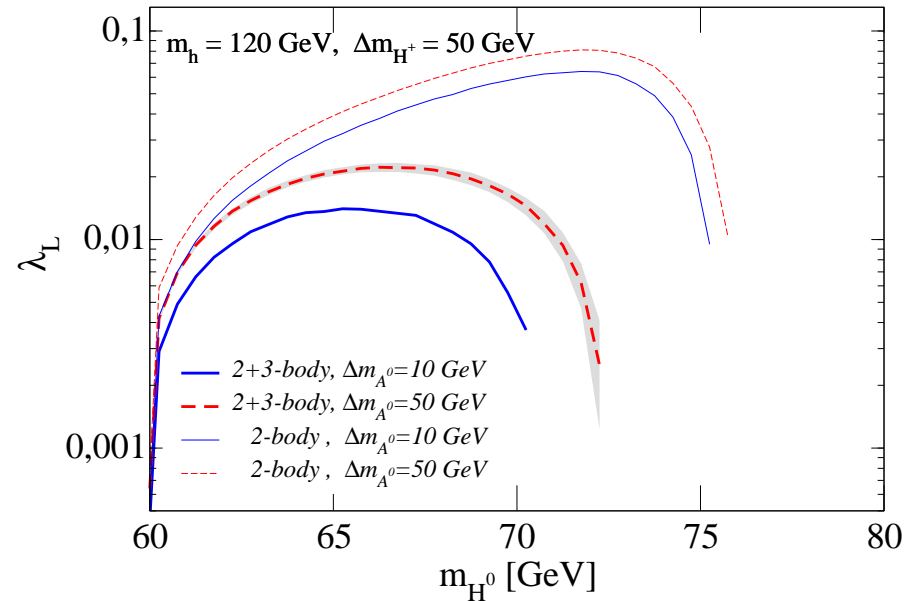
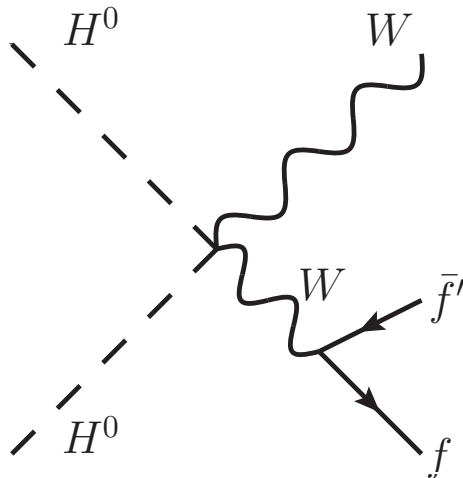


Three-body final states in dark matter annihilations and decays



Based on arXivs:1003.2730 PRD,
1003.3125 (with Laura Lopez),
1003.3401 (with Ki-Young Choi),
and work in progress

Carlos E. Yaguna
UAM and IFT
2010

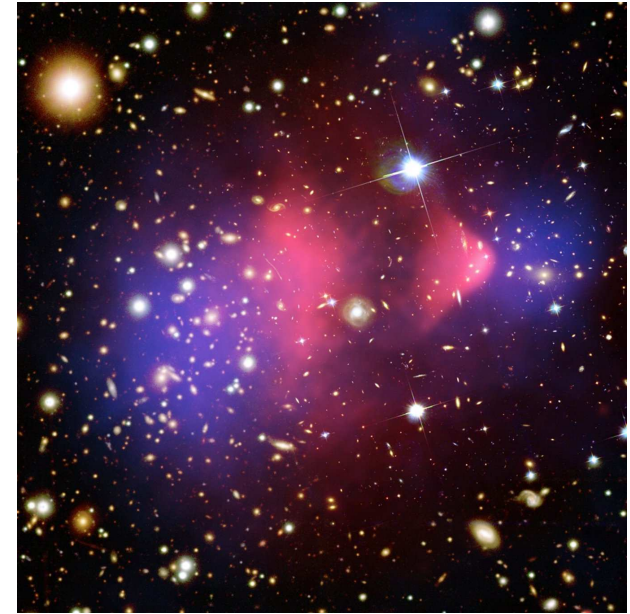
Dark matter constitutes a significant fraction of the energy-density of the Universe

The evidence in favor of DM is overwhelming

Rotation curves

The Bullet Cluster

Gravitational Lensing



The DM density is obtained from CMB data

$$0.097 < \Omega h^2 < 0.122$$

The existence of dark matter is a clear indication of physics beyond the Standard Model

DM candidates should be neutral and stable

Neutrinos?

Neutrinos cannot explain the dark matter

$$\Omega_\nu \ll \Omega_{dm}$$

ν 's are not cold

The SM contains no dark matter candidates

New Physics !

Over the years several dark matter candidates have been considered in the literature

It is not yet known what the DM is

?

SUSY models are the most common scenarios

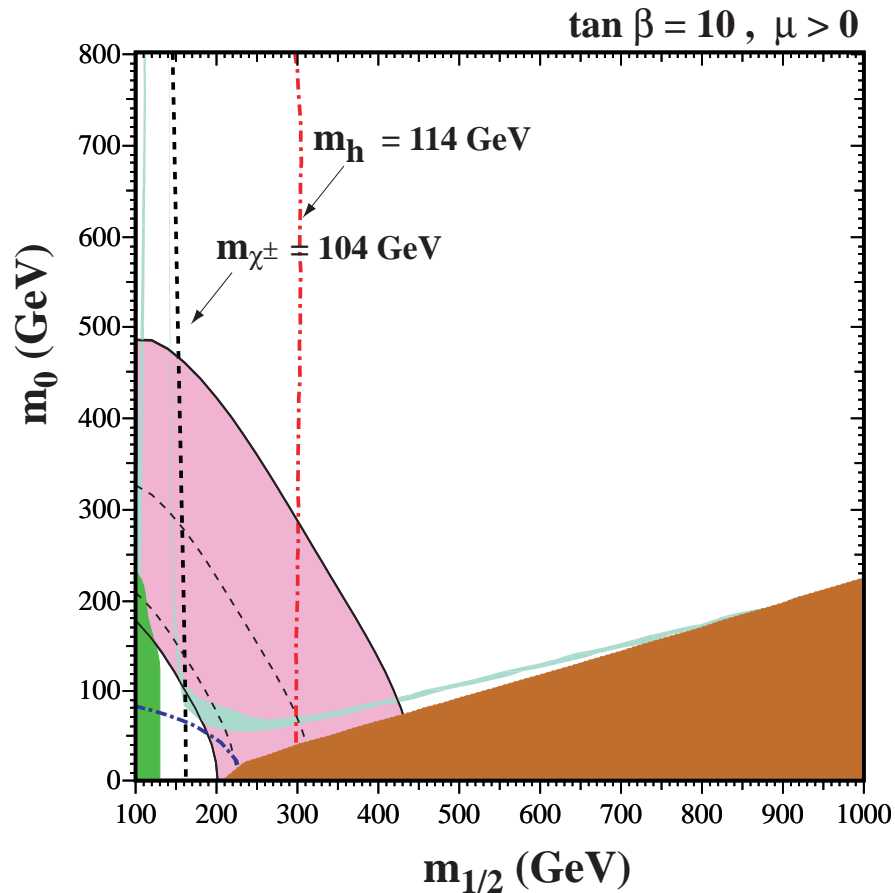
**Neutralino
Gravitino**

Non-SUSY candidates are also interesting

**Singlet scalar
Inert higgs**

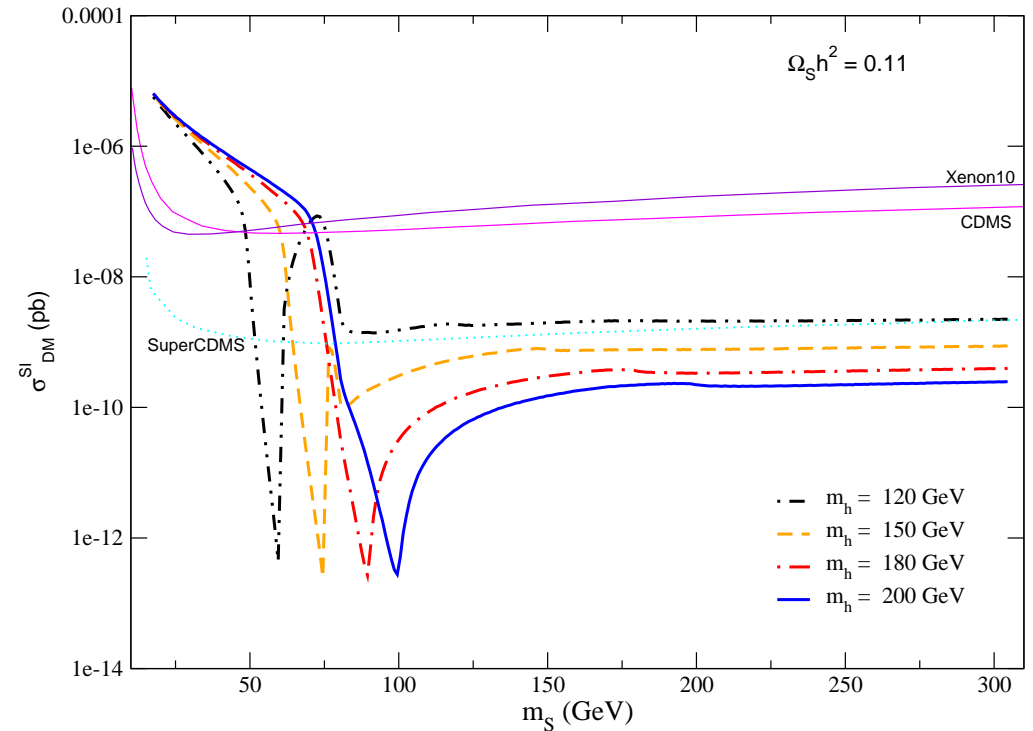
The study of dark matter models involves two main steps

Viability



Ωh^2 , accelerator and precision bounds

Testability



Direct and indirect detection and accelerator searches

The annihilation rate of dark matter particles plays a crucial role in dark matter studies

It affects the prediction of the dm density

$$\dot{n} + 3Hn = -\langle\sigma v\rangle (n^2 - n_{eq}^2)$$

It modifies the viable parameter space

Dark matter constraint

It alters the dark matter detection signals

All of them

Indirect detection $\propto \sigma v$

Up to now most studies have only consider dm annihilations into two-body final states

They are all included in the calculation of Ω

$\chi_i \chi_j \rightarrow 2\text{-bodies}$
at tree-level

Sophisticated software is available

DarkSUSY, micrOMEGAs

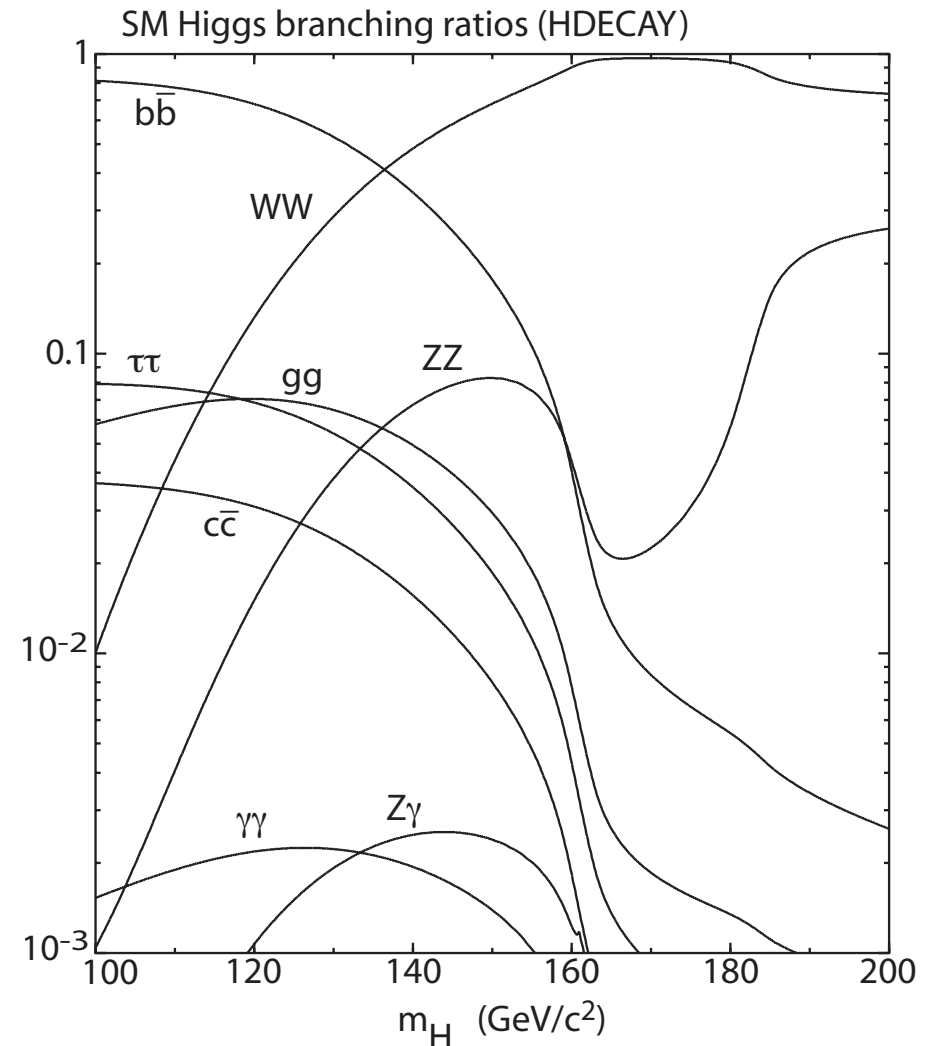
Could there be other relevant processes?

Particle physics processes can be dominated by 3-body final states

Even if 2-body final states are open

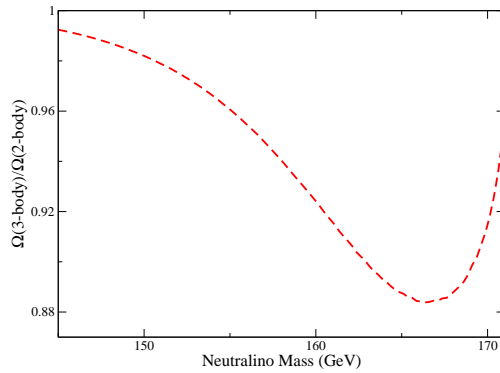
Higgs decays in the SM are a good example

Can dm particles annihilate into WW^* or $t\bar{t}^*$?

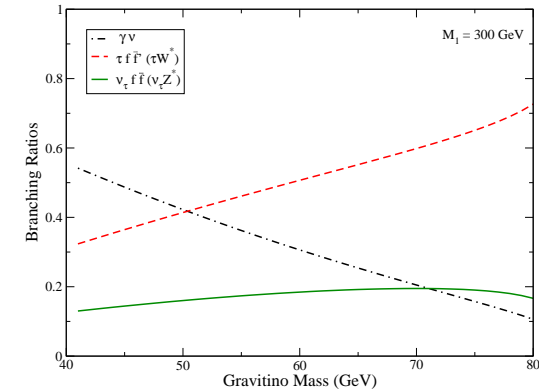


3-body final states will be shown to be relevant in well-known models of dark matter

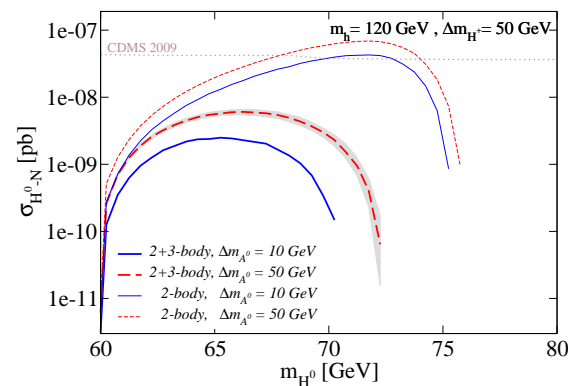
1. Neutralinos in the MSSM



2. Gravitinos in R_p SUSY



3. Inert doublet model

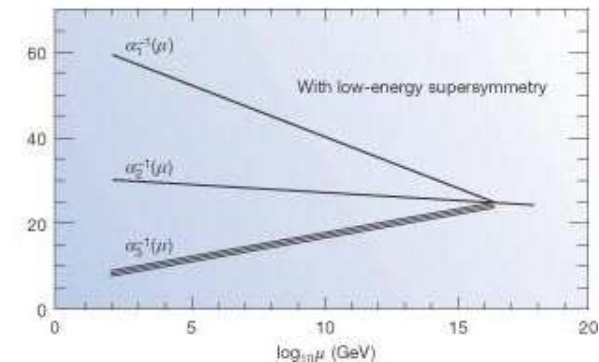
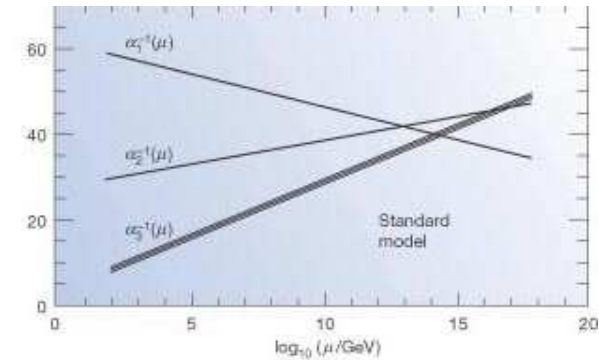


Low energy supersymmetry is one of the best motivated extensions of the standard model

Gauge couplings unify in the MSSM

The lightest susy particle is stable: R_p

The neutralino is a viable dark matter candidate



$$\chi_1 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_d^0 + N_{14}\tilde{H}_u^0$$

For neutralino dark matter, the most relevant 3-body final state is $t\bar{t}^*$

These effects are present if $m_\chi < m_t$

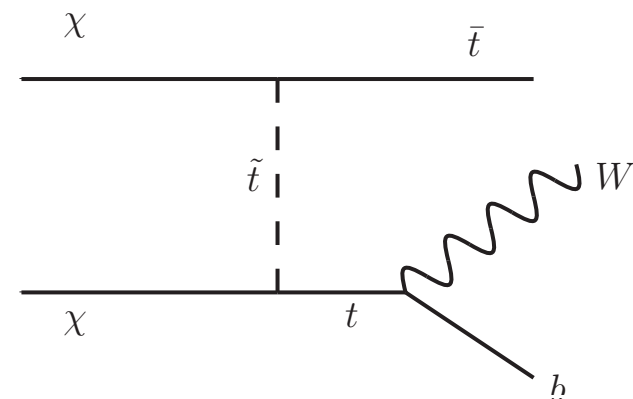
$$\chi\chi \not\rightarrow WW, ZZ$$

$$\chi\chi \rightarrow f\bar{f}$$

The dominant 2-body final state is $b\bar{b}$

$$\sigma v(\chi\chi \rightarrow f\bar{f}) \propto m_f^2$$

$\chi\chi \rightarrow t\bar{t}^* \rightarrow tW\bar{b}$ can also be sizable

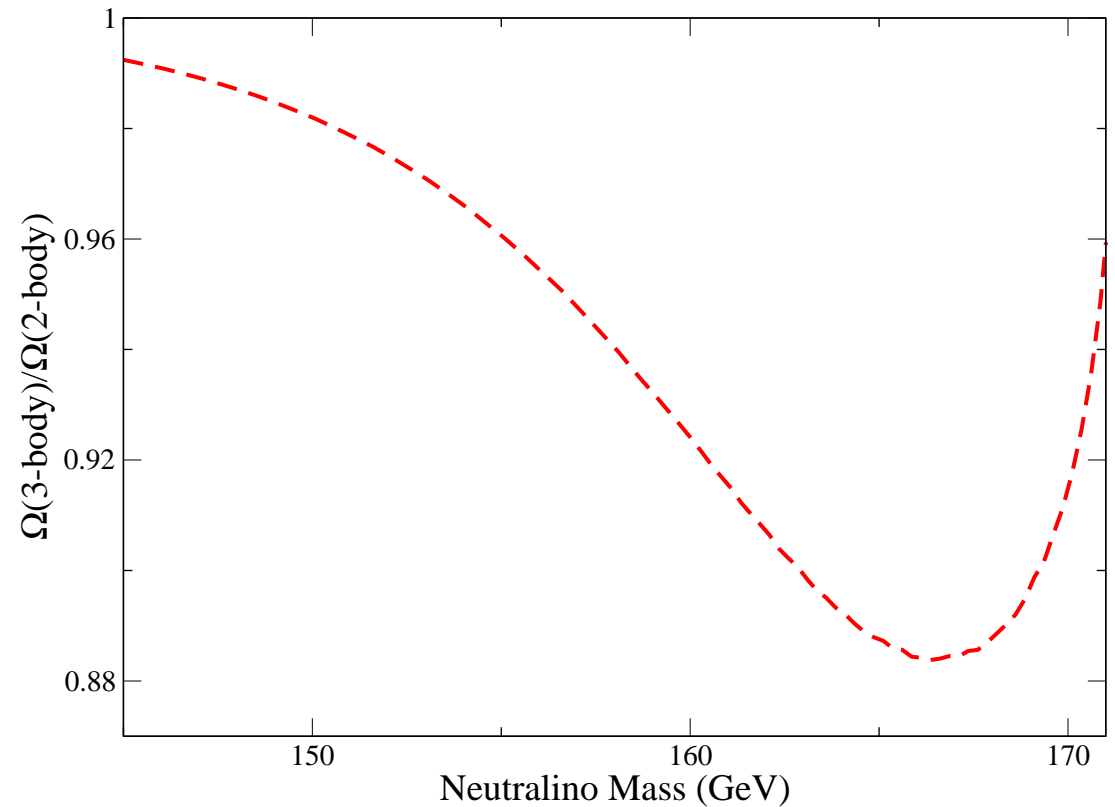


The χ relic density is smaller than that obtained for 2-body final states only

The effect in Ω is largest few GeVs below m_t

It could be more than 10% smaller

DarkSUSY claims a 1% accuracy in Ω

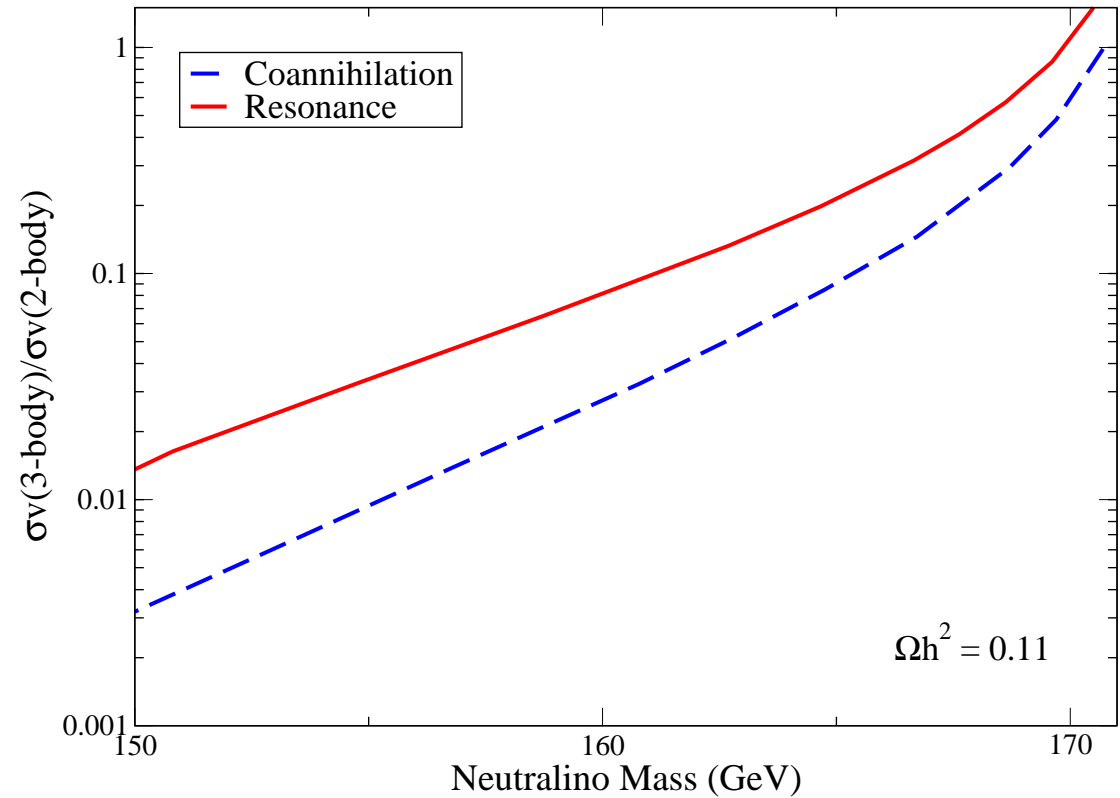


The 3-body neutralino annihilation cross section can be larger than the 2-body one

Close to m_t , σv is about twice as large

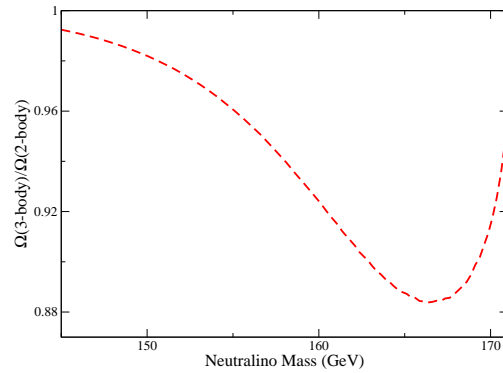
The χ indirect detection signals will be affected

Large 3-body effects are not generic in the MSSM

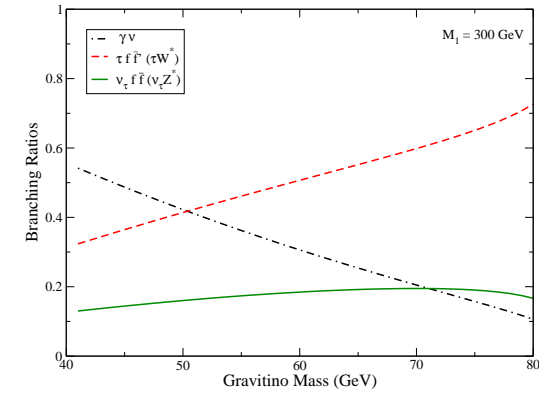


3-body final states will be shown to be relevant in well-known models of dark matter

1. Neutralinos in the MSSM

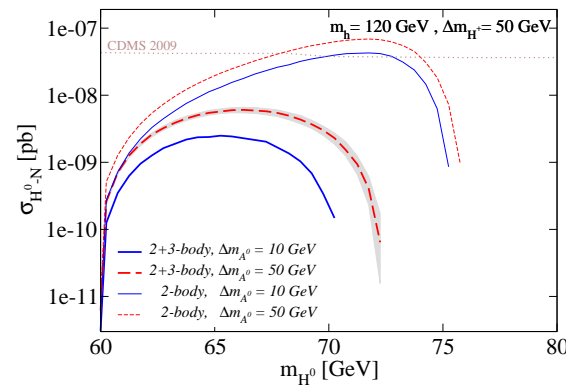


2. Gravitinos in R_p SUSY



arXiv:1003.3401, with Ki-Young Choi

3. Inert doublet model



In susy models with broken R-parity the gravitino is the only viable dm candidate

The LSP becomes unstable

If \tilde{G} is the LSP, it is a dm candidate

We consider bilinear
 $\mathcal{R}_p : \langle \tilde{\nu} \rangle \neq 0$

Neutralino is not a viable dm candidate

\tilde{G} lifetime \gg age of the Universe

Buchmuller, Covi, Ibarra, Moroi, Muñoz, etc

The dominant 2-body decay modes of the gravitino are $\gamma\nu$ and $W\ell$

\tilde{G} decays are determined by $M_i, m_{\tilde{G}}, \langle \tilde{\nu} \rangle$

For $m_{\tilde{G}} < M_W$, $\gamma\nu$ is the only possible 2-body fs

The final states $W^*\ell$ and $Z^*\nu$ may be important

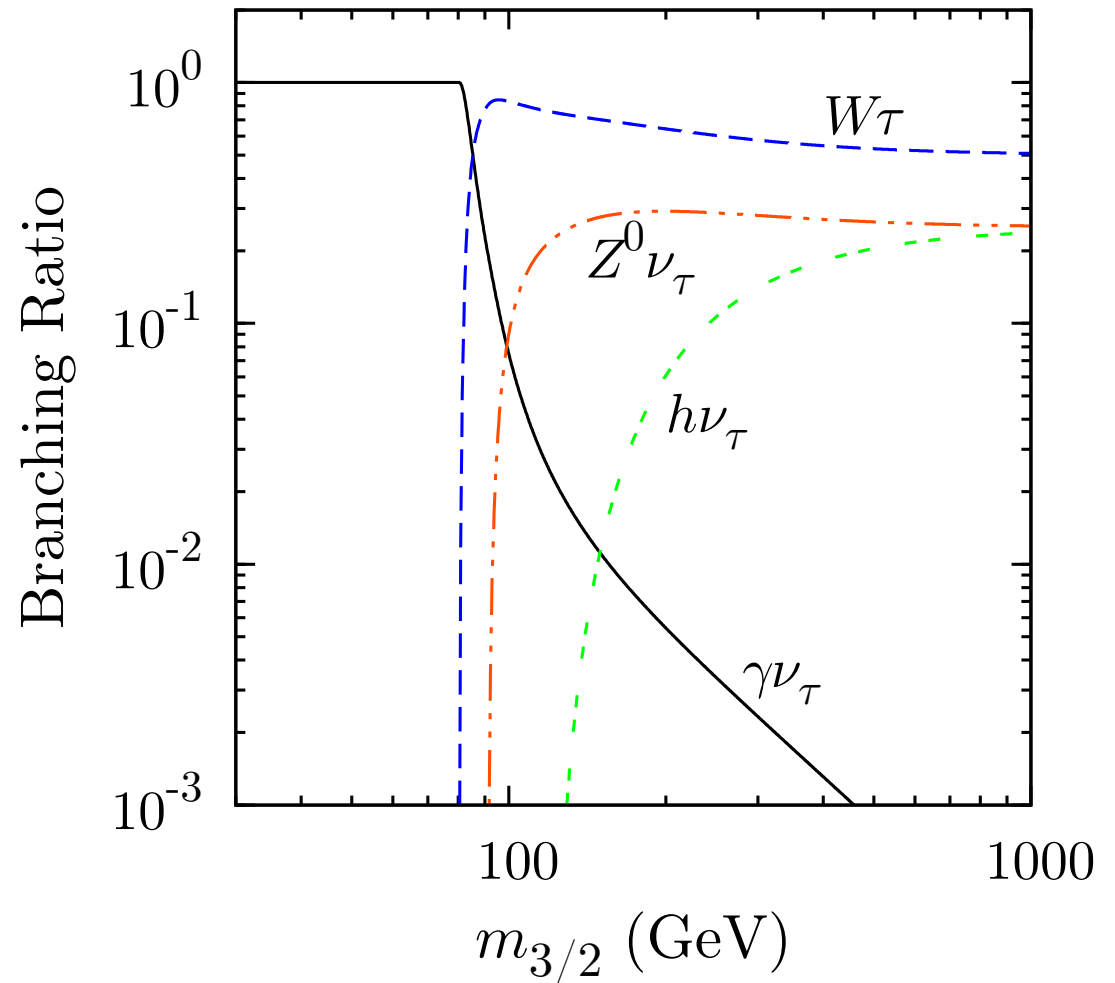


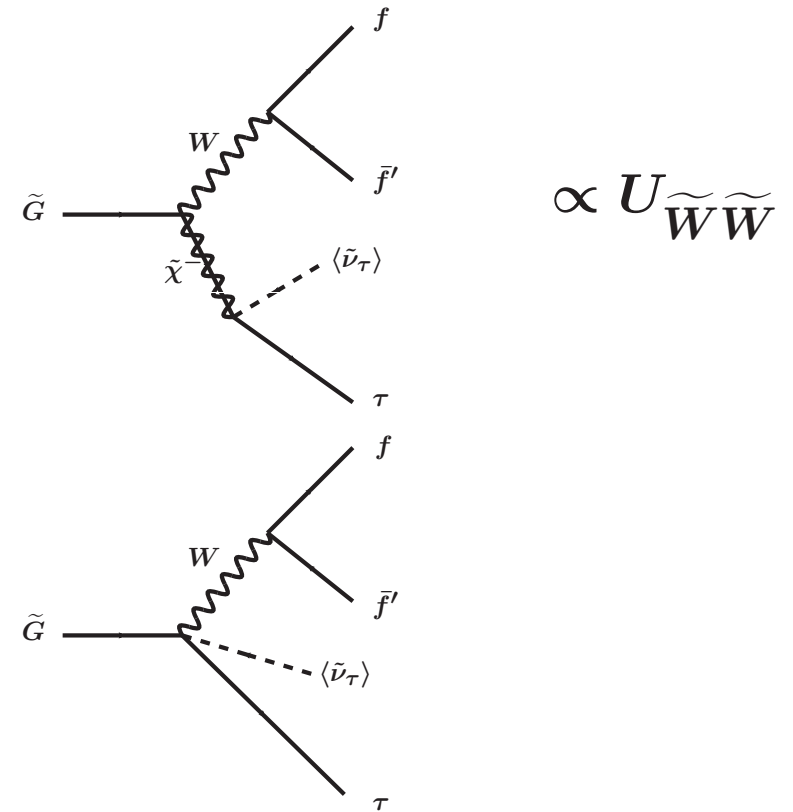
figure from 0809.5030 by Covi et al

Three-body gravitino decays into $W^*\ell$ and $Z^*\nu$ had not been considered before

Two diagrams contribute to these decays

The four-vertex diagram $\not\propto U_{\widetilde{W}\widetilde{W}} \sim M_W/M_2$

The decay into $\gamma\nu$ tends to be suppressed



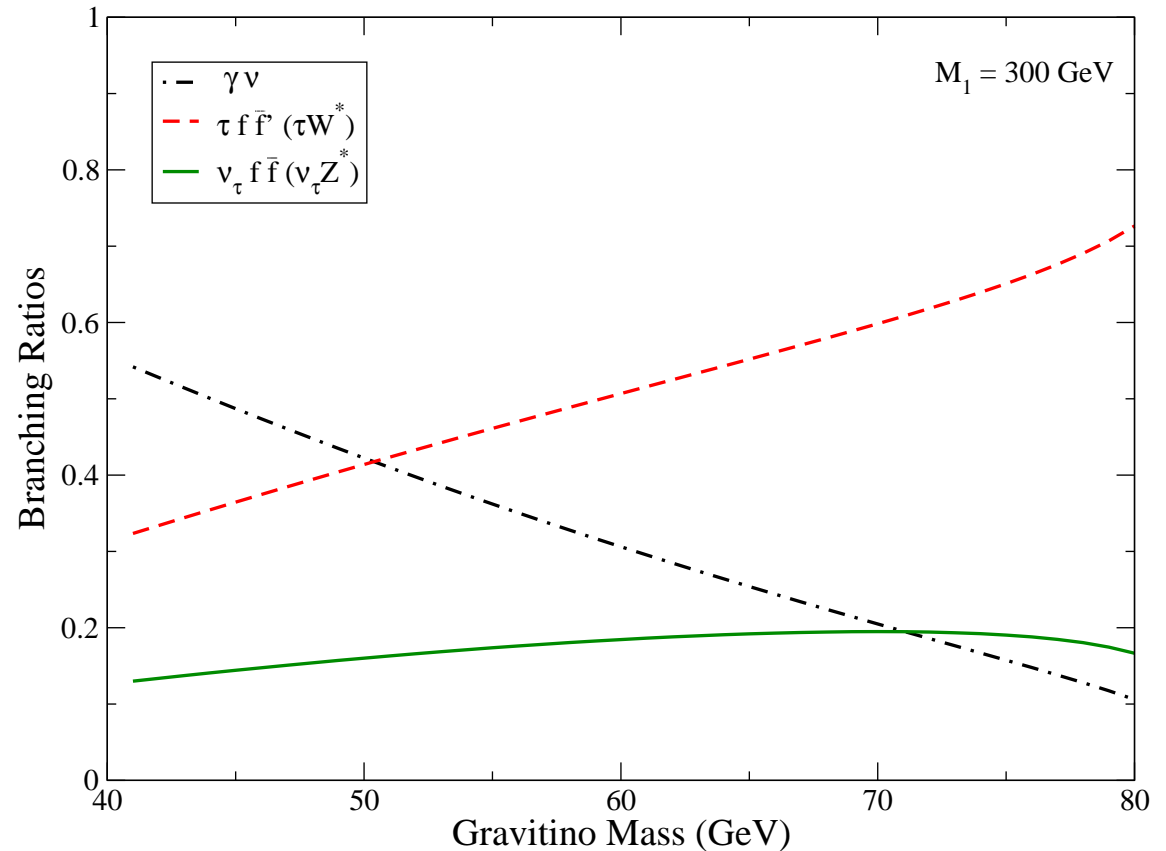
$$\Gamma(\widetilde{G} \rightarrow \gamma\nu_\tau) = \frac{\xi_\tau^2 m_{\widetilde{G}}^3}{64\pi M_P^2} |U_{\widetilde{\gamma}\widetilde{Z}}|^2 \propto 1/M_2^2$$

Gravitino decays can easily be dominated by three-body final states

$W^*\tau$ is dominant for
 $M_W > m_{\tilde{G}} > 50$ GeV

Even $Z^*\nu_\tau$ can be more important than $\gamma\nu$

3-body gravitino decays cannot be neglected

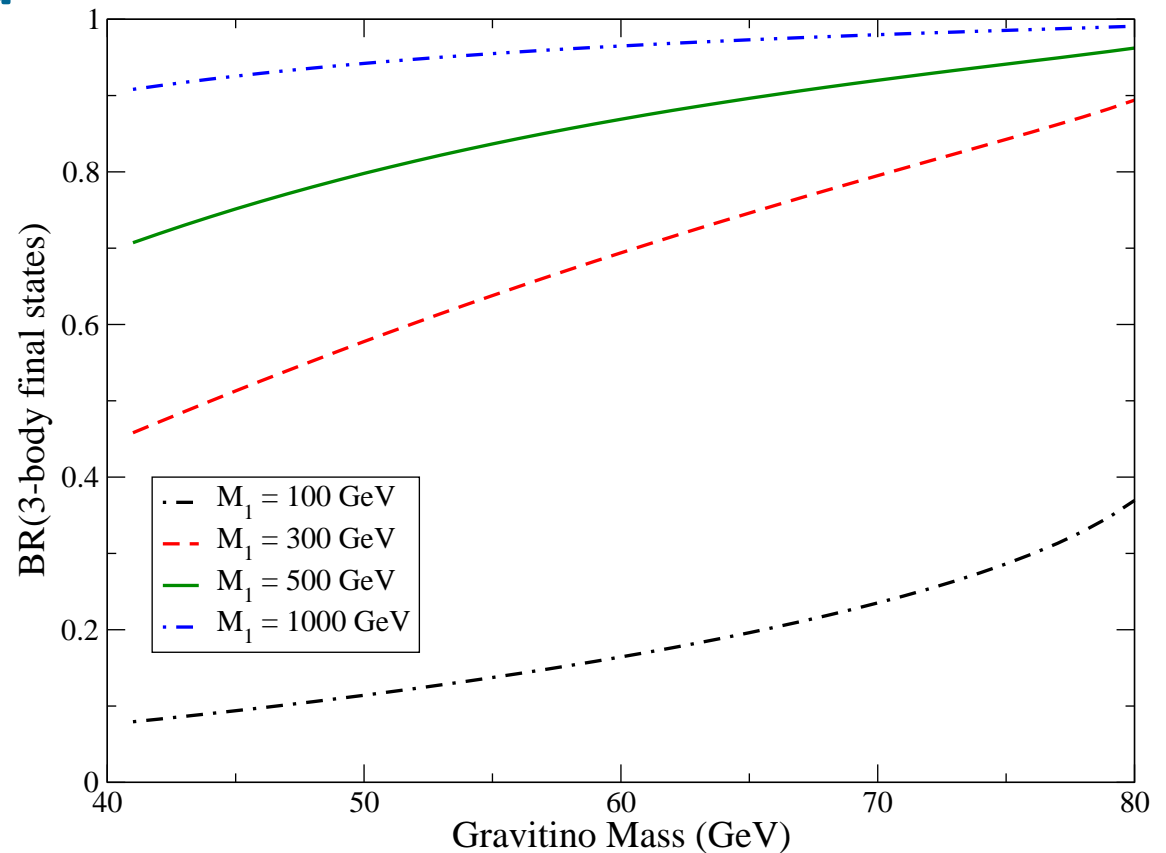


The 3-body final states become more relevant for larger gaugino masses

They can dominate over a wide range of \tilde{G} masses

The effect is significant even for small M_i

For large M_i , $\tilde{G} \rightarrow \gamma\nu$ becomes negligible

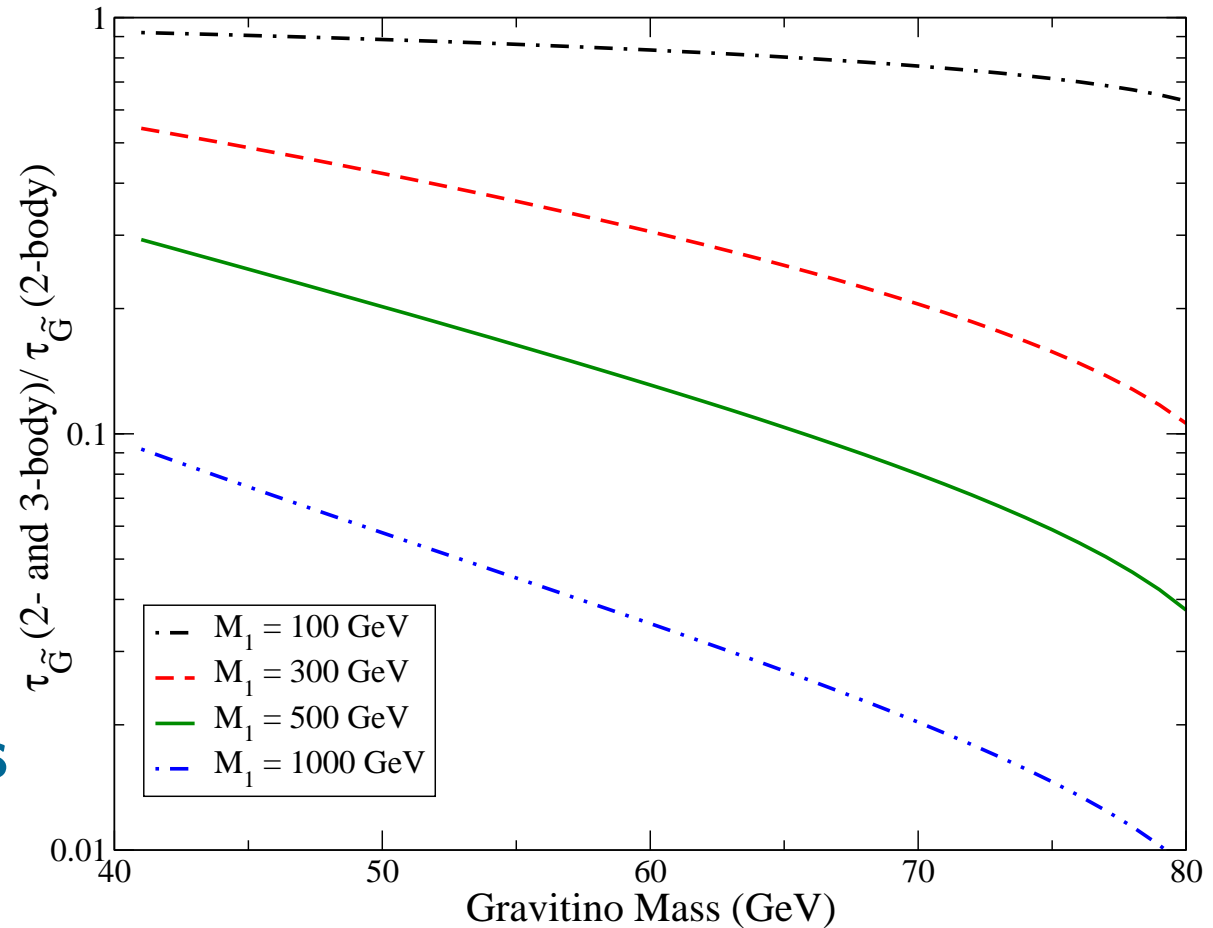


The gravitino lifetime is significantly affected by these new decay modes

It could be more than 100 times smaller

Indirect detection of \tilde{G} dm is strongly affected:

Suppressed γ, ν lines
New continuum of γ s
New antimatter signals

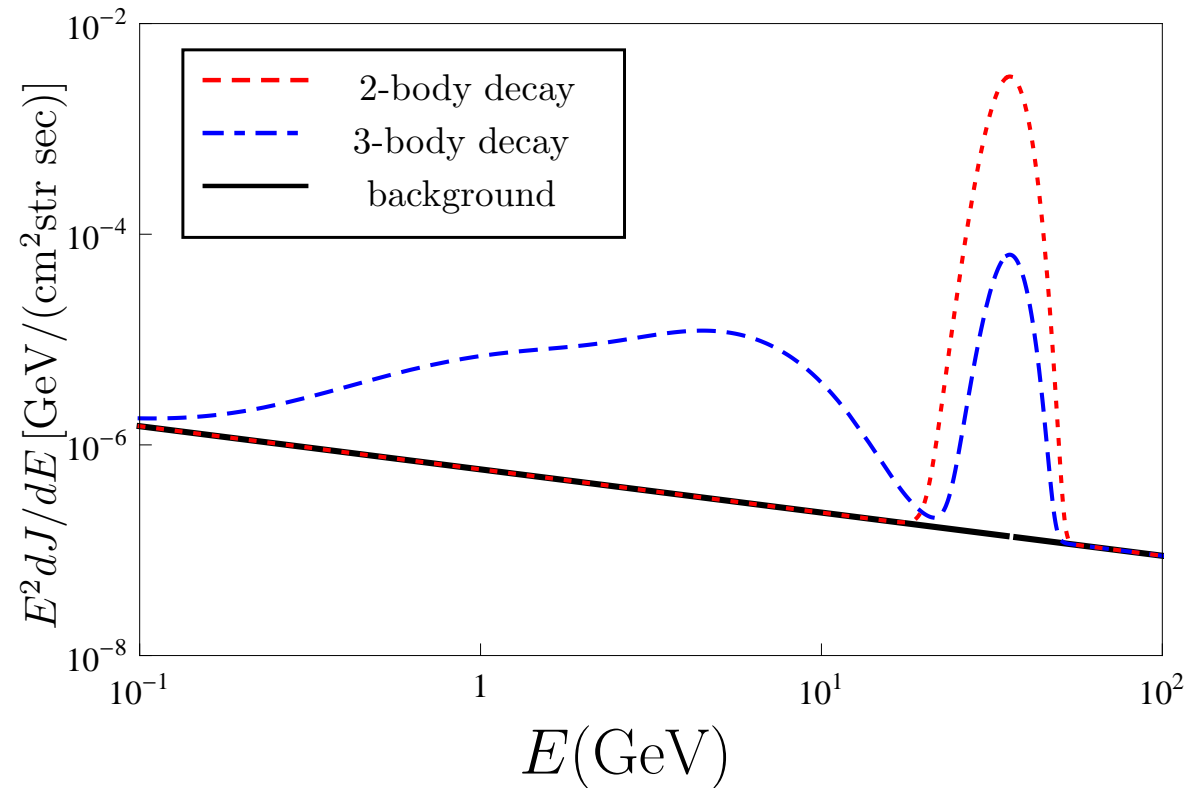


The expected gamma ray flux from gravitino decays is significantly altered

The γ line is less apparent

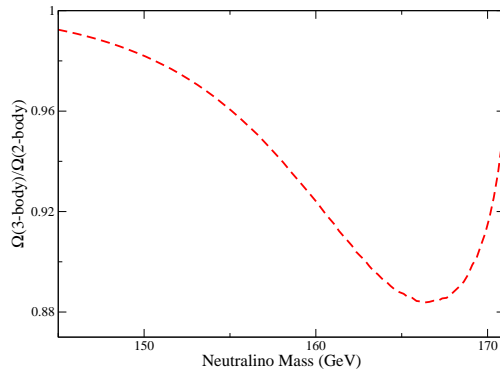
The new γ continuum could be observed

These effects are typically sizable

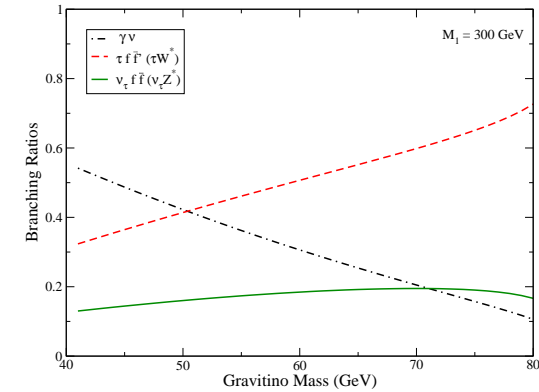


3-body final states will be shown to be relevant in well-known models of dark matter

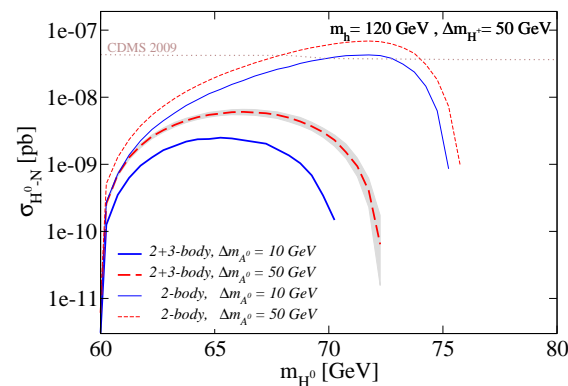
1. Neutralinos in the MSSM



2. Gravitinos in R_p SUSY



3. Inert doublet model



arXiv:1003.3125, with Laura Lopez

In the inert doublet model (IDM) the SM is extended with a second higgs doublet

The IDM contains 3 new scalars

$$H_2 = \begin{pmatrix} H^+ \\ (H^0 + iA^0)/\sqrt{2} \end{pmatrix}$$

H_2 is odd under a new Z_2 symmetry

Lightest component is stable
No coupling to fermions

This model features a rich phenomenology

Barbieri, Bergstrom, Gustafsson, Ma, Tytgat, etc

The inert doublet model can account for the dark matter of the Universe

It includes a viable dm candidate

H^0 has gauge and scalar interactions

The parameter space is rather simple

The lightest odd particle: H^0

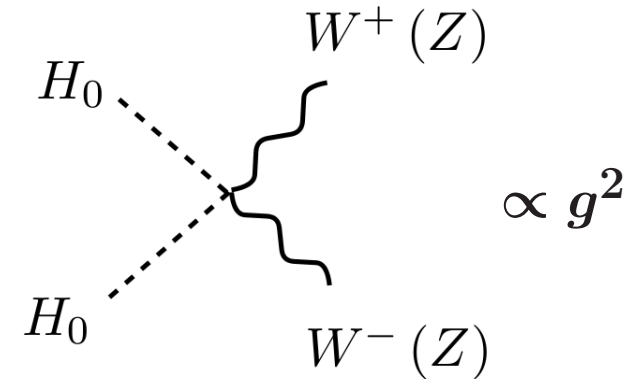
$$V = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} \left[(H_1^\dagger H_2)^2 + \text{h.c.} \right]$$

$$m_{H^0}, m_{A^0}, m_{H^\pm}$$

$$\lambda_L \equiv \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$$

In the IDM the viable parameter space coincides with the region where $H^0 H^0 \rightarrow W W^*$ is important

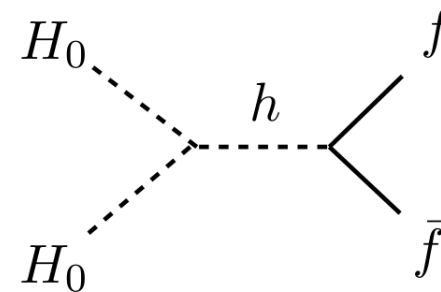
$H^0 H^0 \rightarrow W^+ W^-$ has a purely gauge contribution



The viable parameter space is $m_{H^0} < M_W$

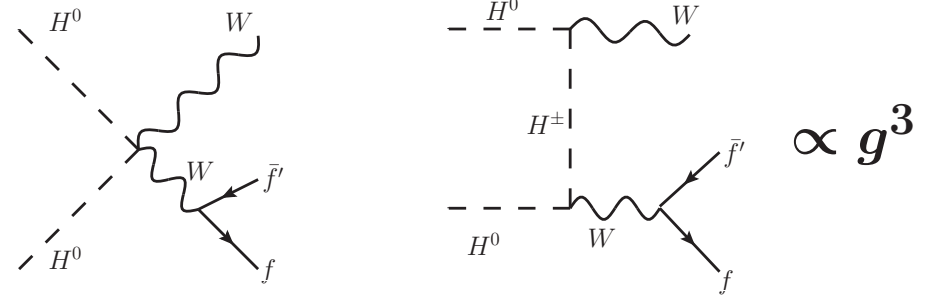
or $m_{H^0} > 500 \text{ GeV}$

In that region, $b\bar{b}$ is the dominant 2-b final state

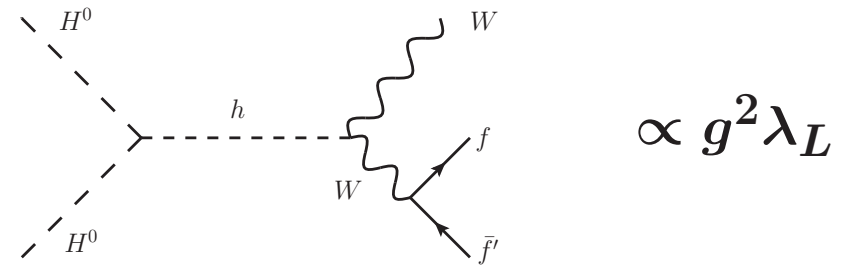


Three different diagrams contribute to $H^0 H^0 \rightarrow WW^* \rightarrow W f \bar{f}'$ in the IDM

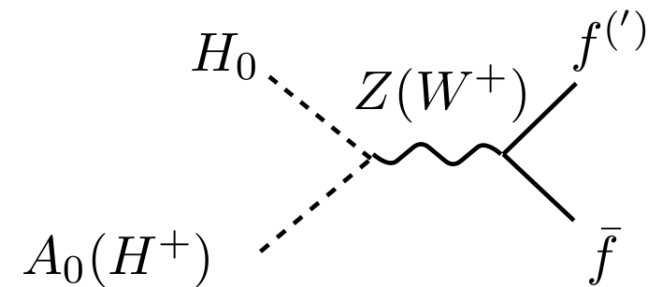
There are two gauge diagrams



And a higgs mediated diagram



Coannihilations may also affect Ω

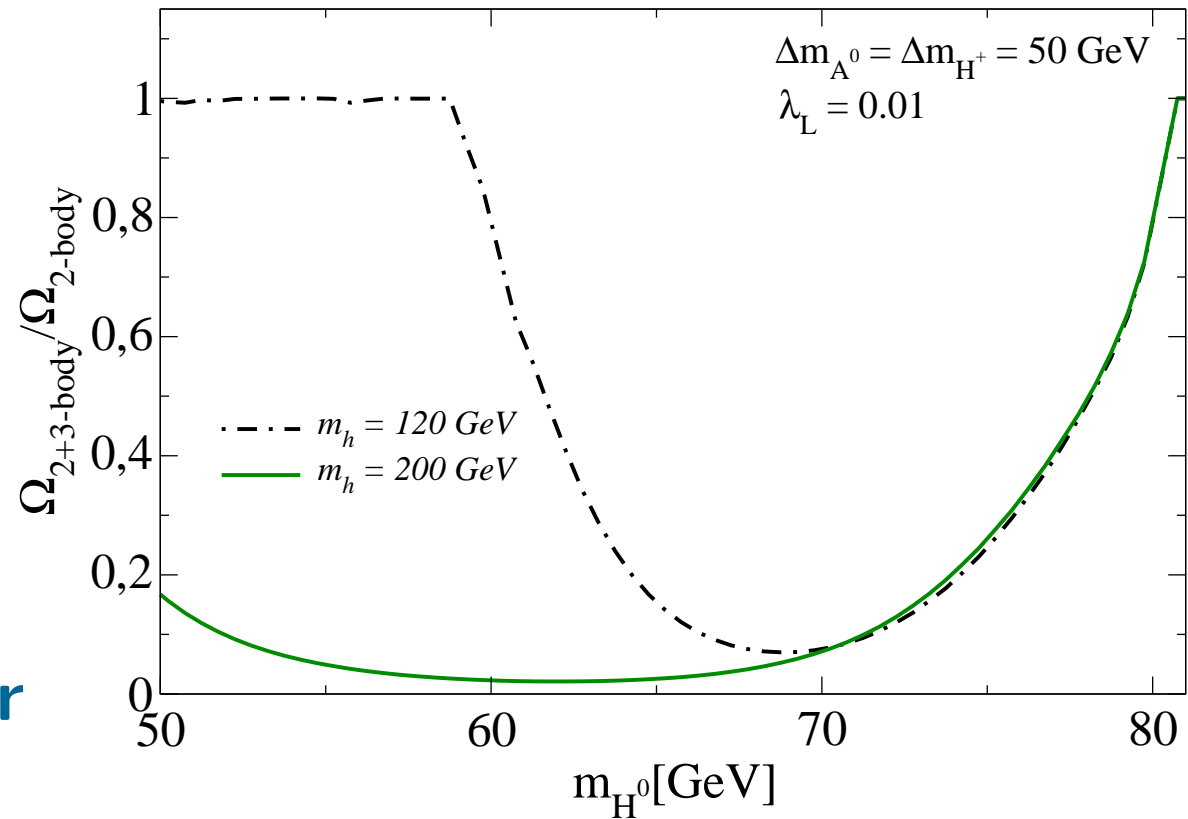


The H^0 relic density is strongly reduced by annihilations into WW^*

This suppression depends on the higgs mass

Ω could be 10 times smaller

$\Omega(3\text{-body}) \ll \Omega(2\text{-body})$ over a wide m_{H^0} range

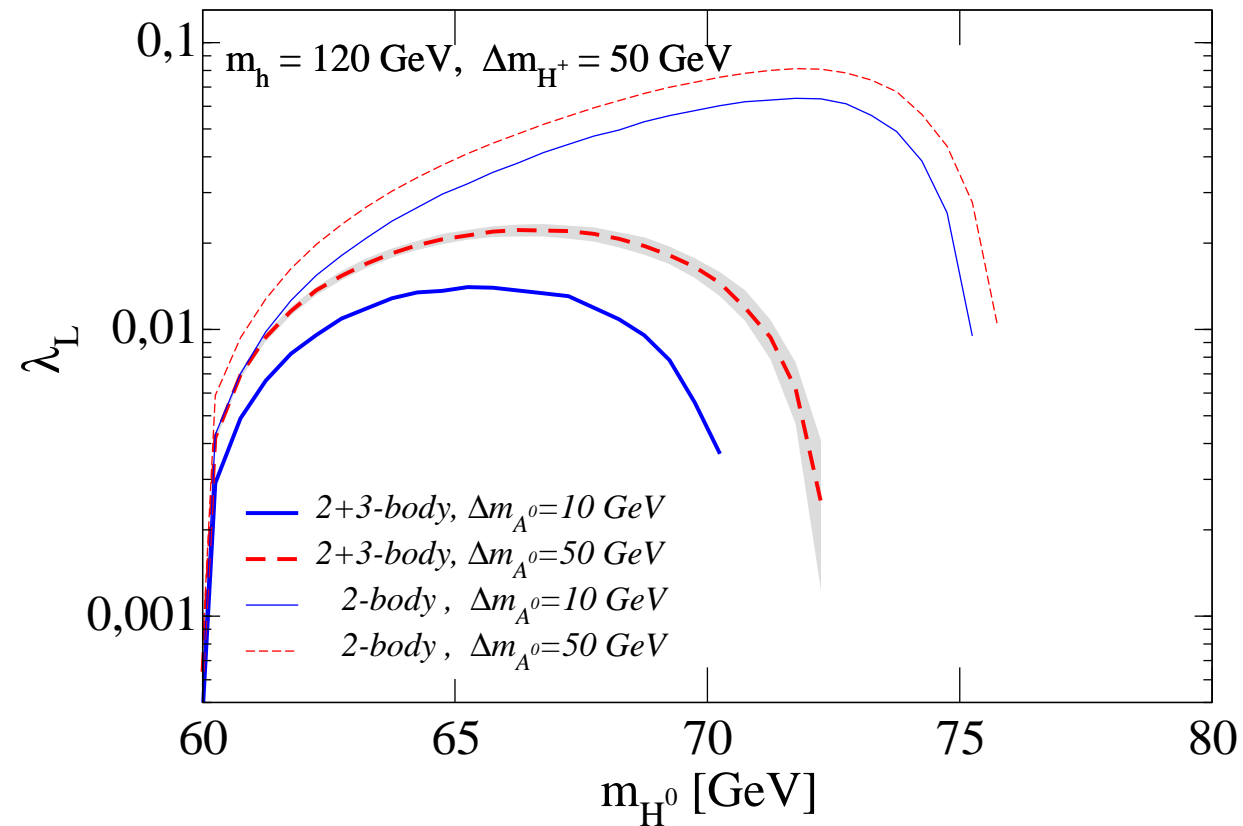


Due to 3-body final states, the viable parameter space of the IDM is substantially modified

The required value of λ_L may be much smaller

The maximum allowed m_{H^0} decreases

The effect is rather generic in the IDM

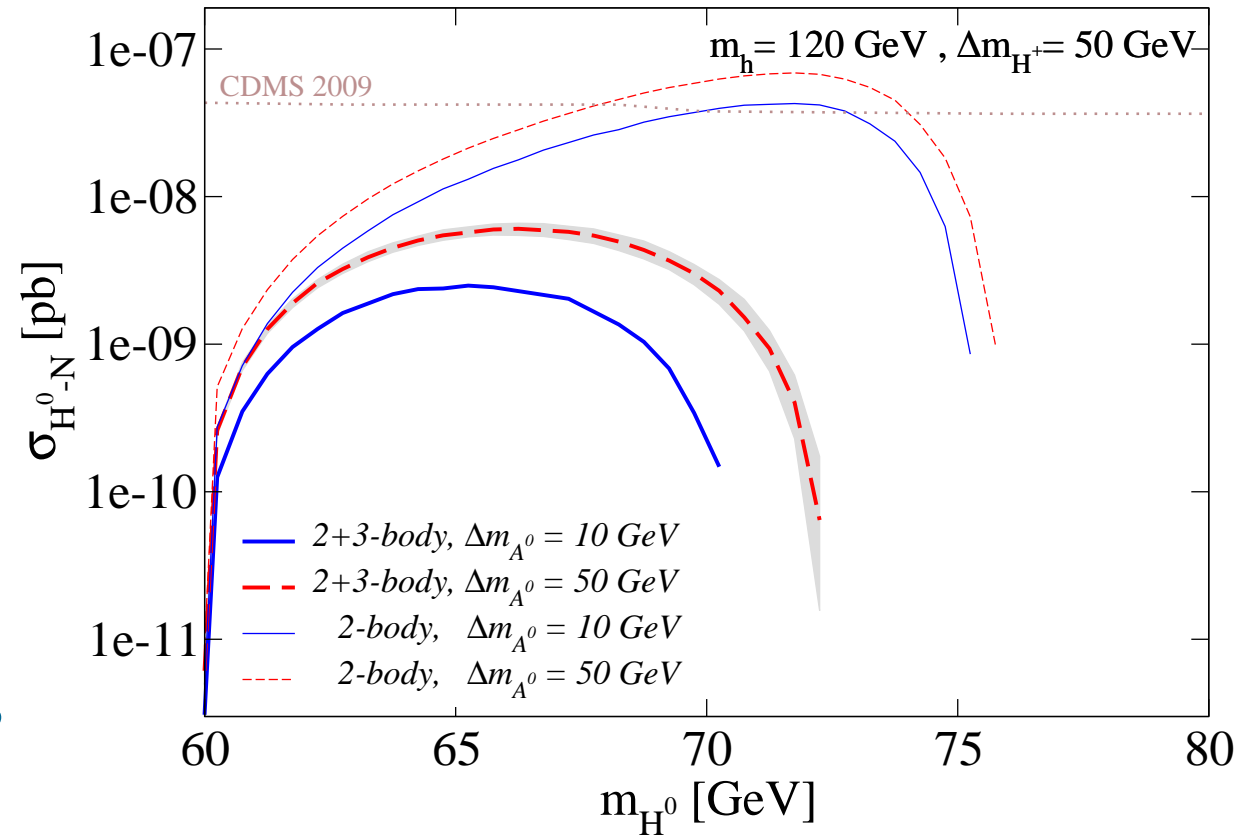


The inert higgs direct detection cross section is much smaller than previously believed

The dd cross section is proportional to λ_L^2

The new σ_{H^0-N} is up to 100 times smaller

Indirect detection signals are also affected



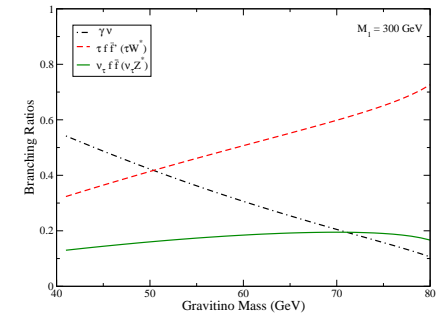
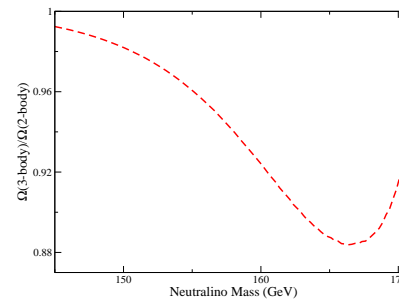
3-body final states are relevant in well-known dark matter models

They modify the viable parameter space

They alter the dm detection prospects

They induce large corrections

1. Neutralinos in the MSSM
2. Gravitinos in \mathcal{R}_p SUSY



3. Inert doublet model

