Dynamical FIMP DM with EWPT

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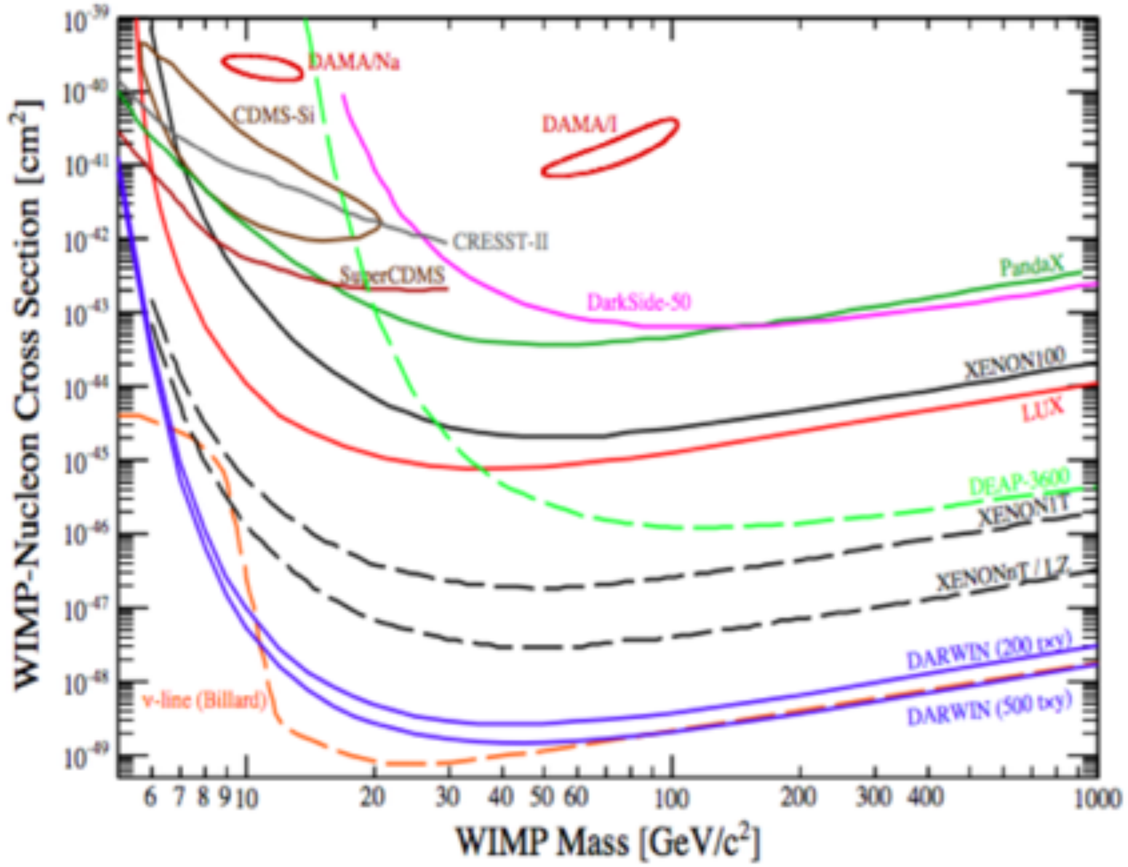
Based on arXiv:1811.03279

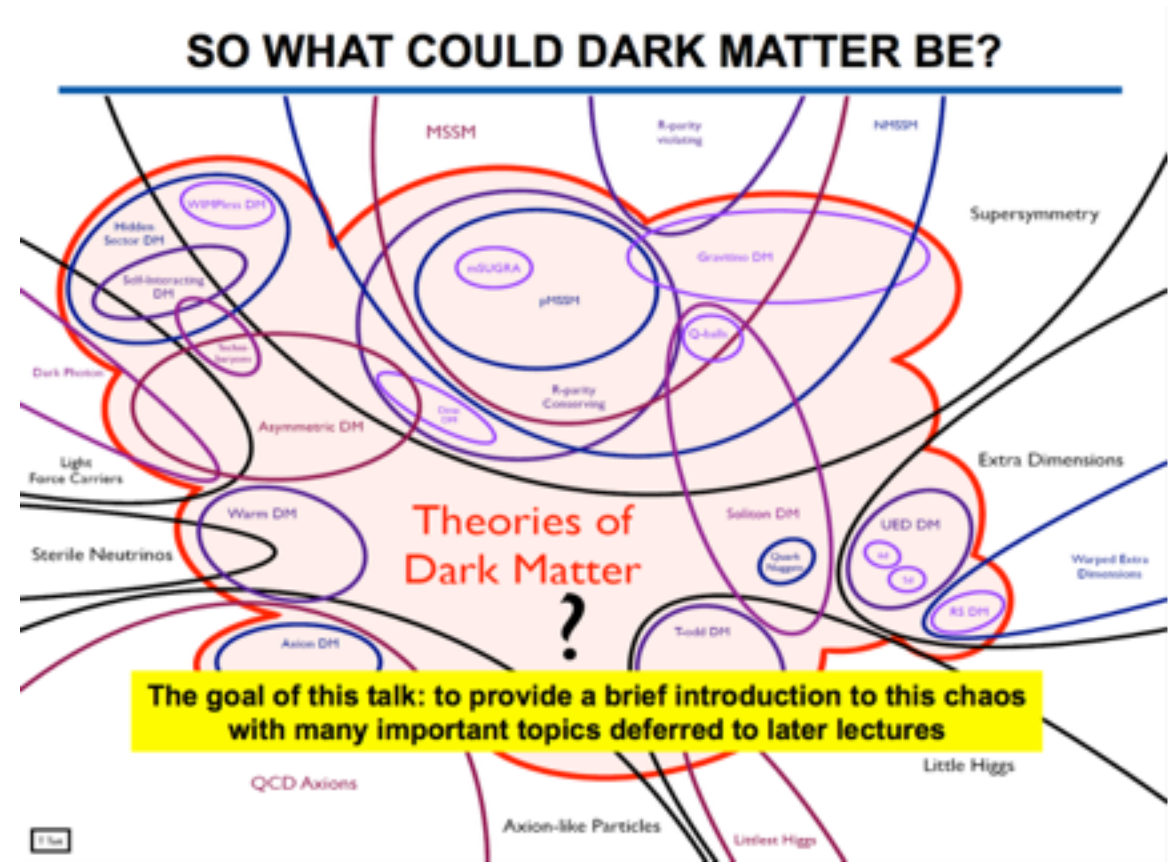
with 刘学文

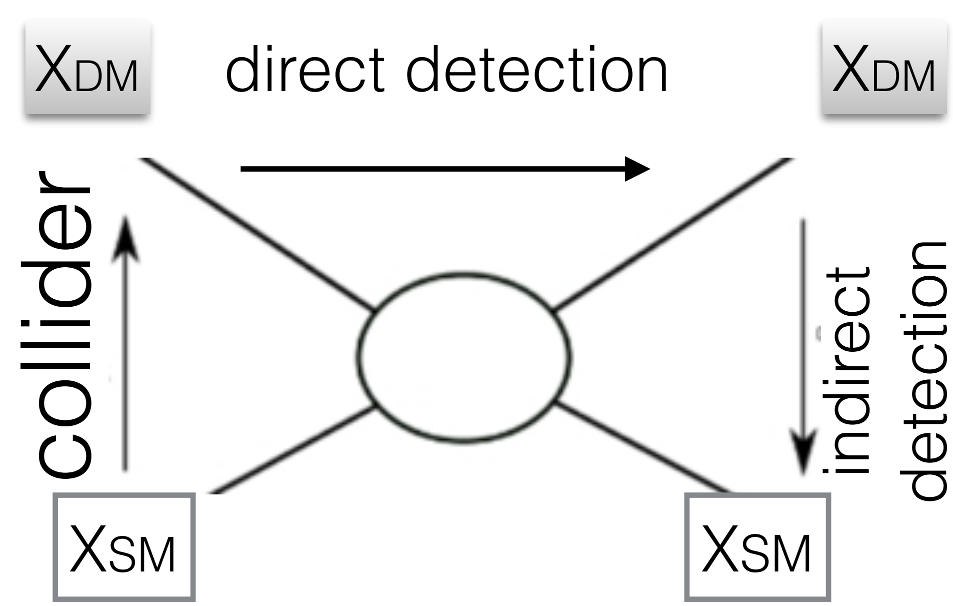
Outline

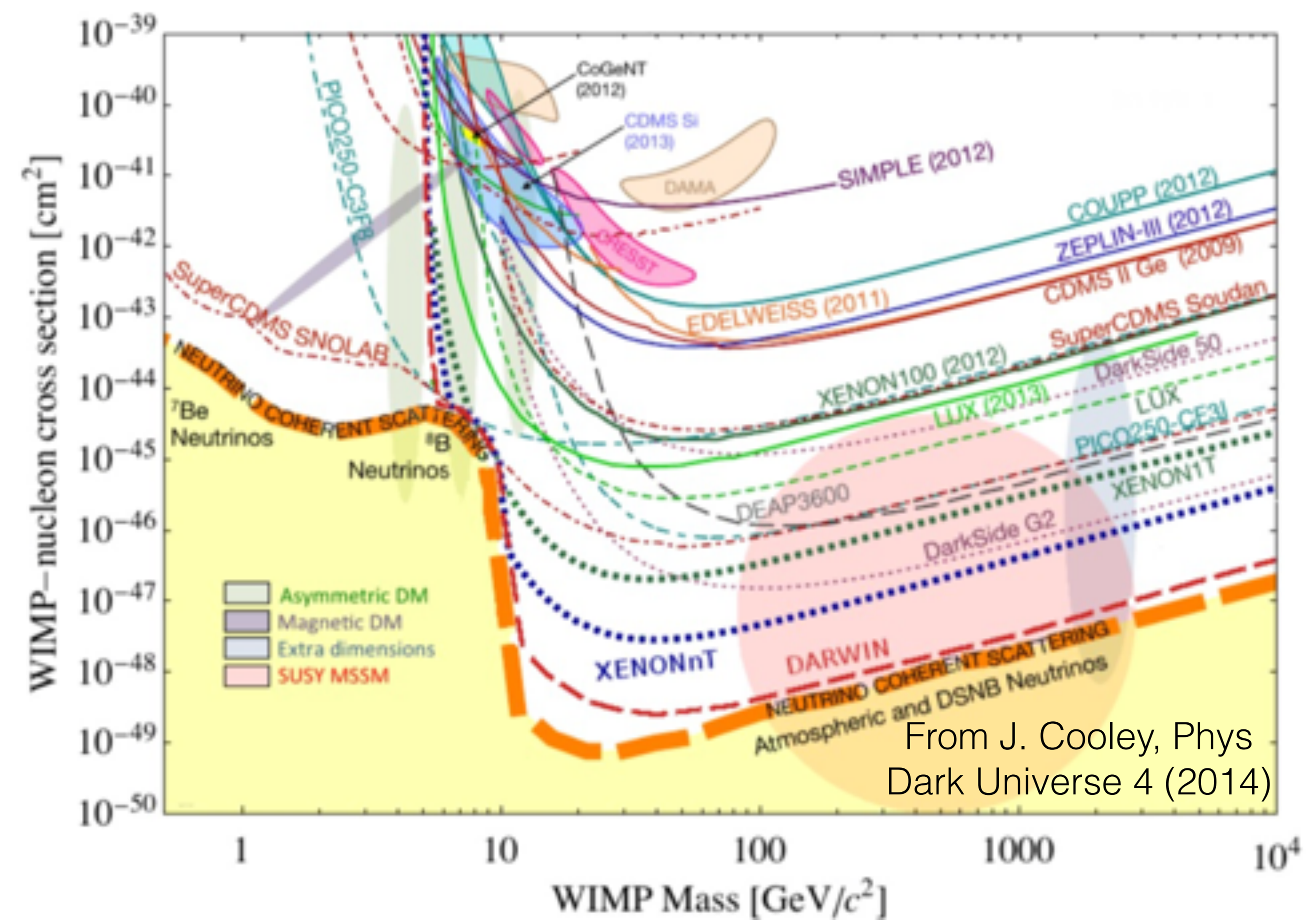
- Motivation
- The scotogenic Model
- The thermal corrected masses
- Dynamical DM
- Gravitational Waves
- Collider searches

WIMPs under tension

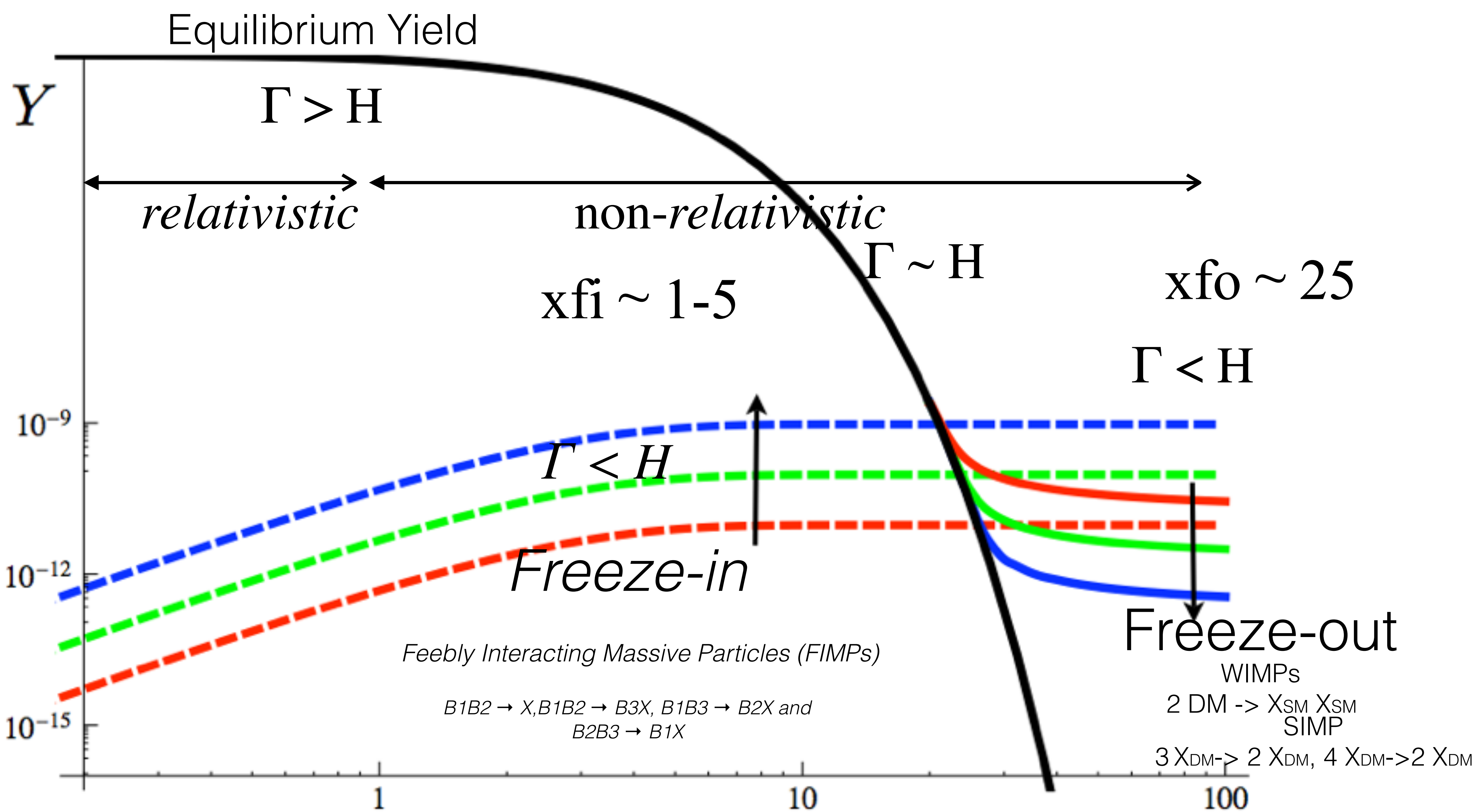








Freeze-in and Freeze-out



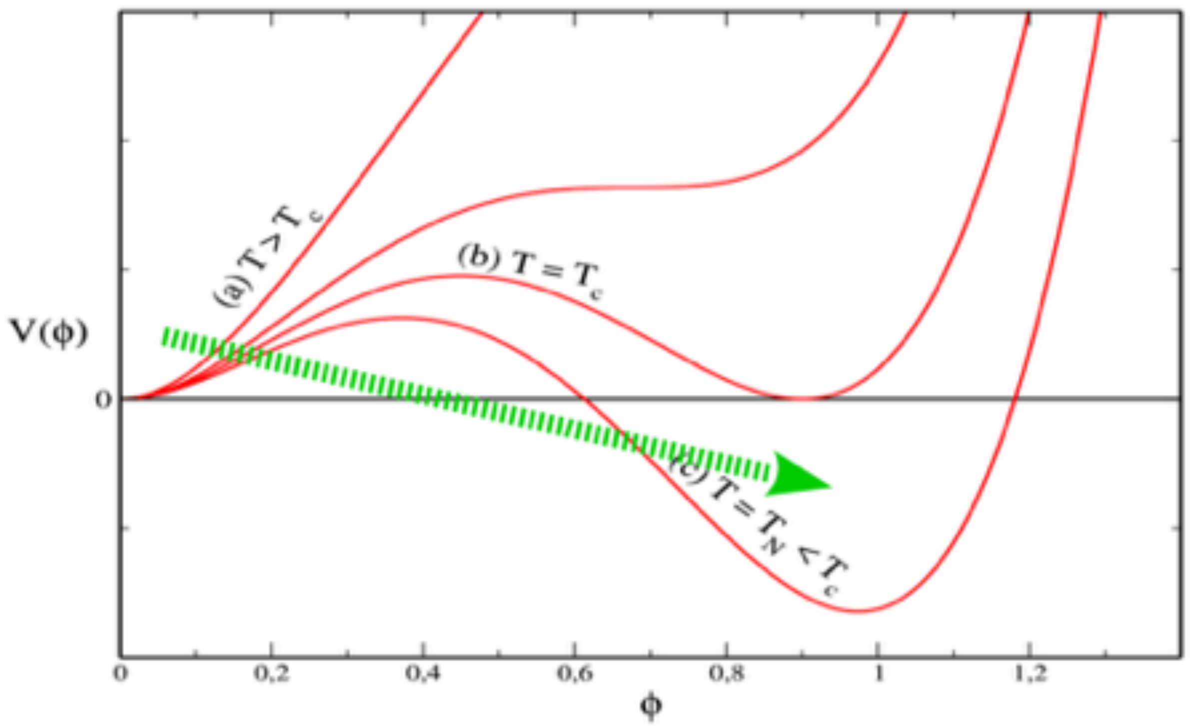
Tfi ~ mDM/xfi~10^2 GeV for mDM~ weak scale

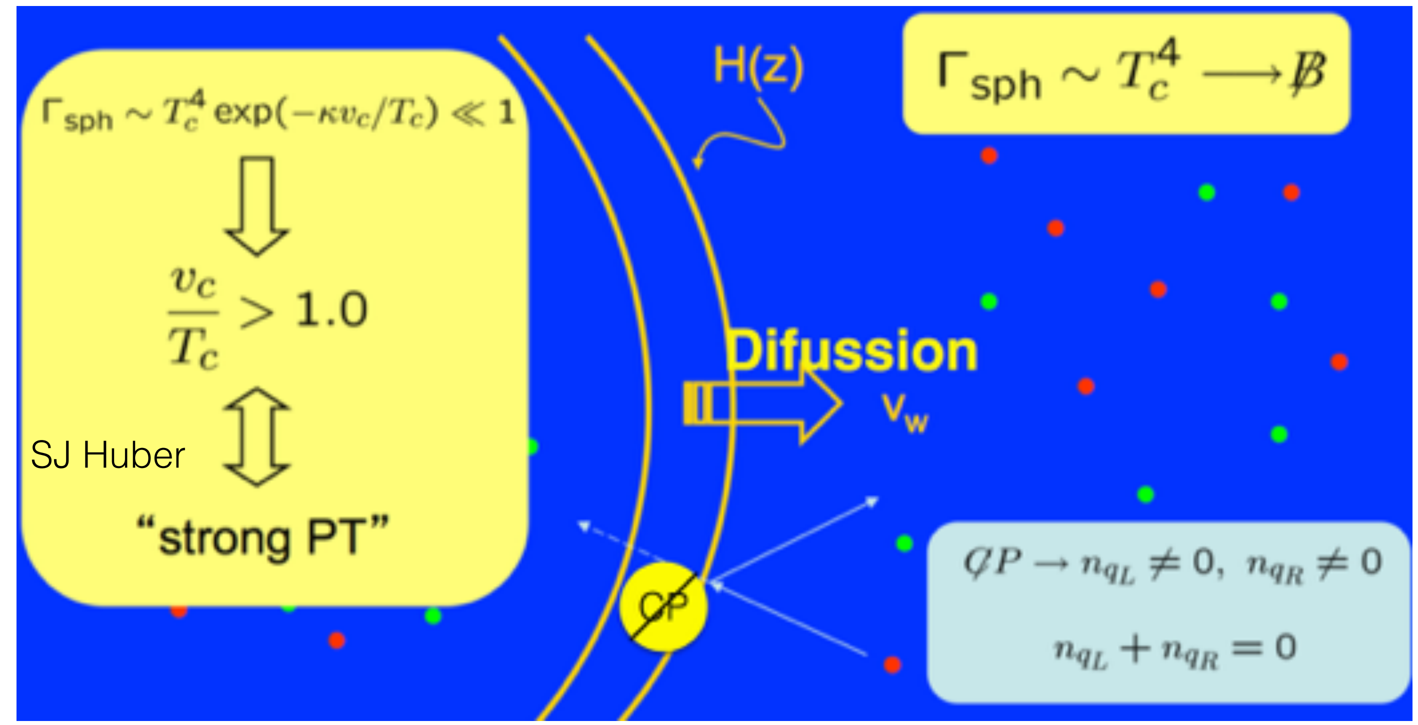
Tfo ~ mDM/xfo~O(1) GeV for mDM~ weak scale

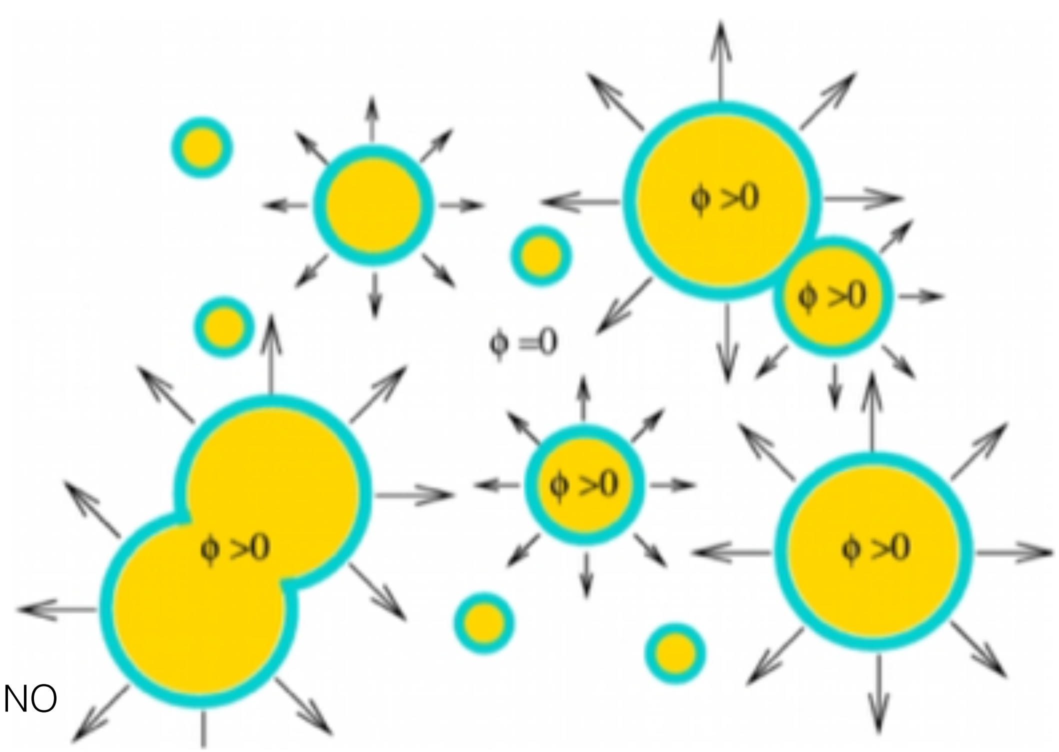
Tn~ 10^2 GeV

EWSB

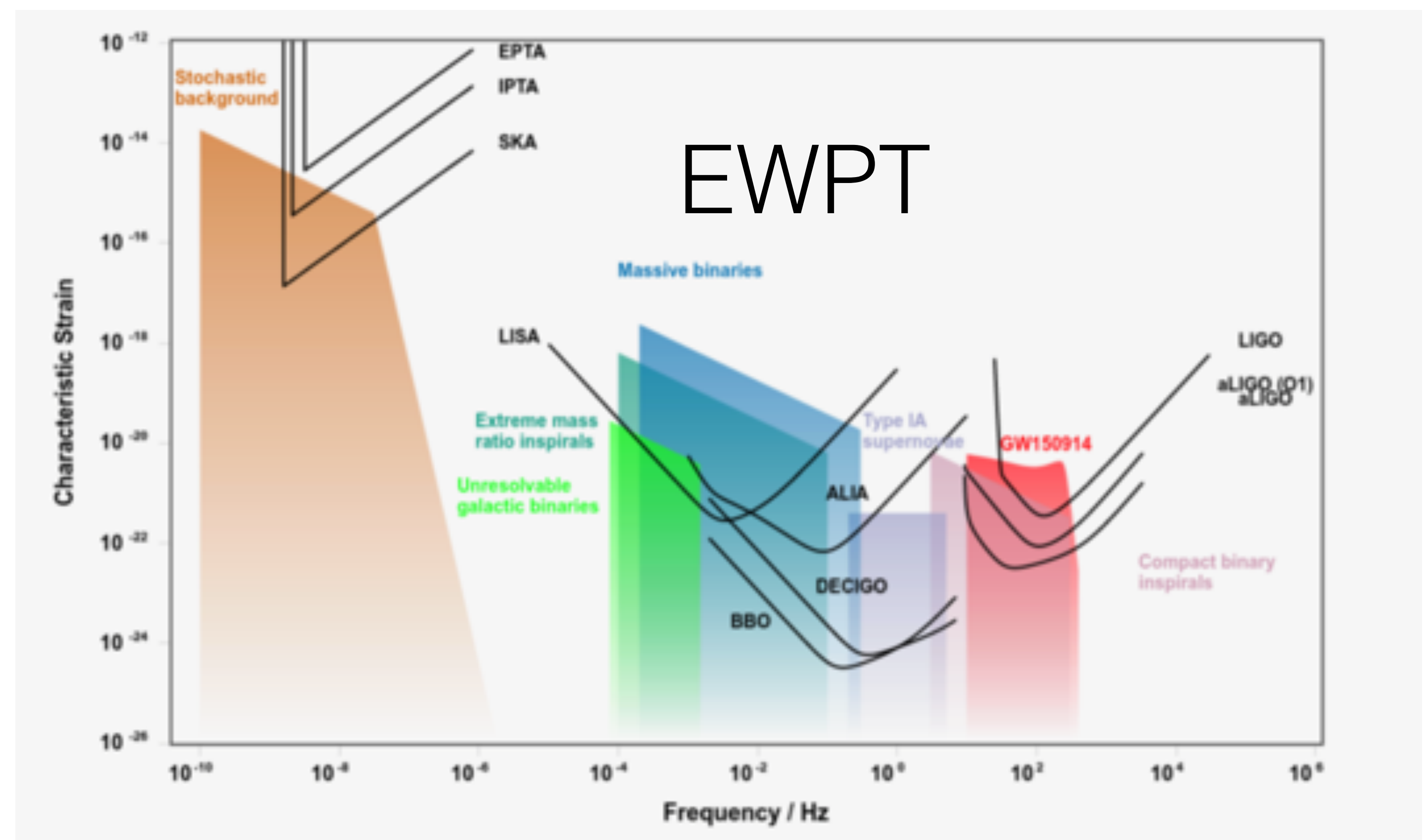
h





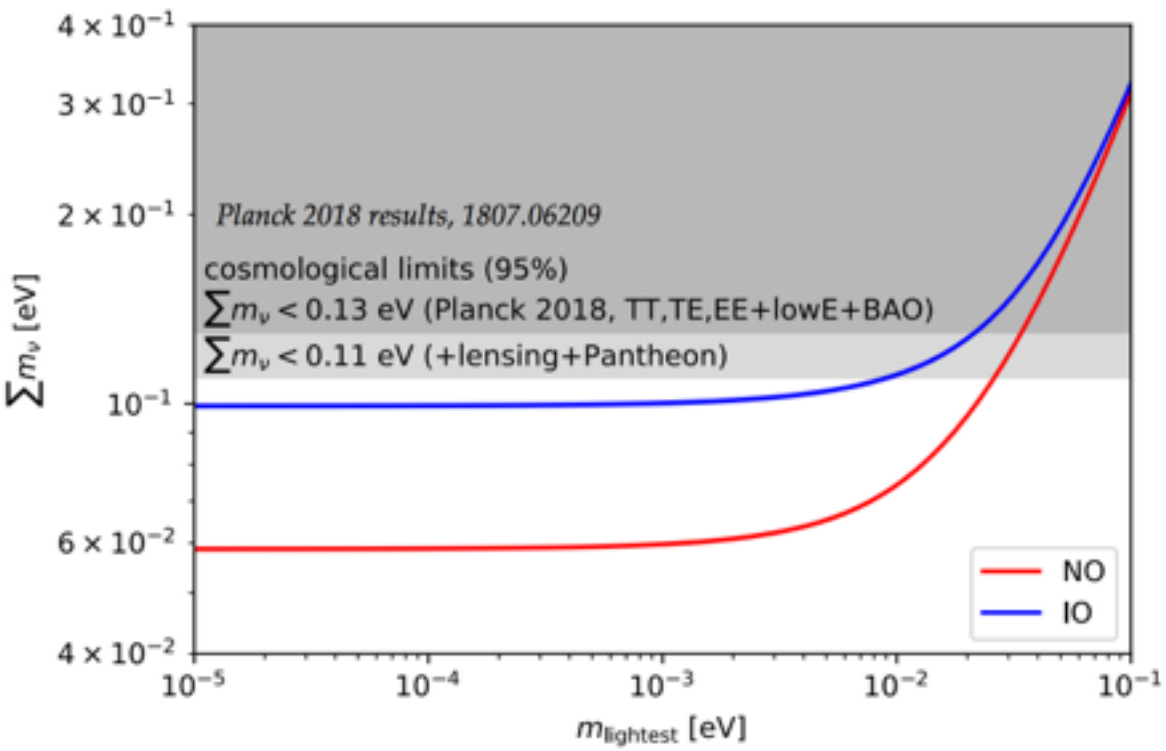


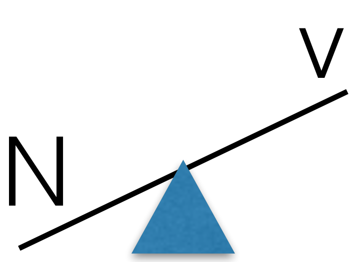
JM NO

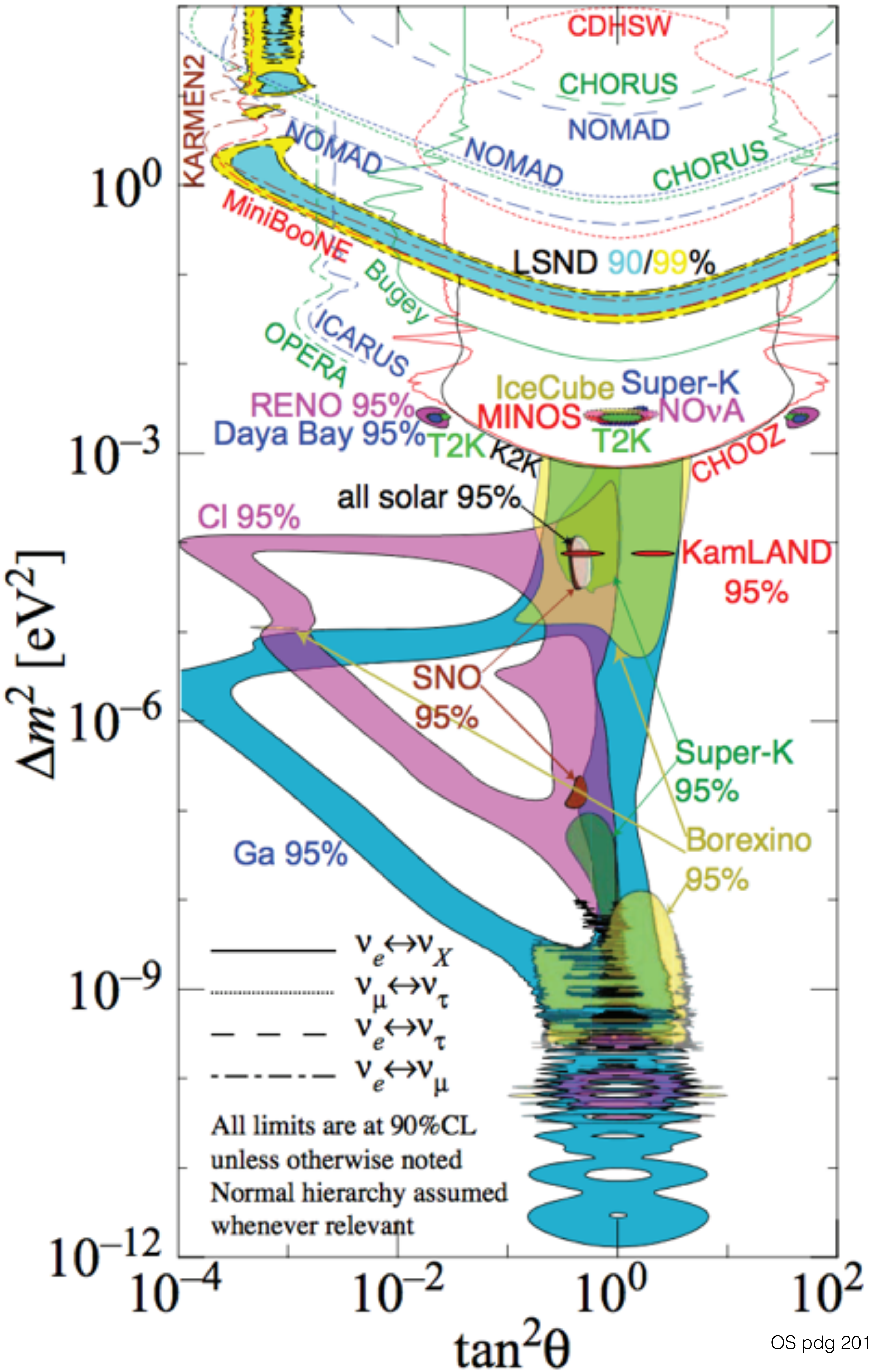


C J Moore et al. Class. Quantum Grav. 32 (2015) 015014.

Massive neutrinos

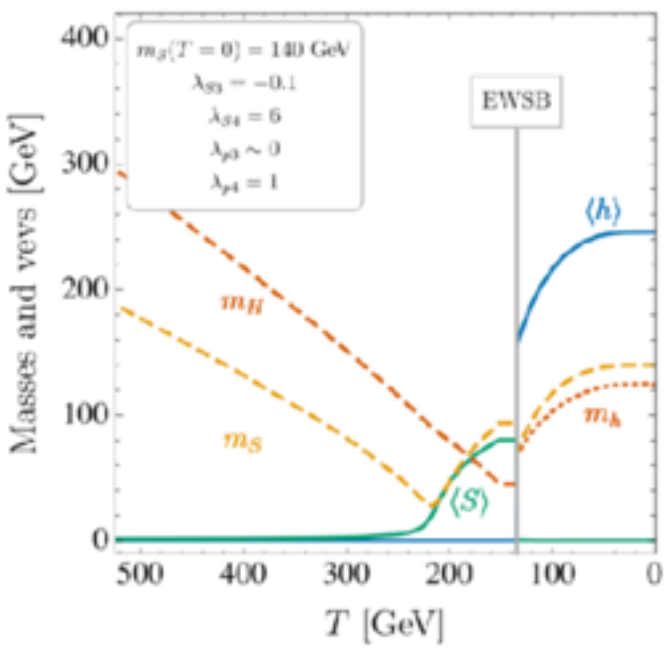


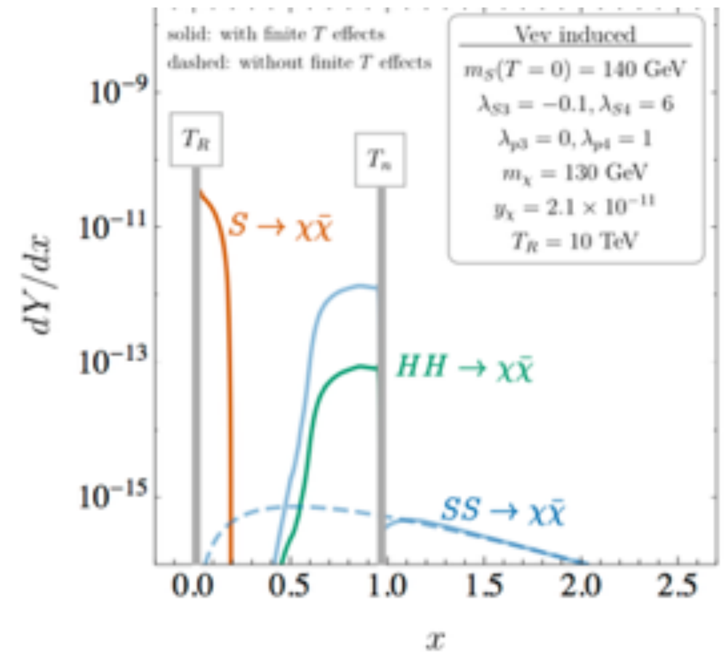
Seesaw 

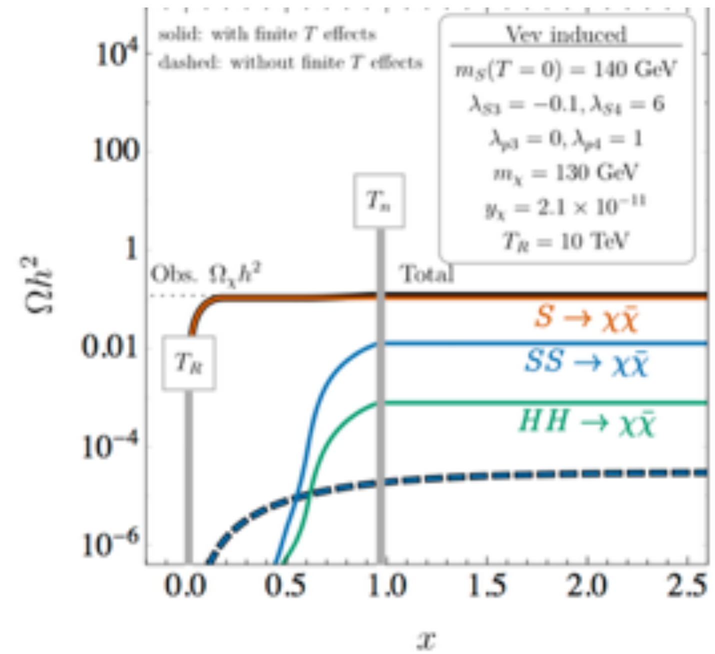


OS pdg 2017

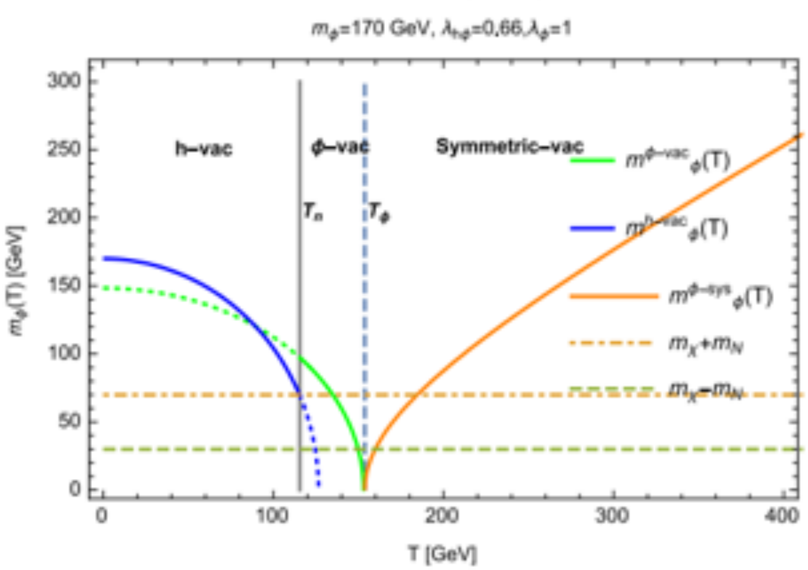
Previous studies

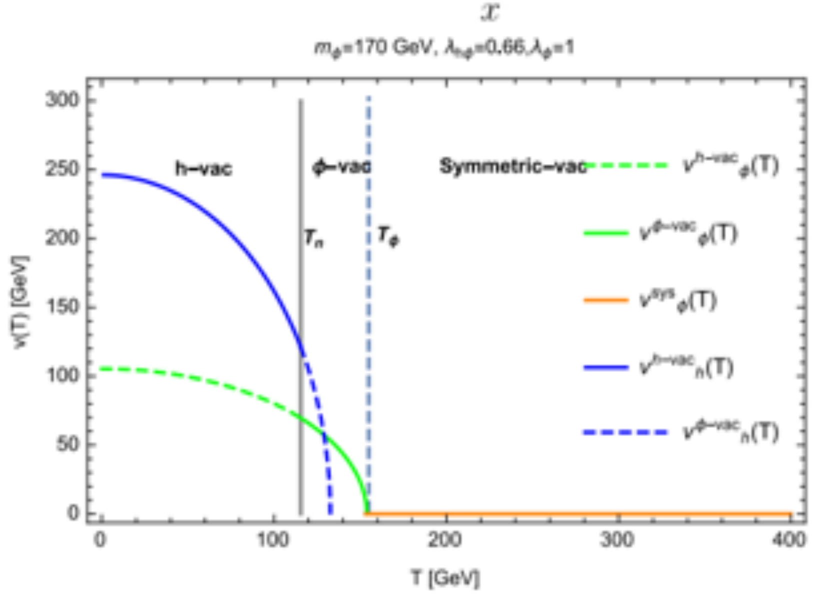




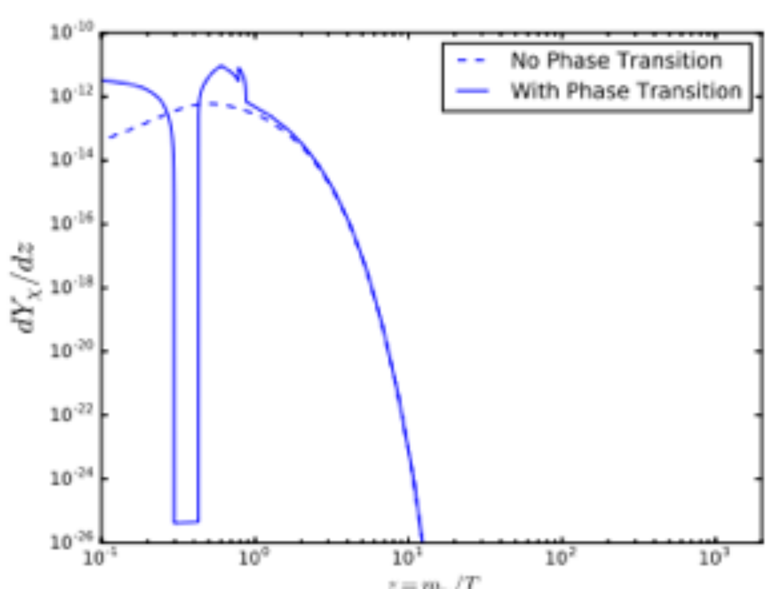


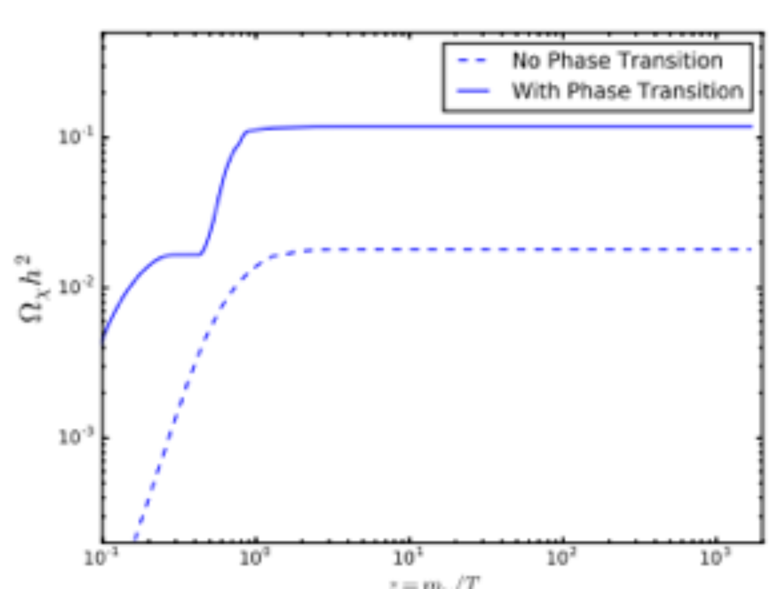
1712.03962,Michael J. Baker et al.





Amplified effects: larger thermal masses before PT





temporarily open of decay channel

1810.03172, L.Bian, Y. Tang

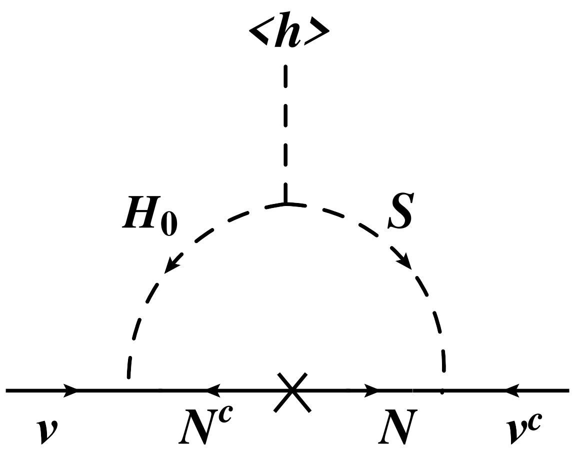
The Scotogenic model

$$\mathcal{L}_Y = f_{\alpha\kappa}\bar{N}_\kappa\left(\frac{1-\gamma_5}{2}\right)(\nu_\alpha H_0 - l_\alpha H^+) + h_{\kappa\beta}\bar{N}_\kappa\left(\frac{1+\gamma_5}{2}\right)\nu_\beta S + \text{h.c.}$$

FIMP f <<1 -> avoiding flavor-changing charged-lepton radiative decays,
E. Molinaro, C. E. Yaguna and O. Zapata, JCAP 1407, 015 (2014)

h: not constrainted by flavor-changing charged-lepton radiative decays,

Y. Farzan and E. Ma, Phys. Rev. D 86, 033007 (2012)



The one-loop Diracc neutrino mass matrix is given by,

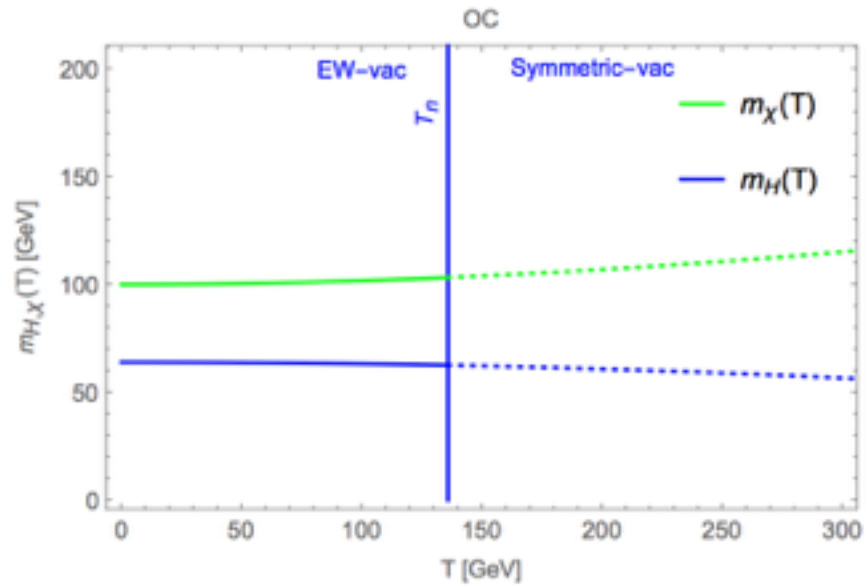
$$(M_\nu)_{\alpha\beta} = \frac{\sin 2\theta}{32\sqrt{2}\pi^2}\sum_\kappa f_{\alpha\kappa}h_{\kappa\beta}m_{N_\kappa}\left[\frac{m_\chi^2}{m_\chi^2 - m_{N_\kappa}^2}\log\frac{m_\chi^2}{m_{N_\kappa}^2} - \frac{m_H^2}{m_H^2 - m_{N_\kappa}^2}\log\frac{m_H^2}{m_{N_\kappa}^2}\right]$$

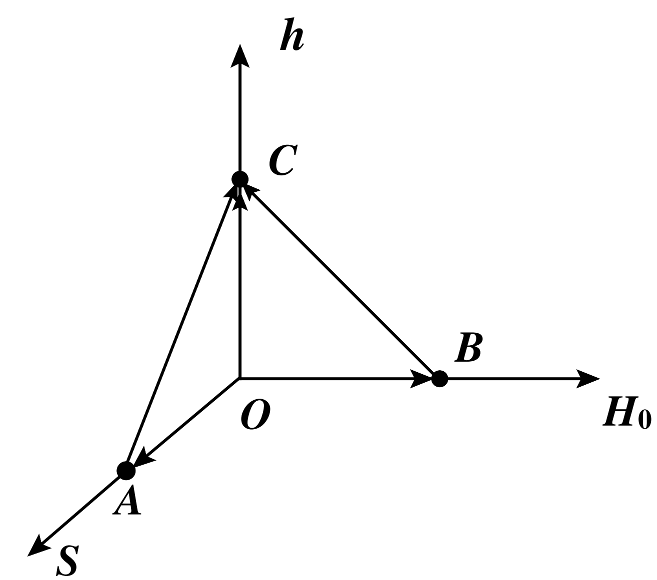
$$\begin{aligned} V &= \mu_\Phi^2\Phi^\dagger\Phi + \mu_\eta^2\eta^\dagger\eta + \frac{\mu_S^2}{2}S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2(\eta^\dagger\eta)^2 + \lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) \\ &+ \lambda_4(\eta^\dagger\Phi)(\Phi^\dagger\eta) + \frac{1}{2}\lambda_5[(\eta^\dagger\Phi)^2 + (\Phi^\dagger\eta)^2] + \frac{\lambda_s}{4}S^4 + \lambda_{s\phi}S^2(\Phi^\dagger\Phi) \\ &+ \lambda_{s\eta}S^2(\eta^\dagger\eta) + \mu_{\text{soft}}S(\Phi^\dagger\eta + \eta^\dagger\Phi)\,, \end{aligned}$$

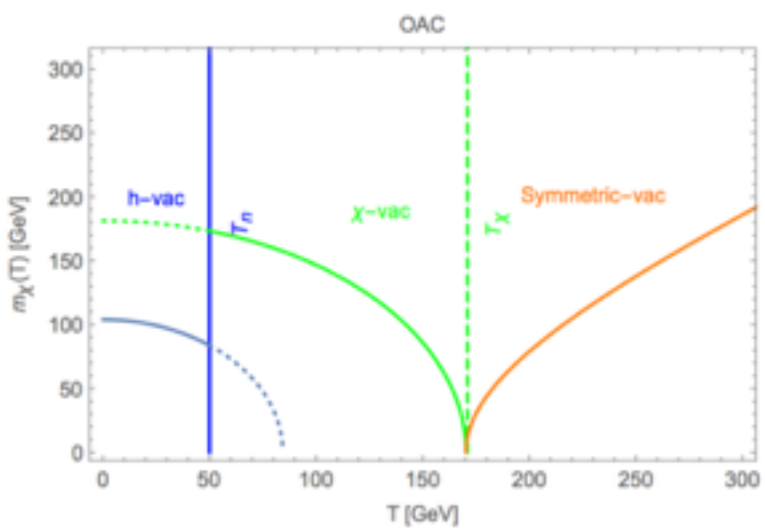
$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \eta = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_0 + iA) \end{pmatrix} \qquad \begin{pmatrix} S \\ H_0 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \chi \\ H \end{pmatrix}$$

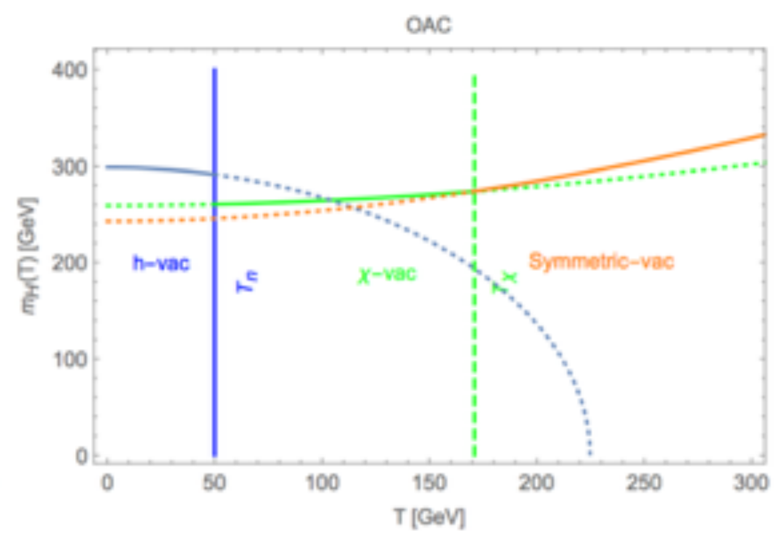
$$\mathbf{M}^2 = \begin{pmatrix} 2\mu_S^2 + v^2\lambda_{s\phi} & v\mu_{\text{soft}} & 0 \\ v\mu_{\text{soft}} & \mu_\eta^2 + v^2\lambda_L & 0 \\ 0 & 0 & \mu_\eta^2 + v^2\lambda_S \end{pmatrix}$$

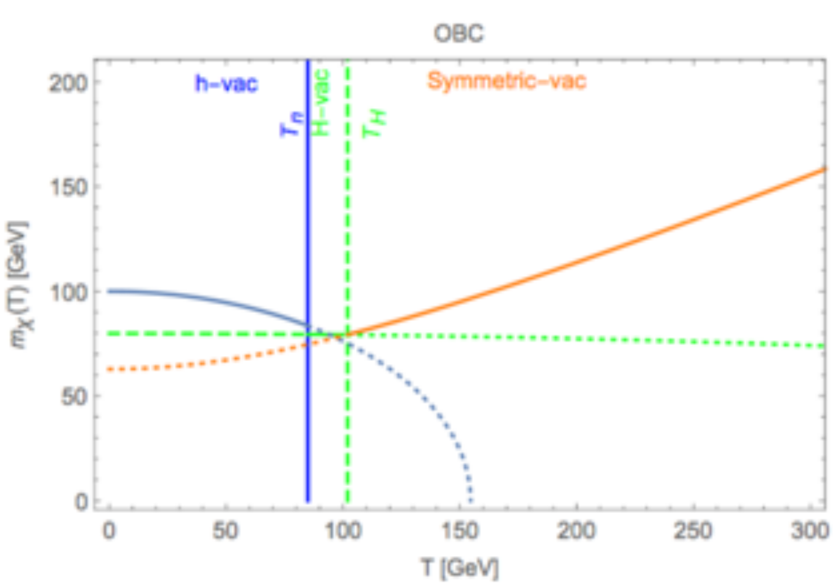
PT patterns and dynamical thermal masses

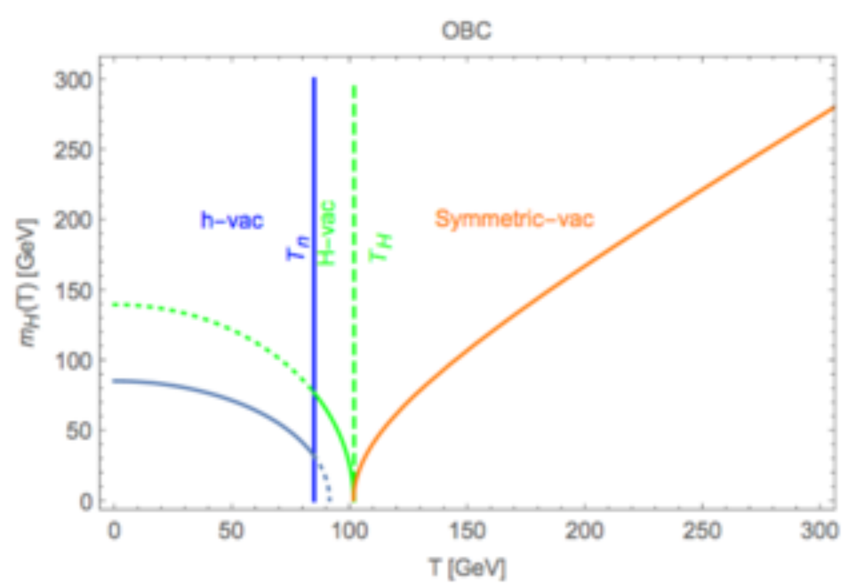


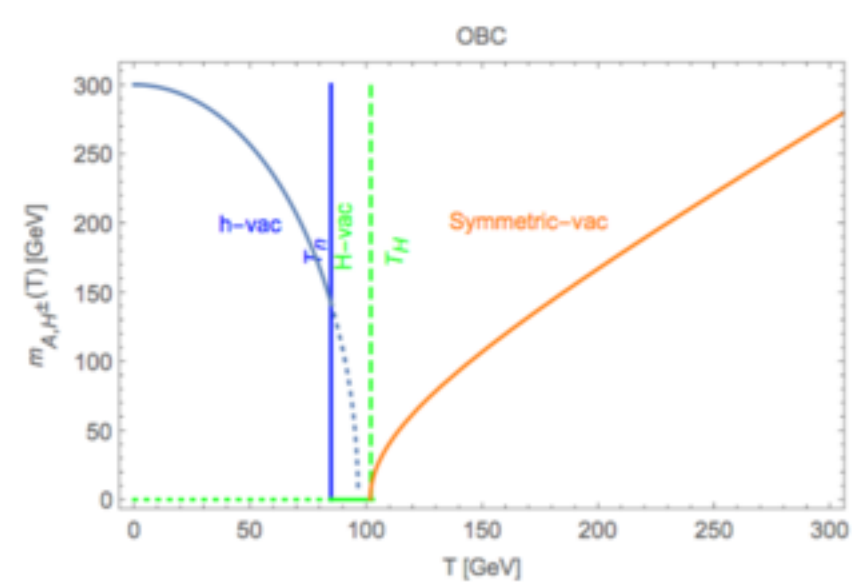




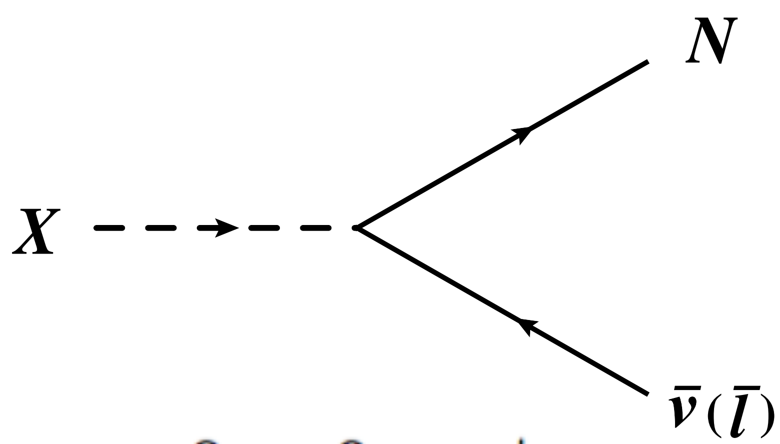






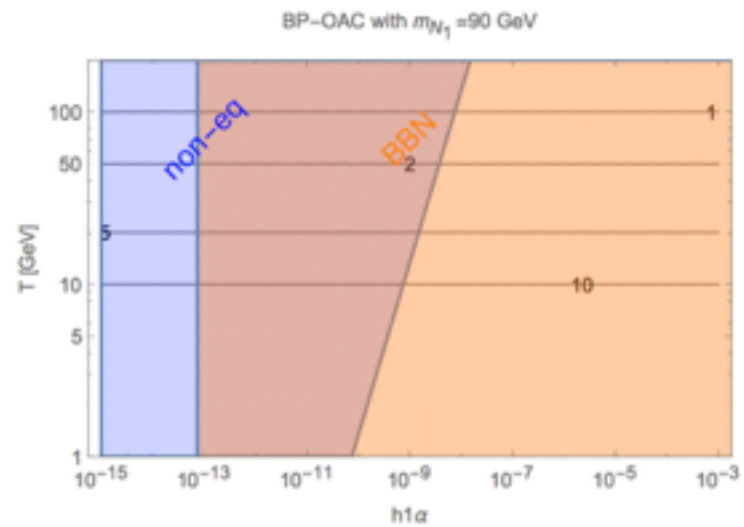


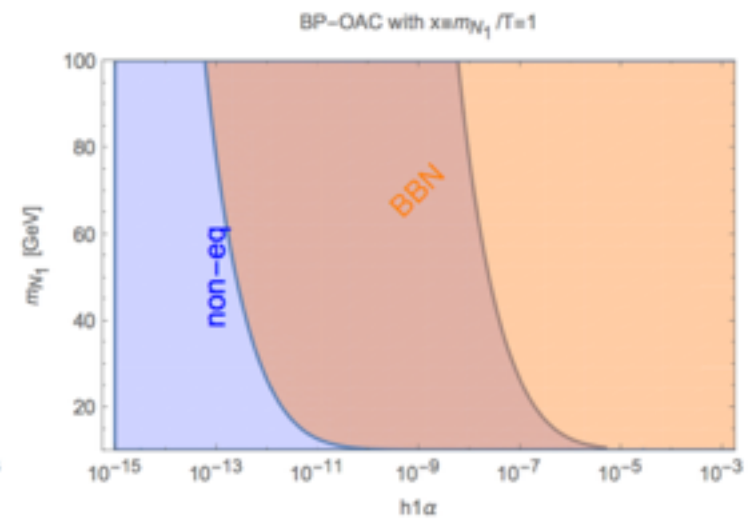
OAC pattern PT DDM

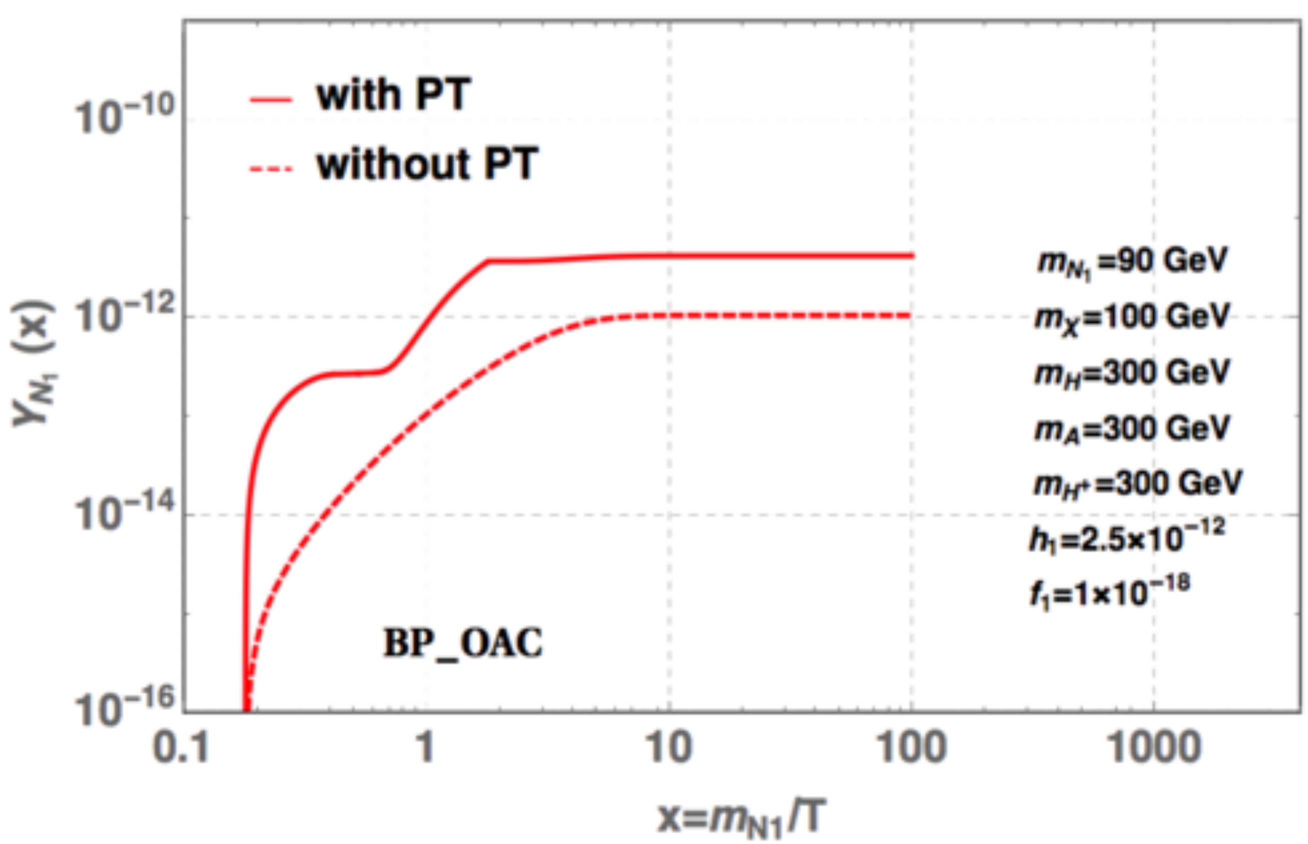


$$X = H^0, A^0, H^\pm, \chi$$

X lives in bath



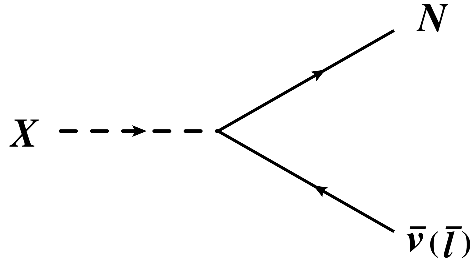


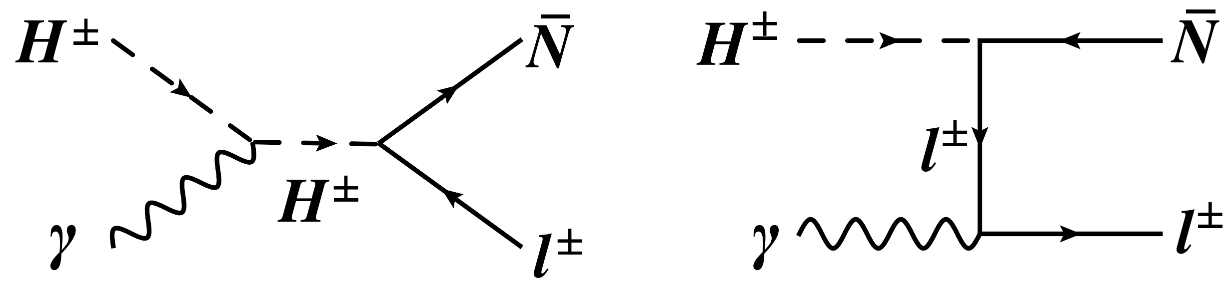


Amplified effects: larger thermal masses before PT

temporarily open of decay channel

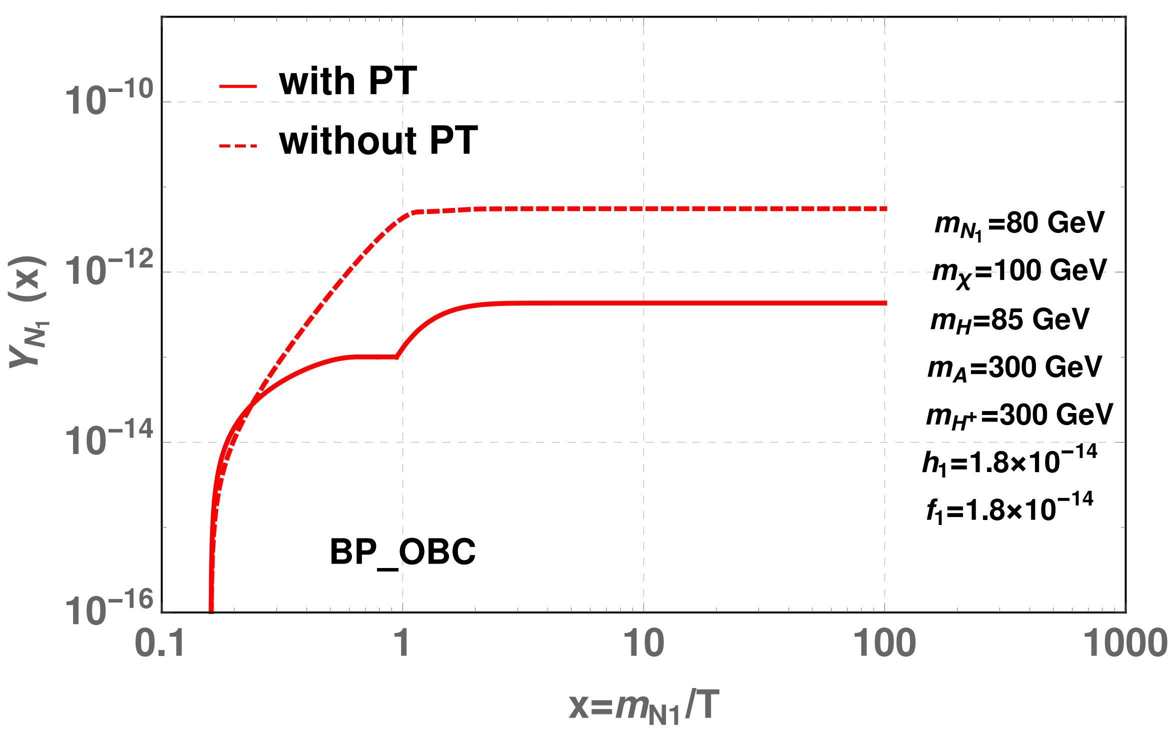
OBC pattern PT DDM





$$X = H^0, A^0, H^\pm, \chi$$

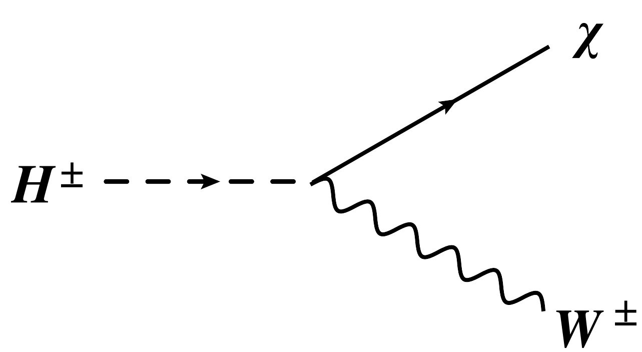
X lives in bath

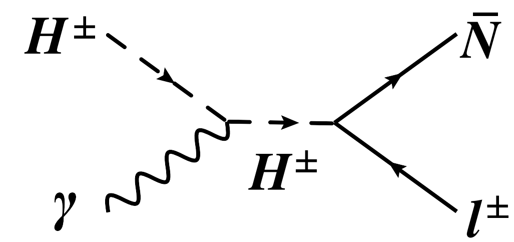


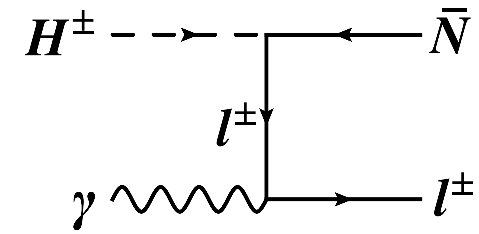
reduction effects: smaller thermal masses before PT

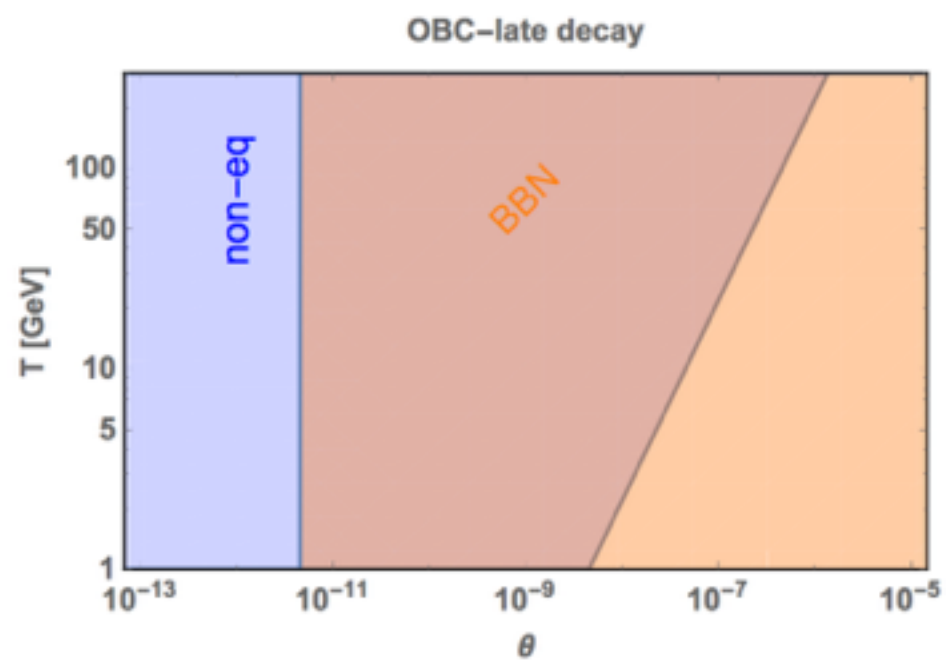
temporarily open of decay channel

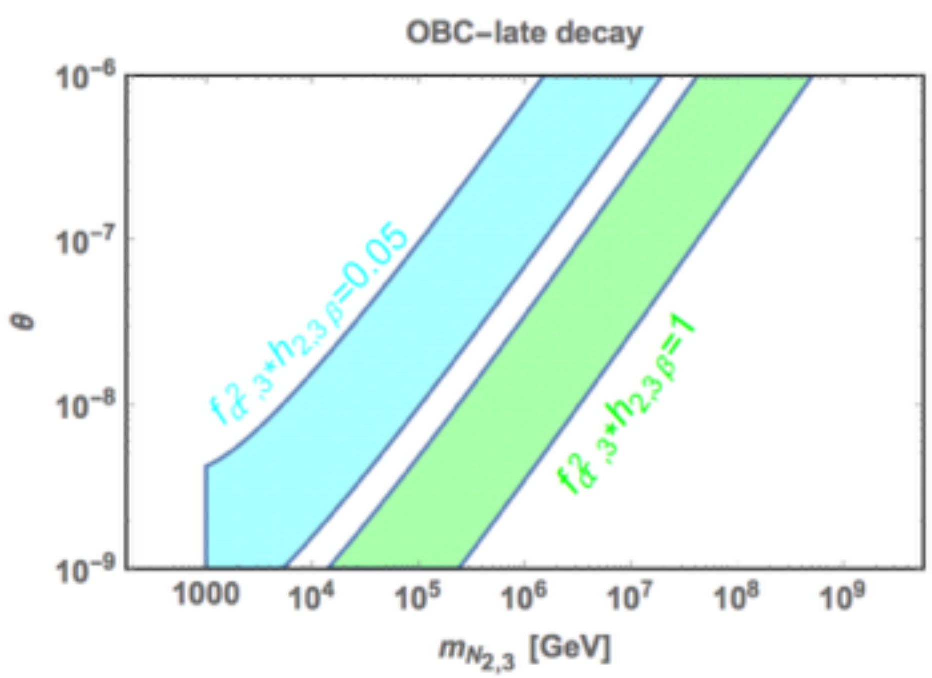
OBC pattern PT DDM-late decay





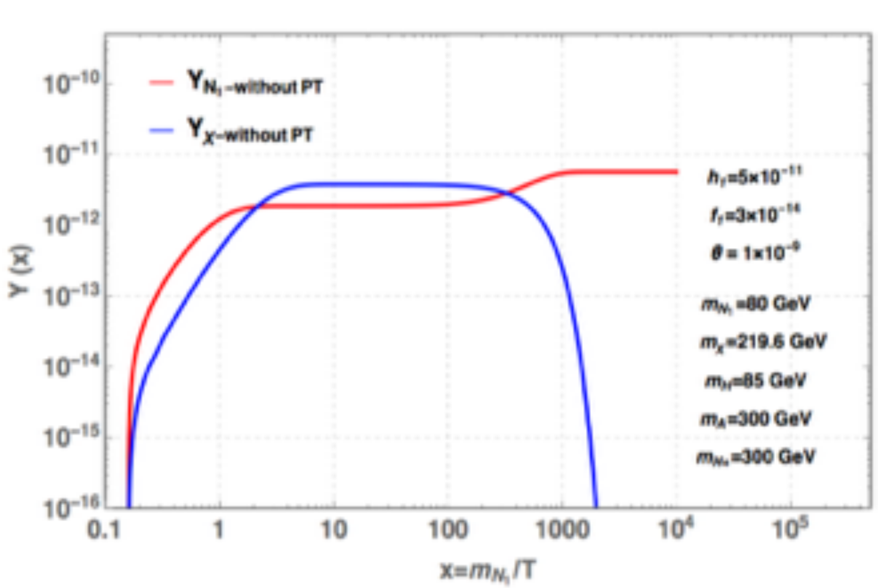


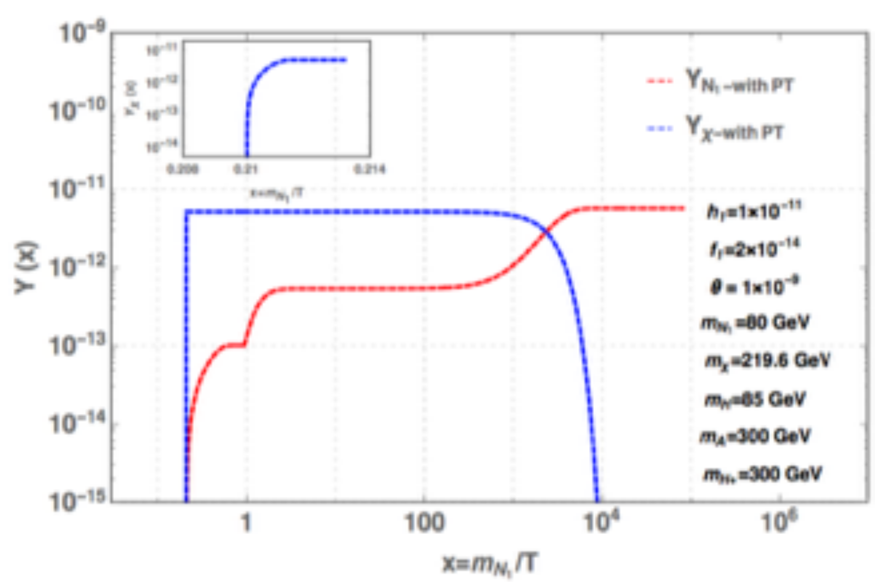


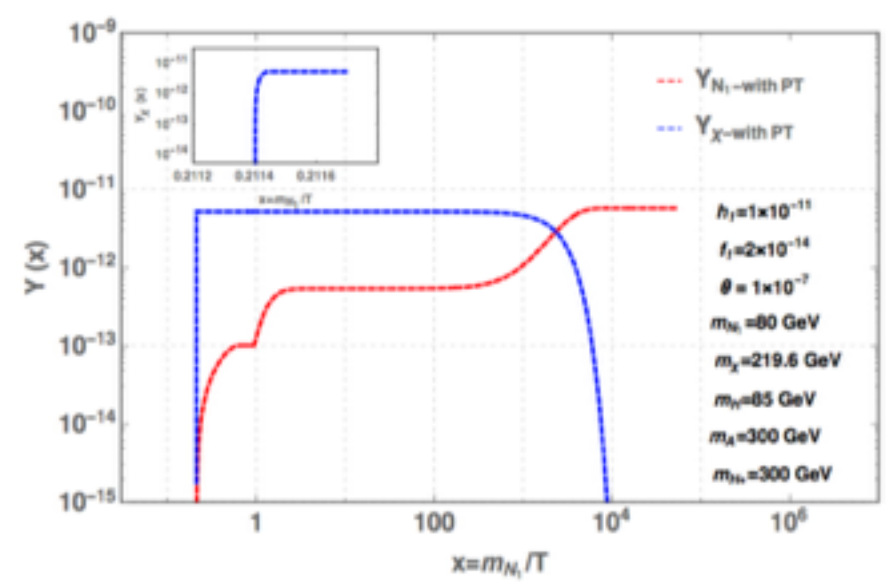


reduction effects: smaller thermal masses before PT

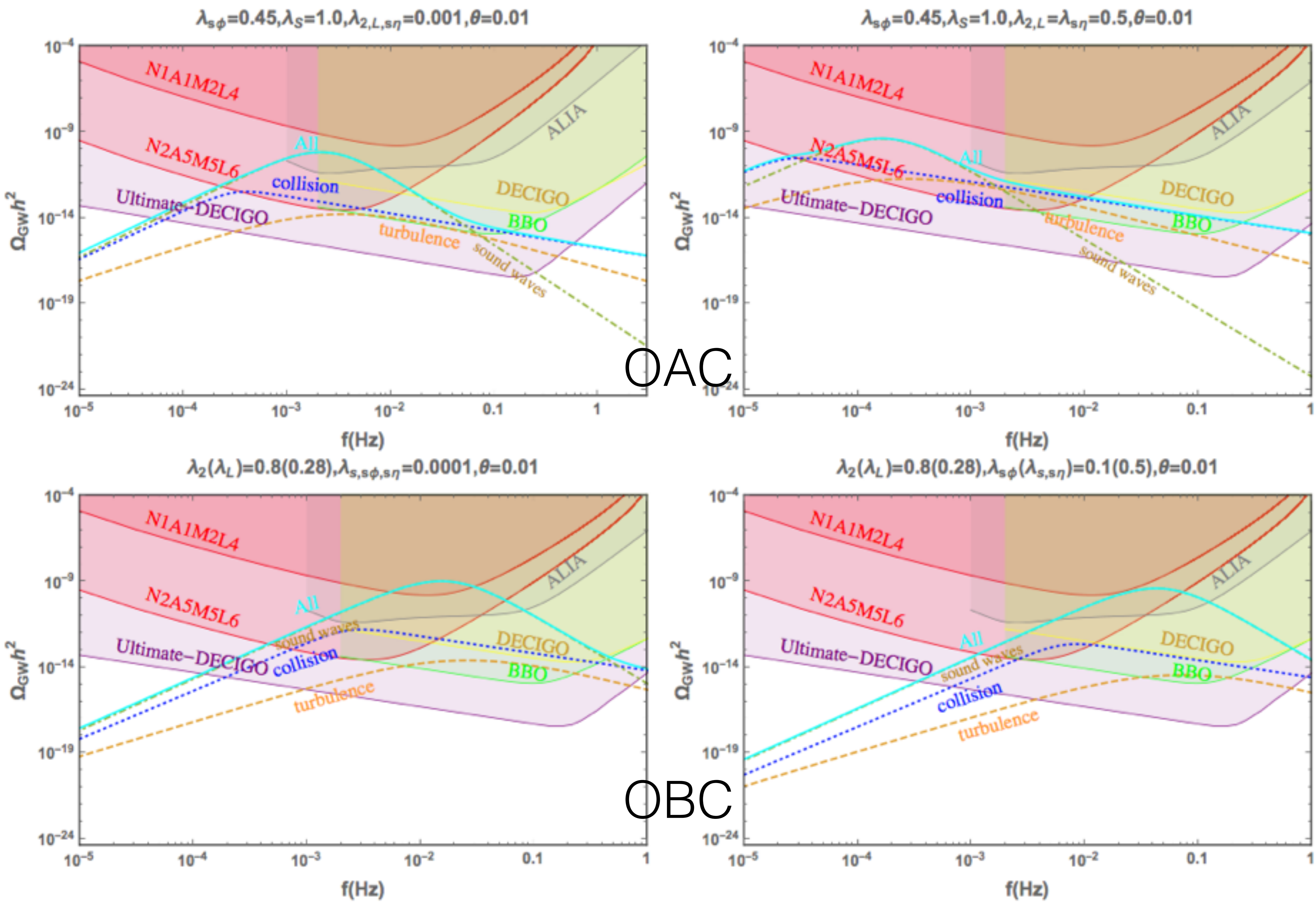
temporarily open of decay channel at high T







GWs from 1st EWPT



GWs

$$\alpha \sim \frac{\text{latent heat}}{\text{radiation energy}} \sim \frac{T\partial_T V(T)}{a g_* T^4}$$

$$v_b \simeq \frac{1/\sqrt{3} + \sqrt{\alpha^2 + 2\alpha/3}}{1+\alpha}, \qquad \kappa \simeq \frac{0.715\alpha + \frac{4}{27}\sqrt{3\alpha/2}}{1 + 0.715\alpha}$$

Bubble size $\langle R \rangle \sim v_b \tau \sim \frac{v_b}{\beta}$ $\qquad \frac{\beta}{H_*} = T_* \frac{d}{dT}\left(\frac{S_3}{T}\right)\Big|_{T_*}$

β reflect the duration of the phase transition

$$\Omega_{\rm col} h^2 = 1.67 \times 10^{-5} \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} \left(\frac{0.11 v_b^3}{0.42 + v_b^2}\right) \frac{3.8(f/f_{\rm env})^{2.8}}{1 + 2.8(f/f_{\rm env})^{3.8}}$$

envelop approximation

$$f_{\rm env} = 16.5 \times 10^{-6} \left(\frac{f_*}{H_*}\right)\left(\frac{T_*}{100\mathrm{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6} \mathrm{Hz}$$

$$\Omega_{\rm sw} h^2 = 2.65 \times 10^{-6} \left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} v_b \left(\frac{f}{f_{\rm sw}}\right)^3 \left(\frac{7}{4 + 3(f/f_{\rm sw})^2}\right)^{7/2} \quad (5.6)$$

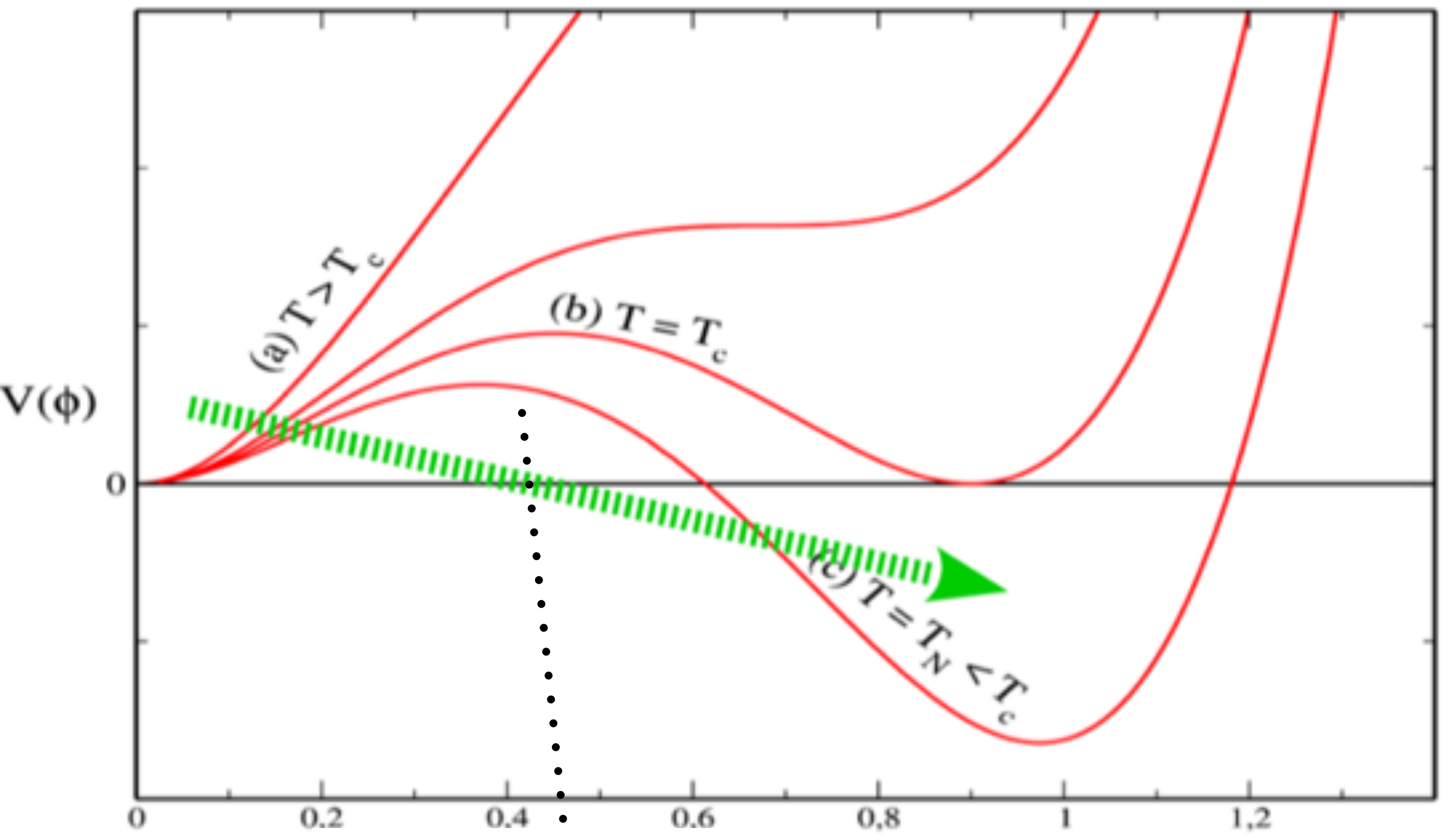
$$\Omega_{\rm turb} h^2 = 3.35 \times 10^{-4} \left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb} \alpha}{1+\alpha}\right)^{3/2} \left(\frac{100}{g_*}\right)^{1/3} v_b \frac{(f/f_{\rm turb})^3}{[1 + (f/f_{\rm turb})]^{11/3}(1 + 8\pi f/h_*)} \quad (5.7)$$

$\kappa_v \approx \alpha(0.73 + 0.083\sqrt{\alpha} + \alpha)^{-1}$ and $\kappa_{\rm turb} \approx 0.1\kappa_v$

$$f_{\rm sw} = 1.9 \times 10^{-5} \frac{1}{v_b}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\mathrm{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6} \mathrm{Hz},$$

kv, kturb: the fraction of latent heat transformed into the bulk motion of the fluid for sound waves and MHD

$$f_{\rm turb} = 2.7 \times 10^{-5} \frac{1}{v_b}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\mathrm{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6} \mathrm{Hz}$$

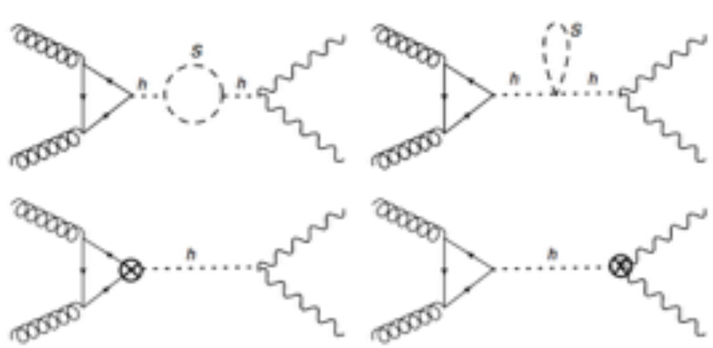


1st Phase transition and the collider search

e+ e- -> Z hh

pp-> hh

- N. Arkani-Hamed, T. Han, M. Mangano and L. T. Wang, Phys. Rept. 652, 1 (2016)
- D. Curtin, P. Meade and C. T. Yu, JHEP 1411, 127 (2014)

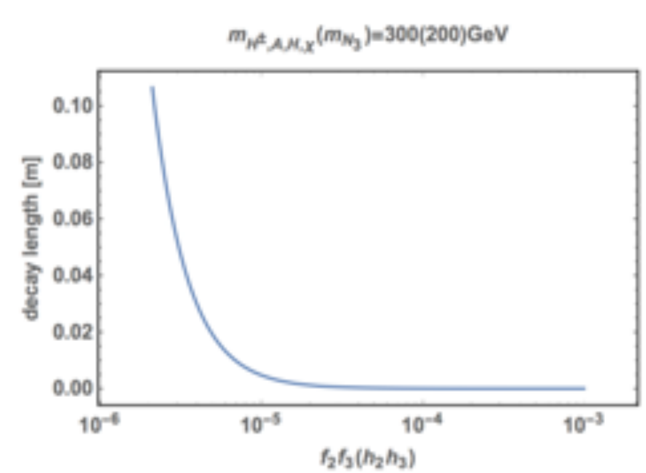


pp-> ZZ

- D. Goncalves, T. Han and S. Mukhopadhyay, Phys. Rev. Lett. 120, no. 11, 111801 (2018)

$$\Gamma'_1(N_3 \to N_2 \overline{\ell_\alpha} \ell_\beta) = \frac{m_{N_3}^5}{6144\,\pi^3\, m^4_{H^\pm,H,A}} \left(|f_{\alpha 2}|^2 |f_{\beta 3}|^2 + |f_{\beta 3}|^2 |f_{\alpha 2}|^2\right)$$

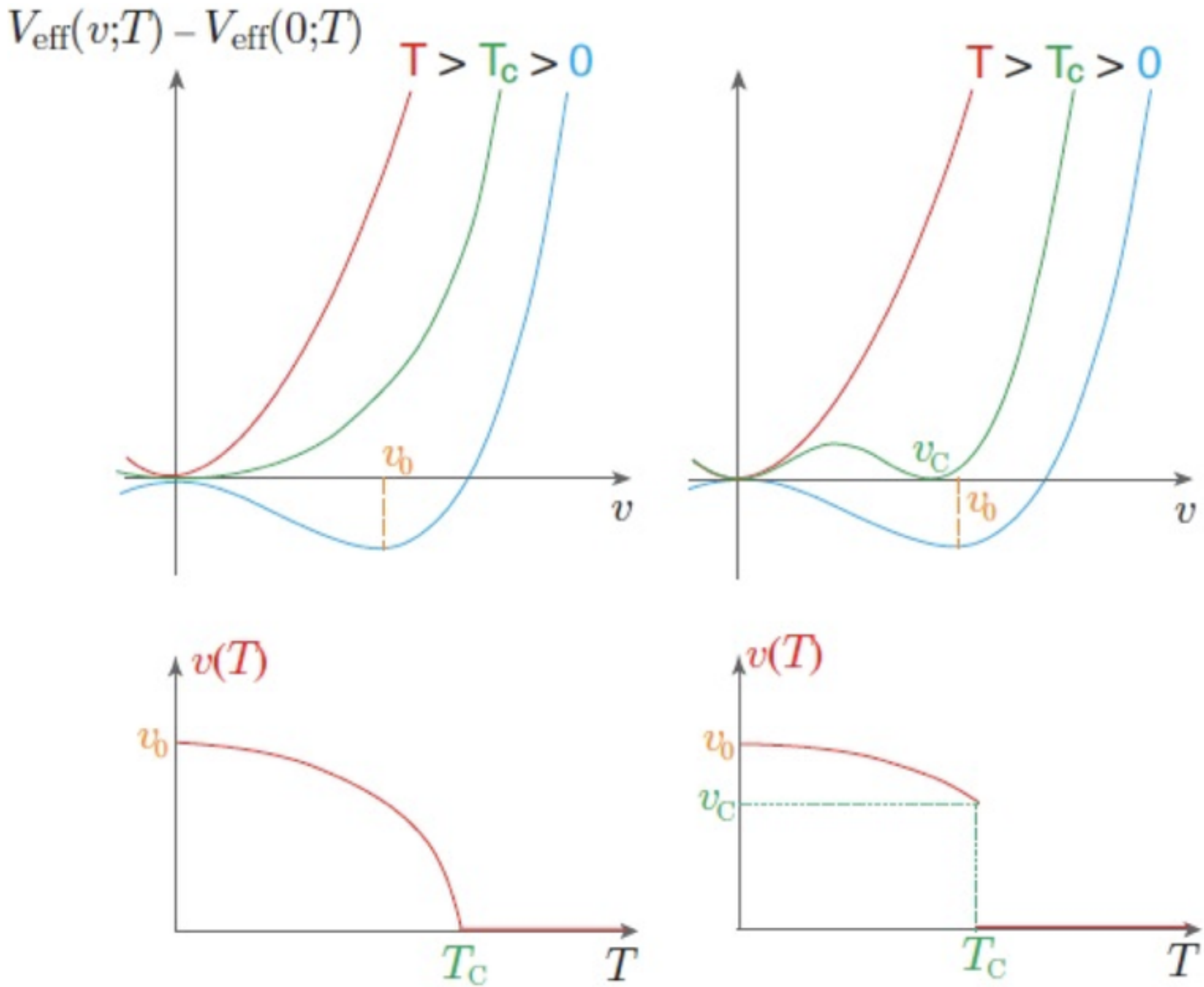
$$\Gamma'_2(N_3 \to N_2 \overline{\ell_\alpha} \ell_\beta) = \frac{m_{N_3}^5}{6144\,\pi^3\, m^4_{\chi}} \left(|h_{\alpha 2}|^2 |h_{\beta 3}|^2 + |h_{\beta 3}|^2 |h_{\alpha 2}|^2\right).$$



1611.09540

Thanks

First or second order



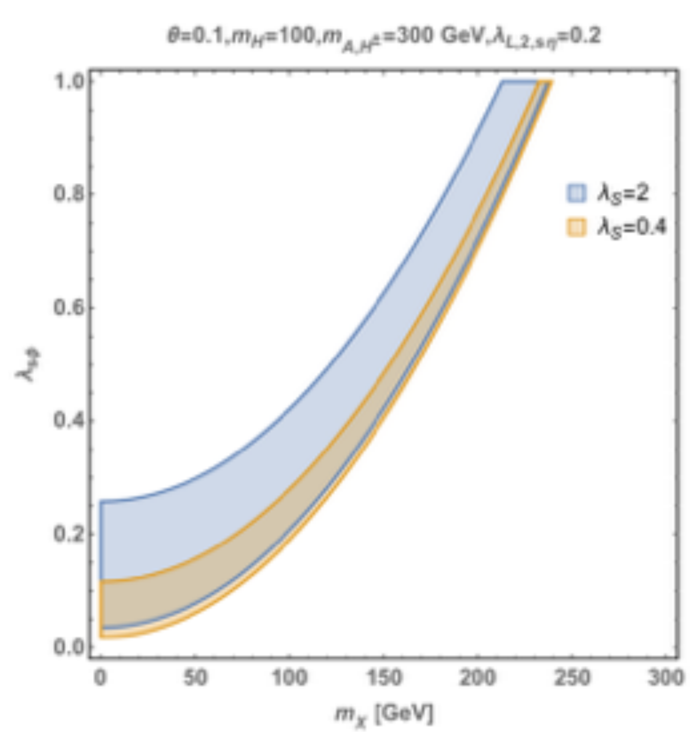
Cross over/ 2nd order PT

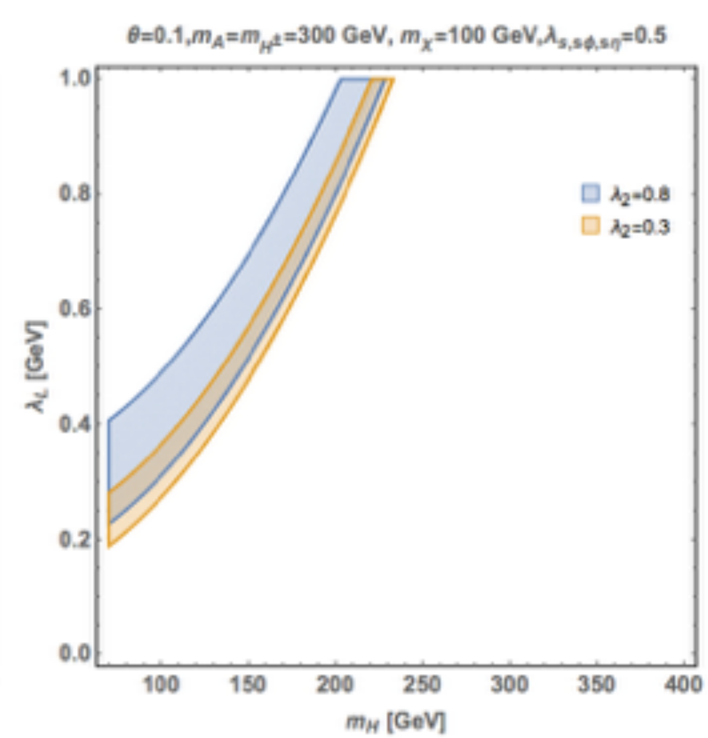
1st order PT

Backup slides

$$V_0(h,H,S) = \frac{\mu_\Phi^2}{2}h^2 + \frac{\mu_\eta^2}{2}H_0^2 + \frac{\mu_S^2}{2}S^2 + \frac{\lambda_1}{4}h^4 + \frac{1}{4}(\lambda_3+\lambda_4+\lambda_5)h^2H_0^2 + \frac{\lambda_2}{4}H_0^4$$
$$+\frac{1}{2}\lambda_{s\phi}h^2S^2 + \frac{1}{2}\lambda_{s\eta}H_0^2S^2 + \frac{\lambda_s}{4}S^4 + \mu_{soft}hH_0S\ ,$$

$$\mu_\Phi^2(T) = \mu_\Phi^2 + c_\Phi T^2\ ,\quad c_\Phi = \frac{6\lambda_1+2\lambda_3+\lambda_4+\lambda_{s\phi}}{12} + \frac{3g^2+g'^2}{16} + \frac{y_t^2}{4}$$
$$\mu_\eta^2(T) = \mu_\eta^2 + c_\eta T^2\ ,\quad c_\eta = \frac{6\lambda_2+2\lambda_3+\lambda_4+\lambda_{s\eta}}{12} + \frac{3g^2+g'^2}{16}$$
$$\mu_S^2(T) = \mu_S^2 + c_S T^2\ ,\quad c_S = \frac{\lambda_S}{4} + \frac{\lambda_{s\phi}+\lambda_{s\eta}}{12}\ .$$





$$M_h^2 = \begin{pmatrix} 3\lambda_1 h^2 + \lambda_L H_0^2 + \lambda_{s\phi} S^2 + \mu_\phi^2 & 2\lambda_L h H_0 + \mu_{soft} S & 2\lambda_{s\phi} h S + \mu_{soft} H_0 \\ 2\lambda_L h H_0 + \mu_{soft} S & \lambda_L h^2 + 3\lambda_2 H_0^2 + \lambda_{s\eta} S^2 + \mu_\eta^2 & 2\lambda_{s\eta} H_0 S + \mu_{soft} h \\ 2\lambda_{s\phi} h S + \mu_{soft} H_0 & 2\lambda_{s\eta} H_0 S + \mu_{soft} h & \lambda_{s\phi} h^2 + 3\lambda_s S^2 + \lambda_{s\eta} H_0^2 + \mu_s^2 \end{pmatrix},$$

$\mu^2_i \to \mu^2_i(T)$

$$M_A^2 = \begin{pmatrix} \lambda_1 h^2 + \lambda_L H_0^2 + \lambda_{s\phi} s^2 + \mu_\phi^2 & \lambda_5 h H_0 + \mu_{soft} S \\ \lambda_5 h H_0 + \mu_{soft} S & \lambda_S h^2 + \lambda_2 H_0^2 + \lambda_{s\eta} S^2 + \mu_\eta^2 \end{pmatrix},$$

$$M_{H^\pm}^2 = \begin{pmatrix} \lambda_1 h^2 + \frac{\lambda_3}{2} H_0^2 + \lambda_{s\phi} s^2 + \mu_\phi^2 & \frac{\lambda_4+\lambda_5}{2} h H_0 + \mu_{soft} S \\ \frac{\lambda_4+\lambda_5}{2} h H_0 + \mu_{soft} S & \frac{\lambda_3}{2} h^2 + \lambda_2 H_0^2 + \lambda_{s\eta} S^2 + \mu_\eta^2 \end{pmatrix}. \quad \text{(C.1)}$$

Symmetry phase

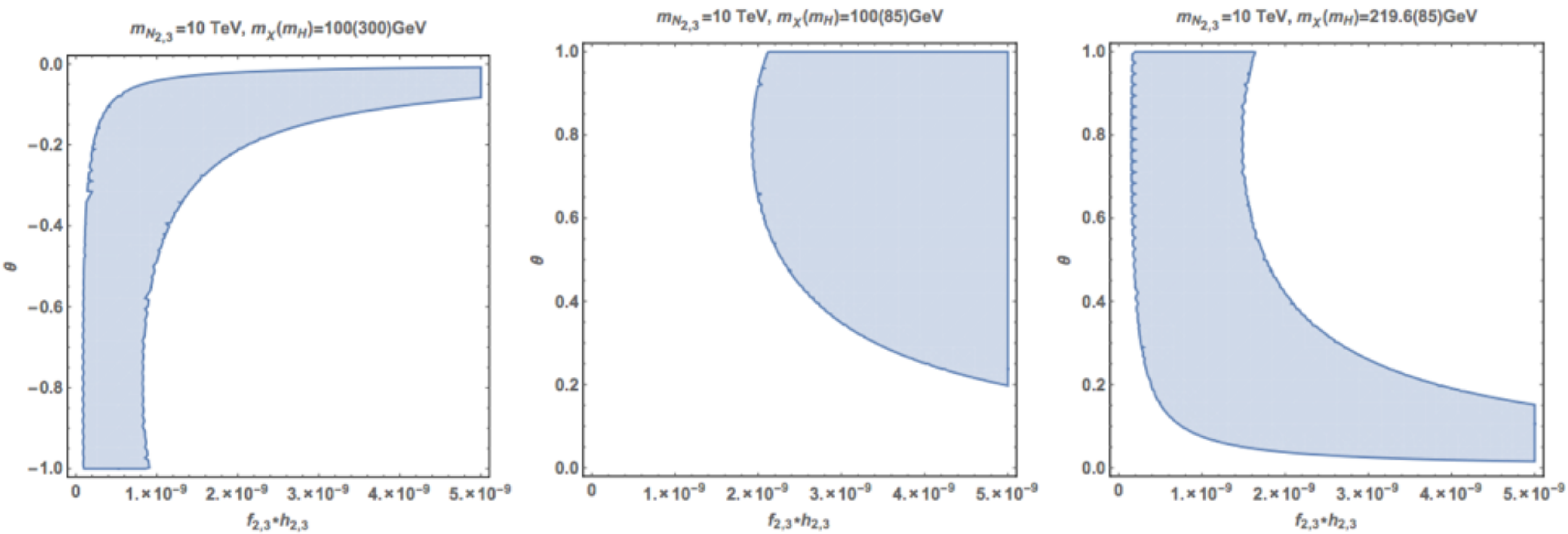
$$M_h^{sys}(T) = M_h(T)|_{\langle h, H_0, S\rangle \to 0},$$
$$M_A^{sys}(T) = M_A(T)|_{\langle h, H_0, S\rangle \to 0},$$
$$M_{H^\pm}^{sys}(T) = M_{H^\pm}|_{\langle h, H_0, S\rangle \to 0}.$$

Z2 broken phase

$$M_h^{\cancel{Z}_2}(T) = M_h(T)|_{\langle h\rangle \to 0, \langle H_0 \text{ or } S\rangle \to v_H(T) \text{ or } v_s(T)},$$
$$M_A^{\cancel{Z}_2}(T) = M_A(T)|_{\langle h\rangle \to 0, \langle H_0 \text{ or } S\rangle \to v_H(T) \text{ or } v_s(T)},$$
$$M_{H^\pm}^{\cancel{Z}_2}(T) = M_{H^\pm}|_{\langle h\rangle \to 0, \langle H_0 \text{ or } S\rangle \to v_H(T) \text{ or } v_s(T)},$$

EW broken phase

$$M_h^{E\cancel{W}}(T) = M_h(T)|_{\langle h\rangle \to v(T), \langle H_0, S\rangle \to 0},$$
$$M_A^{E\cancel{W}}(T) = M_A(T)|_{\langle h\rangle \to v(T), \langle H_0, S\rangle \to 0},$$
$$M_{H^\pm}^{E\cancel{W}}(T) = M_{H^\pm}|_{\langle h\rangle \to v(T), \langle H_0, S\rangle \to 0}.$$



The neutrino mass bounds on mixing angle θ and the multiplication of Yukawa f and h for OAC(left), OBC (middle), OBC with late decay (right).