Interplay of Higgs Boson, Dark matter and Neutrinos

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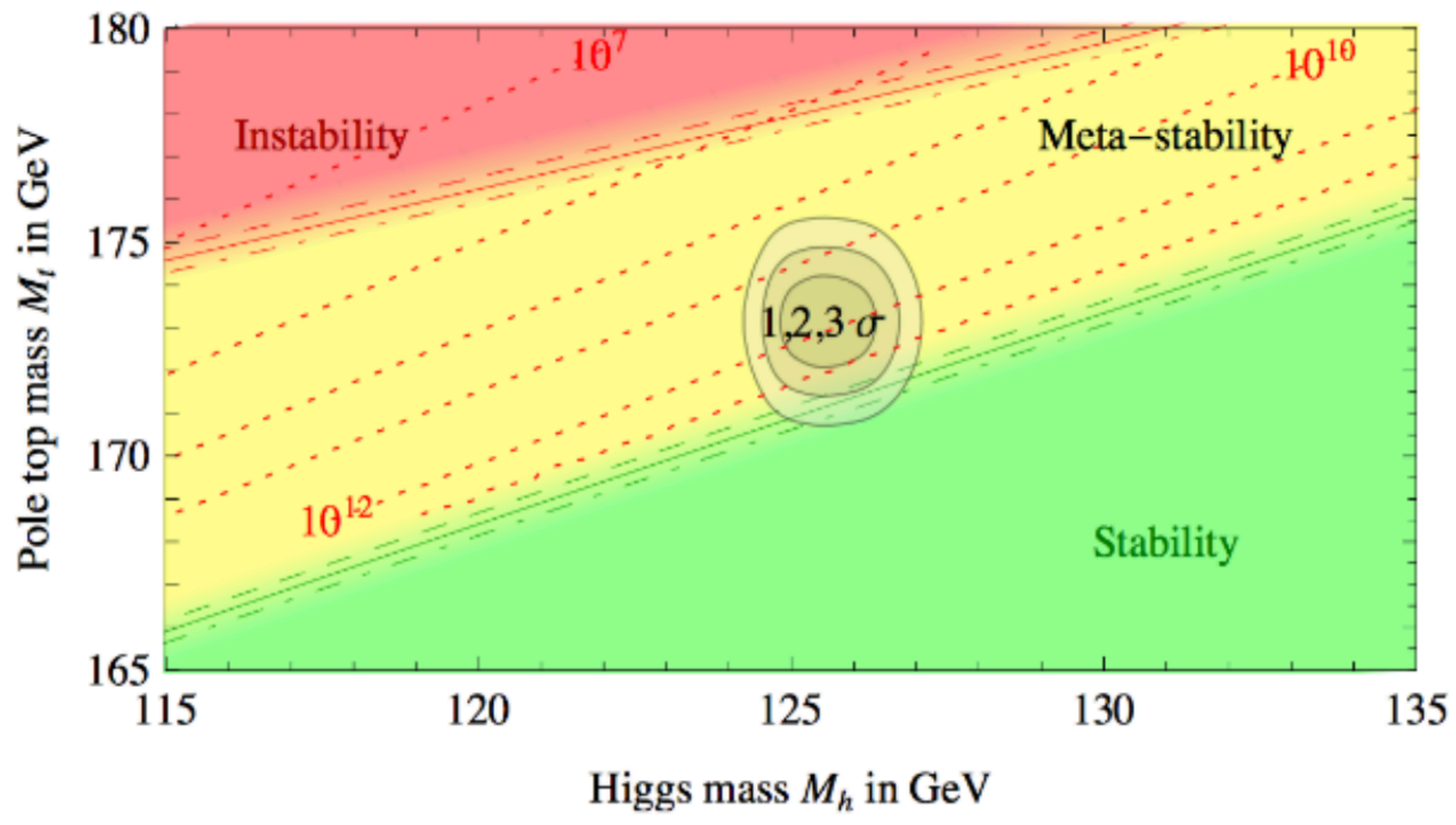
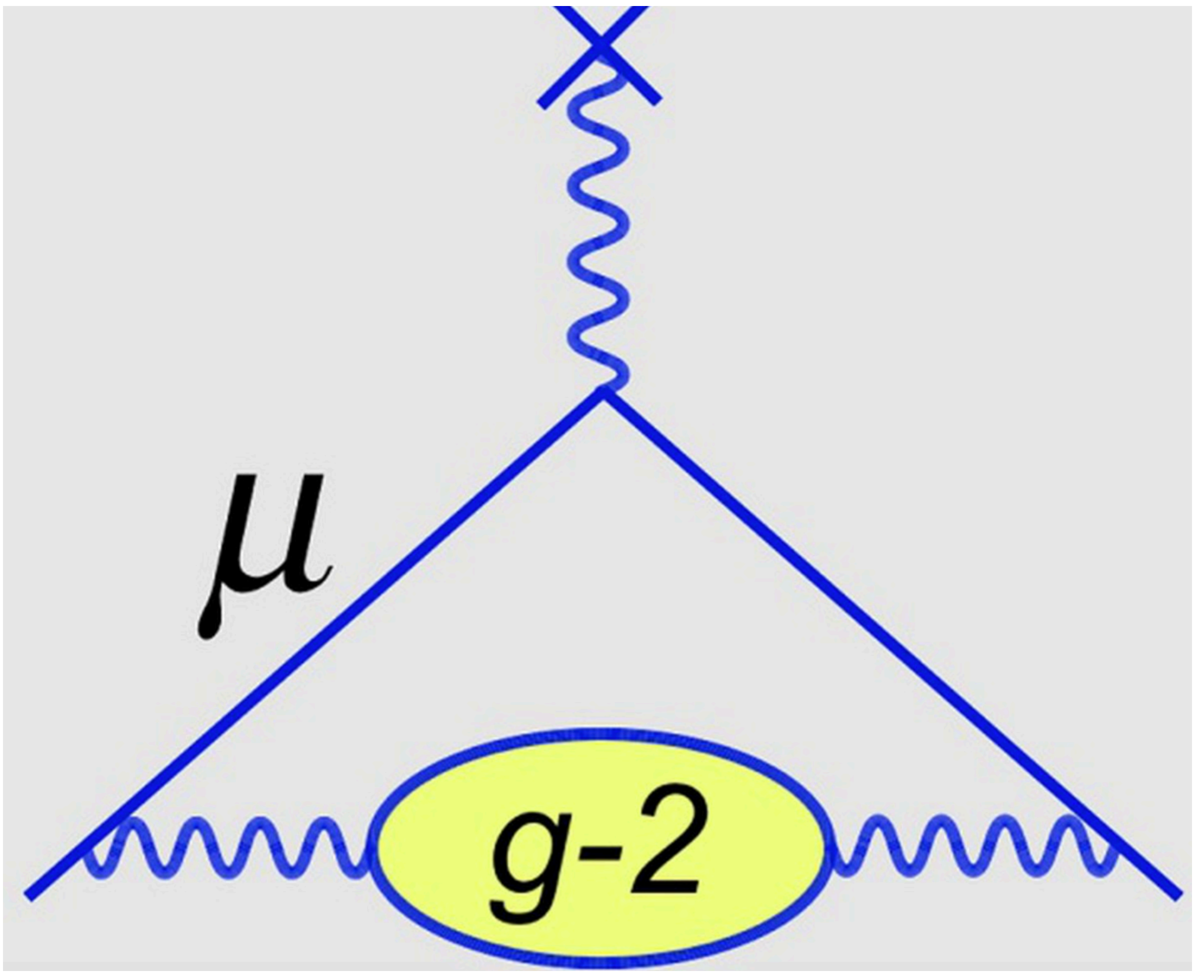
Needs some basic explanations

Meta-stable Vacuum in SM

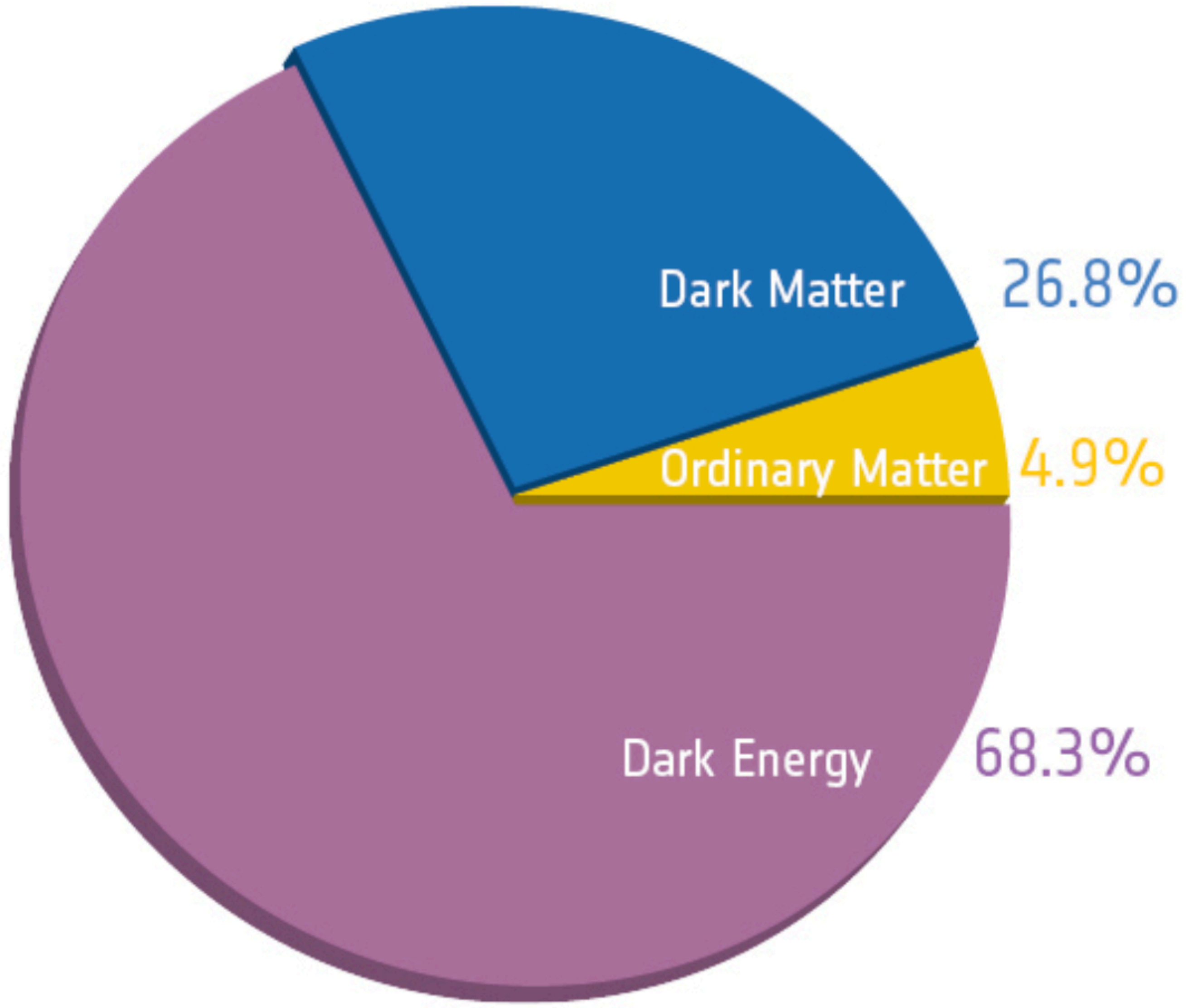


Non-zero neutrino Mass

Muon-(g-2) anomaly

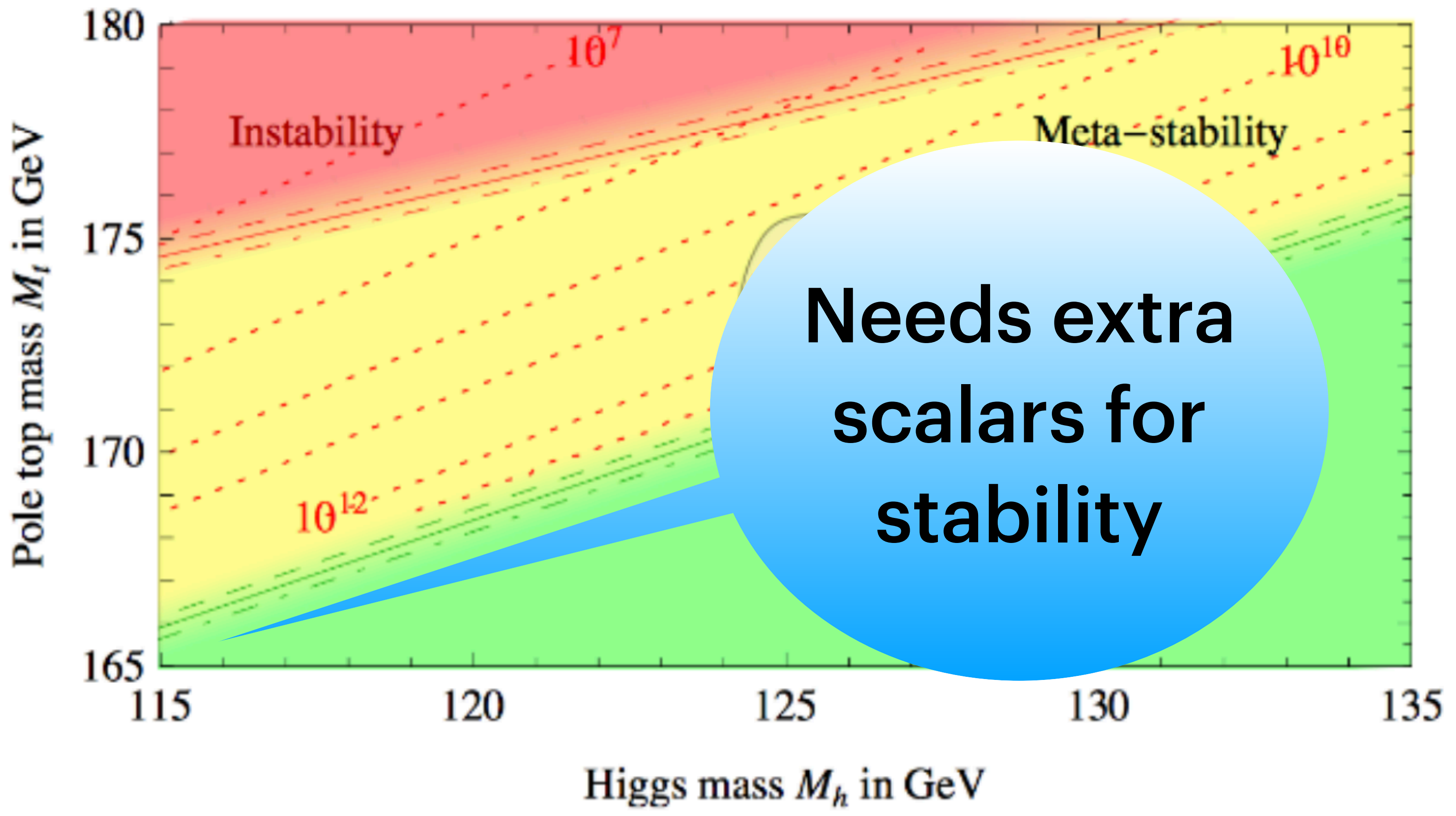


Indirect evidence of Dark Matter



Needs some basic explanations

Meta-stable Vacuum in SM



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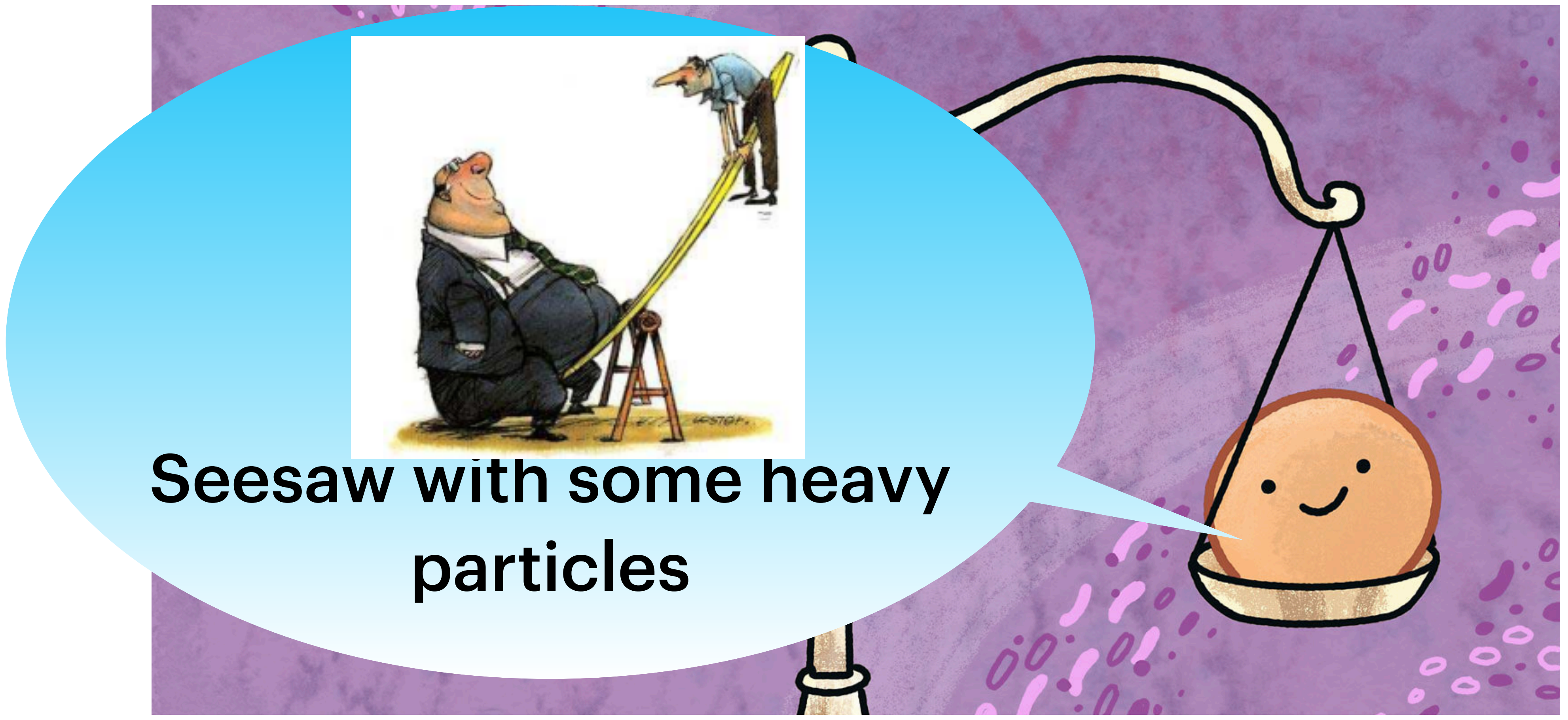
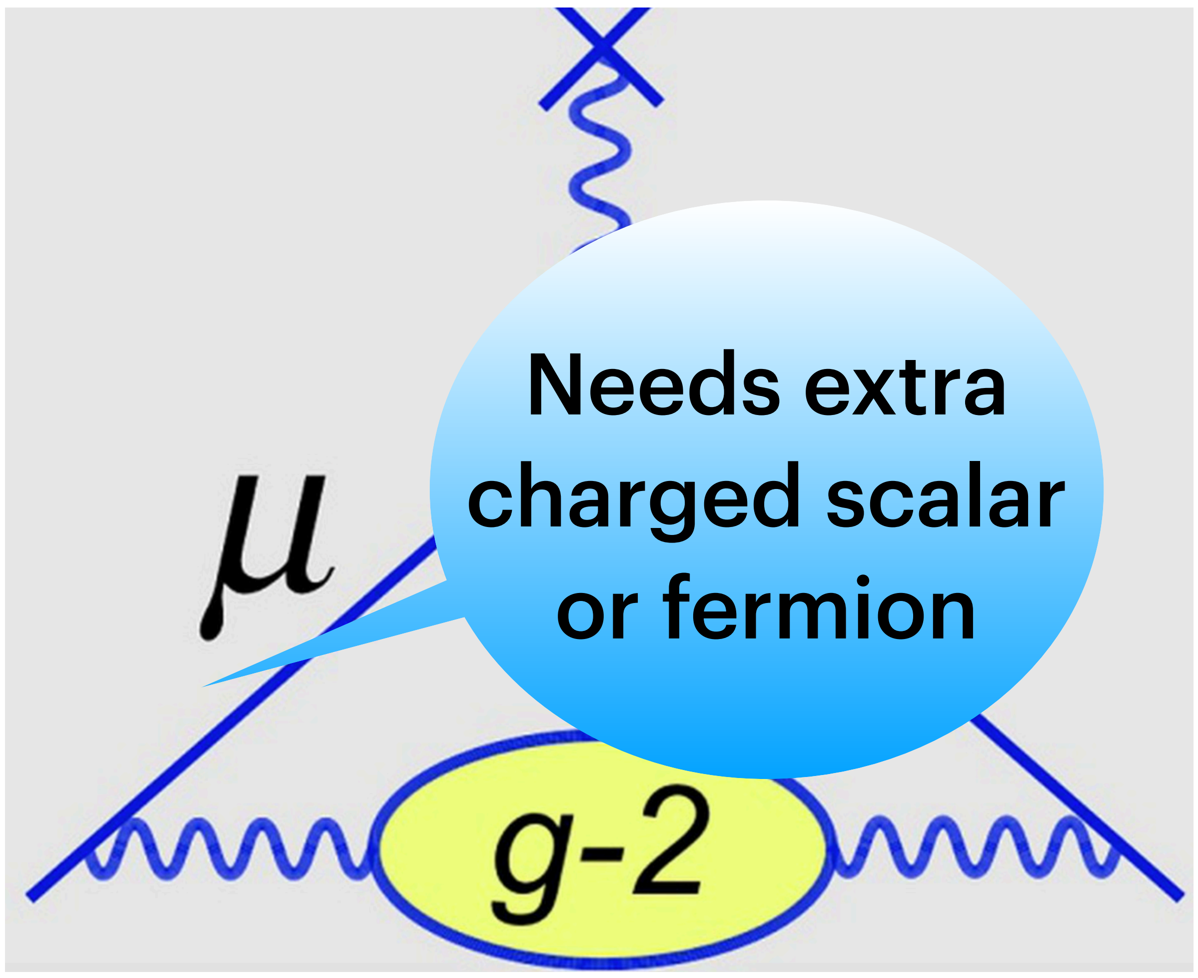
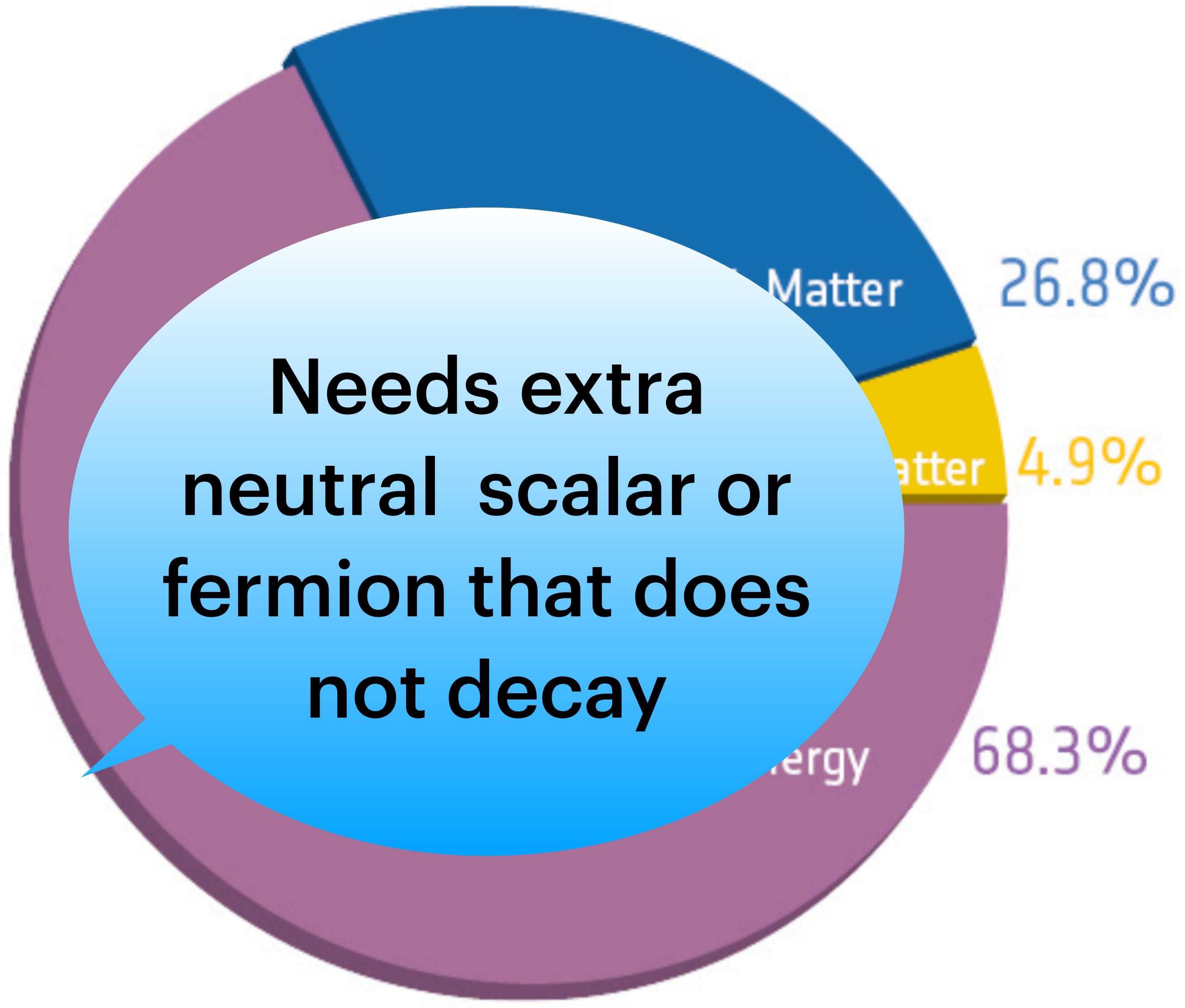


Muon-(g-2) anomaly



Indirect evidence of Dark Matter



Stability bounds

- Higgs couples to fermions via Yukawa couplings $\mathcal{L}_Y = Y_t \bar{Q} \phi t_R$
- At low field values the top quark contribution is important $\mu \frac{d\lambda}{d\mu} \simeq -\frac{3}{8\pi^2} Y_t^4$
- The solution takes a form, $\lambda(\mu) = \lambda - \frac{3}{8\pi^2} \lambda_t^4 \ln \frac{\mu}{v}$, where at some point we hit $\lambda(\mu) < 0$, leading instability to Higgs potential

$$m_h^2 > \frac{3m_t^2}{\pi^2 v^2} \ln \frac{\Lambda}{v}$$

- In the Coleman-Weinberg's effective potential approach the RG-improved potential can be written as

$$V_{\text{eff}}(h,\mu) \simeq \lambda_{\text{eff}}(h,\mu) \frac{h^4}{4}, \quad \text{with } h \gg v\,,$$

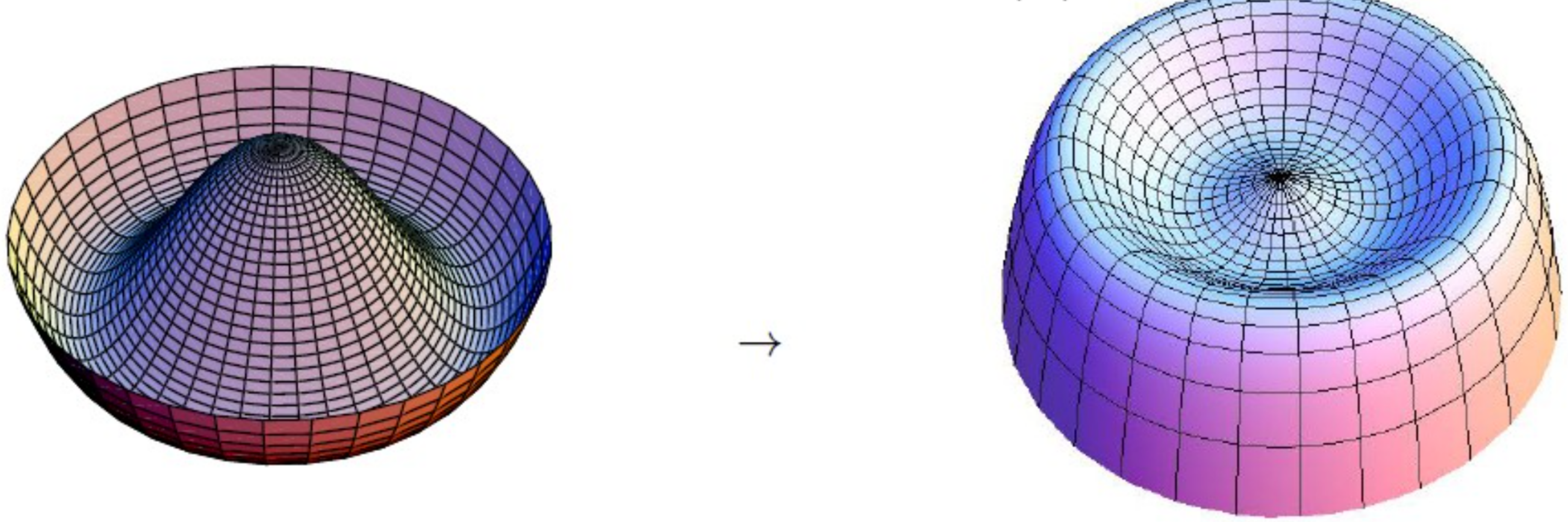
- Where λ_{eff} assimilates the loop effects

$$\lambda_{\text{eff}}(h,\mu) \simeq \underbrace{\lambda_h(\mu)}_{\text{tree-level}} + \underbrace{\frac{1}{16\pi^2} \sum_{\substack{i=W^\pm,Z,t,\\ h,G^\pm,G^0}} n_i \kappa_i^2 \left[\log \frac{\kappa_i h^2}{\mu^2} - c_i\right]}_{\text{Contribution from SM}}$$

Stability of the potential

Stability	Meta-stability	Instability
$\lambda_{\text{eff}} > 0$	$0 > \lambda_{\text{eff}}(\mu) \gtrsim \dfrac{-0.065}{1 - 0.01 \log\left(\frac{v}{\mu}\right)}$	More negative λ_{eff}

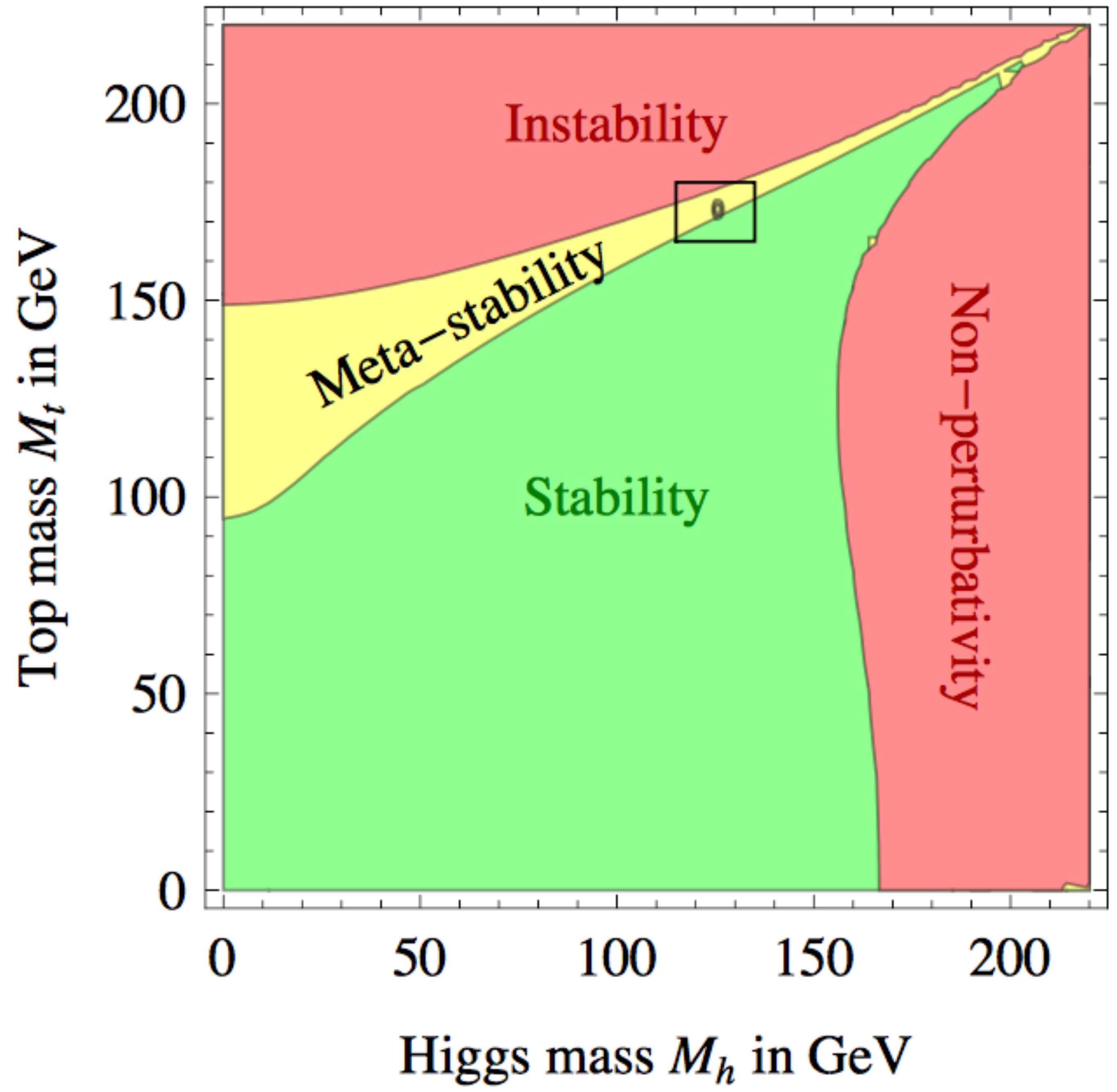
G. Isidori et. al.: NPB 609 (2001) 387

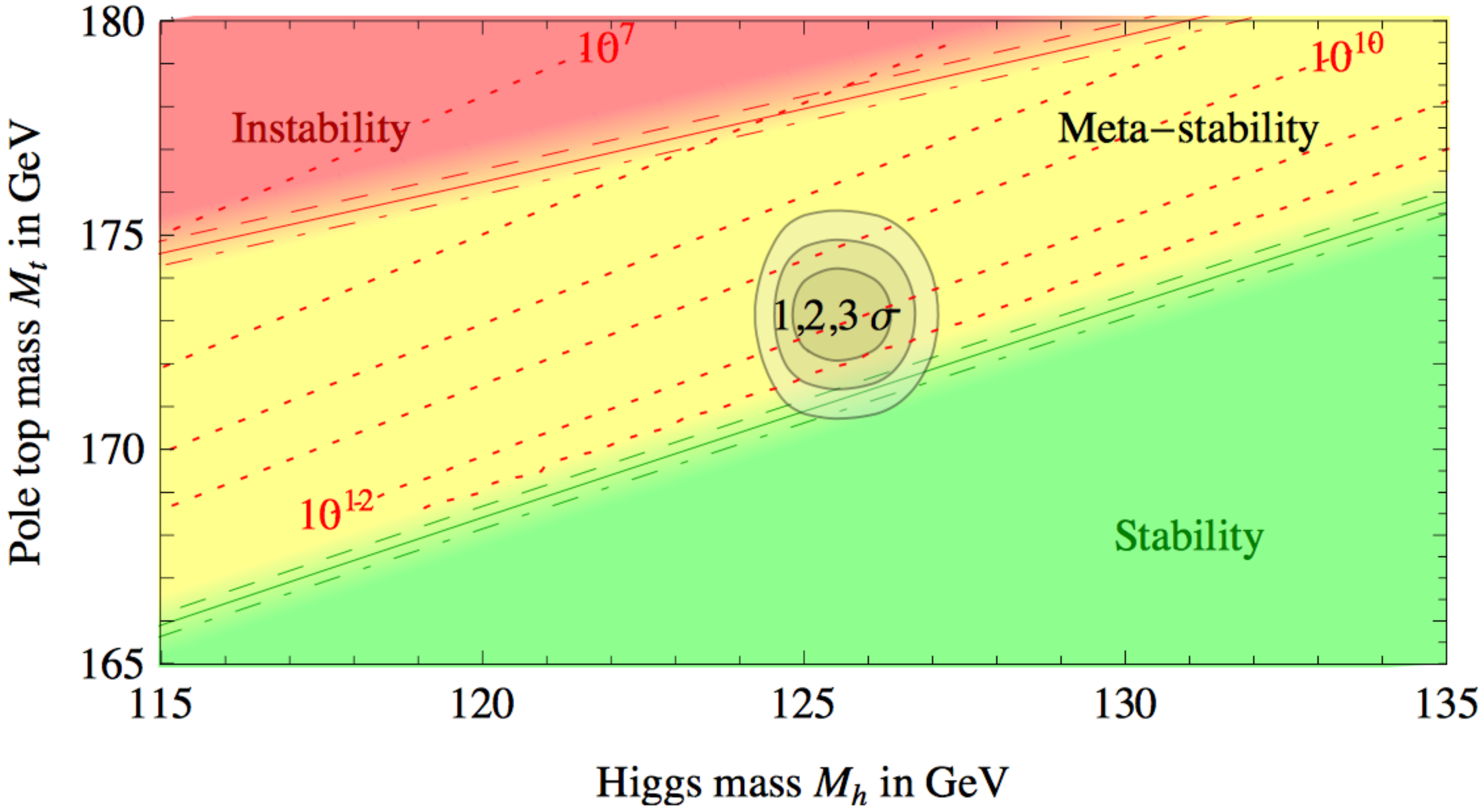


If your mexican hat turns out to be a dog bowl you have a problem...

from A. Strumia

Status of SM





Within the uncertainty of top mass we are in a metastable vacuum

Degrassi et. al. :JHEP 1208, 098 (2012)

What is the rescue?

Addition of scalars: Inert doublet and Inert Triplet

- Any scalar extension of SM will enhance the vacuum stability due to positive quantum correction to λ_{eff}
- Singlet extensions are widely studied

Gonderinger et al., Costa et al., Haba et al., Barger et al., Khan et al. Baek et al.

- We will consider Inert Higgs doublet (Type-I) and Inert Triplet (Y=0) models
- Both the extra SU(2) doublet (Φ_2) and triplet (T) are odd under Z_2 and provide the much needed dark matter candidate
- Inert Higgs doublet:

$$\begin{aligned} V_{\text{scalar}} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ &+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\lambda_5((\Phi_1^\dagger\Phi_2)^2) + h.c], \end{aligned}$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

← Φ_2 is Z_2 odd, does not get vev

- New Higgs bosons $A, H, H^\pm$ are predicted
- The lightest neutral one can be a dark matter candidate

PB, Shilpa Jangid: Eur.Phys.J.C 80 (2020) 8, 715

Addition of scalars: Inert Triplet

- Inert Triplet model: SM is extended Z_2 odd with a Y=0, SU(2) Triplet T

$$T = \frac{1}{2}\begin{pmatrix} T_0 & \sqrt{2}T^+ \\ \sqrt{2}T^- & -T_0 \end{pmatrix} \qquad V = m_h^2\Phi^\dagger\Phi + m_T^2 Tr(T^\dagger T) + \lambda_1|\Phi^\dagger\Phi|^2 + \lambda_t(Tr|T^\dagger T|)^2 + \lambda_{ht}\Phi^\dagger\Phi Tr(T^\dagger T)$$

Z_2 odd, does not get vev

- We have $T_0, T^\pm$ extra Higgs bosons which are degenerated at the tree-level
- Breaks by a quantum mass splitting of $\Delta m = (m_{T^\pm} - m_{T^0}) \simeq 166\,\mathrm{MeV}$

Cirelli et al.: NPB753 (2006) 178

- T_0 is dark matter candidate
- $T^\pm \to \pi^\pm T_0$ predicts displaced pion charged track with ~ cm decay length which can be detected at the LHC

PB, Shilpa Jangid: Eur.Phys.J.C 80 (2020) 8, 715

Addition of scalar makes EW vacuum stable

- Unlike fermions, addition of the scalars make the potential more stable
- The RG-improved effective potential gets contributions from IDM/ITM as

$$V_{\rm eff} = V_0 + V_1^{\rm SM} + V_1^{\rm IDM/ITM}$$

- The effective potential in the SM Higgs direction can be written as

$$V_{\rm eff}(h,\mu) \simeq \lambda_{\rm eff}(h,\mu)\frac{h^4}{4}, \quad \text{with } h \gg v,$$

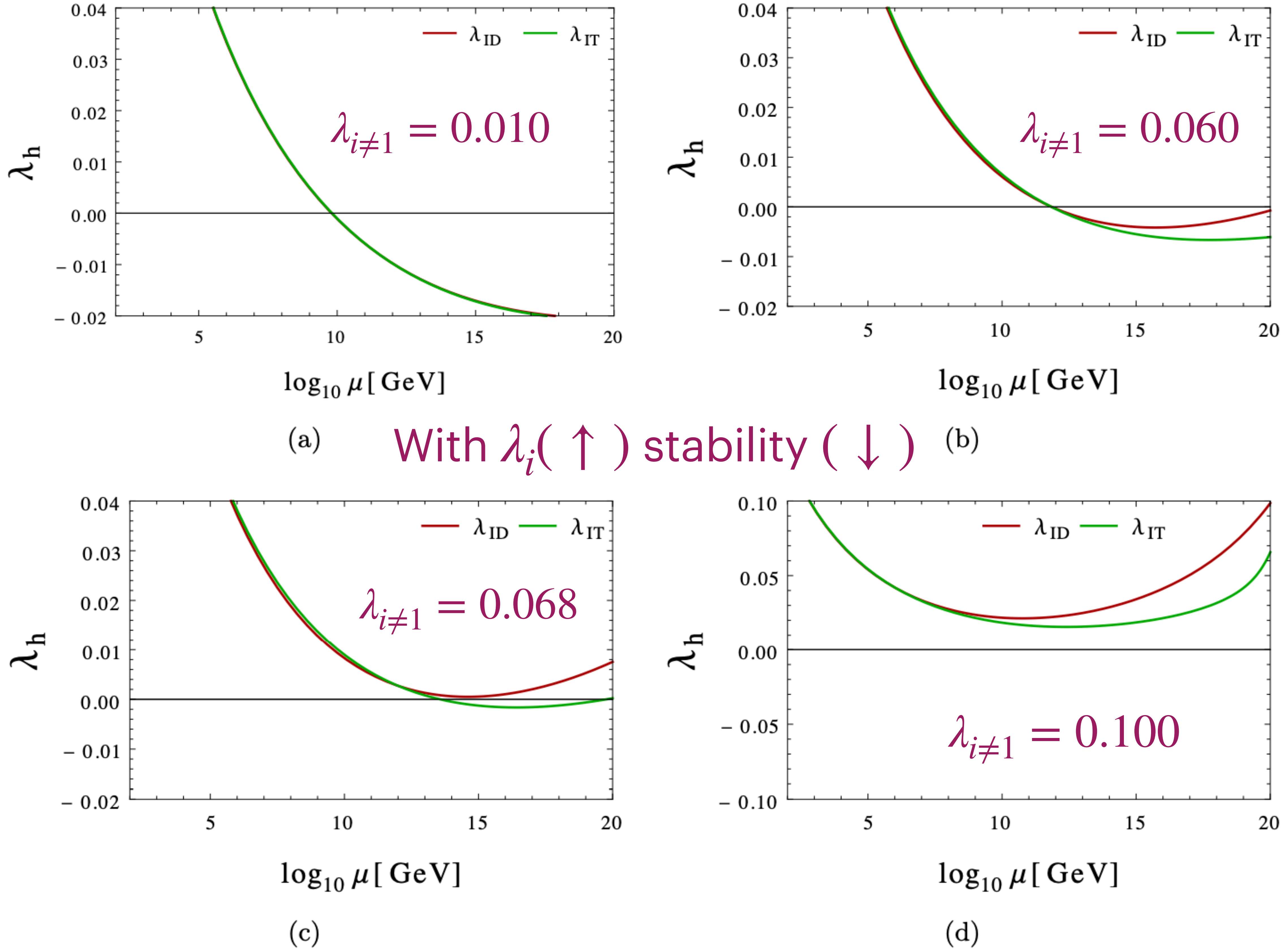
- The $\lambda_{\rm eff}$ gets positive contributions from extra scalars which counters the negative effect of the top quark

$$\lambda_{\rm eff}(h,\mu) \simeq \underbrace{\lambda_h(\mu)}_{\text{tree-level}} + \underbrace{\frac{1}{16\pi^2}\sum_{\substack{i=W^\pm,Z,t,\\ h,G^\pm,G^0}} n_i\kappa_i^2\left[\log\frac{\kappa_i h^2}{\mu^2} - c_i\right]}_{\text{Contribution from SM}} + \underbrace{\frac{1}{16\pi^2}\sum_{i=H,A,H^\pm} n_i\kappa_i^2\left[\log\frac{\kappa_i h^2}{\mu^2} - c_i\right]}_{\text{Contribution from IDM/ITM}};$$

PB, Shilpa Jangid: Eur.Phys.J.C 80 (2020) 8, 715

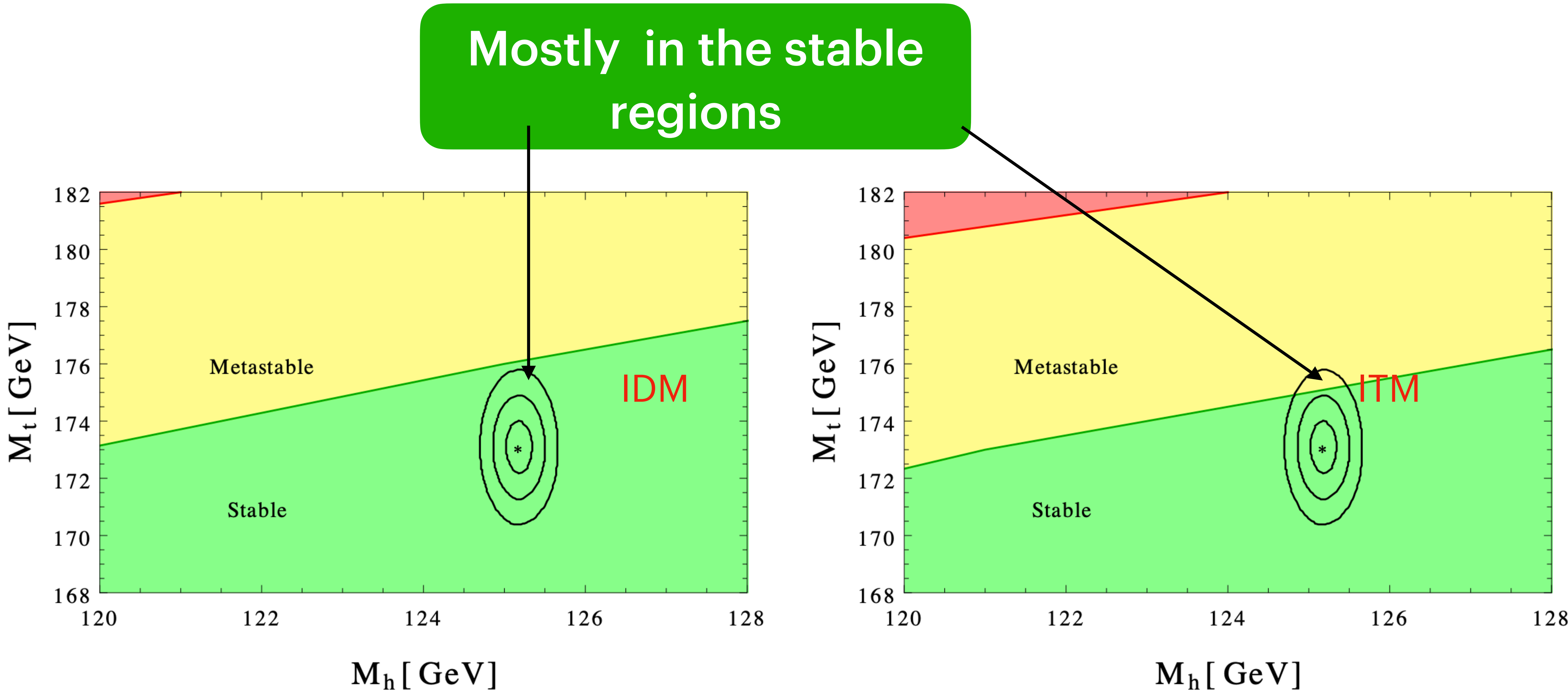
Addition of scalar makes EW vacuum stable

- At one-loop $\lambda_h = \lambda_1$ gets contributions from IDM/ITM and stabilise the vacuum



$$\beta_{\lambda_1}^{\mathrm{IDM}} = \frac{1}{16\pi^2}\left[2\lambda_3^2 + 2\lambda_3\lambda_4 + \lambda_4^2 + 4\lambda_5^2\right].$$

$$\beta_{\lambda_1}^{\mathrm{ITM}} = \frac{1}{16\pi^2}\left[8\lambda_{ht}^2\right].$$



- Higher λ_i are constrained from perturbativity

PB, Shilpa Jangid: EJC 80 (2020) 8, 715

- Models with Type-I, III Seesaw fermions are severely constraints and need extra scalar to stabilise the potential

Type-I →PB, Shilpa Jangid, Bhupal Dev, Arjun Kumar: JHEP 08 (2020) 154
Type-III →PB, Shilpa Jangid, Manimal Mitra: JHEP 02 (2021) 075

Any special scalar is more motivated ?

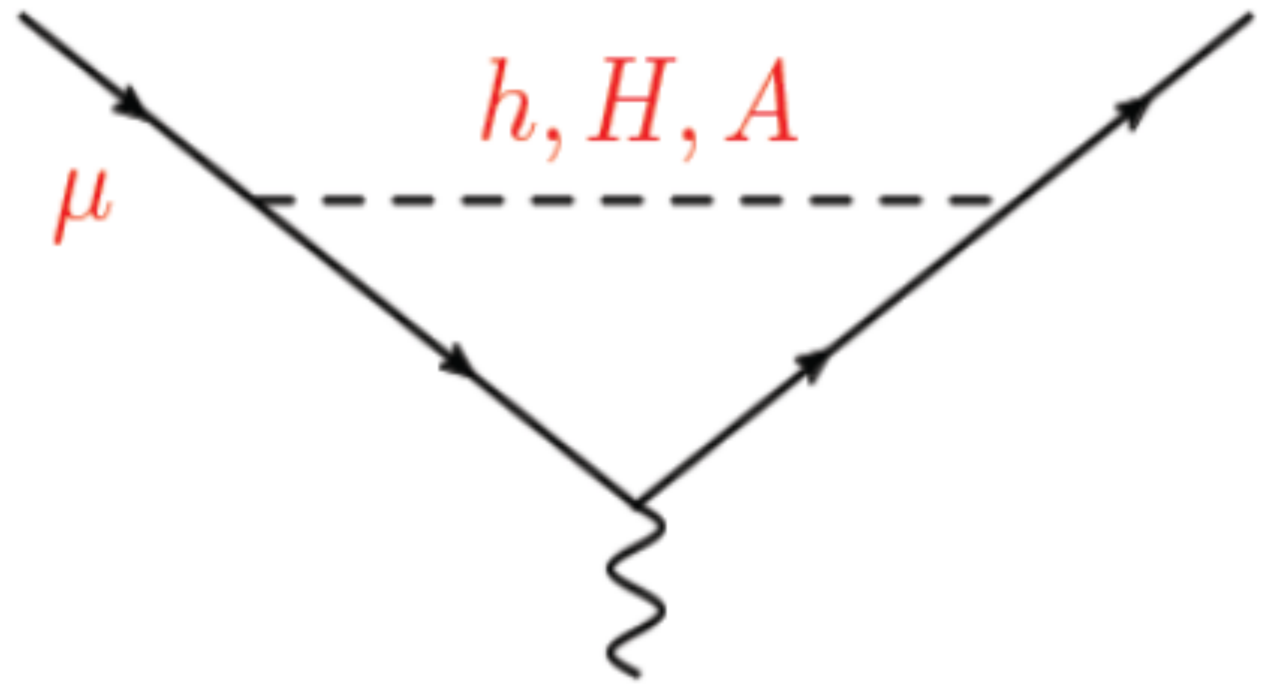
Muon-(g-2):Type-X 2HDM

- The Type-X model is a unique option to explain the muon-(g − 2) anomaly

- Muon-(g-2) measurement at FNAL has 4.2σ discrepancy with the SM value

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

FNAL: PRL126(2021)141801



- A light scalar that couples with lepton can contribute with enhanced Yukawa coupling $\simeq \tan\beta$

- The light pseudoscalar and light charged Higgs boson can still be allowed for Type X

Broggio, Chun, Passera, Patel,Vempati: JHEP 1411 (2014) 058
Chun et al.: PLB779 (2018) 201-205,PLB774 (2017) 20-25 , JHEP 1511 (2015) 099,

Muon-(g-2): Type-X 2HDM

- $B \to X_s \gamma$ does not put bounds on the charged Higgs mass for $\tan\beta > 2$
- Type-X at large $\tan\beta$, being hadrophobic is illusive at the LHC
- $B_s \to \mu^+\mu^-$ is unaffected for $m_A \gtrsim 15\,\mathrm{GeV}$
- Strong constraints come from the lepton universality on $\dfrac{\tan\beta}{m_{H^\pm}}$
- $m_A \lesssim 70\,\mathrm{GeV},\ \tan\beta \lesssim 65$ region is allowed

Abe et. al. : 1504.07-59,
Cao et. al. : 0909.5148
Krawczyk et. al. : 0410248

- But in a simple extension we don't have the dark matter
- A scalar dark matter extension with Type-X 2HD can essentially address the issue of Dark Matter

PB, Eung Jin Chun, Rusa Mandal: PLB 779 (2018) 201-205

- A light charged Higgs of Type-X can have interesting phenomenology with inverse seesaw mechanism

PB, Eung Jin Chun, Rusa Mandal: JHEP 08 (2019) 169

A scalar extension of Type-X 2HDM to address the issue of dark matter

Type-X 2HD with a scalar Dark Matter

- A large parameter space of Type-X 2HDM allowed within $\tan\beta > 30$ and $m_A << m_H, m_{H^\pm} \sim 200 - 400\,\mathrm{GeV}$
- A light pseudoscalar is still a possible scenario
- We introduce a scalar dark matter S with Z_2 odd symmetry of $S \to -S$ which stabilises it
- $$\begin{aligned} V = & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_1\Phi_2^\dagger) \\ & + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\ & + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_1\Phi_2^\dagger)^2\right] \\ & + \frac{1}{2}m_0^2 S^2 + \frac{\lambda_S}{4}S^4 + S^2\left[\kappa_1|\Phi_1|^2 + \kappa_2|\Phi_2|^2\right], \quad (1) \end{aligned}$$

DM self Coupling

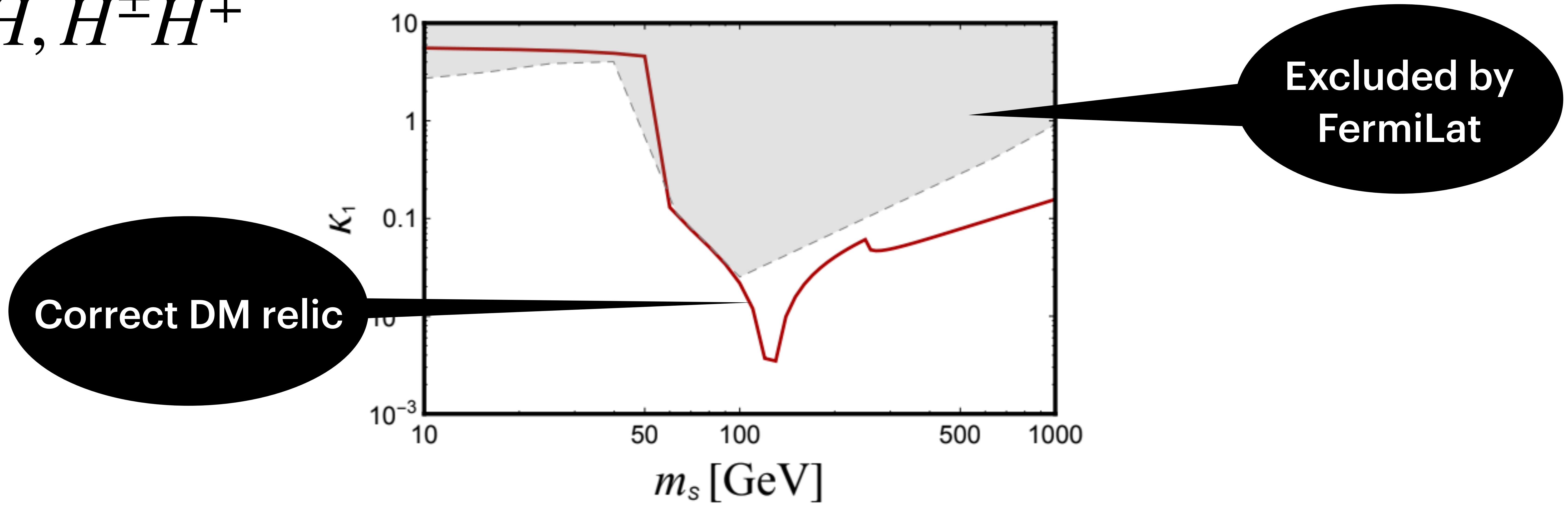
Higgs-DM couplings

- The nucleonic scattering and self-annihilation are featured separately by individual couplings of dark matter to the two Higgs doublets.

PB, Rusa Mandal, Eung Jin Chun
Phys.Lett. B779 (2018) 201-205

Type-X 2HD with a scalar Dark Matter

- κ_1 can be adjusted to obtain the correct relic which is via $SS \to AA, \tau\tau, HH, H^{\pm}H^{\mp}$



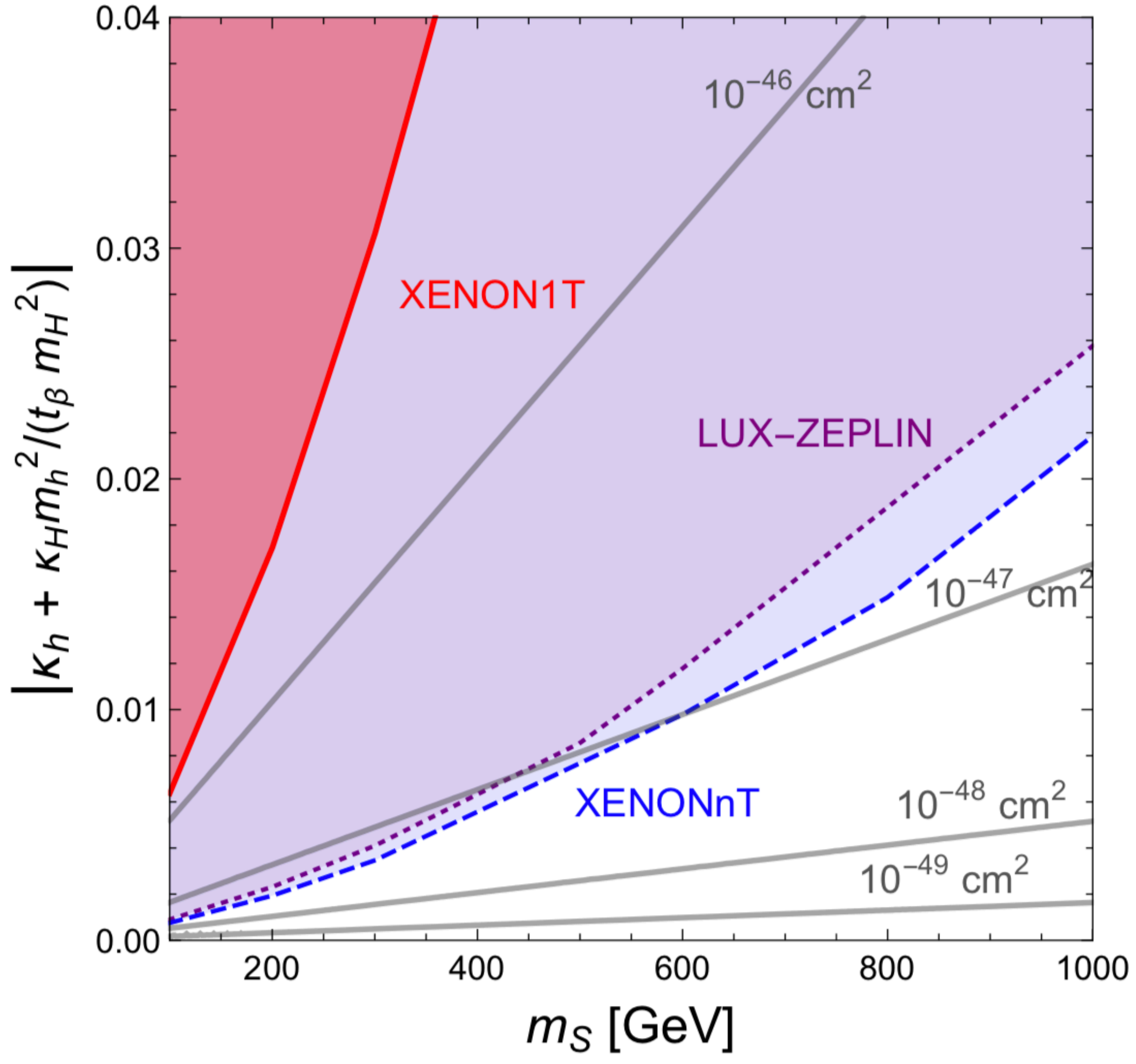
- κ_2 is strongly constrained by the direct DM detection
- The spin-independent (SI) nucleonic cross-section of the DM is given by

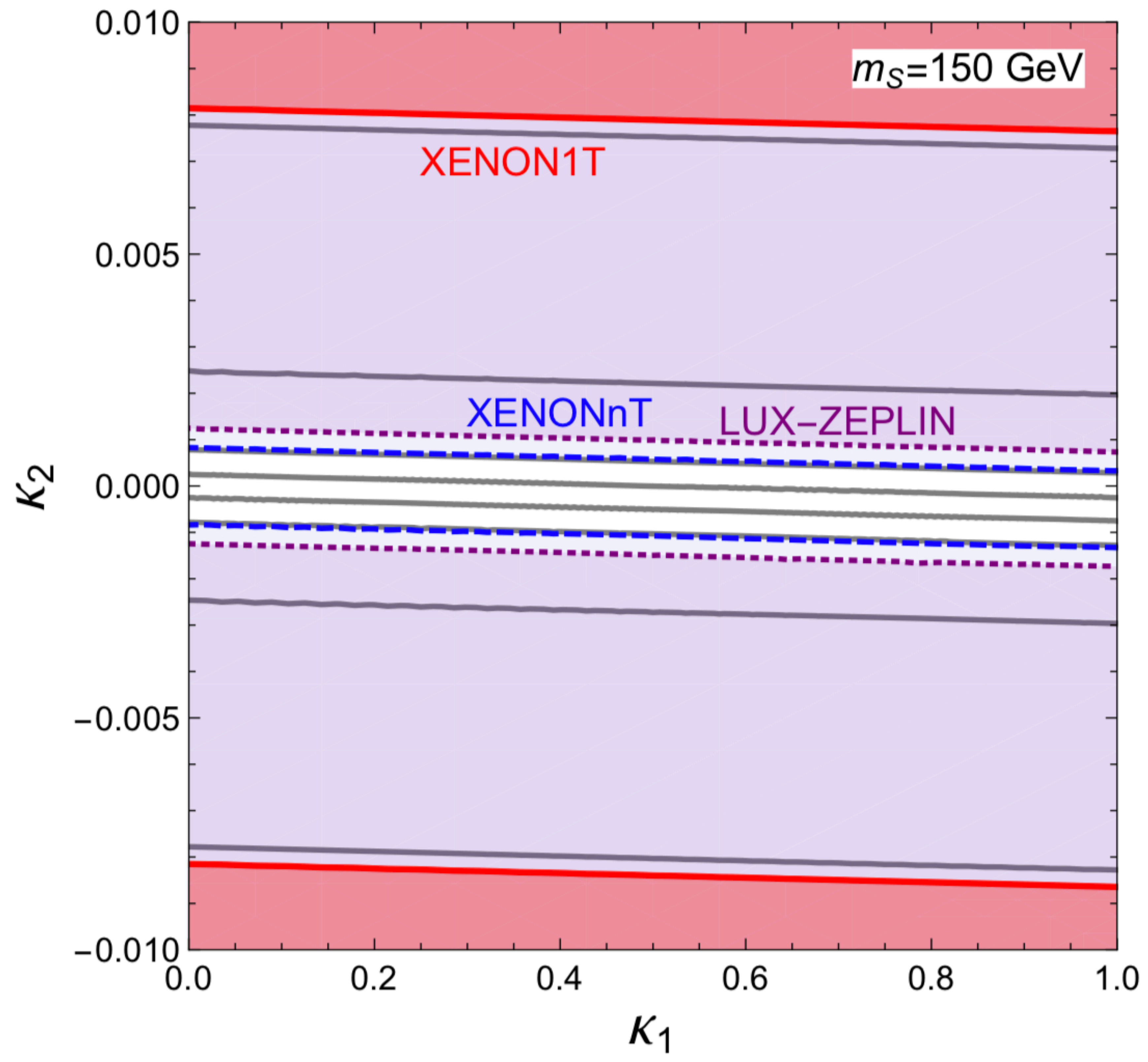
$$\sigma_N = \frac{m_N^2 v^2}{\pi(m_S + m_N)^2}\left(\frac{\kappa_h g_{NNh}}{m_h^2} + \frac{\kappa_H g_{NNH}}{m_H^2}\right)^2, \quad g_{NNh} \approx 0.0011 \;\; \text{and } g_{NNH} \approx g_{NNh}/t_\beta$$

PB, Rusa Mandal, Eung Jin Chun
Phys.Lett. B779 (2018) 201-205

Type-X 2HD with a scalar Dark Matter

$t_\beta >> 1, \; \kappa_h \simeq \kappa_2, \; \kappa_H \simeq 0$





- For $t_\beta >> 1$ and $m_H > m_h$, the combined coupling is dominated simply by κ_2
- Thus strongly it is constrained as in the SM Higgs-portal scenario

PB, Rusa Mandal, Eung Jin Chun
Phys.Lett. B779 (2018) 201-205

Can we address the neutrino mass generation with Type-X?

Type-X in Inverse Seesaw

- We can add a Type-X two-Higgs doublet along with two right-handed Majorana neutrinos

$$-\mathcal{L} = (Y_u \bar{Q}_L \tilde{\Phi}_2 u_R + Y_d \bar{Q}_L \Phi_2 d_R + Y_l \bar{\ell}_L \Phi_1 e_R + Y_N^{(\prime)} \bar{\ell}_L \tilde{\Phi}_{1,2} N_R + M_N \bar{N}_R^c S_2 + \text{h.c.}) + \mu \bar{S}_2^c S_2 + V(\Phi_1, \Phi_2).$$

$$\Phi_{1,2} = \begin{pmatrix} \phi_{1,2}^+ \\ \frac{1}{\sqrt{2}}(v_{1,2} + h_{1,2} + i a_{1,2}) \end{pmatrix} \qquad \tilde{\Phi}_2 = i\sigma_2 \phi_2^*$$

- After EWSB, the neutrino mass spectrum looks like

$$-\mathcal{L}_m^\nu = \mu \bar{S}_2^c S_2 + m_D \bar{\nu}_L N_R + M_N \bar{N}_R^c S_2 + \text{h.c.},$$

- Where $m_D = Y_N^{(\prime)} v_{1,2}/\sqrt{2}$ for Type-X$^{(\prime)}$ respectively
- In the basis of ν_L^c, N_R, S_2 the neutrino mass matrix looks like

$$m_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_N \\ 0 & M_N^T & \mu \end{pmatrix}$$

PB, Rusa Mandal, Eung Jin Chun
JHEP 1908 (2019) 169

Inverse Type-I Seesaw with Type-X

- We work in the SM limit of the theory where $\sin(\beta - \alpha) \to 1$

$$-\mathcal{L}_{int}^{\text{Type-X}} = Y_N \bar{\ell}_L \tilde{\Phi}_1 N_R \quad \text{and} \qquad -\mathcal{L}_{int}^{\text{Type-X}'} = Y'_N \bar{\ell}_L \tilde{\Phi}_2 N_R$$

SM lepton like coupling

- In Type-X:

$$\bar{\ell}_L H^- N_R : \qquad iY_N \sin\beta \left[\bar{\ell}_L H^- N_R + \text{h.c.}\right],$$

$$\bar{\nu}_L A N_R : \qquad \frac{-Y_N \sin\beta}{\sqrt{2}} \left[\bar{\nu}_L A N_R + \text{h.c.}\right]$$

Enhanced at high tanβ

- In the high $\tan\beta$ region $H^\pm \to \ell^\pm N_R$ and $N_R \to A\,\nu_L$ modes are enhanced
- It can have a light pseudoscalar $m_A \sim 50\,\text{GeV}$

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Inverse Type-I Seesaw with Type-X

- The charged Higgs boson has been search via $\nu\,\tau,\ t\,b$ decay modes
- The Type-X charged Higgs production is low due to reduced couplings with the quarks at high $\tan\beta$
- The Type-X charged Higgs remains illusive and can be light also
- The Type-X charged Higgs mostly decays into $AW^{\pm}$ and $\ell^{\pm}\mathrm{N_R}$
- For collider study the chosen benchmark points have $m_{H^{\pm}} \sim 250\,\mathrm{GeV}$ and $m_A \sim 200, 100, 50\,\mathrm{GeV}$

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Final states at the LHC

- We look into the associate pseudoscalar production

$$pp \to AH \to \tau\bar{\tau}N_i\nu_i \to \tau\bar{\tau}W^{\pm}\ell_i^{\mp}\nu_i \to \tau\bar{\tau}\ell_j^{\pm}\nu_j\ell_i^{\mp}\nu_i,$$

$$pp \to AH^{\pm} \to \tau\bar{\tau}N_i\ell_i^{\pm} \to \tau\bar{\tau}W^{\pm}\ell_i^{\mp}\ell_i^{\pm} \to \tau\bar{\tau}\ell_j^{\pm}\nu_j\ell_i^{\mp}\ell_i^{\pm}$$

- $2\tau + 2\ell$ and $2\tau + 3\ell$ are looked into at the LHC

- For light pseudo scalar $4\tau + X$ final states are looked into via $N \to A\,\nu$ decay

$$H^{\pm}H \to Ne^{\pm}N\nu \to 2A + e^{\pm} + 3\nu \to 4\tau + e^{\pm} + \not{p}_T$$

$$H^{\pm}H^{\mp} \to Ne^{+}Ne^{-} \to 4\tau + OSE + \not{p}_T$$

$$AH \to \tau\tau N\nu \to 4\tau + \not{p}_T$$

$$AH^{\pm} \to \tau\tau Ne^{\pm} \to 4\tau + e^{\pm} + \not{p}_T$$

- The inverse seesaw Yukawa coupling is shown to be probed down to $Y_N \sim 0.2$ at HL-LHC with 3000 fb^{-1}

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Drop Type-X
and focus more on
the interplay of Dark matter and neutrino

Freeze-out via RHN

Type-I Seesaw with B-L gauge extension

- We introduce three SM right-handed neutrinos and two SM singlet scalars which are charged under an extended gauge group of $U(1)_{B-L}$

	Q	u^c, d^c	L	e^c	N_i	S	$\phi_{\rm DM}$
$B-L$	$1/3$	$-1/3$	-1	1	-1	2	$q_{\rm DM}$

B-L scalar

RHN

$$\mathcal{L}_{\rm NP} = -m_S^2|S|^2 - \frac{1}{2}\lambda_{SH}|S|^2|\Phi|^2 - \lambda_S(S^\dagger S)^2 - \lambda_{N_i} S\bar{N}_i^c N_i - y_{ij}\bar{L}_i\Phi^\dagger N_j$$
$$- m_D^2|\phi_{\rm DM}|^2 - \frac{1}{2}\lambda_{DH}|\phi_{\rm DM}|^2|\Phi|^2 - \frac{1}{2}\lambda_{DS}|\phi_{\rm DM}|^2|S|^2 - \lambda_D({\phi_{\rm DM}}^\dagger\phi_{\rm DM})^2.$$

Scalar DM

- Type-I Seesaw also generates small neutrino mass

$$\mathcal{M}^\nu_{ij} = y_{ik}y_{jk}\frac{\langle\Phi\rangle^2}{m_{N_k}}.$$

PB, EungJin Chun, Rusa Mandal: PRD 97 (2018) no.1, 015001

Higgs portal dark matter in $U(1)_{B-L}$ with RHN

- We assume vanishing mixing between h, S_0

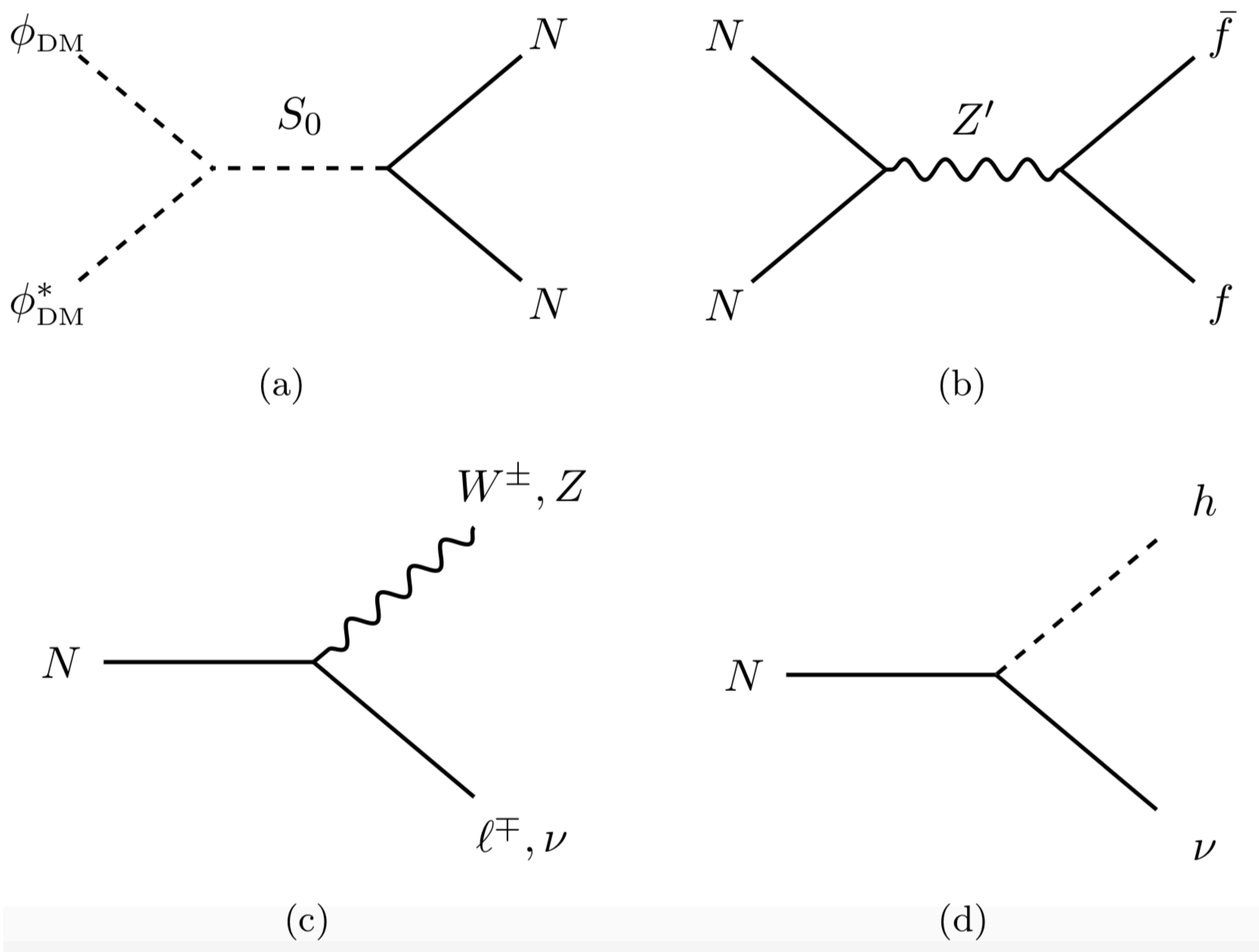
  $\implies \cos\alpha \sim 1$

- The dominant annihilation modes

$$\frac{dY_{\rm DM}}{dx} = -\frac{1}{x^2}\frac{s(m_{DM})}{H(m_{DM})}\langle\sigma v\rangle_{\phi_{\rm DM}\,\phi^*_{\rm DM}\to NN}\left(Y^2_{\rm DM} - Y^2_N\right),$$

$$\frac{dY_N}{dx} = \frac{1}{x^2}\frac{s(m_{DM})}{H(m_{DM})}\langle\sigma v\rangle_{\phi_{\rm DM}\,\phi^*_{\rm DM}\to NN}\left(Y^2_{\rm DM} - Y^2_N\right)$$
$$- \frac{1}{x^2}\frac{s(m_{DM})}{H(m_{DM})}\langle\sigma v\rangle_{NN\to f\bar f}\left(Y^2_N - Y^{\rm eq2}_N\right) - \frac{\Gamma}{H(m_{DM})}x\left(Y_N - Y^{\rm eq}_N\right)$$

$$s(m_{DM}) = \frac{2\pi^2}{45}g_*\,m^3_{DM}, \quad H(m_{DM}) = \frac{\pi}{\sqrt{90}}\frac{\sqrt{g_*}}{M^r_{pl}}m^2_{DM}; \quad M^r_{pl} = 2.44\times 10^{18}\ \text{GeV}$$

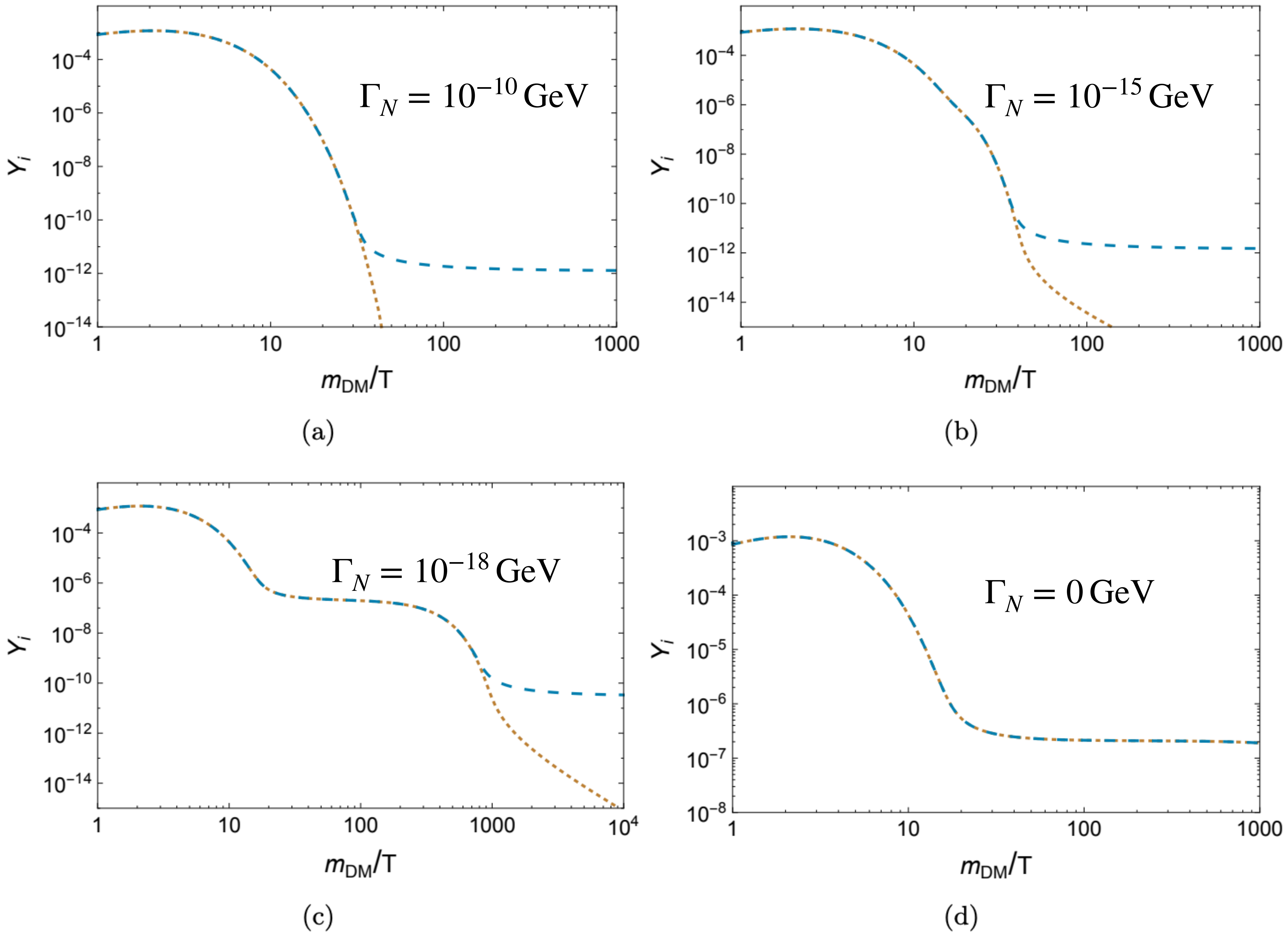


- $Y^{\rm eq}_N$ is the equilibrium number density of RHN

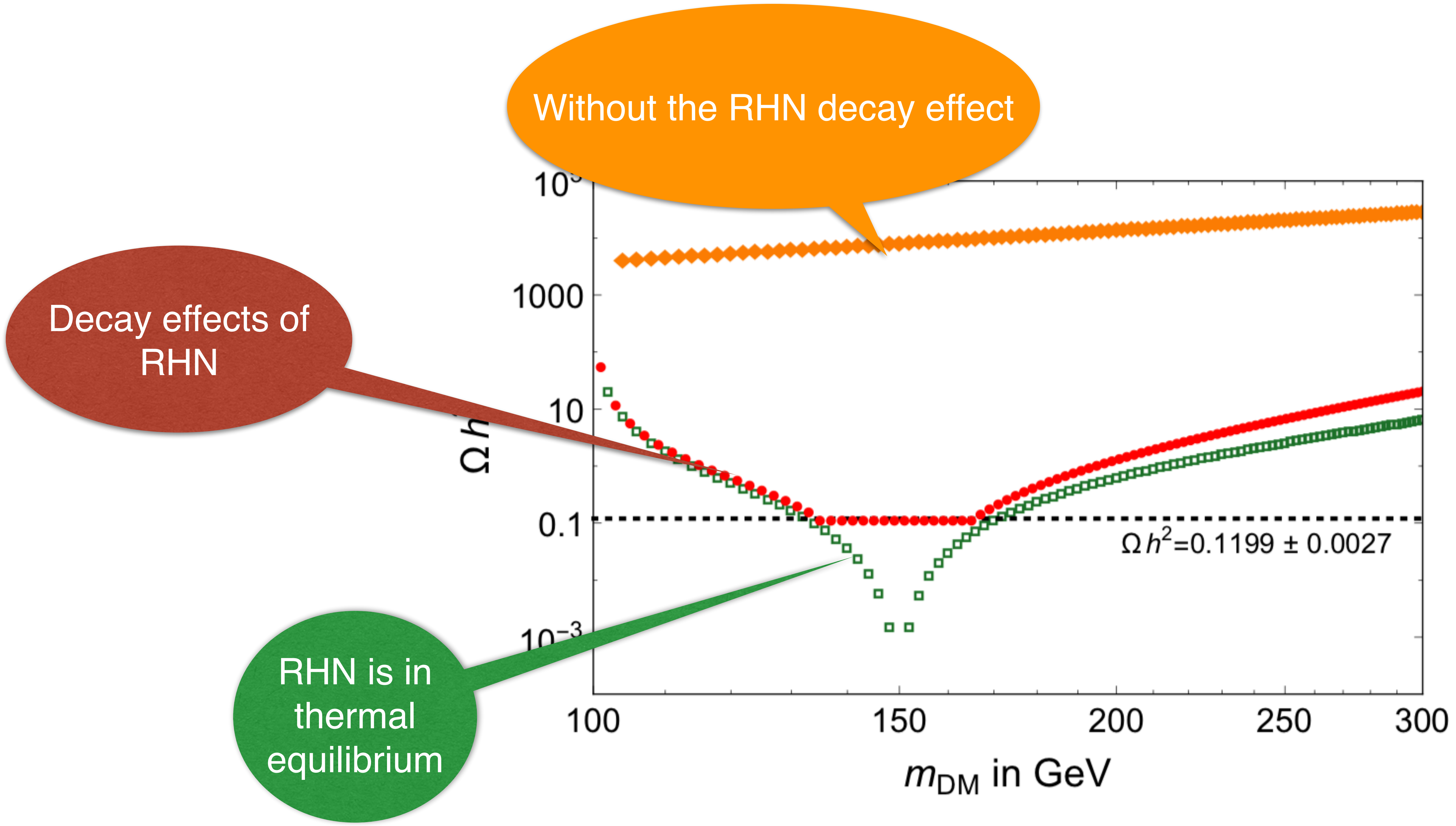
PB, EungJin Chun, Rusa Mandal:
PRD 97 (2018) no.1, 015001

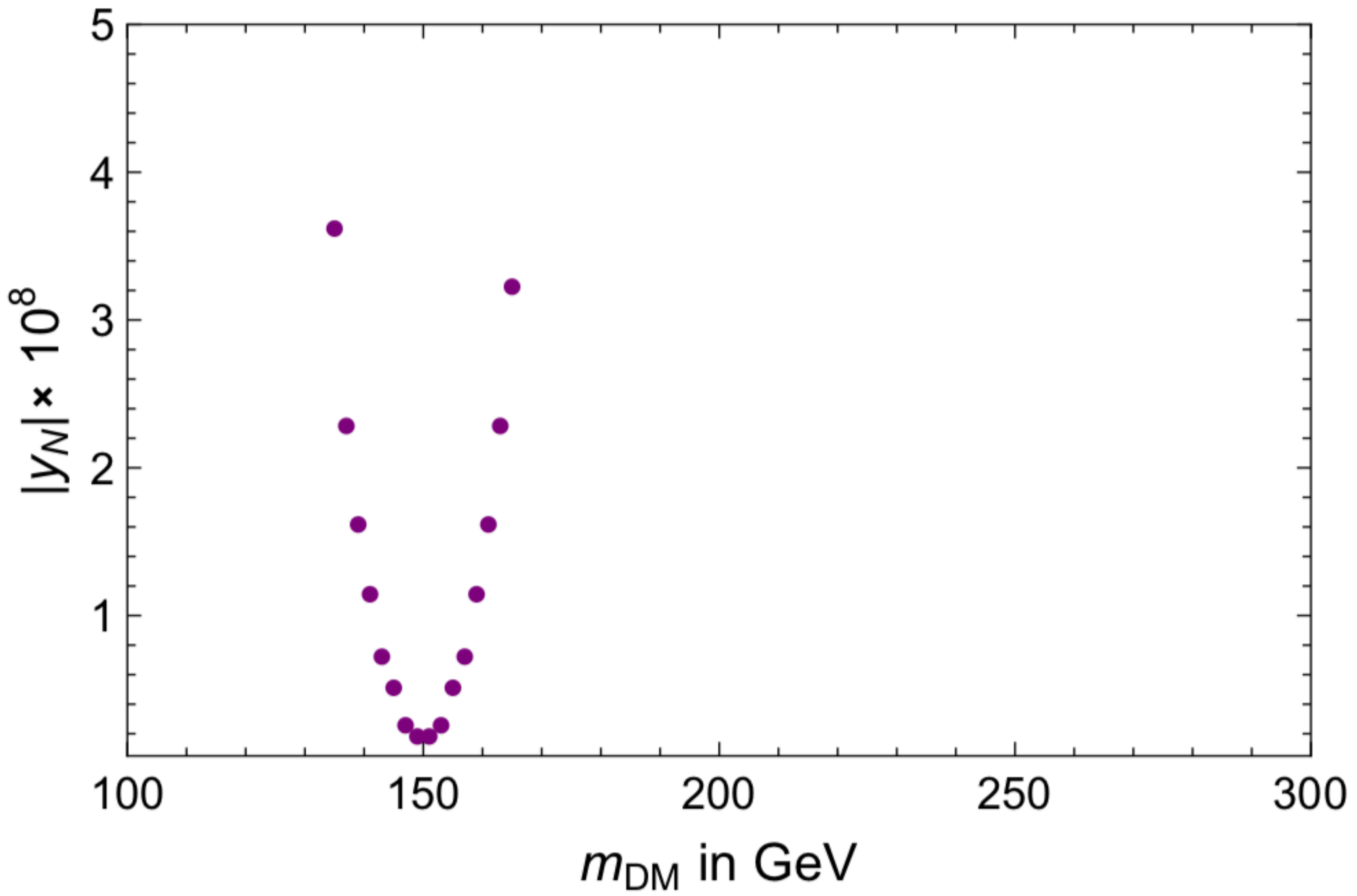
Higgs portal dark matter in $U(1)_{B-L}$ with RHN

- $Y_{\Phi_{\rm DM}}$ is in blue
- Y_N is in brown
- The late decay effect of RHN is visible $\Gamma_N \lesssim 10^{-18}\,\mathrm{GeV}$



Higgs portal dark matter in $U(1)_{B-L}$ with RHN





- The RHN decay effect is visible for $Y_N \lesssim 10^{-8}$ for $m_N \sim 100\,\mathrm{GeV}$
- Thus one neutrino can be very light and one has to rely on the loop induced mass generation

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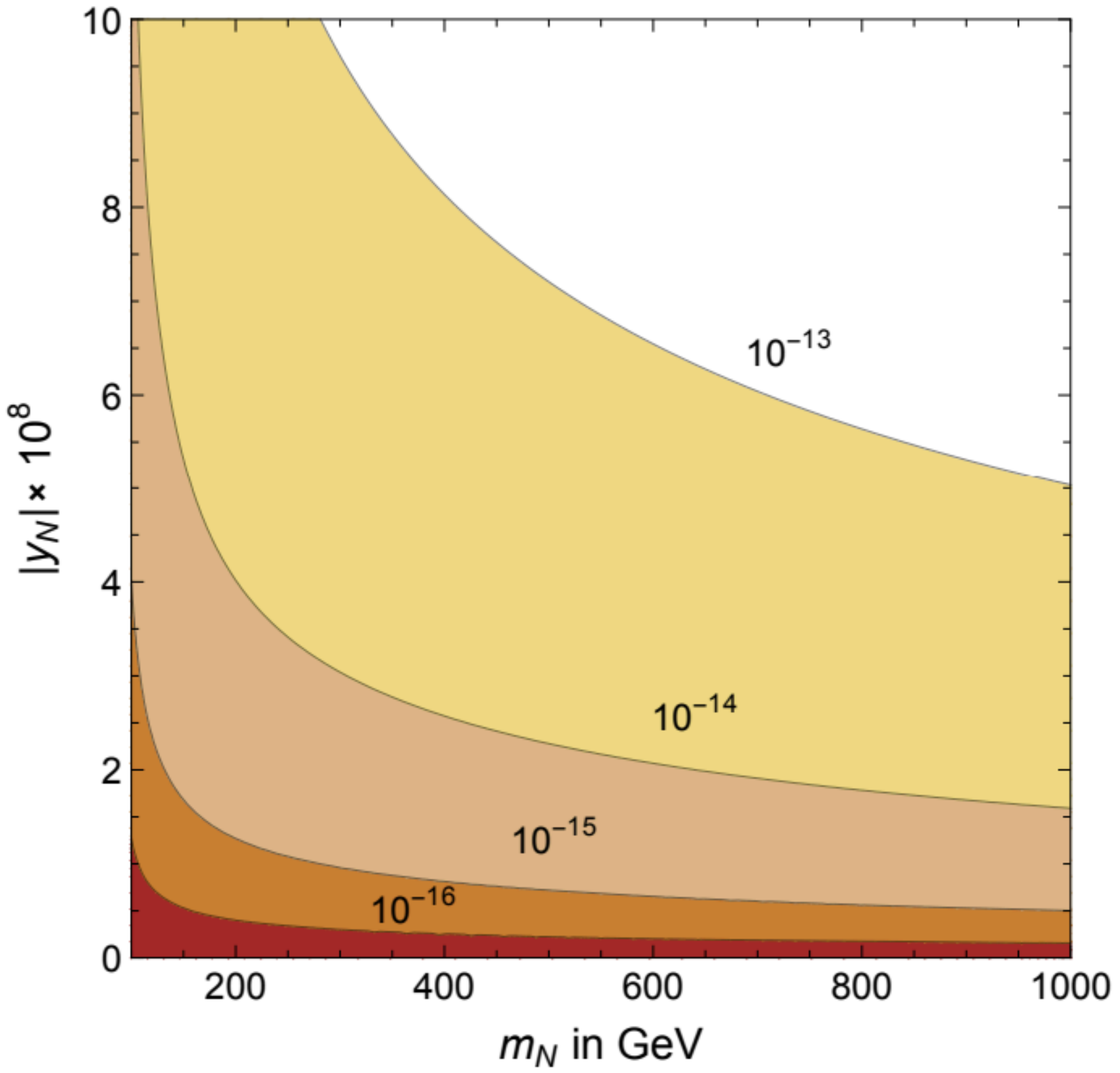
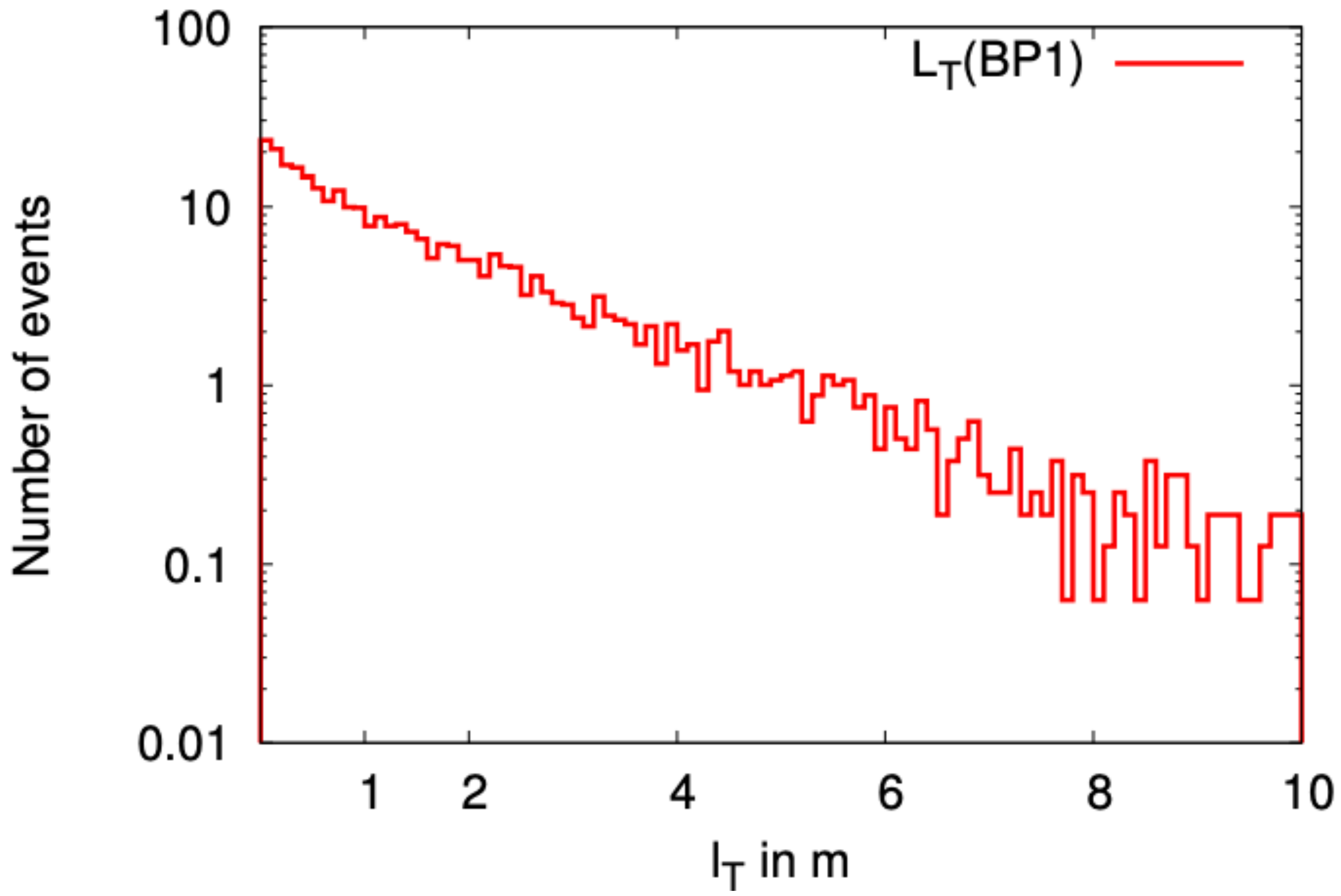
Displaced decay signature of RHN





- Dominant decay modes are $N \to W^{\pm}\ell^{\mp}, Z\nu, h\nu$
- Thus from $pp -> N_i N_i$ and RHN decays we expect displaced di- and tri-lepton signatures along with dispaclced jets

PB, EungJin Chun, Rusa Mandal:
PRD 97 (2018) no.1, 015001

Right-handed neutrino portal

Right-Handed Neutrino portal Dark Matter

- The RHN as a portal to DM was suggested in a simple setup assuming the coupling among RHN, fermion χ and scalar ϕ

$$-\mathcal{L} \subset \frac{1}{2}m_0^2\phi^2 + \kappa\phi^2|H|^2 + \left\{\frac{1}{2}m_\chi\chi\chi + \frac{1}{2}m_N NN + y_N LHN + \lambda N\chi\phi + \text{h.c.}\right\}. \quad (1)$$

Type-I Seesaw term

RHN portal DM

- Both χ and ϕ can be dark matter candidate and for the stability of a DM candidate, we assign Z_2 odd for both of them
- Unlike ϕ, χ does not couple to SM Higgs H

Right-Handed Neutrino portal Dark Matter

- We have to consider the three coupled Boltzmann equations

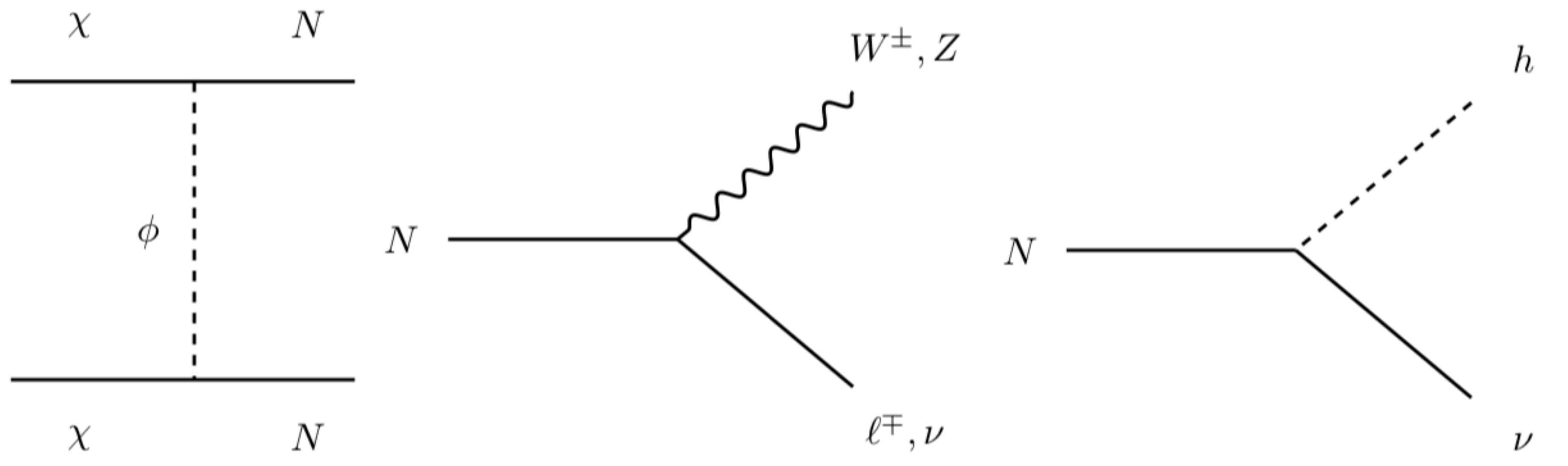
$$\frac{dY_\chi}{dx} = -\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\chi\chi\to NN}\left(Y_\chi^2 - \left(\frac{Y_\chi^{\rm eq}}{Y_N^{\rm eq}}\right)^2 Y_N^2\right) + \frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\phi\phi\to\chi\chi}\left(Y_\phi^2 - \left(\frac{Y_\phi^{\rm eq}}{Y_\chi^{\rm eq}}\right)^2 Y_\chi^2\right), \quad (3)$$

$$\frac{dY_\phi}{dx} = -\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\phi\phi\to\chi\chi}\left(Y_\phi^2 - \left(\frac{Y_\phi^{\rm eq}}{Y_\chi^{\rm eq}}\right)^2 Y_\chi^2\right) - \frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\phi\phi\to NN}\left(Y_\phi^2 - \left(\frac{Y_\phi^{\rm eq}}{Y_N^{\rm eq}}\right)^2 Y_N^2\right) - \frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\phi\phi\to{\rm SM}}\left(Y_\phi^2 - Y_\phi^{\rm eq2}\right), \quad (4)$$

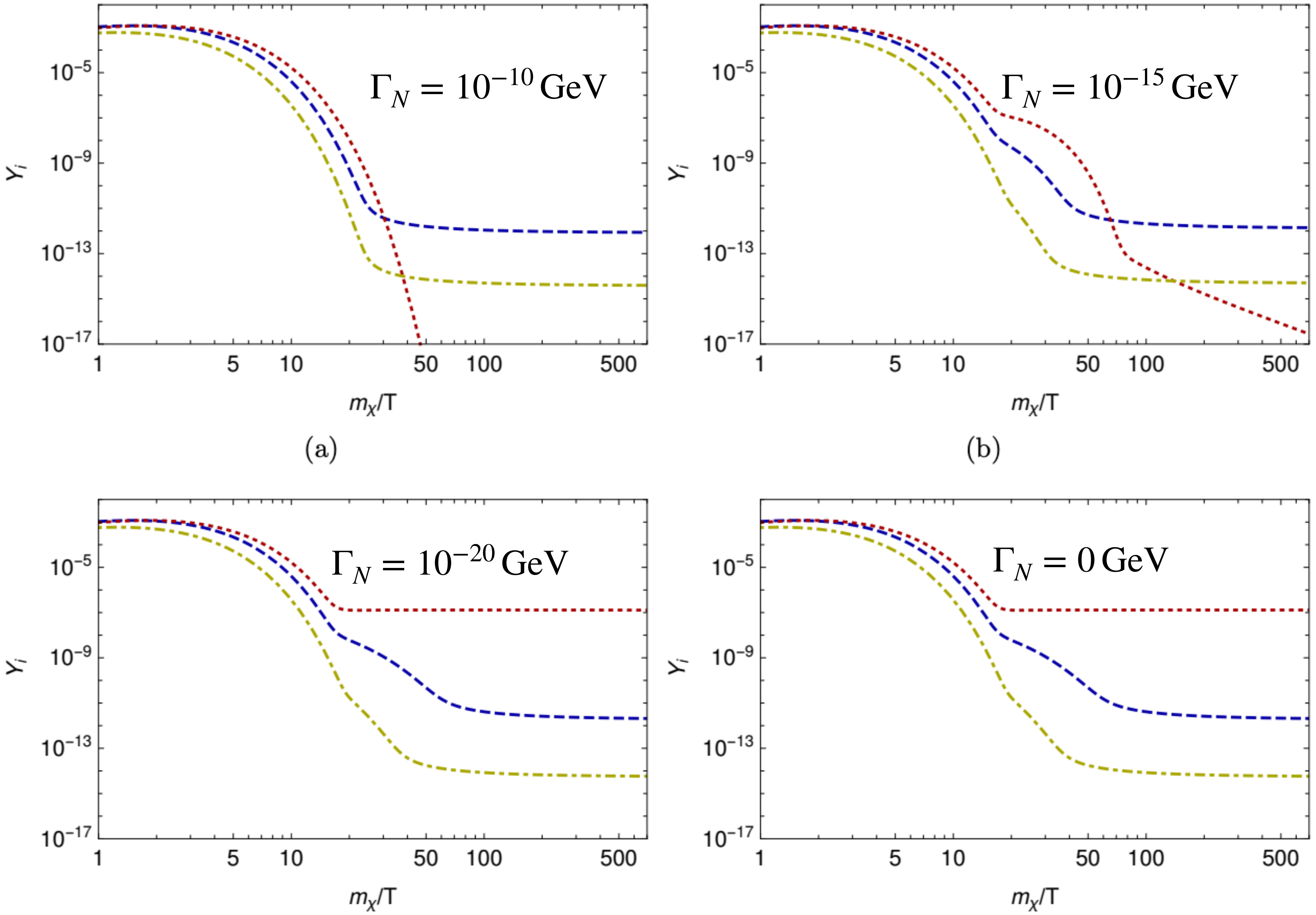
$$\frac{dY_N}{dx} = \frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\chi\chi\to NN}\left(Y_\chi^2 - \left(\frac{Y_\chi^{\rm eq}}{Y_N^{\rm eq}}\right)^2 Y_N^2\right) + \frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle_{\phi\phi\to NN}\left(Y_\phi^2 - \left(\frac{Y_\phi^{\rm eq}}{Y_N^{\rm eq}}\right)^2 Y_N^2\right) - \frac{\Gamma}{H(m_\chi)}x\,(Y_N - Y_N^{\rm eq}). \quad (5)$$

$$m_\chi = n\,m_N = 1/n\,m_\phi \quad n = 1.2,\ m_N = 300\,{\rm GeV} \quad \lambda = 0.4,\ \kappa = 1$$

- RHN decay width affects freeze-out



(a) (b) (c)



(a) (b) (c) (d)

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PLB788 (2019) 530-534

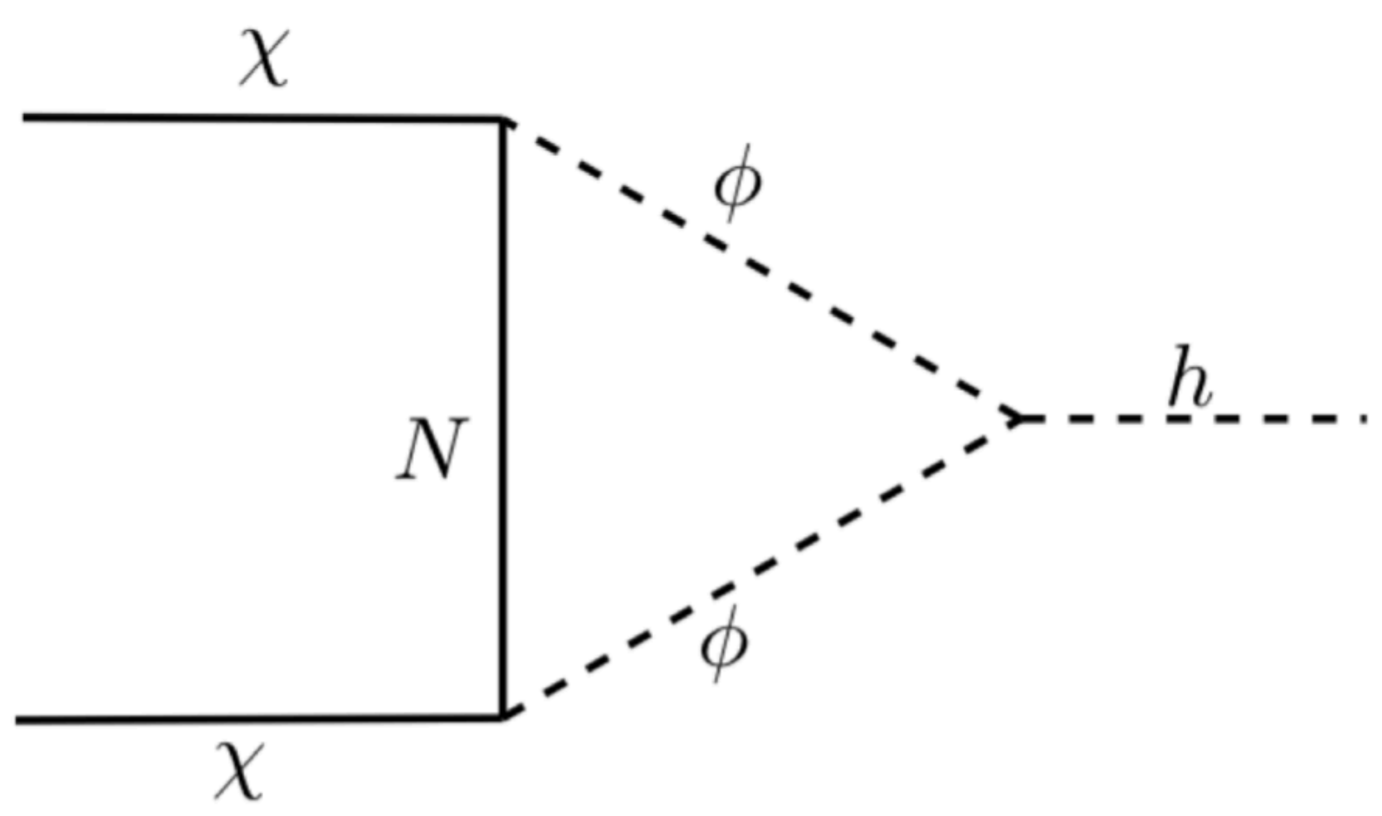
Loop induced Higgs-DM coupling

- No tree-level coupling of the fermionic DM to the Higgs boson
- How to detect a fermonic Dark Matter ?
- However, an effective coupling $h - \chi - \chi$ is generated at one-loop

$$-\mathcal{L}_{h\chi\chi} = \kappa' h \bar{\chi}\chi \quad \text{where}$$

$$\kappa' \equiv \frac{\lambda^2 \kappa v}{16\pi^2} \frac{m_\chi c_1(x) - m_N c_0(x)}{m_\phi^2},$$

and $c_{1,0}(x)$ are loop-functions of $x \equiv m_N^2/m_\phi^2$



- This influences the SI nucleonic cross-sections

$$\sigma_{\rm SI} = \frac{4}{\pi}\mu_r^2 \left(\frac{\kappa' g_{nnh}}{m_h^2}\right)^2$$

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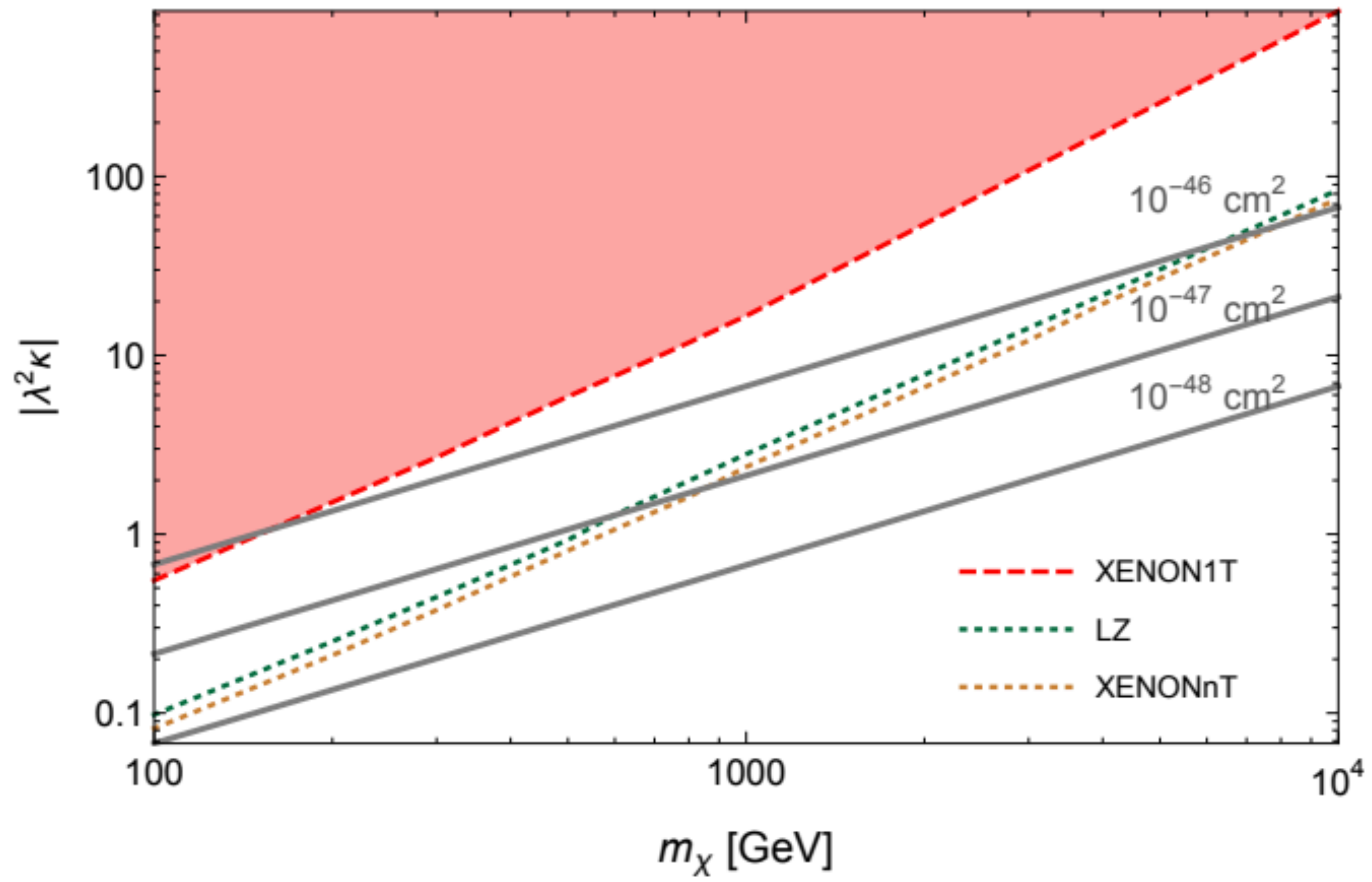
Loop induced Higgs-DM coupling



- XENON1T experiment excludes $|\lambda^2\kappa| \geq \mathcal{O}(1)$ for $m_\chi \leq 150\,\mathrm{GeV}$
- XENONnT can rule out such values of $|\lambda^2\kappa| \geq \mathcal{O}(1)$ for $m_\chi \leq 600\,\mathrm{GeV}$

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Can we have freeze-in with $\lambda N \chi \phi$?

Freeze-in via RHN

- We consider the same RHN portal DM scenario via $\lambda N\chi\phi$
- What happens if the Yukawas are very small?
- Can the RHN portal can generate the Freeze-in scenario?
- We assume their initial number density were zero, where SM fields were in equilibrium

$$-\mathcal{L}_{\rm new} \subset \{\lambda N\chi\phi + y_\nu LHN + {\rm h.c.}\} + \kappa\phi^2|H|^2$$

Higgs portal coupling

- The mass terms would be m_χ, m_N, m_ϕ, respectively for χ, N, ϕ
- Due to the feeble coupling of y_ν , we assume the other two RHNs will generate the desired neutrino masses and mixings
- χ, ϕ are kept Z_2 odd for the stability of the Dark Matter and both of them are suitable candidate

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Freeze-in via RHN

- We assume $m_\chi < m_\phi$, thus χ is a primary dark matter candidate
- However, if ϕ is long-lived, it can serve as decaying dark matter
- The dynamics is determined by the three parameters y_ν, κ, and λ
- The decay rates should be smaller than the expansion of the universe

$$\Gamma < H(T) \sim T^2/M_{Pl}$$

$$\Longrightarrow \; y_\nu \lesssim 10^{-7}, \kappa \lesssim 10^{-7} \text{ and } y_\nu\lambda \lesssim 10^{-7} \text{ for } m_{\chi,N,\phi} \sim 1\,\text{TeV}$$

- The desired relic $\Omega h^2 = 0.1199 \pm 0.0022$ can be obtained via solving the coupled Boltzmann equations involving χ, N, ϕ
- We considered three different scenarios while studying the freeze-in case, however here we focus only on Scenario1 and Scenario3

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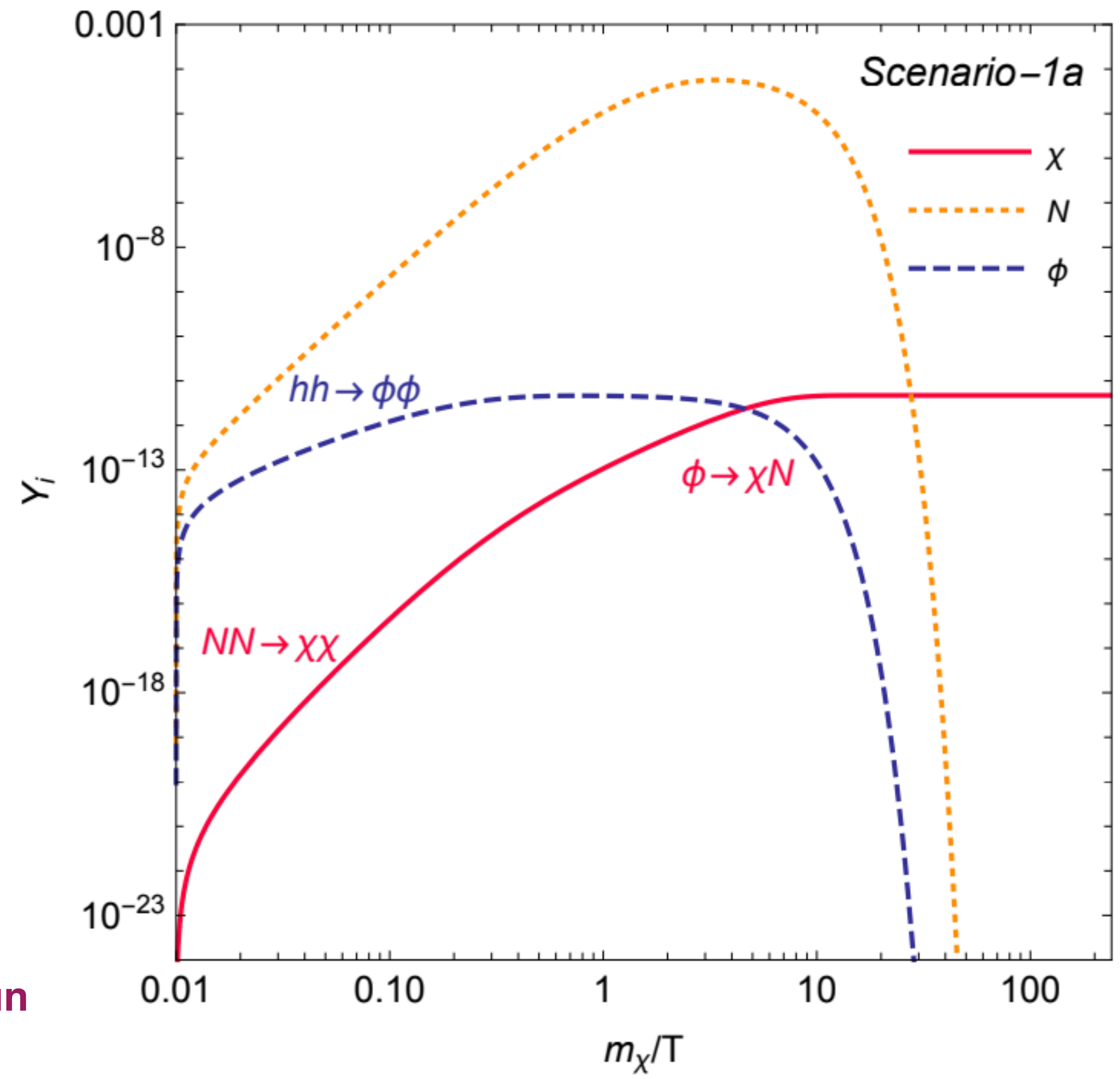
Freeze-in via RHN: Scenario1

- Dark sector is produced via Higgs portal process $hh \to \phi\phi$ with sizeable κ
- The dark matter χ is then produced via $\phi \to \chi N, \chi\nu$ or $\phi\phi \to \chi\chi$
- $\phi \to \chi\nu$ is possible via the mixing of RHN and SM neutrino and proportional to $|y_\nu \lambda|^2$ (scenarios $1b, 1c$)
- Initially $NN \to \chi\chi$ is dominant
- Subsequently $\phi \to \chi N, \chi\nu$ or $\phi\phi \to \chi\chi$ take over

Scenario	Masses in GeV			Couplings		
	m_χ	m_N	m_ϕ	y_ν	κ	λ
1a	100	200	500	10^{-8}	4×10^{-11}	10^{-8}
1b	100	200	180	10^{-8}	2×10^{-11}	10^{-10}
1c	100	500	250	2.5×10^{-12}	10^{-12}	10^{-4}



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Freeze-in via RHN: Scenario3

- Here RHN is heavy enough to allow $N \to \chi\phi$
- y_ν is sufficiently large to produce RHN
- κ becomes irrelevant and can take smaller values
- λ is crucial in determining the decay lifetime of ϕ and N
- For $\kappa = 10^{-12}$, a suitable choice of λ makes ϕ very long lived viz. $\tau_\phi \simeq 1 \times 10^{10}\, s$ and 4.1×10^{12} s for BP 3a and 3b, respectively

Scenario	Masses in GeV			Couplings		
	m_χ	m_N	m_ϕ	y_ν	κ	λ
3a	100	341	241	10^{-7}	10^{-12}	6.1×10^{-11}
3b	1.0×10^6	2.05×10^6	1.05×10^6	10^{-5}	10^{-12}	2.4×10^{-11}

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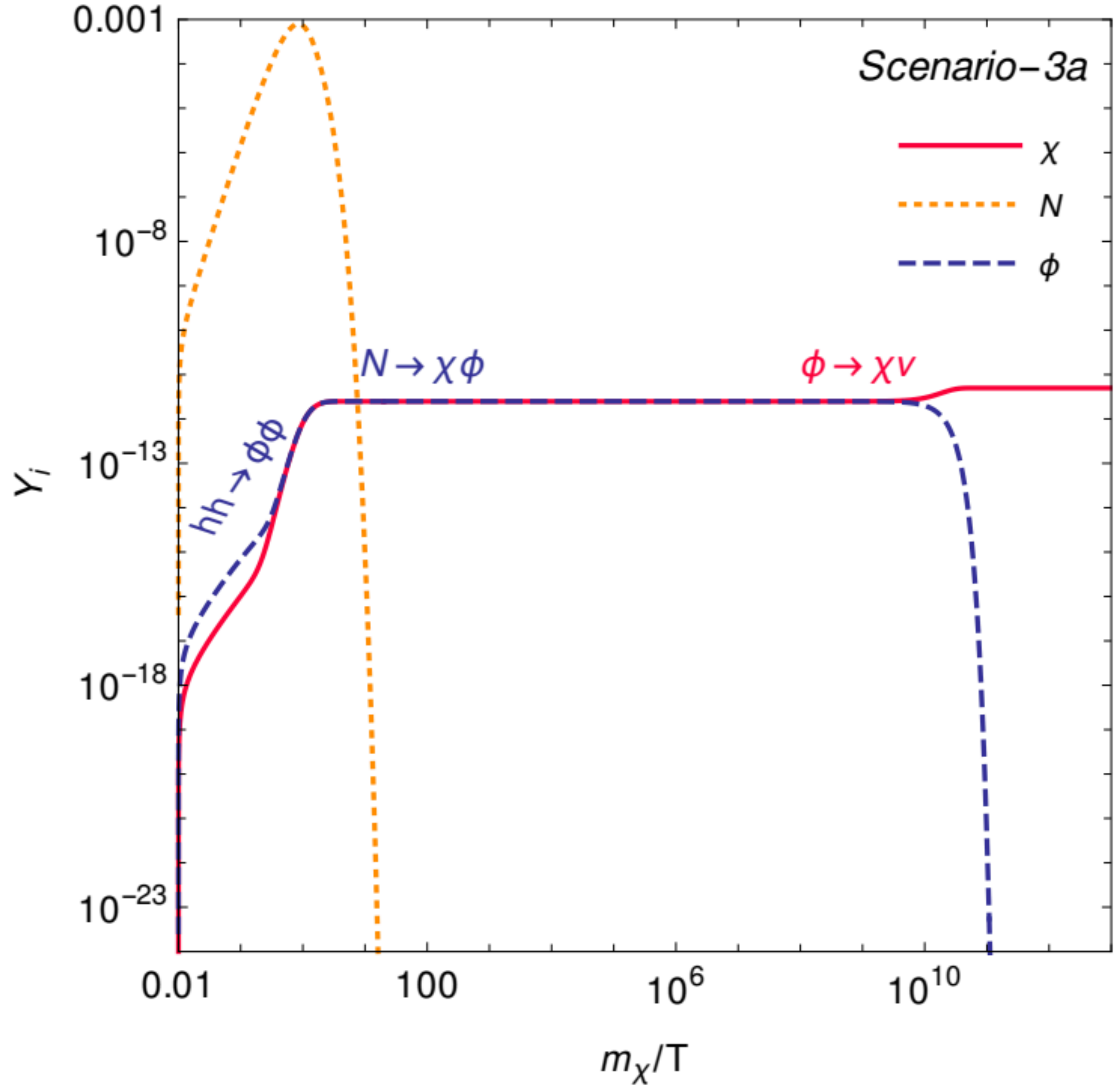
Scenario3: Decaying dark matter

- τ_ϕ is around the matter-radiation equality time ($\sim 10^{12}\,s$)
- $hh \to \phi\phi$ dominates initially for ϕ production
- Later $N \to \chi\phi$ takes over enforcing same density of ϕ, χ for long time
- Finally late decay mode $\phi \to \chi\nu$ determines relic of χ



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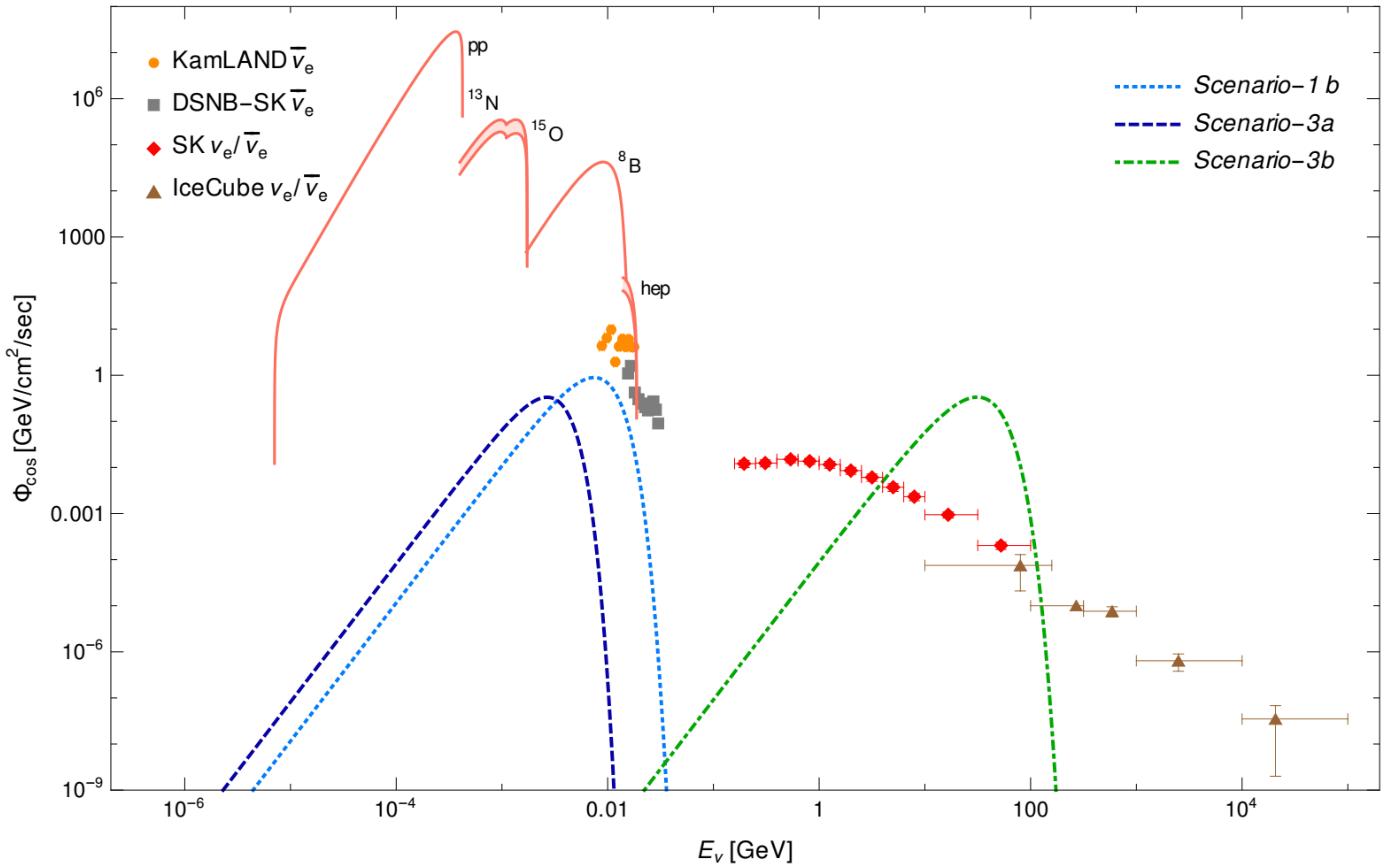
Energetic neutrinos from the dark sector

- $\phi \to \chi\nu$ decay width is proportional to $|y_\nu \lambda|^2$
- This leads to a very late decay of ϕ to energetic neutrinos
- Which broadens the experimental scopes of the DM searches
- Depending on τ_ϕ three situations can occur

1. $1\,s \lesssim \tau_\phi \lesssim t_{\rm eq}$: χ is the legitimate dark matter and the energetic neutrinos produced from the decay of ϕ are red-shifted away for $\tau_\phi \ll t_{\rm eq} = 5.11 \times 10^4\,\rm yrs$ (matter-radiation equality time)
2. $t_{\rm eq} \lesssim \tau_\phi \ll t_0 = 13.87\,\rm Gyrs$ (Age of the Universe): ϕ behaves like a decaying dark matter and has disappeared by now but the produced neutrinos can be detected at the neutrino experiments
3. $\tau_\phi \gtrsim \tau_0$: ϕ is a decaying DM, and the energetic neutrino production puts stringent limit on

Scenario3: Decaying Dark Matter and neutrino detector



- The electron (anti)neutrino fluxes for BPs and the constraints from DSNB at KamLAND , SK and atmospheric data from SK and IceCube
- Scenario-1b and Scenario-3a are allowed whereas Scenario-3b is ruled out

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Conclusions

- Extra scalar are highly motivated for the stability of the Electroweak vacuum
- It can provide the much needed dark matter and explanation to muon-(g-2)
- In particular Type-X 2DHM has an advantage
- Models with Seesaw with relatively large Yukawa have potential problem with stability, which can be restored via addition of scalars
- Compressed spectrum in case of ITM, can be probed via displaced charged track at the LHC
- Neutrino portal DM via $\lambda N \chi \phi$ can have both freeze-out and freeze-in scenarios
- Decaying dark matter signatures can be caught at the neutrino detectors like SuperK and IceCube experiments


THANK YOU!