CP VIOLATION AND THE BARYON ASYMMETRY

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30-JUL-2019@呼和浩特
第17届重味物理与CP破坏研讨会

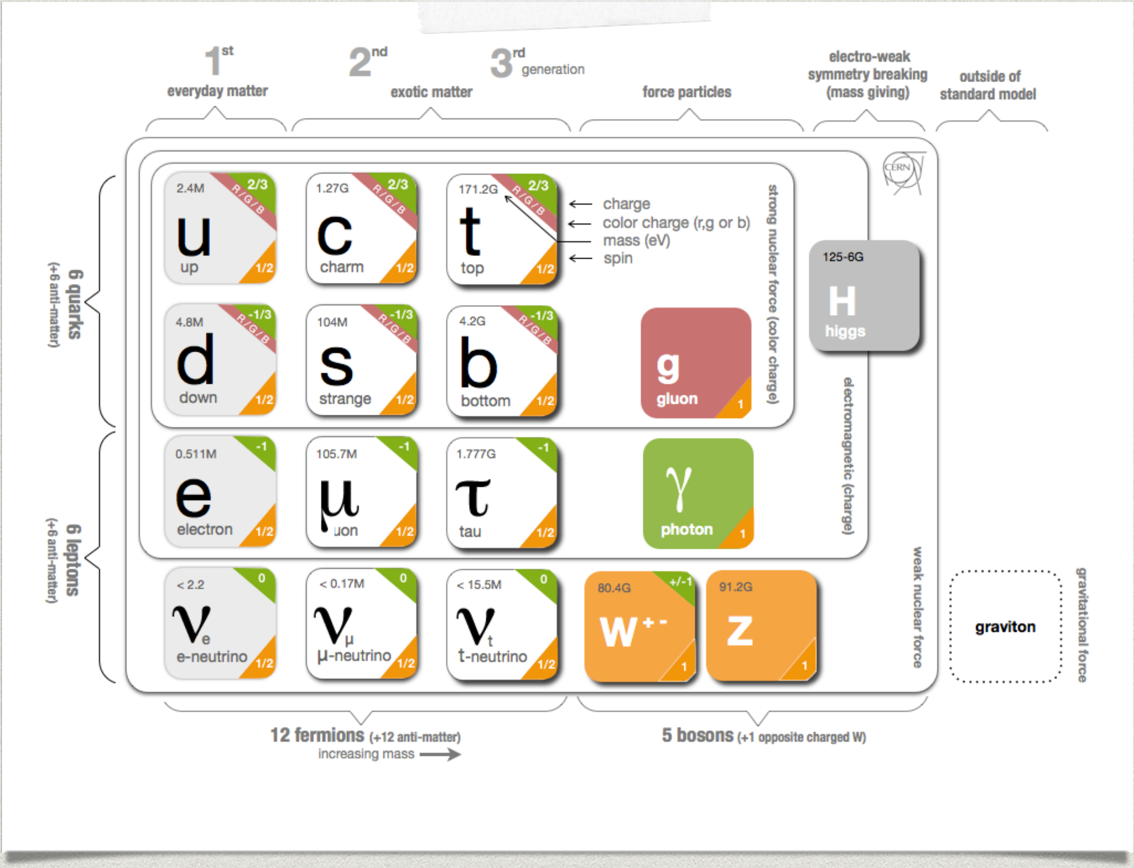
Outline&preview

- Introduction to the baryon asymmetry;
- Brief overview of the EWBG;
- CP violation @finite temperature;
- EWBG from the spontaneous CPV.

Preview

- ***Show you how to generate the baryon asymmetry of the universe with a spontaneous CPV at the finite temperature.***
- ***Show you how to avoid the constraint on the EWBG arising from the EDM measurement.***

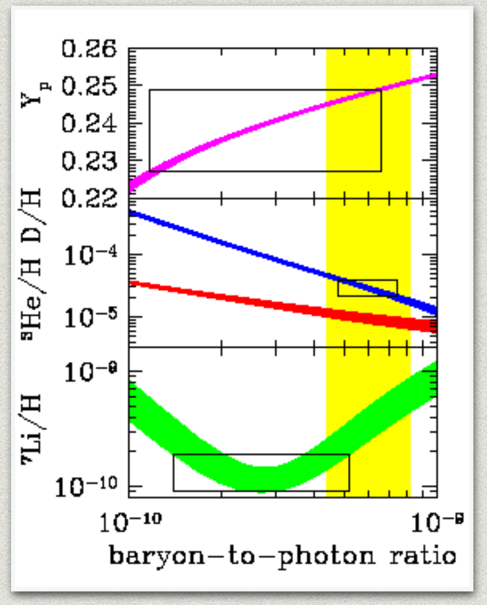
Particle Zoo

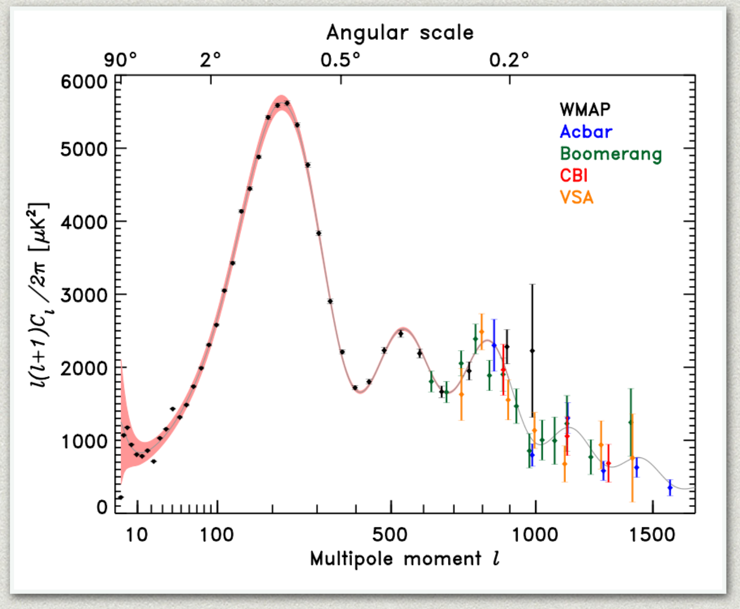


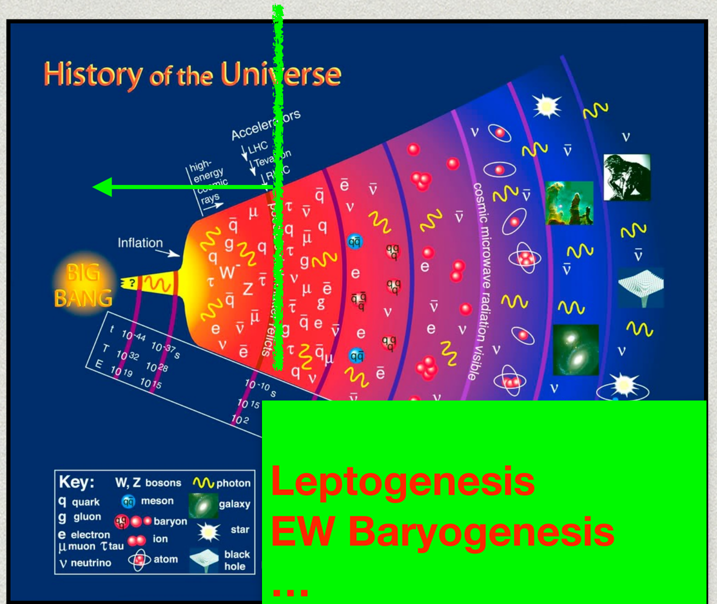
- Neutrino masses
- Dark matter
- Baryon asymmetry

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





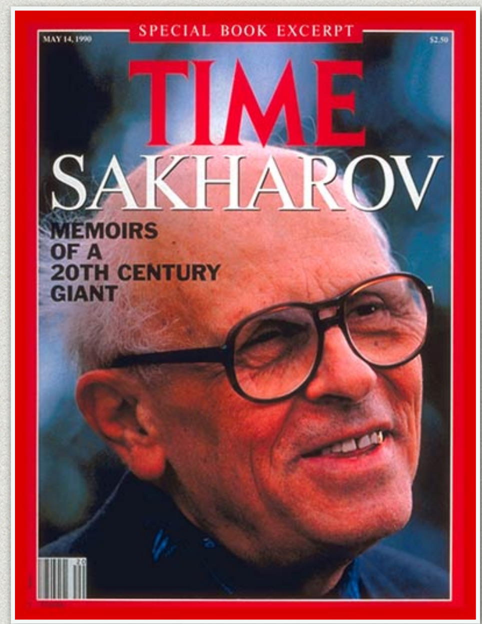


Leptogenesis
EW Baryogenesis
...

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

BAU from First order EWPT

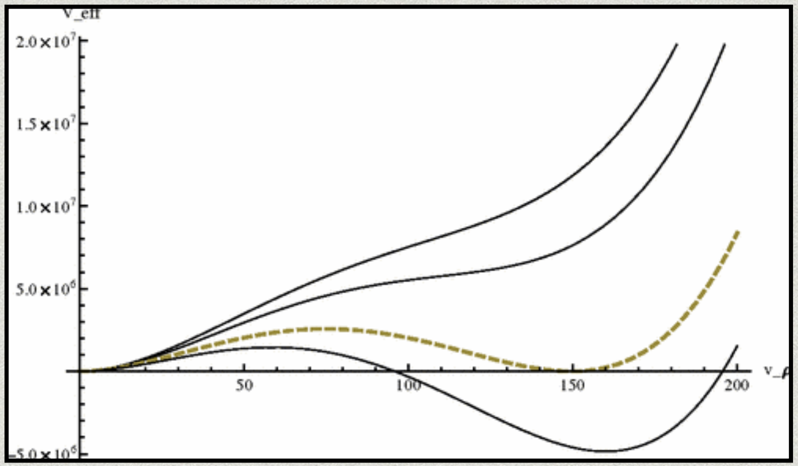
BAU might be generated during the electroweak phase transition

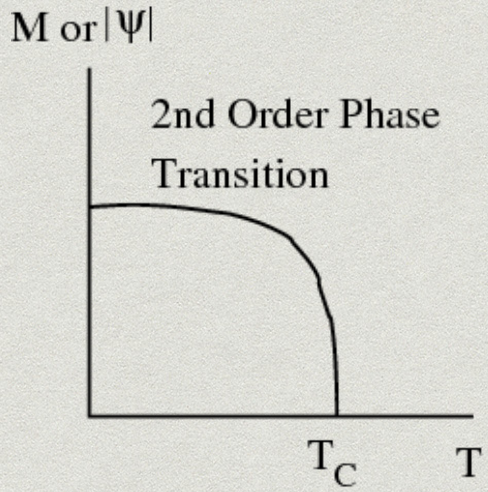


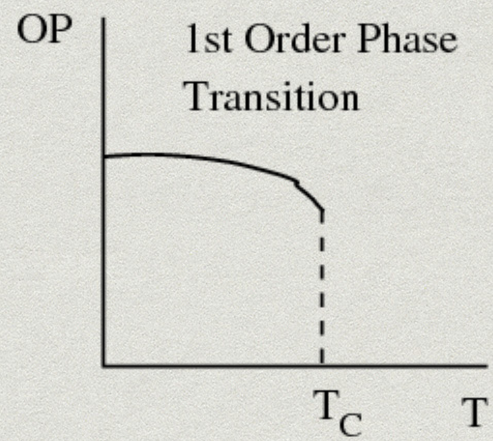
★Baryon number violation
★C&CP violation
★Departure from thermal equilibrium

→

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

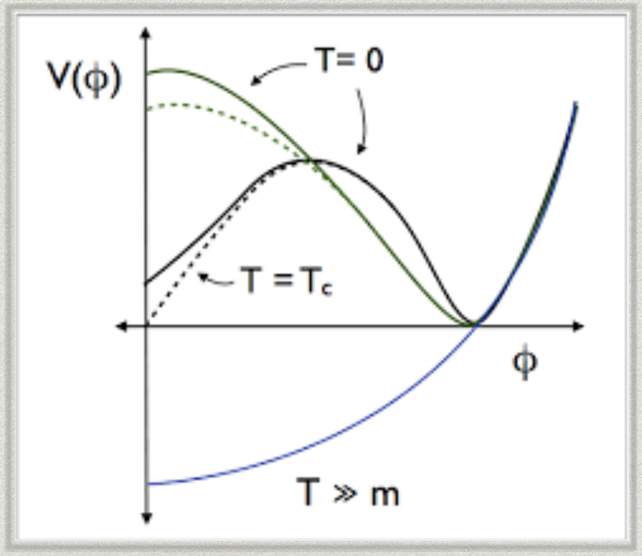


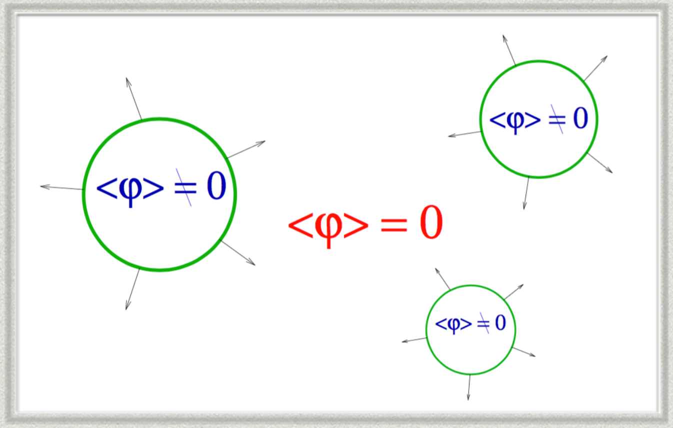




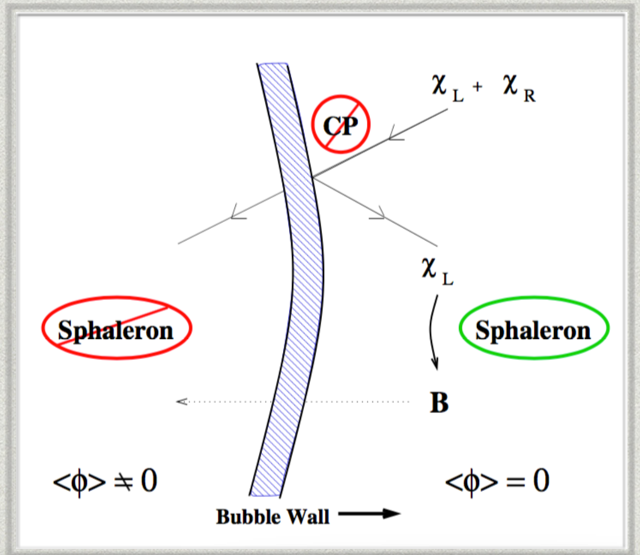
Electroweak Baryogenesis

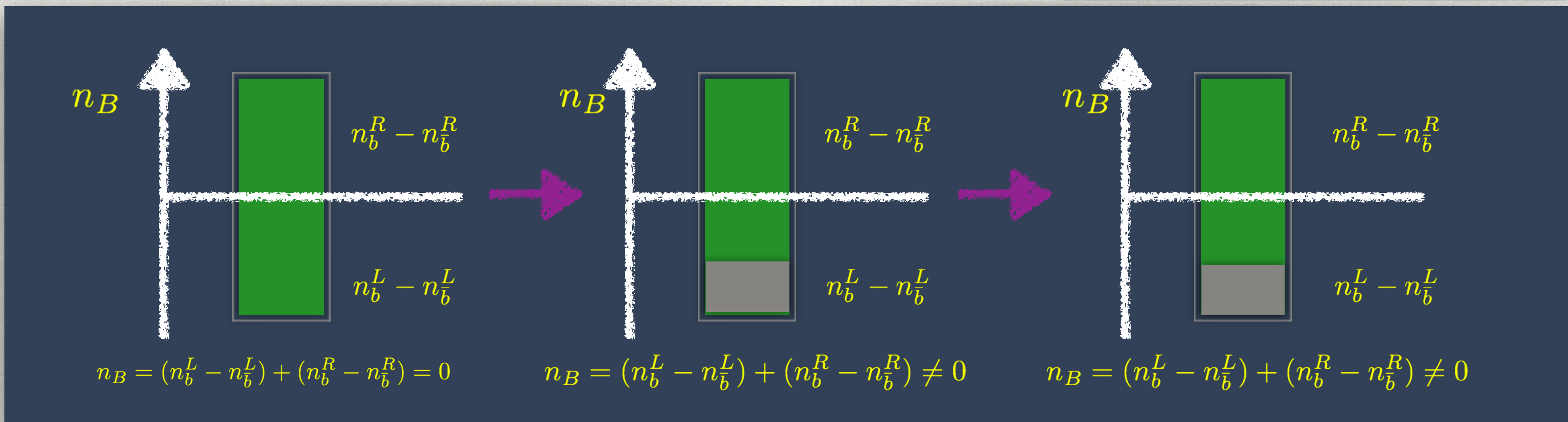
- Generate BAU during the electroweak phase transition





Basic description



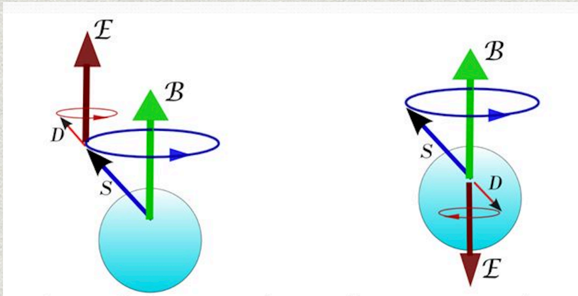


Fate of the EWBG

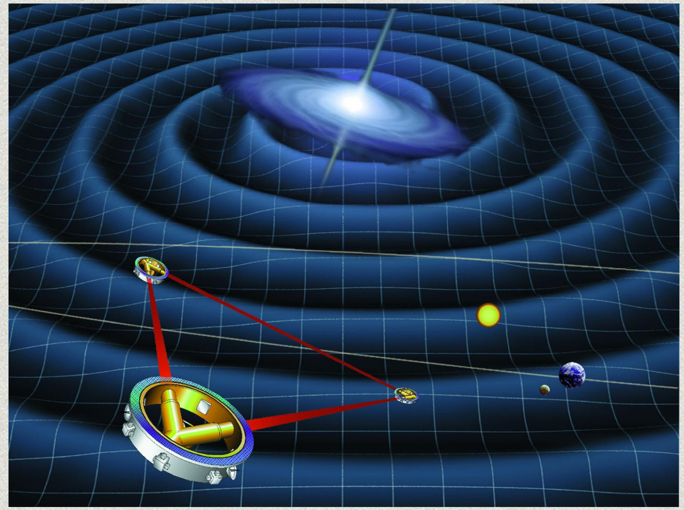
Three Detectives

LHC

EDM



GW



Conventional EWBG mechanism might be found or excluded in the near future when these three detection methods are combined.

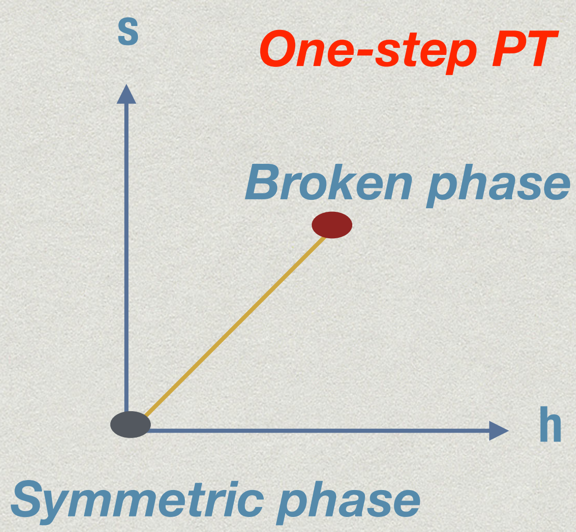
A typical example: Wino-catalyzed EWBG is excluded by the ACME result(intensity frontier) and the Higgs search results at the LHC(energy frontier).

Questions: Is there a mechanism of electroweak baryogenesis that can escape from these hunters?

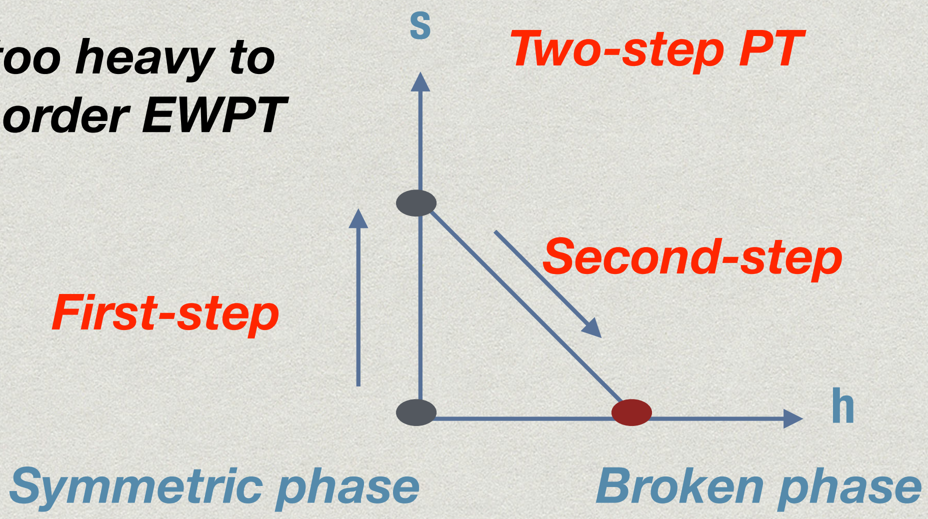
Our little aim: a EWBG with less signature

Exploring the scenario of electroweak baryogenesis that may escape from the combined detection of the cosmic, energy and intensity frontiers.

One observation: **A two-step phase transition may avoid constraint arising from Higgs searches at the LHC**



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**

Our little aim: a EWBG with less signature

Another observation: There exists spontaneous CP phase in the scalar singlet sector

Lemma: Haber, Surujon, 2012

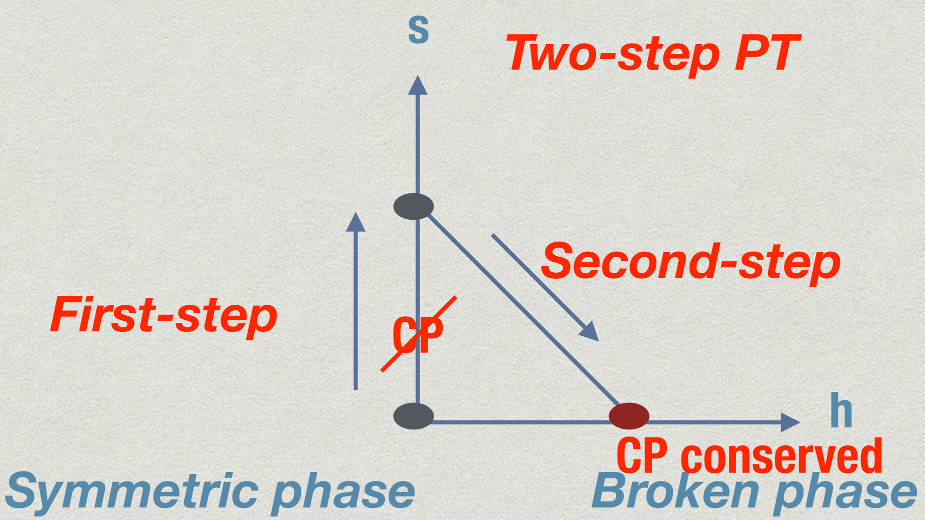
spontaneous CP violation in the theory of one complex scalar field may occur only when the related U(1) is explicitly broken by at least two spurions whose U(1) charges are different in magnitude

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

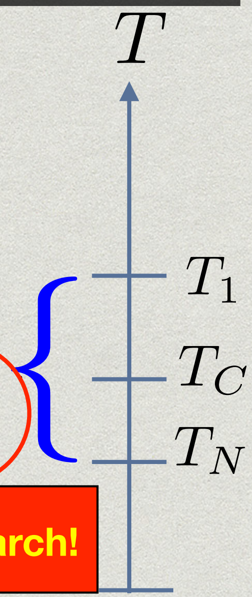
spurions

spurions

A possible strategy: There might be spontaneous CPV phase only at finite T!



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



NO constraint of EDM and Higgs search!

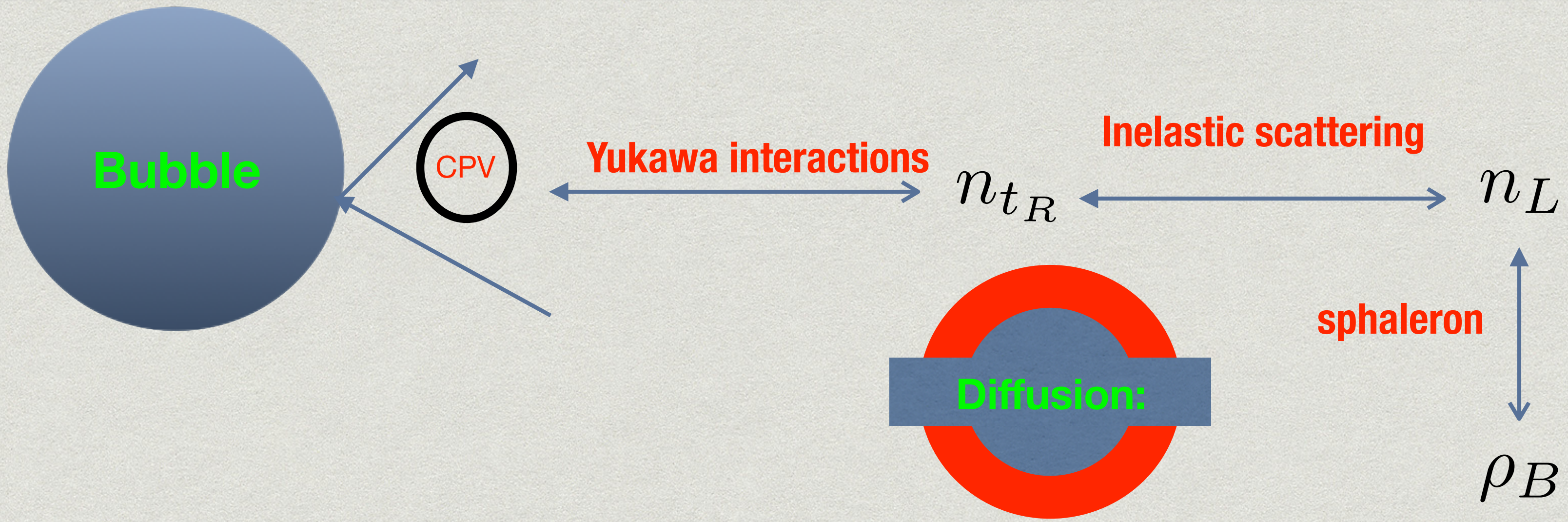
Sketch of the mechanism

Basic description

Sakharov:

- $\not{B}$
- $\not{C}$&$\not{CP}$
- First order EWPT

Sphaleron
Spontaneous CPV
Two-step PT



Transport equation:

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

The model:

SM+ complex scalar singlets

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

Yukawa: $-\mathscr{L} \sim \frac{1}{\Lambda}\overline{Q_L}\tilde{H}St_R + \text{h.c.}$

↑

$-\mathscr{L} \sim \eta\overline{T_L}St_R + M\overline{T_L}T_R + \text{h.c.}$

$T_{L,R}$: vector-like top quark

$$J_{B(F)}(x) = \int_0^\infty dt t^2 \ln\left(1 \mp \exp\{-\sqrt{t^2+x}\}\right)$$

$$V_T = \frac{T^4}{2\pi^2}\left\{\sum_{i\in B} n_i J_B\left[\frac{m_i^2(h,s,\xi)}{T^2}\right] - \sum_{j\in F} n_j J_F\left[\frac{m_j^2(h)}{T^2}\right] - \sum_{k\in G} n_k J_B\left[\frac{m_k^2(h,s,\xi)}{T^2}\right]\right\}$$

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

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

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

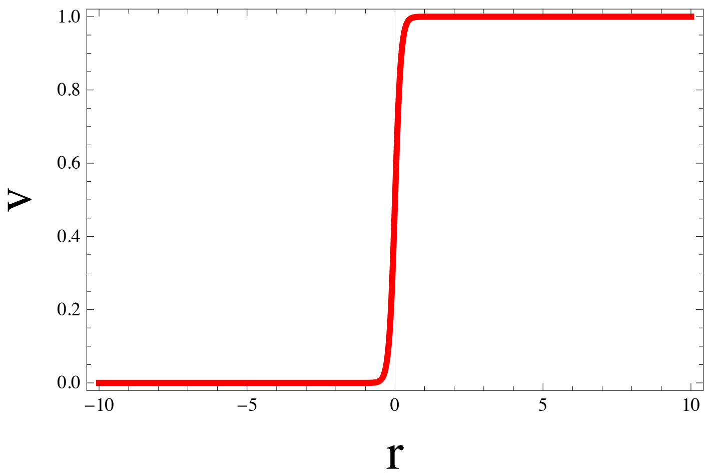
$$V_{\text{CW}} = \frac{1}{64\pi^2}\sum_i (-1)^{2s_i} n_i m_i^4(h,s,\xi)\left[\log\frac{m_i^2(h,s,\xi)}{\mu^2} - C_i\right]$$

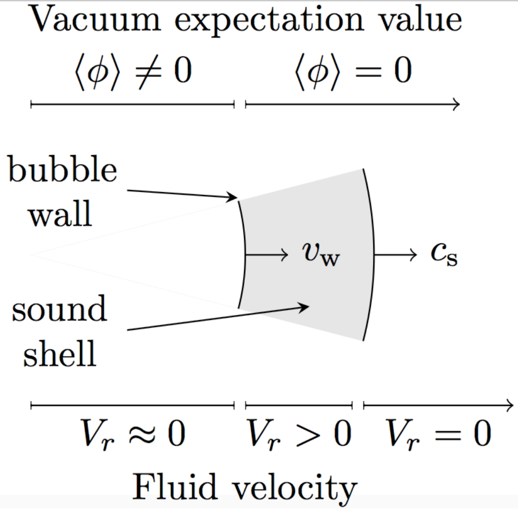
$$V_T^{\text{ring}} = \frac{T}{12\pi}\sum_i n_i\left\{(m_i^2(h,s))^{3/2} - (M_i^2(h,s,T))^{3/2}\right\}$$

Bubble dynamics

1.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 background field	$V(z) = \frac{1}{2}v(T)\left[1 + \tanh\left(3\frac{z}{L_w}\right)\right]$





Bubble dynamics

2. Typical temperatures

Critical temperature T_C:	$V_{\text{eff}}(\phi_{\text{symmetric}}, T)\|_{T_C} = V_{\text{eff}}(\phi_{\text{broken}}, T)\|_{T_C}$
Bubble nucleation Temperature T_n:	$\int_0^{t_n} \Gamma V_H(t) dt = \int_{T_n}^{\infty} \frac{dT}{T} \left(\frac{2\zeta M_{\text{pl}}}{T}\right)^4 e^{-S_3/T} = \mathcal{O}(1),$

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. Physical parameters relating to PT

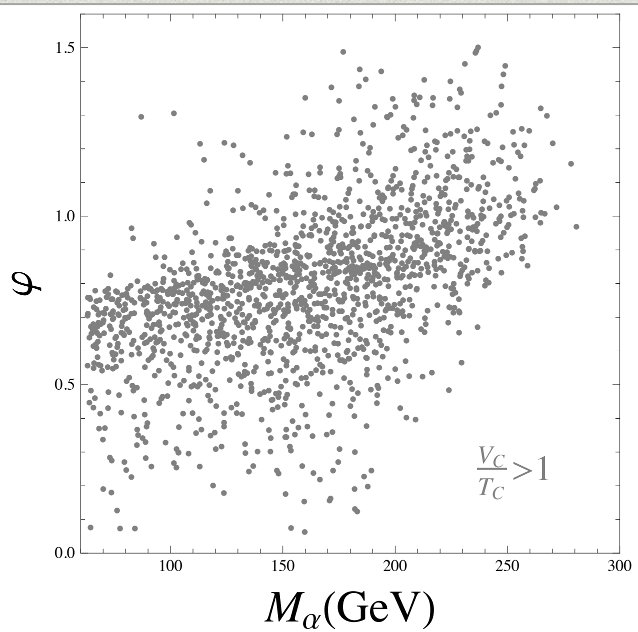
v_w	*Bubble wall velocity*	*calculated numerically*
l_w	*Bubble wall width*	*calculated numerically*
α	*Released energy to radiation energy*	$\alpha = \Lambda / \rho_{\mathrm{rad}}$
κ	*The efficiency factor*	$\kappa = \frac{3}{\varepsilon v_w^3} \int w(\xi) v^2 \gamma^2 \xi^2 d\xi$
Λ	*Latent heat*	$\Lambda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

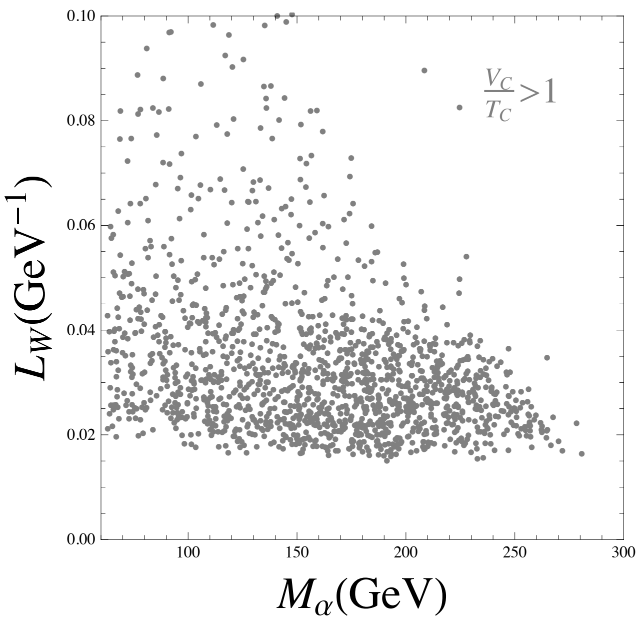
v_w	Relevant to the calculation of baryon number density generated during the EWPT
l_w	

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

CP phase and bubble wall width

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:	$$L_w^2 \approx 1.35 \frac{\lambda + \sqrt{\lambda\lambda_\varrho}}{(\lambda_2 - 2\sqrt{\lambda\lambda_\varrho})[\lambda v_0^2 - \Pi_h(T_C^2)]} \times \left(1 + \sqrt{\frac{\lambda_2^2}{4\lambda\lambda_\varrho}}\right)$$
Spontaneous CP phase:	$$\varphi = \pm\frac{1}{2}\arccos\left[\frac{\lambda_1 - \lambda_3}{2\lambda_3}\frac{m_\beta^2 - m_\alpha^2}{\lambda_2 v^2 - m_\alpha^2 - m_\beta^2 + 2\Pi_\alpha}\right].$$





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:

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

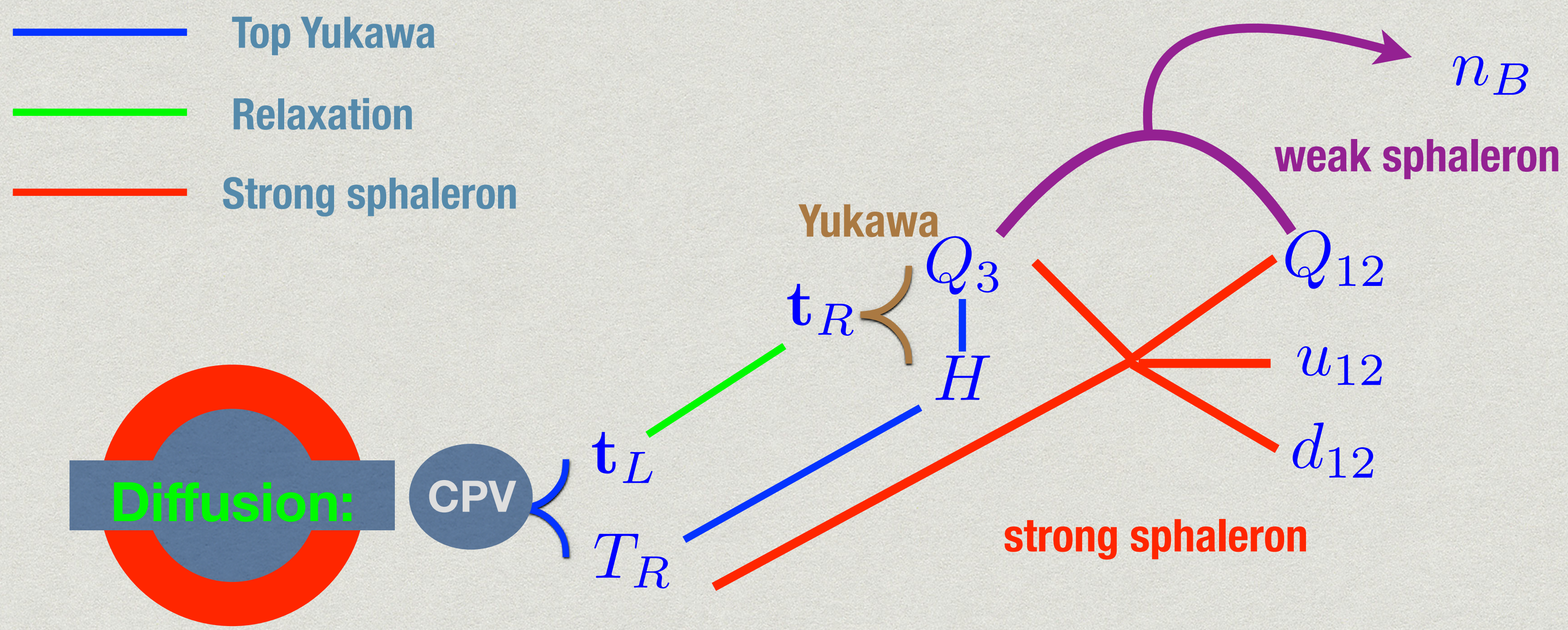
$$\zeta \overline{\mathfrak{t}_L} S t_R + (M_{\mathfrak{t}})\overline{\mathfrak{t}_L}\mathfrak{t}_R + \text{h.c.} \longrightarrow \frac{y_t \zeta}{\Lambda}\overline{Q_3}\widetilde{H} S t_R$$

All equations

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

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

$+\varphi$ + $-\varphi$ =0

No BAU left

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

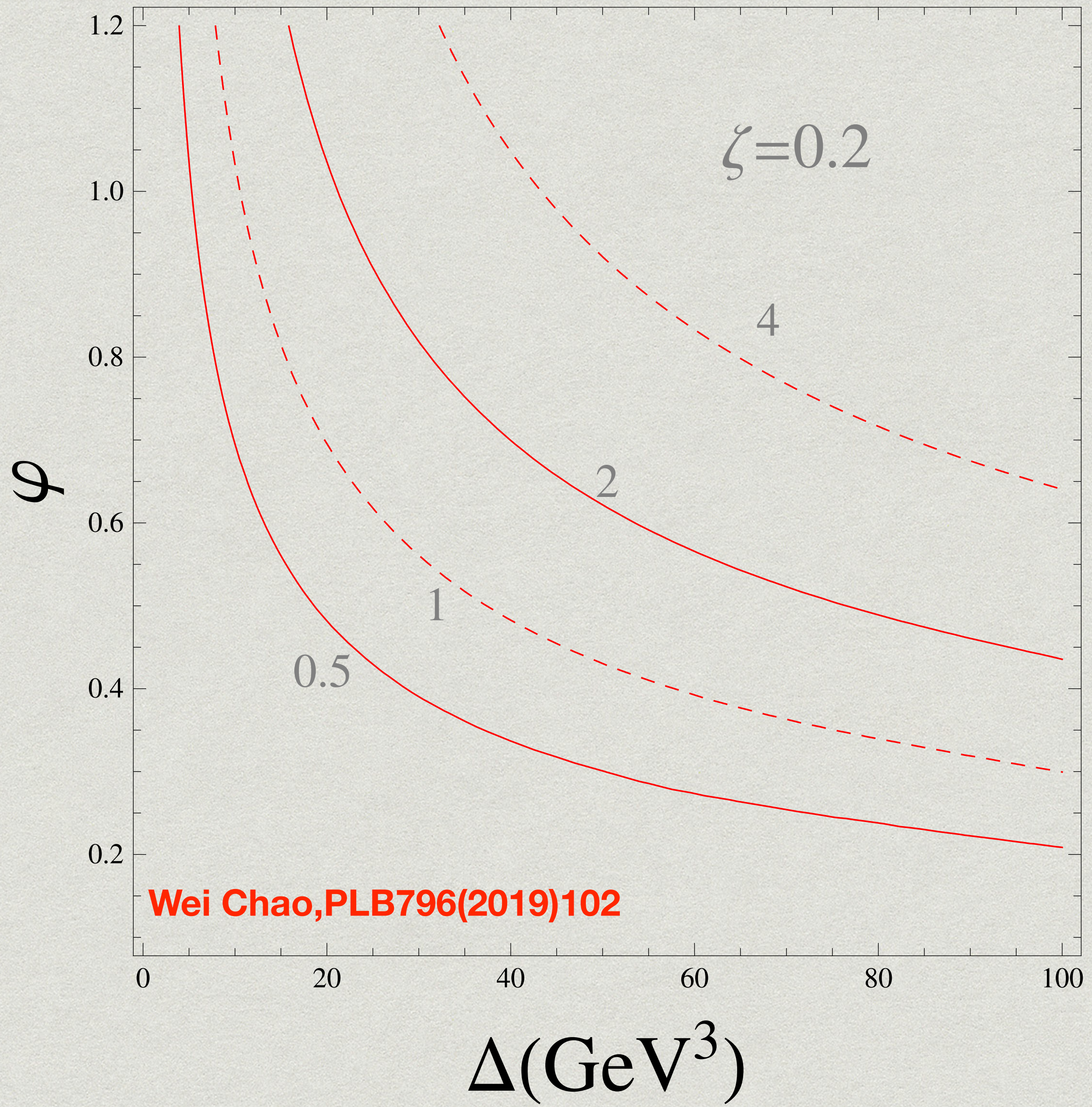
Ratio of bubbles

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

Final BAU

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

Numerical results



Numerical results

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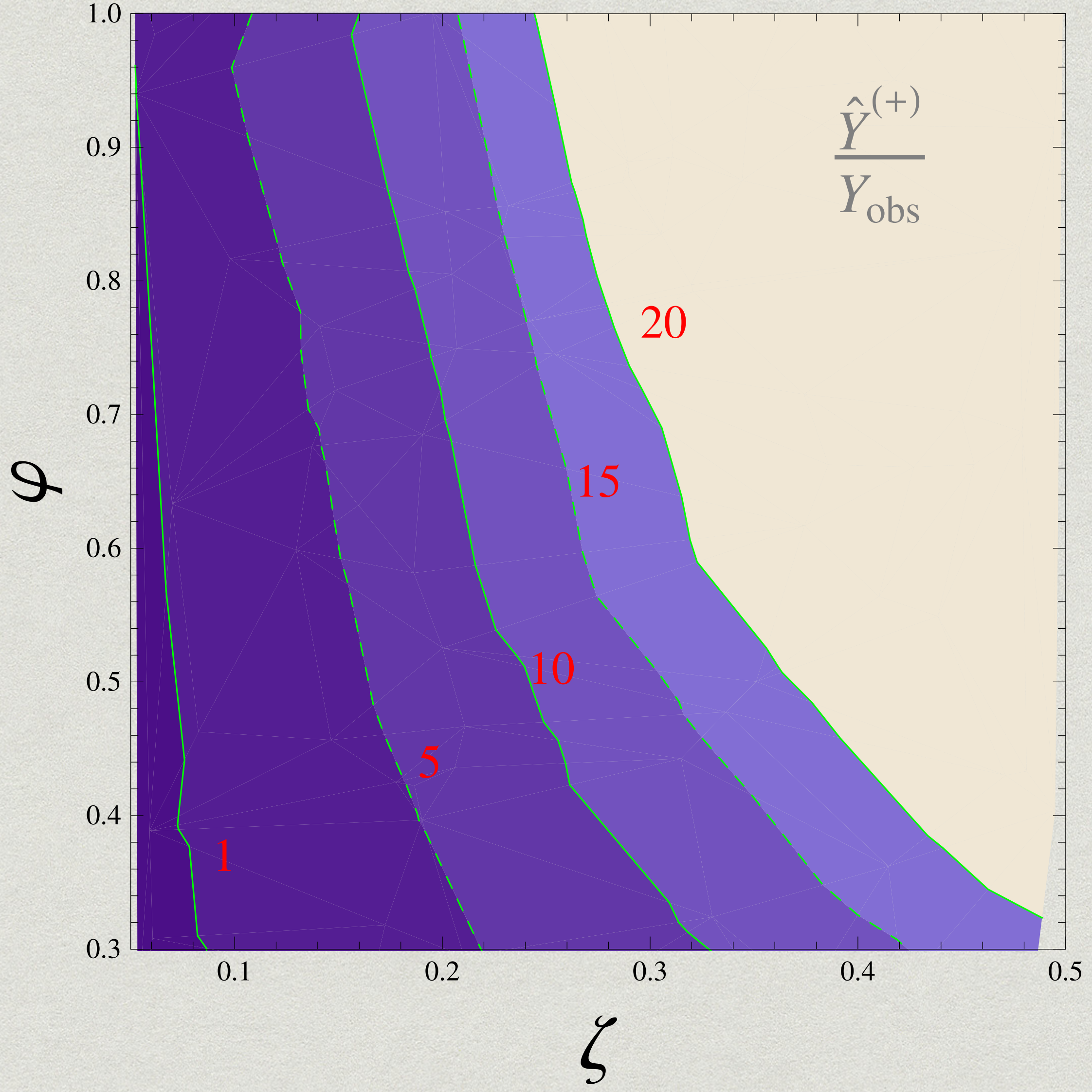

Summary

- Physics relevant to electroweak phase transition are briefly reviewed.
- 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.

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第三届北师大暗物质研讨会

6-9 December 2019
Asia/Shanghai timezone

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暗物质是具有确凿实验证据的超出标准模型的新物理，也是当前高能物理实验和理论研究的前沿热点课题。近年来，暗物质的实验研究不断取得突破性进展，暗物质-核子弹性散射截面的排除线精度不断提高、COHERENT实验观测到中微子-核子相干弹性散射（暗物质直接探测的主要背景）、XENON1T实验观测到双β衰变。此外，WIMP的直接探测也进入了关键时期，各种新的针对轴子和Sub-GeV暗物质的直接探测思想不断涌现。这些都为中国的暗物质研究提供了机遇和挑战。

为了促进国内高能物理界学术交流、推动我国暗物质理论和实验研究的发展、寻求高能物理与其他学科领域交叉的可能性，北京师范大学和北京大学高能物理研究中心将于2019年12月07日至09日在北京师范大学珠海校区联合举办第三届北师大暗物质研讨会。会议主题将针对所有暗物质相关的课题。
诚挚邀请您参加此次会议。

会议地点：北师大珠海校区，珠海市
注册费：1200元（老师和博士后），600元（学生）
注册截止：2019年10月31日。

主办单位：北京师范大学、北京大学高能物理研究中心
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Starts Dec 6, 2019 08:00
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