Extending the Reach of the Cosmological Collider

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Reza Ebadi, Amara McCune, Raman Sundrum

New Physics with Galaxy Clustering II: Trieste
Nov 10, 2023

Particle Physics at High Energies

LHC and other experiments
have provided powerful probes at multi-TeV scales

But…

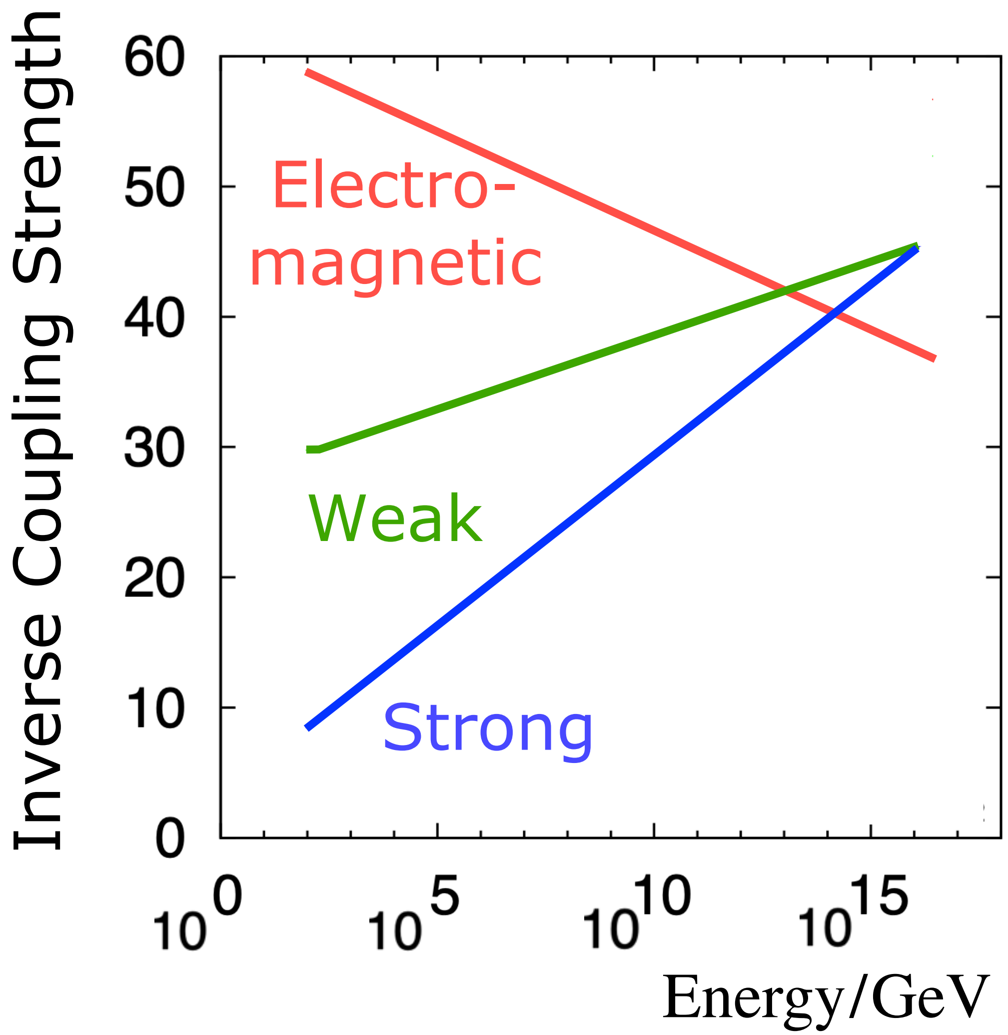
(I) What happens at higher energies?
New particles? New symmetries?

(II) Do forces unify?

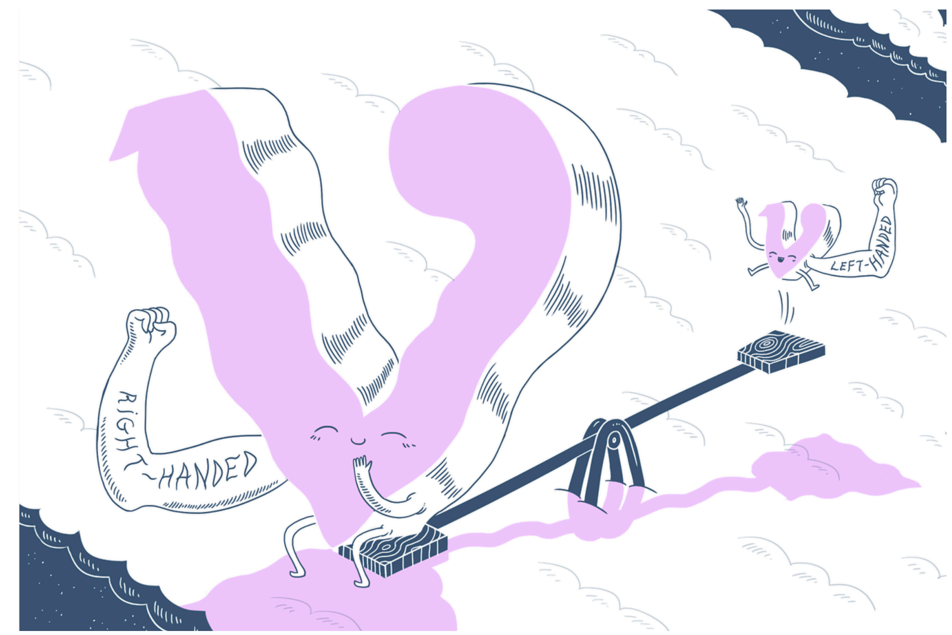
(III) Connection with dark matter?

…

Classic Targets



Standard Model "Unification"
$M_{\text{GUT}} \sim 10^{14} - 10^{16}$ GeV



Symmetry Magazine

$m_\nu \sim (y v_0)^2 / M_N$

See-saw Mechanism
$M_N \sim 10^{14} - 10^{15}$ GeV

How to look for these? Especially, *on-shell* signatures?

On-shell Probes

Probes, e.g., proton decay, but otherwise too heavy to be on-shell *today*

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But the early Universe was energetic, in particular, inflationary Hubble $H \lesssim 5 \times 10^{13}$ GeV!

Planck 2018

GUT-scale states, right-handed neutrinos could have been produced *on-shell*

Need to understand their “fossil records” through cosmological observations!

Varied Phenomenology

Phenomenology varies significantly
depending on the mass of the heavy particle

light-ish to heavy

$$m \sim 0.1H - 10H$$

- Ample production
- Isocurvature fluctuations [Fabian's, Marilena's talks]
- Features on the power spectrum [Ben's talk]
- Oscillatory non-Gaussianity (e.g., cosmological collider) [Oliver's talk]

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superheavy

$m \gg 10H$

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- Localized signatures in position space
- CMB Hotspots
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Outline

Basic idea
&
Reason of going beyond

Inflaton Velocity

Primordial Features

Operator Basis

Dimension	Operator
5	$\mathcal{O}_{5,4} = \phi F_{\mu\nu}\tilde{F}^{\mu\nu}$
6	$\mathcal{O}_{6,1} = (\nabla_\mu \phi)^2 H^\dagger H$
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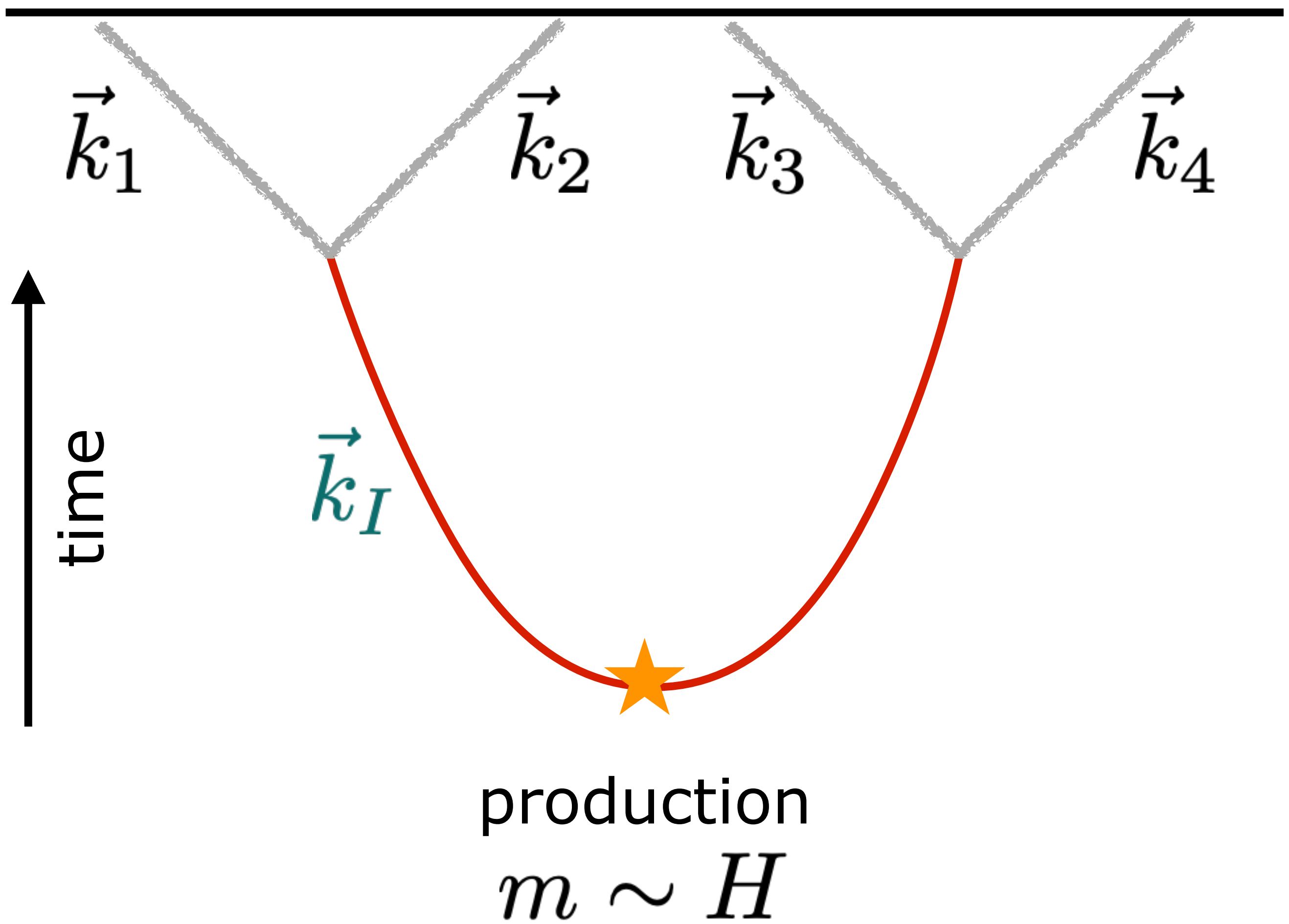
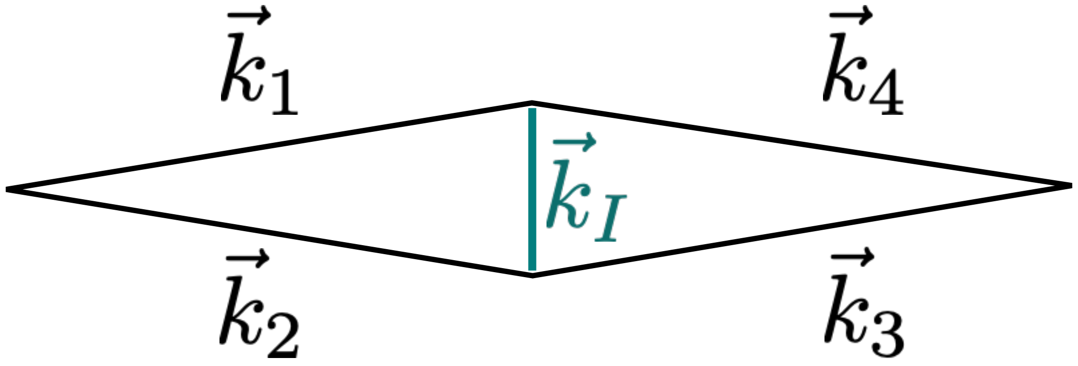
Cosmological Collider





$k_I \ll k_1, k_2, k_3, k_4$

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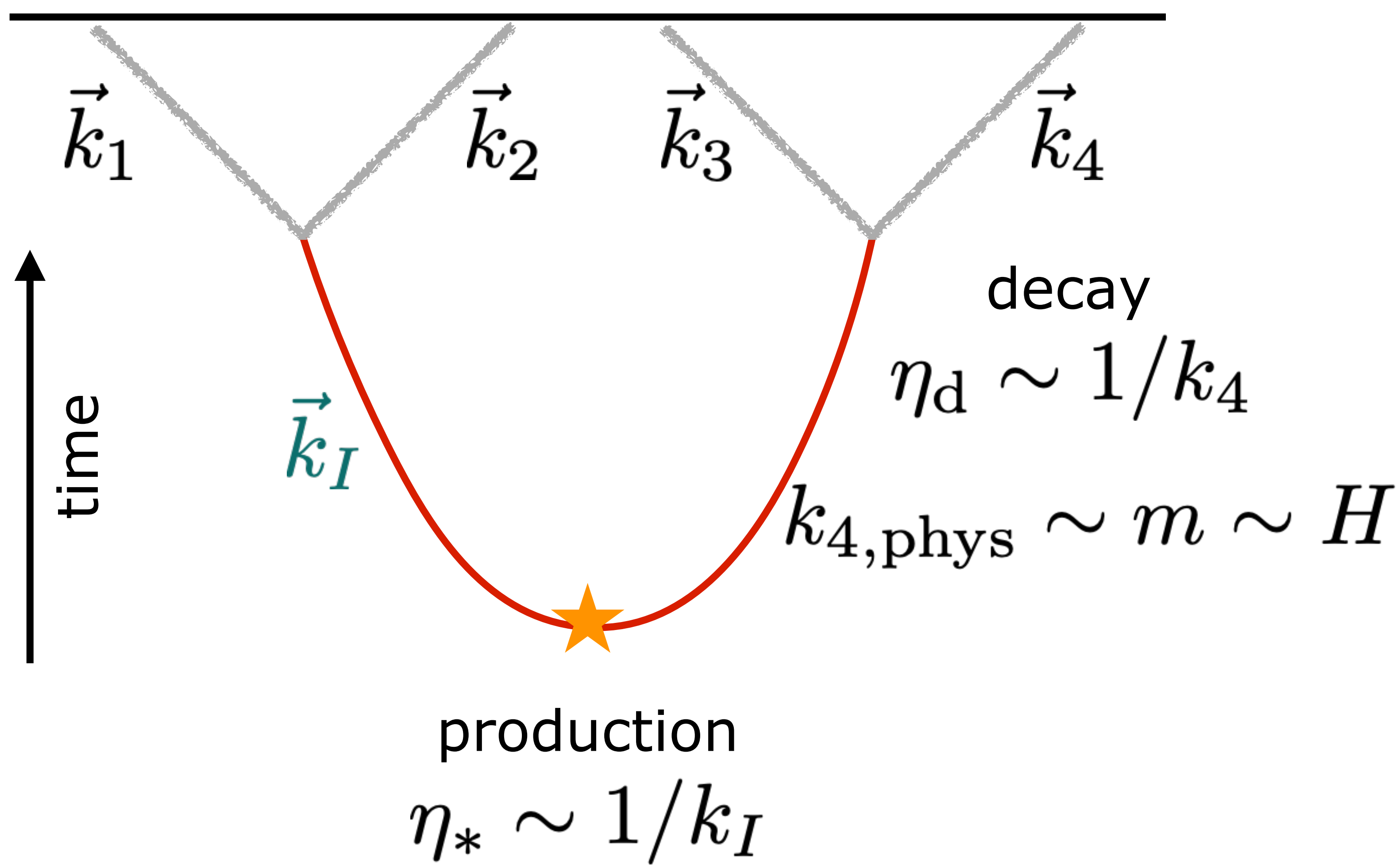
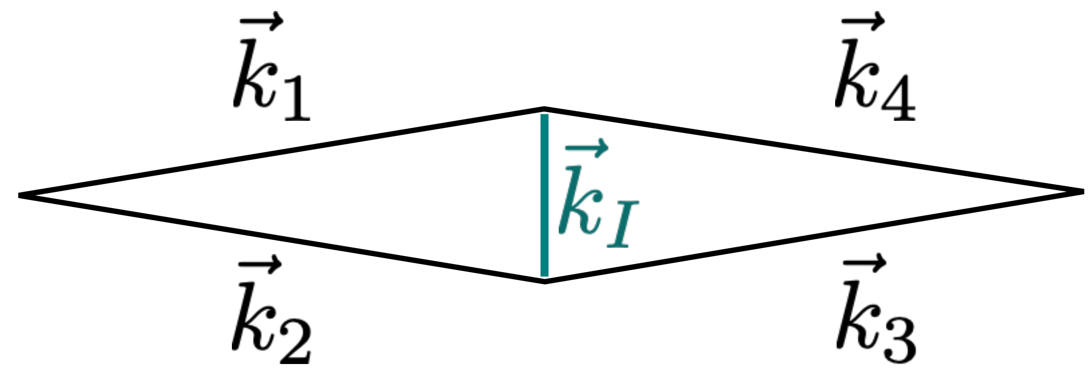


horizon crossing;
modes "sees" the
expansion of spacetime



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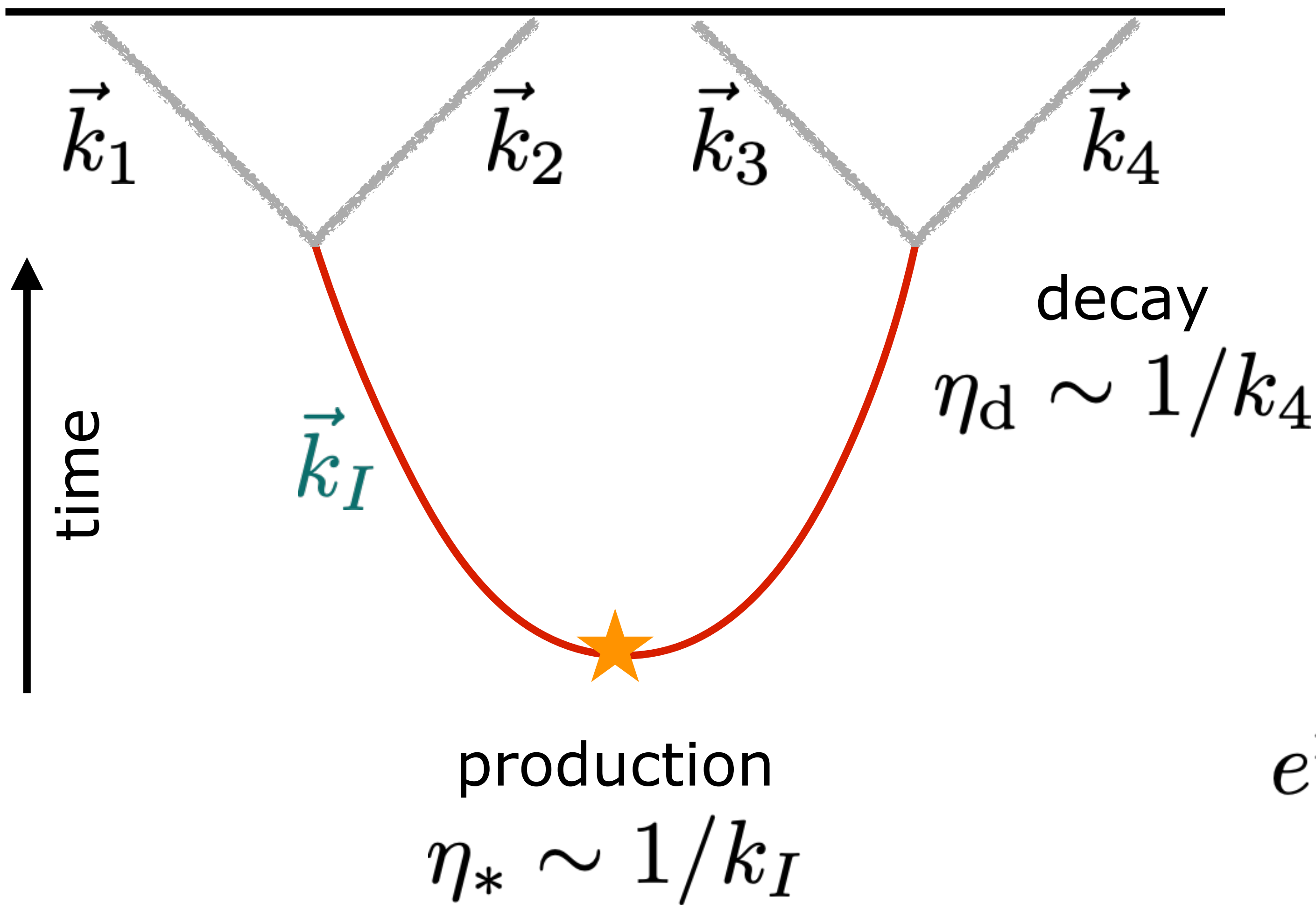
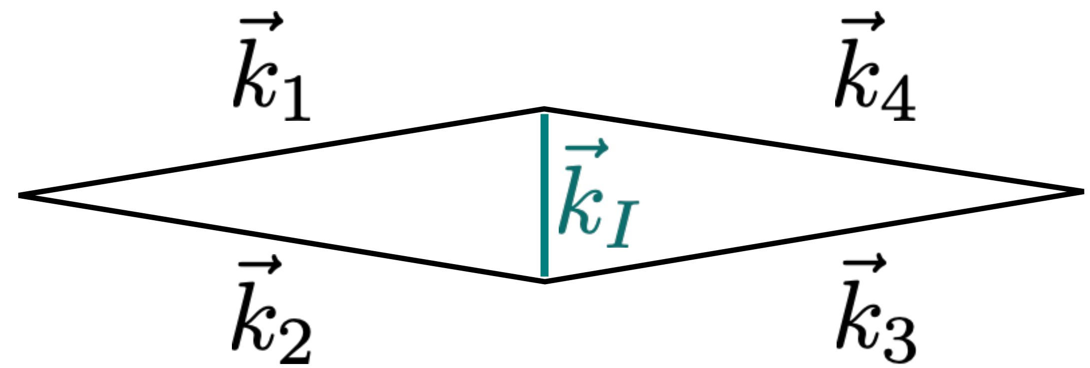




$$k_I \ll k_1, k_2, k_3, k_4$$

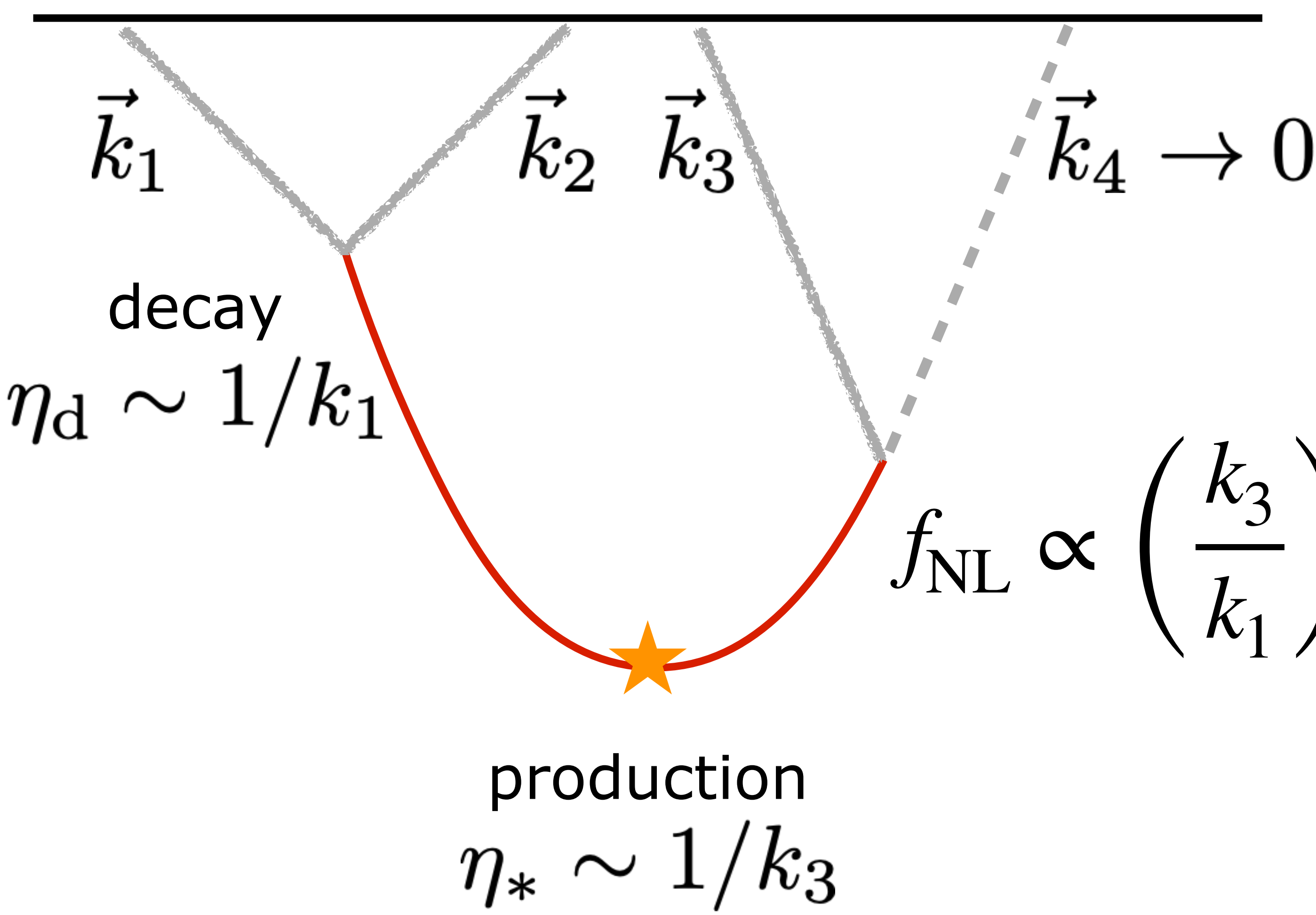
Long oscillation
of the massive particle

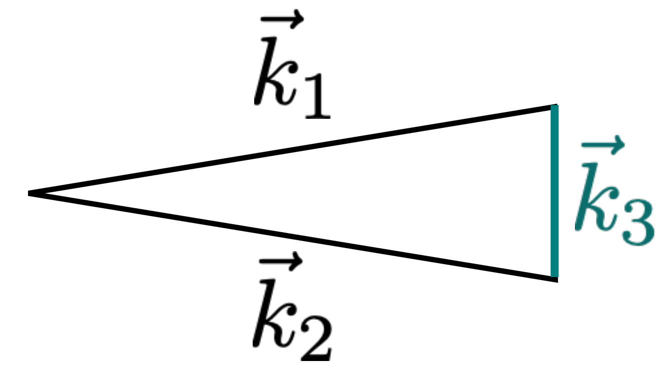
$$e^{\pm im(t_\mathrm{d}-t_*)} \to (\eta_\mathrm{d}/\eta_*)^{\pm im/H}$$

$$\to (k_I/k_4)^{\pm im/H}$$

$$\cos\left(\frac{m}{H}\log\left(\frac{k_I}{k_4}\right)\right)$$

Cosmological Collider





$$k_3 \ll k_1, k_2$$

mass spin

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

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

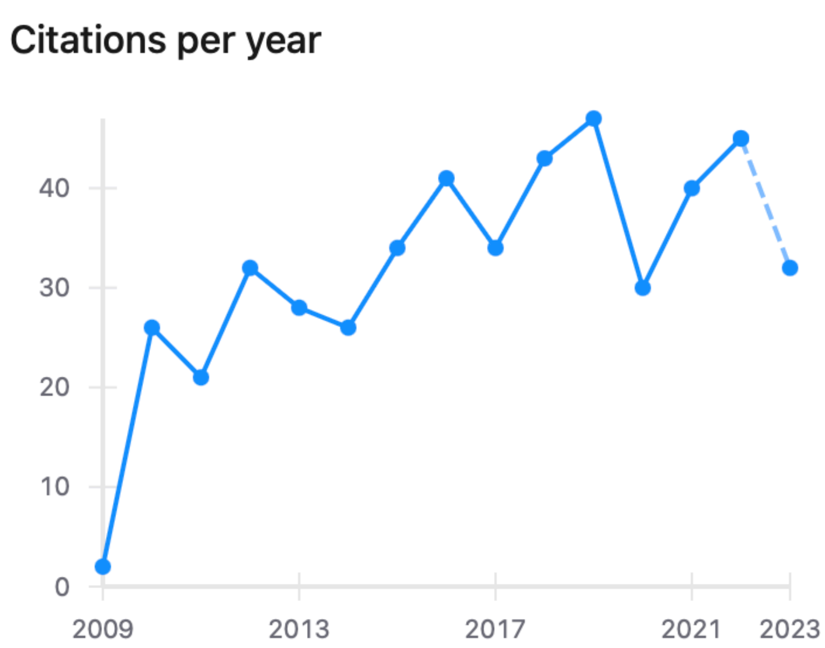
on-shell mass and spin information from bi/trispectrum!

Lots of Interesting Ideas

Azadeh, Ben,
Fabian, Giovanni,
Junwu, Marko,
Misha, Oliver + many more

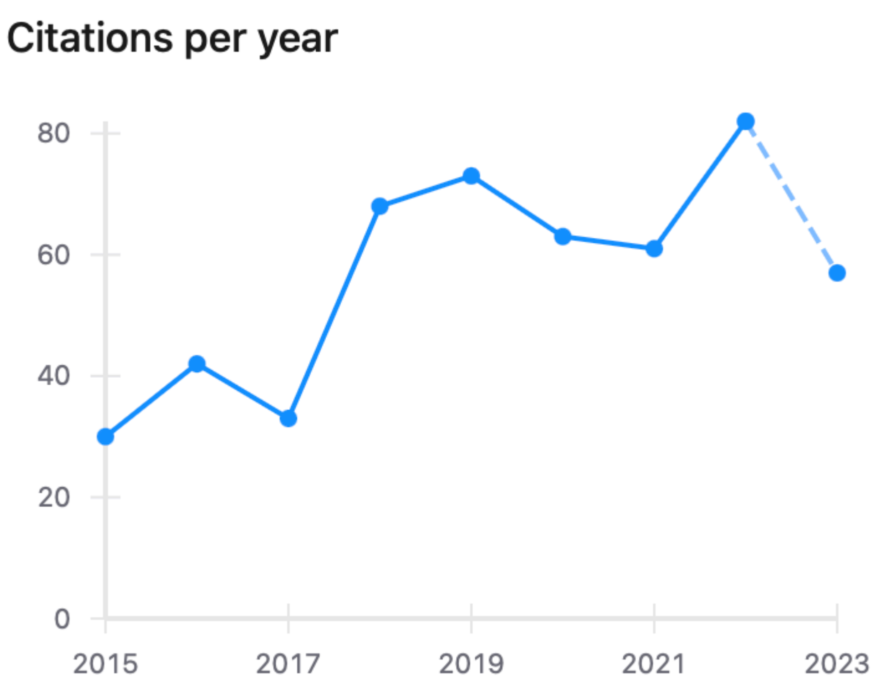
Quasi-Single Field Inflation and Non-Gaussianities

Xingang Chen (Cambridge U., DAMTP and MIT), Yi Wang (McGill U. and Beijing, KITPC)
Nov, 2009



Cosmological Collider Physics

Nima Arkani-Hamed (Princeton, Inst. Advanced Study), Juan Maldacena (Princeton, Inst. Advanced Study)
Mar 27, 2015



Novel computational techniques, cosmological bootstrap

Novel connections with particle physics

Novel ways of probing using CMB and LSS

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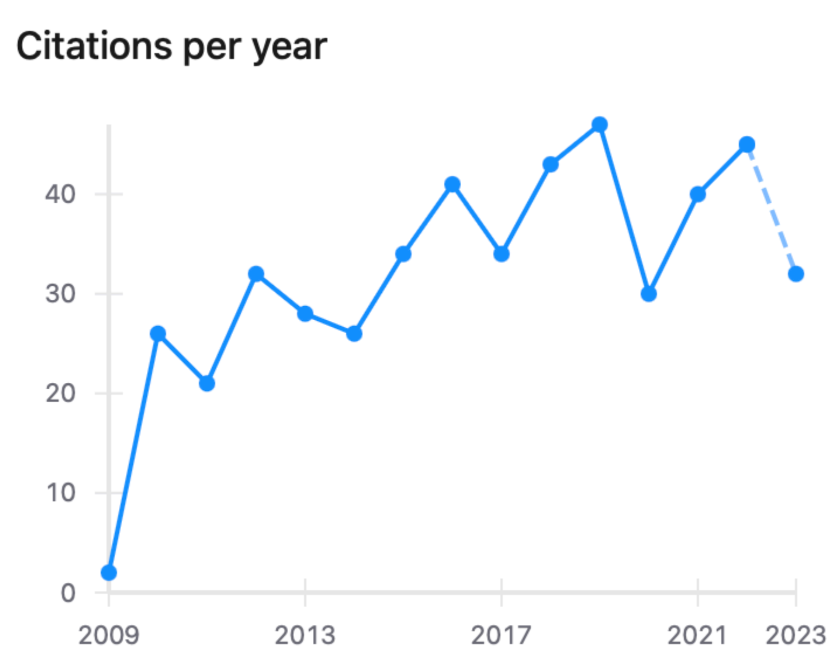

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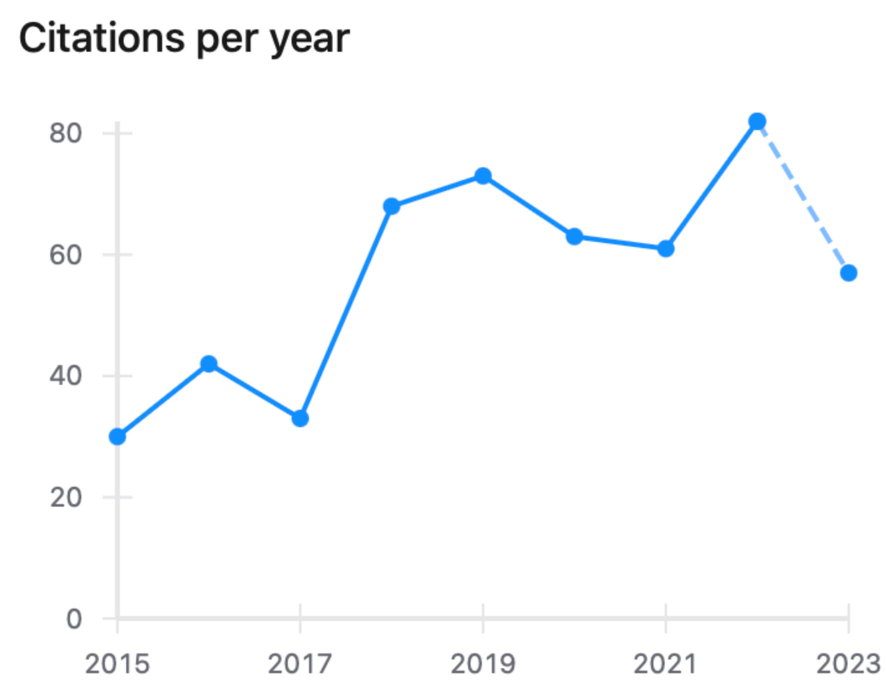


Novel computational techniques, cosmological bootstrap

Novel connections with particle physics → Novel ways of probing using CMB and LSS

Can We Observe This?

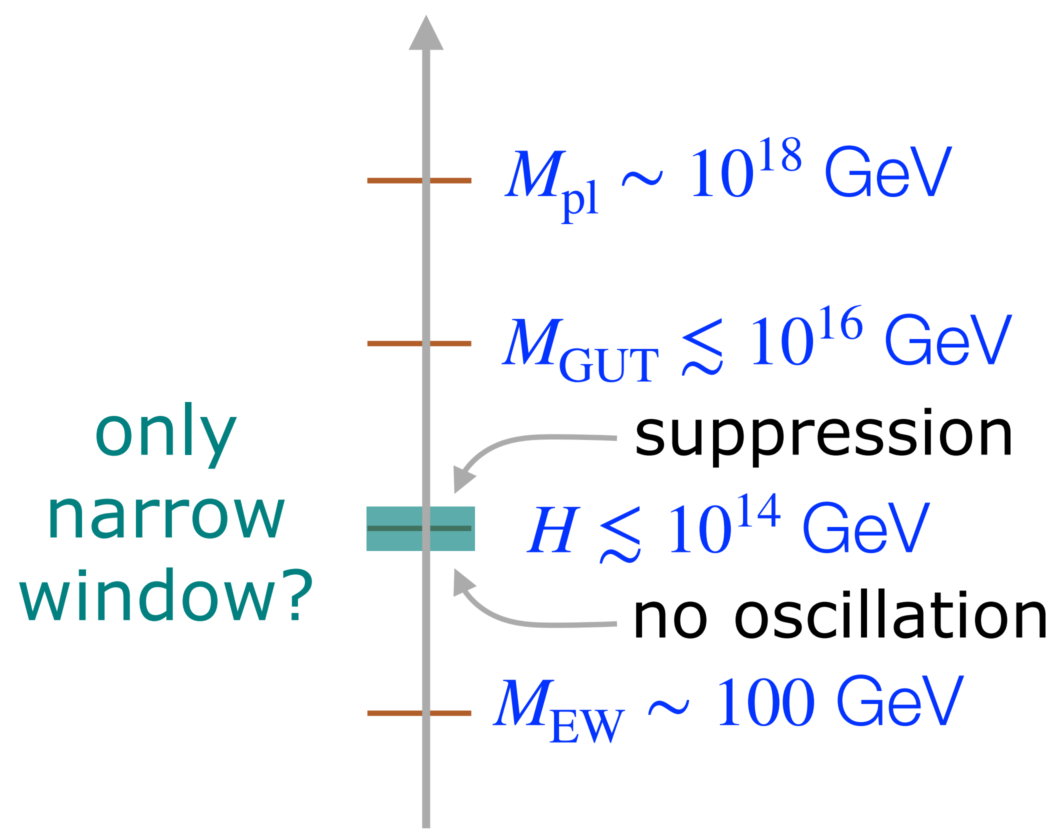
$$f_{\rm NL} \propto c \left(\frac{k_3}{k_1}\right)^{3/2} \cos\left(\mu \log\left(\frac{k_3}{k_1}\right)\right) f_s(\cos\theta)$$

(c ↑ ?)

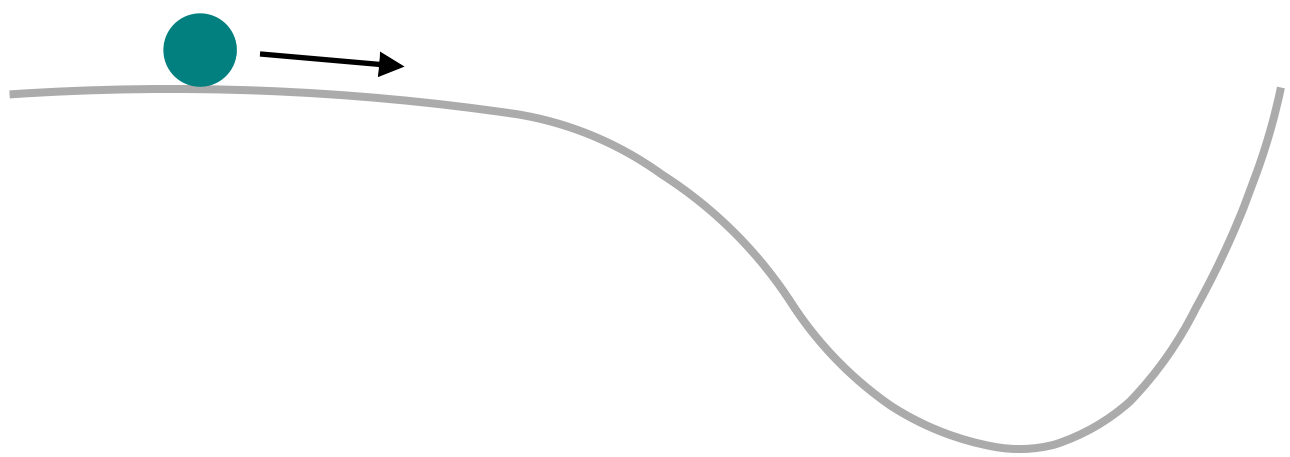
Inflation gives H-scale energy: $c \sim \exp\left(-\frac{\pi m}{H}\right)$

Bad news!

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



More Scales



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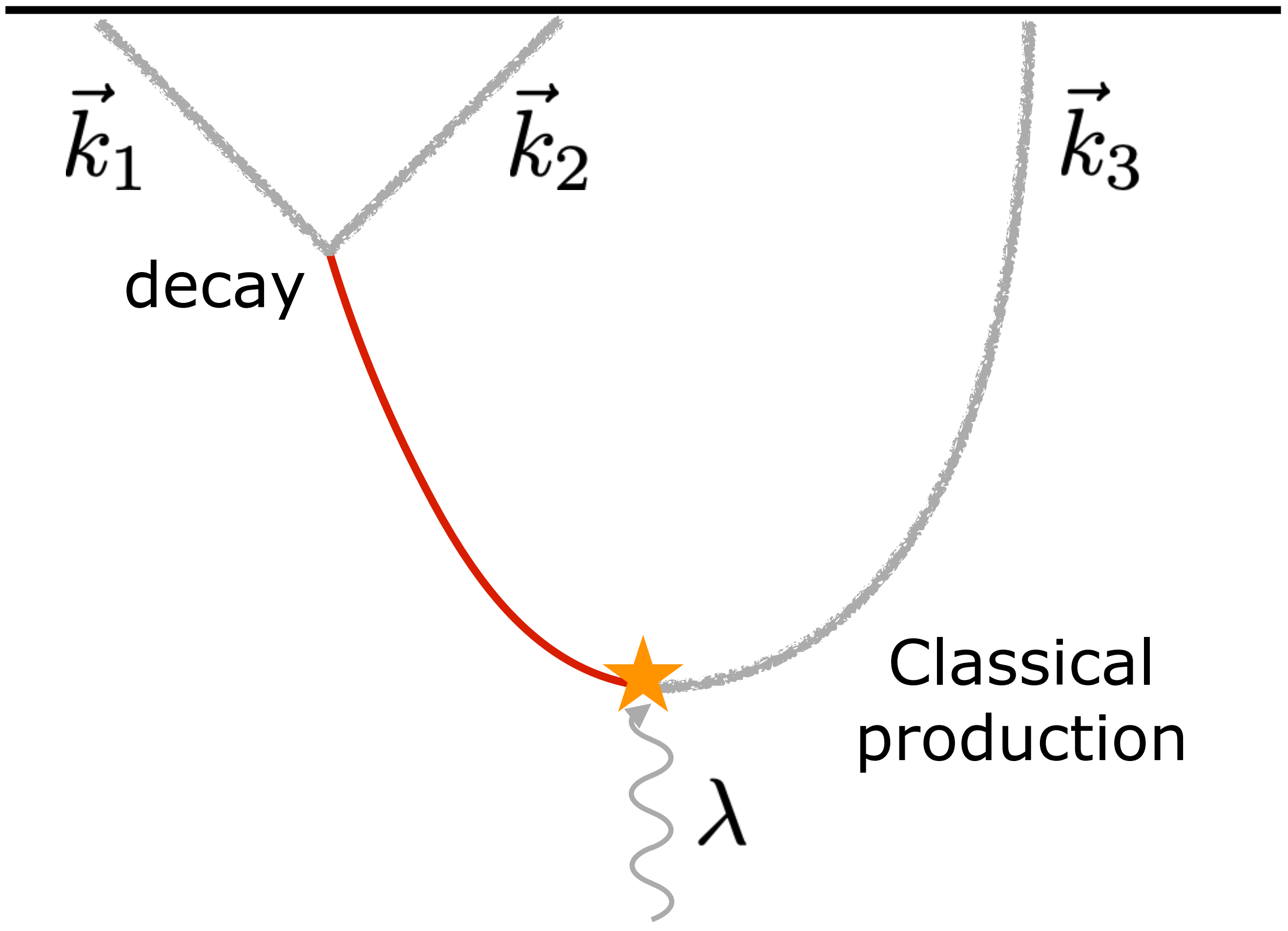
$$m^3\left(e^{-i\phi/\Lambda}\chi + e^{i\phi/\Lambda}\chi^\dagger\right)$$

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

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

rapidly oscillating coupling



The Reach

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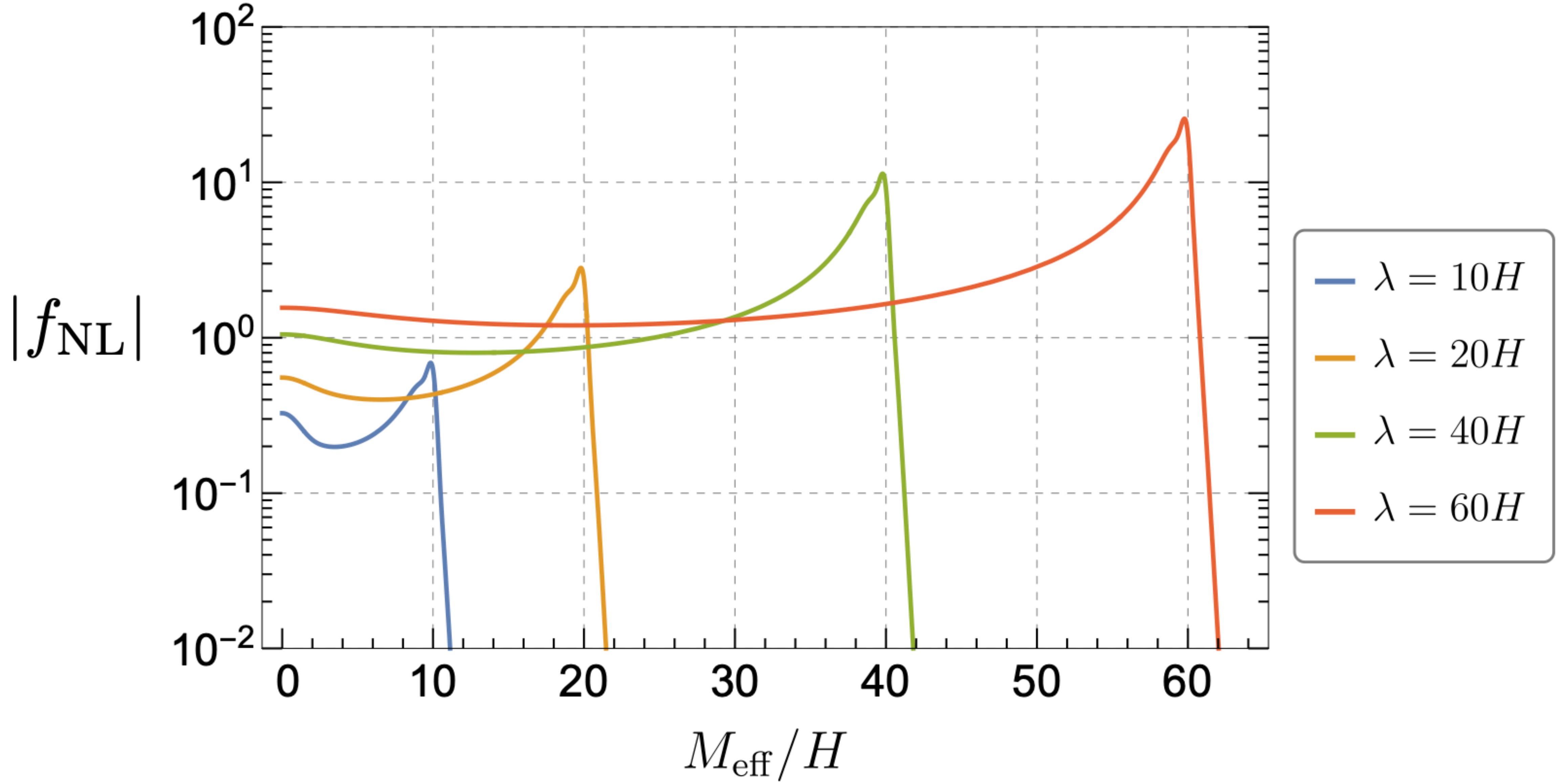
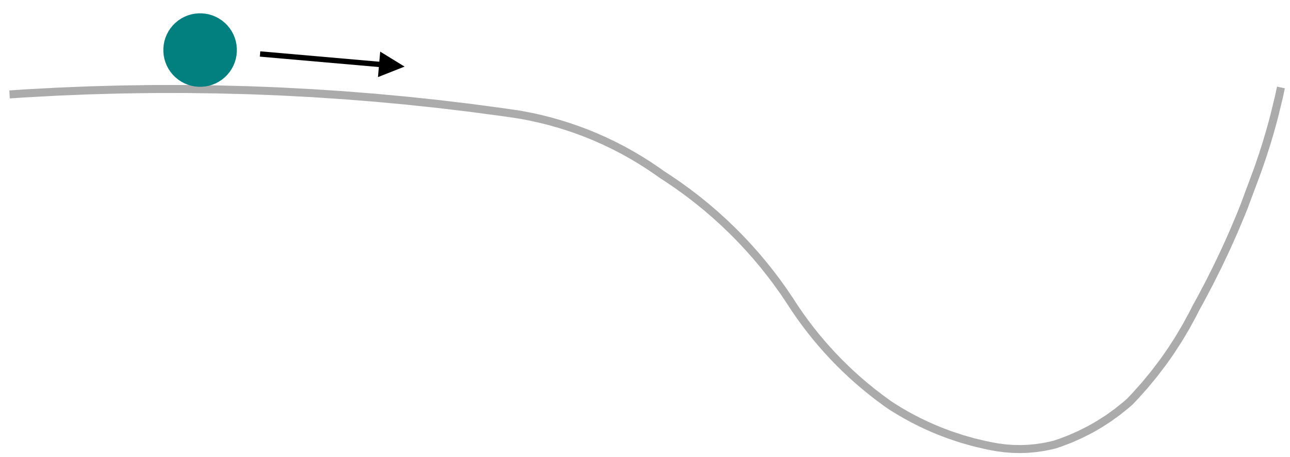


Strong backreaction regime: dissipative dynamics with $f_{\rm NL}^{\rm eq} \simeq \mathcal{O}(10)$

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

More Scales



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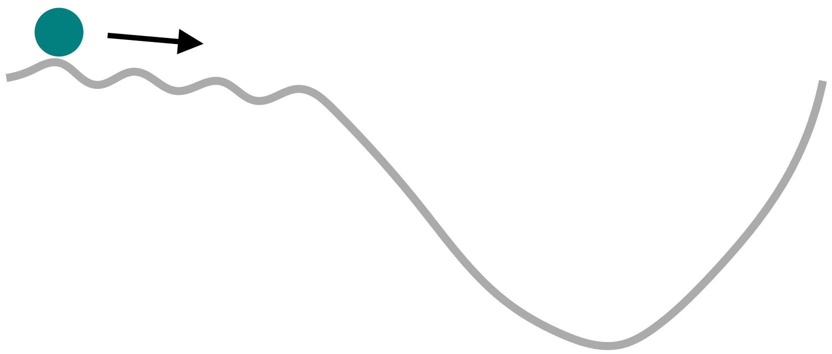


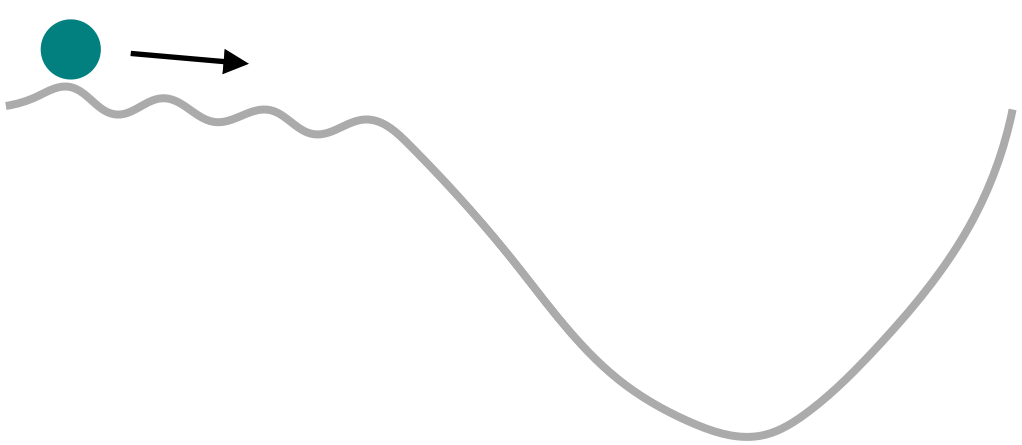
$$\omega_{\text{feature}} \gg H$$

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.**
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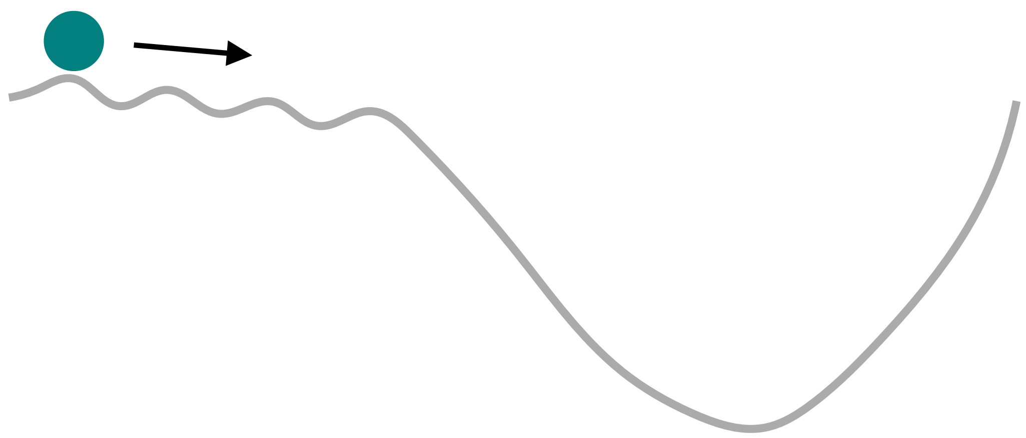


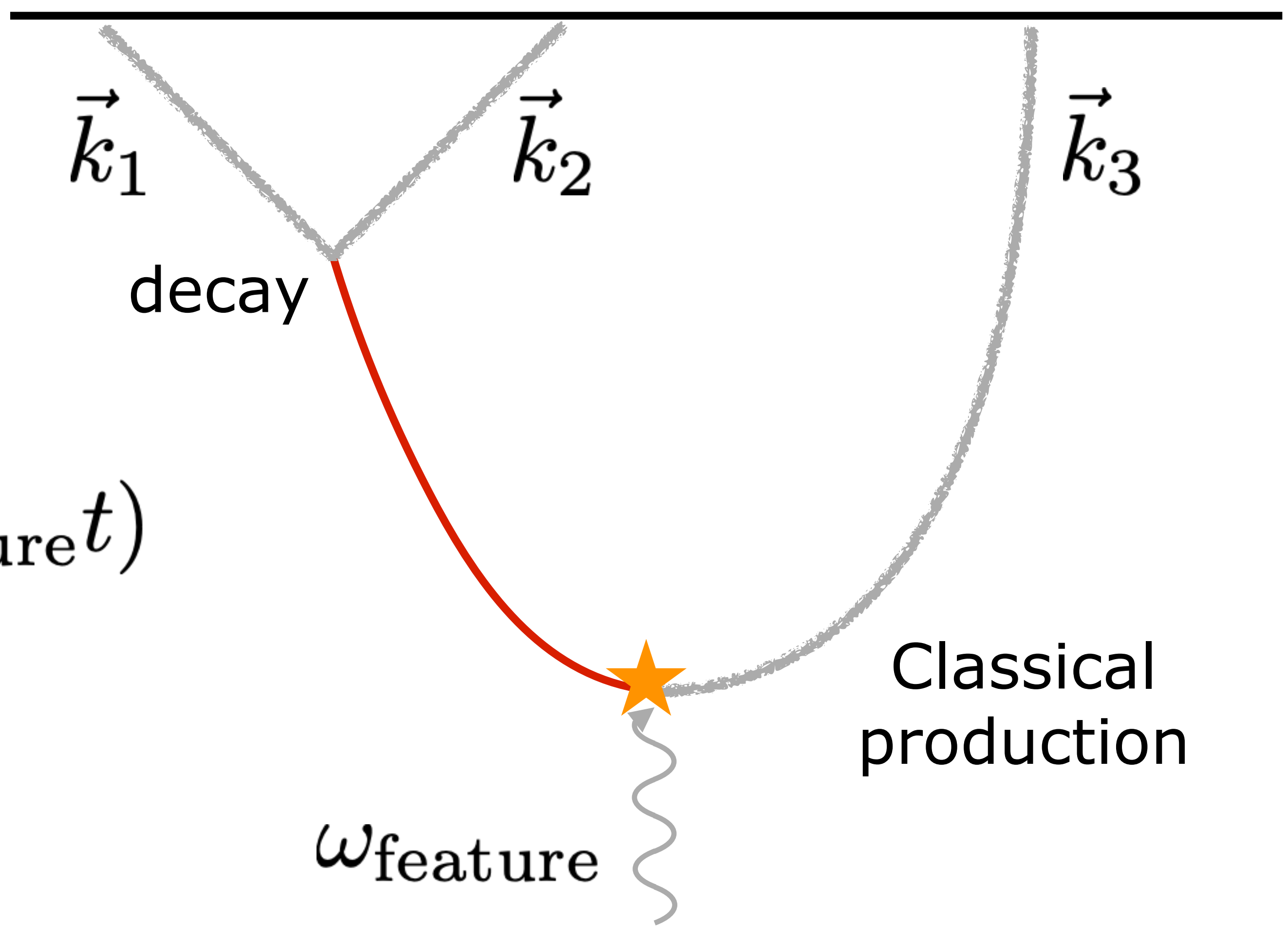
$$\omega_{\rm feature} \gg H$$

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

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

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

rapidly
oscillating
coupling



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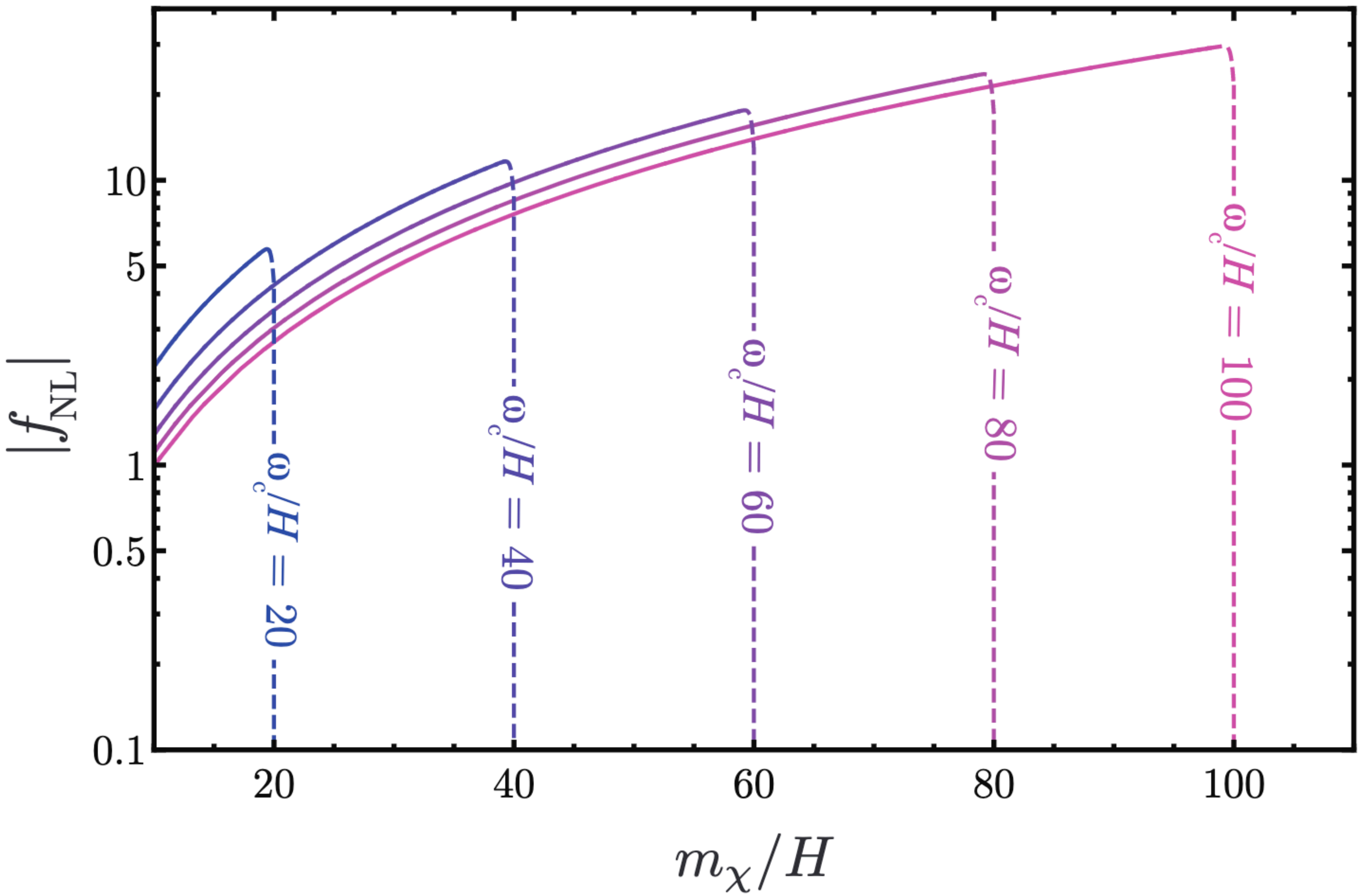

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5	$\mathcal{O}_{5,4} = \phi F_{\mu\nu}\tilde{F}^{\mu\nu}$
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Counting Operators

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

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

$$m^3(e^{-i\phi/\Lambda}\chi + e^{i\phi/\Lambda}\chi^\dagger) \; + \frac{(\partial\phi)^2}{\Lambda^2}|\chi|^2$$

additional term

How to do these systematically?

Certain operators could be related to others via equations of motion / field redefintion etc.

Gauge Higgs Theory

Craig, **S.K.**, McCune
(in progress)

Widely studied in the context of Standard Model EFT

Currently developing the minimal basis
up to dimension 9

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Certain operators at dimension 5 are redundant +
new operators at dimension 8 (not considered before)

Summary and Next Steps

- We have classic targets that predict new particles around $10^{14} - 10^{16}$ GeV
- These superheavy particles could lead to oscillatory bispectrum and/or trispectrum

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- LSS would be powerful since we can probe 3D oscillations
- Search with CMB and LSS data? Especially for $m \sim (1 - 10)H$?

Thanks for your attention!