Overview of Baryogenesis and Leptogenesis

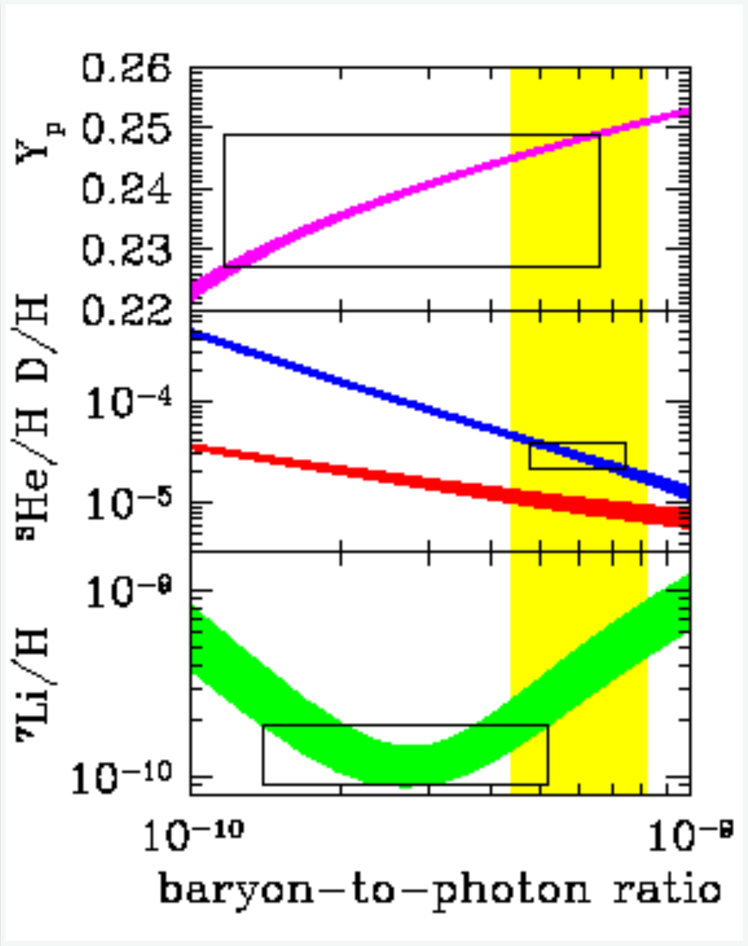
Wei Chao

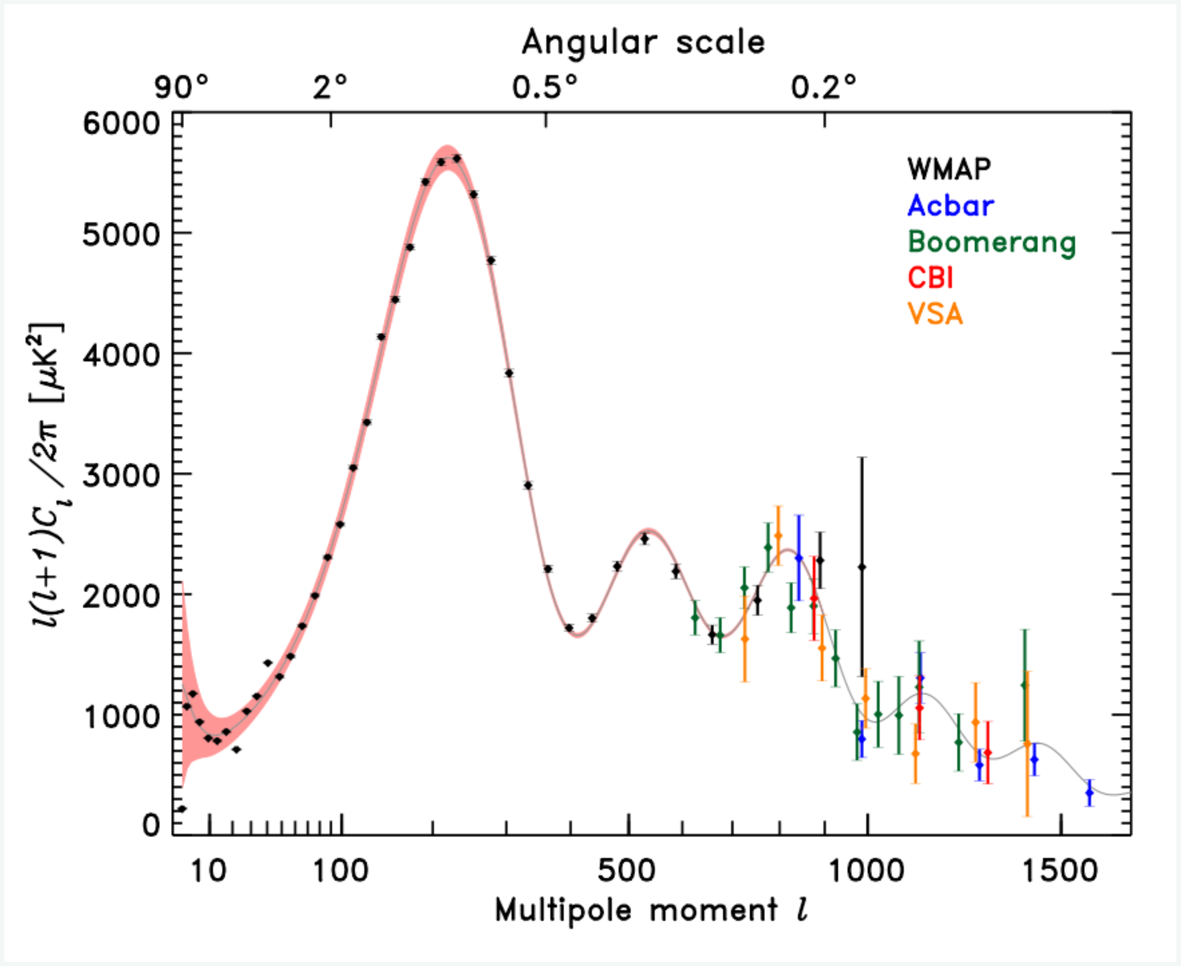
Department of Physics and Astrophysics, Beijing Normal University

New physics—The Baryon asymmetry

Matter-antimatter asymmetry

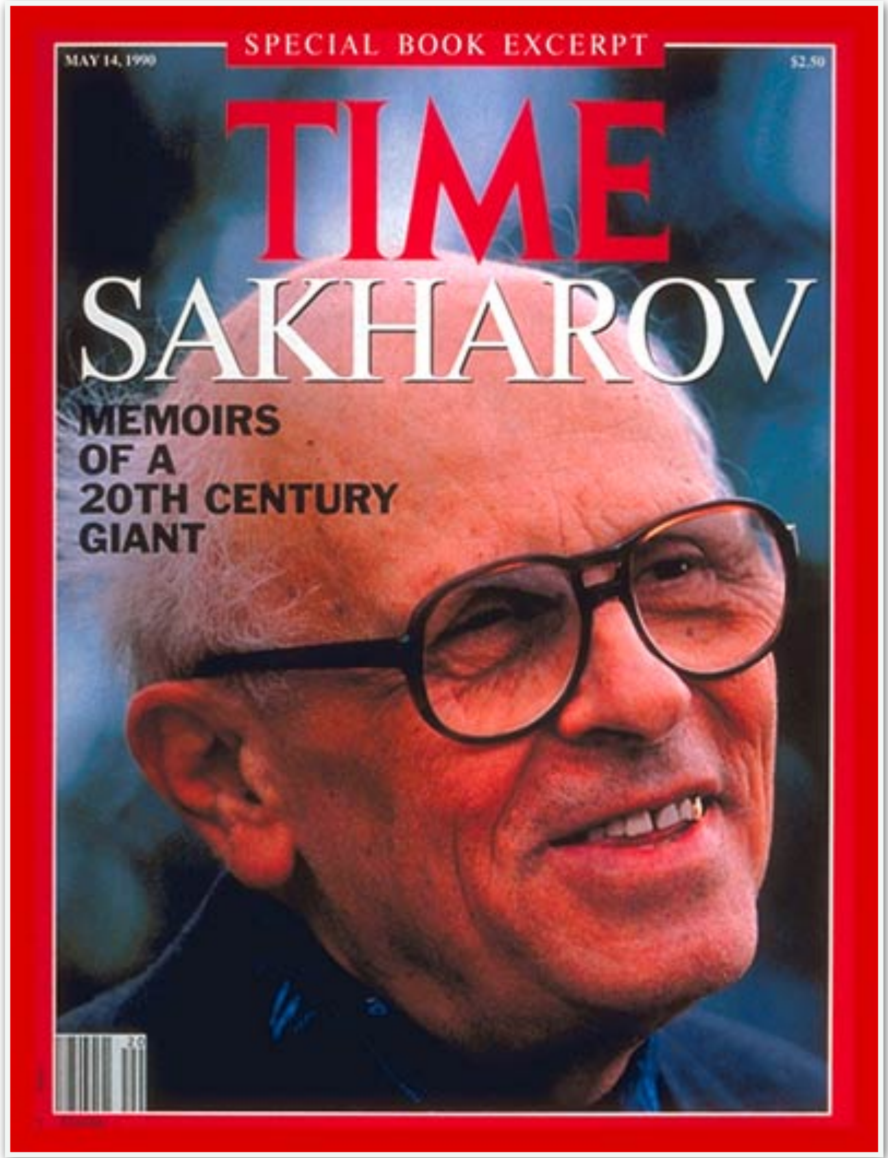
- No galaxy made by ant-baryon is observed
- Baryon asymmetry is measured by the Planck.

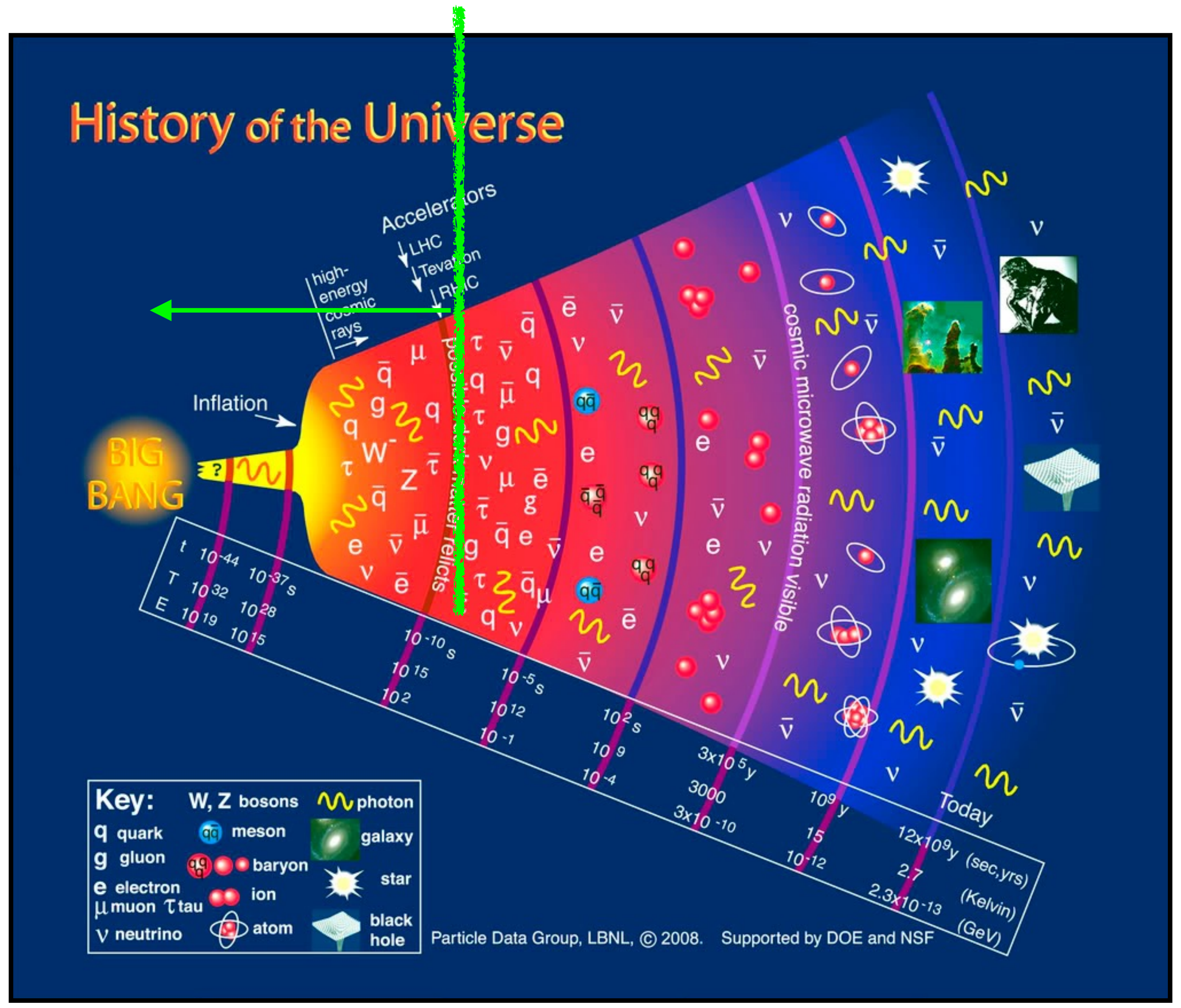




Baryon asymmetry: $Y_B = \frac{\rho_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$ **Planck**

Baryogenesis





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

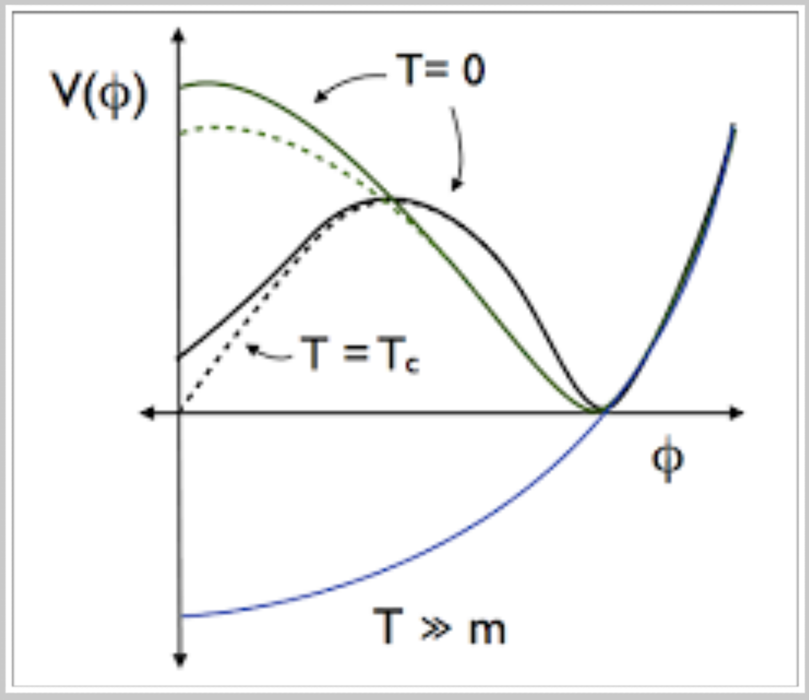
- Leptogenesis
- Electroweak Baryogenesis
- GUT Baryogenesis
- Afleck-Dine Baryogenesis
- Post-sphleron baryogenesis

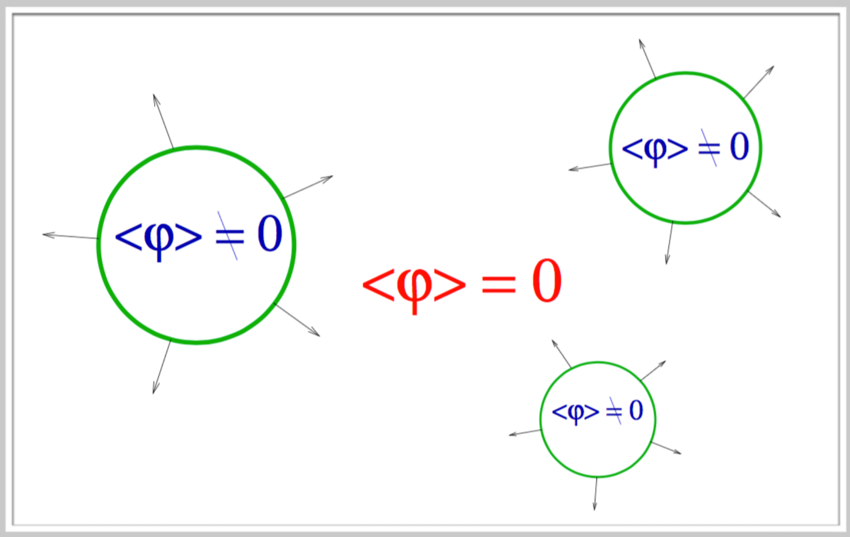
Outline

- Overview of Baryogenesis mechanisms
- Progress based on Electroweak Baryogenesis
  - 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 oder phase transition
- Progress based on traditional Leptogenesis (Backup slides)

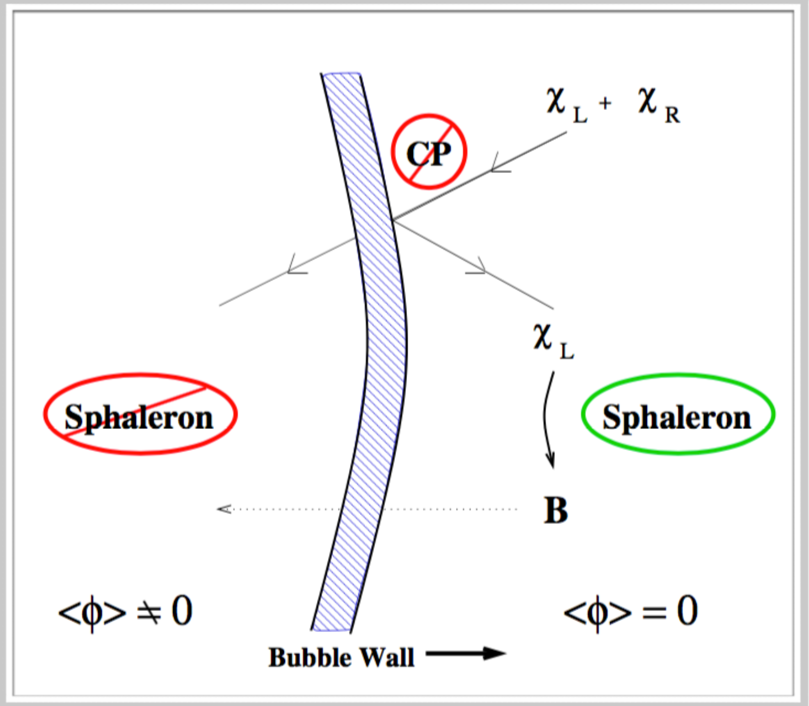
History and development: EW Baryogenesis

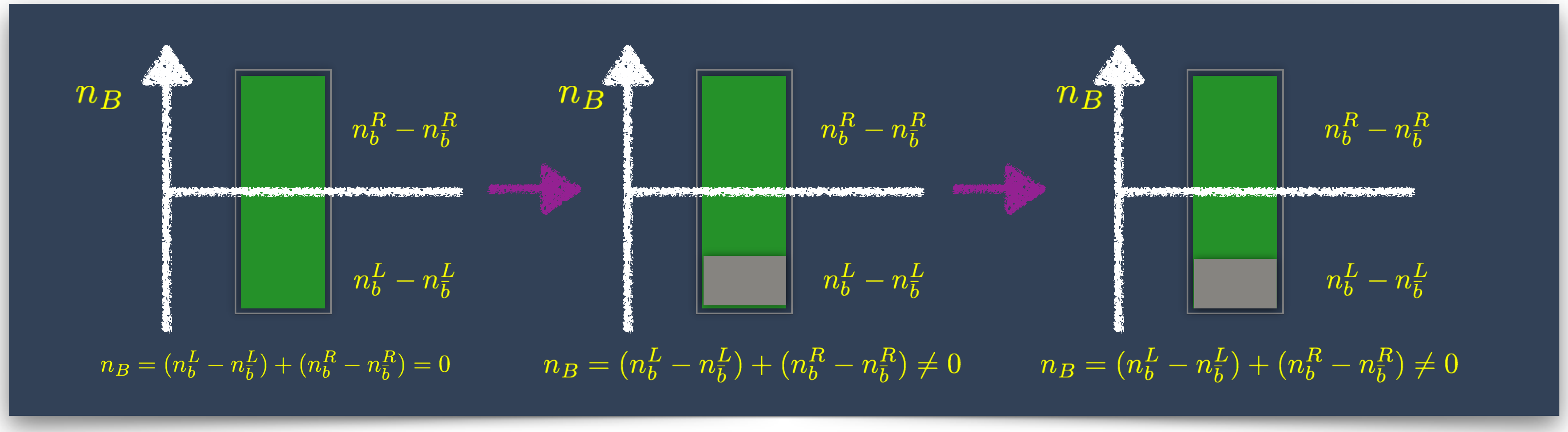
EWBG





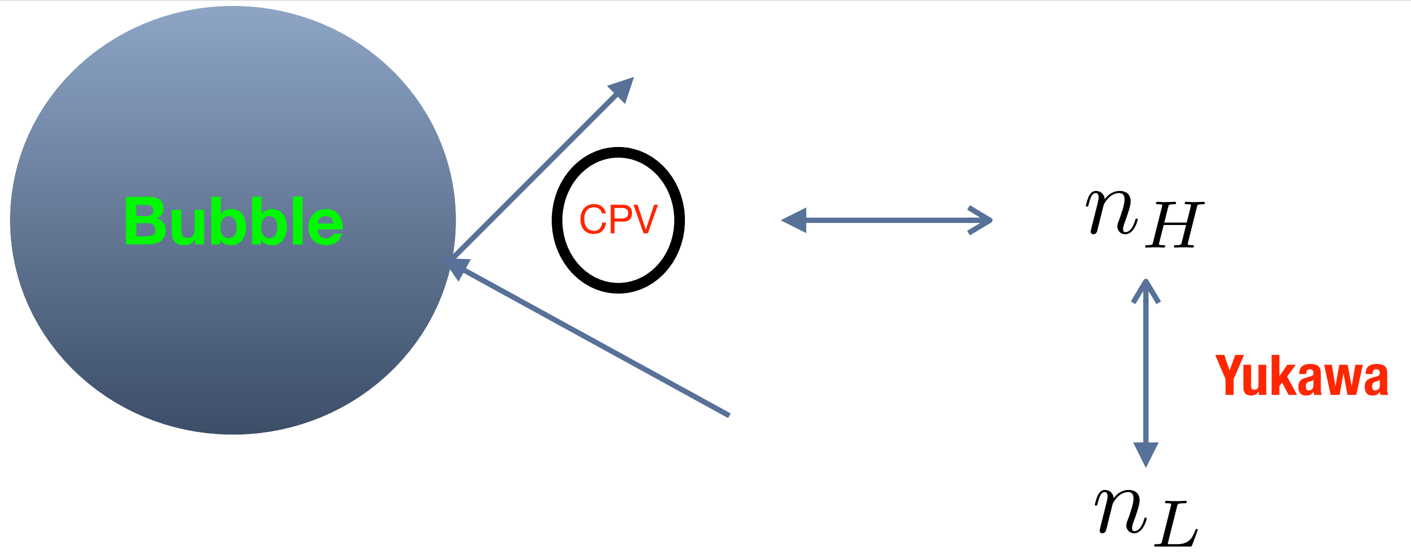
Basic description





Transport equations

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



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

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

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

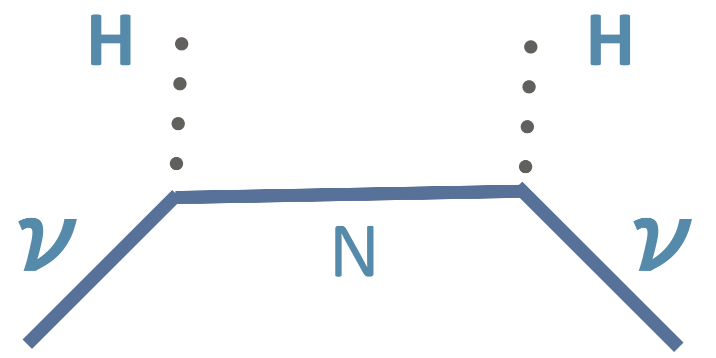
History and development: Leptogenesis

Type-I seesaw mechanism

Lagrangian:

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

Seesaw Mechanism



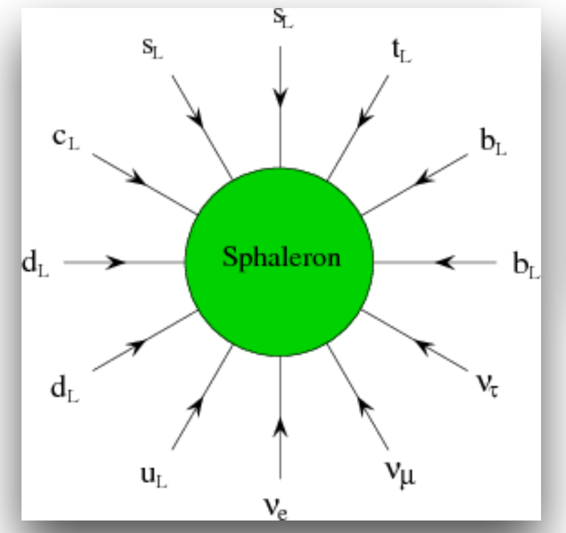
Neutrino mass:

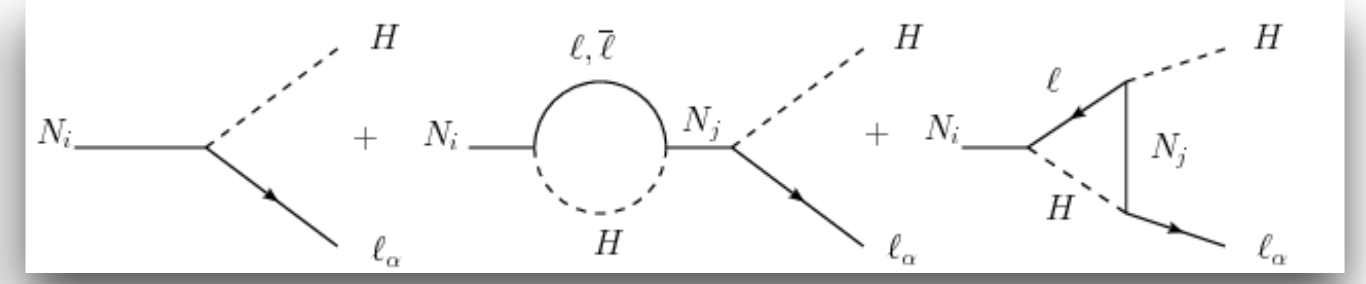
$$M_\nu = -M_D M_R^{-1} M_D^T$$

Elegant but losing testability at colliders!

Leptogenesis (Fukugita&Yanagida 86)

BV | **CPV** | **Out of EQ**



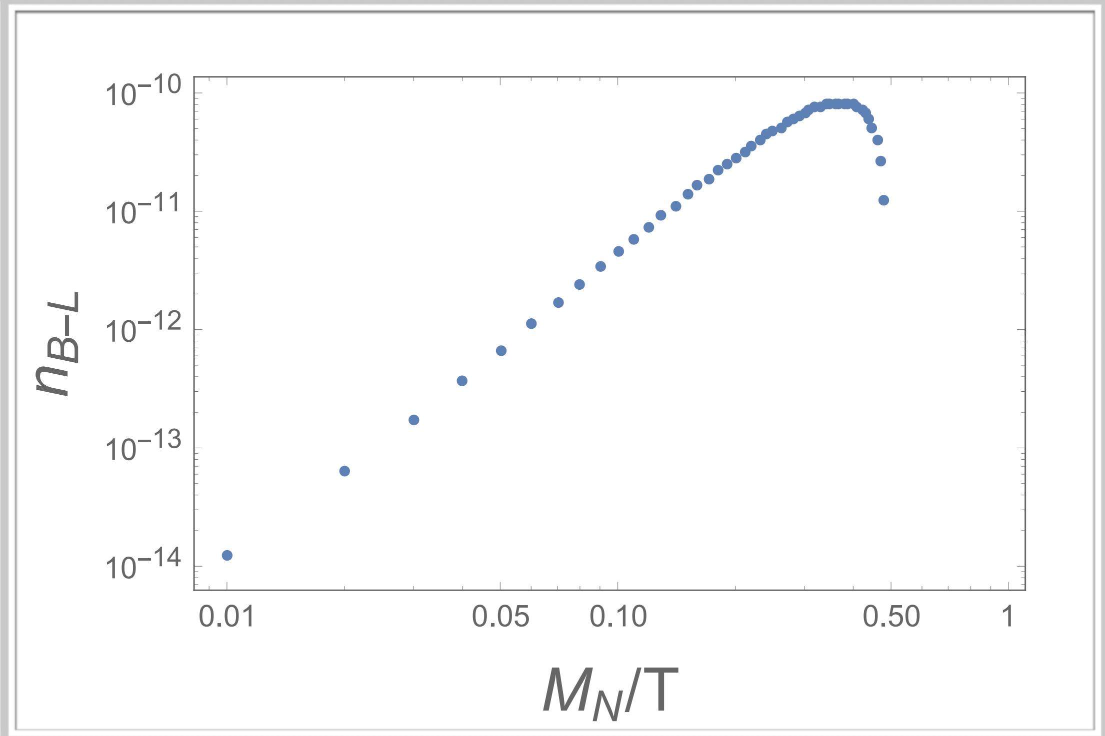


Heavy neutrinos decouple

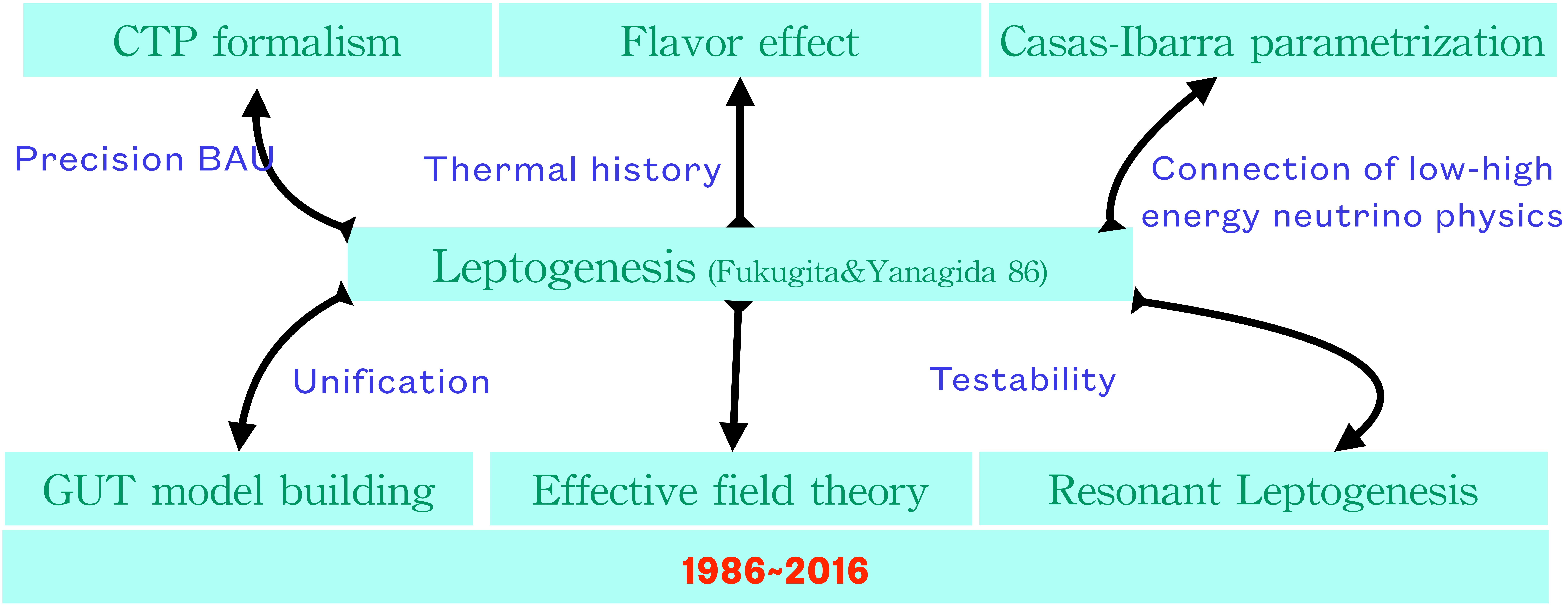
Boltzmann EQ

$$\frac{dN}{dz} = -D(N - N^{\rm eq})$$

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



History and development: Leptogenesis



History and development: Leptogenesis

Contents

- CTP formalism
- Flavor effect
- Casas-Ibarra parametrization
- Effective field theory
- Resonant Leptogenesis

Leptogenesis

- With Gravity
- With inflation
- With axion physics
- With phase transition
- With plasma physics

$t@2015's$

History and development: Afleck-Dine

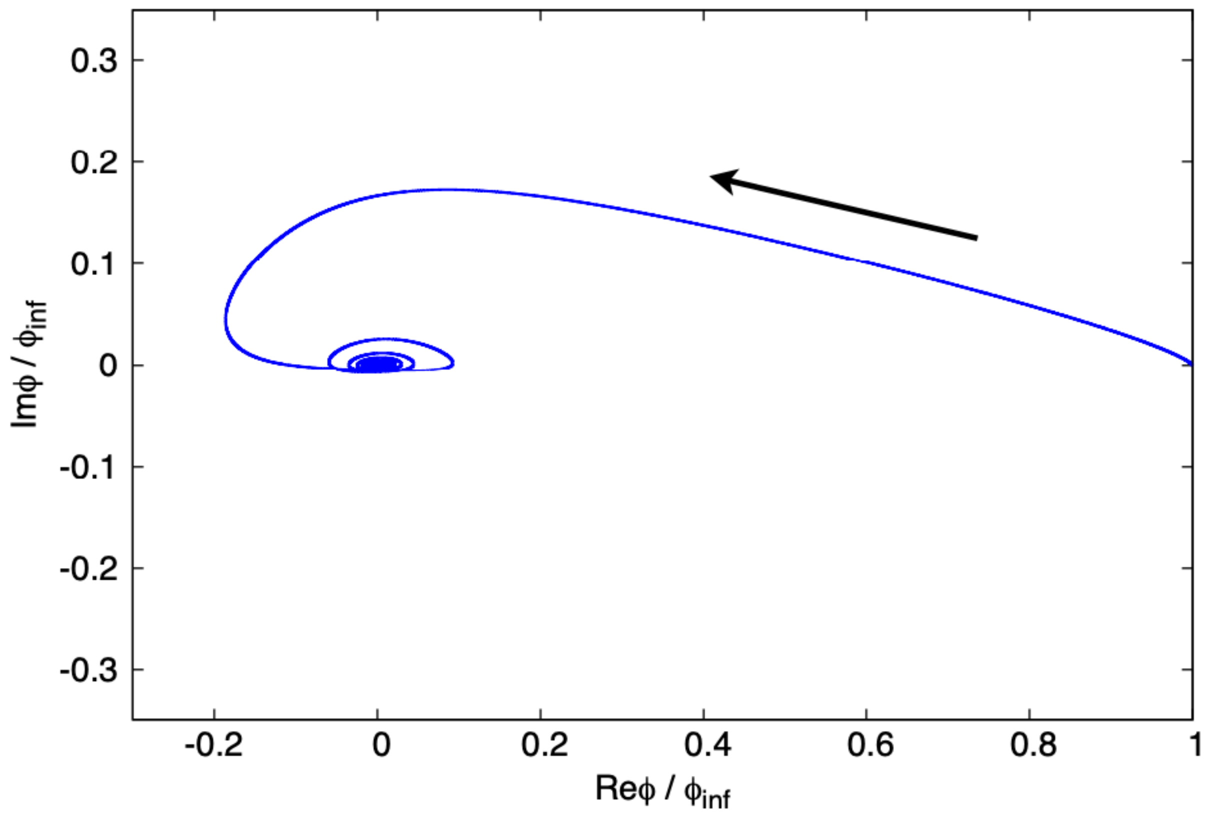
Afleck-Dine Mechanism

Scalars carrying non-zero U(1) charges

Flat directions (AD fields)

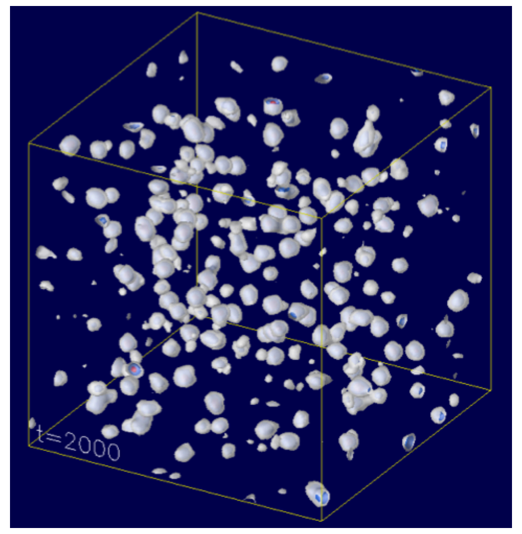
Lifting the potential via B/L violation operators

$$V = (m^2 - cH^2)|\phi|^2 + \lambda|\phi|^4 + \left(\frac{\phi^n}{M^{n-4}} + \mathrm{h.c.}\right)$$



$$\dot{n}_{B,L} + 3Hn_{B,L} = 2\beta \mathrm{Im}\left[\frac{\partial V}{\partial \phi}\phi\right]$$

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

QCD Axion

Strong CP problem → **Peccei-Quinn mechanism** → **Axion**

Pseudo-scalar particle

[Preskill, Wise, Wilczek (1983)]
[Abbott, Sikivie (1983)]
[Dine, Fischler (1983)]

$$d_n = 5.2 \times 10^{-16} \bar{\theta} \mathrm{e} \cdot \mathrm{cm}$$

$$d_n \leq 10^{-26} \mathrm{e} \cdot \mathrm{cm}$$

Misalignment mechanism : $\phi_0 \neq 0, \quad \dot{\phi} = 0$

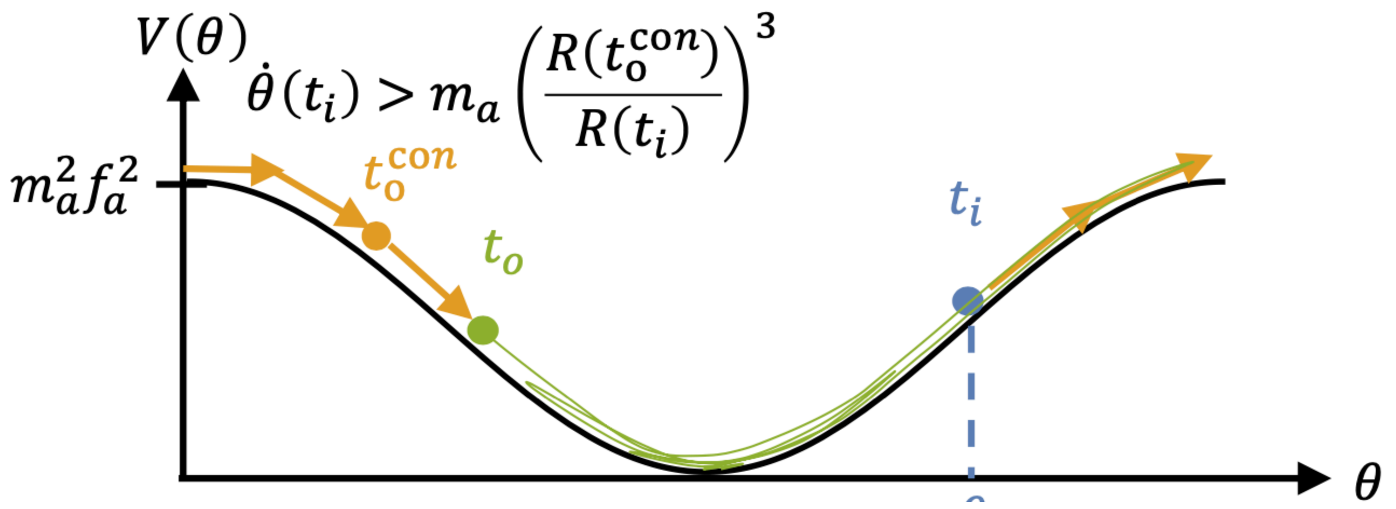
$$\ddot{\phi} + 3H\dot{\phi} + \frac{\Lambda^4(T)}{f^2}\phi = 0$$

$$\Rightarrow \quad \rho_{\rm DM} \sim m_\phi \left[\frac{a(T_{osc})}{a_0}\right]^3 \left[\frac{\Lambda(T_{osc})^4 \theta_i^2}{m_\phi(T_{osc})}\right]$$

Axiogenesis

Kinetic Misalignment mechanism : $\phi_0 \neq 0, \quad \dot{\phi} \neq 0$

[Co, Hall, Harigaya (2019)]
[Chang, Cui (2019)]



Non-zero Peccei-Quinn number→Axiogenesis!

Strong sphaleron ↓ **Quark chiral asymmetry**

$$n_{PQ} = S^2 \dot{\phi}$$

EWsphaleron ↓ **Baryon asymmetry**

Quark chiral asymmetry —EWsphaleron→ **Baryon asymmetry**

PRL, 124, 111602

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

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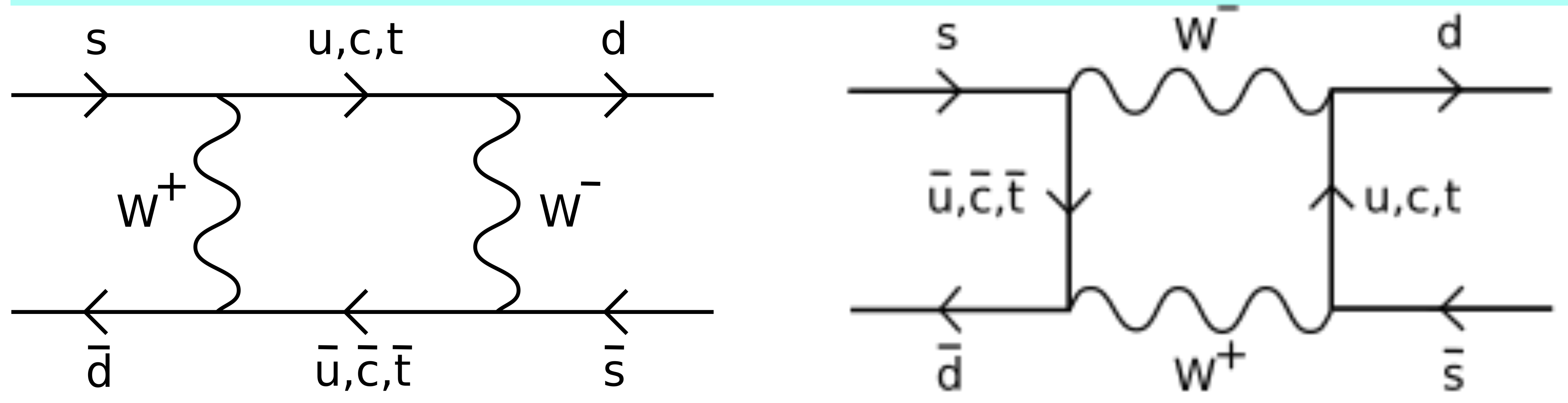
- Leptogenesis（Backup slides） See Chengcheng's talk

EWBG via the SM CP violation

CP violation in the CKM



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

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

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

BAU

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

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

$\sim \mathcal{O}(1) \times 10^{-22}$ ➡ $\left|\frac{n_B}{s}\right| < 6 \times 10^{-27}$

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

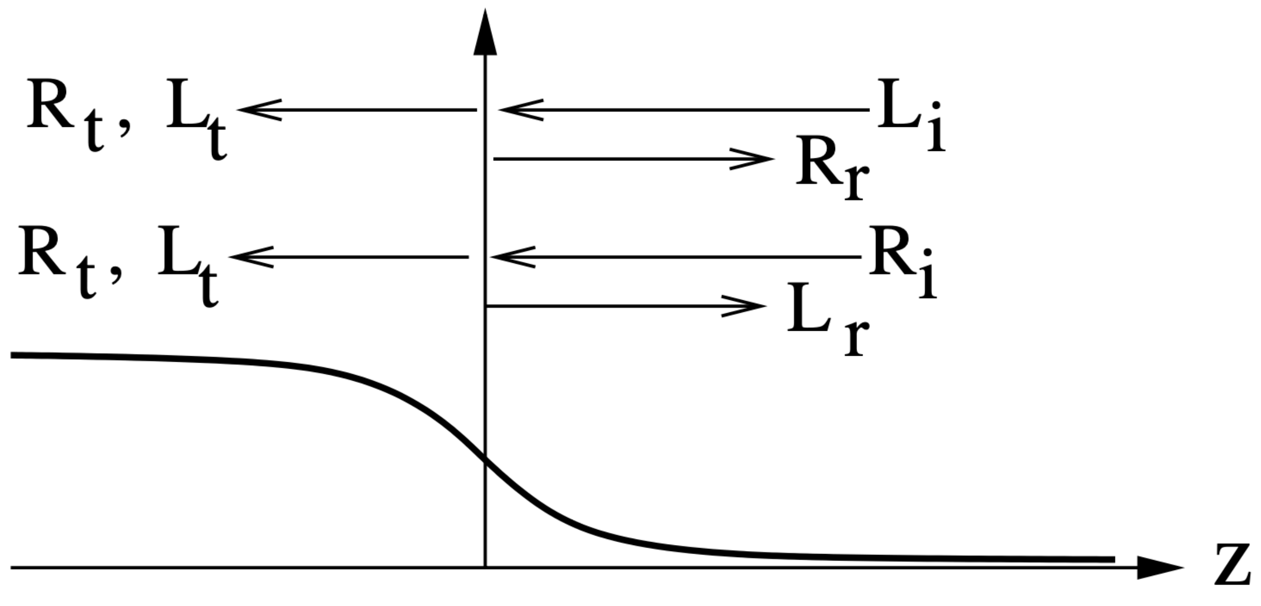
QCD damping effect (quantum decoherence) reduce the BAU to negligible!

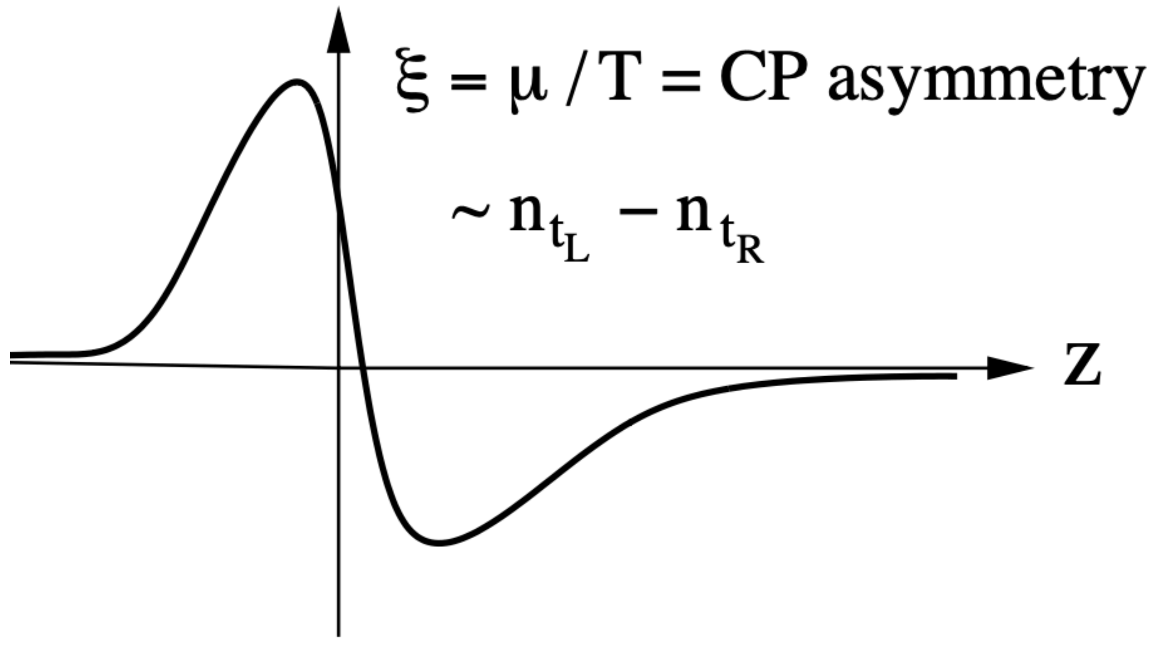
EWBG with new CP violation (example)

CP violation in the top quark sector

$$\mathscr{L}_Y \sim y_t \overline{Q_L^3}\tilde{H}t_R + \frac{\zeta}{\Lambda}\overline{Q_r^L}\tilde{H}\phi t_R$$

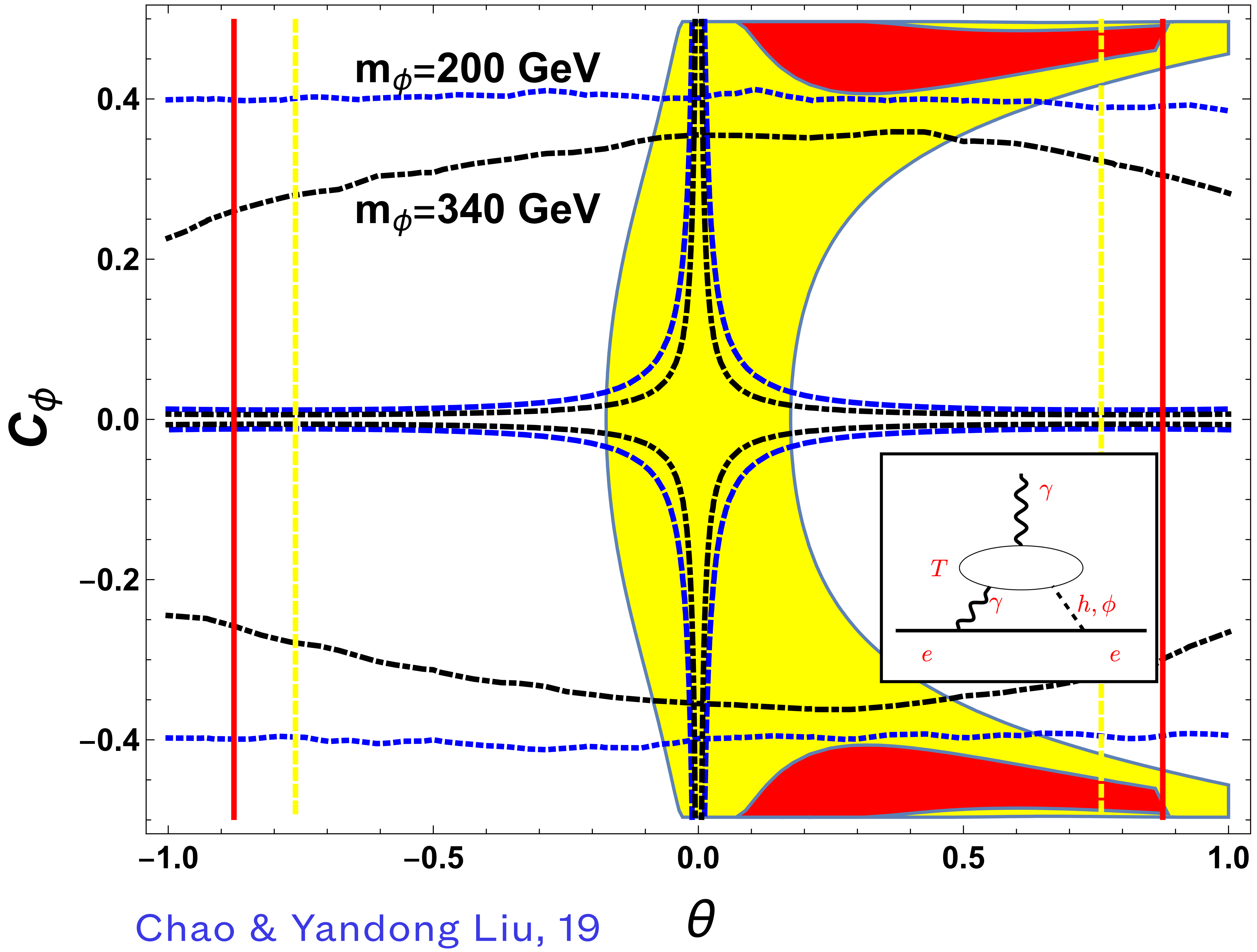
$$\frac{1}{\sqrt{2}}\bar{t}(S_\phi s_\theta + Y_t c_\theta + i\gamma^5 C_\phi s_\theta)t\hat{h} + \frac{1}{\sqrt{2}}\bar{t}(S_\phi c_\theta - Y_t s_\theta + i\gamma^5 C_\phi c_\theta)t\hat{\phi}$$





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

Constraints

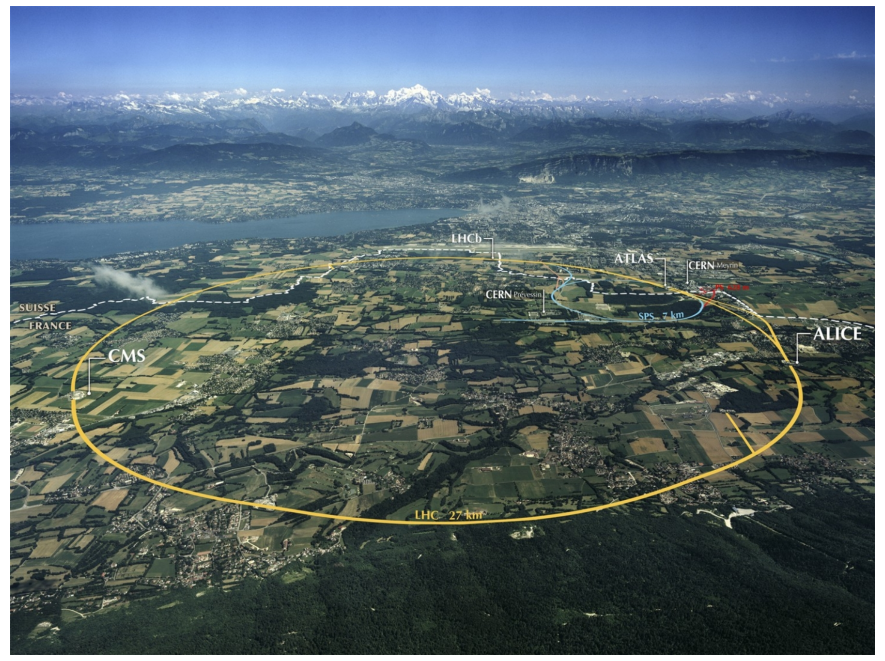


Chao & Yandong Liu, 19

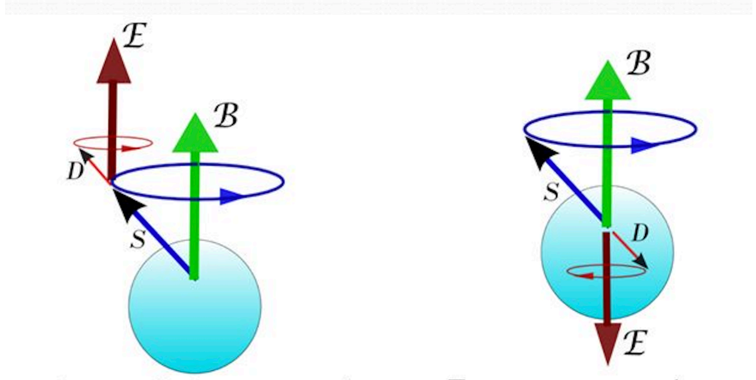
Constraints of the EWBG

Detection methods

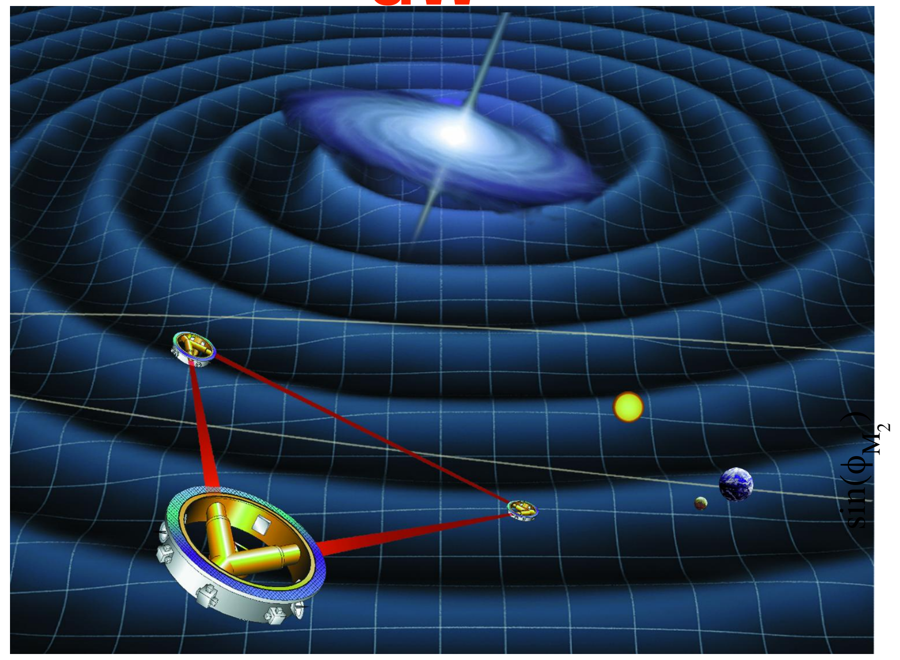
LHC



EDM



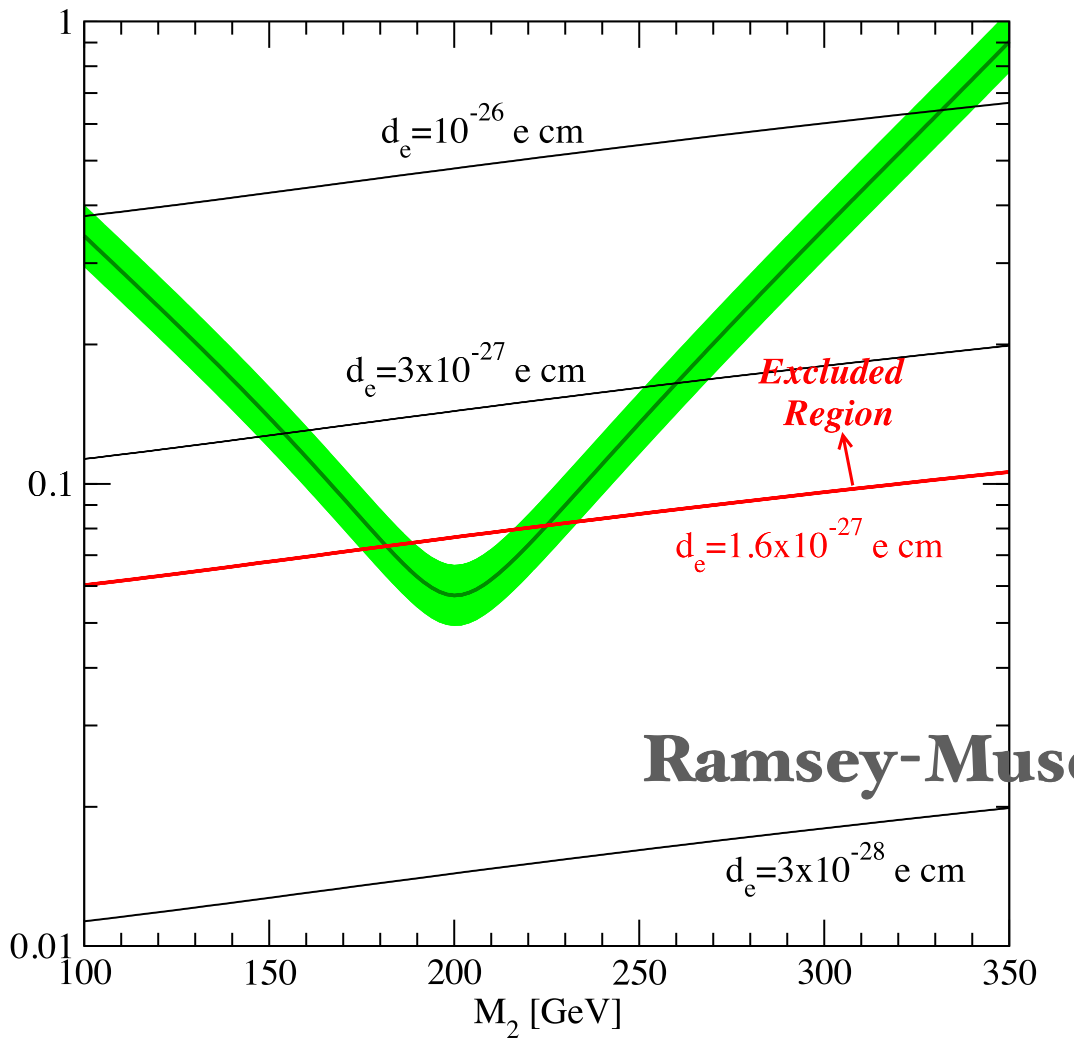
GW

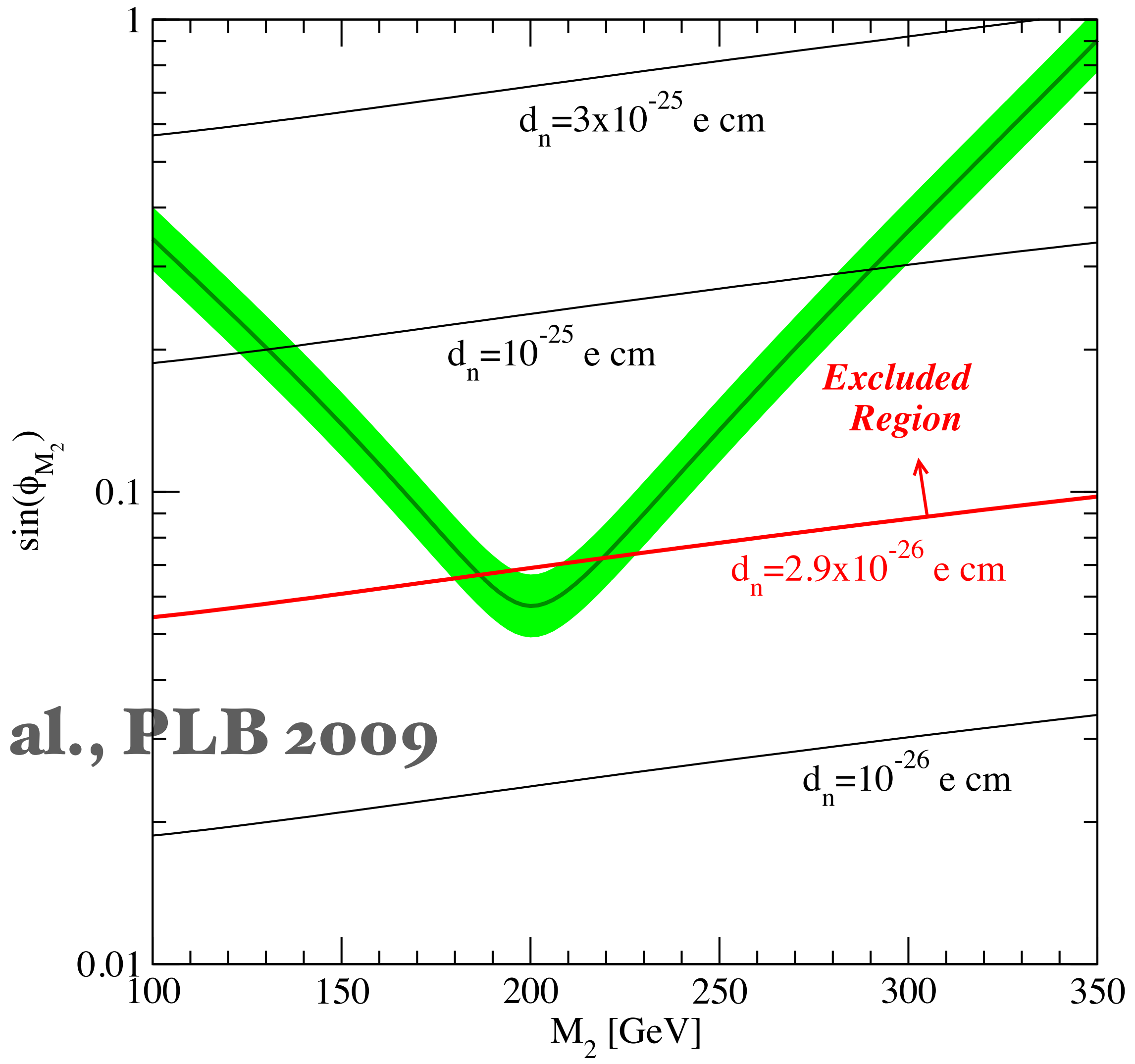


Conventional EWBG mechanism might be found or excluded in the near future when these three detection methods are combined.

- 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





Ramsey-Musolf, et al., PLB 2009

- 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

Lemma: Haber, Surujon, 2012

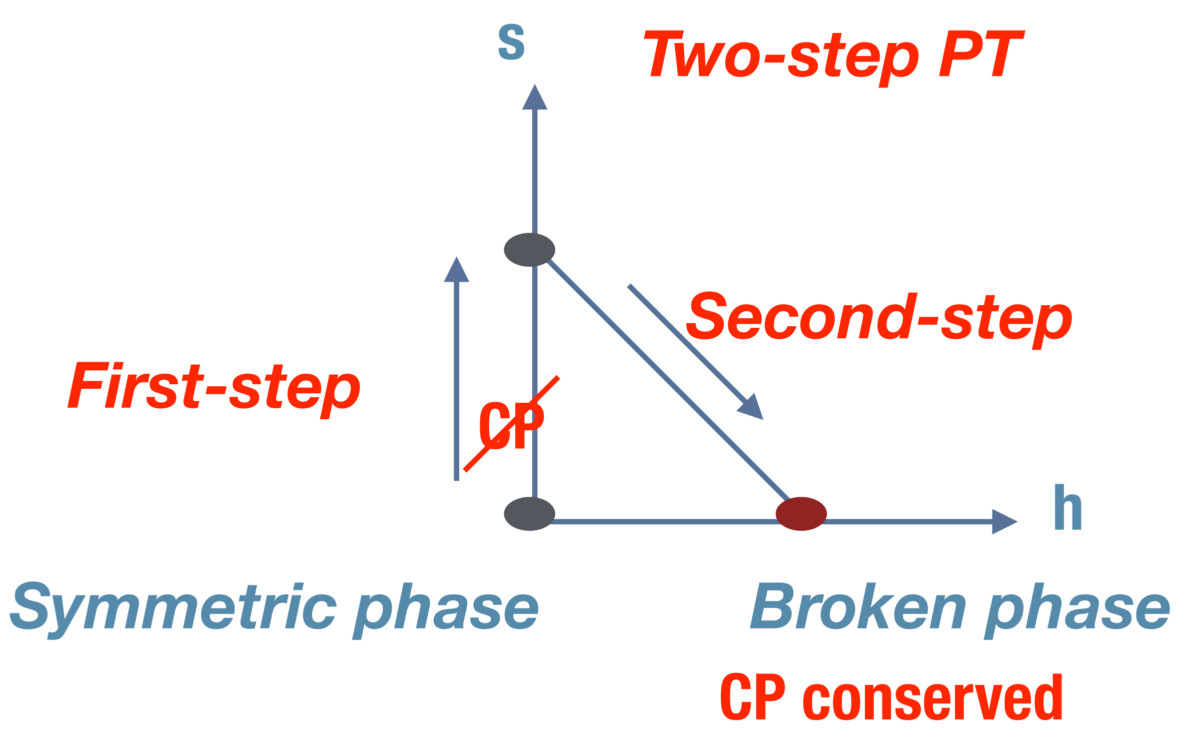
spontaneous CP violation in the theory of one complex scalar field may occur only when the related U(1) is explicitly broken by at least two spurions whose U(1) charges are different in magnitude

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

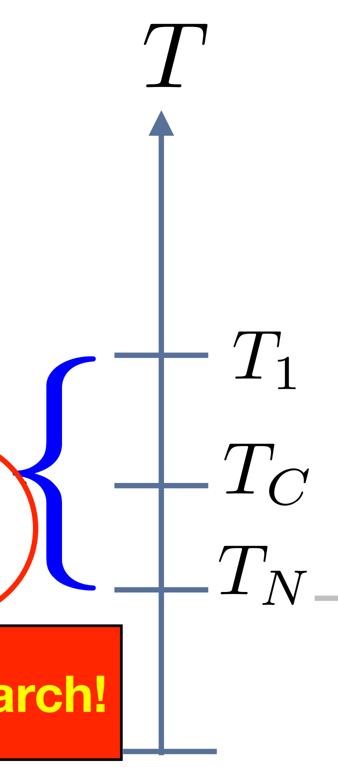
spurions

spurions

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



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



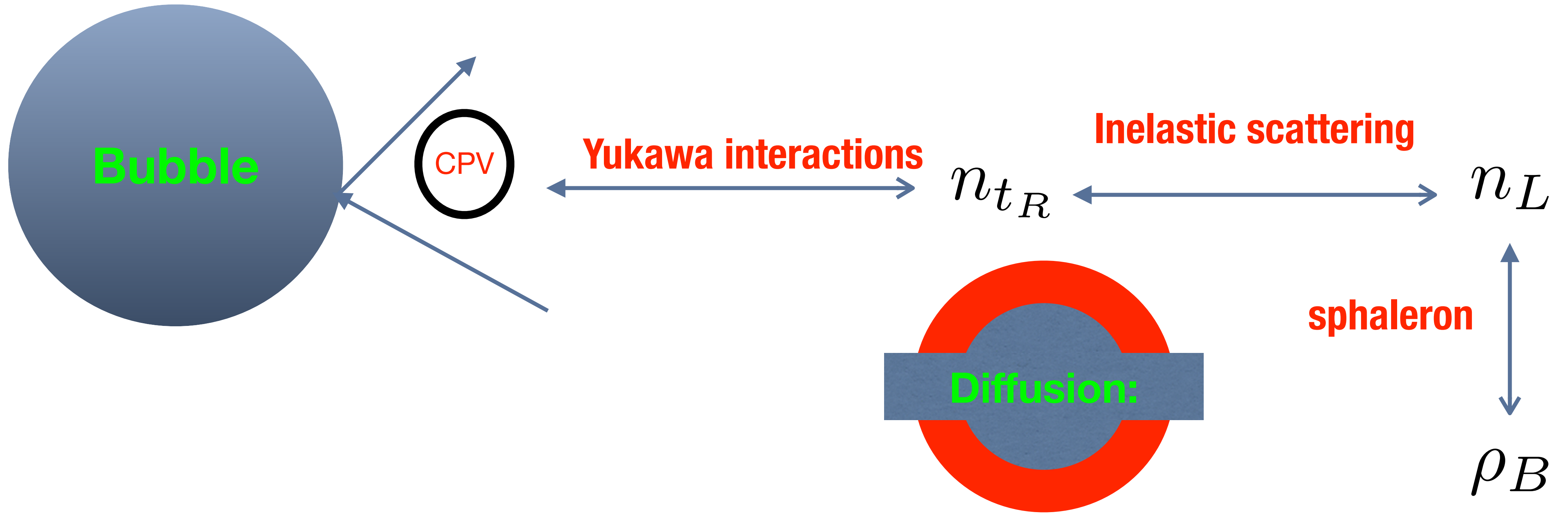
NO constraint of EDM and Higgs search!

EWBG

SM+ complex scalar singlets

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

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

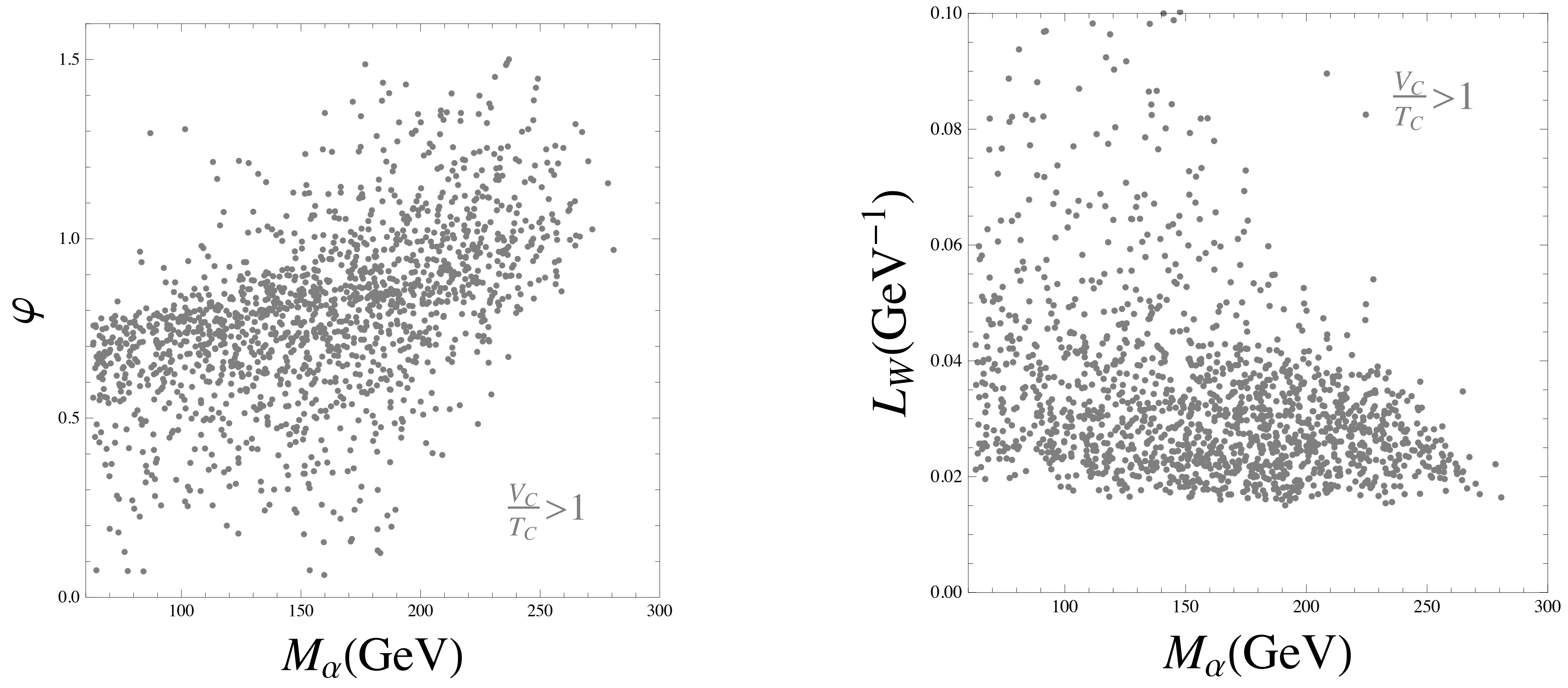


Transport equation: $\partial_t\rho_B(x) - D\bigtriangledown\rho_B(x) = -\Gamma_{\rm ws}F_{\rm ws}(x)[n_L(x) - R\rho_B(x)]$

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



EWBG

Transport EQ

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

Source

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

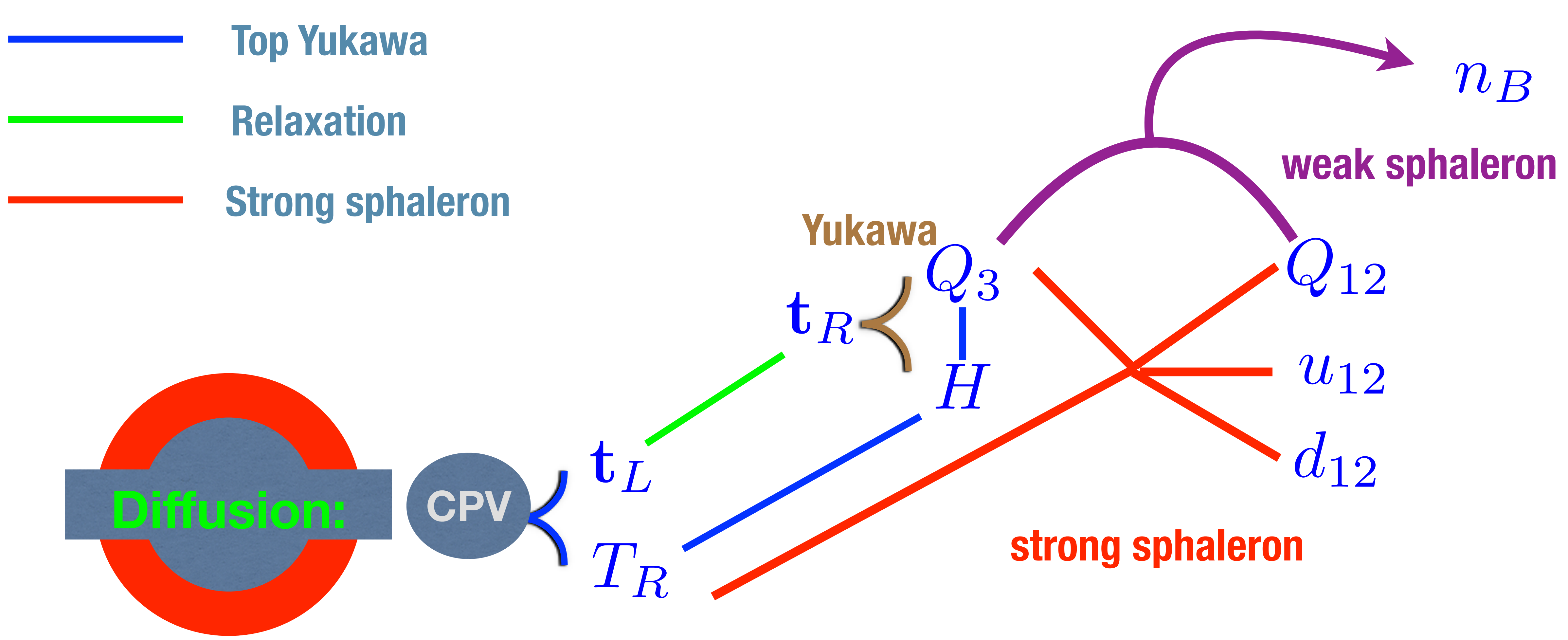
$$\zeta\overline{\mathfrak{t}_L}S\mathfrak{t}_R + (M_\mathfrak{t})\overline{\mathfrak{t}_L}\mathfrak{t}_R + \text{h.c.}$$

All equations

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

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

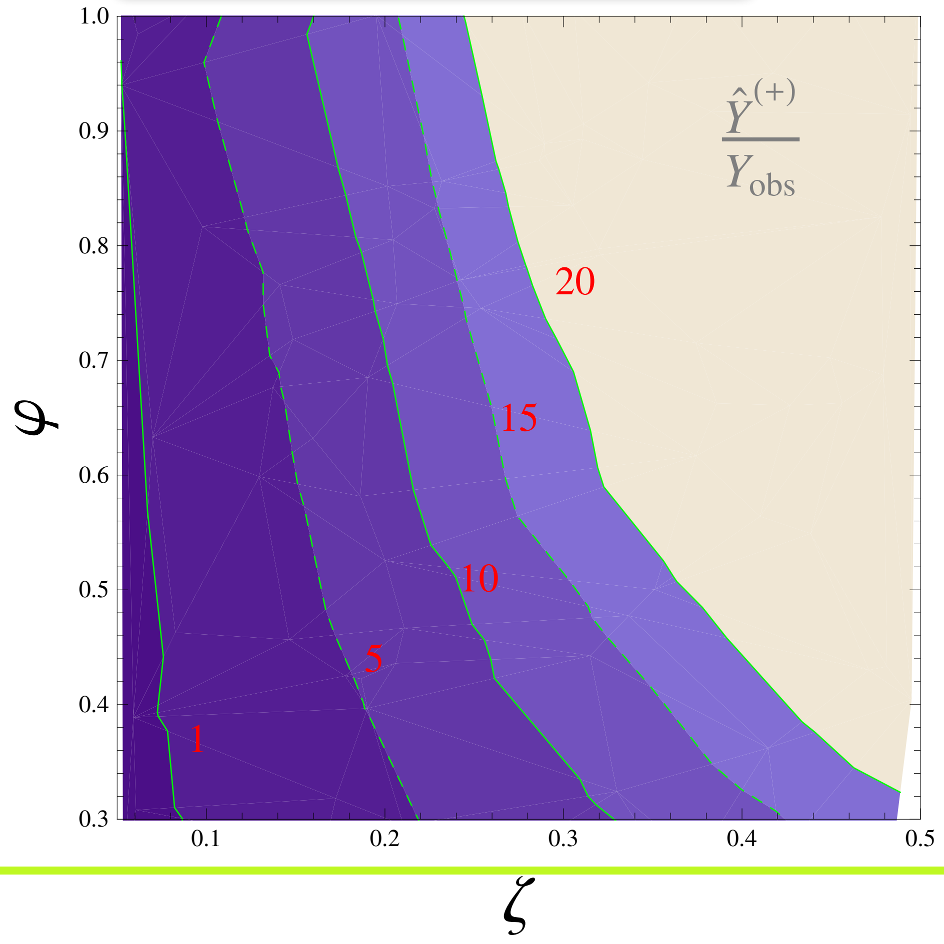
Problem $+\varphi$ + $-\varphi$ =0 ***No BAU left***

Domain wall must decays!

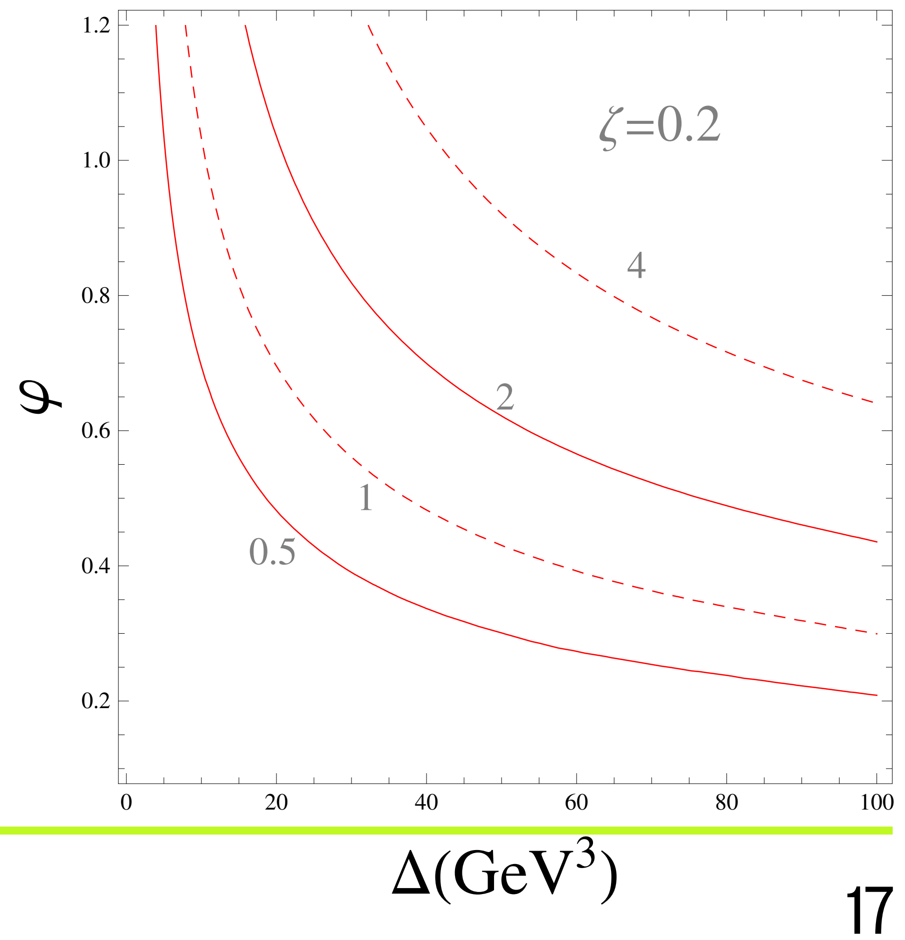
Solutions: Z2 breaking term, Δs+h.c.

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

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

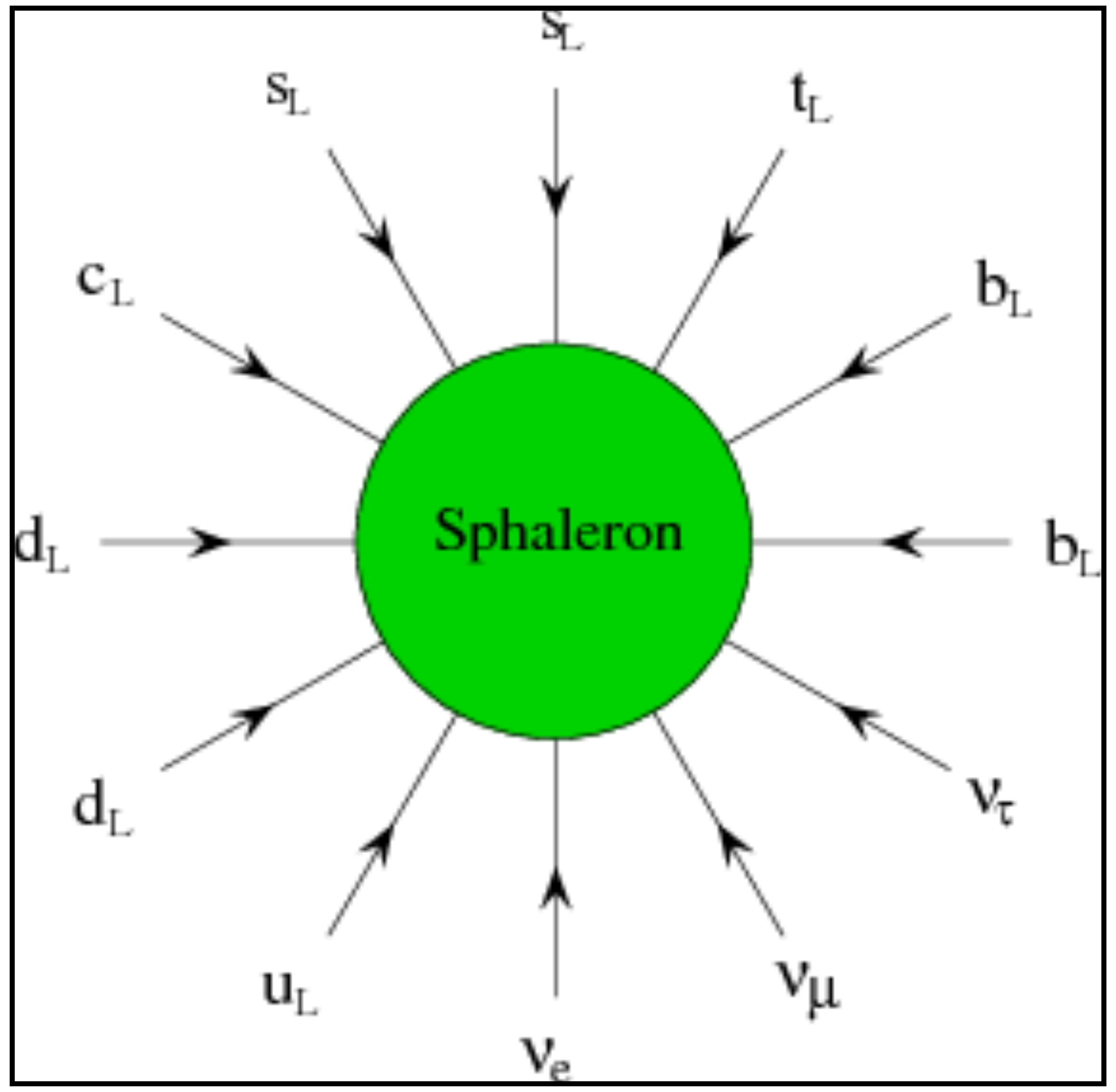


W. Chao PLB



Progress (2): EWBG via Symmetry non-restoration

Push the sphaleron to multi-TeV scale !



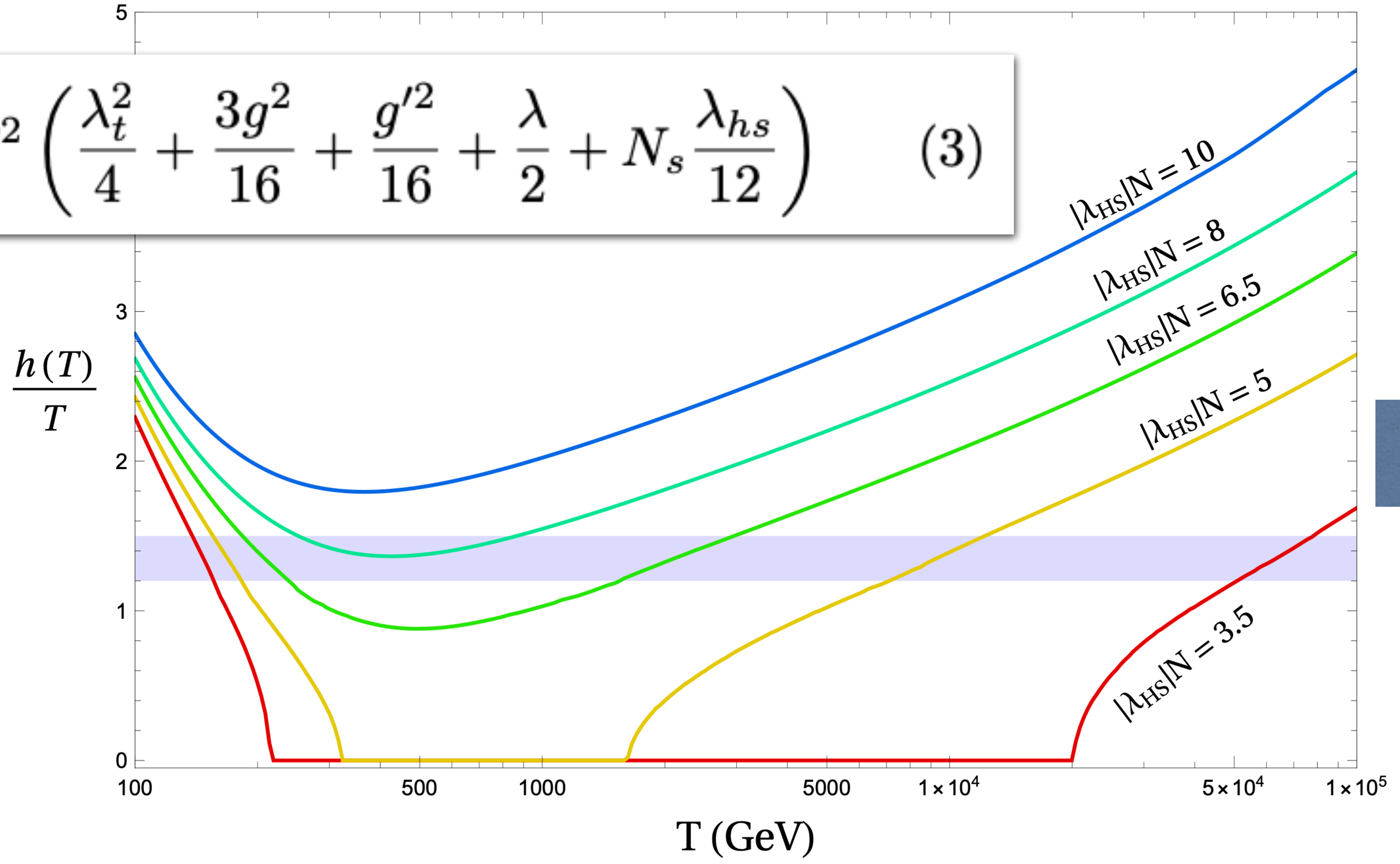
SM+scalars

Freeze-out temperature ～130 GeV

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

Conventional EWBG

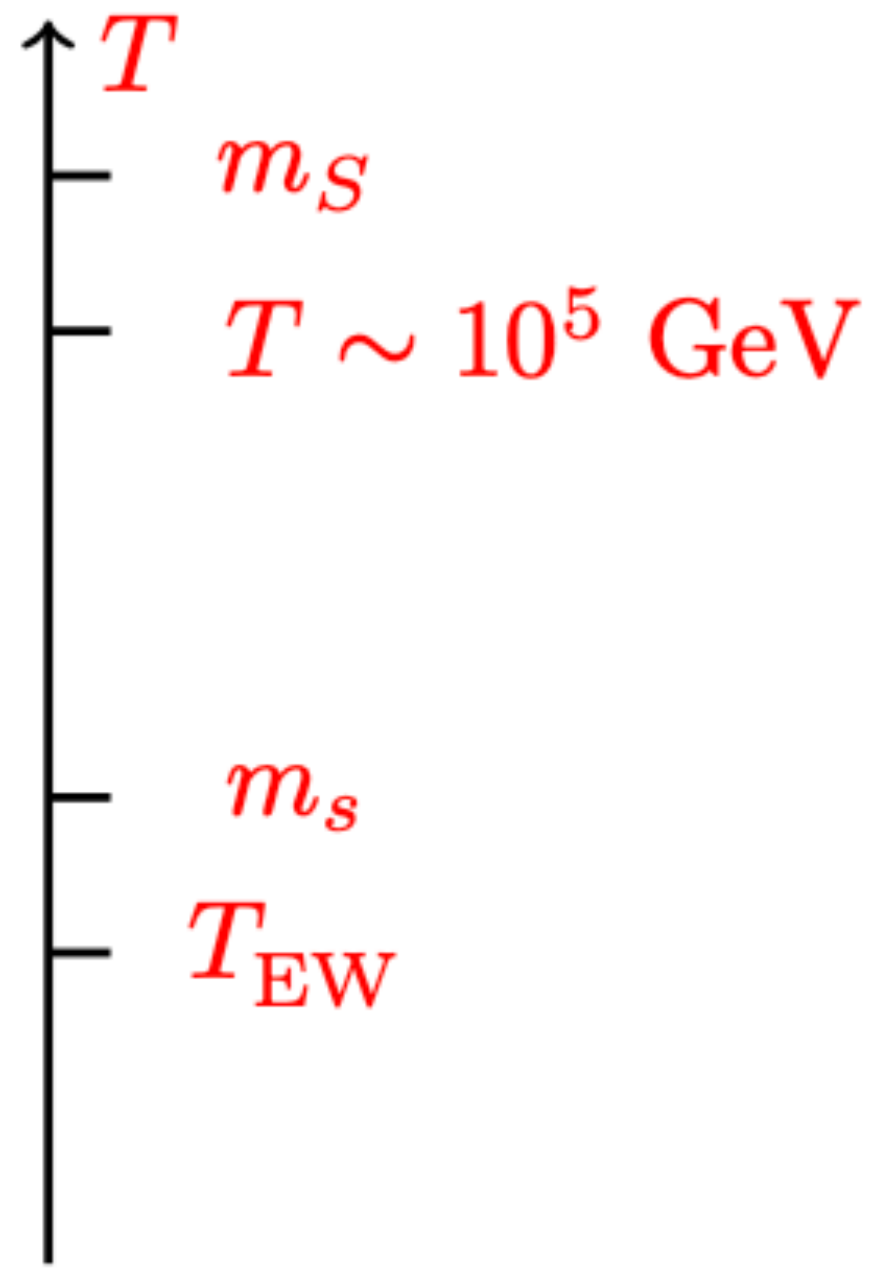
$$\Pi_h = T^2\left(\frac{\lambda_t^2}{4}+\frac{3g^2}{16}+\frac{g'^2}{16}+\frac{\lambda}{2}+N_s\frac{\lambda_{hs}}{12}\right) \qquad (3)$$



Heavy particle may lead to BAU via EWBG-like mechanism

Progress (2): EWBG via Symmetry non-restoration

Basic setup



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

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

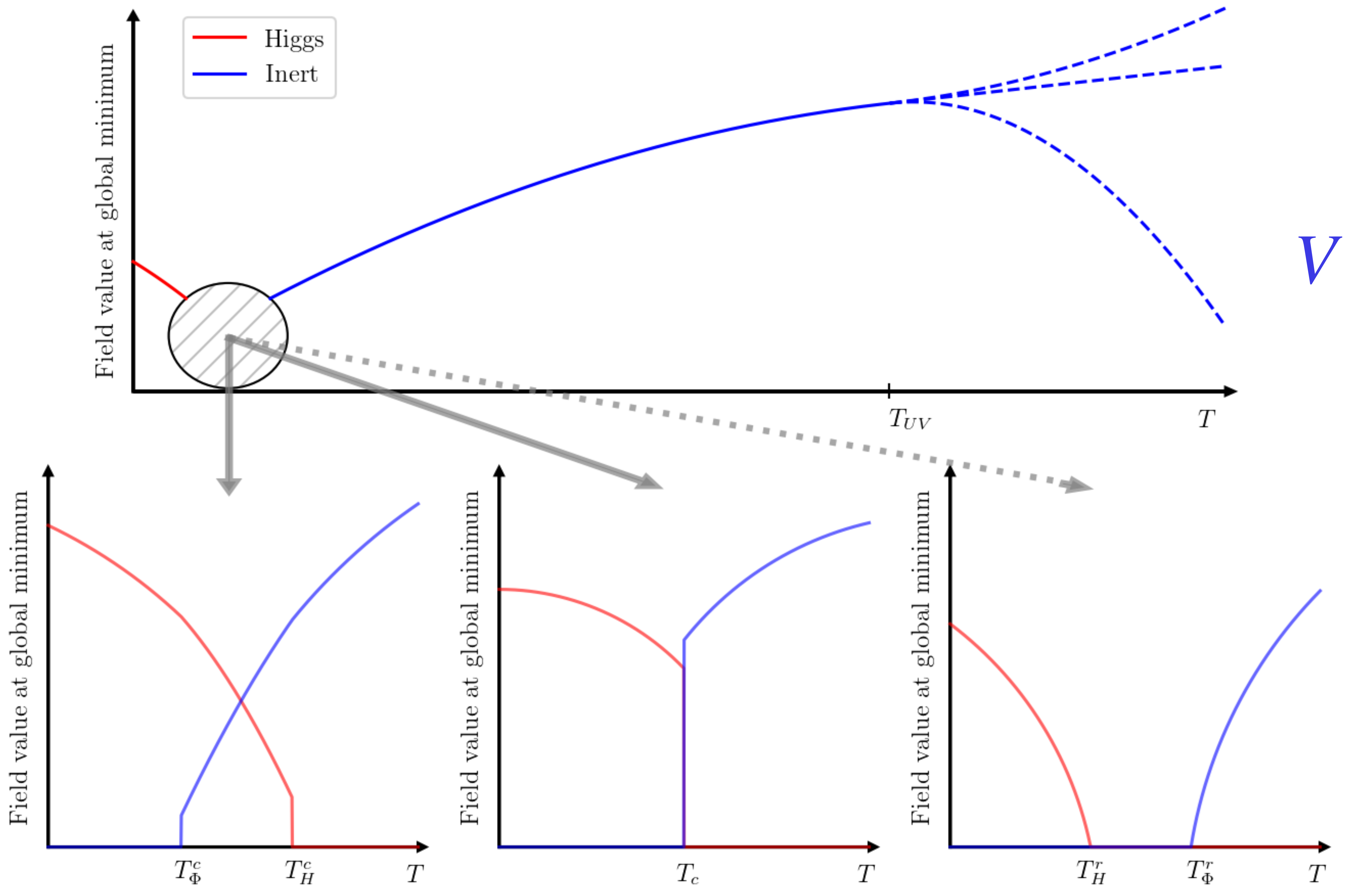
By requiring the SNR T to be 10^5 GeV:

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

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

$$V = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \mu_\Phi^2 (\Phi^\dagger \Phi) + \lambda_\Phi (\Phi^\dagger \Phi)^2$$

$$+\lambda_{H\Phi}(H^\dagger H)(\Phi^\dagger \Phi) + \cdots$$

$$+\frac{1}{2}\mu_i^2 \chi_i^2 + \frac{1}{4}\lambda_i \chi_i^4 + \frac{1}{2}\lambda_{\chi\Phi}^i \chi_i^2 (\Phi^\dagger \Phi)$$

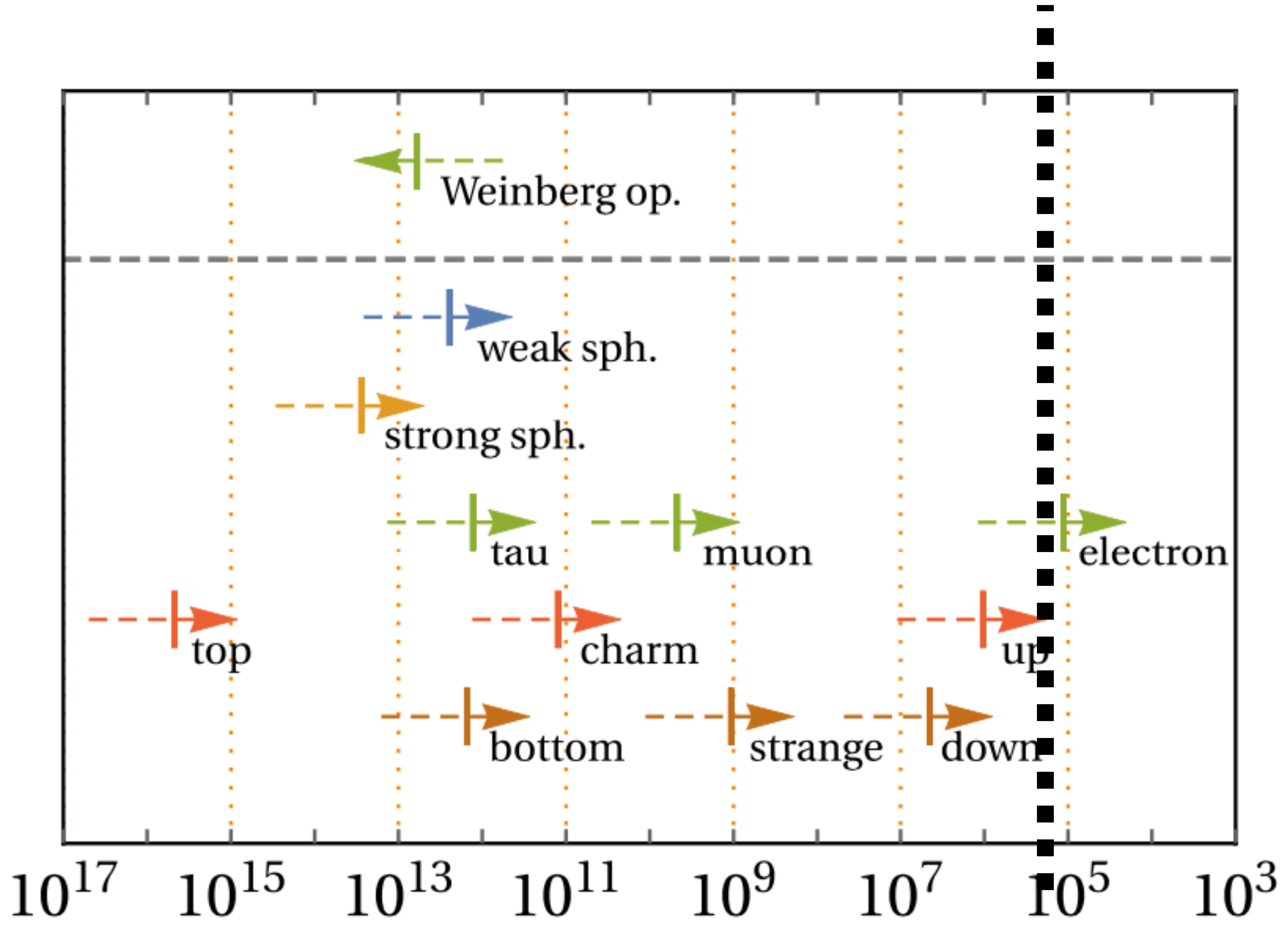
$$+\frac{1}{2}\lambda_{\chi H}^i \chi_i^2 (H^\dagger H) \quad or \quad \frac{1}{\Lambda}\bar{\psi}\psi(\Phi^\dagger \Phi)$$

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	$\kappa_W \frac{m_\nu^2 T^2}{v_{EW}^4}$	$\frac{1}{2}\kappa_{WS}\alpha_2^5$	$\frac{1}{2}\kappa_{SS}\alpha_3^5$	$\kappa_{Y_e} y_e^2$	$\kappa_{Y_e} y_\mu^2$	$\kappa_{Y_e} y_\tau^2$
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	$\kappa_{Y_u} y_u^2$	$\kappa_{Y_u} y_c^2$	$\kappa_{Y_t} y_t^2$	$\kappa_{Y_d} y_d^2$	$\kappa_{Y_d} y_s^2$	$\kappa_{Y_d} y_b^2$
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}

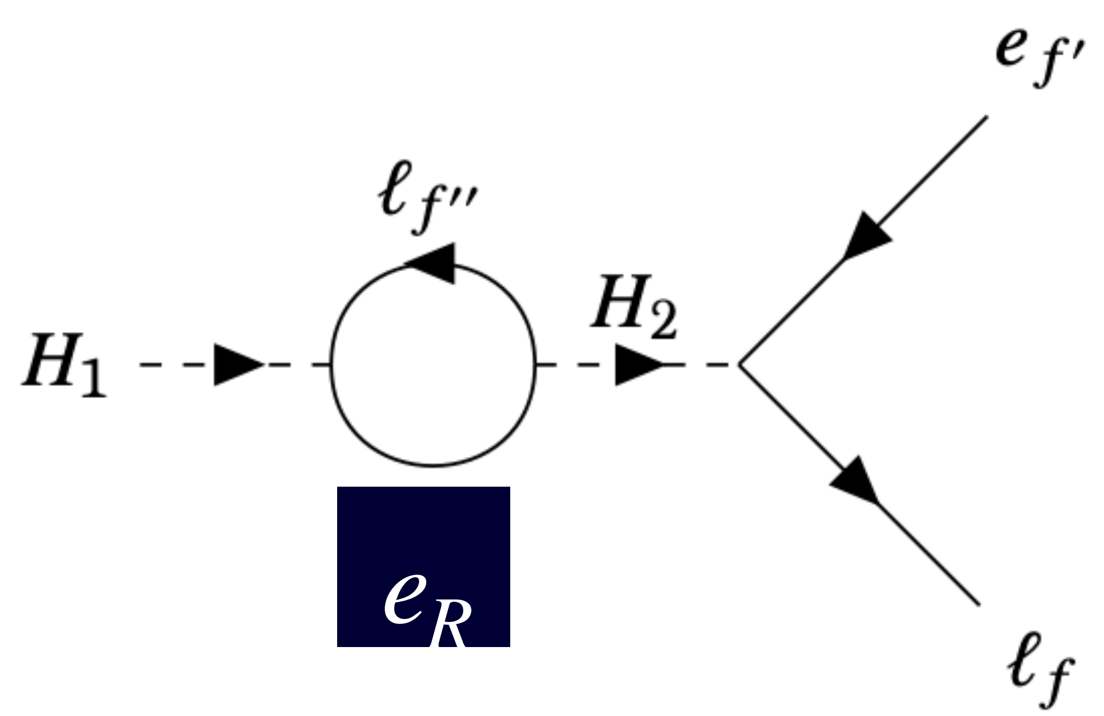
Valerie Domck, Yohei Ema, Kyohei Mukai and Masaki Yamada, JHEP 08(2020)096



* 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**



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

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

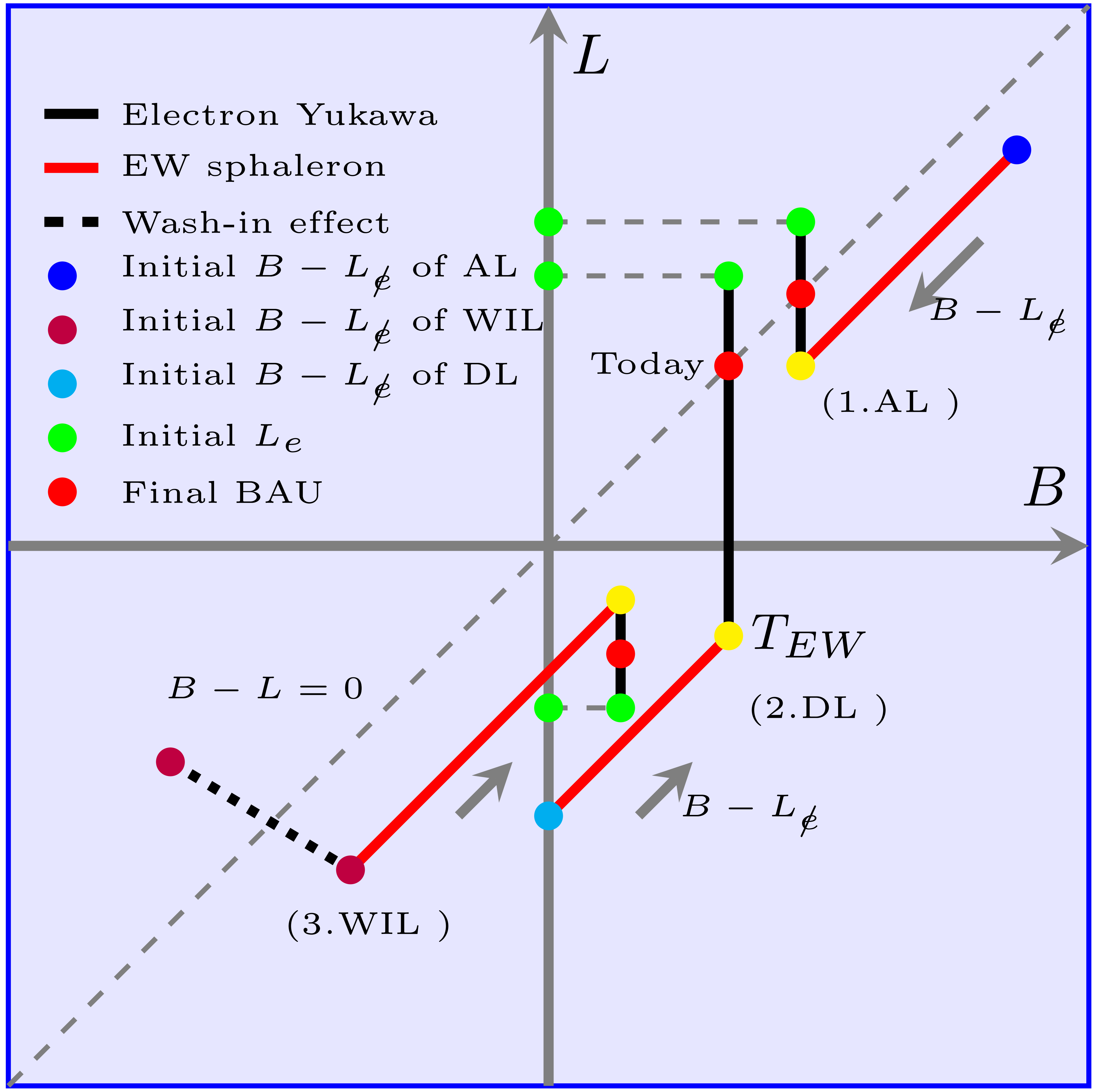
Progress (3): BAU via Symmetry non-restoration

- **Transport equation**

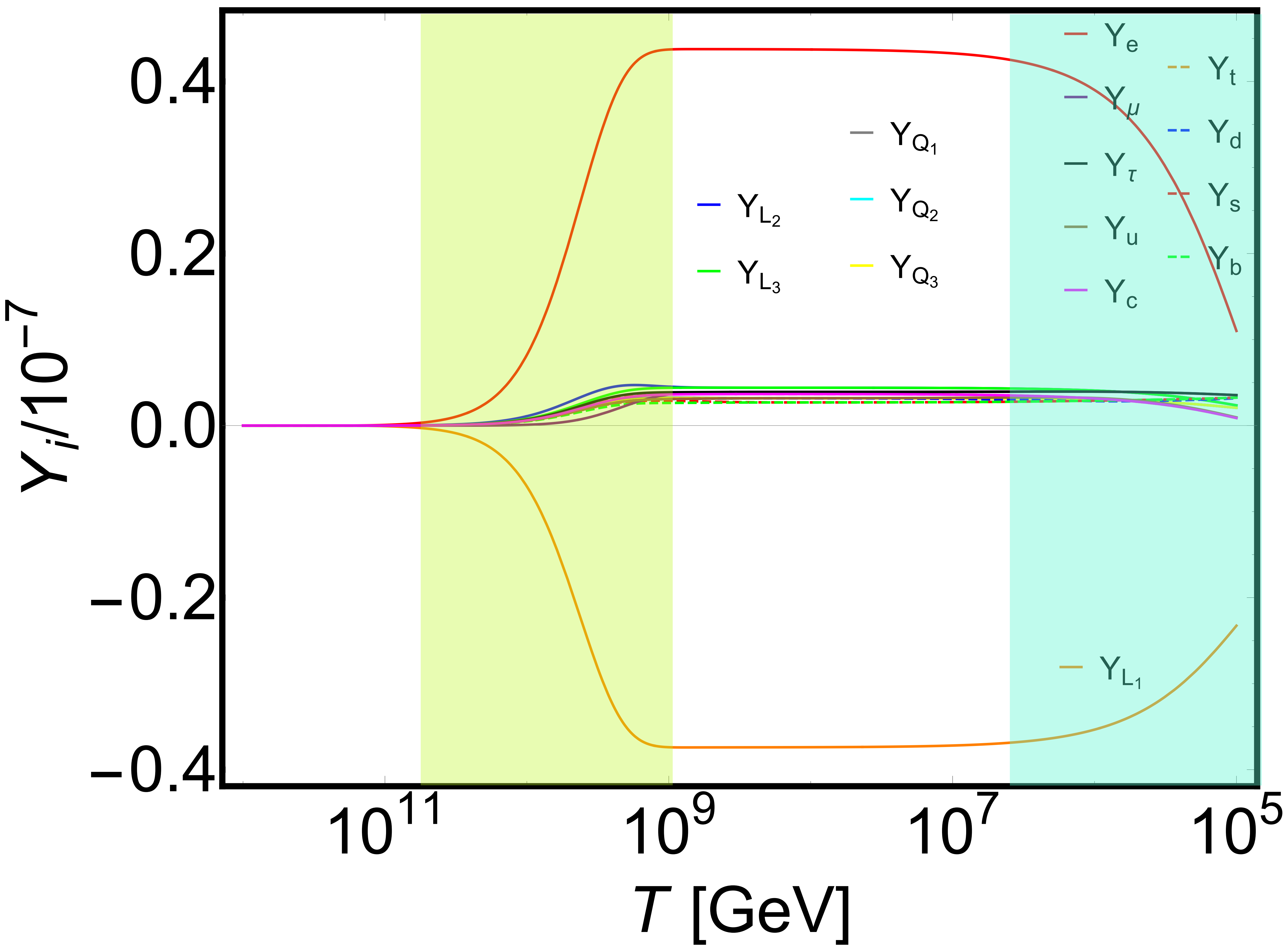
$$-\frac{d}{d\ln T}\left(\frac{\mu_{L_k}}{T}\right) = -\frac{1}{g_{L_k}}\frac{\gamma_{\rm WS}}{H}\left[\sum_{i=1}^{3}\left(\frac{\mu_{L_i}}{T}+3\frac{\mu_{Q_i}}{T}\right)\right] -\frac{1}{g_{L_k}}\frac{\gamma_{Y_{E_k}}}{H}\left(-\frac{\mu_{E_k}}{T}+\frac{\mu_{L_k}}{T}-\frac{\mu_H}{T}\right) +\frac{1}{g_{L_k}}\frac{4\pi^2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

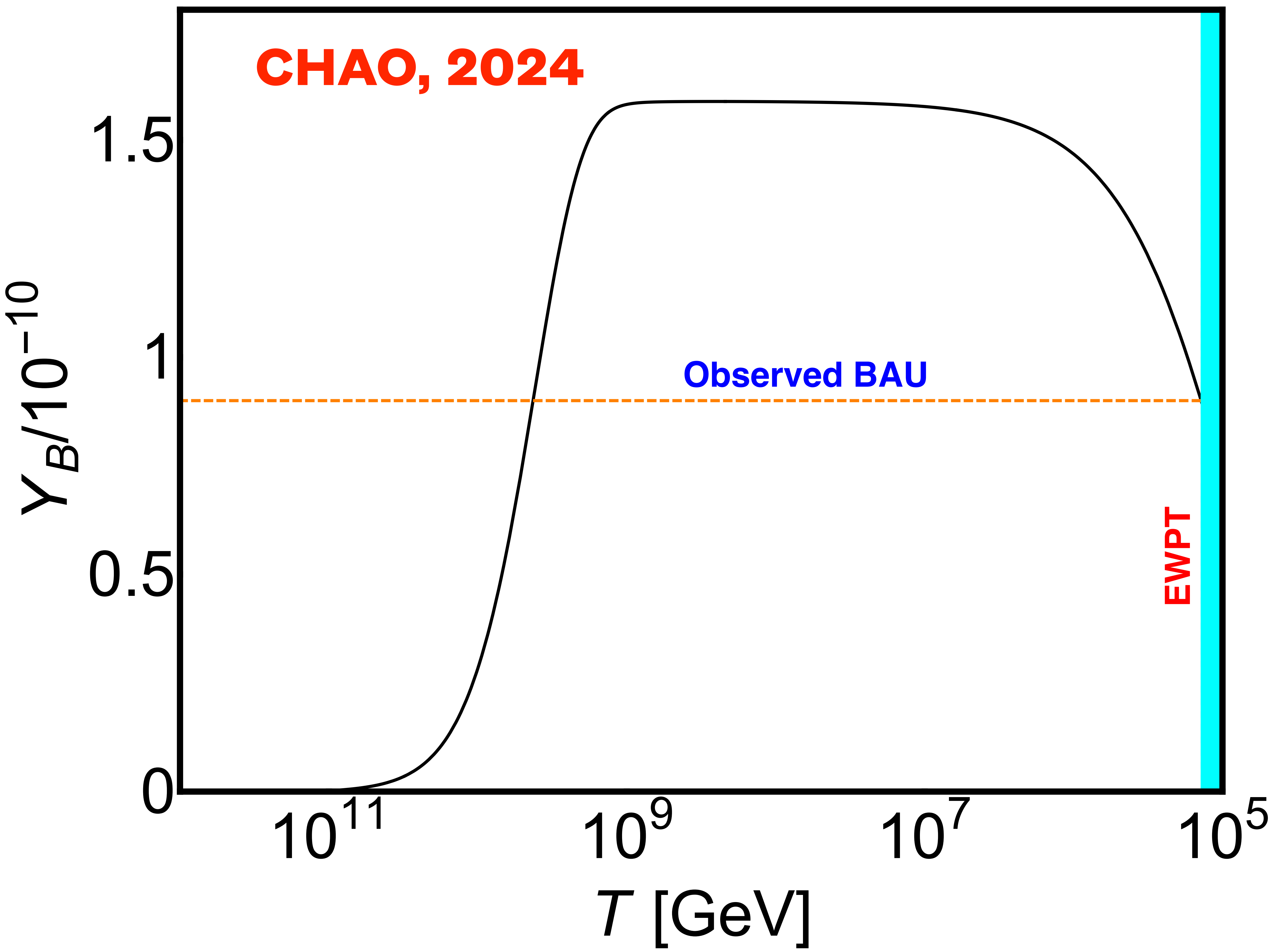
- **BAU**

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



Progress (3): BAU via Symmetry non-restoration

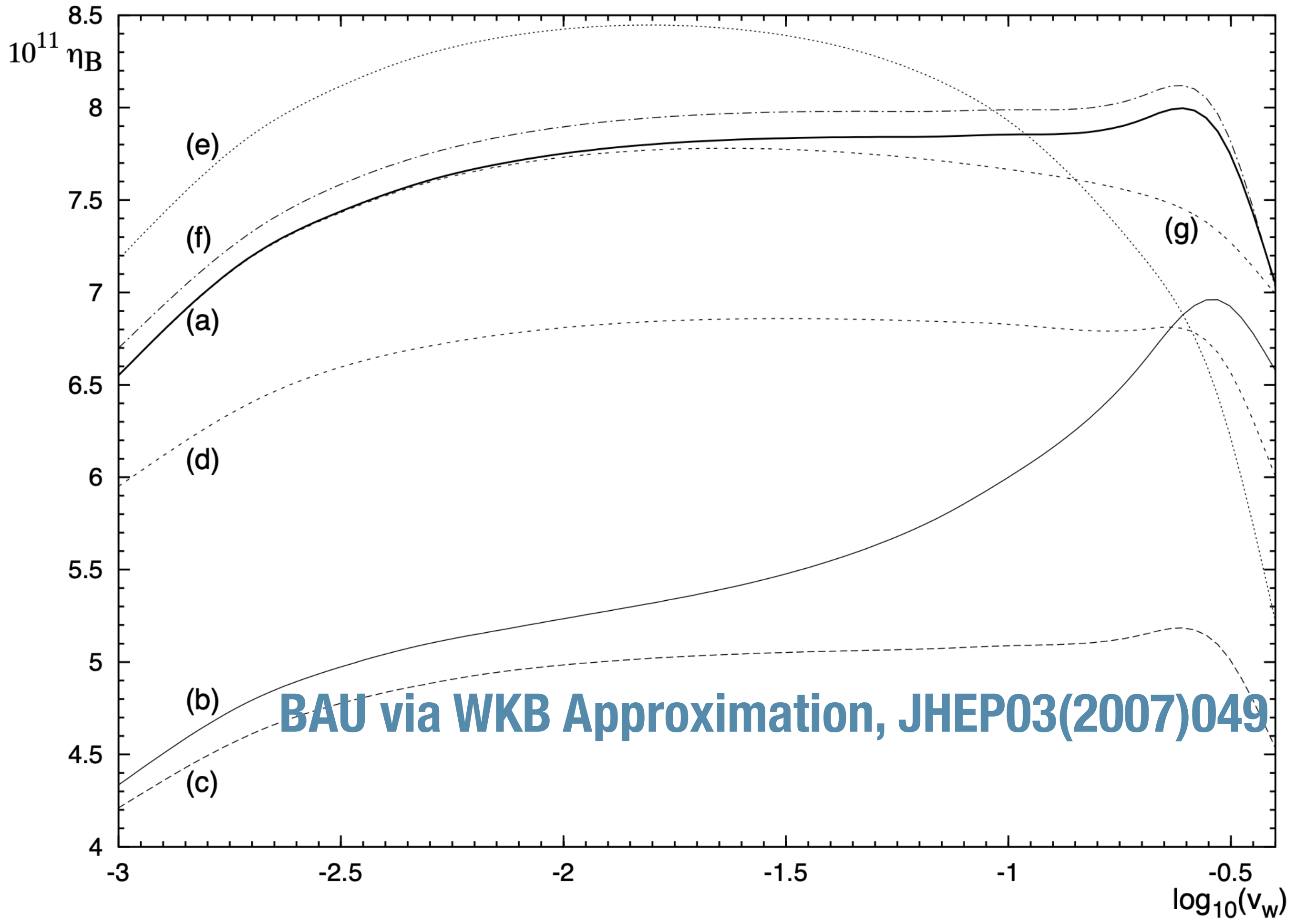




Progress (4): Calculation methods of EWBG

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

Bubble collision	$h^2\Omega_{\rm coll}(f) = 1.67\times10^{-5}\left(\frac{H_n}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac13}\times\left(\frac{0.11v_w^3}{0.42+v_w^2}\right)\left[\frac{3.8(f/f_{\rm coll})^{2.8}}{1+2.8(f/f_{\rm coll})^{3.8}}\right],$
Sound wave	$h^2\Omega_{\rm sw}(f) = 2.65\times10^{-6}\left(\frac{H_n}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac13}\times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left[\frac{7}{4+3(f/f_{\rm sw})^2}\right]^{7/2}$
MHD turbulence	$h^2\Omega_{\rm turb}(f) = 3.35\times10^{-4}\left(\frac{H_n}{\beta}\right)\left(\frac{\kappa_{\rm tu}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*}\right)^{\frac13}\times v_w\frac{(f/f_{\rm tu})^3}{(1+f/f_{\rm tu})^{11/3}(1+8\pi f/h_n)}$



BAU via WKB Approximation, JHEP03(2007)049

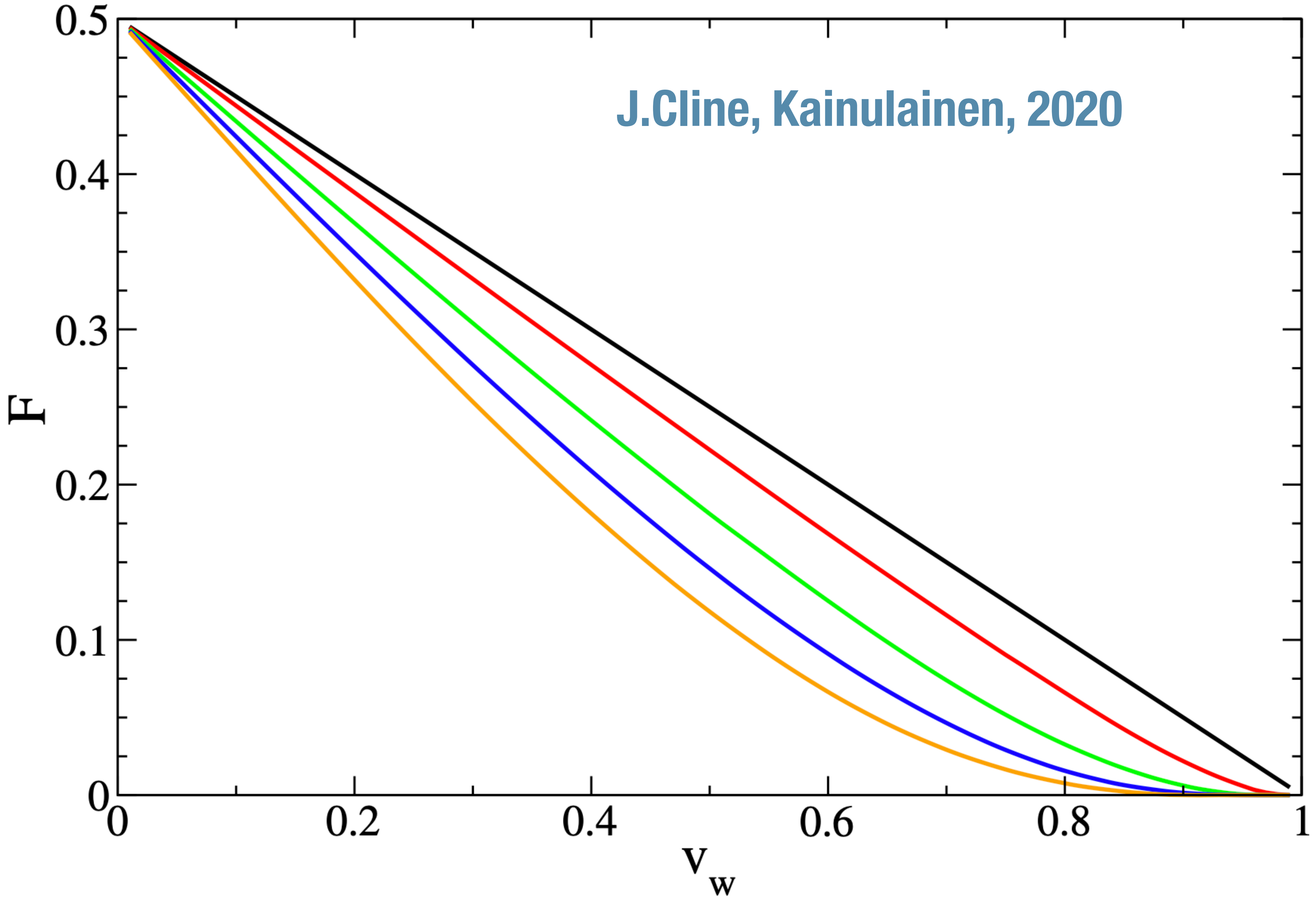
$$M^2_{ij}(y) = M^2_{ij}(x) + (x-y)^\mu\partial_\mu M^2_{ij}(x)$$

Valid in slowly varying bubble wall background

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

BAU via the VEV insertion method

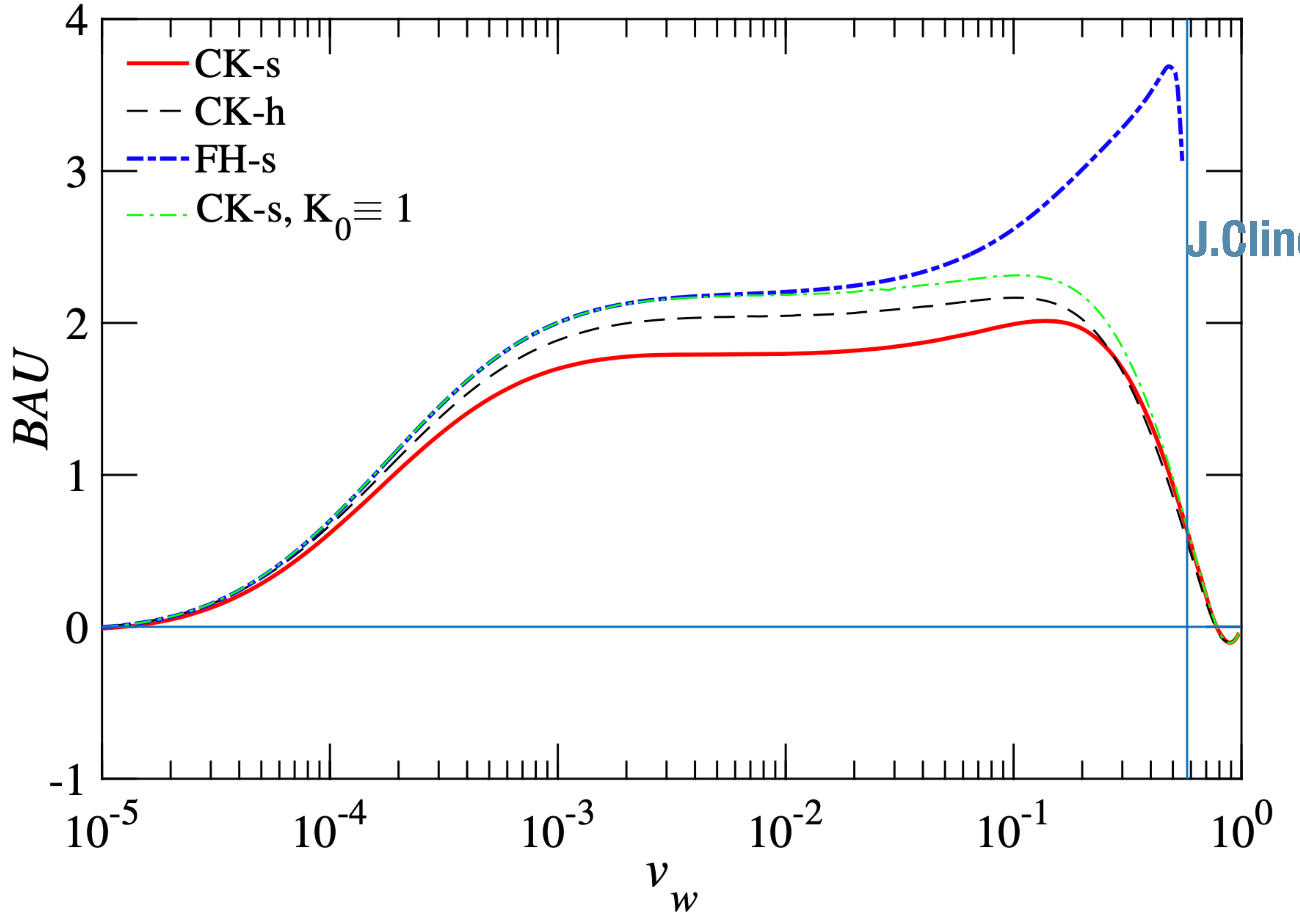
Physics relevant: fraction of plasma that can stay ahead of a bubble wall velocity.



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

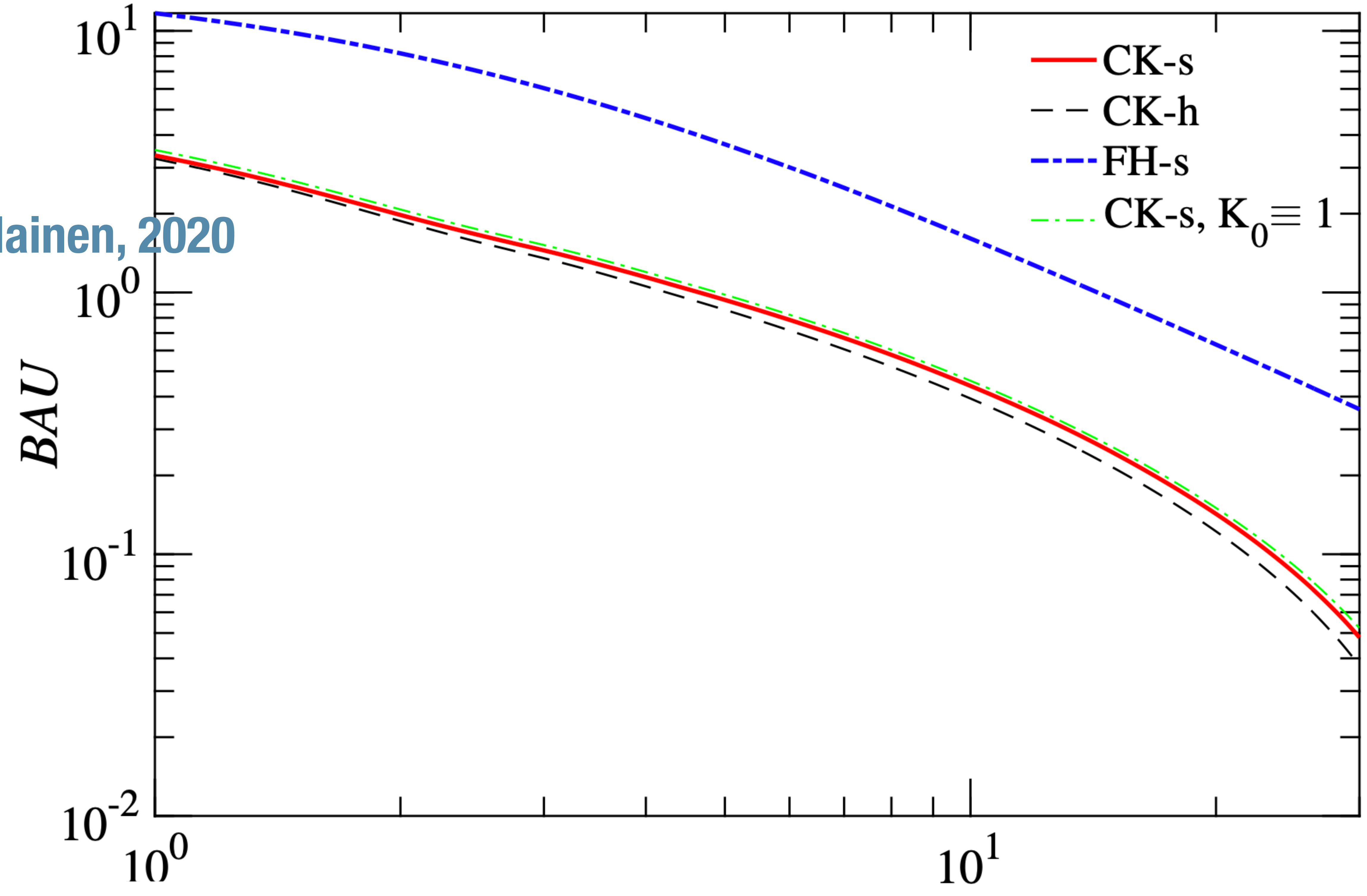
Progress (4): Calculation methods of EWBG

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



J.Cline, Kainulainen, 2020

Top triggered EWBG+two-step EWPT:



$$y_t h(z)\bar{t}_L \left(1 + i\frac{s(z)}{\Lambda}\right) t_R + \text{H.c.},$$ $L_w T$

Progress (4): Calculation methods of EWBG

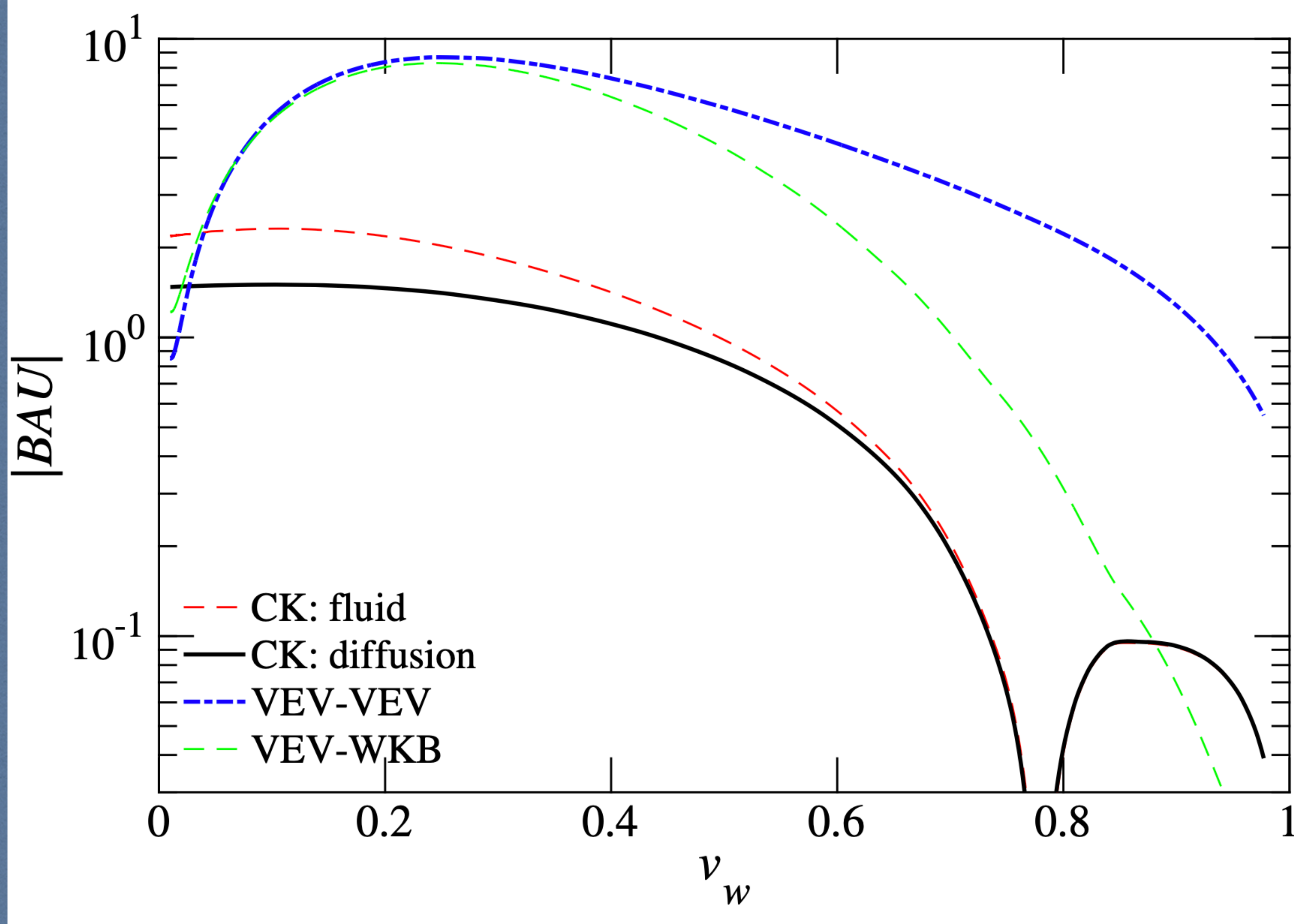
EWBG via the WKB approximation vs via the “VEV-insertion” method

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.



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

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

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

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

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

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

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

Calculations via the KB equation are open question!

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

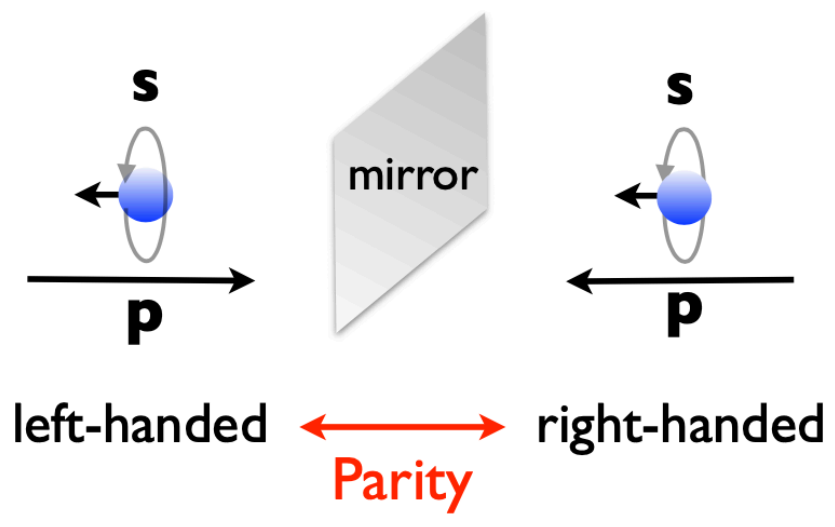
Progress (5): Chiral Magnetic Effect

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!**

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

Chirality of fermions



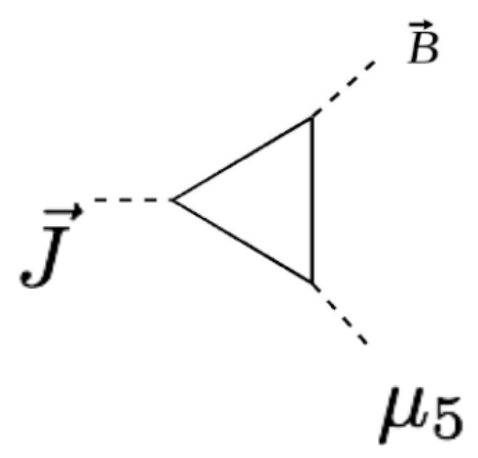
In the presence of a parity odd quantity, electric current can be induced!

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

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

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

- **Maxwell equations**

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

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

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**

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

- **EOM**

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

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

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 babble wall.**
- **Magnetogenesis:** $\Delta N_{CS}^Y \neq 0$ — **No other source term**
- **A third scenario:** $\Delta N_{CS}^Y = 0 \; \& \; B \neq 0$ — **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.

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

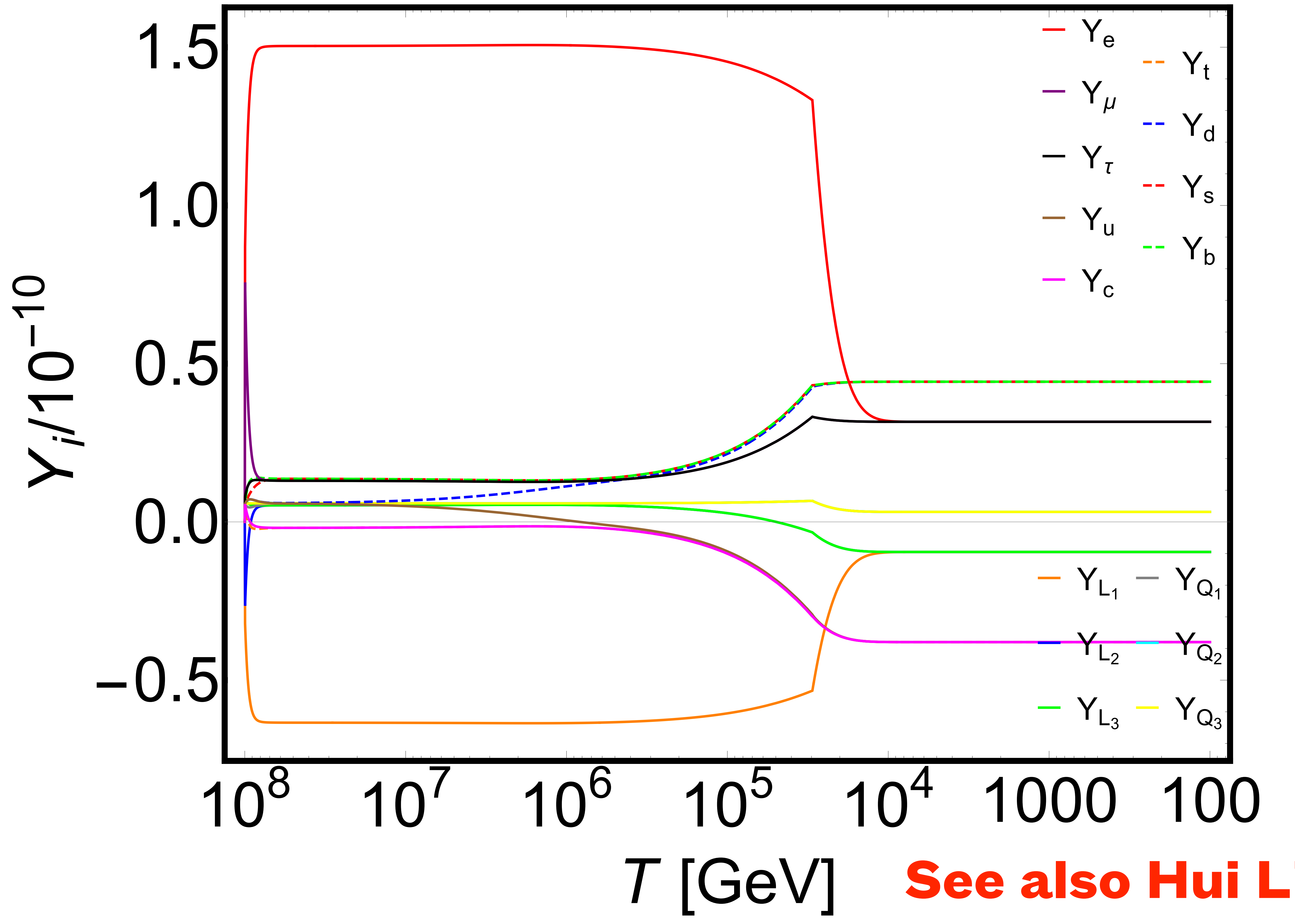
$$\frac{d}{d\ln T}\left(\frac{\mu_{L_i}}{T}\right)=+\frac{1}{g_{L_i}}\frac{\gamma_{E_i}}{H}\left(\frac{\mu_{E_i}}{T}-\frac{\mu_{L_i}}{T}+\frac{\mu_H}{T}\right)-\frac{1}{g_{L_i}}\frac{2\gamma_{WS}}{H}\left[\sum_i\frac{\mu_{L_i}}{T}+3\sum_i\frac{\mu_{Q_i}}{T}\right]-\frac{6}{g_{L_i}}\frac{\alpha}{2\pi}\frac{\partial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

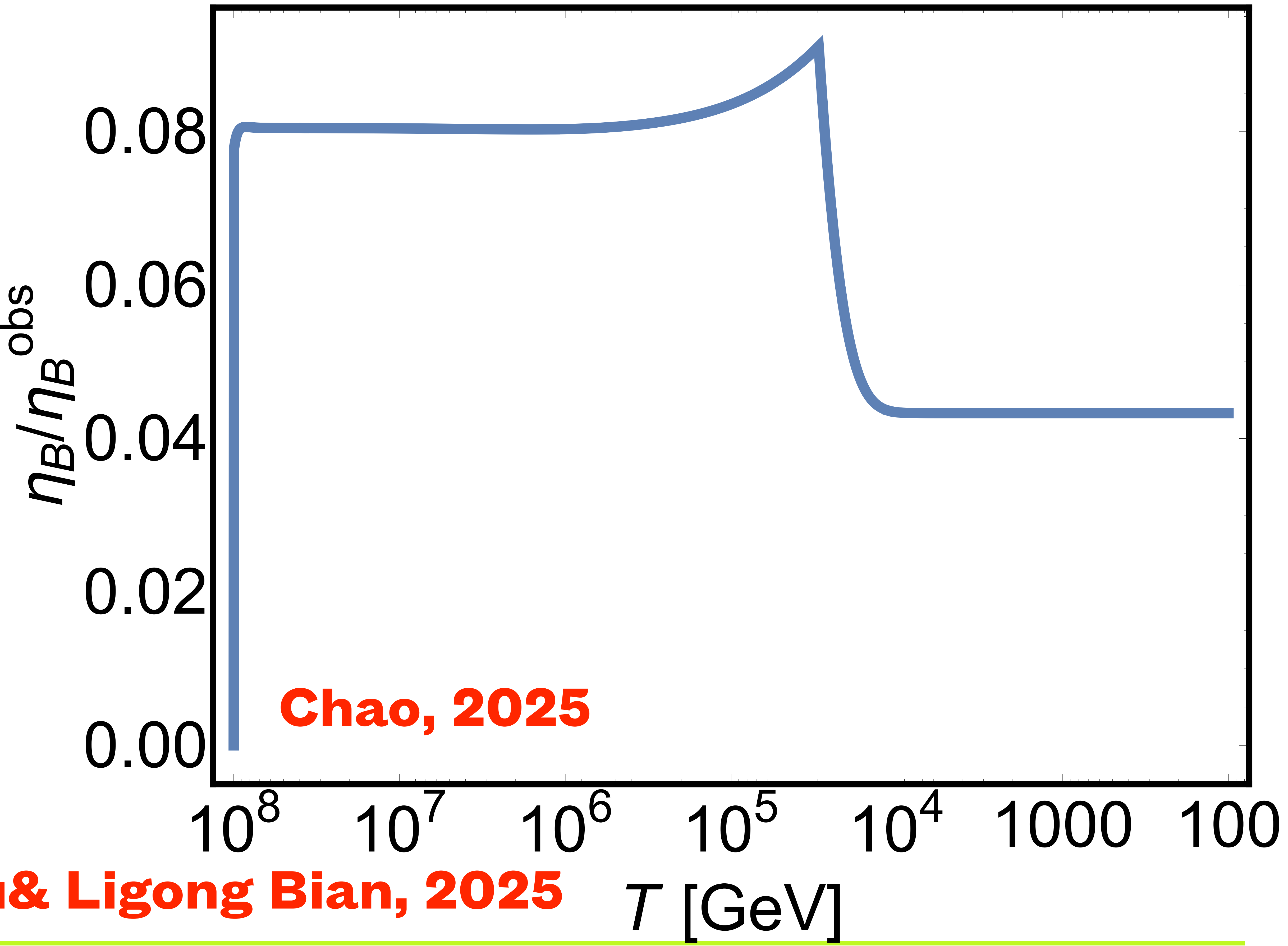
$$-T\frac{\partial h_k}{\partial T}=-\frac{2k^2}{\sigma_0}\frac{T}{H}h_k+\frac{8\alpha}{\pi\sigma_0}\left(\frac{C^Y_{CS}}{T}\right)\frac{T}{H}\rho_k$$

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

Progress (5): Chiral Magnetic Effect

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

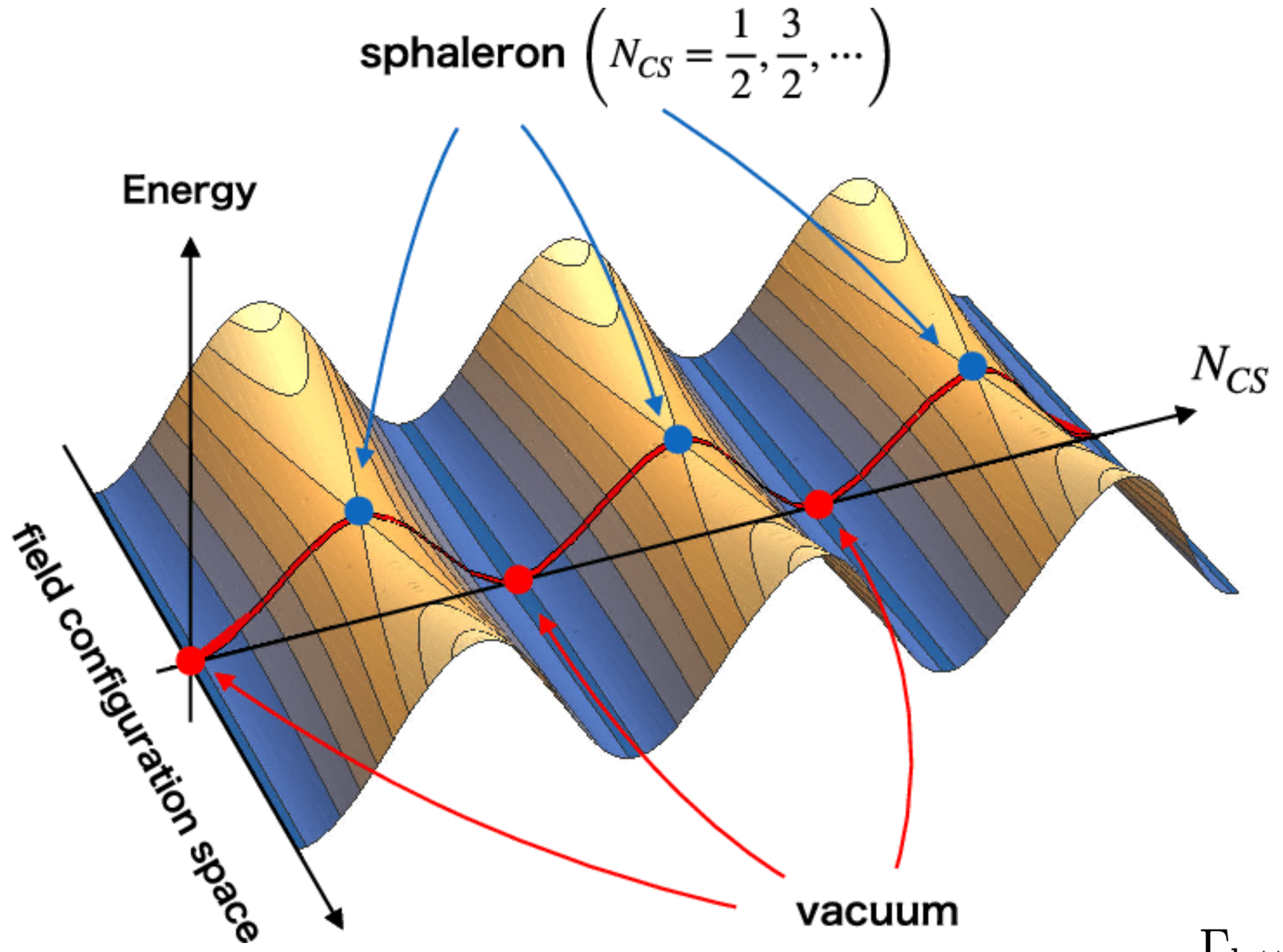




See also Hui Liu& Ligong Bian, 2025

Progress (6): BAU 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** $T_{\text{EW}} = (159.5 \pm 1.5)\ GeV$
- **Sphaleron decouple** $T_{\text{FO}} = 130\ GeV$

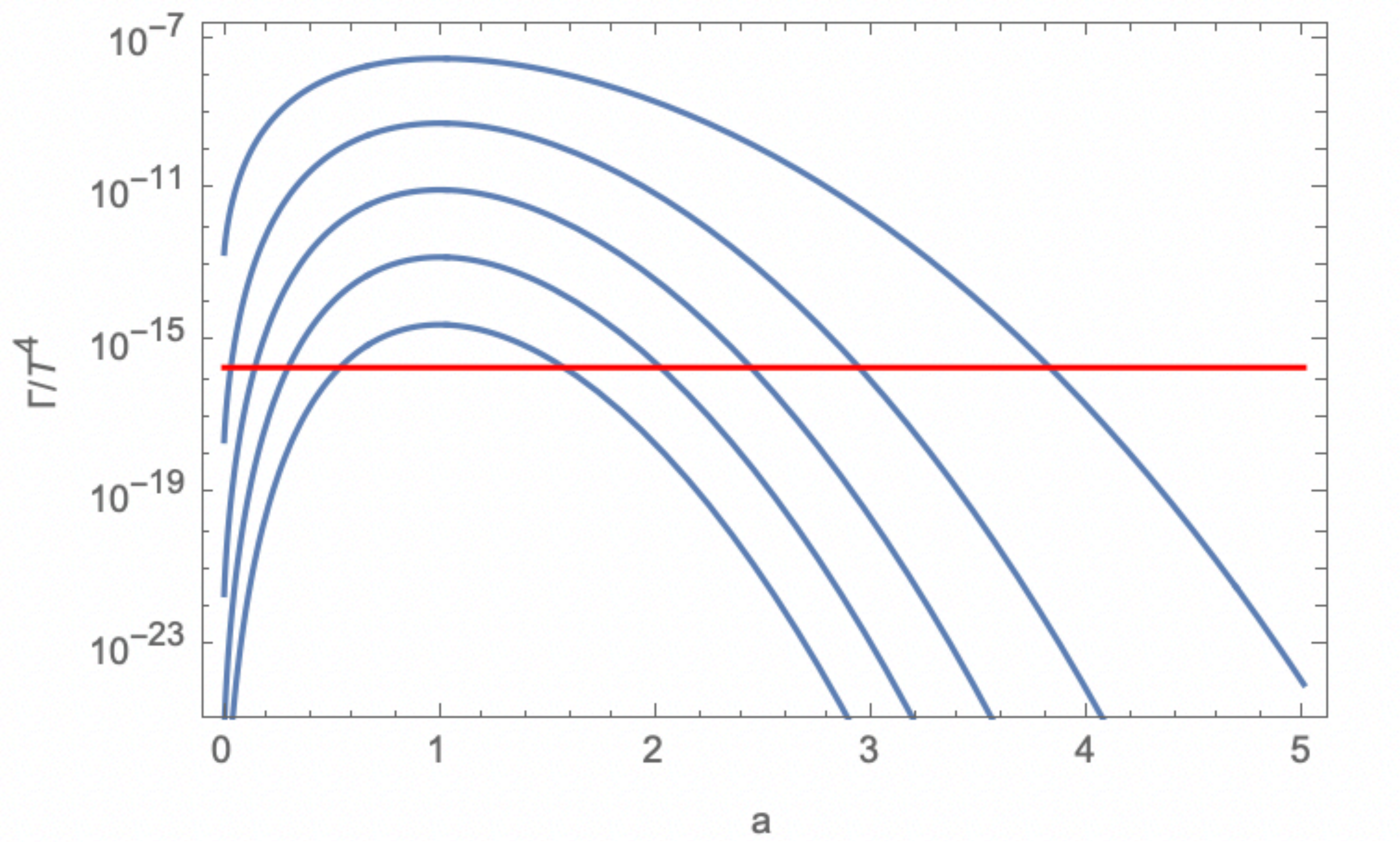
- **Sphaleron rate with size factor** a

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

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

Progress (6): BAU without the first order EWFT

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



CPV induced transition asymmetry at the sphaleron decoupling sector:

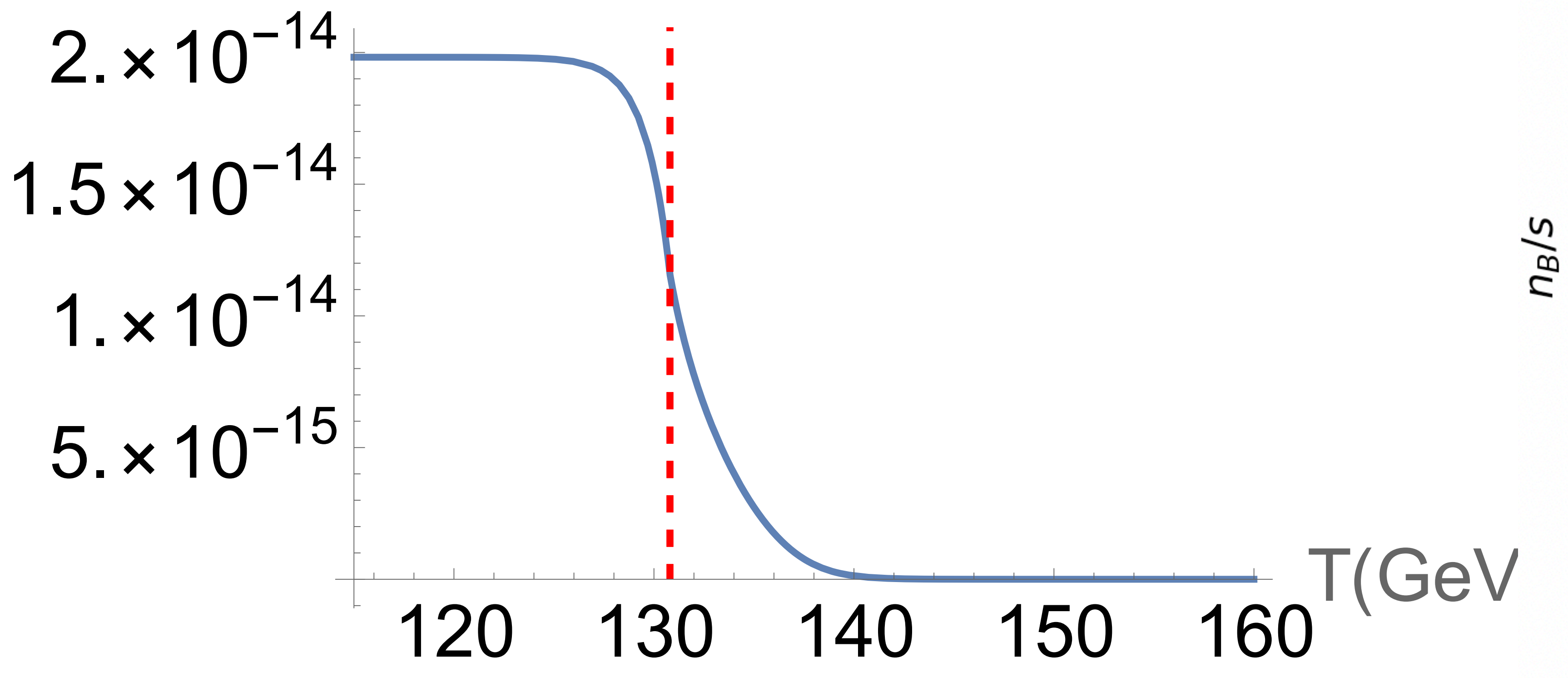
$$A_{\rm CP} \sim 2.5 \times 10^{-10}$$

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

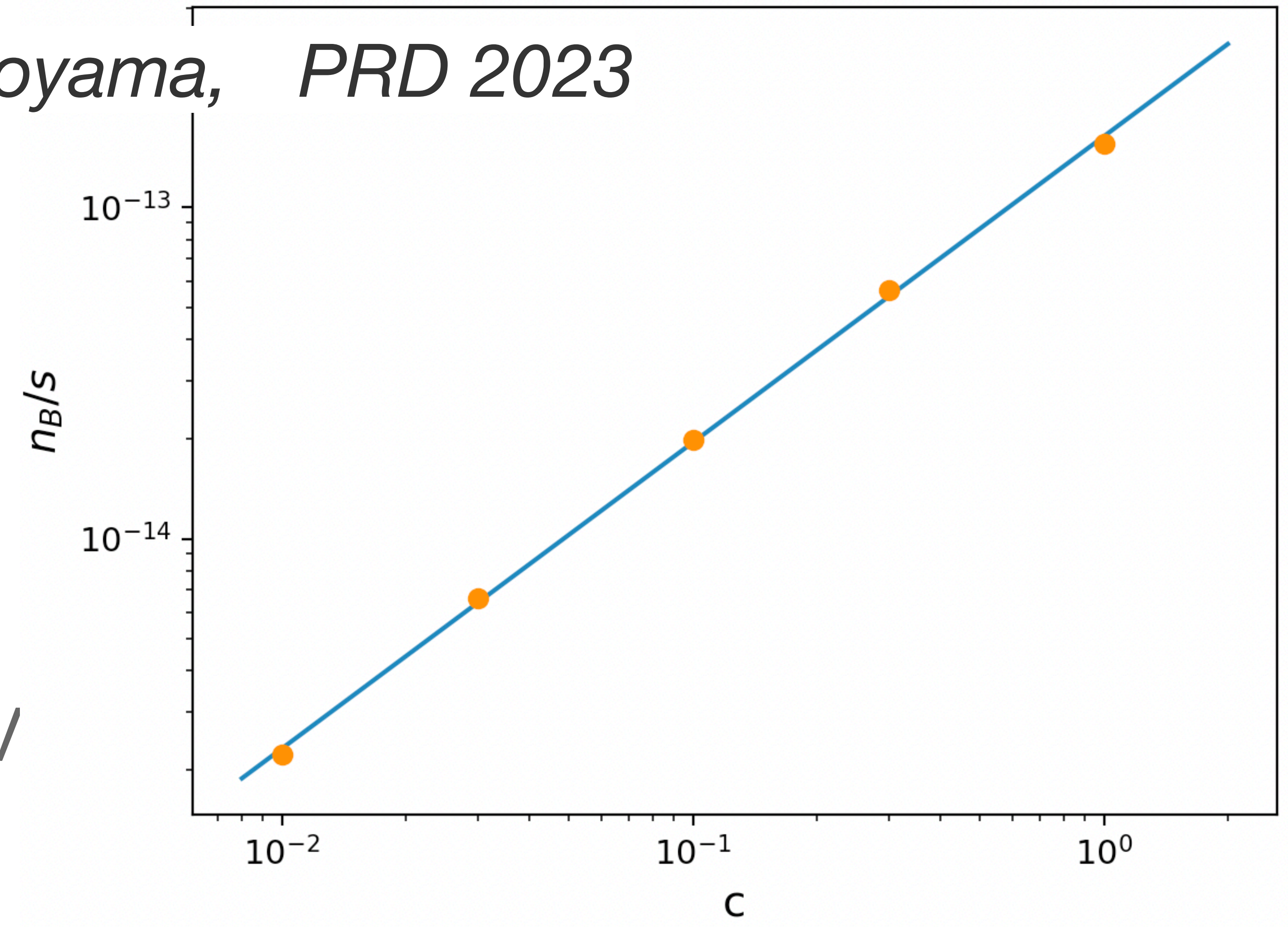
Source term induced by decoupled sphaleron size sector

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

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



Hong, Kamada, Yokoyama, PRD 2023



Baryogenesis Summary

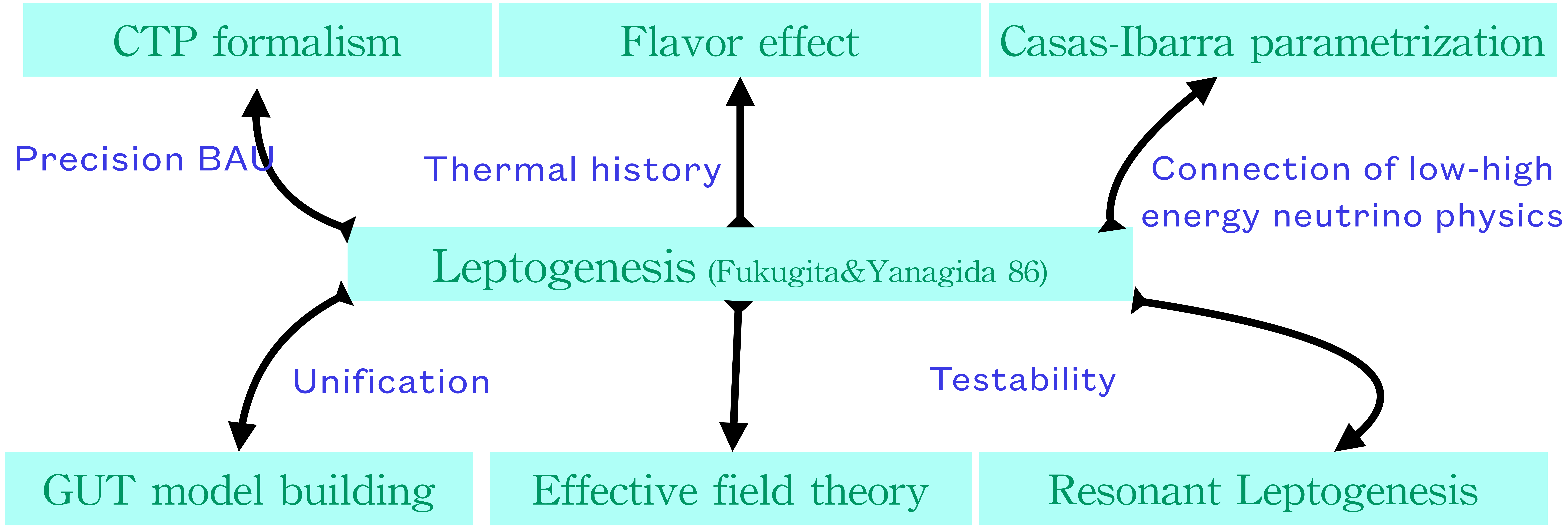
80s~90s	BAU via first oder phase transition and SM CP violation
90s~10s	EWBG in MSSM
10s~20s	Constrains on EWBG from Higgs physics and EDM
15s~20s	EWBG VS stochastic GW signals (PT dynamics)
20s~now	Diverse investigations of Baryogenesis

Thank you for your attention!

Backup sildes

- Leptogenesis
  - History of Leptogenesis
  - Recent progress
  - Testability of Leptogenesis

History and development: Leptogenesis



1986~2016

Gravitational Leptogenesis

Framework

- Gravitational chiral anomaly: $$\partial_\mu j^\mu_L = \frac{A}{16\pi^2} R\tilde{R}$$

A: Counting difference between left-handed and right-handed fermions

- Pseudo-scalar inflation: $$\Delta\mathscr{L} = F(\phi) R\tilde{R}$$ $$h_{L,R} = \frac{1}{\sqrt{2}}(h_+ \mp i h_\times)$$

$$\Theta = \frac{8}{M_{\rm pl}^2} H F' \dot{\phi}$$

- EOM of Gravitational waves $$\Box h_L = -2i\frac{\Theta}{a}\dot{h}'_L \qquad \Box h_R = -2i\frac{\Theta}{a}\dot{h}'_R$$

- BAU $$n = \frac{1}{72\pi^4}\left(\frac{H}{M_{\rm pl}}\right)^2 \Theta H^4 \left(\frac{\mu}{H}\right)^6$$

Alexander, Peskin & Sheikh, 0403069 | Maleknejad, 1604.06520 | Adshead, et al., 1711.04800

Kambiase, et al., 0610905 | Kawai and Kim, 1702.07689 | Co, et al., 2205.01689

Leptogenesis via axion oscillation

- Alexander Kusenko, Kai Schmitz, Tsutomu T. Yanagida, arXiv:1412.2043

❖Axion relaxation after inflation $\ddot{a} + 3H\dot{a} + \partial_a V_{eff}(a) = 0$

❖Axion-like field couples to EW gauge field via the Chern-Simons form

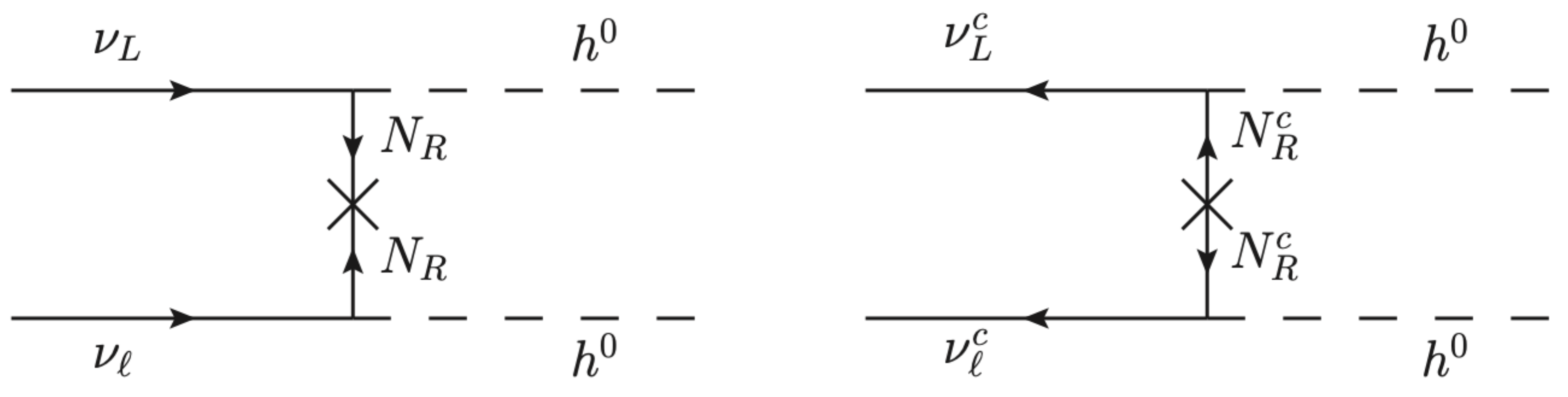
$$\mathscr{L} \sim \frac{a(t)}{f_a}\frac{g_2^2}{32\pi^2}\mathrm{Tr}\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] \rightarrow \frac{\partial_\mu a}{f_a} j_L^\mu \rightarrow \frac{\dot{a}}{f_a} n_L$$

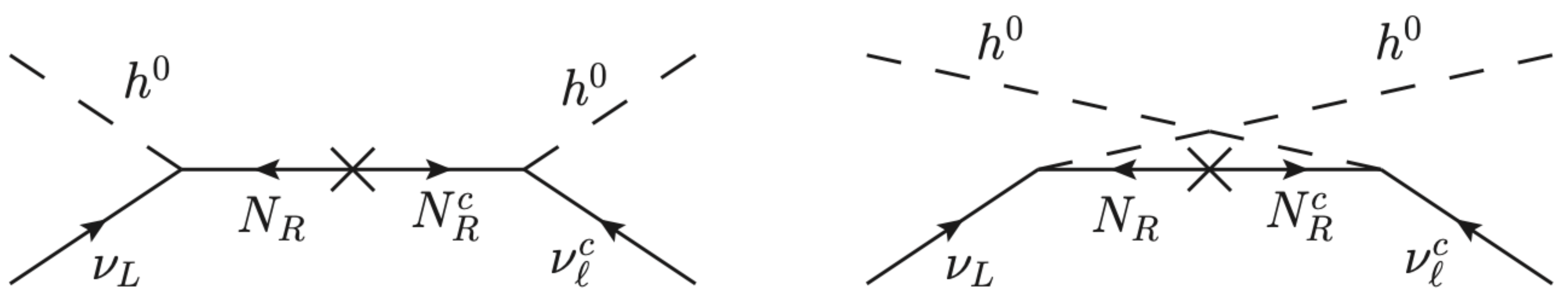
$$n_{\ell,\bar{\ell}}^{\mathrm{eq}} \sim T^3\left(1 \pm \frac{\mu_{eff}}{T}\right)$$

$$n_L^{eq} = n_\ell^{eq} - n_{\bar{\ell}}^{eq} \sim \mu_{\mathrm{eff}} T^2$$

$\dot{a}/f_a$: the effective chemical potential for leptons and anti-leptons

❖LNVs are mediated by the Majorana neutrinos $\dot{n}_L + 3Hn_L \sim -\Gamma_L(n_L - n_L^{\mathrm{eq}})$





Leptogenesis via axion oscillation

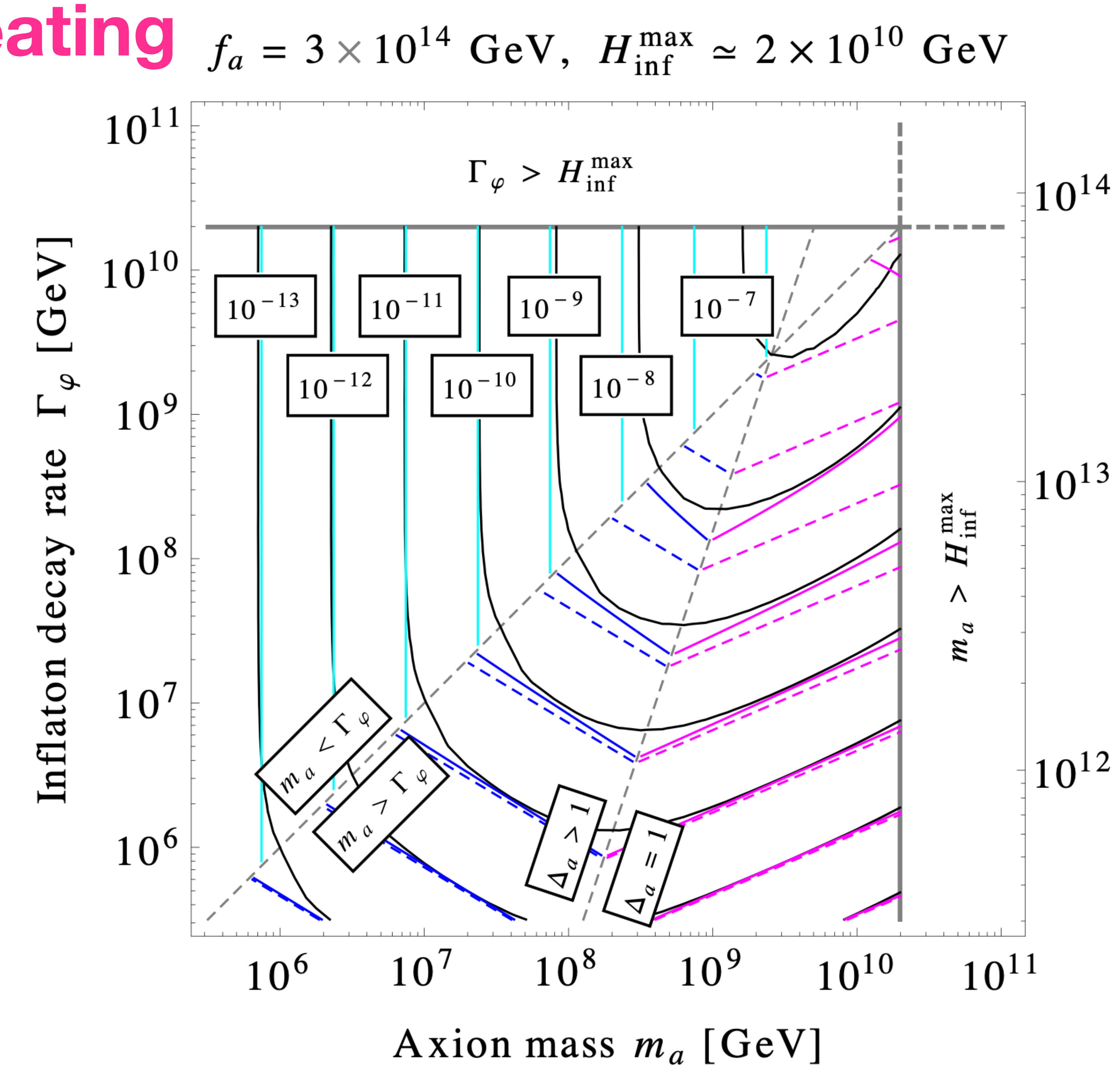
- **Alexander Kusenko, Kai Schmitz, Tsutomu T. Yanagida, arXiv:1412.2043**

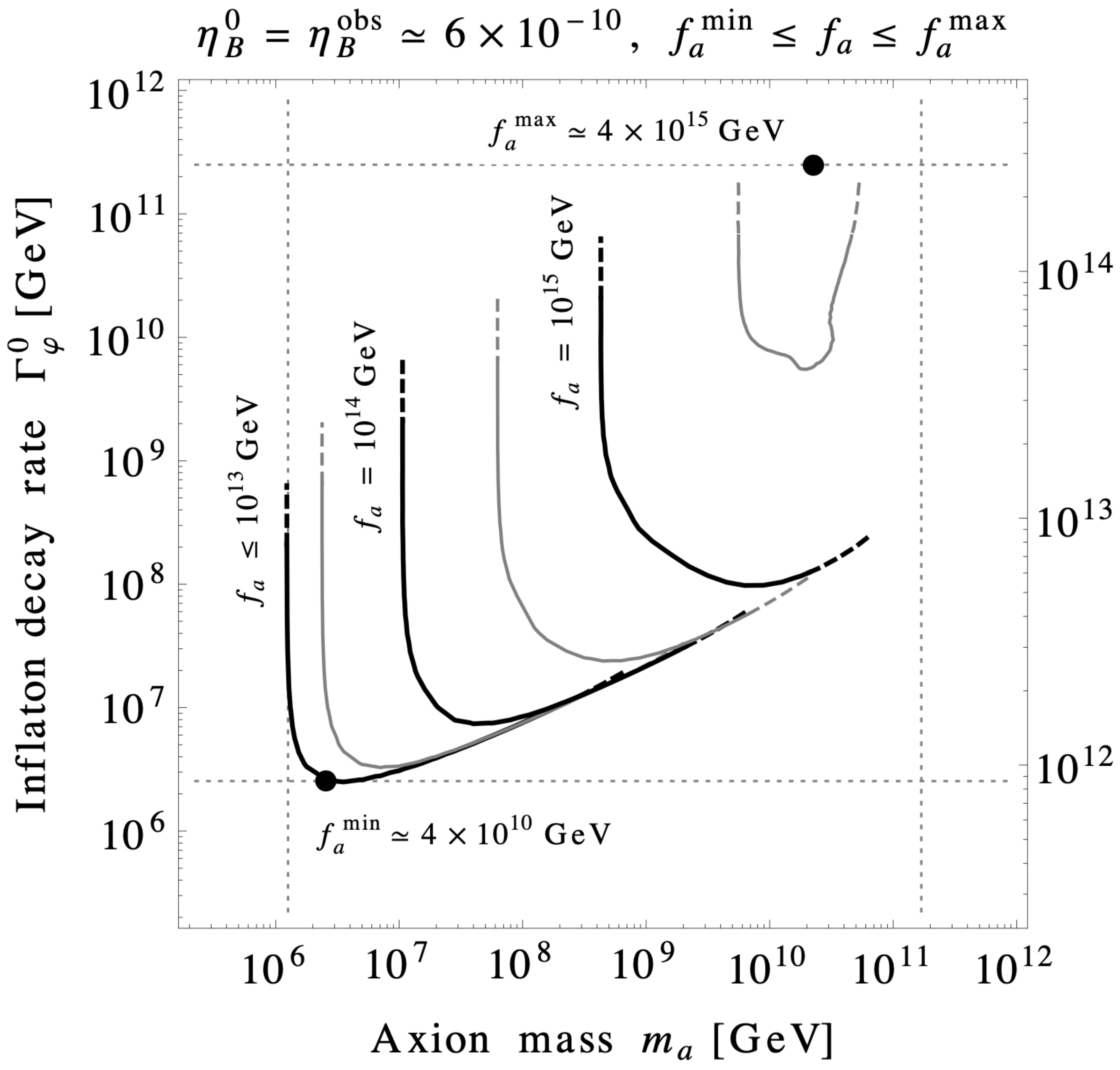
❖ Equations describing the reheating

$$\dot{\rho}_\varphi + 3H\rho_\varphi = -\Gamma_\varphi \rho_\varphi$$

$$\dot{\rho}_R + 4H\rho_R = +\Gamma_\varphi \rho_R$$

$$H^2 = \frac{\rho_\varphi + \rho_R}{3M_{pl}^2}$$





Wash-in Leptogenesis

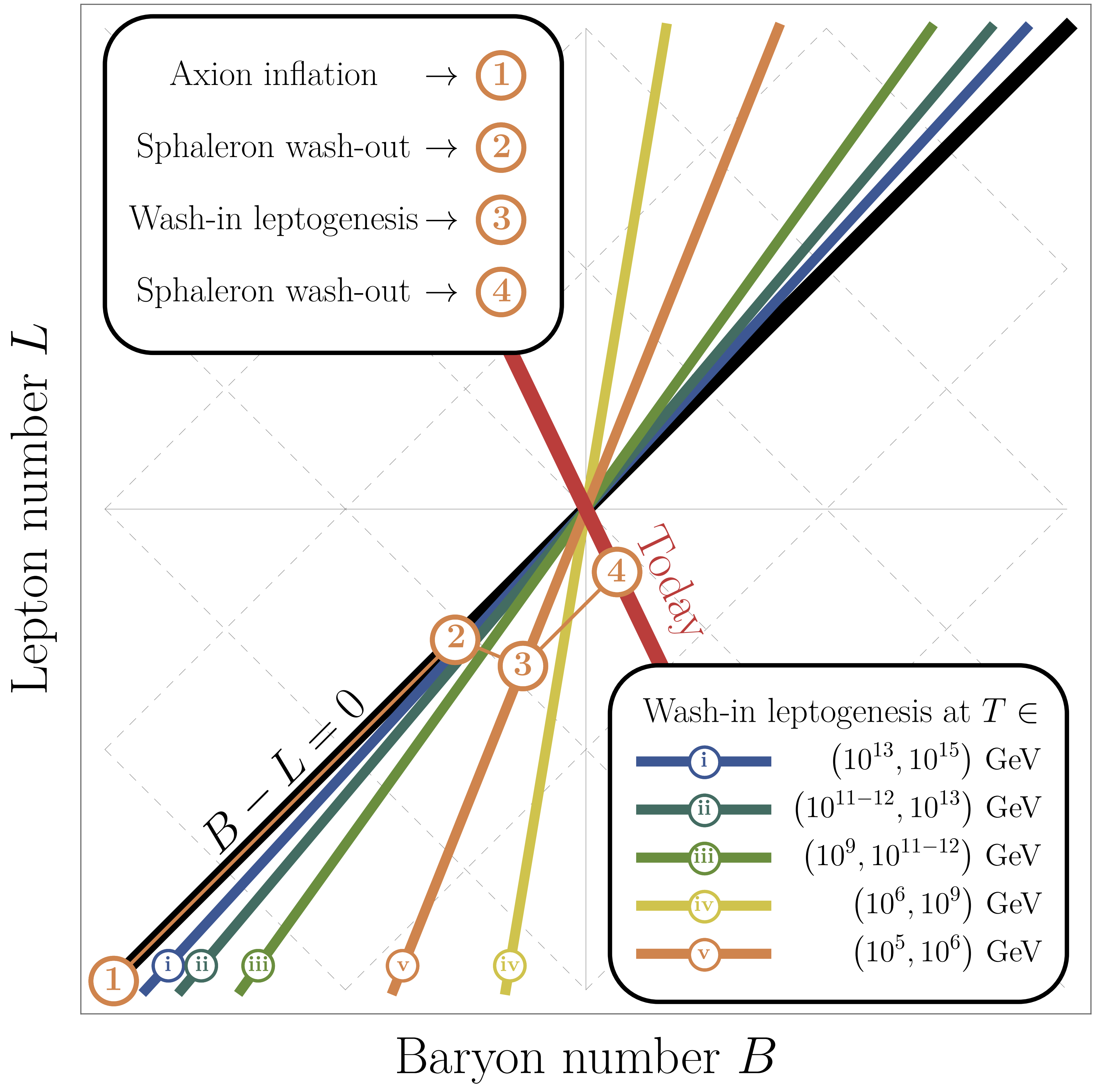
- **Domcke, Kamada, Mukaida, Schmitz and Yamada, arXiv:2011.09347**

Lepton flavor asymmetry: $\Delta_\alpha = \frac{B}{3} - L_\alpha$

Splitting into two parts: $q_{\Delta_\alpha} = q_{\Delta_\alpha}^{\text{thermal}} + q_{\Delta_\alpha}^{\text{wash-in}}$

Boltzman equation: $(\partial_t + 3H) q_{\Delta_\alpha}^{\text{wi}} = \sum_\beta \Gamma_{\alpha\beta}^w \left(q_\beta^0 - \sum_\sigma C_{\beta\sigma} q_{\Delta_\sigma}^{\text{wi}} \right)$

- Right-handed neutrinos can be as light as several hundreds TeV
- No need for the CP violation in the heavy neutrino sector
- Strong wash-out effect is turned into effective wash-in effect,



Affleck-Dine Leptogenesis

- N.Barrie, Chengcheng Han, H.Murayama, arXiv:2106.03381, PRL 128(2022)141801

❖ Generating the net lepton number during the Higgs inflation in the type-II seesaw framework!

$$V(h,\Delta^0) = -m_H^2|h|^2 + m_\Delta^2|\Delta^0|^2 + \lambda_H|h|^4 + \lambda_\Delta|\Delta^0|^4 + \lambda_{H\Delta}|h|^2|\Delta^0|^2 + \left(\mu h^2\Delta^{0*} + \frac{\lambda_5}{M_p}|h|^2h^2\Delta^{0*} + \frac{\lambda_5'}{M_p}|\Delta^0|^2h^2\Delta^{0*} + \text{H.c.}\right) + \cdots . \quad (9)$$

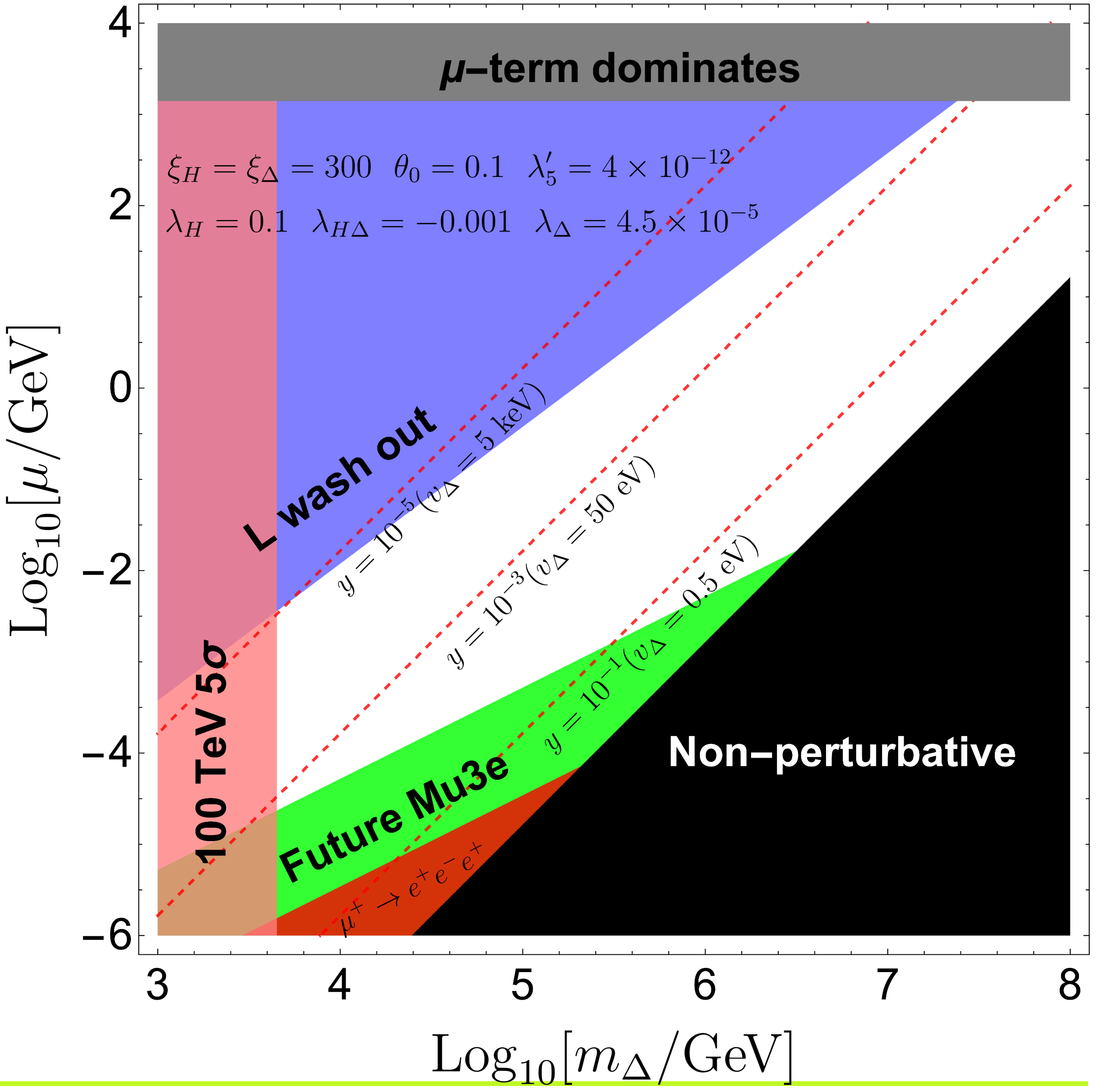
Large LNV

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}M_p^2R - F(H,\Delta)R - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H) - g^{\mu\nu}(D_\mu\Delta)^\dagger(D_\nu\Delta) - V(H,\Delta) + \mathcal{L}_{\text{Yukawa}}. \quad (10)$$

Flatten the Potential

$$\eta = \frac{n_B}{s}\bigg|_{\text{reh}} = \eta_B^{\text{obs}}\left(\frac{|n_{L\text{end}}|/M_p^3}{1.3\times 10^{-16}}\right)\left(\frac{g_*}{112.75}\right)^{-1/4},$$

BAU



History and development: Affleck-Dine

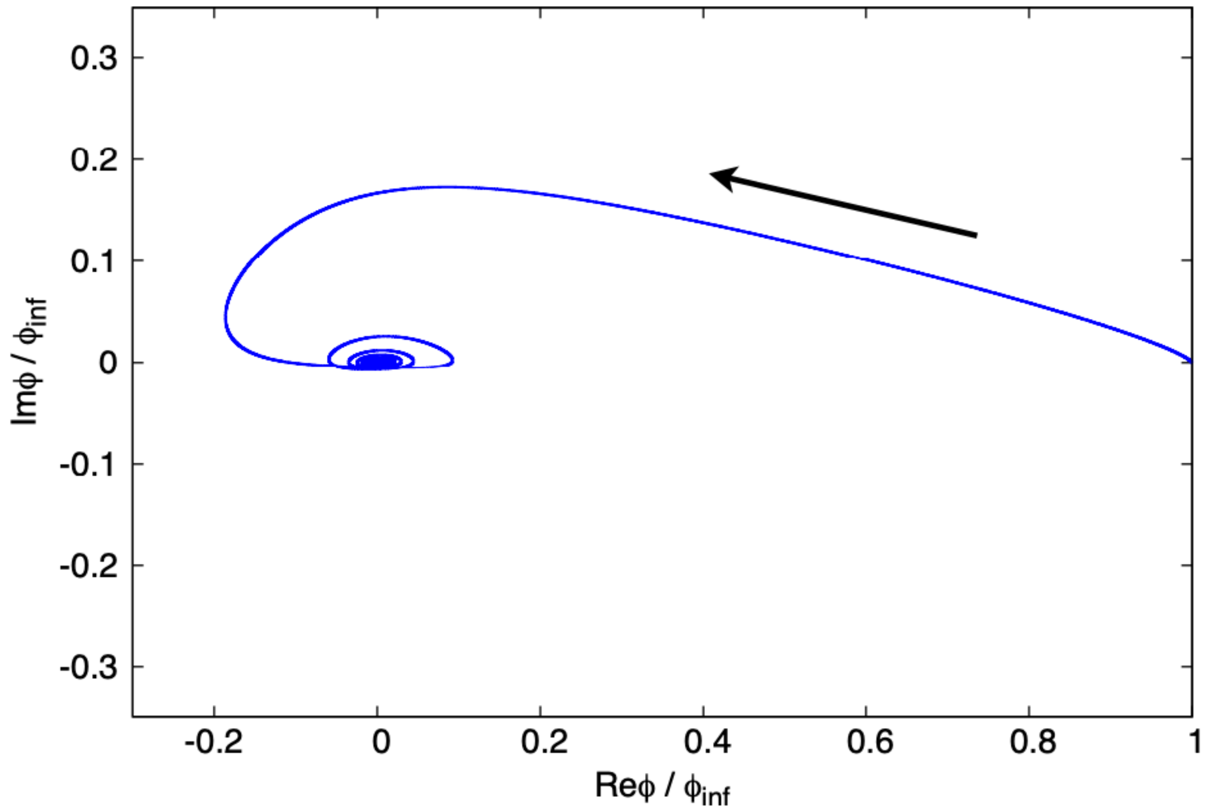
Affleck-Dine Mechanism

Scalars carrying non-zero U(1) charges

Flat directions (AD fields)

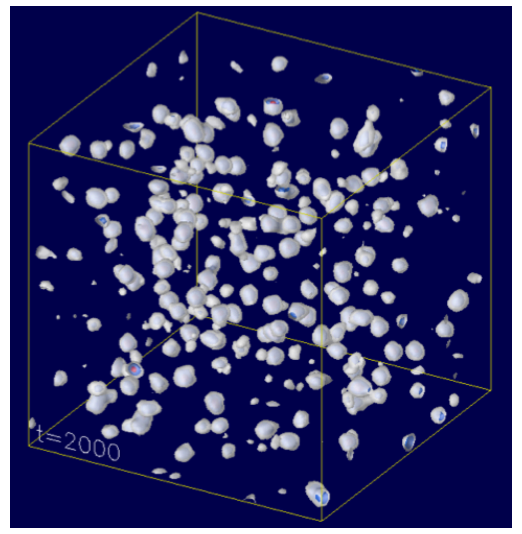
Lifting the potential via B/L violation operators

$$V = (m^2 - cH^2)|\phi|^2 + \lambda|\phi|^4 + \left(\frac{\phi^n}{M^{n-4}} + \mathrm{h.c.}\right)$$



$$\dot{n}_{B,L} + 3Hn_{B,L} \sim 2\mathrm{Im}\left[\frac{\partial V}{\partial \phi}\phi\right]$$

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**

Leptogenesis via Primordial Black Hole

T. Fujita, et al., 1401.1909

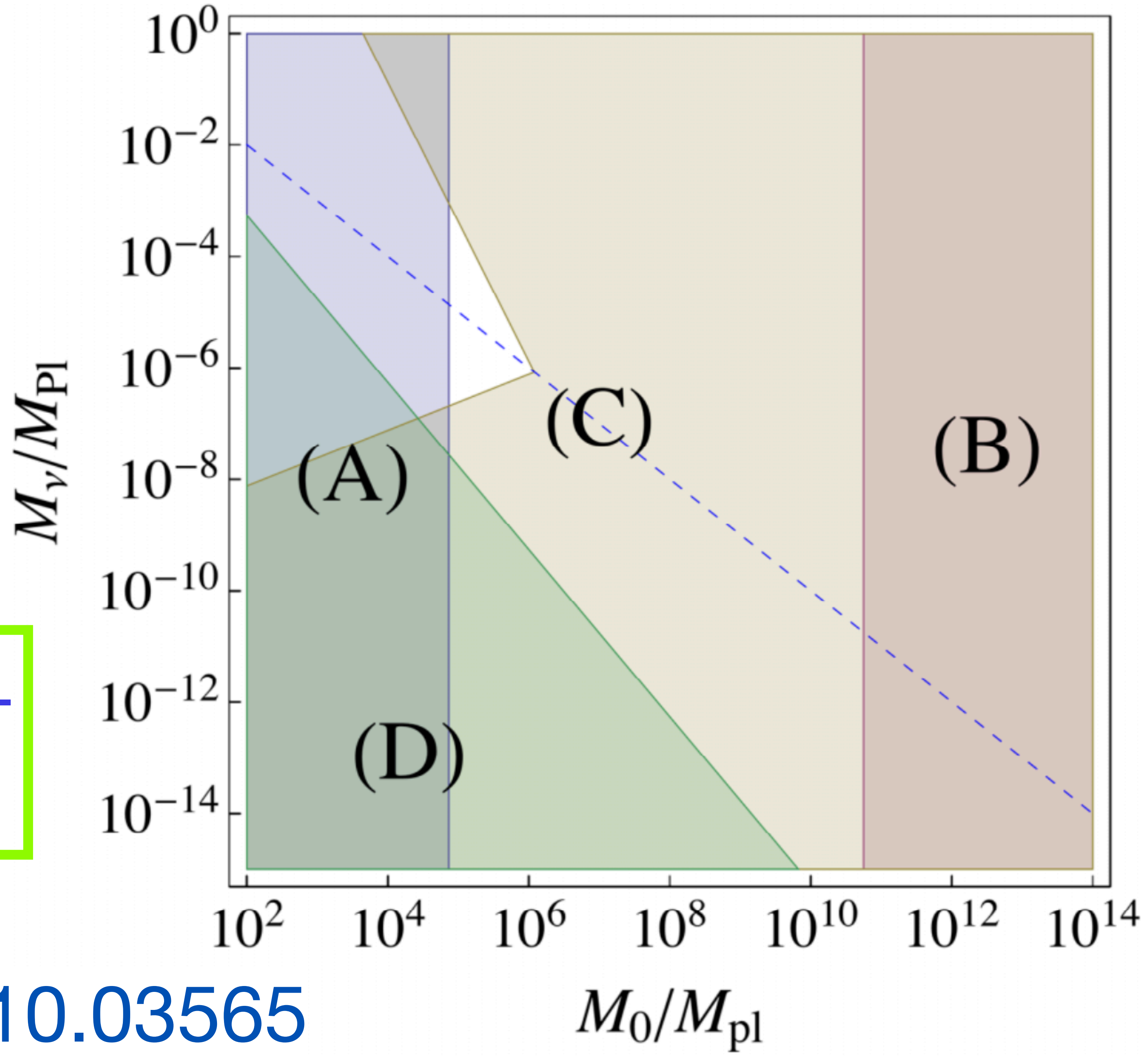
$$(\text{PBH}) \xrightarrow[\times N_\nu]{\text{evaporation}} \begin{pmatrix} \text{right-handed} \\ \text{neutrino} \end{pmatrix} \xrightarrow[\times \epsilon]{\text{decay}} \begin{pmatrix} \text{lepton} \\ \text{number} \end{pmatrix} \xrightarrow[\times \kappa]{\text{sphaleron}} \begin{pmatrix} \text{baryon} \\ \text{number} \end{pmatrix},$$

N_ν: The number of neutrino emitted from one PBH

ϵ: CP asymmetry

κ: efficiency factor

$$\frac{n_B}{s}(t_{\text{now}}) = N_\nu \epsilon \kappa \frac{n_{\text{PBH}}}{s}(t_{\text{evap}})\alpha^{-1}$$
$$\simeq N_\nu \epsilon \kappa \frac{(\pi^2/30) g_* T_{\text{evap}}^4 / M_0}{\alpha (2\pi^2/45) g_* T_{\text{evap}}^3}$$
$$\simeq 0.4 \times \frac{N_\nu \epsilon \kappa}{\alpha} \left(\frac{M_0}{M_{\text{Pl}}}\right)^{-5/2} \left(\frac{g}{100}\right)^{1/2} \left(\frac{g_*}{100}\right)^{-1/4},$$



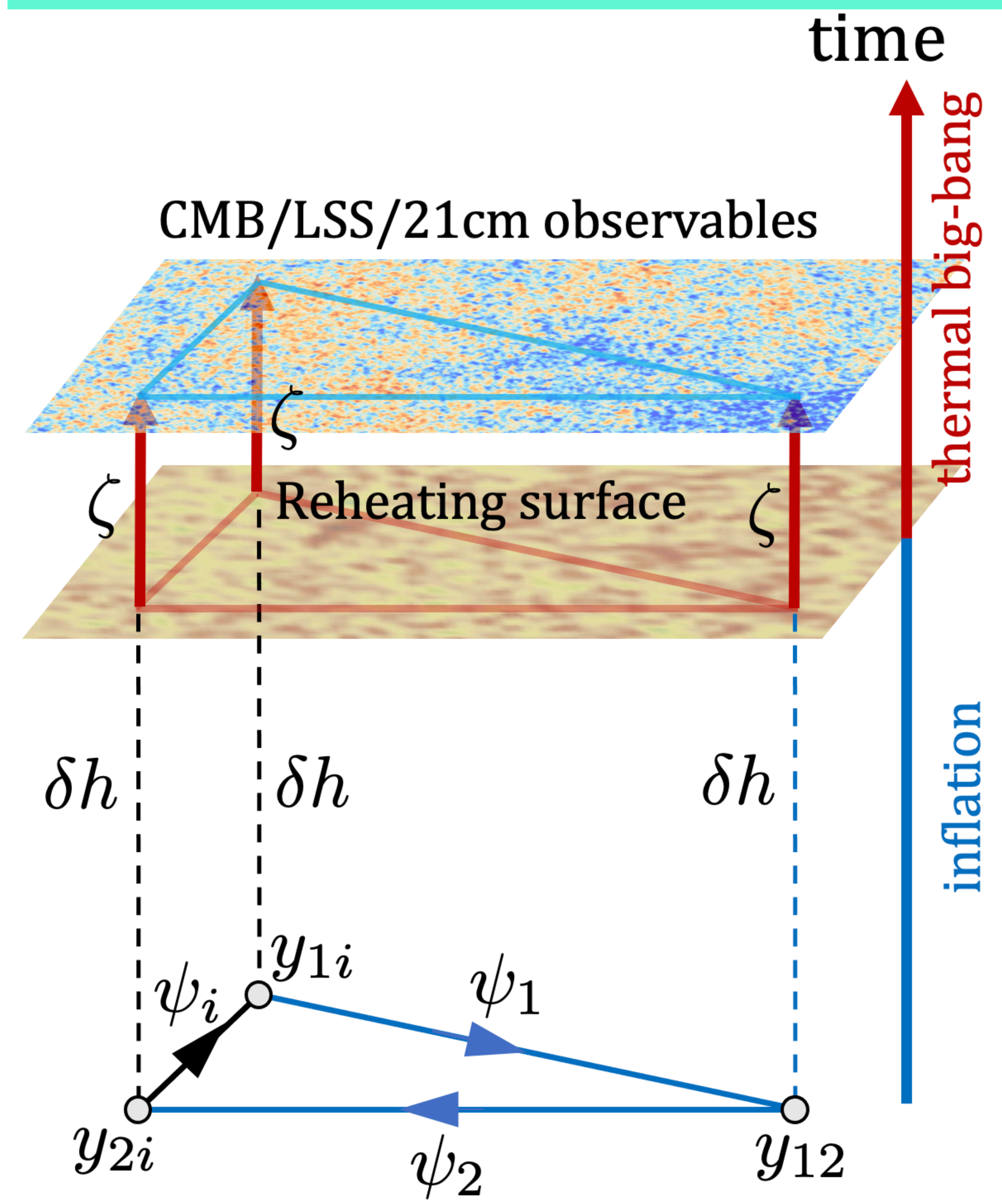
Interplay between thermal right-handed neutrino and non-thermal right-handed neutrinos

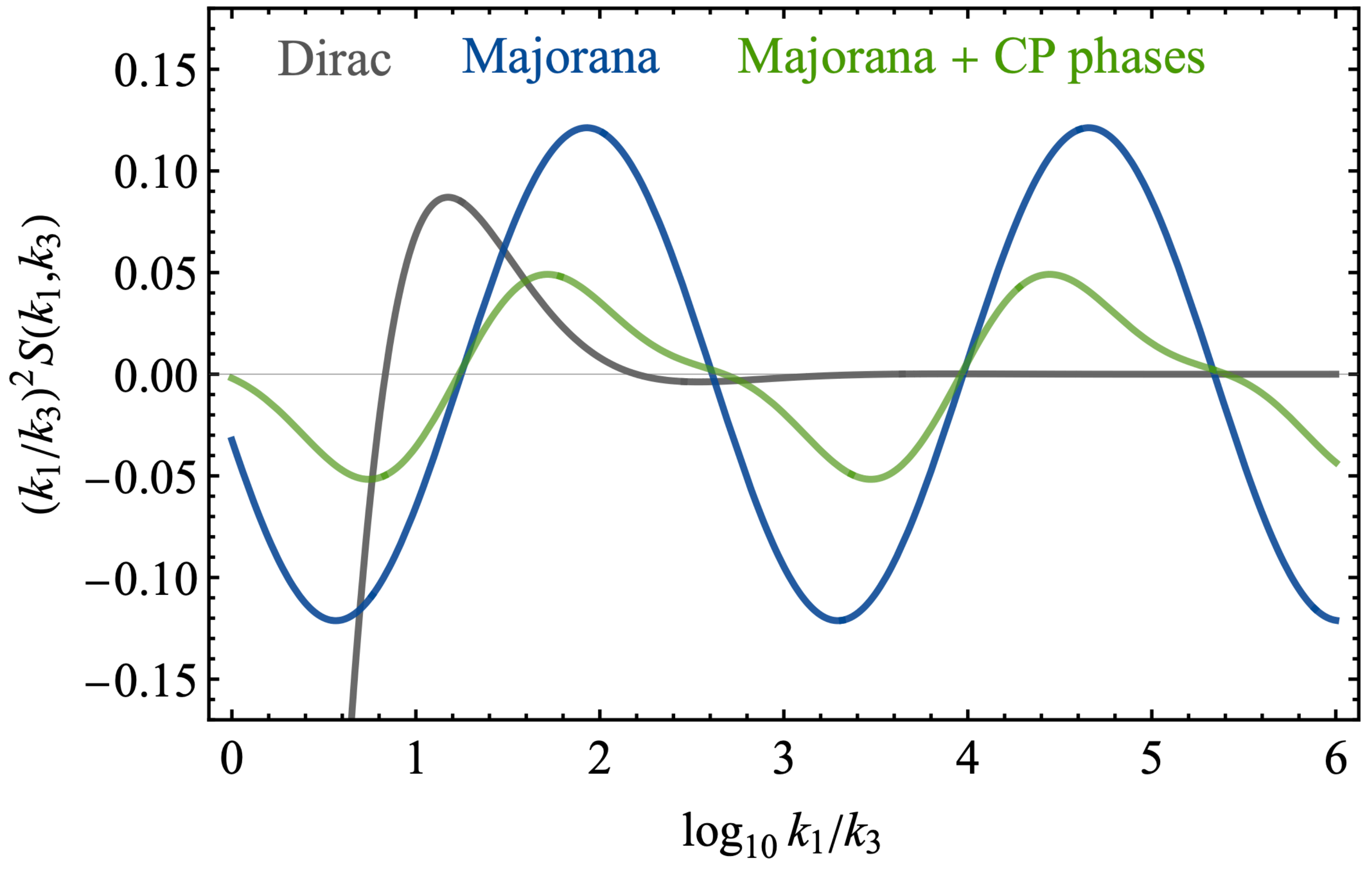
$$aH\frac{dn^{\text{B-L}}}{da} = \varepsilon^1 \left[(n_{N_1}^{\text{TH}} - n_{N_1}^{\text{eq}})\Gamma_{N_1}^T + n_{N_1}^{\text{BH}}\Gamma_{N_1}^{\text{BH}}\right] + W$$

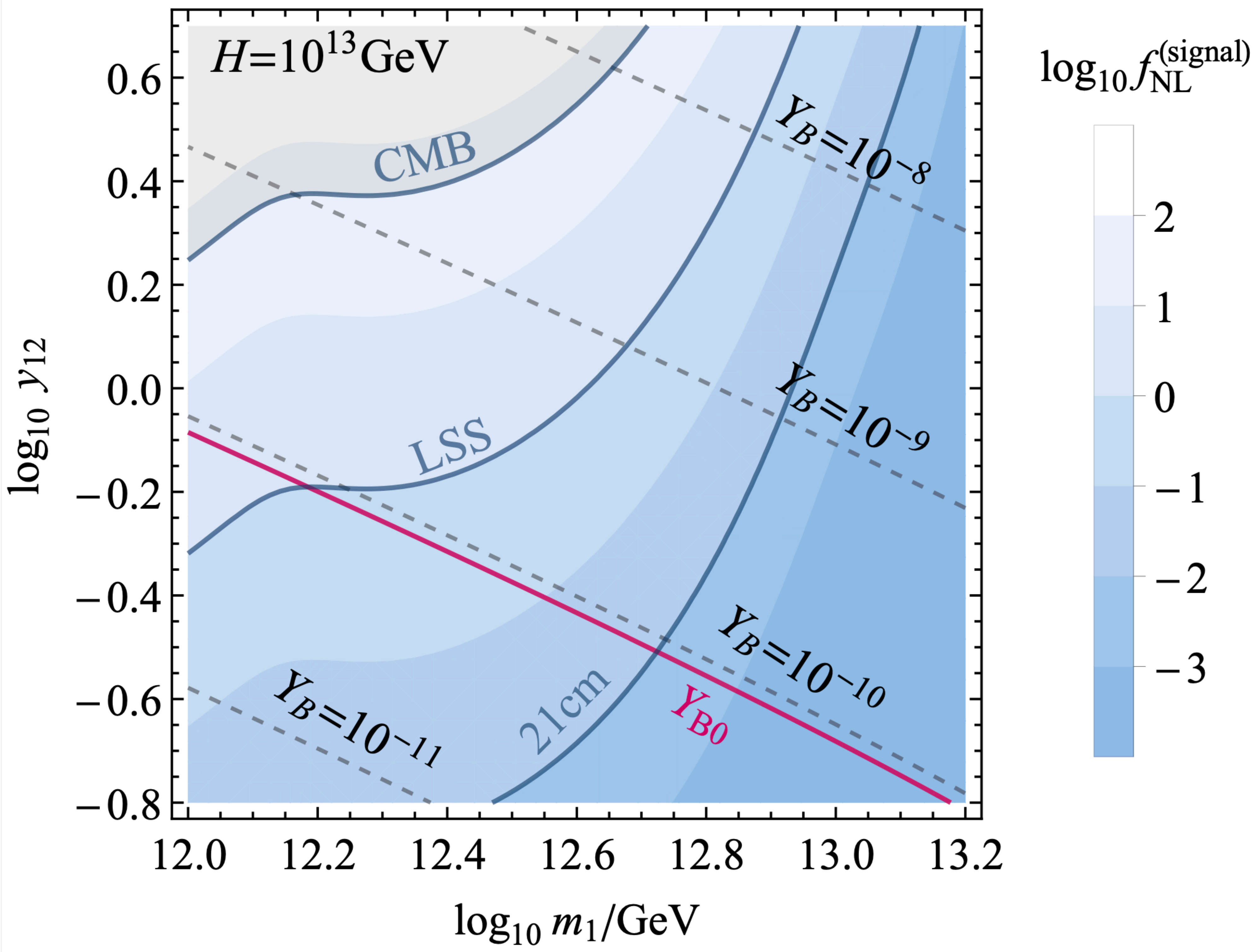
Perez-Gonzalez&Turner, 2010.03565

Detecting Leptogenesis with Cosmological collider

- Yanou Cui and Zhong-zhi Xianyu, arXiv:2112.10793， PRL129(2022)111301

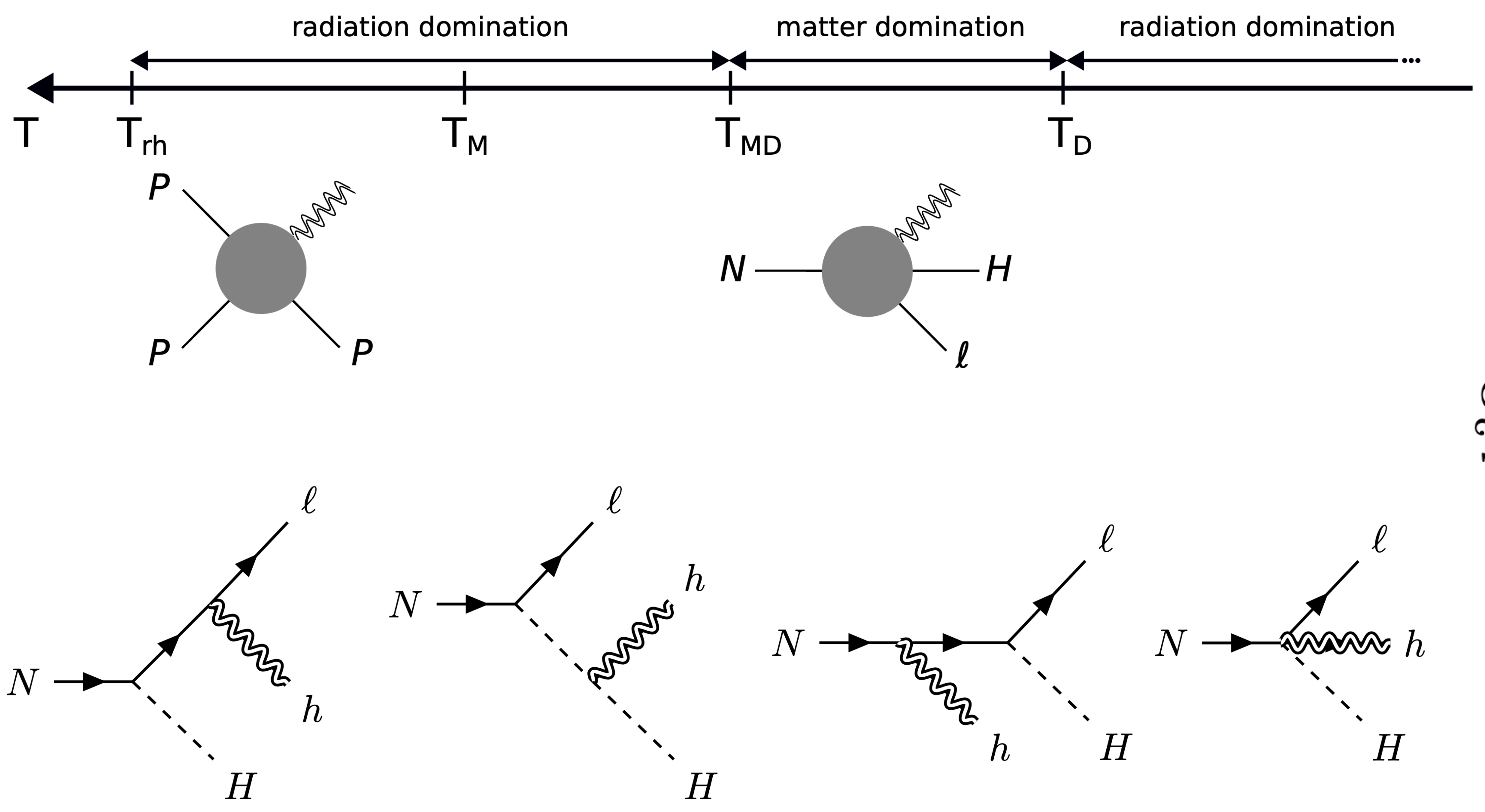


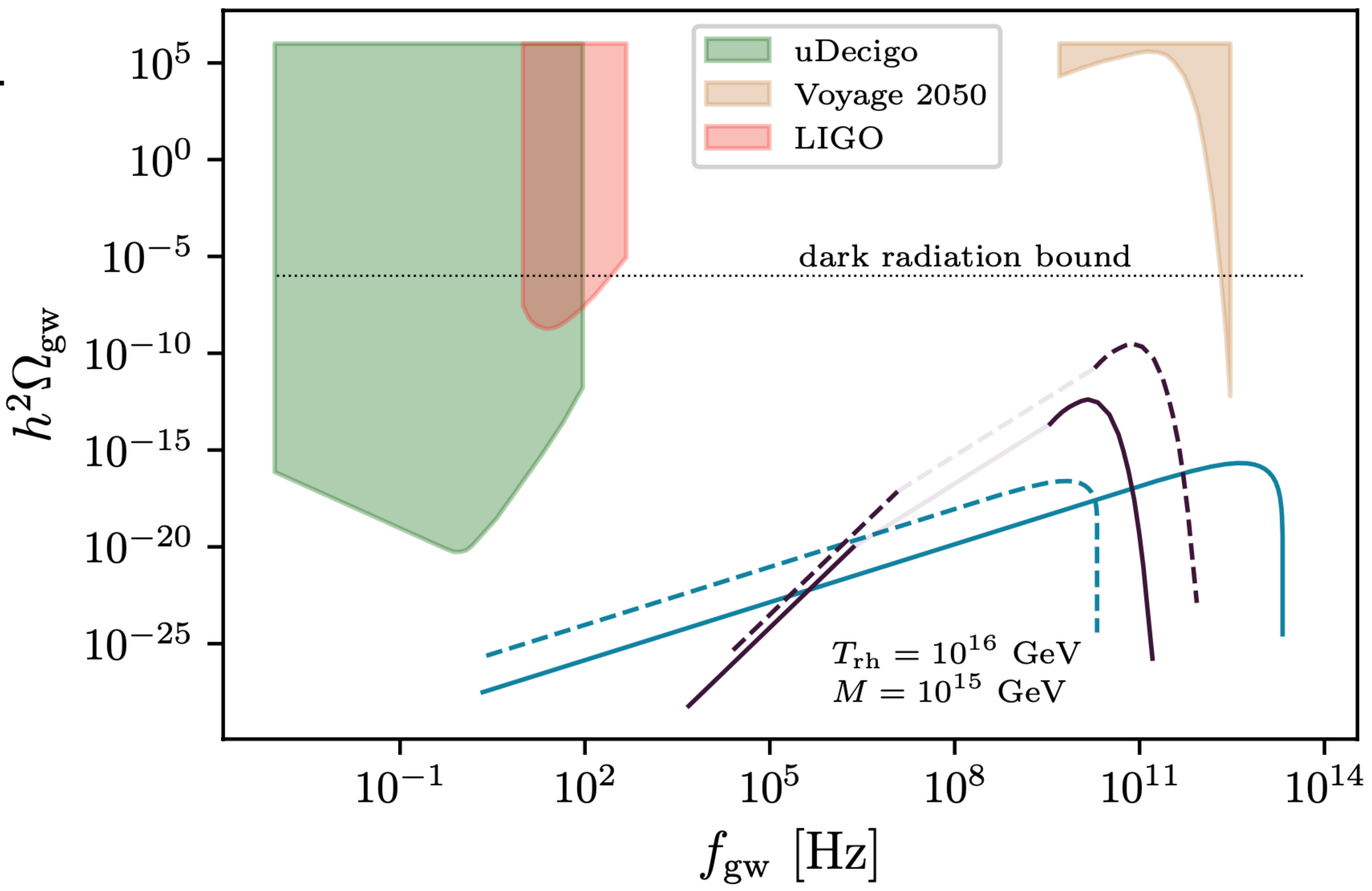




Detecting Leptogenesis with GW

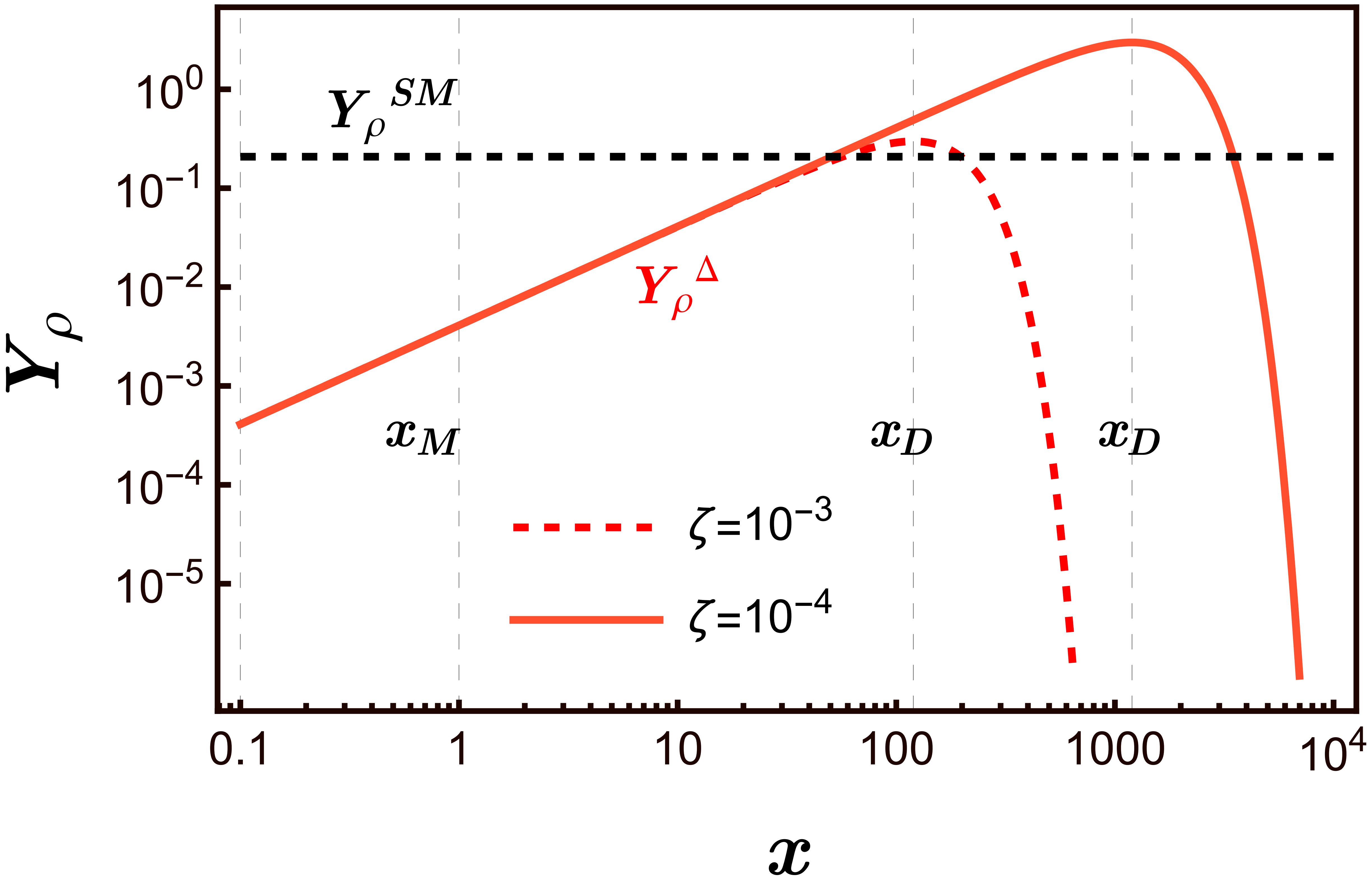
- Murayama, Noether and Schutte-Engel arXiv: 2506.15772

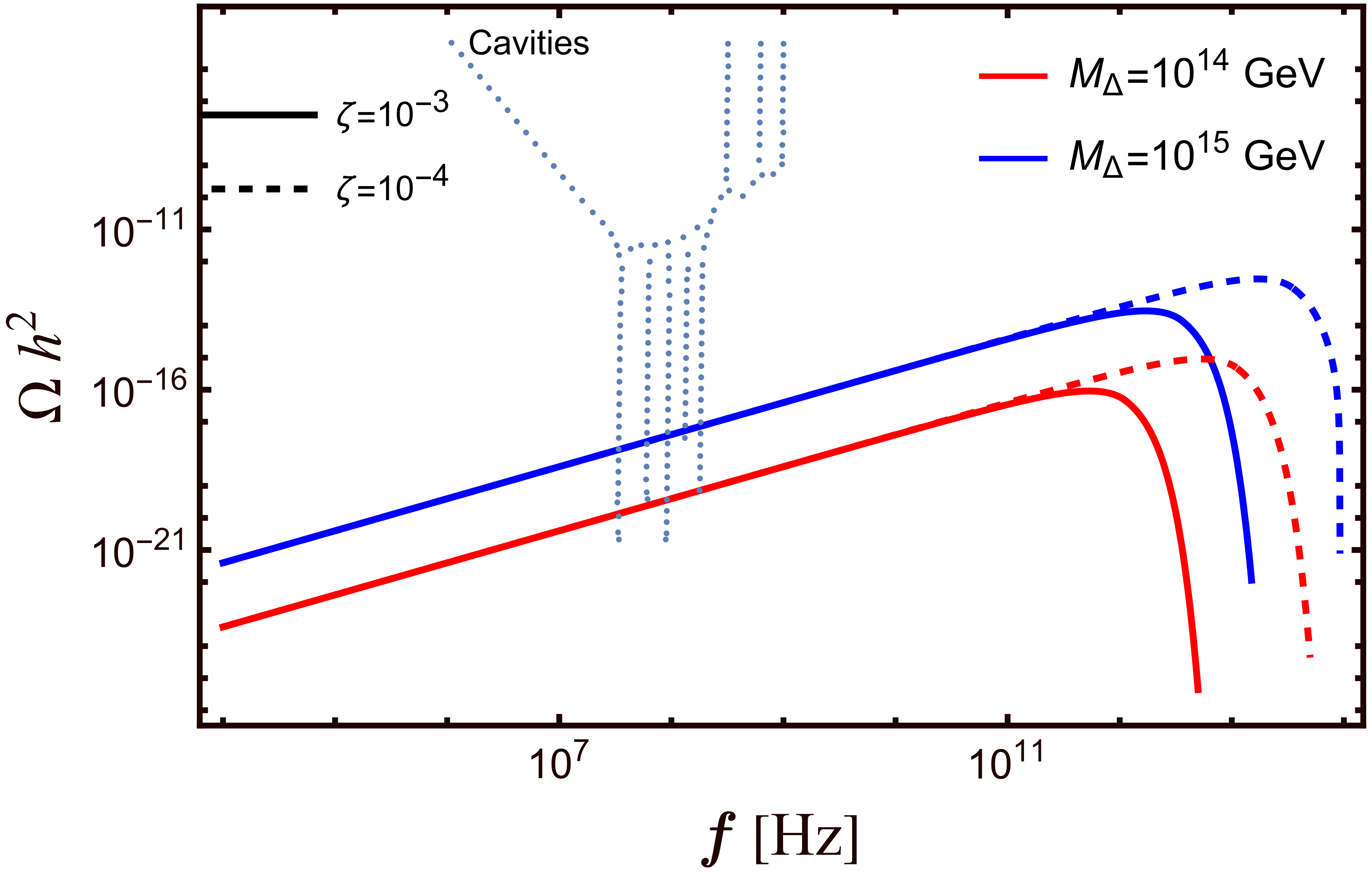




Detecting Leptogenesis with GW

- Yonghua Wang and Wei Chao, arXiv:2510.26235 (The type-II seesaw case)





Leptogenesis Summary

问题本身十分重要，值得持续深入的探索

- CTP formalism
- Flavor effect
- Casas-Ibarra parametrization
- Effective field theory
- Resonant Leptogenesis

Contents

Leptogenesis

- With Gravity
- With inflation
- With axion physics
- With phase transition
- With plasma physics

Time line t