March 13th (2019) @ IPMU

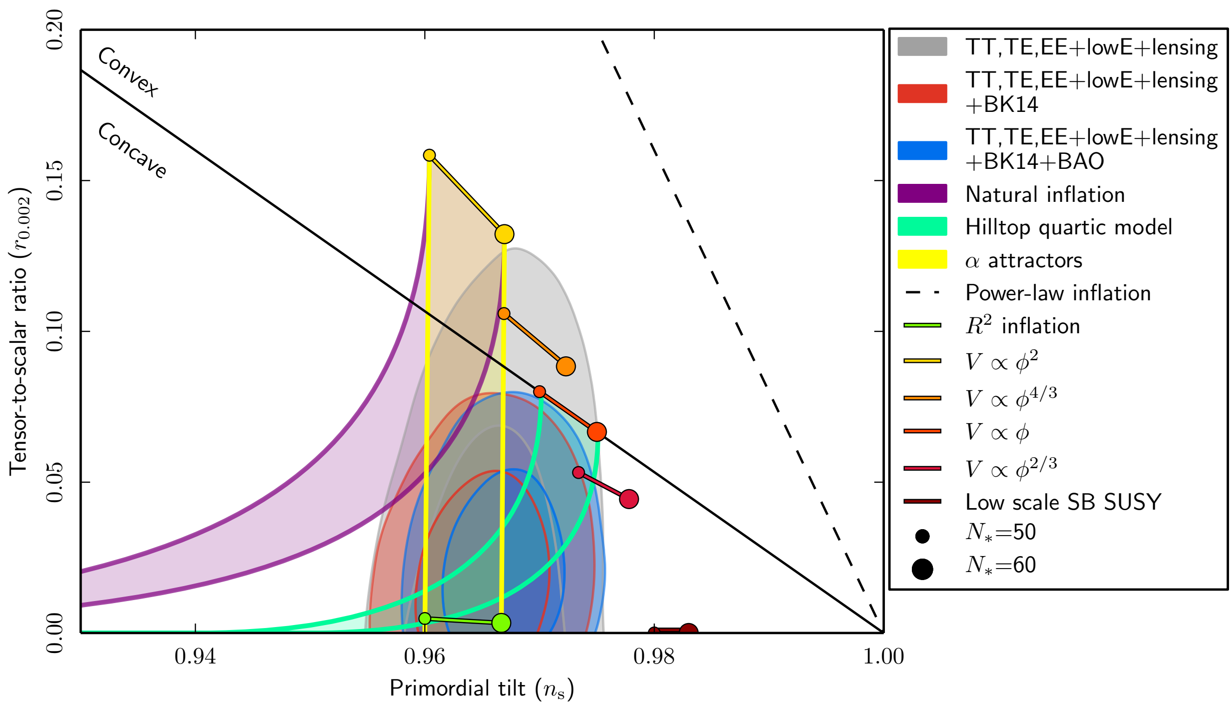
# Higgs signatures in primordial non-Gaussianities

Yi-Peng Wu based on [arXiv:1812.10654]

RESearch Center for the Early Universe (RESCEU)
The University of Tokyo

# Heavy particles during inflation

# Standard single-field inflation with Einstein gravity




PLANCK (2018)

$n_s = 0.9649 \pm 0.0042$ at 68 % CL.

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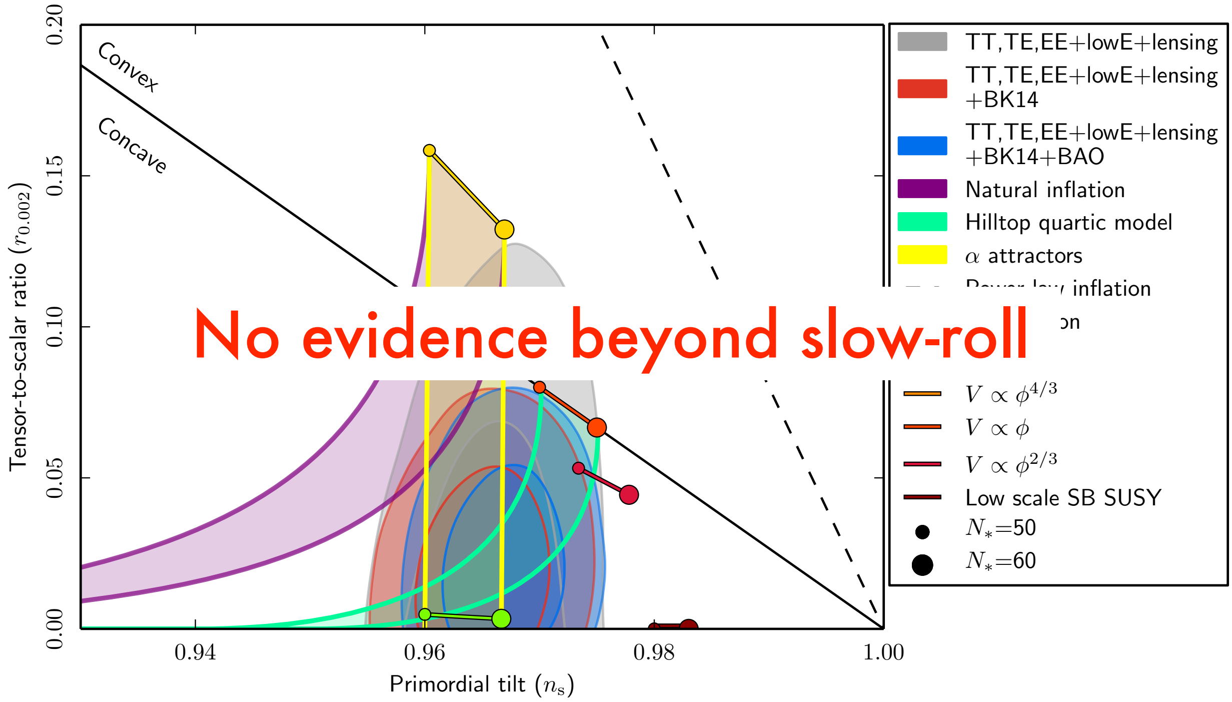


**No evidence beyond slow-roll**

PLANCK (2018)

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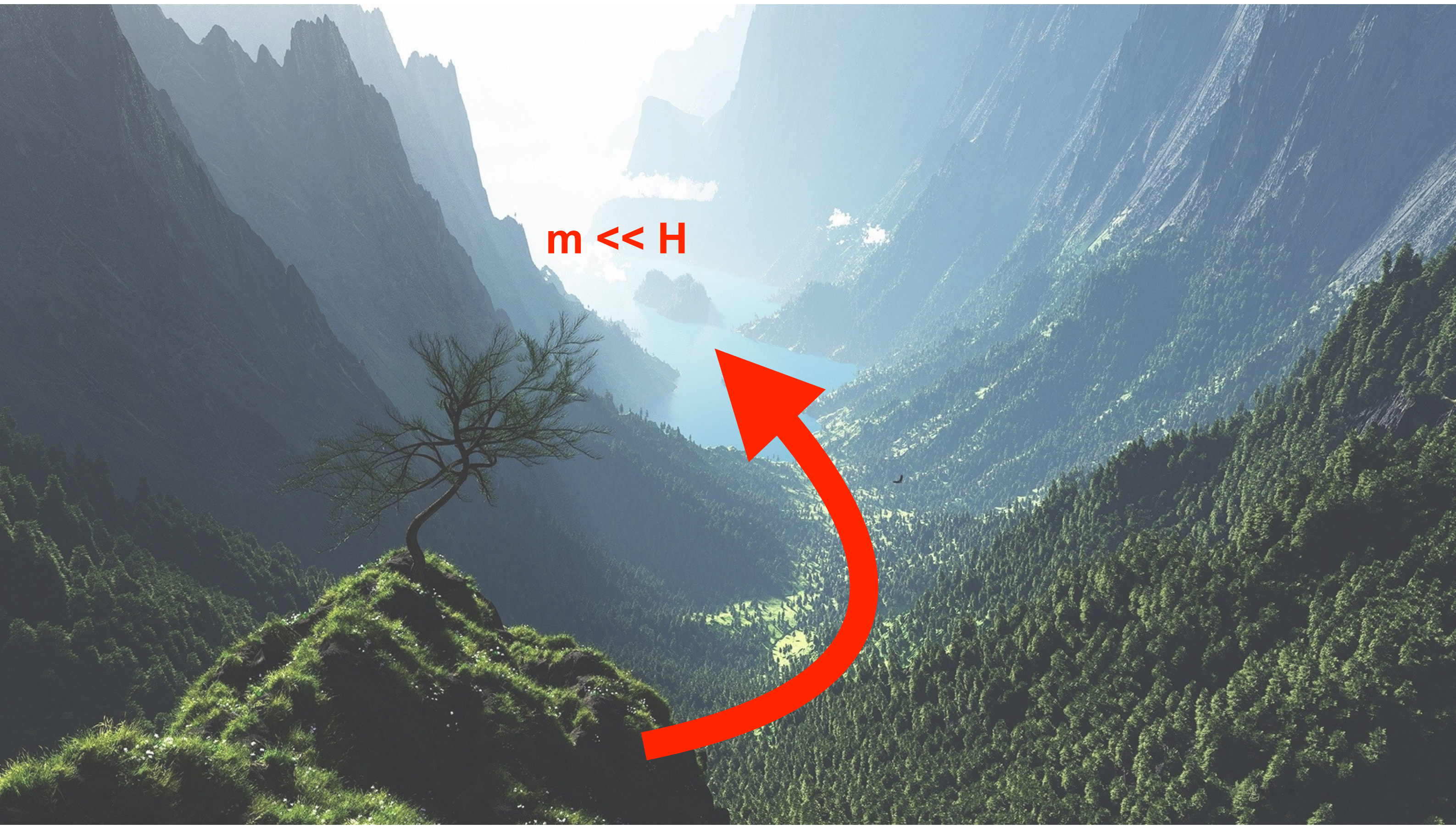
# UV completion of single-field inflation



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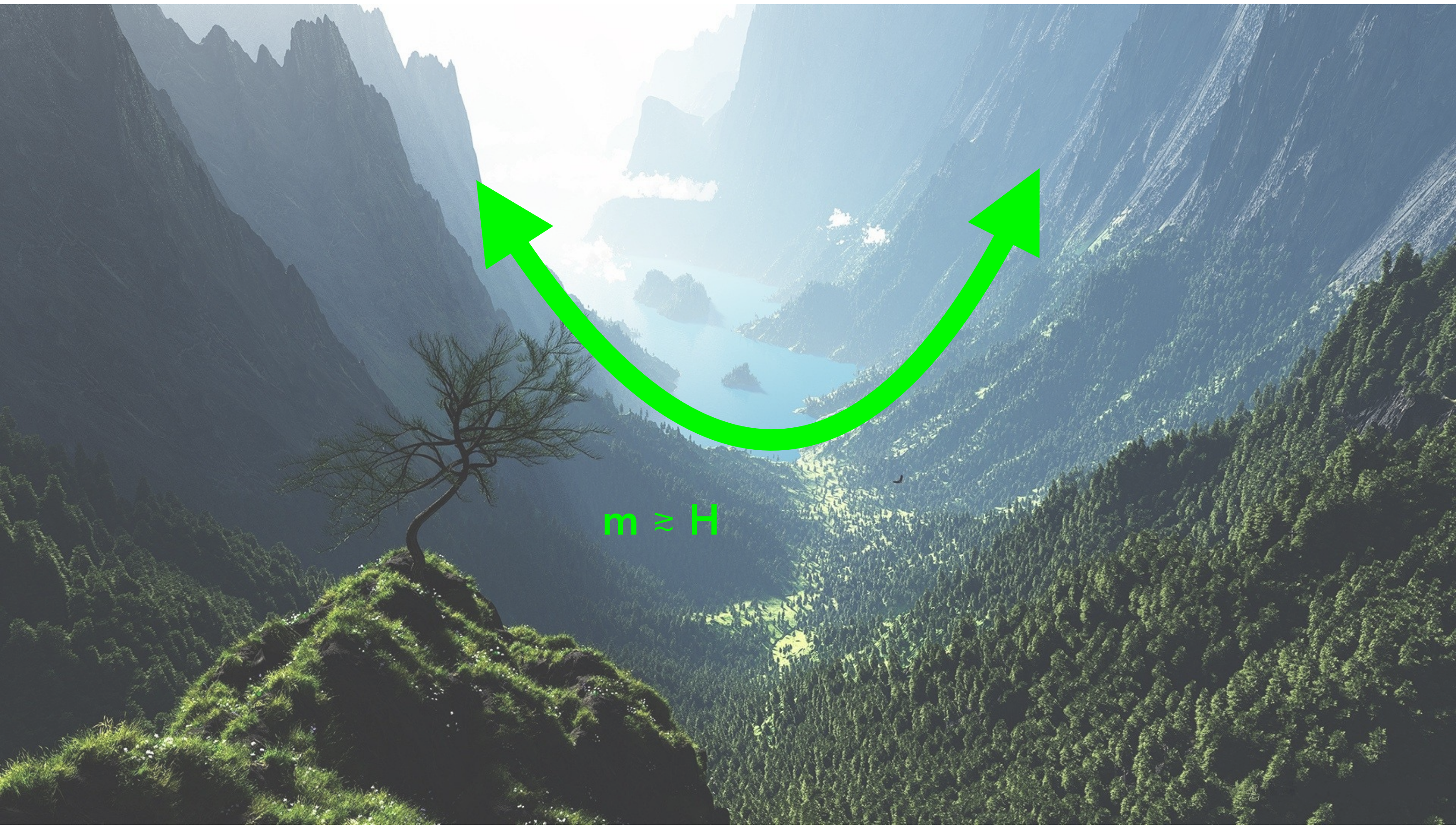

# The origin of heavy particles


- SUSY breaking / SUGRA ?

  Baumann & Green [1109.0292]

  Yamaguchi [1101.2488]

- heavy-lifted SM particles ?

  Chen, Wang & Xianyu [1610.06597]

  Kumar & Sundrum [1711.03988]

- GUT / extra-dim ?

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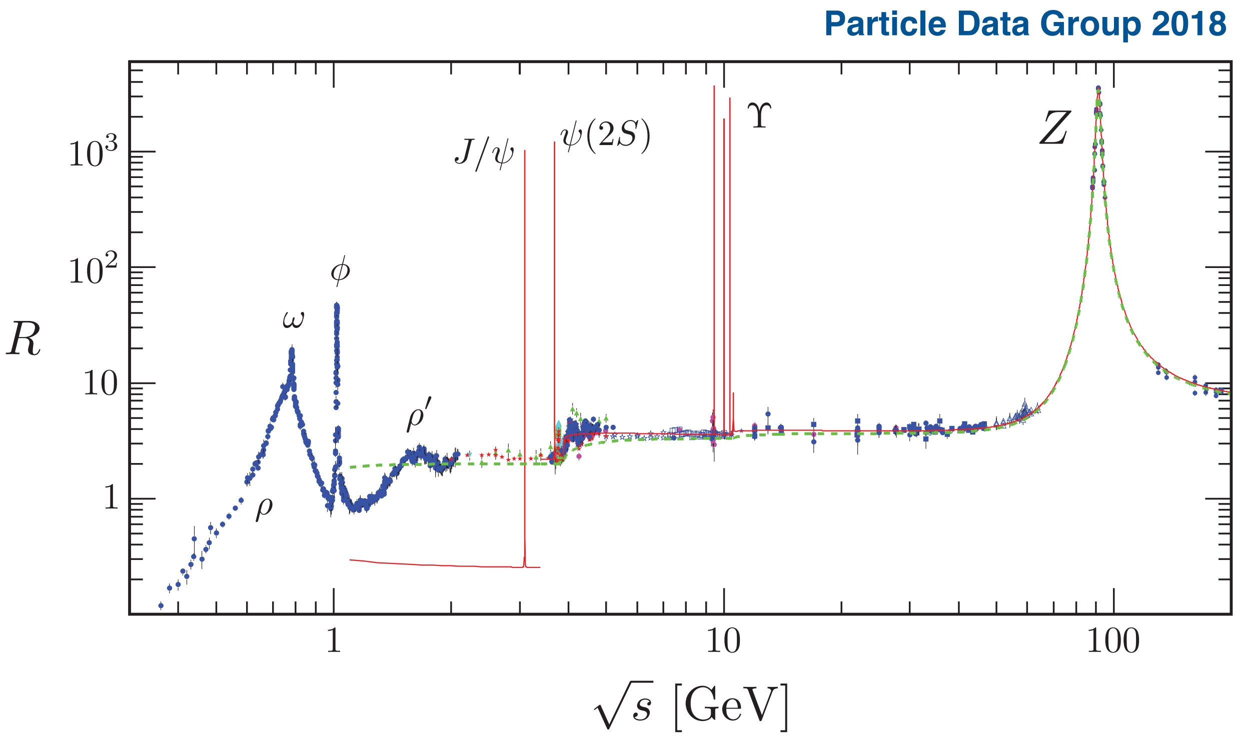
# Particle production
# & non-Gaussianity

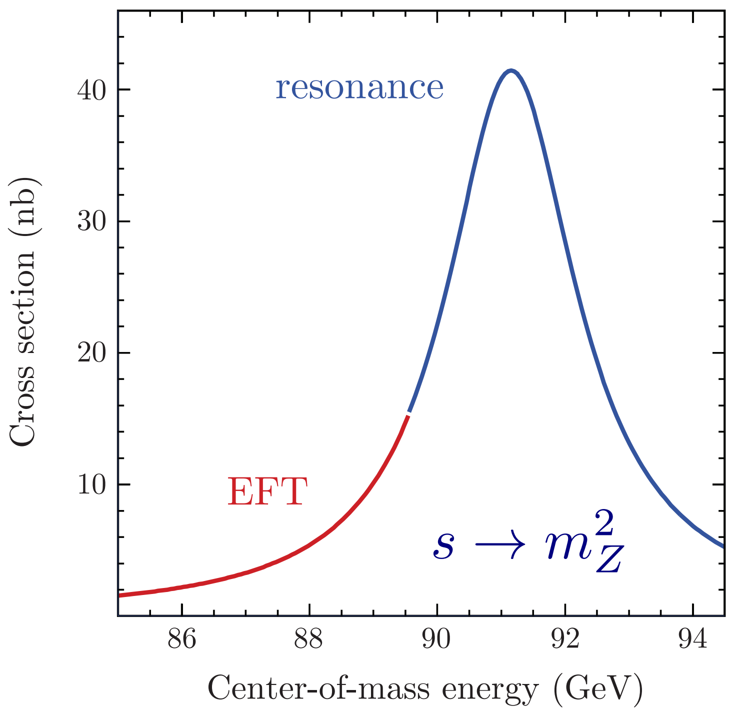
## The resonance peaks



## The Z resonance

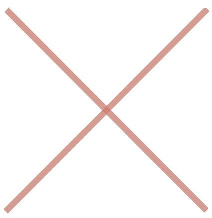
Arkani-Hamed et al. 1811.00024

$$A \sim \frac{g^2}{s - m_Z^2}$$




$$s \ll m_Z^2$$

**EFT at low energy**

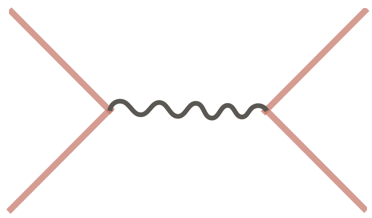


contact interactions

$$s \ll m_Z^2$$

c.f. the 4-Fermi theory

**Resonance at higher energy**

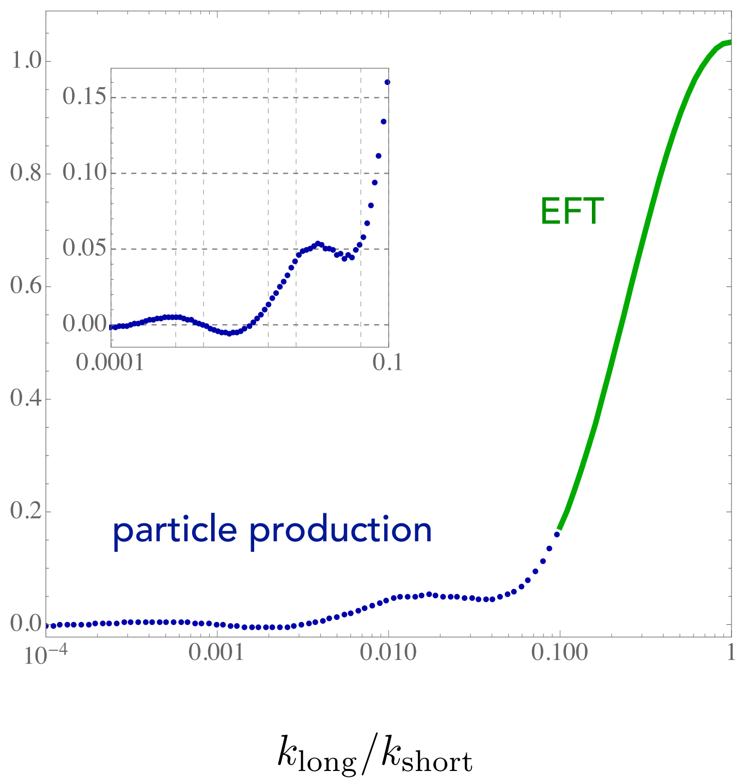


exchange interactions

$$s \to m_Z^2$$

# Analogy in cosmology

## The simplest non-Gaussian observable $\langle\zeta^3\rangle$



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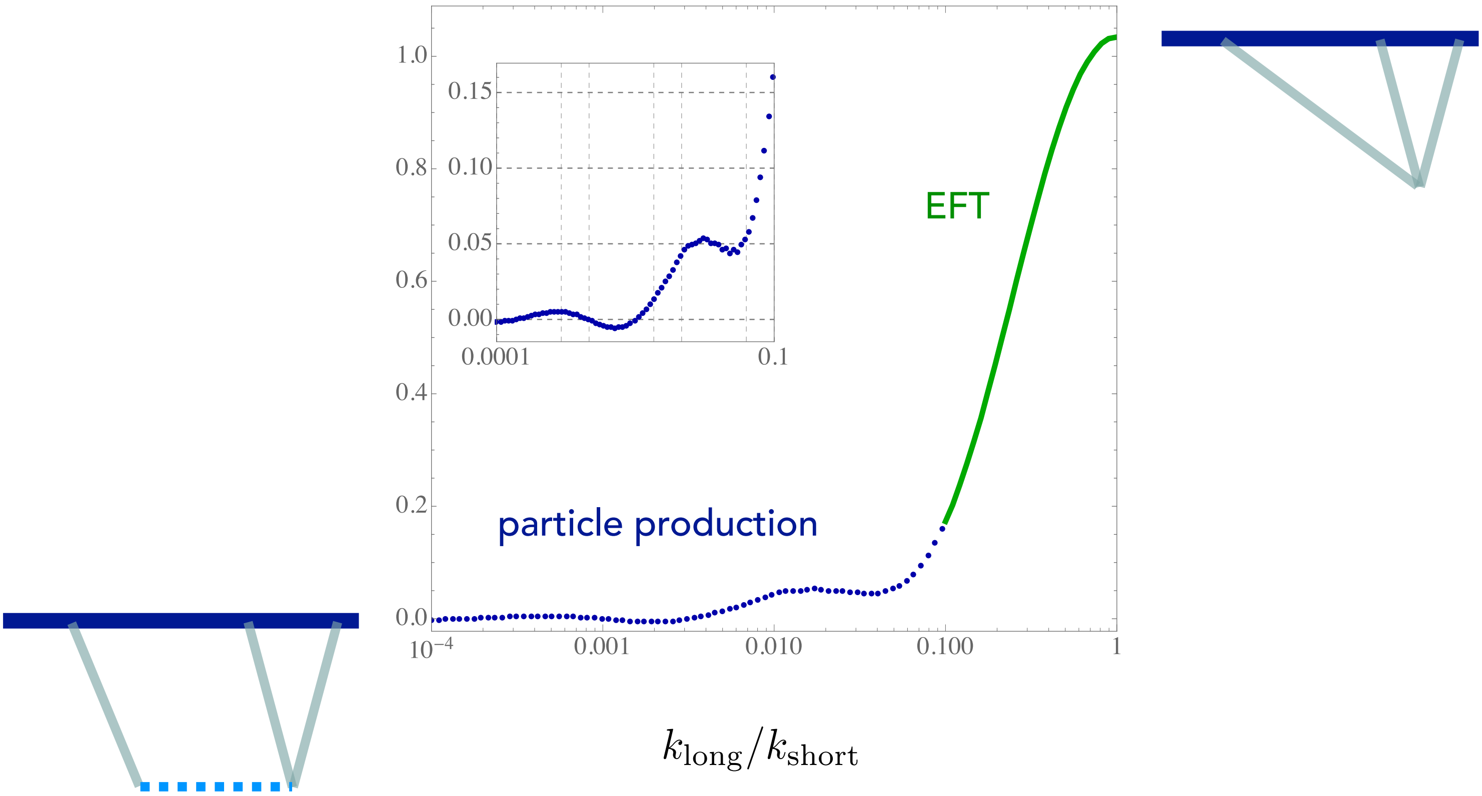
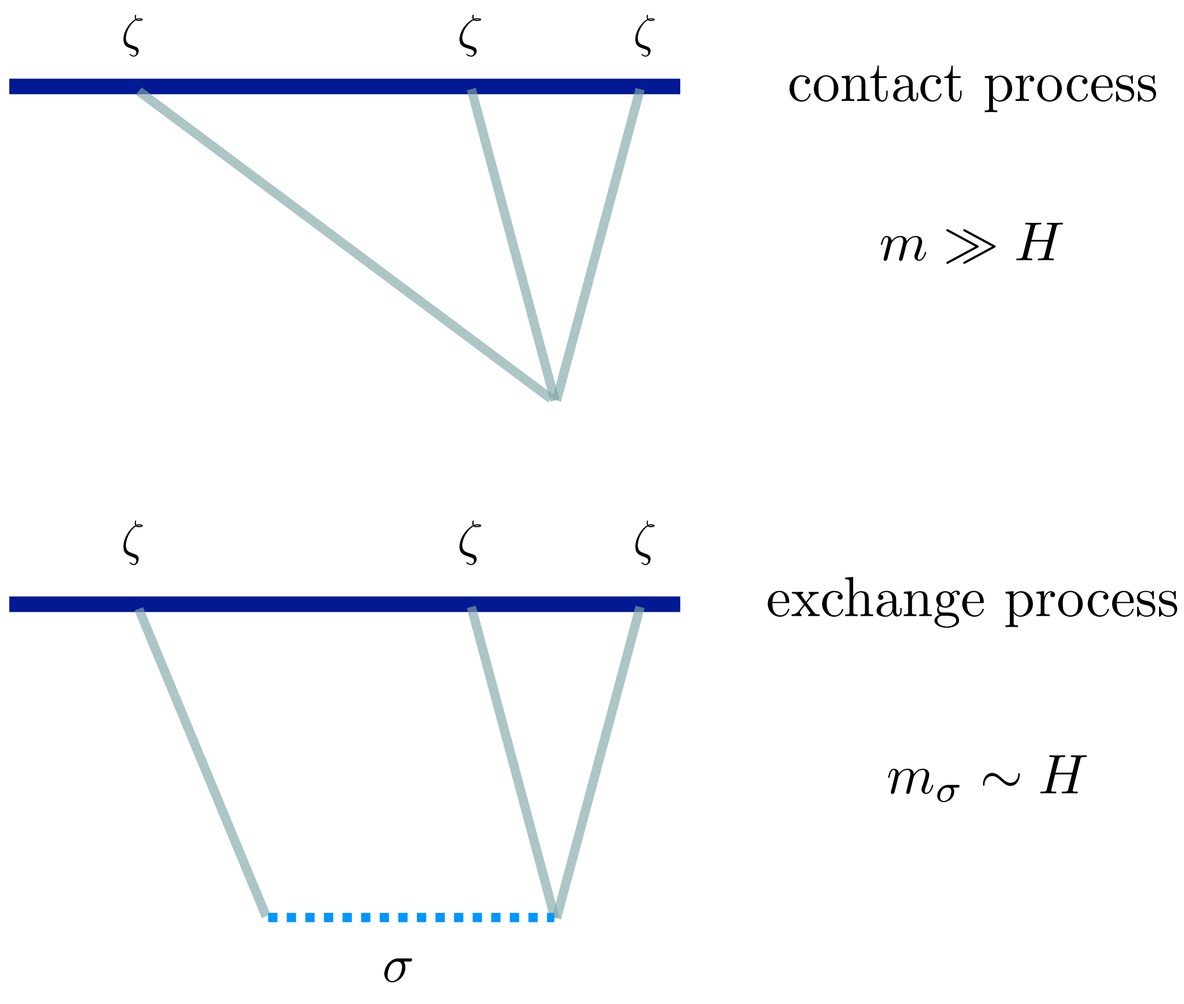


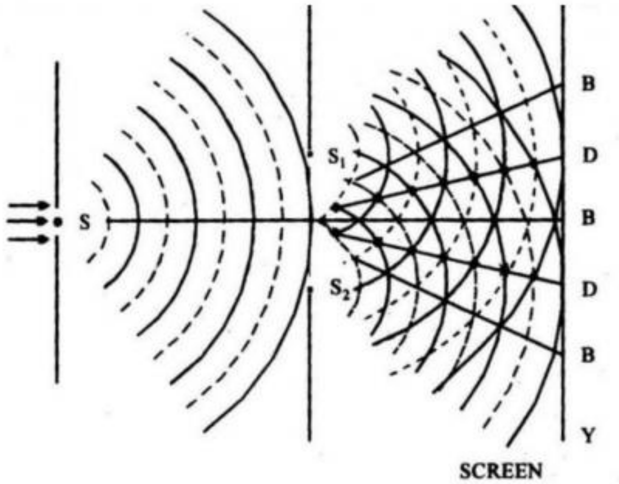


ζ
ζ
ζ
contact process
m ≫ H
ζ
ζ
ζ
exchange process
m_σ ∼ H
σ

## wave interference

### The source

$$\Psi_1(\vec{r},t) = A_1(\vec{r})e^{-i[\omega t - \alpha_1(\vec{r})]}$$
$$\Psi_2(\vec{r},t) = A_2(\vec{r})e^{-i[\omega t - \alpha_2(\vec{r})]}$$




credit: physics@TutorVista.com

### The intensity

$$I(\vec{r}) = \int dt\ \Psi\Psi^*$$
$$\sim A_1^2 + A_2^2 + 2A_1A_2\cos[\alpha_1 - \alpha_2]$$

$$\Psi = \Psi_1 + \Psi_2$$

## cosmological quantum interference

**Two sources in de Sitter space**

$$\zeta(k,\eta) \sim \hat{O}(\mathbf{k})\,\eta^{3/2}$$ analytic waves

$$\sigma(k,\eta) \sim \hat{O}^{+}(\mathbf{k})\,\eta^{\Delta+} + \hat{O}^{-}(\mathbf{k})\,\eta^{\Delta-}$$ analytic + non-analytic waves

fixed by isometries of dS: $\Delta^{\pm} = \frac{3}{2} \pm i\sqrt{\frac{m_\sigma^2}{H^2} - \frac{9}{4}}$

non-analytic effects

**The correlation function**

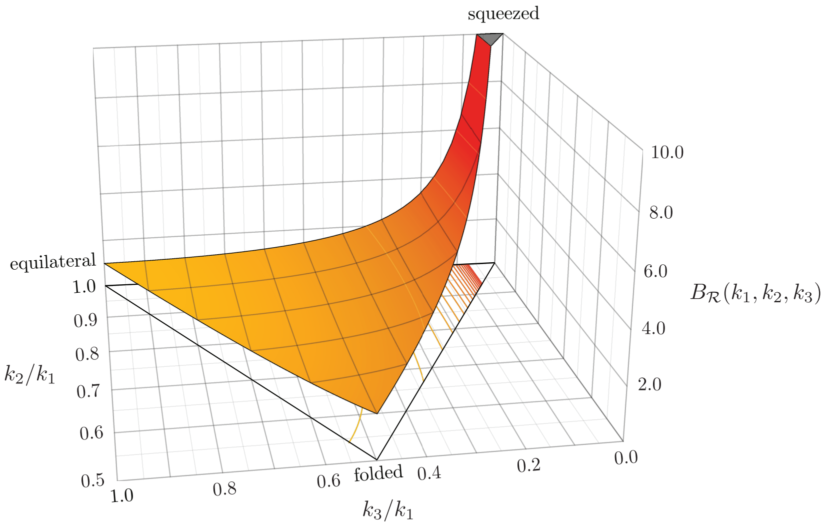
$$\left\langle \hat{Q}[\zeta, \dot{\zeta}, \sigma, \dot{\sigma}] \right\rangle = (\text{non-oscillatory}) + (\text{oscillatory})$$

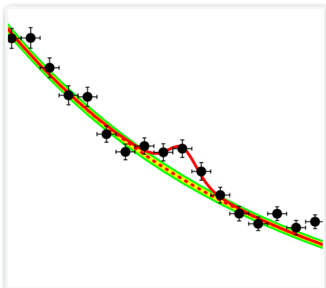
# Cosmological collider

— probing new physics during inflation

Assassi, Baumann & Green (2012)

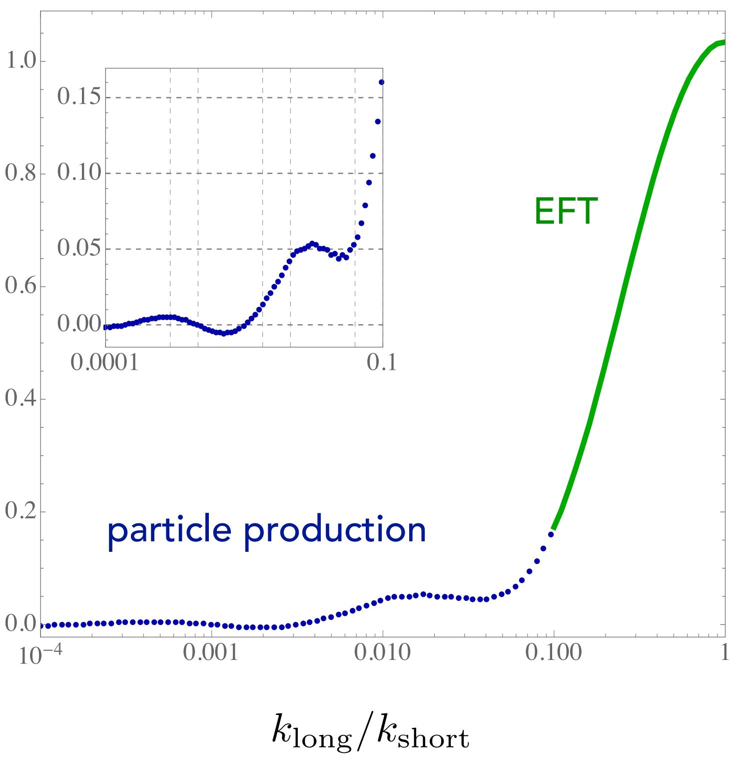
Arkani-Hamed & Maldacena (2015)



From Baumann & McAllister

## The simplest non-Gaussian observable $\langle\zeta^3\rangle$




size ⇒ particle couplings

oscillations ⇒ particle mass

angular dependence ⇒ particle spin

# Standard Model signals (Higgs)

# Cosmological collider

— probing signals of massive fields during inflation

**Steps towards new discovery:**

1. To work out the background signals during inflation.
2. To figure out how new particles enter the bispectrum.

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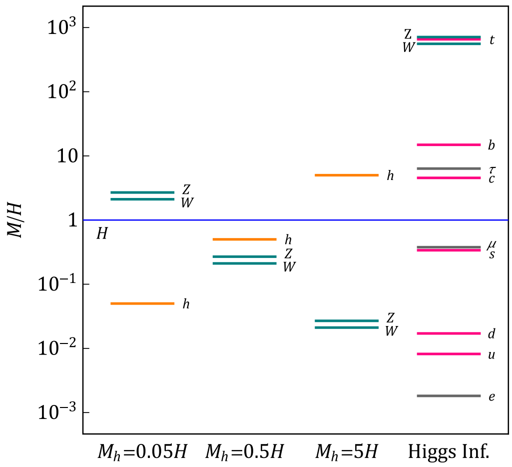


The SM mass spectrum during inflation

The squeezed SM bispectrum:

$$\langle \zeta_{k_1}\zeta_{k_2}\zeta_{k_3}\rangle' \equiv \frac{(2\pi)^4}{(k_1k_2k_3)^2}P_\zeta^2 S(k_1,k_2,k_3),$$

$$S_\alpha = \begin{cases} \mathcal{A}_\alpha\left(\frac{k_L}{k_S}\right)^{a_s-2\mu_s} + (\mu_s \to -\mu_s), & \mu_s \text{ real} \\ 2\mathrm{Re}\left[\mathcal{A}_\alpha\left(\frac{k_L}{k_S}\right)^{a_s-2\mu_s}\right], & \mu_s \text{ complex}, \end{cases}$$

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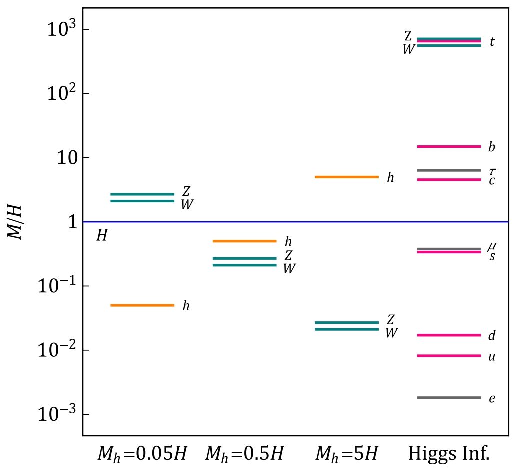
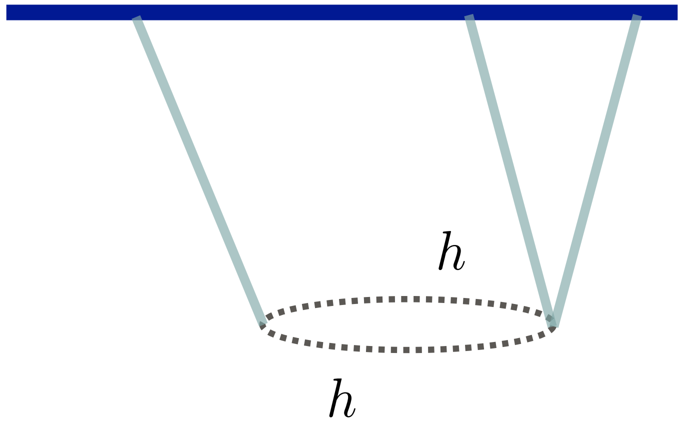


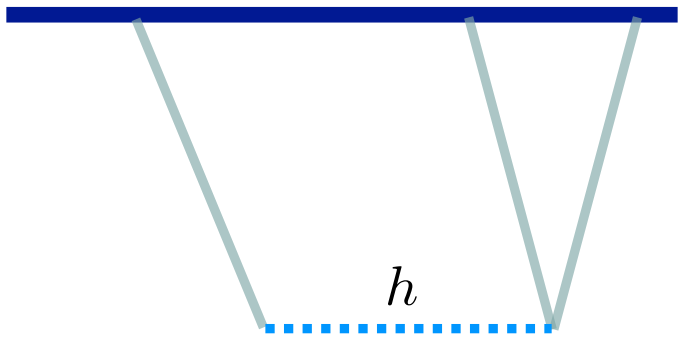

The SM mass spectrum during inflation

**SM corrections are usually negligible…**




Chen, Wang & Xianyu [1610.06597]

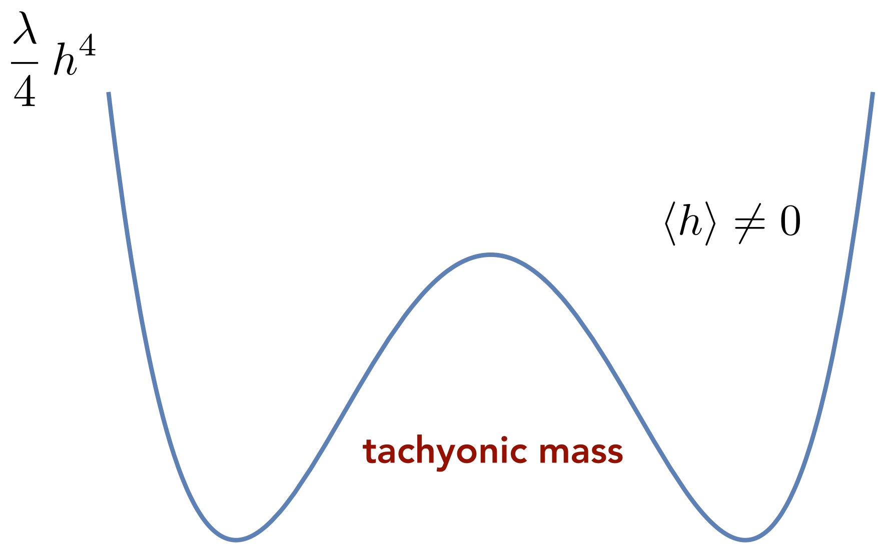
Chen, Wang & Xianyu [1612.08122]




Kumar & Sundrum [1711.03988]

$\Rightarrow$ larger $f_{\rm NL}$

# Spontaneous symmetry breaking during inflation




Kumar & Sundrum [1711.03988]

$-\xi R\, h^2$ or $-F(\phi, \partial_\mu \phi) h^2$ or …?

# Heavy-lifting from EFT

Kumar & Sundrum [1711.03988]

(weak-mixing)

$$\mathcal{L}_{\phi h} = \frac{c_1}{\Lambda}\partial_\mu\phi(\Phi_H^\dagger D^\mu \Phi_H) + \frac{c_2}{\Lambda^2}(\partial_\mu\phi)^2\Phi_H^\dagger\Phi_H + \frac{c_3}{\Lambda^4}(\partial_\mu\phi)^2|D_\mu\Phi_H|^2 + \cdots ,$$

conclusion for non-Gaussianity

$$\Phi_H = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ h\end{pmatrix}$$

| $F$ | Goldstone EFT with $\Lambda \sim 5H$ | Goldstone EFT with $\Lambda \sim 10H$ | Slow-roll Models with $\Lambda \sim 60H$ |
|---|---|---|---|
| $h$ | $1 - 10$ | $0.1 - 1$ | $0.01 - 0.1$ |
| $Z$ | $0.1 - 1$ | $0.01 - 0.1$ | $0.001 - 0.01$ |

## Heavy-lifting from broken symmetry

This work $$\mathcal{L} = \mathcal{L}_{\rm sr}(\phi) - \Phi_H^\dagger \Phi_H \frac{(\partial_\mu \phi)^2}{\Lambda^2} - |D_\mu \Phi_H|^2 - \lambda (\Phi_H^\dagger \Phi_H)^2,$$

non-trivial field space

$$\mathcal{L} \supset -\frac{1}{2}\left(1 + \frac{h^2}{\Lambda^2}\right)(\partial_\mu \phi)^2 - \frac{1}{2}(\partial_\mu h)^2$$

quadratic mixing

$$\delta \mathcal{L}_2 = 2 h_0 \dot{\theta}_0 \delta h \delta \dot{\theta} = \mu \delta h \delta \dot{\theta}_c$$

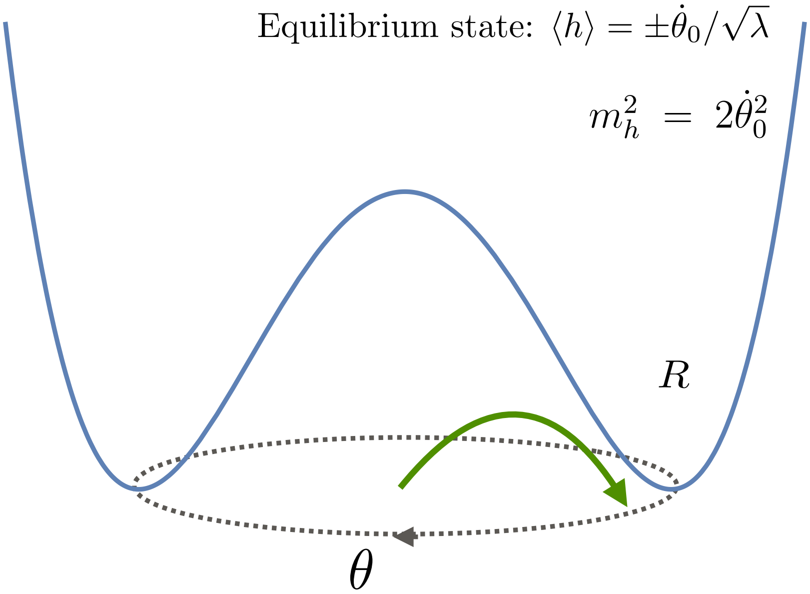
$$\mu \equiv \frac{2 h_0 \dot{\theta}_c}{R^2} = \frac{2 \dot{\theta}_0^2}{\sqrt{\dot{\theta}_0^2 + \lambda \Lambda^2}},$$

# Heavy-lifting from broken symmetry

non-trivial field space

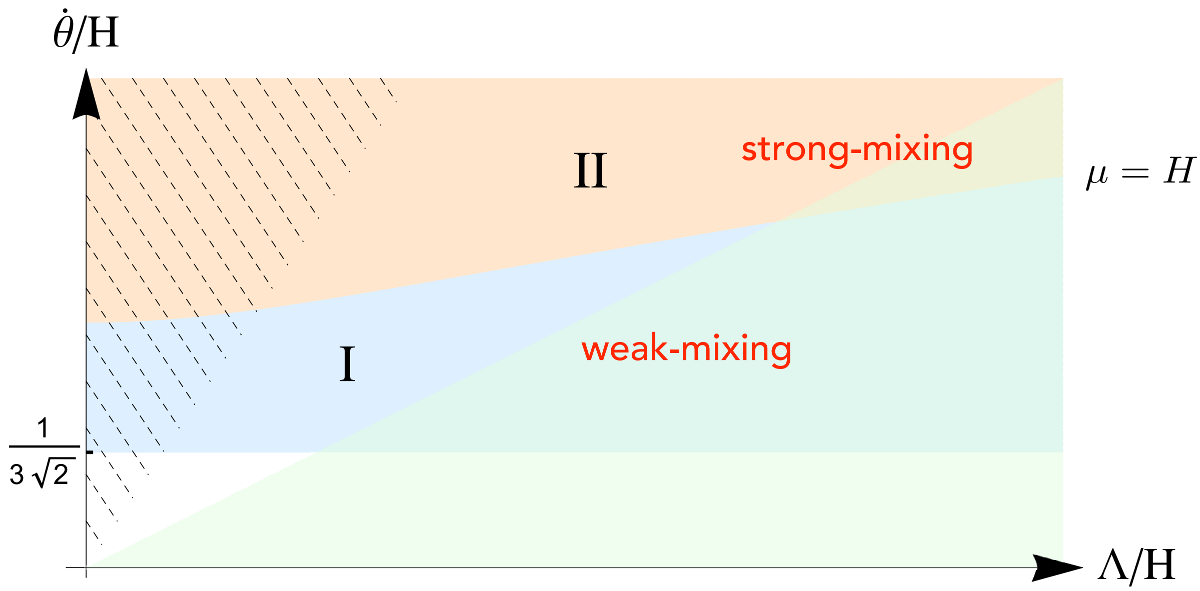
Equilibrium state: $\langle h \rangle = \pm \dot{\theta}_0 / \sqrt{\lambda}$

$$m_h^2 = 2\dot{\theta}_0^2$$



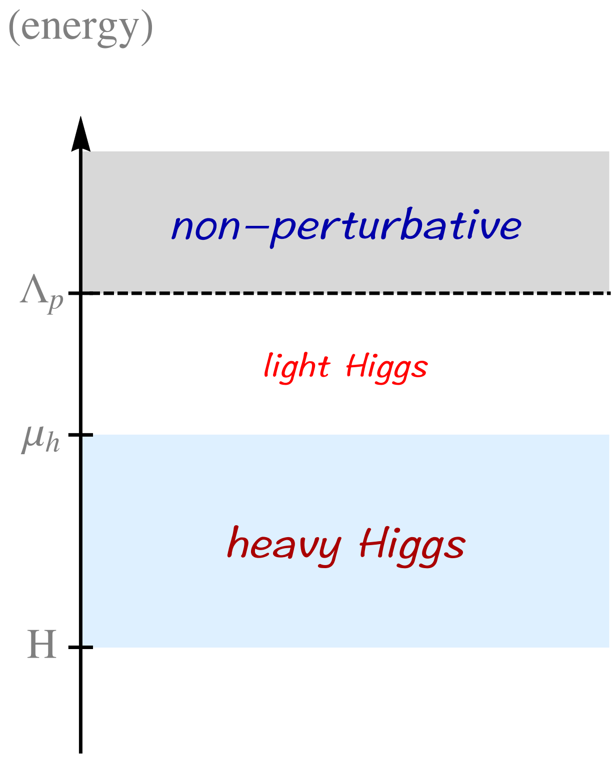

$R = (\Lambda^2 + h^2)^{1/2}, \qquad \theta = \phi/\Lambda,$

# Heavy-lifting from broken symmetry



scale of heavy Higgs

$$\mu_h \equiv (m_h^2 + \mu^2)^{1/2} = m_h / c_h$$

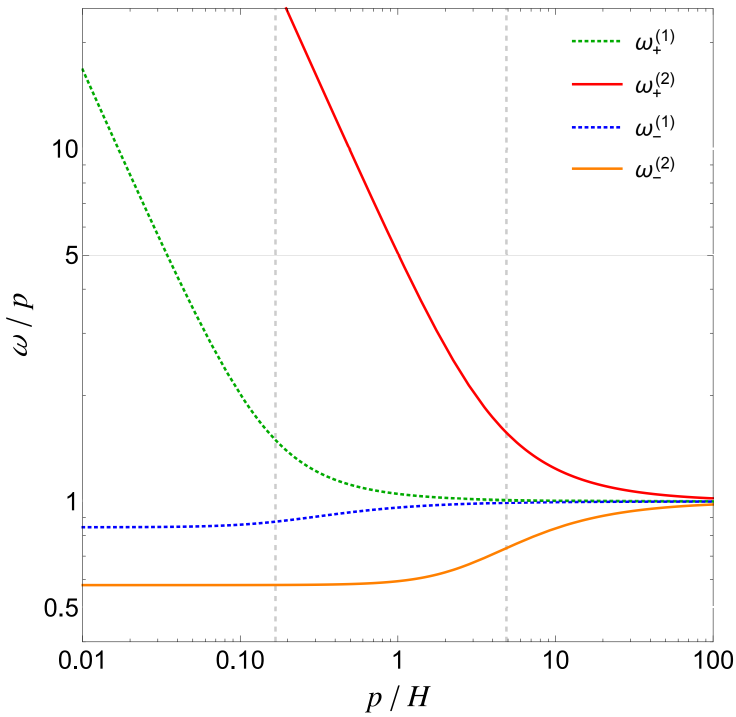



➤ strong-mixing does not necessarily violate perturbativity.

# dispersion relations

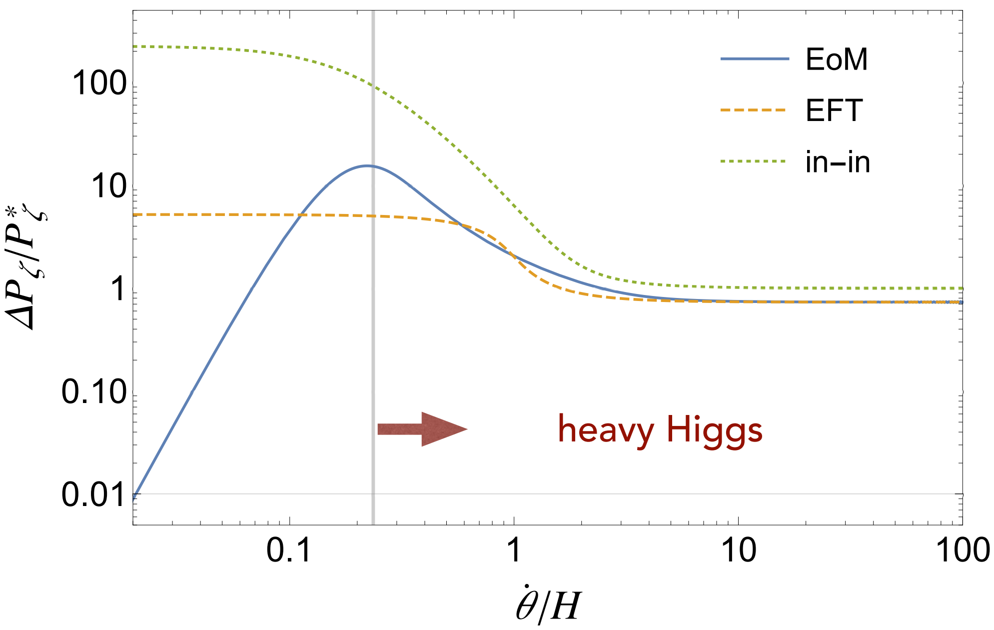
$$(1) \quad \mu_h < H$$

$$(2) \quad \mu_h > H$$



# Power spectrum

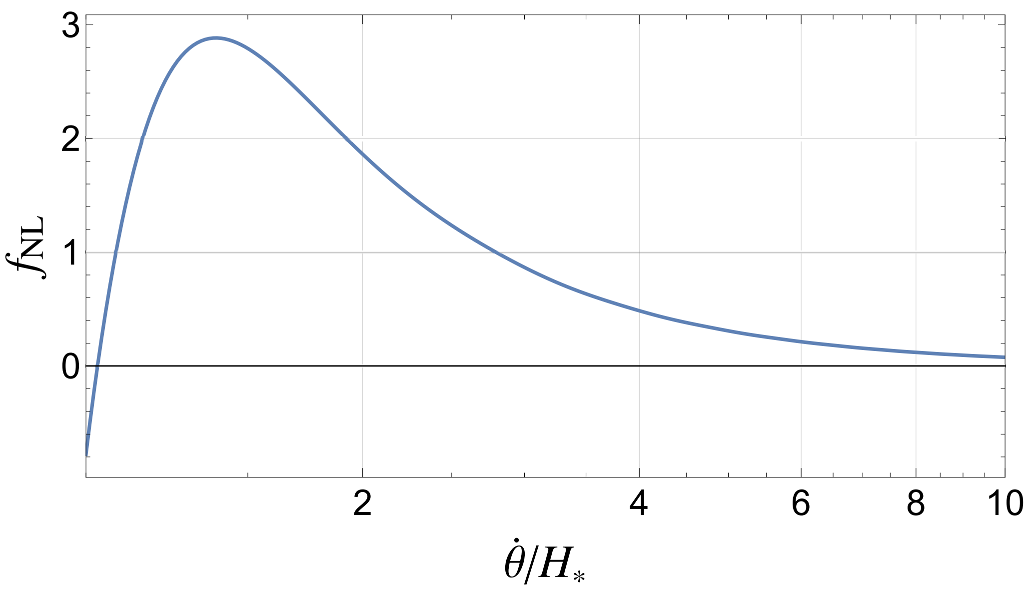
$\Delta P_\zeta$ : Higgs contribution to power spectrum



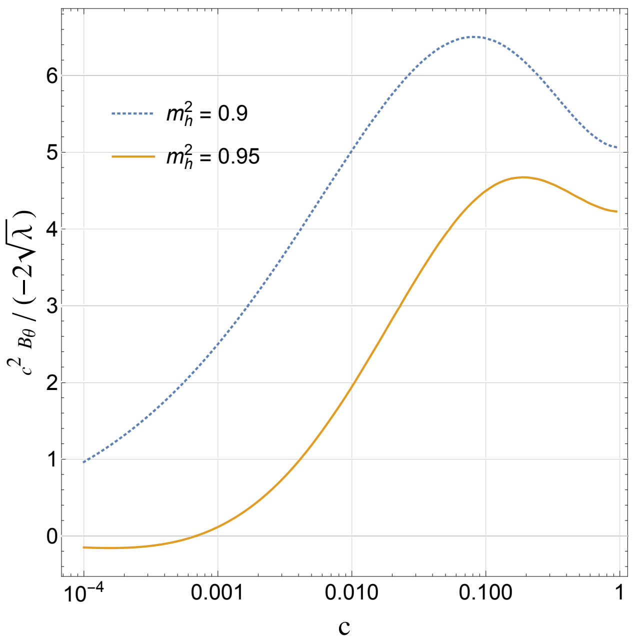

**two-field inflation** ⟷ **quasi-single field inflation**

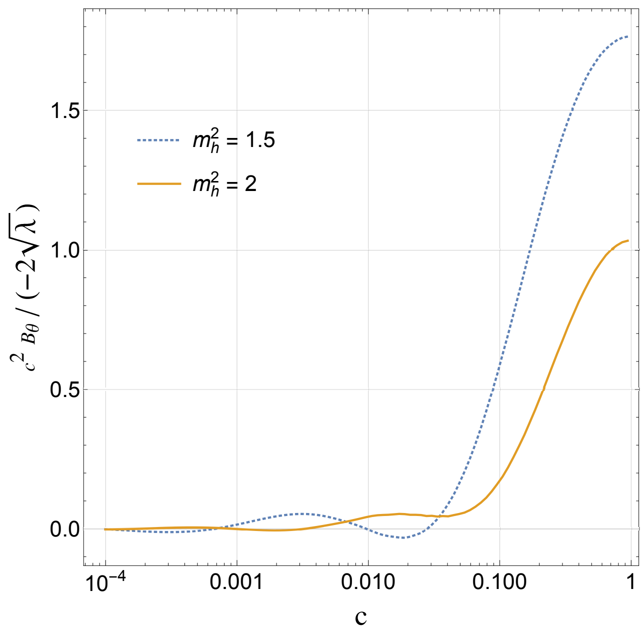
$c_h^2 \to 1$ $c_h^2 \to 1/3$

## Bispectrum (equilateral limit) $k_1 = k_2 = k_3$



## Bispectrum (from equilateral to squeezed) $k_1 = k_2 = ck_3$

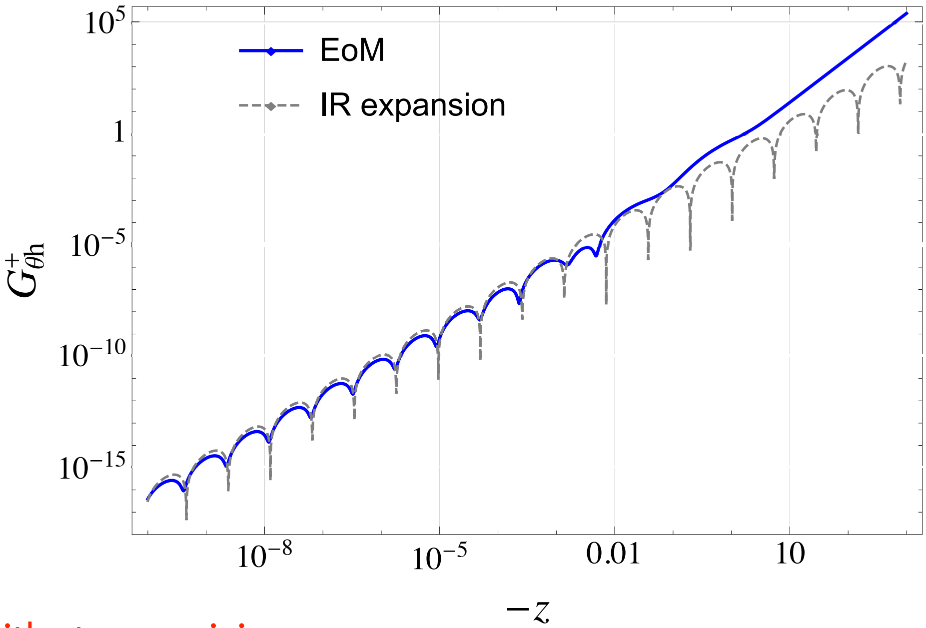



shapes beyond single-field inflation

# Non-analytic scaling

YPW [1812.10654]




the non-analytic scaling with strong-mixing:

$$L_h \to \sqrt{\frac{\mu_h^2}{H^2} - \frac{9}{4}} = \sqrt{\frac{m_h^2}{H^2 c_h^2} - \frac{9}{4}}$$

See also An et. al [1706.09971]
for three-point functions

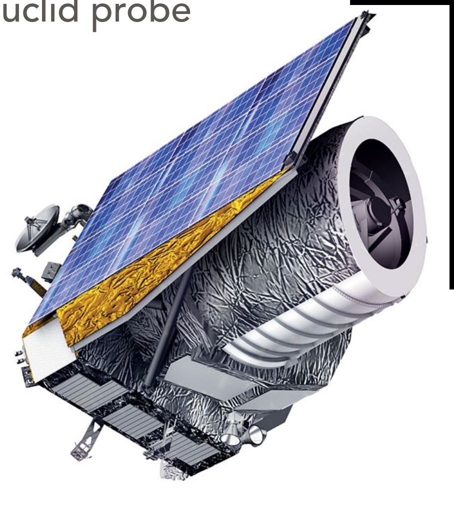
# REMARKS

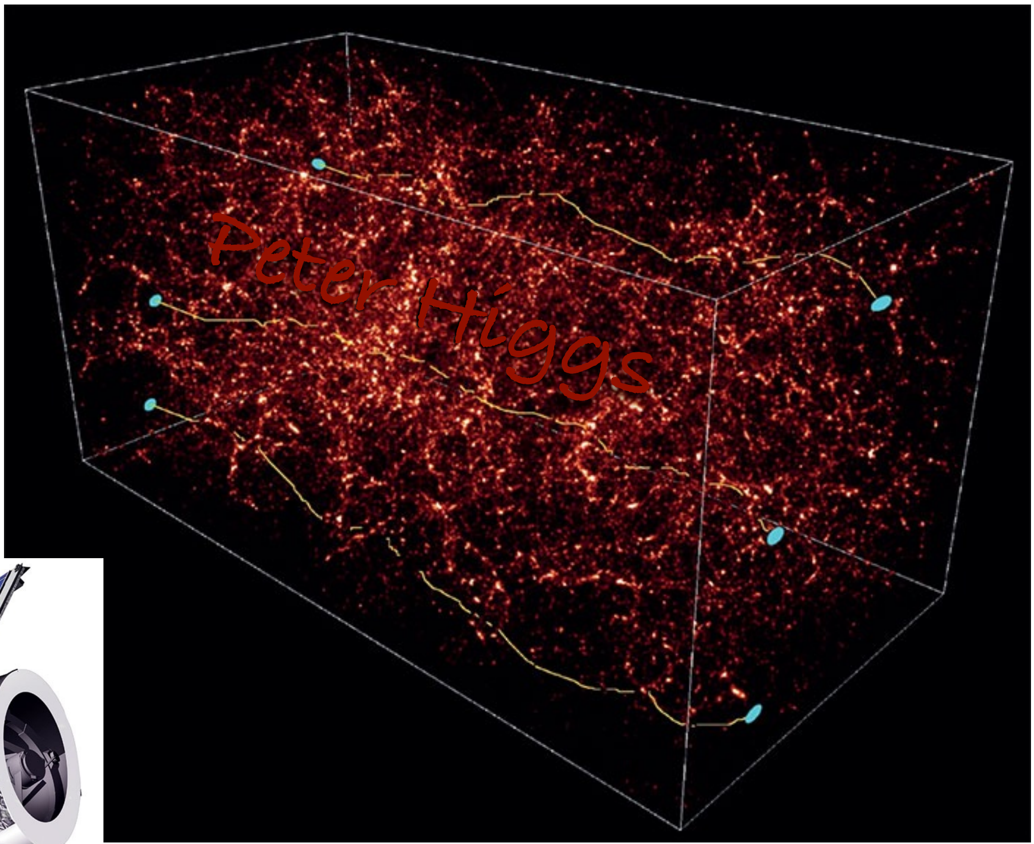
## and outlook

- Signals of heavy particle production are encoded as non-analytic momentum scaling in primordial non-Gaussianities.
- Heavy-lifting improves the observability of SM signals.
- The observability of Higgs signatures is further enhanced by a strong-mixing.
- Challenge for cosmological collider: SM signals or new physics?

$$L_h \to \sqrt{\frac{\mu_h^2}{H^2} - \frac{9}{4}} = \sqrt{\frac{m_h^2}{H^2 c_h^2} - \frac{9}{4}}$$

The Euclid probe






credit: CERNCOURIER