ν EWBG (Nu electroweak baryogenesis)

Fernandez-Martinez, Lopez-Pavon, Ota, Rosauro-Alcaraz, JHEP 10 (2020) 063

Toshi Ota, IFT Madrid

Introduction: EWBG in SM

Baryon number asymmetry

Why is there something rather than nothing?

Planck Collaboration 1807.06209

$$\eta_B \equiv \frac{n_B}{s} \equiv \frac{\#B - \#\overline{B}}{s} = (8.59 \pm 0.08) \cdot 10^{-11}$$

To let there be baryon number, the Universe must fulfill…

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Sakharov conditions

Sakharov (1967)

C&CP violation (1)	B violation (2)	Out of equilibrium (3)
Weak interaction	EW anomaly	1st order PhT
CKM phase	Sphaleron at $T > T_{\rm EW}$	Decoupling of sphaleron

Then, what is the possible baryogenesis scenario in the SM?

Baryogenesis in the SM

Kuzmin Rubakov Shaposhnikov
PLB155 (1985) 36

Suppose EWPT is a 1st-order PT…

Sphaleron: ON	Bubble wall	Sphaleron: OFF
#$\not{B}$ in equi.	$\not{CP}$	#$\not{B}$ out-of-equi.

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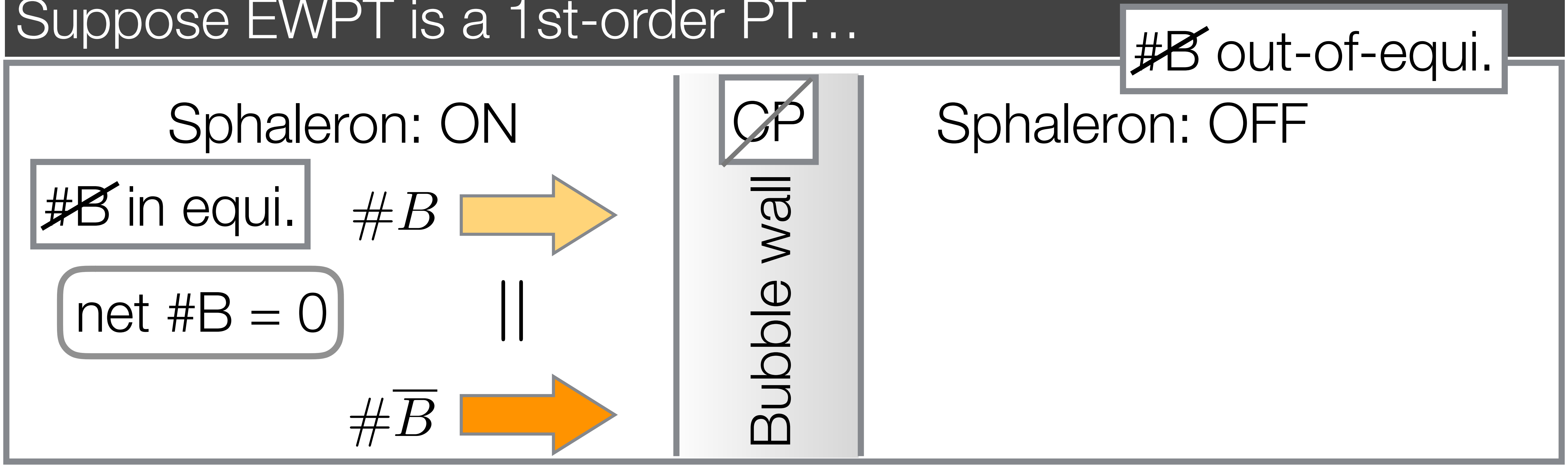

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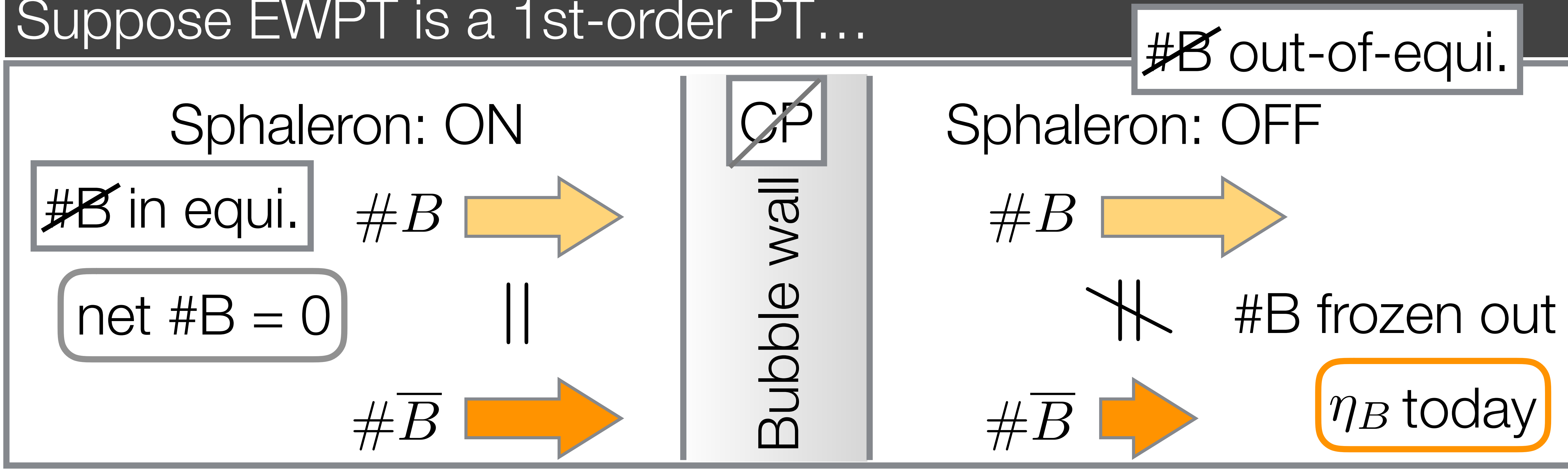

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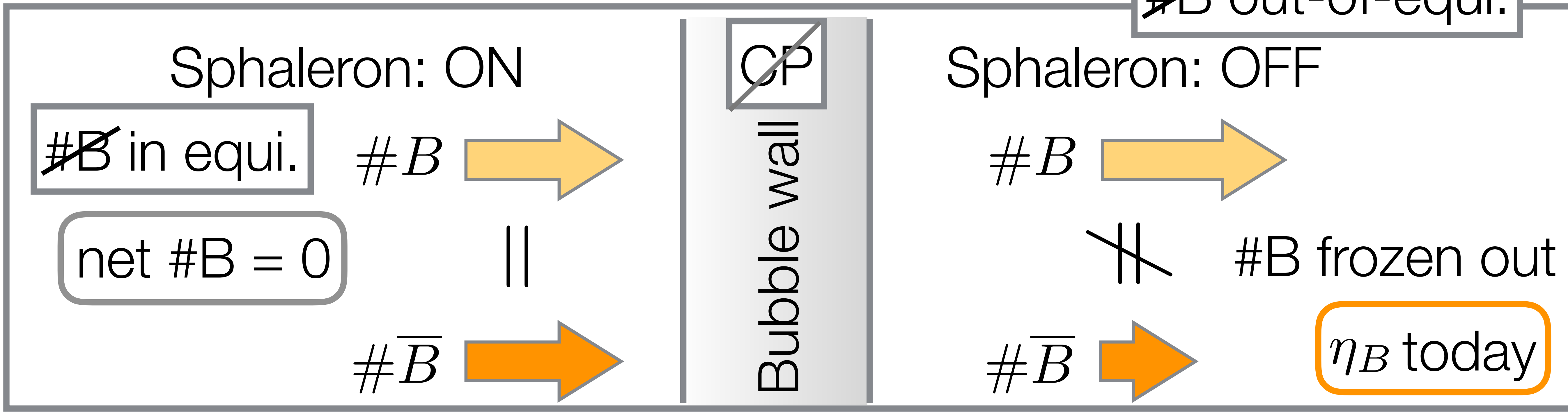

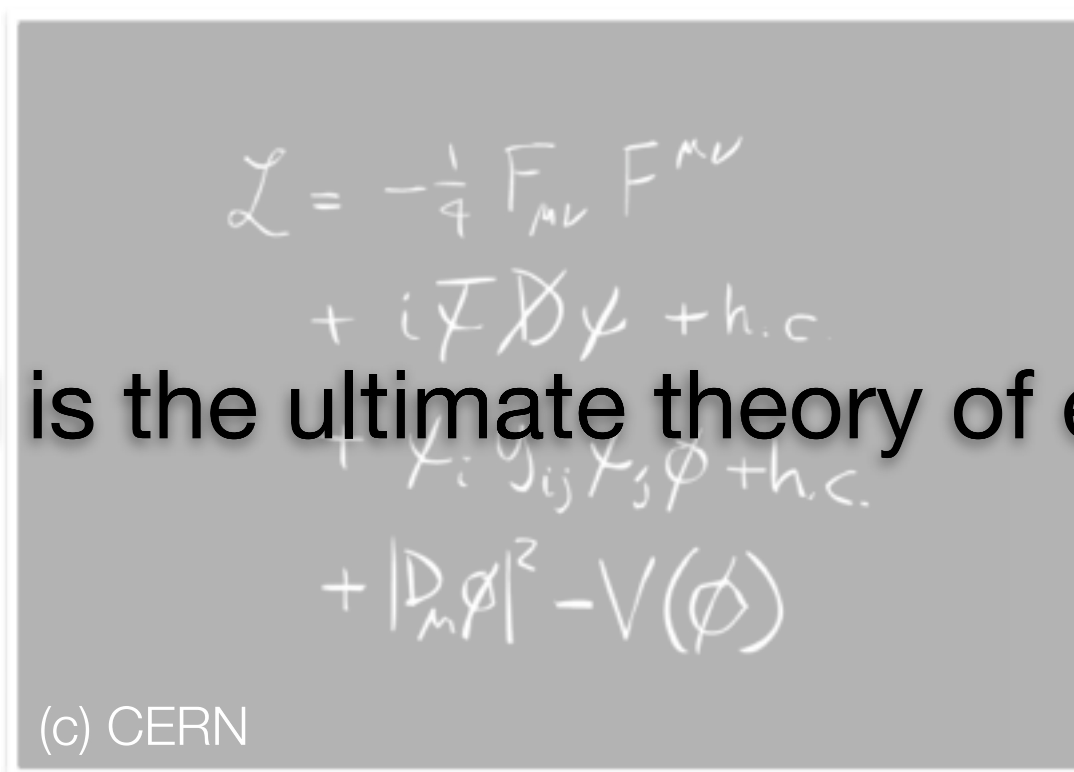

The SM is the ultimate theory of everything.

The End

Baryogenesis in the SM

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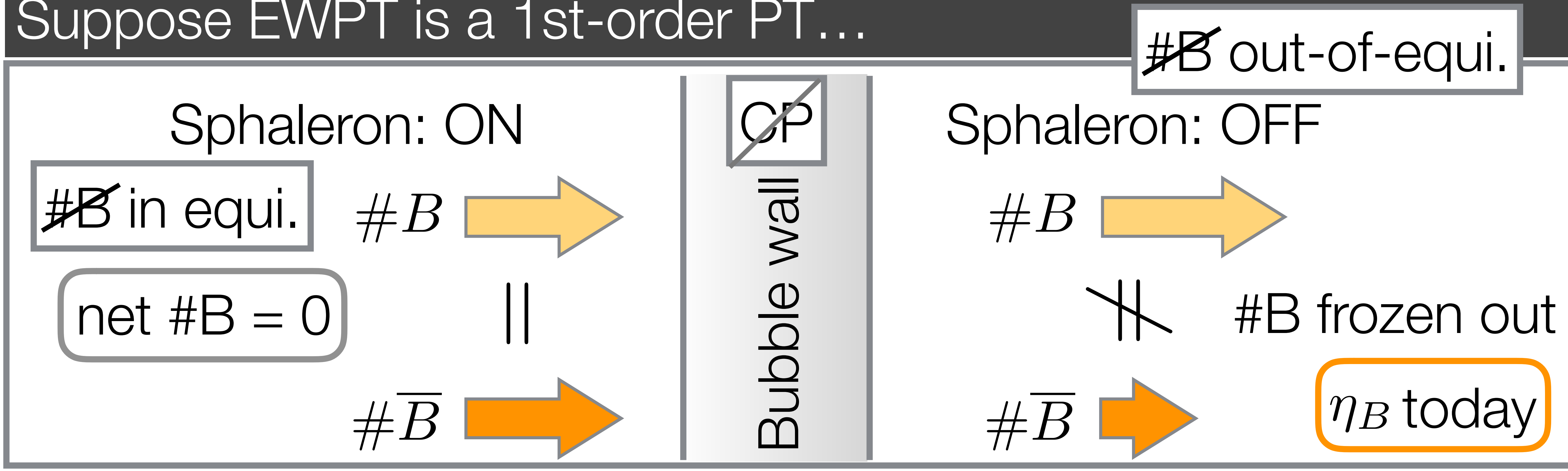

Sounds so natural that it should work, but…

CPV effect must be proportional to

$$\det\left[M_u M_u^\dagger, M_d M_d^\dagger\right] = 2\mathrm{i} F_u F_d J$$

$$F_q \equiv (m_{q_3}^2 - m_{q_2}^2)(m_{q_3}^2 - m_{q_1}^2)(m_{q_2}^2 - m_{q_1}^2)$$

$$J = c_{12} s_{12} c_{23} s_{23} c_{13}^2 s_{13} s_\delta$$ Jarlskog PRL55 (1985) 1039

Gavela et al. 9312215 Huet Sather 9404302

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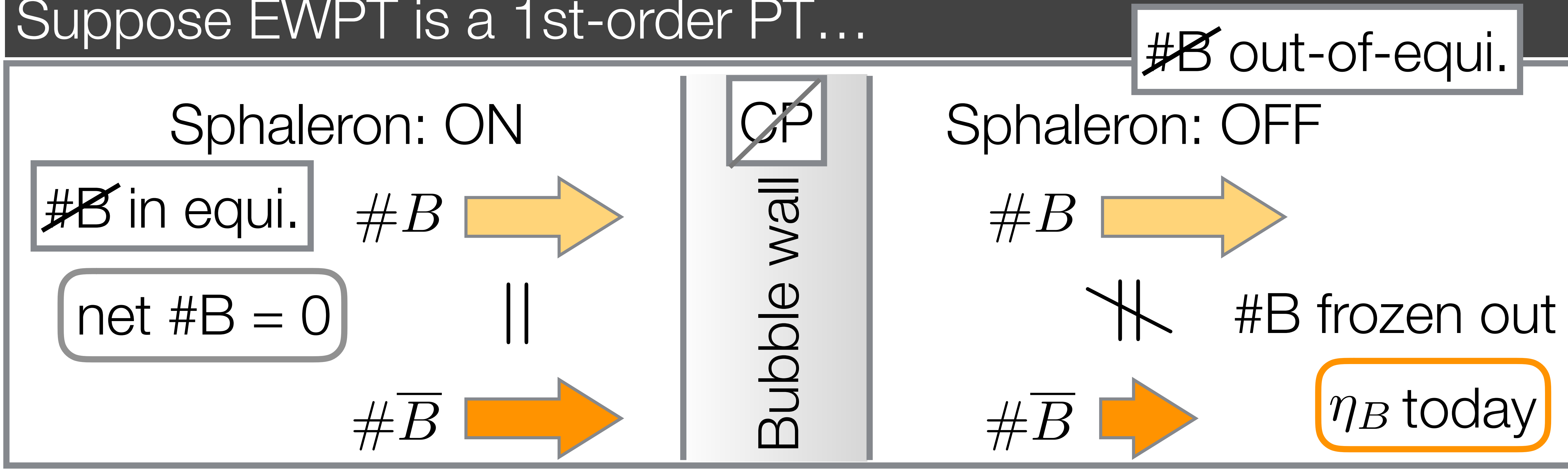

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Far too small

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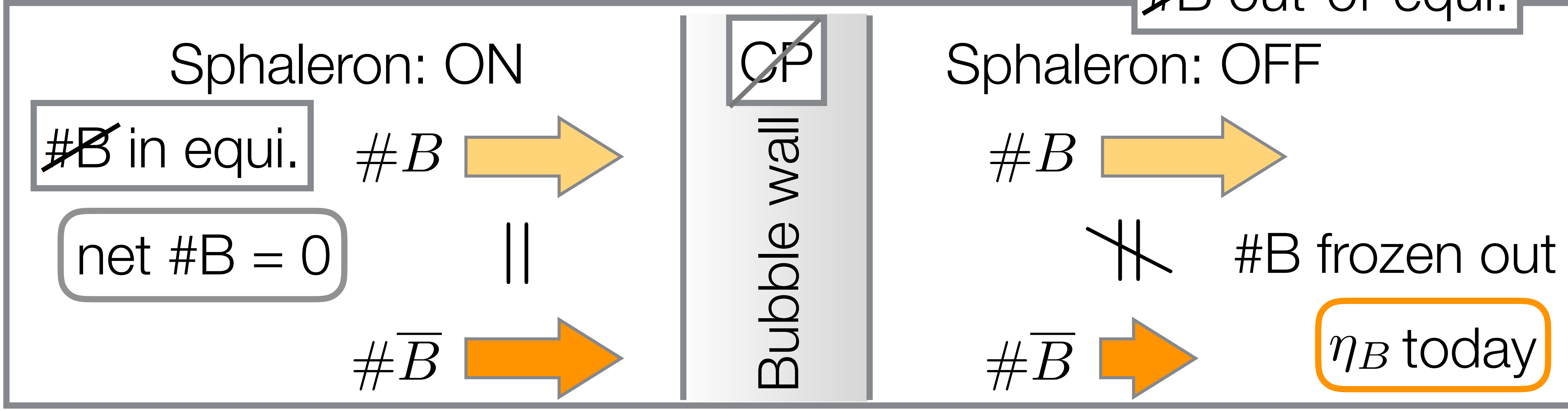

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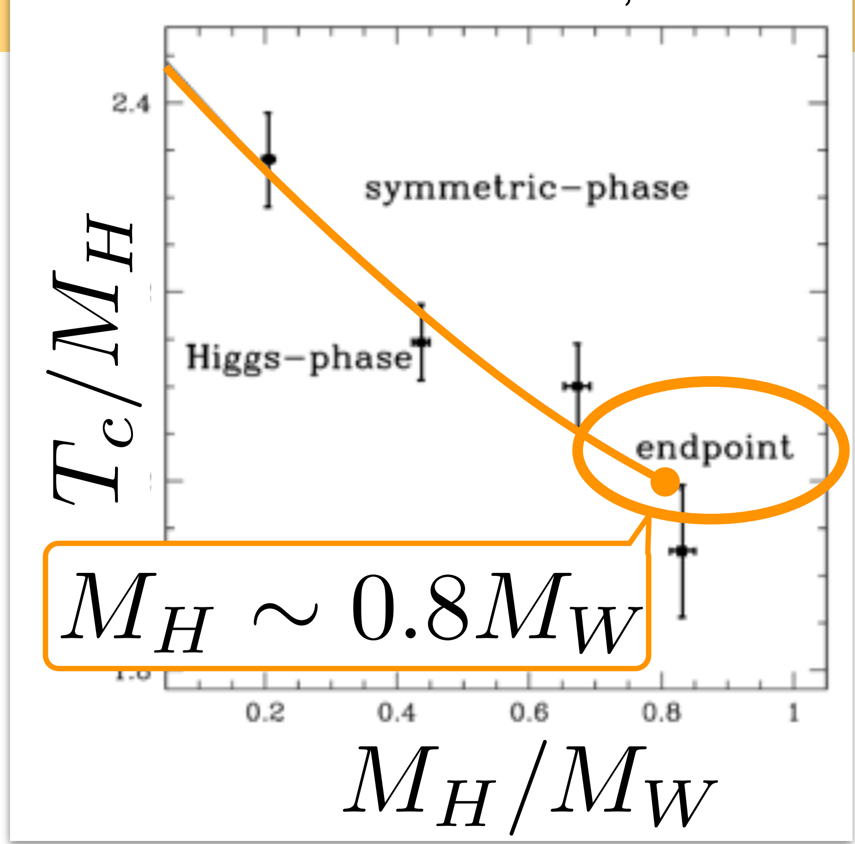
Csikor et al. 980929, & more



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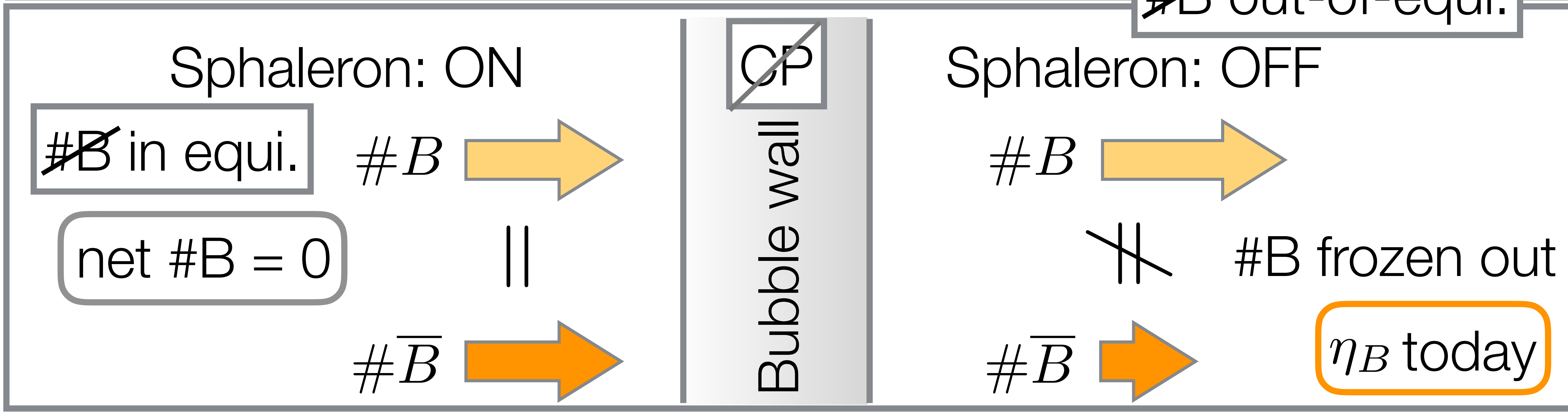

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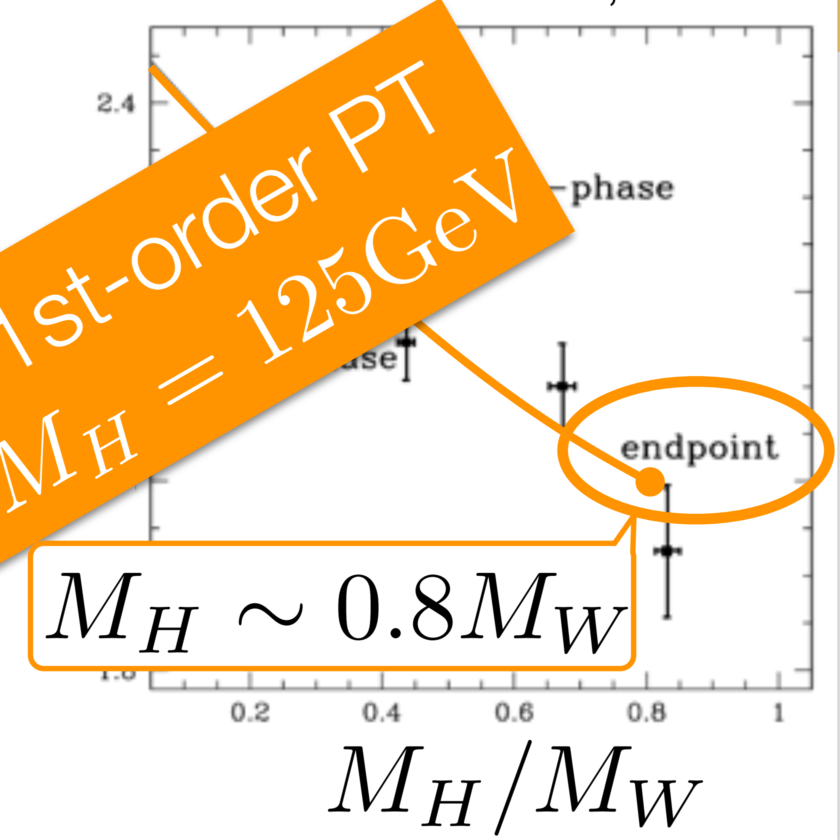


NO 1st-order PT w. $M_H = 125\mathrm{GeV}$

Gavela et al. 9312215 Huet Sather 9404302

We need to go beyond SM for our being

To fix SM's shortcomings, we need*

A trick to make EWPT strong 1st-order (3)

New source of CPV (1)

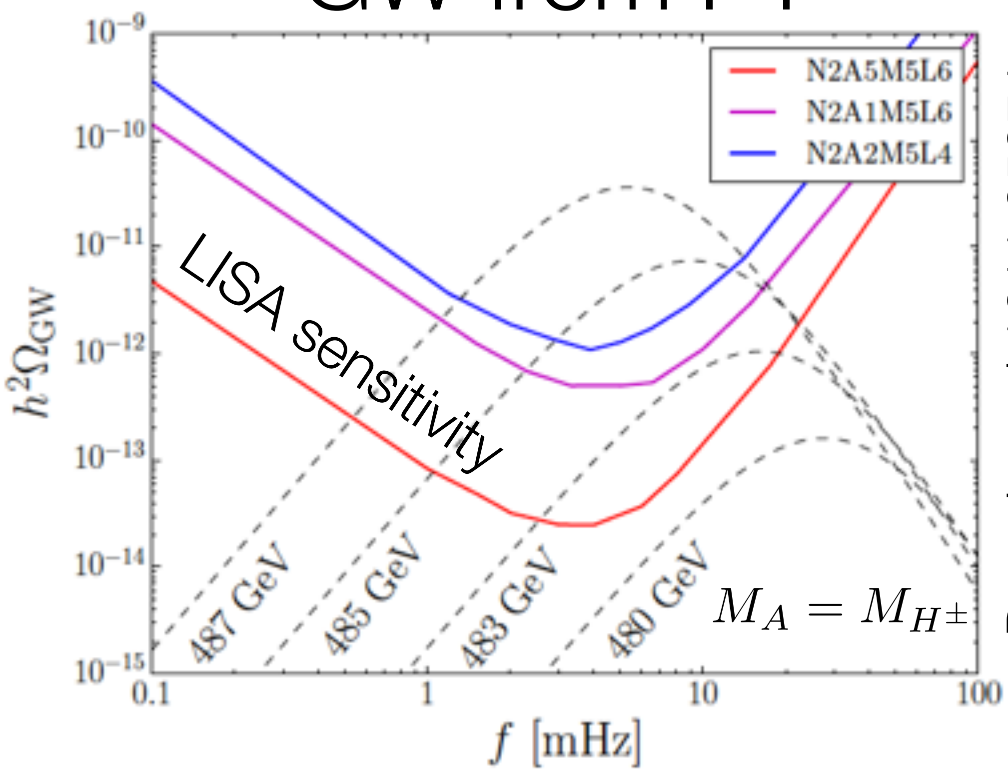
*If we stick to the idea of EWBG

BSM for EWBG

Nelson Kaplan Cohen NPB373 (1992) 453

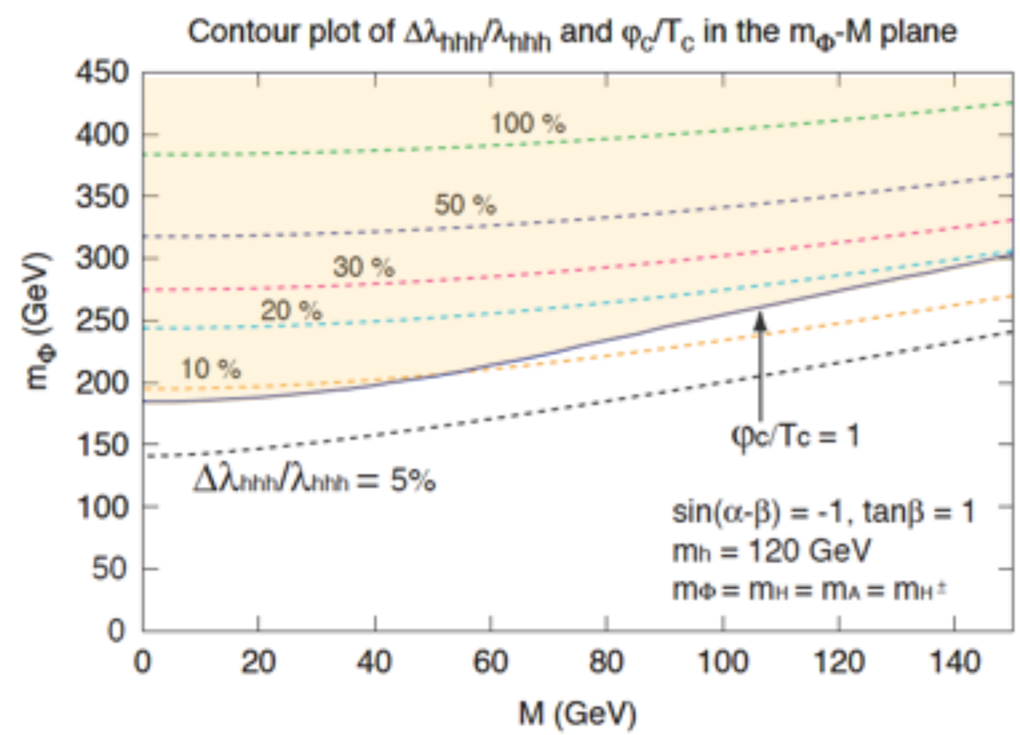
Extended Higgs sector (2HDM) helps achieve strong 1st-oder PT

GW from PT



Dorsch et al.1611.05874

Collider signature of PT



Kanemura Okada Senaha 0411354

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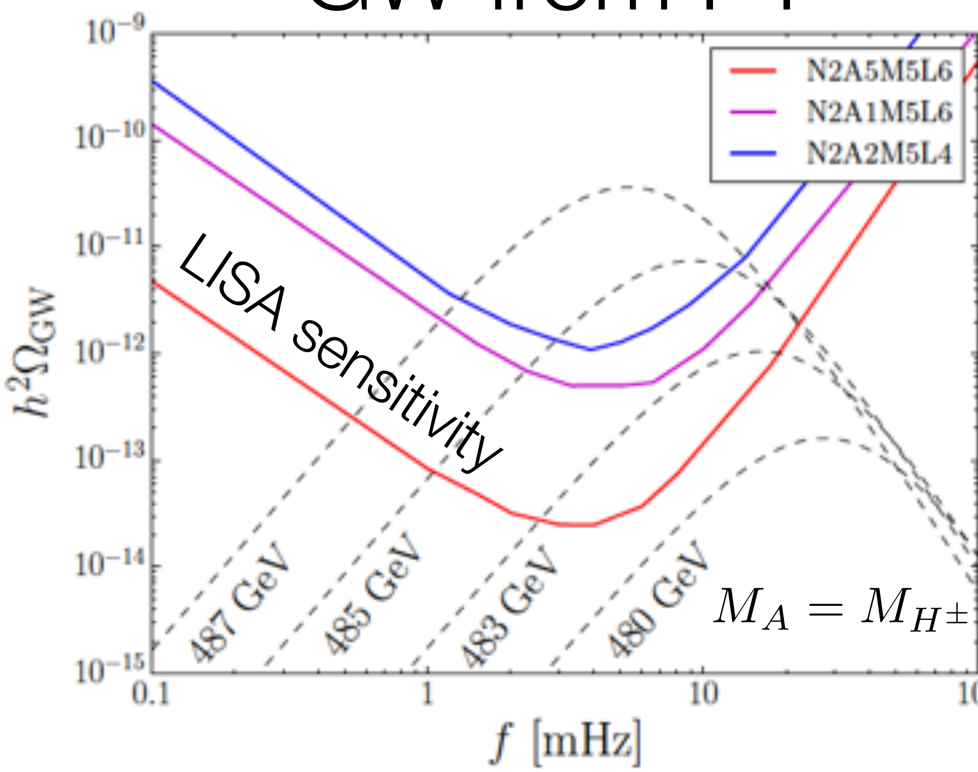

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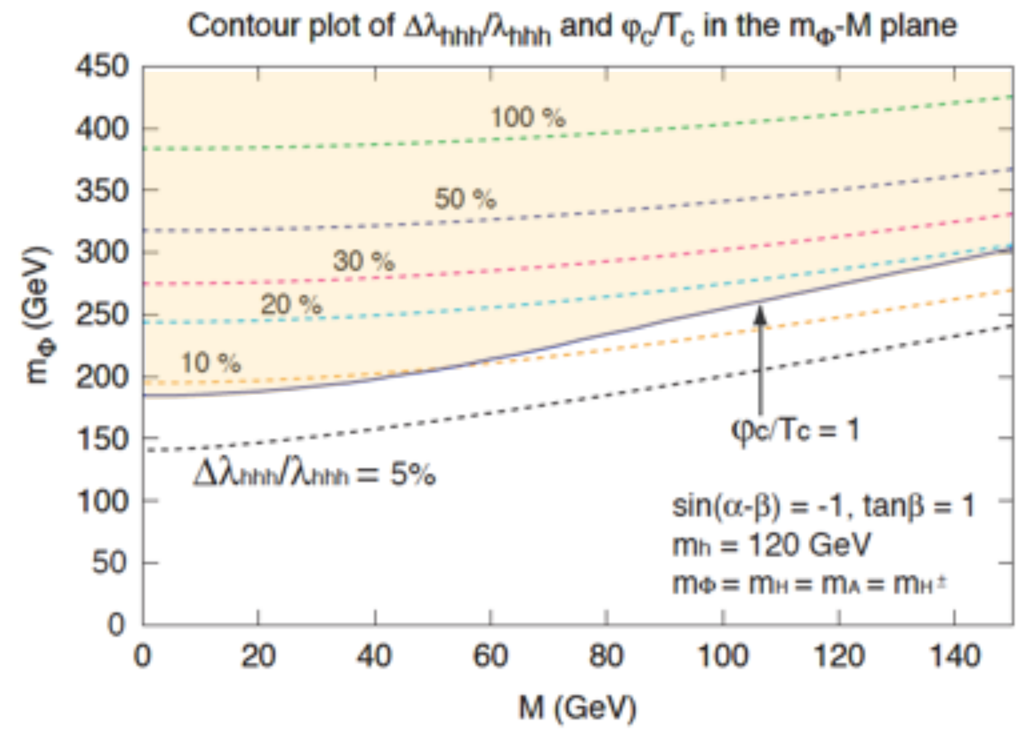

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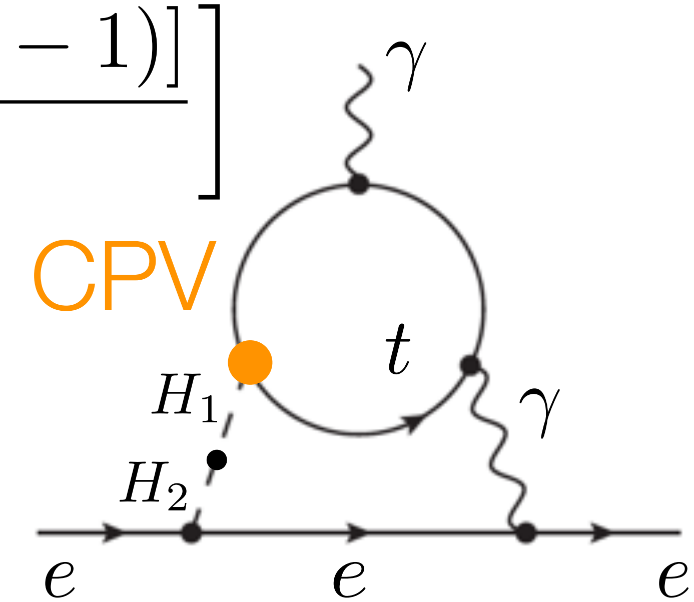
… and brings a new CP phase

$$m_t(z) = \frac{y_t v_1}{\sqrt{2}}\left[\frac{1+\tanh(z/\delta_w)}{2}\right]\exp\left[-i\frac{\Delta\theta[\tanh(z/\delta_w - 1)]}{2}\right]$$

Baryogengesis requires $\Delta\theta$

$\Delta\theta$ is related to parameters at T=0

Strongly constrained from eEDM



Barr Zee PRL65 (1990) 21

Extended neutrino sector for EWBG

ν EWBG

Inspired by low-energy Seesaw models for neutrino masses

$$\mathscr{L} = \frac{1}{2}\overline{\psi^c}\mathcal{M}\psi + \text{H.c.}$$

$$\psi = ({\nu_L}^c, N_R, {N_L}^c)^\mathsf{T}$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^\mathsf{T} & 0 & M_N^\mathsf{T} \\ 0 & M_N & \epsilon \end{pmatrix}$$

$$m_D = Y_\nu \langle H \rangle$$

$$M_N = Y_N \langle \phi \rangle$$

Mohapatra PRL 56 (1986) 561
Mohapatra Valle PRD34 (1986) 1642
Bernabeu et al. PLB187 (1987) 303

$$m_\nu = m_D^* {M_N^{-1}}^\mathsf{T} \epsilon^* M_N^{-1} m_D^\dagger$$ - Inverse seesaw

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$$m_\nu = m_D^* {M_N^{-1}}^\mathsf{T} \epsilon^* M_N^{-1} m_D^\dagger$$ - Inverse seesaw

1 New source of CPV (w. $\epsilon = O$)

$$d_{\rm CP} \equiv \frac{1}{2\mathrm{i}} \det \left[M_N^\dagger M_N, m_D^\dagger m_D \right] = F_{M_N} F_{m_D} J$$

Branco Rebelo Valle PLB225 (1989) 385
Santamaria 9302301

$N_{R,L}$ are SM singlets - avoid the EDM diagrams

For eEDM in inverse seesaw Abada Toma 1605.07643

2 Sphaleron converts CPV in L to B

3 Scalar potential with ϕ is good for 1st-order PhT

cf. e.g., Espinosa Konstandin Riva 1107.5441

vEWBG: How it works

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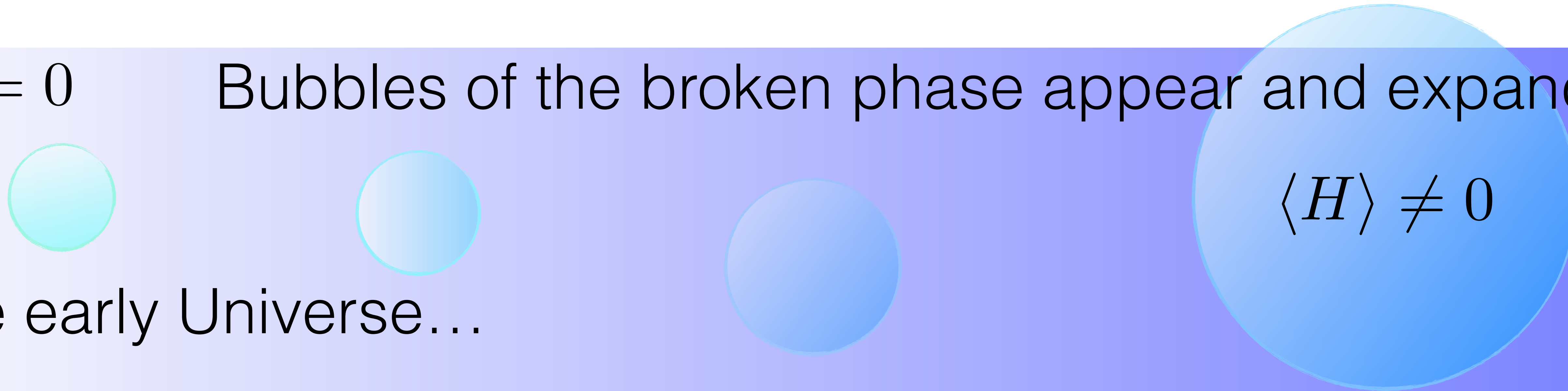
$\langle H \rangle = 0$

In the early Universe…

vEWBG: How it works

$\langle H \rangle = 0$

Bubbles of the broken phase appear and expand

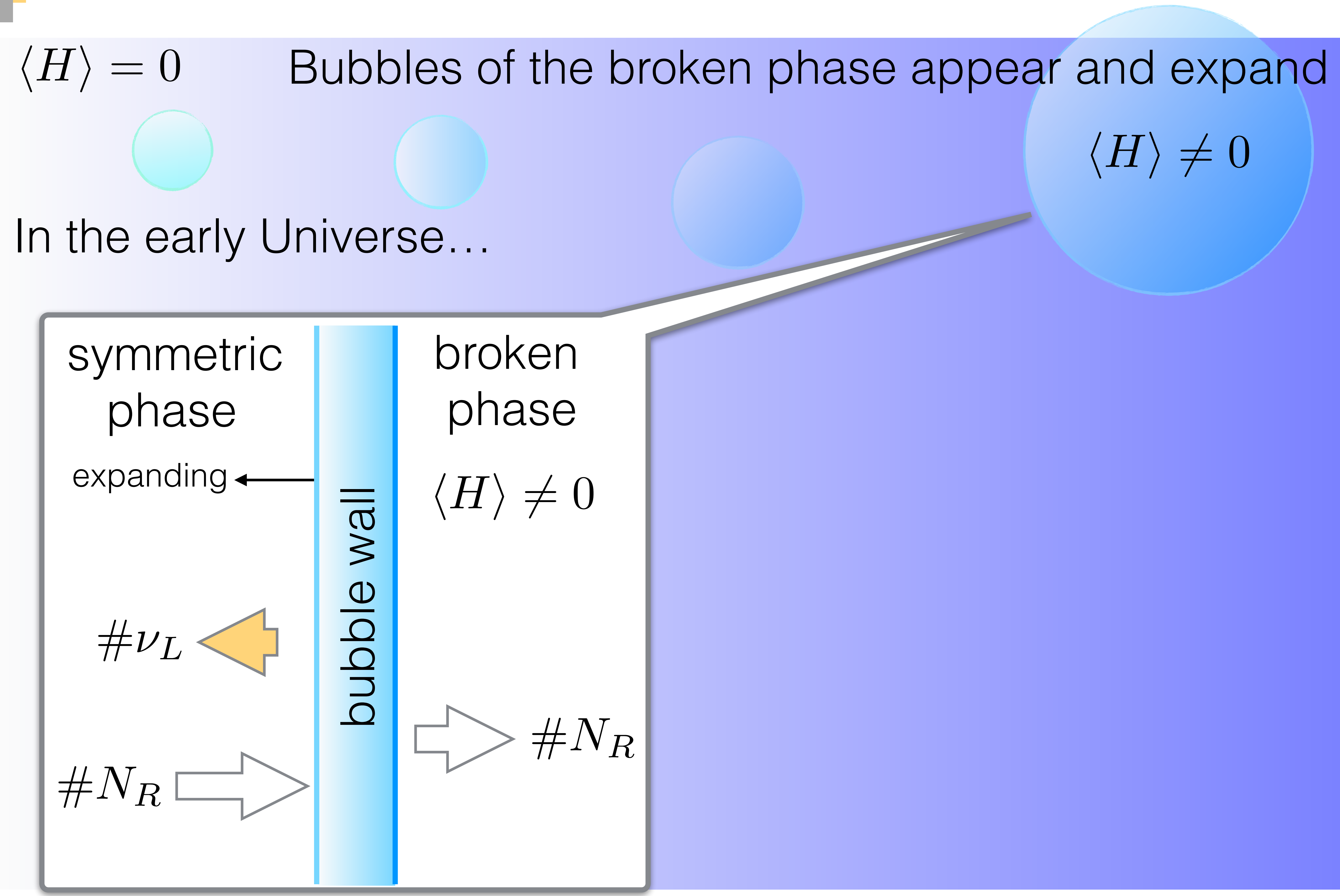


$\langle H \rangle \neq 0$

In the early Universe…

vEWBG: How it works

Hernandez Rius, 9611227



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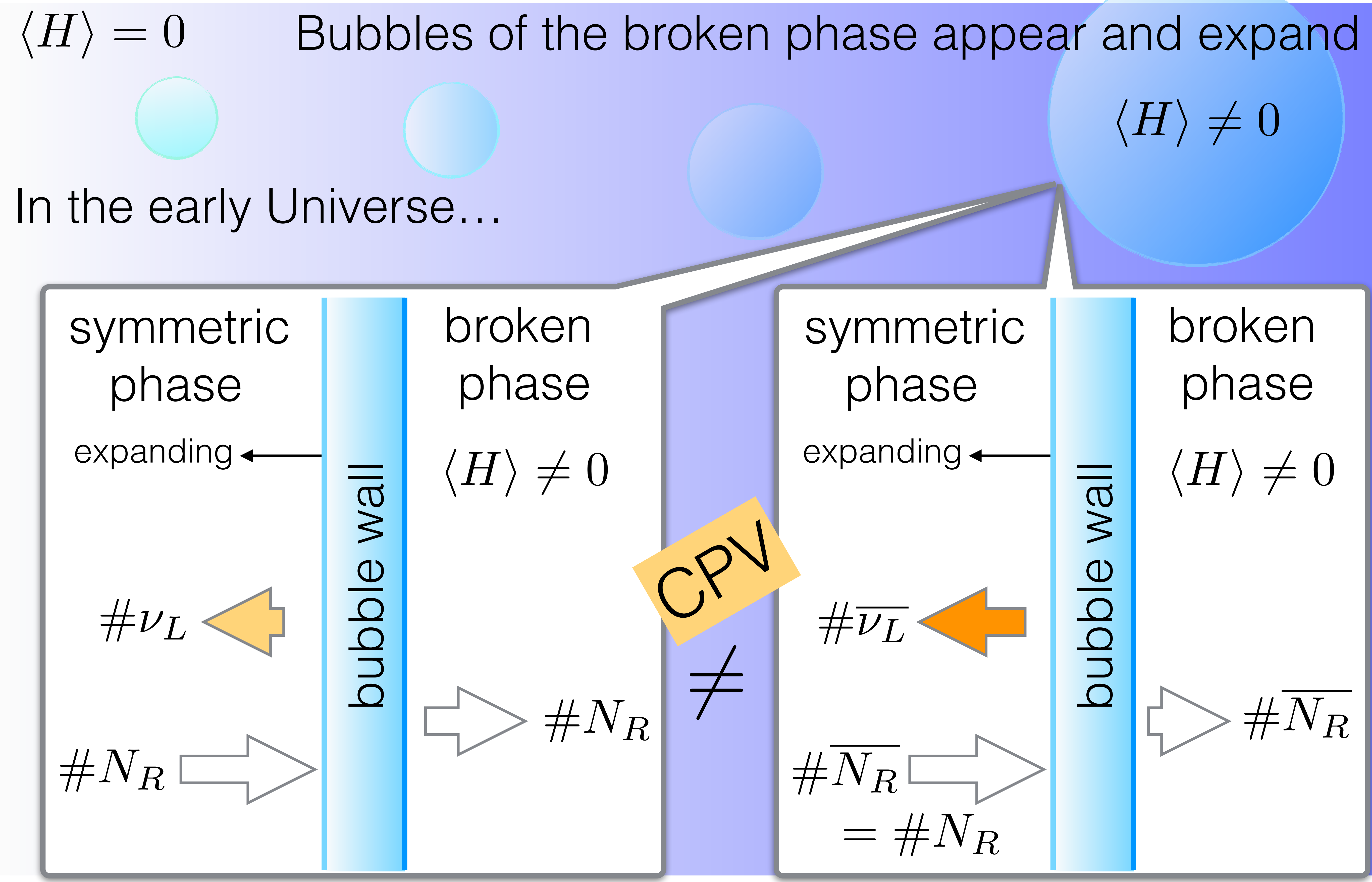

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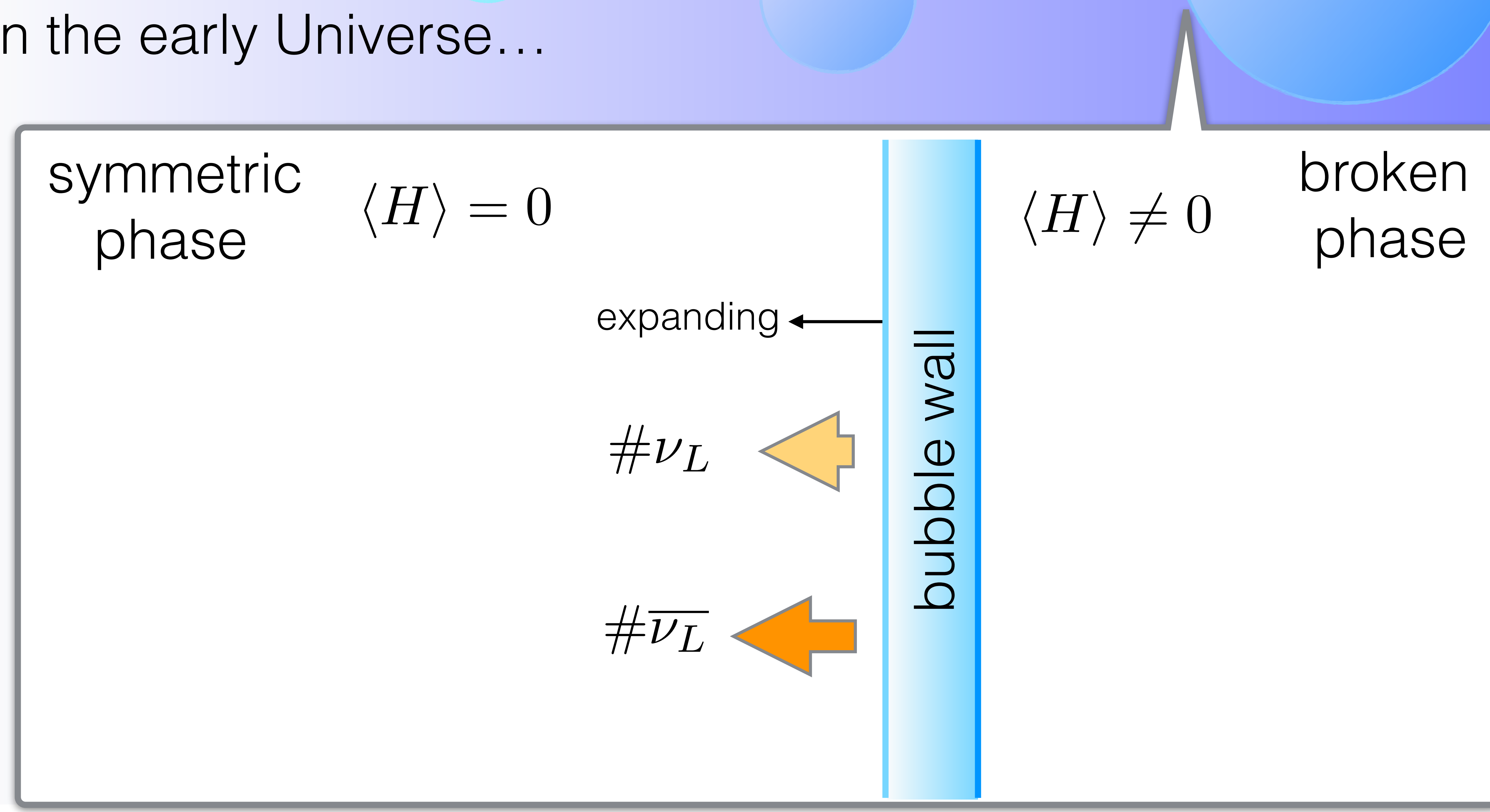

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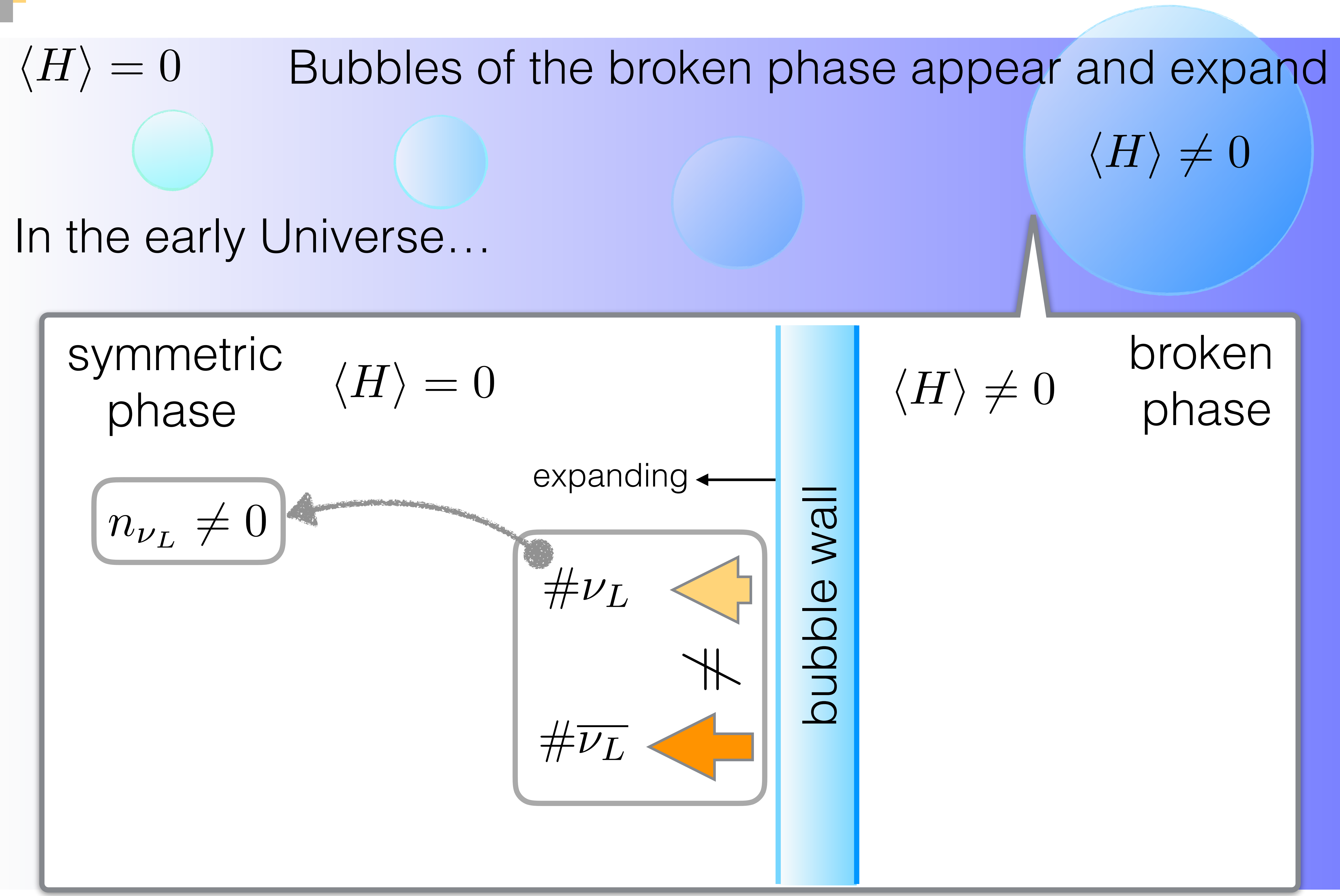

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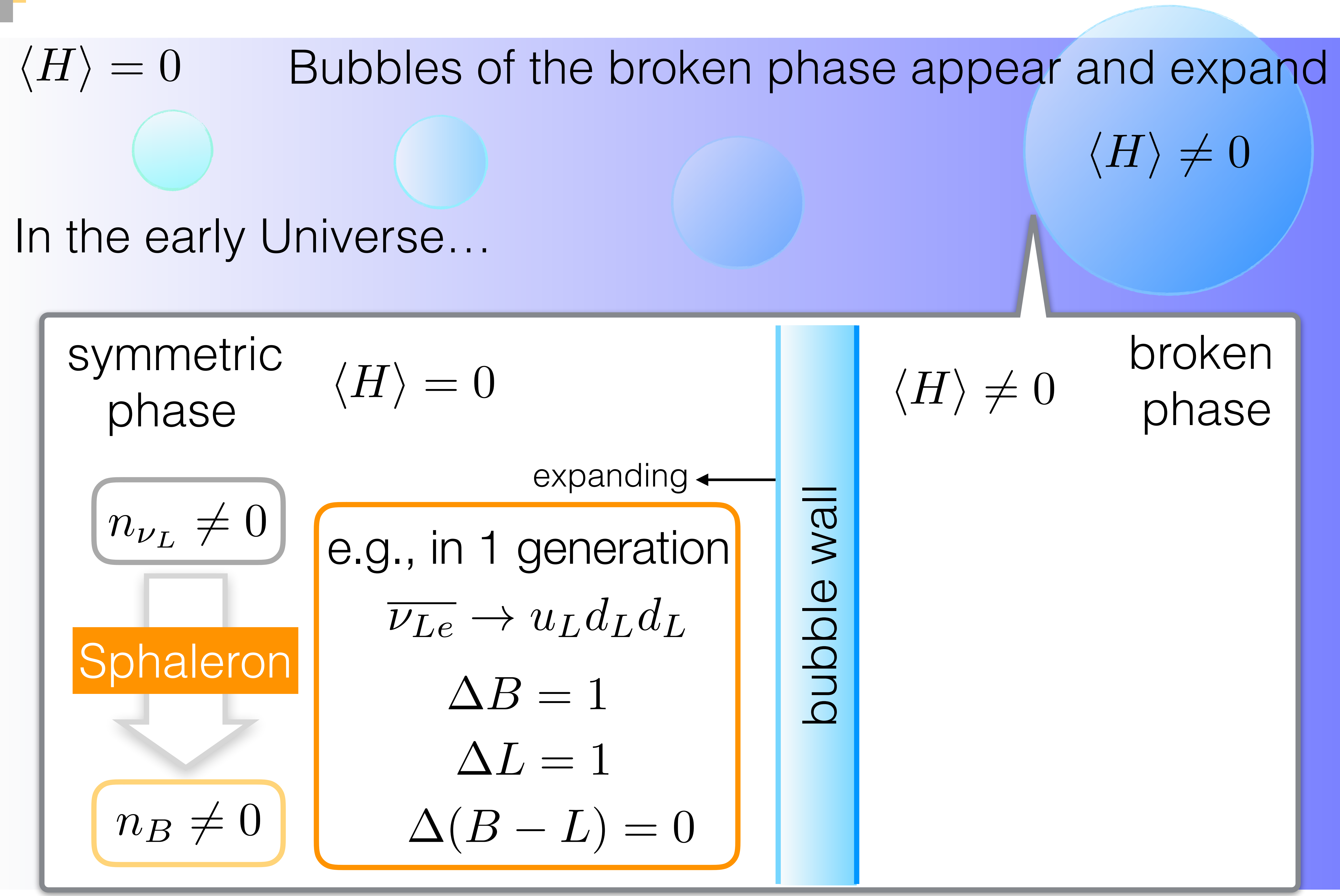

vEWBG: How it works

$\langle H \rangle = 0$

Bubbles of the broken phase appear and expand

$\langle H \rangle \neq 0$

In the early Universe…

symmetric phase

$\langle H \rangle = 0$

broken phase

$\langle H \rangle \neq 0$

expanding

bubble wall

$n_{\nu_L} \neq 0$

Sphaleron

$n_B \neq 0$

e.g., in 1 generation

$$\overline{\nu_{Le}} \to u_L d_L d_L$$

$$\Delta B = 1$$

$$\Delta L = 1$$

$$\Delta(B - L) = 0$$

Hernandez Rius, 9611227

vEWBG: How it works

$\langle H \rangle = 0$ Bubbles of the broken phase appear and expand

$\langle H \rangle \neq 0$

In the early Universe…

bubble wall

Sphaleron: OFF

$\langle H \rangle \neq 0$ broken phase

$$\Gamma_{\rm Sph.}\ [/(\text{time}\cdot\text{volume})] \sim T^4 \exp\left[-\frac{4\pi\langle H\rangle}{gT}\right]$$

To turn it off at T_c $\dfrac{\langle H \rangle}{T_c} \gtrsim 1$ "Strong" 1st order PhT

$n_B \neq 0$ → Baryon number is frozen out → η_B today

Hernandez Rius, 9611227

vEWBG: How it works

3 steps to baryon number…

1 Non-zero n_{ν_L} is generated at the front of a bubble wall

CPV in Yukawa interaction, d_{CP}

Reflection/Transmission rates at the bubble wall

2 n_{ν_L} is converted to n_B

Sphaleron process (B+L violation)

3 n_B is transported into the bubble

Sphaleron off (Out of equil.) = B frozen out

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Wave functions in the wall potential
Nelson Kaplan Cohen NPB373 (1992) 453

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Diffusion equations
Joyce Prokopec Turok 9410281

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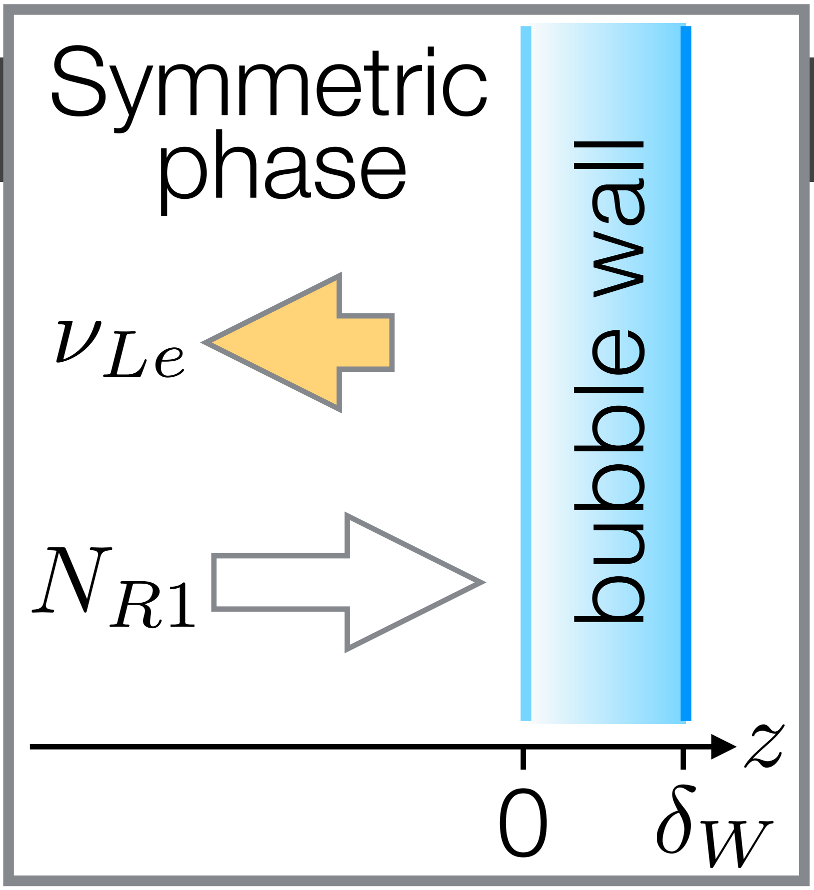
Step 1: CPV at the front of a bubble wall

Generate $n_{\nu_L} \equiv \#\nu_L - \#\overline{\nu_L} \neq 0$

Leptonic CPV at wall front

Wave equations with the wall potential



$$[i\partial_z + Q(z)]\,\psi(z) = 0$$

$$Q(z) = \begin{pmatrix} -E & m_D(z) & 0 \\ -m_D^\dagger(z) & E & -M_N^\dagger(z) \\ 0 & M_N(z) & -E \end{pmatrix}$$

$$\psi(z) = \Big(\nu_L(z), N_R(z), N_L(z)\Big)^{\mathsf{T}}$$

$$m_D(z) = \frac{y_D}{\sqrt{2}} v_H(z) \qquad M_N(z) = Y_N v_\phi(z) \qquad E = |p_z|$$

Reflection rate is calculated as…

e.g.,

Initial condition — Boundary condition

$$\mathcal{R}(N_{R1} \to \nu_{Le}) = |\nu_{Le}(0)|^2 \text{ with } N_R(0) = (1,0,0) \;\&\; \psi_{\leftarrow}(\delta_W) = \mathbf{0}$$

* For anti-neutrinos, $m_D(z) \to -m_D^*(z)$ & $M_N(z) \to -M_N^*(z)$ in $Q(z)$

To compute CPV, we have to fix Yukawas & the wall properties…

Leptonic CPV at wall front

A “wise choice” of the Yukawa structure is…

$$m_D = U_\ell \hat{m}_D V^\dagger \qquad U_\ell = \mathbb{1} \qquad V(\theta = \pi/4\,,\,\delta = \pi/2)$$

$$\hat{m}_D = \hat{m}_{D\tau}\left(\frac{1}{\sqrt{2}}, 0, 1\right)$$

To enhance d_{CP}
- maximal mixing and phase in V
- mass hierarchy in $\hat{m}_D$

To avoid the tight bound to $(\Theta\Theta^\dagger)_{\mu\mu}$

Bubble wall properties

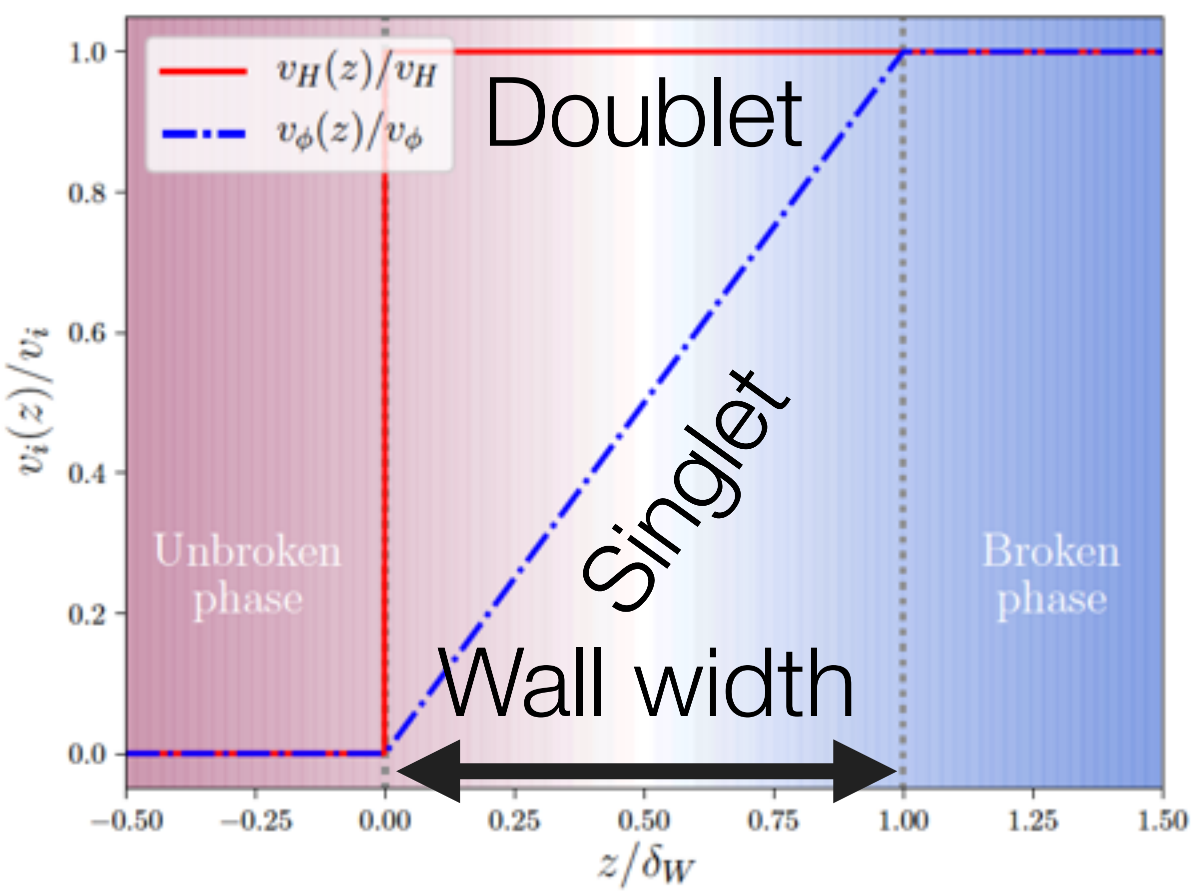
Here we simply assume

Wall width - thin wall regime

$$\delta_W = \{0.10, 0.15\}\mathrm{GeV}^{-1}$$

Wall speed

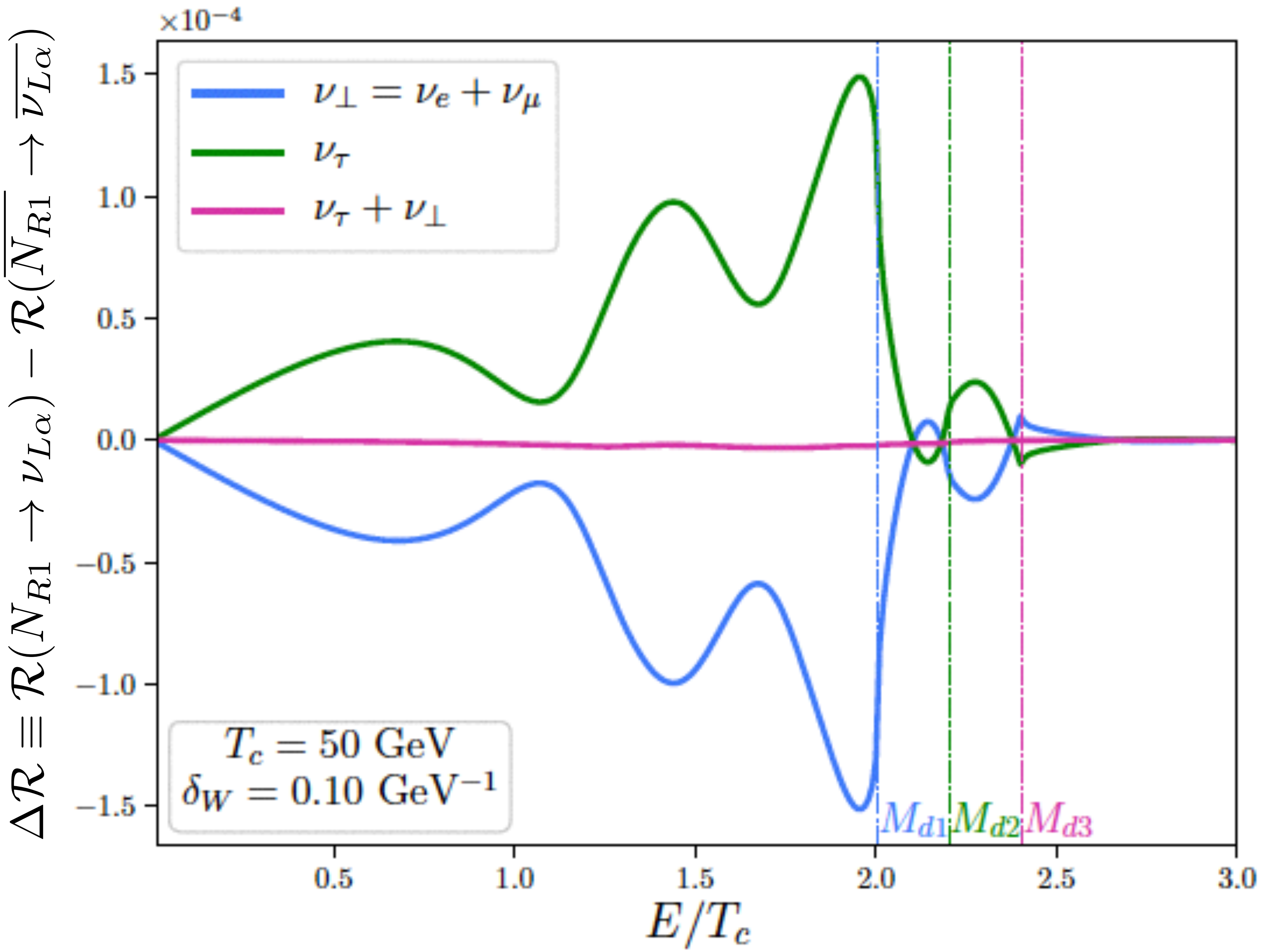
$$v_W = 0.1c$$

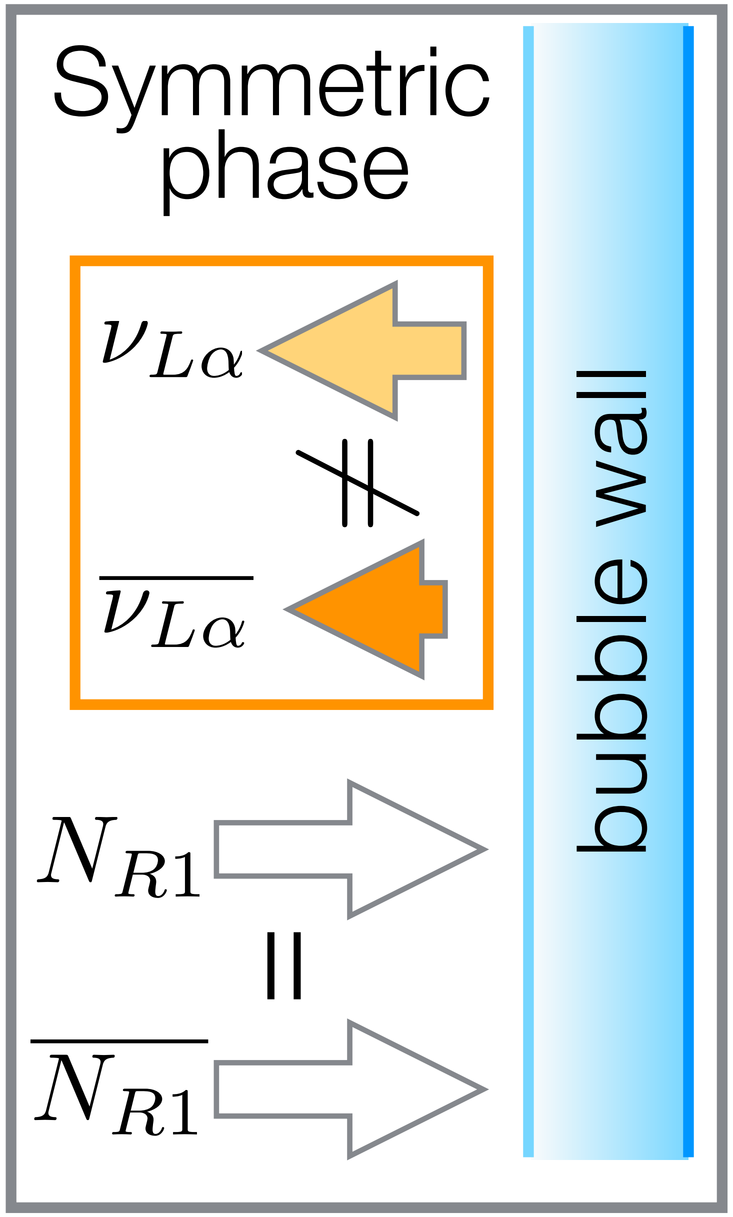


* All the properties must be determined from the scalar potential at T_c .

Leptonic CPV at wall front

CPV after reflection





+ Transmission: $\Delta\mathcal{T} \equiv \mathcal{T}(N_L \to \nu_{L\alpha}) - \mathcal{T}(\overline{N_L} \to \overline{\nu_{L\alpha}})$

Step 2&3: Diffusion equations

n_{ν_L} $\xrightarrow{\text{Sphaleron}}$ n_B $\xrightarrow[\text{the broken phase}]{\text{Transport to}}$ n_B frozen out

CPV to final baryon number

We've calculated

Total CPV flux at the wall front

$$j_{\nu_L} = \sum_\alpha \sum_i \int \mathrm{d}^3\mathbf{p}_{N_{Ri}} \Delta\mathcal{R}(N_{Ri} \to \nu_{L\alpha}) \times (\text{distribution func.of } N_{Ri})$$

+ Contribution from Transmission

CPV to final baryon number

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+ Contribution from Transmission

Diffusion (transportation) equations

Joyce Prokopec Turok 9410281
Hernandez Rius 9611227

$$\begin{cases} D_B \partial_z^2 n_B - v_W \partial_z n_B - 3\Gamma_S \theta(-z) n_B - \Gamma_S \theta(-z) n_L = 0 \\ D_L \partial_z^2 n_L - v_W \partial_z n_L - 3\Gamma_S \theta(-z) n_B - \Gamma_S \theta(-z) n_L = \xi_L j_{\nu_L} \partial_z \delta(z) \end{cases}$$

$$B = n_B(z > 0) = \frac{\Gamma_S}{D_L \kappa_1 \kappa_2 \left[\frac{D_B}{v_W}(\kappa_1 + \kappa_2) - 1 \right]} \frac{\xi_L}{D_L} j_{\nu_L}$$

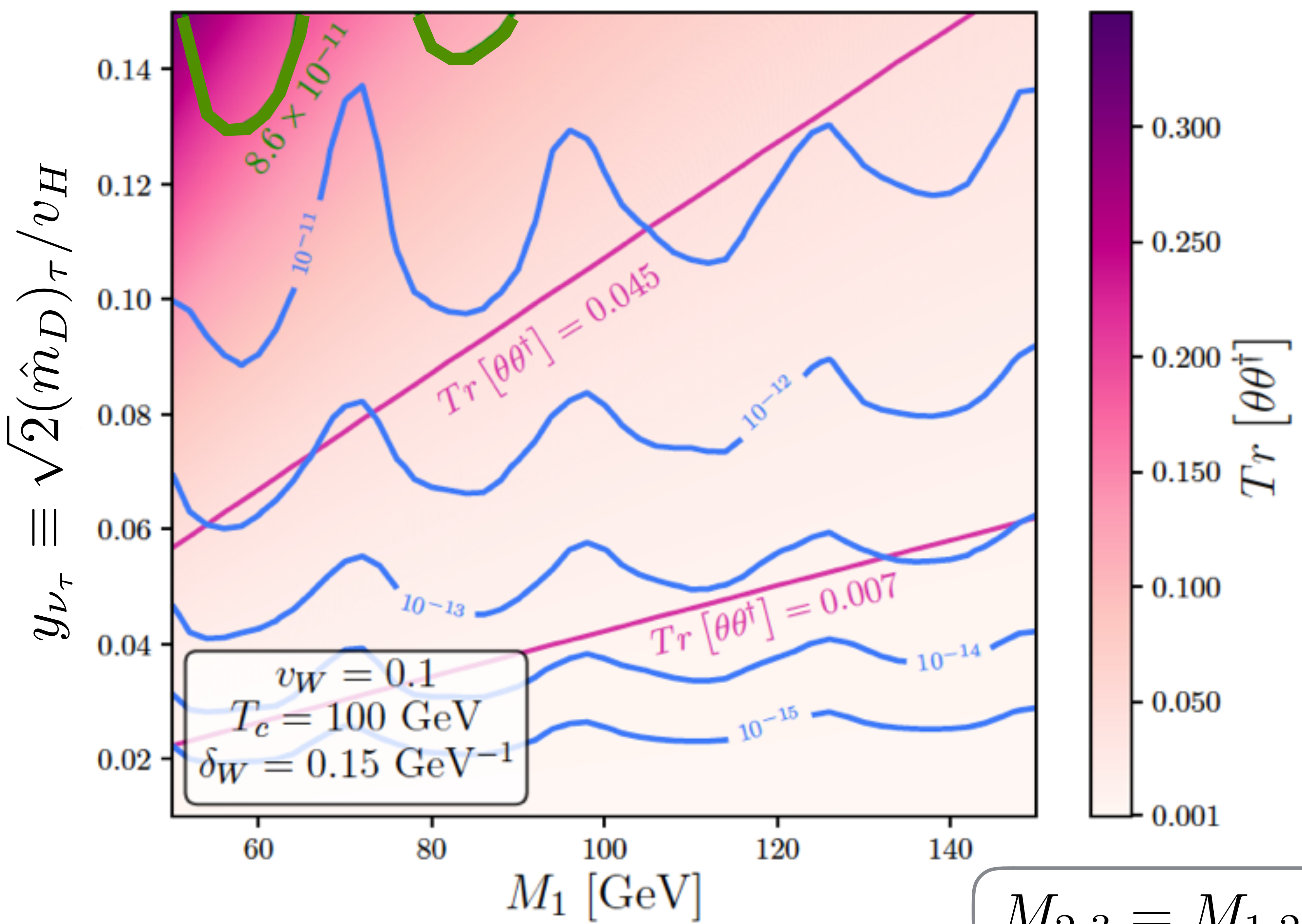
$\kappa_{1,2}$ are given as the two positive solutions of the following cubic eq.

$$D_B D_L \kappa^3 - v_W (D_B + D_L)\kappa^2 + \left[v_W^2 - \Gamma_S (D_B + 3D_L) \right] \kappa + 4 v_W \Gamma_S = 0$$

Let us calculate $\eta_B = B/s(T_c)$ and compare to the observation…

CPV to final baryon number

Baryon number $\eta_B = B/s(T_c)$



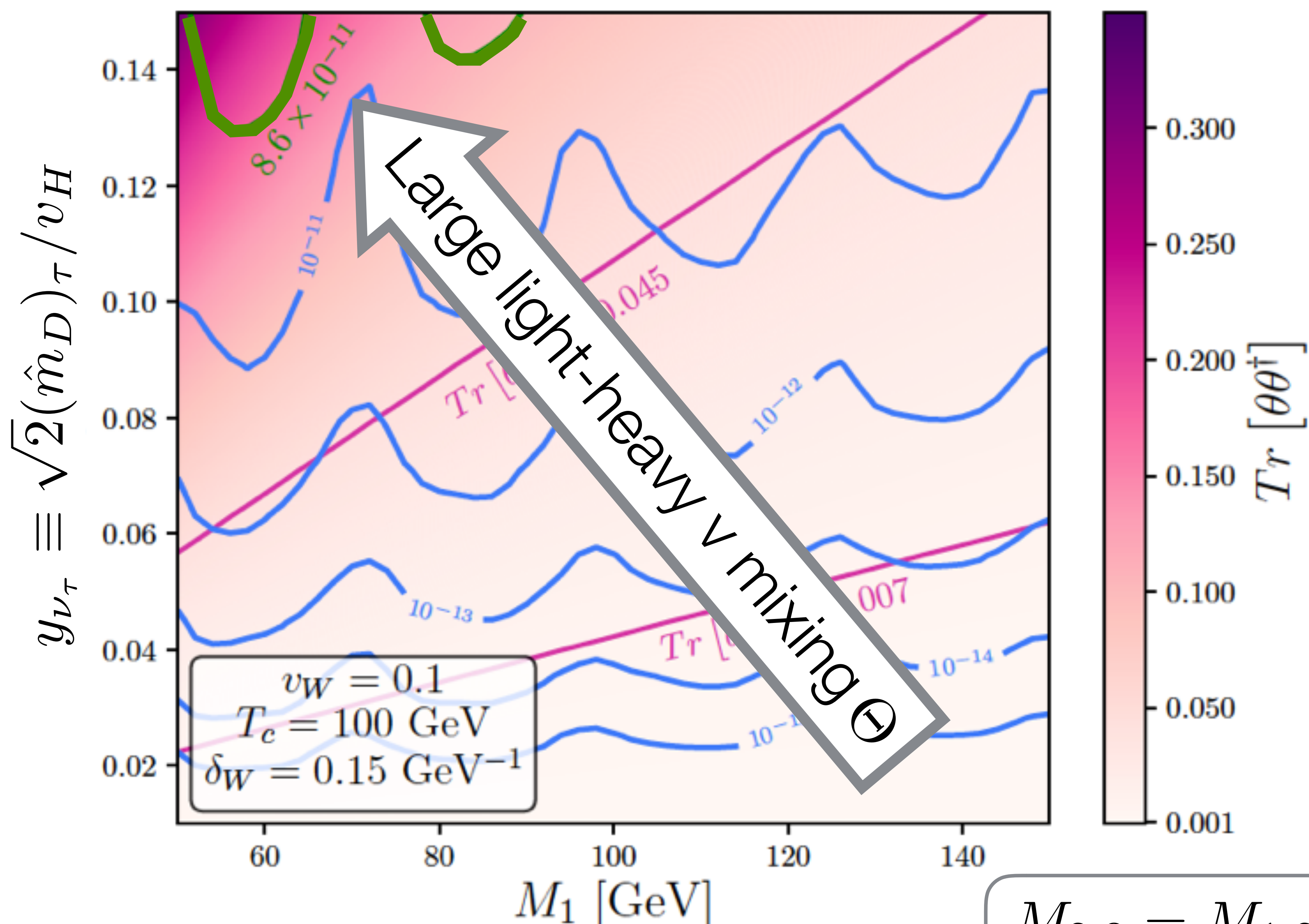
For the bounds from heavy v mixing,
Fernandez-Martinez Hernandez-Garcia Lopez-Pavon
1605.08774

$M_{2,3} = M_{1,2} + 10\text{GeV}$

CPV is too small to reproduce the correct baryon asym today…

CPV to final baryon number

Baryon number $\eta_B = B/s(T_c)$



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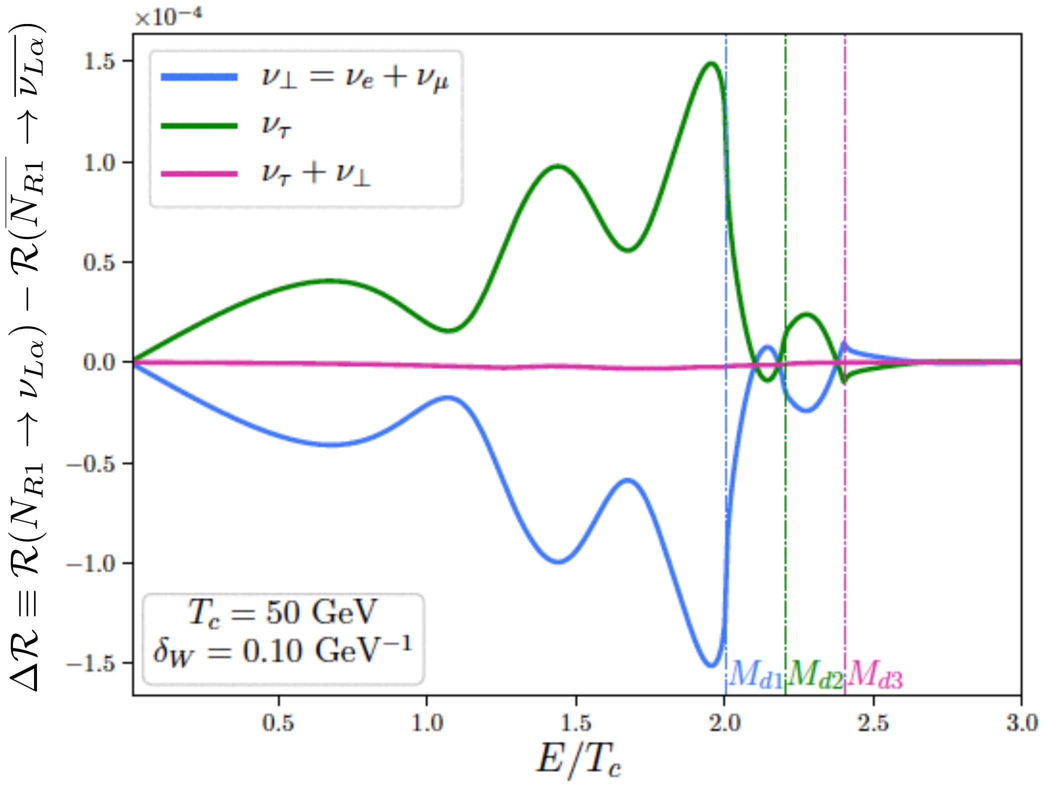
CPV is too small to reproduce the correct baryon asym today…

Is there a way-out?

$$d_{\rm CP} \propto \det\left[M_N^\dagger M_N, m_D^\dagger m_D\right]$$

$$m_D = U_\ell \hat{m}_D V^\dagger \ \&\ M_N = \hat{M}_N$$

The sum of the CPV over the flavour index is very suppressed…



Strong cancelation of CPV among flavors ($\nu_e + \nu_\mu$ + ν_τ = magenta ~ 0),

which is not an accident, but caused by the GIM mechanism

$$j_{\nu_L} \propto \sum_\alpha \Delta\mathcal{R}(N_{R1} \to \nu_{L\alpha}) \propto \sum_{\alpha,\beta} \sum_j d_{\rm CP}(\alpha,\beta,1,j) f(\alpha,\beta,j)$$

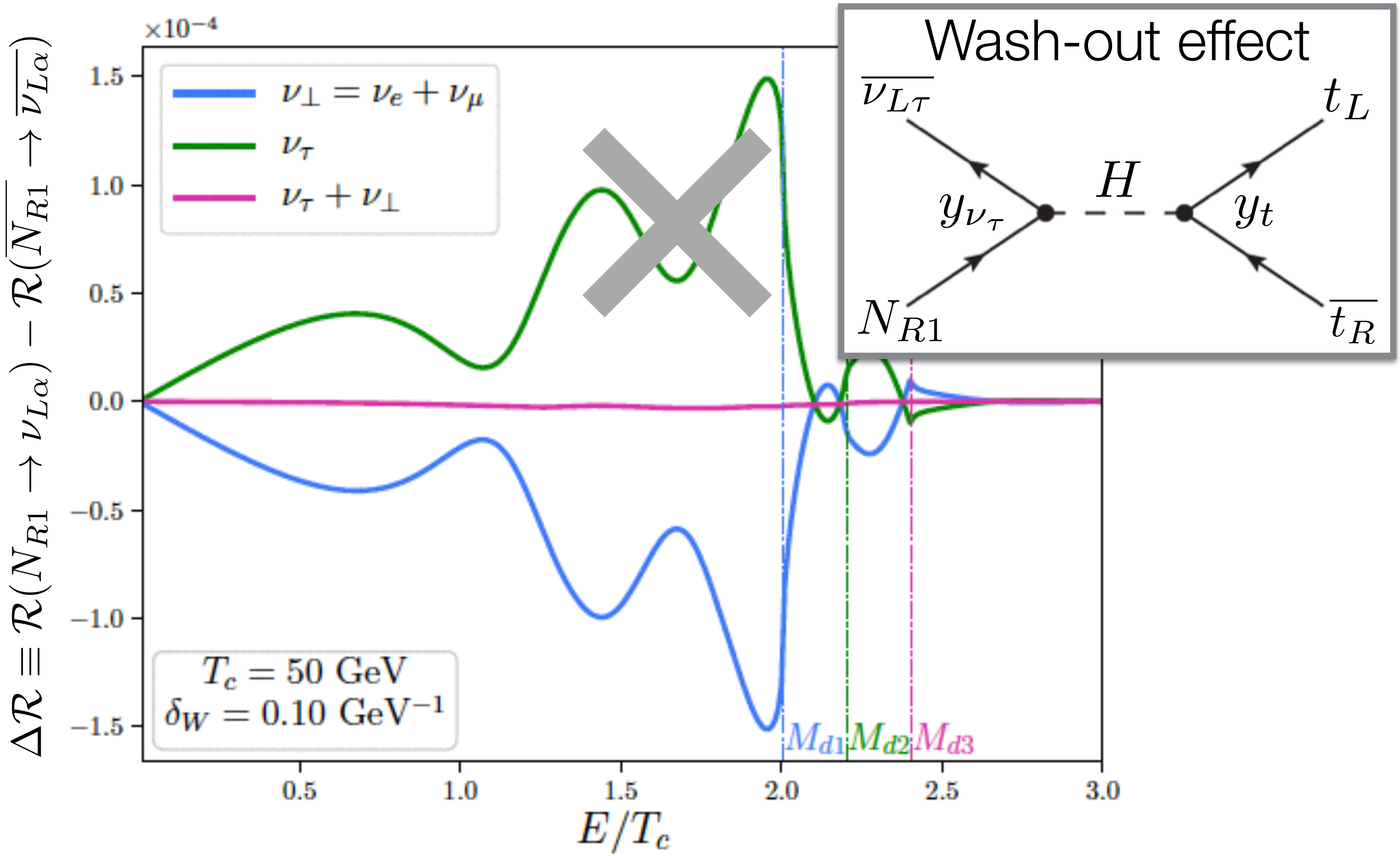
$$\sum_{\alpha,\beta} {\rm Im}\left[V_{\alpha 1} V^*_{\alpha j} V^*_{\beta 1} V_{\beta j}\right] = 0$$

Only stays the part proportional to the mass difference (as GIM).

Reason of our defeat was the sum over the final neutrino flavour

Is there a way-out?

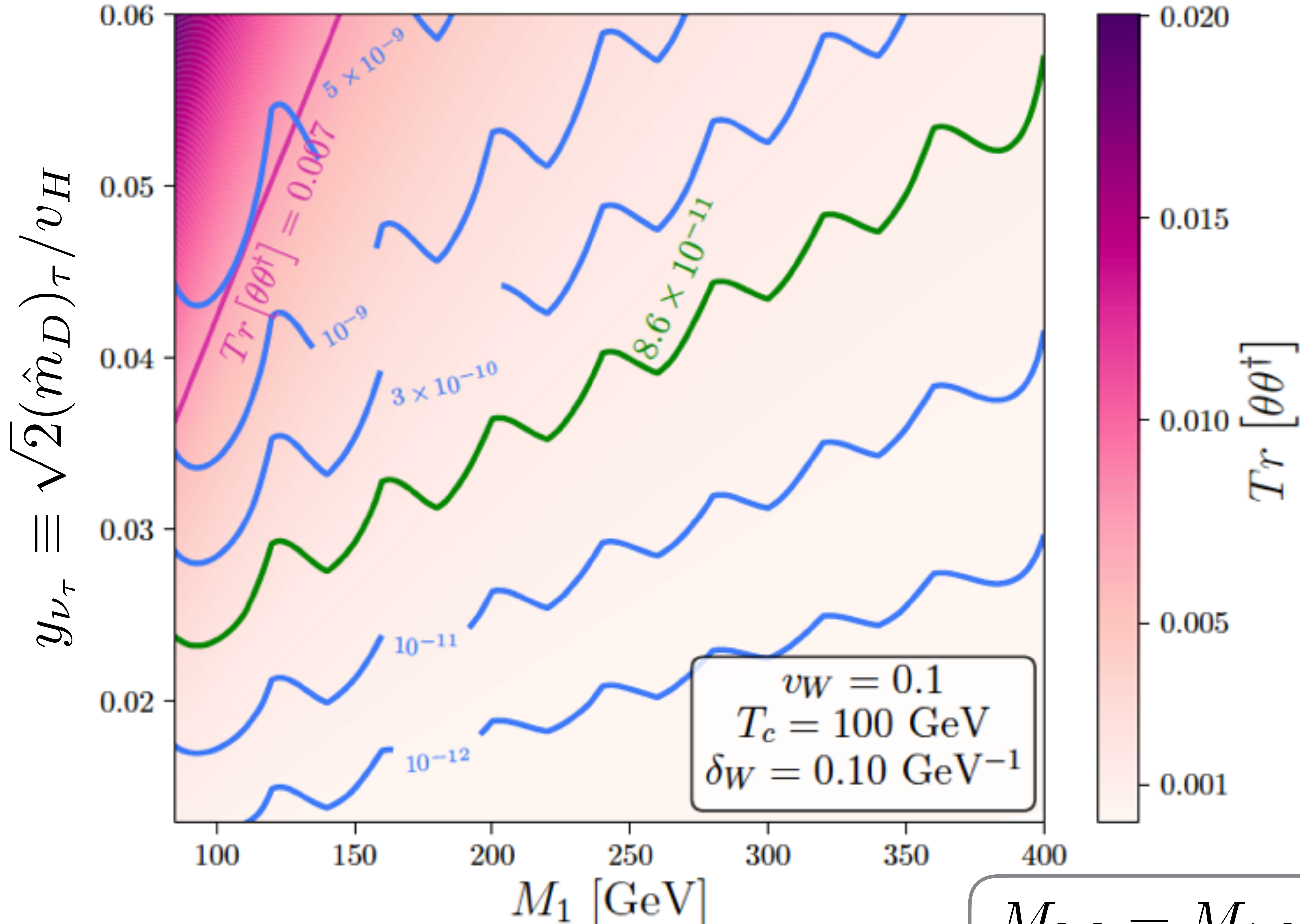
Wash-out allows us to use CPV in each flavour



Solve the diffusion equations with the wash-out effect…

Flavour effect

Baryon number $\eta_B = B/s(T_c)$



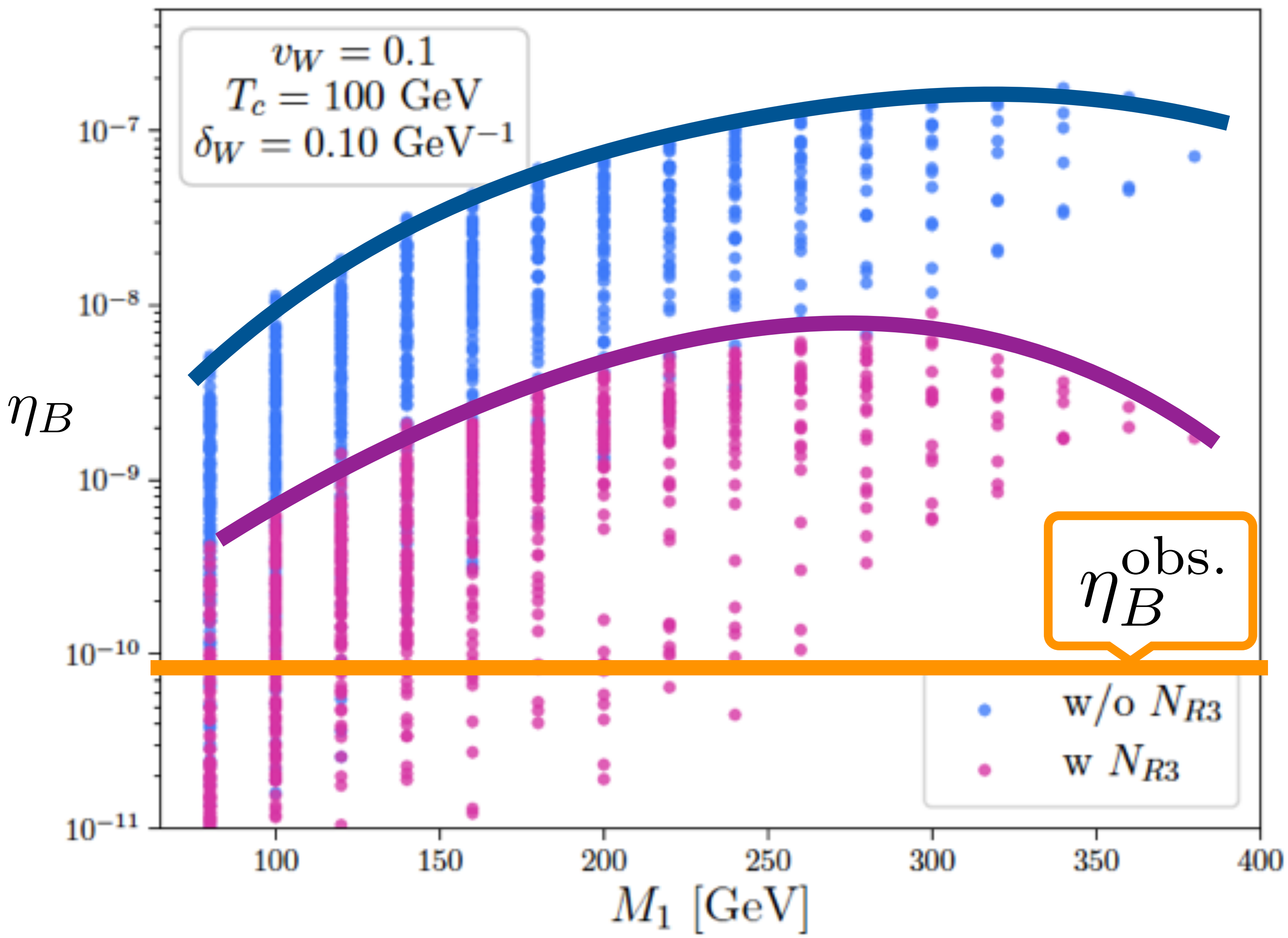
For the bounds from heavy ν mixing,
Fernandez-Martinez Hernandez-Garcia Lopez-Pavon
1605.08774

$M_{2,3} = M_{1,2} + 10\text{GeV}$

Flavour effect is crucial to reproduce the baryon asymmetry

More on flavour effect

Scan the values of $M_{2,3}$ $M_{i+1} = [M_i + 10, 400]$ GeV



Pros&cons of large M_i

- More efficient wash-out but less diffusion
- CPV from transmission gets suppressed with Boltzmann factor
- Large hierarchy in M_i enhances $d_{\rm CP}$

etc.

Not only wash-out but also the asymmetry in N_R comes into the game

Inclusion of N_{R3} reduces CPV → GIM cancellation

We have a good chance to reproduce the correct B/s

Wrap-up & Work in progress

1 vEWBG Maybe we were neutrinos born at a bubble

…overcomes shortcomings of EWBG in the SM;

1st-order EWPT with ϕ, a new CP phase, and neutrino mass

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…suffers the GIM suppression and cannot reproduce B/s.

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Large CPV requires large light-heavy mixings → good for pheno.

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3 Flavour effect (Wash-out effect)

Thanks to the flavor-dependent wash-out effect,
we can access to CPV in each flavour.

To have large wash-out effect, we need large Y_ν
which suggests large M_i but we want to keep Y_N small for diffusion.

We have a good chance to reproduce the correct B/s

Work-in-progress

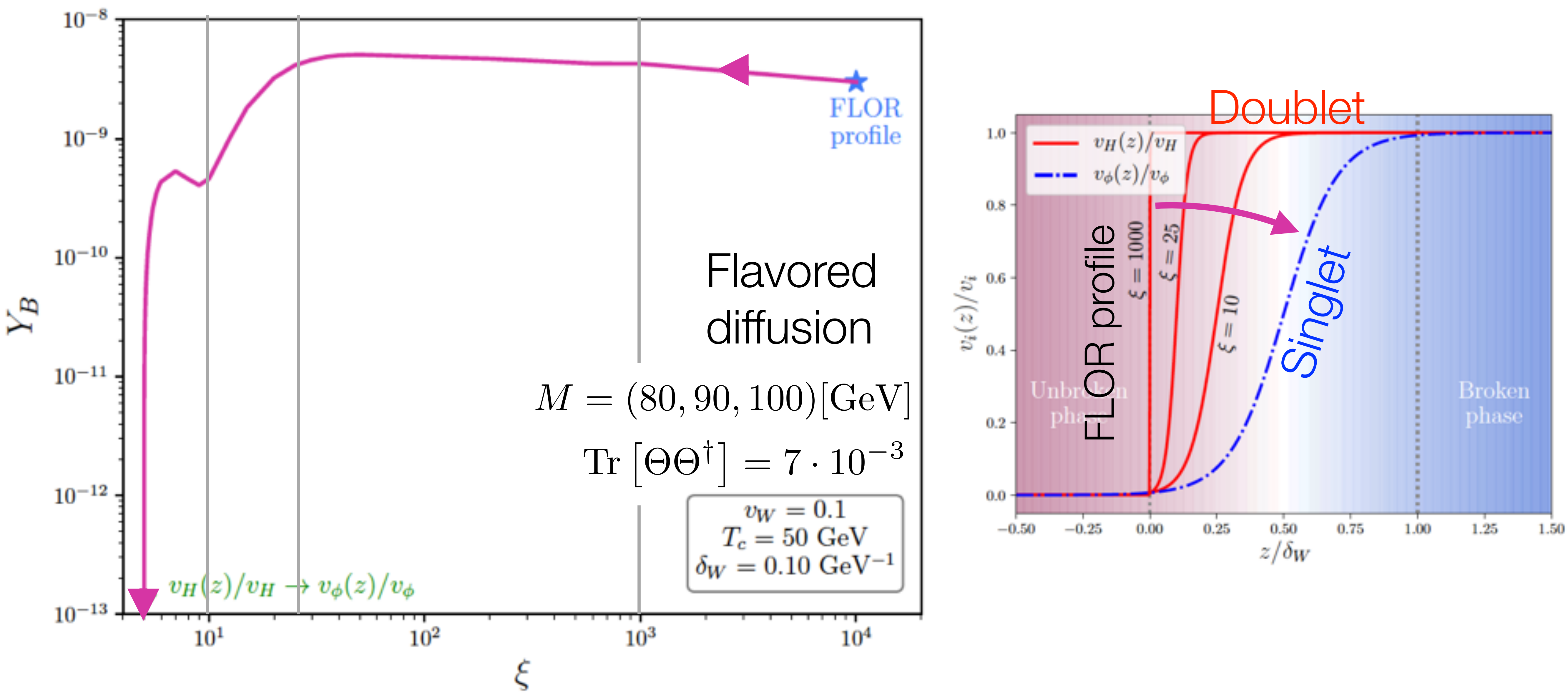
What are realistic wall properties?
 - We should derive wall properties from scalar potentials

We need more discussion on related phenomenologies…
 - vEWBG (Large CPV, Successful PhT etc.) vs Observables

Improve the treatment of the diffusion equations.

Backup

Dependence on wall profile



Offset of the two vevs is necessary for z-dependent CP phase

Nelson Kaplan Cohen NPB373 (1992) 453

FLOR vs HR - 2-3 orders of magnitude different in final B/s

Diffusion eqs w. flavour effect

Joyce Prokopec Turok 9410281

$$\begin{cases} D_B \partial_z^2 n_B - v_W \partial_z n_B - 3\Gamma_{\rm S}\theta(-z) n_B - \Gamma_{\rm S}\theta(-z) n_L = 0 \\ D_L \partial_z^2 n_{\nu_\alpha} - v_W \partial_z n_{\nu_\alpha} - 3\Gamma_{\rm S}\theta(-z) n_B - \Gamma_{\rm S}\theta(-z) n_L \\ \qquad - \sum_i \Gamma_{N_i \nu_\alpha} \left[\frac{1}{2} n_{\nu_\alpha} - n_{N_i} \right] = \xi_L j_{\nu_\alpha} \partial_z \delta(z) \\ D_{N_i} \partial_z^2 n_{N_i} - v_W \partial_z n_{N_i} + \sum_\alpha \Gamma_{N_i \nu_\alpha} \left[\frac{1}{2} n_{\nu_\alpha} - n_{N_i} \right] = \xi_{N_i} j_{N_i} \partial_z \delta(z) \end{cases}$$

$$n_L \equiv \sum_\alpha n_{\nu_\alpha}$$

In the flavored scenario, CPV in n_L is generated with

#1. the wash-out of n_{ν_τ}

#2. the asymmetry in $n_{N_{Ri}}$

CPV: d_CP

$$d_{\mathrm{CP}} = \frac{1}{2\mathrm{i}}\det\left[M_N^\dagger M_N, m_D^\dagger m_D\right]$$

$$F_q \equiv (m_{q_3}^2 - m_{q_2}^2)(m_{q_3}^2 - m_{q_1}^2)(m_{q_2}^2 - m_{q_1}^2)$$

$$= F_{M_N} F_{m_D} \mathrm{Im}\left[V_{ia}V_{ib}^* V_{ja}^* V_{jb}\right]$$

$$m_D = (U_\ell)_{\alpha a}\hat{m}_{Da}(V^\dagger)_{ai}$$

$$= M_1^2 M_2^2 M_3^2 F_{M_N} \mathrm{Im}\left[(\Theta^\dagger\Theta)_{12}(\Theta^\dagger\Theta)_{23}(\Theta^\dagger\Theta)_{31}\right]$$

$$(\Theta)_{\alpha i} \equiv (m_D)_{\alpha i}(M^{-1})_i$$

To have large CPV,

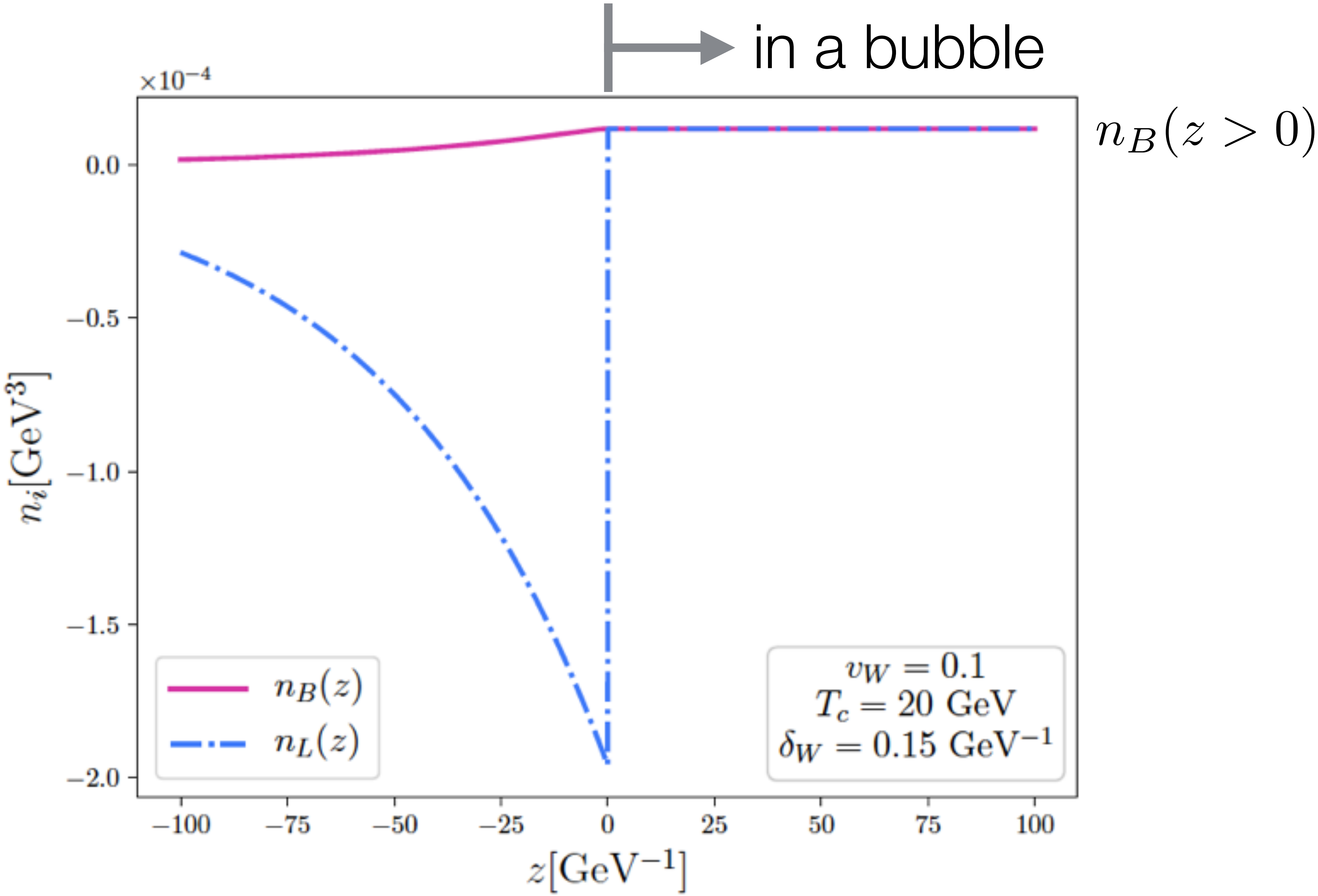
large mass hierarchies F_{M_N} F_{m_D}

&large mixing and phase J

large mass and hierarchy in M_N F_{M_N}

&large light-heavy mixing Θ

Solution of diffusion eqs.



$$
\begin{cases}
D_B \partial_z^2 n_B - v_W \partial_z n_B - 3\Gamma_{\mathrm{S}} \theta(-z) n_B - \Gamma_{\mathrm{S}} \theta(-z) n_L = 0 \\
D_L \partial_z^2 n_L - v_W \partial_z n_L - 3\Gamma_{\mathrm{S}} \theta(-z) n_B - \Gamma_{\mathrm{S}} \theta(-z) n_L = \xi_L j_{\nu_L} \partial_z \delta(z)
\end{cases}
$$