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MultiDark
Multimessenger Approach for Dark Matter Detection

ASTROPARTICLES
Astroparticles and High Energy Physics Group

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

GENERALITAT VALENCIANA

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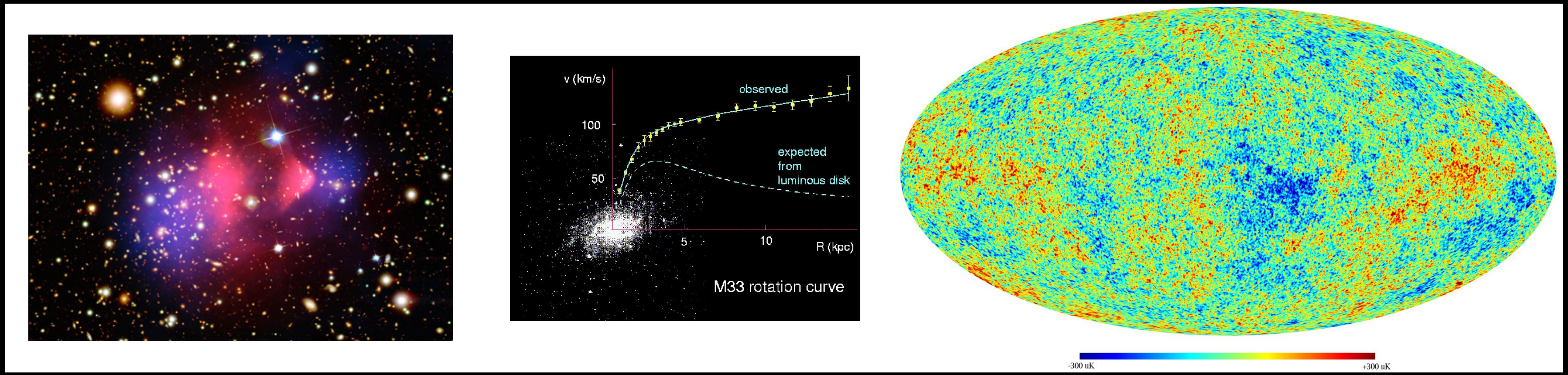
Minimalistic scotogenic scalar dark matter

International Conference on Neutrinos and Dark Matter
11th Jan 2020, Hurghada, Egypt

Based on arXiv:1910.08422 in collaboration with I. M. Ávila, L. Duarte and J. W. F. Valle

There is overwhelming evidence for the existence of dark matter:



CMB anisotropies,s
Clusters (X-rays, lensing),
Large Scale Structures,
Galaxies (rotation curves, fits...)

Cosmological
and astrophysical
observations

The content of the Universe in terms of paellas (after Planck)

26.8% Dark Matter
Black Rice Paella

4.9% Ordinary Matter
Valencian Paella

68.3% Dark Energy
Peppers' Paella

credit: R.A. Lineros

$$\Omega_{\rm CDM}h^2 = 0.1186 \pm 0.0020$$

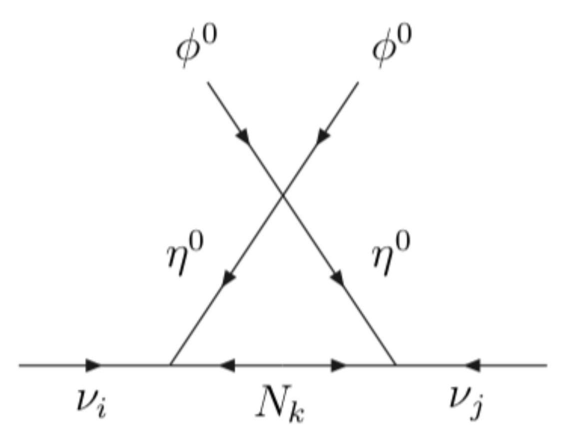
“BORN FROM THE DARK”

- Interesting alternative to the seesaw mechanism to explain the smallness of neutrino masses.
  - Neutrino strictly massless at tree-level, but only non-zero by higher order contribution.

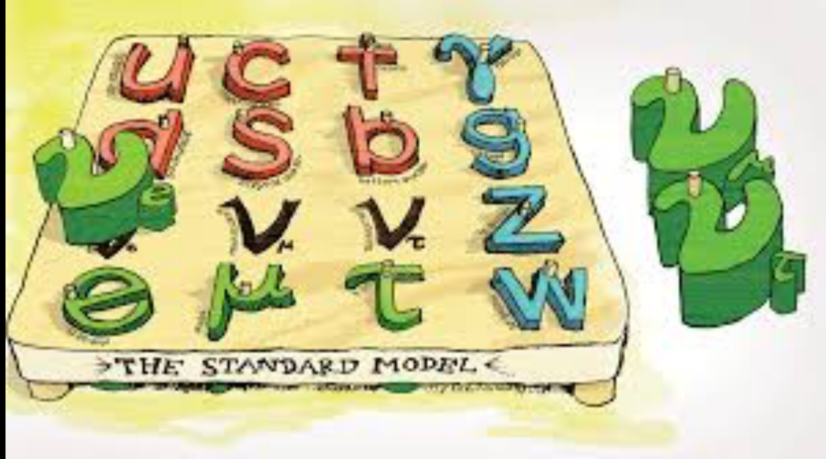
- Basic idea: dark matter is the mediator of neutrino mass generation
  - the same Z_2 symmetry that makes the neutrino mass to have radiative origin also serves to stabilize the dark matter.

- First idea of Scotogenic Model E. Ma, Phys.Rev. D73 (2006) 077301

- The Scotogenic Model has been generalized in different ways making its phenomenology viable and substantially richer. e.g. M. Hirsch et al., JHEP 10 (2013) 149
  E. Ma and D. Suematsu, Mod. Phys. Lett. A24 (2009) 583–589



E. Ma, Phys.Rev. D73 (2006) 077301



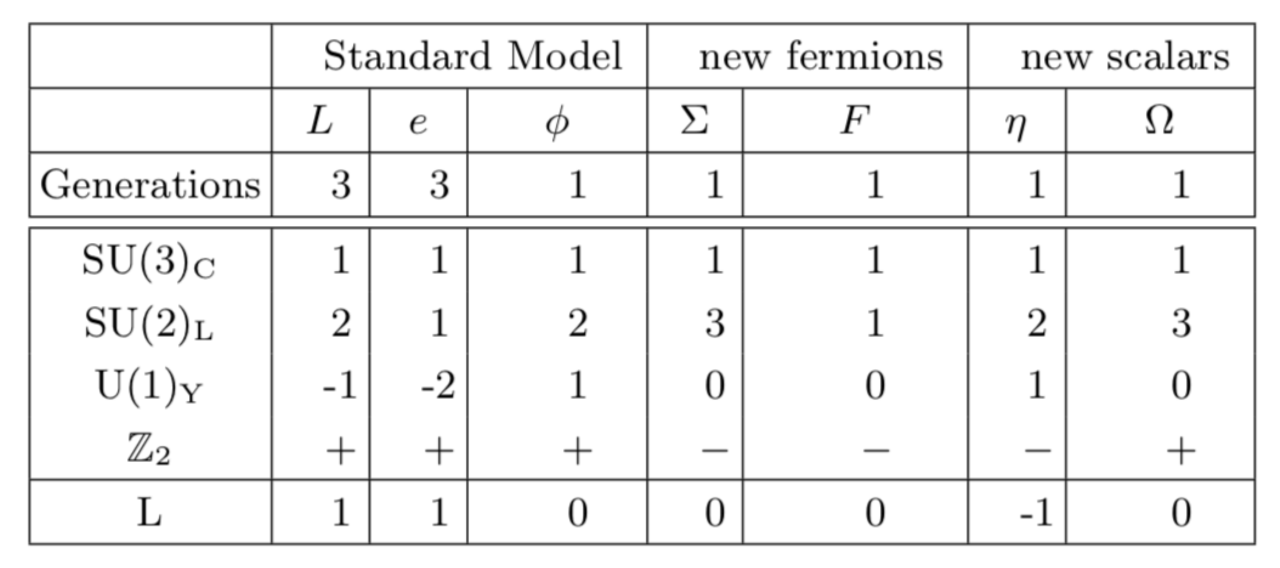
Symmetry Magazine

THE SINGLET + TRIPLET SCOTOGENIC MODEL

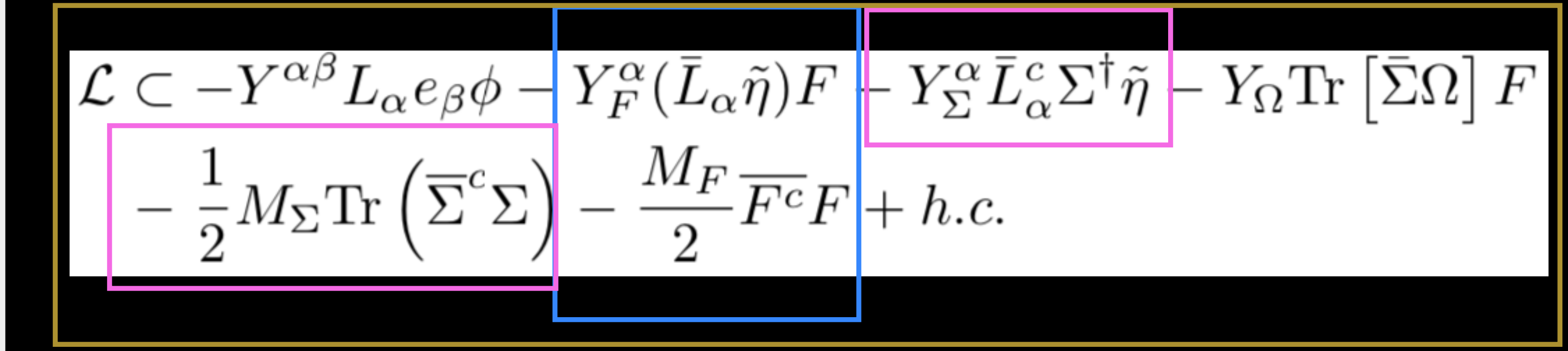
Discrete Z_2 symmetry which makes the lightest Z_2-odd particle stable and ensures the radiative generation of neutrino masses.

The SM particle content is augmented by the inclusion of:

- a Majorana fermion triplet Σ
- a Majorana fermion singlet F
- a new scalar doublet η
- a triplet scalar Ω



	Standard Model			new fermions		new scalars	
	L	e	ϕ	Σ	F	η	Ω
Generations	3	3	1	1	1	1	1
$\mathrm{SU}(3)_\mathrm{C}$	1	1	1	1	1	1	1
$\mathrm{SU}(2)_\mathrm{L}$	2	1	2	3	1	2	3
$\mathrm{U}(1)_\mathrm{Y}$	-1	-2	1	0	0	1	0
$\mathbb{Z}_2$	$+$	$+$	$+$	$-$	$-$	$-$	$+$
L	1	1	0	0	0	-1	0



$$\mathcal{L} \subset -Y^{\alpha\beta} L_\alpha e_\beta \phi - \boxed{Y_F^\alpha (\bar{L}_\alpha \tilde{\eta}) F} - \boxed{Y_\Sigma^\alpha \bar{L}_\alpha^c \Sigma^\dagger \tilde{\eta}} - Y_\Omega \mathrm{Tr}\left[\bar{\Sigma}\Omega\right] F$$

$$\boxed{-\frac{1}{2} M_\Sigma \mathrm{Tr}\left(\overline{\Sigma}^c \Sigma\right)} - \boxed{\frac{M_F}{2} \overline{F^c} F} + h.c.$$

E. Ma Phys.Rev. D73 (2006) 077301
E. Ma et al. Mod. Phys. Lett. A24 (2009) 583
M. Hirsch et al. JHEP 10 (2013) 149
A. Merle et al. JHEP 1607 (2016) 013
M. A. Díaz et al. JHEP 08 (2017) 017
S. Choubey et al. EPJC 78 no. 4, (2018) 302
D. Restrepo and A. Rivera arXiv:1907.11938
…

SCALAR SECTOR

$$\begin{aligned}\mathcal{V} = &-m_\phi^2 \phi^\dagger\phi + m_\eta^2 \eta^\dagger\eta - \frac{m_\Omega^2}{2}\mathrm{Tr}\left(\Omega^\dagger\Omega\right)\\ &+ \frac{\lambda_1}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 + \frac{\lambda_3}{2}\left(\phi^\dagger\phi\right)\left(\eta^\dagger\eta\right) + \lambda_4\left(\phi^\dagger\eta\right)\left(\eta^\dagger\phi\right) + \frac{\boxed{\lambda_5}}{2}\left[\left(\phi^\dagger\eta\right)^2 + \left(\eta^\dagger\phi\right)^2\right]\\ &\boxed{\begin{aligned}&+\mu_1\phi^\dagger\Omega\phi + \mu_2\eta^\dagger\Omega\eta\\ &+ \frac{\lambda_1^\Omega}{2}\left(\phi^\dagger\phi\right)\mathrm{Tr}\left(\Omega^\dagger\Omega\right) + \frac{\lambda_2^\Omega}{4}\left[\mathrm{Tr}\left(\Omega^\dagger\Omega\right)\right]^2 + \frac{\lambda_\eta^\Omega}{2}\left(\eta^\dagger\eta\right)\mathrm{Tr}\left(\Omega^\dagger\Omega\right)\,,\end{aligned}}\end{aligned}$$

Singlet +Triplet
Scotogenic

The spontaneous EW symmetry breaking is driven by ϕ and (sub-dominantly) by the neutral component of Ω, while η cannot acquire a VEV.

The potential must be bounded from below in order to have a stable minimum:

$$\begin{aligned}\lambda_1 \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_2^\Omega \geq 0,\\ \lambda_3 + \sqrt{\lambda_1\lambda_2} \geq 0, \quad \lambda_3 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1\lambda_2} \geq 0,\\ \lambda_1^\Omega + \sqrt{2\lambda_1\lambda_2^\Omega} \geq 0, \quad \lambda_\eta^\Omega + \sqrt{2\lambda_2\lambda_2^\Omega} \geq 0,\\ \sqrt{2\lambda_1\lambda_2\lambda_2^\Omega} + \lambda_3\sqrt{2\lambda_2^\Omega} + \lambda_1^\Omega\sqrt{\lambda_2} + \lambda_\eta^\Omega\sqrt{\lambda_1} + \sqrt{\left(\lambda_3 + \sqrt{\lambda_1\lambda_2}\right)\left(\lambda_1^\Omega + 2\sqrt{\lambda_1\lambda_2^\Omega}\right)\left(\lambda_\eta^\Omega + \sqrt{\lambda_2\lambda_2^\Omega}\right)} \geq 0.\end{aligned}$$

SCALAR SECTOR

$$\eta = \begin{pmatrix} \eta^+ \\ (\eta_R + i\eta_I)/\sqrt{2} \end{pmatrix}, \quad \phi = \begin{pmatrix} \varphi^+ \\ (h_0 + v_\phi + i\psi)/\sqrt{2} \end{pmatrix}, \quad \Omega = \begin{pmatrix} (\Omega_0 + v_\Omega)/\sqrt{2} & \Omega^+ \\ \Omega^- & -(\Omega_0 + v_\Omega)/\sqrt{2} \end{pmatrix}$$

After symmetry breaking there are two charged scalar fields plus three CP-even neutral fields, and one physical CP-odd neutral field.

$$m^2_{H^\pm} = 2\mu_1 \frac{(v_\phi^2 + v_\Omega^2)}{v_\Omega},$$

$$m^2_{\eta^\pm} = m_\eta^2 + \frac{1}{2}\lambda_3 v_\phi^2 + \frac{1}{\sqrt{2}}\mu_2 v_\Omega + \frac{1}{2}\lambda_\eta^\Omega v_\Omega^2.$$

DM candidate

$$\boxed{m^2_{\eta_R} = m_\eta^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v_\phi^2 + \frac{1}{2}\lambda_\eta^\Omega v_\Omega^2 - \frac{1}{\sqrt{2}}\mu_2 v_\Omega,}$$

$$m^2_{\eta_I} = m_\eta^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v_\phi^2 + \frac{1}{2}\lambda_\eta^\Omega v_\Omega^2 - \frac{1}{\sqrt{2}}\mu_2 v_\Omega.$$

- Because of the conservation of the Z_2 symmetry, the Z_2-odd scalar field η does not mix with any other scalar.
- The difference $m^2_{\eta R} - m^2_{\eta I}$ depends only on the parameter λ_5 which is also responsible for the smallness of neutrino masses.
- In the limit $\lambda_5 \to 0$ lepton number conservation is restored.

FERMIONIC SECTOR

The new triplet scalar Ω allows for a mixing between the singlet and triplet fermion fields — F and Σ — through the Yukawa coupling Y_Ω

$$\mathcal{M}_\chi = \begin{pmatrix} M_\Sigma & \frac{1}{\sqrt{2}} Y_\Omega v_\Omega \\ \frac{1}{\sqrt{2}} Y_\Omega v_\Omega & M_F \end{pmatrix} .$$

When the neutral part of Ω acquires a VEV $v_\Omega \neq 0$, the diagonalization of the mass matrix leads to

$$\begin{aligned} m_\chi^\pm &= M_\Sigma, \\ m_{\chi_1^0} &= \frac{1}{2}\left(M_\Sigma + M_F - \sqrt{(M_\Sigma - M_F)^2 + 4(2Y_\Omega v_\Omega)^2}\right), \\ m_{\chi_2^0} &= \frac{1}{2}\left(M_\Sigma + M_F + \sqrt{(M_\Sigma - M_F)^2 + 4(2Y_\Omega v_\Omega)^2}\right), \\ \tan(2\theta) &= \frac{4Y_\Omega v_\Omega}{M_\Sigma - M_F}, \end{aligned}$$

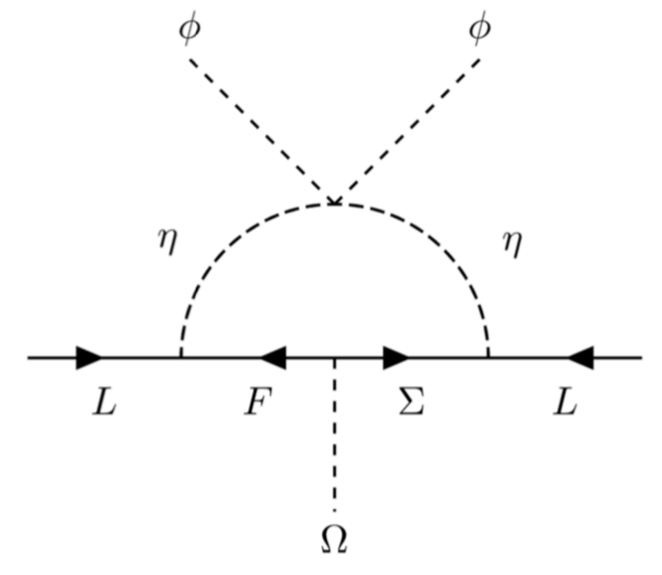
The lightest neutral eigenstate, χ^0_1 or χ^0_2 may also play the role of the dark matter.

M. Hirsch et al. JHEP 10 (2013) 149
S. Choubey et al. EPJC 78 no. 4, (2018) 302
D. Restrepo and A. Rivera arXiv:1907.11938
1912.08215

NEUTRINO MASSES

Since the Z_2 symmetry is exact, all vertices including new particles must contain an even number of Z_2-odd fields: neutrinos cannot acquire a tree-level mass term.

$$\mathcal{M}^{\nu}_{\alpha\beta} = \sum_{\sigma=1,2} \frac{Y^{\nu}_{\alpha\sigma} Y^{\nu}_{\beta\sigma}}{32\pi^2} m_{\chi_\sigma} \left(\frac{m^2_{\eta_R}}{m^2_{\eta_R} - m^2_{\chi_\sigma}} \ln\left(\frac{m^2_{\eta_R}}{m^2_{\chi_\sigma}}\right) - \frac{m^2_{\eta_I}}{m^2_{\eta_I} - m^2_{\chi_\sigma}} \ln\left(\frac{m^2_{\eta_I}}{m^2_{\chi_\sigma}}\right) \right)$$



$$\mathcal{M}^{\nu}_{\alpha\beta} = Y^{\nu}_{\alpha\beta} v_{\phi} \cdot \frac{\mathcal{F}}{v^2_{\phi}} \cdot Y^{\nu,T}_{\alpha\beta} v_{\phi} \sim m_D \frac{1}{M_R} m^T_D,$$

$$\mathcal{F} = \begin{pmatrix} \frac{\mathcal{I}_1}{32\pi^2} & 0 \\ 0 & \frac{\mathcal{I}_2}{32\pi^2} \end{pmatrix}$$

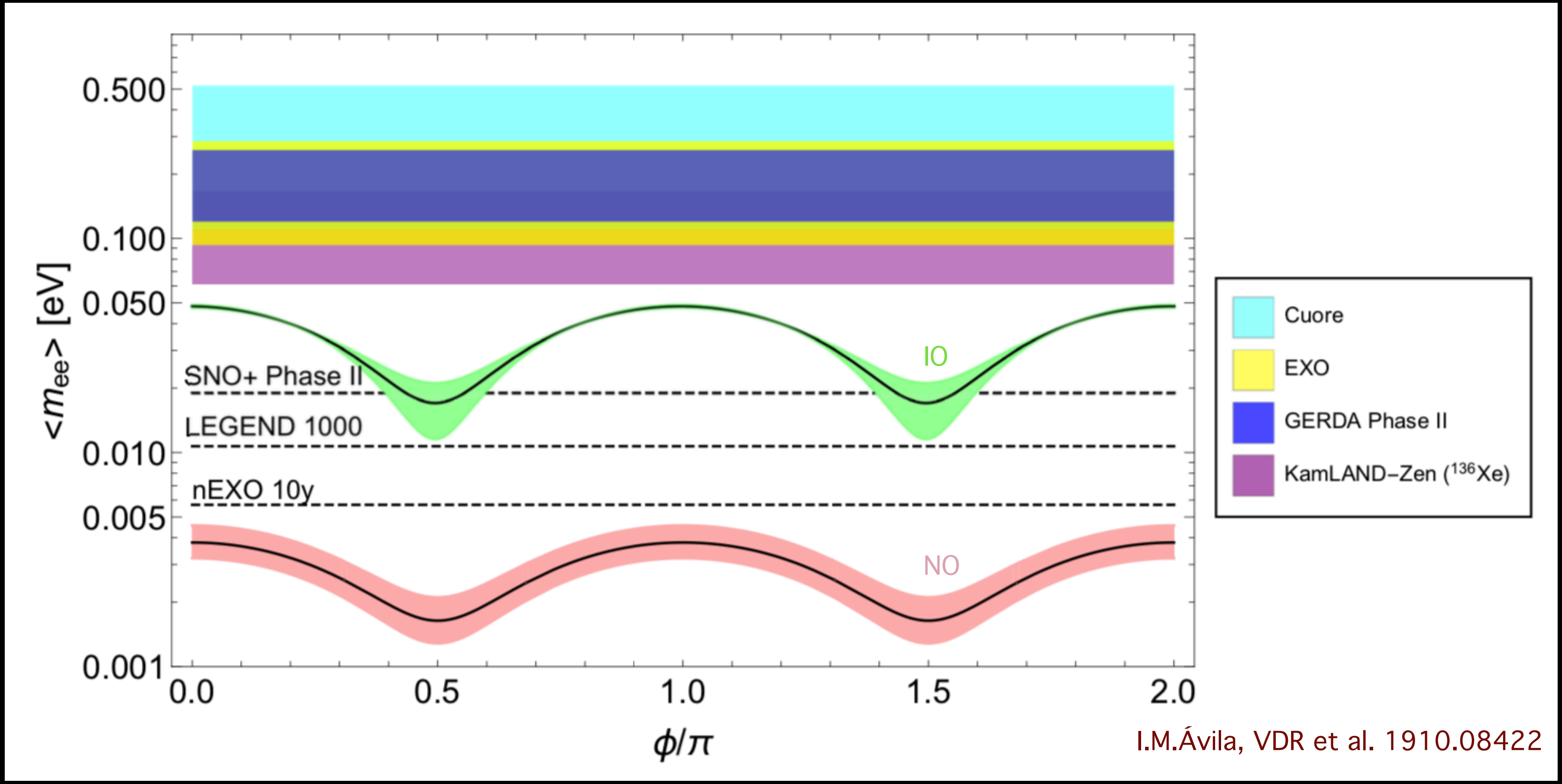
Interesting prediction: the lightest neutrino is massless (there is only one Σ and one F).

J. Schechter and J. W. F. Valle Phys. Rev. D22 (1980) 2227.

NEUTRINOLESS DOUBLE BETA DECAY

$$\langle m_{ee} \rangle = \left| \sum_j U^2_{\nu,ej} m_j \right| = \left| \cos\theta^2_{12} \cos\theta^2_{13} \mathrm{m}_1 + \sin\theta^2_{12} \cos\theta^2_{13} \mathrm{m}_2 \mathrm{e}^{2i\phi_{12}} + \sin\theta^2_{13} \mathrm{m}_3 \mathrm{e}^{2i\phi_{13}} \right|$$

W. Rodejohann and J. W. F. Valle Phys. Rev. D84 (2011) 073011



I.M.Ávila, VDR et al. 1910.08422

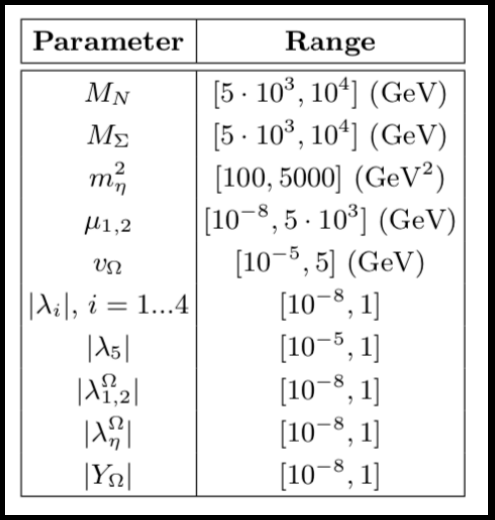
The effective mass parameter describing the 0ν2β decay amplitude has a lower limit.

NUMERICAL ANALYSIS

We want to confront the model with current (and future) observations associated with dark matter and various phenomenological constraints.
We perform a MonteCarlo simulation using a private Python code.

We further use the following numerical tools:

- SARAH: model implementation, computation of all the vertices, mass matrices, one loop correction for tadpole and self-energies.
- SPHENO: physical particle spectrum and low energy observables
- MicrOMEGAs: thermal component to the DM relic abundance and DM-nucleon scattering cross section.
- MadGraph: LHC cross sections.
- Checkmate: test our results against the last constraints given by the LHC.



Parameter	Range
M_N	$[5 \cdot 10^3, 10^4]$ (GeV)
M_Σ	$[5 \cdot 10^3, 10^4]$ (GeV)
m_η^2	$[100, 5000]$ (GeV^2)
$\mu_{1,2}$	$[10^{-8}, 5 \cdot 10^3]$ (GeV)
v_Ω	$[10^{-5}, 5]$ (GeV)
$\lvert\lambda_i\rvert,\ i = 1...4$	$[10^{-8}, 1]$
$\lvert\lambda_5\rvert$	$[10^{-5}, 1]$
$\lvert\lambda_{1,2}^\Omega\rvert$	$[10^{-8}, 1]$
$\lvert\lambda_\eta^\Omega\rvert$	$[10^{-8}, 1]$
$\lvert Y_\Omega\rvert$	$[10^{-8}, 1]$

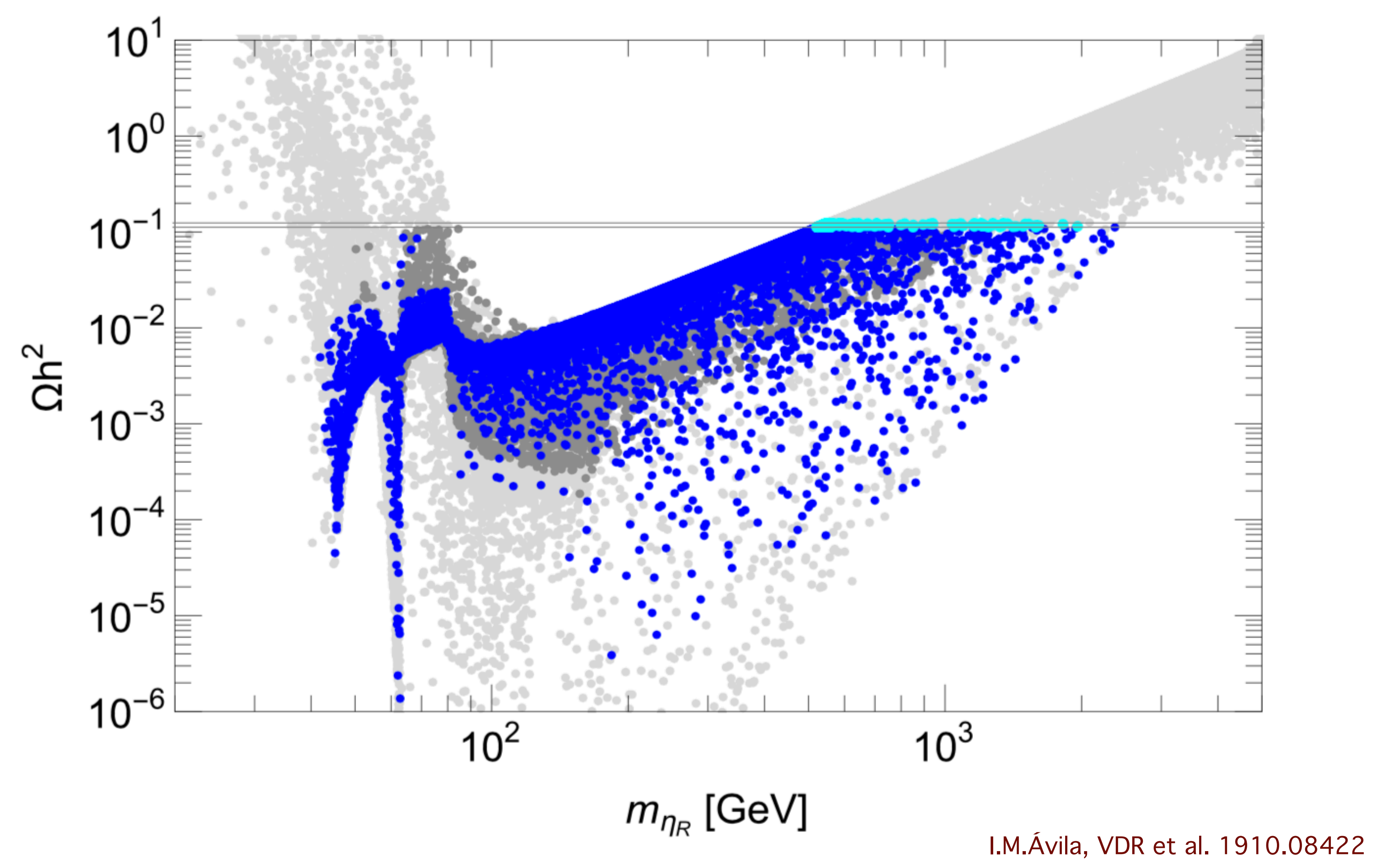
F. Staub, Comput. Phys. Commun. 185 (2014) 1773–1790
W. Porod, Comput. Phys. Commun. 153 (2003) 275–315
W. Porod and F. Staub, Comput. Phys. Commun. 183 (2012) 2458–2469
W. Porod, F. Staub, and A. Vicente, Eur. Phys. J. C74 no. 8, (2014) 2992
G. Bélanger et al. Comput. Phys. Commun. 192 (2015) 322–329
J. Alwall et al. JHEP 07 (2014) 079
D. Dercks et al. Comput. Phys. Commun. 221 (2017) 383–418

CONSTRAINTS

The presence of new particles will induce departures from the SM predictions for a number of observables.

- Theoretical constraints:
  - scalar potential bounded from below;
  - validity of the Z_2 parity symmetry; A. Merle et al., JHEP 1607 (2016) 013
  - the decay width of heavy neutral scalar H should comply with the perturbative unitarity condition;
- Neutrino oscillation parameters P. F. de Salas et al., Phys. Lett. B782 (2018) 633–640
- Lepton flavour violation P. Rocha-Morán and A. Vicente, arxiv:1605.01915
- Electroweak precision tests
- Invisible decay widths of the Higgs boson
- Dipole moments of leptons A. Abada and T. Toma, JHEP 04 (2018) 030,
- Dark matter and cosmological observations
- Colliders

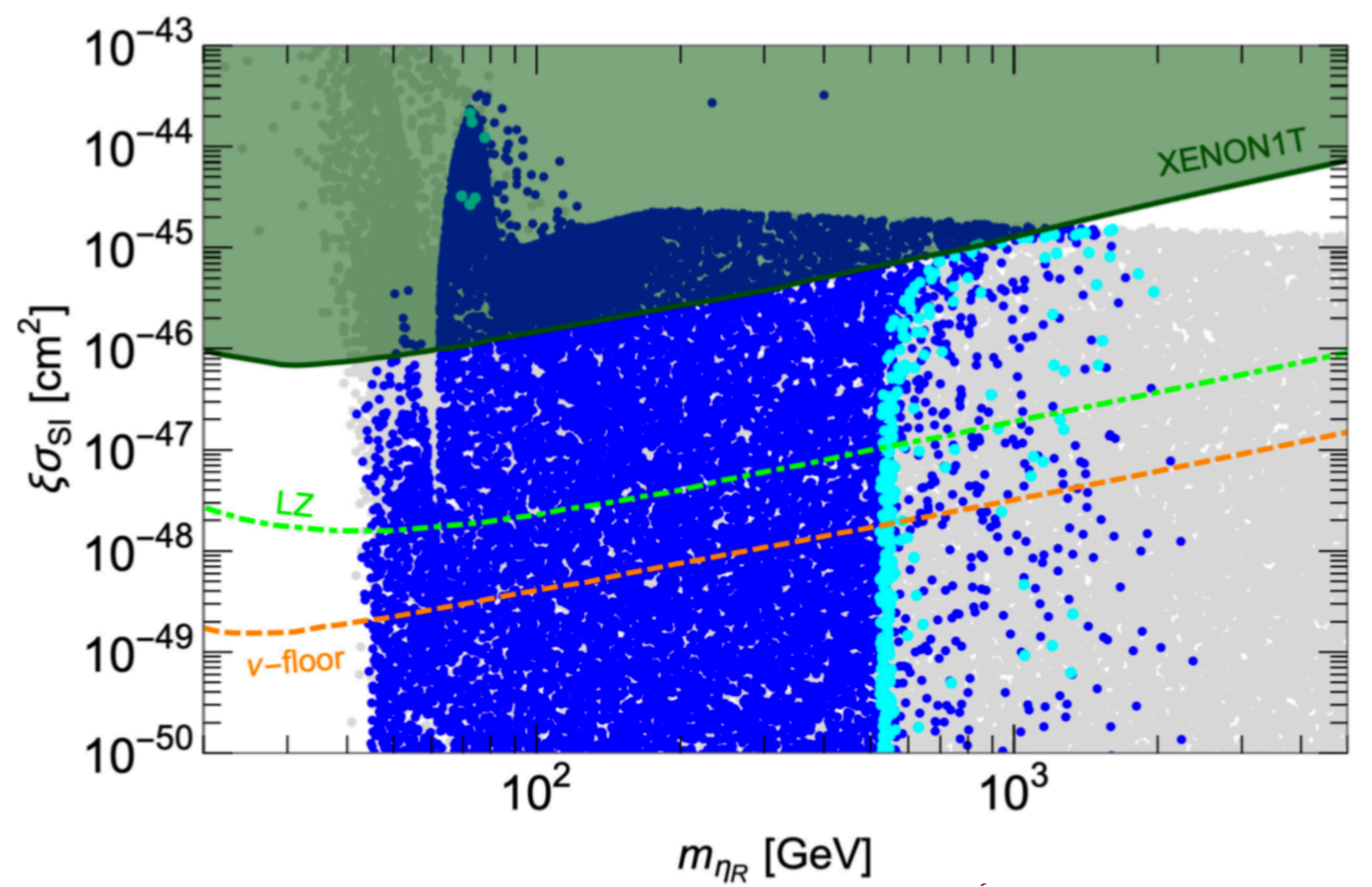
RELIC DENSITY



I.M.Ávila, VDR et al. 1910.08422

Planck Collaboration, N. Aghanim et al., arXiv:1807.06209
XENON Collaboration, E. Aprile et al., Phys. Rev. Lett. 121 no. 11, (2018) 111302

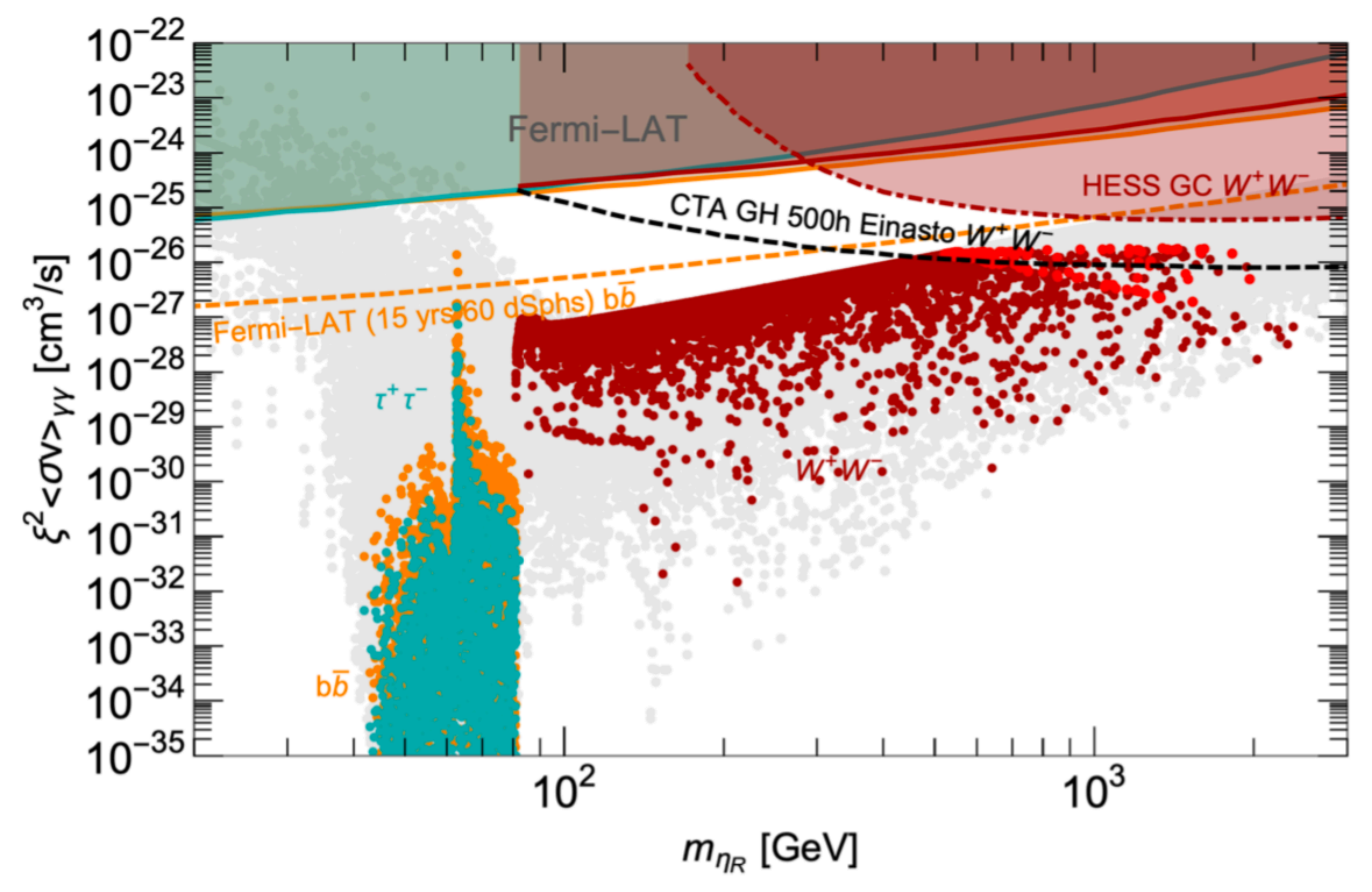
DIRECT DETECTION



I.M.Ávila, VDR et al. 1910.08422

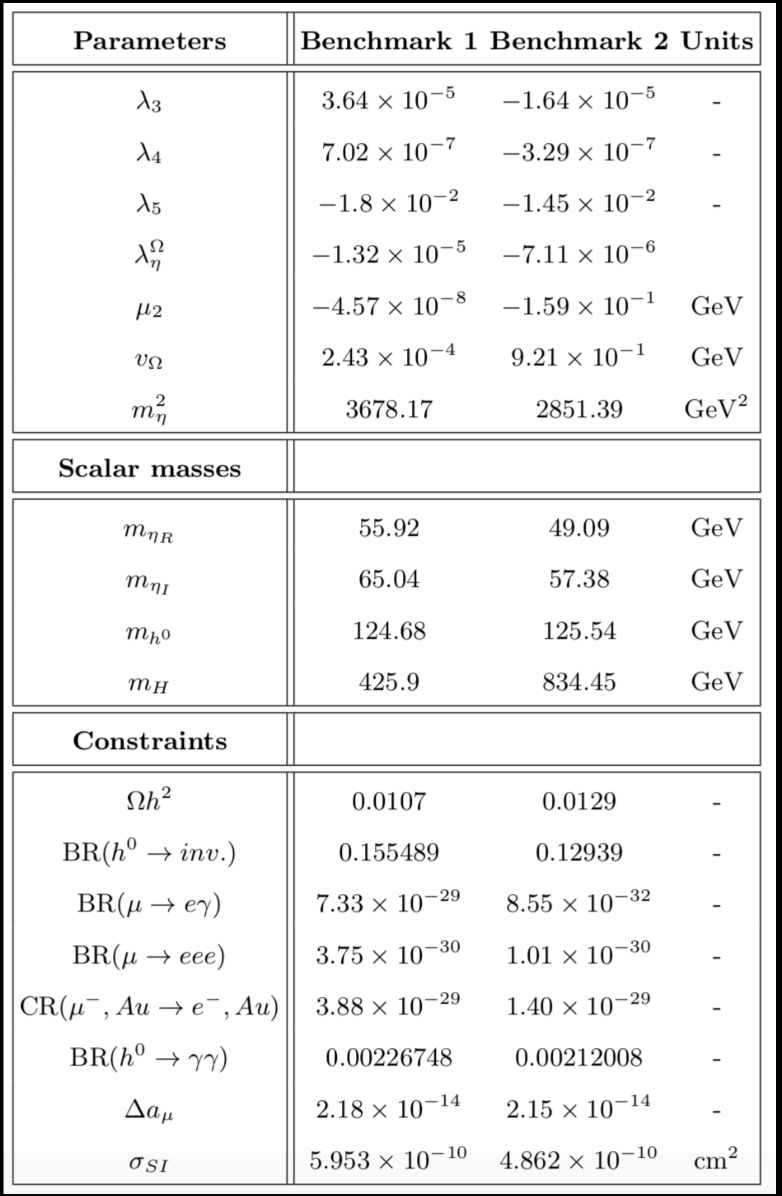
XENON Collaboration, E. Aprile et al., Phys. Rev. Lett. 121 no. 11, (2018) 111302
LUX-ZEPLIN Collaboration, D. S. Akerib et al., arXiv:1802.06039
J. Billard, L. Strigari, and E. Figueroa-Feliciano, Phys. Rev. D89 no. 2, (2014) 023524

INDIRECT DETECTION

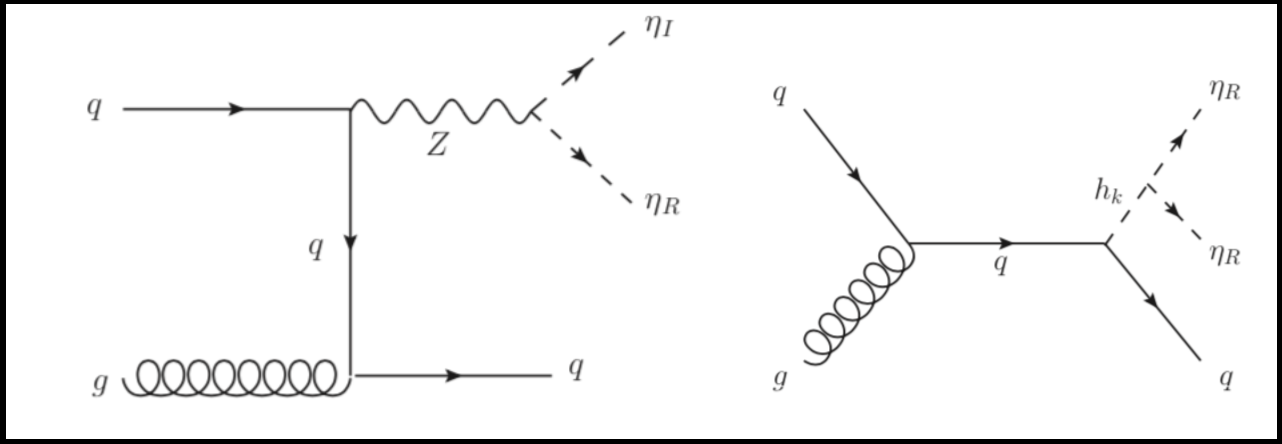


Fermi-LAT Collaboration, M. Ackermann et al., Phys. Rev. Lett. 115 no. 23, (2015) 231301
H.E.S.S. Collaboration, H. Abdallah et al., Phys. Rev. Lett. 117 no. 11, (2016) 111301
Fermi-LAT Collaboration, E. Charles et al., Phys. Rept. 636 (2016) 1–46
CTA Consortium Collaboration, B. S. Acharya et al., arXiv:1709.07997

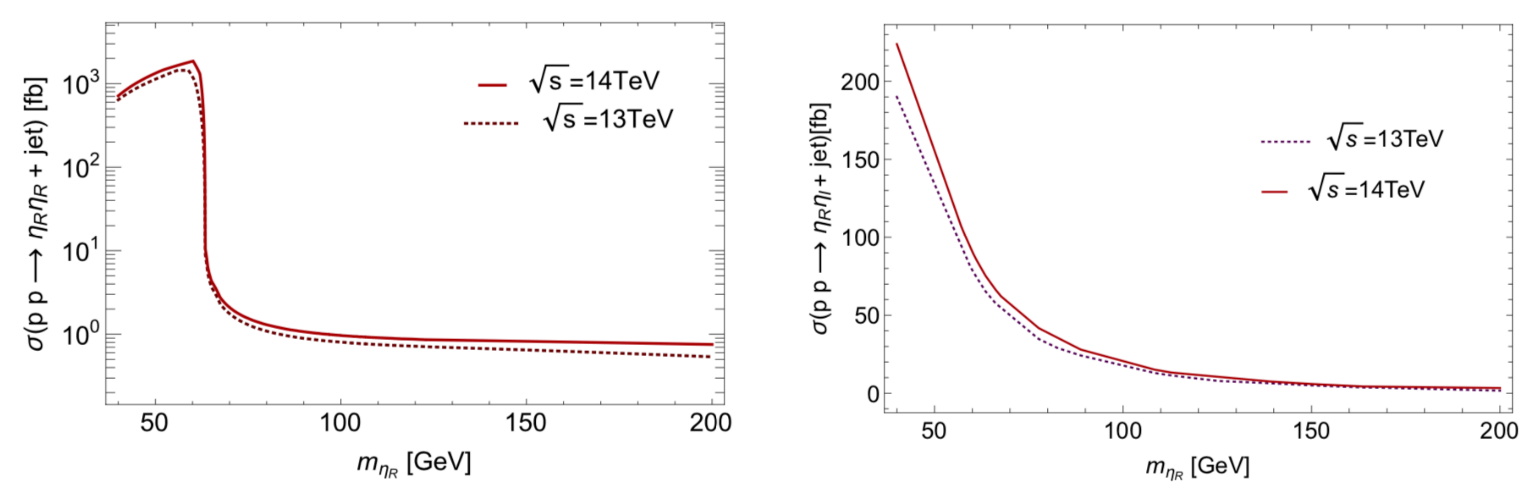
SCALAR DM SIGNATURES AT THE LHC

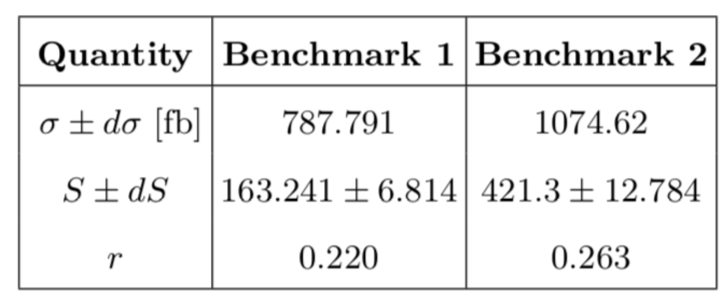


Parameters	Benchmark 1	Benchmark 2	Units
λ_3	3.64×10^{-5}	-1.64×10^{-5}	-
λ_4	7.02×10^{-7}	-3.29×10^{-7}	-
λ_5	-1.8×10^{-2}	-1.45×10^{-2}	-
λ_η^Ω	-1.32×10^{-5}	-7.11×10^{-6}	
μ_2	-4.57×10^{-8}	-1.59×10^{-1}	GeV
v_Ω	2.43×10^{-4}	9.21×10^{-1}	GeV
m_η^2	3678.17	2851.39	GeV^2
Scalar masses			
m_{η_R}	55.92	49.09	GeV
m_{η_I}	65.04	57.38	GeV
m_{h^0}	124.68	125.54	GeV
m_H	425.9	834.45	GeV
Constraints			
Ωh^2	0.0107	0.0129	-
$\mathrm{BR}(h^0 \to inv.)$	0.155489	0.12939	-
$\mathrm{BR}(\mu \to e\gamma)$	7.33×10^{-29}	8.55×10^{-32}	-
$\mathrm{BR}(\mu \to eee)$	3.75×10^{-30}	1.01×10^{-30}	-
$\mathrm{CR}(\mu^-, Au \to e^-, Au)$	3.88×10^{-29}	1.40×10^{-29}	-
$\mathrm{BR}(h^0 \to \gamma\gamma)$	0.00226748	0.00212008	-
Δa_μ	2.18×10^{-14}	2.15×10^{-14}	-
σ_{SI}	5.953×10^{-10}	4.862×10^{-10}	cm^2



As a consequence of its small coupling with quarks, the heavy neutral scalar H does not influence significantly our signal. Results similar to the simple Scotogenic scenario and the Inert Higgs Doublet Model.





Quantity	Benchmark 1	Benchmark 2
$\sigma \pm d\sigma$ [fb]	787.791	1074.62
$S \pm dS$	163.241 ± 6.814	421.3 ± 12.784
r	0.220	0.263

ATLAS Collaboration, M. Aaboud et al., Phys. Rev. D94 no. 3, (2016) 032005

SUMMARY AND OUTLOOK

- We have reexamined the generalized version of the minimal Singlet + Triplet Scotogenic Model.

- It is the minimal scotogenic fully consistent with oscillation data.

- Dark matter emerges naturally as the mediator of neutrino mass generation and its stability follows from the same Z_2 symmetry also responsible for the radiative origin of neutrino masses.

- We have assumed dark matter to be a scalar WIMP and we have presented a full numerical analysis of the signatures expected at dark matter detectors as well as collider experiments.

- We have found a viable light dark matter mass range in the region 50 - 60 GeV. This should encourage future studies at the upcoming high-luminosity run of the LHC.

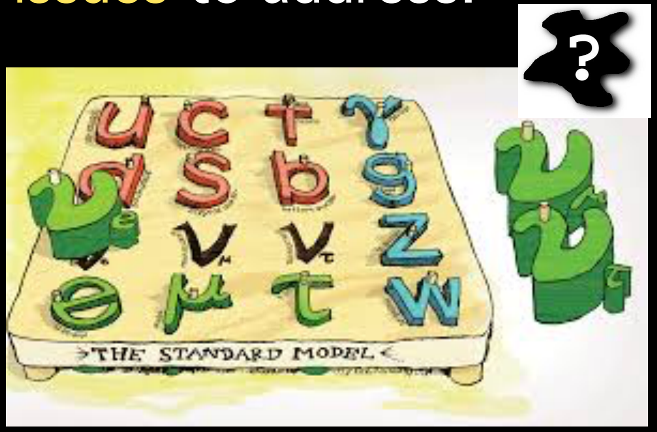
- A detailed background analysis will be required for a HL-LHC analysis.

Thank you!

Backup

New physics beyond the SM?

- The Standard Model can explain most of the experimental results. However, there are some theoretical and observational issues to address:
  - neutrino oscillations
  - dark matter
  - baryon asymmetry of the Universe



Symmetry Magazine

- Neutrino oscillations provide 1st laboratory evidence of New Physics
- The Standard Model must be extended (or embedded in larger framework)
  Many candidate models...
- New Physics actively searched for in many fronts:

- High energy colliders direct searches of new states
- High intensity facilities indirect searches (rare processes, deviations from SM)
- Cosmology & astroparticle physics observations (dark matter, inflation, ...)
- Neutrino experiments

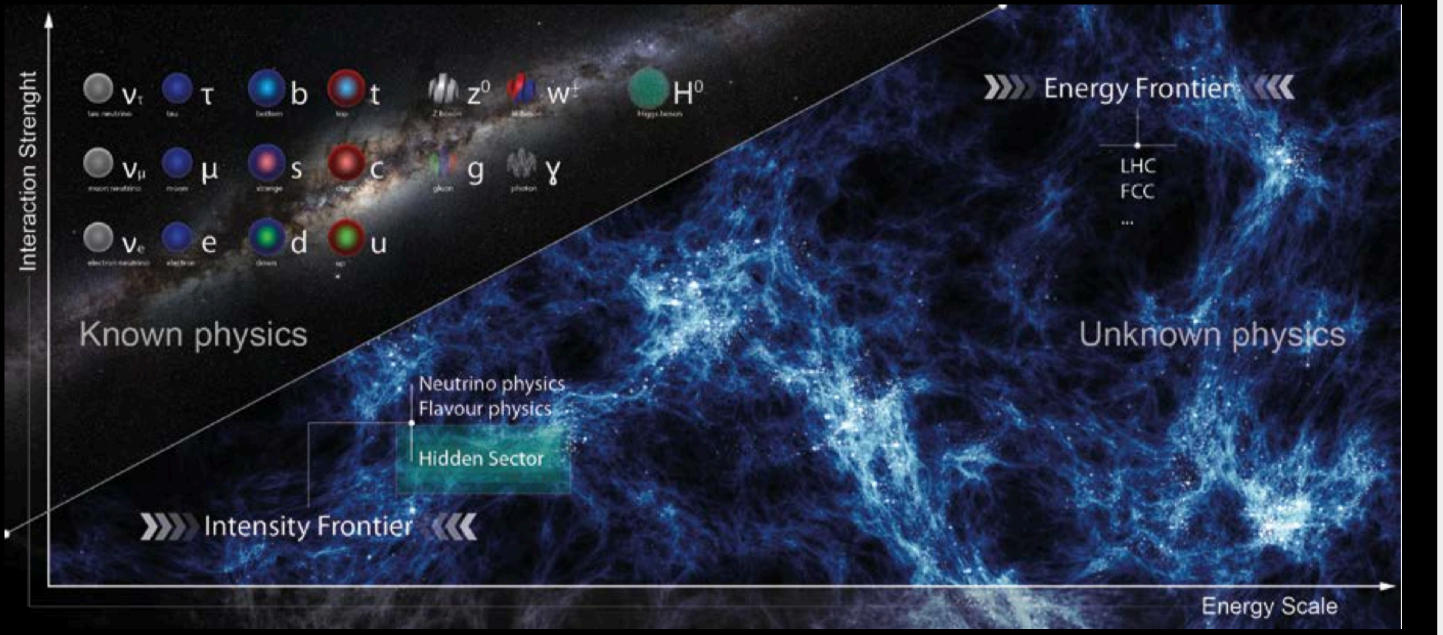
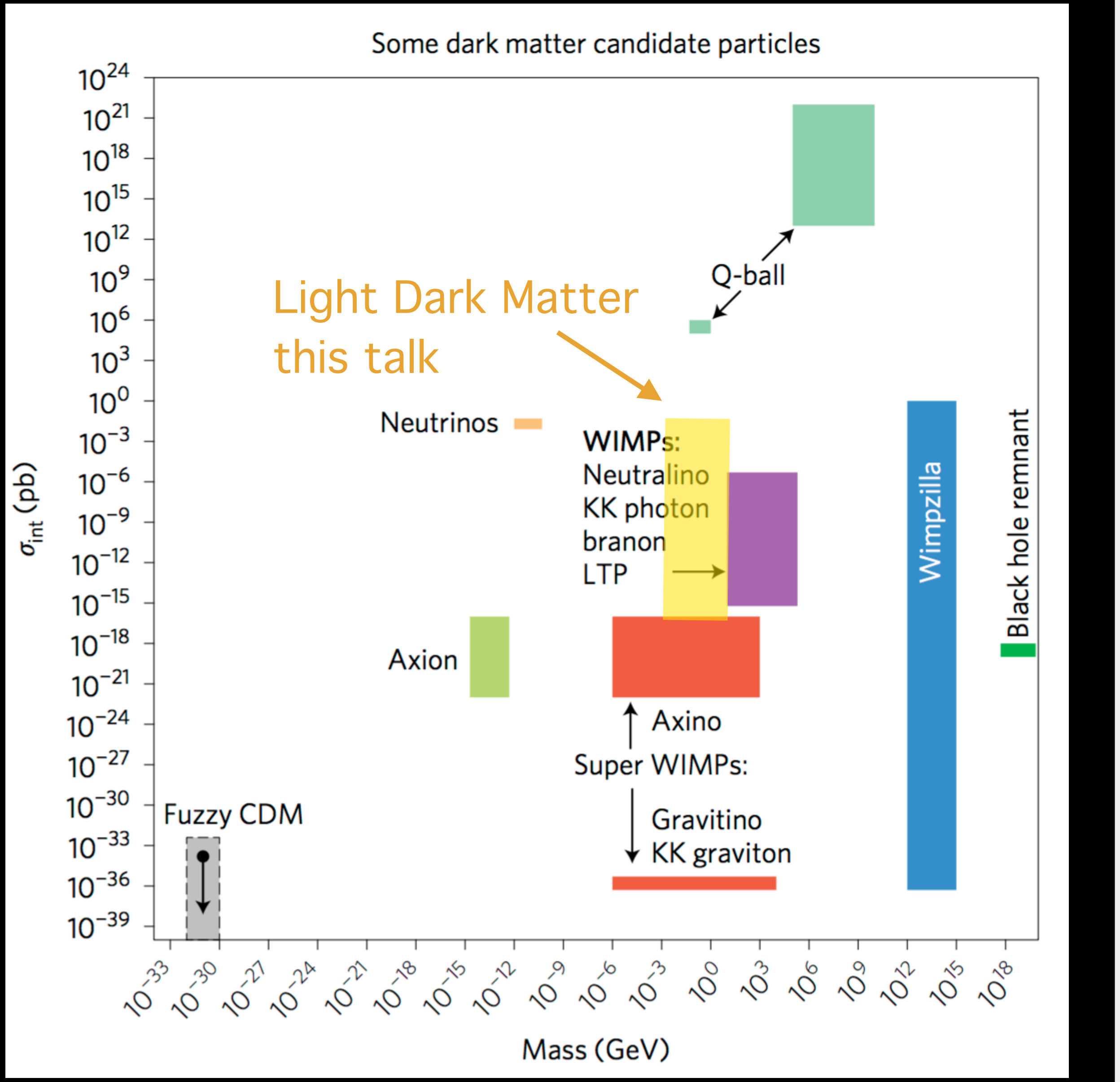


Image from CERN courier 2/2016

What do we know about DM?

- Non-baryonic (BBN, CMB)
- Collisionless (bullet cluster)
- Stable on cosmological scales
  (or lifetime >> t_U ~13.8 Gyr)
- Neutral
- Massive
- Cold or Warm (structure formation)
- Not in conflict/excluded by DM experiments and cosmological data



Light Dark Matter
this talk

Park, E.-K. DMSAG Report on the Direct Detection and Study of Dark Matter (2007)

not included in the Standard Model

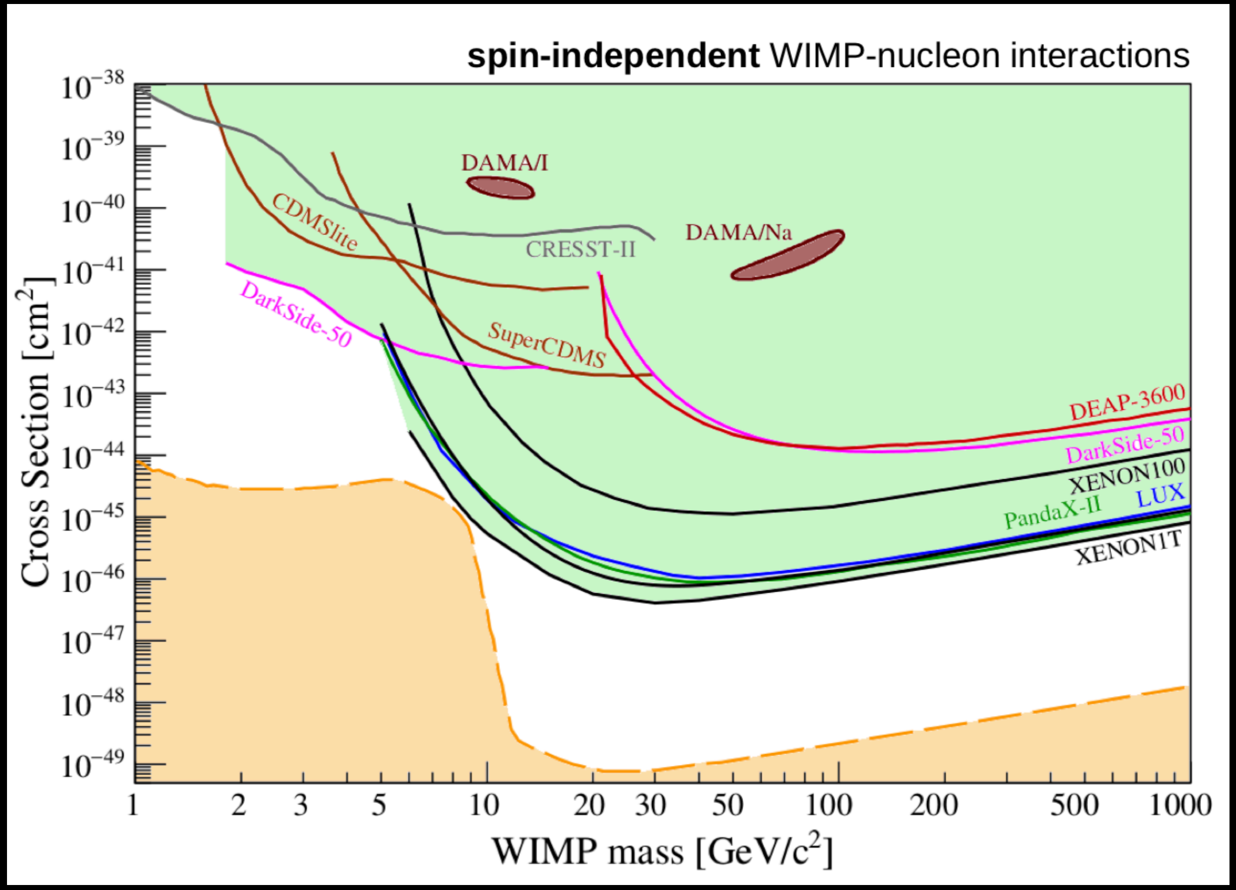
Many candidates in Particle Physics!

If DM is made of particles that interact among themselves and with SM particles we may hope to detect it. Two strategies:

1. DIRECT DETECTION (looks for energy deposited within a detector by the DM-nuclei scattering)

2. INDIRECT DETECTION (looks for WIMP annihilation (or decay) products)

+ complementary searches at colliders



M. Schumann ZPW 2019

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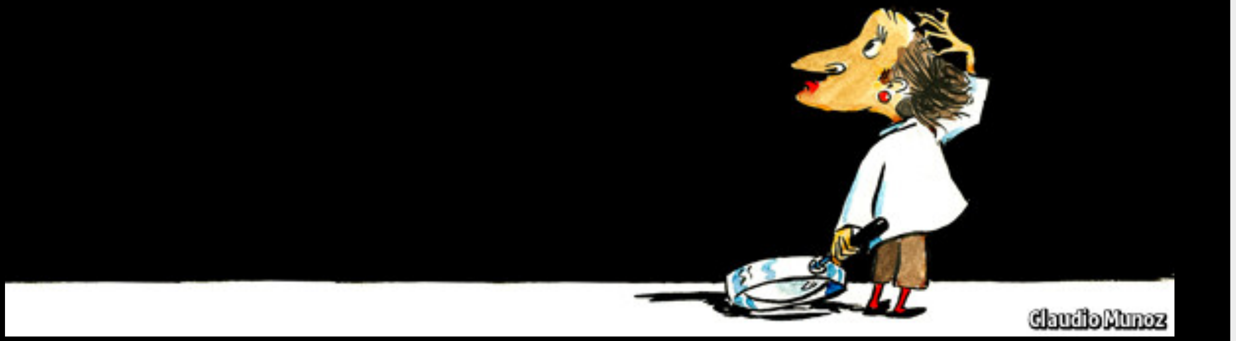

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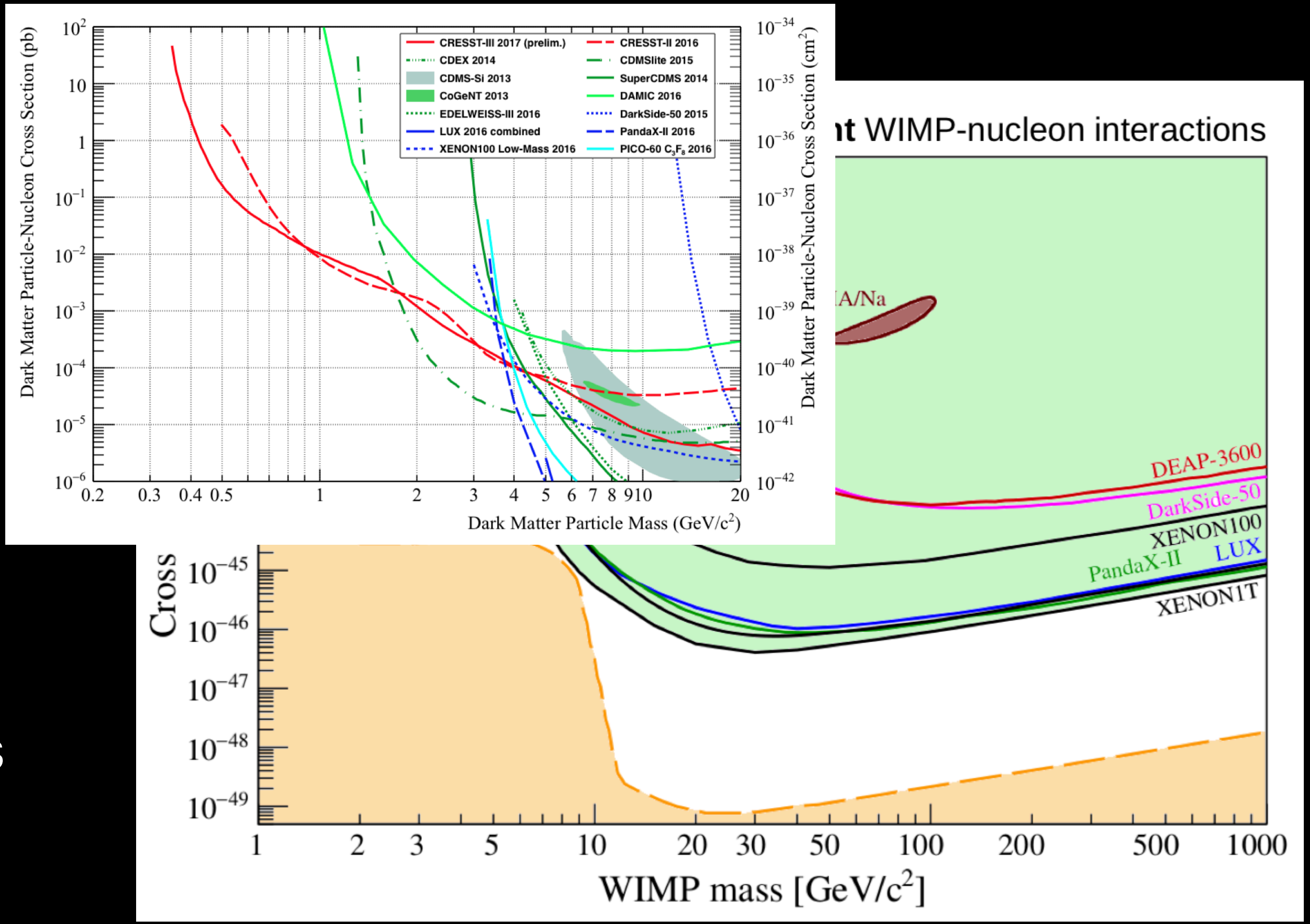

M. Schumann ZPW 2019, CRESST-III exp