ν Electroweak Baryogenesis

Salvador Rosauro-Alcaraz

IRN Neutrino meeting, Annecy

29/06/22

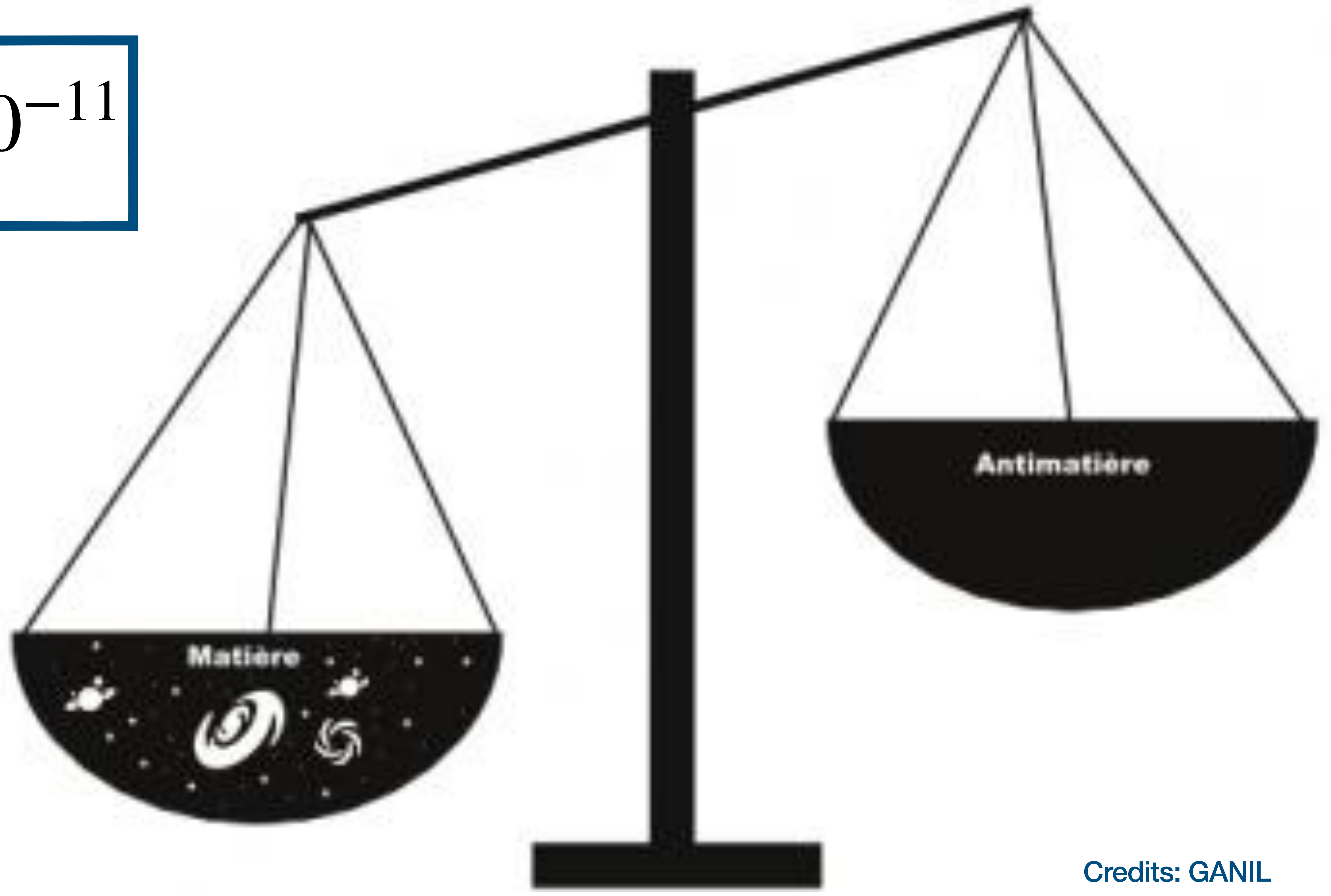
In collaboration with E. Fernández-Martínez, J. López-Pavón & T. Ota based on JHEP 10 (2020) 063

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

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

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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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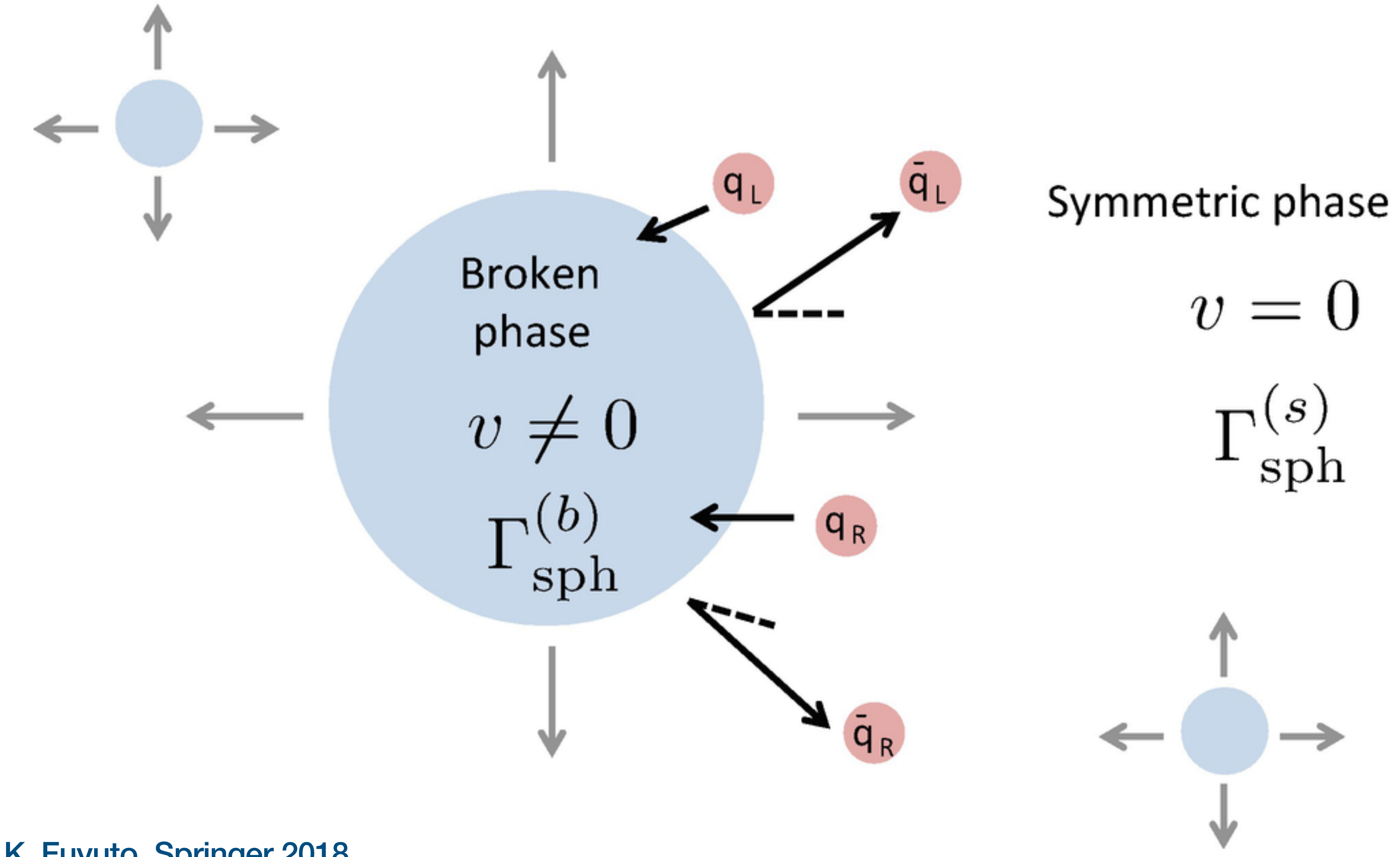

K. Fuyuto, Springer 2018

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

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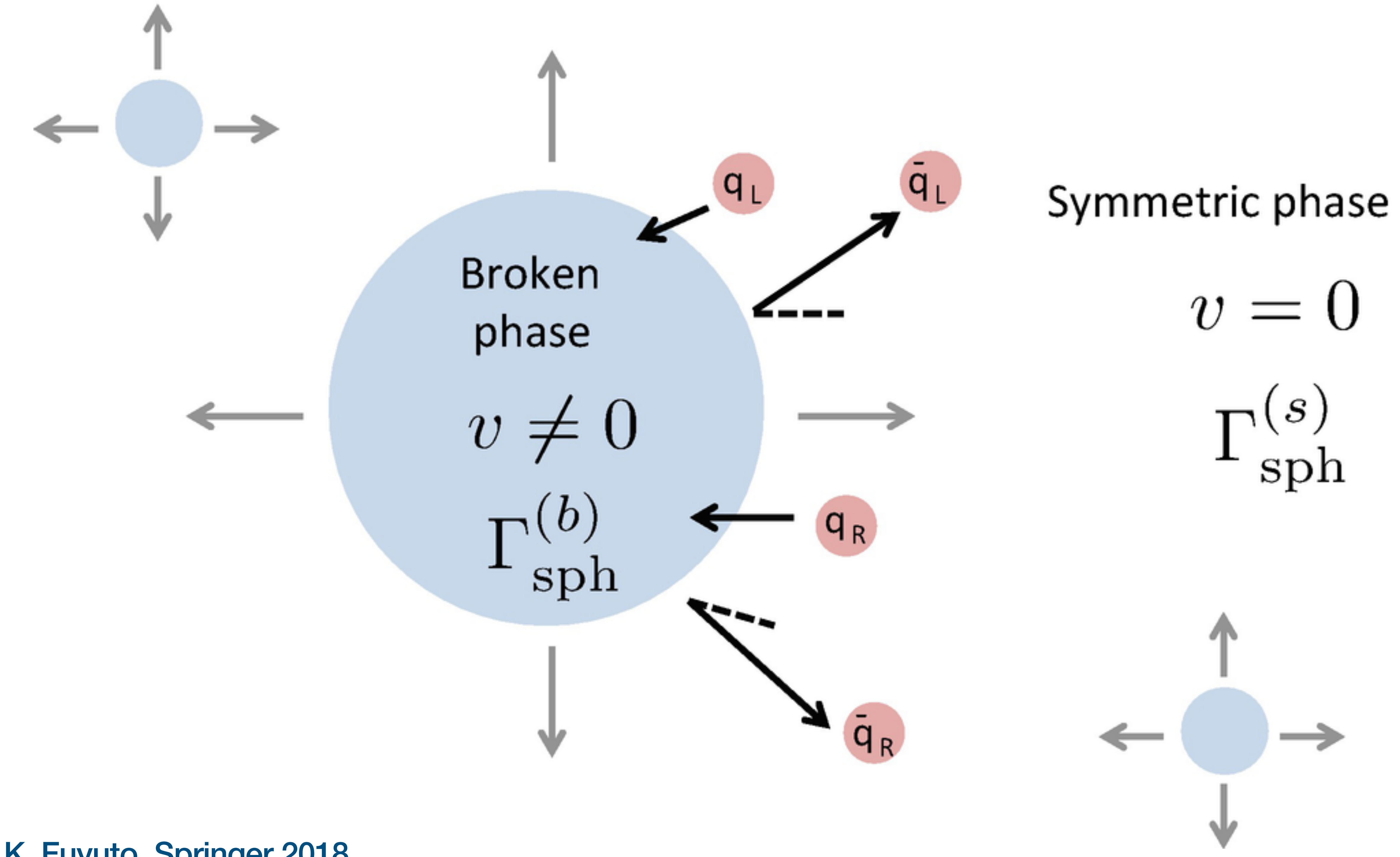

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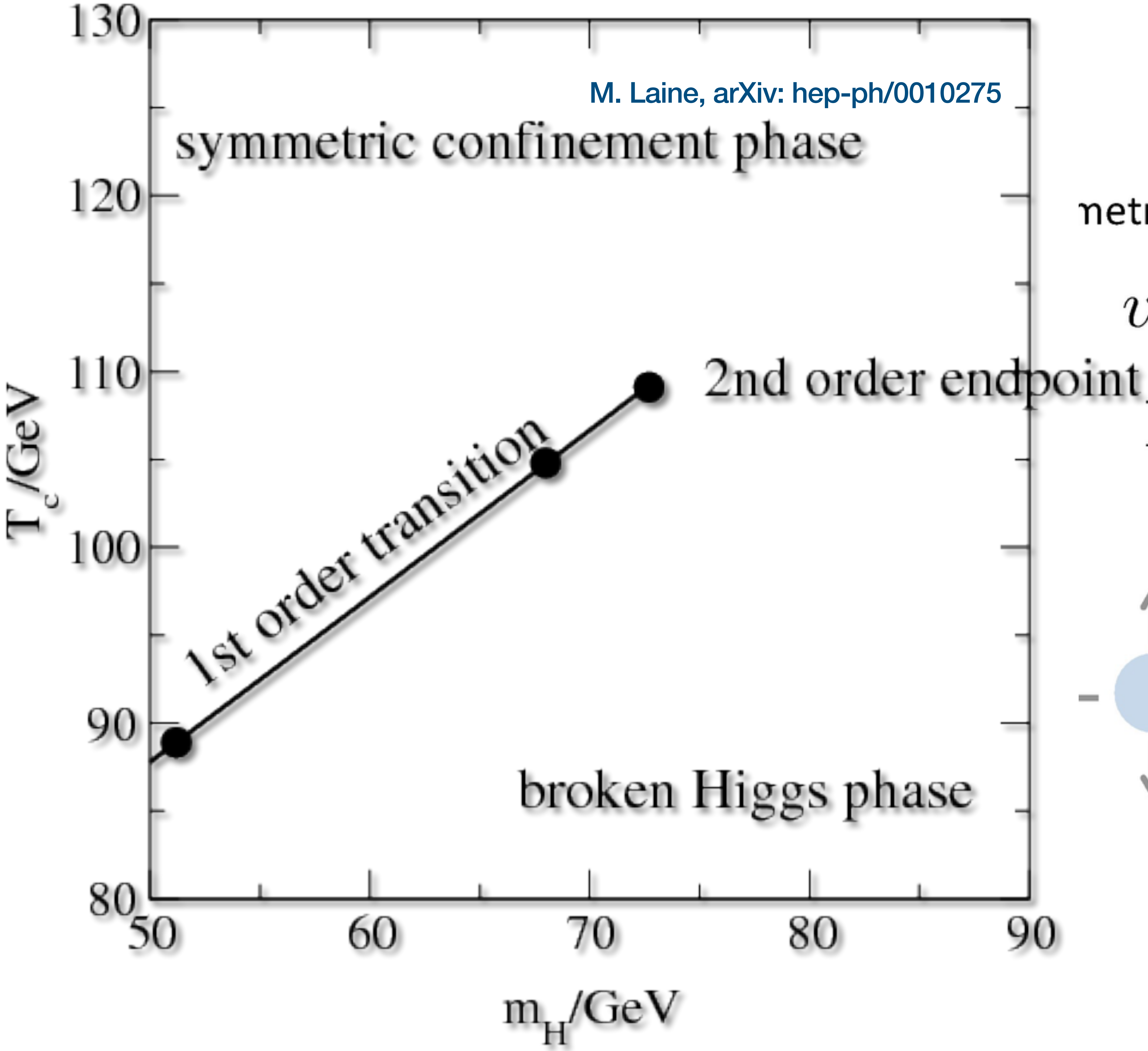
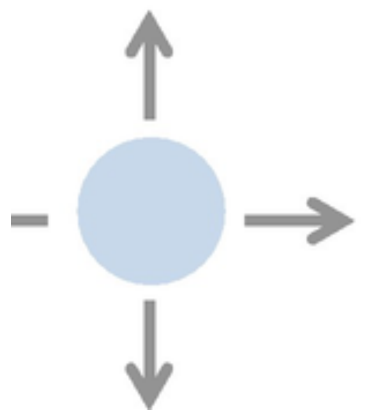
K. Kajantie, M. Laine, K. Rummukainen, & M. E. Shaposhnikov, arXiv:hep-ph/9605288



netric phase

$v = 0$

$\Gamma^{(s)}_{\rm sph}$



Electroweak baryogenesis with new physics

Electroweak baryogenesis

Shaposhnikov, Nucl. Phys B287 (1987)

CP violation from CKM matrix → New sources of CP violation

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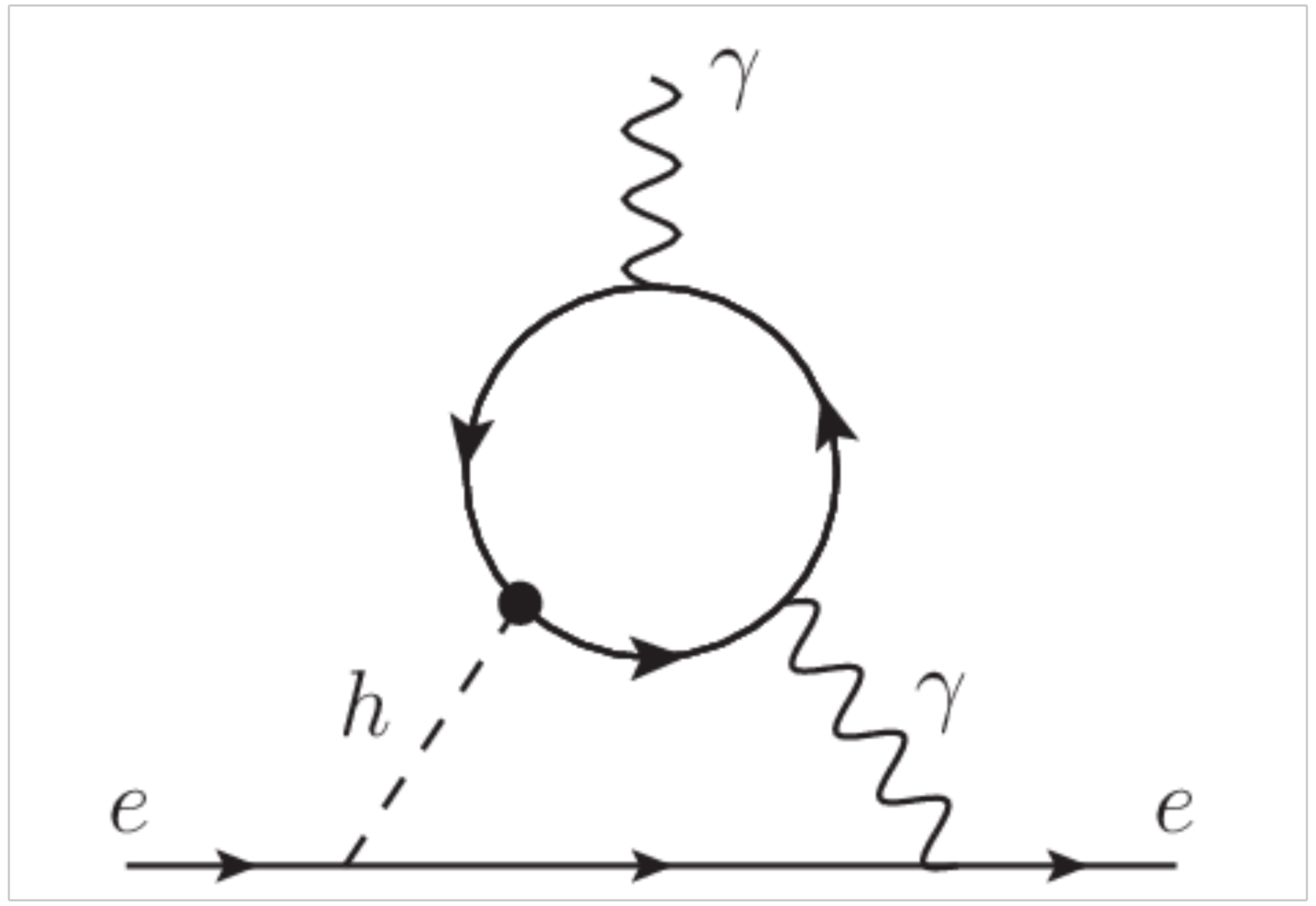
Kuzmin, Rubakov & Shaposhnikov, Phys. Lett. 155B (1985) 36

1^{st} order phase transition

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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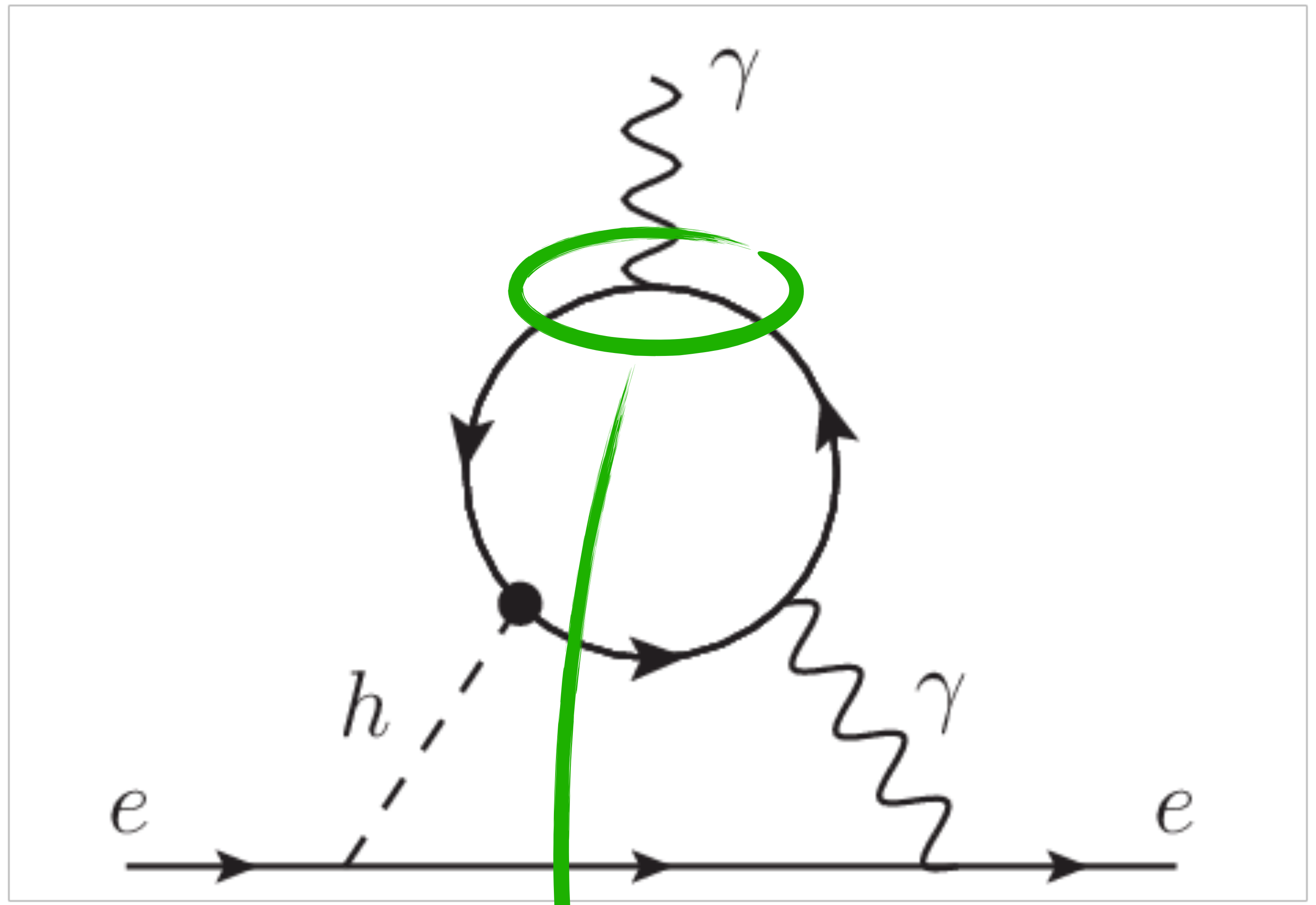

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ν's do not couple to γ

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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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$$m_\nu = 0, \quad \theta \equiv m_D M^{-1}$$

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

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Hierarchical heavy neutrinos

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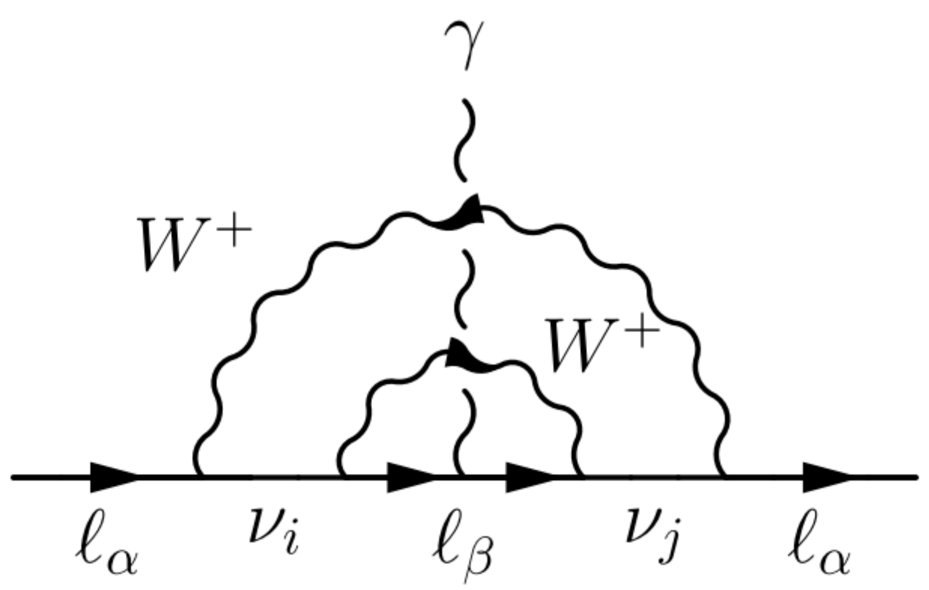

Avoid electric dipole moment bounds

A. Abada & T. Toma, arXiv: 1605.07643

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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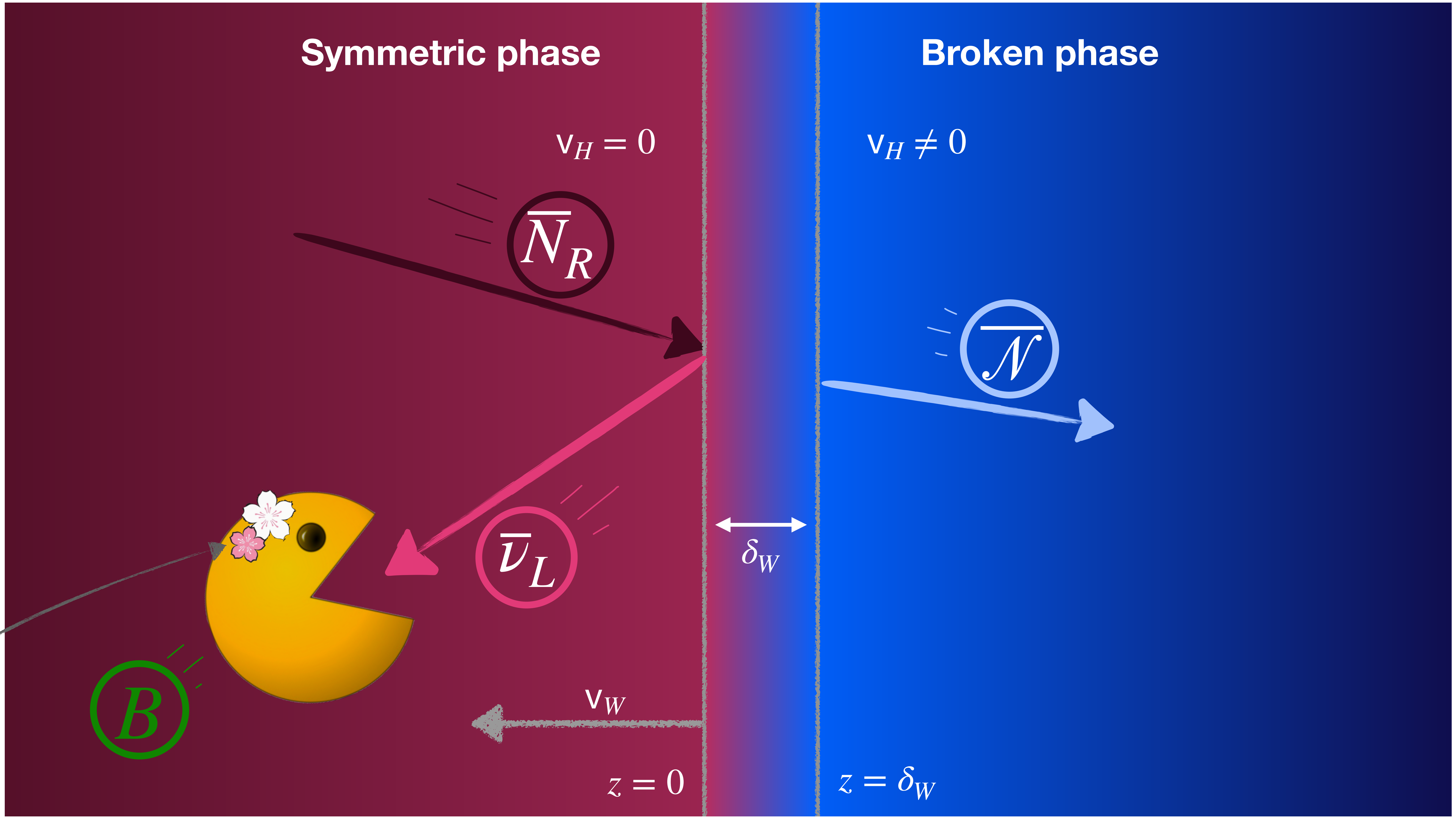
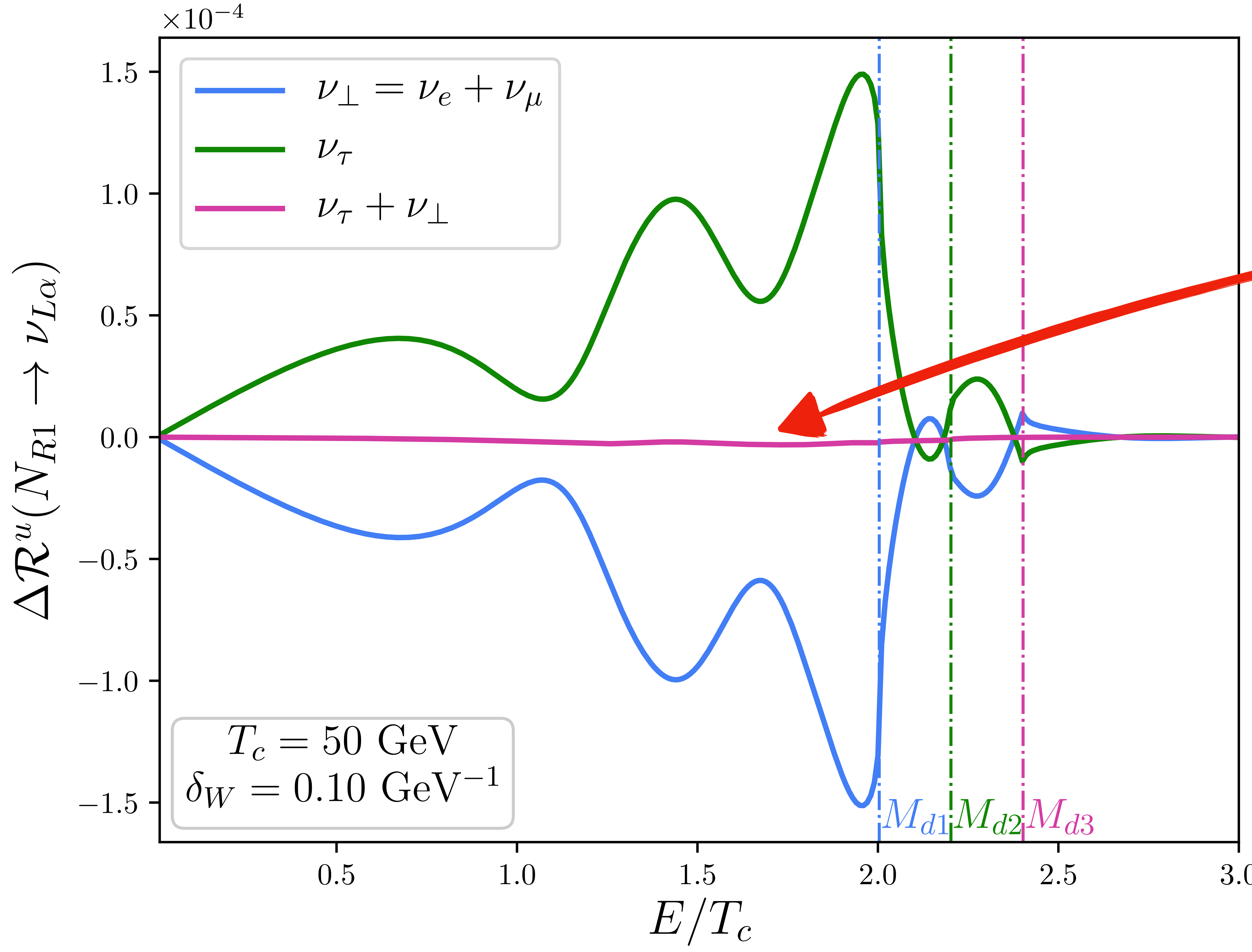


"Artistic" depiction of a sphaleron

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

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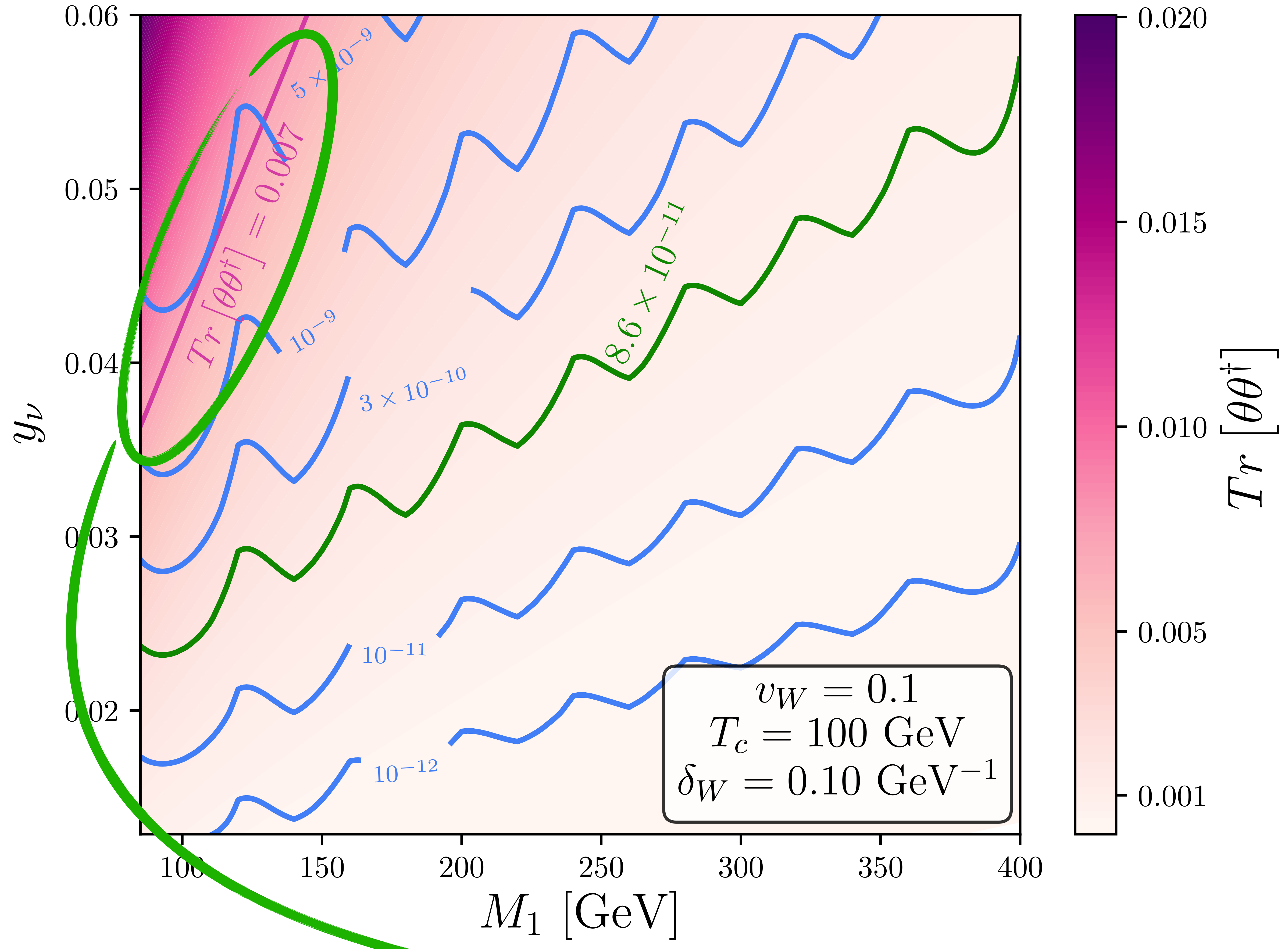
Safe to neglect the wash-out with the τ

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

$M_i \gtrsim 200\ GeV$ → 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

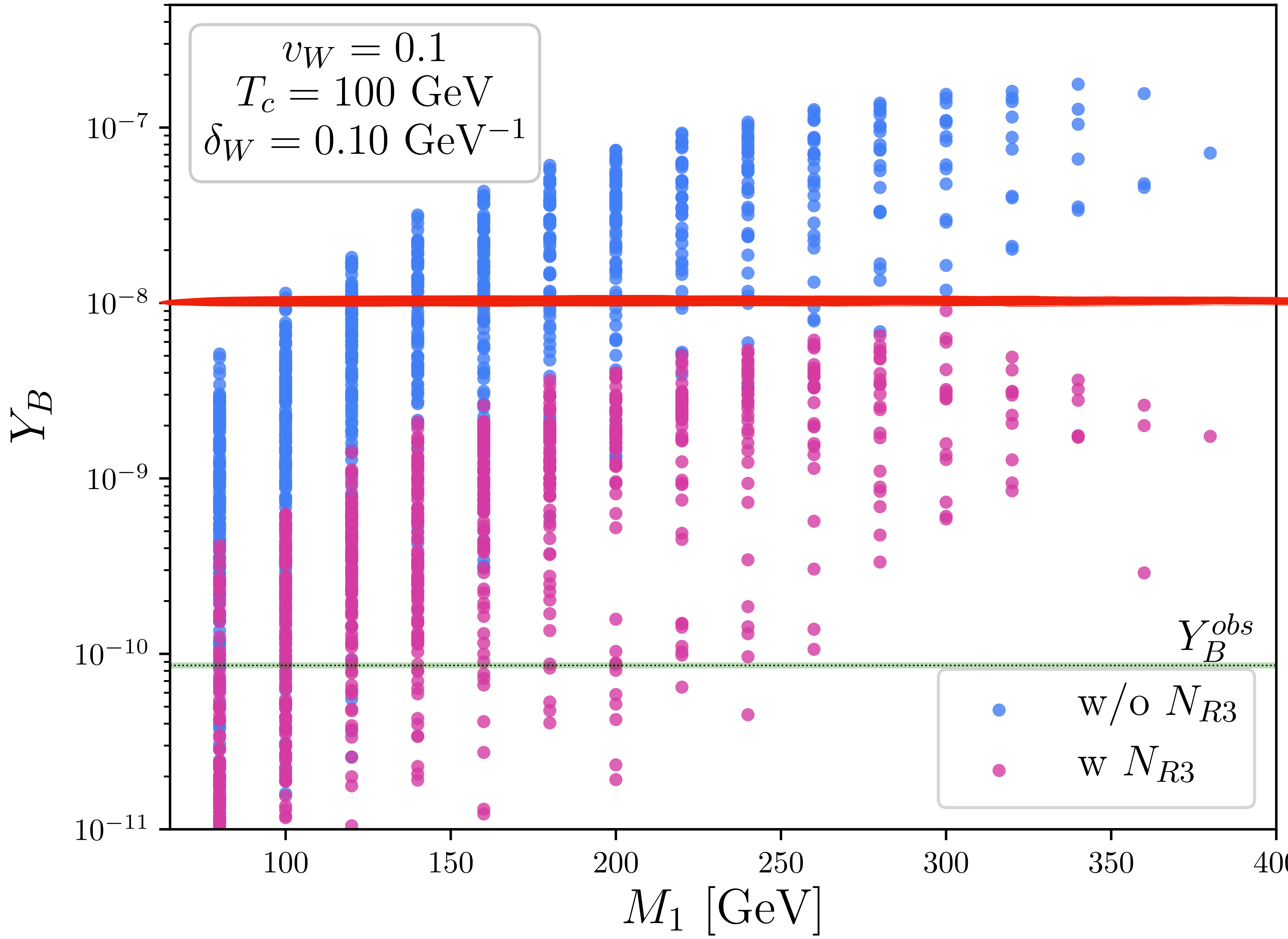
$$N_R \to \nu_L \to B$$

Current bound at 2σ on θ

Diffusion equations

Flavoured scenario

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



Factor ~2 improvement on θ

Reduction of Y_B of 2 orders of magnitude

Electroweak baryogenesis with new physics

Electroweak baryogenesis

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CP violation from CKM matrix

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

Add singlet scalar 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

1^{st} order phase transition

Electroweak baryogenesis and low-scale seesaws

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

Large mixing and CPV

Trigger strong
1st order
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$$V\left(\phi, H^\dagger H\right) = -\frac{1}{2}\mu_h^2 H^\dagger H + \frac{1}{4}\lambda_h (H^\dagger H)^2 + \frac{1}{2}\mu_s^2 \phi^2 + \frac{1}{4}\lambda_s \phi^4$$
$$+\frac{1}{4}\mu_m \phi (H^\dagger H) + \frac{1}{4}\lambda_m \phi^2 (H^\dagger H) + \mu_1^3 \phi + \frac{1}{3}\mu_3 \phi^3$$

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:11075441
T. Robens & T. Stefaniak, arXiv:1501.02234
D. Butazzo, F. Sala & A. Tesi, arXiv:1505.05488
A. V. Kotwal, J. M. No, M. J. Ramsey-Musolf & P. Winslow, arXiv:1605.06123
C. Chen, J. Kozaczuk & I. M. Lewis, arXiv:1704.05844
C. Chiang, Y. Li & E. Senaha, arXiv:1808.01098
M. Carena, Z. Liu & Y. Wang, arXiv:1911.10206
J. Kozaczuk, M. J. Ramsey-Musolf & J. Shelton, arXiv:1911.10210
E. Fuchs, O. Matsedonskyi, I. Savoray & M. Schlaffer, arXiv.2008.12773
A.Papaefstathiou & G. White, arXiv:2010.00597
S. Dawson, P. P. Giardino & S. Homiller, arXiv:2102.02823
M. Carena, J. Kozaczuk, Z. Liu, T. Ou, M. J. Ramsey-Musolf, J. Sherlon, Y. Wang & K. Xie, arXiv:2203.08206

Scalar potential

High-T approximation

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:11075441
M. Quiros, arXiv:hep-ph/9901312

$$V_{HT}(s,h) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$$
$$+ \left[\frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2 + m_3 s\right](T^2 - T_c^2)$$

T-dependent correction

$$V_{HT}(0,0) = V_{HT}(v,w)$$

Critical temperature

Scalar potential

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$$+ \left[\frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2 + m_3 s\right]\left(T^2 - T_c^2\right)$$

$$c_s = \frac{1}{12}\left[2\lambda_m + 3\lambda_s + 2\mathcal{Y}_N^2\right]$$

$$\mathcal{Y}_N^2 \equiv tr(Y_N^\dagger Y_N)$$

Scalar potential

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$$V_{HT}(s,h) = -\frac{1}{2} \ldots$$

$$\ldots{}^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$$

Wish list for a successful phase transition

- Degenerate minima at T_c
- Potential barrier between minima
- Correct minimum ($v_{EW} \sim 246$ GeV) at $T = 0$
- **Nucleation**

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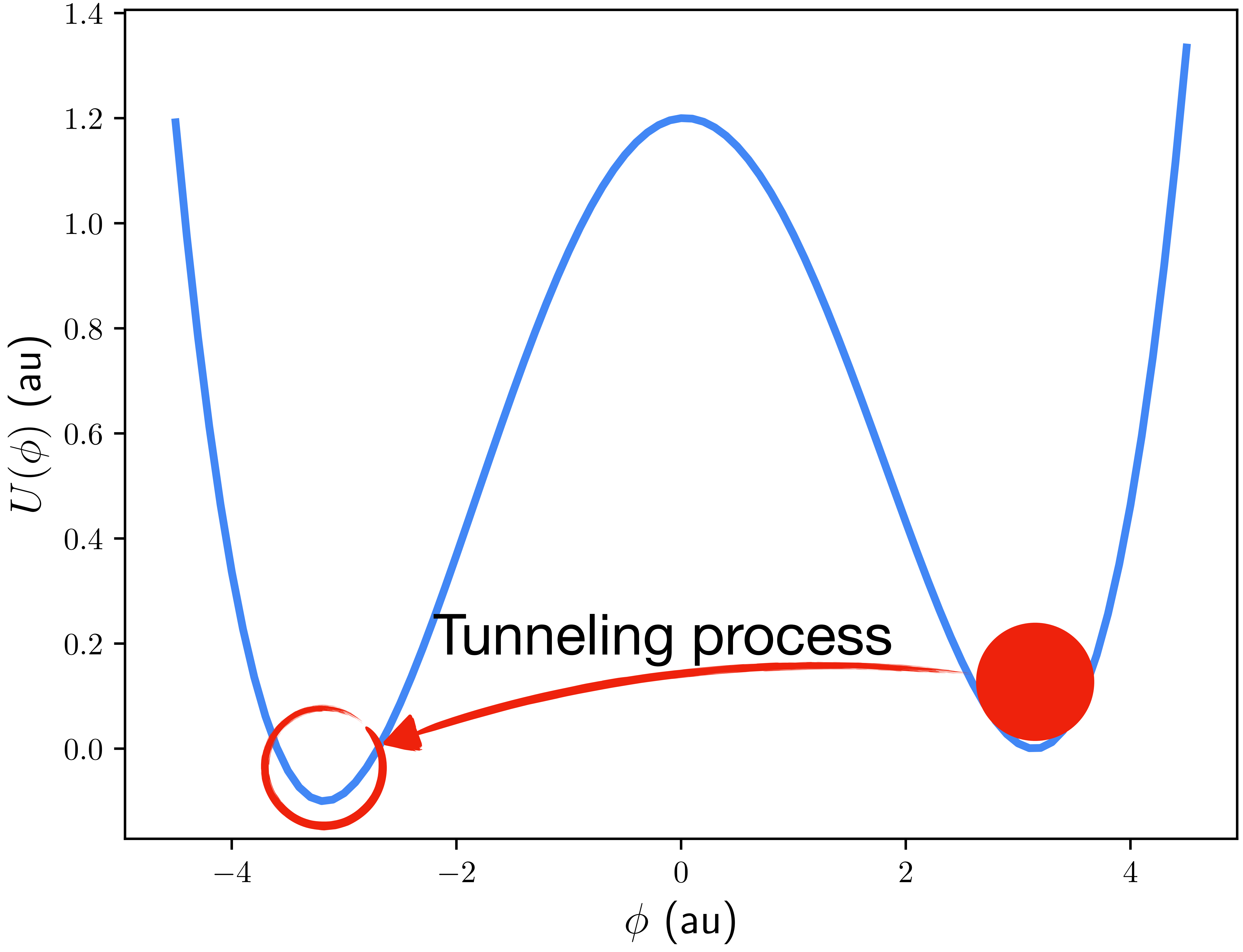
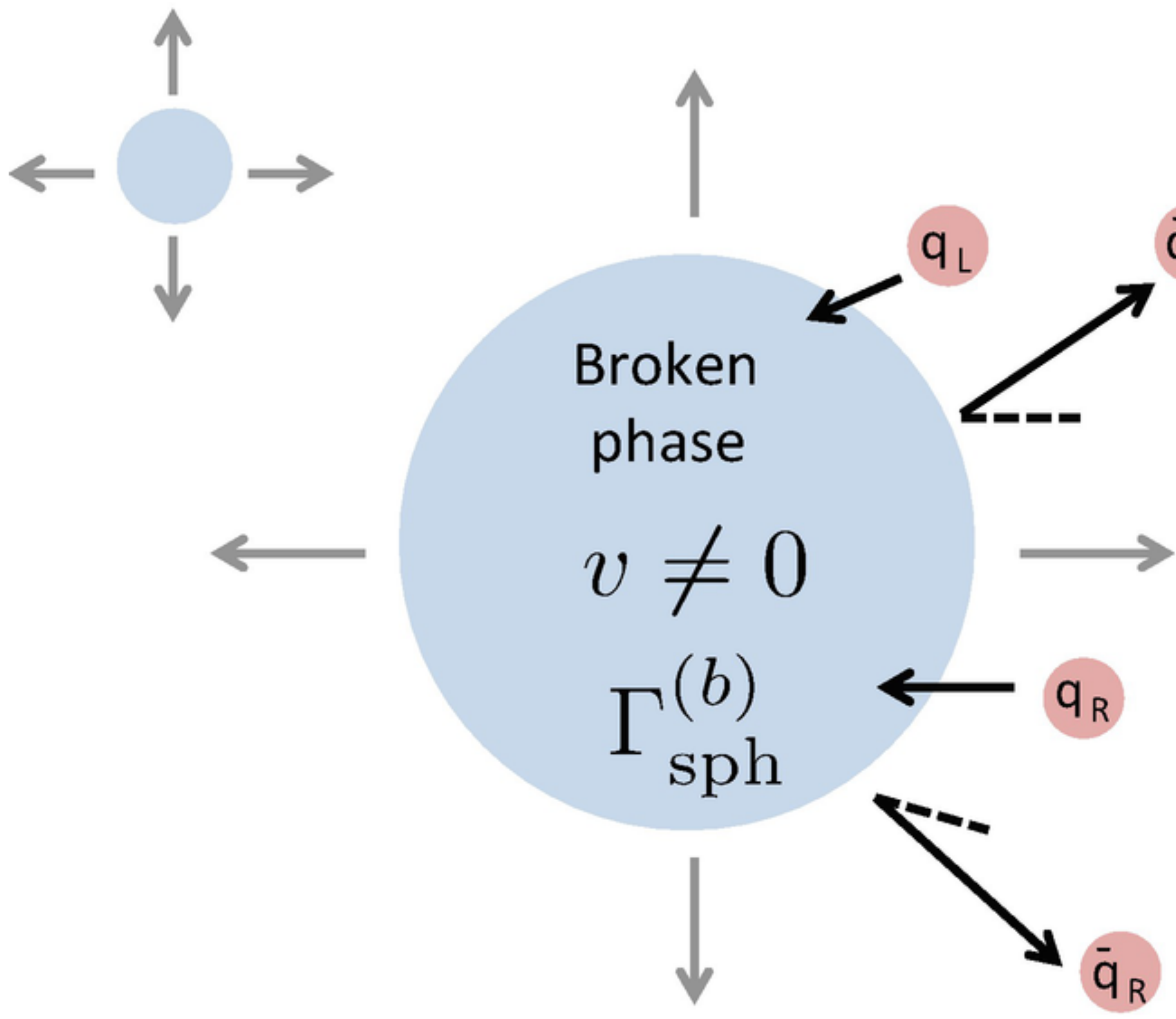
Nucleation

S. Coleman, Phys. Rev. D (1977)
A. Amarati, arXiv:2009.14102





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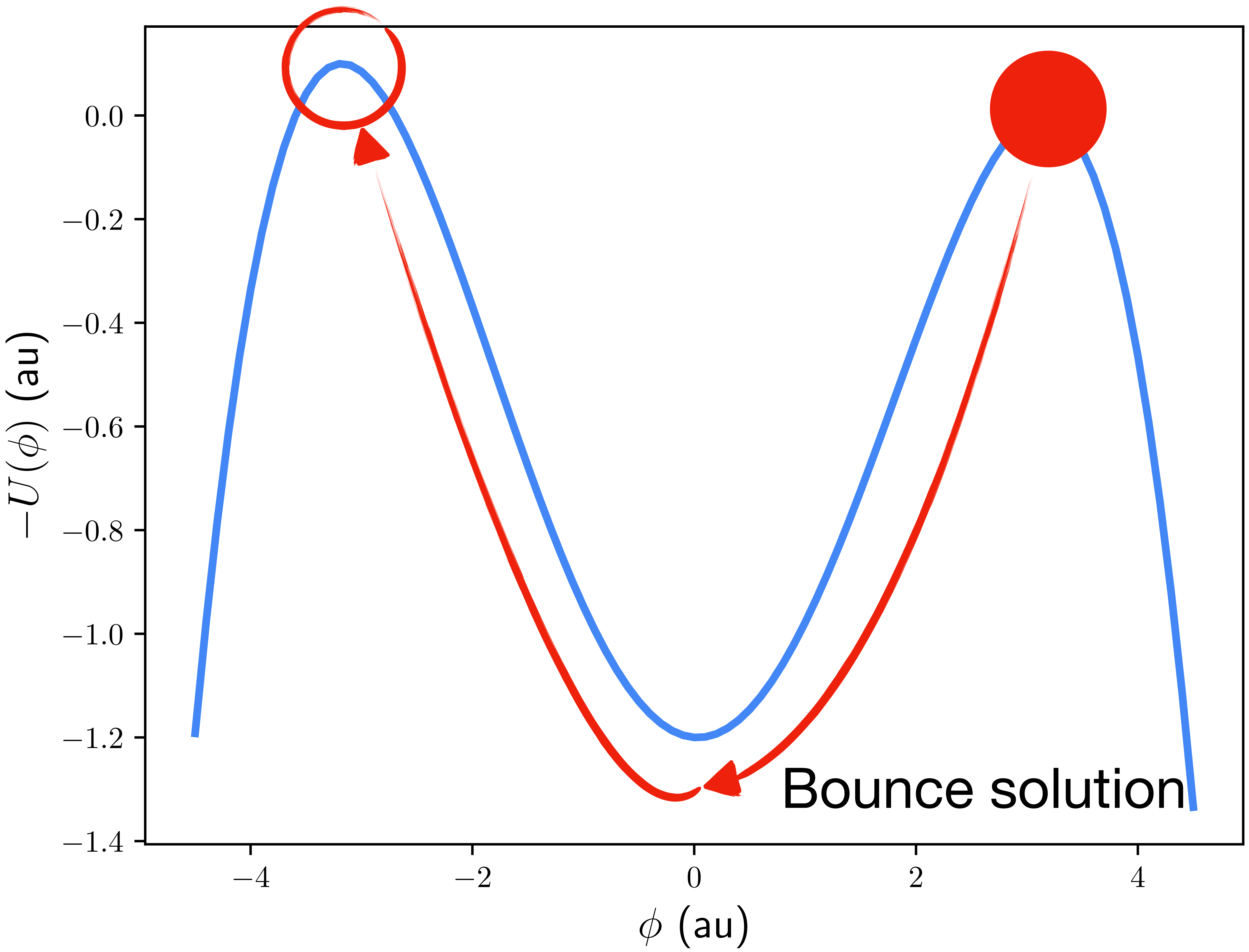


S. Coleman, Phys. Rev. D (1977)
A. Amarati, arXiv:2009.14102

$$\Gamma/V \sim e^{-S_3/T_N} \sim H(T_N)$$

$$S_3/T_N \sim 140$$

Nucleation

E. Fernández-Martínez *et al.*, 22XX.XXXXX

Can potentially nucleate

Phenomenology

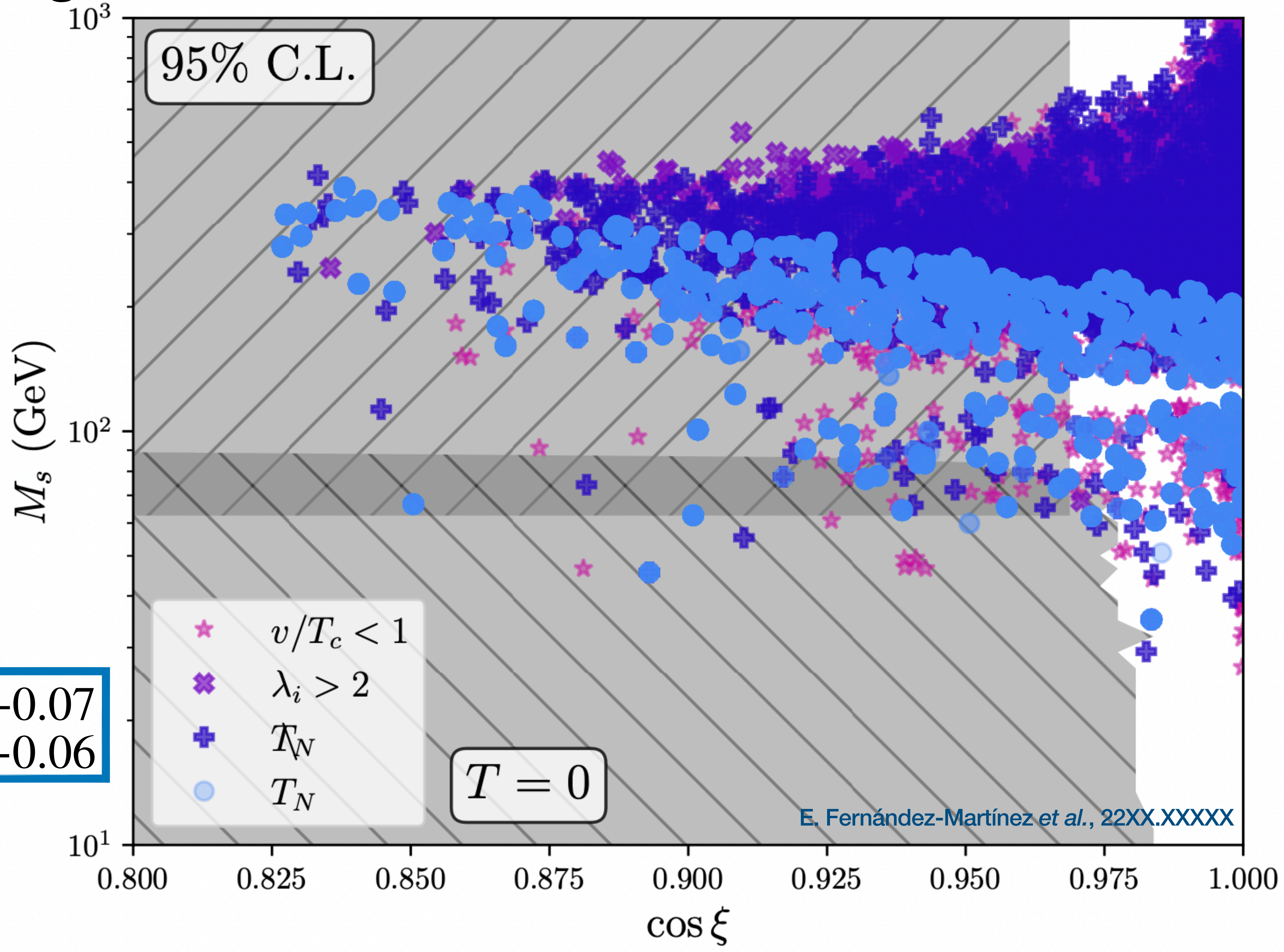
Constraints on scalar mixing

$$h' = \cos\xi h + \sin\xi s$$
$$s' = -\sin\xi h + \cos\xi s$$

Higgs signal strength

$$\cos\xi = \mu \equiv \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

$$\mu_{ATLAS} = 1.11^{+0.09}_{-0.08},\ \mu_{CMS} = 1.02^{+0.07}_{-0.06}$$



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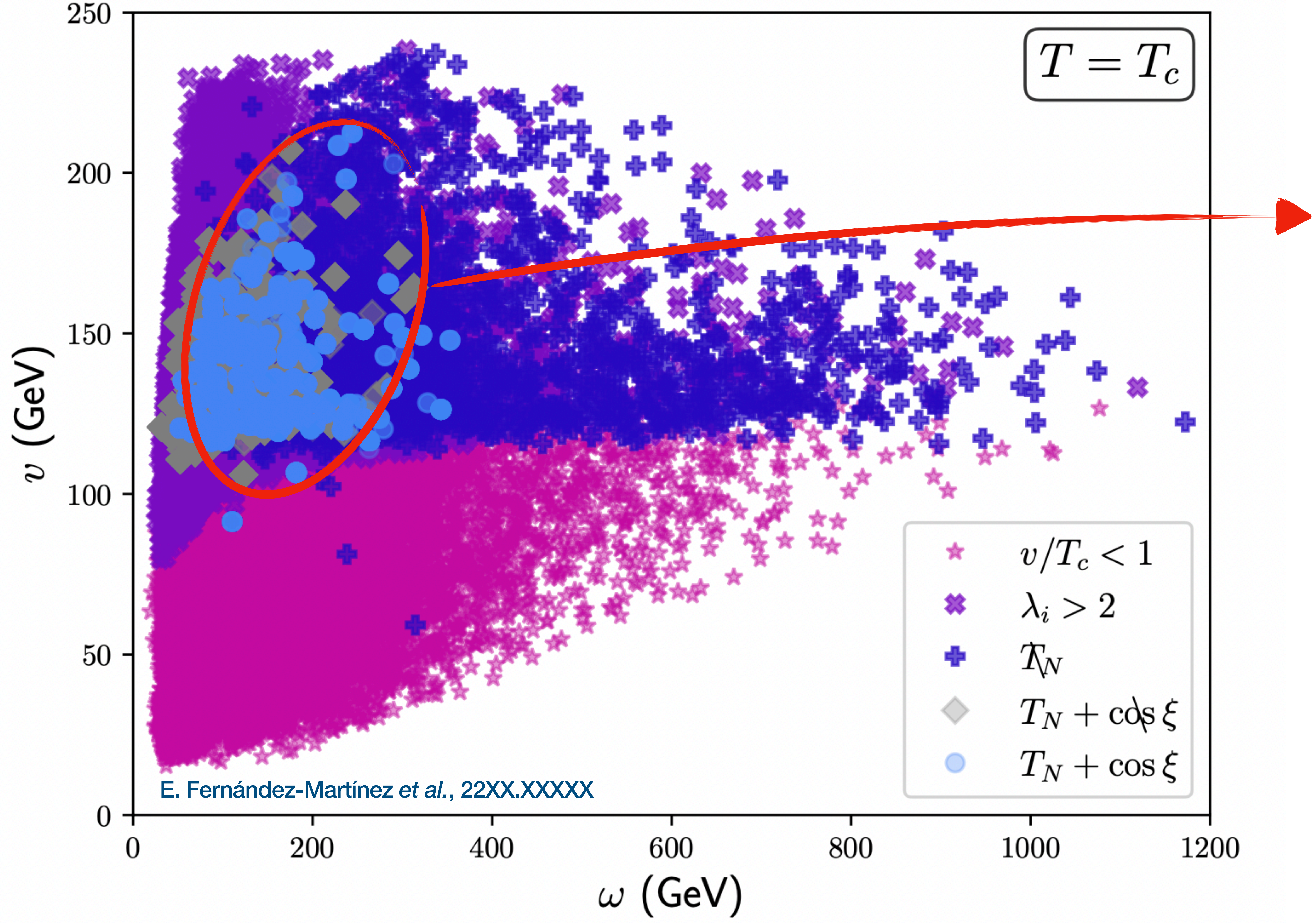
D. Butazzo, F. Sala & A. Tesi, arXiv:1505.05488
S. Dawson, P. P. Giardino & S. Homiller, arXiv:2102.02823
ATLAS Collaboration, arXiv:1909.02845
CMS Collaboration, record/2706103

Phenomenology

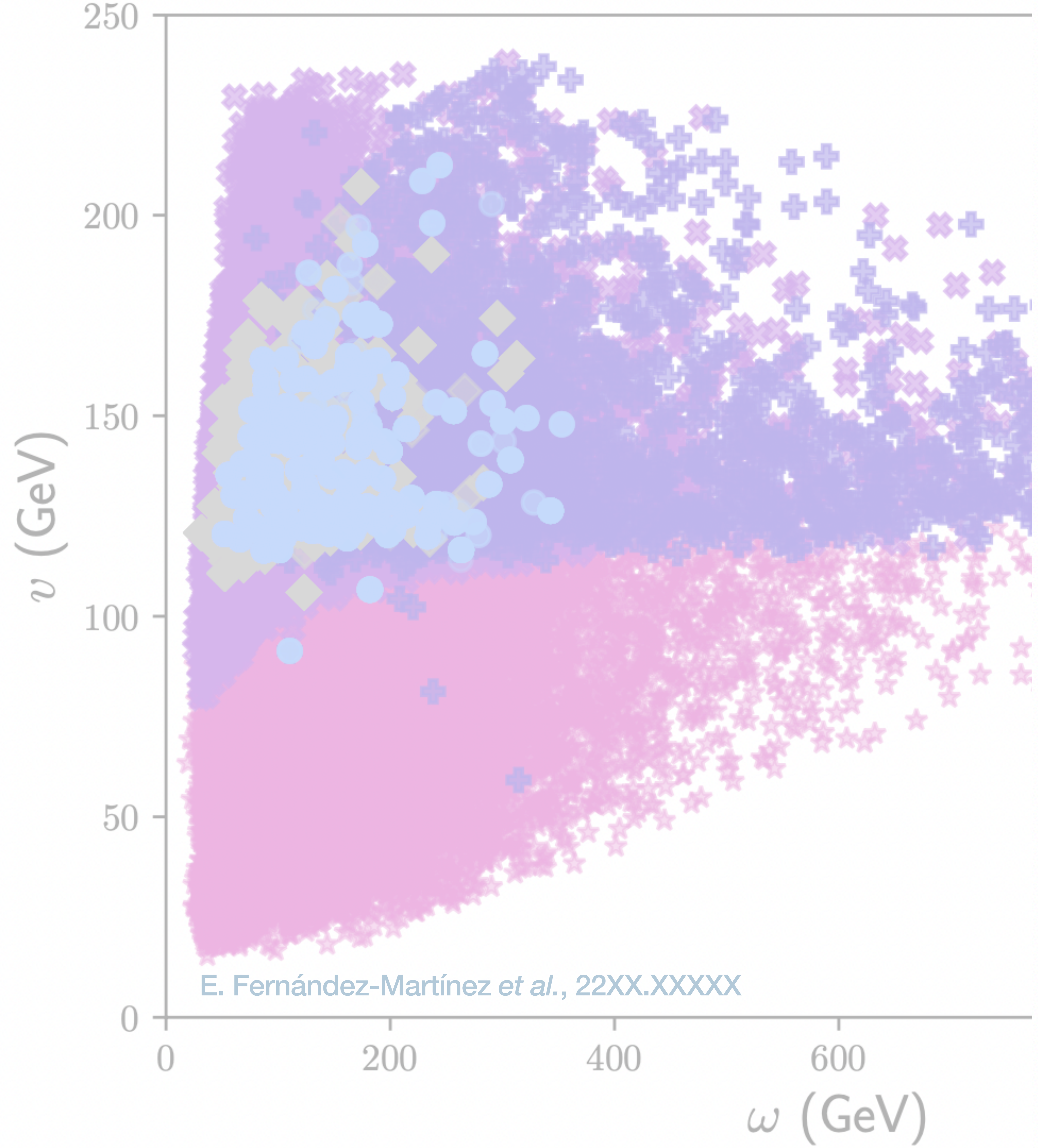
Nucelation + constraints on $\cos\xi$

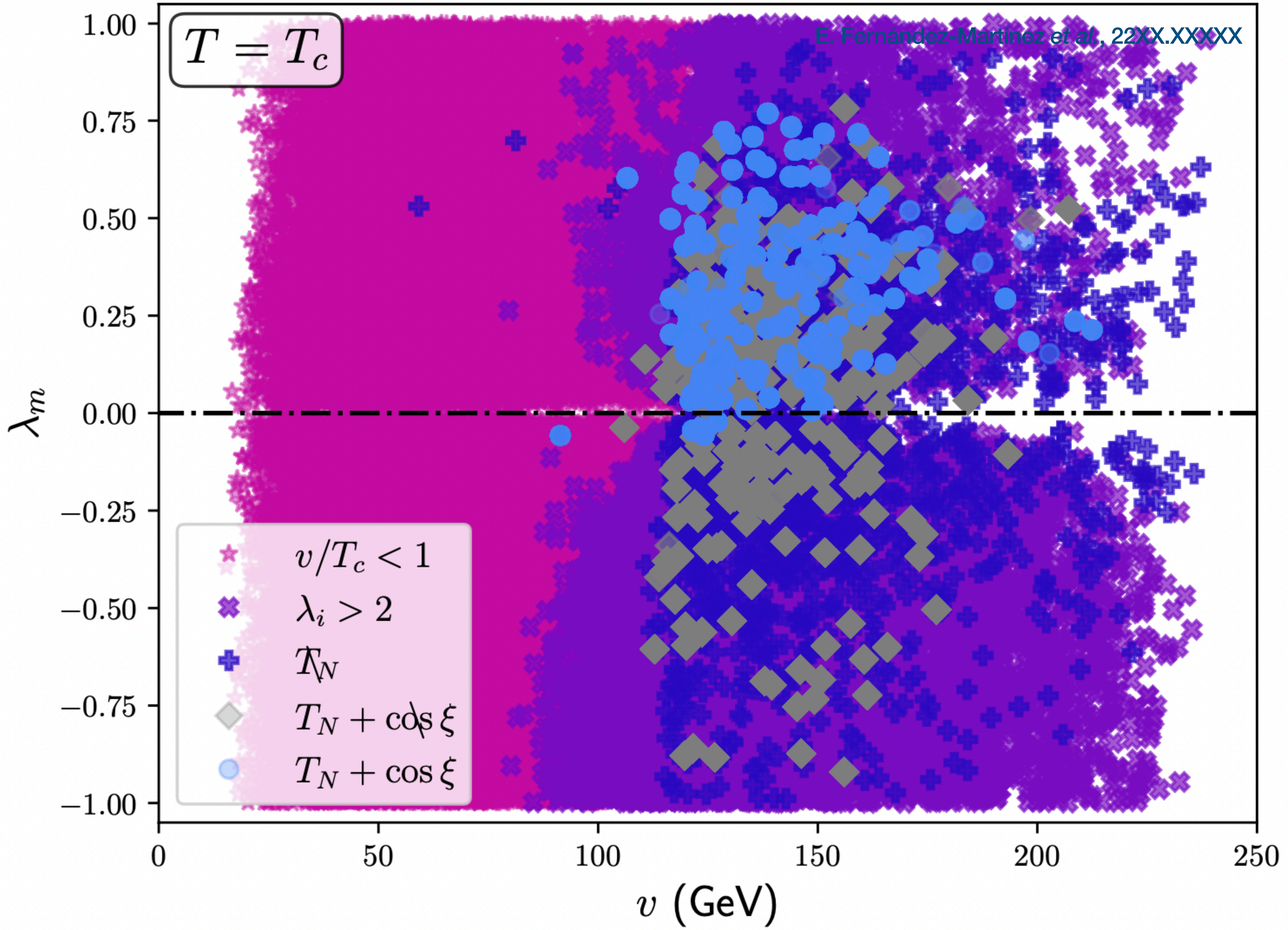


Successful nucleation greatly reduces the parameter space

Phenomenology

Nucelation + constraints on $\cos\xi$





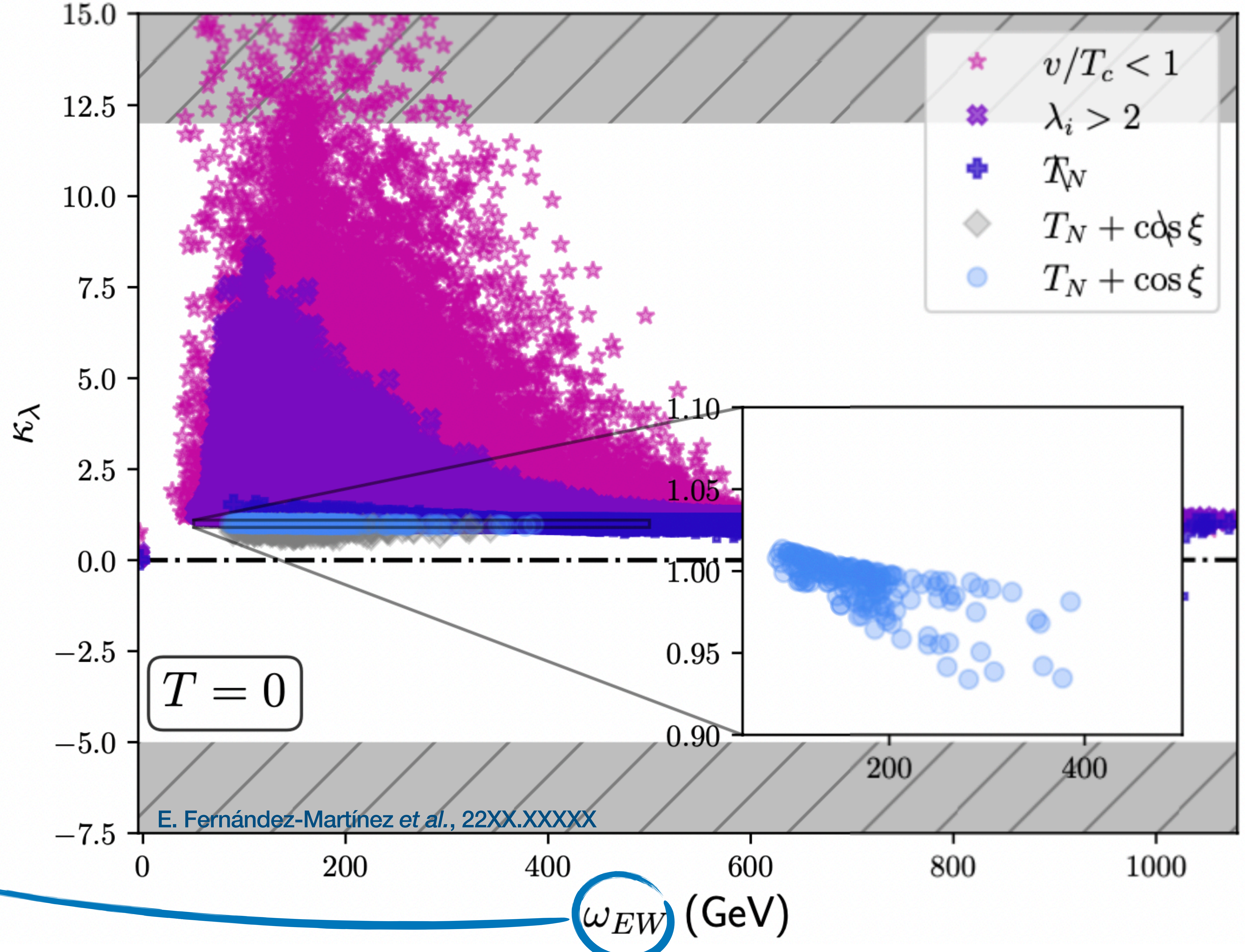
Phenomenology

Higgs trilinear coupling

$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}}$$

$$-5 \leq \kappa_\lambda \leq 12$$

ATLAS Collaboration, arXiv:1906.02025



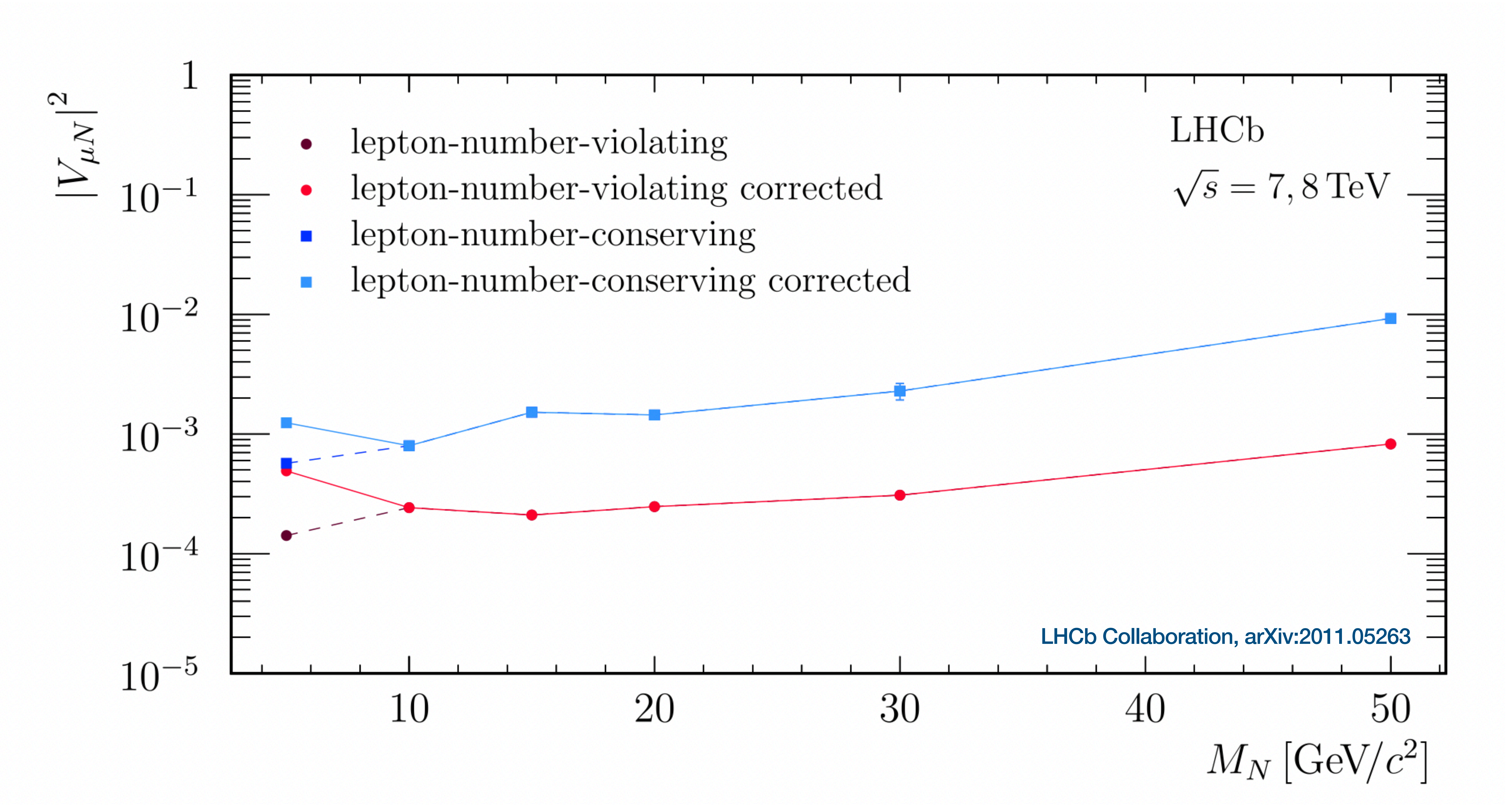
Singlet vev controlling neutrino masses

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**

Conclusions

- Low-scale **neutrino**
- **Flavour effects** pla
- Explain the **BAU** wit **active neutrinos→l**



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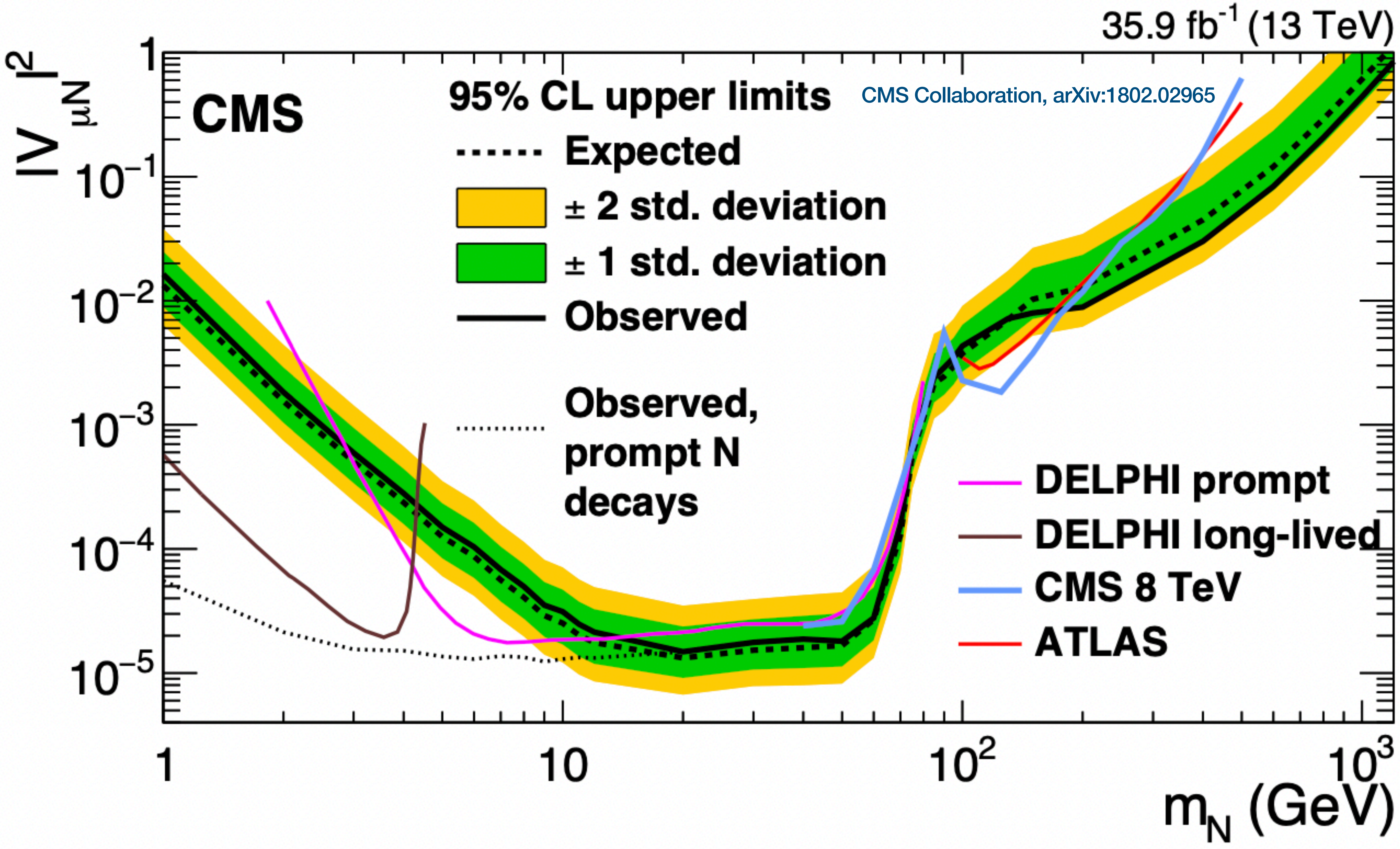

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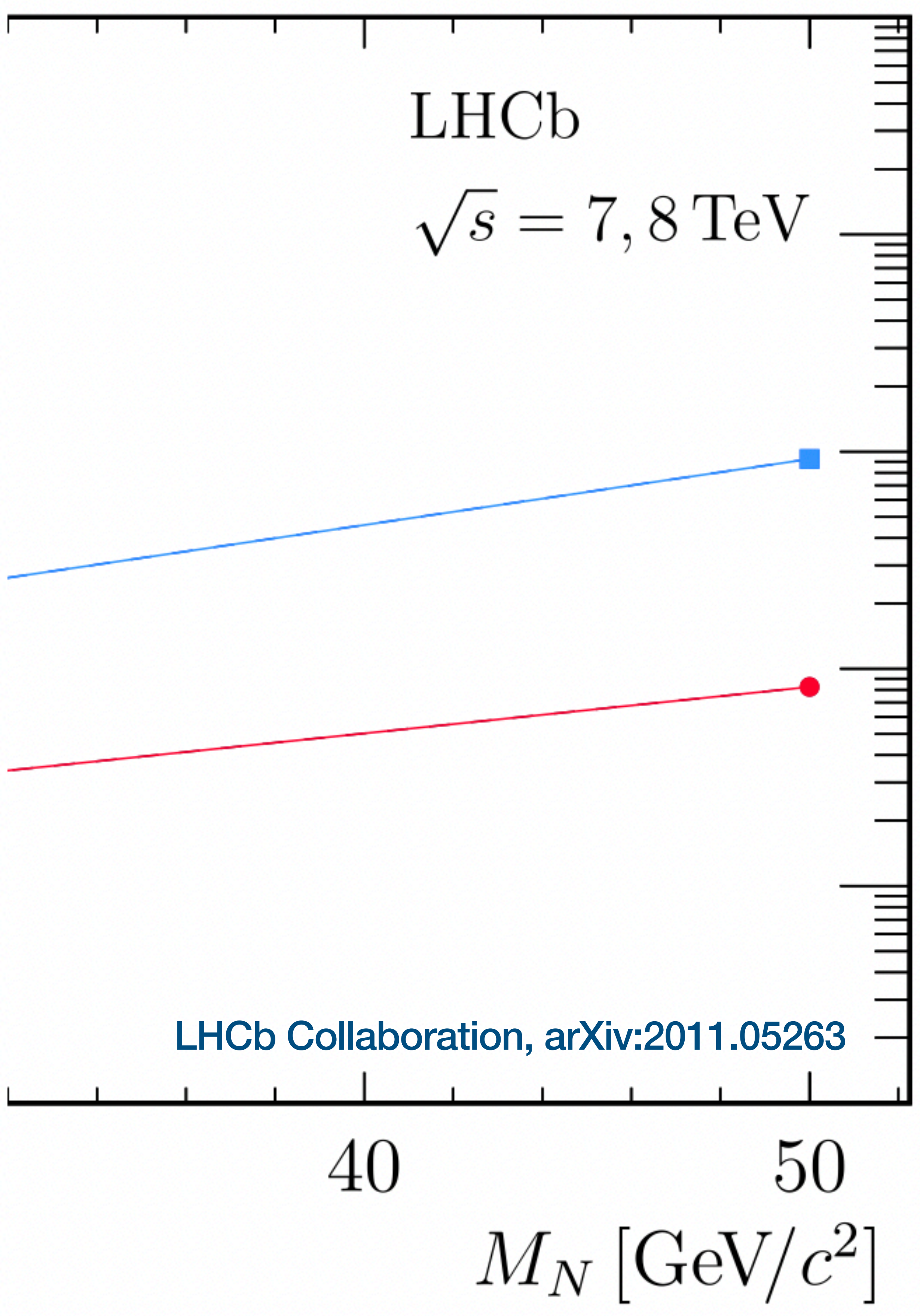
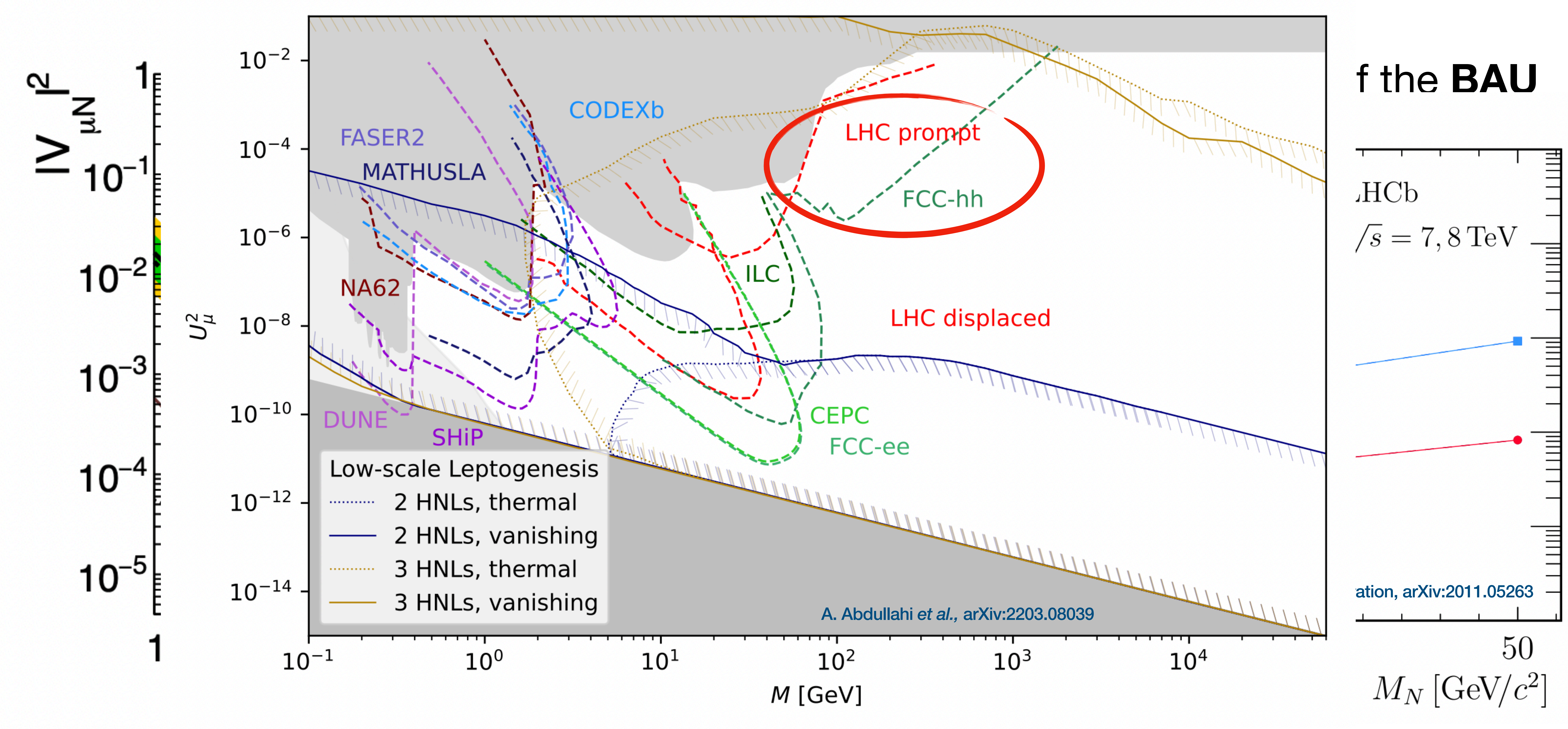


Conclusions

f the **BAU**



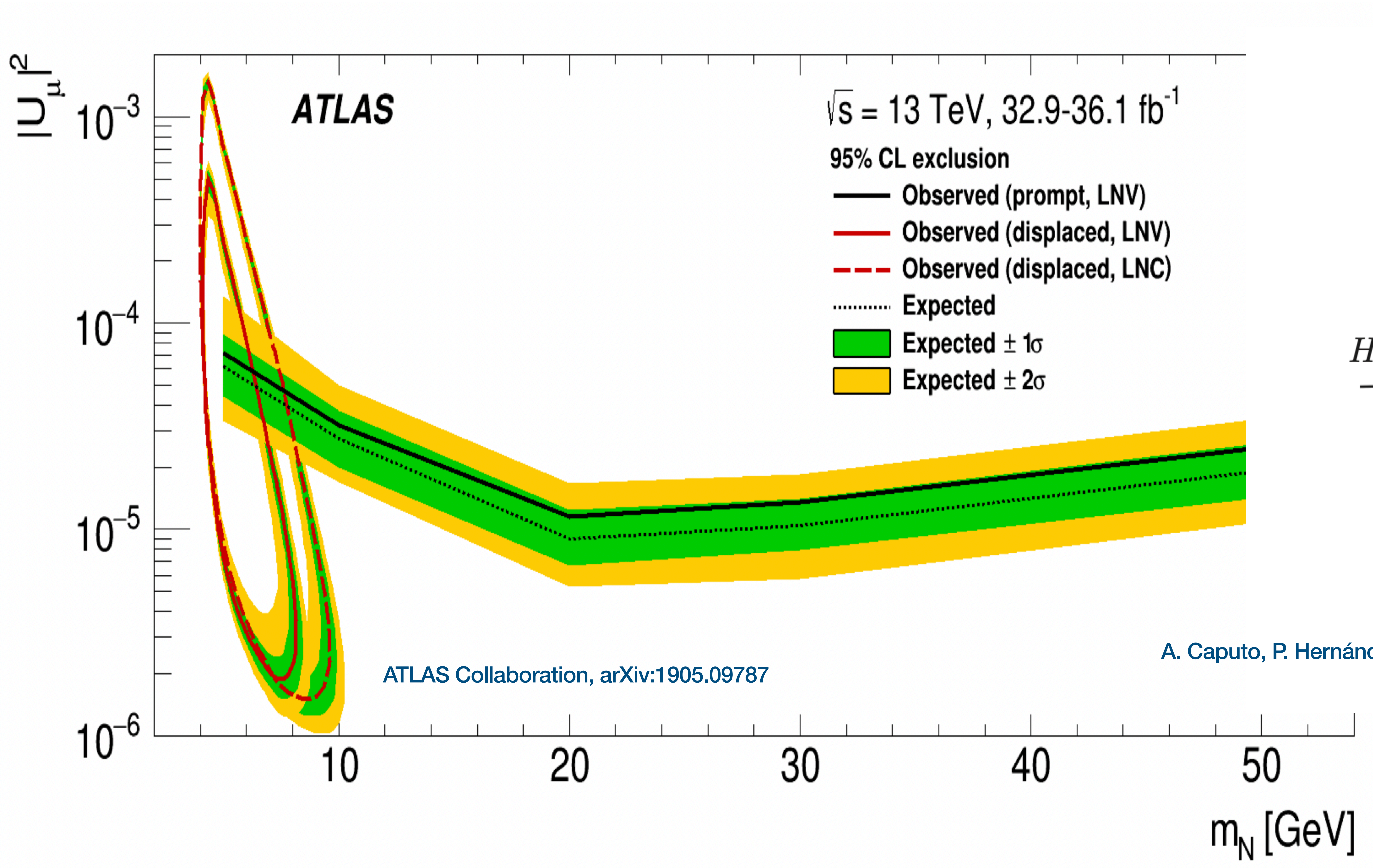
Conclusions

- Need **extra scalar** to have SFOPT. From the scalar potential and a successful **nucleation** the singlet **neutrino mass scale** is fixed

- We expect deviations up to **10%** in the **Higgs trilinear coupling**

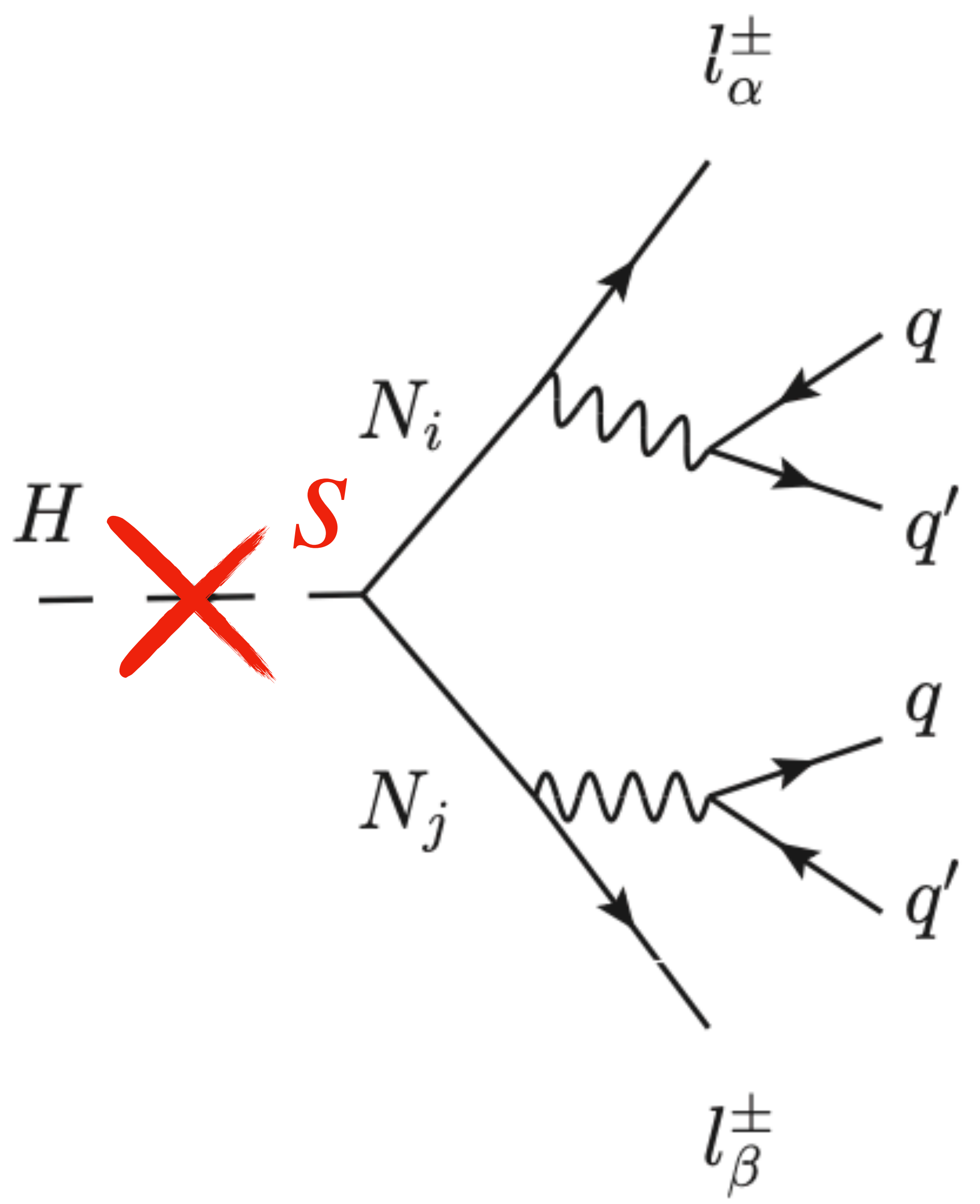
- Interesting interplay and **possible searches** between fermion and scalar sectors

Conclusions



ATLAS Collaboration, arXiv:1905.09787

ful



ctors

A. Caputo, P. Hernández, J. López-Pavón & J. Salvadó, arXiv: 1704.0872

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

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

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

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

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

Unphysical when neglecting charged lepton masses

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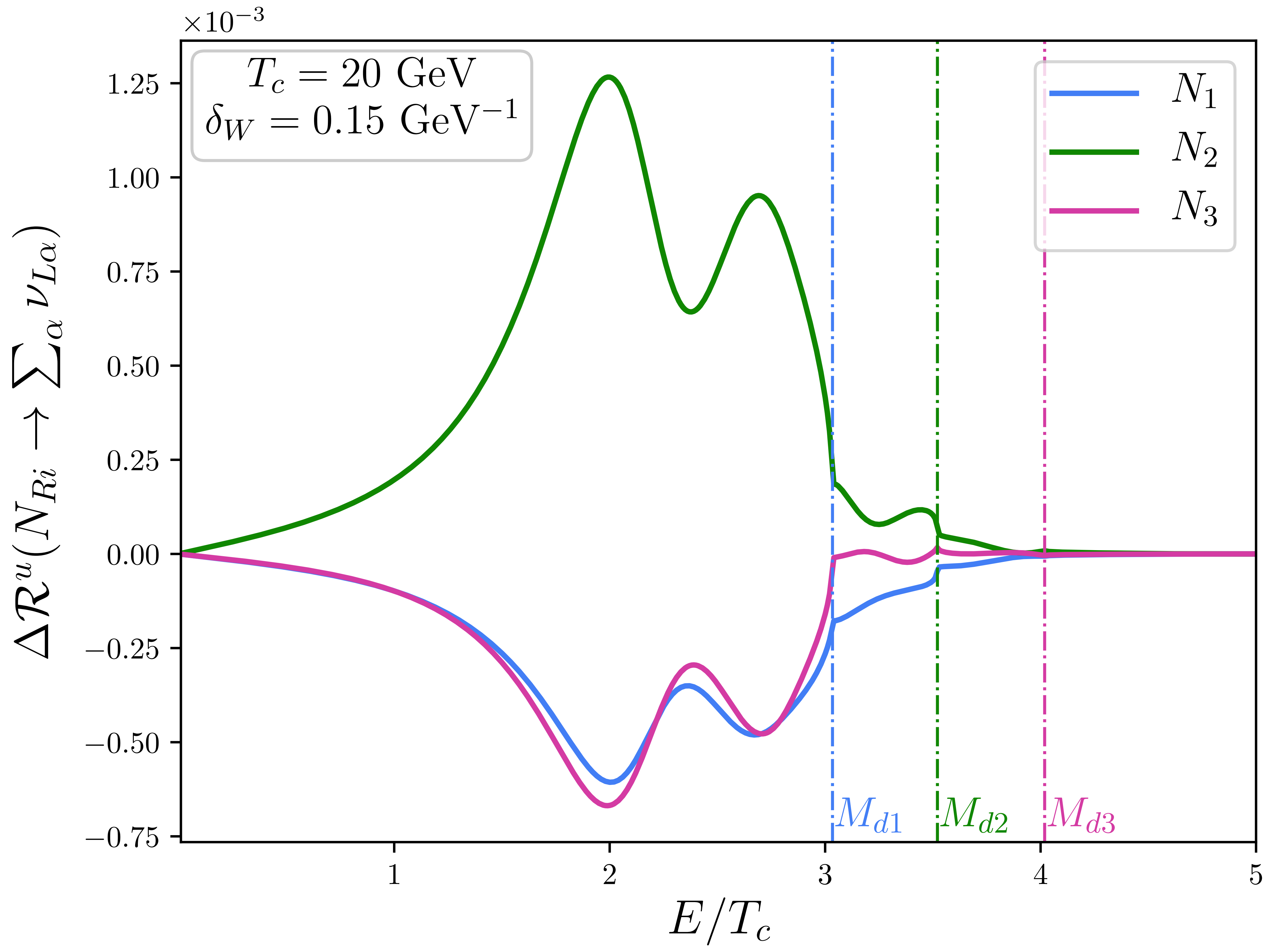
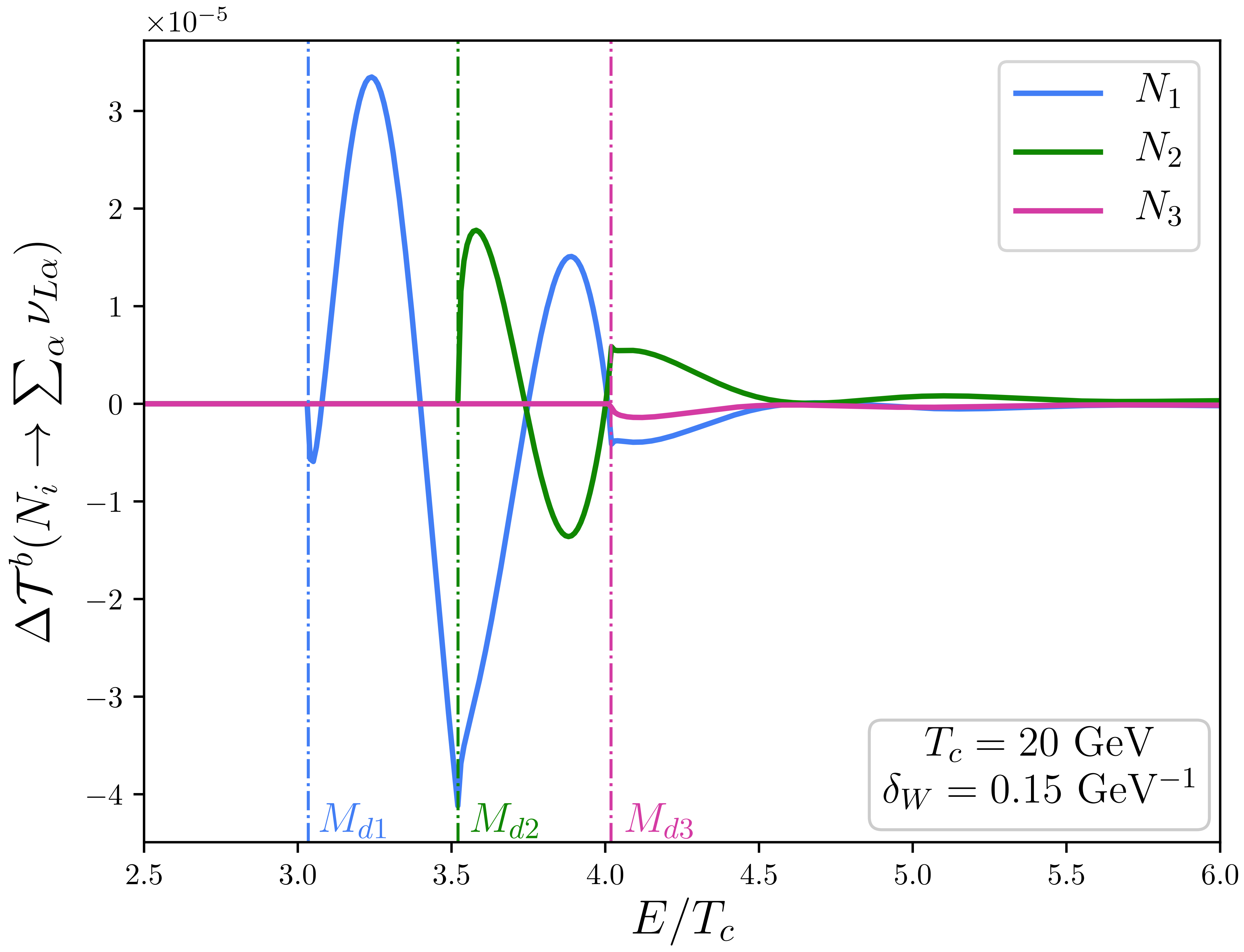
$$m_D \equiv U_l m_d V_R^\dagger$$

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

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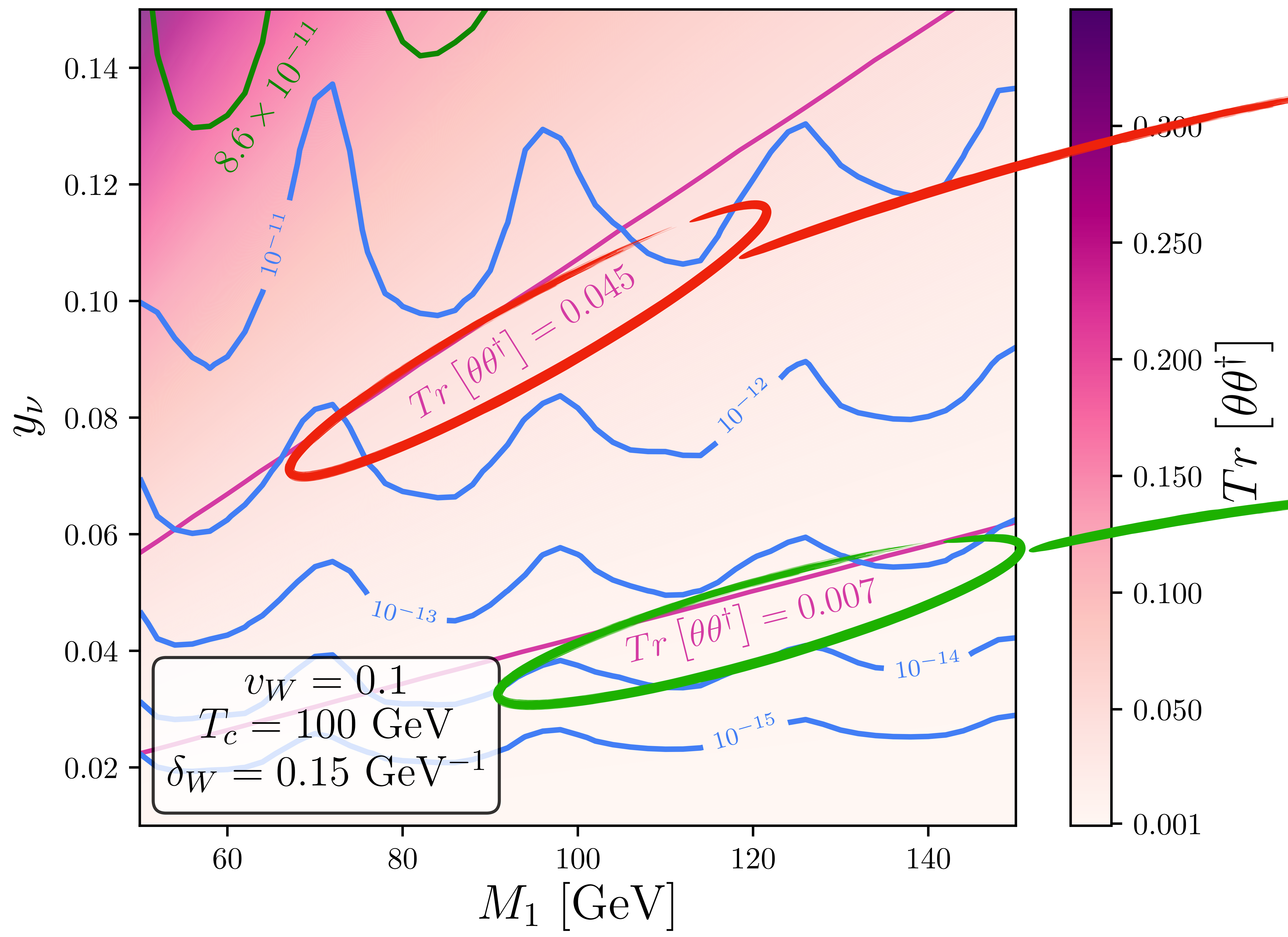
Follow the total B and L asymmetries and their conversion through sphalerons

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

Diffusion equations

Vanilla scenario



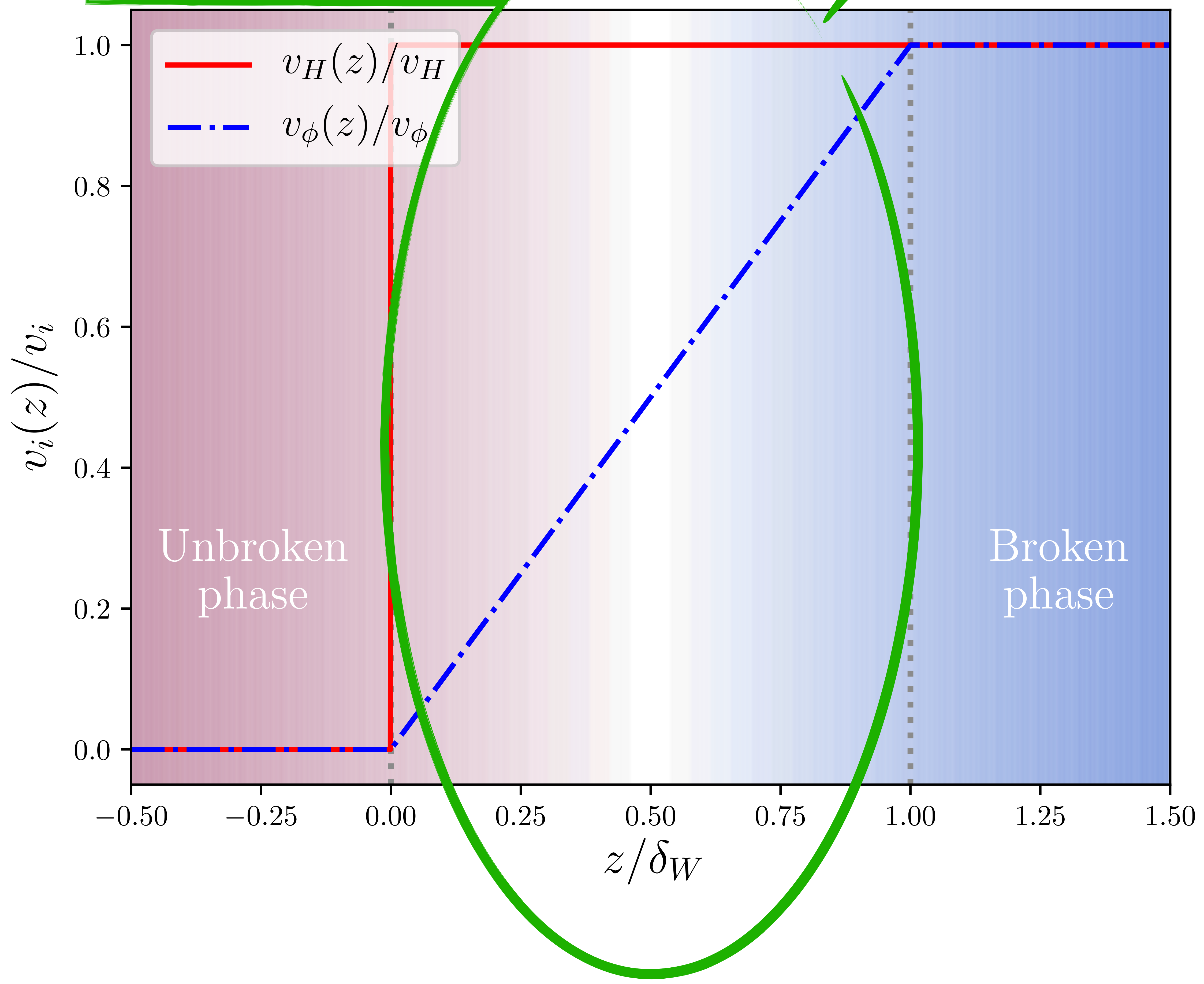
Bound on θ if avoiding the invisible width of the Z boson

Current bound at 2σ on θ

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

Vev profiles in the bubble wall

FLOR profile

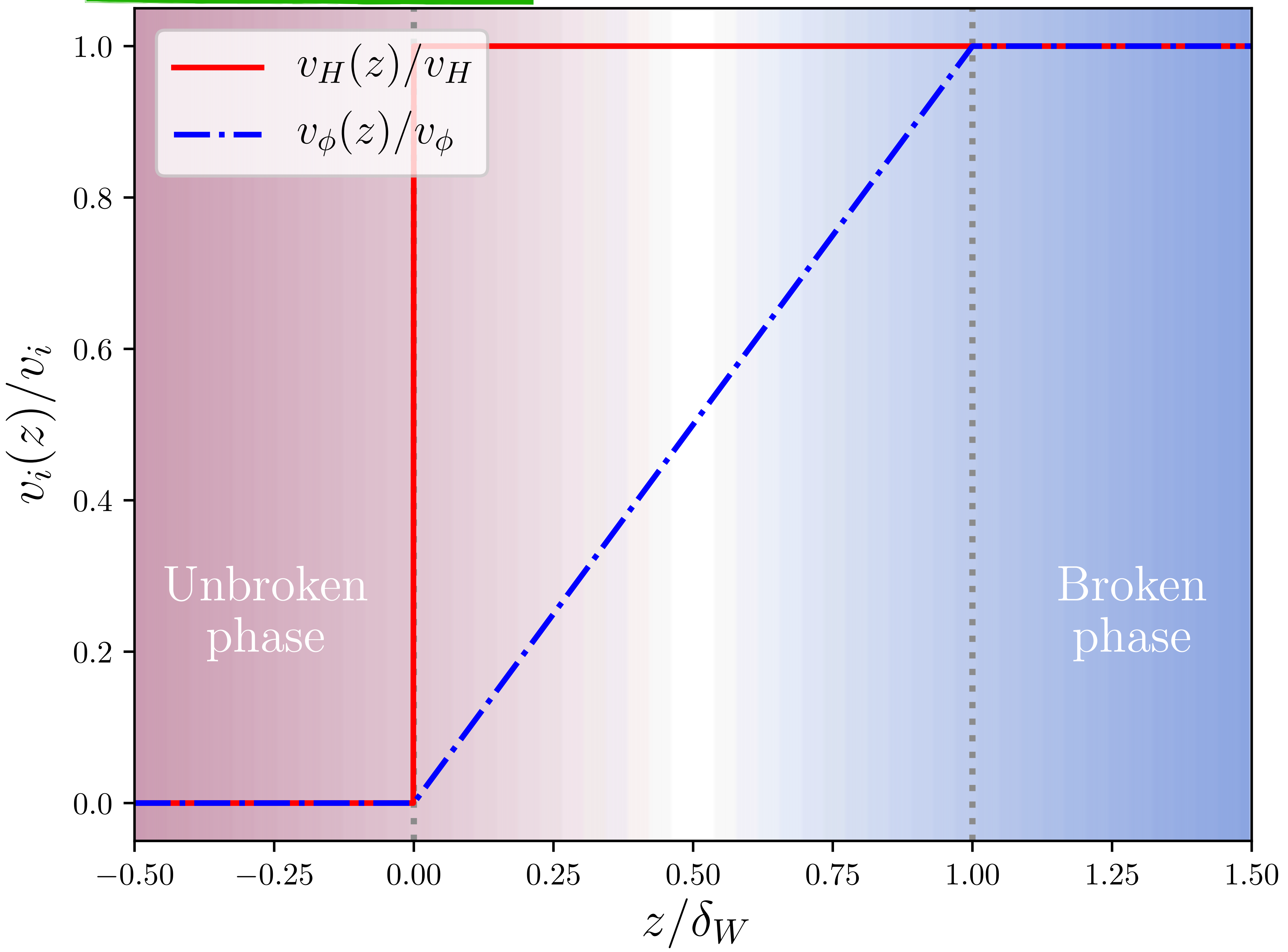


Bubble wall

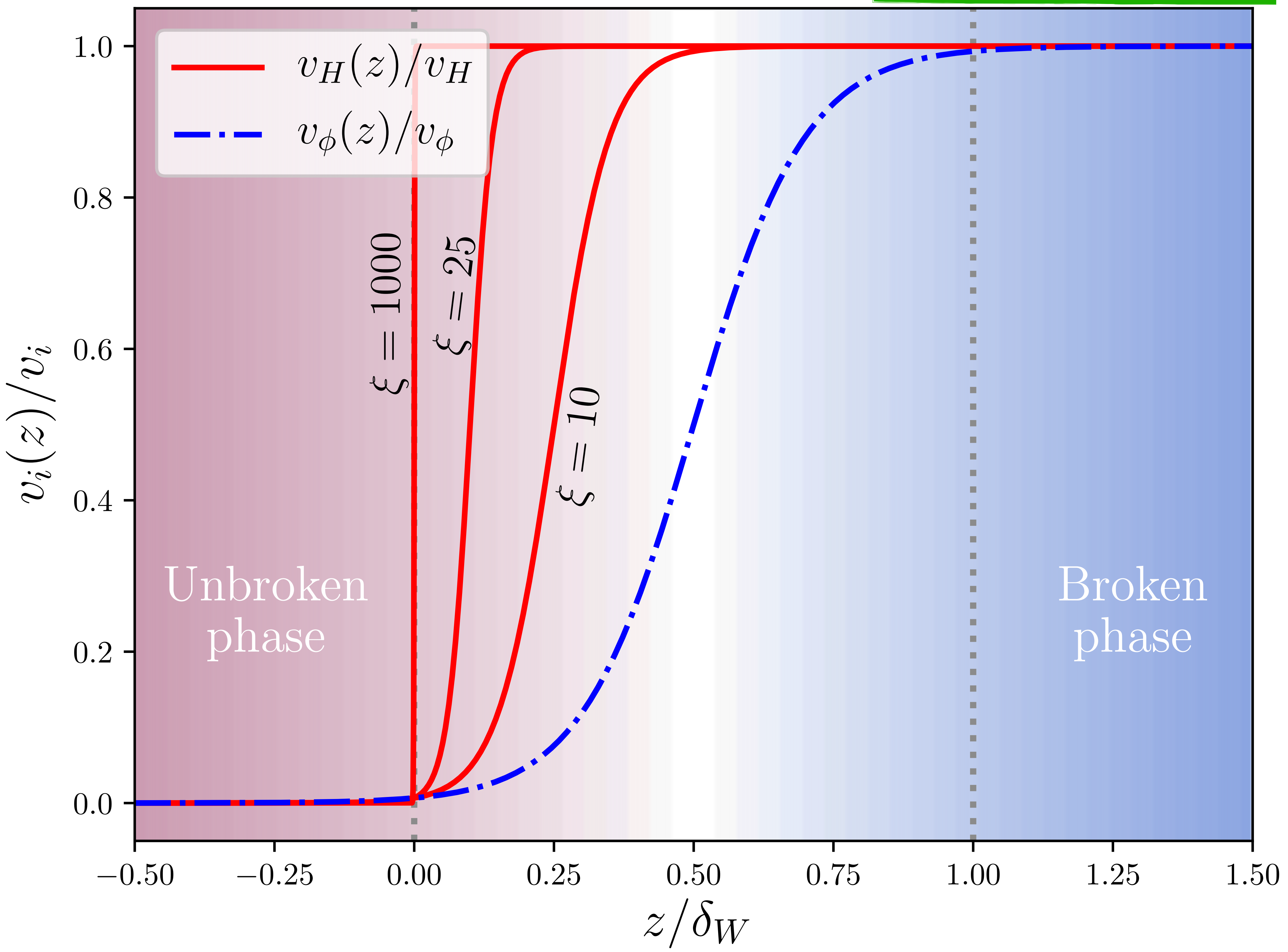
$$\theta(z) = \frac{v_H(z)}{v_\phi(z)} \frac{Y_\nu}{\sqrt{2}} Y_N^{-1}$$

Vev profiles in the bubble wall

FLOR profile



Kink profile



Electroweak baryogenesis and low-scale seesaw

First proposed in

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

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

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

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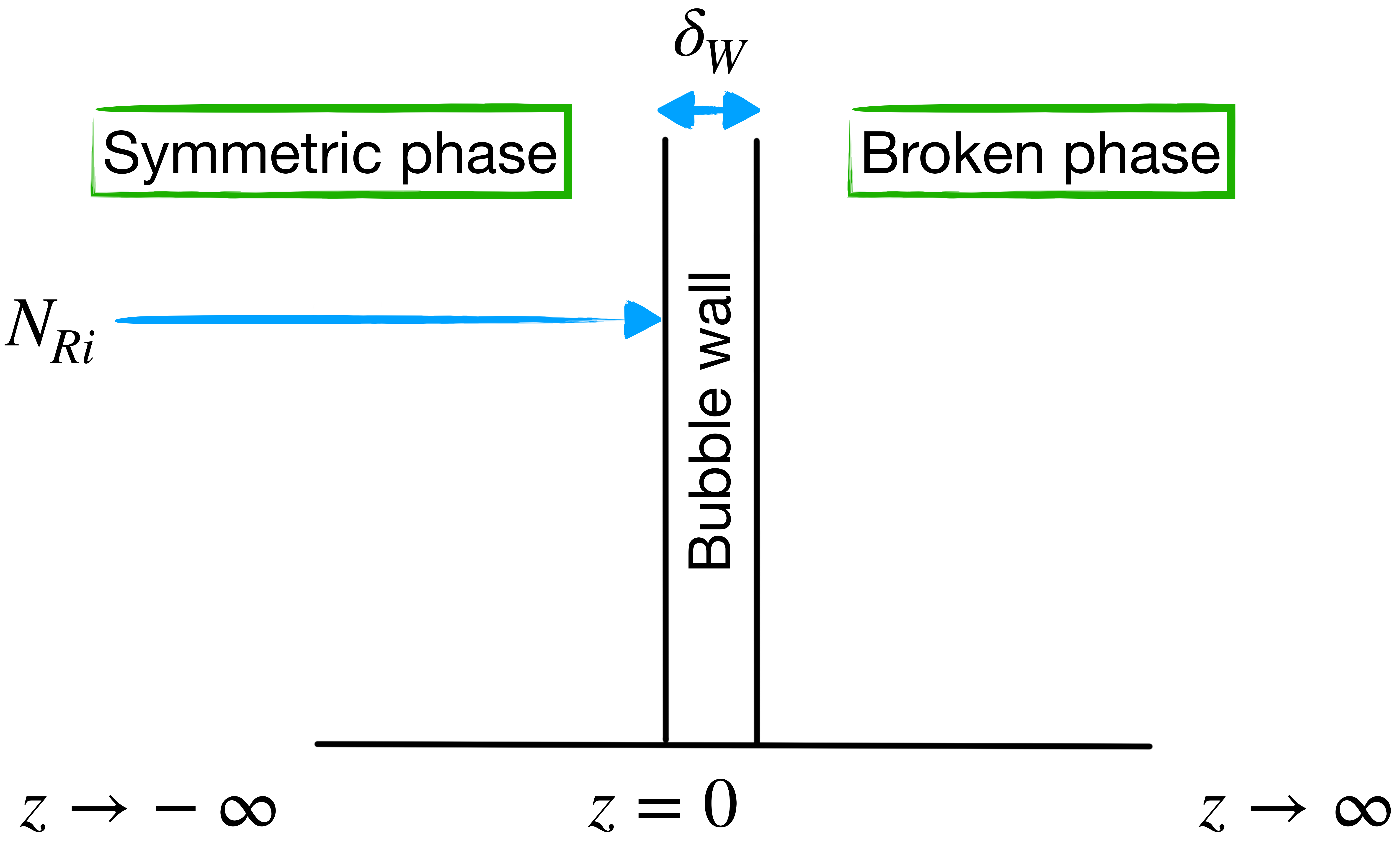

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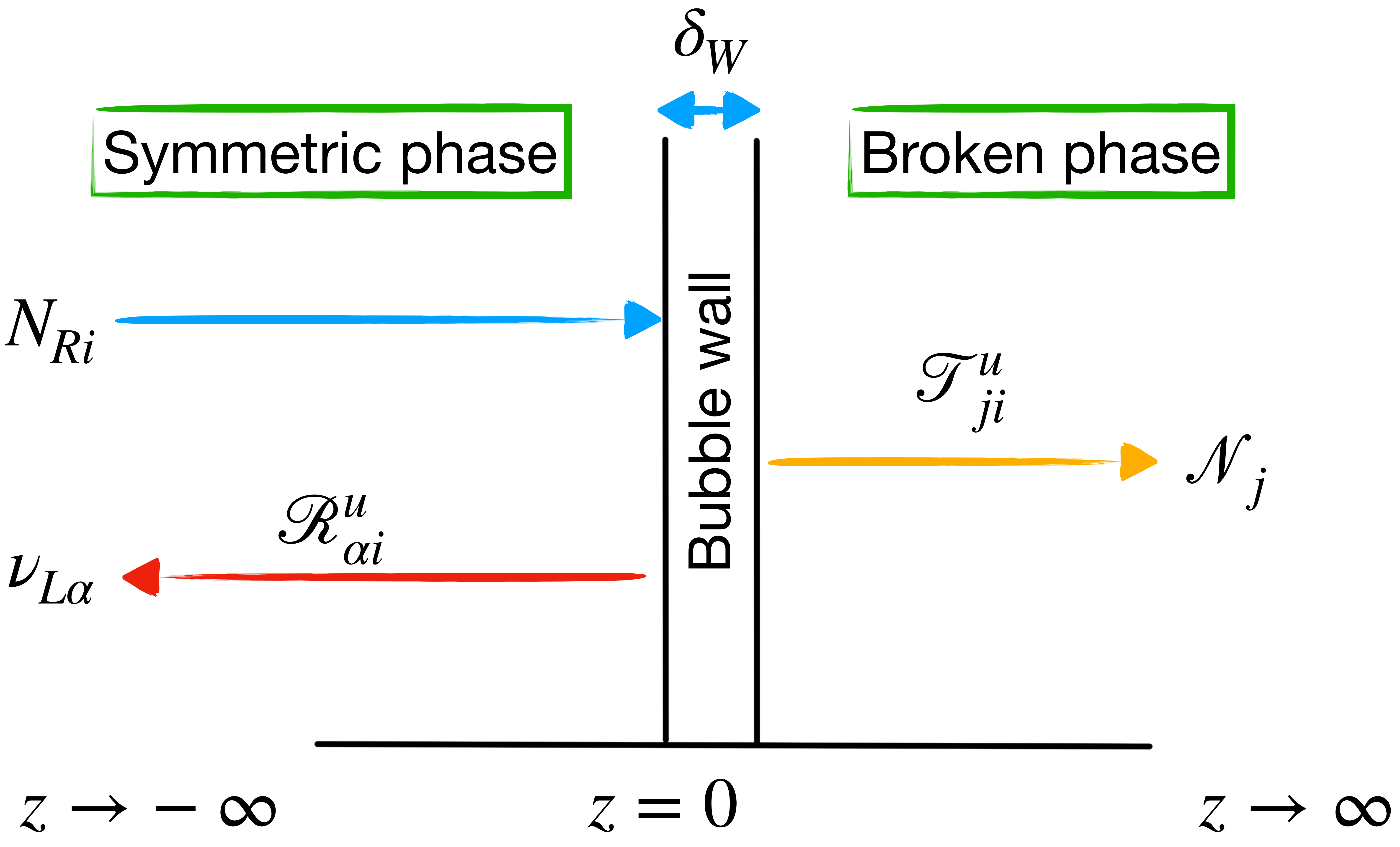


$$\psi = e^{-iEt} \begin{pmatrix} L(z) \\ R(z) \end{pmatrix} \otimes \chi_s$$

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

Diffusion equations

Flavoured scenario

Baryons

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

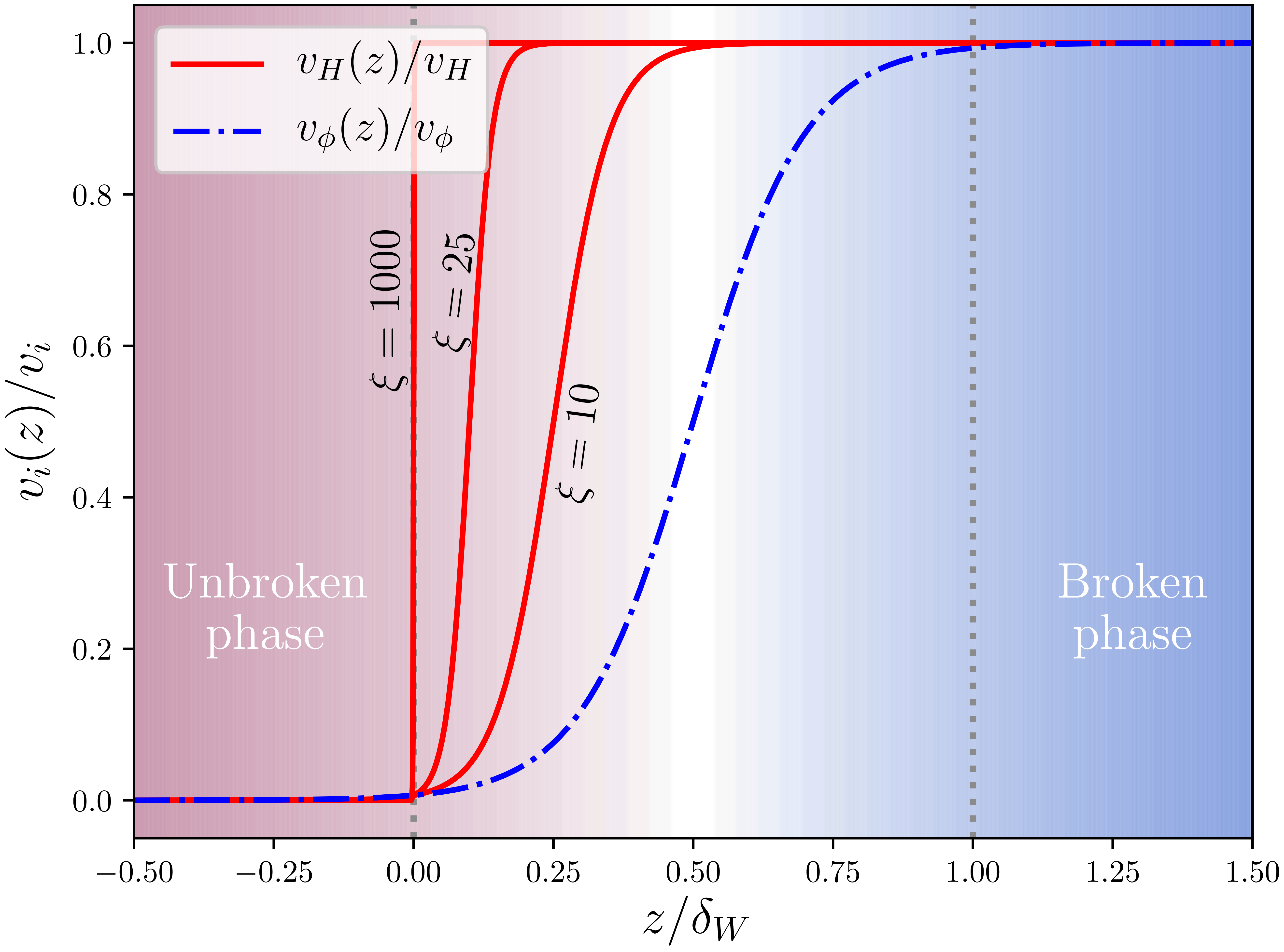
SM ν

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

N_R

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

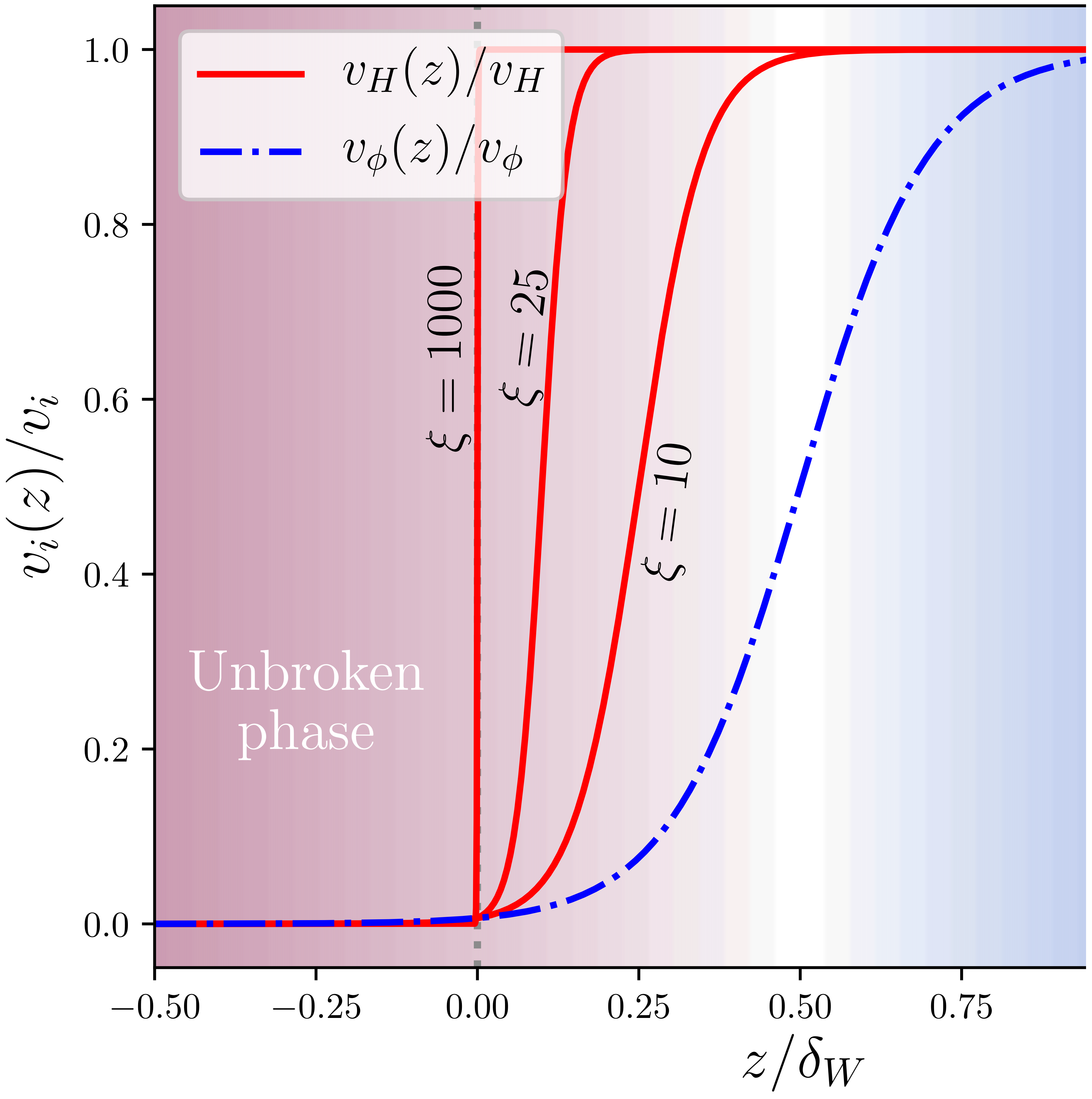
Effect of vev profiles

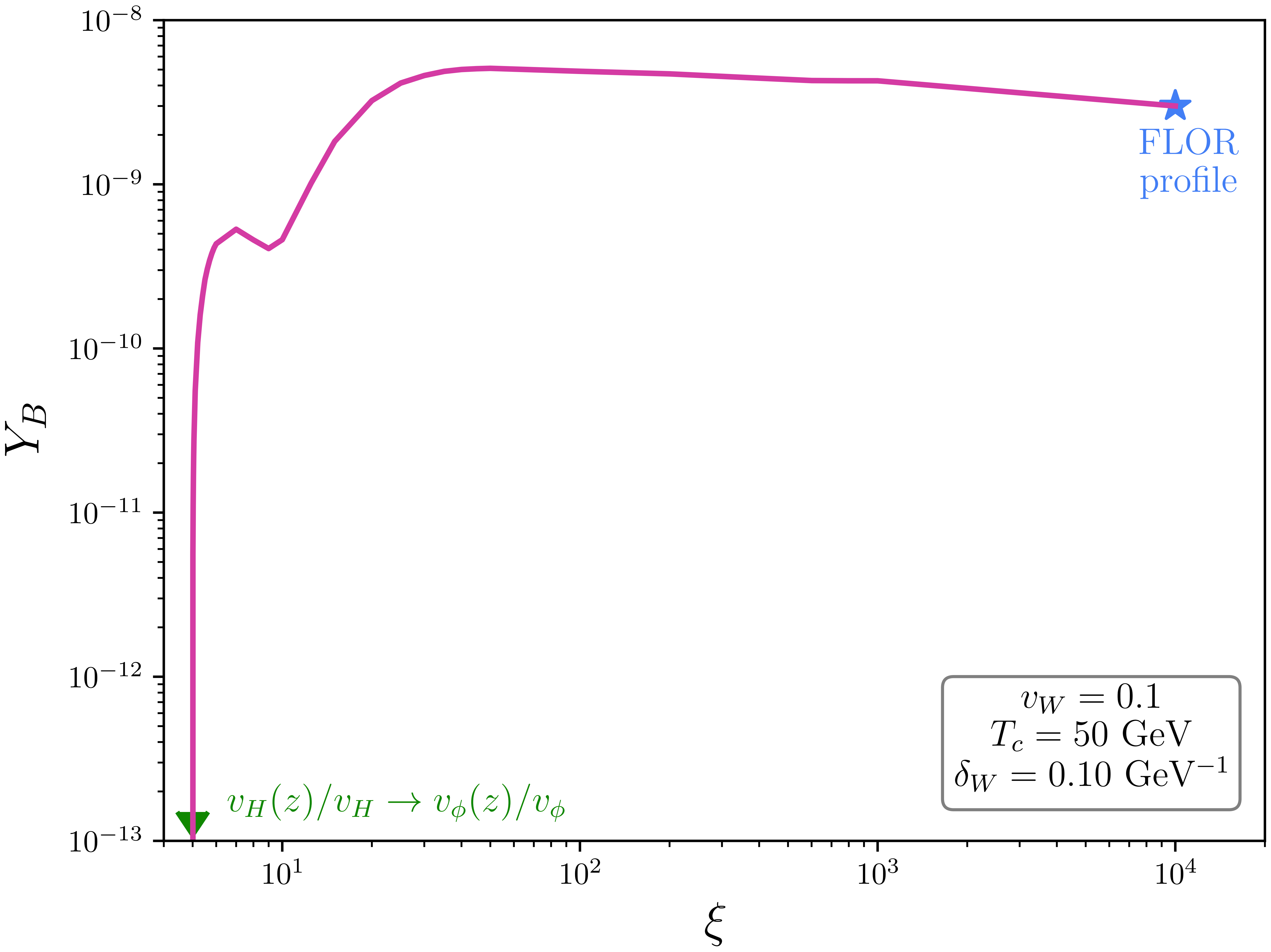


$$v_H(z)/v_H = \frac{1}{2}\left[1 + \tanh\left(\xi \frac{z - (5/\xi)\,\delta_W/2}{\delta_W}\right)\right]$$

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

Effect of vev profiles





Scalar potential

Tree level

$$V\left(s,h\right) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$$

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:11075441

Minima located at $(\langle h\rangle, \langle s\rangle) = (0,0)$ and (v, w) separated by tree-level barrier

Analytical conditions to have

$$V(0,0) \sim V(v,w)$$

Scalar potential

Tree level

$$V(s,h) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$$

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Analytical conditions to have

$V(0,0) \sim V(v,w)$

Need to include finite T corrections

Scalar potential

One-loop potential

S. R. Coleman & E. J. Weinberg, Phys. Rev. D (1983)
J. R. Espinosa, T. Konstandin & F. Riva, arXiv:11075441
M. Quiros, arXiv:hep-ph/9901312

$$V_{1l}(h,s) = \frac{1}{64\pi^2}\sum_\alpha N_\alpha M_\alpha^4(h,s)\left[\log\frac{M_\alpha(h,s)}{Q} - C_\alpha\right]$$

Physical mass as function of (h, s)

Dependence on the renormalization scale

Scalar potential

Finite temperature effects

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:11075441
M. Quiros, arXiv:hep-ph/9901312

$$\delta_\alpha V_T(h,s) = \frac{T^4}{2\pi^2} N_\alpha \int_0^\infty dx x^2 \log\left(1 \pm e^{-\sqrt{x^2 + M_\alpha^2/T^2}}\right) + \frac{T}{12\pi}\delta_{ab} N_\alpha \left[M_\alpha^3 - M_{T,\alpha}^3\right]$$

Physical mass as function of (h, s)

Thermal mass as function of (h, s)

Scalar potential

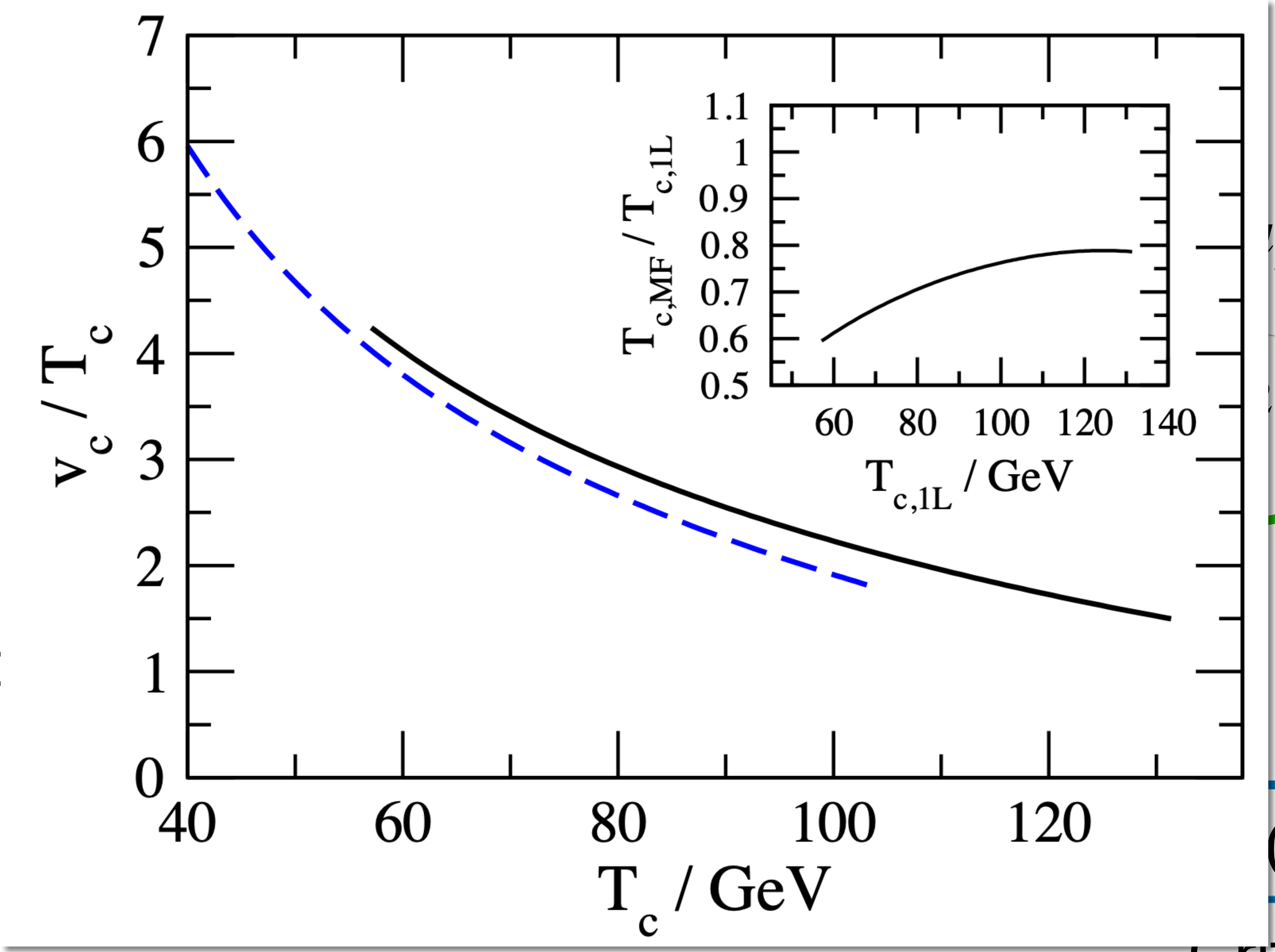
High-T approximation

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:11075441
M. Quiros, arXiv:hep-ph/9901312

$V_{HT}(s,$ ... $_m sh^2 + \frac{1}{4}\lambda_m s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$

$- T_c^2)$

T-depen...



$(0,0) = V_{HT}(v, w)$

Critical temperature

Scalar potential

$T = 0$

$$V_{HT}\left(s,h\right)\Big|_{T=0} = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$$

$$-\left[\frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2 + m_3 s\right] T_c^2$$

We need

$$v\Big|_{T=0} = v_{EW}^{exp} = 246.22 \text{ GeV}$$

$$M_h\Big|_{T=0} = M_h^{exp} = 125.10 \text{ GeV}$$

Scalar potential

$T = 0$

$$V_{HT}(s,h)\Big|_{T=0} = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$$

$$-\left[\frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2 + m_3 s\right] T_c^2$$

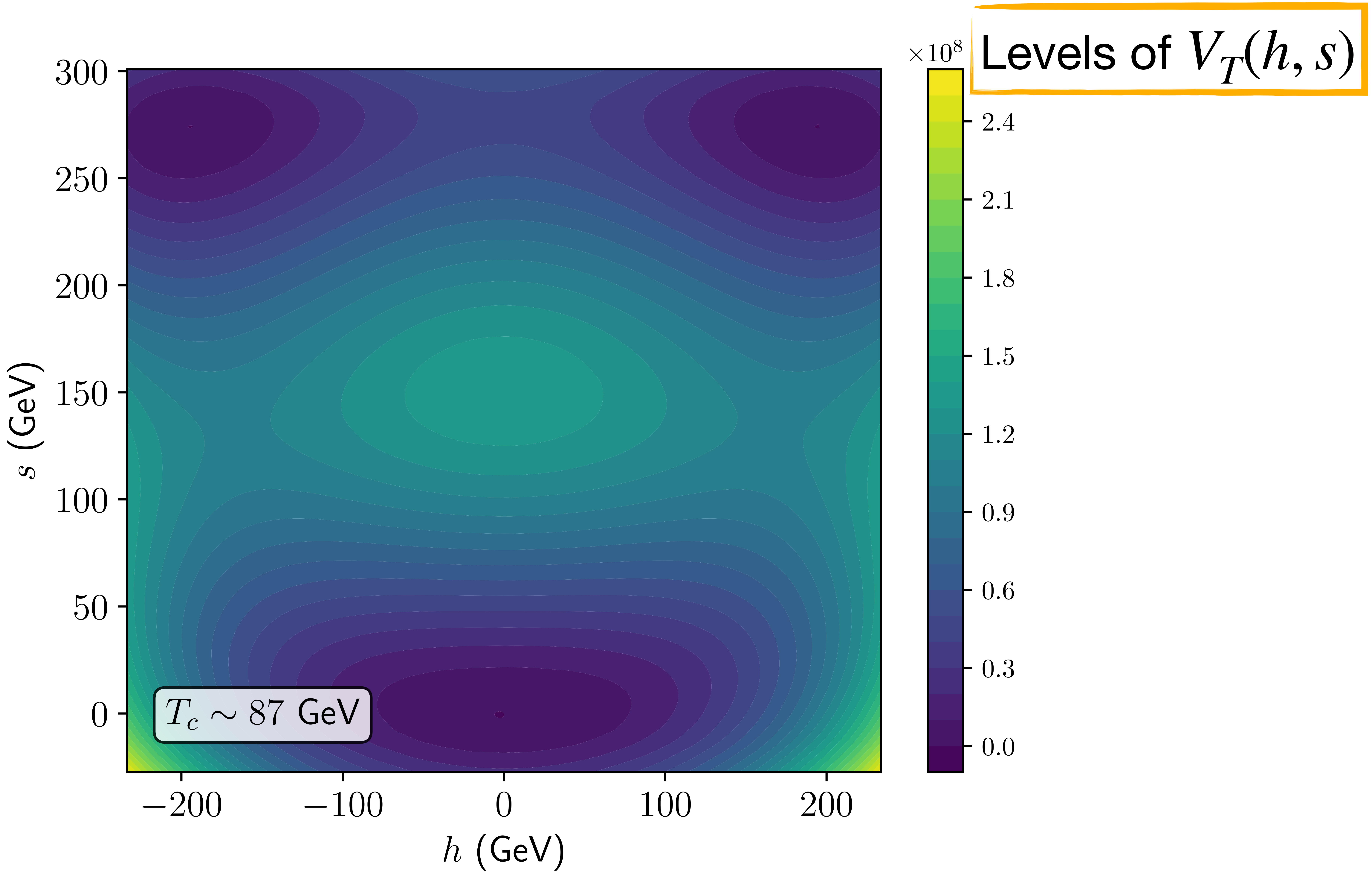
We need

$$v\Big|_{T=0} = v_{EW}^{exp} = 246.22 \text{ GeV}$$

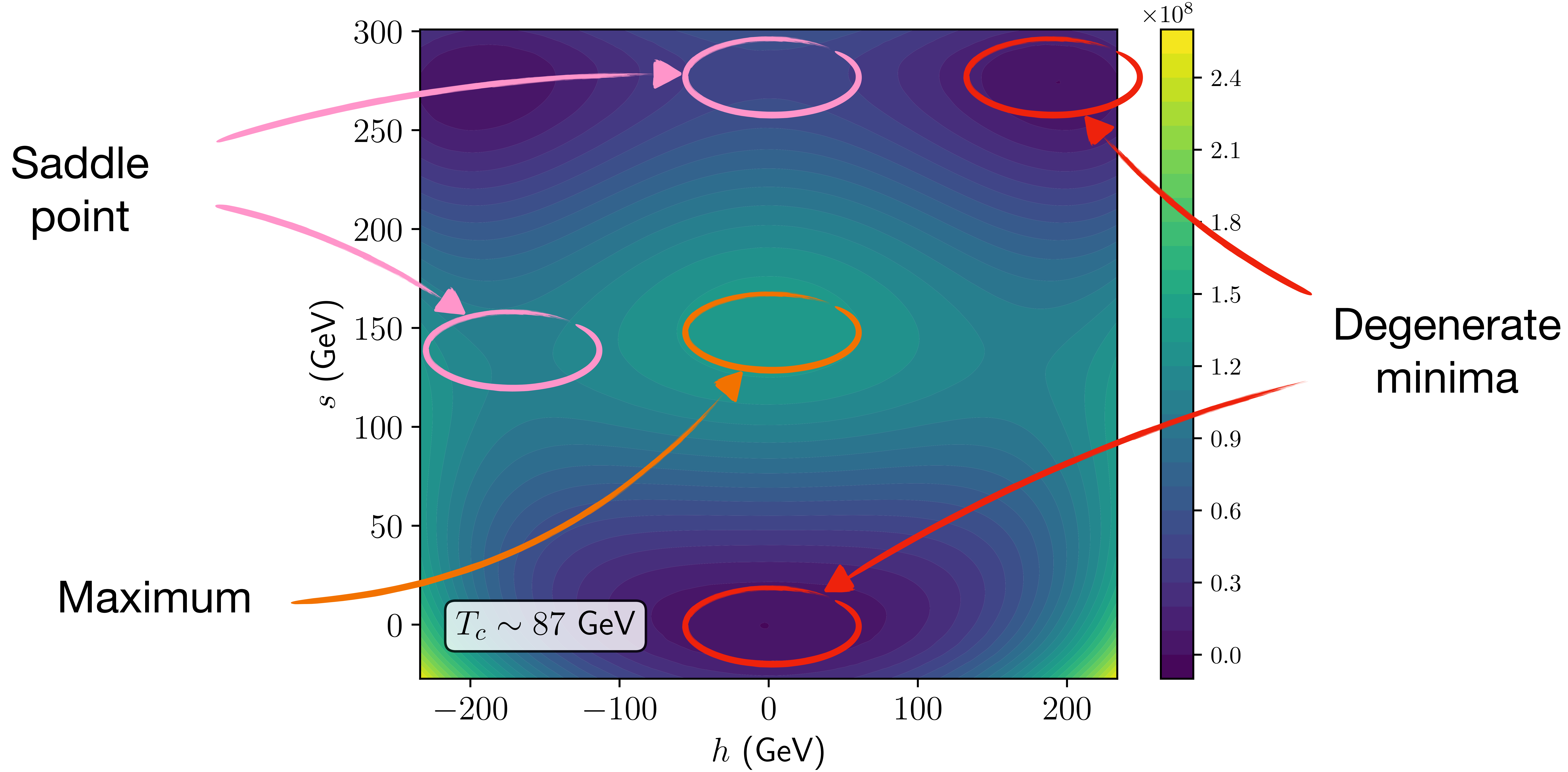
Global minimum

$$M_h\Big|_{T=0} = M_h^{exp} = 125.10 \text{ GeV}$$

Structure of the potential



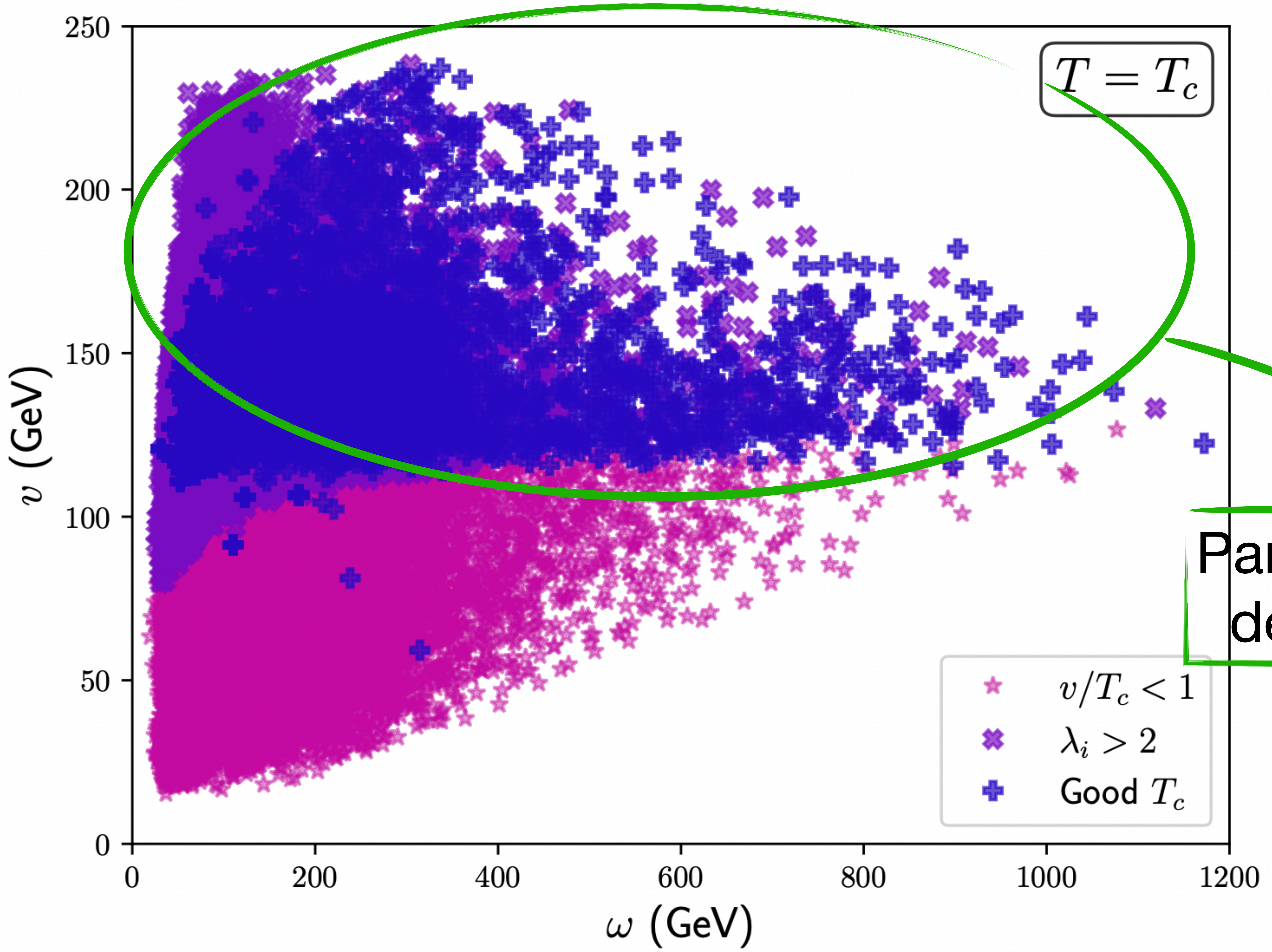
Structure of the potential



Structure of the potential

Saddle point

Maximu



Degenerate minima

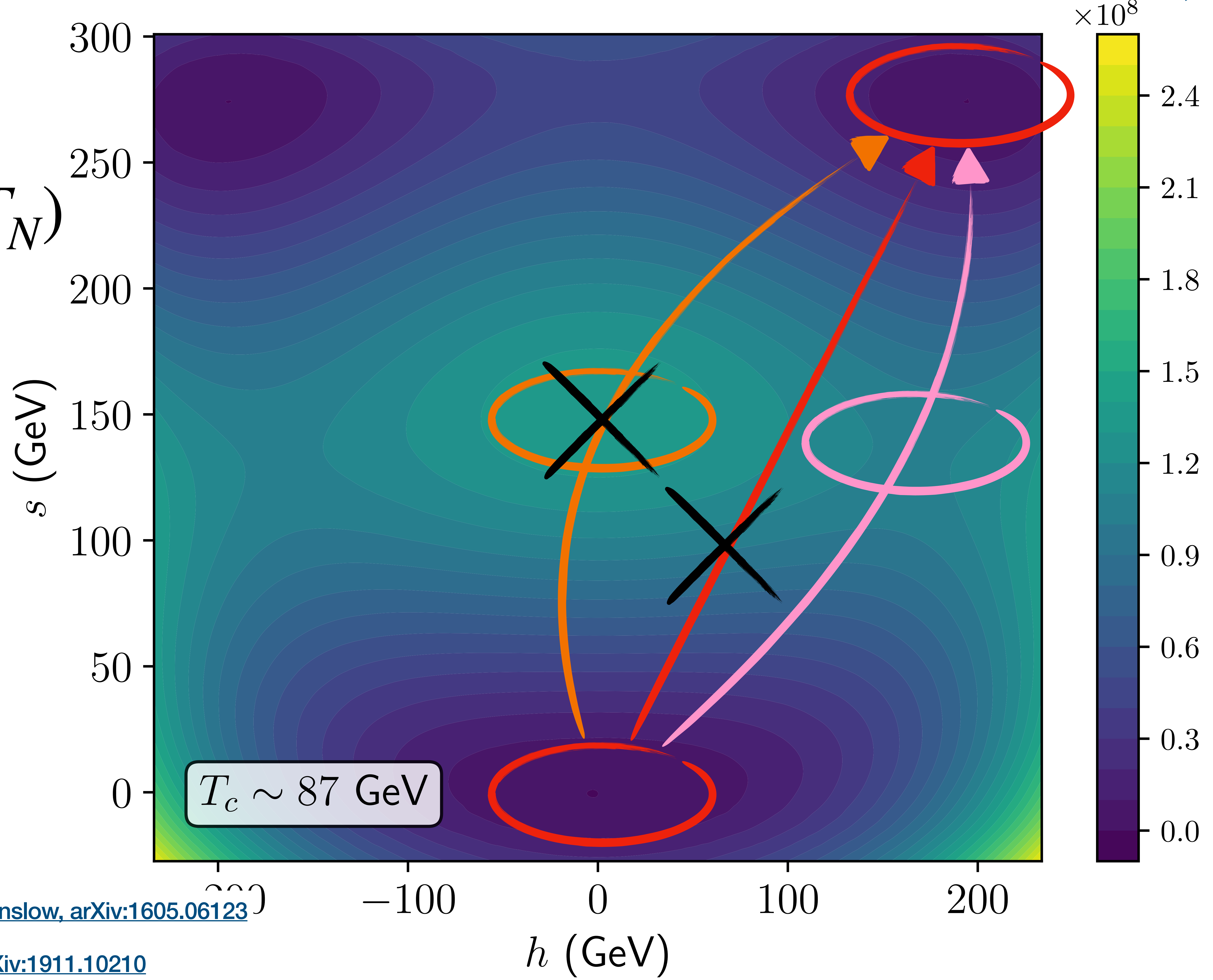
Parameter space with degenerate minima

Nucleation

C. L. Wainwright, arXiv:1109.4189
P. Athron *et al.*, arXiv:1901.03714
V. Guada, M. Nemevsek & M. Pintar, arXiv:2002.00881
P. Athron, C. Balazs, A. F. Y. Zhang, arXiv:2003.02859

$$\Gamma/V \sim e^{-S_3/T_N} \sim H(T_N)$$

$$S_3/T_N \sim 140$$



A. V. Kotwal, J. M. No, M. J. Ramsey-Musolf & P. Winslow, arXiv:1605.06123
M. Carena, Z. Liu & Y. Wang, arXiv:1911.10206
J. Kozaczuk, M. J. Ramsey-Musolf & J. Shelton, arXiv:1911.10210

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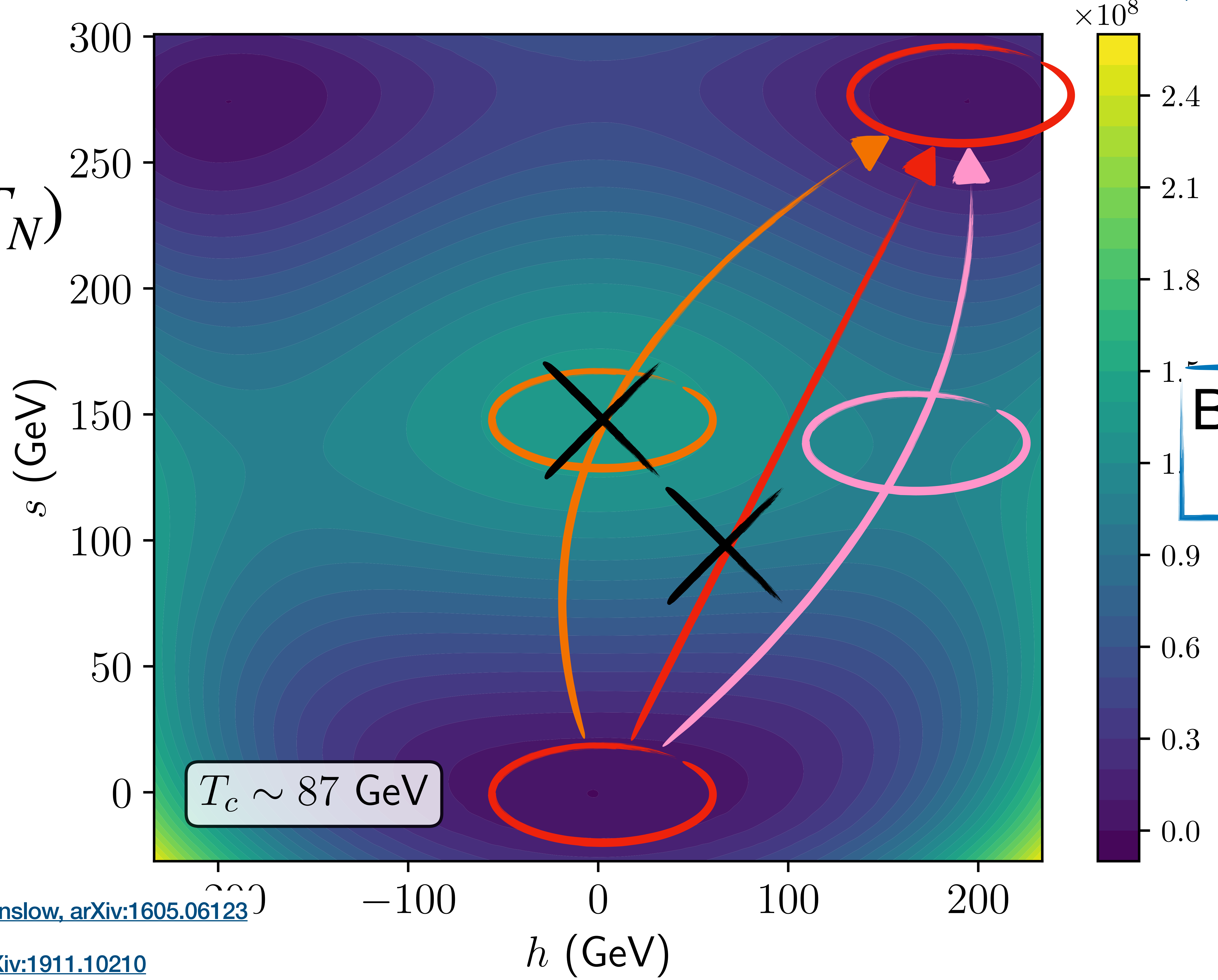


Bounce goes close to saddle point

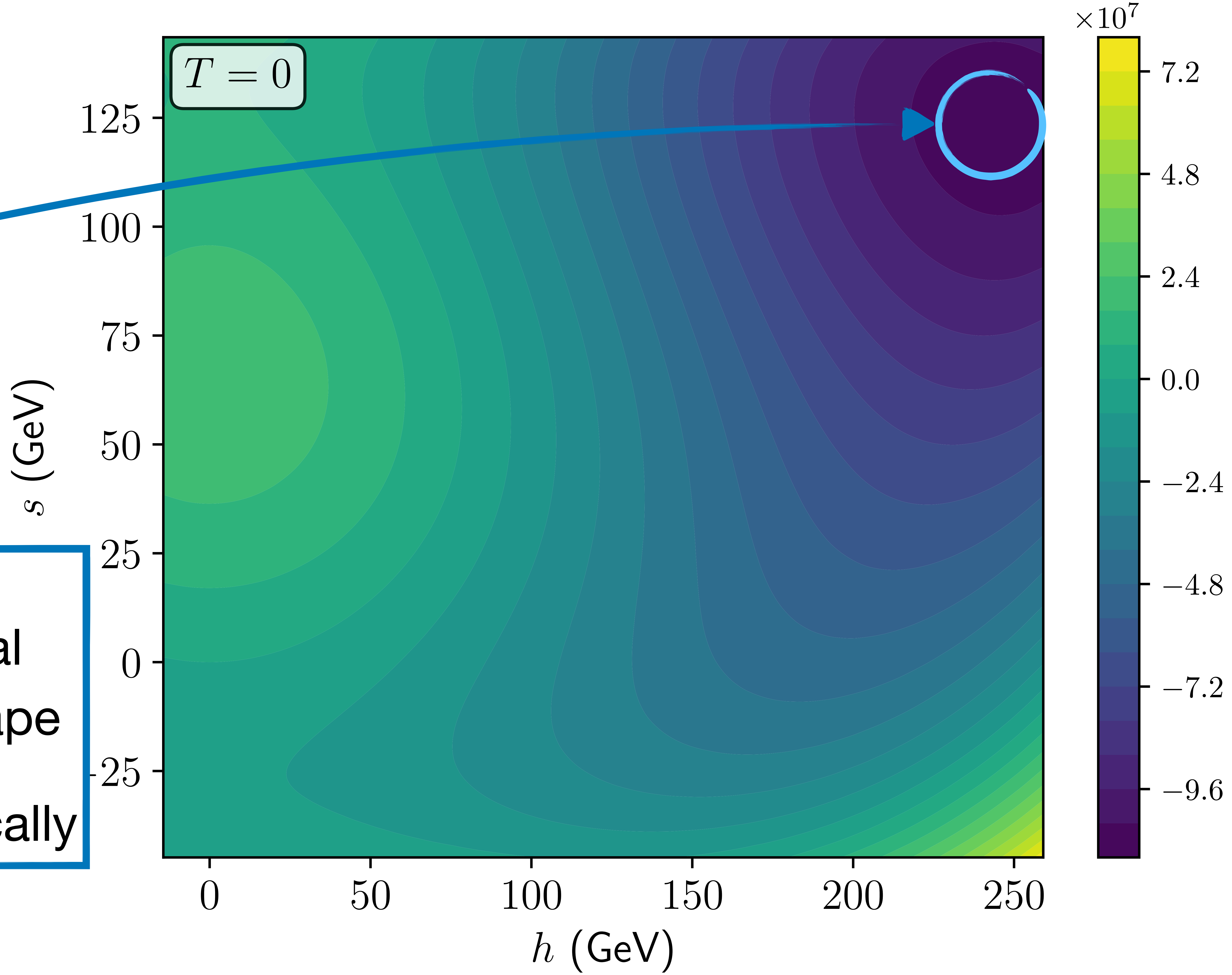
$$S_3/T_N \gg 140$$

in this case

A. V. Kotwal, J. M. No, M. J. Ramsey-Musolf & P. Winslow, arXiv:1605.06123
M. Carena, Z. Liu & Y. Wang, arXiv:1911.10206
J. Kozaczuk, M. J. Ramsey-Musolf & J. Shelton, arXiv:1911.10210

Nucleation

Electroweak minimum



To estimate nucleation

- Rotate to 1D potential
- Approximate by Δ-shape
- Estimate S_3/T_N analytically

A. Amarati, arXiv:2009.14102