ν Electroweak Baryogenesis

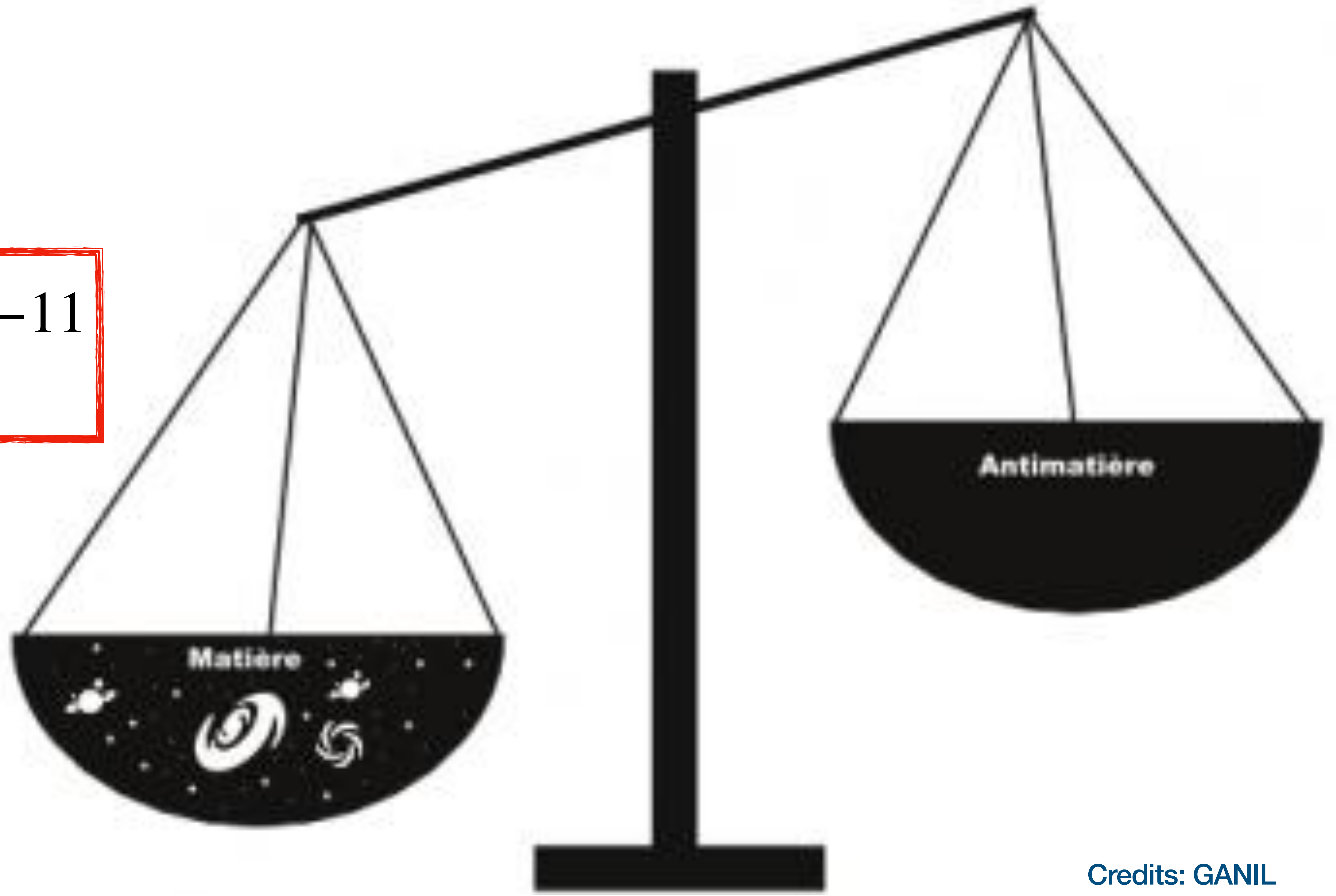
Salvador Rosauro-Alcaraz
Planck2022, Paris
30/05/22

In collaboration with E. Fernández-Martínez, J. López-Pavón
& T. Ota based on JHEP 10 (2020) 063

Introduction

Planck Collaboration, arXiv:1807.06209

$$Y_B^{obs} = \frac{n_b - n_{\bar{b}}}{s} \simeq (8.59 \pm 0.08) \times 10^{-11}$$



Credits: GANIL

Introduction

Generation of a BAU

Sakharov's conditions

- C and CP violation
- B violation
- Out-of-equilibrium conditions

A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5 (1967) 32-35

Introduction

Generation of a BAU

Electroweak baryogenesis

Shaposhnikov, Nucl. Phys B287 (1987)

CP violation from CKM matrix

$B + L$ violation from sphalerons

Kuzmin, Rubakov & Shaposhnikov, Phys. Lett. 155B (1985) 36

1^{st} order phase transition

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Kuzmin, Rubakov & Shaposhnikov, Phys. Lett. 155B (1985) 36

1^{st} order phase transition

K. Kajantie, M. Laine, K. Rummukainen, & M. E. Shaposhnikov, arXiv:hep-ph/9605288

Sakharov's conditions

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Electroweak baryogenesis with new physics

Electroweak baryogenesis

Shaposhnikov, Nucl. Phys B287 (1987)

CP violation from CKM matrix → New sources of CP violation

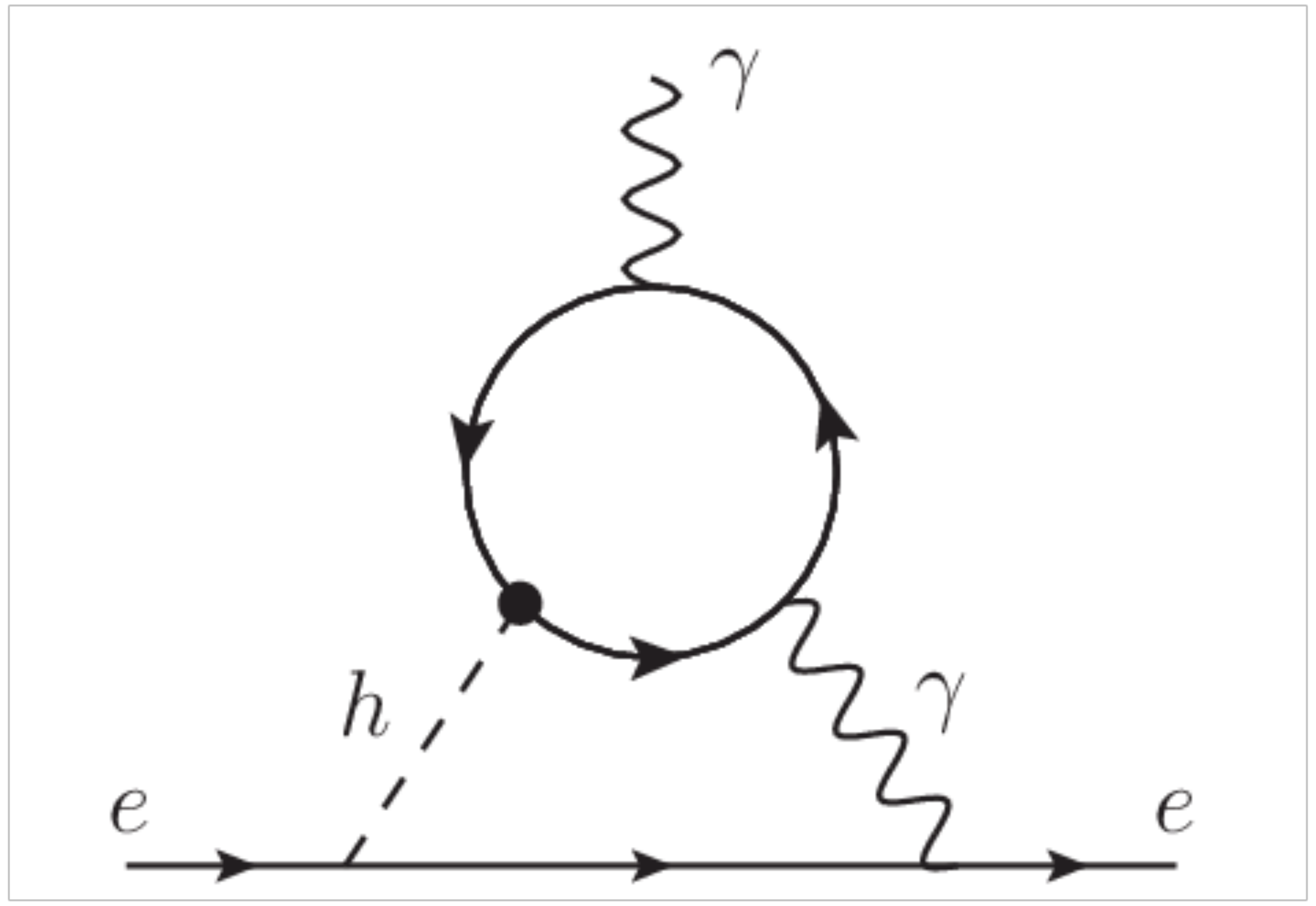
$B + L$ violation from sphalerons

Kuzmin, Rubakov & Shaposhnikov, Phys. Lett. 155B (1985) 36

1^{st} order phase transition → Add scalar singlet ϕ

M. Dine, P. Huet, R. L. Sigleton, Jr & L. Susskind, Phys. Lett. B257 (1991)
J. R. Espinosa, T. Konstandin & F. Riva, arXiv: 1107.5441

Bounds on new CP violation



G. Panico, M. Riembau, T. Vantalon, arXiv:1712.06337

Tight bounds from the electron's EDM

$$|d_e| < 1.1 \times 10^{-29} e \cdot cm$$

ACME Collaboration, Nature 562 (2018)

Rely on some dark sector to introduce new CP violation

E. Hall, T. Konstandin, R. McGehee, H. Murayama & G. Servant, arXiv: 1910.08068
M. Carena, M. Quirós & Y. Zhang, arXiv: 1811.09719

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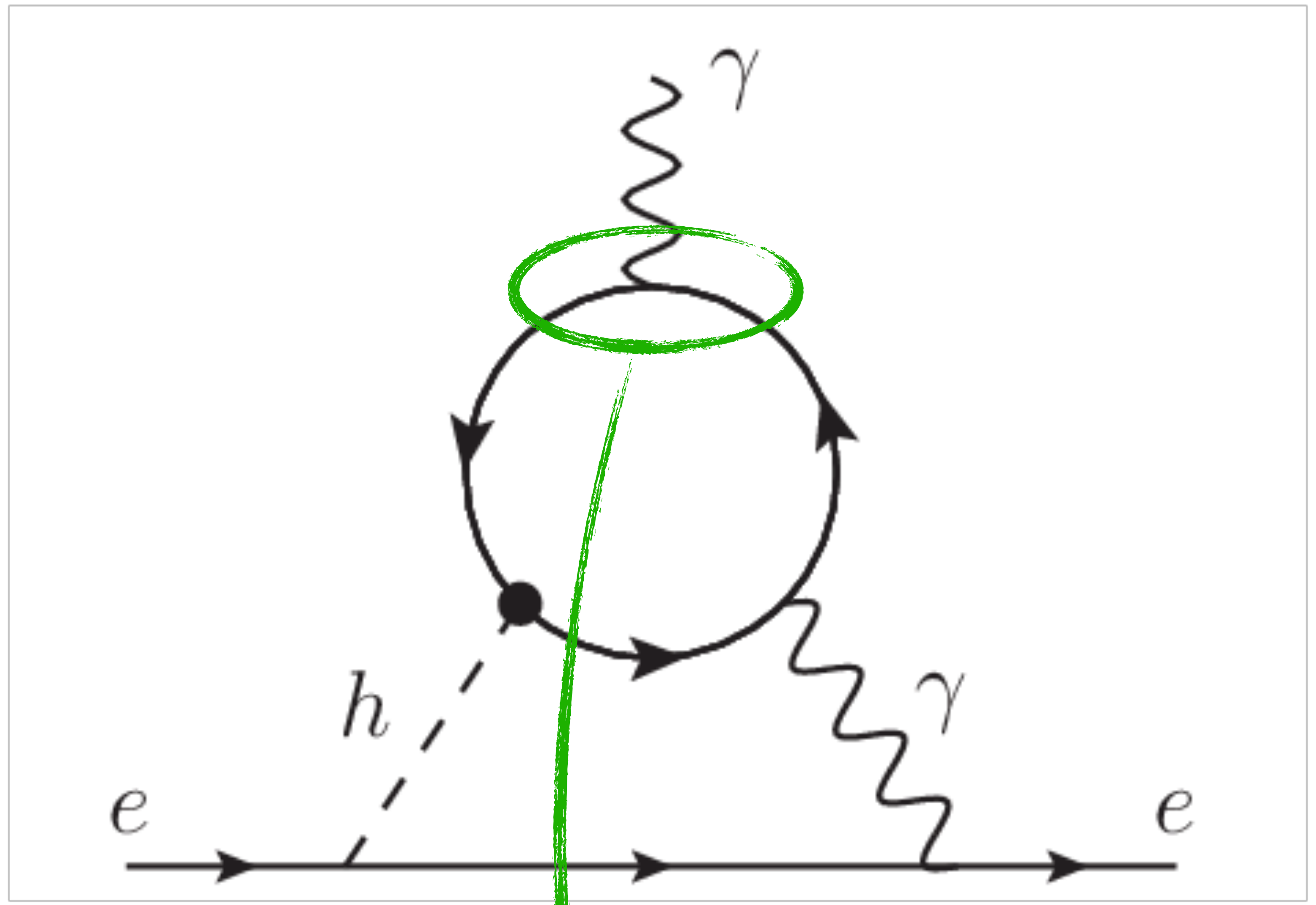

G. Panico, M. Riembau, T. Vantalon, arXiv:1712.06337

ν's do not couple to γ

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ν masses in low-scale seesaws

$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \bar{N}_L \phi Y_N N_R + h.c. - V\left(\phi, H^\dagger H\right)$$

After SSB

$$\mathscr{L} \supset -\bar{\nu}_L m_D N_R - \bar{N}_L M N_R + h.c.$$

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Bounded by EW precision and flavour observables

E. Fernandez-Martinez, J. Hernandez & J. Lopez-Pavon, arXiv: 1605.08774

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E. Fernandez-Martinez, J. Hernandez & J. Lopez-Pavon, arXiv: 1605.08774

Explain light ν masses

Inverse Seesaw

M. Malinsky *et al.*, arXiv:0506296

$$m_\nu \sim \mu_L \theta^2$$

CP violation in low-scale seesaws

$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \bar{N}_L \phi Y_N N_R + h.c. - V\left(\phi, H^\dagger H\right)$$

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$$\boxed{\delta_{CP} \propto (M_1^2 - M_2^2)(M_2^2 - M_3^2)(M_3^2 - M_1^2) Im\left[(\theta^\dagger\theta)_{12}(\theta^\dagger\theta)_{23}(\theta^\dagger\theta)_{31}\right]}$$

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Hierarchical heavy neutrinos

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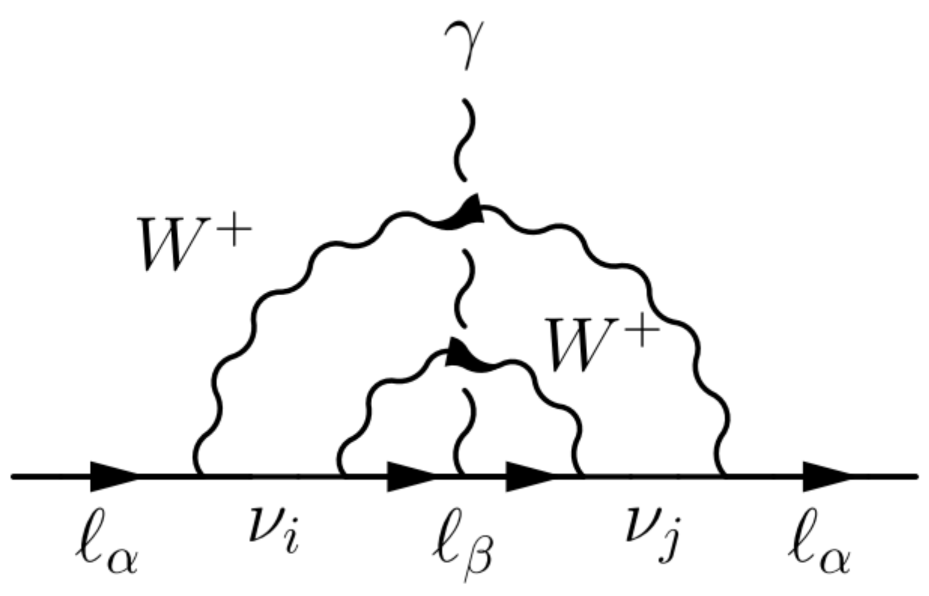
Hierarchical heavy neutrinos



Avoid electric dipole moment bounds

A. Abada & T. Toma, arXiv: 1605.07643

Electroweak baryogenesis and low-scale seesaws

First proposed in

P. Hernandez & N. Rius, arXiv: hep-ph/9611227

$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \bar{N}_L \phi Y_N N_R + h.c. - V\left(\phi, H^\dagger H\right)$$

Large mixing and CPV

Trigger strong
1st order
phase transition

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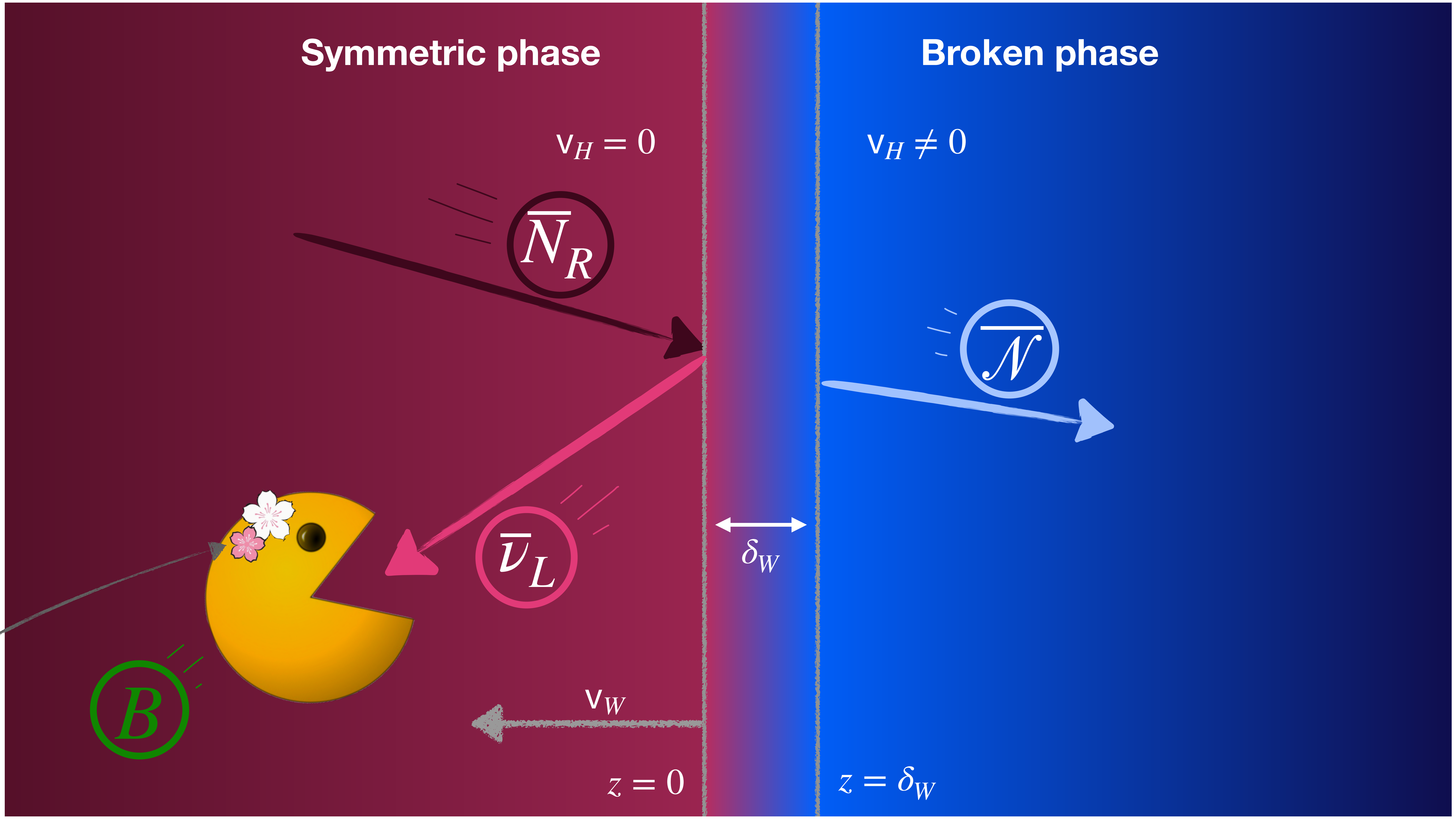
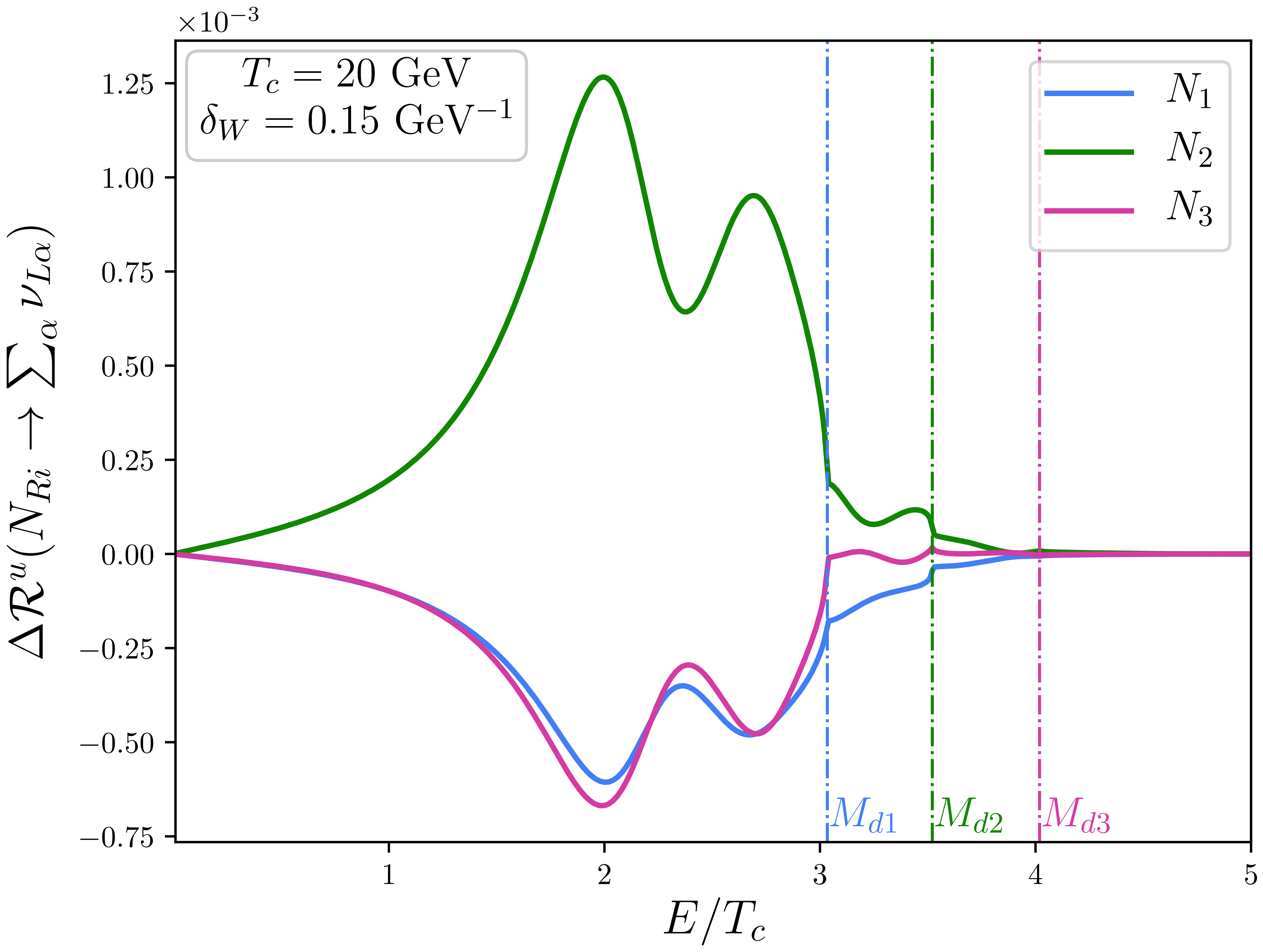
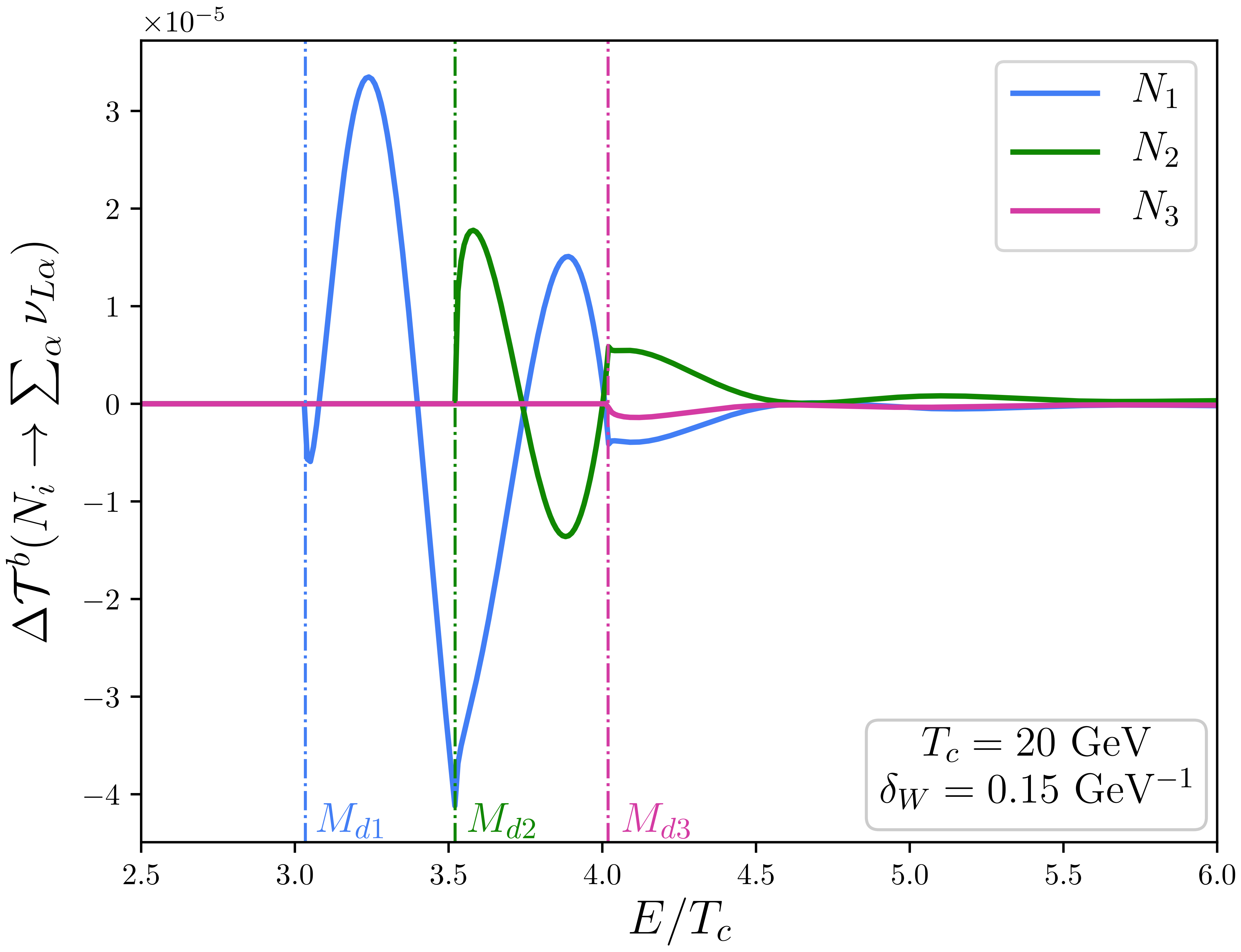


"Artistic" depiction of a sphaleron

CP asymmetries



Reflection



Transmission

Diffusion equations

Vanilla scenario

M. Joyce, T. Prokopec & N. Turok, arXiv: hep-ph/9410281

$$D_B\partial_z^2 n_B - v_W\partial_z n_B - 3\Gamma_S\mathscr{H}(-z)n_B - \Gamma_S\mathscr{H}(-z)n_L = 0$$

P. Hernandez & N. Rius, arXiv: hep-ph/9611227

$$D_L\partial_z^2 n_L - v_W\partial_z n_L - \Gamma_S\mathscr{H}(-z)n_L - 3\Gamma_S\mathscr{H}(-z)n_B = \xi_L j_\nu \partial_z \delta(z)$$

Diffusion equations

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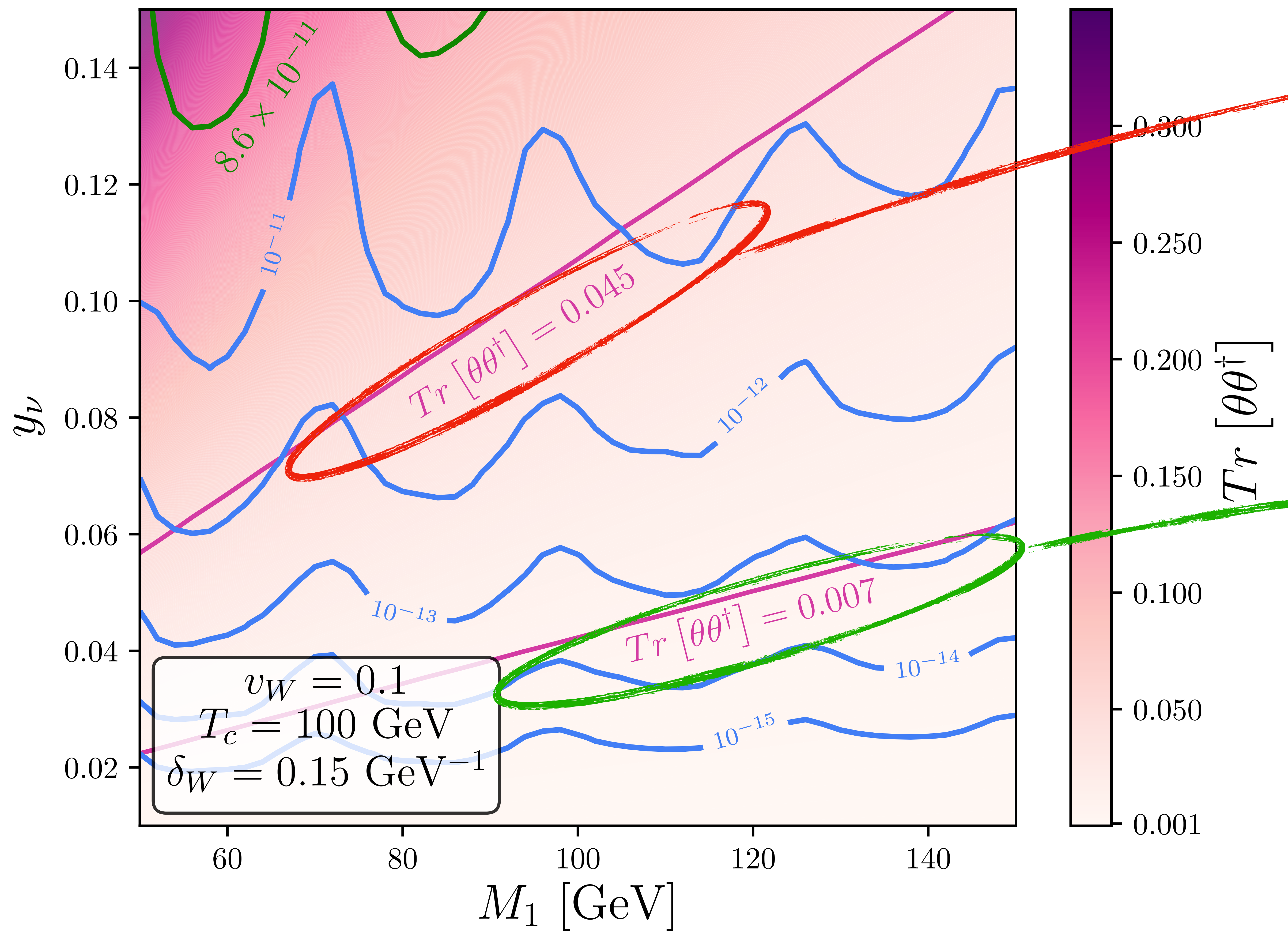
Follow the total B and L asymmetries and their conversion through sphalerons

$$j_\nu = \frac{1}{\gamma} \sum_{i,\alpha} \int \frac{d^3p}{(2\pi)^3} \left\{ \Delta \mathscr{T}^b(N_i \to \nu_{L\alpha}) \frac{|p_{zi}^b|}{E_i^b} f_i^b(p_i^b) + \Delta \mathscr{R}^u(N_{Ri} \to \nu_{L\alpha}) \frac{|p_{zi}^u|}{E_i^u} f_i^u(p_i^u) \right\}$$

Diffusion equations

Vanilla scenario

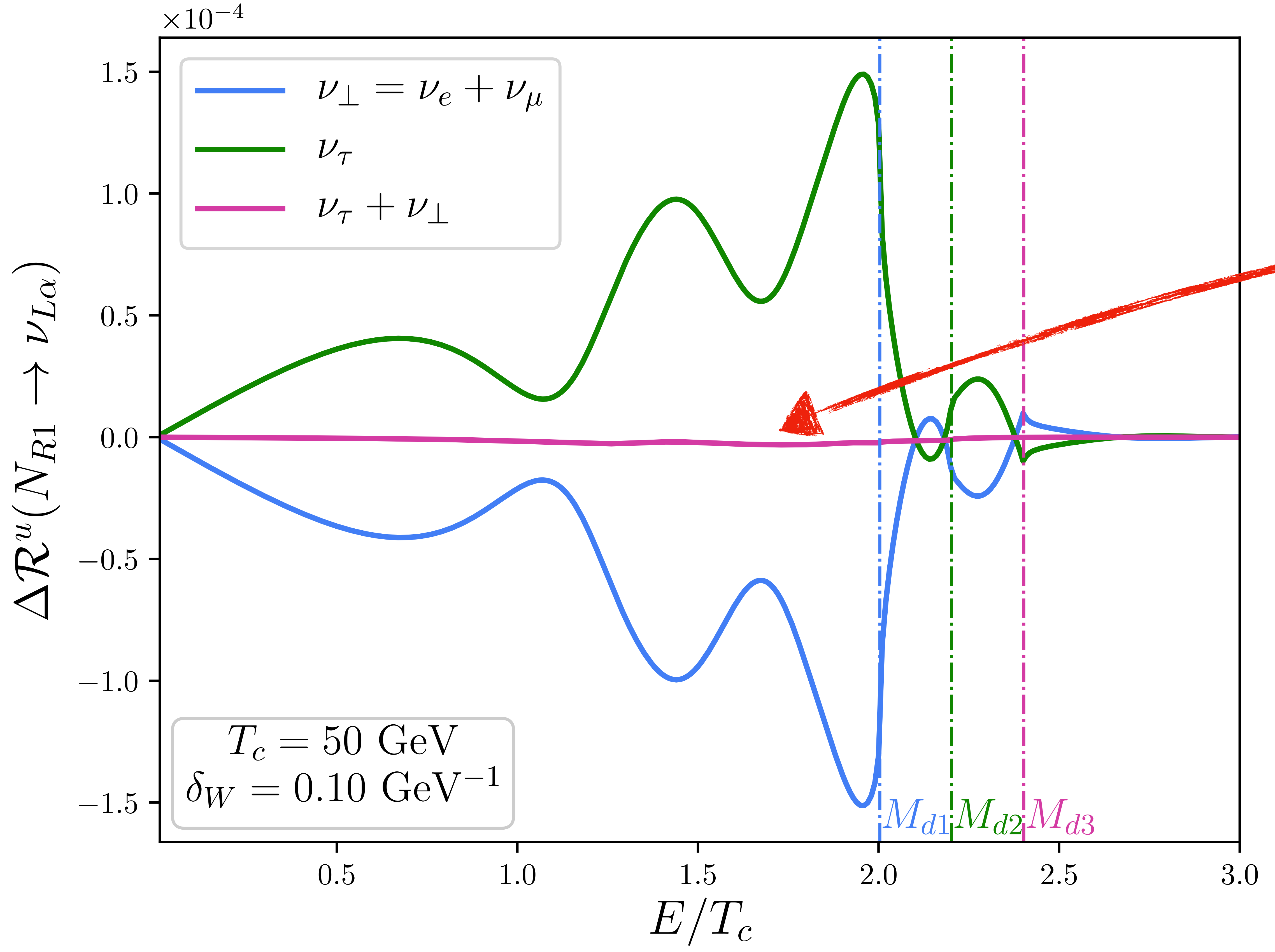


Bound on θ if avoiding the invisible width of the Z boson

Current bound at 2σ on θ

E. Fernandez-Martinez, J. Hernandez & J. Lopez-Pavon, arXiv: 1605.08774

Flavoured CP asymmetries



Reflection

Strong GIM cancellation
when summing over flavours

$$\sum_i \Delta\mathscr{R}^u\left(N_{Ri} \to \nu_{L\alpha}\right) \sim \int_z \sum_{i,j,\beta} f(z) m_{d_\alpha}^2 Im\left(V_{Ri\alpha}V^*_{Ri\beta}V_{Rj\beta}V^*_{Rj\alpha}\right)$$

Diffusion equations

Flavoured scenario

M. Joyce, T. Prokopec & N. Turok, arXiv: hep-ph/9410281

$$\frac{\Gamma_\tau}{T} \sim 0.28\alpha_W Y_\tau^2 \ll \frac{\Gamma_S}{T} = 9\kappa\alpha_W^5$$

Safe to neglect the wash-out with the τ

Diffusion equations

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$$\frac{\Gamma_\tau}{T} \sim 0.28\alpha_W Y_\tau^2 \ll \frac{\Gamma_S}{T} = 9\kappa\alpha_W^5$$

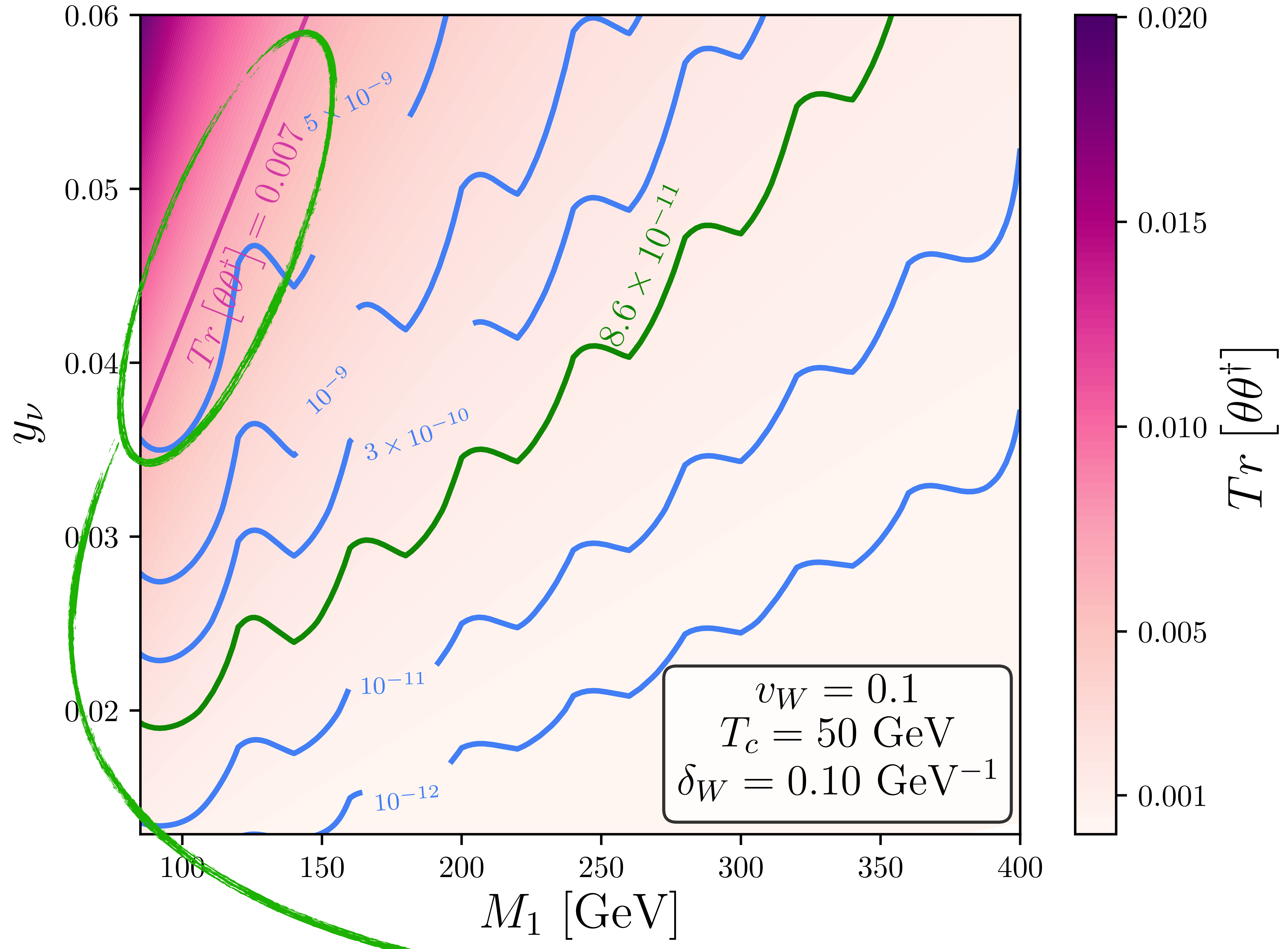
Safe to neglect the wash-out with the τ

$$\frac{\Gamma_{N_{Ri}\nu_{L\alpha}}}{T} \sim \frac{1}{128\pi}\left(Y_t^2 + Y_b^2\right)|(Y_\nu)_{\alpha i}|^2 \sim 0.0024\,|\theta_{\alpha i}|^2\frac{2M_i^2}{v_H^2}$$

$M_i \gtrsim 200\ GeV$ → We need to include the wash-out from the RH neutrinos

Diffusion equations

Flavoured scenario



Larger baryon asymmetry:

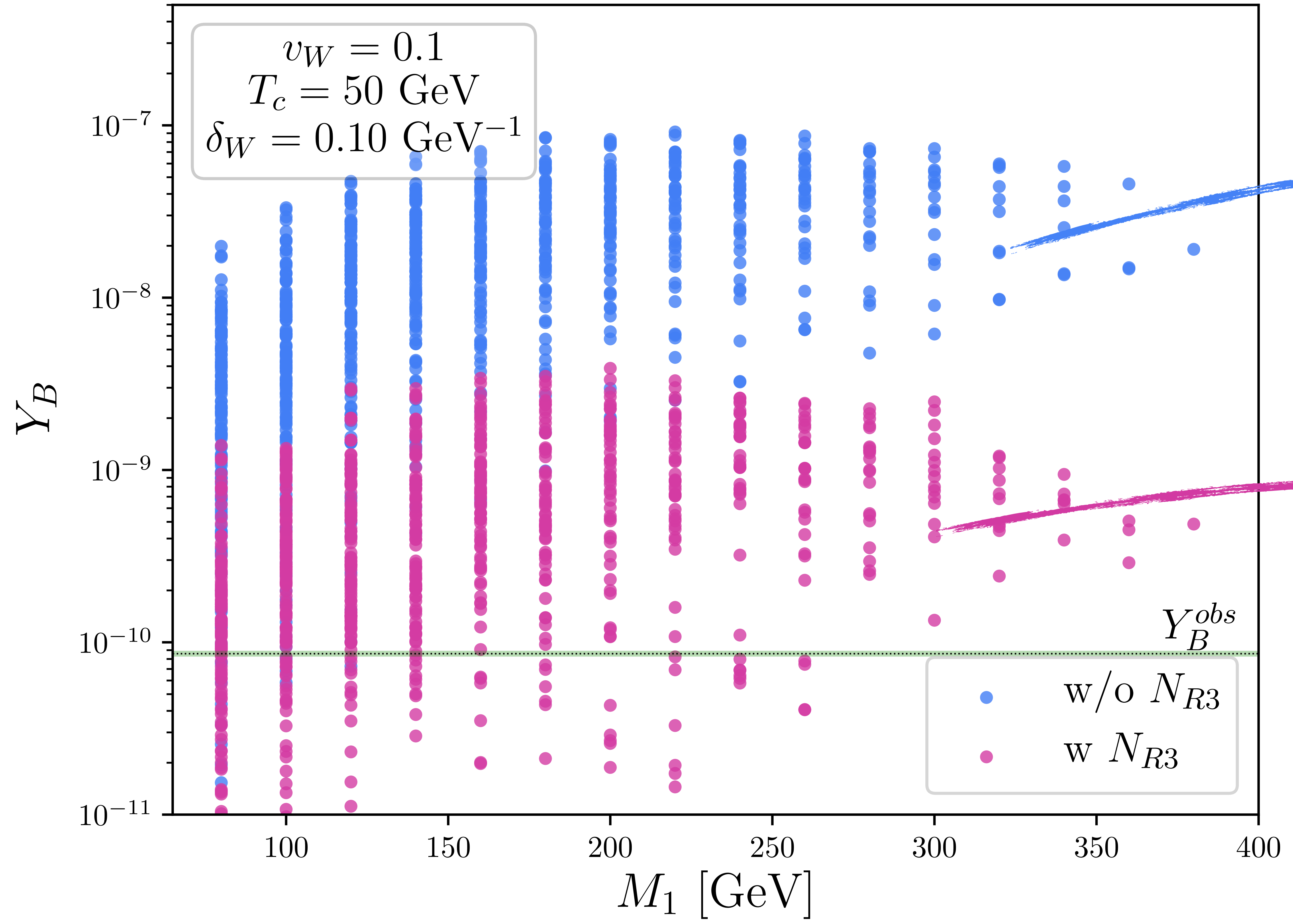
- Breaking of GIM cancellation
- Introduction of N_R asymmetry, which diffuse more than ν_L

$$N_R \rightarrow \nu_L \rightarrow B$$

Current bound at 2σ on θ

Diffusion equations

Flavoured scenario



Neglect the effect of N_{R3}

Overestimate the importance of N_{R3}

Conclusions

- Low-scale **neutrino mass mechanism** could help in the **generation** of the **BAU**

- **Flavour effects** play a crucial role in generating the correct BAU

- Explain the **BAU** with states with $M \sim 100\ GeV$ which **significantly mix with active neutrinos**→In reach for **colliders**

- Move on to study scalar potential and interesting phenomenology

Thank you!

This project has received funding /support from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska -Curie grant agreement No 860881-HIDDeN

Back up slides

CP violation in low-scale seesaws

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$$m_D \equiv U_l m_d V_R^\dagger$$

Unphysical when neglecting charged lepton masses

CP violation in low-scale seesaws

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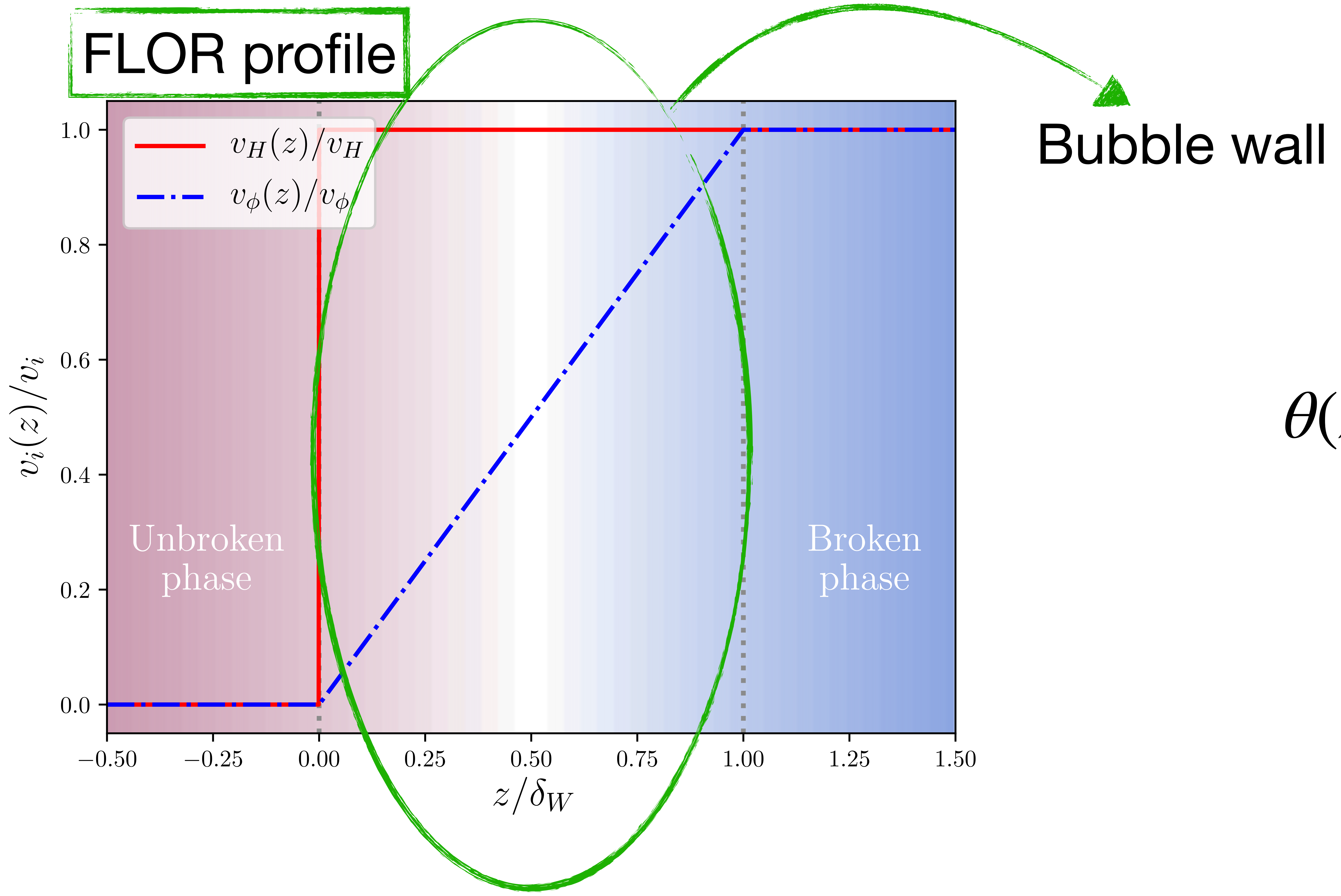
$$m_D \equiv U_l m_d V_R^\dagger$$

$$Tr\left[\theta\theta^\dagger\right] = Tr\left[m_d^2 V_R^\dagger M^{-2} V_R\right]$$

Vev profiles in the bubble wall



$$\theta(z) = \frac{v_H(z)}{v_\phi(z)} \frac{Y_\nu}{\sqrt{2}} Y_N^{-1}$$

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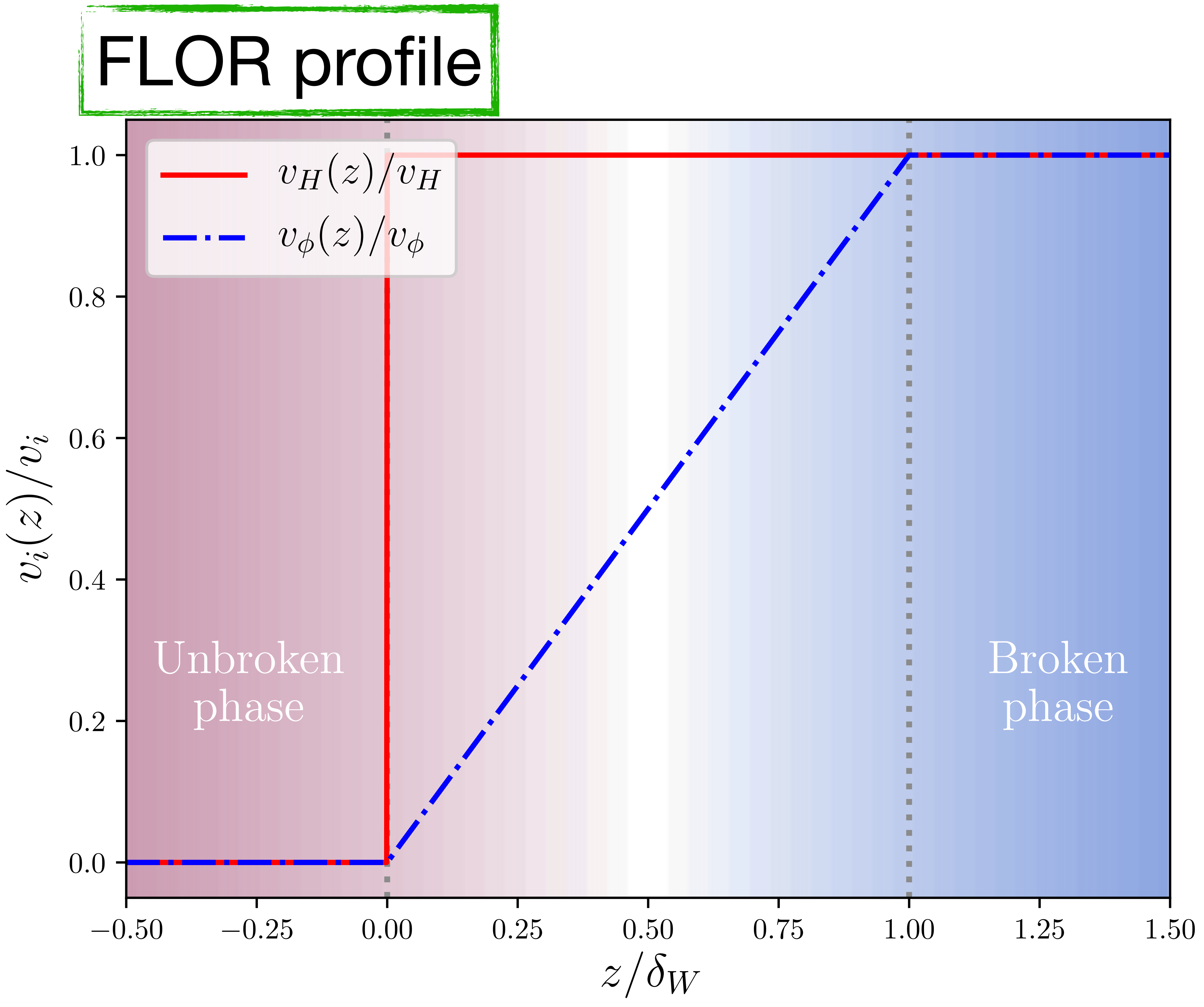

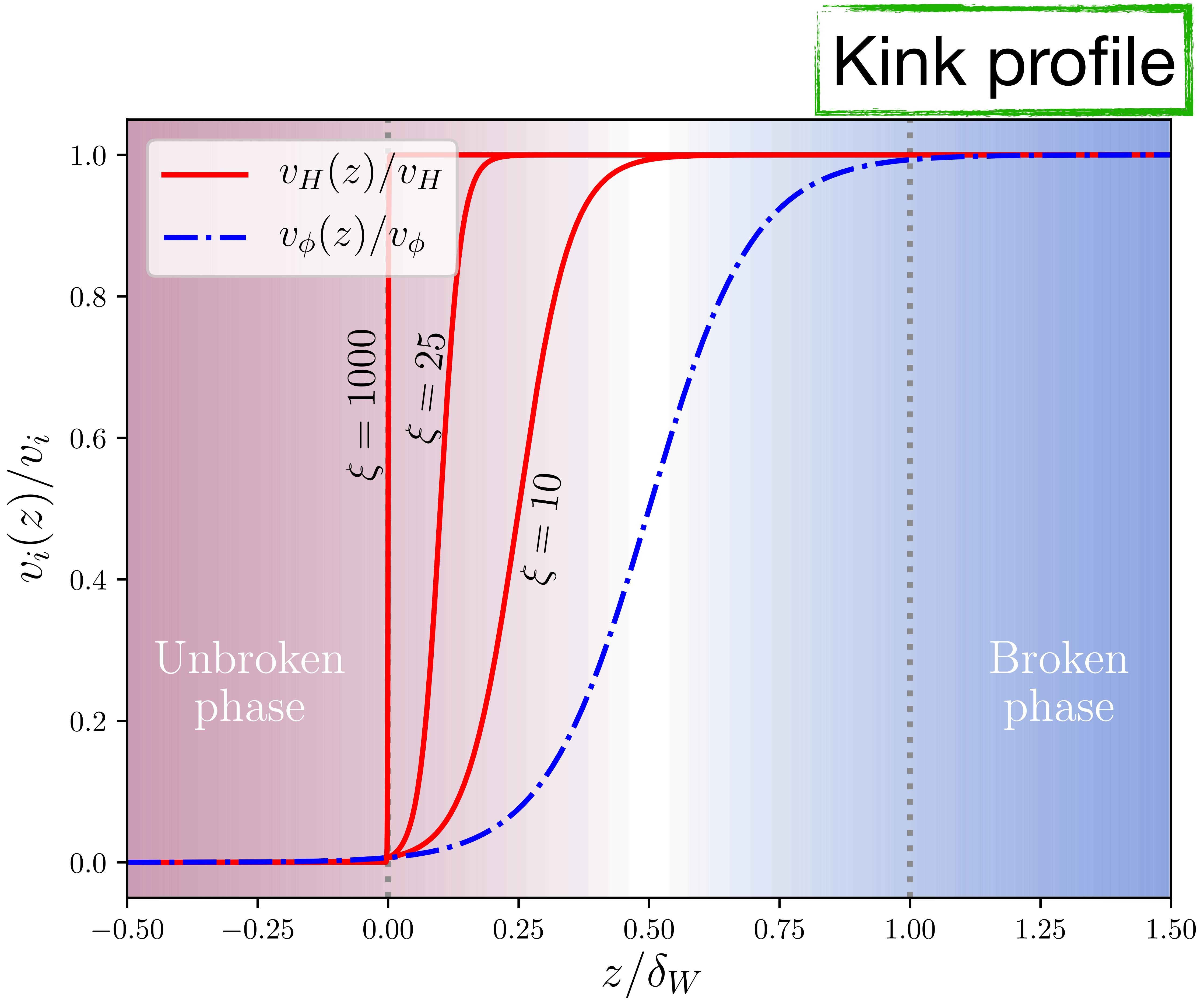

Electroweak baryogenesis and low-scale seesaw

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$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \bar{N}_L \phi Y_N N_R + h.c. - V\left(\phi, H^\dagger H\right)$$

$$\psi = e^{-iEt} \begin{pmatrix} L(z) \\ R(z) \end{pmatrix} \otimes \chi_s$$

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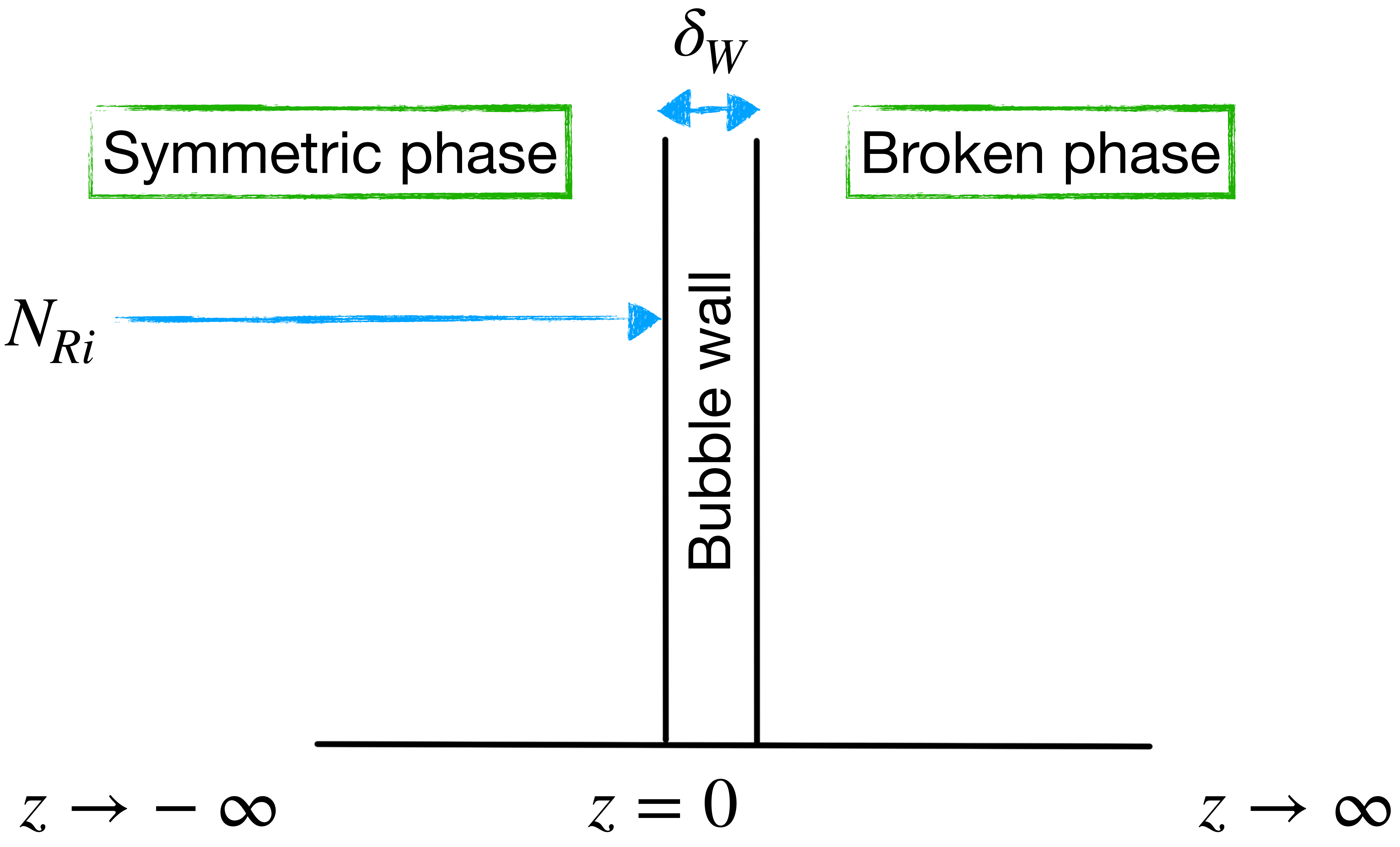

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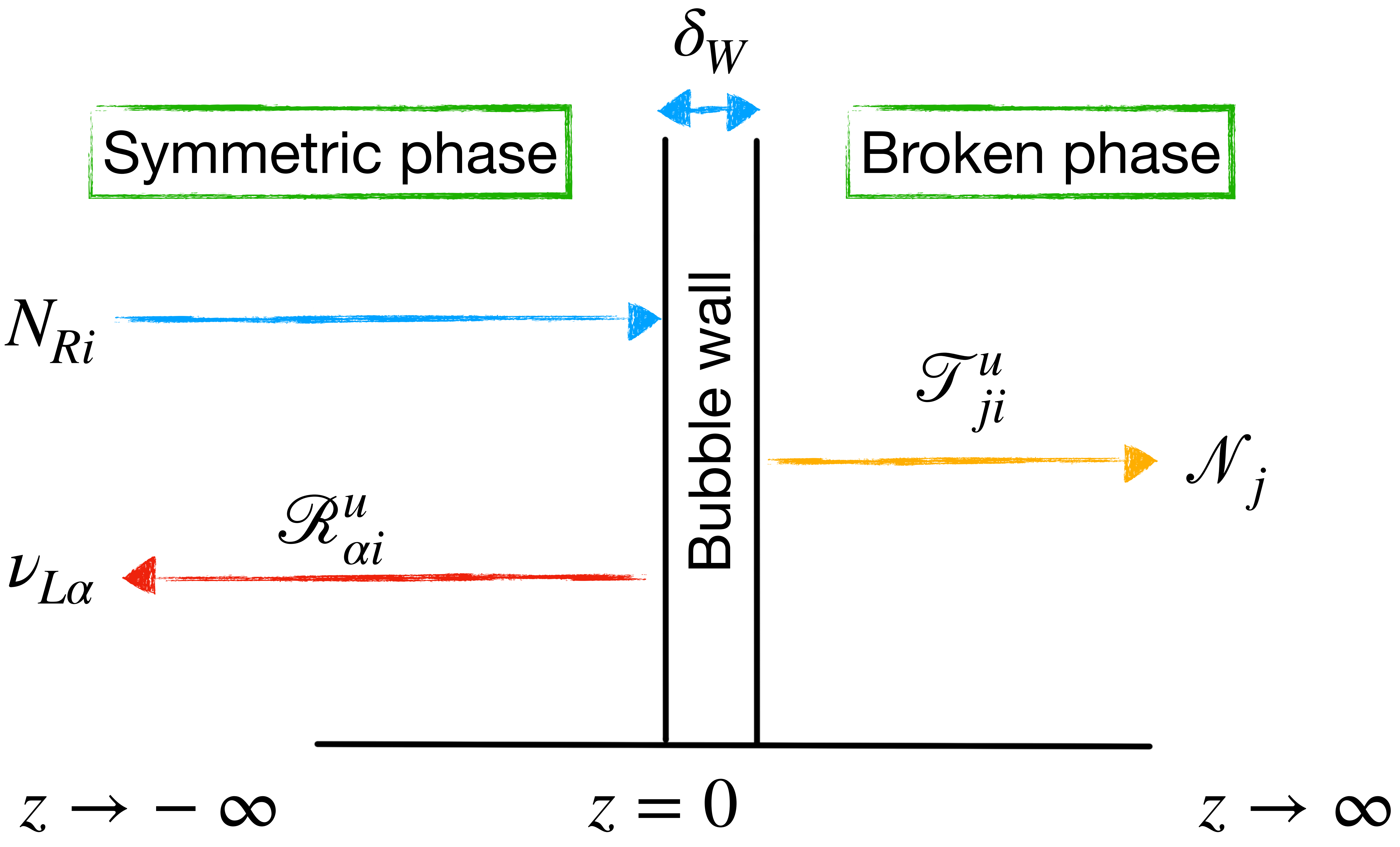

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$$|\mathscr{R}^u|^2 + |\mathscr{T}^u|^2 = 1$$

Diffusion equations

Flavoured scenario

Baryons

$$D_B \partial_z^2 n_B - v_W \partial_z n_B - 3\Gamma_S \mathscr{H}(-z) n_B - \Gamma_S \mathscr{H}(-z) \sum_\alpha n_{\nu_\alpha} = 0$$

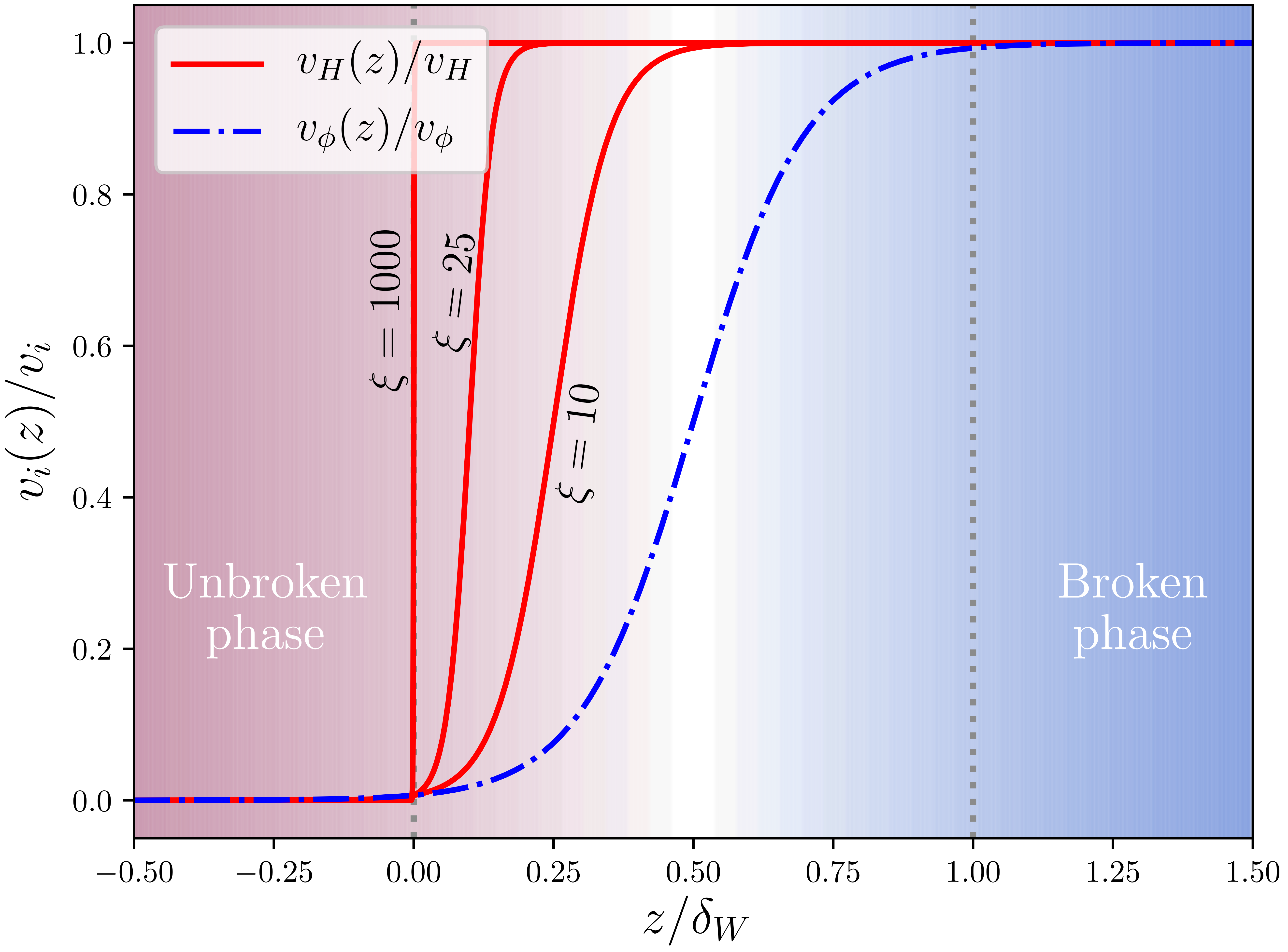
SM ν

$$D_L \partial_z^2 n_{\nu_\alpha} - v_W \partial_z n_{\nu_\alpha} - 3\Gamma_S \mathscr{H}(-z) n_B - \Gamma_S \mathscr{H}(-z) \sum_\beta n_{\nu_\beta} - \sum_i \Gamma_{N_{Ri}\nu_\alpha} \left(\frac{1}{2} n_{\nu_\alpha} - n_{N_{Ri}} \right) = \xi_L j_{\nu_\alpha} \partial_z \delta(z)$$

N_R

$$D_{Ri} \partial_z^2 n_{\nu_{N_{Ri}}} - v_W \partial_z n_{\nu_{N_{Ri}}} + \sum_\alpha \Gamma_{N_{Ri}\nu_\alpha} \left(\frac{1}{2} n_{\nu_\alpha} - n_{N_{Ri}} \right) = \xi_{Ri} j_{N_{Ri}} \partial_z \delta(z)$$

Effect of vev profiles



$$v_H(z)/v_H = \frac{1}{2}\left[1 + \tanh\left(\xi \frac{z - (5/\xi)\,\delta_W/2}{\delta_W}\right)\right]$$

$$v_\phi(z)/v_\phi = \frac{1}{2}\left[1 + \tanh\left(5\frac{z - \delta_W/2}{\delta_W}\right)\right]$$

Effect of vev profiles