CP VIOLATIONS AND ELECTROWEAK BARYOGENESIS

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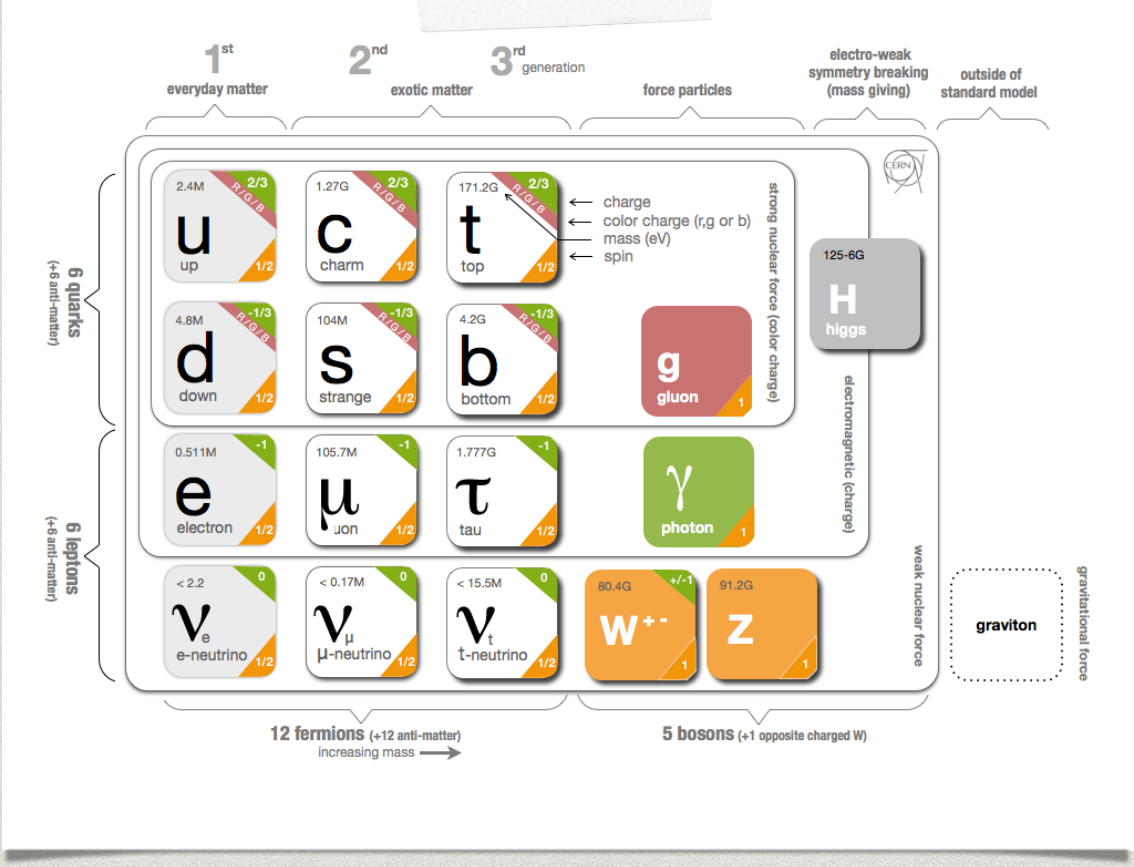
Outline&preview

- Brief overview of EWPT
- EWBG from the Higgs portal
- EWBG from spontaneous CPV

Preview

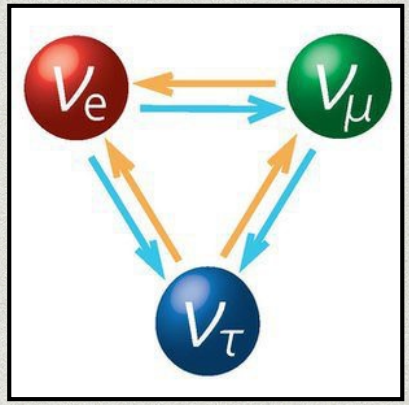
- *Give a quick look at the physics relevant to the electroweak phase transition.*
- *Discussing BAU in a bottom-up strategy and showing you how EWBG can be correlated with the Higgs portal.*
- *Showing you how to generate the BAU with a spontaneous CP phase and a two-step EWPT.*

Particle Zoo

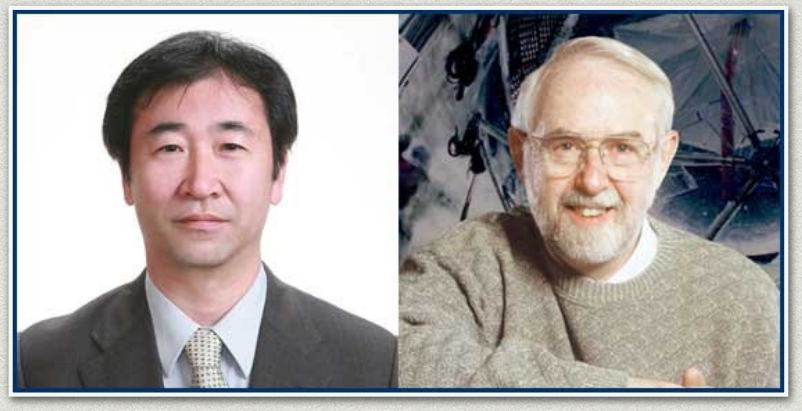


- Neutrino masses
- Dark matter
- Baryon asymmetry

Neutrino masses

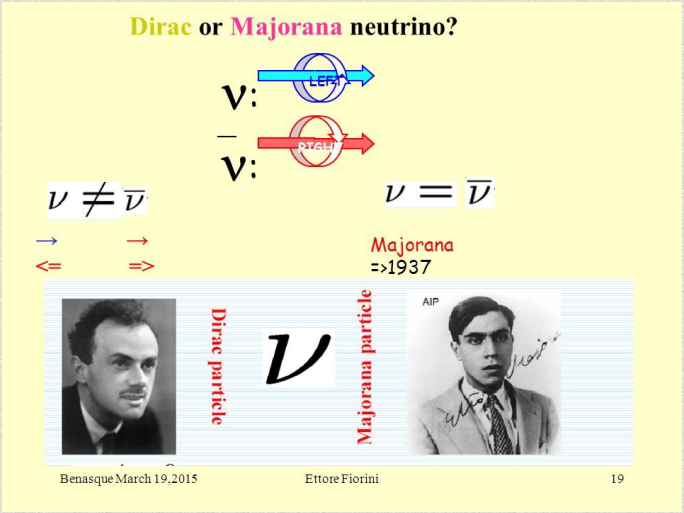


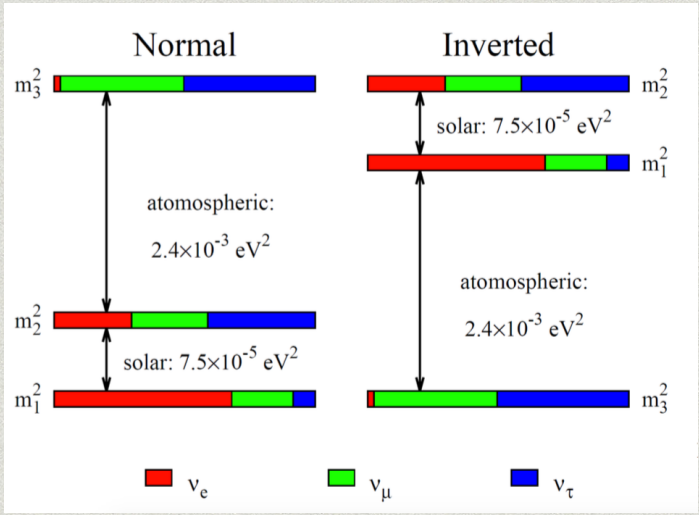
- Super-K
- SNO
- NovA
- Daya Bay
- .....

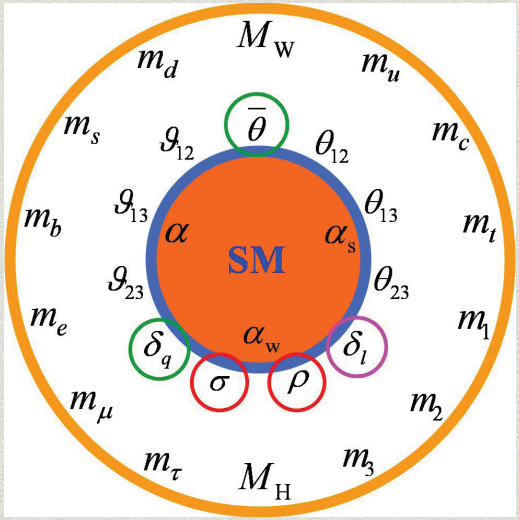


- Neutrino oscillation=>neutrinos are massive!

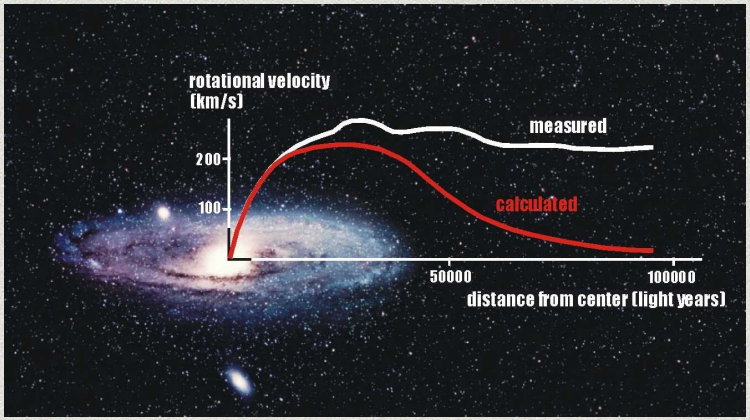
arXiv:1512.04207

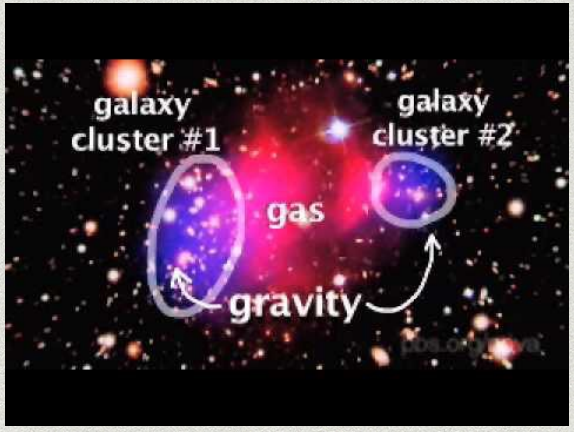


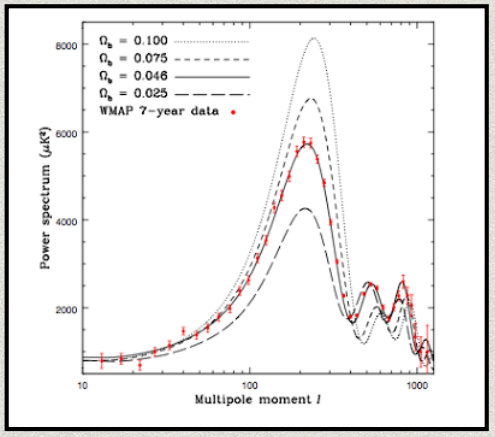




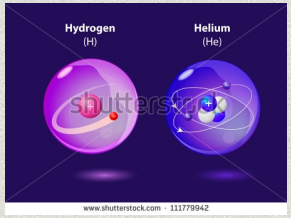
Dark matter





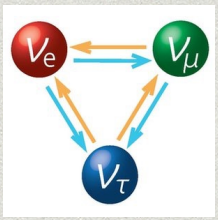


Dark Energy	Dark matter	Matter
68.3%	26.8%	4.9%

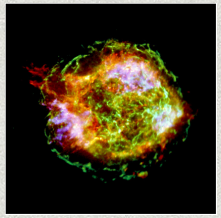


Hydrogen and Helium

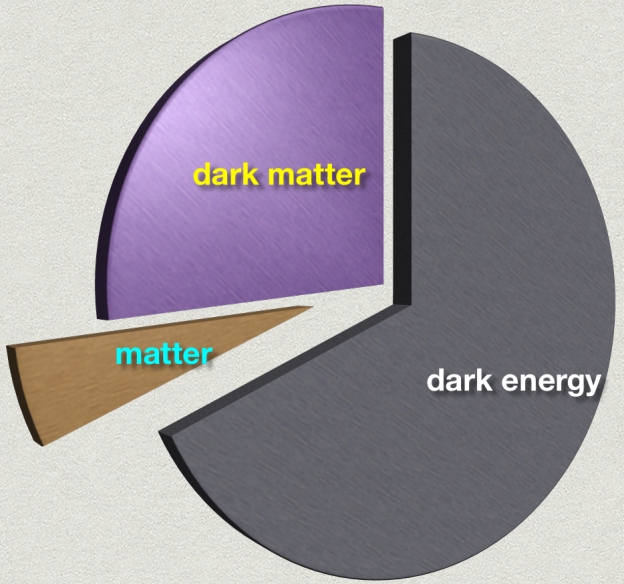
stars



neutrinos



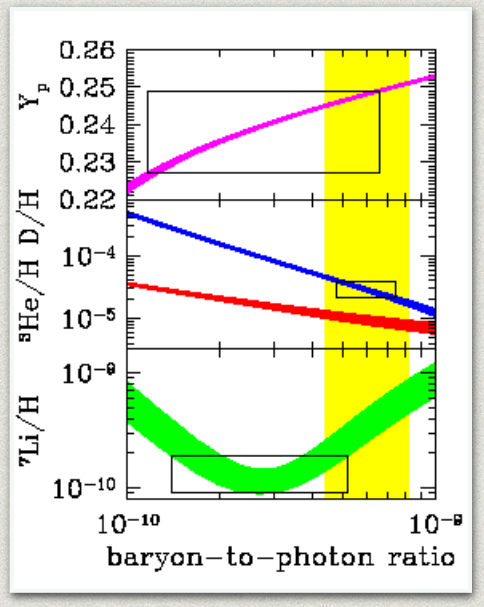
heavy elements

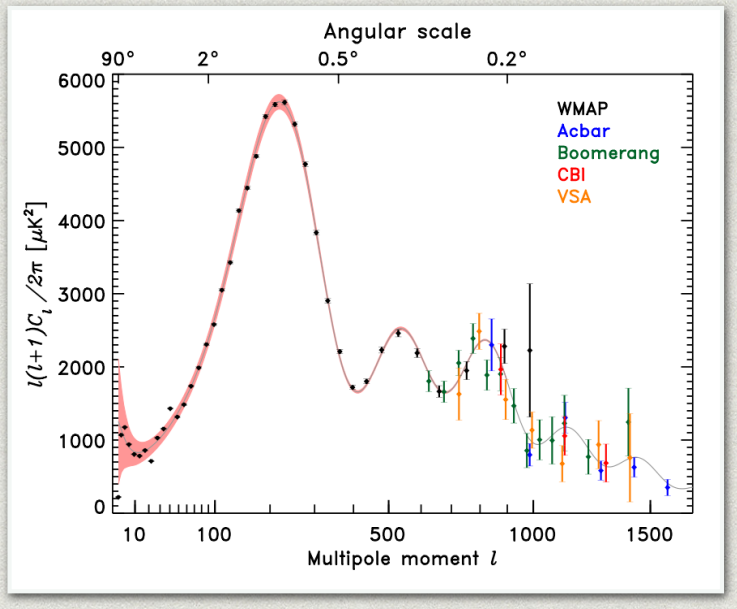


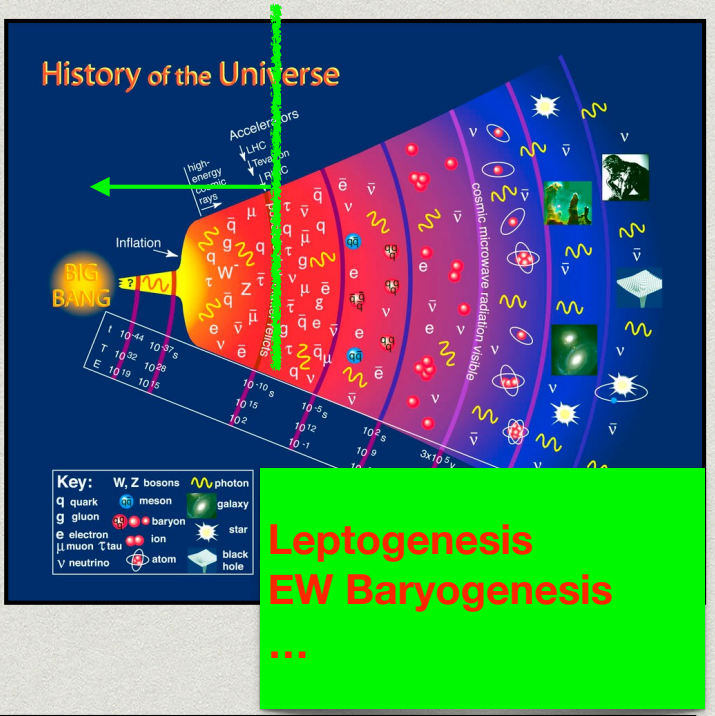
- Dark matter: neutral, colorless, weakly interacted particle

Baryon asymmetry

- No anti-galaxy was observed
- The abundance of the primordial elements and the height of the CMB power spectrum depend on the ratio of of baryon to photons







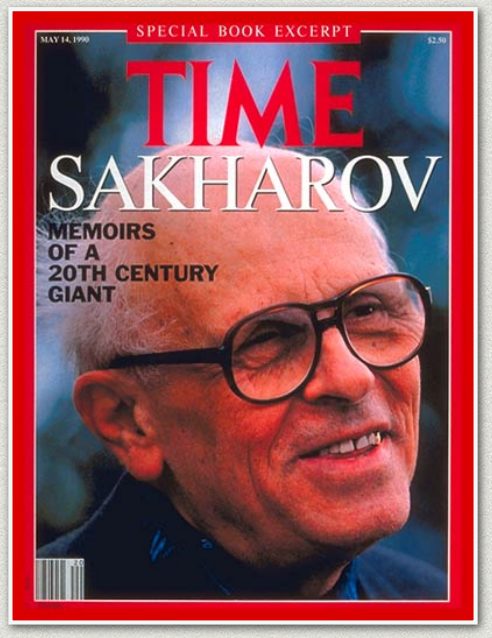
Baryon asymmetry: $Y_B = \frac{\rho_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$ (Planck 2015)

Outline

- **Brief overview of EWPT**
- EWBG from the Higgs portal
- EWBG from the spontaneous CPV

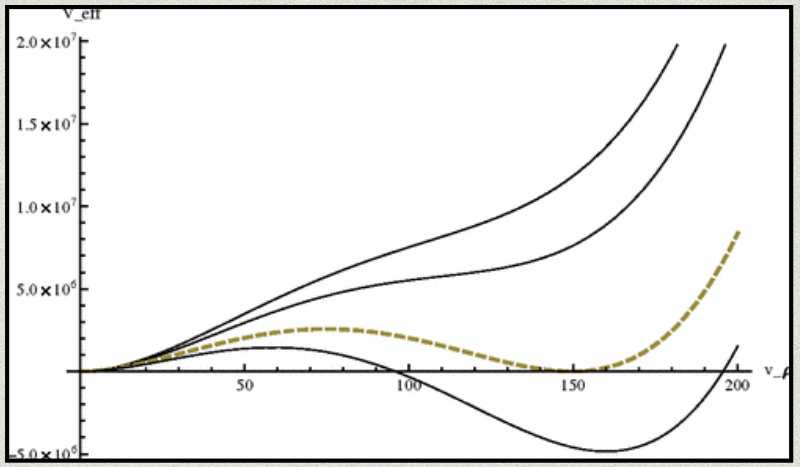
Why First order EWPT

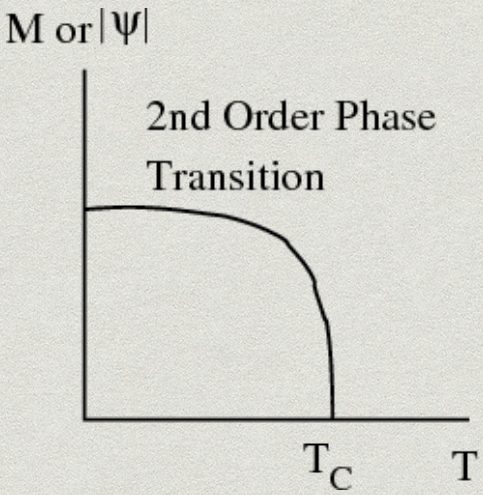
Because we believe that the BAU is generated from the EWBG

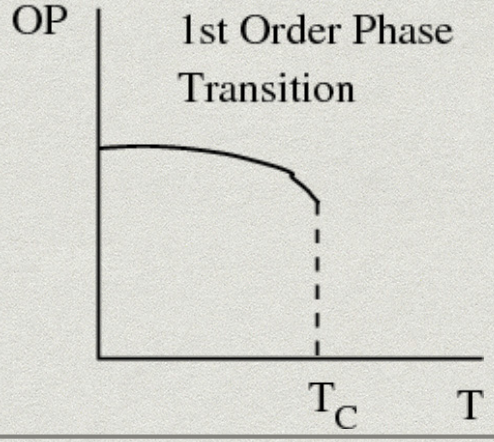


- ★Baryon number violation
- ★C&CP violation
- ★Departure from thermal equilibrium

→ First order electroweak phase transition if baryon asymmetry is generated during the EWPT without CPT violation.

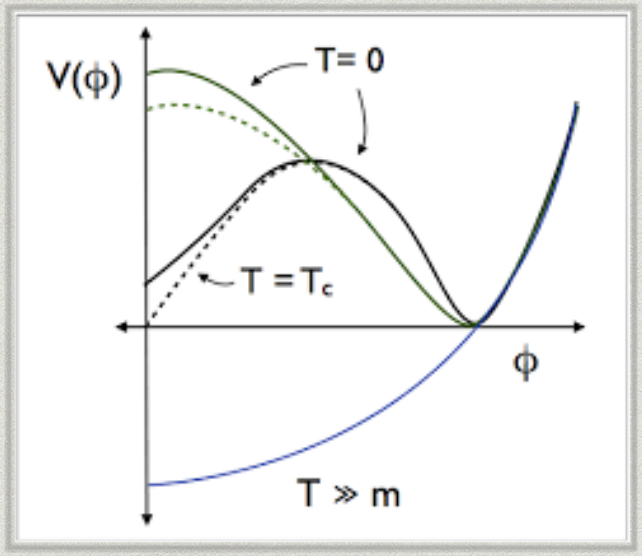


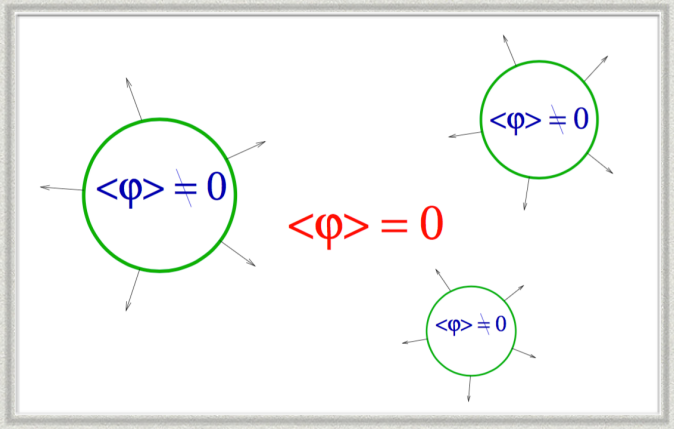




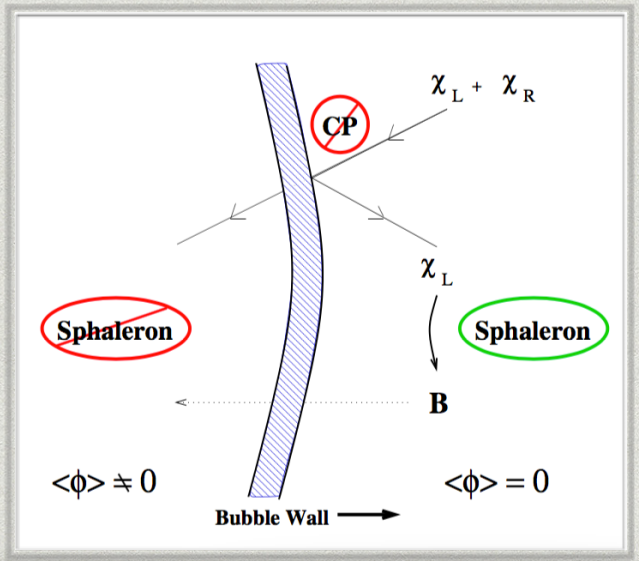
Electroweak Baryogenesis

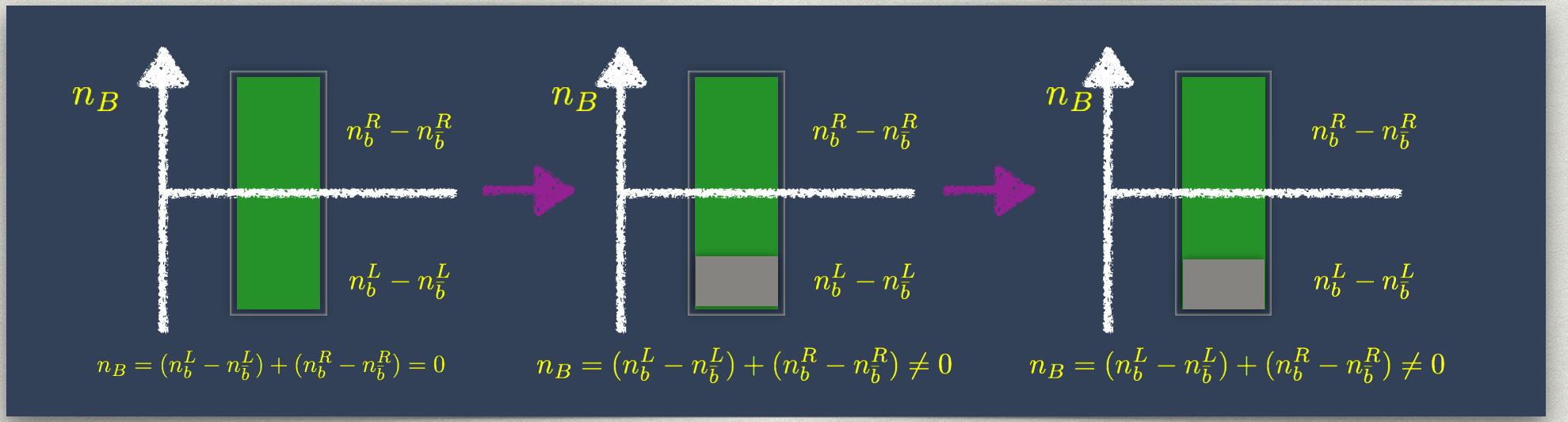
- **Generate BAU during the electroweak phase transition**





Basic description





The effective action

Generating functional (vacuum-to-vacuum amplitude):

$$Z[j] = \langle 0_{\text{out}} | 0_{\text{in}} \rangle = \int d\phi \exp\{i(S[\phi] + \phi j)\}$$

Connected generating functional:

$$Z[j] \equiv \exp\{iW[j]\}$$

The effective action(The Legendre transformation of *W*):

$$\Gamma = W[j] - \int d^4x \frac{\delta W[j]}{\delta j(x)} j(x)$$

$$\Gamma[\phi] = S[\phi] + \frac{i}{2} \text{Tr} \ln[G_0^{-1}(\phi)]$$

The standard 1pI *effective action*

$G_0(\phi)$: The green function in term of the background field!

$\Gamma[\phi]$ *is gauge dependent!*

The reason is that the generate functional is gauge dependent!

The effective potential in the SM

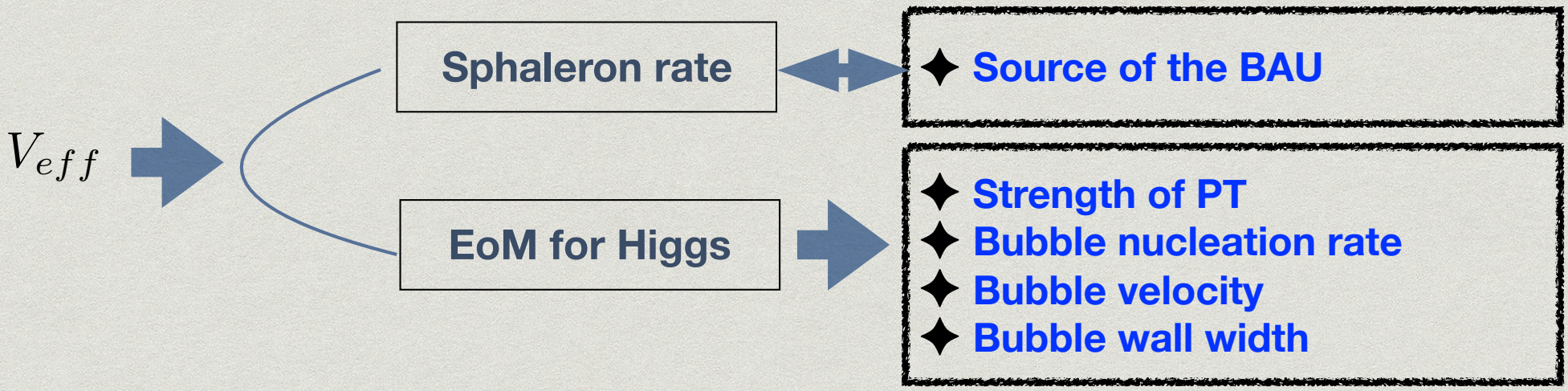
$$J_{B(F)}(x) = \int_0^\infty dt t^2 \ln\left(1 \mp \exp\{-\sqrt{t^2+x}\}\right) \qquad V_T = \frac{T^4}{2\pi^2}\left\{\sum_{i\in B} n_i J_B\left[\frac{m_i^2(h,s,\xi)}{T^2}\right] - \sum_{j\in F} n_j J_F\left[\frac{m_j^2(h)}{T^2}\right] - \sum_{k\in G} n_k J_B\left[\frac{m_k^2(h,s,\xi)}{T^2}\right]\right\}$$

- **V_0: The tree-level potential**
- **V_T: Finite temperature contribution**

$$V_{\rm eff} = V_0 + V_{\rm CW} + V_T + V_{\rm Daisy}$$

- **V_{CW}: Coleman-Weinberg term**
- **V_{ring}: The ring contribution**

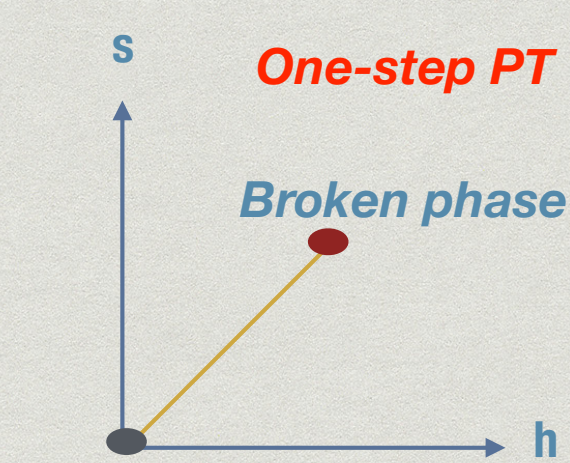
$$V_{\rm CW} = \frac{1}{64\pi^2}\sum_i (-1)^{2s_i} n_i m_i^4(h,s,\xi)\left[\log\frac{m_i^2(h,s,\xi)}{\mu^2} - C_i\right] \qquad V_T^{\rm ring} = \frac{T}{12\pi}\sum_i n_i\left\{(m_i^2(h,s))^{3/2} - (M_i^2(h,s,T))^{3/2}\right\}$$

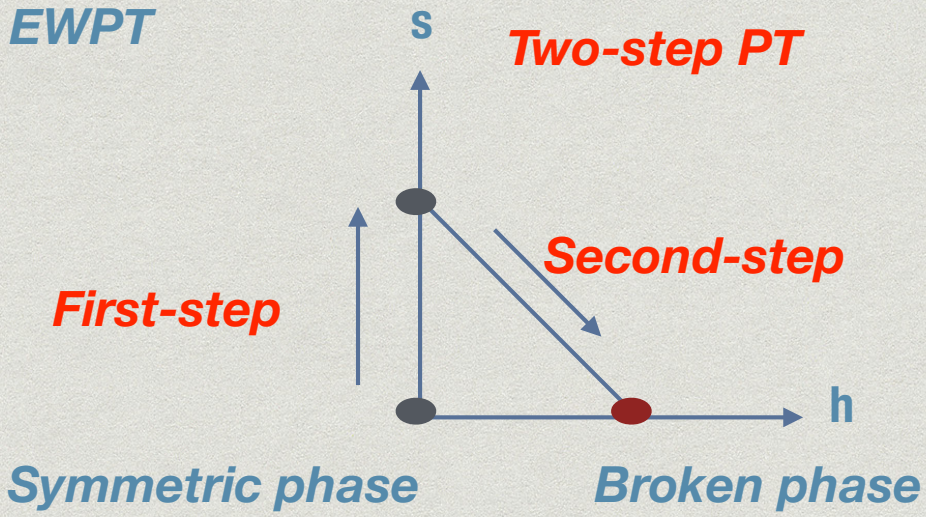


Bubble dynamics

1. Patterns of PT.

SM Higgs is too heavy to saturate first order EWPT





The barrier between the symmetric and the broken phase usually comes from radiative corrections

$$V_{\rm eff}(\phi, T) = \mathcal{A}(T)\phi^2 + \mathcal{B}(T)\phi^3 + \mathcal{C}(T)\phi^4 + \cdots$$

The barrier exists at the tree-level

Merits:

1.No mixing with the SM Higgs

2.Correlated with the dark matter

Bubble dynamics

2. Typical temperatures

Critical temperature T_C:

$$V_{\rm eff}(\phi_{\rm symmetric}, T)|_{T_C} = V_{\rm eff}(\phi_{\rm broken}, T)|_{T_C}$$

Bubble nucleation Temperature T_n:

$$\int_0^{t_n} \Gamma V_H(t) dt = \int_{T_n}^{\infty} \frac{dT}{T} \left(\frac{2\zeta M_{\rm pl}}{T}\right)^4 e^{-S_3/T} = \mathcal{O}(1),$$

Γ	**Bubble nucleation rate**
$V_H(t)$	**One-horizon volume**

PT completed Temperature T_d:

$$f(T_d) = \frac{4\pi}{3} \int_{T_d}^{T_c} \frac{dT}{T} \frac{\Gamma(T)}{H(T)^4} v_w^3 \left(1 - \frac{T_d}{T}\right)^3 \equiv 1$$

$H(T)$	**Hubble constant**
v_w	**Bubble wall velocity**
$f(T)$	**Friction of the universe covered by the broken phase**

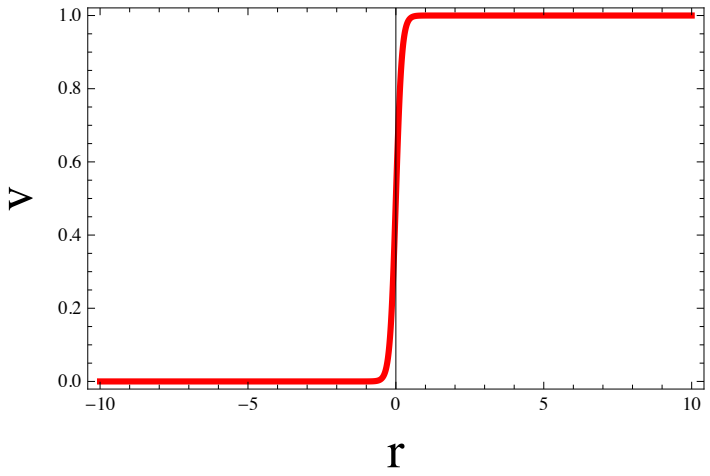
★**Relationships**

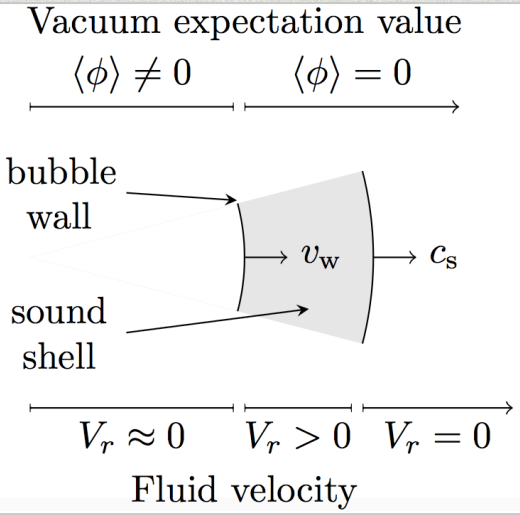
$T_c > T_n > T_d$

Bubble dynamics

3. Bubble nucleation

Euclidean equation of motion	$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} - V''(\phi) = 0$
Euclidean action for the solution of EoM	$S_3 = 4\pi \int r^2 dr \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi)\right]$
Bubble nucleation rate per unit time per unit volume	$\Gamma_n(T) \approx T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} \exp\left[-\frac{S_3(T)}{T}\right]$
Bounce solution to the EoM	$V(z) = \frac{1}{2}v(T)\left[1 + \tanh\left(3\frac{z}{L_w}\right)\right]$





Bubble dynamics

4. Physical parameters relating to PT

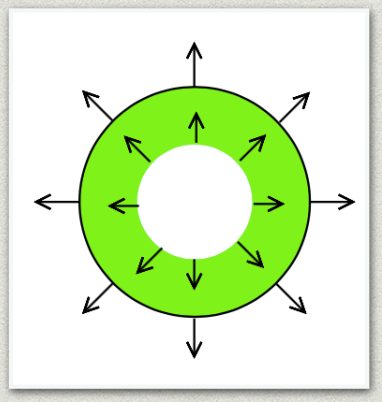
v_w	*Bubble wall velocity*	*calculated numerically*
l_w	*Bubble wall width*	*calculated numerically*
α	*Released energy to radiation energy*	$\alpha = \Lambda/\rho_{\mathrm{rad}}$
κ	*The efficiency factor*	$\kappa = \frac{3}{\varepsilon v_w^3}\int w(\xi)v^2\gamma^2\xi^2 d\xi$
Λ	*Latent heat*	$\Lambda = \Delta\left(V - \frac{dV}{dt}T\right)$

v_w	**Relevant to the calculation of baryon number density generated during the EWPT**
l_w	

α	**Relevant to the calculation of stochastic gravitational wave spectrum emitted during the EWPT**
κ	
Λ	

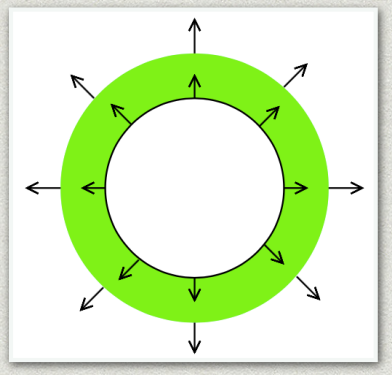
Bubble dynamics

5. Types of bubble



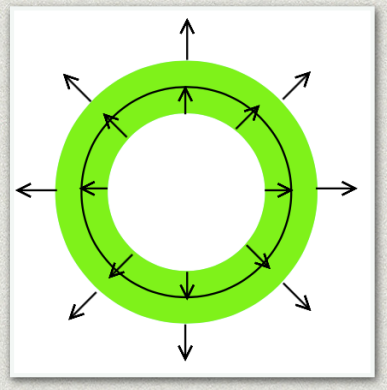
supersonic

Fluid at rest in front of the wall



subsonic

Fluid at rest behind the wall



supersonic

$v_w > c_s = v_- > v_+$

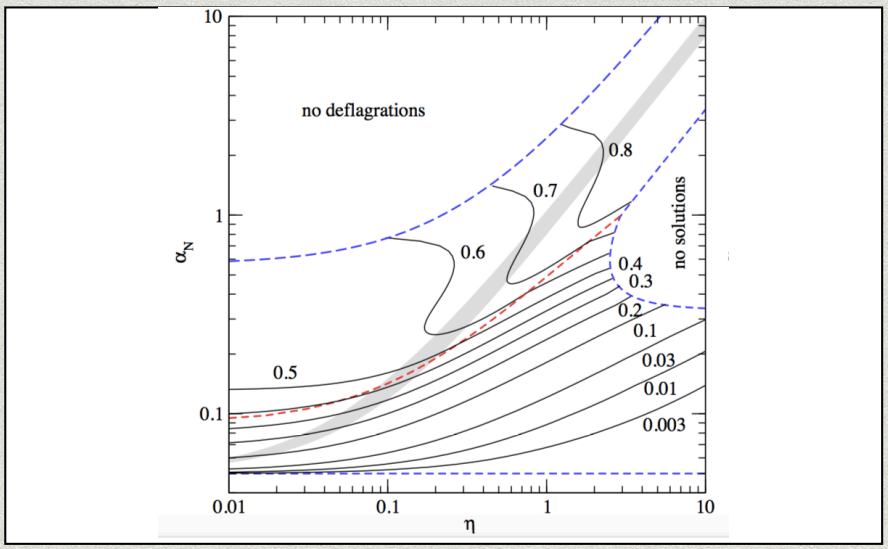
6.Friction

EoM of the Higgs field:

$$\Box\phi + \frac{dV}{d\phi} + \sum_n \frac{dm_n^2}{d\phi} \int \frac{d^3p}{2\pi^3}\frac{1}{2E}[f_n(p,x) + \delta f_n(p,x)] = 0$$

Friction term

Comments: hard to calculate, but it is important for both EWBG and GW studies.



Outline

- Brief overview of EWPT
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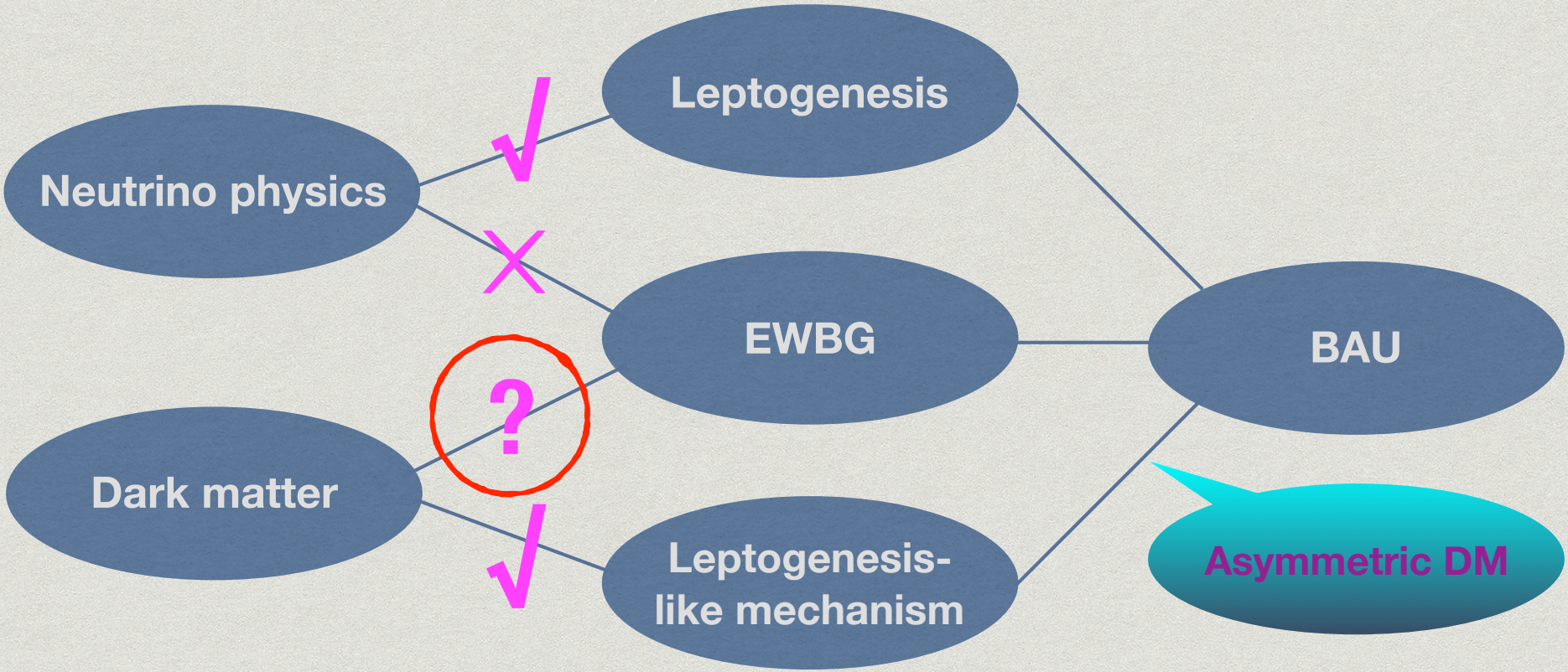
- EWBG from the spontaneous CPV

Who triggered EWBG

- Neutrino mass triggered Leptogeneis!
- What trigged EWBG from the point of view of **Bottom-up**?



Dark Matter from X-portal

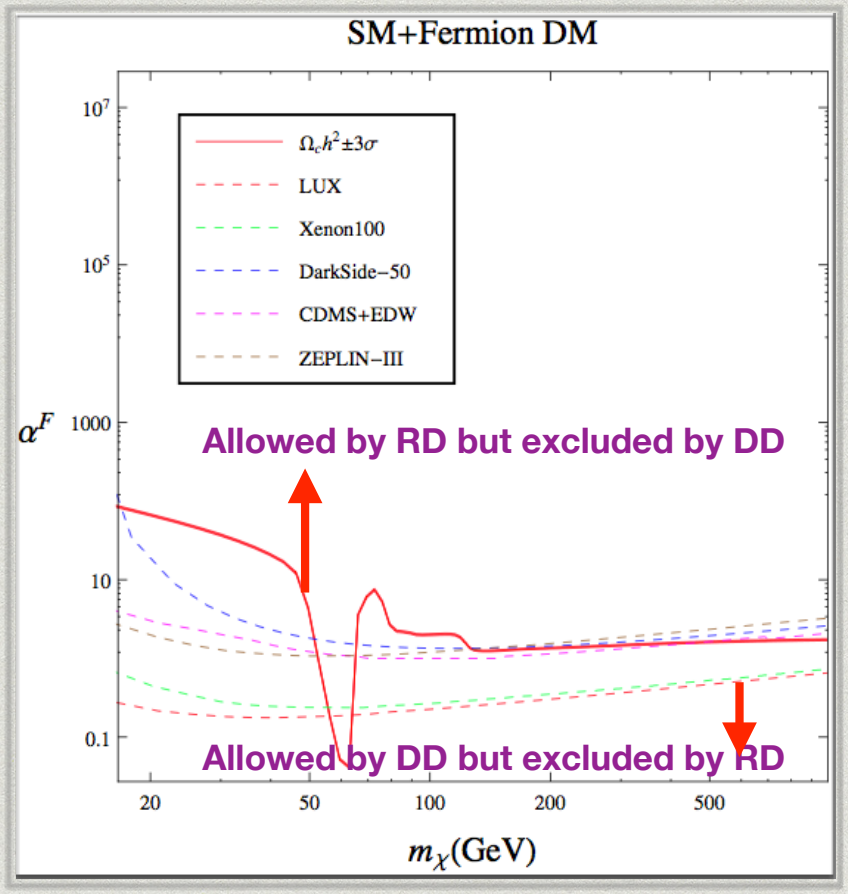
- **Vector portal**
  dark photons
- top portal
  Motivated by the forward-backward asymmetry
- bottom portal
  Motivated by the GeV gamma ray accesses
- neutrino portal
- Axion portal
- Higgs portal

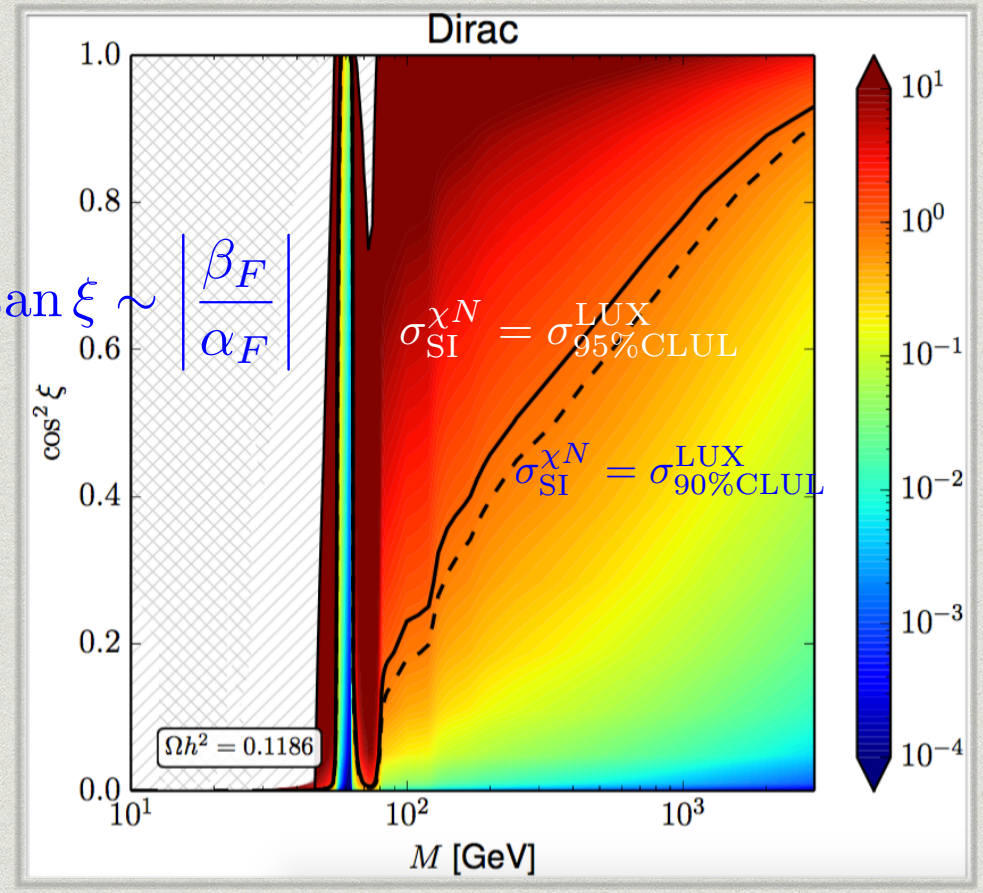
→ Flavored DM

1. ~~B~~
2. ~~CP~~ with Higgs
3. ~~Equilibrium~~

Status of Higgs portal

Wang et al,1404.2283





$\alpha_F \bar{\chi}\chi H^\dagger H$

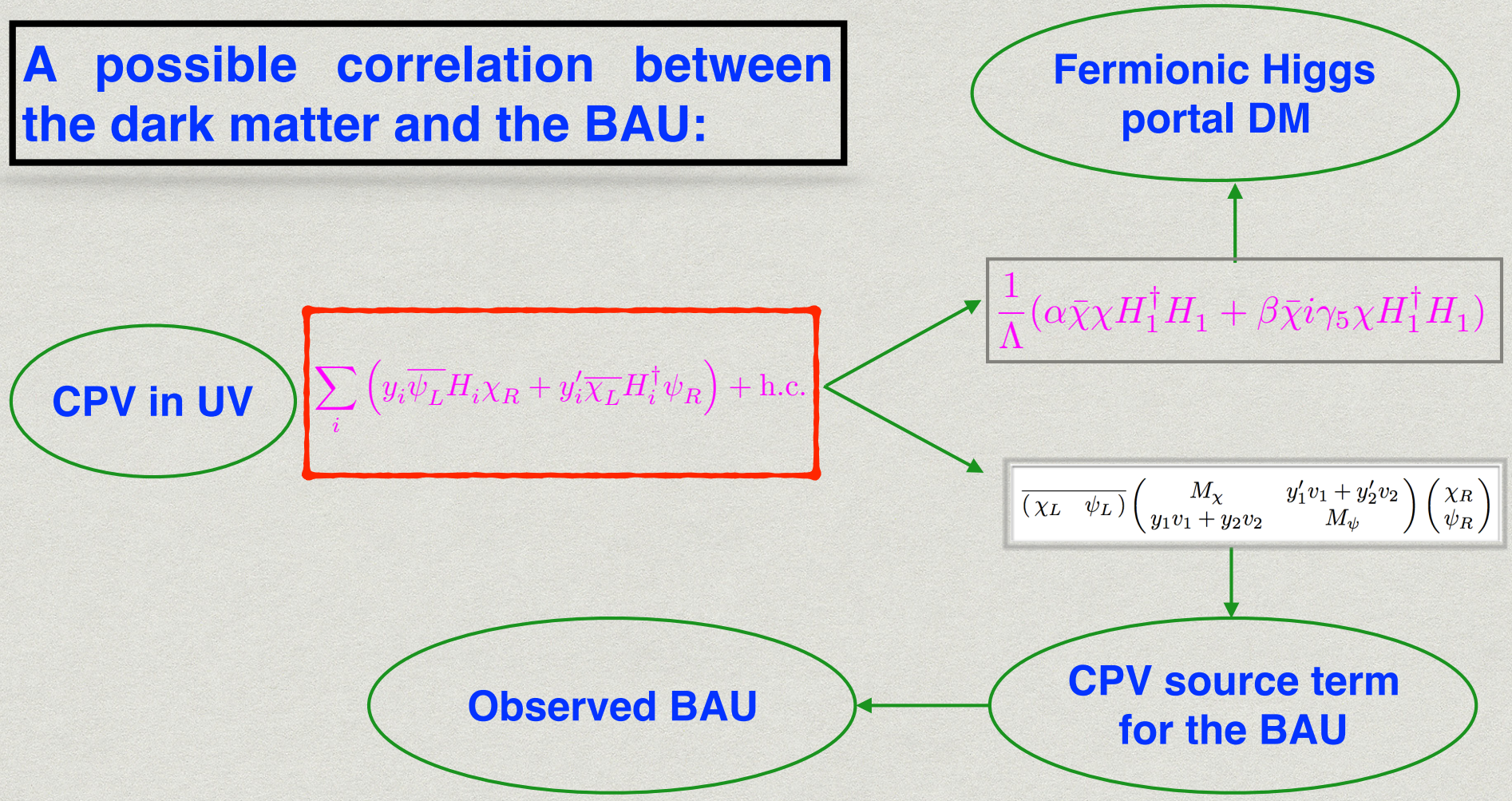
$\alpha_F \bar{\chi}\chi H^\dagger H + \beta_F \bar{\chi} i\gamma_5 \chi H^\dagger H$

Excluded!

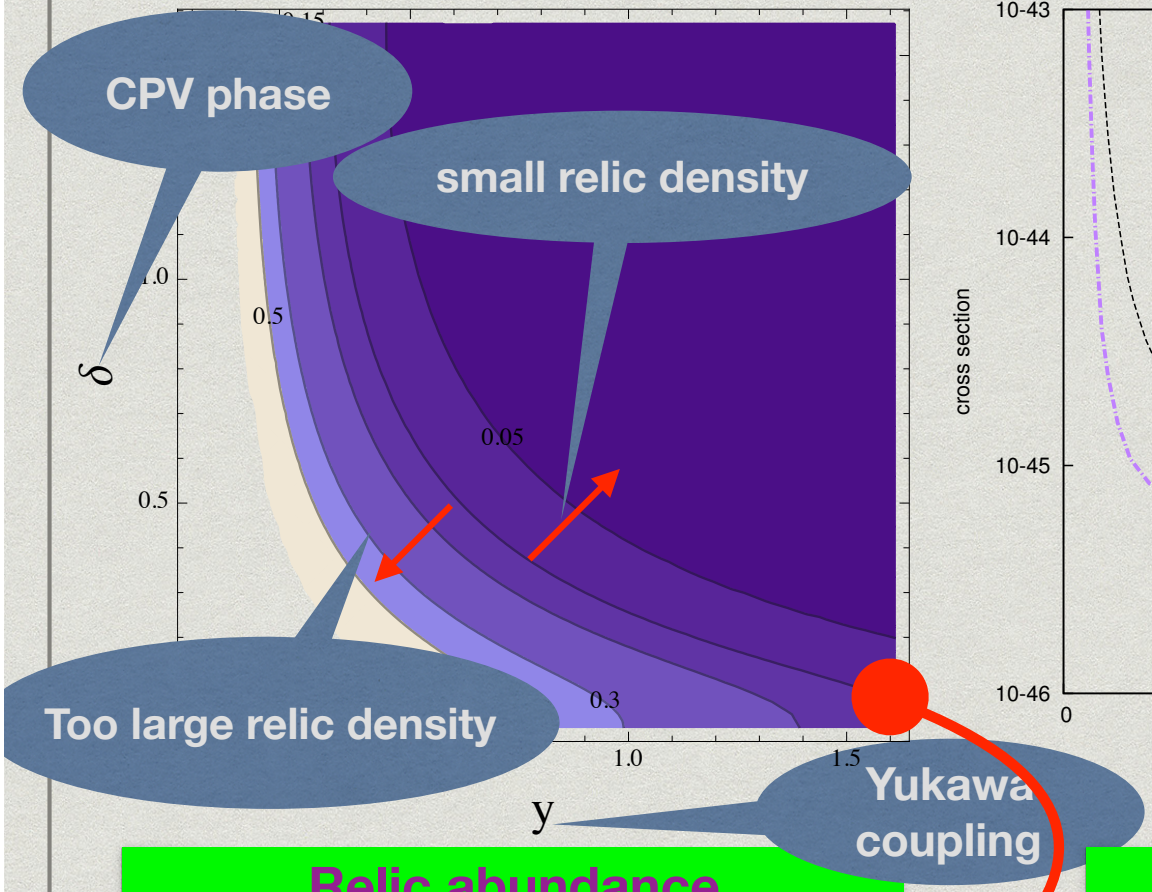
CPV in the dark matter interactions!

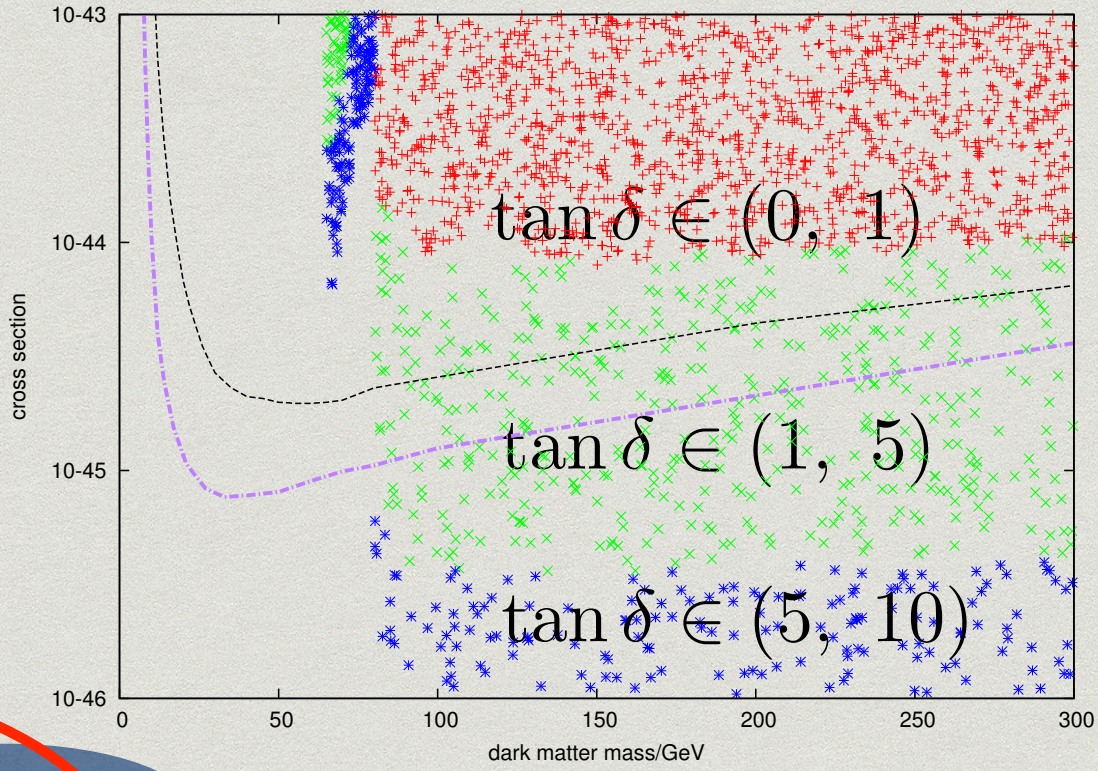
DM&EWBG

A possible correlation between the dark matter and the BAU:



DM in detail





Relic abundance

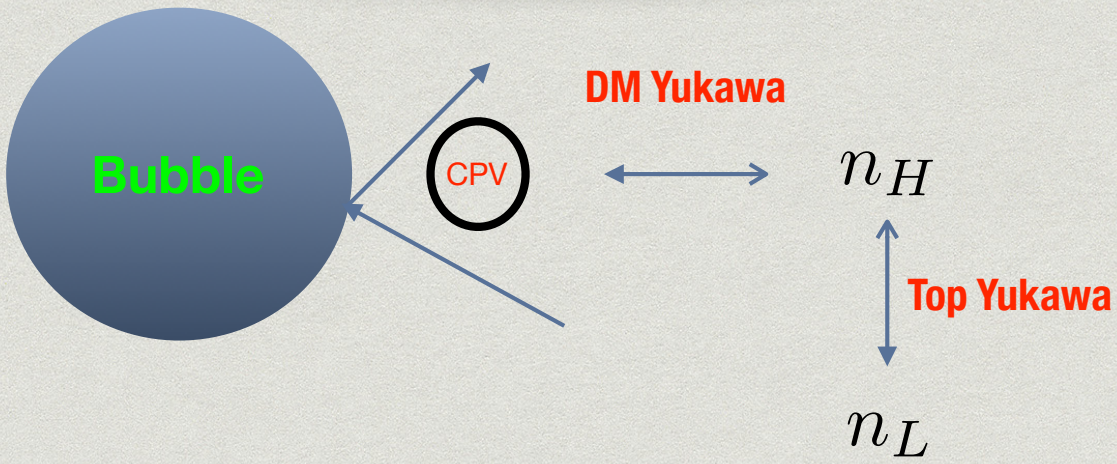
$$\Omega h^2 = 0.1199$$

SI cross section

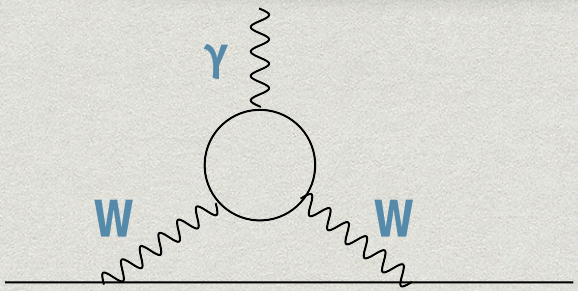
$$\tan\delta \in (0,\ 1), (1,\ 5), (5,\ 10)$$

EWBG in detail (1)

1. 2HDM potential gives rise to a first order EWPT

2. 

3. $\partial_t \rho_B(x) - D \bigtriangledown \rho_B(x) = -\Gamma_{\rm ws} F_{\rm ws}(x)[n_L(x) - R\rho_B(x)]$

4. EDM 

EWBG in detail (2)

- Transport equations:

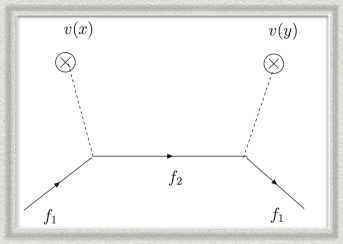
$$\frac{\partial n}{\partial t} + \nabla \cdot j(x) = -\int d^3z \int_{-\infty}^{x_0} dz^0 \mathrm{Tr}[\Sigma^>(x,z)S^<(z,x) - S^>(x,z)\Sigma^<(z,x) + S^<(x,z)\Sigma^>(z,x) - \Sigma^<(x,z)S^>(z,x)]$$

Bubble parameters

- CPV source term: using the VEV-insertion method

$$S^{\psi}_{\mathrm{CP}}(x) = \mathrm{Im}[y_1 y_2^* + y_1' y_2'^*](v_1\dot{v}_2 - \dot{v}_1 v_2) \int \frac{k^2 dk}{\pi^2 \omega_\chi \omega_\psi} \mathrm{Im}\left\{(\mathcal{E}_\psi \mathcal{E}_\chi^* - k^2)\frac{n(\mathcal{E}_\psi) - n(\mathcal{E}_\chi^*)}{(\mathcal{E}_\psi - \mathcal{E}_\chi^*)^2} + (\mathcal{E}_\chi \mathcal{E}_\psi + k^2)\frac{n(\mathcal{E}_\chi) + n(\mathcal{E}_\psi)}{(\mathcal{E}_\chi + \mathcal{E}_\psi)^2}\right\}$$

$$S^{\psi\prime}_{\mathrm{CP}}(x) = \mathrm{Im}[y_1 y_2' + y_1'^* y_2^*](v_1\dot{v}_2 - \dot{v}_1 v_2) \int \frac{k^2 dk}{\omega_\chi \omega_\psi \pi^2} |M_\chi||M_\psi| \mathrm{Im}\left\{\frac{n(\varepsilon_\chi) - n(\varepsilon_\psi^*)}{(\varepsilon_\chi - \varepsilon_\psi^*)^2} - \frac{n(\varepsilon_\chi) + n(\varepsilon_\psi)}{(\varepsilon_\chi + \varepsilon_\psi)^2}\right\}.$$



Yukawa interactions as the CPV sources

- Boltzmann equations

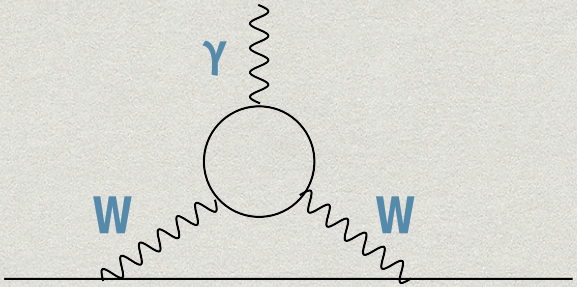
$$\partial_\mu \psi_\mu = +\Gamma^+_\psi \left(\frac{\chi}{k_\chi} + \frac{\psi}{k_\psi}\right) + \Gamma^-_\psi \left(\frac{\chi}{k_\chi} - \frac{\psi}{k_\psi}\right) + \left(\sum_i \Gamma_{y_i}\right)\left(\frac{\chi}{k_\chi} - \frac{H}{k_H} - \frac{\psi}{k_\psi}\right) + S^\psi_{\mathrm{CP}}$$

$$\partial_\mu \chi_\mu = -\Gamma^+_\psi \left(\frac{\chi}{k_\chi} + \frac{\psi}{k_\psi}\right) - \Gamma^-_\psi \left(\frac{\chi}{k_\chi} - \frac{\psi}{k_\psi}\right) - \left(\sum_i \Gamma_{y_i}\right)\left(\frac{\chi}{k_\chi} - \frac{H}{k_H} - \frac{\psi}{k_\psi}\right) - S^\psi_{\mathrm{CP}}$$

$$\partial_\mu H_\mu = \Gamma_{Y_t}\left(\frac{T}{k_T} - \frac{H}{k_H} - \frac{Q}{k_Q}\right) + \left(\sum_i \Gamma_{y_i}\right)\left(\frac{\chi}{k_\chi} - \frac{H}{k_H} - \frac{\psi}{k_\psi}\right) - \Gamma_h \frac{H}{k_H},$$

EDM in detail

- Diagram: Barr-Zee



- Electron EDM:

$$d_e \approx d_e^{(2l)} s_W^{-2} \mathrm{Im}(\mathcal{U}_{L2i}\mathcal{U}^*_{R2i}) \frac{m_\psi + m_i}{m_W^2} f_{WW}(r_1, r_2)$$

Mixing matrix element

masses of new fermions

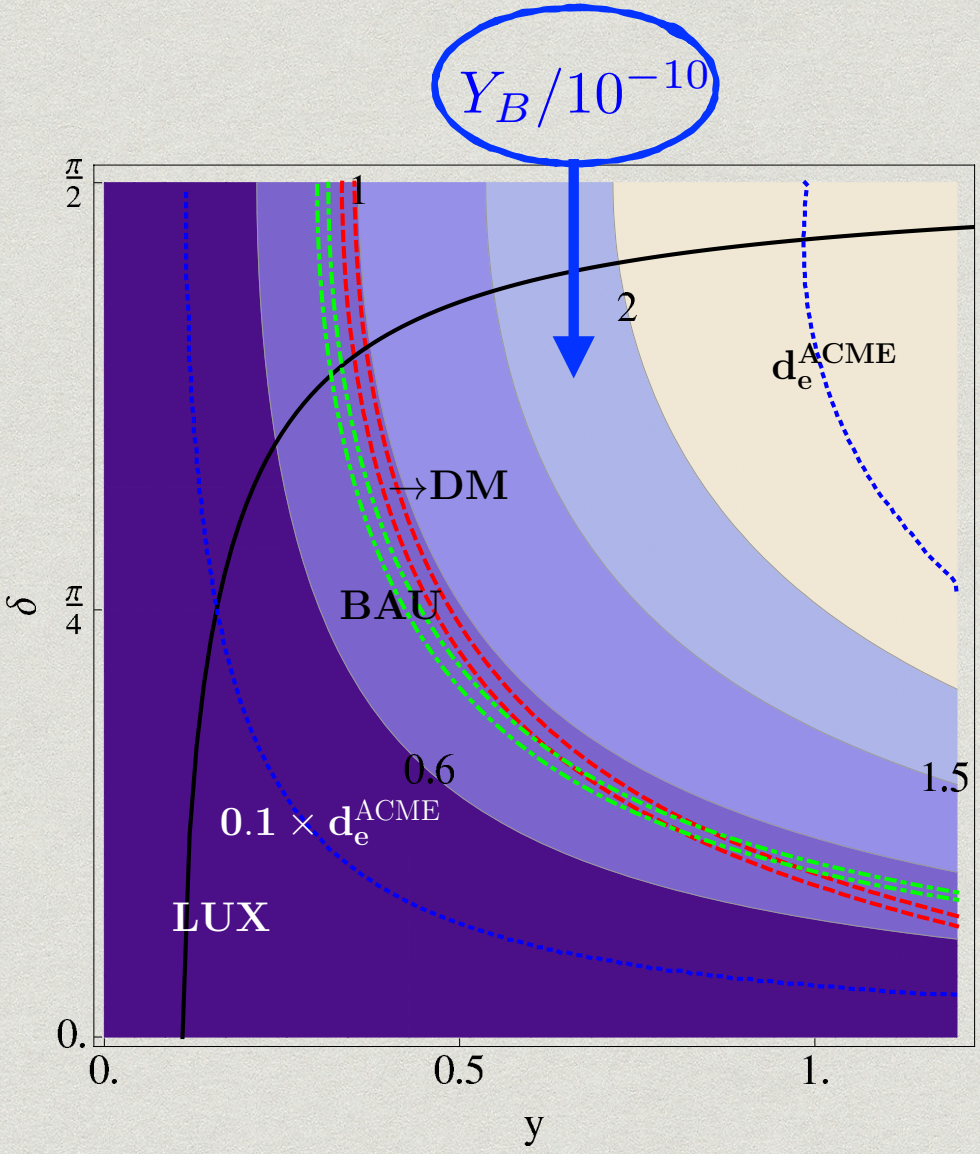
$$d_e^{2l} \sim 2.5 \times 10^{-27} e \cdot \mathrm{cm}$$

- Neutron EDM:

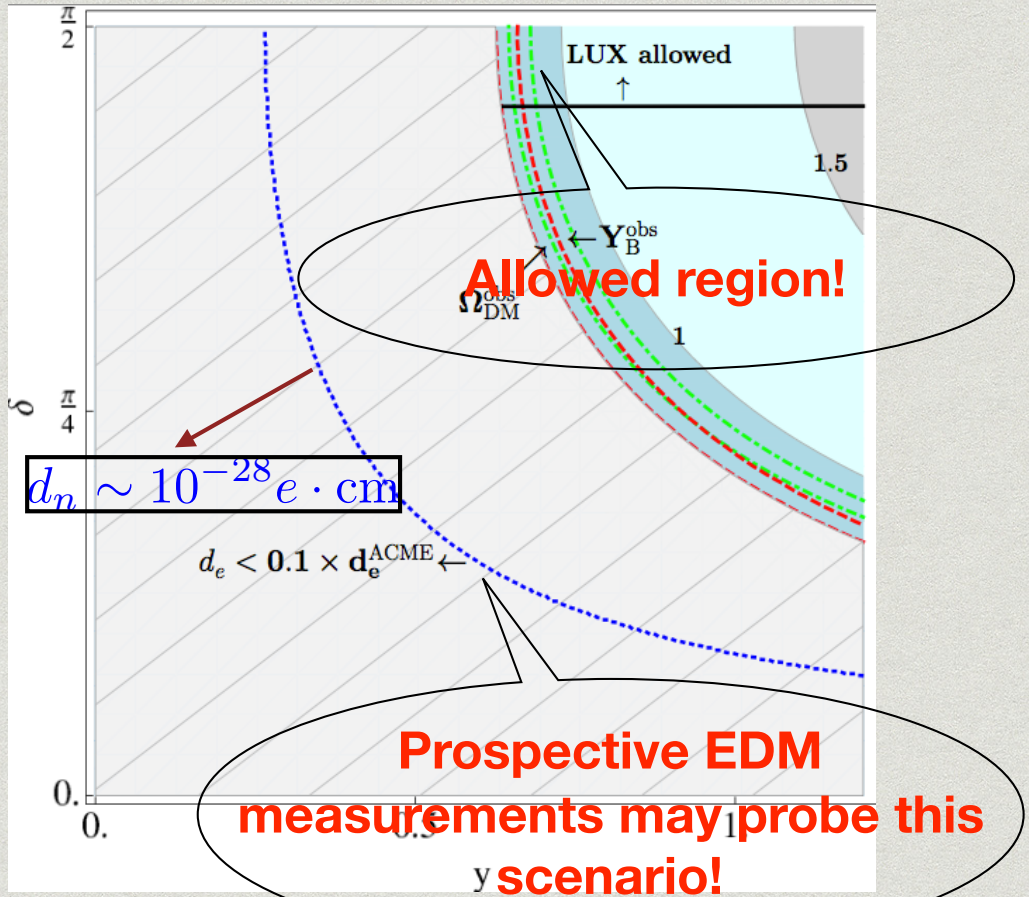
$$\frac{d_e}{dq} \sim \frac{m_e}{m_q} \sim 0.1$$

$$d_n \sim 10 \times d_e$$

Higgs portal versus EWBG



Higgs portal versus EWBG



Outline

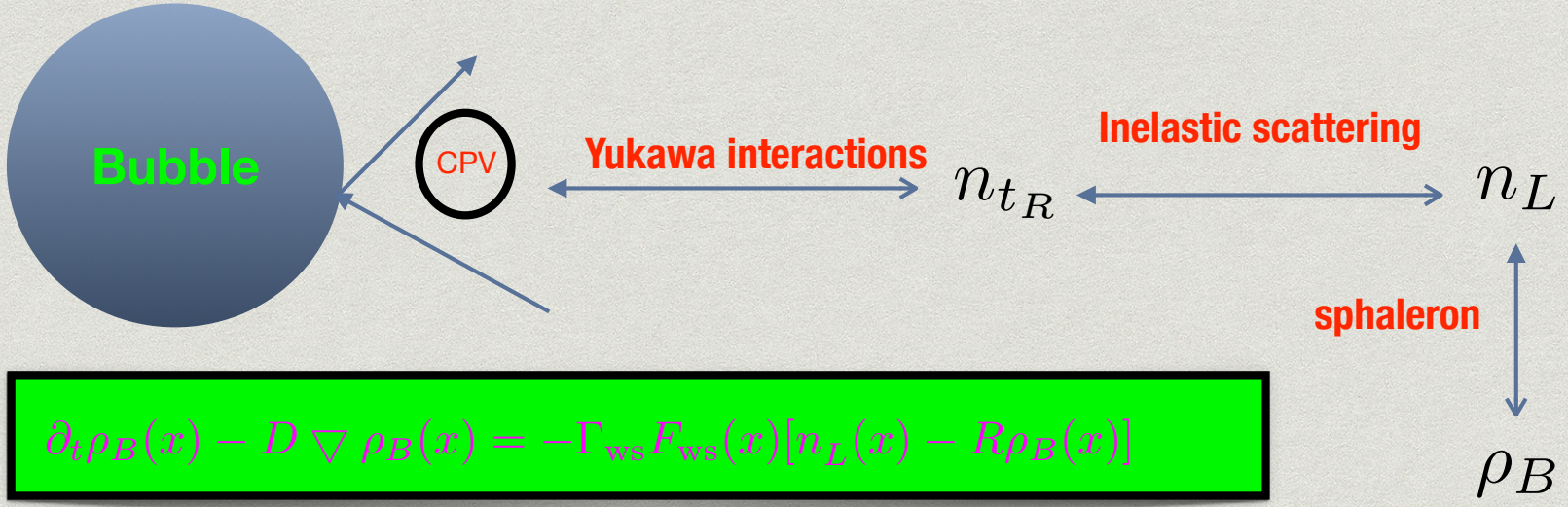
- Brief overview of EWPT
- EWBG from the Higgs portal
- **EWBG from the spontaneous CPV**

BAU during the EWPT

Basic description

Sakharov:

- ~~B~~
- ~~C&CP~~
- **First order EWPT**



Questions: Where the CP violation from? How to avoid the EDM constraint? How to get a first order EWPT

Properties of the EWPT (1)

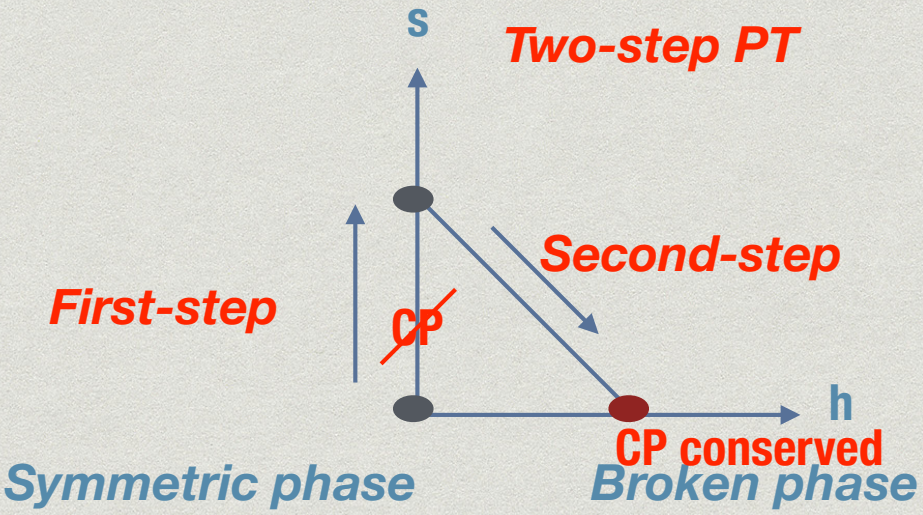
EWBG from spontaneous CP at the finite T

Lemma:
spontaneous CP violation in the theory of one complex scalar field may occur only when the related U(1) is explicitly broken by at least two spurions whose U(1) charges are different in magnitude

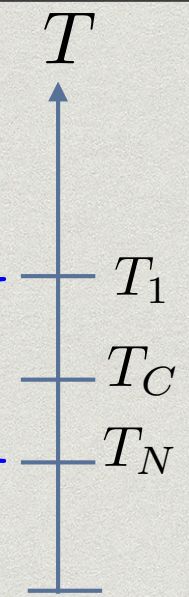
$$V = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 - \mu_A^2(S^\dagger S) + \lambda_1(S^\dagger S)^2 + \lambda_2(H^\dagger H)(S^\dagger S) - \frac{1}{2}\mu_B^2 S^2 + \frac{1}{2}\lambda_3 S^4 + \text{h.c.}$$

spurions spurions

How to avoid the constraint of non-observation of EDMs?



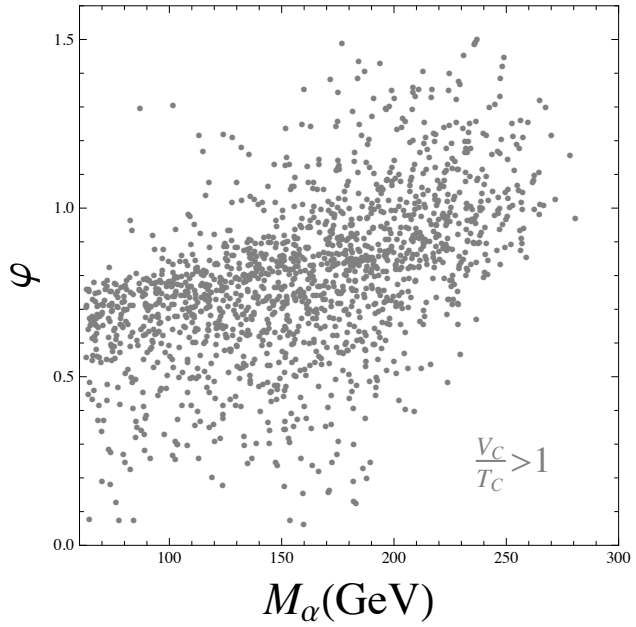
$$\varphi = \pm\frac{1}{2}\arccos\left[\frac{\lambda_1-\lambda_3}{2\lambda_3}\frac{m_\beta^2-m_\alpha^2}{\lambda_2 v^2 - m_\alpha^2 - m_\beta^2 + 2\Pi_\alpha}\right]$$

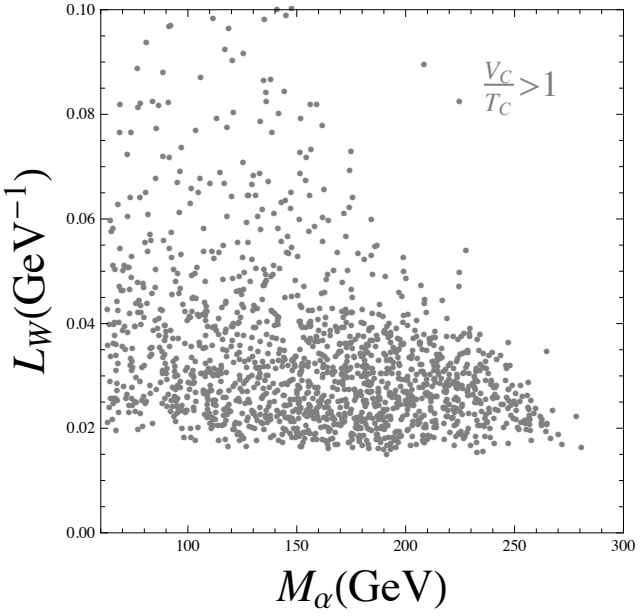


Properties of the EWPT (2)

CP phase and strength of the EWPT

EoM for three background fields:	$\frac{d^2\phi_i}{dr^2}+\frac{2}{r}\frac{d\phi_i}{dr}=\bar{V}'(\vec{\phi})$
Bubble wall width:	$L_w^2 \approx 1.35\frac{\lambda+\sqrt{\lambda\lambda_\varrho}}{(\lambda_2-2\sqrt{\lambda\lambda_\varrho})[\lambda v_0^2-\Pi_h(T_C^2)]}\times\left(1+\sqrt{\frac{\lambda_2^2}{4\lambda\lambda_\varrho}}\right)$





Transport equations

EWBG

Transport equation

$$\frac{\partial n}{\partial t} + \nabla \cdot j(x) = -\int d^3z \int_{-\infty}^{x_0} dz^0 \mathrm{Tr}[\Sigma^>(x,z)S^<(z,x) - S^>(x,z)\Sigma^<(z,x) + S^<(x,z)\Sigma^>(z,x) - \Sigma^<(x,z)S^>(z,x)]$$

Source term:

$$S_{\rm top}^{\rm CPV} = -2\zeta^2 v_s^2 \dot{\varphi} \int \frac{k^2 dk}{\pi^2 \omega_L \omega_R} \mathrm{Im}\left\{(\varepsilon_L \varepsilon_R^* - k^2)\, \frac{n(\varepsilon_L) - n(\varepsilon_R^*)}{(\varepsilon_L - \varepsilon_R^*)^2} + (\varepsilon_L \varepsilon_R + k^2) \frac{n(\varepsilon_L) + n(\varepsilon_R)}{(\varepsilon_L + \varepsilon_R)^2}\right\}$$

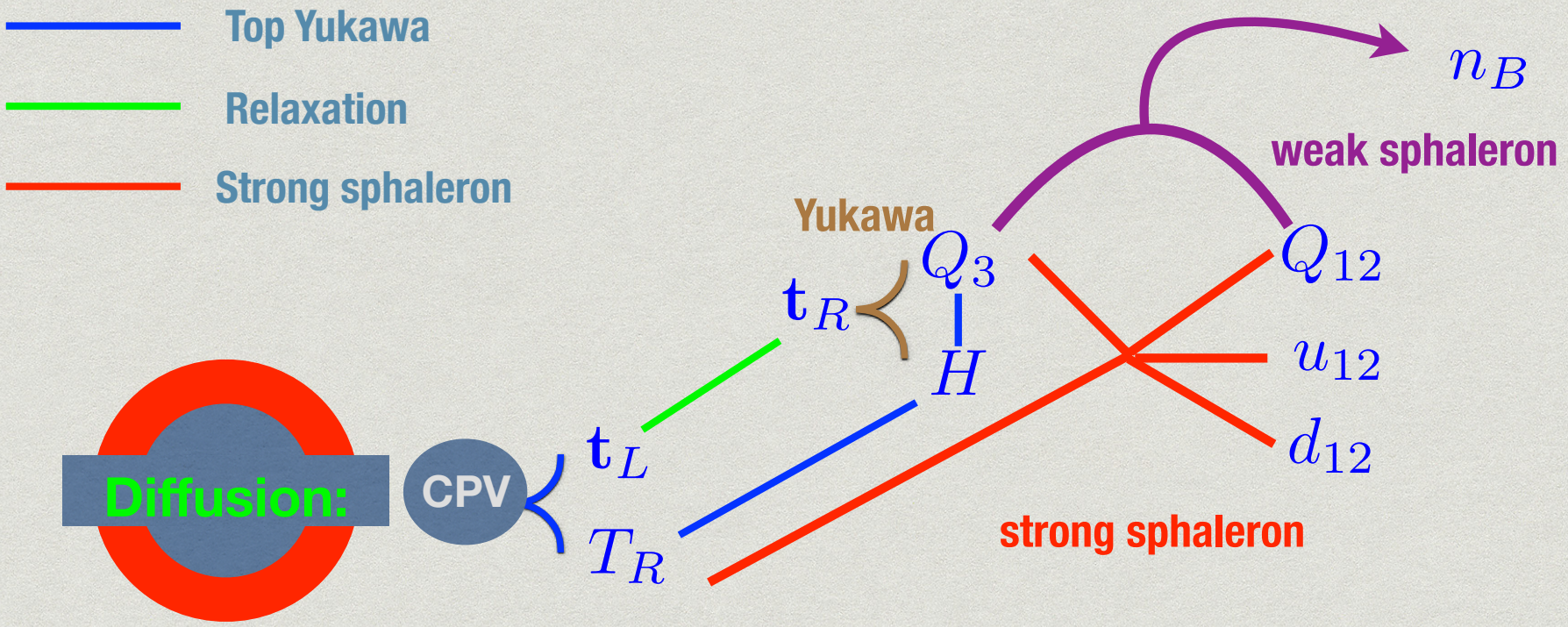
$$\zeta \overline{\mathrm{t}_L} S t_R + (M_{\mathrm{t}}) \overline{\mathrm{t}_L} \mathrm{t}_R + \mathrm{h.c.}$$

All equations

$$\begin{aligned}
\partial^\mu Q_\mu &= +\Gamma_{m_t} \mathcal{R}_T^- + \Gamma_{Y_t} \delta_t + \Gamma_{y'} \delta_{\mathrm{t}'} + 2\Gamma_s \delta_s \\
\partial^\mu T_\mu &= -\Gamma_{m_t} \mathcal{R}_T^- - \Gamma_{Y_t} \delta_t - \Gamma_s \delta_s - \Gamma_\zeta \delta_{\mathrm{t}} \\
&\quad + \Gamma_{\mathrm{t}}^+ \mathcal{R}_{\mathrm{t}}^+ + \Gamma_{\mathrm{t}}^- \mathcal{R}_{\mathrm{t}}^- + S_{\rm top}^{\rm CPV} \\
\partial^\mu \mathrm{t}_\mu &= +\Gamma_{m_{\mathrm{t}}} \mathcal{R}_\Lambda^- - \Gamma_{\mathrm{t}}^+ \mathcal{R}_{\mathrm{t}}^+ - \Gamma_{\mathrm{t}}^- \mathcal{R}_{\mathrm{t}}^- + \Gamma_\zeta \delta_{\mathrm{t}} - S_{\rm top}^{\rm CPV} \\
\partial^\mu \mathrm{t}'_\mu &= -\Gamma_{m_{\mathrm{t}}} \mathcal{R}_\Lambda^- - \Gamma_{y'} \delta_{\mathrm{t}'} \\
\partial^\mu S_\mu &= -\Gamma_\zeta \delta_{\mathrm{t}} \\
\partial^\mu H_\mu &= -\Gamma_{Y_t} \delta_t - \Gamma_{y'} \delta_{\mathrm{t}'} \qquad (13)
\end{aligned}$$

Diffusions

EWBG



Baryon number density: $\hat{n}_B = -\frac{3\Gamma_{ws}}{2D_Q\lambda_+}\int_{-\infty}^{-L_w/2} dz n_L(z)e^{-\lambda_- z}$

Damping of the domain wall

EWBG

Problems

No BAU left

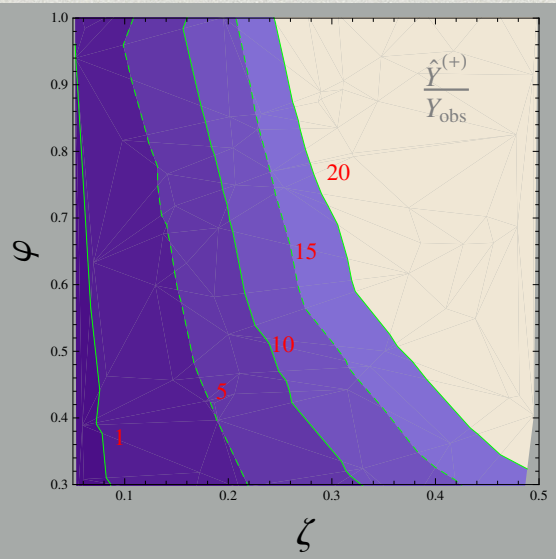
Solution: Adding a Z_2 breaking term to the Higgs potential: Δs+h.c.

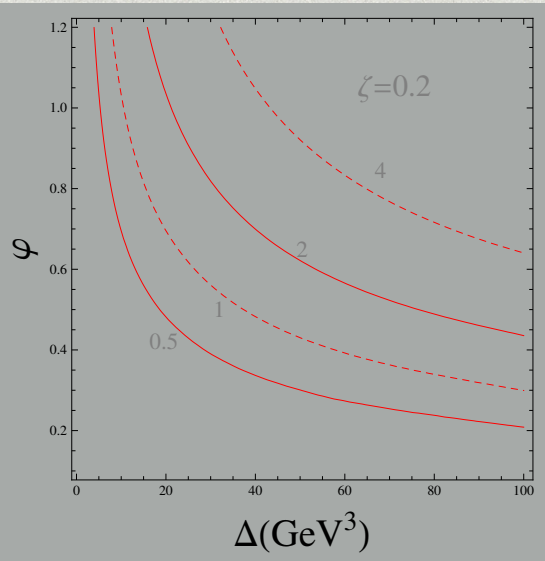
Ratio of bubbles

$$\frac{N_+}{N_-} = \exp\left(\frac{\Delta F}{T}\right)$$

Final BAU

$$n_B = \hat{n}_B^{(+)} \frac{N_+ - N_-}{N_+ + N_-}$$





Summary

- Physics relevant to electroweak phase transition are briefly reviewed. We need to calculate many physical quantities, but many are very hard to do. Further study is needed! (Hard work is really hard.)
- The EWBG may be triggered by the Higgs portal model, killing two birds with one stone!
- The baryon asymmetry of the universe generated during the first order EWPT is discussed, especially I showed how to generate sufficient BAU with the spontaneous CP phase and a two-step EWPT.

Thank you