电弱重子生成机制进展
PROGRESS OF ELECTROWEAK BARYOGENESIS

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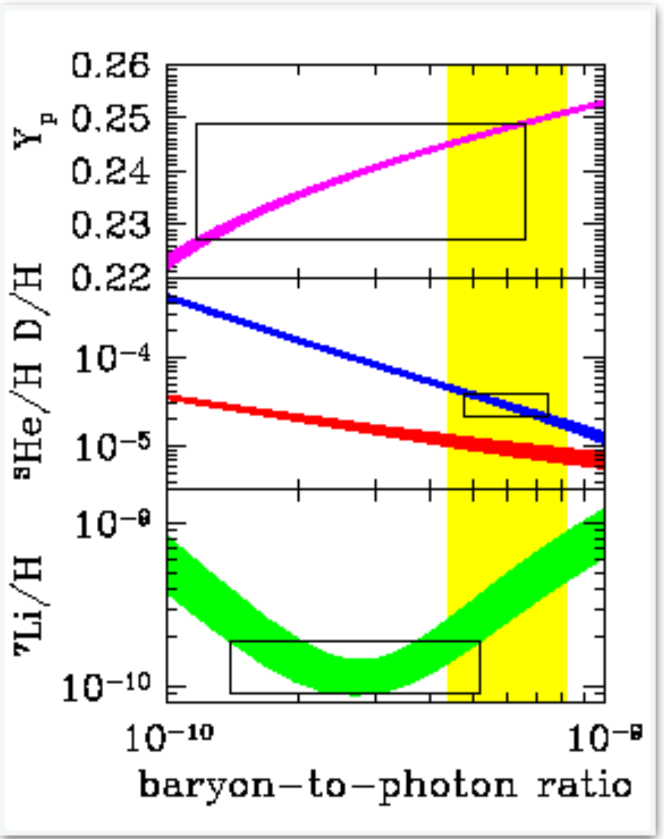
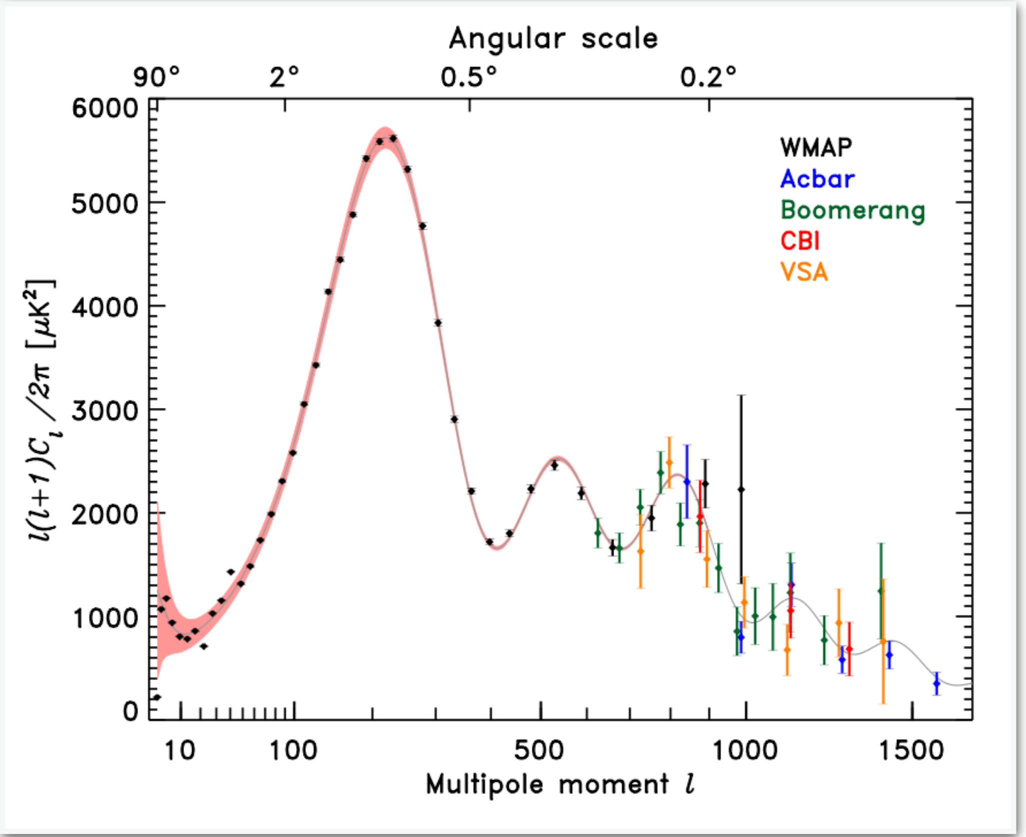
Outline

- Brief overview of EWPT&EWBG
- Recent Progress of EWBG:
  - The tension between the non-observation of CPV and the requirement of a large CP phase by the EWBG **(EWBG from spontaneous CPV or other exotic physics)**
  - The tension between observable stochastic gravitational wave and a sizable BAU generated by the EWBG (**EWBG at high bubble wall velocity**)
  - Progress in the calculation of CPV source term. (**The VEV insertion method**)

Matter-antimatter asymmetry of the Universe

- 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





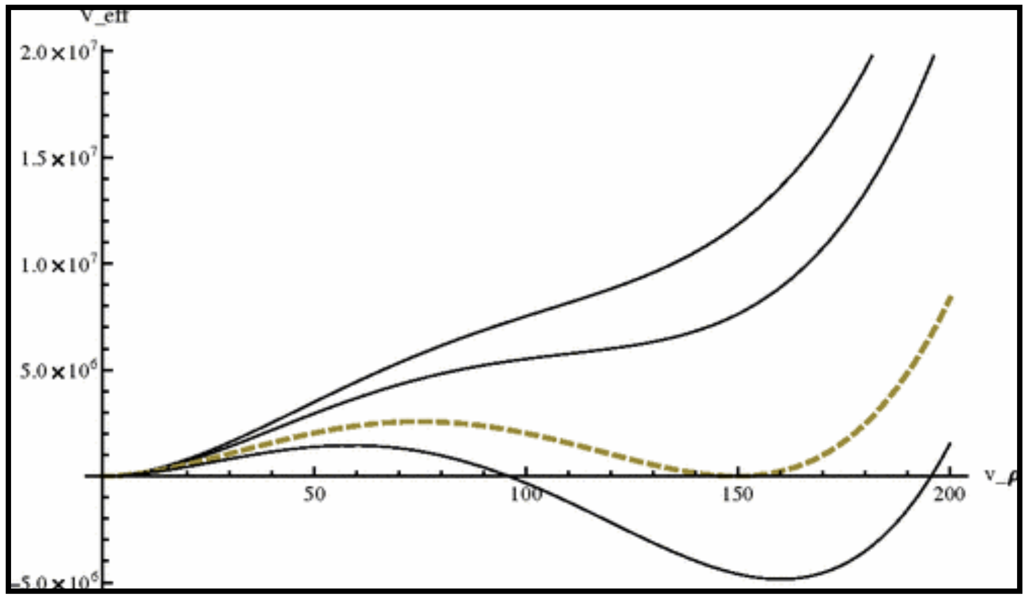
Theories

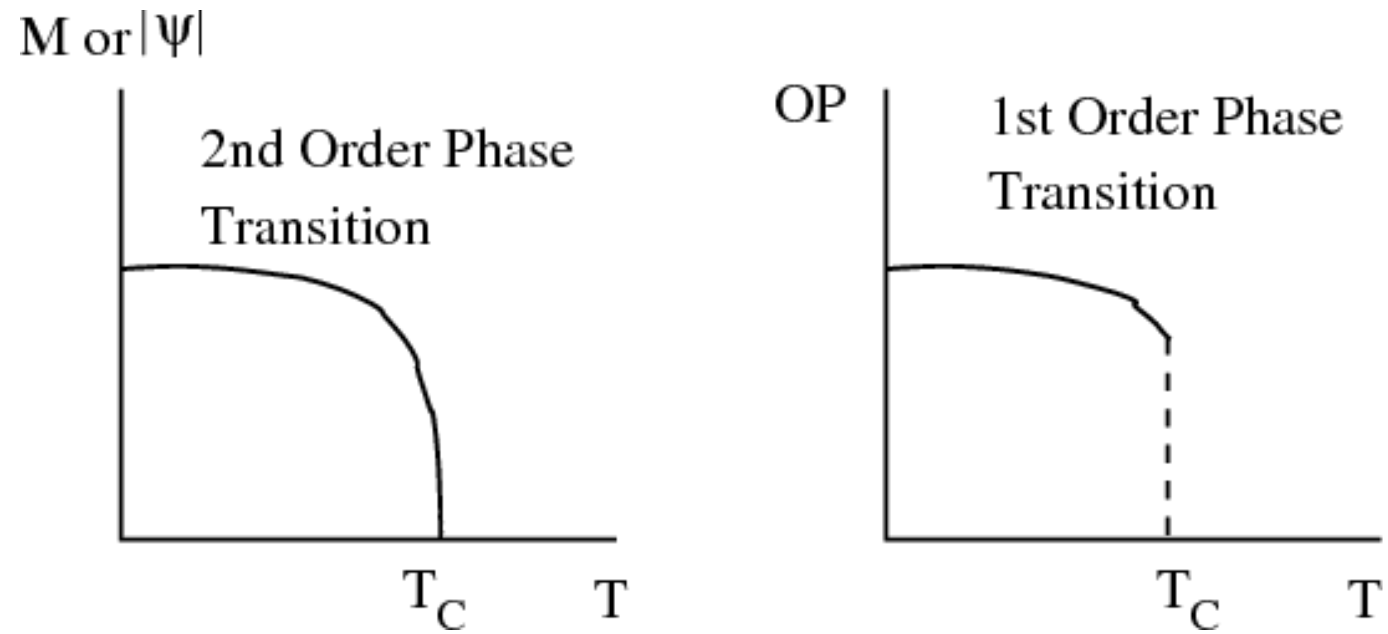
- ★Leptogenesis
- ★GUT baryogenesis
- ★EWBG
- ★Aflick-Dine
- ★Axio-genesis
- ★Spontaneous baryogensis
- ★...

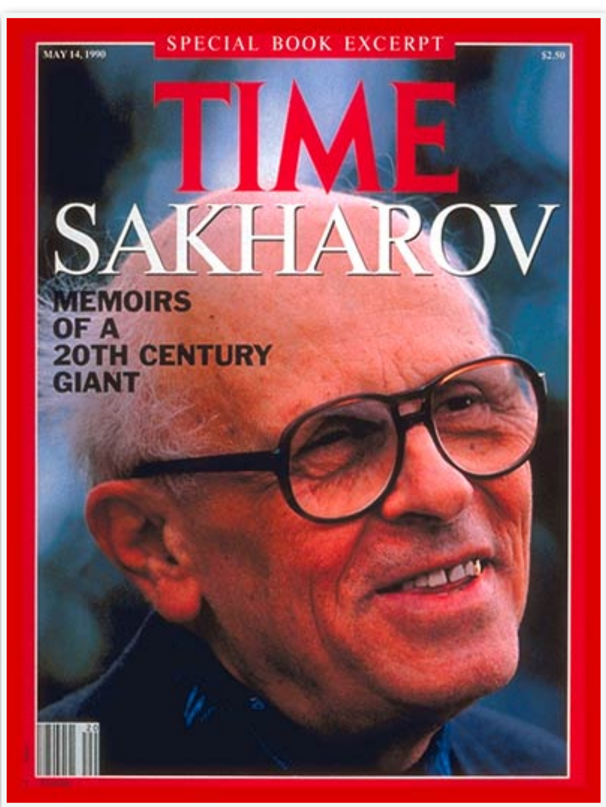
Baryon asymmetry: $$Y_B = \frac{\rho_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$$ **(Planck 2015)**

Baryogenesis via first order EWPT

Excess of matter over anti-matter in the Universe!





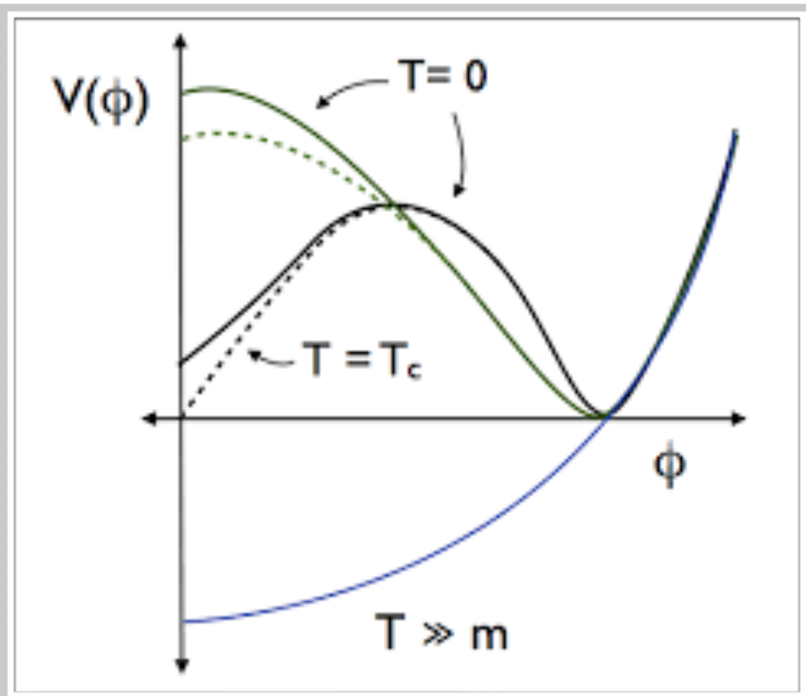


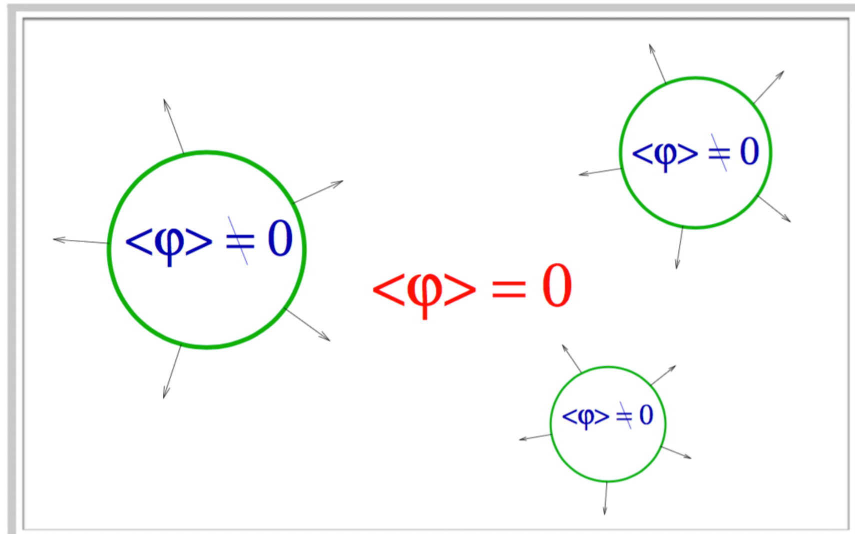
★Baryon number violation
★C&CP violation
★Departure from thermal equilibrium

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

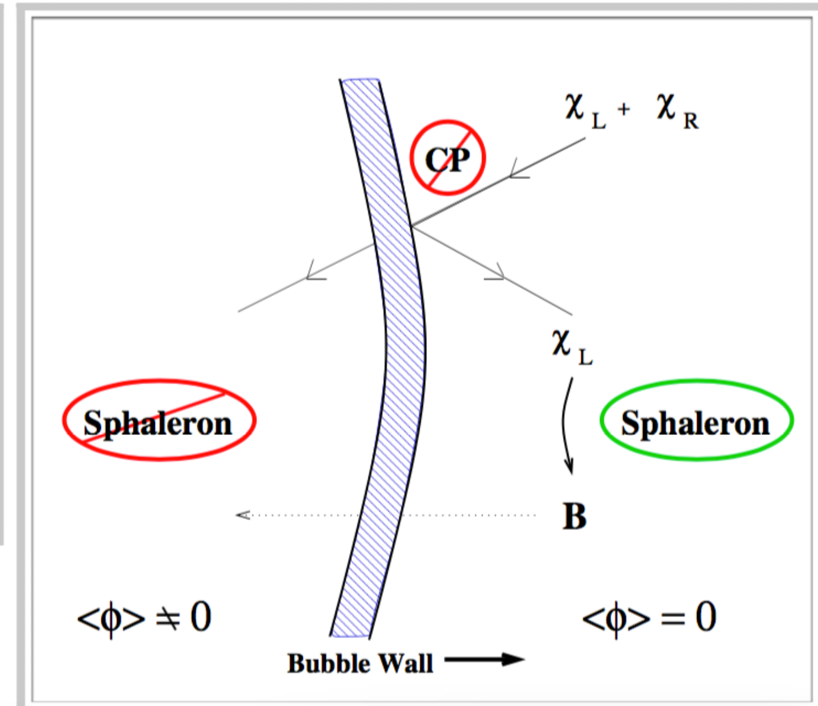
Electroweak Baryogenesis

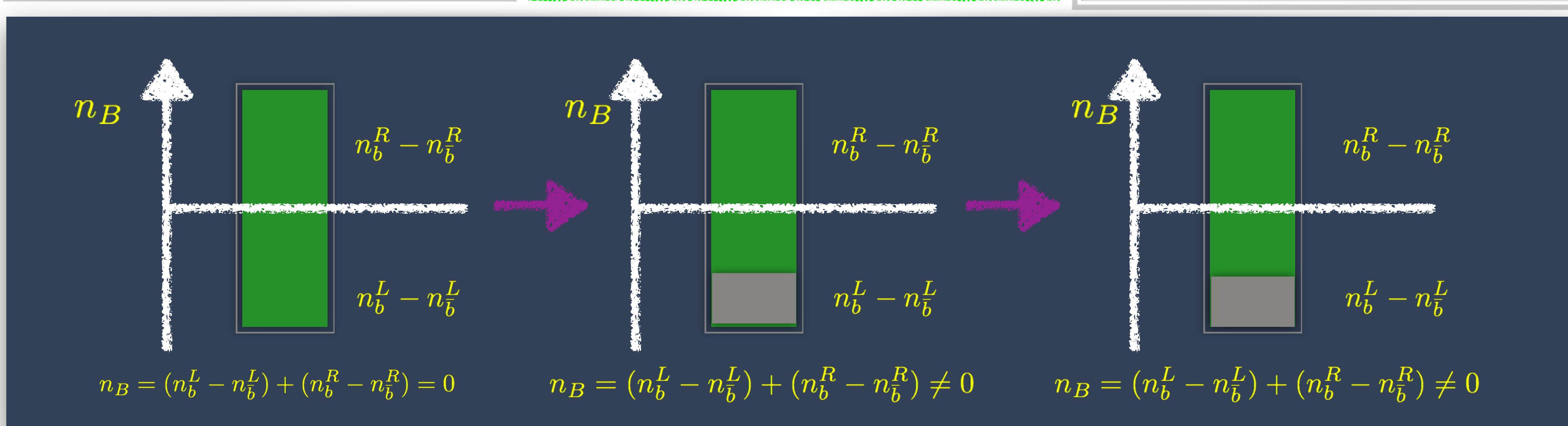
- Generate BAU during the electroweak phase transition





Basic description

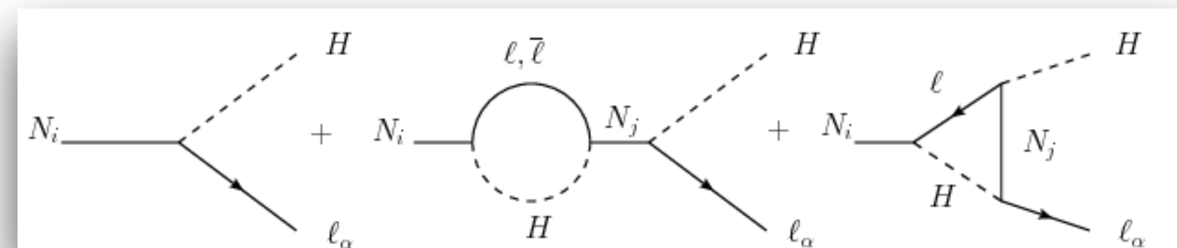




The fate of the EWBG

- 许多“新物理”理论都有其寿命！很无奈～～

Leptogenesis



不老女(男)神！

EWBG

The discovery of Higgs

The observation of gravitational wave

1985 | 2008 | 2012 | 2016 | 20xx | T

Kuzmin, Rubakov & Shaposhnikov

光鲜亮丽

二十多岁

焕发第二春

三四十岁?

回归理性?

The effective potential in the SM

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

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

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

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

细节请关注边立功老师的报告!

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

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

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

More explicitly:

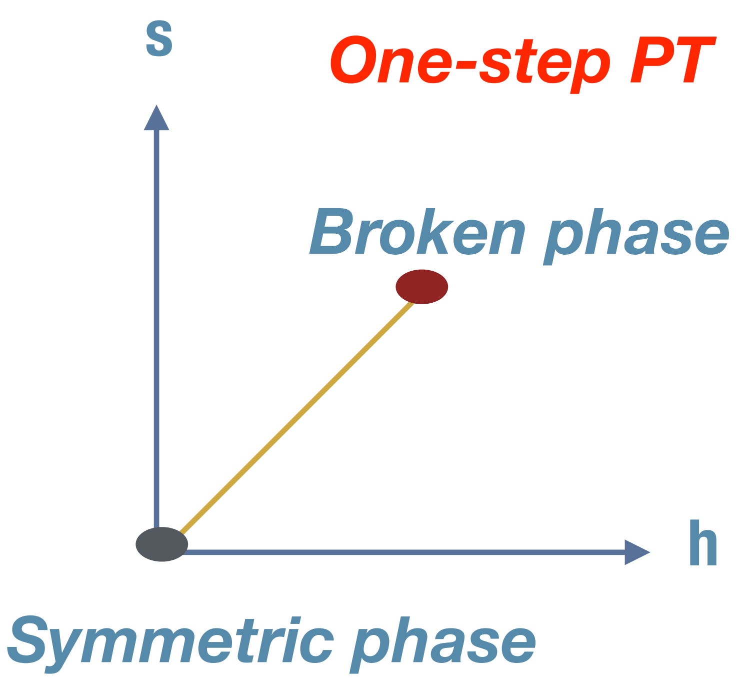
$$\begin{aligned} V_1^{T=0}(h) = {} & \frac{1}{4(4\pi)^2}(m_H^2)^2\left[\ln(\tfrac{m_H^2}{\mu^2}) - \tfrac{3}{2}\right] + \frac{2\times 1}{4(4\pi)^2}(m_G^2+\xi m_W^2)^2\left[\ln(\tfrac{m_G^2+\xi m_W^2}{\mu^2}) - \tfrac{3}{2}\right] \\ & + \frac{1}{4(4\pi)^2}(m_G^2+\xi m_Z^2)^2\left[\ln(\tfrac{m_G^2+\xi m_Z^2}{\mu^2}) - \tfrac{3}{2}\right] + \frac{2\times 3}{4(4\pi)^2}(m_W^2)^2\left[\ln(\tfrac{m_W^2}{\mu^2}) - \tfrac{5}{6}\right] + \frac{3}{4(4\pi)^2}(m_Z^2)^2\left[\ln(\tfrac{m_Z^2}{\mu^2}) - \tfrac{5}{6}\right] \\ & - \frac{2\times 1}{4(4\pi)^2}(\xi m_W^2)^2\left[\ln(\tfrac{\xi m_W^2}{\mu^2}) - \tfrac{3}{2}\right] - \frac{1}{4(4\pi)^2}(\xi m_Z^2)^2\left[\ln(\tfrac{\xi m_Z^2}{\mu^2}) - \tfrac{3}{2}\right] - \text{“free”}, \end{aligned}$$

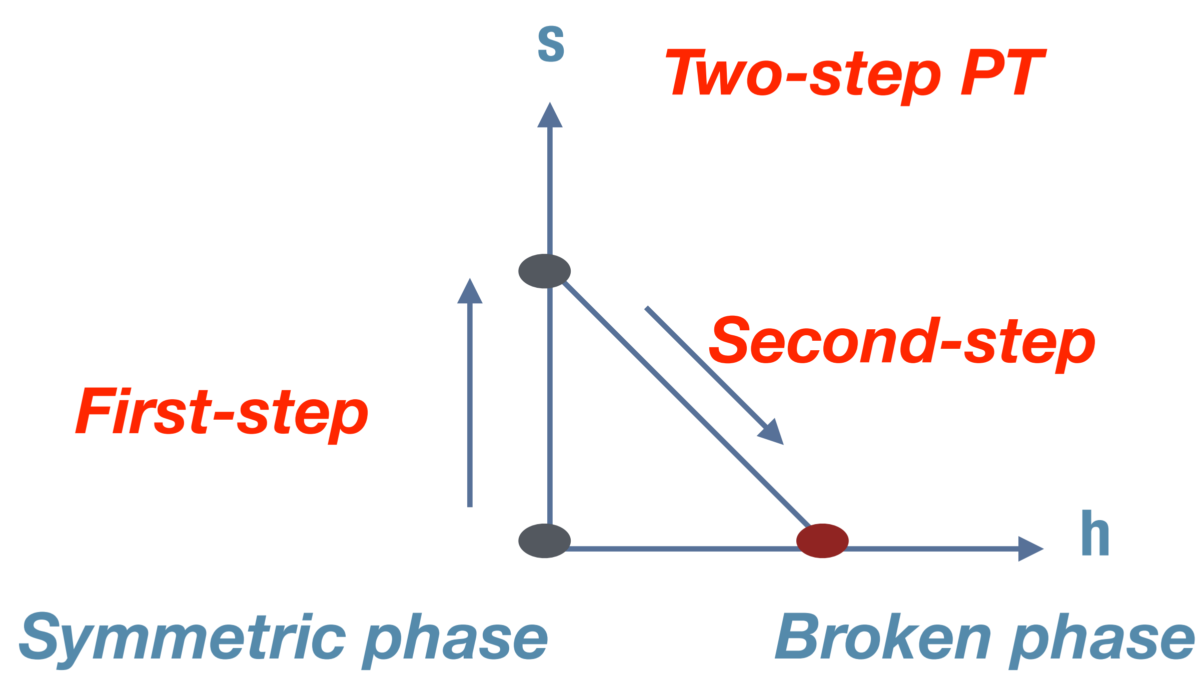
$$\begin{aligned} V_1^{T\neq 0}(h,T) = {} & \frac{T^4}{2\pi^2}\left[J_B\left(\frac{m_H^2}{T^2}\right) + 2\times J_B\left(\frac{m_G^2+\xi m_W^2}{T^2}\right) + J_B\left(\frac{m_G^2+\xi m_Z^2}{T^2}\right)\right] \\ & + \frac{3T^4}{2\pi^2}\left[2\times J_B\left(\frac{m_W^2}{T^2}\right) + J_B\left(\frac{m_Z^2}{T^4}\right) + J_B\left(\frac{m_\gamma^2}{T^4}\right)\right] \\ & - \frac{T^4}{2\pi^2}\left[2\times J_B\left(\frac{\xi m_W^2}{T^2}\right) + J_B\left(\frac{\xi m_Z^2}{T^2}\right) + J_B\left(\frac{\xi m_\gamma^2}{T^2}\right)\right] - \text{“free”}, \end{aligned}$$

EWPT is usually studied in the Landau-gauge!

Bubble dynamics

1. Patterns of PT: SM+ new particles





The barrier between the symmetric and the broken phase usually comes from the gauge fields

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

SM Higgs is too heavy to saturate first order EWPT

The barrier exists at the tree-level

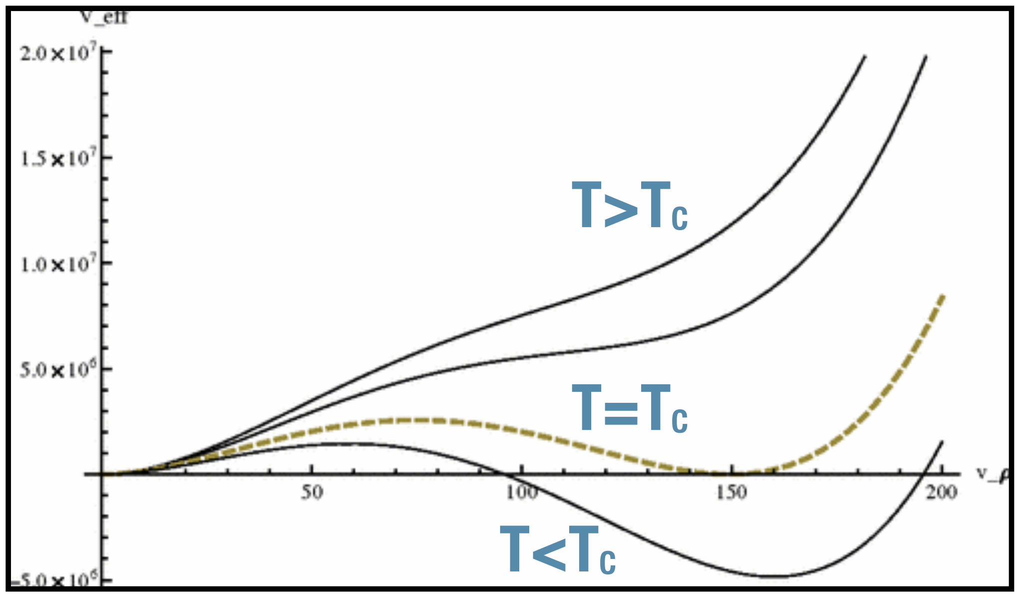
Merits:

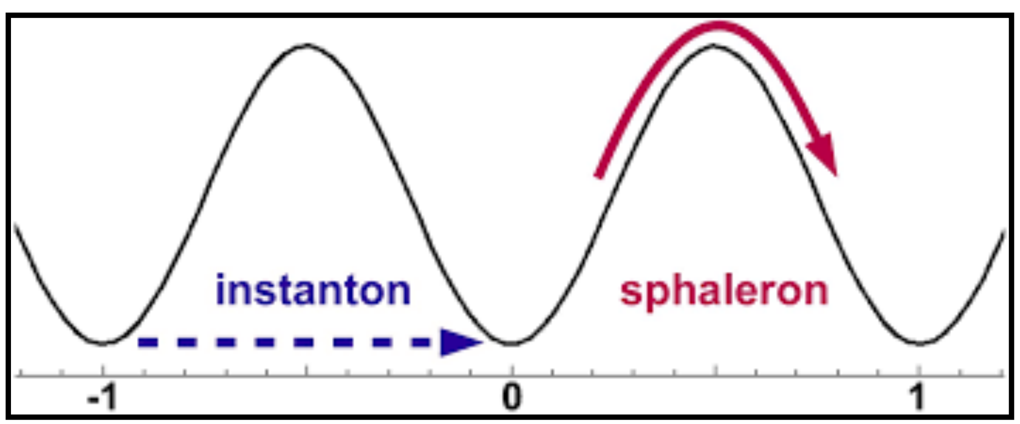
1.No mixing with the SM Higgs

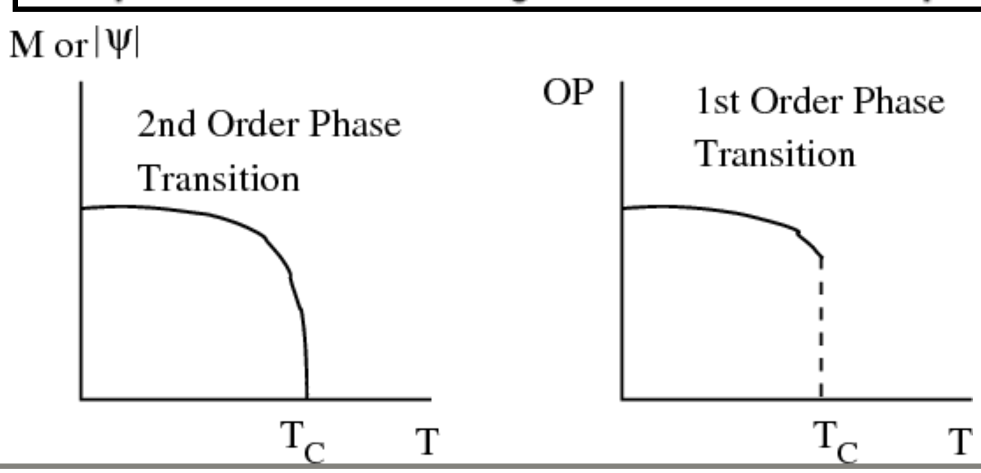
2.Correlated with the dark matter

Bubble dynamics

2. Strongly first order VS First order

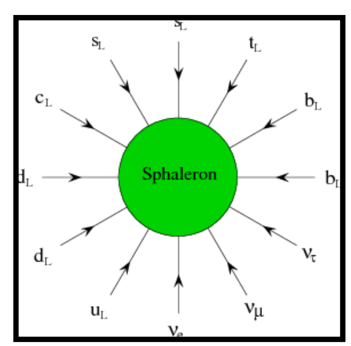




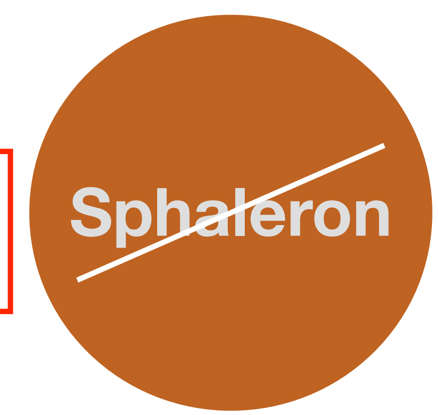


- ***First order EWPT: Bubble nucleation***
- ***Strongly first order EWPT: Sphaleron decoupling inside the bubble***

$$\Gamma_{\text{sph.}}(T) \sim (gT)^4 e^{-E_{sph}/T} < H(T) \approx 1.66\sqrt{g_*}T^2/M_{plank}$$



$$\frac{v}{T} > 1$$



- ***The exact value of v/T needs to be clarified case by case.***

Bubble dynamics

3. 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:

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

Quirós， ACTA PHYSICA POLONICA B 2008

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**

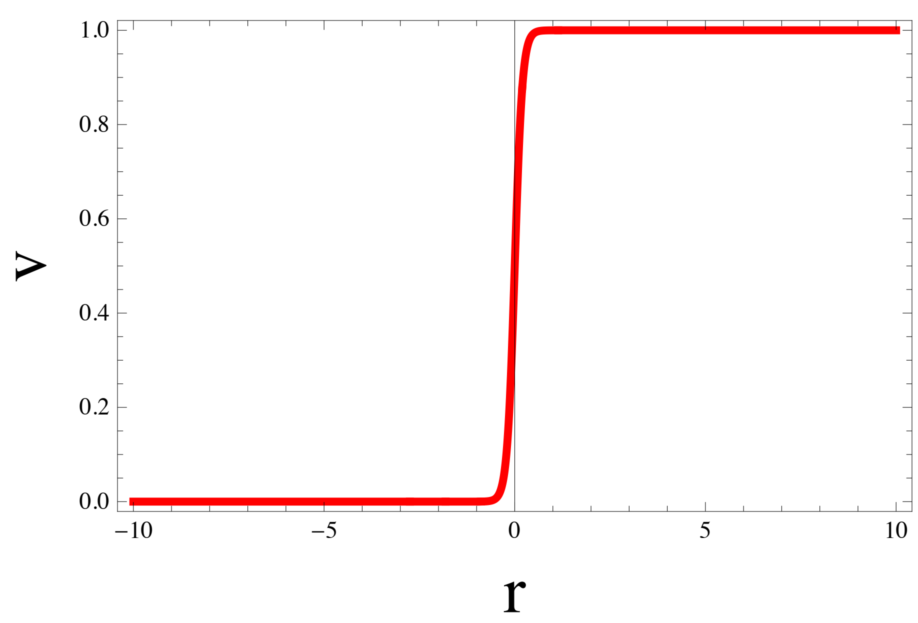
$T_c > T_n > T_d$

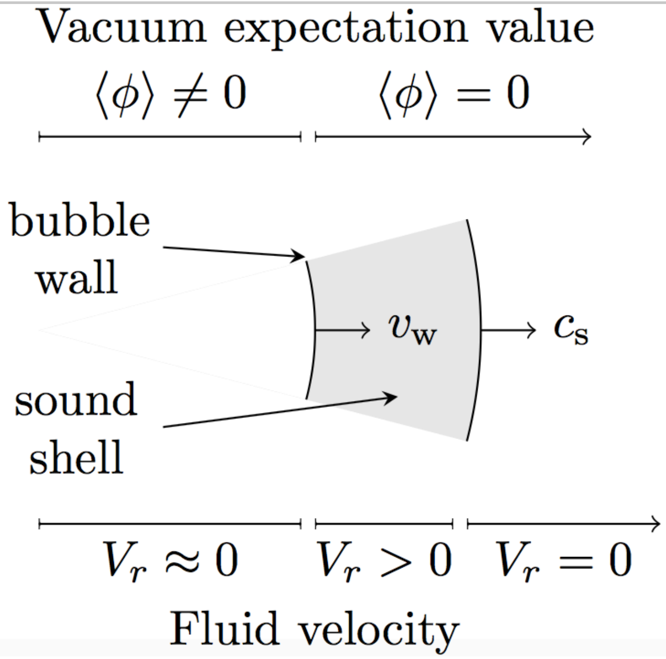
Bubble dynamics

4. Bubble nucleation

Bubble nucleation rate per unit time per unit volume	$$\Gamma_n(T) \approx T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} \exp\left[-\frac{S_3(T)}{T}\right]$$
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	$$S_3 = 4\pi \int r^2 dr \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi)\right]$$

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

5. 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*	$\alpha = \Lambda / \rho_{\rm rad}$
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
l_w

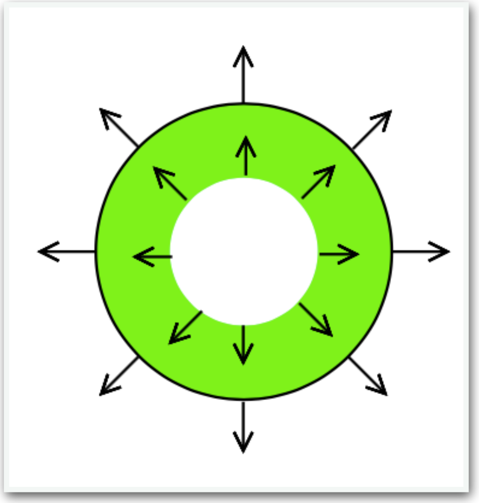
Relevant to the calculation of baryon number density generated during the EWPT

α
κ
Λ

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

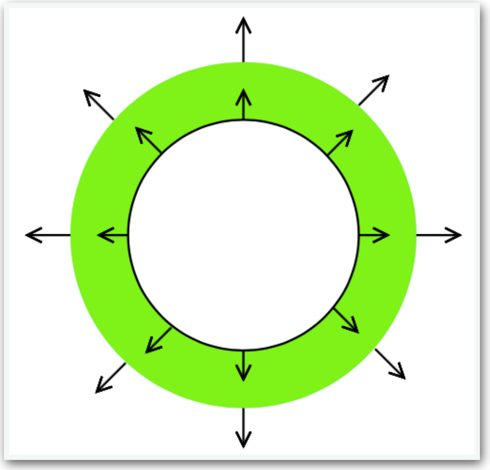
Bubble dynamics

6. Types of bubble from fluid dynamics



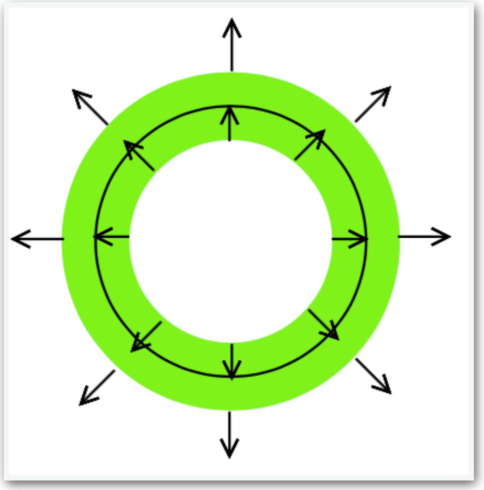
supersonic

Fluid at rest in front of the wall



subsonic

Fluid at rest behind the wall



supersonic

$v_w > c_s = v_- > v_+$

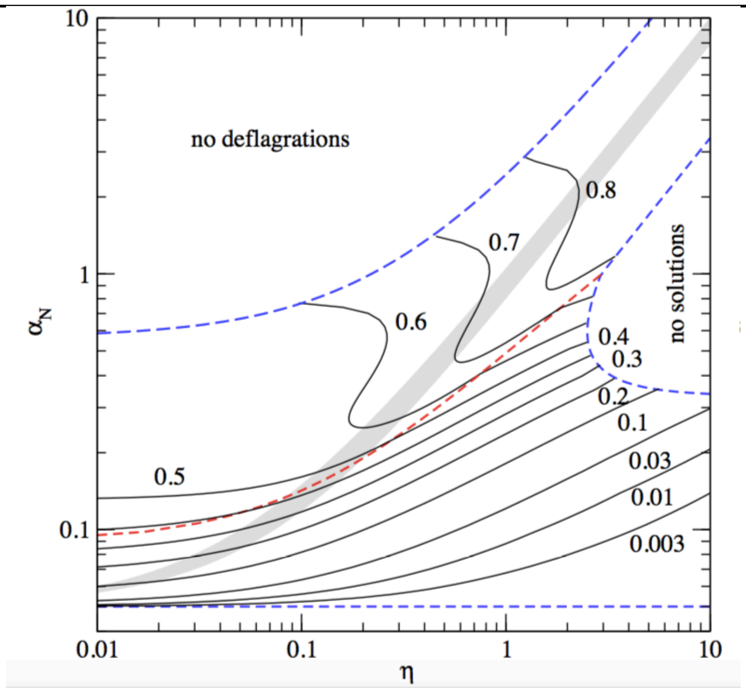
7.Friction

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: Essential for both EWBG and GW studies. ★★★★★



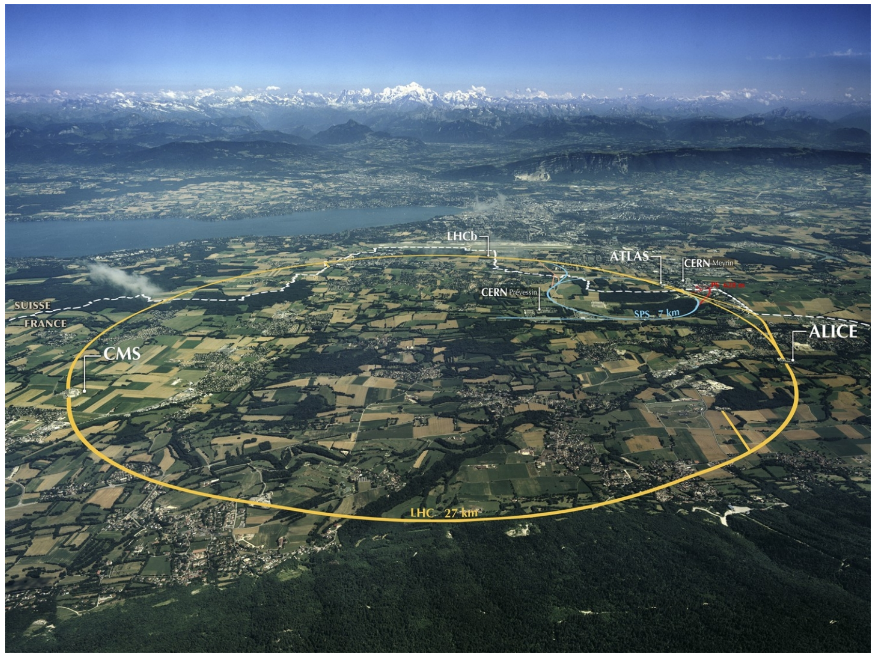
Outline

- Brief overview of EWPT&EWBG
- **Recent Progress:**
  - **The tension between the non-observation of CPV and the requirement of a large CP phase by the EWBG (EWBG from spontaneous CPV or other exotic physics)**
  - The tension between observable stochastic gravitational wave and a sizable BAU generated by the EWBG (EWBG at high bubble wall velocity)
  - Progress in the calculation of CPV source term. (The VEV insertion method)

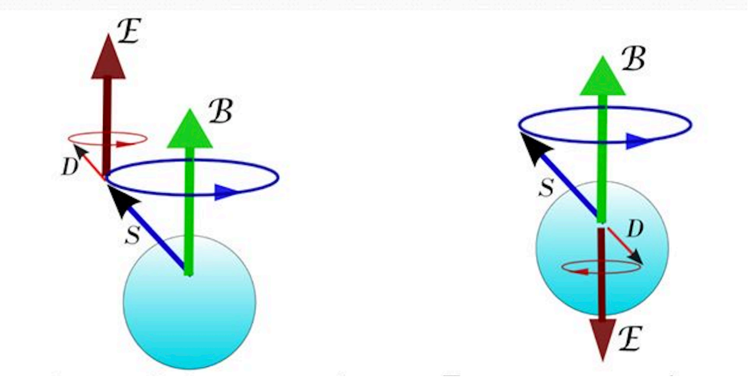
Fate of the EWBG

Three Detection methods

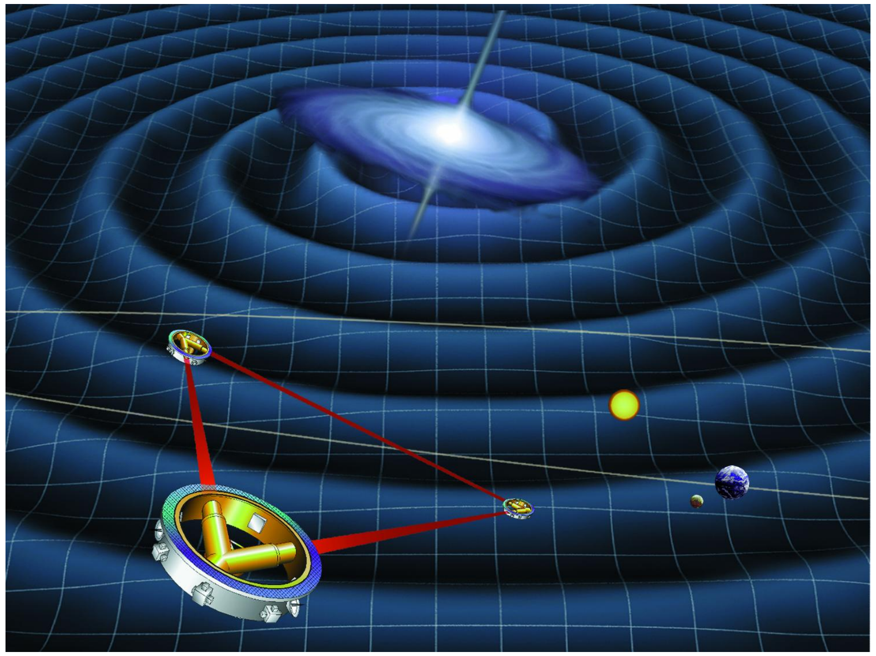
LHC



EDM



GW



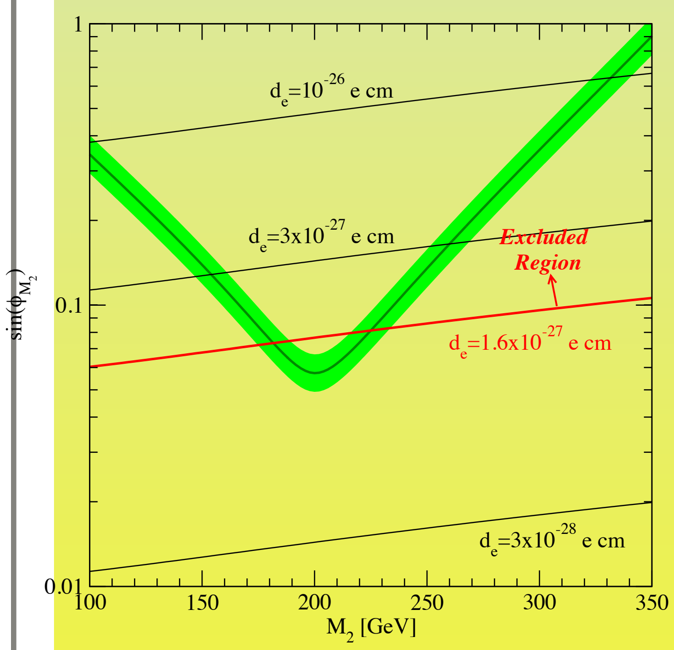
Conventional EWBG mechanism might be found or excluded in the near future when these three detection methods are combined.

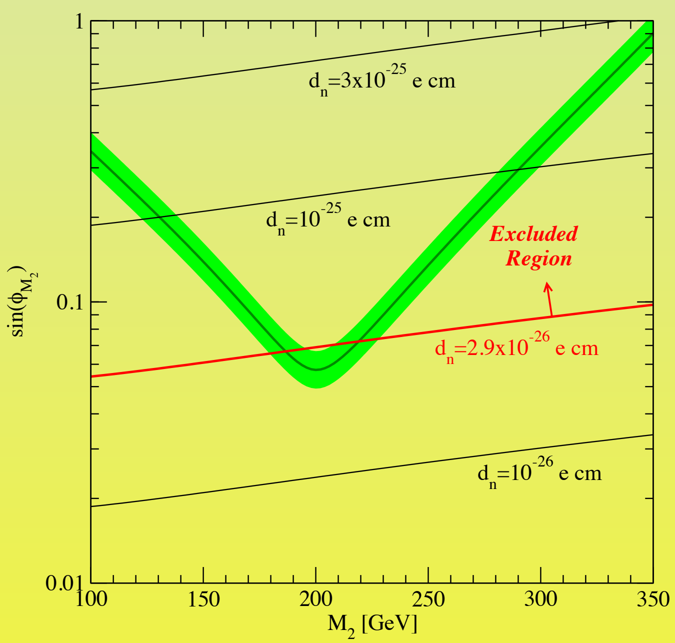
A typical example: Wino-catalyzed EWBG is excluded by the ACME result(intensity frontier) and the Higgs search results at the LHC(energy frontier).

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

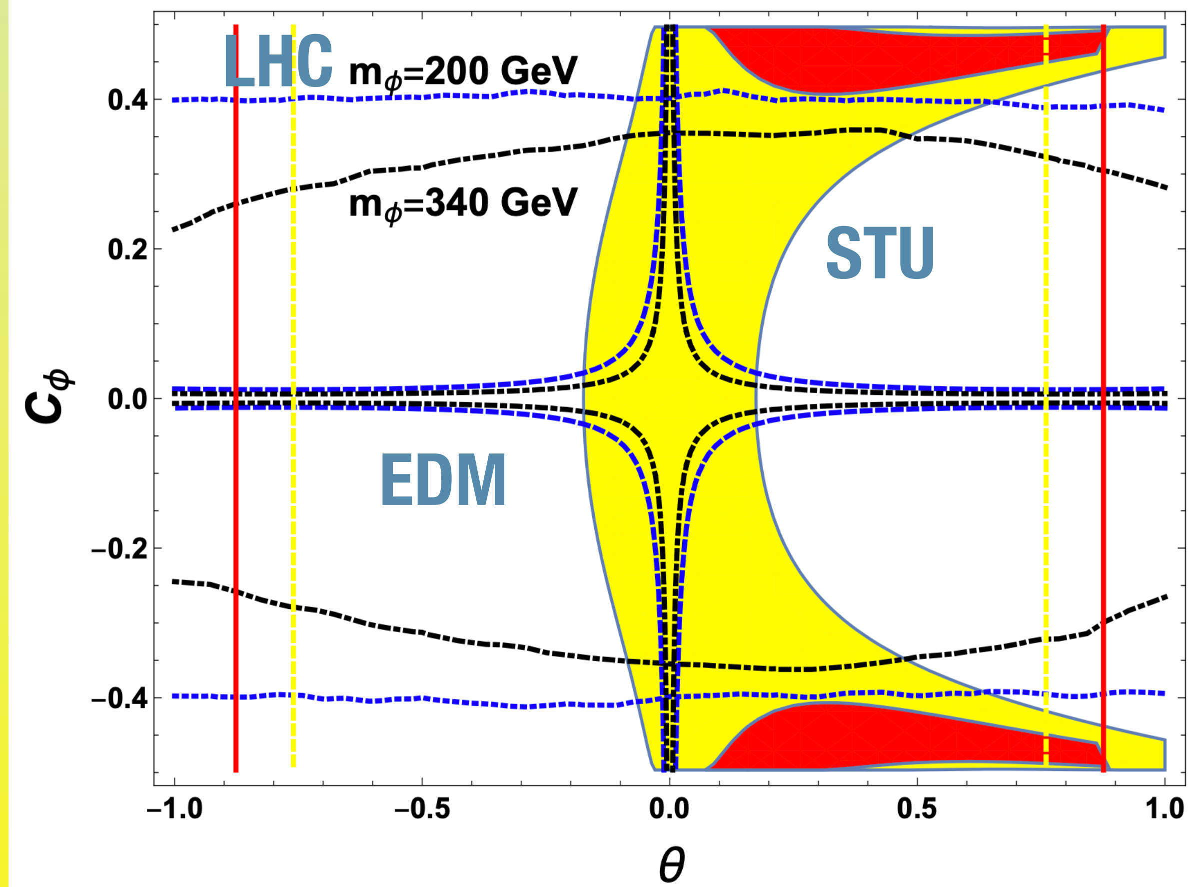
The tension

The tension between the requirement of a large CP phase by the EWBG and the non-observation of CPV in EDM experiments





Phys.Lett. B673 (2009) 95-100



$$\frac{1}{\sqrt{2}}\bar{t}\left(S_\phi s_\theta + Y_t c_\theta + i\gamma^5 C_\phi s_\theta\right) t\hat{h} + \cdots$$

Chao, Yandong Liu, 2019

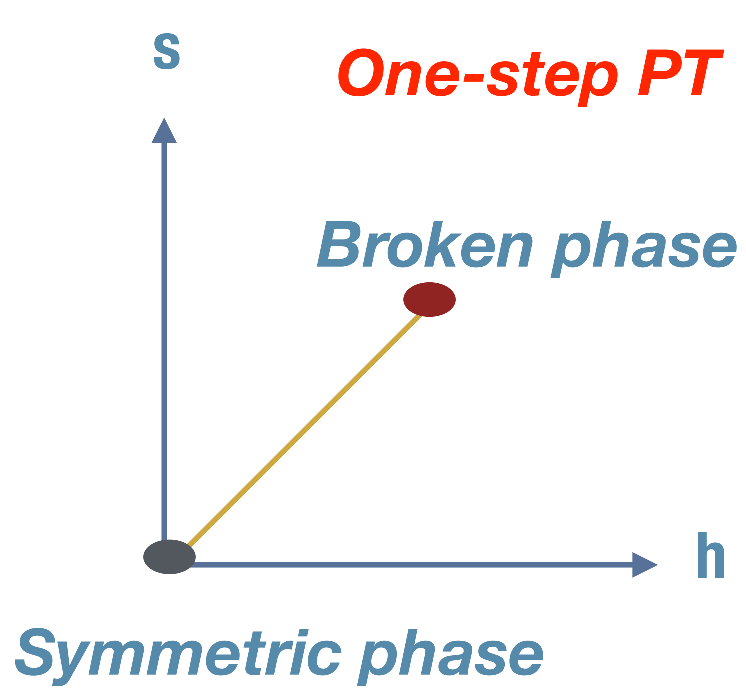
- Wino induced baryon asymmetry was excluded by the ACME result!
- **Is any EWBG that can escape the constraint of EDM?**

Our little aim: a EWBG with less signature

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

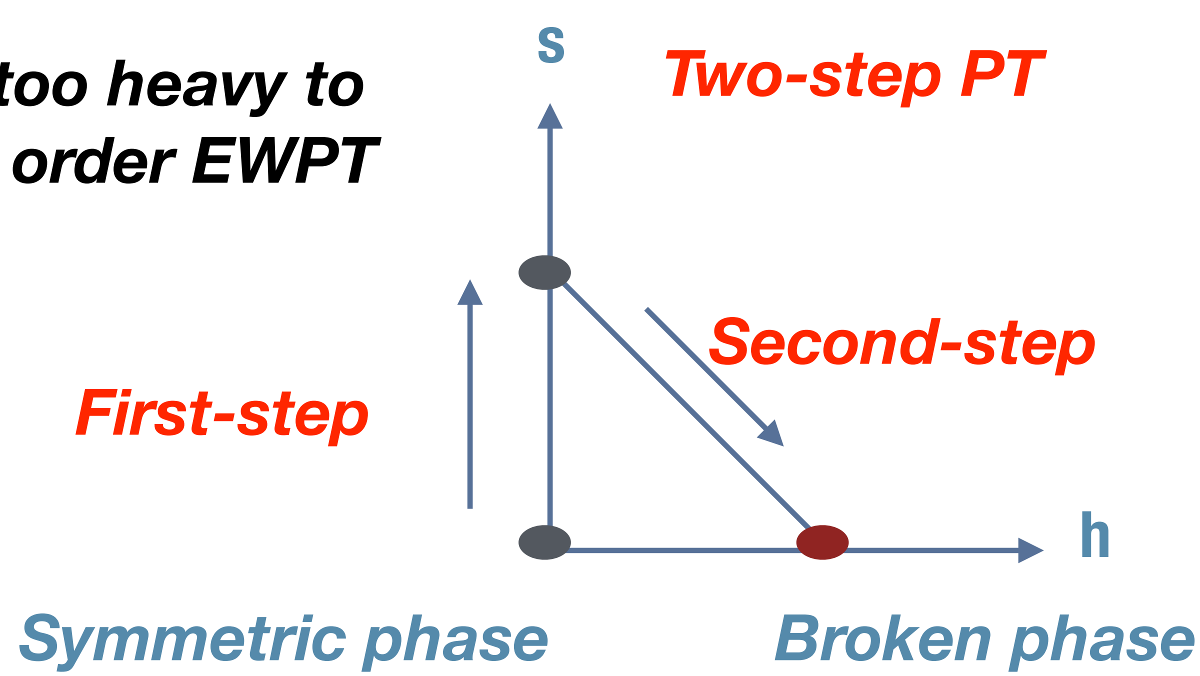
One observation: A two-step phase transition may avoid constraint arising from Higgs searches at the LHC

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

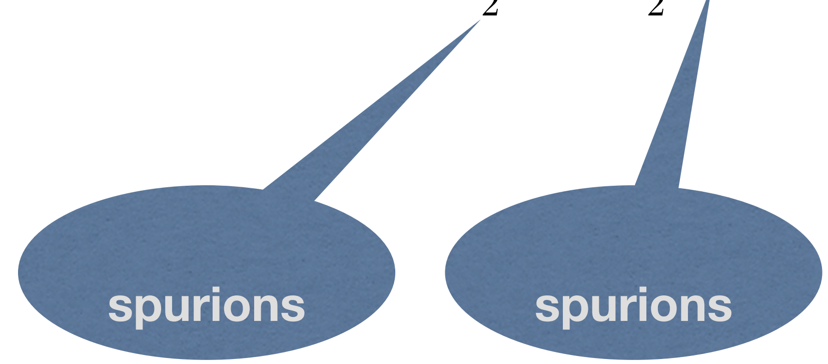
Our little aim: a EWBG with less signature

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

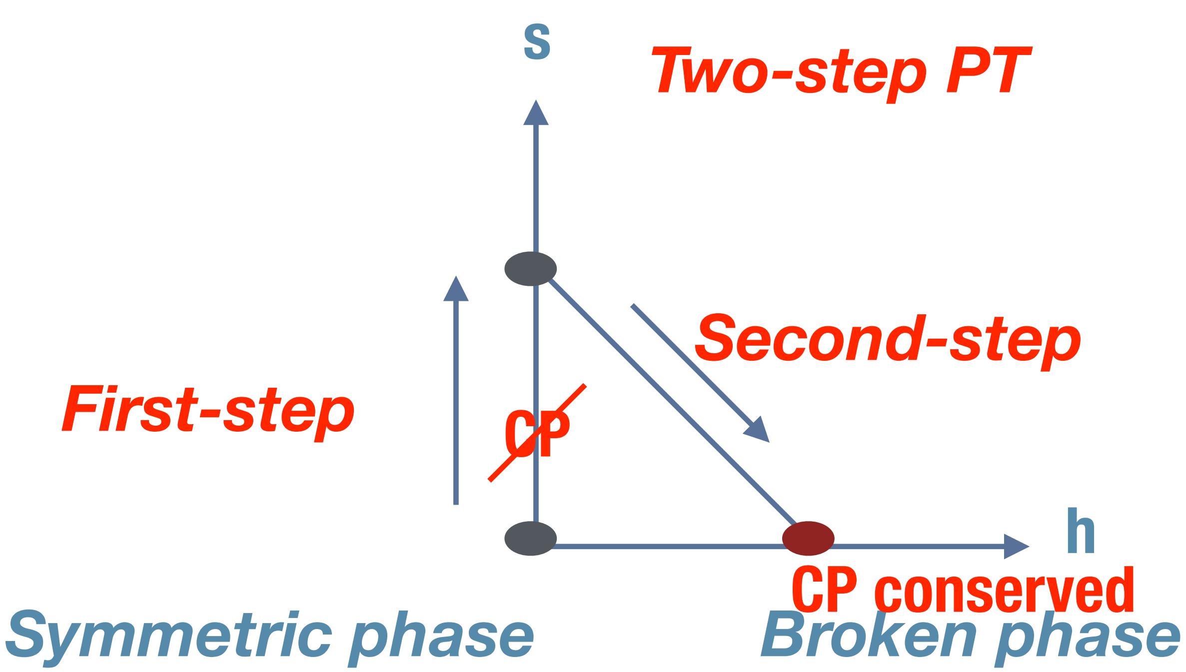
Lemma: Haber, Surujon, 2012

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

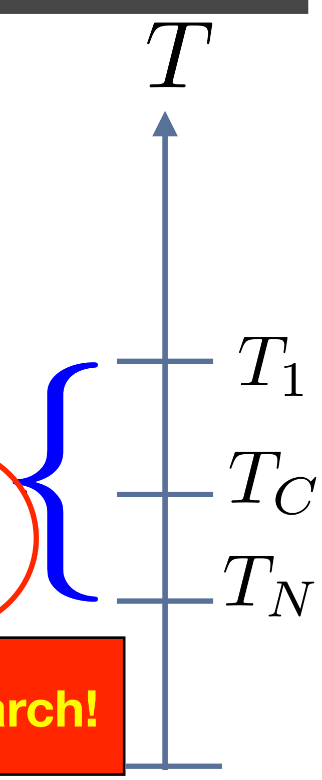
$$V = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 - \mu_A^2(S^\dagger S) + \lambda_1(S^\dagger S)^2 + \lambda_2(H^\dagger H)(S^\dagger S) - \frac{1}{2}\mu_B^2 S^2 + \frac{1}{2}\lambda_3 S^4 + \text{h.c.}$$



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!

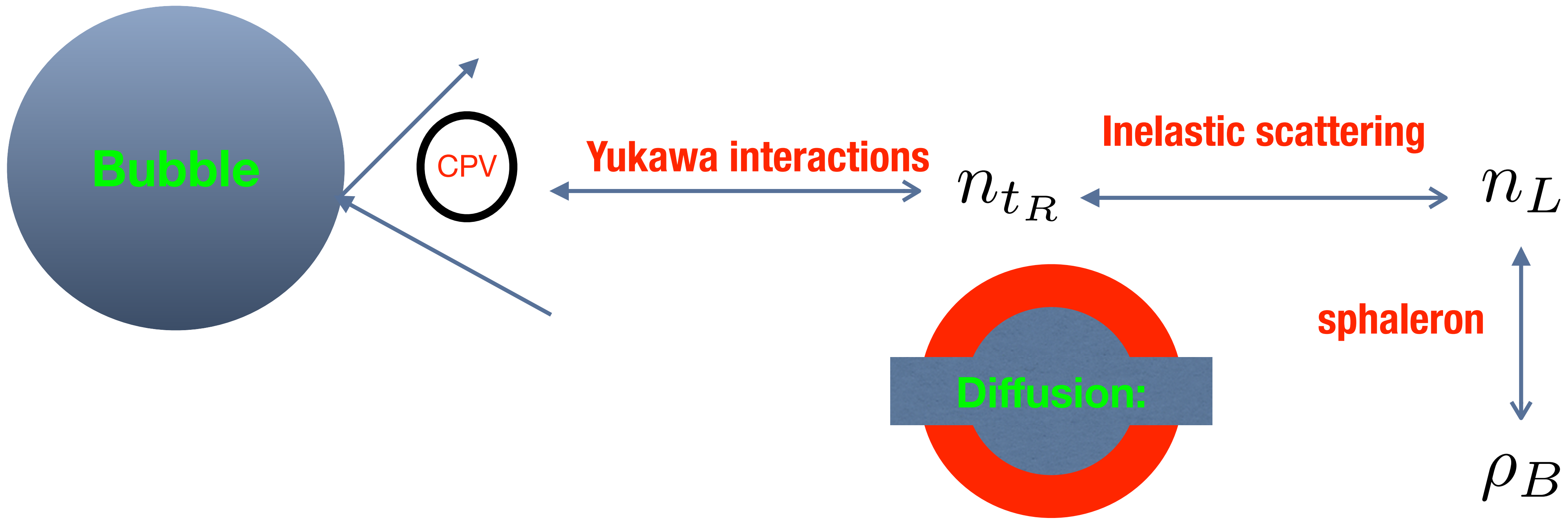
Sketch of the mechanism

Basic description

Sakharov:

- ~~B~~
- ~~C~~&C~~P~~
- First order EWPT

Sphaleron
Spontaneous CPV
Two-step PT



Transport equation:

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

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**

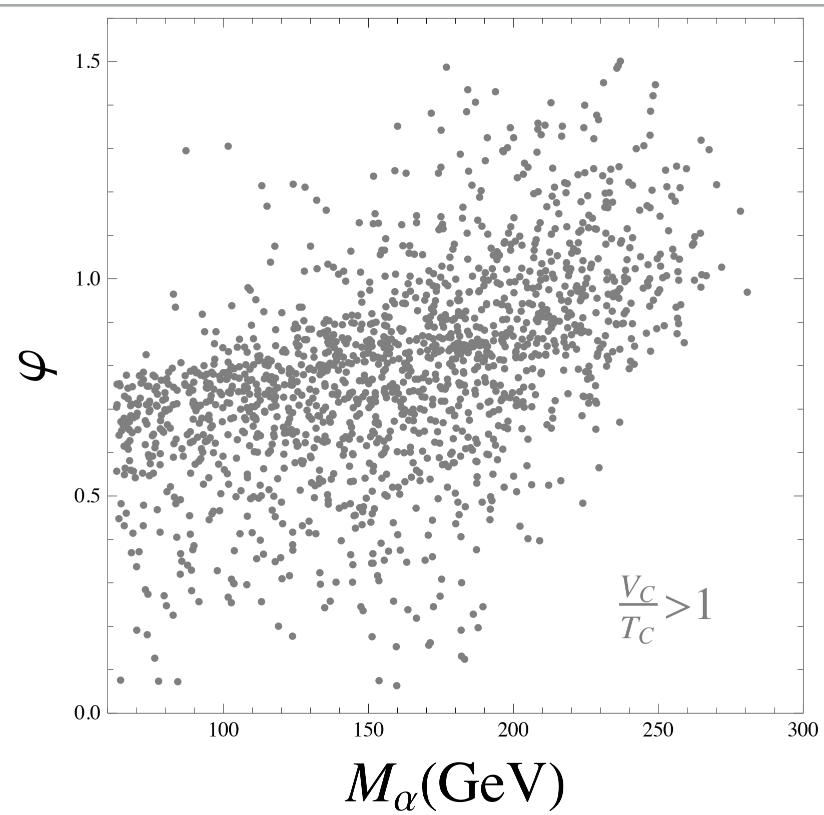
$$V_{\text{CW}} = \frac{1}{64\pi^2}\sum_i (-1)^{2s_i} n_i m_i^4(h,s,\xi)\left[\log\frac{m_i^2(h,s,\xi)}{\mu^2} - C_i\right]$$

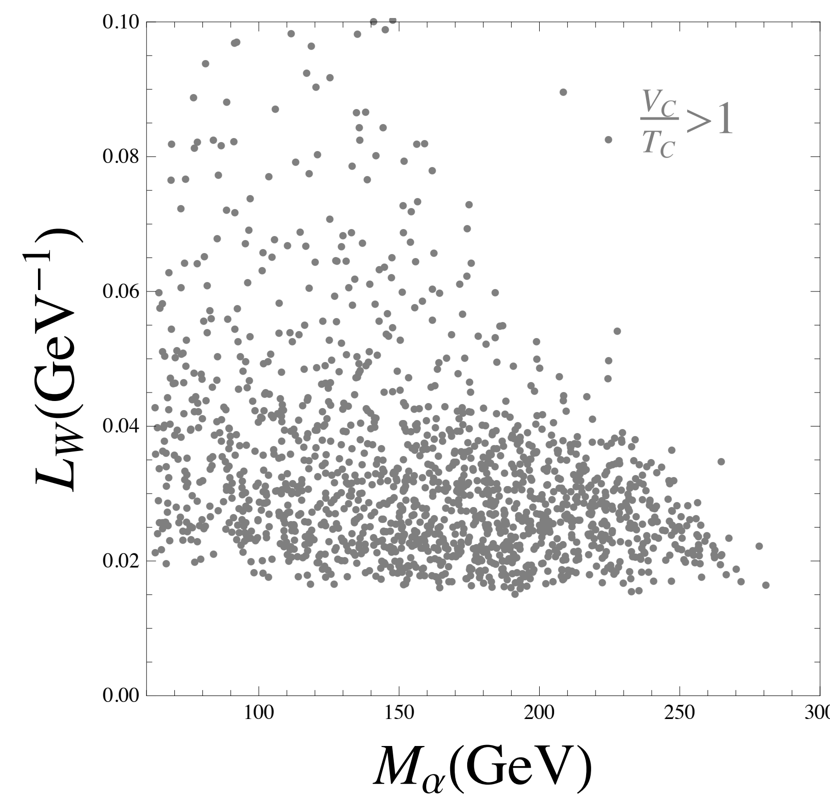
$$V_T^{\text{ring}} = \frac{T}{12\pi}\sum_i n_i\left\{(m_i^2(h,s))^{3/2} - (M_i^2(h,s,T))^{3/2}\right\}$$

BAU during the EWPT

CP phase 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:	$$L_w^2 \approx 1.35 \frac{\lambda + \sqrt{\lambda\lambda_\varrho}}{(\lambda_2 - 2\sqrt{\lambda\lambda_\varrho})[\lambda v_0^2 - \Pi_h(T_C^2)]} \times \left(1 + \sqrt{\frac{\lambda_2^2}{4\lambda\lambda_\varrho}}\right)$$





BAU during the EWPT

Source term and Transport equations

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:

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

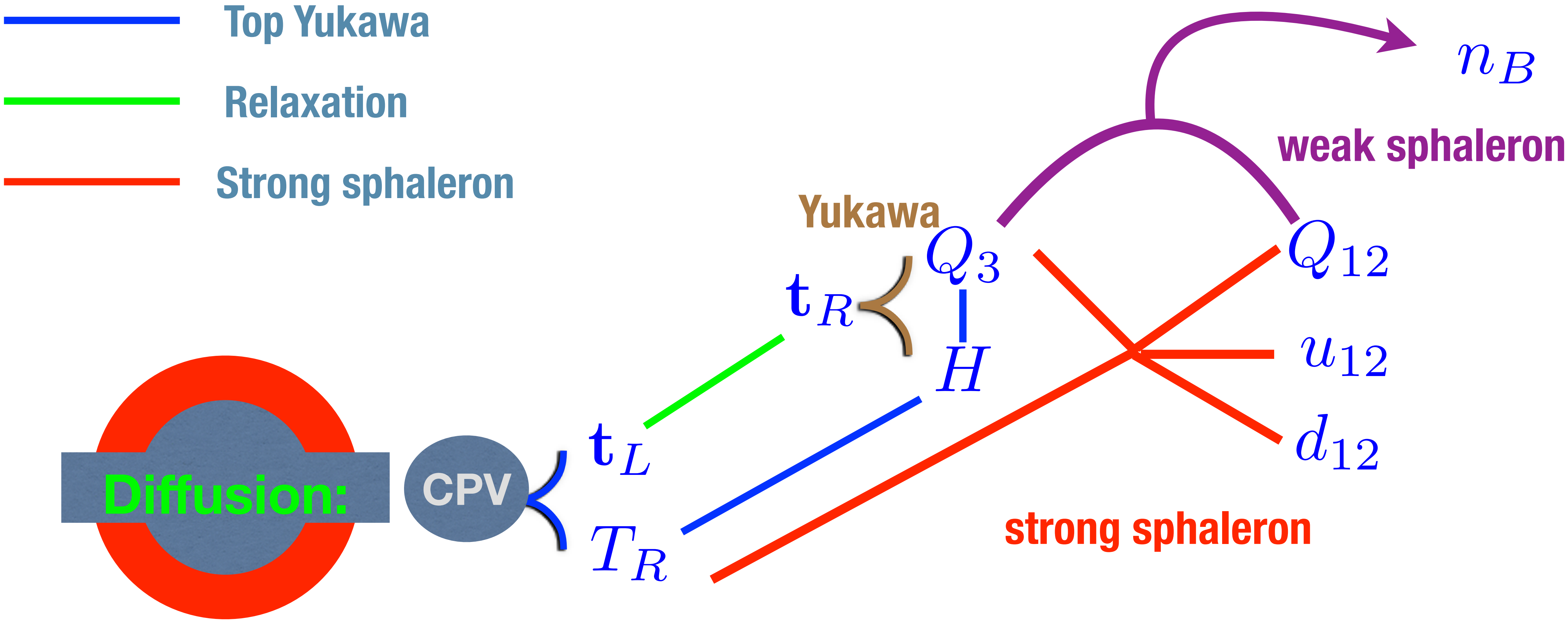
$$\zeta \overline{\mathrm{t}_L} S t_R + (M_{\mathrm{t}})\overline{\mathrm{t}_L}\mathrm{t}_R + \mathrm{h.c.}$$

All equations

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

BAU during the EWPT

Carton of transport:



Baryon number density:

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

BAU during the EWPT

Domain-wall decay!

Problems

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

No BAU left

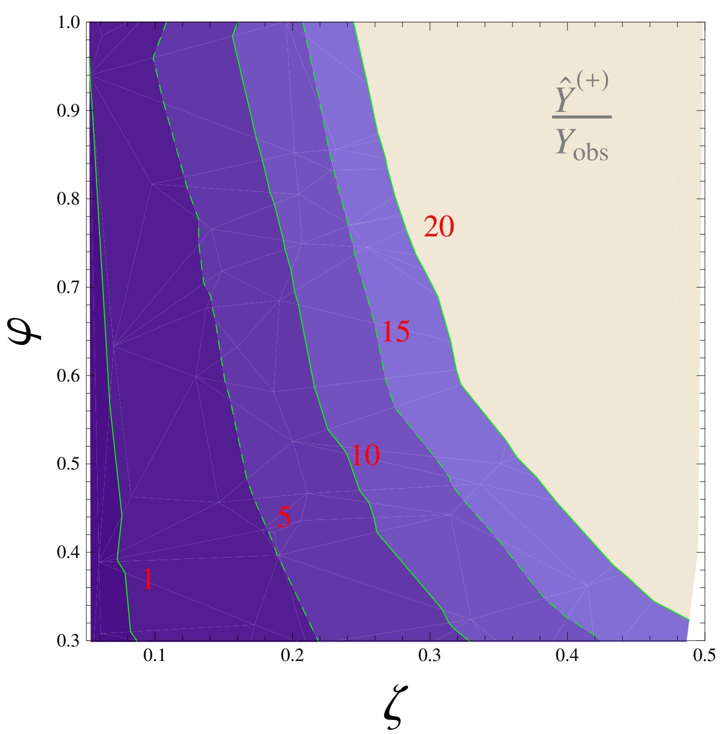
Solutions: Adding a Z_2 breaking term to the Higgs potential: Δs+h.c.

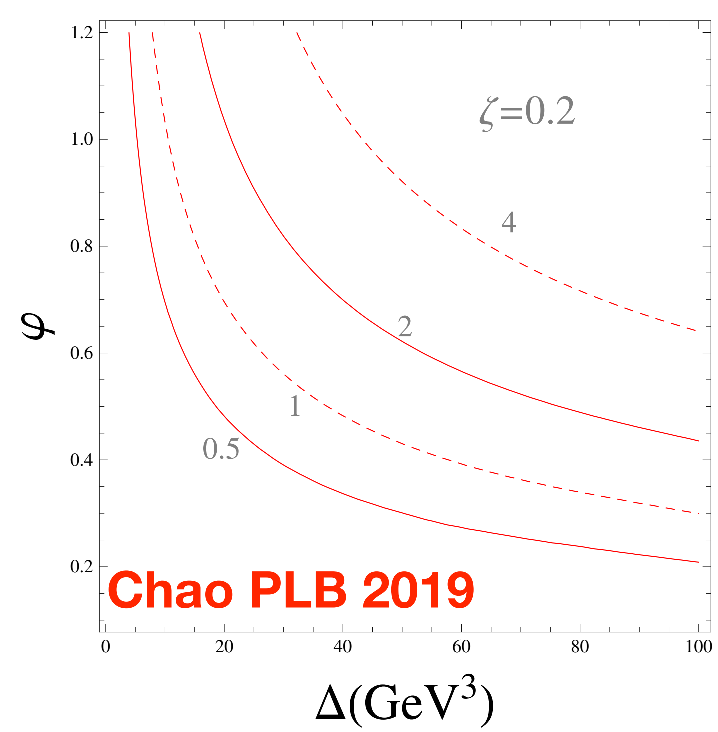
Ratio of bubbles

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

Final BAU

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

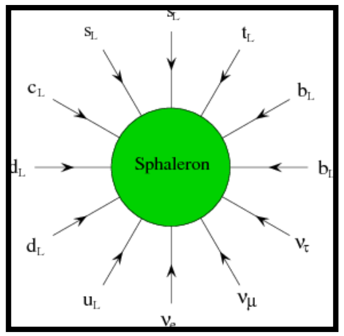




Chao PLB 2019

Another solution: EW symmetry non-restoration

Push the sphaleron to multi-TeV scale !



Freeze-out temperature ~130 GeV → **EWBG**

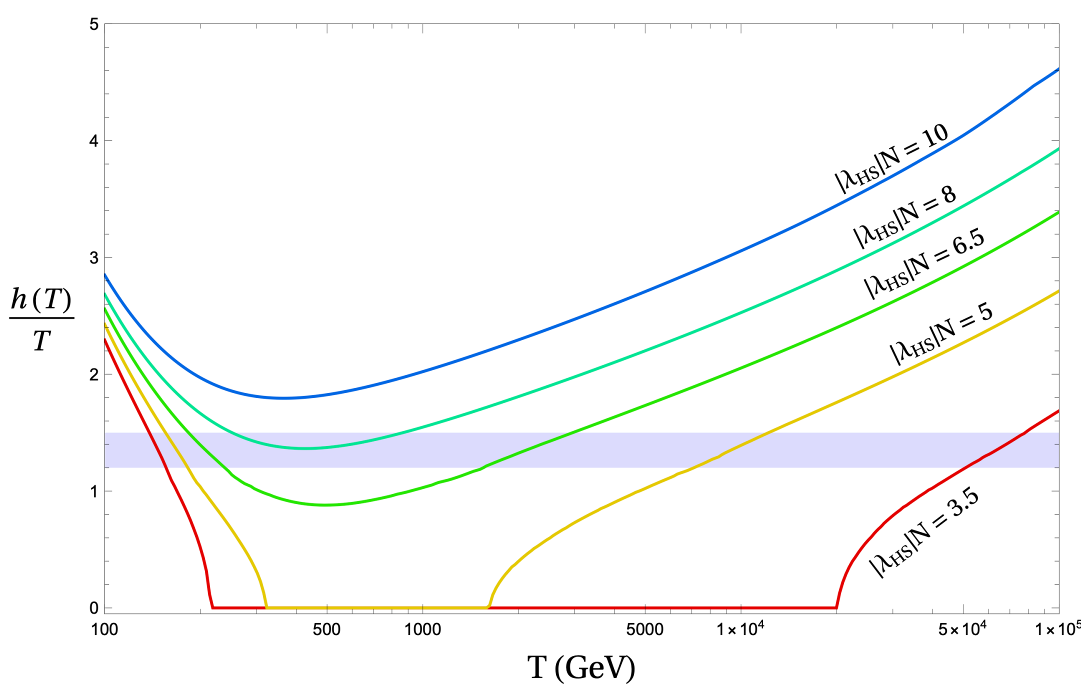
SM+scalars

Alfredo Glioti, Riccardo Rattazzi and Luca Vecchi, JHEP04(2019)027

$$V = m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4}(S^2)^2 + \lambda_{HS} S^2 H^\dagger H,$$

$$m_H^2 \to m_H^2(T) = m_H^2 + \left[\frac{N}{12}\lambda_{HS} + \frac{1}{2}\lambda_H + \frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}y_t^2\right] T^2$$

$$m_S^2 \to m_S^2(T) = m_S^2 + \left[\frac{(2+N)}{12}\lambda_S + \frac{1}{3}\lambda_{HS}\right] T^2,$$



Heavy particle may cause BAU via EWBG-like mechanism

Not natural
$N \sim 1000$!
Many model building papers try to quote this problem

Outline

- Brief overview of EWPT&EWBG
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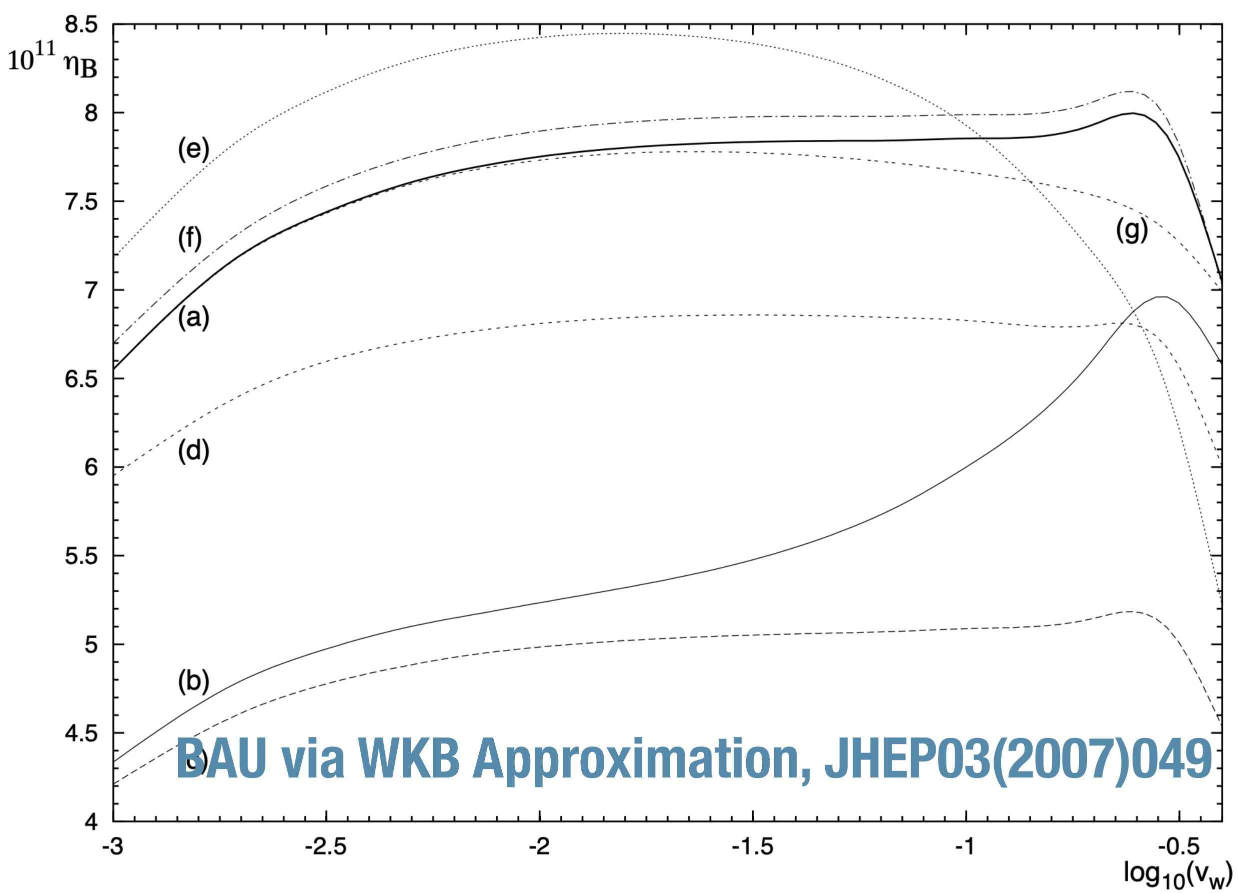
The “tension”

BAU favors low bubble wall velocity, Gravitational wave favors high wall velocity

Bubble collision	$h^2\Omega_{\rm coll}(f) = 1.67\times10^{-5}\left(\frac{H_n}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\times\left(\frac{0.11v_w^3}{0.42+v_w^2}\right)\left[\frac{3.8(f/f_{\rm coll})^{2.8}}{1+2.8(f/f_{\rm coll})^{3.8}}\right],$
Sound wave	$h^2\Omega_{\rm sw}(f) = 2.65\times10^{-6}\left(\frac{H_n}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left[\frac{7}{4+3(f/f_{\rm sw})^2}\right]^{7/2}$
MHD turbulence	$h^2\Omega_{\rm turb}(f) = 3.35\times10^{-4}\left(\frac{H_n}{\beta}\right)\left(\frac{\kappa_{\rm tu}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\times v_w\frac{(f/f_{\rm tu})^3}{(1+f/f_{\rm tu})^{11/3}(1+8\pi f/h_n)}$

For updated results, see Li-gong’s talk



BAU via WKB Approximation, JHEP03(2007)049

$$M_{ij}^2(y) = M_{ij}^2(x) + (x-y)^\mu\partial_\mu M_{ij}^2(x)$$

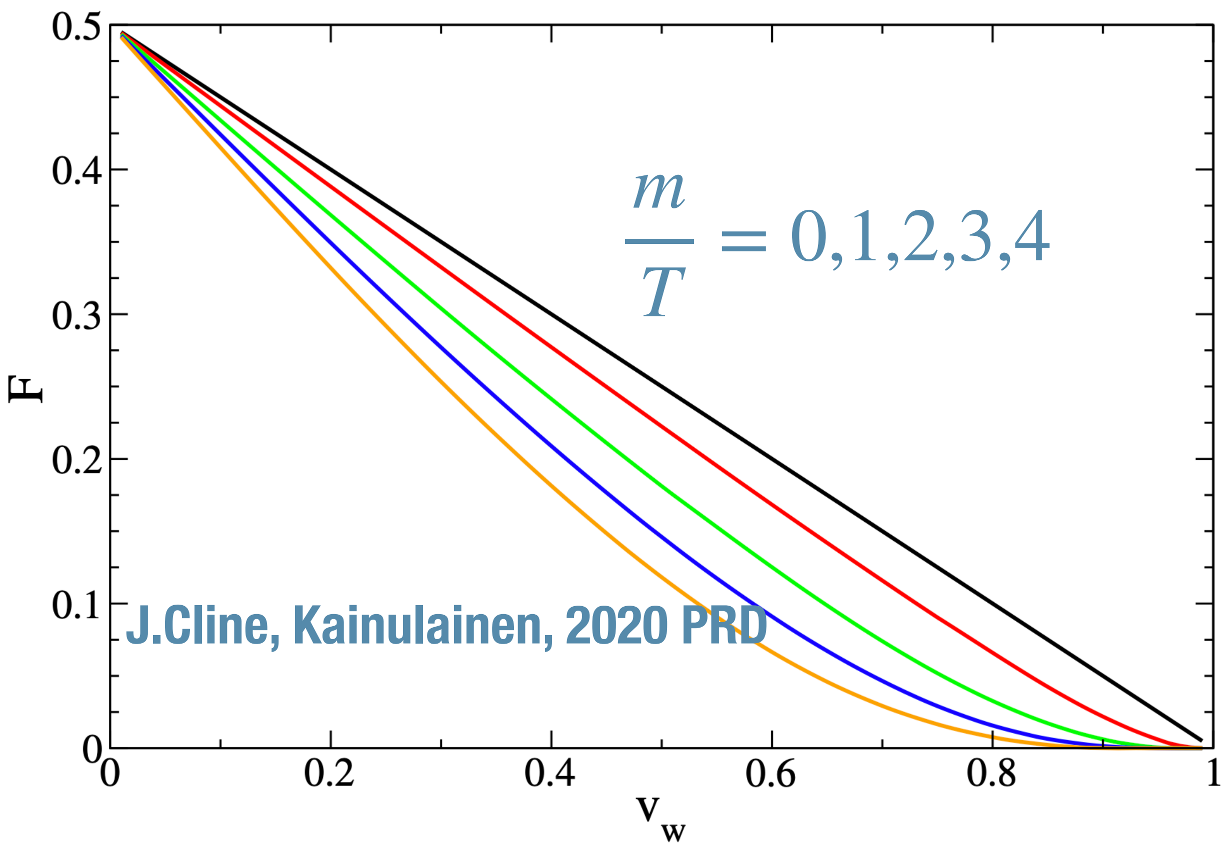
Valid in slowly varying bubble wall background

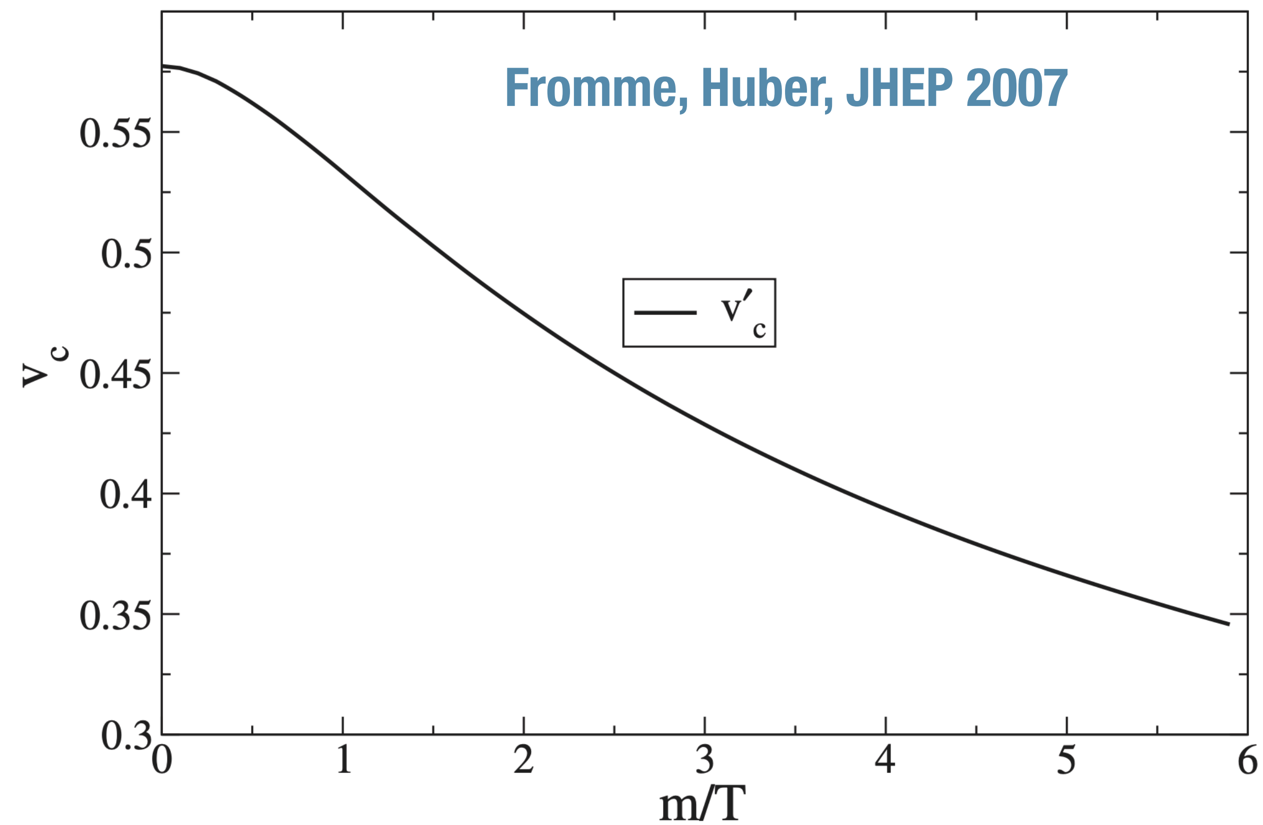
$$S_{CPV}^2 = 2Im[M^2\partial_\mu M^2]\int d^4y(y-x)^\mu\times\left(G_{RR}^<(x,y)G_{LL}^>(y,x) - G_{RR}^>(x,y)G_{LL^<(y,x)}\right)$$

BAU via the VEV insertion method

Improved transport equations

Physics relevant: fraction of plasma that can stay ahead of a bubble wall velocity.





$$\left(v\partial_z + F\partial_p\right) f = \mathscr{C}[f]$$

J.Cline, Kainulainen, 2020 PRD

$$D_\ell \equiv \left\langle \left(\frac{p_z}{E}\right)^\ell f'_{0w} \right\rangle$$

$$\begin{pmatrix} -D_1 & 1 \\ -D_2 & -v_w \end{pmatrix} \begin{pmatrix} \mu \\ u \end{pmatrix}' + (m^2)' \begin{pmatrix} v_w\gamma_w Q_1 & 0 \\ v_w\gamma_w Q_2 & \bar{R} \end{pmatrix} \begin{pmatrix} \mu \\ u \end{pmatrix} = S + \delta C$$

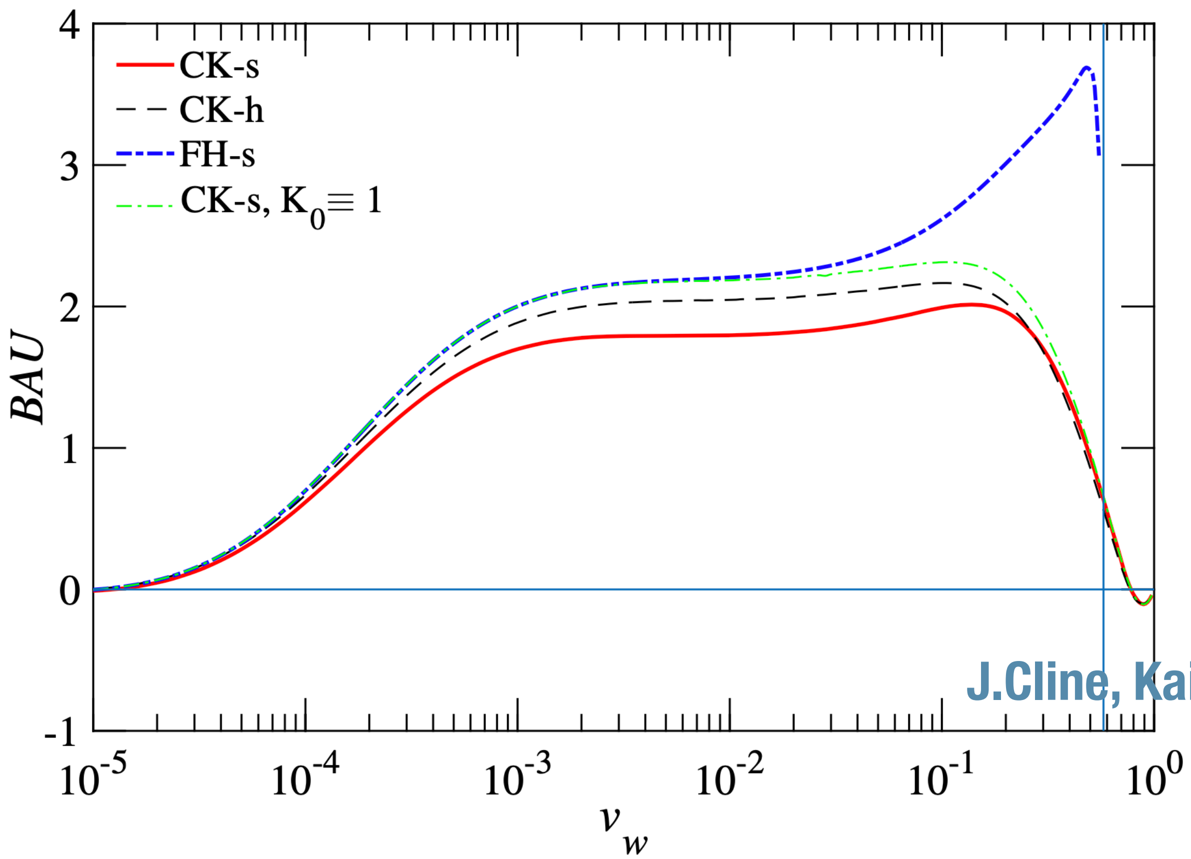
$$\begin{pmatrix} v_w K_1 & 1 \\ -K_4 & -v_w \end{pmatrix} \qquad K_1 = -\left\langle \frac{p_z^2}{E_0} f''_0 \right\rangle \qquad K_1 = \left\langle \frac{p_z^2}{E_0^2} f'_0 \right\rangle$$

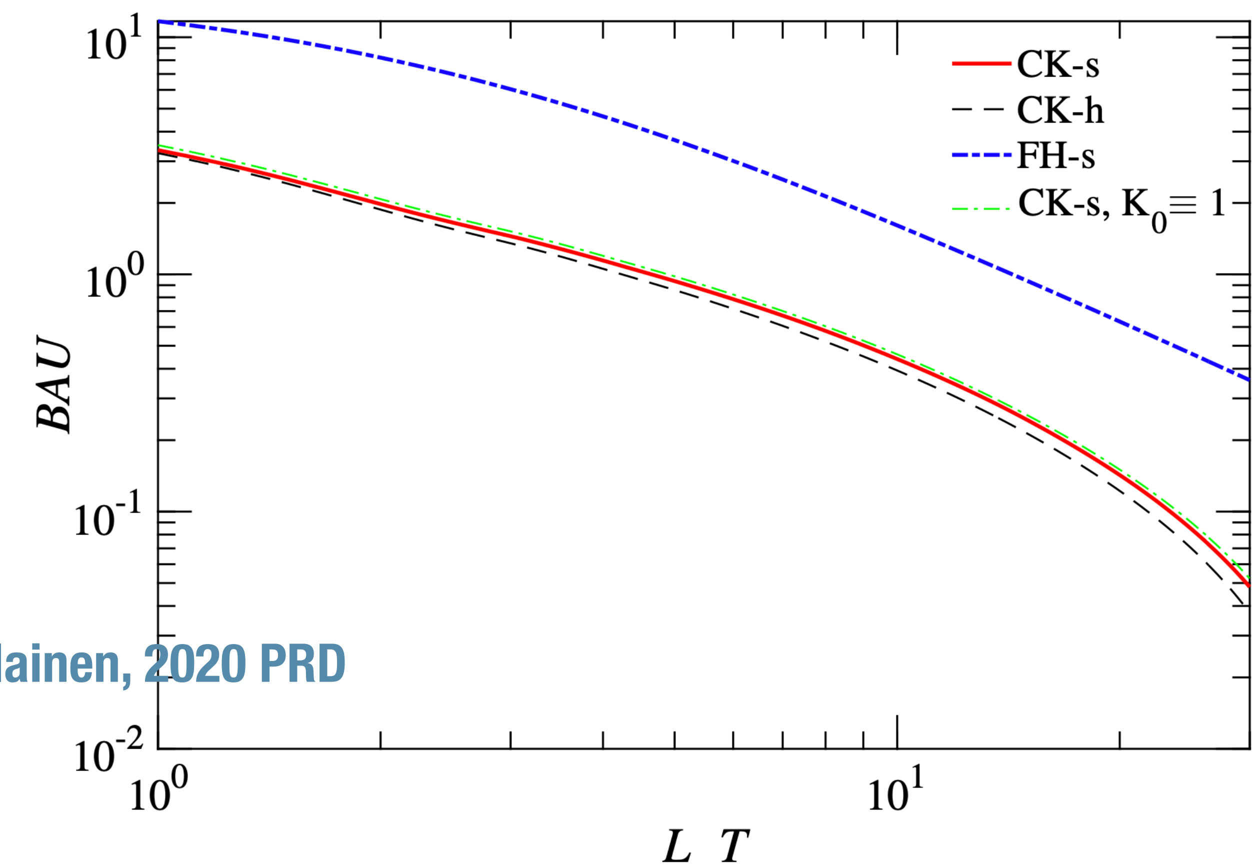
Critical velocity

$$v_c = -\left(\frac{D_2}{D_1}\right)_{v_w = v_c} \rightarrow v_c = 1$$

BAU vs Bubble wall velocity

Conclusion: BAU smoothly evolves to zero with the increase of the wall velocity





J.Cline, Kainulainen, 2020 PRD

CK-s: Improved fluid eq with spin source $s_h = \mathrm{sign}(p_z)$

CK-h: Improved fluid eq with helicity source $s_h = h \times \mathrm{sign}(p_z)$

Top triggered EWBG +two-step EWPT: $y_t h(z) \bar{t}_L \left(1 + i \frac{s(z)}{\Lambda}\right) t_R + \mathrm{H.c.},$

$$h(z) = \frac{v_n}{2}\left(1 - \tanh\frac{z}{L_w}\right), \qquad m_t(z) = y_t h(z)\sqrt{1 + s^2(z)/\Lambda^2}, \qquad v_n = \frac{1}{2} w_n = T_n, \qquad \Lambda = 1\ \mathrm{TeV},$$

$$s(z) = \frac{w_n}{2}\left(1 + \tanh\frac{(z - \delta_w)}{L_s}\right) \qquad \theta(z) = \tan^{-1}\frac{s(z)}{\Lambda}. \qquad L_w = L_s = \frac{5}{T_n}, \qquad \delta_w = 0,$$

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A third tension

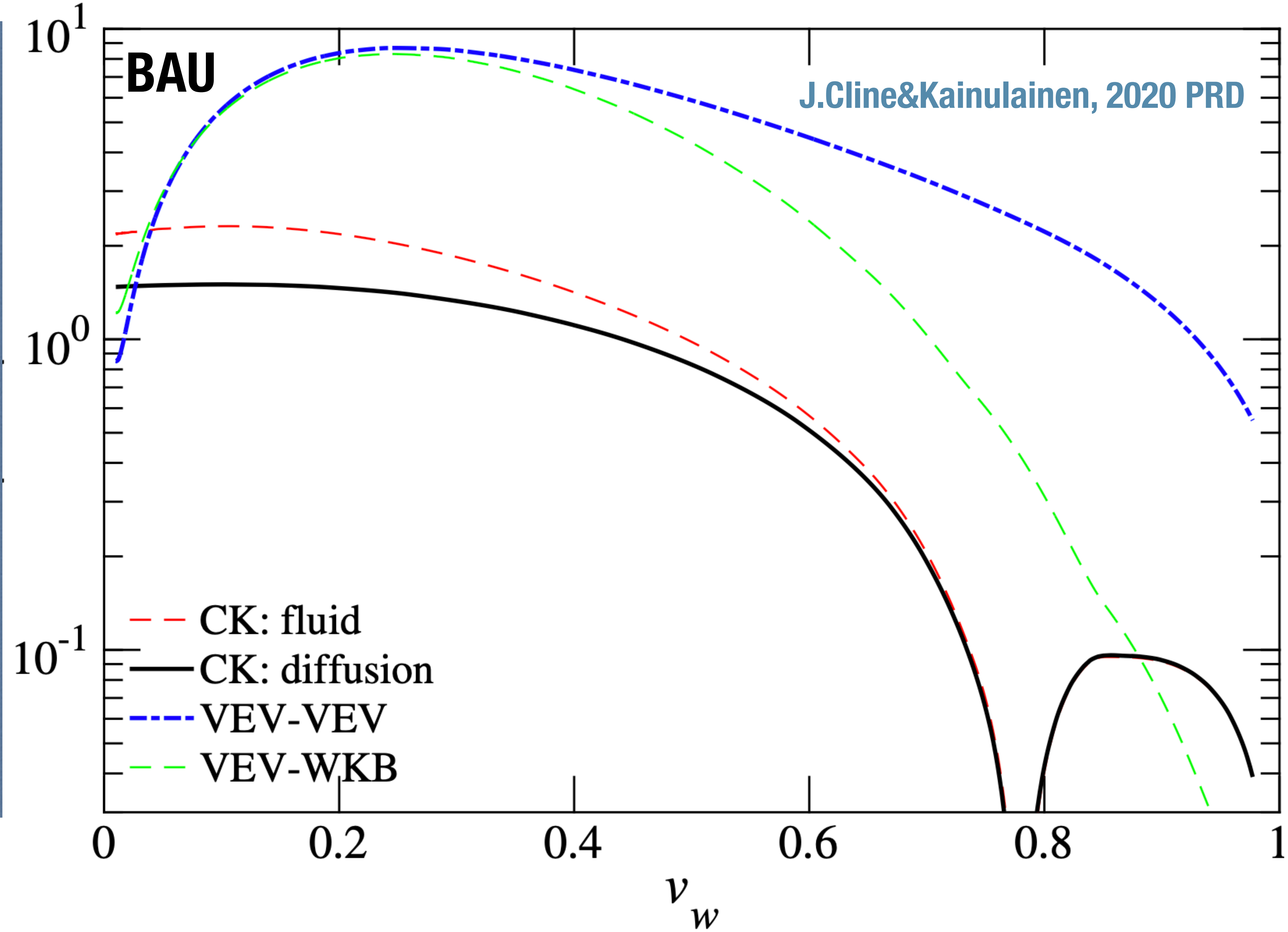
EWBG via the WKB approximation vs via the "VEV-insertion" method

CK-fluid: Full WKB result

CK-diffusion: WKB source + VEV-insertion diffusion équations;

VEV-VEV: Full VEV-insertion method;

VEV-WKB: VEV-insertion source term + WKB transport equations.



Conclusion: the VEV-insertion method seems over-estimate the CPV source term.

Traditional VEV-insertion method

A scalar case in the CTP formalism : analog to stop induced BAU

$$\mathscr{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - \phi^\dagger \mathscr{M}^2 \phi \qquad \mathscr{M}^2 = \begin{pmatrix} M_{LL}^2 & M_{LR}^2 \\ M_{RL}^2 & M_{RR}^2 \end{pmatrix}$$

Kadanoff-Baym equations: Wigner transforming of the Schwinger-Dyson equation

CTP formalism: see Yeling's talk

$$2ik \cdot \partial_x G^\lambda = \frac{1}{2} e^{-i\diamond} \left([\mathscr{M}^2, G^\lambda] + [\Pi^\lambda, G^h] + \frac{1}{2}(\{\Pi^>, G^<\} - \{\Pi^<, G^>\}) \right)$$

Left-handed side:

$$\frac{1}{2}\partial_\mu \int \frac{d^4k}{(2\pi)^4} ik^\mu \left(G^>(k,x) + G^<(k,x) \right) = -\partial_\mu \langle J^\mu(x) \rangle$$

Source term:

$$S_{LL} = -\int \frac{d^4k}{(2\pi)^4} \left([\mathscr{M}^2, G^> + G^<] + [\Pi^> + \Pi^<, G^h] + \{\Pi^>, G^<\} - \{\Pi^<, G^>\} \right)$$

Traditional VEV-insertion method

Self-energy is expanded to 2nd order:

$$\Pi^{\lambda} = -M^2_{IJ} G^{\lambda}_{JJ} M^2_{JI}$$

$$S_{LL} = -2\int d^4y \mathrm{Re}\left[M^2_{LR}(x) G^{<}_{RR}(x,y) M^2_{RL}(y) G^{>}_{LL}(y,x) - M^2_{RL}(x) G^{>}_{RR}(x,y) M^2_{LR}(y) G^{<}_{LL}(y,x)\right]$$

$+$

$$M^2_{ij}(y) = M^2_{ij}(x) + (x-y)^{\mu}\partial_{\mu} M^2_{ij}(x)$$

Valid in slowly varying bubble wall background

$$S^2_{CPV} = 2Im[M^2\partial_{\mu}M^2]\int d^4y(y-x)^{\mu} \times \left(G^{<}_{RR}(x,y)G^{>}_{LL}(y,x) - G^{>}_{RR}(x,y)G_{LL^{<}(y,x)}\right)$$

New insight

Self-energy is given as equilibrium approximation, expanding weightman functions to second order

Marieke Postma, Jorinde van de Vis and Graham White,

arXiv: 2206.01120

$$G^{ab}_{(1),IJ} = \sum_c c\, G^{ac}_{(0),II}(\delta M^2)_{IJ} G^{cb}_{(0),JJ}$$

$$G^{ab}_{(2),II} = \sum_{cd} cd\, G^{ac}_{(0),II}(\delta M^2)_{IJ} G^{cd}_{(0),JJ}(\delta M^2)_{JI} G^{db}_{(0),II}$$

$$\bar{S}^{(2)} = [\delta M^2, (G^{>}_{(1)} + G^{<}_{(1)})] + [M_d^2, (G^{>}_{(2)} + G^{<}_{(2)})] + [\Pi^{>} + \Pi^{<}, G^{h}_{(2)}] + \left(\{\Pi^{>}, G^{<}_{(2)}\} - \{\Pi^{<}, G^{>}_{(2)}\} \right)$$

Commutation term: $S^{(2)}_{M,LL} = |m_{LR}|^4 \rho_L \rho_R \left[(2n_L - 1) - (2n_R - 1) \right] = 2|m_{LR}|^4 \rho_L \rho_R (n_L - n_R),$

Collision term

$$\bar{S}^{(2)}_{C,LL} = \left(\{\Pi^{>}, G^{<}_{(2)}\} - \{\Pi^{<}, G^{>}_{(2)}\} \right)_{LL} = -2|m_{LR}|^4 \gamma_L \rho_L^2 \rho_R (n_L - n_R) \frac{D_L^* D_L}{\gamma_L^2}$$
$$= -2|m_{LR}|^4 \rho_L \rho_R (n_L - n_R)$$

$$\bar{S}^{(2)} = \bar{S}^{(2)}_{M,LL} + \bar{S}^{(2)}_{C,LL} = 0 \quad ! \quad ! \quad !$$

Discussion

其他方面的进展如bubble 动力学参见边立功老师的报告

- 在后希格斯时代EWBG是否值得继续深入研究?

- EWBG与低能精确测量的冲突如何解决?
- EWBG与引力波信号之间有多强的关联?
- 如何从第一性原理出发来精确计算EWBG?
- 其他值得深入探索的冲突或者方向。。。