Cosmic Higgs Switching and its Probes

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Outline

- Motivation: Higgs oscillations in the early Universe and connection to fine-tuning

- Cosmological probes:

a. Particle production and gravitational waves

M. A. Amin, JF, K. Lozanov, M. Reece, 1802.00444, PRD

b. Inflaton spectrum and CMB observables

JF, M. Reece and Yi Wang, 1905.05764

Higgs dynamics in the early Universe

Higgs mass fixed today and measured at the LHC.

Yet in the early Universe, Higgs mass (in general, SM parameters) is not necessarily fixed and could vary with time.

How?

Mass depends on VEVs.

In the early universe, various weakly-coupled scalar fields could have had large field range and the Higgs could couple to them. So effective mass of the Higgs could be different.

Could have had unbroken electroweak symmetry or much more badly broken electroweak symmetry.

Even better, could have ***dynamics — oscillations between different electroweak phases.***

Well motivated theories supply lots of good candidates of scalars with large field range: moduli, saxions, D-flat directions, radion...

Classic example in supersymmetric theories: **modulus/moduli**

A scalar with a flat potential; when the Hubble drops around its mass, it starts to oscillate coherently around the minimum.

Ubiquitous in string construction and low energy pheno models. It couples to the SM through high scale suppressed operators.

A simple model

$$V(\chi, h) = +\frac{1}{2}m_\chi^2\chi^2$$

Modulus potential

modulus

$$- m_h^2 h^\dagger h + \frac{\lambda}{4}|h|^4,$$

SM Higgs potential

$$+ \frac{M^2}{f}\chi h^\dagger h$$

Trilinear coupling between Higgs and modulus

A simple model

$$V(\chi, h) = +\frac{1}{2}m_\chi^2\chi^2$$

$$- m_h^2 h^\dagger h + \frac{\lambda}{4}|h|^4,$$

$$+\frac{M^2}{f}\chi h^\dagger h$$

f: large field range of χ;

M: high energy scale (in SUSY, soft mass/natural Higgs mass without tuning, more later)

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$$V(\chi, h) = +\frac{1}{2}m_\chi^2\chi^2$$

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Effective Higgs mass: $-m_h^2 + \frac{M^2}{f}\chi$

At $\chi_0 = \frac{m_h^2}{M^2} f$ **, Higgs mass changes sign!**

A simple model

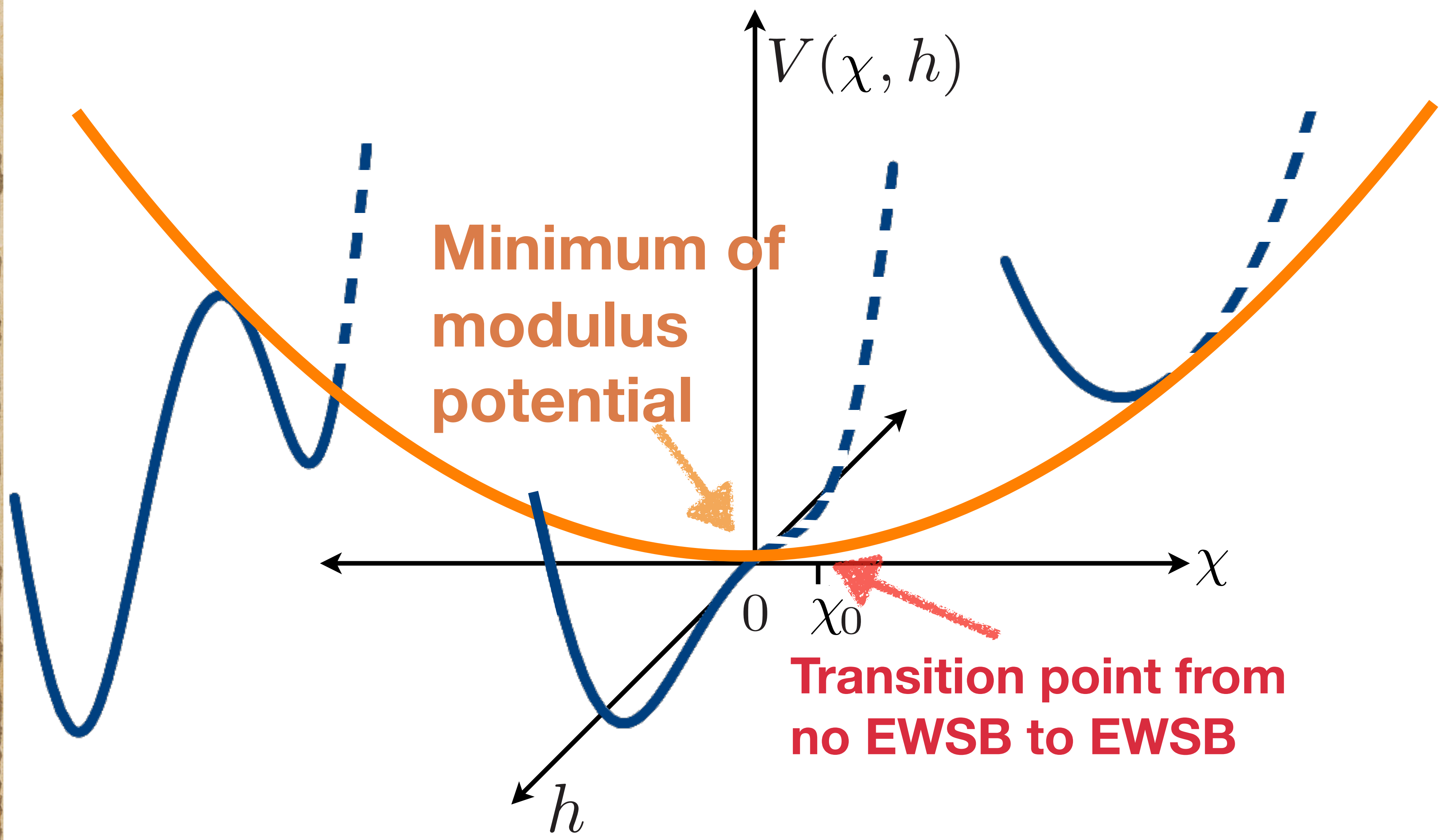
$$V(\chi, h) = +\frac{1}{2}m_\chi^2\chi^2$$
$$- m_h^2 h^\dagger h + \frac{\lambda}{4}|h|^4,$$
$$+ \frac{M^2}{f}\chi h^\dagger h$$

f: large field range of χ;

M: high energy scale (in SUSY, soft mass/natural Higgs mass without tuning, more later).

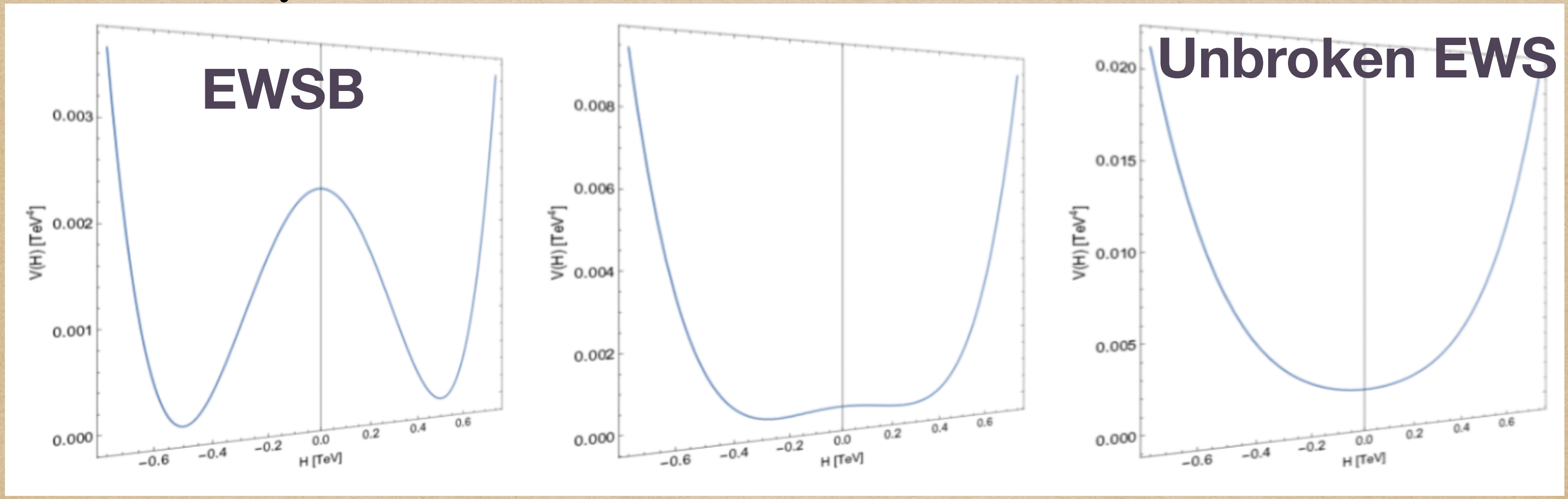
$M^2 >> m_h^2$ (fine-tuned), trilinear coupling dominates

Modulus-Higgs potential



Connection to Fine-tuning

Fine-tuning: if we could change SM parameters, e.g., Higgs mass parameter, the electroweak physics could be changed dramatically.



Today, SM parameters are fixed. Yet in the early Universe, the toy model I just present realizes the dynamics associated with fine-tuning: *oscillations between different electroweak phases.*

Embed the toy model in SUSY

Modulus superfield: $\boldsymbol{X} \supset X + F_X \theta^2$

$\langle \boldsymbol{X} \rangle = X_0 + F_{X,0}\theta^2, \quad \text{where} \quad X_0 \sim m_{\rm pl}, \quad F_{X,0} \sim m_{3/2} m_{\rm pl}.$

$$\int d^4\theta \frac{\xi_{XZ}}{m_{\rm pl}^2} \boldsymbol{X}^\dagger \boldsymbol{X} \boldsymbol{Z}^\dagger \boldsymbol{Z}$$

Z: generic chiral superfield (e.g., Higgs superfield)

$$\xi_{XZ} \frac{|F_X|^2}{m_{\rm pl}^2} Z^\dagger Z,$$

soft mass: $m_{3/2}^2$

$$\frac{2\xi_{XZ} \mathrm{Re}(F_{X,0} m_X)}{m_{\rm pl}^2} \mathrm{Re}(X) Z^\dagger Z.$$

trilinear coupling: $m_{3/2}^2/m_{\rm pl}$

High-scale/meso-tuned SUSY

Given the current LHC data, nature is probably tuned or more precisely "meso-tuned": Higgs is the only light scalar with a little hierarchy (tuned at percentage level or worse) and no other random light scalars around.

$$V(\chi, h) = +\frac{1}{2} m_\chi^2 \chi^2$$
$$- m_h^2 h^\dagger h + \frac{\lambda}{4}|h|^4,$$
$$+ \frac{M^2}{f}\chi h^\dagger h$$

$M^2 \sim m_{3/2}^2 >> |m_h^2|$

Embed in meso-tuned high-scale SUSY

- There should be a dynamical explanation for the Higgs mass and a solution to the big hierarchy problem like SUSY.
- Not trying to construct a new (cosmic) solution to the little hierarchy problem. Instead, we want to explore whether there could be interesting cosmological signatures arising from fine-tuning/little hierarchy.

Possibility 1: Particle production and fragmentation

Amin, Fan, Lozanov, Reece, '18

When the Higgs mass flips sign, there could be a tachyonic instability:

$$\ddot{h}_k + \omega_k^2 h_k = 0, \quad \text{with} \quad \omega_k(t)^2 = k^2 + m_{\text{eff}}^2(\chi)$$

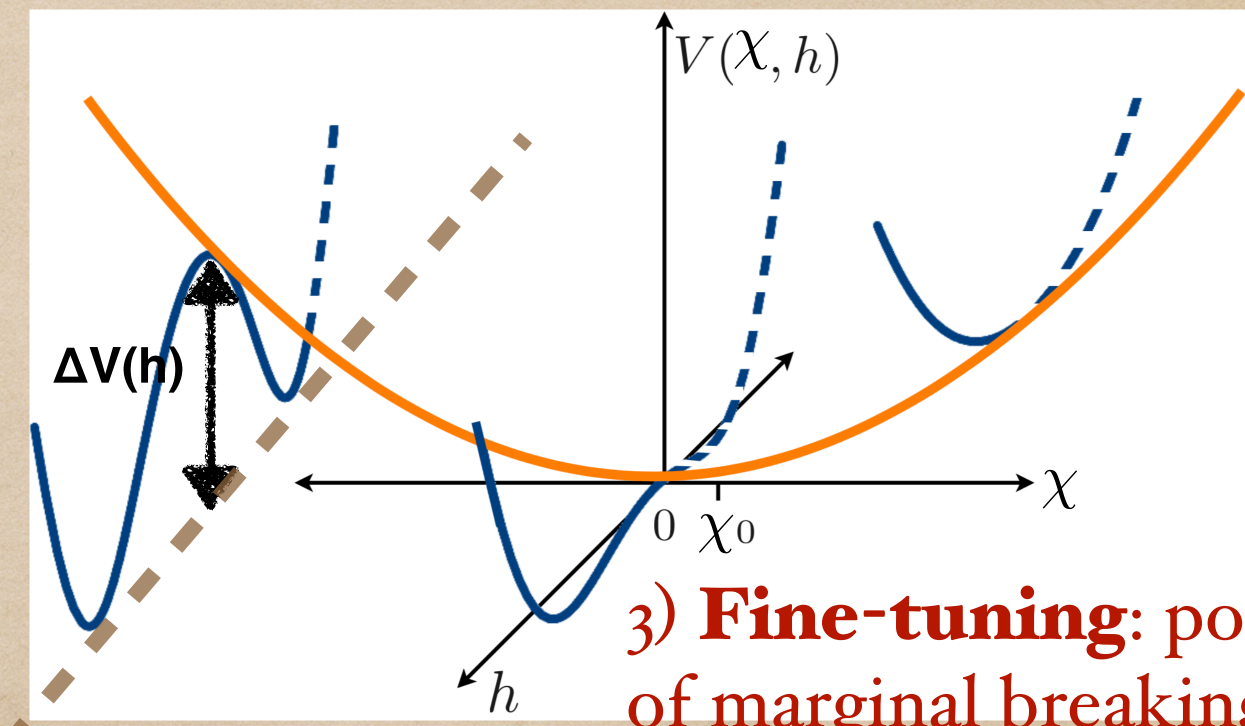
When $\omega_k^2 < 0$, the Higgs modes grow exponentially.

That is, there is a tachyonic particle production process when the modulus flips to the tachyonic side, converting modulus energy into the Higgs energy.

The produced Higgs could back-react on the modulus and fragment the modulus field.

We argued, with a combination of numerical and analytic computations, that this requires three conditions:

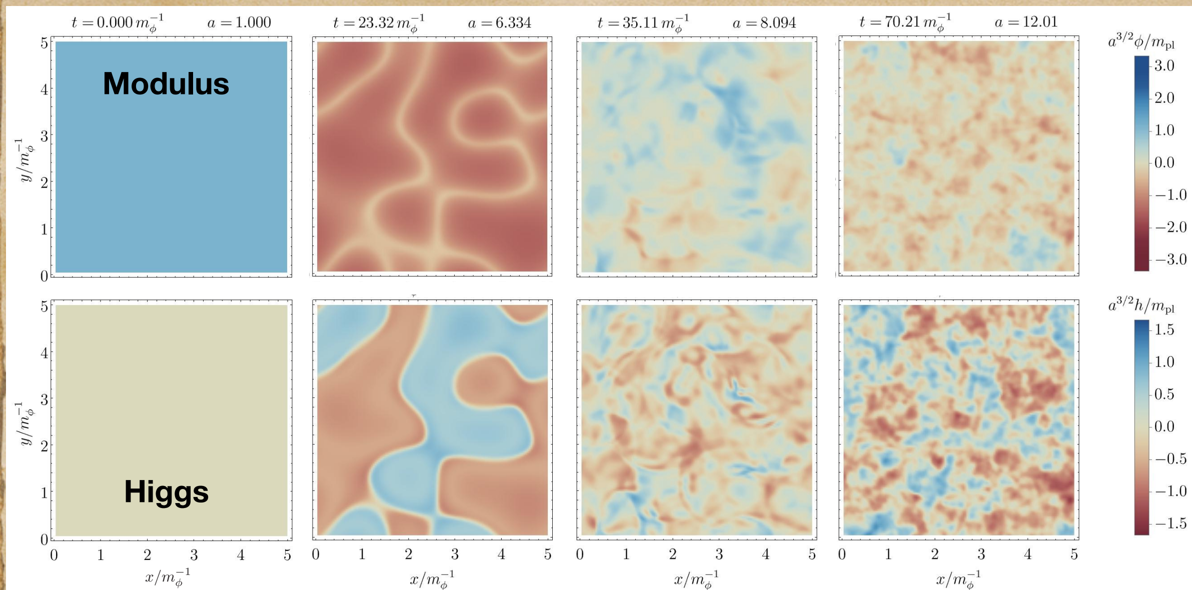
1) $\Delta V \sim V$, **nearly flat direction**



3) **Fine-tuning**: point of marginal breaking near minimum

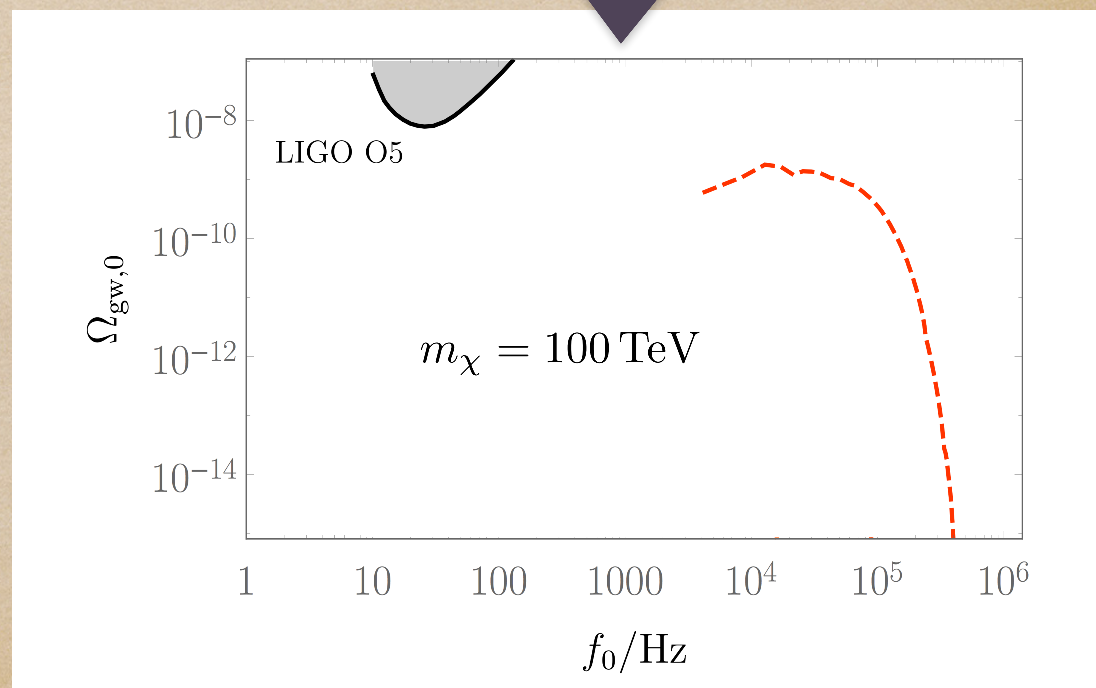
2) **Light modulus**: $m_\chi < M$

Suggestive: apply to fine-tuned SUSY Higgs boson with a flat direction in the field space.



Fragmentation

Gravitational waves



Possibility 2: imprint on the inflaton spectrum

Fan, Reece, Wang, 1905.05764

Consider a low-scale inflation model. On top of the toy model I showed, include the Higgs coupling to the inflaton.

modulus

$$V(\chi, h, \phi) = +\frac{1}{2}m_\chi^2\chi^2$$

inflaton

$$- m_h^2 h^\dagger h + \frac{\lambda}{4}|h|^4,$$

$$+ V(\phi)$$

Inflaton potential

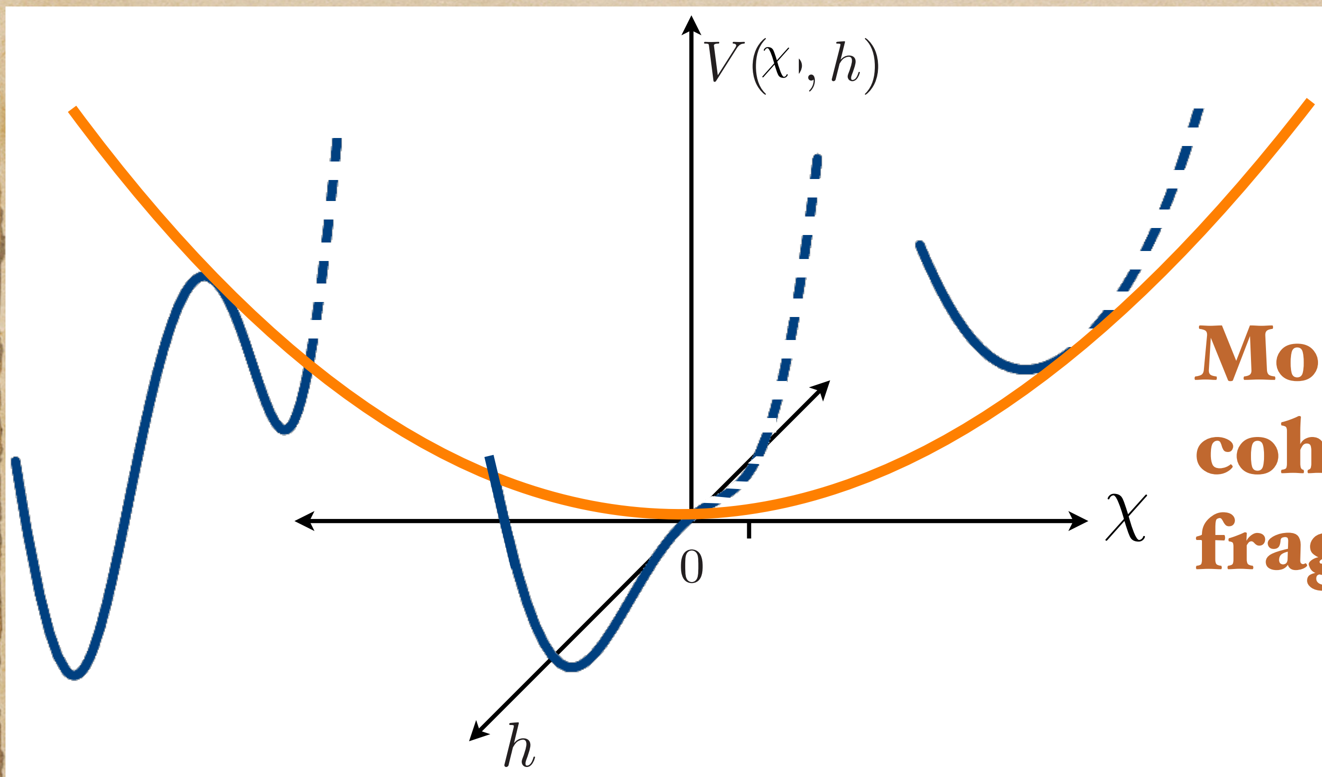
$$+ \frac{M^2}{f}\chi h^\dagger h$$

$$+ \frac{y}{\Lambda^2}(\partial\phi)^2 h^\dagger h$$

coupling between inflaton and the Higgs

Consider: *a)* energy density is dominated by inflaton. *b)* interactions between the higgs and inflaton could be treated as perturbations; *c)* back-reaction from Higgs to modulus is small.

modulus field range	f
energy scale suppressing Higgs and inflaton coupling	Λ
natural Higgs mass	M
modulus mass	m_χ
weak scale	m_h
Hubble	H



Modulus oscillates coherently (no fragmentation)

Higgs oscillates between different phases

How will the Higgs oscillations affect the inflaton spectrum through $(\partial\phi)^2 h^2$ **?**

Classical primordial clocks

Chen, Namjoo, Wang, ... '11 - present

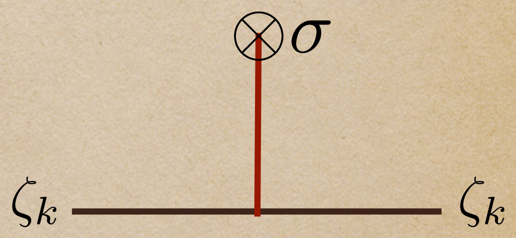
Heavy fields could always be present during inflation (heavy fields from UV physics, SUSY breaking; SM fields obtain masses of Hubble through gravitational coupling...)

Classical oscillation of a massive field (due to a sharp turn in the inflaton trajectory)

$$\sigma \propto e^{imt} \ .$$

Density fluctuation (subhorizon)

$$\zeta_{\mathbf{k}} \propto e^{-ik\tau}$$



Correction to the spectrum

$$\langle \zeta_{\mathbf{k}}^2 \rangle \supset \int e^{i(mt-2k\tau)} d\tau \ .$$

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Resonances: (saddle point approximation)

$$\frac{d}{dt}(mt - 2k\tau) = 0 \qquad d\tau = dt/a(t)$$

$$\frac{k}{a} = \frac{m}{2} \Rightarrow \qquad a(t_*) = a(\tau_*) = 2k/m$$

Inverse function

Correlation function

$$\langle \zeta_{\mathbf{k}}^2 \rangle \supset e^{i(mt_* - 2k\tau_*)} \quad \Rightarrow \quad \langle \zeta_{\mathbf{k}}^2 \rangle \supset \exp\left[im\, t(2k/m) - 2ik\, \tau(2k/m)\right] \ ,$$

Scale factor evolution directly recorded in the phase.

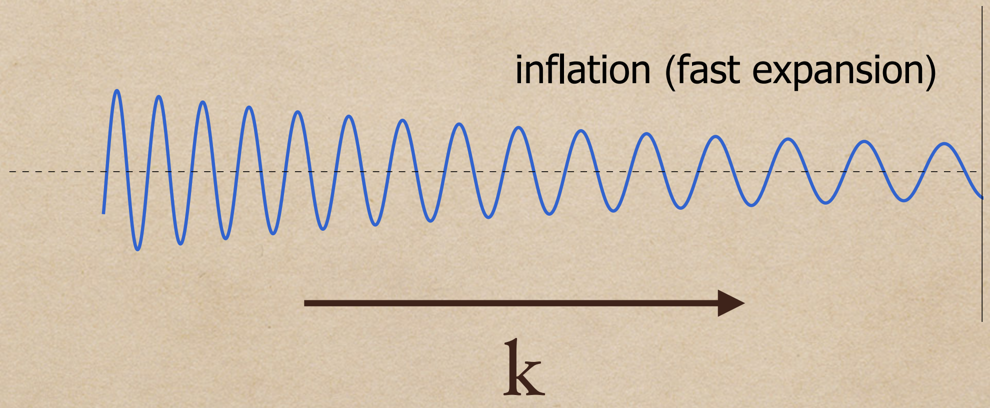
Could be used to distinguish inflation and alternatives.

Inflation $a(t) = e^{Ht}$

Resonances $a(t_*) = a(\tau_*) = 2k/m$ → $t_* \sim \frac{1}{H} \log(k/m)$

Correction to two-point function

$\langle \zeta_k^2 \rangle \supset e^{i(mt_* - 2k\tau_*)} + h.c.$ → $\langle \zeta_k^2 \rangle \sim \sin\left(\frac{m}{H} \log(k/m)\right)$



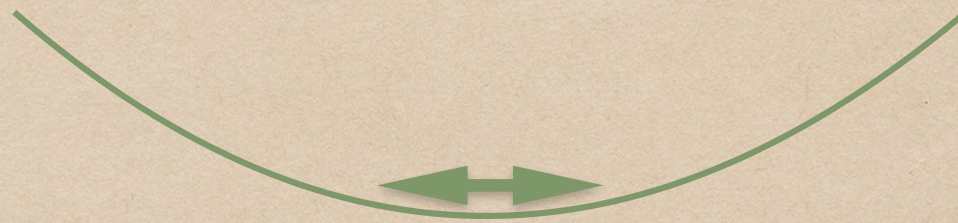
As an aside, quantum fluctuations of massive field modify the bi-spectrum (non-Gaussianity).

e.g, quasi-single inflation: Chen, Wang '09 ...

could be used to:

a) differentiate inflation and alternatives: Chen, Namjoo, Wang, '15...;
b) probe masses and spins of heavy fields: "Cosmological collider physics" Arkani-Hamed, Maldacena '15 ... In particular, could be used to probe Higgs sector and high dimensional GUT, Kumar and Sundrum '17, '18.

Back to our model, for the modulus, when back-reaction is negligible,



$$\chi = f a^{-3/2} \cos(m_\chi t)$$

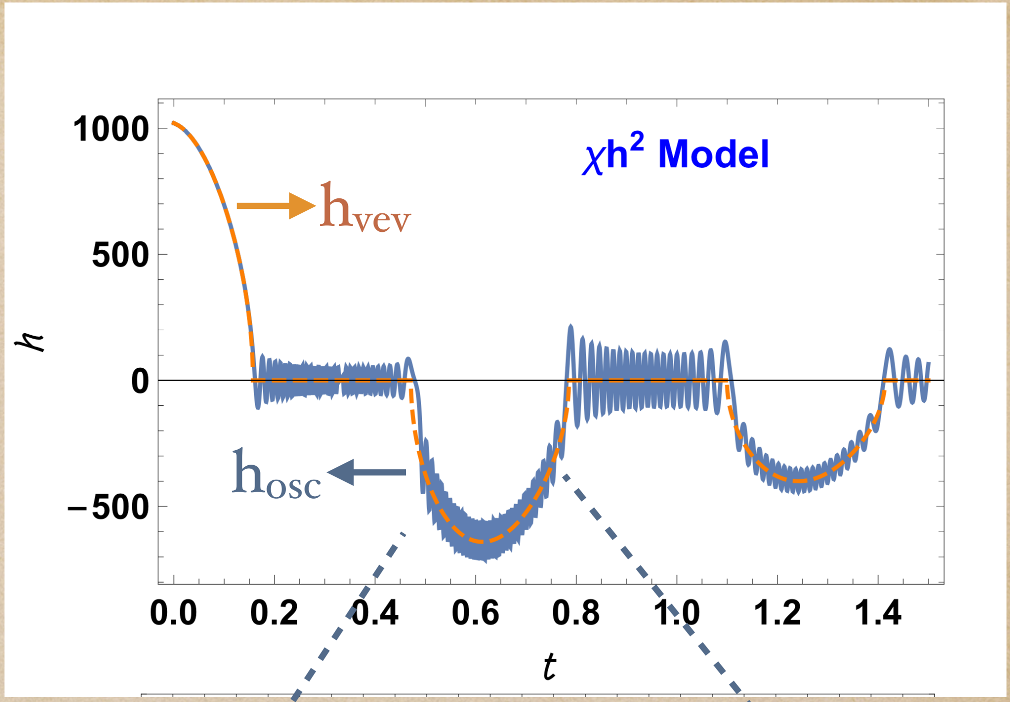
For the Higgs,

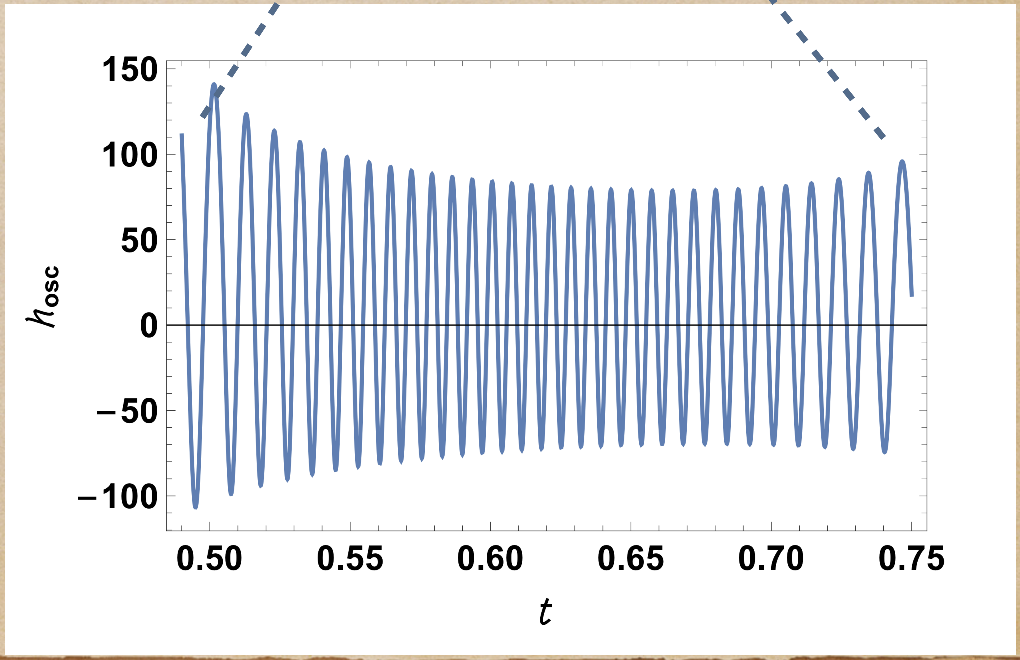
$$h = h_{\text{vev}} + h_{\text{osc}}$$

small freq: m_χ

large freq: M

$$h_{\text{osc}} \ll h_{\text{vev}}$$





Imprint on the inflaton spectrum $(\partial\phi)^2 h^2$

$h^2 \approx h_{\rm vev}^2 + 2h_{\rm vev}h_{\rm osc}$ dominated by broken phase

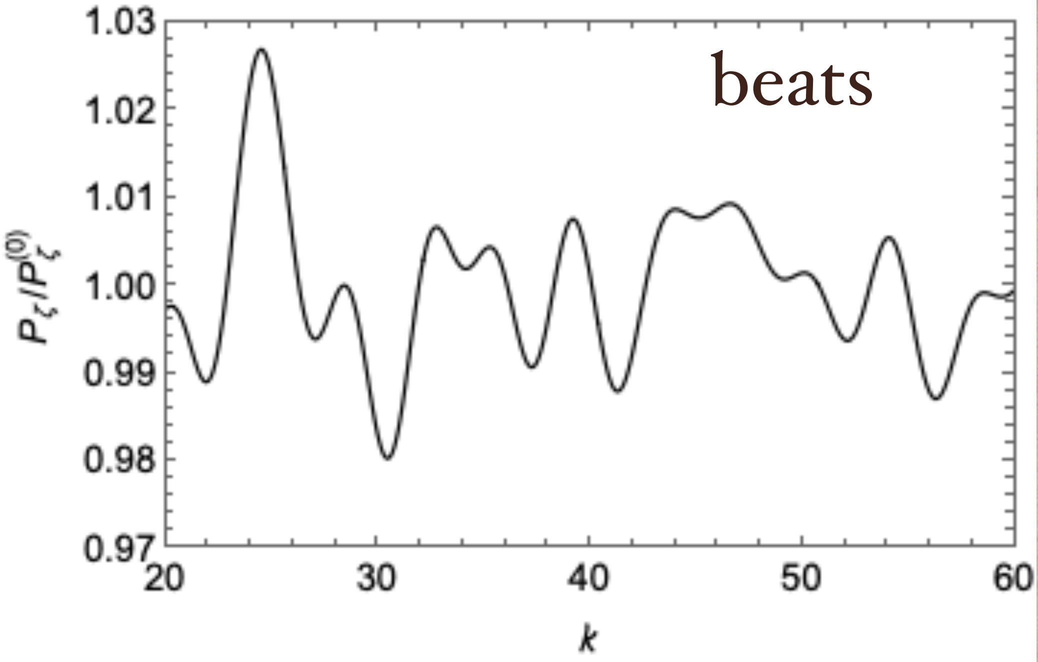
small freq: m_χ

large freq: M

Low k modification

$$c_1 \sin\left(\frac{2k}{H}e^{-\frac{\pi H}{2m_\chi}}\right) + c_2 \sin\left(\frac{2k}{H}e^{-\frac{3\pi H}{2m_\chi}}\right)$$
$$+ c_3 \sin\left(\frac{2k}{H}e^{-\frac{5\pi H}{2m_\chi}}\right)$$

almost identical



Imprint on the inflaton spectrum $(\partial\phi)^2 h^2$

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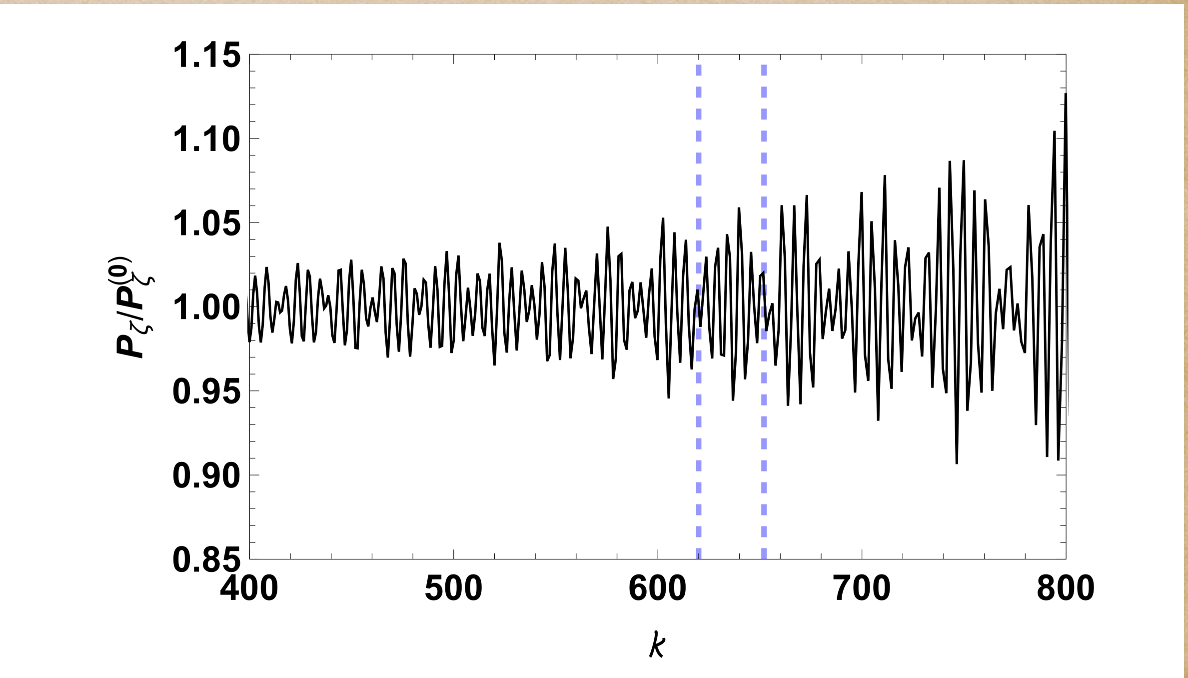
large freq: M

Large k modification:

"***k - wave packet***"

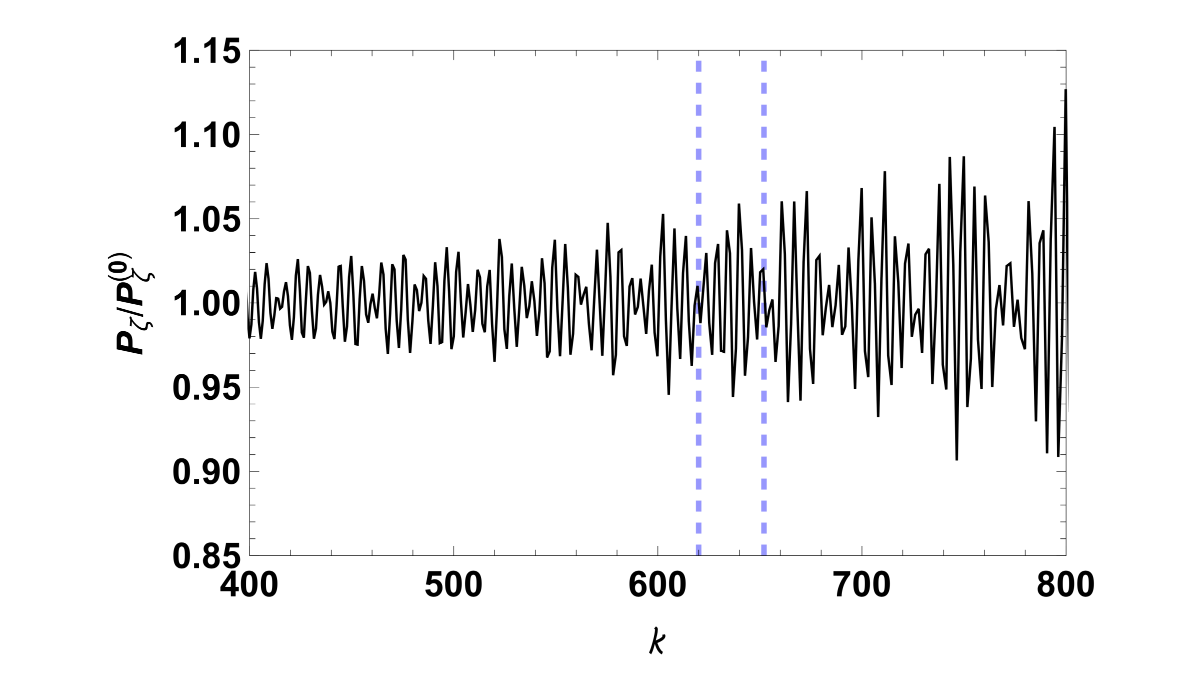


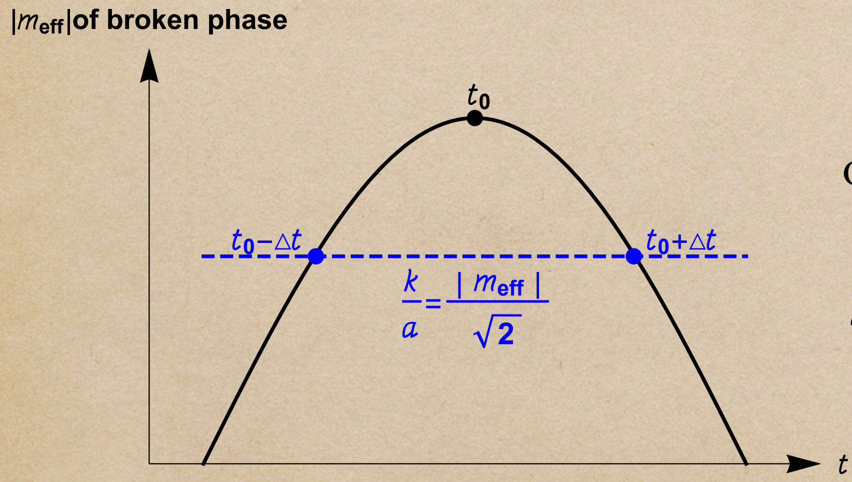
Resonances:

$$\frac{k}{a(t)} = \frac{|m_{\rm eff}(t)|}{\sqrt{2}}$$

effective Higgs mass

$$m_{\rm eff}^2(t) \sim M^2 \cos(m_\chi t)$$





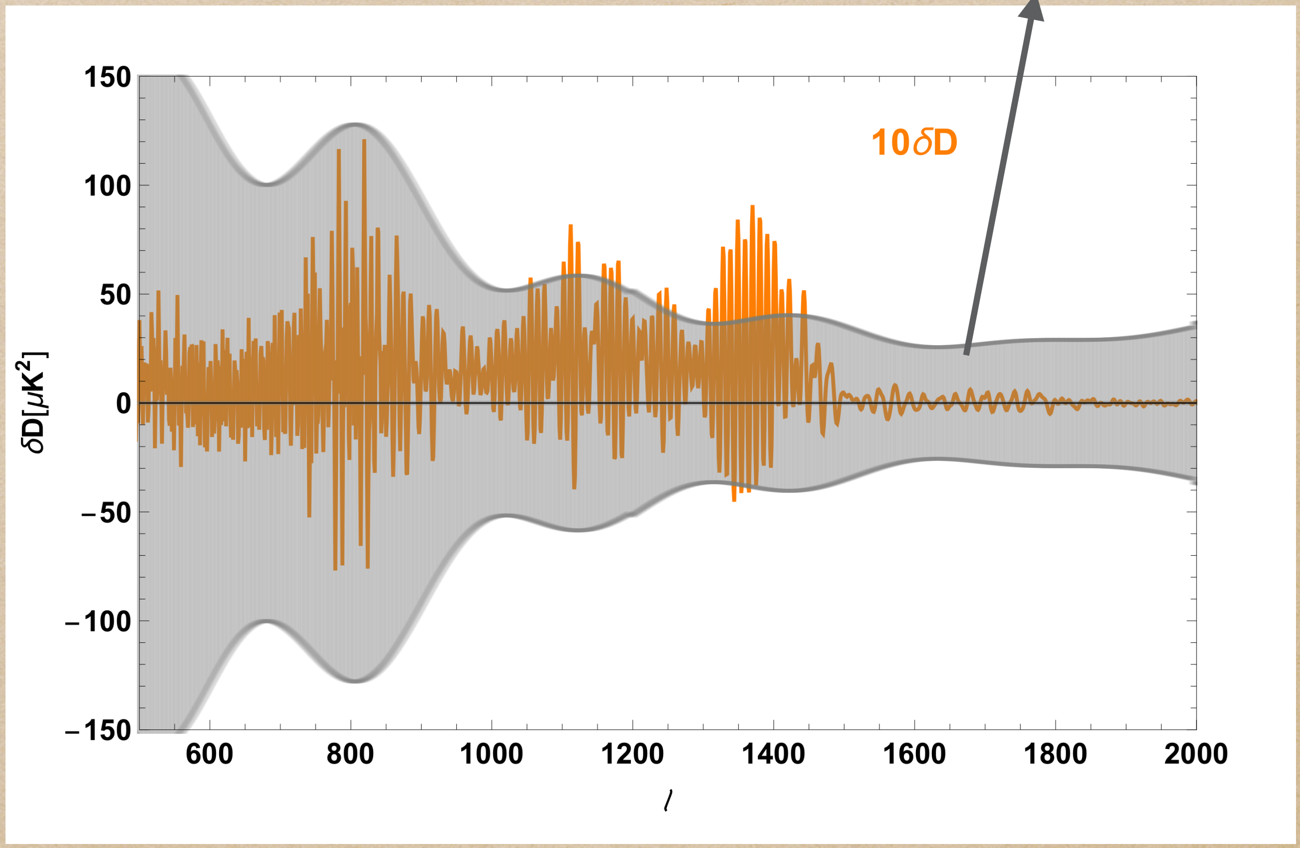
$$\cos\left(\frac{2k}{H} + \frac{2\pi k}{m_\chi}\right) + \cos\left(\frac{2k}{H} - \frac{2\pi k}{m_\chi}\right)$$

$$\sim \cos\left(\frac{2k}{H}\right)\cos\left(\frac{2\pi k}{m_\chi}\right)$$

Potential Observable: fine structure in CMB

unbinned Planck uncertainty (per ℓ)

Correction to temperature harmonics (x10)



~ 10% correction in primordial spectrum $\Longrightarrow$ ~1 % correction in the temperature spectrum

$$C_\ell \equiv \frac{1}{2\pi^2}\int \frac{dk}{k}\Theta_\ell^2(k)\mathcal{P}_\zeta(k),$$

Yet the correction over a large range of ℓ ;

Need a more thorough analysis to see whether it is within current sensitivity.

In the near future, LSS, CMB Stage-4 will improve sensitivity by one order of magnitude (Slosar et.al. '19 "inflationary archaeology")

Summary and outlook

Higgs dynamics in the early Universe could be highly non-trivial: e.g., oscillations between different phases.

Possible consequences (depend on parameters and couplings)

1. Particle production, field fragmentation and generation of gravitation waves;

2. Imprints on the inflaton spectrum: novel "k-wavepacket" features and lead to fine-structure in the CMB spectrum.

Many open questions:

— Other possible cosmic probes?

— What scenario allows a direct test level of fine-tuning and what are the associated observables?

Thank you!

Recap

- Higgs could oscillate between different phases in the early Universe if Higgs couples to weakly-coupled oscillating scalar with a large field range.

- This possibility could arise in BSM scenarios explaining the origin of the Higgs potential, for instance, in a meso-tuned SUSY scenario with moduli and natural Higgs mass >> weak scale.

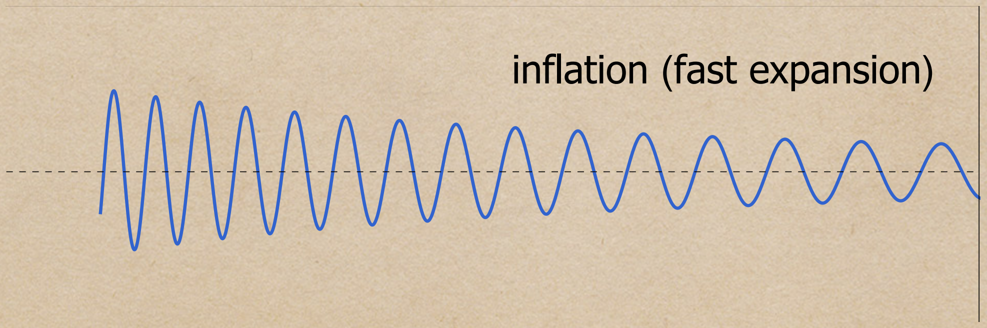
Inflation $a(t) = e^{Ht}$

Resonances $a(t_*) = a(\tau_*) = 2k/m$ ➡ $t_* \sim \frac{1}{H}\log(k/m)$

$$\tau_* \sim -\frac{1}{H}\frac{m}{2k}$$

Correction to two-point function

$\langle \zeta_k^2 \rangle \supset e^{i(mt_* - 2k\tau_*)} + h.c.$ ➡ $\langle \zeta_k^2 \rangle \sim \sin\left(\frac{m}{H} + \frac{m}{H}\log\left(\frac{k}{m}\right)\right)$



Side comments:

a) Do not discuss modulus-inflaton coupling. It leads to some well-known modifications of the inflaton spectrum (similar to signal of classical primordial clock).
b) How do oscillations start: multiple possibilities. Modulus starts from the flat part of its potential and starts to oscillate when it rolls to the non-flat part of the potential.

Imprint on the inflaton spectrum $(\partial\phi)^2 h^2$

$$h^2 \approx h_{\rm vev}^2 + 2h_{\rm vev}h_{\rm osc}$$ dominated by broken phase

small freq: m_χ

large freq: M

Low k modification

$$c_1 \sin\left(\frac{2k}{H}e^{-\frac{\pi H}{2m_\chi}}\right) + c_2 \sin\left(\frac{2k}{H}e^{-\frac{3\pi H}{2m_\chi}}\right)$$
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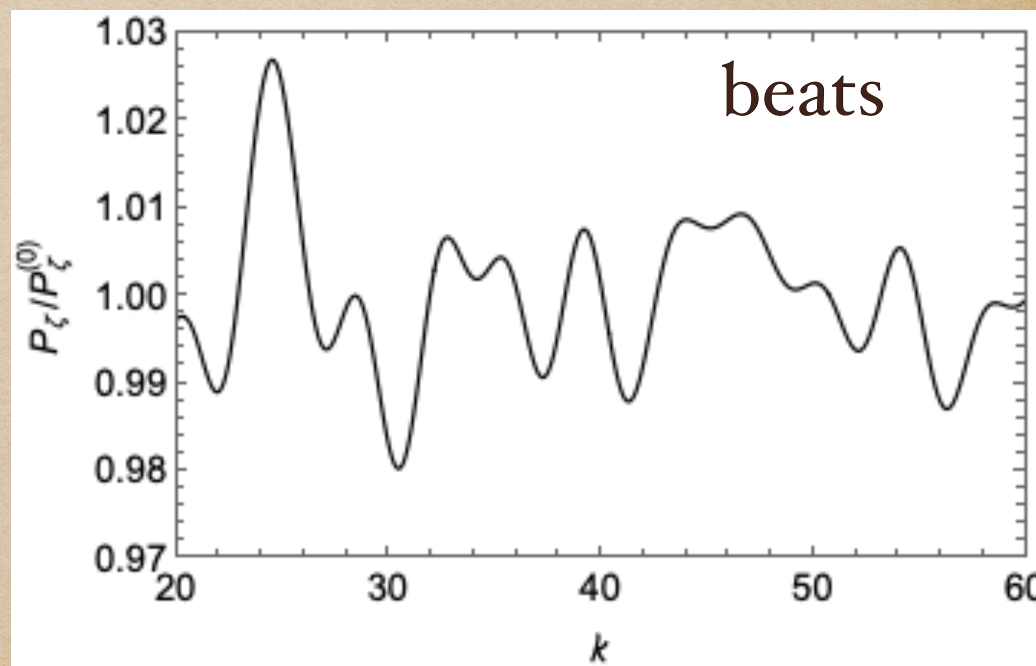


Imprint on the inflaton spectrum $(\partial\phi)^2 h^2$

$h^2 \approx h_{\rm vev}^2 + 2h_{\rm vev}h_{\rm osc}$ dominated by broken phase

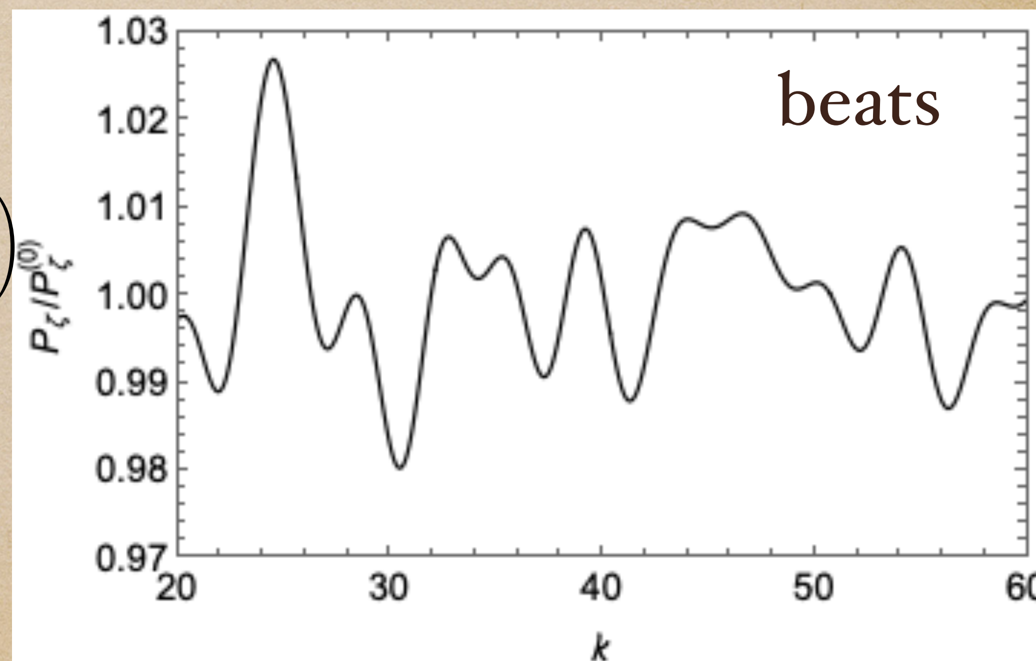
small freq: m_χ

piece-wise cosine function:

(full cosine function leads to a sin(log(k)) spectrum).

Low k modification

$$c_1 \sin\left(\frac{2k}{H} e^{-\frac{\pi H}{2m_\chi}}\right) + c_2 \sin\left(\frac{2k}{H} e^{-\frac{3\pi H}{2m_\chi}}\right) + c_3 \sin\left(\frac{2k}{H} e^{-\frac{5\pi H}{2m_\chi}}\right)$$



Comparison between different models