拡張ヒッグス模型と電弱相転移

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東京女子大学セミナー　2024年11月21日

Plan to talk

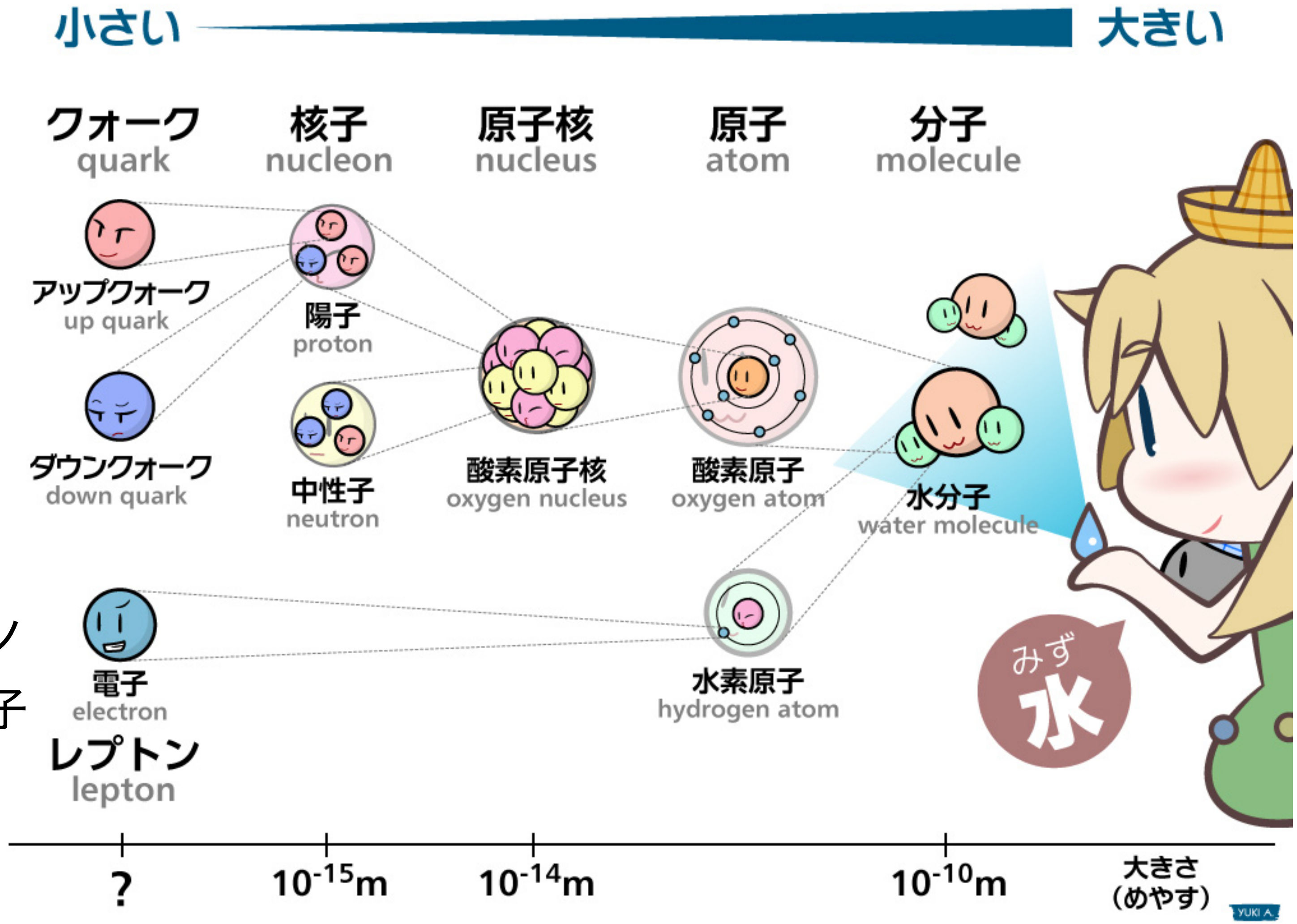
- イントロダクション
  - 電弱相転移
- Two Higgs doublet model
- Two Higgs doublet modelの電弱相転移
- 研究紹介(Exotic intermediate phases)

  MA, Biermann, Borschensky, Ivanov, Mühlleitner, Shibuya,
  JHEP 02 (2024) 232

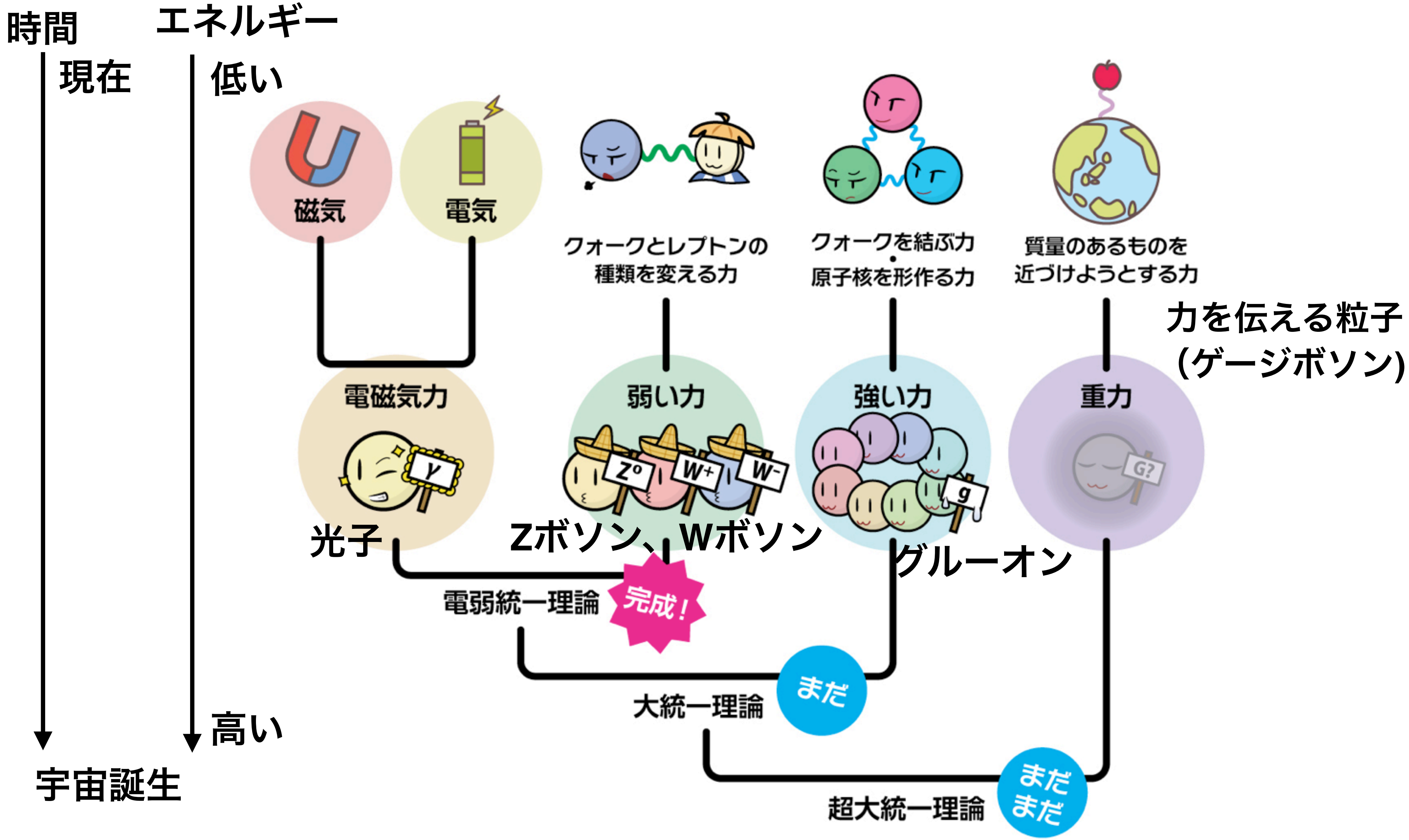
素粒子

* クォークや電子など、物質を構成する最小単位となる粒子のこと

他に、
光子
ニュートリノ
ヒッグス粒子
など



力の統一

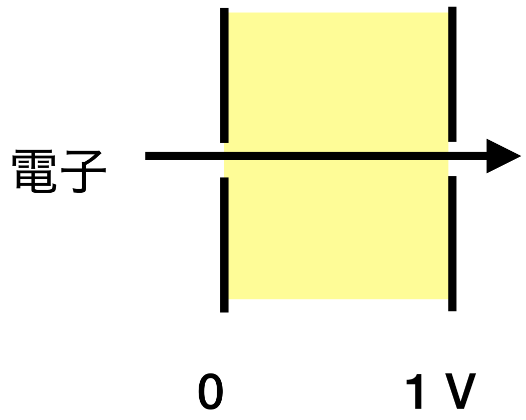


時間
現在
宇宙誕生
エネルギー
低い
高い
磁気
電気
クォークとレプトンの
種類を変える力
クォークを結ぶ力
・
原子核を形作る力
質量のあるものを
近づけようとする力
力を伝える粒子
(ゲージボソン)
電磁気力
γ
光子
弱い力
Z0
W+
W-
Zボソン、Wボソン
強い力
g
グルーオン
重力
G?
電弱統一理論
完成！
大統一理論
まだ
超大統一理論
まだ
まだ

単位とスケール

・eV (電子ボルト)

1[eV] = e[C]×1[V] = 1.6×10^{-19}[J]



・自然単位系を用いる。 $c = 1, \quad \hbar = 1$

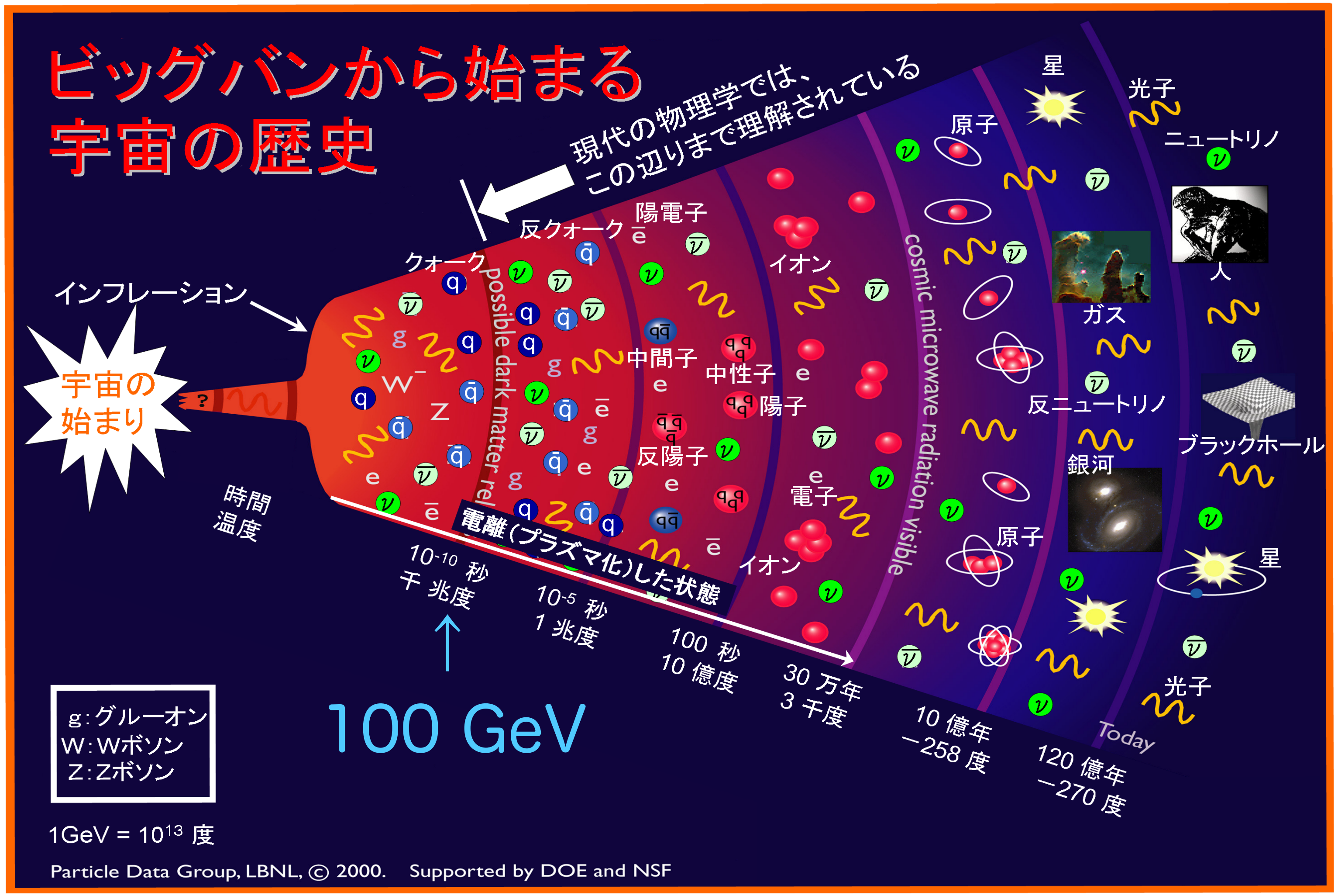
質量、エネルギー、運動量が同じ単位で表せる。

[長さ] = 1/[エネルギー]

ミクロの世界は、高エネルギーの世界

初期宇宙の世界

単位とスケール



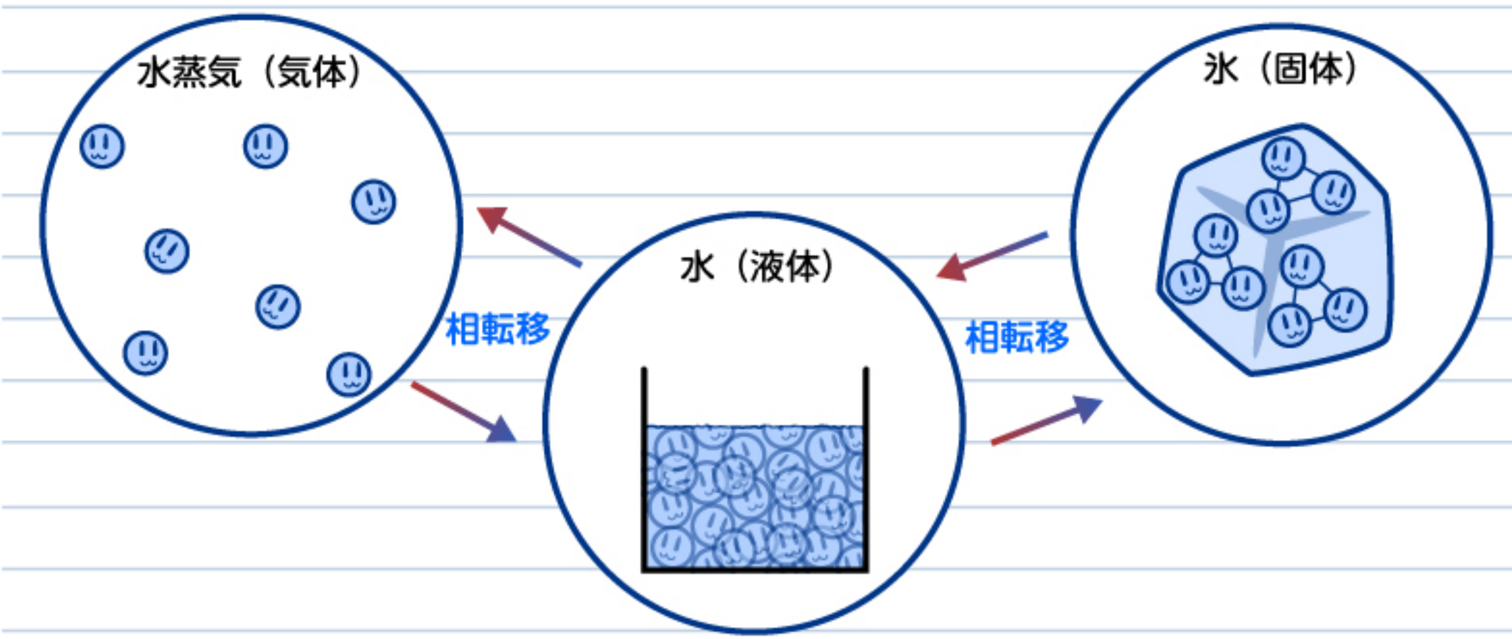
現在：2.7 K
”ゼロ温度の宇宙”

10^{12}	T	テラ
10^{9}	G	ギガ
10^{6}	M	メガ
10^{3}	k	キロ
10^{-3}	m	ミリ
10^{-6}	μ	マイクロ
10^{-9}	n	ナノ

$1\,\mathrm{eV} = 1.6^{-19}\mathrm{J}$ ～ **10000度**

相転移

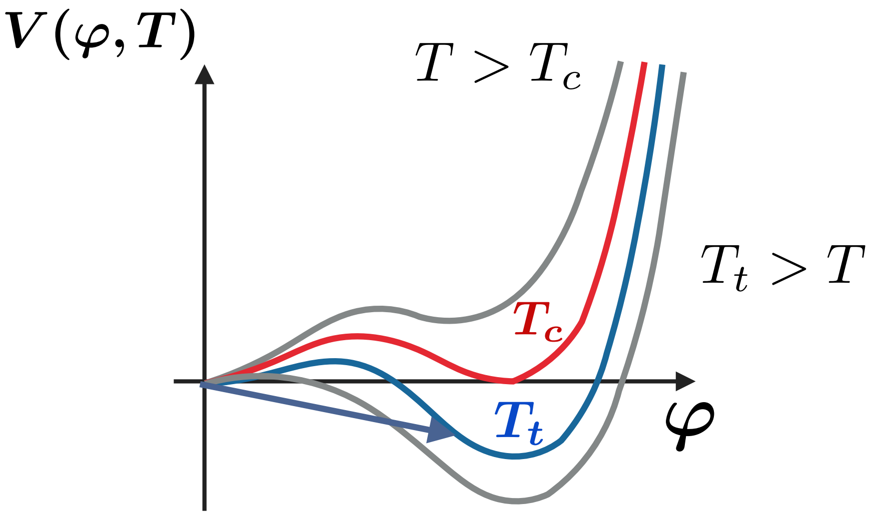
温度などを変えたとき、ミクロな性質は変わらないまま、マクロな性質が大きく変化すること。



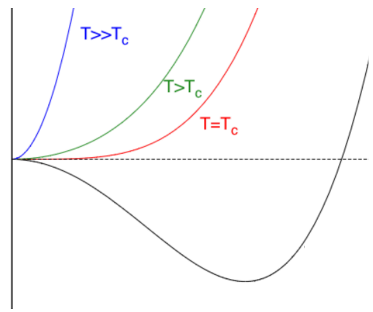
一次相転移

一次相転移 : ギブスエネルギーの一次微分が不連続

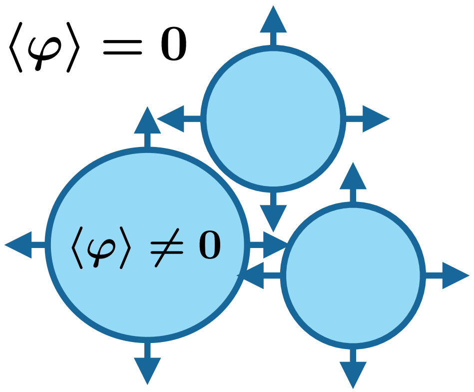
$$\left(\frac{\partial G}{\partial T}\right)_P = -S \qquad \left(\frac{\partial G}{\partial p}\right)_T = -V$$

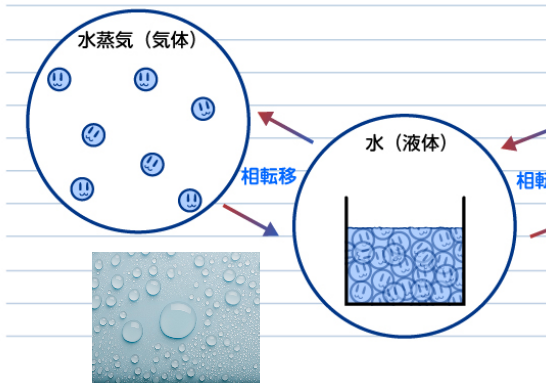


二次相転移



臨界温度 Tc, 相転移が起こる温度(核生成) Tt



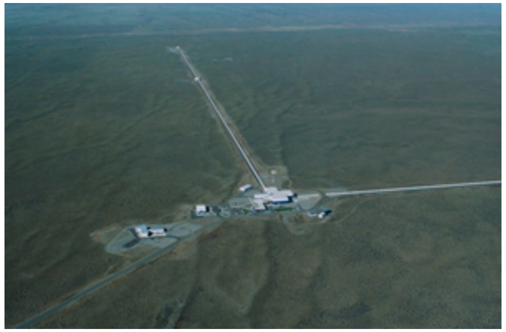


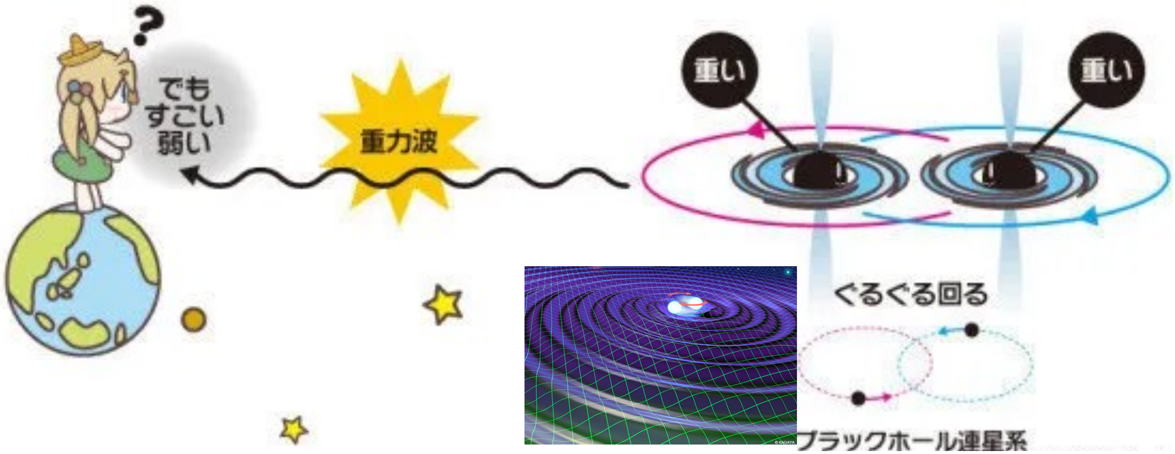
重力波

アインシュタインが提唱した一般相対性理論で予想された時空の歪みが伝搬する波動現象

- 2015年9月 重力波の初検出
  - レーザー干渉計重力波天文台（LIGO）

    太陽質量の数十倍の**BH-BH**連星の合体から生じたとされる重力波を初めて検出



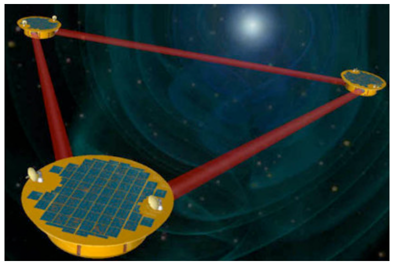


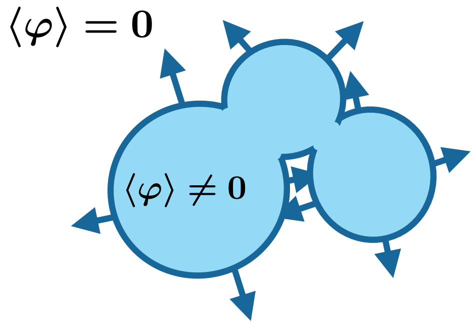
- **宇宙の一次相転移 背景重力波**

- **LISA** (Laser Interferometer Space Antenna)

  宇宙重力波望遠鏡

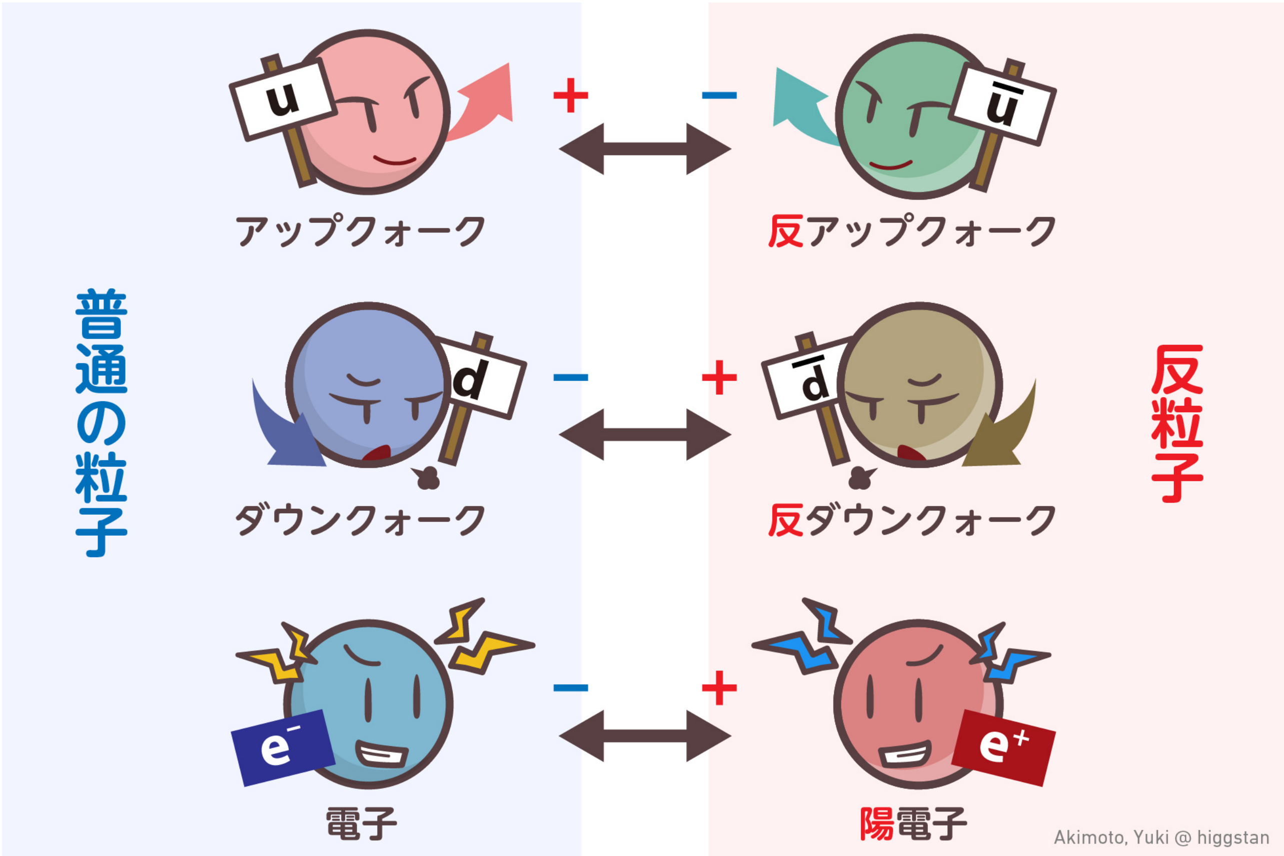
  - 欧州宇宙機関(ESA)が2035年打ち上げ予定
  - 基線長 約250万km



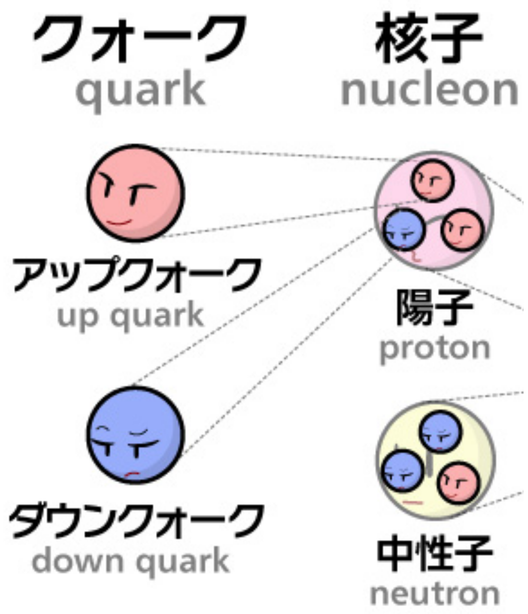


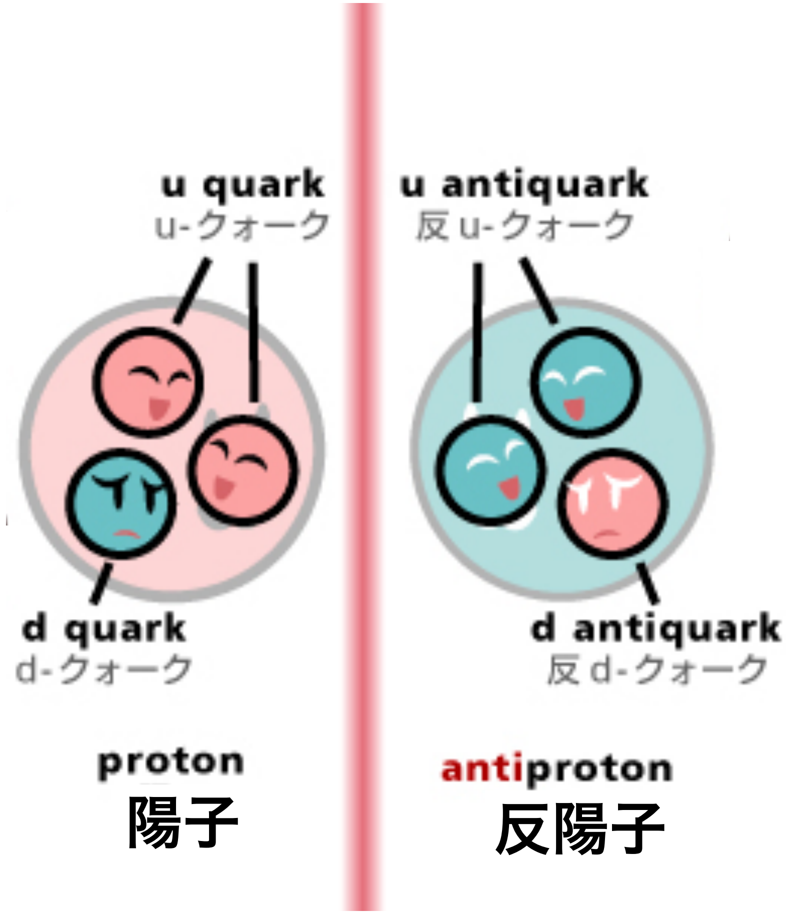
消えた反物質

- なぜ宇宙は「物質」だけでできているのか? というのが問題



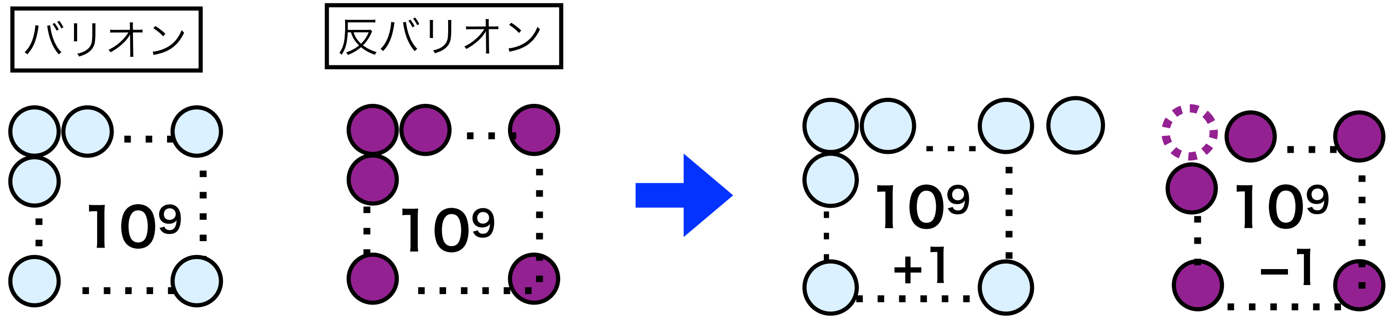
消えた反物質



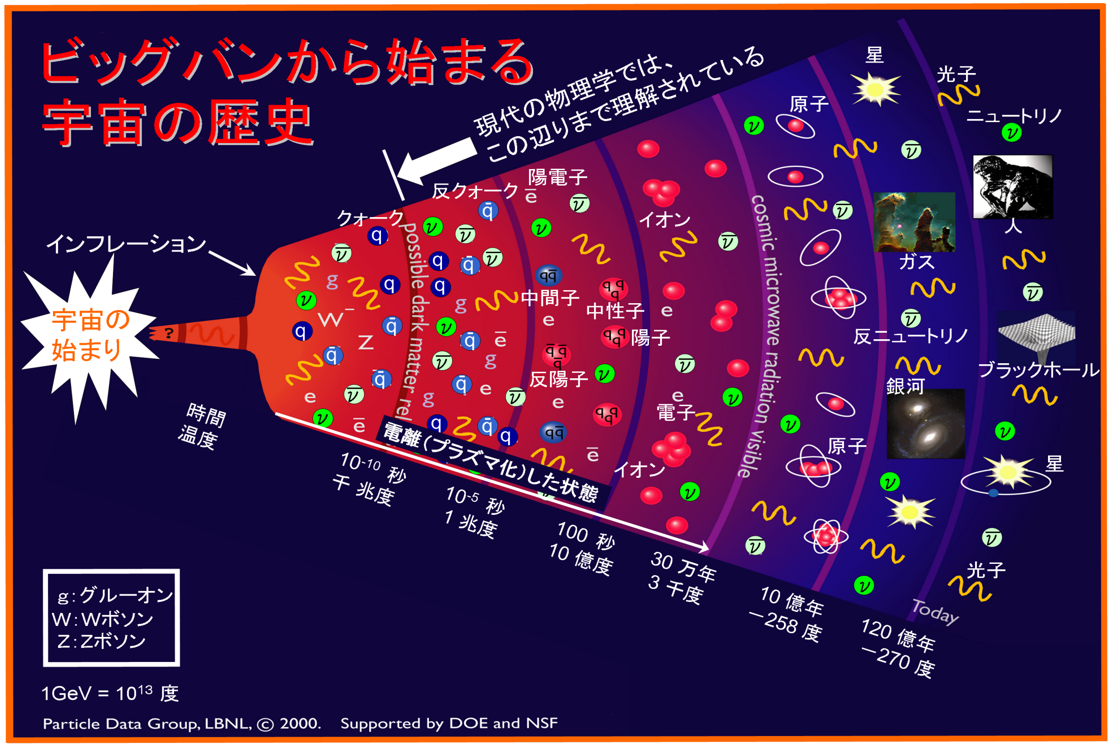


バリオン　　反バリオン

消えた反物質



10億個　　10億個



消えた反物質

物質と反物質の非対称性を生成するための条件

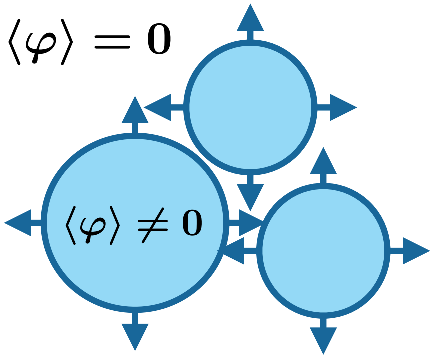
サハロフの3条件 Sakharov (1967)

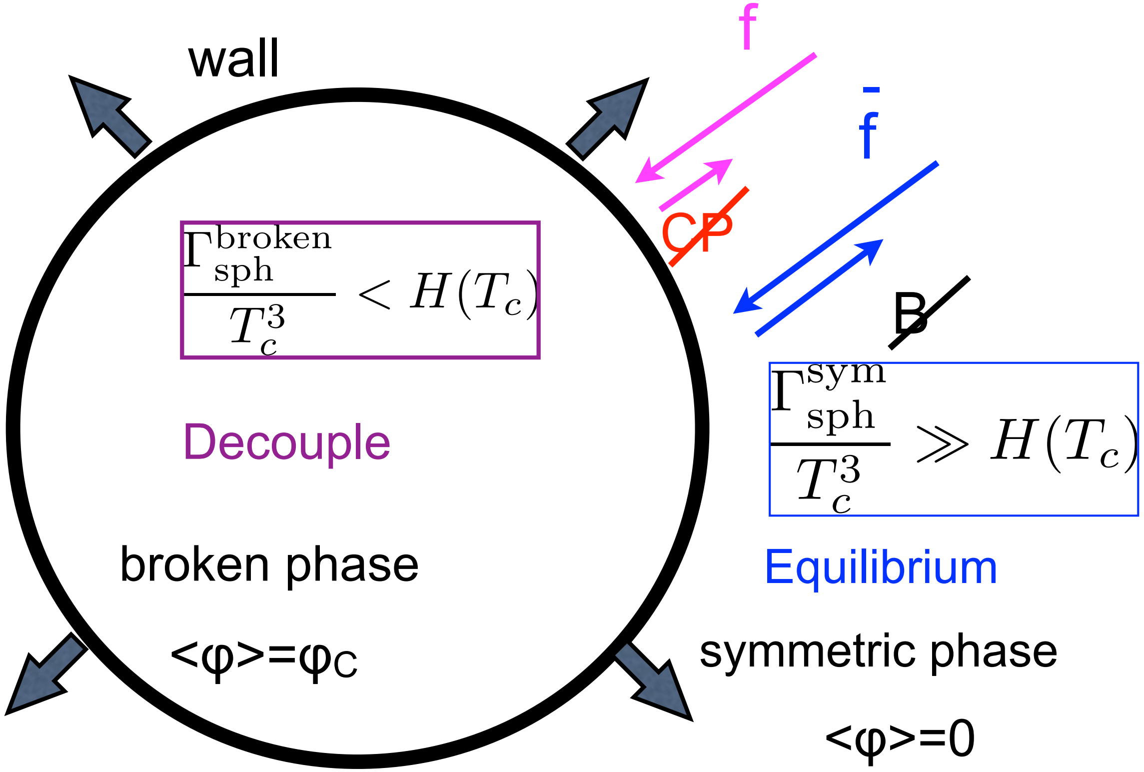
- バリオン数を破る相互作用 (B-violation)

- 荷電共役変換の破れ 及び 荷電共役変換とパリティ変換の破れ
  (C- and CP-violation)

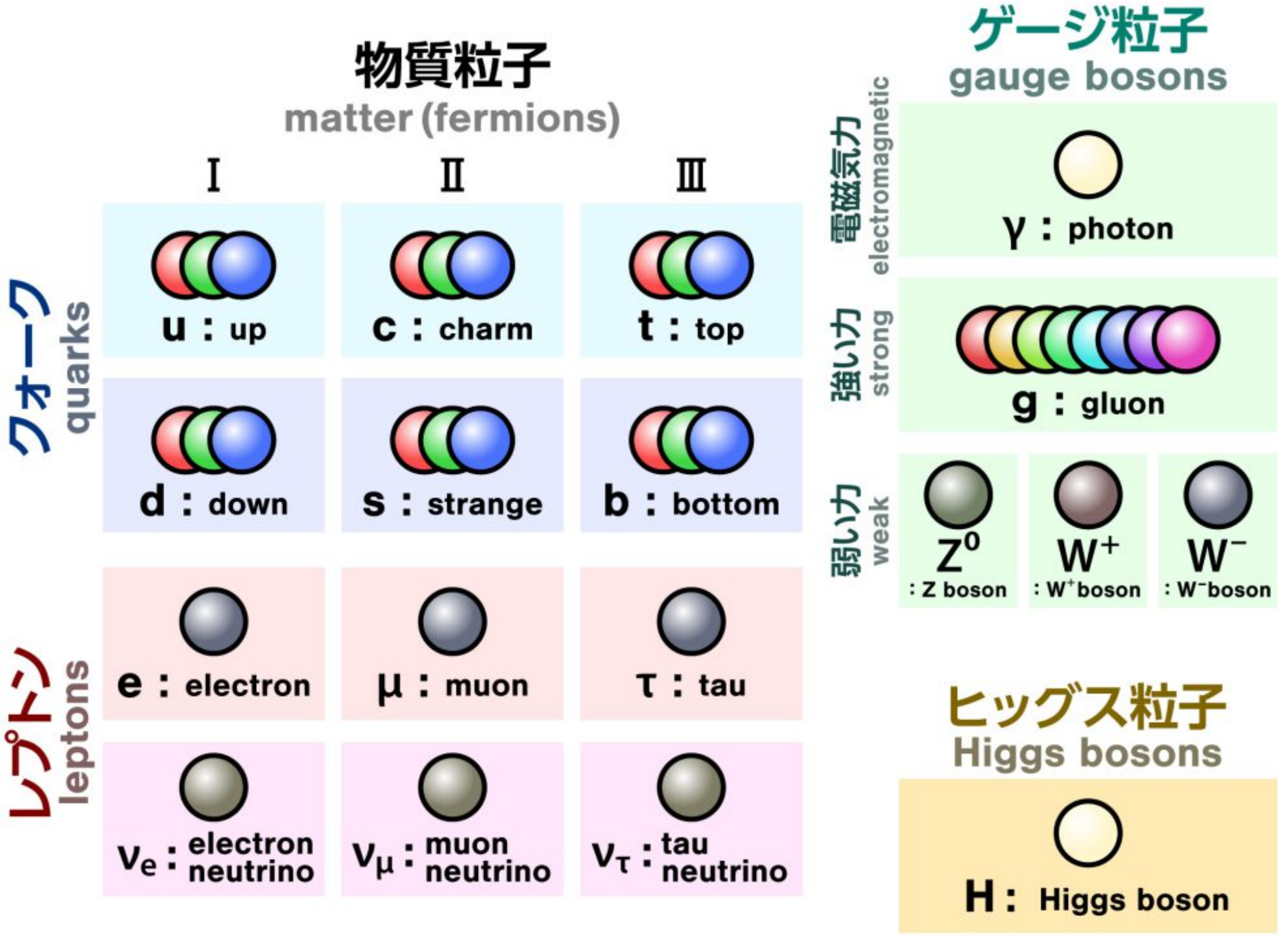
- 熱平衡からのずれ
  強い一次相転移か宇宙膨張による非平衡などを利用

電弱バリオン数生成シナリオ

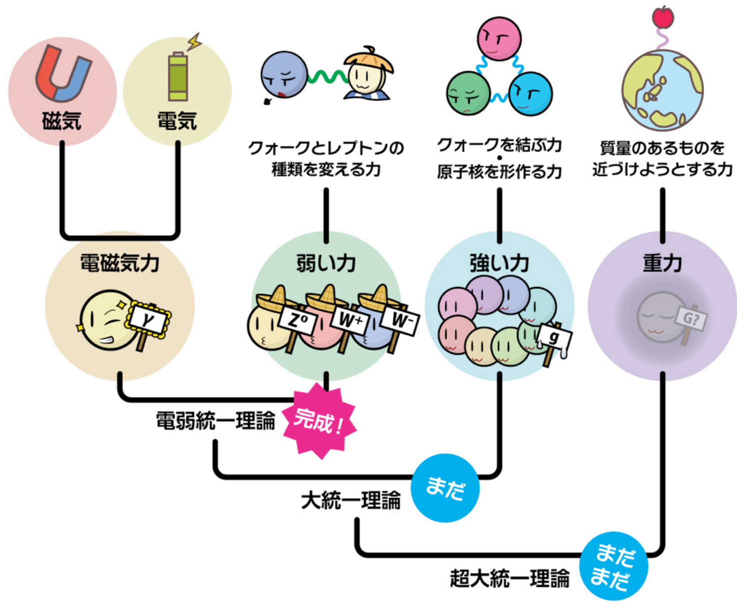




標準模型



物質粒子
matter (fermions)
I
II
III
クォーク
quarks
u : up
c : charm
t : top
d : down
s : strange
b : bottom
レプトン
leptons
e : electron
μ : muon
τ : tau
νe : electron neutrino
νμ : muon neutrino
ντ : tau neutrino
ゲージ粒子
gauge bosons
電磁気力
electromagnetic
γ : photon
強い力
strong
g : gluon
弱い力
weak
Z0
: Z boson
W+
: W+ boson
W−
: W− boson
ヒッグス粒子
Higgs bosons
H : Higgs boson



磁気
電気
クォークとレプトンの
種類を変える力
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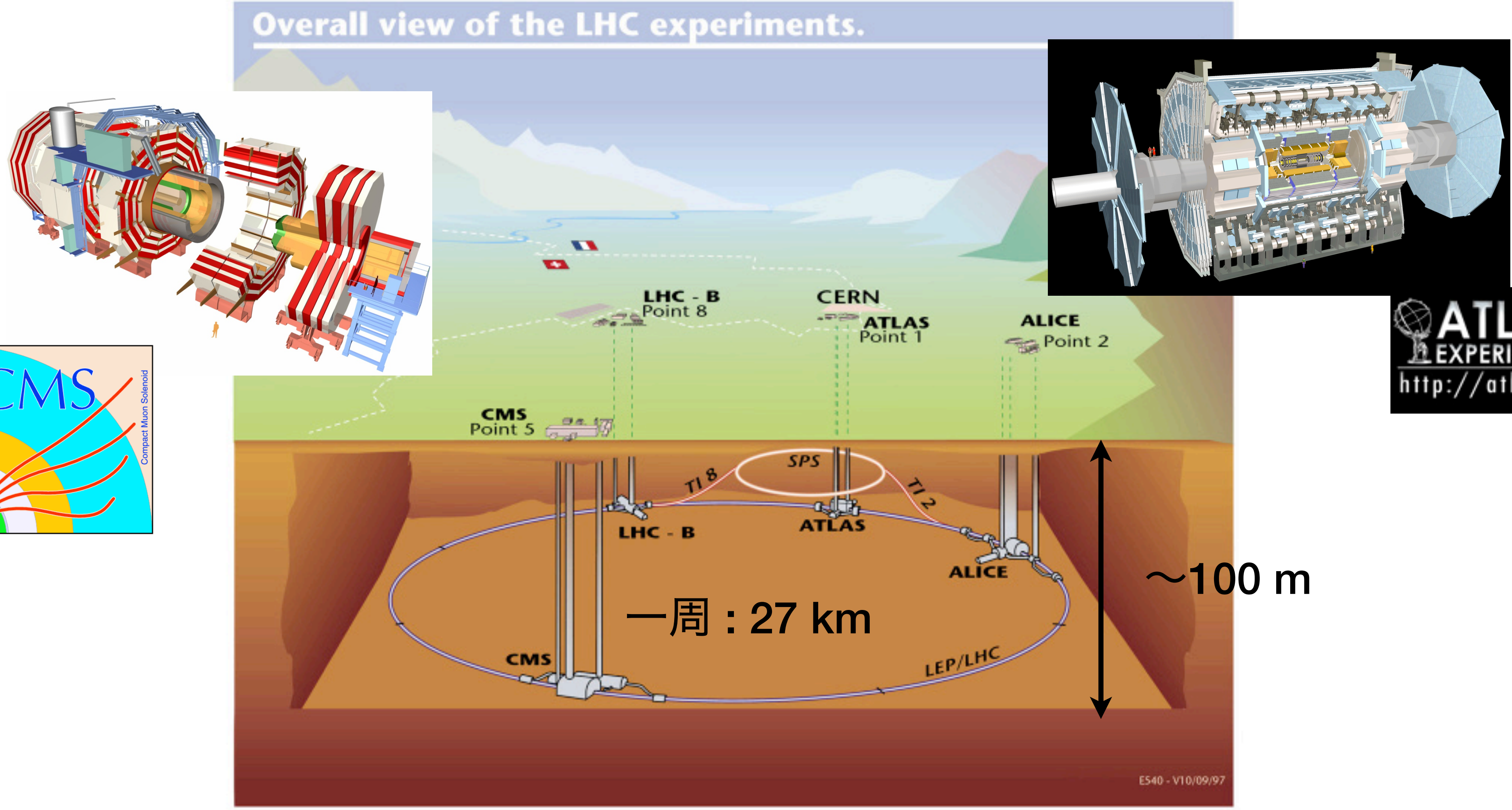
近づけようとする力
電磁気力
弱い力
強い力
重力
電弱統一理論
完成！
大統一理論
まだ
超大統一理論
まだ
まだ

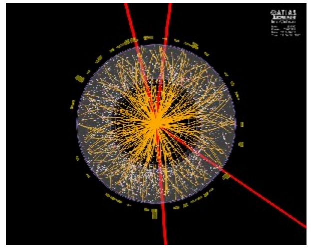
大型ハドロン加速器 (LHC)

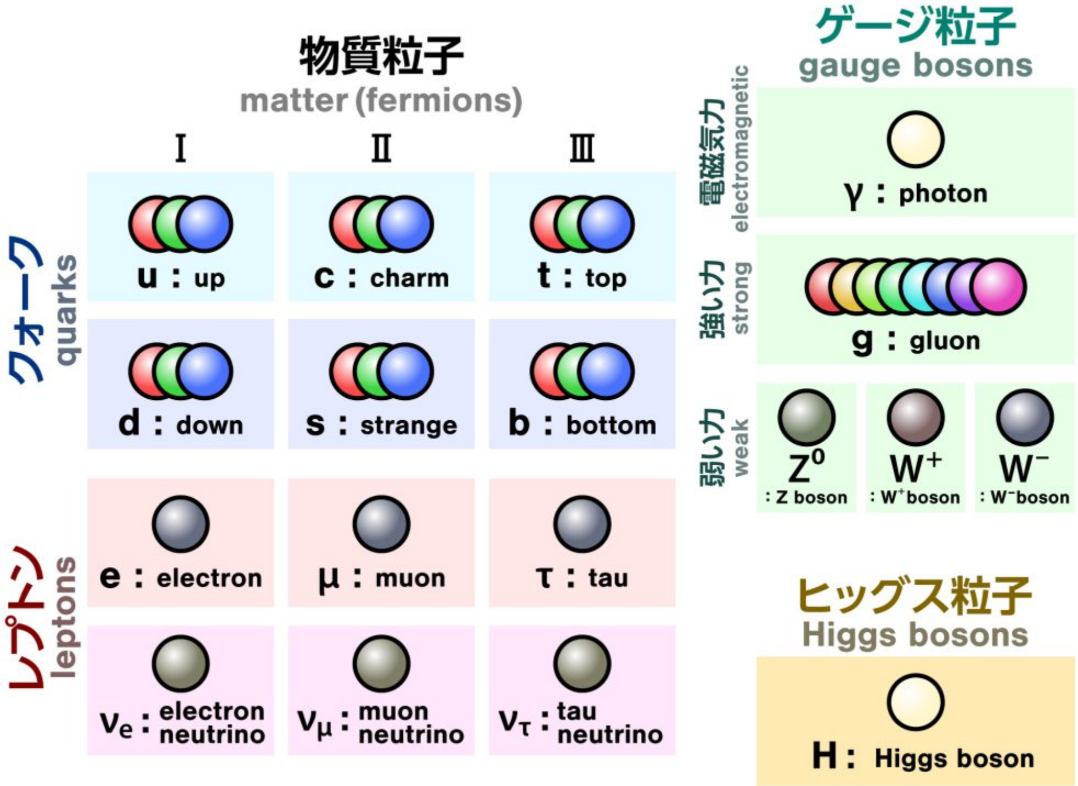


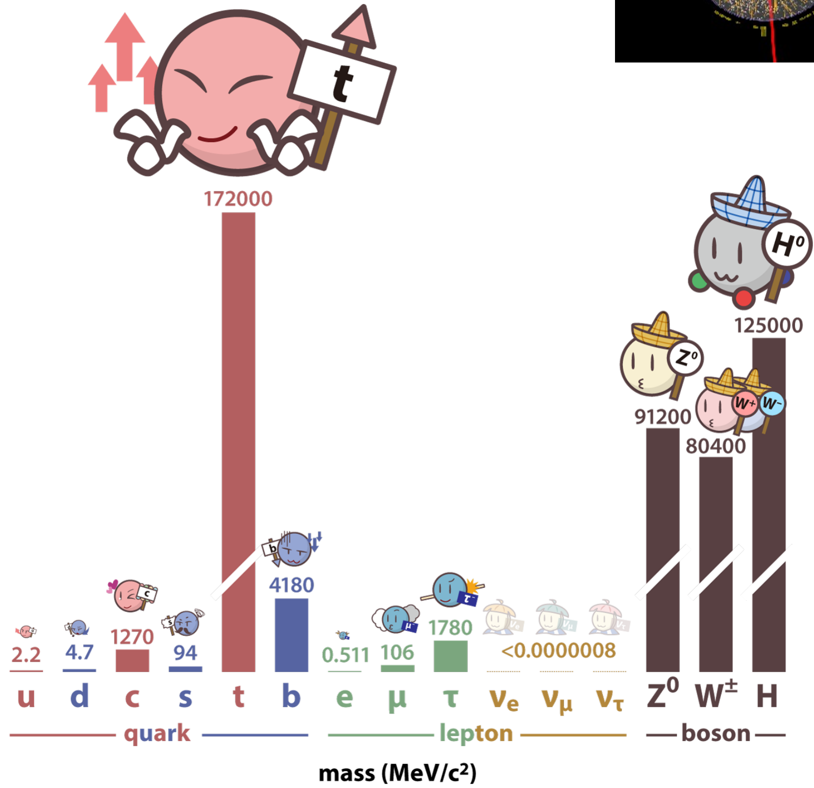
- 陽子と陽子をほぼ光の速さでぶつける (重心系衝突エネルギー 13.6 TeV)

質量

- **ヒッグス粒子の質量** $m_h \simeq 125\ \mathrm{GeV}$
  - → 標準模型では一次相転移は実現しない





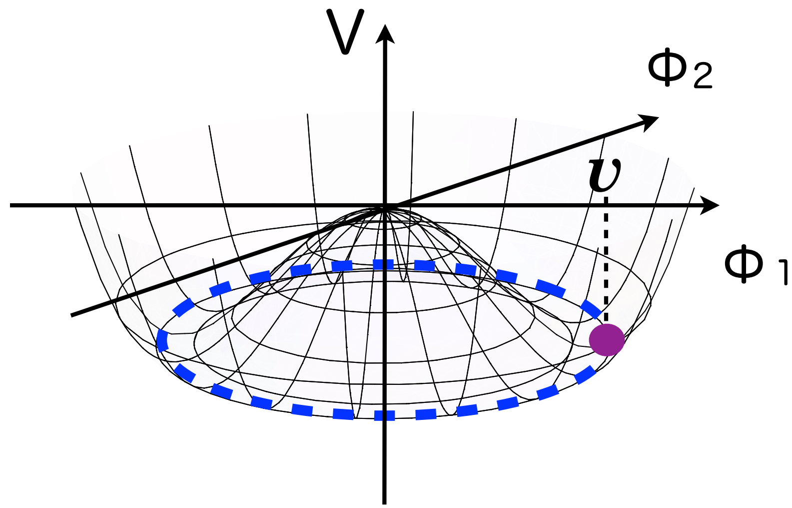


自発的対称性の破れ

例：　複素スカラー場：　$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$

$$V = -\mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2$$

U(1)対称性を持っている：　$\phi \to e^{-ie\Lambda}\phi$



Φ1=v, Φ2=0 の周りで展開：

$$\phi(x) = \frac{1}{\sqrt{2}}(v + h(x) + i\chi(x))$$

$$V = \lambda v^2 h^2 + \lambda v (h\chi^2 + h^3) + \frac{\lambda}{2} h^2 \chi^2 + \frac{1}{4}\lambda h^4 + \frac{1}{4}\lambda \chi^4 + C$$

質量　$m_h = \sqrt{2\lambda} v$

$m_\chi = 0$

hは質量を得るが、χの質量はゼロ。

χ :南部ゴールドストン(NG)ボソン

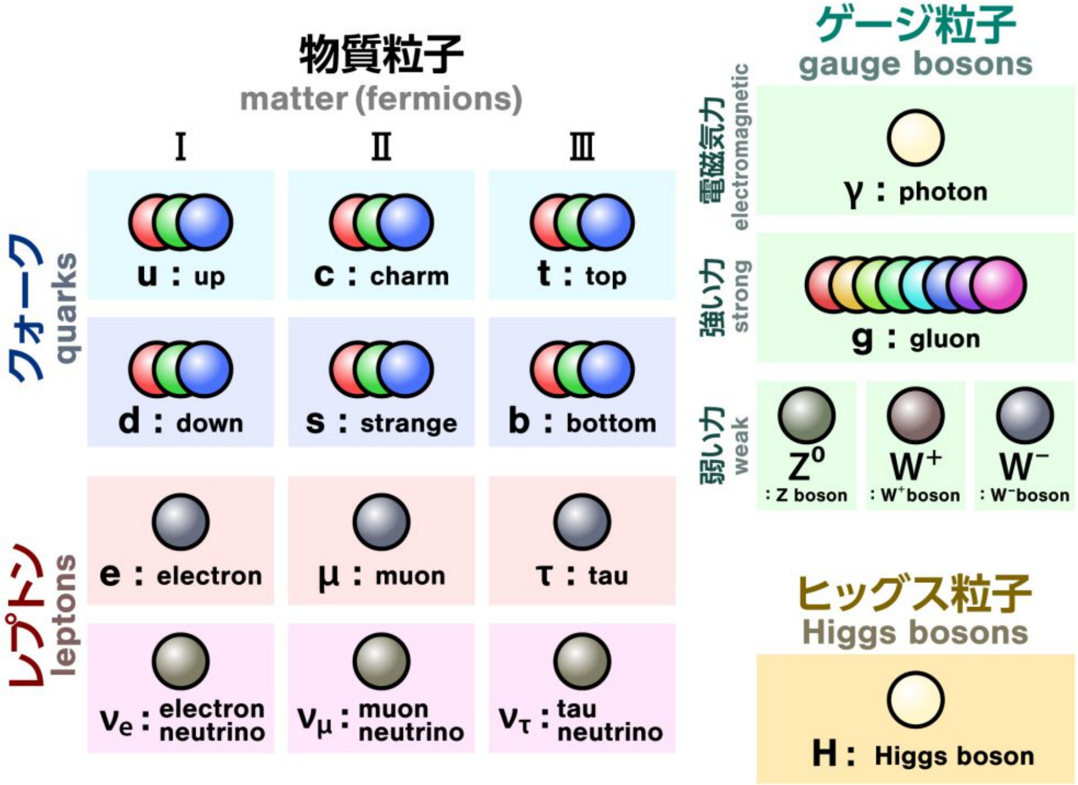
南部ーゴールドストンの定理 **(1961)**

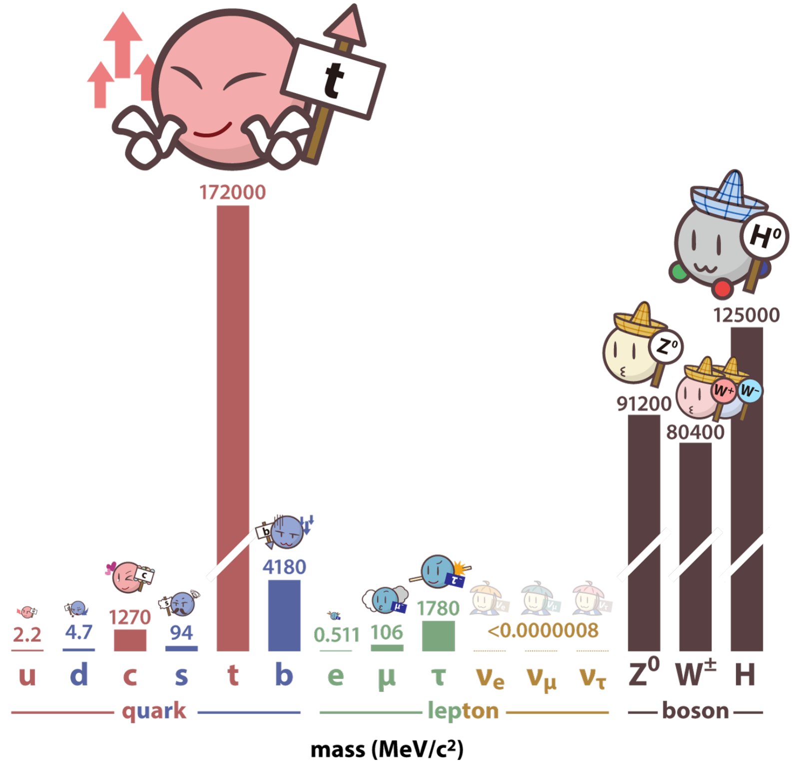
→真空が自発的に破れると質量ゼロの粒子が現れる

素粒子の質量

- **ヒッグス粒子の質量**　$m_h \simeq 125\ \mathrm{GeV}$

　→　標準模型では一次相転移は実現しない





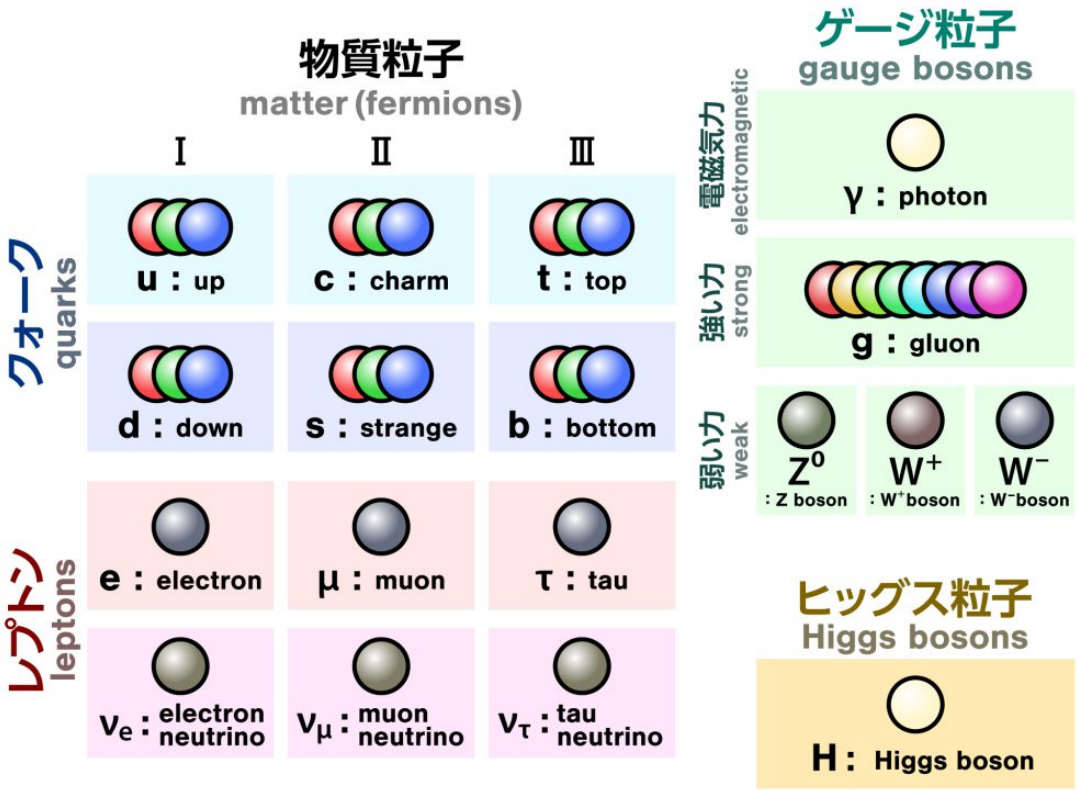
- **ゲージ対称性の破れ**　$\mathrm{SU(2)}_L \times \mathrm{U(1)}_Y \to \mathrm{U(1)}_{\mathrm{em}}$

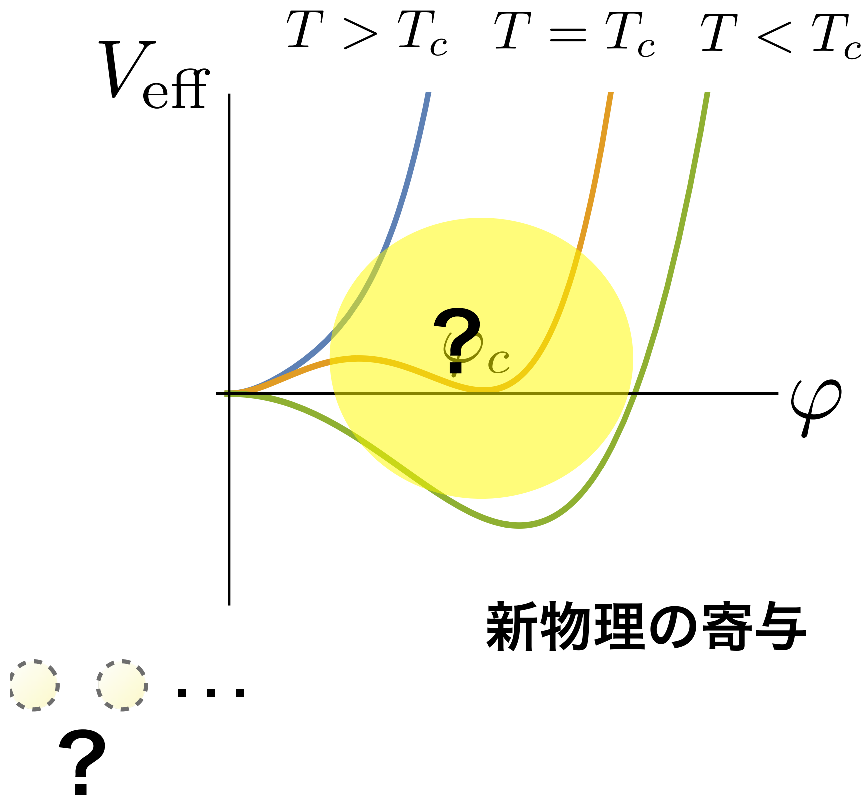
$$\Phi = \begin{pmatrix} \rho + i\eta \\ \frac{1}{\sqrt{2}}(v + h + i\chi) \end{pmatrix}$$

$v = 246\ \mathrm{GeV}$

3つのNGボソン

ヒッグスポテンシャル





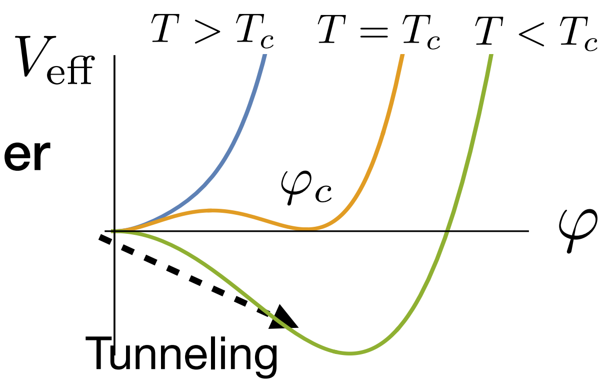
- ヒッグスポテンシャルの形状はまだきちんとわかっていない

拡張ヒッグス模型

Electroweak phase transition

❖ **1st order phase transition (PT) :**

There is a sufficiently high and wide potential barrier separating the two degenerate vacua at T=Tc.



❖ **High temperature expansion :**

$$V_{\rm eff}(\varphi, T) = D(T^2 - T_0^2)\varphi^2 - ET|\varphi|^3 + \frac{\lambda_T}{4}\varphi^4$$

- Two degenerate minima : $\varphi = 0 \text{ and } \varphi_c.$ $\quad \varphi_c = \frac{2ET_c}{\lambda_{T_c}}$

- The condition for the strong 1st order PT : $\frac{\varphi_c}{T_c} = \frac{2E}{\lambda_{T_c}} > 1$

The magnitude of *E* is crucial for the strong 1st order PT.

Electroweak phase transition

❖ **One-loop thermal potential :**

$$V_T = \frac{T^4}{2\pi^2}\left[\sum_f n_f J_F\left(\frac{m_f^2}{T^2}\right) + \sum_B n_B J_B\left(\frac{m_B^2}{T^2}\right)\right]$$

m : field dependent mass

✱ Boson-loop:

$$J_B(y) \approx -\frac{\pi^4}{45} + \frac{\pi^2}{12}y - \frac{\pi}{6}y^{\frac{3}{2}} - \frac{1}{32}\,y^2\log\left(\frac{|y|}{a_b}\right) + \mathcal{O}(y^3)\,,$$

✱ Fermion-loop:

$$J_F(y) \approx -\frac{7\pi^4}{360} + \frac{\pi^2}{24}y + \frac{1}{32}\,y^2\log\left(\frac{|y|}{a_f}\right) + \mathcal{O}(y^3)$$

$$a_b = 16\pi^2\exp(3/2 - 2\gamma_E),\quad a_f = \pi^2\exp(3/2 - 2\gamma_E)\qquad \gamma_E = 0.57721\ldots$$

The cubic term arises from the bosonic thermal corrections.

Electroweak phase transition

- **The cubic term arises from the bosonic thermal corrections.**

  - Standard Model (SM) :

$$E = \frac{1}{12\pi v^3}\left(6m_W^3 + 3m_Z^3\right) \qquad \sim 0.01$$

  - 1st order PT :

$$\frac{\varphi_c}{T_c} = \frac{2E}{\lambda_{T_c}} > 1 \qquad \rightarrow \qquad 50\ \text{GeV} \gtrsim m_h$$

  - Beyond the SM (BSM) :

$$E = \frac{1}{12\pi v^3}\left(6m_W^3 + 3m_Z^3 + \cdots\right)$$

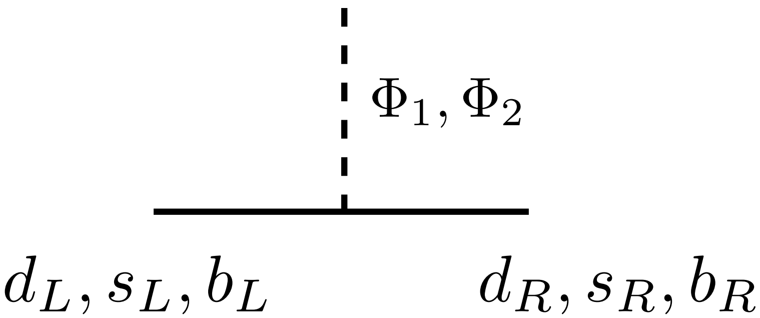
↑ extra bosonic degree of freedom

Two Higgs Doublet Model (2HDM)

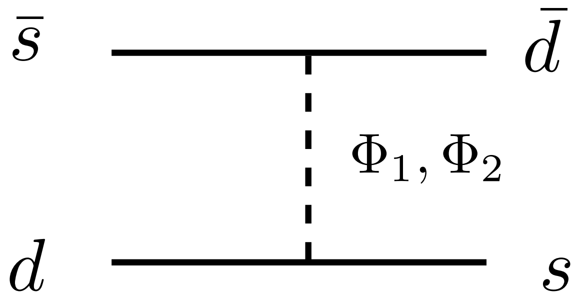
Two Higgs Doublet Model

	$\mathbf{SU(2)_L}$	$\mathbf{U(1)}$	$\mathbf{Z_2}$ (softly broken)
Φ_1	2	1/2	+
Φ_2	2	1/2	−

❖ **Flavor Changing Neutral Current (FCNC) @tree level**



$K^0 - \bar{K^0}$ mixing



- To avoid FCNC, give different charges to Φ1 and Φ2

Z_2 symmetry : $\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2$

Two Higgs Doublet Model

- **Tree level potential :**

$$V_{\text{tree}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right],$$

$$\Phi_1 = \begin{pmatrix} \omega_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + i z_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \omega_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + i z_2) \end{pmatrix}$$

$$v \equiv \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV} \qquad \tan\beta \equiv \frac{v_2}{v_1}$$

- **Theoretical constraints :**
  - Bounded from below (BFB)

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad -\sqrt{\lambda_1 \lambda_2} < \lambda_3, \quad -\sqrt{\lambda_1 + \lambda_2} < \lambda_3 + \lambda_4 - \lambda_5$$

  - Perturbativity $\quad |\lambda_n| < 4\pi \ (n = 1, 2, \cdots 5)$

Two Higgs Doublet Model

- **Physical eigenstates** Neutral (CP-even, CP-odd) Charged

$$\underbrace{h, \quad H}_{\text{CP-even}}, \quad \underbrace{A}_{\text{CP-odd}}, \quad H^{\pm}$$

- **Parameters in the Higgs potential**

$$m_{11}^2,\ m_{22}^2,\ m_{12}^2,\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5$$

$$\downarrow$$

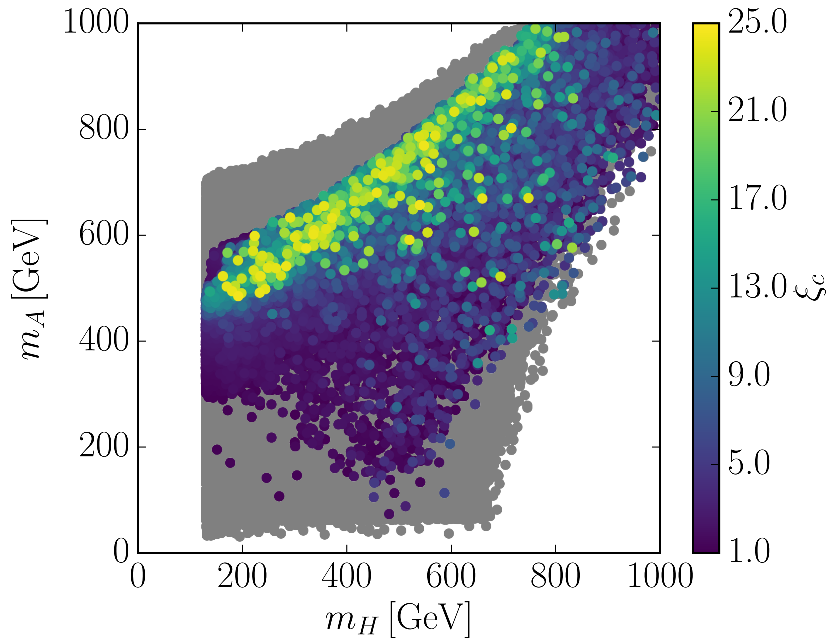
$$m_h,\ m_H,\ m_A,\ m_{H^\pm},$$

125 GeV

$$v, \quad \tan\beta, \quad \cos(\beta-\alpha), \quad m_{12}^2$$

246 GeV

Basler et al. JHEP (2017)

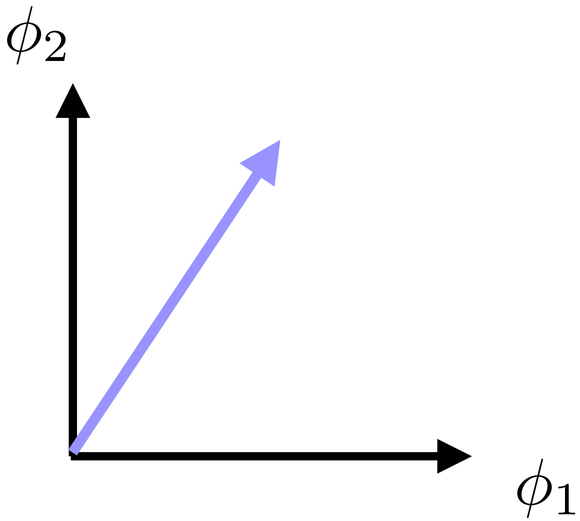


Color points have a PT of strong first order.

Multistep Phase Transition

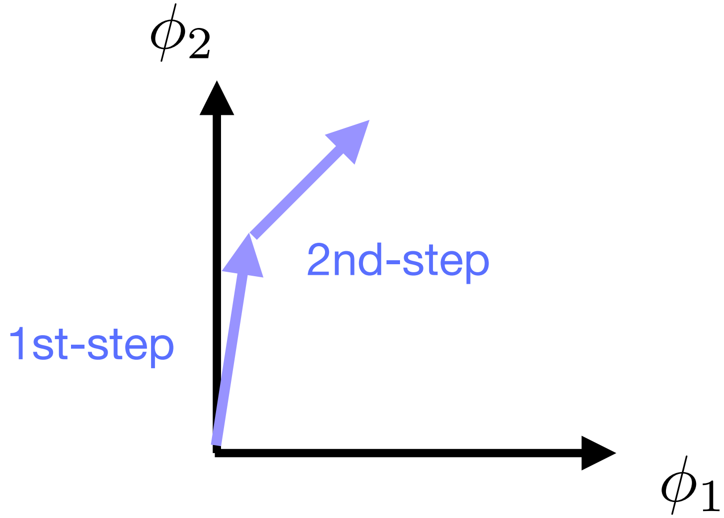
$$\Phi_1 = \begin{pmatrix} 0 \\ \frac{\phi_1}{\sqrt{2}} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} 0 \\ \frac{\phi_2}{\sqrt{2}} \end{pmatrix}$$

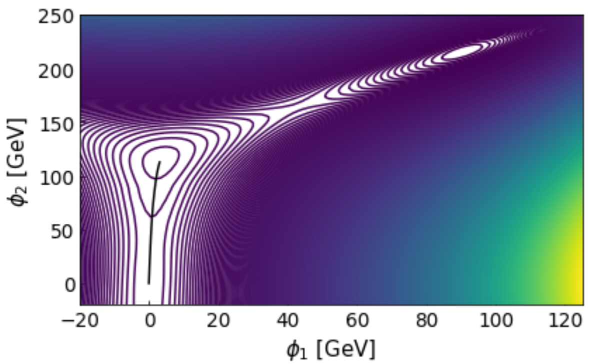
1 step

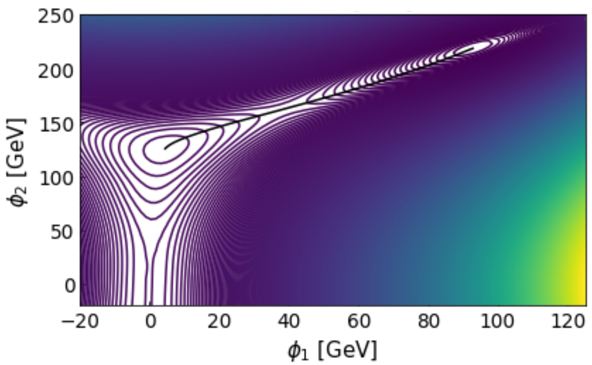


2 step

MA, Komatsu, Shibuya, PTEP (2022)







Multistep Phase Transition

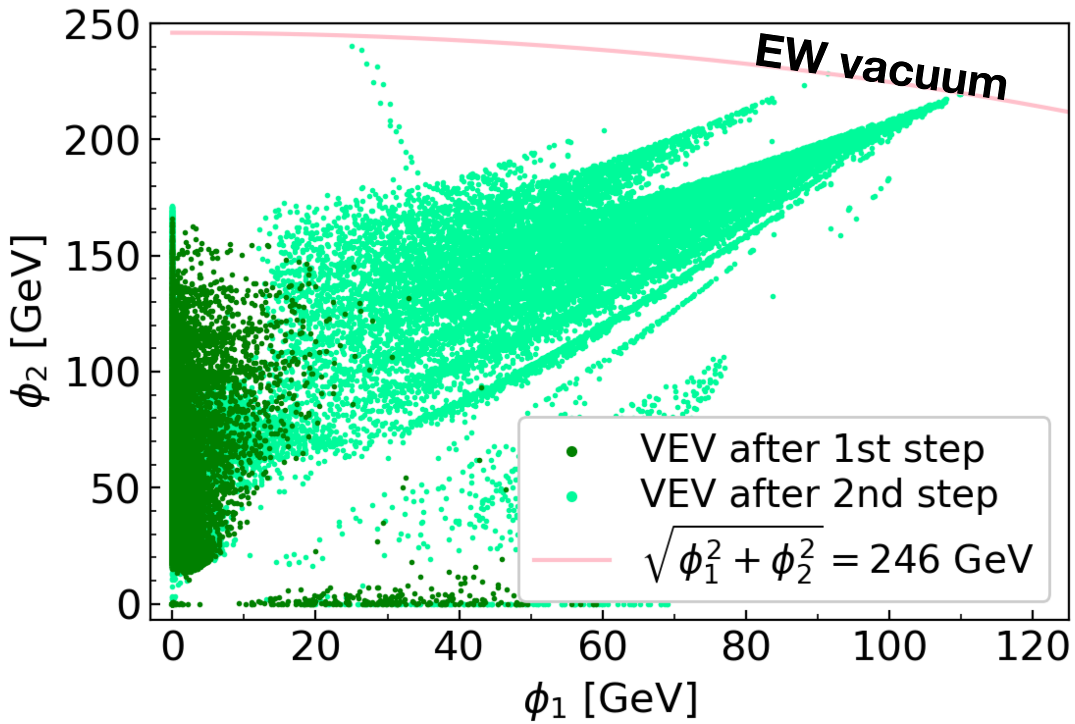
Type-I ($m_A = m_{H^\pm}$)

MA, Komatsu, Shibuya, PTEP (2022)

m_A [GeV]	m_H [GeV]	$\tan\beta$	$\cos(\beta-\alpha)$	m_3 [GeV]
180–1000(/10)	130–1000(/10)	2–10(/0.5)	−0.25–0.25(/0.05)	0–100(/5)

❖ 2-step PT

The VEVs after each step of the 2-step PTs



The first step in the 2-step PT tends to occur along the ϕ_2 axis.

Exotic intermediate phases?

MA, Biermann, Borschensky, Ivanov, Mühlleitner, Shibuya, JHEP 02 (2024)

Exotic intermediate phases

- **The CB phase were analyzed within the high-T approximation of the 2HDM potential.**

Ivanov, Acta Phys. Polon. B 40 (2009).
Ginzburg, Ivanov and Kanishev, PRD81 (2010).

- The sequence of phases from high-T to the EW vacuum at T = 0:

EW symmetric → neutral → charge-breaking (CB) → EW vacuum

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + \bar{\omega}_1 + i\psi_1 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + \bar{\omega}_{\rm CB} + i\eta_2 \\ \zeta_2 + \bar{\omega}_2 + i\left(\psi_2 + \bar{\omega}_{\rm CP}\right) \end{pmatrix}.$$

Present vacuum (T=0) : $v_j = \bar{\omega}_j\big|_{T=0} \qquad v_{\rm CB} = v_{\rm CP} = 0,$

Questions：

- Does such an intermediate CB phase indeed exist within a more accurate analysis with the effective potential?
- Is it possible that some of these phase transitions become first-order?

Tree level potential

- **Tree level potential :**

$$V_{\rm tree} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + {\rm h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + {\rm h.c.}\right],$$

  - We assume CP conservation.

A toy model (m^2_{12}=0)

- a toy model: **2HDM with an exact Z2 symmetry** $m_{12}^2 = 0$

  High-T approximation

$$m_{11}^2(T) = m_{11}^2 + c_1 T^2\,,\qquad c_1 = \frac{1}{12}(3\lambda_1 + 2\lambda_3 + \lambda_4) + \frac{1}{16}(3g^2 + g'^2)\,,$$

$$m_{22}^2(T) = m_{22}^2 + c_2 T^2\,.\qquad c_2 = \frac{1}{12}(3\lambda_2 + 2\lambda_3 + \lambda_4) + \frac{1}{16}(3g^2 + g'^2) + \frac{1}{12}(y_\tau^2 + 3y_b^2 + 3y_t^2)\,,$$

- T=0
  - CB vacuum :

Ivanov, Acta Phys. Polon. B 40 (2009).
Ginzburg, Ivanov and Kanishev, PRD81 (2010).

- BFB conditions
- $\lambda_4 > |\lambda_5|\,,\quad |\lambda_3| < \sqrt{\lambda_1\lambda_2}$ The sign of λ3 is not fixed.

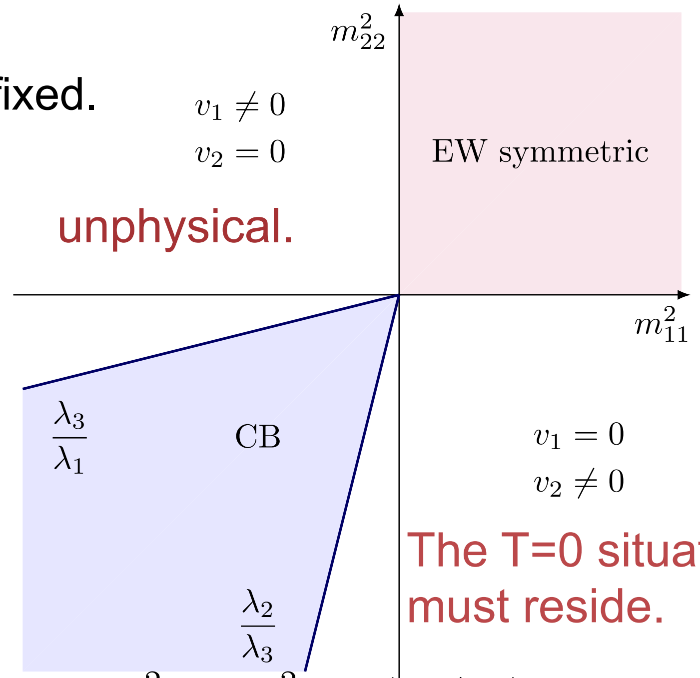
$$m_{11}^2\sqrt{\lambda_2} + m_{22}^2\sqrt{\lambda_1} < 0\,,\quad m_{11}^2 < m_{22}^2\frac{\lambda_3}{\lambda_2}\,,\quad m_{22}^2 < m_{11}^2\frac{\lambda_3}{\lambda_1}\,.$$

$\lambda_3 > 0$ ⇒

$$m_{11}^2 < 0,\quad m_{22}^2 < 0$$

$$|m_{11}^2|\frac{\lambda_3}{\lambda_1} < |m_{22}^2| < |m_{11}^2|\frac{\lambda_2}{\lambda_3}$$

wedge-like



$m_{22}^2 = m_{11}^2 \times (\lambda_2/\lambda_3)$

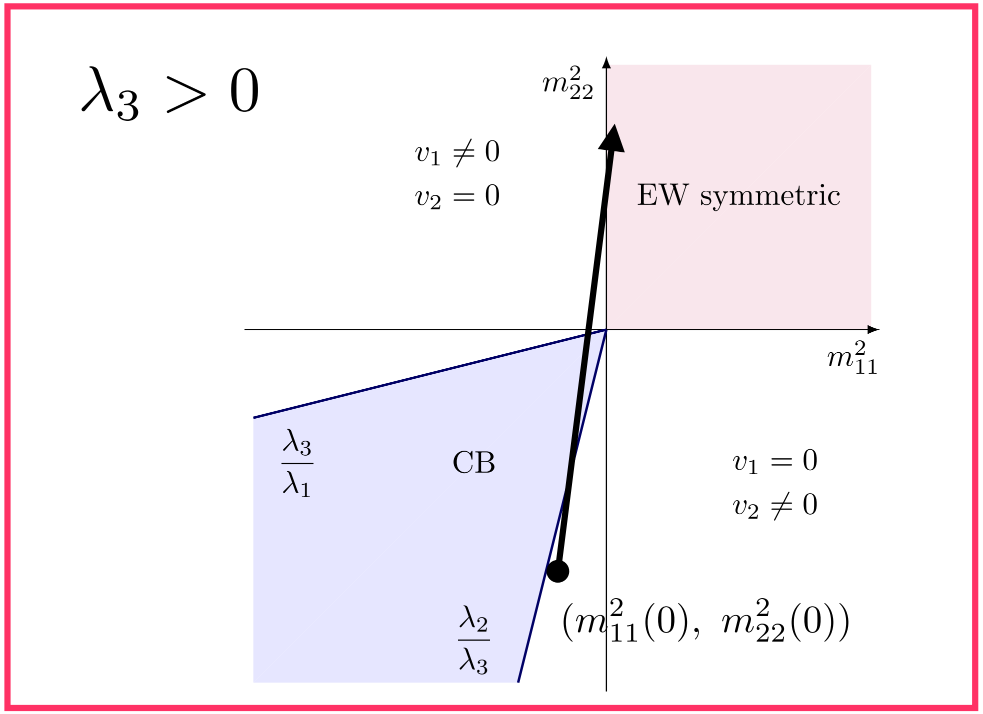
The T=0 situation must reside.

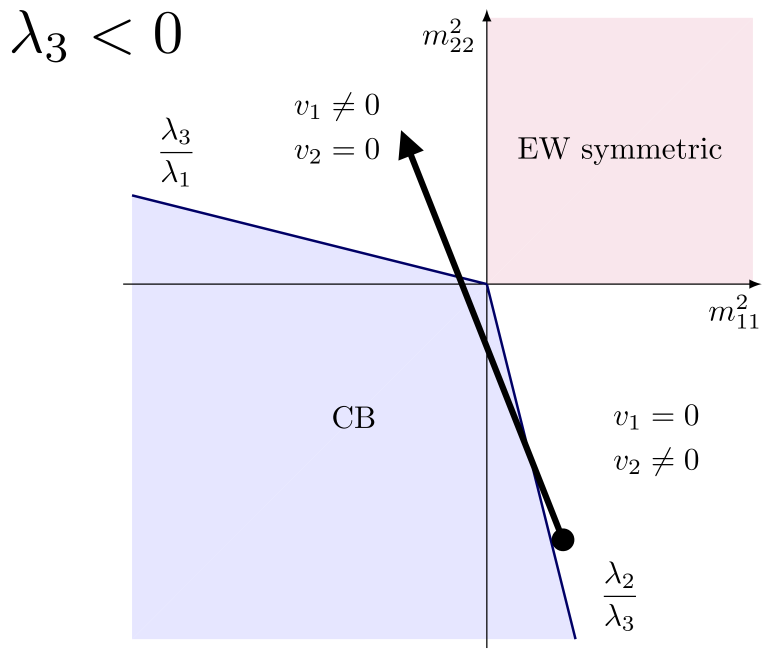
- EW symmetric vacuum (v=0) :

$$m_{11}^2 > 0,\quad m_{22}^2 > 0$$

A toy model (m^2_{12}=0)

- Temperature evolution
  - **Phase transition sequence with an intermediate CB**





A toy model (m^2_{12}=0)

- The ray rises steeper than the wedge:

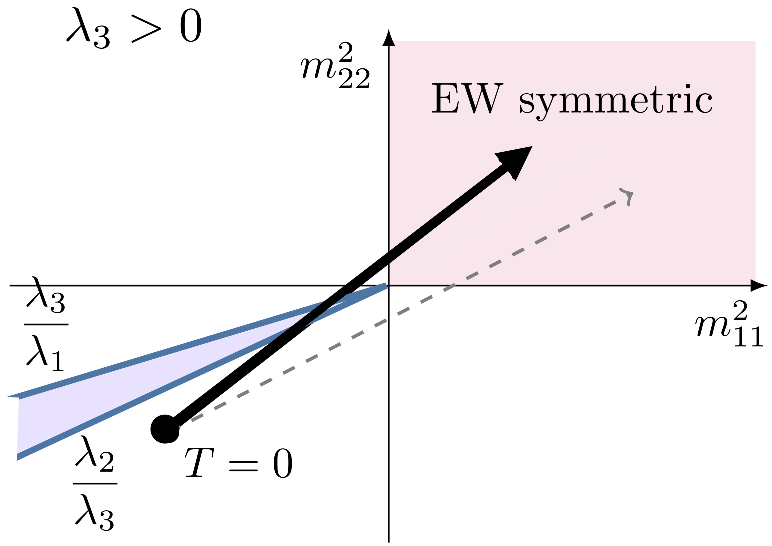
$$\frac{c_2}{c_1} > \frac{|m^2_{22}|}{|m^2_{11}|} > \frac{\lambda_2}{\lambda_3}$$

e.g.)

$$\lambda_1 = 2, \quad \lambda_2 = 0.25, \quad \lambda_3 = 0.6, \quad \lambda_4 = 2.8, \quad \frac{|m^2_{22}|}{|m^2_{11}|} = \frac{2}{3}$$

$$\longrightarrow \quad c_2/c_1 \approx 0.78, \;\; \lambda_2/\lambda_3 \approx 0.42$$

$$v^2 = v_2^2 = \frac{2|m^2_{22}|}{\lambda_2}, \quad \frac{m^2_{h_{\rm SM}}}{v^2} = \lambda_2, \longrightarrow \quad \lambda_2 \approx 1/4$$



- If we drop the top-quark contribution to c_2, we miss the charge-breaking region.

- The charged Higgs boson mass: $$m^2_{H^\pm} = \frac{1}{2}\lambda_3\left(1 - \frac{m^2_{11}}{m^2_{22}}\frac{\lambda_2}{\lambda_3}\right)v^2$$

If the starting point approaches the boundary of CB phase, the $m^2_{H^\pm}$ vanishes.

$$m_{H^\pm} \approx 82 \text{ GeV}$$

We need the larger λ3 or a larger $\frac{m^2_{22}}{m^2_{11}}$.

→ It leads a large λ1. $|\lambda_3| < \sqrt{\lambda_1\lambda_2}$

Avoiding a dangerously small $m^2_{H^\pm}$ is not an easy task.

A toy model ($m^2_{12} \neq 0$)

A toy model with softly broken Z_2 symmetry . $(m^2_{12} \neq 0)$

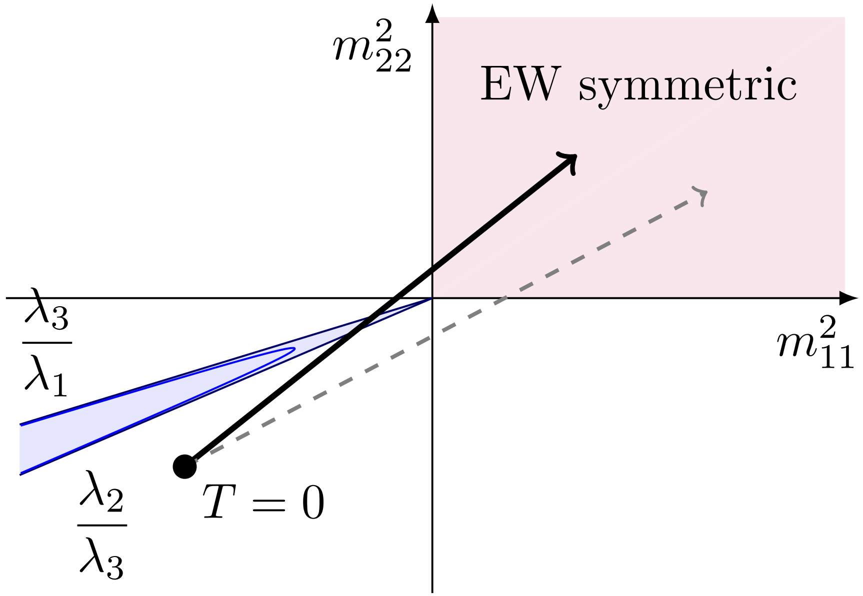
- **CB vacuum :**

$$\frac{\mu_1^2}{a_1^2} + \frac{\mu_2^2}{a_2^2} < 1\,,$$

$$\mu_1 = \left| \frac{2\sqrt[4]{\lambda_1\lambda_2}\, m_{12}^2}{m_{11}^2\sqrt{\lambda_2} + m_{22}^2\sqrt{\lambda_1}} \right|, \quad a_1 = \frac{\lambda_4 + \lambda_5}{\sqrt{\lambda_1\lambda_2} + \lambda_3}\,,$$

$$\mu_2 = \left| \frac{m_{11}^2\sqrt{\lambda_2} - m_{22}^2\sqrt{\lambda_1}}{m_{11}^2\sqrt{\lambda_2} + m_{22}^2\sqrt{\lambda_1}} \right|, \quad a_2 = \frac{\sqrt{\lambda_1\lambda_2} - \lambda_3}{\sqrt{\lambda_1\lambda_2} + \lambda_3}\,.$$

hyperbolic conical section



- The larger m^2_{12} , the further the CB region retracts from the origin.

→ The evolution can miss the CB region more easily.

Effective potential

❖ **The one-loop corrected effective potential at the finite temperature :**

$$V = V_0 + V_{\rm CW} + V_{\rm CT} + V_T \qquad \Phi_i = \begin{pmatrix} 0 \\ \frac{\phi_i}{\sqrt{2}} \end{pmatrix}$$

* The Coleman-Weinberg potential :

$$V_{\rm CW}(\phi_1, \phi_2) = \pm \frac{1}{64\pi^2} \sum_k n_k m_k^4(\phi_1, \phi_2) \left[\log \frac{m_k^2(\phi_1, \phi_2)}{\mu^2} - c_k \right]$$

+(-) for boson (fermion) $\quad k = H^\pm, H, h, A, W, Z, \gamma, t, b, \tau$

* The counter term potential : $V_{\rm CT}$

* The one-loop thermal contributions : V_T

Symmetry (non-)restoration

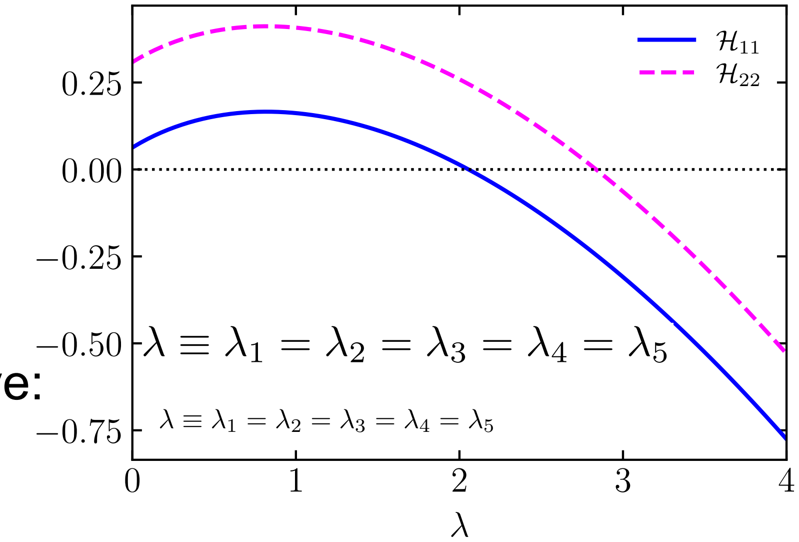
- **Symmetry (non-)restoration:**
  - the curvature of V_T with respect to the EW VEVs around the origin.

The Hessian matrix : $$H_{ij} \equiv \left. \frac{\partial^2 V_T}{\partial \bar{\omega}_i \partial \bar{\omega}_j} \right|_{\bar{\omega}_{i,j}=0}, \quad i,j=1,2.$$

$$\lim_{T\to\infty} \begin{pmatrix} \frac{H_{11}}{T^2} & \frac{H_{12}}{T^2} \\ \frac{H_{21}}{T^2} & \frac{H_{22}}{T^2} \end{pmatrix} = \begin{pmatrix} \mathcal{H}_{11} & 0 \\ 0 & \mathcal{H}_{22} \end{pmatrix},$$

$$\mathcal{H}_{11},\ \mathcal{H}_{22}$$

$$\mathcal{H}_{11} = c_1 - \frac{1}{16\pi}\left[\sqrt{2}\left(3g^3 + g'^3\right) + 4\left(3\sqrt{c_1}\lambda_1 + \sqrt{c_2}\left(2\lambda_3 + \lambda_4\right)\right)\right],$$
$$\mathcal{H}_{22} = c_2 - \frac{1}{16\pi}\left[\sqrt{2}\left(3g^3 + g'^3\right) + 4\left(3\sqrt{c_2}\lambda_2 + \sqrt{c_1}\left(2\lambda_3 + \lambda_4\right)\right)\right],$$



$$\lambda \equiv \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5$$

- In order for the stationary point at the origin to be a minimum, all eigenvalues are required to be positive:

$$\mathcal{H}_{11} > 0 \quad \text{and} \quad \mathcal{H}_{22} > 0\,.$$

Yukawa interactions

❖ Four types of Yukawa interactions

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type-I	+	−	−	−	−	+
Type-II	+	−	−	+	+	+
Type-X	+	−	−	−	+	+
Type-Y	+	−	−	+	−	+

Numerical analysis

MA, Biermann, Borschensky, Ivanov, Mühlleitner, Shibuya, JHEP02(2024)

- **Scan ranges:**

Parameter	Scan range
$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	$[0, 4\pi]$
λ_5	$[-4\pi, 4\pi]$
m_{11}^2, m_{22}^2	$[-10^6, 0]$ GeV^2
m_{12}^2	$[0, 10^6]$ GeV^2

- All relevant theoretical and experimental constraints are satisfied.

Experimental constraints

- Electroweak precision data

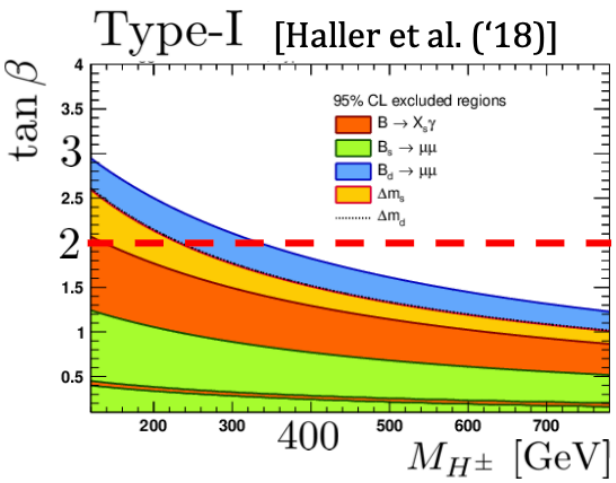
$$m_{H^\pm} = m_A \text{ or } m_H$$

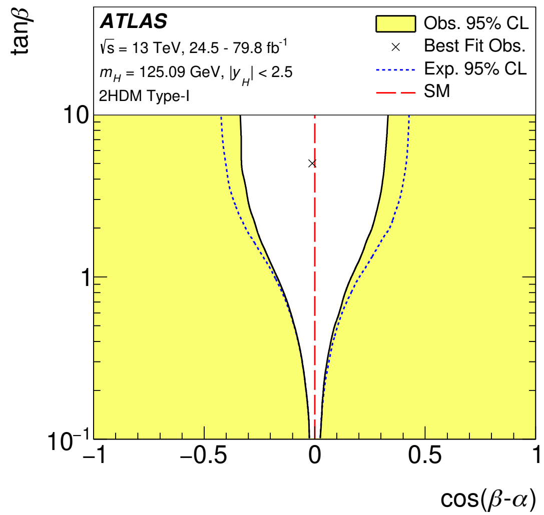
- Flavor experiments

$$B_d \to \mu\mu \quad \tan\beta \gtrsim 2$$

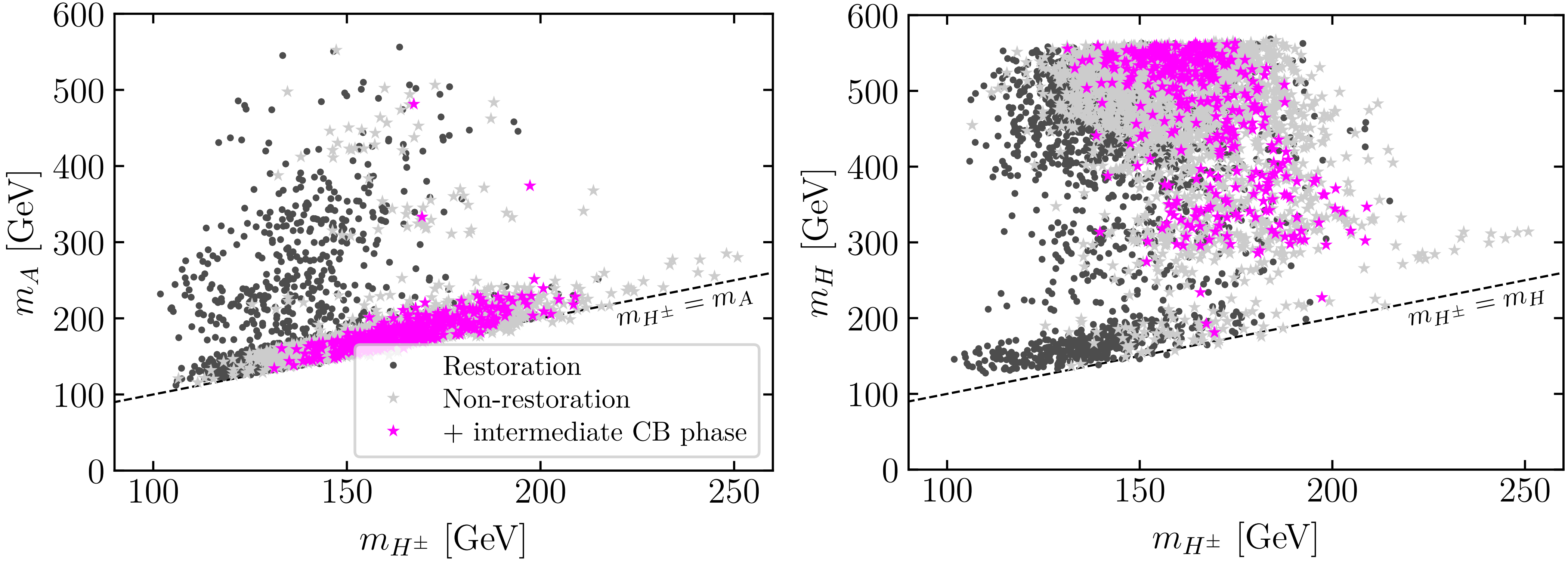
- Higgs couplings strength

$$|\cos(\beta - \alpha)| \lesssim 0.25$$



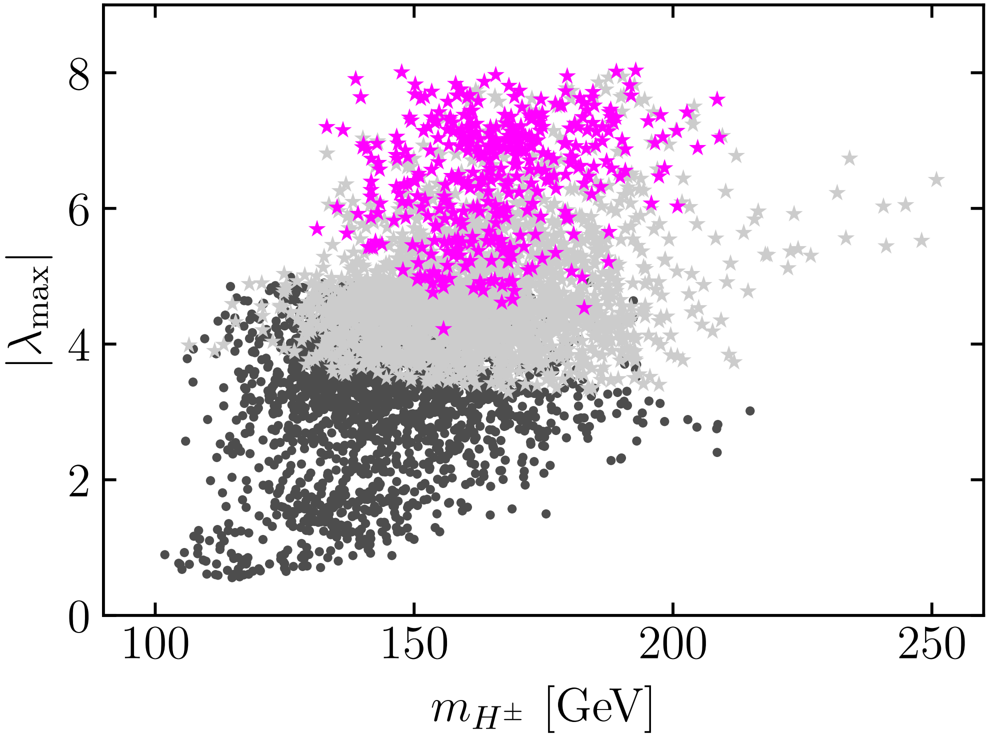


Numerical analysis



- Relatively low charged Higgs masses : $m_{H^\pm} \lesssim 210$ GeV
- Degenerate configuration : $m_{H^\pm} \approx m_A$

Numerical analysis



$$|\lambda_{\rm max}| \equiv \max(|\lambda_1|, |\lambda_2|, |\lambda_3|, |\lambda_4|, |\lambda_5|)$$

- **Only points with $\lambda_{max} < 5$ lead to EW symmetry restoration.**

Intermediate CB phase :

- **a relatively large maximum scalar coupling:** $4 \lesssim |\lambda_{\rm max}| \lesssim 8$

When requiring the parameter points to fulfill the all three constraints simultaneously, no viable points are found.

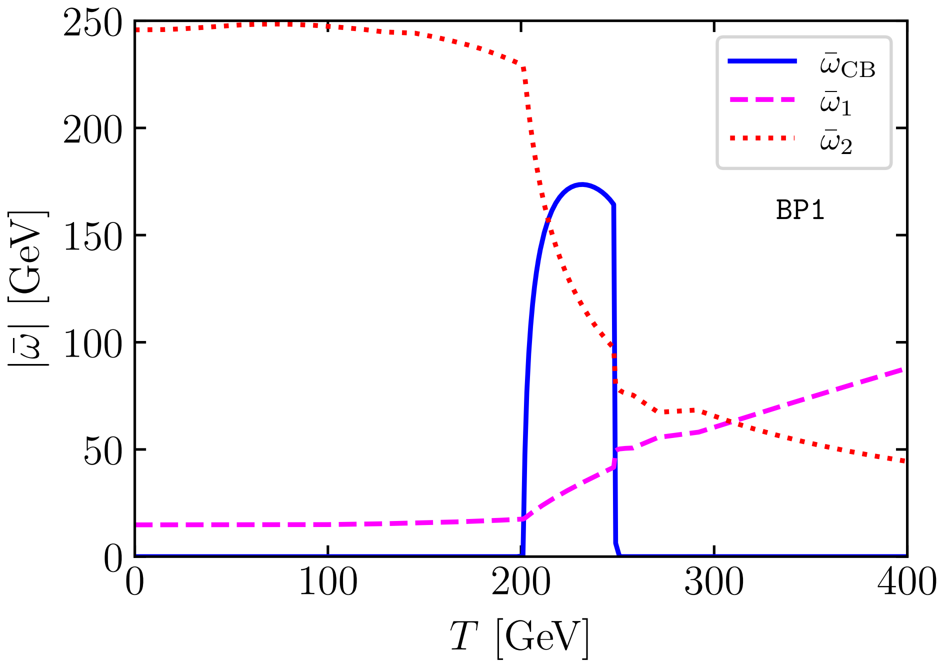
- an intermediate CB phase
- EW symmetry restoration
- the experimental constraints

Temperature evolution

❖ Temperature evolution of the absolute values of the EW and CB VEVs. $\bar{\omega}_1,\ \bar{\omega}_2,\ \bar{\omega}_{\rm CB}$

- Benchmark points:

	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$	$\cos(\beta-\alpha)$	m_{12}^2 [GeV^2]
BP1	562.84	168.56	164.51	16.58	0.128	18933.44



- The sequence of phases from high temperatures to the EW vacuum at T = 0:

Neutral → CB → EW vacuum.

- We find a first-order phase transition from the electrically neutral to the CB phase.

Summary

- We investigated the possibility of an intermediate CB phase in the 2HDM type I using the full one-loop corrected effective potential.

- The appearance of a CB phase favours rather low charged Higgs masses and large quartic couplings.

- If we accept symmetry non-restoration:

  Typical collider features : $H \to AZ$ or $H \to H^{\pm}W^{\mp}$

まとめ

- 電磁気力と弱い力は高エネルギーでは統一されており、電弱相転移によって2つに分かれた。
- 電弱相転移が一次相転移の場合、背景重力波が観測される可能性や物質-反物質非対称性を説明できる可能性がある。
- 標準模型では電弱一次相転移は起こらないが、拡張模型では実現可能。
- 2HDMは、標準模型のヒッグス場と同様の場を1つ加えたシンプルな拡張の模型。しかし、ポテンシャルはとてもリッチな相転移ダイナミクスを引き起こす。
- マルチステップ相転移やIntermediate CB相の物理もリッチ。