First Order Electroweak Phase Transition from sub-GeV Physics

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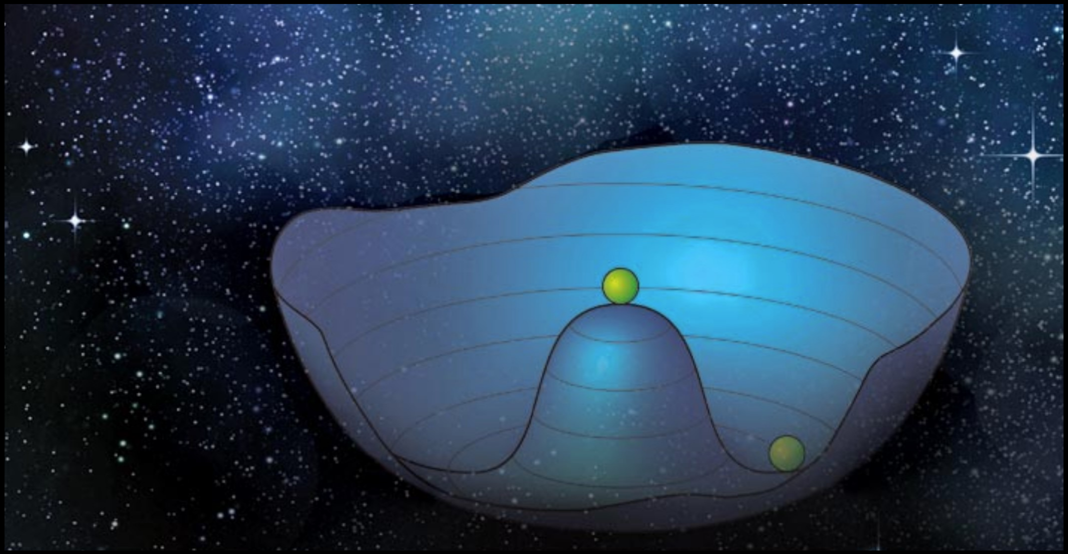


Based on: H.D., Phys.Rev.D 103 (2021) 8, 083534; 2101.05319 [hep-ph]

DPF21 (virtual), July 12-14, 2021

Introduction:

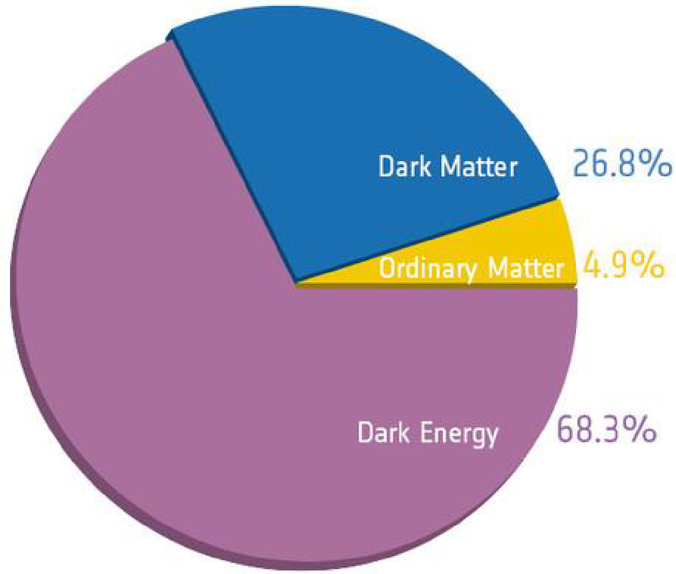
- A mostly "dark" Universe of unknown physics

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

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

- Known physics (atoms)

- But how did it come about?



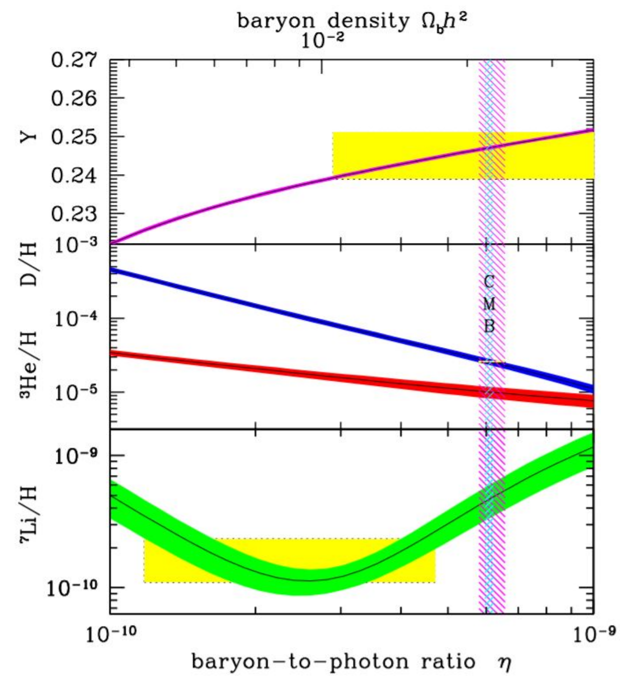
Planck

- Matter dominates over anti-matter

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

- Baryon asymmetry established after inflation

- Need a *baryogenesis* mechanism



PDG

- Baryogenesis generally requires *departure from equilibrium*
  Sakharov, 1967

- Could be satisfied for first order phase transition (FOPT)

- Typically assumed that EW FOPT requires

Critical temperature T_c, Higgs vev v

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

- 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 $m_W, m_Z \propto v$, FOPT for $\lambda_H \to \sim \lambda_H/10$ ($m_H \sim 40$ GeV)

- Motivates beyond SM (BSM) physics

- Typically, expect states near weak scale and significant coupling to Higgs

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

This talk*:

Different approach with sub-GeV physics weakly coupled to Higgs

- *Basic idea: λ_H small before EWPT, grows to SM value afterwards*
- Stability near weak scale suggests small top Yukawa before EWPT
- Extension: Yukawa couplings for all SM fermions *after* 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

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

- $M \gg m_H$; $0 < \mu \ll m_H$; softly broken $\mathbb{Z}_2$ acting on ϕ
- Solutions with $\partial_h V = \partial_\phi V = \partial_\eta V = 0$; set $\langle\eta\rangle = 0$
- Background value of ϕ at $T = 0$ (tadpole term $\propto \phi H^\dagger H$)

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

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

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

- Parameterize $\lambda_0 = \varepsilon\lambda_H$, with $\varepsilon \lesssim 0.1$
- Thermal effects $\propto \kappa$ from η: $\dfrac{\phi}{M} \ll 1$ for $T \gtrsim 10$ GeV ($\kappa \sim 10^{-4}, m_\eta \sim 10$ TeV)
- Benchmark values: $\boxed{\varepsilon = 0.1 \quad \text{and} \quad M = 4.0 \times 10^3 \text{ TeV}}$; fix $\bar{\phi}$ from (A)

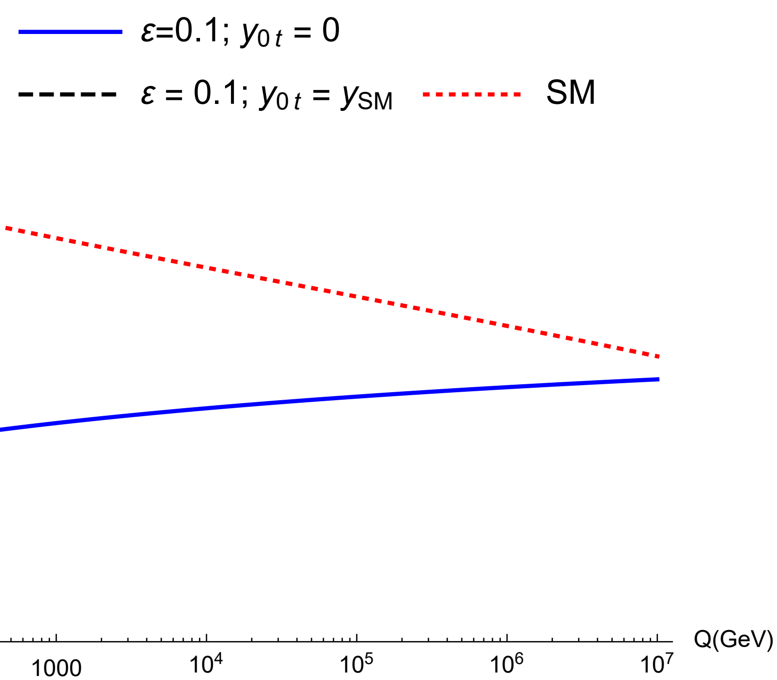
UV Stability

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

$\{g, g'\}$ are $\{SU(2)_L,\ U(1)_Y\}$ gauge couplings, $t \equiv \ln Q/Q_0$, with $Q_0 = 100$ GeV reference scale

- Benchmark values: $\lambda_0 < 0$ ("instability") for $Q \gtrsim 170$ GeV; too close to T_c
- *Arrange for vanishing* y_t *before FOPT* [$Q_L = (t, b)_L; t_R\ \mathbb{Z}_2$ odd]

$$O_t = \frac{\phi}{M_t} H^* \epsilon \bar{Q}_L t_R + \text{H.C.} \Rightarrow\ y_t^{\text{SM}}(Q_0) = y_{0t}(Q_0) + \frac{\bar{\phi}}{M_t}$$



$\lambda_0(Q_0) = 0.1\lambda_H$, with $Q_0 = 100$ GeV; $y_{0t} = 0$; for $y_t^{\text{SM}}(Q_0) \approx 0.92 \to M_t \approx 1.1 \times 10^3$ TeV

Flavor from ϕ

- Extending ϕ-induced Yukawa coupling to all fermions F: SM $SU(2)_L$ doublet

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

- Assuming vanishing initial Yukawa couplings

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

- *Direct* coupling of the fermion f to ϕ: $\xi_f = \langle H \rangle / M_f$
- Including mixing, total coupling $\bar{\xi}_f \equiv \xi_f + \theta \, y_f^{\text{SM}}$ (One can show $\theta \, y_f \sim \xi_f$ in this model)
- Benchmark values: ϕ decay length typically macroscopic   (missing energy signal)

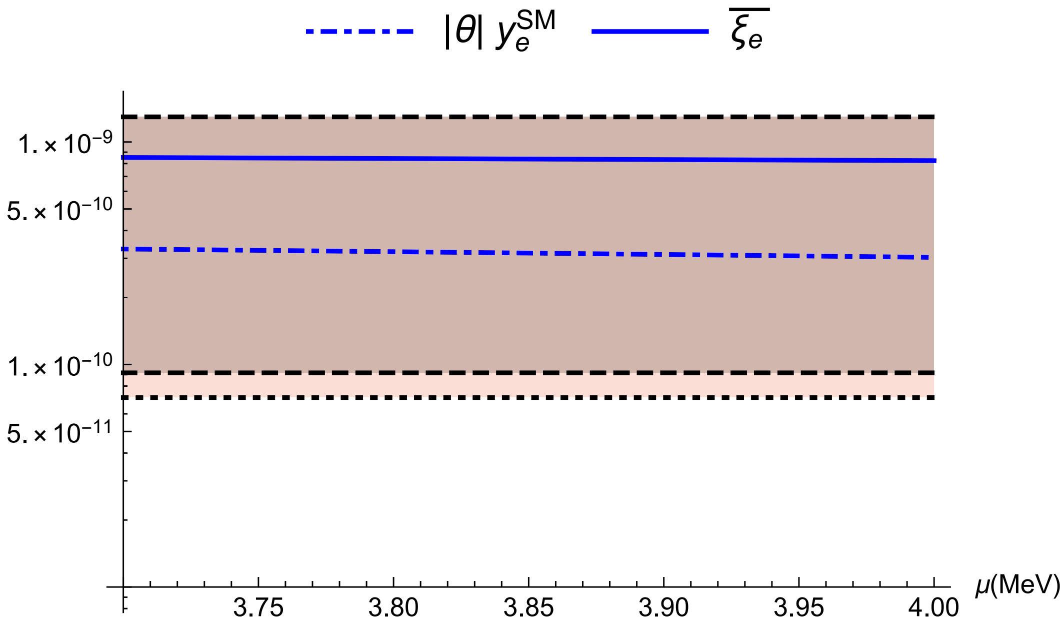
$$c \, \tau_\phi \approx \frac{8\pi}{\bar{\xi}_e^2 \, m_\phi} \approx 8.4 \times 10^3 \text{ km} \left(\frac{8.4 \times 10^{-20}}{\bar{\xi}_e^2} \right) \left(\frac{7 \text{ MeV}}{m_\phi} \right)$$

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

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

Benchmark input parameters

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



- Allowed region between dashed lines

G. Krnjaic, 2015

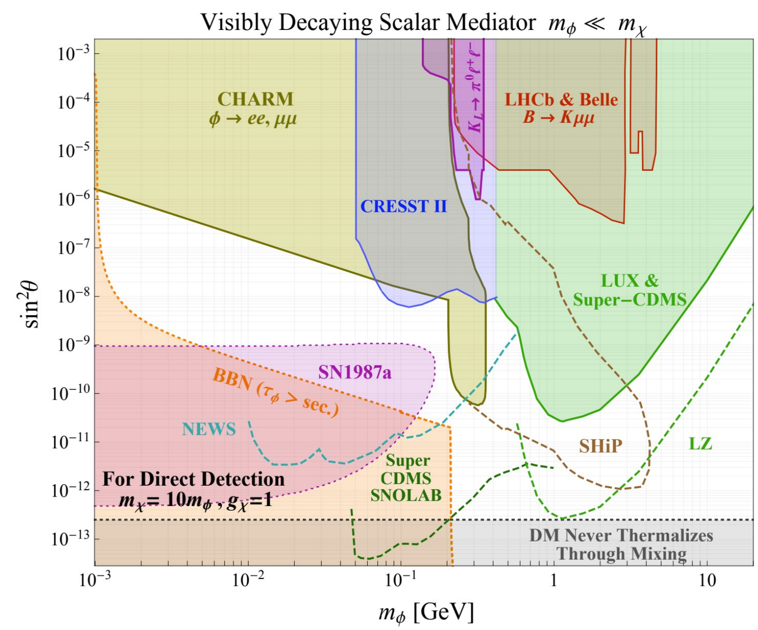
- Revised SN bounds

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: key element in EW baryogenesis, not feasible in SM with $m_H \approx 125$ GeV
- Typical extensions: particles near weak scale with $\mathcal{O}(1)$ couplings to get FOPT
- We propose that a smaller *initial* Higgs quartic λ_H could result in a FOPT
- Proposal: dynamics of a weakly coupled sub-GeV scalar ϕ later yields SM
- Stability: top Yukawa initially small or zero, grows with ϕ to observed value
- Extension to all fermions: governed by scales $\sim 10^3$ TeV (t) to $\sim \bar{M}_{\rm P}$ (Dirac ν)
- ϕ typically long-lived, can give missing energy signals 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