV}$$

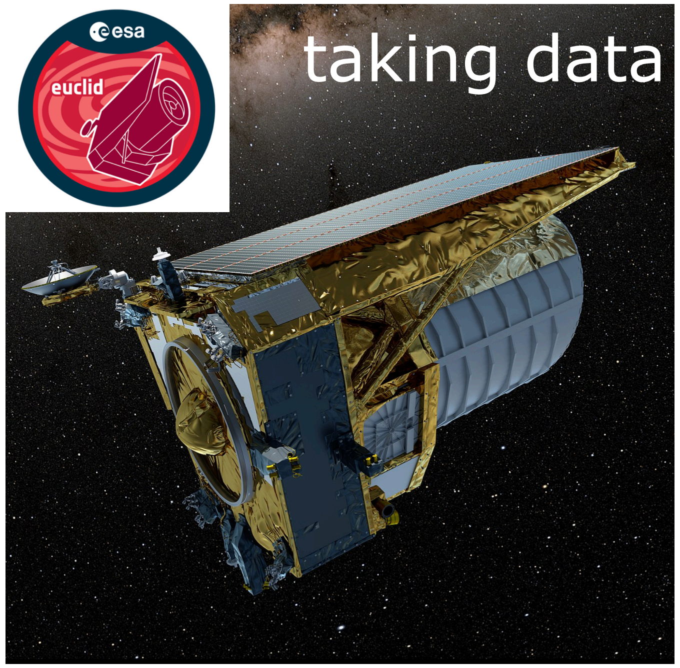
Test of: GUT, Neutrino mass, SUSY, Extra dimensions …

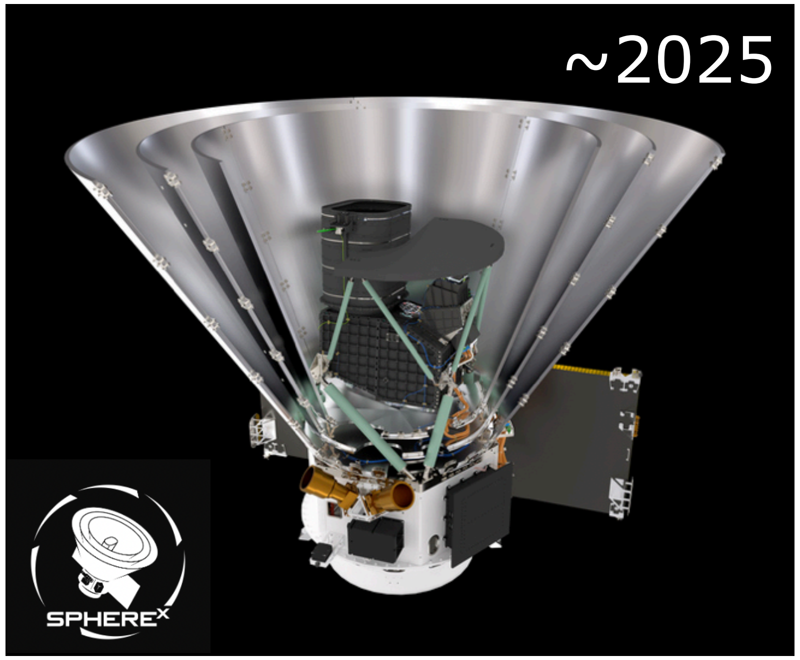
Playground for developing novel QFT tools

Amplitude techniques, Bootstrap, positivity bounds …

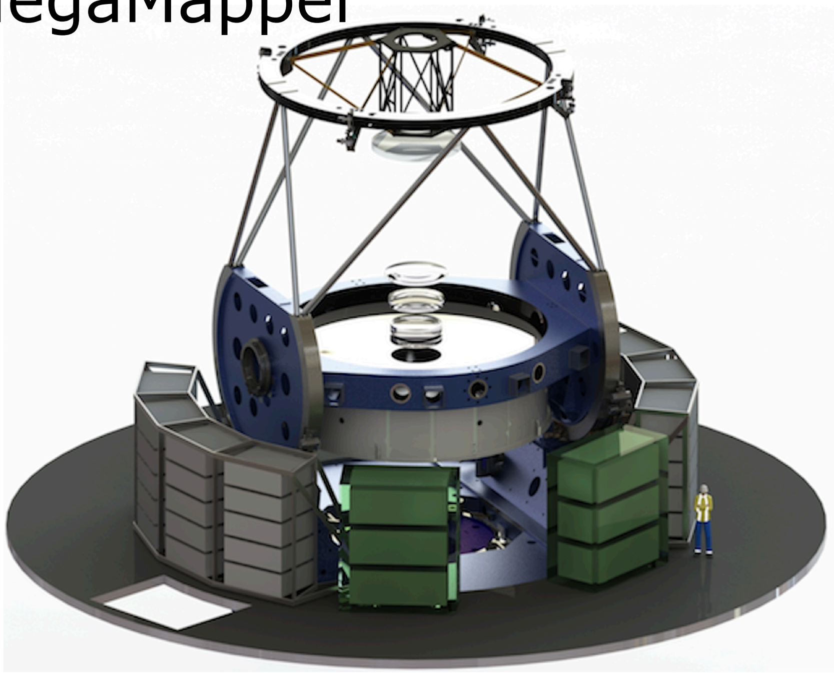
Cf. talks by Amara, Lingfeng, Priyesh, Samuel…

Observations coming soon!



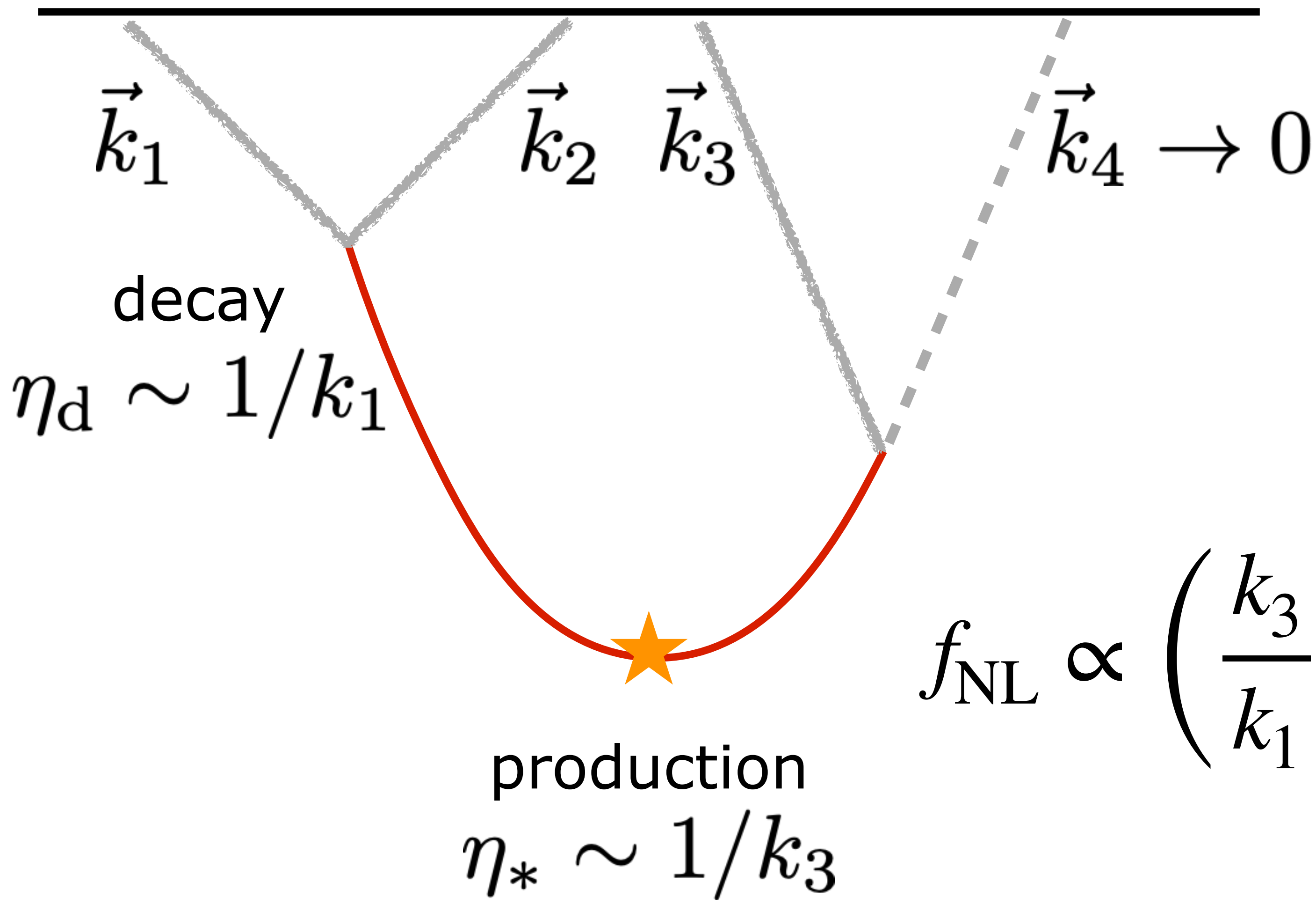


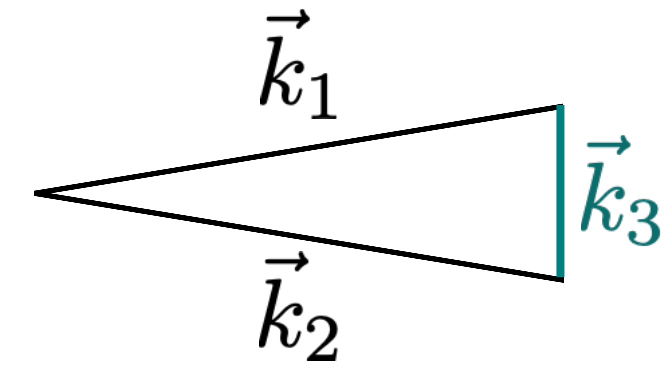
MegaMapper



This talk: how to use these to learn about ultra-high energy particle physics

Cosmological Collider





$k_3 \ll k_1, k_2$

mass

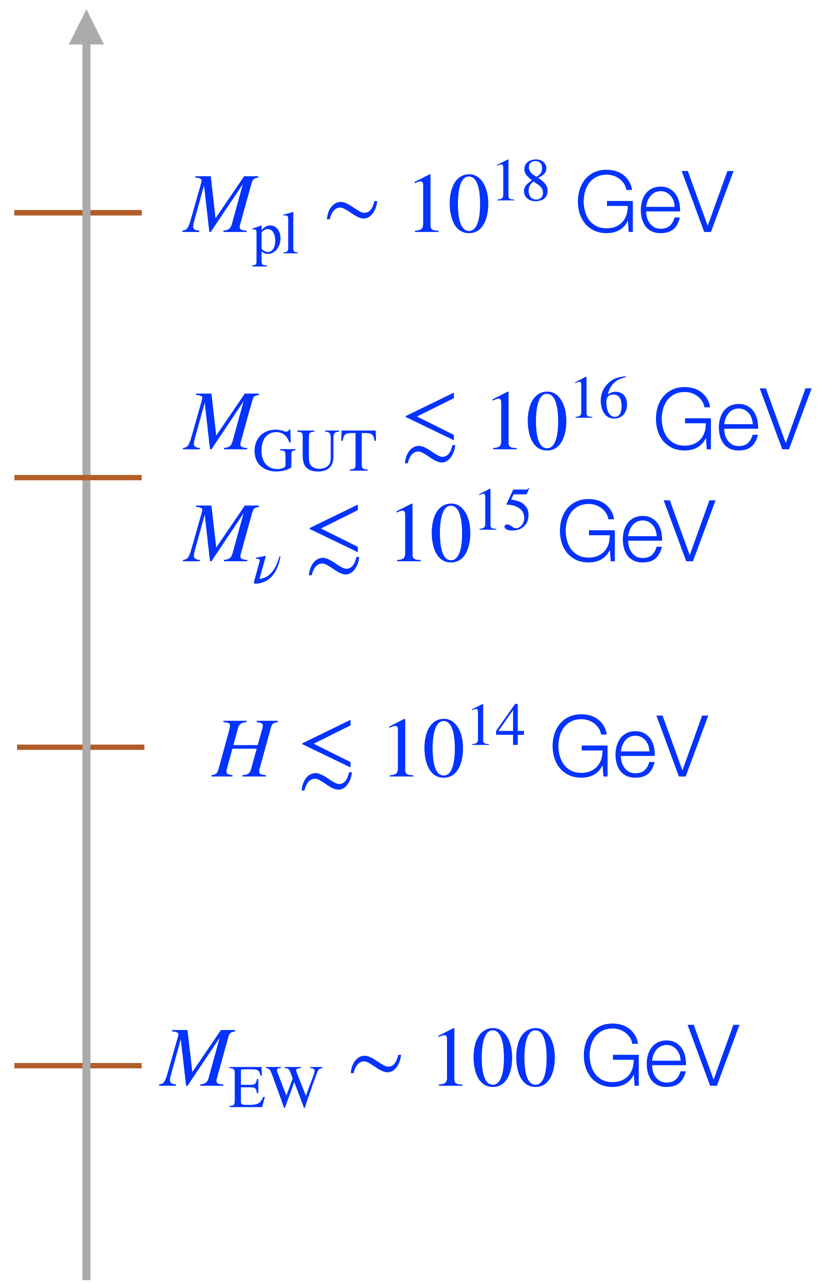
spin

$$f_{\rm NL} \propto \left(\frac{k_3}{k_1}\right)^{3/2} \cos\left(\mu \log\left(\frac{k_3}{k_1}\right)\right) f_s(\theta)$$

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}} \qquad \cos\theta = \hat{k}_1 \cdot \hat{k}_3$$

on-shell mass and spin information from bi/trispectrum!

What are the targets?

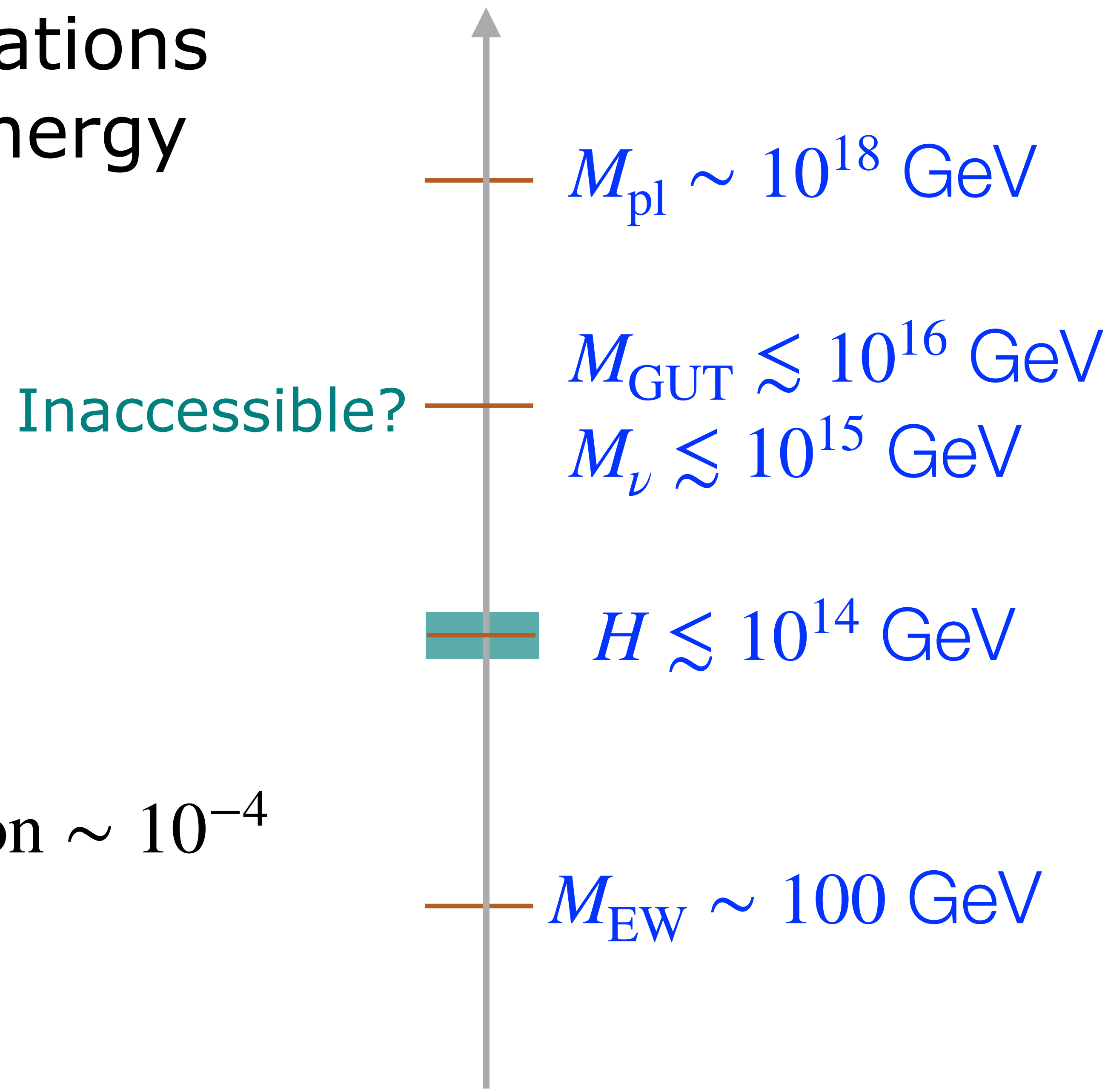


Particle physics scales

What are the targets?

$$f_{\rm NL} \sim \exp\left(-\frac{\pi m}{H}\right)\left(\frac{k_3}{k_1}\right)^{3/2} \cos\left(\frac{m}{H}\log\left(\frac{k_3}{k_1}\right)\right) f_s(\theta)$$

Quantum fluctuations
have H-scale energy

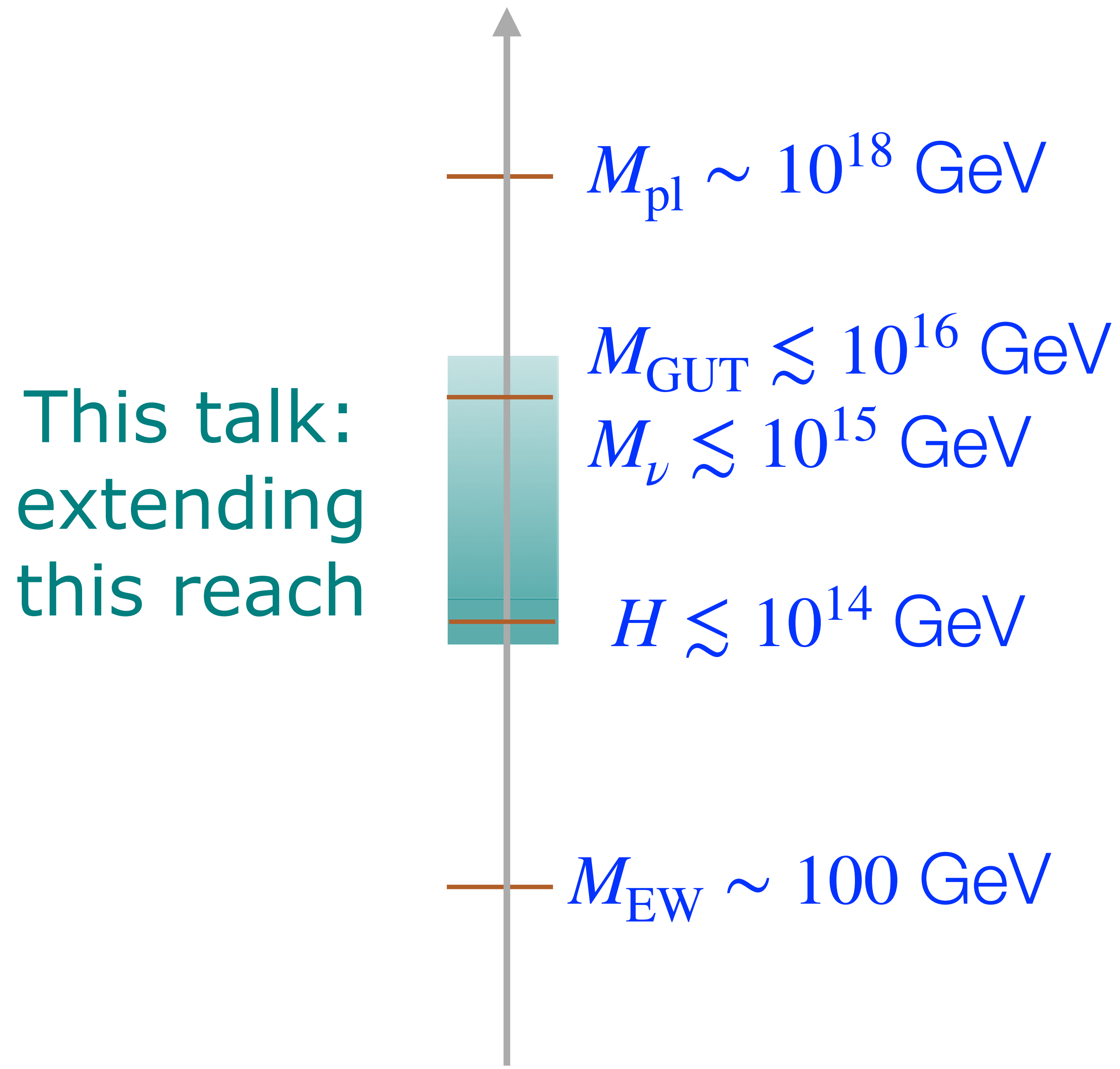


Bad news!

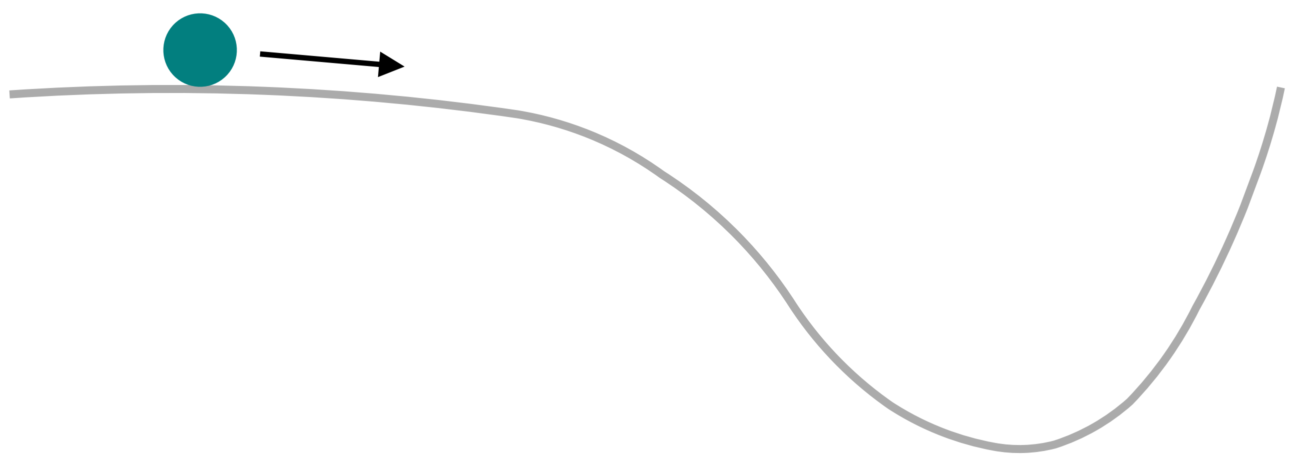
$m \simeq 3H \rightarrow$ suppression $\sim 10^{-4}$

What are the targets?

$$f_{\mathrm{NL}} \sim \exp\left(\frac{m}{H}\right)\left(\frac{k_3}{k_1}\right)^{3/2}\cos\left(\frac{m}{H}\log\left(\frac{k_3}{k_1}\right)\right)f_s(\theta)$$



More Scales



Cf. talks by Ben, Eva

Slowly rolling inflaton has kinetic energy

$$\mathcal{P}_\zeta \sim \frac{H^4}{\dot{\phi}_0^2}$$

$$\dot{\phi}_0 \sim (60H)^2 \gg H^2$$

Inflaton potential can have "features"

$$\omega_{\rm feature} \gg H$$

Coupling to Inflaton Velocity

Bodas, **S.K.**, Sundrum
2010.04727

Consider a complex scalar field, like a Higgs

$$\frac{1}{\Lambda}\partial_\mu \phi J^\mu \qquad\qquad J^\mu = \chi \partial^\mu \chi^\dagger - \chi^\dagger \partial^\mu \chi$$

If J^μ is conserved then no effect

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$$\frac{1}{\Lambda}\partial_\mu \phi J^\mu + m^3(\chi + \chi^\dagger)$$

sources production

$$\chi \to e^{-i\phi/\Lambda}\chi$$

$$m^3(e^{-i\phi/\Lambda}\chi + e^{i\phi/\Lambda}\chi^\dagger)$$

Energy Injection

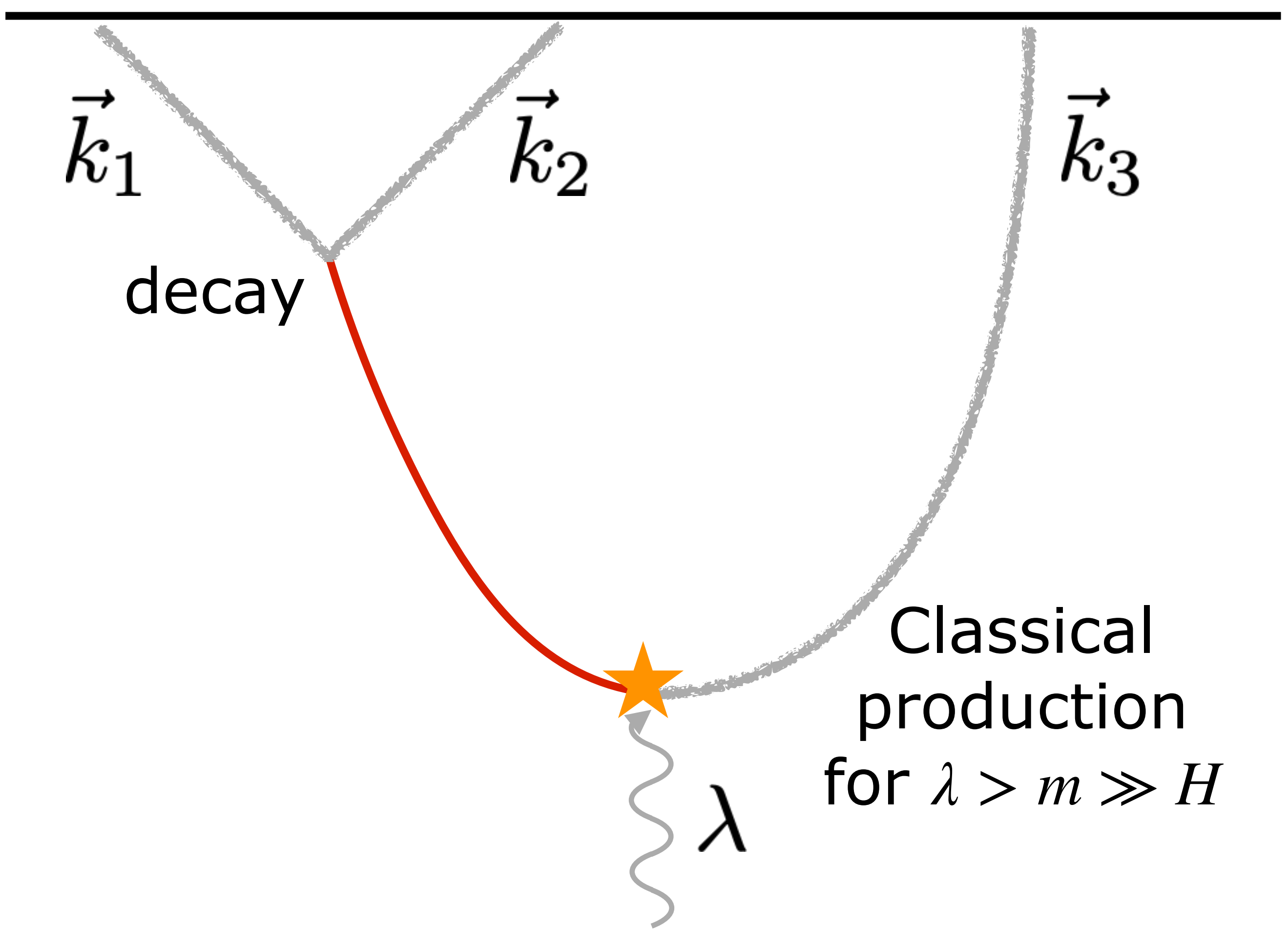
Bodas, **S.K.**, Sundrum
2010.04727

$$m^3(e^{-i\phi/\Lambda}\chi + e^{i\phi/\Lambda}\chi^\dagger)$$

$$\frac{\phi}{\Lambda} = \underbrace{\frac{\dot{\phi}_0}{\Lambda}}_{\equiv \lambda \gg H} t + \frac{\delta\phi}{\Lambda} t$$

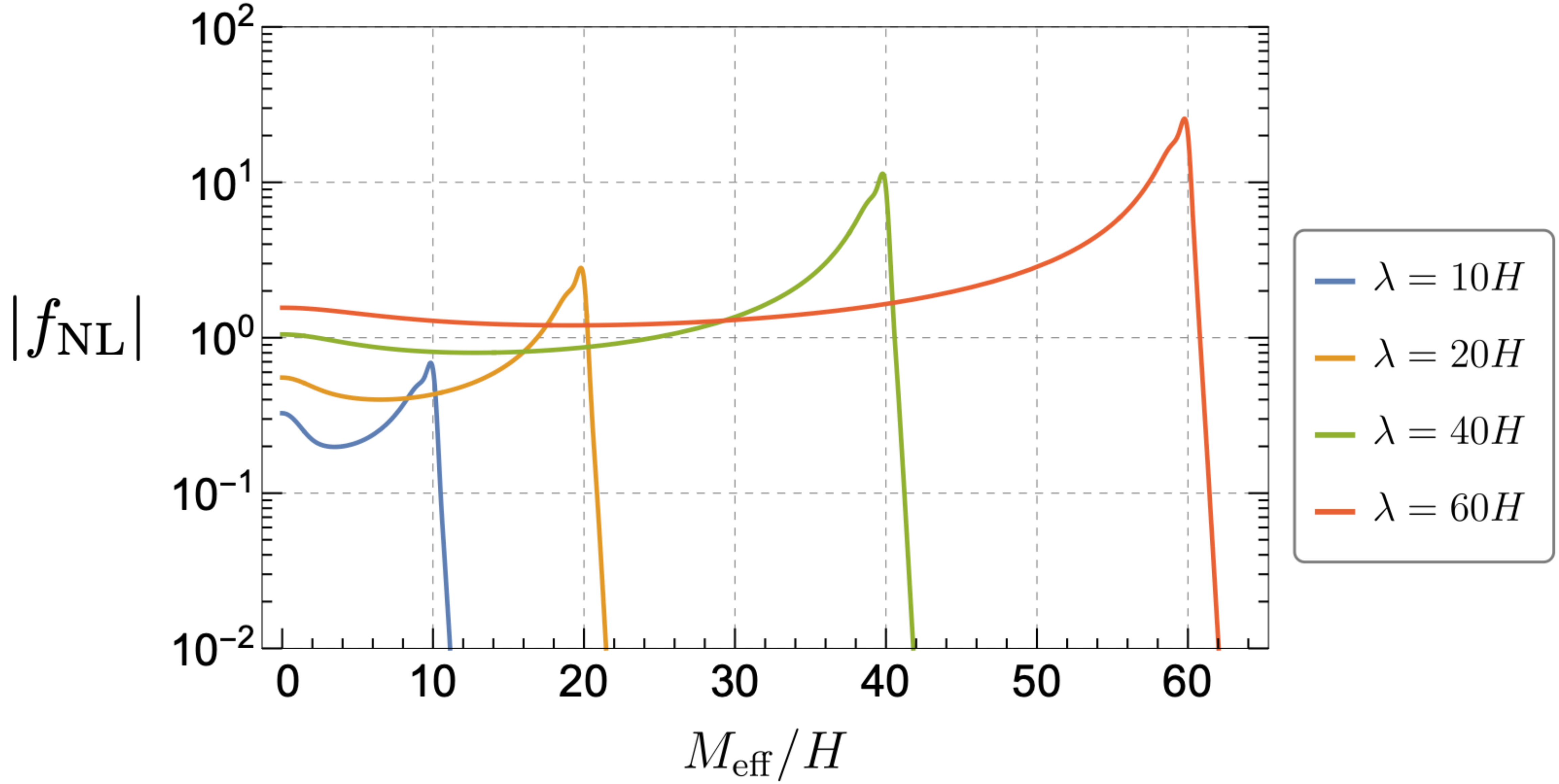
$$\frac{m^3}{\Lambda} e^{-i\lambda t} \delta\phi\chi$$

rapidly oscillating coupling



The Reach

Bodas, **S.K.**, Sundrum
2010.04727



Strong backreaction regime: dissipative dynamics with $f_{\rm NL}^{\rm eq} \simeq \mathcal{O}(10)$

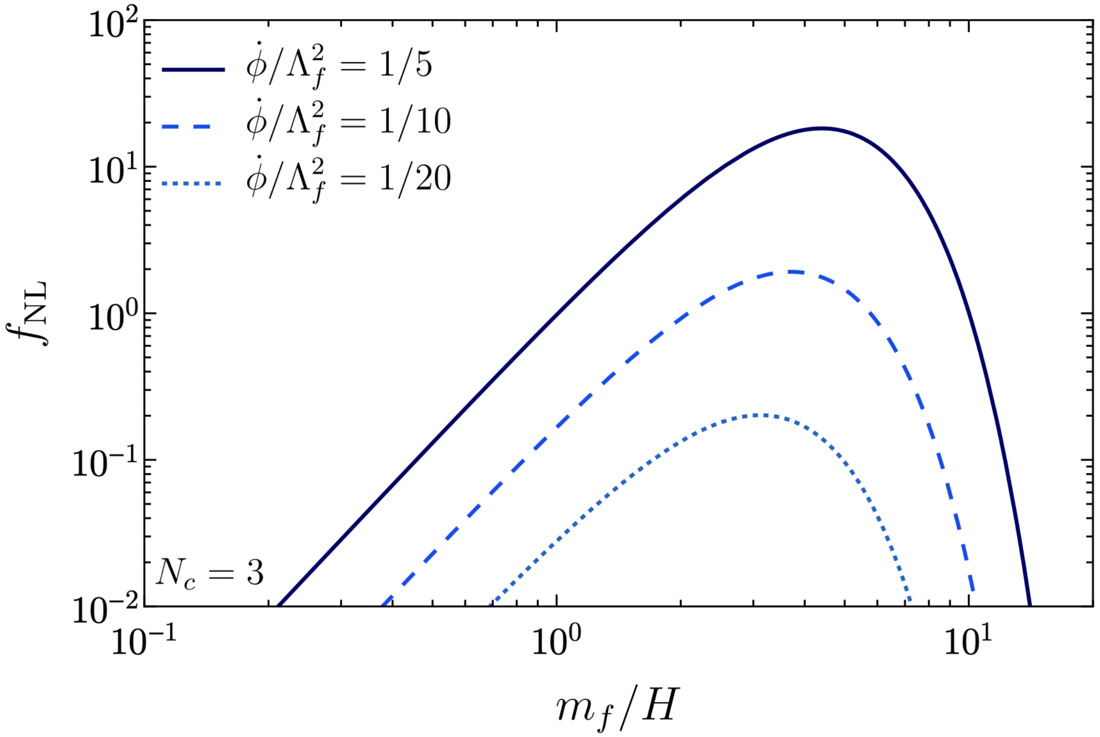
Creminelli, **S.K.**, Salehian, Santoni
2023

Including Spin

Fermions

$$\mathscr{L} \supset \frac{\partial_\mu \phi \bar{f} \gamma^\mu \gamma^5 f}{\Lambda_f}$$

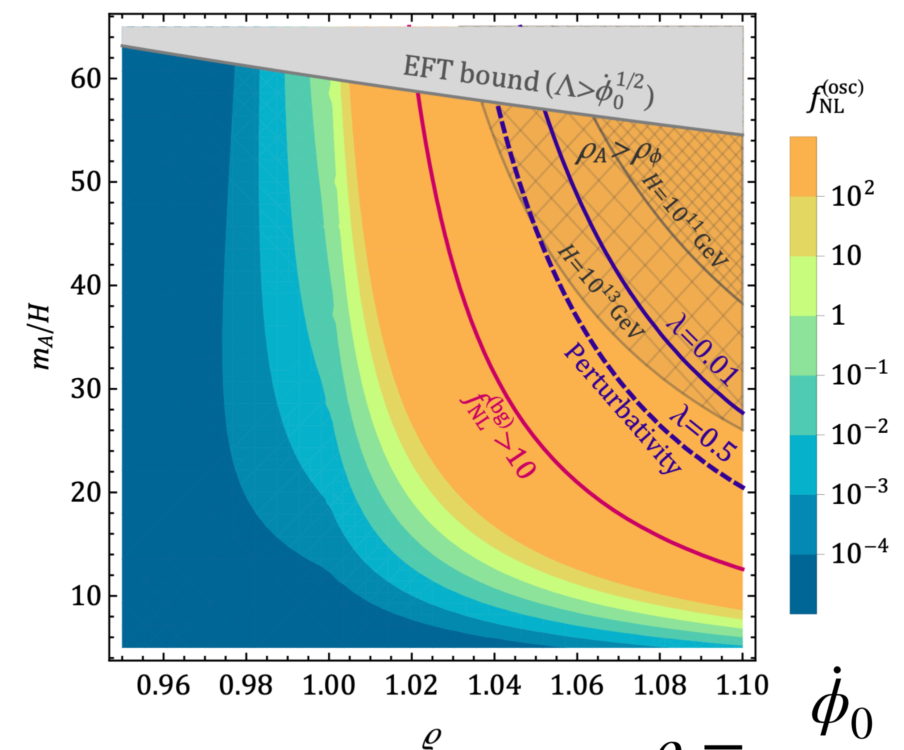
Hook, Huang, Racco
1907.10624



Also Chen, Wang, Xianyu
1805.02656

Gauge bosons

$$\mathscr{L} \supset \frac{1}{4\Lambda_F} \phi F \tilde{F}$$



$$\rho = \frac{\dot\phi_0}{m_A \Lambda_F}$$

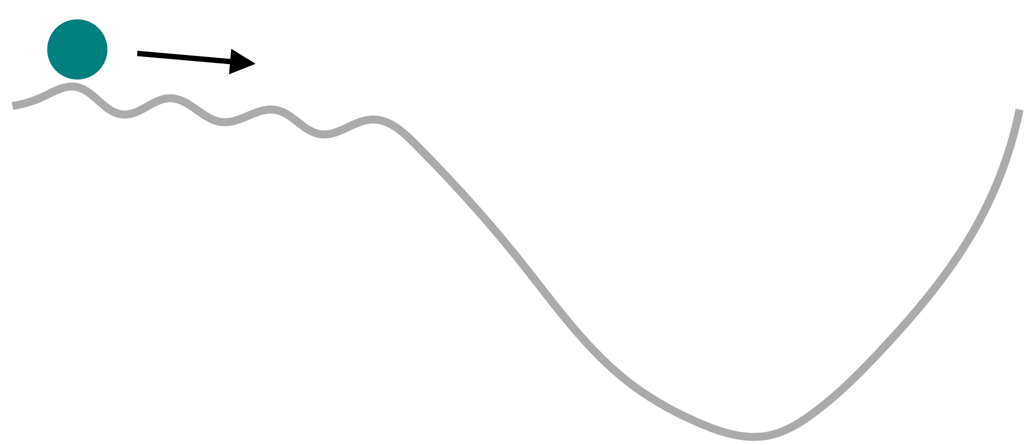
Xianyu, Wang
2004.02887

Primordial Features

Chen, Ebadi, **S.K.**
2205.01107

What happens with a real scalar field?

$$\frac{1}{\Lambda}\partial_\mu \phi J^\mu \qquad J^\mu = \chi\partial^\mu\chi^\dagger - \chi^\dagger\partial^\mu\chi$$



$$\omega_{\text{feature}} \gg H$$

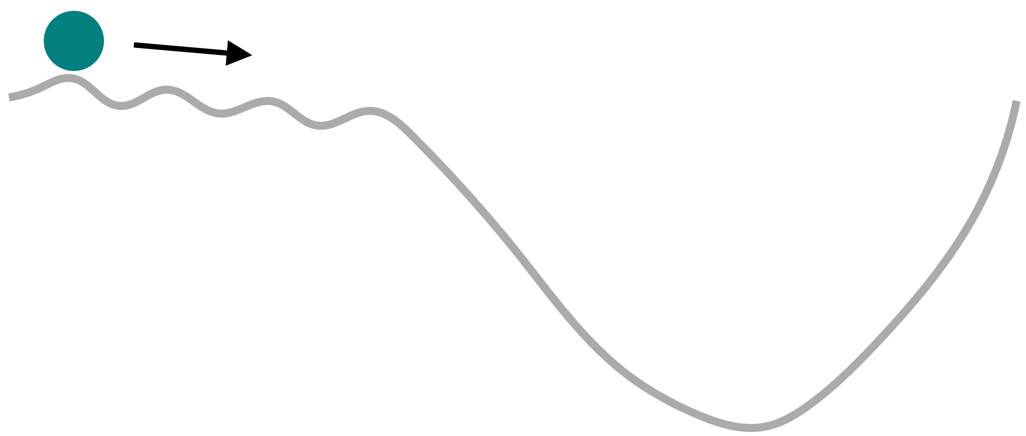
usual slow-roll

$$\phi_{\text{background}} = \phi_0(t) + \phi_1(t)$$

oscillating, encodes ω_{feature}

Energy Injection

Chen, Ebadi, **S.K.**
2205.01107



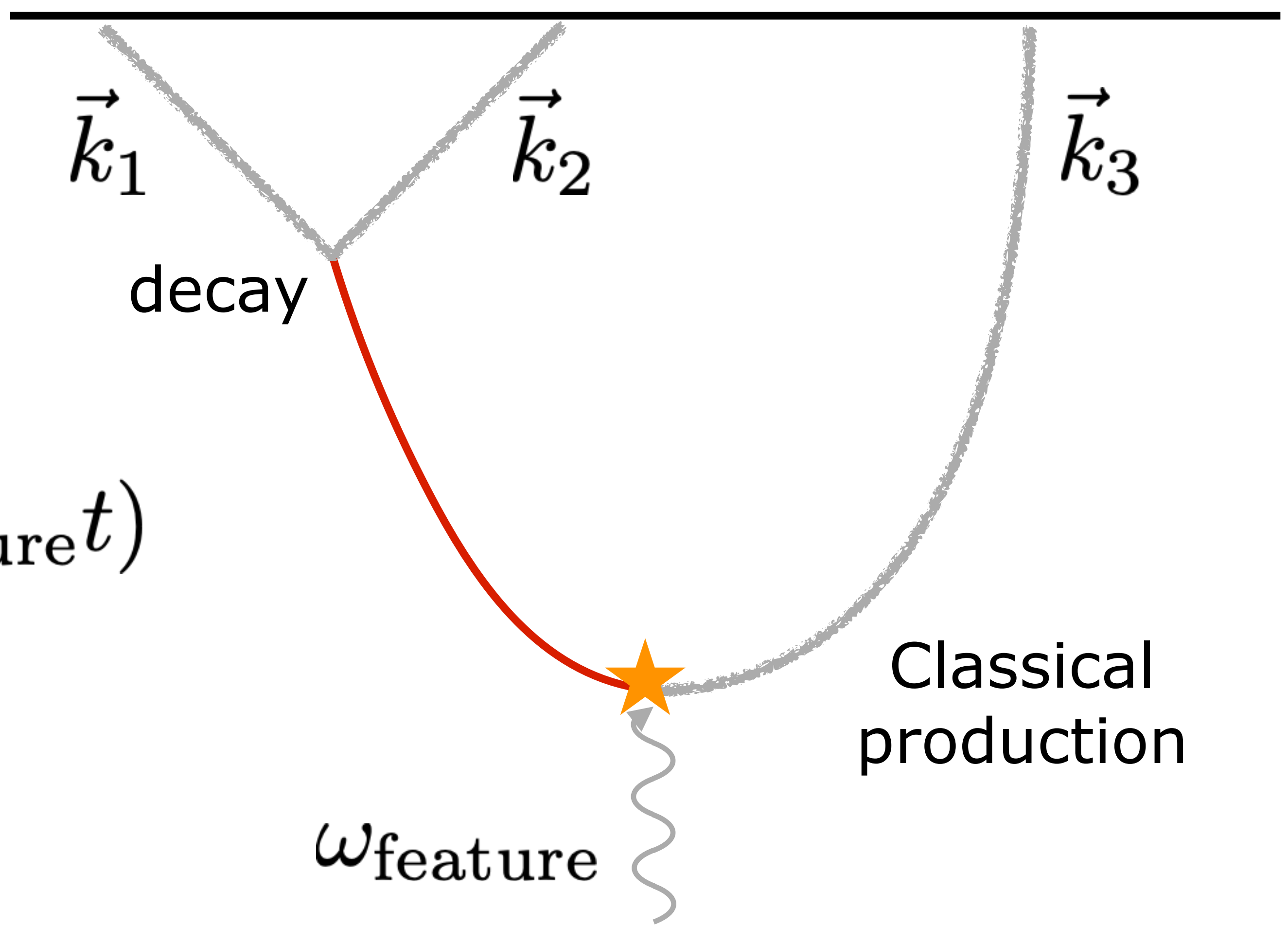
$$\omega_{\text{feature}} \gg H$$

$$\phi_{\text{background}} = \phi_0(t) + \phi_1(t)$$

$$\sim \cos(\omega_{\text{feature}} t)$$

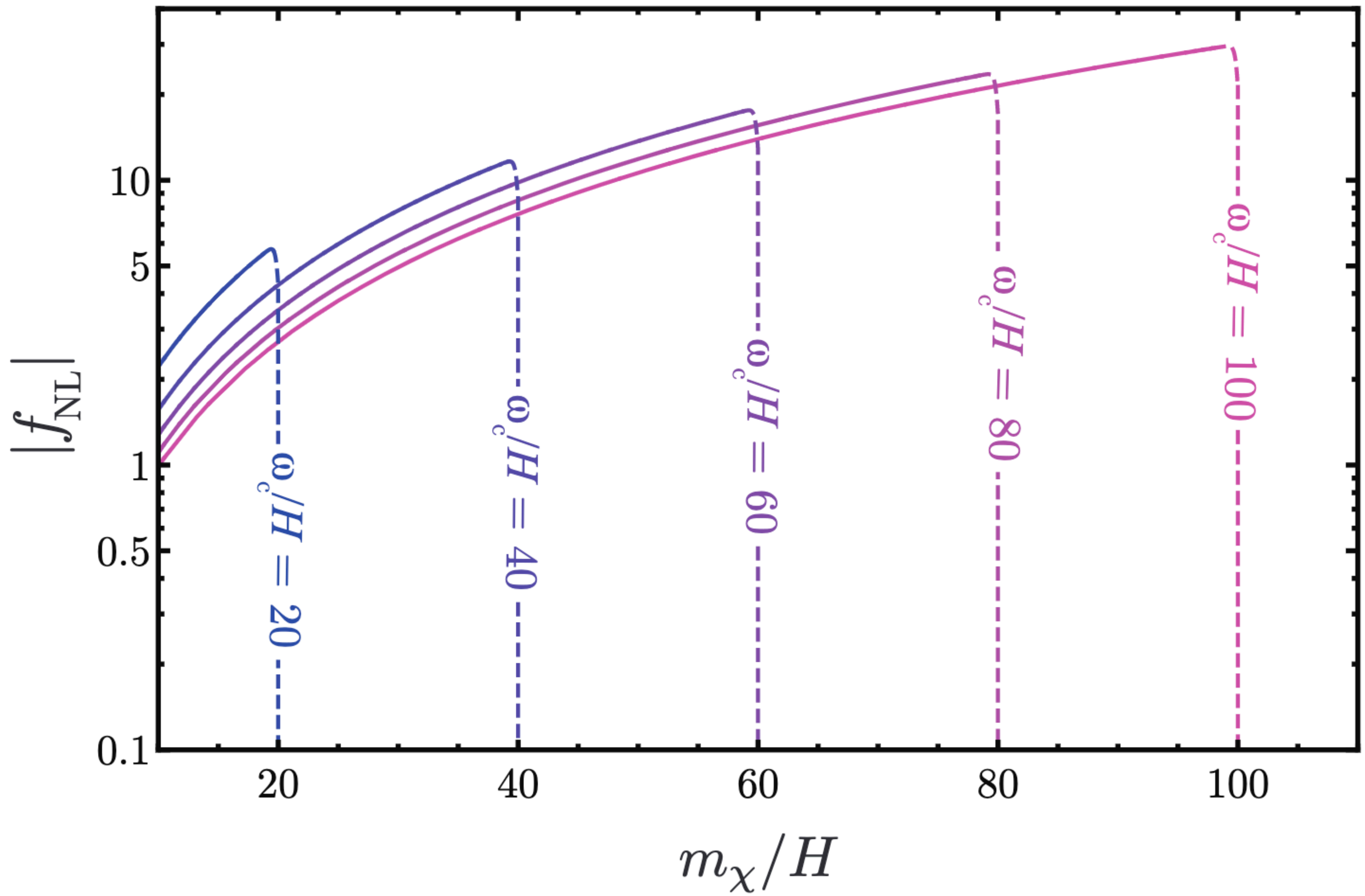
$$\frac{1}{\Lambda}(\partial\phi)^2\chi \supset \frac{\dot{\phi}_1}{\Lambda}\dot{\delta\phi}\chi$$

rapidly
oscillating
coupling



The Reach

Chen, Ebadi, **S.K.**
2205.01107



BSM at the Cosmological Collider

SUSY

Baumann & Green 1109.0292
Craig & Green 1403.7193
Alexander et al. 1907.05829
…

Operator Bases

Craig, **S.K.,** & McCune
2401.10976
…

Right-handed Neutrinos

Chen, Wang, & Xianyu
1805.02656
…

Higgs Physics

Chen, Wang, & Xianyu
1612.08122
S.K. & Sundrum 1711.03988
Hook, Huang, & Racco
1907.10624
…

Extra dimensions

S.K. & Sundrum
1811.11200
…

Baryogenesis

Wu, Pinetti, Petraki, & Silk
2109.00118
Cui & Xianyu 2112.10793
…

Axions

Lu 2103.05958
Chen, Fan, Li
2303.03406
Chakraborty, Stout
2311.09219
…

Future Steps: Surveys and Theory

- New *Planck* and BOSS constraints already constrain mass up to $m \sim 1 - 5H$! Can we go heavier? Cabass et al. 2404.01894 Sohn et al. 2404.07203
- High frequency oscillations: having a large hierarchy and number of bins between k_{min} (larger volume) and k_{max} would be important
- Improved theory modeling for gravitational non-linearities
- Implementations of these mechanisms within specific particle physics scenarios (SUSY, GUTs, see-saw etc.)

Thank you!