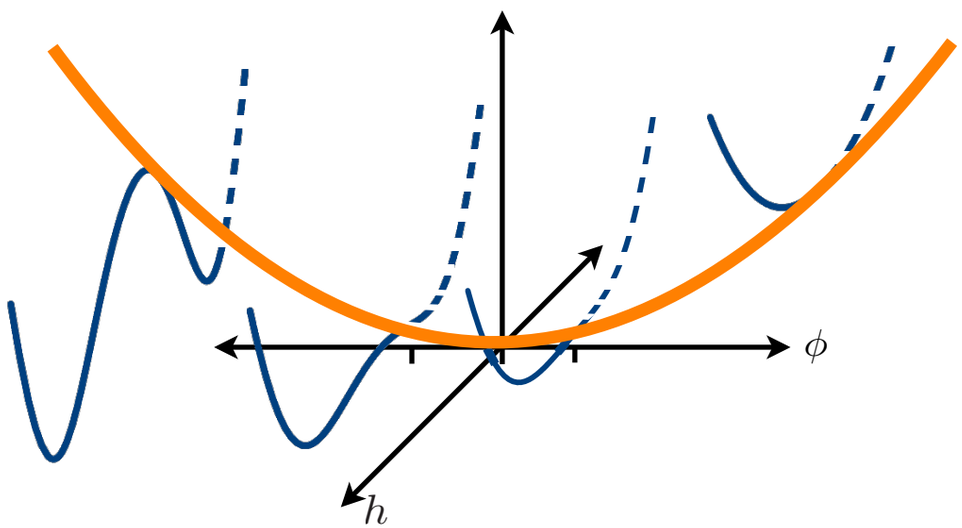
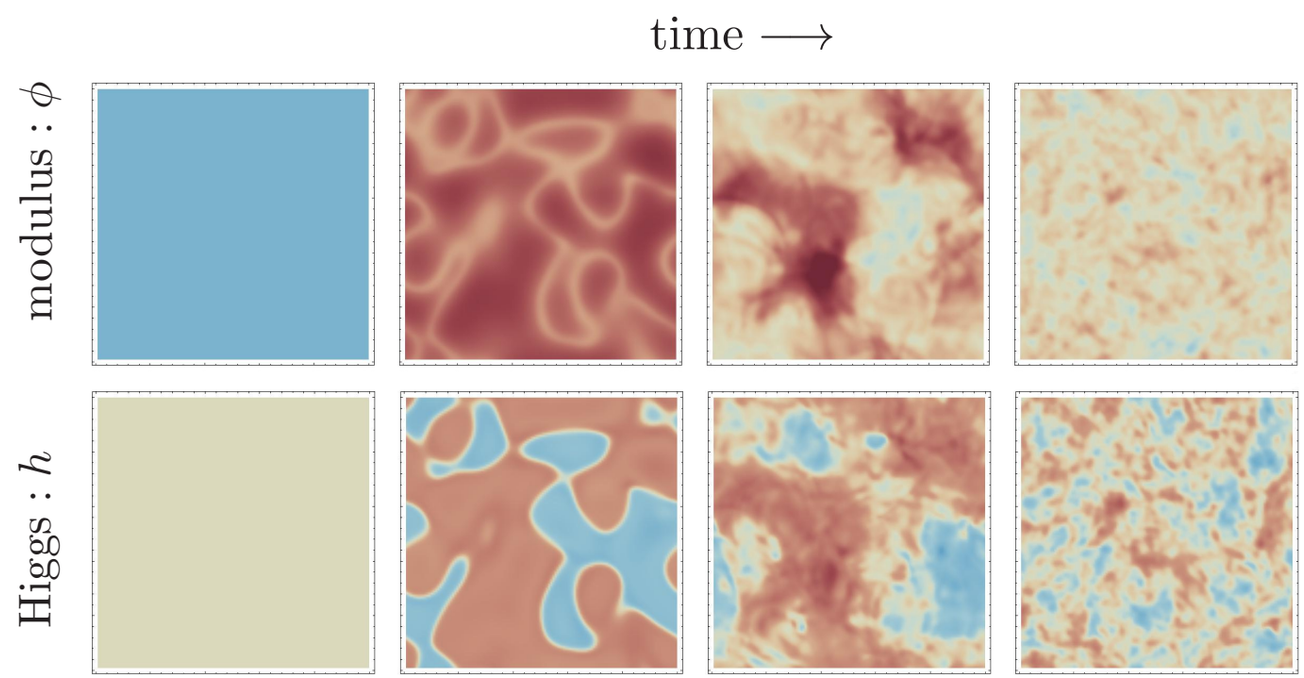
arXiv: 1802.00444

Cosmological Dynamics of Higgs Fine Tuning





Mustafa A. Amin

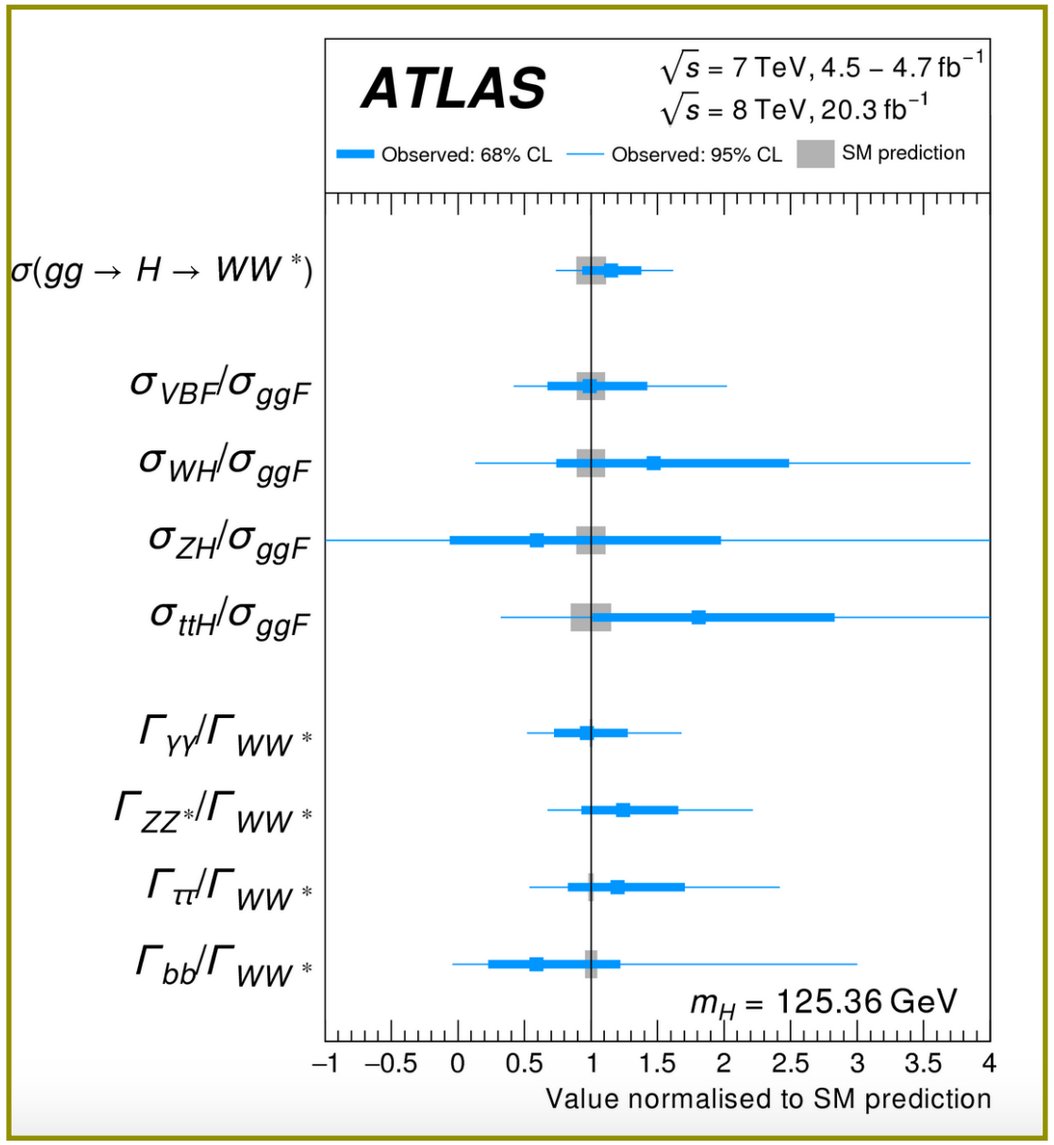
with Jiji Fan, Kaloian Lozanov & Matthew Reece

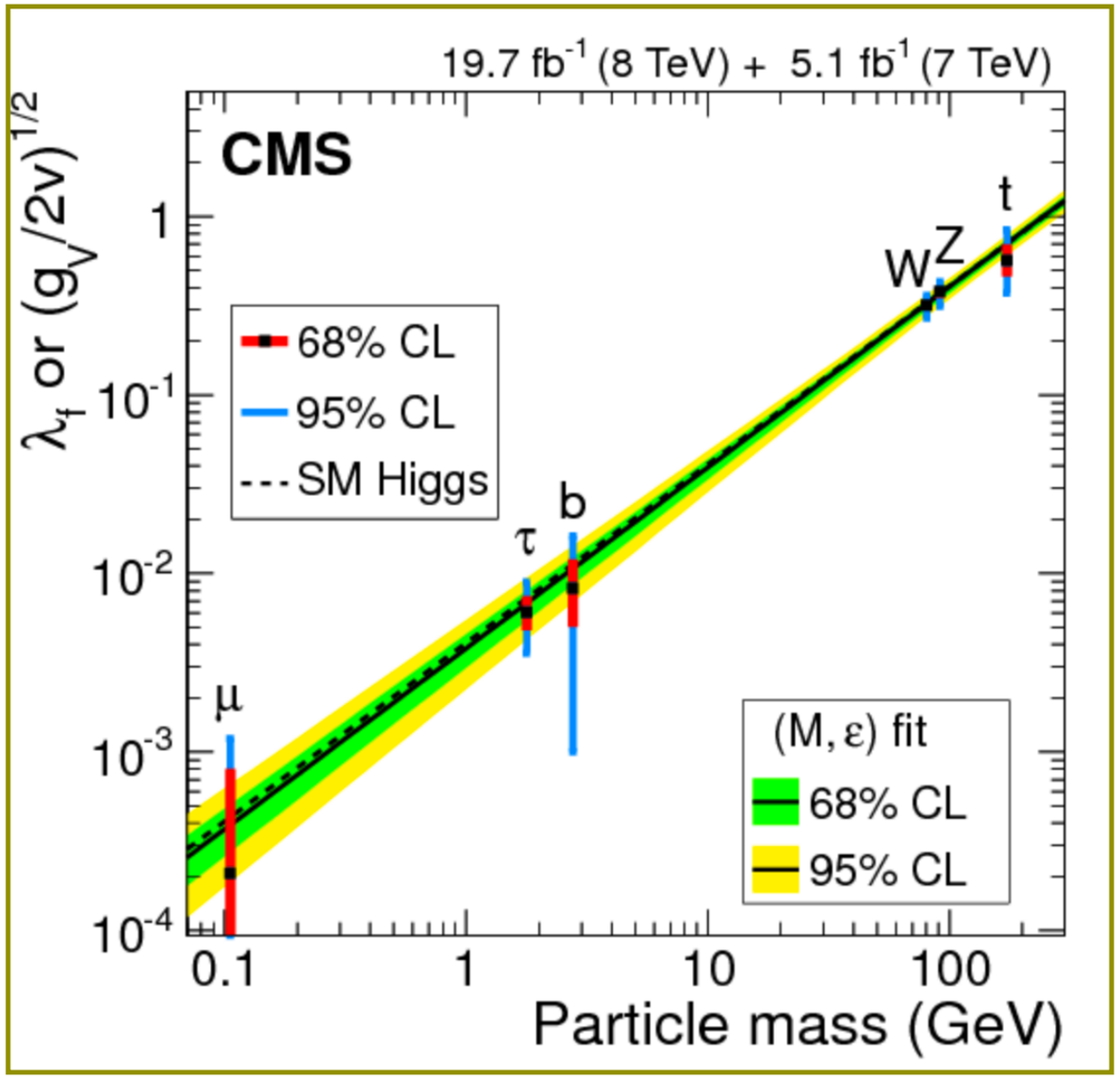
RICE

main suggestion

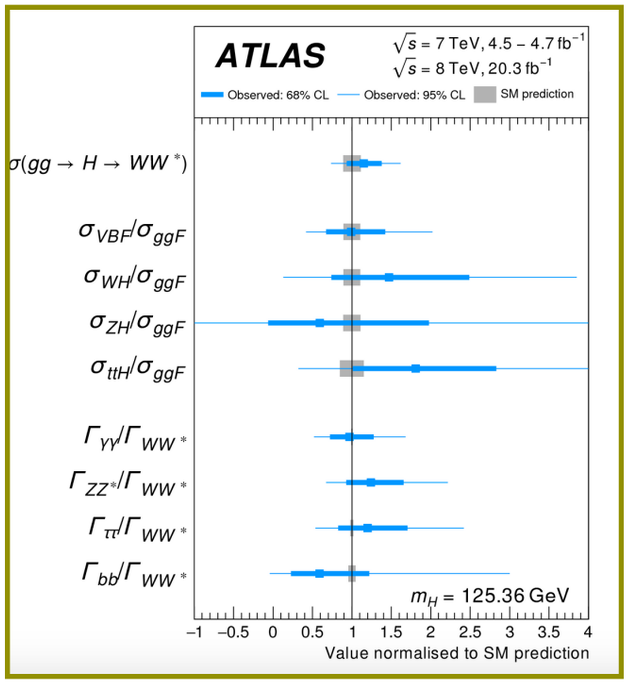
If the Higgs potential is fine-tuned, there might be cosmological implications from the early universe: eq. of state + gravitational waves

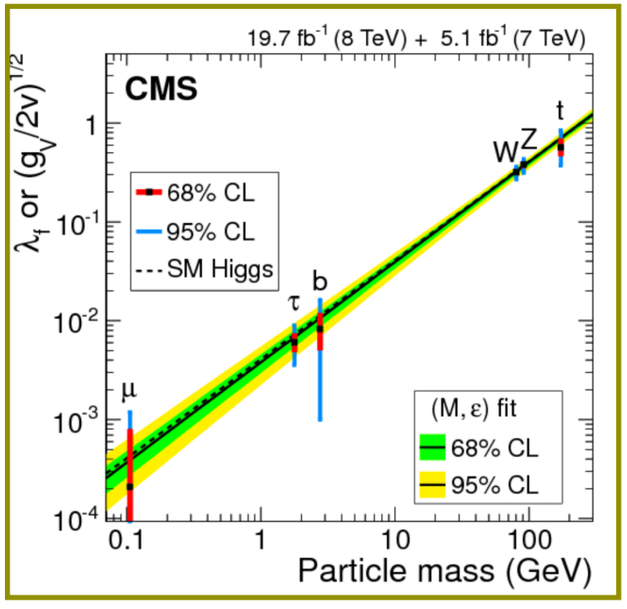
LHC: Standard Model Higgs but nothing else …





LHC: Standard Model Higgs — tuned Higgs mass/ potential



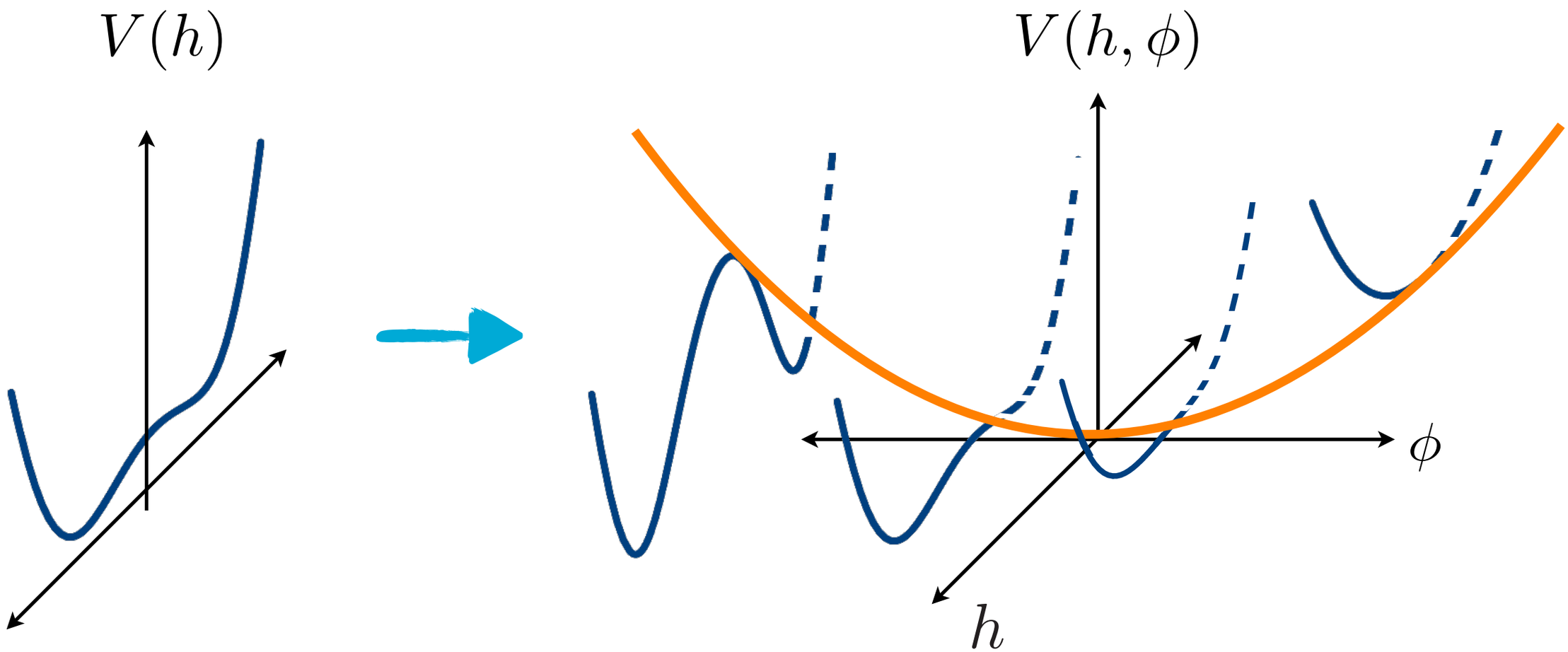


no new particles, does not necessarily rule out SUSY

Higgs mass/potential is "*tuned*"

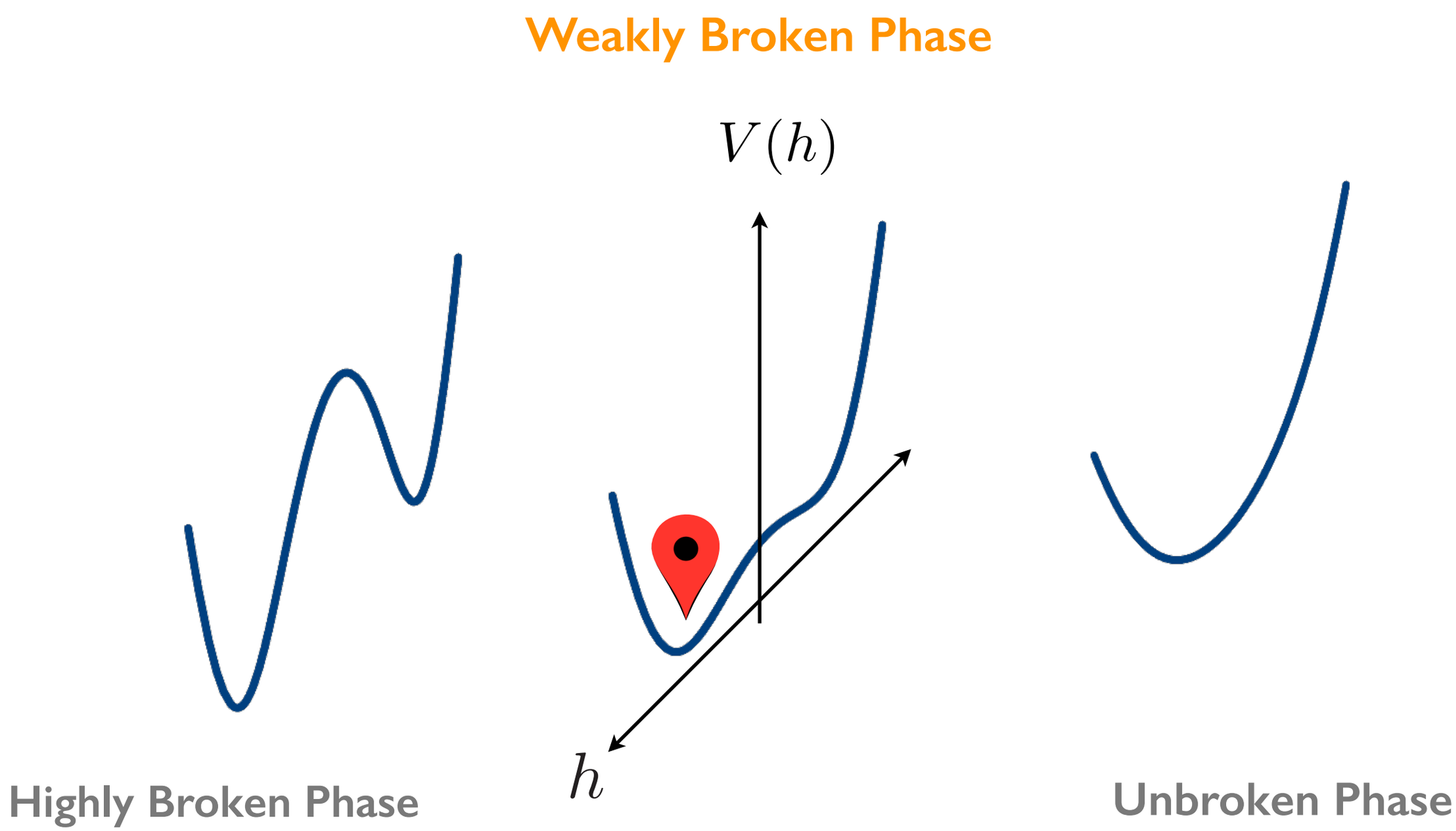
(Higgs is *accidentally* light)

SUSY: field-dependent Higgs mass/potential

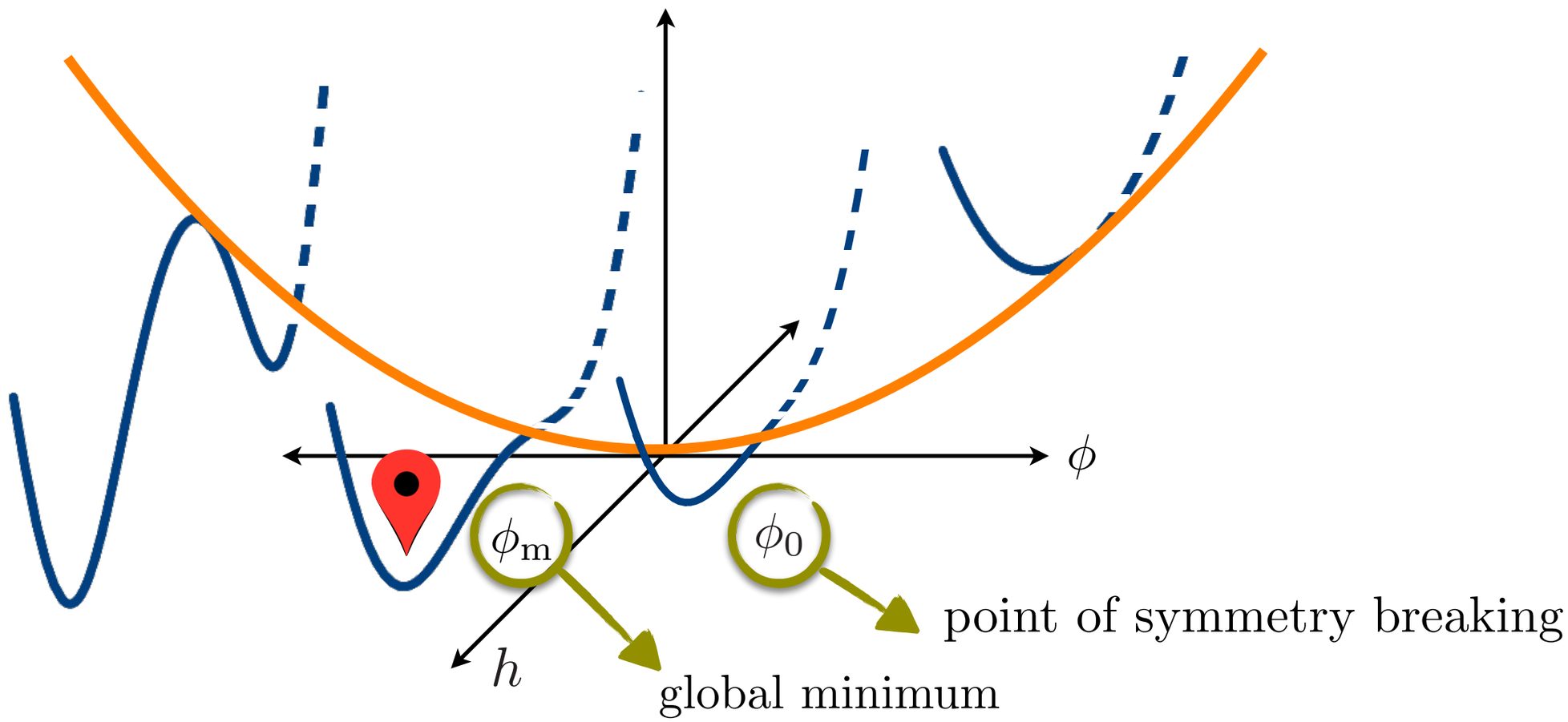


ϕ = modulus = could be the inflaton

accidentally light/tuned Higgs
= precarious balance between broken and unbroken phase



fine tuned / weakly broken potential: possible if global min. *close to* symmetry breaking point

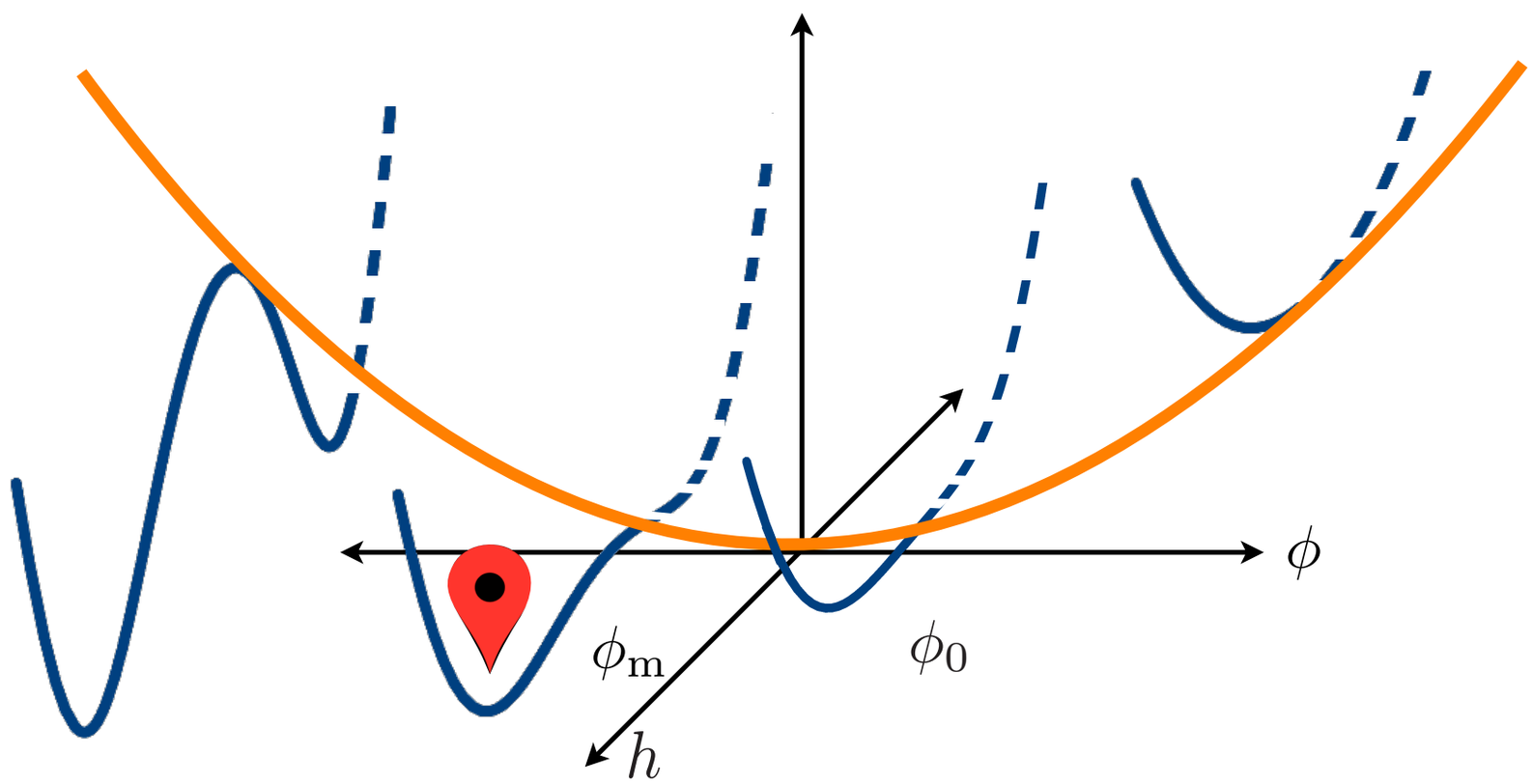


Necessary Fine Tuning $\Leftrightarrow$ $\dfrac{\phi_{\rm m} - \phi_0}{f} \ll 1$

f = typical field range of modulus

light Higgs:
possible if global min. *close to* symmetry breaking point

$$V(\phi, h) = \frac{1}{2} m_\phi^2 \phi^2 + M^2 \frac{(\phi - \phi_0)}{f} h^\dagger h + \lambda (h^\dagger h)^2 + V_0$$



$$m_h^2 = 2M^2\Delta^2 \ll M^2$$

fine-tuning $\rightarrow$ small Higgs mass

$$\Delta \equiv \frac{\phi_0 - \phi_{\rm m}}{f} \ll 1$$

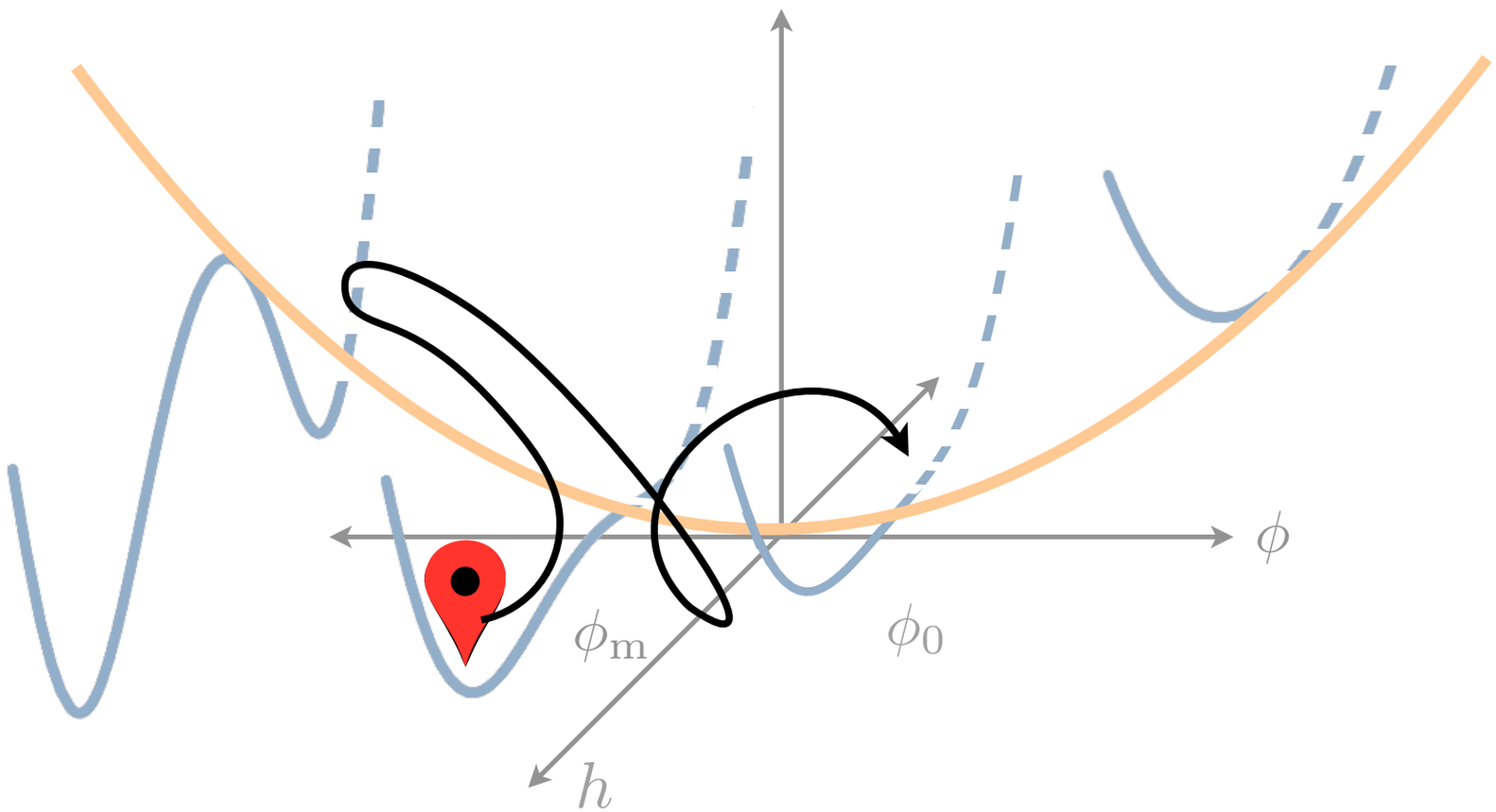
fine tuning

M = SUSY breaking scale

* we take this to be the quantum corrected effective potential rather than the tree-level potential; we do not have to compute shifts in VEVs induced by loop corrections.

how would we know today ?

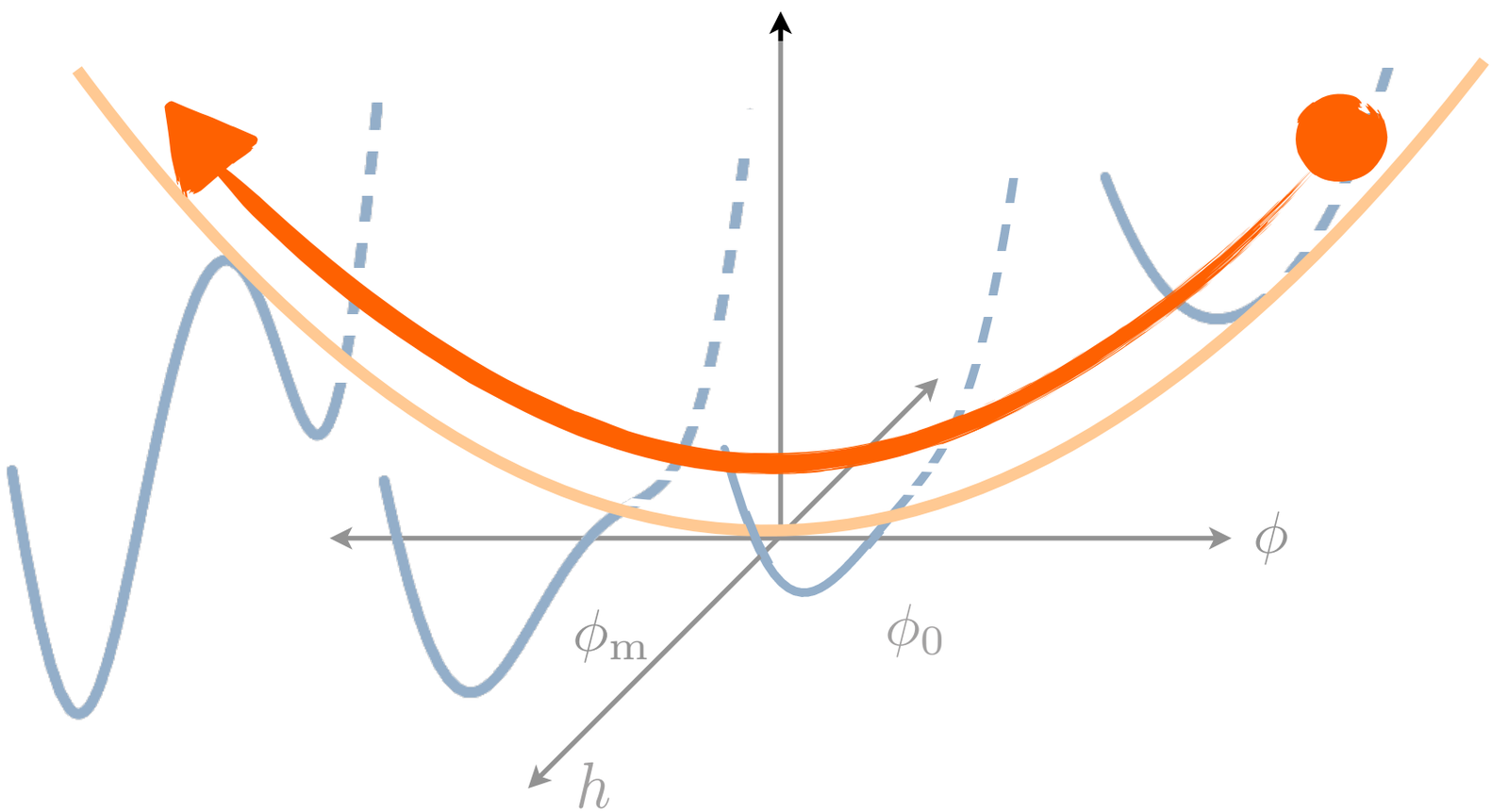
we cannot really go exploring in this field space, fixed couplings/masses



Necessary Fine Tuning $\Leftrightarrow$ $\dfrac{\phi_{\rm m} - \phi_0}{f} \ll 1$

how would we know?
early universe to the rescue

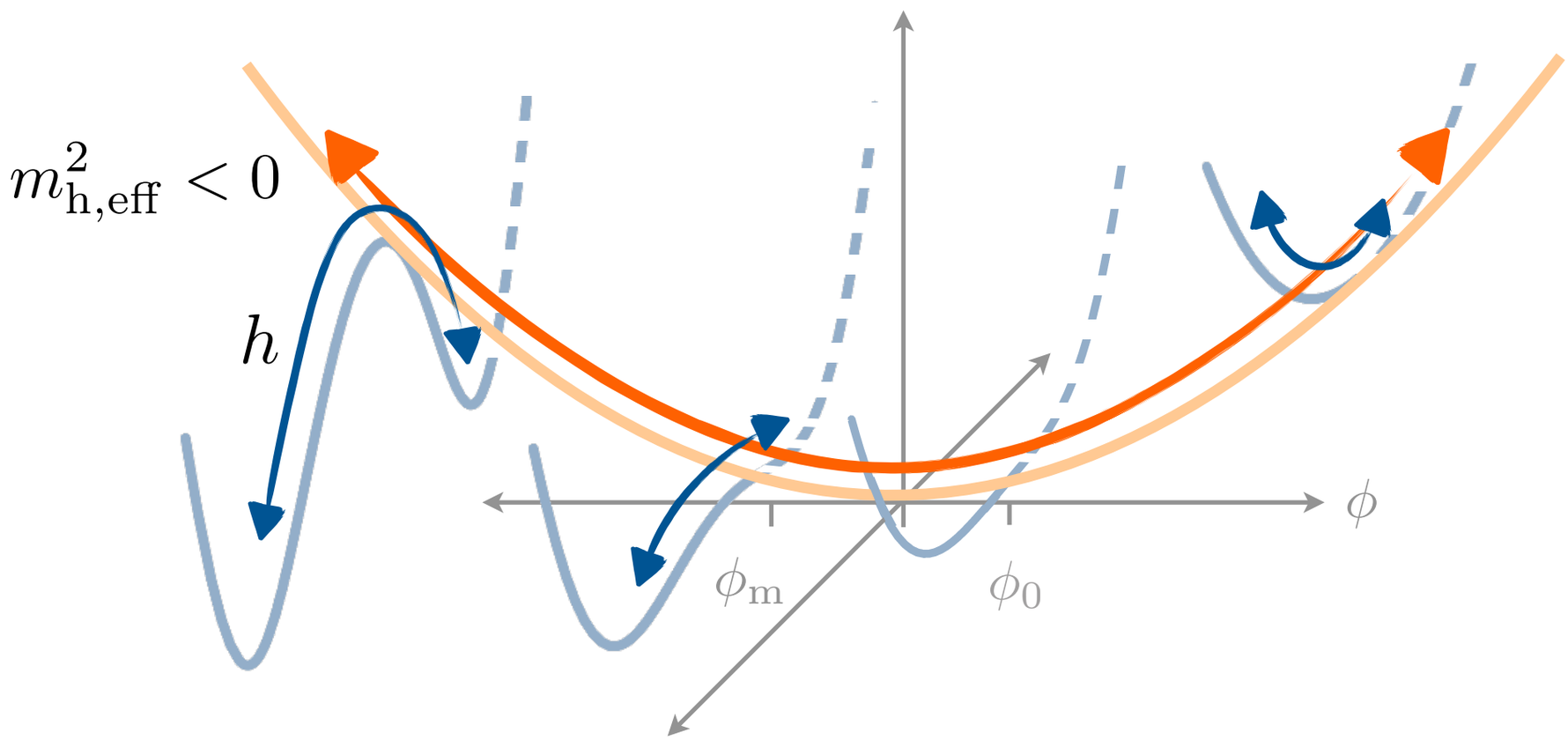
a displaced **modulus** will naturally explore different **Higgs potentials**



$$\text{Necessary Fine Tuning} \Leftrightarrow \quad \frac{\phi_{\rm m} - \phi_0}{f} \ll 1$$

complex dynamics of the Higgs-modulus system

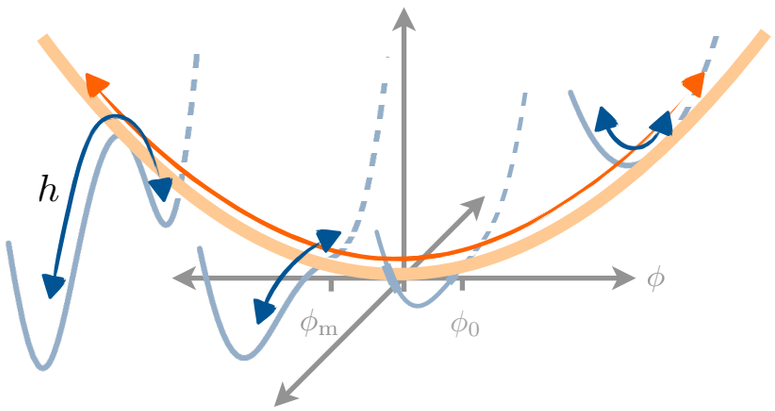
tachyonic particle production and backreaction



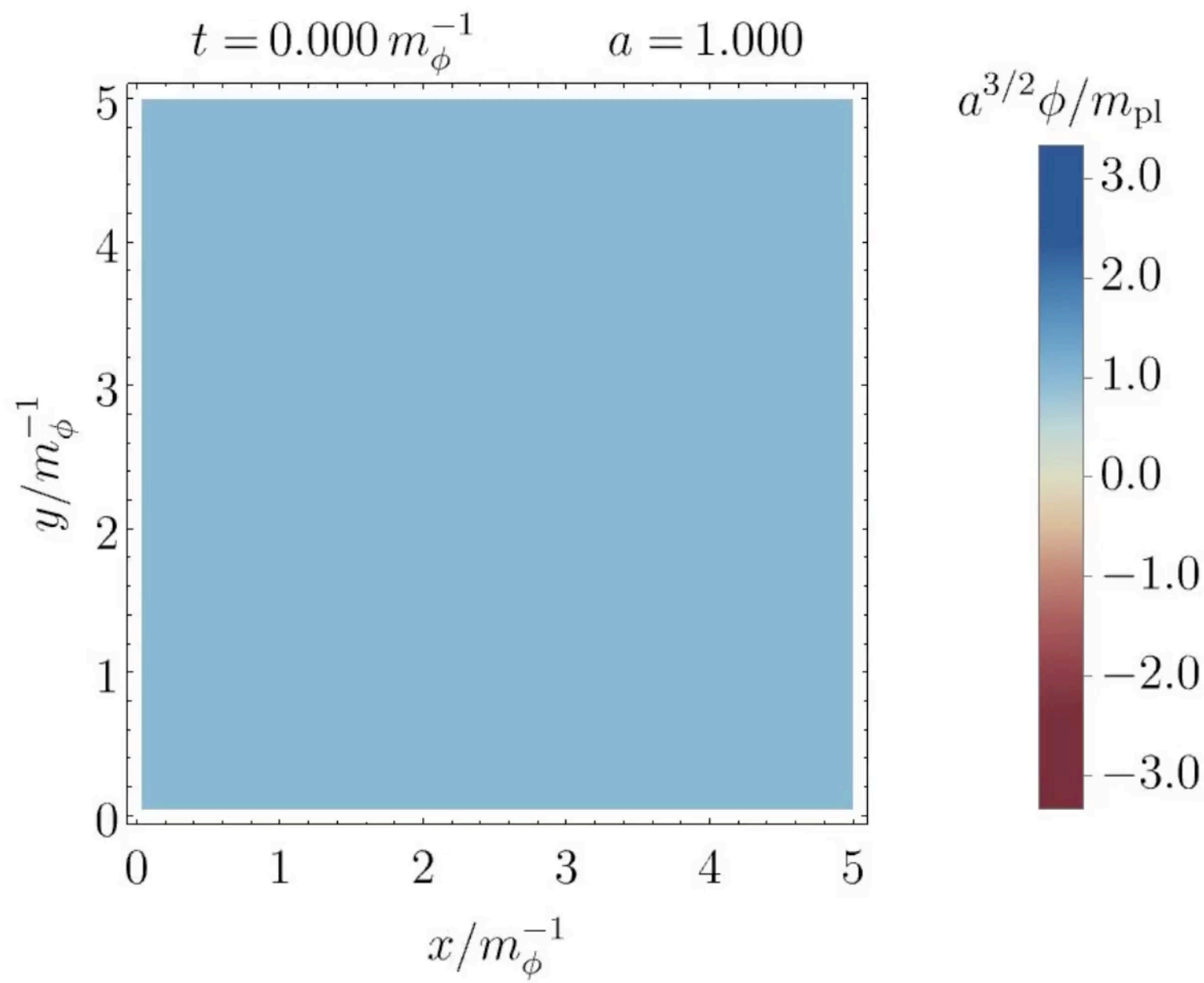
$$\text{Necessary Fine Tuning} \Leftrightarrow \quad \frac{\phi_{\mathrm{m}} - \phi_0}{f} \ll 1$$

* related, but not identical dynamics in hybrid inflation, Dufaux et. al (2006)

modulus dynamics

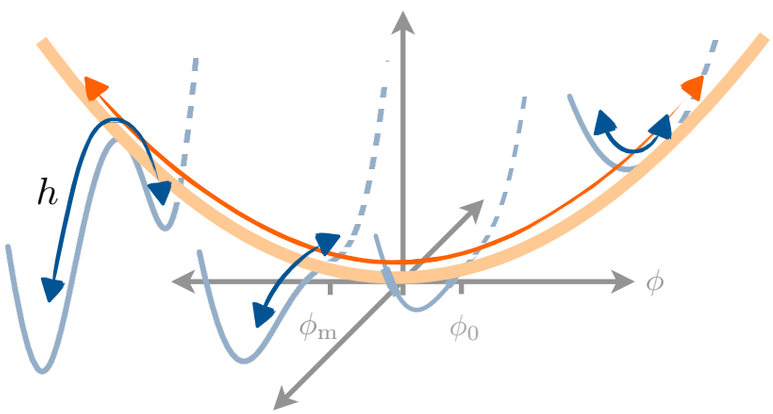


initial oscillation,
then fragmentation
from backreaction

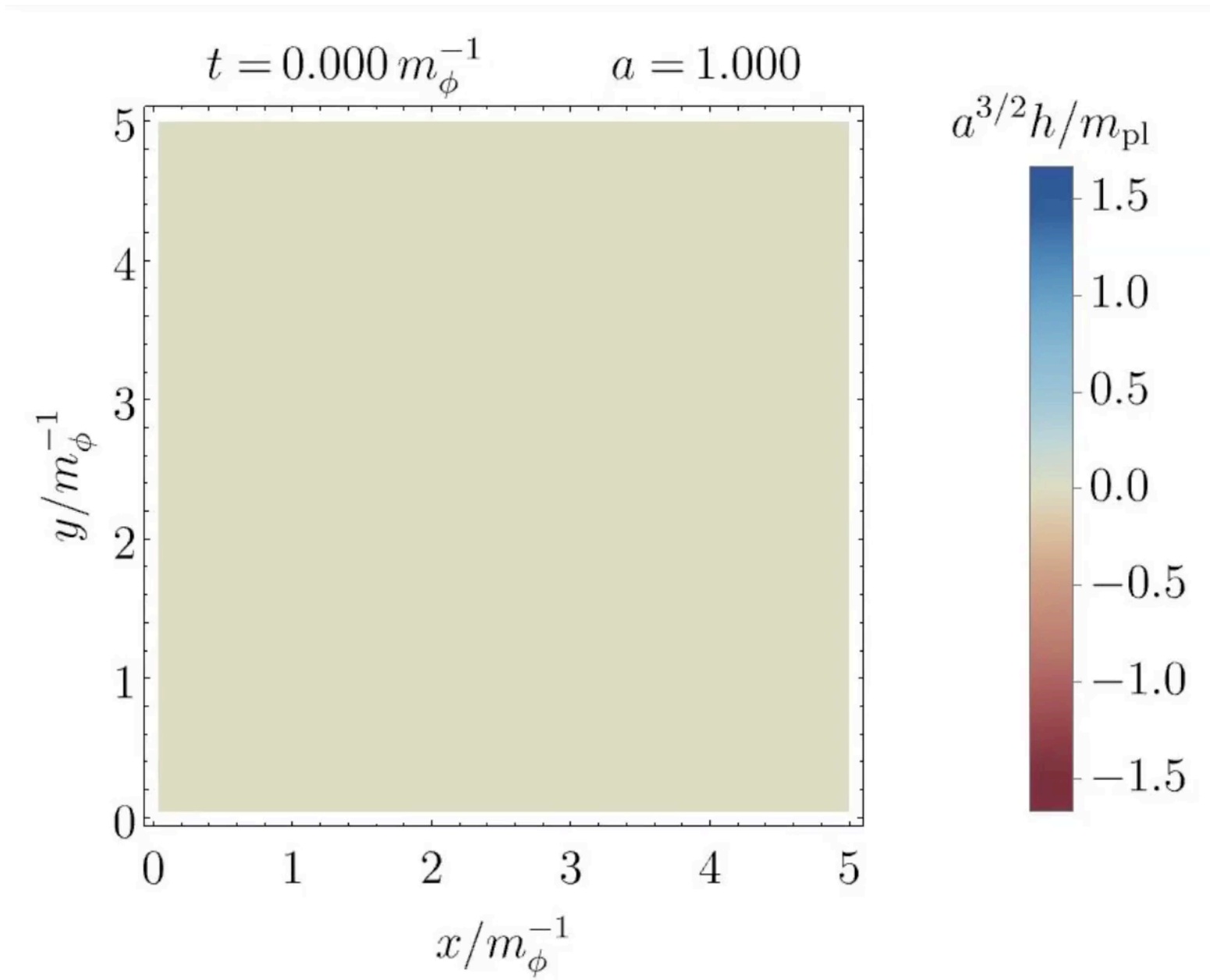


* under certain conditions, later in the talk

Higgs dynamics



tachyonic particle production and fragmentation



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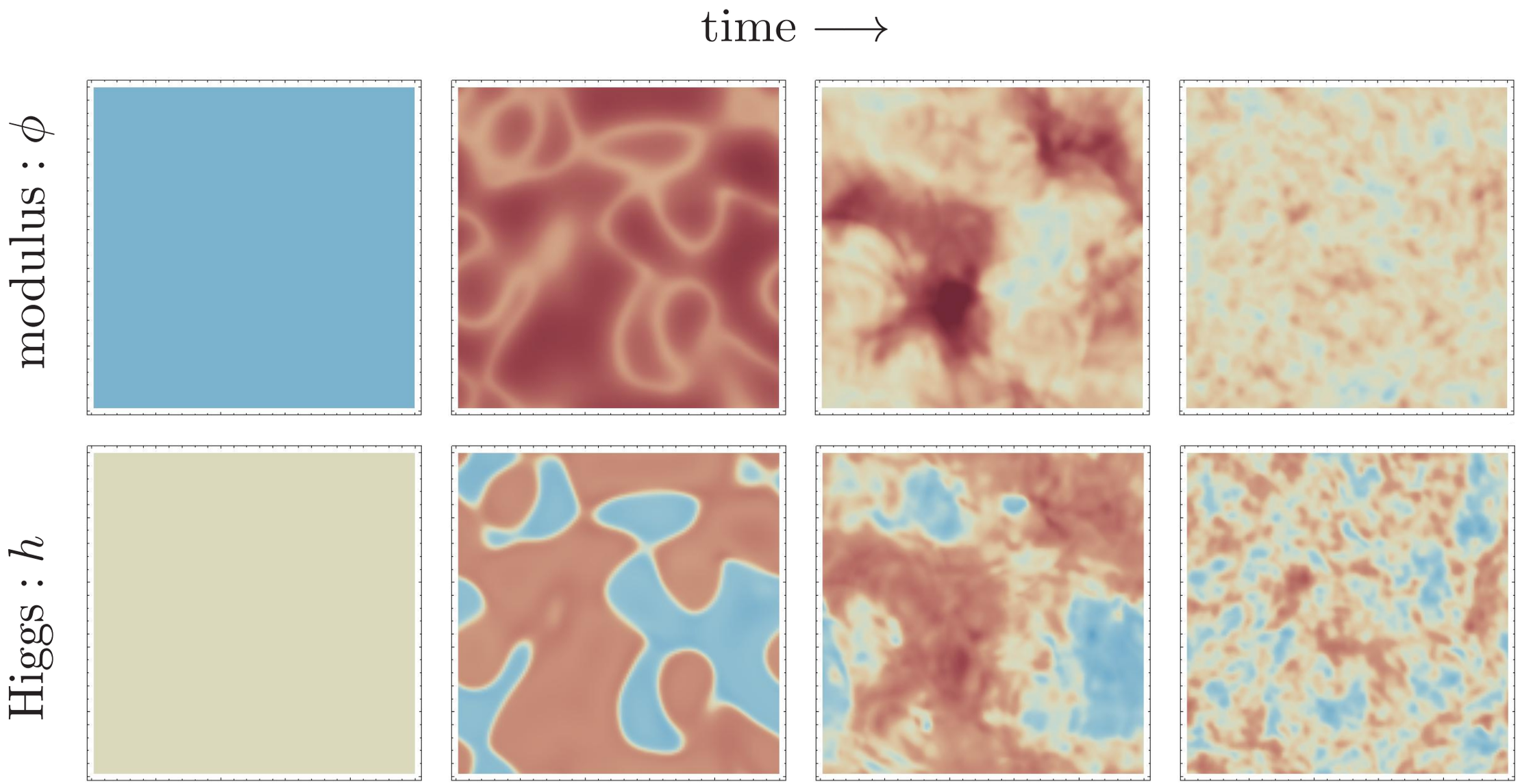
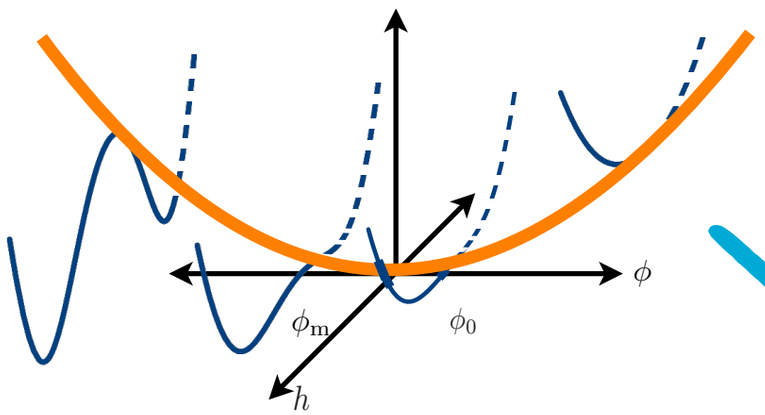
complex dynamics of the Higgs-modulus system



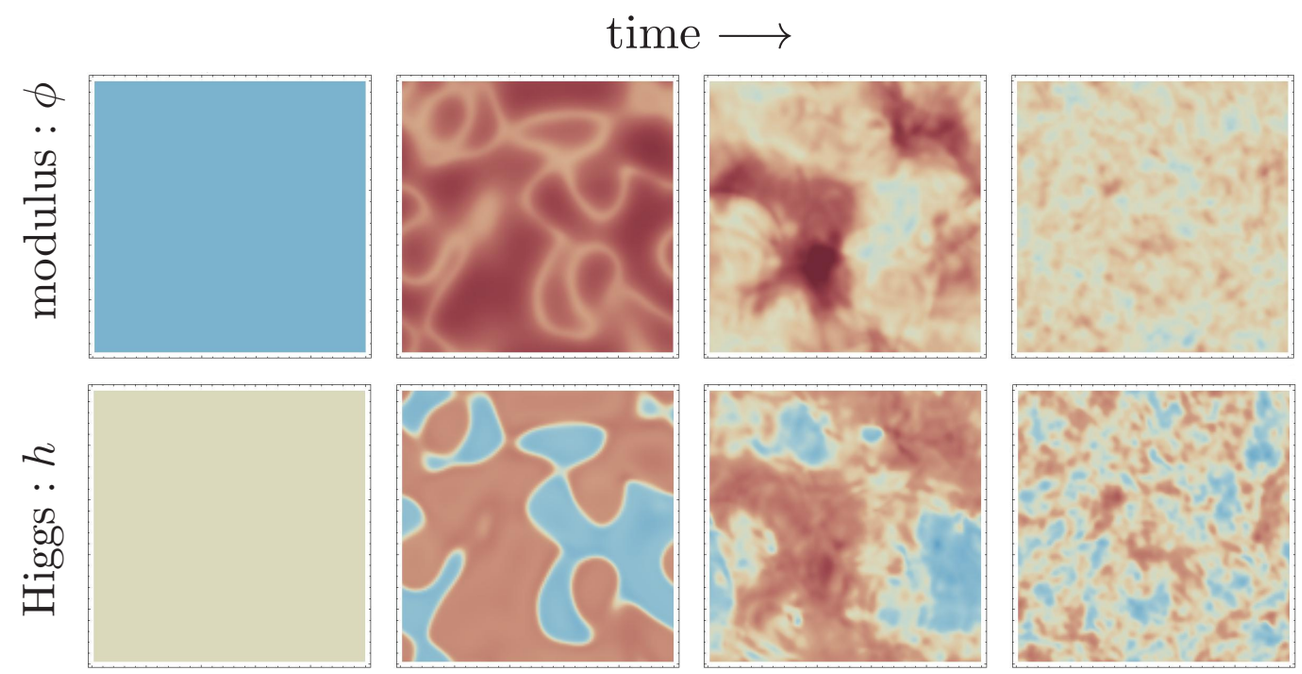
* under certain conditions, later in the talk

* 3D simulation with "real" Higgs, actual Higgs is complex— higher dimension in field space

fine tuning — non-perturbative dynamics — implications



Necessary Fine Tuning $\Leftrightarrow$ $\dfrac{\phi_{\rm m} - \phi_0}{f} \ll 1$



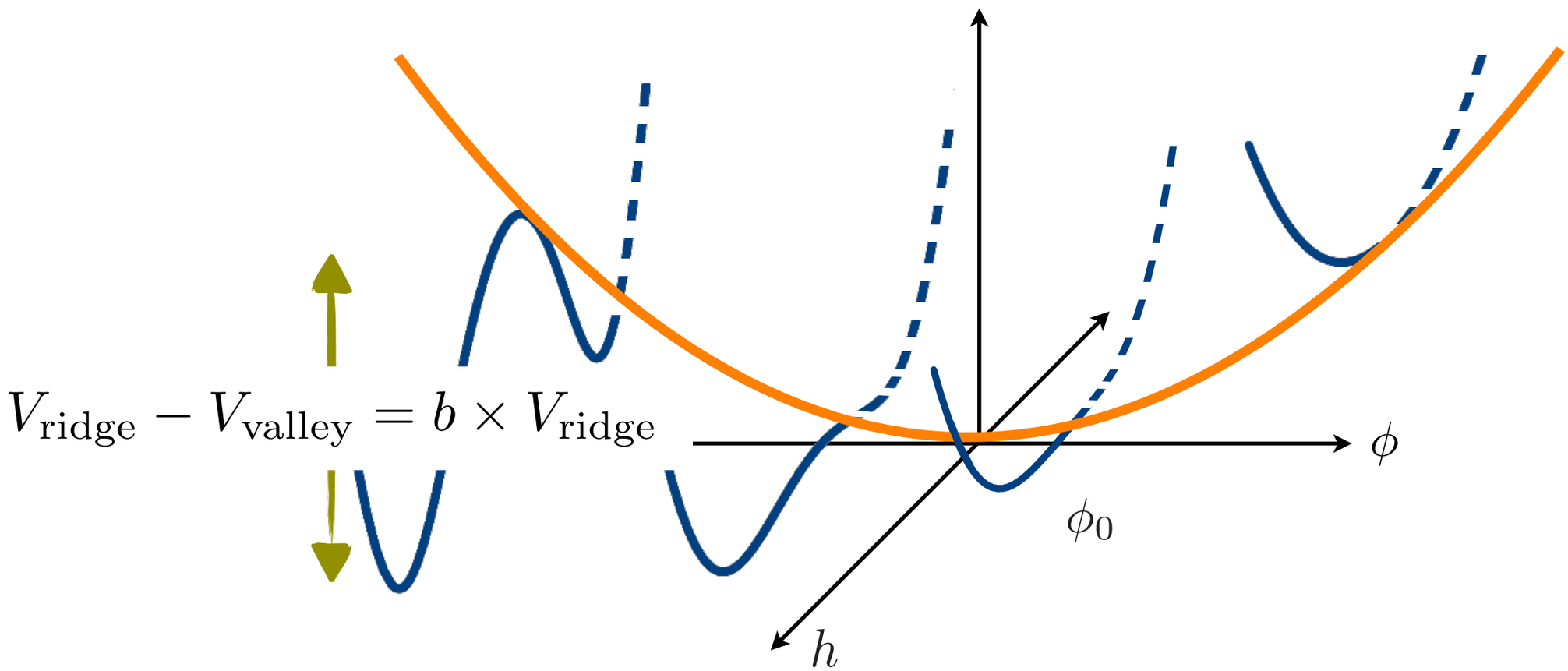
stochastic gravitational waves

non-trivial eq. of state

* under certain conditions, next up

an important parameter in the Higgs-modulus potential

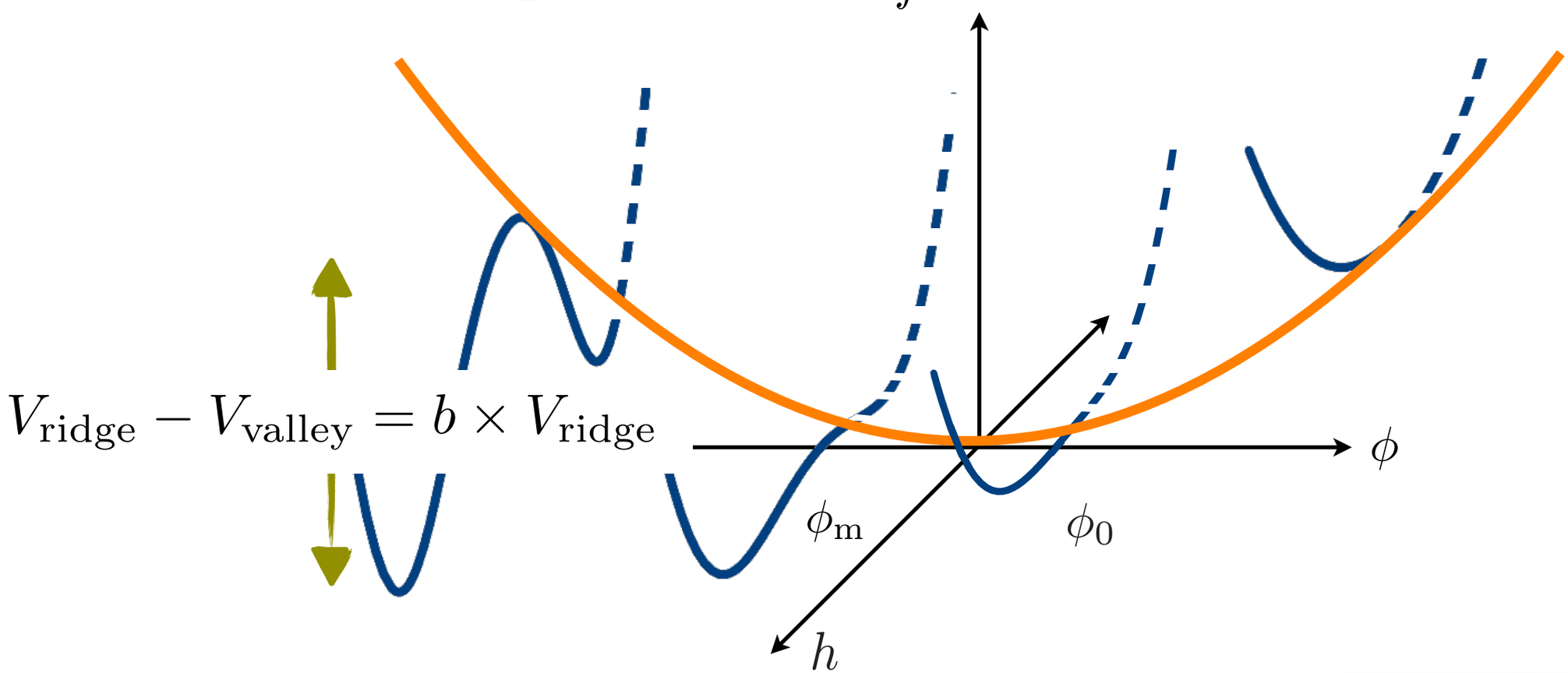
$$V(\phi, h) = \frac{1}{2} m_\phi^2 \phi^2 + M^2 \frac{(\phi - \phi_0)}{f} h^\dagger h + \lambda (h^\dagger h)^2 + V_0$$



$$0 \leq \boxed{\text{fragmentation efficiency parameter} \qquad b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2}} \leq 1$$

for violent nonlinear dynamics: 2 conditions

$$V(\phi, h) = \frac{1}{2} m_\phi^2 \phi^2 + M^2 \frac{(\phi - \phi_0)}{f} h^\dagger h + \lambda (h^\dagger h)^2 + V_0$$



$$b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \sim \mathcal{O}(1)$$

fragmentation efficiency

$$\Delta \equiv \frac{\phi_0 - \phi_{\rm m}}{f} \ll 1$$

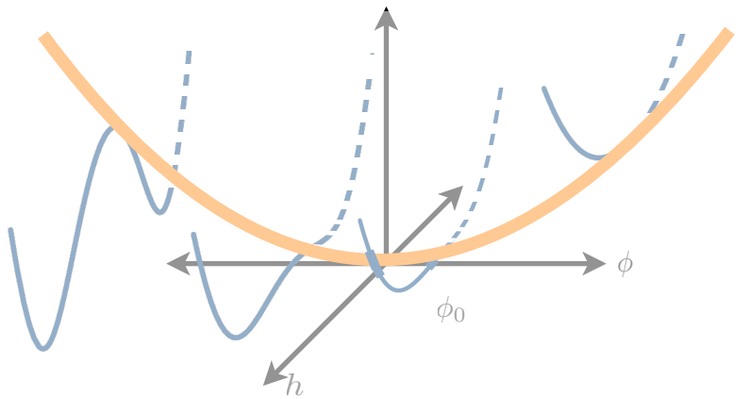
fine tuning

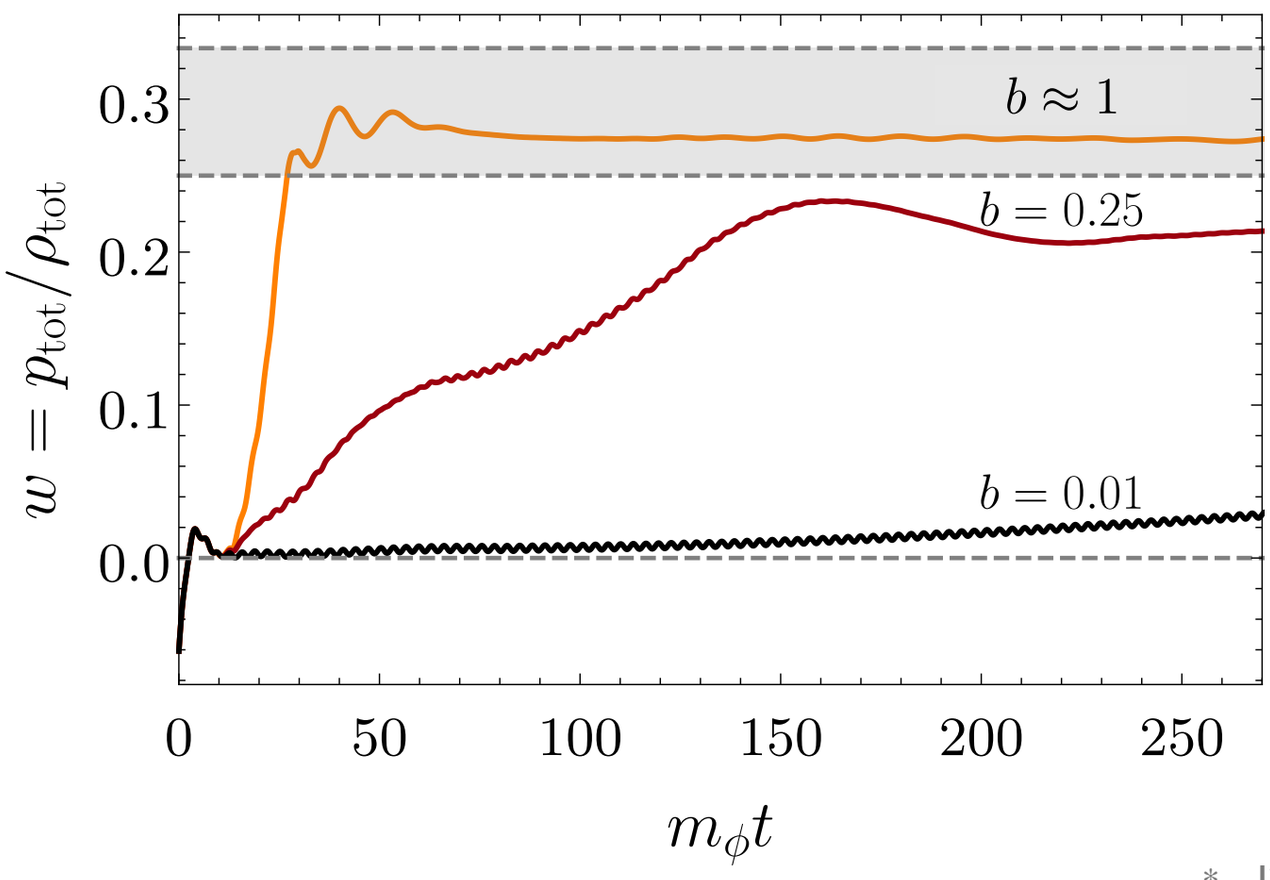
* b ~ O(1) is possible, but non-trivial for model building. Use flat directions in SUSY

non-perturbative dynamics — non-trivial eq. of state

$$V(\phi, h) = \frac{1}{2} m_\phi^2 \phi^2 + M^2 \frac{(\phi - \phi_0)}{f} h^\dagger h + \lambda (h^\dagger h)^2 + V_0$$

fragmentation efficiency $\quad b \equiv \dfrac{M^4}{2\lambda f^2 m_\phi^2}$





fragmentation $\quad$ radiation

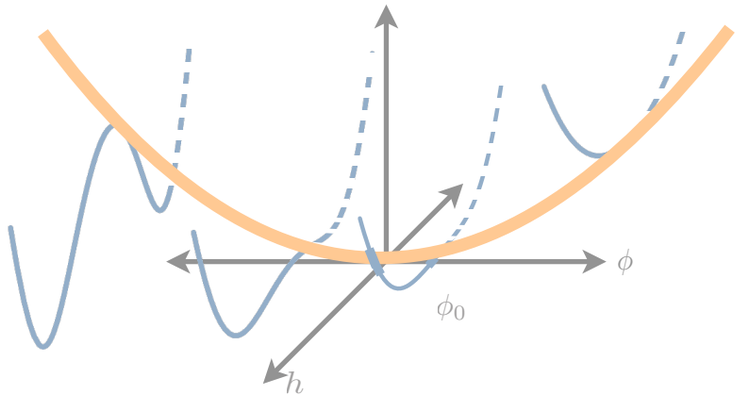
homogeneous $\quad$ matter

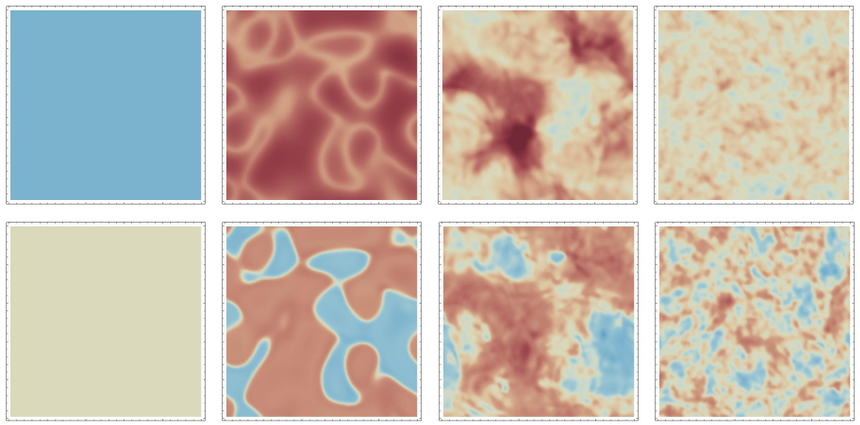
* likely returns to matter domination at late times, unless there are other decay channels. We cannot simulate very long times

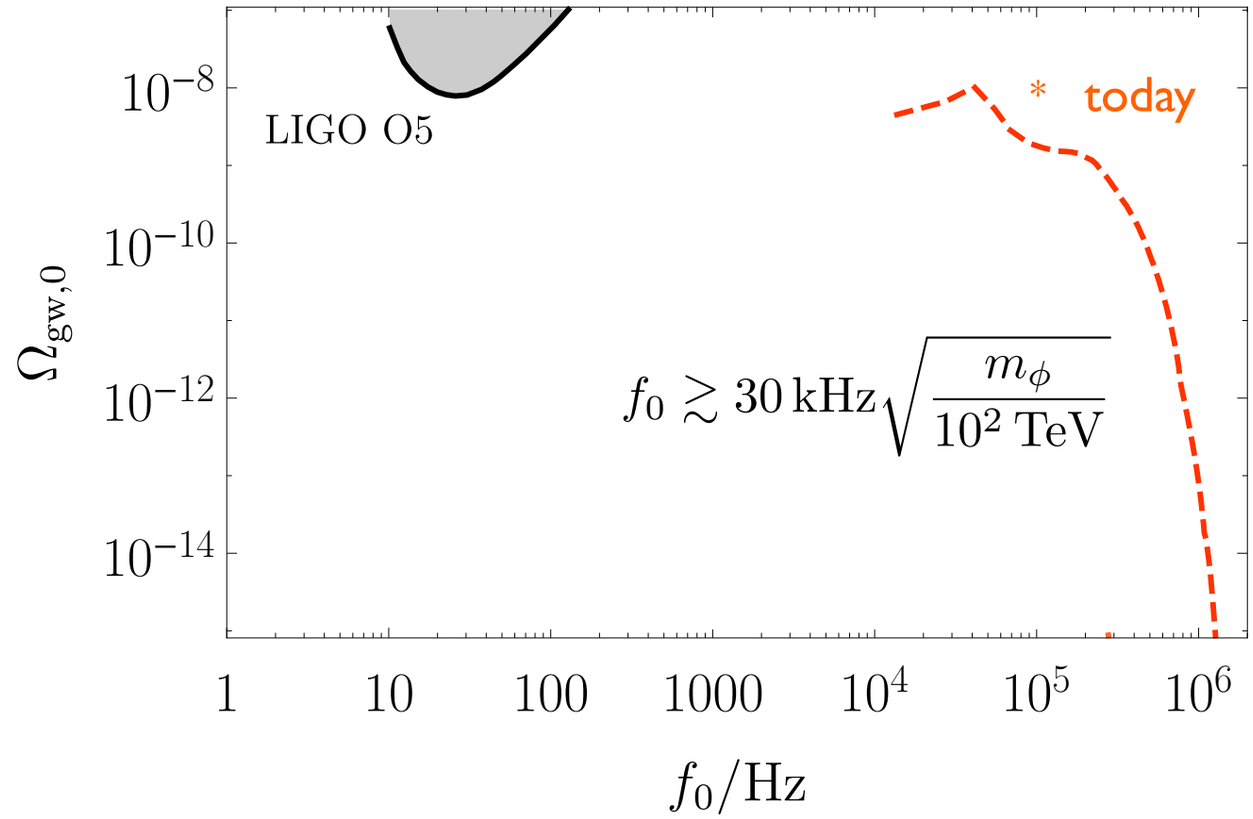
non-perturbative dynamics — stochastic gravitational waves

$$V(\phi, h) = \frac{1}{2} m_\phi^2 \phi^2 + M^2 \frac{(\phi - \phi_0)}{f} h^\dagger h + \lambda (h^\dagger h)^2 + V_0$$

fragmentation efficiency $\quad b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \sim \mathcal{O}(1)$







for high frequency gw-detection ideas see:
Akutsu et. al (2010), Goryachev & Tobar (2014), Arvanitaki & Geraci (2016)

non-perturbative dynamics — stochastic gravitational waves

$$V(\phi, h) = \frac{1}{2} m_\phi^2 \phi^2 + M^2 \frac{(\phi - \phi_0)}{f} h^\dagger h + \lambda (h^\dagger h)^2 + V_0$$

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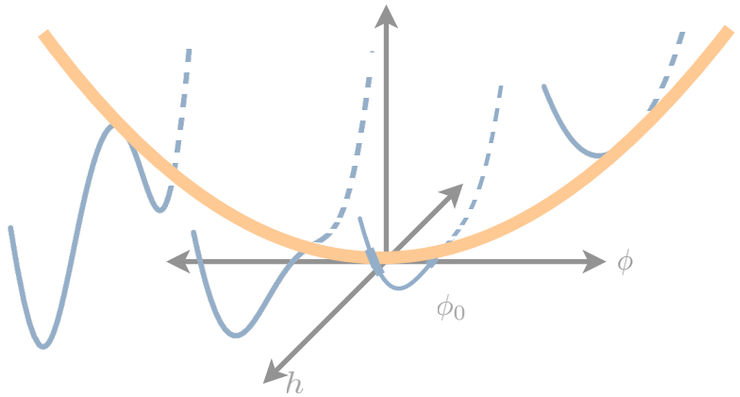
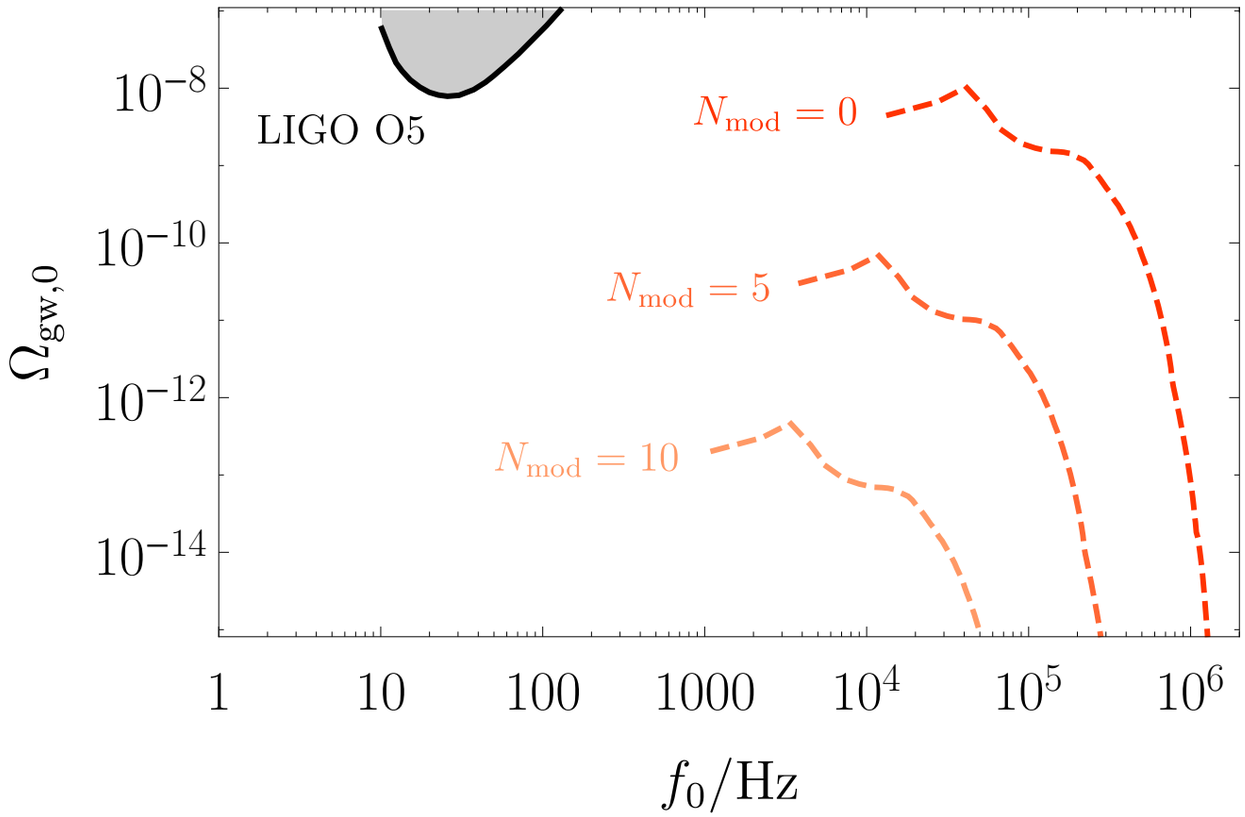


* IF universe becomes matter dominated for $N_{\rm mod}$ e-folds again before BBN

$$f_0 \sim 30\,\mathrm{kHz} \times e^{-\frac{N_{\rm mod}}{4}(1-3w_{\rm mod})} \sqrt{\frac{m_\phi}{10^2\ \mathrm{TeV}}}$$

$$\Omega_{\rm gw,0} \sim 10^{-8} \times e^{-N_{\rm mod}(1-3w_{\rm mod})}$$



caveats and future directions

* we are not necessarily *explaining* the fine tuning; we are exploring the implications of fine tuning

* inclusion of gauge fields + complex Higgs

* initial conditions

* model building

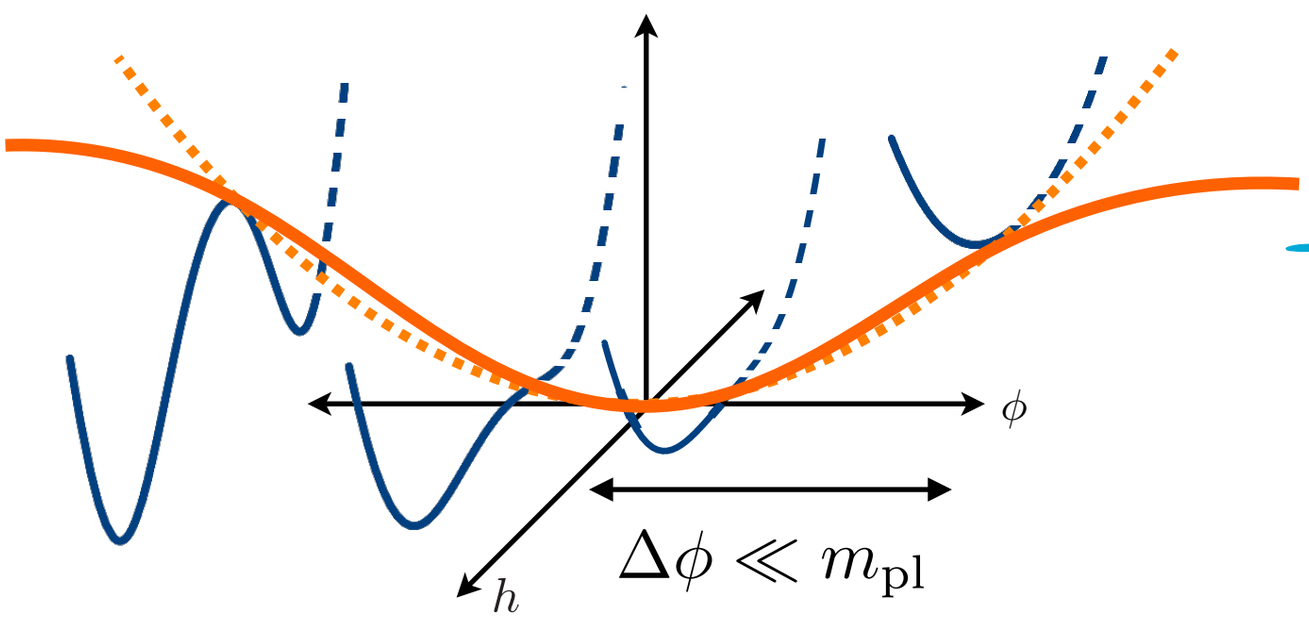
caveats and future directions

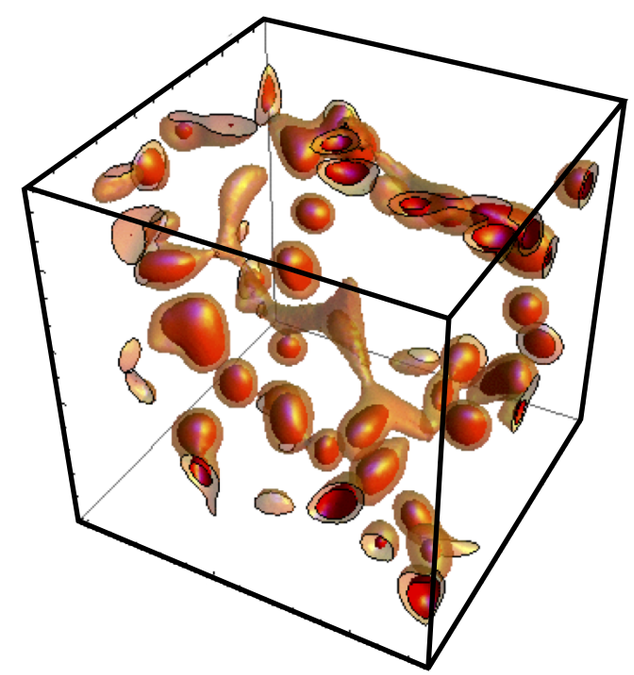
* we are not necessarily explaining the fine tuning, we are exploring the implications of fine tuning

* inclusion of gauge fields + complex Higgs

* model building

* inclusion of self-interactions in the moduli: oscillons

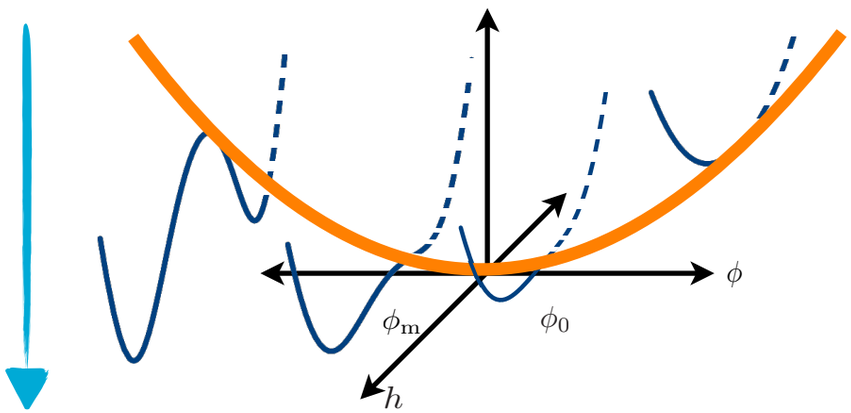


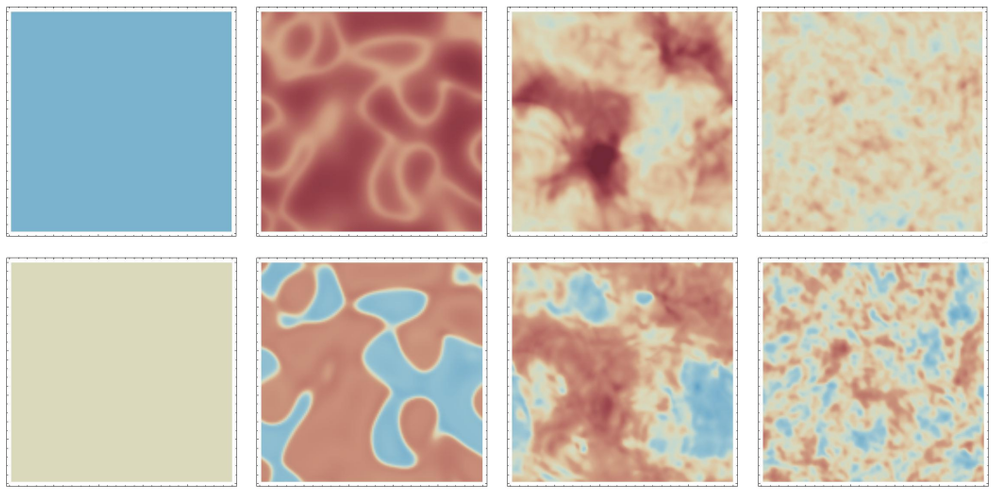


summary: Cosmological Dynamics of Higgs Fine Tuning

arXiv: 1802.00444

nothing but Higgs at the LHC



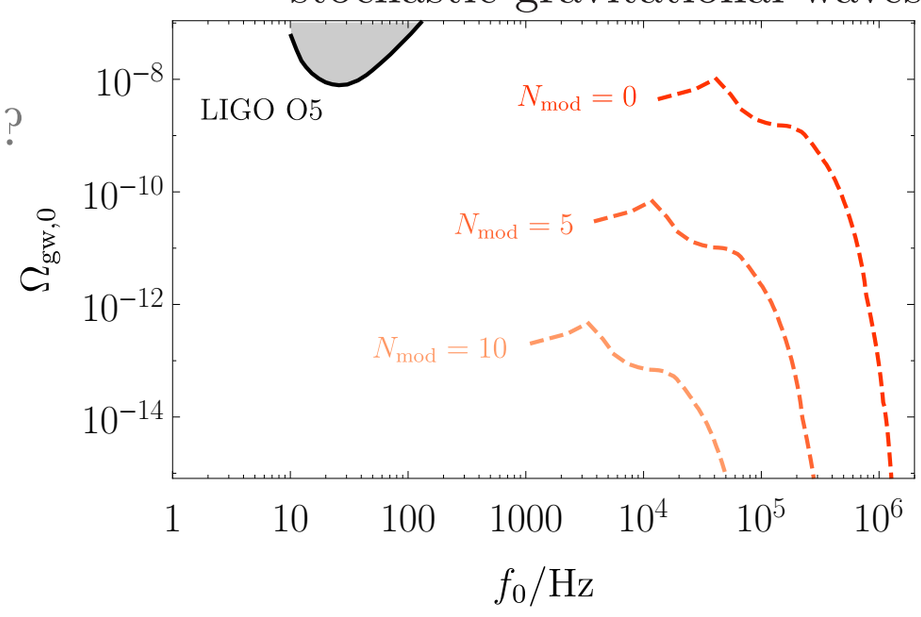


$$V(\phi, h) = \frac{1}{2} m_\phi^2 \phi^2 + M^2 \frac{(\phi - \phi_0)}{f} h^\dagger h + \lambda (h^\dagger h)^2 + V_0$$

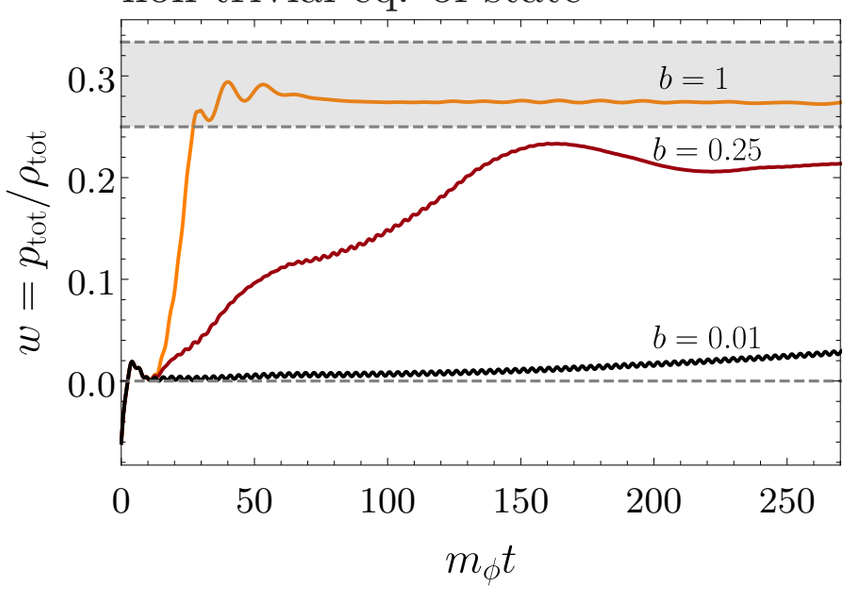
$$b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \sim \mathcal{O}(1) \quad \text{fragmentation efficiency}$$

Necessary Fine Tuning $\Leftrightarrow$ $\dfrac{\phi_{\rm m} - \phi_0}{f} \ll 1$

stochastic gravitational waves



non-trivial eq. of state



* future
  * related phenomenon ?
  * gauge fields
  * complex Higgs
  * self-interactions
  * model building

extra slides

Simulation Details: 3+1 dimensional Lattice Simulations

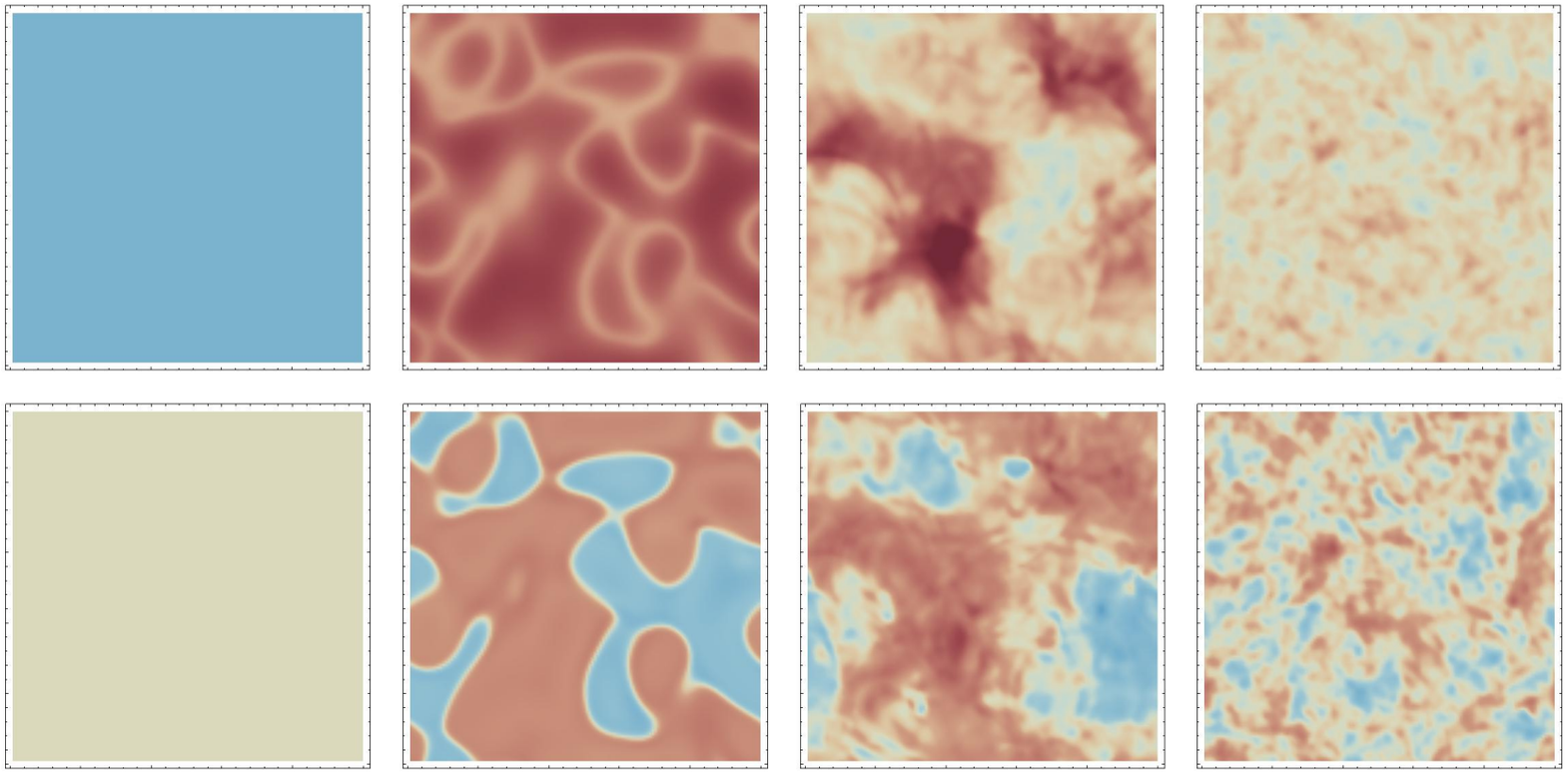
$\mathcal{O}[10^2] \sim \mathcal{O}[10^3]$ CPU Hours

$256^4 - 512^3$

$L_{\rm in} = 0.5 H_{\rm in}^{-1} - 2.5 H_{\rm in}^{-1}$

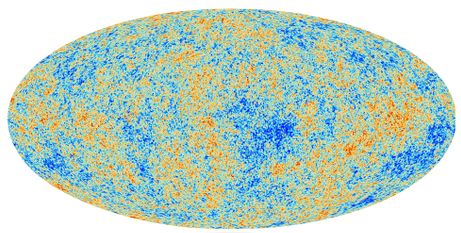
$dt = 0.00125 m_\phi^{-1}$ to $0.000625 m_\phi^{-1}$

$a_{\rm in} = 1$, with $a_{\rm end} \sim \mathcal{O}[\text{few } e\text{-folds}]$



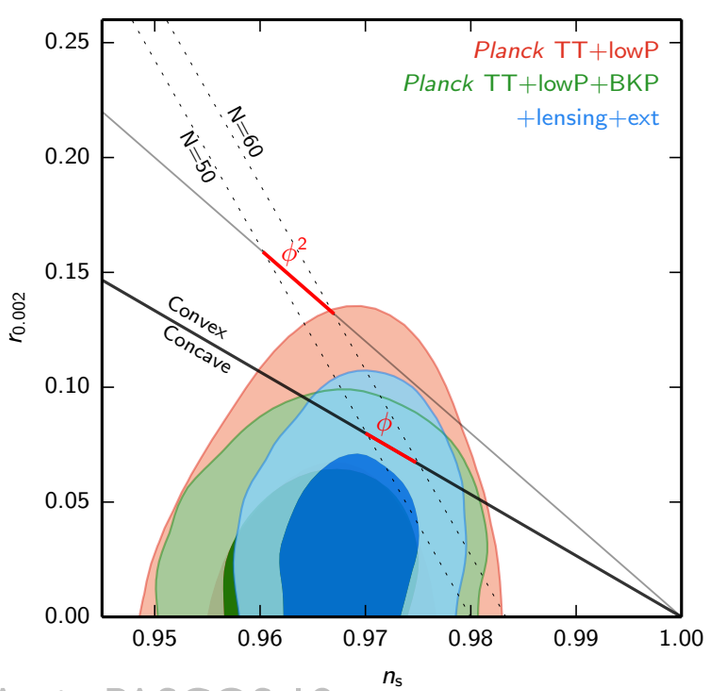
Initial conditions: Vacuum fluctuations in Minkowski space

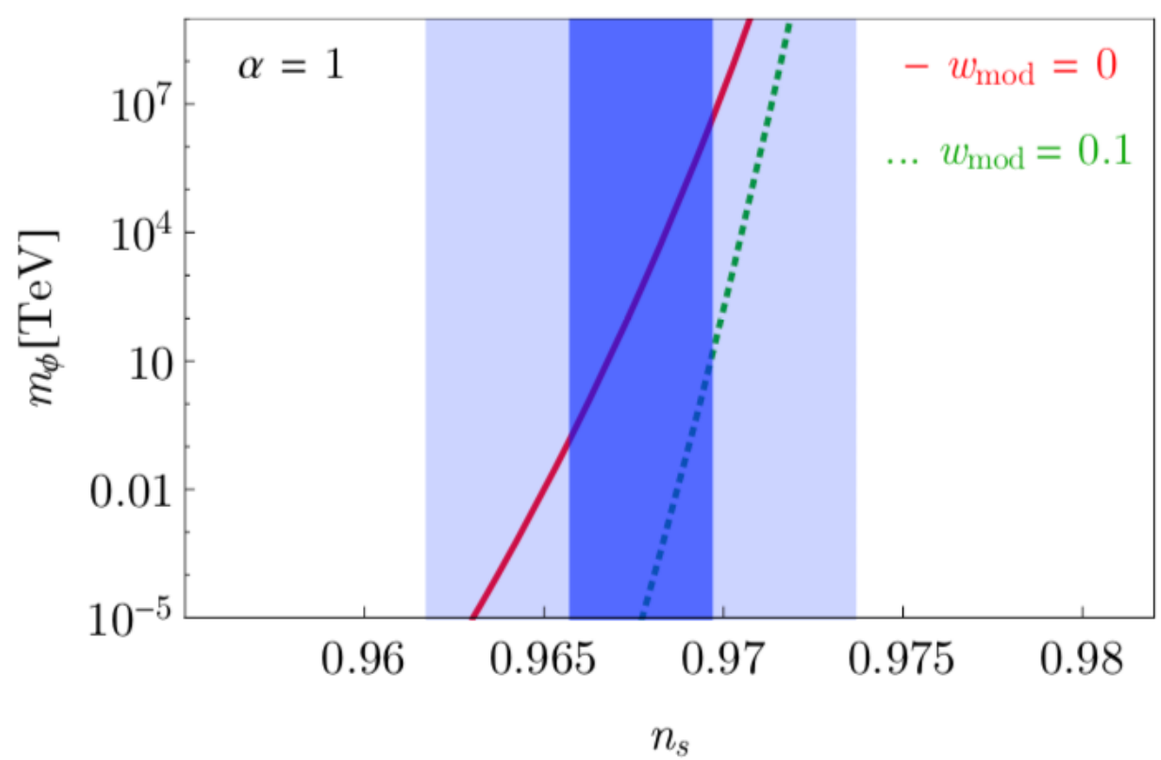
other implications of non-trivial eq. of state



* assuming an inflationary model, the eq. of state can significantly affect the lower bound on the modulus mass

$$m_\phi^2 \gtrsim \frac{3(1+w_{\rm mod})}{2c} m_{\rm pl}^2 \exp\left(-\frac{6(1+w_{\rm mod})}{1-3w_{\rm mod}}\left(-N_k + 57 + \frac{1}{4}\ln r + \frac{1}{4}\ln\left(\frac{\rho_k}{\rho_{\rm end}}\right)\right)\right)$$





model building

$$V(\phi, h) = \frac{1}{2} m_\phi^2 \phi^2 + M^2 \frac{(\phi - \phi_0)}{f} h^\dagger h + \lambda (h^\dagger h)^2 + V_0$$

$$b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \sim \mathcal{O}(1)$$ fragmentation efficiency

$a) m_\phi \lesssim M \ll f \sim M_{\rm pl}, \lambda \ll 1$

$b) m_\phi \ll M \ll f \sim M_{\rm pl}, \lambda \sim 1$

D-flat directions in SUSY can help with small λ

gravitational waves: scalings

$$f_0 = \frac{1}{2\pi}\frac{k}{a_0} = \frac{1}{2\pi}\left(\frac{k}{a_{\rm g}H_{\rm g}}\right)\sqrt{H_{\rm g}H_0}\left(\frac{a_{\rm g}}{a_{\rm th}}\right)^{(1-3w_{\rm mod})/4}\left(\frac{g_{\rm th}}{g_0}\right)^{-1/12}\Omega_{\rm r,0}^{1/4}$$

scale at production

red-shifting

$$\Omega_{\rm gw,0} = \Omega_{\rm gw} \times \left(\frac{a_{\rm g}}{a_{\rm th}}\right)^{1-3w_{\rm mod}}\left(\frac{g_{\rm th}}{g_0}\right)^{-1/3}\Omega_{\rm r,0}$$

$$\Omega_{\rm gw} \sim \left(\frac{a_{\rm g}H_{\rm g}}{k}\right)^2 \delta_\pi^2$$

$\delta_\pi \sim 1/3$ gradients/total

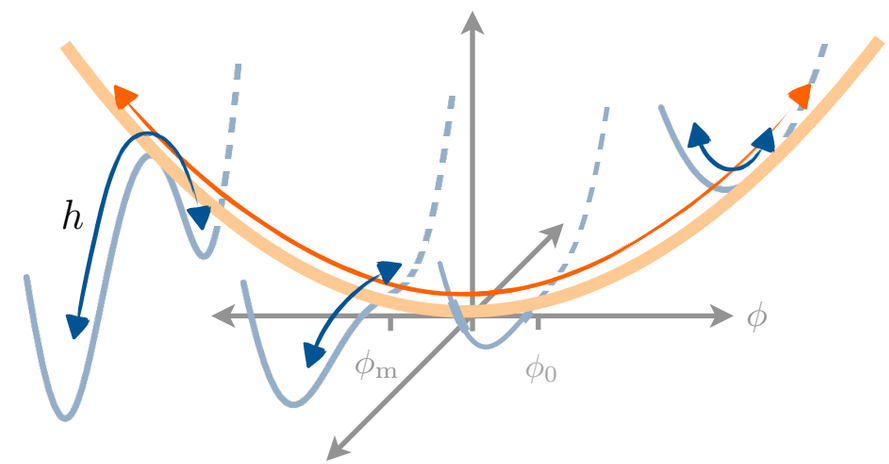
$$\Omega_{\rm gw} = \frac{1}{\rho_{\rm g}}\frac{d\ln\rho_{\rm gw}}{d\ln k}$$

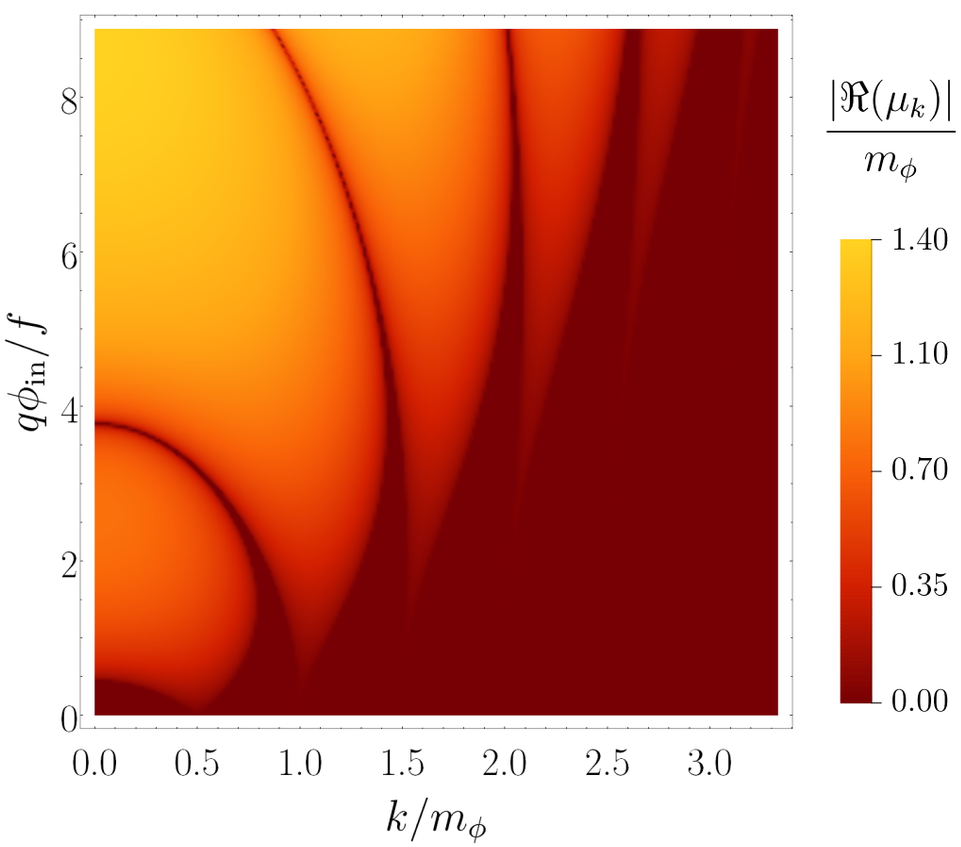
fragmentation: a closer look

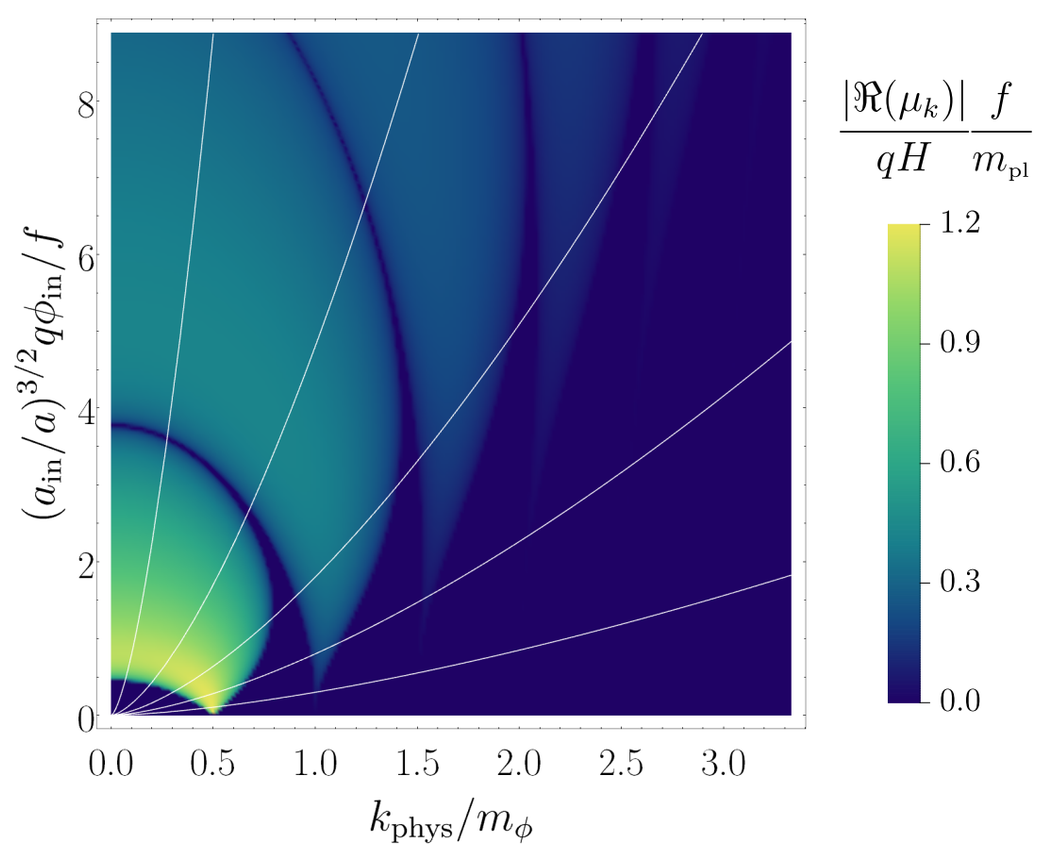
$$\delta h_k \propto e^{\mu_k t}$$

$$\mu_k \propto \sqrt{q}$$

$$q = \frac{M^2}{m_\phi^2} \gg 1 \Longrightarrow \text{Efficient Particle Prod.}$$







power spectrum: higgs/modulus