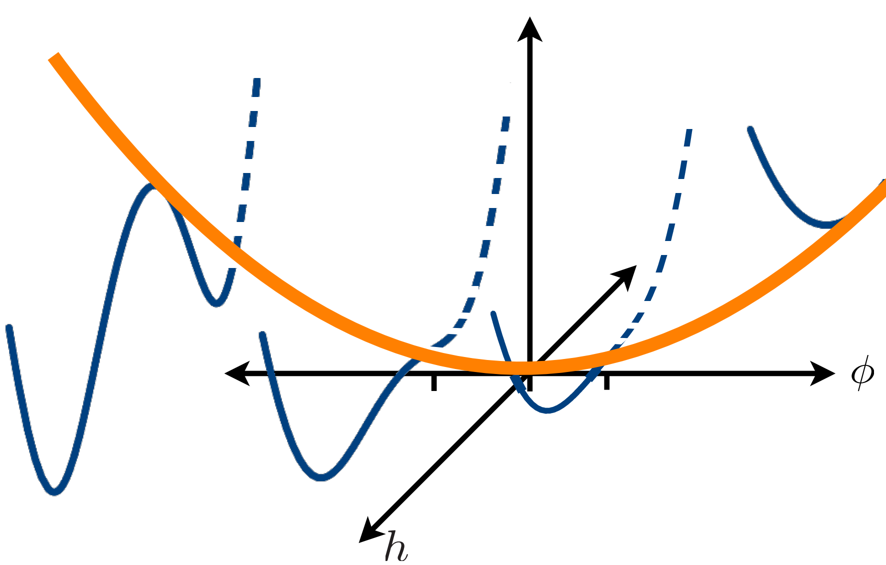
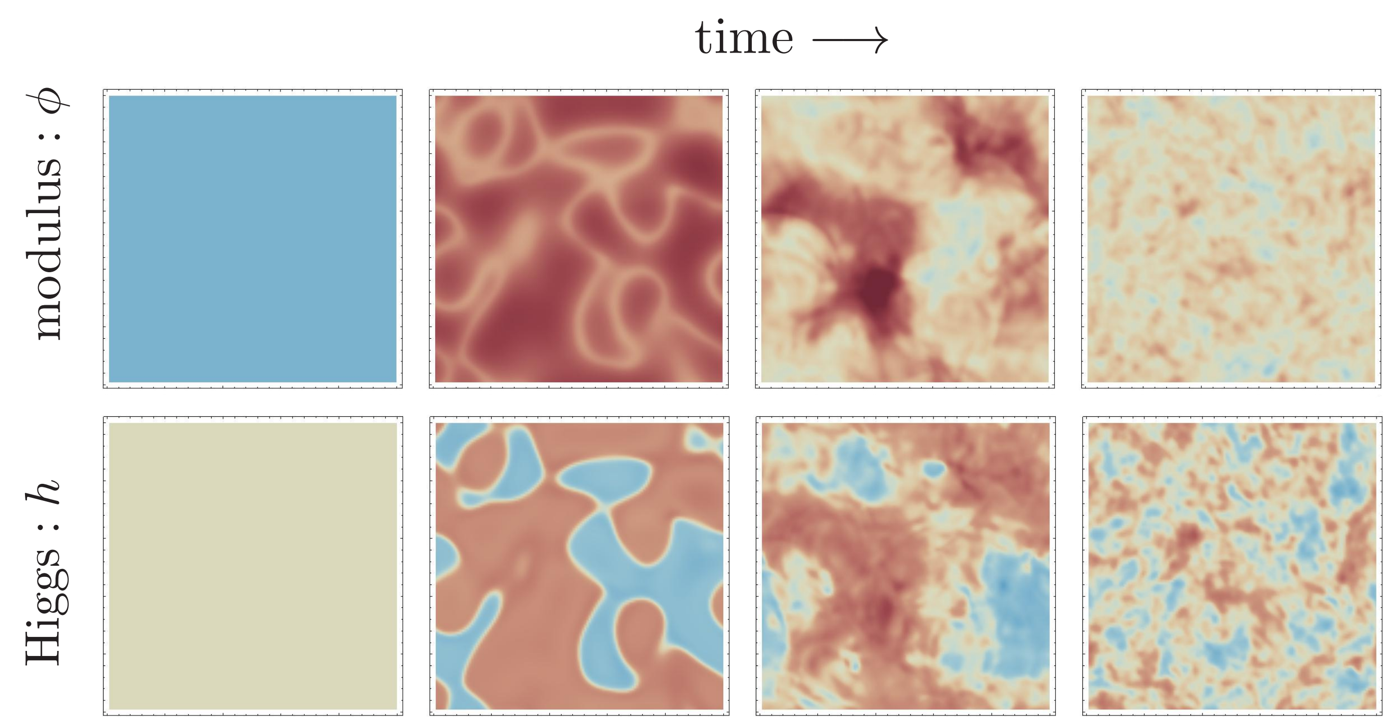
The Violent Cosmic History of the Higgs

based on "Cosmological dynamics of Higgs potential fine tuning", Phys. Rev. D 99, 035008 (2019)





Mustafa A. Amin
with Jiji Fan, Kaloian Lozanov & Matthew Reece

IIT KANPUR
Indian Institute of Technology, Kanpur

RICE

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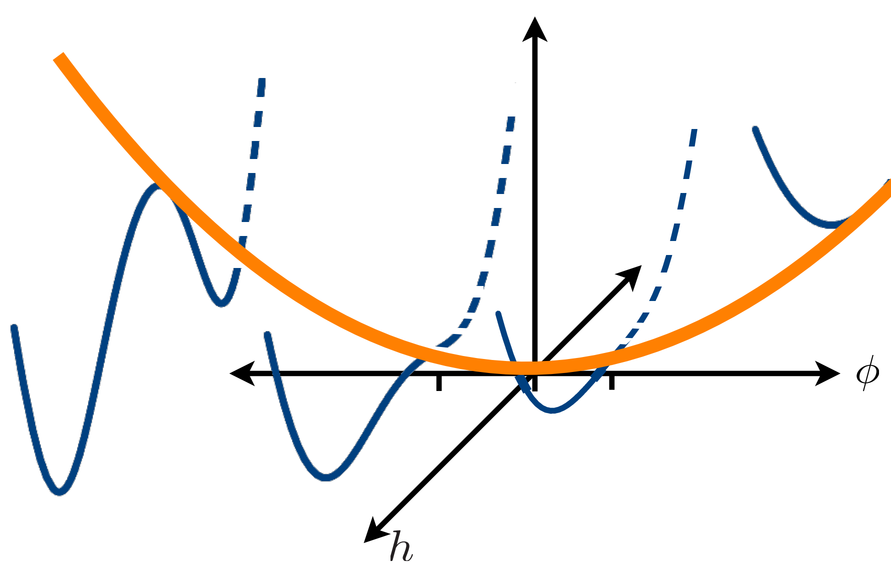

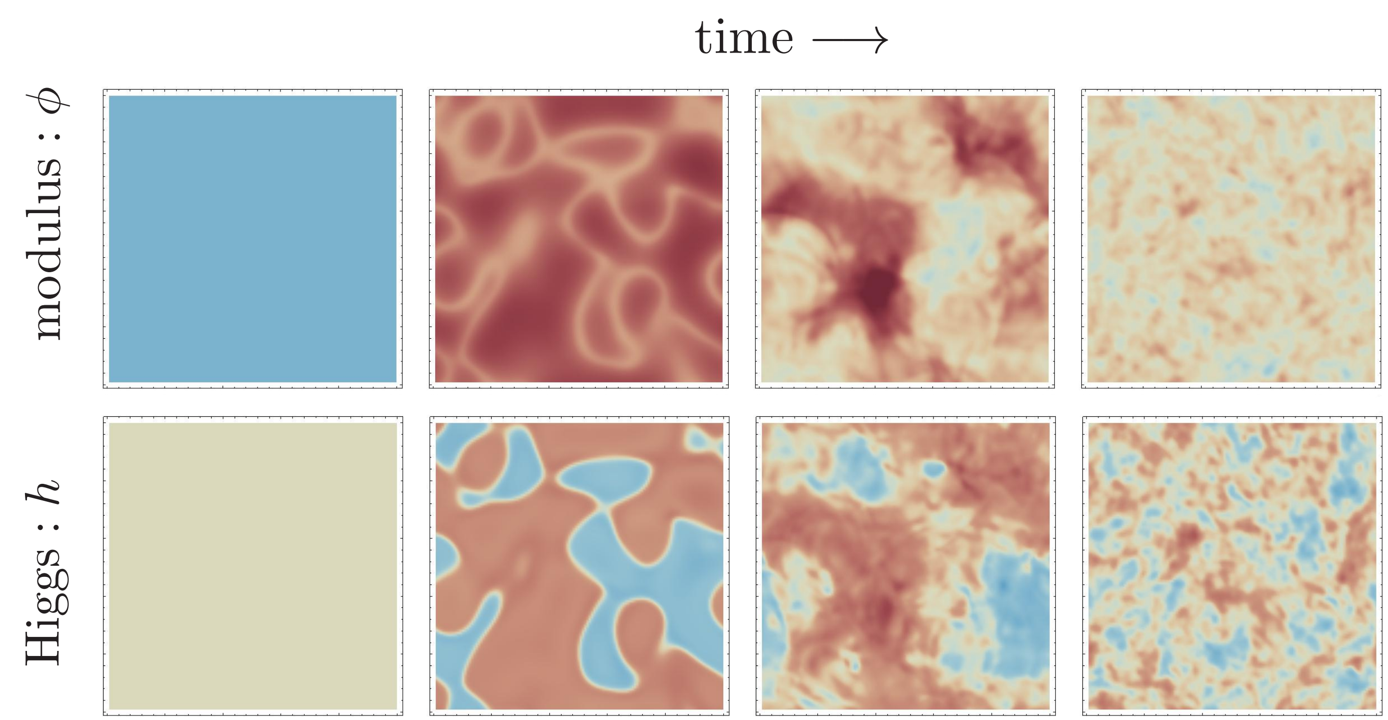

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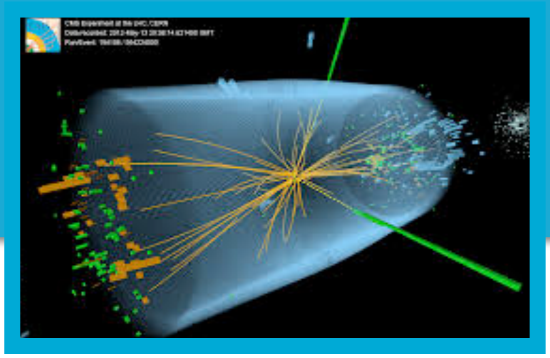
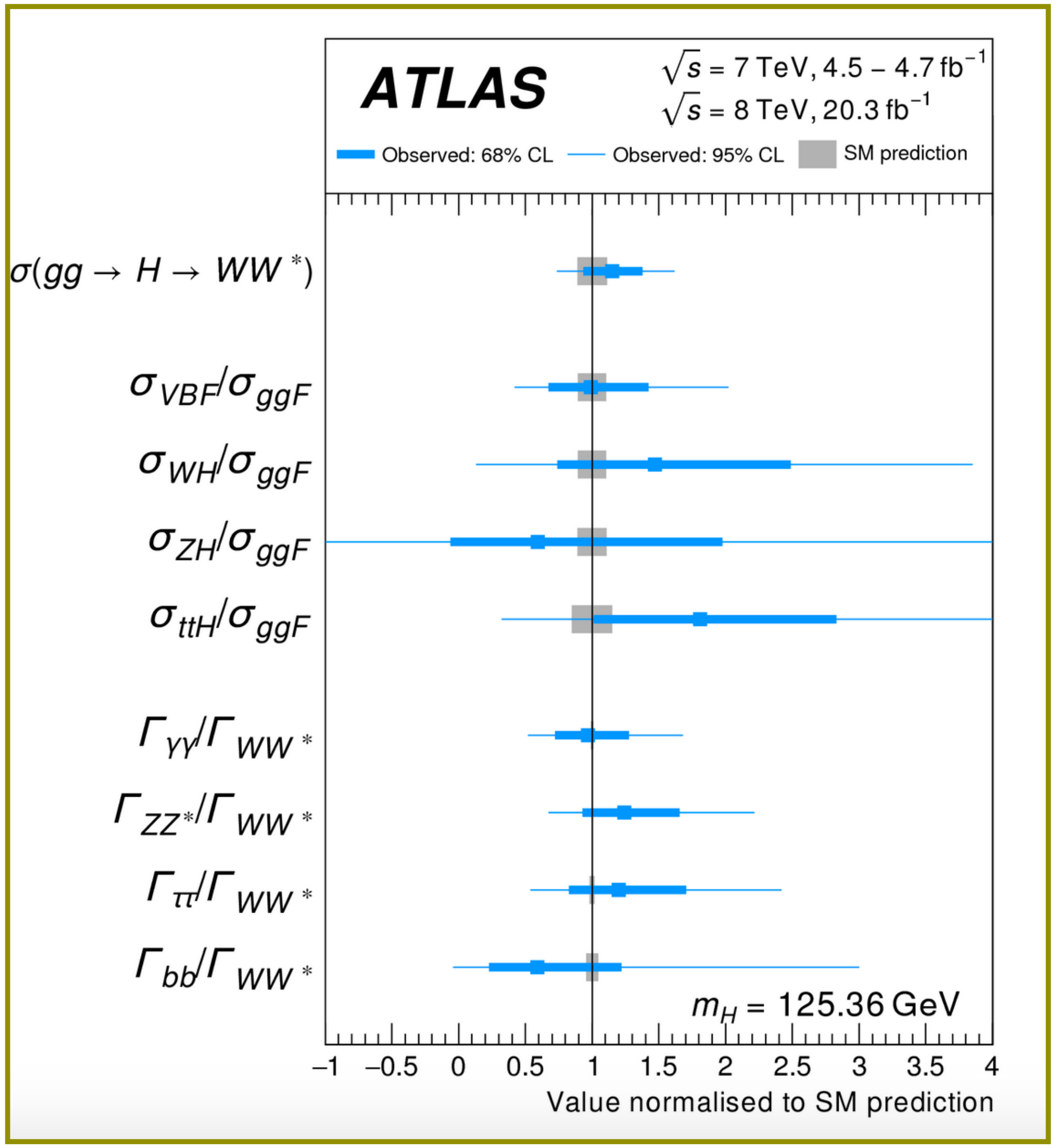
main suggestion

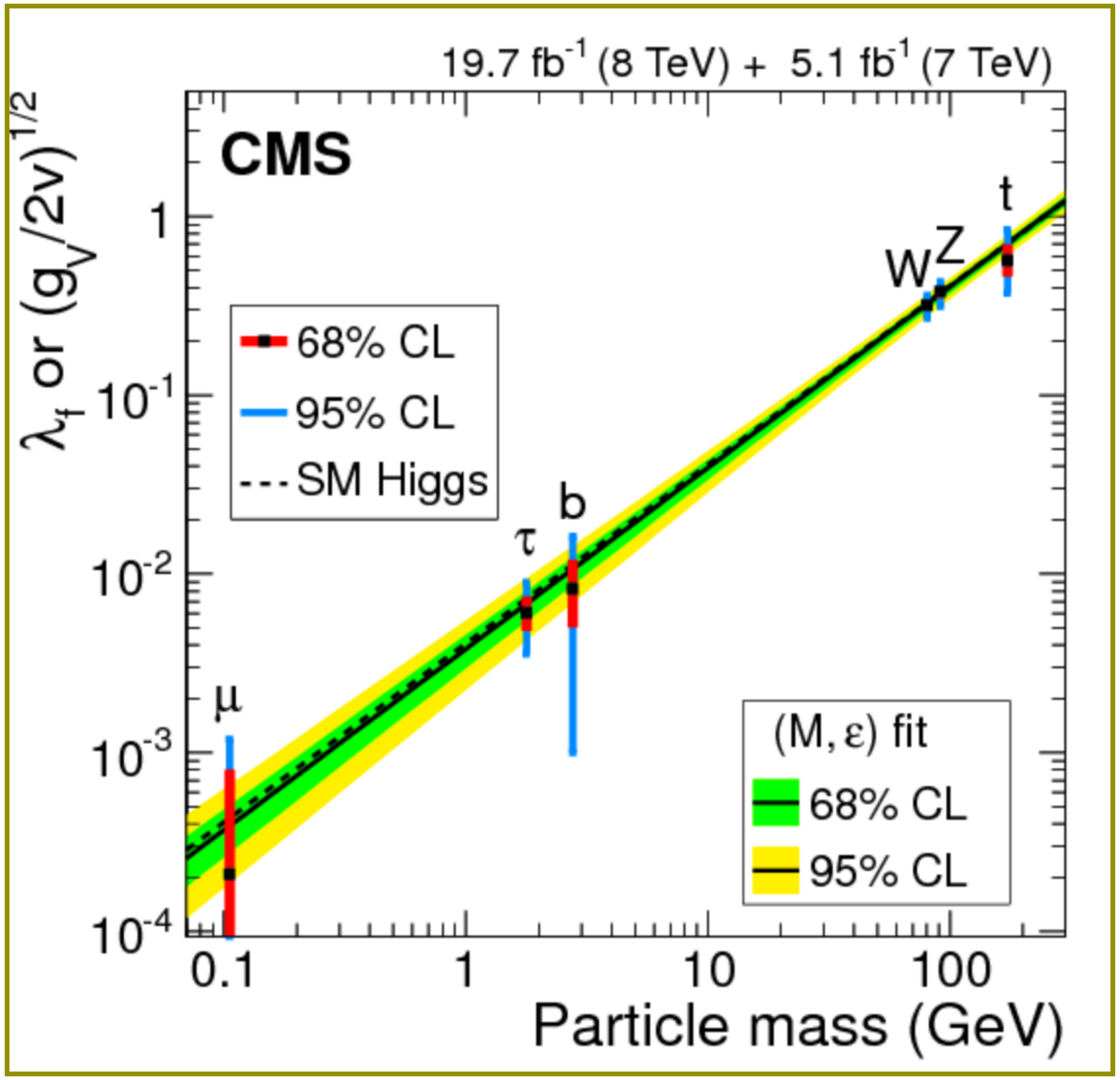
If the Higgs potential is fine-tuned, there might be cosmological implications from the early universe: eq. of state + gravitational waves

motivation

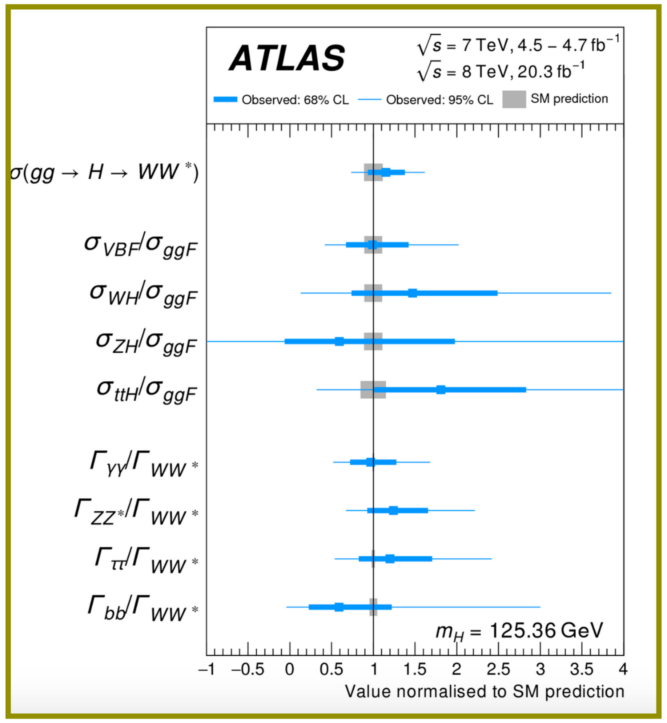
LHC: Standard Model Higgs but nothing else …

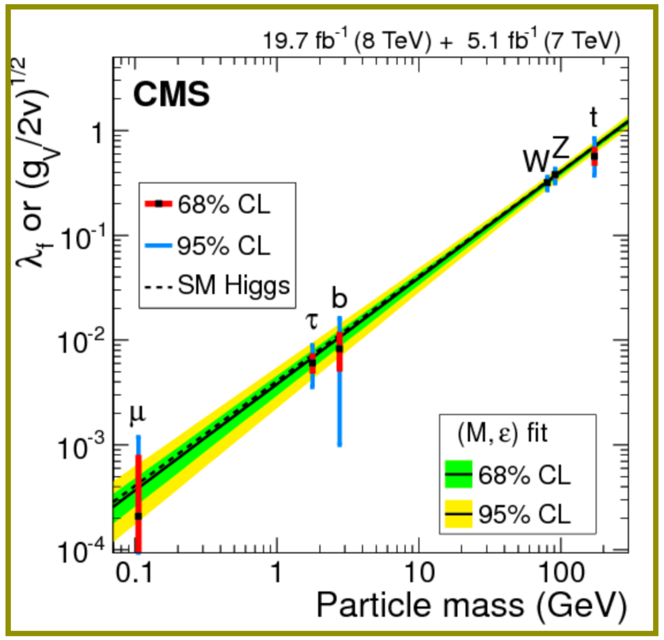






LHC: Standard Model Higgs — tuned Higgs mass/ potential



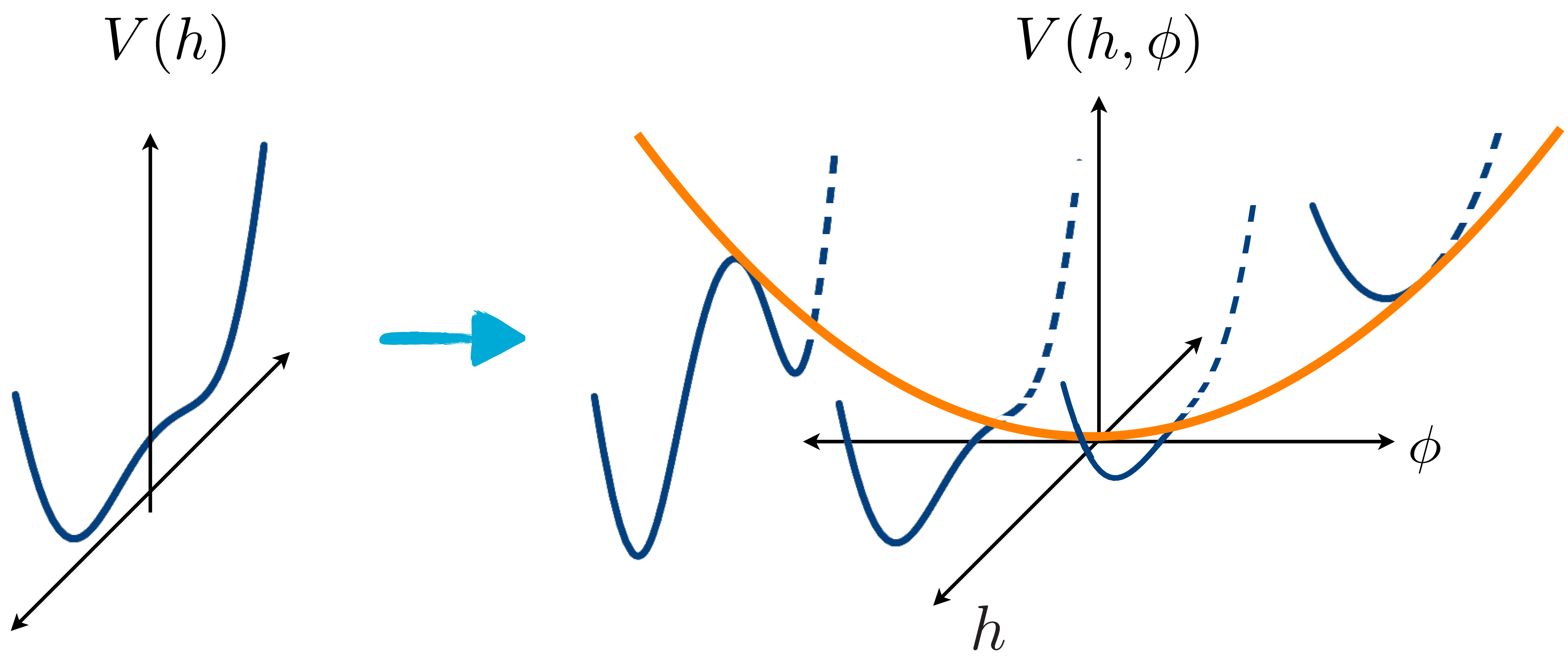


no new particles, does not necessarily rule out SUSY

Higgs mass/potential is “*tuned*”

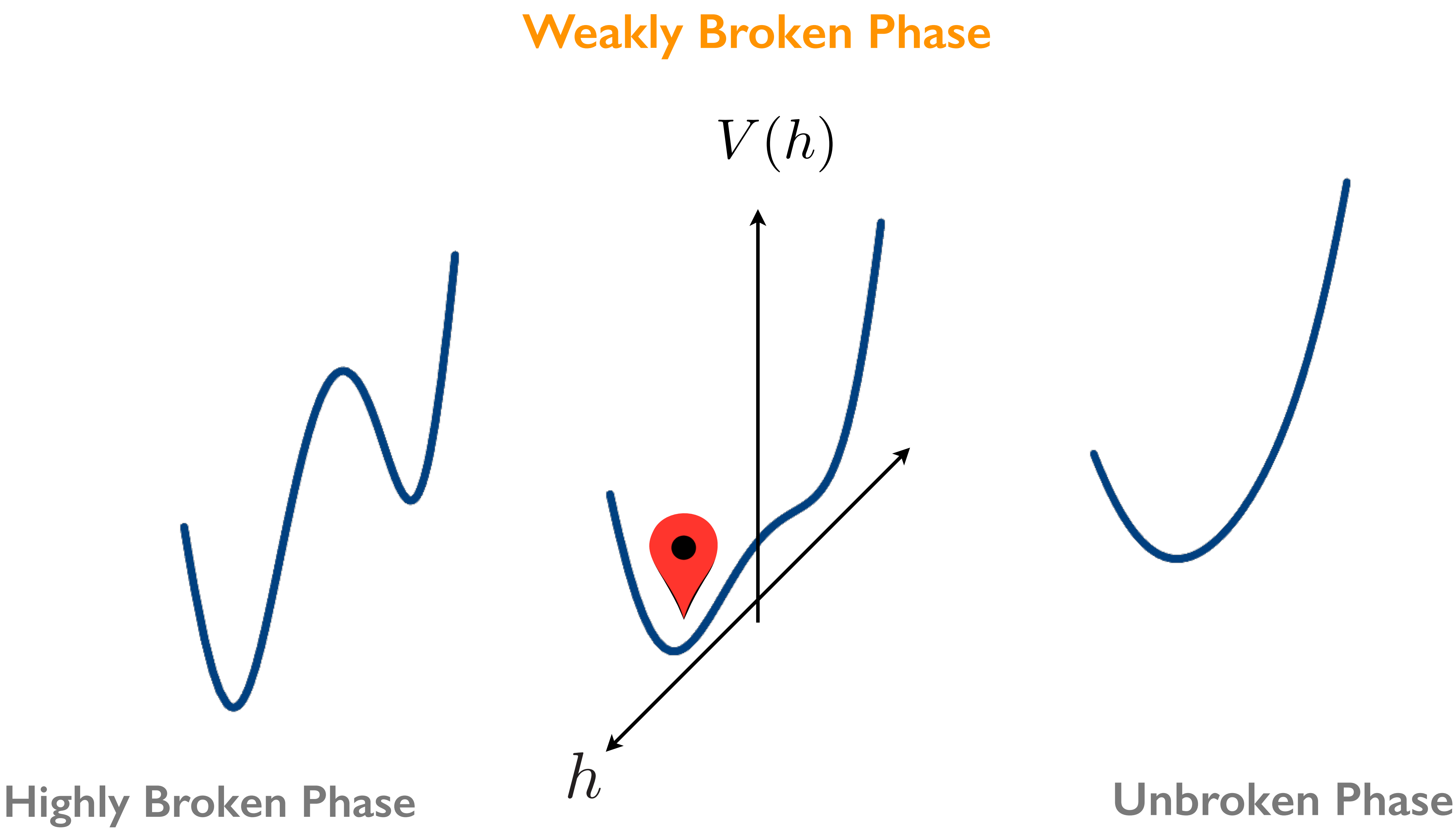
(Higgs is *accidentally* light)

SUSY: field-dependent Higgs mass/potential

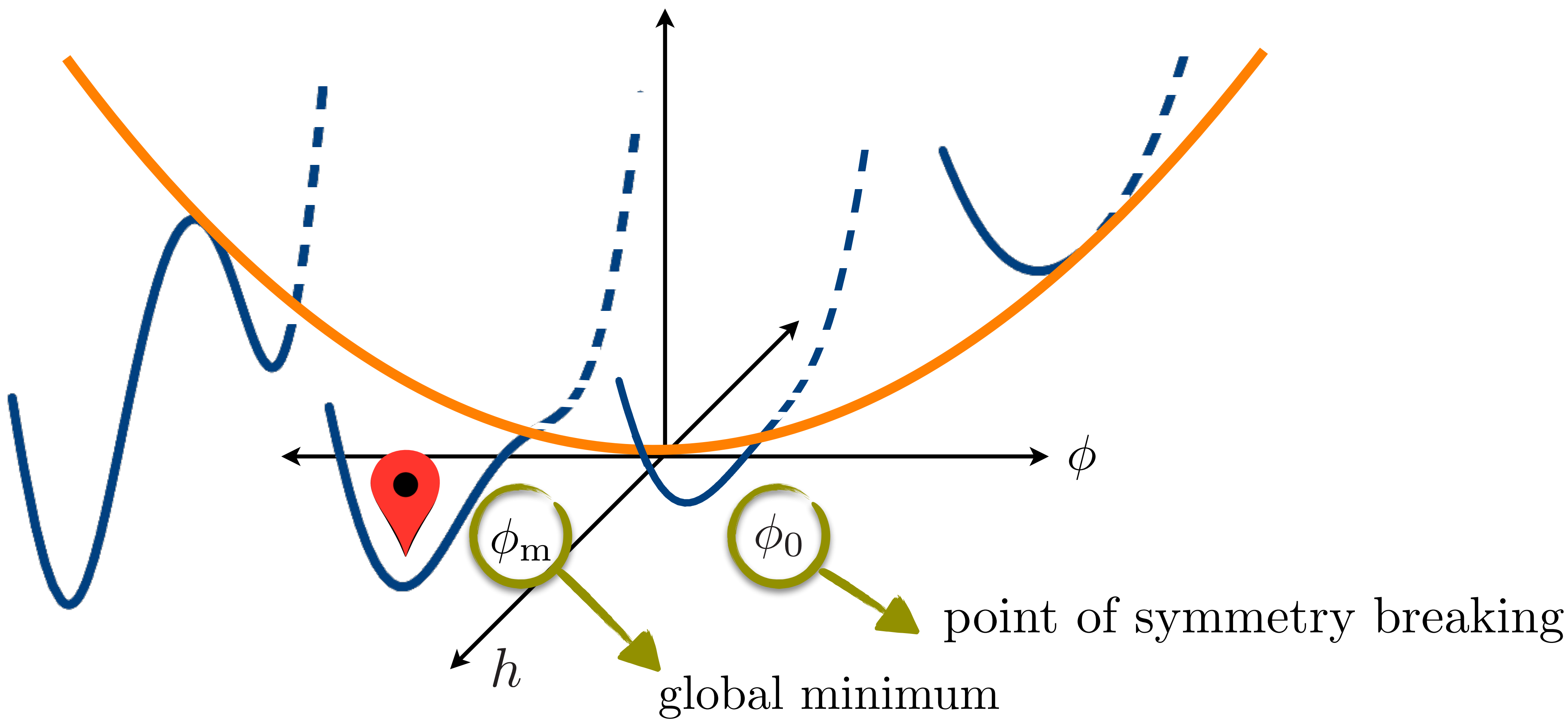


ϕ = modulus = could be the inflaton

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

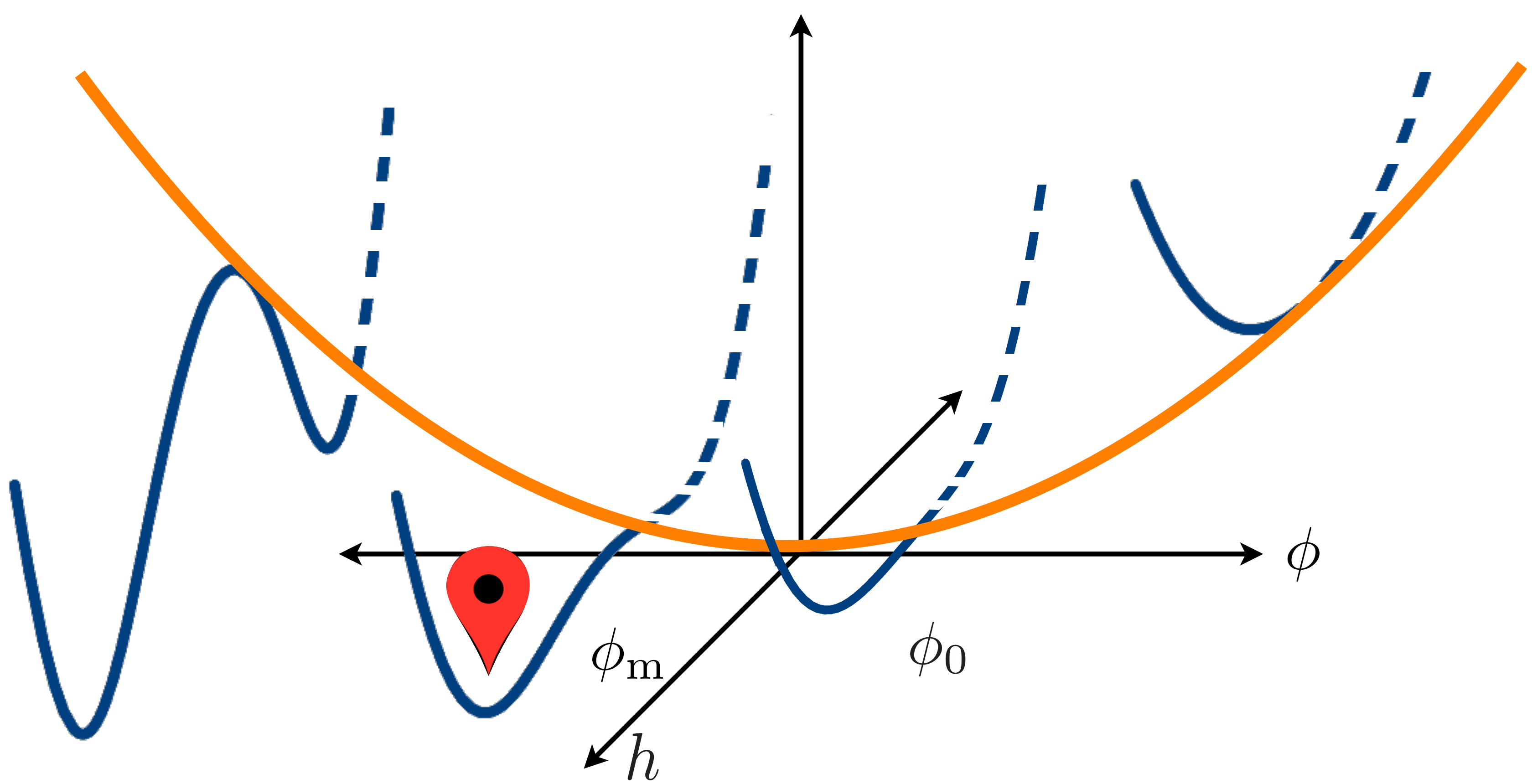


$$\text{Necessary Fine Tuning} \Leftrightarrow \quad \frac{\phi_{\mathrm{m}} - \phi_0}{f} \ll 1$$

f = typical field range of modulus

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

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



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

fine-tuning $\rightarrow$ small Higgs mass

$M =$ SUSY breaking scale

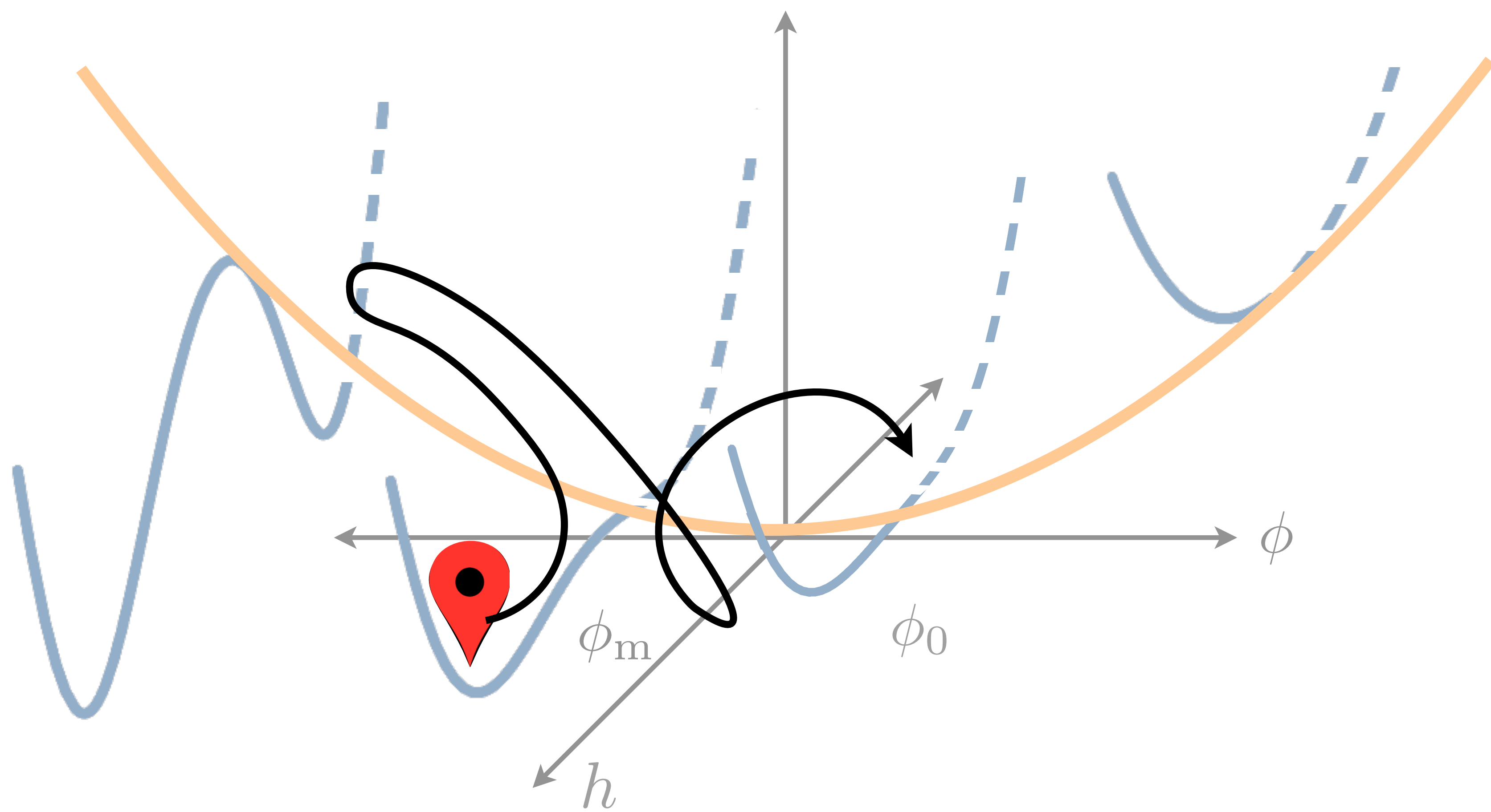
$$\Delta \equiv \frac{\phi_0 - \phi_{\rm m}}{f} \ll 1$$

fine tuning

* 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 ?

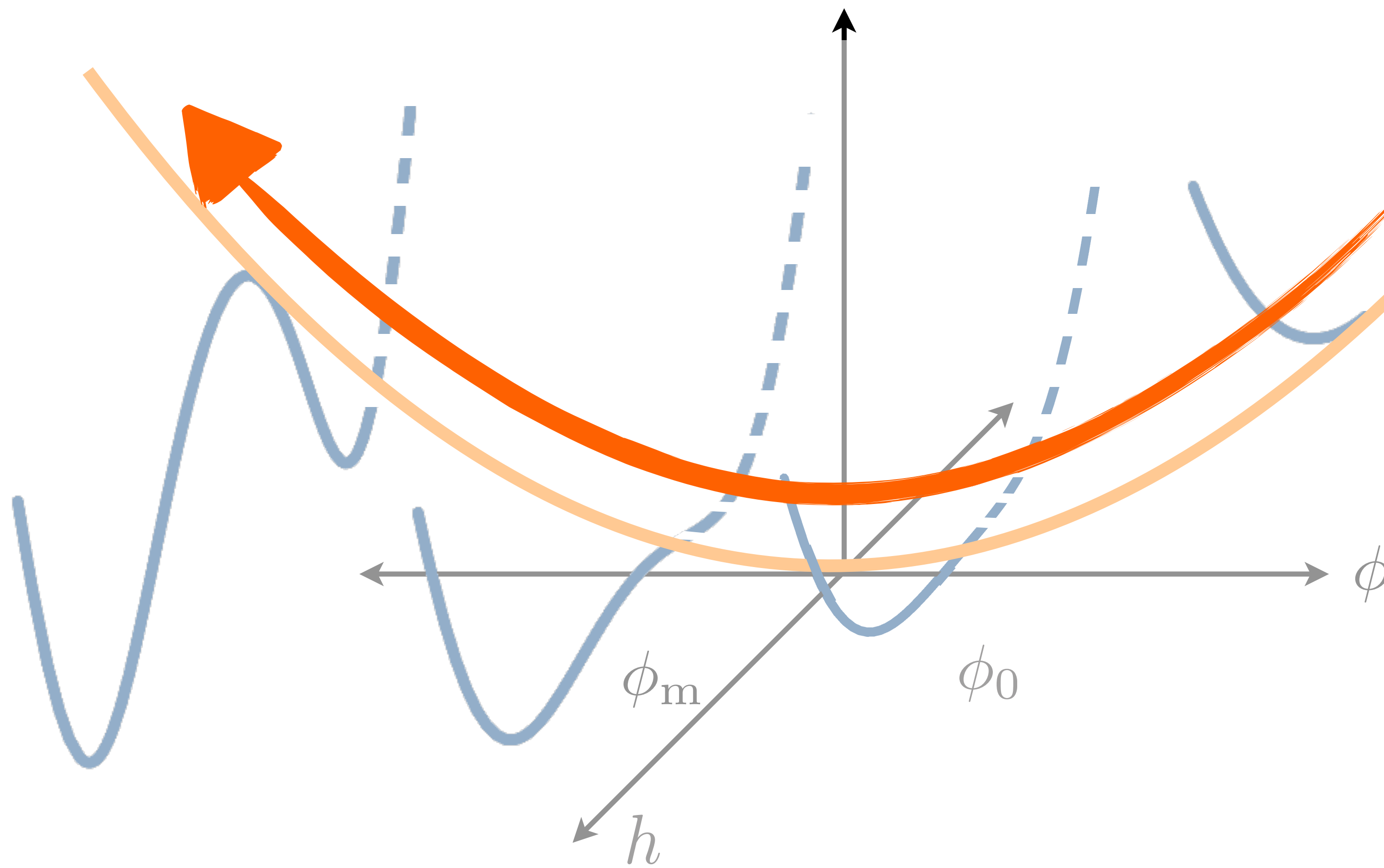
we cannot really go exploring in this field space, fixed couplings/masses



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

how would we know?
early universe to the rescue

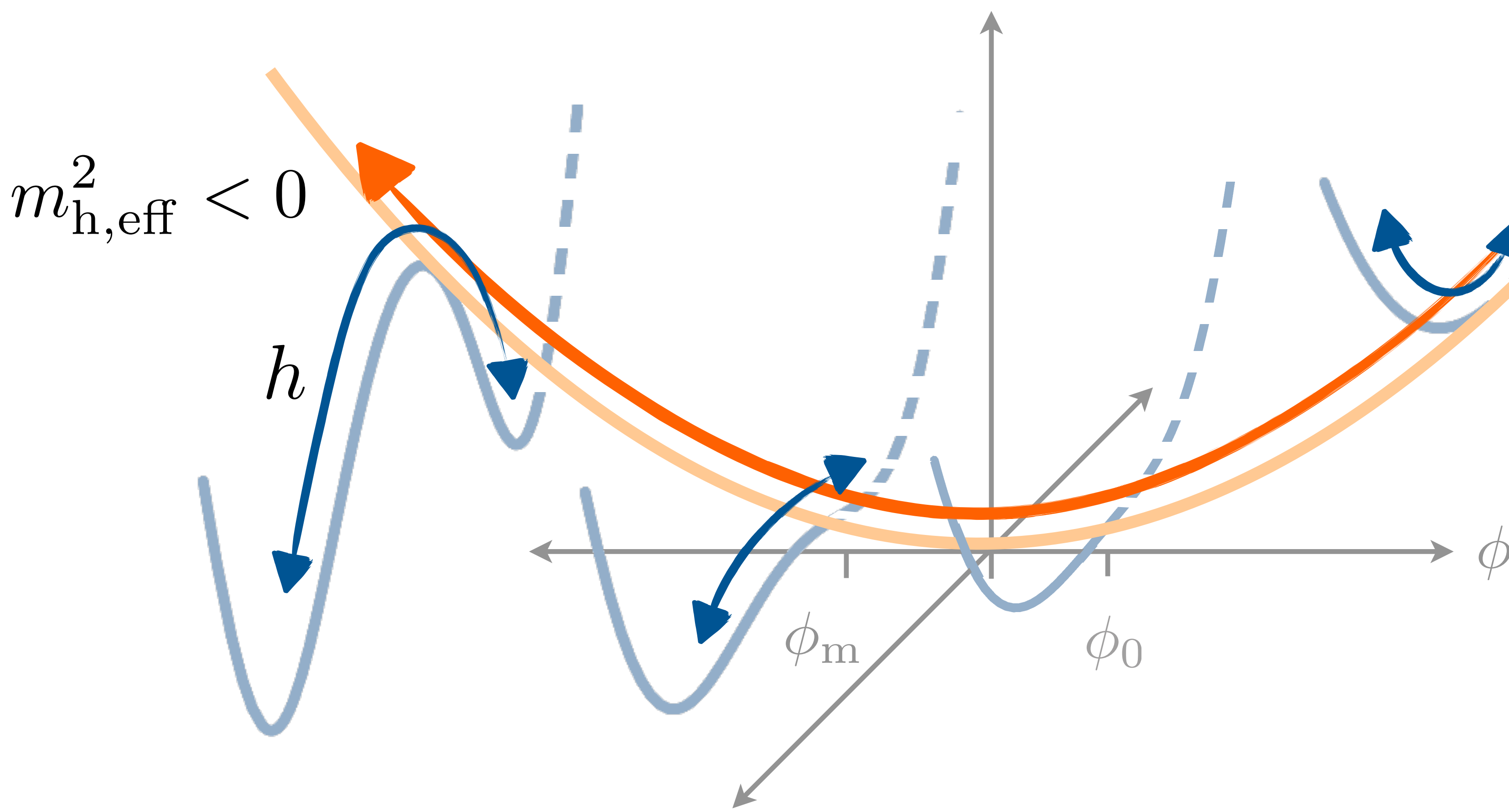
a displaced **modulus** will naturally explore different **Higgs potentials**



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

complex dynamics of the Higgs-modulus system

tachyonic particle production and backreaction



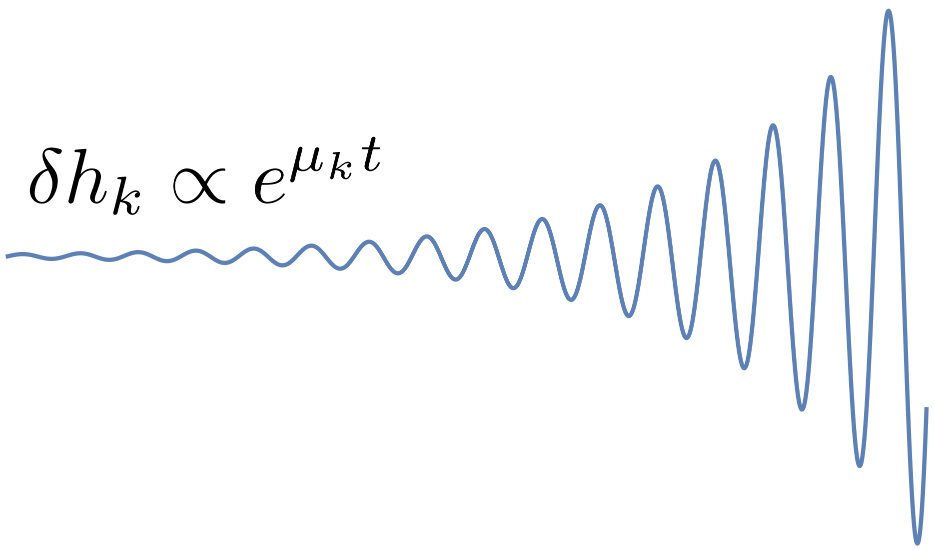
Necessary Fine Tuning $\Leftrightarrow \quad \dfrac{\phi_{\mathrm{m}} - \phi_0}{f} \ll 1$

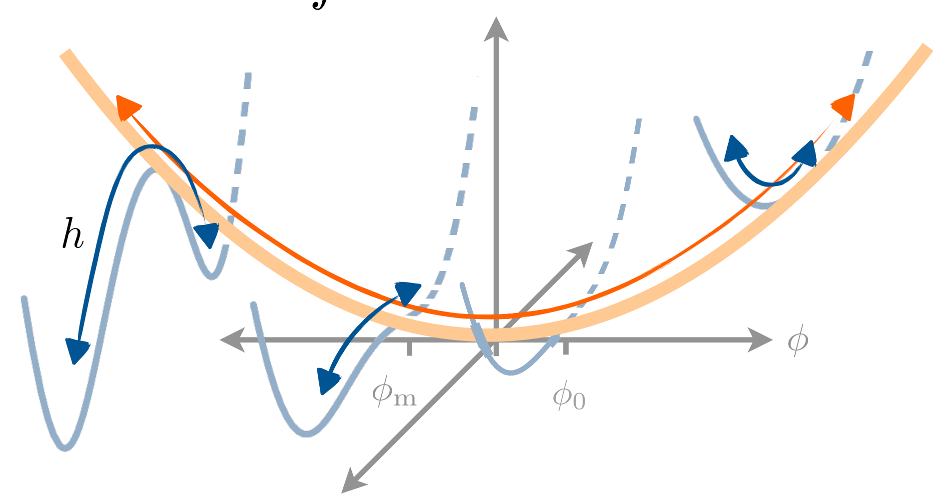
* related, but not identical dynamics in hybrid inflation, Dufaux et. al (2006)

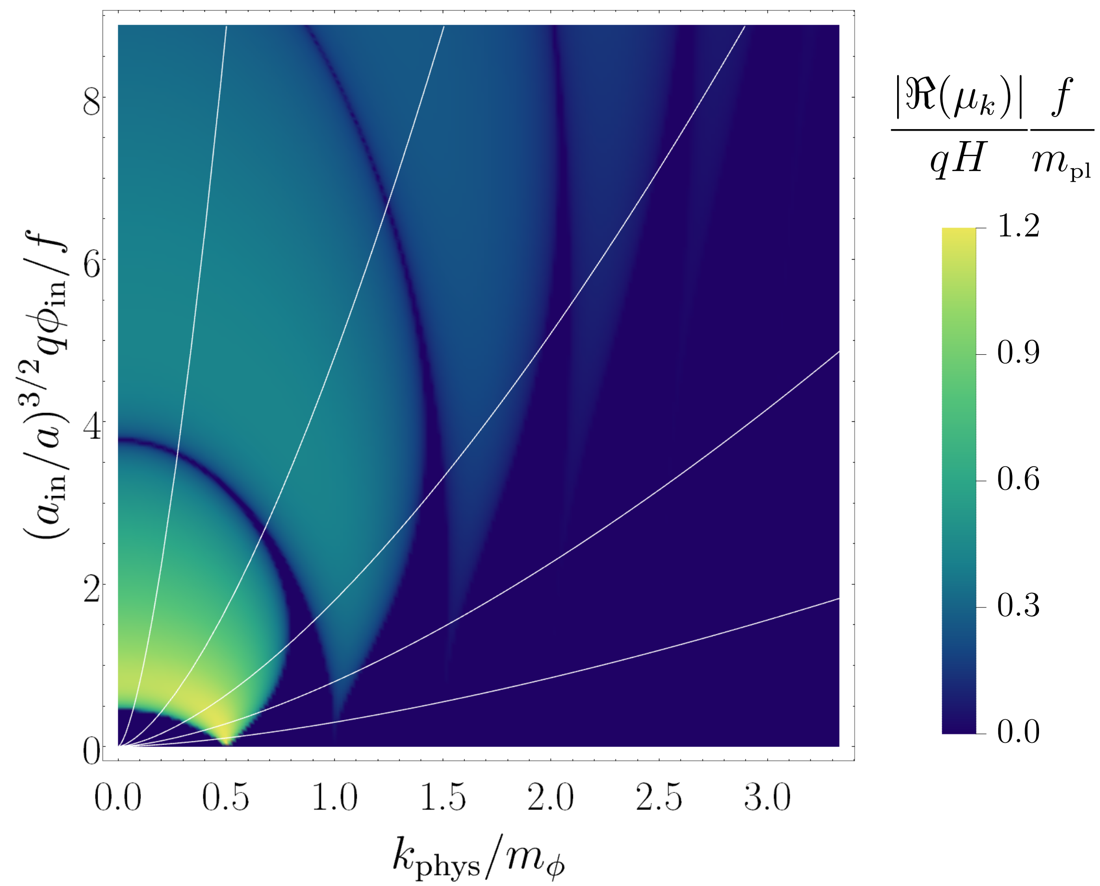
Higgs tachyonic particle production

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

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



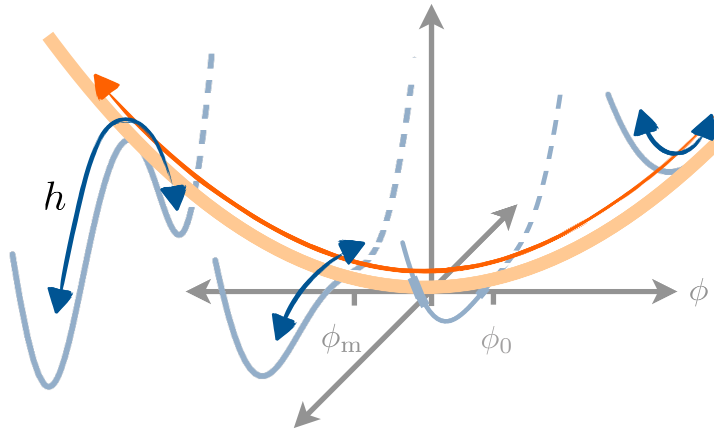




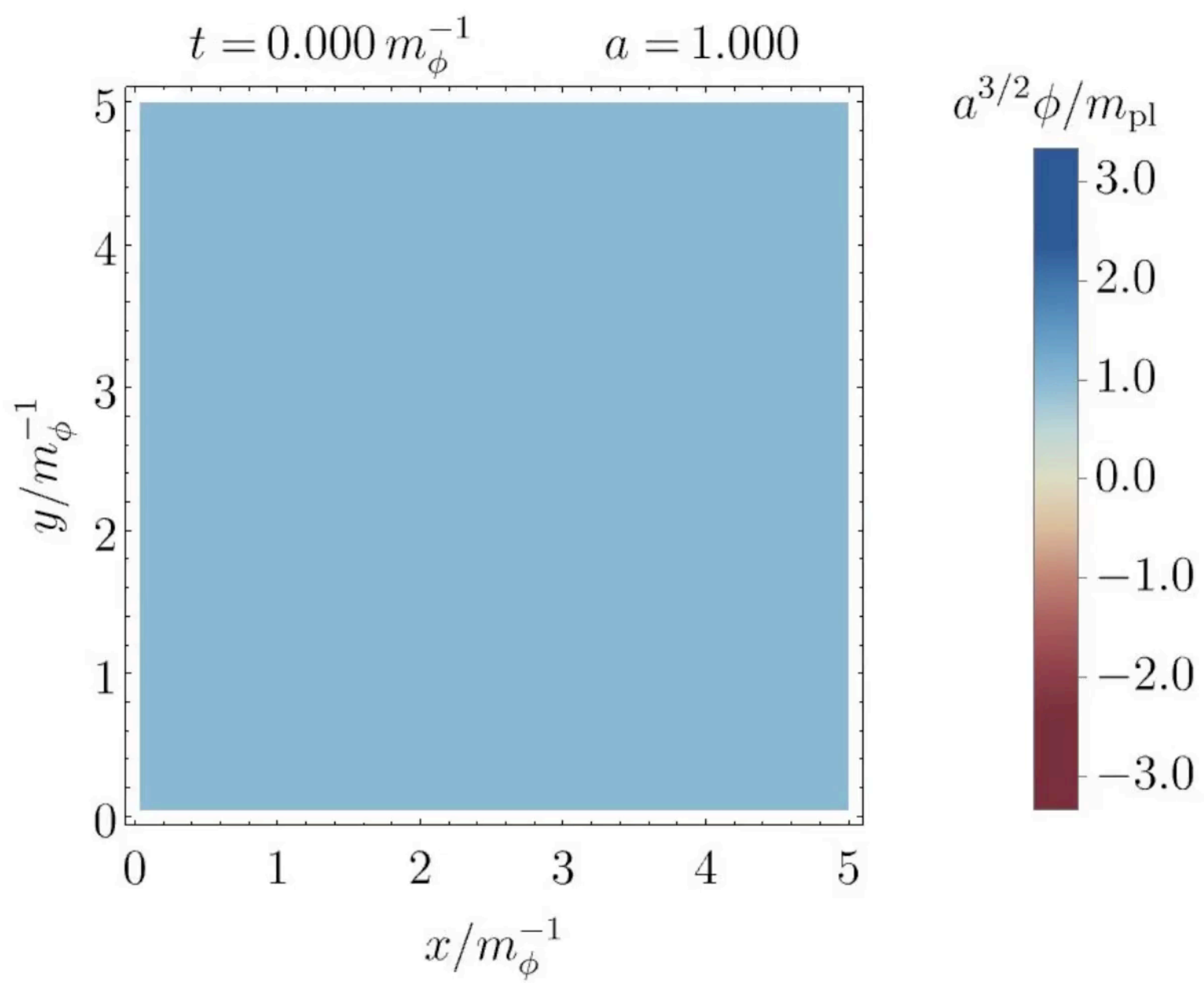
$$\mu_k \propto \sqrt{q}$$

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

modulus dynamics

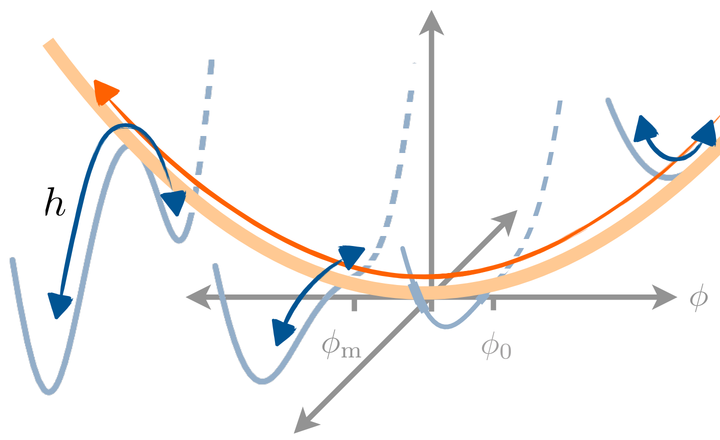


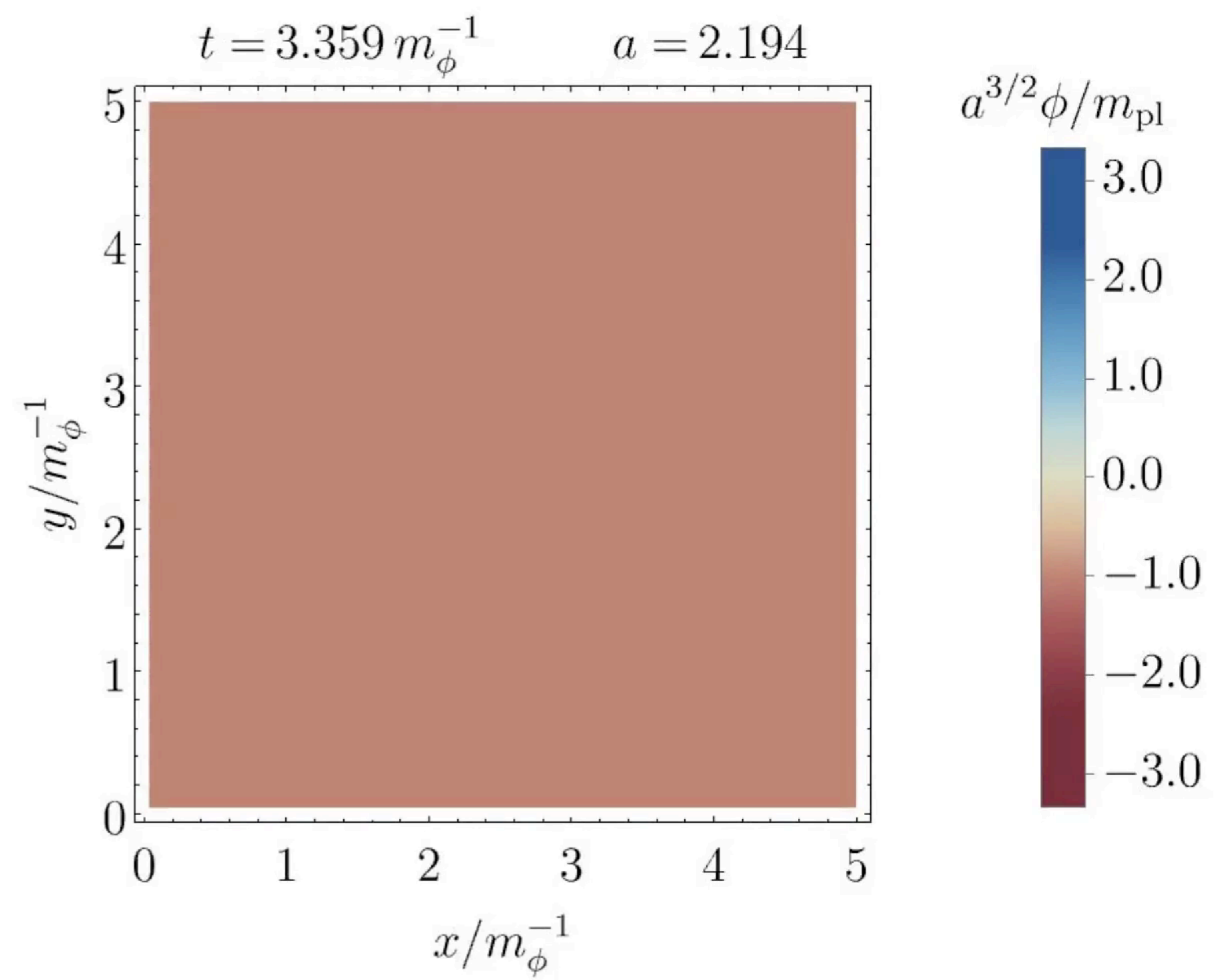
initial oscillation,
then fragmentation
from backreaction



* under certain conditions, later in the talk

modulus dynamics





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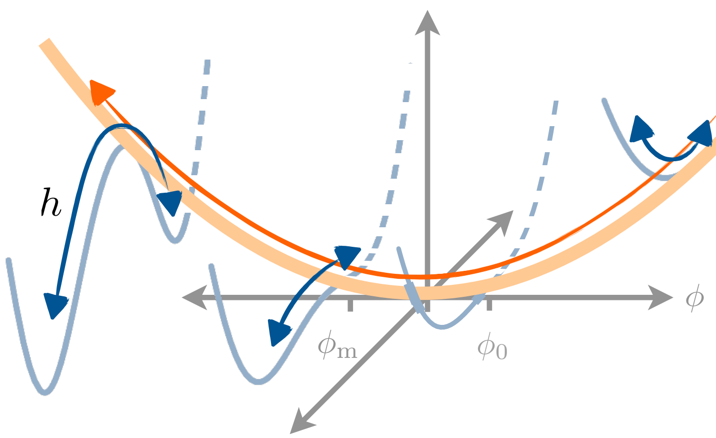

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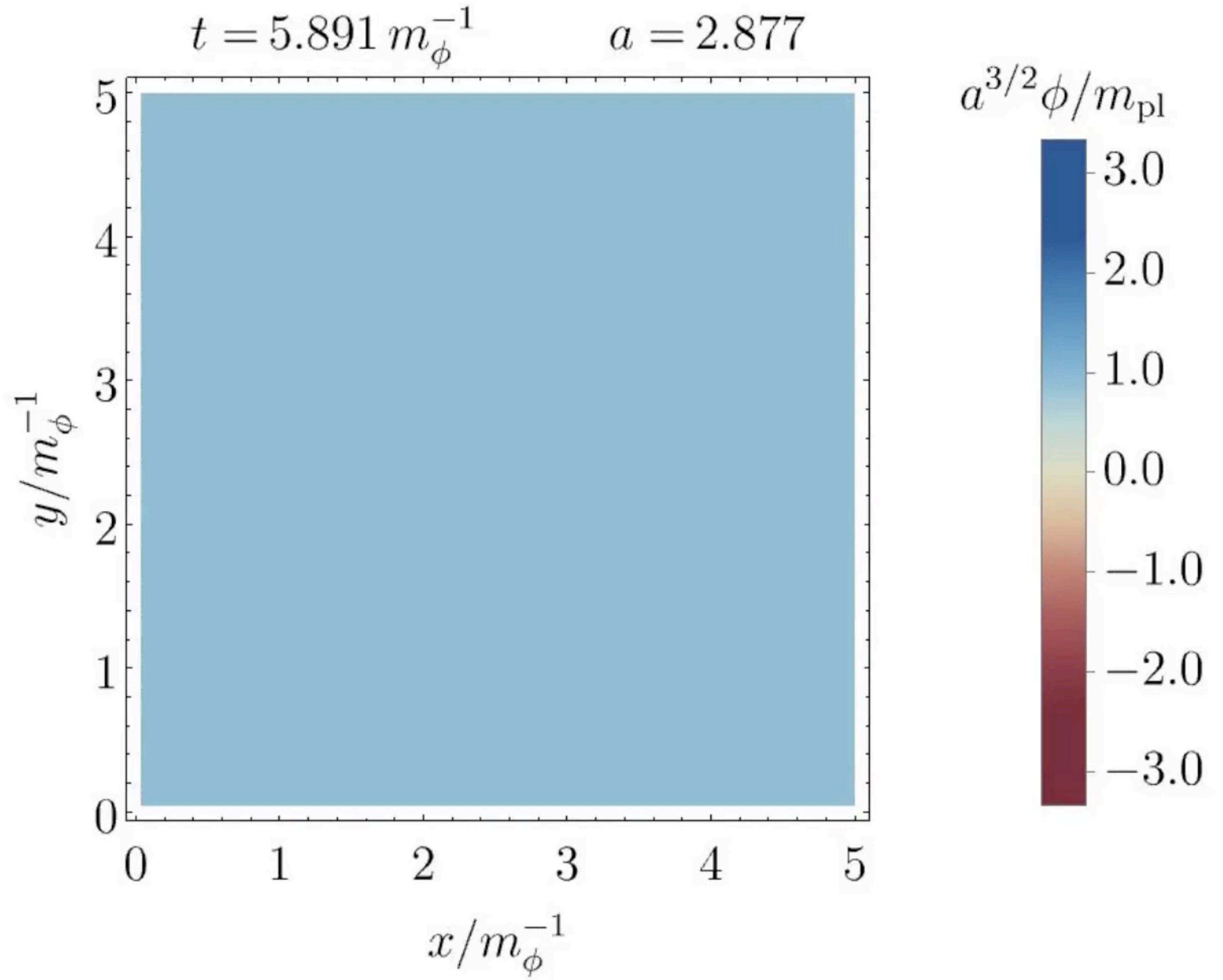

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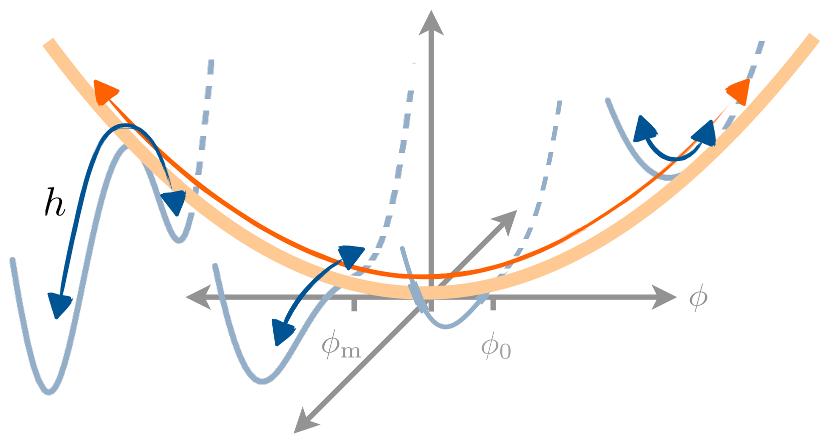

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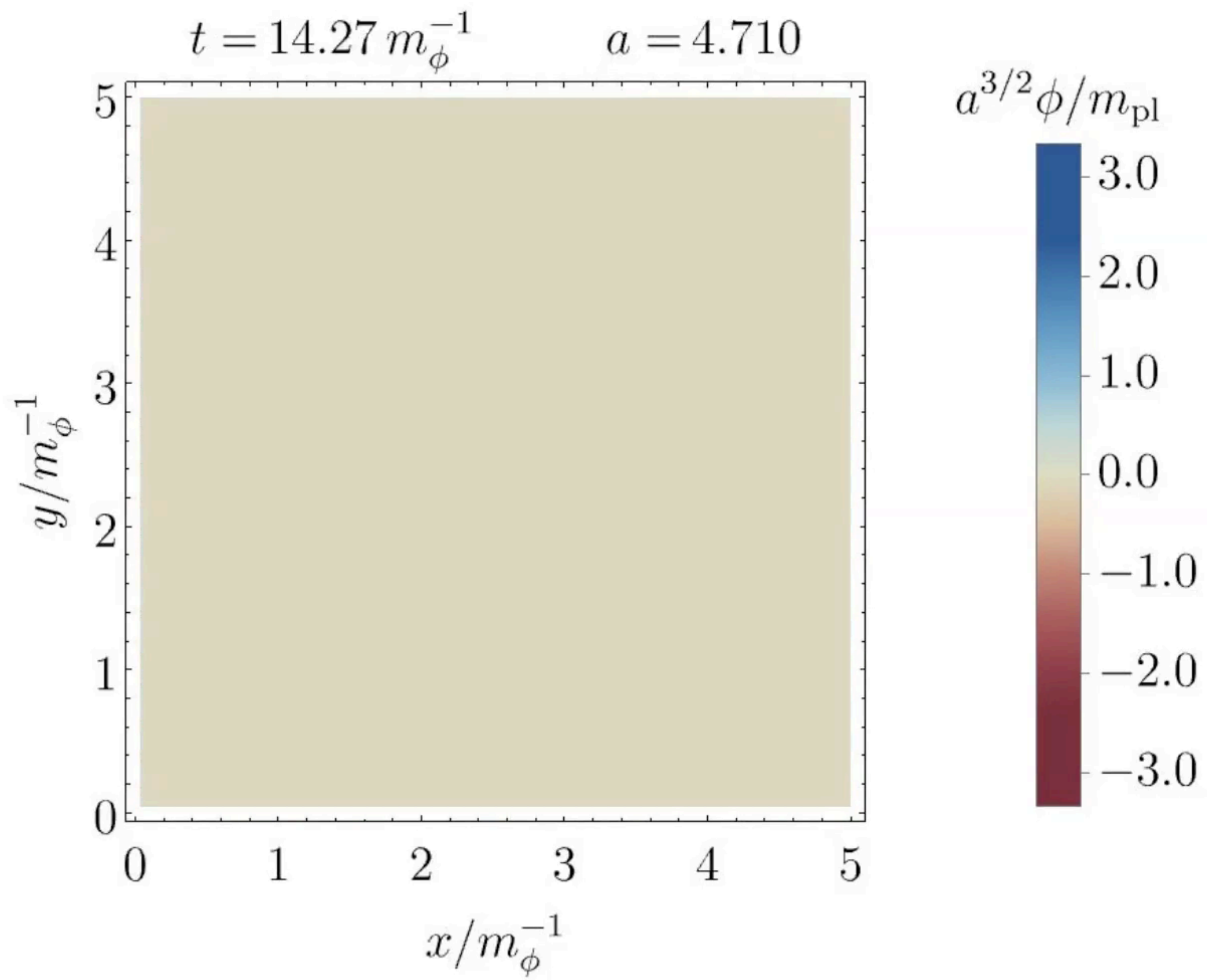

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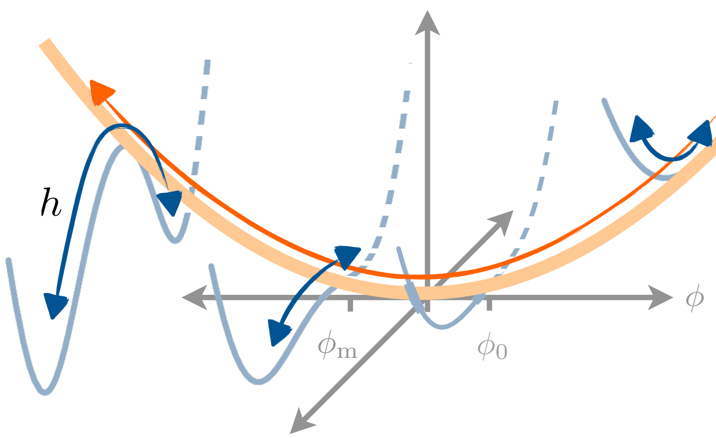

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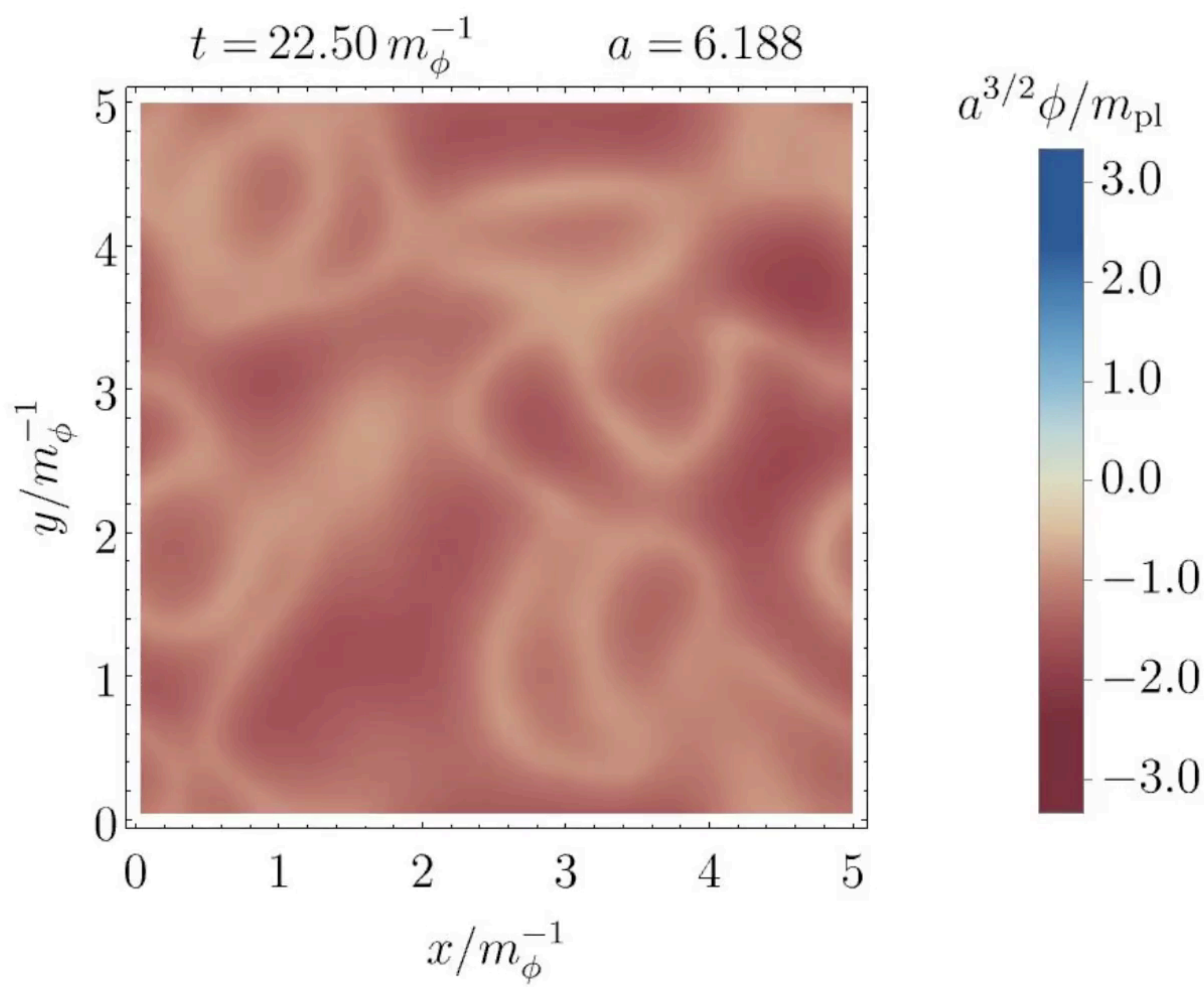

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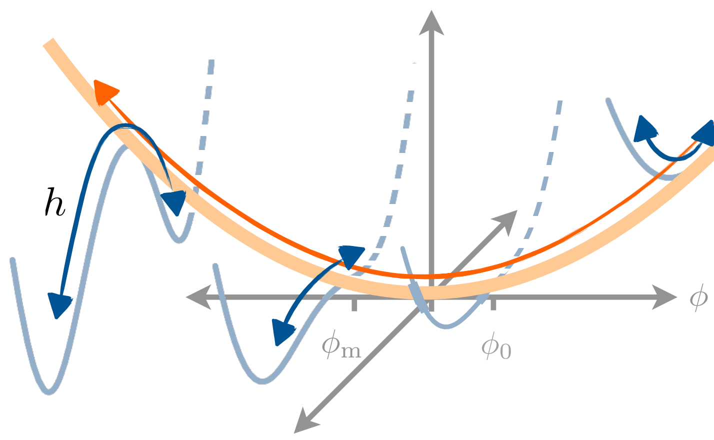

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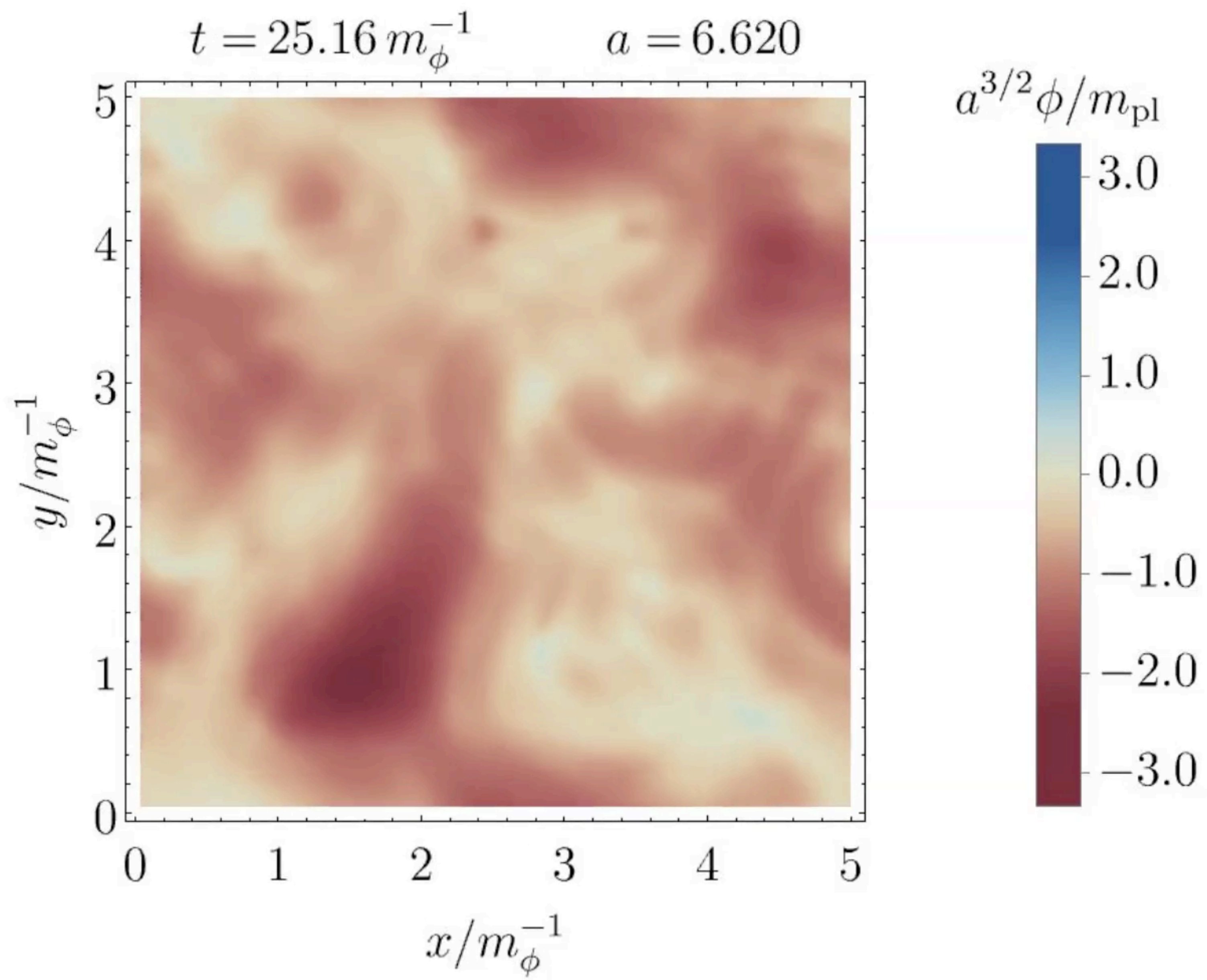

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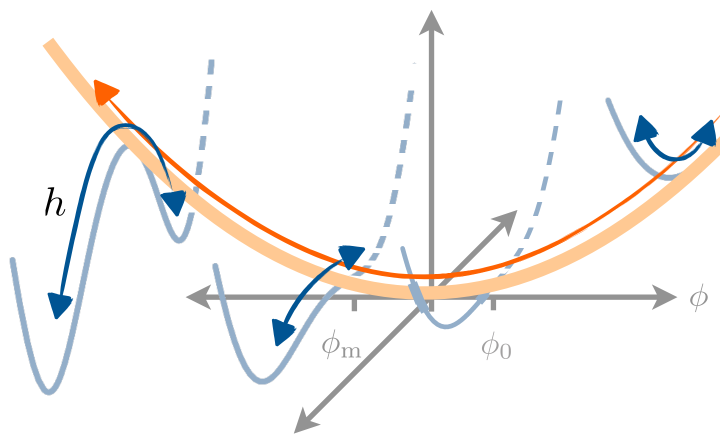

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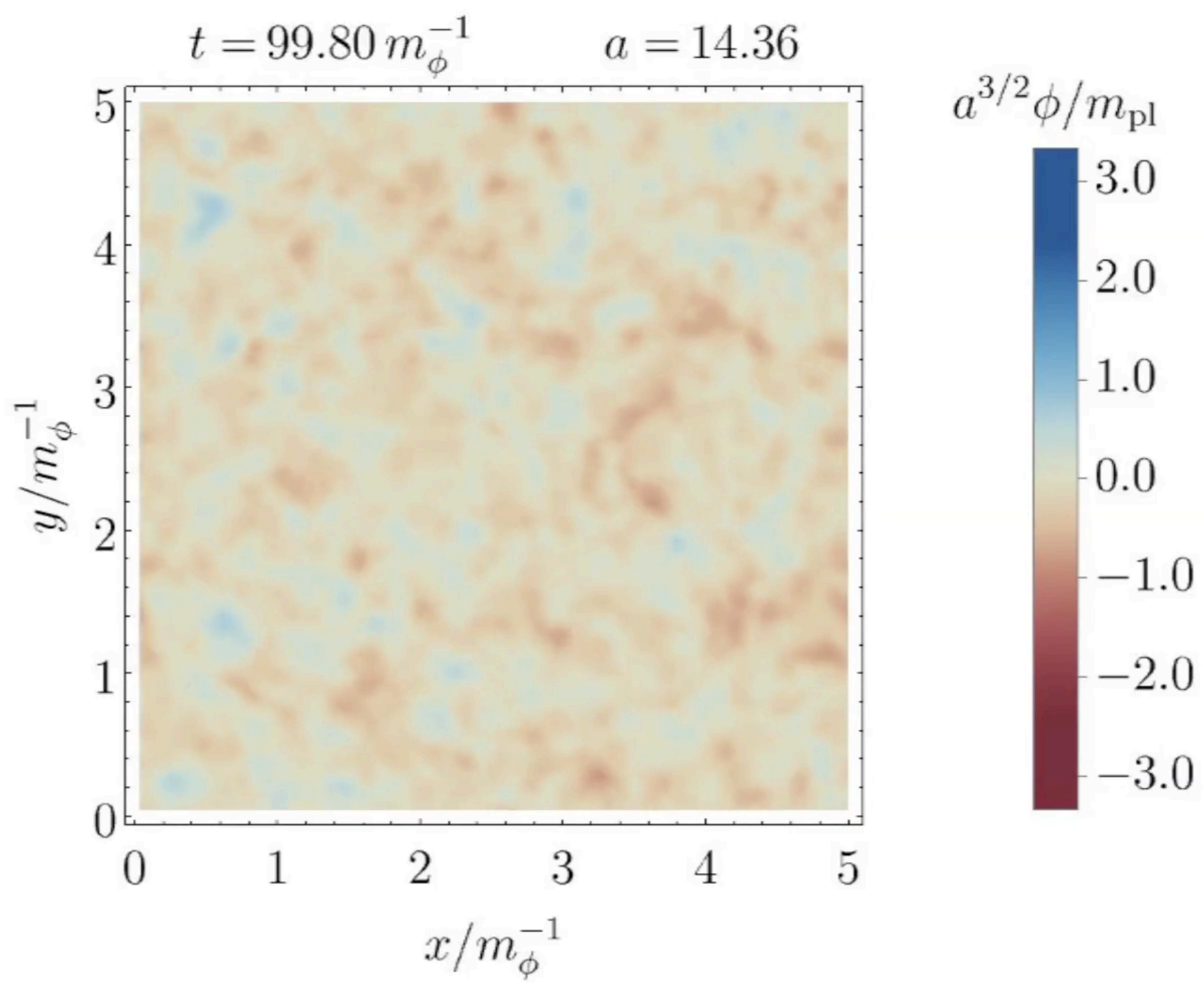

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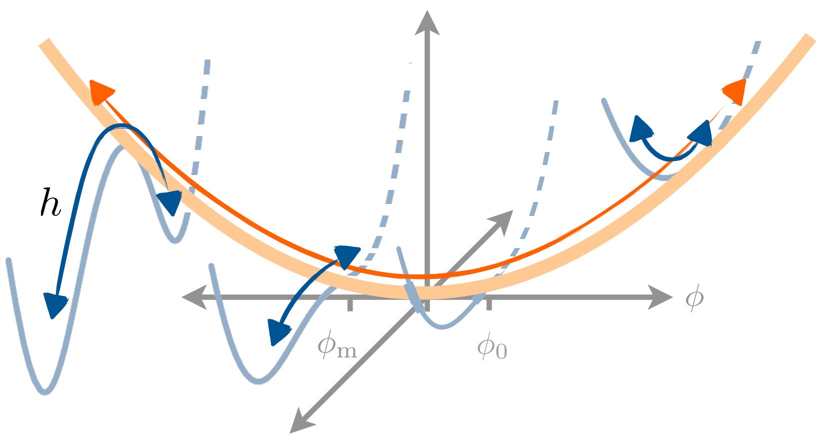
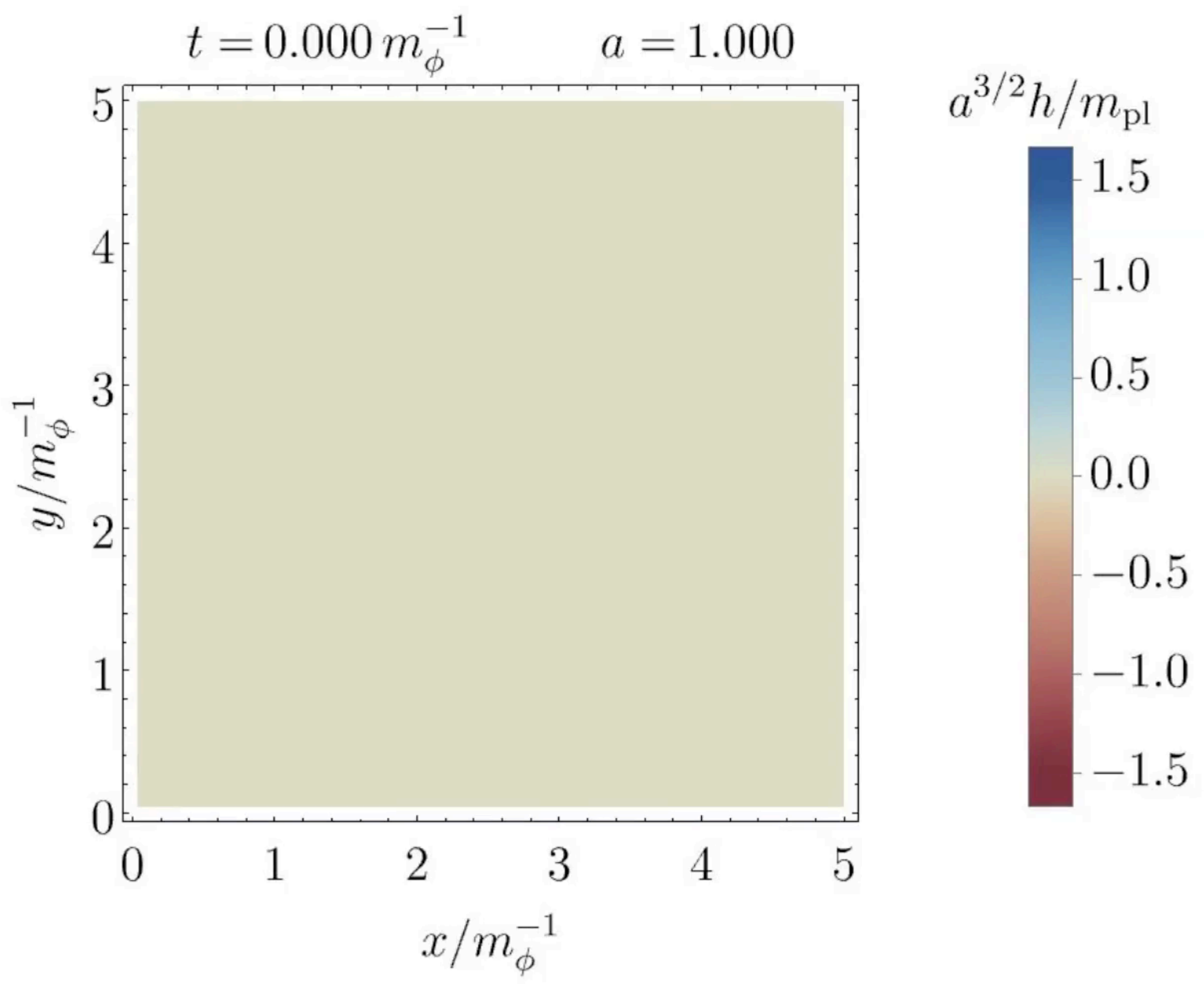
Higgs dynamics



tachyonic particle production and fragmentation



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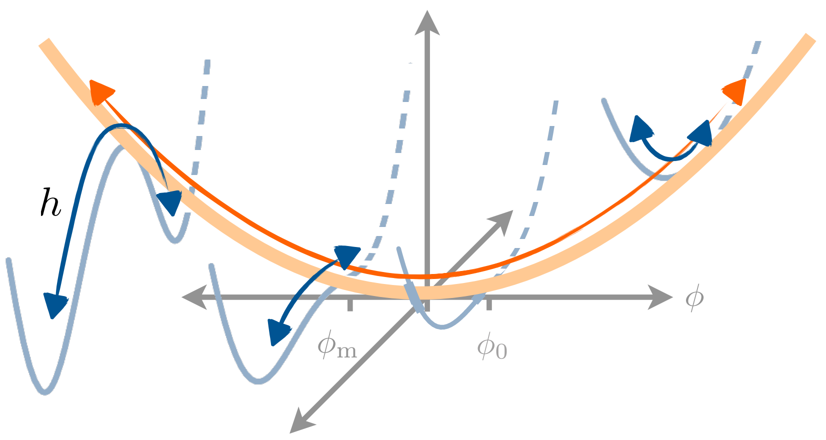
Higgs dynamics



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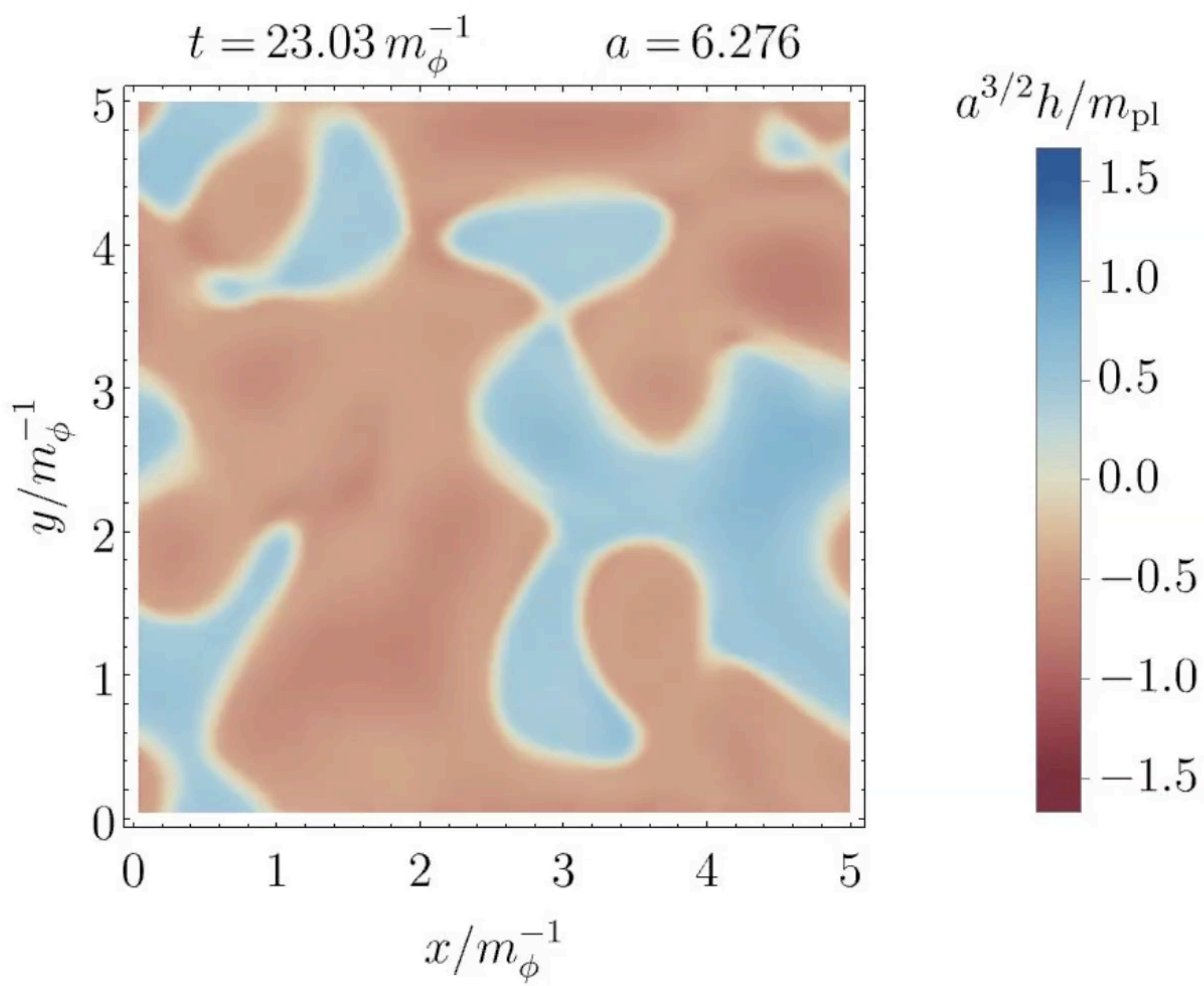

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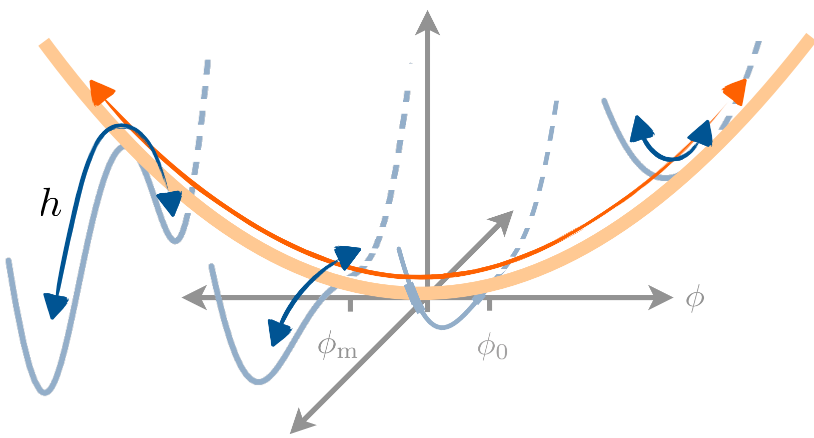
Higgs dynamics



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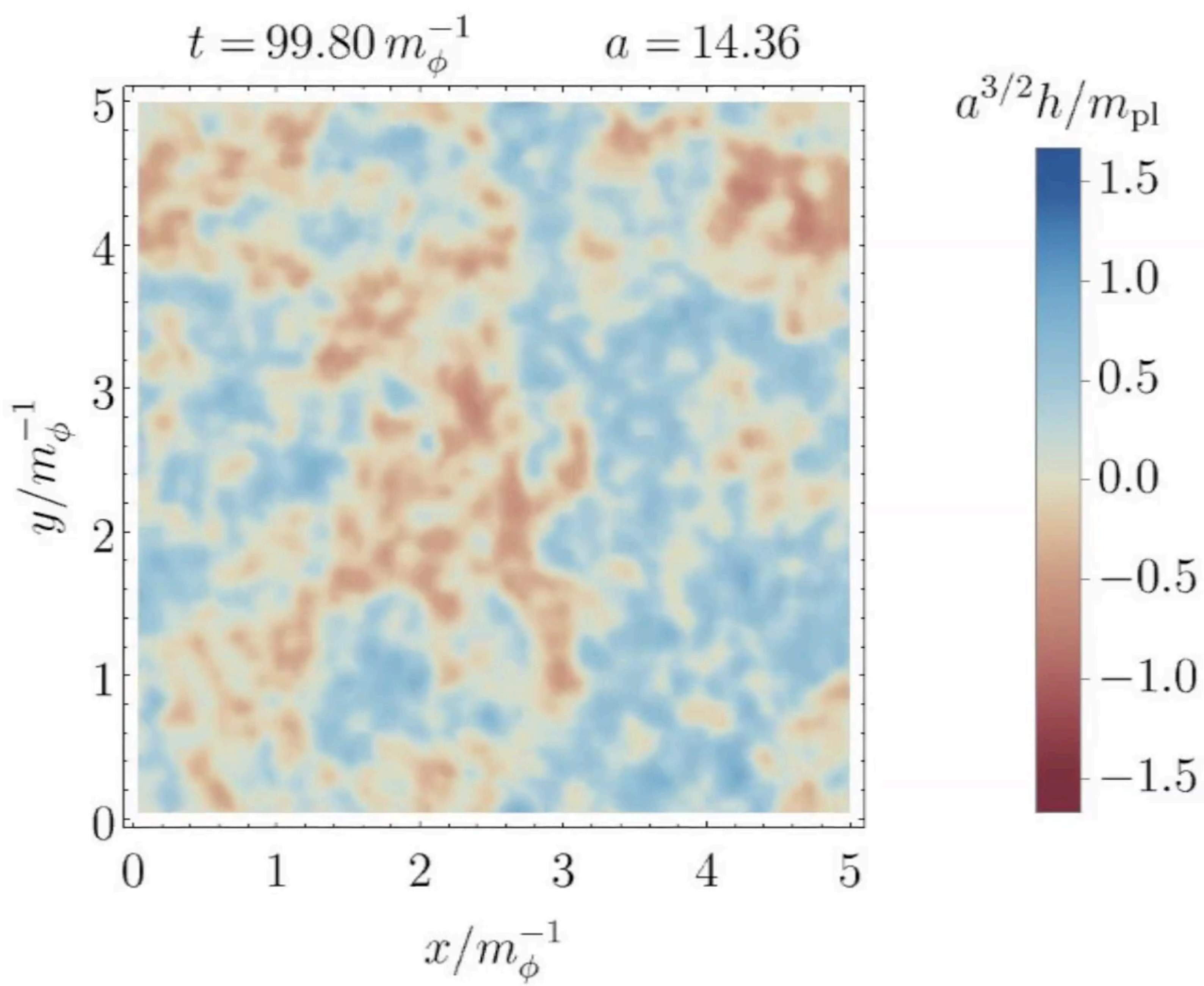
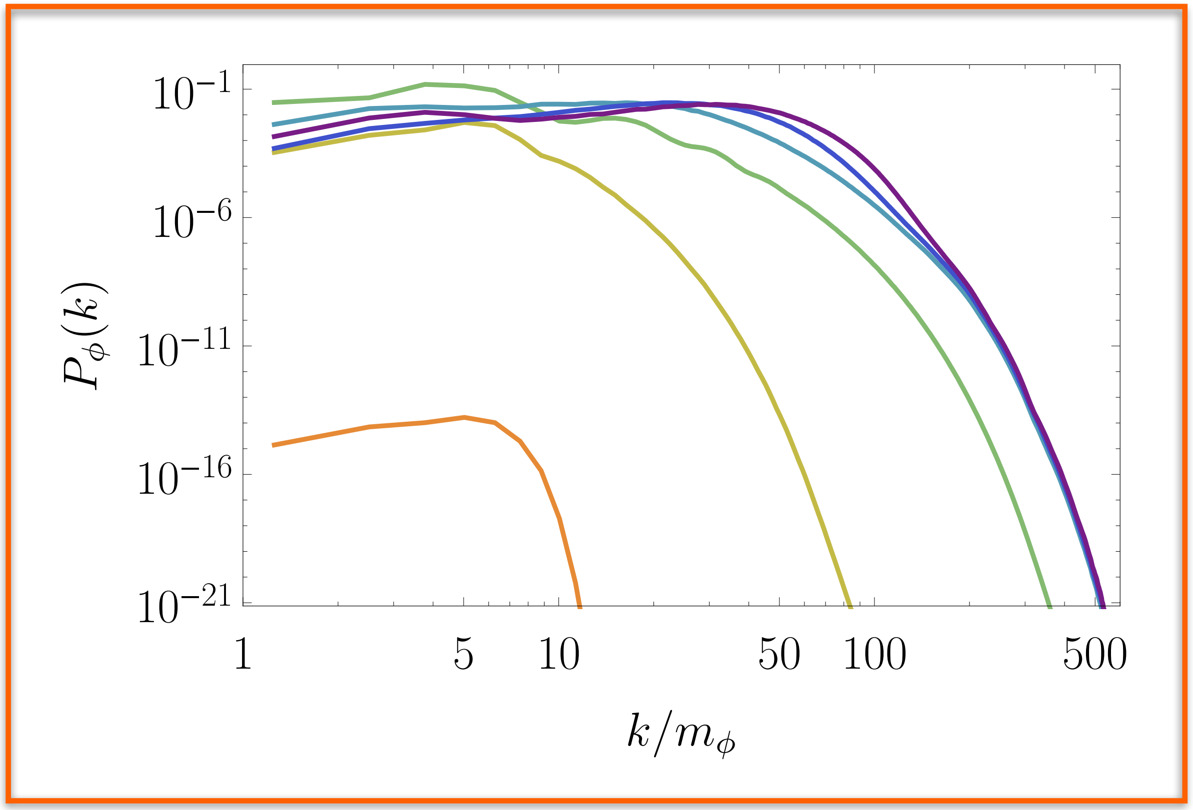
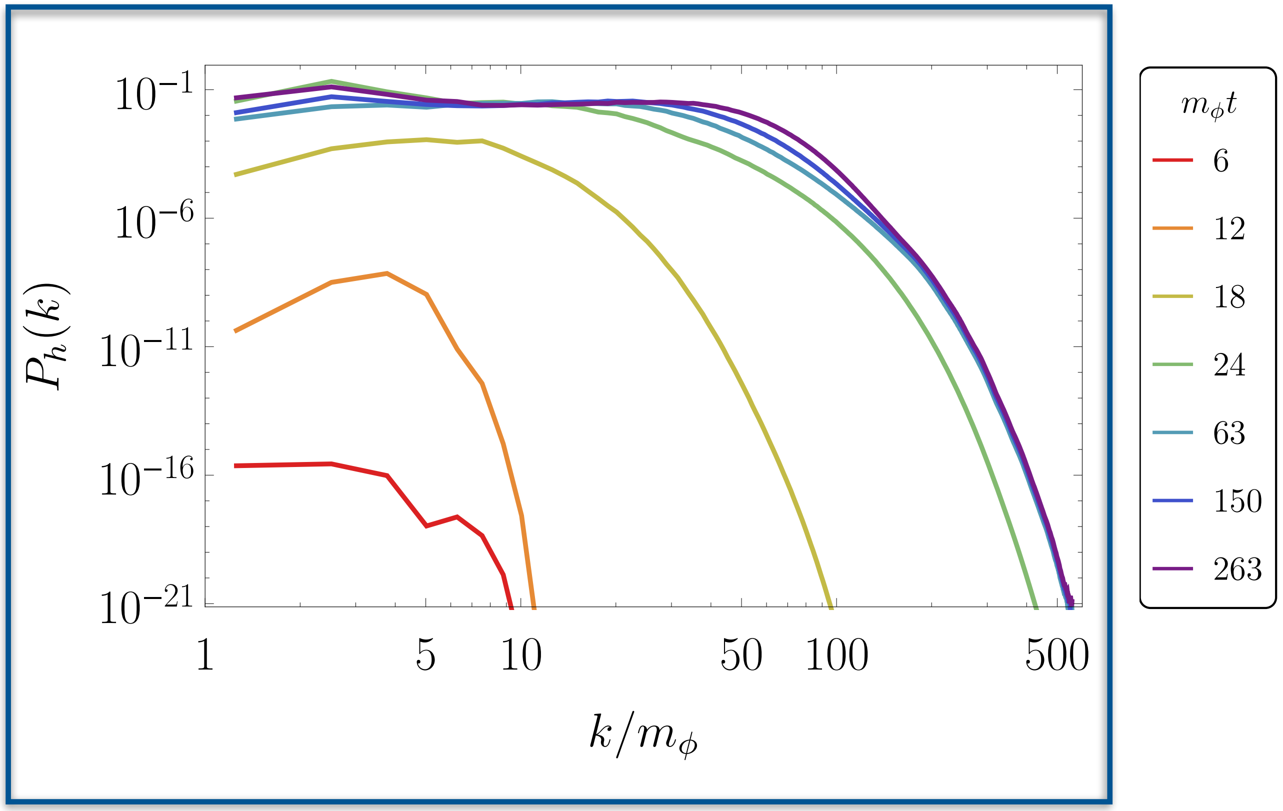
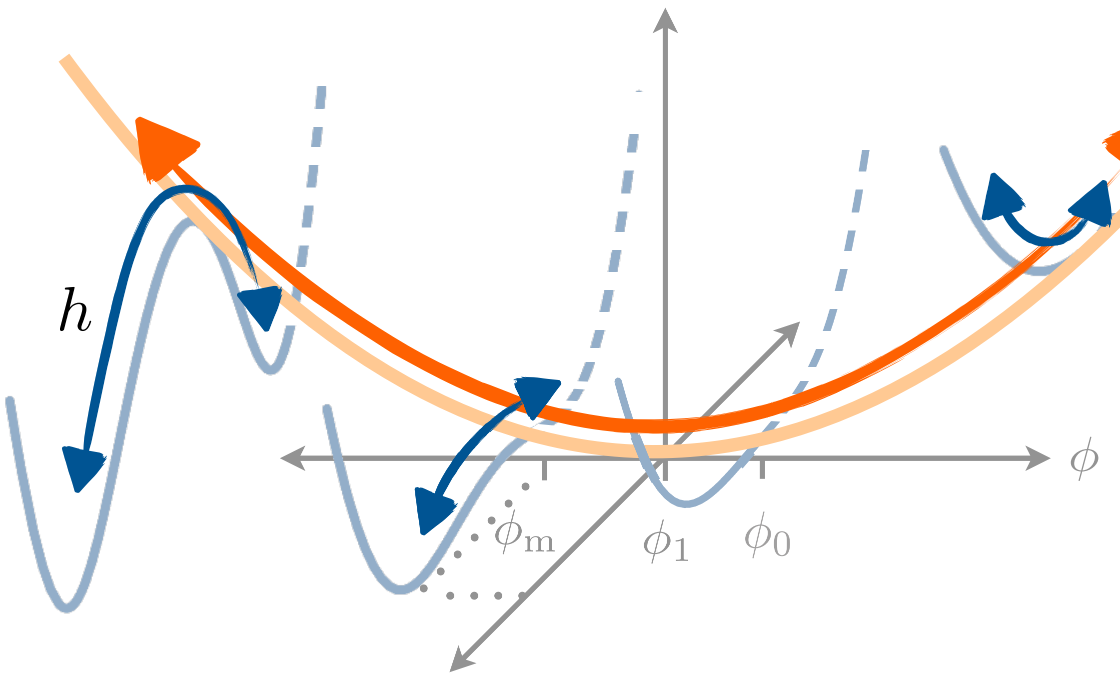


* under certain conditions, later in the talk

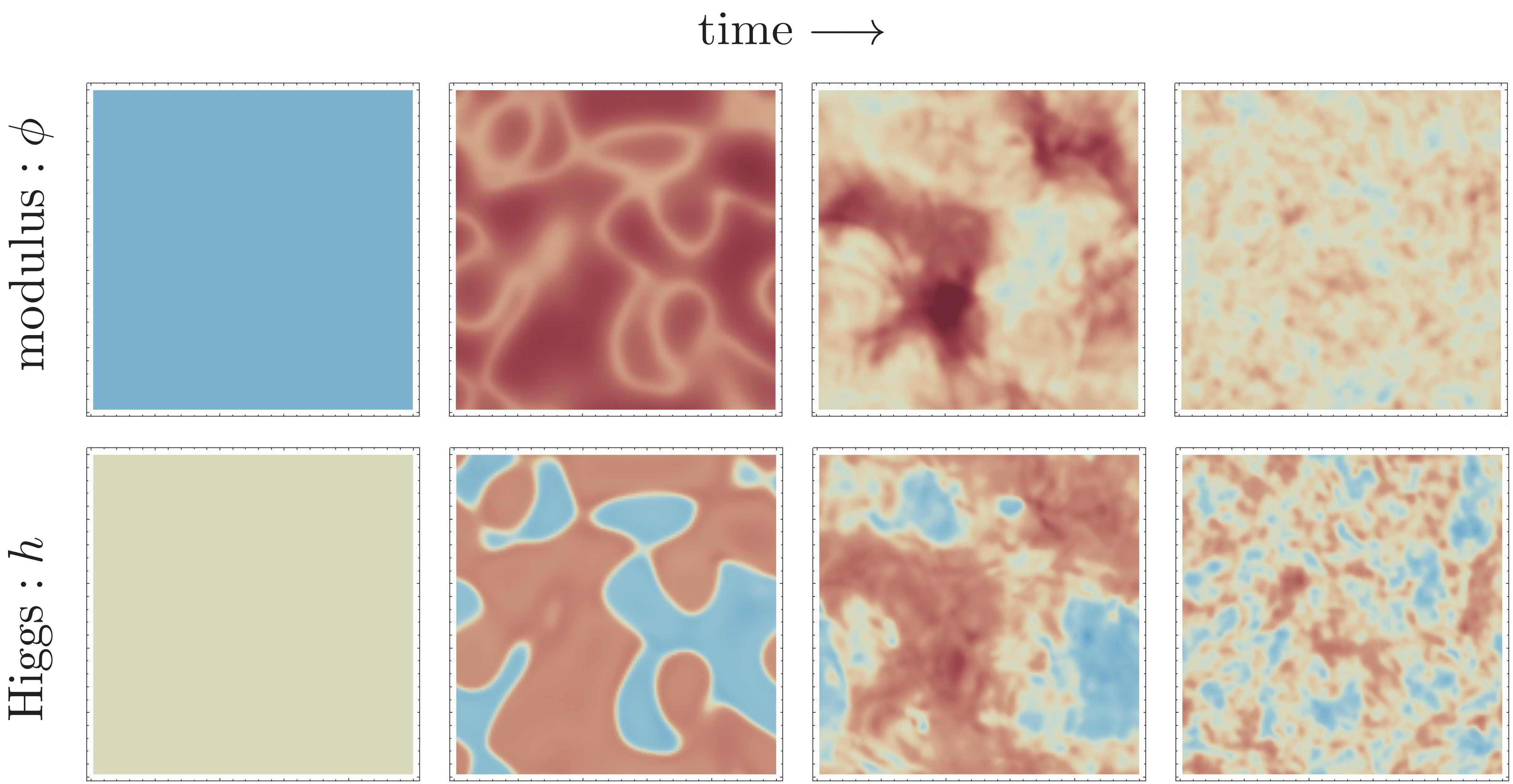
power spectrum: higgs/modulus







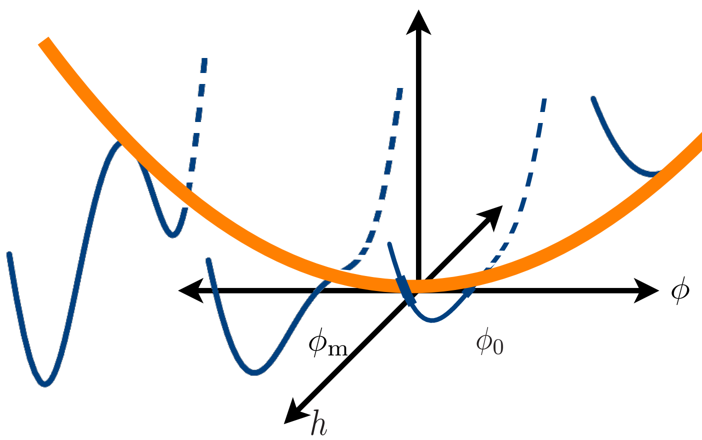
complex dynamics of the Higgs-modulus system



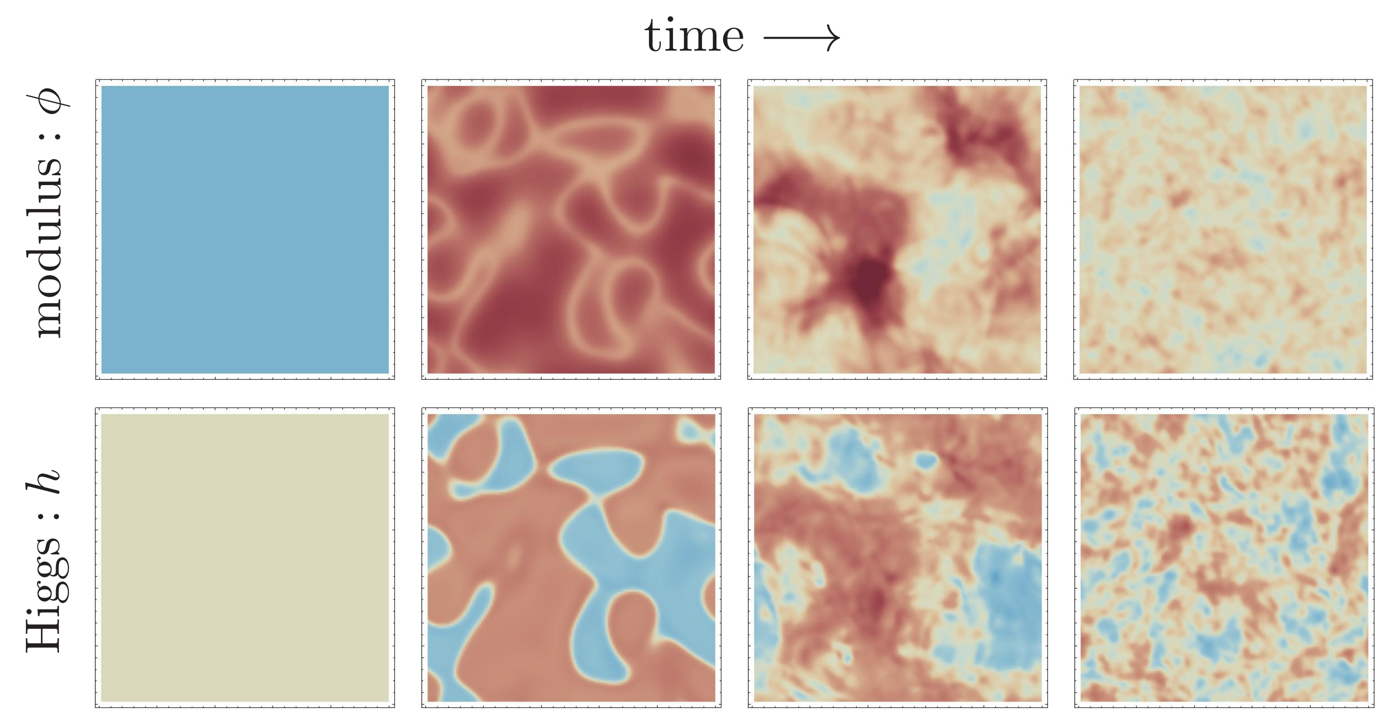
* under certain conditions, later in the talk

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

fine tuning — non-perturbative dynamics — implications



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



stochastic gravitational waves

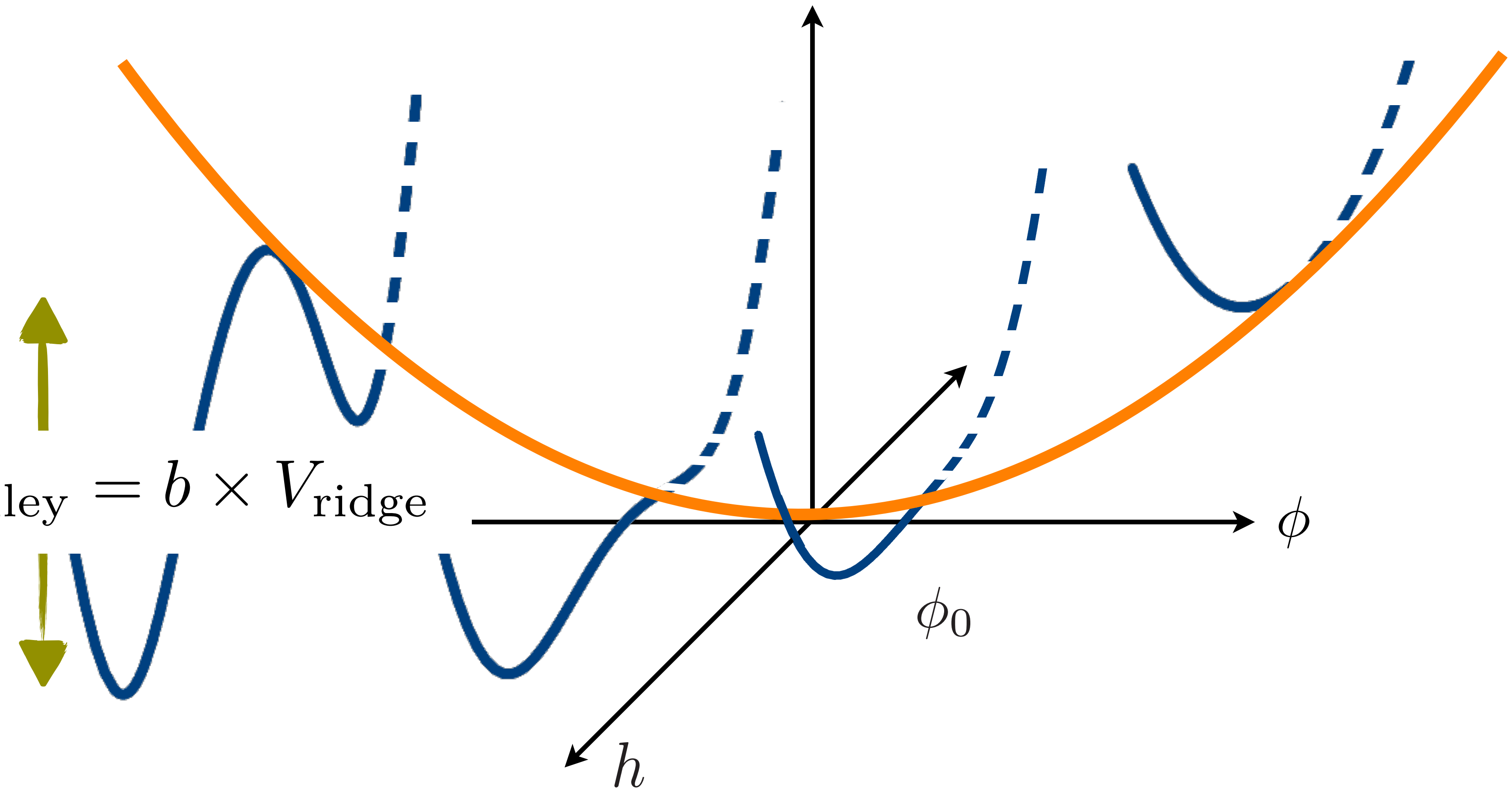
non-trivial eq. of state

* under certain conditions, next up

an important parameter in the Higgs-modulus potential

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

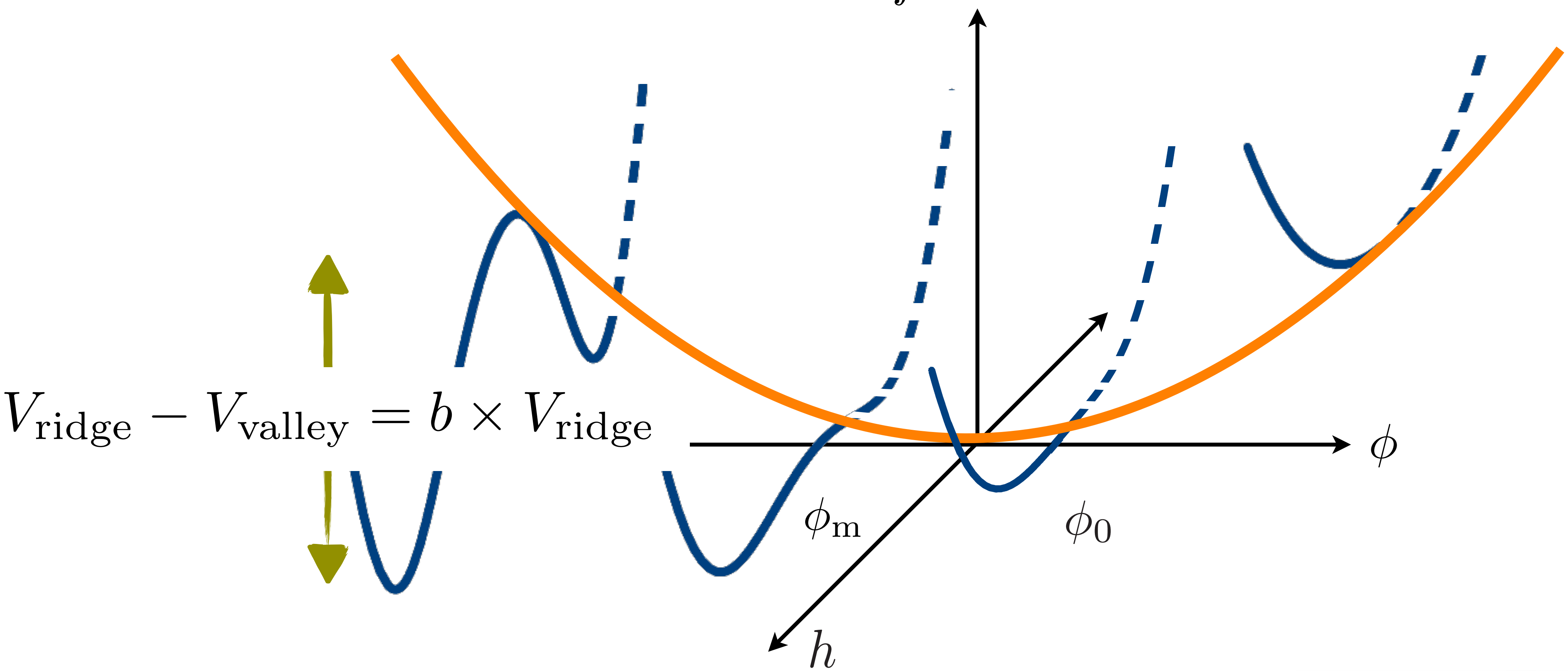
$$V_{\text{ridge}} - V_{\text{valley}} = b \times V_{\text{ridge}}$$



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

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

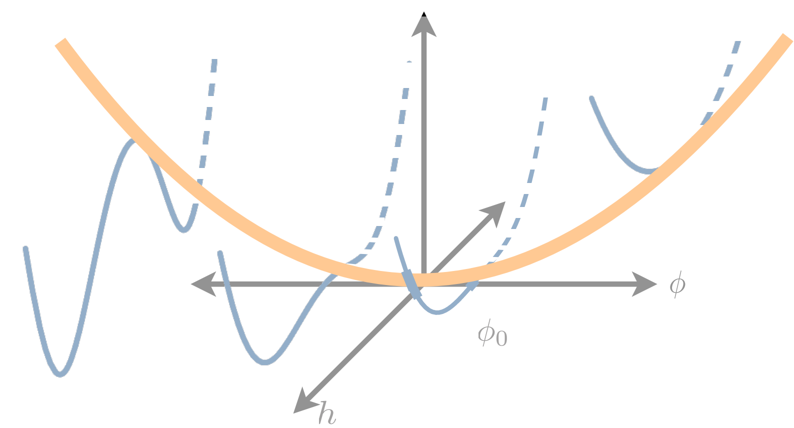
$$\Delta\equiv\frac{\phi_0-\phi_{\rm m}}{f}\ll 1$$

fine tuning

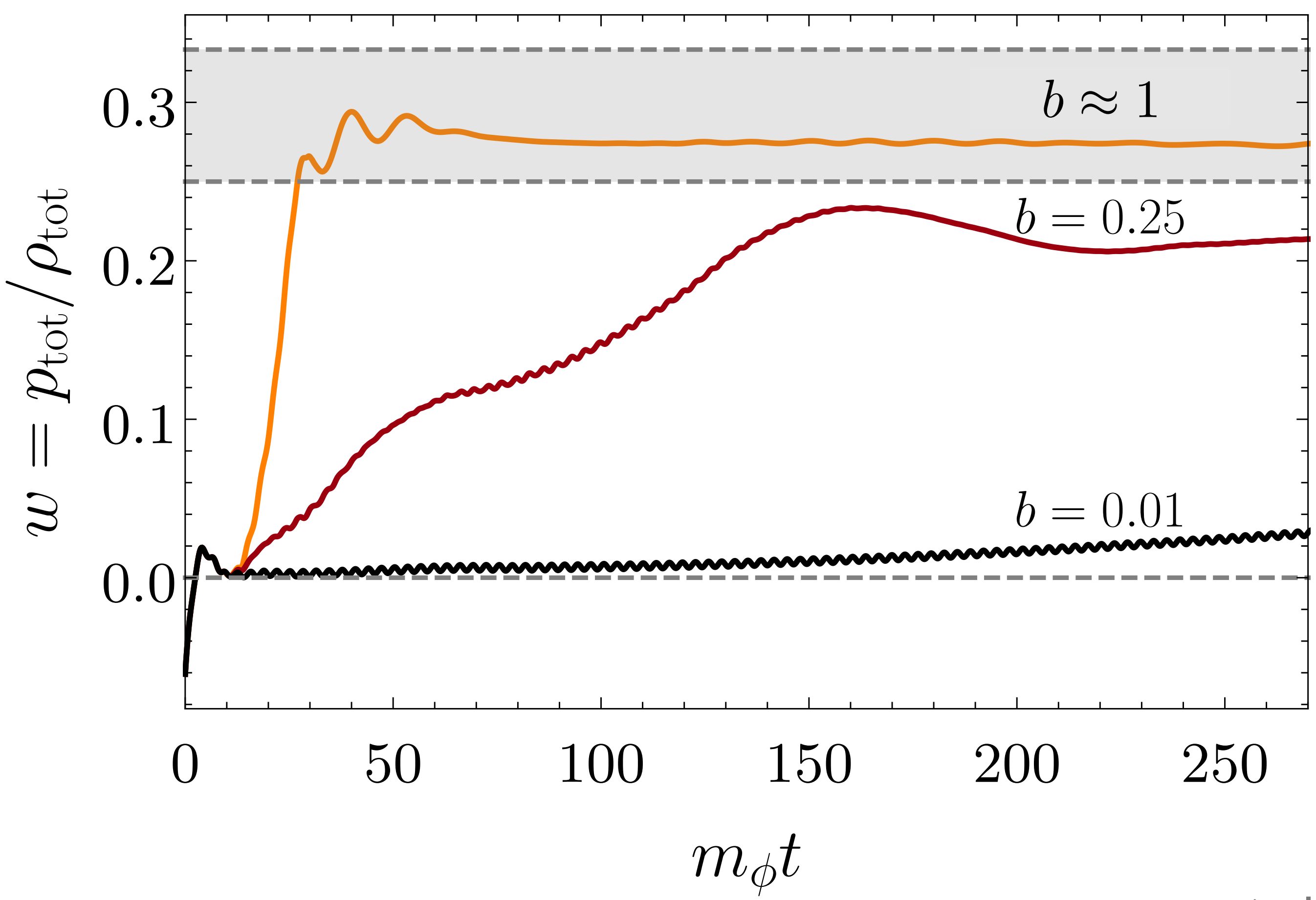
* b ~ O(1) is possible, but non-trivial for model building. Use flat directions in SUSY

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



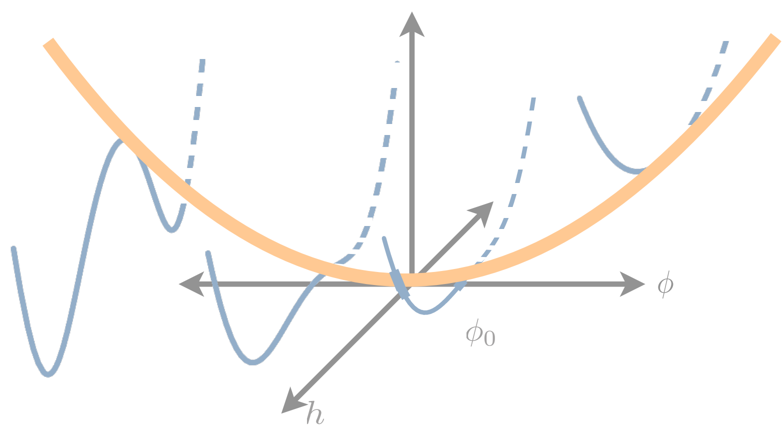
fragmentation ← homogeneous

radiation ← 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

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



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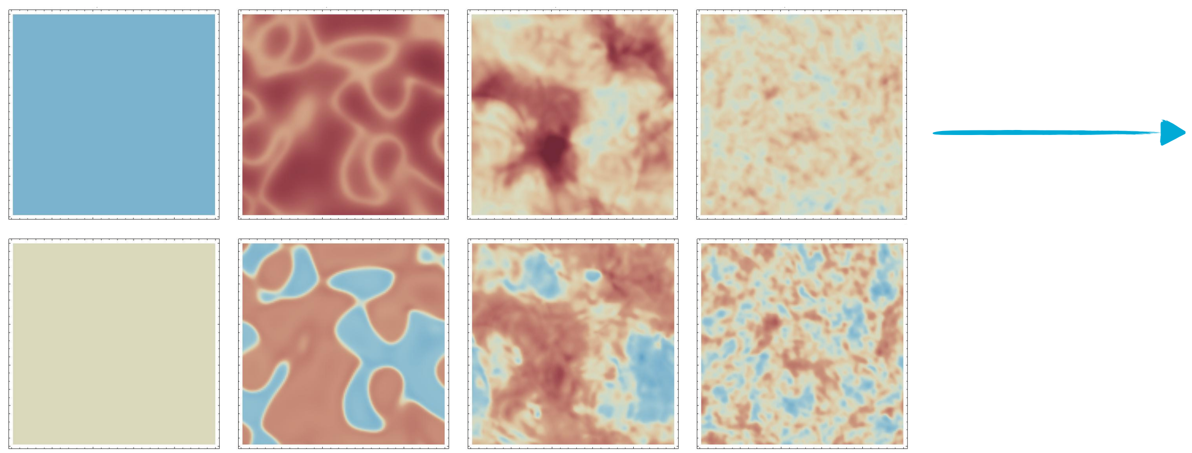
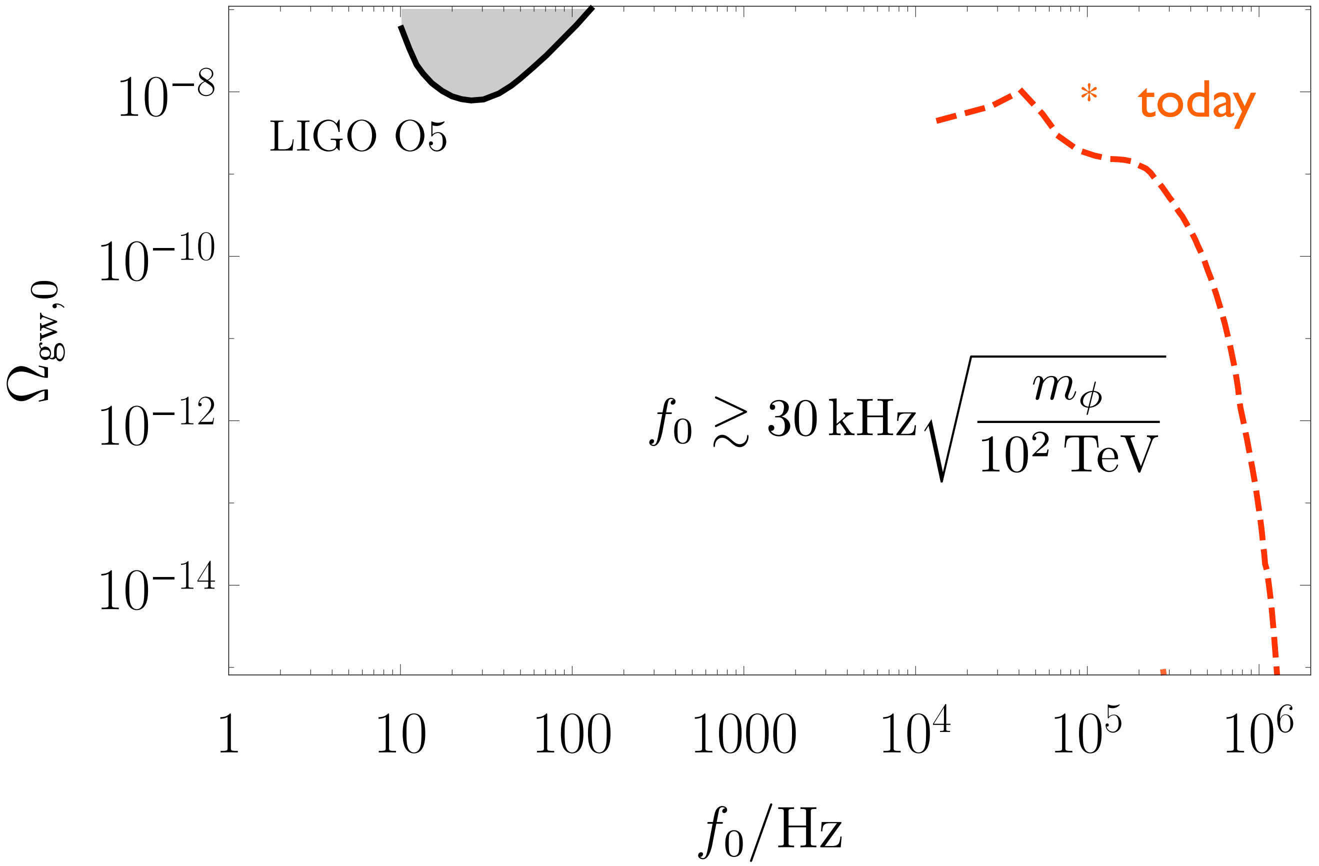
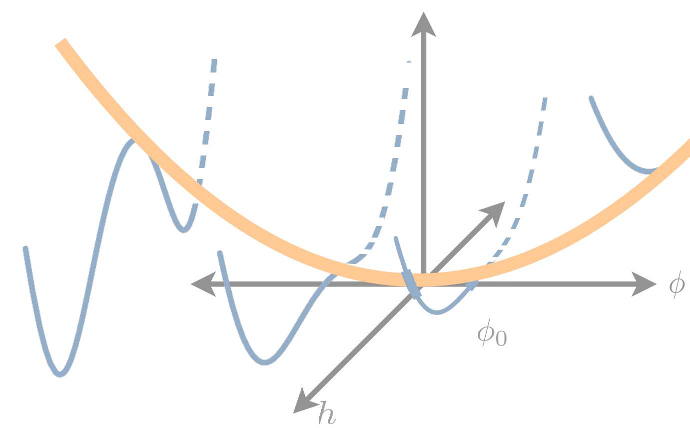




for high frequency gw-detection ideas see:
Akutsu et. al (2010), Goryachev & Tobar (2014), Arvanitaki & Geraci (2016)

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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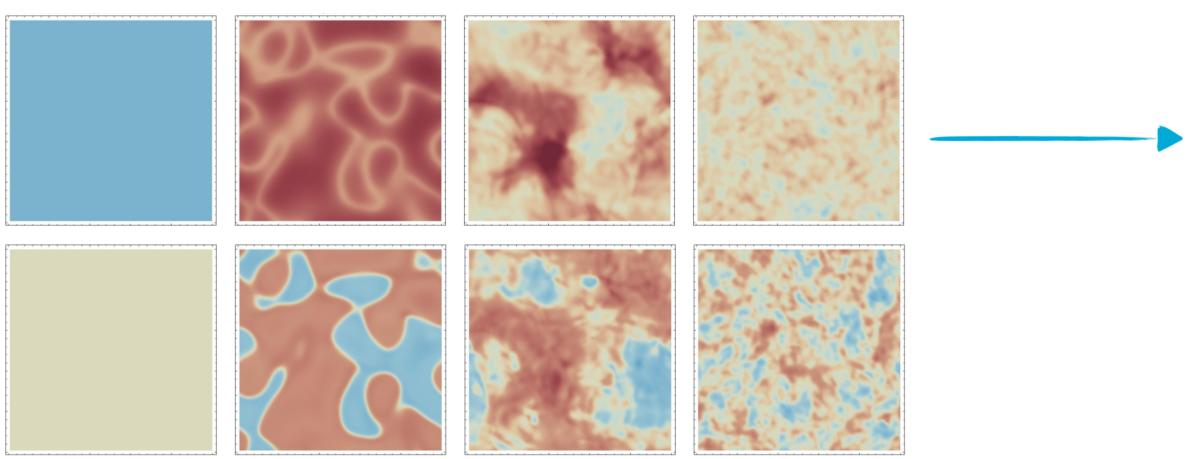

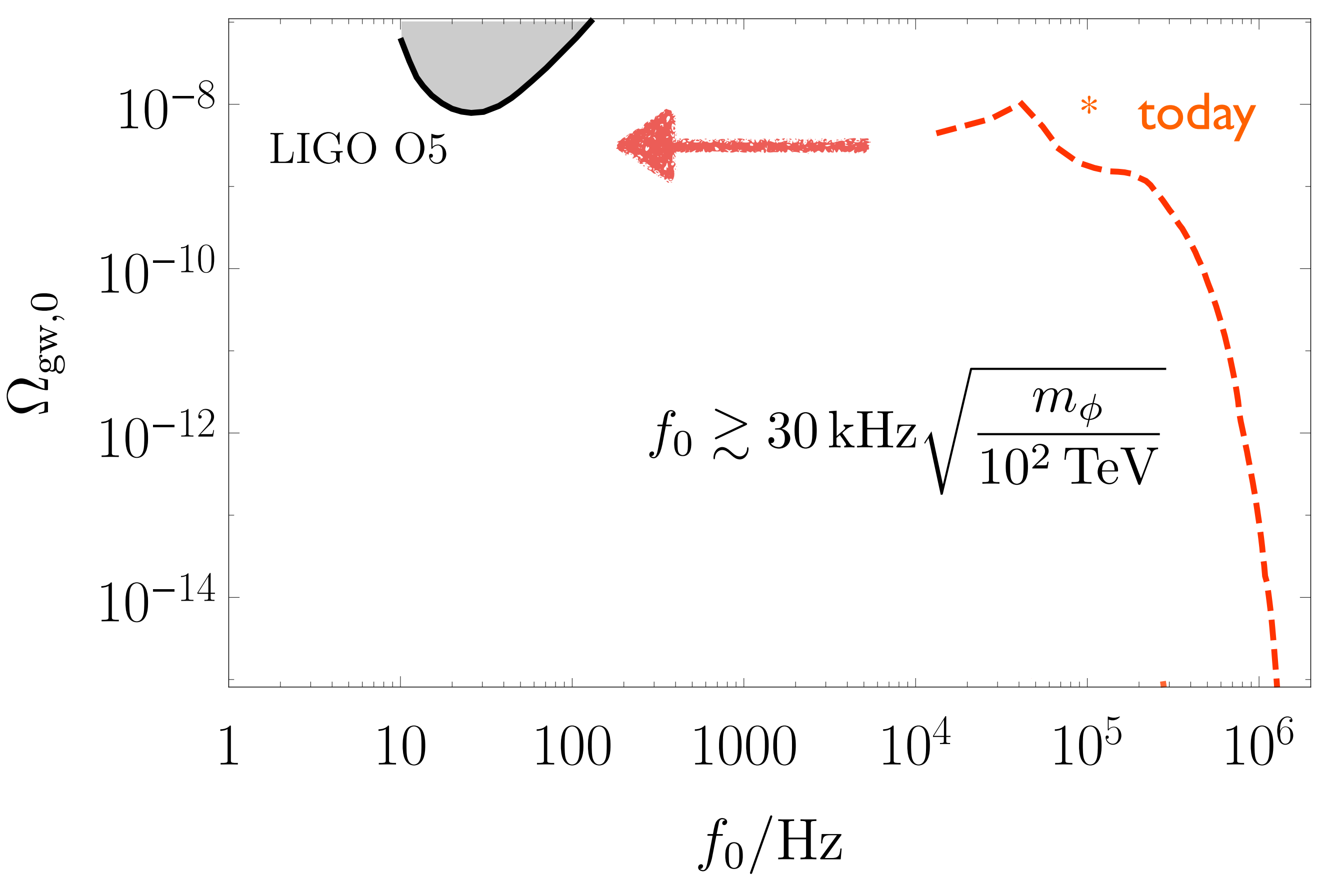

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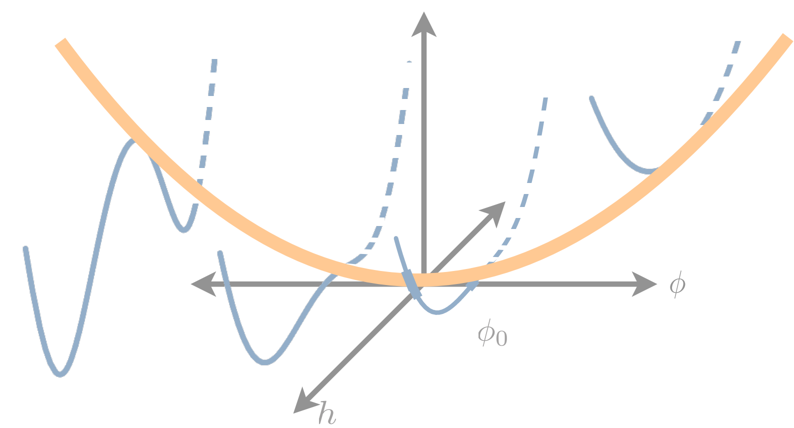
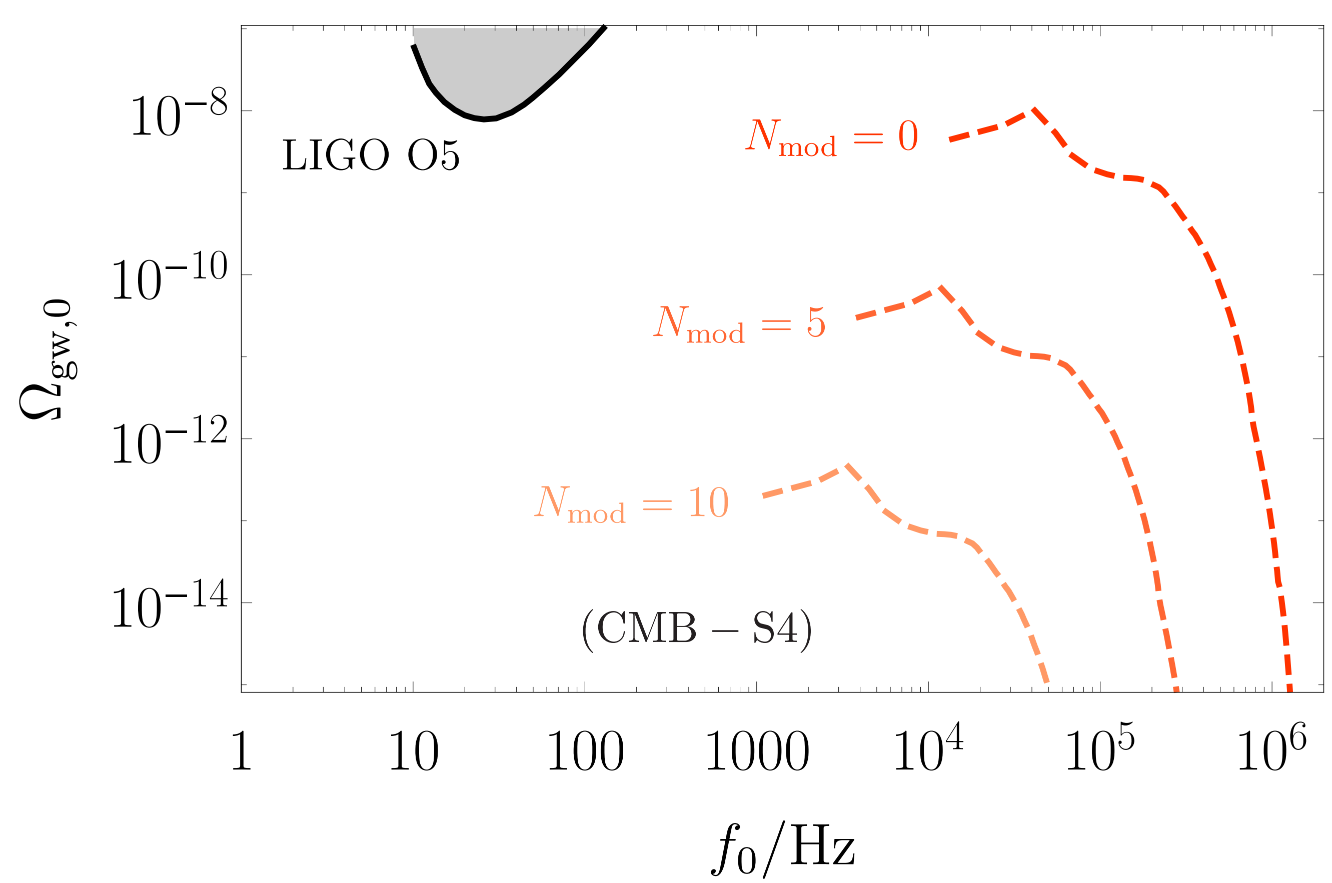


* IF universe becomes matter dominated for $N_{\rm mod}$ e-folds again before BBN

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

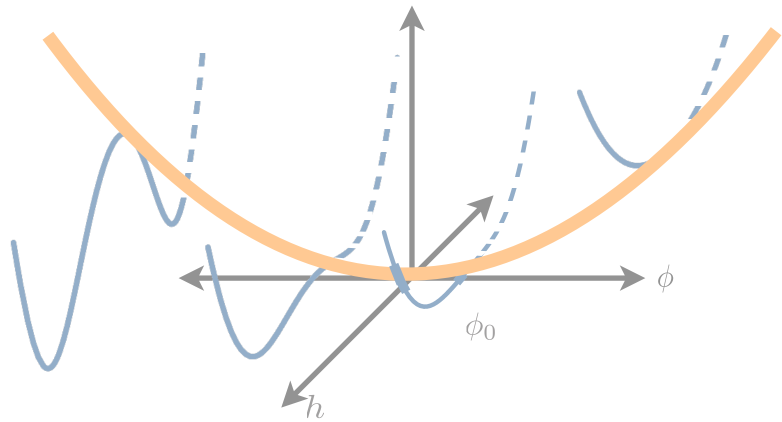
$$\Omega_{\rm gw,0} \sim 10^{-8} \times e^{-N_{\rm mod}(1-3w_{\rm mod})}$$



non-perturbative dynamics — stochastic gravitational waves

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

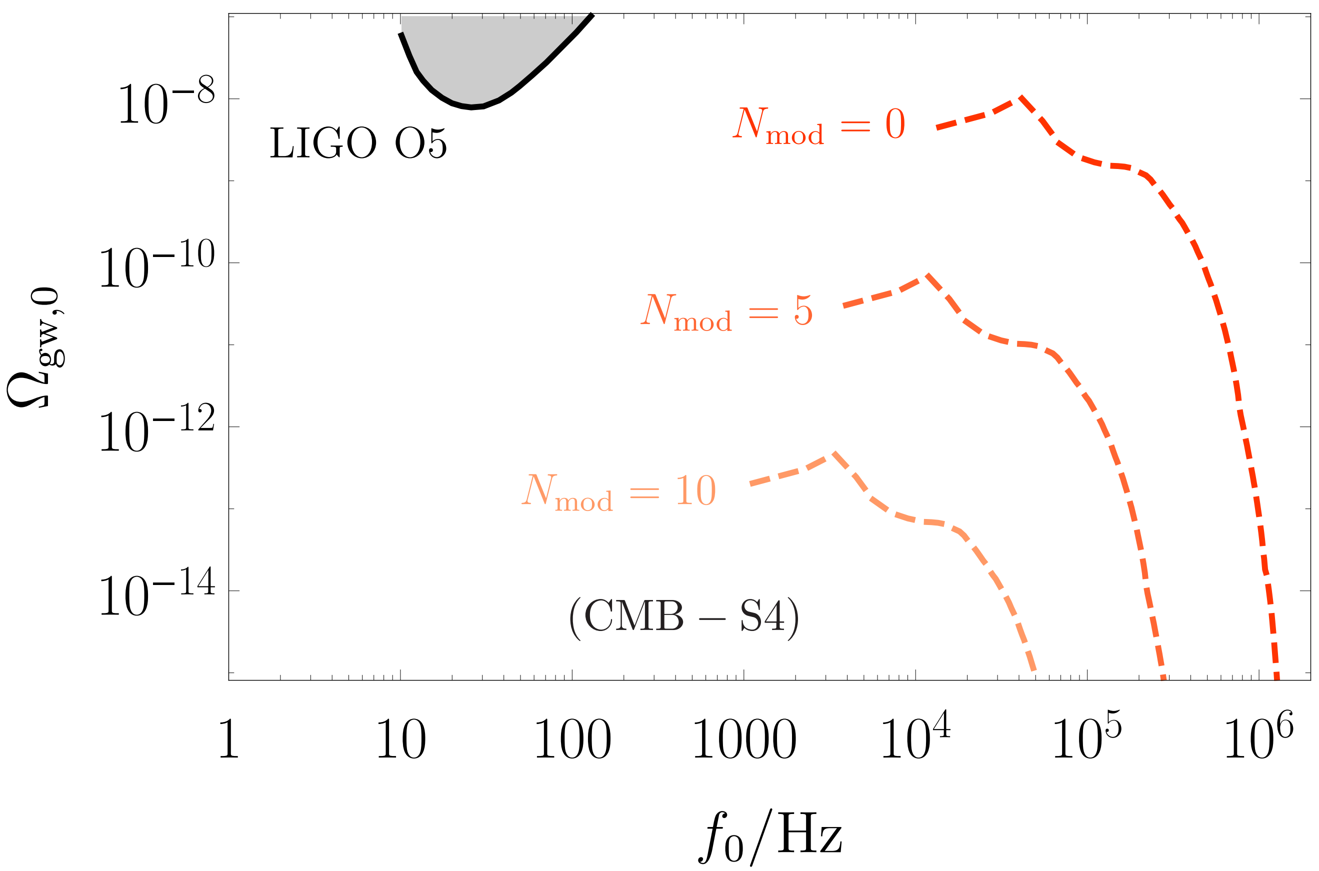
fragmentation efficiency $\quad b \equiv \dfrac{M^4}{2\lambda f^2 m_\phi^2} \sim \mathcal{O}(1)$



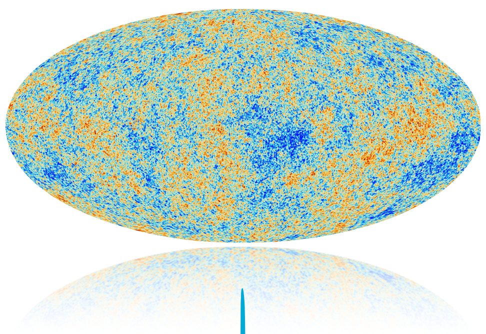
* Constraints from effective number of relativistic species

$$\frac{\Omega_{\mathrm{gw},0}h^2}{\Omega_{\gamma,0}h^2} = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Delta N_{\mathrm{eff}}$$

$$\Omega_{\mathrm{gw},0}h^2 \lesssim 1.12 - 1.68\times 10^{-7}$$

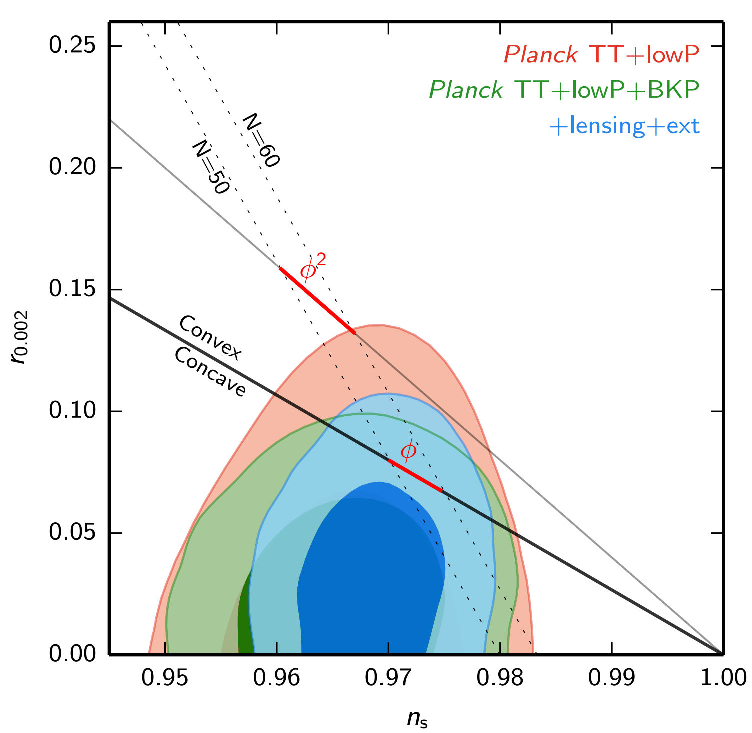


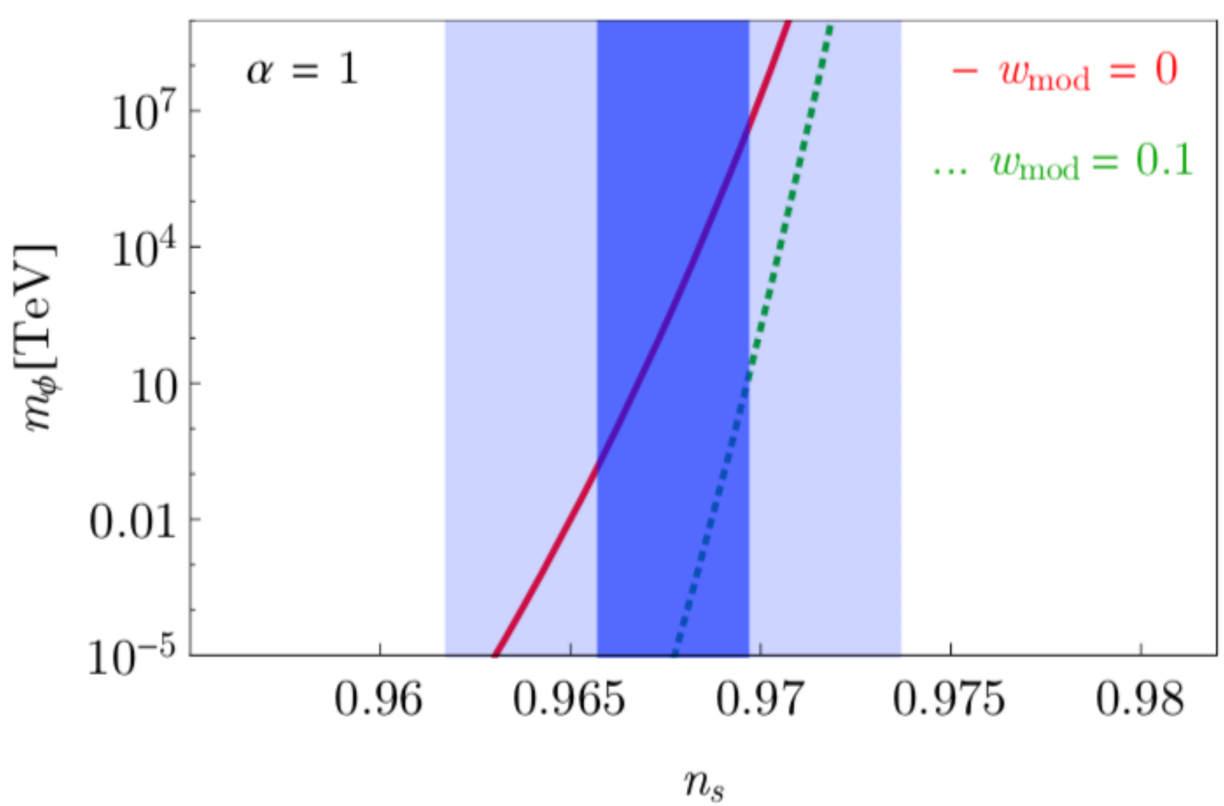
other implications of non-trivial eq. of state



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

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





caveats and future directions

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

caveats and future directions

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

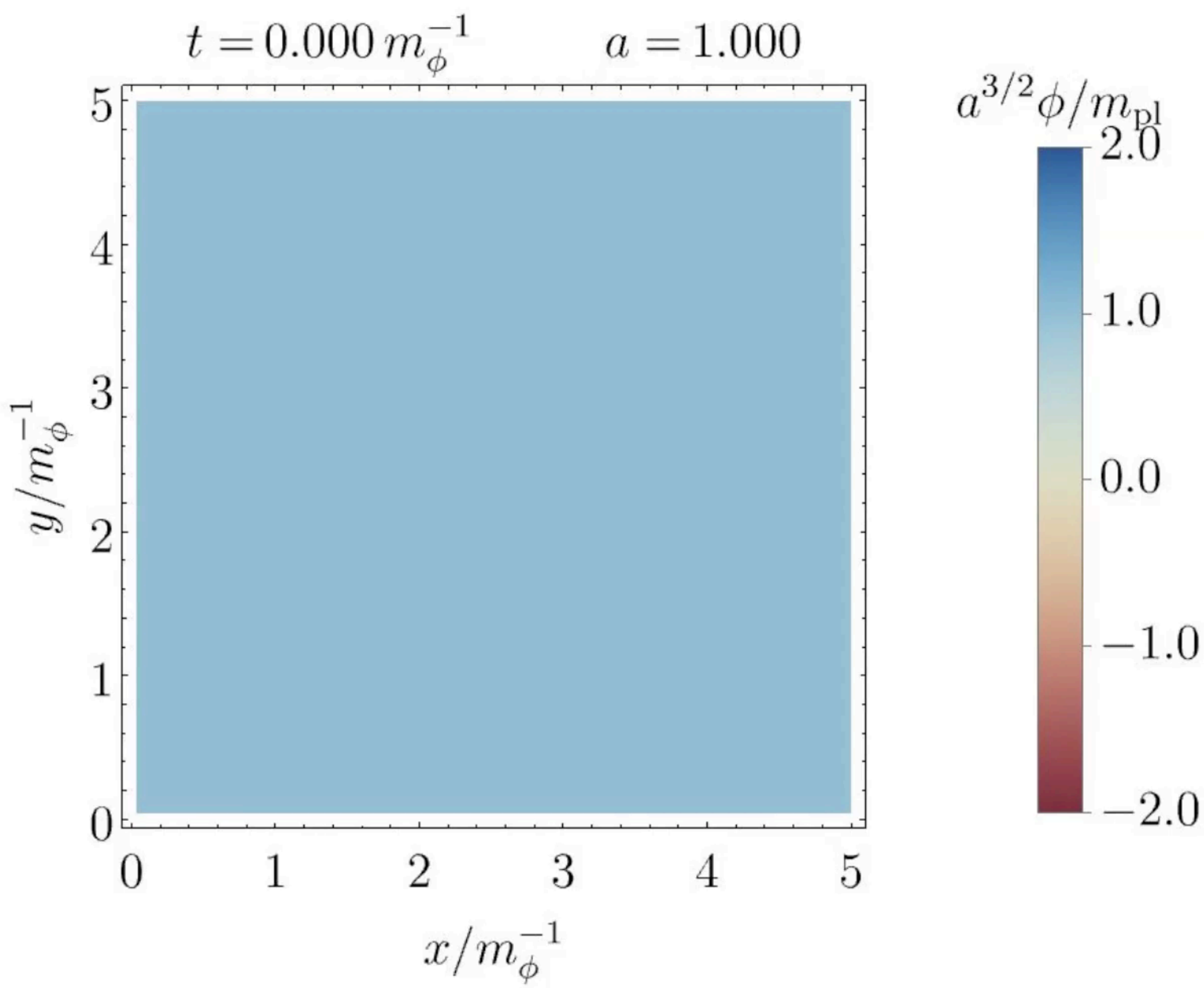
* what if no fine tuning ?

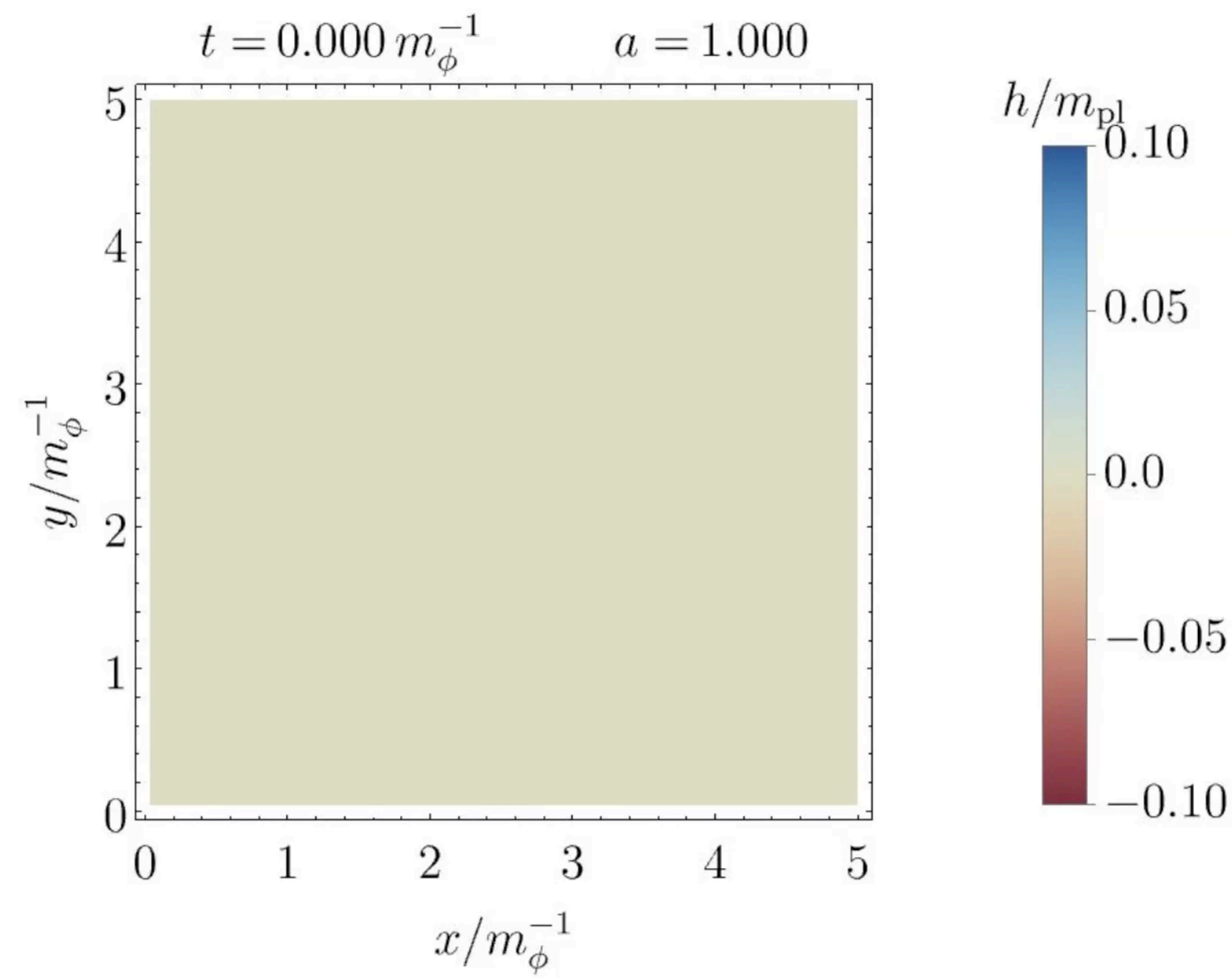
no significant backreaction — $\boxed{\text{eq. of state } w \approx 0}$

$b \sim 1$

$$\boxed{\Delta = \frac{\phi_0 - \phi_\mathrm{m}}{f} \sim \mathcal{O}[1]}$$

~~fine tuning~~





caveats and future directions

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

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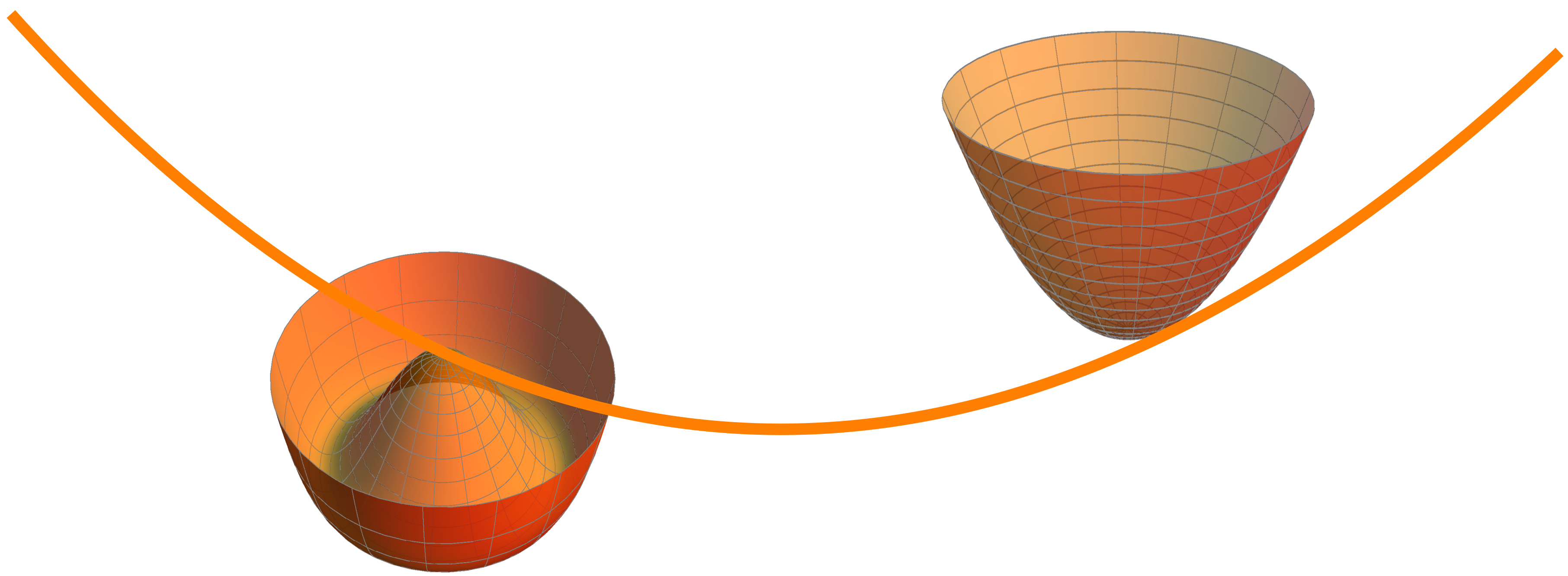
* Higgs is a complex doublet, with associated gauge fields (include decays, future work)



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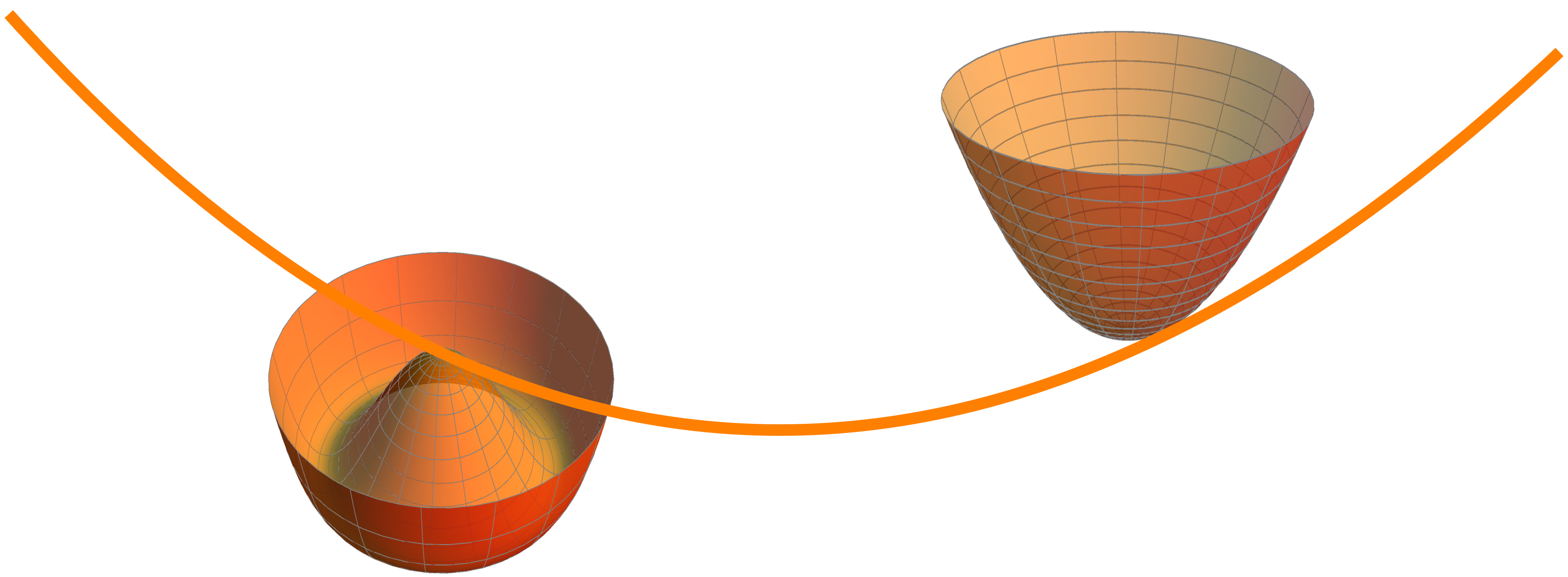


GFiRe: a Gauge Field integrator for Reheating

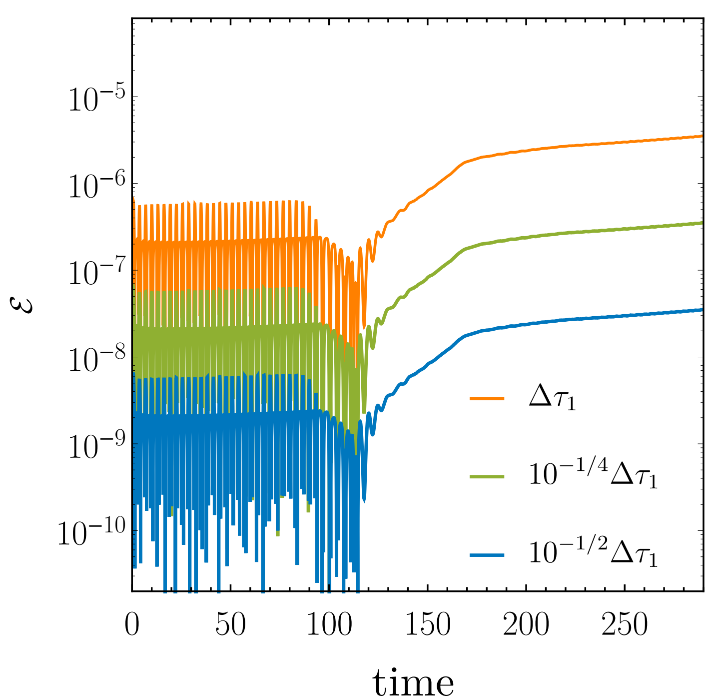
Kaloian D. Lozanov & MA [arXiv:1911.06827]

New algorithm and code, **GFiRe**, to simulate nonlinear dynamics of *Charged Scalars Fields* coupled to *Abelian Gauge Fields* in an expanding universe

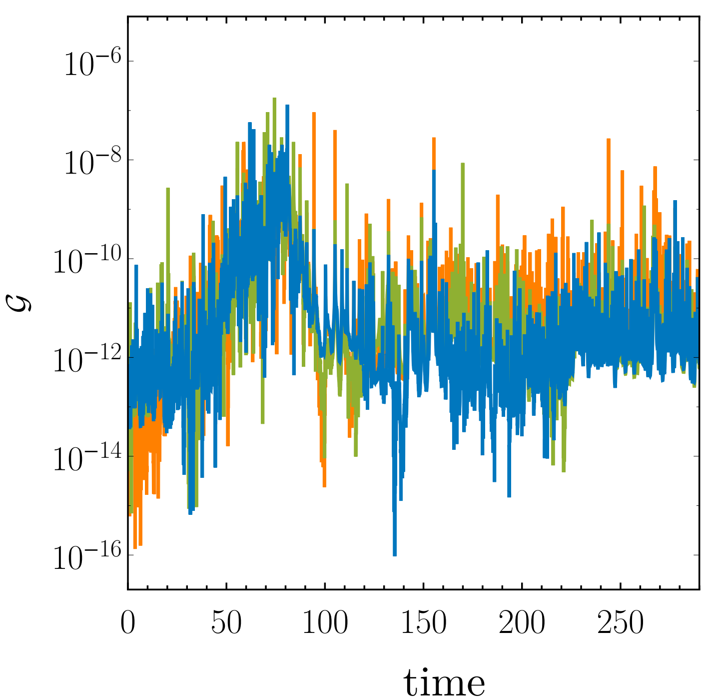
- algorithm uses link variables and includes self-consistent expansion

- algorithm is symplectic (arbitrary order) and has "exact" preservation of Gauss constraint

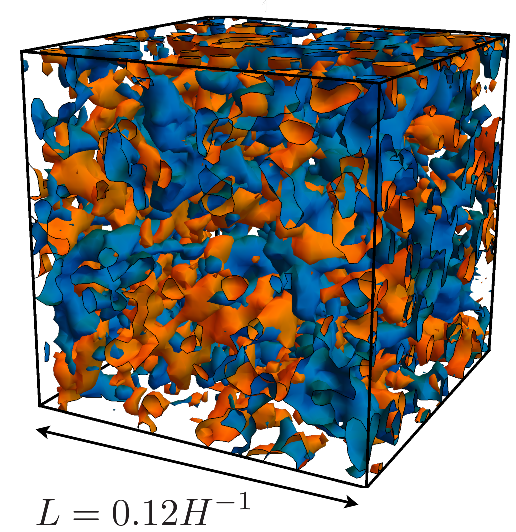
Energy Constrain Violation



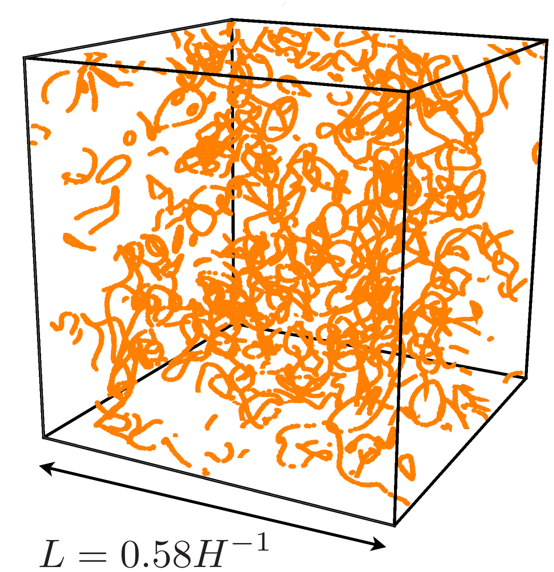
Gauss Constrain Violation



Resonant Production of Electric & Magnetic Fields



Formation & Evolution of "Local" cosmic Strings



caveats and future directions

* not necessarily *explaining* the fine tuning; we are exploring the implications of fine tuning
* what if no fine tuning ?
* Higgs is a complex doublet, with associated gauge fields (future work)
* model building

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

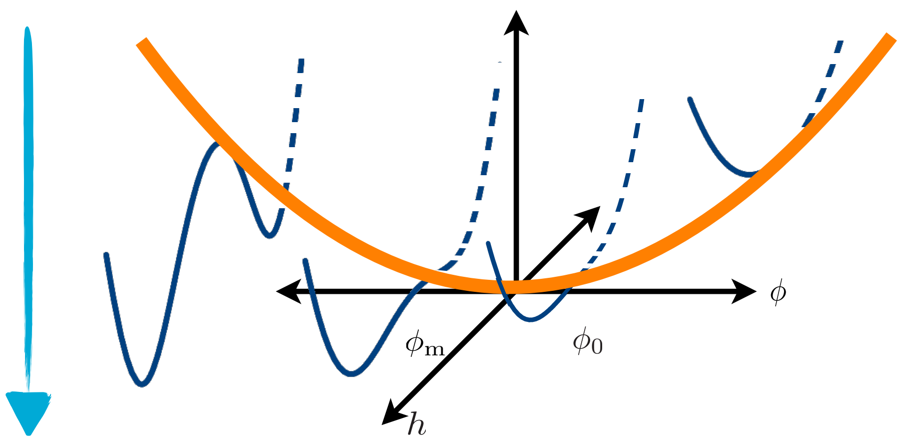
caveats and future directions

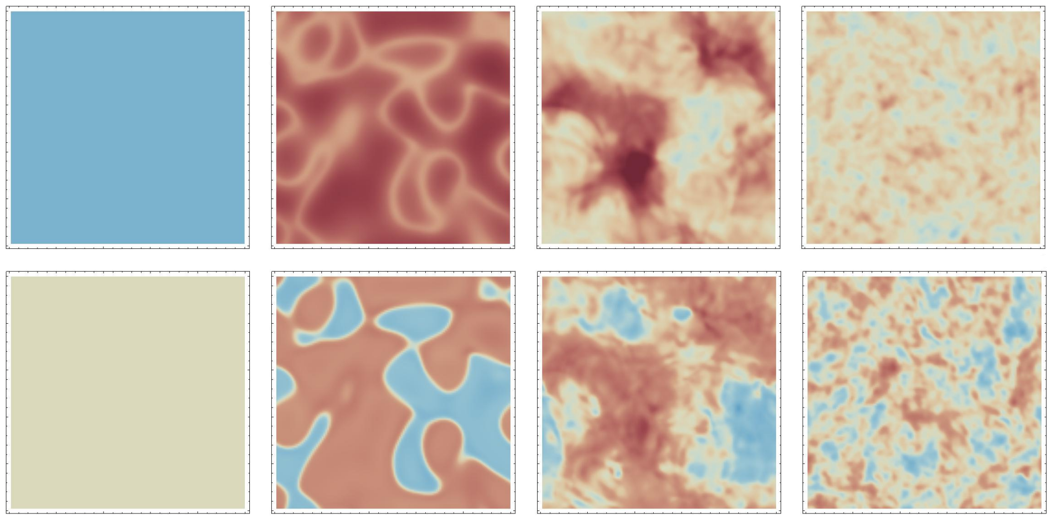
* **not necessarily *explaining* the fine tuning; we are exploring the implications of fine tuning**
* Higgs is a complex doublet, with associated gauge fields (future work, interested ?)
* model building (collaborators needed)
* implications for colliders ? (collaborators needed)

summary: Cosmological Dynamics of Higgs Fine Tuning

arXiv: 1802.00444

nothing but Higgs at the LHC





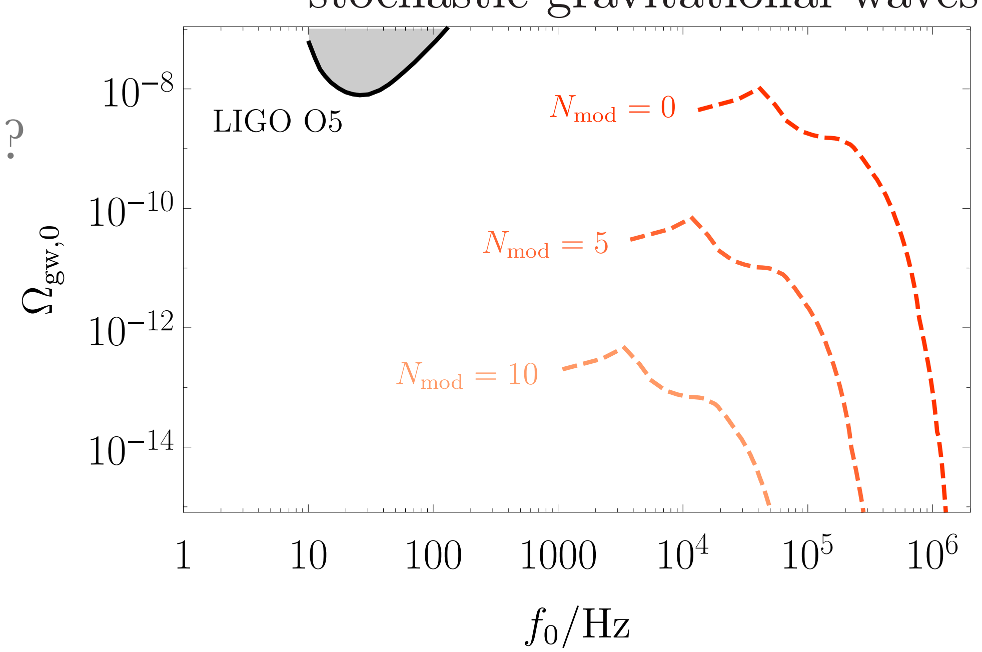
$$V(\phi, h) = \frac{1}{2} m_\phi^2 \phi^2 + M^2 \frac{(\phi - \phi_0)}{f} h^\dagger h + \lambda (h^\dagger h)^2 + V_0$$

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

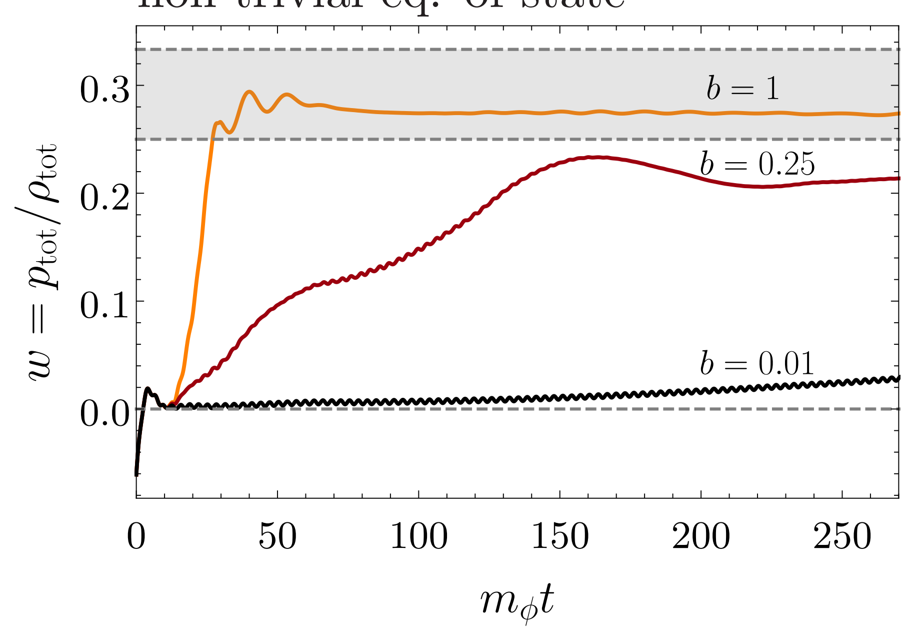
$$b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \sim \mathcal{O}(1)$$ fragmentation efficiency

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

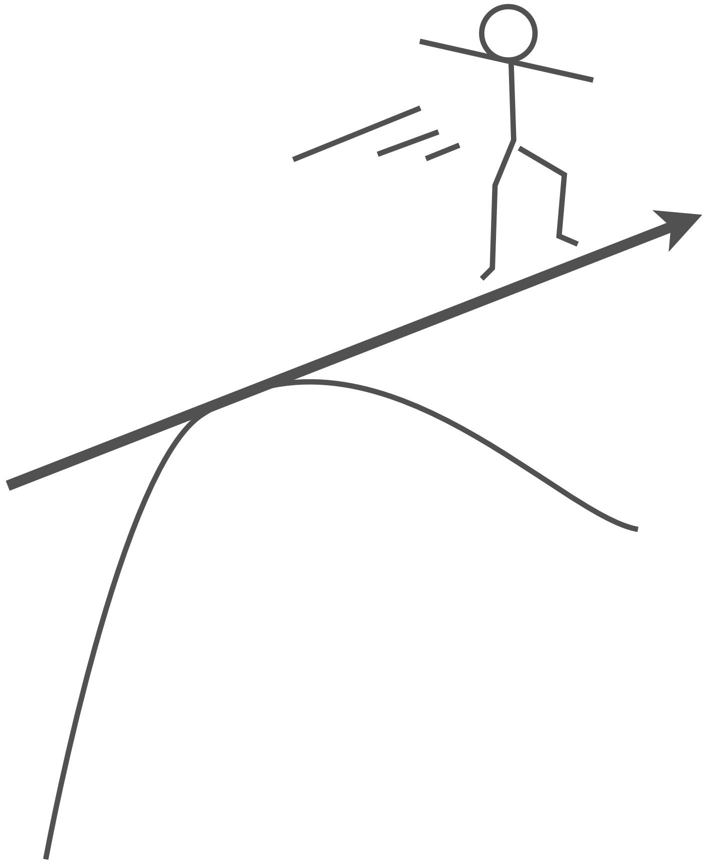
stochastic gravitational waves



non-trivial eq. of state



tangential digressions into other projects



reheating after inflation

inflaton dominated, "cold" universe

scalar & gauge bosons + fermions

particle production

time

inflation

preheating

non-linear regime

perturbative regime

thermalization

gravitational perturbations
(non-gaussianity, gravitational waves)

topological & non-topological solitons
(strings, textures, bubbles, Q-balls, oscillons)

+

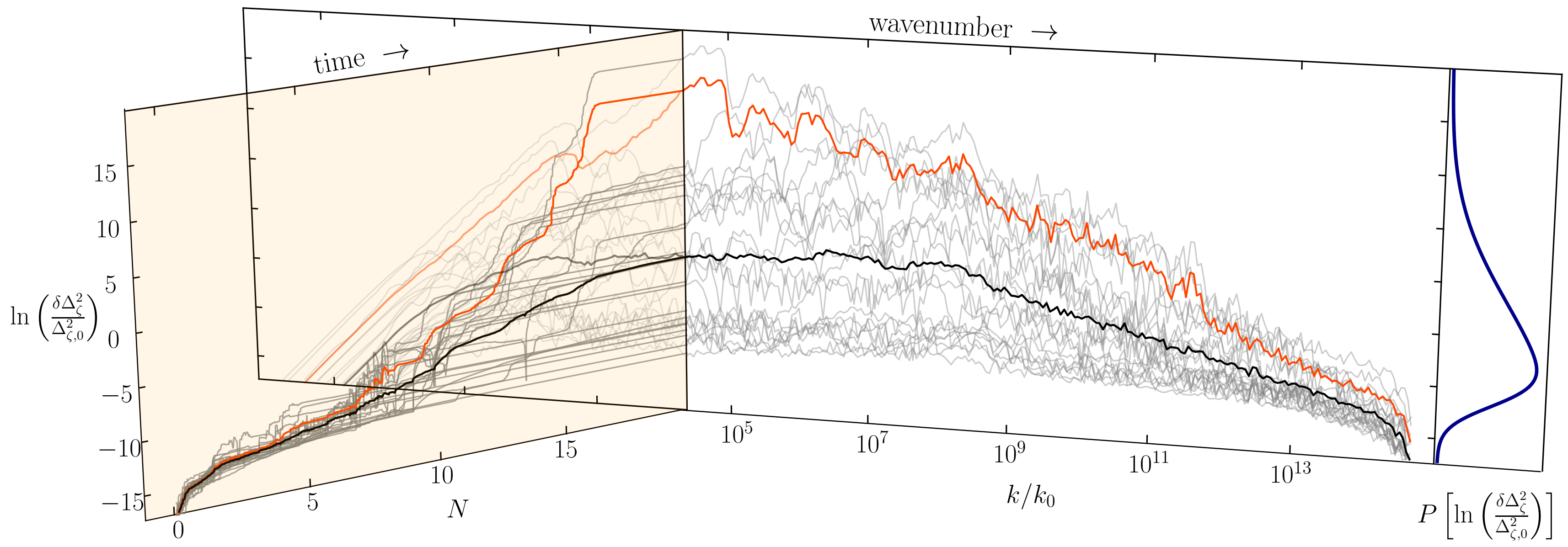
expansion history, baryogenesis …

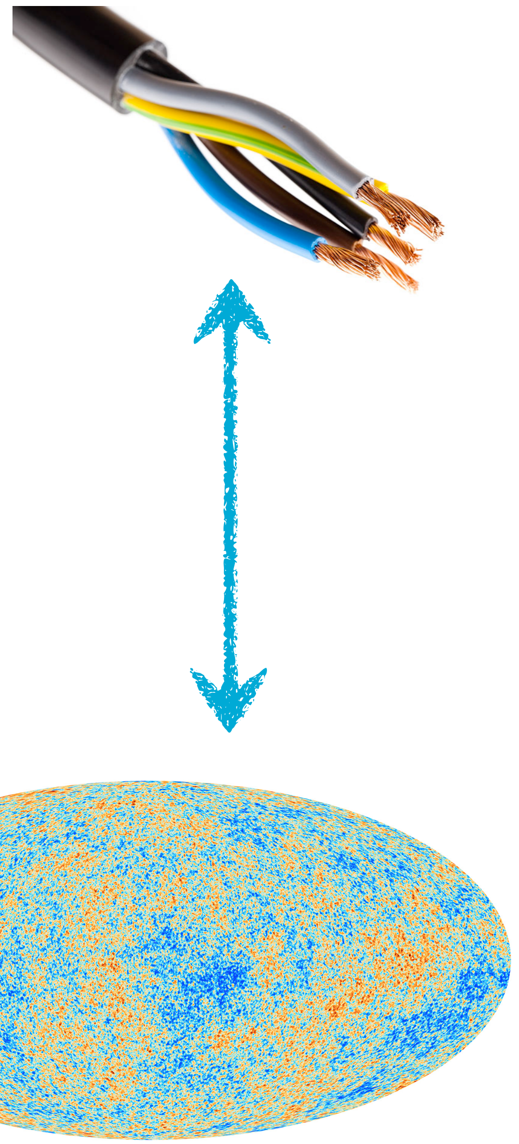
radiation dominated, thermal universe

from review: MA, Kaiser, Karouby & Hertzberg (2013)

sufficiently complex models of inflation and reheating

appropriate for sufficiently complex models of inflation





- Wires to Cosmology
  (MA & Baumann 1512.02637)
- Multifield Stochastic Particle Production
  (MA, Garcia, Wen & Xie 1706.02319)
- Stochastic Particle Production in deSitter Space
  (Garcia, MA, Carlsten & Green 1902.06736)
- Curvature Perturbations from Stochastic Particle Production during Inflation
  (Garcia, MA & Green 2001.09158)

Also see recent work by D. Green in 2015. Early work in context of noise in preheating: Zanchin et. al 1997, Bassett 1998

The Equation of State & Duration to Radiation Domination After Inflation

Kaloian D. Lozanov & Mustafa A. Amin, *Phys. Rev. Lett.* 119, 061301 (2017) [arXiv: 1608.01213]

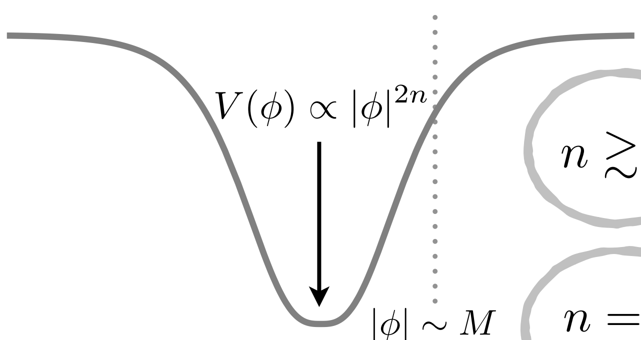
arXiv: 1710.06851

the question:

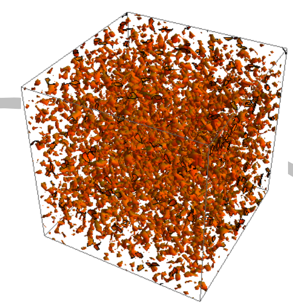
Inflation (accelerated space expansion) → how ? how long ? → **radiation domination (Hot Big Bang *)**

what we found:

inflaton potential



$n \gtrsim 1$ — field eventually fragments



eq. of state

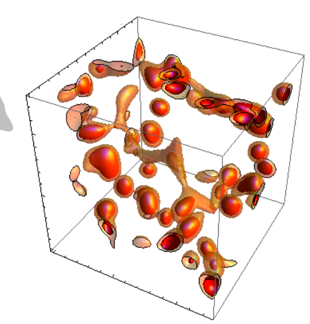
$$w \equiv \frac{\text{pressure}}{\text{density}} \to 1/3$$

"reheating" e-folds (how much the universe expands)

- increases with M
- increases as n moves away from 2
- for $M << m_{\rm Pl}$, reheating e-folds < 1

radiation domination

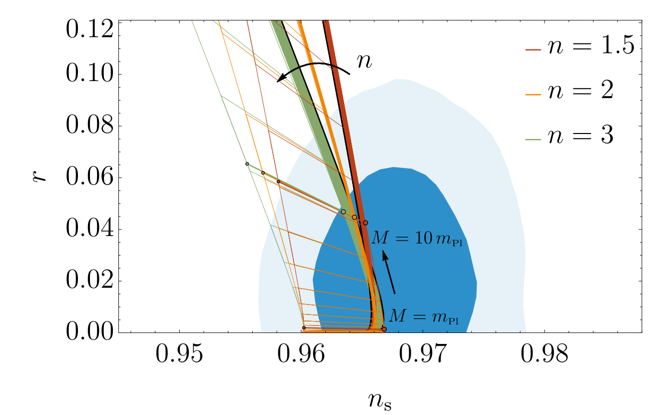
$n = 1$



eq. of state

$w \to 0$

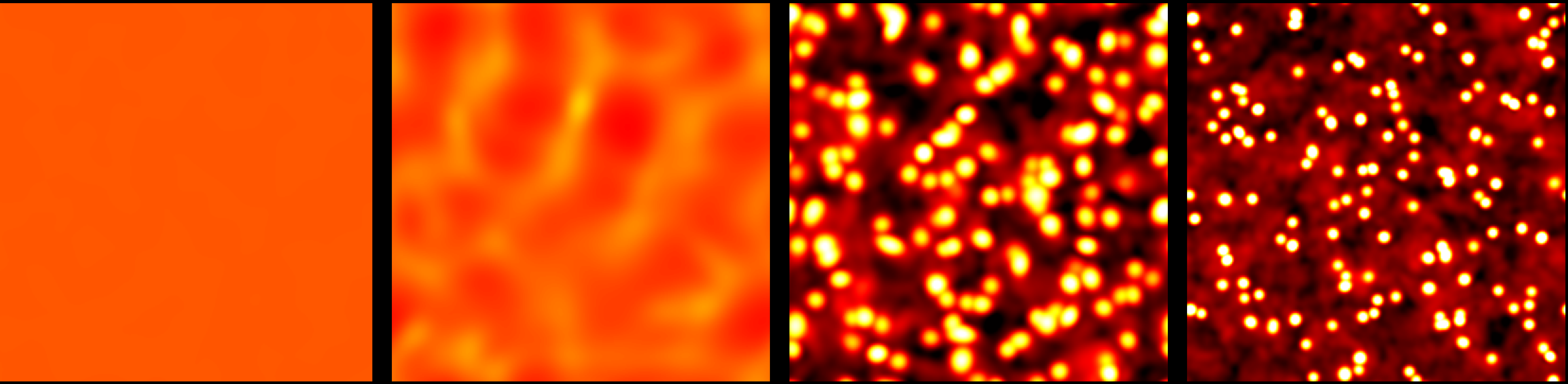
Reduction in theoretical uncertainty of inflationary observables



NEW ? (1) Included effects from field fragmentation in a broad class of observationally consistent inflaton potentials
(2) Provided upper bound on duration to radiation domination, which can be reached even without coupling to other fields

Oscillon Formation After Inflation and in Dark Matter

* including gravitational effects



MA et. al
arXiv: 1106.3335

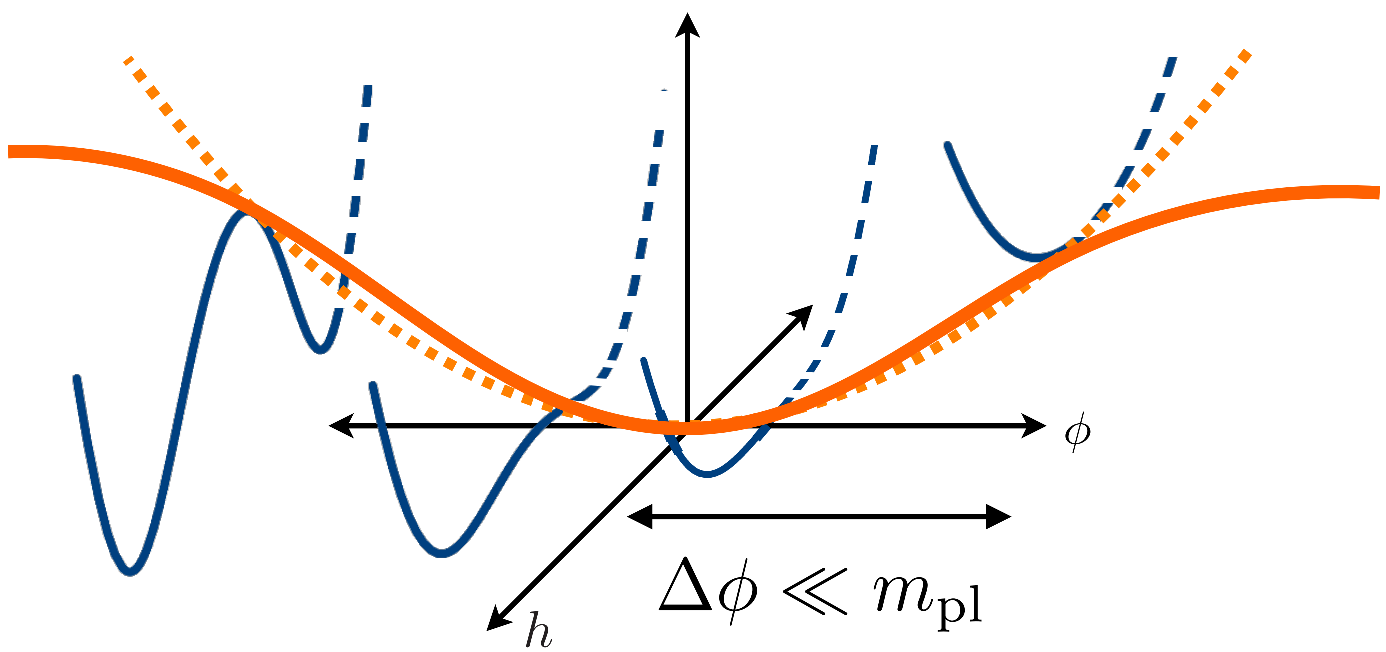
Mocs & MA
arXiv: 1902.07261

Lozanov & MA
arXiv:1902.06736

Zhang et. al
arXiv:2004.01202

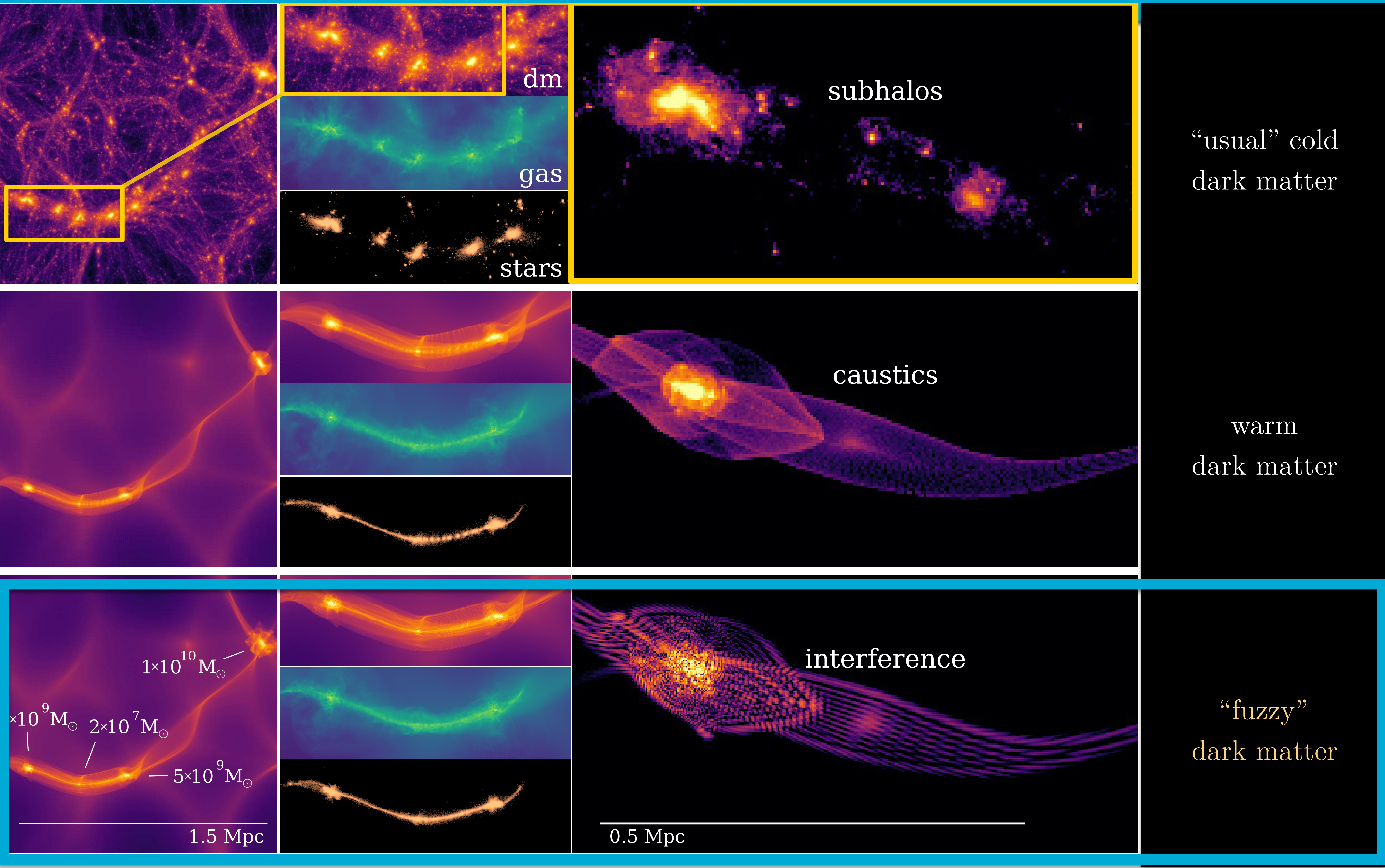
caveats and future directions (in the Higgs project)

* inclusion of self-interactions in the moduli: oscillons



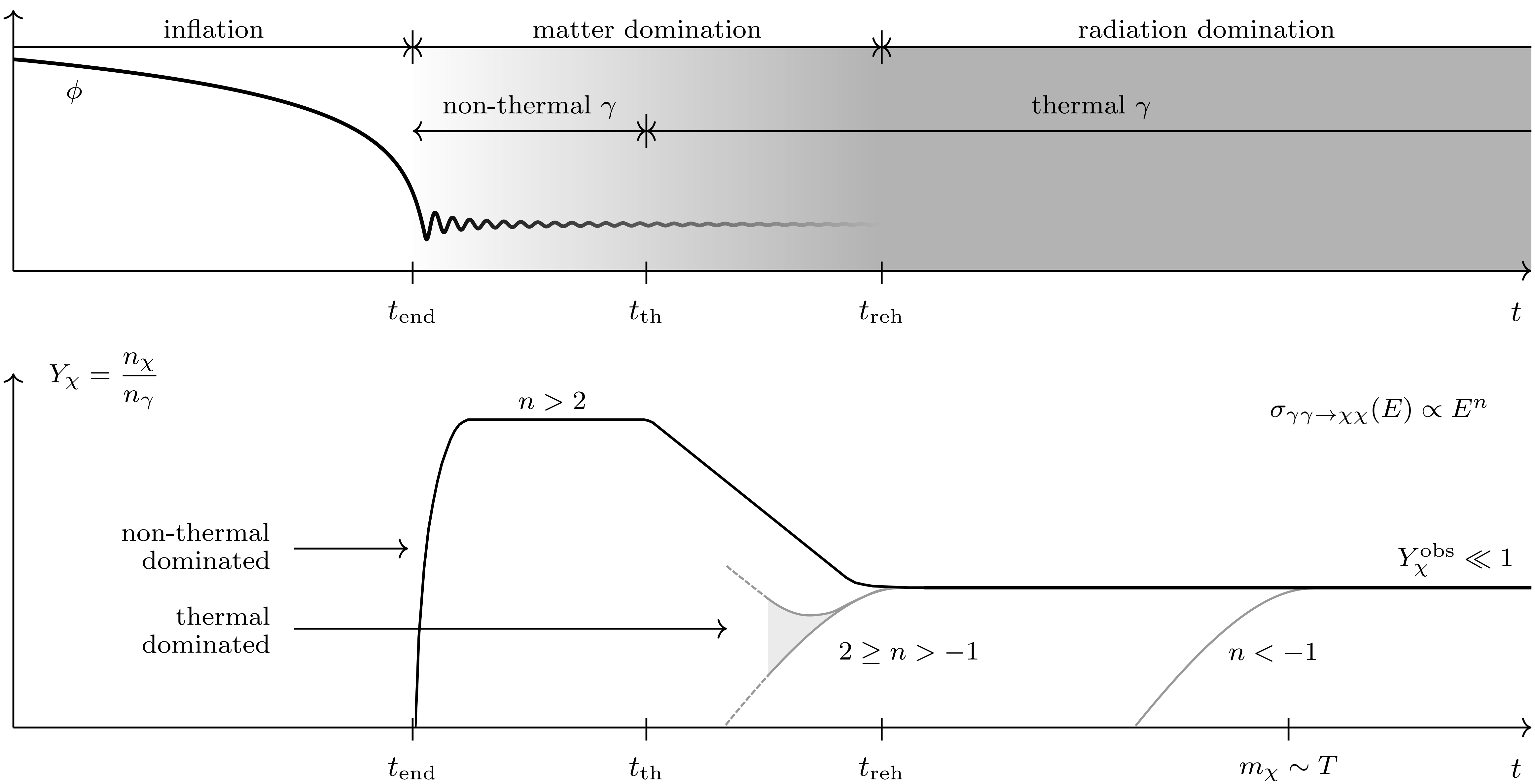
structure formation with light scalar fields

Mocz, +MA, et. al (2019)

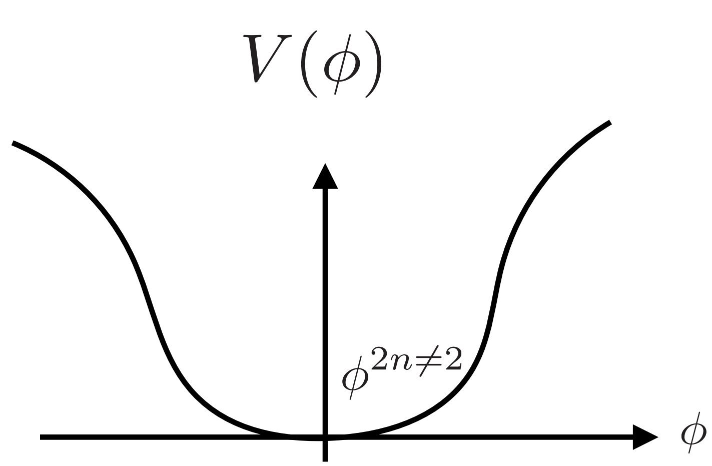


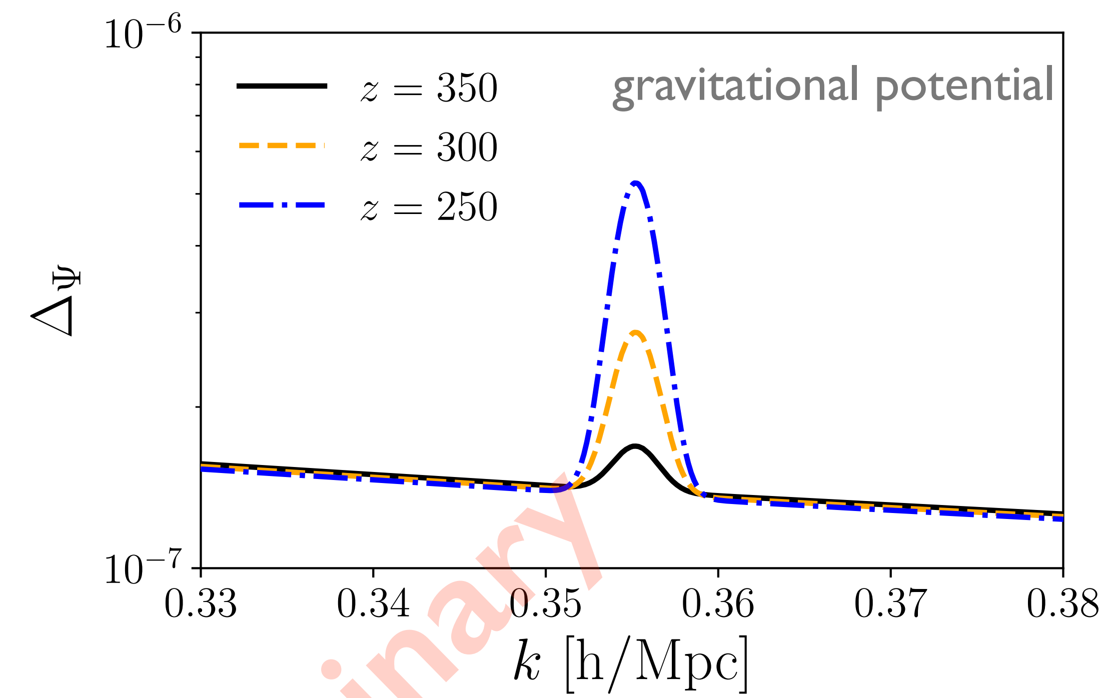
Pre-thermalization production of dark matter

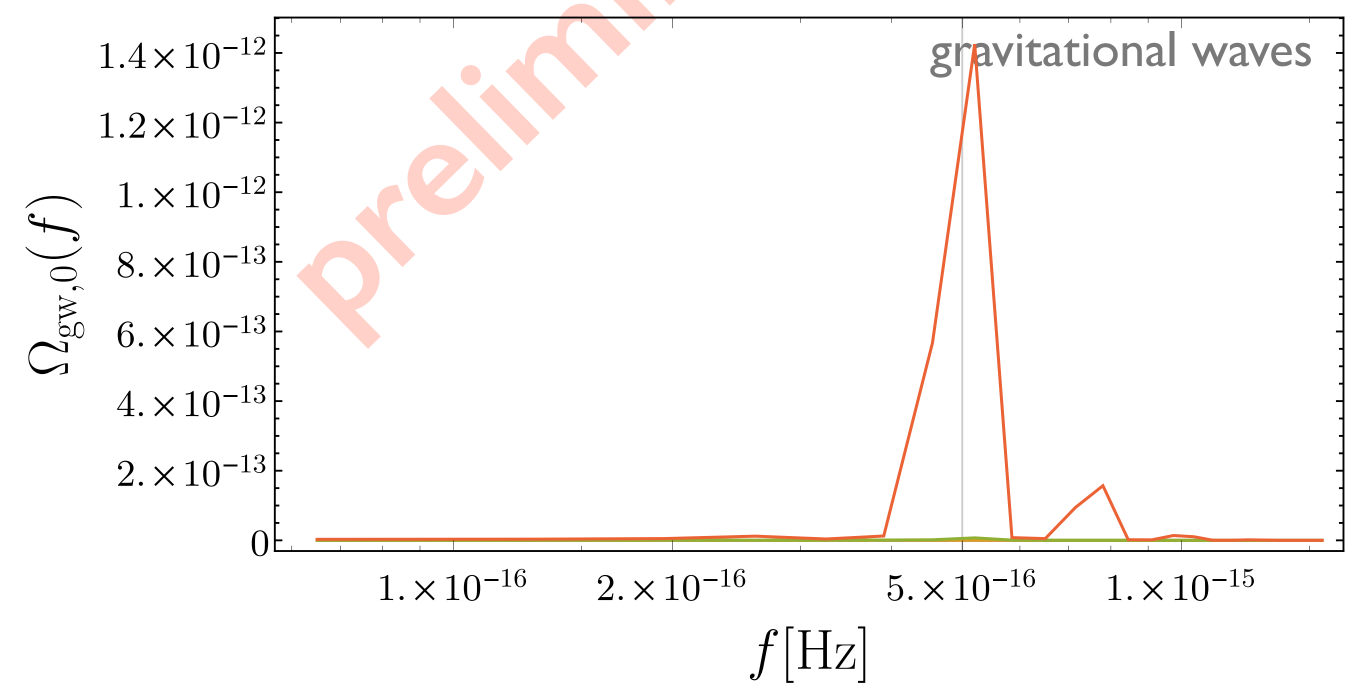
arXiv:1806.01865 M. Garcia and MA



“Hubble Tension” resolution — some novel implications







*no-solitons

Smith, Poulin & MA (2019), MA, Lozanov & Smith (in progress)

thanks!