Modulating Fields and the CMB

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Outline

Modulating fields are scalar fields which control couplings/masses. If they have non-trivial temporal or spatial variations over cosmological scales, they can lead to interesting dynamics that could be probed by the CMB. I will present two different stories of modulating fields.

Cosmic Higgs switching: JF, Matt Reece, Yi Wang, JHEP, 1905.05764

Repeated electroweak phase transitions during inflation, triggered by an oscillating modulus scalar, lead to interesting features on the inflaton 2-point function.

Cosmic Microscope: JF, Zhongzhi Xianyu, JHEP, 2005.12278

Modulating fields with spatially varying backgrounds modulate cosmic preheating, and imprint the non-linear effects at tiny scales on large scale fluctuations.

Higgs dynamics in the early Universe

Higgs mass is 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/Couplings depend on values of a modulating scalar field.

A toy model

Higgs

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

modulus

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

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

f : large field range of χ;

$M > m_\chi$: ***Higgs mass scale*** when χ oscillates with an amplitude ~ f.

A toy model

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

modulus

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

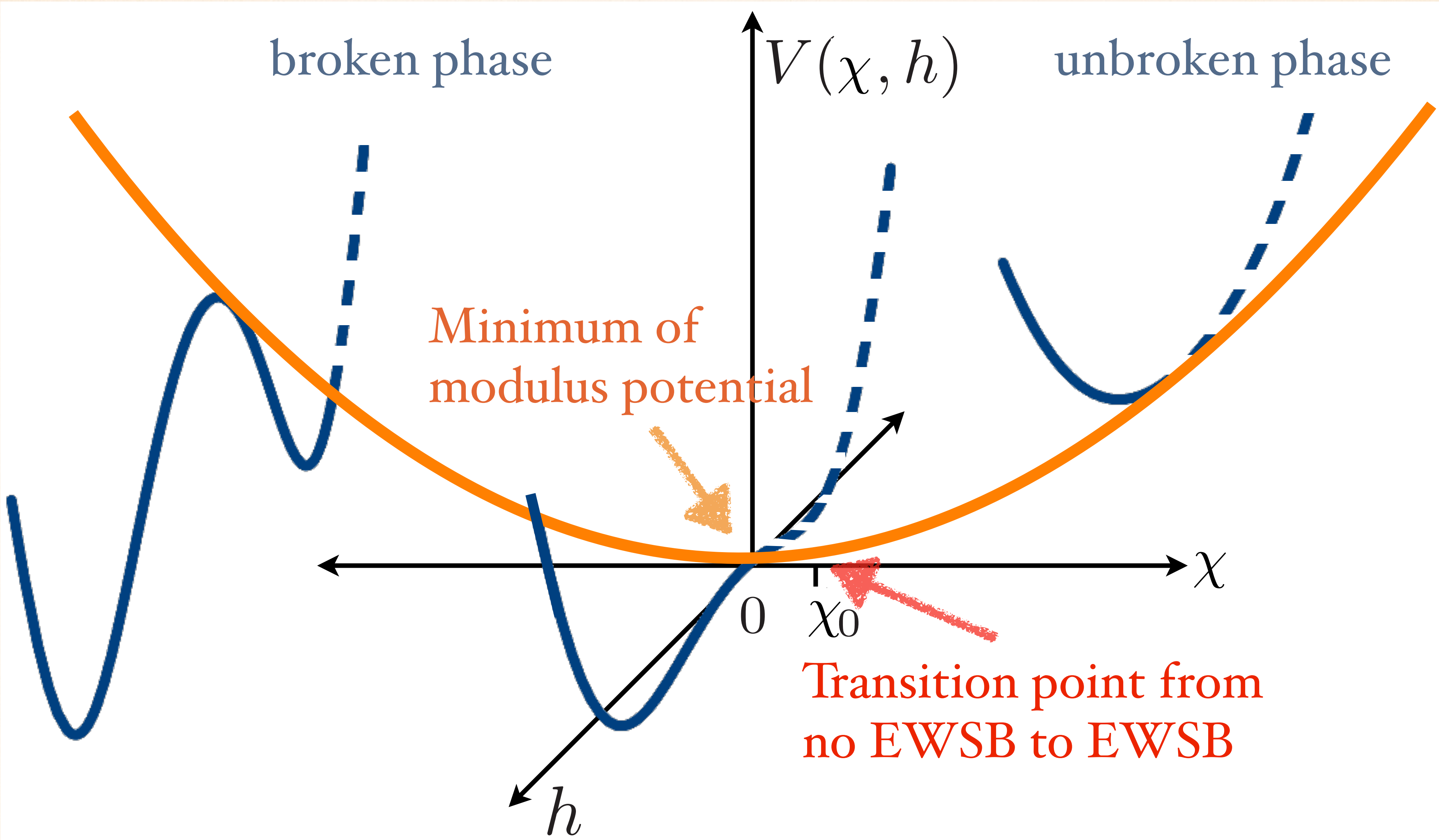
$$+ \frac{M^2}{f}\chi h^\dagger h$$

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

When $M^2 \gg |m_h|^2$, trilinear term dominates;

When modulus oscillates to the negative side, Higgs mass squared ***switches sign***!

Modulus-Higgs potential



Cosmic Higgs switching

Fan, Reece (Harvard), Wang (HKUST), JHEP, 1905.05764

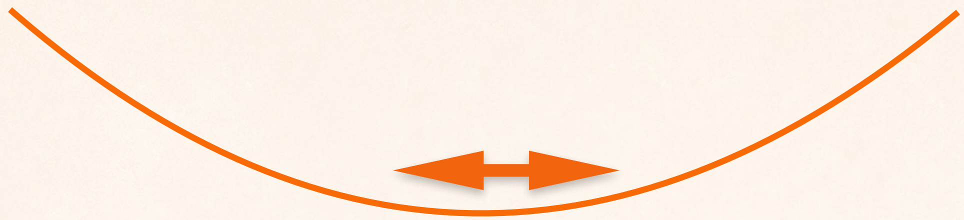
Consider a low-scale inflation model ($H \lesssim$ weak scale). On top of the toy model I showed, include the Higgs coupling to the inflaton.

inflaton

modulus

$$
\begin{aligned}
V(\chi, h, \phi) = &+\frac{1}{2}m_\chi^2\chi^2 \\
&- m_h^2 h^\dagger h + \frac{\lambda}{4}|h|^4, \\
&+ \frac{M^2}{f}\chi h^\dagger h \\
&+ V(\phi) \qquad \text{inflaton potential} \\
&+ \frac{y}{\Lambda^2}(\partial\phi)^2 h^\dagger h \qquad \text{coupling between inflaton and the Higgs}
\end{aligned}
$$

For the modulus χ, when back-reaction is negligible,



$$\chi = \chi_0 \underbrace{a^{-3/2}}_{\text{redshift}} \underbrace{\cos(m_\chi t)}_{\text{oscillate}}$$

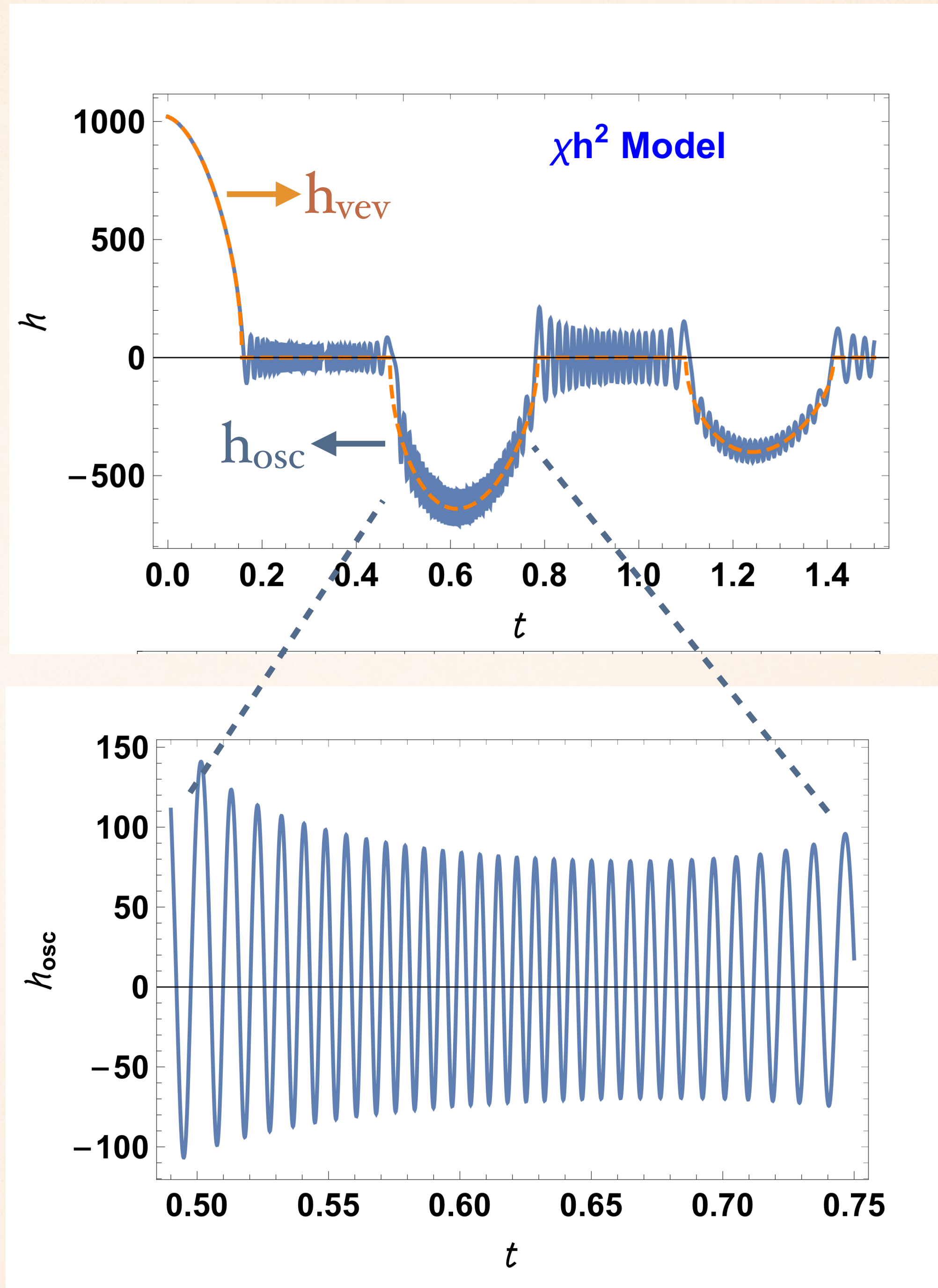
For the Higgs h,

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

small freq: m_χ

large freq: $M > m_\chi$

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



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

$$h^2 \approx h_{\rm vev}^2 + 2h_{\rm vev}h_{\rm osc}$$

dominated by broken phase

small freq: m_χ

large freq: $M > m_\chi$

Low k modification (beats: superposition of multiple periodic functions with similar periods

Large k modification

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

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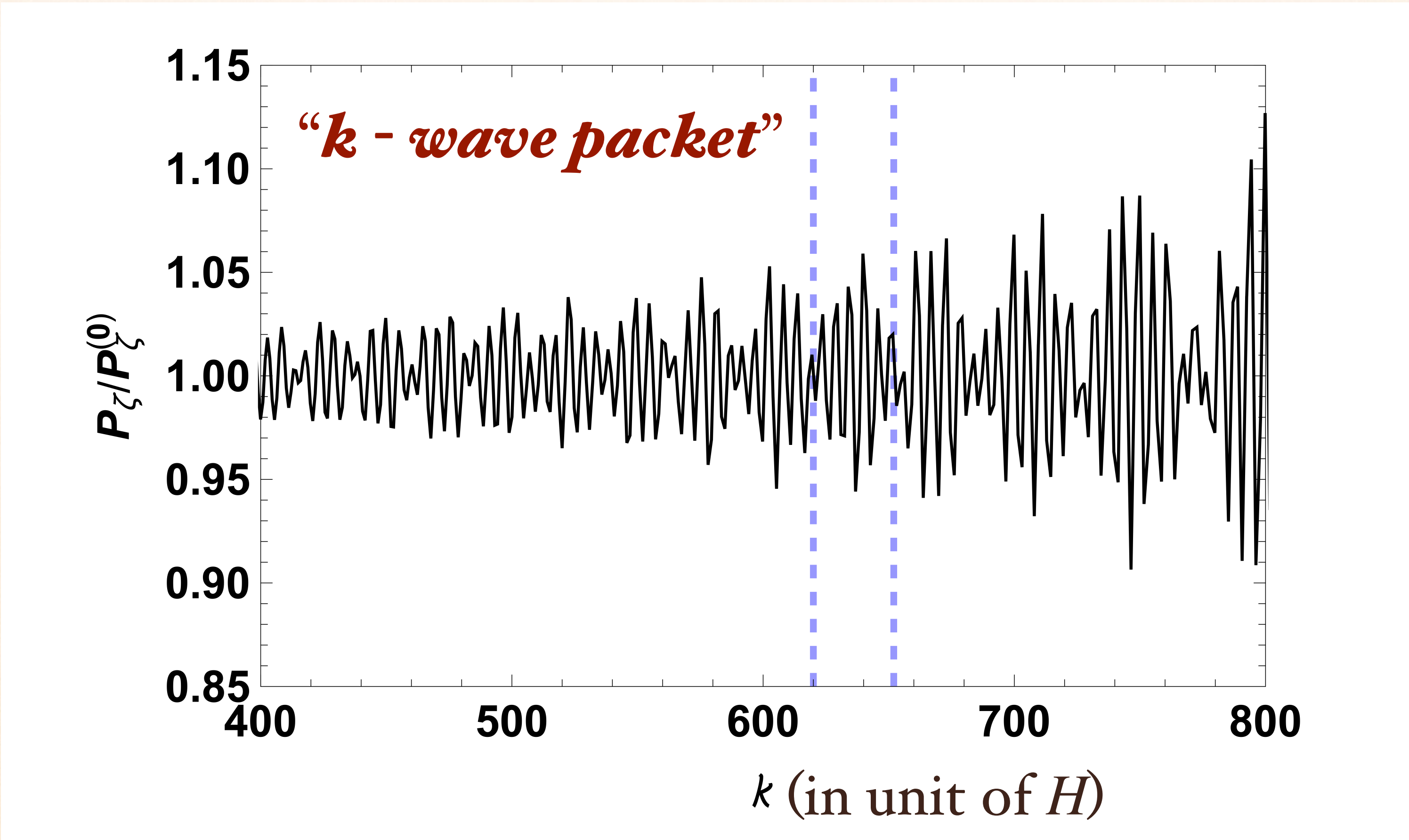
Large k modification

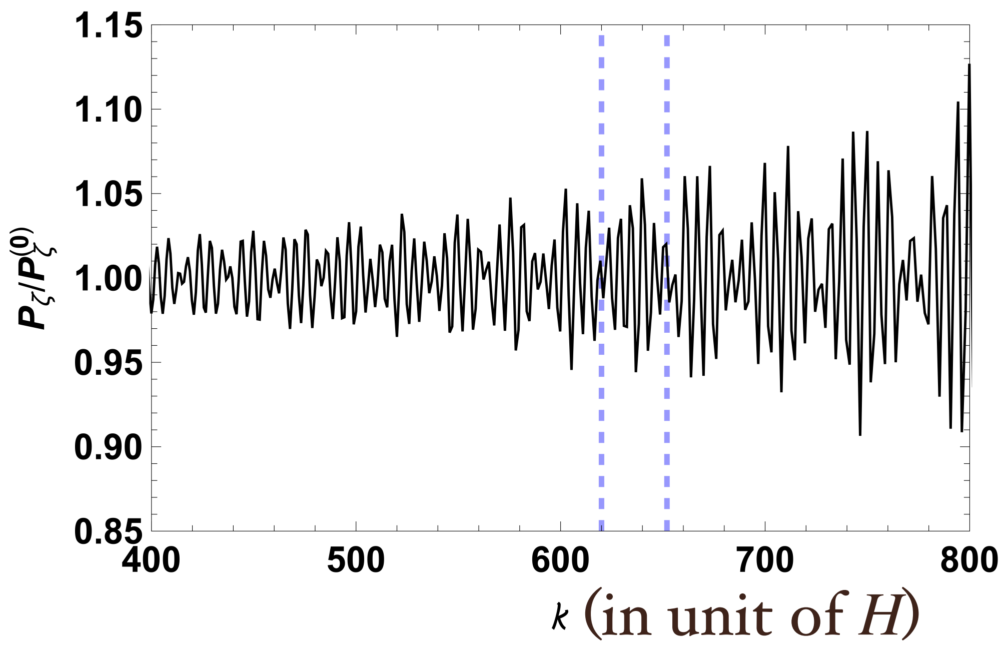


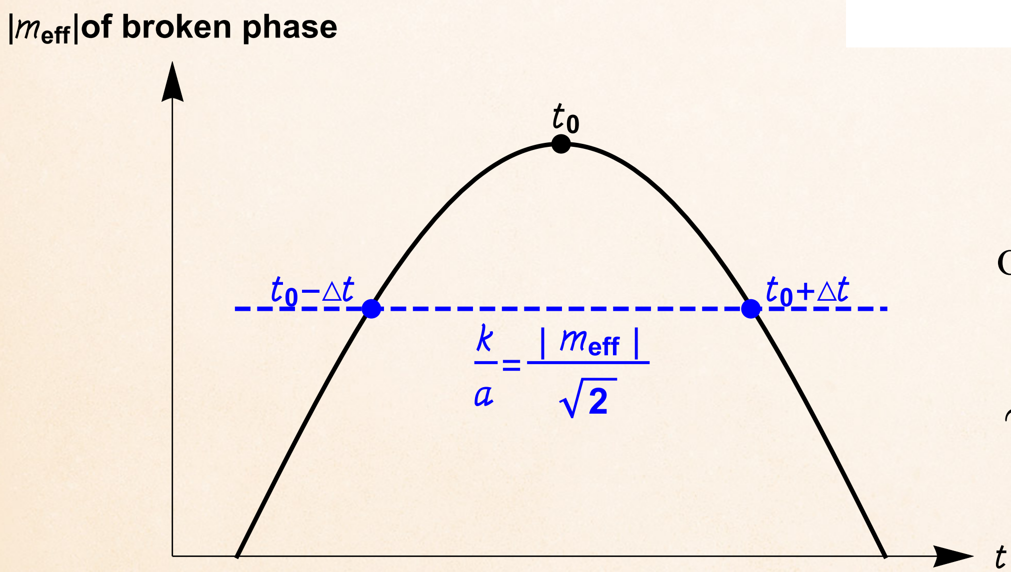
Resonances:

effective Higgs mass

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

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





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

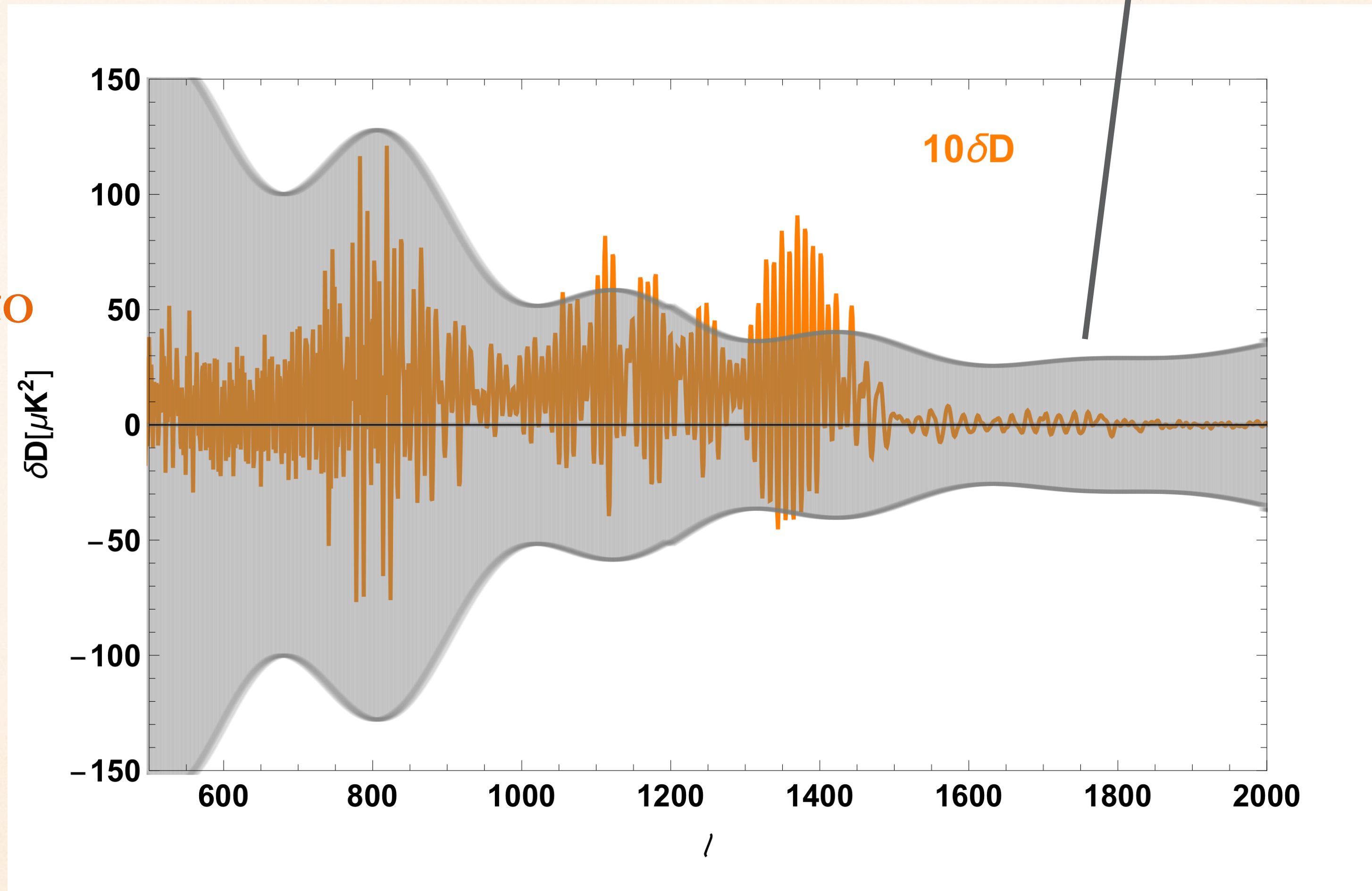
$$\sim \cos\left(\frac{2k}{H}\right)\cos\left(\frac{2\pi\,k}{m_\chi}\right)$$ slow modulation

fast oscillation

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

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

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")

Cosmic microscope

Preheating: non-perturbative and out-of-equilibrium processes that transfer energy from inflaton to daughter particles.

Happens soon when inflaton starts to oscillate after inflation and before perturbative reheating.

Not many observables: happens at scales tens of e-folds smaller than the CMB scale and thus little impact on large scale observables.

Fan and Zhongzhi Xianyu (Qinghua), JHEP, 2005.12278

use results from an earlier paper: Amin (Rice), Fan, Lozanov (UIUC) and Reece (Harvard), PRD, 1802.00444.

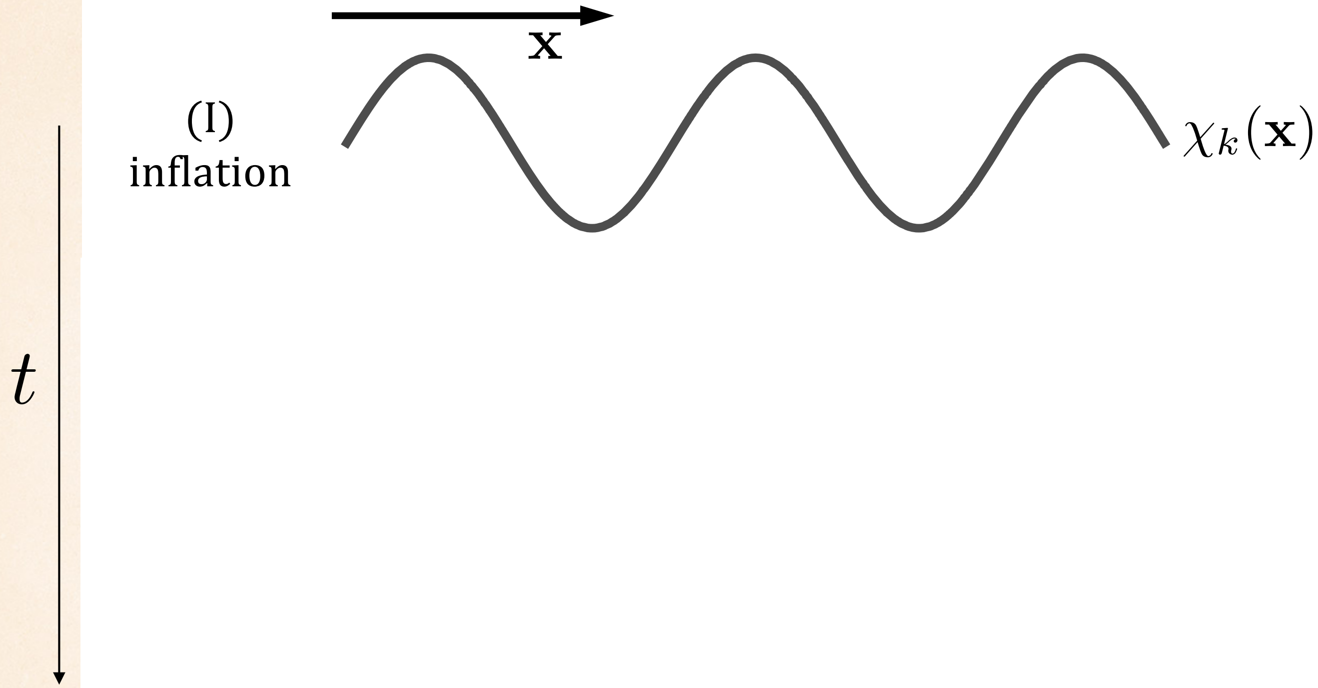
Modulating field

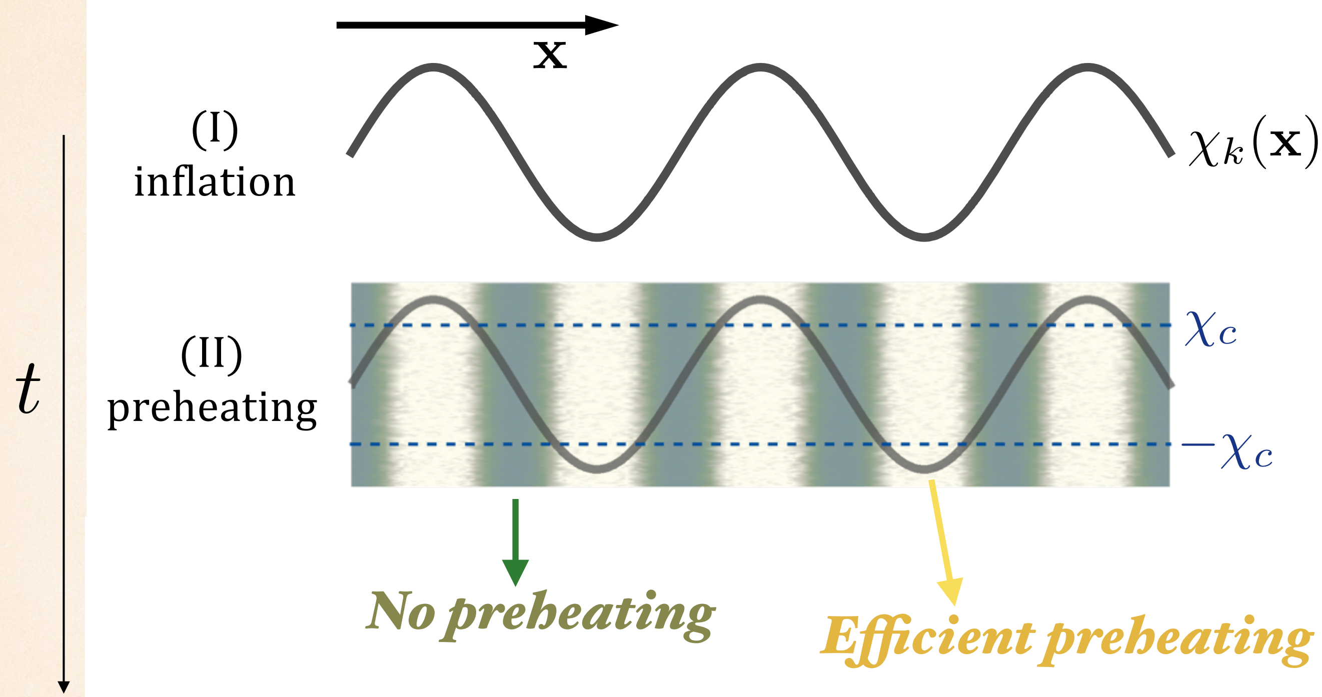
Key idea: probe/perturb the preheating dynamics by an additional light scalar field χ, the **"modulating" field**. (χ : modulating field; σ : direct daughter of inflaton ϕ.)

During inflation: $\chi(x)$ is light and acquires a nearly ***scale-invariant Gaussian*** background. Its field value is ***spatially dependent***.

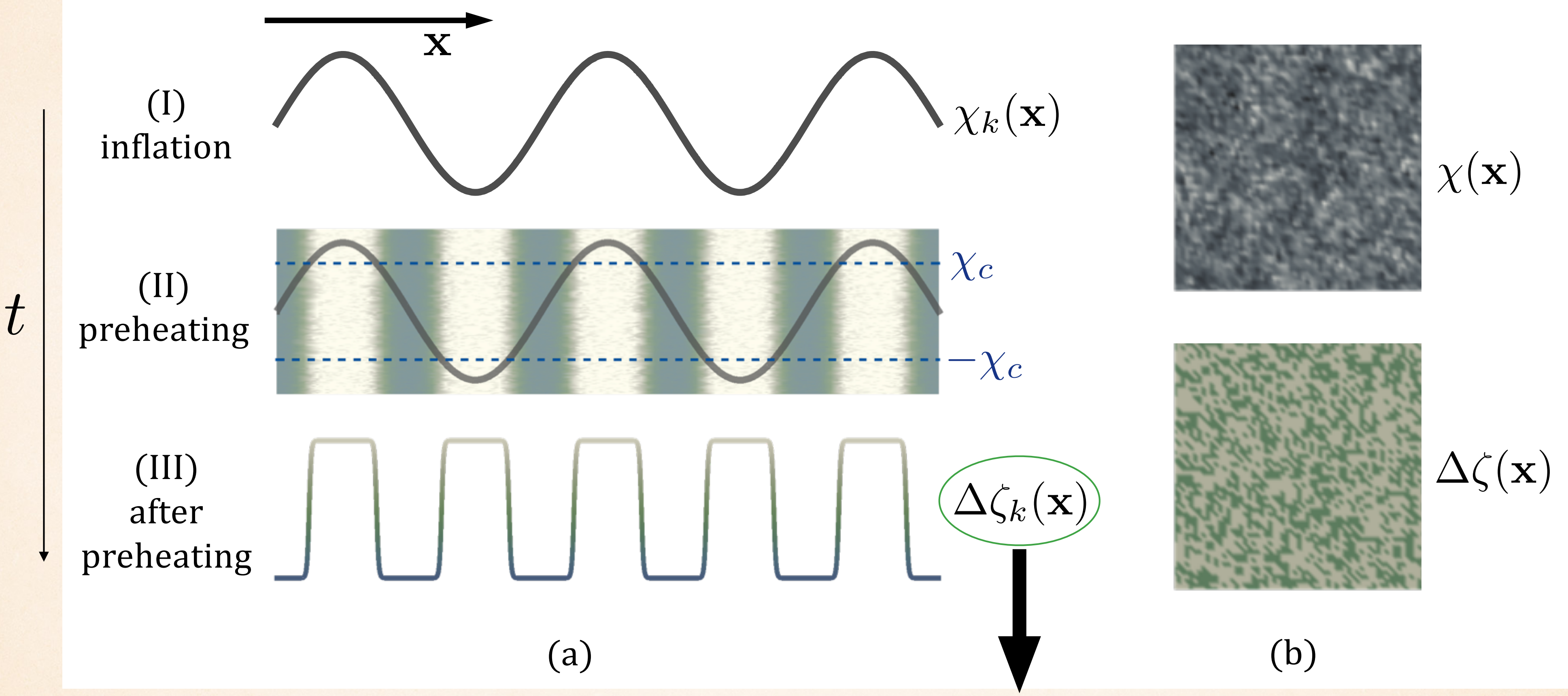
After inflation: $\chi(x)$ becomes the effective coupling that controls preheating in each Hubble patch. In model with $g\,\phi\,\sigma^2$, $g = g(\chi) = \dfrac{\chi^2}{\Lambda}$.

In each Hubble patch, g and χ are constants. But g and χ could ***vary across many different Hubble patches***.


$\mathbf{x}$
(I)
inflation
$\chi_k(\mathbf{x})$
t

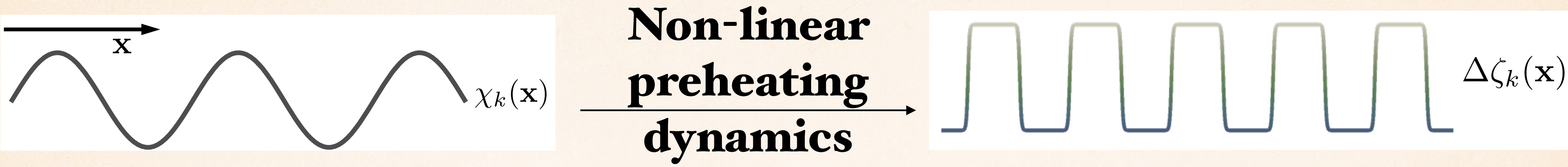


Different Hubble patches have ***different expansion histories*** and thus ***different evolutions*** of curvature perturbations.



curvature perturbation

Cosmic Microscope

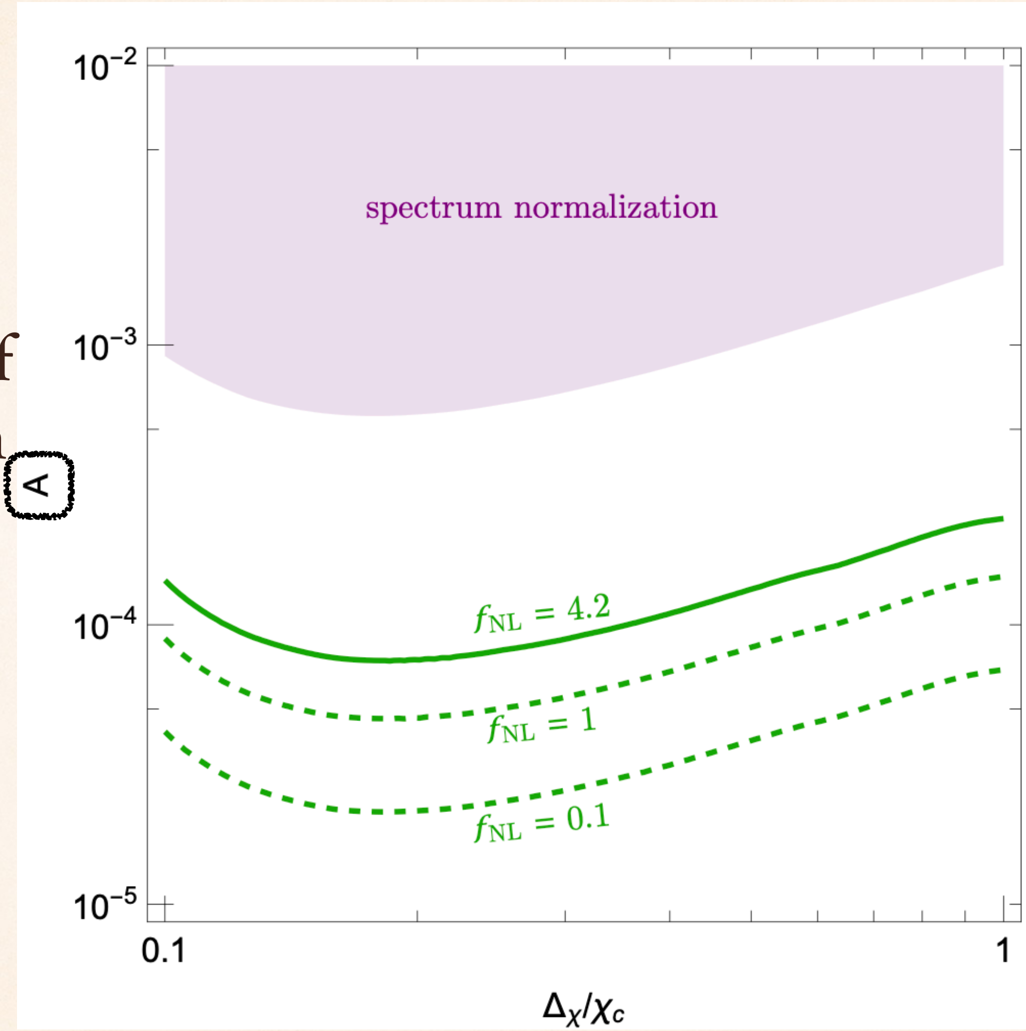


Preheating dynamics which happens at tiny scales could imprint on large scale fluctuations (CMB scales): ***cosmic microscope***.

Local non-Gaussianity of n-point (n≥3) correlators of curvature perturbations.

Side comment on modulated reheating: a small spatial variation in χ induces a small variation in the perturbative decay rate of inflaton and a small curvature perturbation. It leads to a ***smooth*** linear relation between incoming χ and outgoing $\Delta\zeta$. Dvali, Gruzinov, Zaldarriaga; Kofman 2003

A: proportional to the fraction of energy density in inflaton going through modulated preheating



O(1) non-Gaussianity, within the reach of next-generation measurements.

Δ_χ/χ_c: ratio of fluctuation amplitude of χ and critical χ.

Even a subdominant fraction of energy density going through modulated preheating gives a testable signal in NG.

Conclusions

Couplings/masses in low-energy effective theories, instead of being constants, could originate from dynamical fields in their UV completions.

This general idea has been applied to construct interesting particle physics models quite often.

If the time/spatial dependent coupling/mass exists in the early Universe (e.g., during inflation or preheating), they could lead to interesting CMB observables (spectrum and bispectrum), that could be probed by near-future CMB measurements.

Thank you!

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

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)

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

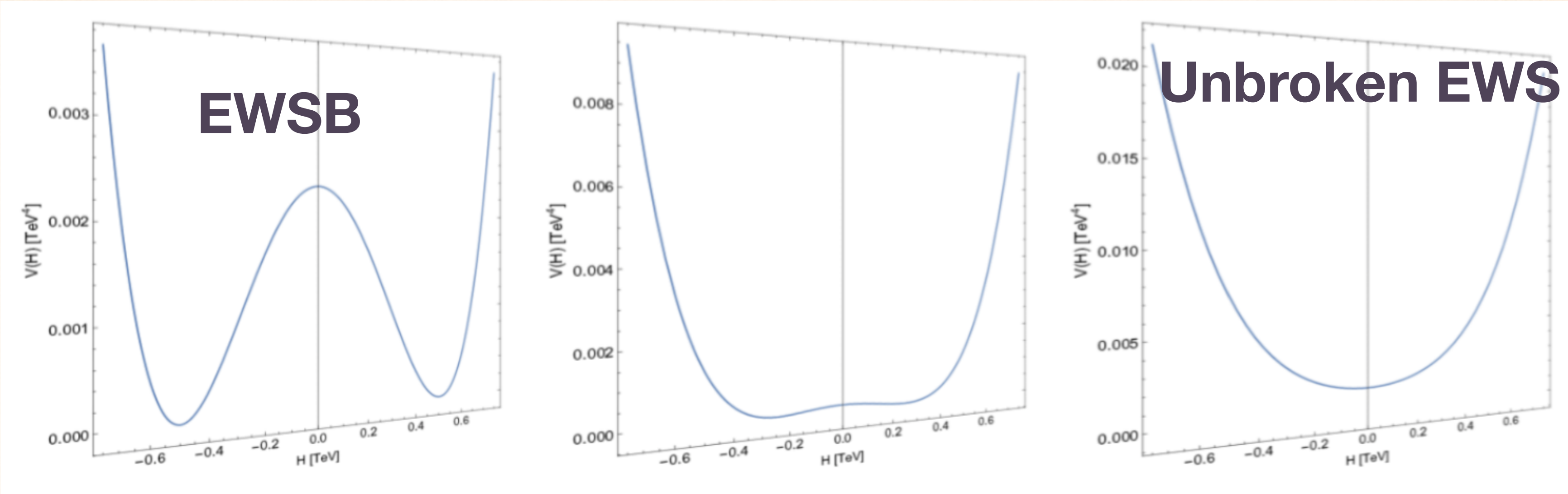
$$\frac{2\xi_{XZ} \mathrm{Re}(F_{X,0} m_X)}{m_{\rm pl}^2} \mathrm{Re}(X) Z^\dagger Z.$$

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

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

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.*

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.

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 and no other random light scalars around, e.g., mini-split SUSY scenario (Hall et. al; Arkani-Hamed et al.; Arvanitaki et al., ... 2012).

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

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

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

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

Embed in high-scale SUSY

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	$f \sim \|\chi_0\|$
energy scale suppressing Higgs and inflaton coupling	Λ
Higgs mass	M
modulus mass	m_χ
weak scale	m_h
Hubble	H

Classical primordial clocks

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

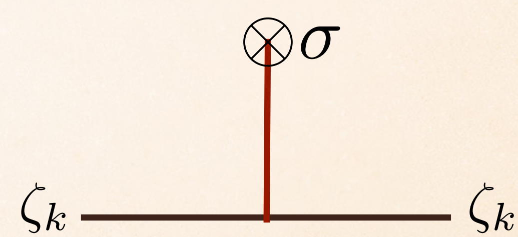
Heavy fields could always be present during inflation (heavy fields from UV physics, SUSY breaking; SM fields obtain masses of Hubble through gravitational coupling...)

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

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

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

Resonances: (saddle point approximation)

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

$$\Rightarrow \quad a(t_*) = a(\tau_*) = 2k/m$$

Inverse function

Correlation function

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

Scale factor evolution directly recorded in the phase.

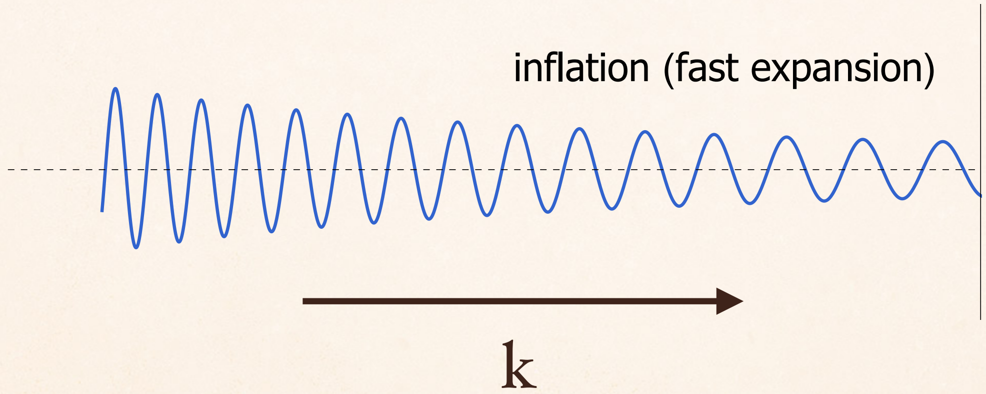
Could be used to distinguish inflation and alternatives.

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

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

Correction to two-point function

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



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.

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).

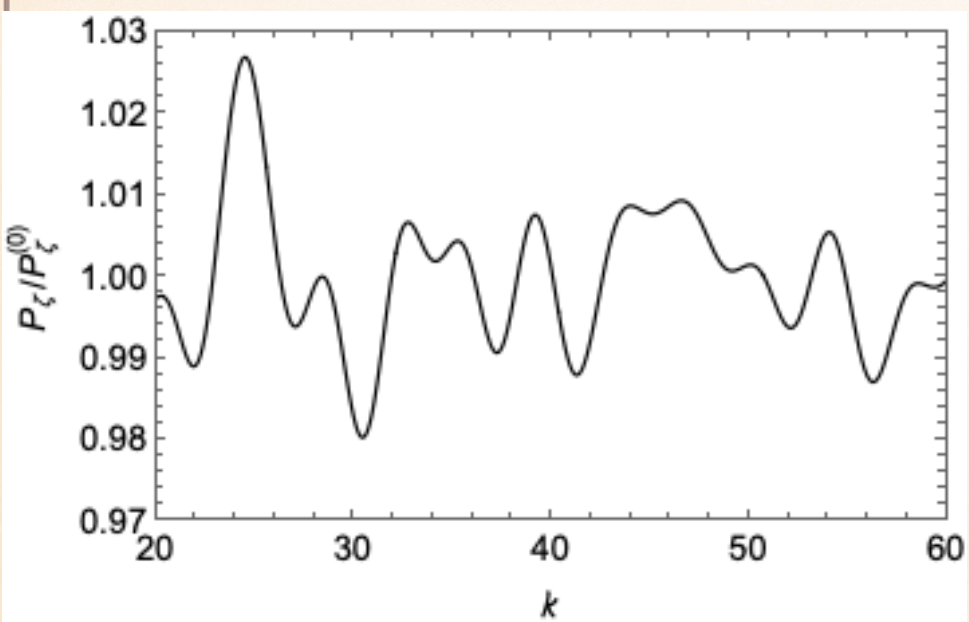
b) How do oscillations start: multiple possibilities. Modulus starts from the flat part of its potential and starts to oscillate when it rolls to the non-flat part of the potential.

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

$$h^2 \approx h_{\rm vev}^2 + 2h_{\rm vev}h_{\rm osc}$$

small freq: m_χ

Low k modification



piece-wise cosine function (full cosine function leads to a $\sin(\ln k)$ spectrum as in the classical primordial clock scenario by Chen, Namjoo, Wang 2011)

beats: superposition of multiple periodic functions with similar periods

Comparison between different models