HIDDeN
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

ν Electroweak Baryogenesis

Salvador Rosauro-Alcaraz, 24/01/22

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

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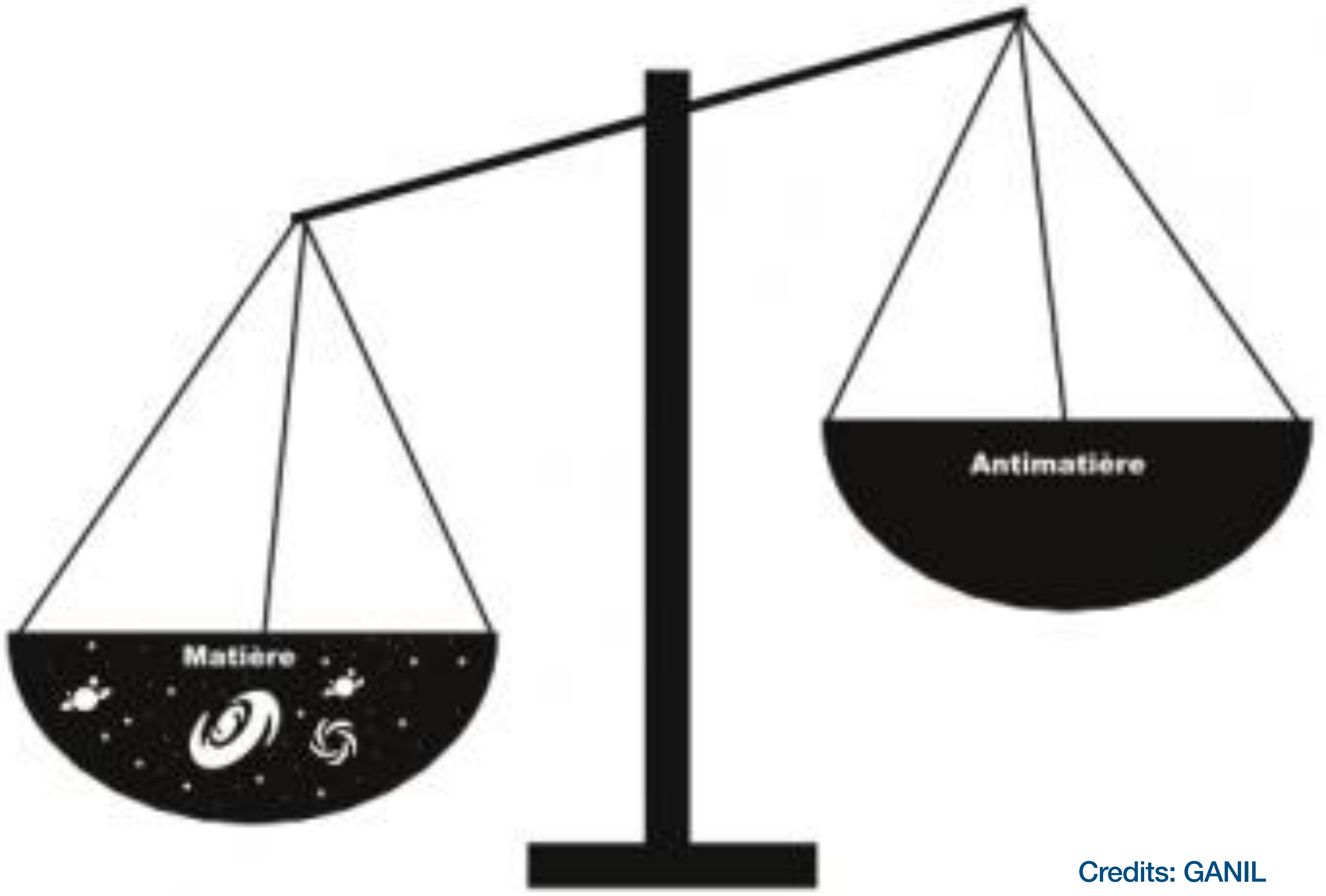
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Introduction

Baryon asymmetry of the Universe



Credits: GANIL

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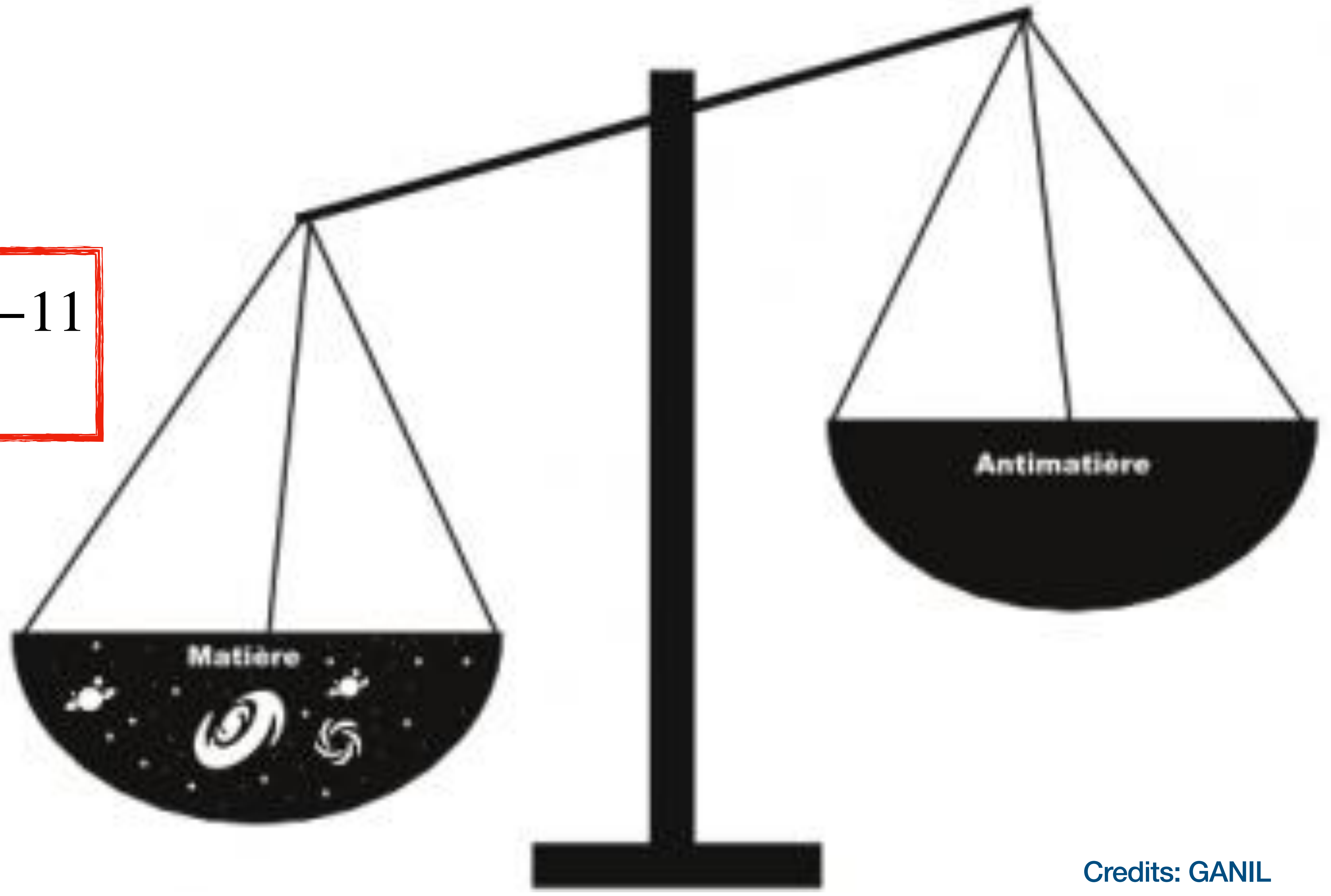
Planck Collaboration, arXiv:1807.06209

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



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Baryon asymmetry of the Universe

Generation of a BAU

- C and CP violation

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

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1^{st} order phase transition ← •Out-of-equilibrium conditions

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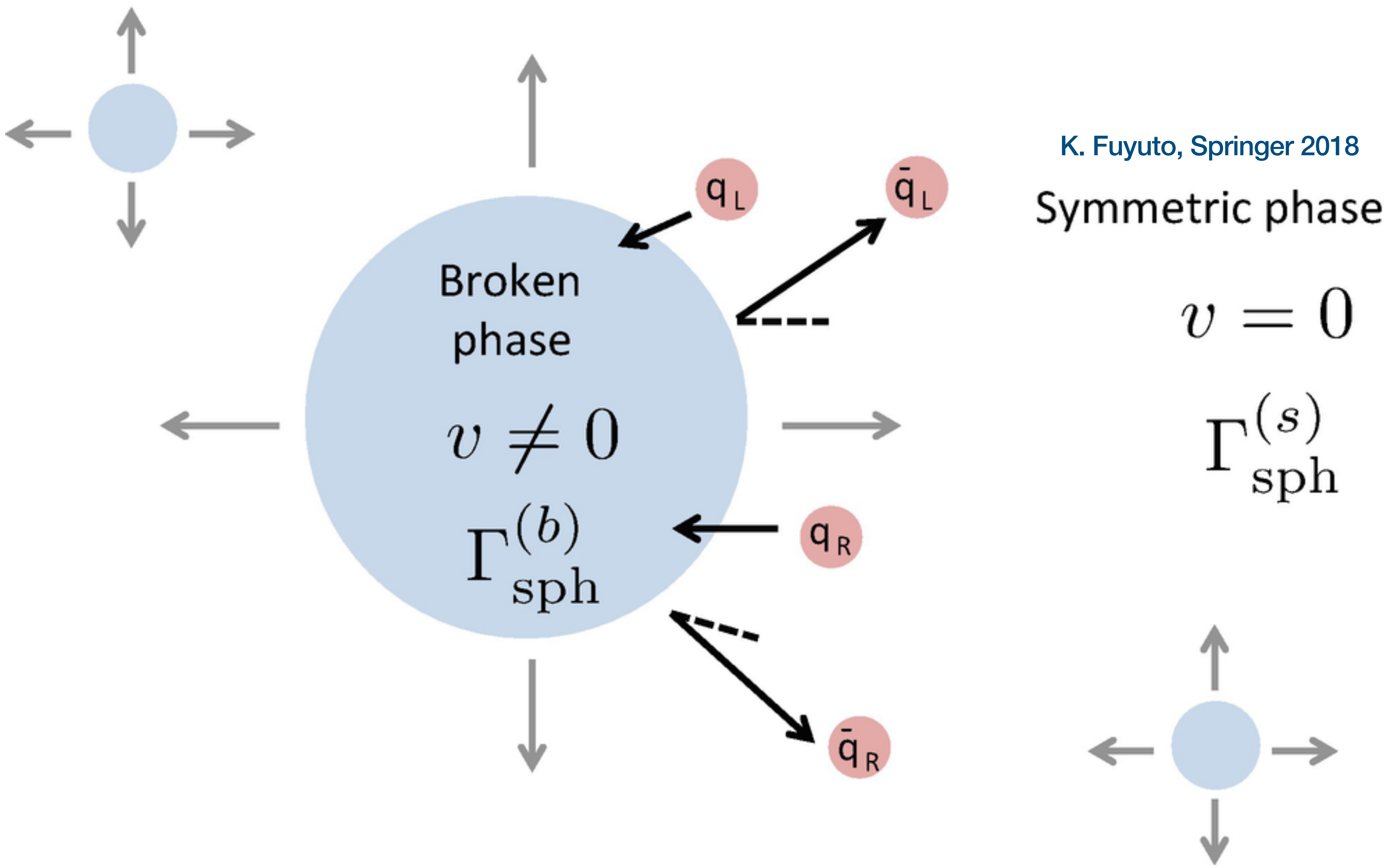
K. Fuyuto, Springer 2018



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CP violation from CKM matrix

M. B. Gavela, P. Hernandez, J. Orloff & O. Pene, arXiv:hep-ph/9312215

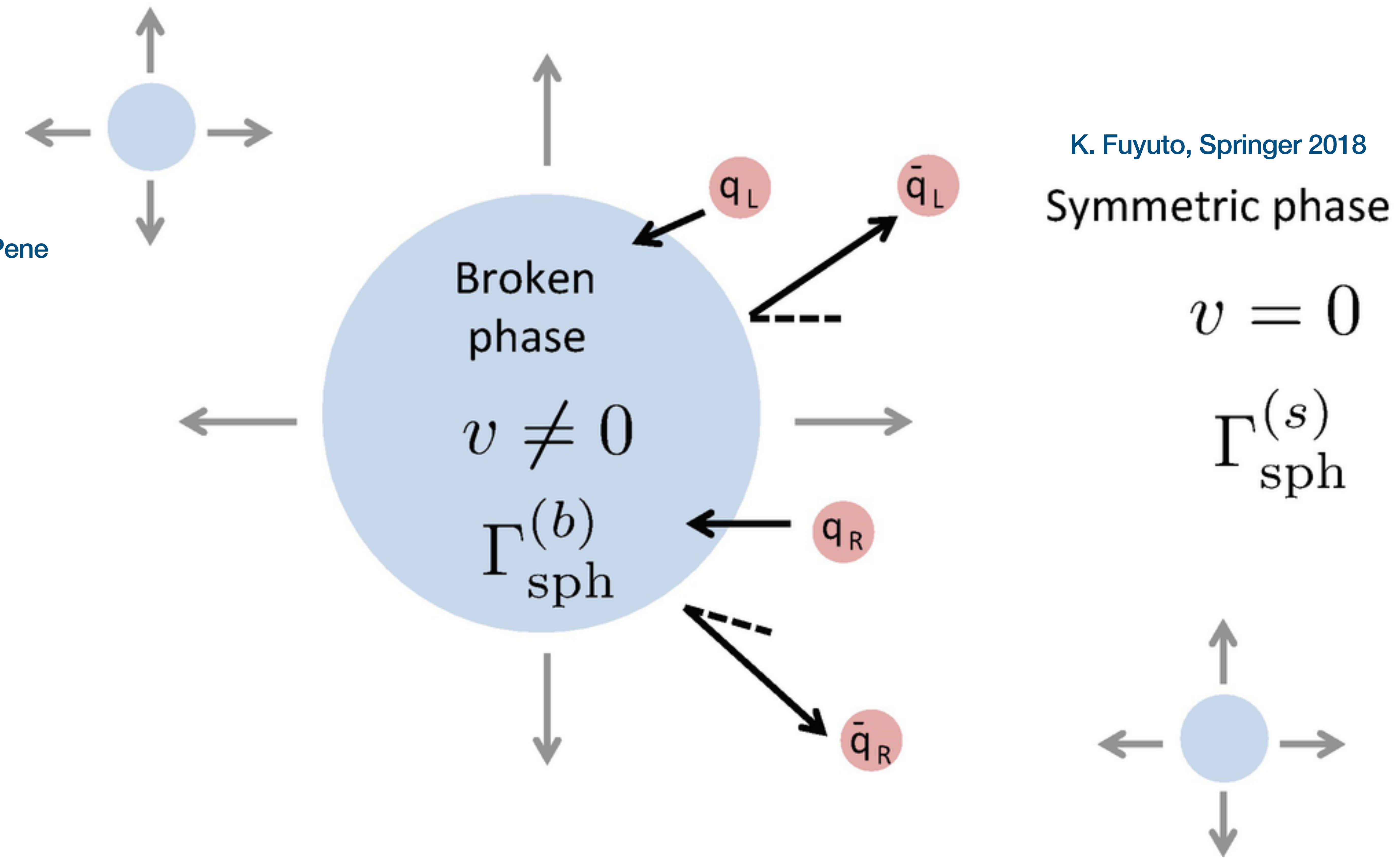
M. B. Gavela, P. Hernandez, J. Orloff, O. Pene & C: Quimbay, arXiv:hep-ph/9406289

$B + L$ violation from sphalerons

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



K. Fuyuto, Springer 2018

Electroweak baryogenesis with new physics

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CP violation from CKM matrix

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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

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Electroweak baryogenesis

Shaposhnikov, Nucl. Phys B287 (1987)

CP violation from CKM matrix → New sources of CP violation

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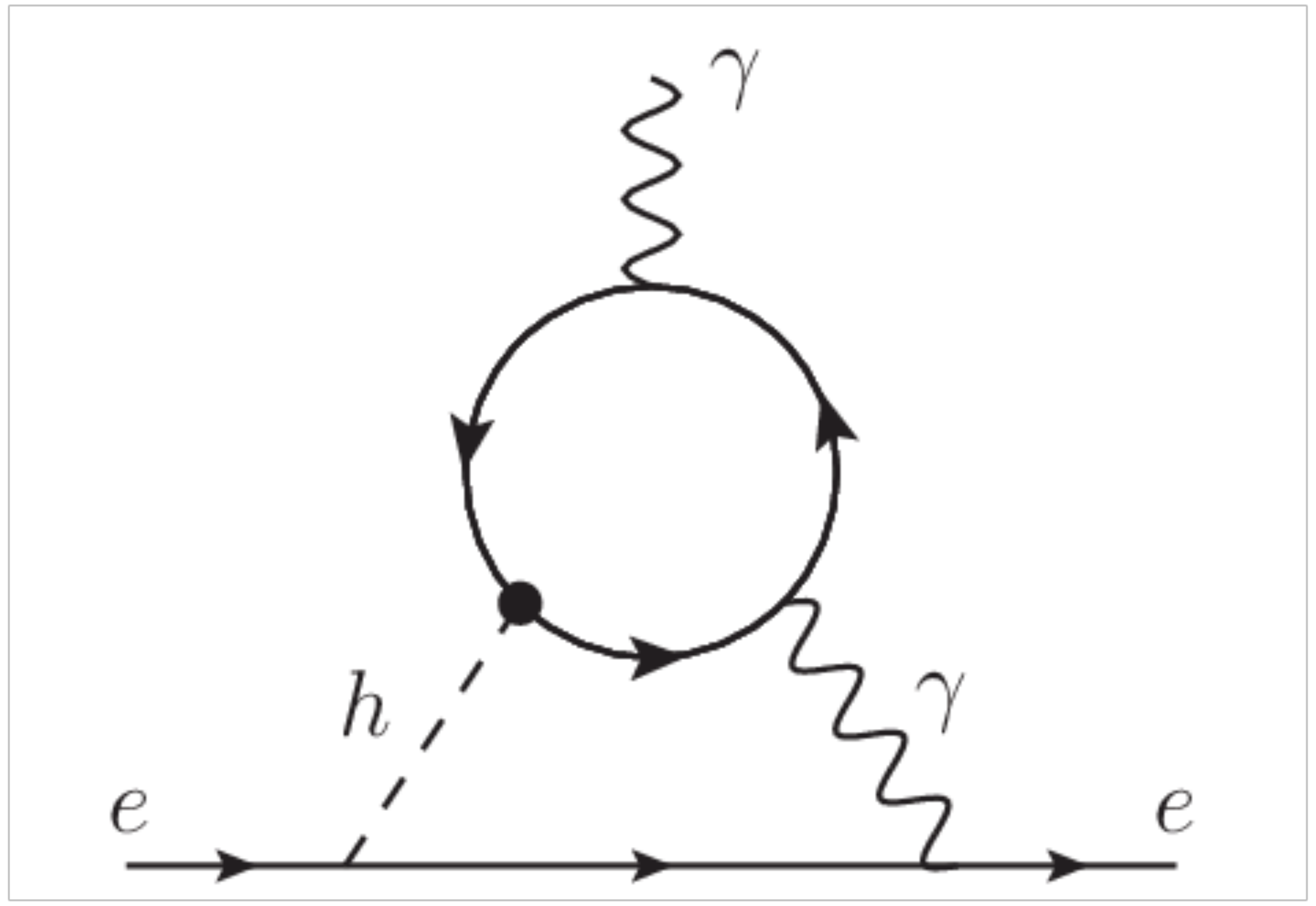
Bounds on new CP violation



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
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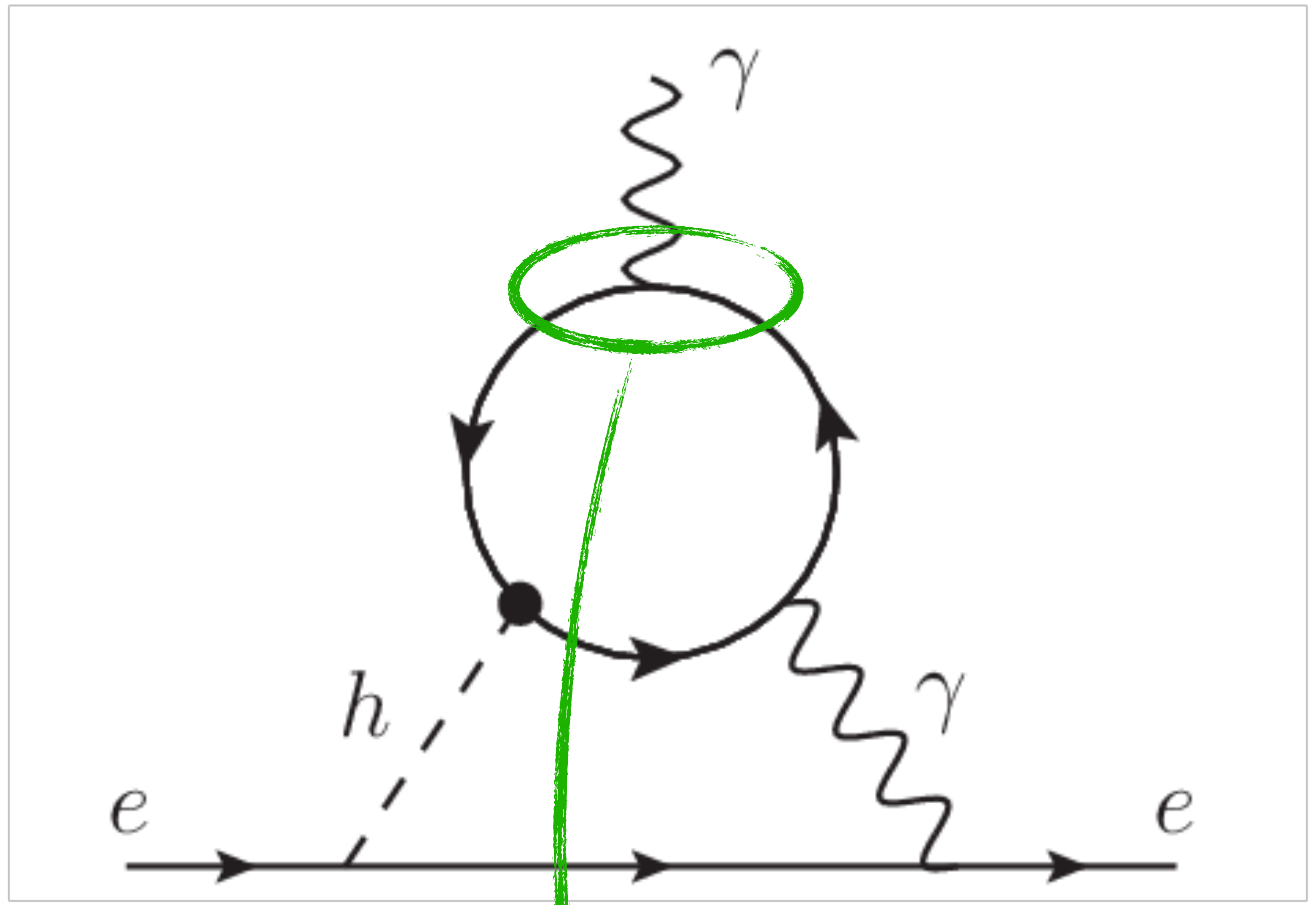

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ν do not couple to γ

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First proposed in

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

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

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Trigger strong 1st order phase transition

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Large mixing and CPV

Trigger strong 1st order phase transition

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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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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

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

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Hierarchical heavy neutrinos

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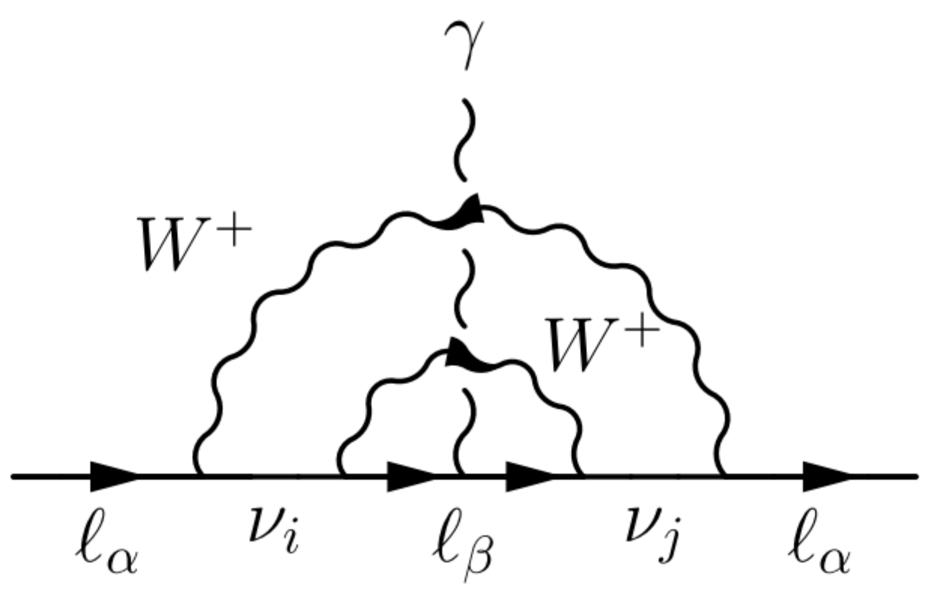

Avoid electric dipole moment bounds

A. Abada & T. Toma, arXiv: 1605.07643

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$$\boxed{\eta_B \sim \frac{\delta_{CP}}{T^6}}$$

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

Unphysical when neglecting charged lepton masses

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

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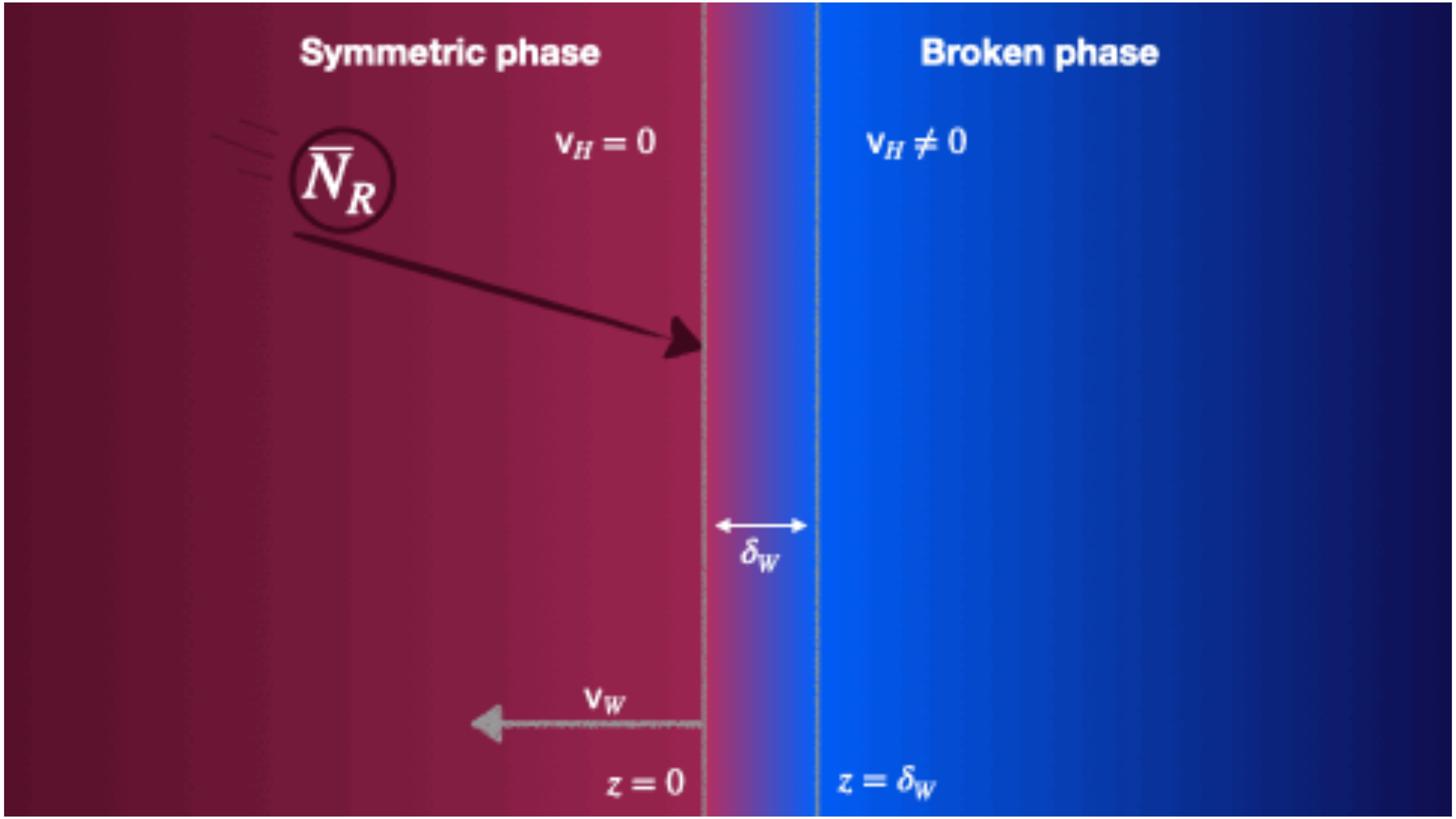

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$$\psi = e^{-iEt} \begin{pmatrix} L(z) \\ R(z) \end{pmatrix} \otimes \chi_s$$

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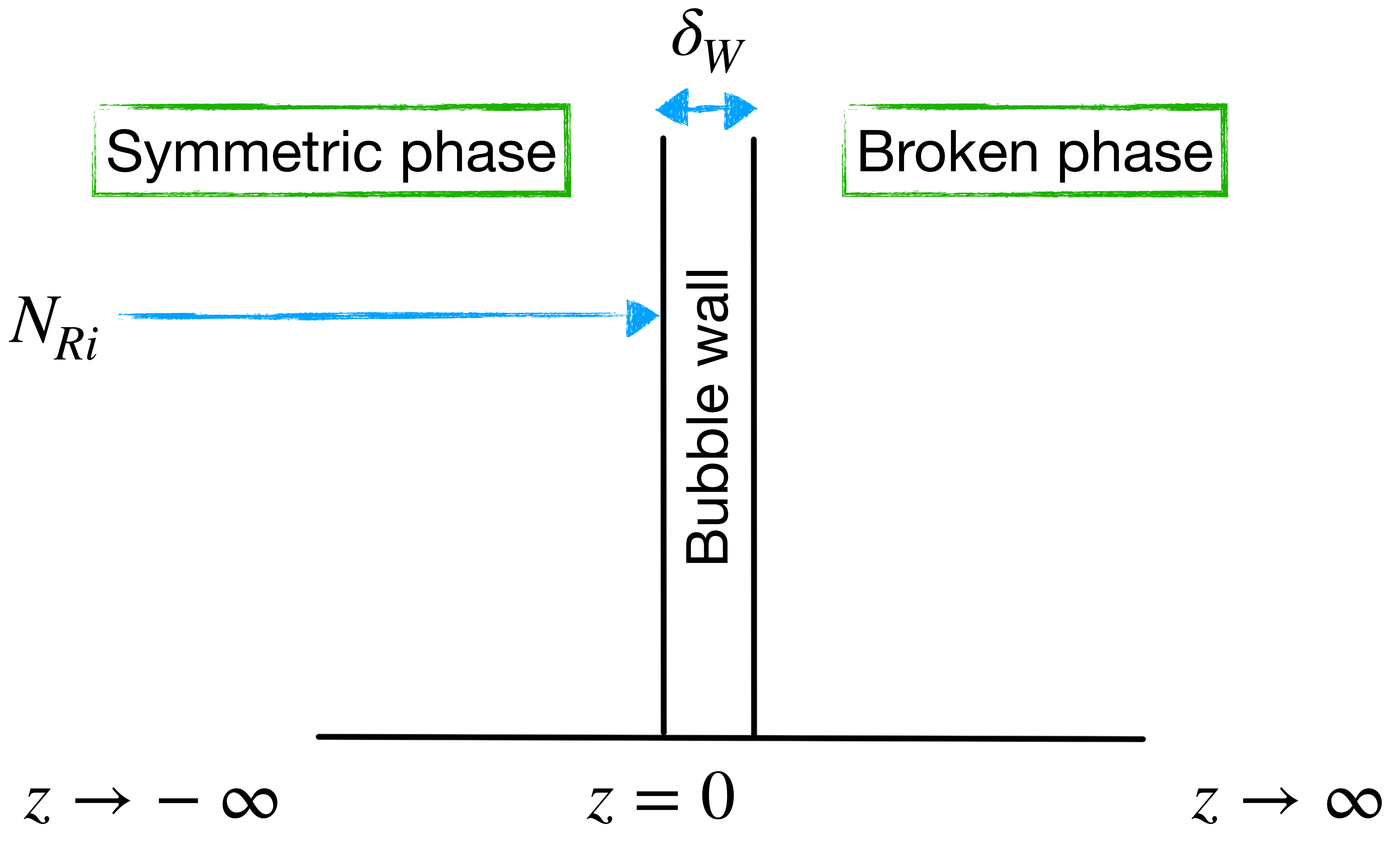

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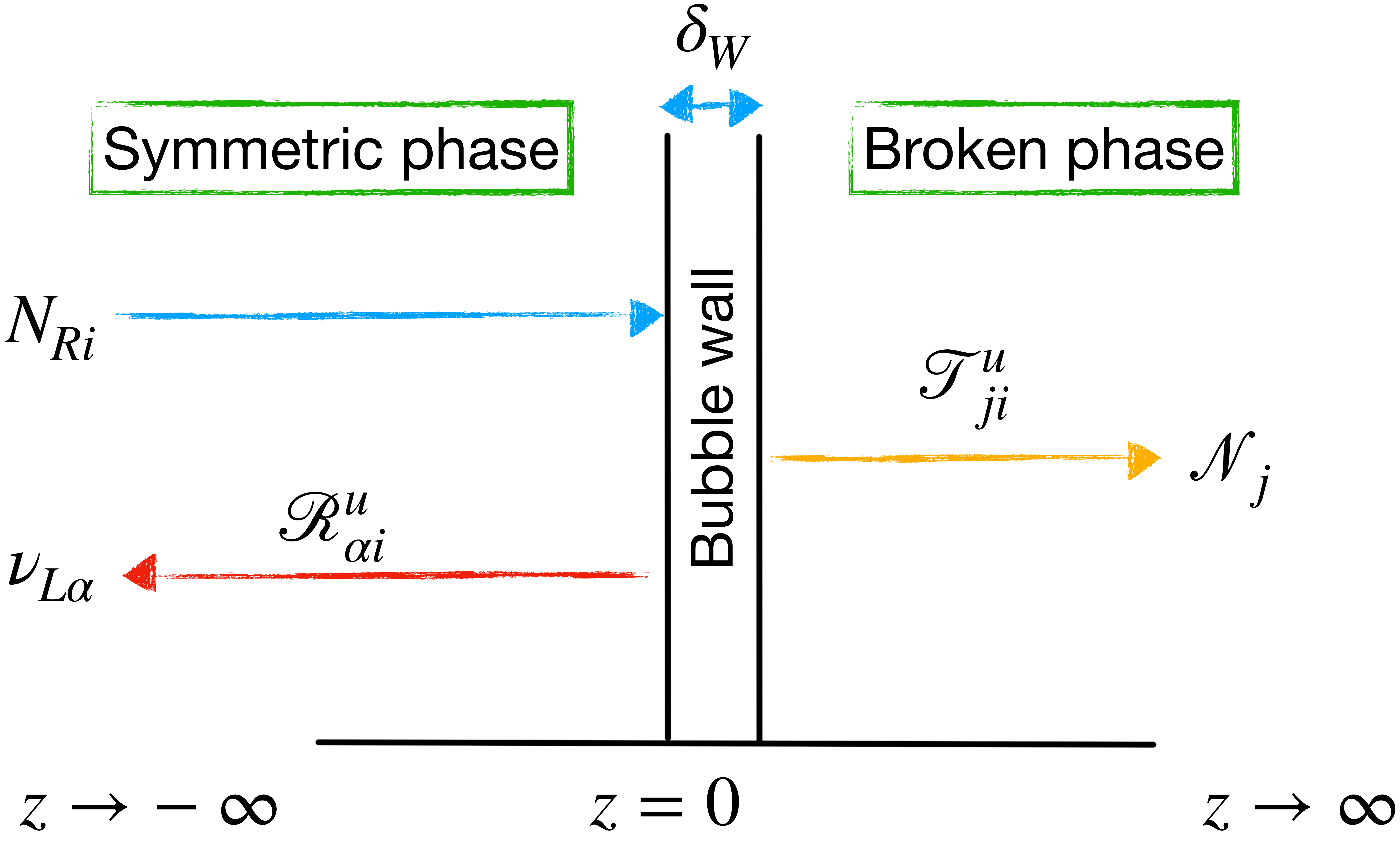

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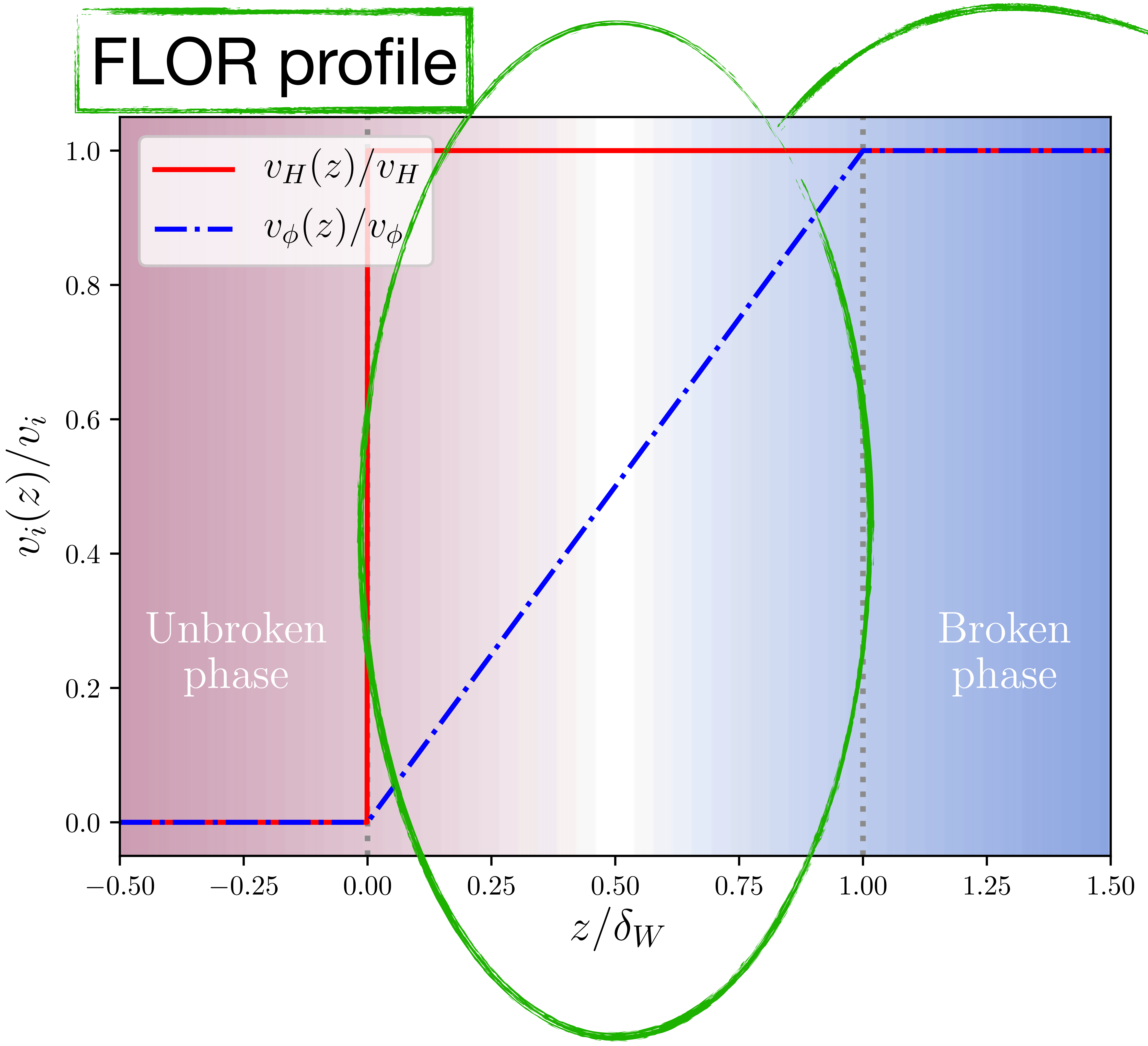
$$|\mathscr{R}^u|^2 + |\mathscr{T}^u|^2 = 1$$

Vev profiles in the bubble wall

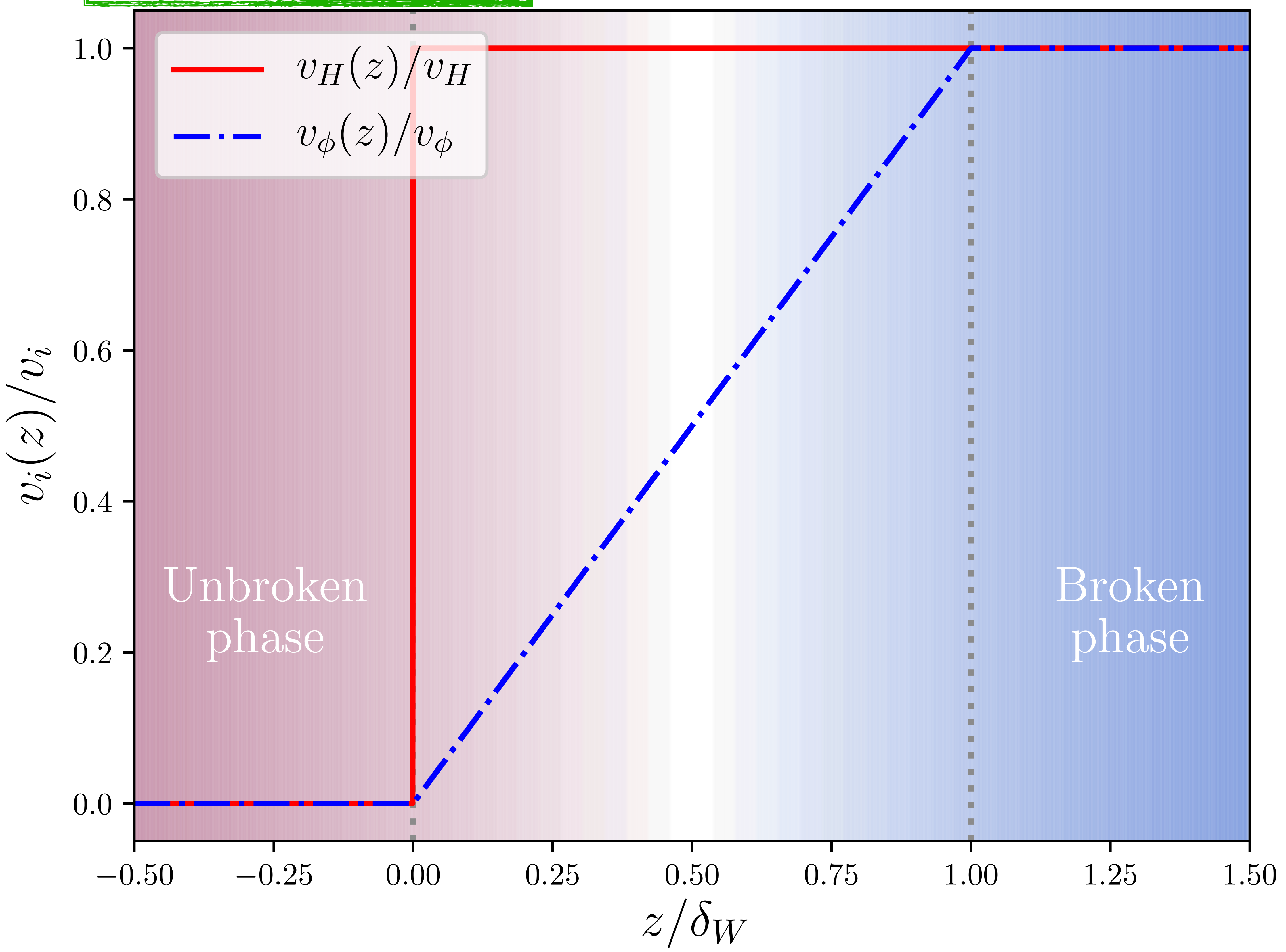


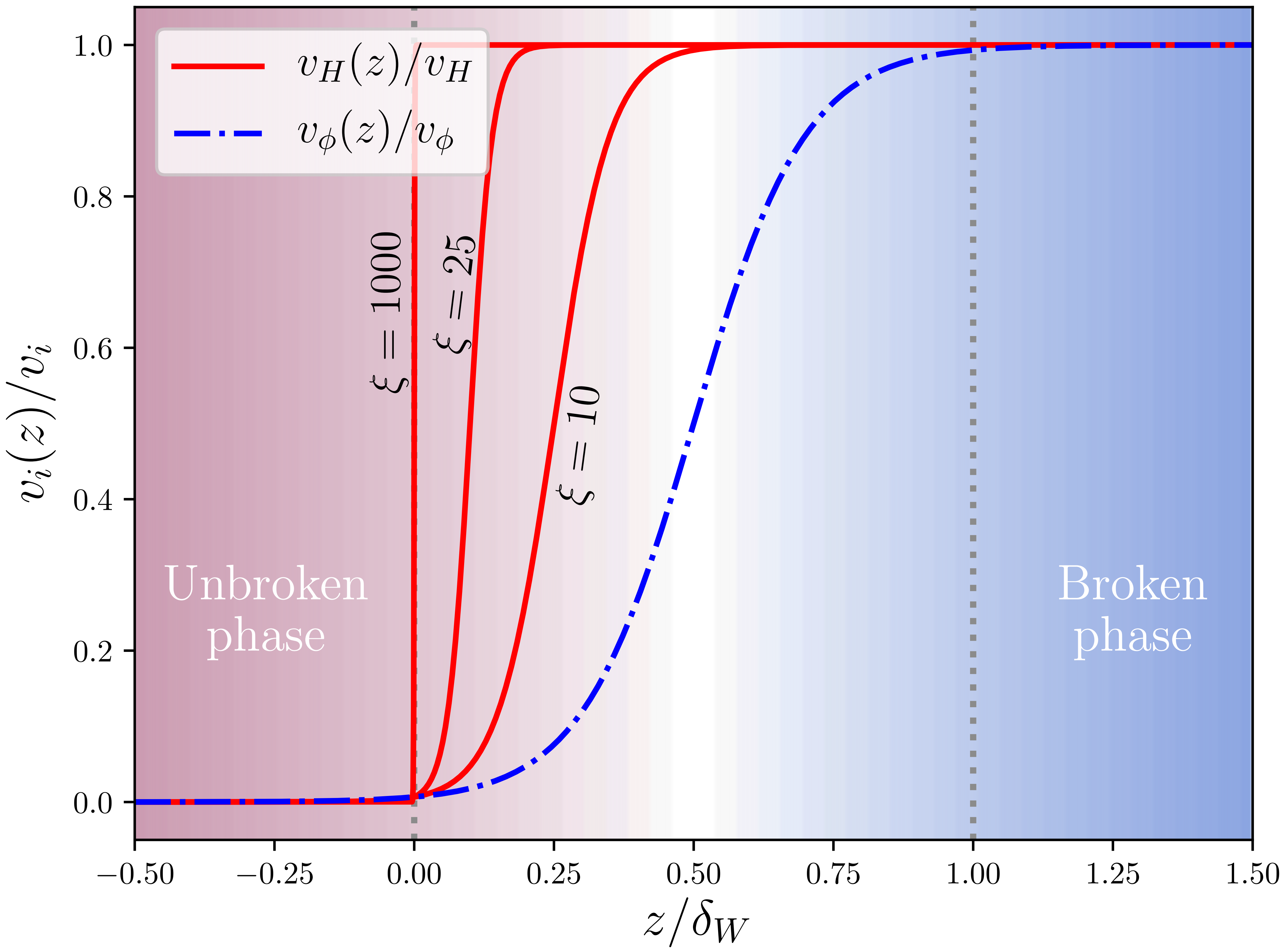
Bubble wall

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

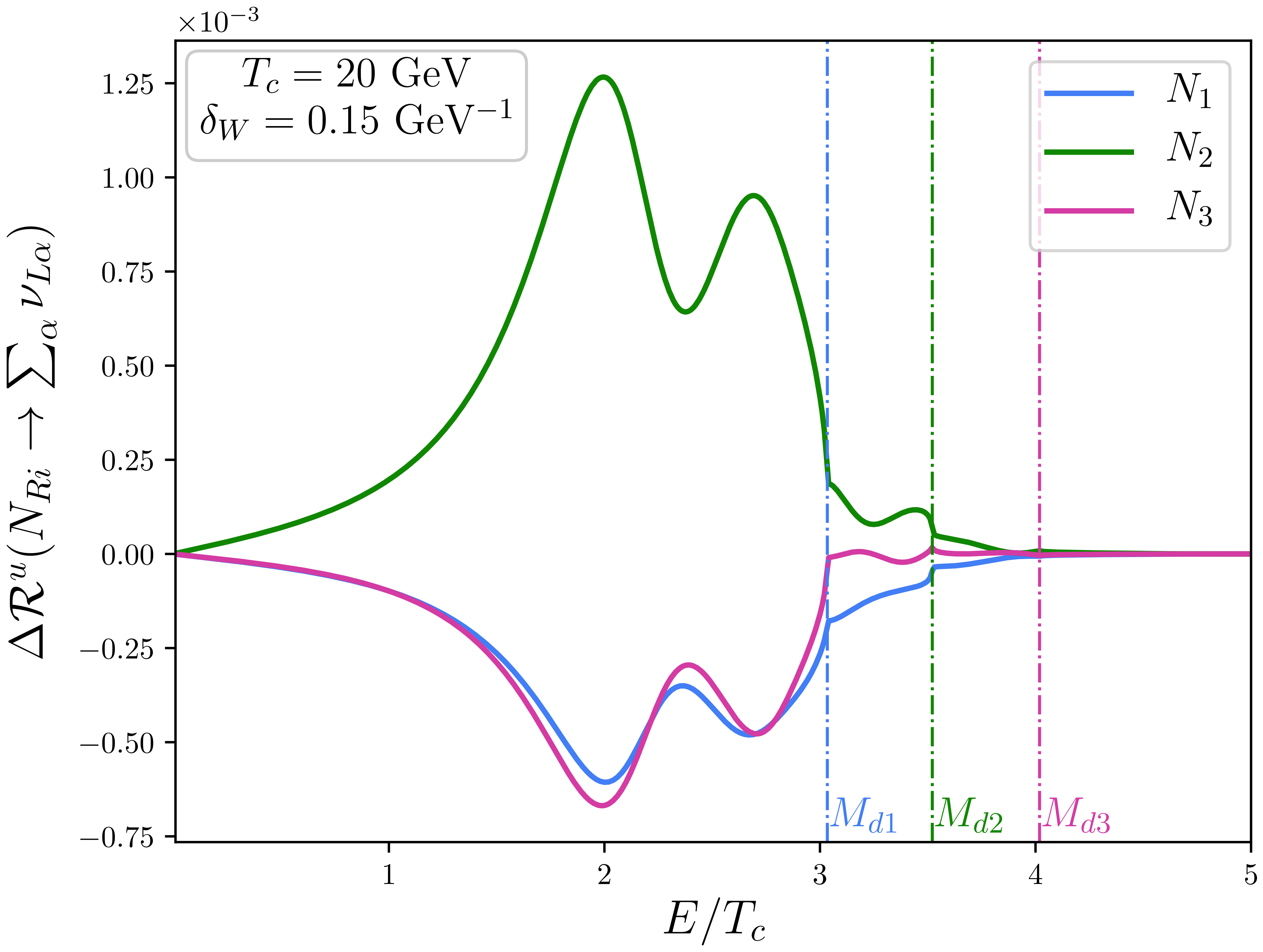
Vev profiles in the bubble wall

FLOR profile

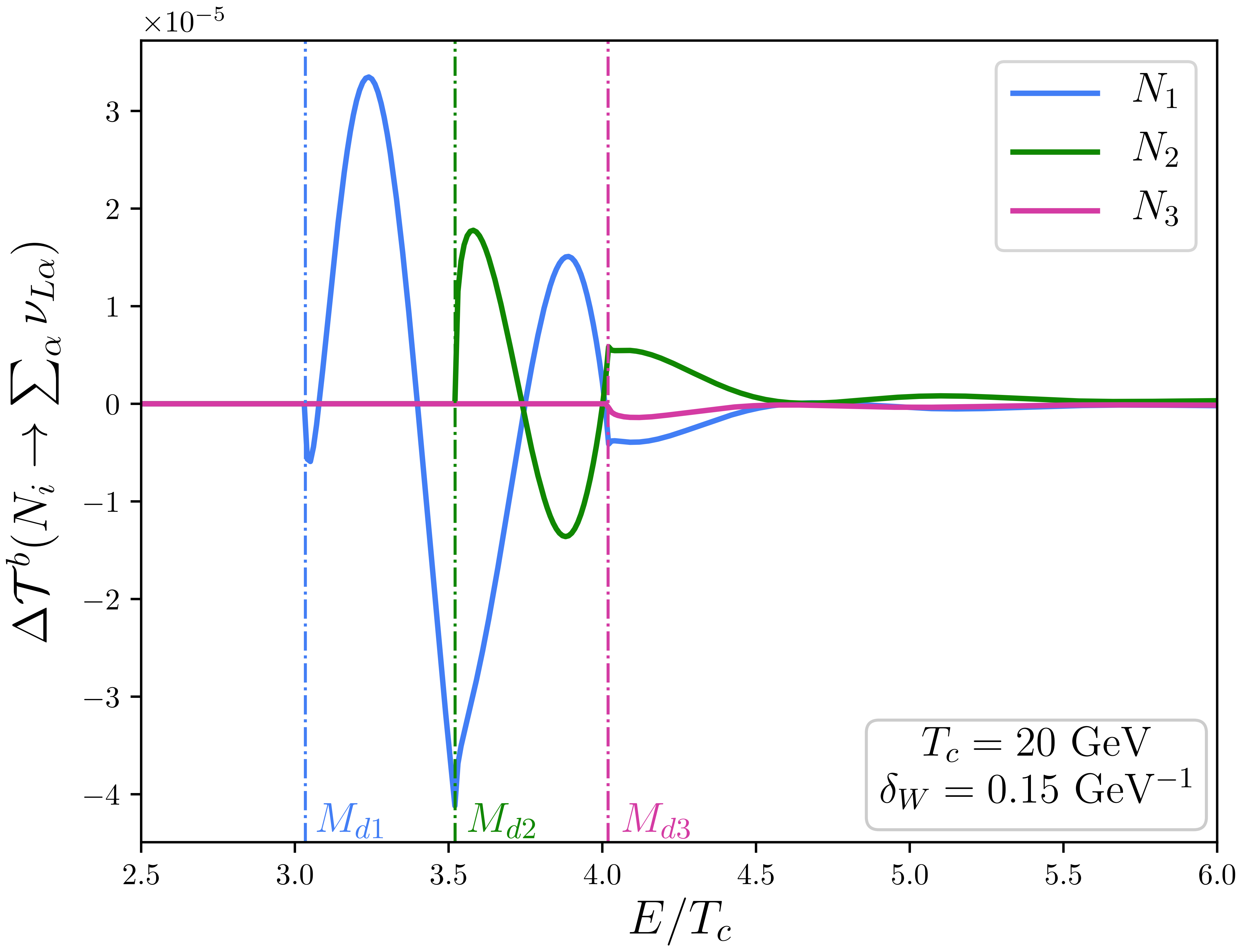




CP asymmetries



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

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

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

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

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

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$$\boxed{B \propto \Gamma_S v_W \xi_L j_\nu \to Y_B = \frac{B}{s(T_c)}}$$

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Does not work

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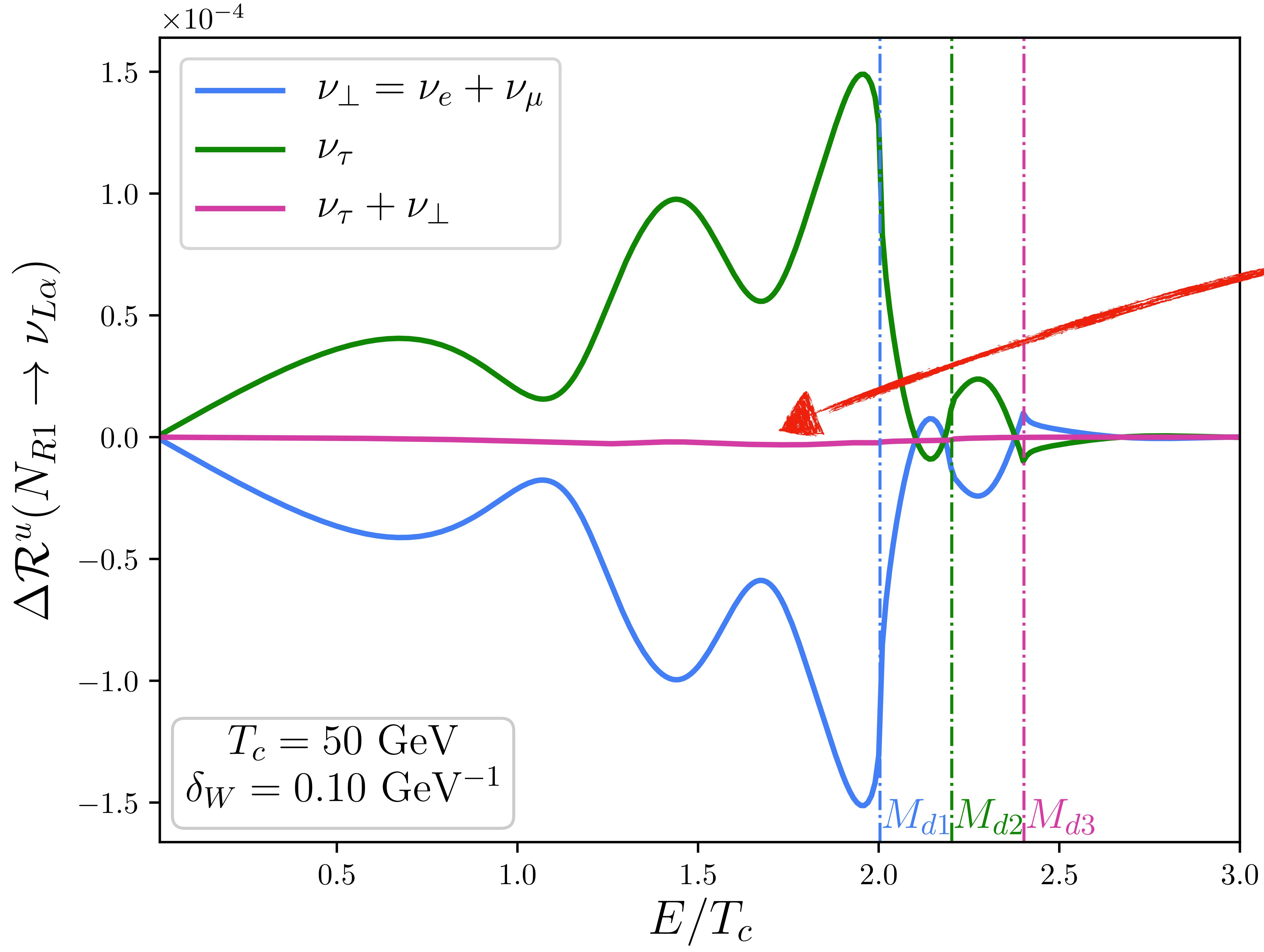
Flavoured CP asymmetries



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

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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

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Safe to neglect the wash-out with the τ

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

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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

Baryons

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

SM ν

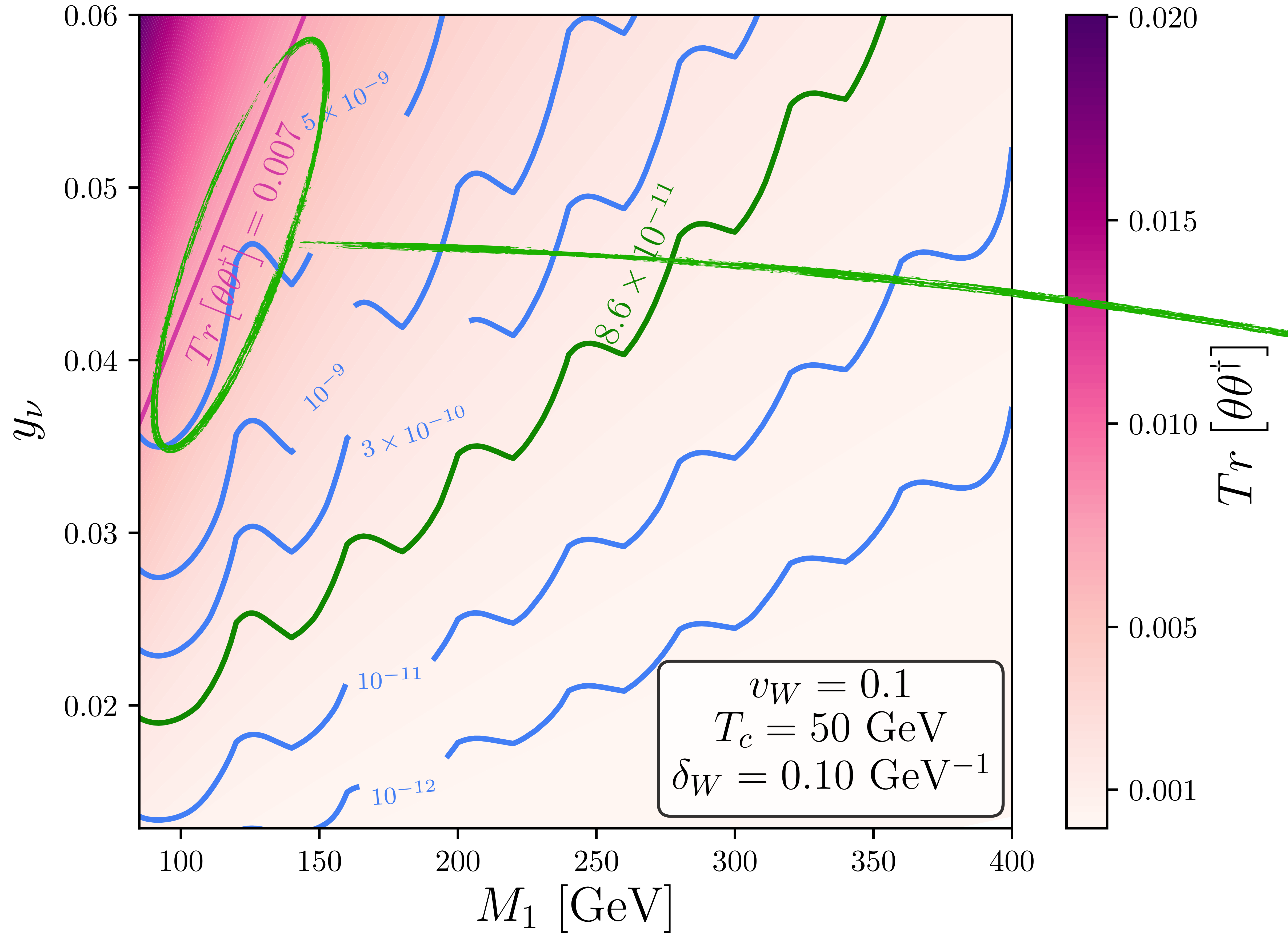
$$D_L \partial_z^2 n_{\nu_\alpha} - v_W \partial_z n_{\nu_\alpha} - 3\Gamma_S \mathcal{H}(-z) n_B - \Gamma_S \mathcal{H}(-z) \sum_\beta n_{\nu_\beta} - \sum_i \Gamma_{N_{Ri}\nu_\alpha} \left(\frac{1}{2} n_{\nu_\alpha} - n_{N_{Ri}} \right) = \xi_L j_{\nu_\alpha} \partial_z \delta(z)$$

N_R

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

Diffusion equations

Flavoured scenario



Current bound at 2σ on θ

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

Diffusion equations

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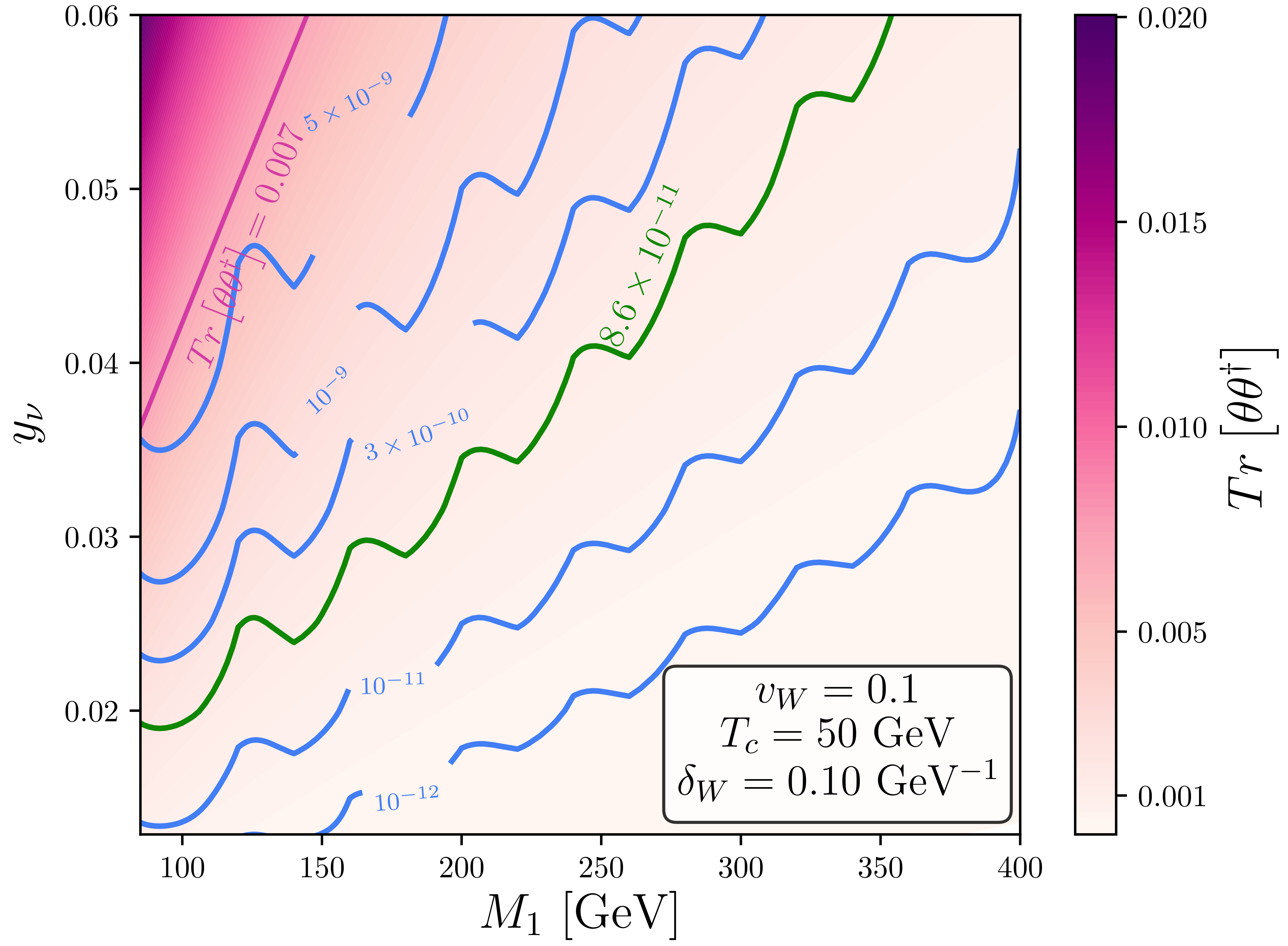


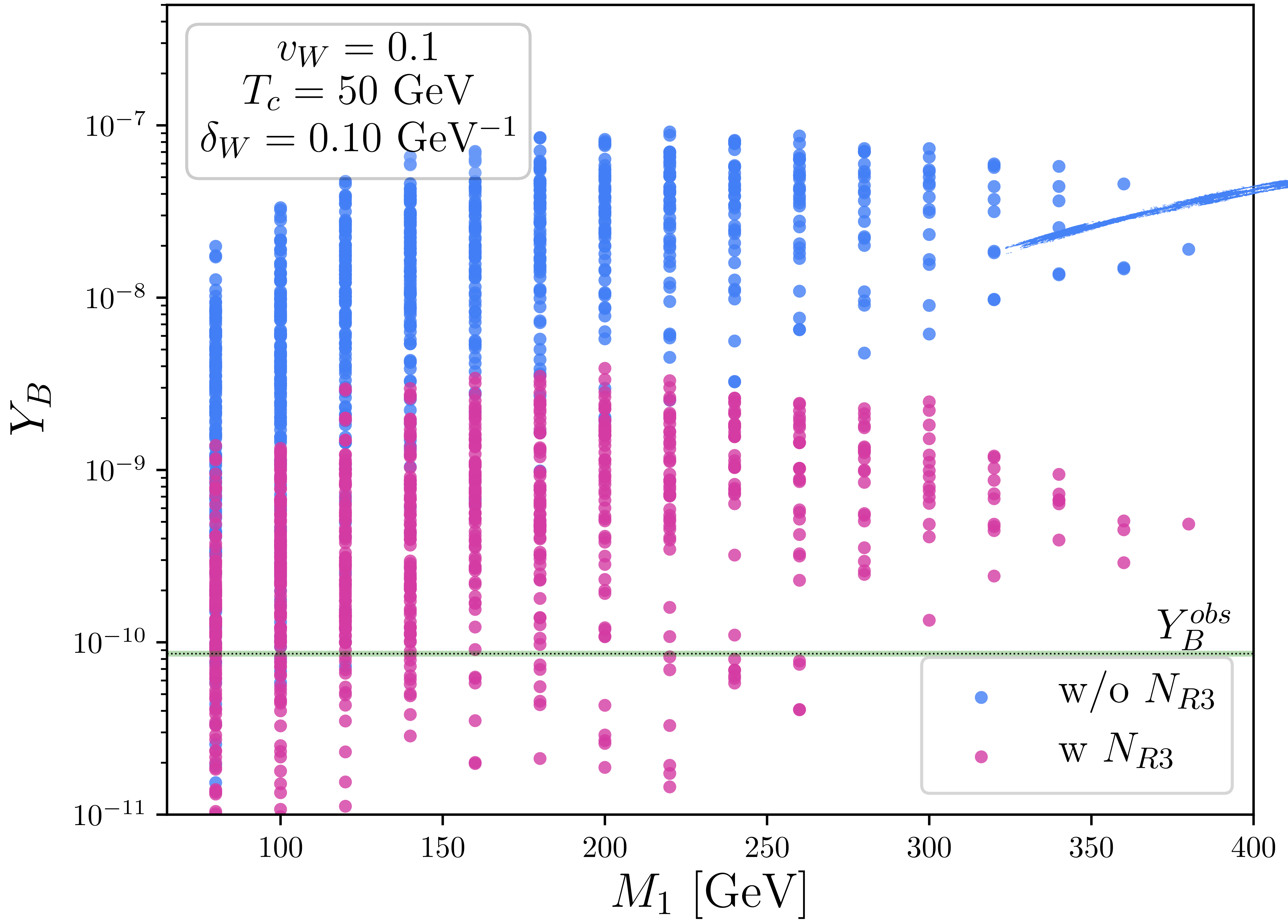
Larger baryon asymmetry:

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

$$N_R \to \nu_L \to B$$

Diffusion equations

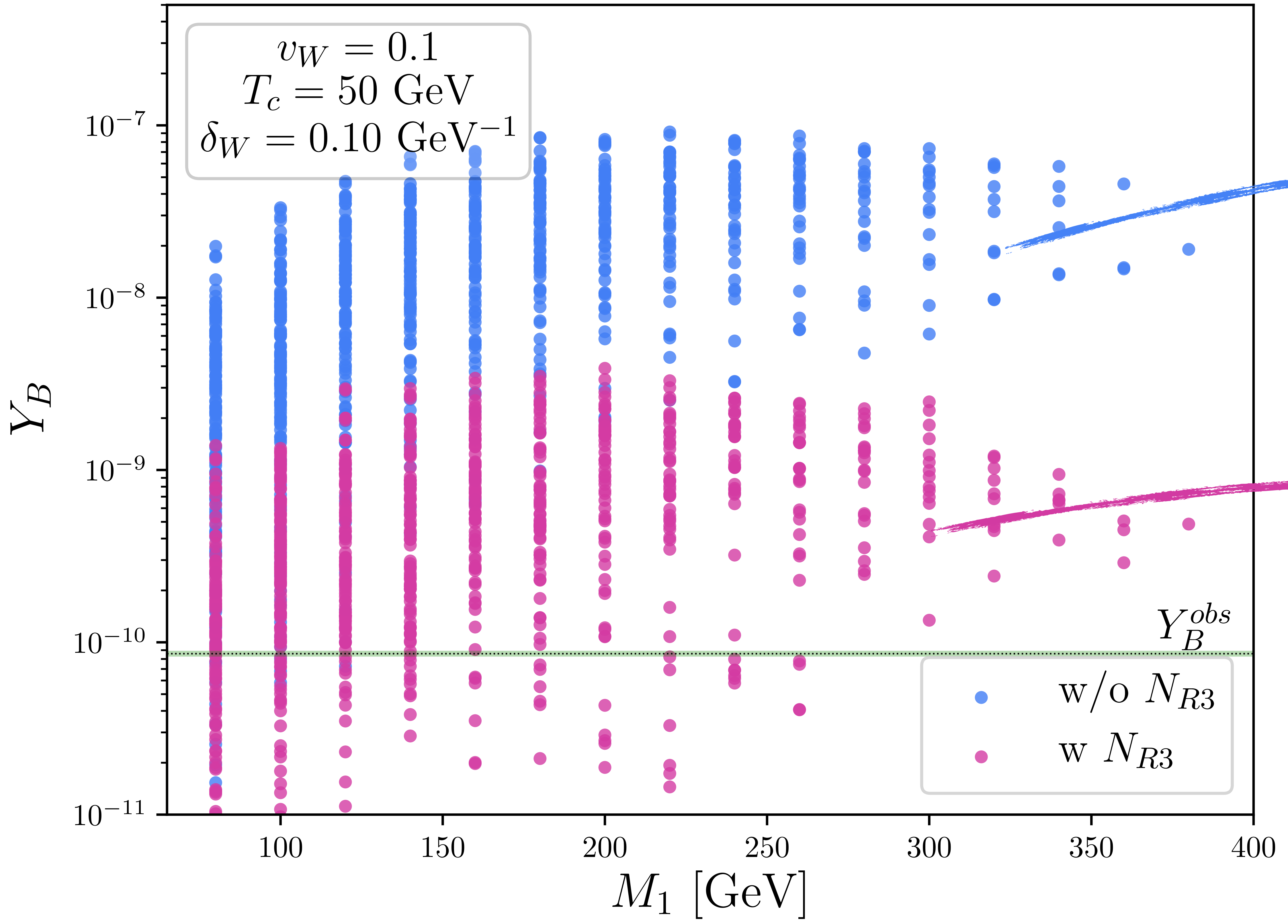
Flavoured scenario



Neglect the effect of N_{R3}

Diffusion equations

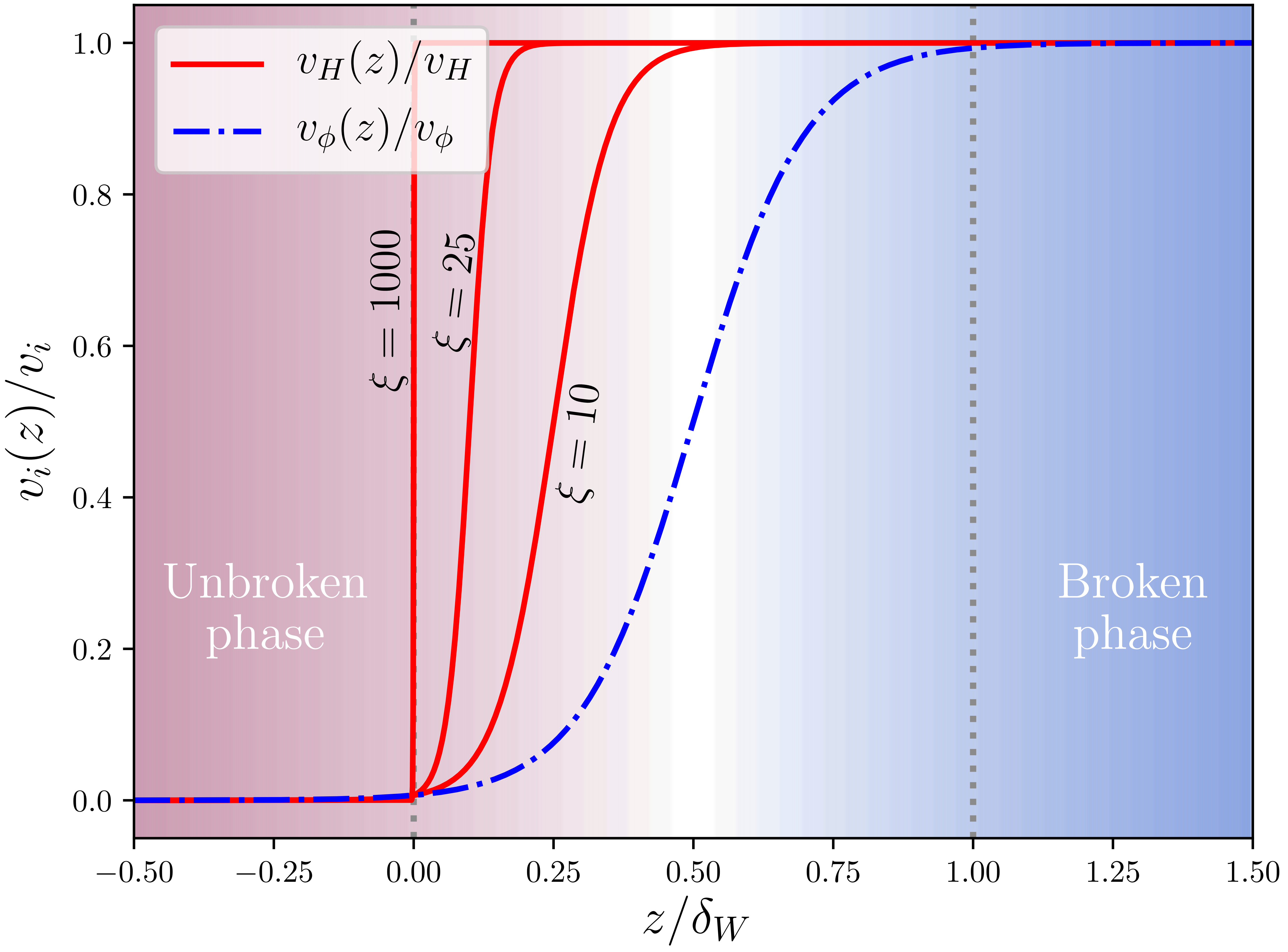
Flavoured scenario



Neglect the effect of N_{R3}

Overestimate the importance of N_{R3}

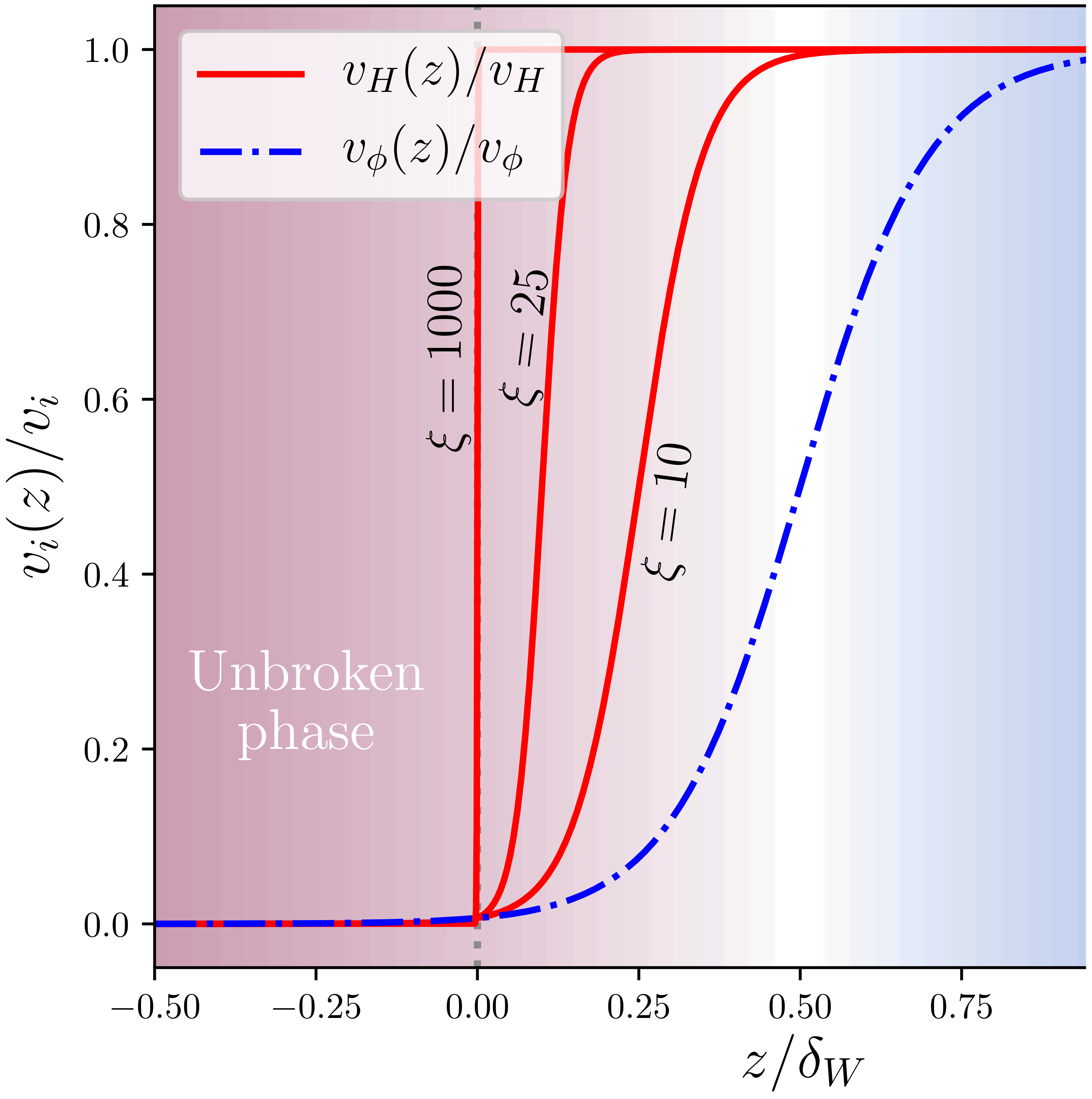
Effect of scalar vevs

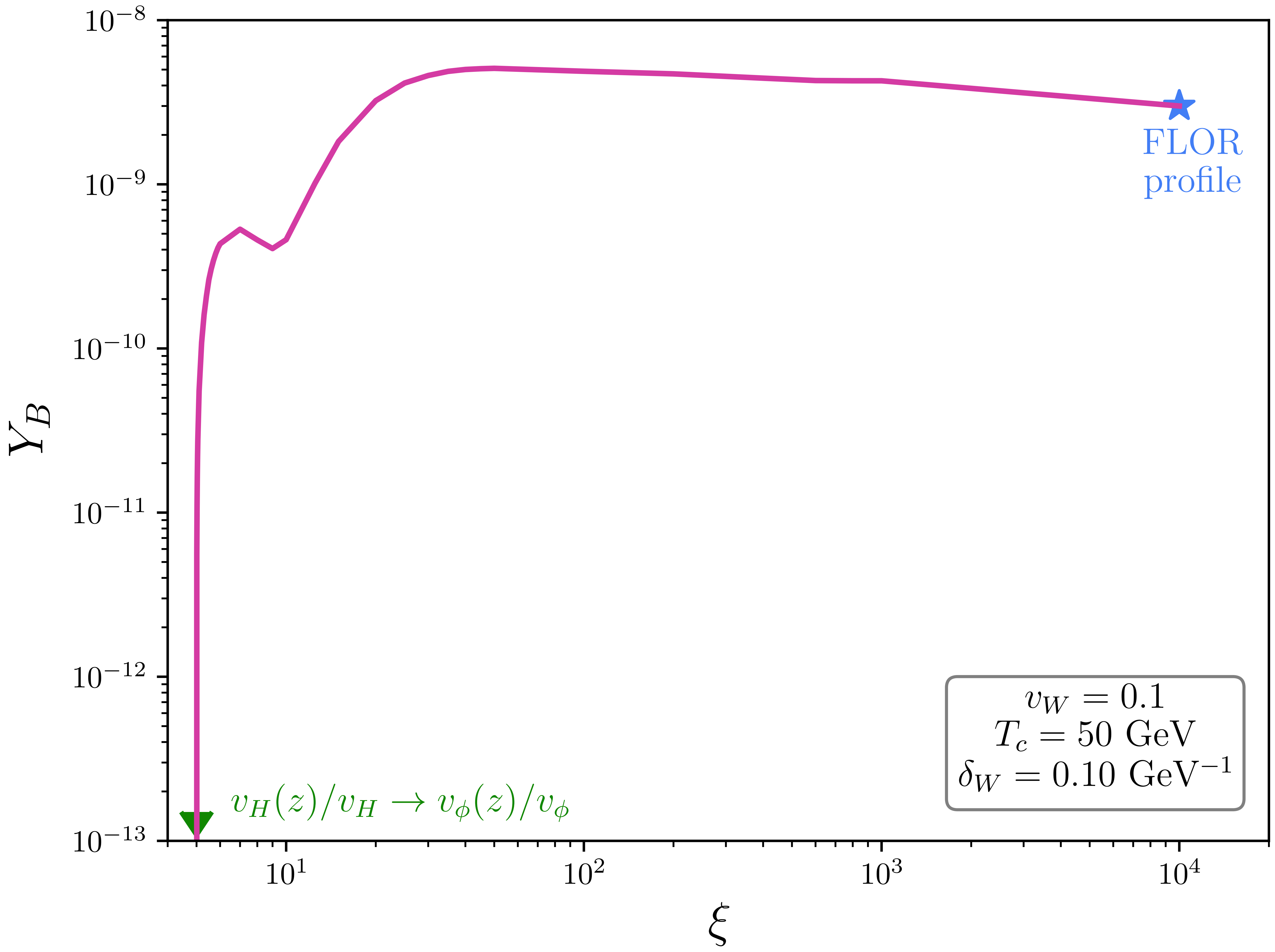


$$v_H(z)/v_H = \frac{1}{2}\left[1 + \tanh\left(\xi\frac{z - (5/\xi)\,\delta_W/2}{\delta_W}\right)\right]$$

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

Effect of scalar vevs





Conclusions

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

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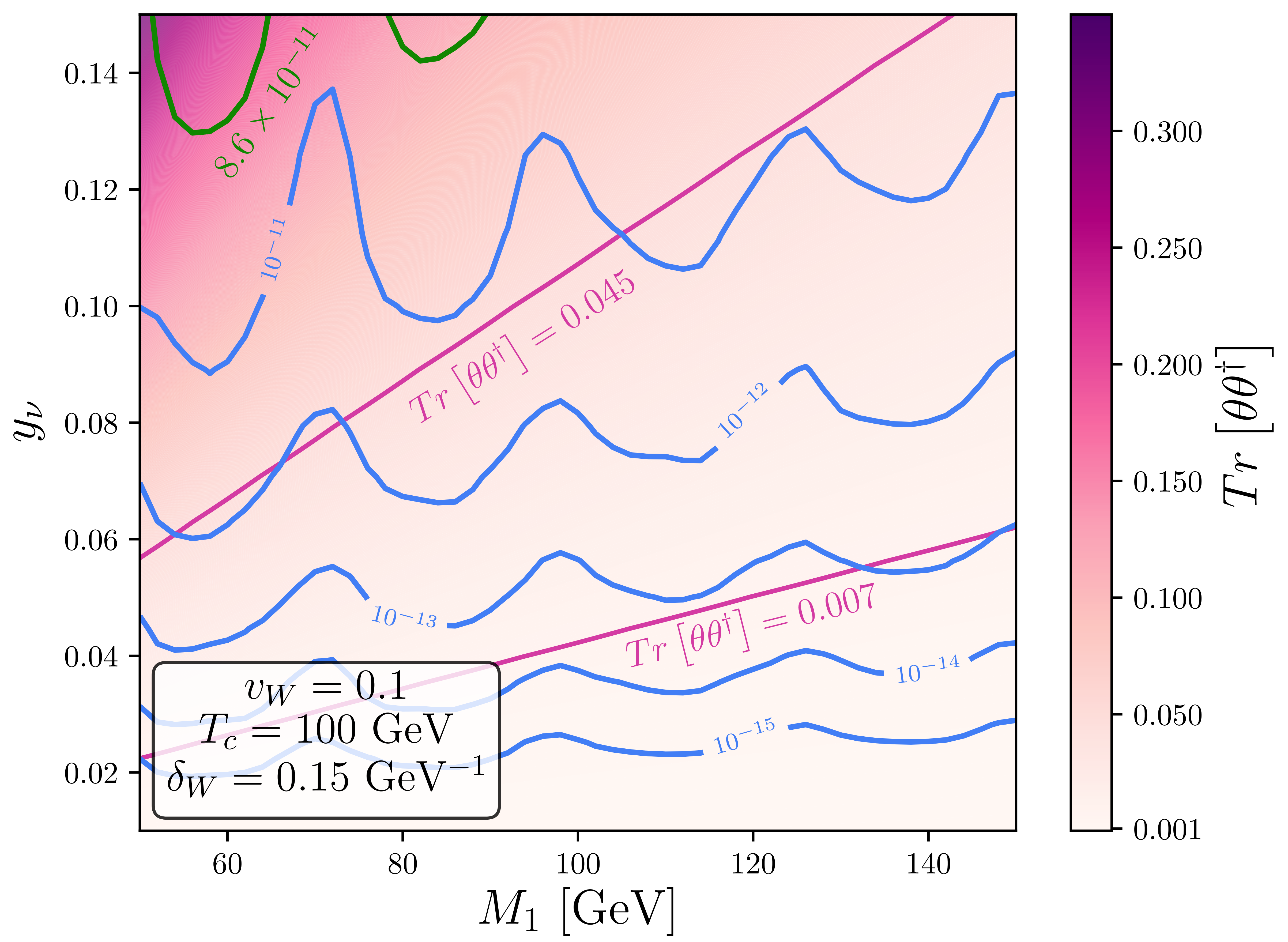
- Still need to study scalar potential and could improve BAU calculation

Back up slides

Diffusion equations

Vanilla scenario



Diffusion equations

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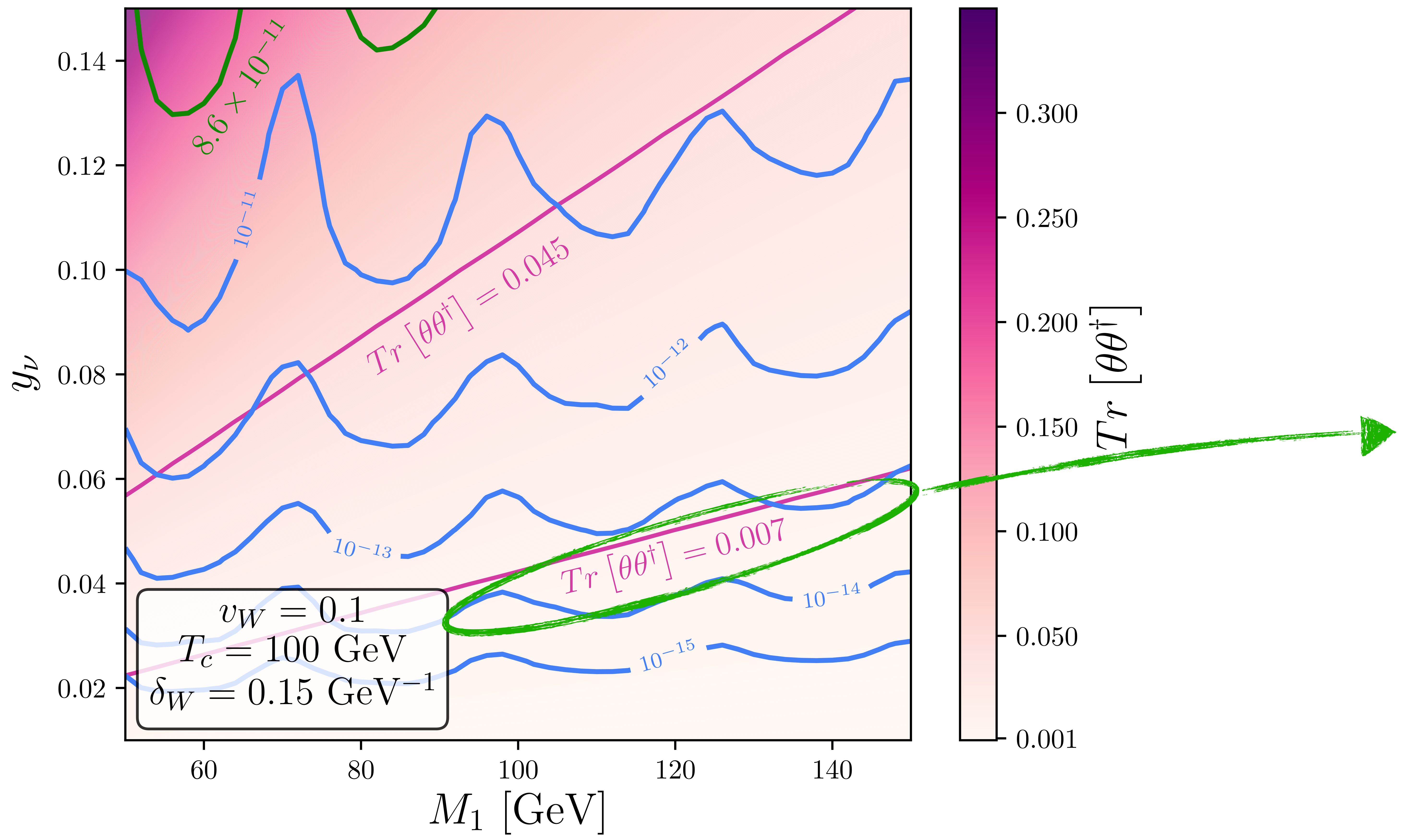

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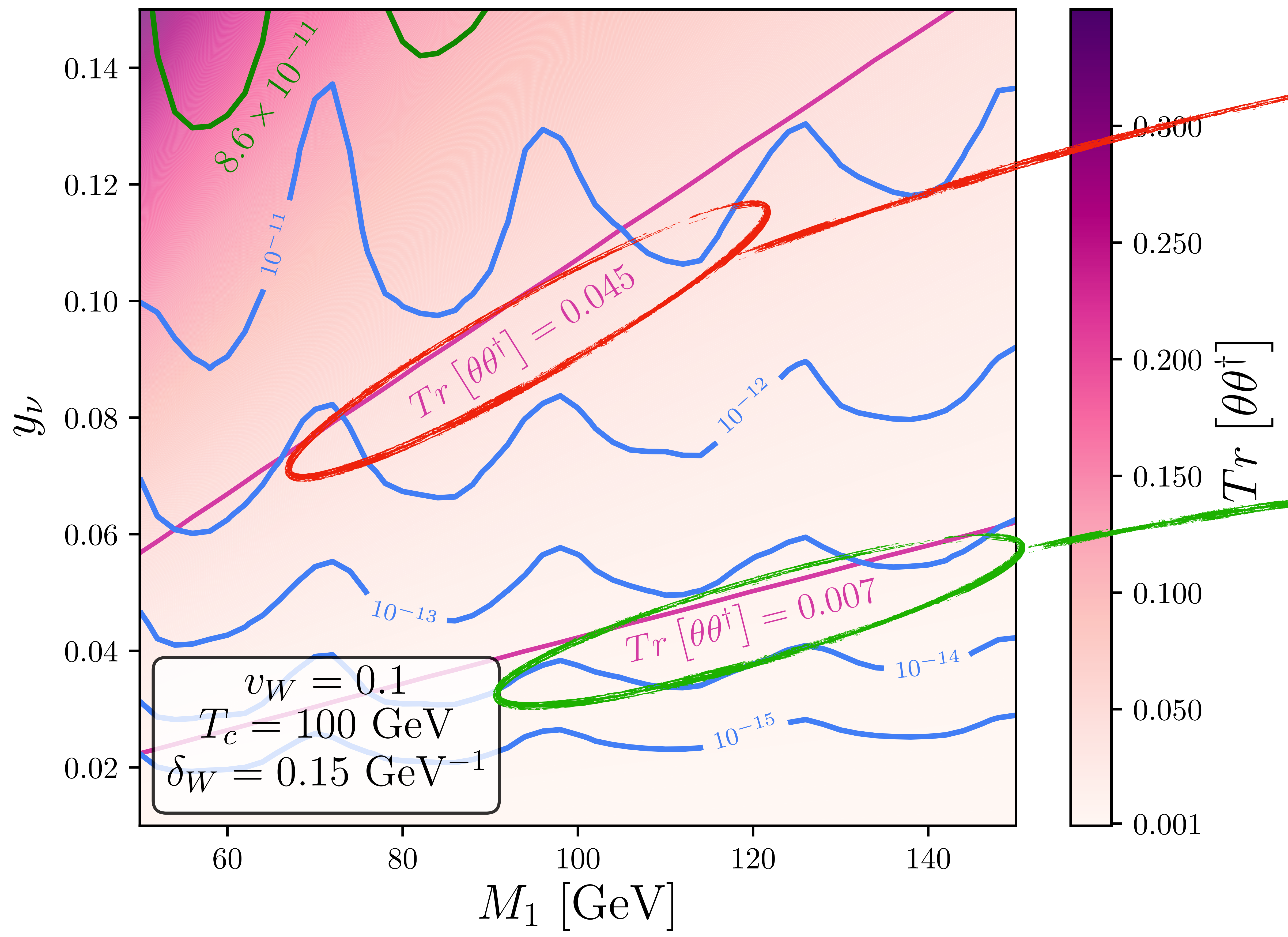

Bound on θ if avoiding the invisible width of the Z boson

Current bound at 2σ on θ

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

Scalar sector

Add real scalar singlet

Espinosa, Konstandin & Riva, arXiv: 1107.5441

$$V(\phi, H^\dagger H) = -\frac{1}{2}\mu_h^2 H^\dagger H + \frac{1}{4}\lambda_h (H^\dagger H)^2 + \frac{1}{2}\mu_\phi^2 \phi^2 + \frac{1}{4}\lambda_\phi \phi^4 + \frac{1}{4}\mu_m \phi H^\dagger H + \frac{1}{4}\lambda_m \phi^2 H^\dagger H + \mu_1^3 \phi + \frac{1}{3}\mu_3 \phi^3$$

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After SSB $\rightarrow \langle H \rangle = \begin{pmatrix} 0 \\ v_H \end{pmatrix}, \quad \langle \phi \rangle = v_\phi$

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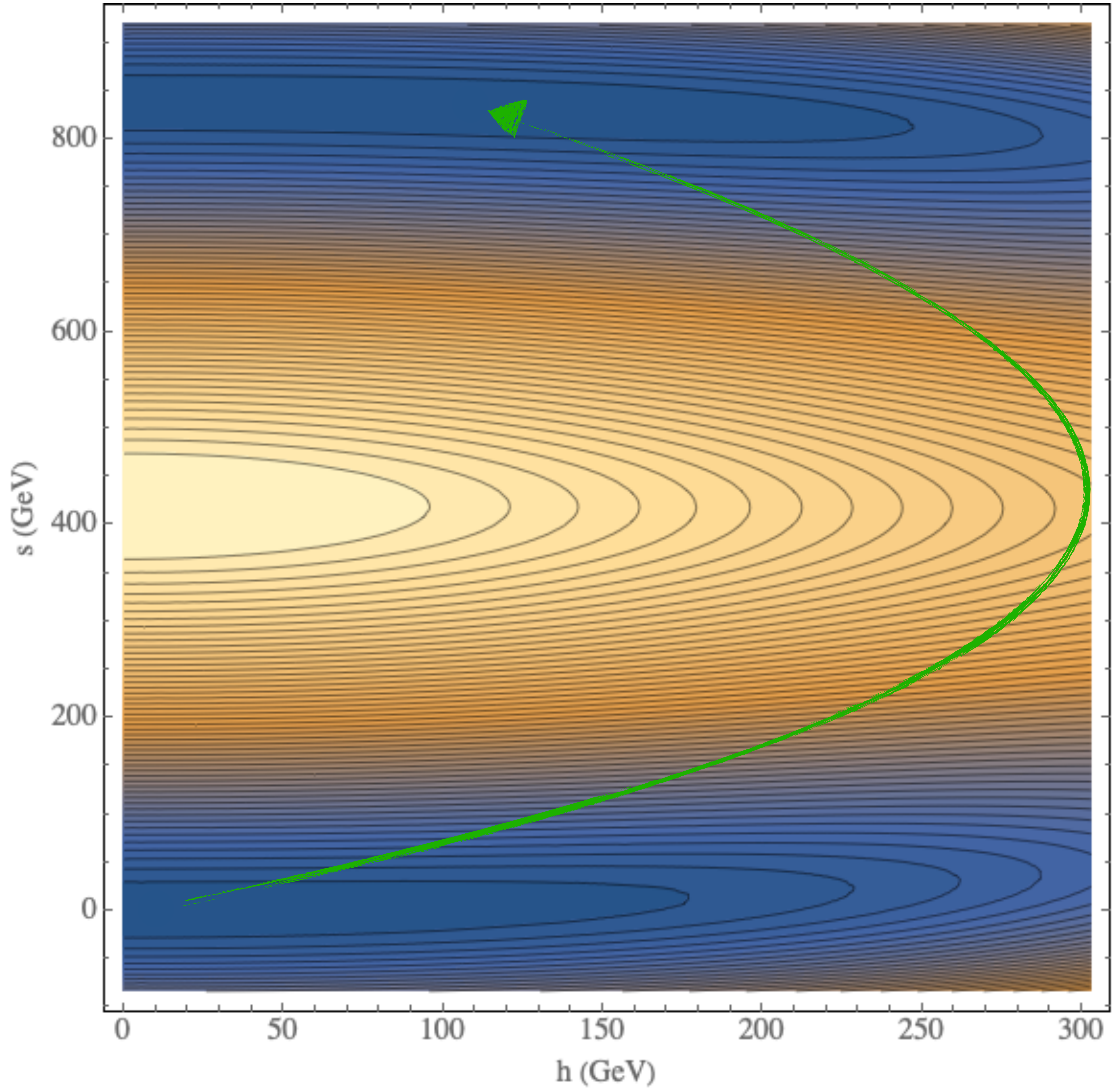
Study T dependence

in the mean field approximation

T_c when $V(0,0,T_c) = V(v_H(T_c), v_\phi(T_c), T_c)$

Scalar sector



$T_c \sim 115$ GeV

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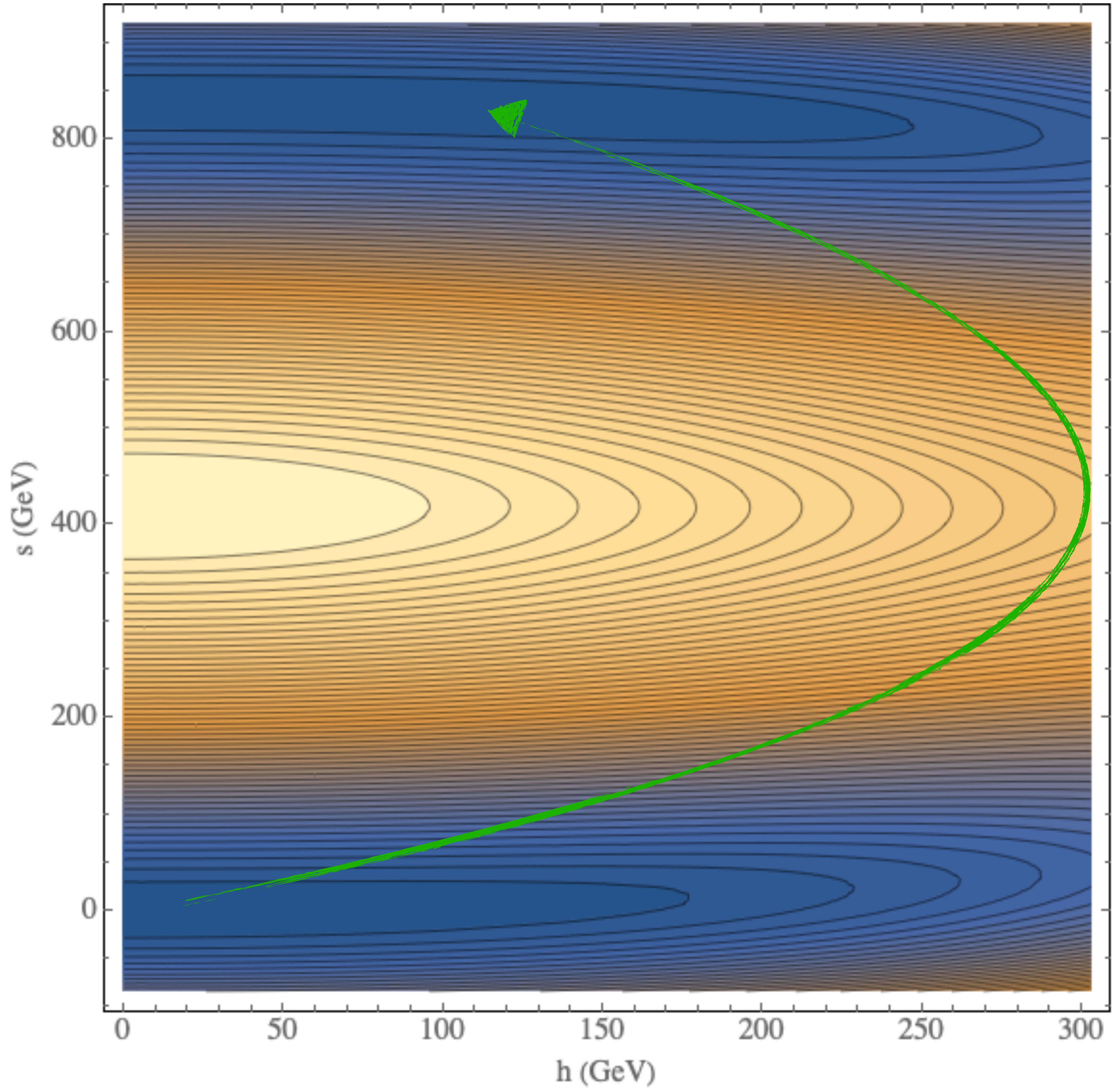

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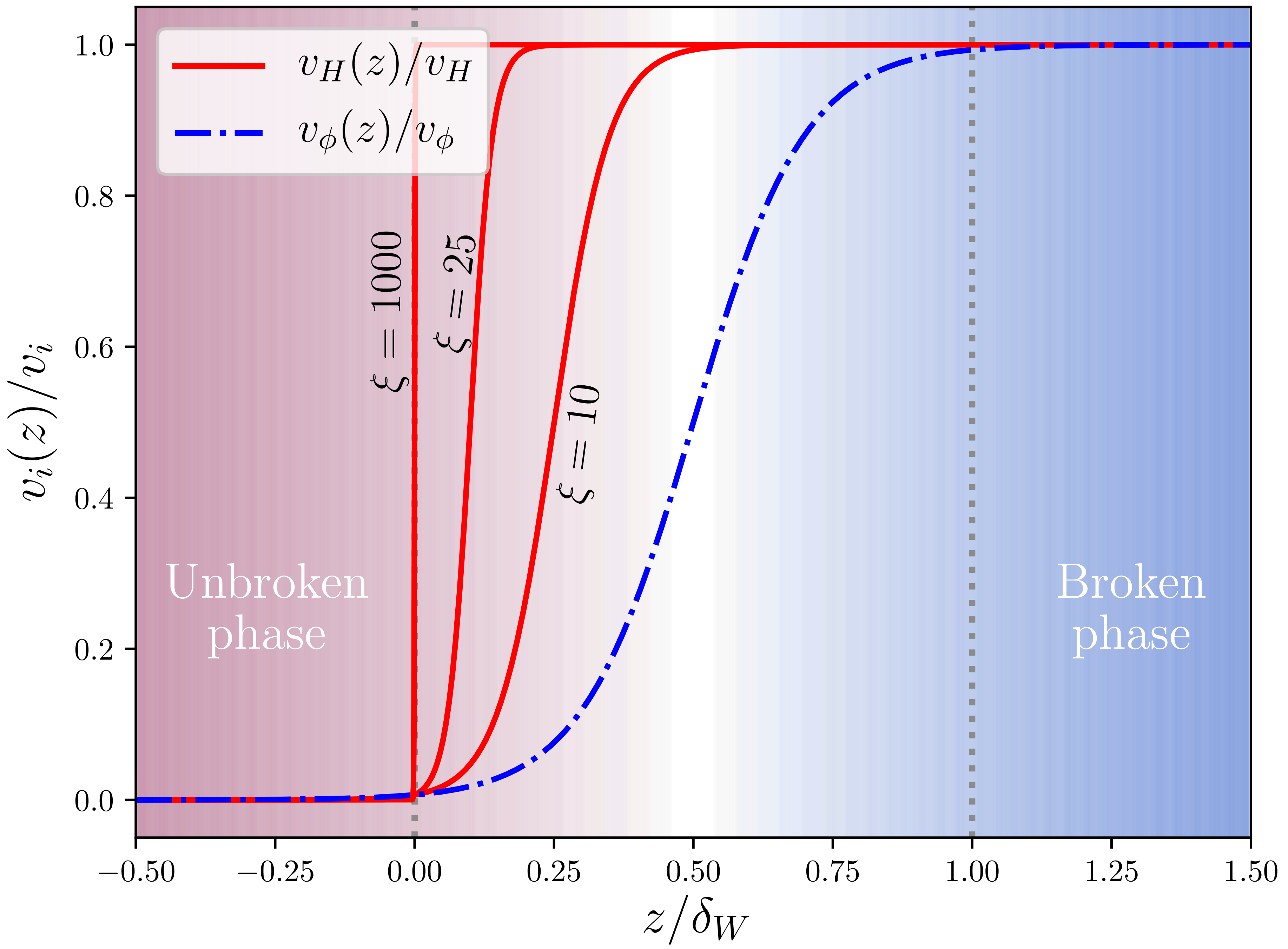

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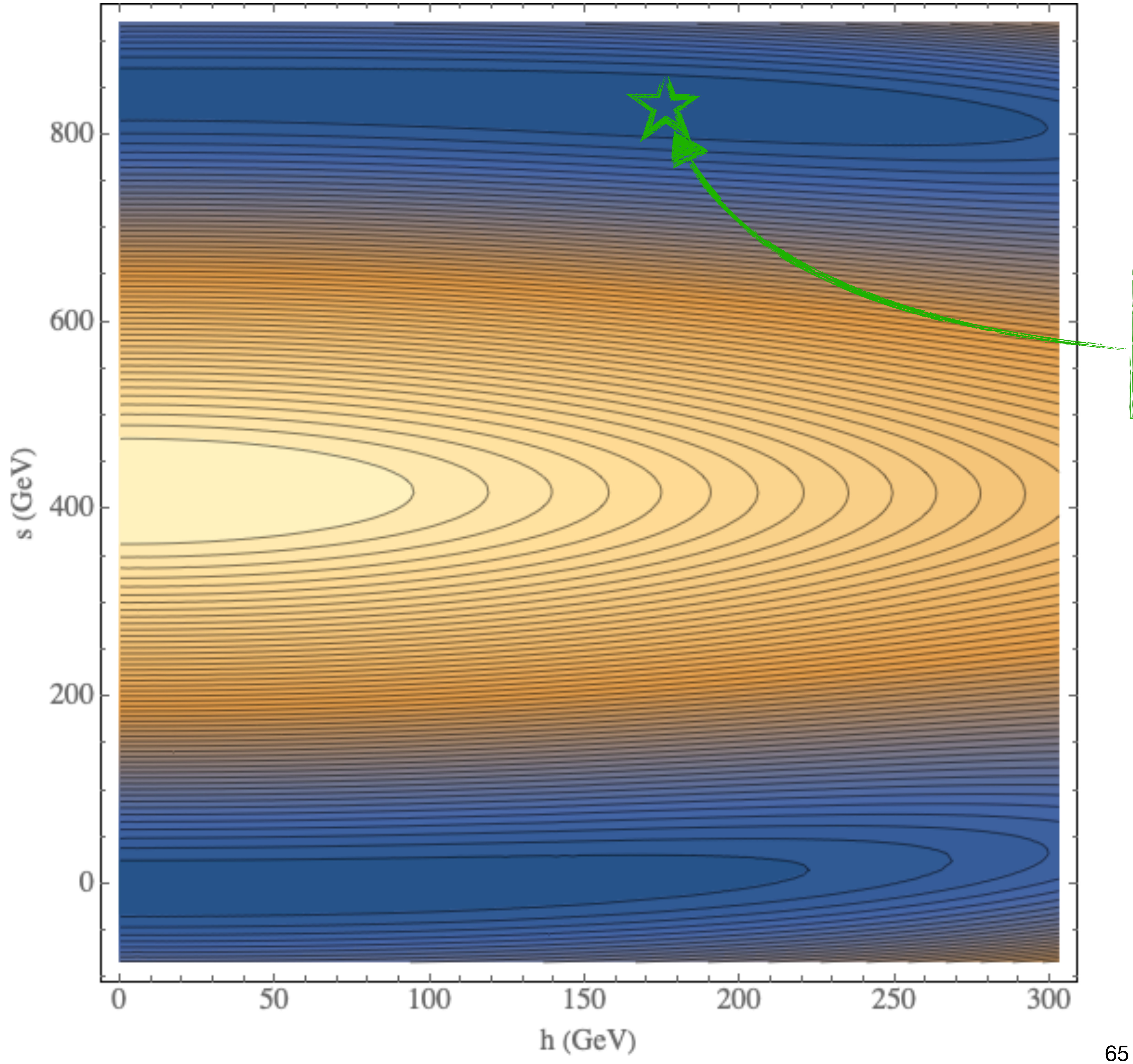

$T = 0$ GeV

Absolute minimum at $\left(v_H^{exp}, 830 \text{ GeV}\right)$

Difference between T_c and T_n

Compare $\Gamma_n \propto e^{-S_3/T}$ with the expansion rate $H(T)$

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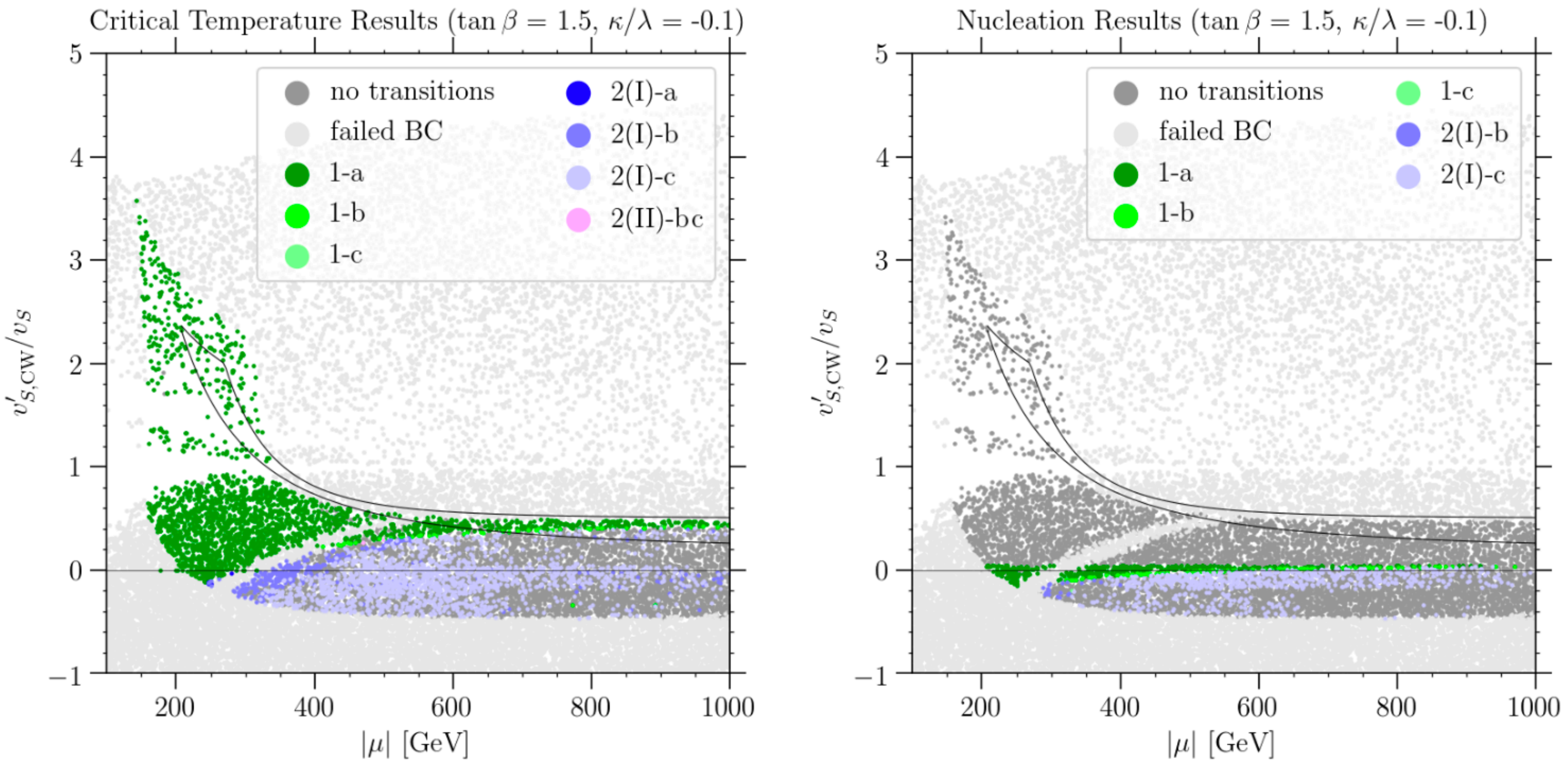
Baum *et al.*, arXiv.2009.10743



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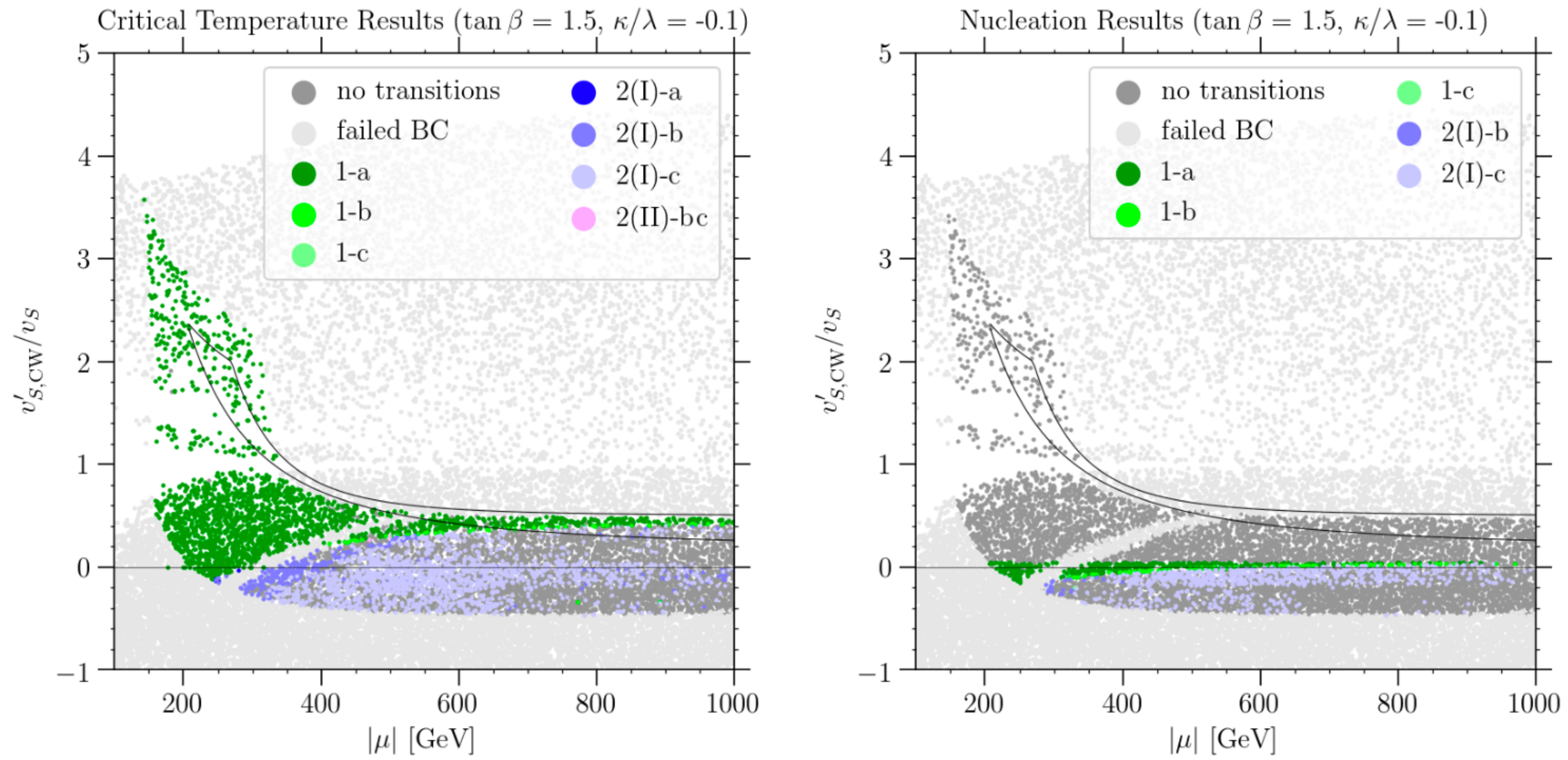


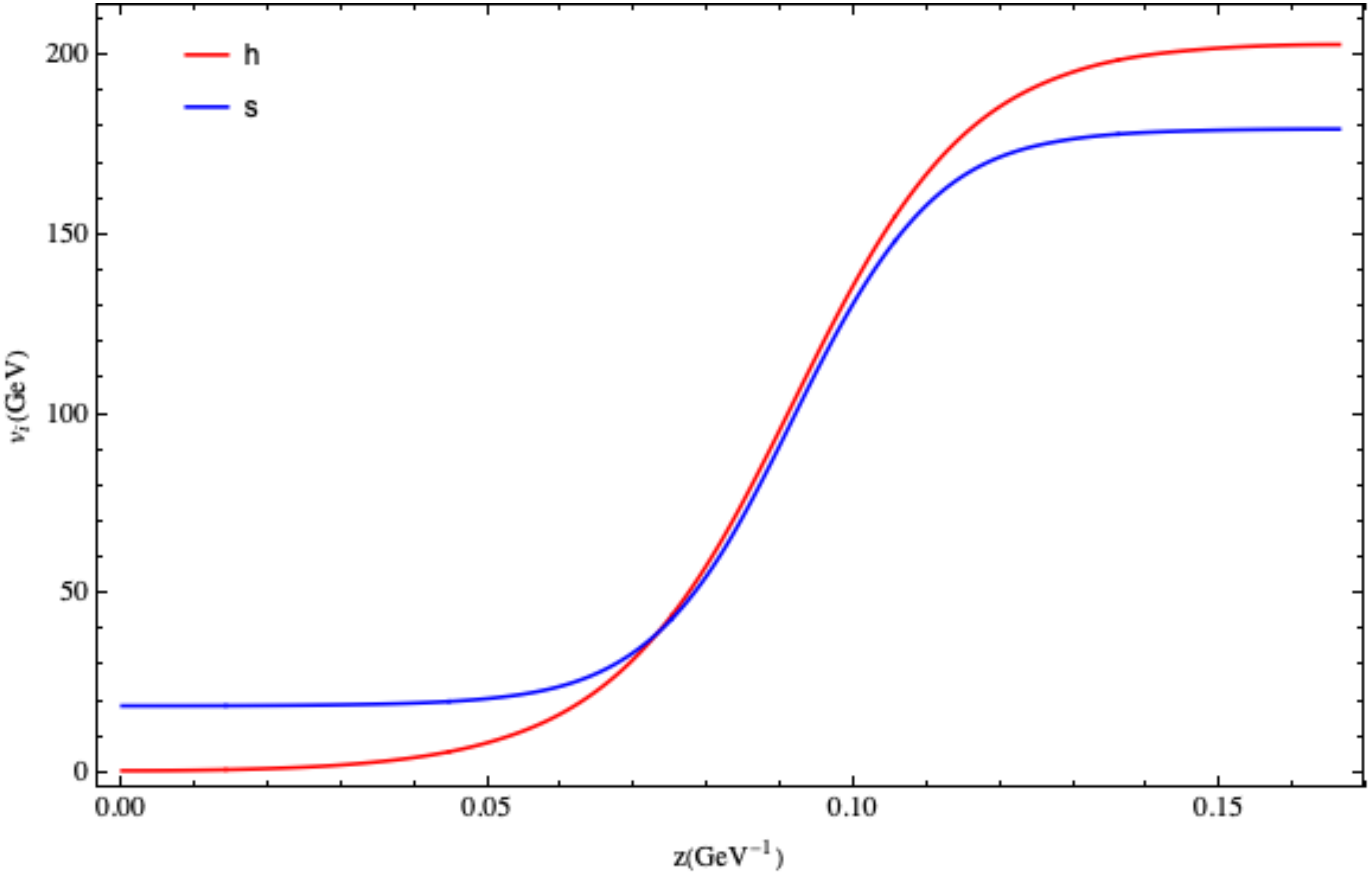
Bubbles nucleate at $T_n < T_c$ when $S_3/T_n \sim 140$

Find bounce solution to compute S_3

Difference between T_c and T_n

Bubbles nucleate at $T_n < T_c$ when $S_3/T_n \sim 140$

Example point



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