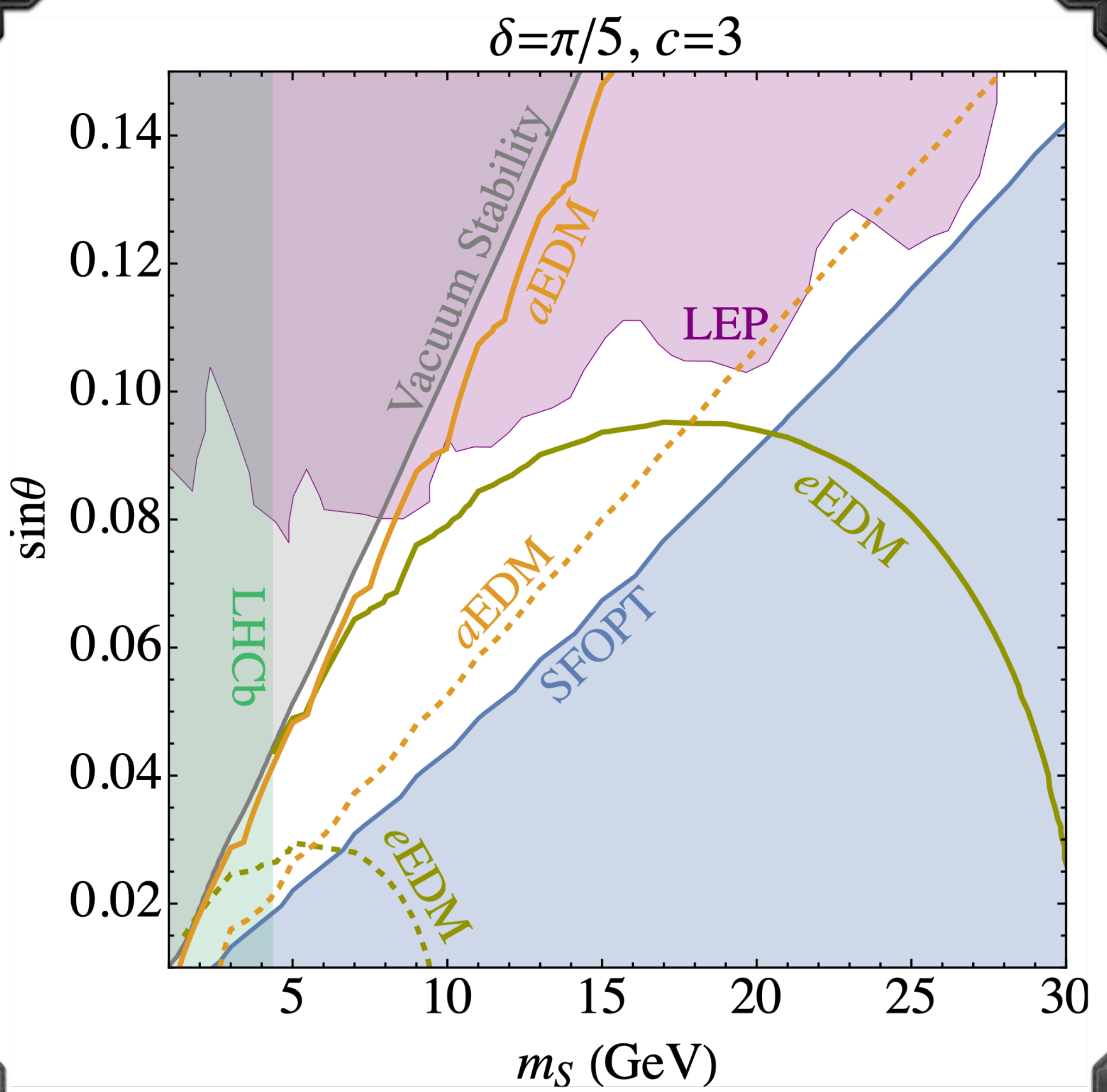
ALP-Assisted Electroweak Phase Transition

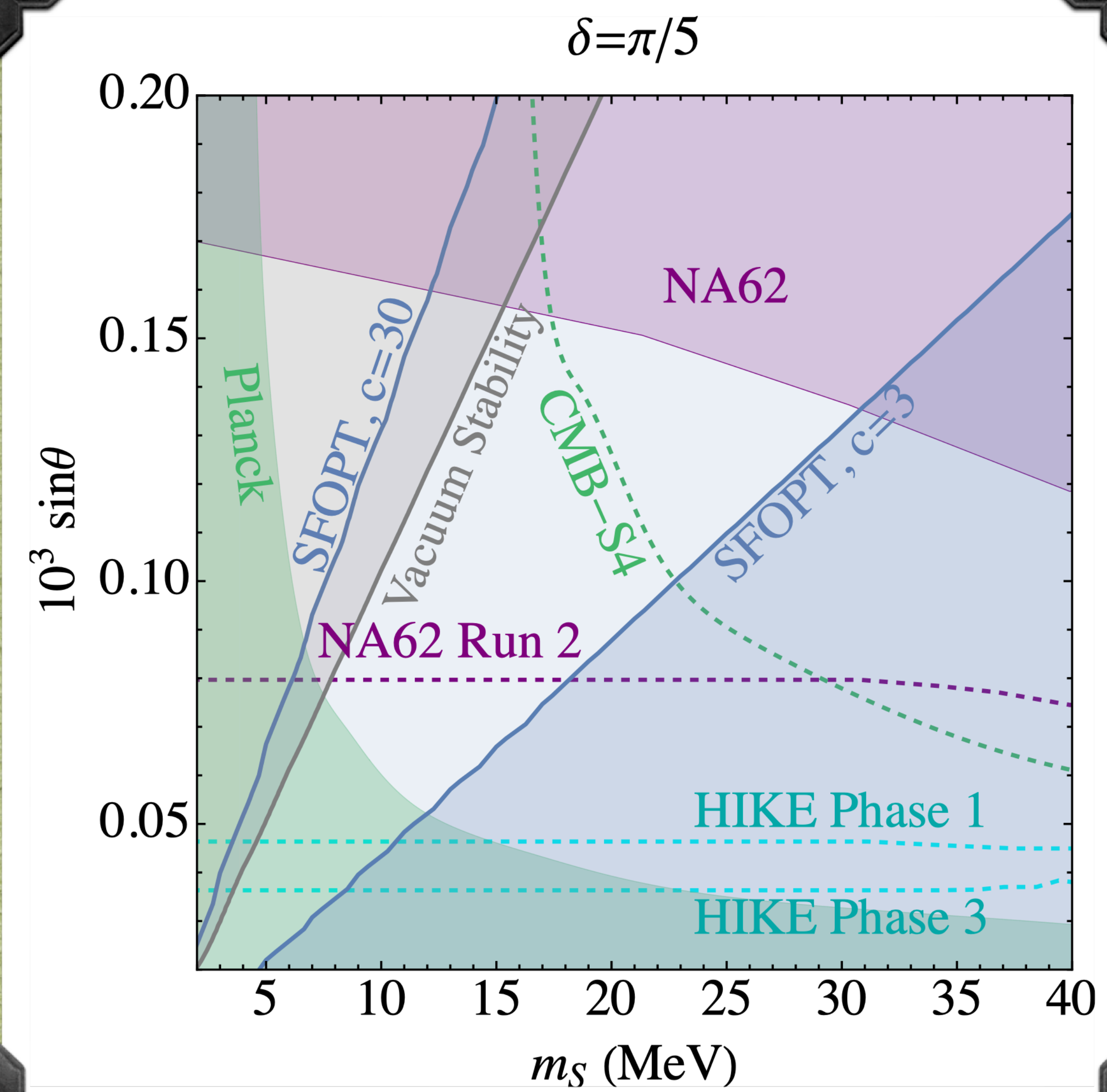
Isaac Wang

Fermilab

In collaboration with: Keisuke Harigaya

arXiv: 2309.00587





A Quick View

Probing ALP in various experiments

Table of Contents

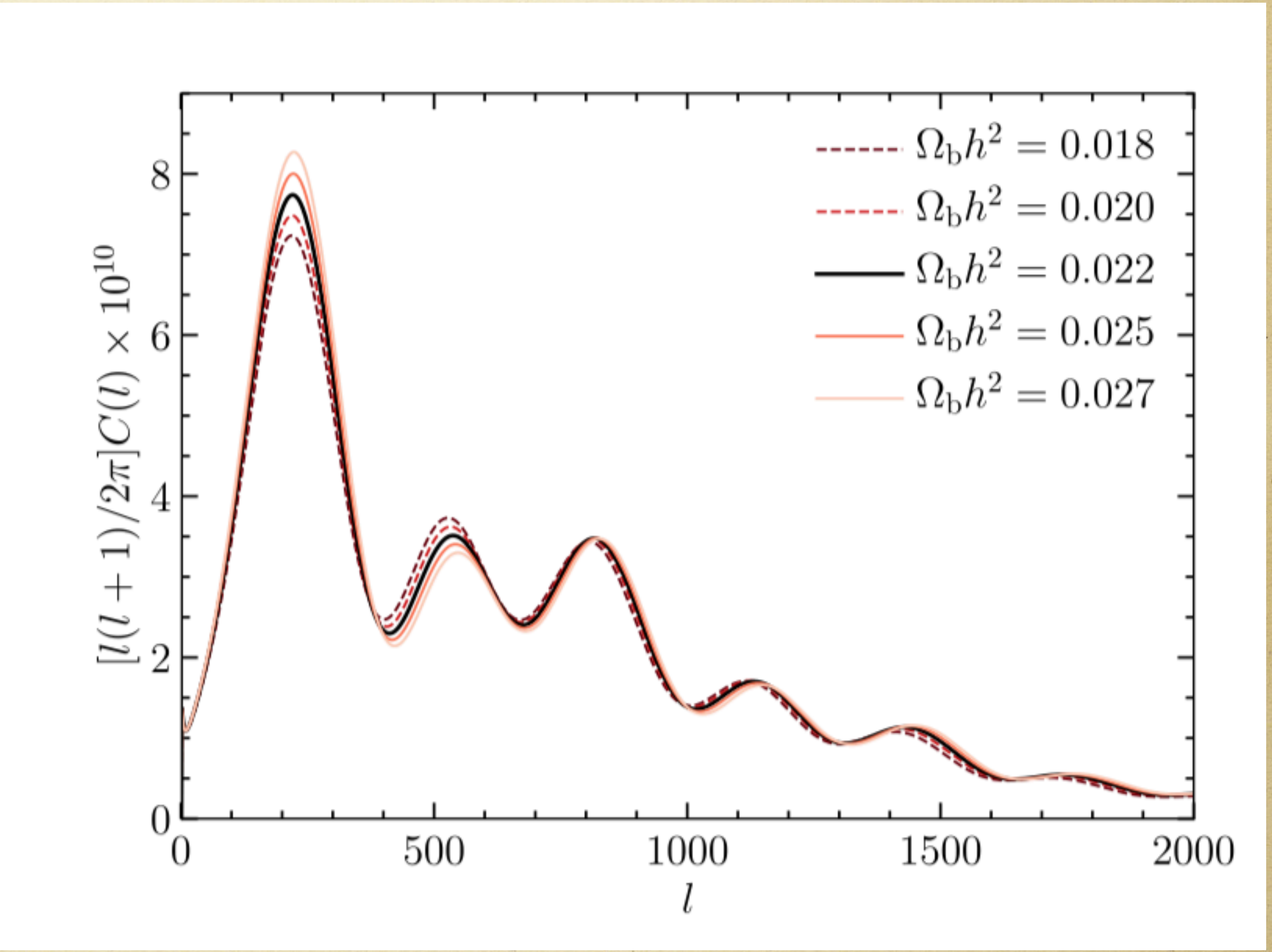
- Introduction: challenges of electroweak baryogenesis
- Axion-like particle assisting EWPT
- Experimental probes: EDM, beam-dump, collider

Table of Contents

- Introduction: challenges of electroweak baryogenesis
- Axion-like particle assisting EWPT
- Experimental probes: EDM, beam-dump, collider

Baryogenesis problem

- Matter > antimatter
- $\frac{n_B}{s} \simeq 9 * 10^{-11}$
- Why?



Planck 2018b

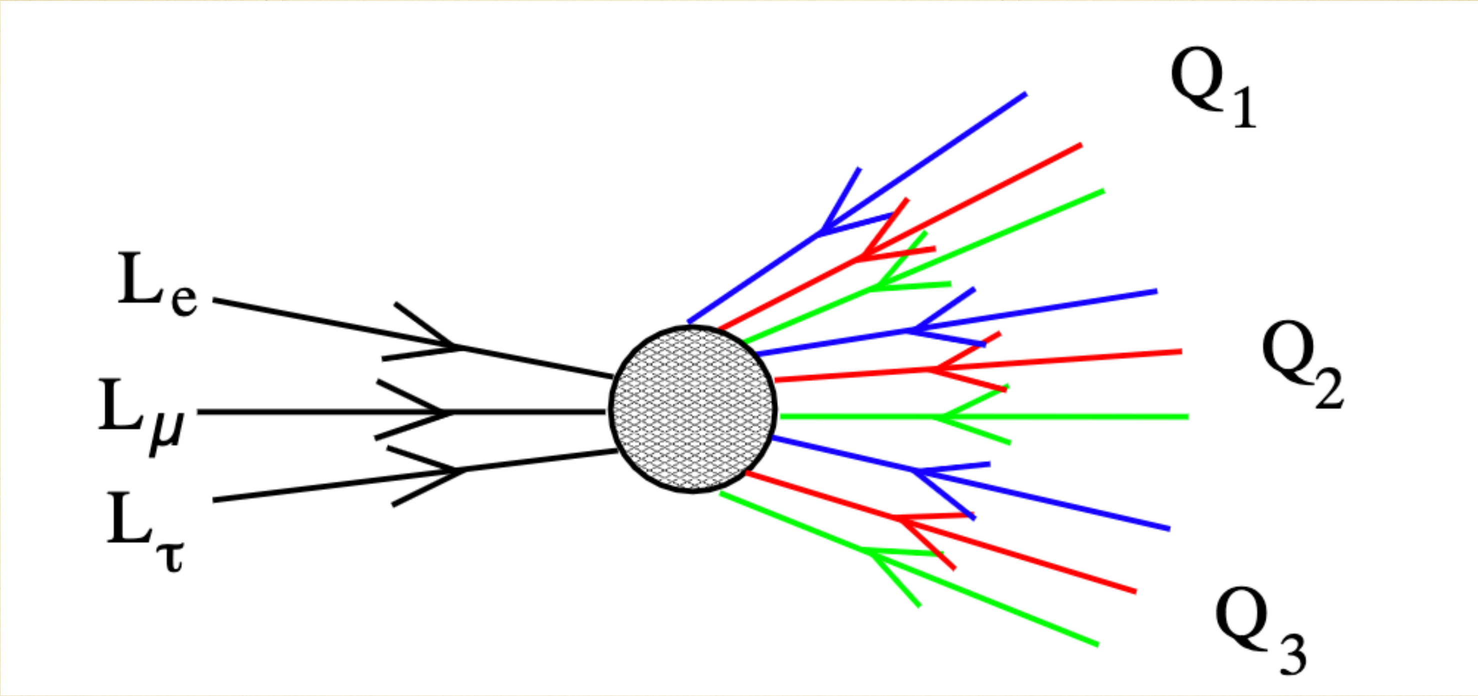
Necessary condition for baryogenesis

- B violation: sphaleron process
- C and CP violation: model-dependent
- Out of equilibrium: ?

  Electroweak phase transition?

[Sakharov, 1967]

Sphaleron



- *B* and *L* number are anomalous!
- $$\partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \frac{3g^2}{32\pi^2} W\tilde{W}$$
- $B - L$ is conserved.

[G. 't Hooft, Phys. Rev. Lett. 37, 8 (1976)]

Electroweak phase transition

- Higgs potential
- $T = 0$: $V = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$, symmetry breaking
- $T > 0$: finite temperature correction.
- Very high T: "symmetry restoration"
- T_c: $h = 0$ and $h = v$ degenerate, "critical temperature"

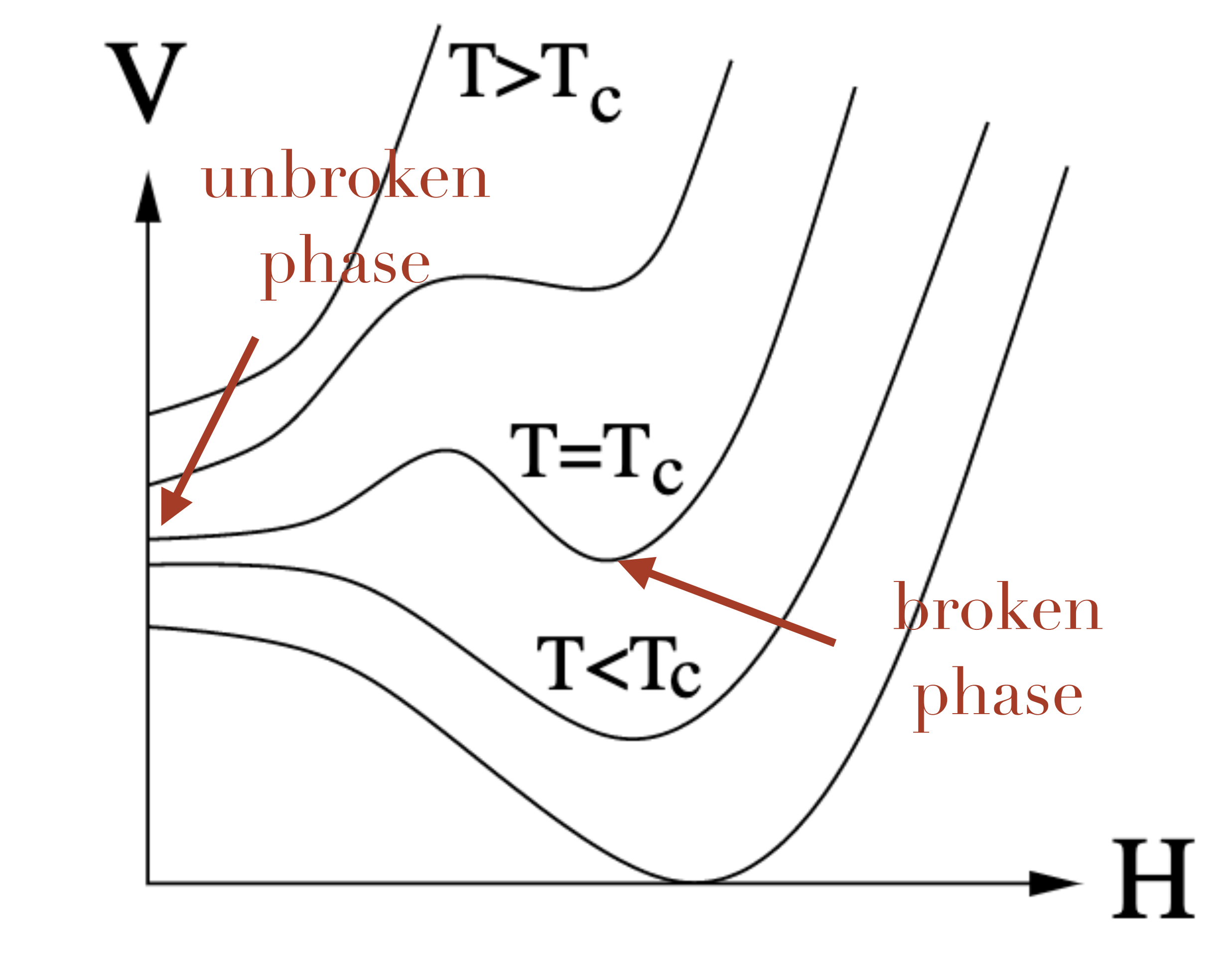
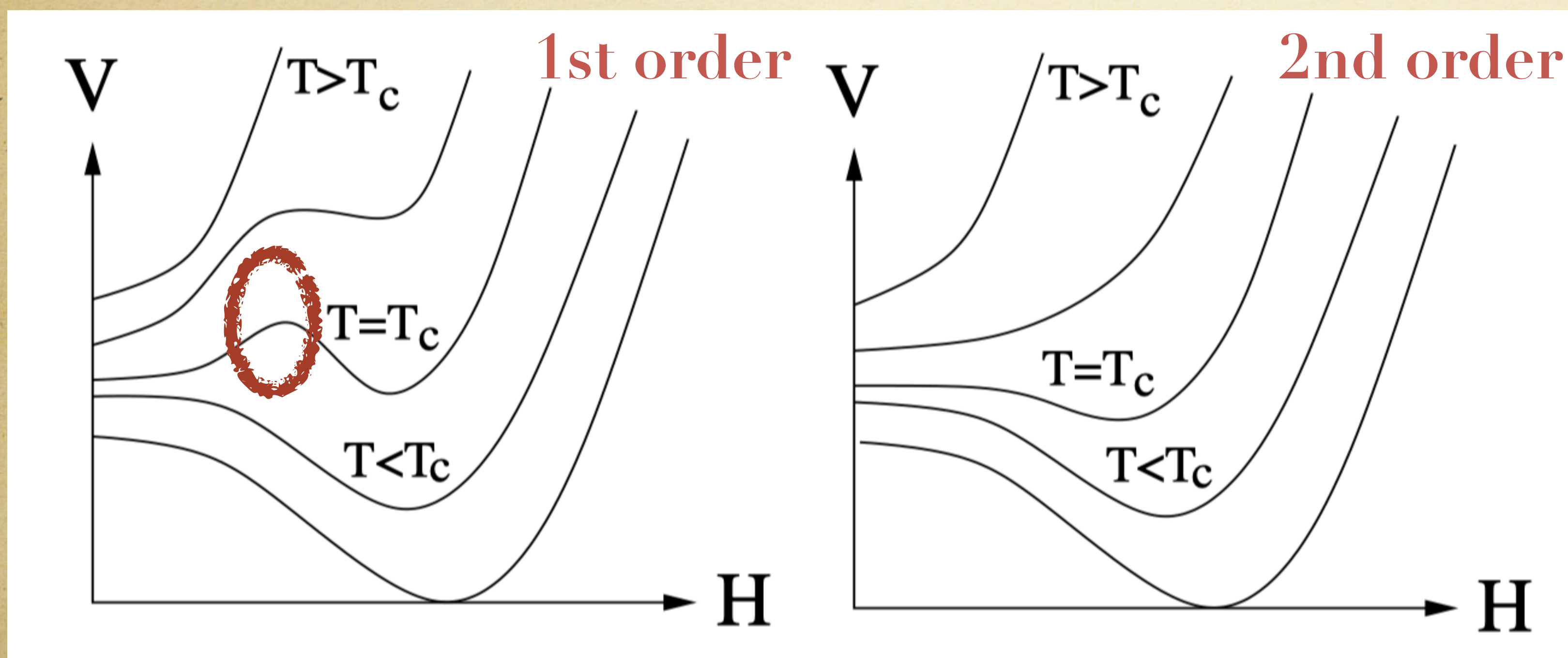
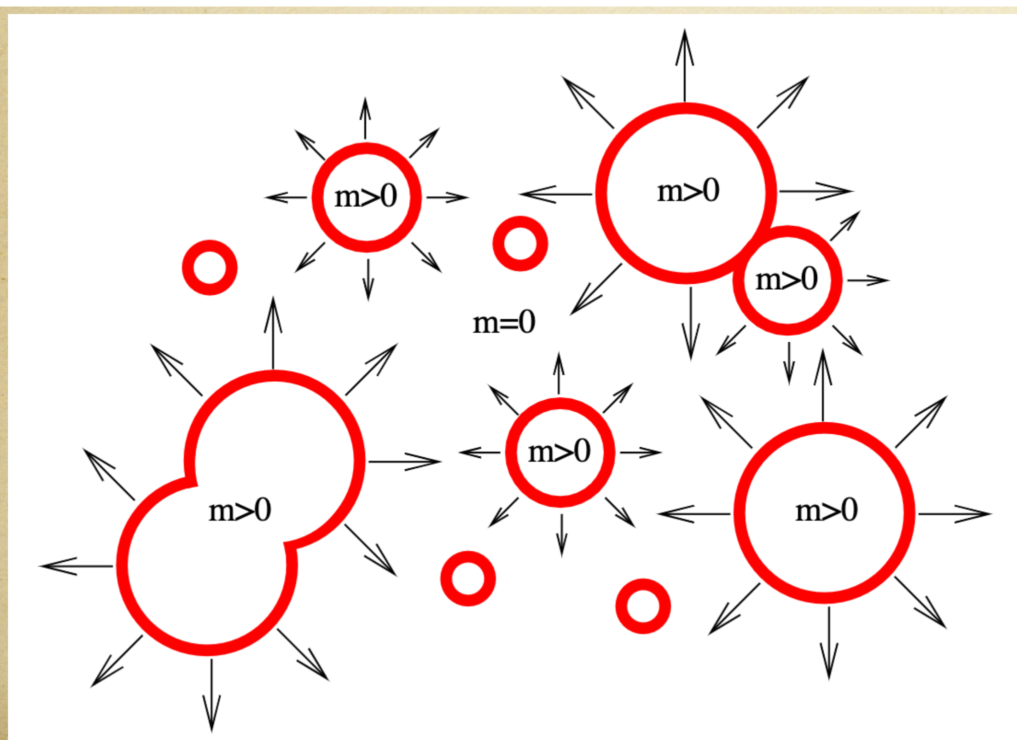


Figure from: J Cline: hep-ph/0609145

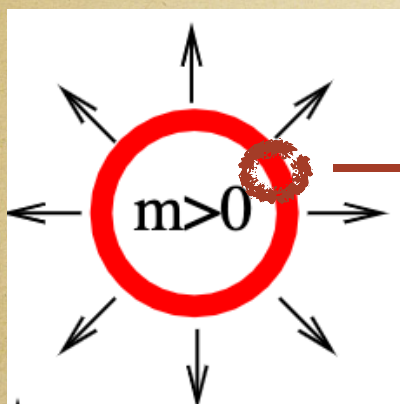
1st order vs 2nd order

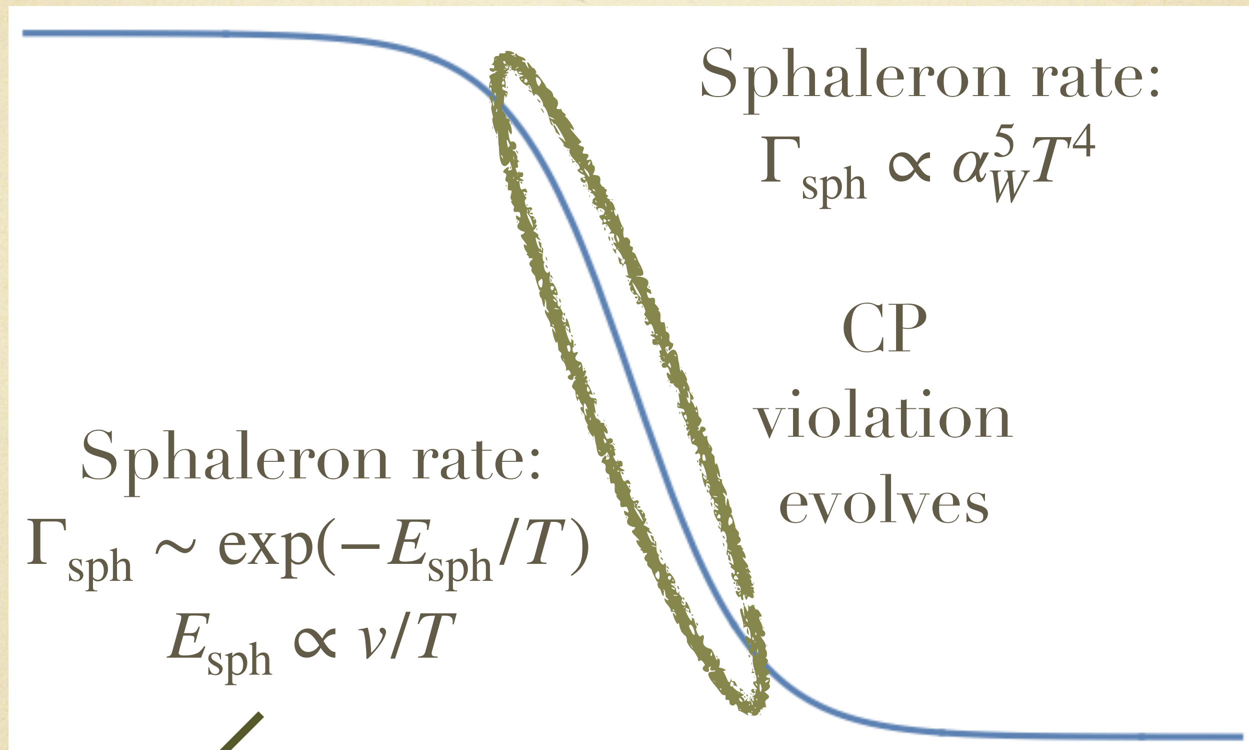




- 1st: well-defined barrier, bubble nucleation
- 2nd: smooth crossover

Electroweak baryogenesis





Should turn-off:

$$\frac{v_n}{T_n} \geq 1 \text{ (strongly 1st-order)}$$

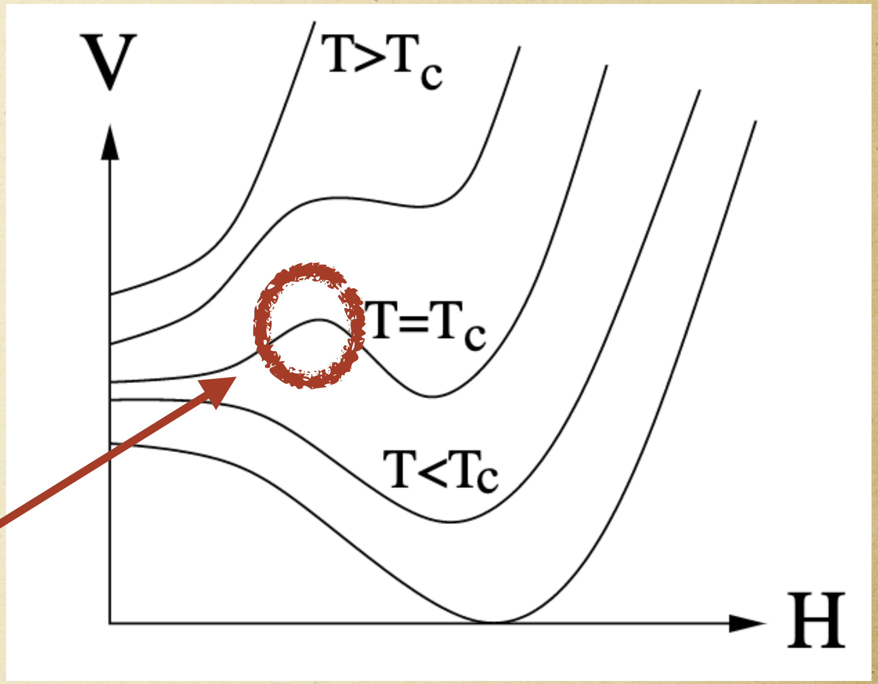
T_n: nucleation

Typically $\dfrac{v_n}{T_n} \simeq \dfrac{v_c}{T_c}$

[V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B 155, 36 (1985)]
[M. E. Shaposhnikov, JETP Lett. 44, 465 (1986),Nucl. Phys. B 287, 757 (1987)]

Phase transition strength

- Finite-T: thermal correction to the effective potential V.
- Boson contribution: $\frac{T^4}{2\pi^2} n_B\left(\frac{\pi^2}{12}\left(\frac{m}{T}\right)^2 - \frac{\pi}{6}\left(\frac{m}{T}\right)^3 + \ldots\right)$, n_B: d.o.f.
- Fermion contribution: $\frac{T^4}{2\pi^2} n_F\left(\frac{\pi^2}{24}\left(\frac{m}{T}\right)^2 + \ldots\right)$, n_F: d.o.f.
- Total: $V = DT^2h^2 - \frac{1}{2}\mu^2h^2 - ETh^3 + \frac{1}{4}\lambda h^4$, cubic from bosons
- $\frac{v(T_c)}{T_c} = \frac{2E}{\lambda}$ (strongly 1st order)



Only for intuition.
Needs full form to compute!

Challenges on EWBG

- Is EWPT strongly 1st order? How to assist?
- CP-violating effect: EDM constraint!

Challenge 1: PT strength

Lattice result: EWPT crossover for $m_H \gtrsim 70$ GeV.

How to enhance?

$$\frac{v}{T} \simeq \frac{2E}{\lambda}$$

$$m_H \simeq \sqrt{2\lambda} v$$

General way: introduce singlet $S(1,1,0)$.

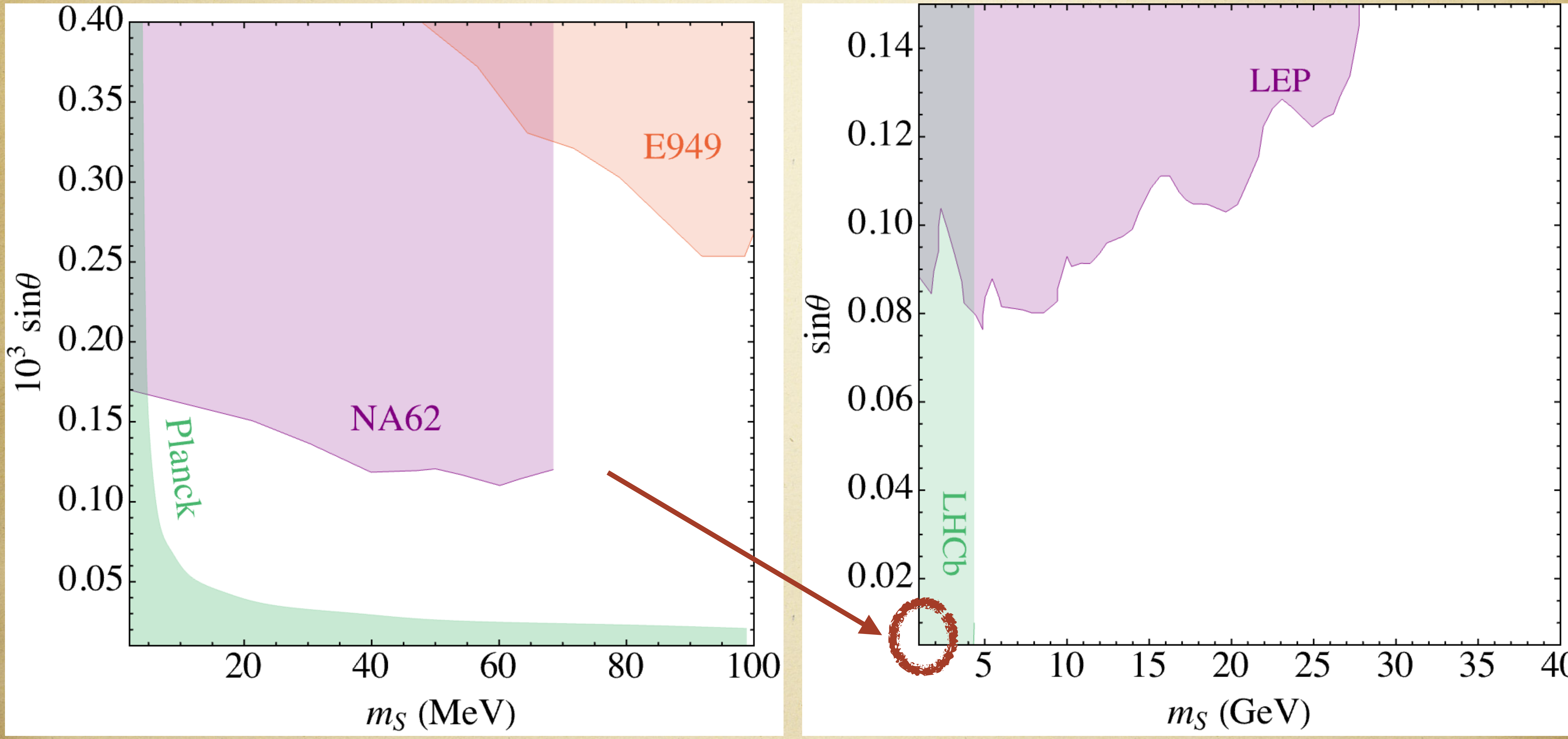
Self interaction: $\mathscr{L} \supset \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4$

Z_2 symmetric: S^2H^2, enhance E from thermal effect.

Z_2 breaking: additional S^3, SHH, etc. Enhance from tree-level.

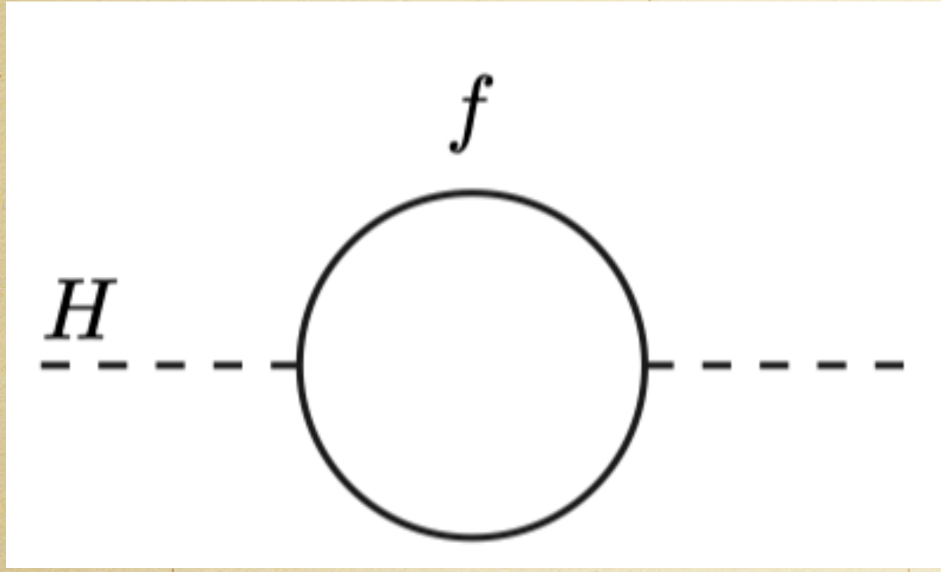
[K. Jansen, hep-lat/9509018], [K. Kajantie et al, hep-lat/9510020]
[K. Rummukainen, hep-lat/9608079], [K. Kajantie et al, hep-ph/9605288.]
[M. Gurtler et al, hep-lat/9704013], [F. Csikor et al, hep-ph/9809291]
[M. Laine and K. Rummukainen, hep-ph/9804255, hep-lat/9804019]
[K. Rummukainen et al, hep-lat/9805013], [Z.Fodor, hep-lat/9909162]

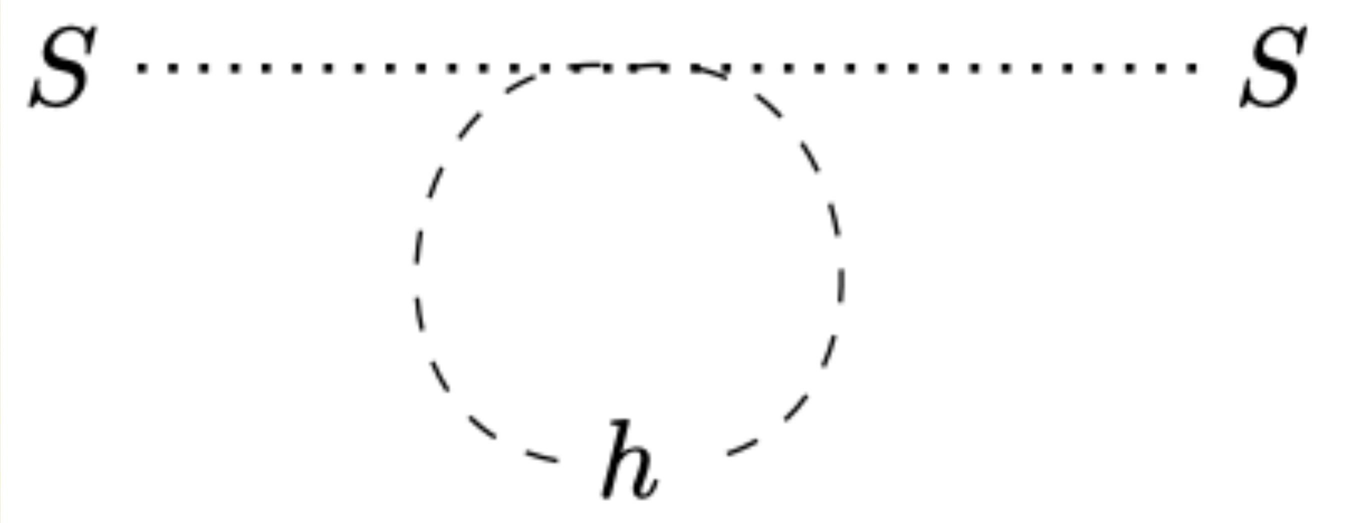
Intensitve scalar search



Stringent bound

Extra hierarchy problem





Higgs mass correction

$$\delta m_H^2 = -\frac{y_f^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2$$

Huge quantum corrections!

Scalar mass correction:

Leading: $\frac{1}{4}\lambda h^2 S^2$

$$\delta m_S^2 = \frac{\lambda_{hs}}{16\pi^2}\Lambda_{\mathrm{UV}}^2$$

Extra hierarchy problems

Challenge 2: EDM

CP-violating required!

In general

$$d_f \simeq \left(\frac{m_f}{M^2}\right)\frac{\alpha_f}{4\pi}\sin\delta_{CP}\; e\ \mathrm{cm}$$

α_f: coupling that produces EDM for fermion f

[D. Morrissey, M. Ramsey-Musolf, 1206.2942]

Example: local EWBG

$O = \frac{\alpha_2}{M^2} H^2 W\tilde{W} = \frac{H^2}{M^2}\dot{n}_B \equiv \theta \dot{n}_B$, CP violating.

Integratal by part:

$\partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \frac{3g^2}{32\pi^2} W\tilde{W}$

$O = \dot{\theta} n_B$

This induces a minimum value: $n_{B0} = \dot{\theta} T^2$

$\dot{n}_B = -3\Gamma_{\rm sph}(n_B - \dot{\theta}T^2)$.

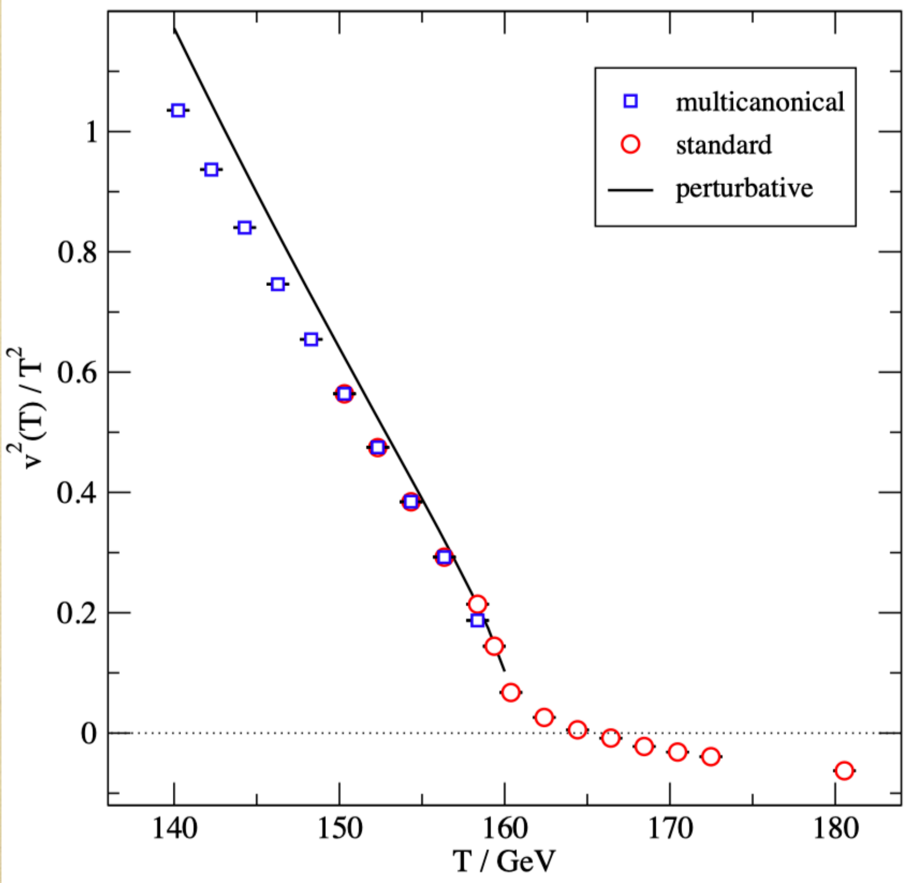
Start from $n_B = 0$, difficult to achieve n_{B0}, ignore it.

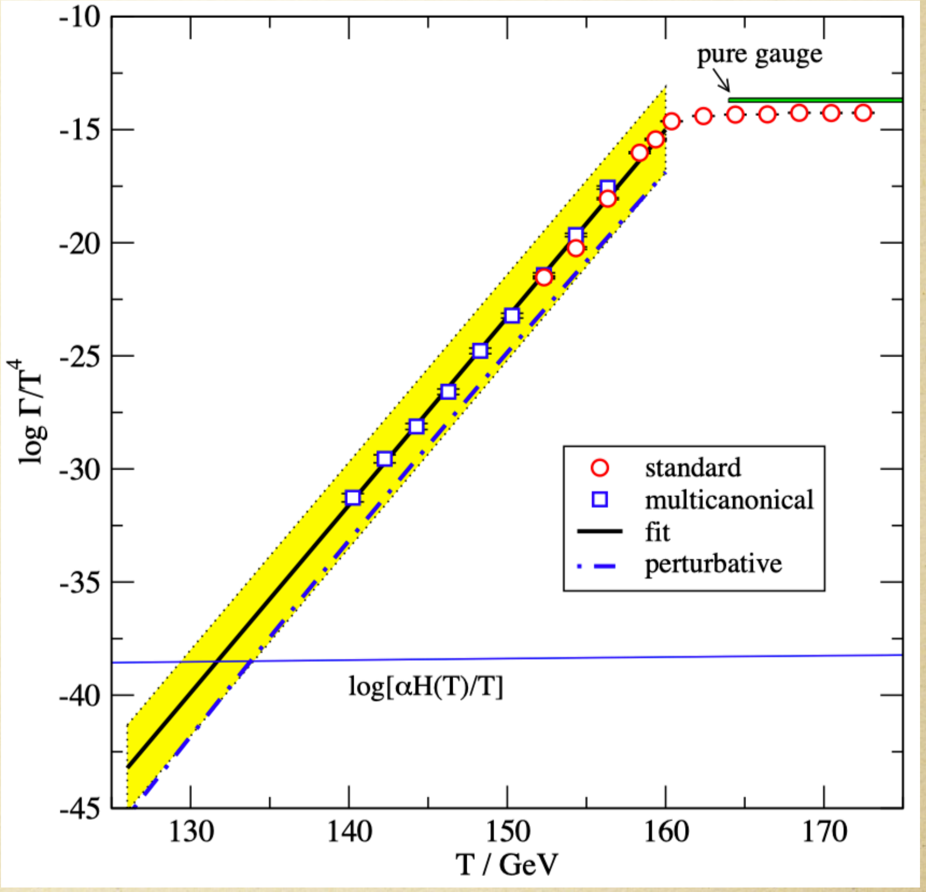
$n_B = 3\Gamma_{\rm sph} T^2 \Delta\theta$.

[Dine, et al, 1991]

[Dine, hep-ph/9206220]

Example: local EWBG





$$n_B = 3\Gamma_{\rm sph} T^2 \Delta\theta\,.$$

$\Delta\theta$: field value shift $\delta h^2/M^2$ during PT

before sphaleron rate starts to drop

$\delta h \simeq 0.3 T_c$

Small δh

Small n_B

Require small M

EDM!

[M. D'Onofrio et al, 1404.3565]

Facing the challenge

What do we need?

- (Naturally) light (avoid extra hierarchy problem)
- Weakly interacting
- Large UV scale (for EDM), large field value shift

The answer is…

Table of Contents

- Introduction: challenges of electroweak baryogenesis
- Axion-like particle assisting EWPT
- Experimental probes: EDM, beam-dump, collider

The axion-like particle

$P = (f + \Phi)^2 \exp(iS/f)$ S: angular mode, axion or ALP

Couple with Higgs:

$$V = -\frac{1}{2}(\mu_H^2 - Af\cos\delta)h^2 + \frac{1}{4}\lambda h^4$$
$$+\mu_S^2 f^2 \left(1 - \cos(\frac{S}{f})\right) - \frac{1}{2}Af\left(h^2 - 2v^2\right)\cos(\frac{S}{f} - \delta)\,.$$

Convention: $\langle h \rangle = \sqrt{2}v$. $\delta \in [0,\pi/2]$

[Jeong et al, 2018]

[K.Harigaya and IRW, 2309.00587]

Vacuum structure

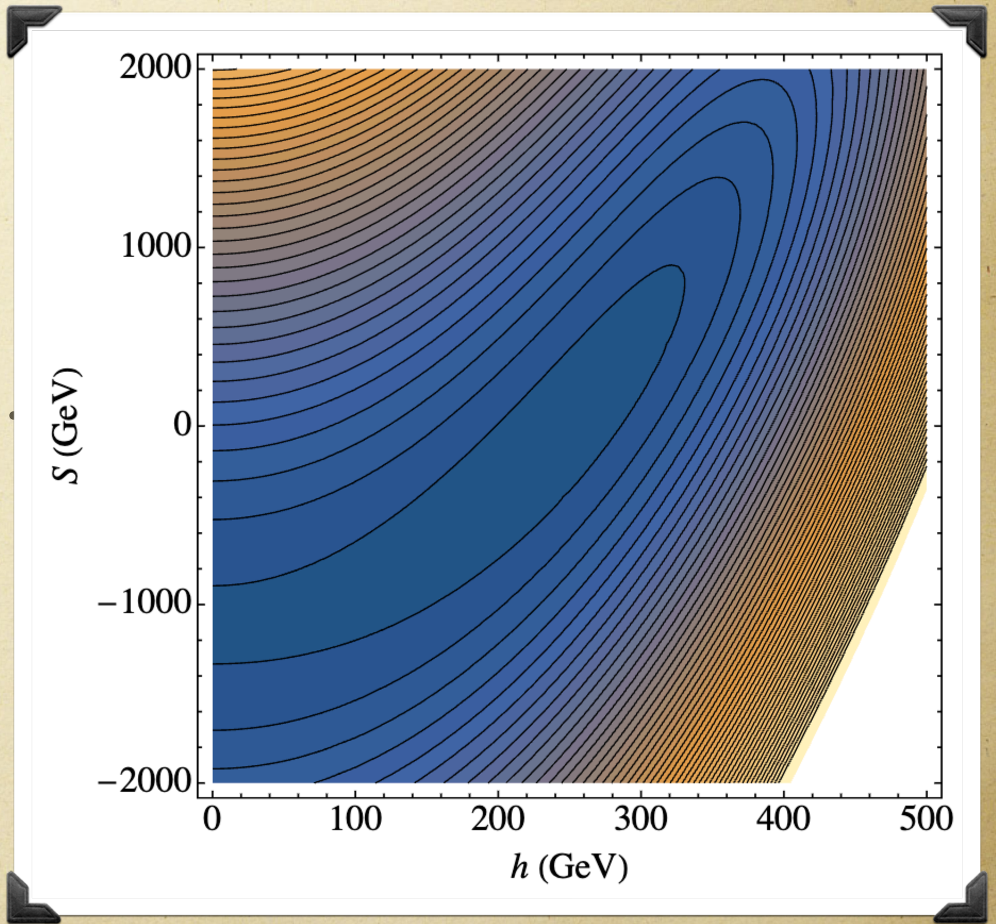
$$V = -\frac{1}{2}(\mu_H^2 - Af\cos\delta)h^2 + \frac{1}{4}\lambda h^4 + \mu_S^2 f^2\left(1-\cos(\frac{S}{f})\right) - \frac{1}{2}Af\left(h^2 - 2v^2\right)\cos(\frac{S}{f} - \delta)\,.$$

Symmetry: $S \to S + \delta S$

Define $\langle S \rangle = 0$: by $h^2 - 2v^2$

S minimum "valley":

$$\langle S\rangle(h) = f\arctan\left(\frac{A(h^2-2v^2)\sin(\delta)}{2f\mu_S^2 + A(h^2-2v^2)\cos(\delta)}\right).$$



A too large or f too small:

$V(0,\langle S\rangle(0)) < V(\langle h\rangle, \langle S\rangle\langle h\rangle)$

"Stability issue"

[K.Harigaya and IRW, 2309.00587]

Mass spectrum

At $\langle h \rangle = \sqrt{2}v, \langle S \rangle = 0$

$$m_{hh}^2 = 6\lambda v^2 - \mu_H^2$$

$$m_{SS}^2 = \mu_S^2$$

$$m_{hS}^2 = -Ah\sin\delta$$

mixing angle!

$$A = \frac{1}{2\sqrt{2}v}(m_h^2 - m_S^2)\sin(2\theta)\csc(\delta),$$

$$\lambda = \frac{1}{8v^2}\left(m_h^2 + m_S^2 + (m_h^2 - m_S^2)\cos(2\theta)\right),$$

$$\mu_H^2 = \frac{1}{4}\left(m_h^2 + m_S^2 + (m_h^2 - m_S^2)\cos(2\theta)\right),$$

$$\mu_S^2 = \frac{1}{2}\left(m_h^2 + m_S^2 - (m_h^2 - m_S^2)\cos(2\theta)\right).$$

[K.Harigaya and IRW, 2309.00587]

Enhancing the PT

Leading order effect

$$\mu_S^2 f^2 \cos(\frac{S}{f}) \to \frac{1}{2}\mu_S^2 S^2$$

Mass term

$$-\frac{1}{2}Afh^2\cos(\frac{S}{f}-\delta) \to -\frac{1}{2}Ah^2 S\sin\delta + \frac{1}{4}\frac{A}{f}h^2S^2\cos\delta$$

Z_2 breaking

[K.Harigaya and IRW, 2309.00587]

Enhancing the PT

Leading order effect

$$S = \frac{Af(h^2 - 2v^2)\sin\delta}{2f\mu_S^2 + A(h^2 - 2v^2)\cos\delta}$$ along "valley"

$$\simeq \frac{Afv^2 \sin\delta}{Av^2\cos\delta - f\mu_S^2} + \frac{Af^2\mu_S^2 \sin\delta}{2(Av^2\cos\delta - f\mu_S^2)^2}h^2 + \frac{A^2f^2\mu_S^2 \sin\delta\cos\delta}{4(Av^2\cos\delta - f\mu_S^2)^3}h^4 + O(h^6)\,.$$

Quartic: $\frac{1}{4}\lambda h^4 \to \frac{1}{4}(\lambda - \frac{A^2f^3\mu_S^4 \sin^2\delta}{2(\mu_S^2 f - Av^2\cos\delta)^3})h^4$

Negative for successful SFOPT parameter

Additional: $O(h^6)$

Positive, guarantee vev stability

[K.Harigaya and IRW, 2309.00587]

Thermal potential

$$V_{\text{eff}} = V_0 + V_{\text{CW}} + V_{\text{FT}}$$

$$V_{\text{CW}} = \frac{1}{64\pi^2}\left(\sum_B n_B\left(\log\left(\frac{m_B^2(h,S)}{Q^2}\right) - c_B\right) - \sum_F n_F\left(\log\left(\frac{m_F^2(h,S)}{Q^2}\right) - c_F\right)\right)$$

$$V_{\text{FT}} = \frac{T^4}{2\pi^2}\left(\sum_B n_B J_B\left(\frac{m_B^2(h,S)}{T^2}\right) + \sum_F n_F J_F\left(\frac{m_F^2(h,S)}{T^2}\right)\right),$$

$$J_{B,F}(x^2) = \pm\int_0^\infty dy\, y^2 \log\left(1 \mp \exp\left(-\sqrt{y^2+x^2}\right)\right).$$

Resummation: all boson masses replaced by thermal mass:

$m^2 \to m^2 + \Pi,\ \Pi \sim g^2T^2$

Thermal phase transition

Again, only for intuition.
Needs full form to compute!

High-T expansion:

$$V_{\rm highT} = -\frac{1}{2}(\mu_H^2 - Af\cos\delta)h^2 + D_{\rm SM}T^2h^2 - E_{\rm SM}Th^3 + \frac{1}{4}\lambda h^4$$
$$-\frac{1}{2}Af\cos\left(\frac{S}{f}-\delta\right)\left(h^2-2v^2+\frac{1}{3}T^2\right)$$
$$-f^2\mu_S^2\cos\left(\frac{S}{f}\right).$$

One-step PT.

$(0, \langle S\rangle(0,T))$
$\to (v(T), \langle S\rangle(v(T),T))$

$$\langle S\rangle(h,T) = f\arctan\left(\frac{A(3(h^2-2v^2)+T^2)\sin(\delta)}{6f\mu_S^2 + A(3(h^2-2v^2)+T^2)\cos(\delta)}\right).$$

Parametrize f in terms of S shift when $h: 0 \to \sqrt{2}v$:

Large f: $\langle S\rangle(h,T) \simeq \frac{1}{2}\frac{A}{\mu_S^2}(h^2-2v^2+\frac{1}{3}T^2)\sin\delta\,.$

$$f_c \equiv \frac{A}{\mu_S^2}v^2\sin\delta,\ f = cf_c$$

Light S has large field value shift.

[K.Harigaya and IRW, 2309.00587]

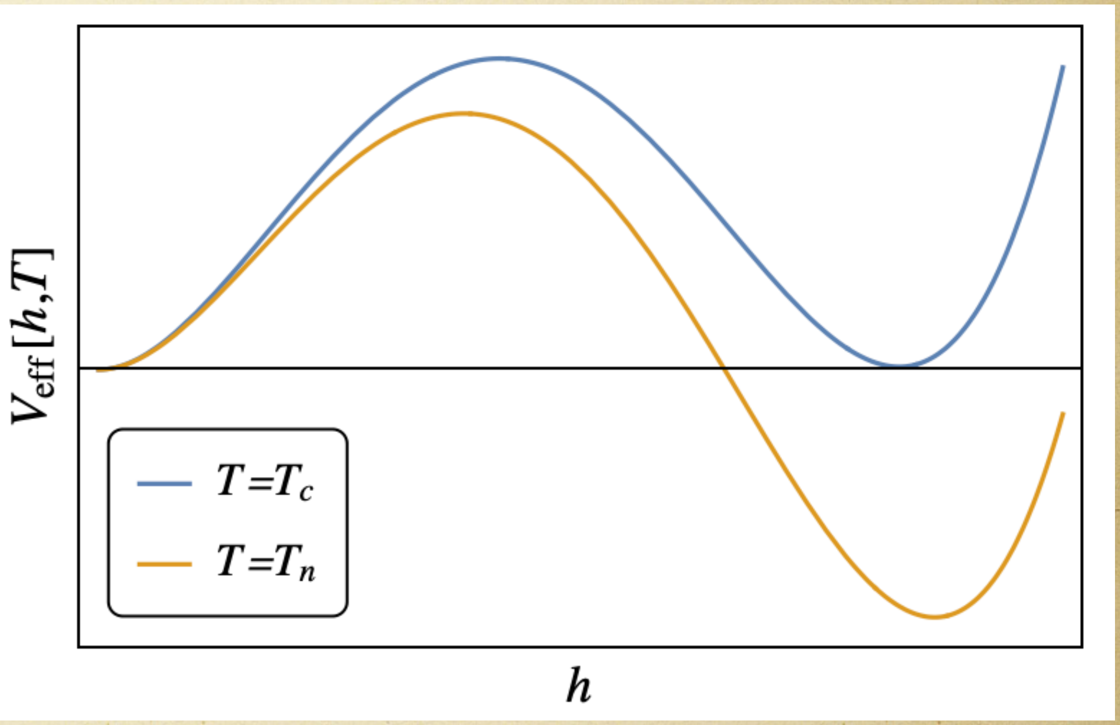
Bubble nucleation

- From $T = T_c$: transition allowed.
- Transition rate: $\Gamma \simeq T^4 \exp(-S_3/T)$

  $S_3 \equiv \int r^2(\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi))dr,$

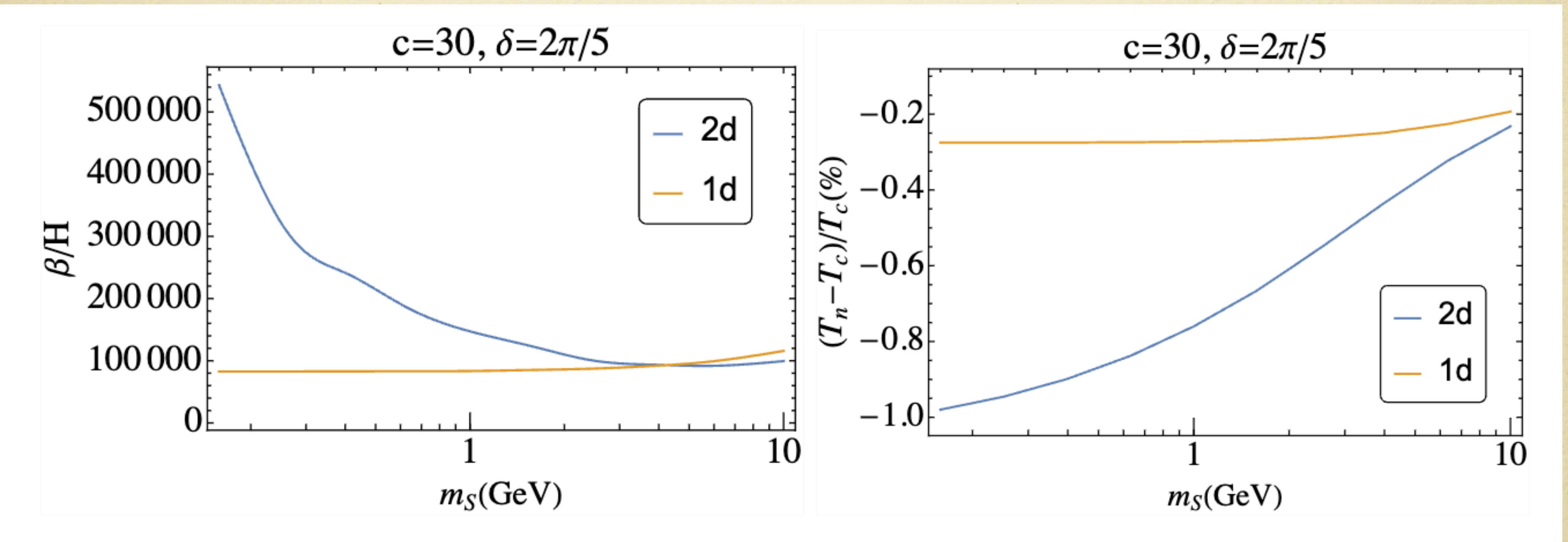
  decrease as universe cools down.

  r: radius of the 3d space.
- Nucleation temperature T_n: $\Gamma/H^3 \simeq H$
- Condition: $\frac{S_3}{T} \simeq 140.$
- Inverse time duration: $\frac{\beta}{H} \equiv T_n \frac{d}{dT}\left(\frac{S_3}{T}\right)|_{T_n}$



Bubble nucleation

2d: correct. 1d: ignore S.

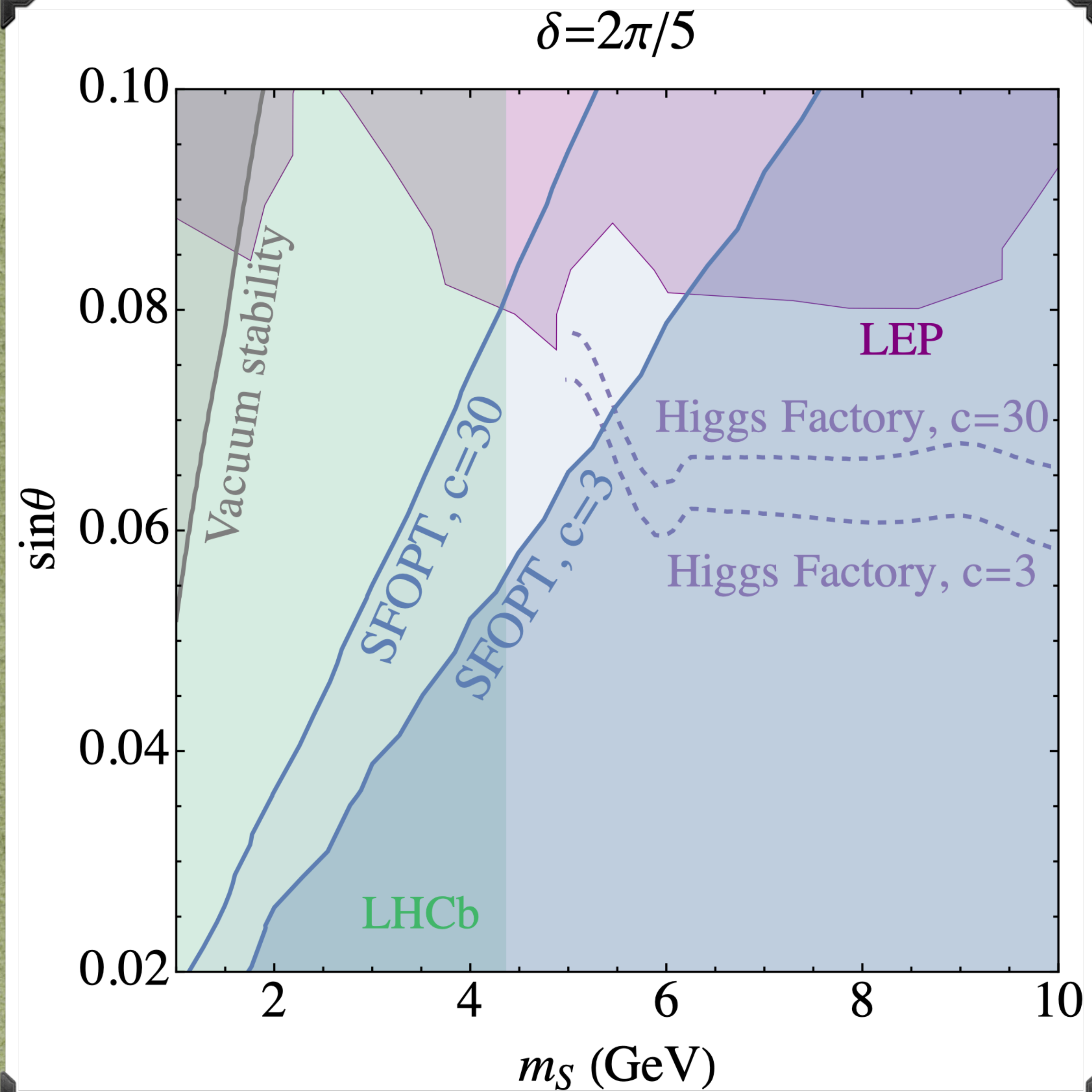


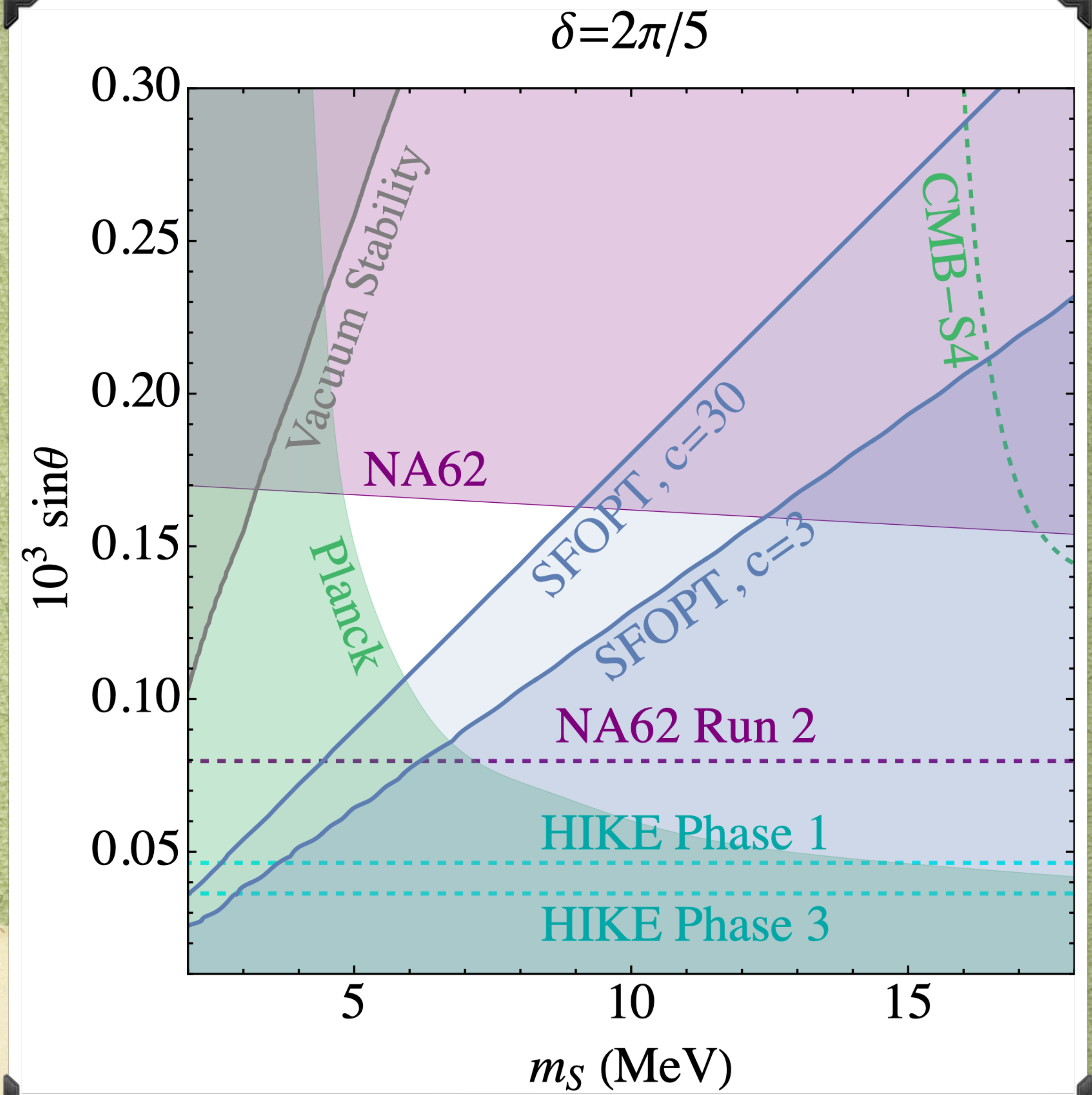
$$S_3 = \int dr \frac{1}{2}\left(\frac{dh}{dr}\right)^2 + \frac{1}{2}\left(\frac{dS}{dr}\right)^2 + V$$

Huge kinetic energy

Huge β/H. GW signal hopeless. T_n not so far from T_c

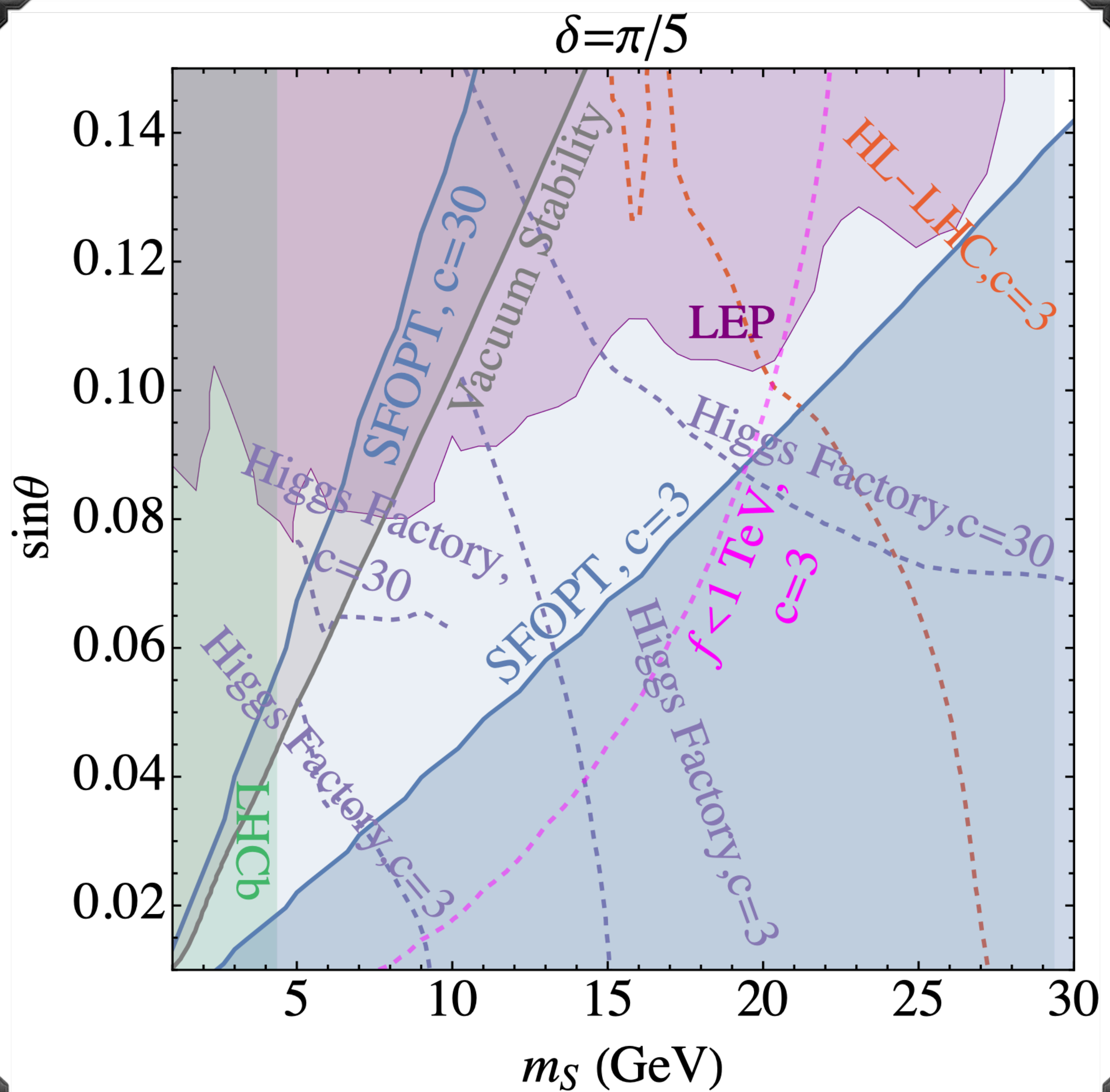
[K.Harigaya and IRW, 2309.00587]

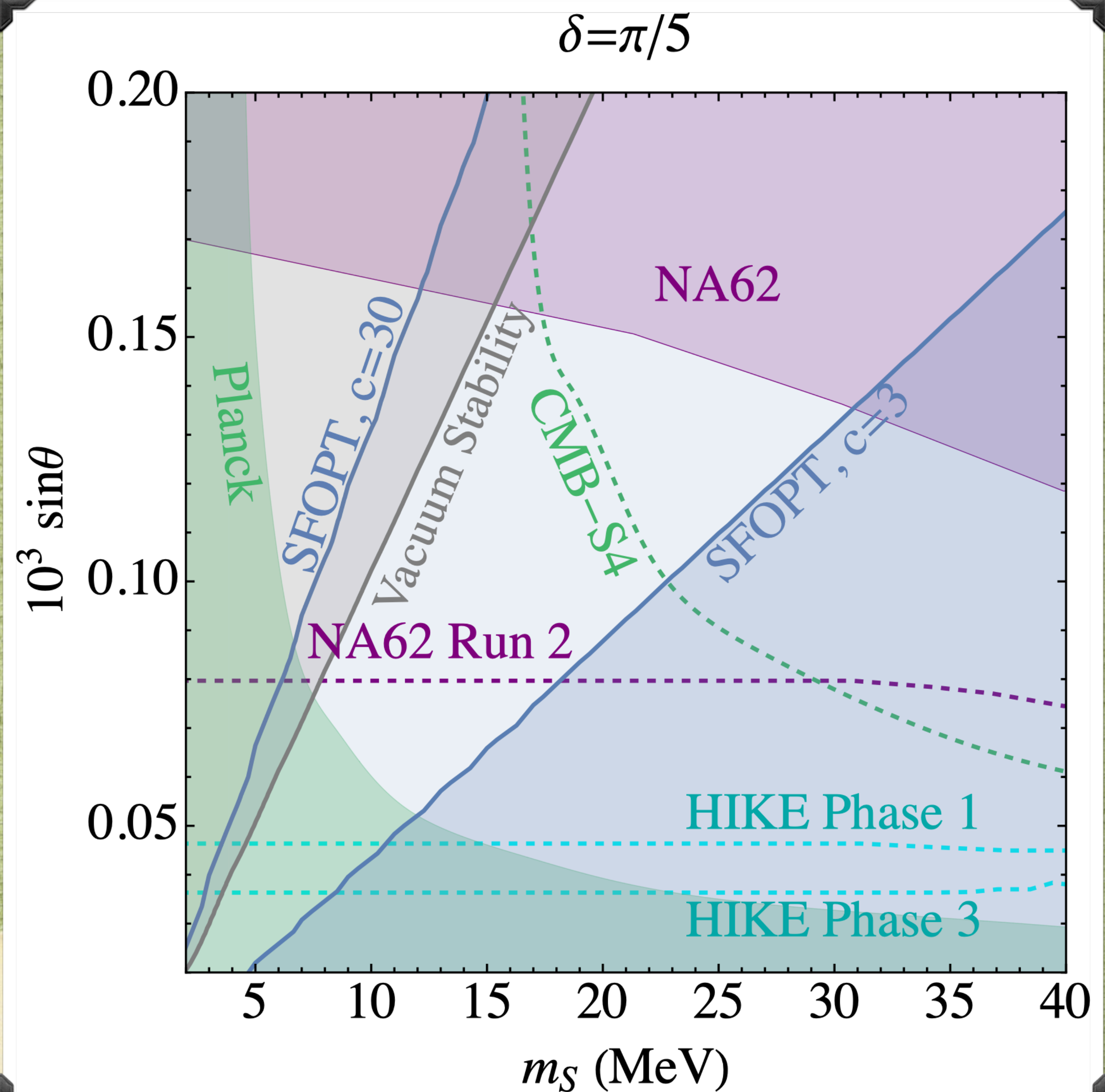




Results: $\delta = 2\pi/5$

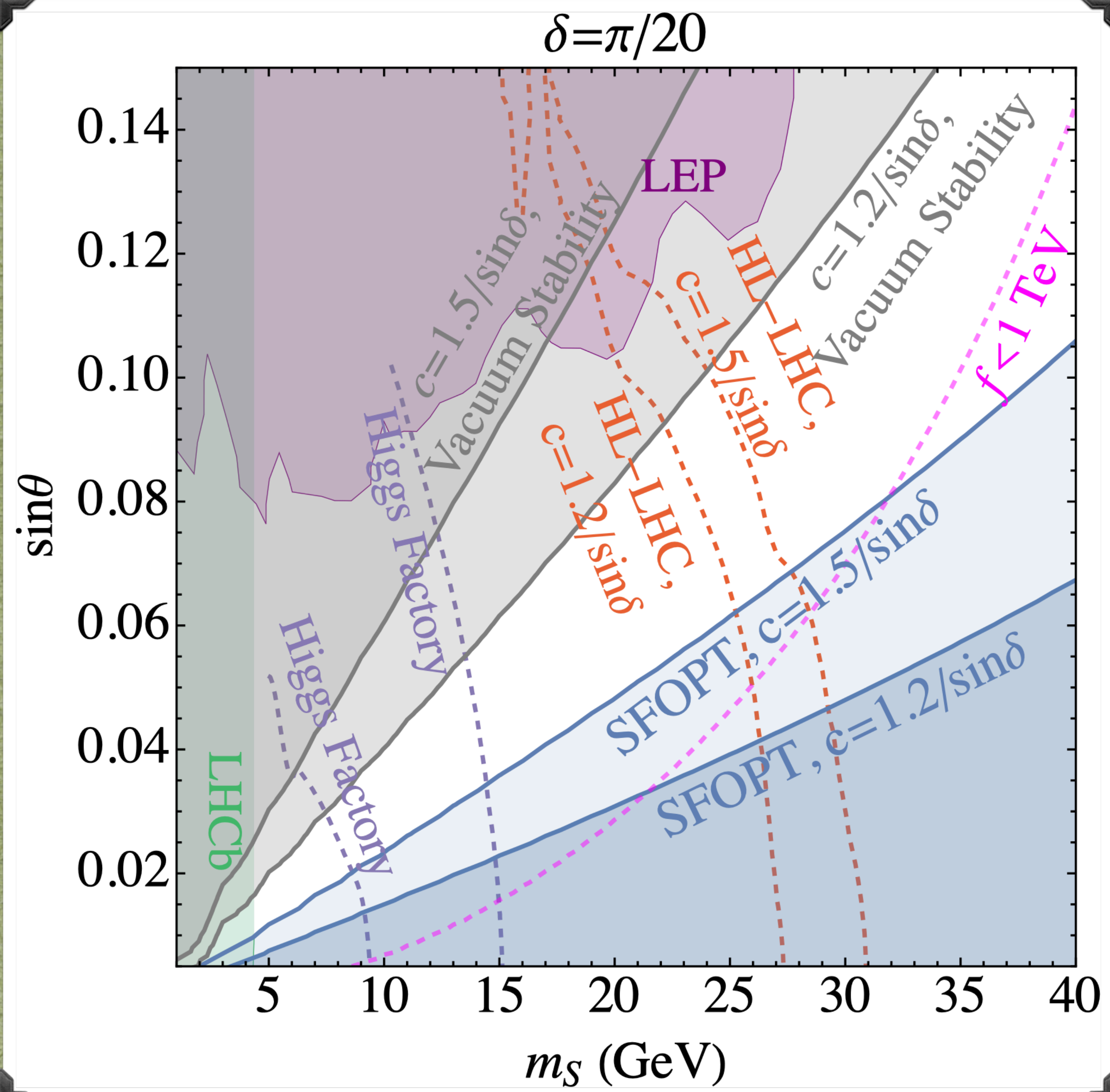
Constraints to be explained later

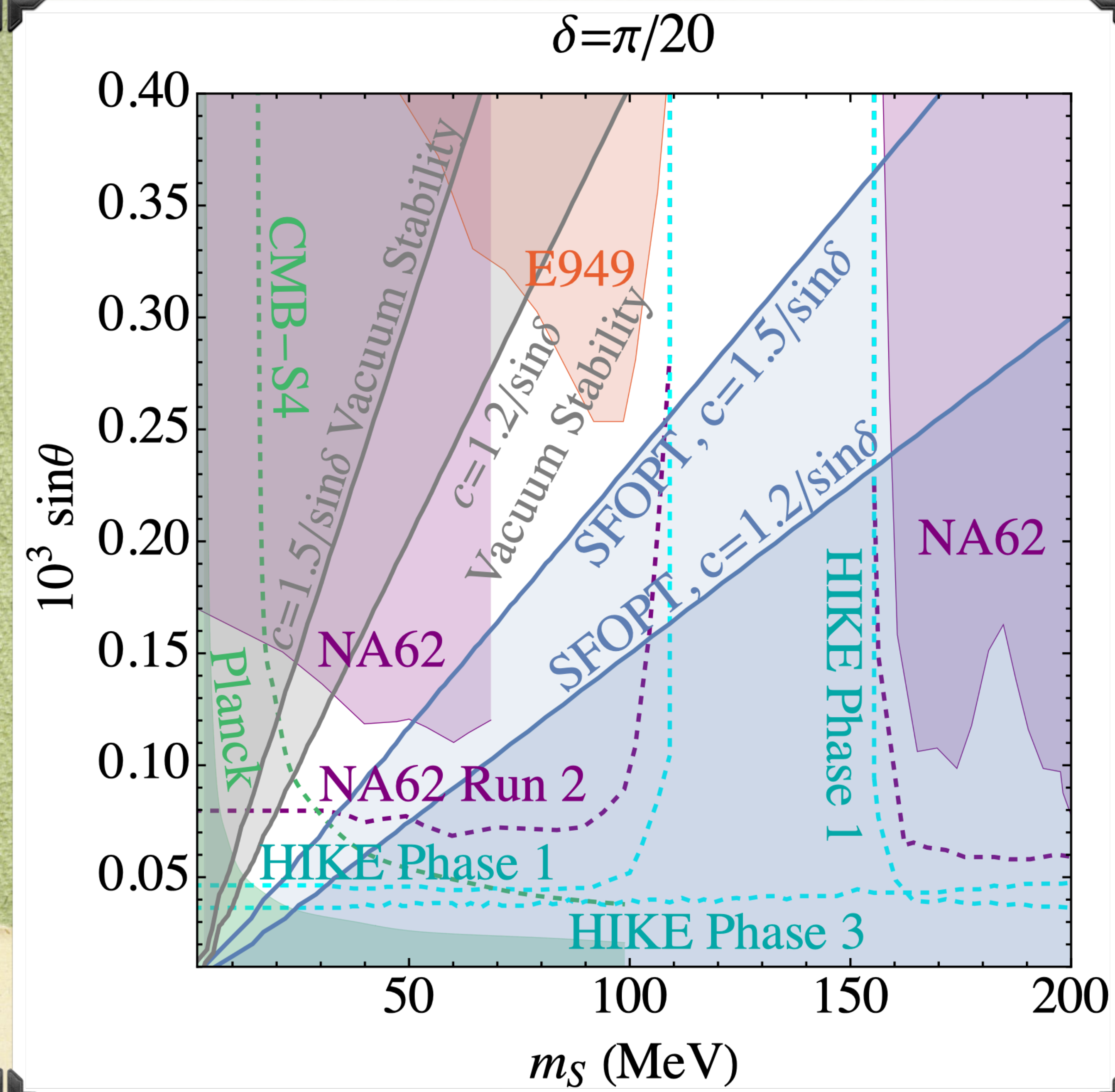




Results: $\delta = \pi/5$

Constraints to be explained later





Results: $\delta = \pi/20$

Constraints to be explained later

Table of Contents

- Introduction: challenges of electroweak baryogenesis
- Axion-like particle assisting EWPT
- Experimental probes: EDM, beam-dump, collider

Possible signals

- UV model independent: scalar production, Higgs exotic decay, rare meson decay, CMB…
- UV model dependent: EDM (electron+atomic), heavy fermions, local EWBG…

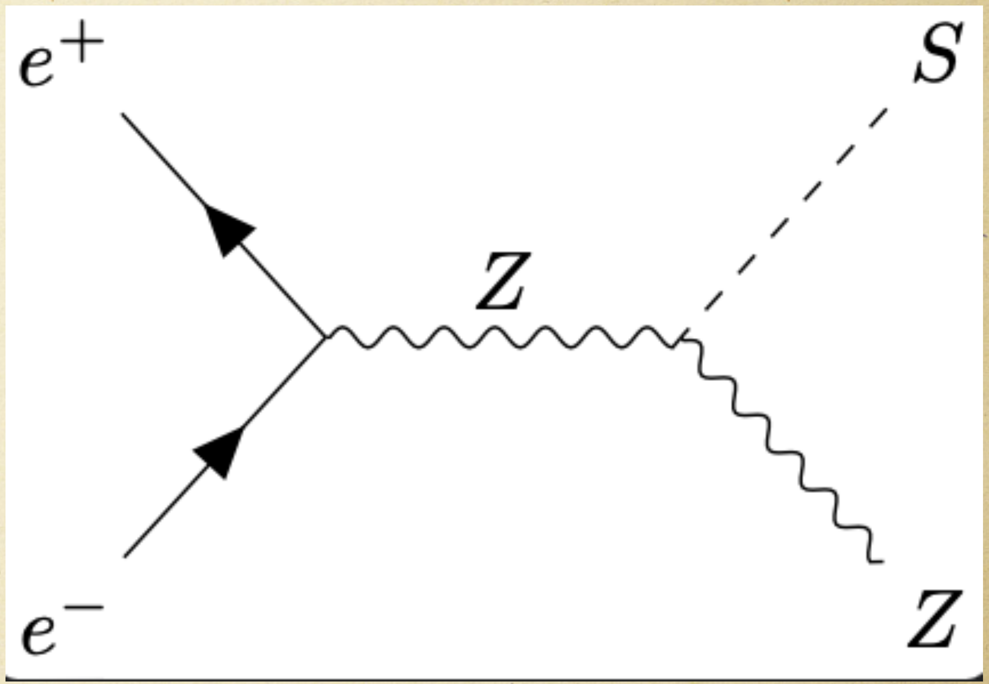
Collider Signals

Vertices: hSS, hhS, h^3…

with mixing angle insertion.

Signals:

- Direct production: $\mathrm{SM} \to S + \mathrm{SM}$
- Higgs exotic decay: $h \to SS$



The production channel of the current best bound.

[L3 collaboration, Phys. Lett. B 385 (1996) 454–470.]

[K. Harigaya and IRW, 2309.00587]

Rare meson decay and ΔN_{eff}

- Extra decay channel for B and K:
  - $B^0 \to K^0 S, B^+ \to K^+ S$, searched by LHCb at 200 MeV $< m_S <$ 4 GeV
  - $K^+ \to \pi^+ S, K^0 \to \pi^0 S$, searched by NA62, KLEVER.... for MeV scale.
- MeV scale m_S: large energy density when neutrino decouples.
  - S decays into γ: negative ΔN_{eff}

[E. Goudzovski et al, 2201.07805]
[NA62 Collaboration, 2010.07644, 2103.15389]
[KLEVER Project Collaboration, 1901.03099]
[M. Ibe et al, 2112.11096], [Planck Collaboration, 1807.06209]
[LHCb Collaboration, 1508.04094, 1612.07818, 1703.08501]
[CMB-S4 Collaboration, 1610.02743],[K. Harigaya and IRW, 2309.00587]

Local EWBG

Consider $O \propto \frac{S}{M} W\tilde{W}$

In general, M is not necessarily f

Completely depends on UV model.

$$n_B \propto \frac{\Delta S}{M}$$

Enhance: $\Delta S \gg \delta h$, and M suppression is linear.

$$\langle S \rangle (h, T) \simeq \frac{1}{2} \frac{A}{\mu_S^2} (h^2 - 2v^2 + \frac{1}{3} T^2) \sin \delta \, .$$

Electric dipole moment

- Electron: $d_e/e \simeq \frac{y_e}{(16\pi^2)^2}\frac{A\sin\delta}{Mv}$.
    - $d_e <= 10^{-29}\ e$ cm
- Atomic: $g_N = \frac{\sin\theta}{3\sqrt{2}}\frac{m_N}{v}, g_f = \frac{m_f}{M}.$
    - $g_N g_e \leq 10^{-31}\left(\frac{m_S}{\text{eV}}\right)^2$
    - Depend on the existence of CP-violating g_f in UV model.

Bound computed with M that produces the correct n_B

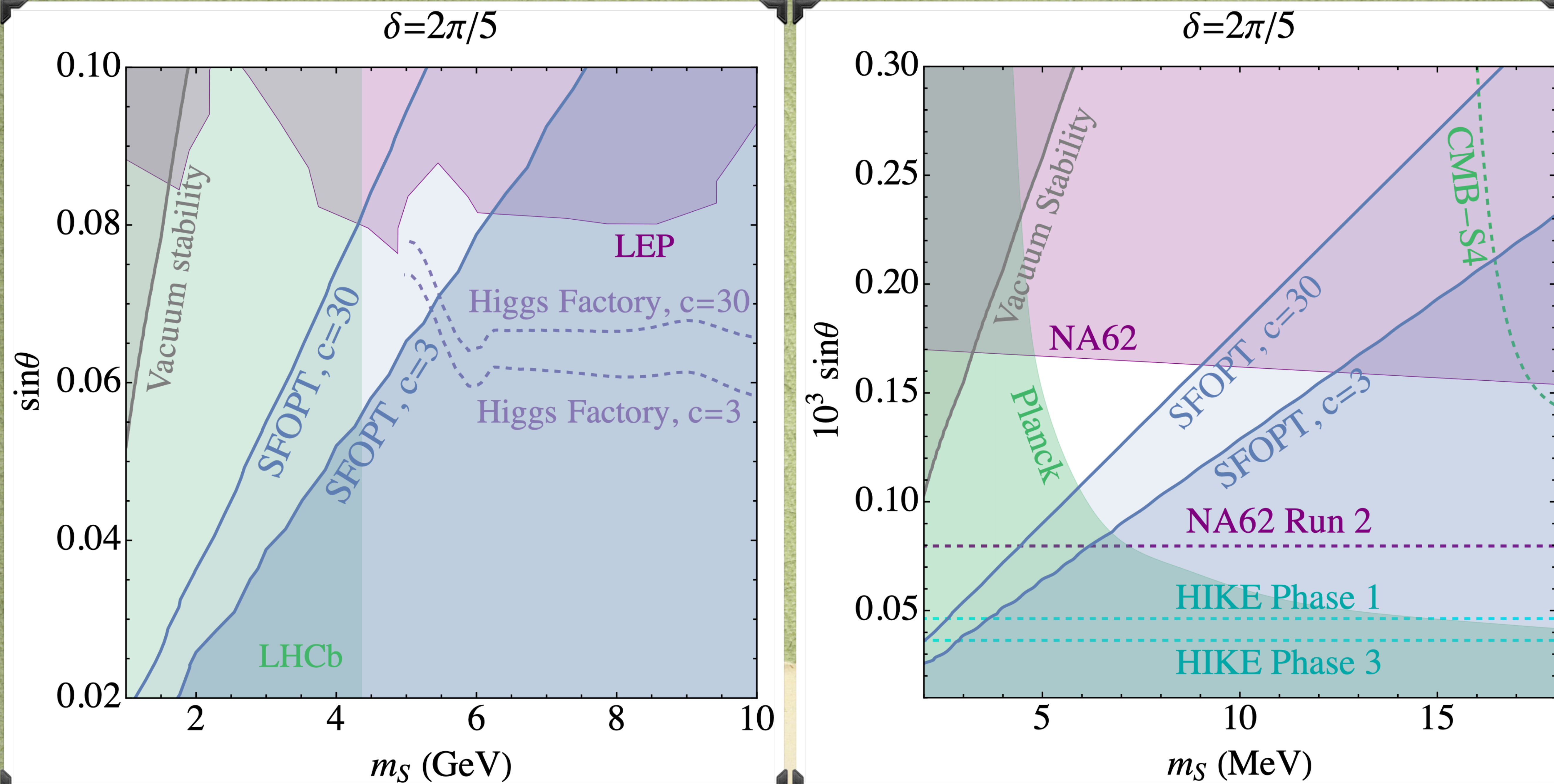
[V.A.Dzuba et al, 1805.01234]

[ACME Collaboration, 2018]

Heavy fermions?

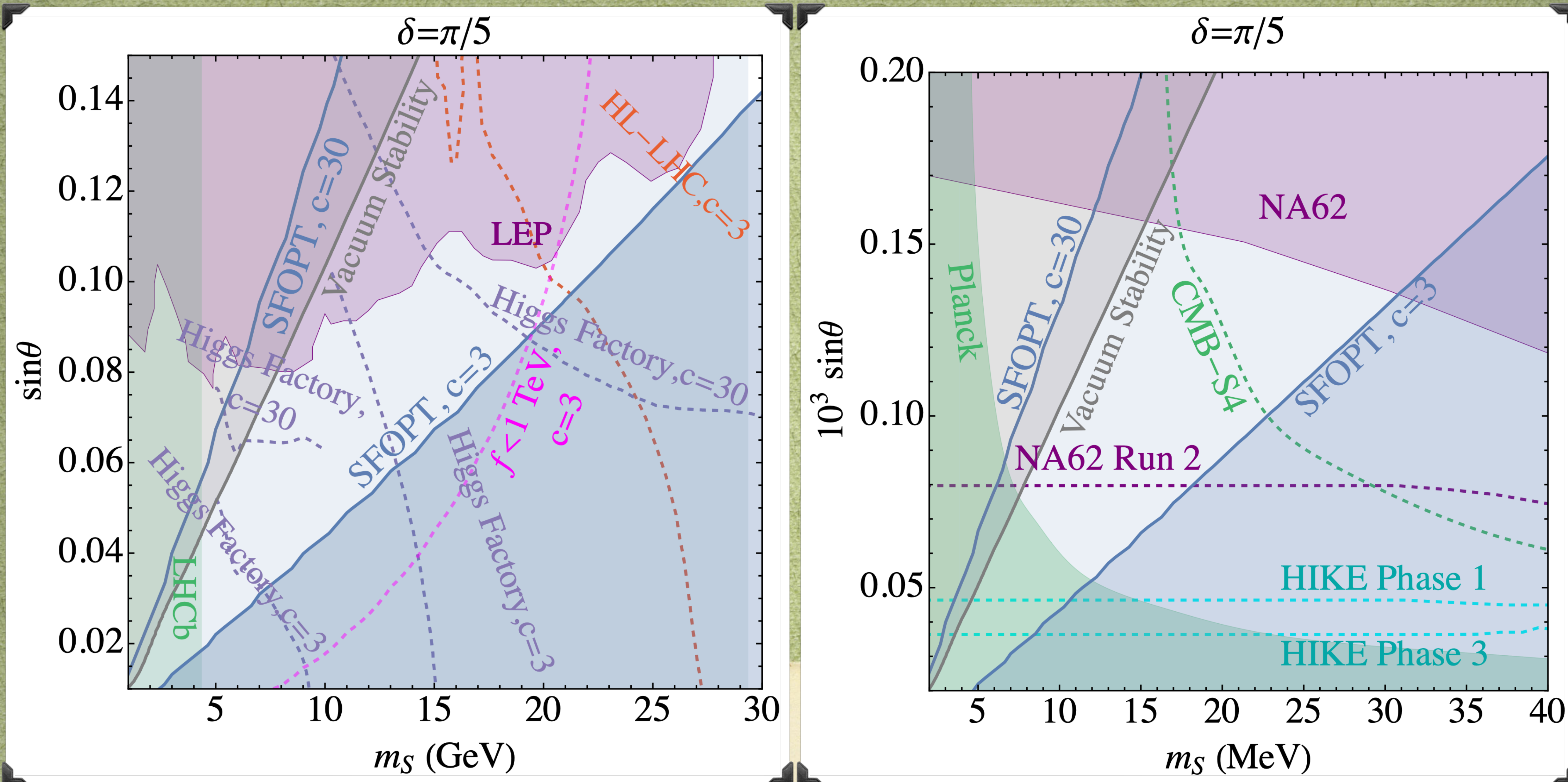
In general, UV model of S contains heavy fermions.

- Model dependent.
- Generally, expect $f > 1$ TeV to avoid collider bounds.
- Not a very solid bound. Depends on model.



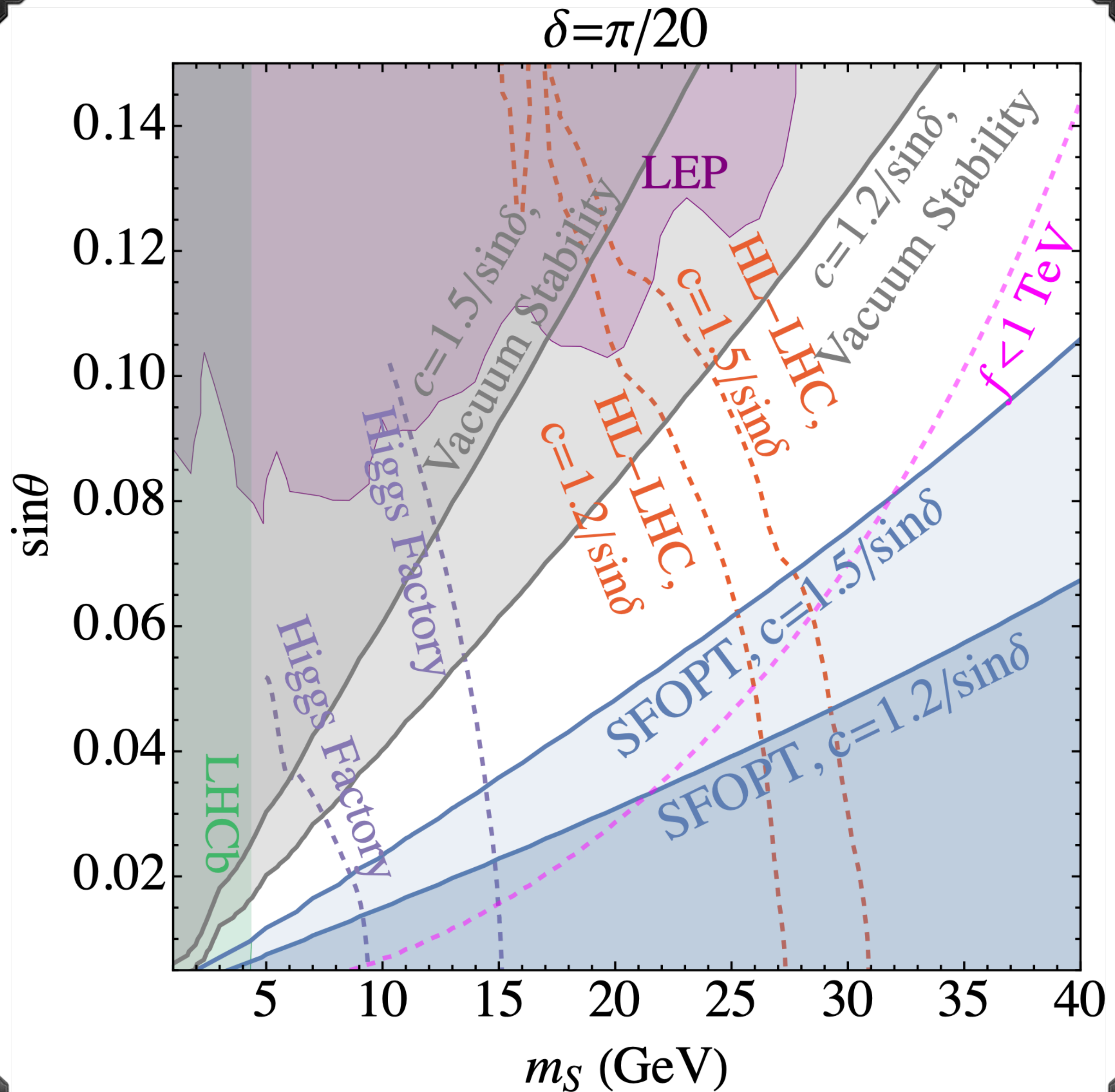
Results: $\delta = 2\pi/5$

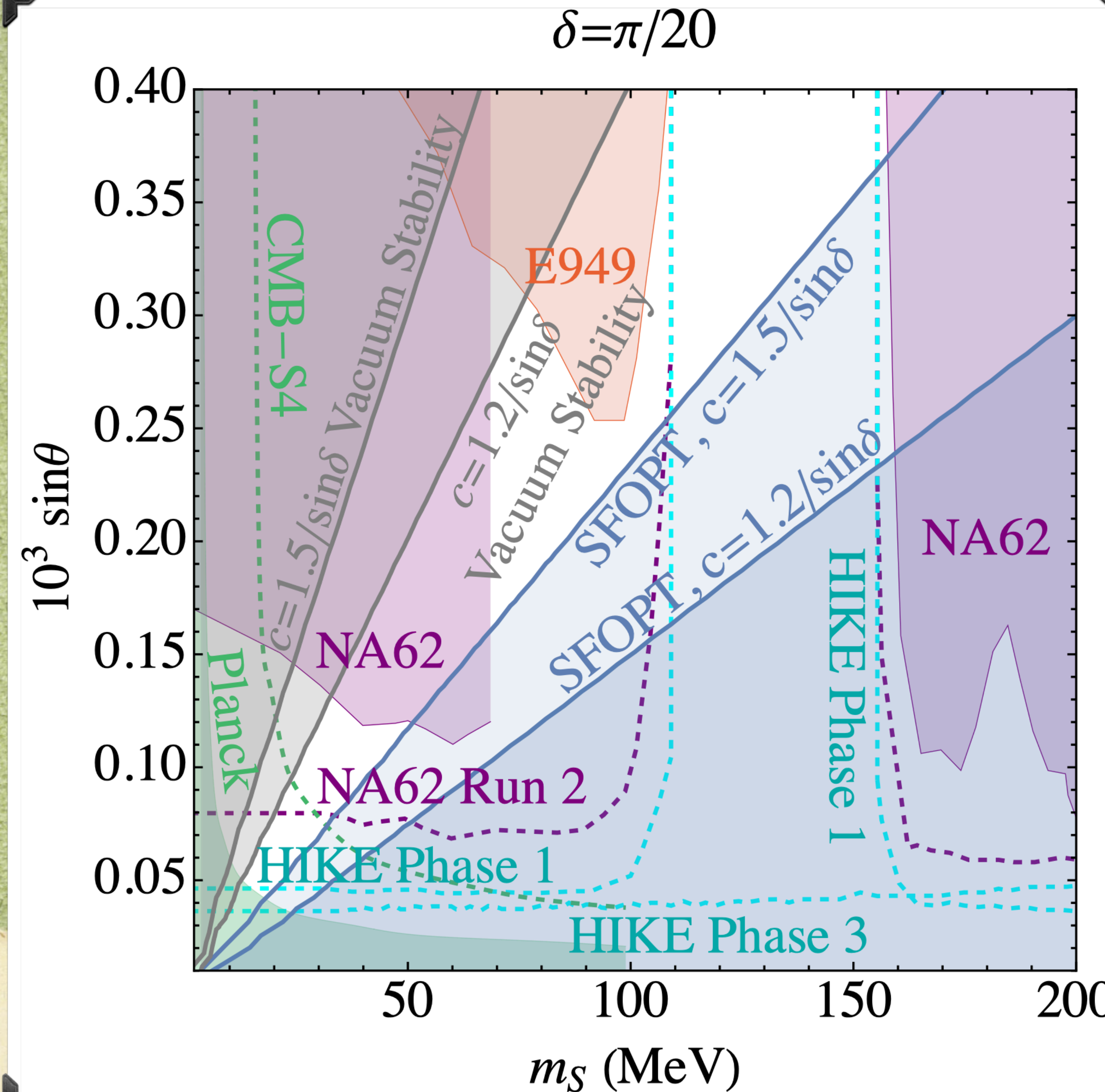
Constraints to be explained later



Results: $\delta = \pi/5$

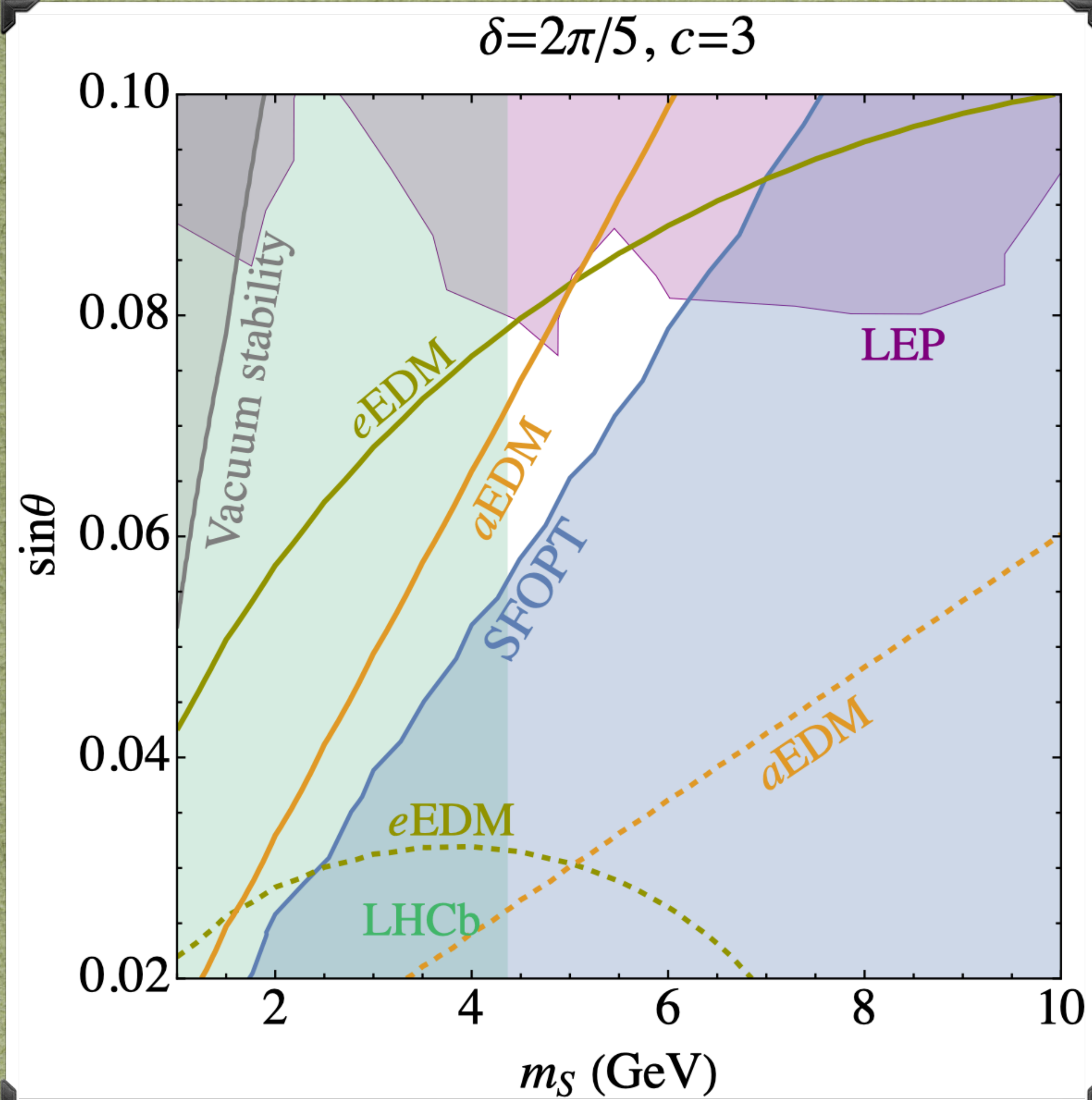
Constraints to be explained later

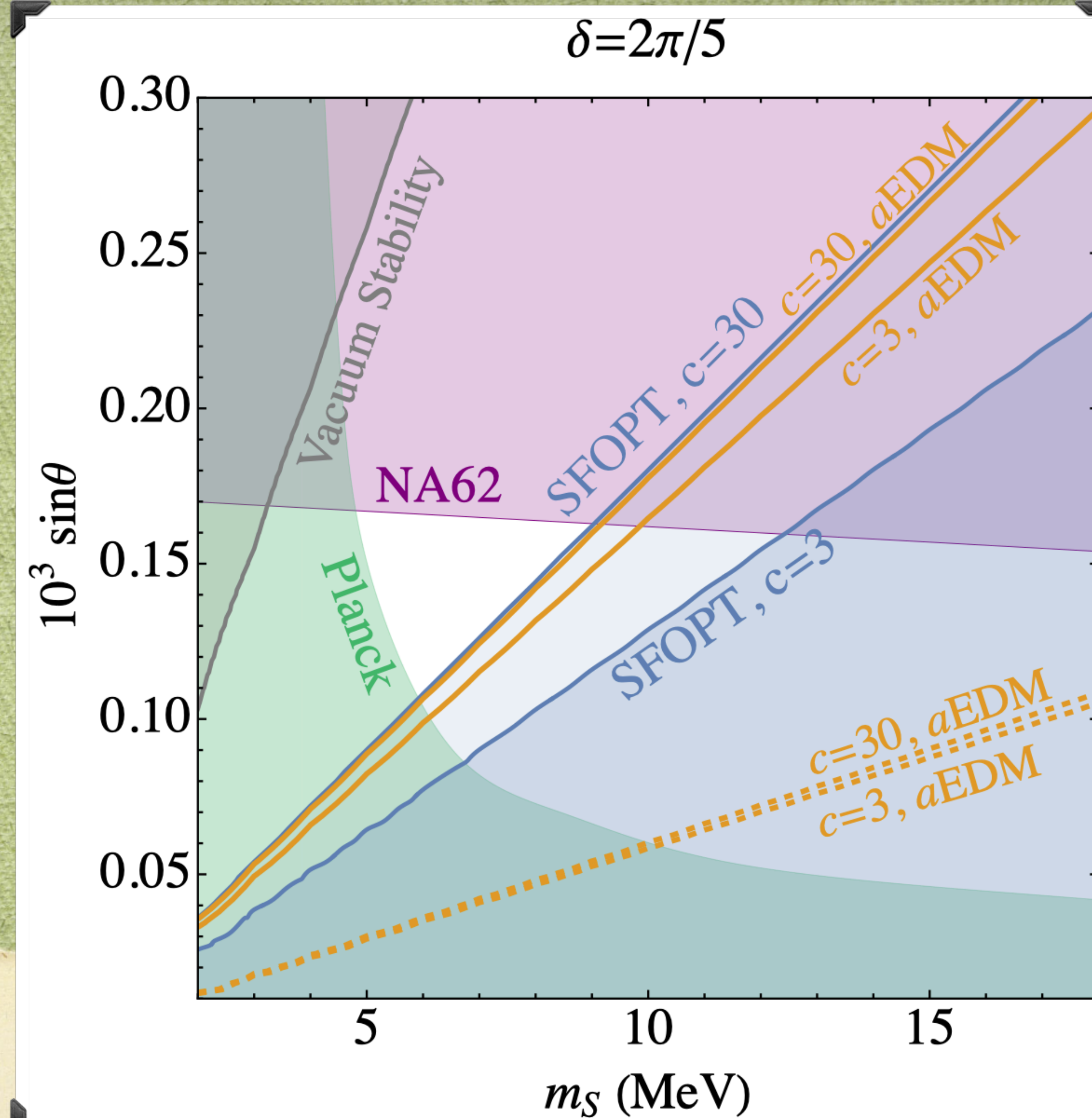




Results: $\delta = \pi/20$

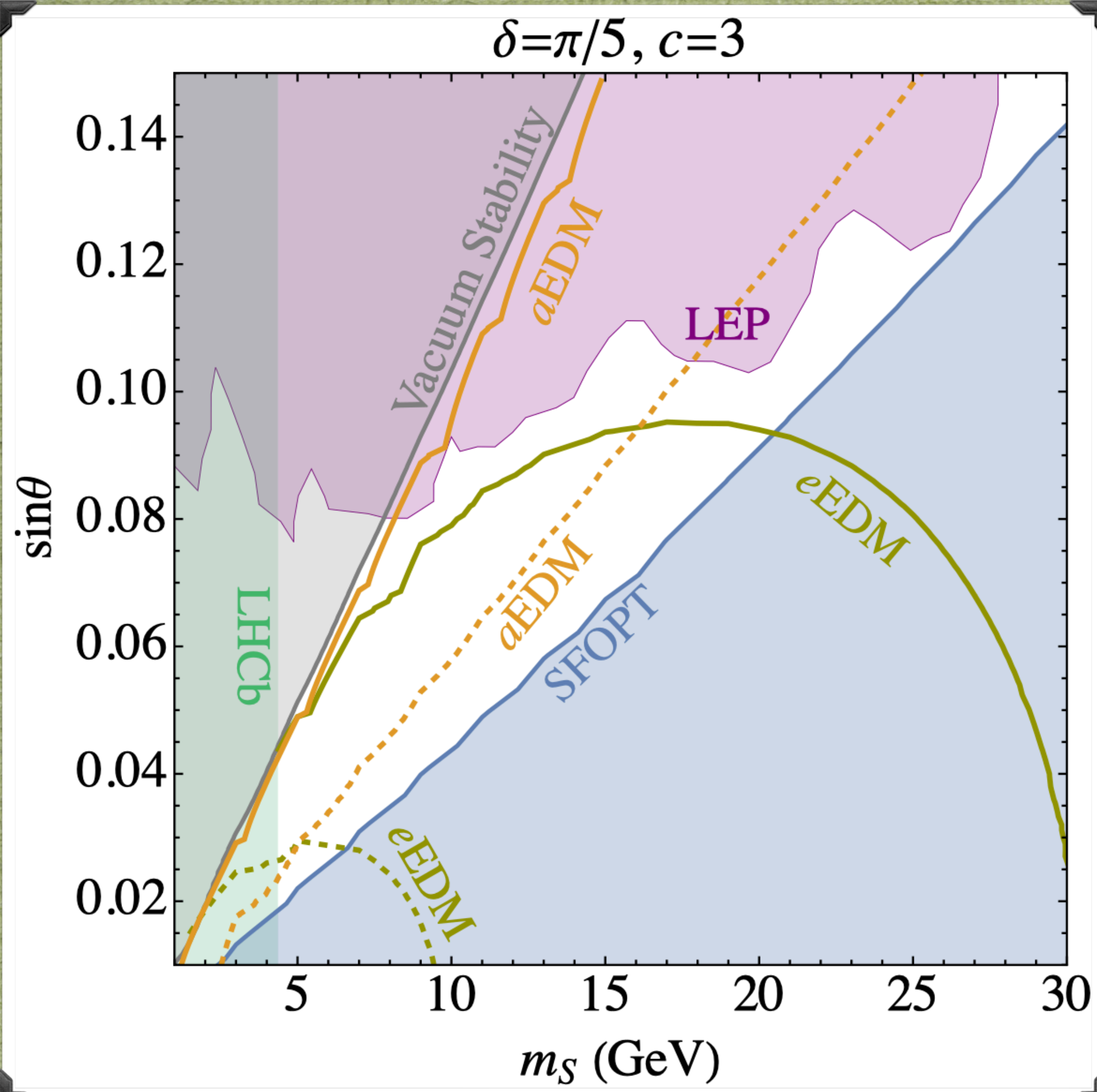
Constraints to be explained later

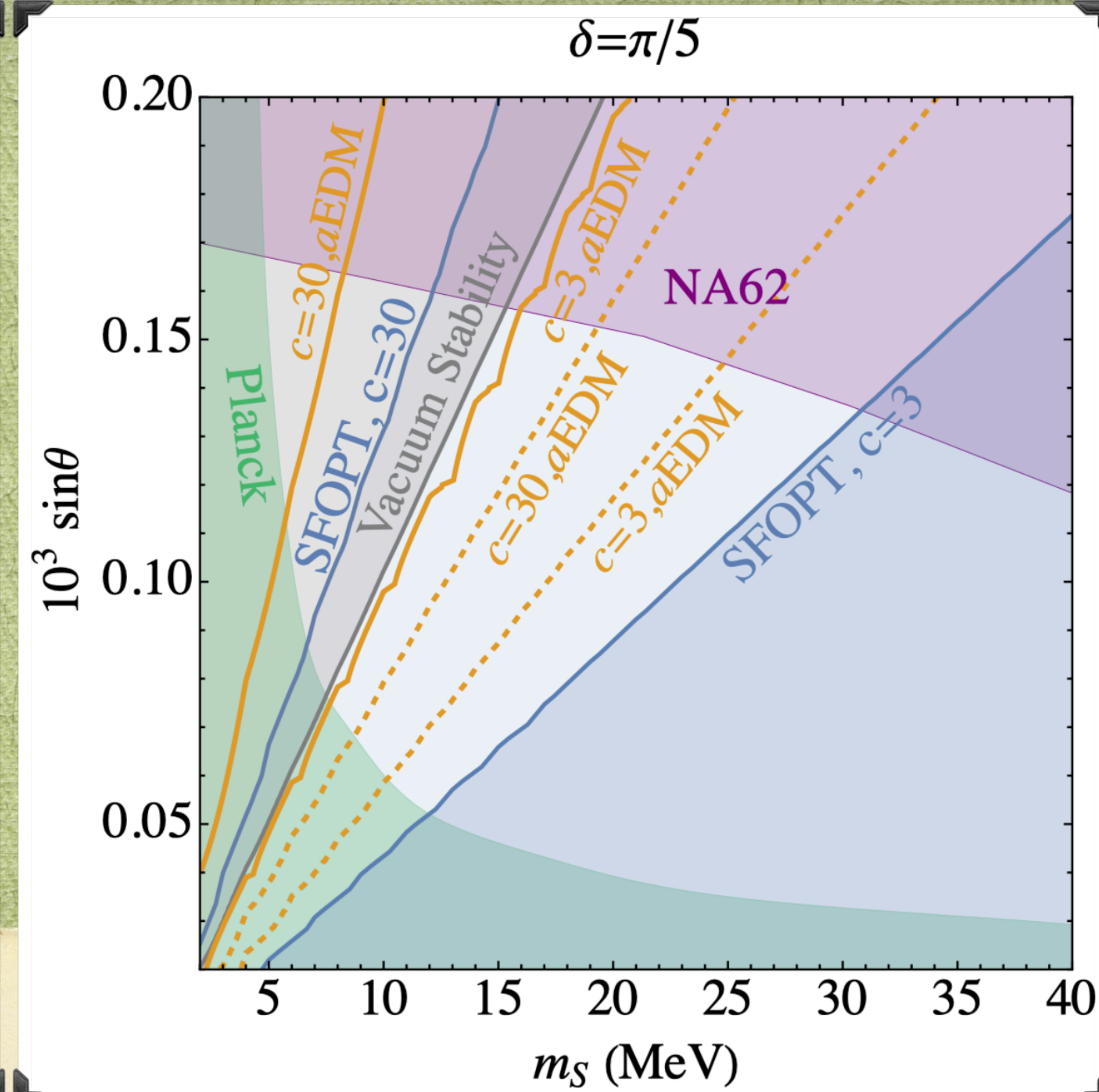




EDM: $\delta = 2\pi/5$

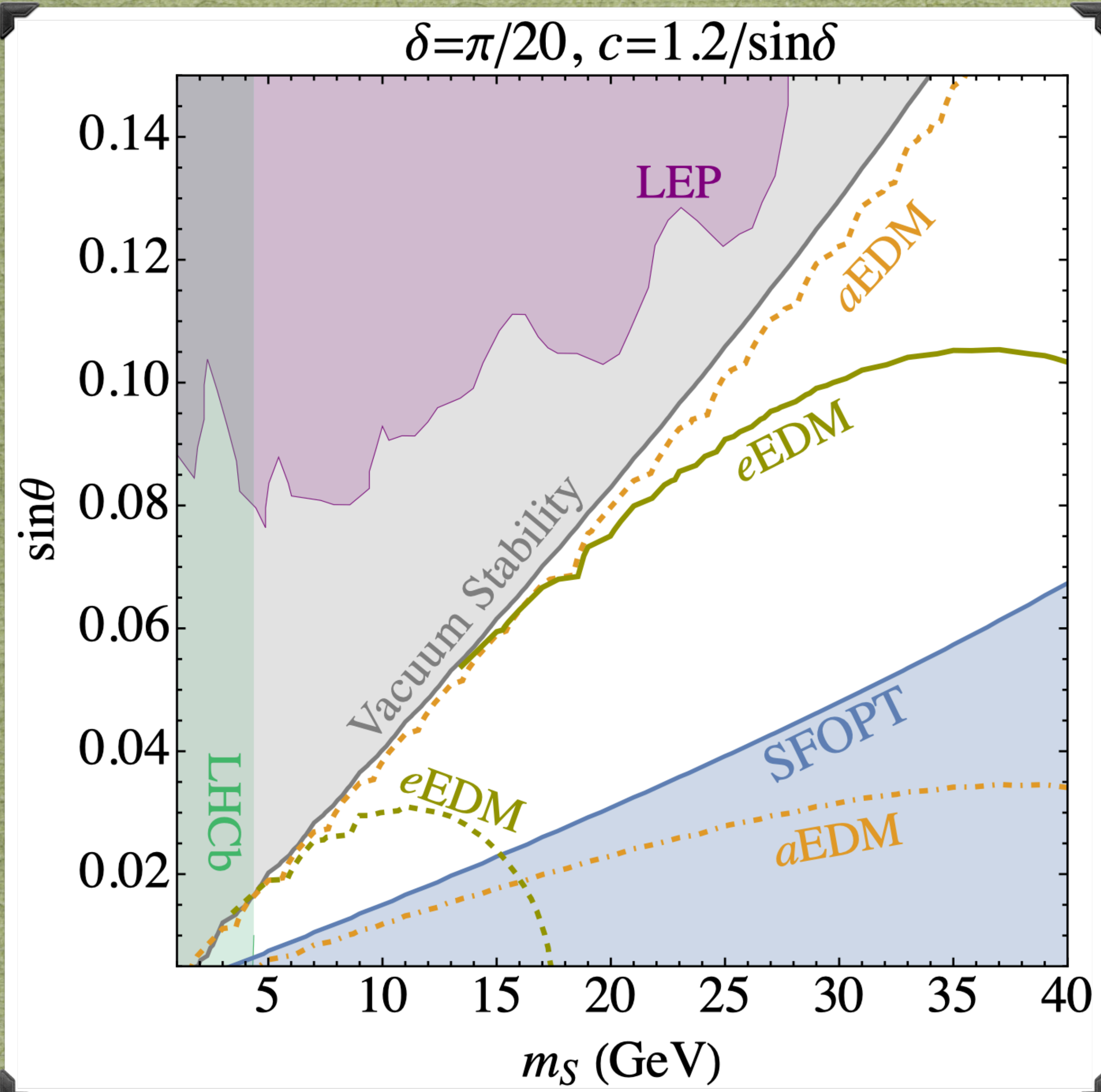
Solid: current. Dashed: improve by 10.

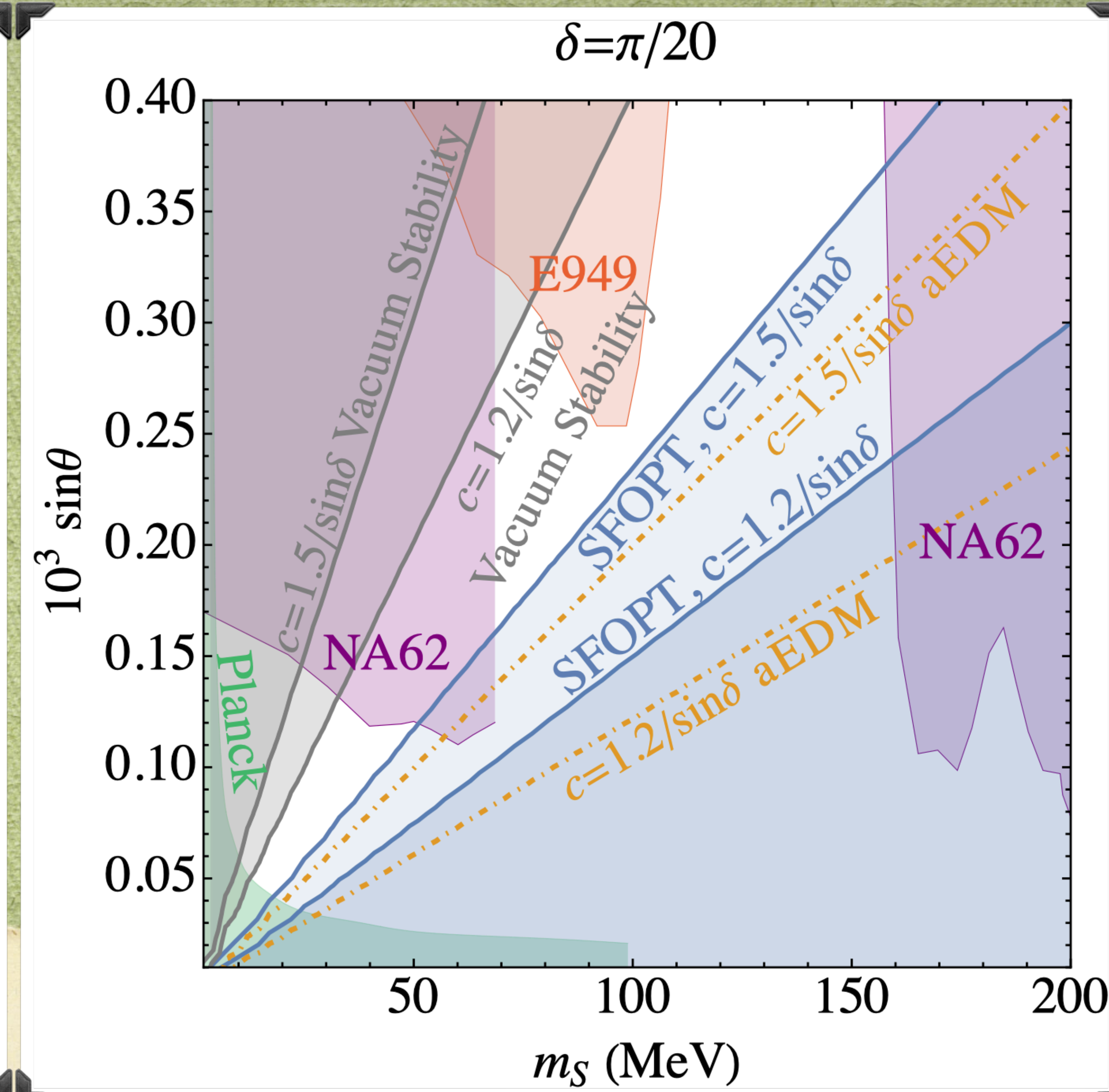




EDM: $\delta = \pi/5$

Solid: current. Dashed: improve by 10.





EDM: $\delta = \pi/20$

Dashed: improve by 10. Dot-dashed: improve by 100

Summary

- ALP can assist the EWBG by:
  - Enhancing the EWPT strength.
  - Enhancing n_B produced by local EWBG mechanism
- Can be probed by: Electron and atom EDM, collider search, rare meson decay, CMB bound on $\Delta N_{\rm eff}$