



# Synergies between the scalar and neutrino sector for an EW phase transition

**Salvador Rosauro-Alcaraz, Pôle Théorie IJCLab**



In collaboration with E. Fernandez-Martinez, J. Lopez-Pavon, J. M. No & T. Ota

**Neutrino Platform Pheno Week, 16/03/2023**

# Introduction

Planck Collaboration, arXiv:1807.06209

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

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## Generation of a BAU

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### 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<sup>st</sup> order phase transition

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Pene, arXiv:hep-ph/9312215

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& C. Quimbay, arXiv:hep-ph/9406289

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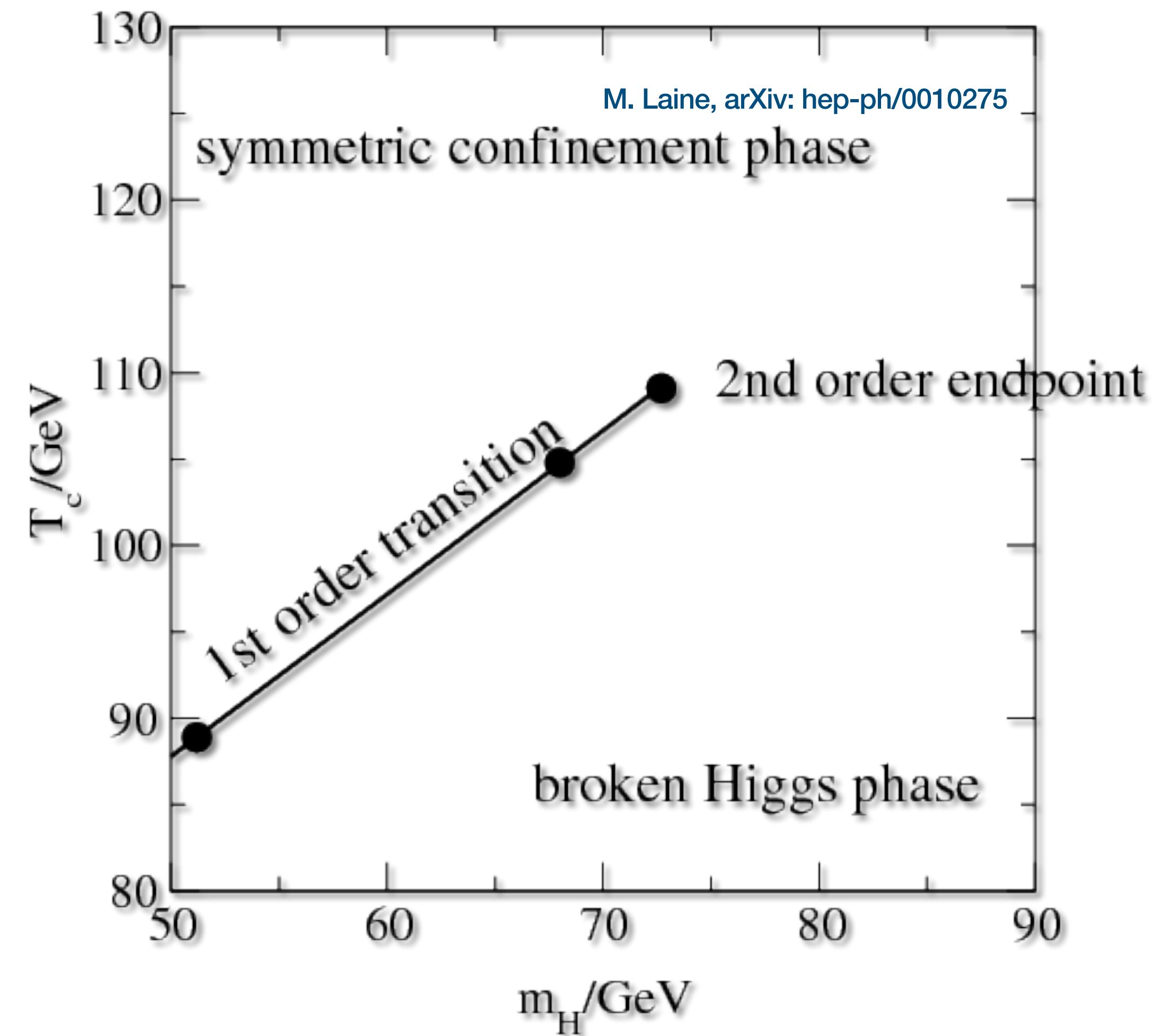
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K. Kajantie, M. Laine, K. Rummukainen, & M. E. Shaposhnikov, arXiv:hep-ph/9605288



# Electroweak baryogenesis with new physics

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New sources of CP violation

# Electroweak baryogenesis and low-scale seesaws

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N'_R - \bar{N}'_L s Y_N N'_R + h.c. - V(\Phi^\dagger \Phi, s)$$



P. Hernandez & N. Rius, arXiv: hep-ph/9611227  
E. Fernandez-Martinez, J. Lopez-Pavon, T. Ota & SRA, arXiv:2007.11008

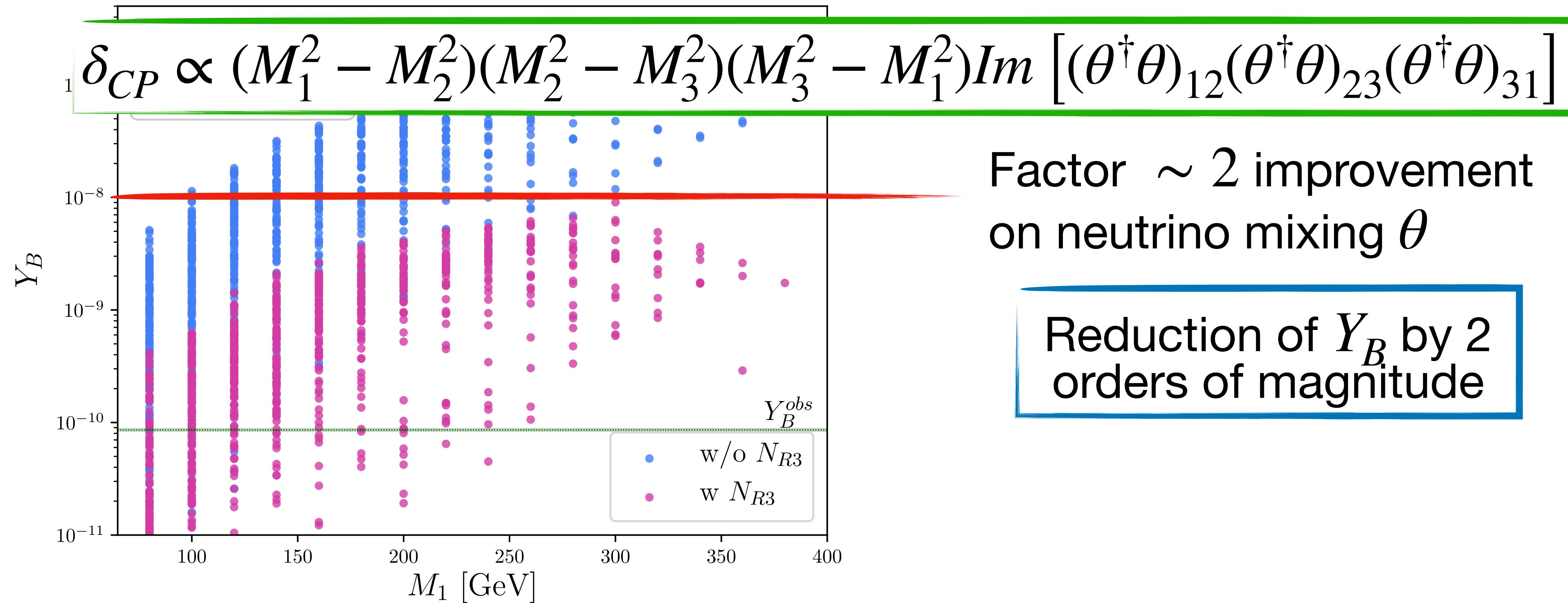
Large mixing and CPV

$$\theta = \frac{\nu}{\sqrt{2}\omega} Y_\nu Y_N^{-1}$$

# Electroweak baryogenesis and low-scale seesaws

$$\mathcal{L} \supset -\bar{L}_I Y_\nu \tilde{\Phi} N'_R - \bar{N}'_I s Y_N N'_R + h.c. - V(\Phi^\dagger \Phi, s)$$

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# Phase transition with dark sectors

## Electroweak baryogenesis

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

~~1<sup>st</sup> order phase transition~~

Add singlet scalar  $s$

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

# Phase transition with dark sectors

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N'_R - \bar{N}'_L s Y_N N'_R + h.c. - V(\Phi^\dagger \Phi, s)$$

E. Fernandez-Martinez, J. Lopez-Pavon, T. Ota & SRA, arXiv:2007.11008

$$\begin{aligned} V(\Phi^\dagger \Phi, s) = & -\frac{1}{2} \tilde{\mu}_h^2 \Phi^\dagger \Phi + \frac{1}{4} \lambda_h (\Phi^\dagger \Phi)^2 + \frac{1}{2} \tilde{\mu}_s^2 s^2 + \frac{1}{4} \lambda_s s^4 \\ & + \frac{1}{4} \mu_m s \Phi^\dagger \Phi + \frac{1}{4} \lambda_m s^2 \Phi^\dagger \Phi + \tilde{\mu}_1^3 s + \frac{1}{3} \mu_3 s^3 \end{aligned}$$

[J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441](#)

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

## Tree level

$$V(h, s) = -\frac{1}{2}\tilde{\mu}_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\tilde{\mu}_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \tilde{\mu}_1^3 s + \frac{1}{3}\mu_3 s^3$$

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441

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

Analytical conditions to have

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

# Scalar potential

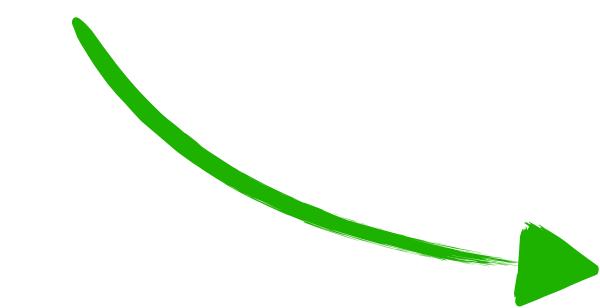
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Minima located at  $(\langle h \rangle, \langle s \rangle) = (0,0)$  and  $(v, \omega)$   
separated by tree-level barrier

Analytical conditions to have



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

Need to include finite  $T$  corrections

# Scalar potential

## One-loop - Finite temperature effects

High temperature approximation

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441  
M. Quiros, arXiv:hep-ph/9901312

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

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

$T$ -dependent correction

# Scalar potential

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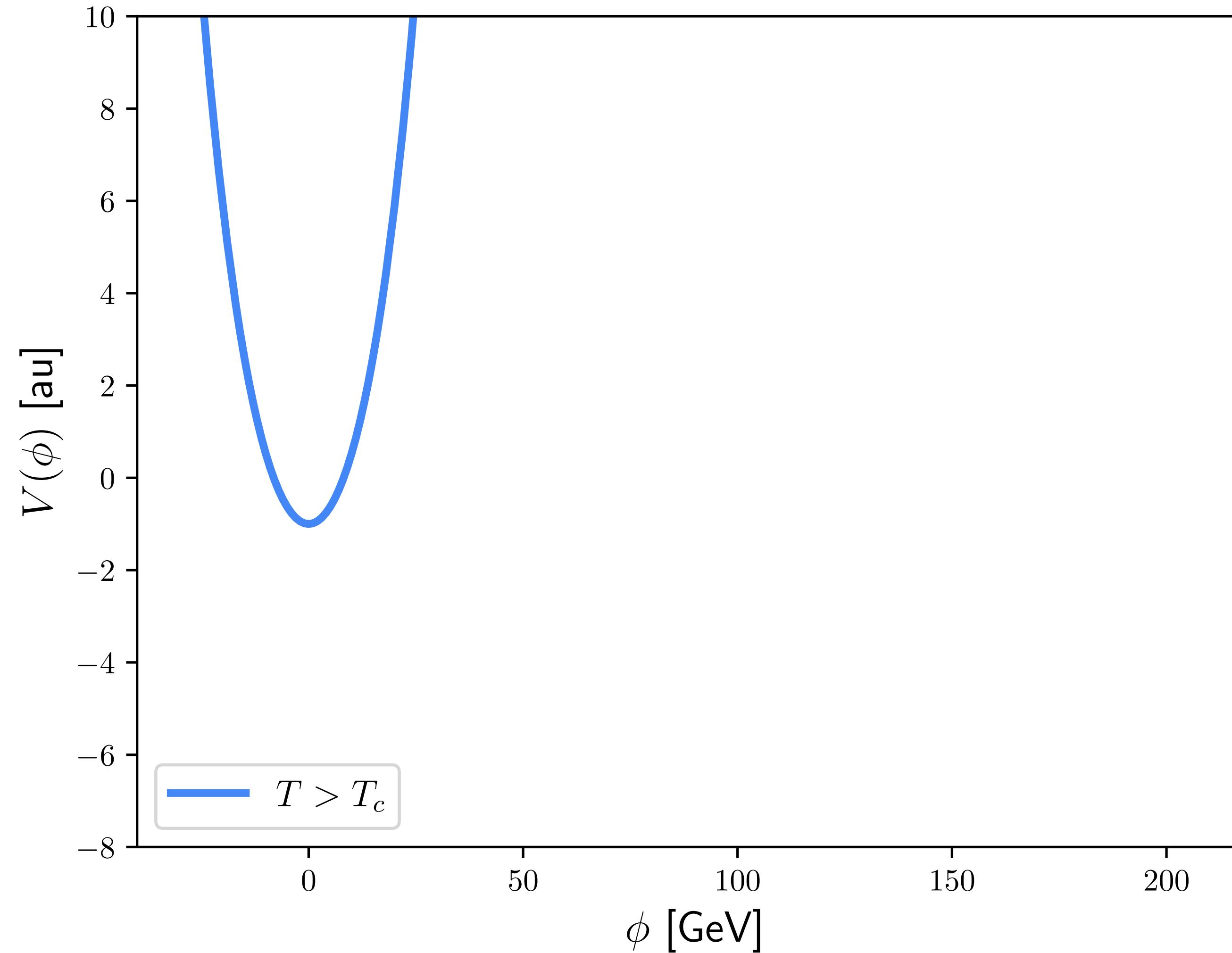


$$c_s = \frac{1}{12} [2\lambda_m + 3\lambda_s + 2\mathcal{Y}_N^2]$$

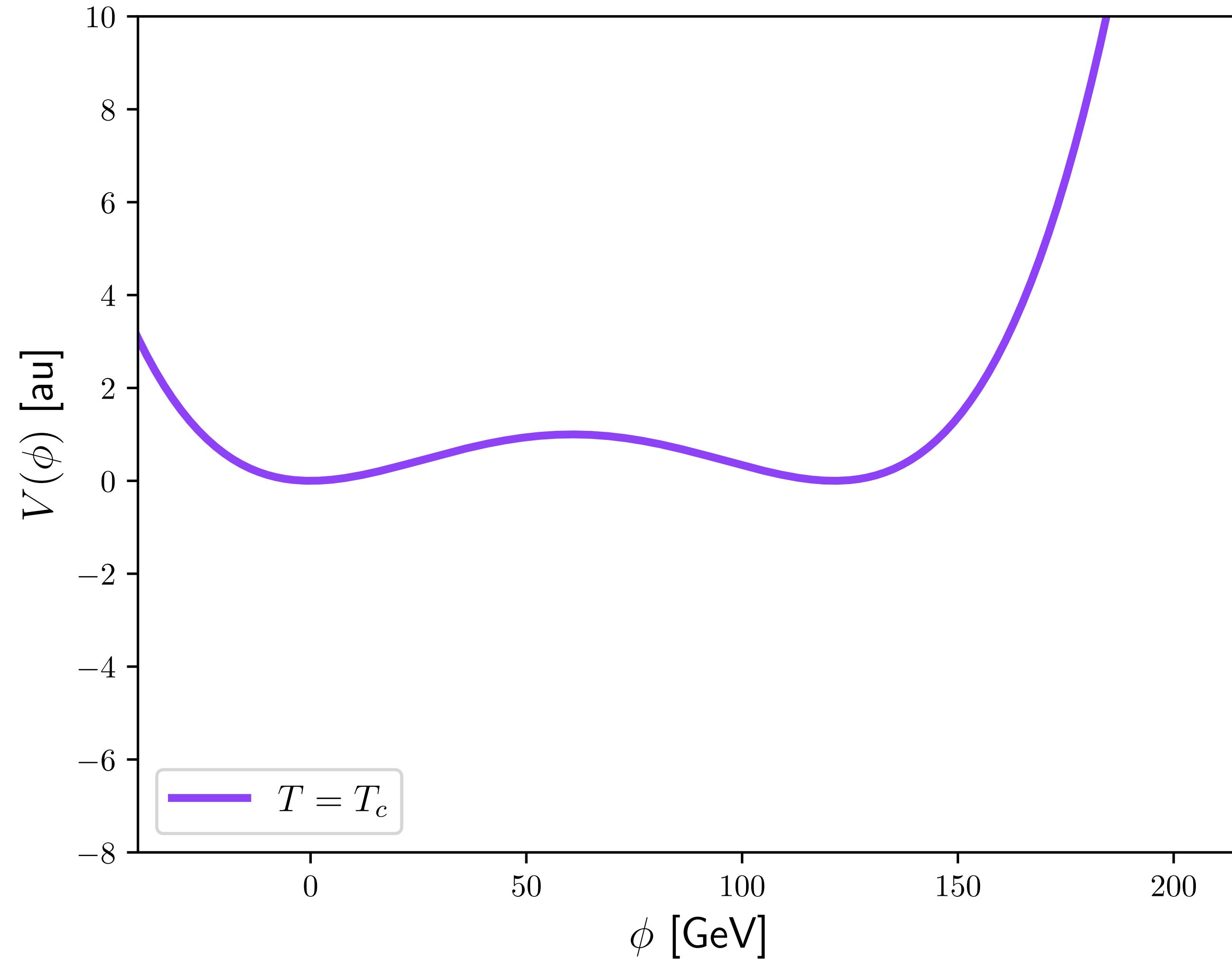
Neutrino Yukawa couplings

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

# Nucleation



# Nucleation



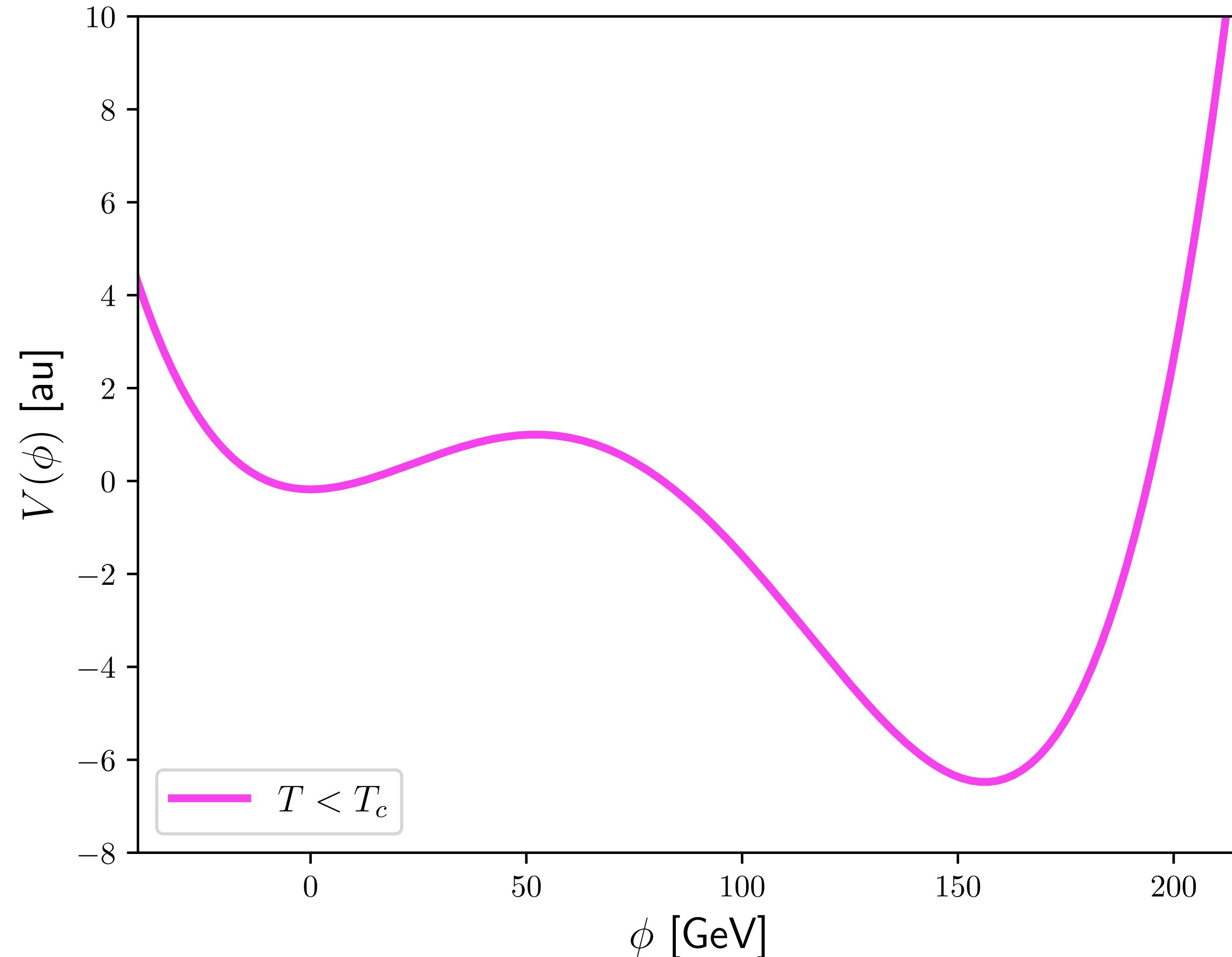
S. Coleman, Phys. Rev. D (1977)  
A. Amarati, arXiv:2009.14102

$$\Gamma/V \sim e^{-S}$$

$$\lim_{T \rightarrow T_c} S \sim 1/\Delta V^3 \rightarrow \infty$$

The transition can only  
happen at  $T < T_c$

# Nucleation



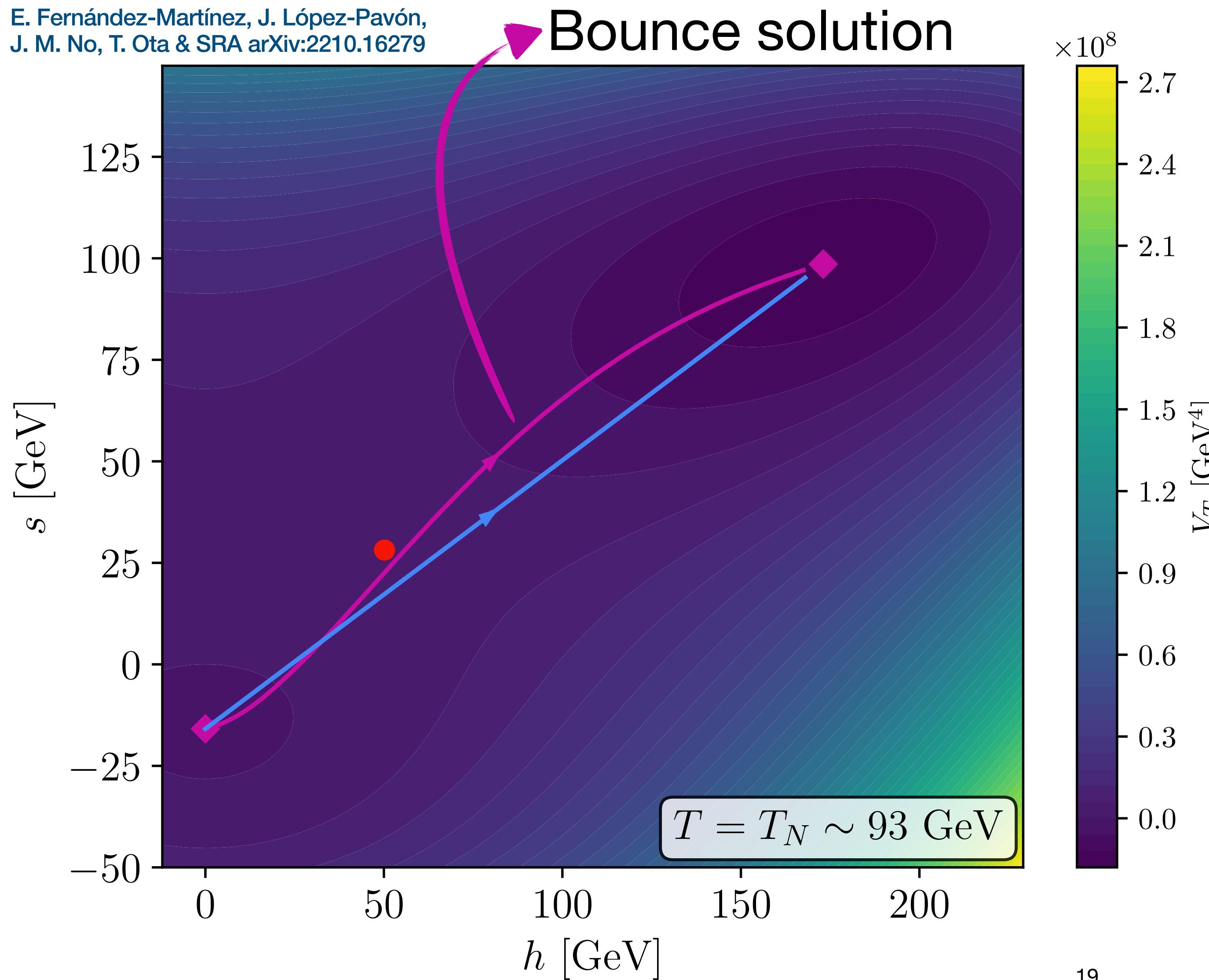
$$\Gamma/V \sim e^{-S_3/T_N} \sim H(T_N)$$

$$S_3/T_N \sim 140$$

Need to solve  
equations of motion

# Nucleation

E. Fernández-Martínez, J. López-Pavón,  
J. M. No, T. Ota & SRA arXiv:2210.16279



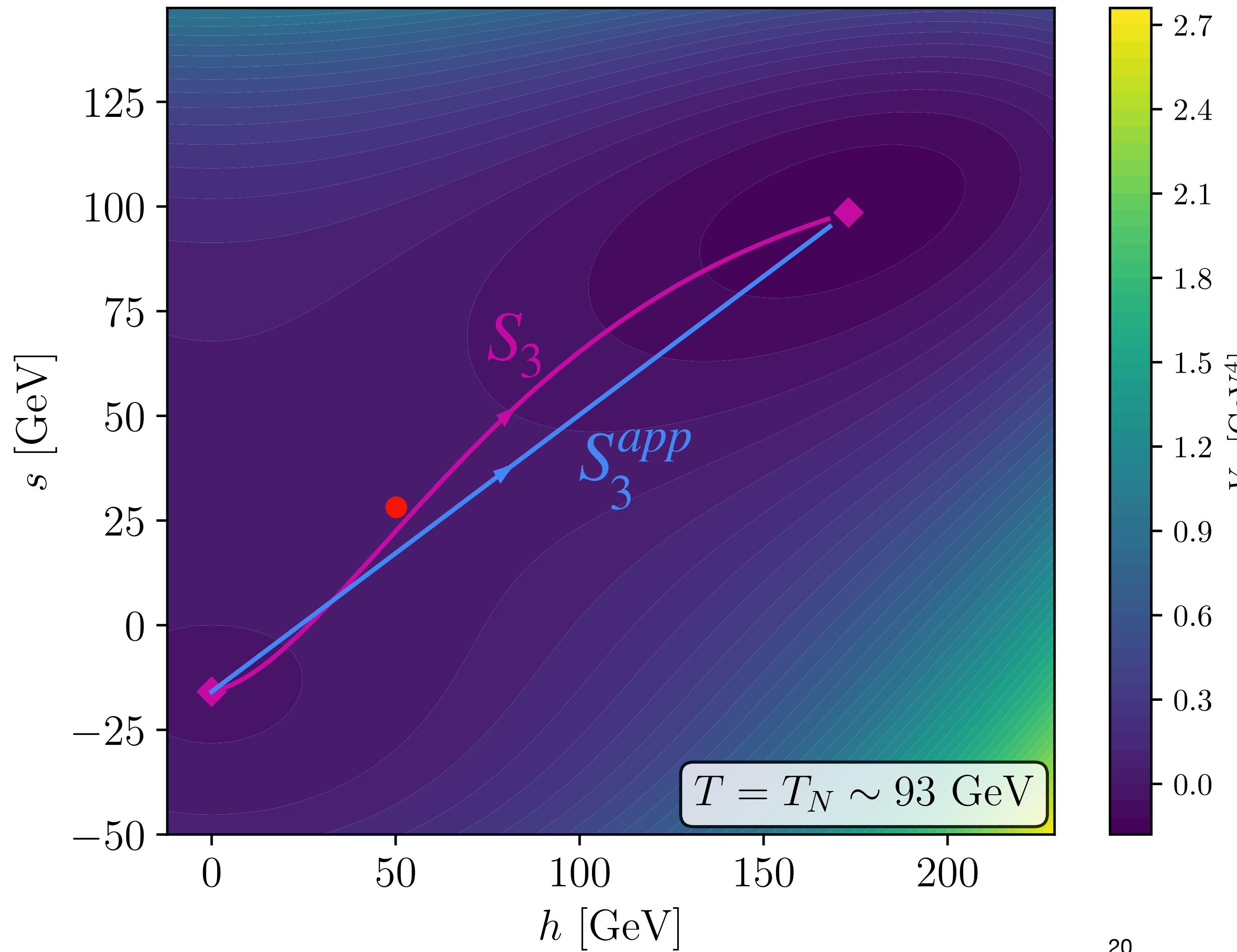
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# Nucleation

E. Fernández-Martínez, J. López-Pavón,  
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Use straight path between minima

$$S_3^{app} \geq S_3$$

$$S_3^{app}/T_N \sim 140$$

Efficiently scan the parameter space

# Phenomenology

## Constraints on scalar mixing

$$h = \nu_{EW} + \cos \xi H + \sin \xi S$$

$$s = \omega_{EW} - \sin \xi H + \cos \xi S$$

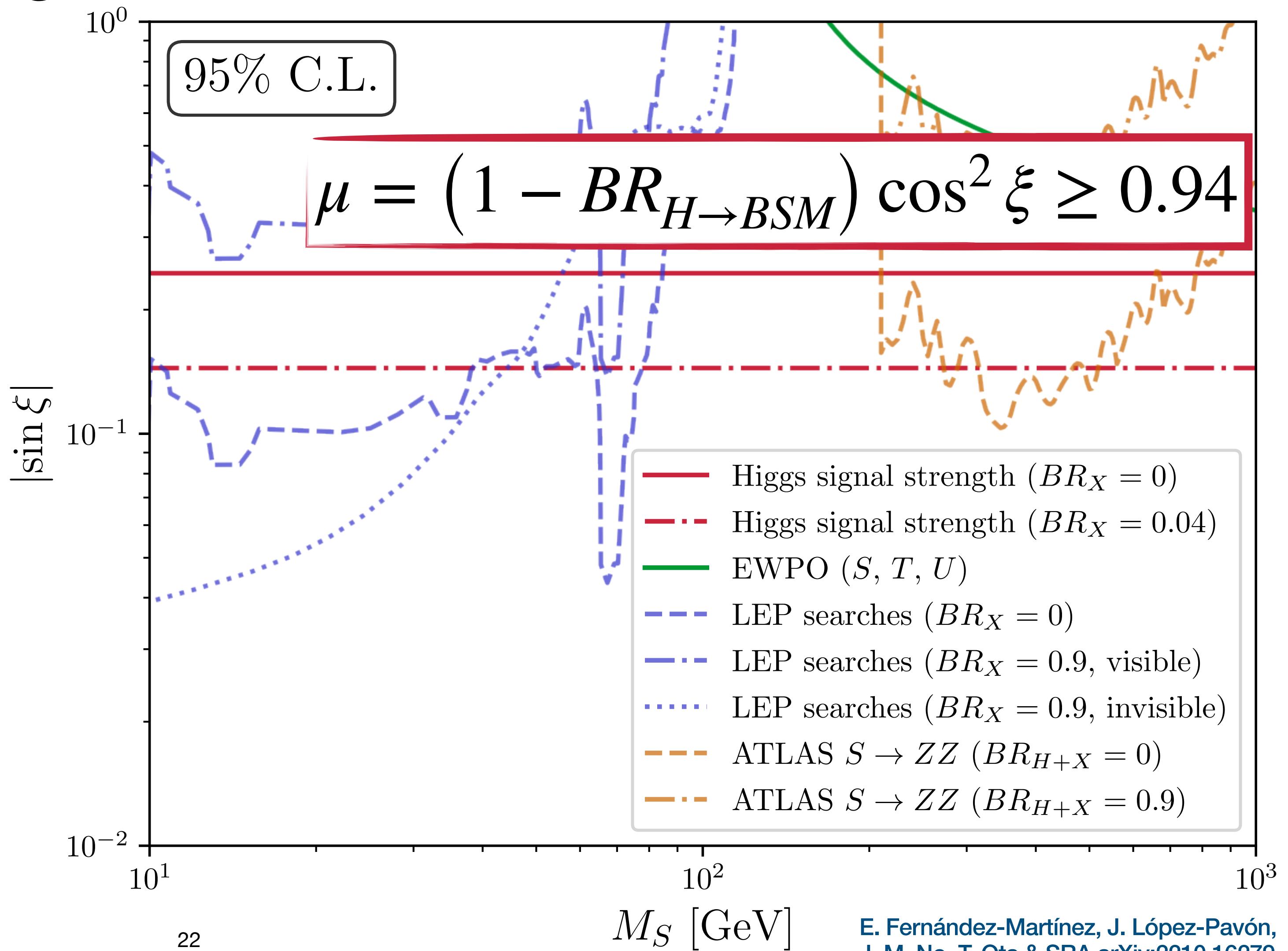
# Phenomenology

## Constraints on scalar mixing

Higgs signal strength

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

ATLAS Collaboration, arXiv:1909.02845  
CMS Collaboration, record/2706103



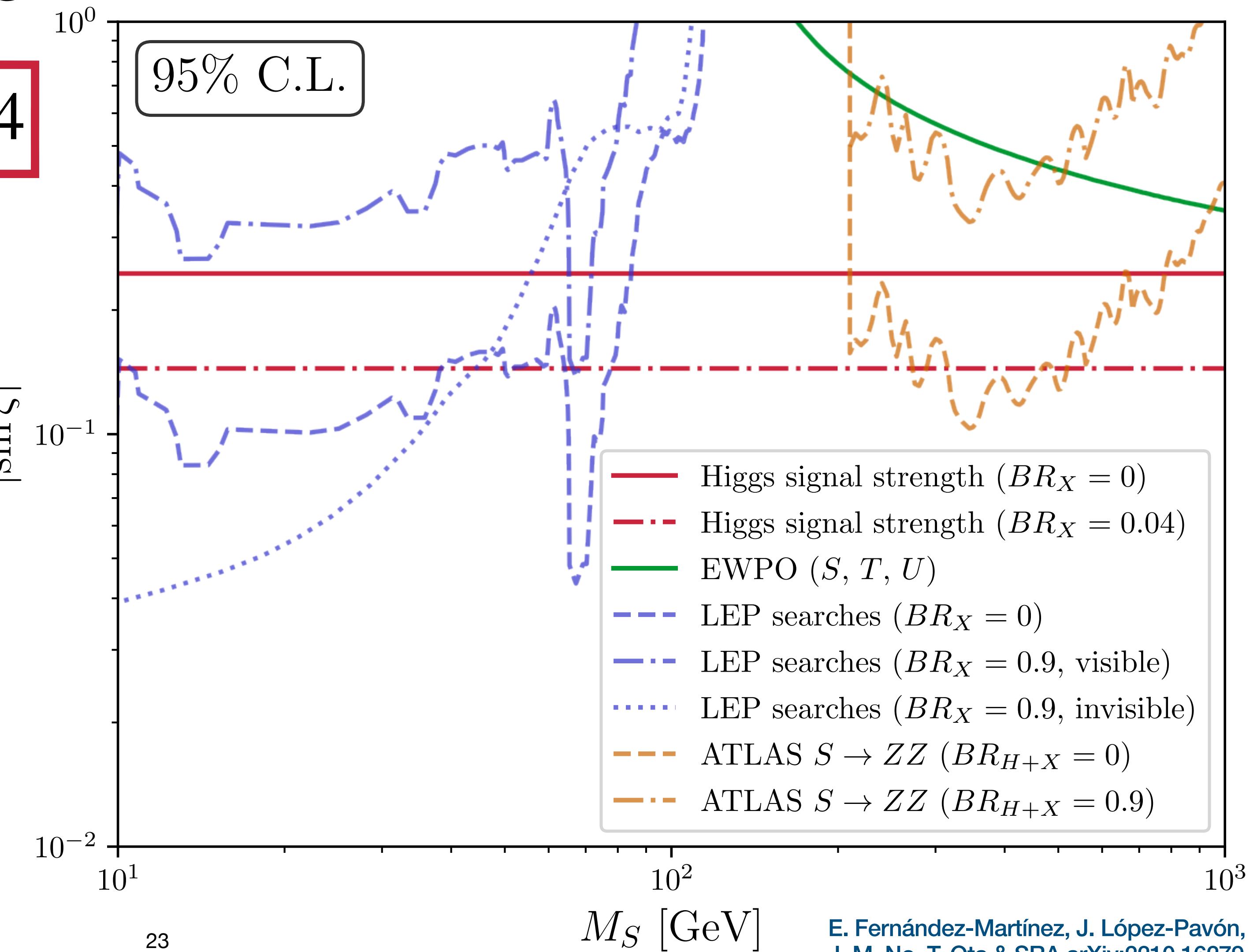
# Phenomenology

## Constraints on scalar mixing

$$\mu = (1 - BR_{H \rightarrow BSM}) \cos^2 \xi \geq 0.94$$

E. Fernández-Martínez, J. López-Pavón,  
J. M. No, T. Ota & SRA arXiv:2210.16279

In our case, for example,  $H \rightarrow N\bar{N}$



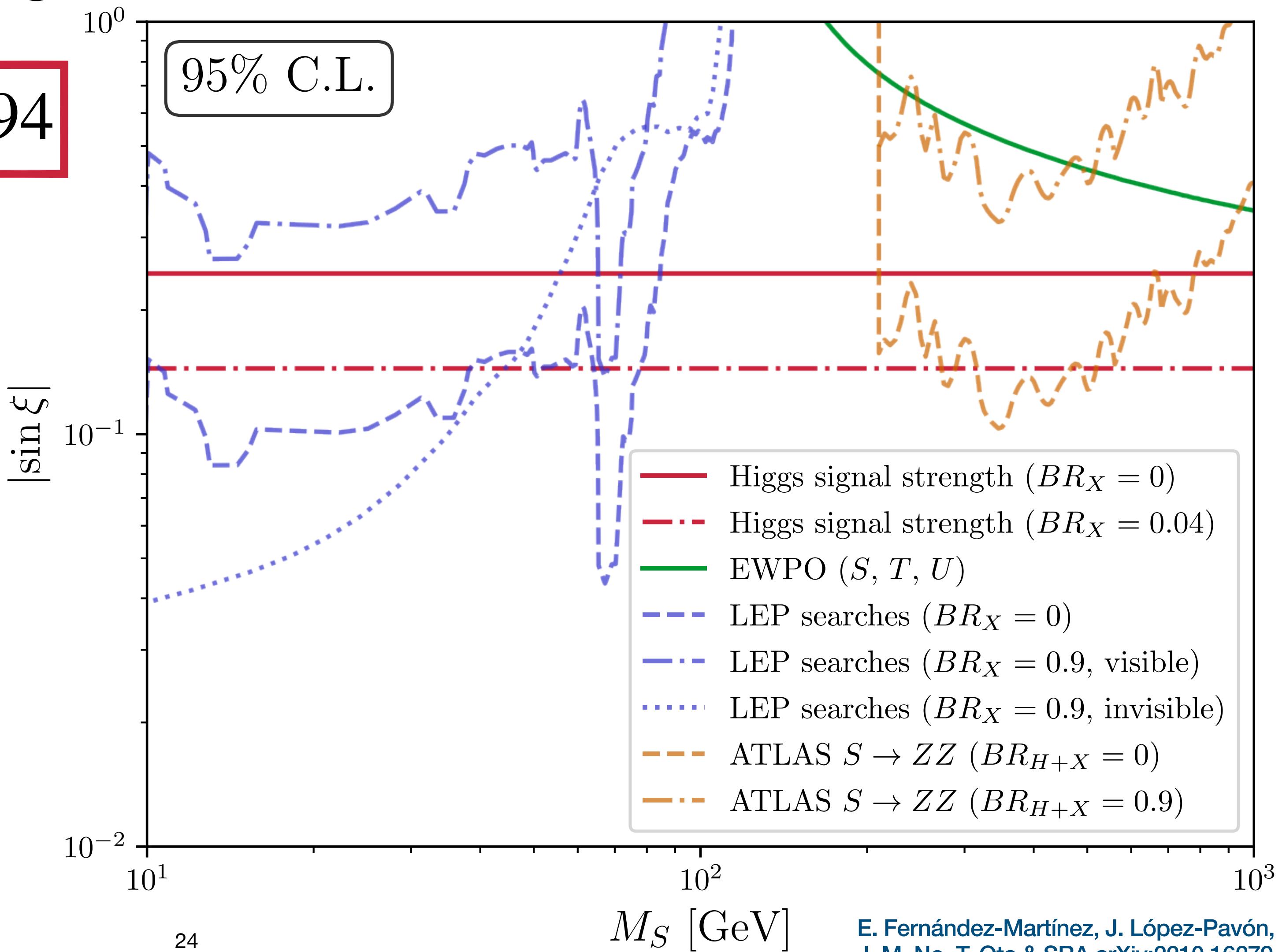
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E. Fernández-Martínez, J. López-Pavón,  
J. M. No, T. Ota & SRA arXiv:2210.16279

EW precision observables



# Phenomenology

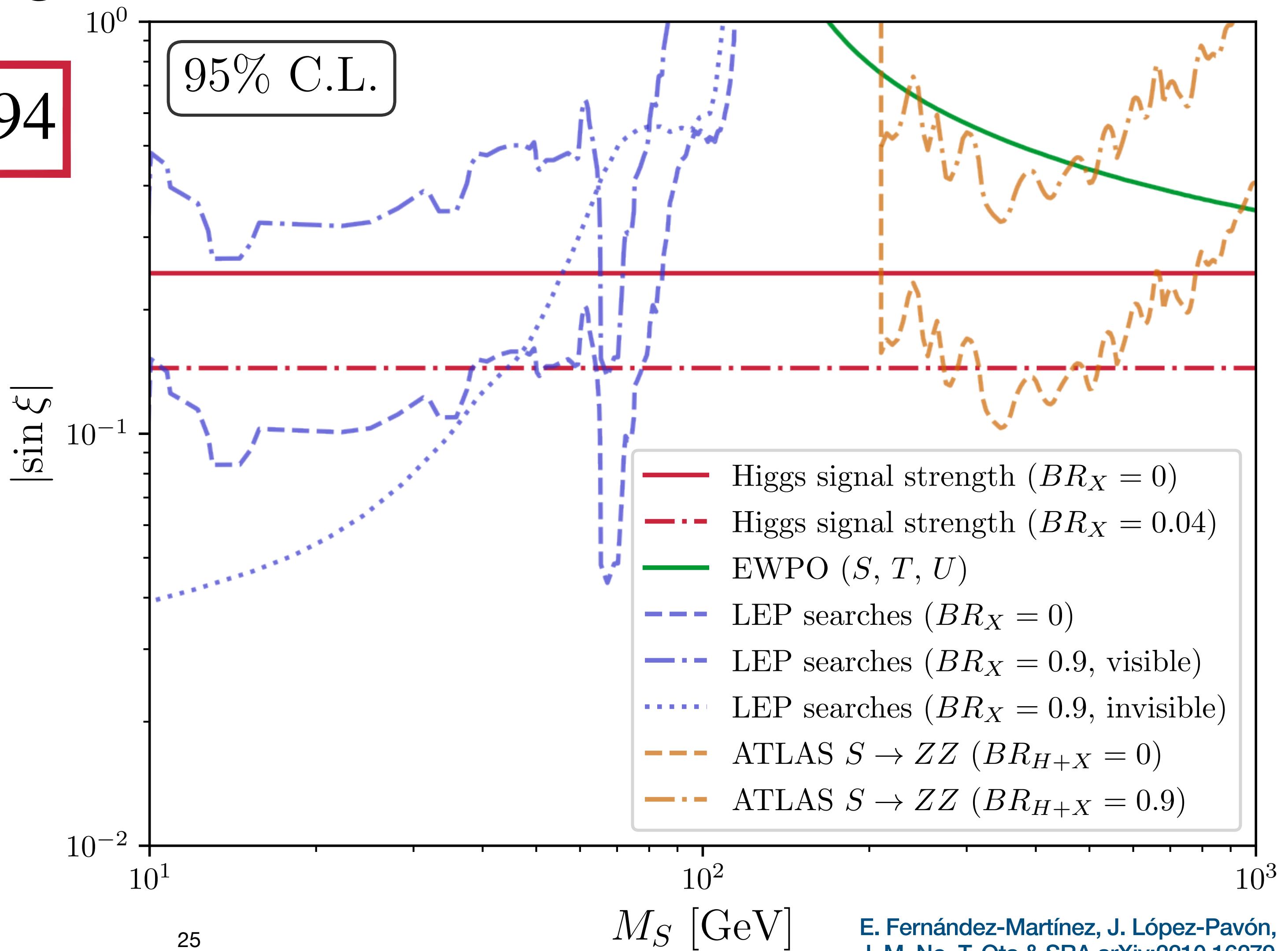
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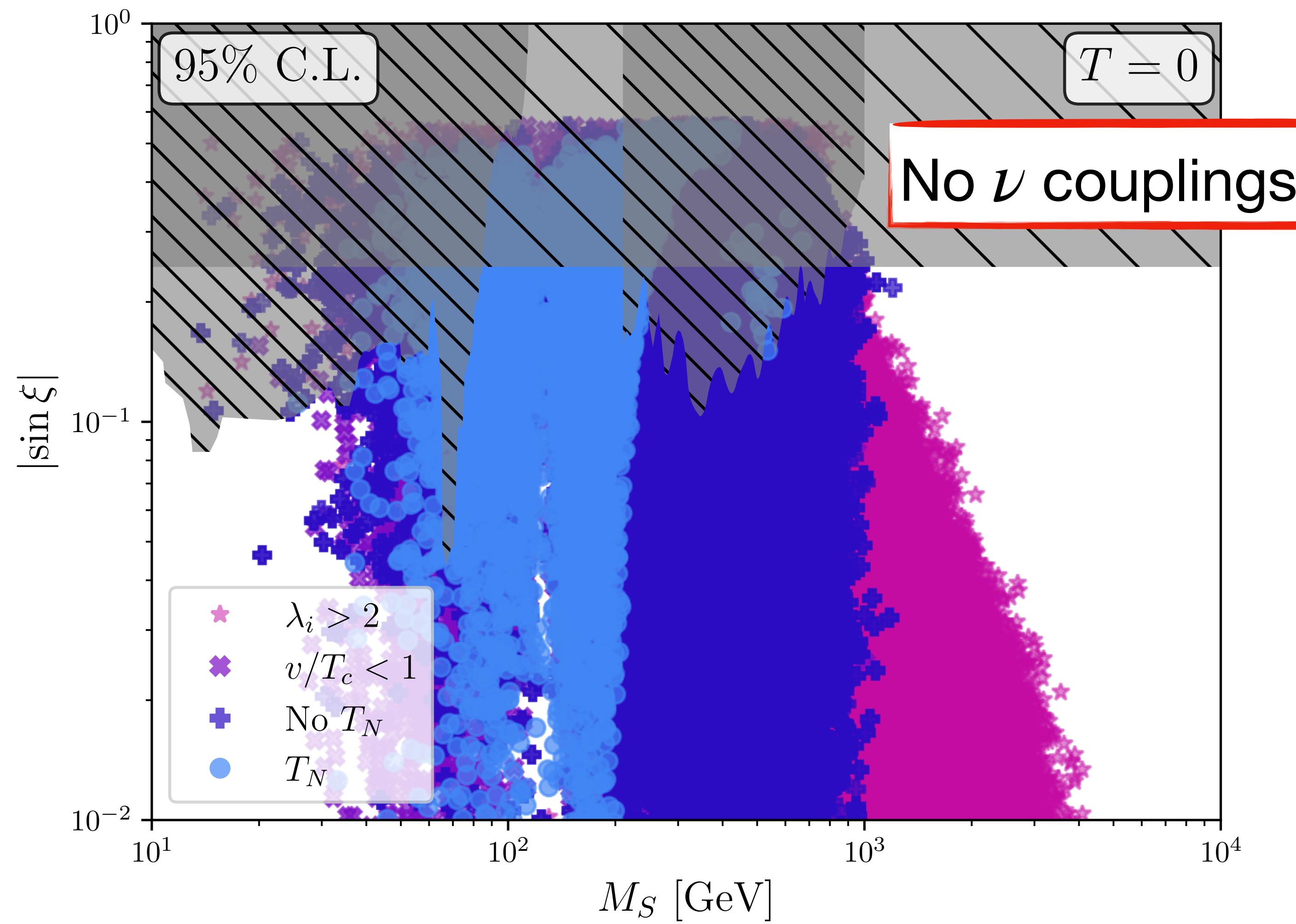
EW precision observables

LEP and LHC searches



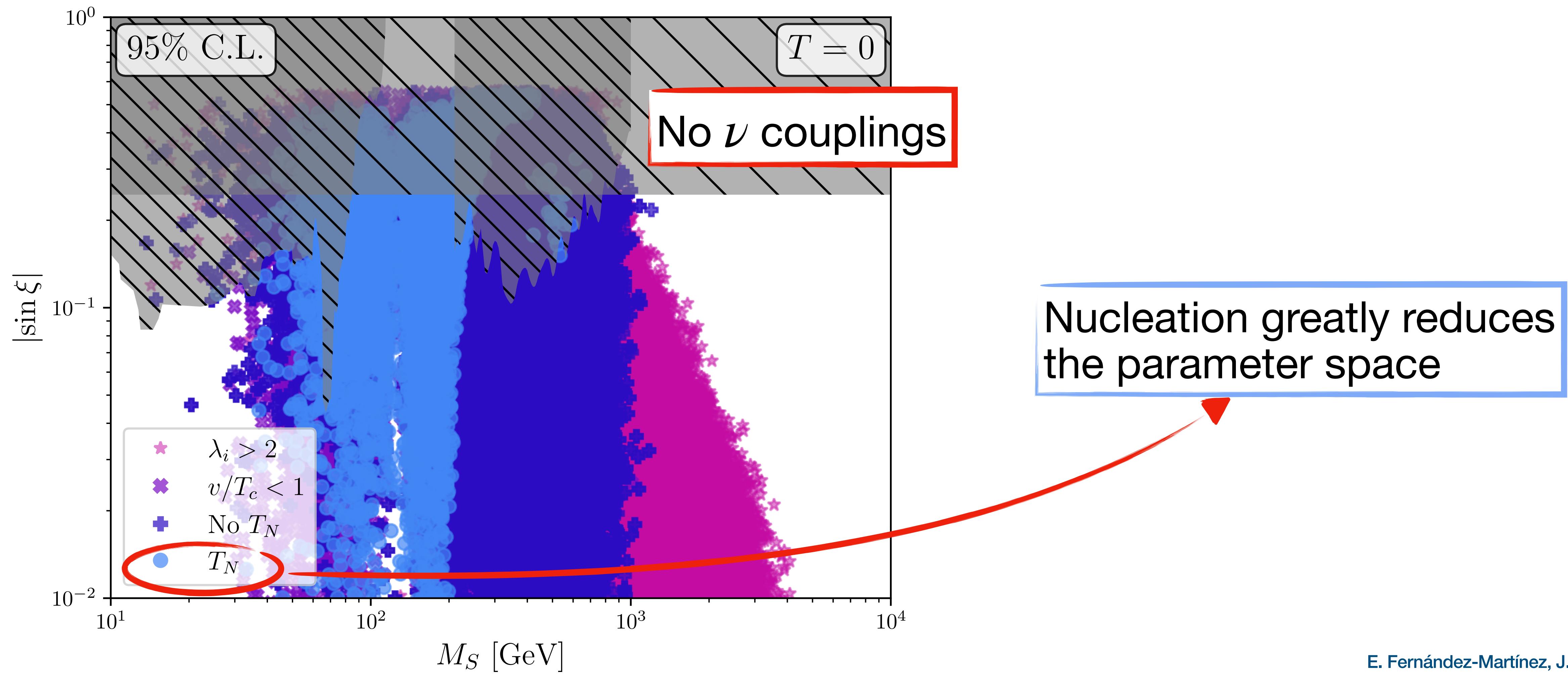
# Results

## Comparison w/o neutrinos



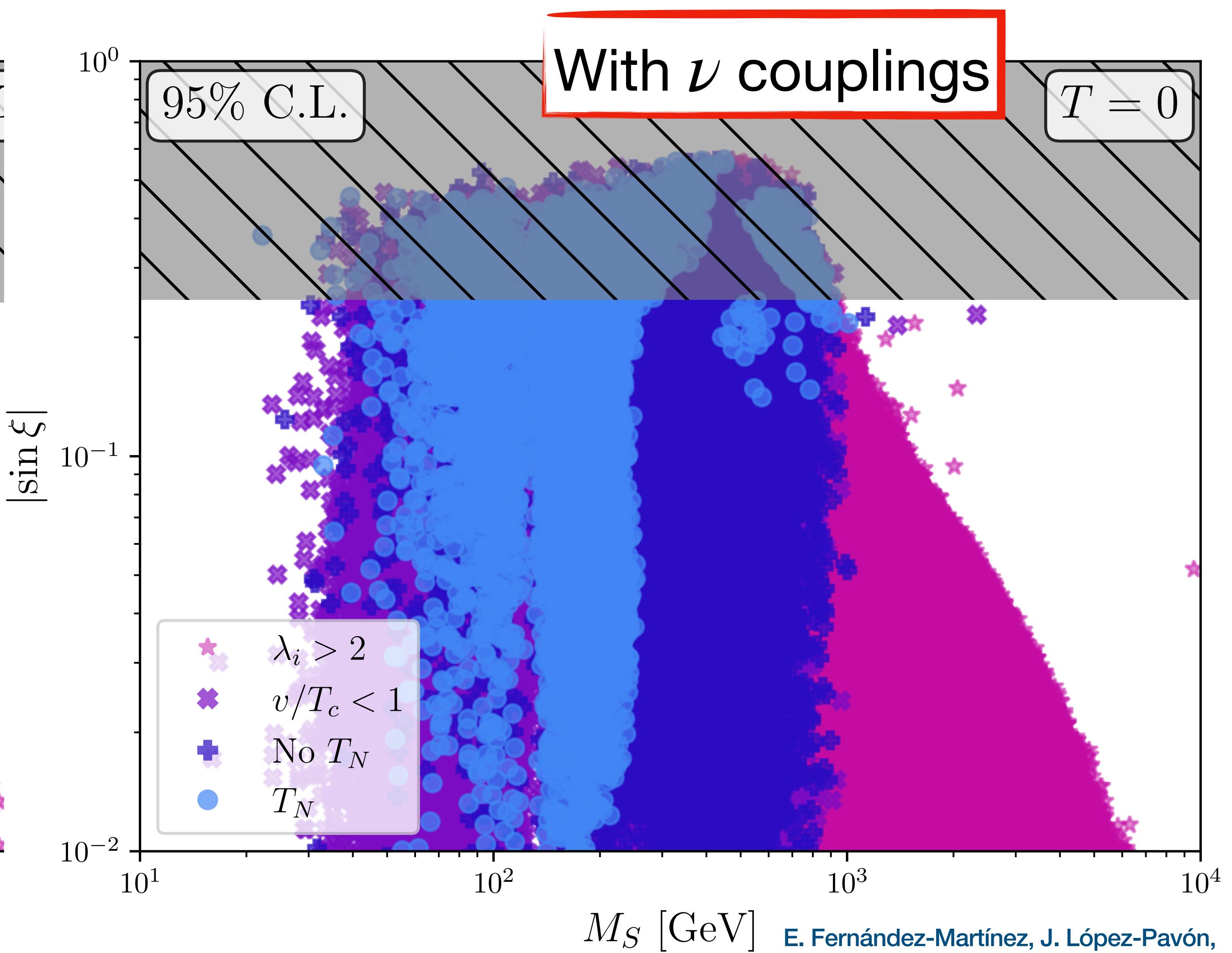
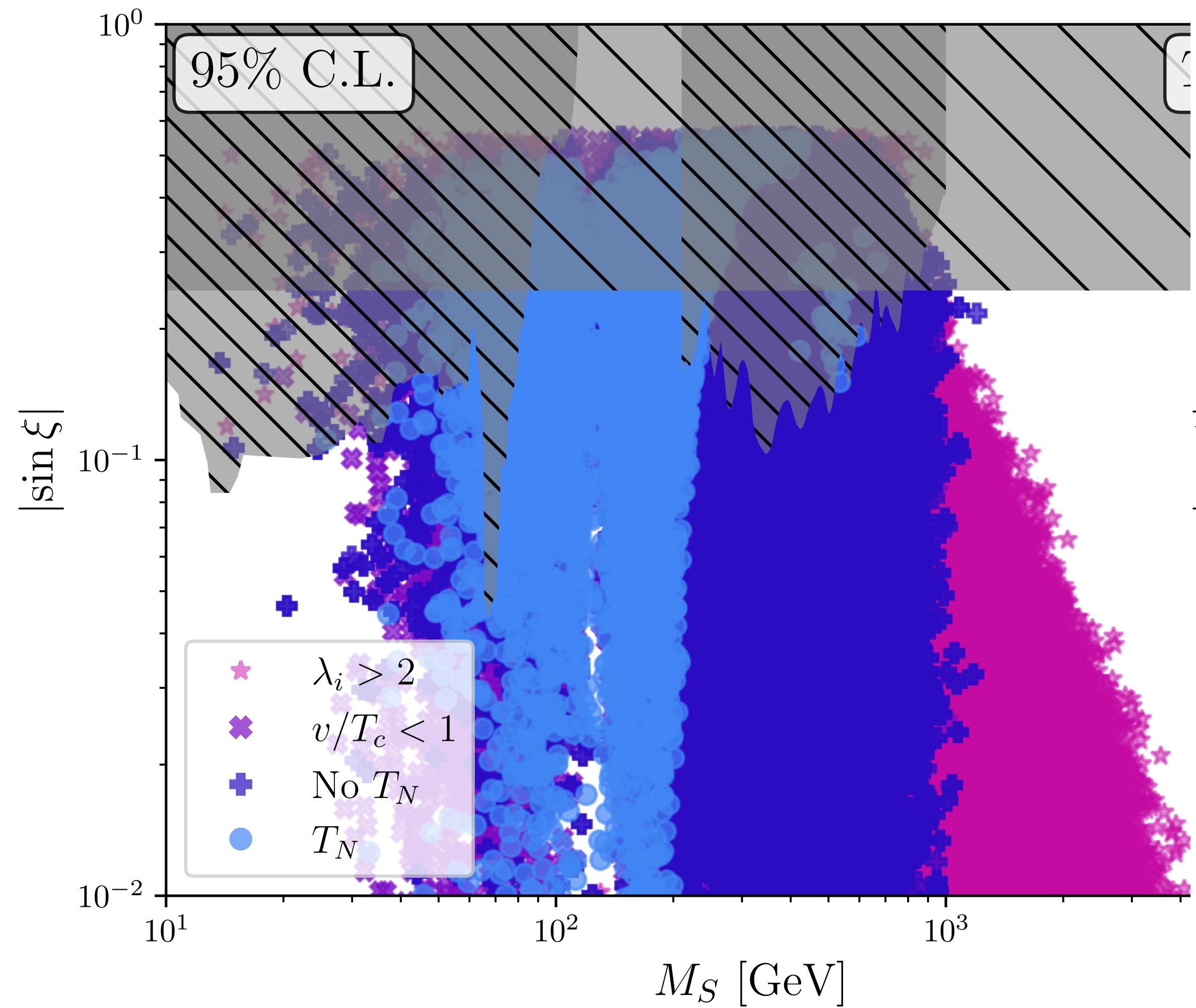
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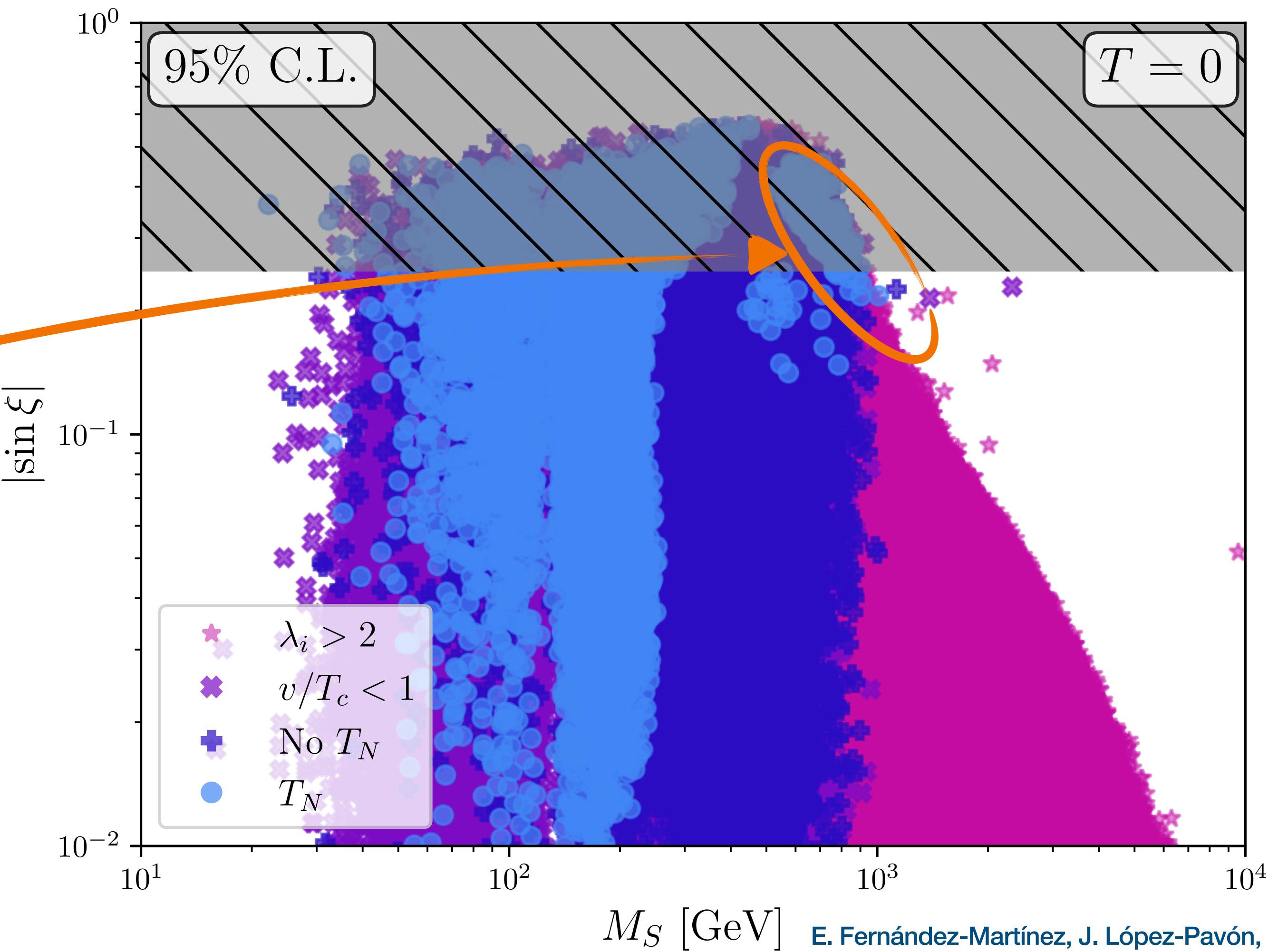
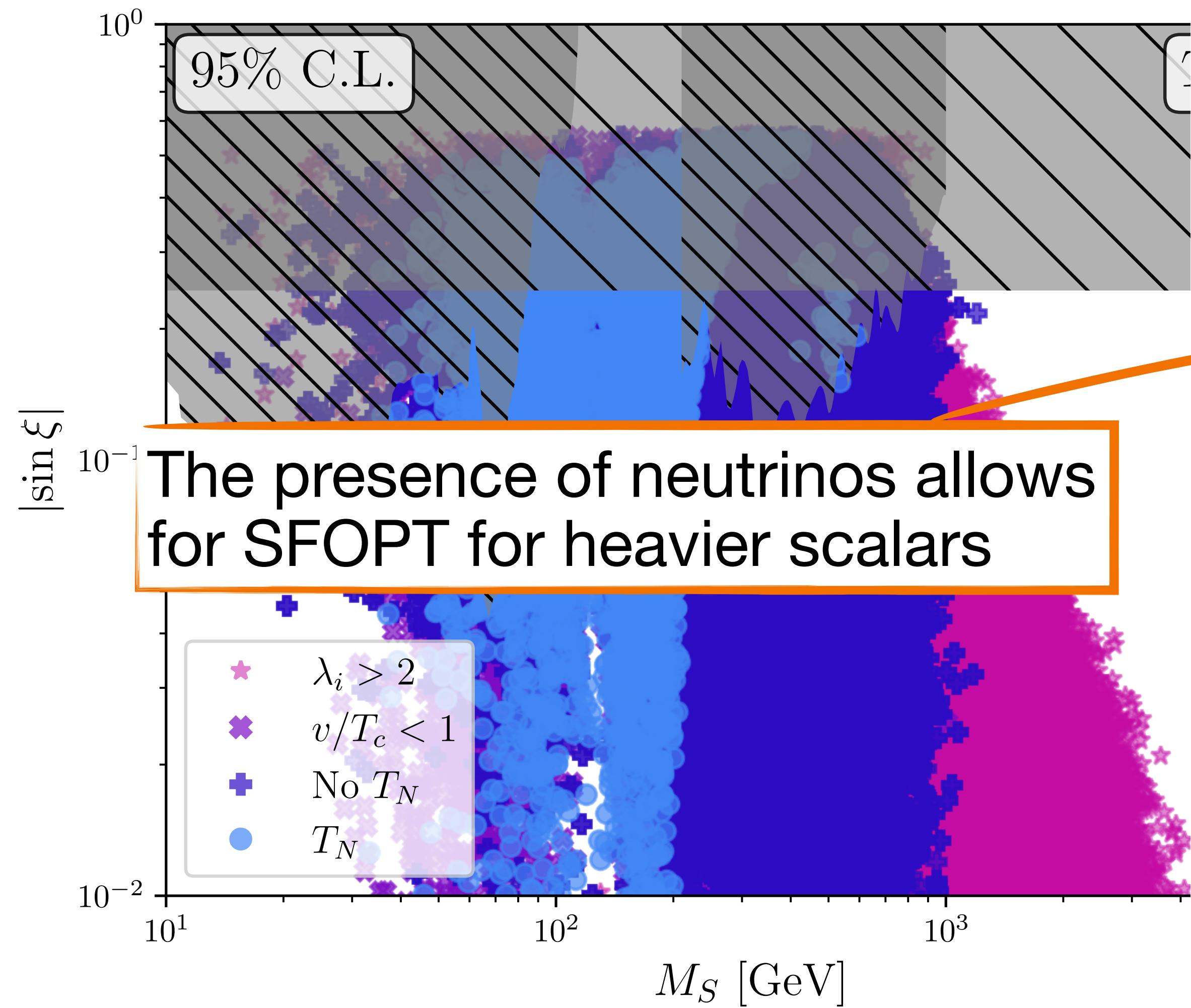
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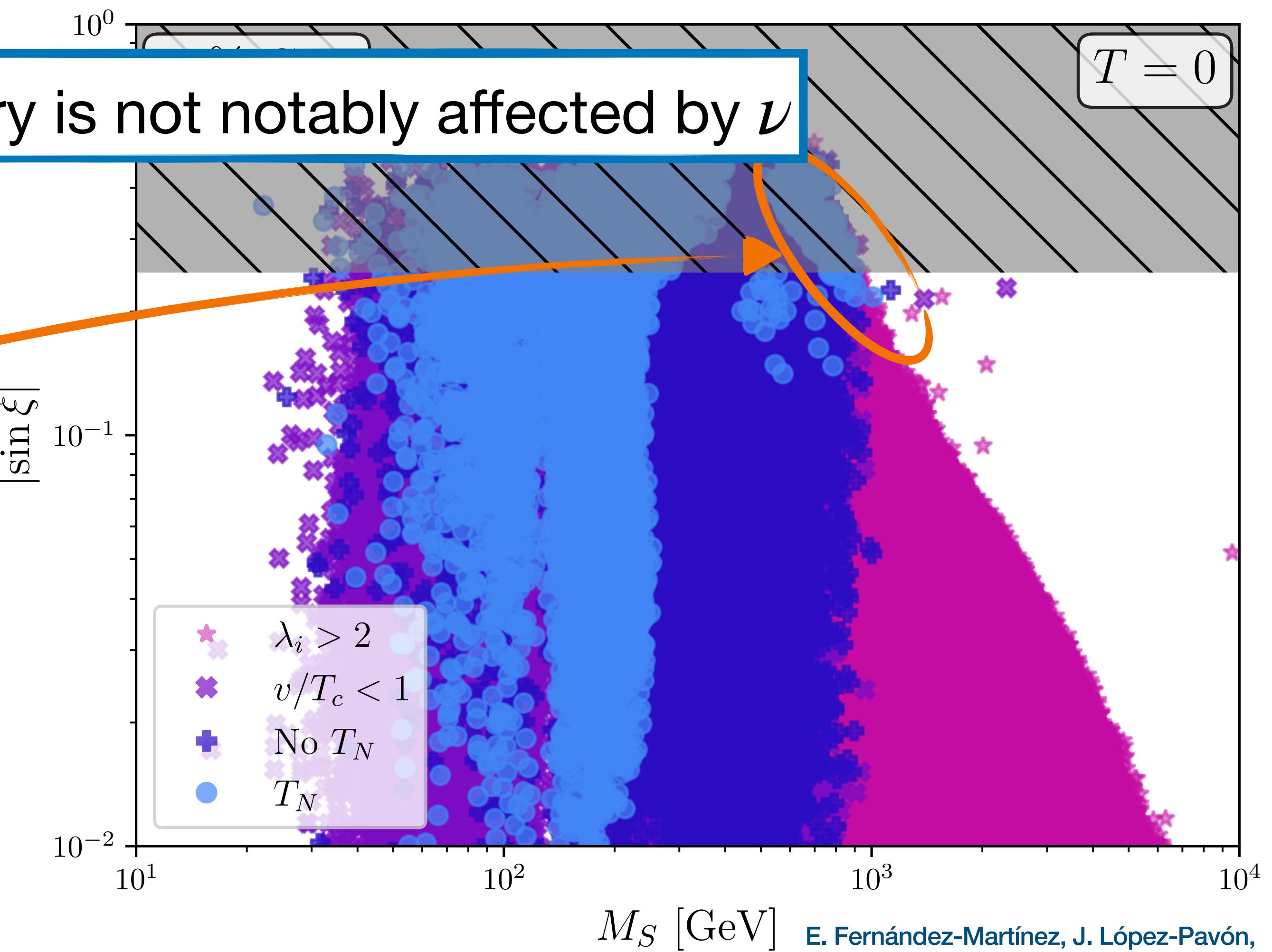
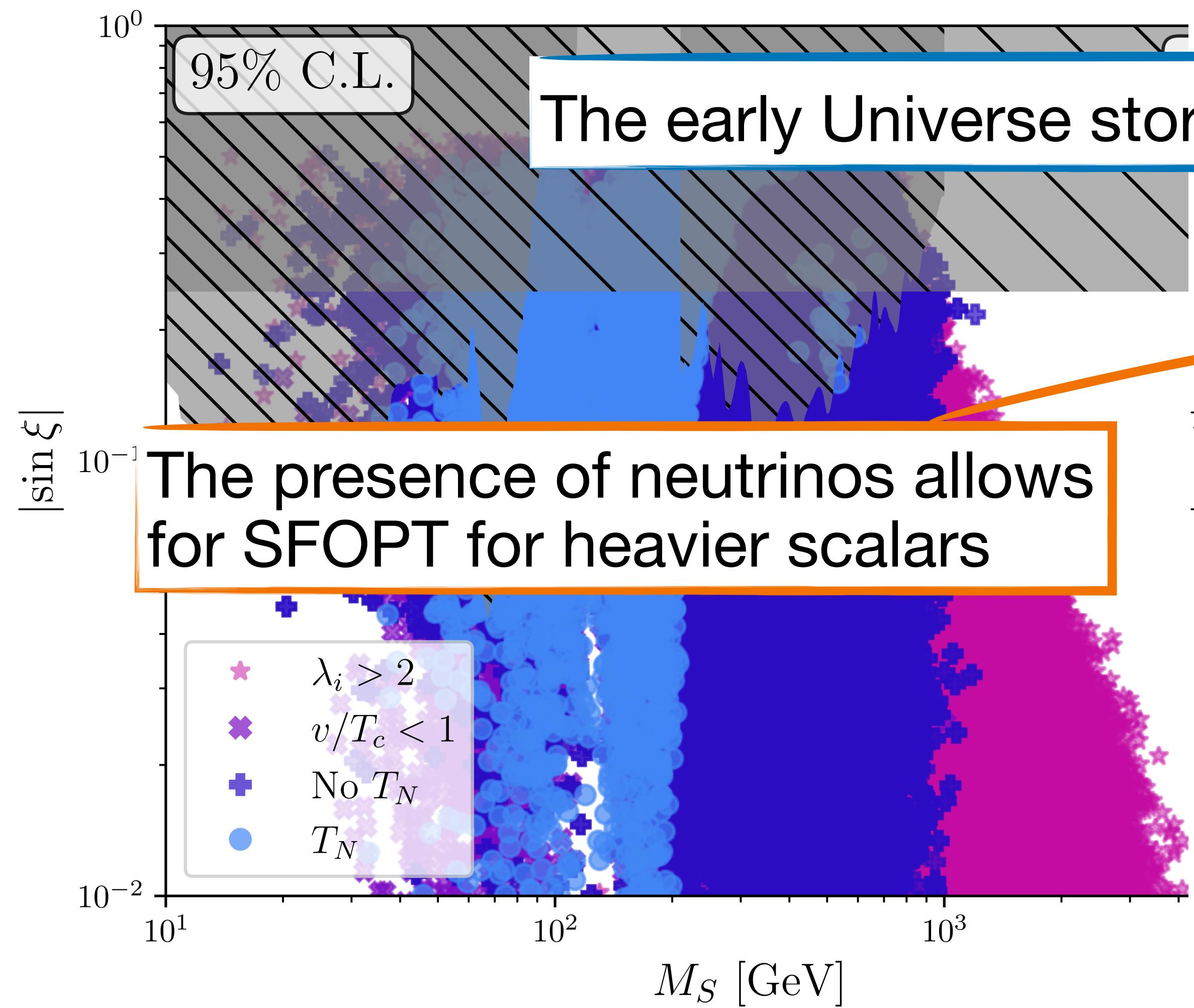
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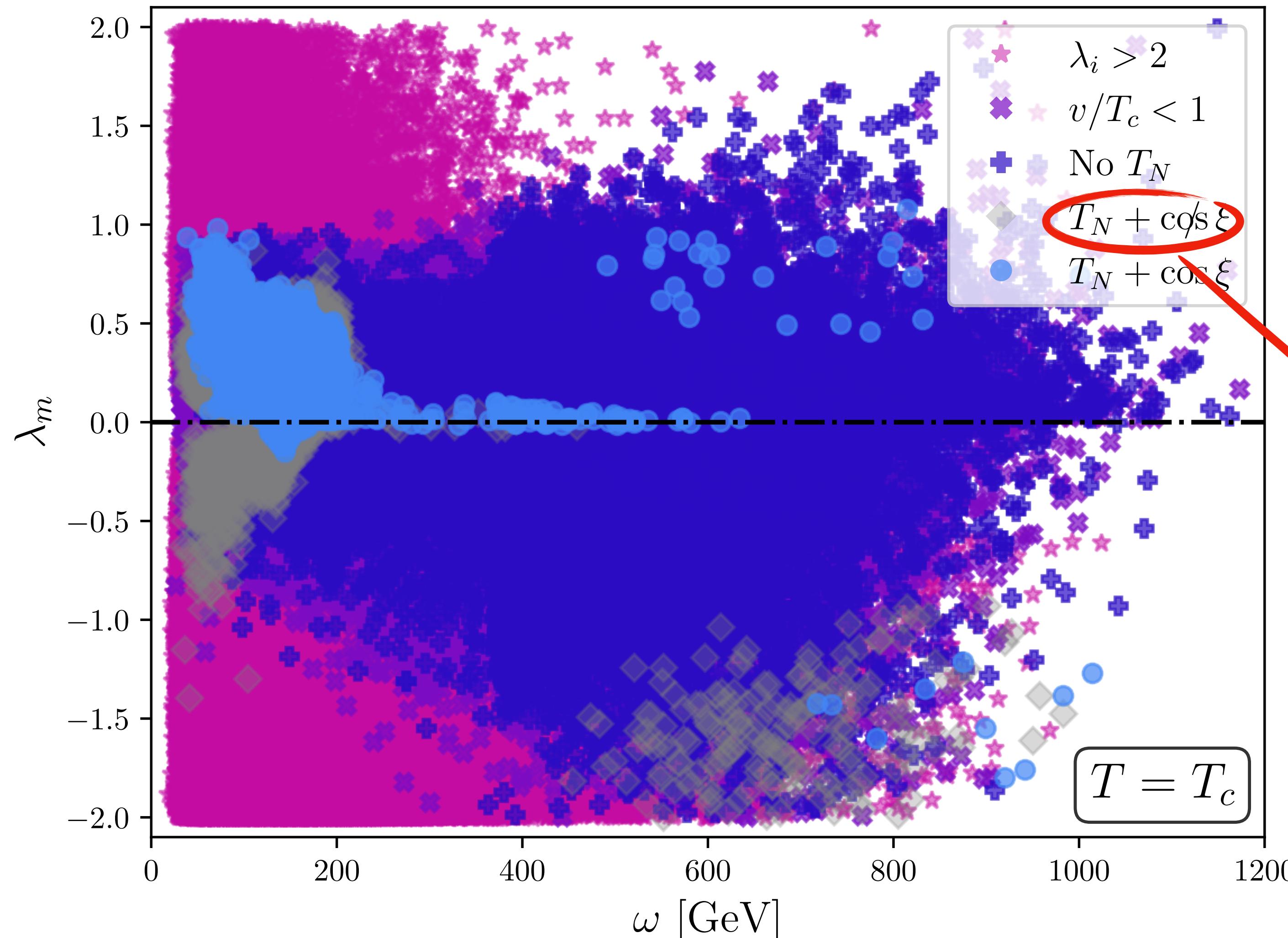
# Results

## Comparison w/o neutrinos



# Results

## Nucleation + constraints on $\cos \xi$



Constraint assuming  $BR_{H \rightarrow N\bar{N}} = 0$

# Results

## Higgs decay to heavy neutrinos

E. Fernández-Martínez, J. López-Pavón,  
J. M. No, T. Ota & SRA arXiv:2210.16279

$$\mathcal{L} \supset \frac{1}{\omega_{EW}} (\cos \xi S + \sin \xi H) \sum_i \bar{N}_i M_{N_i} N_i$$

# Results

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$$\mathcal{L} \supset \frac{1}{\omega_{EW}} (\cos \xi S + \sin \xi H) \sum_i \bar{N}_i M_{N_i} N_i$$

Higgs signal strength measurements

$$(1 - BR_{H \rightarrow N\bar{N}}) \cos^2 \xi \geq 0.94$$

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$$(1 - BR_{H \rightarrow N\bar{N}}) \cos^2 \xi \geq 0.94$$

$$\Gamma_{H \rightarrow N\bar{N}} \sim \frac{\sin^2 \xi}{8\pi} M_H \sum_i Y_{N_i}^2 \left( 1 - \frac{4\omega_{EW}^2}{M_H^2} Y_{N_i}^2 \right)^{3/2}$$

# Results

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Maximum for degenerate  $N_i$

$$\mathcal{Y}_N^2 = n Y_{N_1}^2$$

Minimum for hierarchical  $N_i$

$$\mathcal{Y}_N^2 = Y_{N_1}^2$$

# Results

## Higgs decay to heavy neutrinos

E. Fernández-Martínez, J. López-Pavón,  
J. M. No, T. Ota & SRA arXiv:2210.16279

$$\mathcal{L} \supset \frac{1}{\omega_{EW}} (\cos \xi S + \sin \xi H) \sum_i \bar{N}_i M_{N_i} N_i$$

Higgs signal strength measurements

$$(1 - BR_{H \rightarrow N\bar{N}}) \cos^2 \xi \geq 0.94$$

Two regimes

$$\mathcal{Y}_N^2 = \sum_i Y_{N_i}^2 \left\{ \begin{array}{l} \boxed{\omega_{EW}^2 \mathcal{Y}_N^2 < (M_H/2)^2} \\ \boxed{\omega_{EW}^2 \mathcal{Y}_N^2 > (M_H/2)^2} \end{array} \right.$$

# Results

## Higgs decay to heavy neutrinos

$$\mathcal{L} \supset \frac{1}{\omega_{EW}} (\cos \xi S + \sin \xi H) \sum_i \bar{N}_i M_N$$

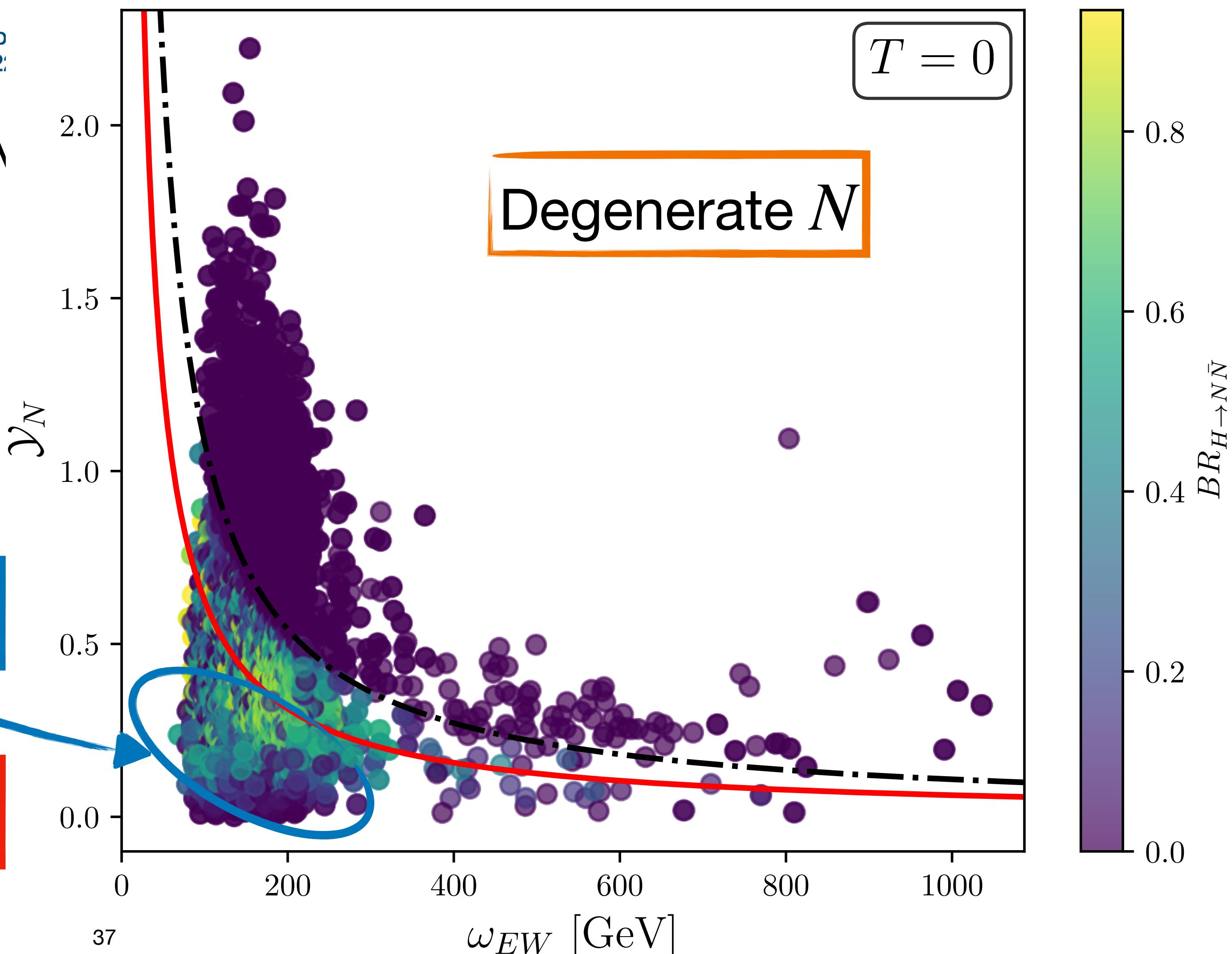
E. Fernández-Martínez, J. López  
J. M. No, T. Ota & SRA arXiv:21

Higgs signal strength measurements

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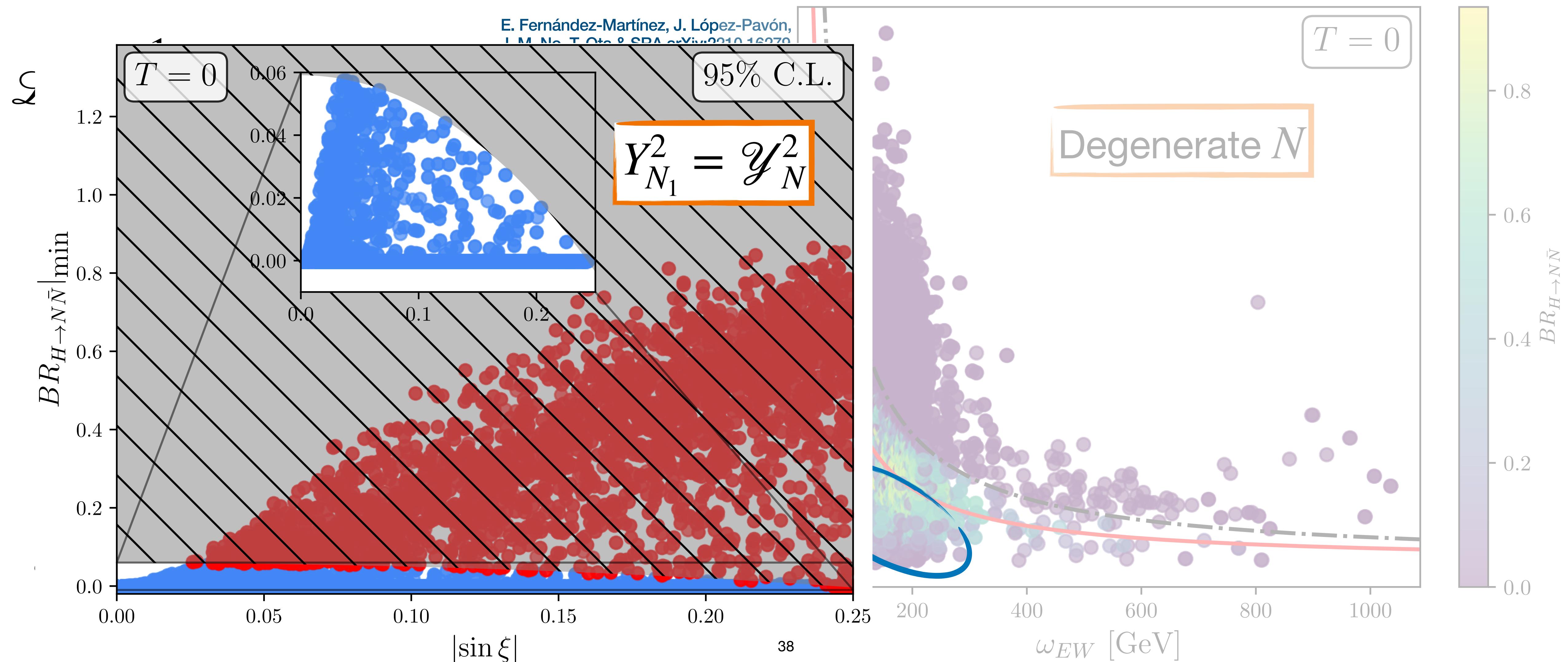
Two regimes

$$\gamma_N^2 = \sum_i Y_{Ni}^2 \left\{ \begin{array}{l} \omega_{EW}^2 \gamma_N^2 < (M_H/2)^2 \\ \omega_{EW}^2 \gamma_N^2 > (M_H/2)^2 \end{array} \right.$$



# Results

## Higgs decay to heavy neutrinos



# Conclusions

## Early Universe

EW baryogenesis is could explain the BAU with NP at  $\mathcal{O}(100)$  GeV

Successful nucleation translates into a huge reduction of the parameter space

Early Universe evolution is not affected much by  $\nu$ -scalar interactions

# Conclusions

## Phenomenology

We could tell apart the case of just a singlet scalar or a non minimal dark sector in colliders

Thanks to scalar mixing, heavy neutrinos could be copiously produced in Higgs decays → Higgs signal strength measurements

Direct searches for a signal with prompt  $N$  decays or displaced vertices other than the usual Drell-Yan production should provide better constraints

# Thank you!

# Back up slides

# Electroweak baryogenesis with new physics

## 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<sup>st</sup> order phase transition~~

New sources of CP violation

Tight bounds from the electron's EDM

ACME Collaboration, Nature 562 (2018)

Introduce CP in some dark sector

# Electroweak baryogenesis and low-scale seesaws

First proposed in

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

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N'_R - \bar{N}'_L s Y_N N'_R + h.c. - V(\Phi^\dagger \Phi, s)$$

After SSB

$$\mathcal{L} \supset -\bar{\nu}_L m_D N'_R - \bar{N}'_L M N'_R + h.c.$$

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

Bounded by EW precision  
and flavour observables

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

# Electroweak baryogenesis and low-scale seesaws

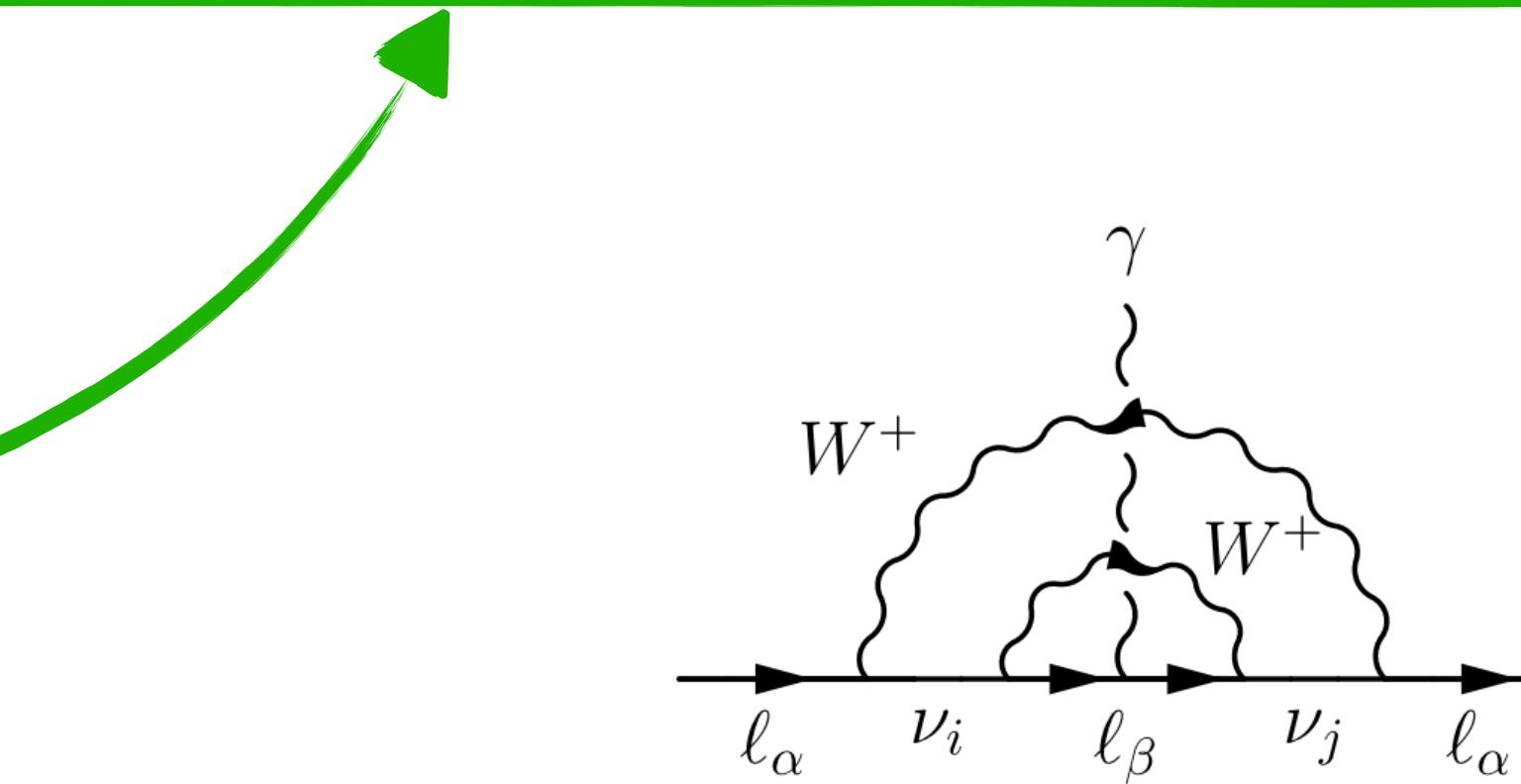
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$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N'_R - \bar{N}'_L s Y_N N'_R + h.c. - V(\Phi^\dagger \Phi, s)$$

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

Hierarchical heavy neutrinos



Avoid electric dipole  
moment bounds

A. Abada & T. Toma, arXiv: 1605.07643

# Scalar potential

## One-loop - Coleman Weinberg contribution

S. R. Coleman & E. J. Weinberg, Phys. Rev. D (1983)  
J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441  
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

We limit the size of our couplings for this contribution to be under control

# Scalar potential

## Finite temperature effects

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441  
M. Quiros, arXiv:hep-ph/9901312

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

Physical mass as function of  $(h, s)$

Thermal mass as function of  $(h, s)$

# Scalar potential

## One-loop - Finite temperature effects

High temperature approximation

J. R. Espinosa, T. Konstandin & F. Riva, arXiv:1107.5441  
M. Quiros, arXiv:hep-ph/9901312

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

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

$T$ -dependent correction

$$V_{HT}(0,0) = V_{HT}(v, \omega)$$

Critical temperature

# Scalar potential

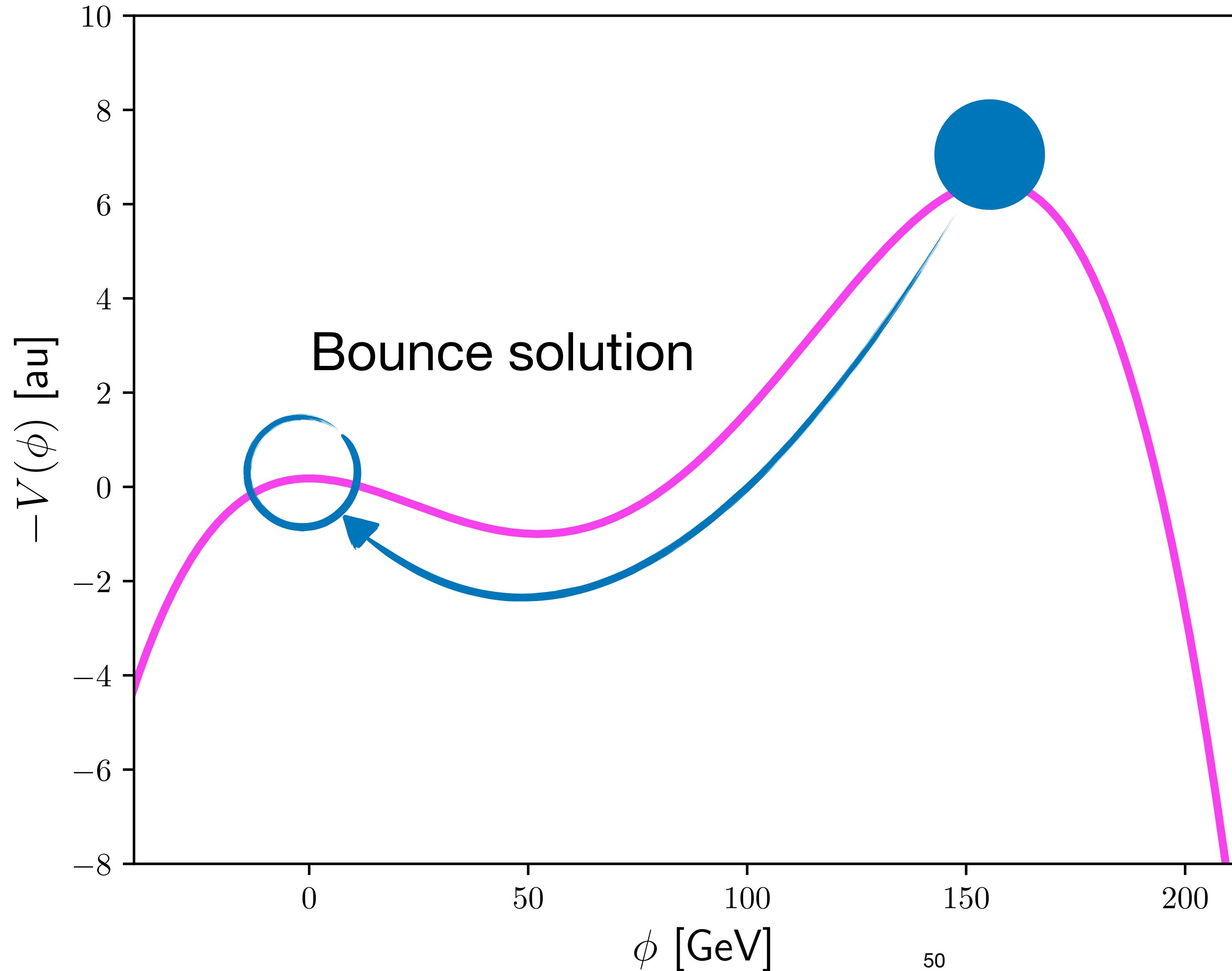
$$T = 0$$

$$\begin{aligned} V_T(h, s, T = 0) = & -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3 \\ & - \left[ \frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2 + m_3 s \right] T_c^2 \end{aligned}$$

Relation between potential terms at  $T_c$  and  $T = 0$

$$\begin{aligned} \tilde{\mu}_h^2 &= \mu_h^2 + c_h T_c^2 \\ \tilde{\mu}_s^2 &= \mu_s^2 - c_s T_c^2 \\ \tilde{\mu}_1^3 &= \mu_1^3 - m_3 T_c^2 \end{aligned}$$

# Nucleation



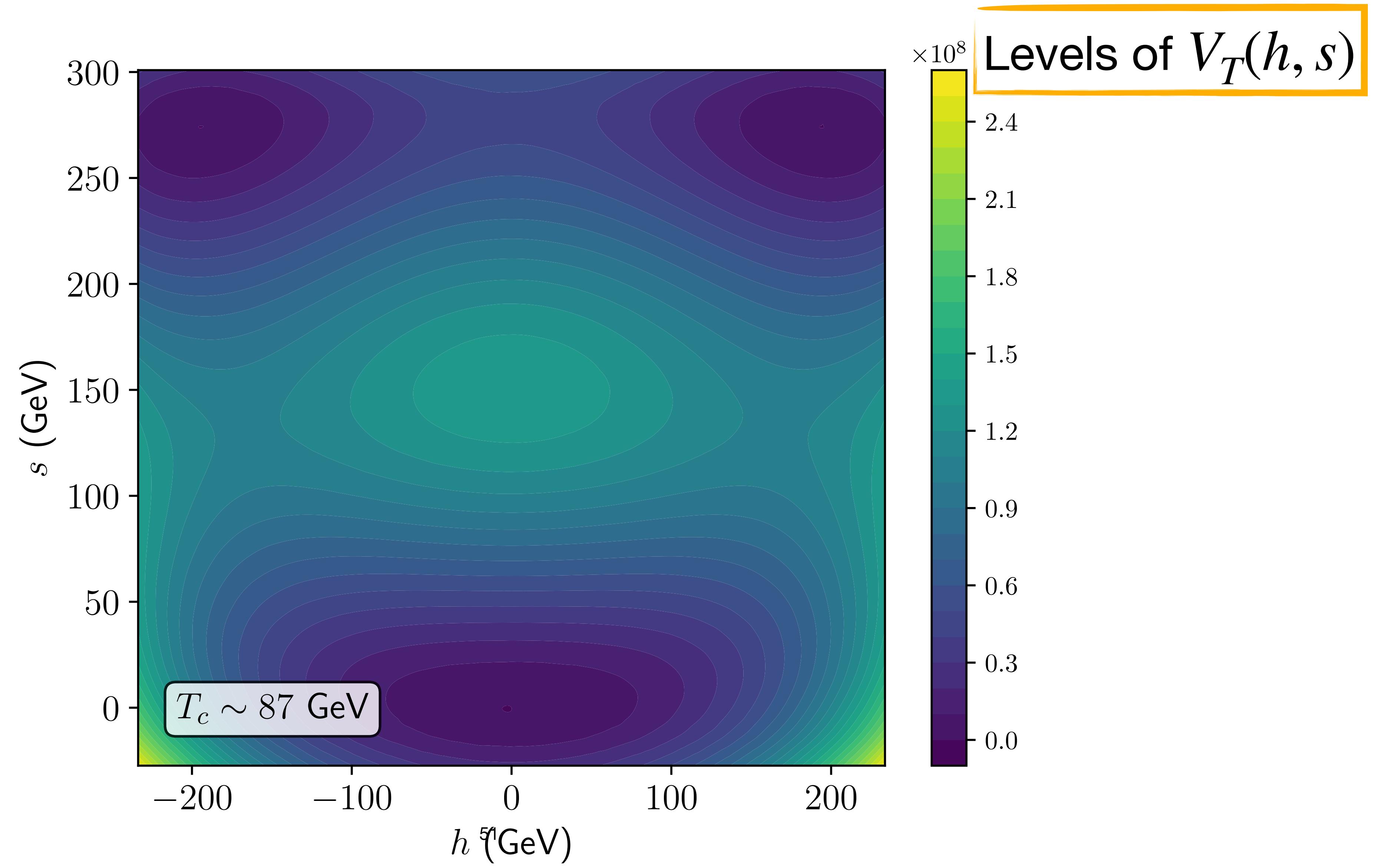
S. Coleman, Phys. Rev. D (1977)  
A. Amarati, arXiv:2009.14102

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

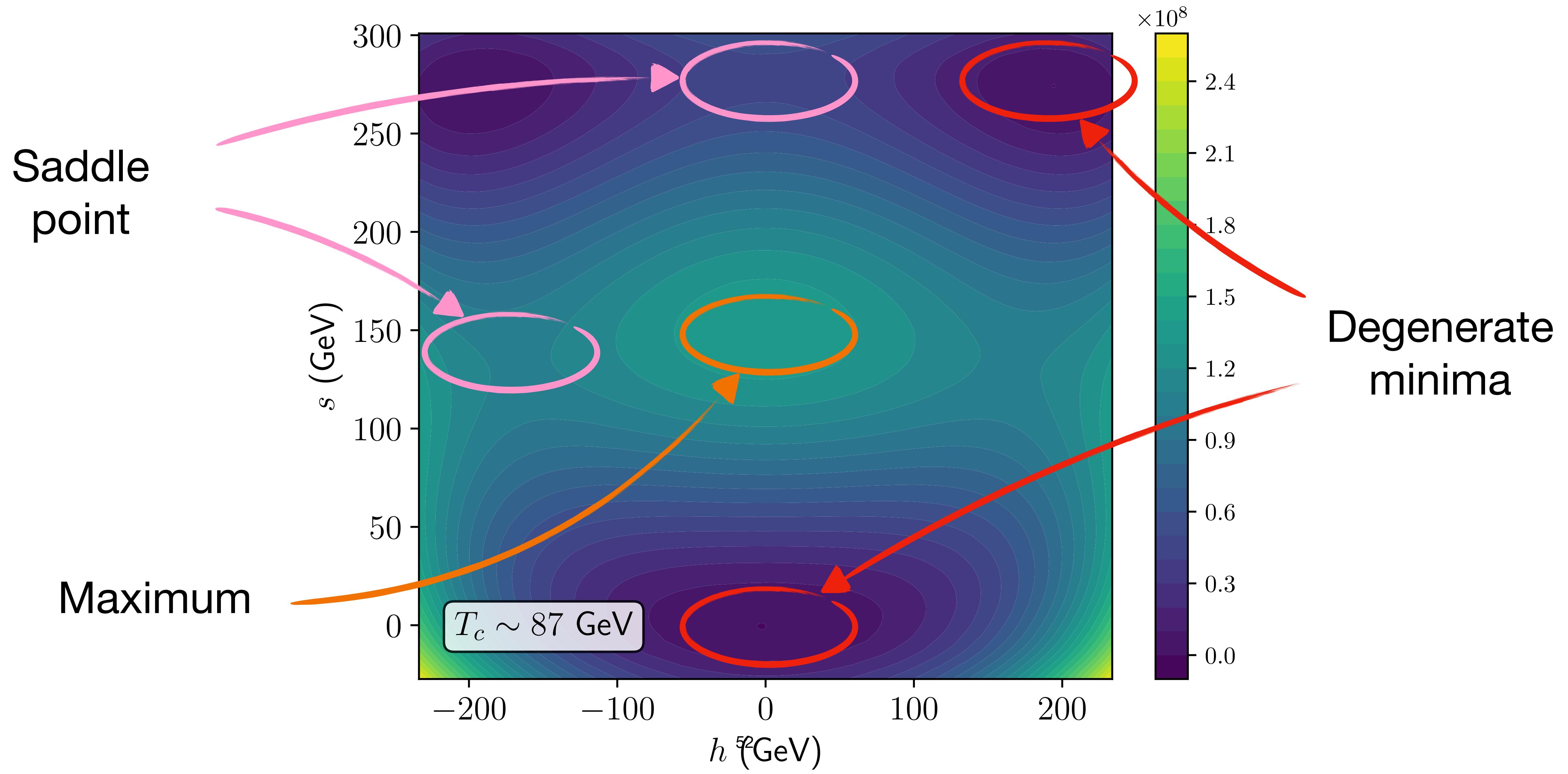
$$S_3/T_N \sim 140$$

Need to solve  
equations of motion

# Structure of the potential



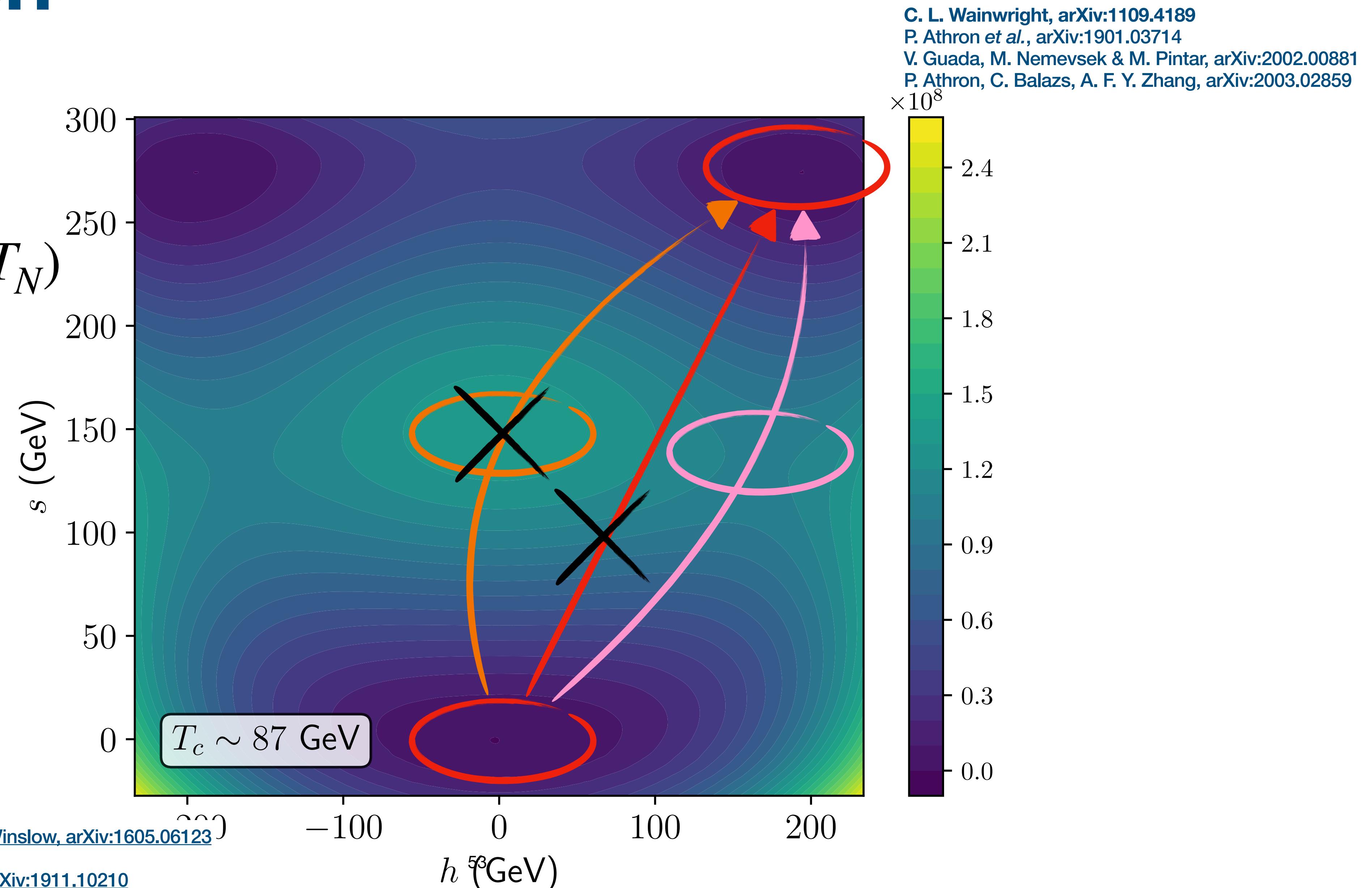
# Structure of the potential



# Nucleation

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

$$S_3/T_N \sim 140$$



A. V. Kotwal, J. M. No, M. J. Ramsey-Musolf & P. Winslow, arXiv:1605.06123

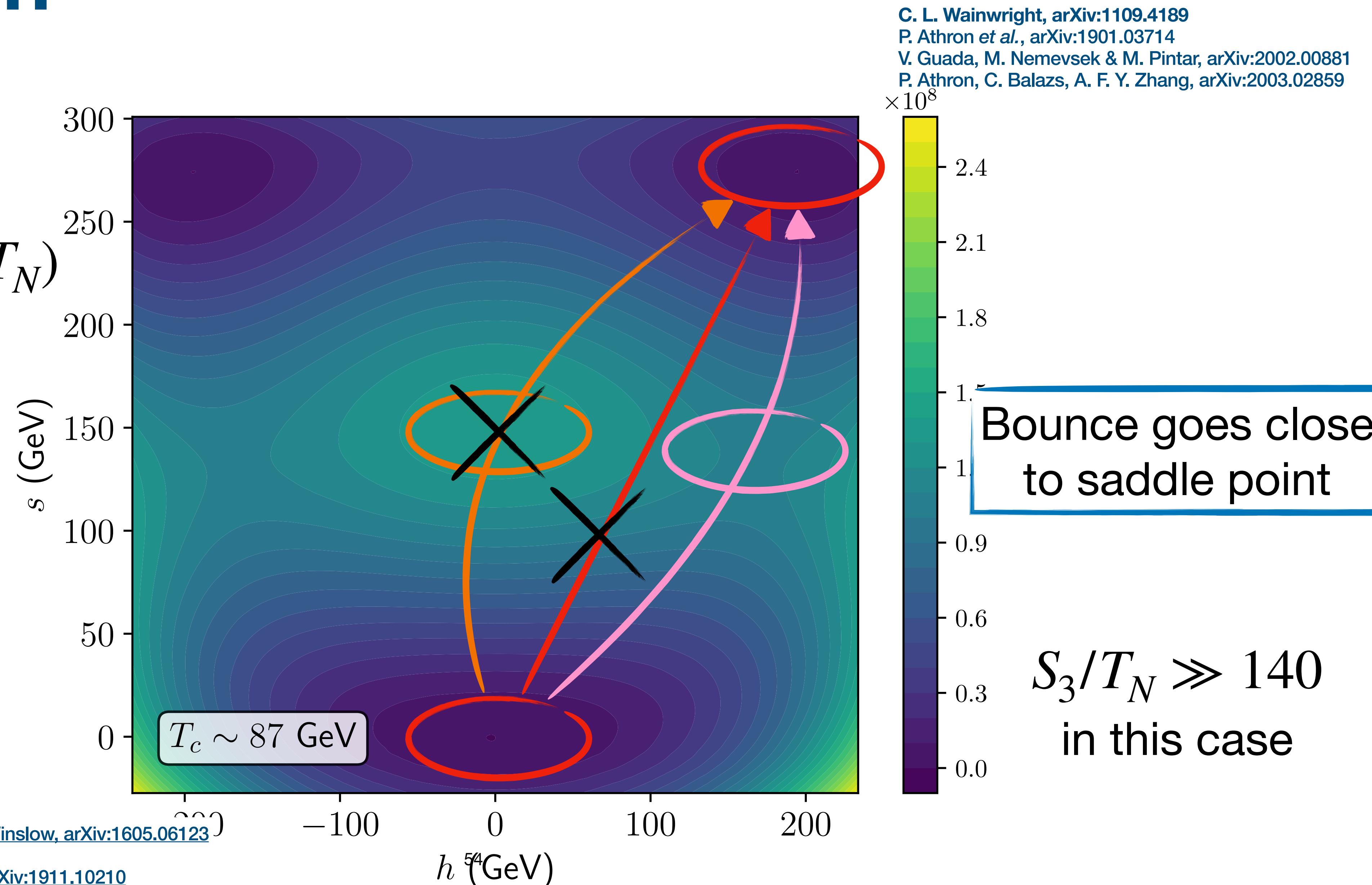
M. Carena, Z. Liu & Y. Wang, arXiv:1911.10206

J. Kozaczuk, M. J. Ramsey-Musolf & J. Shelton, arXiv:1911.10210

# Nucleation

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

$$S_3/T_N \sim 140$$



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

# Results

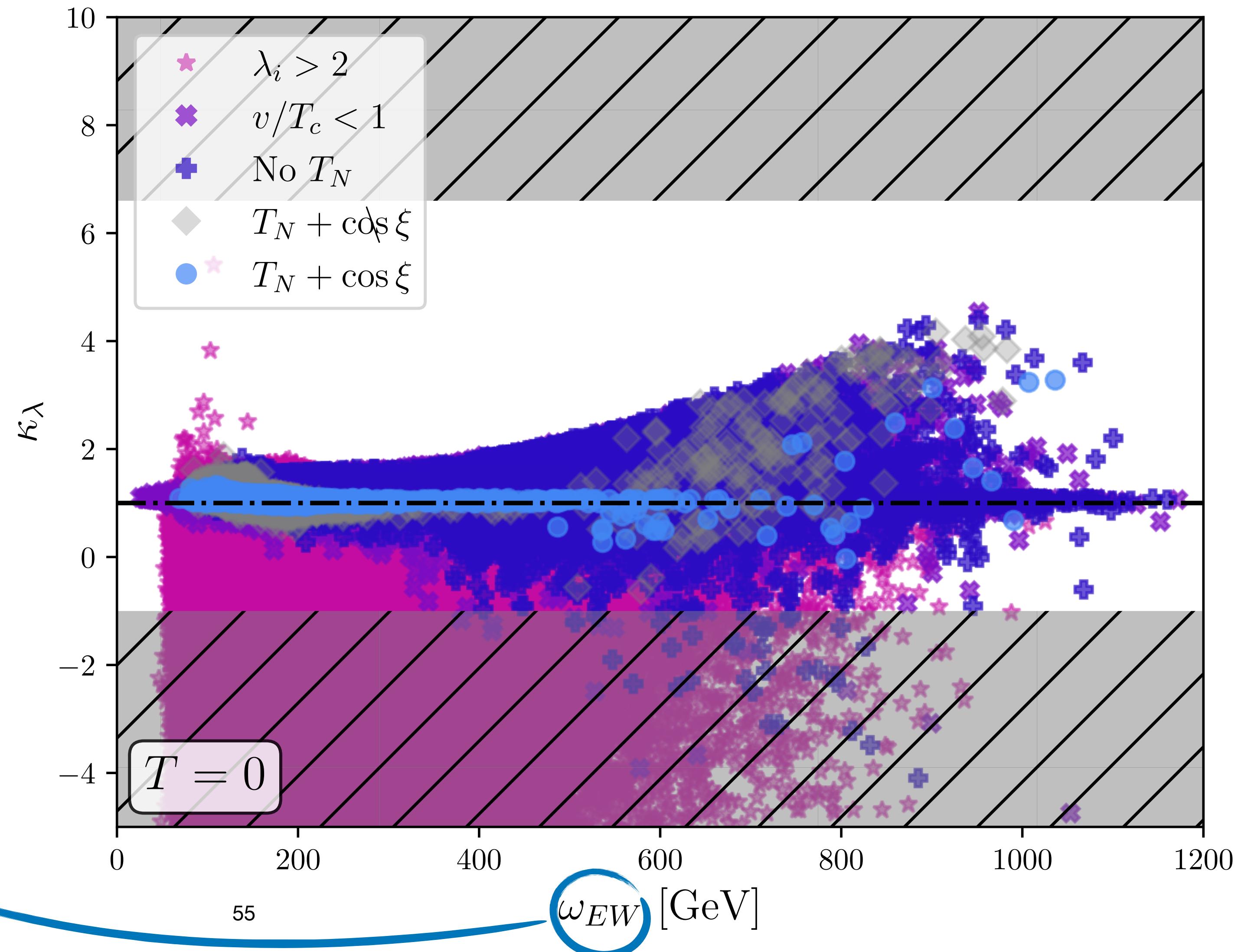
## Higgs trilinear coupling

Deviation in Higgs boson trilinear

$$\kappa_\lambda \equiv \frac{\lambda_{HHH} + \Delta\lambda_{HHH}^{1-loop}}{\lambda_{HHH}^{SM}}$$

$$-1.0 \leq \kappa_\lambda \leq 6.0$$

Singlet vev controlling  
neutrino masses

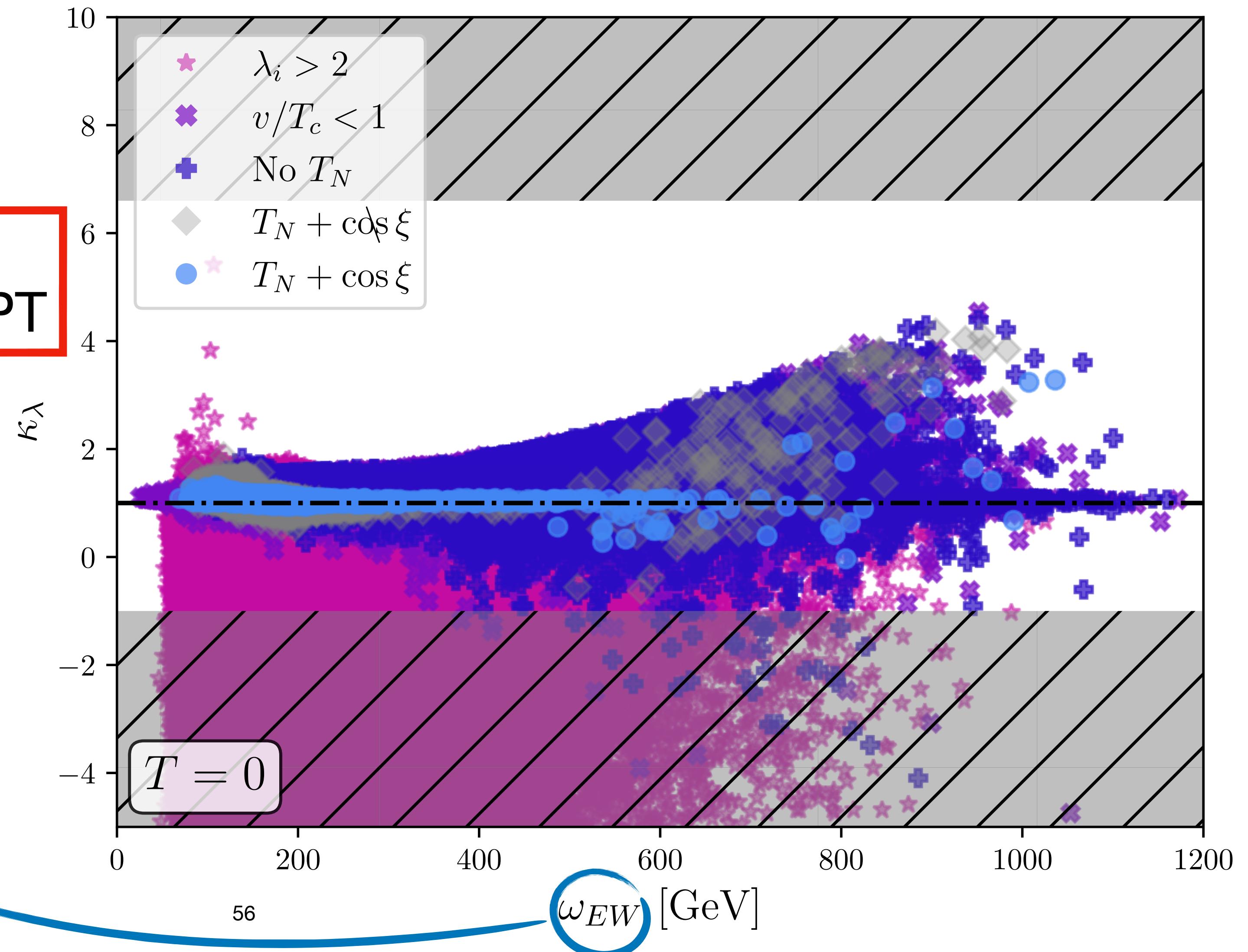


# Results

## Higgs trilinear coupling

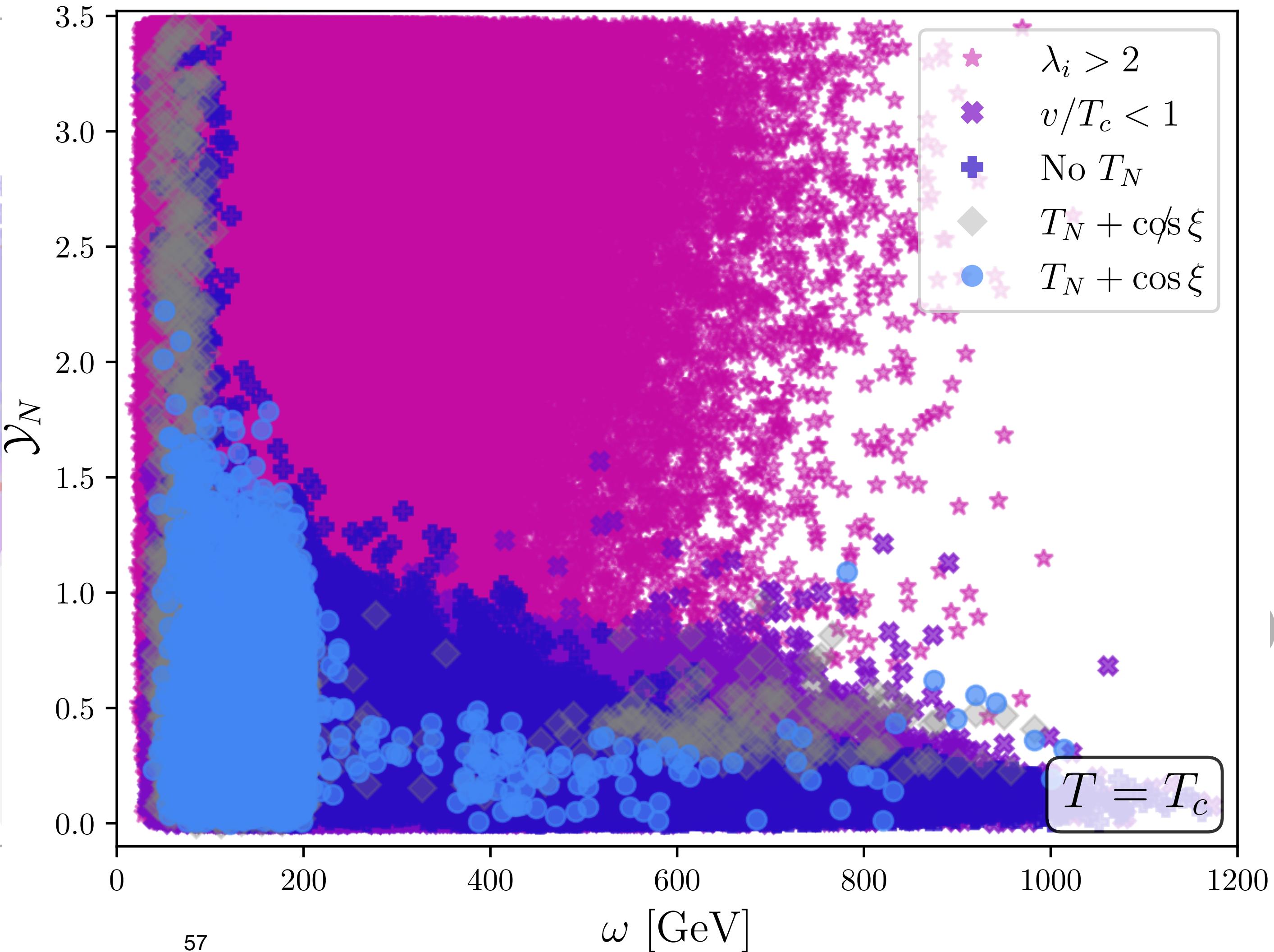
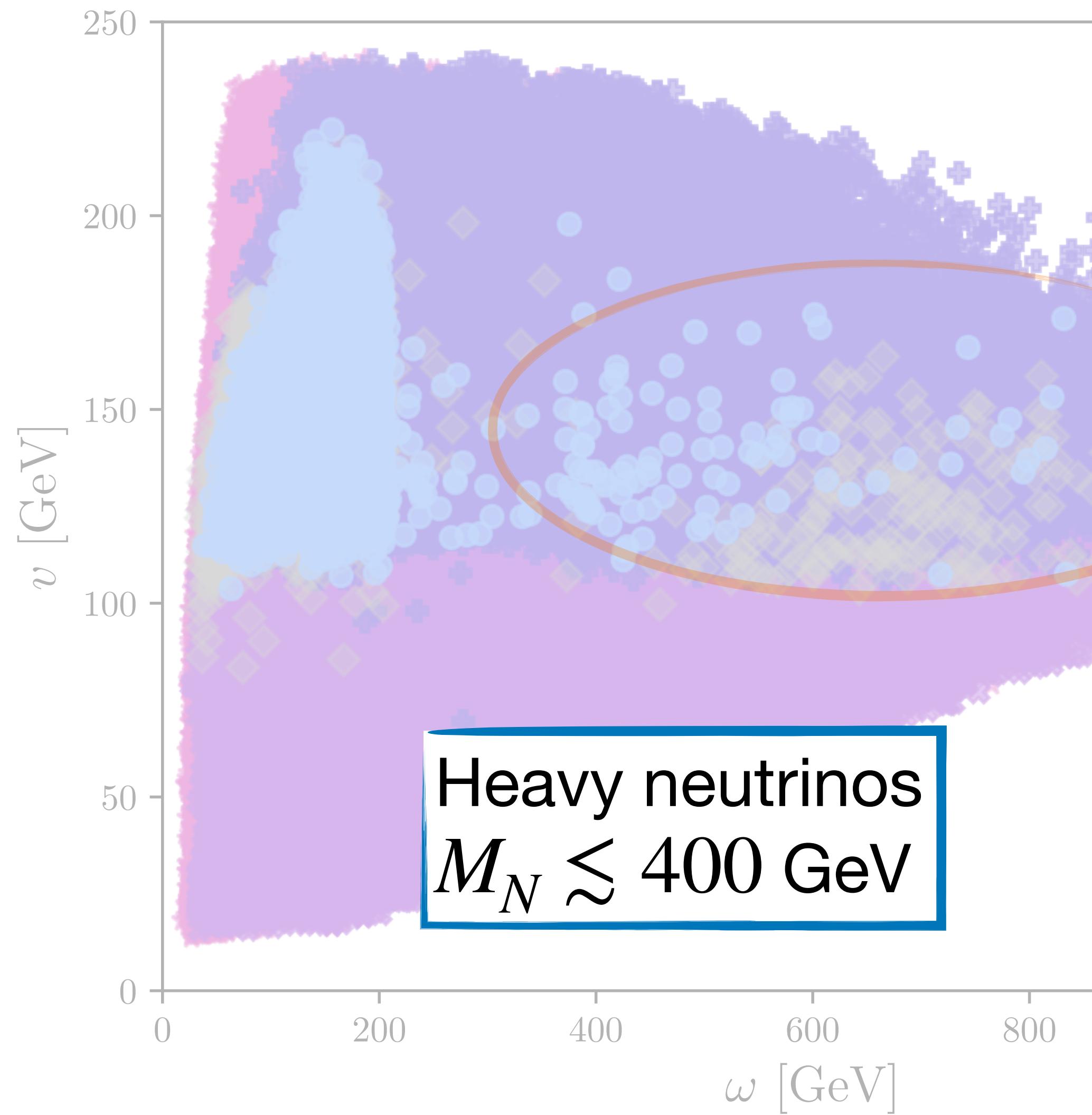
Significant deviations from 1  
disfavor such scenario for a SFOPT

Singlet vev controlling  
neutrino masses



# Results

## Nucleation + constraints on $\cos \xi$



# Results

## Nucleation + constraints on $\cos \xi$

