기초과학연구원
Institute for Basic Science

Electroweak Baryogenesis

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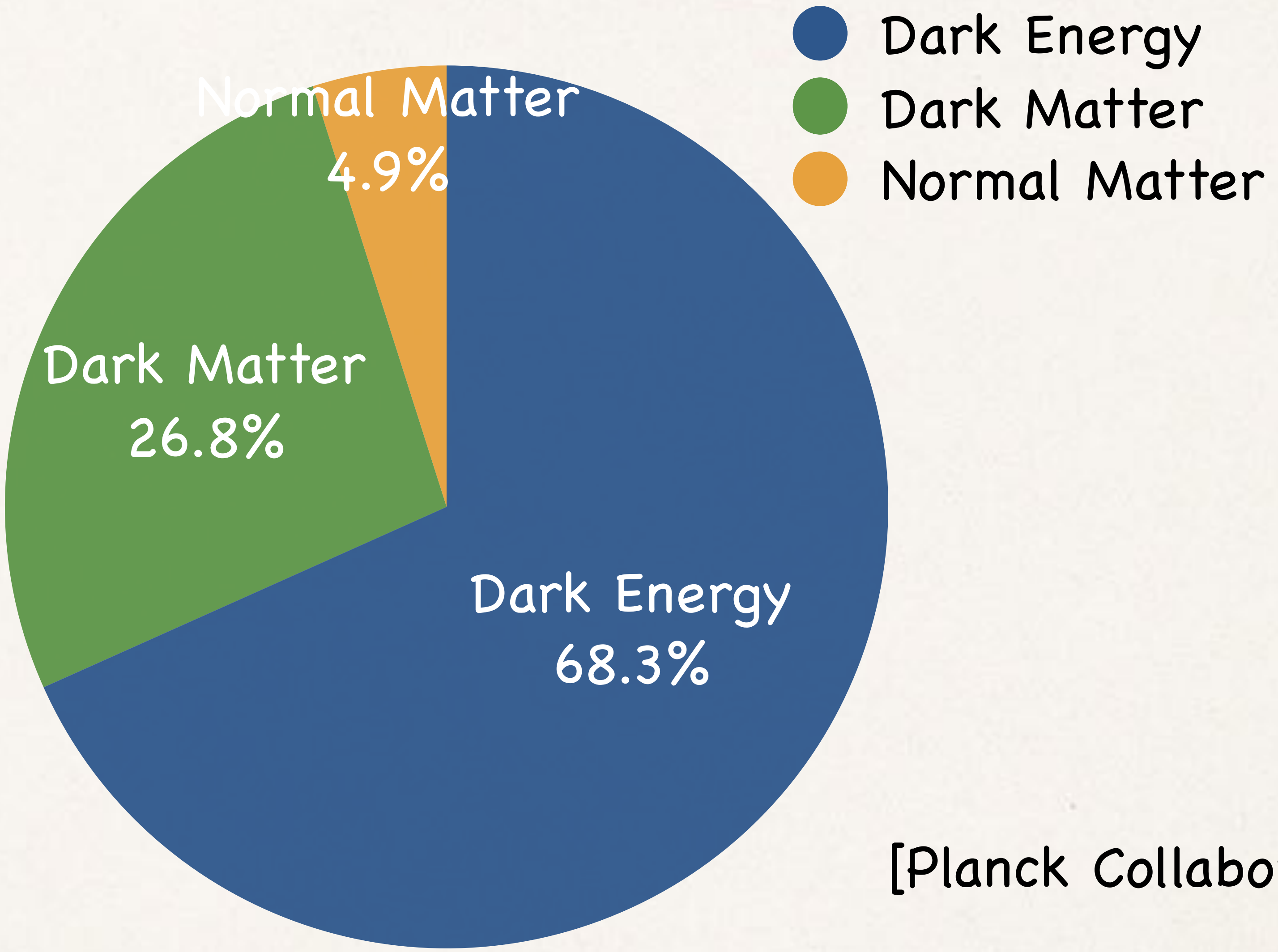
2019 Summer School on Cosmology and Particle Physics

Outline

- Introduction
    - Baryon asymmetry of the Universe (BAU)
- Electroweak baryogenesis
  (1) Electroweak phase transition (EWPT) and its consequences
  (2) BAU-related CP violation
- Remaining issues
- Summary

What we don't know

- Energy budget of the Universe



[Planck Collaboration]

- 95% of the Universe is made of dark objects.
- There remains a mystery in the visible sector as well.

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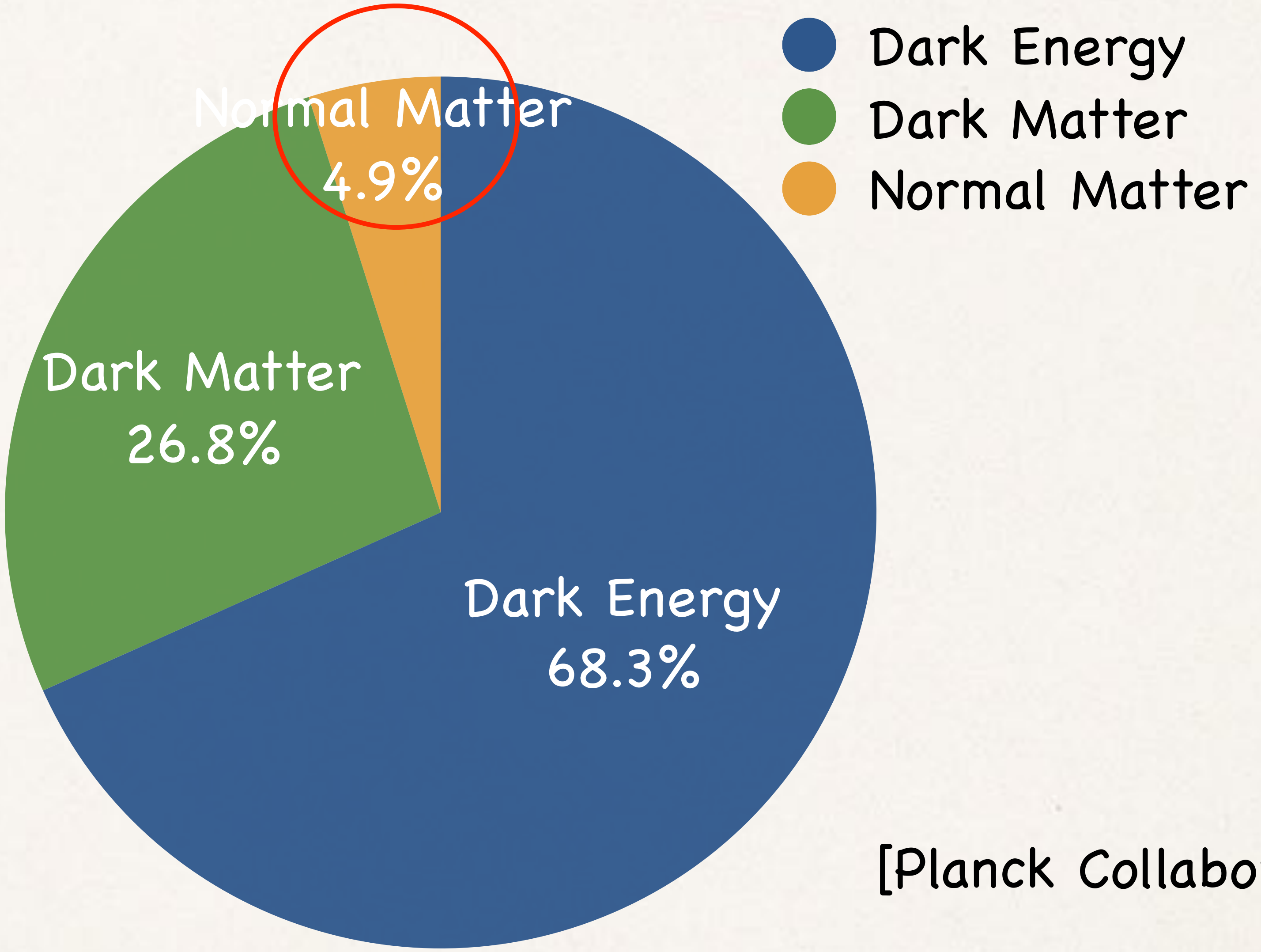

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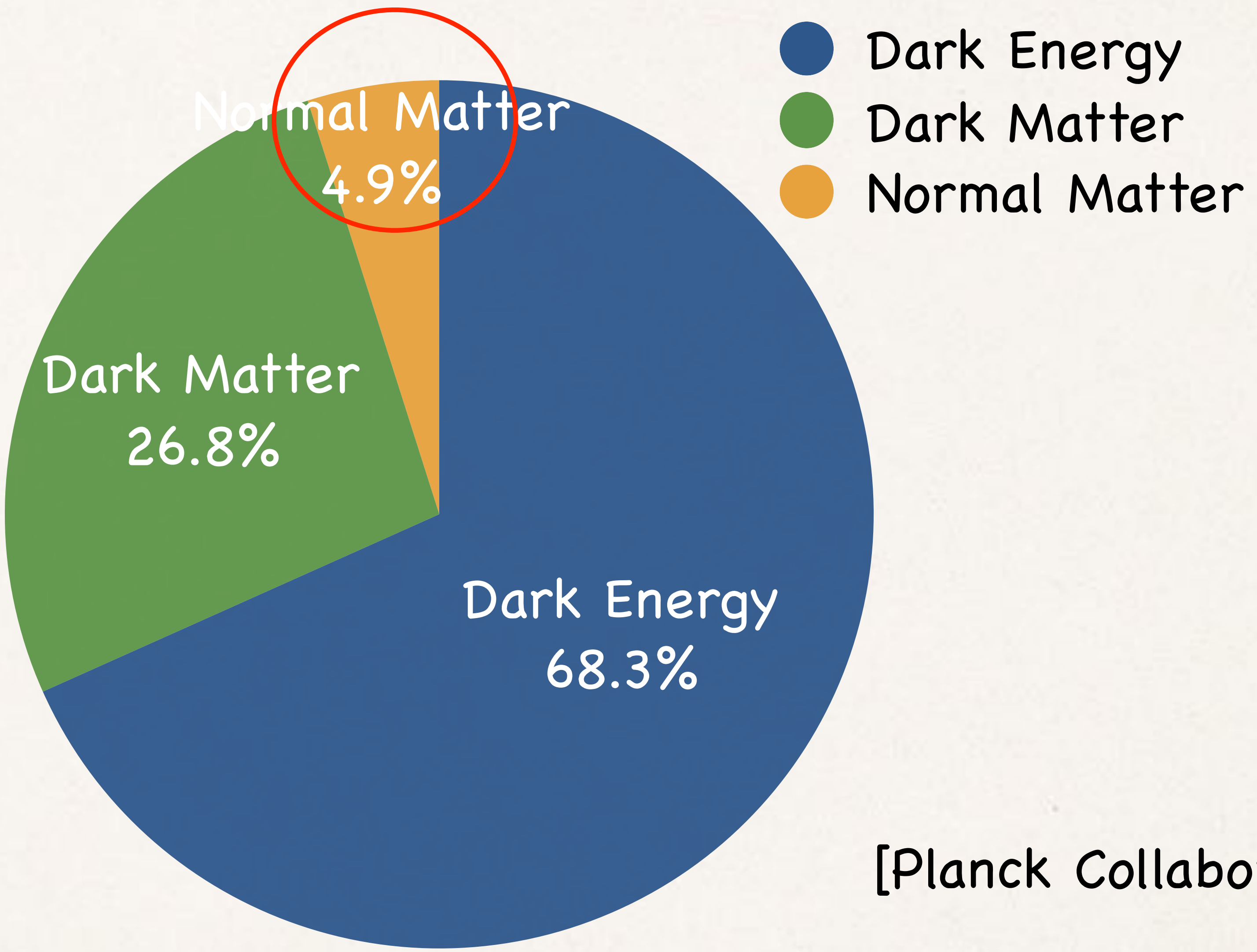

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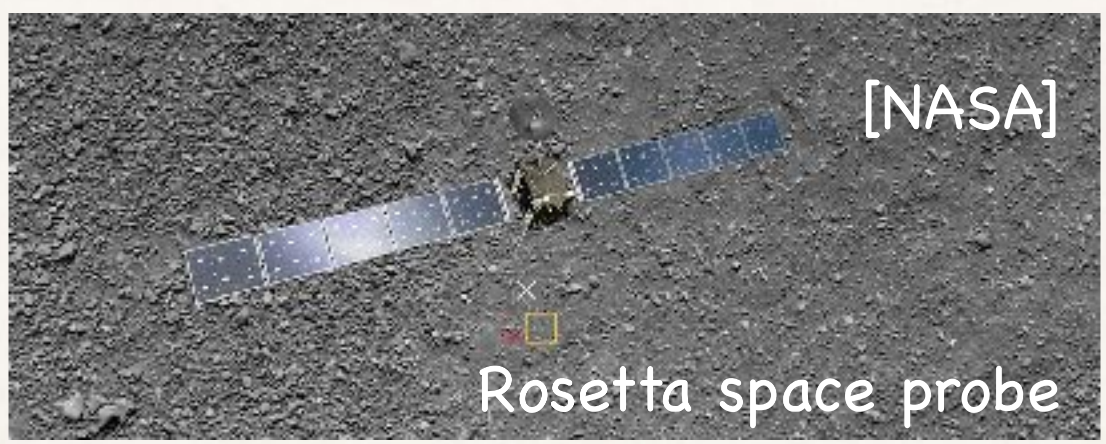
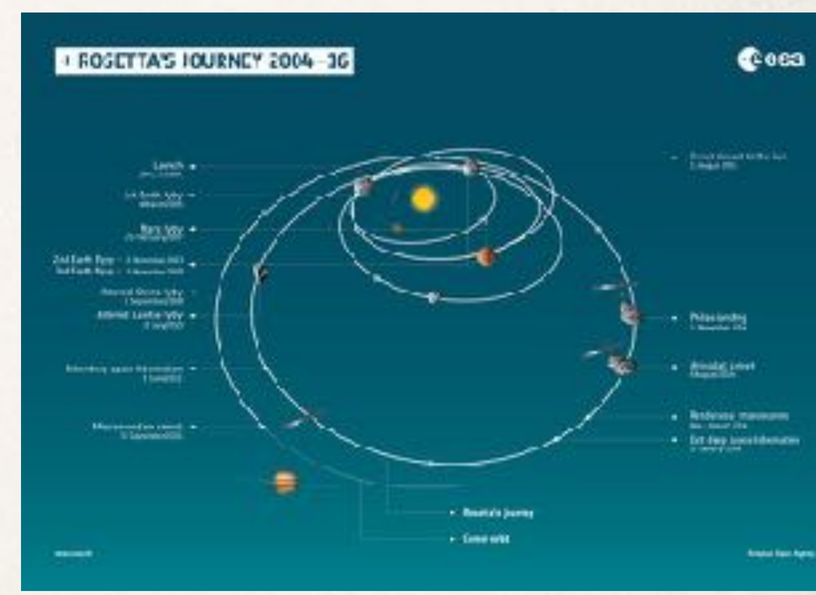
Where is antimatter?

Where is antimatter world?

"Touching" experiments

We have touched the Moon, the Mars, Comets, etc.





No annihilation!

→ Those are made of ordinary matter.

How about faraway galaxies?

Where is antimatter world?

Antimatter searches:

Cosmic ray experiments (AMS, PAMELA, BESS-Polar etc): search for antihelium, etc.

So far, no signal yet.

*anti-proton is secondary produced.

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Cosmological difficulty: separation mechanism?

Separation between matter and antimatter at galaxy cluster scale ($\sim 10^{12} M_{\odot}$) is causally impossible.

[Steigman, Ann. Rev. Astron. Astrophys.14 (1976)]

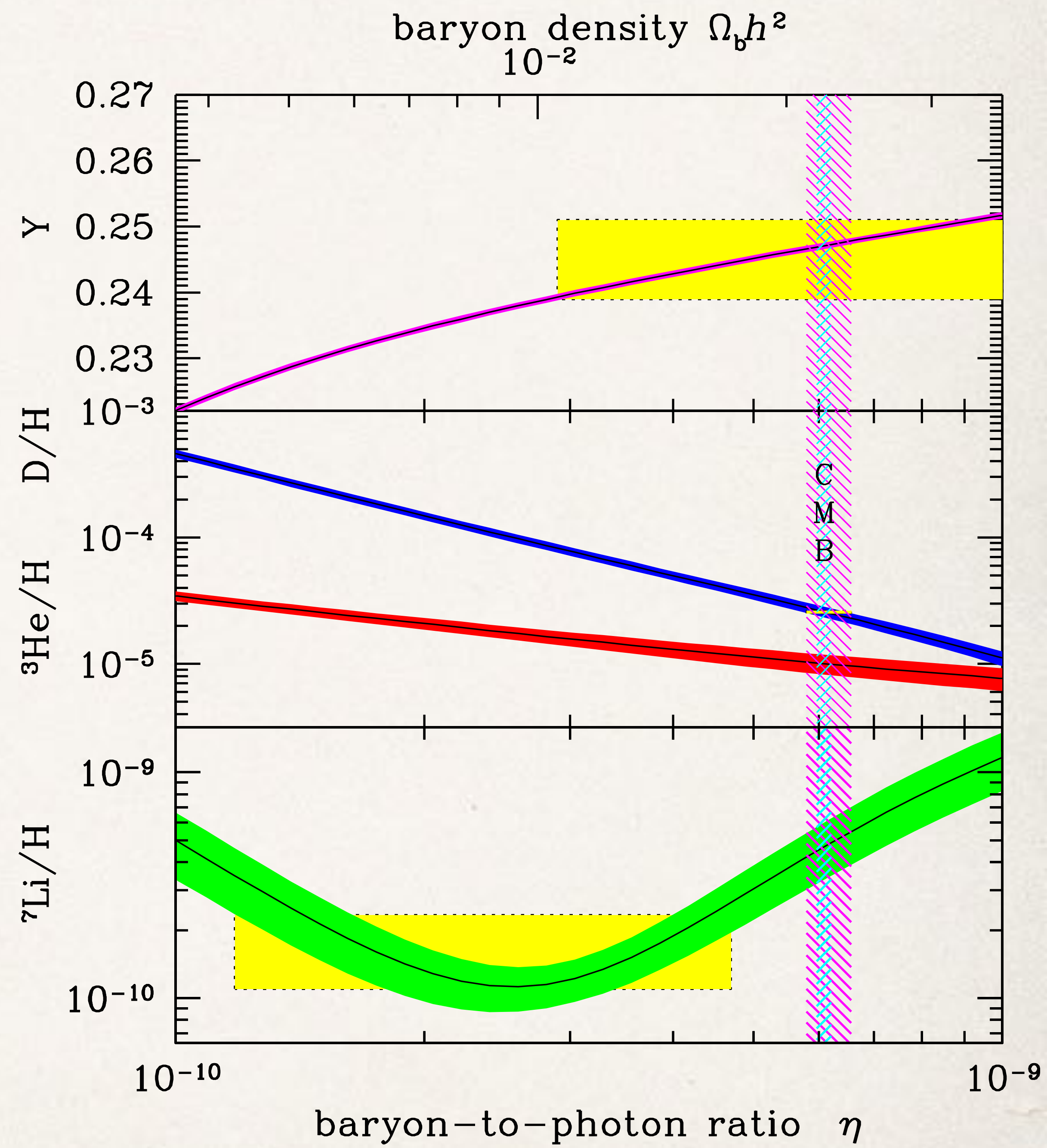
Baryon Asymmetry of the Universe (BAU)

❒ Our Universe is baryon-asymmetric.

$$\eta^{\rm BBN} = \frac{n_B}{n_\gamma} = (5.8 - 6.6) \times 10^{-10},$$
$$\eta^{\rm CMB} = \frac{n_B}{n_\gamma} = (6.09 \pm 0.06) \times 10^{-10}.$$

$$n_B = (\text{number density of baryons} - \text{number density of antibaryons})$$

❒ If the BAU is generated before T≃O(1) MeV, the light element abundances (D,^{3}He,^{4}He,^{7}Li) can be explained by the standard Big-Bang cosmology.



PDG 2018

Baryogenesis = generate right η

How do we create baryon asymmetry?

Sakharov's conditions

[Sakharov, JETP Lett. 5 (1967) 24]

To get the BAU from initially baryon symmetric Universe, the following conditions must be satisfied.

(1) Baryon number violation
(2) C and CP violation
(3) Out of equilibrium

N.B. (1) does not mean $[B(t=0),H]=0 \to [B(t>0),H]\neq 0$

B is not conserved charge from the beginning.

(3) is exempted if CPT is broken.

Without Sakharov's conditions

(1) If [B,H]=0 with B(t=0)=0, B(t>0)=0.

(2) Let's consider if [C,H]=[CP,H]=0.

Expectation value of operator O (Schrodinger picture):

$$\langle \mathcal{O} \rangle (t) = \mathrm{Tr}[\rho(t)\mathcal{O}] \qquad \rho : \text{density operator}$$

Liouville eq.

$$i\hbar \frac{\partial \rho(t)}{\partial t} = [H, \rho(t)]$$

Formal solution:

$$\rho(t) = e^{-\frac{i}{\hbar}Lt}\rho_0 \qquad L = L(H, \rho_0)$$

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$$\equiv L\rho(t)$$

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Without Sakharov's conditions

Suppose that [C,H]=[P,H]=[T,H]=0,

$$C\rho(t)C^{-1} = \rho(t), \quad CP\rho(t)(CP)^{-1} = \rho(t)$$

Thus

$$\langle B\rangle(t) = \mathrm{Tr}[\rho(t)B] = \mathrm{Tr}[\rho(t)B\mathcal{O}^{-1}\mathcal{O}] = \mathrm{Tr}[\rho(t)\mathcal{O}B\mathcal{O}^{-1}]$$
$$= -\mathrm{Tr}[\rho(t)B] = -\langle B\rangle(t)$$

where we have used $\mathcal{O}B\mathcal{O}^{-1} = -B$ for $\mathcal{O} = C$ and CP.

N.B.

$CPT\rho(t)(CPT)^{-1} \neq \rho(t)$ since $T\rho(t)T^{-1} = e^{+\frac{i}{\hbar}Lt}\rho_0 \neq \rho(t)$

*T is anti-unitary operator

Without Sakharov's conditions

(3) If the system is in thermal equilibrium, $\rho_{\rm eq} = e^{-H/T}$

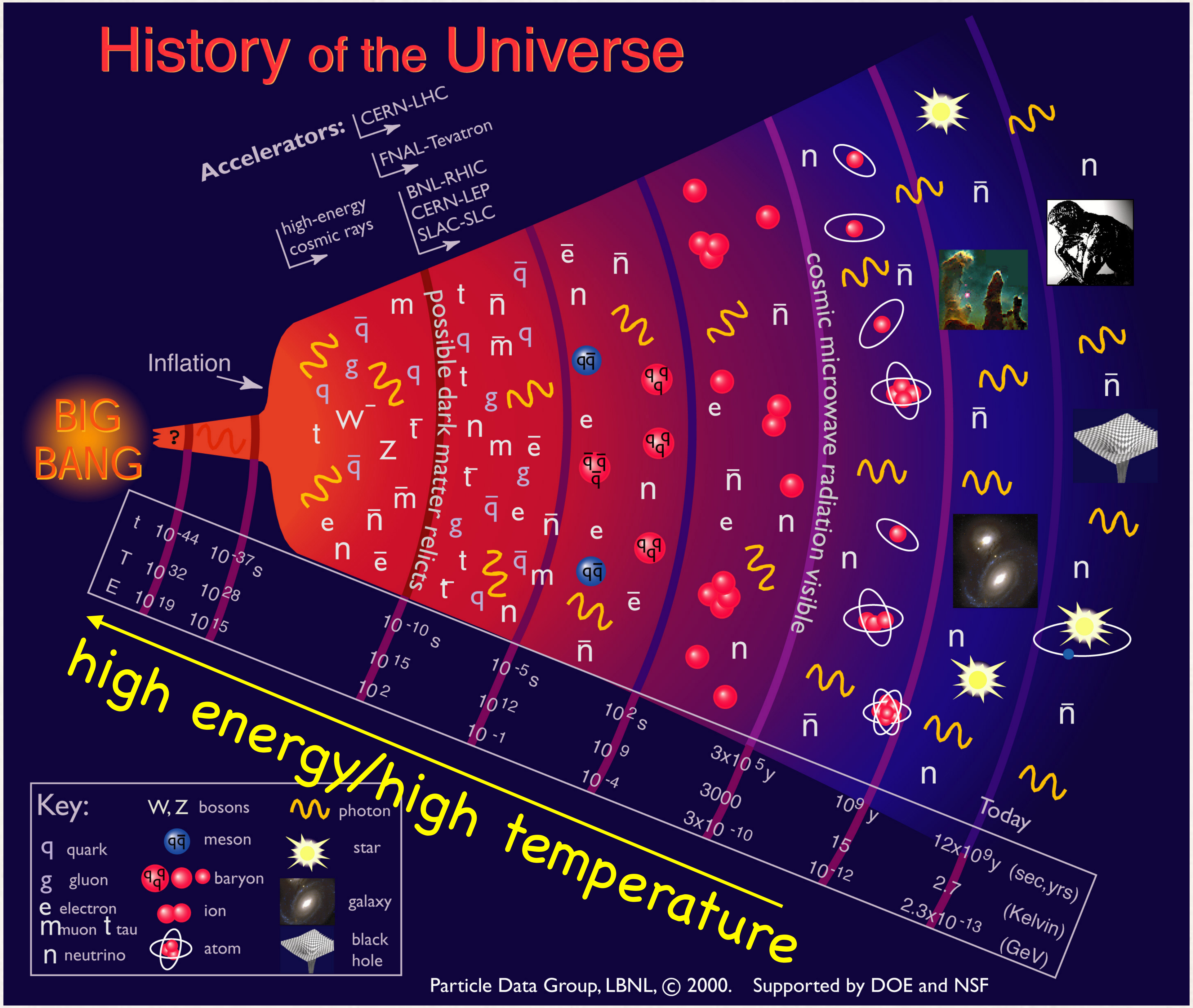
$$CPT \rho_{\rm eq} (CPT)^{-1} = \rho_{\rm eq}$$

$$\begin{aligned} \langle B \rangle &= {\rm Tr}[\rho_{\rm eq} B] = {\rm Tr}[\rho_{\rm eq} B (CPT)^{-1} (CPT)] \\ &= {\rm Tr}[\rho_{\rm eq} (CPT) B (CPT)^{-1}] = -{\rm Tr}[\rho_{\rm eq} B] = -\langle B \rangle, \end{aligned}$$

Therefore, to avoid <B>=0,

system has to be in out of equilibrium
or [CPT,H]≠0.

When BAU arise?



- after inflation (scale is model dependent)
- before Big-Bang Nucleosynthesis (T≃O(1) MeV)

what scenarios are possible?

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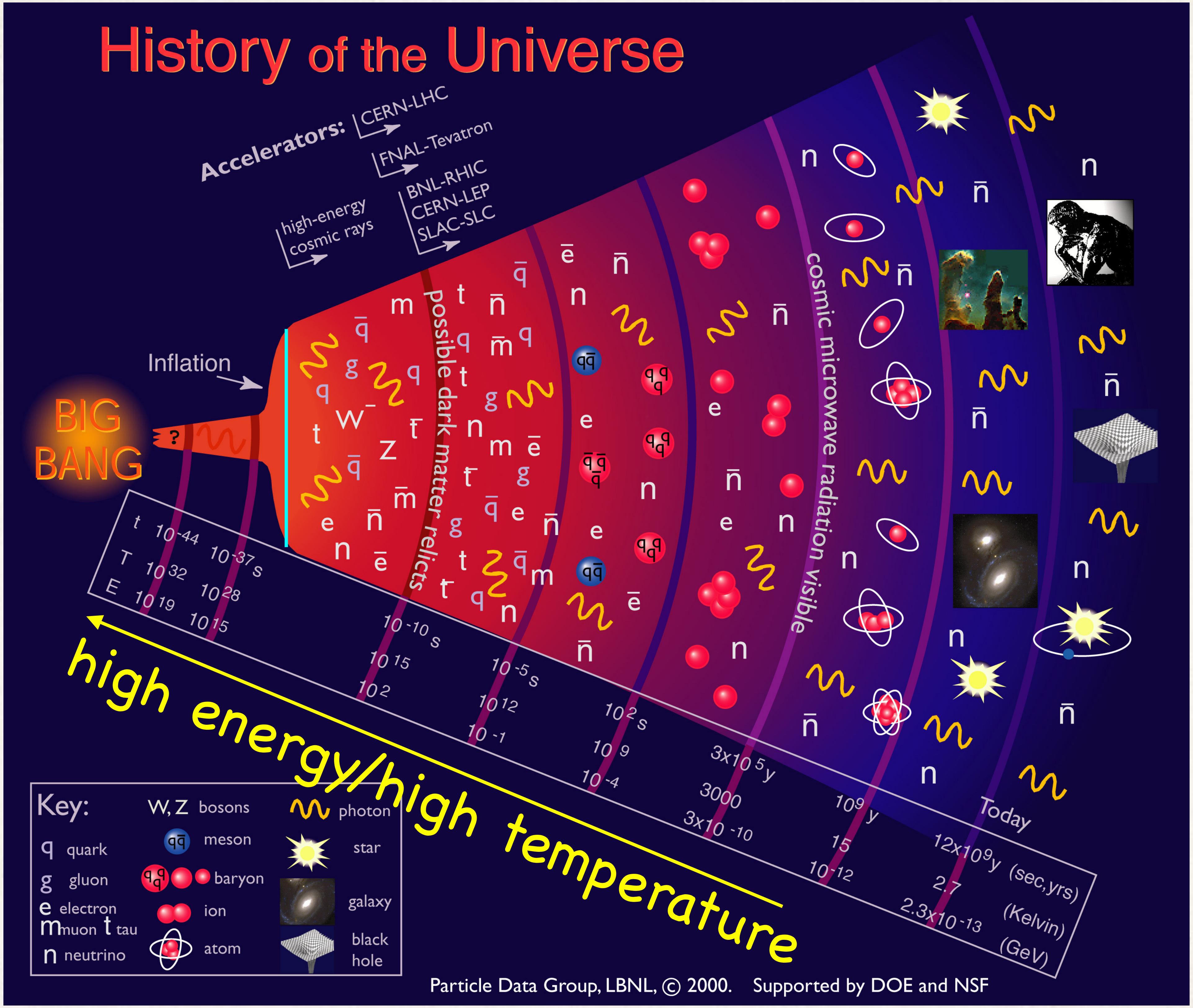

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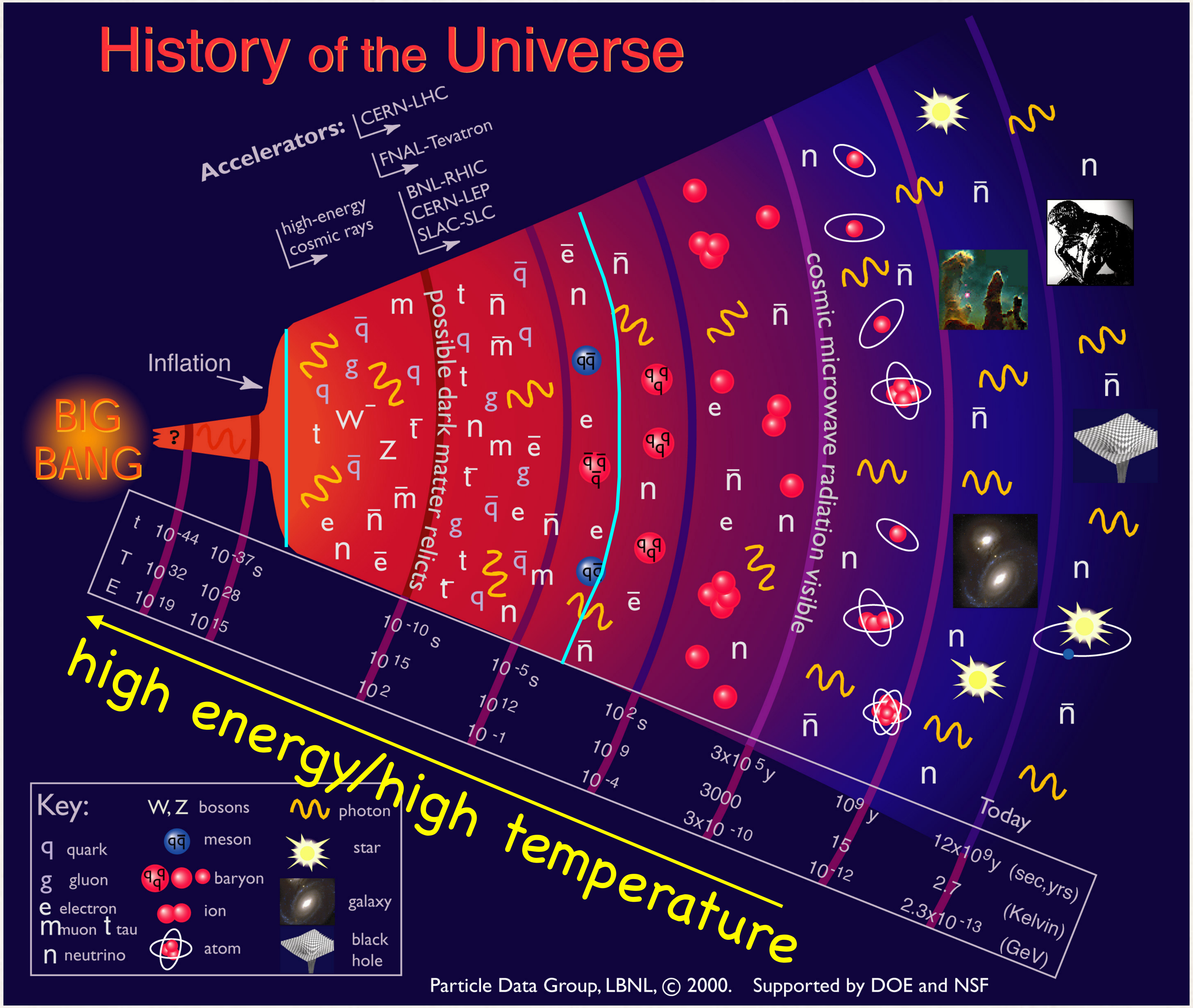

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what scenarios are possible?

Many possibilities

[Shaposhnikov, J.Phys.Conf.Ser.171:012005,2009.]

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

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~ personal view ~

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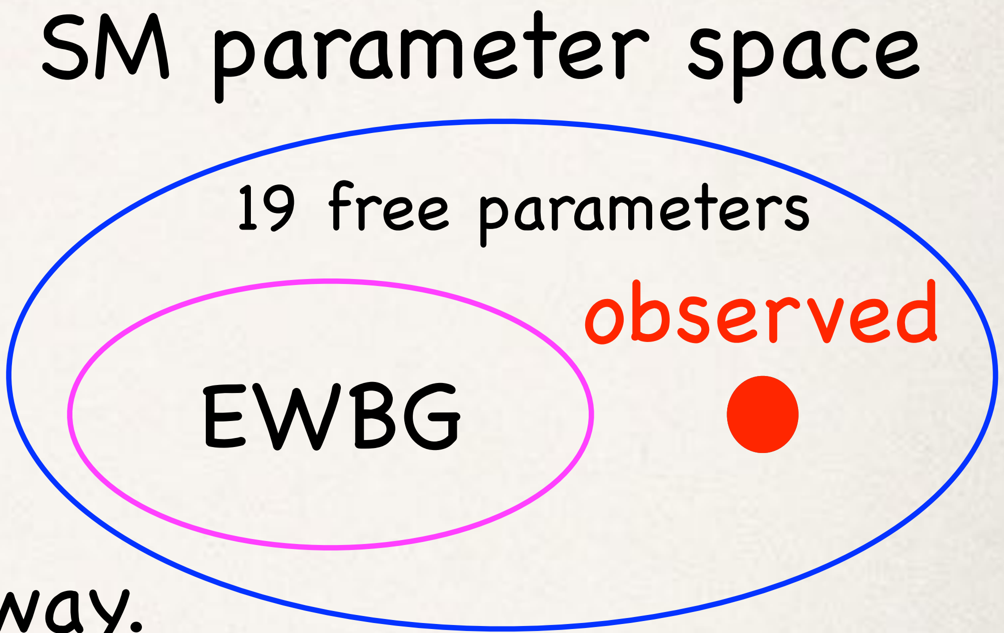
(1) Theoretical framework is already in hand.

In principle, EWBG is possible within the Standard Model (SM).

- Observed point is not consistent with EWBG region.
- But, mechanism is too good to throw away.



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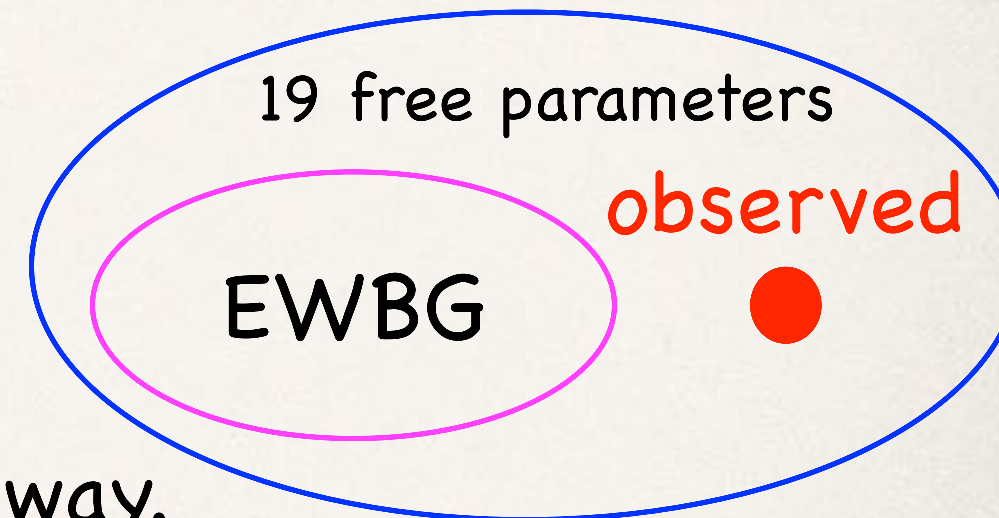

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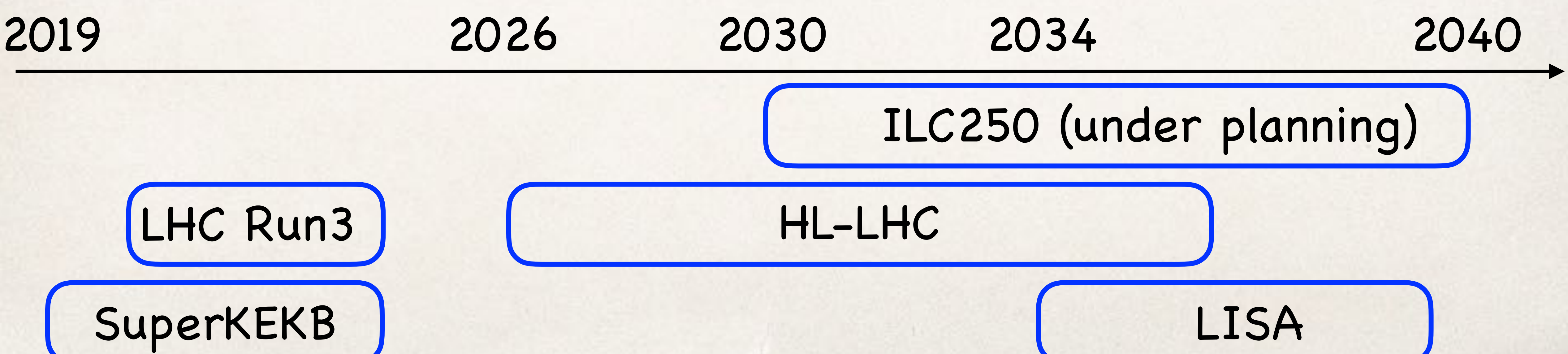
(2) Testability and Urgency

can be probed "now or soon"

EWBG is based on known physics + something unknown.



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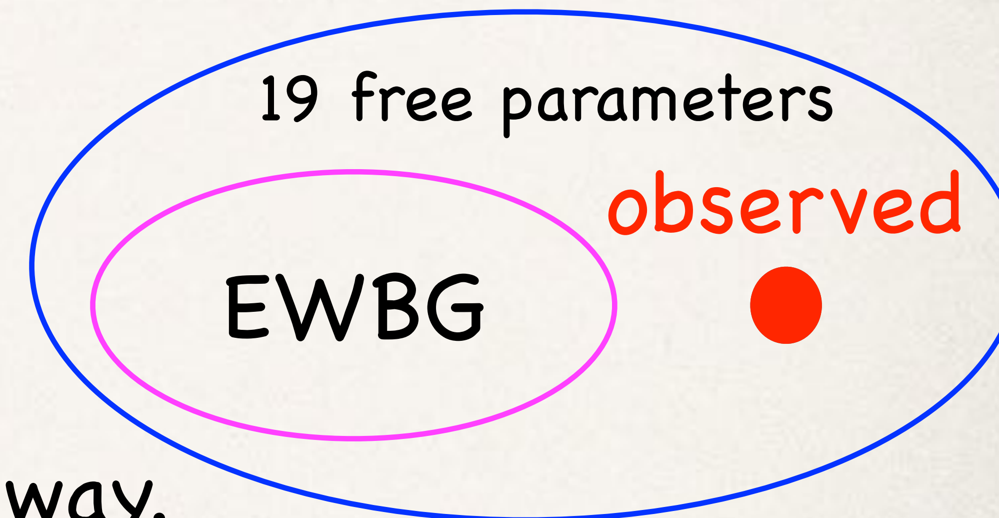

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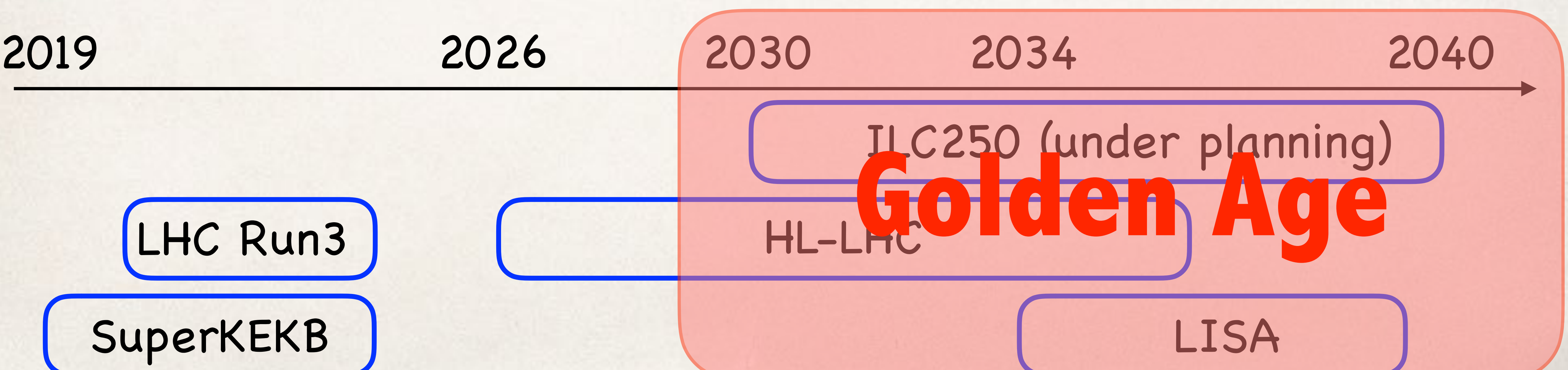
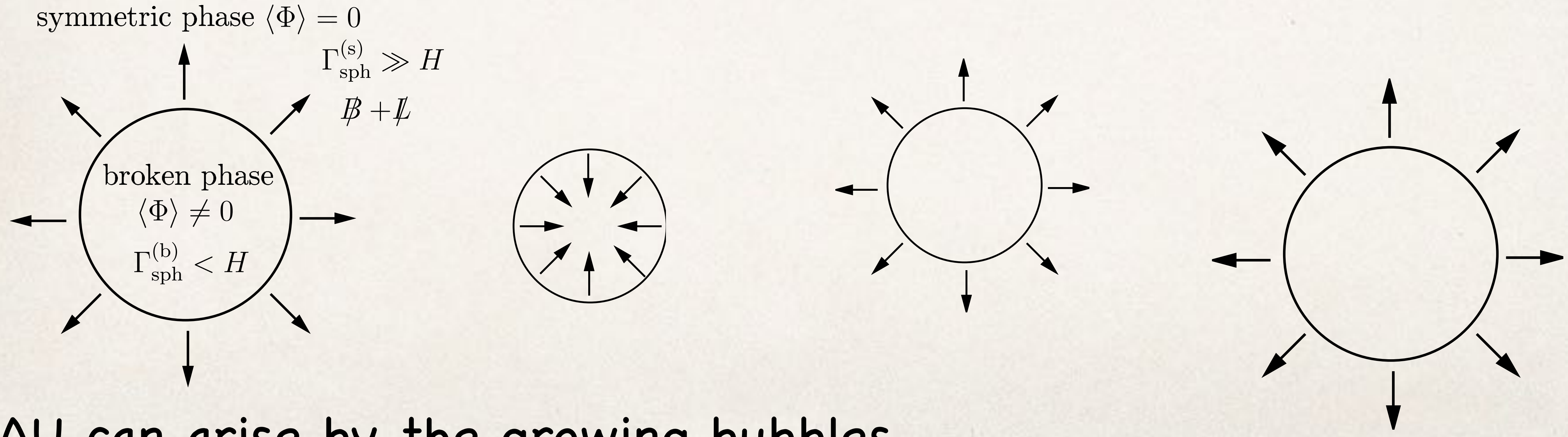


EW baryogenesis (EWBG)

Sakharov's conditions

[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]

- B violation: anomalous (sphaleron) process (see later)
- C violation: chiral gauge interaction
- CP violation: KM phase and/or other sources in beyond the SM
- Out of equilibrium: 1st-order EW phase transition (EWPT) with expanding bubble walls



BAU can arise by the growing bubbles.

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NEW PHYSICS wanted

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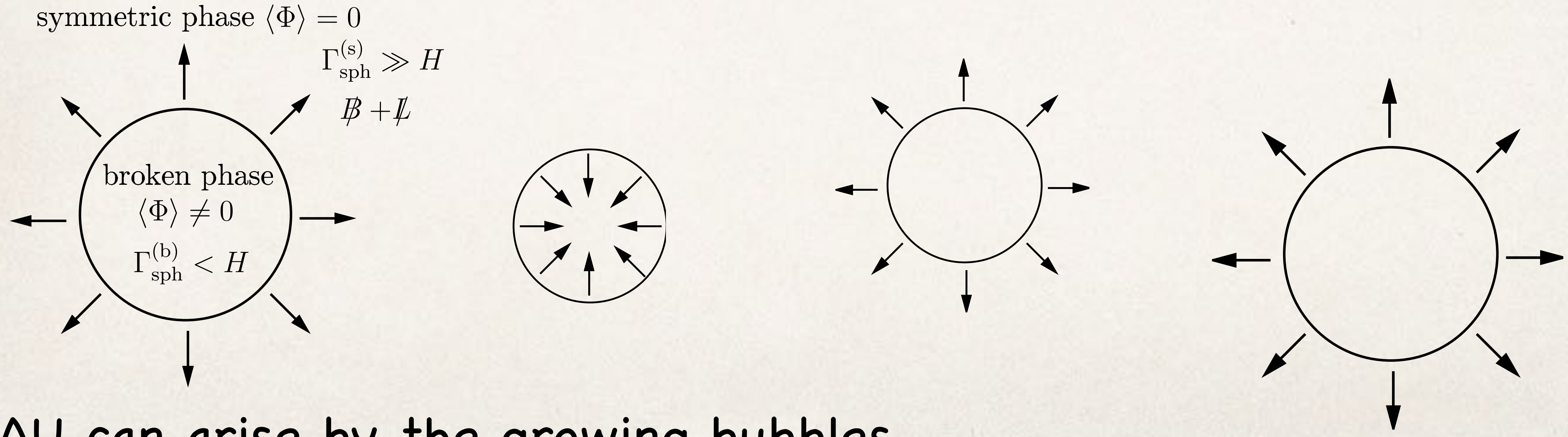


BAU can arise by the growing bubbles.

Sphaleron

σ ϕ α λ ε ρ ο s (sphaleros) "ready to fall"

[F.R.Klinkhamer and N.S.Manton, PRD30, 2212 (1984)]

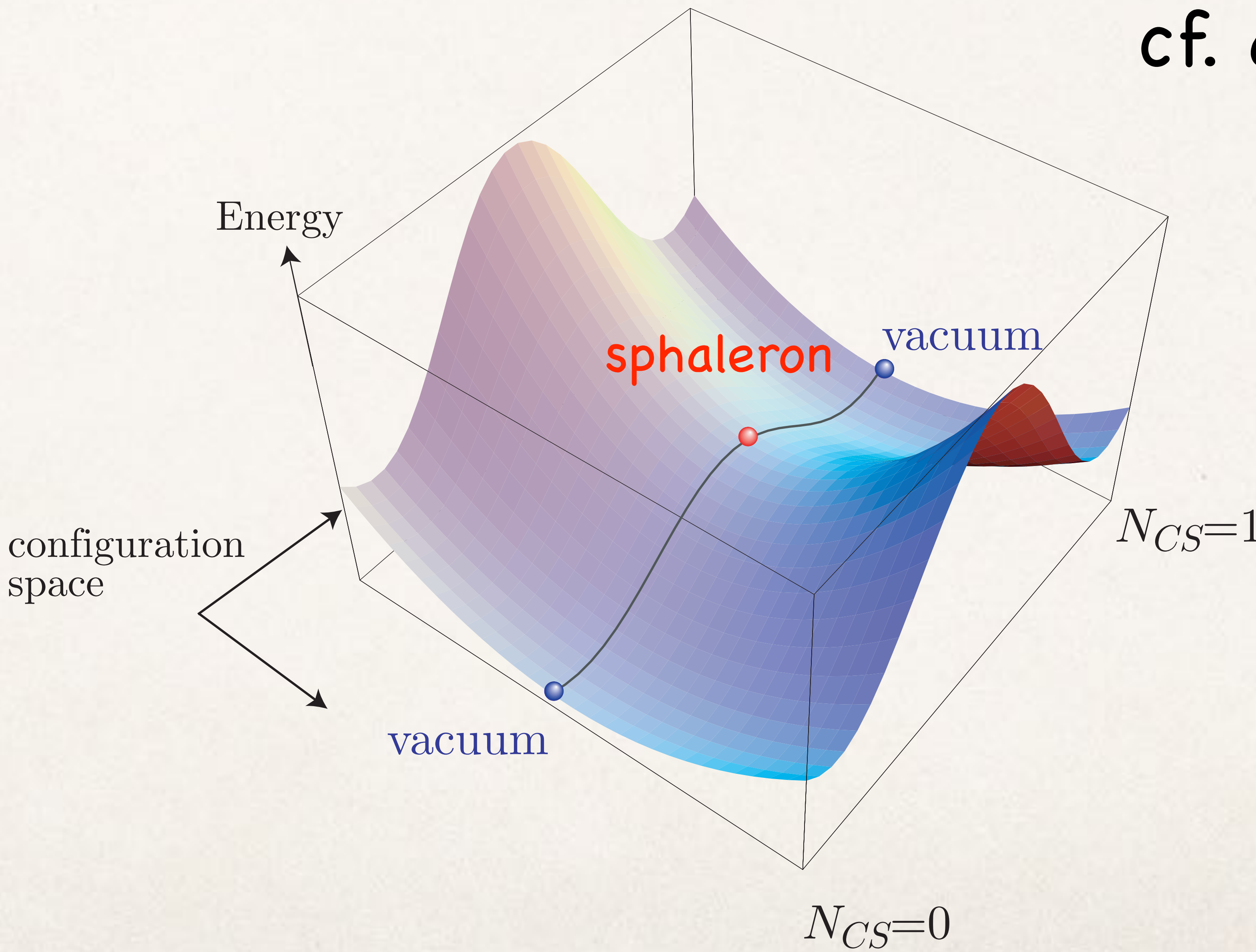
cf. asphalt

ἄσφαλτος

(ásphaltos)

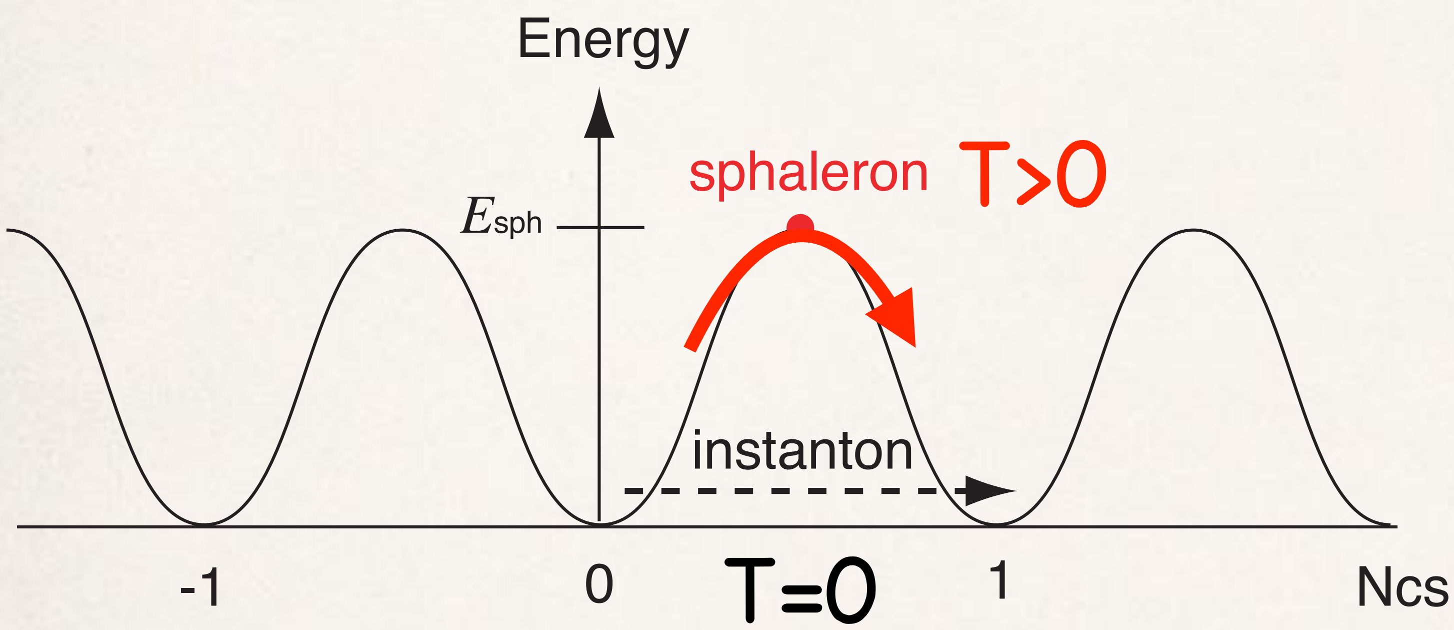
[wikipedia]

not+fall



B+L violation

- A static saddle point solution w/ finite energy of the gauge-Higgs system. [N.S. Manton, PRD28 ('83) 2019]



$\underline{\Delta B \neq 0}$

Instanton: quantum tunneling

Sphaleron: thermal fluctuation

$$\Delta(B+L) = 3\Delta N_{CS}$$

B+L anomaly

$$\partial_\mu j^\mu_{B+L} = \frac{3}{16\pi^2}\left[g_2^2 \mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) - g_1^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right],$$

$$\partial_\mu j^\mu_{B-L} = 0,$$

# of Left-handed fermions can change!!

$$0 \leftrightarrow \sum_{i=1,2,3} (3q^i_L + l^i_L)$$

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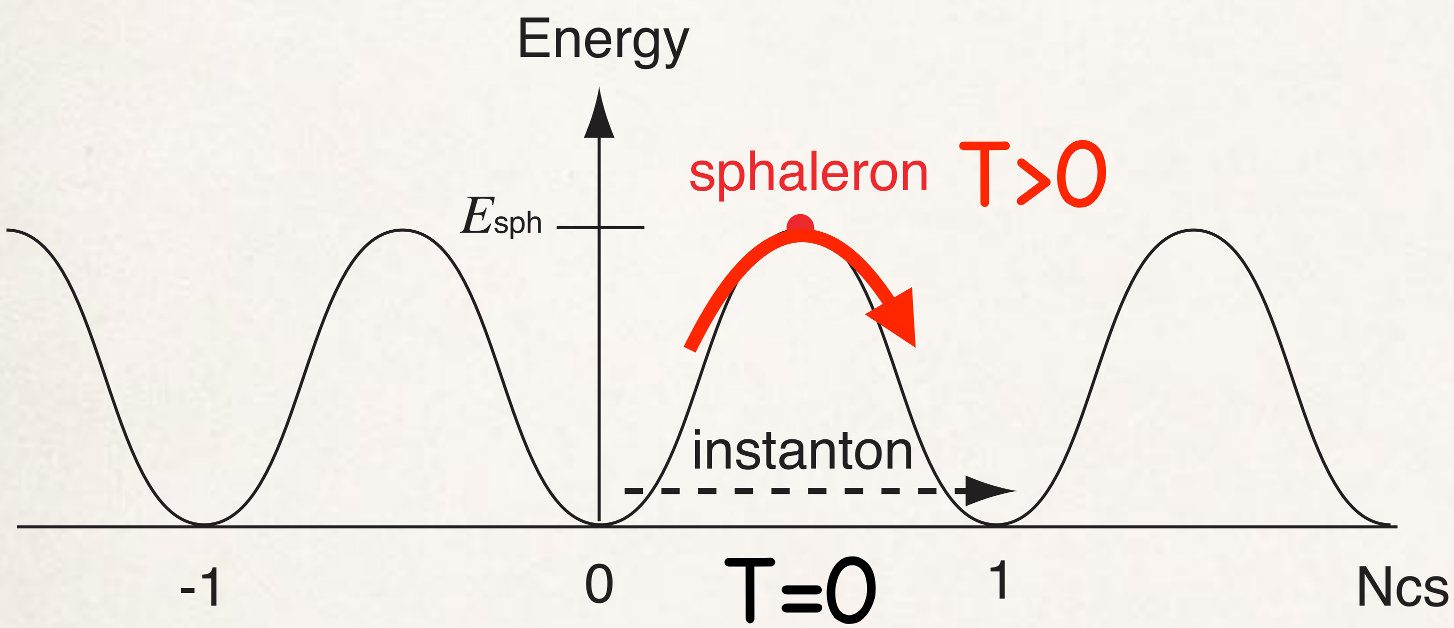

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LHC can see this process?

Q. What is the probability that B violation might even in principle be observable in a supercollider?

Table 1

Participants in the Santa Fe Workshop on Baryon Number Violation at the SSC (April 1990) (ref. [9]). Shown in parentheses are their answers to the question, "What is the probability that baryon number violation might even in principle be observable in a supercollider?" This poll was conducted by L. Okun.

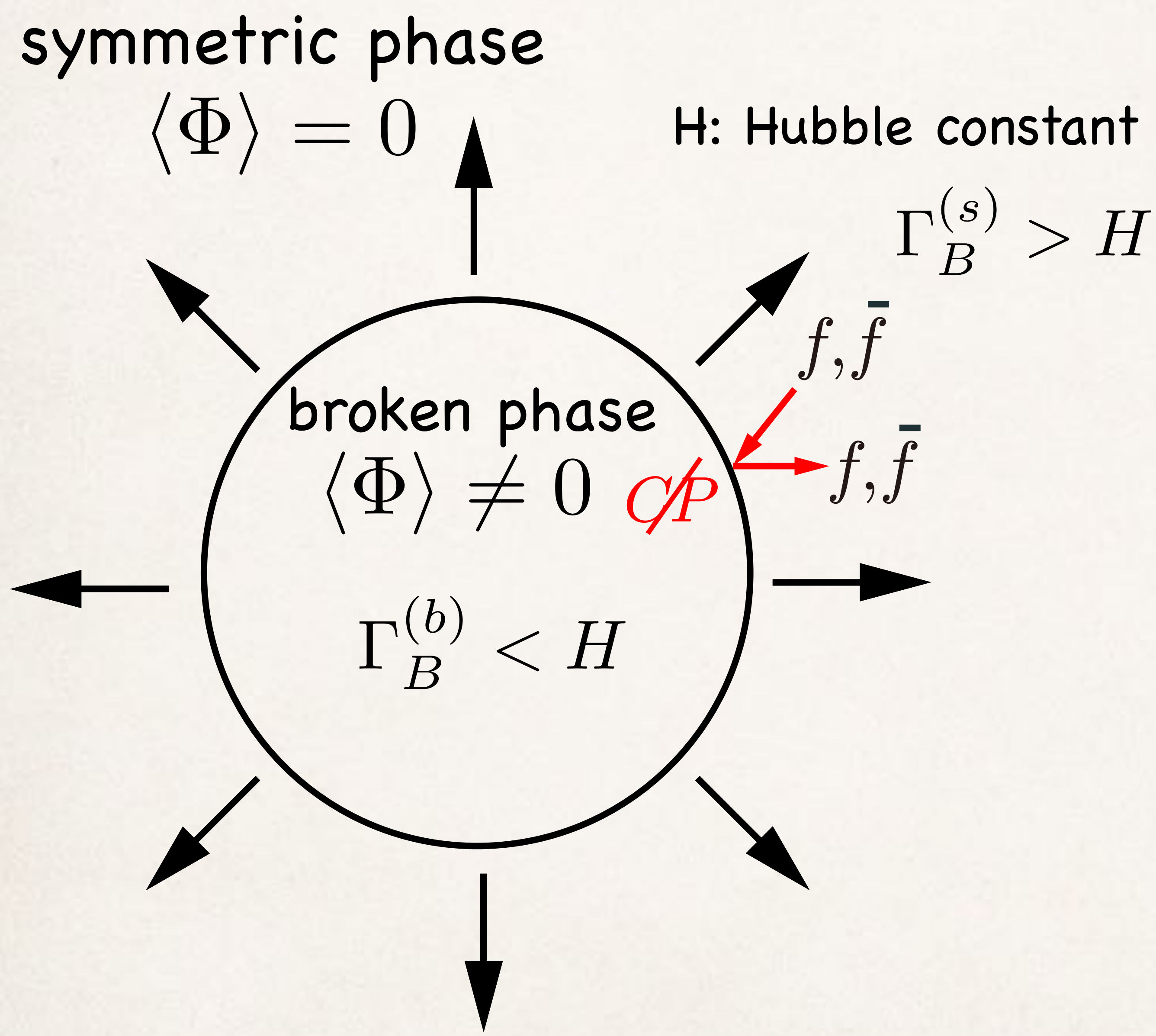
Ken Aoki (10%) UCLA	Peter Arnold (10%) Argonne National Lab.	Zvi Bern (0.1%) Los Alamos National Lab.
Kevin Cahill (0%) Univ. of New Mexico	James Cline [$\exp(-2\pi/\alpha_w)$] Ohio State University	Mike Cornwall (10%) UCLA
Michael Dugan (10%) M.I.T	Olivier Espinosa (50%) CALTECH	Glennys Farrar [$\exp(-2S_{cl})$] Rutgers University
Haim Goldberg (10%) Northeastern University	Eduardo Guendelman (5%) Los Alamos National Lab.	Peter Herczeg (7%) Los Alamos National Lab.
Robert Jaffe (10^{-2}) M.I.T	David Kosower ($10^{-100\pm10}$) FERMILAB	Olaf Lechtenfeld (10^{-100}) City College, CUNY
Aneesh Monohar (10%) U.C. San Diego	Michael Mattis (5%) Los Alamos National Lab.	Pawel Mazur (10%) UCLA
Larry McLerran (66.7%) Univ. of Minnesota	Emil Mottola (5%) Los Alamos National Lab.	Lev Okun (10%) ITEP
Stuart Raby (5%) Ohio State University	Andreas Ringwald (50%) DESY	Z. Ryzak (3.3%) Harvard University
E.V. Shuryak (10^{-1}) Brookhaven National Lab.	Arkady Vainshtein (30%) Univ. of Minnesota	John Vergados (1%) Univ. of Ioannina
M. Voloshin (90%) Univ. of Minnesota	Geoffrey West ($O(\alpha)$%) Los Alamos National Lab.	Laurence Yaffe (1%) Univ. of Washington

still under debate...

M. Mattis, Phys.Rept.214 (1992) 159

EWBG mechanism

[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]



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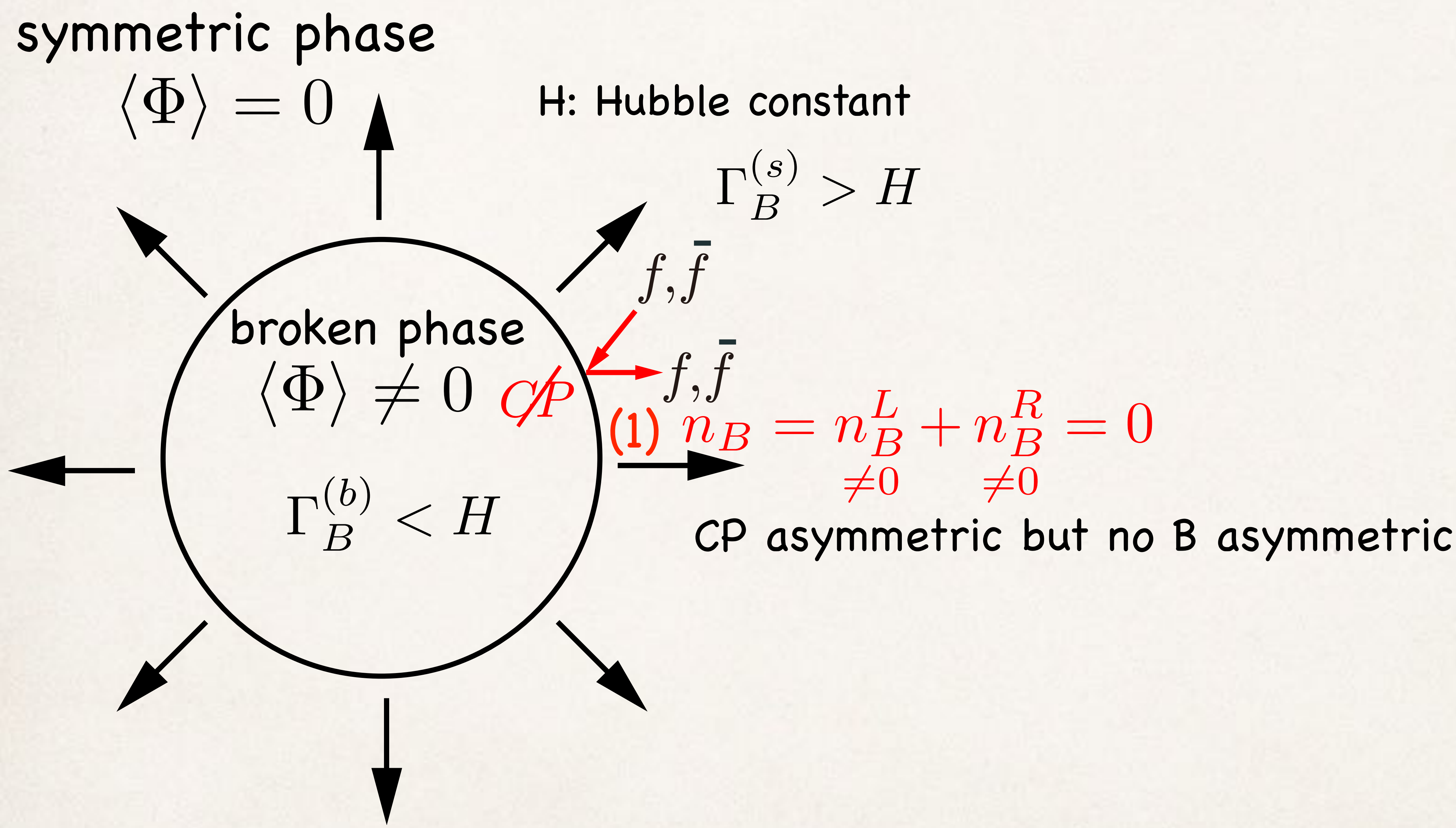

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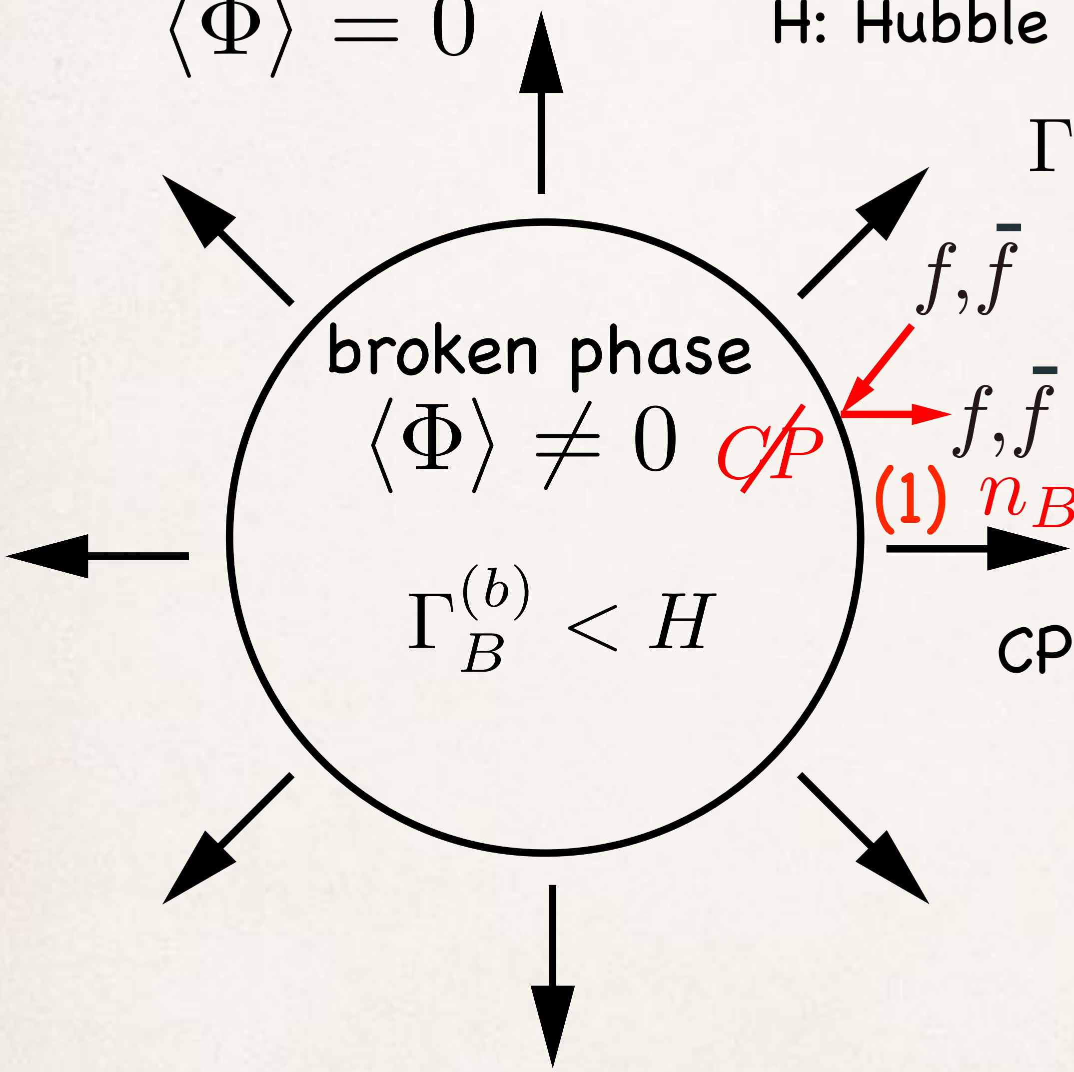
symmetric phase

$\langle \Phi \rangle = 0$



H: Hubble constant

$\Gamma_B^{(s)} > H$

changed by sphaleron. $t_{\rm wall} < t_{\rm sph}$

(2) $n_B = n_B^L + n_B^R \rightarrow n_B \neq 0$

baryogengesis!!

(1) $n_B = \underset{\neq 0}{n_B^L} + \underset{\neq 0}{n_B^R} = 0$

CP asymmetric but no B asymmetric

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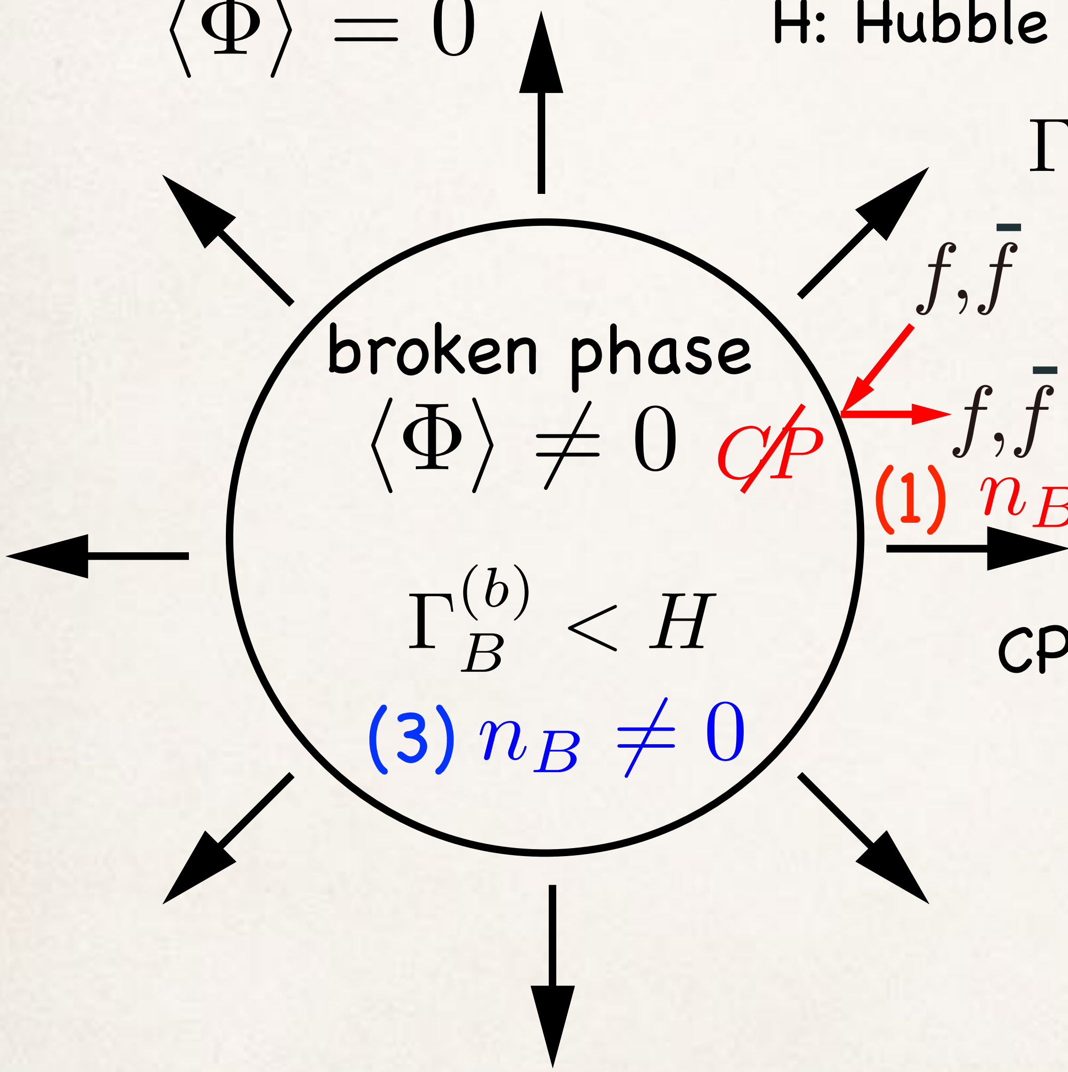

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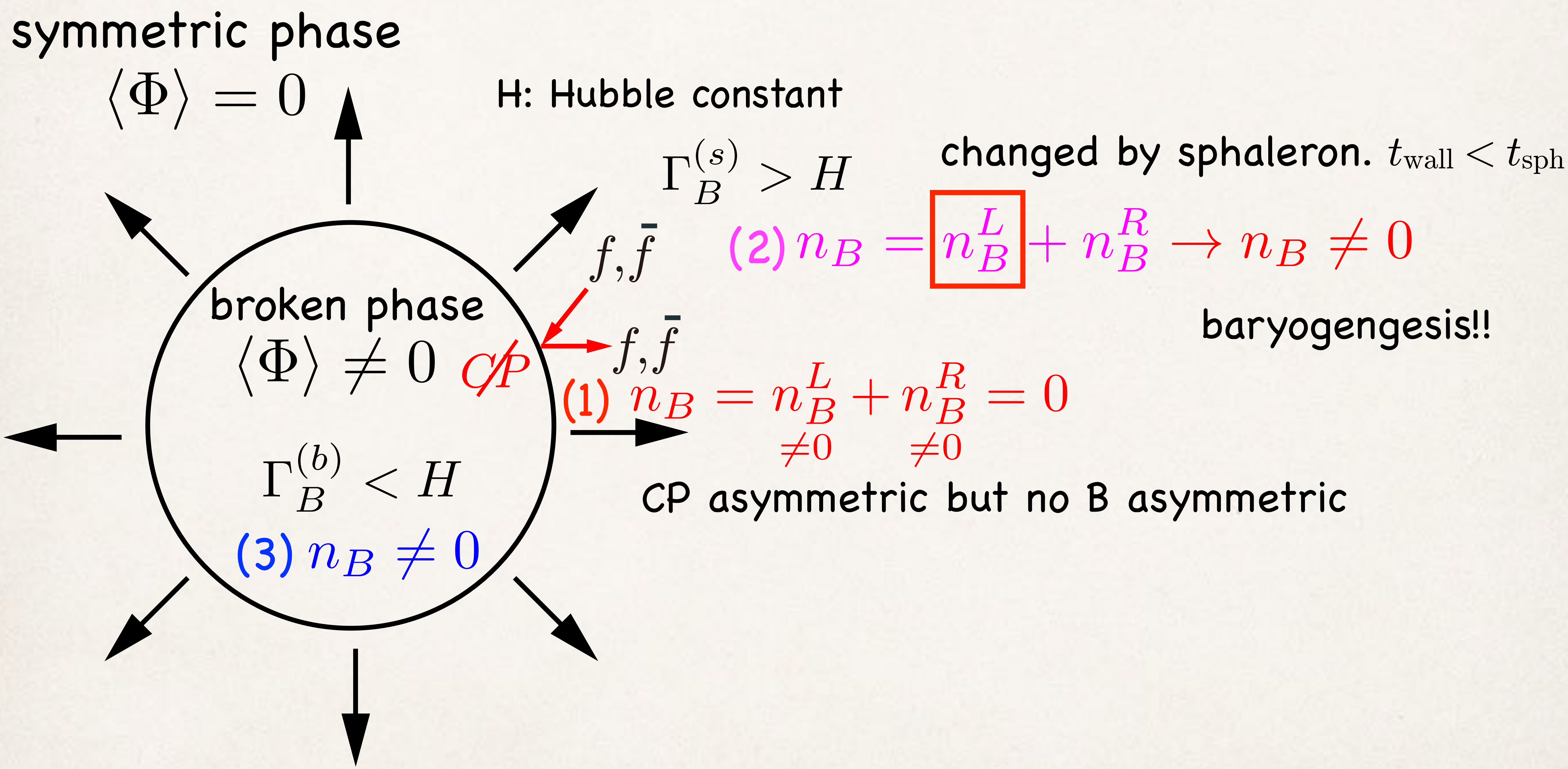

To satisfy Γ_B<H, EWPT has to be 1st order (next page).

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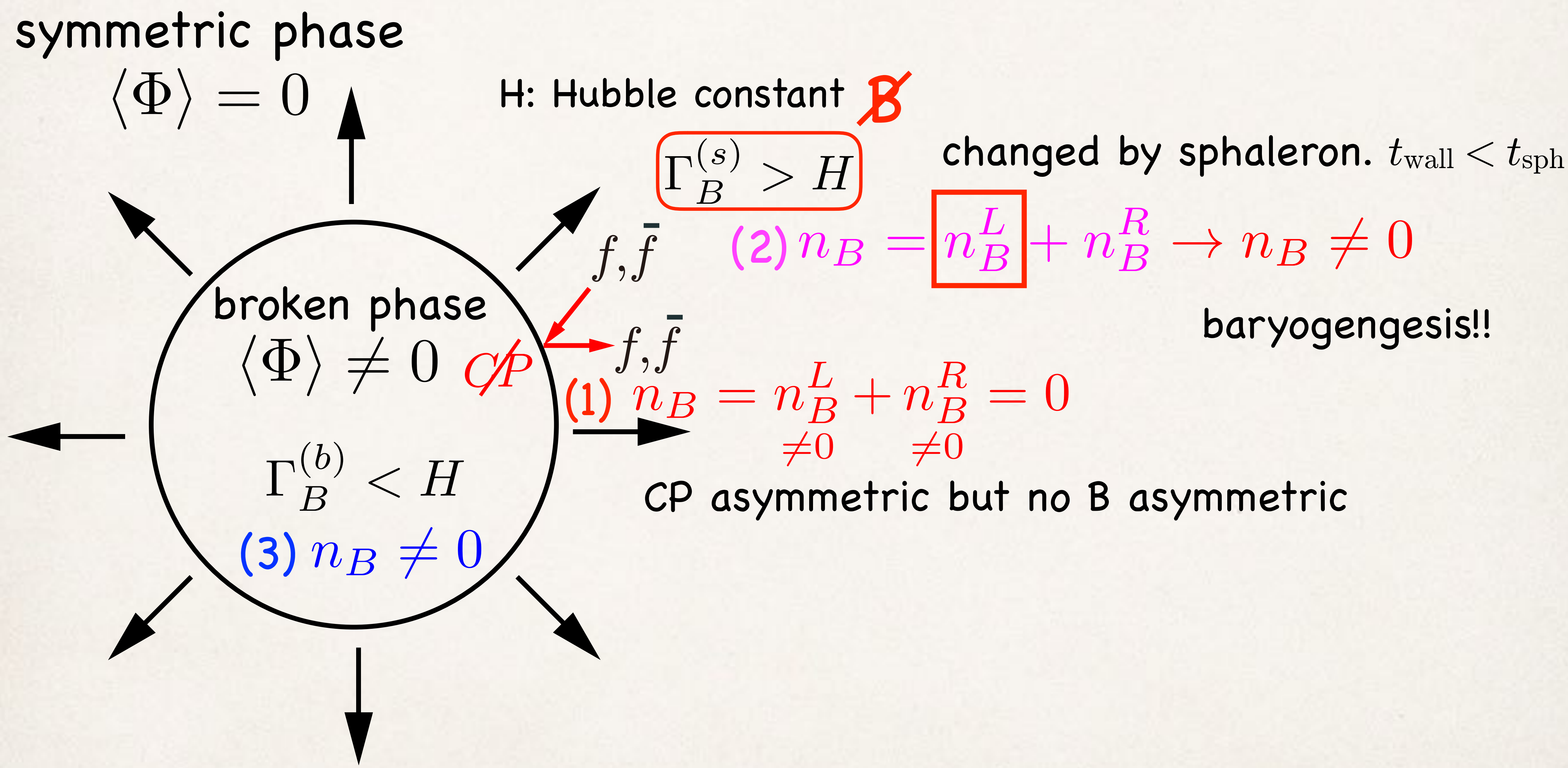

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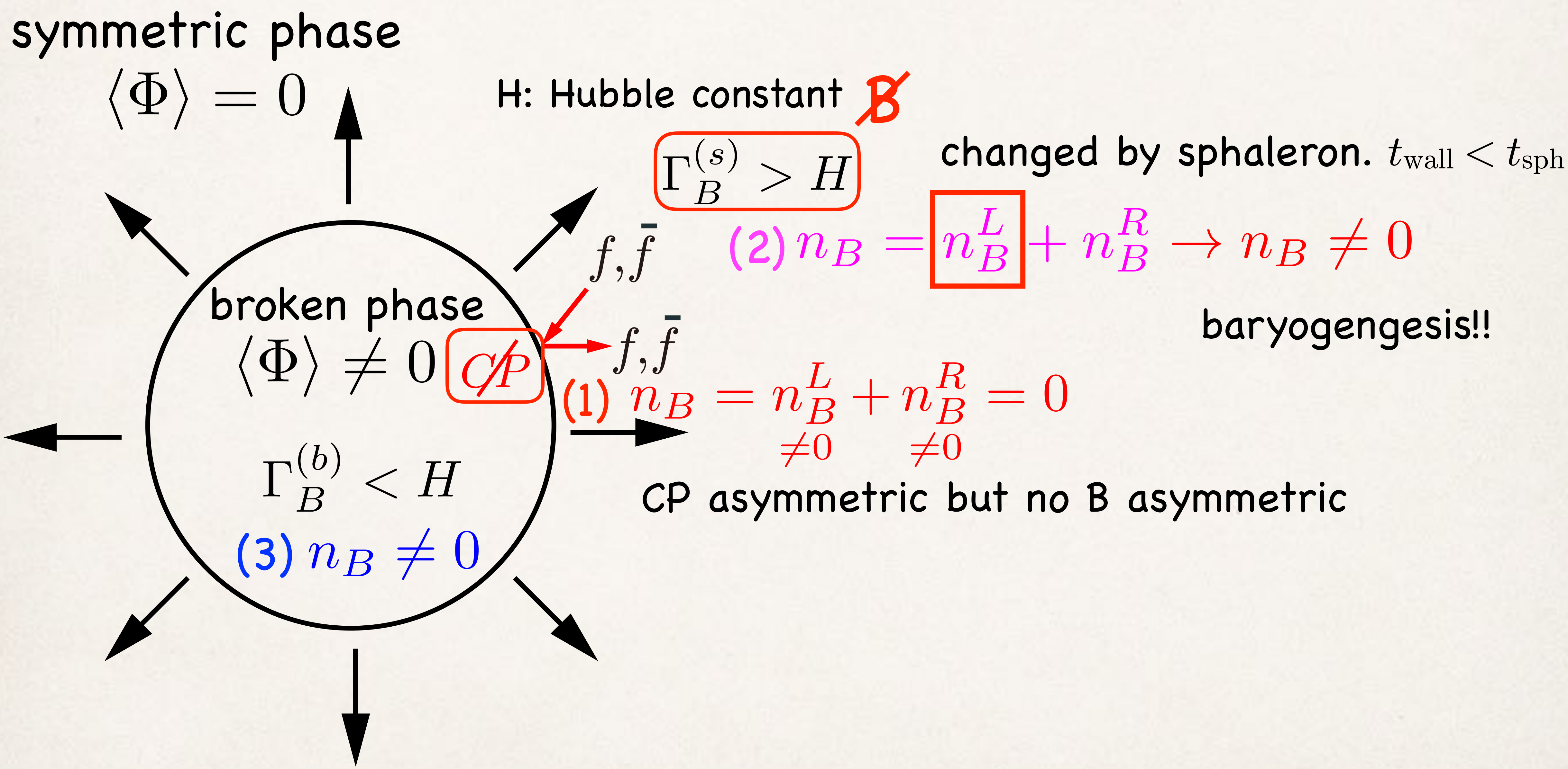

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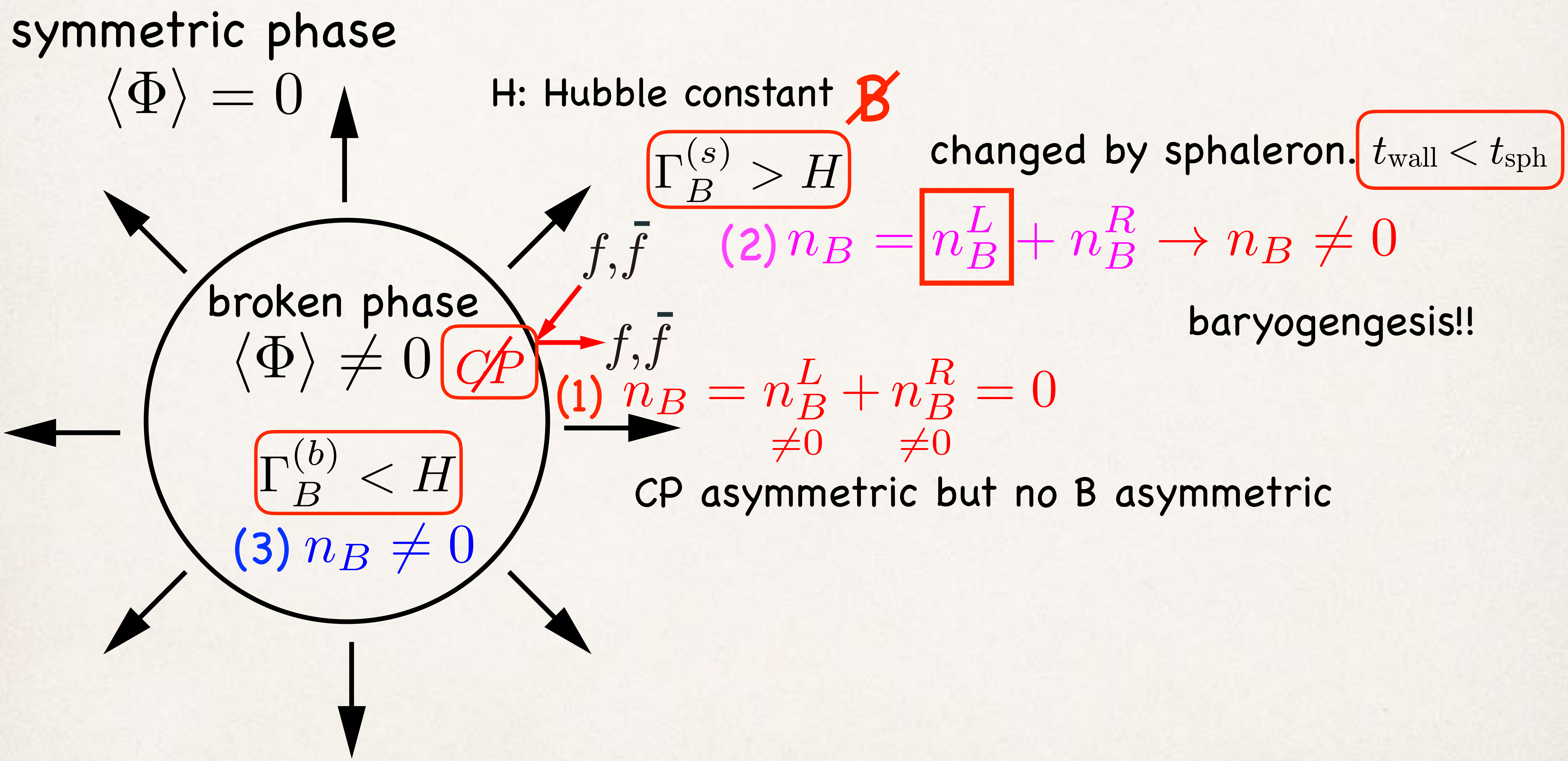
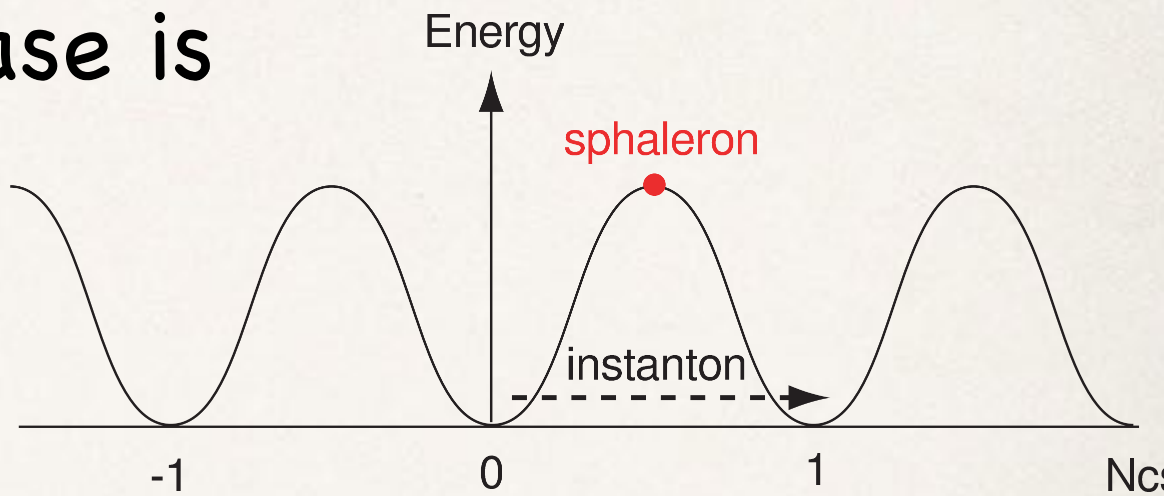


To satisfy Γ_B<H, EWPT has to be 1st order (next page).

$$\Gamma_B^{(b)} < H$$

B-changing rate in the broken phase is

$$\Gamma_B^{(b)} \simeq (\text{prefactor}) e^{-E_{\text{sph}}/T}$$



$\Delta B = 3\Delta n_{\text{CS}}$

E_{sph} is proportional to the Higgs VEV

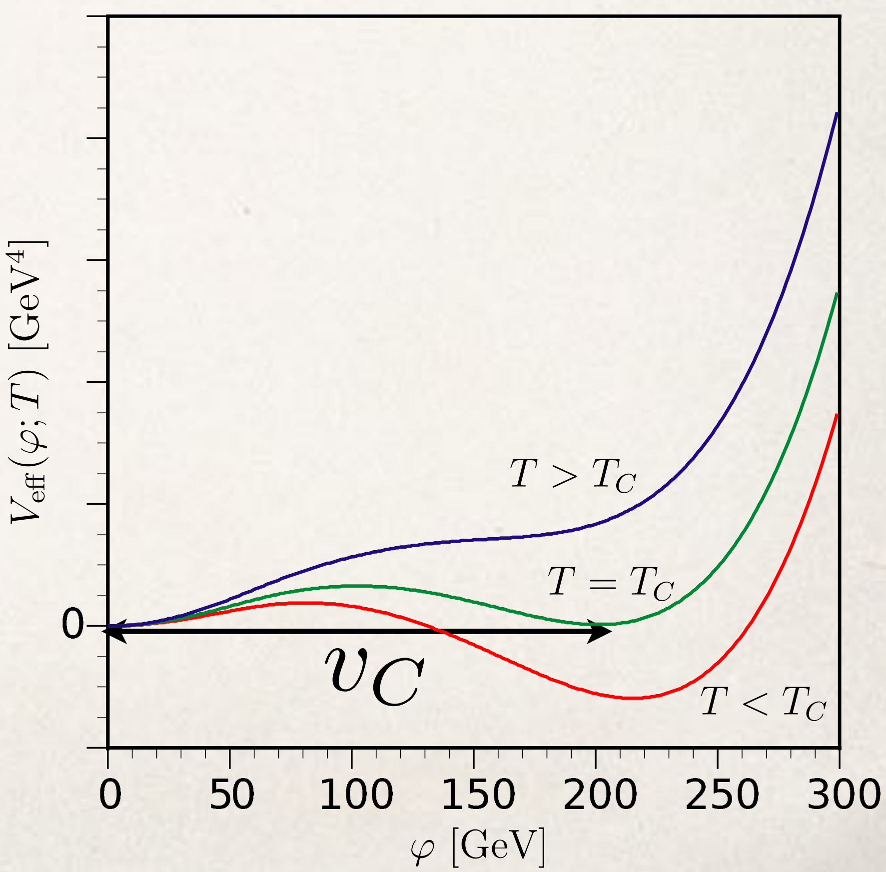
$$E_{\text{sph}} \propto v(T)$$

<u>what we need is</u>

large Higgs VEV after the EWPT

→ EWPT has to be "**strong**" 1st order!!

$$\Gamma_B^{(b)}(T_C) < H(T_C) \quad \rightarrow \quad \frac{v_C}{T_C} \gtrsim 1$$



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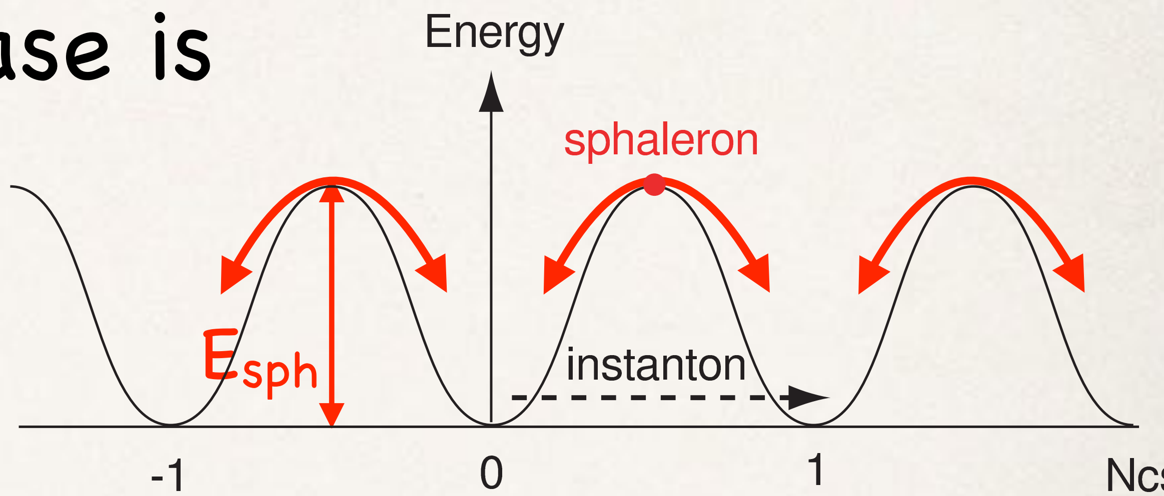

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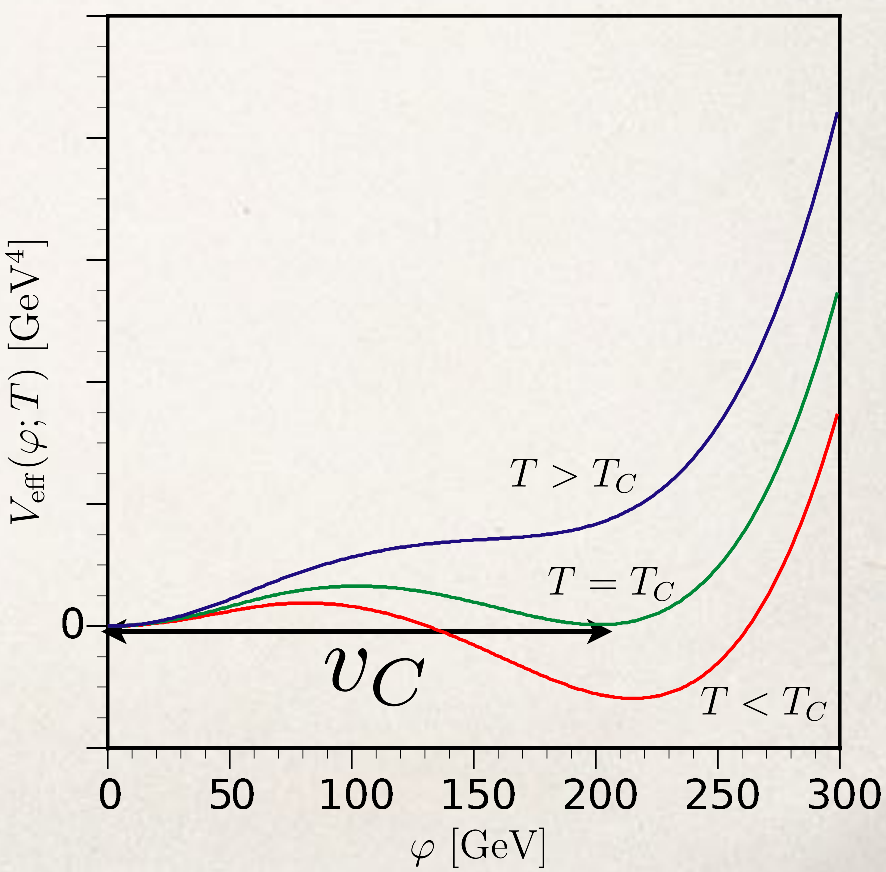

How do we test EWBG?

Can we redo EW phase transition in lab. experiments?

No!

- Relevant temperature $\simeq$ 100 GeV.
- Currently achievable temperature $\simeq$ 0.1 GeV.

It's not easy to increase temperature since

$T \propto E^{1/4}$ (Stefan-Boltzmann law)

So, how do we test EWBG, then??

EWBG tests

- We test Sakharov's conditions instead.

Sakharov's conditions	$\not{B}$	$\not{CP}$	out of equilibrium
	sphaleron	CPV bubble-particle ints.	1st-order EWPT w/ bubbles

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Colliders: B physics, etc.; Higgs couplings/spectrum

- Higgs couplings and spectrum are determined by "$v_C/T_C \gtrsim 1$".

Tested EWBG models

Tested EWBG models

- SM EWBG was excluded.

∵ No 1^{st}-order PT for m_h=125 GeV.

[Kajantie at al, PRL77,2887 ('96); Rummukainen et al, NPB532,283 ('98); Csikor et al, PRL82, 21 ('99); Aoki et al, PRD60,013001 ('99). Laine et al, NPB73,180('99)]

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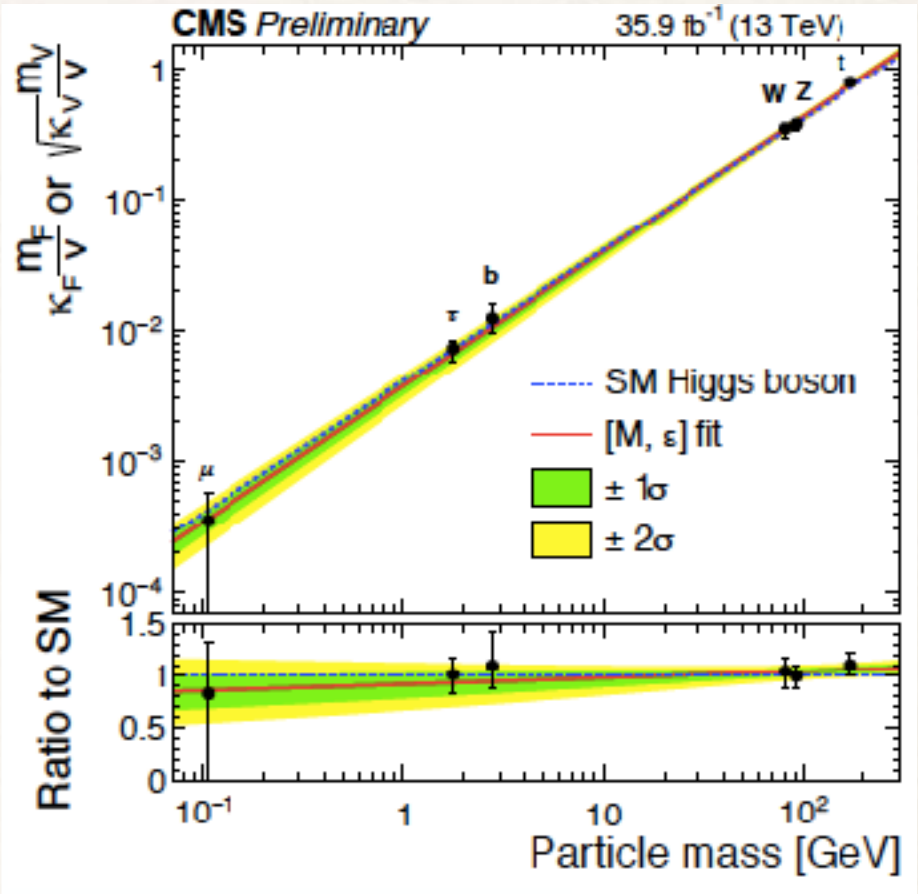
What EWBG scenarios are compatible with current LHC data?

EWBG in our time

LHC data indicate

Higgs sector = SM-like



What is "SM-like Higgs sector" compatible with EWBG?

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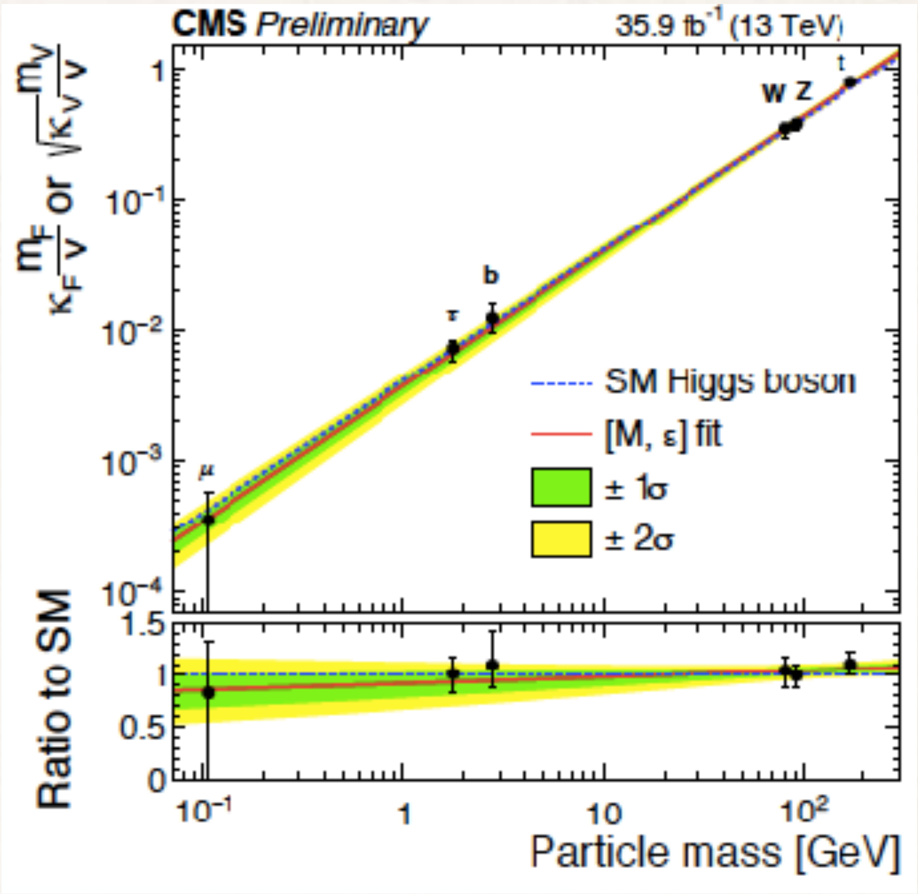

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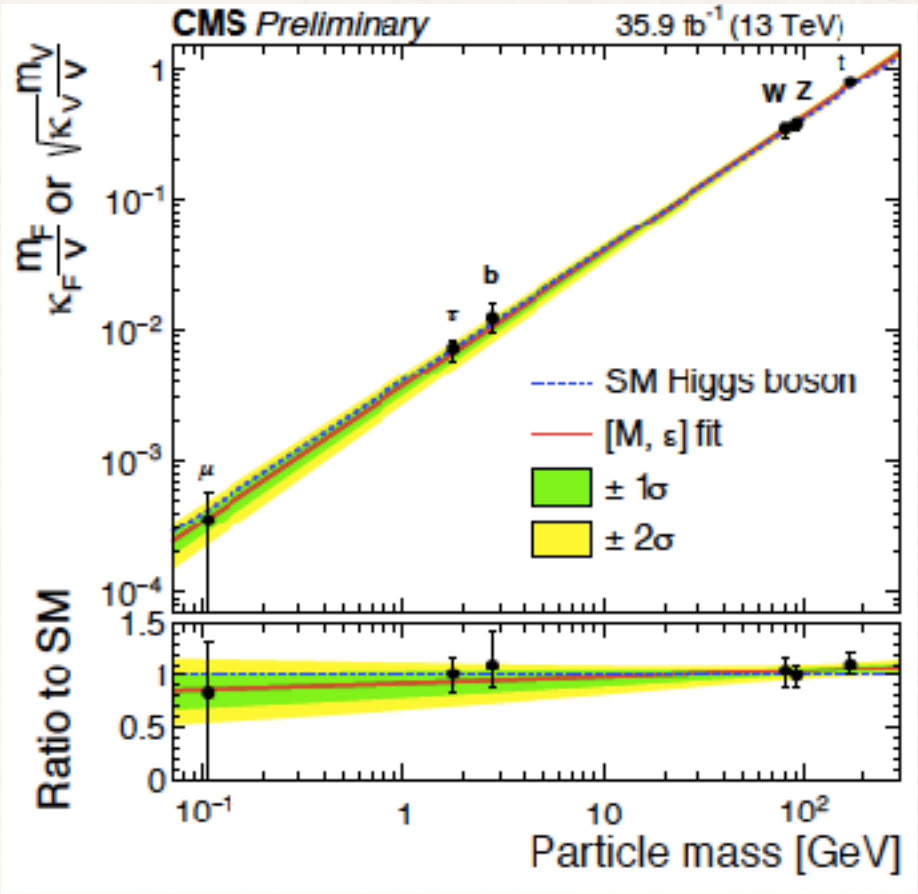

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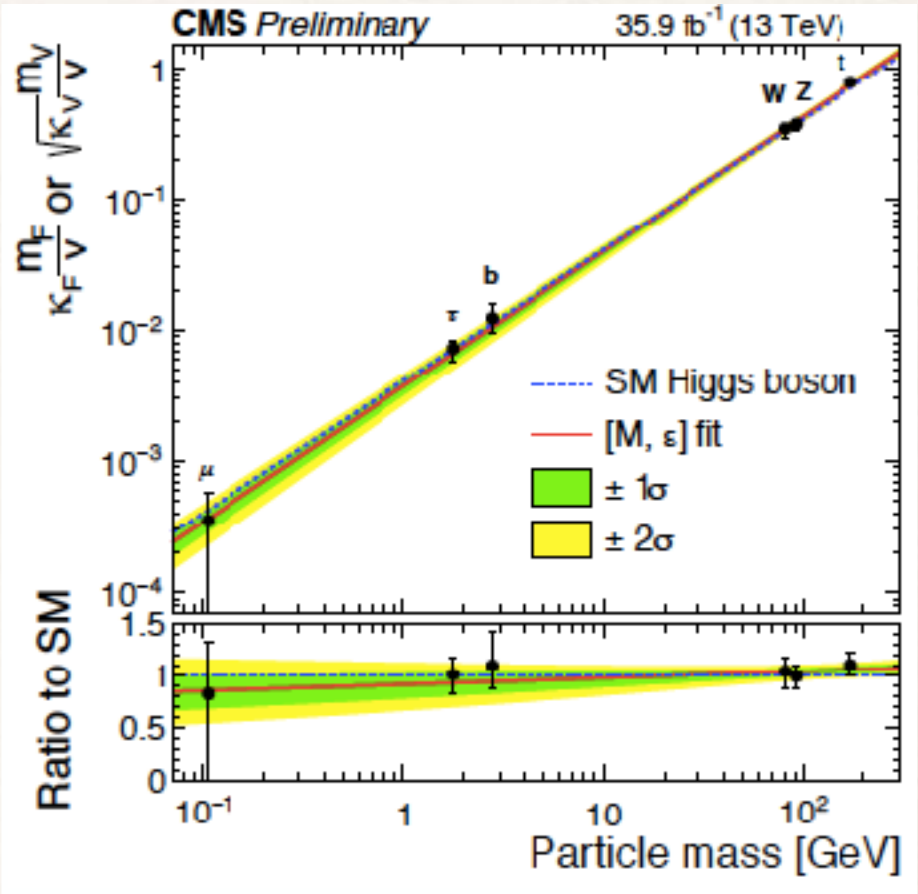

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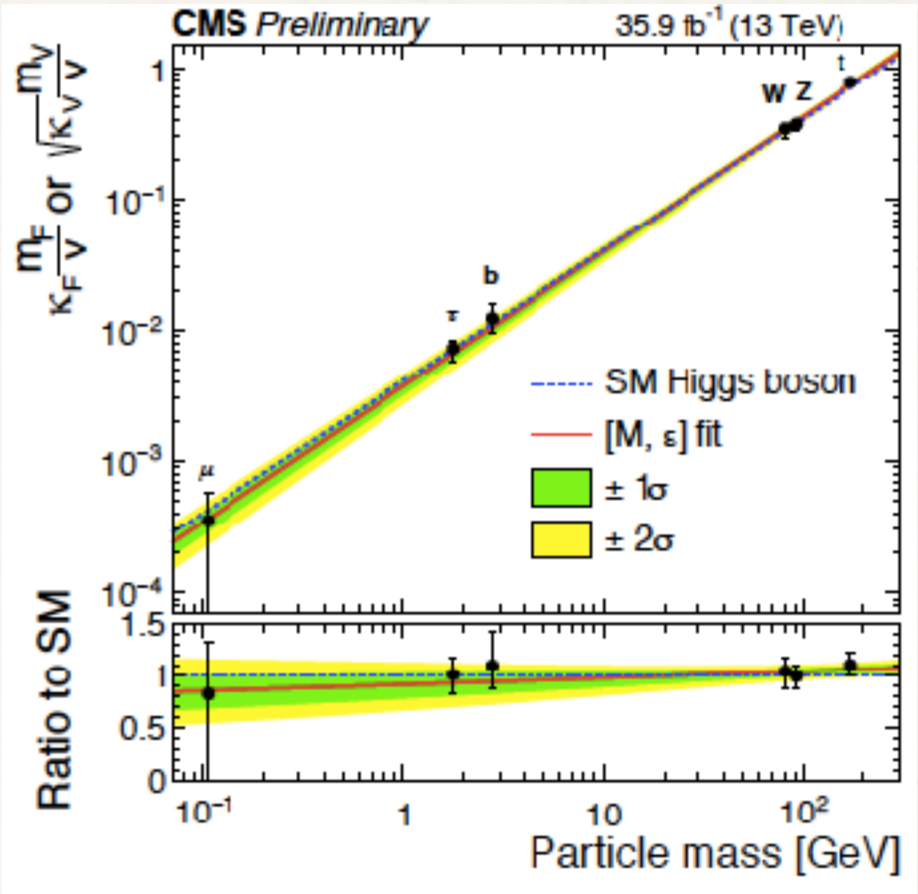

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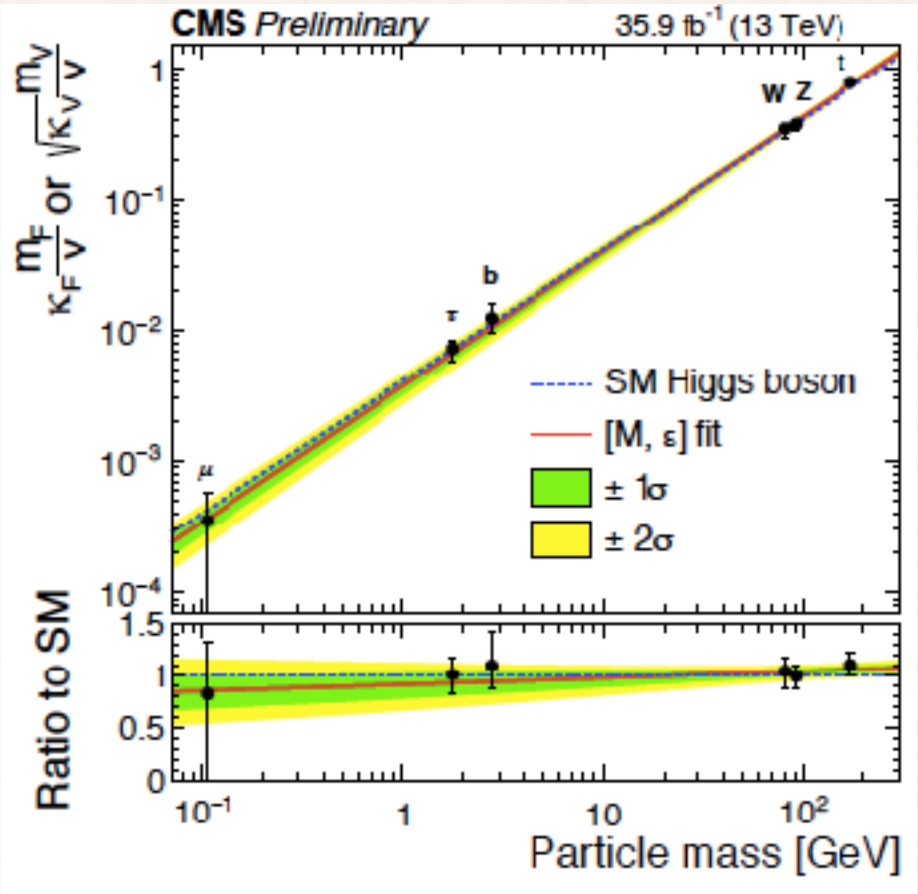

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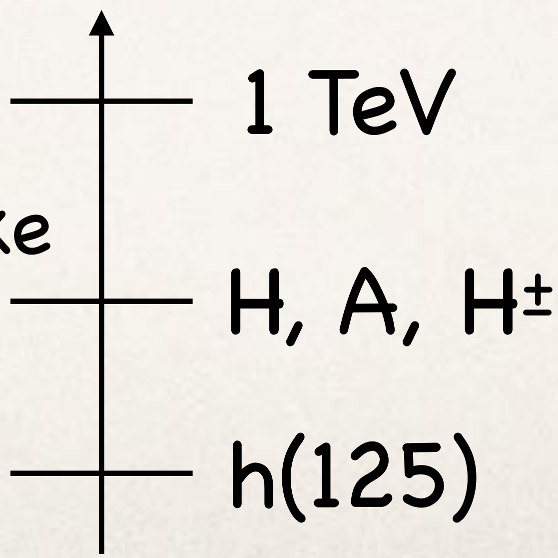

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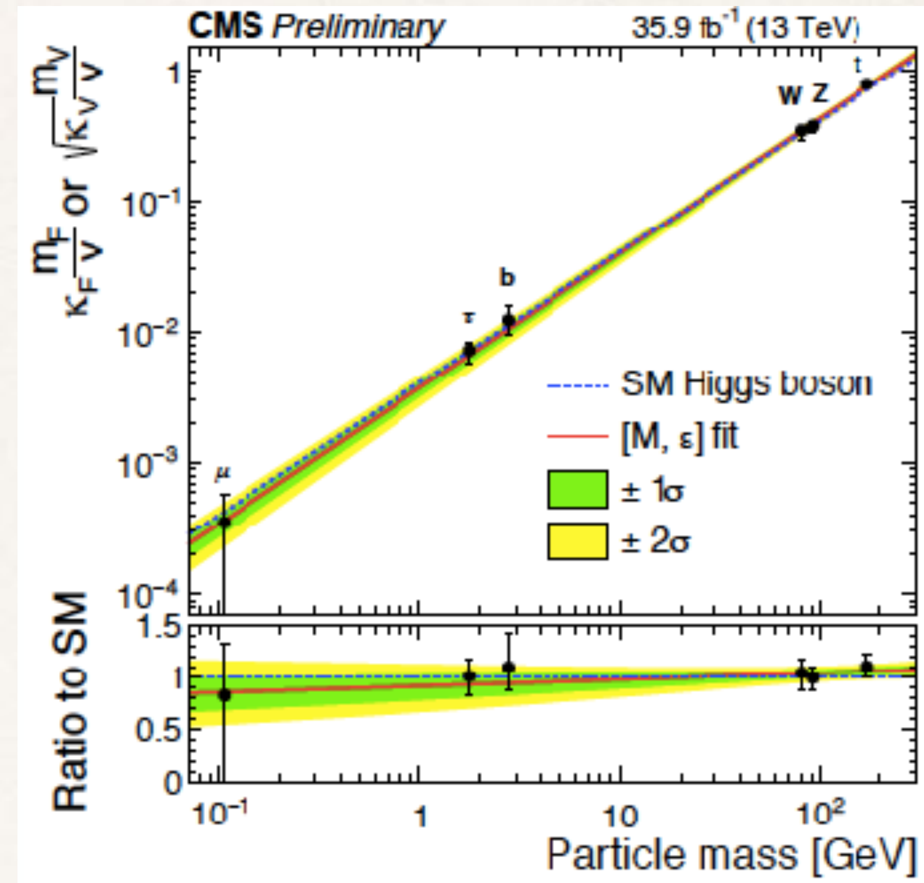

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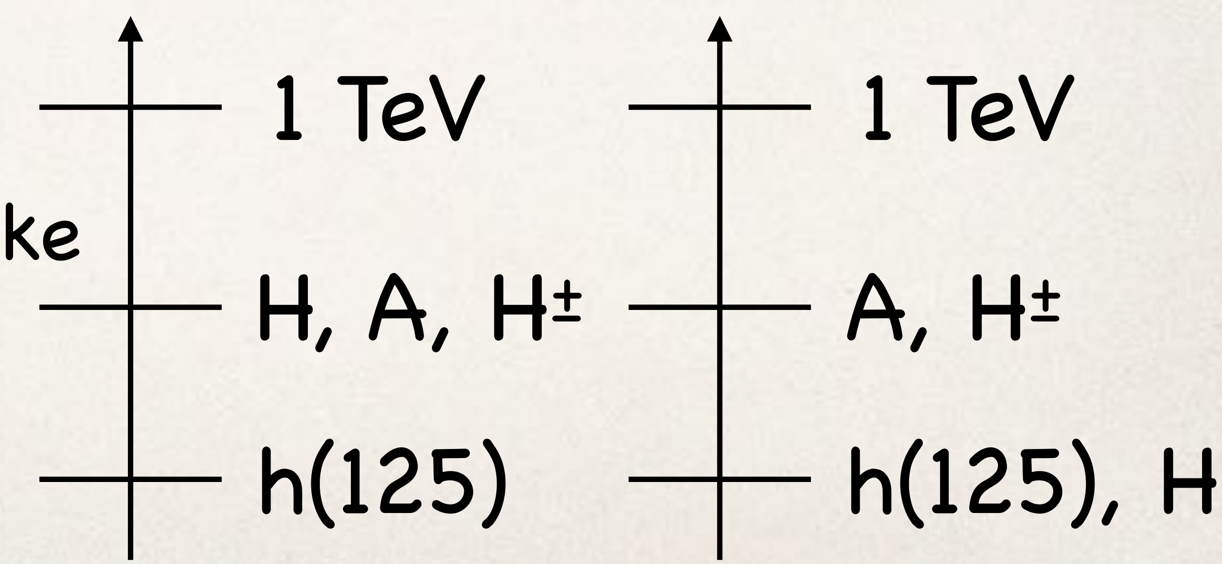
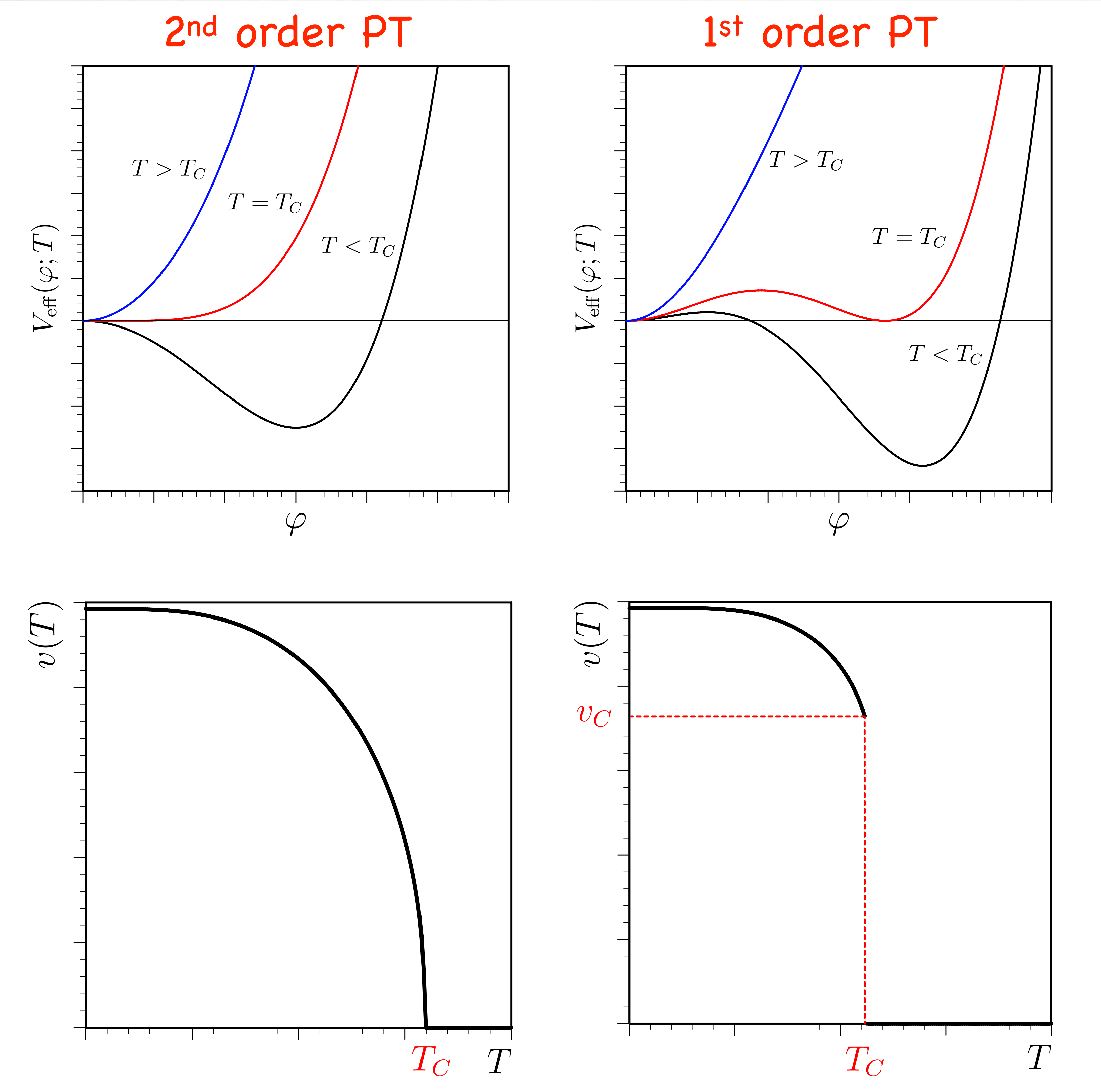


Lessons from SM EWBG

1^{st}-order EWPT

How do we get 1st-order EWPT?

1st(2nd) order PT=discontinuities in 1st(2nd) derivatives of free energy (V_{eff})



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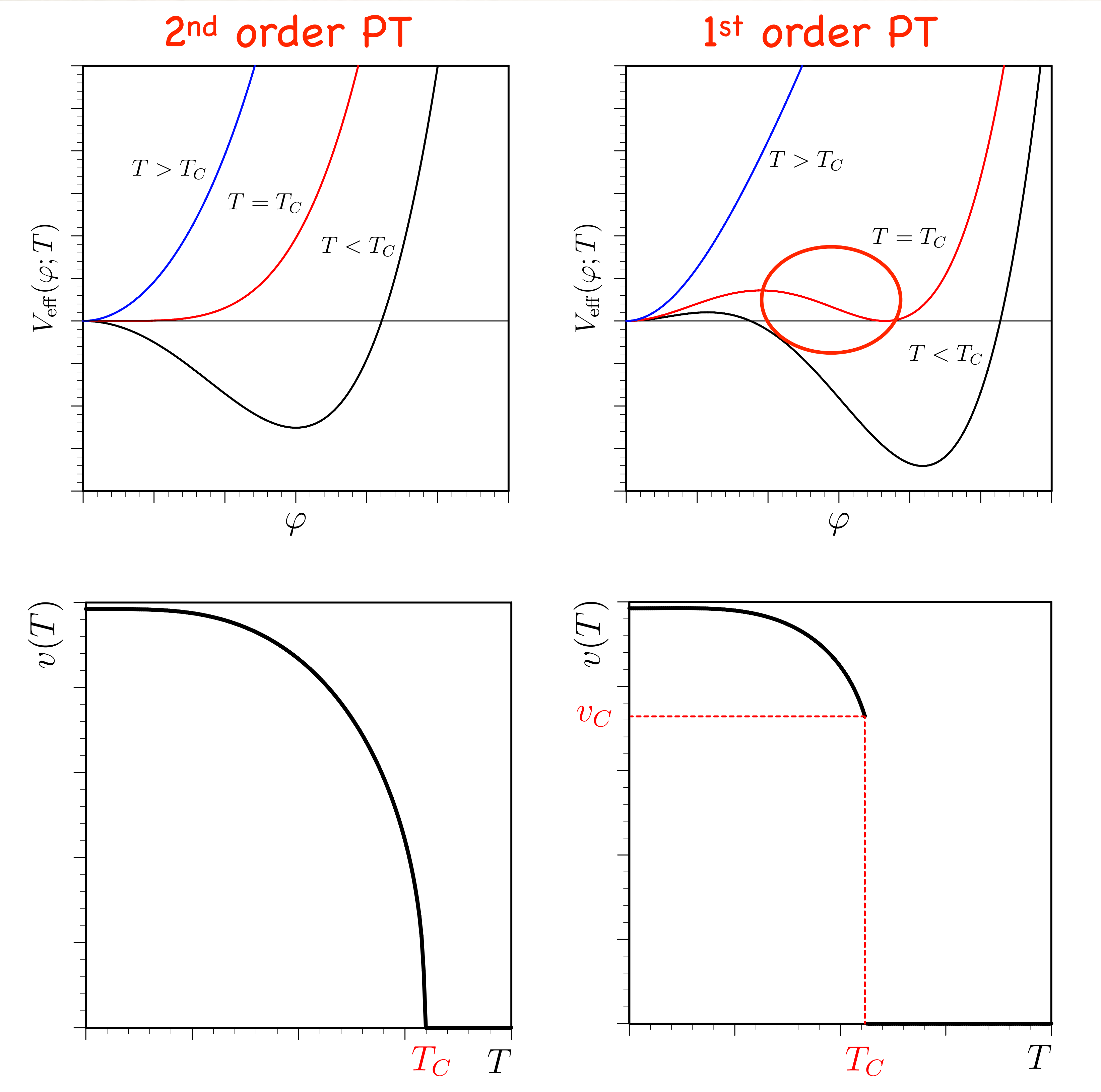

1st-order PT

$\Downarrow$

Negative contributions in V_{eff}.

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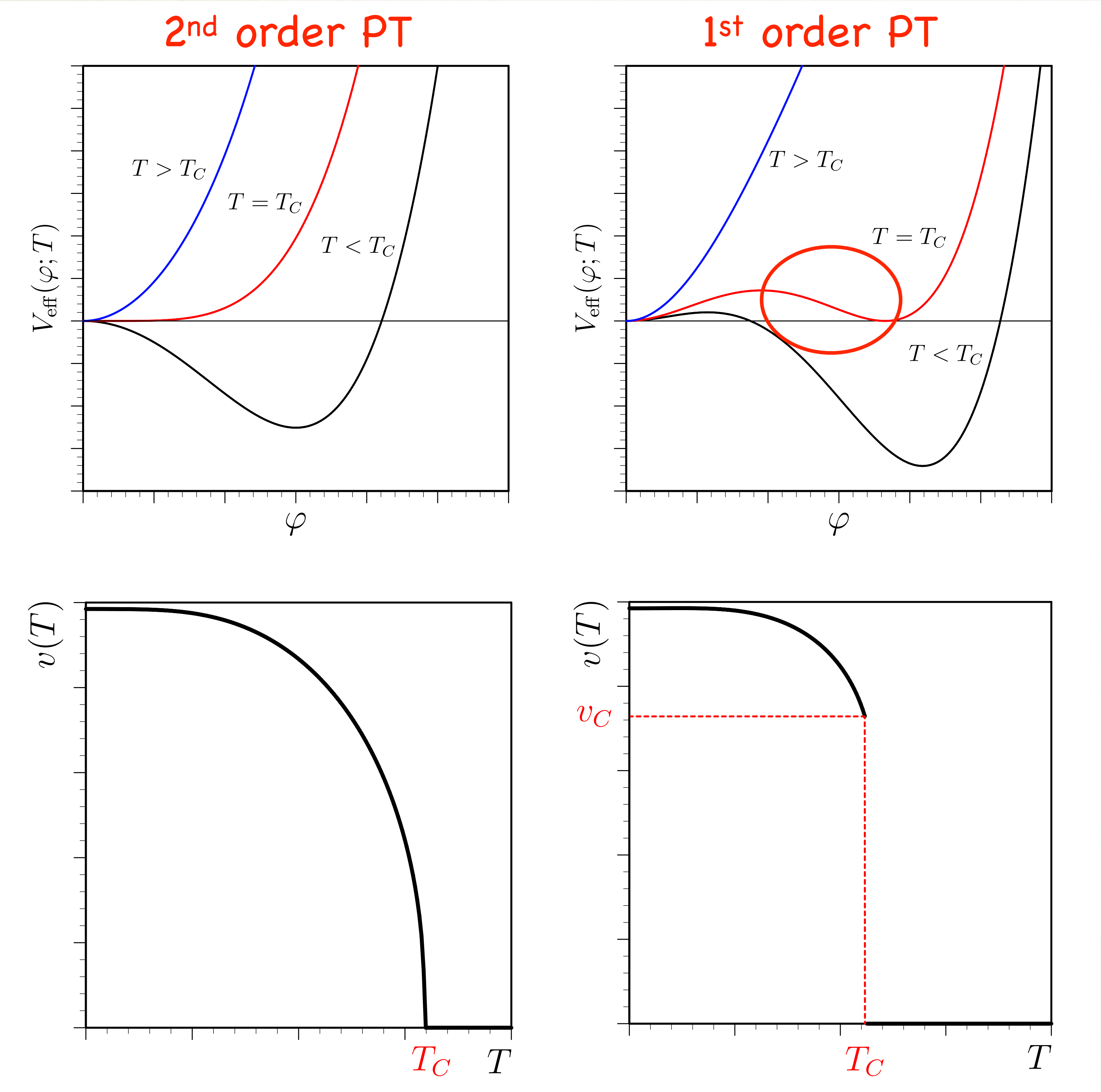

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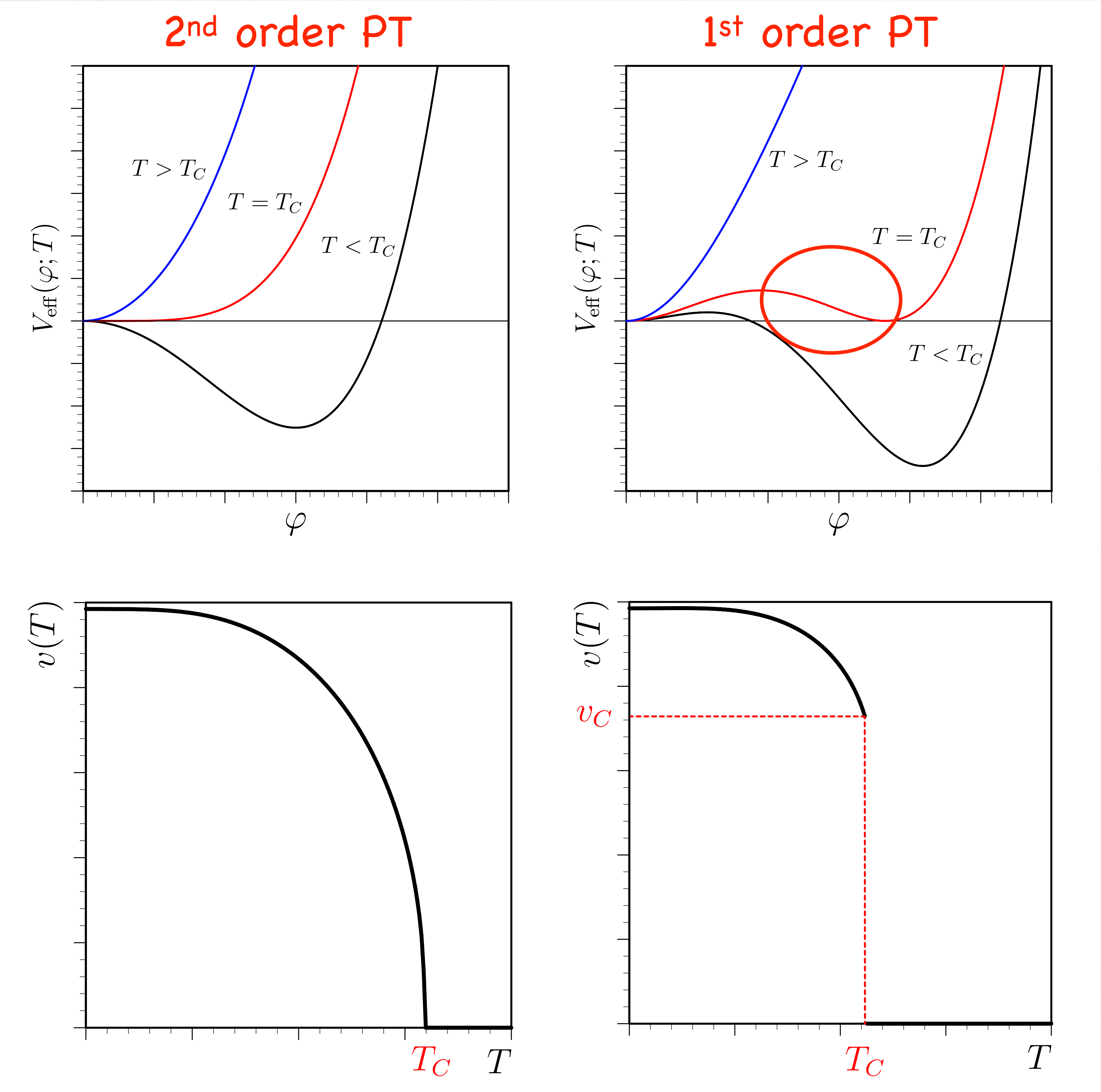

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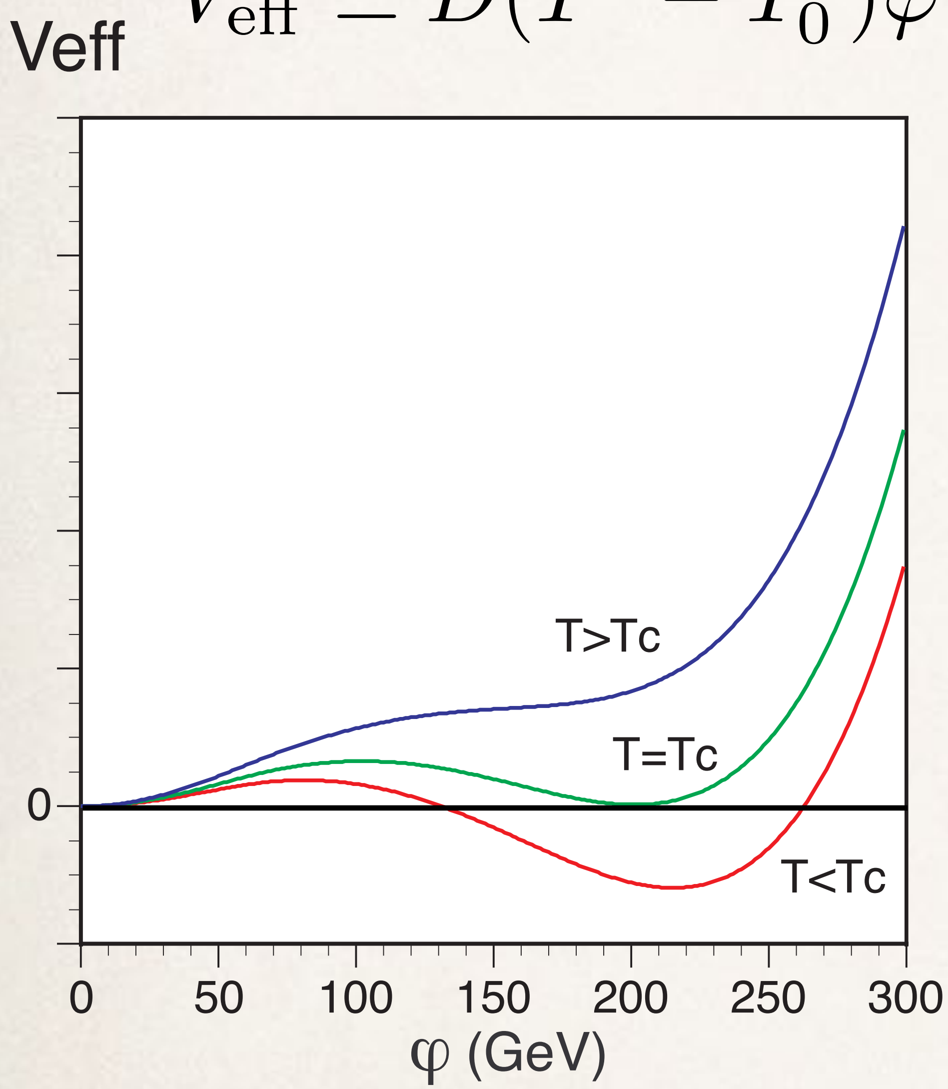
e.g.
thermal cubic term!!

1st-order phase transition

$$V_{\rm eff} \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 \underset{T=T_C}{\rightarrow} \frac{\lambda_{T_C}}{4}\varphi^2(\varphi - v_C)^2$$



$$v_C = \frac{2ET_C}{\lambda_{T_C}} \quad \Rightarrow \quad \frac{v_C}{T_C} = \frac{2E}{\lambda_{T_C}}$$

SM:

$$E_{\rm SM} \simeq \frac{1}{4\pi v^3}(2m_W^3 + m_Z^3) \simeq 0.01$$

$$\lambda_{T_C} \simeq \lambda = m_h^2/(2v^2)$$

$$\frac{v_C}{T_C} \gtrsim 1 \quad \Longrightarrow \quad m_h \lesssim 48 \text{ GeV}$$

but, m_h = 125 GeV

How to solve: increase E by adding bosons, e.g., scalar.

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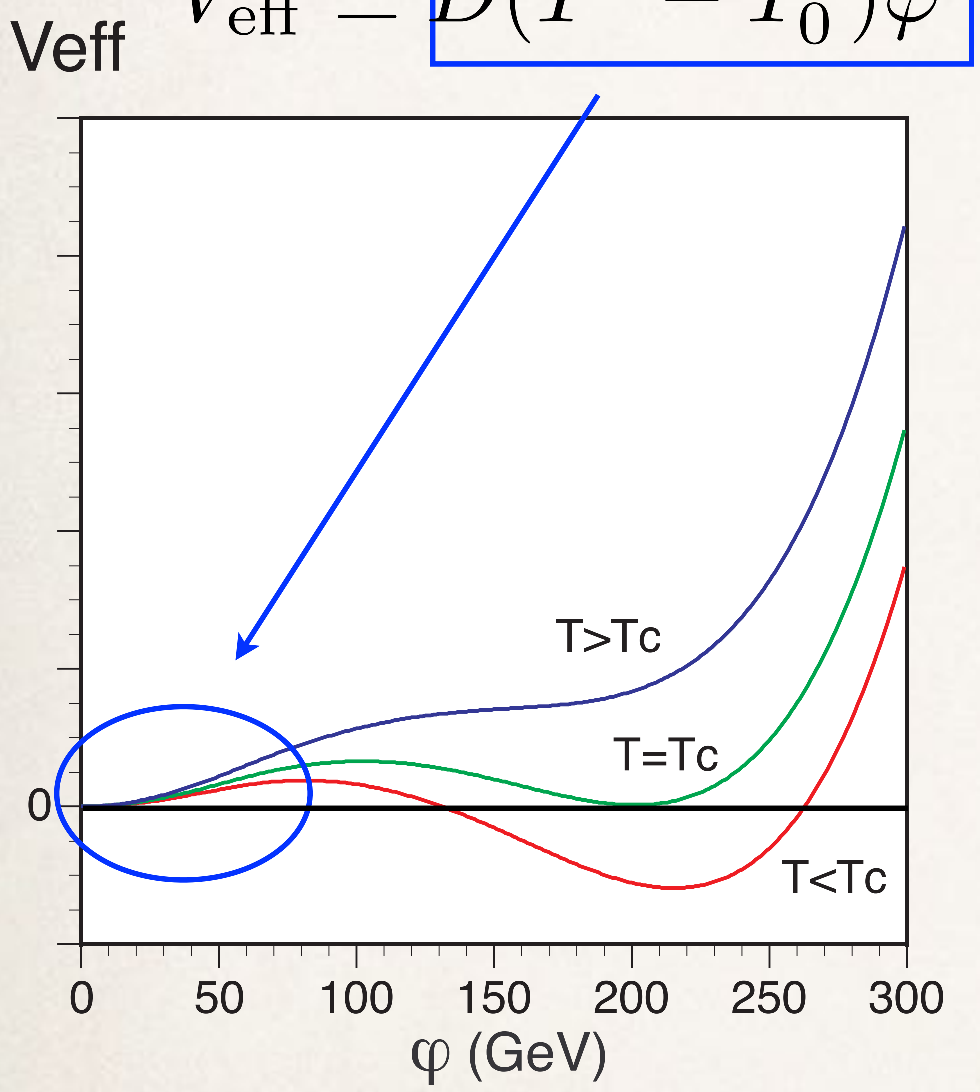

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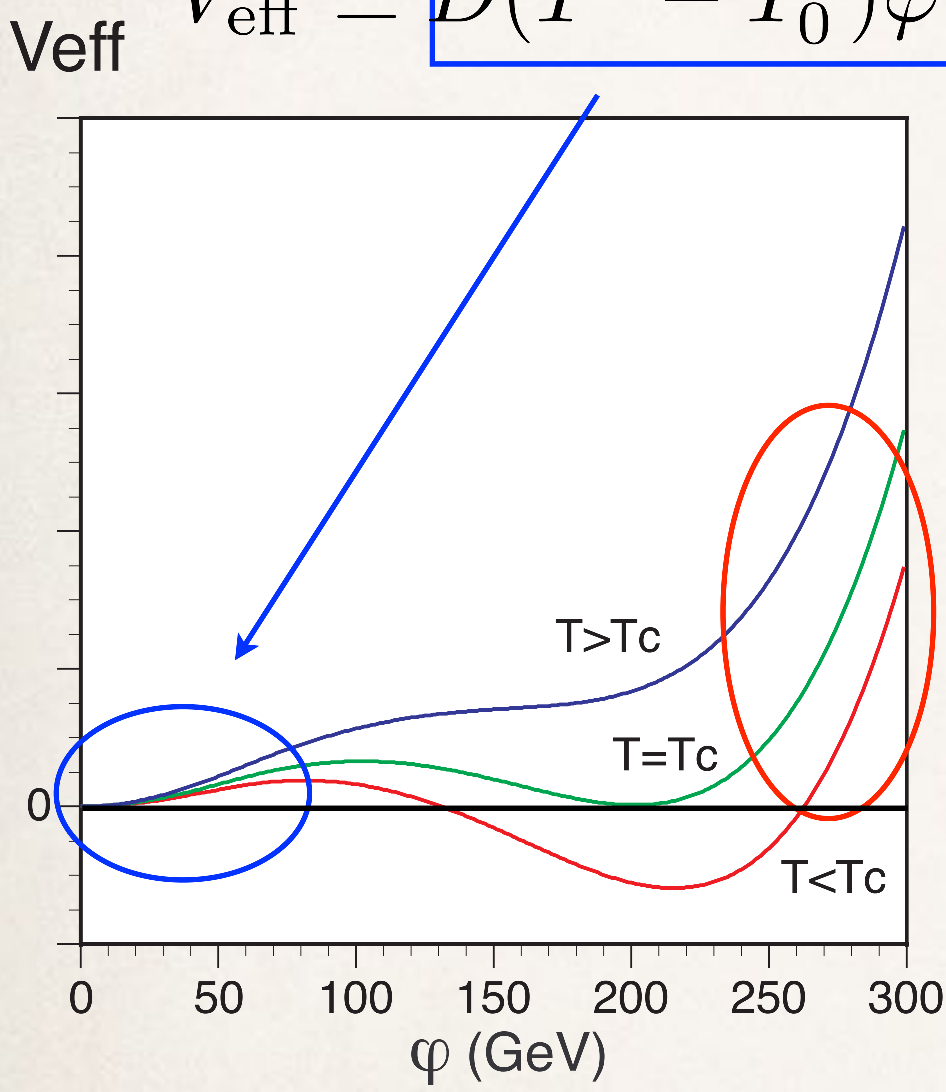

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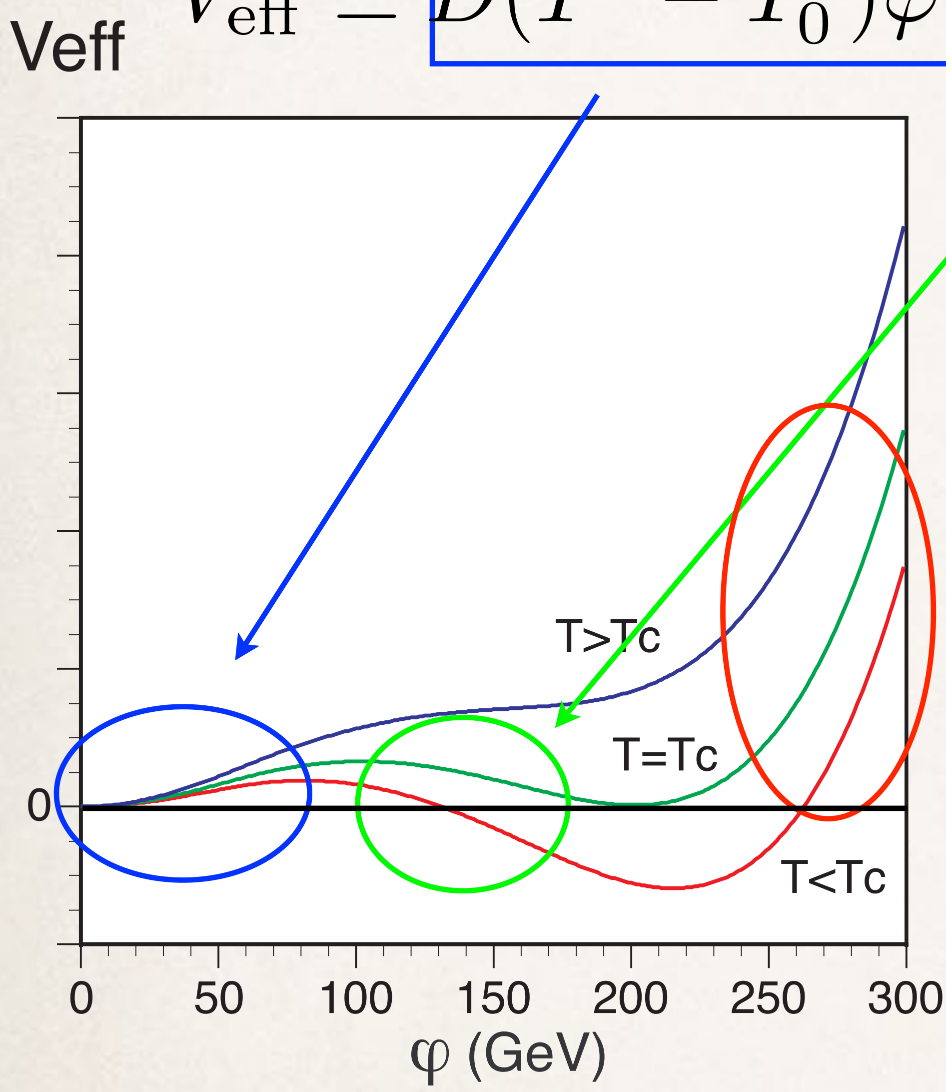

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NOTE

"Scalar" does not always play a role.

e.g., in 2HDM, heavy Higgs loops can enhance E.

$$m^2_{i=H,A,H^\pm} = M^2 + \tilde{\lambda}_i \varphi^2$$

$$V_{\rm eff} \ni \begin{cases} -\tilde{\lambda}^{3/2} T \varphi^3 \left(1 + \frac{M^2}{\tilde{\lambda}\varphi^2}\right)^{3/2}, & \text{for } M^2 \ll \tilde{\lambda}\varphi^2, \\ -|M|^3 T \left(1 + \frac{\tilde{\lambda}\varphi^2}{M^2}\right)^{3/2}, & \text{for } M^2 \gtrsim \tilde{\lambda}\varphi^2. \end{cases}$$

non-decoupling scalar $\Rightarrow$ $E = E_{SM} + \Delta E$ $\Rightarrow$ v_c/T_c ⤴

Requirements: 1. large coupling λ, 2. small M^2

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This leads to interesting phenological consequences (see later).

EWPT in 2HDM

[update of Kanemura, Okada, E.S., PLB606,(2005)361]

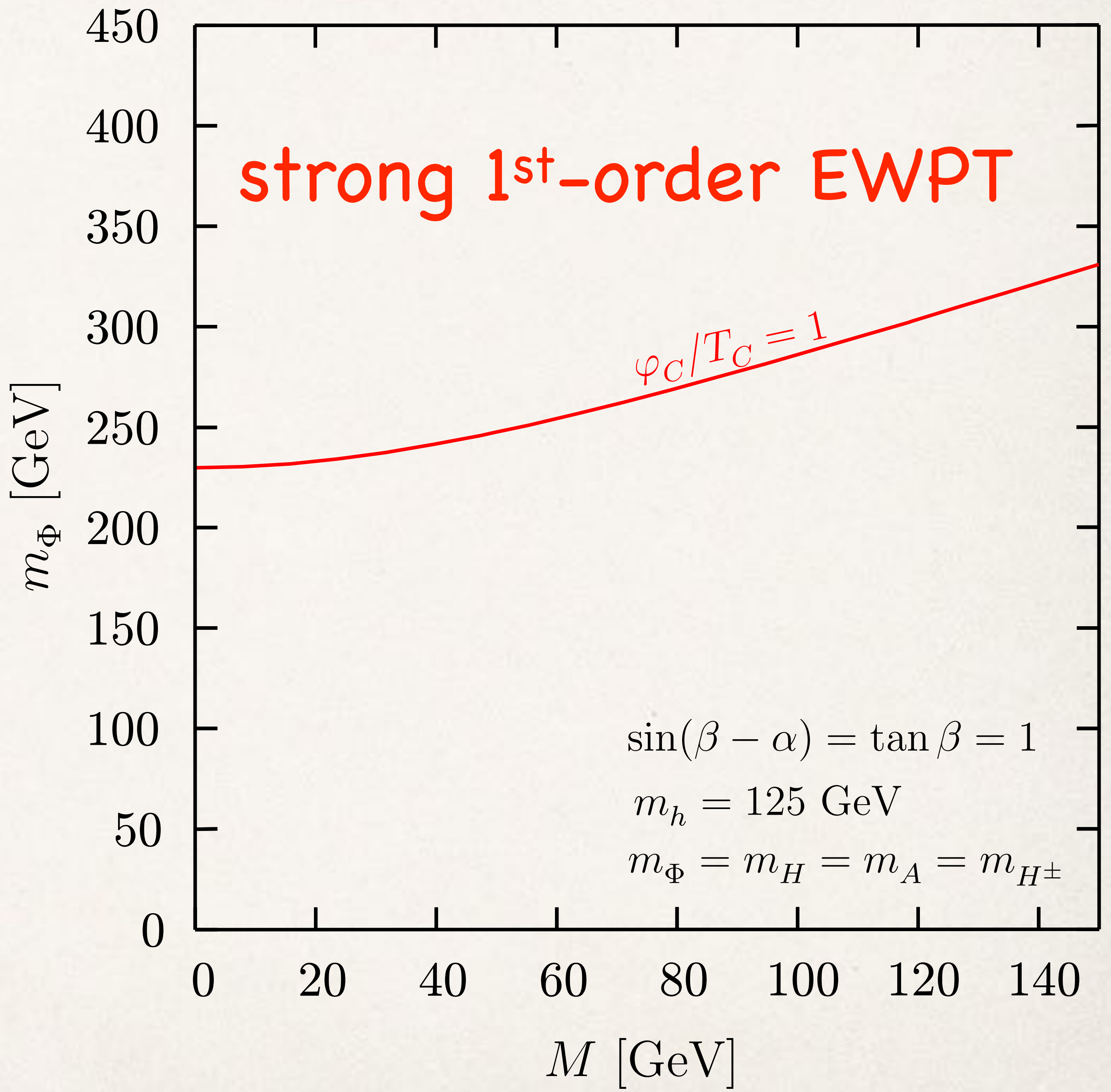
Heavy Higgs masses:

$$m_\Phi^2 = M^2 + \tilde{\lambda}_i v^2$$

$$M = \sqrt{\frac{m_3^2}{\sin\beta\cos\beta}}$$

In v_C/T_C region,

$$m_\Phi^2 \simeq \tilde{\lambda}_i v^2 \gg M^2.$$



What are consequences of non-decoupling scalars?

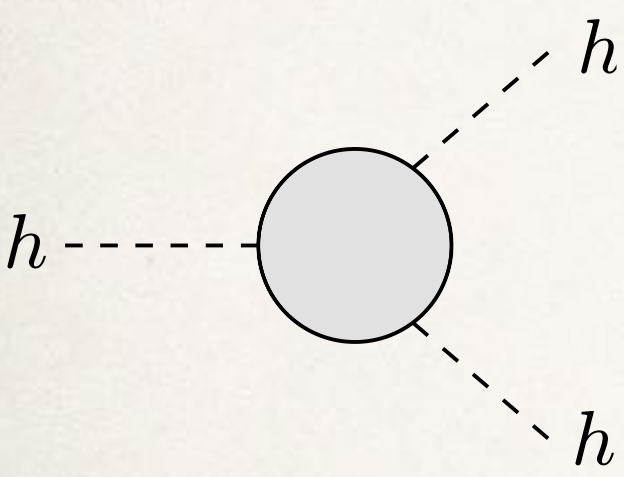
Pheno. consequences of $v_c/T_c \gtrsim 1$

1. Triple Higgs coupling

2. Higgs -> 2γ

λ_{hhh} coupling in 2HDM

[S. Kanemura, S. Kiyoura, Y. Okada, E.S., C.-P. Yuan, PLB558 (2003) 157]



For $\sin(\beta-\alpha)=1$ (alignment limit)

$$\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\sum_{\Phi=H,A,H^\pm}\frac{c}{12\pi^2}\frac{m_\Phi^4}{m_h^2 v^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3\right].$$

c=1(2) for neutral (charged Higgs bosons)

$$m_\Phi^2 \simeq M^2+\lambda_i v^2, \quad M^2 = m_3^2/(\sin\beta\cos\beta).$$

For $M^2 \ll \lambda_i v^2$ ($m_\Phi^2 \simeq \lambda_i v^2$), the quantum corrections would grow with m_Φ^4.

$\Rightarrow$ nondecoupling loop effect.

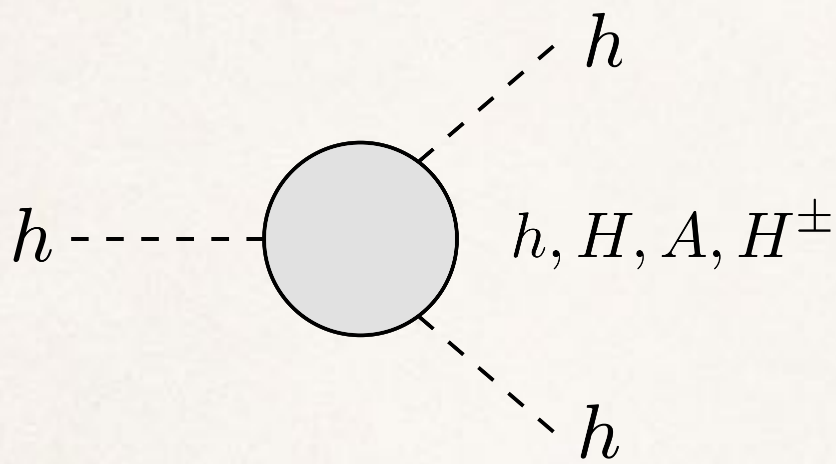
For $M^2 \gg \lambda_i v^2$ ($m_\Phi^2 \simeq M^2$), the quantum corrections would be suppressed.

$\Rightarrow$ ordinary decoupling limit

Strong correlation between v_C/T_C and λ_{hhh}!!

EWPT-λ_{hhh} correlation in 2HDM

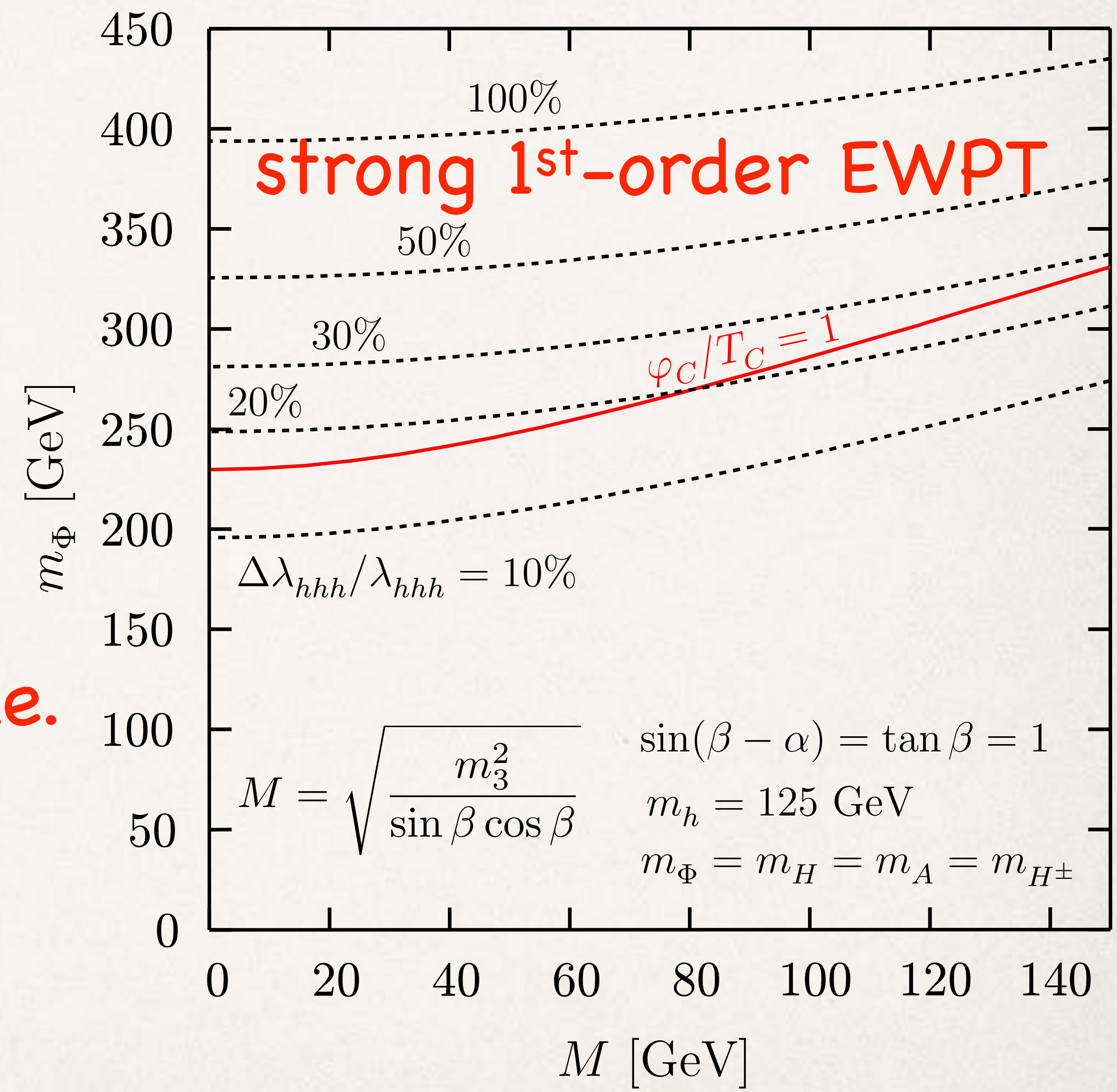
[update of Kanemura, Okada, E.S., PLB606,(2005)361]



- 1st-order EWPT is induced by heavy Higgs bosons.

- hVV and hff can be SM-like.

- $(\Delta\lambda_{hhh})/\lambda_{hhh}$>(15-20)%



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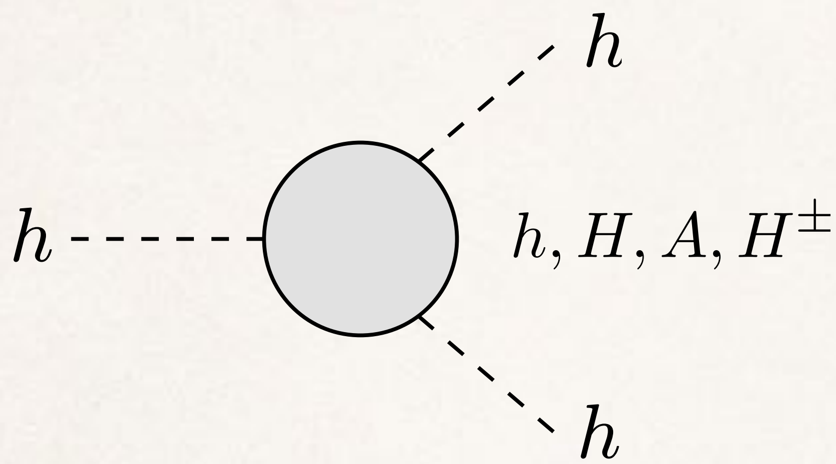

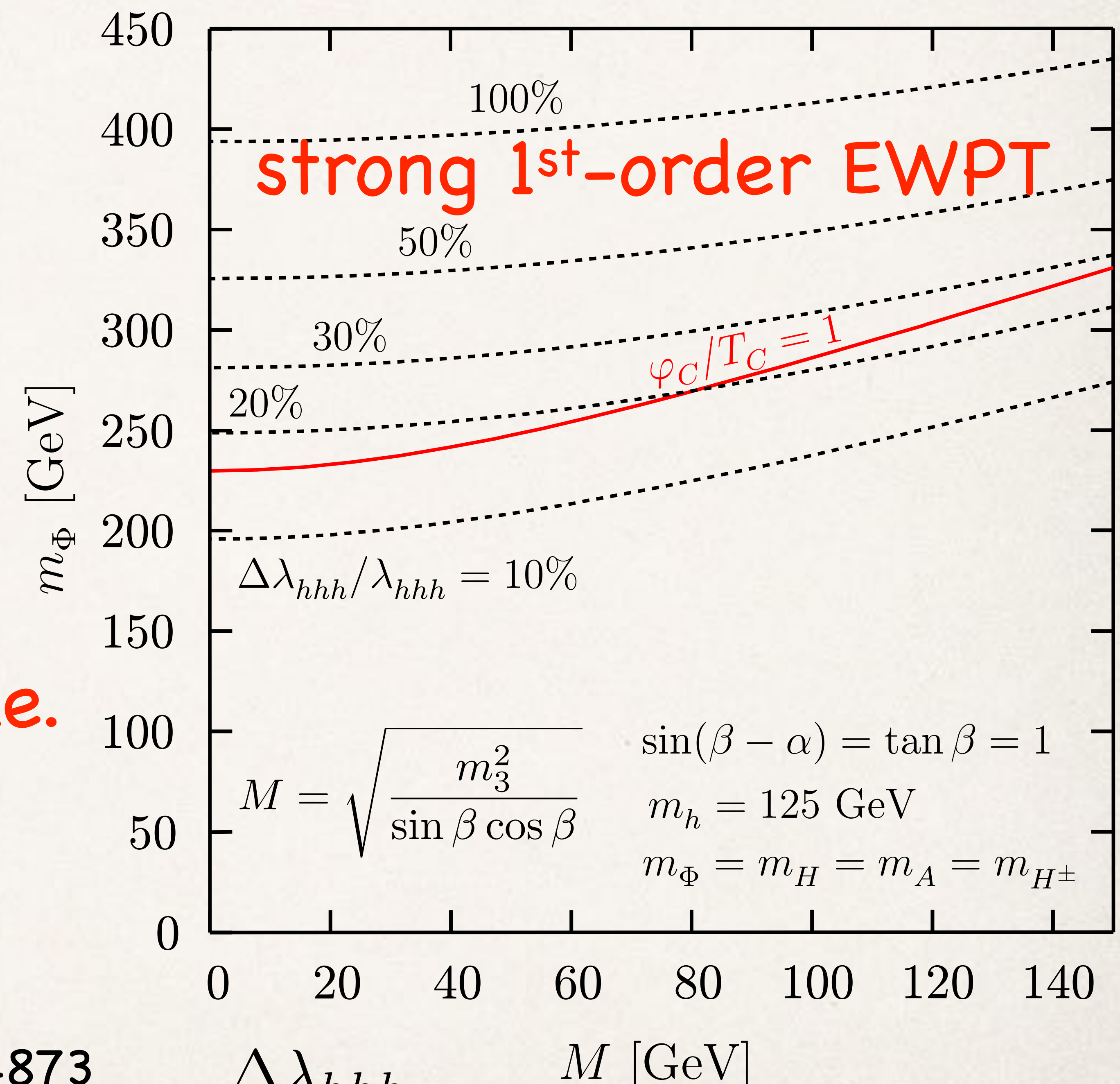

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$$\kappa_{3\lambda} \in \begin{cases} (-8.2, 13.2) \text{ (ATLAS)} & \text{1807.04873} \\ (-11, 17) \text{ (CMS)} & \text{1806.00408} \end{cases}$$

$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}} = \kappa_{3\lambda} - 1$$

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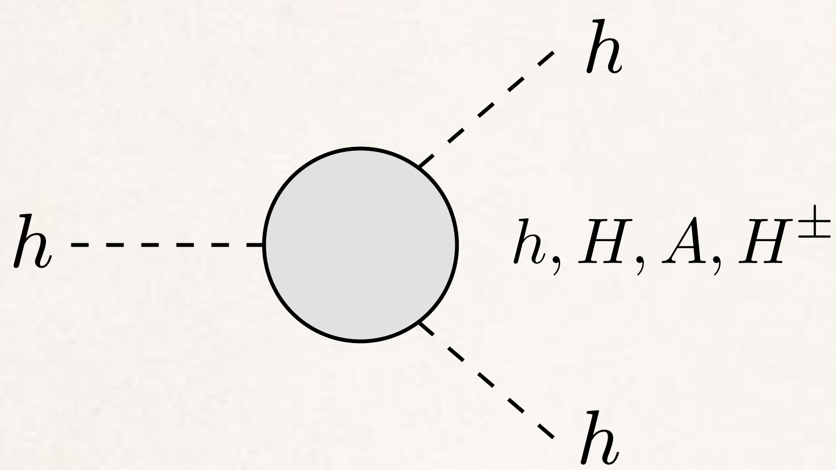

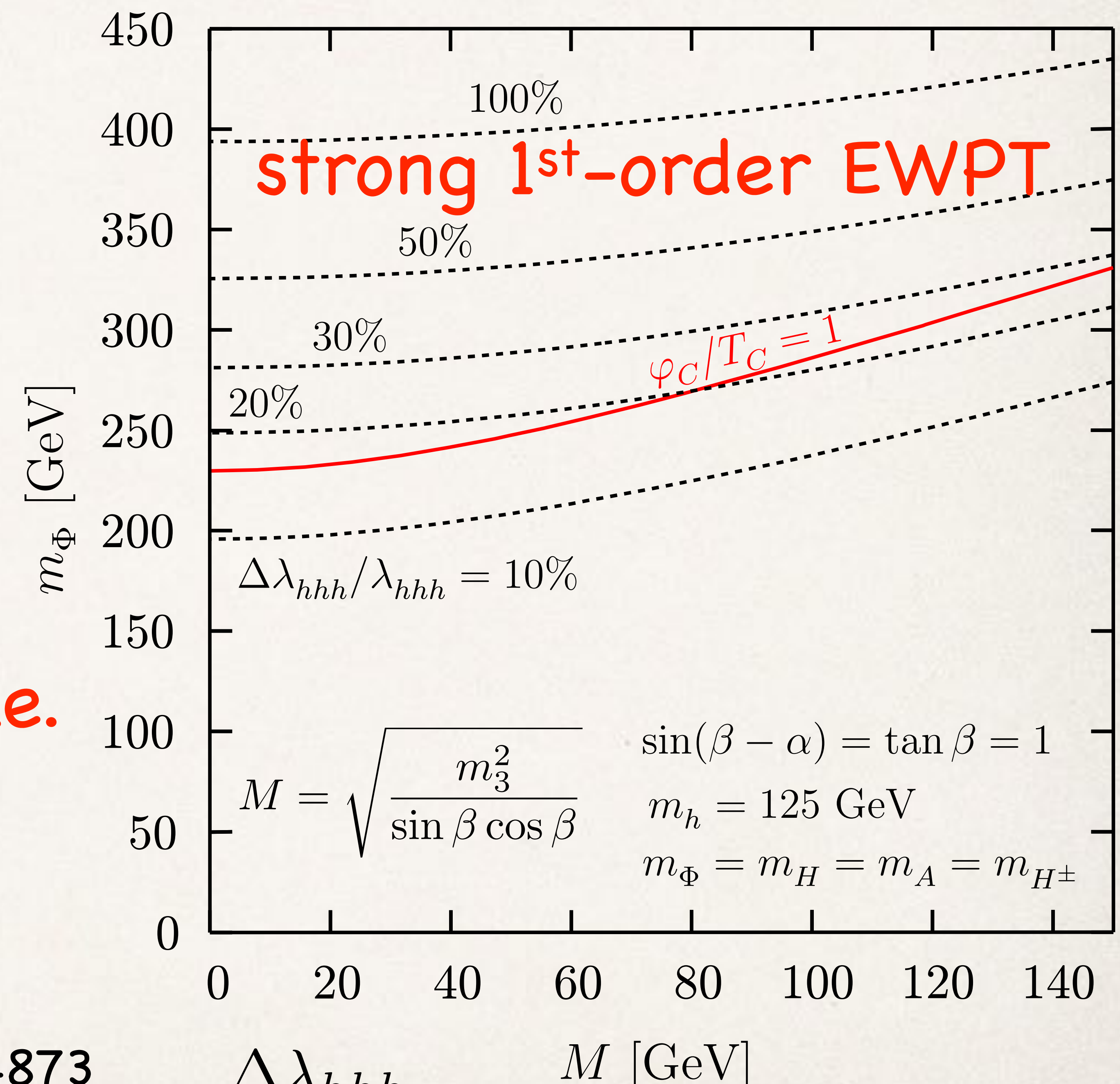

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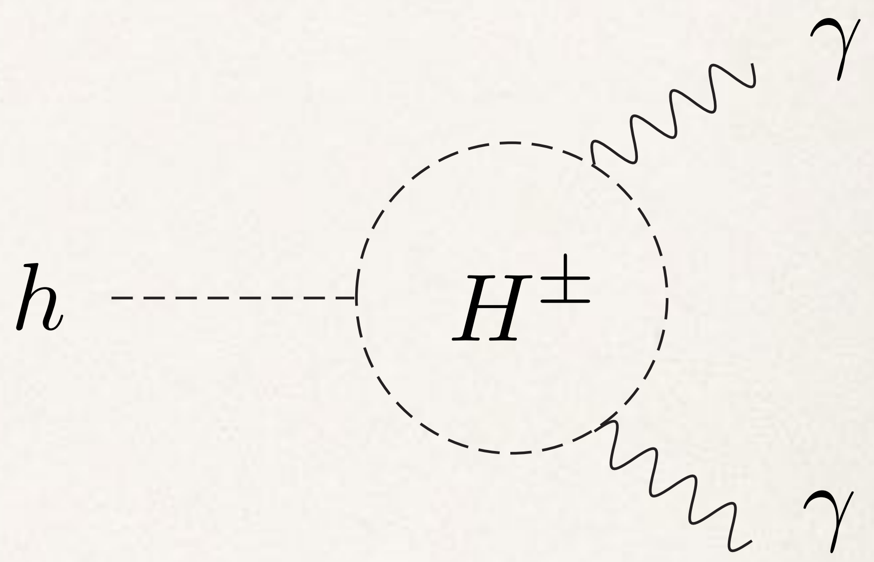
For recent studies on EWPT in 2HDM, see, Basler et al 1711.0409, Bernon et al, 1712.08430.

EWPT-$\mu_{\gamma\gamma}$ correlation in 2HDM

Charged Higgs contributes to h-> γ γ

$$\mu_{\gamma\gamma} = \left|1 + \frac{1}{3\mathcal{A}_{\rm SM}}\left(1 - \frac{M^2}{m_{H^\pm}^2}\right)\right|^2$$



$$\mathcal{A}_{\rm SM} = -6.49 \qquad m_{H^\pm}^2 = M^2 - \frac{1}{2}(\lambda_4 + \lambda_5)v^2$$

$m_{H^\pm}^2 \gg M^2$ is necessary to have strong 1st-order EWPT

-> charged Higgs loop does not decouple in this case.

[I.Ginzburg, M.Krawczyk, P.Osland, hep-ph/0211371]

$$\mu_{\gamma\gamma} \underset{m_\Phi^2 \gg M^2}{\simeq} \left|1 + \frac{1}{3\mathcal{A}_{\rm SM}}\right|^2 \simeq 0.9$$

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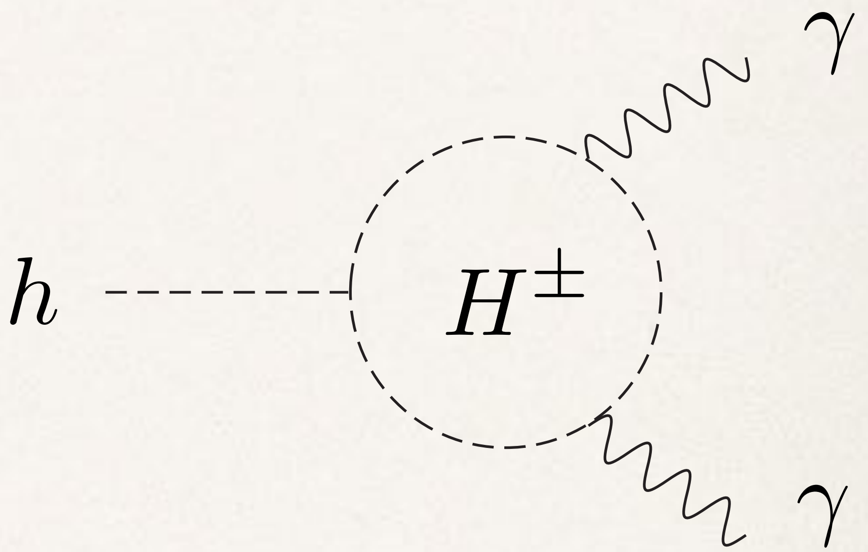

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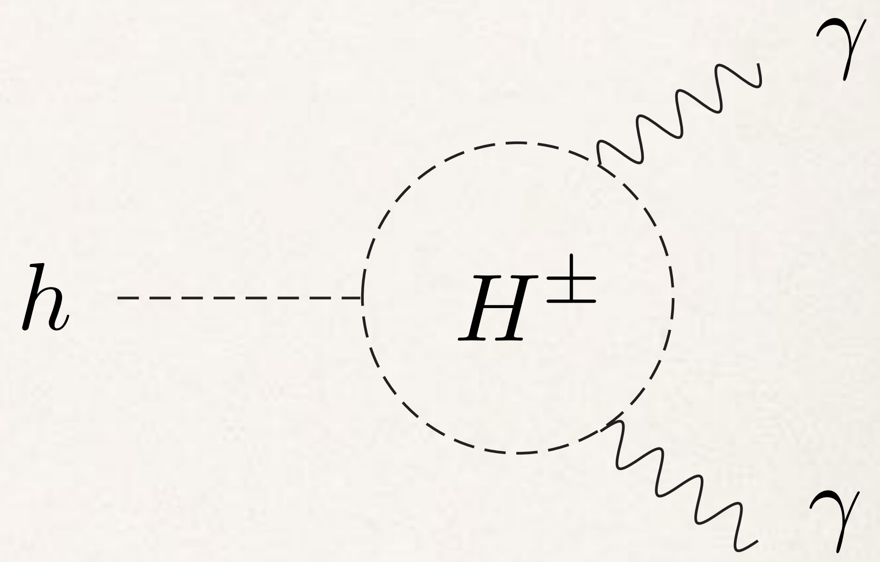

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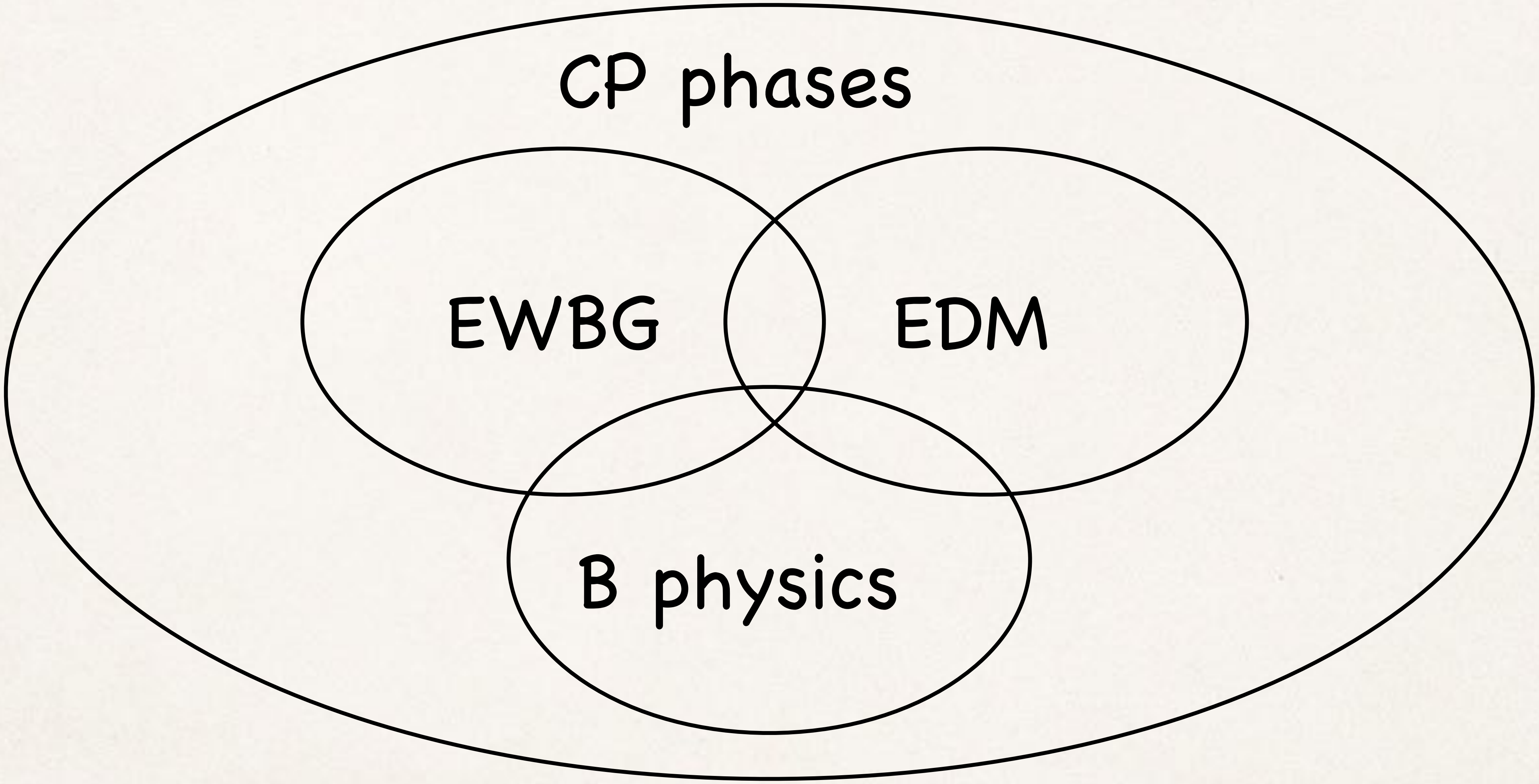
$$\mu_{\gamma\gamma} = \begin{cases} 1.18^{+0.17}_{-0.14}\ \text{(CMS)} & \text{1804.02716} \\ 0.99^{+0.15}_{-0.14}\ \text{(ATLAS)} & \text{1802.04146} \end{cases}$$

CP violation

EWBG-related CP violation

CPV is needed for baryogengesis.



What is BAU-related CP violation?

-> CP violation between the bubble wall (Higgs VEV) and some particles with masses of O(100) GeV.

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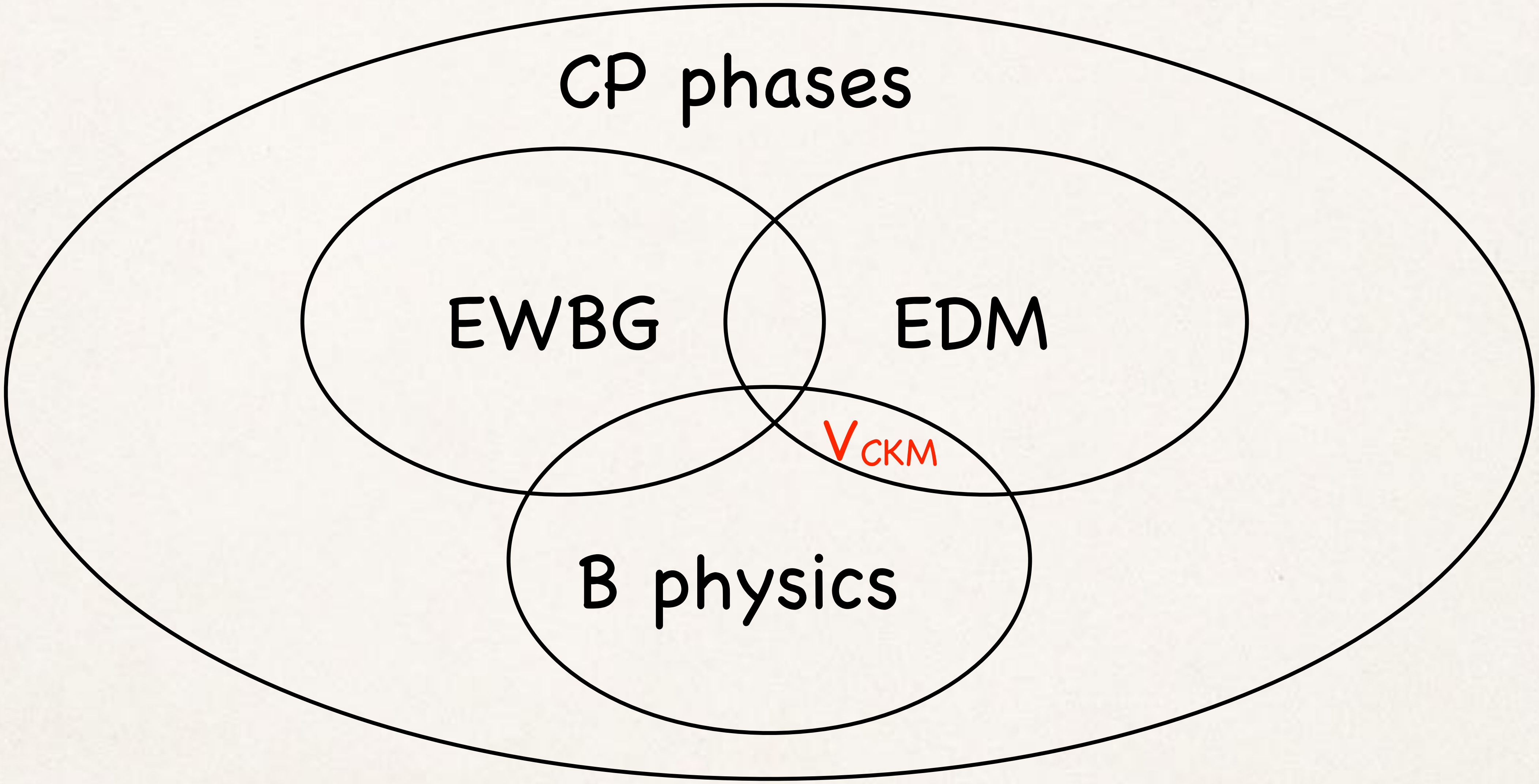

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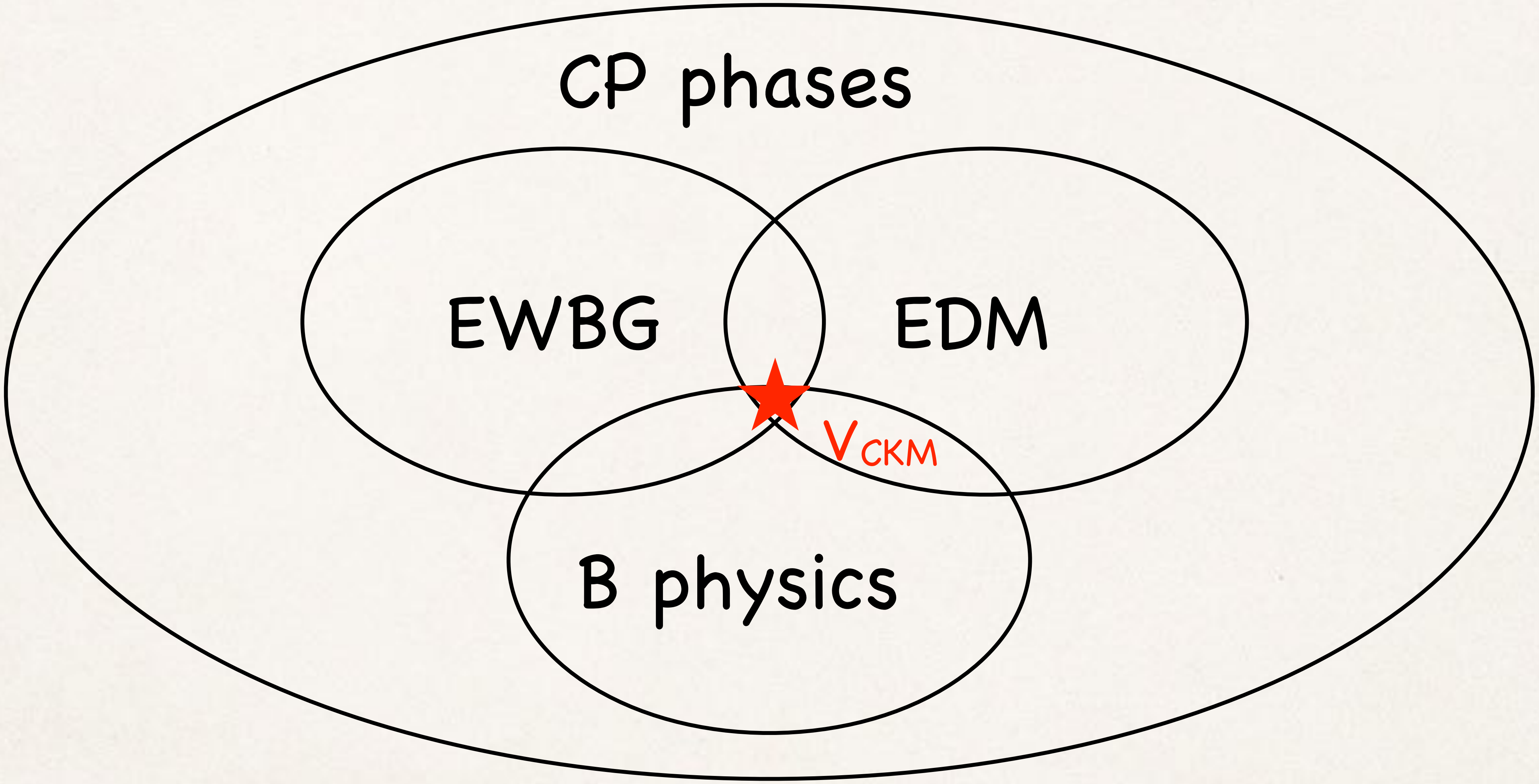

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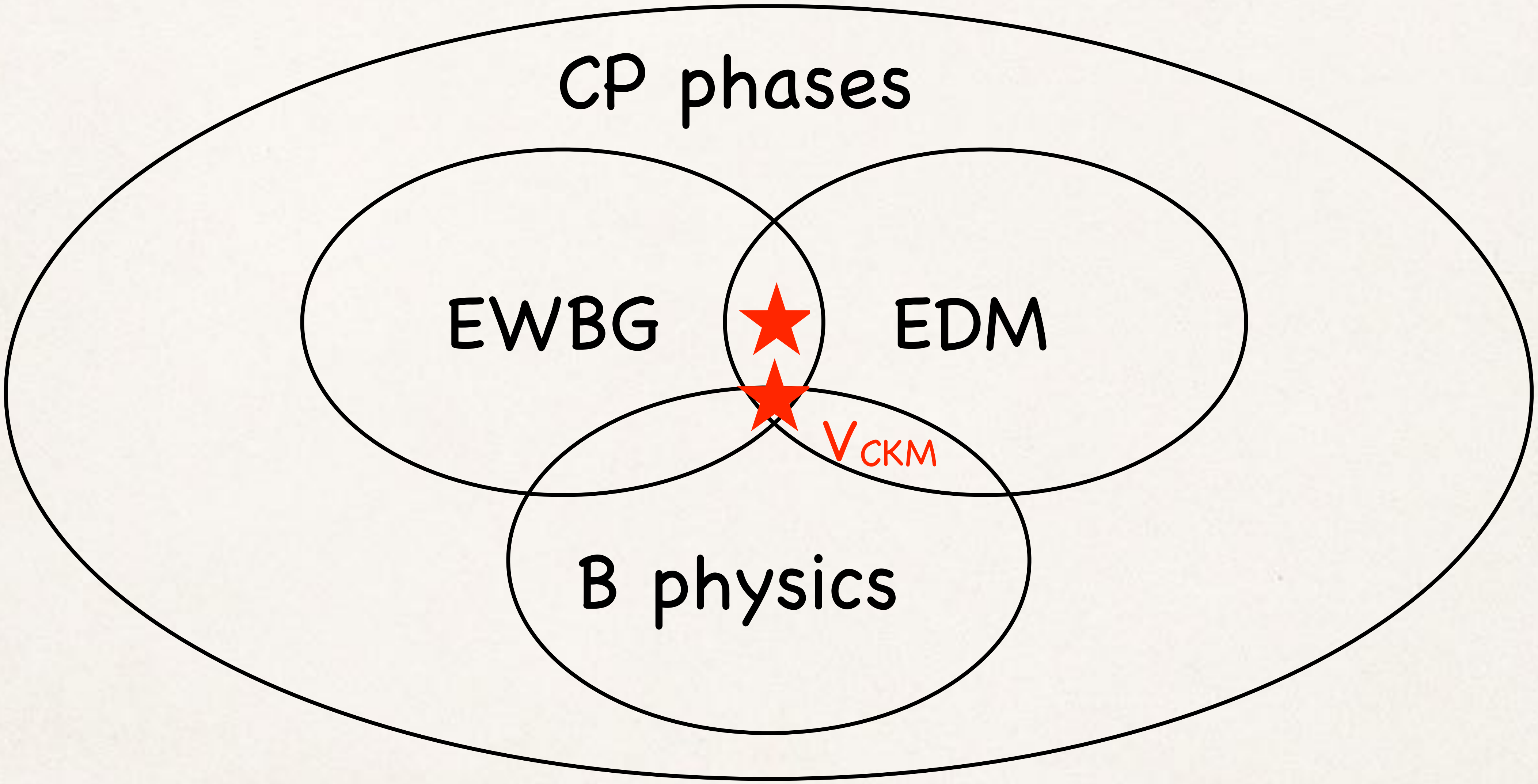

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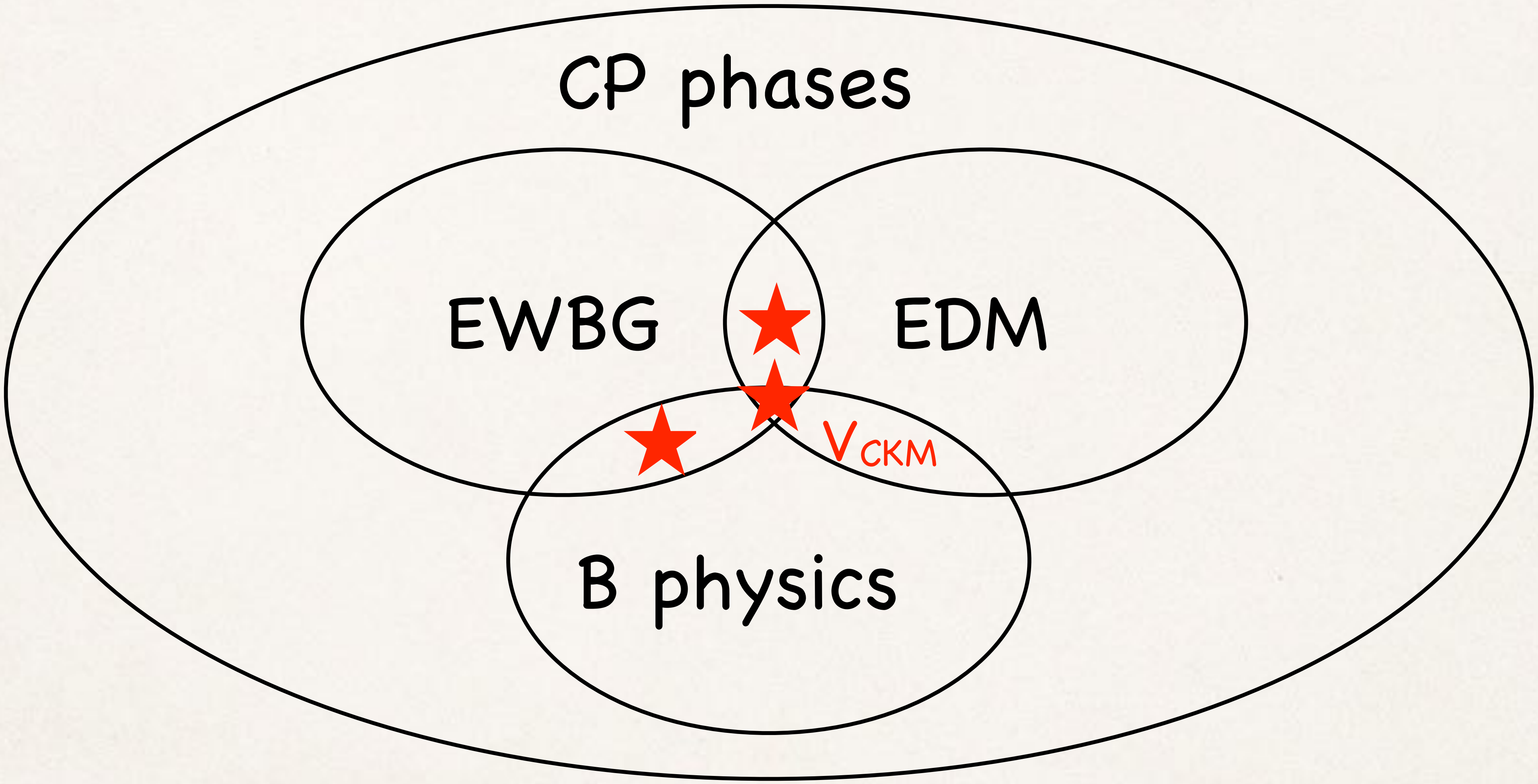

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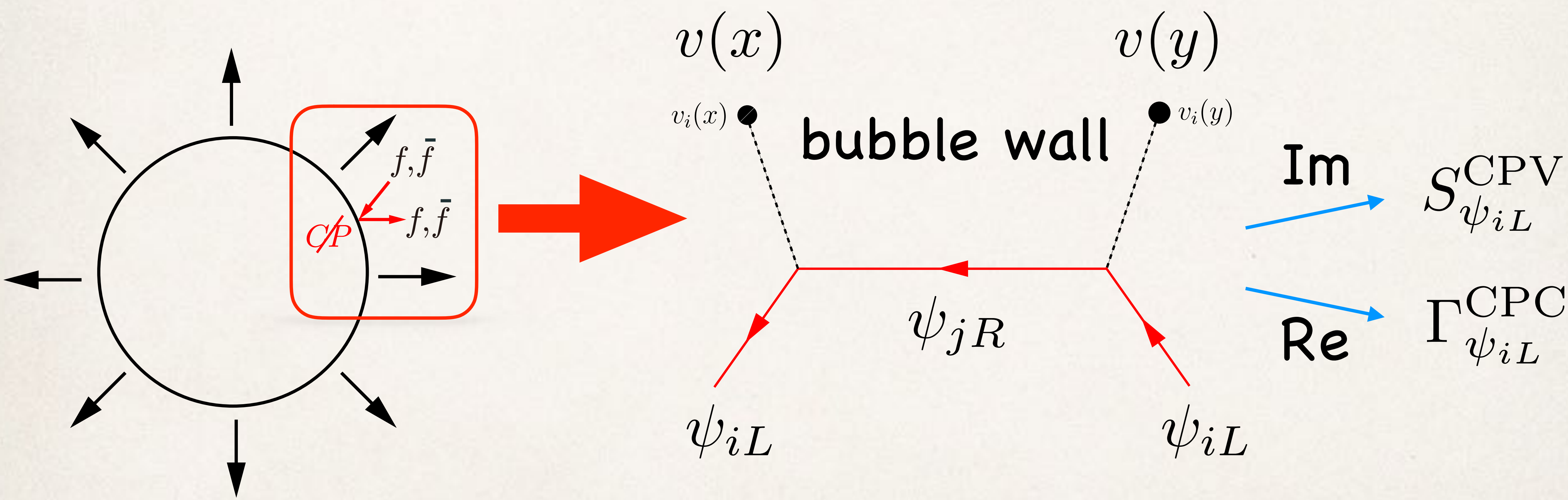
EWBG-related CP violation

Diffusion eq. for n_B: $\bar{z}<0$: sym-phase, $\bar{z}>0$: br-phase

$$D_Q n''_B(\bar{z}) - v_w n'_B(\bar{z}) - \theta(-\bar{z})\mathcal{R}n_B(\bar{z}) = \theta(-\bar{z})\frac{3}{2}\Gamma_B^{(\mathrm{sym})} n_{\mathrm{left}}(\bar{z})$$

diffusion const. wall velocity back reaction sph. rate

n_{left} is generated by scatterings btw particles and bubbles.



$$n_B \propto n_{\mathrm{left}} \propto S_{\psi_{iL}}^{\mathrm{CPV}} \Big/ \sqrt{\Gamma_{\psi_{iL}}^{\mathrm{CPC}}}$$

top-driven EWBG

[K. Fuyuto, W.-S. Hou, E.S., 1705.05034 (PLB)]

General 2HDM (no Z_2 symmetry)

$$-\mathcal{L}_Y = \bar{q}_{iL}(Y_{1ij}\tilde{\Phi}_1 + Y_{2ij}\tilde{\Phi}_2)q_{jR} + \text{h.c.}$$

$$S^{\text{CPV}}_{\psi_{iL}}(x) \underset{v_{1,2}\in\mathbb{R}}{=} C_{\text{BAU}}\text{Im}\Big[(Y_1)_{tj}(Y_2)^*_{tj}\Big]v^2(x)\dot{\beta}(x) \quad j = c, t$$

For Z_2-2HDM, $v_i(x)$ must be complex.

$$S^{\text{CPV}}_{\psi_{iL}}(x) = C_{\text{BAU}}|Y_i|^2|v_i(x)|^2\dot{\theta}_i(x) \qquad \theta_i = \text{Arg}(v_i)$$

BAU-related CPV in the broken phase

$$V_L^{u\dagger}(Y_1 c_\beta + Y_2 s_\beta)V_R^u = \mathrm{diag}(y_u, y_c, y_t) \equiv Y_{\mathrm{diag}}$$

$$V_L^{u\dagger}(-Y_1 s_\beta + Y_2 c_\beta)V_R^u = \rho$$

t-c case

$$\longrightarrow \quad \mathrm{Im}\Big[(Y_1)_{tc}(Y_2)^*_{tc}\Big] = \mathrm{Im}\Big[(V_L^u Y_{\mathrm{diag}} V_R^{u\dagger})_{32}(V_L^u \rho V_R^{u\dagger})_{32}\Big]$$

Simplified case: Guo et al, 1609.09849 [PRD].

$$Y_{i=1,2} = \begin{pmatrix} (Y_i)_{uu} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & (Y_i)_{tc} & (Y_i)_{tt} \end{pmatrix}, \quad \tan\beta = 1, \quad (Y_1)_{tt} = (Y_2)_{tt}$$

$$\longrightarrow \quad \mathrm{Im}\Big[(Y_1)_{tc}(Y_2)^*_{tc}\Big] = -y_t \mathrm{Im}(\rho_{tt}), \quad \rho_{ct} = 0, \quad m_c = 0.$$

ρ_{tt} is the main contributor to the BAU!!

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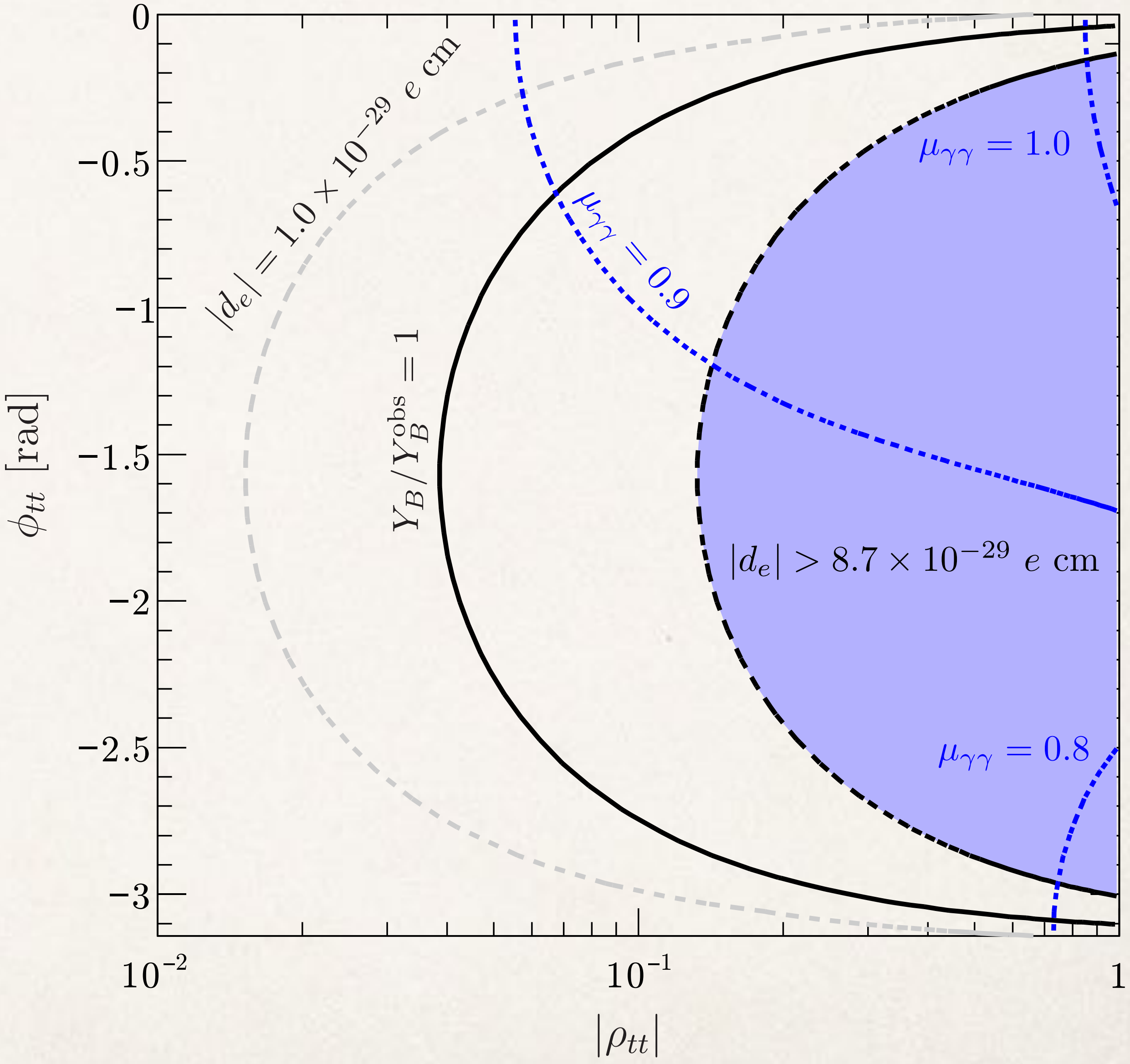
[K. Fuyuto, W.-S. Hou, E.S., 1705.05034 (PLB)]

$m_H = m_A = m_{H^\pm} = 500$ GeV, $c_{\beta-\alpha} = 0.1$

$\rho_{tt} = |\rho_{tt}| e^{i\phi_{tt}}$



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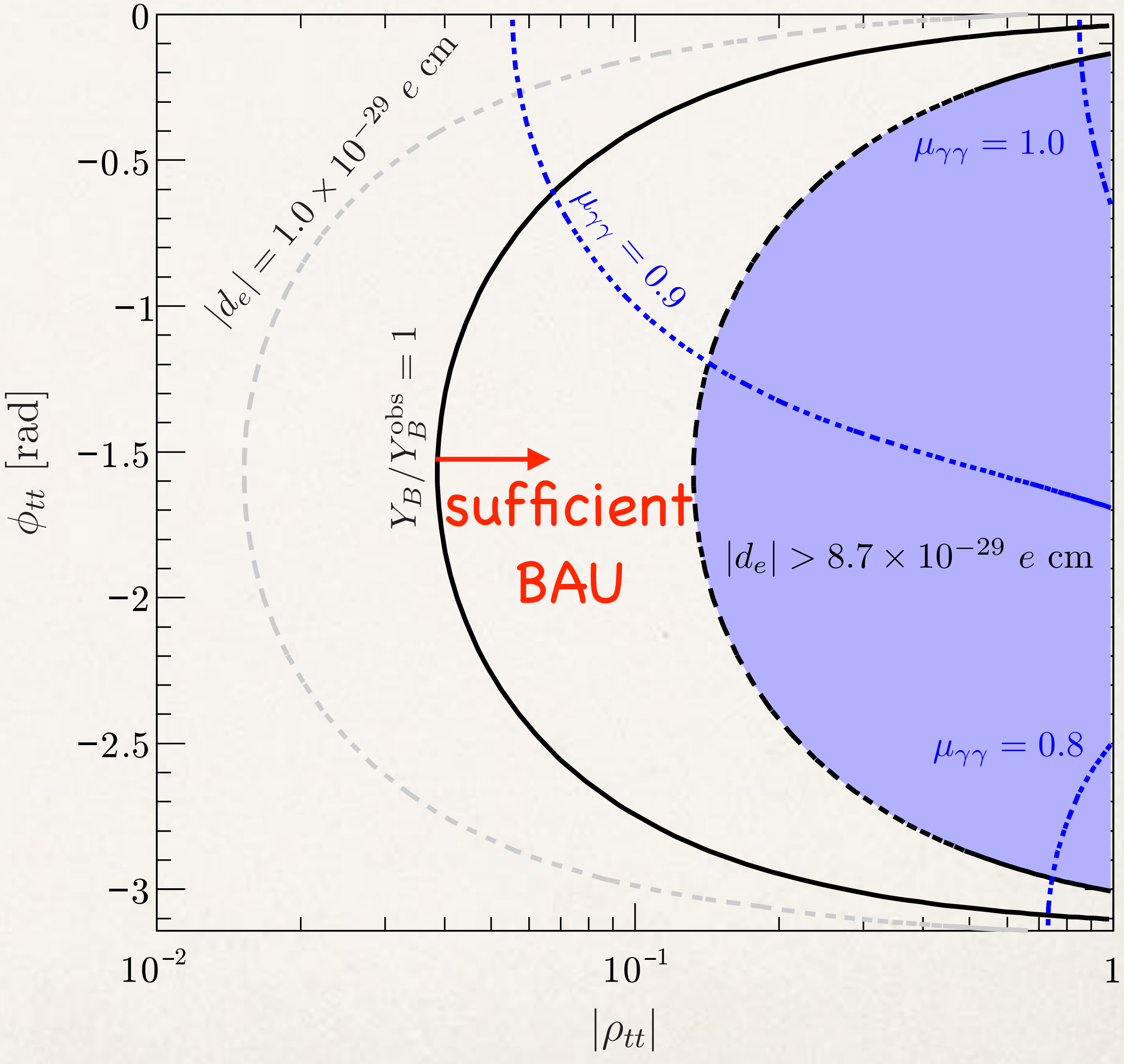

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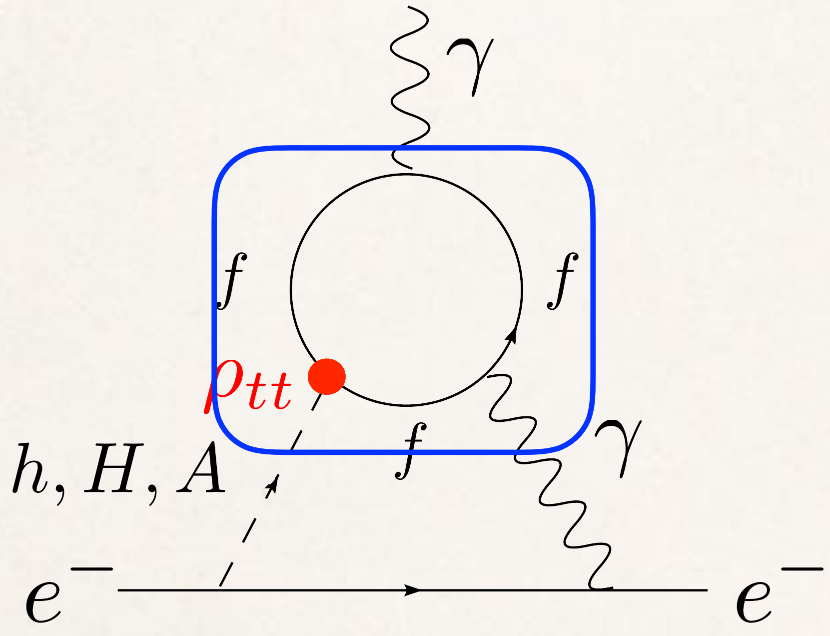

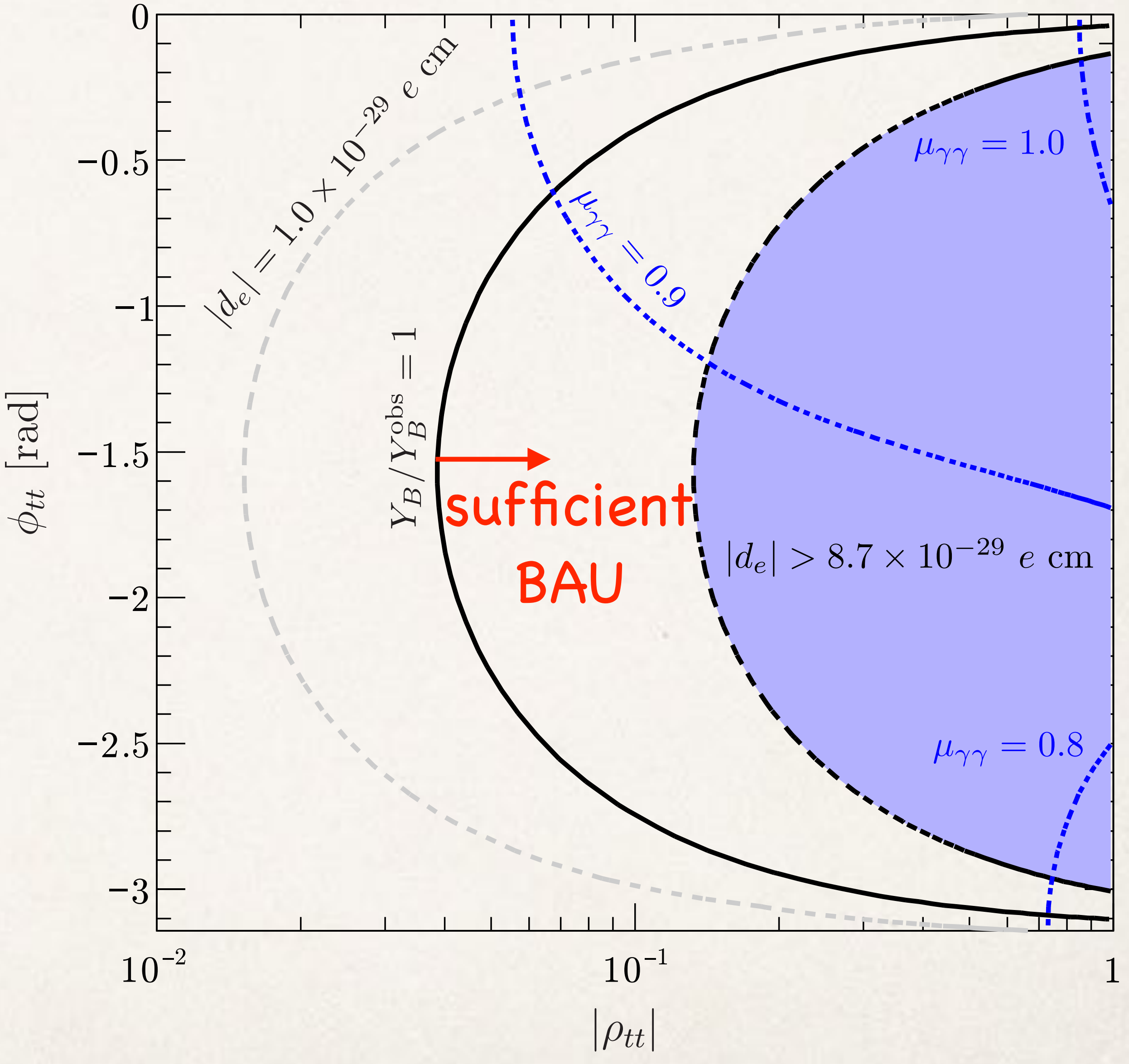

eEDM bound:

$|d_e| < 8.7 \times 10^{-29}\ e\ {\rm cm}$ (ACME13)

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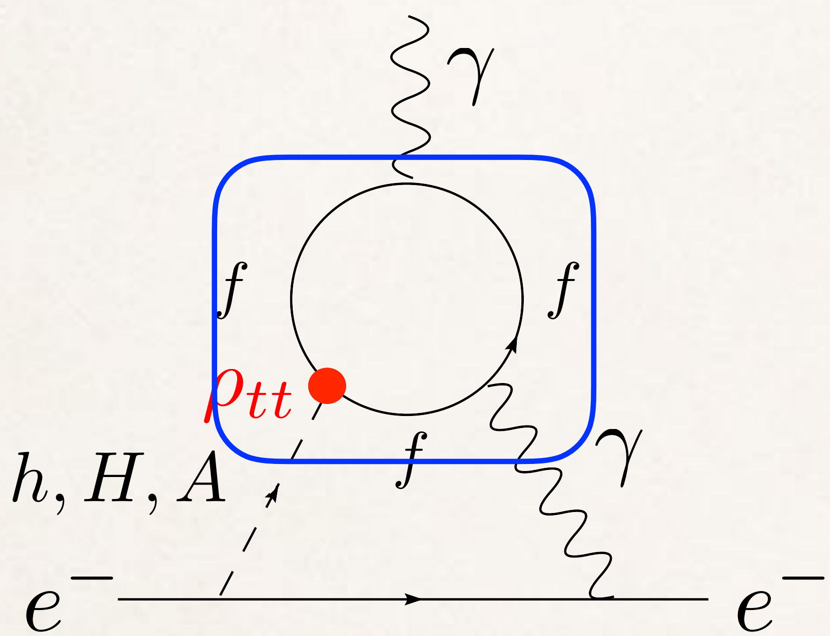

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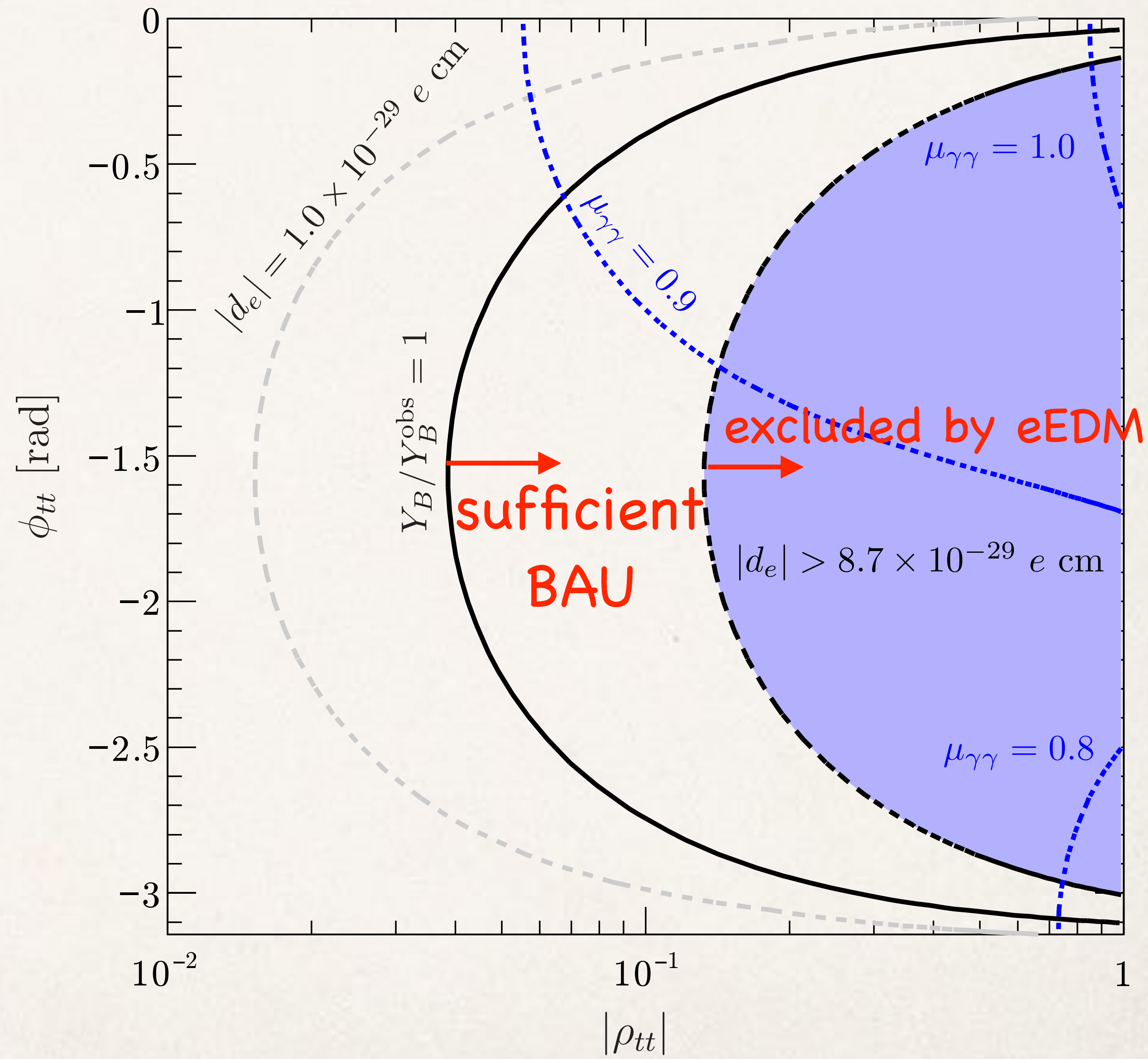

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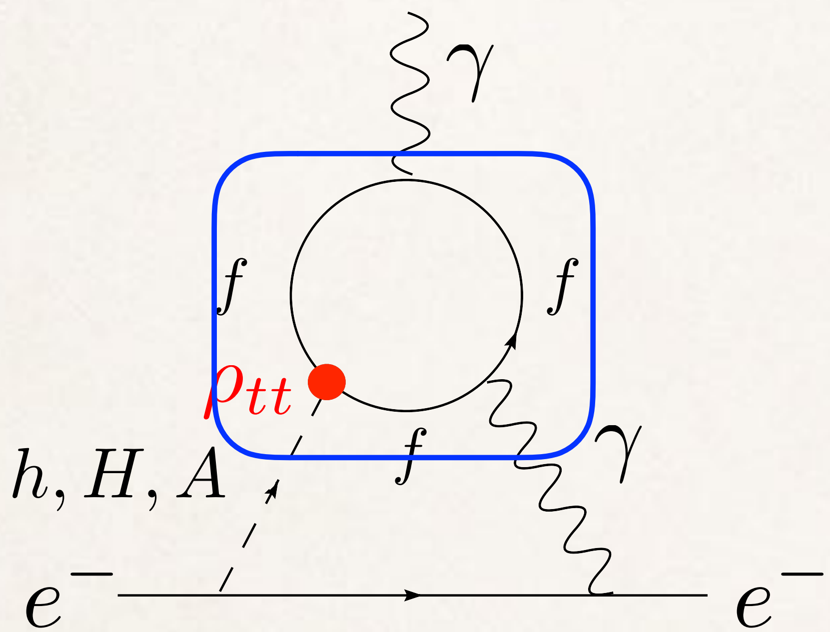

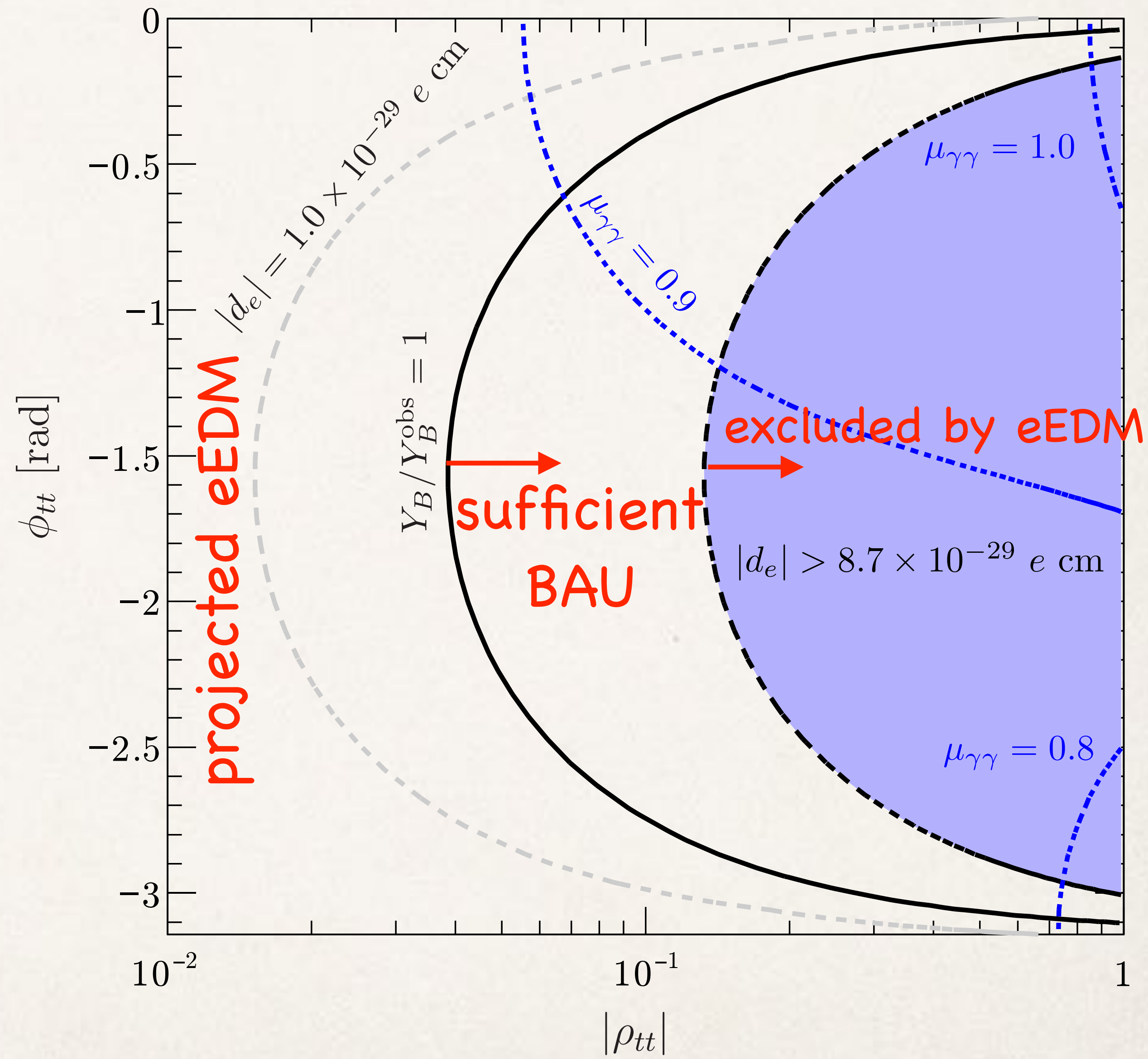

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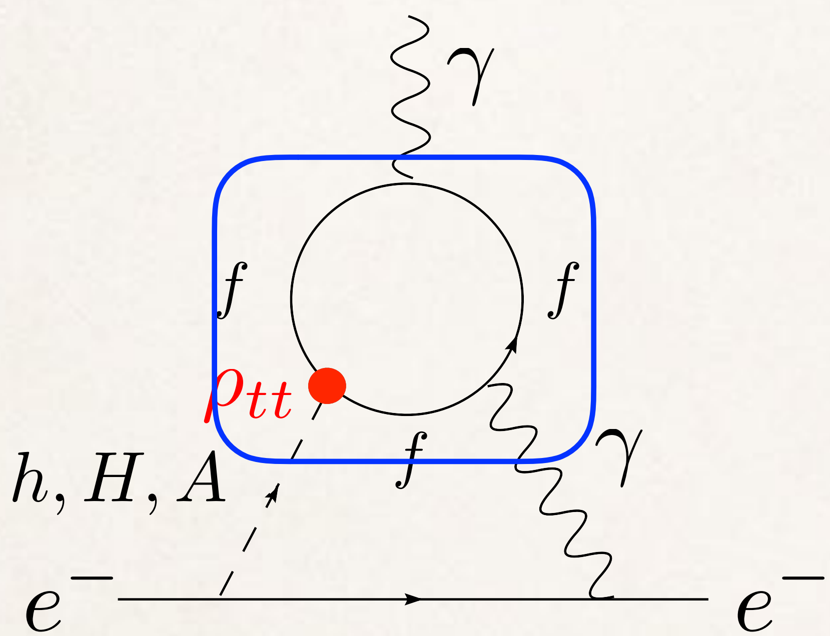

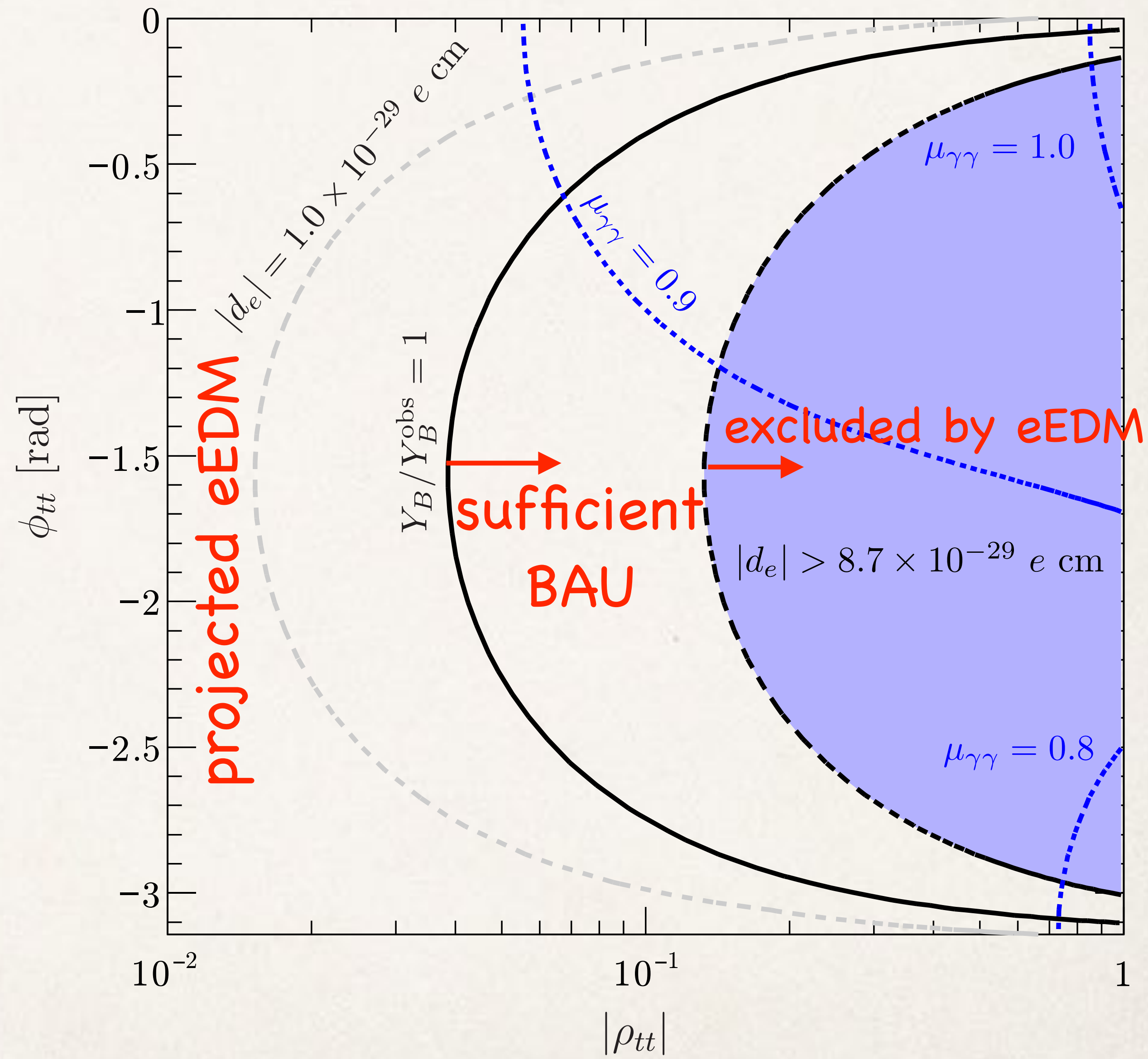

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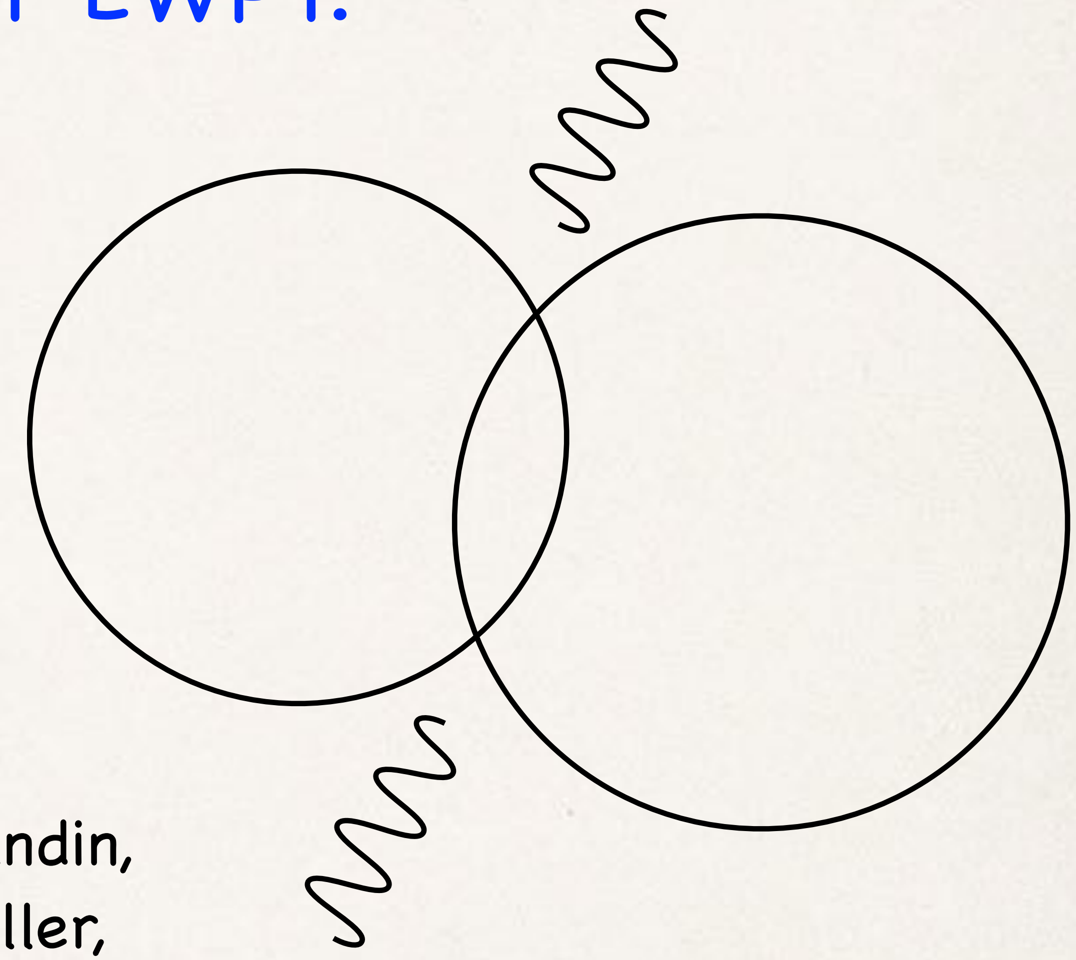
wayout: cancellation can happen if extra CP phases exist.

Gravitational Waves from 1st-order EWPT

GWs are induced by the 1st-order EWPT.

Sources of GW

(1) Bubble collisions,
(2) Sound waves,
(3) Turbulence



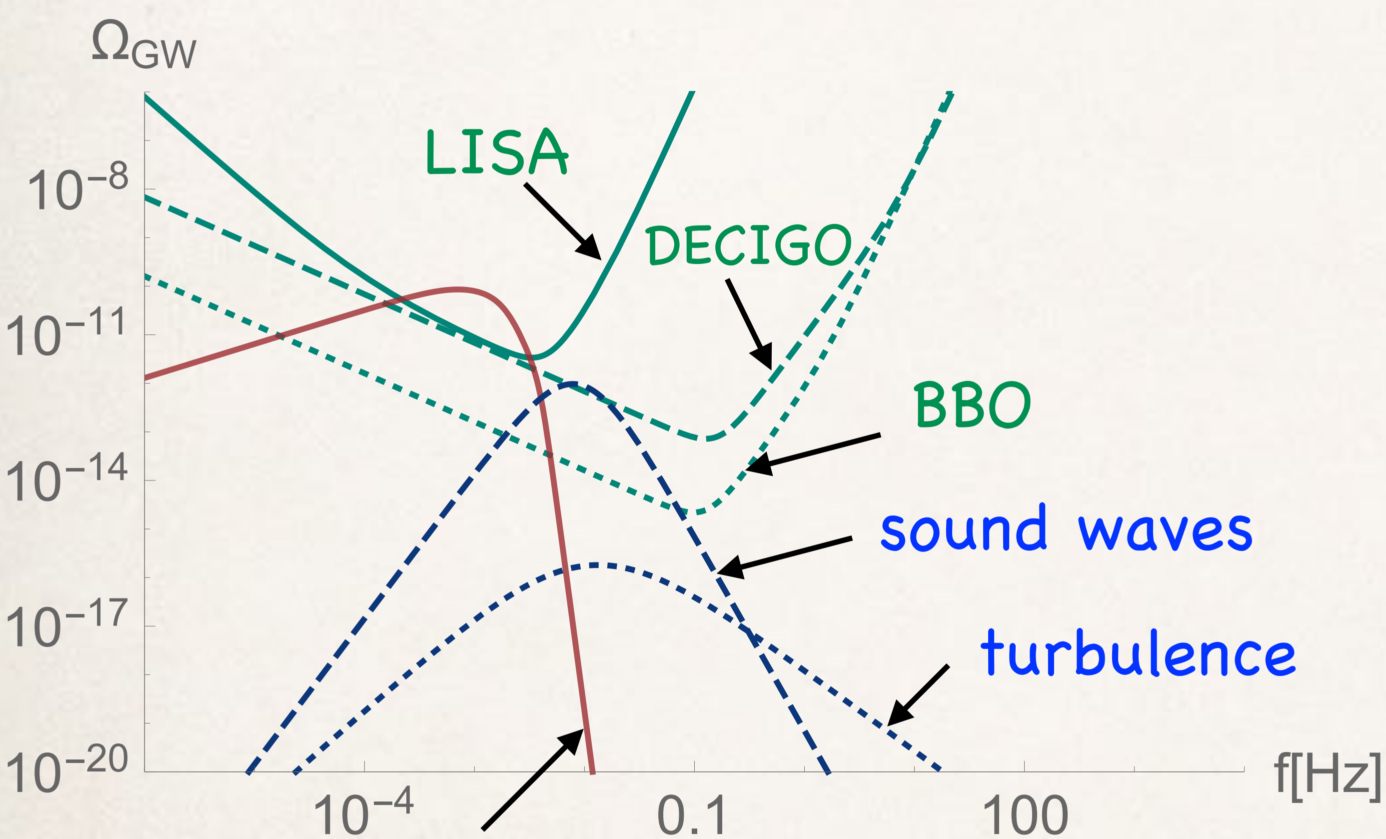
See Ref.[C.Caprini, M.Hindmarsh, S.Huber, T.Konstandin, J.Kozaczuk, G.Nardini, J.M.No, A.Petiteau, P.Schwaller, G.Servant, 1512.06239(JCAP)]

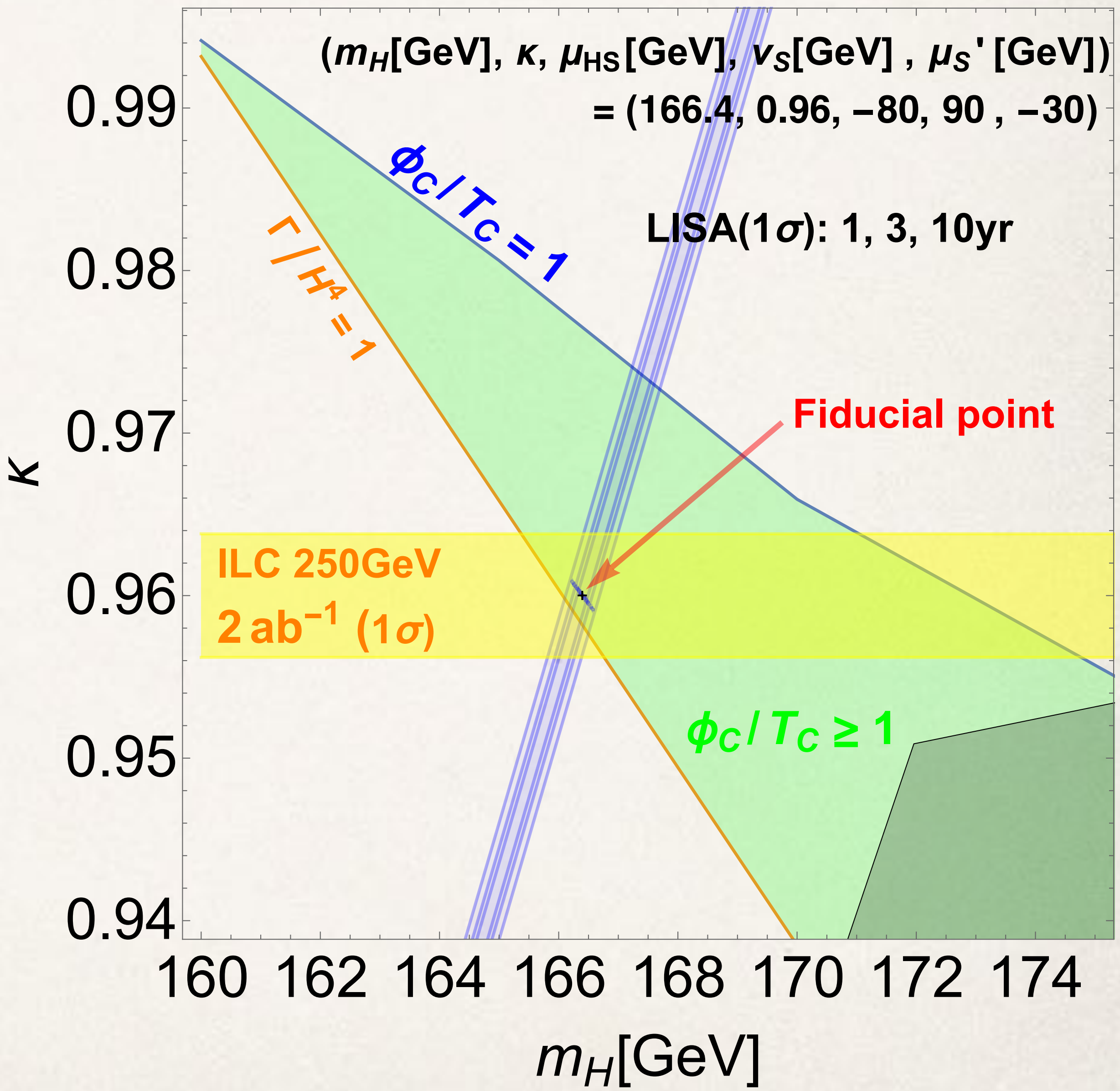
- GWs play a complementary role in probing Higgs sector.

Gravitational Waves from 1st-order EWPT

[K.Hashino, R.Jinno, M.Kakizaki, S.Kanemura, T.Takahashi, M.Takimoto, 1809.04994]

e.g. SM+S





GWs also provide exquisite probes of the Higgs sector!!

Remaining issues

EWBG calculation is subject to a lot of uncertainties.

(1) Electroweak phase transition

- Standard perturbative treatment of v_C/T_C is gauge-dependent.
- Necessity of refined (gauge-inv.) thermal resummation
- Bubble wall profile (width, velocity)

(2) Sphaleron

- Refinement of $\Gamma_B < H$

(3) BAU calculation   Closed-time-path formalism

- Beyond the VEV insertion approximation
- Beyond derivative expansion (more challenging)

Summary

EWBG was tested, is being tested and will be tested.

(1) $\Gamma_B < H$ ($v_C/T_C \gtrsim 1$) plays an important role.

$$\Rightarrow \quad \min < \left| \frac{\delta g}{g^{\rm SM}} \right| < \max$$

Higgs spectrum — constrained by exp. data

*details are model dependent

Higgs sector = "Alignment without decoupling"

(2) CP violation & BAU

- BAU-related CPV = CPV btw bubble wall (VEV) & particles

eEDM bound (ACME18) is overwhelmingly stringent.

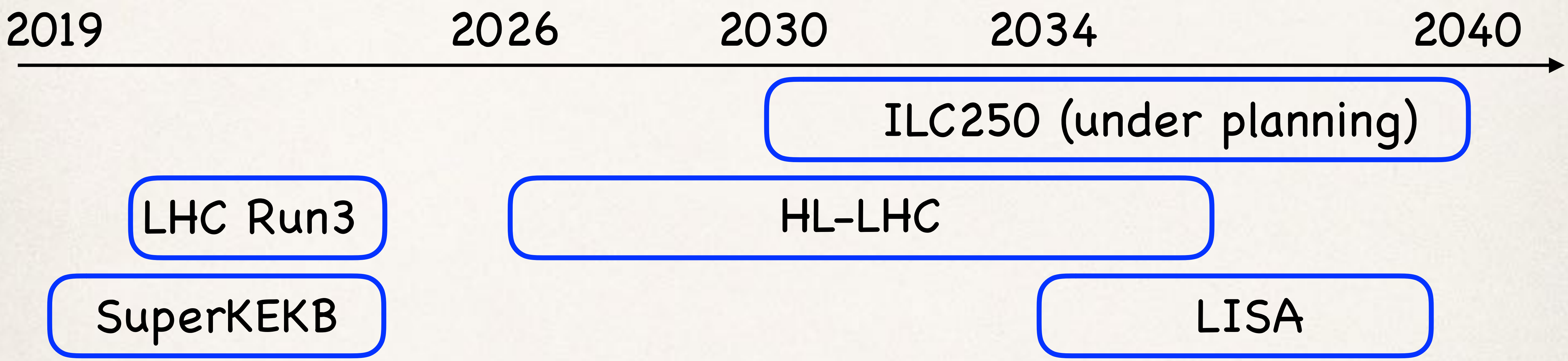
- BAU is still order-of-magnitude estimate,

but is in the right ballpark $\sim 10^{-10}$ within theoretical uncertainties.

Very encouraging!!

Golden Age

Golden Age (2030's) is coming soon!!



+ EDM experiments:
  - electron EDM (ACME, JILA, etc)
  - proton EDM (IBS-CAPP, BNL, etc)

EWBG would be completely tested!!

Backup

Review papers

- A.G. Cohen, D.B. Kaplan, A.E. Nelson, hep-ph/9302210
- M. Quiros, Helv.Phys.Acta 67 ('94)
- V.A. Rubakov, M.E. Shaposhnikov, hep-ph/9603208
- K. Funakubo, hep-ph/9608358
- M. Trodden, hep-ph/9803479
- A. Riotto, hep-ph/9807454
- W. Bernreuther, hep-ph/0205279

BAU-related CPV

Suppose we have 2 Higgs doublets and 2 EW-interacting fermions (ψ).

ψ_i: Dirac fermion

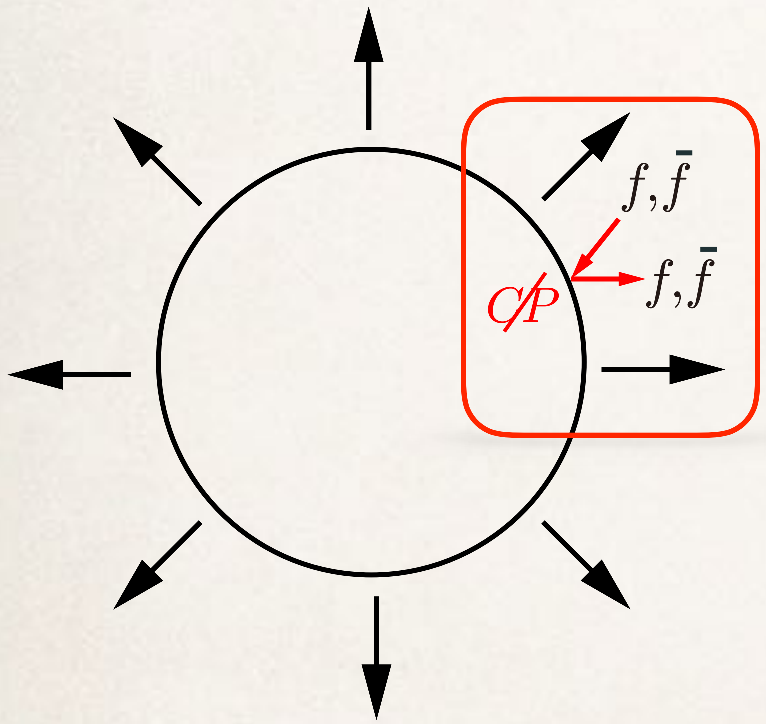
ψ_j: Majorana fermion

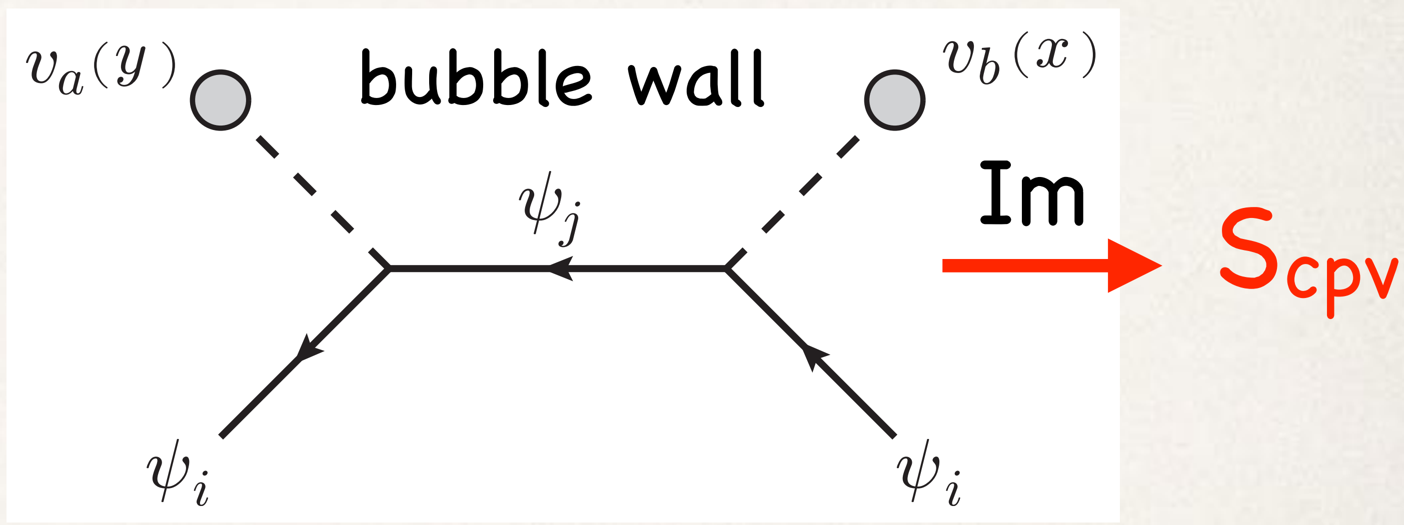
e.g.

Bino-driven EWBG,

Singlino-driven EWBG

$$\mathcal{L} = \frac{1}{\sqrt{2}}\bar{\psi}_i(c_L v_a P_L + c_R v_b P_R)\psi_j + \text{h.c.}$$





$$n_B \propto S_{\rm CPV} = C_{\rm BAU}\,{\rm Im}(c_L c_R^*)$$

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complex parameters

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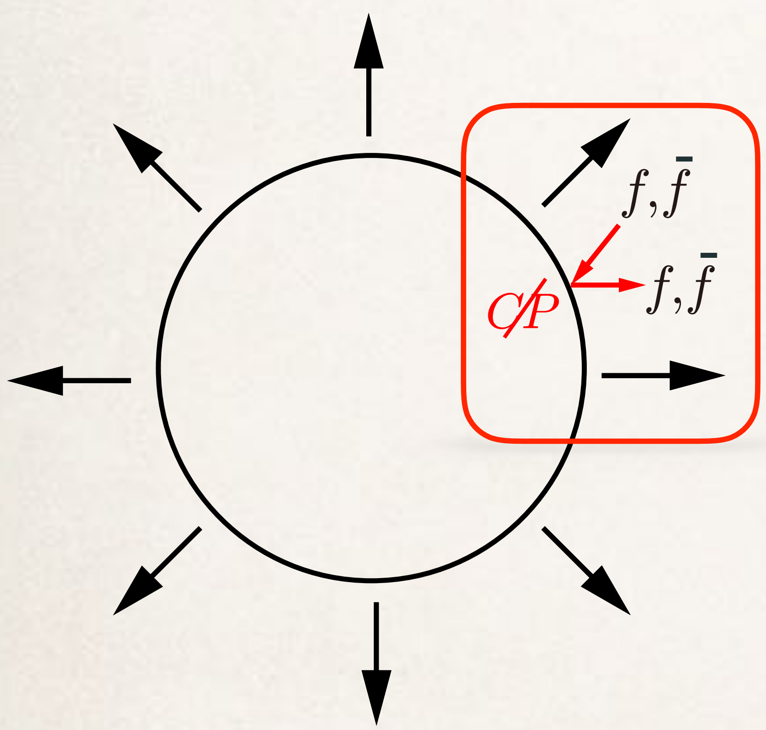
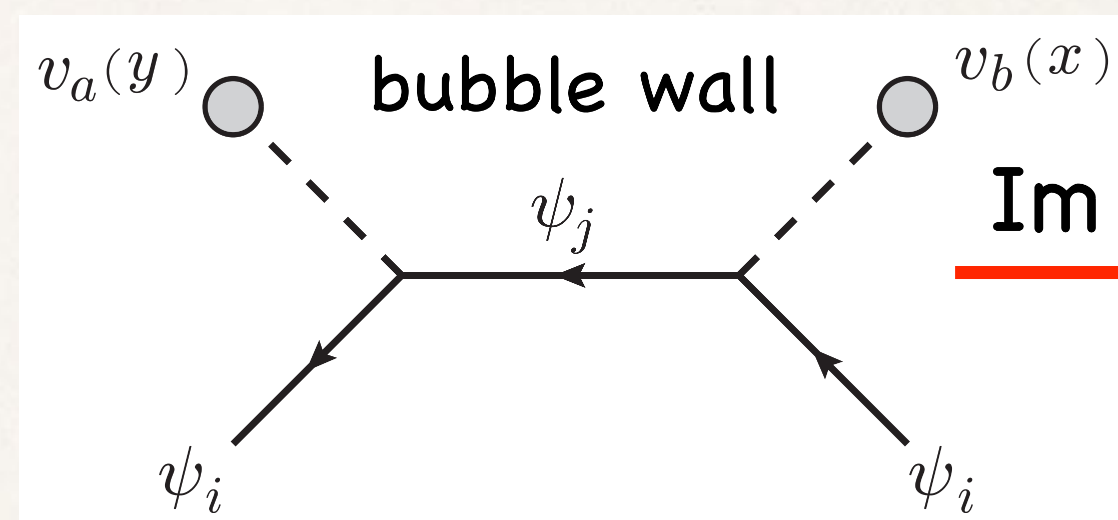


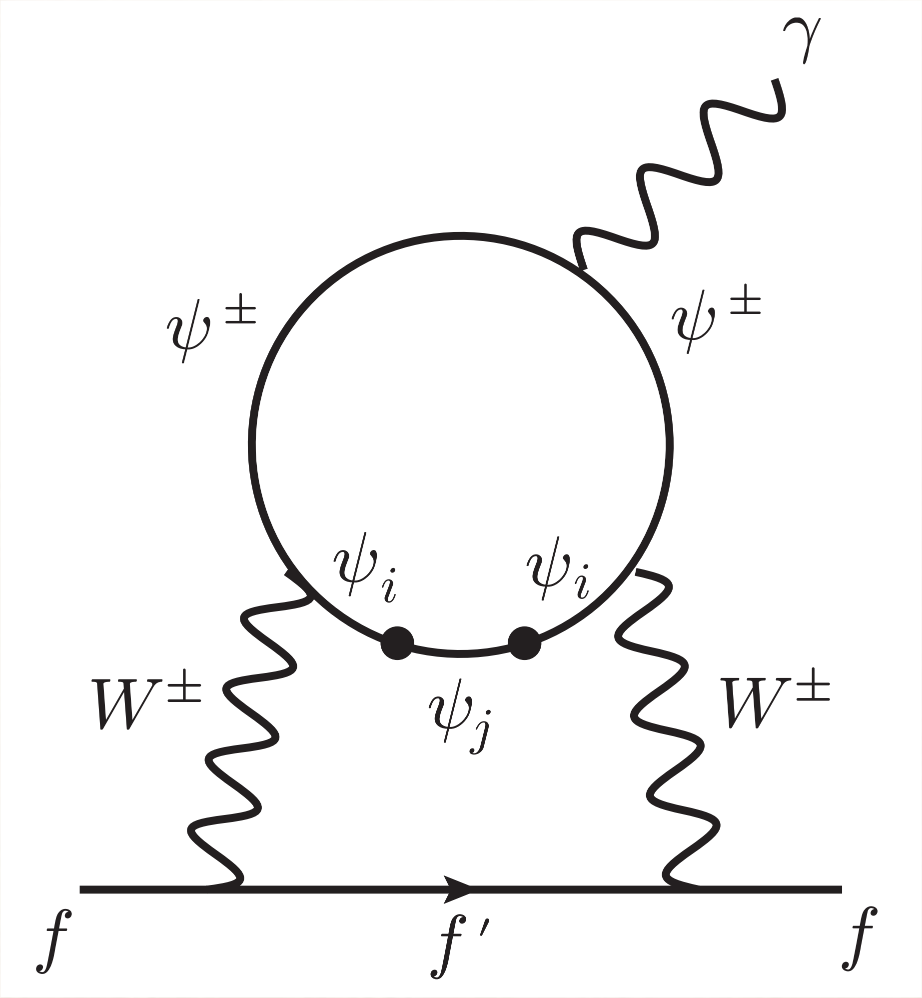


S_{cpv}

$$n_B \propto S_{\text{CPV}} = C_{\text{BAU}}\text{Im}(c_L c_R^*)$$

Electric Dipole Moments (EDMs)

The same CP-violating phase induces the following Barr-Zee diagram.



$$\mathcal{L} = \frac{g}{\sqrt{2}}\left(\overline{\psi^+}\gamma^\mu\psi_i W^+_\mu + \overline{\psi}_i\gamma^\mu\psi^+ W^-_\mu\right)$$

$$\frac{d_f^{WW}}{e} = C^{WW}_{\rm EDM}\,{\rm Im}(c_L c_R^*)$$

Therefore, S_{cpv} is linearly correlated with EDM.

$$S_{\rm CPV} = \frac{C_{\rm BAU}}{C^{WW}_{\rm EDM}}\left(\frac{d_f^{WW}}{e}\right)$$

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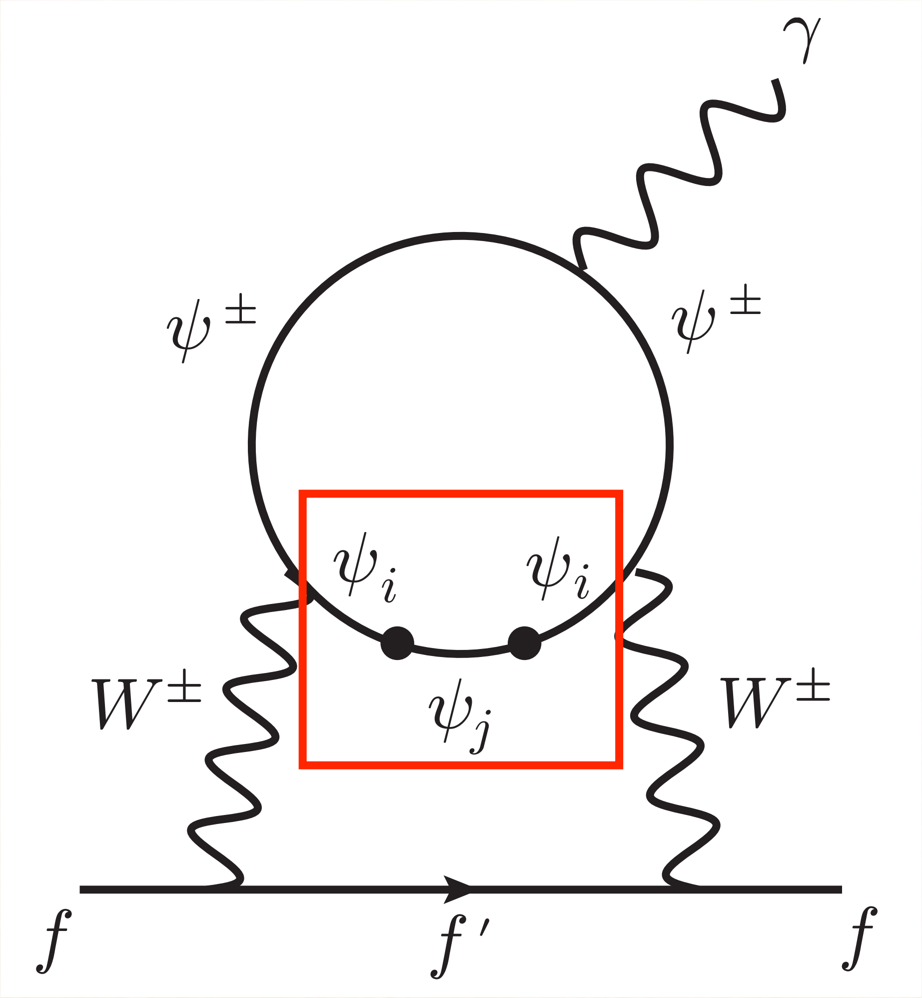

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Extra fermion-driven EWBG

[K. Fuyuto, J. Hisano, E.S., 1510.04485 (PLB)].

Next-to-MSSM-like model

particles	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Z_2
Φ_1	$(\mathbf{1},\ \mathbf{2},\ 1/2)$	$-$
Φ_2	$(\mathbf{1},\ \mathbf{2},\ 1/2)$	$+$
S	$(\mathbf{1},\ \mathbf{1},\ 0)$	$-$
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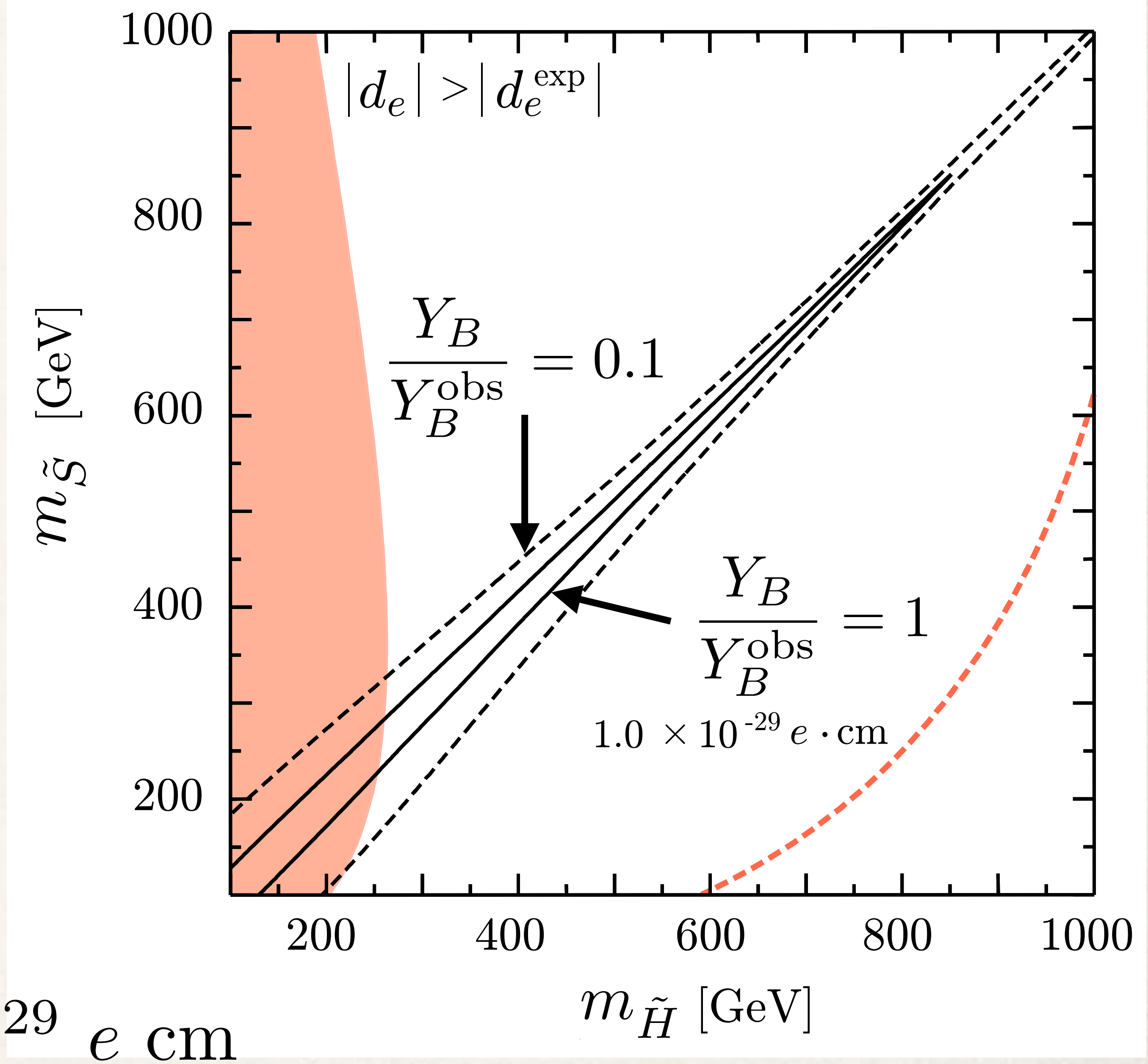

Case 1: BAU-related CPV dominantly exists.

current bound: $|d_e| < 1.1 \times 10^{-29}\ e\ {\rm cm}$

[ACME, Nature 562,355(2018)]

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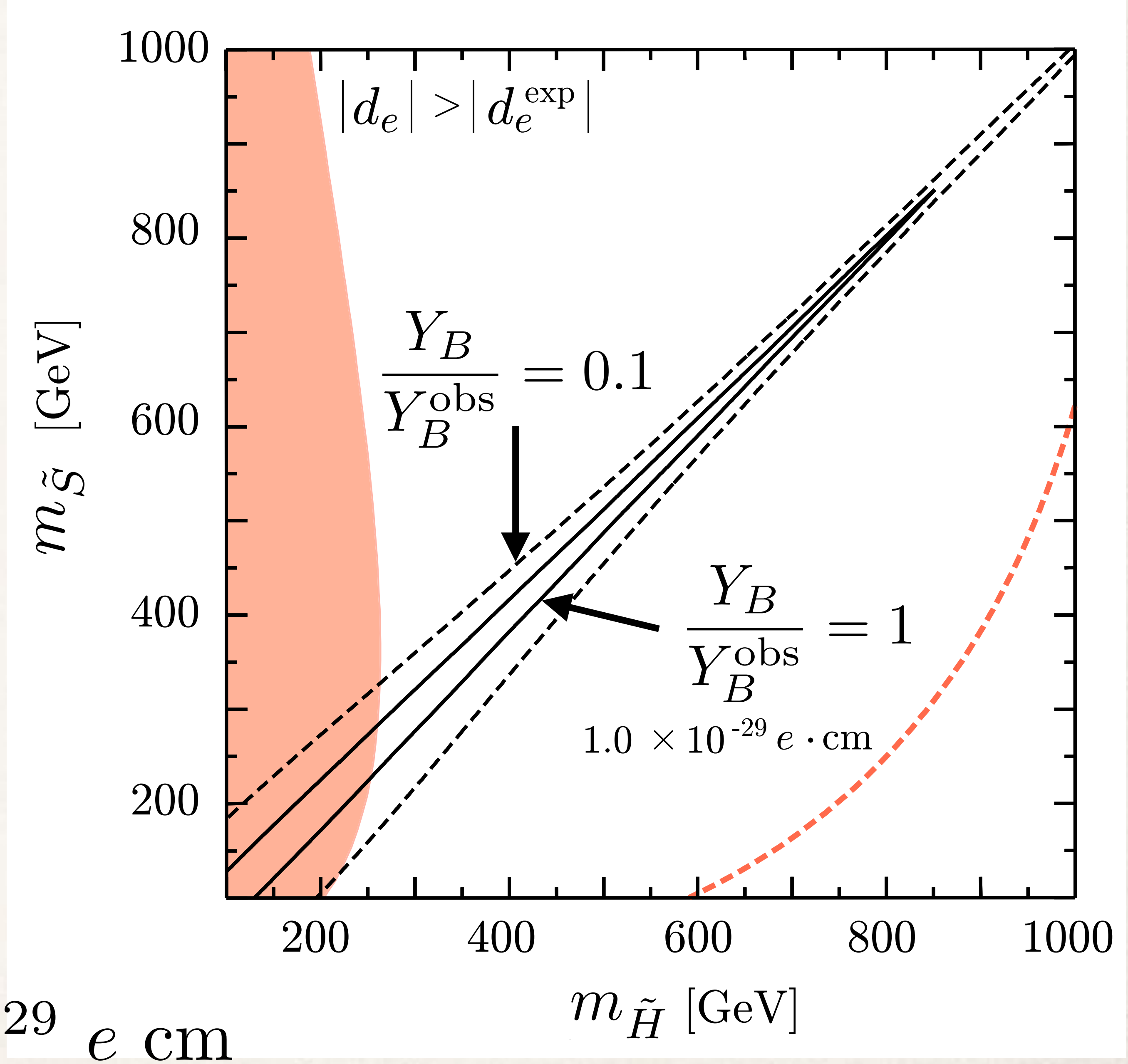

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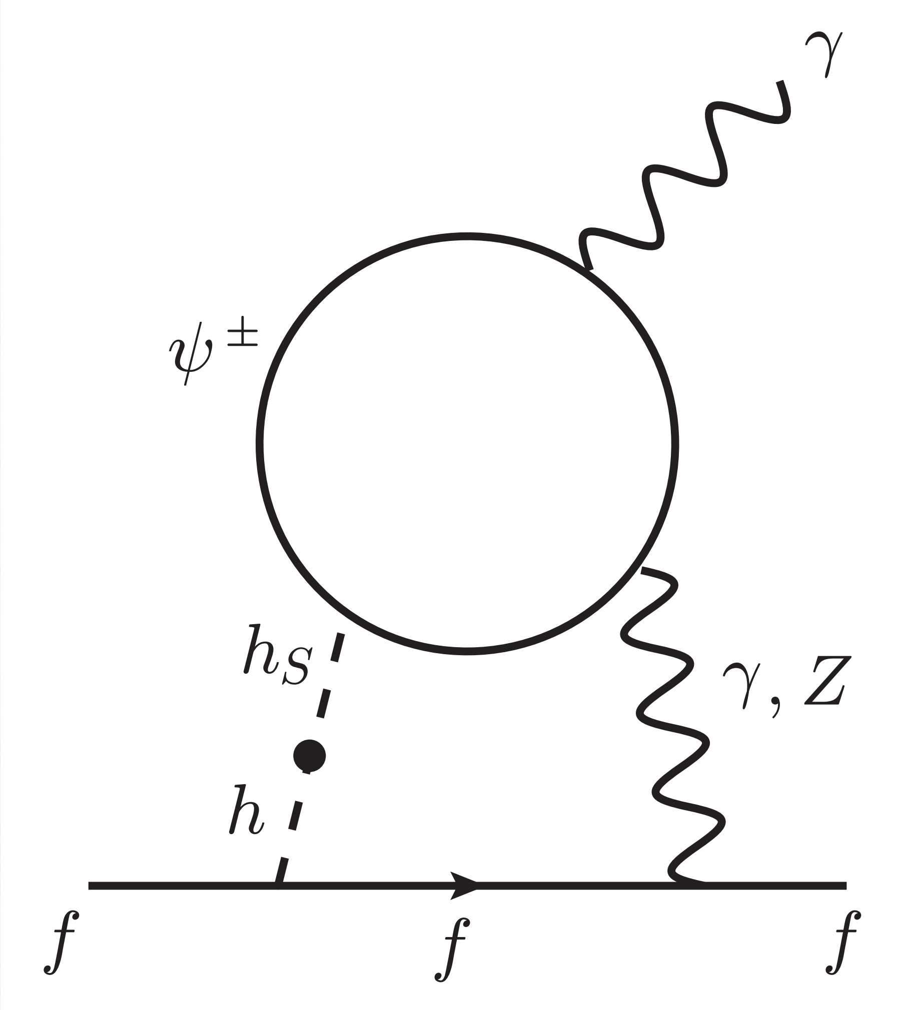
However, this can be avoided if a cancellation mechanism is at work.

BAU-unrelated CP violation

- If strong 1st-order EWPT is realized due to the presence of singlet Higgs, another CPV can come into play.



$$\mathcal{L} = \overline{\psi^+}(g^S + i\gamma_5 g^P)\psi^+ S$$

Nonzero doublet-singlet Higgs mixing induces another Barr-Zee diagram.

$$d_f^{\rm sum} = d_f^{WW} + d_f^{H\gamma} + d_f^{HZ}$$

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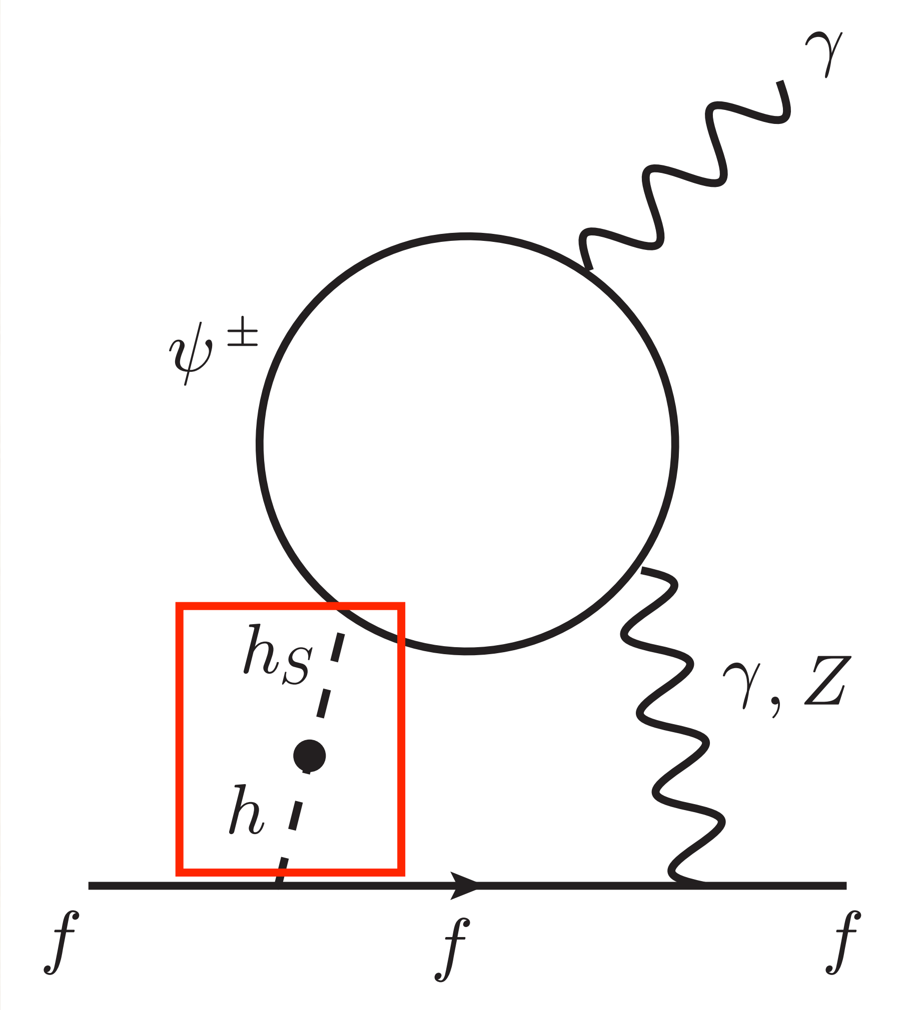

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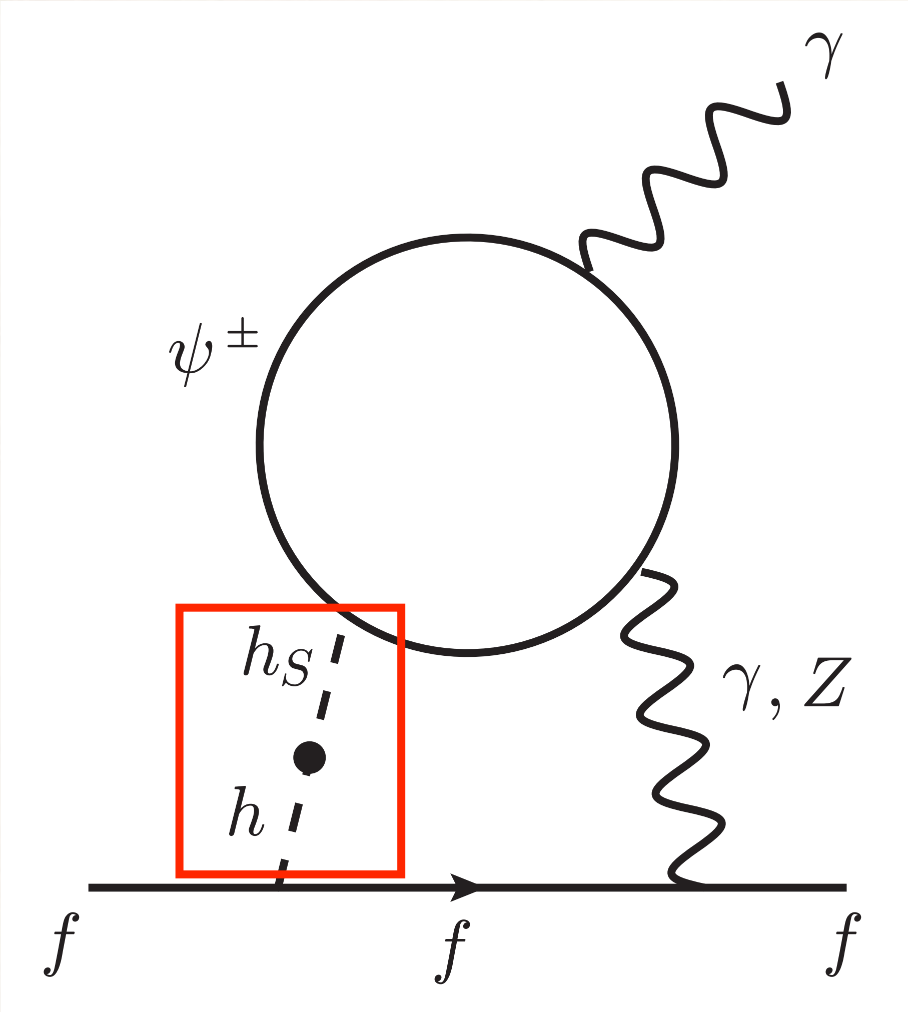

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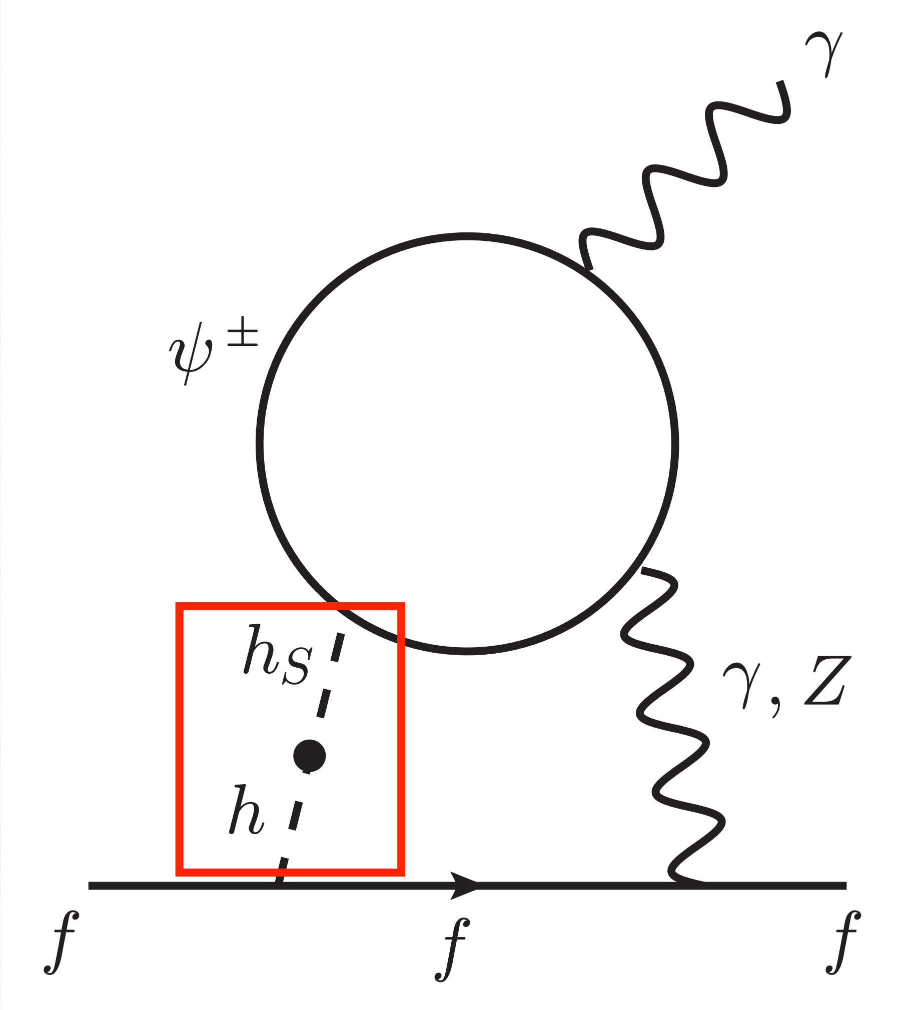

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BAU-related CPV | BAU-unrelated CPV

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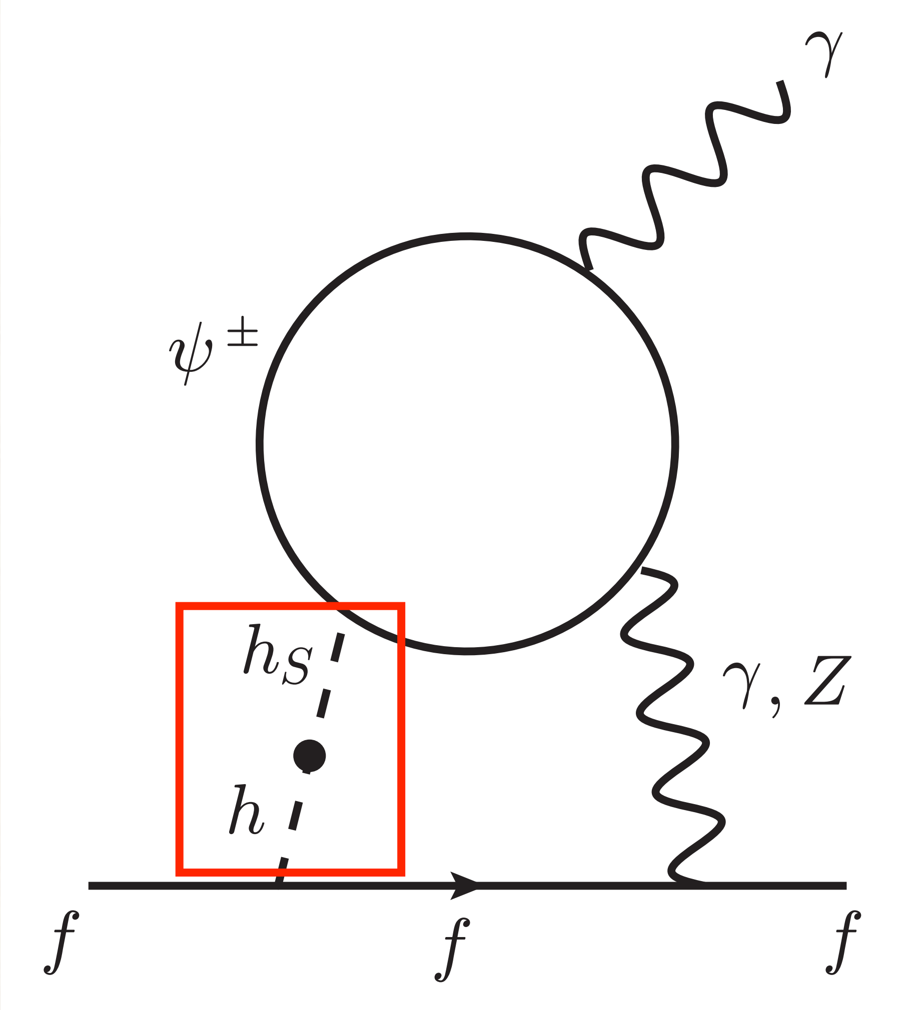

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BAU-related CPV　BAU-unrelated CPV

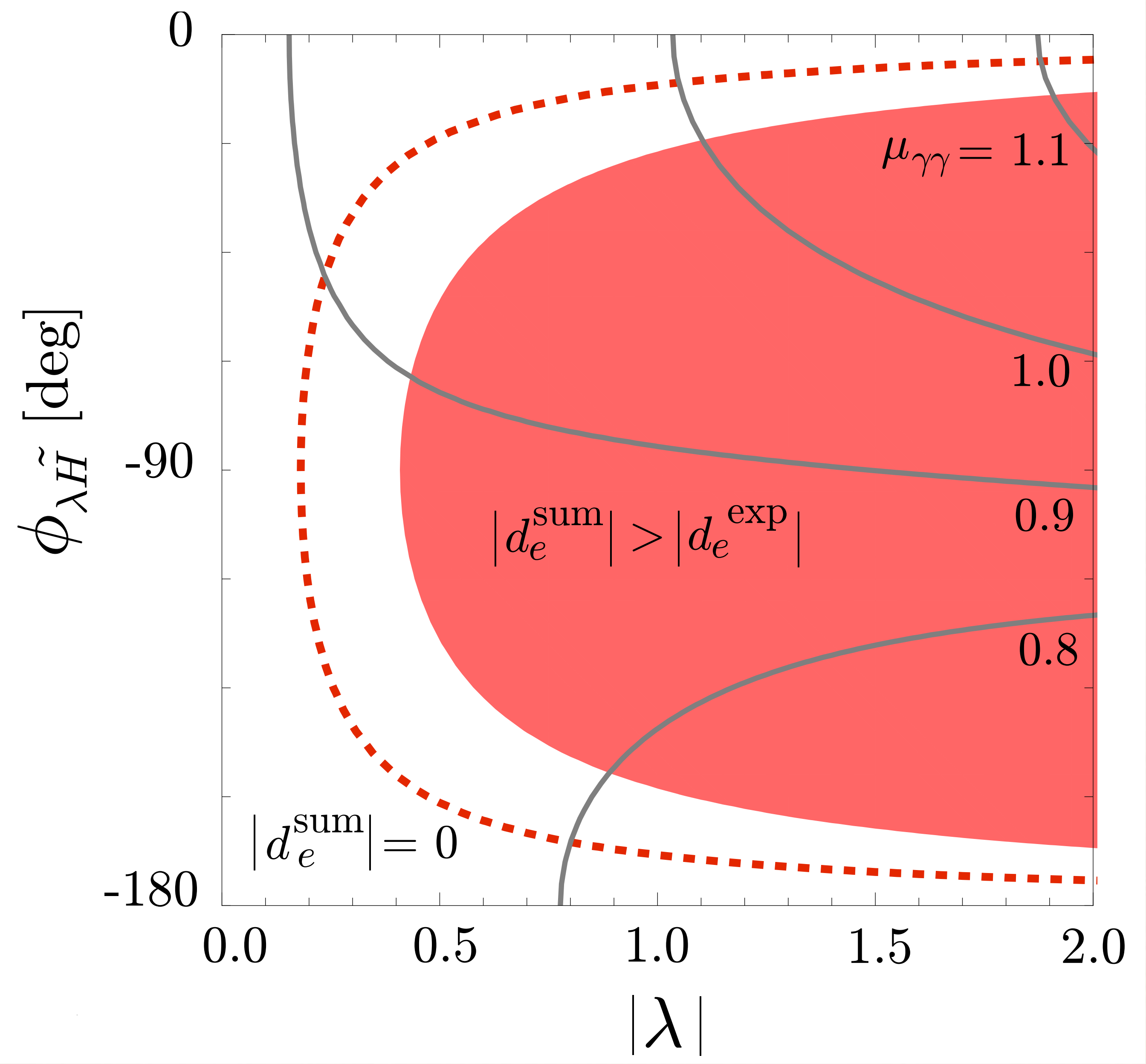
$$d_f^{\rm sum} = \boxed{d_f^{WW}} + \boxed{d_f^{H\gamma} + d_f^{HZ}}$$

cancellation could happen!!

- Linear correlation between $S_{\rm cpv}$ and EDM is lost.

Impact of BAU-unrelated CPV

[K. Fuyuto, J. Hisano, E.S., 1510.04485 (PLB)].



Case 2: BAU-unrelated CPV comes into action.

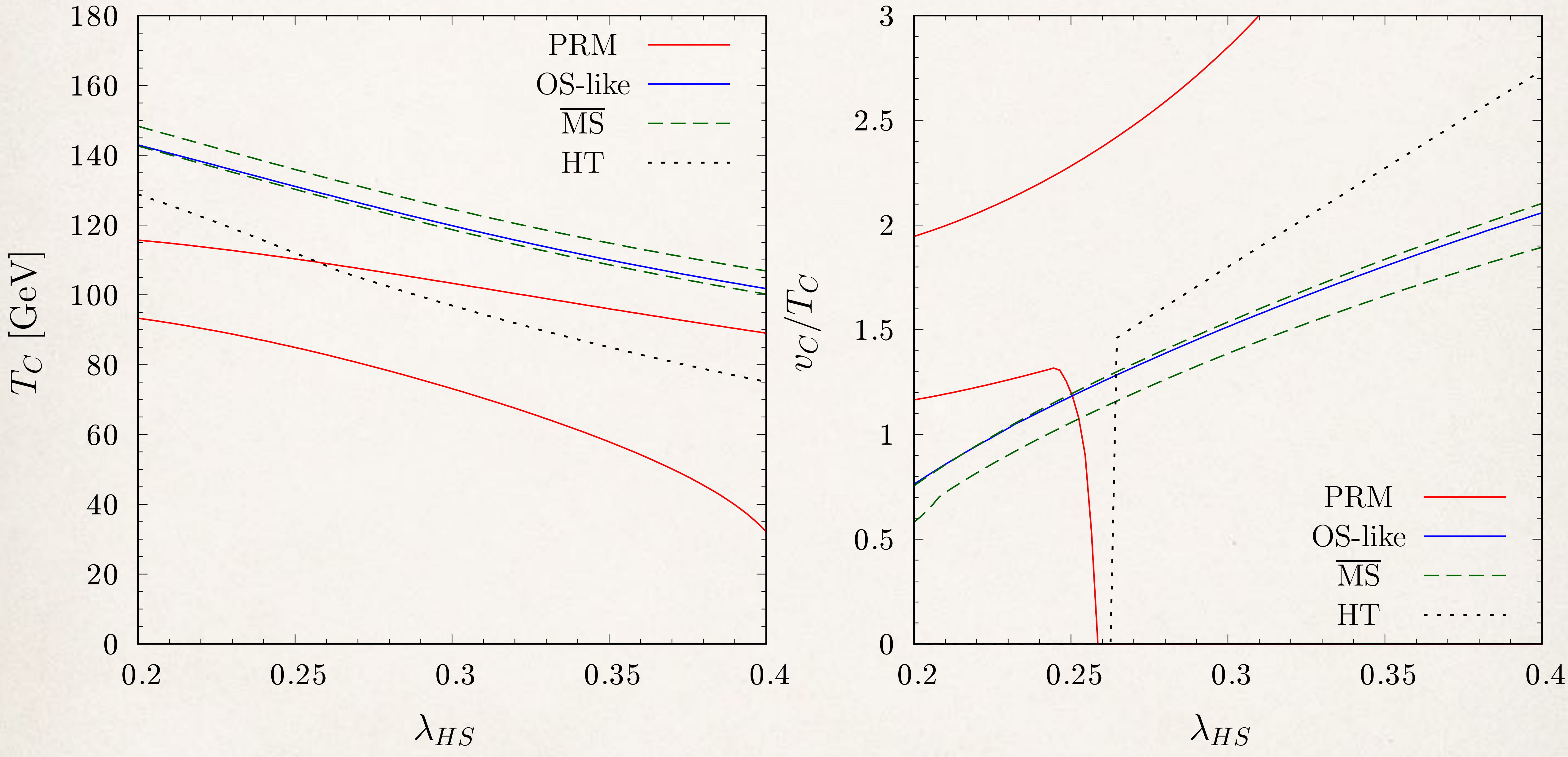
$$d_e^{\rm sum} = d_e^{WW} + d_e^{H\gamma} + d_e^{HZ}$$

$\mu_{\gamma\gamma}$: signal strength of h(125) -> γγ

- Electron EDM can be zero due to the cancellation.
- But still testable with the help of Higgs physics.

Scheme dependences in SM+S w/Z_2

C-W Chiang, Y-T. Lee, E.S., 1808.01098



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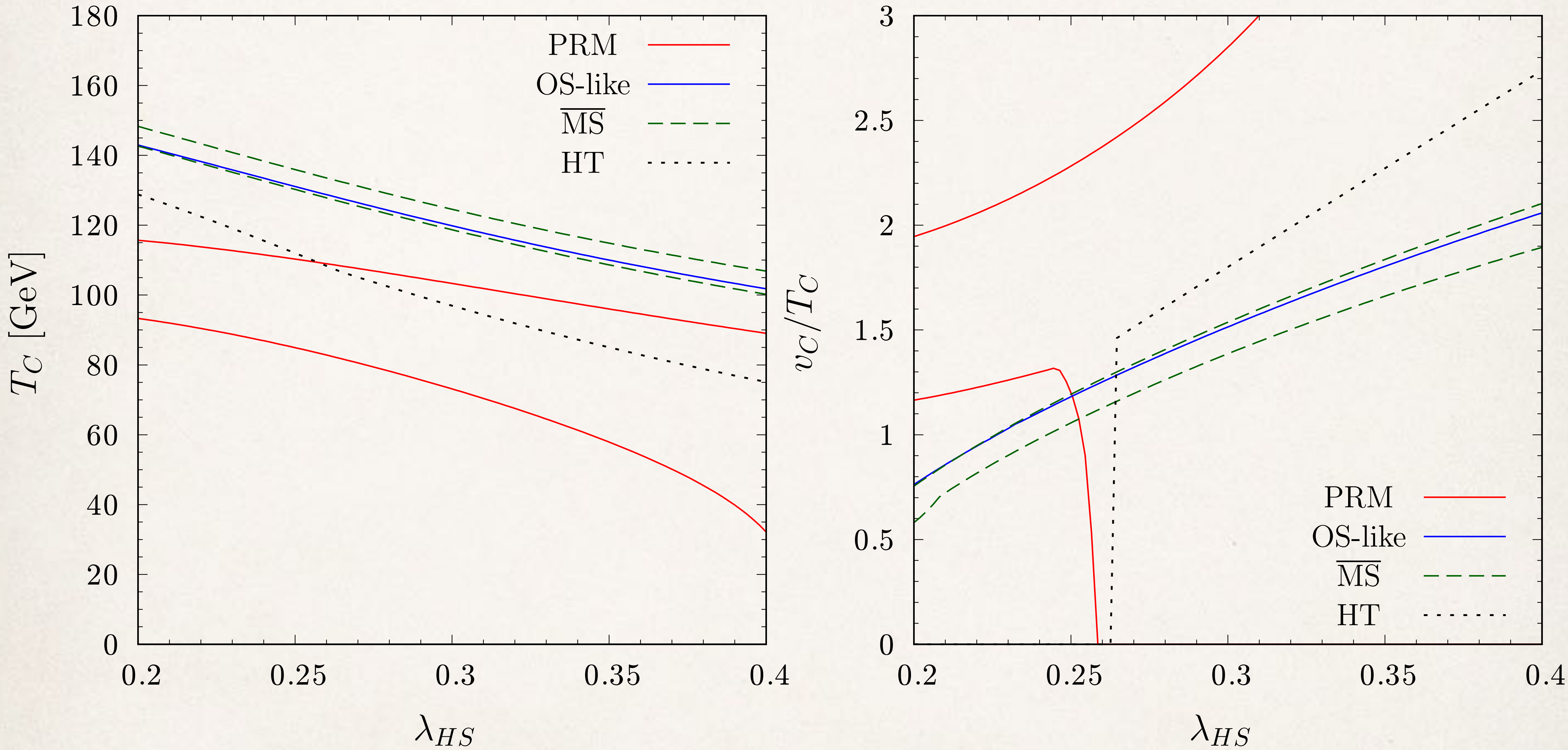

- All the schemes are qualitatively consistent.

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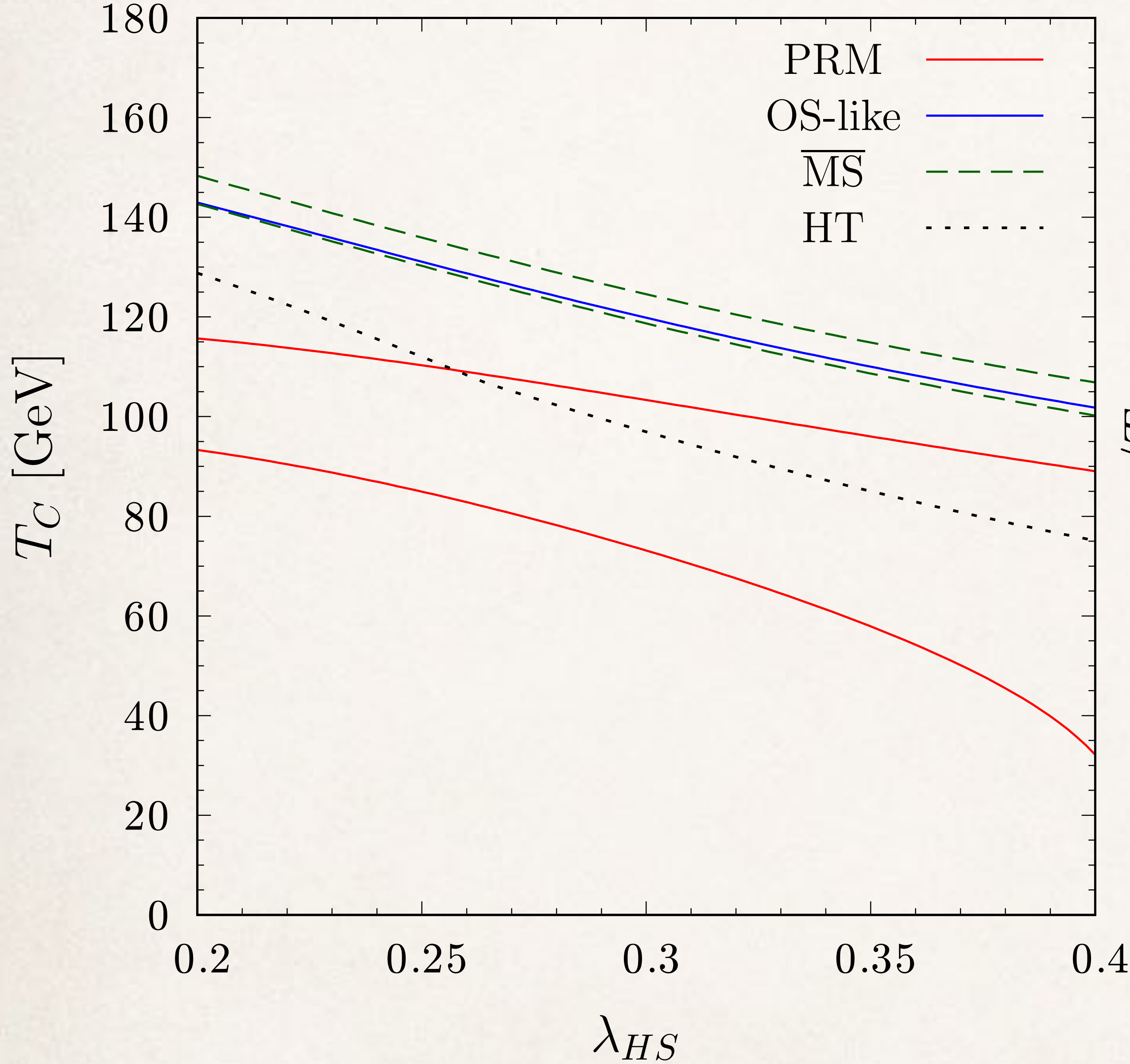
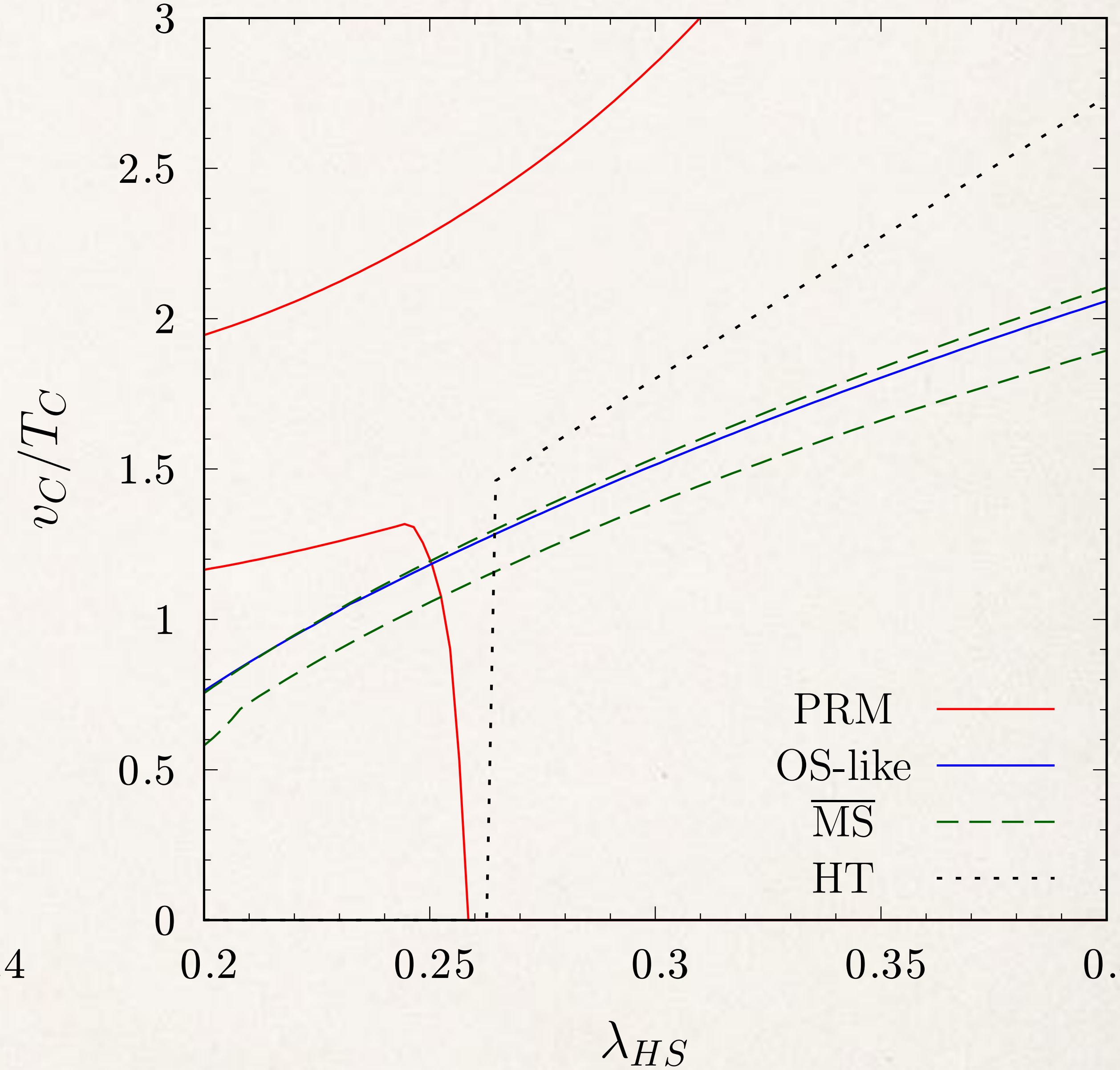




- All the schemes are qualitatively consistent.
- Higher order corrections are necessary for quantitative studies.

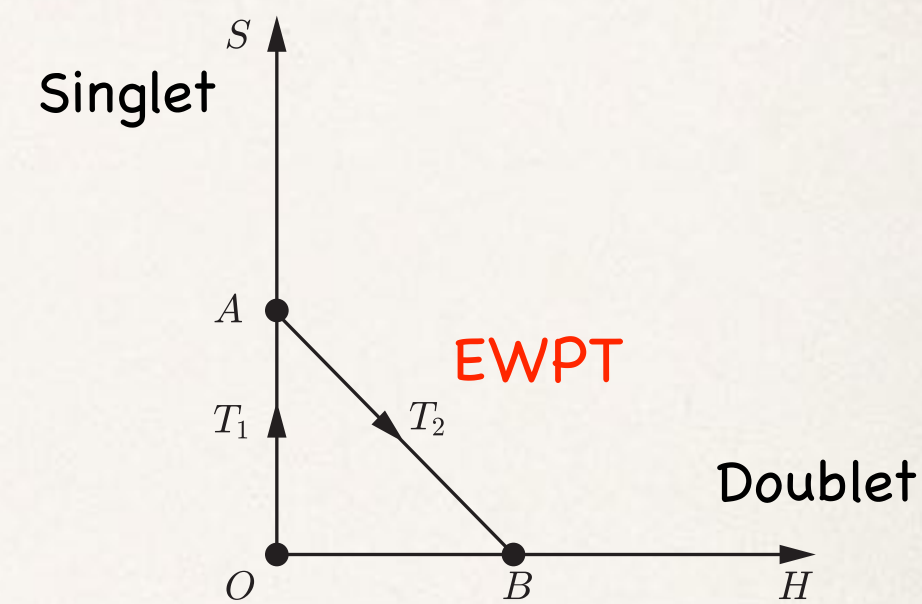
2-step PT

2 step PT expands EWBG possibilities. [Funakubo et al, PTP114 (2005) 369.]

- Phase transitions occur twice.

1st: O -> A, 2nd: A -> B (EWPT).

This has to be 1st-order for EWBG.



Goodness of 2-step PT:

- Increase of λ_{HS} makes the vacuum energy of phase A smaller.

⟶ T_C ($T@E_A=E_B$) gets lowered.

⟶ v_C/T_C ↗