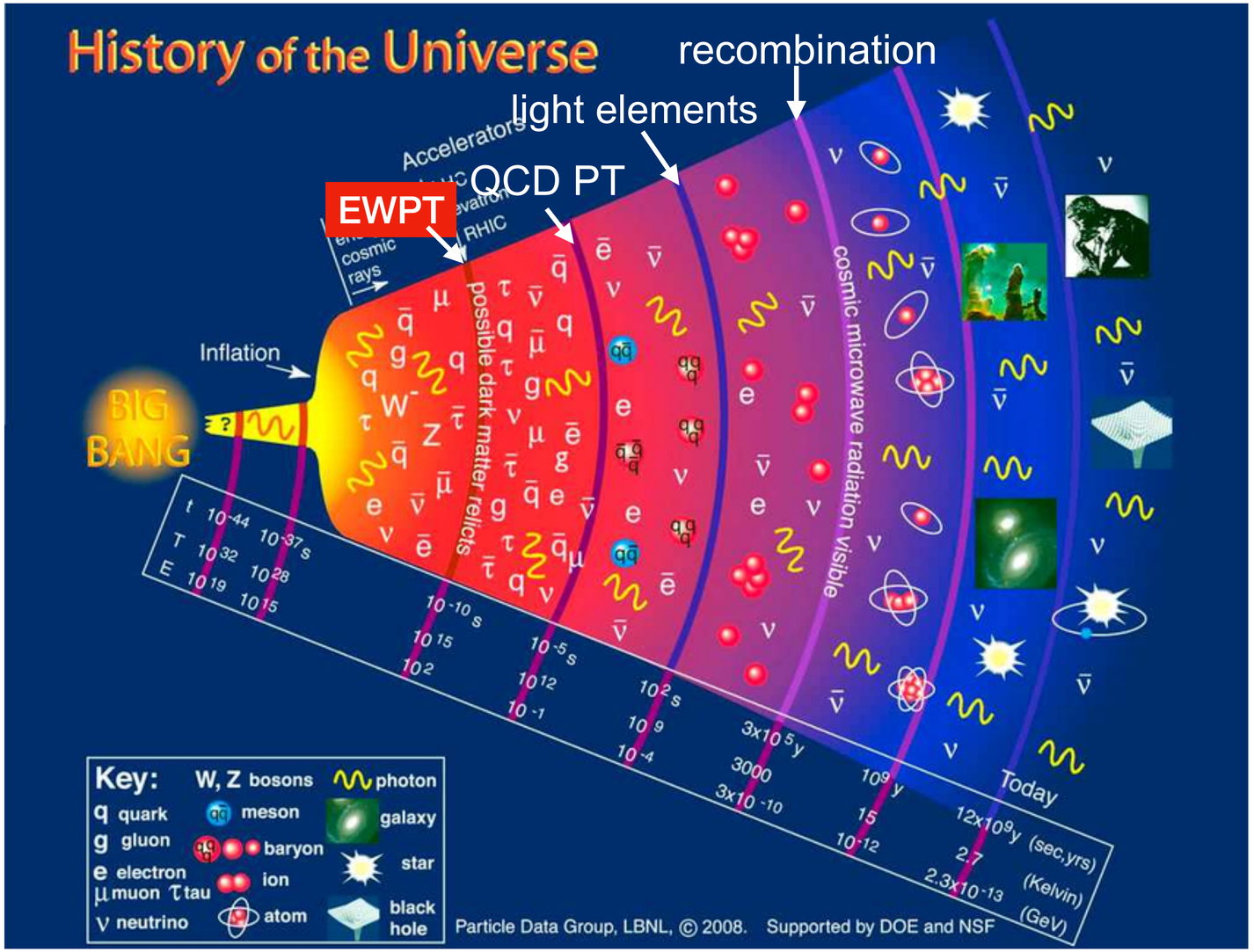
Nikhef

THE ELECTROWEAK PHASE TRANSITION: IS EFFECTIVE FIELD THEORY JUST A TOY?

Marieke Postma
May 2021

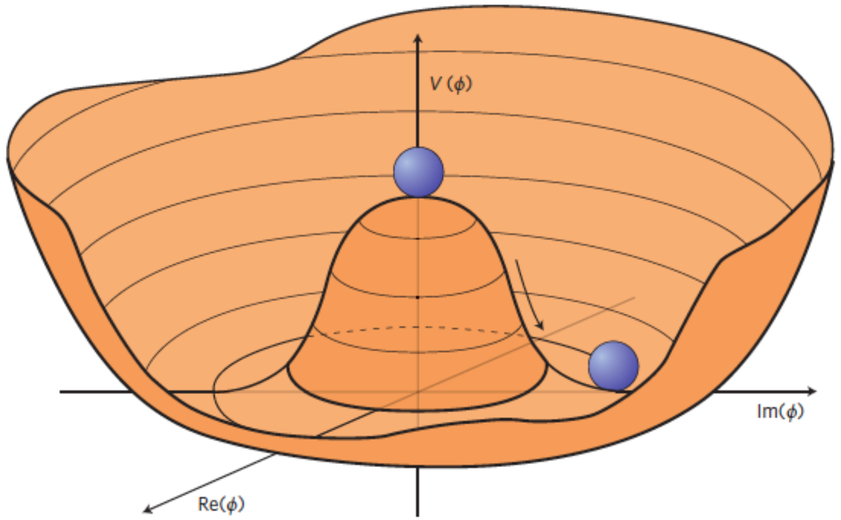
1710.04061, 2012.03953
w/ Jordy de Vries, Jorinde van der Vis & Graham White

ELECTROWEAK PHASE TRANSITION



deviations from thermal equilibrium

HIGGS POTENTIAL

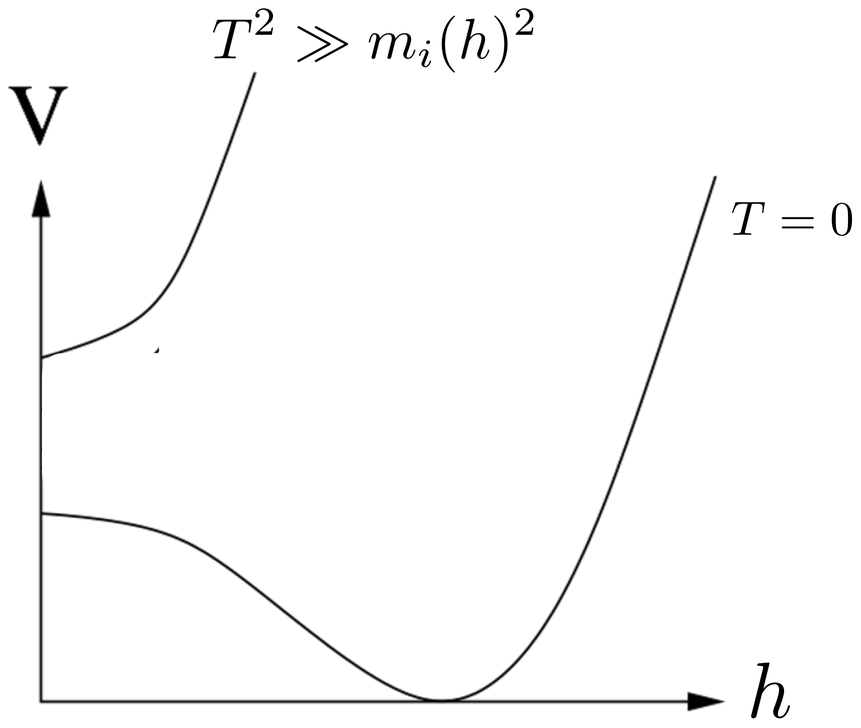


$$T = 0$$

$$V = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

HIGGS POTENTIAL

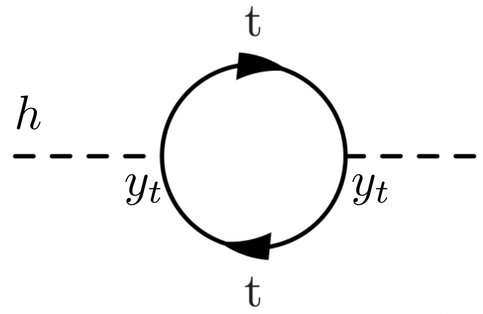
$$V_T = a\,T^4 + b\,T^2 h^2 + \ldots$$



$$\langle \phi^\dagger \phi \rangle = \frac{1}{2} h^2$$

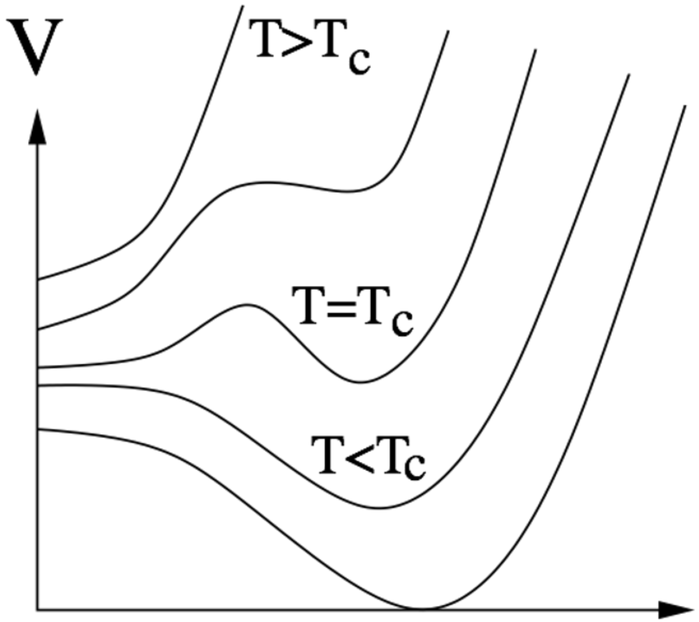
$$V = -\mu^2 |\phi|^2 + \lambda |\phi|^4 + V_T(\phi, T)$$

e.g.

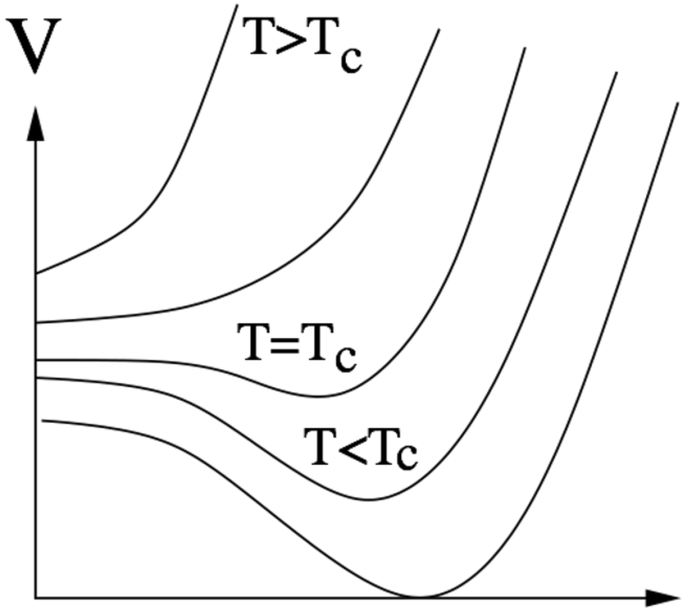


HIGGS POTENTIAL

$$V_T = a\,T^4 + b\,T^2 h^2 + c\,h^3 T + \ldots$$



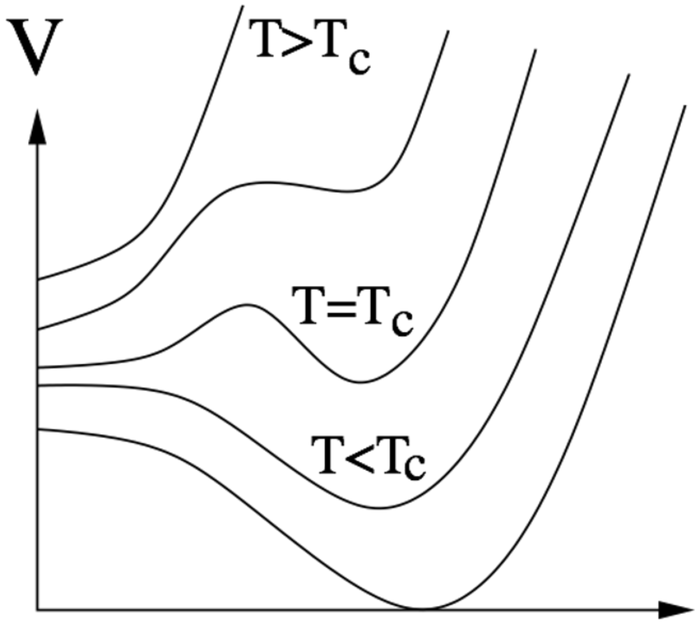
1st order



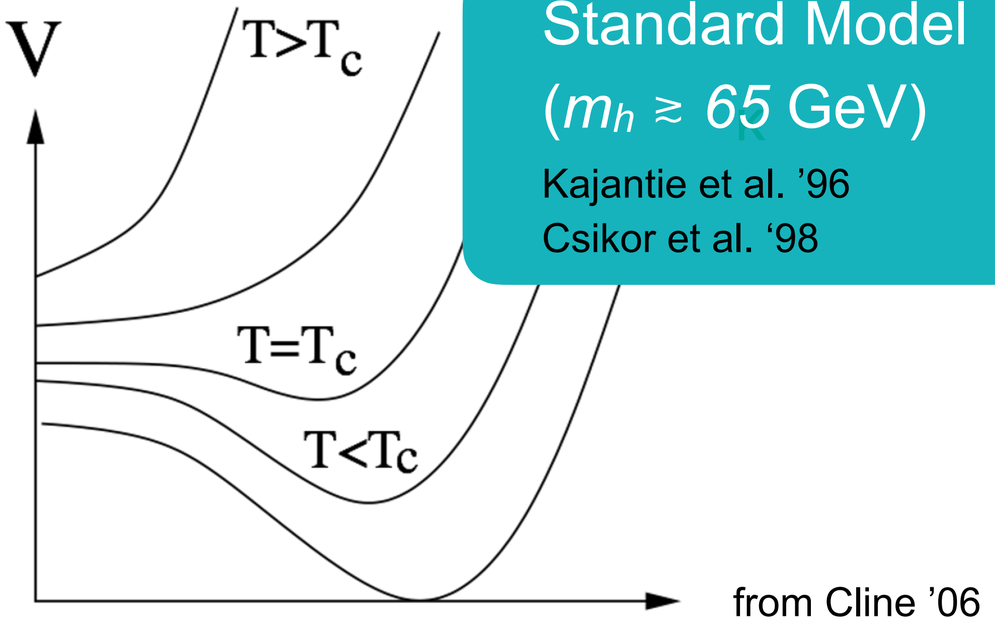
2nd order/cross over

HIGGS POTENTIAL

$$V_T = a\,T^4 + b\,T^2 h^2 + c\,h^3 T + \ldots$$



1st order



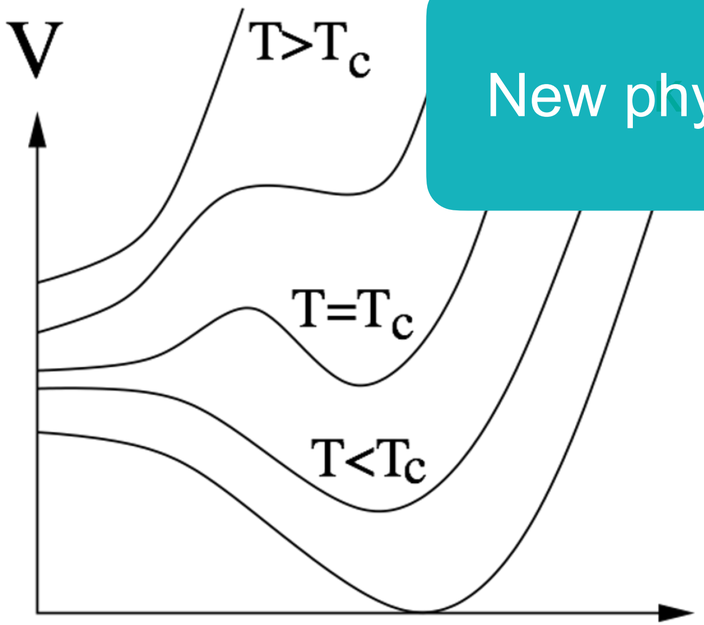
Standard Model
($m_h \gtrsim 65$ GeV)

Kajantie et al. ’96
Csikor et al. ‘98

from Cline ’06

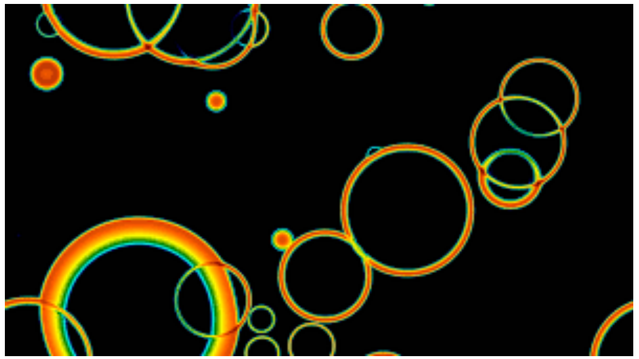
2nd order/cross over

HIGGS POTENTIAL



New physics

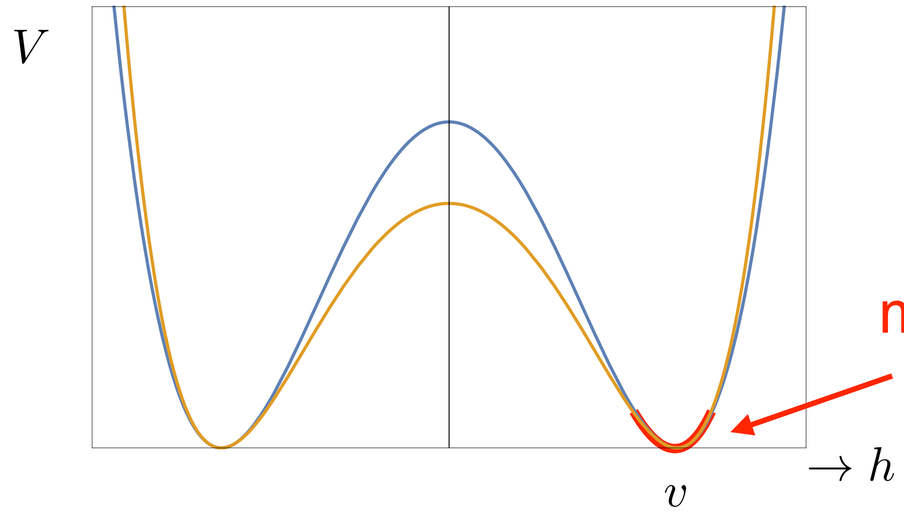
1st order



Weir ’17

ELECTROWEAK PHASE TRANSITION

exact nature of Higgs potential unknown

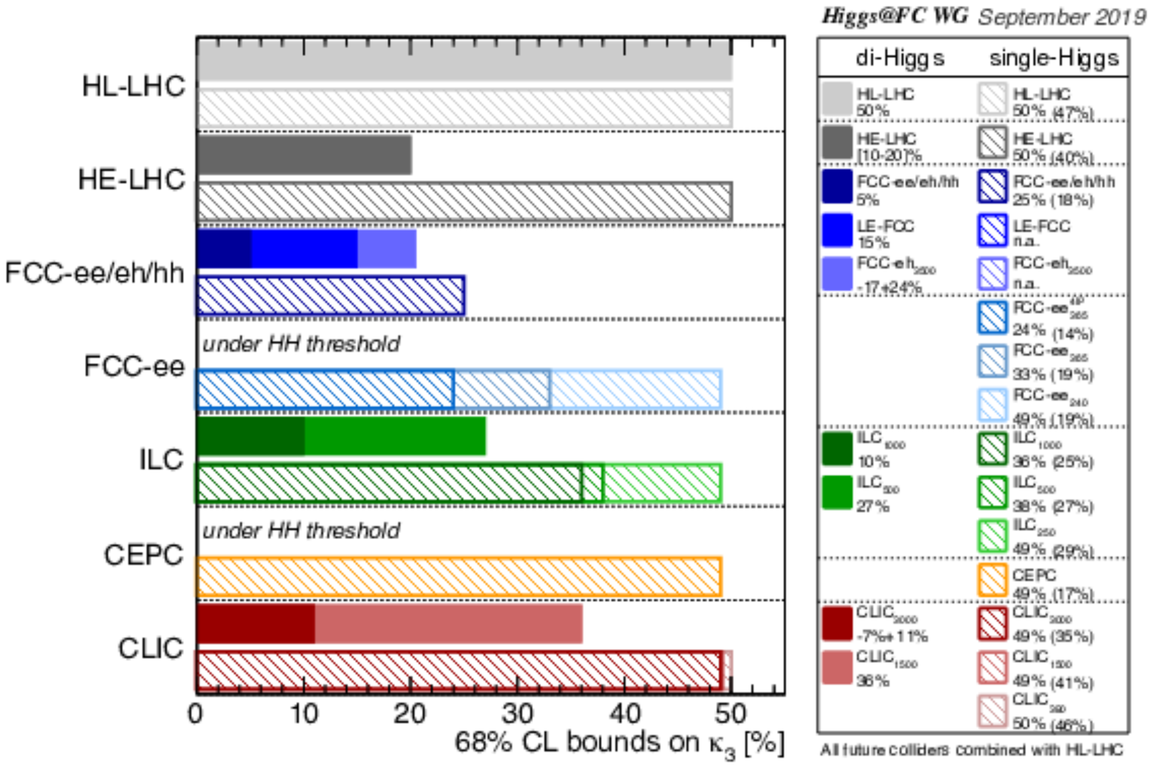


$$m_h = 125.3\,\mathrm{GeV}$$

$$v = 246\,\mathrm{GeV}$$

ELECTROWEAK PHASE TRANSITION

exact nature of Higgs potential unknown

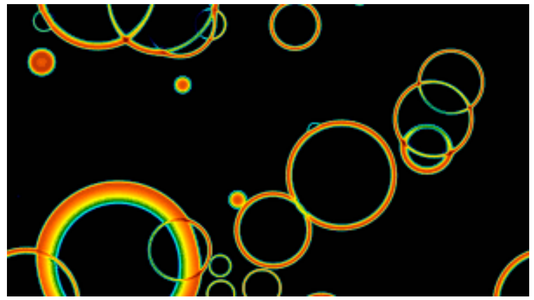


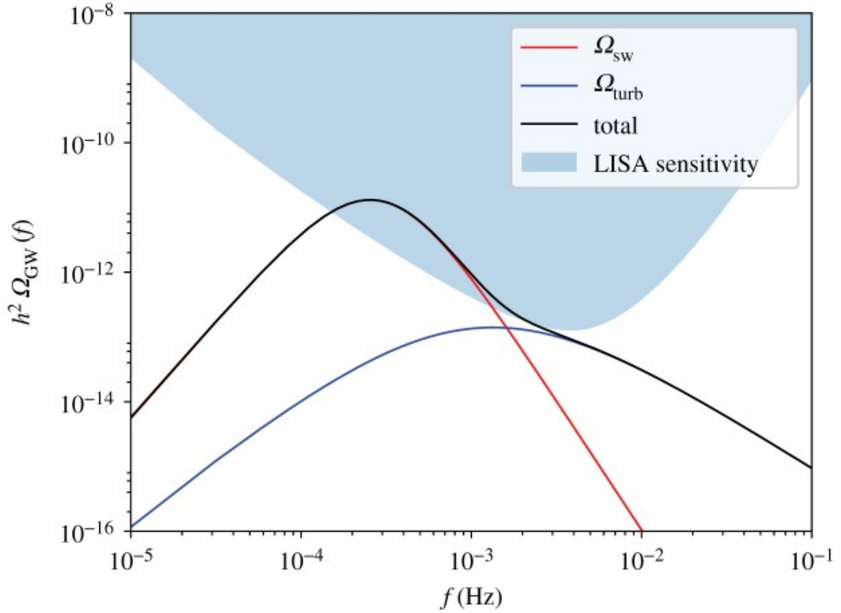
sensitivity at 68% probability on the Higgs cubic self-coupling at future colliders (Blas et al. ’19)

ELECTROWEAK PHASE TRANSITION

cosmological probes:

- gravitational waves





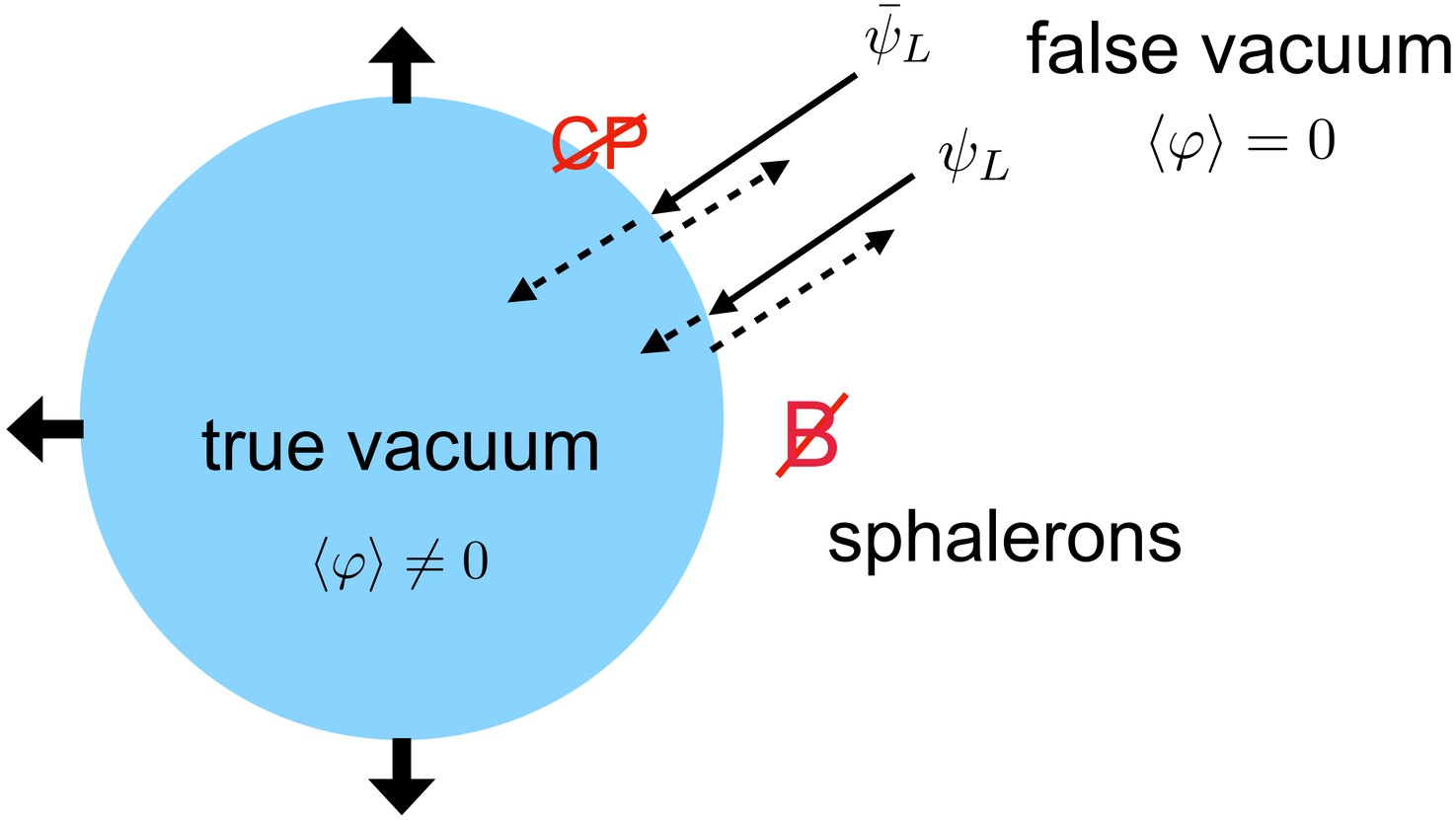
Weir ’17

ELECTROWEAK PHASE TRANSITION

cosmological probes:

- gravitational waves

- baryogenesis



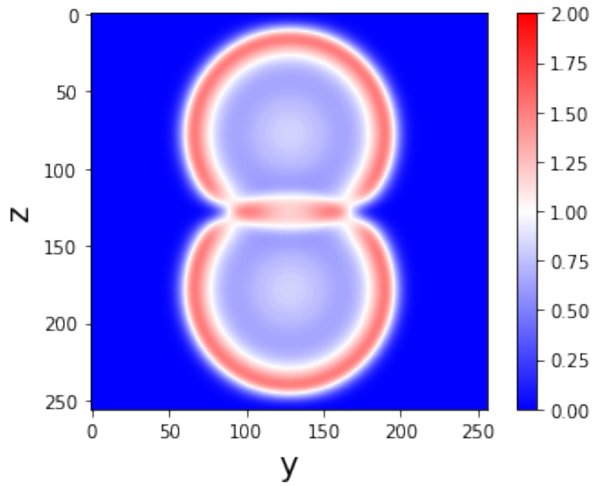
ELECTROWEAK PHASE TRANSITION

cosmological probes:

- gravitational waves

- baryogenesis

- magnetic fields



Zhang et al. ’19

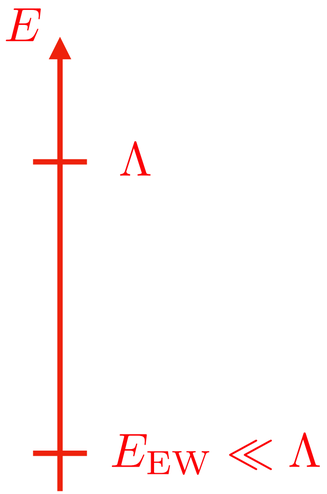
STANDARD MODEL EFFECTIVE FIELD THEORY

SM-EFT

effective Lagrangian: $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i c_i \frac{\mathcal{O}_i}{\Lambda^{d_i-4}}$

light SM d.o.f.

scale of new physics



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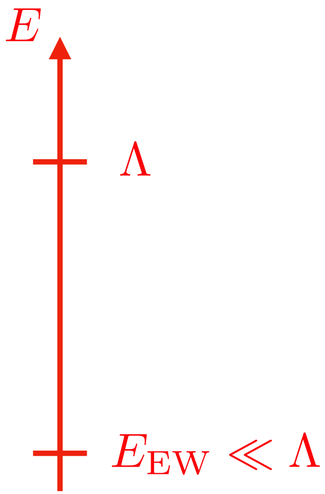
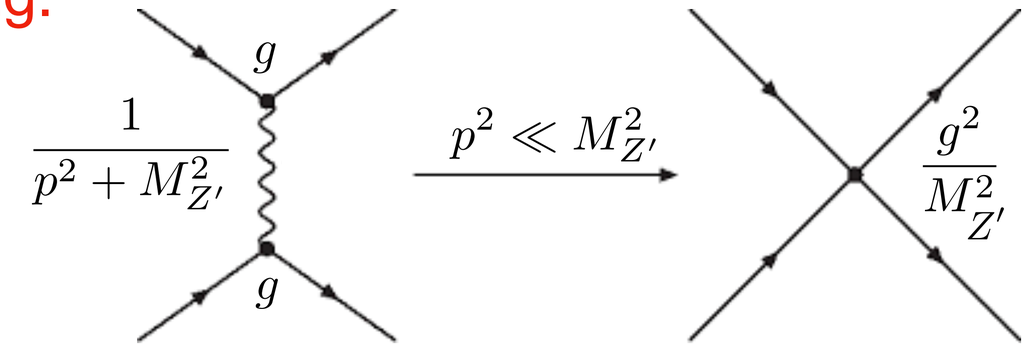


e.g.



$+\ldots$

SM-EFT

effective Lagrangian: $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i c_i \frac{\mathcal{O}_i}{\Lambda^{d_i-4}}$

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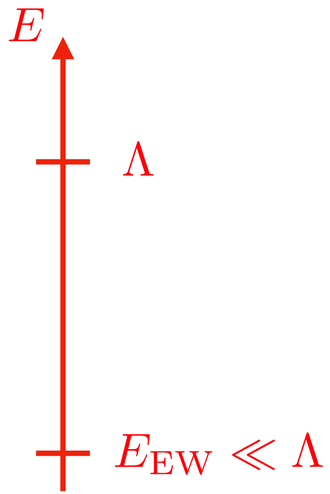

- model independent
- systematic expansion if separation of scales

SEPARATION OF SCALES IN EW PHASE TRANSITION?

SM-EFT AND ELECTROWEAK PHASE TRANSITION

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + c_{\phi\Box}|\phi|^2\Box|\phi|^2 + c_{\phi D}|\phi D_\mu \phi|^2 + c_\phi^{(6)}|\phi|^6 + c_\phi^{(8)}|\phi|^8$$

dim-6 dim-8

SM-EFT AND ELECTROWEAK PHASE TRANSITION

$$\mathcal{L} = \mathcal{L}_{\rm SM} + c_{\phi\Box}|\phi|^2\Box|\phi|^2 + c_{\phi D}|\phi D_\mu \phi|^2 + c_\phi^{(6)}|\phi|^6 + c_\phi^{(8)}|\phi|^8$$

- neutral Higgs field $\quad \langle|\phi|^2\rangle = \frac{1}{2}\tilde{h}^2$

- canonical field $\quad h = \tilde{h} + \frac{1}{3}(\frac{1}{4}c_{\phi D} - c_{\phi\Box})\,\tilde{h}^3 + ...$

$$V = \frac{1}{2}a_2 h^2 + \frac{1}{4}a_4 h^4 + \frac{1}{6}\frac{h^6}{\Lambda^2} + \frac{c_8}{8}\frac{h^8}{\Lambda^4}$$

- physical quantities $\quad (a_2, a_4) \leftrightarrow (m_h, v)$

SM-EFT AND ELECTROWEAK PHASE TRANSITION

1st order PT:

$$\Lambda^2 \sim (2 - 4)\frac{v^4}{m_h^2} \sim (685 - 978\,\mathrm{GeV})^2$$

$$V^{\mathrm{tot}} = -\frac{1}{4}m_h^2(1 - \frac{2v^4}{m_h^2\Lambda^2}) + \frac{1}{8}\frac{m_h^2}{v^2}(1 - \frac{4v^4}{m_h^2\Lambda^2}) + \frac{1}{6}\frac{h^6}{\Lambda^2} + V_{\mathrm{CW}} + V_T$$

$\gtrsim 0$ $\lesssim 0$ perturbative

SM-EFT AND ELECTROWEAK PHASE TRANSITION

1st order PT: $\Lambda^2 \sim (2 - 4)\frac{v^4}{m_h^2} \sim (685 - 978\,\mathrm{GeV})^2$

EFT expansion valid: $\frac{c_8 v^2}{\Lambda^2} < \frac{1}{2}$

$$V = \frac{1}{2}a_2 h^2 + \frac{1}{4}a_4 h^4 + \frac{1}{6}\frac{h^6}{\Lambda^2} + \frac{c_8}{8}\frac{h^8}{\Lambda^4}$$

SM-EFT AND ELECTROWEAK PHASE TRANSITION

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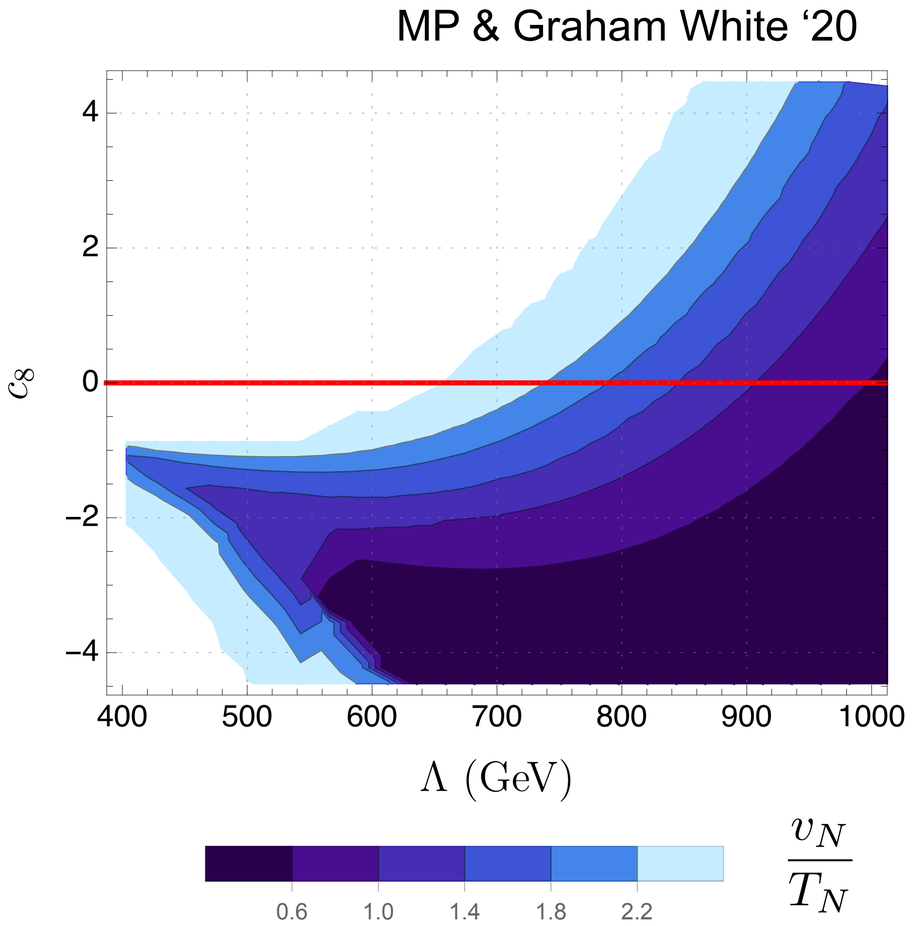

SM-EFT AND ELECTROWEAK PHASE TRANSITION

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EFT expansion valid: $$\frac{c_8 v^2}{\Lambda^2} < \frac{1}{2}$$

10% accuracy: $$|c_8| \lesssim 1$$

NB. dependence on c_8 also noted for electroweak baryogenesis in de Vries, van der Vis, White & MP ’17

$$V = \frac{1}{2}a_2 h^2 + \frac{1}{4}a_4 h^4 + \frac{1}{6}\frac{h^6}{\Lambda^2} + \frac{c_8}{8}\frac{h^8}{\Lambda^4}$$

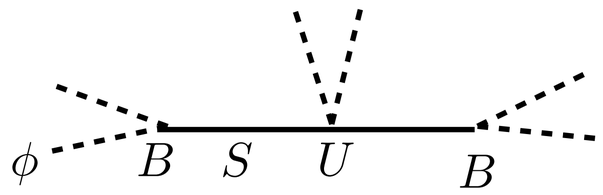
UV COMPLETIONS

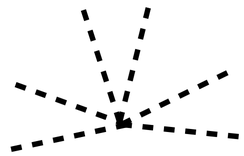
SINGLE NEW (SCALAR) DEGREE OF FREEDOM

$$\mathcal{L}_{\rm UV} = (S^\dagger B(\phi) + \text{ h.c.}) + S^\dagger(-D^2 - M^2 - U(\phi))S + \mathcal{O}(S^3)$$

Henning et al. ‘16

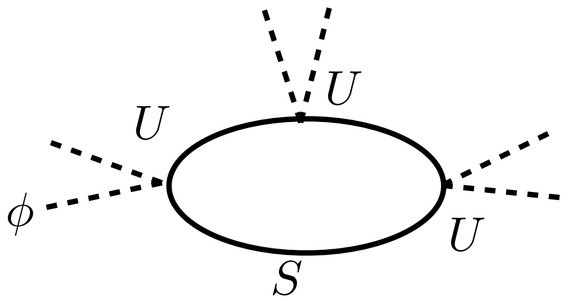
Tree level matching: $B \neq 0$





Loop level matching $B = 0$

$(Z_2$ symmetry$)$



$$\delta\mathcal{L} = c_\phi \frac{|\phi|^6}{M^2}$$

LOOP LEVEL MATCHING

$$\mathcal{L}_{\rm UV} = \cdot\, S^\dagger(-D^2 - M^2 - U(\phi))S + \mathcal{O}(S^3) \qquad \text{with} \qquad U = \kappa|\phi|^2$$

$$\mathcal{L}_{\rm eff} = \frac{c_S}{(4\pi)^2}\left[-\frac{1}{6}\frac{U^3}{M^2} + \frac{1}{24}\frac{U^4}{M^4} + ...\right] \qquad \text{up to subdominant } (\partial^n U) \text{ terms}$$

1st order PT: $$\frac{c_S\kappa^2}{(4\pi)^2}\frac{U}{M^2} \sim \frac{4m_h^2}{v^2} \approx 0.5$$

LOOP LEVEL MATCHING ✗

$$\mathcal{L}_{\rm UV} = \cdot\, S^\dagger(-D^2 - M^2 - U(\phi))S + \mathcal{O}(S^3) \qquad \text{with} \qquad U = \kappa|\phi|^2$$

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1st order PT:

$$\frac{c_S\kappa^2}{(4\pi)^2}\frac{U}{M^2} \sim \frac{4m_h^2}{v^2} \approx 0.5$$

$\ll 1 \quad \ll 1$

perturbativity & EFT validity

TREE LEVEL MATCHING

$$\mathcal{L}_{\rm UV} = (S^\dagger B(\phi) + .\text{h.c.}) + S^\dagger(-D^2 - M^2 - U(\phi))S + \mathcal{O}(S^3)$$

eom: $$S = \frac{B}{D^2 + M^2 + U}$$

EW precision:
- singlet
- doublet ✘ (wrong sign dim-6 term)

TREE LEVEL MATCHING — SINGLET

$$\mathcal{L}_{\rm UV} = (S^\dagger B(\phi) + .{\rm h.c.}) + S^\dagger(-D^2 - M^2 - U(\phi))S + \mathcal{O}(S^3) \qquad \text{with} \quad U = \kappa|\phi|^2$$

$$B \sim A|\phi|^2$$

$$\mathcal{L}_{\rm eff} = \frac{1}{8}\frac{A^2 h^4}{M^2}\left[\frac{U}{M^2} + \frac{U^2}{M^4} + ..\right] \qquad \text{up to subdominant } (\partial^n U) \text{ terms}$$

1st order PT: $\dfrac{A^2}{M^2}\dfrac{U}{M^2} \sim \dfrac{4}{3}\dfrac{m_h^2}{v^2} \approx 0.2$

$\ll (4\pi)^2 \ll 1$

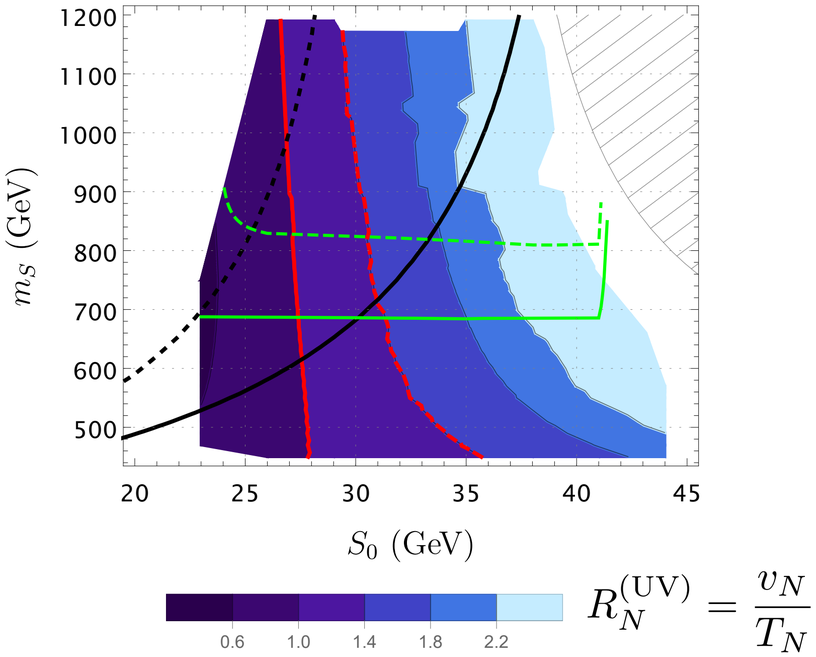
marginal

TREE LEVEL MATCHING — SINGLET

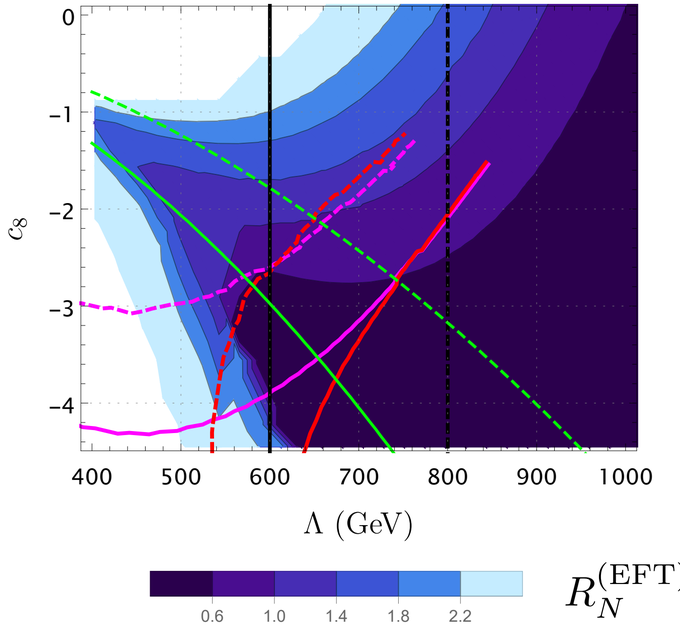
MP & Graham White ‘20

qualitative agreement w/ Damgaard et al. ’16

$\kappa = 4$



$R_N^{(\mathrm{UV})} = \dfrac{v_N}{T_N}$



$R_N^{(\mathrm{EFT})} = \dfrac{v_N}{T_N}$

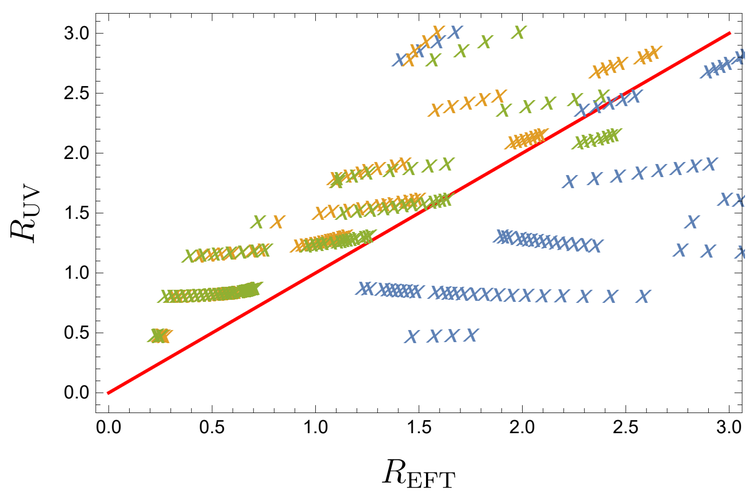
— $R_N^{(\mathrm{UV})} = 1\ (1.2)$

— $\dfrac{c_8 v^2}{\Lambda^2} = 0.5\ (0.3)$

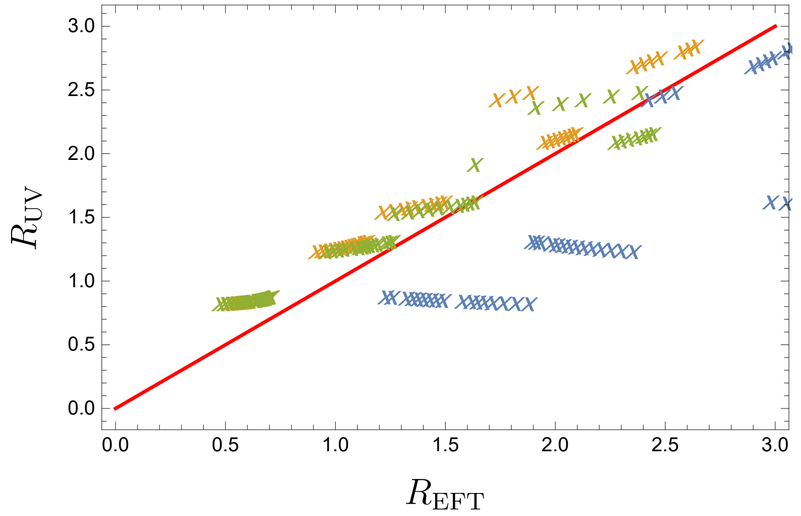
— $\Lambda = 600\ (800)$ GeV

TREE LEVEL MATCHING — SINGLET

MP & Graham White ‘20



all points $\frac{c_8 v^2}{\Lambda^2} < 0.5$



points with $\frac{c_8 v^2}{\Lambda^2} < 0.3$

- dim 6
- dim 6 + 8
- dim 6 + 8 + derivative

CONCLUSIONS

first order electroweak phase transition

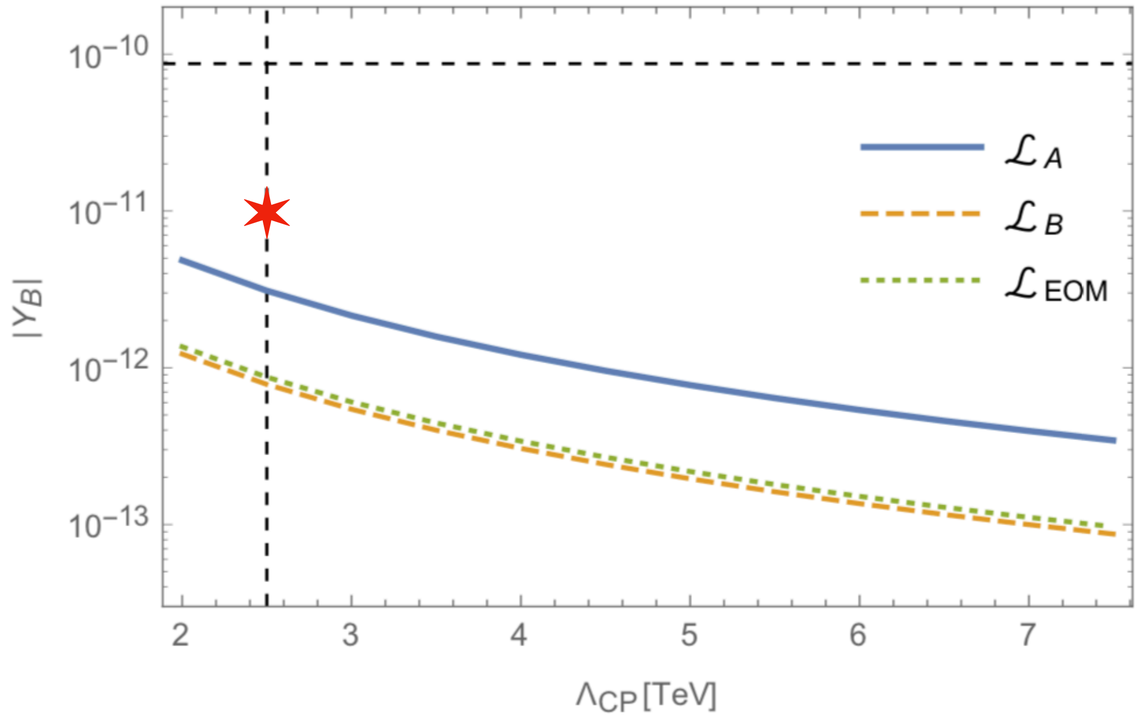
- requires new physics
- cosmological probes: gravitational waves, baryogenesis, ..

SM-EFT description not useful

- only singlet extension w/o Z_2-symm, only in part of parameter space, include dim-8 terms

results can be generalized to dark sector phase transitions

RESULTS FOR BARYON ASYMMETRY



Planck bound

✶ - including tau leptons