Electroweak phase transition in maximally symmetric composite Higgs model

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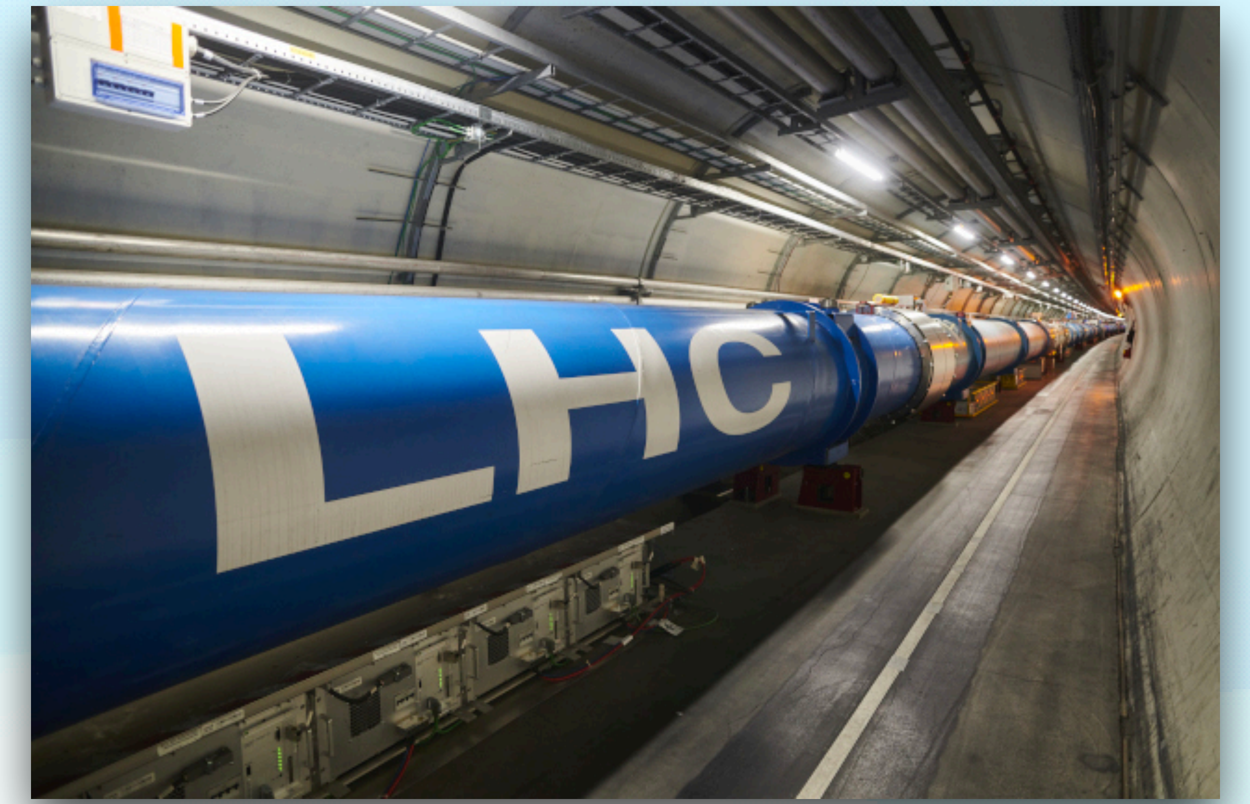
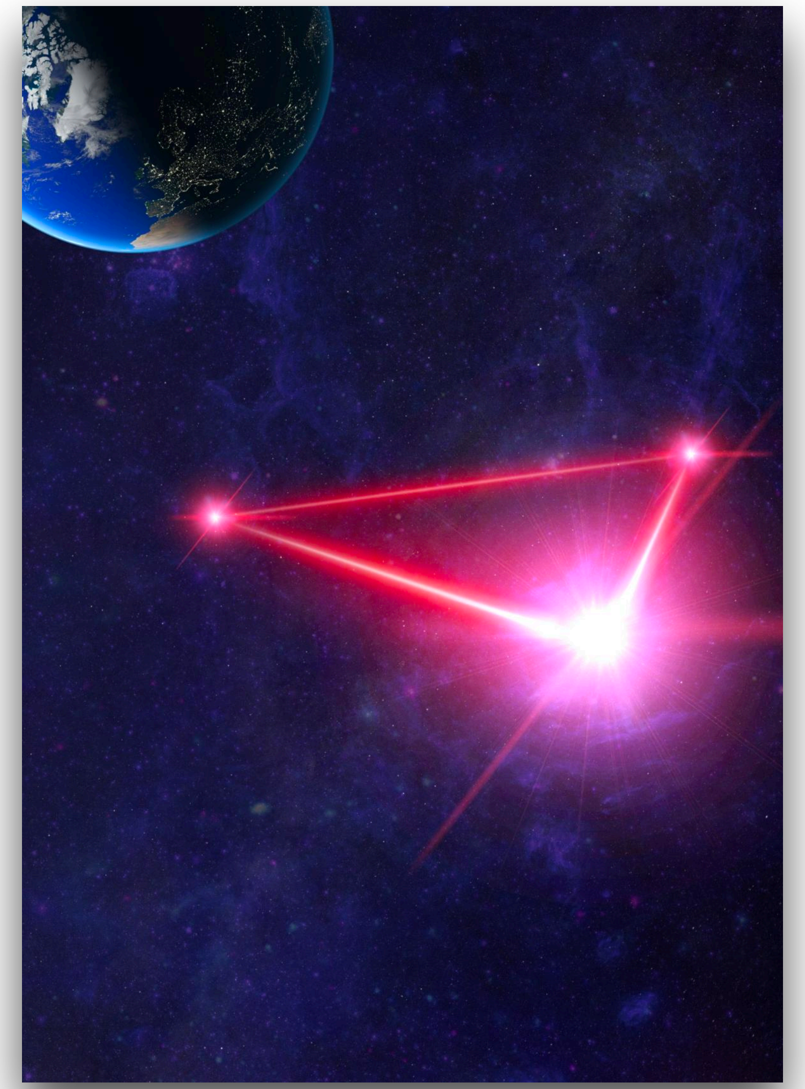
2406.14633: with A. Banerjee and I. Nałęcz

Motivation

- Hierarchy problem of the Higgs mass—> SM as EFT
- Baryon asymmetry
  - Sakharov conditions—> B, CP violation and out-of-equilibrium
  - Phase transitions during the early universe
  - Gravitational waves from plasma sound waves can be detectable



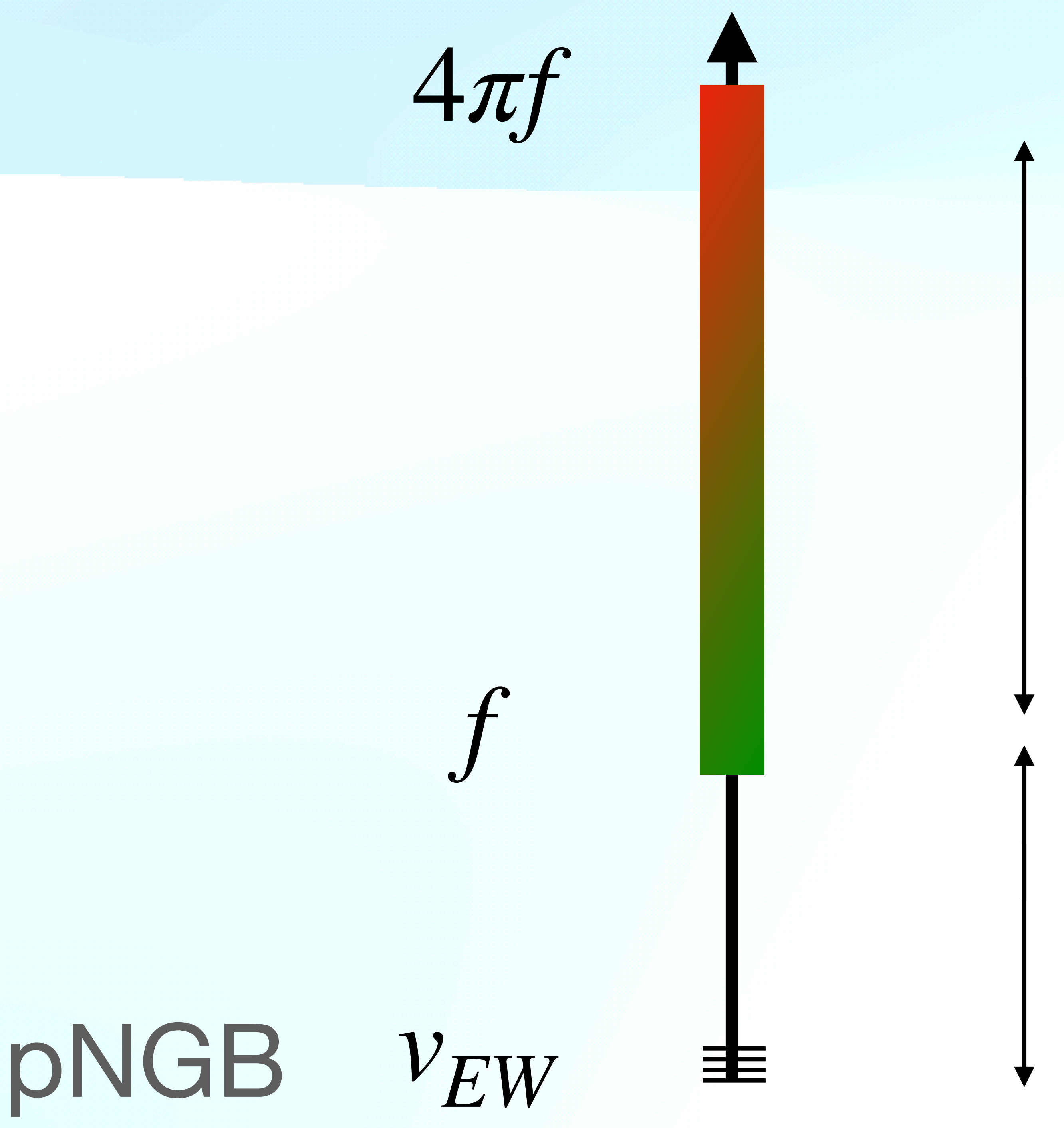


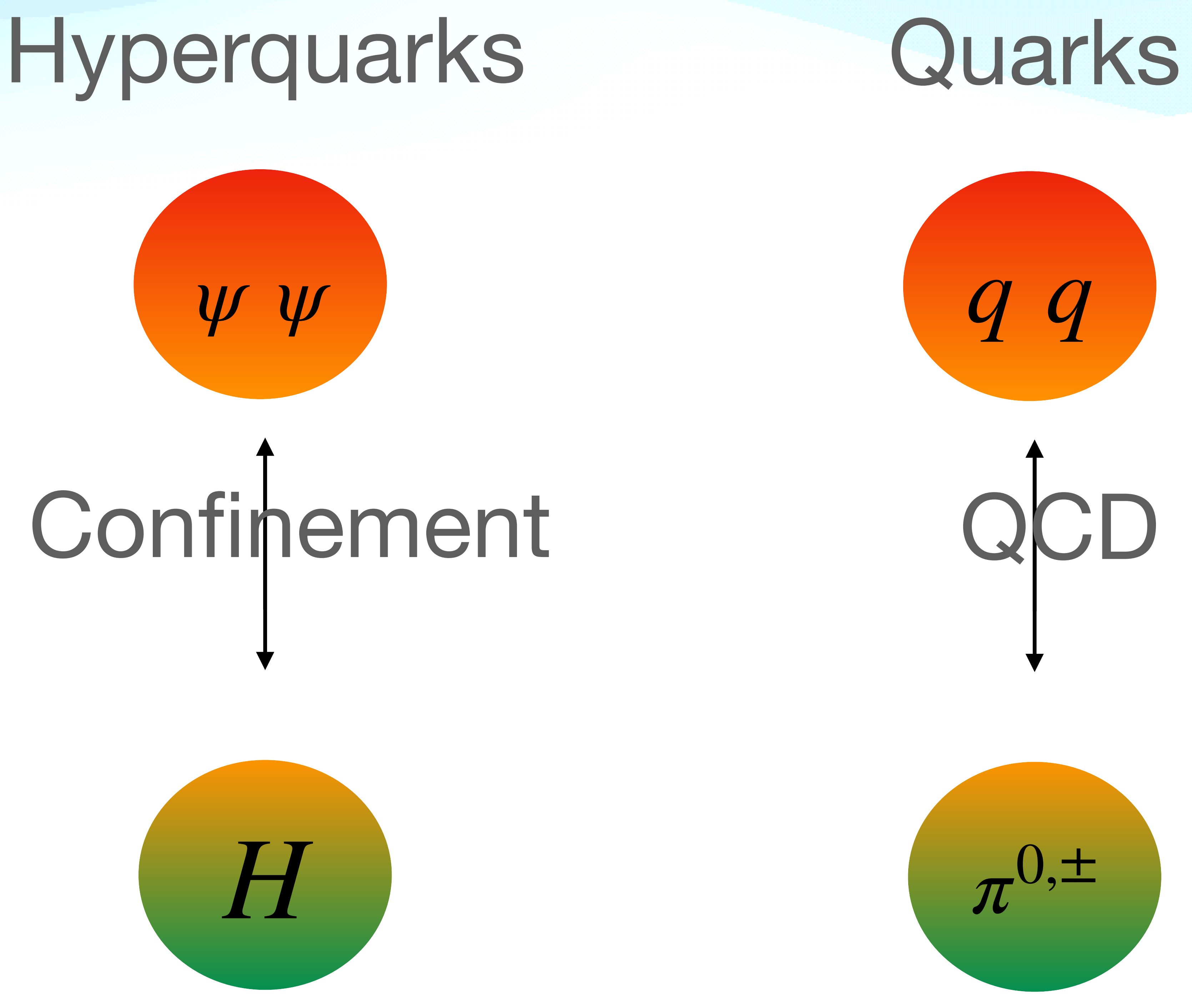
Is the Higgs boson a truly fundamental particle?

Answer: We don't know!
It might as well be a composite state, just like a pion!

Dimensional transmutation, large hierarchy of scales!

$$\log\left(\frac{M_p}{f}\right) \sim \frac{16\pi^2}{g_s^2}$$

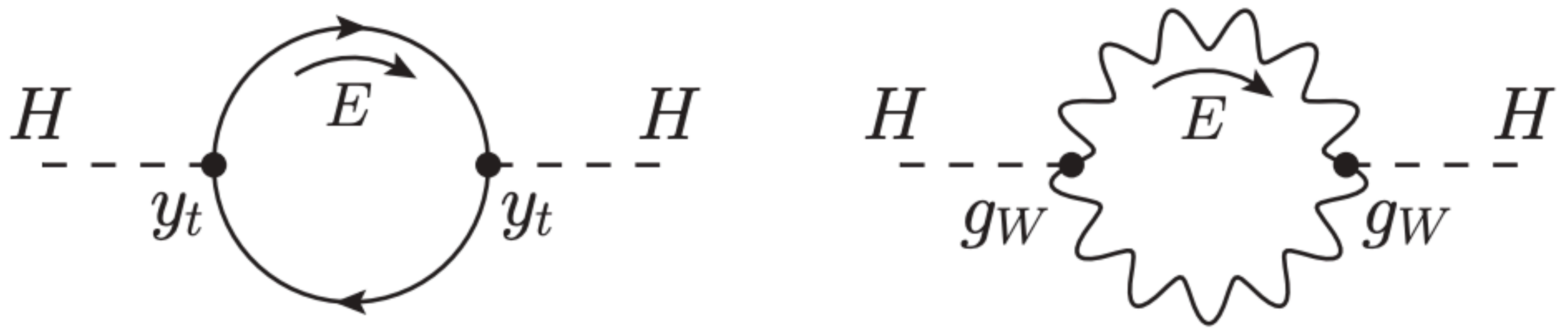




The Model

- Next-to-minimal coset: $\frac{G}{H} = \frac{SU(4)}{Sp(4)} \cong \frac{SO(6)}{SO(5)} \cong S^5$ –> SM+singlet

- Minimal Higgs hypothesis:



- Maximal Symmetry: potential is finite and fully calculable Next!

What is maximal symmetry?

Csaki, Ma, Shu: 1702.00405

$$\mathcal{L}_t = \bar{q}_L^i \gamma^\mu p_\mu \left[\Pi_0^L(p^2) + \Pi_1^L(p^2)\,\mathrm{Tr}(A_L^i \Sigma^\dagger)\mathrm{Tr}(\Sigma A_L^{i\dagger})\right] q_L^i$$

$$+\bar{t}_R \gamma^\mu p_\mu \left[\Pi_0^R(p^2) + \Pi_1^R(p^2)\,\mathrm{Tr}(A_R^\dagger \Sigma)\mathrm{Tr}(\Sigma^\dagger A_R)\right] t_R$$

$$+\bar{q}_L^i \left[\Pi_2^{LR}(p^2)\,\mathrm{tr}(A_L^i \Sigma^* A_R \Sigma^\dagger) + \Pi_1^{LR}(p^2)\,\mathrm{tr}(A_L^i \Sigma^\dagger)\mathrm{tr}(\Sigma^\dagger A_R)\right] t_R + \mathrm{h.c.}$$

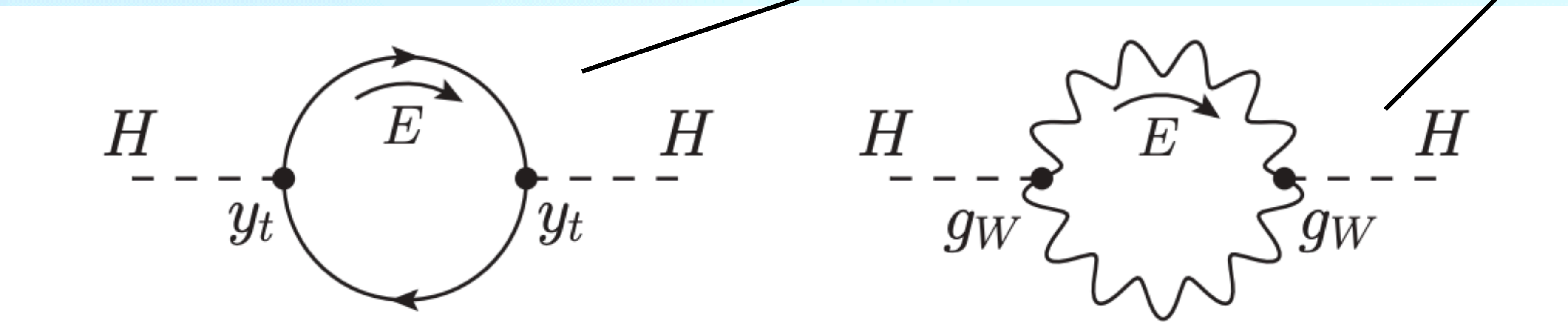
$$\Sigma \equiv \exp(i\sqrt{2}\pi^a \hat{T}^a / f)$$

$$\Pi_1^{L,R} = \Pi_1^{LR} = 0 \qquad \Pi_0^{L,R} = \frac{|\lambda_5^{L,R}|^2 f^2}{p^2 + M_5^2}, \qquad \Pi_2^{LR} = \frac{\lambda_5^L \lambda_5^{R*} f^2 M_5}{p^2 + M_5^2},$$

$$m_t = \left| \frac{\Pi_2^{LR}(0)\mathcal{F}_t(v, v_\eta)}{\sqrt{(1+\Pi_0^L(0))(1+\Pi_0^R(0))}} \right| = F_t\,|\mathcal{F}_t(v, v_\eta)|$$

The scalar potential

$$V_{1\text{-loop}}(h,\eta) = V_t + V_g + V_H$$



Hyperquark mass term

$$V_H = Bf^3 \mathrm{tr}\left[\mu_H \Sigma + \Sigma^\dagger \mu_H^\dagger\right]$$

$$V_{CW} = \frac{1}{2}\mathrm{Tr}\int \frac{d^4p}{(2\pi)^4} \log\left[p^2 + M^2(p^2)\right]$$

Non-trivial momentum dependence very different from elementary scalar case

- Singlet η gets a vev v_η
- CP violation
- Contribution numerically small but relevant!

$$V_{CW} = \frac{N_{\text{eff}}}{2}\int \frac{d^4p}{(2\pi)^4} \log\left[1 + \frac{m^2_{\text{SM}}(\phi) m_1^2 m_2^2}{p^2(p^2+m_1^2)(p^2+m_2^2)}\right]$$

Finite temperature potential

$$V_{1\text{-loop}} = \frac{N_{\text{eff}}}{2} \int \frac{d^4p}{(2\pi)^4} \log\left[1 + \frac{m^2_{\text{SM}}(\phi) m_1^2 m_2^2}{p^2(p^2+m_1^2)(p^2+m_2^2)}\right]$$

- Imaginary time formalism

$$\int dp^0 d^3p\, f(p^2) \to 2\pi T \sum_{n=-\infty}^{\infty} \int d^3p\, f(\omega_n^2 + |\vec{p}\,|^2)$$

- Effect of heavy resonances is Boltzmann suppressed

$$V_{1\text{-loop}} = V_{\text{CW}}^{(T=0)}(\tilde{m}_i) + N_{\text{eff}} \frac{T^4}{2\pi^2} \sum_{i=1}^{3} J_B\left(\frac{\tilde{m}_i}{T}\right)$$

- Effective potential is fully calculable

$$V_{\text{CW}}^{(T=0)}(\tilde{m}_i) \equiv \frac{N_{\text{eff}}}{32\pi^2} \sum_{i=1}^{3} \tilde{m}_i^4 \log\left(\frac{\tilde{m}_i}{\mu}\right)$$

$$J_B(x) \equiv \int_0^\infty dy\, y^2 \log\left[1 - e^{-\sqrt{y^2+x^2}}\right]$$

Dolan & Jackiw: 10.1103/PhysRevD.9.3320

Leading-log approximation

$$V^{LL}_{1\text{-loop}} = -F_T|\mathcal{F}_t(h,\eta)|^2 + F_G\mathcal{F}_g(h,\eta) + F_H\mathcal{F}_H(h,\eta) \qquad \pi_0 \equiv \sqrt{h^2+\eta^2}$$

Top quarks $\longrightarrow$ $$\mathcal{F}_t(h,\eta) \equiv \frac{h s_{\pi_0}}{\pi_0^2}\left[c_\beta\left(\pi_0 c_{\pi_0} - i\eta s_{\pi_0}\right) - e^{i\gamma}s_\beta\left(\pi_0 c_{\pi_0} + i\eta s_{\pi_0}\right)\right]$$

Gauge bosons $\longrightarrow$ $$\mathcal{F}_g(h,\eta) \equiv \frac{h^2}{4\pi_0^2}s^2_{\pi_0}$$ "universal" contribution

Hyperquarks $\longrightarrow$ $$\mathcal{F}_H(h,\eta) \equiv \left[(1+c_\delta)c_{\pi_0} + s_\delta\frac{\eta}{\pi_0}s_{\pi_0}\right]$$

Pheno constraints

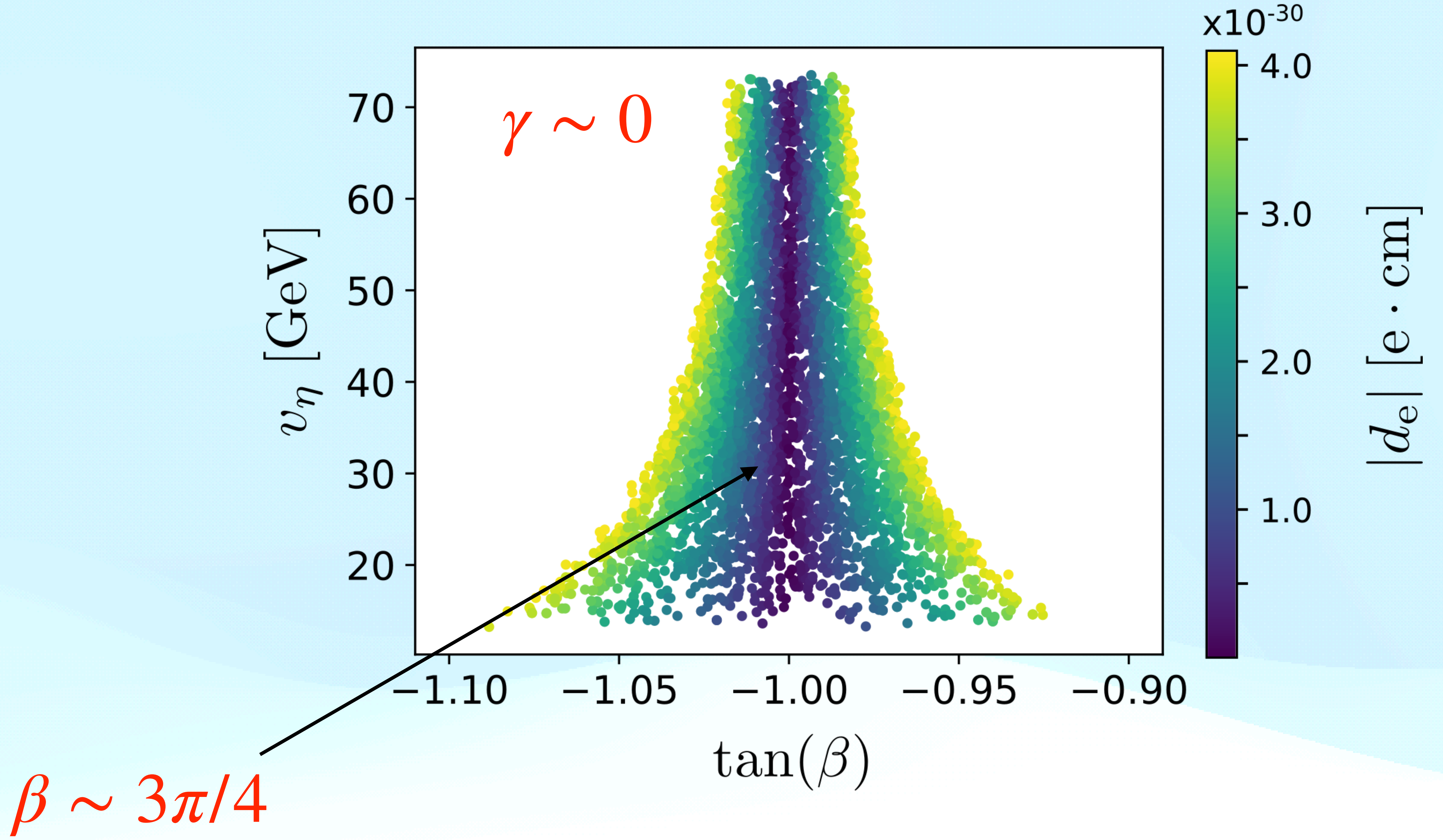
- Higgs coupling deviations → $f = 1$ TeV, $|\sin\theta| \leq 0.2$, $m_\eta \geq 2m_h$
- EW precision measurements
- LHC bounds → $M_5 > 1$ TeV, $m_{\rho,a} \geq 1.5$TeV
- EWSB & top quark mass
- electron edm → $\gamma \approx 0 \quad \to \quad \beta \approx 3\pi/4$
- 1st-order phase transition → $F_G \gg F_T \gg |F_H|$

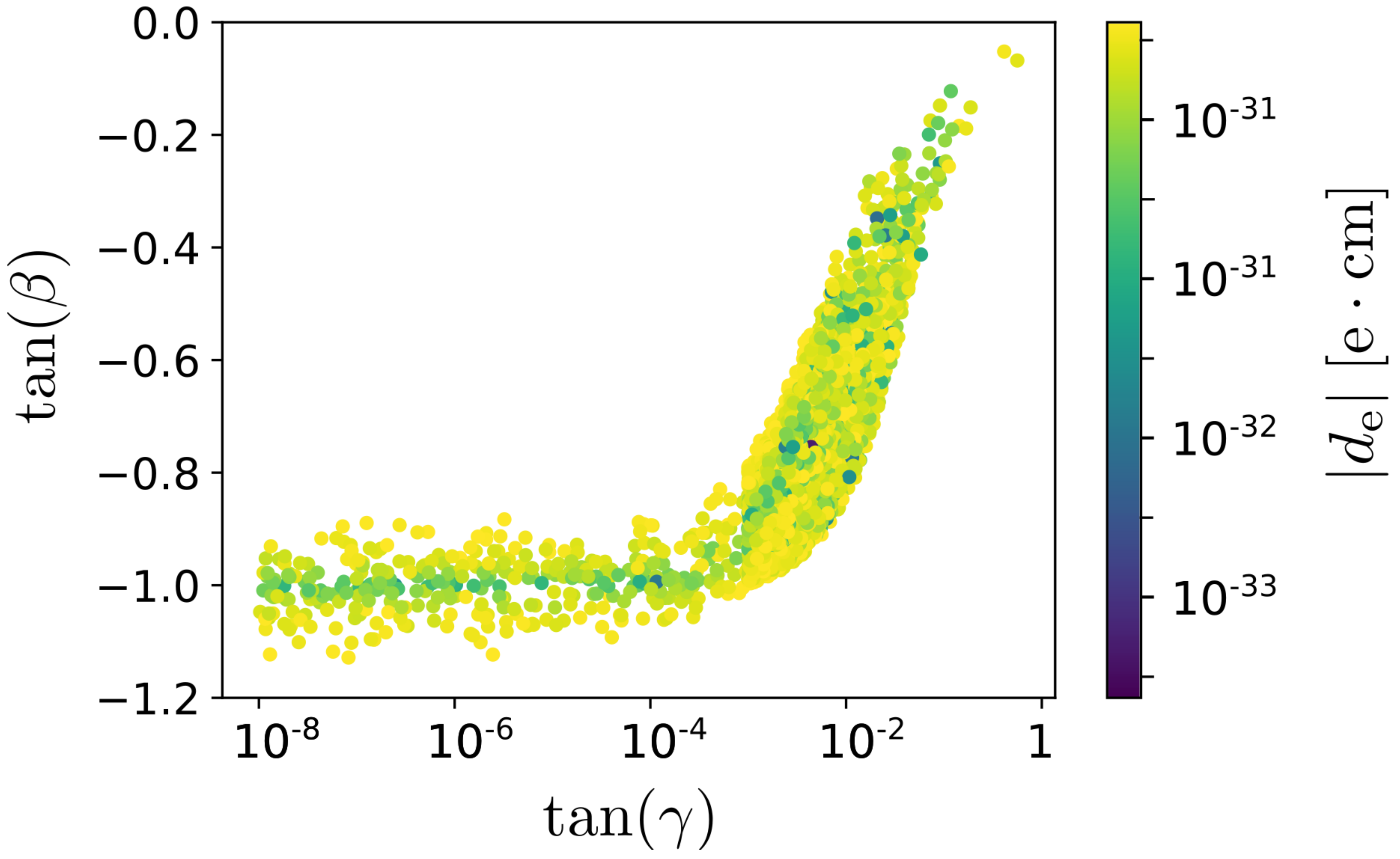
CP-violation & EDM

- Non-zero vev induces CP-violation

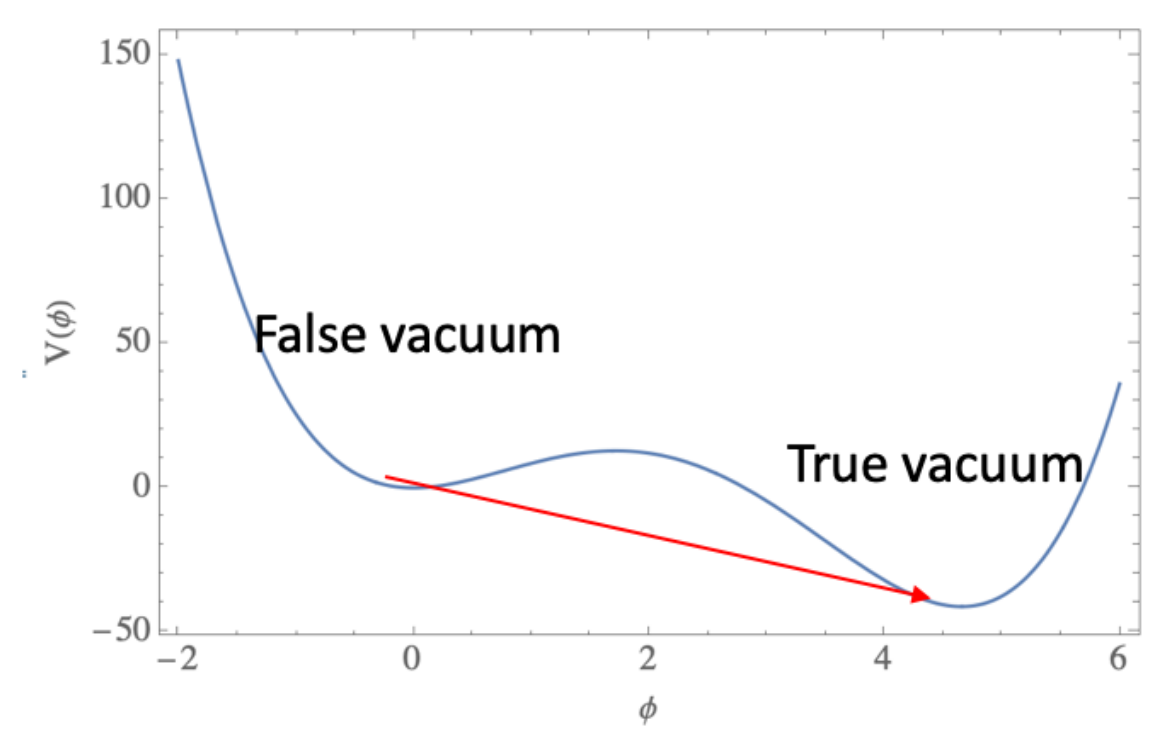
- Stringent constraint from electron edm
  $|d_e| < 4.1 \times 10^{-30} e$ cm

- δ is not directly constrained. Hyperquark term does not contribute to the tth coupling

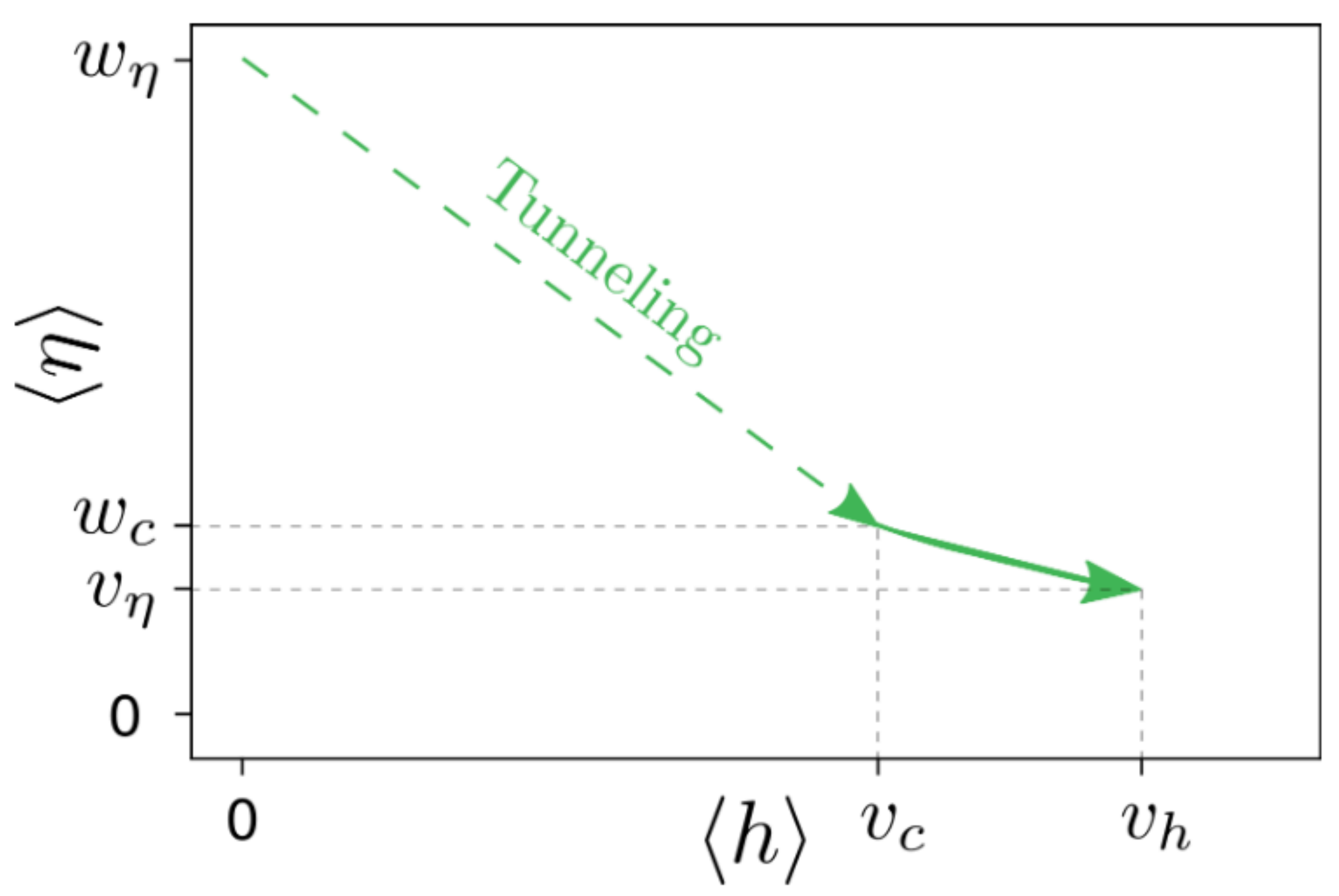




Electroweak phase transition: $T < f$



- Bubble nucleation: $\Gamma(T) = \left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} T^4 \mathrm{e}^{-S_3/T}$ $\quad \left.\frac{S_3}{T}\right|_{T=T_n} \approx 140$
- Latent heat: $\alpha \equiv \frac{1}{\rho_r}\left(\Delta V(h,\eta,T) - \frac{T}{4}\Delta\frac{\partial V(h,\eta,T)}{\partial T}\right)\Big|_{T=T_n}$
- Duration: $\beta = HT\frac{d}{dT}S_3/T$



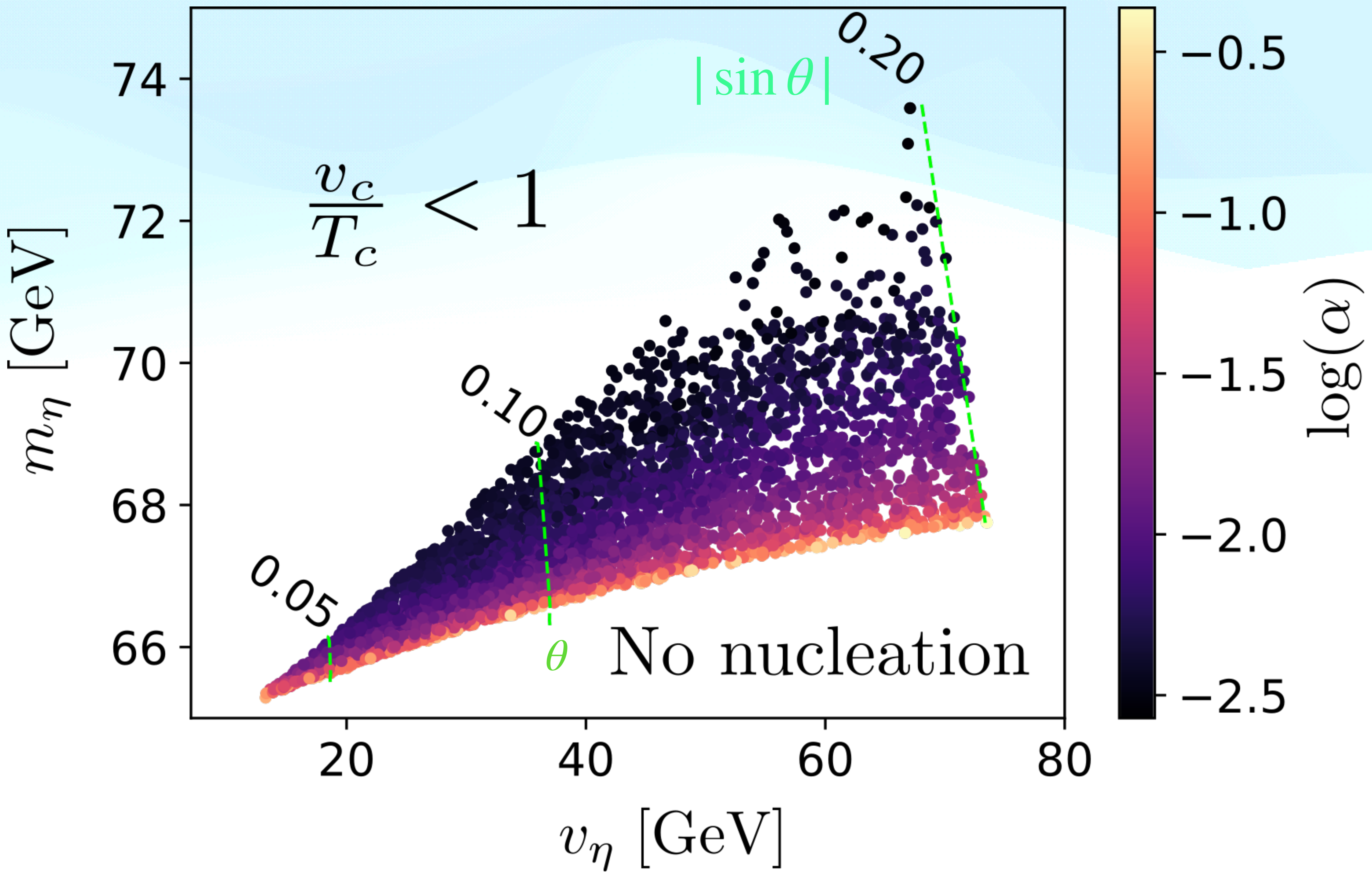
Requirement of a strong PT

1.The upper bound on the mixing angle fixes the singlet vev

2. Region above is ruled out by perturbativity requirement. Not useful for electroweak baryogenesis

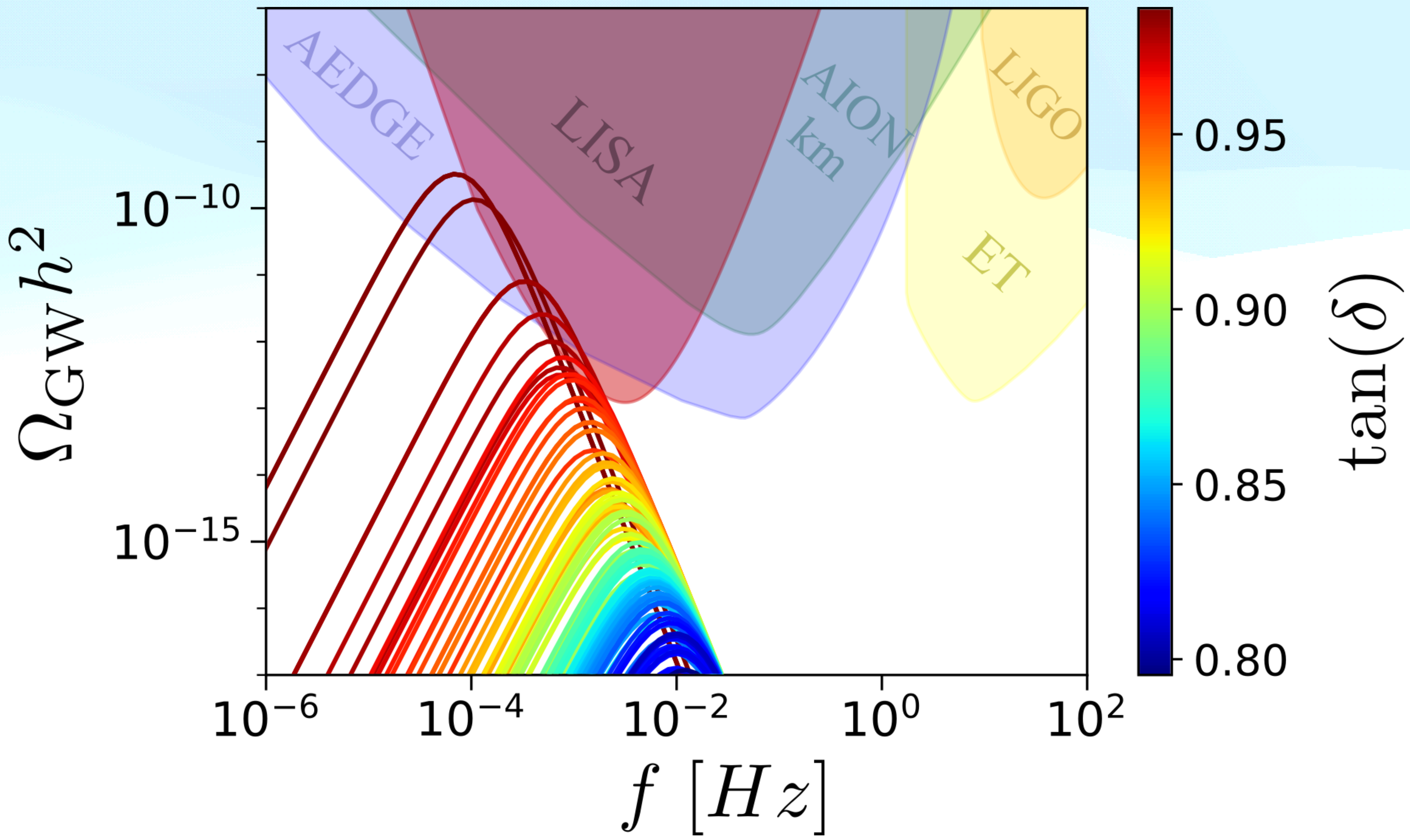
3.region below does not satisfy the nucleation condition

4. Strongest PT delinate a one-to-one correspondence between singlet vev and mass



Gravitational waves vs CP violation

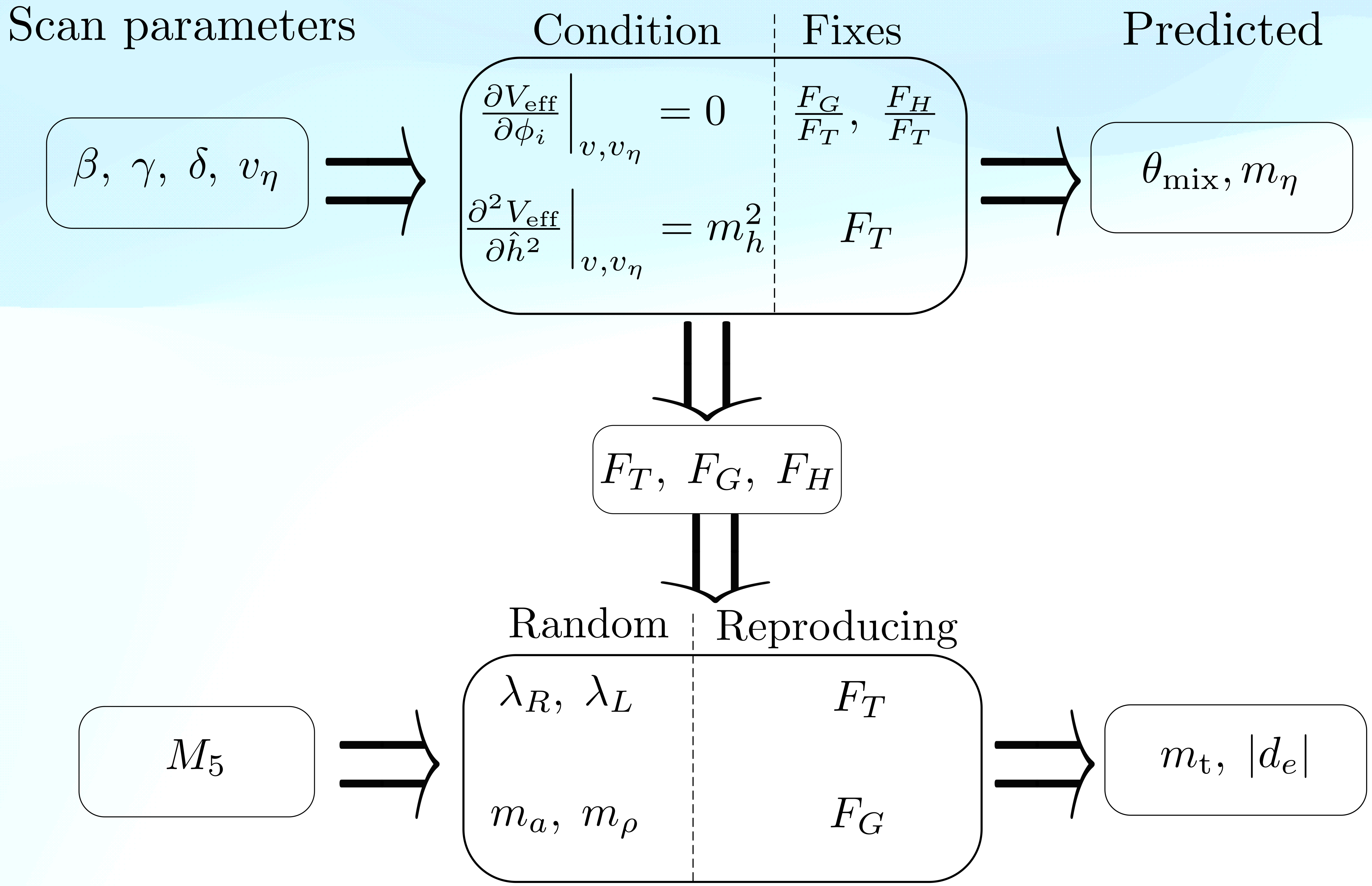
1. Clearly, larger values of $\tan(\delta)$ lead to stronger FOPTs, implying that the amount of CP violation is the main predicting factor for the strength of the PT
2. Observation of GW signal would inform us about the amount of CP violation, through the angle δ

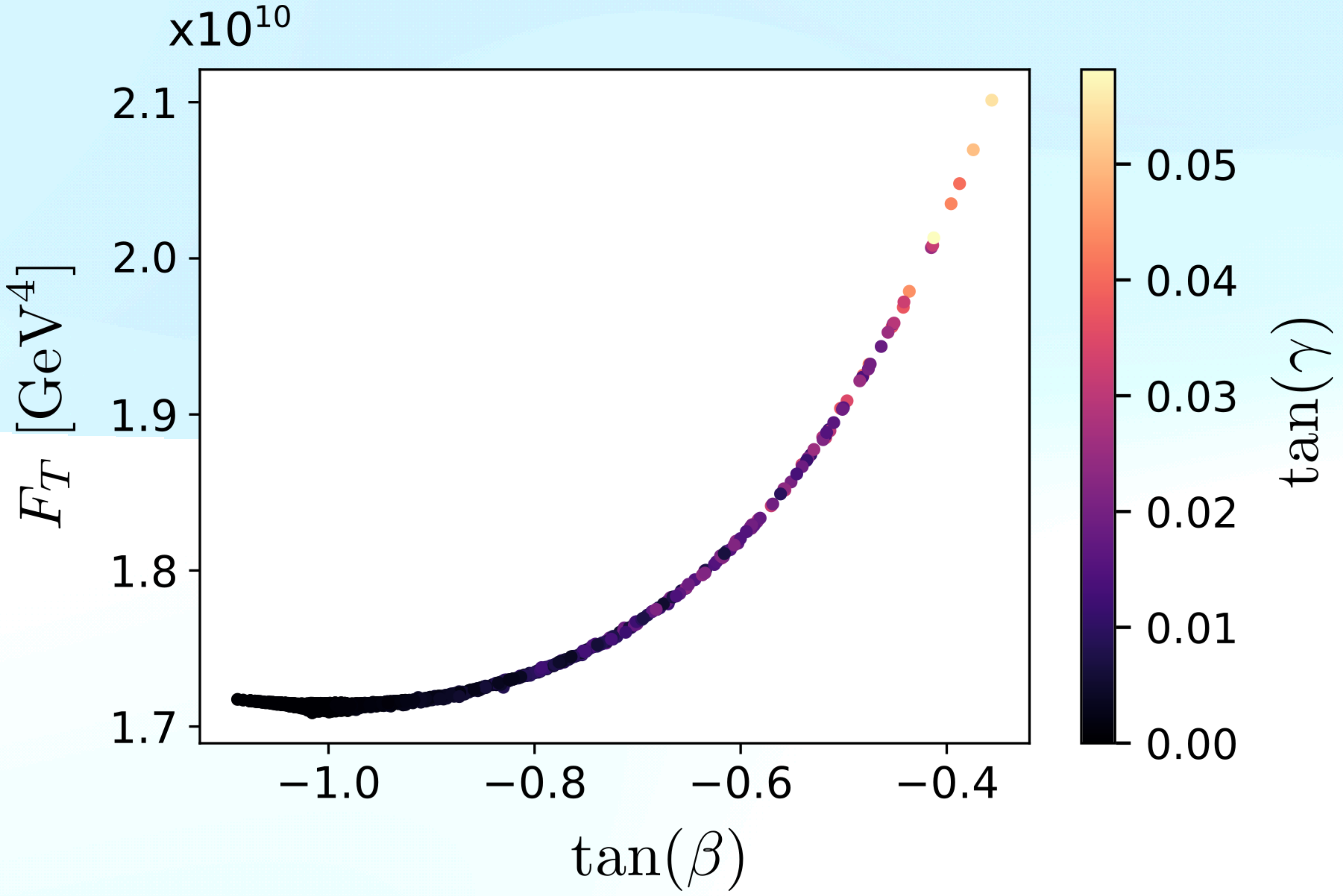


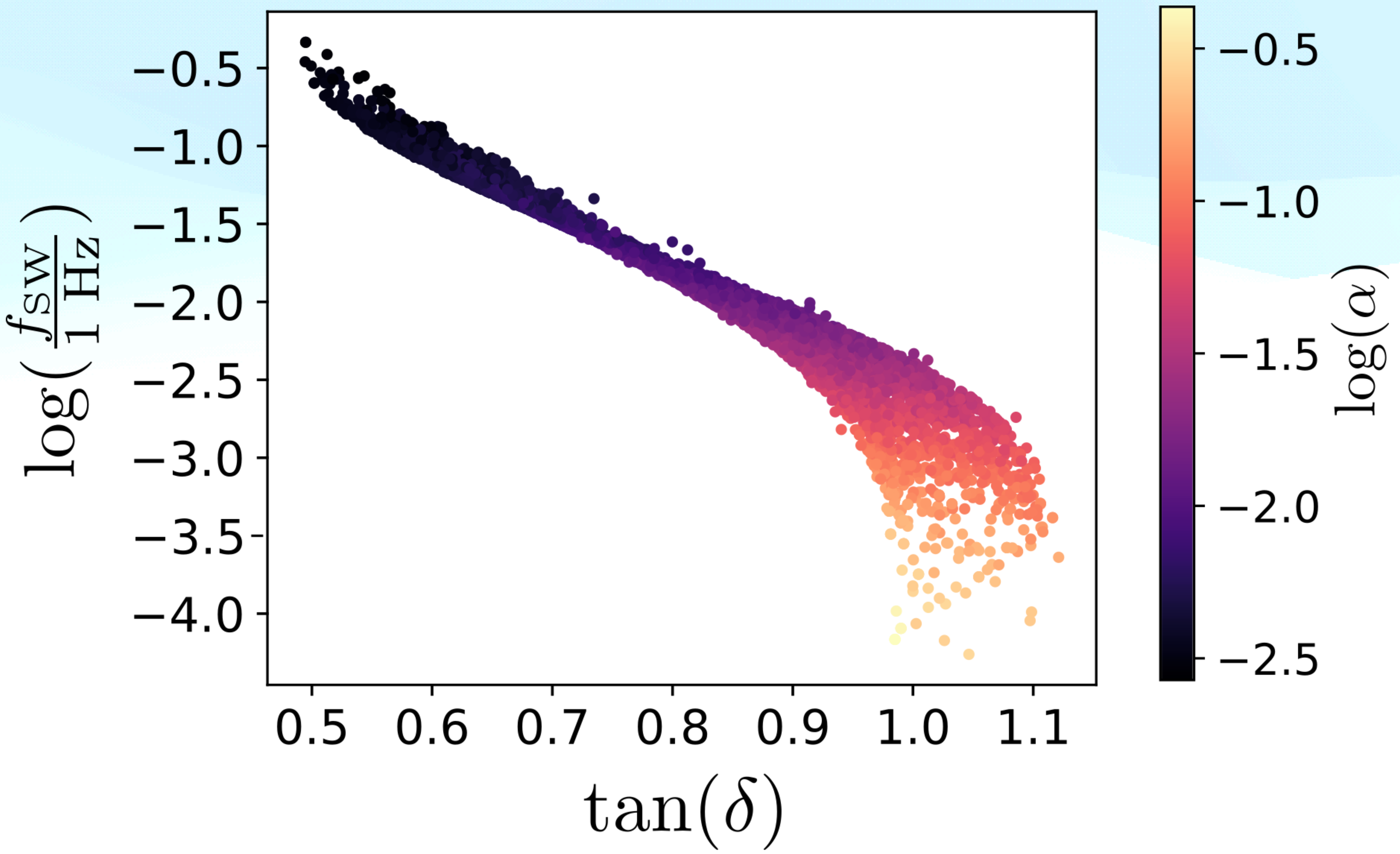
Conclusions

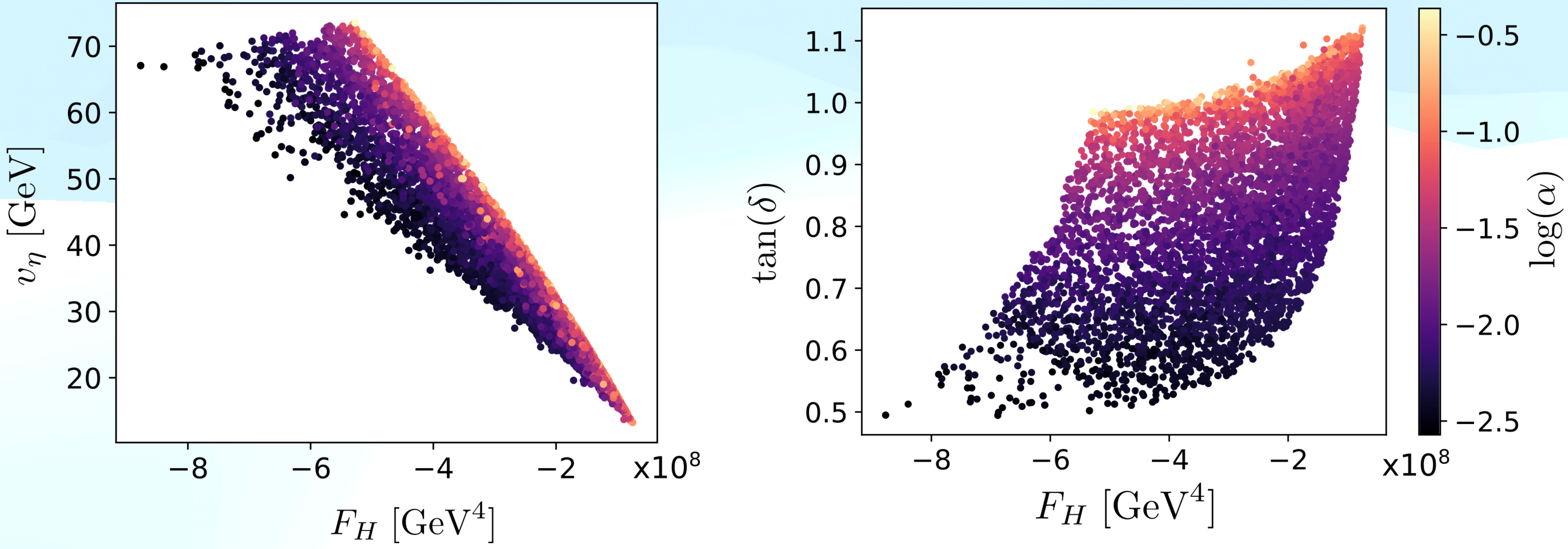
- CHM remains as an enticing extension, alleviating the hierarchy problem
- The coset SU(4)/Sp(4) leads to a pseudoscalar singlet pNGB in addition to the Higgs doublet whose contribution to the potential allows the electroweak phase transition to be first-order
- Due to explicit CP breaking, the singlet gets a vev, crucial for obtaining FOPTs
- We can learn a lot about the scalar potential from current experimental constraints
- If a stochastic GW background is discovered it will provide us with even more constraints

Benchmarking Scheme




x10^10
2.1
2.0
1.9
1.8
1.7
F_T [GeV^4]
−1.0
−0.8
−0.6
−0.4
tan(β)
0.05
0.04
0.03
0.02
0.01
0.00
tan(γ)


−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
$\log(\frac{f_{\rm SW}}{1\ \rm Hz})$
0.5
0.6
0.7
0.8
0.9
1.0
1.1
tan(δ)
−0.5
−1.0
−1.5
−2.0
−2.5
log(α)


70
60
50
40
30
20
v_η [GeV]
−8
−6
−4
−2
x10^8
F_H [GeV^4]
1.1
1.0
0.9
0.8
0.7
0.6
0.5
tan(δ)
−8
−6
−4
−2
x10^8
F_H [GeV^4]
−0.5
−1.0
−1.5
−2.0
−2.5
log(α)

The composite Higgs landscape

Top partial compositeness, next-to-minimal

- Asymptotic freedom->Number of fermions
- Outside conformal IR window
- Minimal coset
- Custodial symmetry

Coset	HC	ψ	χ	$-q_\chi/q_\psi$	Baryon	Name	Lattice
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{SO(6)}$	SO(7)	$5 \times \mathbf{F}$	$6 \times \mathbf{Sp}$	5/6	$\psi\chi\chi$	M1	
	SO(9)	$5 \times \mathbf{F}$	$6 \times \mathbf{Sp}$	5/12	$\psi\chi\chi$	M2	
	SO(7)	$5 \times \mathbf{Sp}$	$6 \times \mathbf{F}$	5/6	$\psi\psi\chi$	M3	
	SO(9)	$5 \times \mathbf{Sp}$	$6 \times \mathbf{F}$	5/3	$\psi\psi\chi$	M4	
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{Sp(6)}$	Sp(4)	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	5/3	$\psi\chi\chi$	M5	✓
$\frac{SU(5)}{SO(5)} \times \frac{SU(3)^2}{SU(3)}$	SU(4)	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	5/3	$\psi\chi\chi$	M6	✓
	SO(10)	$5 \times \mathbf{F}$	$3 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	5/12	$\psi\chi\chi$	M7	
$\frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{SO(6)}$	Sp(4)	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	1/3	$\psi\psi\chi$	M8	✓
	SO(11)	$4 \times \mathbf{Sp}$	$6 \times \mathbf{F}$	8/3	$\psi\psi\chi$	M9	
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(6)}{SO(6)}$	SO(10)	$4 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	$6 \times \mathbf{F}$	8/3	$\psi\psi\chi$	M10	
	SU(4)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	2/3	$\psi\psi\chi$	M11	✓
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(3)^2}{SU(3)}$	SU(5)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}_2})$	4/9	$\psi\psi\chi$	M12	

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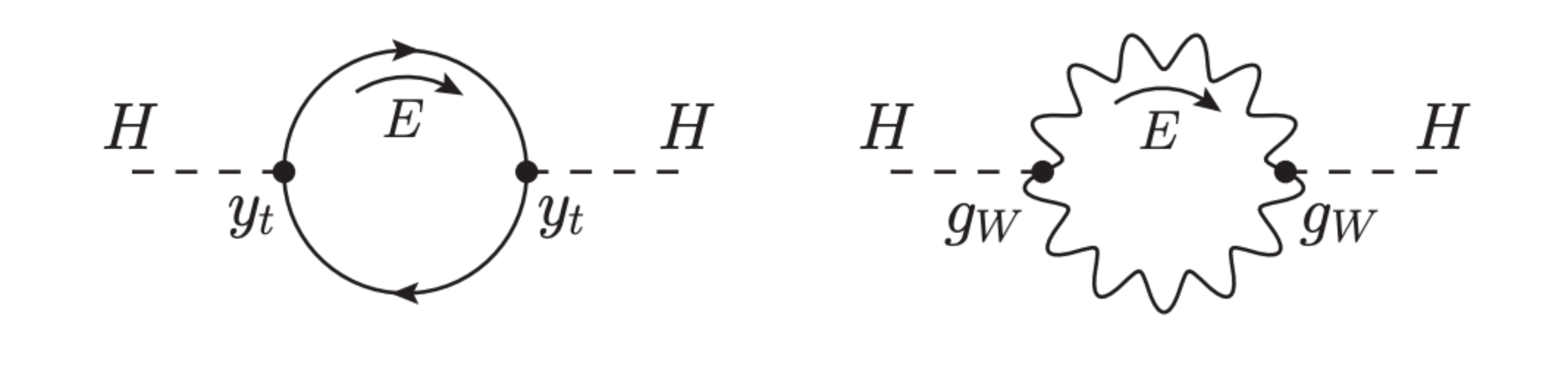
Minimal Higgs Hypothesis

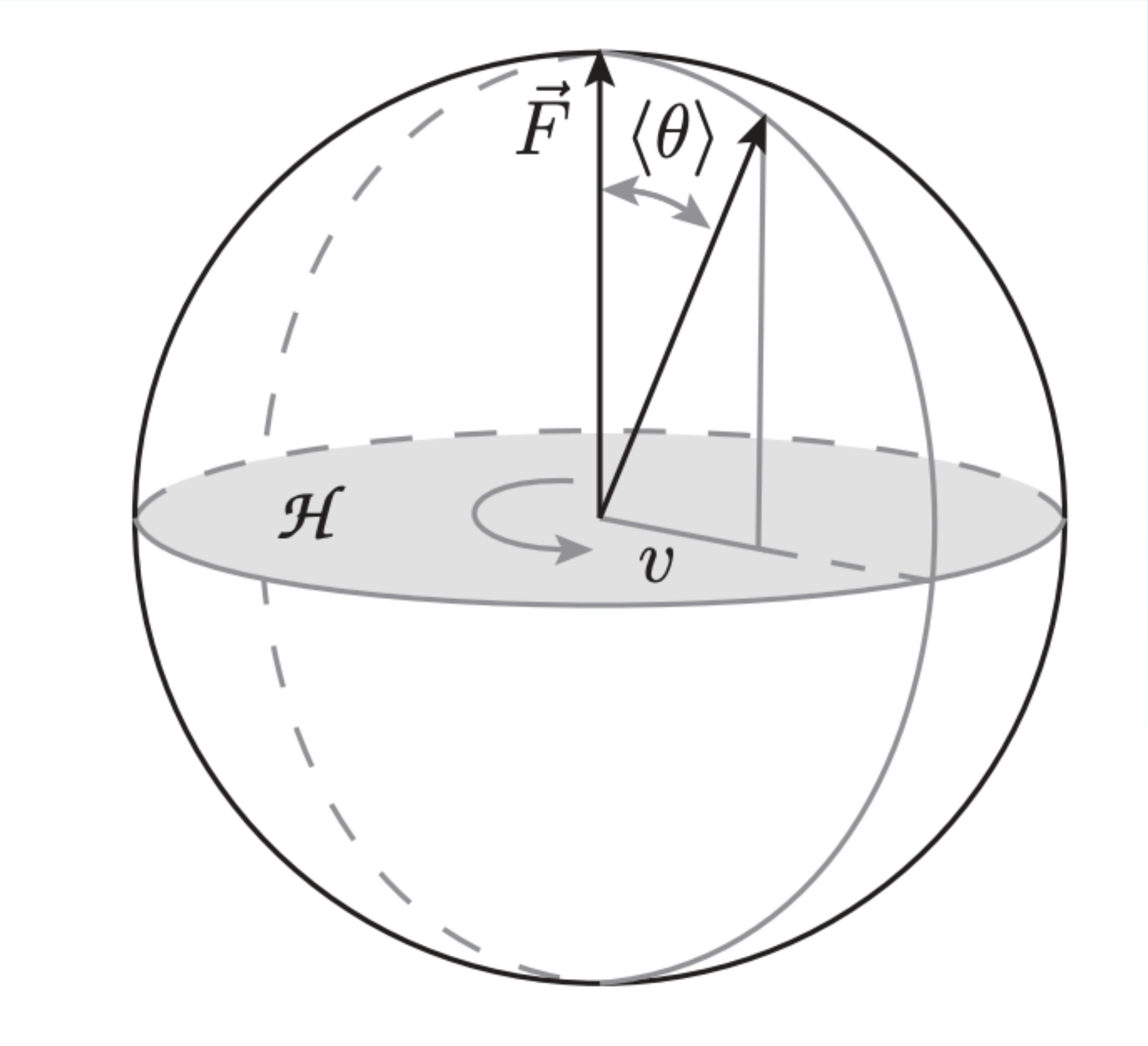
Effective potential arises from IR-effects by the Coleman-Weinberg mechanism



$$V^{CW} = \frac{1}{2}\mathrm{Tr}\int \frac{d^4p}{(2\pi)^4} \log\left[p^2 + M^2\right] \propto M^4 \log\left(\frac{M^2}{\Lambda^2}\right)$$

Divergent contribution which requires renormalization in an elementary scalar theory!

The model: $\frac{G}{H} = \frac{SU(4)}{Sp(4)} \cong \frac{SO(6)}{SO(5)} \cong S^5$



$$[T^a, T^b] = if^{abc}T^c, \quad [T^{\hat{a}}, T^{\hat{b}}] = if^{\hat{a}\hat{b}c}T^c, \quad [T^a, T^{\hat{b}}] = if^{a\hat{b}\hat{c}}T^{\hat{c}}$$

pNGB matrix $\longrightarrow$ $\Sigma \equiv \exp(i\sqrt{2}\pi^a\hat{T}^a/f)$

$SU(2)_L$ Higgs doublet + singlet pseudo-scalar