Probing EWPTs with GWs

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Higgs Potential 2024

(Higgs potential and BSM opportunities)

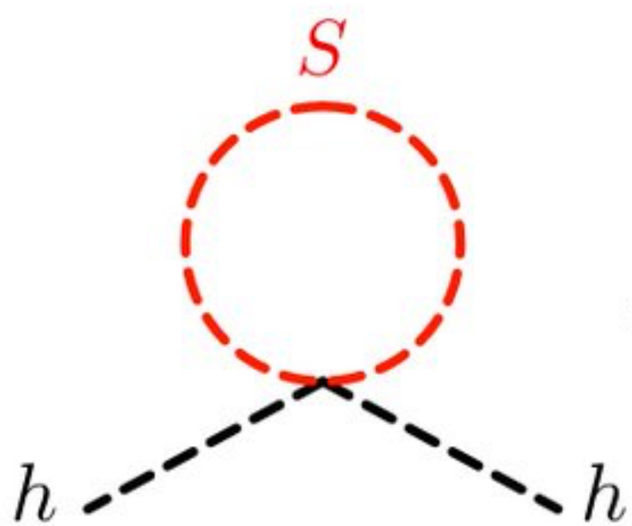
USTC @ 2024-12-21 @ 16:20-16:40

Electroweak scale

Fine-tuning problem is not a problem of SM but a potential problem for all BSM !

$$\mathcal{L} \supset \lambda_S |H|^2 S^2$$

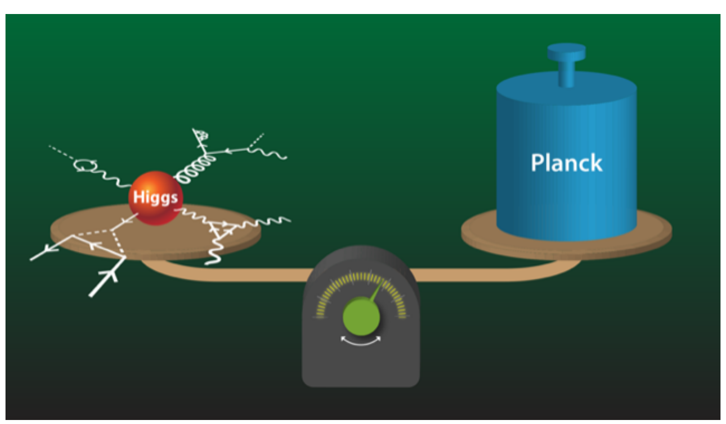
this is **not** the hierarchy problem
the regulator is not physical



$$= \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 - 2m_S^2 \ln\left(\frac{\Lambda_{\mathrm{UV}}}{m_S}\right) + \cdots\right]$$

this is the hierarchy problem

the Higgs mass is quadratically sensitive to the mass of any new particles that couple to it



Hierarchy problem?

Naturalness problem?

[Credit from Philip Tanedo]

There is no hierarchy problem in SM as there is only one energy scale $v_{\mathrm{EW}} \simeq 246$ GeV

There is no naturalness problem in SM as it only appears when compared to a NP scale

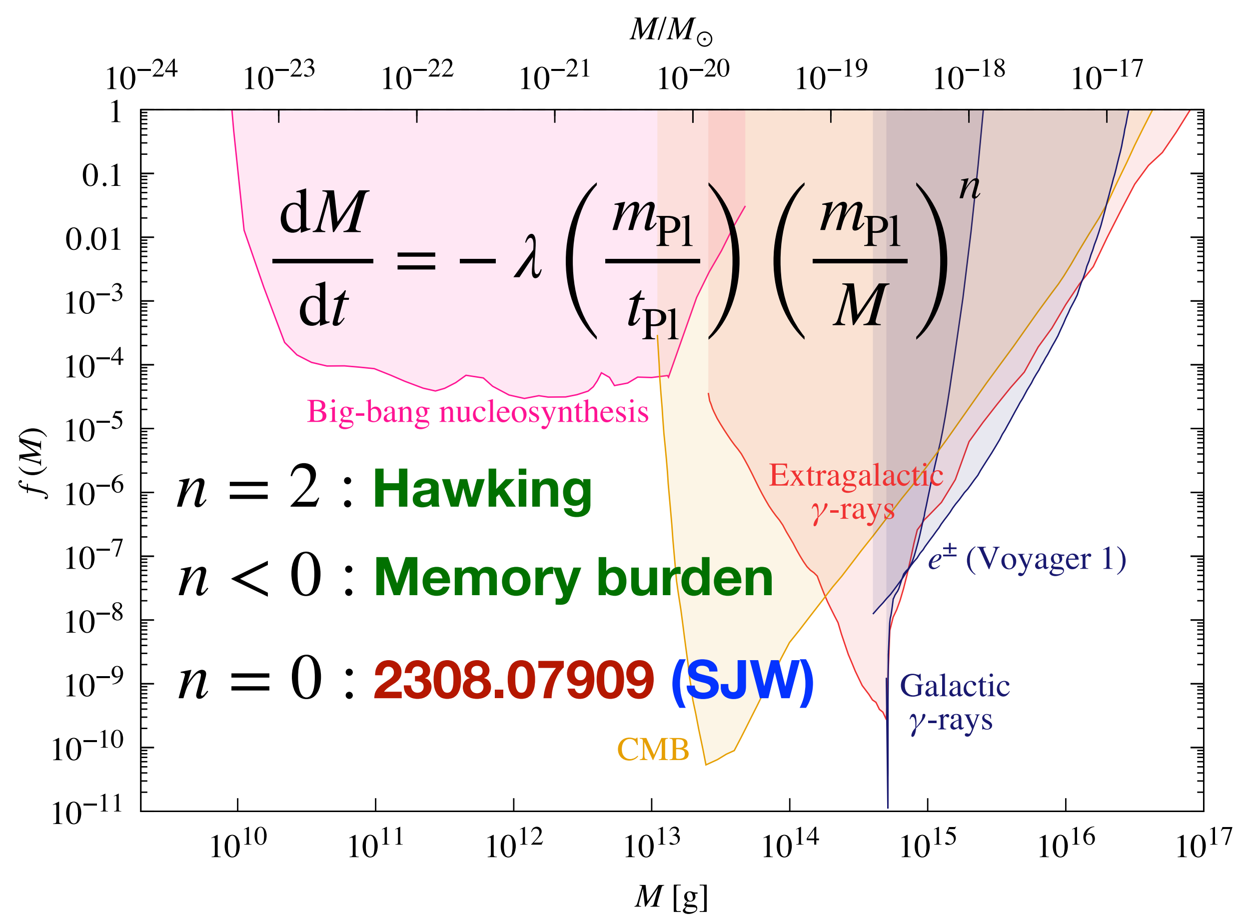
Electroweak scale

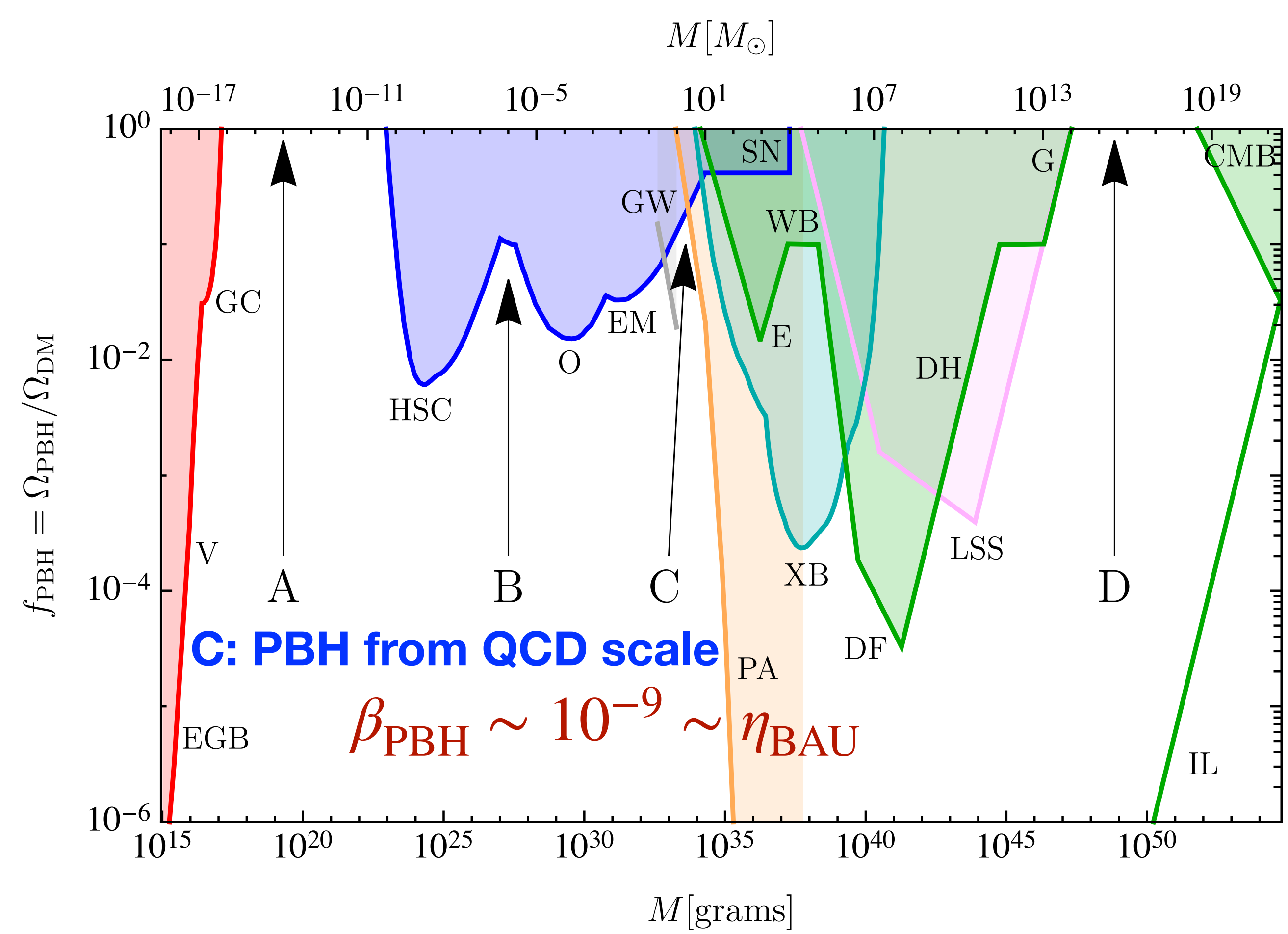
SM fails to generate more matter (than antimatter) and dark matter, is that so ?

Electroweak Baryogenesis and WIMP Miracle all seems to fail for their minimal types

1. **Leptogenesis**
2. **Electroweak baryogenesis**
3. **WIMP baryogenesis**
4. **Particle-antiparticle oscillations**
5. **Mesogenesis**
6. **Axion baryogenesis**

1. **Elementary (particle-/wave-like)**
2. **Bound state (QCD/EW-bound states)**
3. **Compact objects (Nuclear/Gravitational)**
4. **DM (un)charged under SM**
5. **DM charged under dark force/gravitation**
6. **Composite/topological/asymmetric DM**





[Credit from Carr & Kuhnel 2006.02838]

Electroweak scale

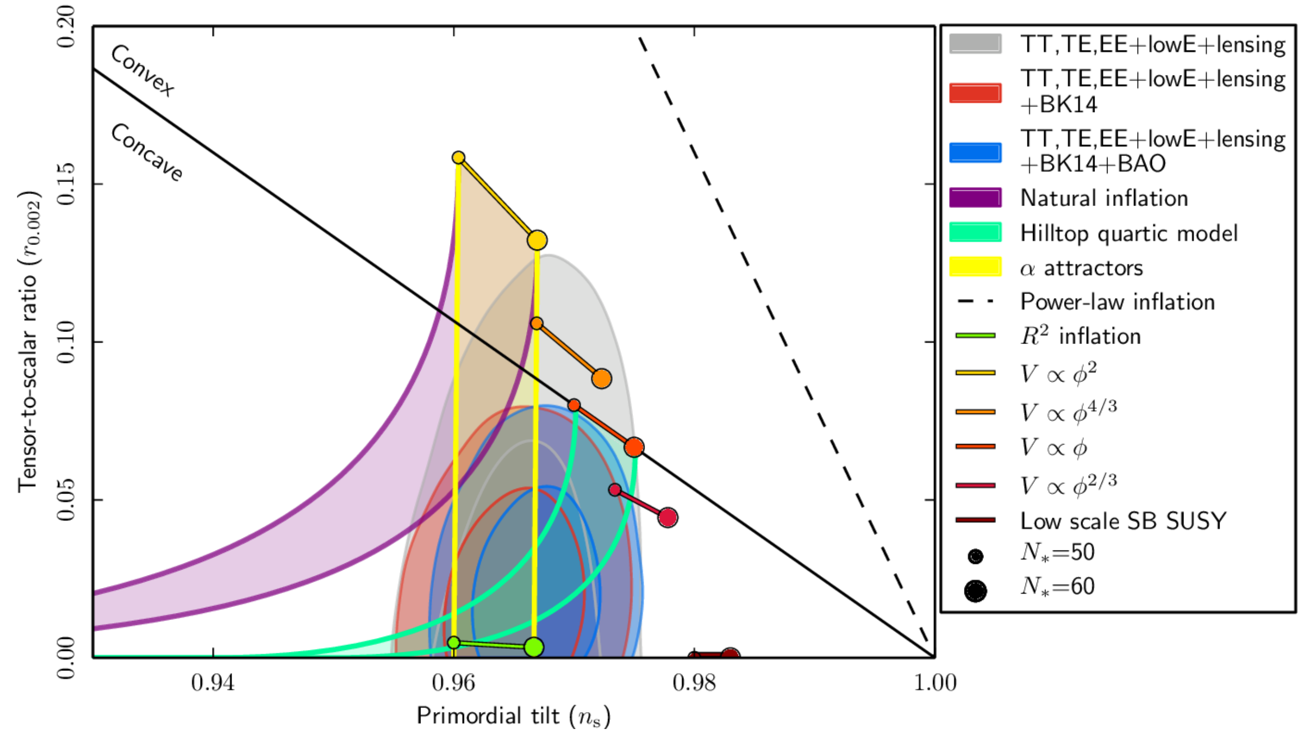
Electroweak scale is actually a very special scale that almost calls for conspiracy?

Starobinsky

$$S=\int d^4x\sqrt{-g}\left(\frac{M^2}{2}R+\frac{R^2}{16\alpha^2}\right)=\frac{M^2}{2}\int d^4x\sqrt{-g}\left(R+\frac{R^2}{\Lambda^2}\right)$$

$$\approx\int d^4\sqrt{-\tilde{g}}\left(\frac{M_{\rm Pl}^2}{2}\tilde{R}-\frac{1}{2}(\tilde{\nabla}S)^2-\alpha^2M_{\rm Pl}^4\left(1-e^{-\sqrt{\frac{2}{3}}\frac{S}{M_{\rm Pl}}}\right)^2\right)$$

$\alpha\approx10^{-5}$ $\quad\Lambda=\sqrt{8}\alpha M\sim10^{13}\mathrm{GeV}\ll M_{\rm Pl}$



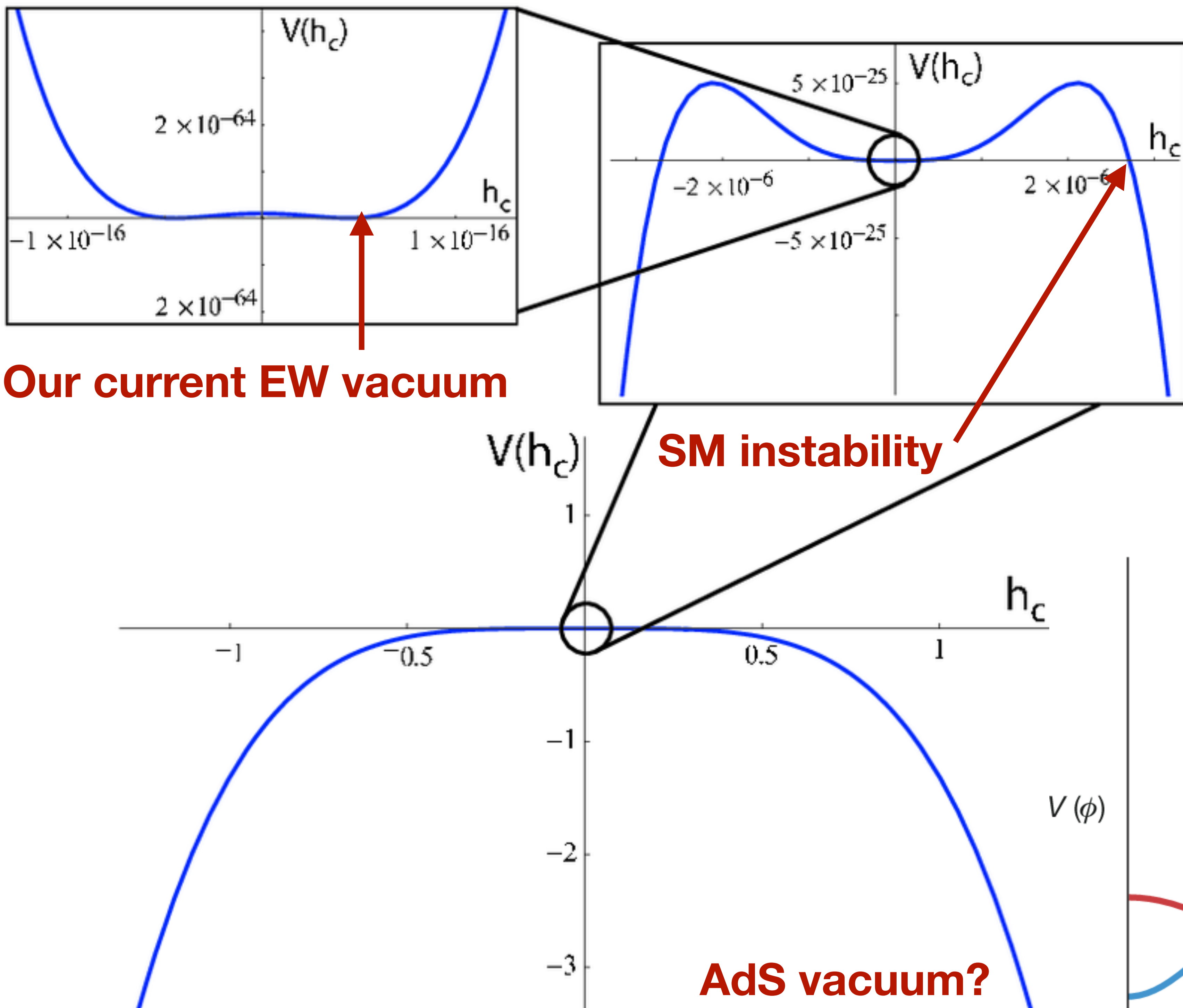
H_0	$\Lambda_{\rm DE}$	$v_{\rm EW}$	$H_{\rm inf}$	$\Lambda_{\rm inf}$	$M_{\rm Pl}$	**GeV**
10^{-42}	10^{-12}	10^{2}	10^{14}	10^{16}	10^{18}	

$\Lambda_{\rm DE}^2\sim H_0M_{\rm Pl}$ $\quad v_{\rm EW}^2\sim\Lambda_{\rm DE}\Lambda_{\rm inf}$ $\quad\Lambda_{\rm inf}^2\sim H_{\rm inf}M_{\rm Pl}$

$\rho_\Lambda\sim2.58\times10^{-47}\,\mathrm{GeV}^4$ ⟺ $\dfrac{V(h=0)^2}{\alpha^2M_{\rm Pl}^4}=\dfrac{\lambda^2v^8}{16\alpha^2M_{\rm Pl}^4}=4\times10^{-48}\,\mathrm{GeV}^4,\quad\lambda_{\rm tree}\approx0.13$

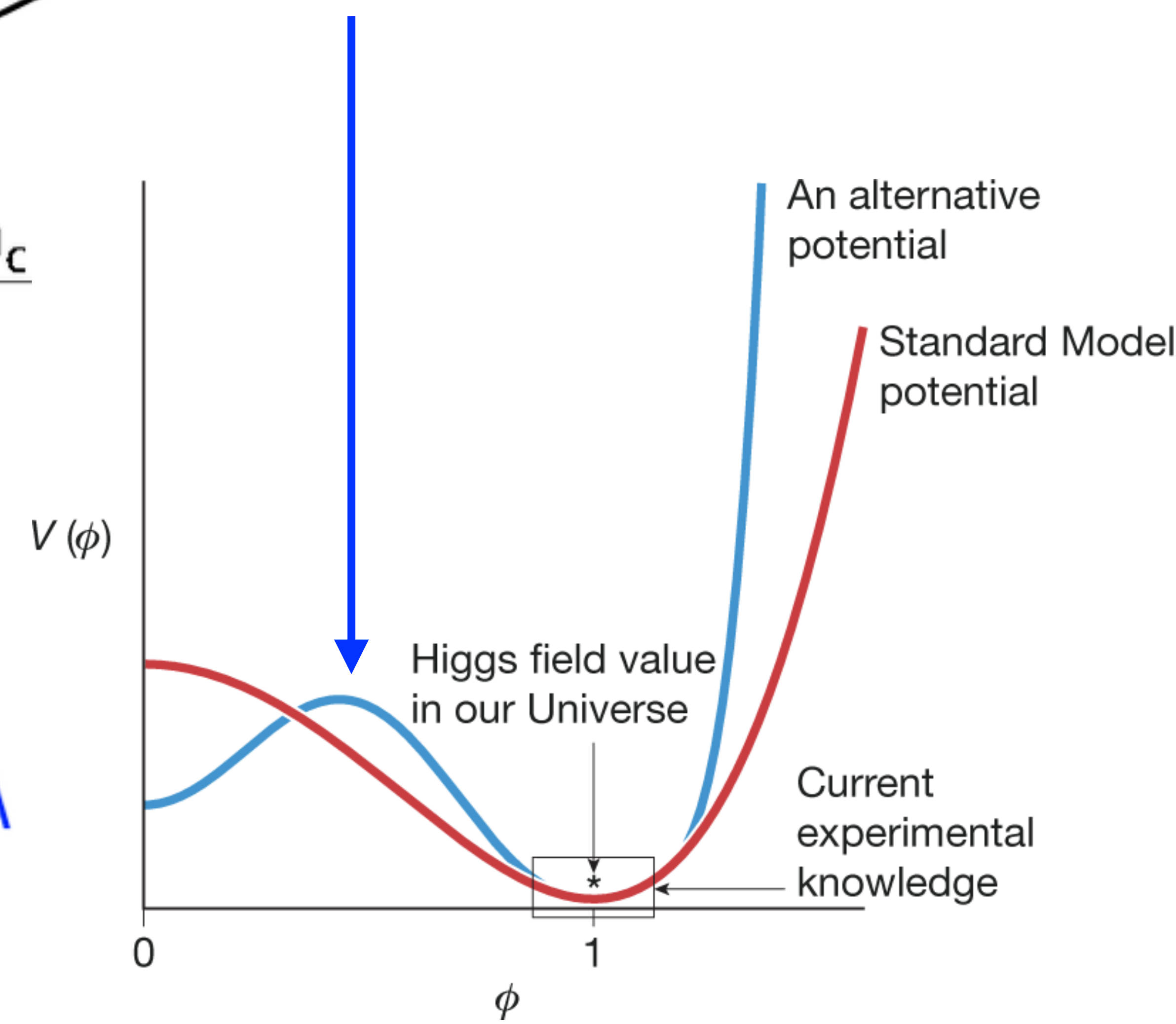
1810.06445 Shao-Jiang Wang "Electroweak relaxation of cosmological hierarchy" PRD 99 (2019) 2, 023529

Electroweak FOPT



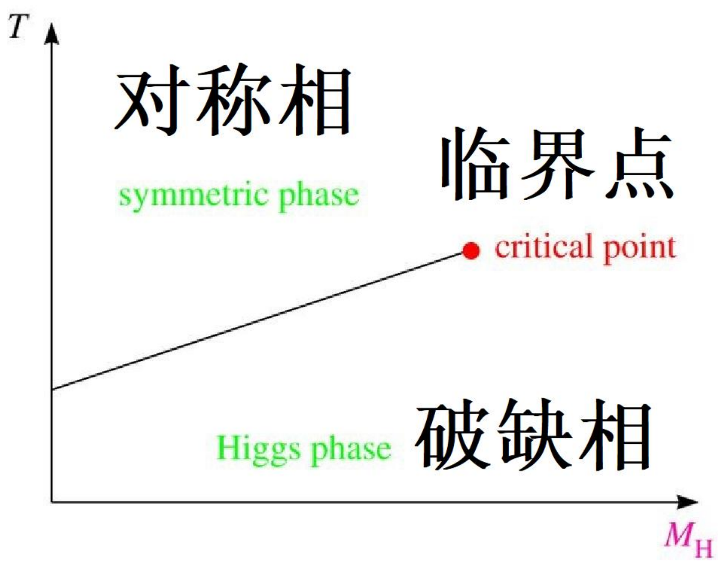
Current colliders only probe the local shape of the Higgs potential at the EW vacuum

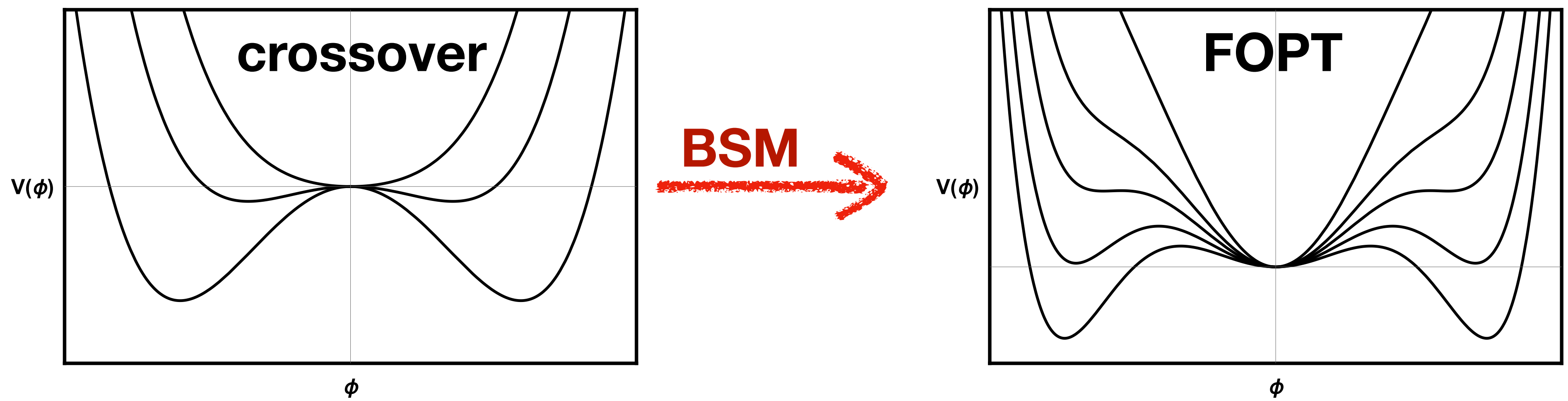
We need GWs from FOPT of BSM NP to probe whatever potential barriers around us



If we don't modify SM Higgs potential, this might be a problem during inflation

Electroweak FOPT





EFT extensions Dimension-three Dimension-six Dimension-eight

Scalar extensions Gauge singlet/non-singlet (2HDM, EW inert doublet/triplet/quadruplet)

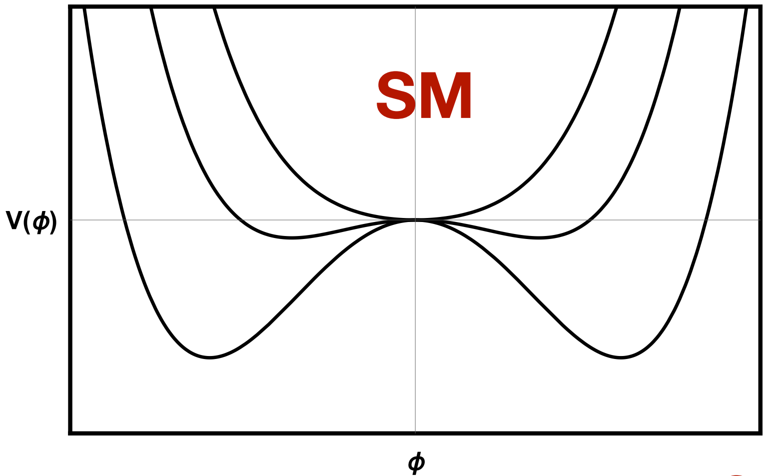
Composite Higgs SO(7)/SO(6) SO(6)/SO(5) SO(5)/SO(4) Twin Higgs

SUSY extensions MSSM, NMMSM(singlet extension of MSSM, SUSY custodial triplet)

Wrap extra dimensions Classical scale invariance model QCD-induced EWPT

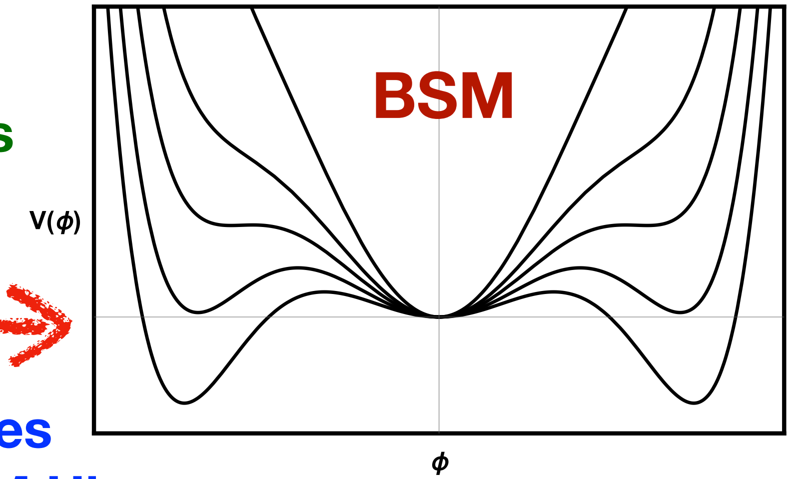
Dark hidden sectors DM, baryogenesis, gauge/flavour hierarchy, chiral PT, composite dark sector, quiver-type GUTs, Pati-Salam extensions of the SM, SUSY-breaking hidden sectors, dark gauge symmetry breaking, Peccei-Quinn symmetry breaking, (dark) QCD PTs, … …

Electroweak FOPT



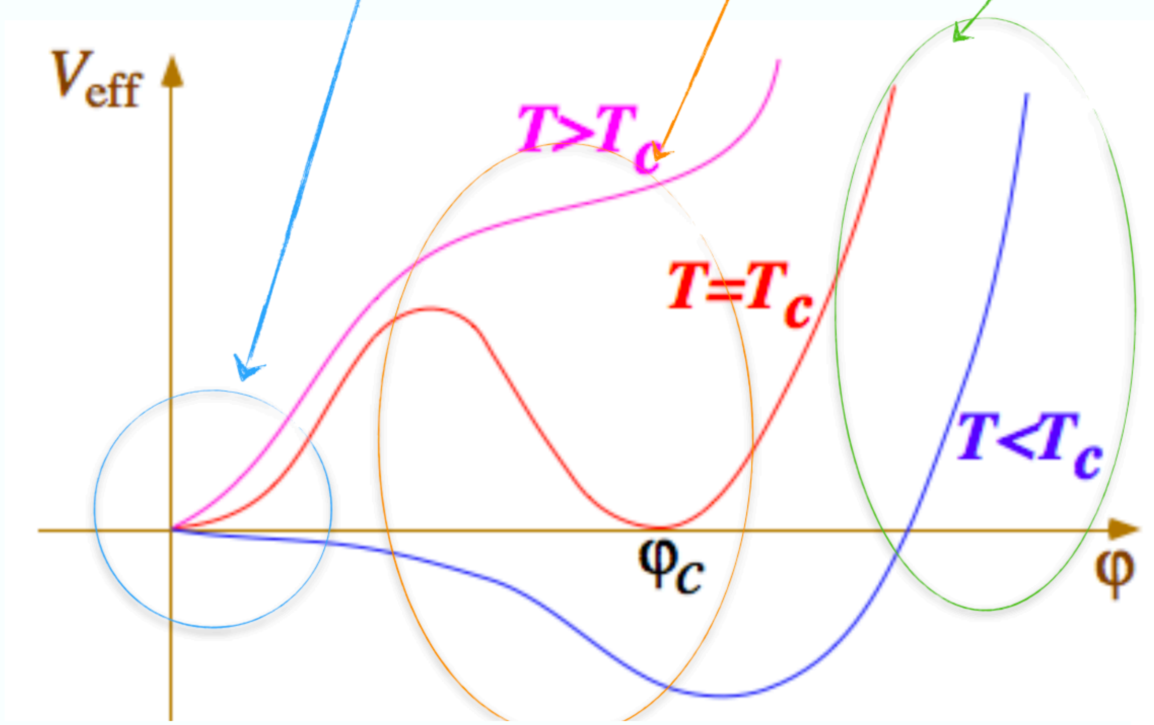
EFT extensions
SUSY extensions
Composite Higgs

Scalar extensions
Wrap extra dimensions
Dark/hidden sectors



EFT description? Clear separation of scales
V.S. low-scale d.o.f. with large corrections to SM Higgs

$$V_{\rm eff}(\varphi;T) \simeq D(T^2-T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4$$



$$E=\frac{1}{2\pi v_0^3}\left(2m_W^3+m_Z^3+\text{new scalar mass}\right)$$

2103.14022 José Eliel Camargo-Molina, Rikard Enberg, Johan Löfgren, "A new perspective on the electroweak phase transition in the Standard Model Effective Field Theory" JHEP 10 (2021) 127

In this work we stress that a first-order EWPT is also possible when the barrier between minima is generated radiatively, the quartic coupling is positive, the scale of new physics is higher, and there is good agreement with experimental bounds

More scalars⇒More φ^3 terms⇒Stronger EWPT

EFT descriptions

$$V_0(\Phi_1, \Phi_2) = -\mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_{12}|\Phi_1|^2|\Phi_2|^2$$

$$\Phi_1 = \begin{pmatrix} G^{\pm}, \\ \frac{1}{\sqrt{2}}(h + iG^0) \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_{1,i} \\ \phi_2 + i\phi_{2,i} \\ \vdots \\ \phi_N + i\phi_{N,i} \end{pmatrix}, \quad N \equiv 2I_{\Phi_2} + 1,$$

Cai, Hashino, Yu, SJW 2022

General model (SM + an isospin N-plet scalar field Φ_2)

A heavy scalar field Φ_2

3. A model with high dimensional operator

$$V(\Phi_1) = -\mu_1^2|\Phi_1|^2 + \lambda_1|\Phi_1|^4 + \gamma|\Phi_1|^6$$

EFT description of EWSB

A light scalar field Φ_2

1. A model with CSI

$$V(\Phi_1, \Phi_2) = \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_{12}|\Phi_1|^2|\Phi_2|^2$$

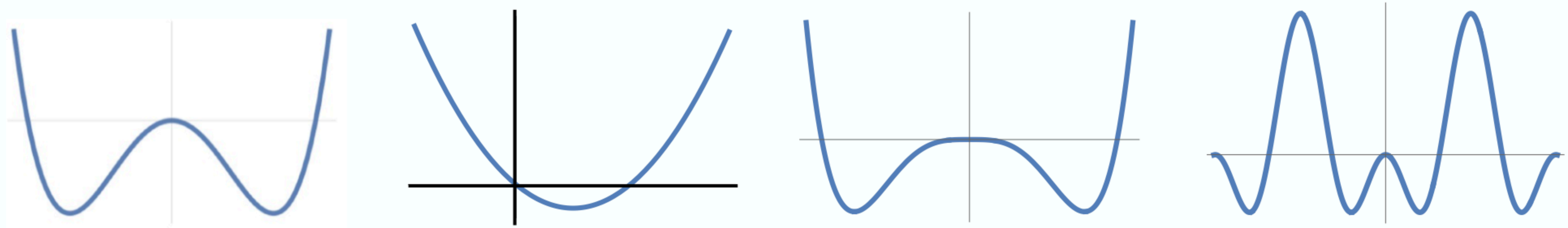
Radiative symmetry breaking

2. A model without CSI **Higgs mechanism**

$$V(\Phi_1, \Phi_2) = -\mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_{12}|\Phi_1|^2|\Phi_2|^2,$$

EFT descriptions

Landau-Ginzburg Higgs | Tadpole-induced Higgs | Coleman Weinberg Higgs | Pseudo-Goldstone Higgs



$V(\phi) = -m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$

$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$

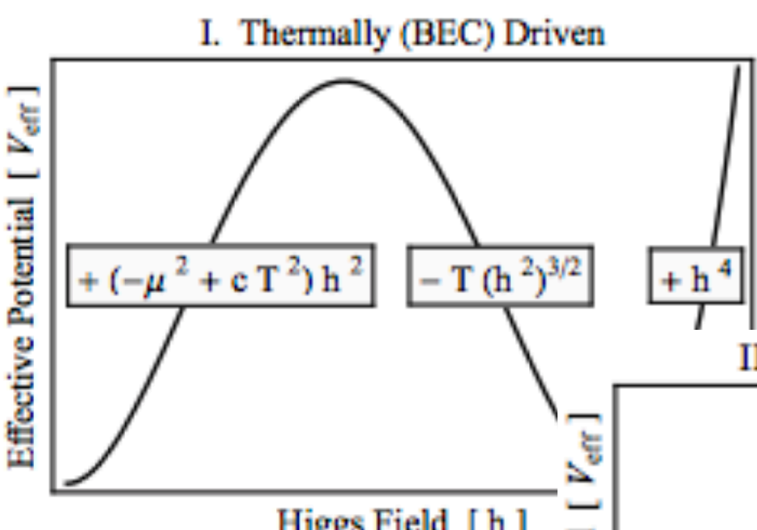
$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$

$V(\phi) = -a\sin^2(\phi/f) + b\sin^4(\phi/f)$

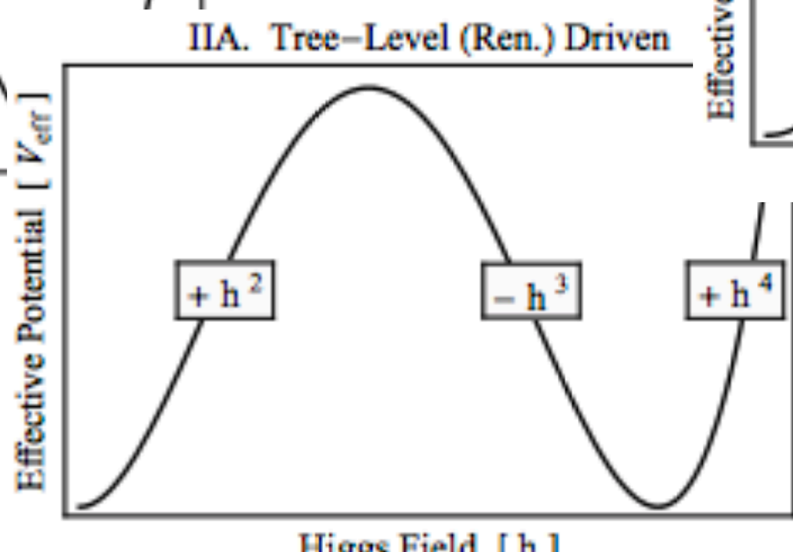
Fundamental particle → Partial Fundamental (condensate) → Conformal particle → Composite particle

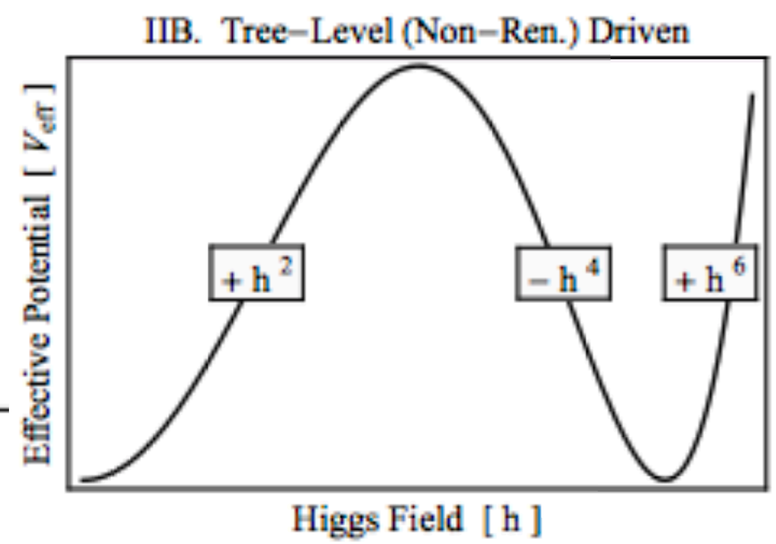
[Agrawal, Saha, Xu, Yu, Yuan, PRD 2021]

[Chung, Long, Wang, 2014]

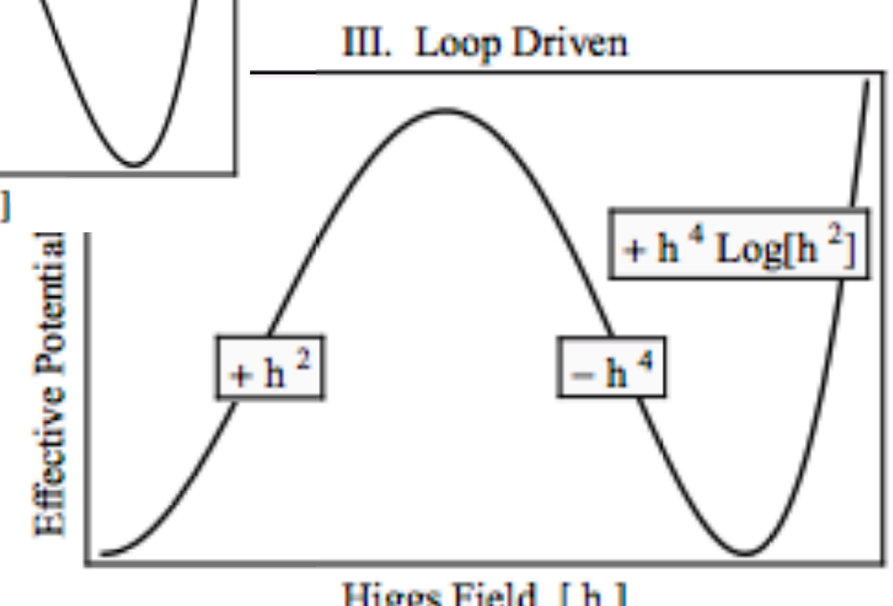


Scalar Extensions





Conformal Higgs



SUSY Composite Higgs

Fermion Extensions

EFT descriptions

General model (SM + an isospin N-plet scalar field Φ_2)

Cai, Hashino, Yu, SJW 2022

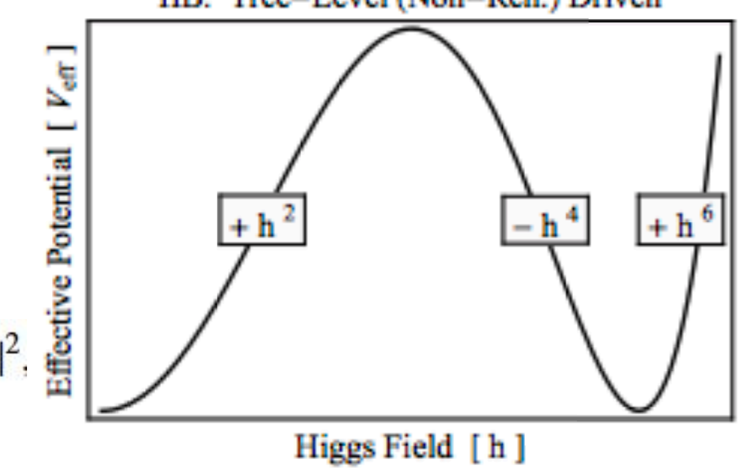
A heavy scalar field Φ_2

A light scalar field Φ_2

3. A model with high dimensional operator

$$V(\Phi_1) = -\mu_1^2|\Phi_1|^2 + \lambda_1|\Phi_1|^4 + \gamma|\Phi_1|^6$$

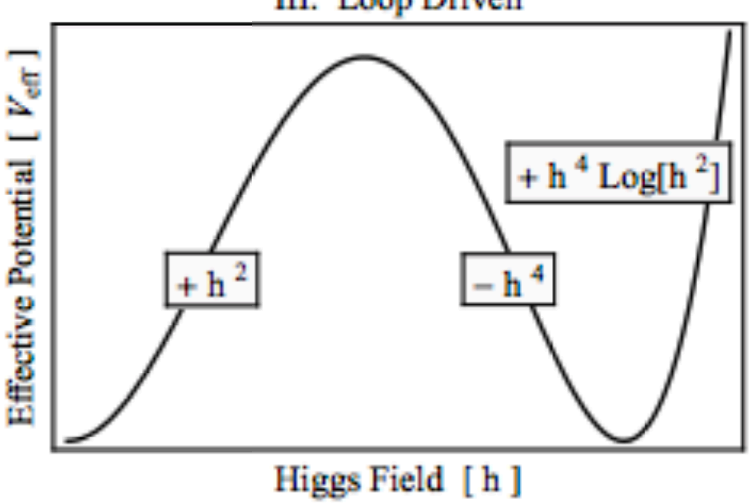
IIB. Tree–Level (Non–Ren.) Driven



1. A model with CSI

$$V(\Phi_1,\Phi_2) = \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_{12}|\Phi_1|^2|\Phi_2|^2$$

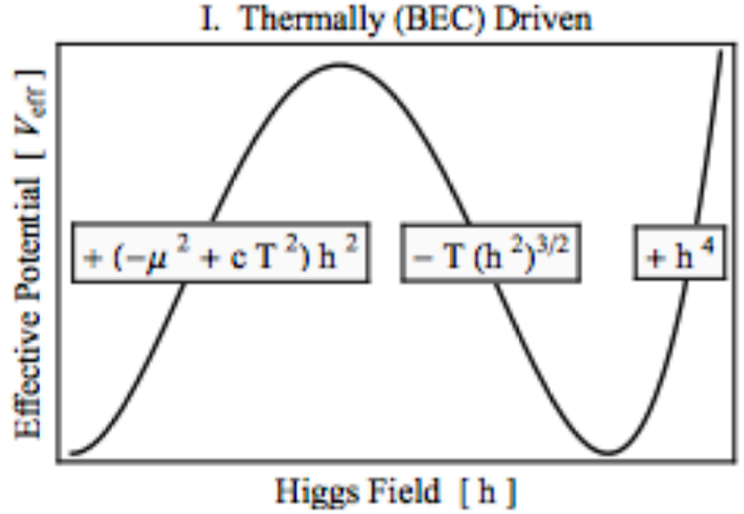
III. Loop Driven



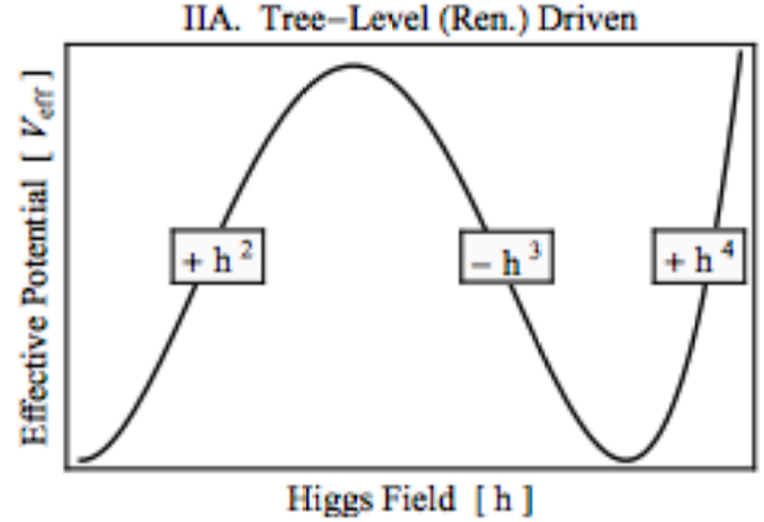
2. A model without CSI

$$V(\Phi_1,\Phi_2) = -\mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_{12}|\Phi_1|^2|\Phi_2|^2,$$

I. Thermally (BEC) Driven



IIA. Tree–Level (Ren.) Driven



Predictions of FOPTs

$$V_p = C_2\phi^2 + C_3\phi^3 + C_4\phi^4 + C_6\phi^6$$

Model	$C_2\phi^2$	$C_3\phi^3$	$C_4\phi^4$	$C_6\phi^6$
I	Loop	Loop	Loop	None
II	Tree	Loop	Tree	None
III	Tree	Loop	Tree	Tree

Table 1. The potential forms in the three types of the models where the EWSB occurs via (I) radiative symmetry breaking; (II) Higgs mechanism; (III) EFT description. Here, ϕ is order parameter, and C_n is the effective coupling of ϕ^n. The cubic term can be produced by thermal loop effects of bosons. To generate a sizable barrier, the cubic term will be negative in models I and II. In the model III, the quartic term can be negative to generate the barrier.

Model	$C_2\phi^2$	$C_3\phi^3$	$C_4\phi^4$	$C_6\phi^6$	GW features
I	Loop	Loop	Loop	None	Small λ_2 and small I_{Φ_2}
II	Tree	Loop	Tree	None	Small λ_2 and small I_{Φ_2}
III	Tree	Loop	Tree	Tree	Large λ_{12} and large I_{Φ_2}

Table 2. The potential forms in the three types of the models where the EWSB can be realized by (I) radiative symmetry breaking, (II) Higgs mechanism and (III) EFT description of EWSB, respectively. The last column shows the source of detectable GW spectrum in these models. Otherwise, the same as Tab. 1.

Cai, Hashino, Yu, SJW 2022

Bubble wall velocity

arXiv > hep-ph > arXiv:2409.20045

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High Energy Physics – Phenomenology

[Submitted on 30 Sep 2024 (v1), last revised 21 Nov 2024 (this version, v2)]

Bubble wall velocity from number density current in (non)equilibrium

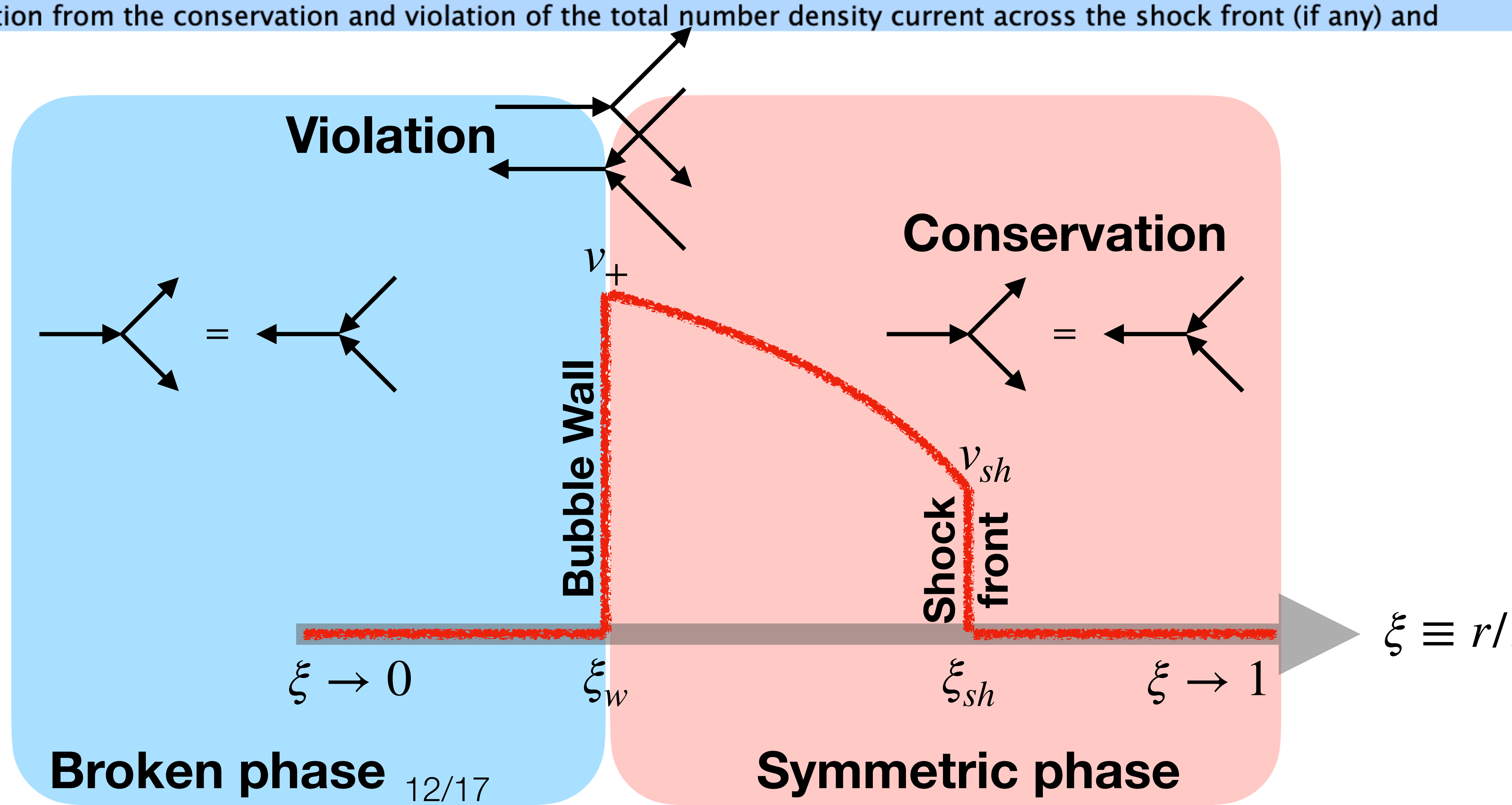
Zi-Yan Yuwen, Jun-Chen Wang, Shao-Jiang Wang

Cosmological first-order phase transitions (FOPTs) serve as comprehensive probes into our early Universe with associated generations of stochastic gravitational waves and superhorizon curvature perturbations or even primordial black holes. In characterizing the FOPT, phenomenological parameters like transition temperatures, strength factors, bubble separations, and energy budgets can be easily extracted from the macroscopic equilibrium features of the underlying particle physics models except for the terminal wall velocity of the bubble expansion, making it the last key parameter to be determined most difficultly due to the non-equilibrium nature of the microscopic transition model. In this paper, we propose a new model-independent approach to calculate the bubble wall velocity by virtue of an extra junction condition from the conservation and violation of the total number density current across the shock front (if any) and bubble wall, respectively.

宇文子炎　　王俊谌

Zi-Yan Yuwen

(On postdoc market)

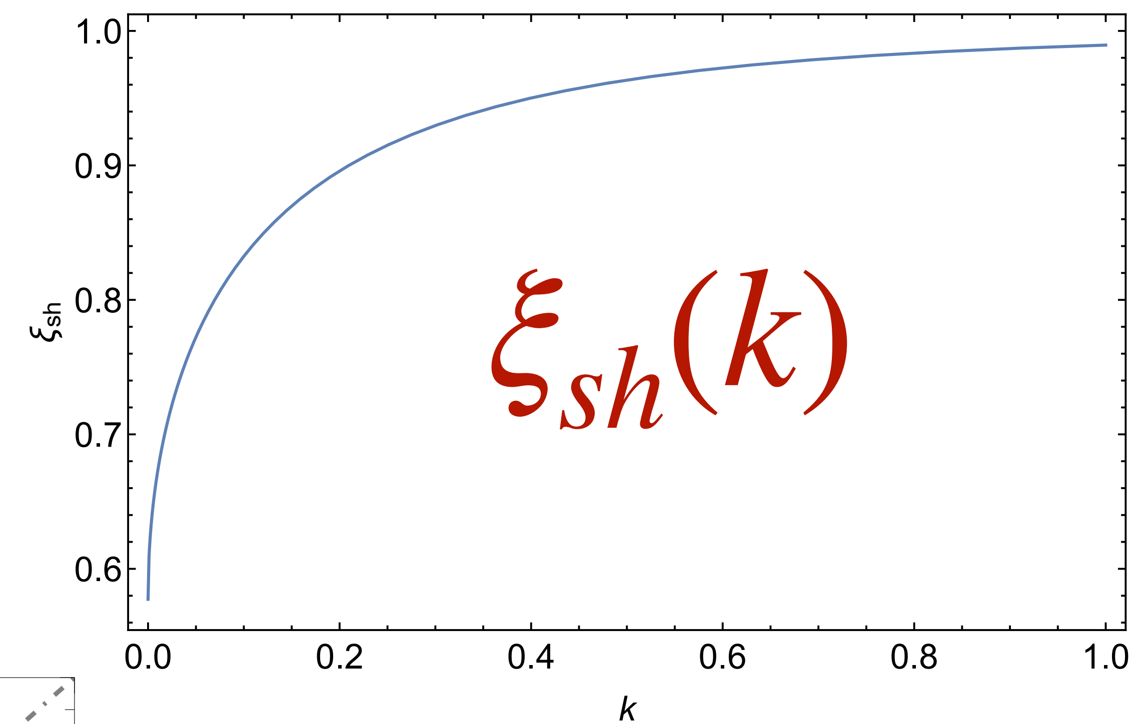


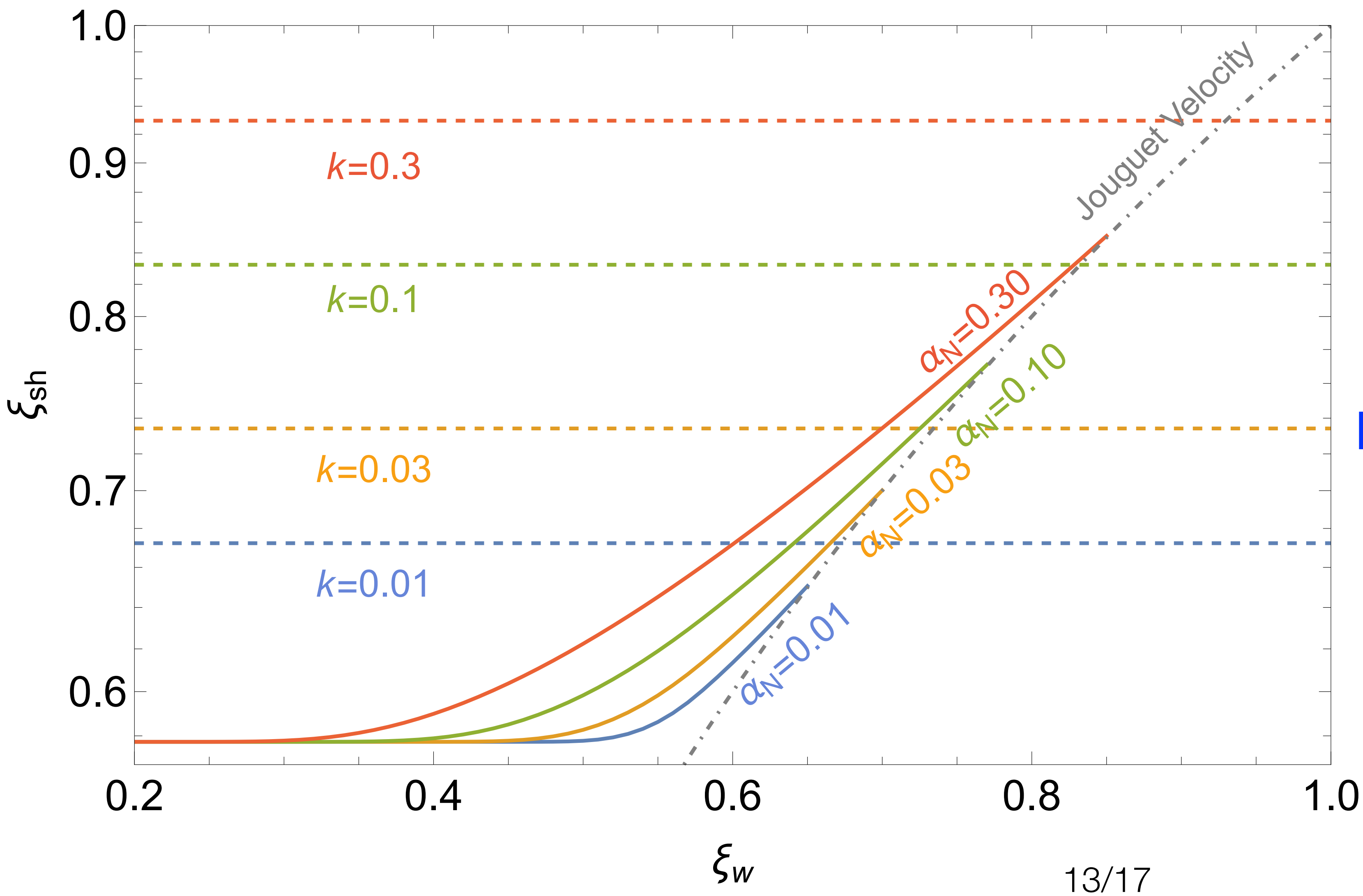
Deflagration/hybrid

Conserved number density current across shock front

$$\frac{n_+\gamma_+(\xi_{sh}-v_+)}{n_-\gamma_-(\xi_{sh}-v_-)} = \frac{1+k}{\left(\frac{9\xi_{sh}^2-1}{3(1-\xi_{sh}^2)}\right)^{3/4}+k} \cdot \frac{\xi_{sh}\sqrt{-1+10\xi_{sh}^2-9\xi_{sh}^4}}{1-\xi_{sh}^2} = 1$$

$$k_\pm = \frac{n_{\phi,\pm}}{b_+T_+^3} \qquad b = \frac{\zeta(3)}{\pi^2}\left(\sum_{\text{light Bosons}} g_B + \frac{3}{4}\sum_{\text{light Fermions}} g_F\right)$$





First-order hydrodynamics

$\Downarrow$

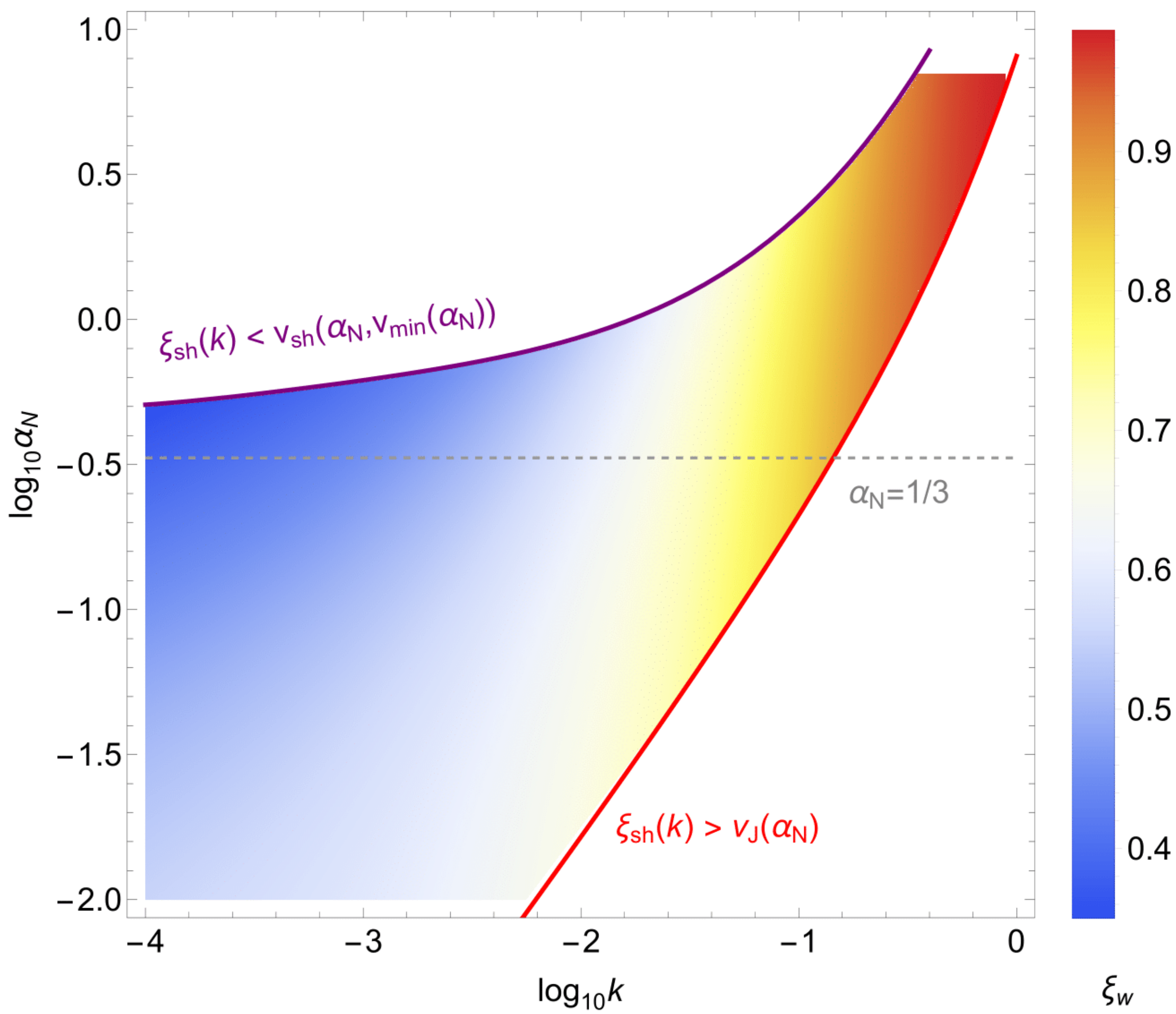
$\xi_{sh}(\xi_w;\alpha_N)$

Bubble wall velocity is solved from

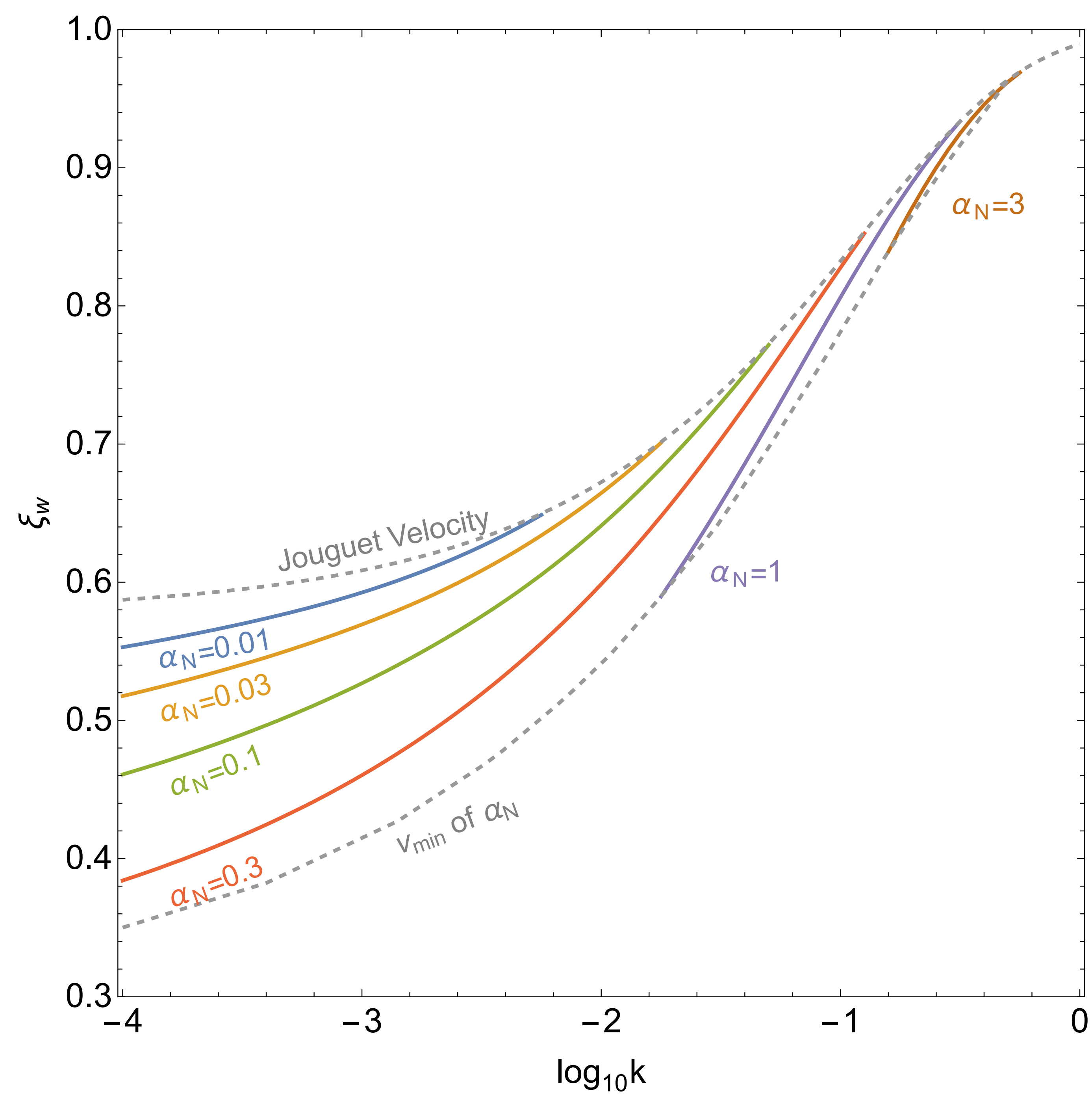
$$\xi_{sh}(k) = \xi_{sh}(\xi_w;\alpha_N) \Rightarrow \xi_w(\alpha_N,k)$$

for a large range of α_N

Deflagration/hybrid

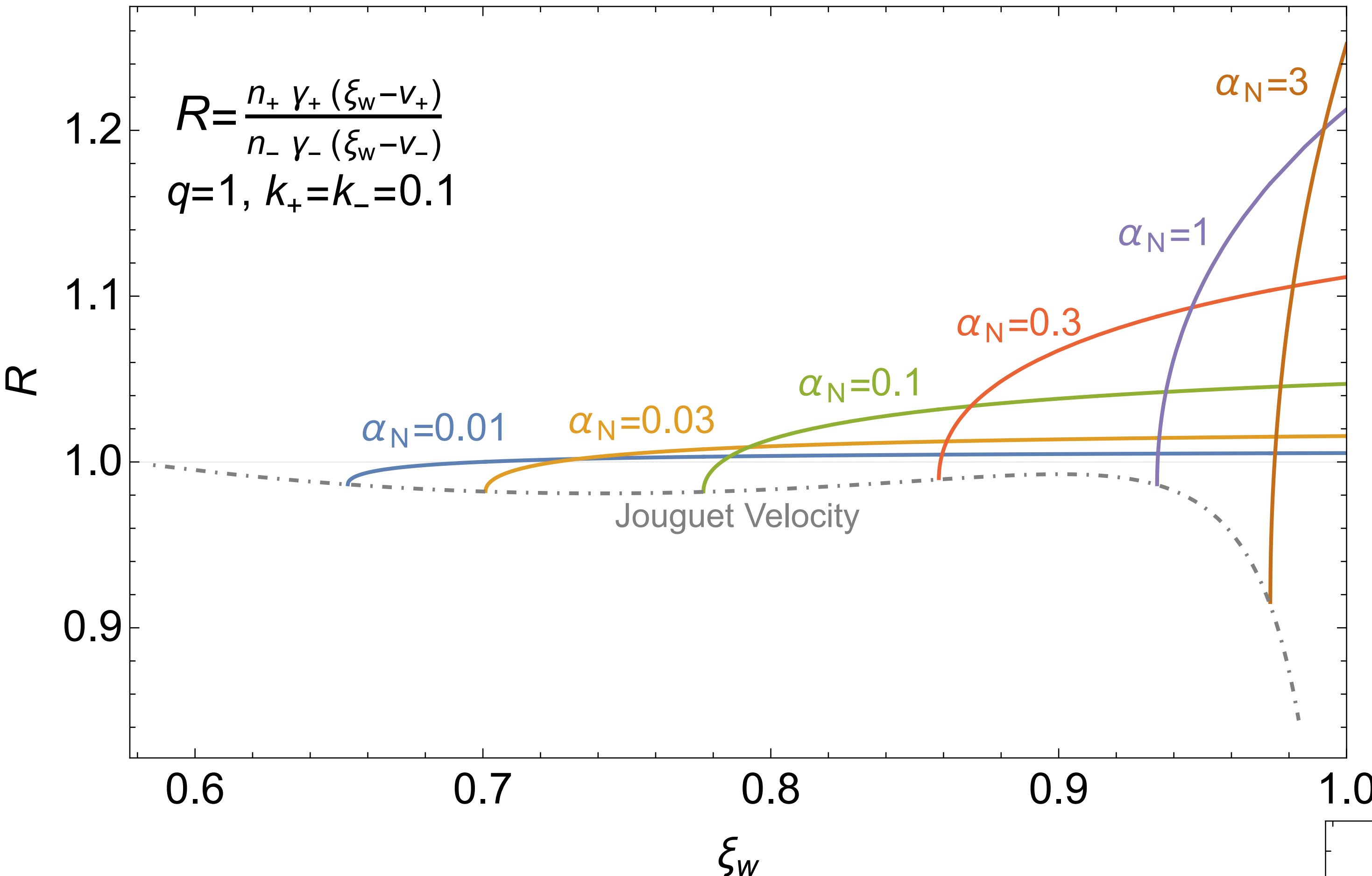


$$\alpha_N(\xi_w, k)$$



$$\xi_w(\alpha_N, k)$$

Detonation



Slightly broken number density current across bubble wall due to particle splitting/decaying process

$$\frac{n_+\gamma_+(\xi_w - v_+)}{n_-\gamma_-(\xi_w - v_-)} = \Gamma_w \lesssim 1$$

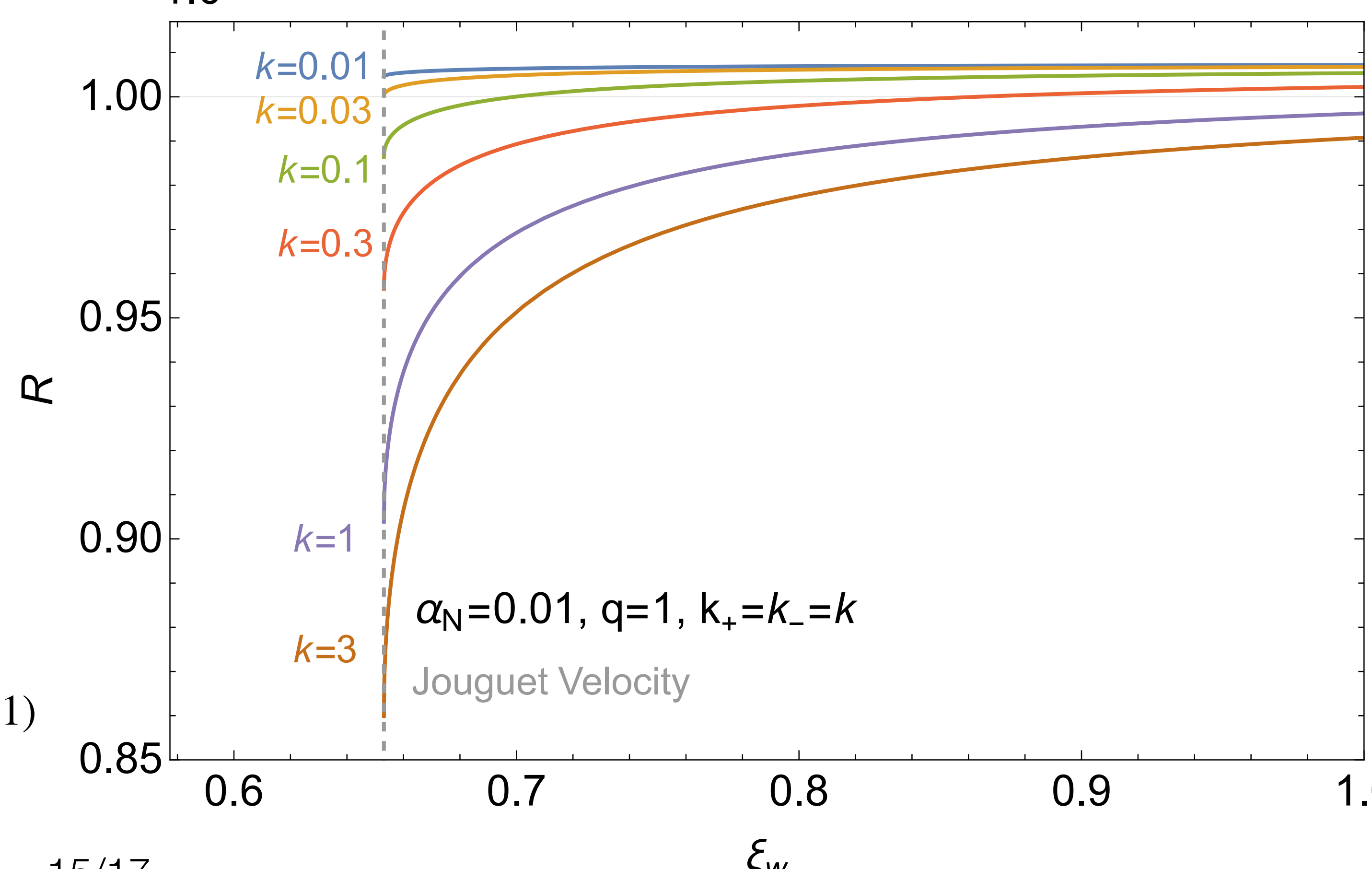
Weak detonation

$$\frac{n_+}{n_-} \cdot \frac{\xi_w}{\gamma_-(\xi_w - v_-)} = \Gamma_w$$

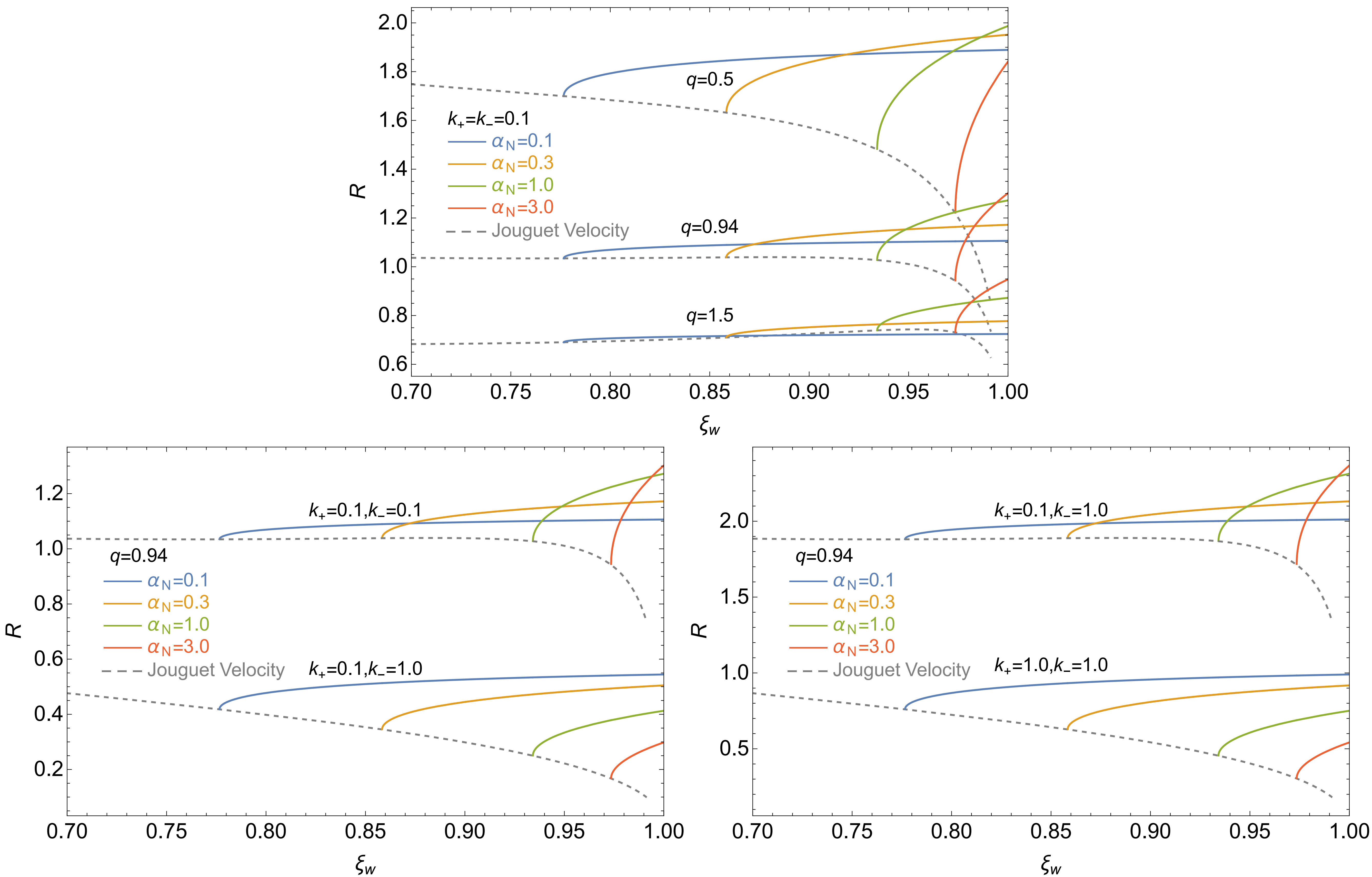
$$\frac{n_+}{n_-} = \frac{b_+T_+^3 + n_{\phi,+}}{b_-T_-^3 + n_{\phi,-}} = \frac{1+\frac{n_{\phi,+}}{b_+T_+^3}}{\frac{b_-}{b_+}\left(\frac{T_-}{T_+}\right)^3 + \frac{n_{\phi,-}}{b_+T_+^3}} \equiv \frac{1+k_+}{\frac{b_-}{b_+}\left(\frac{w_-}{w_+}\Big/\frac{a_-}{a_+}\right)^{3/4} + k_-}$$

$$k_\pm = \frac{n_{\phi,\pm}}{b_+T_+^3} \;\&\; q = \frac{b_-a_+^{3/4}}{b_+a_-^{3/4}} \Rightarrow \xi_w(\alpha_N; R, q, k_\pm)$$

EW: $q = \frac{b_-}{b_+}\Big/\left(\frac{a_-}{a_+}\right)^{3/4} = \frac{76.5}{95.5}\Big/\left(\frac{86.25}{106.75}\right)^{3/4} \simeq 0.94 \sim O(1)$



Detonation



q=0.5
q=0.94
q=1.5
k+=k−=0.1
αN=0.1
αN=0.3
αN=1.0
αN=3.0
Jouguet Velocity
R
ξw
k+=0.1,k−=0.1
q=0.94
αN=0.1
αN=0.3
αN=1.0
αN=3.0
Jouguet Velocity
k+=0.1,k−=1.0
R
ξw
k+=0.1,k−=1.0
q=0.94
αN=0.1
αN=0.3
αN=1.0
αN=3.0
Jouguet Velocity
k+=1.0,k−=1.0
R
ξw

Conclusions and discussions

EW FOPT will shape our understandings of many profound questions

Universality: An EFT description of EWPTs is needed to test them once for all

We propose a EFT description of EWPTs using a scalar N-plet model to cover (1) radiative symmetry breaking with classical scale invariance, (2) Higgs mechanism in generic scalar extension, and (3) higher dimensional operators

Distinguishability: Bubble wall velocity is need to break model degeneracies

We propose a new model-independent approach from number density current conservation (at shock front) and violation (non-equilibrium at bubble wall)

Thank you