Singlet-doublet fermion and triple scalar Dark Matter with radiative neutrino masses

J. Fiaschi, M. Klasen, S. May

JHEP 1905 (2019) 015

arXiv: 1812.11133 [hep-ph]

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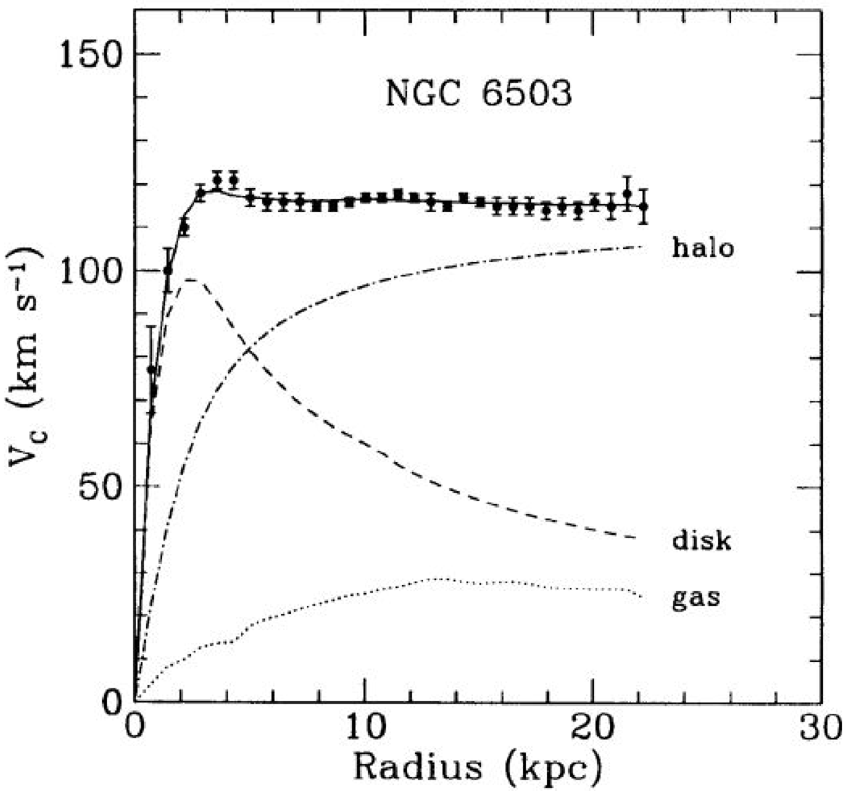
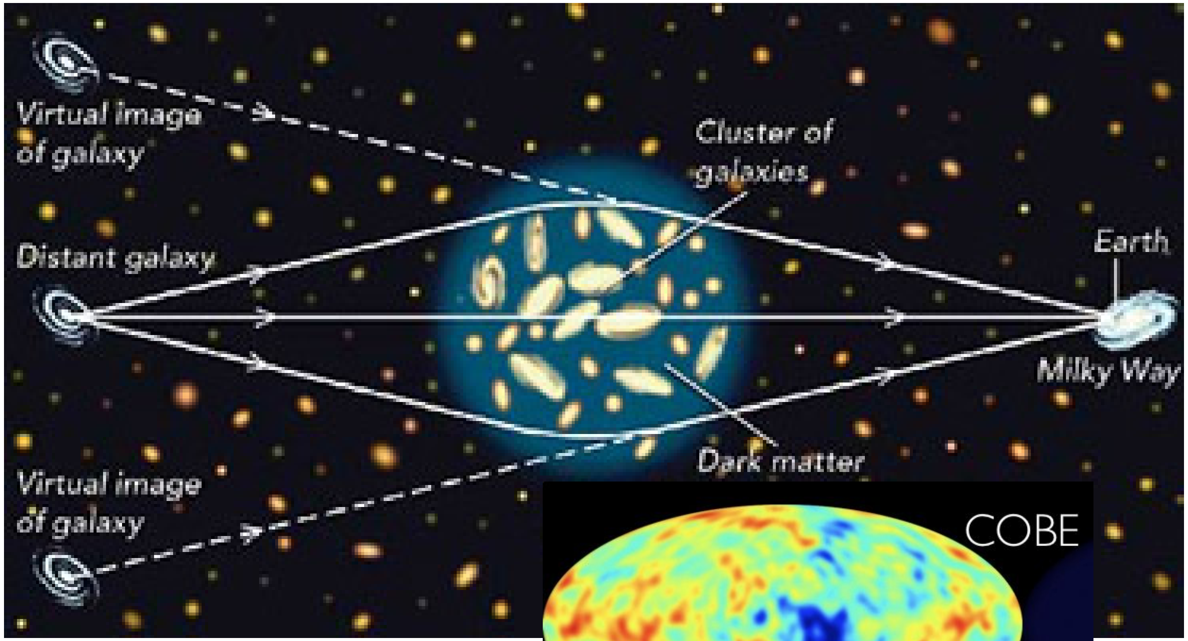
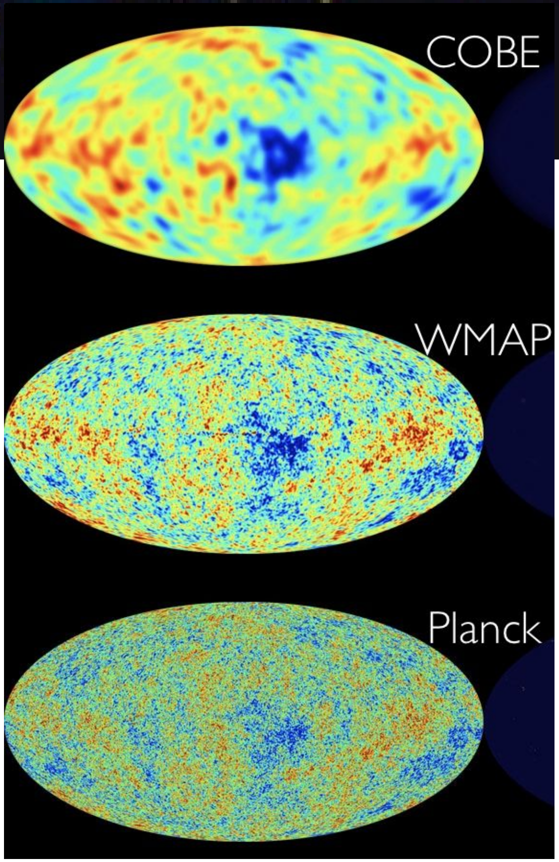
Topics of this talk

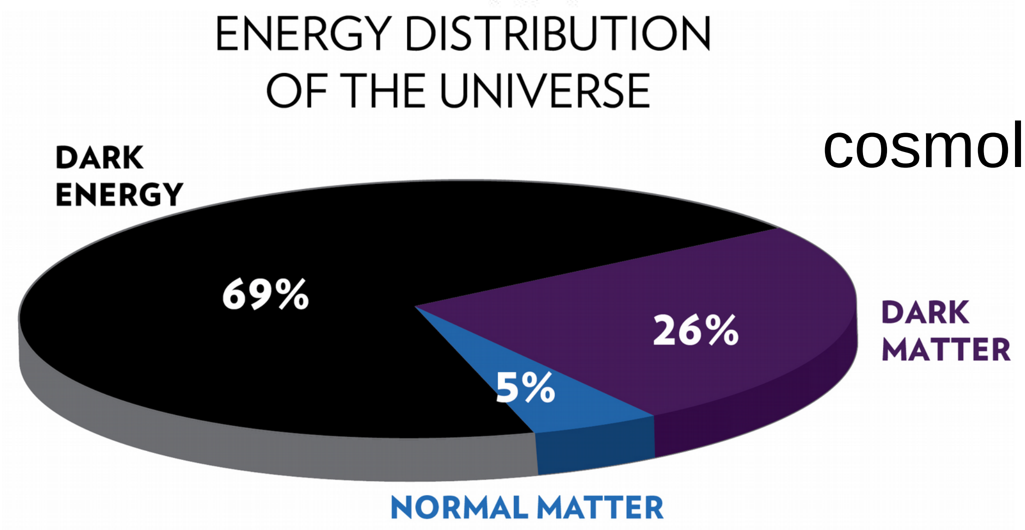
- **Minimal DM models with radiative neutrino masses**
- **The model T1-3-B (α = 0) and its features**
- **Results from the parameter scan**
- **Conclusions**

Evidences for Dark Matter



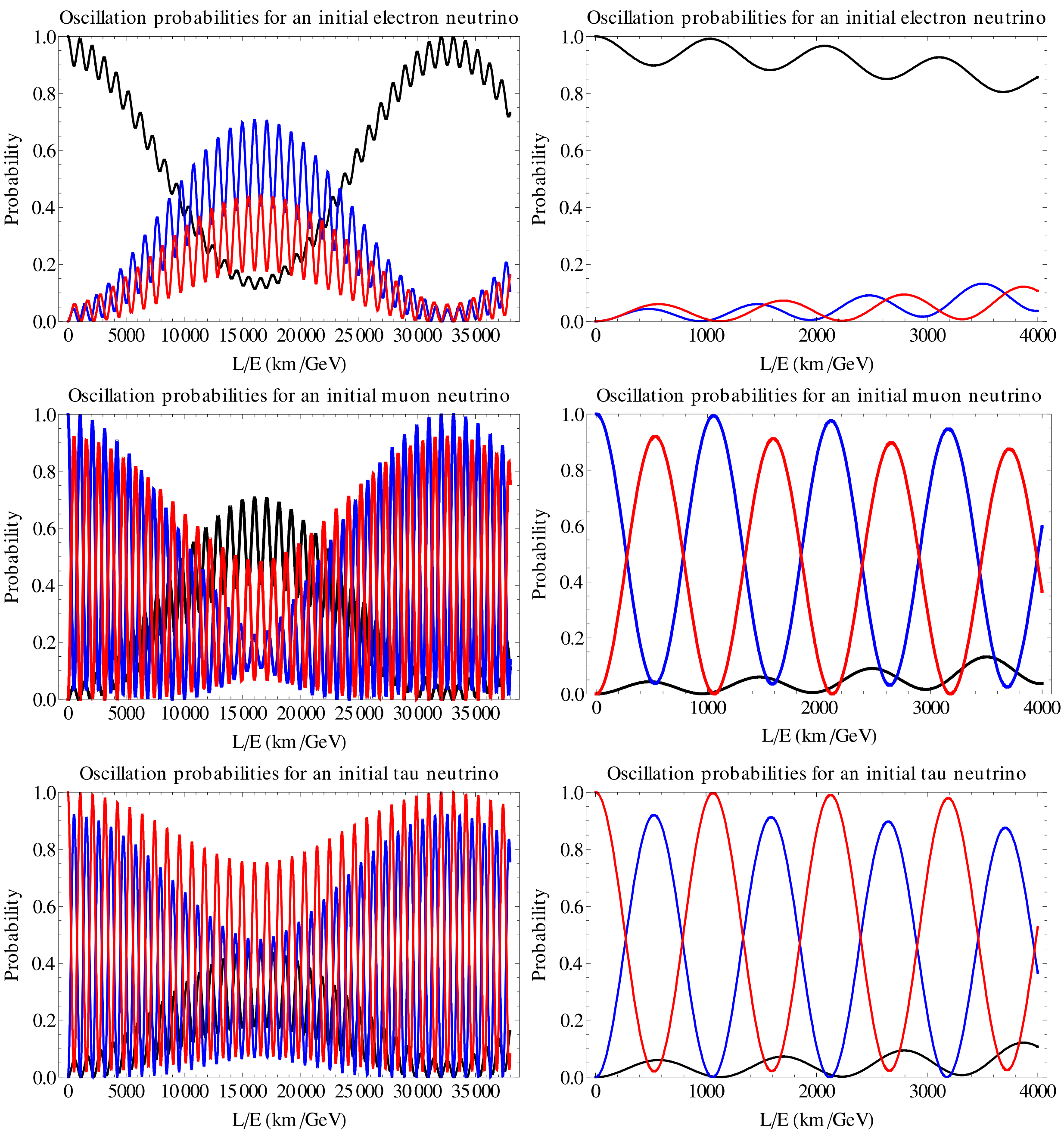


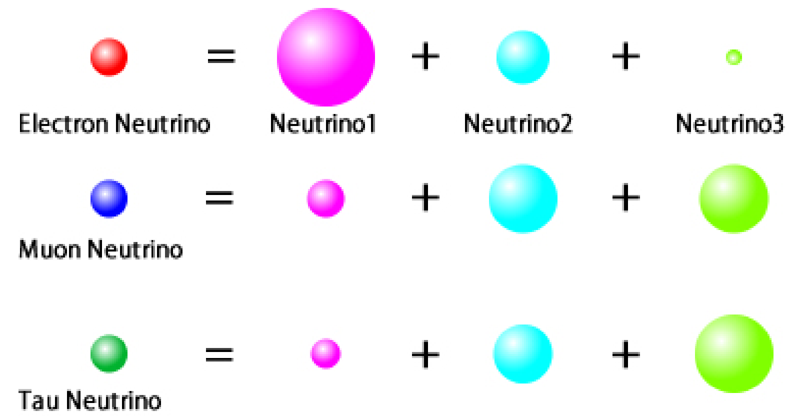




ΛCDM
cosmological model

Evidences for neutrino masses





The interpretation is:

Neutrinos have mass

Minimal models

Can we address both issues with a single BSM theory?
(A real pleasure for theorists)

Minimal DM models with radiative neutrino masses

Introduce the least possible amount of BSM fields

- ≤ 4 new scalar / fermion multiplets
- *SU(3)* color singlets
  SU(2) singlets, doublets, triplets
- Additional stabilising discrete Z_2 symmetry

Models belonging to this family of models have been classified according to the topology of the diagram generating the neutrino masses:

D. Restrepo, O. Zapata, C. E. Yaguna: **JHEP 1311 (2013) 011**

Examples:
"Scotogenic model" : E. Ma: **Phys.Rev. D73 (2006) 077301**
T1-3-A ($\alpha = 0$) : S. Esch, M. Klasen, D. R. Lamprea, C. E. Yaguna: **Eur.Phys.J. C78 (2018) no.2, 88**
T1-2-A ($\alpha = 0$) : S. Esch, M. Klasen, C. E. Yaguna: **JHEP 1810 (2018) 055**

Constraints

How to build a consistent model?

First requirement is a suitable DM candidate:

Stable

- Electrically neutral
- Colour singlet
- Anomaly free theory

Experimental constraints

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Stable → Lightest odd particle under Z_2 symmetry (no new charged stable particles)

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Experimental constraints → Relic density
Collider exclusions (High energy)
Flavour observables (Low energy)
Direct detection cross sections
Indirect detection annihilation products

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- Direct detection cross sections

Indirect detection annihilation products

In this talk → Collider exclusions (High energy), Flavour observables (Low energy)

The model T1-3-B ($\alpha = 0$)

Field	Generations	Spin	Lorentz rep.	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
Ψ	1	$\frac{1}{2}$	$(\frac{1}{2}, 0)$	$\mathbf{1}$	$\mathbf{1}$	0	-1
ψ	1	$\frac{1}{2}$	$(\frac{1}{2}, 0)$	$\mathbf{1}$	$\mathbf{2}$	-1	-1
ψ'	1	$\frac{1}{2}$	$(\frac{1}{2}, 0)$	$\mathbf{1}$	$\mathbf{2}$	1	-1
ϕ_i	2	0	$(0, 0)$	$\mathbf{1}$	$\mathbf{3}$	0	-1

$$\Psi = \Psi^0, \quad \psi = \begin{pmatrix} \psi^0 \\ \psi^- \end{pmatrix}, \quad \psi' = \begin{pmatrix} \psi'^+ \\ \psi'^0 \end{pmatrix}, \quad \phi_i = \begin{pmatrix} \frac{1}{\sqrt{2}}\phi_i^0 & \phi_i^+ \\ \phi_i^- & -\frac{1}{\sqrt{2}}\phi_i^0 \end{pmatrix}$$

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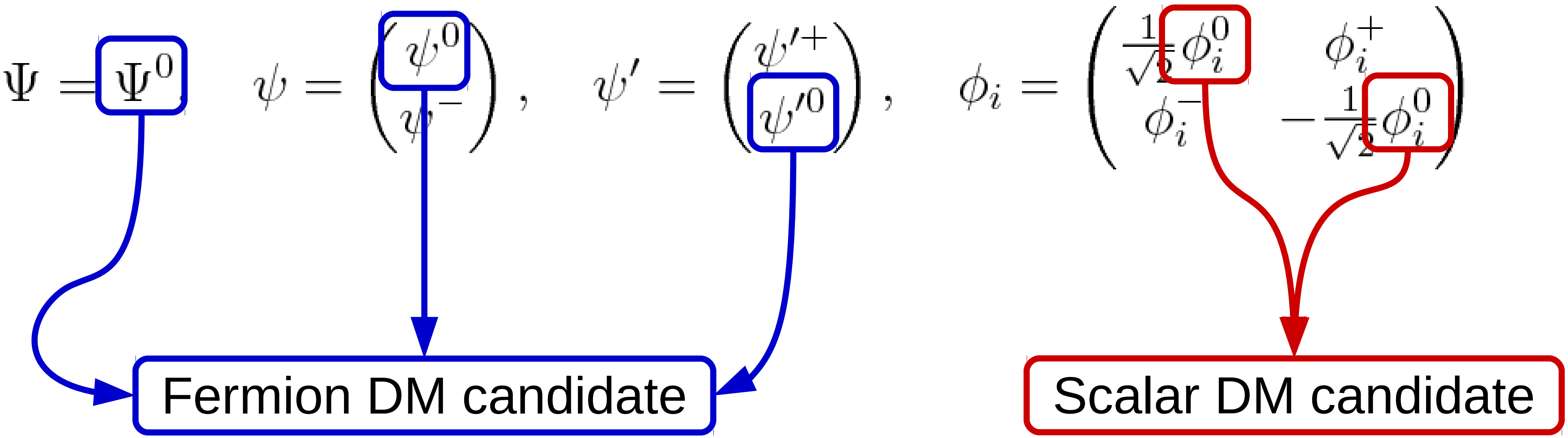

The model T1-3-B (α = 0)

Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} - \frac{1}{2}(M_\phi^2)^{ij}(\phi_i\phi_j) - \frac{1}{2}M_\Psi \Psi\Psi + {\rm H.c.} - M_{\psi\psi'}\psi\psi' + {\rm H.c.}$$
$$-(\lambda_1)^{ij}(H^\dagger H)(\phi_i\phi_j) - (\lambda_2)^{ij} H^\dagger \phi_i \phi_j H - (\lambda_3)^{ijkm}(\phi_i\phi_j\phi_k\phi_m)$$
$$-\lambda_4 (H^\dagger \psi')\Psi + {\rm H.c.} - \lambda_5 (H\psi)\Psi + {\rm H.c.} - (\lambda_6)^{ij} L_i \phi_j \psi' + {\rm H.c.}$$

Parameters of the model:

- Masses of BSM fields
- 6 new interaction terms (*i,j,k,m* indices run over the scalar generations):
  - $\boldsymbol{\lambda_1}$ and $\boldsymbol{\lambda_2}$ can be combined together using some identities.
    They mix the new scalar triplets with the SM Higgs doublet.
  - $\boldsymbol{\lambda_3}$ generates a mixing between the new scalar triplet generations.
    No impact on DM phenomenology (will be neglected in the following).
  - $\boldsymbol{\lambda_4}$ and $\boldsymbol{\lambda_5}$ have the function of Yukawa terms linking the fermion singlet and doublets new fields to the SM Higgs.
  - $\boldsymbol{\lambda_6}$ connects the SM lepton doublets to the new fields.
    Responsible for radiatively generated neutrino masses and for LFV processes.

Interesting feature:

The model allows for the correct Higgs boson mass, couplings of natural size, masses in the TeV range and gauge coupling unification at a scale of O(10^{13} GeV)

The model T1-3-B (α = 0)

Mass eigenstates after EWSB and mixing:

- Fermions:
  - Charged fermions do not mix (only one field for each charge value);
  - Neutral fermions mix into the mass eigenstates χ^0_i:

$$\chi^0 = U_\chi \begin{pmatrix} \Psi^0 \\ \psi^0 \\ \psi'^0 \end{pmatrix} \qquad U_\chi^* M_{\mathrm{f},0} U_\chi^\dagger = \mathrm{diag}(m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}) \qquad M_{\mathrm{f},0} = \begin{pmatrix} M_\Psi & \frac{\lambda_5 v}{\sqrt{2}} & \frac{\lambda_4 v}{\sqrt{2}} \\ \frac{\lambda_5 v}{\sqrt{2}} & 0 & M_{\psi\psi'} \\ \frac{\lambda_4 v}{\sqrt{2}} & M_{\psi\psi'} & 0 \end{pmatrix}$$

- Scalars:
  - Charged and neutral scalars mix with the same orthogonal matrix:

$$\eta^{0,\pm} = O_\eta \begin{pmatrix} \phi_1^{0,\pm} \\ \phi_2^{0,\pm} \end{pmatrix} \qquad O_\eta M^2_{\phi^{0,\pm}} O_\eta^T = \mathrm{diag}(m^2_{\eta_1^{0,\pm}}, m^2_{\eta_2^{0,\pm}})$$

  - Charged and neutral mass eigenstate are degenerate at tree-level.
  - A small splitting arises at one-loop making the neutral components lighter than the charged ones.

Neutrino masses

Dim. 5 Weinberg operator: $(\bar{L}^c i\sigma_2 H)(H^T i\sigma_2 L) \longrightarrow \text{“}HHLL\text{”}$

- non-renormalizable ⟶ effective operator
- generates Majorana neutrino masses after EWSB
- breaks lepton number symmetry ⟶ LFV constraints

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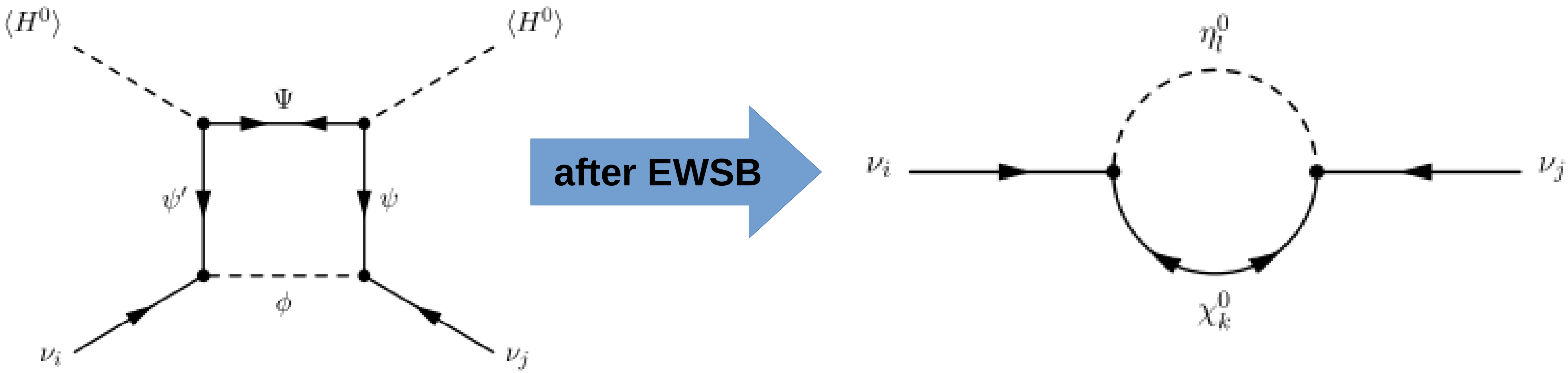
In the T1-3-B (α = 0) model:



Neutrino masses

Neutrino mass matrix:

$$(M_\nu)_{ij} = \frac{1}{32\pi^2}\sum_{l=1}^{n_\mathrm{s}} \lambda_6^{im}\lambda_6^{jn}(O_\eta)_{lm}(O_\eta)_{ln}\sum_{k=1}^{n_\mathrm{f}} (U_\chi)^{*}_{k3}{}^2 \frac{m^3_{\chi^0_k}}{m^2_{\eta^0_l} - m^2_{\chi^0_k}} \ln\frac{m^2_{\chi^0_k}}{m^2_{\eta^0_l}}$$

$$= \frac{1}{32\pi^2}\sum_{l=1}^{n_\mathrm{s}} A_l \lambda_6^{im}\lambda_6^{jn}(O_\eta)_{lm}(O_\eta)_{ln}$$

2 generations of scalars to produce
2 non-zero neutrino masses.

Naturally small neutrino masses:

$$M_\nu \approx 100\ \mathrm{meV}\ \frac{M_\Psi}{1\ \mathrm{TeV}} \left(\frac{\lambda_6^{ij}\lambda_{4,5}}{10^{-5}}\right)^2$$

Neutrino masses

Neutrino mass matrix:

$$(M_\nu)_{ij} = \frac{1}{32\pi^2}\sum_{l=1}^{n_s}\lambda_6^{im}\lambda_6^{jn}(O_\eta)_{lm}(O_\eta)_{ln}\sum_{k=1}^{n_f}(U_\chi)^{*\,2}_{k3}\frac{m^3_{\chi^0_k}}{m^2_{\eta^0_l}-m^2_{\chi^0_k}}\ln\frac{m^2_{\chi^0_k}}{m^2_{\eta^0_l}}$$

$$= \frac{1}{32\pi^2}\sum_{l=1}^{n_s}A_l\boxed{\lambda_6^{im}\lambda_6^{jn}}(O_\eta)_{lm}(O_\eta)_{ln}$$

2 generations of scalars to produce
2 non-zero neutrino masses.

Diagonalization through PMNS matrix:

$$U_\nu^\dagger M_\nu \boxed{U_\nu} = \mathrm{diag}(\boxed{m_{\nu_1}, m_{\nu_2}, m_{\nu_3}})$$

Neutrino masses will automatically satisfy experimental constraints by fixing the appropriate **λ_6** coupling
(residual rotation angle θ free parameter)

Casas-Ibarra method:

Normally:
ν masses from parameters

Invert relation:
λ_6 parameter from **PMNS matrix** and **ν masses**.
(we will assume one massless neutrino)

J. A. Casas, A. Ibarra: **Nucl. Phys. B618 (2001) 171**

Model’s parameters scan

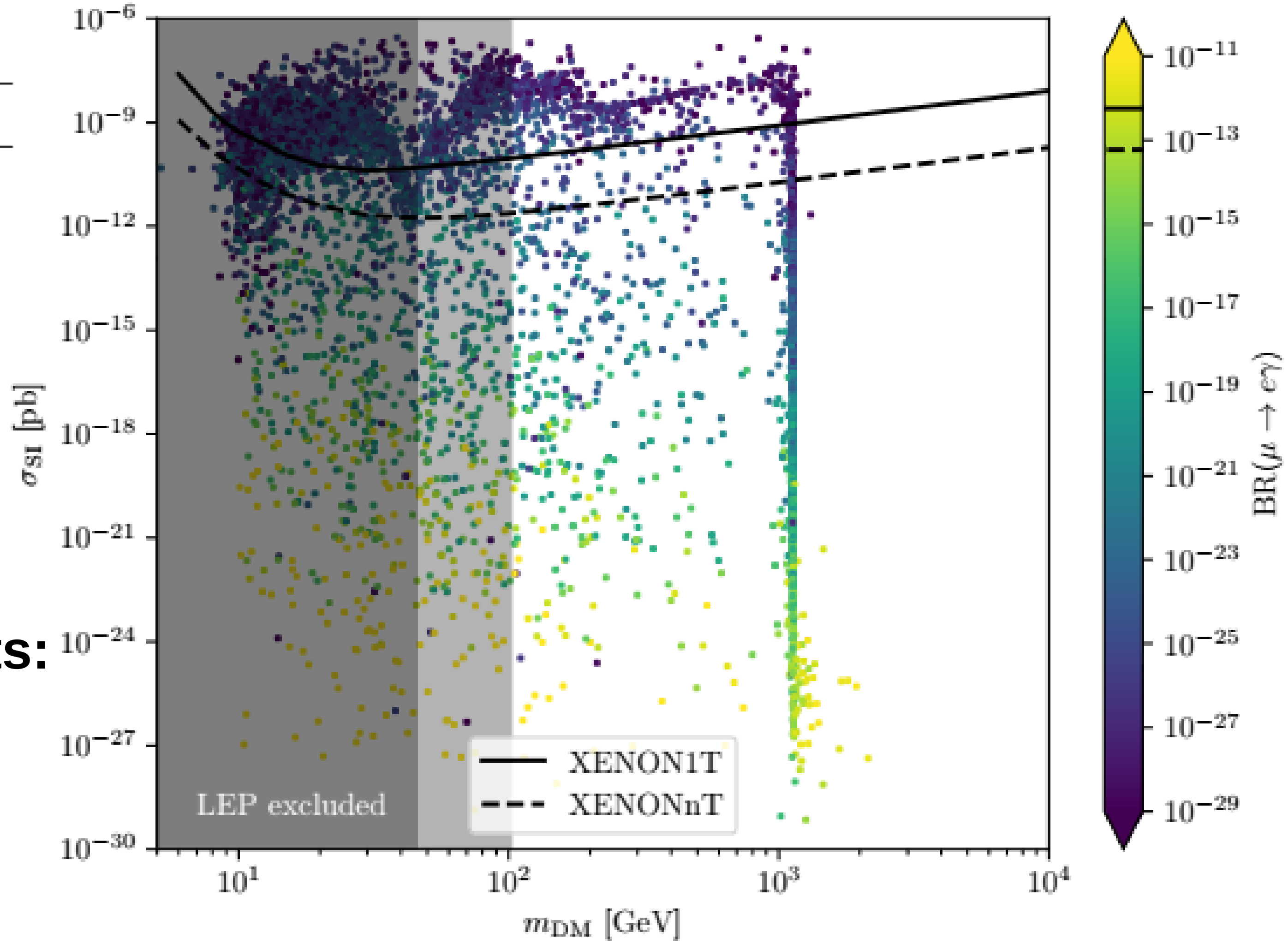
Chain of tools for the analysis:

- Independent code has been used to produce the **SARAH** model files from the model Lagrangian
- **SARAH** code used to produce **SPheno** source code and **micrOMEGAs** model files.
- **SPheno** to produce spectrum files in SLHA format from input parameters + output some relevant observables: LFV observables, neutrino masses.
- Spectrum file to **micrOMEGAs** to produce some relevant observables: DM relic density, spin independent cross sections.
- Random scan over model parameters (masses and couplings).

Fermion Dark Matter

Parameter scan:

Parameter	Value
$(M_\phi)^{ij}$	$[10,\ 10^4]$ GeV
$M_\Psi, M_{\psi\psi'}$	$[10,\ 10^4]$ GeV
$\lambda_{1,4,5}$	$[10^{-6}, 1]$
$\text{sign}(\lambda_{1,5})$	$\pm$
$\text{sign}(\lambda_4)$	$+$
$\lambda_6(\theta)$	from C.I.
θ	$[0,\ 2\pi]$



Experimental constraints:

- Z invisible width
- Heavy charged fermions (conservative limit assuming small doublet splitting)
- Relic density $\Omega_c h^2 = 0.120 \pm 0.001$
- LFV observables (most stringent limit from $\mu \to e\gamma$)

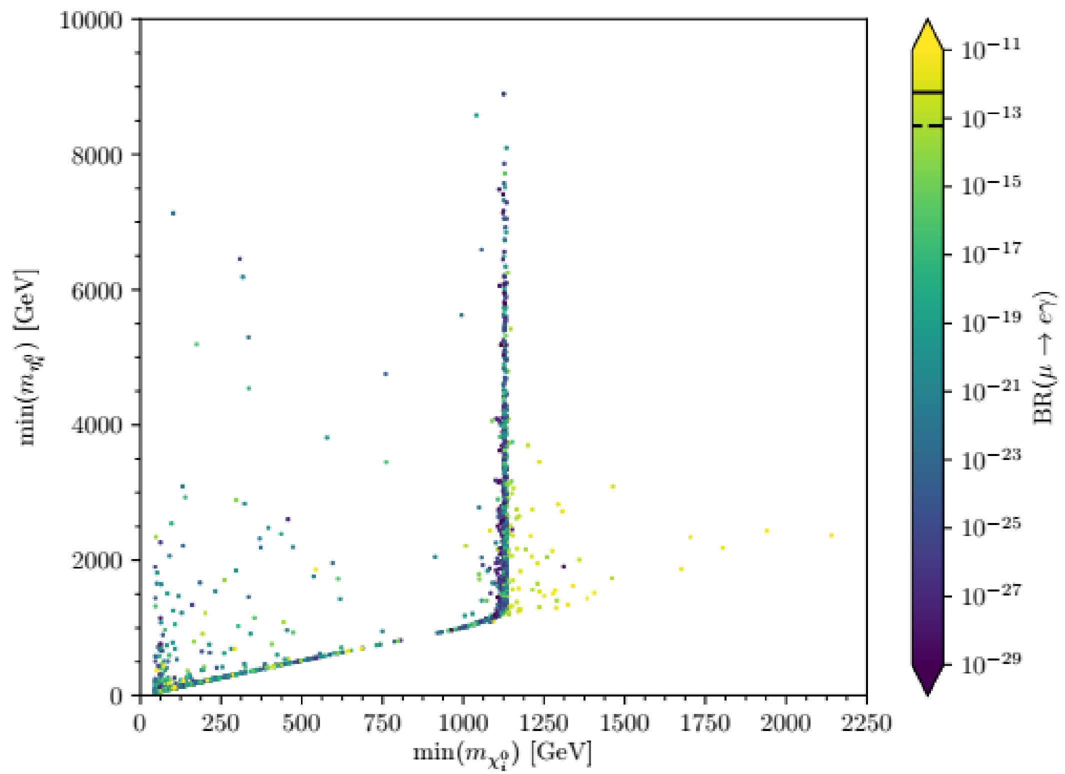
Fermionic DM mass spans region between 100 GeV and 1 TeV

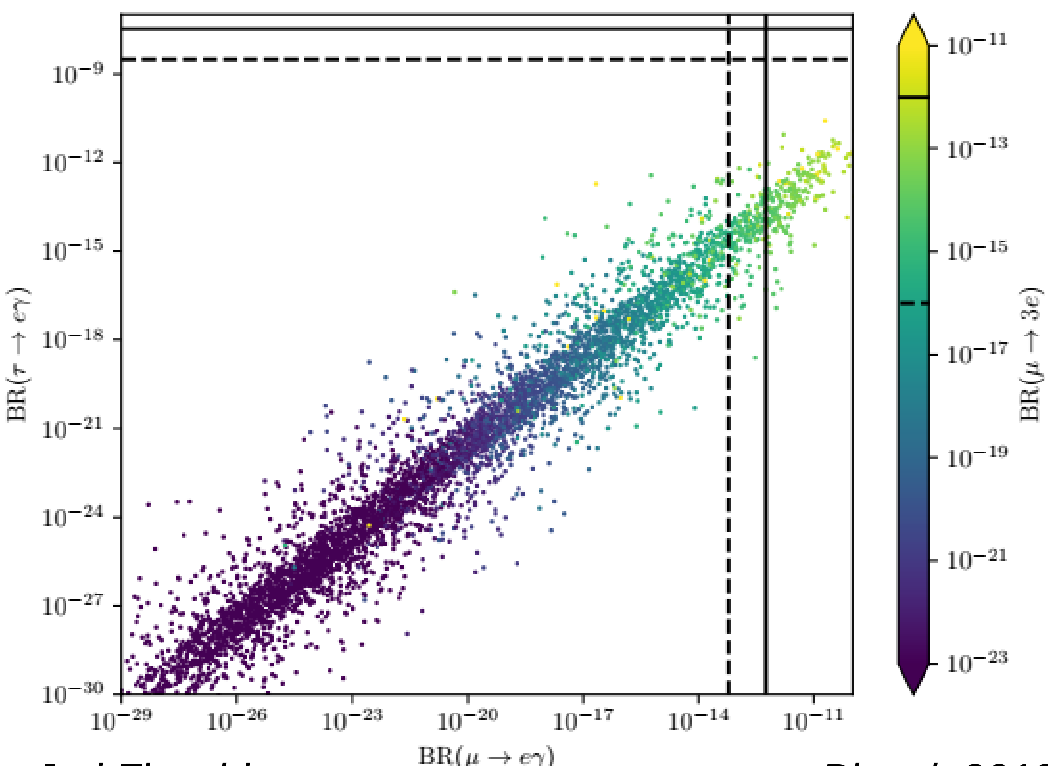
Fermion Dark Matter

Keep the points satisfying all constraints.

<u>Near degeneracy</u> between DM lightest fermion and lightest scalar up to masses of 1.1 TeV (relevant coannihilation contribution)

Line of models with <u>constant fermion mass</u> at 1.1 TeV and scalar masses up to the decoupling region.





Correlation between LFV observables:

μ → eγ and *μ → 3e* are competitive

τ → eγ has no sensitivity to this model

Scalar Dark Matter

Parameter scan:

Parameter	Value
$(M_\phi)^{ij}$	$[10,\ 10^4]$ GeV
$M_\Psi, M_{\psi\psi'}$	$[10,\ 10^4]$ GeV
$\lambda_{1,4,5}$	$[10^{-6}, 1]$
$\text{sign}(\lambda_{1,5})$	$\pm$
$\text{sign}(\lambda_4)$	$+$
$\lambda_6(\theta)$	from C.I.
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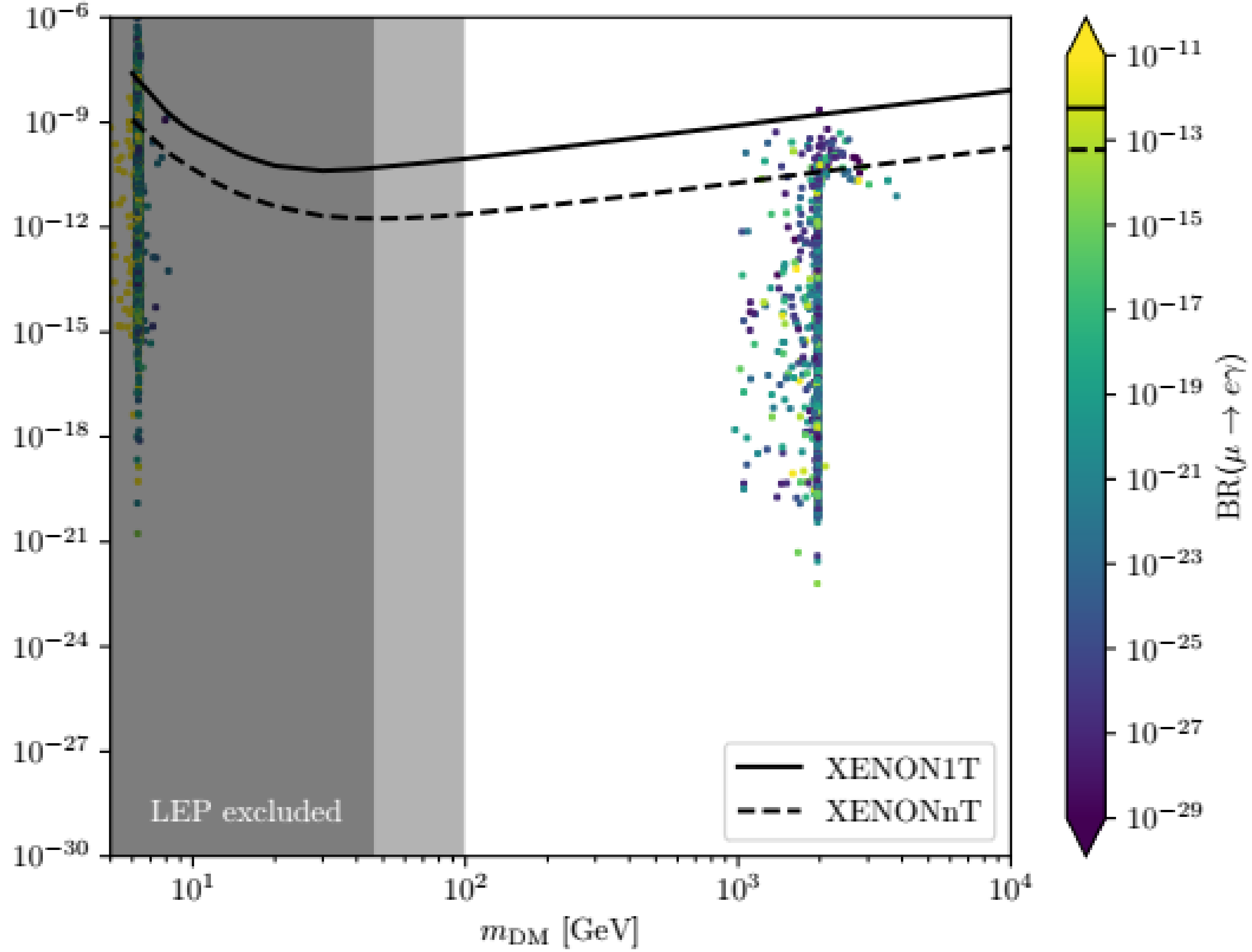


Experimental constraints:

- Z invisible width
- Heavy charged scalar
  (small splitting in scalar triplets)
- Relic density
  $\Omega_c h^2 = 0.120 \pm 0.001$
- LFV observables
  (most stringent limit from $\mu \to e\gamma$)

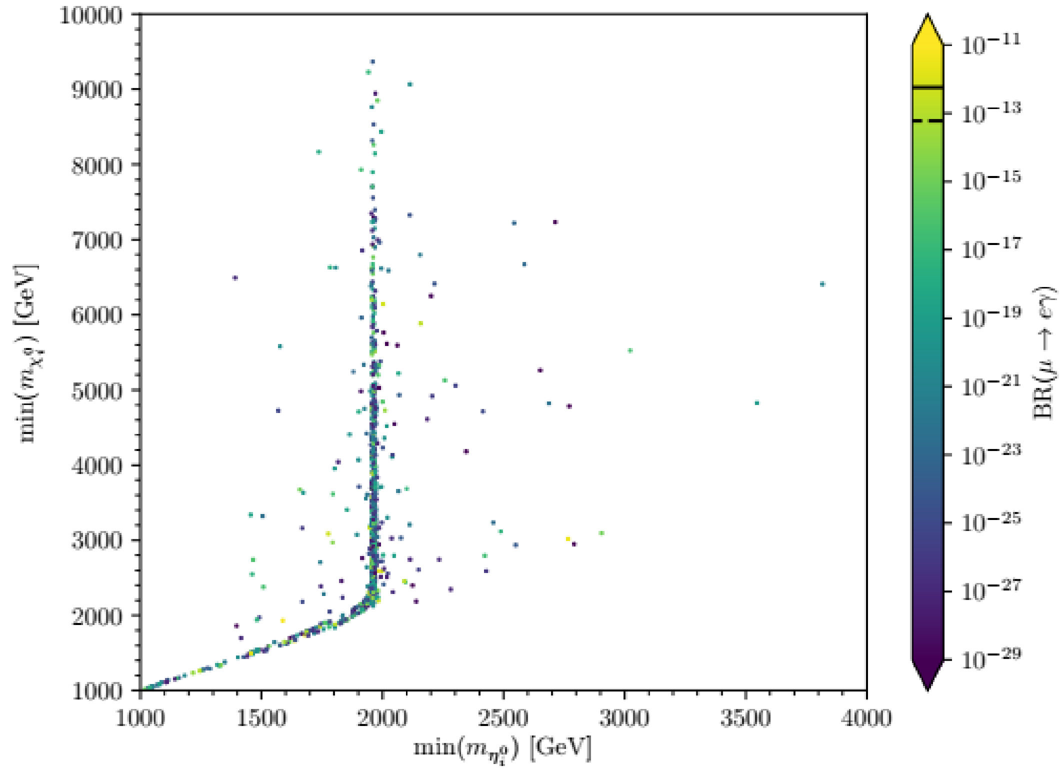
Scalar DM mass spans region between 1 TeV and 4 TeV

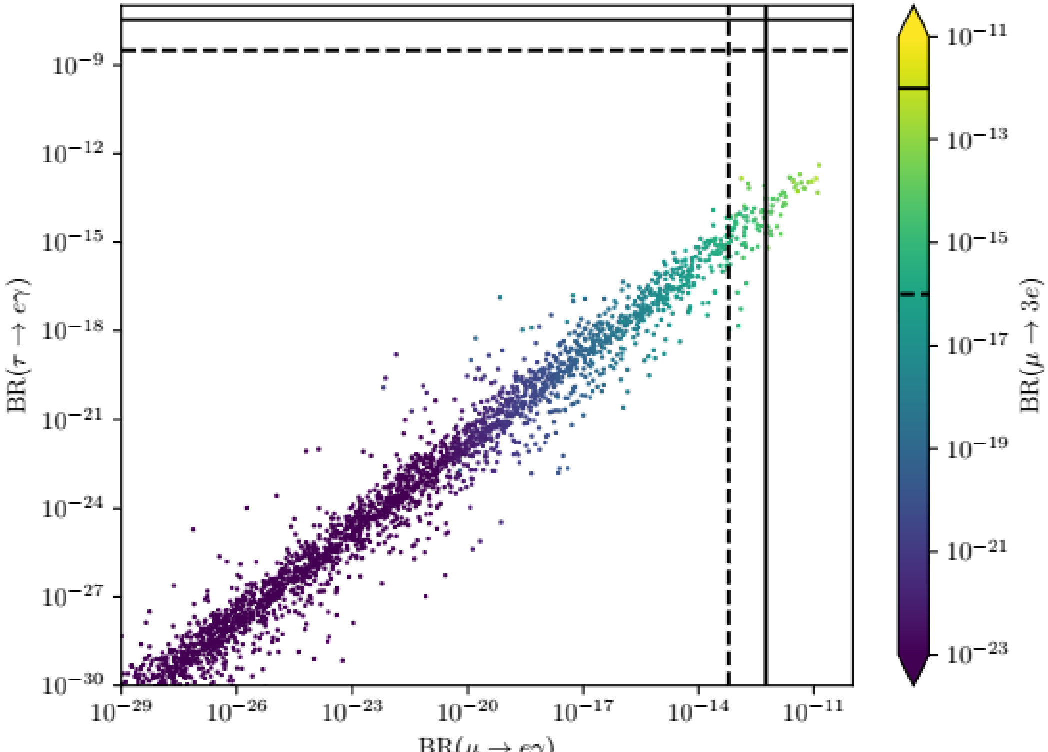
Scalar Dark Matter

Keep the points satisfying all constraints.

Near degeneracy between DM lightest scalar and lightest fermion up to masses of 2 TeV. Despite the degeneracy, coannihilation is rare due to small λ_6 coupling.

Line of models with constant scalar mass at 2 TeV and fermion masses up to the decoupling region.





Correlation between LFV observables:

$\mu \to e\gamma$ and $\mu \to 3e$ are competitive

$\tau \to e\gamma$ has no sensitivity to this model

Conclusions

- Presented BSM model explaining both Dark Matter and small neutrino masses with a minimal number of new fields; furthermore it features gauge coupling unification.
  From the classification related to the topology generating the neutrino masses and hypercharges assignment, it takes the name of **T1-3-B (α = 0)**.

- Model studied using a chain of suitable public codes **SARAH**, **SPheno**, **micrOMEGAs**.

- Scan over the parameter space of the model, implementing Casas-Ibarra parametrization to satisfy experimental constraints in the neutrino sector (masses and mixing angles).

- Separate studies on the case of fermionic and scalar Dark Matter, analysing constraints from:
  - Collider (model independent constraints from LEP).
  - Direct detection Spin-Independent cross sections.
  - Lepton Flavour Violation measurements.

- Fermionic DM covers the mass region between 100 GeV and 1 TeV.
  Scalar DM covers the mass region between 1 TeV and 4 TeV.

- In both cases we have observed that a small splitting between fermionic and scalar multiplets is important to obtain the correct relic density, through the mechanism of coannihilation.

- Interesting complementarity between the expectations for XENONnT and for LFV experiments.

Thank you!

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Casas-Ibarra parametrization

Factorize explicit dependence on the couplings from neutrino mass matrix:

$$M_\nu = \lambda_6 M \lambda_6^\mathsf{T} = \lambda_6 U_M^\dagger D_M U_M \lambda_6^\mathsf{T}$$

Neutrino mass matrix can be diagonalized using PMNS matrix:

$$U_\nu^\dagger M_\nu U_\nu = \mathrm{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$$

Combining this two expression we can write:

$$D_\nu = U_\nu^\dagger \lambda_6 U_M^\dagger D_M U_M \lambda_6^\mathsf{T} U_\nu$$

equivalently:

$$\mathrm{diag}(0,1,1) = \mathrm{D}_\nu^{-\frac{1}{2}} \mathrm{U}_\nu^\dagger \lambda_6 \mathrm{U}_\mathrm{M}^\dagger \mathrm{D}_\mathrm{M} \mathrm{U}_\mathrm{M} \lambda_6^\mathsf{T} \mathrm{U}_\nu \mathrm{D}_\nu^{-\frac{1}{2}}$$

Left hand side can be written as **diag(0,1,1) =** ***R*^†*R*** with R a rotation matrix:

$$R = \begin{pmatrix} 0 & \cos(\theta) & \sin(\theta) \\ 0 & -\sin(\theta) & \cos(\theta) \end{pmatrix} \qquad R = D_M^{\frac{1}{2}} U_M \lambda_6^\mathsf{T} U_\nu D_\nu^{-\frac{1}{2}}$$

Inverting this relation we obtain an expression for the coupling in terms of the other quantities:

$$\lambda_6 = U_\nu^* D_\nu^{\frac{1}{2}} R^\mathsf{T} D_M^{-\frac{1}{2}} U_M^*$$

Fermionic Dark Matter

Decouple scalar sector:

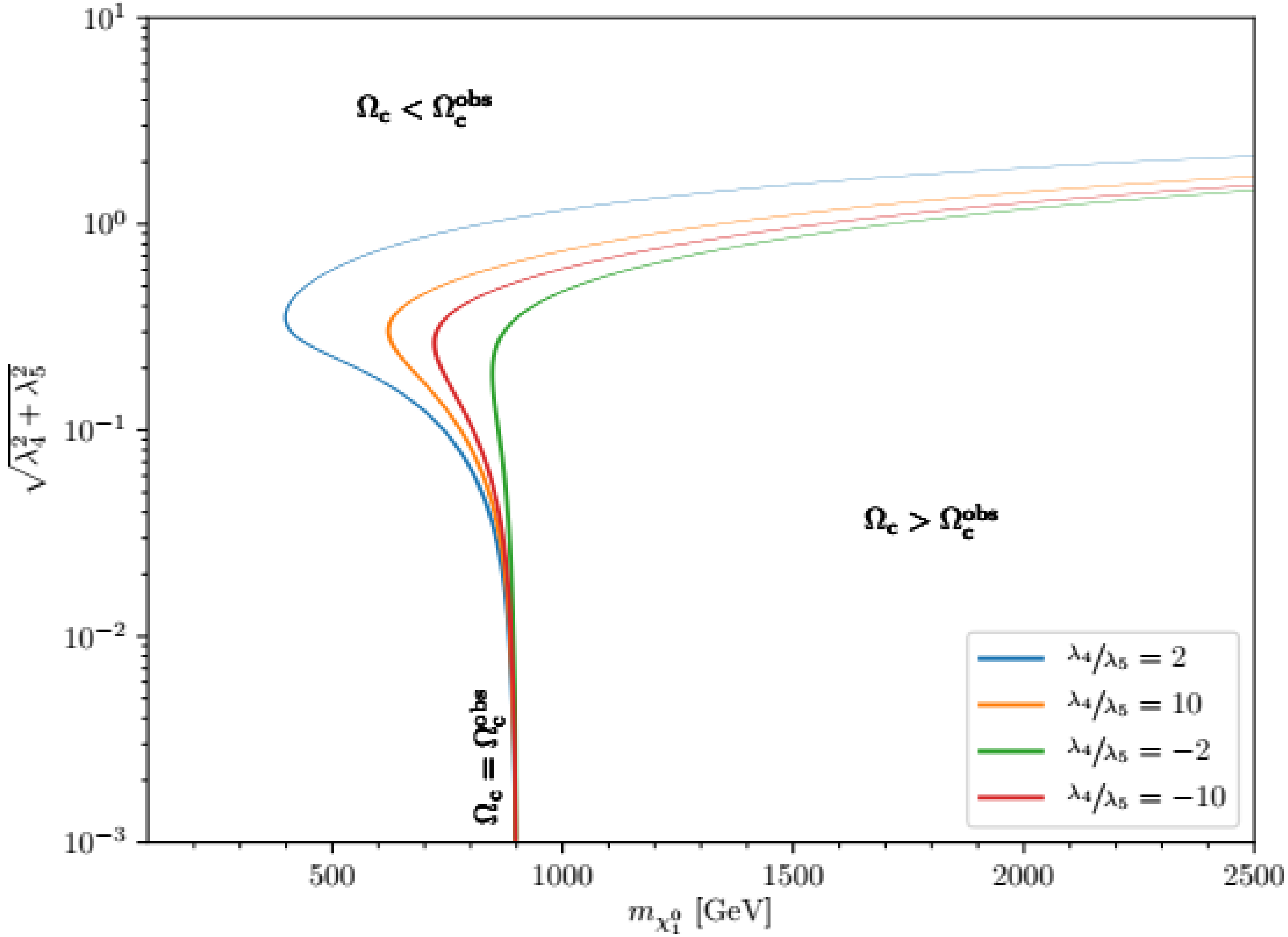
$$M_\phi \gg M_\Psi, \;\; M_{\psi\psi'}$$

$$\lambda_1 = \lambda_3 = \lambda_6 = 0$$

Special case:

$$M_\Psi = M_{\psi\psi'}$$

Mass splitting depending on the relative size of λ_4 & λ_5. Controls the impact of coannihilation processes.



Small Yukawas → small mixing, small annihilation cross section into gauge and Higgs bosons → large DM relic density

Large Yukawas → $\lambda_4^2 + \lambda_5^2 \geq (0.4)^2$ Efficient annihilation channels → DM mass rises quickly