

第四届新物理数值计算与模拟前沿讲习班
河南师范大学
2026-07-07



Progress of Baryogenesis

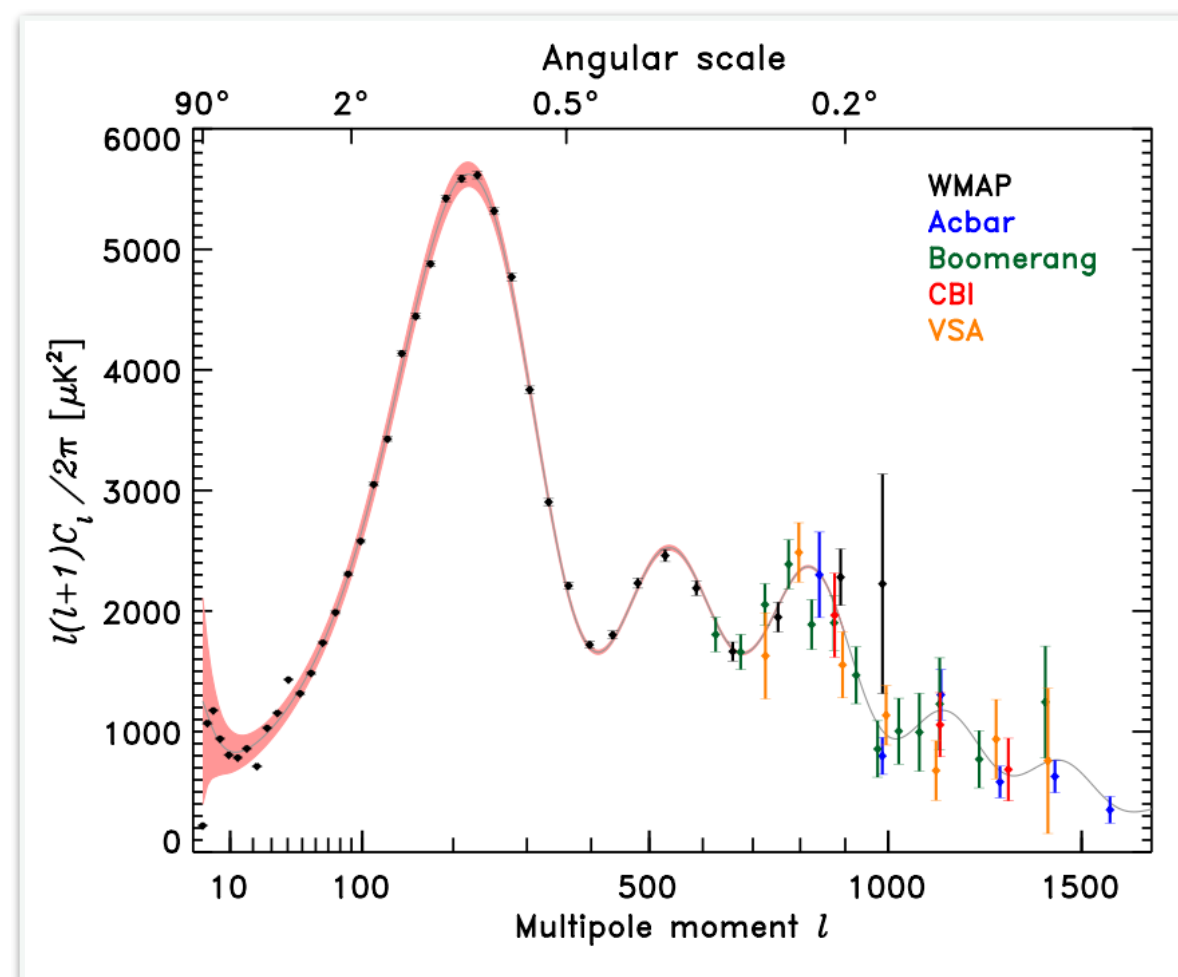
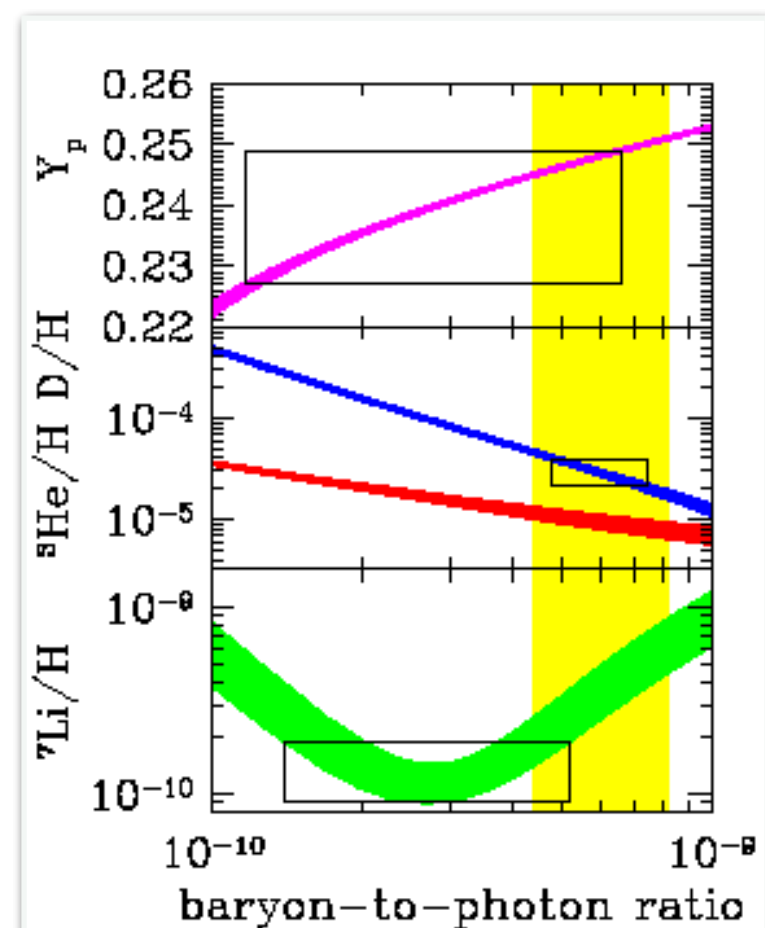
Wei Chao

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New physics—The Baryon asymmetry

Matter-antimatter asymmetry

- ✱ No galaxy made by ant-baryon is observed
- ✱ Baryon asymmetry is measured by the Planck.

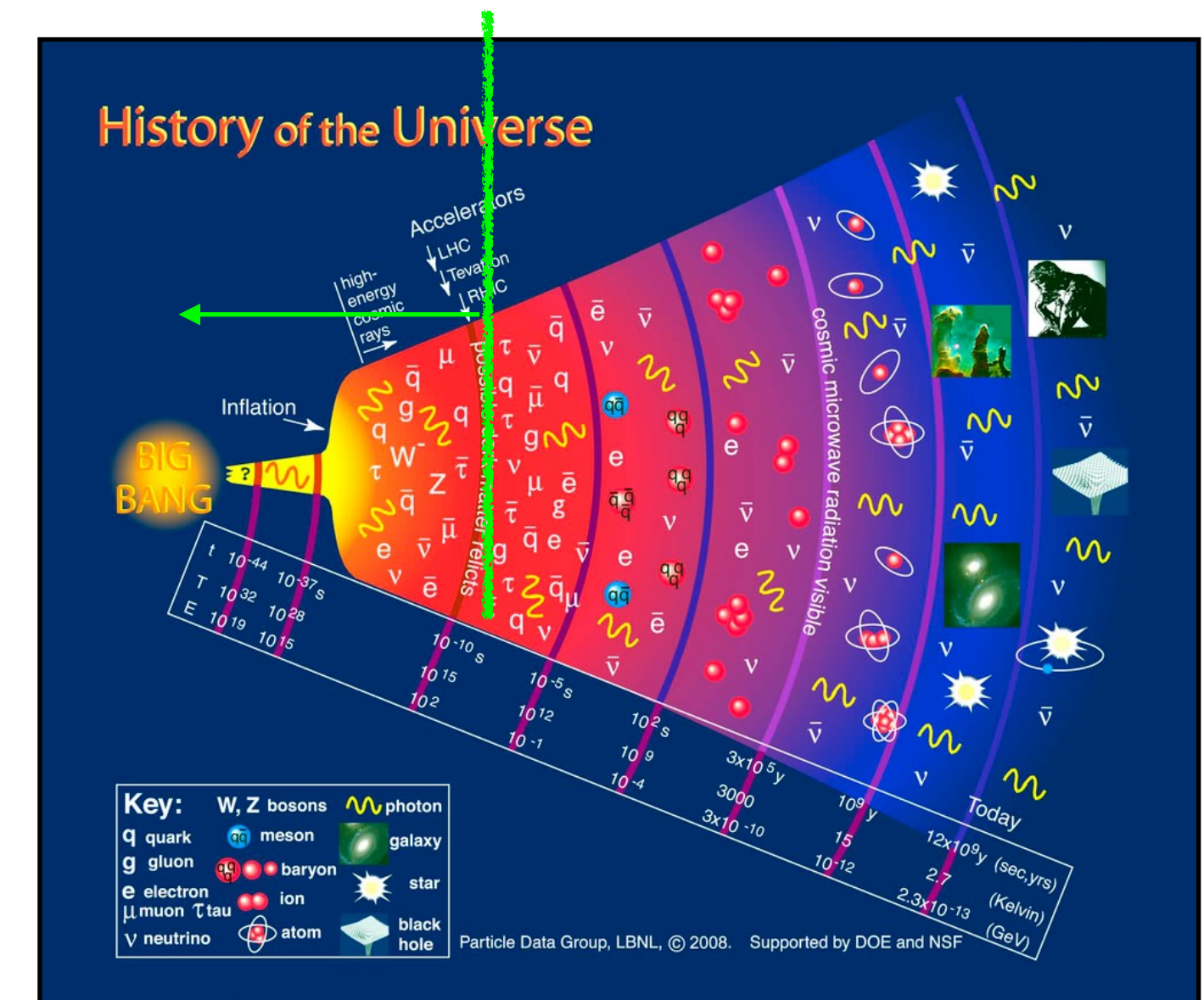


Baryon asymmetry: $Y_B = \frac{\rho_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$ Planck

Baryogenesis



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



- Leptogenesis
- Electroweak Baryogenesis
- GUT Baryogenesis
- Affleck-Dine Baryogenesis
- Post-sphaleron baryogenesis

Outline

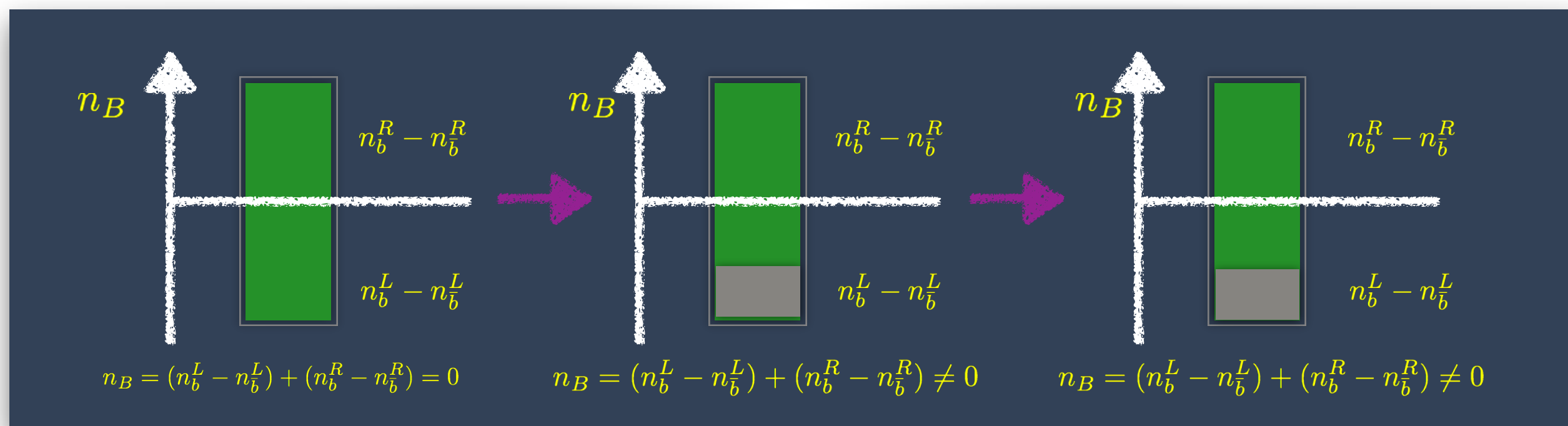
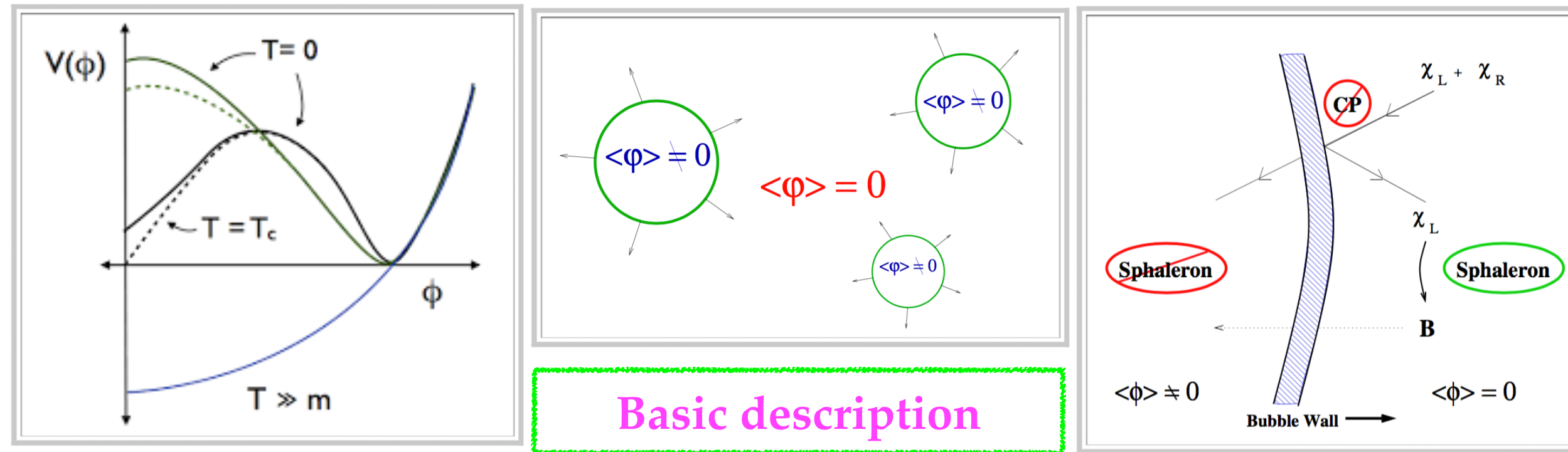
❖ Overview of Baryogenesis mechanisms

❖ Recent Progress

- Basic setup of the Electroweak Baryogenesis
- Progress(1) EWBG vs EDM constraints
- Progress(2) EWBG via symmetry non-restoration(SNR)
- Progress(3) Baryogenesis via SNR
- Progress(4) EWBG vs bubble dynamics
- Progress(5) Chiral magnetic effects
- Progress(6) Baryogenesis without first order phase transition

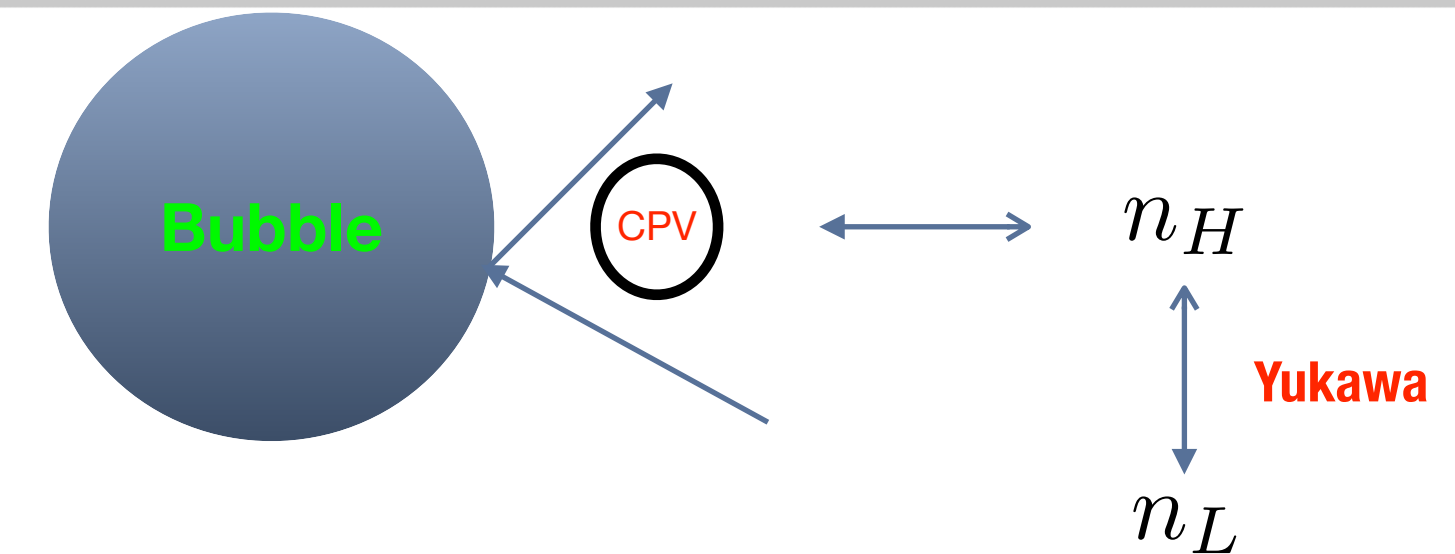
History and development: EW Baryogenesis

EWBG



Transport equations

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



$$\begin{aligned} \partial_\mu \psi_\mu &= +\Gamma_\psi^+ \left(\frac{\chi}{k_\chi} + \frac{\psi}{k_\psi} \right) + \Gamma_\psi^- \left(\frac{\chi}{k_\chi} - \frac{\psi}{k_\psi} \right) + \left(\sum_i \Gamma_{y_i} \right) \left(\frac{\chi}{k_\chi} - \frac{H}{k_H} - \frac{\psi}{k_\psi} \right) + S_{\text{CP}}^\psi \\ \partial_\mu \chi_\mu &= -\Gamma_\psi^+ \left(\frac{\chi}{k_\chi} + \frac{\psi}{k_\psi} \right) - \Gamma_\psi^- \left(\frac{\chi}{k_\chi} - \frac{\psi}{k_\psi} \right) - \left(\sum_i \Gamma_{y_i} \right) \left(\frac{\chi}{k_\chi} - \frac{H}{k_H} - \frac{\psi}{k_\psi} \right) - S_{\text{CP}}^\psi \\ \partial_\mu H_\mu &= \Gamma_{Y_t} \left(\frac{T}{k_T} - \frac{H}{k_H} - \frac{Q}{k_Q} \right) + \left(\sum_i \Gamma_{y_i} \right) \left(\frac{\chi}{k_\chi} - \frac{H}{k_H} - \frac{\psi}{k_\psi} \right) - \Gamma_h \frac{H}{k_H}, \end{aligned}$$

History and development: Leptogenesis

Type-I seesaw mechanism

Neutrino physics

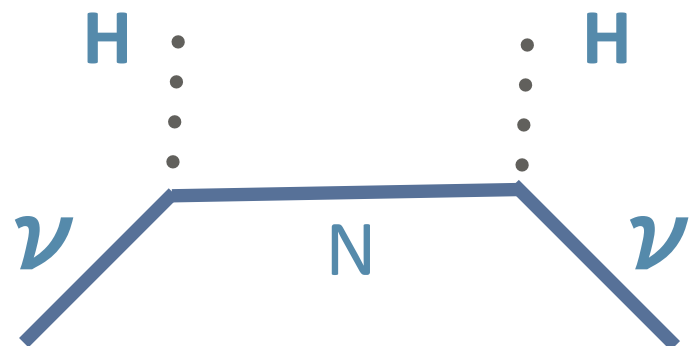
Leptogenesis via seesaw

BAU

Lagrangian:

$$-\mathcal{L} = Y_\nu \bar{\ell}_L \tilde{H} N_R + \frac{1}{2} \overline{N_R^C} M_R N_R + \text{h.c.}$$

Seesaw Mechanism



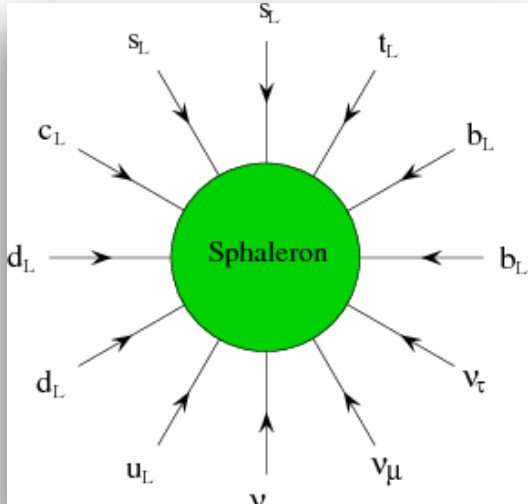
Neutrino mass:

$$M_\nu = -M_D M_R^{-1} M_D^T$$

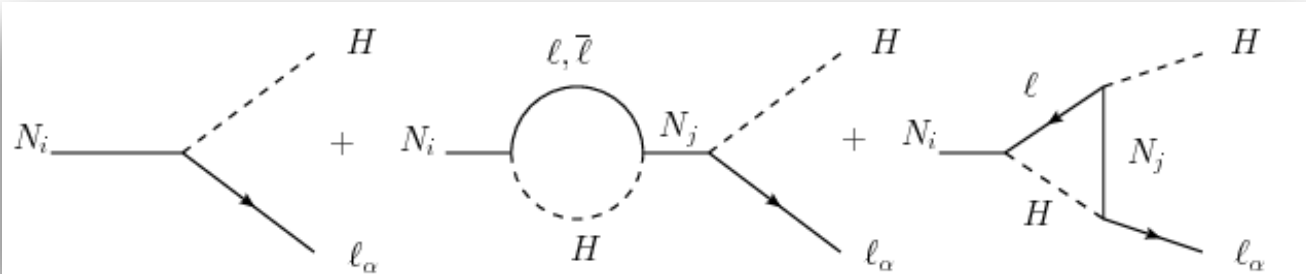
Elegant but losing testability at colliders!

Leptogenesis (Fukugita&Yanagida 86)

BV



CPV

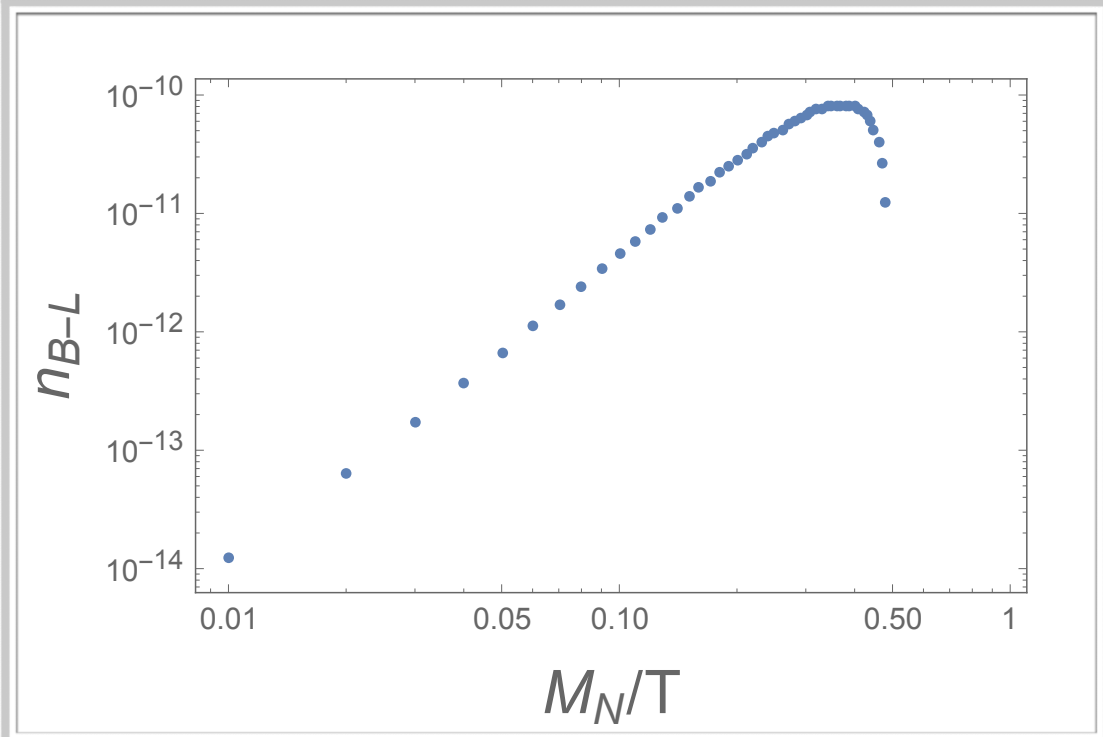


Out of EQ

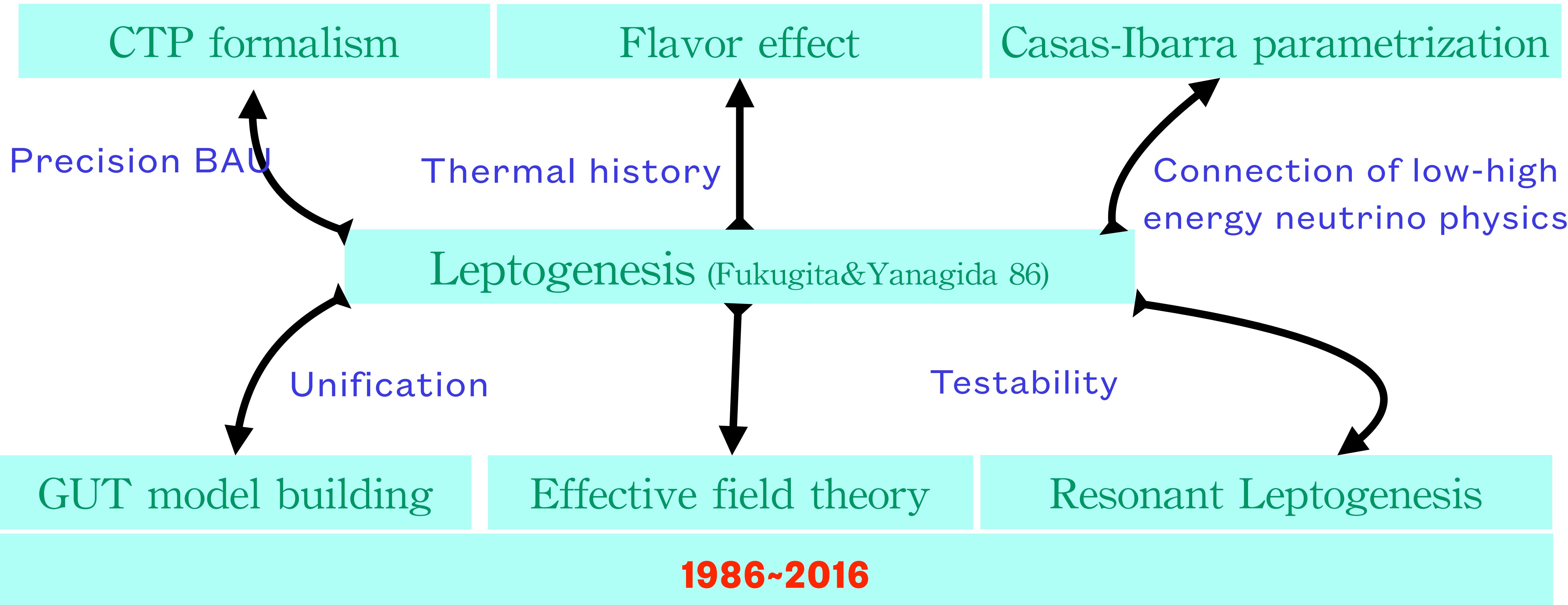
Heavy neutrinos decouple

Boltzmann EQ

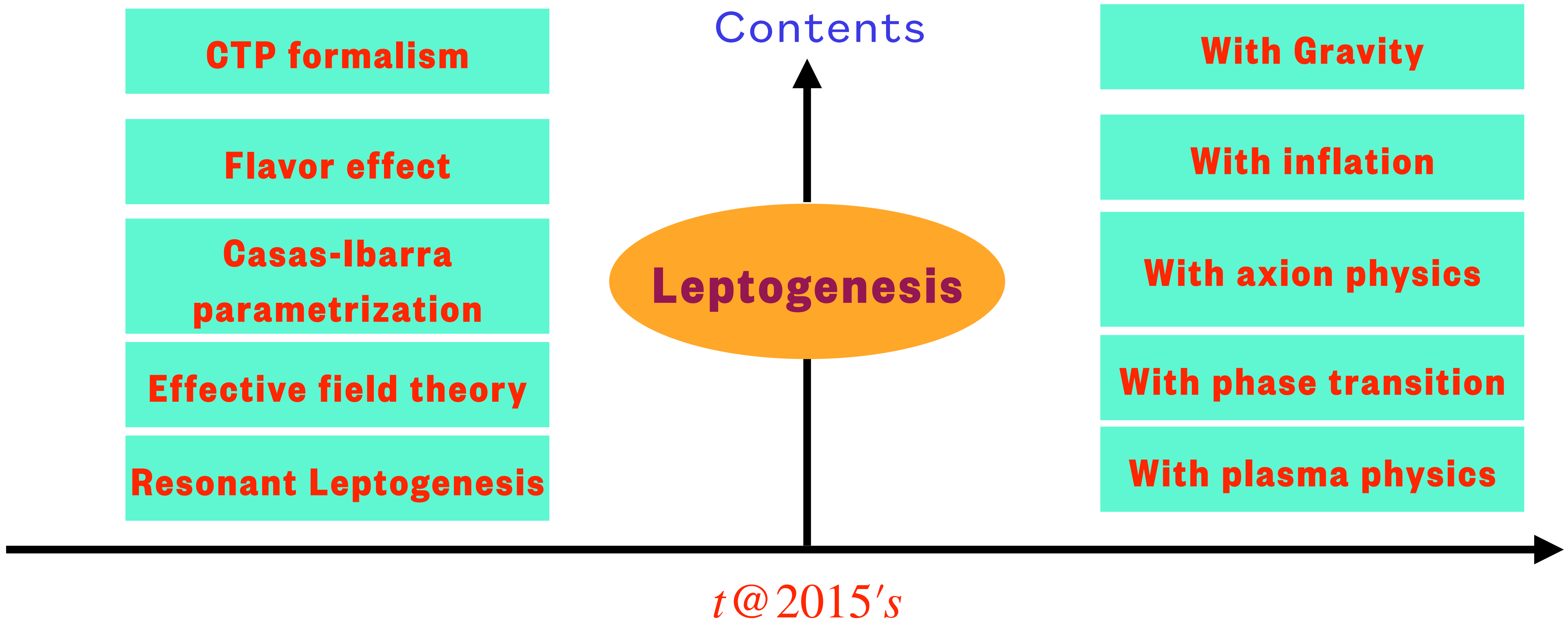
$$\frac{dN}{dz} = -D(N - N^{\text{eq}})$$
$$\frac{dN_{B-L}}{dz} = -\epsilon D(N - N^{\text{eq}}) + W_{\text{ID}} N_{B-L}$$



History and development: Leptogenesis



History and development: Leptogenesis



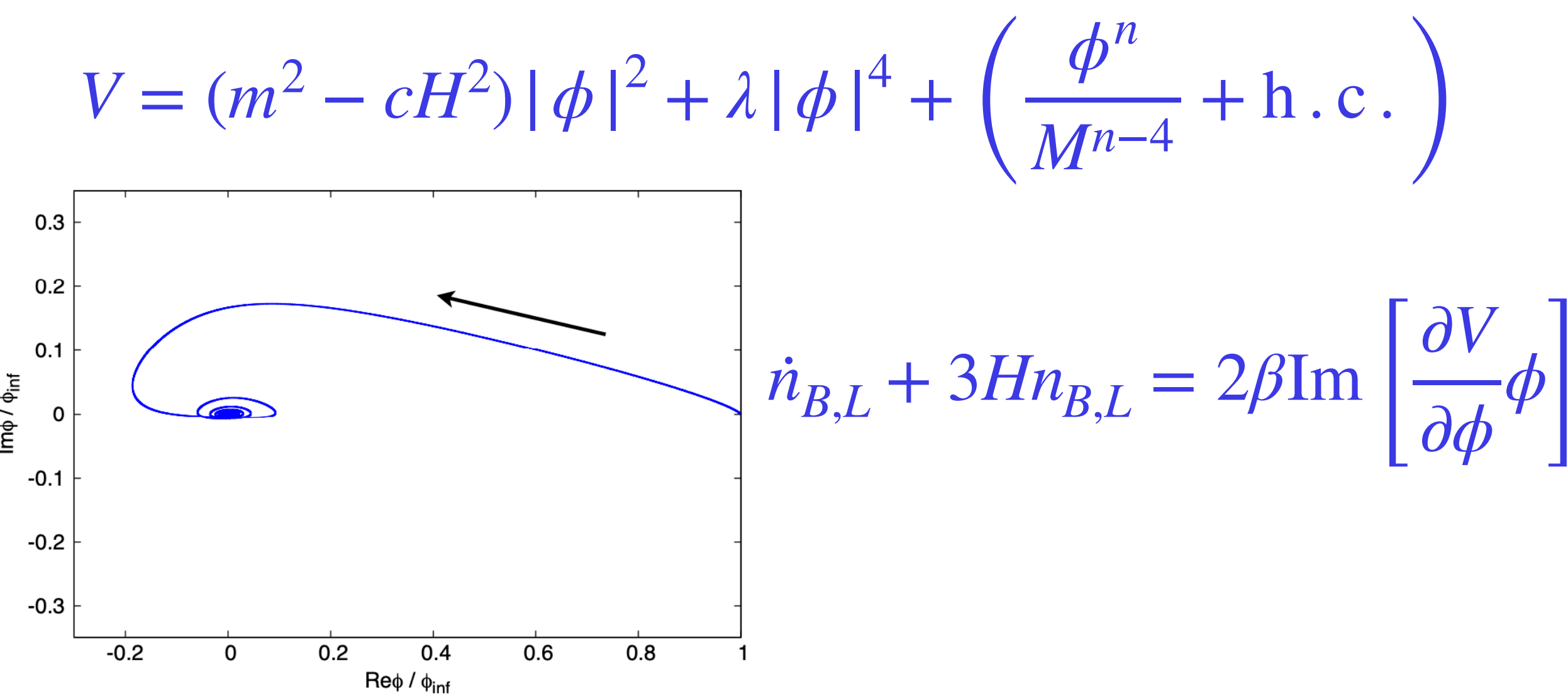
History and development: Afleck-Dine

Affleck-Dine Mechanism

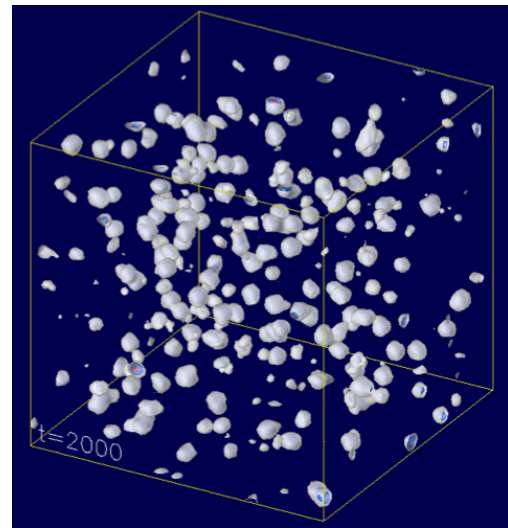
Scalars carrying non-zero U(1) charges

Flat directions (AD fields)

Lifting the potential via B/L violation operators



Q-ball formation (Non-topological soliton in scalar field theory)



Oscillation of AD field

Q-ball formation

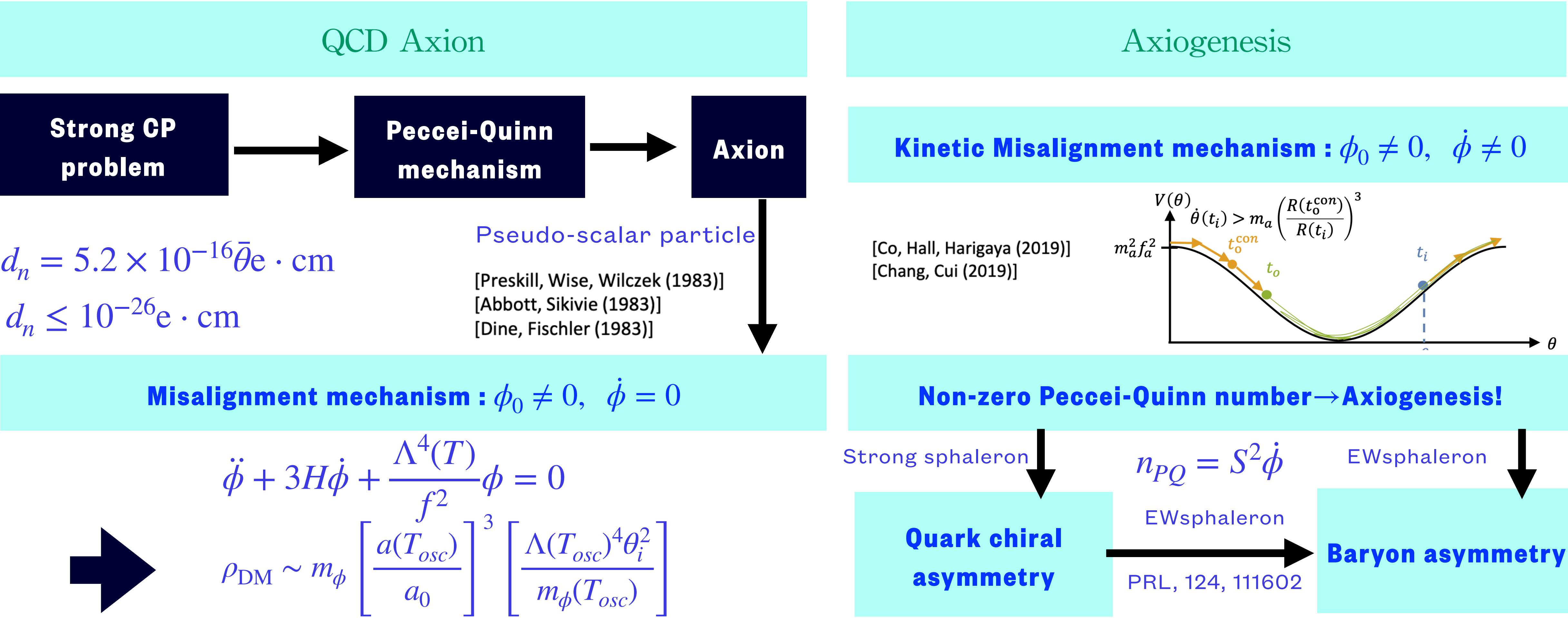
Long lived Q-ball

DM candidate

Evaporation

BAU when sphaleron erase is irrelevant

History and development: Axiogenesis



Status for Baryogenesis

Primordial B-L Conservation

- Electroweak Baryogenesis Bochkarev et al 1990
- Leptogenesis YANAGIDA et al. 1986
- Wash-in Leptogenesis DOMCKE et al 2021
- Electrogenesis CHAO, 2024

Primordial B-L violation via ~~CPT~~

- Magnetogenesis JOYCE et al 1997
- Axion-inflaton Leptogenesis Alexande et al 2004
- Affleck-Dine field oscillation Affleck et al 1985
- Axion Baryogenesis CO et al 2019

Outline

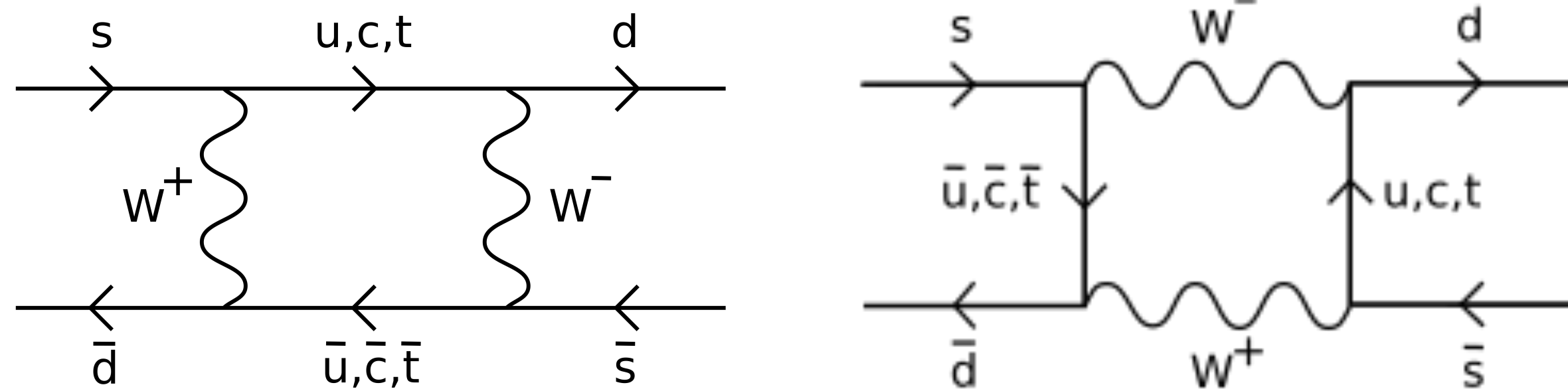
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EWBG via the SM CP violation

CP violation in the CKM



$$V_{\text{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{aligned} \sin \theta_{12} &= 0.22650 \pm 0.00048, & \sin \theta_{13} &= 0.00361^{+0.00011}_{-0.00009}, \\ \sin \theta_{23} &= 0.04053^{+0.00083}_{-0.00061}, & \delta &= 1.196^{+0.045}_{-0.043}. \end{aligned}$$

❖ Jarlskog in CKM $J = (3.00^{+0.15}_{-0.09}) \times 10^{-5}$

BAU

$$n_B = \frac{1}{3} \left\{ \int \frac{d\omega}{2\pi} [n_L^u(\omega) - n_R^u(\omega)] - \int \frac{d\omega}{2\pi} [n_L^b(\omega) - n_R^b(\omega)] \right\} \times \Delta(\omega)$$

$$\Delta(\omega) = \left[\sqrt{\frac{3\pi}{2}} \frac{\alpha_W T}{32\sqrt{\alpha_s}} \right]^3 J \times \frac{(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)}{M_W^6} \frac{(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_b^2 - m_d^2)}{(2\gamma)^9}$$

$$\sim \mathcal{O}(1) \times 10^{-22}$$

$$\Rightarrow \left| \frac{n_B}{s} \right| < 6 \times 10^{-27}$$

Huet, et al., PhysRevD.51(1995)379

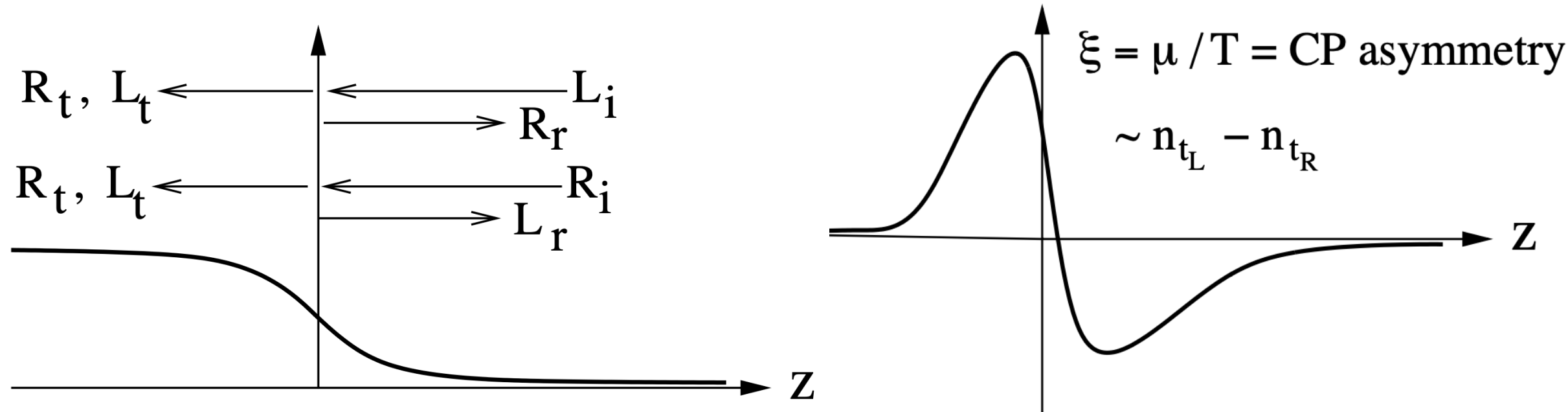
❖ QCD damping effect (quantum decoherence) reduce the BAU to negligible!

EWBG with new CP violation (example)

CP violation in the top quark sector

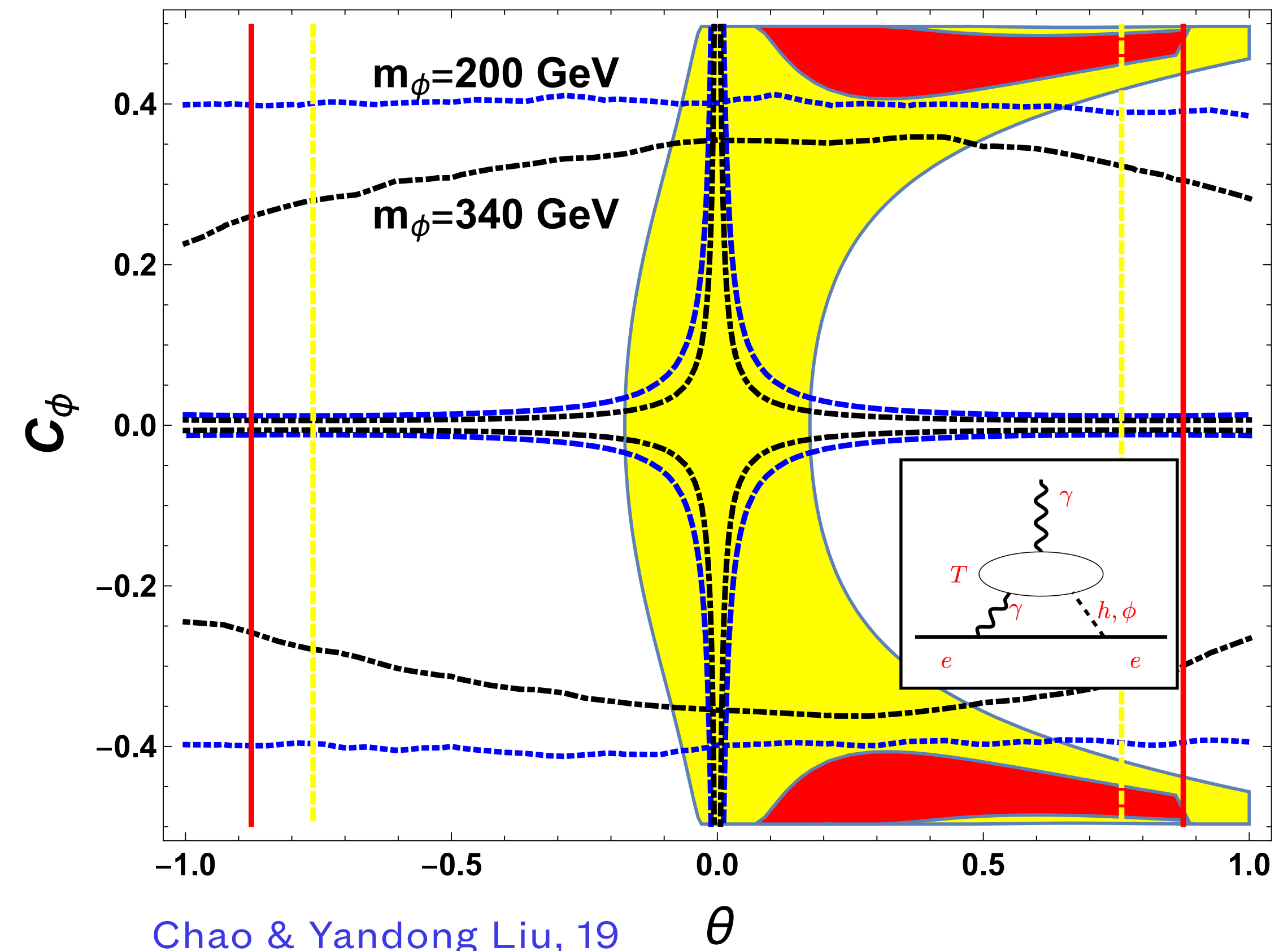
$$\mathcal{L}_Y \sim y_t \overline{Q}_L^3 \tilde{H} t_R + \frac{\zeta}{\Lambda} \overline{Q}_r^L \tilde{H} \phi t_R$$

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



$$\frac{dn_B}{dt} \sim 3\Gamma_{sph}\xi - c\Gamma_{sph}\frac{n_B}{T^2}$$

Constraints



Chao & Yandong Liu, 19

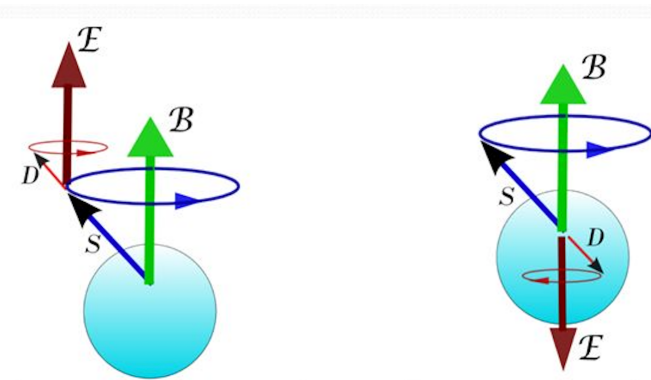
Constraints of the EWBG

Detection methods

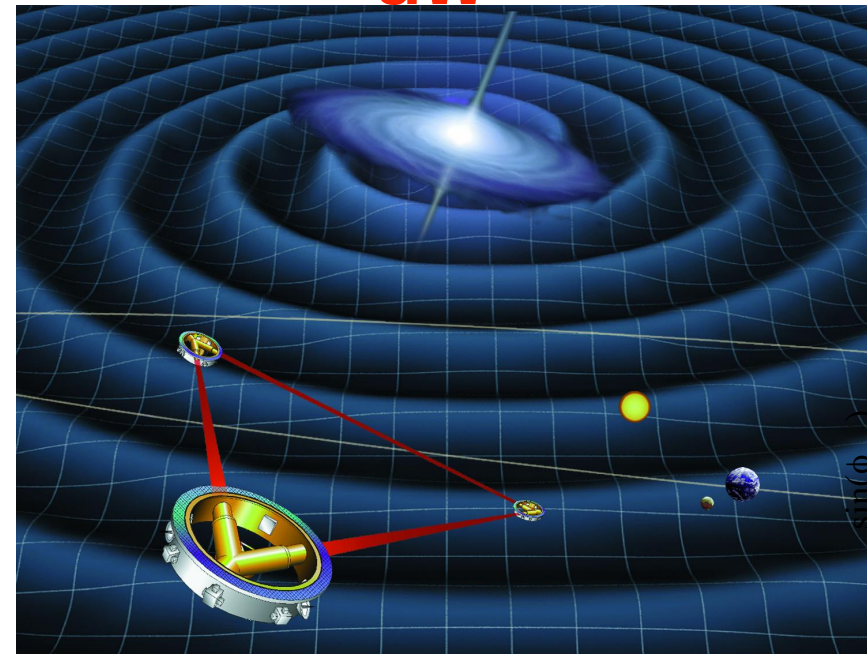
LHC



EDM



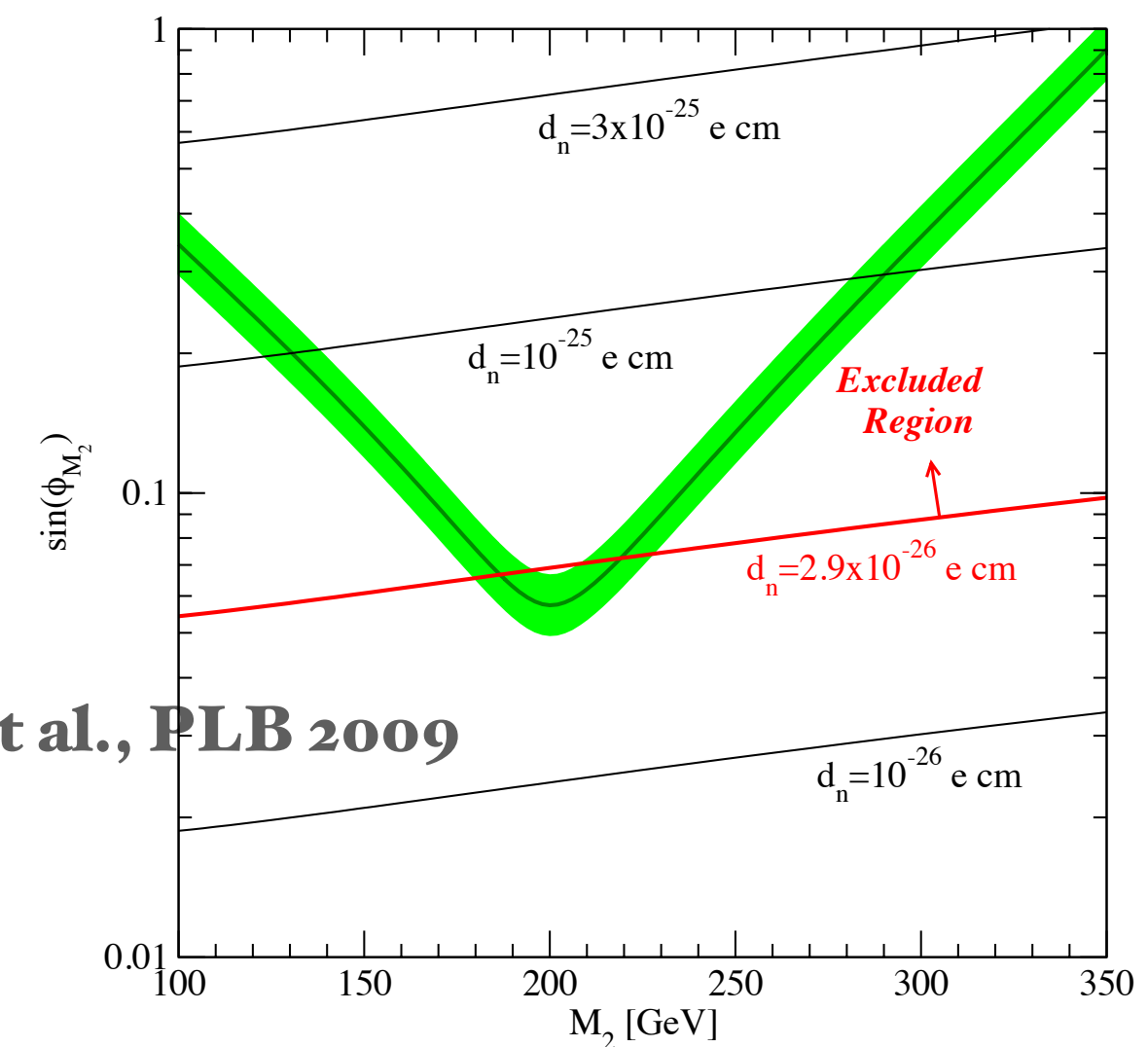
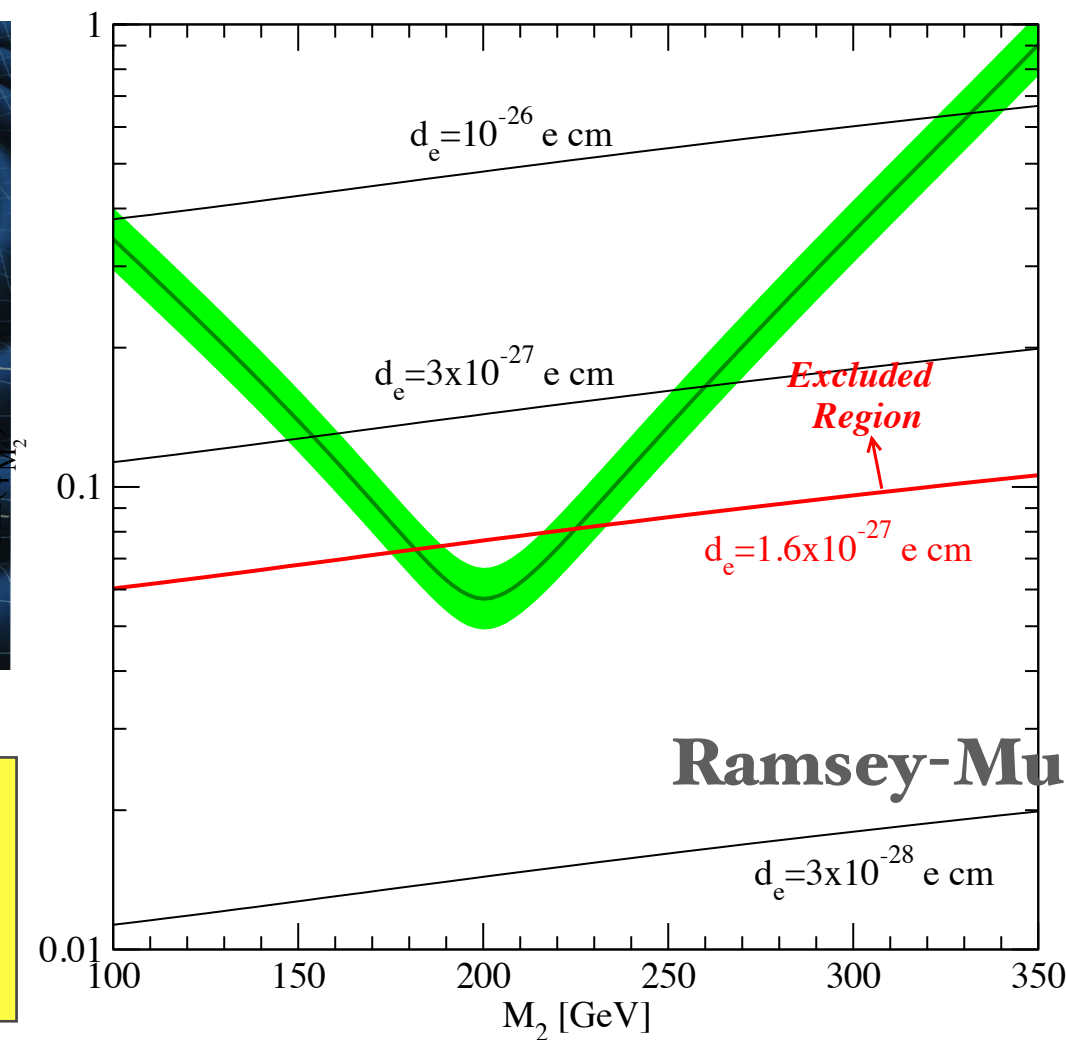
GW



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

- Can LHC measurements confirm the patter of EWPT?
- Can GW measurements exclude the possibility of EWBG?
- Can EDM measurements exclude the case of EWBG?

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



* Wino induced baryon asymmetry was excluded by the ACME result!

* Can any EWBG model escape the constraint of EDM?

Progress (1): EWBG via CPV at finite T

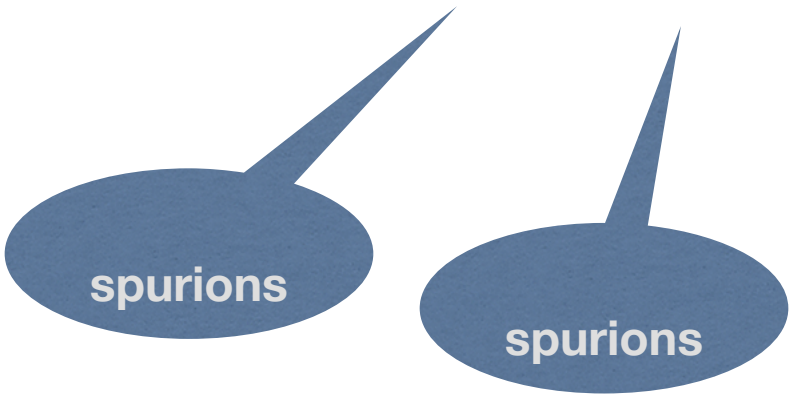
Observation:

There exists spontaneous CP phase in the scalar singlet sector

EWBG

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

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



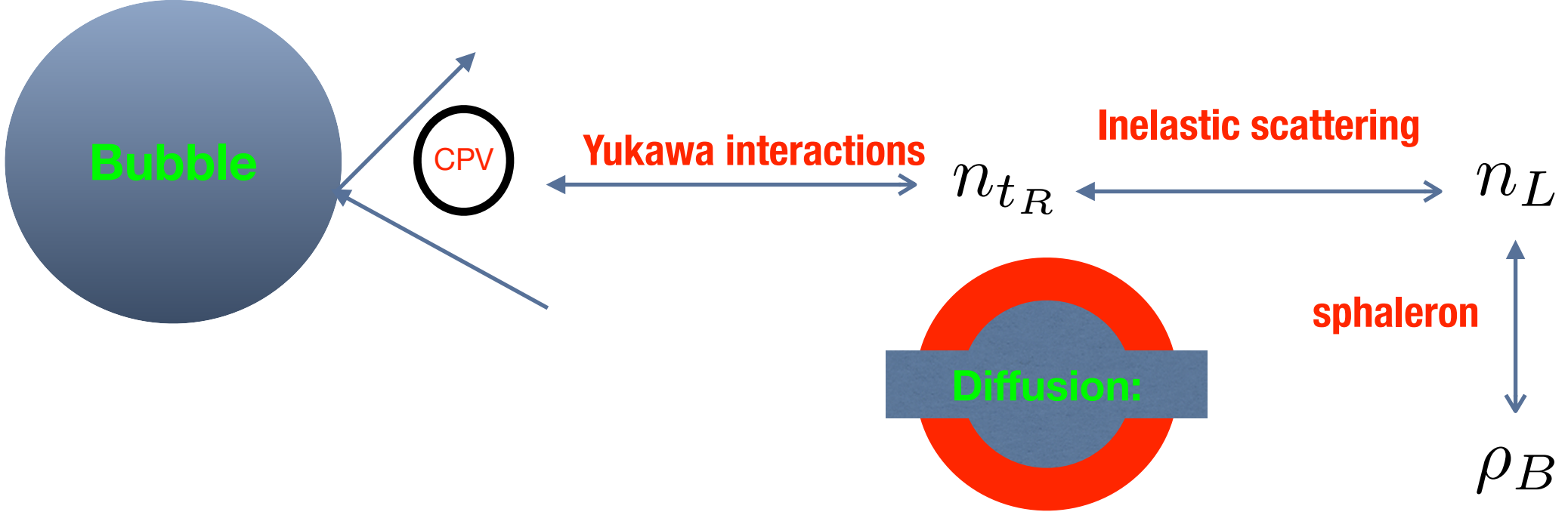
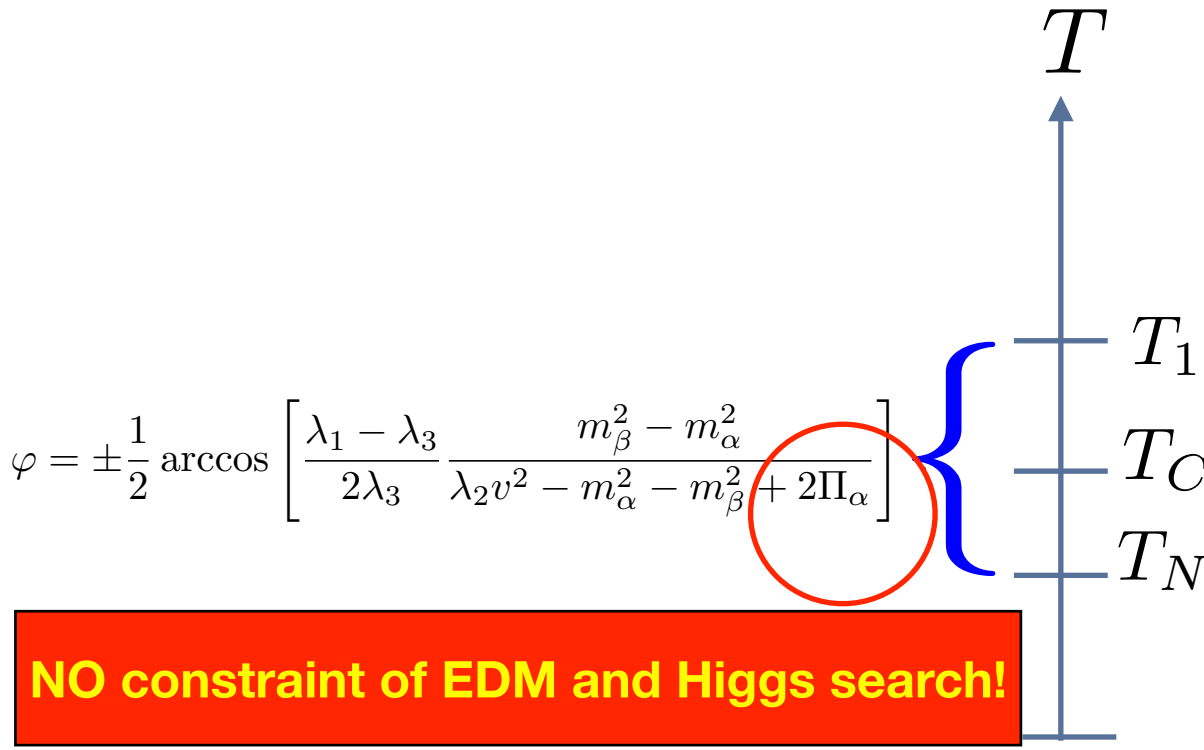
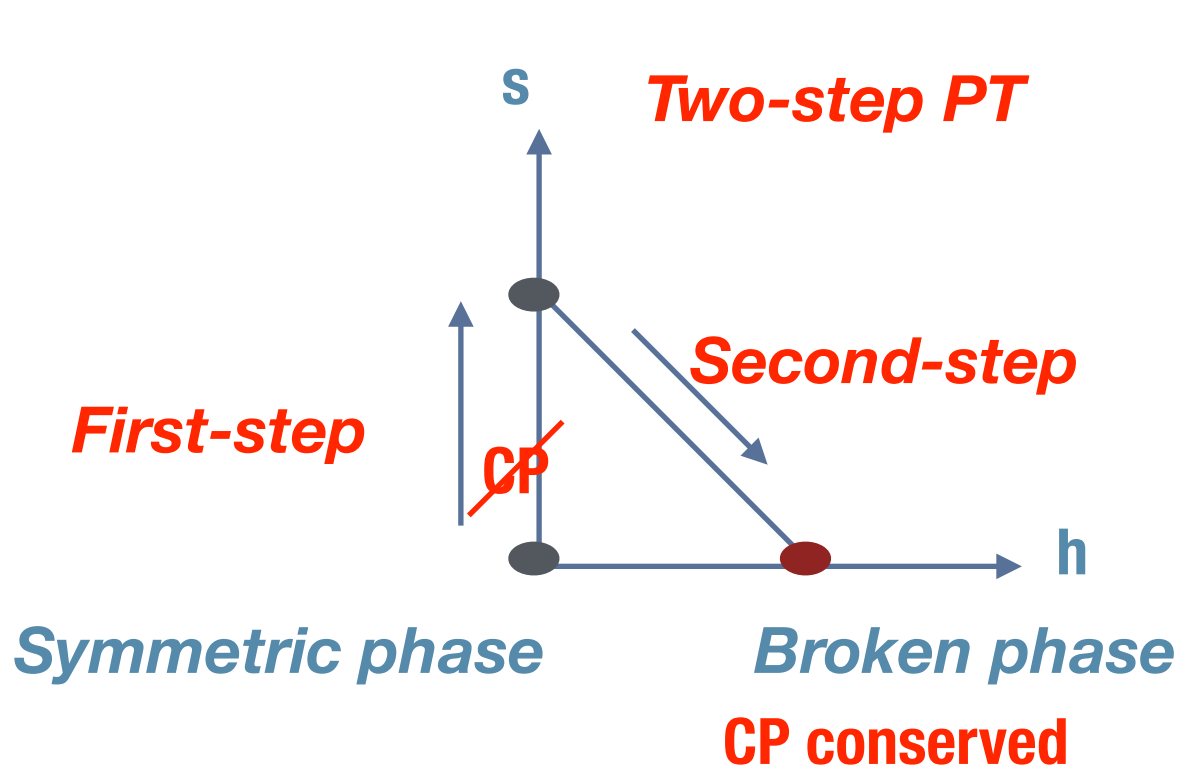
SM+ complex scalar singlets

Yukawa: $-\mathcal{L} \sim \frac{1}{\Lambda} \overline{Q}_L \tilde{H} S t_R + \text{h.c.}$

$-\mathcal{L} \sim \eta \overline{T}_L S t_R + M \overline{T}_L T_R + \text{h.c.}$

A possible strategy:

There might be spontaneous CPV phase only at finite T!



Transport equation:

$$\partial_t \rho_B(x) - D \nabla^2 \rho_B(x) = -\Gamma_{ws} F_{ws}(x) [n_L(x) - R \rho_B(x)]$$

Progress (1): EWBG via CPV at finite T

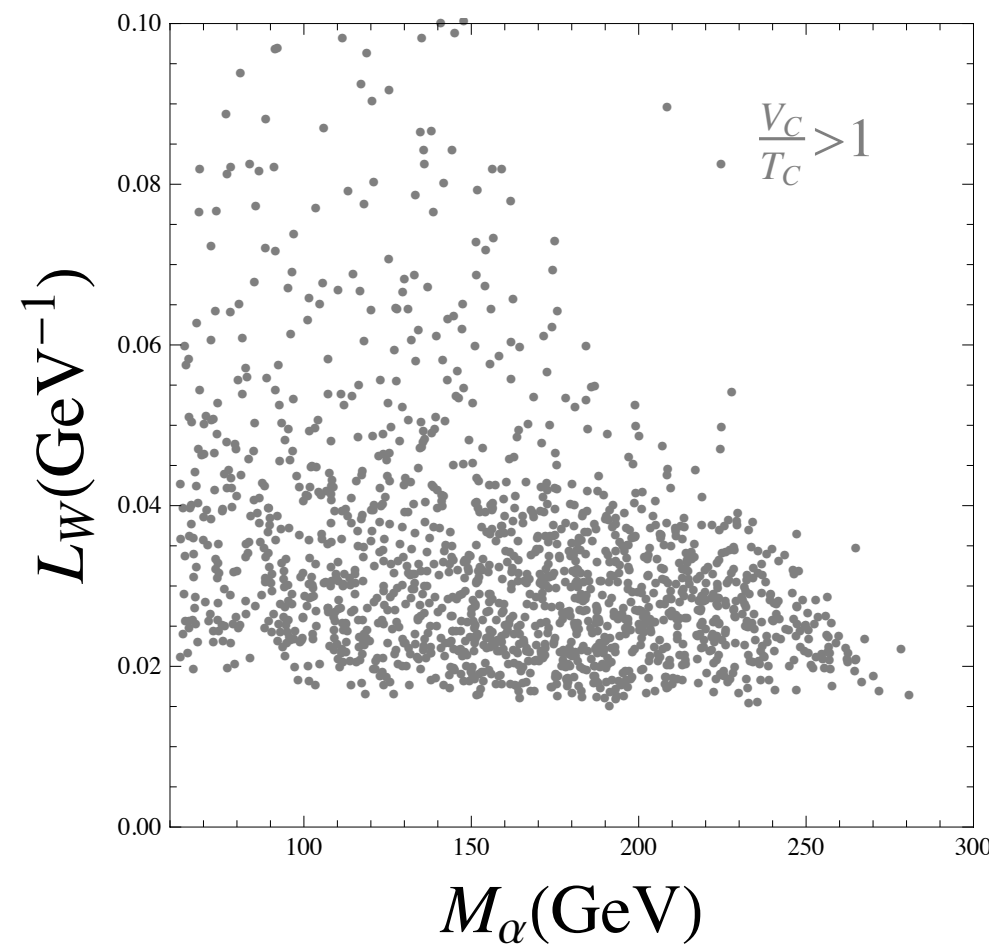
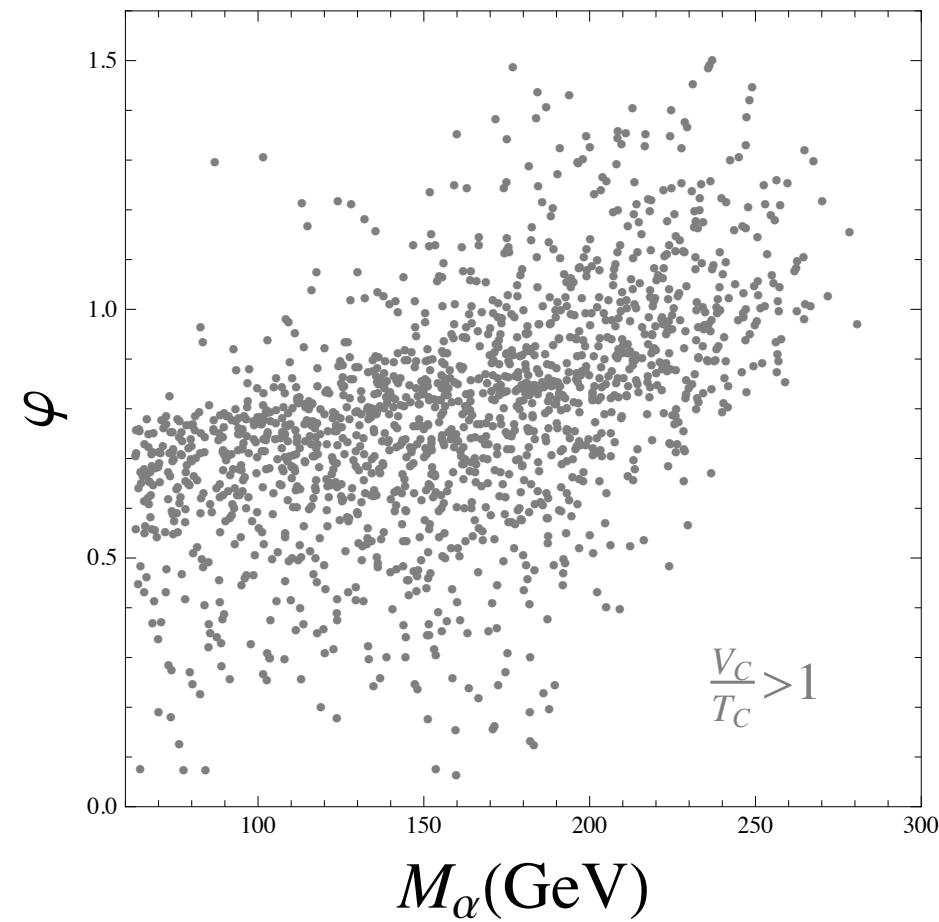
First order EWPT

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:

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



EWBG

Transport EQ

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

Source

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

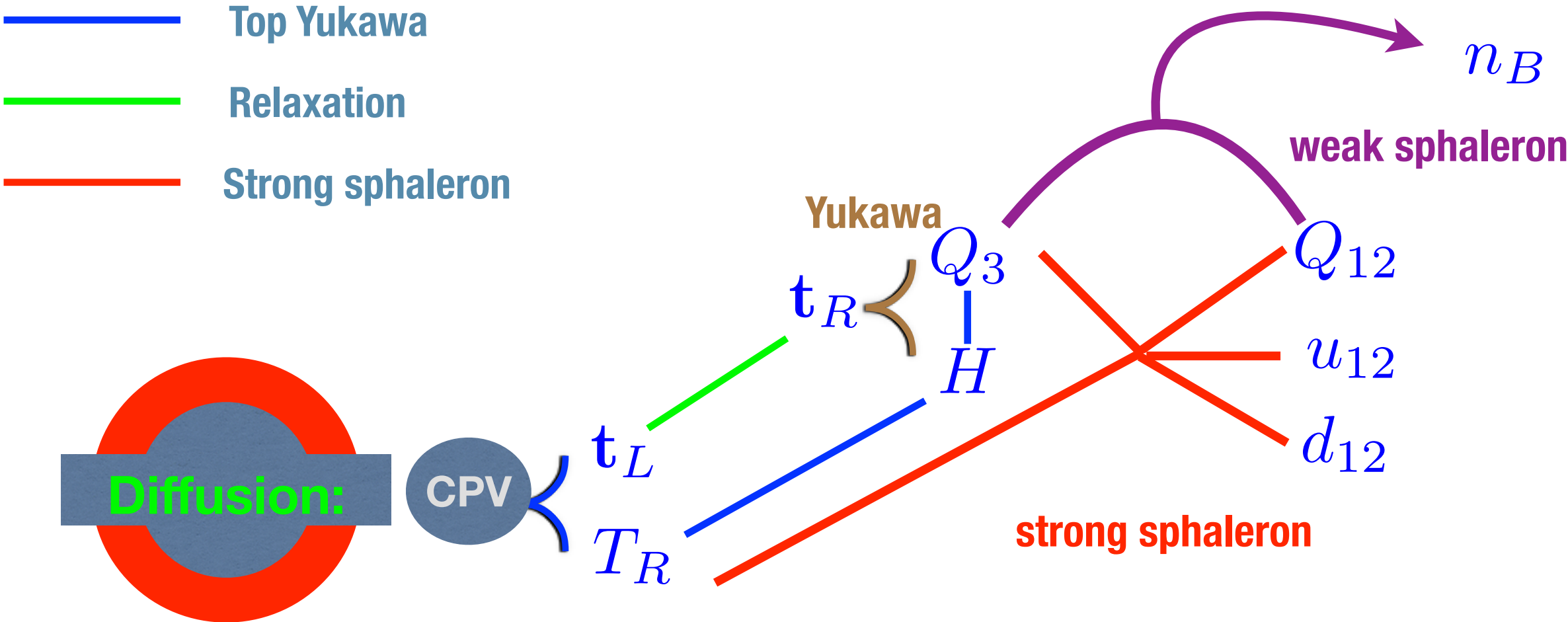
$$\zeta \bar{t}_L S t_R + (M_t) \bar{t}_L t_R + \text{h.c.}$$

All equations

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

Progress (1): EWBG via CPV at finite T

Cartoon for diffusion processes



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

Problem

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

No BAU left

Domain wall must decays!

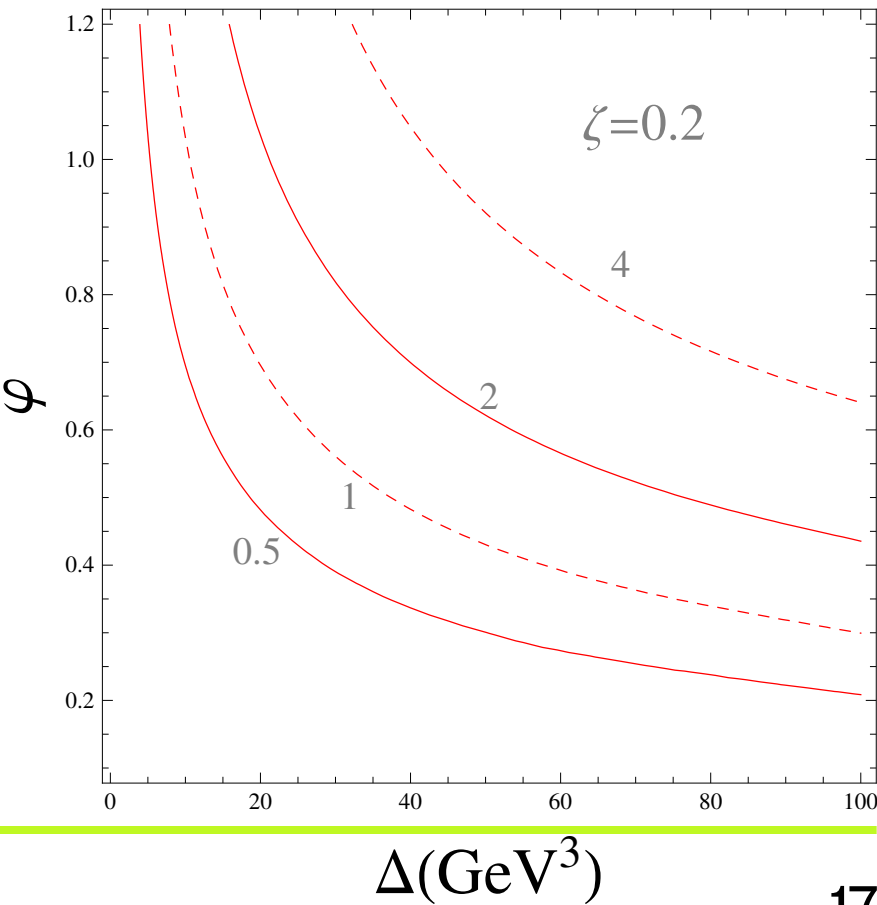
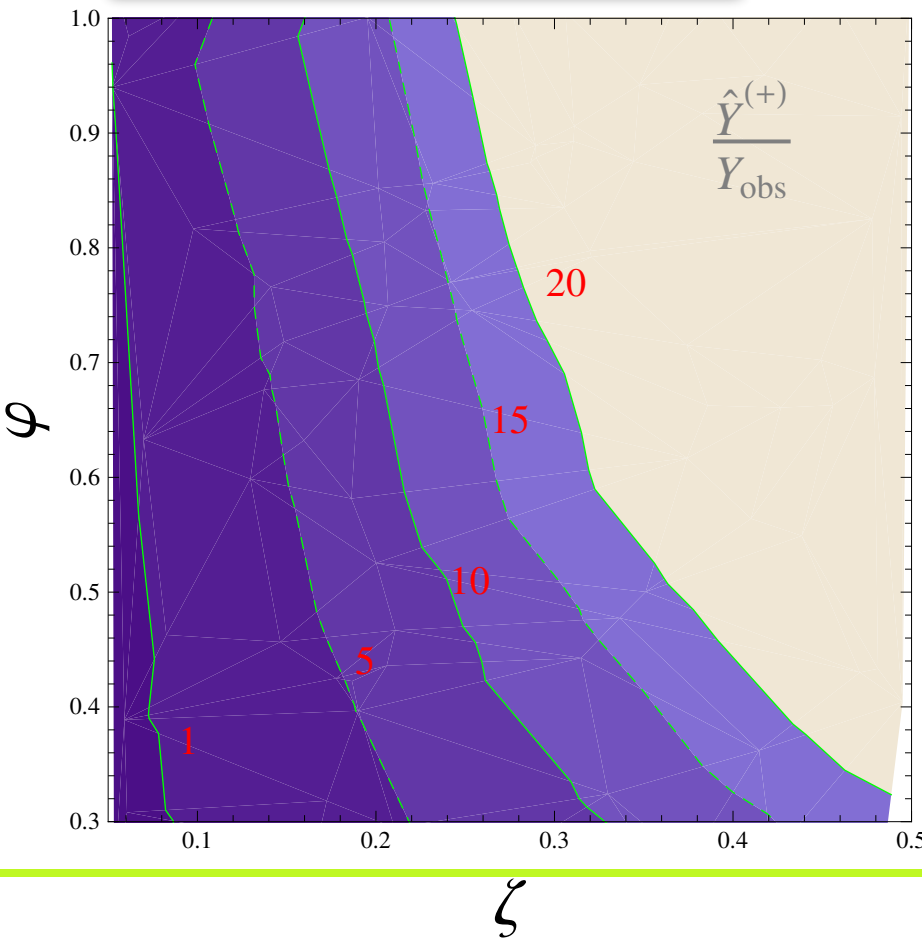
Solutions: Z2 breaking term, $\Delta s + h.c.$

Ratio of bubbles

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

Final BAU

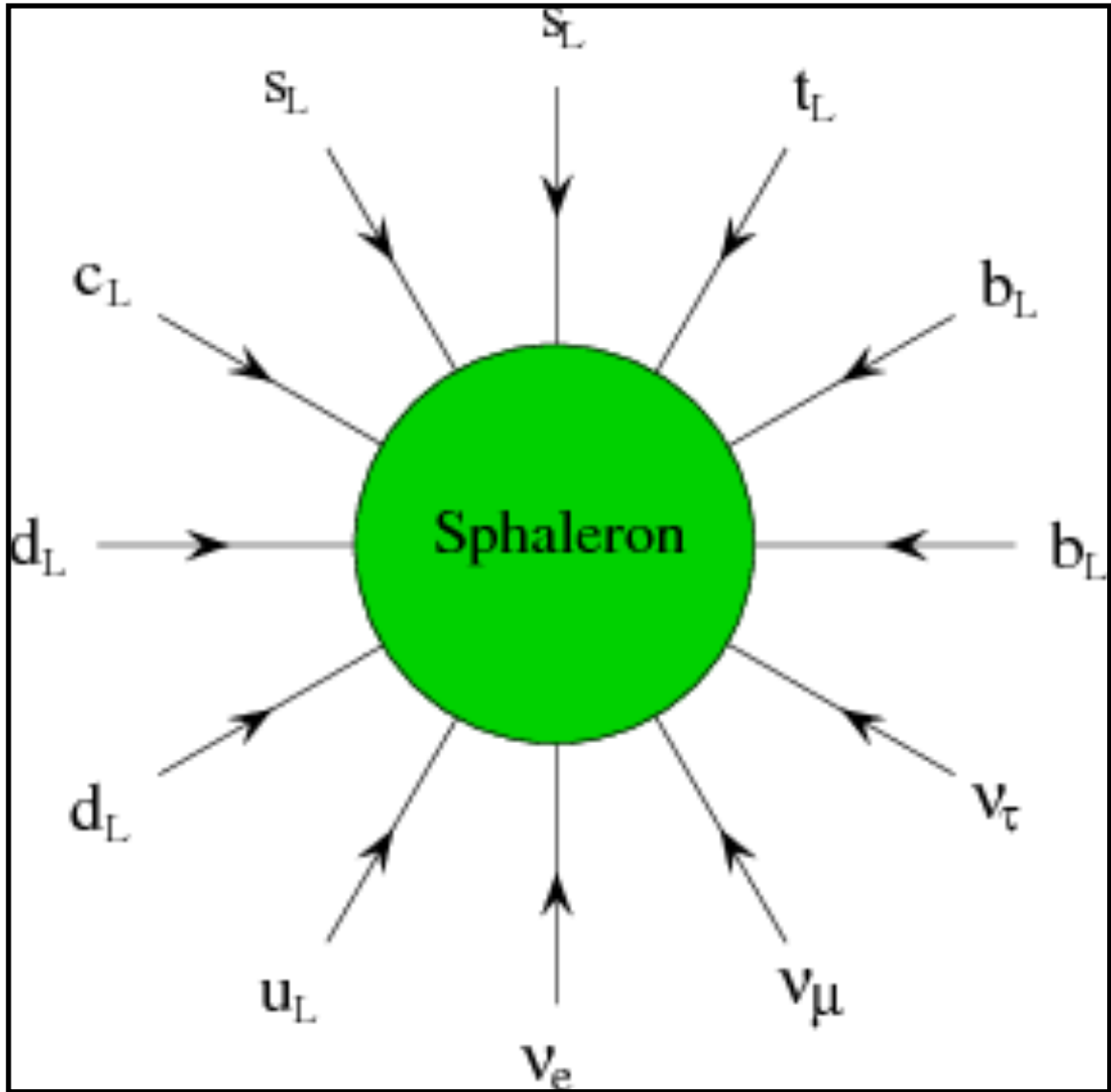
$$n_B = \hat{n}_B^{(+)} \frac{N_+ - N_-}{N_+ + N_-}$$



W. Chao PLB

Progress (2): EWBG via **Symmetry non-restoration**

Push the sphaleron to multi-TeV scale !

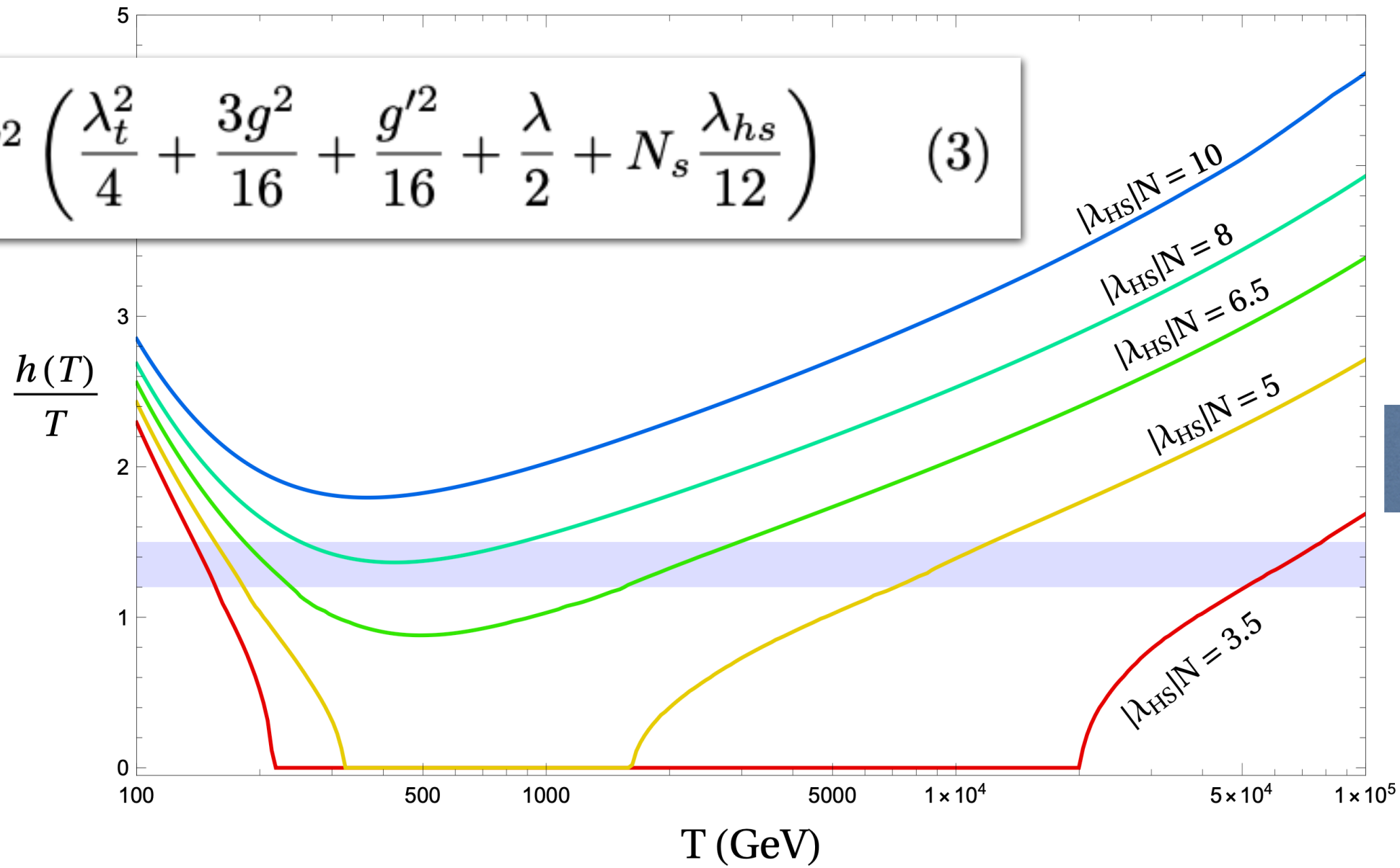


SM+scalars

Freeze-out temperature ~ 130 GeV

Alfredo Glioti, et al., JHEP04(2019)027

$$\Pi_h = T^2 \left(\frac{\lambda_t^2}{4} + \frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} + N_s \frac{\lambda_{hs}}{12} \right) \quad (3)$$

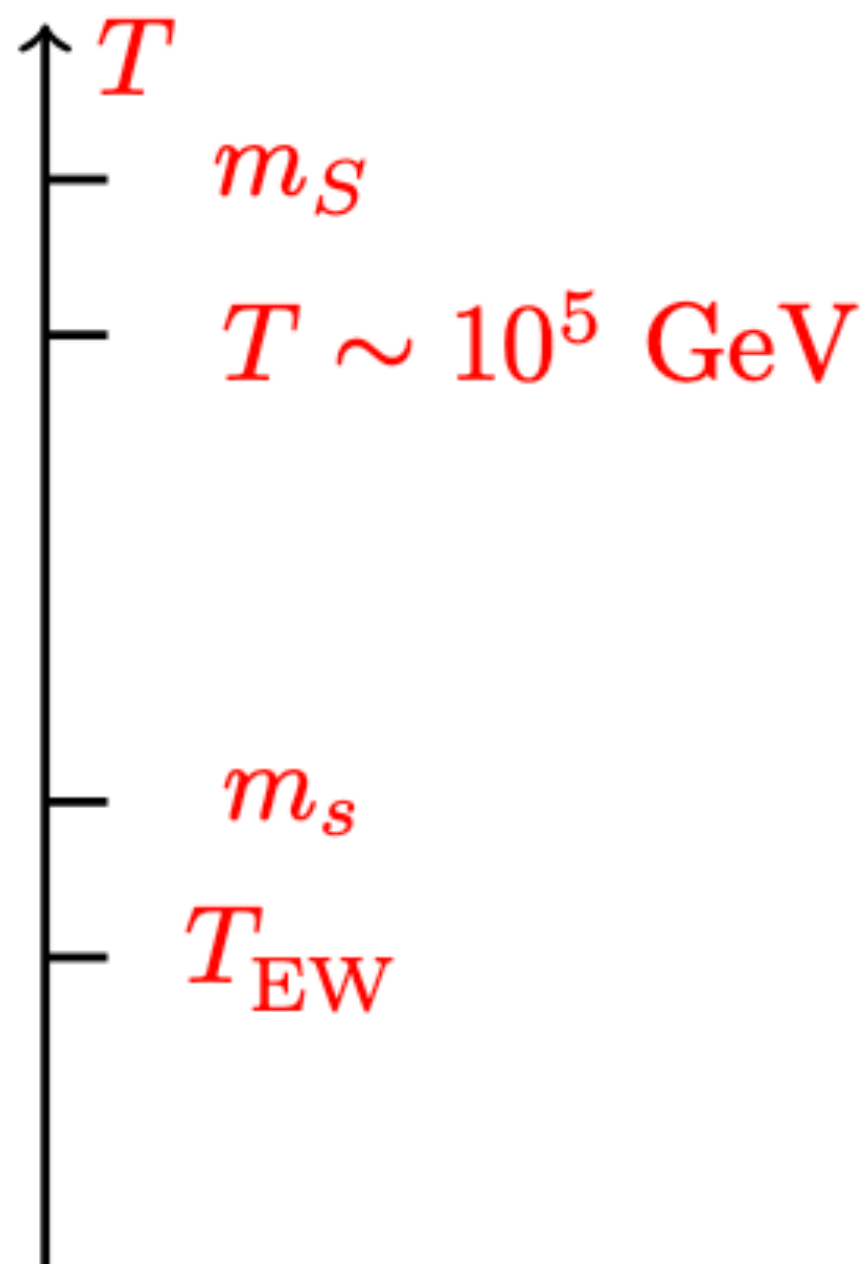


**Conventional
EWBG**

**Heavy particle
may lead to
BAU via
EWBG-like
mechanism**

Progress (2): EWBG via **Symmetry non-restoration**

Basic setup



$$\Gamma_{\text{sph}}^{\text{brok}}(T) = \kappa_{\text{brok}} \alpha_W^4 T^4 \exp\left(-\frac{E_{\text{sph}}}{T}\right) \quad E_{\text{sph}} > T \log\left(\frac{\kappa_{\text{brok}} \alpha_W^4 M_P}{3T}\right)$$

$$E_{\text{sph}} = \frac{4\pi v}{g} \int_0^\infty d\xi \left[4(f')^2 + \frac{8}{\xi^2} f^2(1-f)^2 + \frac{\xi^2}{2} (h')^2 + h^2(1-f)^2 + \frac{\xi^2}{16} \sigma^2 (h^2 - 1)^2 \right]$$

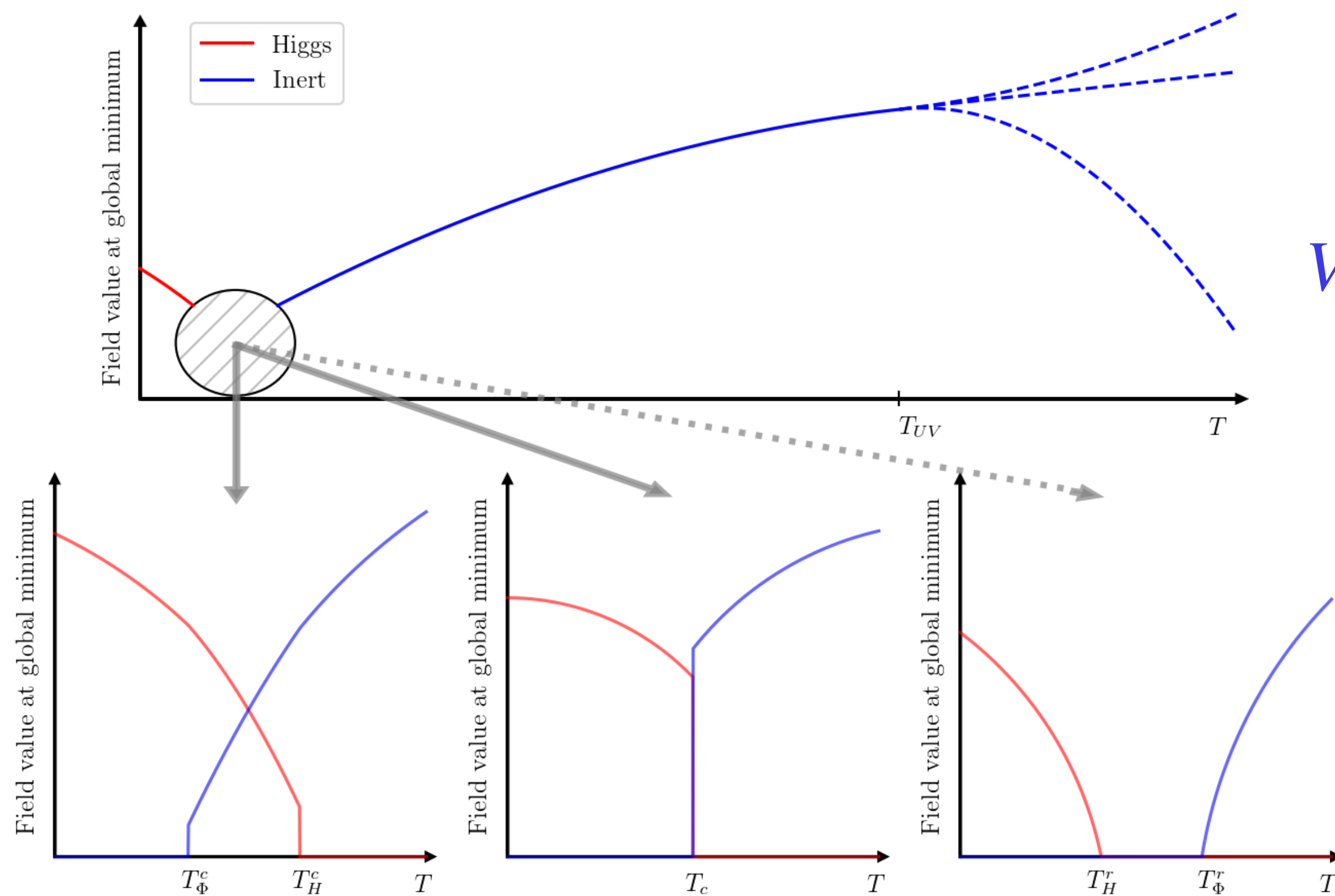
By requiring the SNR T to be 10^5 GeV :

$$\rightarrow N_s \lambda_{hs} < -4.82$$

EW symmetry should be restored in the early universe, in order to have a workable EWBG

Progress (2): EWBG via **Symmetry non-restoration**

2HDM (with inert Higgs)+ a scalar singlet or Fermion dark matter



Picture taken from Marcela Carena, Claudius Krause, Zhen Liu, and Yikun Wang, PRD 2021

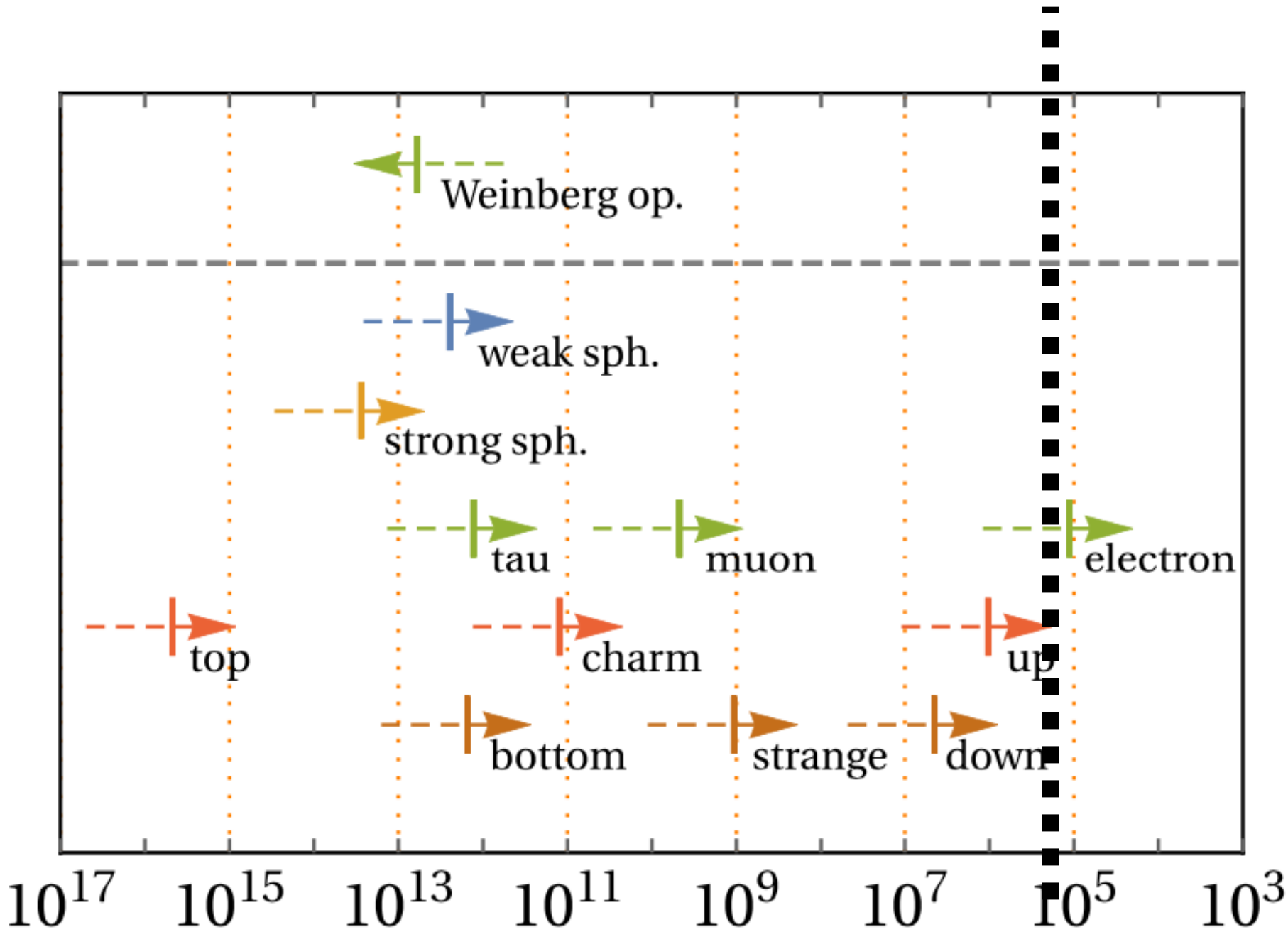
$$\begin{aligned}
 V = & -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \mu_\Phi^2 (\Phi^\dagger \Phi) + \lambda_\Phi (\Phi^\dagger \Phi)^2 \\
 & + \lambda_{H\Phi} (H^\dagger H) (\Phi^\dagger \Phi) + \dots \\
 & + \frac{1}{2} \mu_i^2 \chi_i^2 + \frac{1}{4} \lambda_i \chi_i^4 + \frac{1}{2} \lambda_{\chi\Phi}^i \chi_i^2 (\Phi^\dagger \Phi) \\
 & + \frac{1}{2} \lambda_{\chi H}^i \chi_i^2 (H^\dagger H) \quad \text{or} \quad \frac{1}{\Lambda} \bar{\psi} \psi (\Phi^\dagger \Phi)
 \end{aligned}$$

Progress (3): BAU via **Symmetry non-restoration**

Sphaleron may quench before the electron Yukawa interaction entering the equilibrium

Interaction	Weinberg	WS	SS	Y_e	Y_μ	Y_τ
Γ_α/T^4	$\kappa_W \frac{m_\nu^2 T^2}{v_{EW}^4}$	$\frac{1}{2} \kappa_{WS} \alpha_2^5$	$\frac{1}{2} \kappa_{SS} \alpha_3^5$	$\kappa_{Y_e} y_e^2$	$\kappa_{Y_\mu} y_\mu^2$	$\kappa_{Y_\tau} y_\tau^2$
T_α [GeV]	6.0×10^{12}	2.5×10^{12}	2.8×10^{13}	1.1×10^5	4.7×10^9	1.3×10^{12}
Interaction	Y_u	Y_c	Y_t	Y_d	Y_s	Y_b
Γ_α/T^4	$\kappa_{Y_u} y_u^2$	$\kappa_{Y_c} y_c^2$	$\kappa_{Y_t} y_t^2$	$\kappa_{Y_d} y_d^2$	$\kappa_{Y_s} y_s^2$	$\kappa_{Y_b} y_b^2$
T_α [GeV]	1.0×10^6	1.2×10^{11}	4.7×10^{15}	4.5×10^6	1.1×10^9	1.5×10^{12}

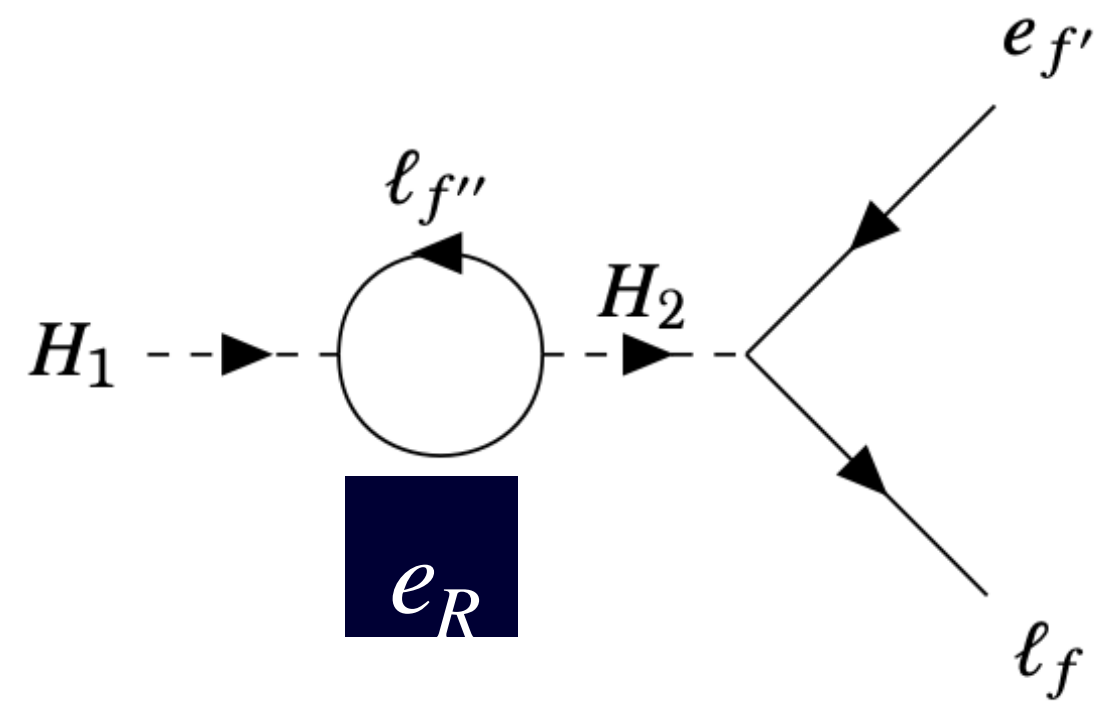
Valerie Domck, Yohei Ema, Kyohei Mukai and Masaki Yamada, JHEP 08(2020)096



*Left-handed Electron asymmetry can be transported to the BAU via sphaleron.

Progress (3): BAU via **Symmetry non-restoration**

- **Higgs doublet decay into chiral electrons with CP violation**



$$\varepsilon = \frac{1}{8\pi} \frac{\text{Im} \left[Y_{fg}^1 Y_{gf}^{2\dagger} \text{tr}(Y^{1\dagger} Y^2) \right]}{\text{tr}(Y^{1\dagger} Y^1)} f \left(\frac{M_{\Phi_2}}{M_{\Phi_1}} \right)$$

- **Chiral asymmetries are generated in the first generation.**
- **No primordial B-L violation is generated!**
- **No matter right-handed neutrinos exist or not!**

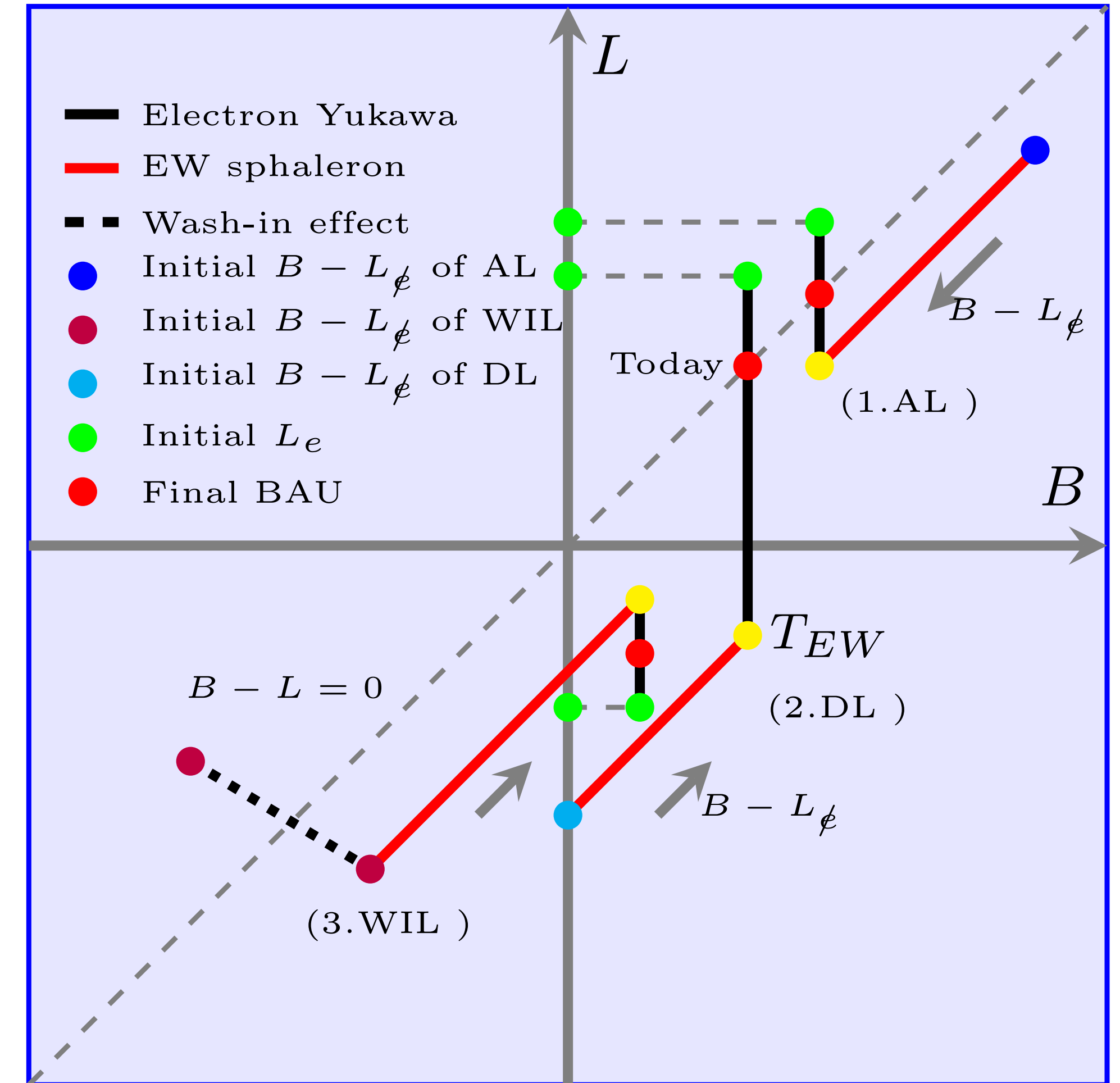
Progress (3): BAU via Symmetry non-restoration

• Transport equation

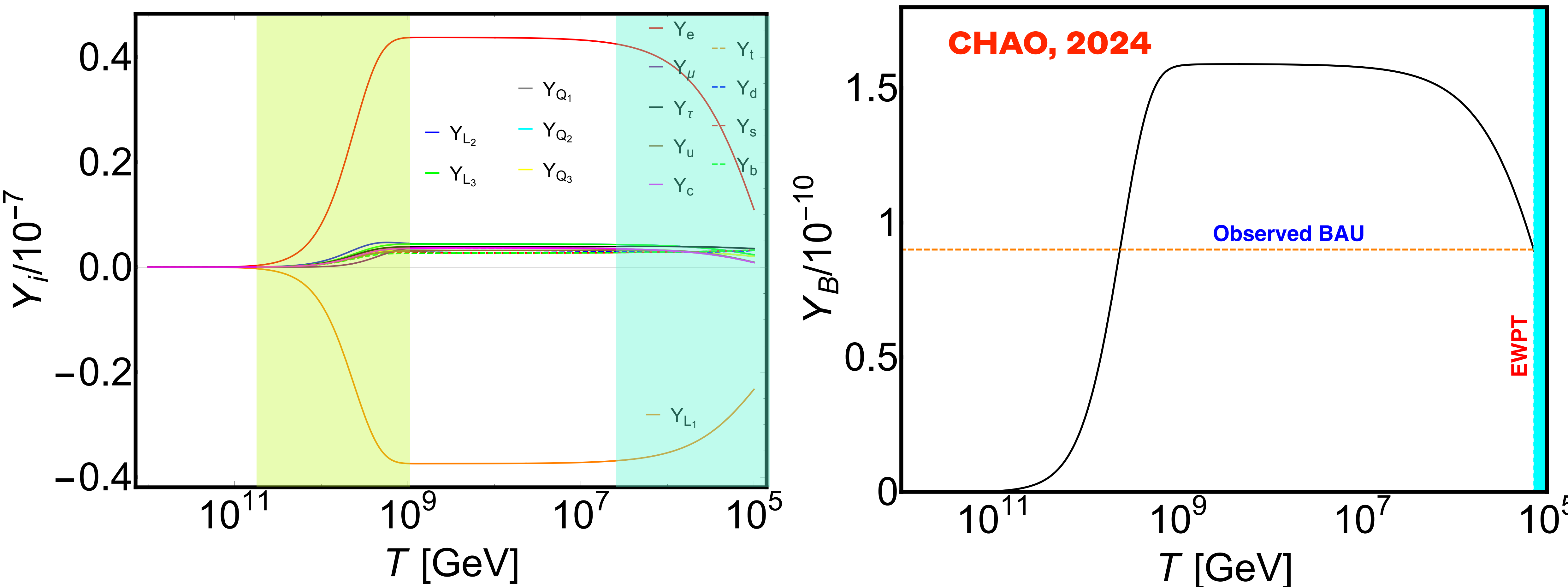
$$\begin{aligned}
 -\frac{d}{d \ln T} \left(\frac{\mu_{L_k}}{T} \right) = & -\frac{1}{g_{L_k}} \frac{\gamma_{WS}}{H} \left[\sum_{i=1}^3 \left(\frac{\mu_{L_i}}{T} + 3 \frac{\mu_{Q_i}}{T} \right) \right] \\
 & -\frac{1}{g_{L_k}} \frac{\gamma_{Y_{E_k}}}{H} \left(-\frac{\mu_{E_k}}{T} + \frac{\mu_{L_k}}{T} - \frac{\mu_H}{T} \right) \\
 & +\frac{1}{g_{L_k}} \frac{4\pi^2 g_{*s}}{15} \frac{\gamma_D}{H} \varepsilon \left(Y_\Sigma - Y_\Sigma^{\text{EQ}} \right) \\
 & -\frac{2}{g_{L_k}} g_\Phi \frac{\gamma_D}{H} \left(\frac{8}{3} \frac{\mu_{L_k}}{T} - \frac{\mu_\Phi}{T} \right) \quad (19)
 \end{aligned}$$

• BAU

$$Y_B = \frac{n_B}{s} = \frac{15}{4\pi^2 g_{*s}(T_0)} \frac{\mu_B}{T}$$



Progress (3): BAU via **Symmetry non-restoration**

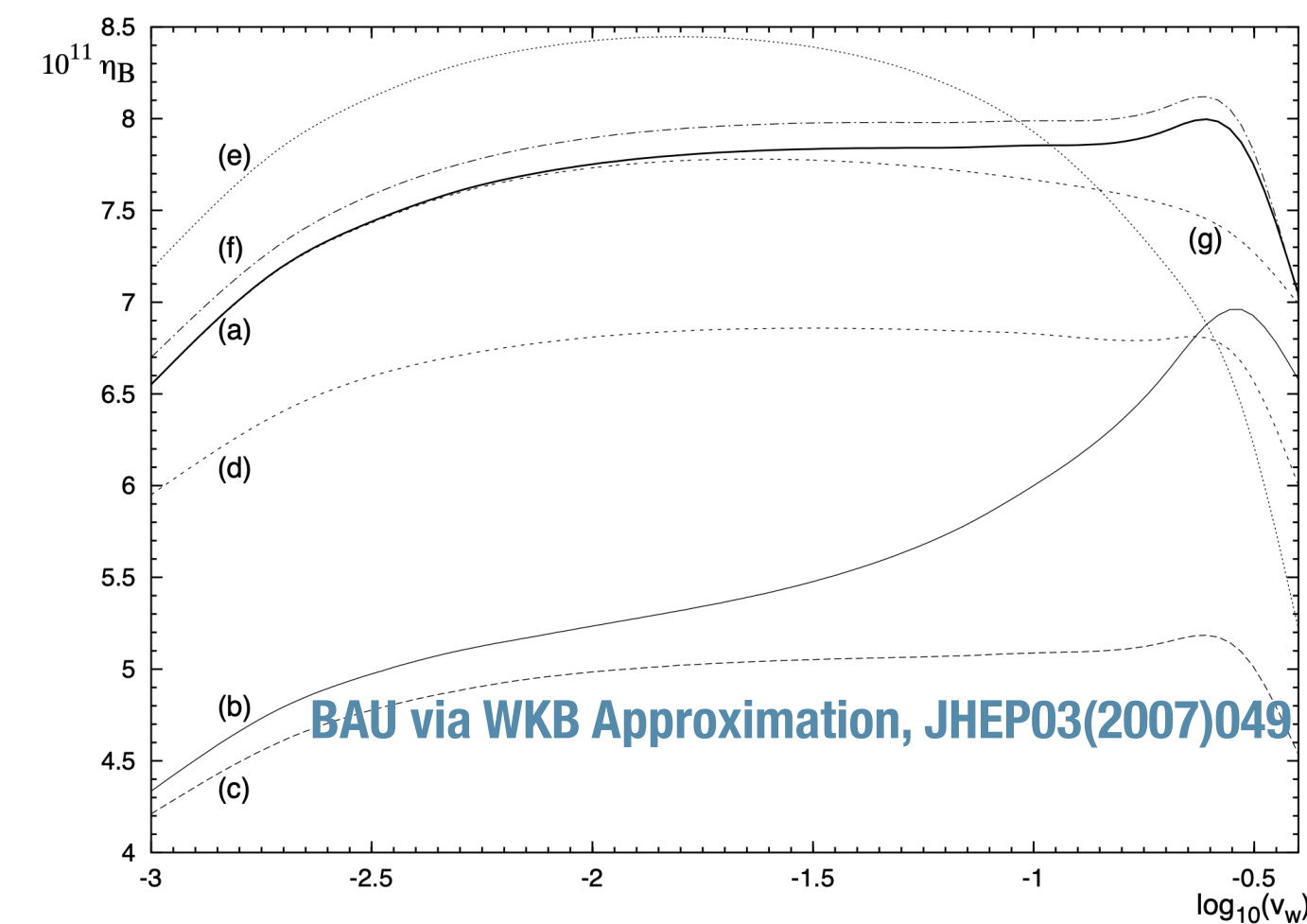
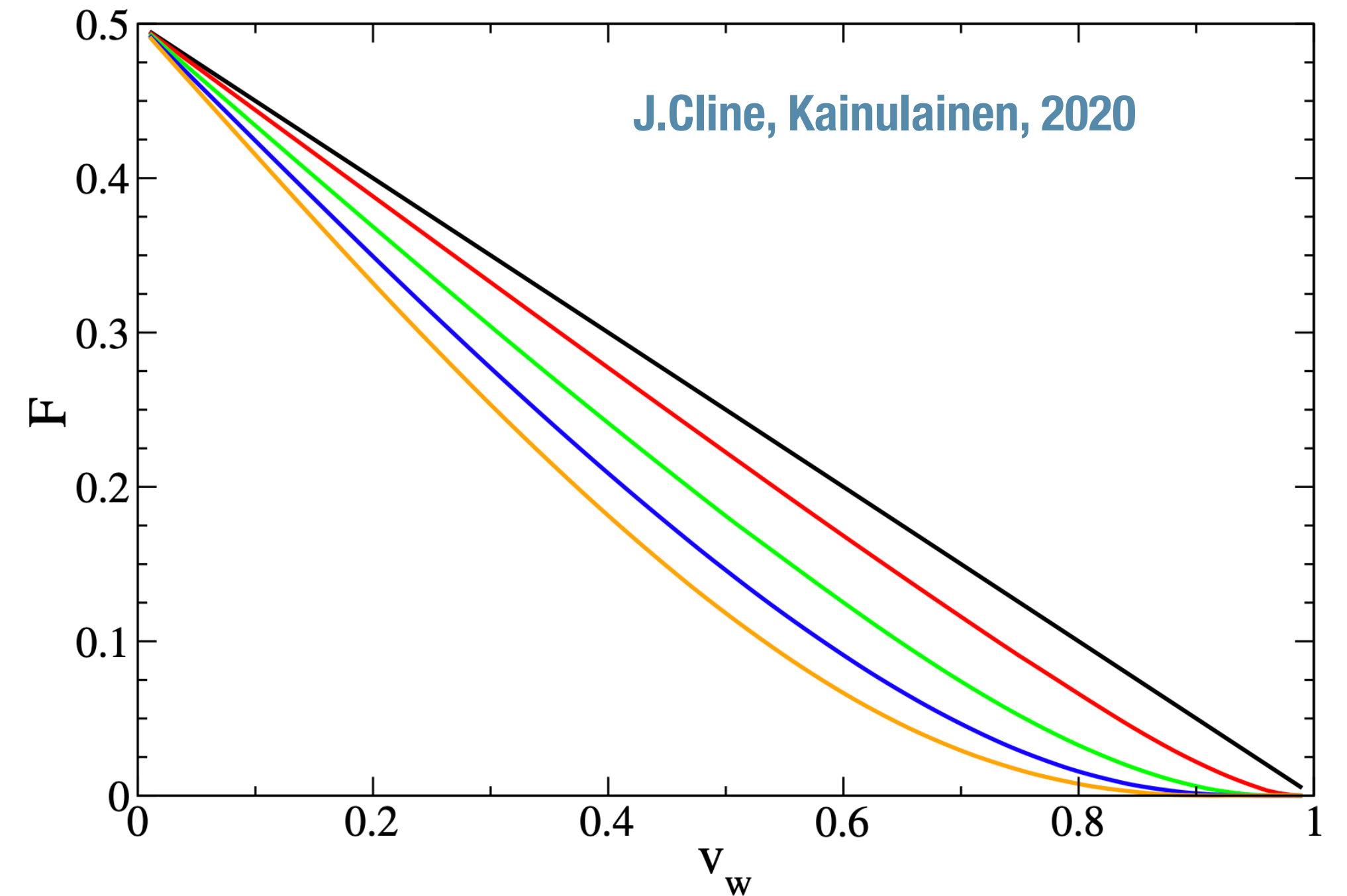


Progress (4): Calculation methods of EWBG

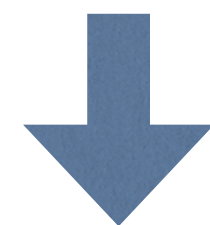
BAU favors low bubble wall velocity, Gravitational wave favors high wall velocity

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

Bubble collision	$h^2\Omega_{\text{coll}}(f) = 1.67 \times 10^{-5} \left(\frac{H_n}{\beta}\right)^2 \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{\frac{1}{3}} \times \left(\frac{0.11v_w^3}{0.42+v_w^2}\right) \left[\frac{3.8(f/f_{\text{coll}})^{2.8}}{1+2.8(f/f_{\text{coll}})^{3.8}}\right],$
Sound wave	$h^2\Omega_{\text{sw}}(f) = 2.65 \times 10^{-6} \left(\frac{H_n}{\beta}\right) \left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{\frac{1}{3}} \times v_w \left(\frac{f}{f_{\text{sw}}}\right)^3 \left[\frac{7}{4+3(f/f_{\text{sw}})^2}\right]^{7/2}$
MHD turbulence	$h^2\Omega_{\text{turb}}(f) = 3.35 \times 10^{-4} \left(\frac{H_n}{\beta}\right) \left(\frac{\kappa_{\text{tu}}\alpha}{1+\alpha}\right)^{3/2} \left(\frac{100}{g_*}\right)^{\frac{1}{3}} \times v_w \frac{(f/f_{\text{tu}})^3}{(1+f/f_{\text{tu}})^{11/3}(1+8\pi f/h_n)}$



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



Valid in slowly varying bubble wall background

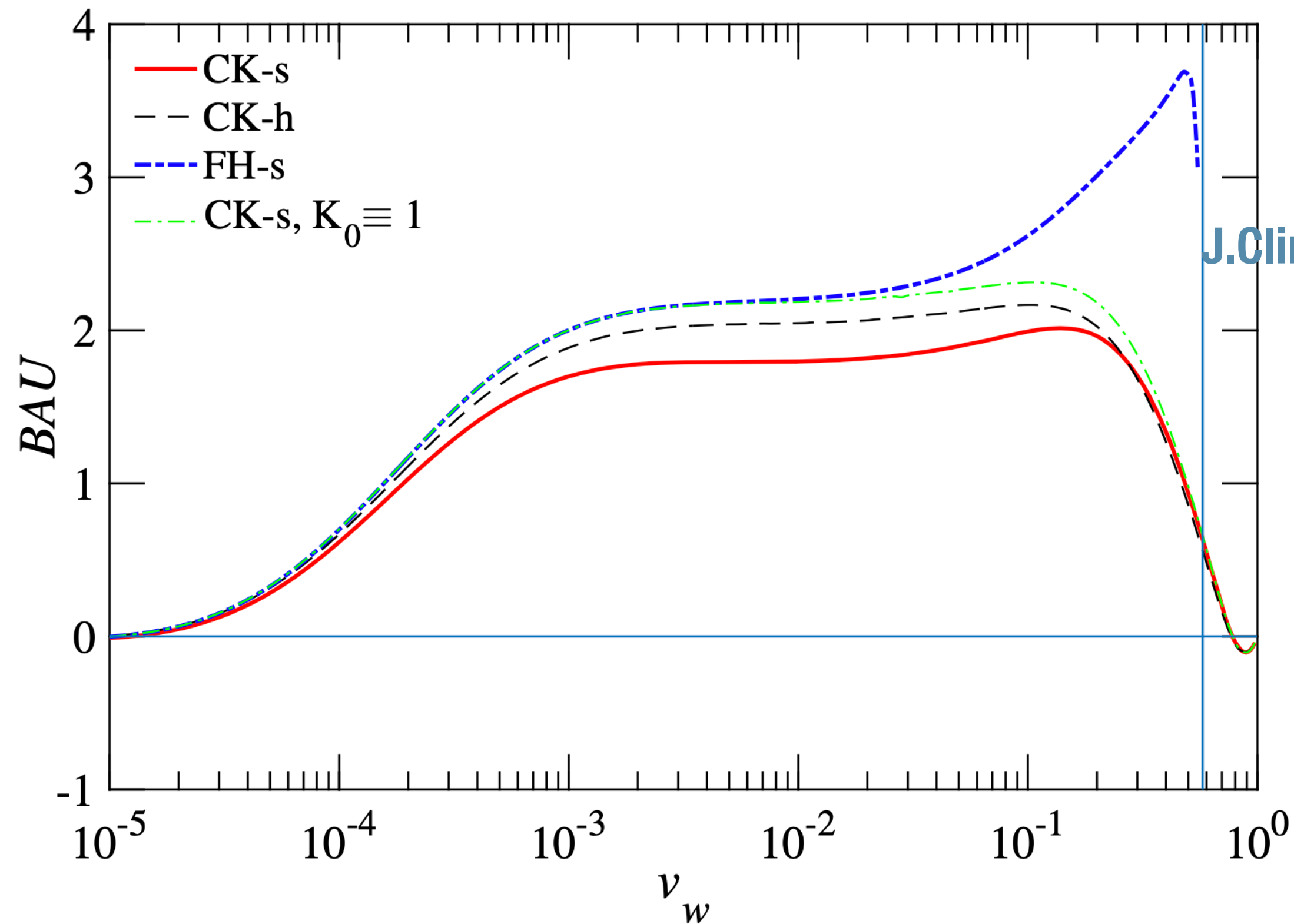
$$S_{CPV}^2 = 2\text{Im}[M^2\partial_\mu M^2] \int d^4y (y-x)^\mu \times (G_{RR}^<(x,y)G_{LL}^>(y,x) - G_{RR}^>(x,y)G_{LL}^<(y,x))$$

BAU via the VEV insertion method

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

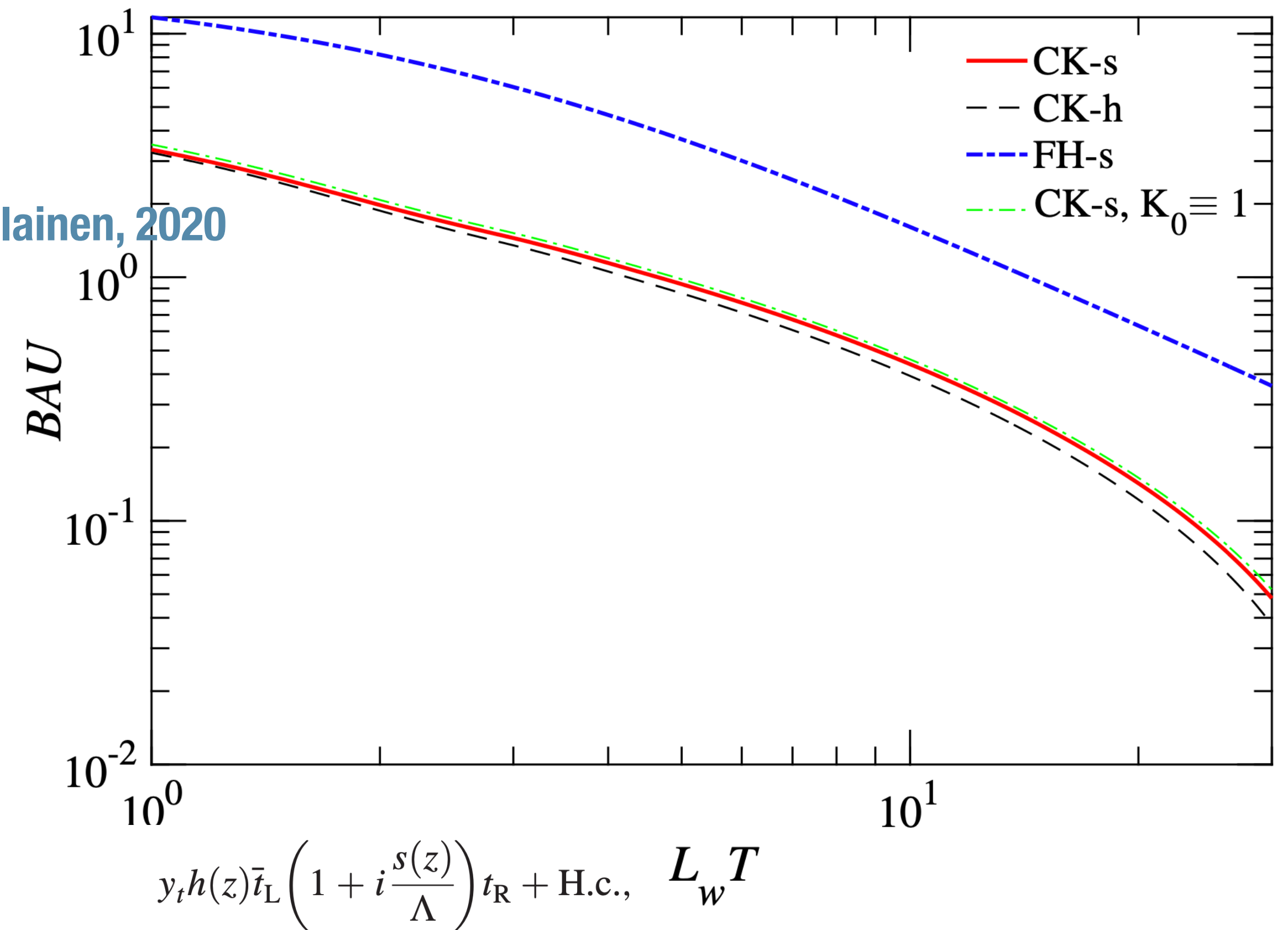
Progress (4): Calculation methods of EWBG

Conclusion: BAU smoothly evolves to zero with the increase of the wall velocity, a large velocity is allowed



Top triggered EWBG+two-step EWPT:

J.Cline, Kainulainen, 2020



Progress (4): Calculation methods of EWBG

EWBG via the WKB approximation vs via the “VEV-insertion” method

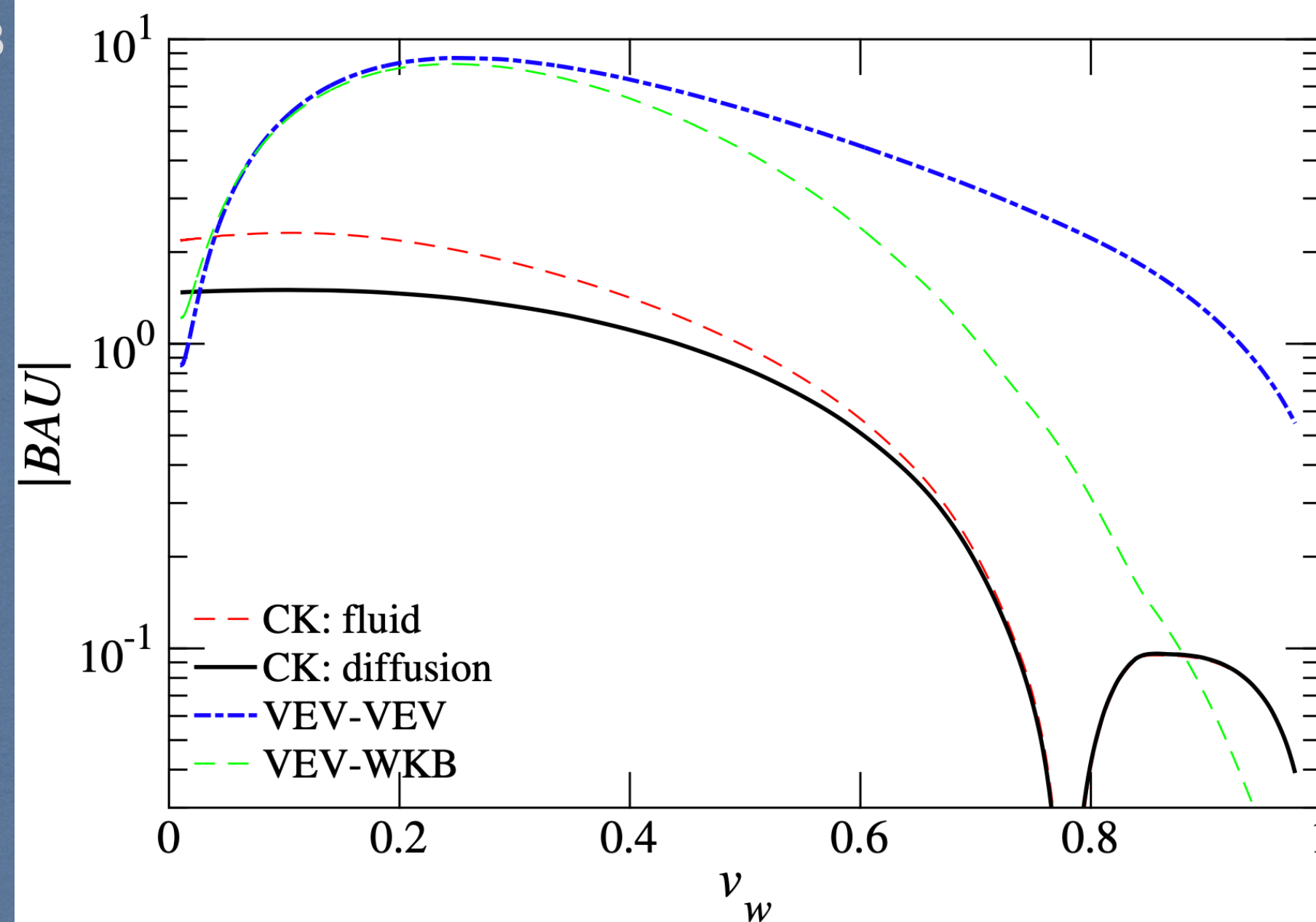
A scalar example in the CTP formalism : analog to stop induced BAU

CK-fluid: Full WKB result

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

VEV-VEV: Full VEV-insertion method;

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



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

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

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

Left-handed side: $\frac{1}{2} \partial_\mu \int \frac{d^4 k}{(2\pi)^4} i k^\mu (G^>(k, x) + G^<(k, x)) = -\partial_\mu \langle J^\mu(x) \rangle$

Source term: **VEV-i Postma, Jorinde van de Vis and White, JHEP 2022**

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

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

Calculations via the KB equation are open question!

Recent progress: Li, Ramsey-Musolf, and Yu, 2024

Progress (5): Chiral Magnetic Effect

CME: When a medium with a chiral asymmetry is exposed to a magnetic field there is an induced electric current.

• Electric current induced by magnetic field in usual media?

NO!

Chirality of fermions

$$P : j \rightarrow -j \quad E \rightarrow -E \quad B \rightarrow B$$

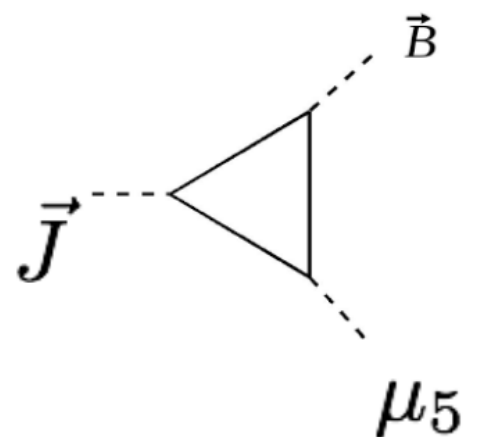
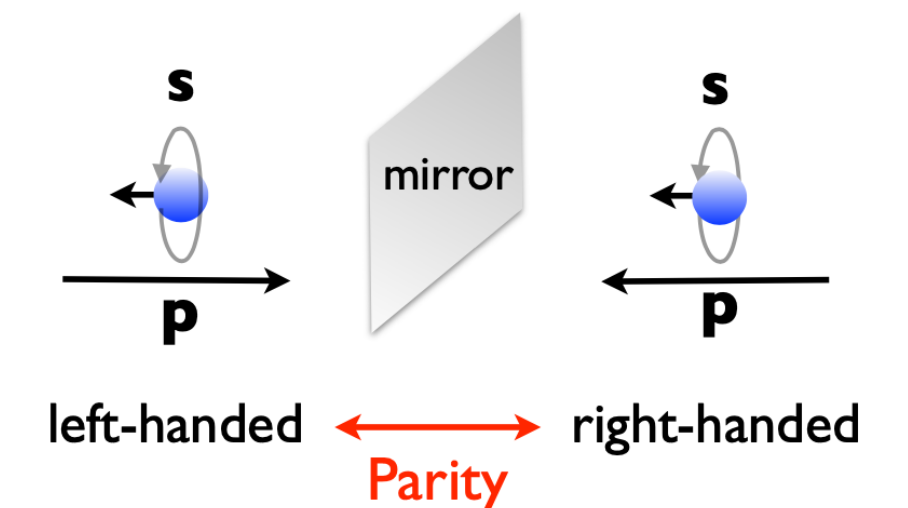
In the presence of a parity odd quantity, electric current can be induced!

Chiral chemical potential can be generated due to topological transition.

$$\mu_5 \neq 0$$

In the presence of magnetic field, electric current is generated

$$\partial_\mu j^\mu = \frac{e^2}{32\pi^2} F \widetilde{F} \rightarrow \vec{J} = \frac{e^2}{2\pi^2} \mu_5 \vec{B}$$



Progress (5): Chiral Magnetic Effect

Thermal Field: Lagrangian/Action for hyper magnetic field in the presence of chemical potential

$$-\mathcal{L} \sim \frac{1}{4} Y_{\mu\nu} Y^{\mu\nu} + C_{EW} n_{CS}^{EW} + C_Y N_{CS}^Y + j^\mu Y_\mu + \dots$$

$$C_Y = \sum_{i=1}^3 \left[-2\mu_{R_i} + \mu_{L_i} - \frac{2}{3}\mu_{d_i} - \frac{8}{3}\mu_{u_{Ri}} + \frac{1}{3}\mu_{Q_i} \right] \quad N_{CS}^Y = \frac{g'^2}{32\pi^2} 2Y \cdot B_Y$$

• Maxwell equations

$$\frac{\partial E}{\partial \eta} - \nabla \times B + J = 0 \quad \frac{\partial B}{\partial \eta} + \nabla \times E = 0 \quad \nabla \cdot E = \rho \quad \nabla \cdot B = 0$$

$$J = \sigma(E + v \times B) + \frac{2\alpha}{\pi} C_Y B$$

CME: When a medium with a chiral asymmetry is exposed to a magnetic field there is an induced electric current

Progress (5): Chiral Magnetic Effect

EOM for helicity and the energy density of magnetic field

• Definition

$$h = \int \frac{d^3x}{V} A \cdot B = \int dk h_k \quad \rho_B = \int \frac{d^3x}{V} \frac{1}{2} B^2 = \int dk \rho_k$$

• EOM

$$\frac{\partial h}{\partial \eta} = \lim_{V \rightarrow \infty} \int \frac{d^3x}{V} \left(2B \cdot \nabla^2 A \frac{1}{\sigma} + \frac{4\alpha}{\pi} \frac{C_{CS}}{\sigma} B_Y^2 \right)$$

$$-T \frac{\partial h_k}{\partial T} = -\frac{2k^2}{\sigma_0} \frac{T}{H} h_k + \frac{8\alpha}{\pi \sigma_0} \left(\frac{C_{CS}^Y}{T} \right) \frac{T}{H} \rho_k \quad -T \frac{\partial \rho_k}{\partial T} = -\frac{2k^2}{\sigma_0} \frac{T}{H} \rho_k + \frac{2\alpha k^2}{\pi \sigma_0} \left(\frac{C_{CS}^Y}{T} \right) \frac{T}{H} h_k$$

Progress (5): Chiral Magnetic Effect

B&L violations via the Triangle anomalies

$$\Delta B = \Delta L = N_g(\Delta N_{CS}^W - \Delta N_{CS}^Y) \qquad \Delta N_{CS}^Y = \frac{g_Y^2}{16\pi^2} \Delta H$$

- **Traditional Baryogenesis:**

$$\Delta N_{CS}^Y = 0$$

Source term comes from the LNV decay of seesaw particles or CPV interaction on the bubble wall.

- **Magnetogenesis:**

$$\Delta N_{CS}^Y \neq 0$$

No other source term

- **A third scenario:**

$$\Delta N_{CS}^Y = 0 \text{ \& } B \neq 0$$

There might be non-helical magnetic field in the early universe.

Progress (5): Chiral Magnetic Effect

Transport equations for EWBG when CME effects are included.

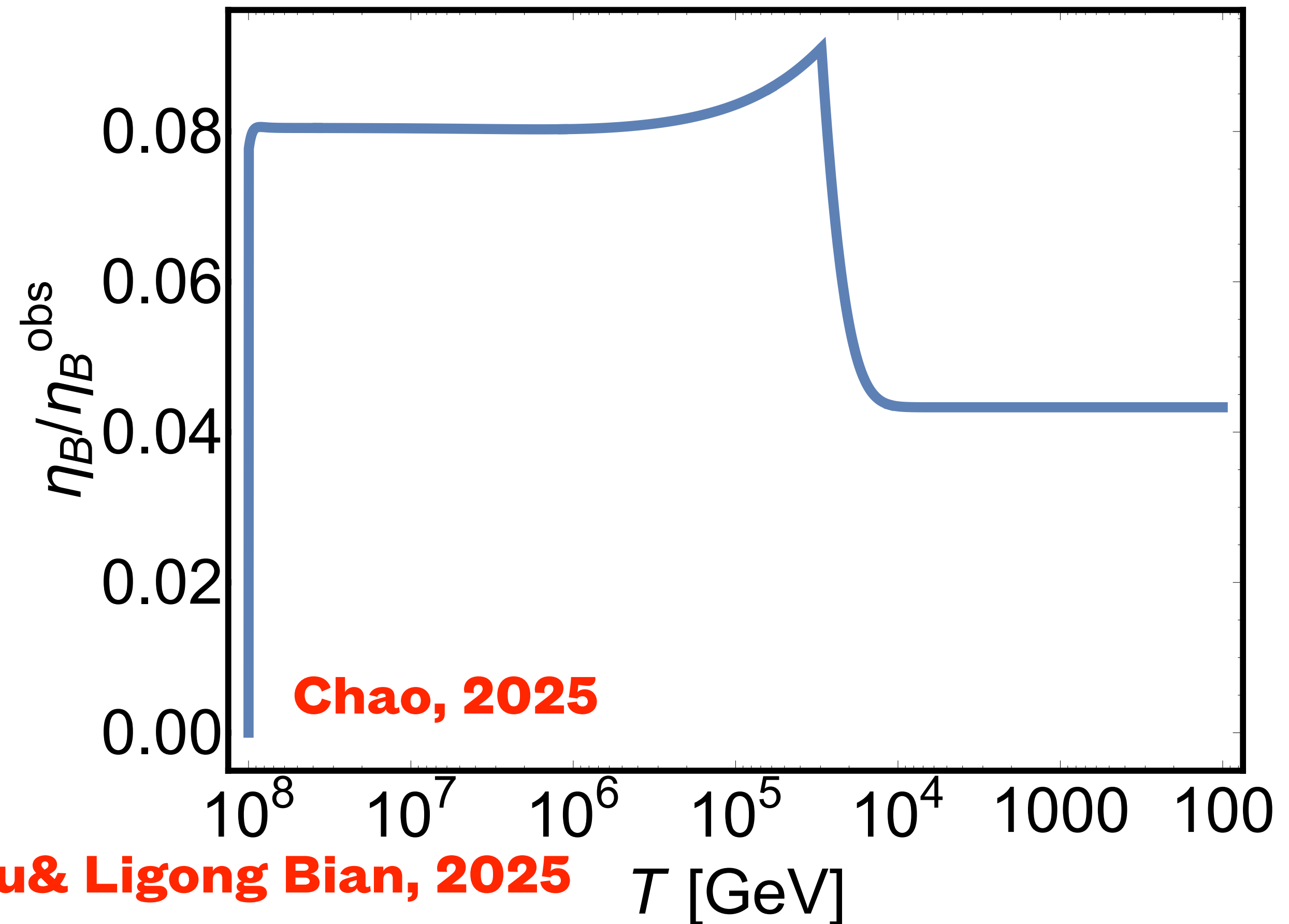
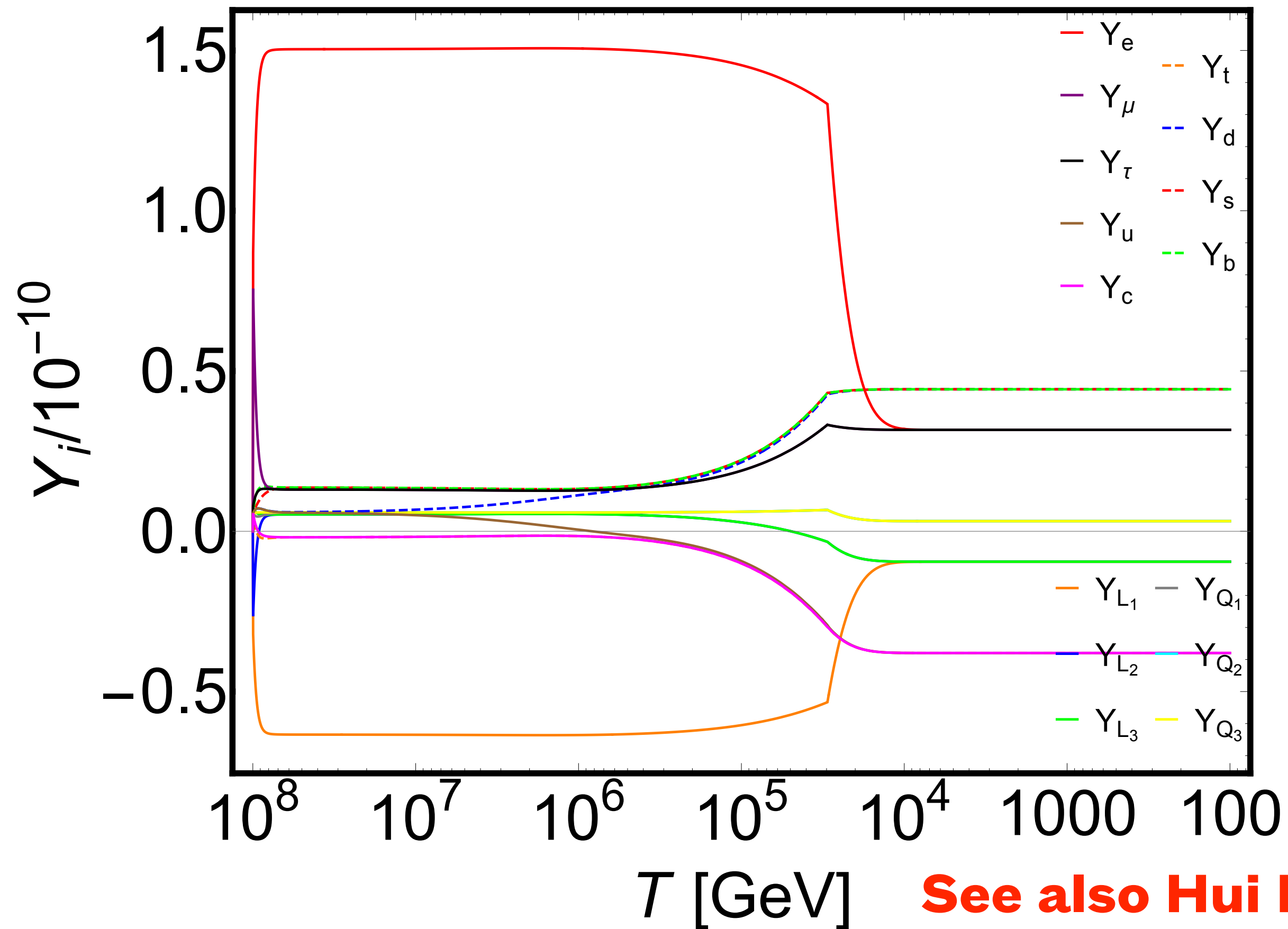
$$-\frac{d}{d \ln T} \left(\frac{\mu_{E_i}}{T} \right) = -\frac{1}{g_{E_i}} \frac{\gamma_{E_i}}{H} \left(\frac{\mu_{E_i}}{T} - \frac{\mu_{L_i}}{T} + \frac{\mu_H}{T} \right) + \frac{6}{g_E} \frac{\alpha}{2\pi} \frac{\partial h}{\partial \ln T}$$

$$\frac{d}{d \ln T} \left(\frac{\mu_{L_i}}{T} \right) = +\frac{1}{g_{L_i}} \frac{\gamma_{E_i}}{H} \left(\frac{\mu_{E_i}}{T} - \frac{\mu_{L_i}}{T} + \frac{\mu_H}{T} \right) - \frac{1}{g_{L_i}} \frac{2\gamma_{WS}}{H} \left[\sum_i \frac{\mu_{L_i}}{T} + 3 \sum_i \frac{\mu_{Q_i}}{T} \right] - \frac{6}{g_{L_i}} \frac{\alpha}{2\pi} \frac{\partial h}{\partial \ln T}$$

$$-T \frac{\partial h_k}{\partial T} = -\frac{2k^2}{\sigma_0} \frac{T}{H} h_k + \frac{8\alpha}{\pi\sigma_0} \left(\frac{C_{CS}^Y}{T} \right) \frac{T}{H} \rho_k \quad -T \frac{\partial \rho_k}{\partial T} = -\frac{2k^2}{\sigma_0} \frac{T}{H} \rho_k + \frac{2\alpha k^2}{\pi\sigma_0} \left(\frac{C_{CS}^Y}{T} \right) \frac{T}{H} h_k$$

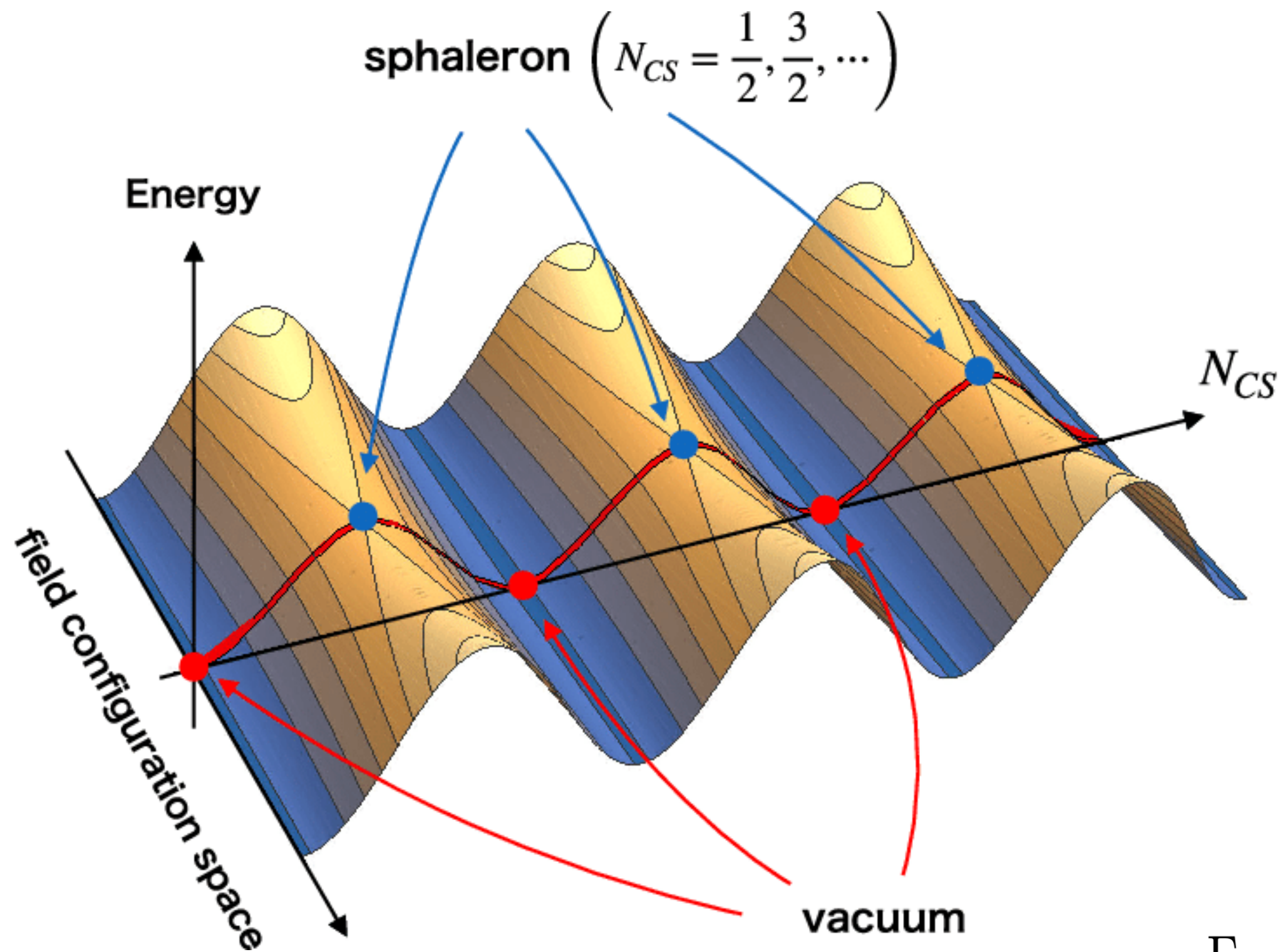
Progress (5): Chiral Magnetic Effect

- No primordial B-L asymmetry and no primordial helical magnetic field



Progress (6): BAO without the first order EWFT

- Sphaleron decoupling as the third condition for the baryogenesis



- D. Kharzeev, E. Shuryak, and I. Zahed, *Phys. Rev. D* 102 no. 7, (2020) 073003,

- **Sphaleron rate**

$$\begin{cases} \Gamma_{\text{lattice, sph}}(T)/T^4 = (8.0 \pm 1.3) \times 10^{-7} & (T > T_{\text{EW}}) \\ \log(\Gamma_{\text{lattice, sph}}(T)/T^4) = (0.83 \pm 0.01)T/\text{GeV} - (147.7 \pm 1.9) & (T < T_{\text{EW}}), \end{cases}$$

- **EWPT temperature** $T_{\text{EW}} = (159.5 \pm 1.5) \text{ GeV}$

- **Sphaleron decouple** $T_{\text{FO}} = 130 \text{ GeV}$

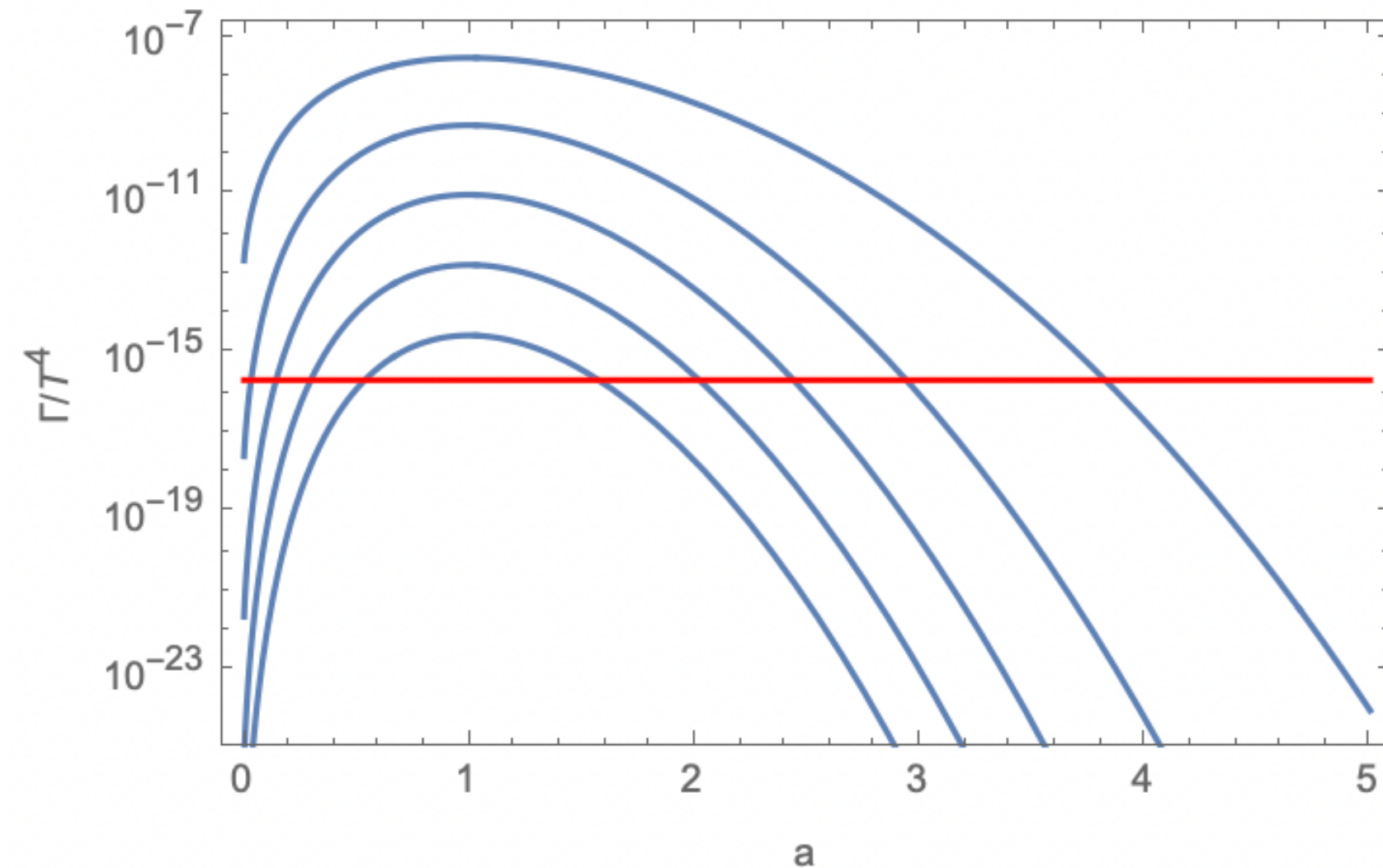
- **Sphaleron rate with size factor a**

$$\Gamma_{\text{lattice, sph}}(T) = \int da \Gamma_{\text{sph}}(T, a), \quad \text{with} \quad \Gamma_{\text{sph}}(T, a) = \frac{e^{-M(T, a)/T}}{\int da' e^{-M(T, a')/T}} \cdot \Gamma_{\text{lattice, sph}}(T),$$

- Hong, Kamada, Yokoyama, *Phys.Rev.D* 108 (2023) 6, 6

Progress (6): BAO without the first order EWFT

Hong, Kamada, Yokoyama, *Phys.Rev.D* 108 (2023) 6, 6



CPV induced transition asymmetry at the sphaleron decoupling sector:

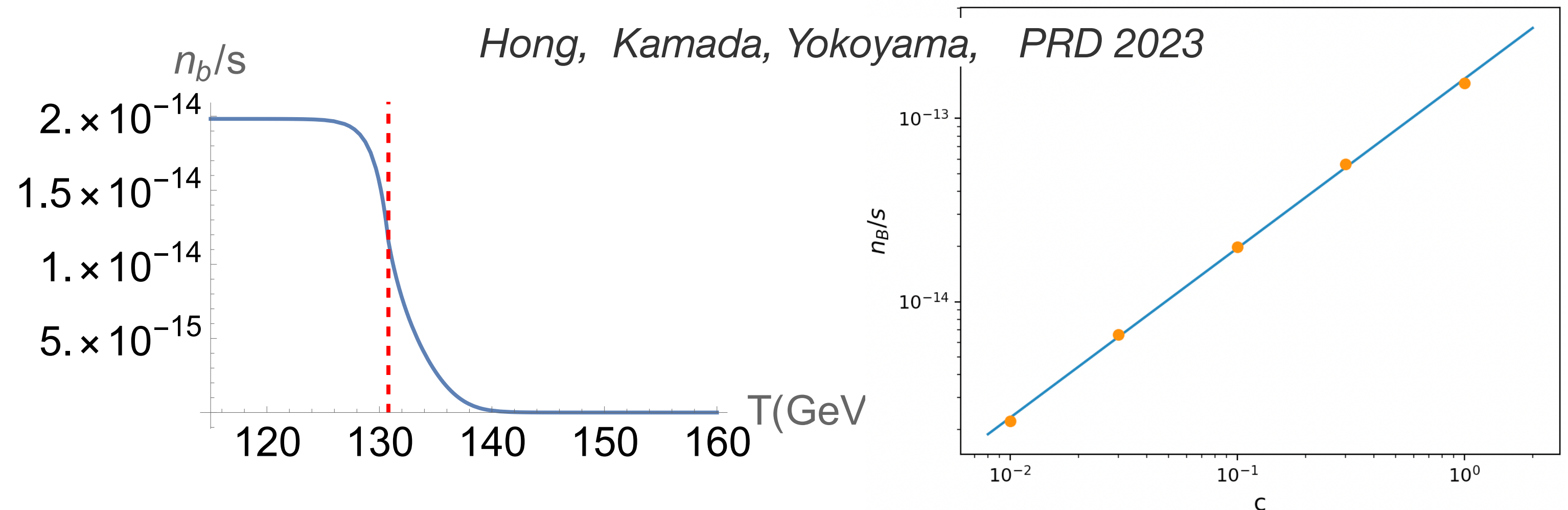
$$A_{\text{CP}} \sim 2.5 \times 10^{-10}$$

- D. Kharzeev, E. Shuryak, and I. Zahed, *Phys. Rev. D* 102 no. 7, (2020) 073003,

Source term induced by decoupled sphaleron size sector

$$P(T) = \begin{cases} \left(\int_{a_{\min}}^{a_l} da \Gamma_{\text{sph}}(T, a) + \int_{a_u}^{a_{\max}} da \Gamma_{\text{sph}}(T, a) \right) \cdot 3A_{\text{CP}}, & \text{for } T_c < T \leq T_{\text{EW}}, \\ \Gamma_{\text{lattice, sph}} \cdot 3A_{\text{CP}}, & \text{for } T \leq T_c, \end{cases}$$

Transport equations: $\frac{dn_B}{dt} + 3Hn_B = -\frac{39}{4} \frac{\Gamma_{\text{sph}, \bar{a}}}{T^3} n_B + P(T)$



Baryogenesis Summary

80s~90s	BAU via first order phase transition and SM CP violation
90s~10s	EWBG in MSSM
10s~20s	Constrains on EWBG from Higgs physics and EDM
15s~20s	EWBG VS stochastic GW signals (PT dynamics)
20s~now	Diverse investigations of Baryogenesis

Thank you for your attention!