Walls, Bubbles and Doom: the Cosmology of the HEFT

Durham University

IP3

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The 5th NPKI Workshop @ Busan

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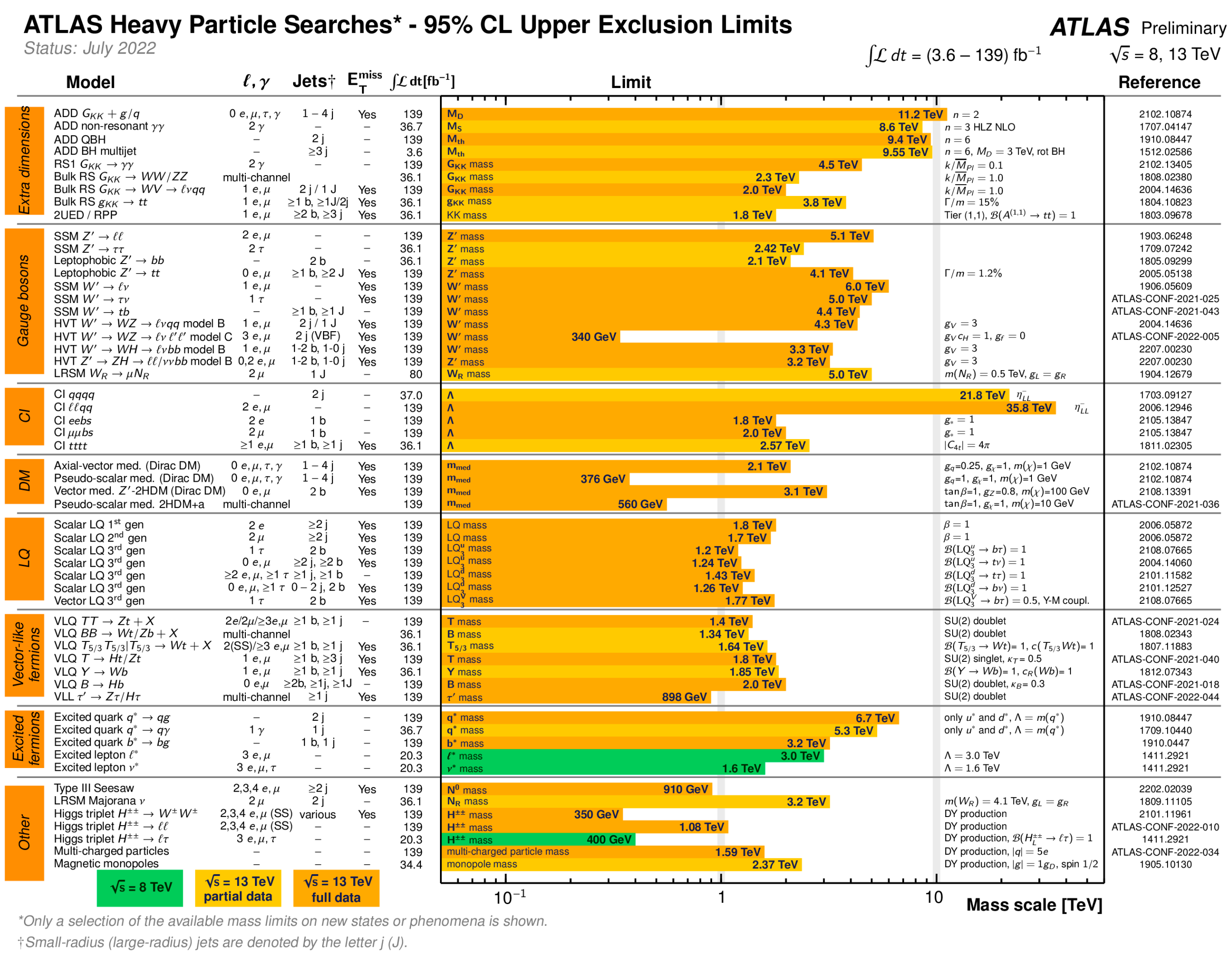
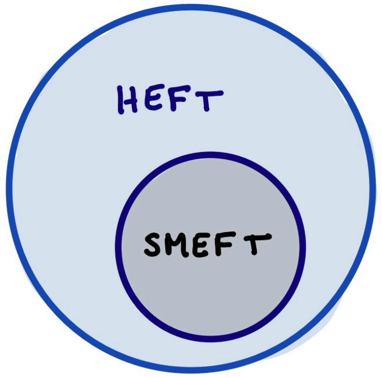
In Collaboration with Rodrigo Alonso, Mia West (Durham), and Juan Criado (Granada U.)

Introduction



- New physics has not been very obvious
- We are in the precision regime for EW physics
- We may instead see indirect signals of decoupled new physics
- EFT’s are increasingly useful to classify these signals

SMEFT vs. HEFT



SMEFT

- Invariant under the gauge group

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Linearly realized EW symmetry

HEFT

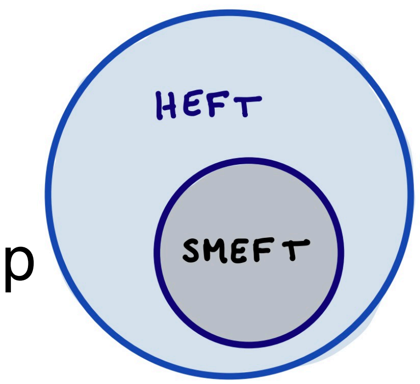
- Invariant under the gauge group

$$SU(3)_c \times U(1)_{\rm em}$$

- Nonlinearly realized EW symmetry

Weinberg (1979)
Feruglio (1993)

SMEFT vs. HEFT



SMEFT

- Invariant under the gauge group

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Linearly realized EW symmetry

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix} \qquad H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_4 + i\phi_3 \end{pmatrix}$$

$$V_{\text{SMEFT}} = V(H^\dagger H)$$

- $V(H^\dagger H)$ contains higher dimensional operators

HEFT

- Invariant under the gauge group

$$SU(3)_c \times U(1)_{\text{em}}$$

- Nonlinearly realized EW symmetry

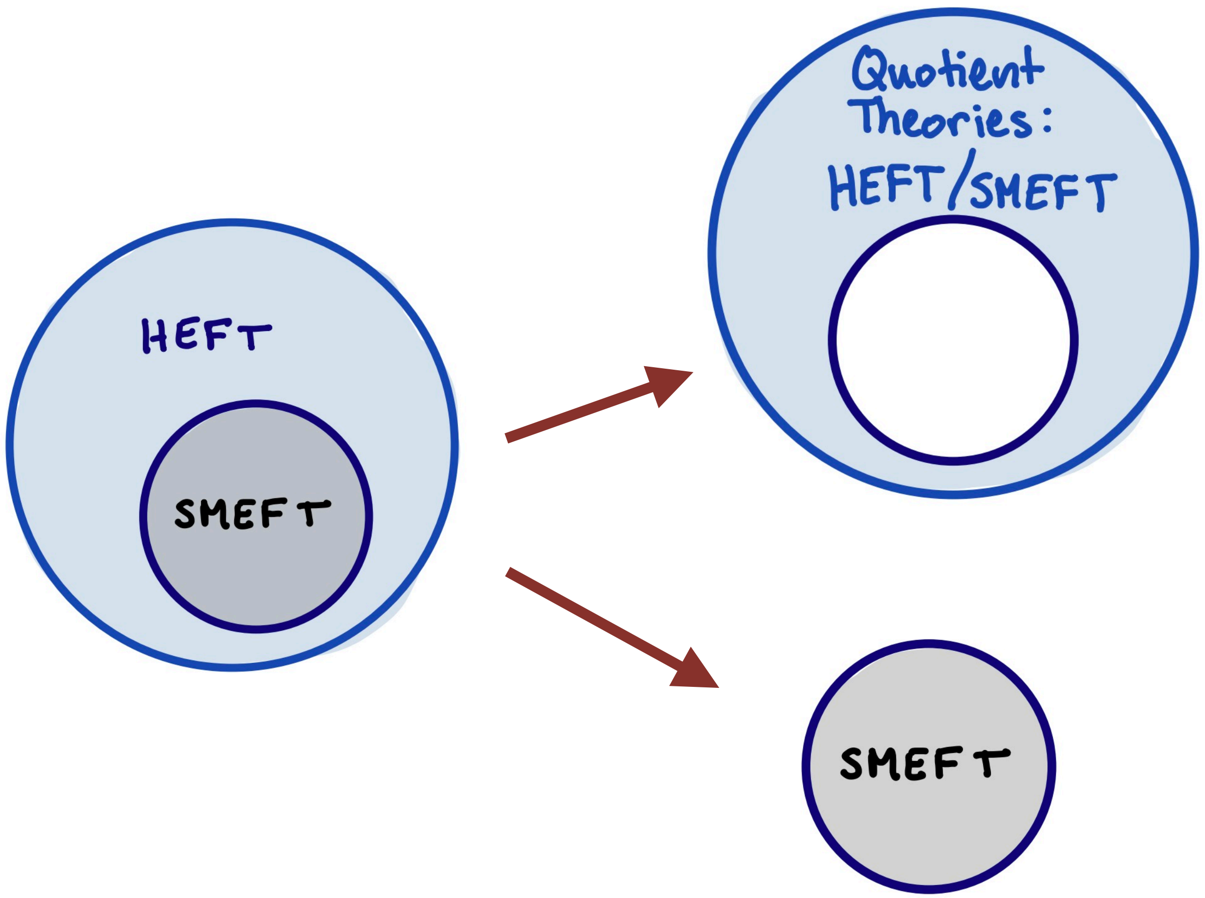
$$\phi = (v+h) \begin{pmatrix} u_1(\varphi) \\ u_2(\varphi) \\ u_3(\varphi) \\ u_4(\varphi) \end{pmatrix} = \left(1 + \frac{h}{v}\right) \begin{pmatrix} \varphi_1 \\ \varphi_1 \\ \varphi_1 \\ \sqrt{v^2 - \vec{\varphi} \cdot \vec{\varphi}} \end{pmatrix}$$

$$\mathcal{L}_{\text{HEFT}} = \frac{1}{2}(\partial h)^2 + \frac{1}{2}\left[vF(h)\right]^2 (\partial\vec{\varphi})^2 - V(h)$$

- $V(h)$ contains higher dimensional operators

HEFT vs. SMEFT

- The HEFT is the more general EFT:



- This talk focuses on the signals of quotient theories: HEFT/SMEFT
- Quotient theory examples
  - Integrate out a state that gets all its mass from EWSB
  - Integrate out BSM sources of EWSB

Cohen, Craig, Lu, Sutherland (2020)

Banta, Cohen, Craig, Lu, Sutherland (2021)

Cohen, Craig, Lu, Sutherland (2021)

Quotient Theories

- In the HEFT, h and φ_i span a 4-dimensional manifold **Alonso, Jenkins, Manohar (2015)**

SMEFT: $O(4)$

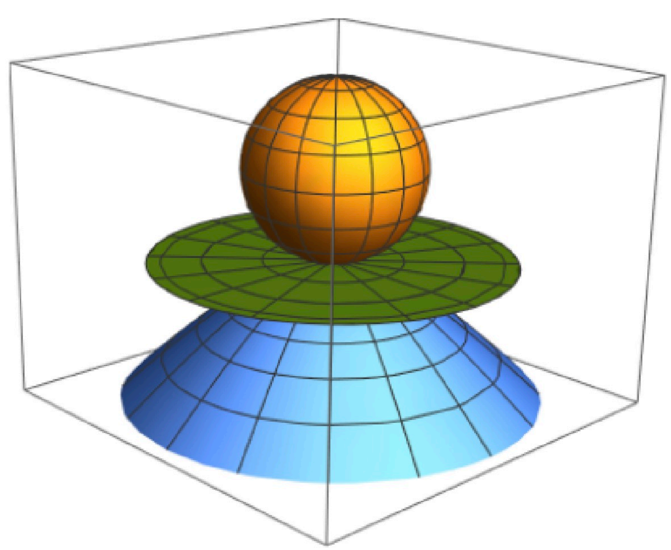
$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix} \qquad H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_4 + i\phi_3 \end{pmatrix}$$

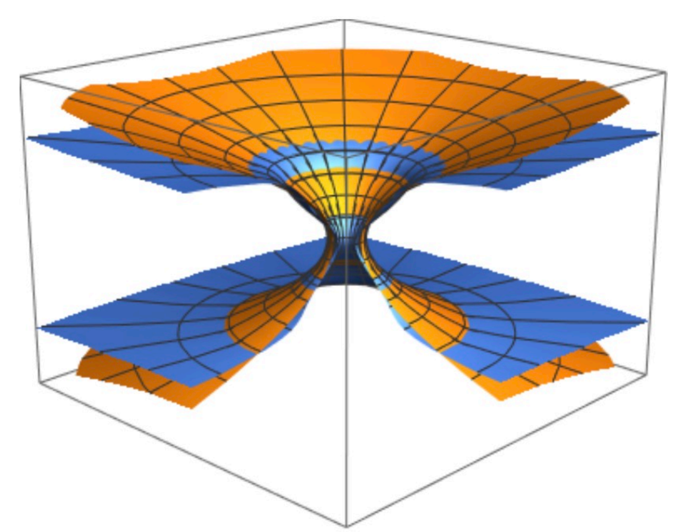
HEFT: $O(4) \to O(3)$

$$\phi = \left(1 + \frac{h}{v}\right) \begin{pmatrix} \varphi_1 \\ \varphi_1 \\ \varphi_1 \\ \sqrt{v^2 - \vec{\varphi} \cdot \vec{\varphi}} \end{pmatrix}$$

- If the $O(4)$ invariant point is present in the manifold, the theory can be parameterized in the SMEFT

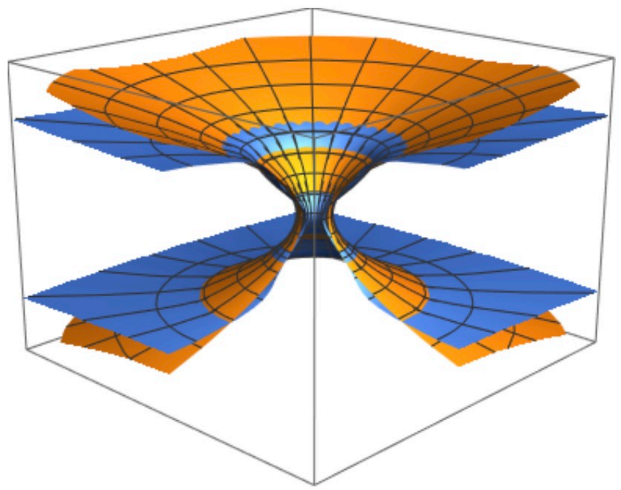
Cohen, Craig, Lu, Sutherland (2020)



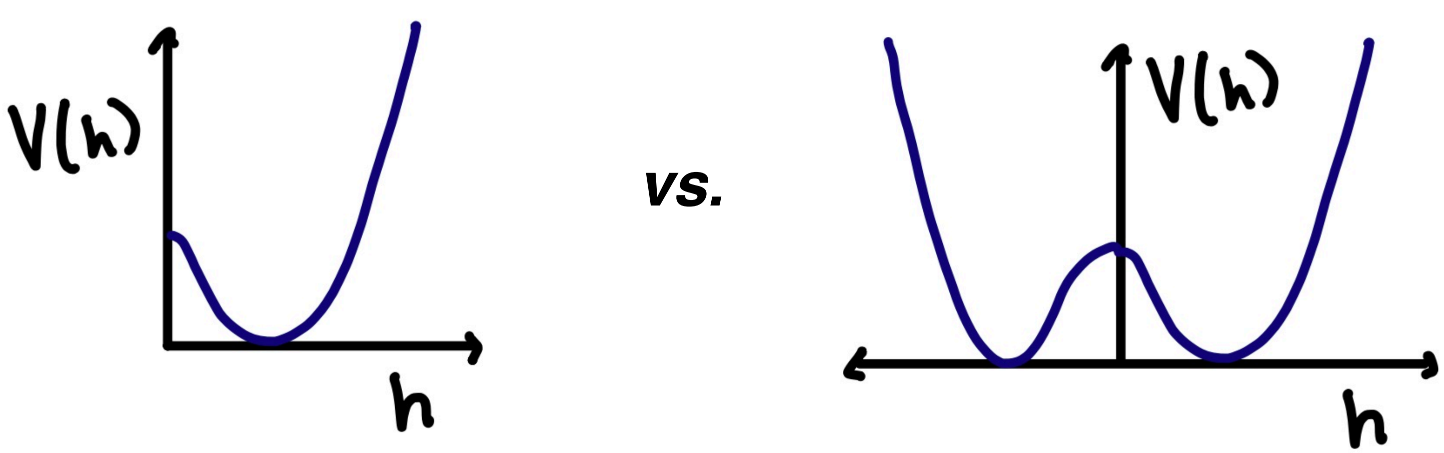


Alonso, West (2021)

Quotient Theories

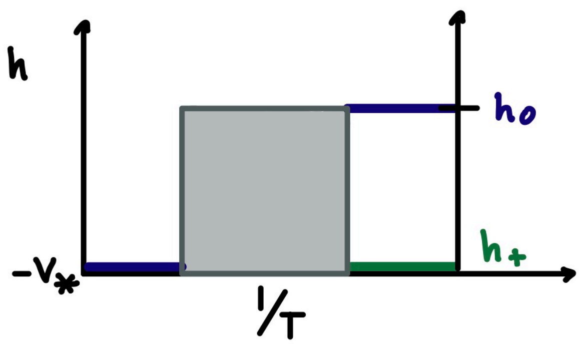


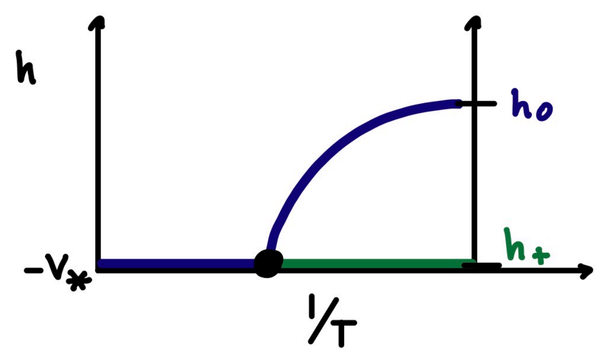
- Scattering experiments can only probe to higher terms in the Taylor expansion around the vacuum, inherently local
- If the manifold gets very close the $O(4)$ point, quotient theories become difficult to identify at colliders
- Cosmology offers a global point of view
- The HEFT manifold can allow h in $(-\infty, \infty)$, doubling the range & revealing new minima

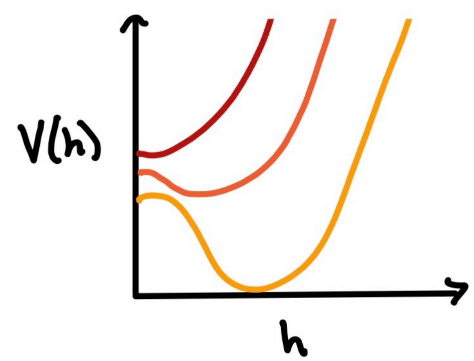


History of Extrema

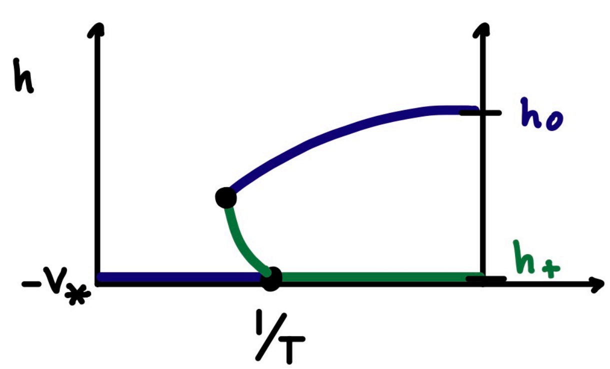
- The evolution of minima in the SMEFT

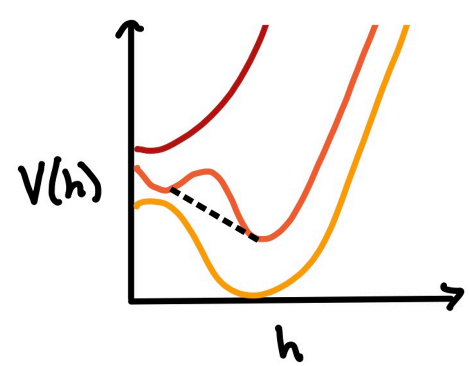






- SM-like, crossover transition

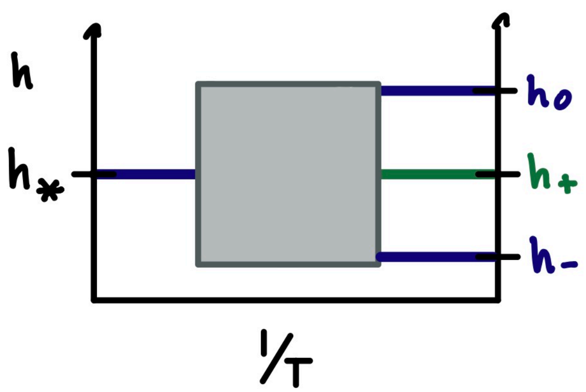


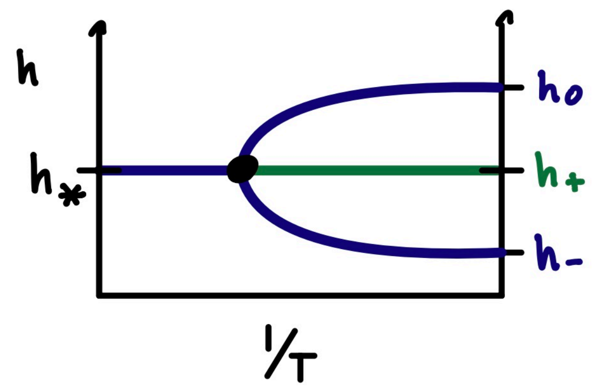


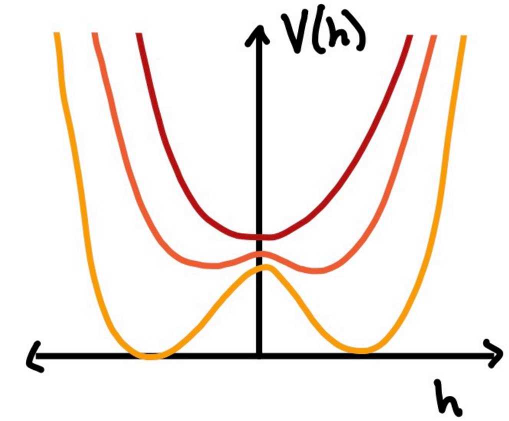
- First order phase transition, bubble nucleation

History of Extrema

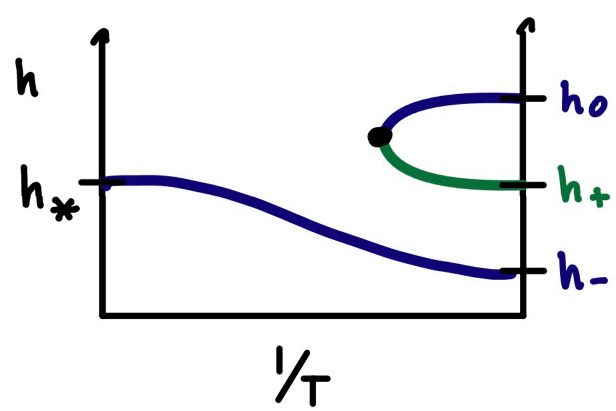
- The evolution of minima in the HEFT

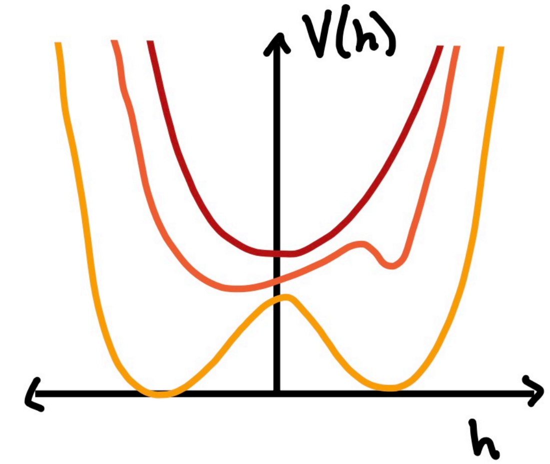






- Domain walls





- Possible crossover phase transition, possible bubble nucleation

HEFT at Tree Level

- The tree level Lagrangian for this quotient theory

$$\mathcal{L} = \frac{1}{2}(\partial h)^2 + \frac{F^2(h)}{2}\frac{v^2}{2}\mathrm{Tr}\left[D_\mu U D^\mu U^\dagger\right] - V(h) - \left(\frac{F(h)v}{\sqrt{2}}\bar{\psi}_L Y U \psi_R + h.c.\right)$$

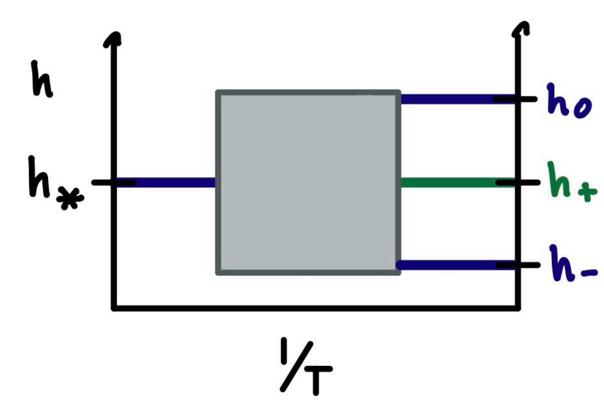
where $$F(h) = \sqrt{\sin^2\beta + \cos^2\beta\left(1 + \frac{h}{v_*}\right)^2}$$

- Around the $h = 0$ minimum, matter interactions reproduce the SM

$$m_W(h) = \frac{gv}{2}F(h) \qquad m_Z(h) = \frac{v}{2}F(h)\sqrt{g^2 + g_Y^2}$$

- There is an approximate mirror symmetry, more obvious using

$$\phi = h + v_* = h + \frac{v_h}{\gamma_a} \qquad \phi \to -\phi$$

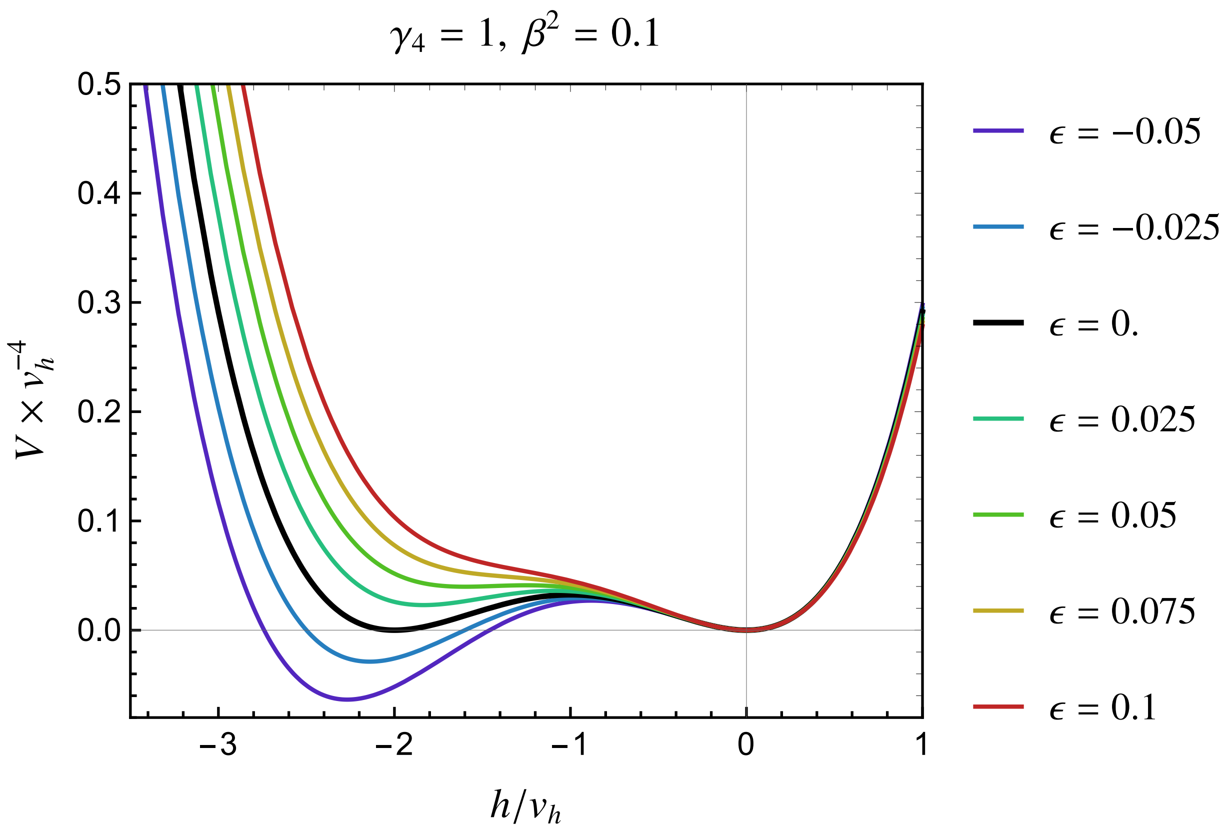


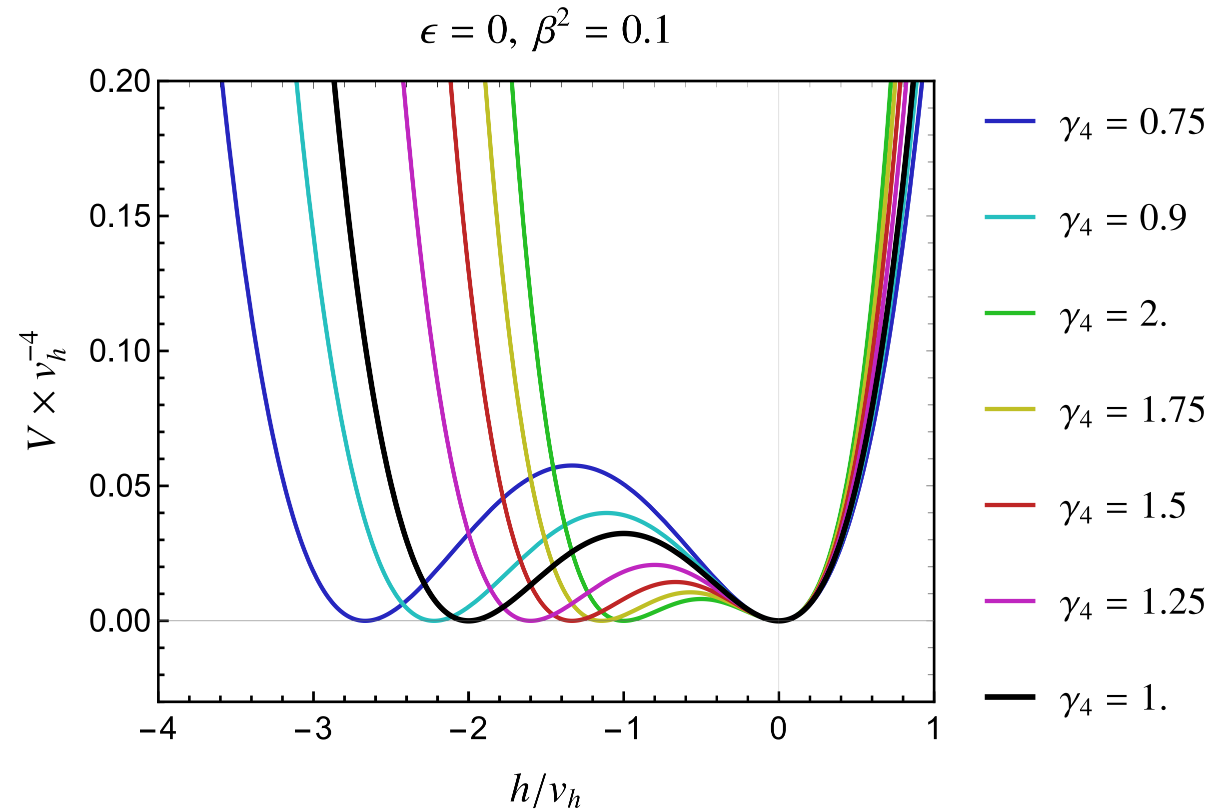
HEFT at Tree Level

- The tree level potential: $$V(h) = \frac{m_h^2}{2}h^2 + \frac{m_h\sqrt{\lambda}}{2}\gamma_4(1-\epsilon)h^3 + \frac{\lambda}{8}\gamma_4^2 h^4$$

➡ ϵ sets the tilt of the minima

➡ γ_4 sets the distance between minima





Useful to classify cosmological history

The Finite T Effective Potential of the HEFT

Quiros (1999)

- The 1-loop corrections to the potential are given by:

$$\Delta V(h)_{\rm CW} = \frac{1}{64\pi^2}\sum_i \left\{ m_i^4(h)\left(\log\frac{m_i^2(h)}{m_i^2(0)} - \frac{3}{2}\right) + 2m_i^2(h)m_i^2(0)\right\}$$

where field-dependent masses are:

Alonso, Jenkins, Manohar (2015)

Alonso, Kanshin, Saa (2017)

$$m_t^2(h) = m_t^2(0)F(h)^2 \qquad m_h^2(h) = V''(h)$$

$$m_{\{W,Z\}}^2(h) = m_{\{W,Z\}}^2(0)F(h)^2 \qquad m_{\{W,Z\}_L}^2(h) = (\log F)'V' + m_{\{W,Z\}}^2(h)$$

- In the early universe, the thermal bath alters the Higgs potential

$$\Delta V_{\rm th}(h,T) = \frac{T^4}{2\pi^2}\sum n_i J_{B/F}\left(\frac{m_i^2(h)}{T^2}\right) \qquad J_{B/F}\left(\frac{m_i^2}{T^2}\right) = \int_0^\infty y^2 dy \log\left(1 \mp e^{-\sqrt{m_i^2/T^2+y^2}}\right)$$

Finite T Potential

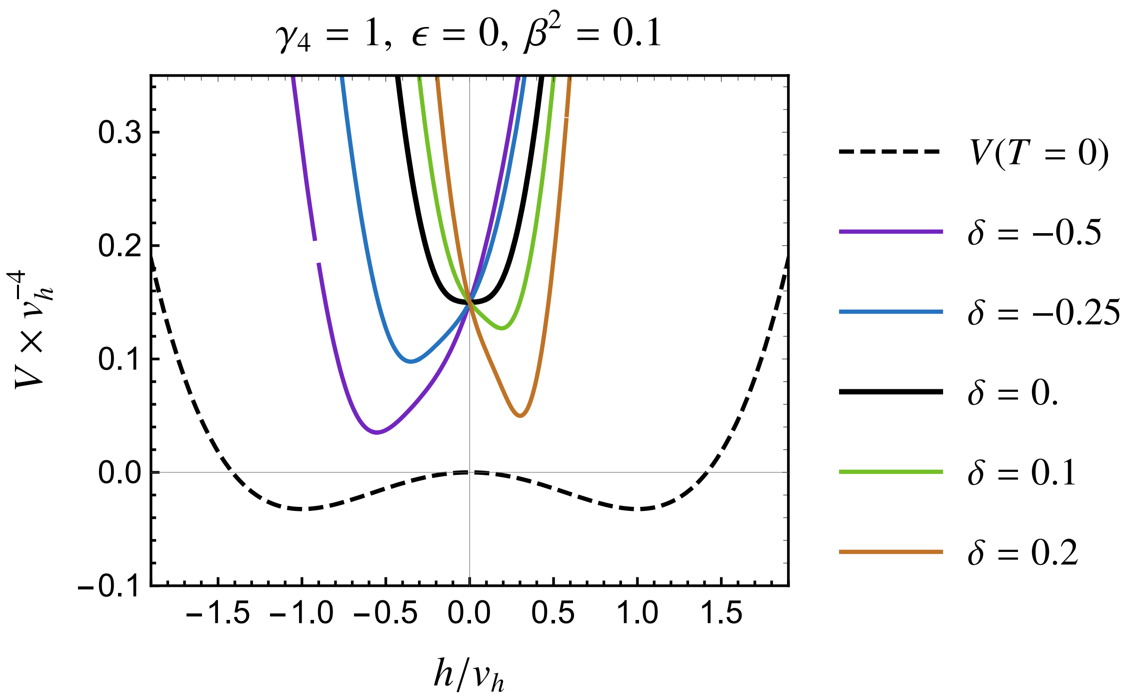
- Parameters that affect the finite T potential

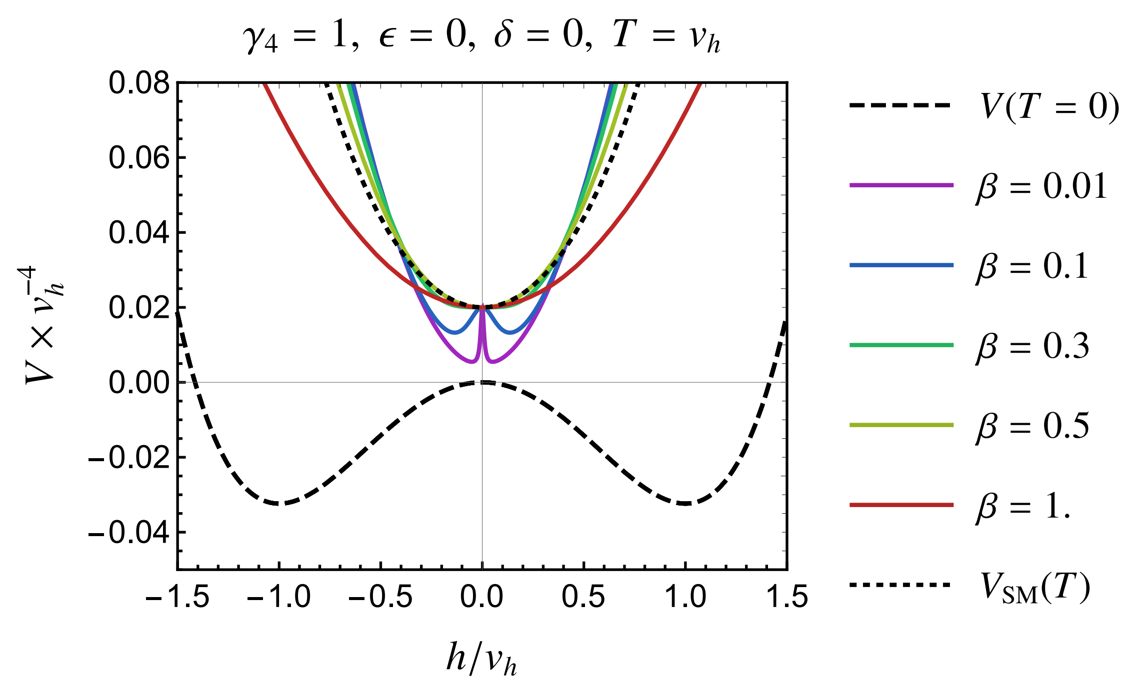
$$\delta = \frac{h_* - h_+}{v_h} = \frac{1}{\gamma_4}\frac{3(1-\epsilon) - \sqrt{1+9(\epsilon^2-2\epsilon)}}{2} + \frac{1}{\gamma_a}$$

$$F(h) = \sqrt{\sin^2\beta + \cos^2\beta\left(1+\frac{h}{v_*}\right)^2}$$

➡ δ sets the tilt of high-T potential

➡ β affects Higgs-matter interactions





Useful to classify cosmological history

Regime of Validity

- Finite T field theory suffers from an IR problem due to high bosonic mode occupation at high temperatures

Linde (1980)

$$g^2 \to g^2 n_B(E,T) = \frac{g^2}{e^{E/T}-1}$$

➡ Grows with T

Croon, Gould, Schicho, Tenkanen, White (2020)

- Lose perturbativity in the effective loop expansion parameter

Arnold, Espinosa (1992)

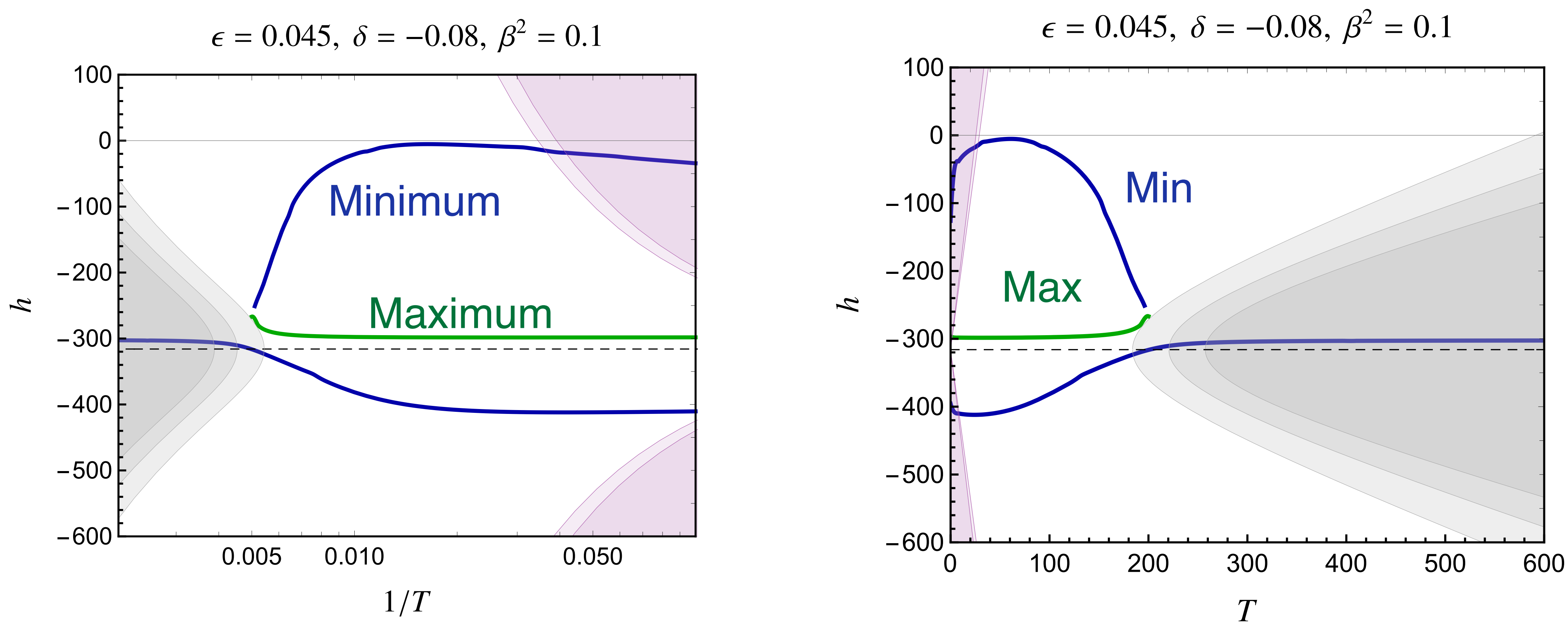
$$\epsilon_{IR} = \frac{g^2 T}{\pi m_{ew}(\phi)}$$

➡ One can employ resummation, etc, to ameliorate but not fully solve this issue

- We define an IR band, within which we do not claim to track the critical point evolution

$$\left(\frac{\phi}{T}\right)^2 > \frac{1}{\gamma_a^2}\left[\left(\frac{2g}{C\pi\cos\beta}\right)^2 - \tan^2\beta\frac{v_h^2}{T^2}\right]$$

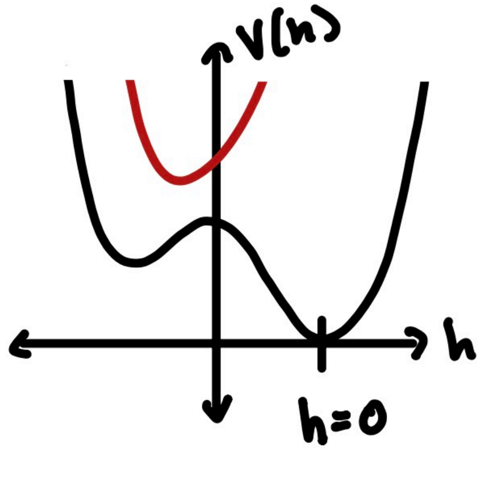
Critical Point evolution

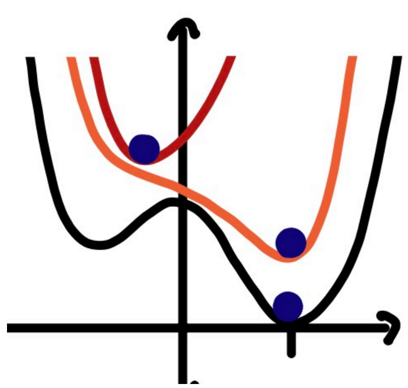


- The gray region is the IR band. If the critical points emerge in that region, we cannot say whether there was a FOPT or a crossover
- The pink region is where the high-T expansion for the J functions is no longer valid

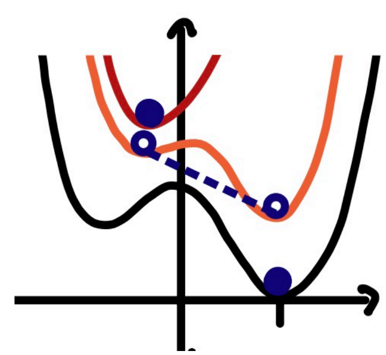
Cosmological Histories, $\epsilon > 0$

$\underline{\delta < 0}$:





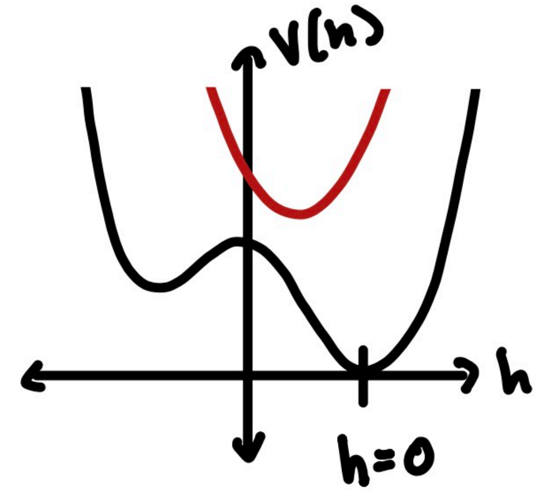
Crossover PT

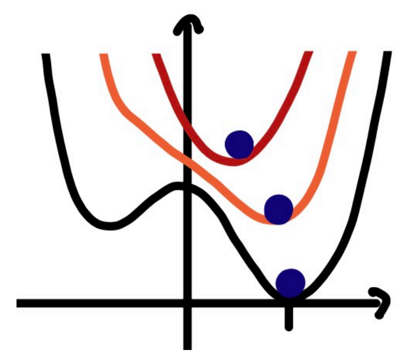


HEFT first order PT

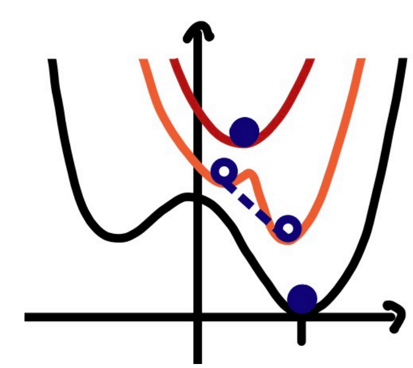
Bubble Nucleation possible

$\underline{\delta > 0}$:





Crossover PT

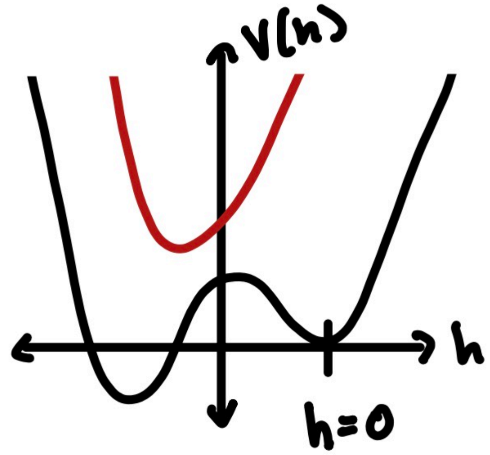


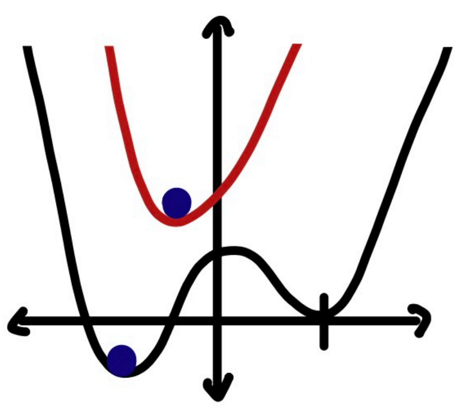
SMEFT-like FOPT

Bubble Nucleation possible

Cosmological Histories, $\epsilon < 0$

$\delta < 0$:

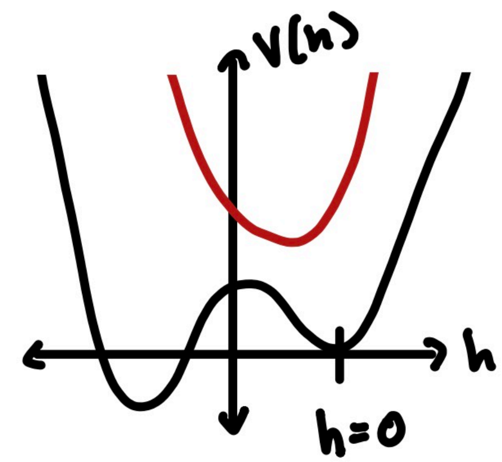


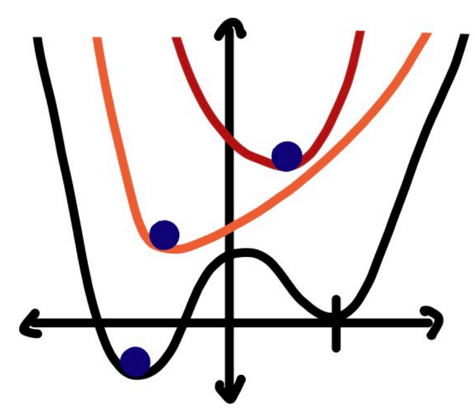


Never biased towards h=0 minima

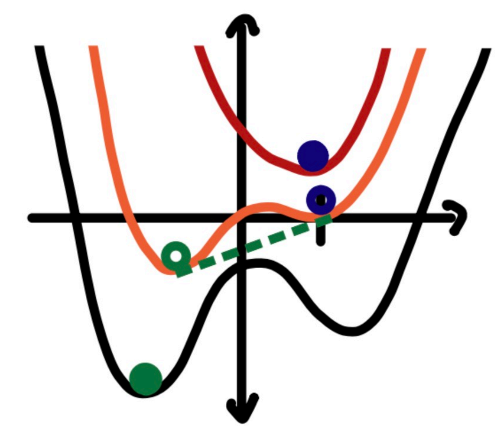
Unphysical

$\delta > 0$:





Unphysical



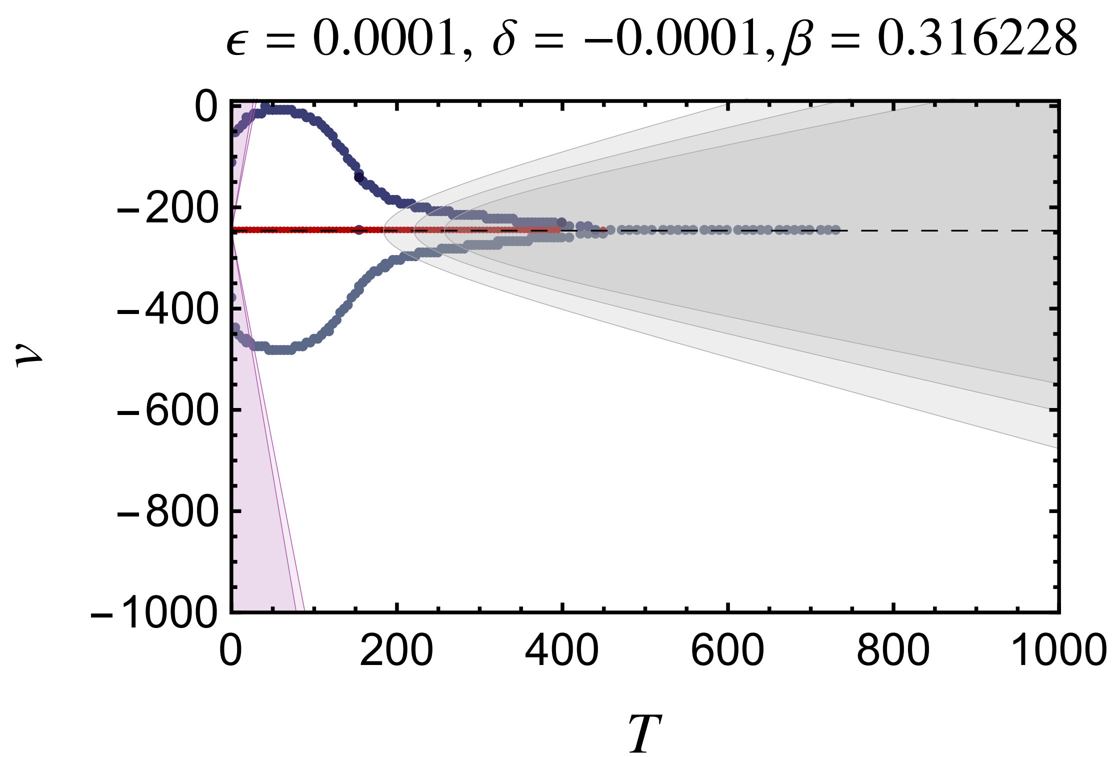
Bubble nucleation

Doomsday Scenario?

Domain Walls

- If $V(h)$ is nearly symmetric under $\phi \to -\phi$, domain walls form

Gelmini, Glesier, Kolb (1988)



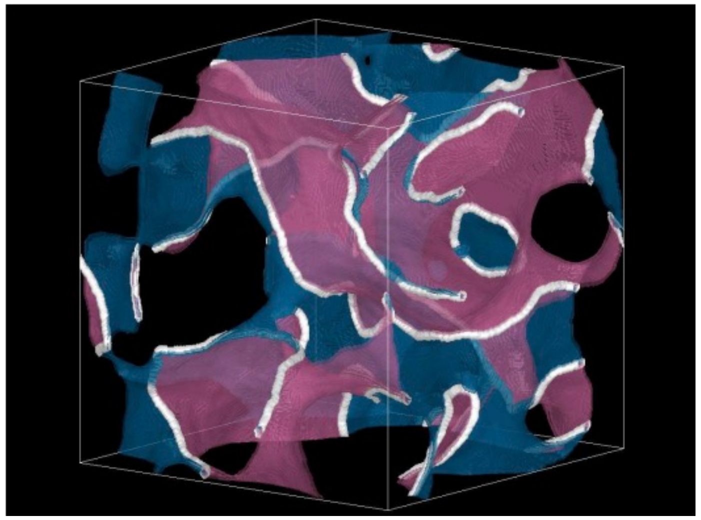
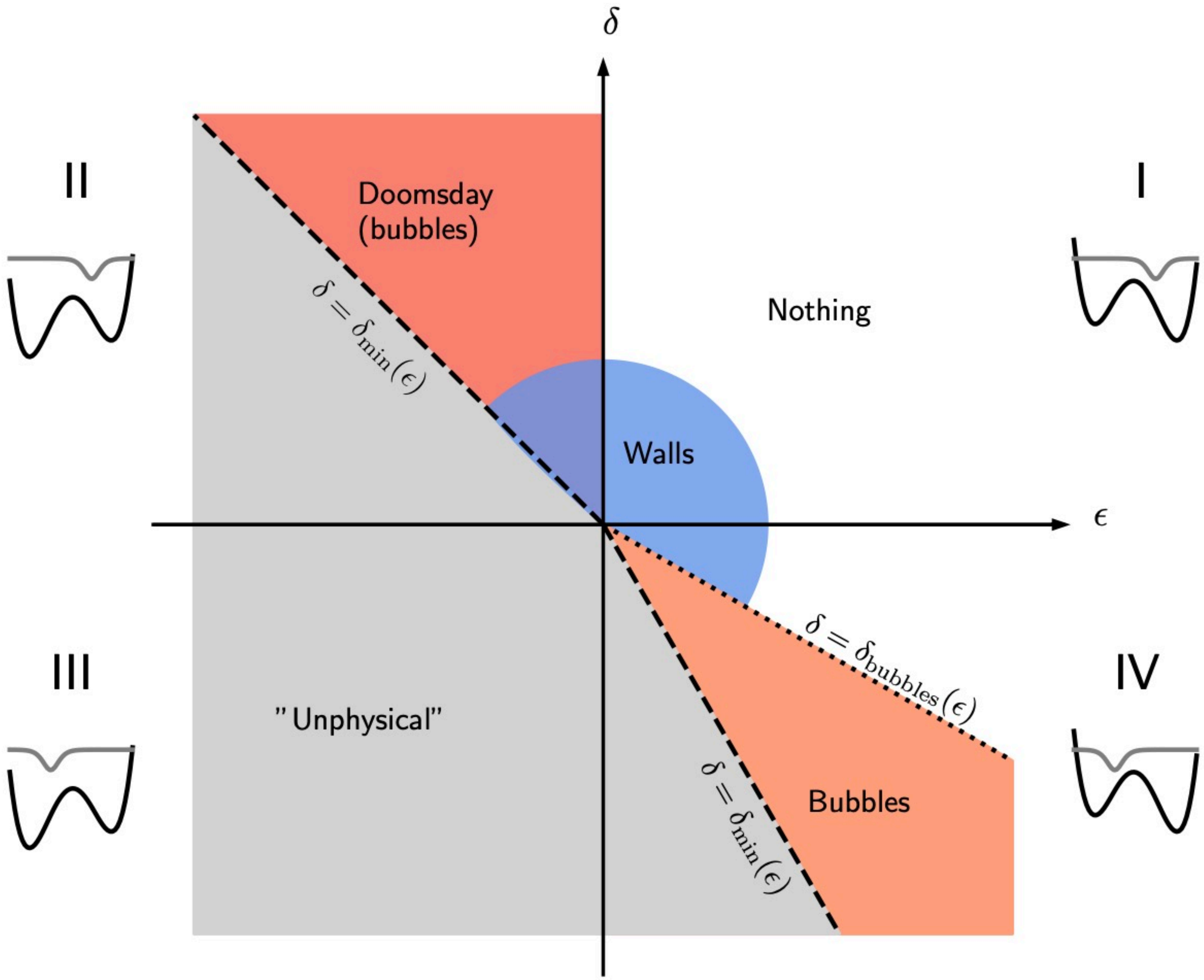


Image lifted from Hiramatsu, Kawasaki, Saikawa, Sekiguchi, arXiv:1207.3166

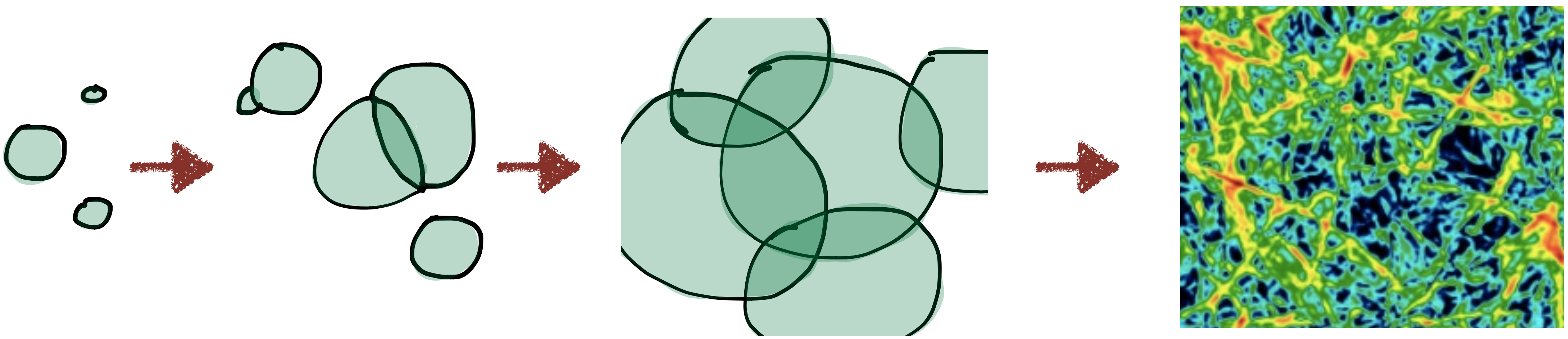
- These walls evaporate if there is a bias in the $T=0$ potential ($\epsilon \neq 0$), leaving behind GW signals

Gelmini, Pascoli, Vitagliano, Zhou (2020)

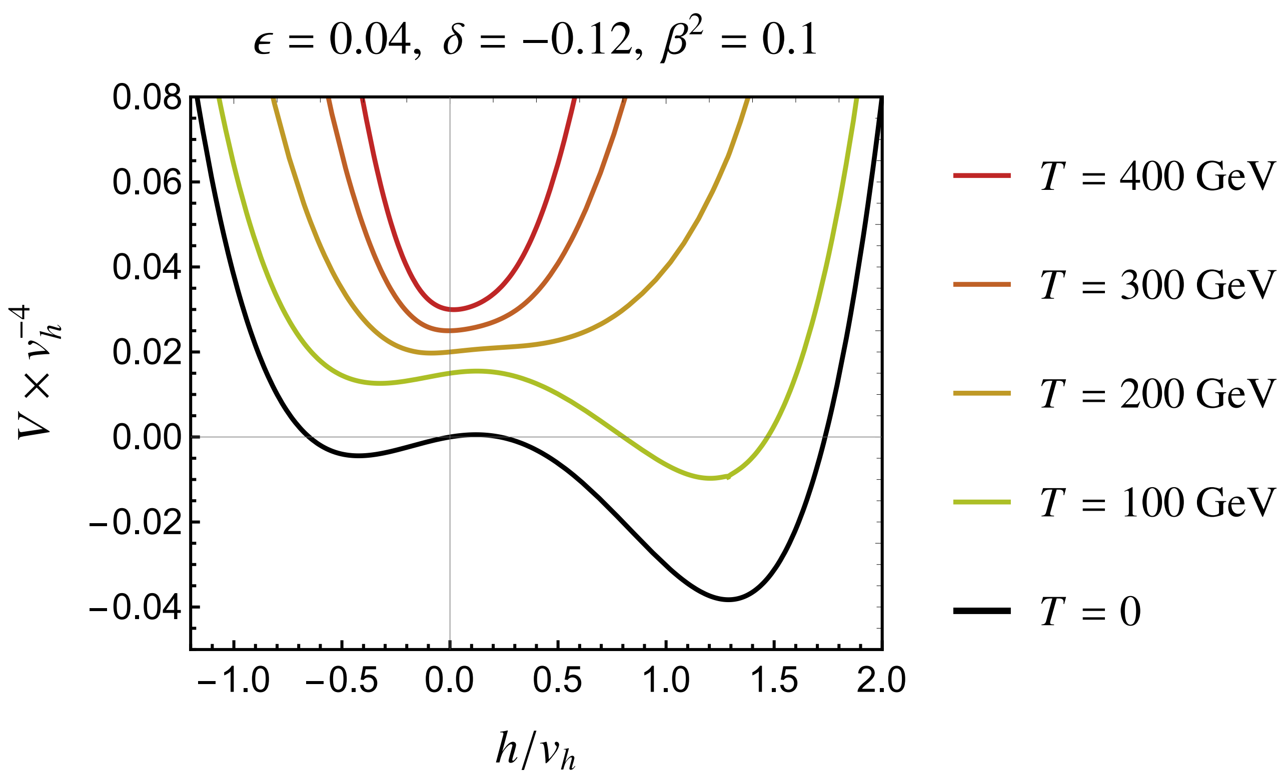
Sketch of HEFT Cosmology



Bubble Nucleation in the Early Universe

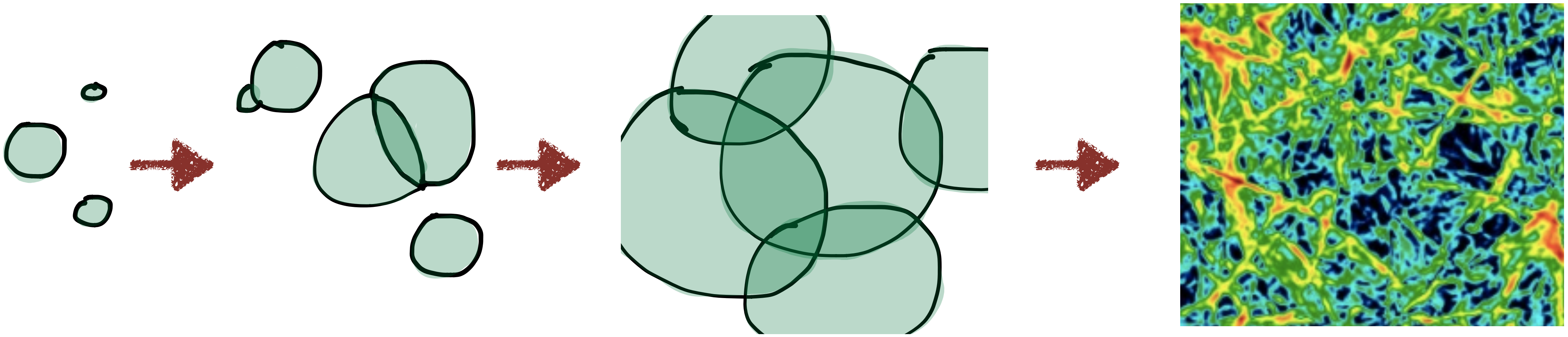


Weir, “The sound of gravitational waves from a [confinement] phase transition,” saoghal.net/slides/ectstar/



- Find the bounce solution to describe the tunneling from the false vacuum
- Calculate the frequency and power spectrum of the stochastic GW background

Phase Transition in the Early Universe



Weir, “The sound of gravitational waves from a [confinement] phase transition,” saoghal.net/slides/ectstar/

- Dynamics from tunneling to the $T = 0$ vacuum give:
- Interested in the power spectrum

$$\Omega_{GW}\left(\alpha, \frac{\beta}{H}\right), \quad f_{GW}|_{\text{peak}}\left(T_N, \frac{\beta}{H}\right)$$

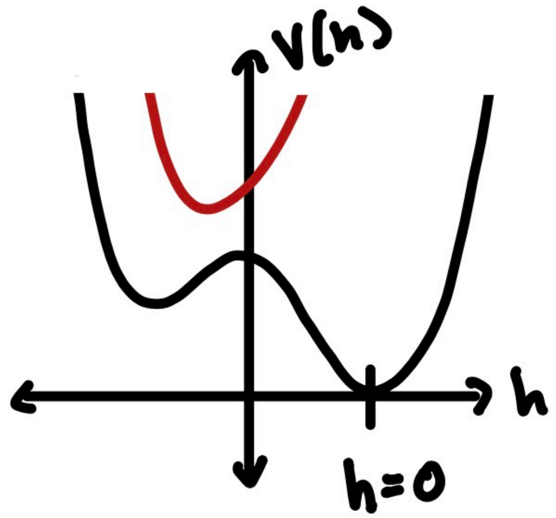
$\alpha =$ Latent heat, $\dfrac{\Delta\mathcal{L}}{\rho_{\text{rad}}}$

$\dfrac{\beta}{H} =$ Parameterizes speed of the phase transition

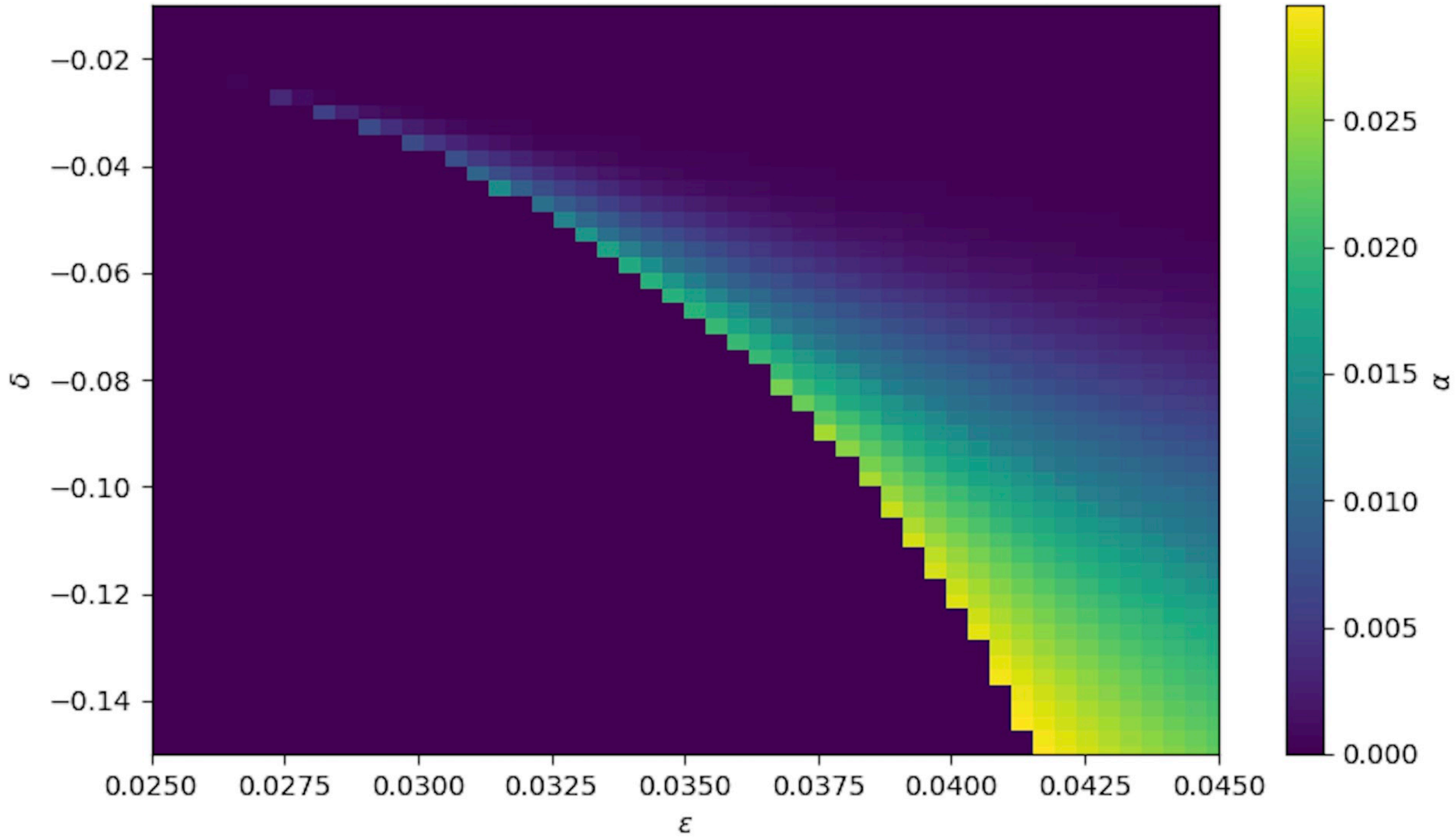
$T_N =$ Nucleation temperature

Bubble Nucleation

δ sets the tilt of high-T potential



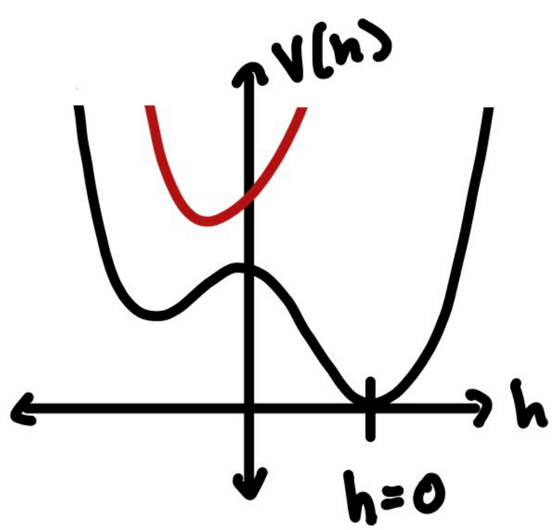
$\gamma_4 = 1.4$



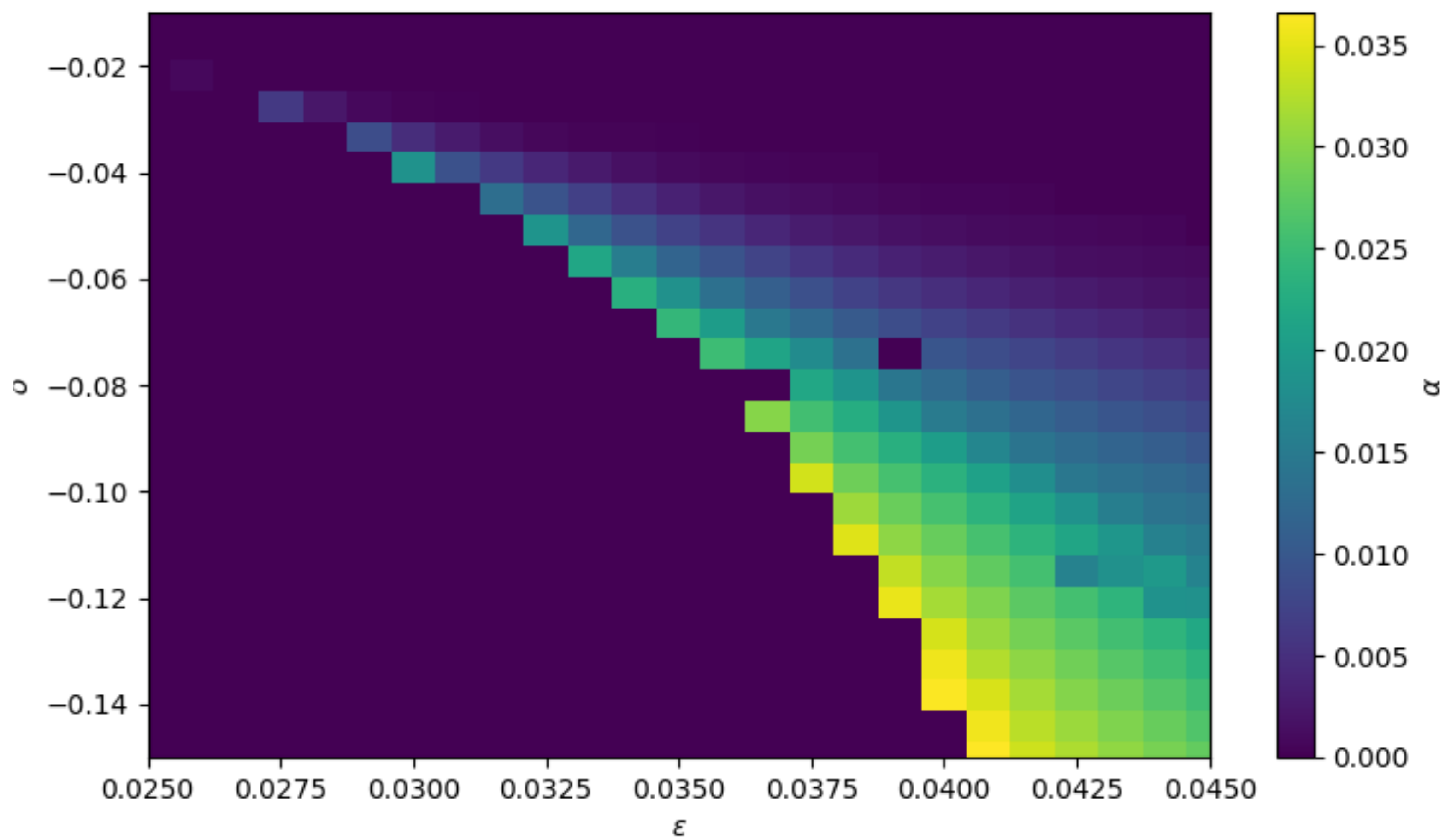
ϵ sets the tilt of the minima

Bubble Nucleation

δ sets the tilt of high-T potential



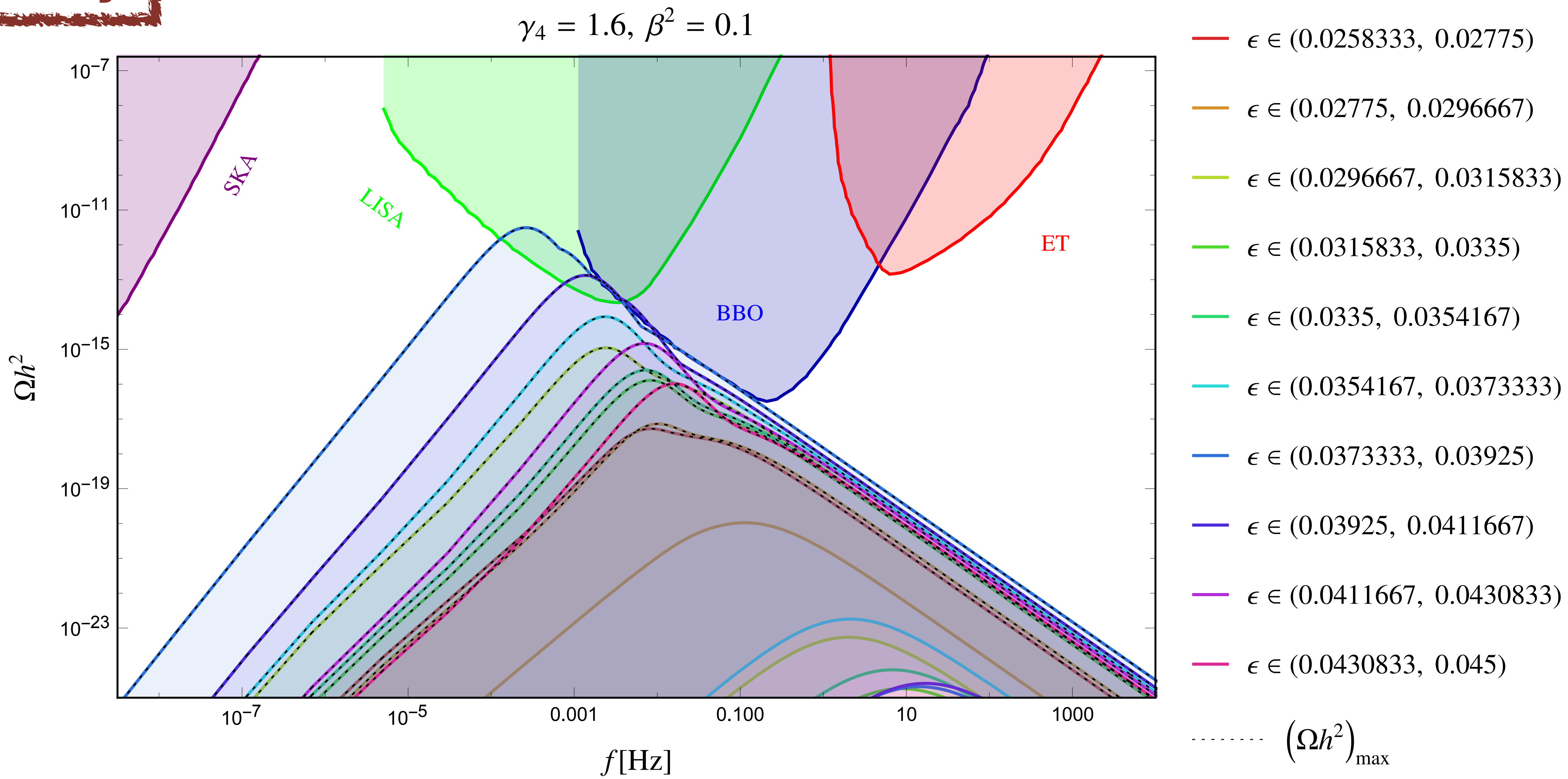
$$\gamma_4 = 1.6$$



ϵ sets the tilt of the minima

Gravitational Waves

Preliminary

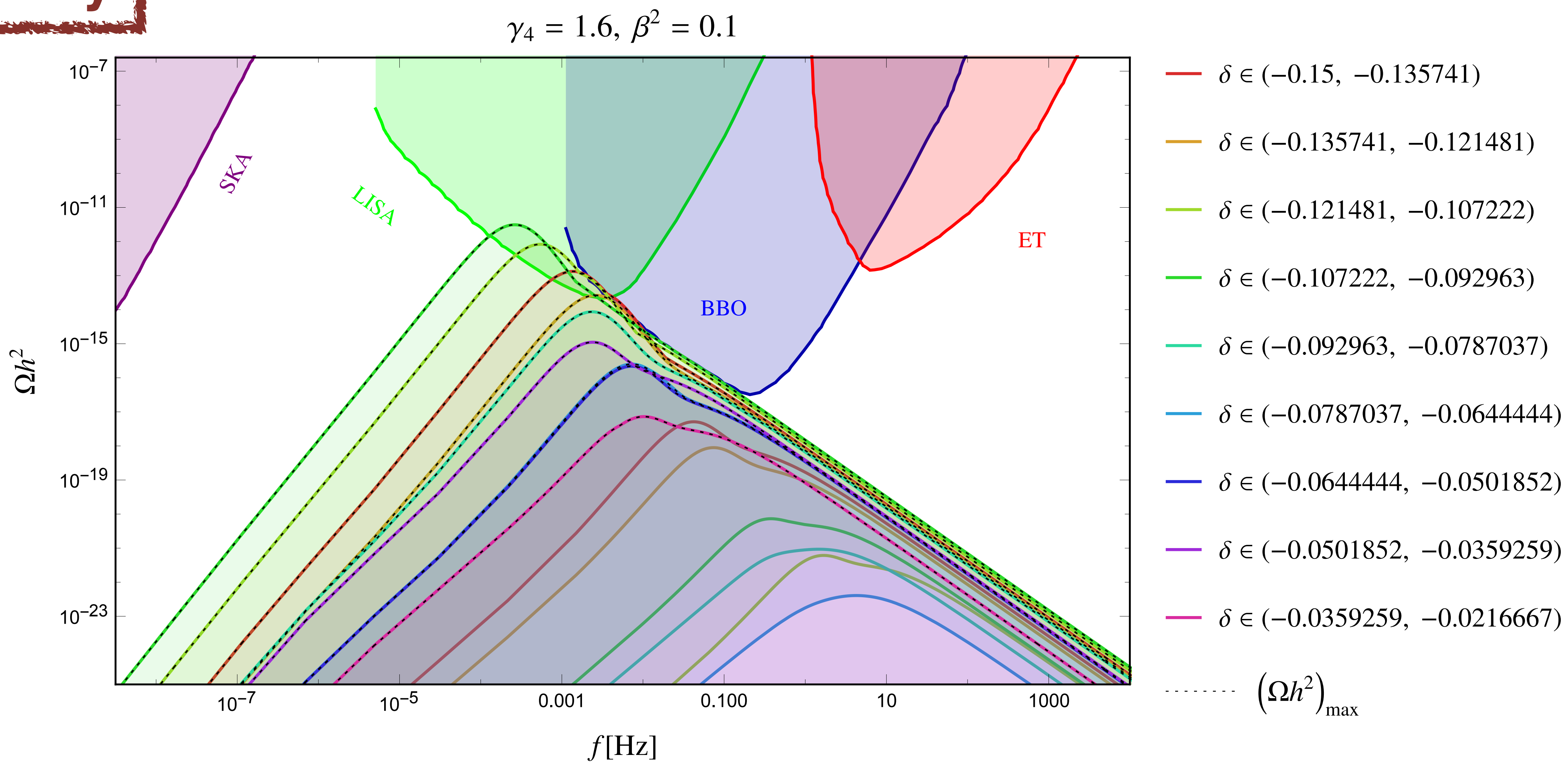


Hindmarsh, Huber, Rummukainen, Weir (2017)

Espinosa, Konstandin, No, Servant (2010)

Gravitational Waves

Preliminary

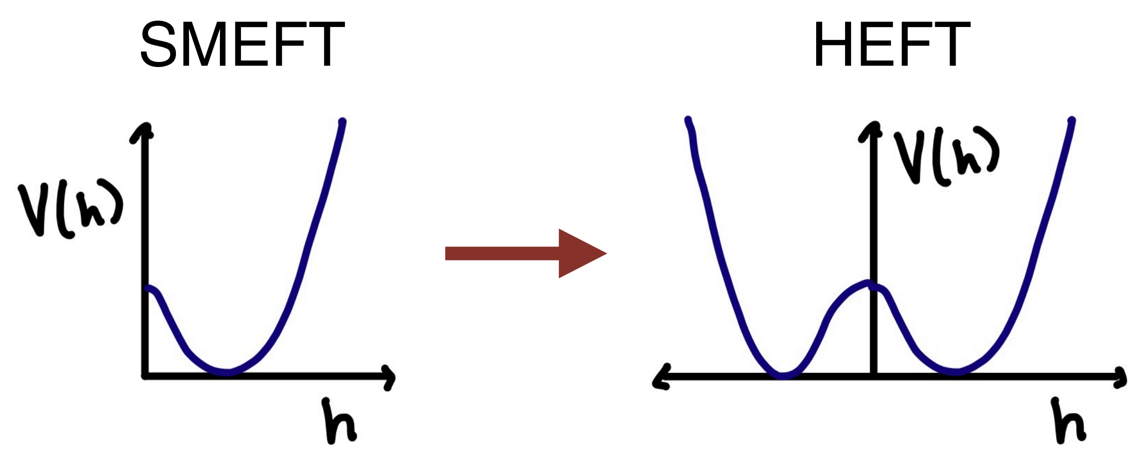


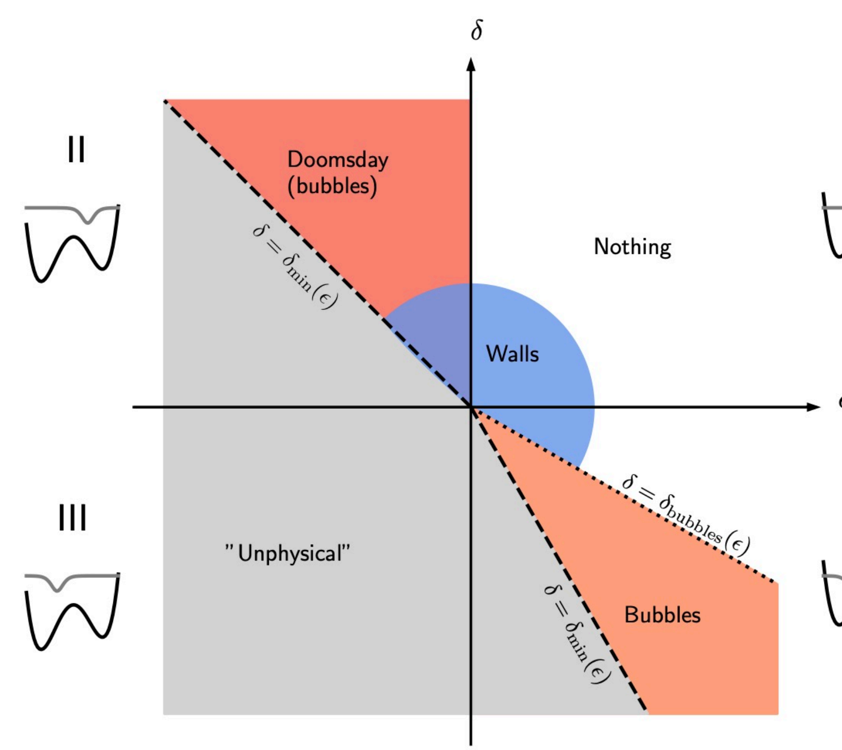
Hindmarsh, Huber, Rummukainen, Weir (2017)

Espinosa, Konstandin, No, Servant (2010)

Conclusion

- Reviewed the unique cosmology of a class of HEFT/SMEFT quotient theories
- Classified phenomenologically interesting cosmological histories
    - Domain wall network decay
    - New FOPTs and bubble nucleation
    - Doomsday scenario
- Promising prospects for GW detection
- Cosmology is a window to provide evidence for quotient theories





Thank you!