Phenomenological aspects of scotogenic models

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Phenomenological aspects of scotogenic models

Motivation for scotogenic models

Review and introduction to T1-2A model

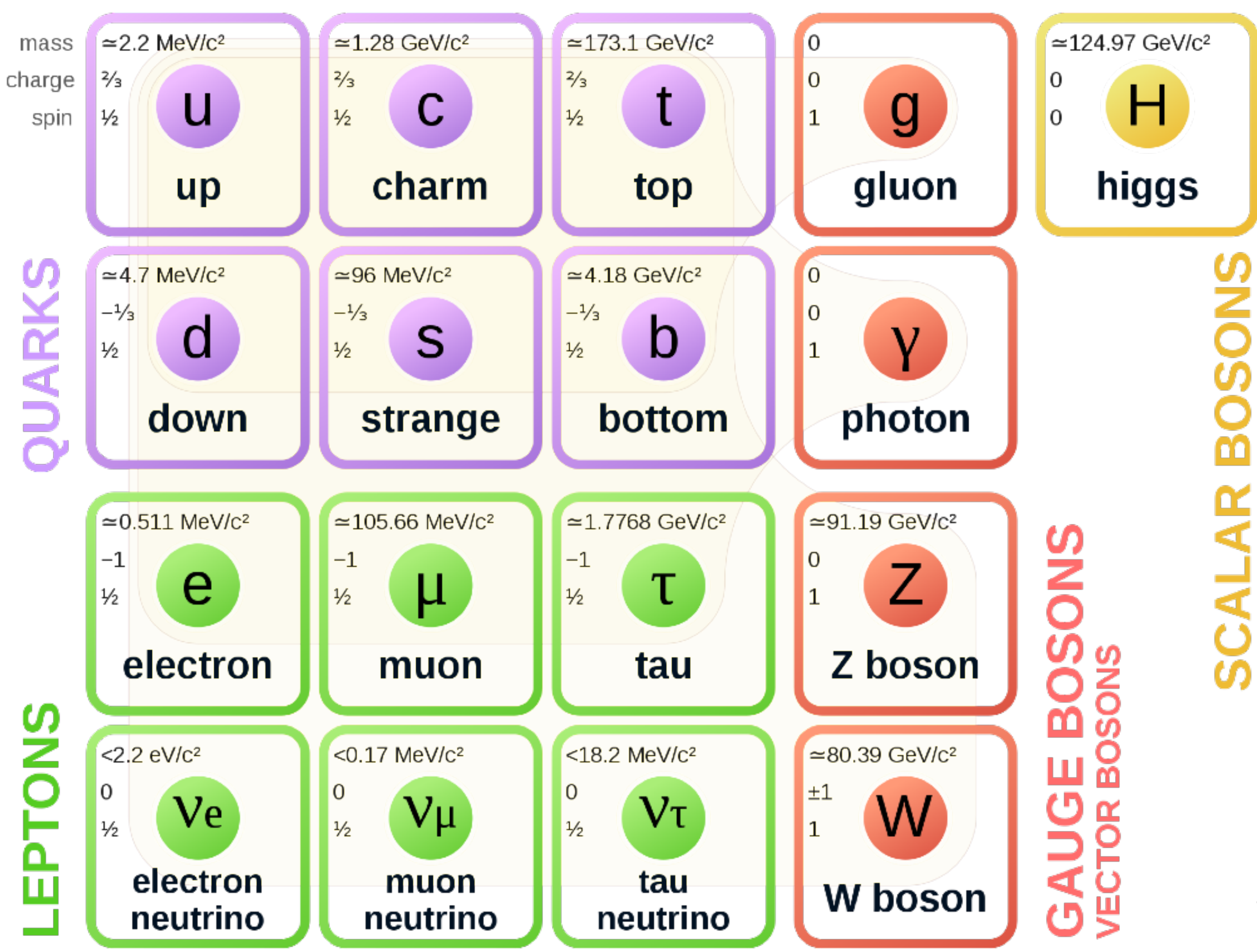
Phenomenology of the T1-2A model

Extensions of the T1-2A model

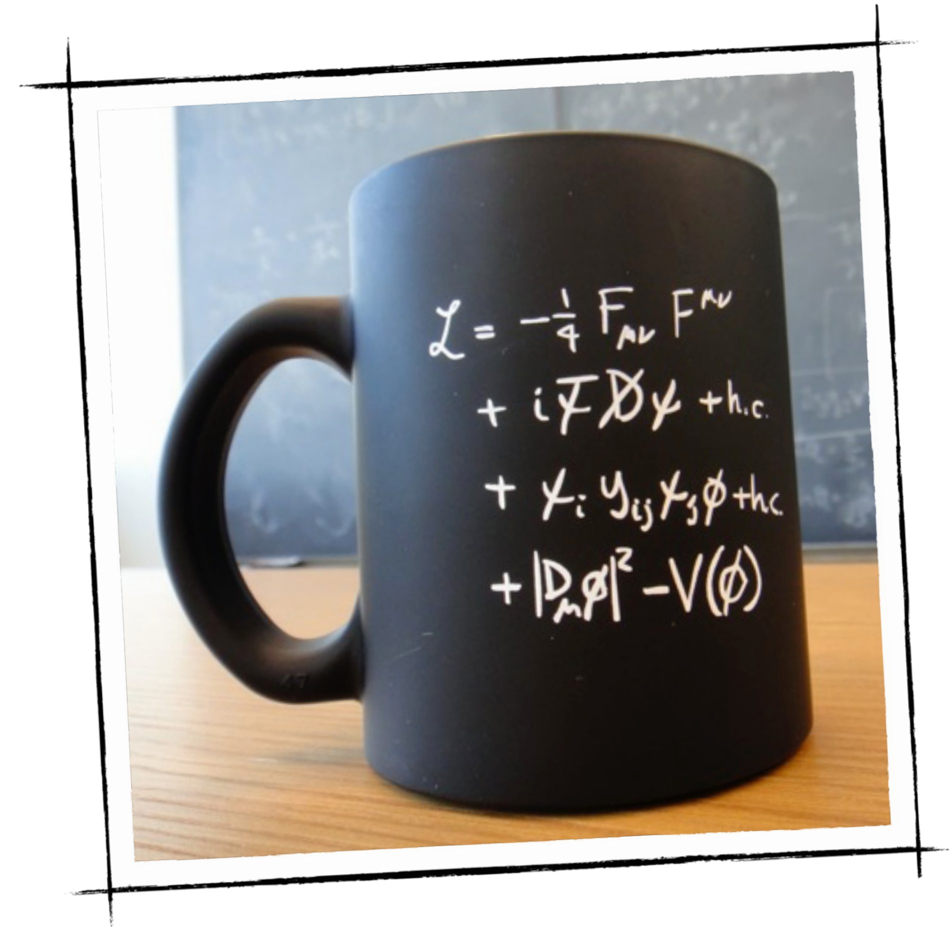
Summary and perspectives

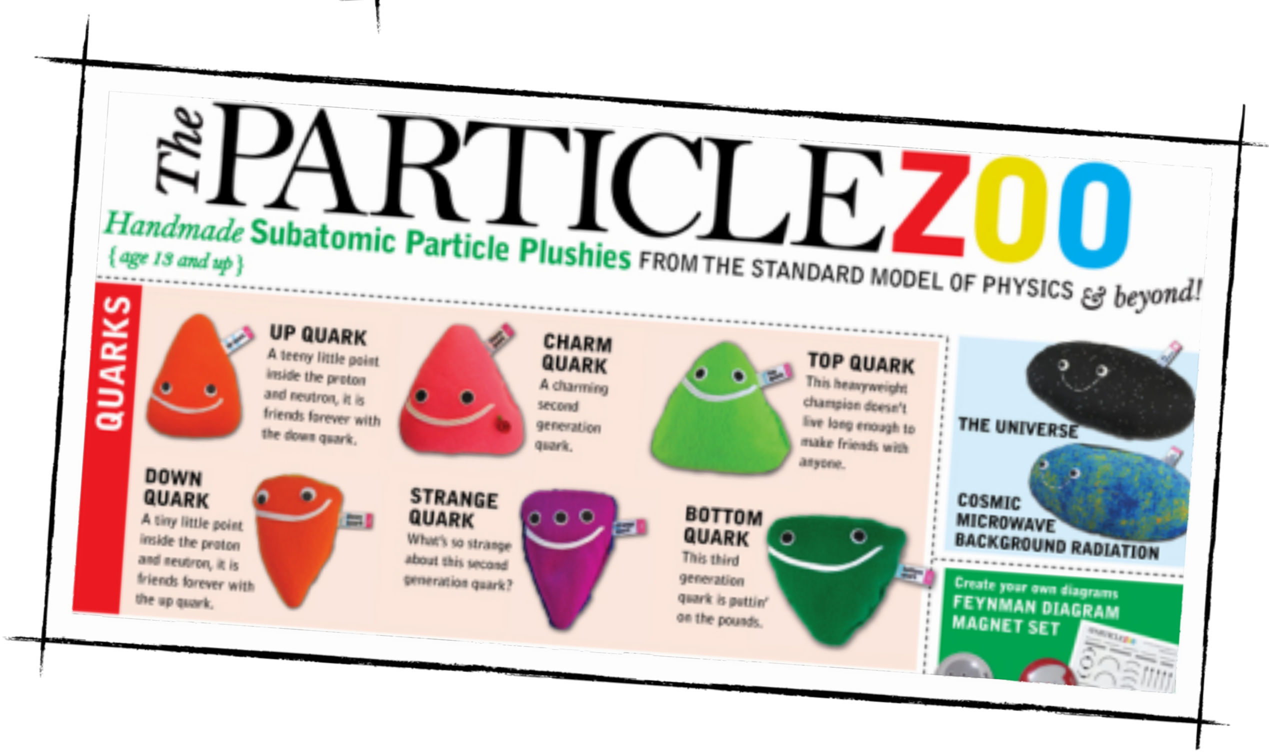
M. Sarazin, B. Herrmann, J. Bernigaud — JHEP 03 (2019) 067 — arXiv:1812.07463 [hep-ph]
A. Alvarez, A. Banik, R. Cepedello, B. Herrmann, W. Porod, M. Sarazin, M. Schnelke — JHEP 05 (2022) 156 — arXiv:2111.10199 [hep-ph]
T. Guérandel, B. Herrmann — *to be completed…*
U. de Noyers, M. Sarazin, B. Herrmann — *to be published…*

The Standard Model...

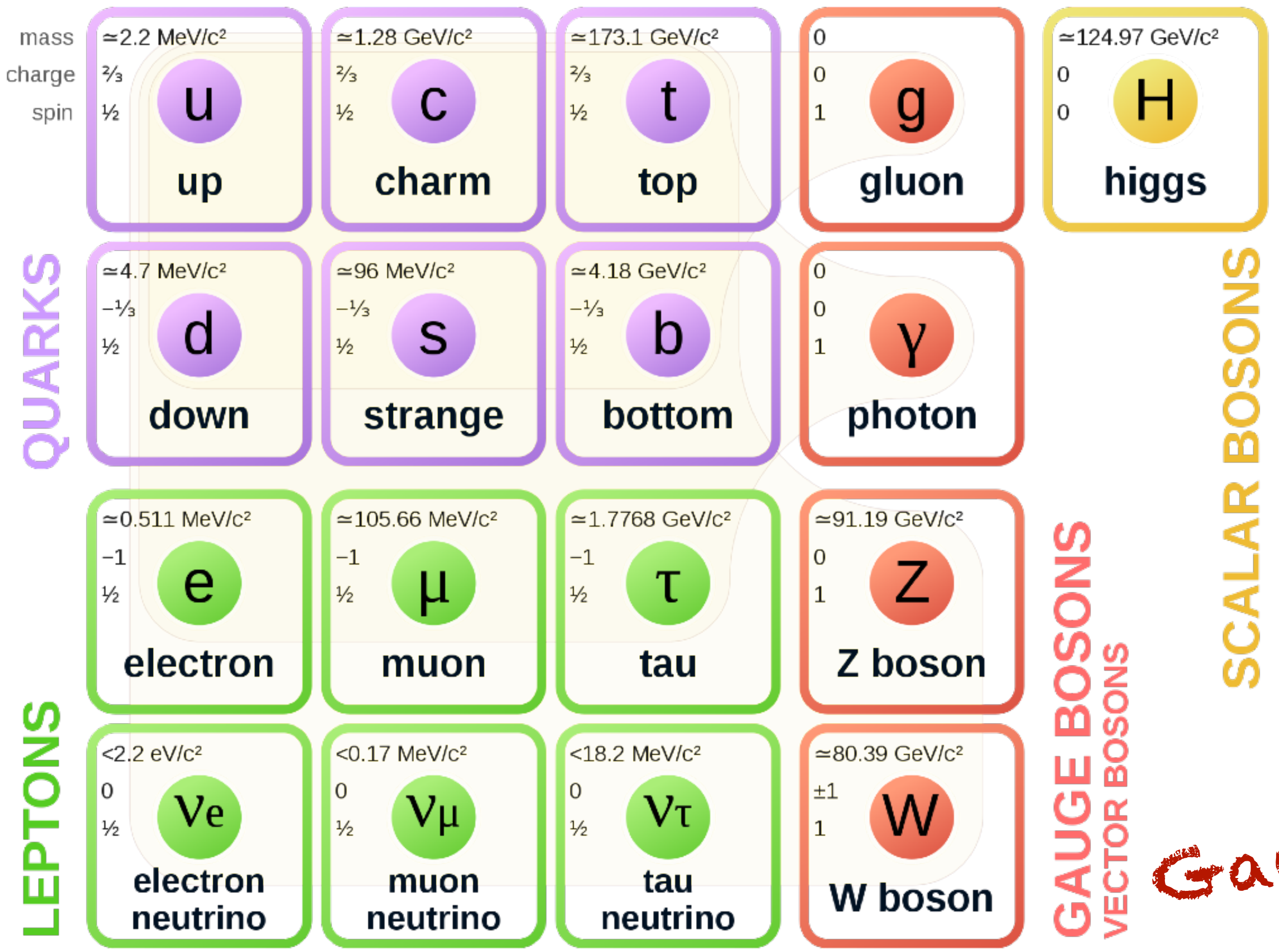


en.wikipedia.org/wiki/Standard_Model





The Standard Model... and its shortcomings



Flavour problem...?

Hierarchy problem...?

Baryon asymmetry...?

Gauge coupling unification...?

Gravity...?

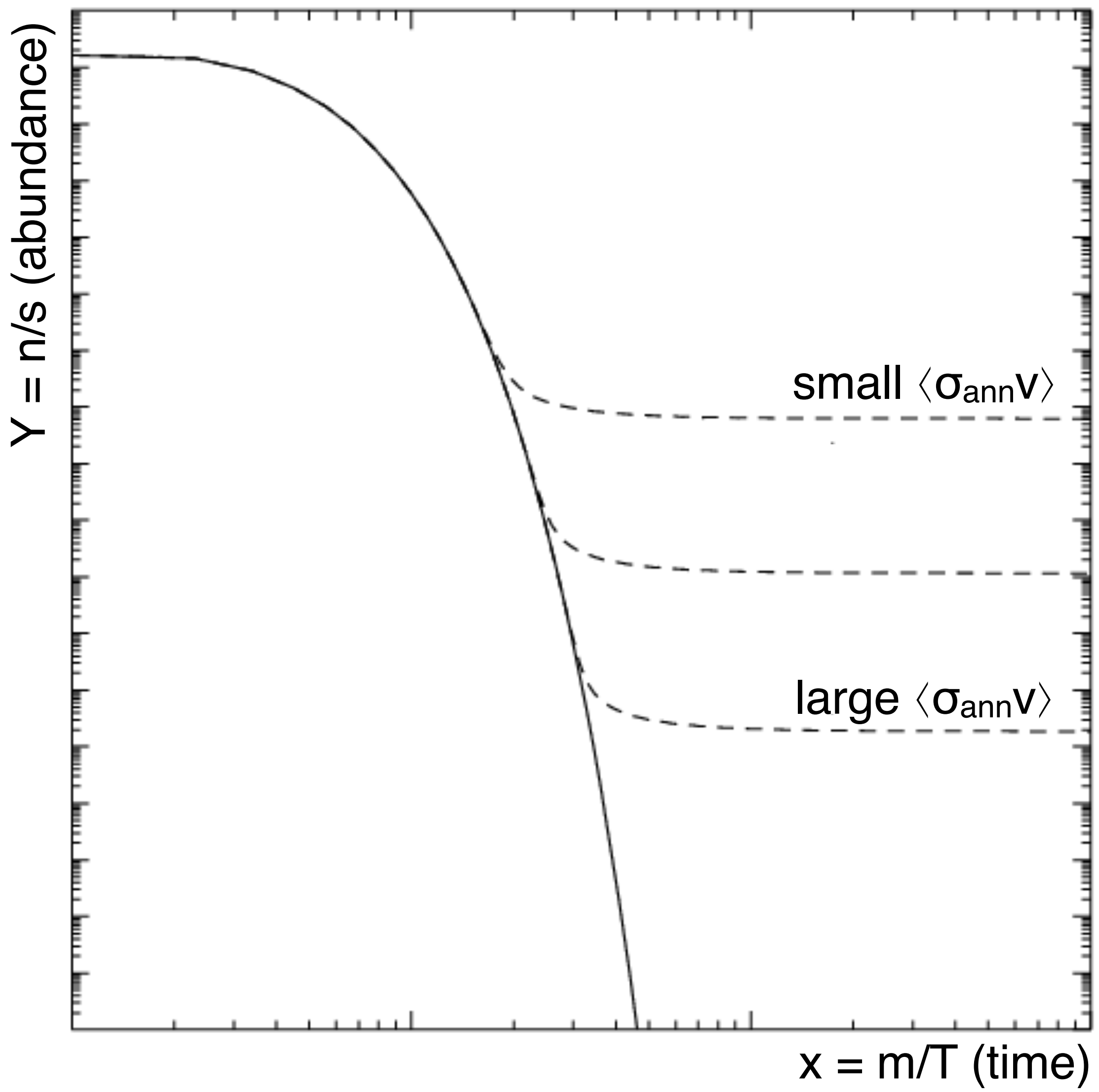
Muon g-2...?

Neutrino masses...?

Dark matter in the Universe...?

Lepton-flavour non-universality...?

Dark matter in the Universe — relic abundance



Time evolution of number density of the relic particle described by Boltzmann equation

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -3Hn - \langle \sigma_{\mathrm{ann}} v \rangle \left(n^2 - n_{\mathrm{eq}}^2 \right)$$

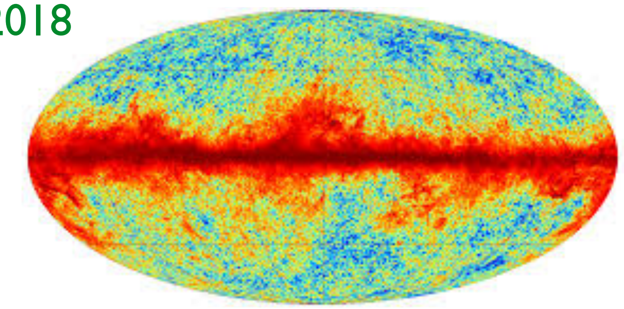
Prediction of dark matter relic density
(if masses and interactions are known)

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_{\mathrm{crit}}} \sim \frac{1}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

(dis)favoured parameter regions…?

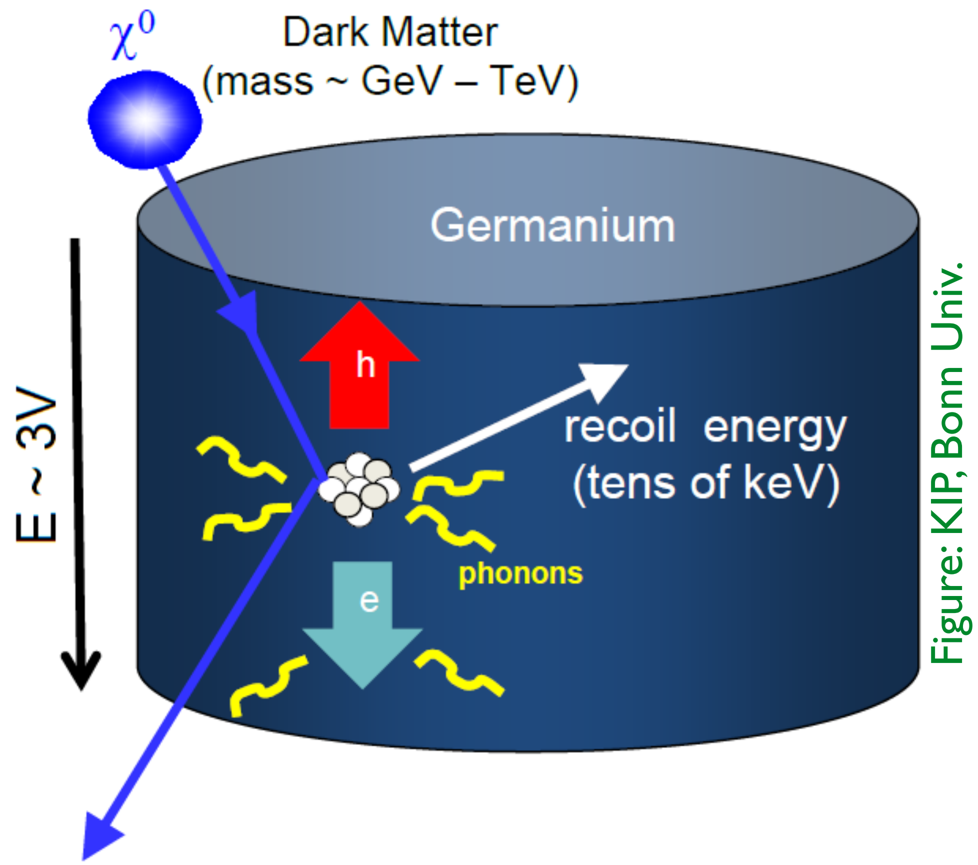
$$\Omega_{\mathrm{CDM}} h^2 = 0.1200 \pm 0.0012$$

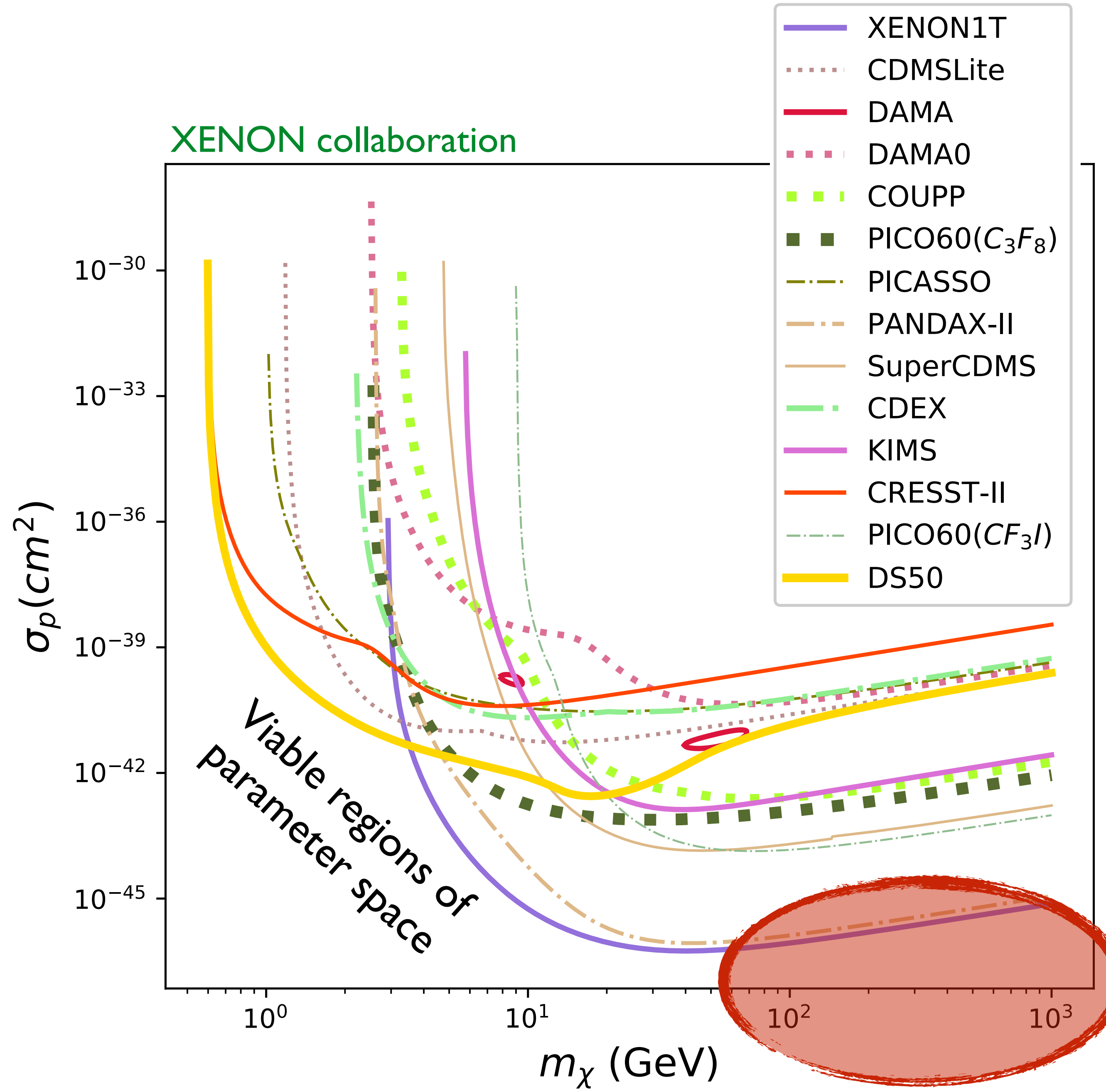
Planck 2018



Dark matter candidate…? WIMP…?

Dark matter in the Universe — direct searches

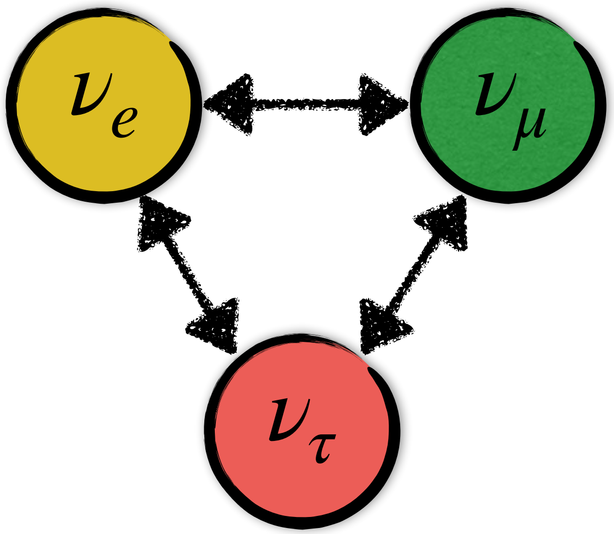




100 GeV — 2 TeV
typical masses in scotogenic models

Dark matter candidate...? WIMP...?

Neutrino masses and mixing



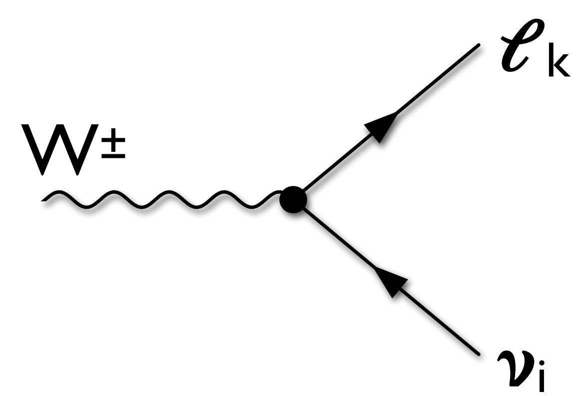
$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = V_\nu \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{\text{PMNS}} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$V_{\text{PMNS}} = V_\ell^\dagger V_\nu$$

Δm^2_{12}	$[7.0; 7.84] \cdot 10^{-23}$
Δm^2_{13}	$[2.47; 2.57] \cdot 10^{-21}$
θ_{12}	$[31.90; 34.98]$
θ_{13}	$[8.33; 8.81]$
θ_{23}	$[46.8; 51.6]$
δ_{CP}	$[143; 251]$

NuFit Collaboration 2021

+ 2 Majorana phases…?



$$\propto \left(V_{\text{PMNS}}\right)_{ik}$$

Mechanism for neutrino mass generation…?

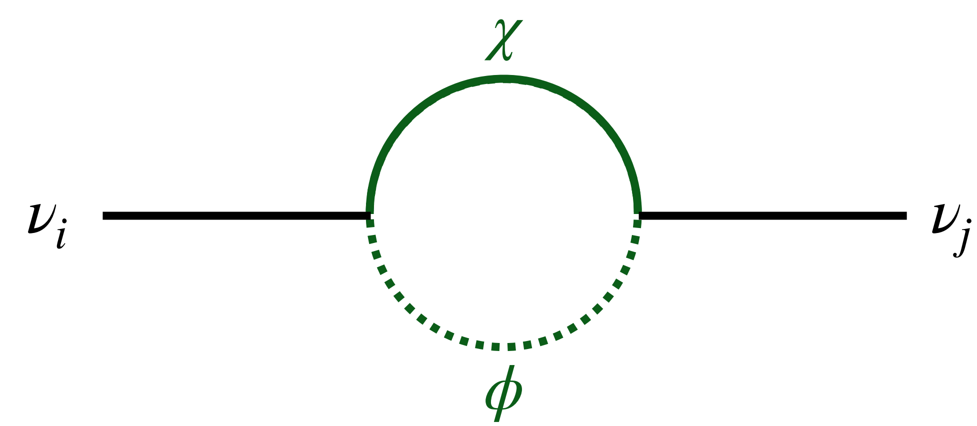
Extensions of the scotogenic type

"σκότος" — "darkness"

"γεννώ" — "give birth"

Standard Model + **new scalars** + **new fermions**

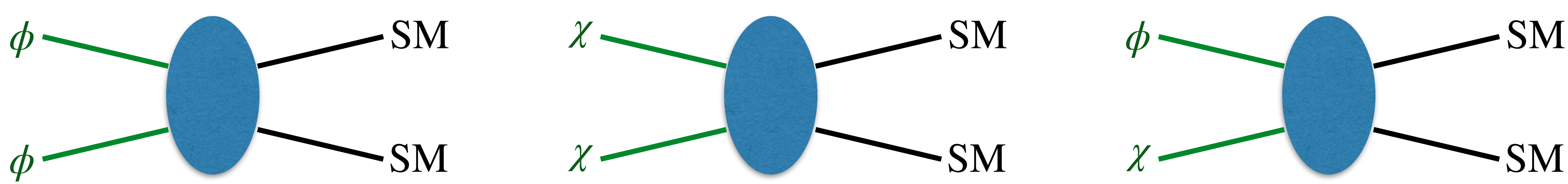
— radiative generation of neutrino masses



$\mathbb{Z}_2$ **symmetry**

— stable dark matter candidate (scalar or fermion)

— implications on collider phenomenology



PHYSICAL REVIEW D **73,** 077301 (2006)

Verifiable radiative seesaw mechanism of neutrino mass and dark matter

Ernest Ma

Physics Department, University of California, Riverside, California 92521, USA

(Received 27 January 2006; published 14 April 2006)

Neutrino oscillations have established that neutrinos ν_i have very small masses. Theoretically, they are believed to arise through the famous seesaw mechanism from their very heavy and unobservable Dirac mass partners N_i. It is proposed here in a new minimal extension of the standard model with a second scalar doublet (η^+, η^0) that the seesaw mechanism is actually radiative, and that N_i and (η^+, η^0) are experimentally observable at the forthcoming Large Hadron Collider, with the bonus that the lightest of them is also an excellent candidate for the dark matter of the Universe.

First and simplest scotogenic model:

SM + scalar doublet + 3 fermionic singlets

Models with radiative neutrino masses and viable dark matter candidates

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October 14, 2013

JHEP 11 (2013) 011

Classification of models w.r.t. particle content and topologies

A singlet-doublet model (T1-2A)

scalar doublet + singlet

	Ψ_1	Ψ_2	F	Φ	S
$SU(2)_L$	**2**	**2**	**1**	**2**	**1**
$U(1)_Y$	-1	1	0	1	0

fermionic doublet + singlet

$$-\mathscr{L}_{\text{scalar}} = \mu_H^2 |H|^2 + \lambda_H |H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{4S} S^4 + \mu_\Phi^2 |\Phi|^2 + \lambda_{4\Phi} |\Phi|^4 + \frac{1}{2}\lambda_S S^2 |H|^2 + \lambda_\Phi |\Phi|^2 |H|^2 + \lambda'_\Phi |H\Phi^\dagger|^2 + \frac{1}{2}\lambda''_\Phi \left\{ (H\Phi^\dagger)^2 + \text{h.c.} \right\} + T\left\{ SH\Phi^\dagger + \text{h.c.} \right\}$$

$$-\mathscr{L}_{\text{fermion}} = \frac{1}{2} M_F F^2 + M_\Psi \Psi_1 \Psi_2 + y_1 \Psi_1 H F + y_2 \overline{\Psi}_2 H \overline{F} + \text{h.c.}$$

$$-\mathscr{L}_{\text{int}} = g_\Psi^i \Psi_2 L_i S + g_F^i \Phi L_i F + g_R^i L^c_{\text{R}i} \Phi^\dagger \Psi_1$$

23 parameters in model Lagrangian — **need for an efficient parameter space study…**

The model T1-2A — scalar sector

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left[v + h^0 + iG^0\right] \end{pmatrix} \qquad \Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}\left[\phi^0 + iA^0\right] \end{pmatrix} \qquad S$$

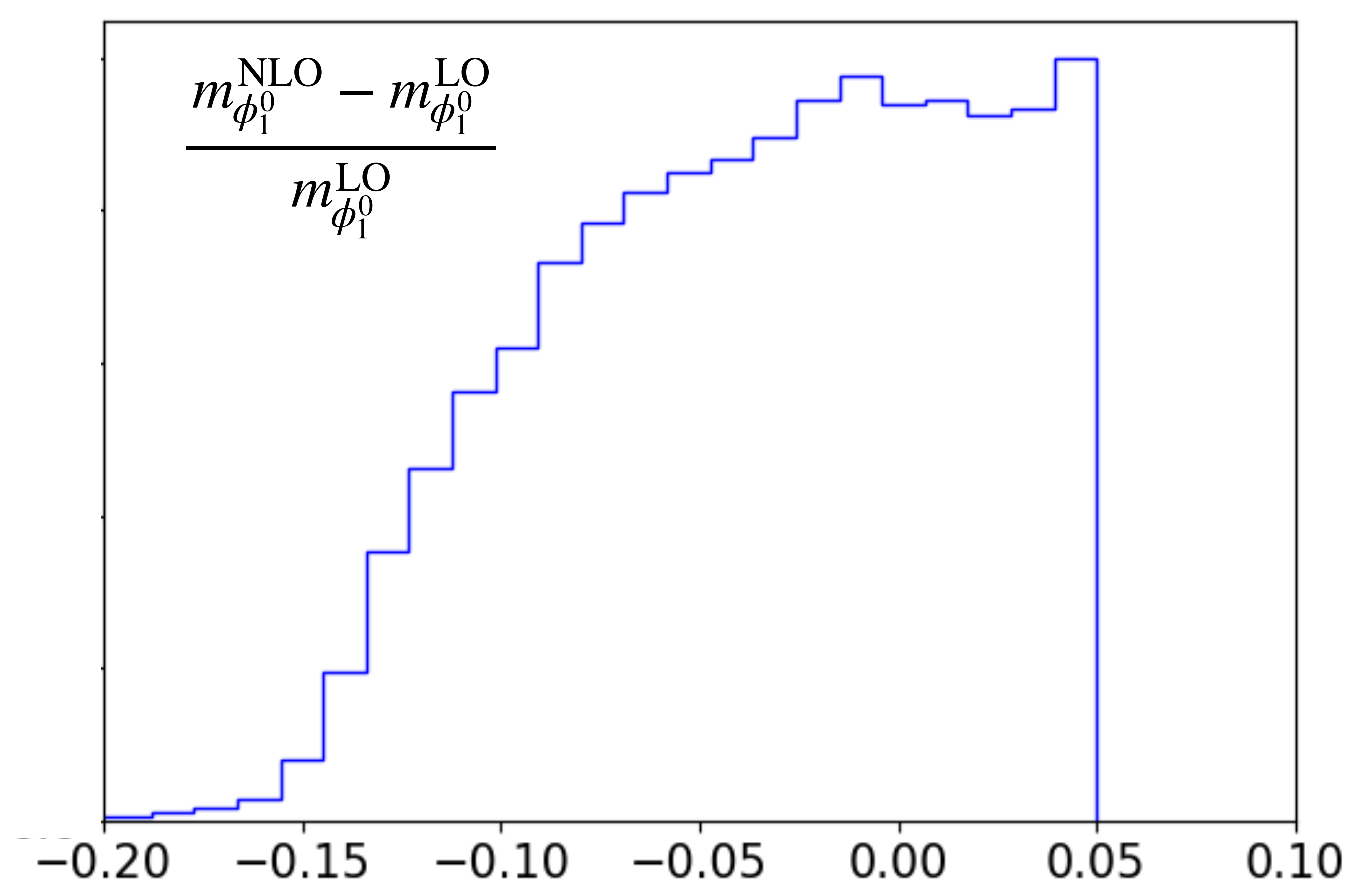
Higgs boson + 2 neutral scalars + 1 pseudoscalar + 1 charged scalar

— mixing between singlet and doublet (for the neutral scalars)

— one-loop corrections to the masses amount typically to up to about 10 percent

$$\mathscr{M}_\phi^2 = \begin{pmatrix} \mu_S^2 + \frac{1}{2}v^2\lambda_S & vT \\ vT & \mu_\Phi^2 + \frac{1}{2}v^2\lambda_L \end{pmatrix}$$

$$\begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} = U_\phi \begin{pmatrix} S \\ \phi^0 \end{pmatrix}$$



The model T1-2A — fermion sector

$$\Psi_1 = \begin{pmatrix} \Psi_1^0 \\ \Psi_1^- \end{pmatrix} \qquad \Psi_2 = \begin{pmatrix} -\left(\Psi_2^-\right)^\dagger \\ \left(\Psi_2^0\right)^\dagger \end{pmatrix} \qquad F$$

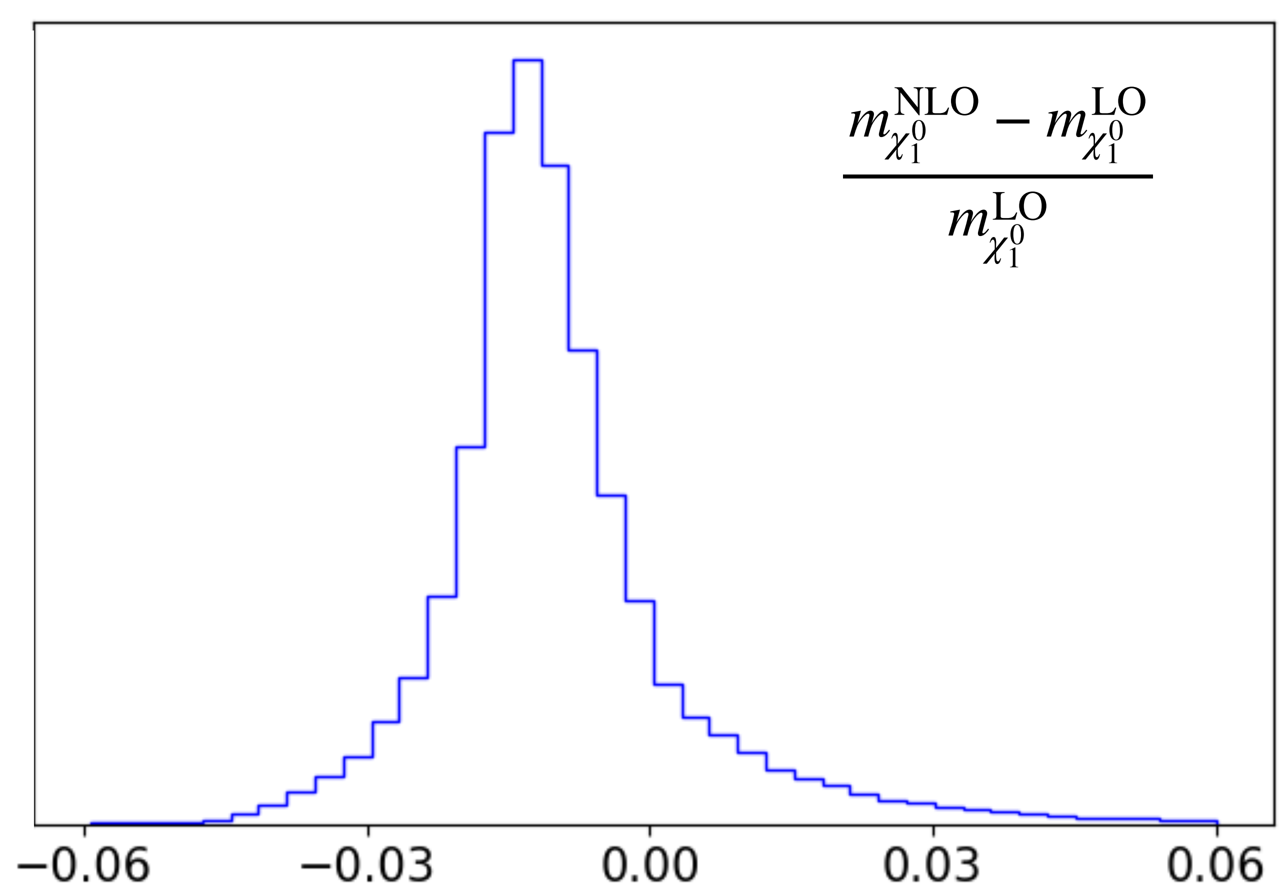
3 neutral Majorana fermions + **1 charged fermion**

— mixing between singlet and doublet (for the neutral fermion)

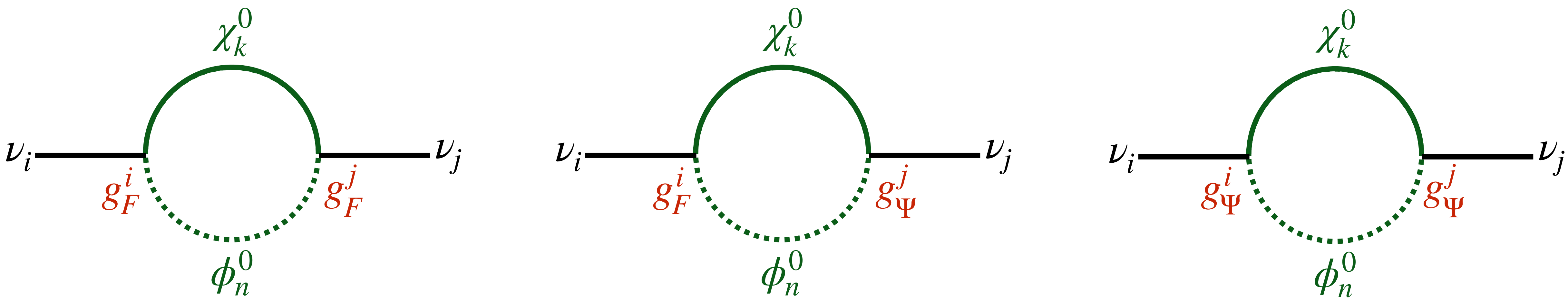
— one-loop corrections to the masses amount typically to a few percent

$$\mathscr{M}_\chi = \begin{pmatrix} M_F & vy_1 & vy_2 \\ y_1 & 0 & M_\Psi \\ y_2 & M_\Psi & 0 \end{pmatrix}$$

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix} = U_\chi \begin{pmatrix} F \\ \Psi^1 \\ \Psi_2 \end{pmatrix}$$



Neutrino masses and coupling parameters

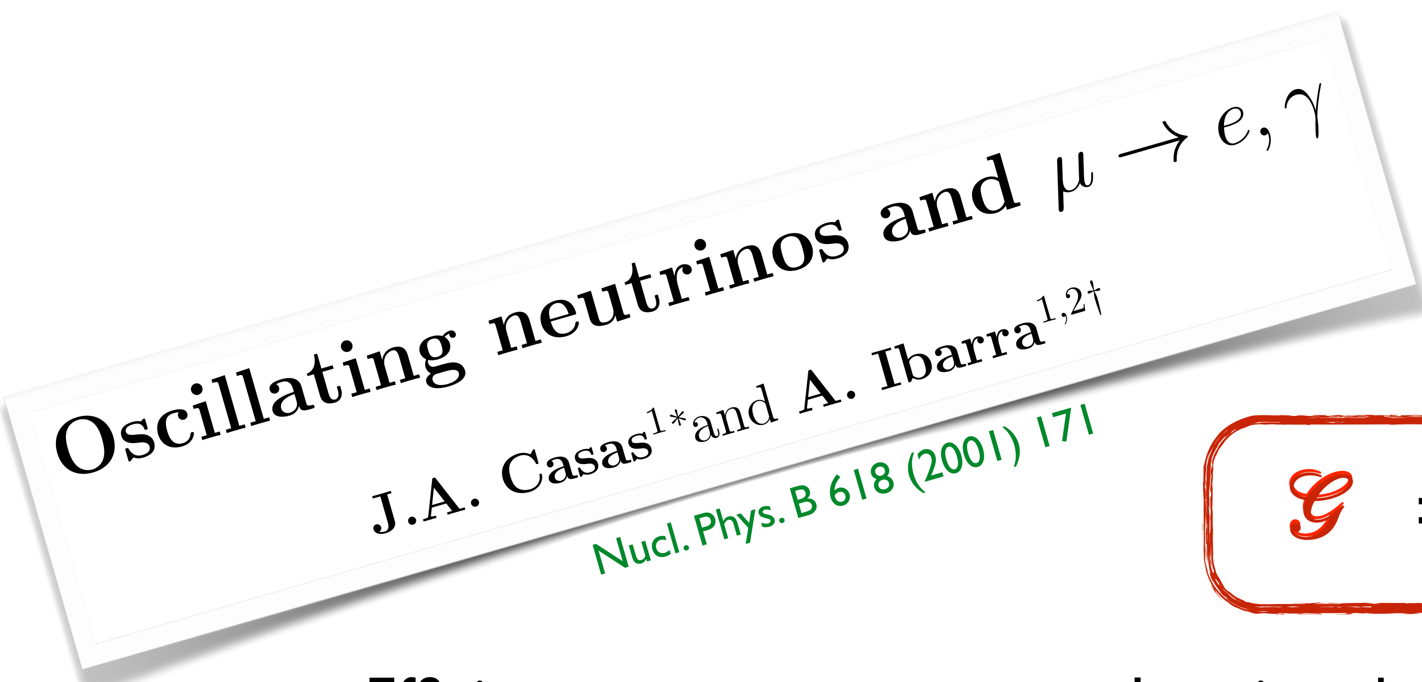


$$\sim g_F^j \frac{m_{F_k}}{16\pi^2} B_0(0; m_{\chi_k}, m_{\phi_n})\ g_F^i$$

$$\mathscr{M}_\nu = \mathscr{G}^t M_{\rm Loop}\, \mathscr{G}$$

Neutrino mass matrix

$$\mathscr{G} = \begin{pmatrix} g_\Psi^1 & g_\Psi^2 & g_\Psi^3 \\ g_F^1 & g_F^2 & g_F^3 \end{pmatrix}$$


Oscillating neutrinos and $\mu \to e, \gamma$

J.A. Casas[1*] and A. Ibarra[1,2†]

Nucl. Phys. B 618 (2001) 171

Rotation matrix

Neutrino masses and mixing angles

$$\mathscr{G} = U_L\, D_L^{-1/2}\, R\, D_\nu^{1/2}\, U^*_{\rm PMNS}$$

Efficient parameter space exploration thanks to **Casas-Ibarra parametrization**

The model T1-2A — recap

Standard Model + $\phi_1^0,\ \phi_2^0,\ \ A^0,\ \ \phi^\pm$ + $\chi_1^0, \chi_2^0, \chi_3^0,\ \ \chi^\pm$

Scalars

Fermions

λ_H	$[0.1; 0.4]$
$\mu_S^2,\ \mu_\Phi^2$	$[0.5\times 10^6; 4\times 10^6]$
T	$[-1000; 1000]$
$\lambda_\Phi,\ \lambda'_\Phi,\ \lambda''_\Phi$	$[-2; 2]$
$\lambda_S,\ \lambda_{4S},\ \lambda_{4\Phi}$	$[-2; 2]$

$M_F,\ M_\Psi$	$[700; 2000]$
$y_1,\ y_2$	$[-1.2; 1.2]$
$g_R^i\ (i=1,2)$	$[-1.2; 1.2]$
g_R^3	$[-2.0; 2.0]$
r	$[-1; 1]$

Neutrino sector and related couplings

Δm_{12}^2	$[7.0; 7.84]\cdot 10^{-23}$
m_{ν_2}	$[8.367; 8.854]\cdot 10^{-12}$
Δm_{13}^2	$[2.47; 2.57]\cdot 10^{-21}$
m_{ν_3}	$[4.96; 5.07]\cdot 10^{-11}$

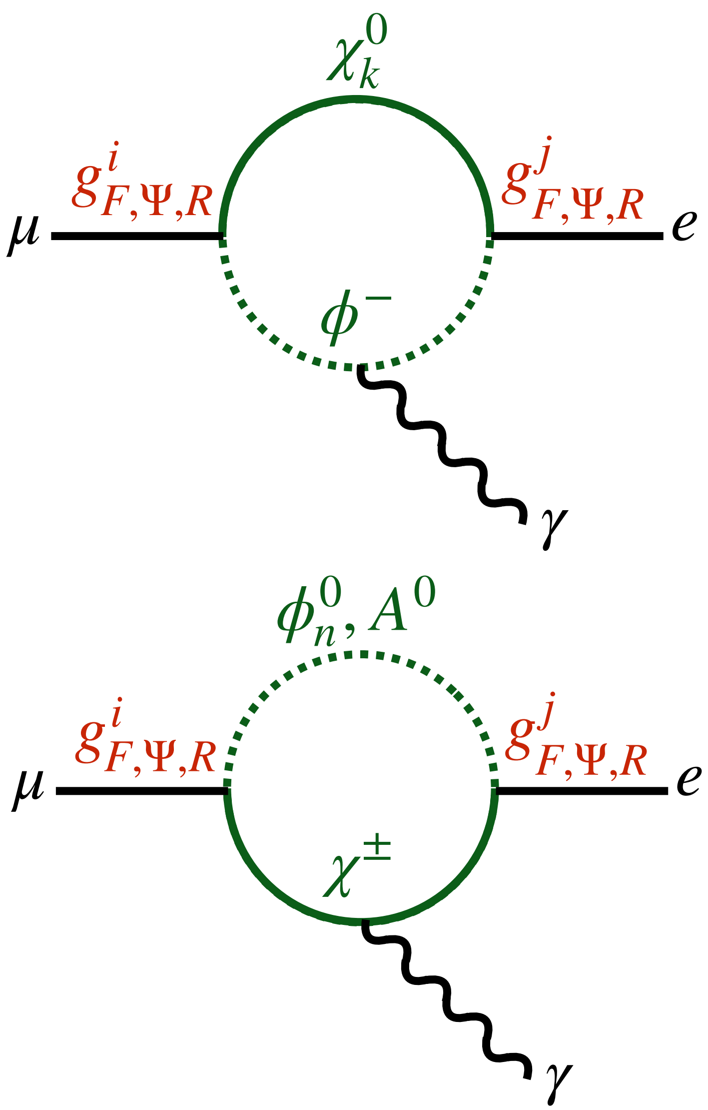
$m_{\nu_1} = 0$

θ_{12}	$[31.90; 34.98]$
θ_{13}	$[8.33; 8.81]$
θ_{23}	$[46.8; 51.6]$
$\delta_{\rm CP}$	$[143; 251]$

NuFit Collaboration 2021

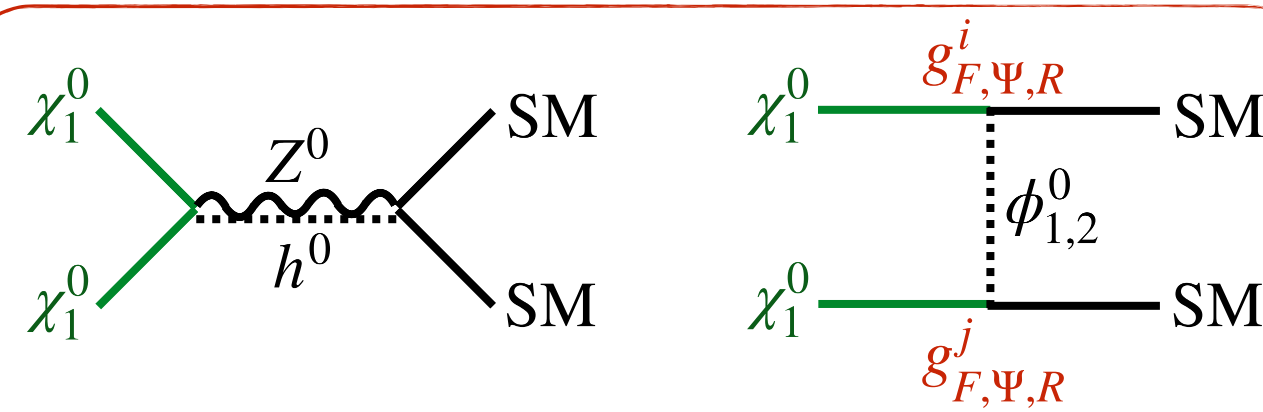
$$\longrightarrow\ \mathscr{G} = \begin{pmatrix} g_\Psi^1 & g_\Psi^2 & g_\Psi^3 \\ g_F^1 & g_F^2 & g_F^3 \end{pmatrix}$$

Parameters and constraints



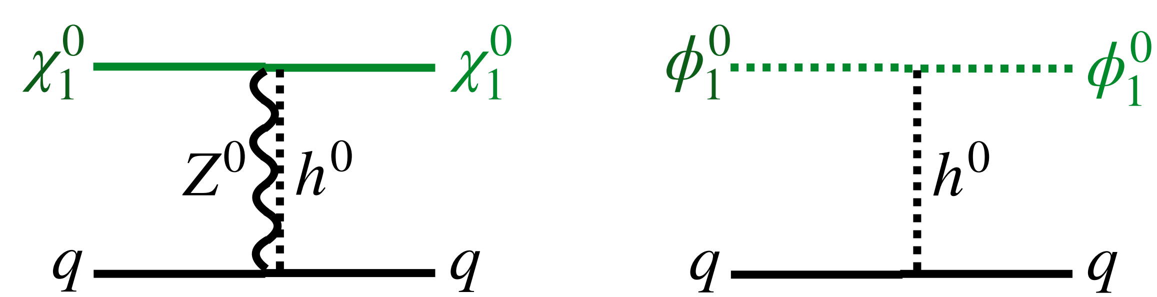
+ 2 "bubble" diagrams

$\mu \to e\gamma$



- 2 similar diagrams for scalar dark matter
- co-annihilation diagrams

Dark matter annihilation



Dark matter direct detection

Parameters and constraints

Observable	Constraint
m_H	125.0 ± 3.0 GeV
$\Omega_{\rm CDM}h^2$	0.1198 ± 0.0042
$\mathrm{BR}(\mu^- \to e^-\gamma)$	$< 4.2 \cdot 10^{-13}$
$\mathrm{BR}(\tau^- \to e^-\gamma)$	$< 3.3 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^-\gamma)$	$< 4.4 \cdot 10^{-8}$
$\mathrm{BR}(\mu^- \to e^-e^+e^-)$	$< 1.0 \cdot 10^{-12}$
$\mathrm{BR}(\tau^- \to e^-e^+e^-)$	$< 2.7 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^-\mu^+\mu^-)$	$< 2.1 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^+e^-e^-)$	$< 1.5 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^-e^+e^-)$	$< 2.1 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to e^+\mu^-\mu^-)$	$< 1.7 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to e^-\mu^+\mu^-)$	$< 2.7 \cdot 10^{-8}$

Observable	Constraint
$\mathrm{BR}(Z^0 \to e^\pm\mu^\mp)$	$< 7.5 \cdot 10^{-7}$
$\mathrm{BR}(Z^0 \to e^\pm\tau^\mp)$	$< 9.8 \cdot 10^{-6}$
$\mathrm{BR}(Z^0 \to \mu^\pm\tau^\mp)$	$< 1.2 \cdot 10^{-5}$
$\mathrm{BR}(\tau^- \to e^-\pi^0)$	$< 8.0 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^-\pi^0)$	$< 1.1 \cdot 10^{-7}$
$\mathrm{BR}(\tau^- \to e^-\eta)$	$< 9.3 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to e^-\eta')$	$< 1.6 \cdot 10^{-7}$
$\mathrm{BR}(\tau^- \to \mu^-\eta)$	$< 6.5 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^-\eta')$	$< 1.3 \cdot 10^{-7}$
$\mathrm{CR}_{\mu\to e}(\mathrm{Ti})$	$< 4.3 \cdot 10^{-12}$
$\mathrm{CR}_{\mu\to e}(\mathrm{Pb})$	$< 4.6 \cdot 10^{-11}$
$\mathrm{CR}_{\mu\to e}(\mathrm{Au})$	$< 7.0 \cdot 10^{-13}$

+ dark matter direct detection limits

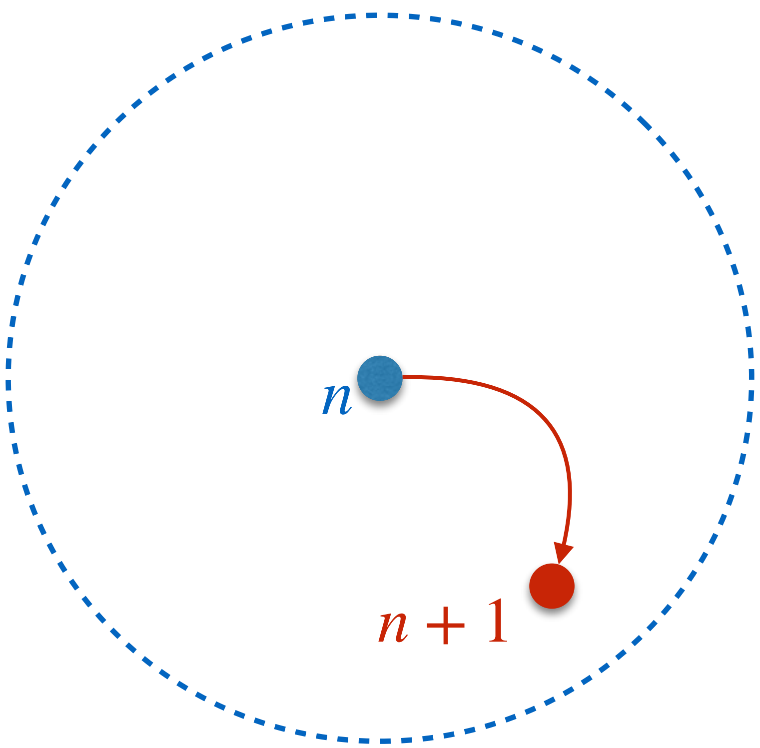
Numerical evaluation — **SARAH** + **SPheno** Staub, Porod, Goodsell (2003-2024)

— **micrOMEGAs** Bélanger, Boudjema, Pukhov, Semenov *et al.* (2004-2024)

Parameter space exploration

23 free parameters in model Lagrangian + numerous constraints

— **need for an efficient algorithm…** — **Markov Chain Monte Carlo**



$$\mathscr{L}_n = \Pi_i \mathscr{L}_n^i = \Pi_j \mathscr{L}_n^j \, \Pi_k \mathscr{L}_n^k$$

intervals

e.g. m_h, $\Omega_{CDM}h^2$

upper limits

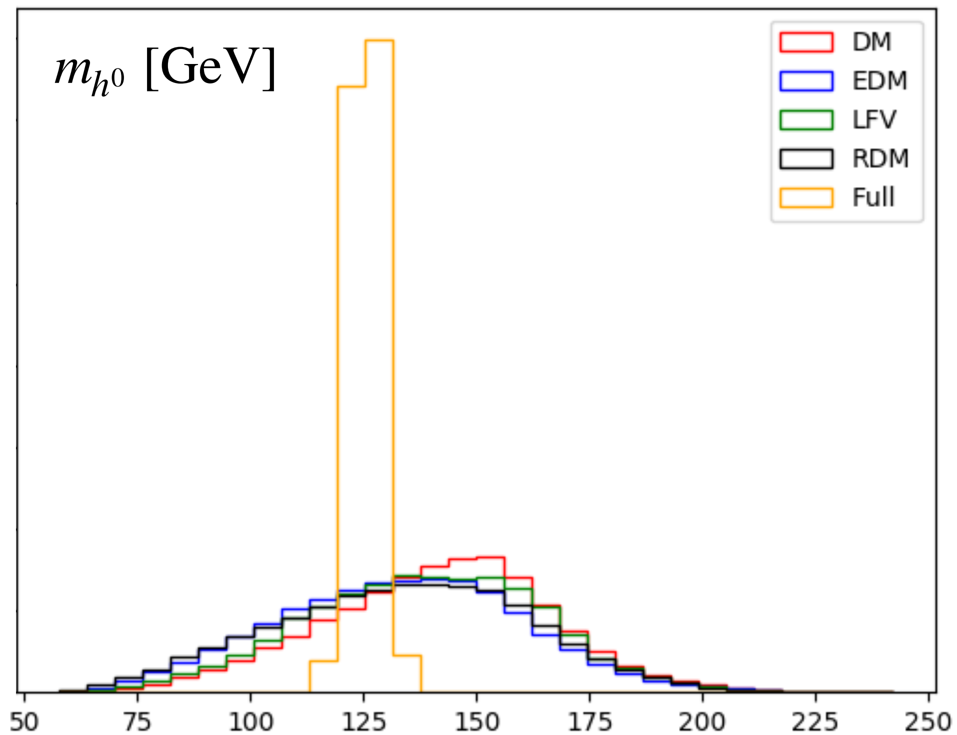
e.g. $\mu \to e\gamma$, DD

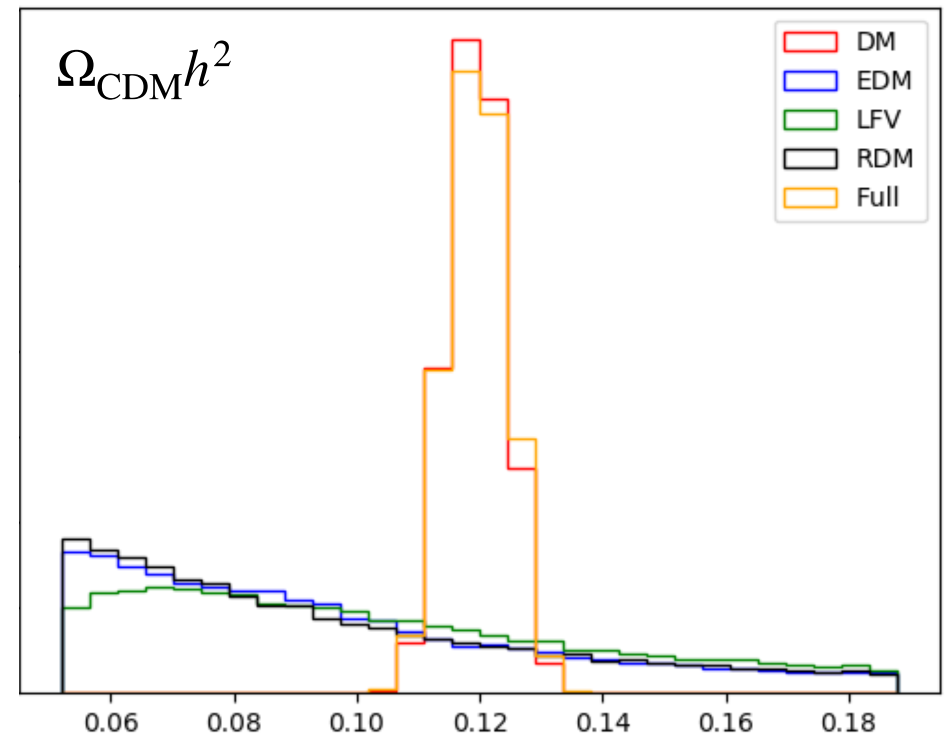
$\mathscr{L}_{n+1} \overset{?}{>} \mathscr{L}_n$

✓ → **accept new point** (and iterate…)

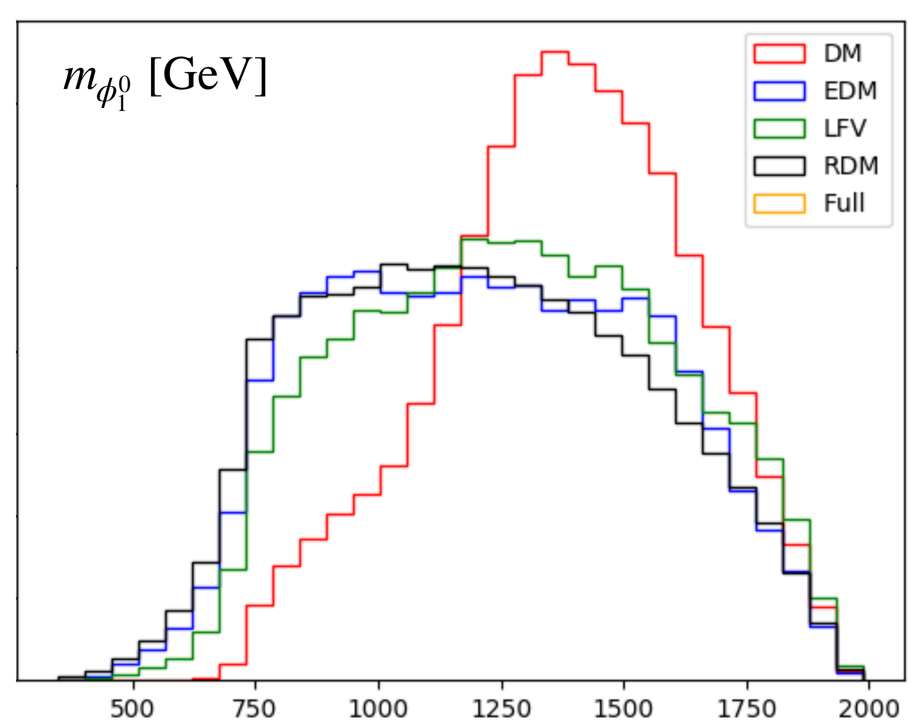
✗ → accept new point with probability $\mathscr{L}_{n+1}/\mathscr{L}_n$

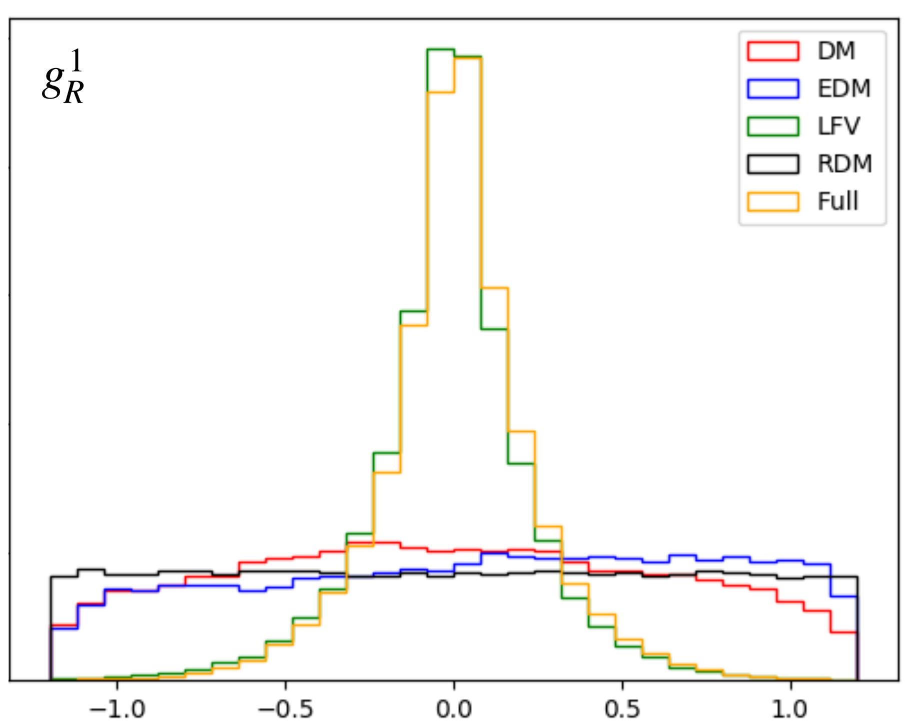
MCMC — Constraints… and predictions



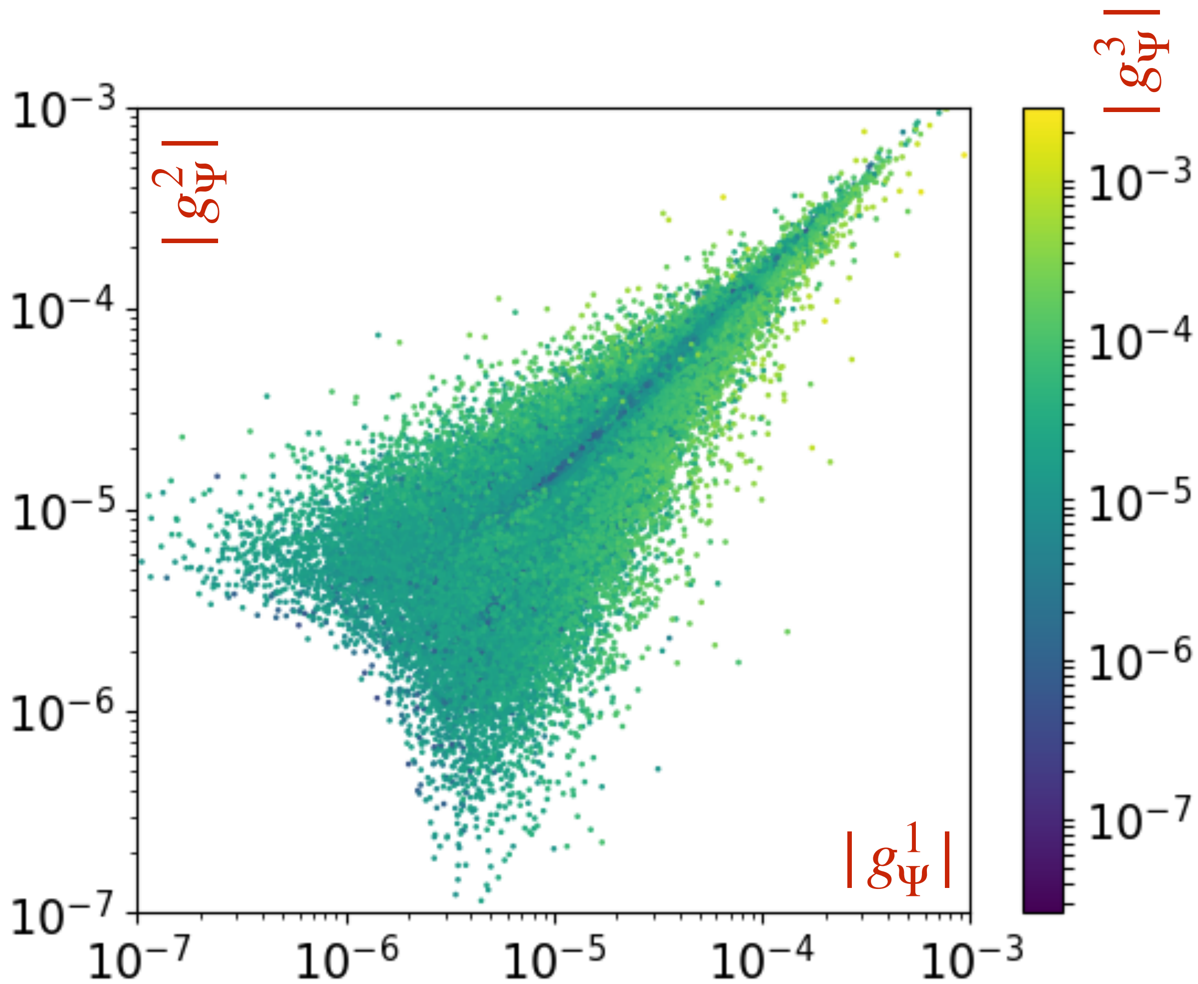


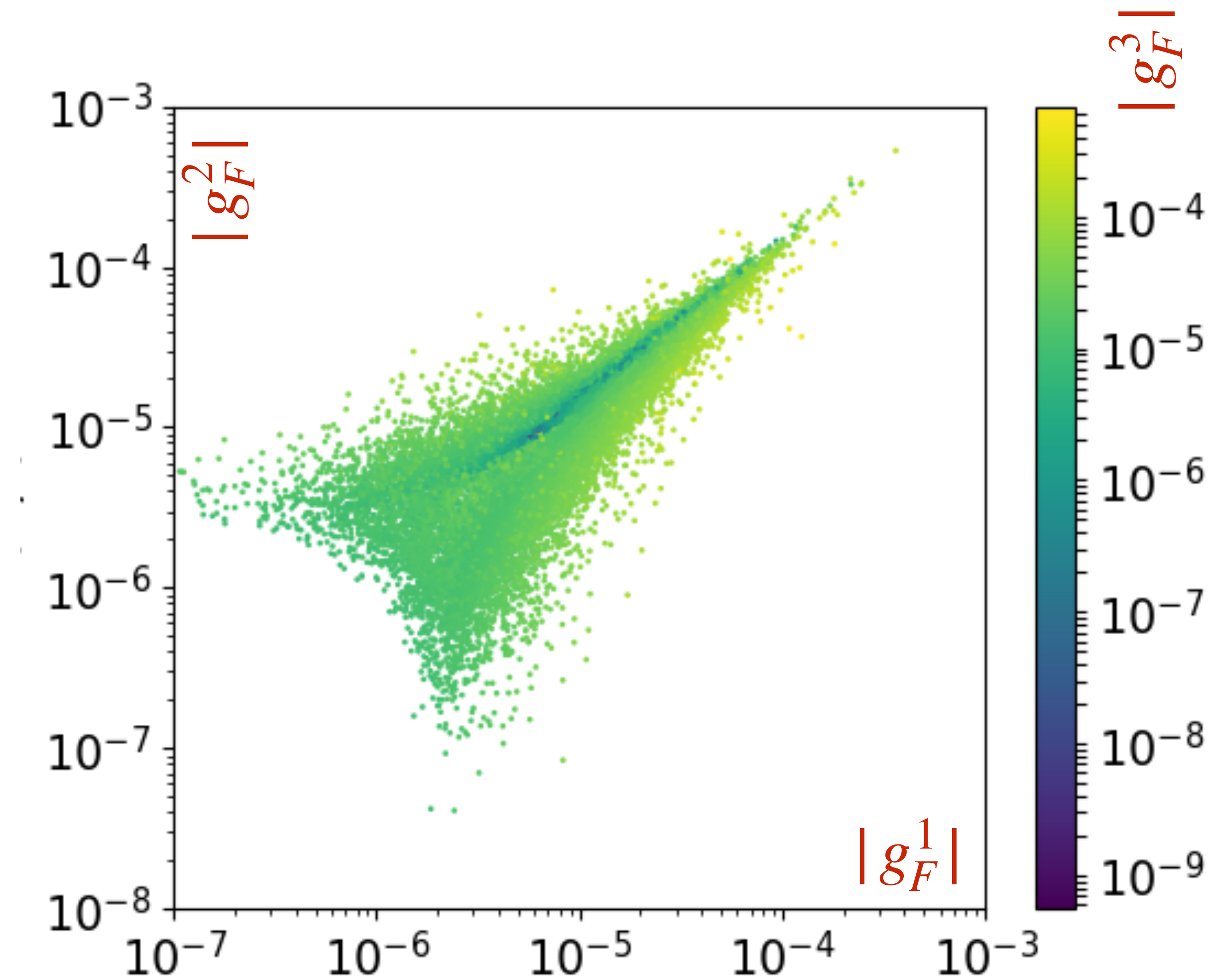
MCMC study
with a total of
~80 000 points





Coupling parameters

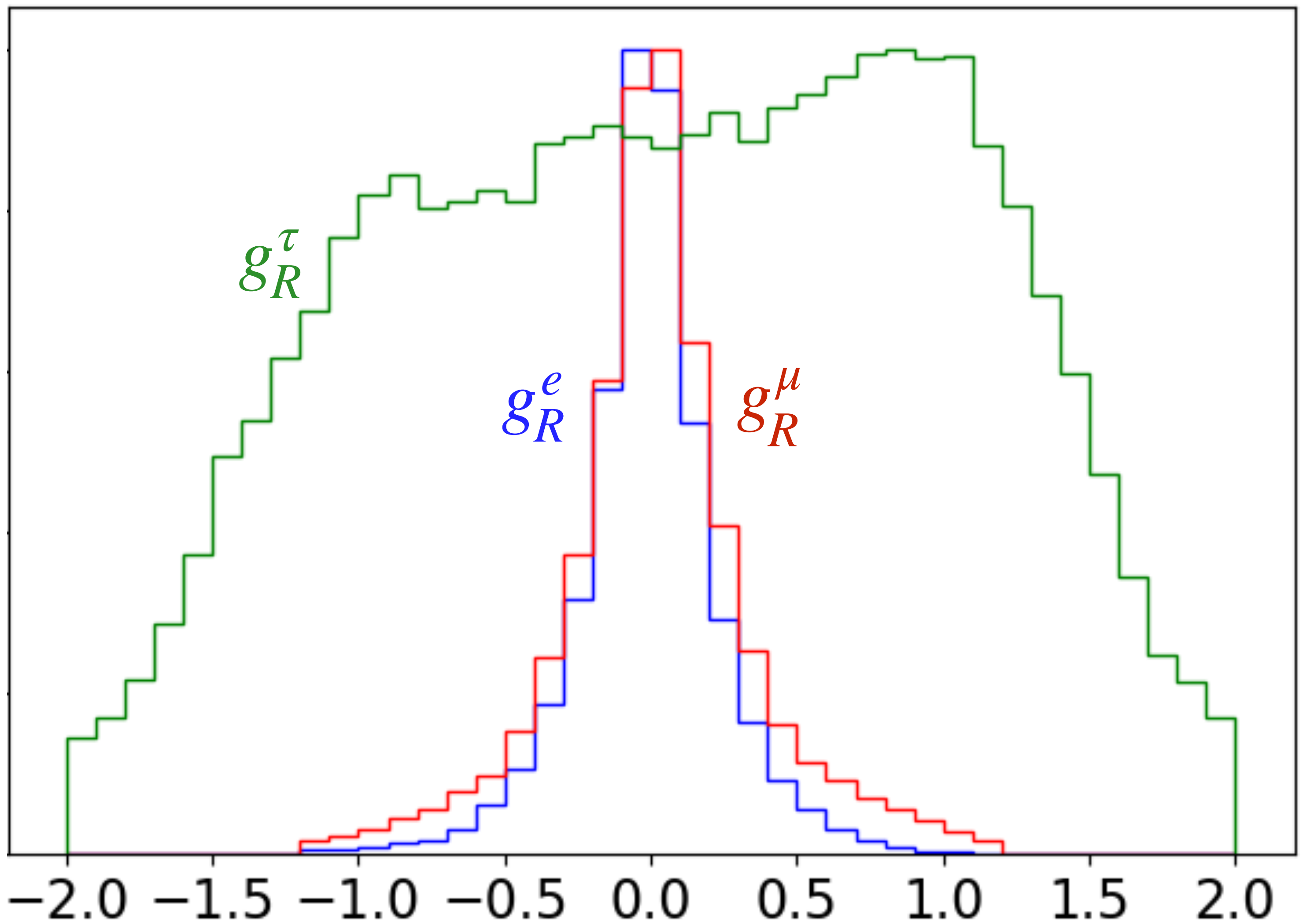


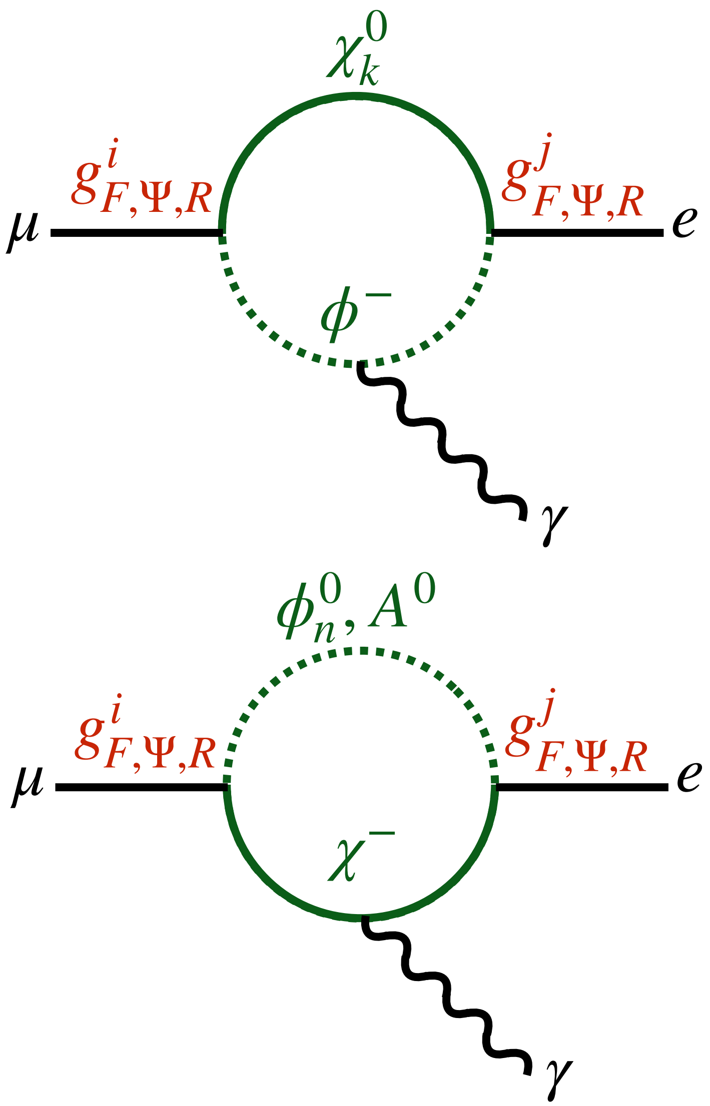


Couplings g_F and g_Ψ mainly bound by **neutrino mass constraints**
(via Casas-Ibarra parametrization)

$$\bar{\mathcal{G}} = \left(g_\Psi^1 g_\Psi^2 g_\Psi^3 g_F^1 g_F^2 g_F^3\right)^{1/6} \sim 10^{-5} - 10^{-4}$$

Coupling parameters

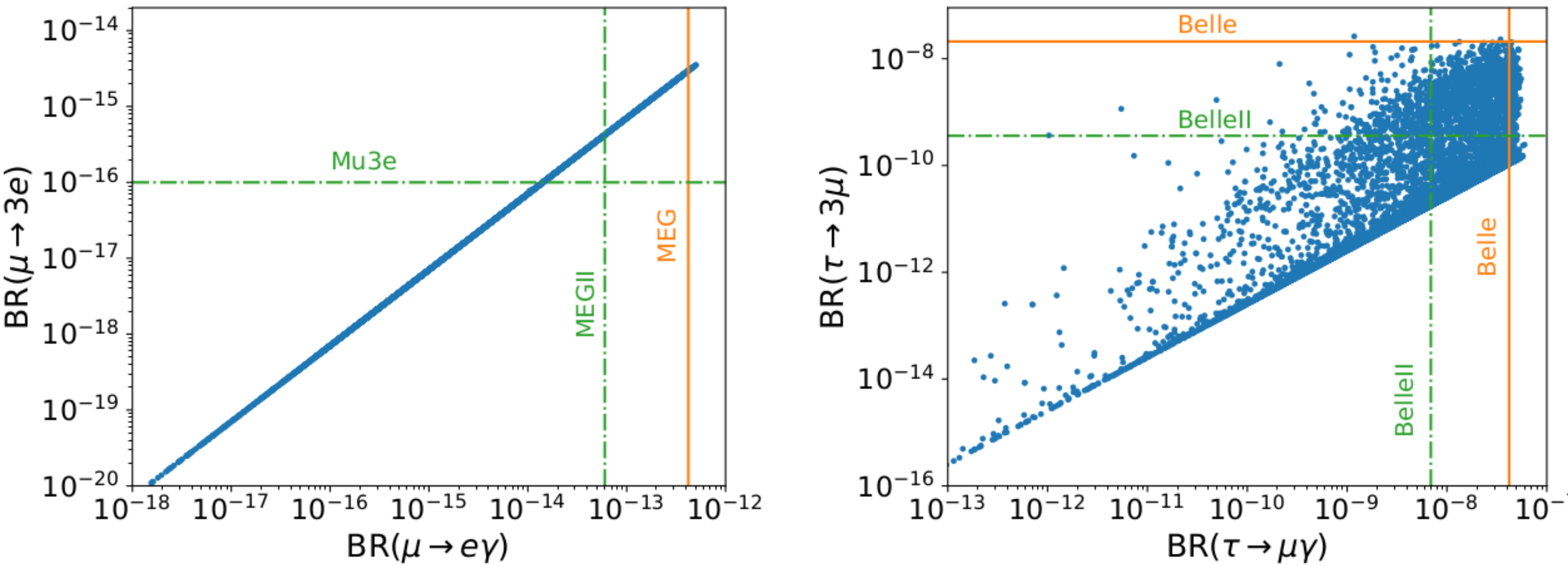




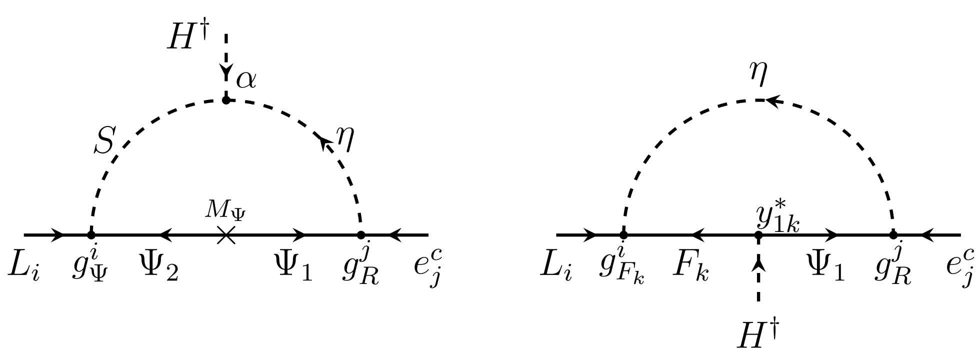
Couplings g_R constrained by **lepton-flavour violating processes**

(in particular $\mu \to e\gamma$)

Lepton flavour violating decays



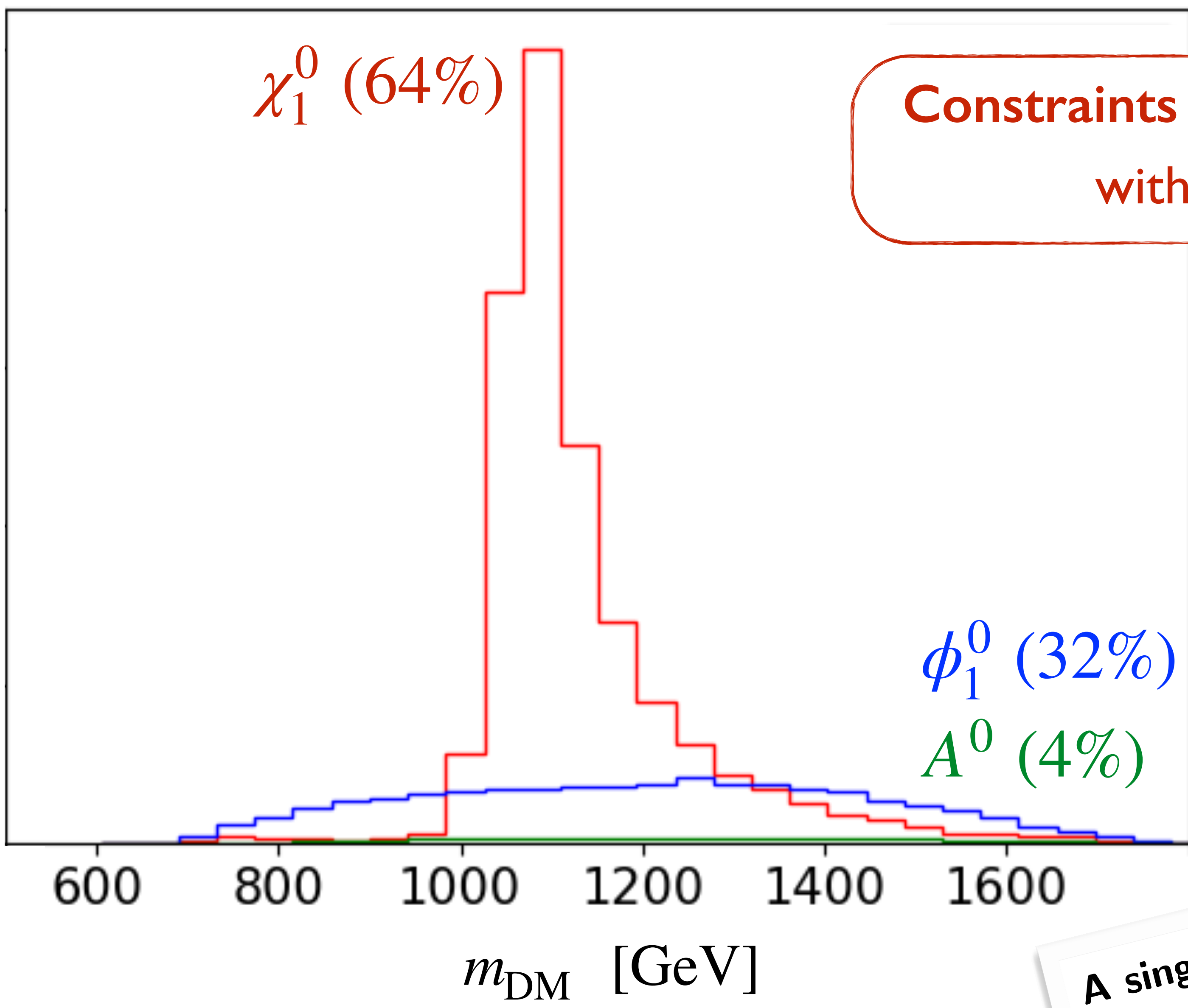
Muon decays dominated by **dipole contributions**, **box contributions** to $\tau \to 3\mu$ may be sizeable



Decay $\tau \to \mu e e$ on the edge of projected sensitivity, decays $\tau \to e\gamma$ and $\tau \to 3e$ not reachable…

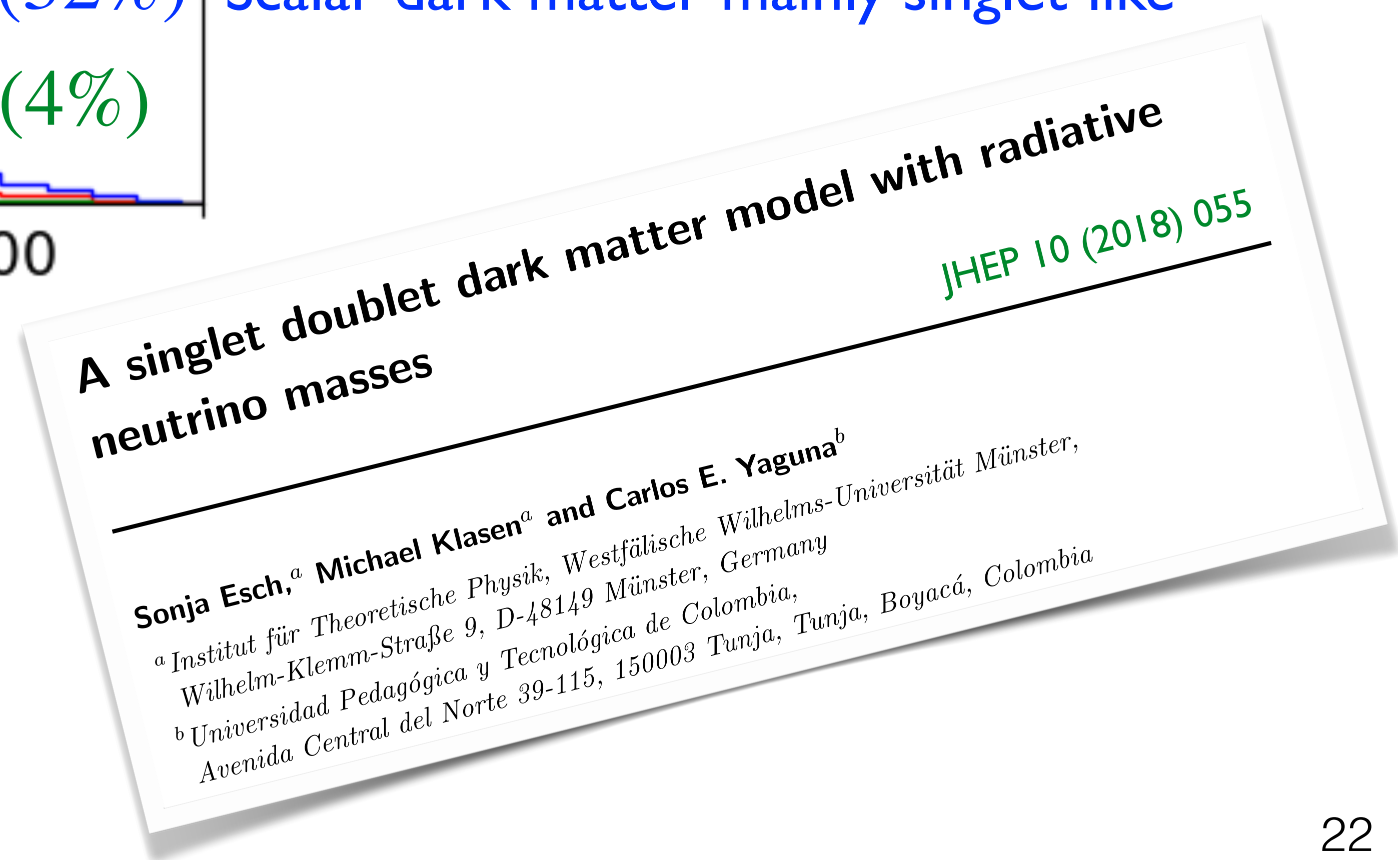
Limits from conversion rates in nuclei competitive with LFV decays…

Dark matter mass and nature



Constraints prefer fermionic dark matter with $m_{\chi_1^0} \sim 1.0 - 1.2$ TeV

Scalar dark matter mainly singlet-like



JHEP 10 (2018) 055

A singlet doublet dark matter model with radiative neutrino masses

Sonja Esch,[a] Michael Klasen[a] and Carlos E. Yaguna[b]

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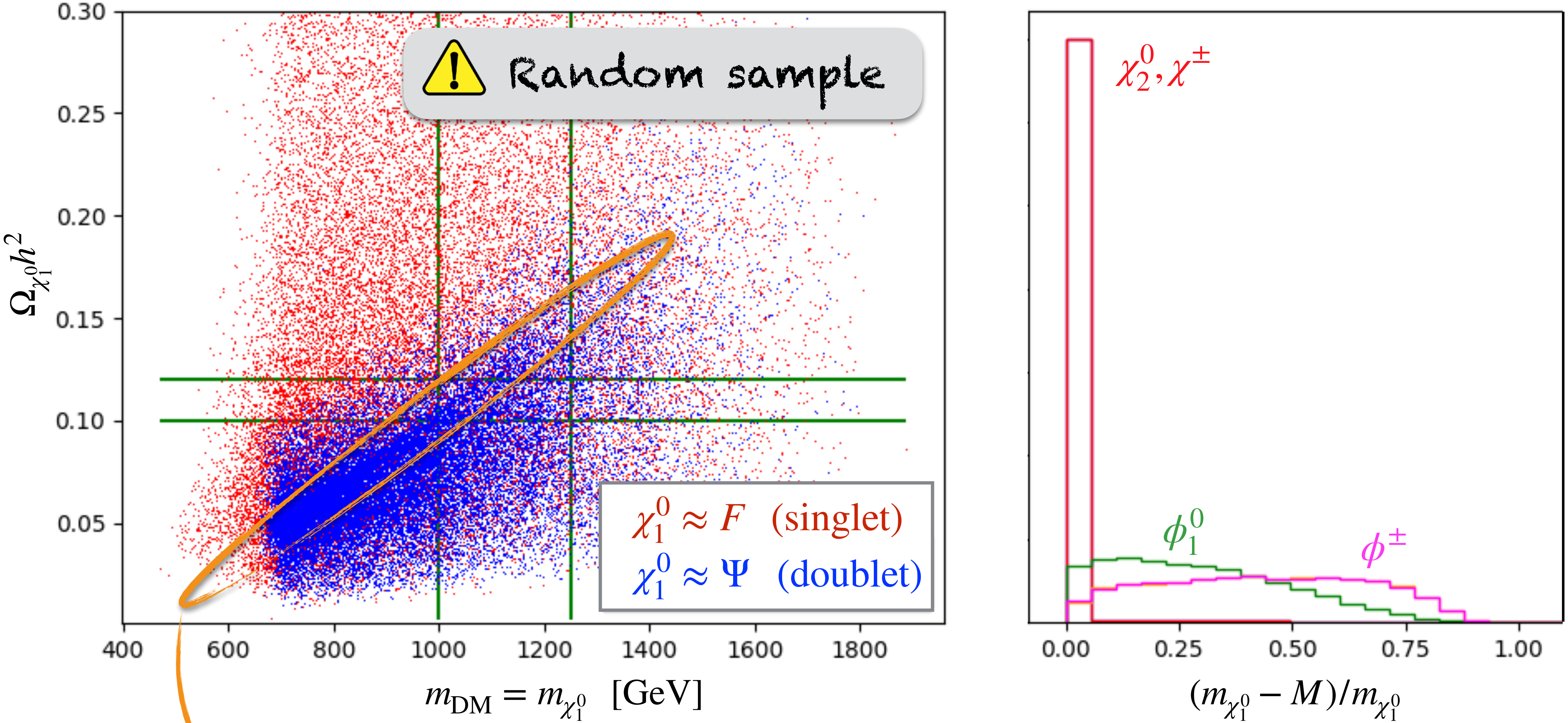
[b] *Universidad Pedagógica y Tecnológica de Colombia, Avenida Central del Norte 39-115, 150003 Tunja, Tunja, Boyacá, Colombia*

(Co)annihilation channels — fermionic dark matter

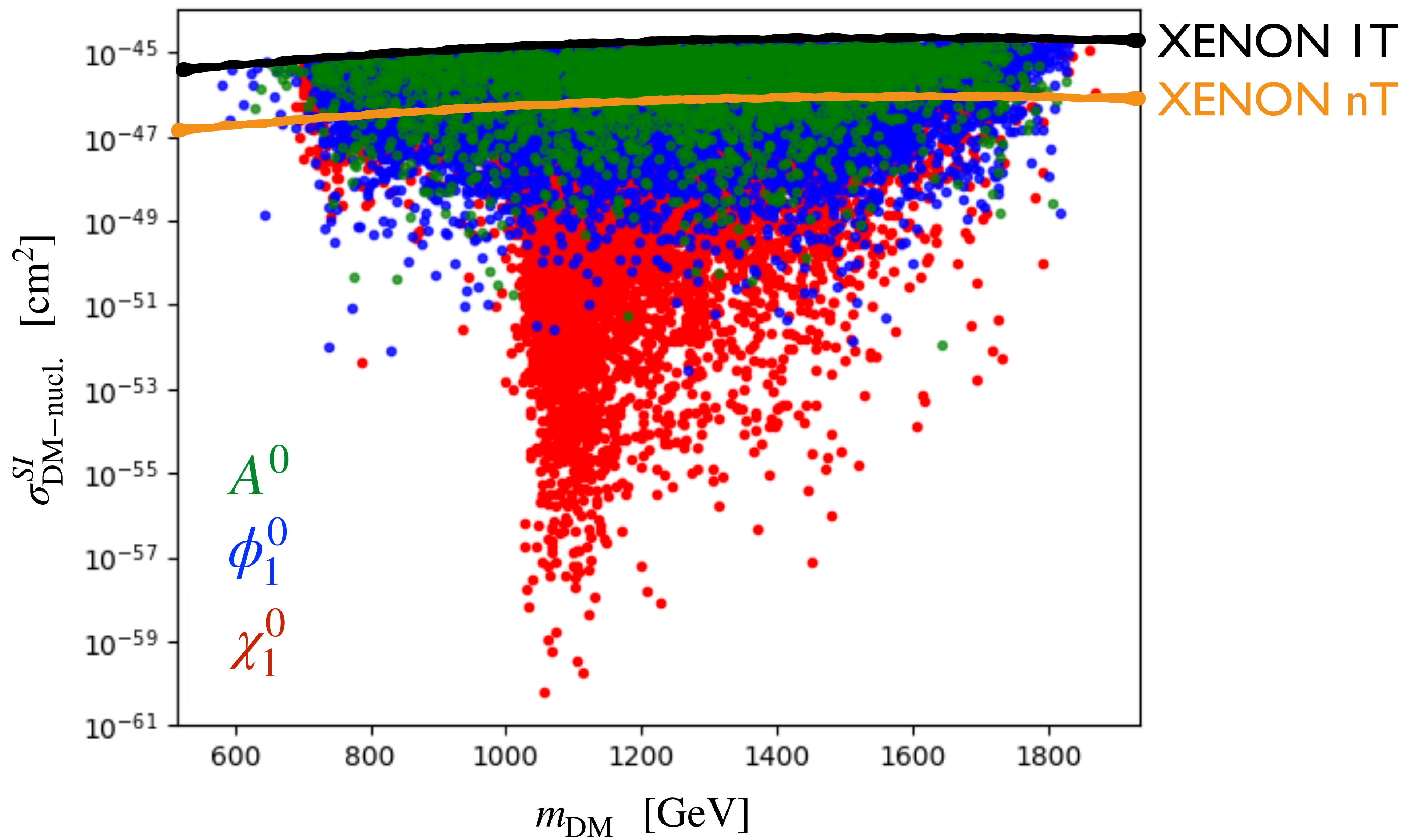


Dark matter fermion is mainly doublet-like

— **relic density governed by co-annihilations with other fermions**

— “correct” value achieved for $m_{\chi_1^0} \sim 1 - 1.2$ TeV

Direct detection



Upcoming experiments will constrain mainly (doublet-like) scalar dark matter

Fermionic dark matter (especially the doublet) difficult to constrain

— efficient co-annihilation around $m_{\mathrm{DM}} \sim 1 - 1.2$ TeV allows for small couplings

Comment on muon $(g-2)$

T1-2A can in principle explain the **observed deviation** between SM prediction and measurement

$$a_\mu^{\rm BSM} \;=\; a_\mu^{\rm exp} - a_\mu^{\rm SM} \;=\; \left(251 \pm 59\right) \times 10^{-11}$$

Tensions between $(g-2)_\mu$ and LFV constraints alleviated by adding additional degrees of freedom — example "T1-2A+F_2": introduce one **extra fermionic singlet**

$$\begin{aligned}\mathscr{L} \supset & -\frac{1}{2}M_{ij}F_iF_j - M_\Psi \Psi_1\Psi_2 - y_{1i}\Psi_1 H F_i - y_{2i}\Psi_2 H F_i \qquad\qquad (i=1,2) \\ & - g_\Psi^k \Psi_2 L_k S - g_{F_j}\phi L_k F_j - g_R^k e_k^c \eta \Psi_1 + \mathrm{h.c.}\end{aligned}$$

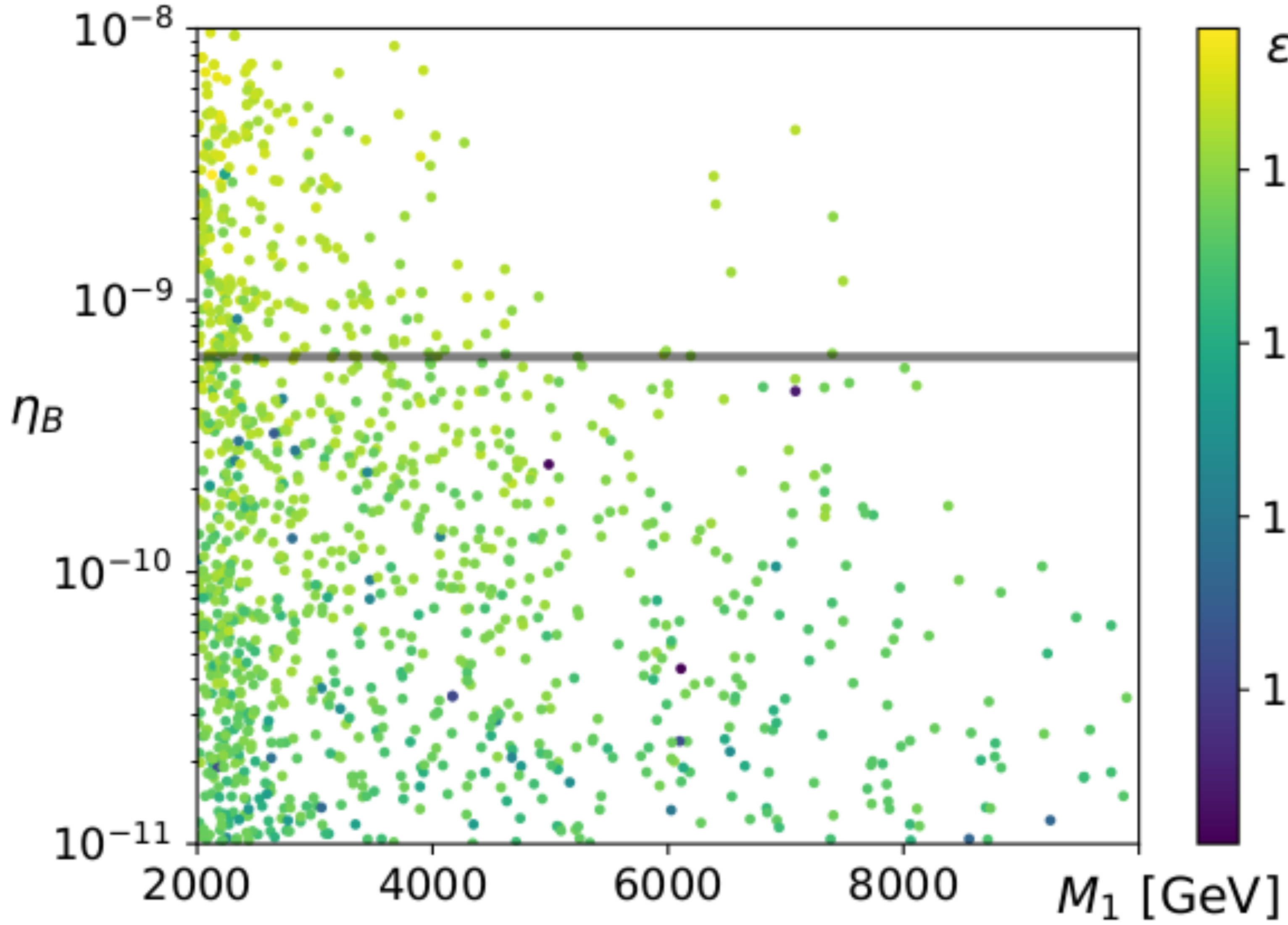
Specific coupling hierarchy allows simultaneous accommodation of $(g-2)_\mu$ and LFV constraints — in practice: selecting angles of **rotation matrix** in Casas-Ibarra parametrization and **fitting g_R**

$$\mathcal{G} \sim \begin{array}{c} \begin{array}{ccc} e & \mu & \tau \end{array} \\ \begin{pmatrix} \lesssim 10^{-5} & \sim 1 & \lesssim 10^{-3} \\ \lesssim 10^{-3} & \lesssim 10^{-3} & \lesssim 10^{-3} \\ \lesssim 10^{-3} & \lesssim 10^{-3} & \lesssim 10^{-3} \end{pmatrix} \end{array} \begin{array}{l} \leftarrow g_\Psi \\ \leftarrow g_{F_1} \\ \leftarrow g_{F_2} \end{array}$$

NB: The new degree of freedom allows to generate **three non-zero neutrino masses**

Comment on leptogenesis

Ingredients: **Heavy Majorana fermions**, **lepton number violation**, **complex couplings**



→ Observed baryon asymmetry can be explained for a narrow region of parameter space

→ **Fermionic doublet dark matter** seems preferred in this context

A singlet-doublet-triplet model (T1-2G)

scalar doublet + singlet

	Ψ_1	Ψ_2	Σ_1	Σ_2	η	S
$SU(2)_L$	**2**	**2**	**3**	**3**	**2**	**1**
$U(1)_Y$	-1	1	0	0	1	0

$$\eta = \begin{pmatrix} \eta^+ \\ \frac{1}{\sqrt{2}}(\eta^0 + iA^0) \end{pmatrix}$$

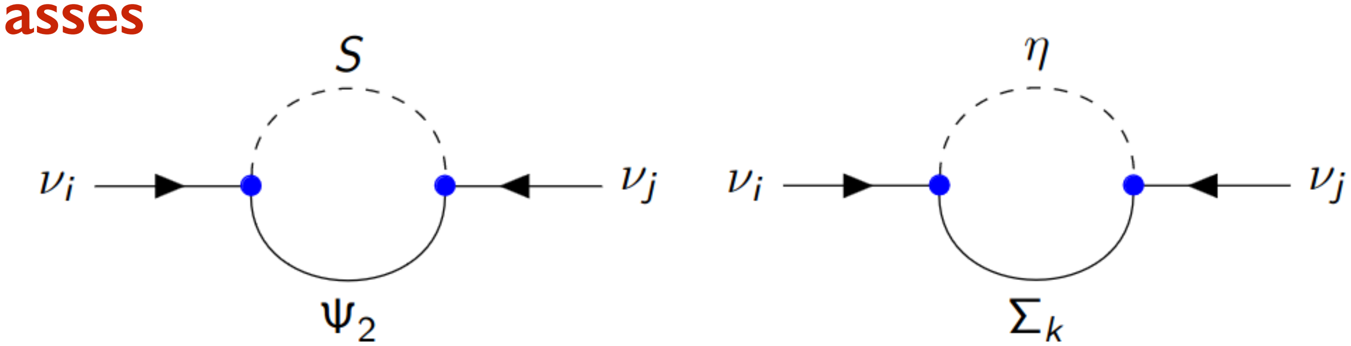
fermionic doublet
+ 2 fermionic triplets

$$\Psi_1 = \begin{pmatrix} \Psi_1^0 \\ \Psi_1^- \end{pmatrix} \qquad \Psi_2 = \begin{pmatrix} -\Psi_2^+ \\ (\Psi_2^0)^\dagger \end{pmatrix} \qquad \Sigma_j = \begin{pmatrix} \frac{\Sigma_j^0}{\sqrt{2}} & \Sigma_j^+ \\ \Sigma_j^- & -\frac{\Sigma_j^0}{\sqrt{2}} \end{pmatrix}$$

Physical mass eigenstates and dark matter candidates

$$\{\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0\} \qquad \{\chi_1^\pm, \chi_2^\pm, \chi_3^\pm\} \qquad \{\phi_1^0, \phi_2^0, A^0\} \qquad \{\phi_1^\pm\}$$

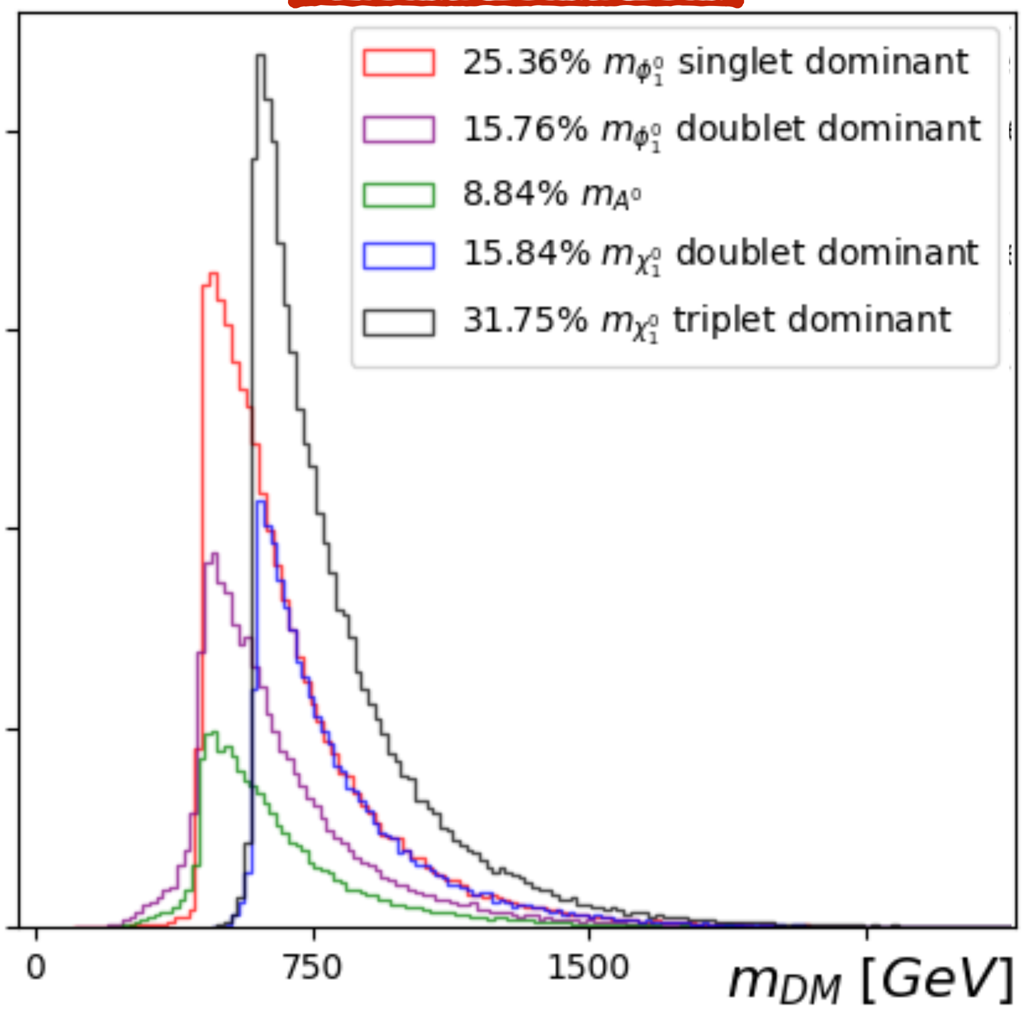
Generation of **three non-zero neutrino masses**



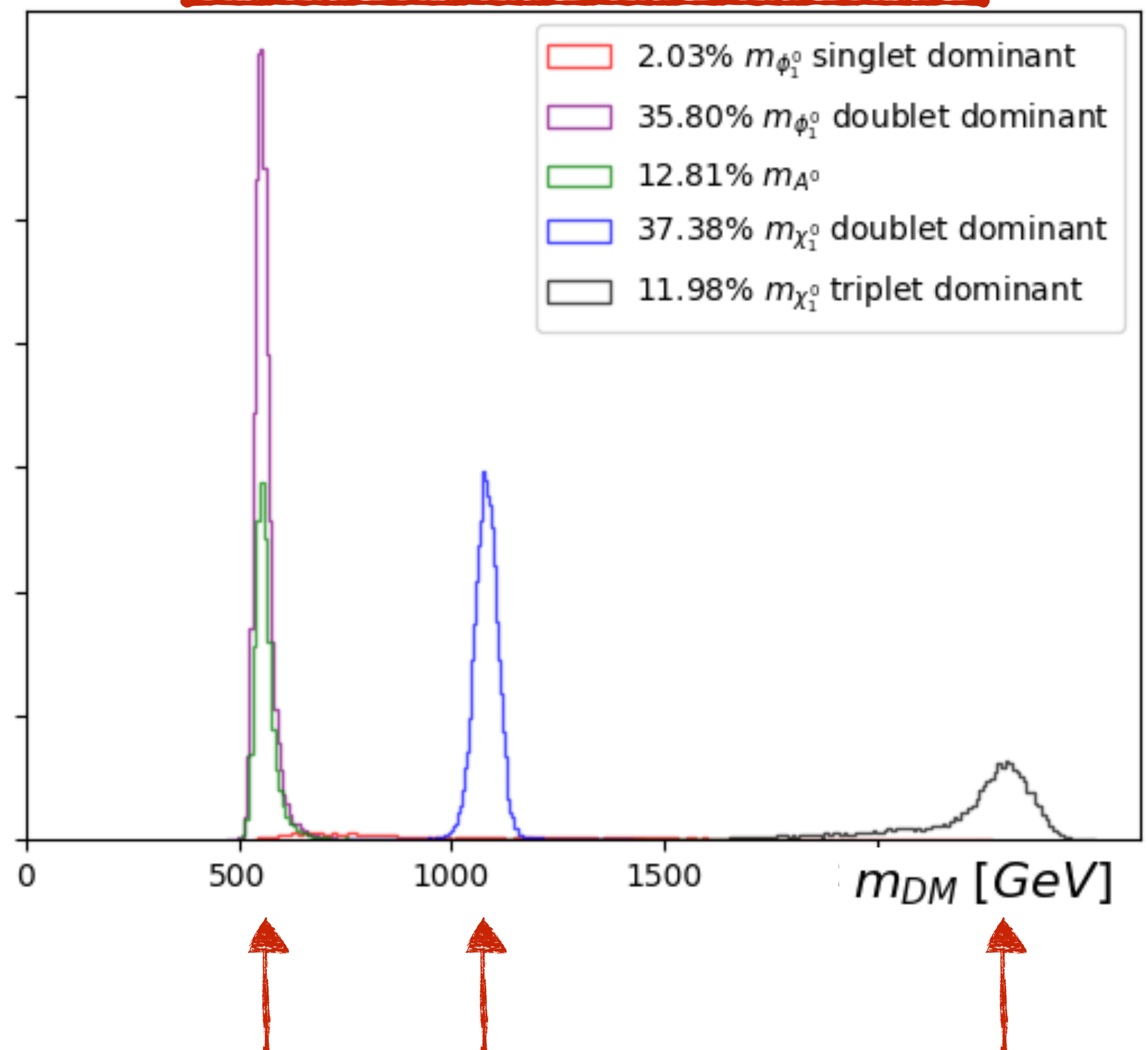
Parameter space exploration using **Markov Chain Monte Carlo** scanning technique…

Dark matter phenomenology

Random sample



MCMC study (~100 000 points)

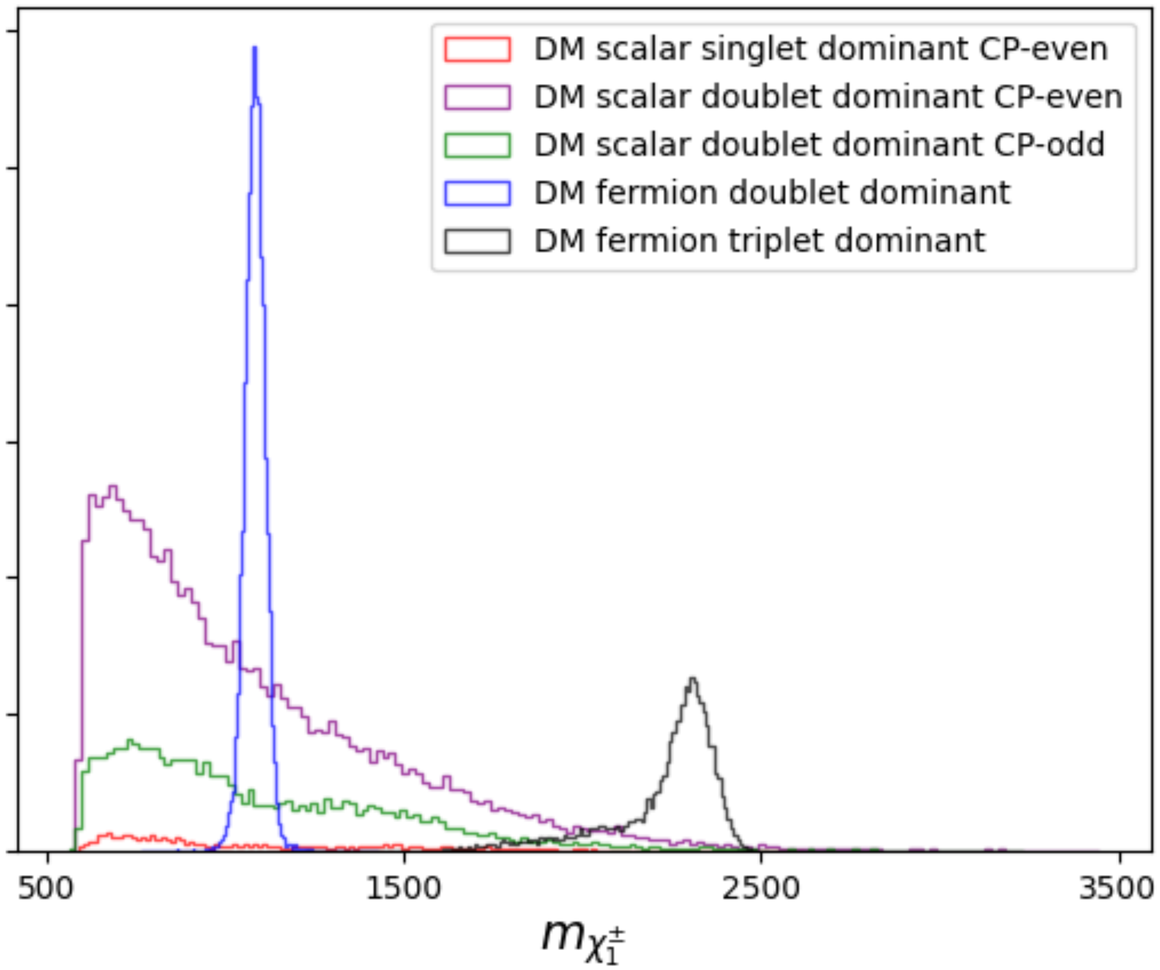


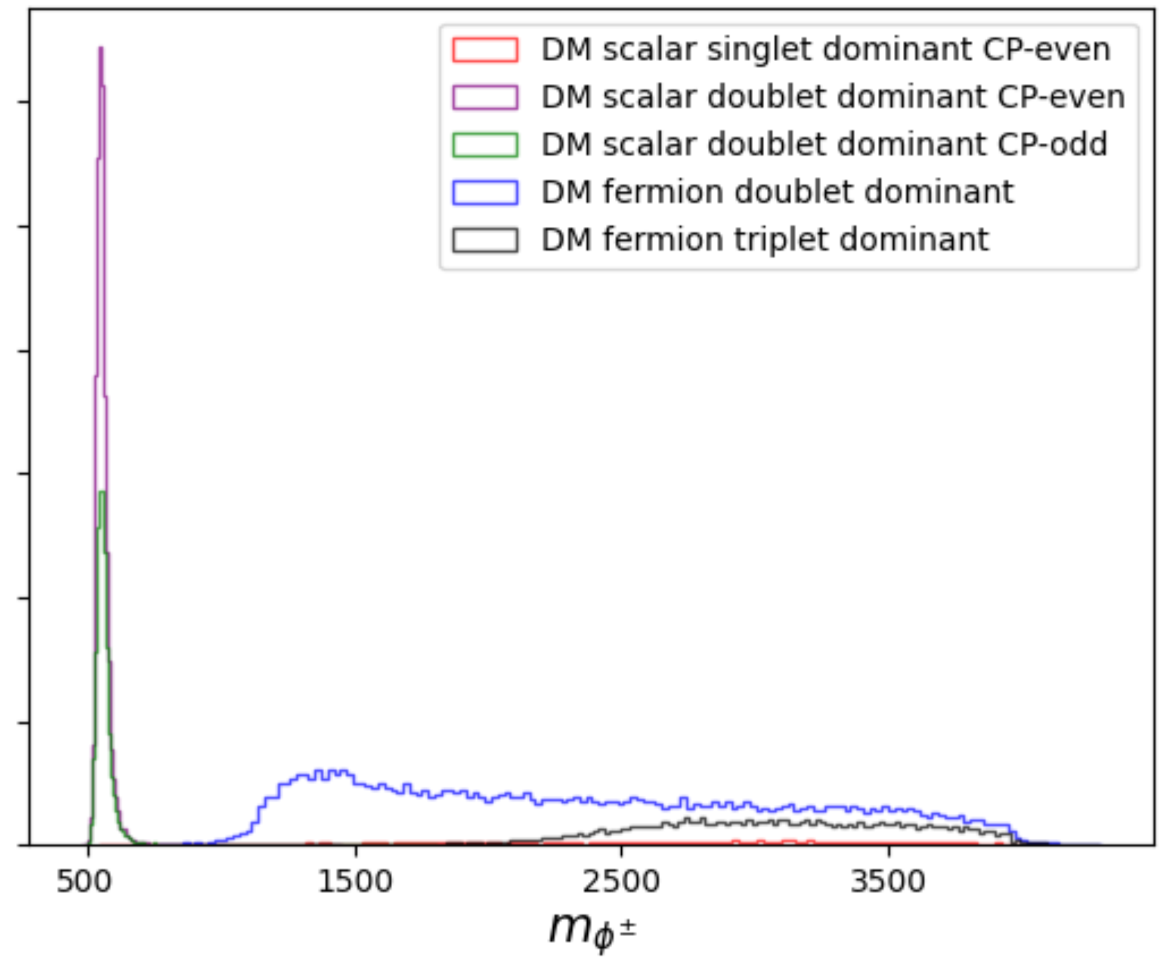
Configurations featuring co-annihilations preferred

→ **doublet** and **triplet** configurations favoured

(also for scalar dark matter)

Particle masses for collider studies





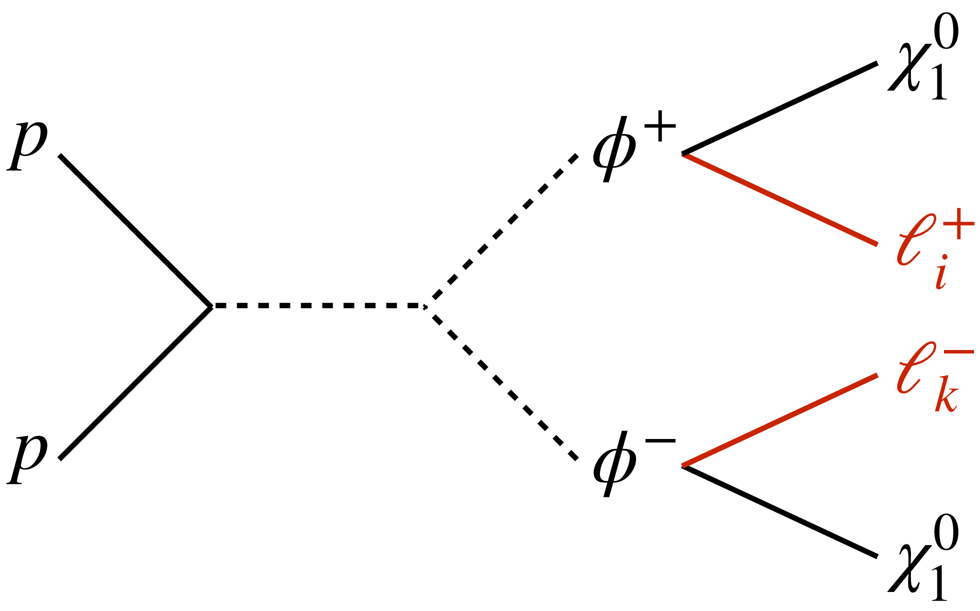
Mass distributions directly linked to dark matter mass distributions (singlet, doublet, triplet DM)

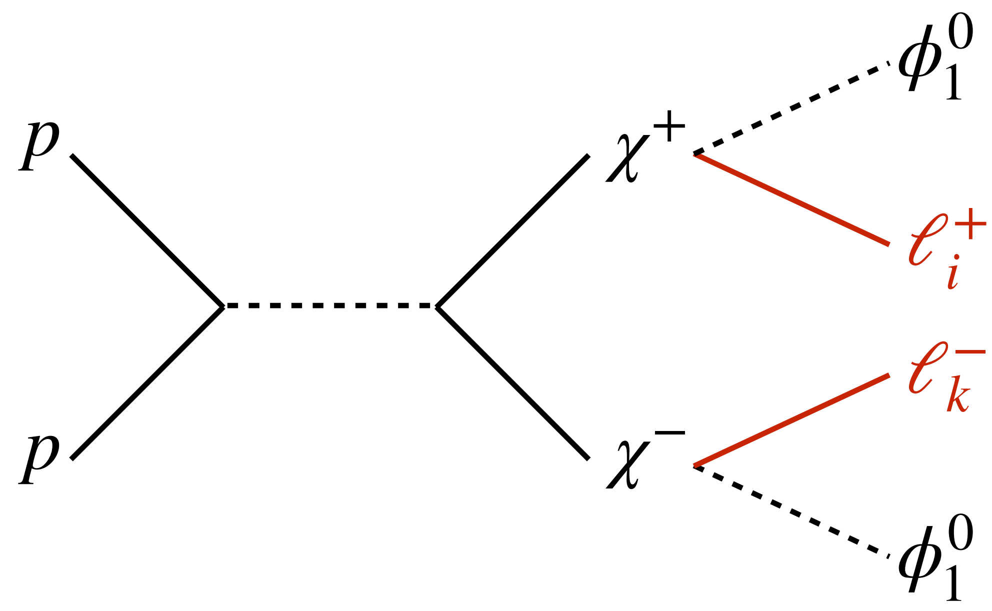
— Charged particles around 500 GeV to 4000 GeV…

— **Production cross-sections** not sizeable (but maybe not negligible either!)

$m_{\chi^\pm}$ (GeV)	500	600	700	800	900	1000	1100	
13 TeV	4.5	1.9	0.89	0.44	0.23	0.13	0.07	pb
14 TeV	5.4	2.3	1.1	0.56	0.30	0.17	0.09	pb

Expected collider signatures





Interesting LFV signatures…?

$$pp \to \ell_i^+ \ell_k^- E_T^{\mathrm{miss}}$$

Long-lived particles…?

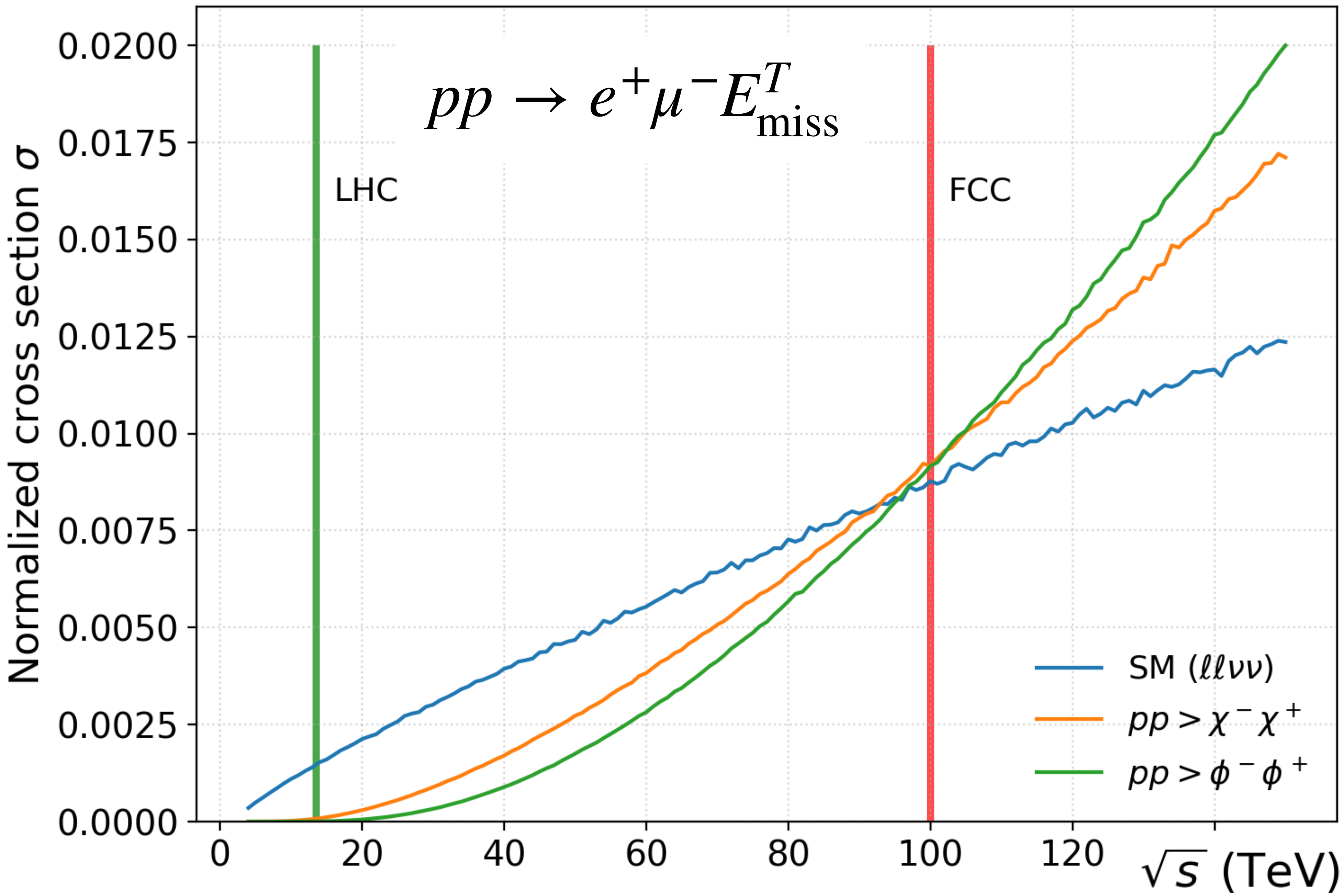
$$m_{\chi^\pm} - m_{\chi_1^0} \lesssim 1 \text{ GeV}$$

Standard Model background…?

Production cross-sections…?

$$m_\chi \sim 1 \text{ TeV}$$

Expected collider signatures



— High $\sqrt{s}$ needed to efficiently separate LFV signal from SM background (→FCC…?)

— Wider and more detailed study needed…

Summary and outlook

Scotogenic models allow to generate neutrino masses while providing viable dark matter candidates

Very predictive concerning dark matter mass (co-annihilation favoured)

Explanation of muon $(g-2)$ and leptogenesis possible

Collider signatures…?

Freeze-in dark matter…?

M. Sarazin, B. Herrmann, J. Bernigaud — JHEP 03 (2019) 067 — arXiv:1812.07463 [hep-ph]
A. Alvarez, A. Banik, R. Cepedello, B. Herrmann, W. Porod, M. Sarazin, M. Schnelke — JHEP 05 (2022) 156 — arXiv:2111.10199 [hep-ph]
T. Guérandel, B. Herrmann — *to be completed…*
U. de Noyers, M. Sarazin, B. Herrmann — *to be published…*

Backup

PHYSICAL REVIEW D **73**, 077301 (2006)

Verifiable radiative seesaw mechanism of neutrino mass and dark matter

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(Received 27 January 2006; published 14 April 2006)

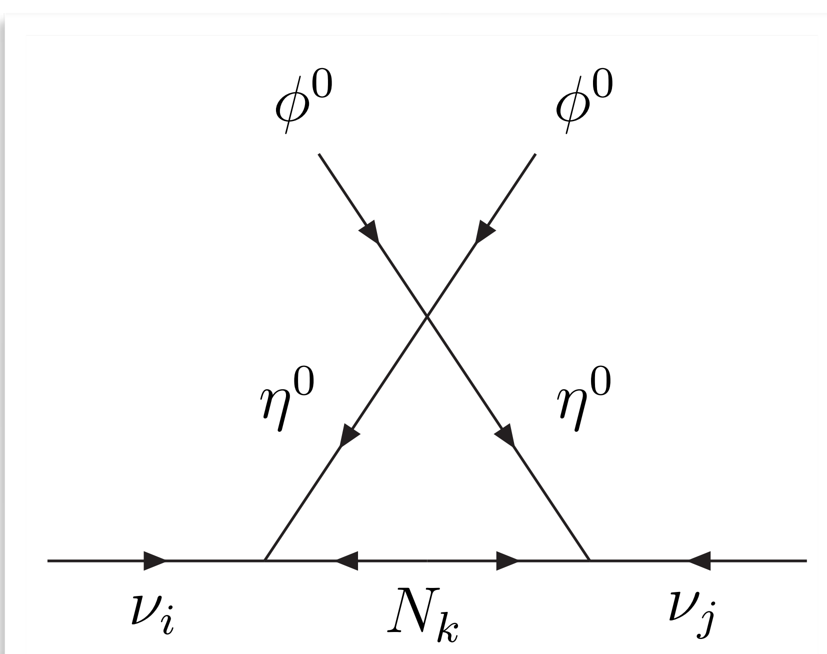
Neutrino oscillations have established that neutrinos ν_i have very small masses. Theoretically, they are believed to arise through the famous seesaw mechanism from their very heavy and unobservable Dirac mass partners N_i. It is proposed here in a new minimal extension of the standard model with a second scalar doublet (η^+, η^0) that the seesaw mechanism is actually radiative, and that N_i and (η^+, η^0) are experimentally observable at the forthcoming Large Hadron Collider, with the bonus that the lightest of them is also an excellent candidate for the dark matter of the Universe.

First and simplest scotogenic model:

SM + scalar doublet + 3 fermionic singlets

$$(\nu_i, l_i) \sim (2, -1/2; +), \quad l_i^c \sim (1, 1; +), \quad N_i \sim (1, 0; -),$$

$$(\phi^+, \phi^0) \sim (2, 1/2; +), \quad (\eta^+, \eta^0) \sim (2, 1/2; -).$$



$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik} h_{jk} M_k}{16\pi^2} \left[\frac{m_R^2}{m_R^2 - M_k^2} \ln \frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2} \ln \frac{m_I^2}{M_k^2} \right]$$

Classification of models w.r.t. particle content and topologies


Models with radiative neutrino masses and viable dark matter candidates

Diego Restrepo,* Oscar Zapata,†
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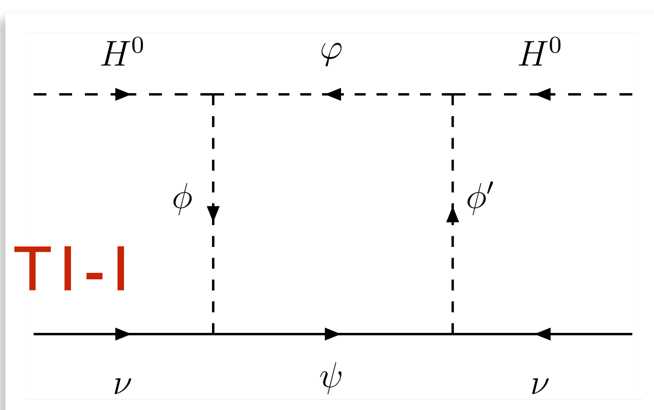
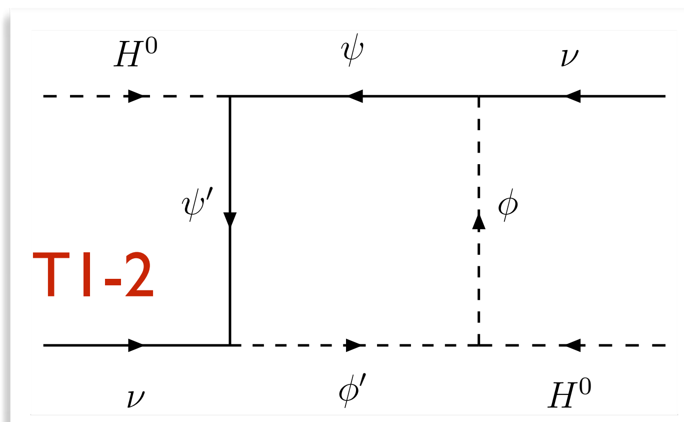
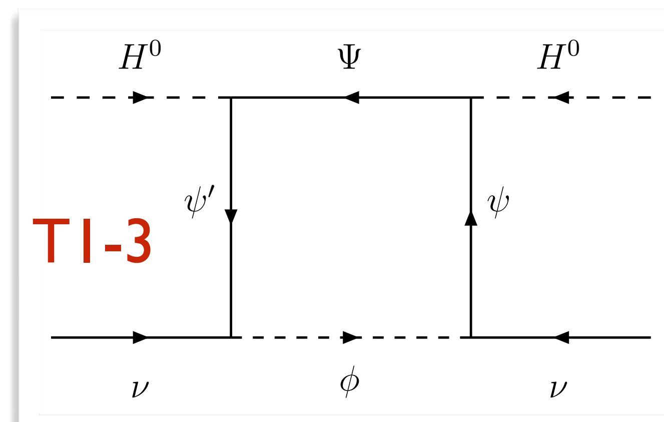
Institut für Theoretische Physik, Universität Münster, Wilhelm-Klemm-Straße 9, D-48149 Münster, Germany

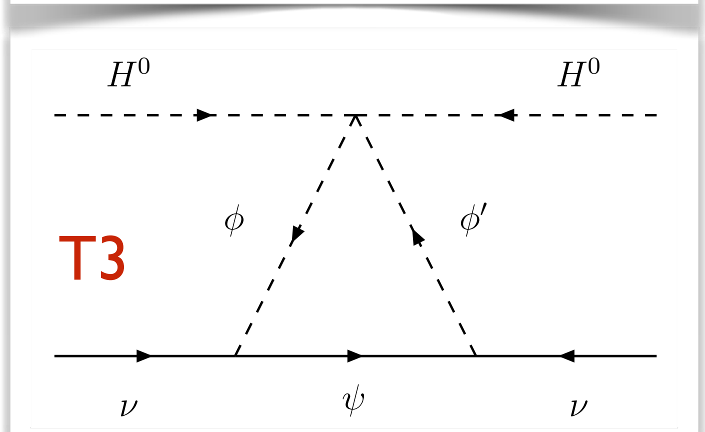
October 14, 2013

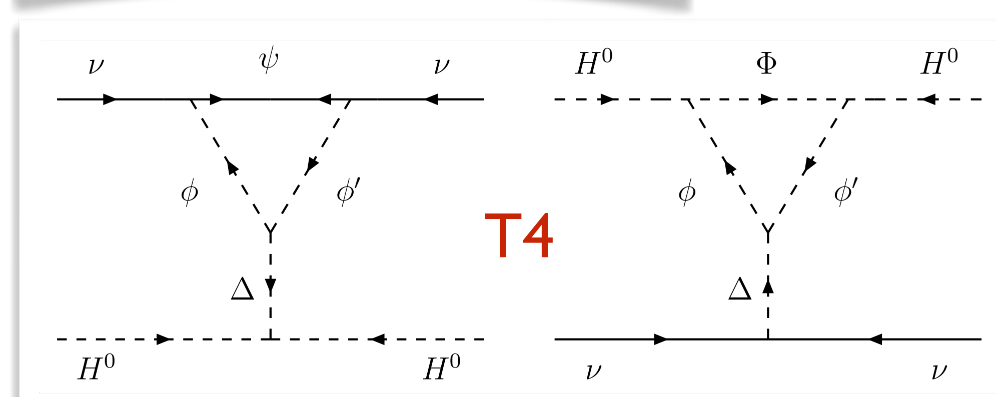
JHEP 11 (2013) 011











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Classification of models w.r.t. particle content and topologies

Summary of T1-1

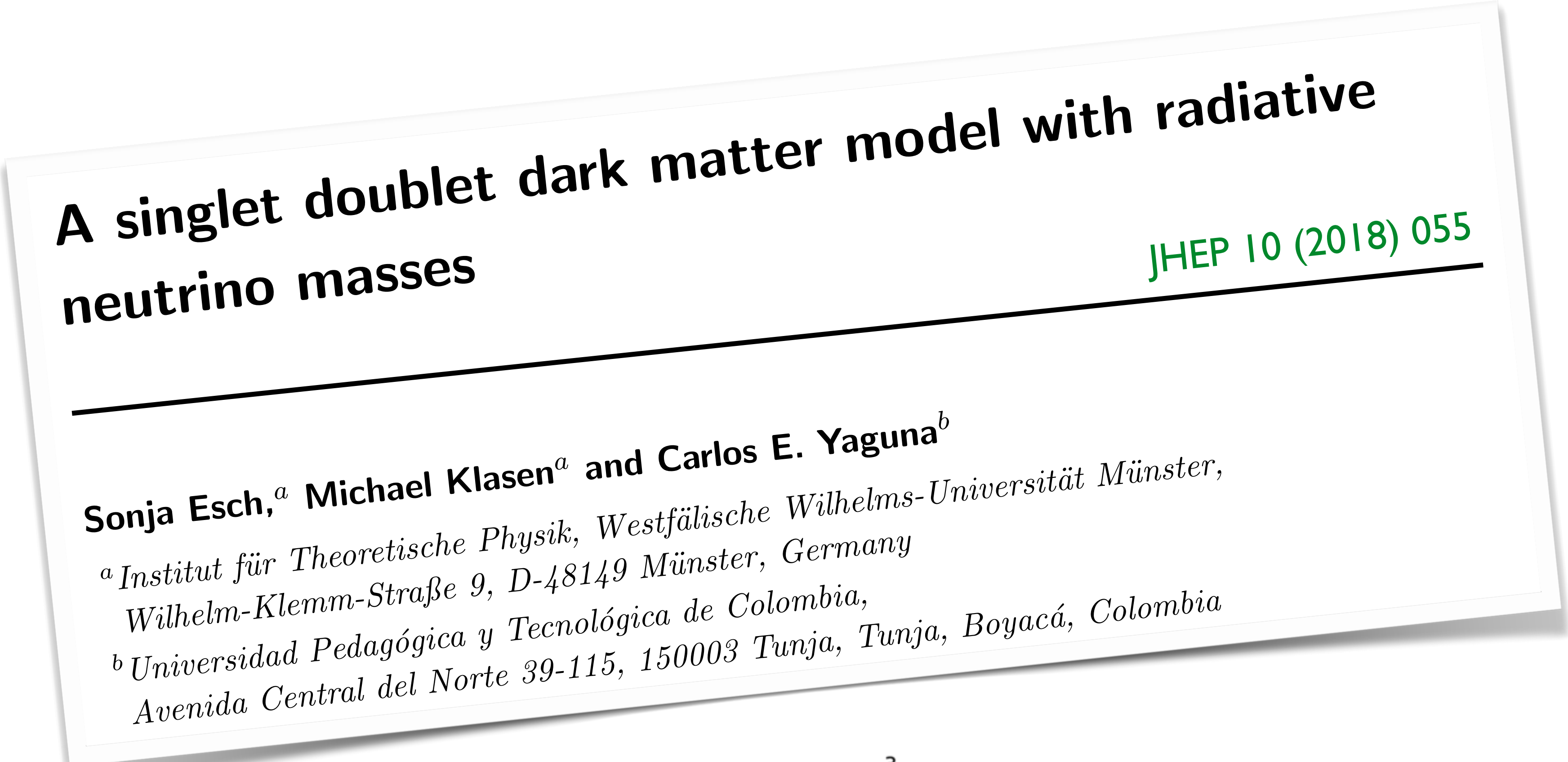
Model	α	Fermionic		Scalar		Exotic charges	# of N'plets
		DM	DD	DM	DD		
T1-1-A	±2	×	×	$2_{\pm1}$	✓	✓	4
	0	1_0	✓	$1_0, 2_{\pm1}$	✓	×	3
T1-1-B	±2	$3_{\pm2}$	×	$2_{\pm1}$	✓	✓	4
	0	3_0	✓	$1_0, 2_{\pm1}$	✓	×	3
T1-1-C	±1	$2_{\pm1}$	×	$1_0, 2_{\pm1}$	✓	✓	4
T1-1-D	1	2_1	×	$1_0, 2_1, 3_2$	✓	✓	4
	-1	2_{-1}	×	$2_{-1}, 3_0$	✓	×	4
T1-1-F	±1	$2_{\pm1}$	×	$2_{\pm1}, 3_0, 3_{\pm2}$	✓	✓	4
T1-1-G	±2	×	×	$2_{\pm1}, 3_{\pm2}$	✓	✓	[illegible]
	0	1_0	✓	$2_{\pm1}, 3_0$	✓	×	[illegible]
T1-1-H	±2	$3_{\pm2}$	×	$2_{\pm1}, 3_{\pm2}$	✓	✓	[illegible]
	0	3_0	✓	$2_{\pm1}, 3_0$	✓	×	[illegible]

Summary of T1-2

Model	α	Fermionic		Scalar		Exotic charges	# of N'plets
		DM	DD	DM	DD		
T1-2-A	0	$1_0, 2_1$	✓	$1_0, 2_1$	[illegible]	×	4
	-2	2_{-1}	×	2_{-1}	✓	×	4
T1-2-B	0	$1_0, 2_1$	✓	$2_1, 3_0$	✓	×	4
	-2	2_{-1}	×	$2_{-1}, 3_{-2}$	✓	✓	4
T1-2-D	1	$2_1, 3_2$	×	2_1	✓	✓	4
	-1	$2_{-1}, 3_0$	✓	$1_0, 2_{-1}$	✓	×	4
T1-2-F	1	$2_1, 3_2$	×	$2_1, 3_2$	✓	✓	4
	-1	$2_{-1}, 3_0$	✓	$2_{-1}, 3_0$	✓	×	4

Summary of T1-3

Model	α	Fermionic		Scalar		Exotic charges	# of N'plets
		DM	DD	DM	DD		
T1-3-A	0	$1_0, 2_{\pm1}$	✓	1_0	✓	×	3
T1-3-B	0	$1_0, 2_{\pm1}$	✓	3_0	✓	×	3
T1-3-C	±1	$1_0, 2_{\pm1}$	✓	2_1	✓	×	4
T1-3-D	1	$2_1, 3_0$	✓	2_1	✓	×	4
	-1	$1_0, 2_{-1}, 3_{-2}$	✓	2_{-1}	✓	✓	4
T1-3-F	±1	$2_{\pm1}, 3_0, 3_{\pm2}$	✓	$2_{\pm1}$	✓	✓	4
T1-3-G	0	$2_{\pm1}, 3_0$	✓	1_0	✓	×	3
T1-3-H	0	$2_{\pm1}, 3_0$	✓	3_0	✓	×	3



A singlet doublet dark matter model with radiative neutrino masses

JHEP 10 (2018) 055

Sonja Esch,[a] **Michael Klasen**[a] **and Carlos E. Yaguna**[b]

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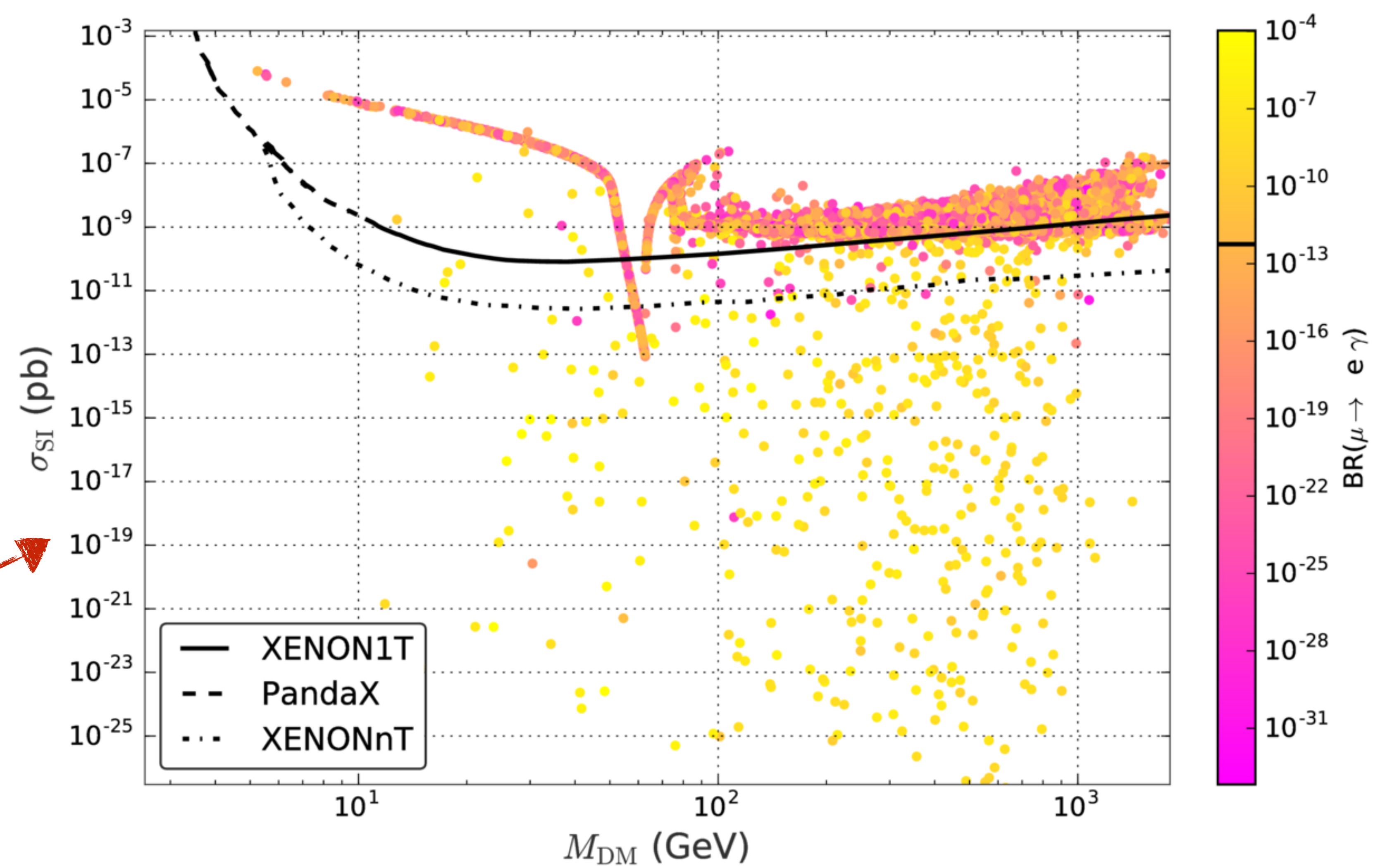
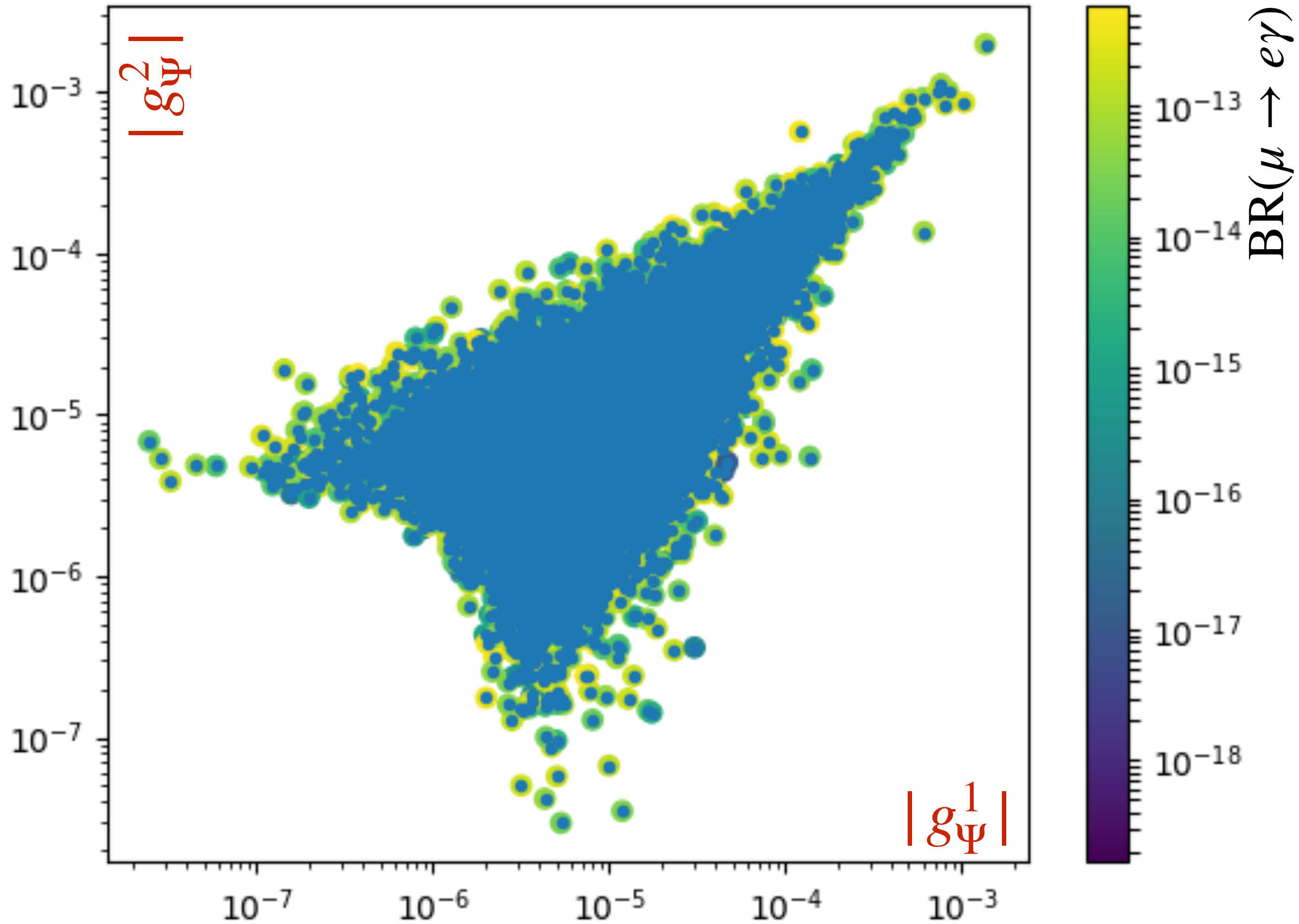
[b] *Universidad Pedagógica y Tecnológica de Colombia, Avenida Central del Norte 39-115, 150003 Tunja, Tunja, Boyacá, Colombia*

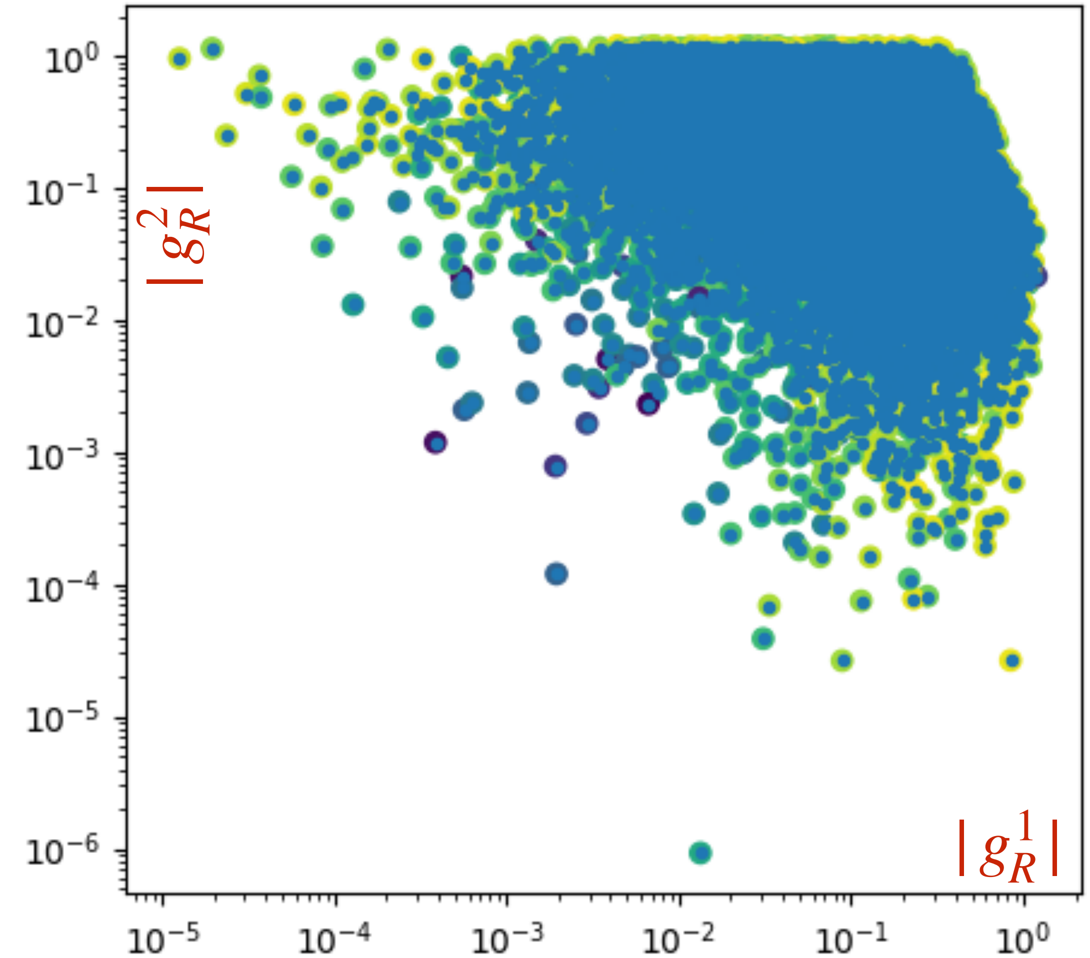
focus on scalar dark matter

neglect coupling g_R



Coupling parameters

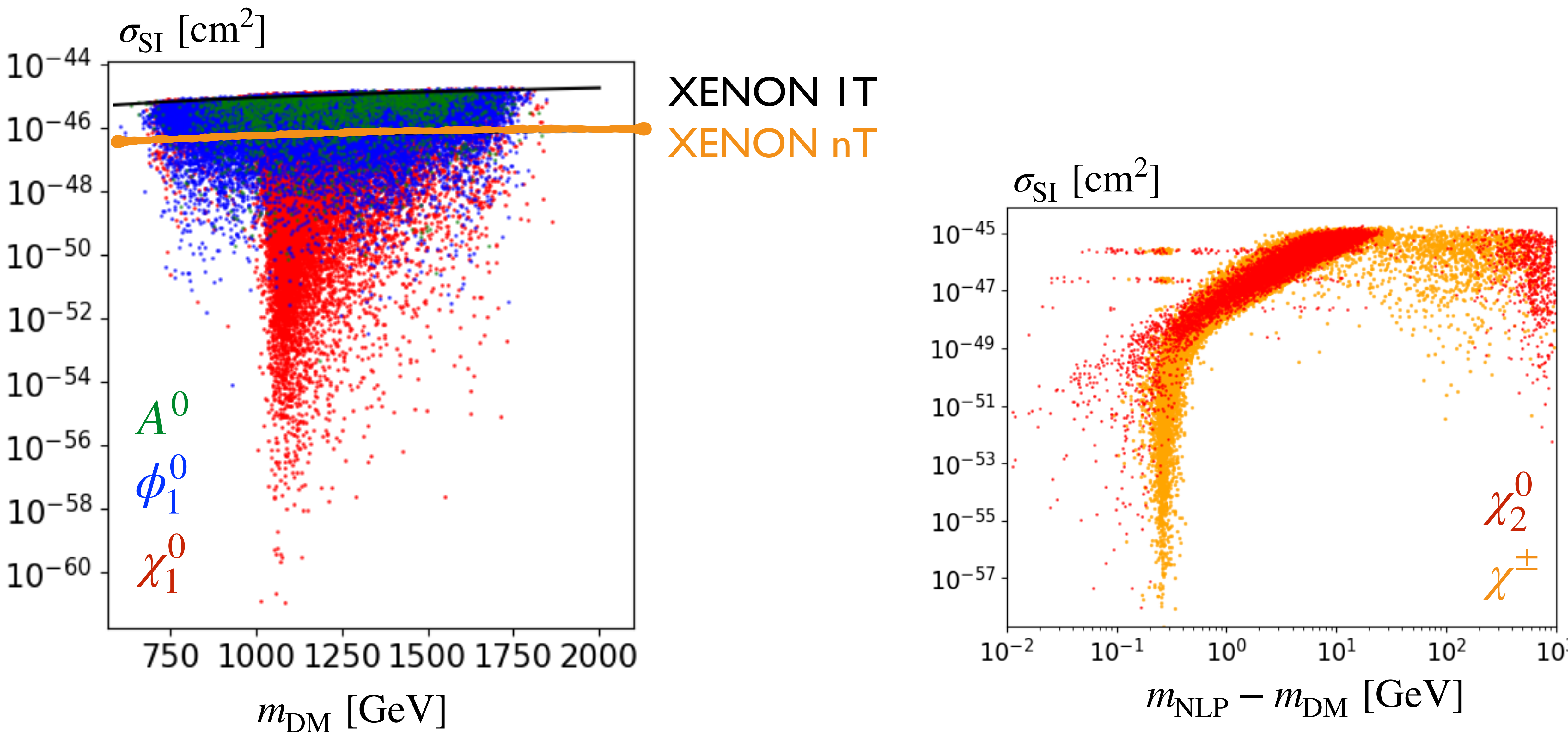




Couplings g_F and g_Ψ mainly bound by **neutrino mass constraints** (via Casas-Ibarra parametrization)

Couplings g_R constrained by **lepton-flavour violating processes** (in particular $\mu \to e\gamma$)

Direct detection in the T1-2A model

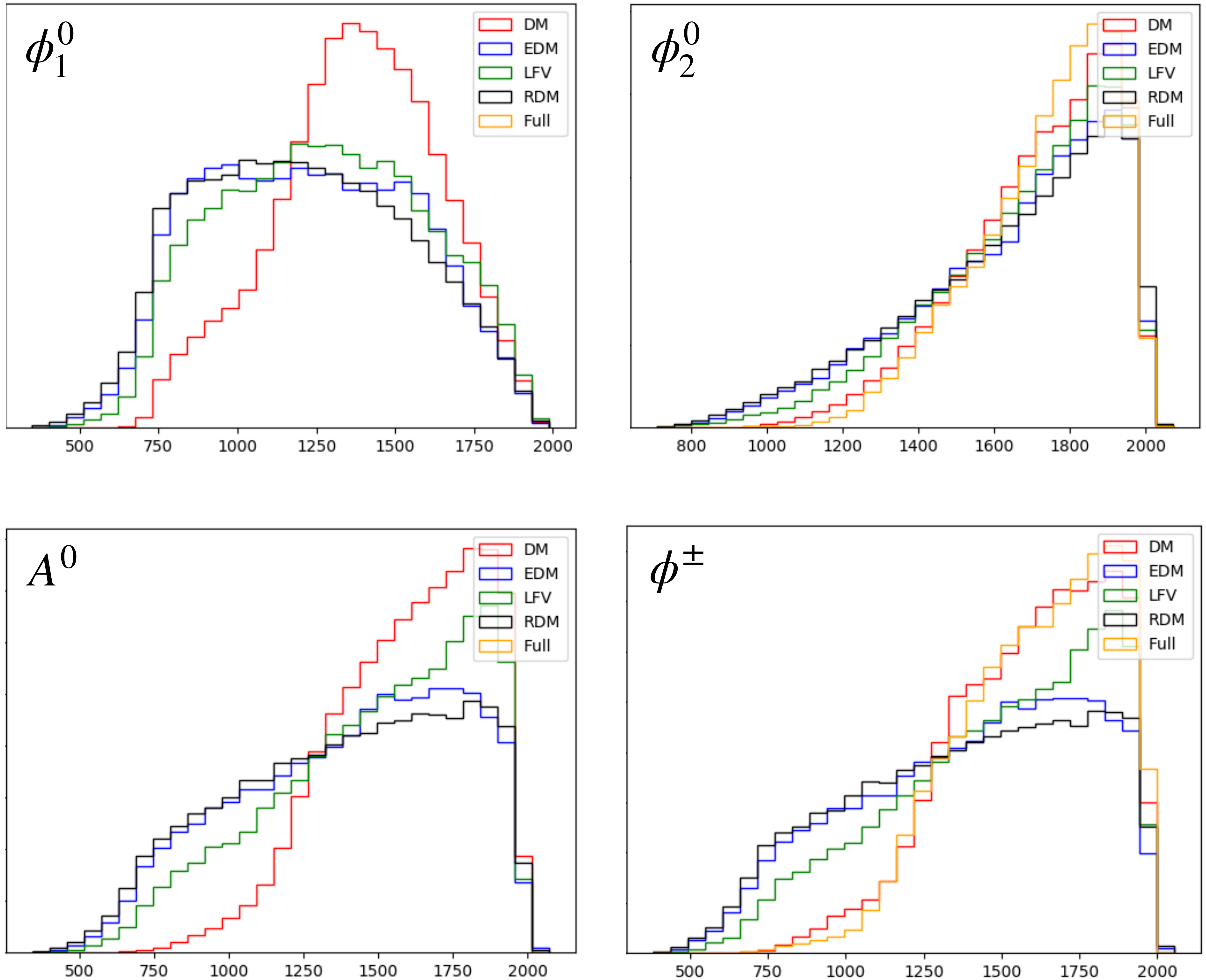


Upcoming experiments will constrain mainly (doublet-like) scalar dark matter

Fermionic dark matter (especially the doublet) difficult to constrain

— efficient co-annihilation around $m_{DM} \sim 1 - 1.2$ TeV allows for small couplings

Particle masses — scalars (T1-2A)



Particle masses — fermions (T1-2A)