First Order Electroweak Phase Transition from sub-GeV Physics and Possible Link to Flavor

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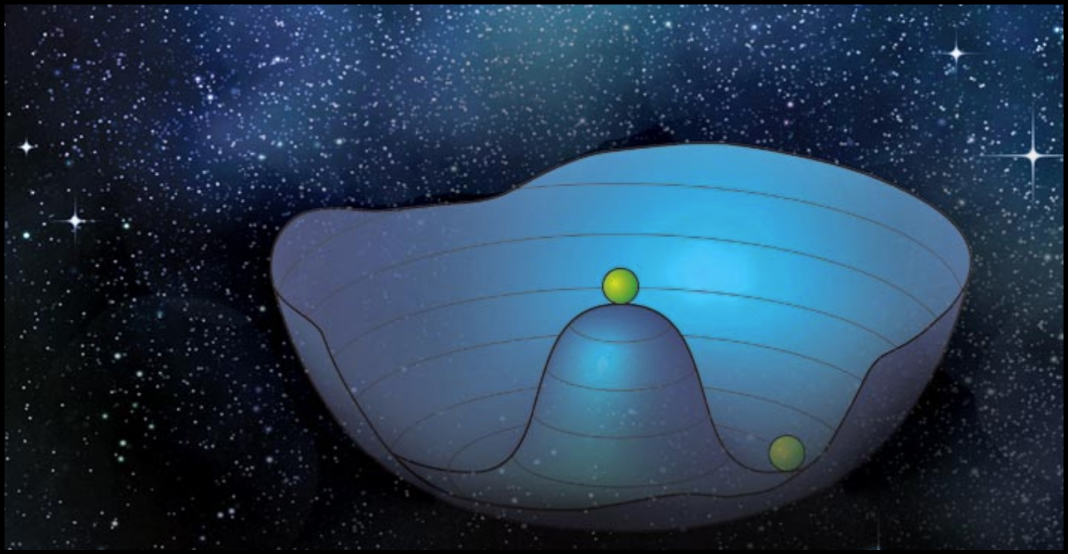


Based on: H.D., 2101.05319

Introduction:

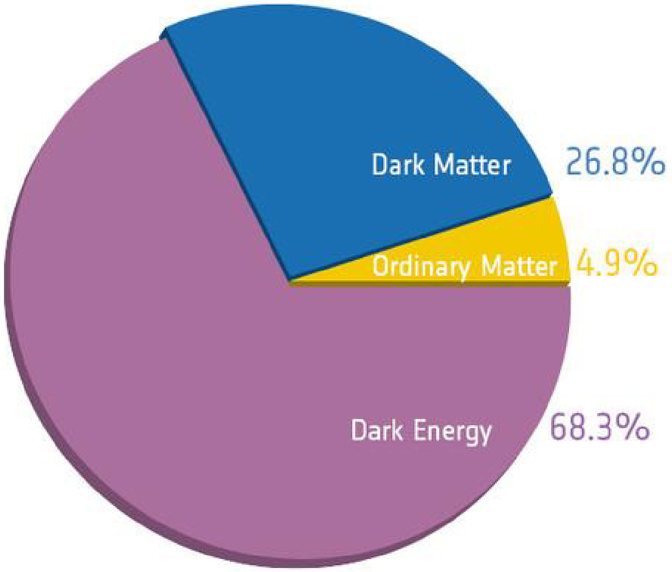
- A mostly "dark" Universe of unknown physics

Dark Energy: $\sim 68\%$; Dark Matter: $\sim 27\%$

- "Visible" Universe: $\sim 5\%$

- Known physics (atoms)

- But how did it come about?



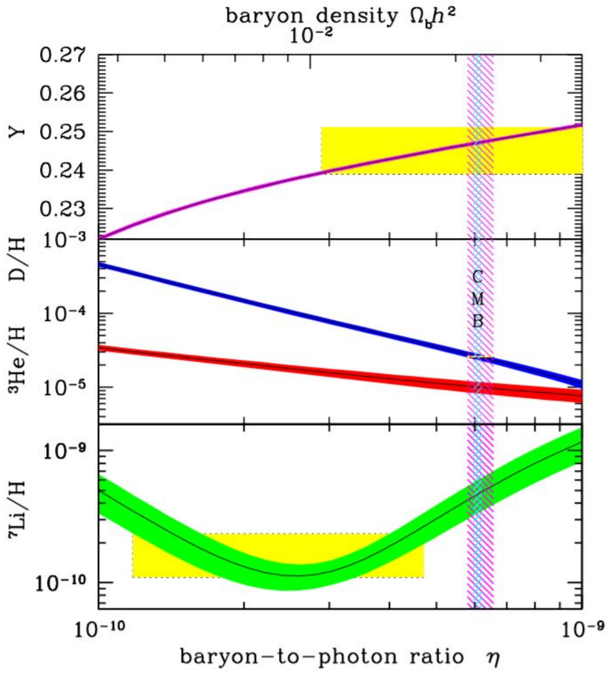
Planck

- Matter dominates over anti-matter

- Lack of cosmic annihilation signals, CMB, . . .

- Baryon asymmetry established after inflation

- Need a *baryogenesis* mechanism



PDG

- Baryogenesis generally requires three Sakharov conditions:

Sakharov, 1967

(i) Baryon number violation

(ii) C and CP violation

(iii) Departure from equilibrium

- SM does not provide sufficient levels of (ii) and (iii)

- Baryon asymmetry strongly motivates physics beyond SM (BSM)

- Sakharov condition (iii): needed to avoid erasing the asymmetry

- SM could have supplied (iii) if EW Phase Transition (EWPT) was first order
- Yet the measured Higgs mass ≈ 125 GeV too large, implies this was not the case
- Motivates BSM in order to have an EW First Order Phase Transition (FOPT)
- It is typically assumed that EW FOPT requires

Critical temperature T_c, Higgs vev v

$$\frac{v(T_c)}{T_c} \gtrsim 1$$

JodyDole/GettyImages

- SM: thermal contributions of W, Z gauge bosons *E.g.*, Quiros, 1999

$$\frac{v(T_c)}{T_c} = \frac{2m_W^3 + m_Z^3}{3\pi\lambda_H\, v^3} \approx 0.1$$

- SM Higgs quartic coupling $\lambda_H \approx 0.13$ for $m_H \approx 125$ GeV

$v = 246$ GeV, $\langle H \rangle = v/\sqrt{2}$

- Since $m_W, m_Z \propto v$, for $\lambda_H \to \sim \lambda_H/10$, a FOPT with $m_H \sim 40$ GeV

Assuming SM gauge couplings

- There have been numerous proposals for realizing an EW FOPT via BSM
- Adding new weak scale states with $\mathcal{O}(1)$ coupling to the Higgs
  - Thermal effects suppressed for states with masses $\gg \langle H \rangle$
- Addition of $(H^\dagger H)^{(2+n)}/\Lambda^n$ operators; $\Lambda \sim 1$ TeV
  - Allowing for deviations of λ_H to allow a FOPT
- Typically, expect states near weak scale and significant coupling to Higgs

See, e.g., Ramsey-Musolf, 1912.07189, and references therein

This talk*: a different approach, using sub-GeV physics weakly coupled to Higgs

- *Basic idea: λ_H starts small before EWPT, grows to its SM value afterwards*

- Stability of our model near weak scale suggests small top Yukawa before EWPT

- Conjecture: vanishing Yukawa couplings for all SM fermions before EWSB

- Other works considering alternative approaches include

- Using weakly coupled intermediate mass $\gtrsim 10$ GeV scalars:
Jeong, Jung, Shin, 1806.02591; Kozaczuk, Ramsey-Musolf, Shelton, 1911.10210

- Via axion-like particles: Jeong, Jung, Shin, 1811.03294

* We will not specify a baryogenesis mechanism, but consider FOPT as a potential key ingredient

A Model:

H.D., 2101.05319

$$\boxed{V(\phi, H, \eta) = \frac{m_{0\phi}^2}{2}\phi^2 - (\mu_0^2 + 2\mu\,\phi)H^\dagger H + (\lambda_0 + 2\frac{\phi^2}{M^2})(H^\dagger H)^2 + \frac{\kappa}{4}\phi^2\eta^2}$$

- $m_{0\phi}^2 > 0$, $\mu_0^2 > 0$, $\lambda_0 > 0$, and $0 < \mu \ll m_H$
- Scale $M \gg m_H$ descends from some ultraviolet (UV) dynamics
- Scalar η coupled to ϕ with $0 < \kappa \ll 1$, to allow a thermal "slow-roll" for ϕ
- η is initially massless
- Potential V consistent with a softly broken $\mathbb{Z}_2$ acting on ϕ
- Vacuum solutions with $\partial_h V = \partial_\phi V = \partial_\eta V = 0$; we will set $\langle\eta\rangle = 0$

$H \to (0, v + h)^T/\sqrt{2}$, with $\langle h\rangle = v = 246$ GeV

- Background value of ϕ at $T = 0$

$$\bar{\phi} = \frac{\mu\, v^2\, M^2}{m_{0\phi}^2 M^2 + v^4}$$

Induced by the tadpole term $\propto \phi H^\dagger H$

- To get SM values, $\mu_H \approx 89$ GeV and $\lambda_H \approx 0.13$, at $T = 0$

$$\mu_H^2 = \mu_0^2 + 2\mu\,\bar{\phi} \quad \text{and} \quad \lambda_H = \lambda_0 + 2\frac{\bar{\phi}^2}{M^2} \qquad \text{(A)}$$

- Parameterize $\lambda_0 = \varepsilon\lambda_H$, with $\varepsilon \lesssim 0.1$
- Higgs and ϕ mix after EWSB, governed by mixing angle

$$\theta \approx \frac{2v^2}{m_H^2}\left(\frac{2\bar{\phi}\,v}{M^2} - \frac{\mu}{v}\right)$$

- For $|\theta| \ll 1$, $m_H \approx \sqrt{2}\,\mu_H$ (approximately SM) and lightest scalar mass

$$m_\phi^2 \approx m_{0\phi}^2 + \frac{v^4}{M^2} - \theta^2\,m_H^2$$

- We choose benchmark values; fix $\bar{\phi}$ from (A) above

$$\boxed{\varepsilon = 0.1 \quad \text{and} \quad M = 4.0 \times 10^3 \text{ TeV}}$$

- With $\bar{\phi}$ fixed $\Rightarrow$ $m_{0\phi}$ and θ functions of μ

- (I) Stable potential: $m^2_{0\phi} > 0$ (II) triggering symmetry breaking: $\mu_0^2 > 0$

$$\text{(I) and (II)} \Rightarrow \frac{\bar{\phi}\, v^2}{M^2} < \mu < \frac{\mu_H^2}{2\bar{\phi}} \qquad \text{(B)}$$

- For benchmark values: $\boxed{5\ \text{MeV} \lesssim m_\phi \lesssim 10\ \text{MeV}}$

Thermal Evolution

- Degenerate minimum at critical temperature $T_c \approx \frac{T_0}{\sqrt{1 - E^2/(\lambda_0\, D)}}$

\- Barrier disappears at $T = T_0$

$$T_0^2 = \frac{m^2_{0H} - 8Bv_0^2}{4D}\ ;\ B = \frac{3(2m_W^4 + m_Z^4 - 4m_t^4)}{64\pi^2 v^4}$$
$$D = \frac{2m_W^2 + m_Z^2 + 2m_t^2}{8v^2}\ ;\ E = \frac{2m_W^3 + m_Z^3}{6\pi v^3}$$

\- Initial values ($\langle\phi\rangle = 0$): $m_{0H} = \sqrt{2}\,\mu_0$, and $v_0^2 = \mu_0^2/\lambda_0$

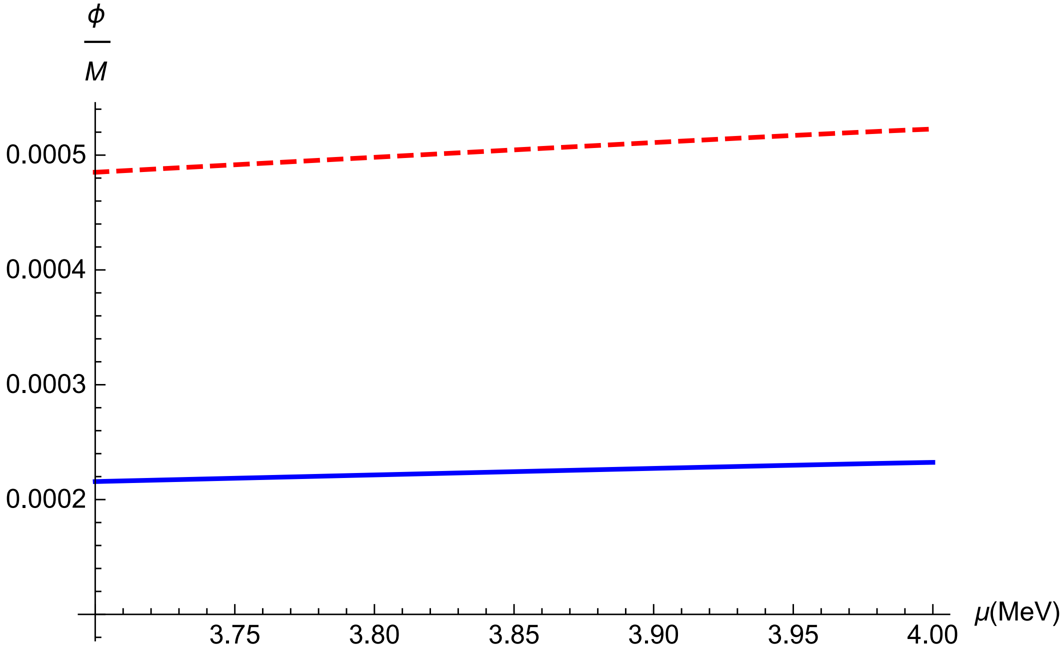
\- $m_t = 0$ (vanishing top Yukawa) chosen here, for vacuum stability as explained later

- $T_c = 0$ not sensible at upper limit in (B); choose a slightly smaller upper limit

$\boxed{3.7\ \text{MeV} \le \mu \le 4.0\ \text{MeV}} \Rightarrow 38\ \text{GeV} \le T_c \le 90\ \text{GeV}$ and $37\ \text{GeV} \le T_0 \le 87\ \text{GeV}$

- Underlying assumption: FOPT is achieved for $\phi \approx 0$
- Thermal effects mediated by η that are $\propto \kappa$ pin ϕ near origin

$$\frac{\phi(T)}{M} = \frac{\mu\, h^2(T)}{m_\phi^2(T) M} \quad \text{where} \quad m_\phi^2(T) = m_{0\phi}^2 + \frac{h^4(T)}{M^2} + \frac{\kappa}{24}T^2$$



ϕ/M at T_c (solid) and T_0 (dashed), for benchmark parameters and $\kappa = 10^{-4}$

- Numerical inspection: ϕ/M remains small down to $T \sim 10$ GeV
- One can show that η and ϕ in thermal equilibrium
- $m_\eta \sim \kappa^{1/2}\bar{\phi} \sim 10$ TeV; η can decay fast, *e.g.* via $\eta F_{\mu\nu}F^{\mu\nu}/M_\eta$, with $M_\eta \lesssim 10^{18}$ GeV

UV Stability

- FOPT through small $\lambda_0 \sim 0.01$ can lead to instability
- This is a quantum (running) effect from $y_t \sim 1$ top Yukawa

$$16\pi^2 \frac{d\lambda_0}{dt} = 24\lambda_0^2 + \lambda_0(12y_t^2 - 9g^2 - 3g'^2) - 6y_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2 g'^2$$

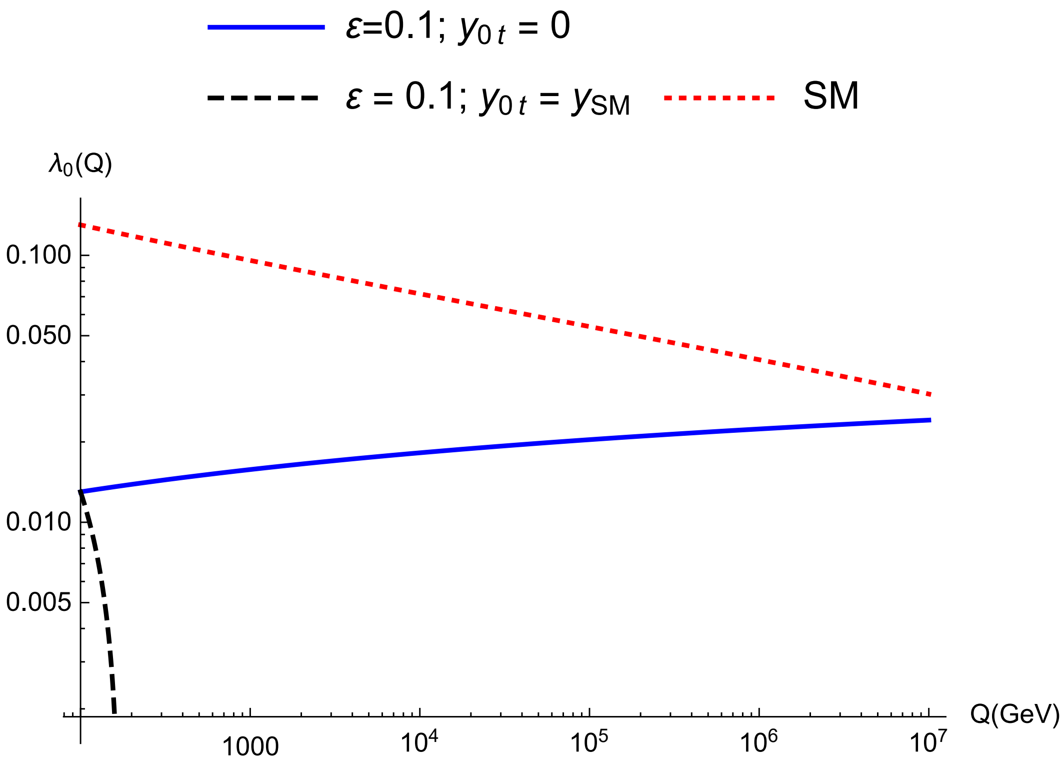
- $\{g, g'\}$ are $\{SU(2)_L,\ U(1)_Y\}$ gauge couplings, respectively
- $t \equiv \ln Q/Q_0$, with $Q_0 = 100$ GeV reference scale
- With our benchmark choices λ_0 goes negative ("instability") for $Q \gtrsim 170$ GeV
- Too close to $T_c \sim 100$ GeV to allow for a reasonable theory
- If $y_t \ll 1$ *initially* one could avoid this problem
- After FOPT, dynamics of ϕ could allow for y_t to rise to SM value

- We introduce

$$O_t = \frac{\phi}{M_t} H^* \epsilon\, \bar{Q}_L t_R + \text{H.C.} \qquad [Q_L = (t,b)_L; t_R\ \mathbb{Z}_2\ \text{odd}]$$

$$\Rightarrow\ y_t^{\text{SM}}(Q_0) = y_{0t}(Q_0) + \frac{\bar{\phi}}{M_t}$$

- Initial dim-4 top Yukawa $y_{0t} = 0$; for $y_t^{\text{SM}}(Q_0) \approx 0.92 \rightarrow M_t \approx 1.1 \times 10^3$ TeV



Running of λ_0, for $\lambda_0(Q_0) = 0.1\lambda_H$, with $Q_0 = 100$ GeV

Flavor from ϕ

- $\mathbb{Z}_2$ odd t_R not fundamentally different from other fields in our model
- We thus extend ϕ-induced Yukawa coupling to all fermions; schematically

$$O_f = \frac{\phi}{M_f} H \, \bar{F}_L f_R + \text{H.C.}$$

F: $SU(2)_L$ doublet containing flavor f

\- In general, one needs a Yukawa matrix defined by flavor-dependent coefficients

- Assuming vanishing initial Yukawa couplings

$$y_f^{\text{SM}}(Q_0) = \frac{\bar{\phi}}{M_f} \quad \Rightarrow \quad M_f = \frac{y_t^{\text{SM}}(Q_0)}{y_f^{\text{SM}}(Q_0)} M_t$$

\- After mass matrix diagonalization

- *Direct* coupling of the fermion f to ϕ: $\xi_f = \langle H \rangle / M_f$

ε	κ	M (TeV)	M_t (TeV)
0.1	10^{-4}	4.0×10^3	1.1×10^3

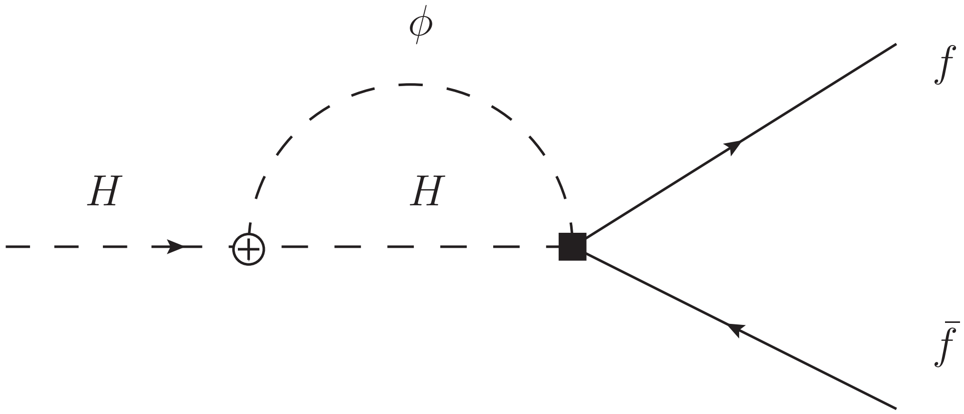
Benchmark input parameters

- Softly broken $\mathbb{Z}_2$: loop-induced Yuakwa couplings
- For top quark, with our reference parameters

$$\delta y_t(Q_0) \sim \frac{\mu}{16\pi^2 M_t} \ln(M_t/Q_0) \sim 10^{-10},$$

- Completely negligible, does not affect stability

- Smaller for lighter fermions



$\oplus$: $\mathbb{Z}_2$ soft-breaking interaction $\propto \mu$; ■: dimension-5 O_f operator

Couplings of ϕ to Fermions

- Including mixing, the total coupling $\bar{\xi}_f \phi\, \bar{f}_L f_R +$ H.C. given by

$$\boxed{\bar{\xi}_f \equiv \xi_f + \theta\, y_f^{\text{SM}}}$$

- One can show that in our model $\theta\, y_f \sim \xi_f$

- For electron Yukawa we find $M_e \approx 3.3 \times 10^{11}$ GeV

- Assuming Dirac neutrinos with $y_\nu^{\text{SM}}(Q_0) \sim 10^{-12} \Rightarrow M_\nu \sim 4 \times 10^{18}$ GeV

- Close to, but below, Planck mass $M_P \sim 10^{19}$ GeV

- All flavor can arise from ϕ dynamics coupled to scales $\sim 10^3$ TeV $- M_P$

- Alternatively, the UV scale $\sim 10^3$ TeV, with hierarchic ϕ couplings to fermions

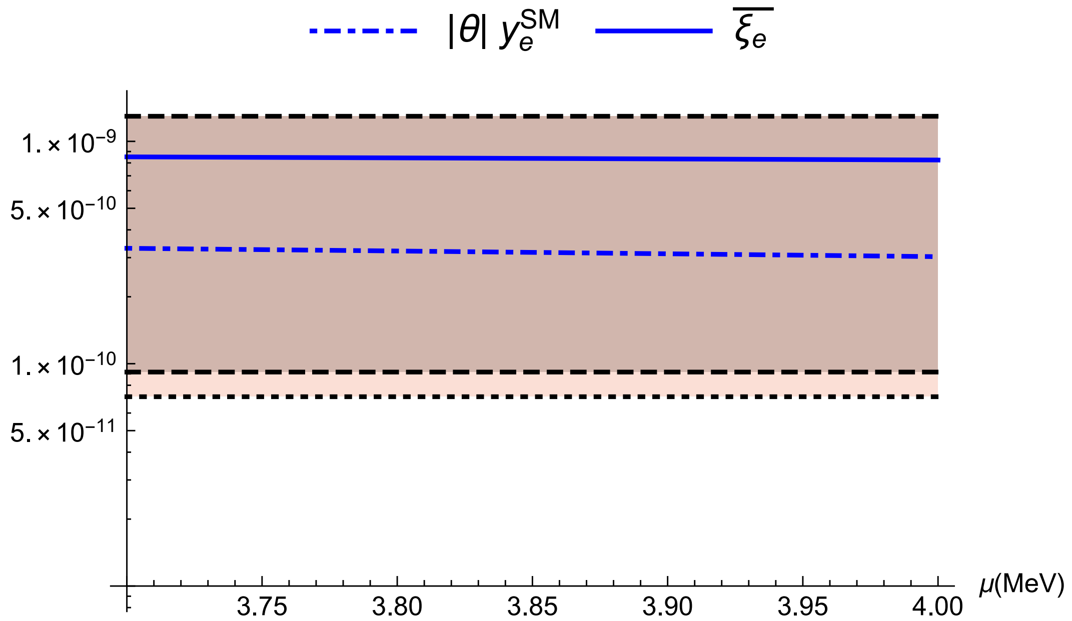
- For benchmark values, ϕ decay length typically macroscopic

$$c\,\tau_\phi \approx \frac{8\pi}{\bar{\xi}_e^2\, m_\phi} \approx 8.4 \times 10^3 \text{ km} \left(\frac{8.4 \times 10^{-20}}{\bar{\xi}_e^2}\right)\left(\frac{7 \text{ MeV}}{m_\phi}\right) \qquad (m_\phi < 2m_\mu)$$

c speed of light and $y_e \approx 2.9 \times 10^{-6}$ SM electron Yukawa coupling

- Generally expect ϕ to escape as missing energy in laboratory experiments

- For purposes of illustration, let $m_\phi = 7$ MeV (typical for our parameters)



- Allowed region between dashed lines

G. Krnjaic, 2015

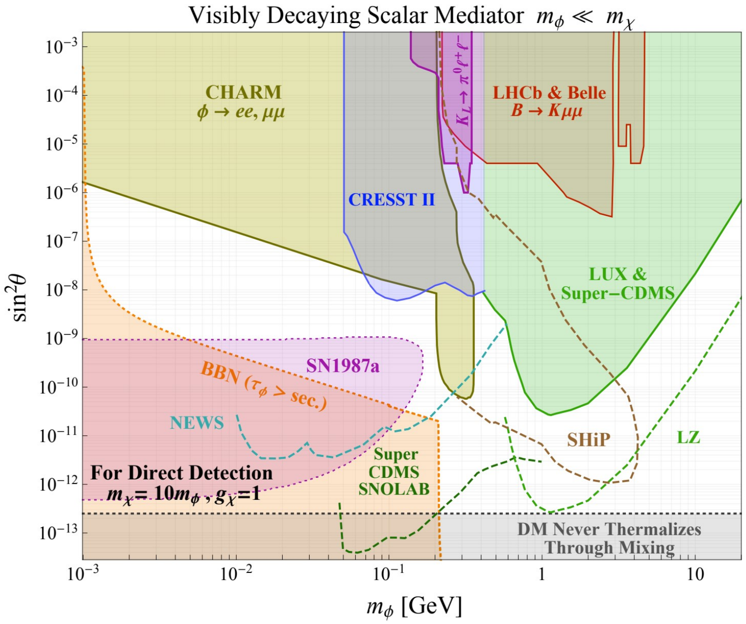
- Revised SN bounds

Dev, Mohapatra, Zhang, 2020

\- BBN sets lower limit, dotted line

- We get $\bar{\xi}_t \approx 2.6 \times 10^{-4}$; allowed by known bounds

See, *e.g.*, Foroughi-Abari, Ritz, 2020



From G. Krnjaic, Phys. Rev. D 94, 073009 (2016), 1512.04119

Low Energy Tests

- ϕ can appear as missing energy in rare meson decays

- Example: KOTO, measuring $K_L \to \pi^0 \bar{\nu}\nu$, to $\sim 10\%$

- SM prediction for branching fraction: $3.4 \pm 0.6 \times 10^{-11}$

Cirigliano, Ecker, Neufeld, Pich, Portoles, 2011; Egana-Ugrinovic, Homiller, Meade, 2019

- A few anomalous events were observed by KOTO   Shinohara (KOTO), 2020

- ϕ-top coupling in the 1-loop penguin diagram for $K_L \to \pi^0 \phi$ can mimic the events

- ϕ-top coupling $\sim 2 \times 10^{-4}$ and $m_\phi \lesssim 50$ MeV could yield a 2σ explanation

Egana-Ugrinovic, Homiller, Meade, 2019; Kitahara, Okui, Perez, Soreq, Tobioka, 2019

- KOTO has since concluded events are consistent with background

Ahn *et al.* (KOTO), 2020

- Future KOTO measurements can potentially probe $\bar{\xi}_t \lesssim 10^{-5}$

- Generically, also expect gravitational waves from the FOPT

\- Possibly detectable by *e.g.* LISA   See, for example, Caprini *et al.*, 2019

Summary

- FOPT, a possible key element in weak scale baryogenesis, not feasible in SM with $m_H \approx 125$ GeV

- Typically need to extend SM with particles near weak scale with $\mathcal{O}(1)$ couplings to get FOPT

- We propose that a smaller *initial* Higgs quartic could result in a FOPT

- Proposal: dynamics of a weakly coupled sub-GeV scalar can yield the late time SM Higgs potential

- Stability of our scenario suggests top Yukawa coupling initially small or vanishing

- Natural extension to all fermions: flavor turns on after EWSB, via operators suppressed by scales $\sim 10^3$ TeV (top) to near Planck mass (Dirac neutrinos)

- The sub-GeV scalar is typically long-lived, can show up as missing energy in rare meson decays

- KOTO, for example, can probe this scenario in $K_L \to \pi^0 +$ "missing energy"

- Generically also expect primordial gravitational waves from weak scale FOPT

\- Potential signal for future observatories, like LISA