Multicomponent Dark Matter signatures in supersymmetric models

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(some) DM candidates in SUSY models

1. Neutralino
2. Right-handed sneutrino
3. Gravitino
4. Axino

In R-parity conserving models, where the Lightest SUSY Particle (LSP) is stable.

And also in some R-parity breaking scenarios!

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And also in some R-parity breaking scenarios!

Usually one considers a single DM candidate...

Can we obtain extra signatures from multiple DM candidates?

(some) DM candidates in SUSY models

Two DM candidates coexisting $\longrightarrow$ **extra signatures**

for example:

RH sneutrino + gravitino $\longrightarrow$ in the NMSSM+RHN (R-parity conserving)

Axino + gravitino $\longrightarrow$ in $\mu\nu$SSM (R-parity breaking)

DM in R-parity conserving models

JCAP 04 (2021) 067
Nucl.Phys.B 974 (2022) 115637
JCAP 04 (2023) 050

DM in R-parity conserving models

NMSSM+RHN (with RH neutrinos)

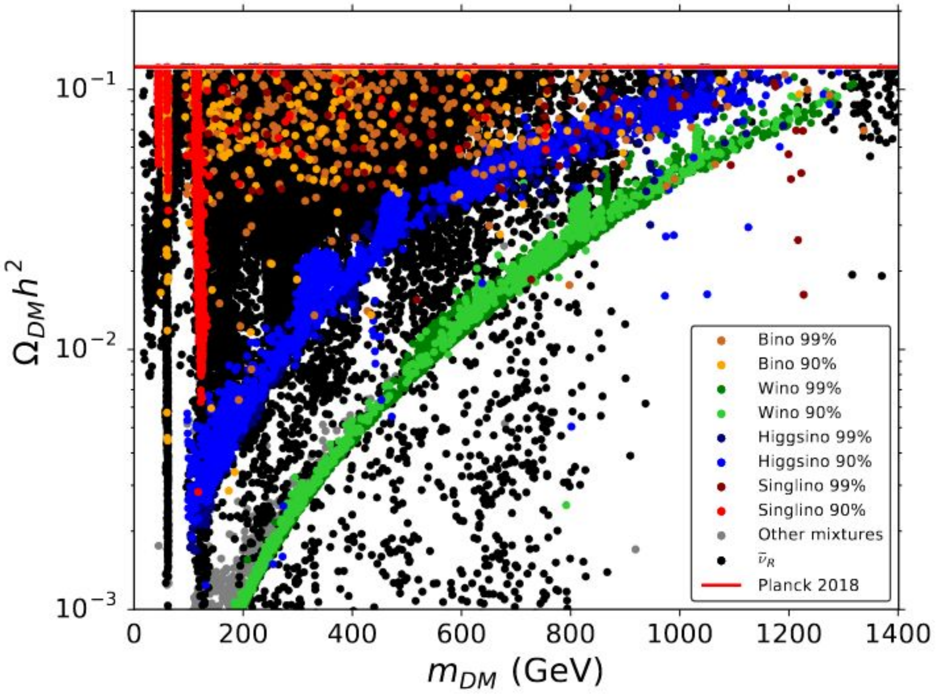
DM candidates:

- Neutralino

or

- Right-handed sneutrino

For both candidates,
WIMP direct, indirect and
collider signatures



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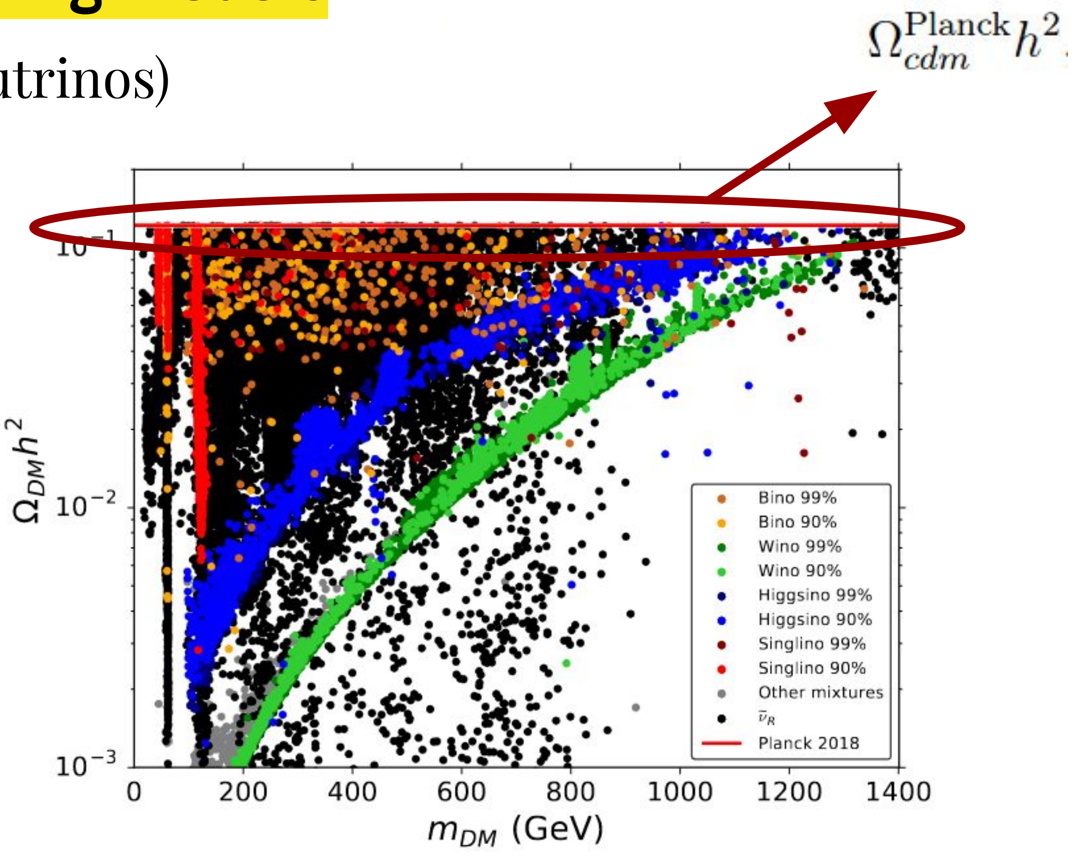


DM in R-parity conserving models

NMSSM+RHN (with RH neutrinos)

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

Gravitino

depends on the
reheating temperature

RH sneutrino

scan of the
parameter space

DM in R-parity conserving models

NMSSM+RHN (with RH neutrinos)

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

Gravitino LSP + **RH sneutrino NLSP**

completely stable

decays to the LSP

↓

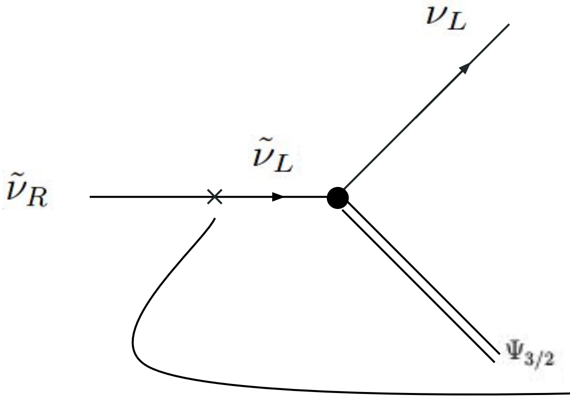
but with a long lifetime>> age of the Universe

↓

without fine-tuning the masses
(as in the neutralino + gravitino case)

DM in R-parity conserving models

RH sneutrino NLSP decay to gravitino LSP



NMSSM+RHN

LH-RH sneutrino mixing parameter $10^{-8} \leq \theta_{\tilde{\nu}} \leq 10^{-6}$

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

DM in R-parity conserving models

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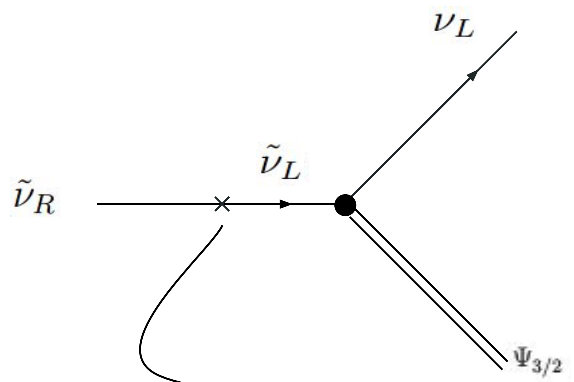

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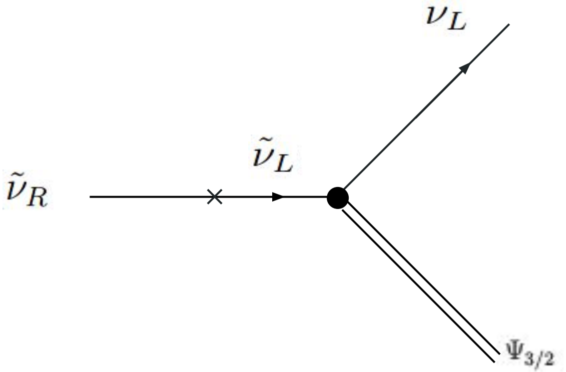
DM in R-parity conserving models

2 DM candidates coexisting

RH sneutrino NLSP decay to gravitino LSP



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

DM in R-parity conserving models

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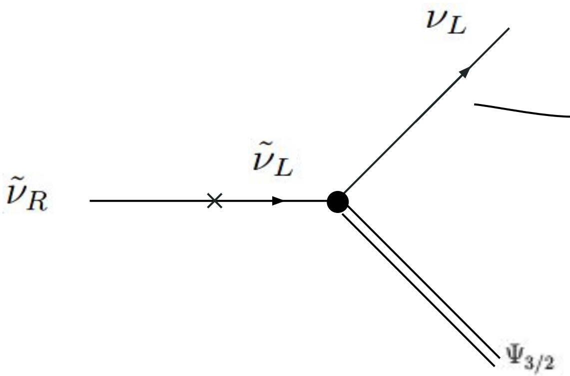

extra neutrino signal (in addition to WIMP signatures & constraints)

NMSSM+RHN

LH-RH sneutrino mixing parameter $10^{-8} \leq \theta_{\tilde{\nu}} \leq 10^{-6}$

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

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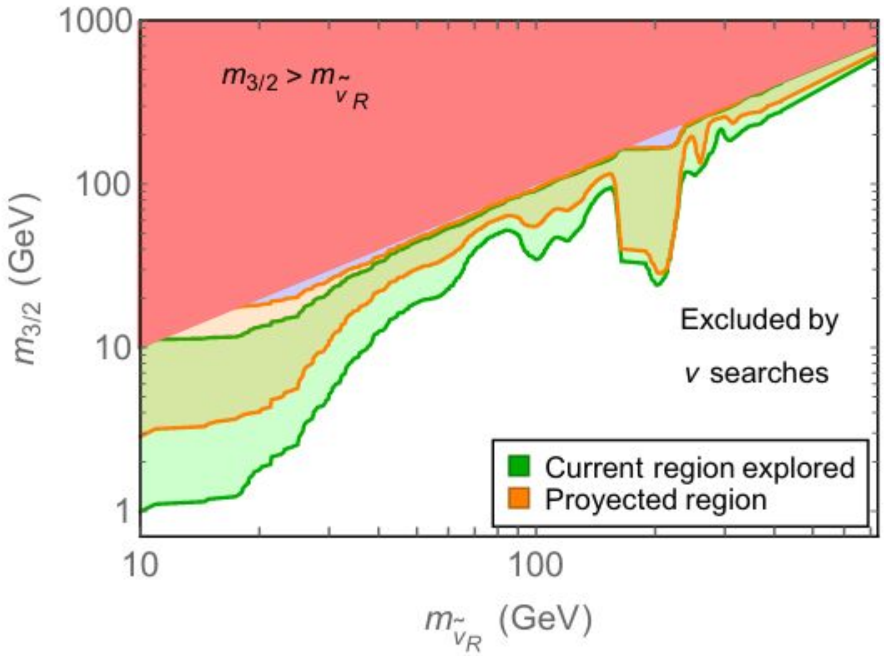
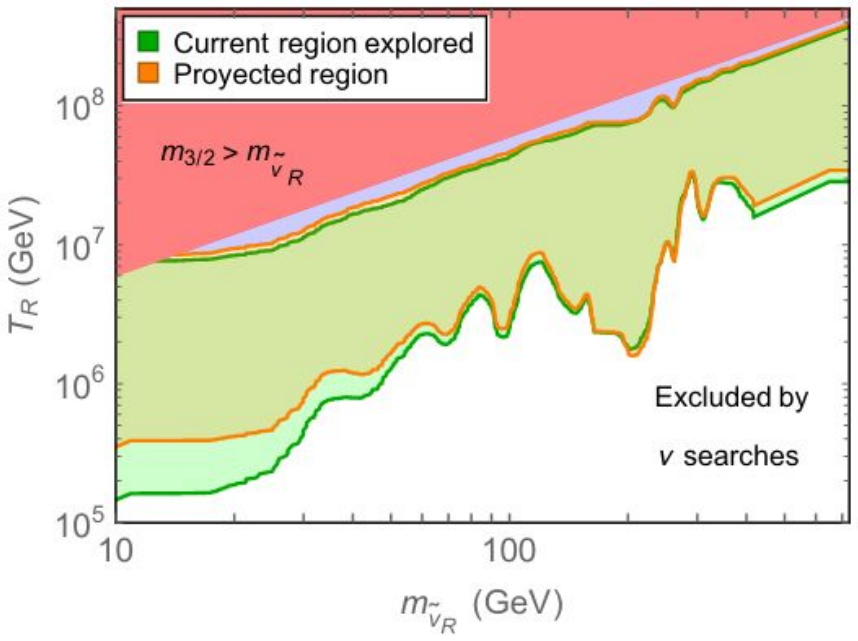
DM in R-parity conserving models

RH sneutrino NLSP and gravitino LSP





DM in R-parity breaking models

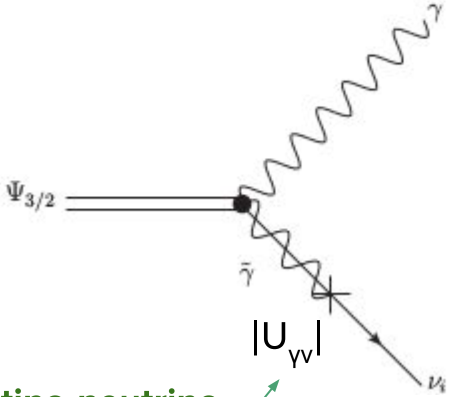
JCAP 03 (2017) 047
JCAP 01 (2020) 058
Astropart.Phys. 125 (2021) 102506

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

photino–neutrino mixing parameter

DM in R-parity breaking models

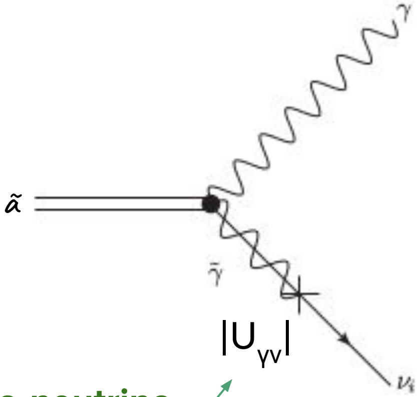
Only gravitino DM



photino-neutrino mixing parameter

$$\Gamma(\psi_{3/2} \to \gamma\nu_i) \simeq \frac{m_{3/2}^3}{32\pi M_P^2} |U_{\tilde{\gamma}\nu}|^2$$

Only axino DM



photino-neutrino mixing parameter

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

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

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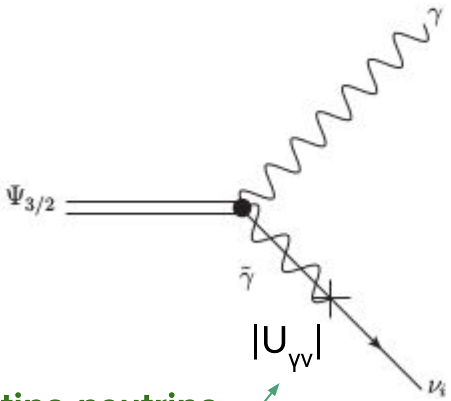

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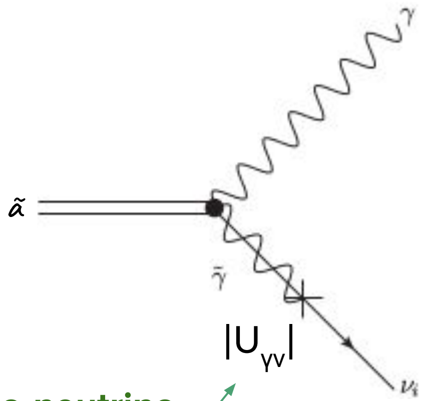
$\mu\nu$SSM

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

$$\Gamma(\psi_{3/2} \to \gamma\nu_i) \simeq \frac{m_{3/2}^3}{32\pi M_P^2}|U_{\tilde{\gamma}\nu}|^2$$

$$\Gamma^{-1}(\psi_{3/2} \to \gamma\nu_i) \simeq 3.8 \times 10^{33}\, s \left(\frac{10^{-8}}{|U_{\tilde{\gamma}\nu}|}\right)^2 \left(\frac{0.1\,\text{GeV}}{m_{3/2}}\right)^3$$

Only axino DM



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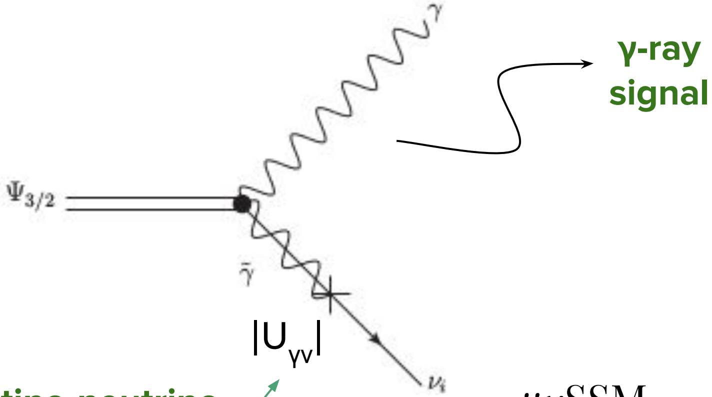
$$|U_{\tilde{\gamma}\nu}|^2 = \sum_{i=1}^{3} |N_{i1}\,\cos\theta_W + N_{i2}\,\sin\theta_W|^2$$

photino-neutrino mixing parameter

DM in R-parity breaking models

Only gravitino DM



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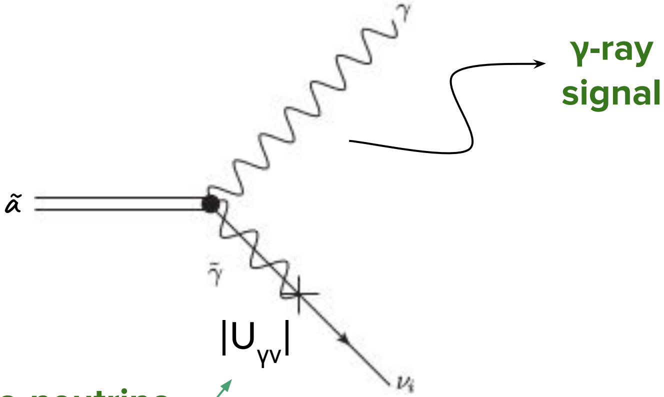

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DM in R-parity breaking models

Gravitino NLSP	+	**Axino LSP**
decays to photons		decays to photons
↓		↓
but with a long lifetime>> age of the Universe		but with a long lifetime>> age of the Universe

DM in R-parity breaking models

Gravitino NLSP + **Axino LSP**

decays to photons

↓

but with a long lifetime>> age of the Universe

decays to photons

↓

but with a long lifetime>> age of the Universe

Gravitino - Axino - axion **interaction**

Is the gravitino stable at cosmological times?

DM in R-parity breaking models

Gravitino NLSP + **Axino LSP**

decays to photons → but with a long lifetime>> age of the Universe

decays to photons → but with a long lifetime>> age of the Universe

Gravitino NLSP ***decays to*** **Axino LSP + axions** → dark radiation

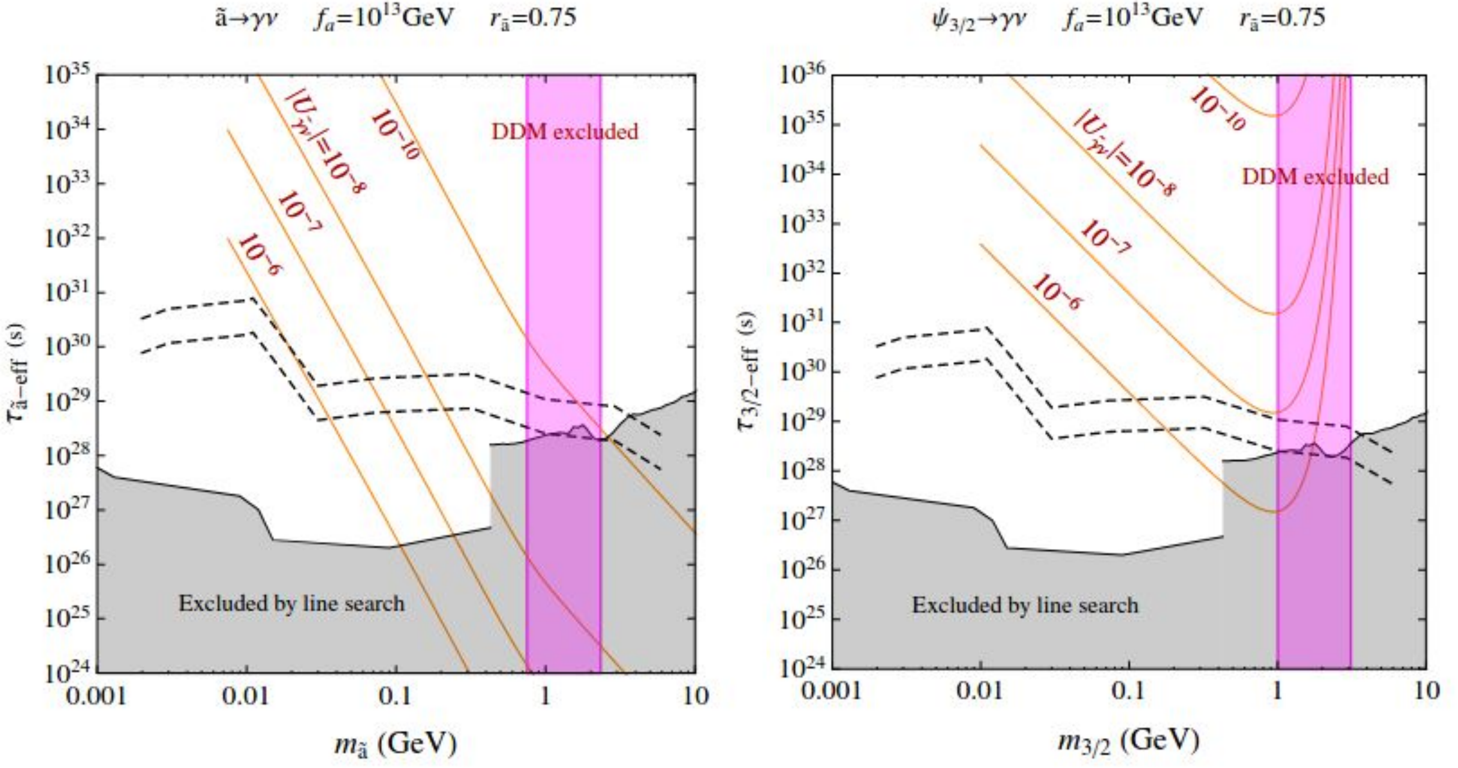
$$\Gamma(\psi_{3/2} \to \tilde{a}\, a) \simeq \frac{m_{3/2}^3}{192\pi M_P^2}(1 - r_{\tilde{a}})^2(1 - r_{\tilde{a}}^2)^3$$

$$\tau_{3/2} \simeq \Gamma^{-1}(\psi_{3/2} \to a\, \tilde{a}) \simeq 2.3 \times 10^{15} s \left(\frac{1\,\mathrm{GeV}}{m_{3/2}}\right)^3$$

$$r_{\tilde{a}} \equiv \frac{m_{\tilde{a}}}{m_{3/2}}$$

DM in R-parity breaking models

2 DM candidates coexisting

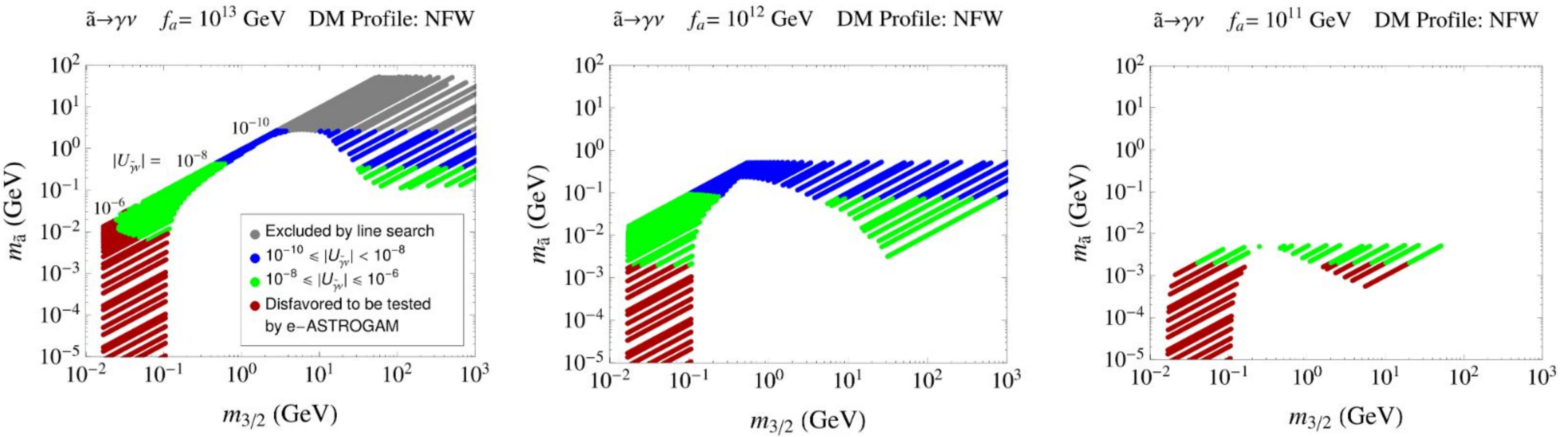


- the heavier particle decays to the other (with long lifetimes)
- axino decay to photons
- gravitino decay to photon

2 signatures

DM in R-parity breaking models

Gravitino NLSP and Axino LSP in the $\mu\nu$SSM



- for all the points gravitino + axino relic density = measured value
- no dark radiation excess (axions)
- can cover several orders of magnitud $10^{-4} < m_a/m_{3/2} < 0.95$

Conclusions

Multicomponent DM scenarios can appear naturally in R-parity conserving and breaking SUSY models

- RH sneutrino + gravitino — in the NMSSM+RHN (R-parity conserving)

  → neutrino line signal in addition to usual WIMP constraints

- Axino + gravitino — in $\mu\nu$SSM (R-parity breaking)

  → two γ-ray lines

Thank you!

Back-up

DM in R-parity conserving models

MSSM+RHN (with RH neutrinos)

$$W = \epsilon_{\alpha\beta}\Big(Y_e^{ij}\,\hat{H}_d^\alpha\,\hat{L}_i^\beta\,\hat{e}_j + Y_d^{ij}\,\hat{H}_d^\alpha\,\hat{Q}_i^\beta\,\hat{d}_j + Y_u^{ij}\,\hat{Q}_i^\alpha\,\hat{H}_u^\beta\,\hat{u}_j + Y_N^{ij}\,\hat{L}_i^\alpha\,\hat{H}_u^\beta\,\hat{N}_j\Big) + \mu\,\hat{H}_u^\alpha\,\hat{H}_d^\beta + \frac{1}{2}M_N^{ij}\,\hat{N}_i\,\hat{N}_j,$$

Next-to-MSSM+RHN (with RH neutrinos)

$$W = \epsilon_{\alpha\beta}\Big(Y_e^{ij}\,\hat{H}_d^\alpha\,\hat{L}_i^\beta\,\hat{e}_j + Y_d^{ij}\,\hat{H}_d^\alpha\,\hat{Q}_i^\beta\,\hat{d}_j + Y_u^{ij}\,\hat{Q}_i^\alpha\,\hat{H}_u^\beta\,\hat{u}_j + Y_N^{ij}\,\hat{L}_i^\alpha\,\hat{H}_u^\beta\,\hat{N}_j + \lambda\,\hat{S}\,\hat{H}_u^\alpha\,\hat{H}_d^\beta\Big) + \lambda_N^{ij}\,\hat{S}\,\hat{N}_i\,\hat{N}_j + \frac{\kappa}{3}\hat{S}\,\hat{S}\,\hat{S},$$

effective μ-term

effective RH neutrino Majorana mass term

when the scalar singlet develops a VEV $\langle s\rangle = \frac{v_s}{\sqrt{2}}.$

DM in R-parity conserving models

MSSM+RHN (with RH neutrinos)

$$W = \epsilon_{\alpha\beta}\left(Y_e^{ij}\,\hat{H}_d^\alpha\,\hat{L}_i^\beta\,\hat{e}_j + Y_d^{ij}\,\hat{H}_d^\alpha\,\hat{Q}_i^\beta\,\hat{d}_j + Y_u^{ij}\,\hat{Q}_i^\alpha\,\hat{H}_u^\beta\,\hat{u}_j + Y_N^{ij}\,\hat{L}_i^\alpha\,\hat{H}_u^\beta\,\hat{N}_j\right)$$
$$+ \mu\,\hat{H}_u^\alpha\,\hat{H}_d^\beta + \frac{1}{2}M_N^{ij}\,\hat{N}_i\,\hat{N}_j,$$

Neutrino masses:

Dirac mass term

$$m_D \simeq Y_N\,v_u = Y_N\,v\,\sin\beta$$

$$Y_N\,\sin\beta \sim 10^{-13}\left(\frac{m_{\nu_L}^2}{2.8\times10^{-3}\mathrm{eV}^2}\right)$$

$$Y_N \sim 10^{-13}.$$

DM in R-parity conserving models

Next-to-MSSM+RHN (with RH neutrinos)

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$$+ \lambda\,\hat{S}\,\hat{H}_u^\alpha\,\hat{H}_d^\beta\Big) + \lambda_N^{ij}\,\hat{S}\,\hat{N}_i\,\hat{N}_j + \frac{\kappa}{3}\,\hat{S}\,\hat{S}\,\hat{S},$$

effective μ-term

effective RH neutrino Majorana mass term

when the scalar singlet develops a VEV $\langle s\rangle = \frac{v_s}{\sqrt{2}}.$

$$\mu_{eff} = \frac{\lambda v_s}{\sqrt{2}},\ v_s = O(\text{GeV-TeV}) \qquad M_N^i = \frac{\lambda_N^i v_s}{\sqrt{2}} \sim O(\text{GeV-TeV})$$

$$\lambda \text{ and } \lambda_N^i \quad O(0.1-1)$$

DM in R-parity conserving models

Next-to-MSSM+RHN (with RH neutrinos)

$$W = \epsilon_{\alpha\beta}\Big(Y_e^{ij}\,\hat{H}_d^\alpha\,\hat{L}_i^\beta\,\hat{e}_j + Y_d^{ij}\,\hat{H}_d^\alpha\,\hat{Q}_i^\beta\,\hat{d}_j + Y_u^{ij}\,\hat{Q}_i^\alpha\,\hat{H}_u^\beta\,\hat{u}_j + Y_N^{ij}\,\hat{L}_i^\alpha\,\hat{H}_u^\beta\,\hat{N}_j$$

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Neutrino masses:

See-saw mechanism

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

$$m_{\nu_L} \simeq -m_D\,M_N^{-1}\,m_D^T$$

$$m_{\nu_L} \simeq \frac{Y_N^2\,v_u^2}{\lambda_N\,v_s} \sim Y_N^2 \times \mathrm{EW\ scale}$$

$$Y_N \sim 10^{-6}$$

DM in R-parity conserving models

Sneutrino sector:

$$M^2_{\tilde{\nu}} = \begin{pmatrix} m^2_{\mathbb{RR}} & 0_{6\times 6} \\ 0_{6\times 6} & m^2_{\mathbb{II}} \end{pmatrix}$$

$$M^2_{\mathbb{RR}} = \begin{pmatrix} m^2_{L_i} & A_i^+ \\ (A_i^+)^T & m^2_{R_i} + B_i \end{pmatrix}, \quad M^2_{\mathbb{II}} = \begin{pmatrix} m^2_{L_i} & A_i^- \\ (A_i^-)^T & m^2_{R_i} - B_i \end{pmatrix}$$

		MSSM+RHN	NMSSM+RHN
A_i^+	$=$	$Y_N^i\,(A_N^i\,v_u + M_N^i\,v_u - \mu\,v_d)\,,$	$Y_N^i\,(A_N^i\,v_u + 2\,\lambda_N^i\,v_u\,v_s - \lambda\,v_d\,v_s)\,,$
A_i^-	$=$	$Y_N^i\,(A_N^i\,v_u - M_N^i\,v_u - \mu\,v_d)\,,$	$Y_N^i\,(A_N^i\,v_u - 2\,\lambda_N^i\,v_u\,v_s - \lambda\,v_d\,v_s)\,,$
B_i	$=$	$-b_N^i\,M_N^i,$	$2\,\lambda_N^i\,\left(A_{\lambda_N}^i\,v_s + \kappa\,v_s^2 - \lambda\,v_u\,v_d\right),$
$m^2_{L_i}$	$=$	$m^2_{\tilde{L}_i} + (Y_N^i)^2\,v_u^2 + \frac{1}{2}\,m_Z^2\,\cos 2\beta,$	$m^2_{\tilde{L}_i} + (Y_N^i)^2\,v_u^2 + \frac{1}{2}\,m_Z^2\,\cos 2\beta,$
$m^2_{R_i}$	$=$	$m^2_{\tilde{N}_i} + (Y_N^i)^2\,v_u^2 + (M_N^i)^2,$	$m^2_{\tilde{N}_i} + (Y_N^i)^2\,v_u^2 + 4\,(\lambda_N^i)^2\,v_s^2,$

DM in R-parity conserving models

Sneutrino sector:

$$m^2_{\tilde{\nu}_{L_i}} \simeq m^2_{\tilde{L}_i} + \frac{1}{2} m^2_Z \cos 2\beta, \qquad m^2_{\tilde{\nu}_{R_i}} \simeq m^2_{R_i} \pm B_i$$

MSSM+RHN $\quad m^2_{\tilde{\nu}_{R_i}} \sim m^2_{\tilde{N}_i} + (M^i_N)^2 \mp (b^i_N M^i_N),$

NMSSM+RHN $\quad m^2_{\tilde{\nu}_{R_i}} \sim m^2_{\tilde{N}_i} + (2\,\lambda^i_N\, v_s)^2 \pm \lambda^i_N\,\left(2\,A^i_{\lambda_N}\, v_s + 2\,\kappa\, v_s^2\right)$

DM in R-parity conserving models

LH-RH sneutrino mixing:

$$\tan 2\theta_{\tilde{\nu}} \;\simeq\; \frac{2\,A^{\pm}}{m_L^2 \,-\, (m_R^2 \,\pm\, B)}$$

MSSM+RHN

$$T_N \,=\, A_N Y_N \,\sim\, O(\mathrm{EW})$$

$$\tan 2\theta_{\tilde{\nu}} \simeq \frac{2\,T_N\,v_u}{m_{\tilde{\nu}_L}^2 \,-\, m_{\tilde{\nu}_R}^2} \sim O(0.01-1)$$

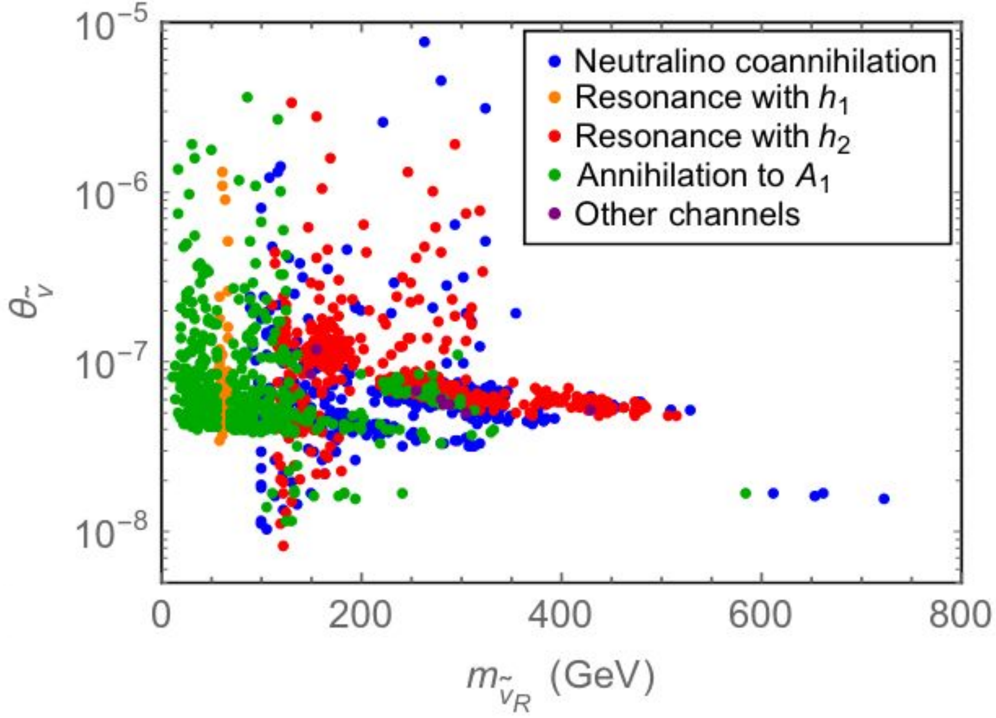
NMSSM+RHN

$$\tan 2\theta_{\tilde{\nu}} \simeq \frac{2\,Y_N\,(\,A_N\,v_u \,\pm\, 2\,\lambda_N\,v_u\,v_s \,-\, \lambda\,v_d\,v_s\,)}{m_{\tilde{L}}^2 \,+\, \frac{1}{2}\,m_Z^2\,\cos 2\beta \,-\, m_{\tilde{N}}^2 \,-\, 4\,\lambda_N^2\,v_s^2 \,\mp\, 2\,\lambda_N\,(\,A_{\lambda_N}\,v_s \,+\, \kappa\,v_s^2 \,-\, \lambda\,v_u\,v_d\,)}$$

$$\sim \frac{Y_N\,\lambda_N\,v_s\,v_u}{m_{\tilde{L}}^2 \,+\, \frac{1}{2}\,m_Z^2\,\cos 2\beta \,-\, m_{\tilde{N}}^2 \,-\, \lambda_N^2\,v_s^2} \sim 10^{-2} \times Y_N \sim O(10^{-8})$$

DM in R-parity conserving models

LH-RH sneutrino mixing:



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

DM in R-parity conserving models

Relic density:

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

scan of the parameter space

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

reheating temperature

gluino mass (from the scan)

function of T_R

DM in R-parity conserving models

Neutrino signal from NLSP to LSP decay:

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

relic density fraction of the decaying DM

lifetime of the decaying DM

$$r_{\tilde\nu_R} = \frac{\Omega_{\tilde\nu_R}}{\Omega_{cdm}^{\rm Planck}}$$

Effective lifetime

$$\tau_{\tilde\nu_R\text{-eff}} = \frac{\Gamma^{-1}(\tilde\nu_R \to \Psi_{3/2}\,\nu_L)}{r_{\tilde\nu_R}}$$

Energy of the neutrino line

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

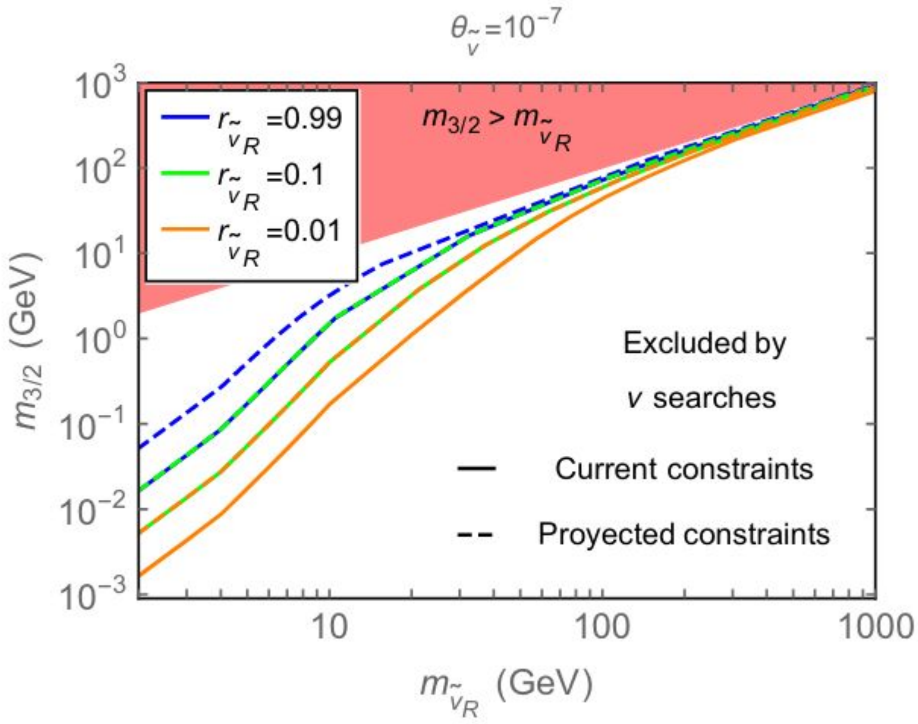
DM in R-parity conserving models

Gravitino and RH sneutrino DM

Exclusion limits fixing:

- the LH-RH sneutrino mixing angle

- the RH sneutrino relic density fraction



DM in R-parity conserving models

Neutralino + gravitino

photino fraction of the neutralino

$$\Gamma(\chi \to \gamma \tilde{G}) = \frac{|N_{11}\cos\theta_W + N_{12}\sin\theta_W|^2}{48\pi M_*^2} \frac{m_\chi^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_\chi^2}\right]^3 \left[1 + 3\frac{m_{\tilde{G}}^2}{m_\chi^2}\right]$$

$$\tau = \frac{1.78 \times 10^{13}\ sec}{|N_{11}\cos\theta_W + N_{12}\sin\theta_W|^2} \left(\frac{GeV}{\Delta m}\right)^3$$

Neutralino + axino

$$\Gamma(\tilde{a} \to \chi_i + \gamma) = \frac{\alpha_{em}^2 C_{a\chi_i\gamma}^2}{128\pi^3} \frac{m_{\tilde{a}}^3}{f_a^2} \left(1 - \frac{m_{\chi_i}^2}{m_{\tilde{a}}^2}\right)^3$$

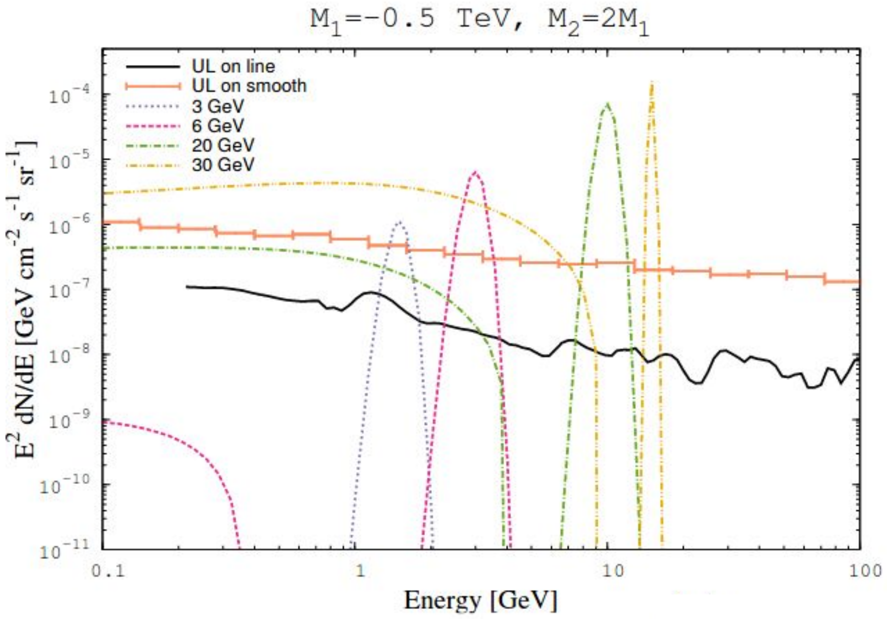
$$C_{a\chi_i\gamma} = (C_{aYY}/\cos\theta_W) Z_{\chi_i B}$$

bino fraction of the i-th neutralino

DM in R-parity breaking models

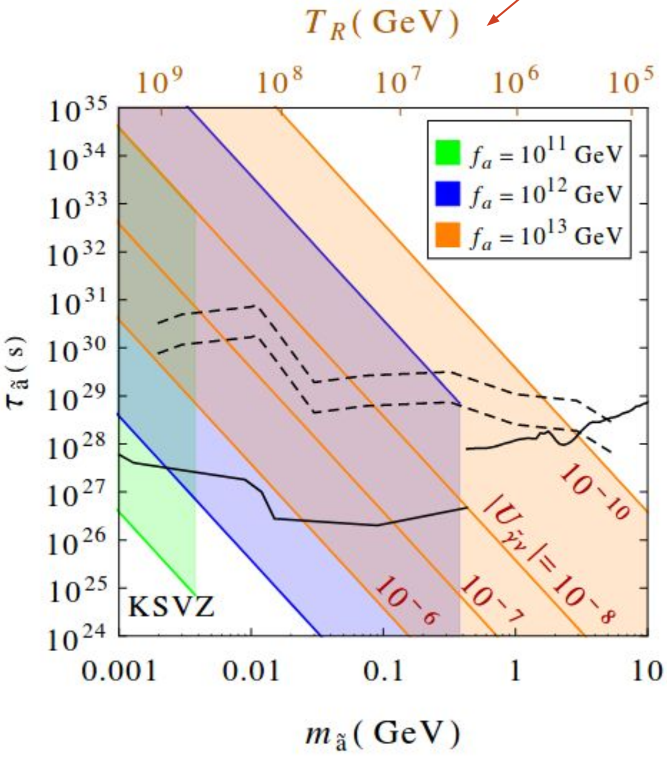
Reheating temperature to obtain axino DM abundance = measured value

Gravitino DM



gravitino γ-ray spectra

Axino DM



$$r_{\tilde{a}} \equiv \frac{m_{\tilde{a}}}{m_{3/2}}$$

DM in R-parity breaking models

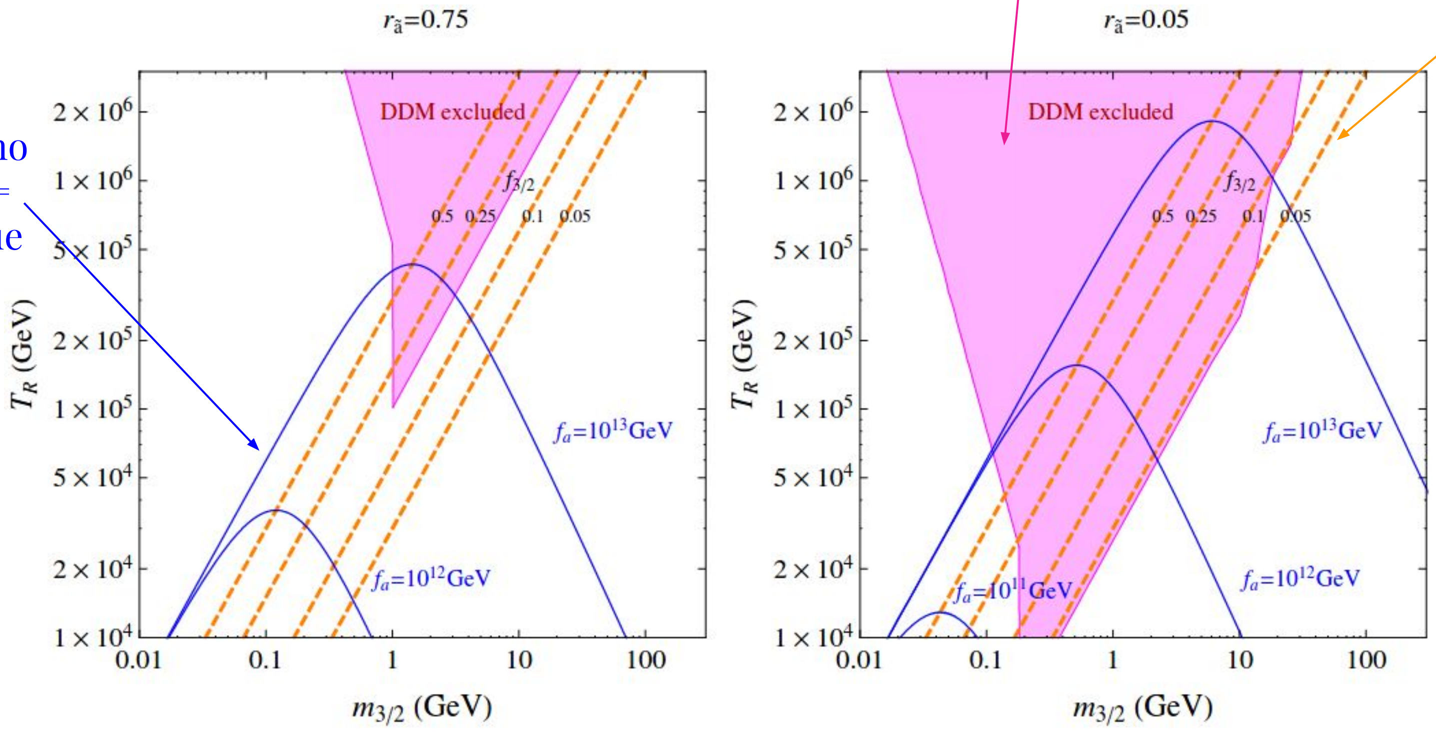
Gravitino and Axino DM (axino LSP)

too much 'dark radiation'

gravitino DM abundance fraction

gravitno + axino relic density = measured value

(above this line, DM over production)



DM in R-parity breaking models

Axino relic density

$$\Omega_{\tilde{a}}^{\rm TP} h^2 \simeq 0.3\ (g_3(T_R))^4 \left(\frac{F(g_3(T_R))}{23}\right)\left(\frac{m_{\tilde{a}}}{1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right)\left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)^2$$

Axion relic density

$$\Omega_a h^2 \simeq 0.18\ \theta_i^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19}$$

$$\frac{\Gamma(\tilde{a} \to \gamma \nu_i)}{\Gamma(\psi_{3/2} \to \gamma \nu_i)} \simeq 10^5 \left(\frac{10^{13}\,\mathrm{GeV}}{f_a}\right)^2 r_{\tilde{a}}^3$$

DM in R-parity breaking models

Axino relic density (TP)

$$\Omega_{\tilde{a}}^{\rm TP} h^2 \simeq 0.3\,(g_3(T_R))^4 \left(\frac{F(g_3(T_R))}{23}\right)\left(\frac{m_{\tilde{a}}}{1\ \rm GeV}\right)\left(\frac{T_R}{10^4\ \rm GeV}\right)\left(\frac{10^{12}\ \rm GeV}{f_a}\right)^2$$

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

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

$$\begin{aligned} \Omega_{3/2} h^2 &\approx 0, \\ \Omega_{\tilde{a}} h^2 &\approx \Omega_{\tilde{a}}^{\rm TP} h^2 + r_{\tilde{a}}\ \Omega_{3/2}^{\rm TP} h^2 \end{aligned} \qquad \text{if}\ \ \tau_{3/2} \ll t_{today}$$