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Neutrino Physics and dark matter signals in simple and well-motivated supersymmetric models

NuDM-2022, September 2022, Sharm El-Sheikh, Egypt (virtual)

Supersymmetry is still the most compelling theory for physics beyond the standard model

The Minimal Supersymmetric Standard Model, **MSSM :**

As for the standard model, neutrino physics is not included

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● **Maintaining R-parity as symmetry**

Most SUSY searches at LHC assume R parity conservation (RPC), thus the LSP is stable, requiring missing energy in the final state for its detection.

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As we will discuss here: possible multiple dark matter candidates with neutrino signals.

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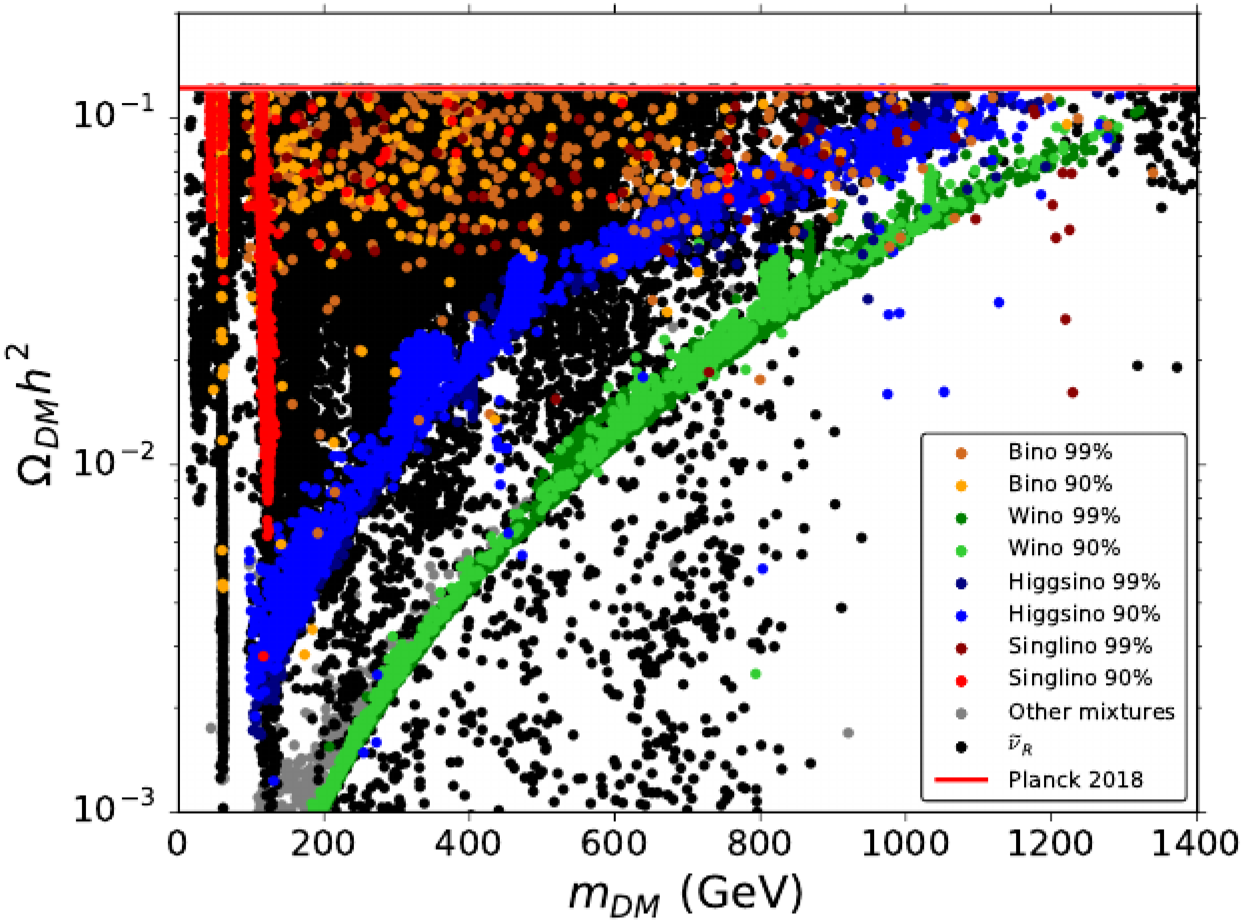
● **R-parity violation**

If R parity is violated (RPV), SUSY particles can decay to standard model particles, and the bounds become significantly weaker.
The Number of LHC analyses with motivated by R-parity breaking are increasing giving new constraints and the possibility of a discovery.
The **$\mu\nu$SSM:** very interesting model in this context (see Carlos Muñoz Monday talk).

NMSSM + RH neutrinos

$$
\begin{aligned}
W \;=\;& \epsilon_{\alpha\beta}\Big(Y_e^{ij}\,\hat{H}_d^\alpha\,\hat{L}_i^\beta\,\hat{e}_j + Y_d^{ij}\,\hat{H}_d^\alpha\,\hat{Q}_i^\beta\,\hat{d}_j + Y_u^{ij}\,\hat{Q}_i^\alpha\,\hat{H}_u^\beta\,\hat{u}_j + \underbrace{Y_N^{ij}\,\hat{L}_i^\alpha\,\hat{H}_u^\beta\,\hat{N}_j}_{\text{RH neutrino}} + \underbrace{\lambda\,\hat{S}\,\hat{H}_u^\alpha\,\hat{H}_d^\beta}_{\text{NMSSM}}\Big)\\
&+ \underbrace{\lambda_N^{ij}\,\hat{N}_i\,\hat{N}_j\,\hat{S}}_{\text{RH neutrino}} + \underbrace{\frac{\kappa}{3}\,\hat{S}^3}_{\text{NMSSM}},
\end{aligned}
$$

$$
\begin{aligned}
V_{soft} \;=\;& \Big[\epsilon_{\alpha\beta}\Big(A_e^{ij}\,Y_e^{ij}\,H_d^\alpha\,\tilde{L}_i^\beta\,\tilde{e}_j + A_d^{ij}\,Y_d^{ij}\,H_d^\alpha\,\tilde{Q}_i^\beta\,\tilde{d}_j + A_u^{ij}\,Y_u^{ij}\,\tilde{Q}_i^\alpha\,H_u^\beta\,\tilde{u}_j + A_N^{ij}\,Y_N^{ij}\,\tilde{L}_i^\alpha\,H_u^\beta\,\tilde{N}_j\\
&+ A_\lambda\,\lambda\,S\,H_u^\alpha\,H_d^\beta\Big) + A_{\lambda_N}^{ij}\,\lambda_N^{ij}\,\tilde{N}_i\,\tilde{N}_j\,S + \frac{A_\kappa\,\kappa}{3}\,S^3\Big] + h.c.\\
&+ m^2_{\phi_{ij}}\,\phi_i^\dagger\,\phi_j + m^2_{\theta_{ij}}\,\theta_i\,\theta_j^* + m^2_{H_d}\,H_d^\dagger\,H_d + m^2_{H_u}\,H_u^\dagger\,H_u + m_S^2\,S\,S^*\\
&+ \frac{1}{2}\,M_1\,\tilde{B}\,\tilde{B} + \frac{1}{2}\,M_2\,\tilde{W}^i\,\tilde{W}^i + \frac{1}{2}\,M_3\,\tilde{g}^a\,\tilde{g}^a,
\end{aligned}
$$

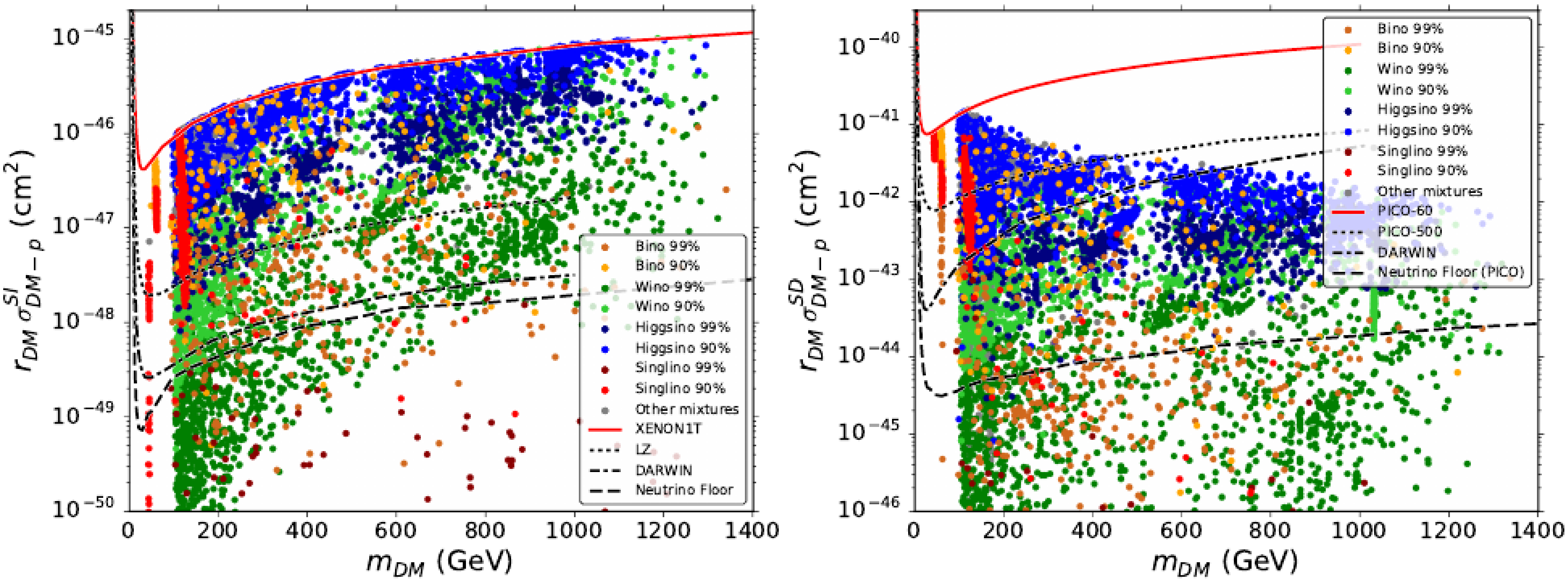


Relic density versus LSP mass for the parameter points that fulfill all the constraints considered in this work. The color coding represents the LSP identity, and in the case of neutralino, the dominant composition as labeled. The red solid line corresponds to the amount of DM measured by the Planck Collaboration.

Figure from:

L-F, Andres Perez, Roberto Ruiz de Austri. ArXiv:2102.08986 [hep-ph] (JCAP **04** 2021)

Neutralino

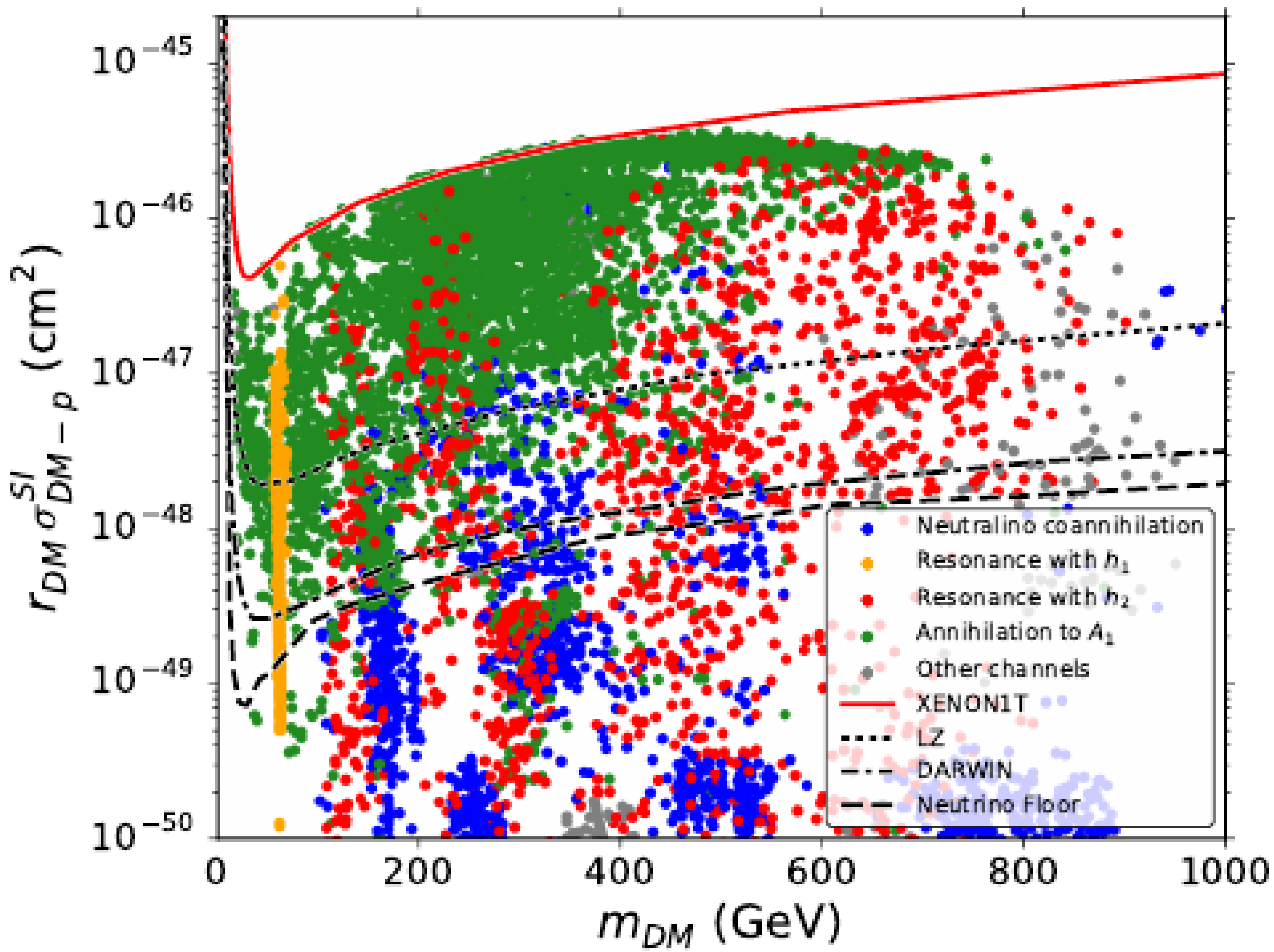


The first row presents the scaled spin-independent (top-left) and spin-dependent (top-right) direct detection cross sections for neutralino DM, the color coding represents its composition.

Figures from:

L-F, Andres Perez, Roberto Ruiz de Austri. ArXiv:2102.08986 [hep-ph] (JCAP **04** 2021)

Sneutrino



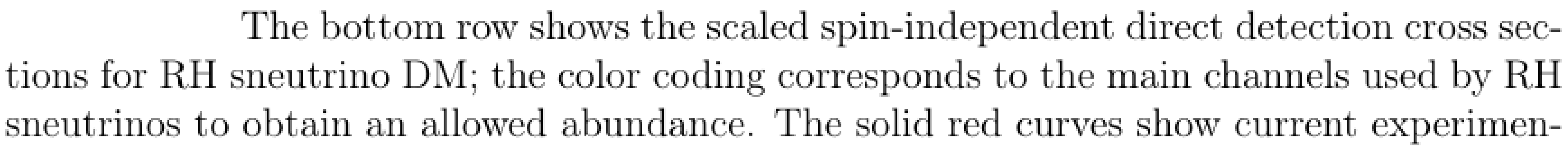

The bottom row shows the scaled spin-independent direct detection cross sections for RH sneutrino DM; the color coding corresponds to the main channels used by RH sneutrinos to obtain an allowed abundance. The solid red curves show current experimen-

Figure from:

L-F, Andres Perez, Roberto Ruiz de Austri. arXiv:2102.08986 [hep-ph] (JCAP **04** 2021)

Multiple dark matter candidates: gravitino (LSP) + RH sneutrino (NLSP)

In the NMSSM + RH it is possible to have the gravitino (LSP) plus RH sneutrino (NLSP) with a lifetime bigger than the age of the universe thanks to small neutrino yukawas

Case analysed in detail in:

L-F, Andres Perez, Roberto Ruiz de Austri. arXiv:2206.04715 [hep-ph]

RH sneutrino NLSP decay to gravitino LSP

$$\Gamma(\tilde{\nu}_R \to \Psi_{3/2}\,\nu_L) = \frac{1}{48\,\pi\,M_P^2}\,\frac{m_{\tilde{\nu}_R}^5}{m_{3/2}^2}\,\left(1-\frac{m_{3/2}^2}{m_{\tilde{\nu}_R}^2}\right)^4\,\sin^2\theta_{\tilde{\nu}},$$

$\sin\ \theta_{\tilde{\nu}}\ \simeq\ \theta_{\tilde{\nu}}$ Mixing between RH sneutrino and LH sneutrino

$10^{-8} \leq \theta_{\tilde{\nu}} \leq 10^{-6}$

$$\tau_{\tilde{\nu}_R} \simeq \Gamma^{-1}(\tilde{\nu}_R \to \Psi_{3/2}\,\nu_L) \simeq 5.7\times 10^{23}s\left(\frac{10\ \mathrm{GeV}}{m_{\tilde{\nu}_R}}\right)^5\left(\frac{m_{3/2}}{0.1\ \mathrm{GeV}}\right)^2\left(\frac{10^{-8}}{\sin\theta_{\tilde{\nu}}}\right)^2.$$

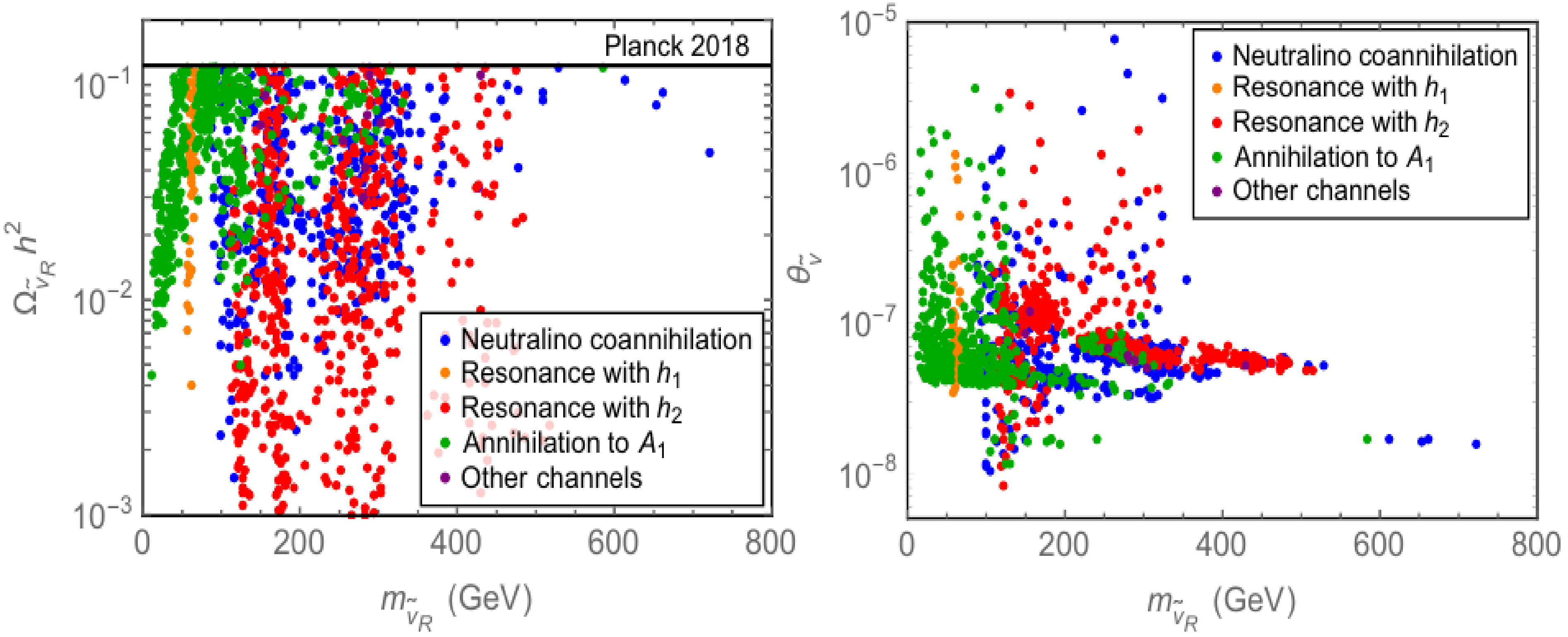
Relic density (sneutrino + gravitino)

$$\Omega_{\tilde{\nu}_R}h^2 + \Omega_{3/2}h^2 = \Omega_{cdm}^{\mathrm{Planck}}h^2,$$

$$\Omega_{3/2}^{TP}h^2 \simeq 0.02\left(\frac{T_R}{10^5\ \mathrm{GeV}}\right)\left(\frac{1\ \mathrm{GeV}}{m_{3/2}}\right)\left(\frac{M_3(T_R)}{3\ \mathrm{TeV}}\right)^2\left(\frac{\gamma(T_R)/(T_R^6/M_P^2)}{0.4}\right),$$

Multiple dark matter: sneutrino (NLSP) + gravitino (LSP)

RH sneutrino as DM candidate with a significant contribution to the total DM relic density (greater than 1% of the current measured value)



Relic density and mixing angle in the sneutrino sector versus RH sneutrino mass. The color coding represents the main channels used by RH sneutrinos to obtain an allowed relic density, with h_i (A_i) a neutral CP-even (CP-odd) scalar of the Higgs-singlet sector.

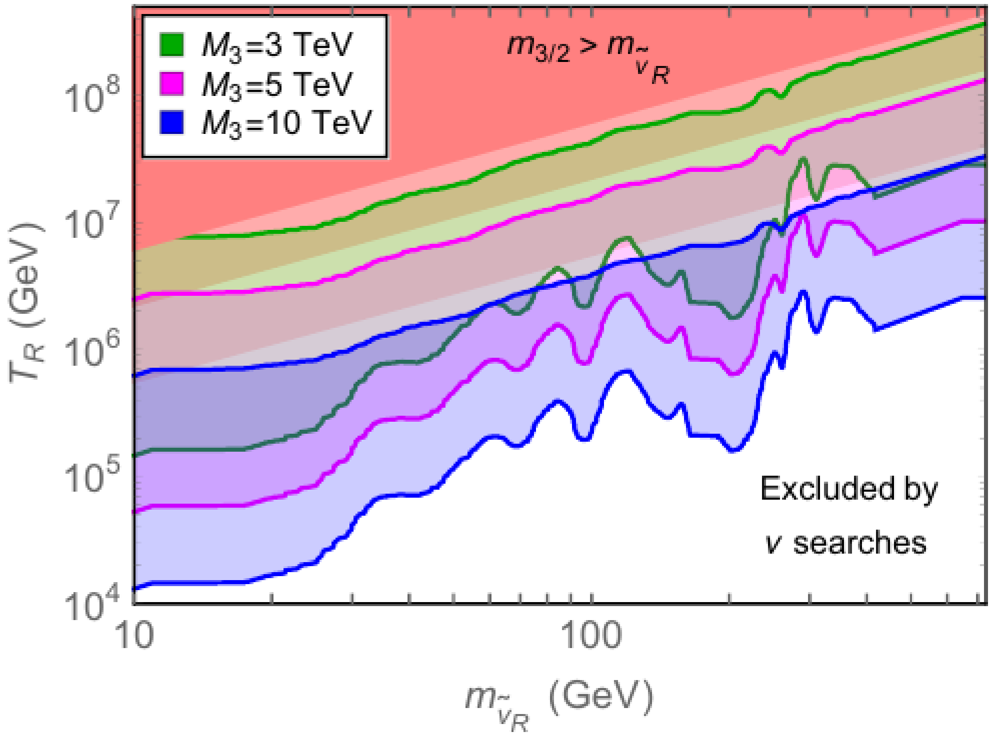
Figures from:

L-F, Andres Perez, Roberto Ruiz de Austri. arXiv:2206.04715 [hep-ph]

Important: Neutrino signal from the decay of the NLSP to the LSP

$$\frac{d\Phi_\nu^{\rm halo}}{dE d\Omega} = \frac{r_{DM}}{4\,\pi\,\tau_{DM}\,m_{DM}}\,\frac{1}{\Delta\Omega}\,\frac{dN_\nu^{\rm total}}{dE}\int_{\Delta\Omega}\cos b\,db\,d\ell\int_0^\infty ds\,\rho_{\rm halo}(r(s,\,b,\,\ell))\ ,$$

$$E_\nu = \frac{m_{\tilde{\nu}_R}^2 - m_{3/2}^2}{2m_{\tilde{\nu}_R}}.$$



Effect of the gluino mass parameter, M_3, (see Eq. (30)) on the T_R versus $m_{\tilde{\nu}_{RH}}$ space. Three values are considered $M_3 = 3, 5,$ and 10 TeV in green, magenta, and blue, respectively. In this figure each region corresponds to the sensibility that will be probed by the next generation of neutrino telescopes (the $M_3 = 3$ TeV case is shown on the right panel of Fig. 5). Notice that the curve denoting the $m_{3/2} > m_{\tilde{\nu}_{RH}}$ also depends on M_3, and is always close to the upper solid curves of the corresponding colored region.

Figures from:

L-F, Andres Perez, Roberto Ruiz de Austri. arXiv:2206.04715 [hep-ph]

μ -from- ν Supersymmetric Standard Model
μνSSM

The same superfield solves the mu-problem of the NMSSM and gives mass to the neutrino

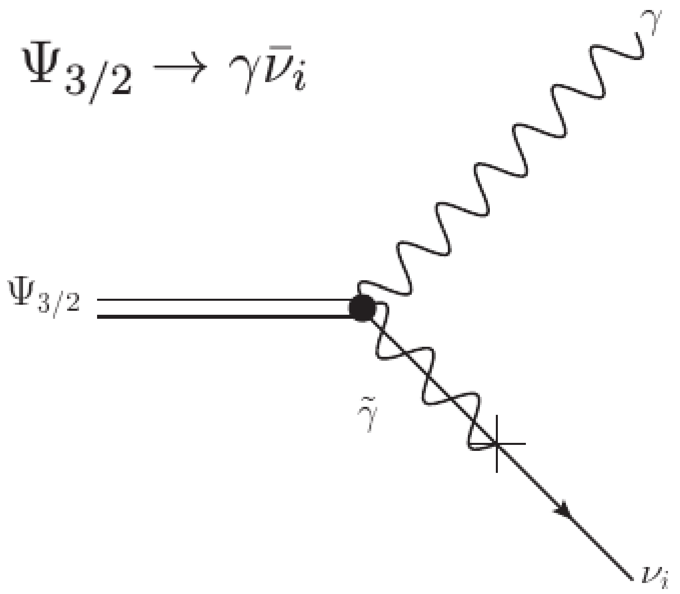
$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + \underline{Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c}\right)$$

$$- \underline{\epsilon_{ab}\lambda^i\,\hat{\nu}_i^c\,\hat{H}_1^a\hat{H}_2^b} + \underline{\frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c}\,,$$

$$\begin{aligned}
-\mathcal{L}_{\rm soft} &= m_{H_1}^2\,H_1^{a*}\,H_1^a + m_{H_2}^2\,H_2^{a*}H_2^a + (m_{\tilde{\nu}^c}^2)^{ij}\,\tilde{\nu}_i^{c*}\,\tilde{\nu}_j^c + \ldots \\
&+ \left[\epsilon_{ab}(A_\nu Y_\nu)^{ij}\,H_2^b\,\tilde{L}_i^a\,\tilde{\nu}_j^c + \ldots + \frac{1}{3}(A_\kappa\kappa)^{ijk}\tilde{\nu}_i^c\tilde{\nu}_j^c\tilde{\nu}_k^c \; + \mathrm{H.c.}\right] \\
&- \frac{1}{2}\left(M_3\,\tilde{\lambda}_3\,\tilde{\lambda}_3 + M_2\,\tilde{\lambda}_2\,\tilde{\lambda}_2 + M_1\,\tilde{\lambda}_1\,\tilde{\lambda}_1 + \mathrm{H.c.}\right)\,.
\end{aligned}$$

Gravitino dark matter and interesting signal

$$\Psi_{3/2} \to \gamma \bar{\nu}_i$$



$$\Gamma(\Psi_{3/2} \to \sum_i \gamma \nu_i) \simeq \frac{m_{3/2}^3}{64\pi M_P^2} |U_{\tilde{\gamma}\nu}|^2$$

$$M_P \simeq 2.4 \times 10^{18}\,\mathrm{GeV}$$

$$|U_{\tilde{\gamma}\nu}|^2 = \sum_{i=1}^{3} |N_{i1}\,\cos\theta_W + N_{i2}\,\sin\theta_W|^2$$

Works on the topic:

Choi, L-F, Muñoz, Ruiz de Austri, JCAP 1003 (2010) 028 [arXiv:0906.368]

Gomez-Vargas, L-F, Muñoz, Perez, Ruiz de Austri arxiv:1608.08640 (JCAP)

C. Muñoz, Grefe, Weniger

Works by Fermi-Lat:
Albert, Bloom, Charles, Gómez-Vargas, Mazziotta, Morselli

Axino LSP dark matter

$$\Gamma(\tilde{a} \rightarrow \sum_i \gamma\nu_i) \simeq \frac{m_{\tilde{a}}^3}{128\pi^3 f_a^2}\alpha_{em}^2 C_{a\gamma\gamma}^2 |U_{\tilde{\gamma}\nu}|^2$$

$$10^{-10} \lesssim |U_{\tilde{\gamma}\nu}| \lesssim 10^{-6}$$

$$\tau_{\tilde{a}} = \Gamma^{-1}(\tilde{a} \rightarrow \sum_i \gamma\nu_i) \simeq 3.8 \times 10^{26}\, s \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^2 \left(\frac{10^{-8}}{|U_{\tilde{\gamma}\nu}|}\right)^2 \left(\frac{0.1\,\mathrm{GeV}}{m_{\tilde{a}}}\right)^3$$

assuming the conservative limit $T_R \gtrsim 10^4$ GeV, an upper bound for $m_{\tilde{a}}$ is obtained from

$$m_{\tilde{a}} \lesssim 0.526\ \mathrm{GeV} \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^2$$

Constraints on lifetime versus mass for axino DM. The region below the black solid line on the left (right) is excluded by line searches in the Galactic halo by COMPTEL (*Fermi*-LAT). The region below the upper (lower) black dashed line could be probed by e-ASTROGAM with observations of the Galactic center assuming Einasto B (Burkert) DM profile. (KSVZ axion model):

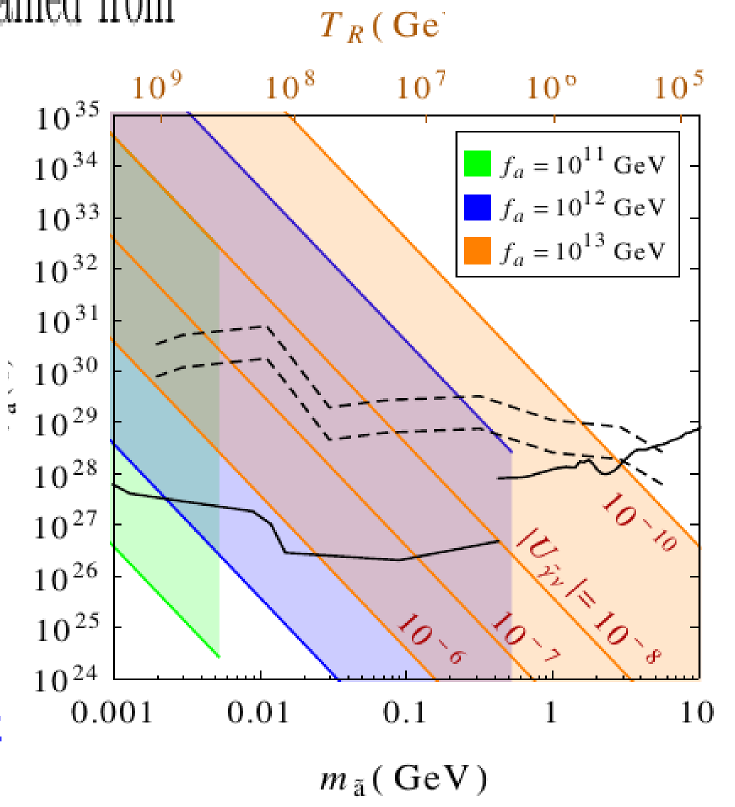


Figure from:

German Gomez-Vargas, D L, Carlos Muñoz, Andres Perez
ArXiv: 1911.03191 (JCAP)

Multiple dark matter candidates

Axino LSP + Gravitino NLSP dark matter

Gravitino LSP + Axino NLSP dark matter

Axino LSP + Gravitino NLSP dark matter

$$10^{-10} \lesssim |U_{\tilde{\gamma}\nu}| \lesssim 10^{-6}$$

Axino LSP

$$\tau_{\tilde{a}} = \Gamma^{-1}(\tilde{a} \to \sum_i \gamma\nu_i) = 3.8 \times 10^{26}\, s \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^2 \left(\frac{10^{-8}}{|U_{\tilde{\gamma}\nu}|}\right)^2 \left(\frac{0.1\,\mathrm{GeV}}{m_{\tilde{a}}}\right)^3$$

Assuming gravitino NLSP

$$\Gamma(\psi_{3/2} \to \tilde{a}\, a) = \frac{m_{3/2}^3}{192\pi M_P^2}(1 - r_{\tilde{a}})^2 (1 - r_{\tilde{a}}^2)^3 \qquad r_{\tilde{a}} \equiv m_{\tilde{a}}/m_{3/2}$$

$$\tau_{3/2} \simeq \Gamma^{-1}(\psi_{3/2} \to a\, \tilde{a}) \simeq 2.3 \times 10^{12} s \left(\frac{10\,\mathrm{GeV}}{m_{3/2}}\right)^3$$

Still we have the decay: $\psi_{3/2} \to \sum_i \gamma\nu_i$ $\qquad \Gamma(\psi_{3/2} \to \sum_i \gamma\nu_i) \simeq \frac{m_{3/2}^3}{64\pi M_P^2}|U_{\tilde{\gamma}\nu}|^2$

Work: **German Gomez-Vargas, D L, Carlos Muñoz, Andres Perez**
ArXiv: 1911.03191 (JCAP)

$$\Omega_{3/2}h^2 \;=\; \Omega_{3/2}^{\rm TP}h^2 e^{-(t_{\rm today}-t_0)/\tau_{3/2}}$$

$$\Omega_{\tilde a}h^2 \;=\; \Omega_{\tilde a}^{\rm TP}h^2 + \Omega_{\tilde a}^{\rm NTP}h^2$$

$$\Omega_{3/2}^{\rm TP}h^2 \simeq 0.02\left(\frac{T_R}{10^5\ {\rm GeV}}\right)\left(\frac{1\ {\rm GeV}}{m_{3/2}}\right)\left(\frac{M_3(T_R)}{3\ {\rm TeV}}\right)^2\left(\frac{\gamma(T_R)/(T_R^6/M_P^2)}{0.4}\right)$$

Here, $M_3(T_R)$ is the running gluino mass, and the last factor parametrizes the effective production rate ranging $\gamma(T_R)/(T_R^6/M_P^2) \simeq 0.4 - 0.35$ for $T_R \simeq 10^4 - 10^6$ GeV

$$\Omega_{\tilde a}^{\rm NTP}h^2 = r_{\tilde a}\,\Omega_{3/2}^{\rm TP}h^2\,\left(1 - e^{-(t_{\rm today}-t_0)/\tau_{3/2}}\right)$$

$$\frac{d\Phi_\gamma^{\rm DM_\mathit{i}}}{dE d\Omega} = f_{\rm DM_\mathit{i}}\frac{d\Phi_\gamma^{100\%\ \rm DM_\mathit{i}}}{dE d\Omega}$$

$$\begin{aligned} f_{3/2}(\tau_{3/2}, t_{\rm today}) &= f_{3/2}\ e^{-(t_{\rm today}-t_0)/\tau_{3/2}}, \\ f_{\tilde a}(\tau_{3/2}, t_{\rm today}) &= f_{\tilde a} + r_{\tilde a}\ f_{3/2}\ \left(1 - e^{-(t_{\rm today}-t_0)/\tau_{3/2}}\right), \end{aligned}$$

$$f_{\rm DM_\mathit{i}} \equiv \frac{\Omega_{\rm DM_\mathit{i}}}{\Omega_{cdm}^{\rm Planck}}.$$

$$f_{\rm DM_\mathit{i}} \rightarrow f_{\rm DM_\mathit{i}}(\tau_{3/2}, t_{\rm today})$$

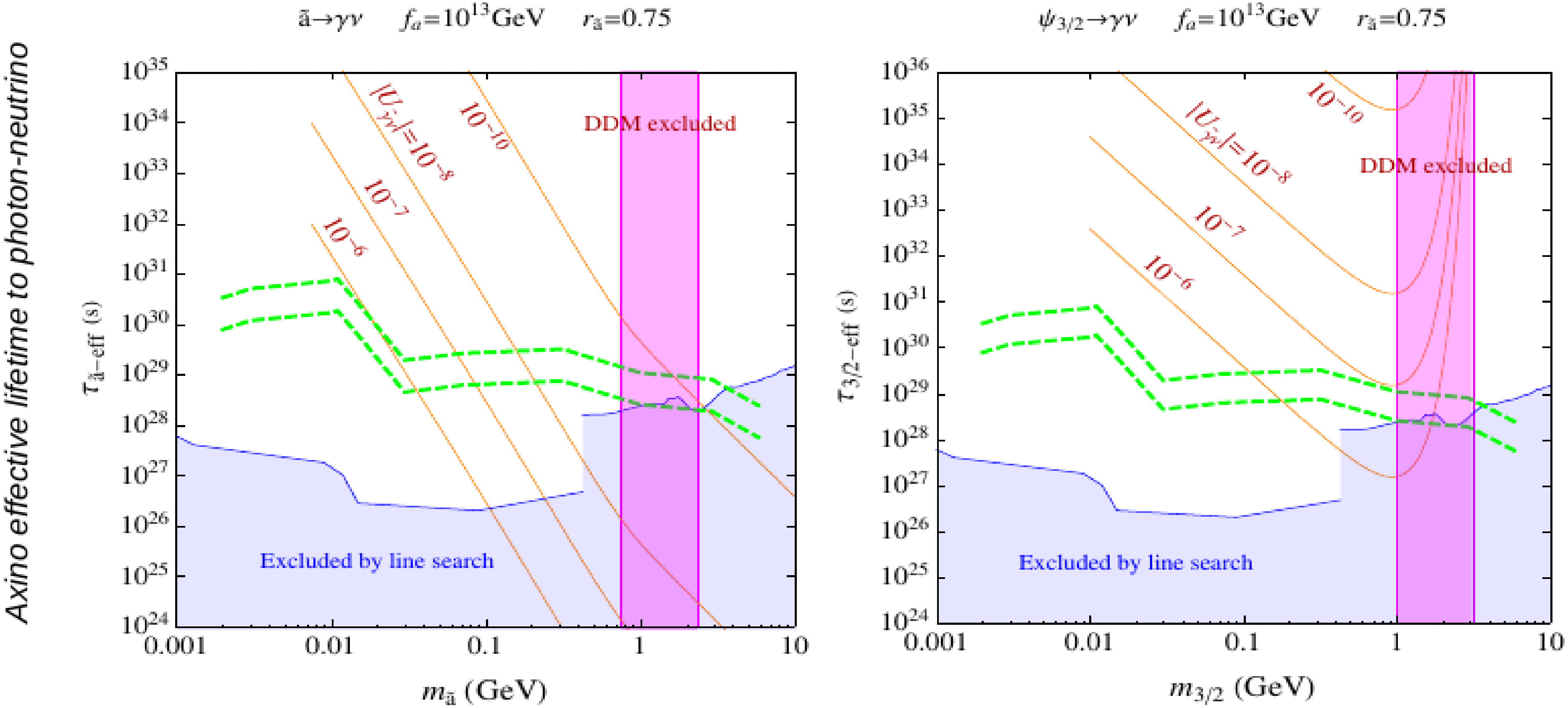
We impose constraints on dark radiation from: Poulin, Serpico, Lesgourgues, arXiv:1606.02073

Obviously, if $\tau_{3/2} \ll t_{today}$, we get the usual relations

$$\begin{aligned} \Omega_{3/2}h^2 &\approx 0, \\ \Omega_{\tilde a}h^2 &\approx \Omega_{\tilde a}^{\rm TP}h^2 + r_{\tilde a}\ \Omega_{3/2}^{\rm TP}h^2. \end{aligned}$$

See for instance:
Covi, Kim, Roszkowski hep-ph/9905212
Baer, Choi, Kim, Roszkowski, arXiv:1407.0017

Axino LSP and Gravitino NLSP effective lifetime



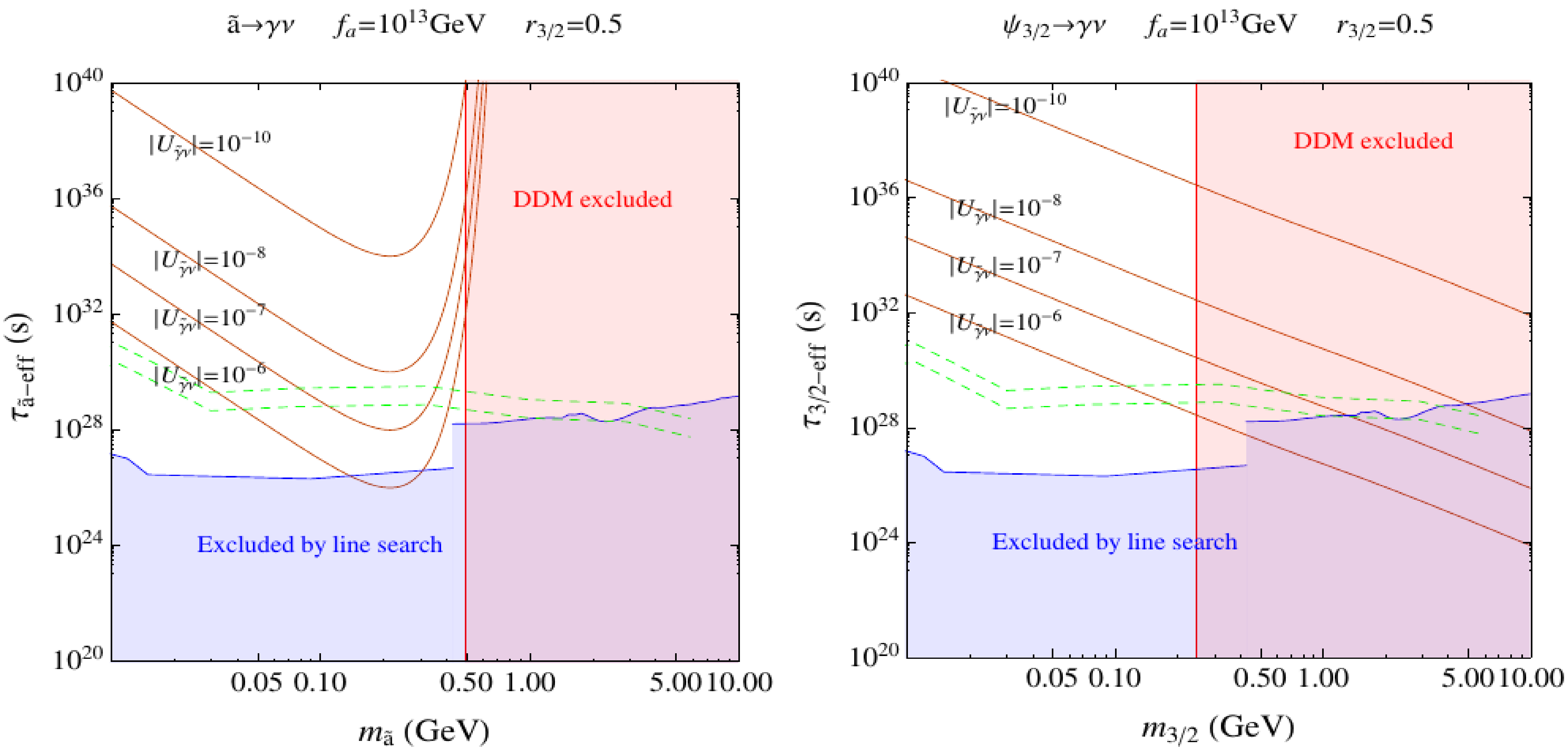
Region between **orange curves** reproduces neutrino data for different values of $|U_{\gamma\nu}|$

Blue region: excluded by γ-ray line searches (e.g. Fermi-LAT)

Red region: excluded by cosmological observations → i.e. constraints to the fraction of NLSP that decays to dark radiation (relativistic species)

Green curves: projected e-ASTROGAM max. sensibility (DM profile dependent)

Gravitino LSP and Axino NLSP effective lifetime



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German Gomez-Vargas, D L, Carlos Muñoz, Andres Perez ArXiv: 1911.08550 (Astropart. Phys.)

Paulina Knees, L-F, Carlos Muñoz ArXiv: 2207.10689

Another interesting possibility: Sterile Neutrino as dark matter candidate

$$\Gamma(\nu_s \to \nu_i \nu \bar{\nu}) = \sum_{j,k} \Gamma(\nu_s \to \nu_i \nu_j \bar{\nu}_k) = \sum_{j,k} \frac{G_F^2 m_{\nu_s}^5}{6\pi^3} \; (O_{si} O_{jk})^2 \, ,$$

where $G_F = \sqrt{2} g^2 / 8 m_W^2$ is the Fermi constant, and

$$O_{pq} = -\frac{1}{2} U_{p6}^V U_{q6}^V + \frac{1}{2} U_{p7}^V U_{q7}^V - \frac{1}{2} \sum_{r=1}^{3} U_{pr}^V U_{qr}^V ,$$

$$\Gamma(\nu_s \to \nu_i \gamma) = \frac{9 G_F^2 \alpha m_{\nu S}^5}{256 \pi^4} \; \left(U_{si}^V\right)^2$$

m_{ν_S} (keV)	κ_2	λ_2	$(U_{si}^V)^2$
7	3.30×10^{-9}	2×10^{-7}	2.54×10^{-11}
8	3.77×10^{-9}	2×10^{-7}	1.95×10^{-11}
9	4.25×10^{-9}	2×10^{-7}	1.54×10^{-11}
10	$\mathbf{4.80 \times 10^{-9}}$	$\mathbf{6 \times 10^{-8}}$	$\mathbf{1.08 \times 10^{-12}}$
11	5.19×10^{-9}	6×10^{-8}	9.73×10^{-13}
12	$\mathbf{5.66 \times 10^{-9}}$	$\mathbf{8 \times 10^{-8}}$	$\mathbf{9.18 \times 10^{-13}}$
13	$\mathbf{6.13 \times 10^{-9}}$	$\mathbf{7 \times 10^{-8}}$	$\mathbf{9.04 \times 10^{-13}}$
14	$\mathbf{6.60 \times 10^{-9}}$	$\mathbf{7 \times 10^{-8}}$	$\mathbf{7.80 \times 10^{-13}}$
15	$\mathbf{7.08 \times 10^{-9}}$	$\mathbf{5 \times 10^{-8}}$	$\mathbf{3.46 \times 10^{-13}}$

Conclusion

- Multicomponent DM scenarios are very interesting
- Constraints from: Cosmological observations, γ-ray experiments and neutrino physics.
- NMSSM + RH
  - Gravitino + RH sneutrino (potentially detectable Neutrino)
- munuSSM
  - gravitino and axino can decay to a photon and a neutrino, giving a potentially detectable γ-ray signal.
  - In some special parameter regions a double line ‘smoking gun’ could be present simultaneously from both candidates.

Thank you

END