This slide was left intentionally dark

Contents

1) Motivation for dark matter

   DM production: Weakly-Interacting Massive Particles (WIMPs)
   (see also the course by Francesc Ferrer)

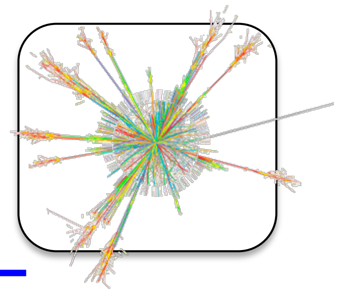
2) DM (WIMP) detection

   - direct searches
     - Searches in SuperCDMS)
     - reconstruction of DM parameters
   - Indirect searches
   - collider searches

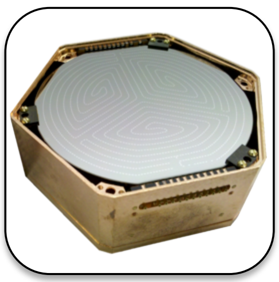
3) (some) DM models

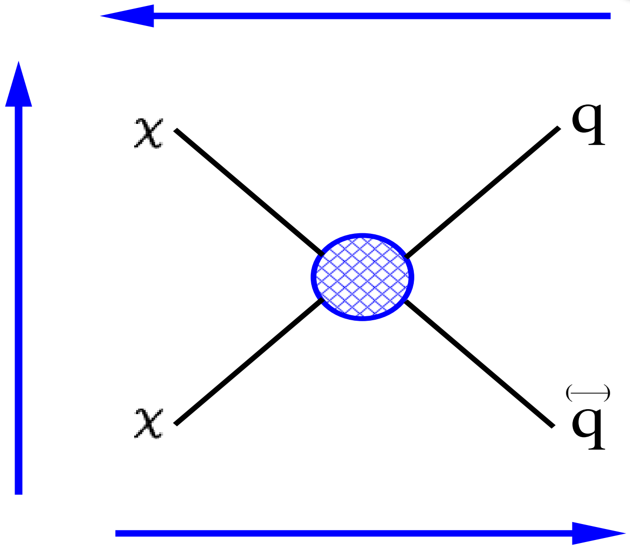
... probing DIFFERENT aspects of their interactions with ordinary matter

Accelerator Searches (production)



Direct Detection
(scattering)

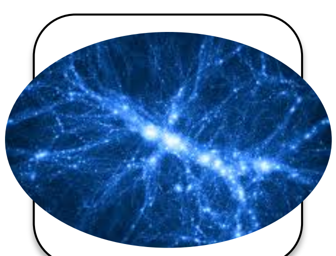


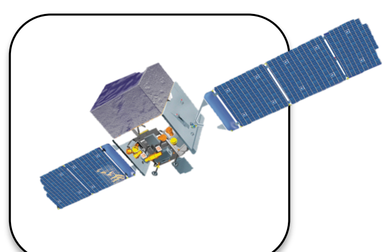


Constraints in one sector affect observations in the other two.

"**Redundant**" detection can be used to extract DM properties.

Indirect Detection
(annihilation or decay)





In the past ~20 yrs we have had numerous potential signatures for DM. Some remain unexplained while many have been attributed to backgrounds or statistical fluctuations.

These are shaping our theoretical approach to the DM problem making us look in (often conflicting) directions

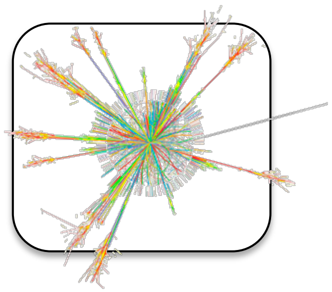
Astro/Cosmo Probes

Warm DM (Simulations)

Self-interacting DM

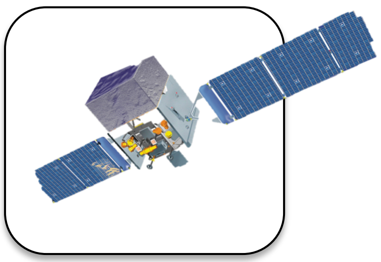
3.5 keV line

LHC



Diphoton at 750 GeV

Indirect Detection

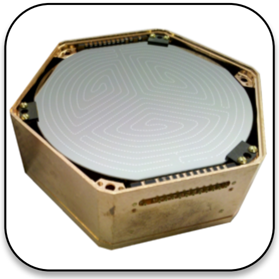


PAMELA-AMS

Fermi-LAT:
- Galactic Centre
- 135 gamma line

511 eV emission

Direct Detection

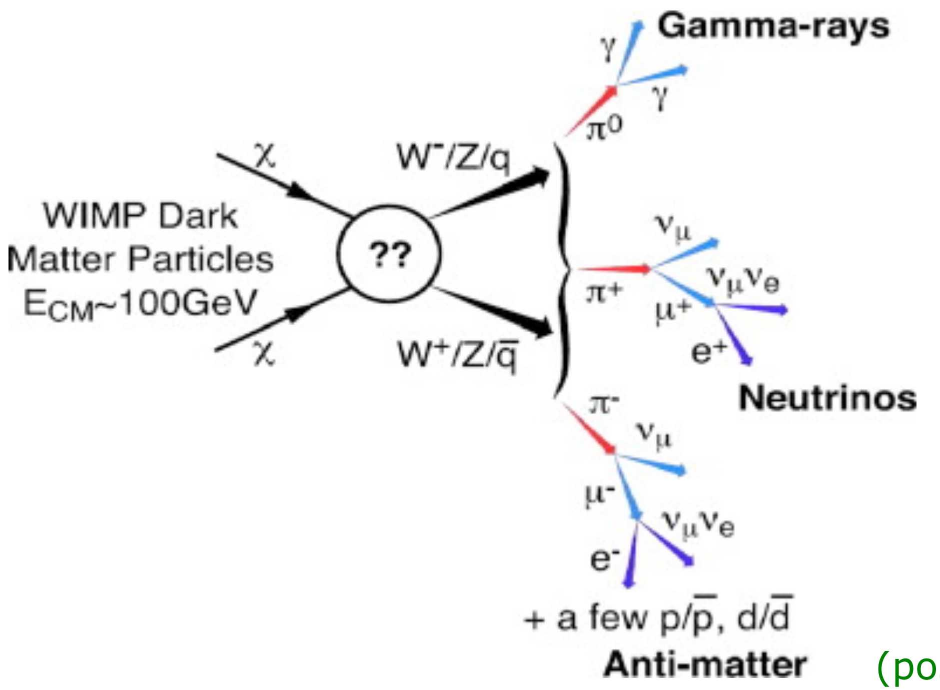


DAMA annual modulation

Low-mass craze (CDMS, CoGeNT, CRESST)

Indirect detection, signals or backgrounds?

Observe the products of Dark Matter annihilation (or decay!)



(e.g., from the galactic centre or other galaxies)

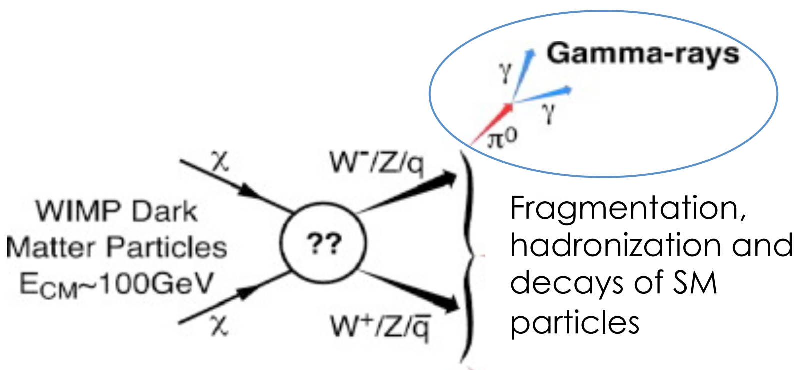
(from the centre of the Sun or the Earth)

(positrons, antiprotons, antideuterons)

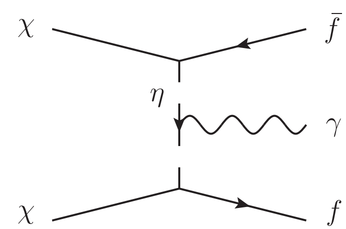
Subject to large uncertainties and very dependent on the halo parameters

Gamma Rays searches

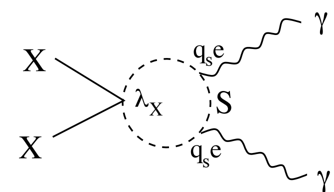
Continuum (secondary photons)



Direct gamma emission (features, lines)



Internal bremsstrahlung



Loop processes

$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right) = \sum_i \frac{dN^i_\gamma}{dE_\gamma} \langle\sigma_i v\rangle \frac{1}{8\pi m_{DM}^2} \int d\Omega \int_{l.o.s.} \rho^2(r(l,\Psi))\, dl$$

Theoretical input

Astrophysical input

DM annihilation cross section IN THE HALO

$$\langle\sigma v\rangle \approx a + bv^2$$

$$v^2_{Decoupling} \approx 1/20$$

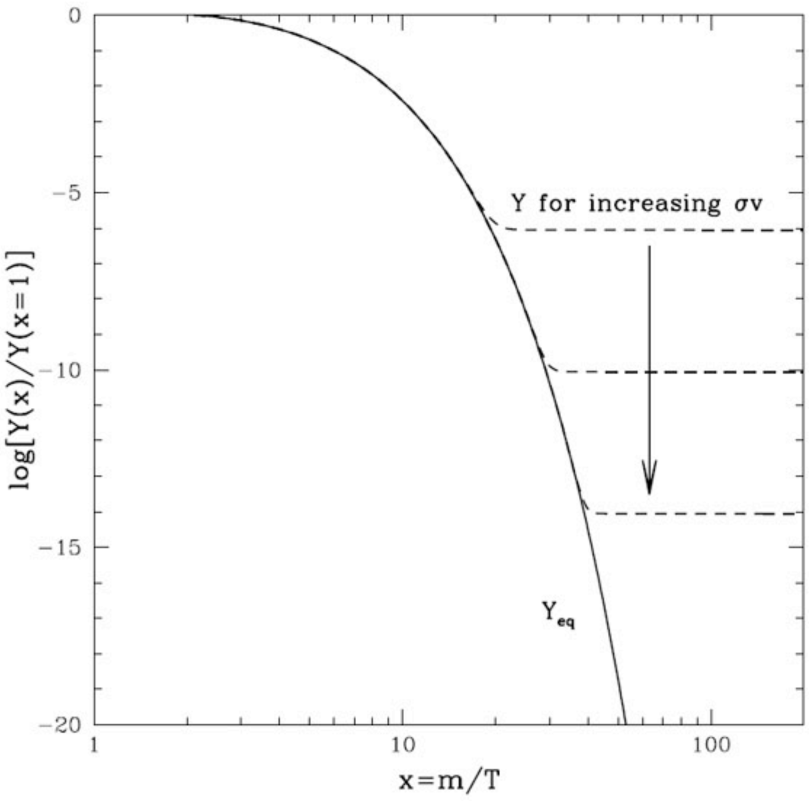
$$v^2_{halo} \approx 10^{-7}$$

DM Density profile

Region of observation (backgrounds)

WIMPs can be thermally produced in the early universe in just the right amount

The freeze-out temperature (and hence the relic abundance) depends on the DM annihilation cross-section



$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle}$$

$$T_o \approx 10^{-13}\,\text{GeV}$$

$$H_{100} = 100\,\text{km sec}^{-1}\,\text{Mpc} \approx 10^{-42}\,\text{GeV}$$

$$M_{Planck} = 1/G_N^{1/2} = 10^{19}\,\text{GeV}$$

A generic (electro)Weakly-Interacting Massive Particle can reproduce the observed relic density.

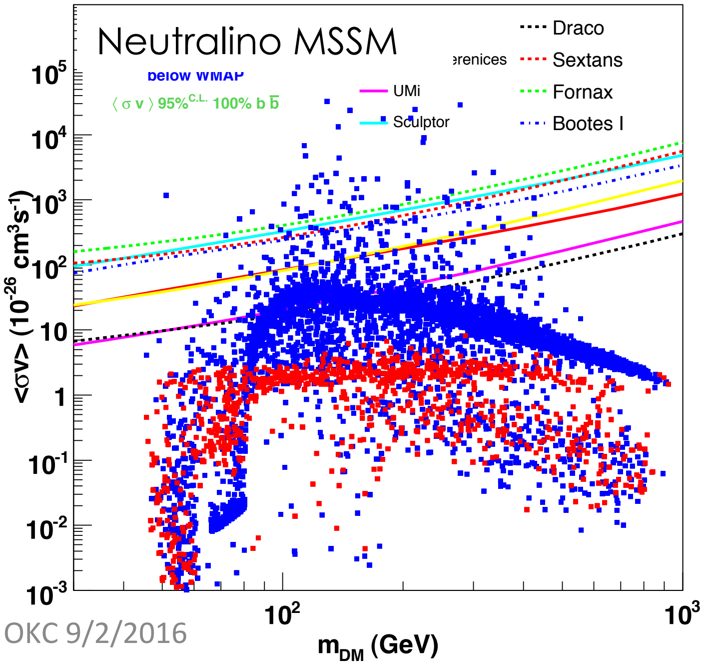
Fermi-LAT can provide constraints for light WIMPs

Fermi-LAT observation of Dwarf Spheroidals

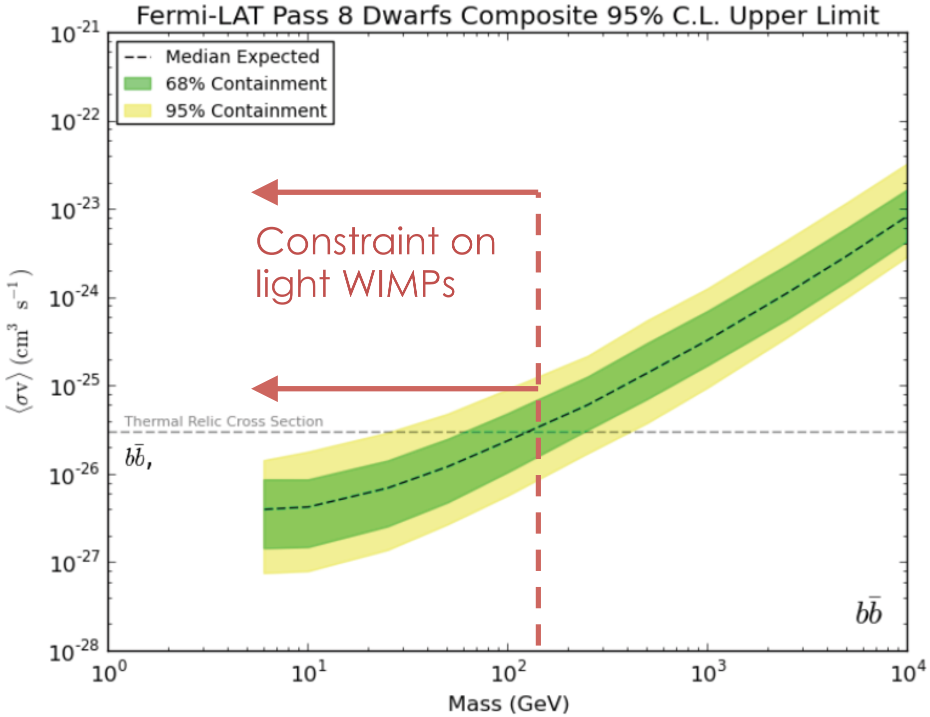
Fermi-LAT

Thermal cross-section excluded for some channels (bb and ττ)

m>100 GeV for the bb channel



Fermi-LAT '14



"Thermal" DM might have a smaller <σv> in the halo

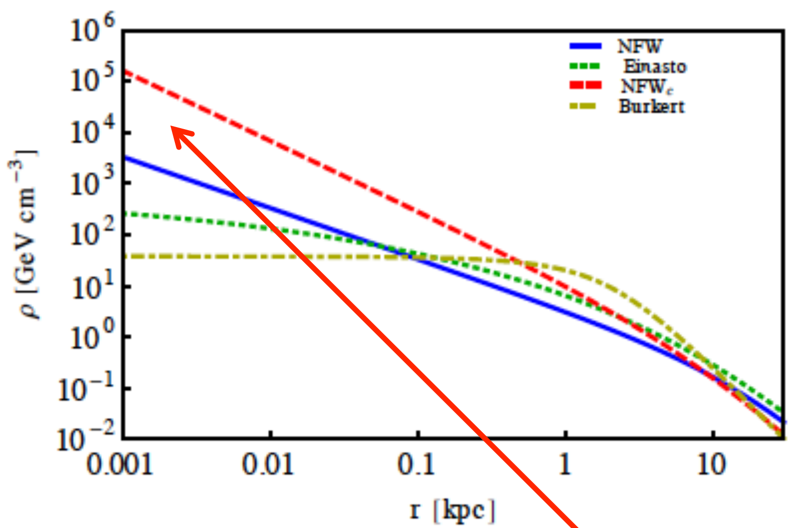
Coannihilation effects, velocity-dependent cross-section resonances

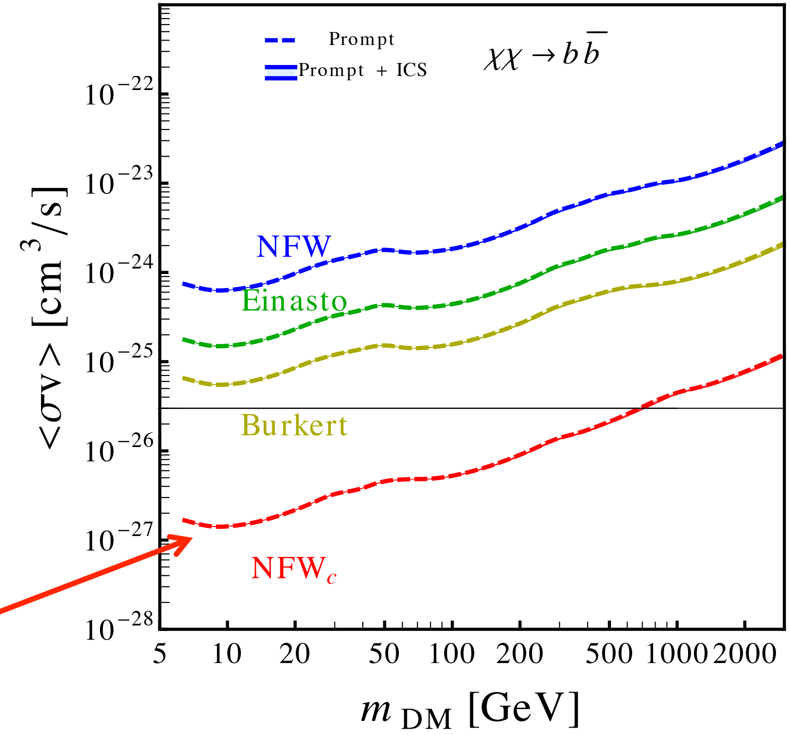
Abdo et al. 1001.4531

These bounds depend significantly on the properties of the DM halo

It has been argued that the DM density in the Galactic Centre can be enhanced due to the effect of baryons, in a process known as “adiabatical contraction”.

Gómez-Vargas, DGC et al. with the FERMI Collaboration 2013



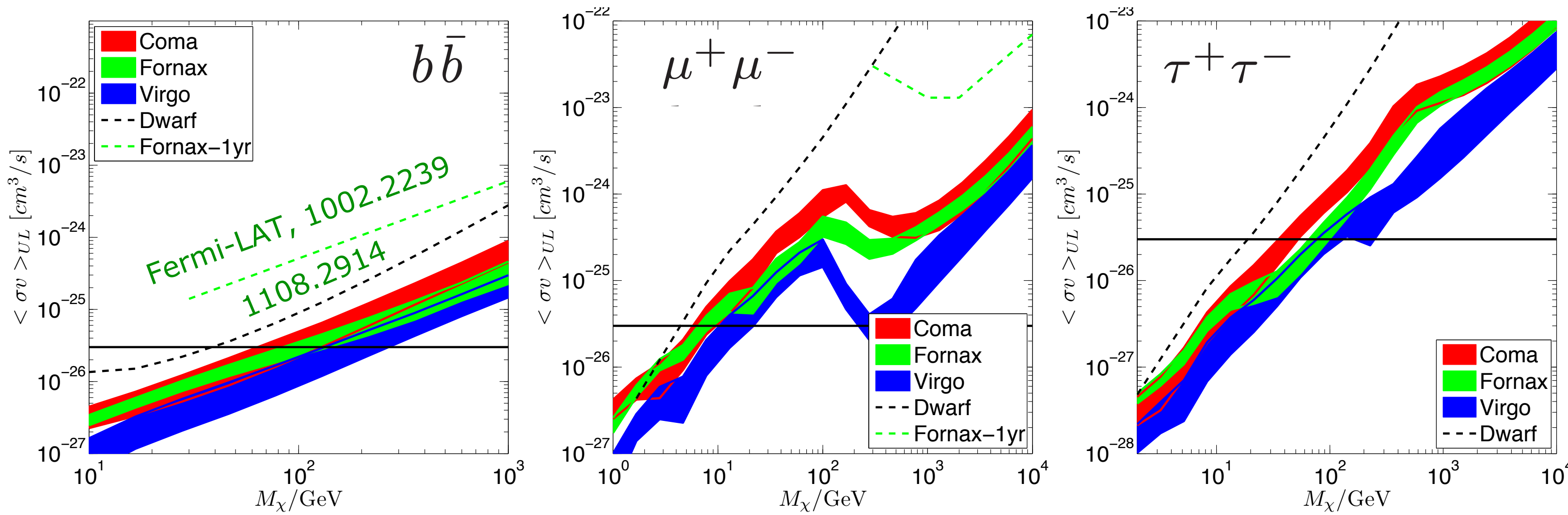


Very strong for COMPRESSED haloes

Fermi-LAT constraints have also been extracted on DM clusters

- They are more distant, but more massive than dSphs
- Very dark matter dominated like dSphs
- Typically lie at high galactic latitudes where the contamination from galactic gamma-ray background emission is low

No excess is observed in the Fermi-LAT data from the first 3 year



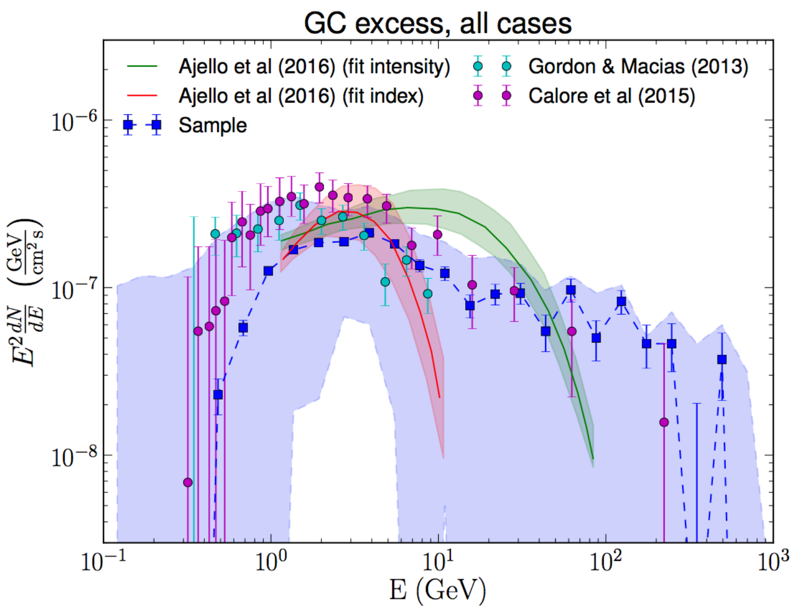
Han et al., 1207.6749

This assumes a large boost factor coming from the contributions due to subhaloes

$$b(M_{200}) = \mathcal{J}_{sub}/\mathcal{J}_{NFW} = 1.6 \times 10^{-3}(M_{200}/\mathrm{M}_\odot)^{0.39}$$

Gao et al., 1107.1916

Excess at low energies in Fermi-LAT data from the GC



Compatible with the annihilation of a light WIMP ~10-50 GeV

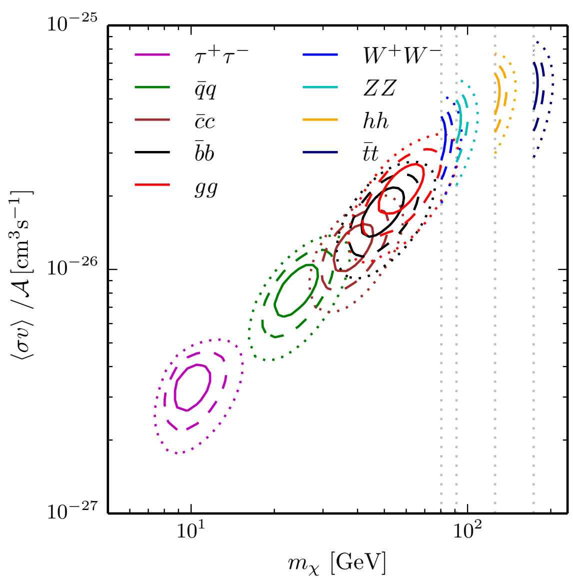
Hooper, Goodenough 2010
Hooper, Linden 2011

or millisecond pulsars, cosmic ray effects or different spectrum at galactic centre.

Abazajian 1011.4275
Chernyakova 1009.2630
Boyarsky, Malyshev, Ruchayskiy, 1012.5839

Most recent analysis by Fermi-LAT confirms the excess

Fermi-LAT 1704.03910



Fits normally done for pure annihilation channels

Compatible with WIMP DM

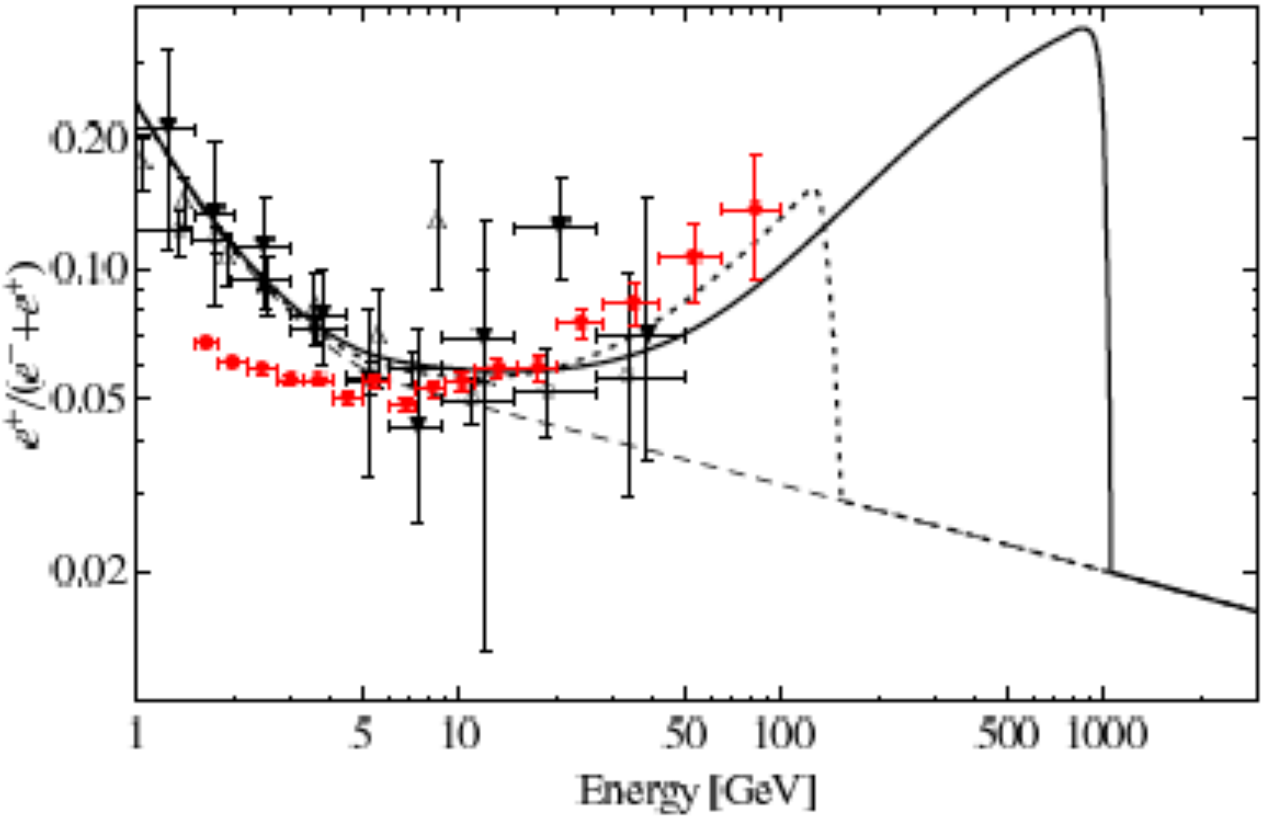
$$m_{DM} \sim 20 - 100 \text{ GeV}$$

$$\langle \sigma v \rangle \sim 10^{-26} \text{ cm}^3/\text{s}$$

Calore et al. 1411.4647

The antimatter puzzle...

PAMELA satellite revealed an excess in the positron fraction but no excess in the antiproton signal.



Is this an evidence of DM annihilation?

Even Decaying DM could account for it

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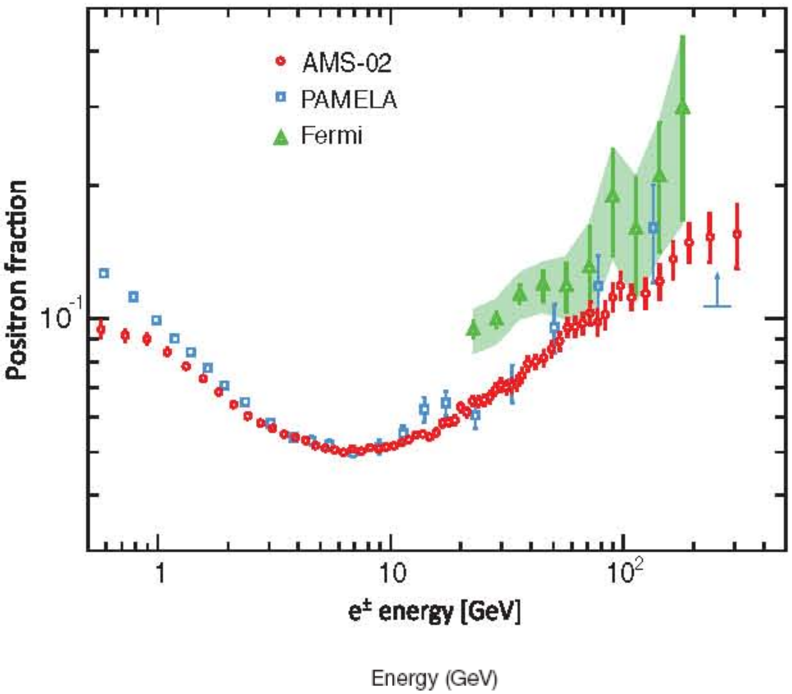


The interpretation in terms of DM is very complicated

Too small signals in canonical models (WIMP)

- boost factors (inhomogeneities? IMBH?)
- play with propagation parameters
- non-thermal DM
- decaying dark matter

Why are there no antiprotons?

- Majorana fermions disfavoured (neutralino)
- Leptophilic dark matter

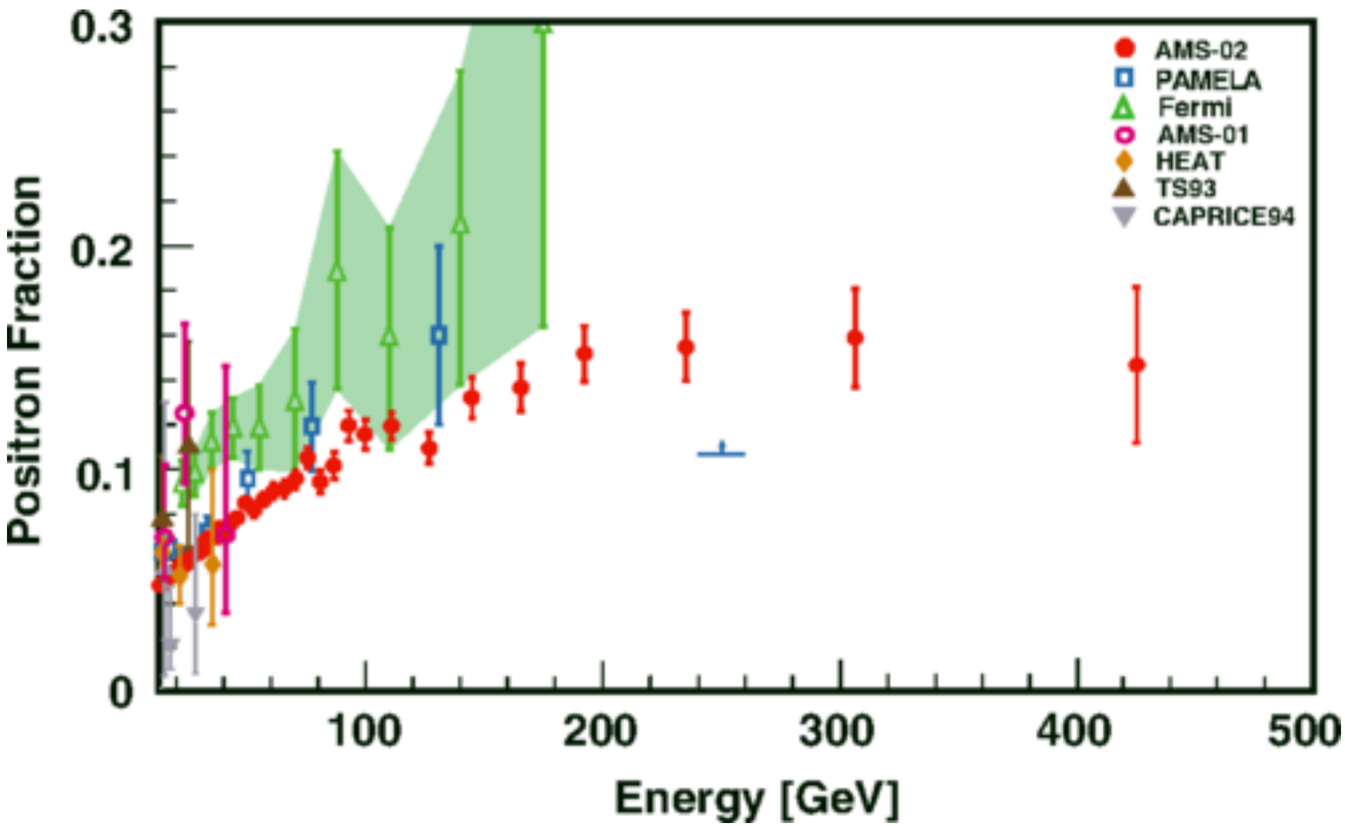
No evidence for associated gamma ray excess

- decaying dark matter

Astrophysical explanation in terms of pulsars is plausible. See e.g., Delahaye et al. 2010

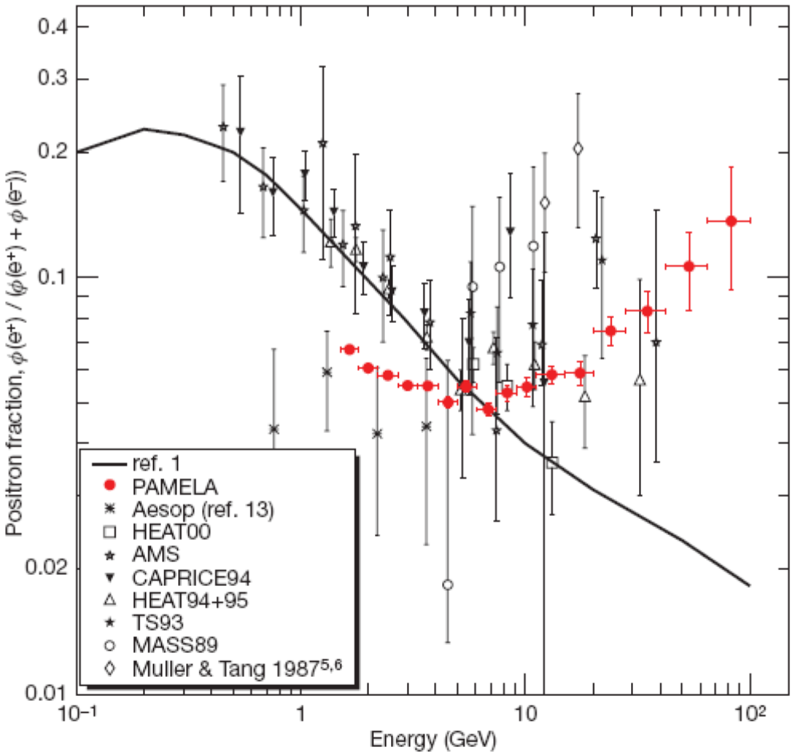
The antimatter puzzle...

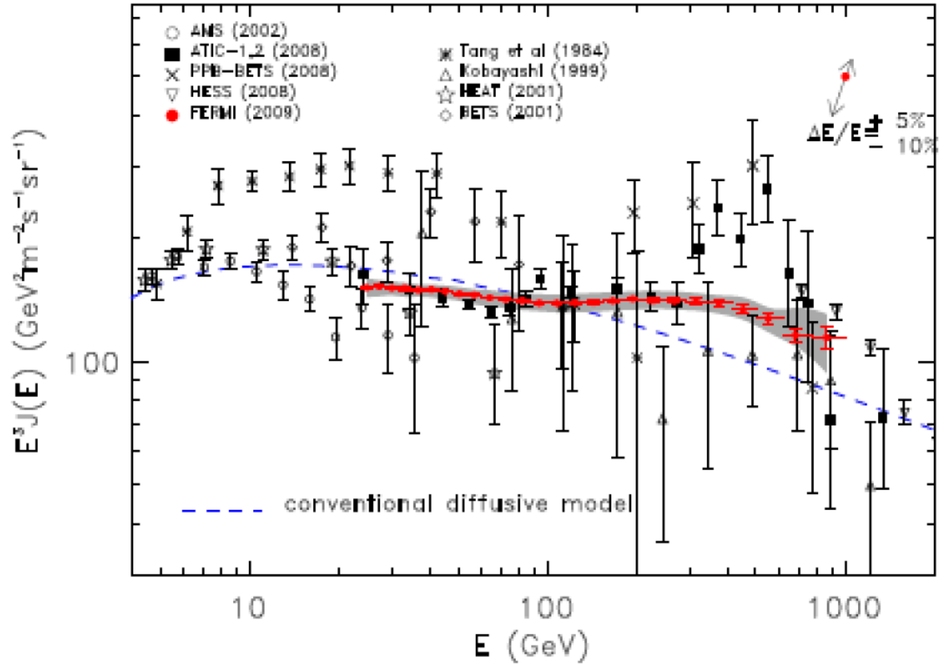
New AMS results up to 500 GeV shows a “plateau” (or is it starting to decrease??)



AMS 2014

Fermi data on total flux of positrons and electrons came as a further constraint



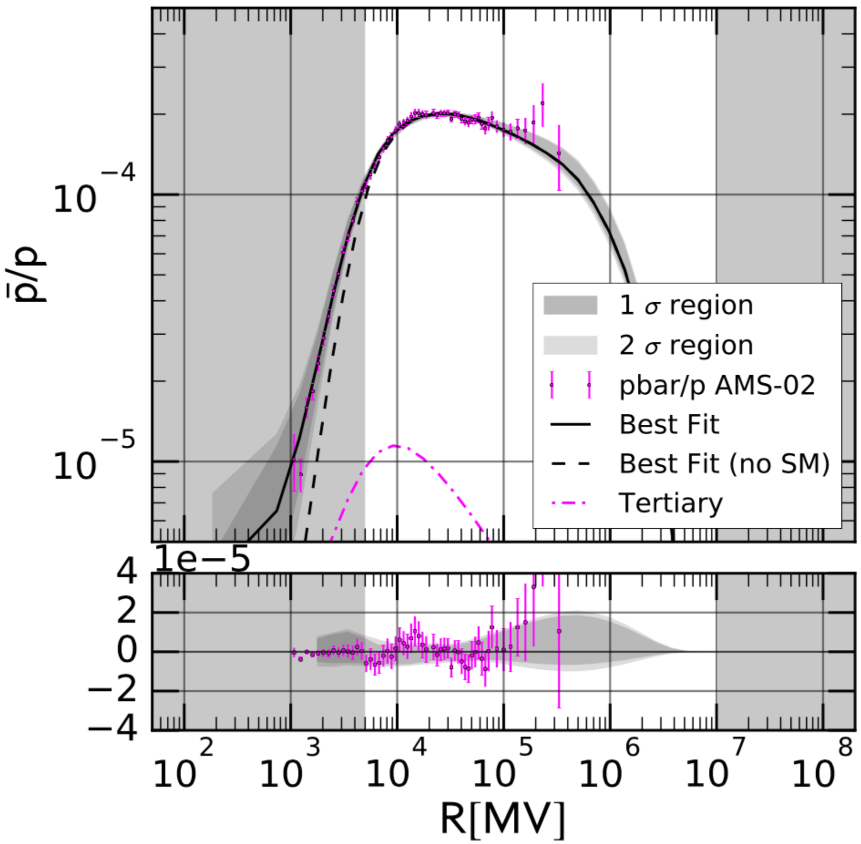


Astrophysical explanation in terms of pulsars is plausible.

See e.g., Delahaye et al. 2010

Antimatter searches (antiprotons)

The AMS detector has also observed an excess in the measured antiproton flux

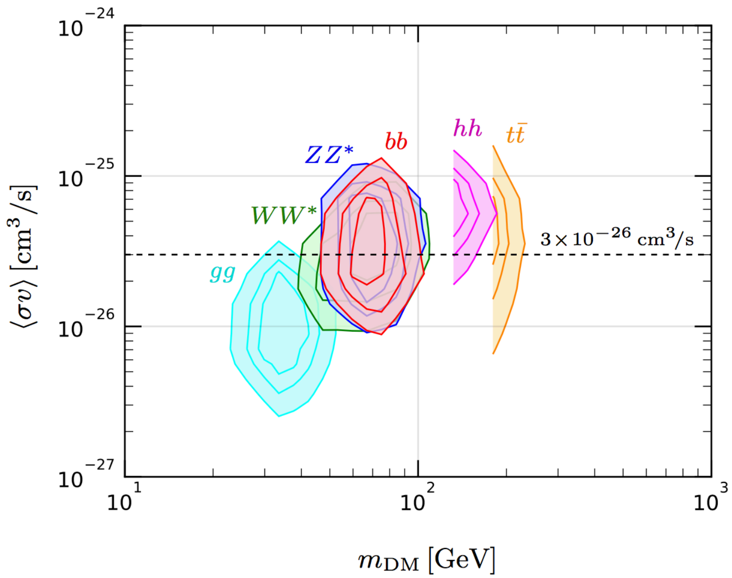


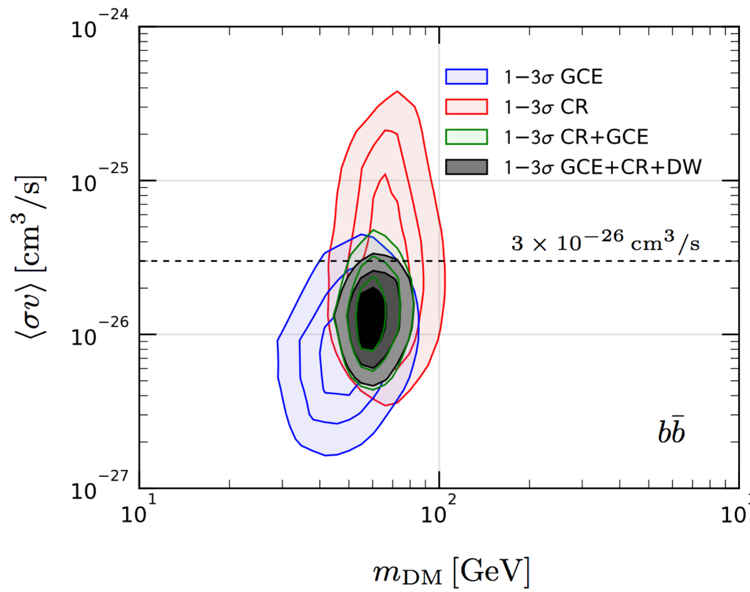
Cuoco et al. 1610.03071
Cui, Yuan, Tsai, Fan 1610.03840

Care must be taken with the treatment of the propagation parameters

The AMS excess is compatible with the Fermi-LAT excess

If interpreted in terms of DM annihilation, both excesses can be fit with DM particles that have the annihilation cross section of a typical WIMP and that annihilate **mostly into quarks or W, Z bosons**.





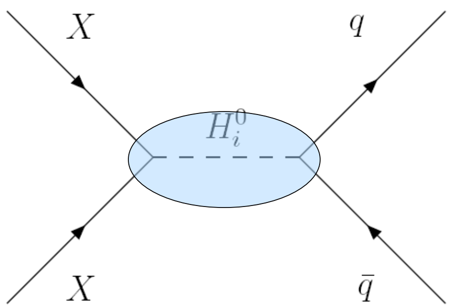
Cuoco et al. 1704.08258

This is extremely interesting, as it gives us hints on how to build consistent models to account for these excesses

DM signals in colliders (LHC)

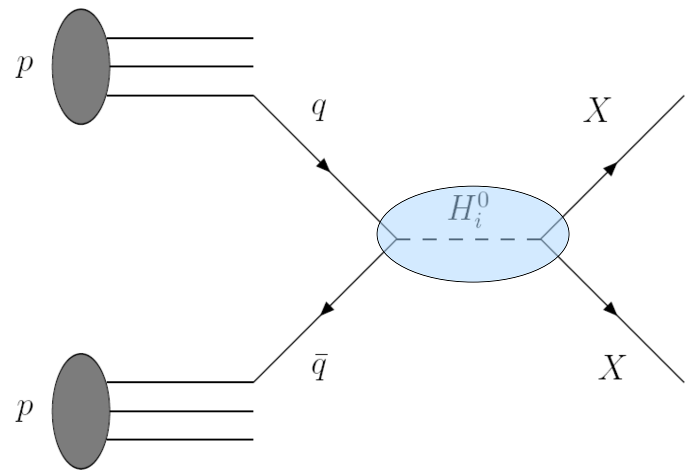
Direct DM production (pp → XX) does not leave a good signal

DM annihilation (Early Universe)



Inverse process

DM Production in colliders?



Missing transverse energy

Does not leave a good signal (no hard energy deposition for detectors to trigger upon)

We might not be able to test directly the DM couplings to SM matter (problem for estimating the relic abundance)

MAKES IT DIFFICULT TO TAKE A MODEL INDEPENDENT APPROACH.

DM signals in colliders (LHC)

Direct DM production (pp → XX) does not leave a good signal

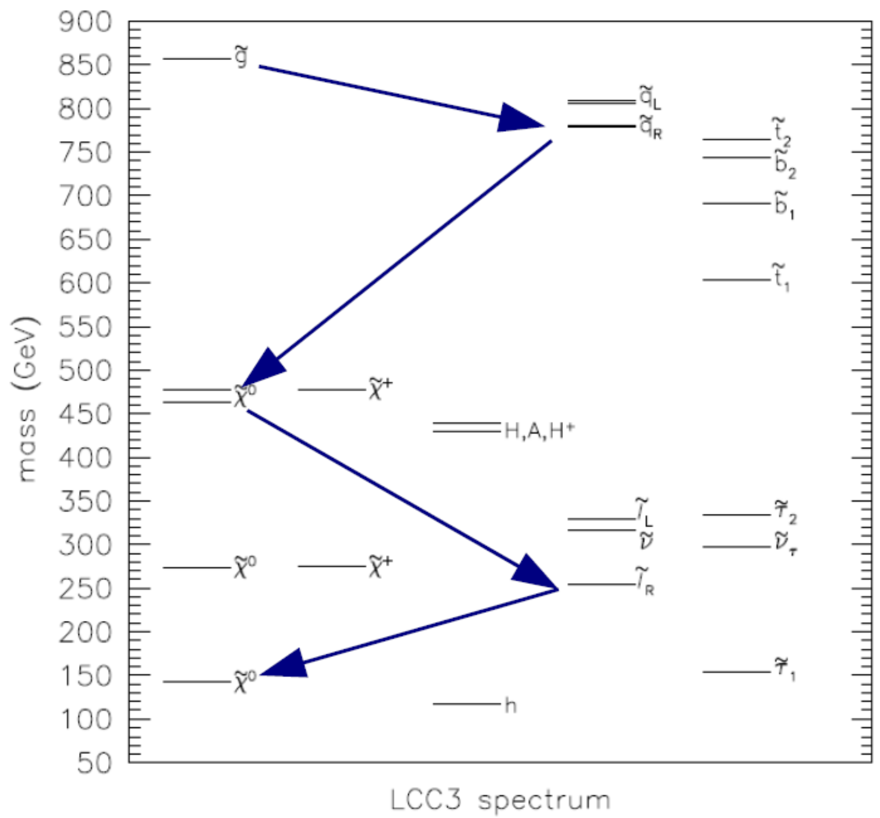
Look for jets + extra leptons

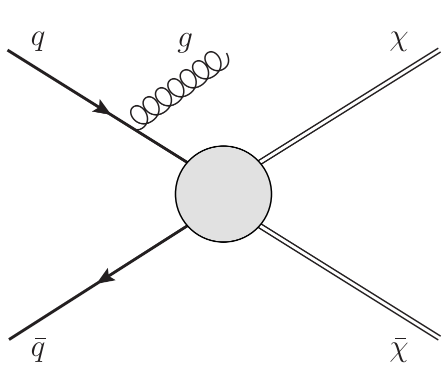
New coloured particles are produced through the interaction with quarks and gluons

E.g., in SUSY dominant production will be in

$$\tilde{g}\tilde{g} \quad \tilde{g}\tilde{q} \quad \tilde{q}\tilde{q}$$

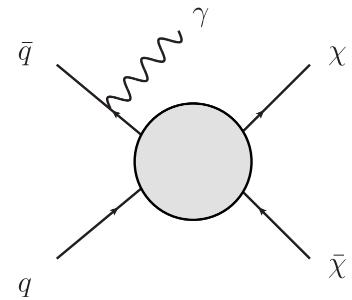
These subsequently decay in lighter particles and eventually in the LSP





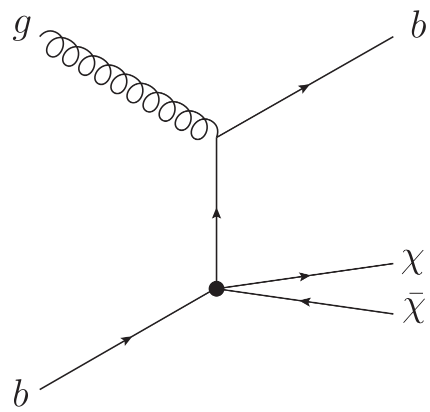
Monojet

1502.01518



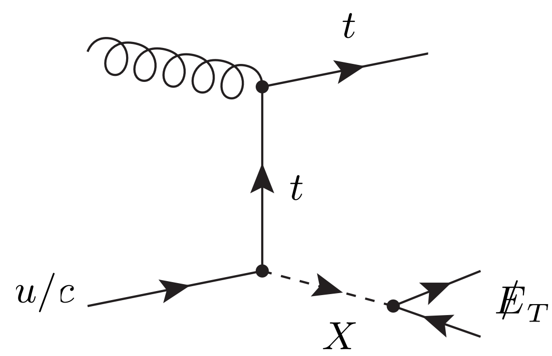
Monogamma

1411.1559



Heavy quarks

1410.4031

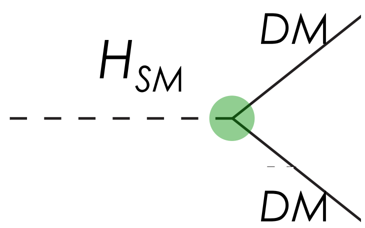


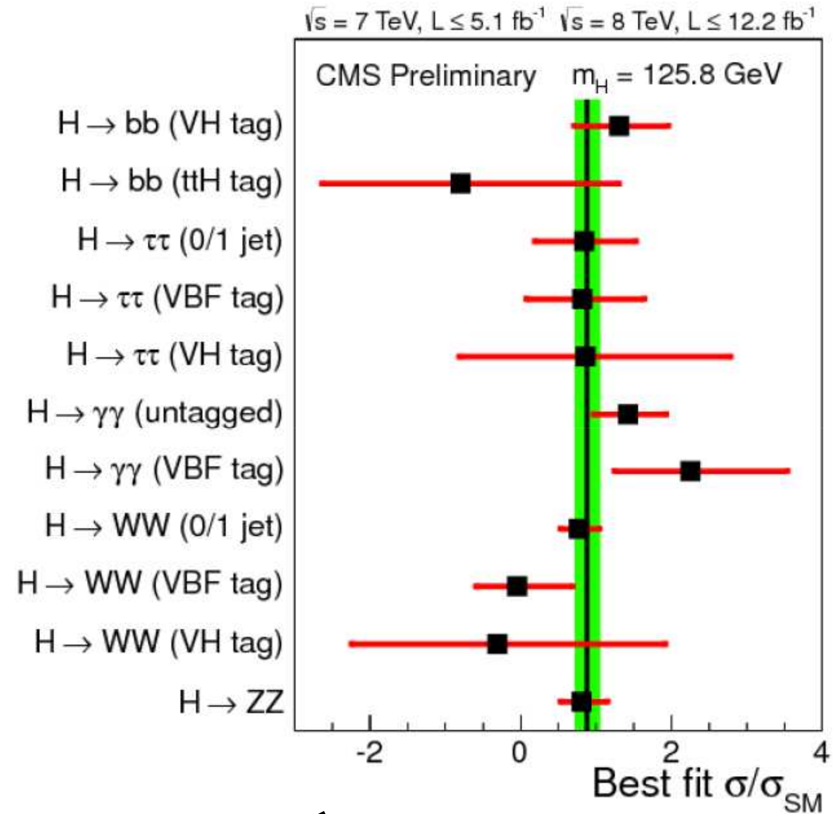
Single top

1410.5404

Observation of (a/the) SM-like Higgs boson with mH~125 GeV

A bound on the invisible decay width of the Higgs can be derived

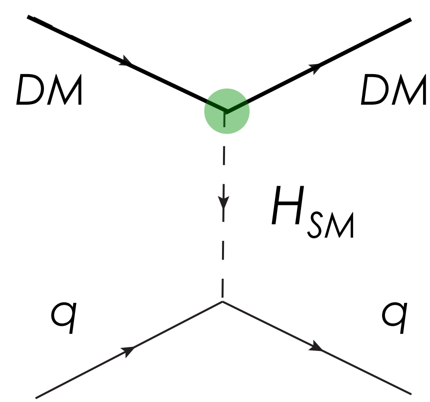




$$\mathrm{BR}(h^0_{SM} \to inv) \lesssim 0.20$$

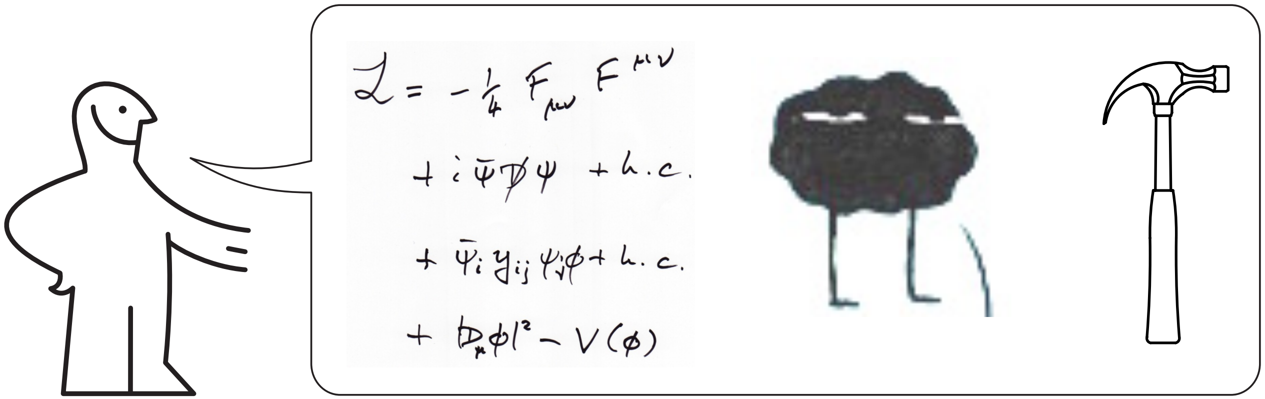
Important for light WIMPs ($m_{DM} < m_H/2$)

This has implications for the relic density and scattering cross section of DM particles



Particle models for Dark Matter

MÖRK MATERIA MODELL



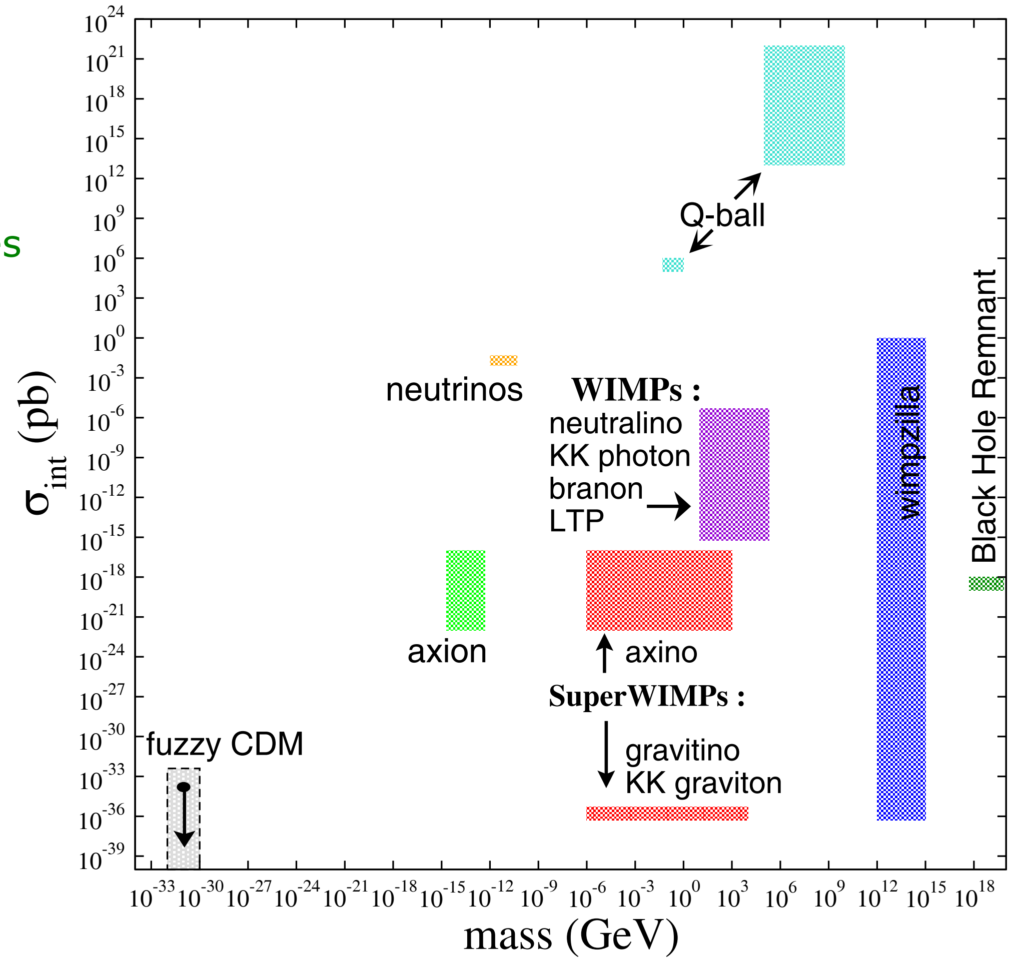
Good candidates for Dark Matter have to fulfil the following conditions

- Neutral
- Stable on cosmological scales (*)
- Cold, non-relativistic, when structures are formed (**)
- Reproduce the correct relic abundance
- Not excluded by current searches
- No conflicts with BBN or stellar evolution

We don’t know yet what DM is... but we do know many of its properties

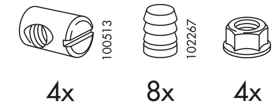
Many candidates in Particle Physics

- Axions
- Weakly Interacting Massive Particles (WIMPs)
- SuperWIMPs and Decaying DM
- WIMPzillas
- Asymmetric DM
- SIMPs, CHAMPs, SIDMs, ETCs...



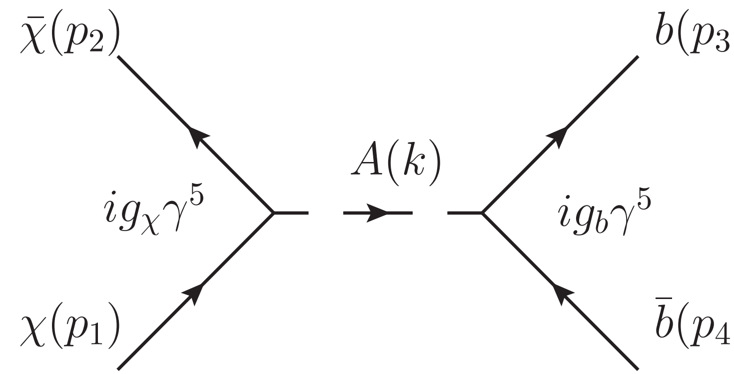
They have very different properties and cannot be searched for iun the same way

A simple example: fermion DM + Pseudoscalar mediator + SM



Let us assume that the DM particle is a fermion X, which connects to SM particles through the exchange of a pseudoscalar A

$$\mathcal{L} = i\left(g_\chi \bar{\chi}\gamma^5\chi + g_b \bar{b}\gamma^5 b\right) A$$



Is it viable?

- Is the relic density correct?

$$\langle\sigma v\rangle_{ij} = a_{ij} + \frac{b_{ij}}{x} = a_{ij} + b_{ij}v^2$$

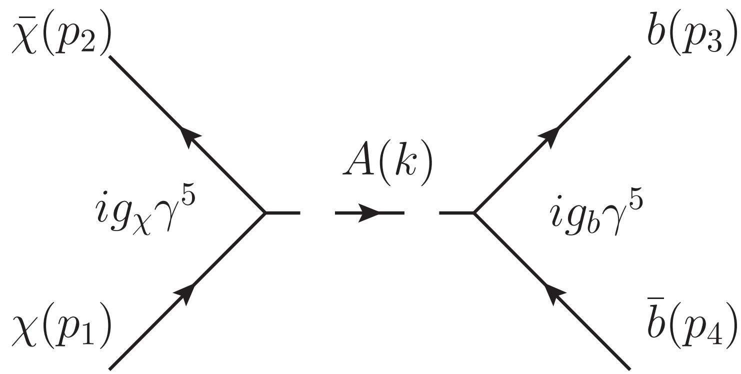
$$a_{ij} \quad = \quad \frac{1}{m_\chi^2}\left(\frac{N_c}{32\pi}\beta(s, m_i, m_j)\frac{1}{2}\int_{-1}^{1} d\cos\theta_{CM}|\mathcal{M}_{\chi\chi\to ij}|^2\right)_{s=4m_\chi^2}$$

$$\beta(s, m_i, m_j) = \left(1 - \frac{(m_i + m_j)^2}{s}\right)^{1/2}\left(1 - \frac{(m_i - m_j)^2}{s}\right)^{1/2}$$

A simple example: fermion DM + Pseudoscalar mediator + SM

This results in

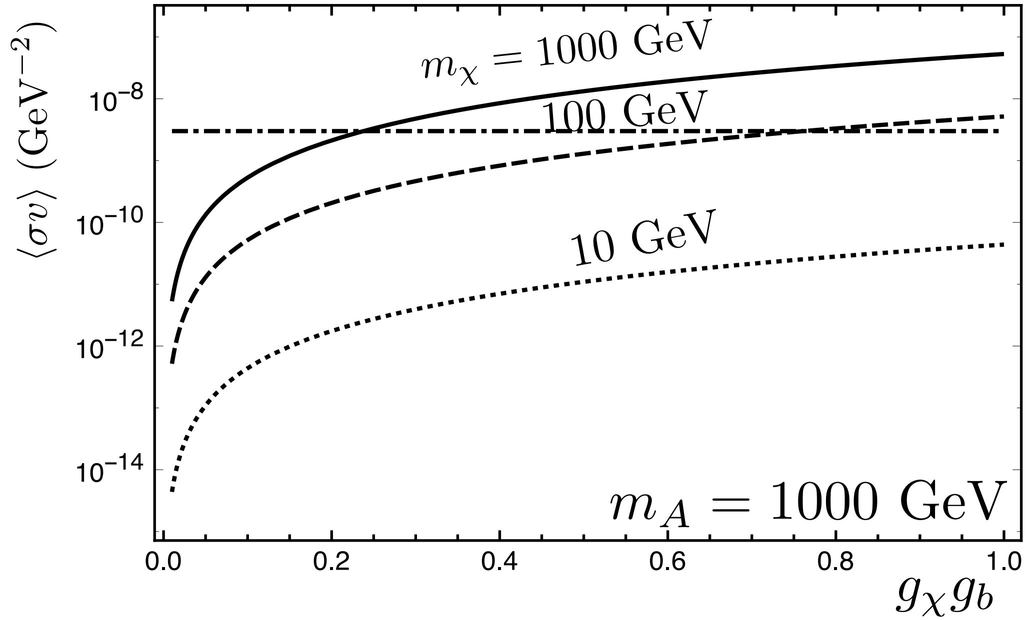
$$\langle \sigma v \rangle \approx \frac{3}{2\pi} \frac{(g_\chi g_b)^2 m_\chi^2 \sqrt{1 - m_b^2/m_\chi^2}}{(4m_\chi^2 - m_A^2)^2 + m_A^2 \Gamma_A^2}$$



Using the expression of the relic density

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-10}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

$$g_\chi g_b \sim 0.1 - 1$$



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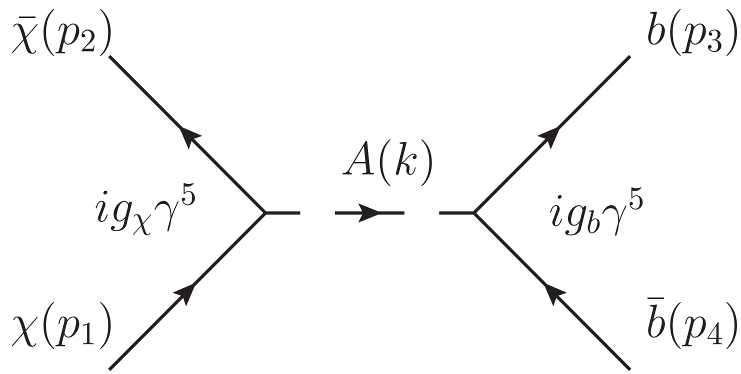

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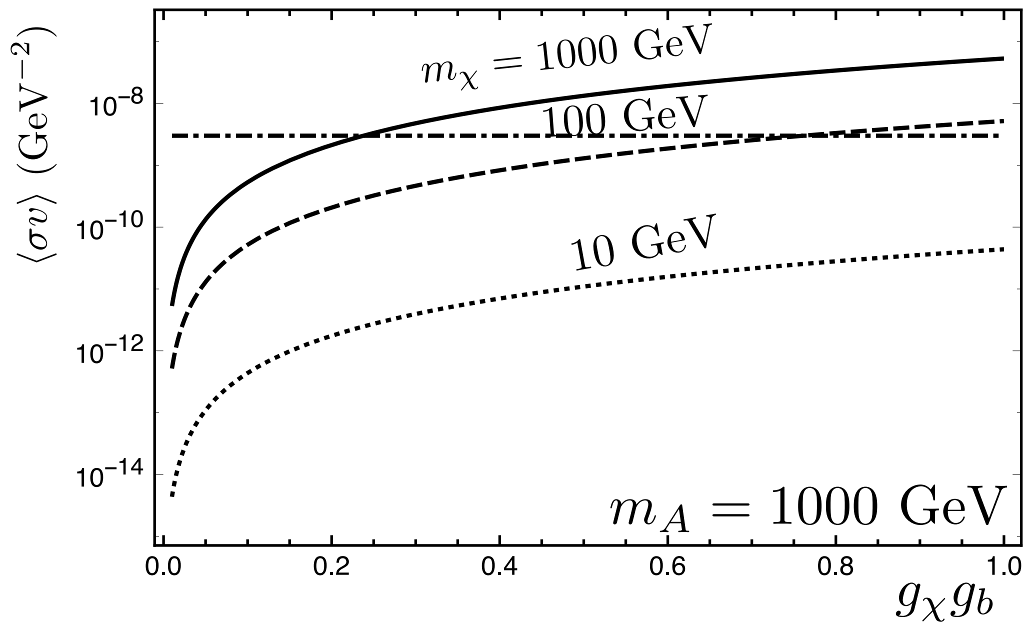

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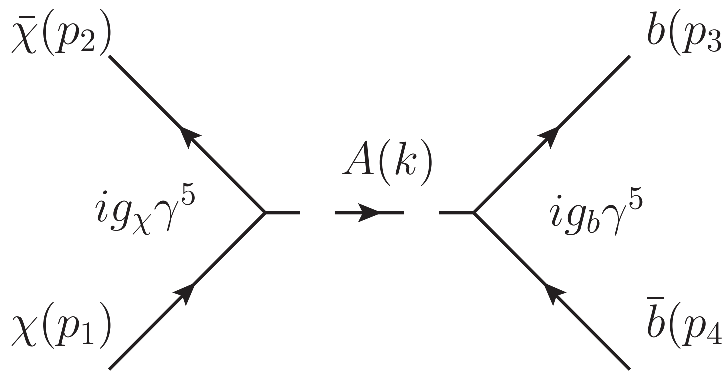


Using the expression of the relic density

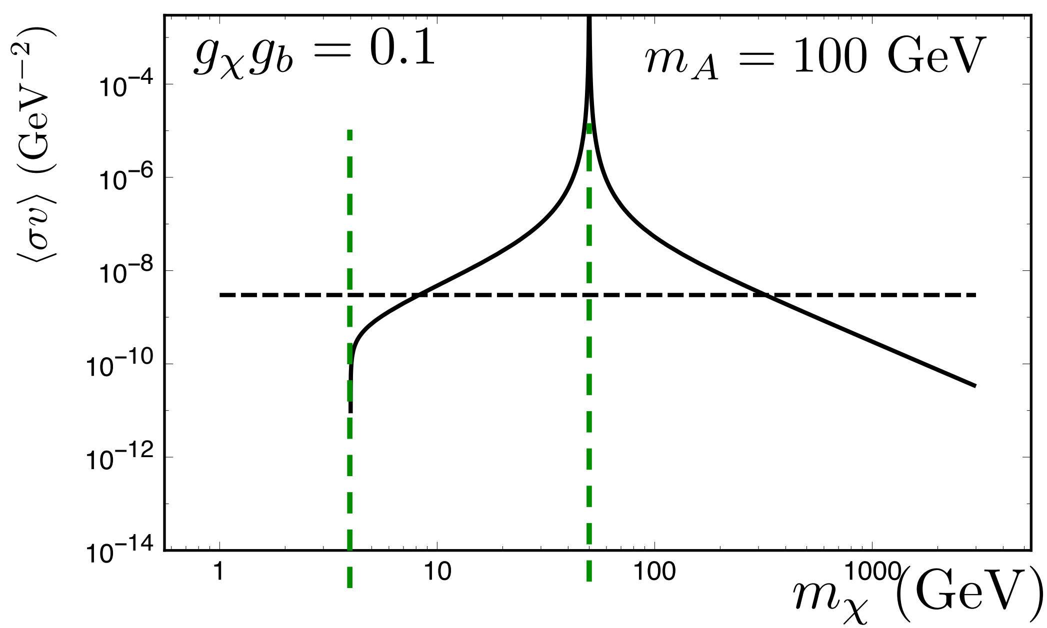
$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-10}\ \text{GeV}^{-2}}{\langle \sigma v \rangle}$$

Production threshold

$$m_\chi = m_b$$

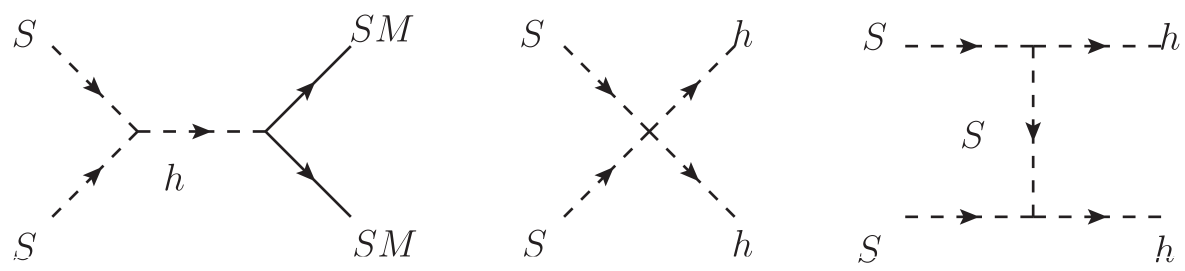
Resonance

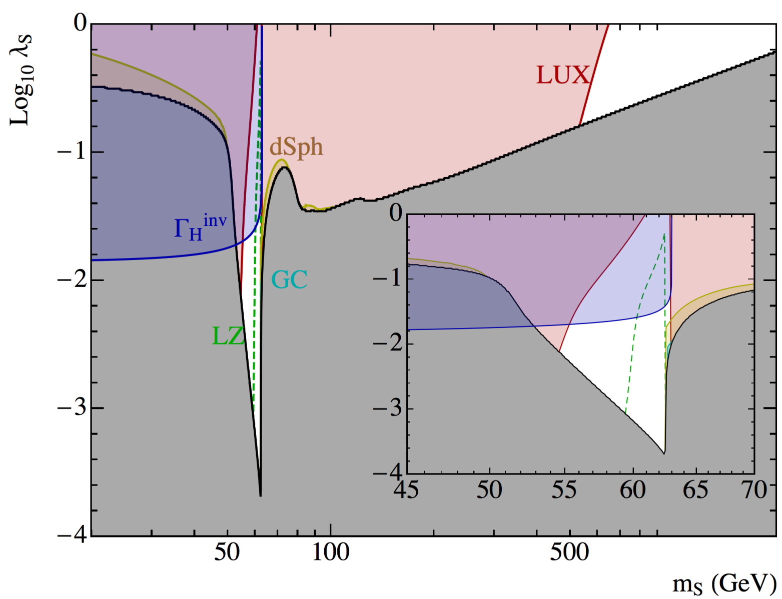
$$m_\chi = \frac{1}{2} m_A$$



Tension in some simplified models

The singlet scalar Higgs portal is extremely constrained by a combination of direct-indirect-LHC constraints



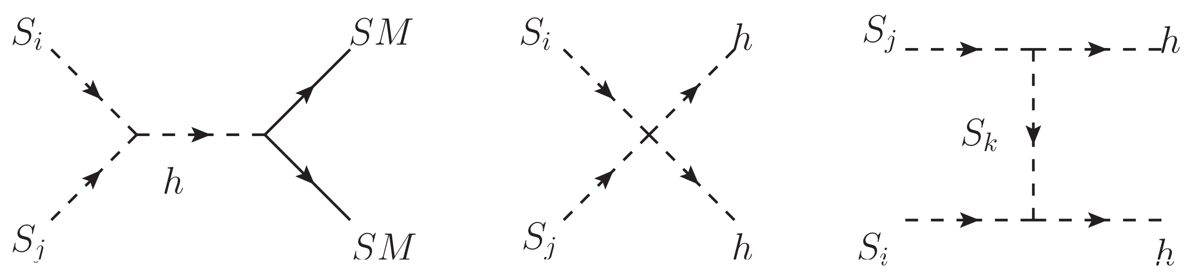


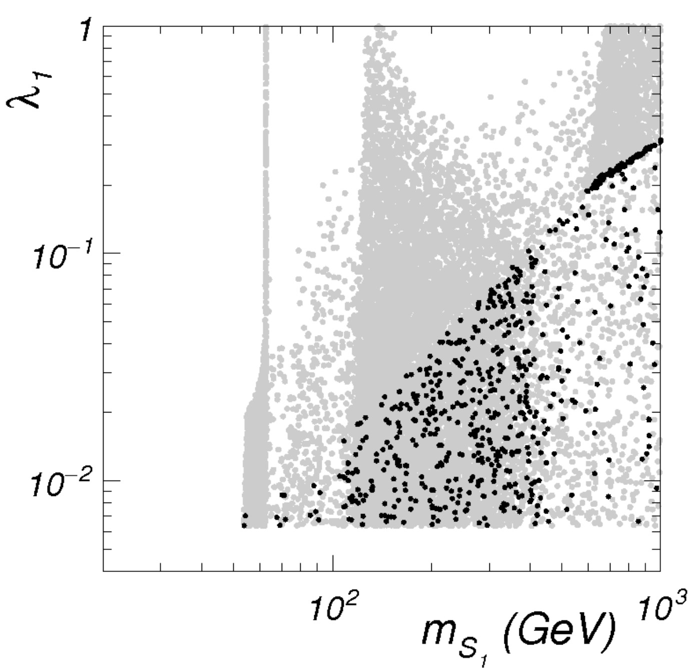
Casas, DGC, Moreno, Quilis 1701.08134
See also GAMBIT 1705.07931

- Best bounds are from direct detection (LUX, XENON1T)
- Future LZ completely explores it below ~1TeV
- Indirect constraints from Fermi-LAT to explore resonance region

Tension in some simplified models

This tension can be alleviated with the inclusion of a second scalar Higgs





- Direct detection bounds can be less effective
- DM particles as light as ~100 GeV are possible

Casas, DGC, Moreno, Quilis 1701.08134

SUSY Dark Matter

Particle Physics models for dark matter

Well motivated DM models in theories beyond the Standard Model (e.g., Supersymmetry)

Minimal SUSY extension

Squarks	$\tilde{u}_{R,L}$, $\tilde{d}_{R,L}$ $\tilde{c}_{R,L}$, $\tilde{s}_{R,L}$ $\tilde{t}_{R,L}$, $\tilde{b}_{R,L}$
Sleptons	$\tilde{e}_{R,L}$, $\tilde{\nu}_e$ $\tilde{\mu}_{R,L}$, $\tilde{\nu}_\mu$ $\tilde{\tau}_{R,L}$, $\tilde{\nu}_\tau$
Neutralinos	$\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_{1,2}$
Charginos	$\tilde{W}^\pm$, $\tilde{H}^\pm_{1,2}$
Gluino	$\tilde{g}$

WIMPs

Neutralino

Good annihilation cross section. it is a WIMP

Sneutrino

Viable candidates in scenarios with Right-Handed sneutrinos

eWIMPs

Gravitino (Superpartner of the graviton)

Axino (Superpartner of the axion)

Neutralino in the MSSM

Linear Superposition of Bino, Wino and Higgsinos

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 \end{pmatrix}$$

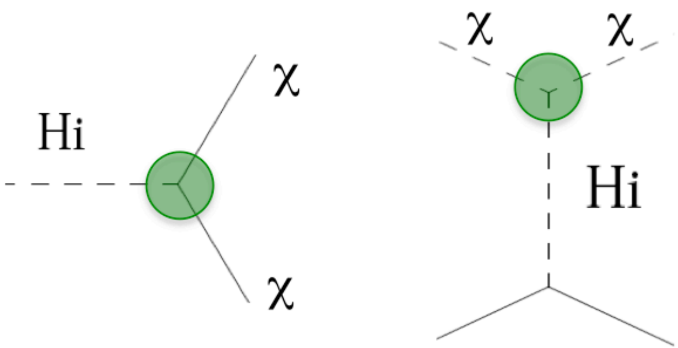
Its detection properties depend crucially on its composition

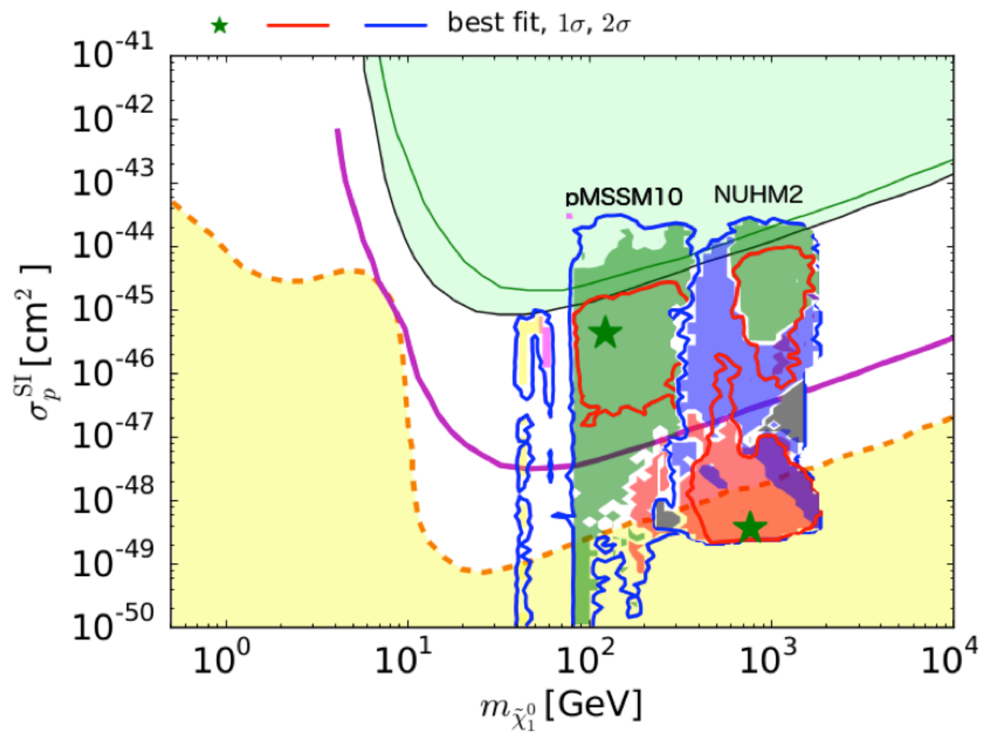
$$\tilde{\chi}_1^0 = \underbrace{N_{11}\,\tilde{B}^0 + N_{12}\,\tilde{W}_3^0}_{\text{Gaugino content}} + \underbrace{N_{13}\,\tilde{H}_d^0 + N_{14}\,\tilde{H}_u^0}_{\text{Higgsino content}}$$

Neutralino in the MSSM

Impose LHC1 bounds and explore the predictions of MSSM parameter space

- Bounds on SUSY masses
- Low-energy observables
- Invisible Higgs decay





MSSM after LHC1
Bagnaschi et al. 2015

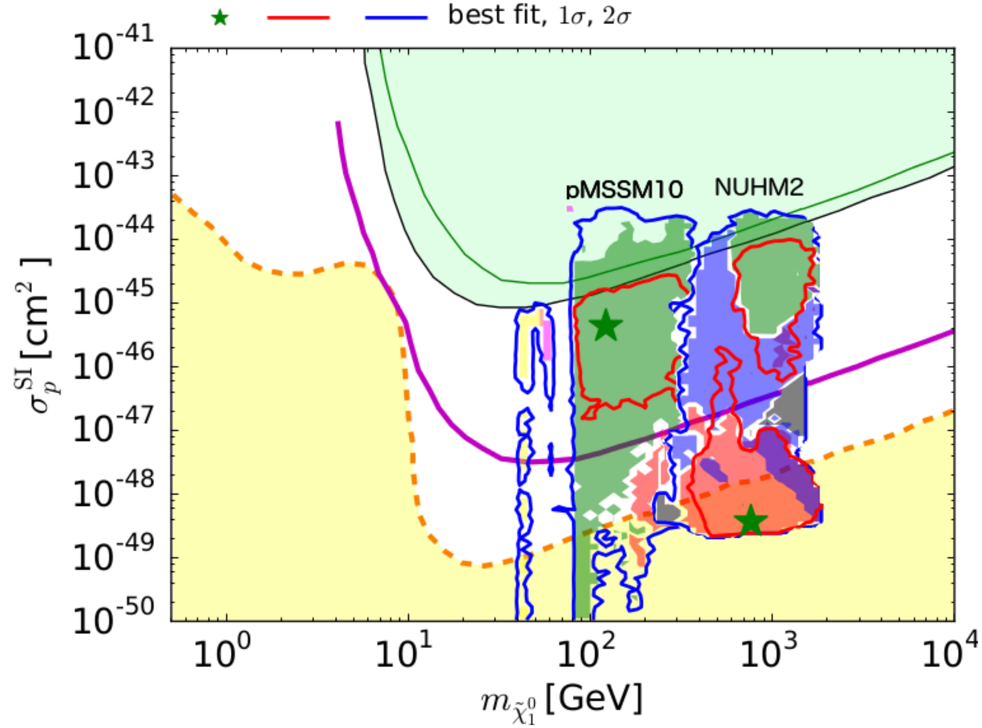
The current bound on BR(H→ inv) sets constraints on the DM-Higgs coupling

This also translates into (upper) bounds for the scattering cross section of low-mass WIMPs

Neutralino in the MSSM

Impose LHC1 bounds and explore the predictions of MSSM parameter space

- Bounds on SUSY masses
- Low-energy observables
- Invisible Higgs decay
- Correct DM relic density



MSSM after LHC1
Bagnaschi et al. 2015

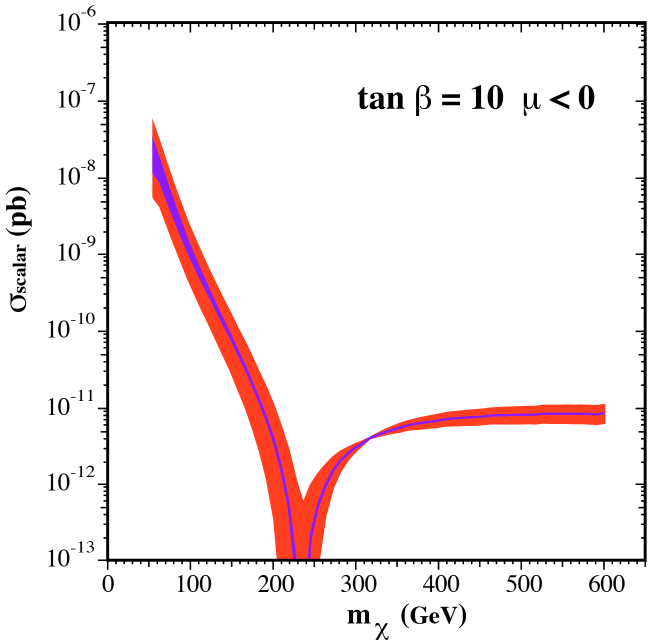
The predictions for the scattering cross section still span many orders of magnitude

(excellent motivation for more sensitive detectors)

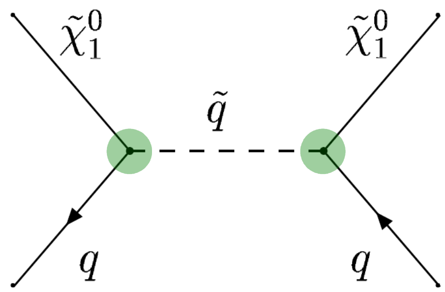
Combined with LHC + Indirect searches → excellent coverage of SUSY parameter space

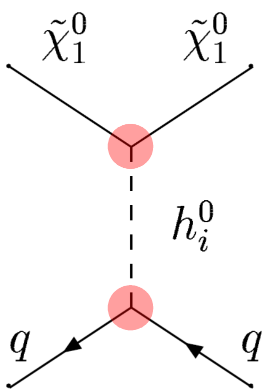
Blind spots in Direct Detection experiments

The neutralino nucleus scatterinc cross section might contain accidental cancelations due to contribution of different diagrams



Ellis, Ferstl, Olive 2000





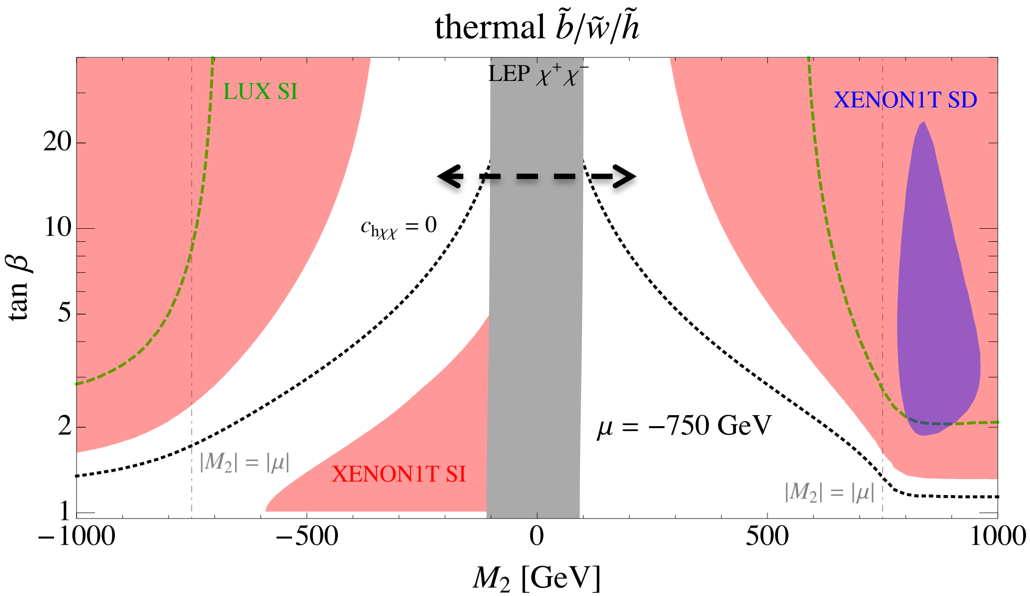
$$\alpha_{3i} = -\frac{1}{2(m_{1i}^2 - m_\chi^2)} Re\left[(X_i)(Y_i)^*\right] - \frac{1}{2(m_{2i}^2 - m_\chi^2)} Re\left[(W_i)(V_i)^*\right]$$

$$- \frac{g m_{qi}}{4 m_W B_i}\left[Re\left(\delta_{1i}[gZ_{\chi 2} - g' Z_{\chi 1}]\right) D_i C_i \left(-\frac{1}{m_{H_1}^2} + \frac{1}{m_{H_2}^2}\right) + Re\left(\delta_{2i}[gZ_{\chi 2} - g' Z_{\chi 1}]\right)\left(\frac{D_i^2}{m_{H_2}^2} + \frac{C_i^2}{m_{H_1}^2}\right)\right]$$

Cancellations in the Higgs-exchange diagrams imply that the scattering is only due to squark exchange (and thus very small ~ $10^{-12\,-14}$ pb)

Blind spots in Direct Detection experiments

There are directions in the neutralino parameter space where direct detection might be inviable. They have been recently characterised (both in MSSM and NMSSM)



Cheung et al. 2012

Some of these regions can be reached with LHC

The cancellation can occur at different points for the WIMP-proton or WIMP-neutron cross section due to different contributions from different quarks (leading to a sizable isospin-dependence)

Crivellin et al. 2015

The Next-to-Minimal Supersymmetric Standard Model (NMSSM)

In the NMSSM the field structure of the MSSM is modified by the addition of a new superfield $\hat{S}$, which is a singlet under the SM gauge group:

$$\text{NMSSM} \quad = \quad \text{MSSM} + \hat{S} \begin{cases} 2 \text{ extra Higgs (CP} - \text{even, CP} - \text{odd)} \\ 1 \text{ additional Neutralino} \end{cases}$$

- This leads to the following new terms in the superpotential

$$W = Y_u H_2 Q u + Y_d H_1 Q d + Y_e H_1 L e - \lambda S H_1 H_2 + \frac{1}{3}\kappa S^3$$

- When Electroweak Symmetry Breaking occurs the Higgs field takes non-vanishing VEVs:

$$\langle H_1^0 \rangle = v_1 \quad ; \quad \langle H_2^0 \rangle = v_2 \quad ; \quad \langle S \rangle = s \, (= \frac{\mu}{\lambda})$$

EW-scale Higgsino-mass parameter

The Next-to-Minimal Supersymmetric Standard Model (NMSSM)

In the NMSSM the field structure of the MSSM is modified by the addition of a new superfield $\hat{S}$, which is a singlet under the SM gauge group:

$$\text{NMSSM} \quad = \quad \text{MSSM} + \hat{S} \begin{cases} 2 \text{ extra Higgs (CP -- even, CP -- odd)} \\ 1 \text{ additional Neutralino} \end{cases}$$

- New tree-level corrections to the Higgs mass → m_H=126 GeV with less fine-tuning

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \boxed{\lambda^2 v^2 \sin^2 2\beta} + \delta(m_h^2)$$

- Very interesting DM and collider phenomenology (e.g., large neutralino cross section)

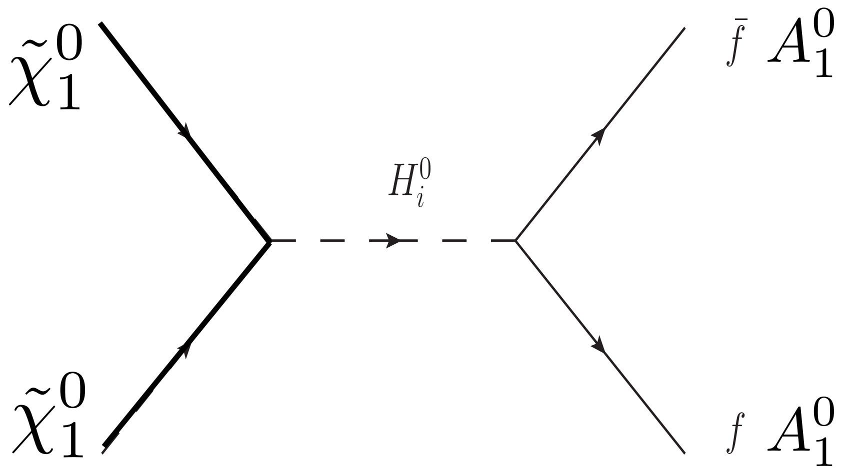
Light neutralino DM in the NMSSM

Easier to accommodate than in the MSSM:

- The neutralino can be singlino-like (singlino parameter less constrained by LHC)

- New light states (e.g., very light scalar and pseudoscalar Higgses) provide new annihilation channels + resonances

  (Useful to obtain light neutralinos)



Scan in the parameter space

$$2.89 \times 10^{-4} < \mathrm{BR}(b \to s\gamma) < 4.21 \times 10^{-4}$$

$$1.5 \times 10^{-9} < \mathrm{BR}(B_s \to \mu^+\mu^-) < 4.3 \times 10^{-9}$$

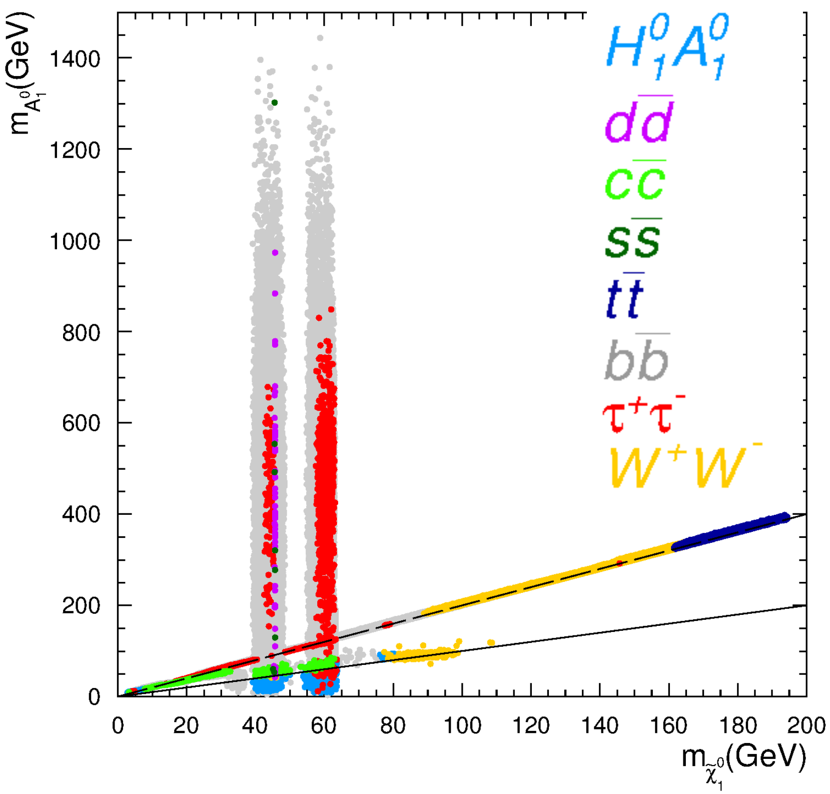
$$0.85 \times 10^{-4} < \mathrm{BR}(B^+ \to \tau^+\nu_\tau) < 2.89 \times 10^{-4}$$

Parameter	Scan 1	Scan 2	Scan 3
M_1	$[1, 200]$	$[1, 40]$	$[1, 200]$
M_2	$[200, 1000]$	$[200, 1000]$	$[700, 1000]$
$\tan\beta$	$[4, 20]$	$[4, 20]$	$[2, 50]$
λ	$[0.1, 0.6]$	$[0.1, 0.6]$	$[0.001, 0.1]$
κ	$[0, 0.1]$	$[0, 0.1]$	$[0.1, 0.6]$
A_λ	$[500, 5000]$	$[500, 5000]$	$[500, 1100]$
A_κ	$[-50, 50]$	$[-30, 0]$	$[-50, 50]$
μ_{eff}	$[110, 250]$	$[160, 250]$	$[200, 400]$

Obtaining the correct relic abundance is possible but fine-tuned

$$\Omega_{\tilde{\chi}_1^0} h^2 < 0.13$$

- Resonances with *Z* and *H* boson
- Resonance with *A*
- Pair annihilation into *AA*



Normalise direct and indirect detection rate by the relative DM abundance

$$\xi = \min[1, \Omega h^2/0.11]$$

Indirect DM detection of (light) neutralino in NMSSM

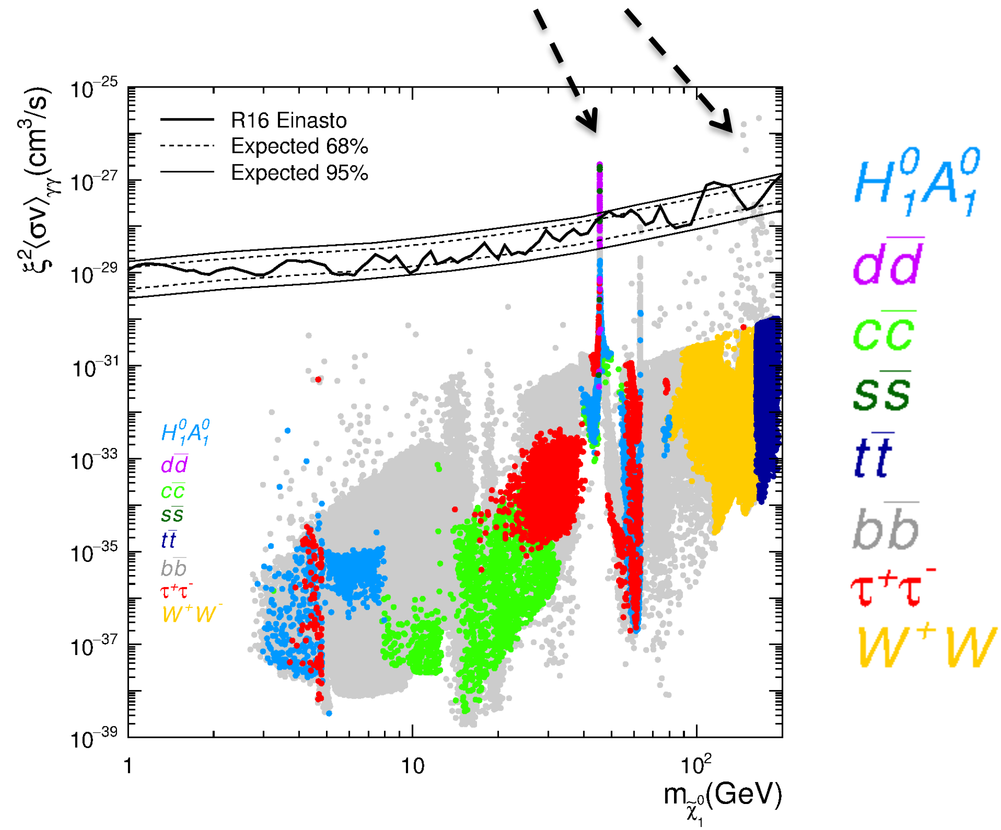
Very light neutralinos are viable

$$m_{\tilde{\chi}_1} > 3\ \text{GeV}$$

Resonant annihilation can lead to a Breit-Wigner enhancement of the annihilation cross section in the DM halo

The decay width of the Z is larger and therefore the BW effect more pronounced.

Resonance with Z or H boson

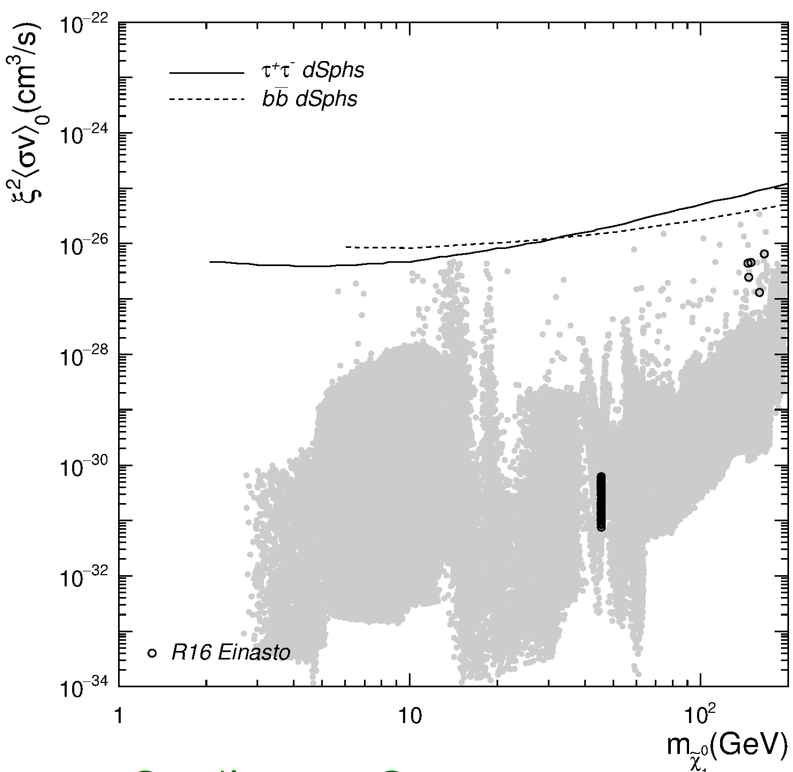


Gamma ray lines

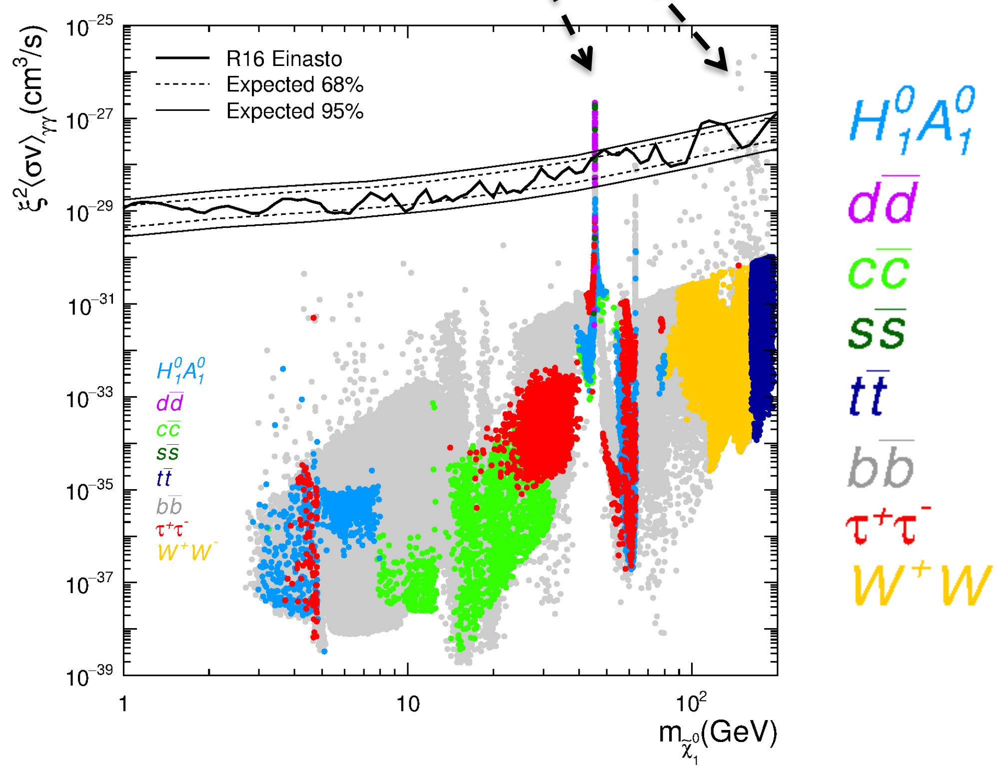
Indirect DM detection of (light) neutralino in NMSSM

Resonance with Z or H boson

Fermi-LAT bound on dSph



Continuous Gamma

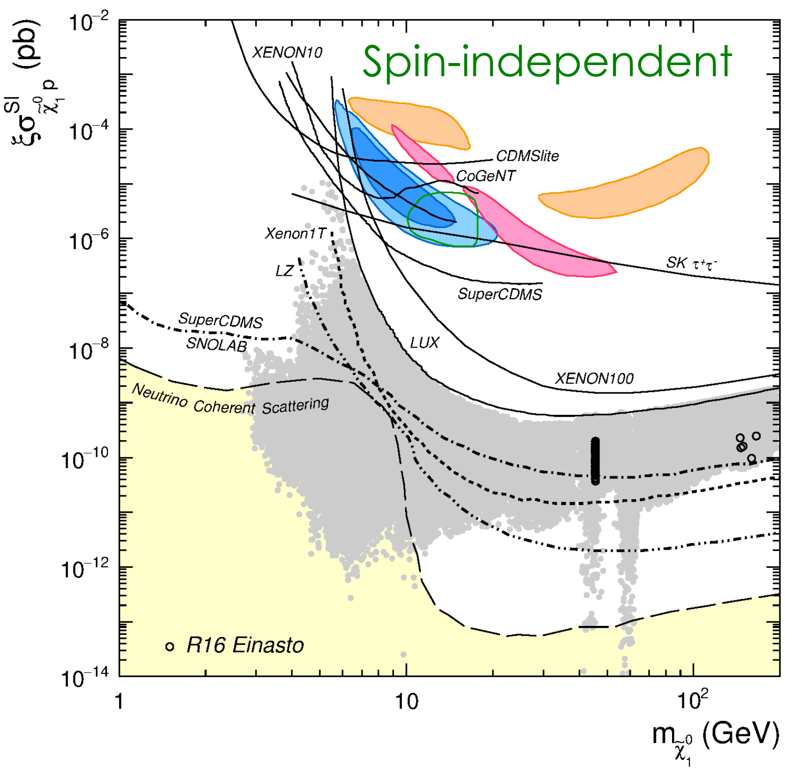


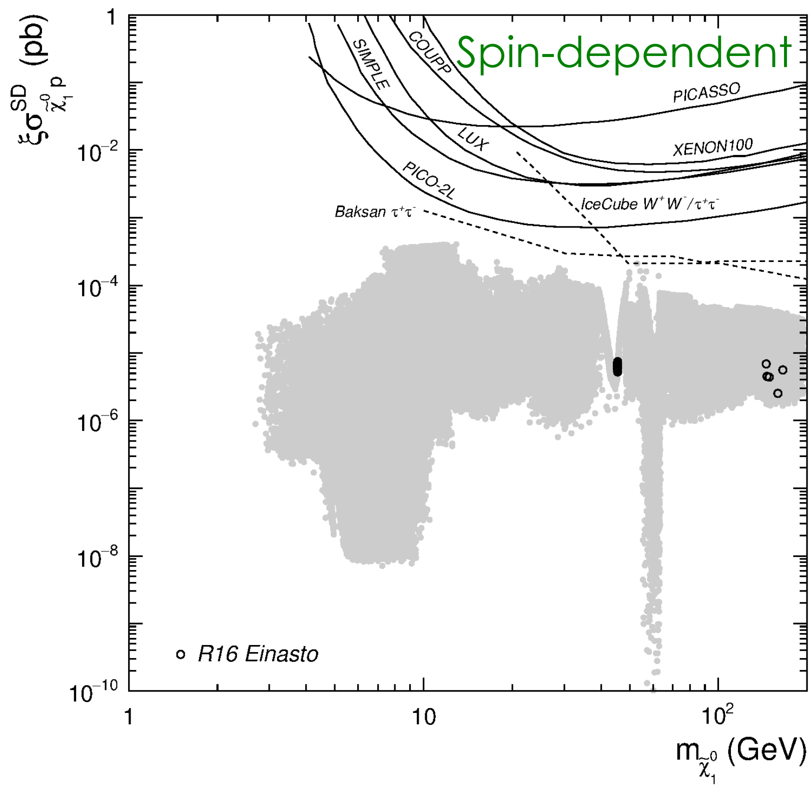
Gamma ray lines

Processes with internal bremstrahlung are also possible for heavier neutralinos

Direct detection of (light) neutralino in NMSSM

Neutralinos populate the whole region with low-masses





Relatively large SD cross section. Some points in the vicinity of current constraints, also by neutrino experiments (e.g. Antares or IceCube)

Right-handed sneutrino in the NMSSM

- Addition of TWO new superfields, ***S***, ***N***, singlets under the SM gauge group

$$\text{NMSSM} \quad = \quad \text{MSSM} + \hat{S} \begin{cases} 2 \text{ extra Higgs (CP-even, CP-odd)} \\ 1 \text{ additional Neutralino} \end{cases}$$

$$+ N \begin{cases} 1 \text{ additional (right-handed) Neutrino} \\ \text{and sneutrino} \end{cases}$$

- New terms in the superpotential

$$W = Y_u\, H_2\, Q\, u + Y_d\, H_1\, Q\, d + Y_e\, H_1\, L\, e - \lambda\, S\, H_1 H_2 + \frac{1}{3}\kappa S^3$$

$$W \quad = \quad W_{\text{NMSSM}} + \lambda_N S N N + y_N L \cdot H_2 N$$

- After Radiative Electroweak Symmetry-Breaking

$$\langle H_1^0 \rangle = v_1 \quad ; \quad \langle H_2^0 \rangle = v_2 \quad ; \quad \langle S \rangle = s$$

$$\begin{cases} \mu\, H_1\, H_2 \\ m_N\, N\, N \end{cases}$$

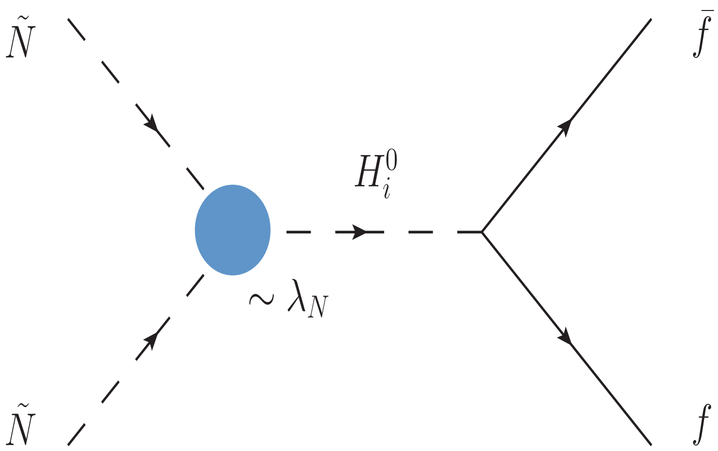
EW-scale Higgsino-mass parameter & Majorana neutrino mass

Majorana mass of order of the EW scale → the Yukawa is small

$$m_{\nu_L} = \frac{y_N^2 v_2^2}{M_N} \longrightarrow y_N = \mathcal{O}(10^{-6})$$

This determines the LR mixing of the neutrino/sneutrino sector

Pure Right and Left-handed fields



The correct relic density can be obtained for λ_N~0.1 (it is a WIMP) and a wide range of sneutrino masses

DGC, Muñoz, Seto '07
DGC, Seto '09

Light RH sneutrinos are viable and with a large scattering cross section

DGC, Huh, Peiró, Seto '11

The RH sneutrino mass can be tuned (as well as the relic density) using the three free parameters of the model, without affecting the NMSSM spectrum

$$m^2_{\tilde{N}_1} = m^2_{\tilde{N}} + |2\lambda_N v_s|^2 + |y_N v_2|^2 \pm 2\lambda_N \left(A_{\lambda_N} v_s + (\kappa v_s^2 - \lambda v_1 v_2)^\dagger \right)$$

Small RH sneutrino mass can be obtained with O(100 GeV) soft terms

Parameter	Range
$\tan\beta$	$[4, 10],\ [10, 20]$
λ	$[0.1, 0.6]$
κ	$[0.01, 0.1]$
A_λ	$[500, 1100]$
A_κ	$[-50, 50]$
μ	$[110, 250]$
λ_N	$[0.07, 0.4]$
A_{λ_N}	$[-1100, -500]$
$m_{\tilde{N}_1}$	$[1, 50]$

Random scan on the parameter space and impose low-energy constraints

$$2.89 \times 10^{-4} < \mathrm{BR}(b \to s\gamma) < 4.21 \times 10^{-4}$$
$$1.5 \times 10^{-9} < \mathrm{BR}(B_s \to \mu^+\mu^-) < 4.3 \times 10^{-9}$$
$$0.85 \times 10^{-4} < \mathrm{BR}(B^+ \to \tau^+\nu_\tau) < 2.89 \times 10^{-4}$$

We contemplate the possibility that the RH sneutrino is only a part of all the DM

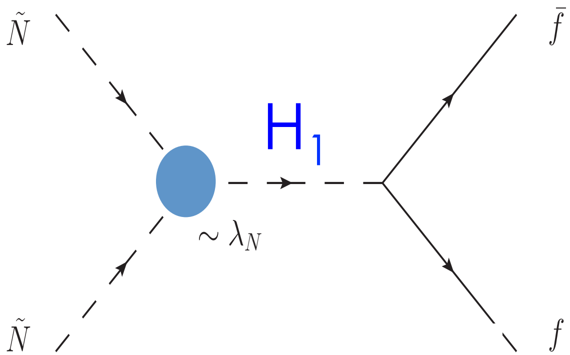
$$0.001 < \Omega_{\tilde{N}_1} h^2 < 0.13$$

Spectrum and low-energy observables

Higgs constraints + Relic abundance →

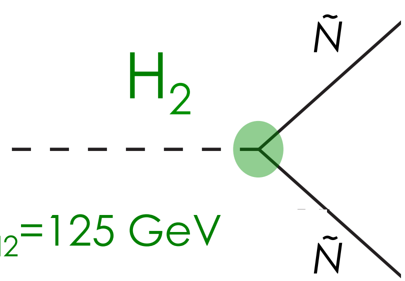
the RH sneutrino couples to a very light singlet-like Higgs

or annihilates into pair of A_1A_1

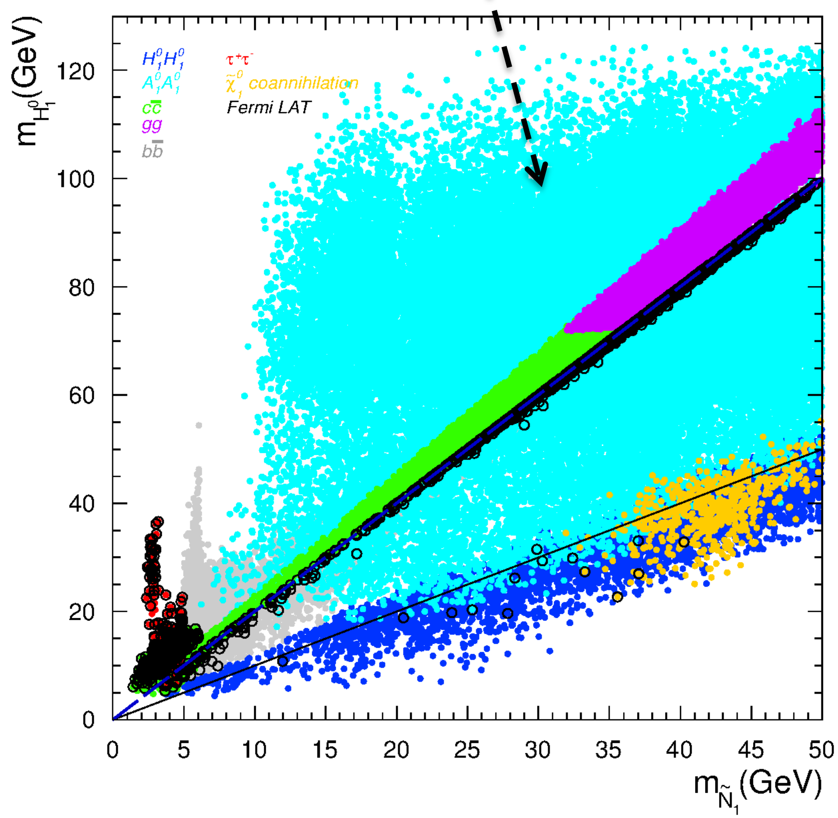


m_{H1}<100 GeV

The SM Higgs branching ratios are fulfilled

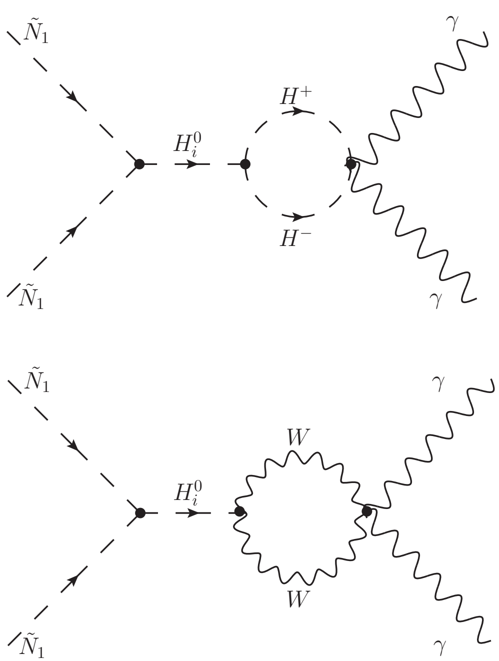


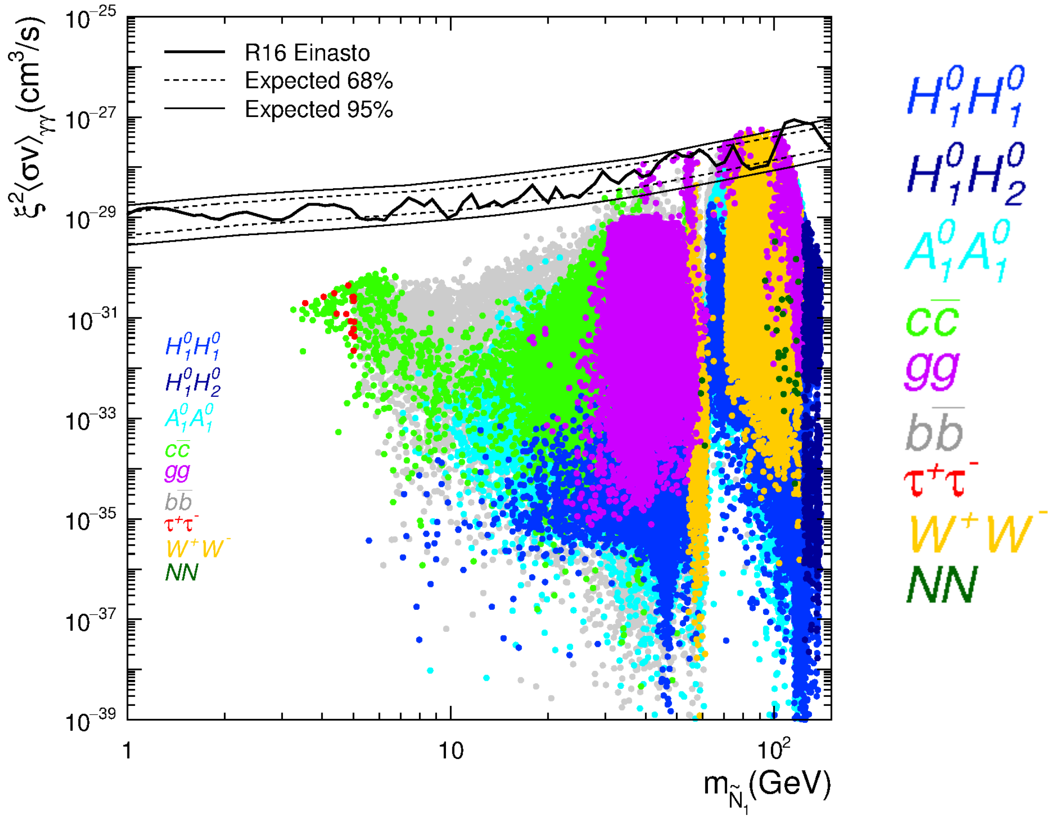
m_{H2}=125 GeV



RH sneutrinos can also be looked for in gamma ray lines

Various contributions at 1 loop





Breit Wigner effects with the lightest CP-even Higgs

Threshold enhancement for channels with W loops and charginos

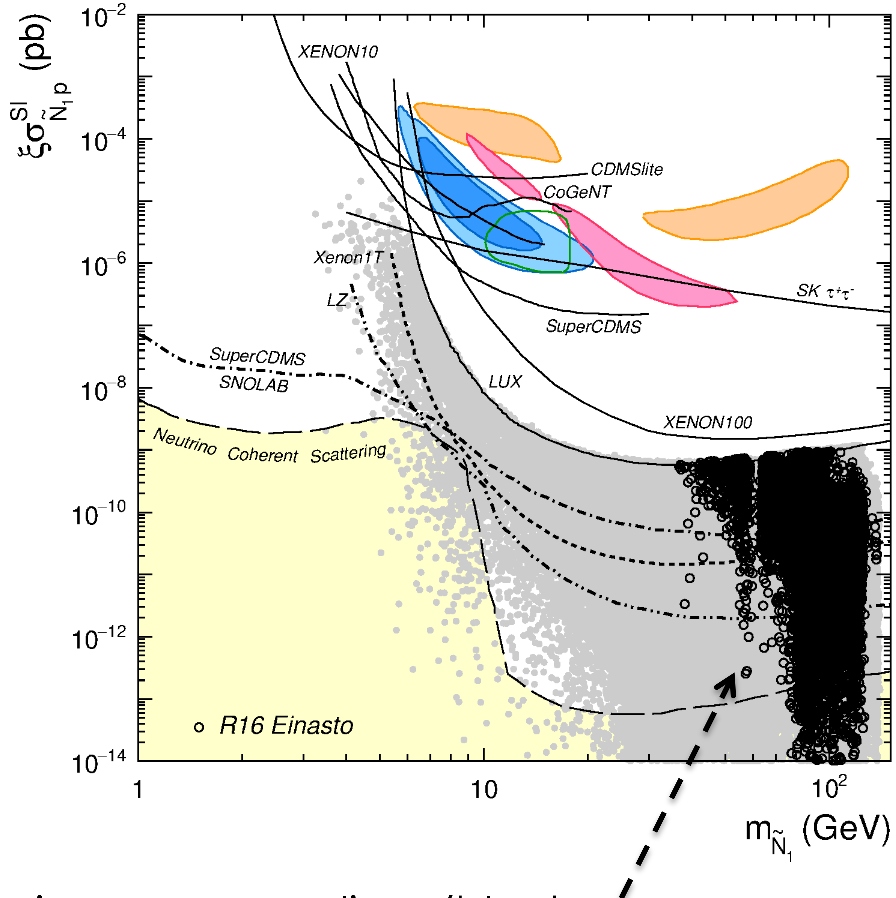
Direct detection predictions for (light) RH sneutrinos

The parameter space is more flexible

$$m_{\tilde{N}_1} > 3 \text{ GeV}$$

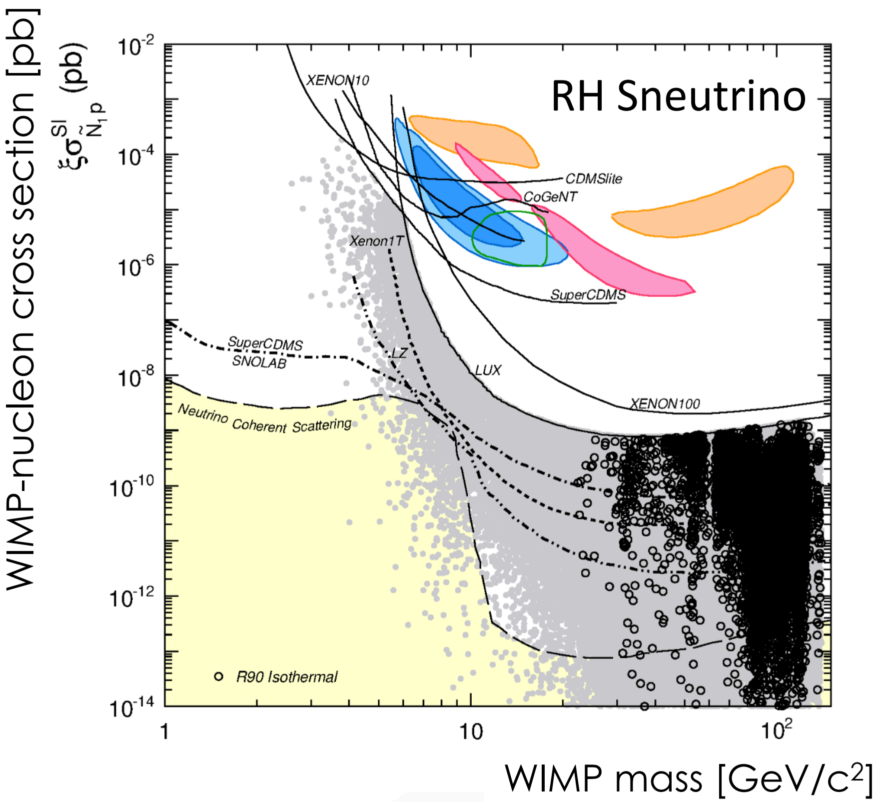
Scattering cross section spans many orders of magnitude

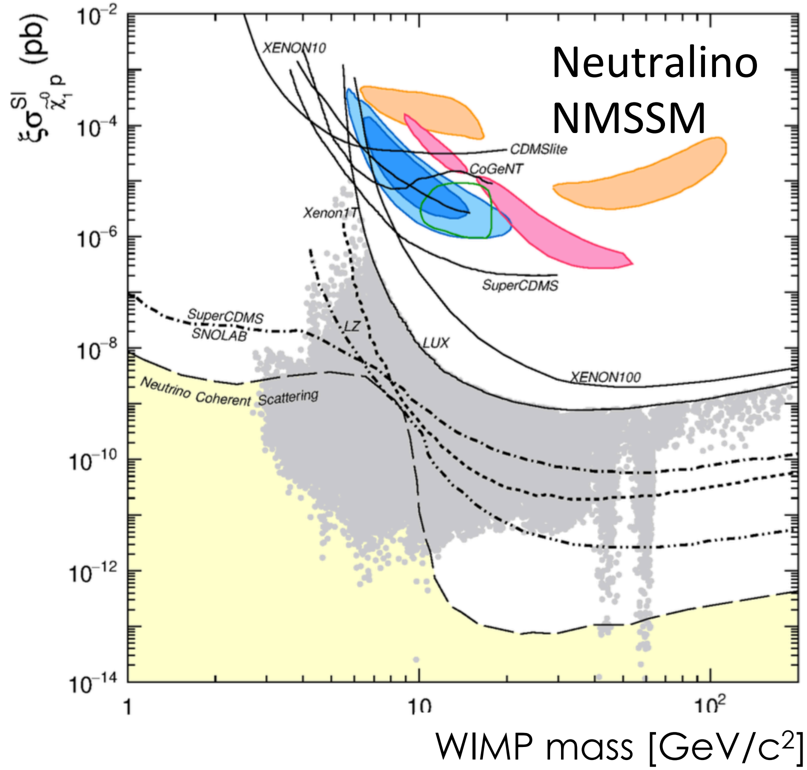
Excellent motivation for low-threshold direct detection experiments



Complementarity with indirect probes via gamma ray lines (black dots)

Light WIMPs are viable in extensions of the MSSM





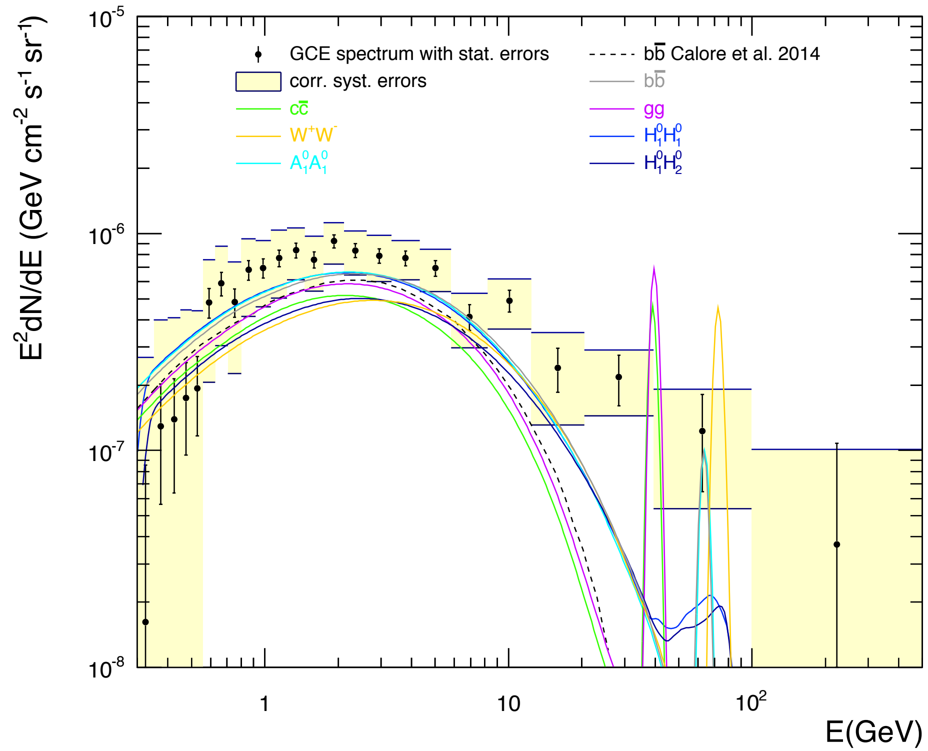
DGC, Peiró, Robles JCAP 08 (2014) 005
DGC, Peiró Robles 2015

Excellent motivation for low-mass WIMP searches

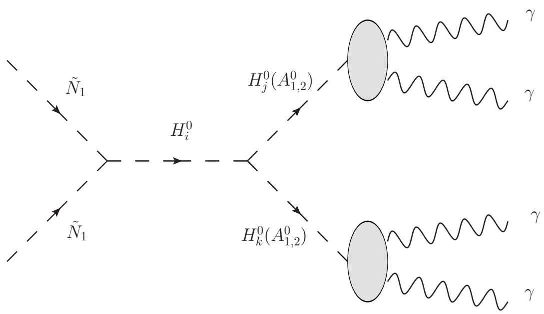
RH Sneutrinos and the GCE

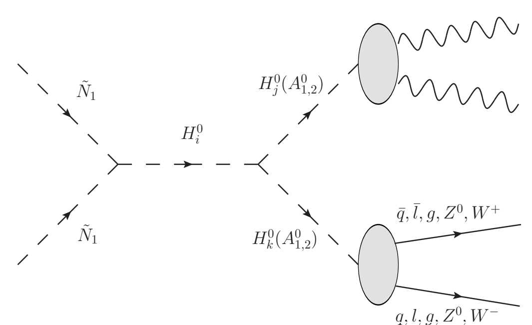
The RH sneutrino can also provide a good fit to the GCE

- Light sneutrinos with a variety of final annihilation products
- Correct relic abundance (annihilation cross section)



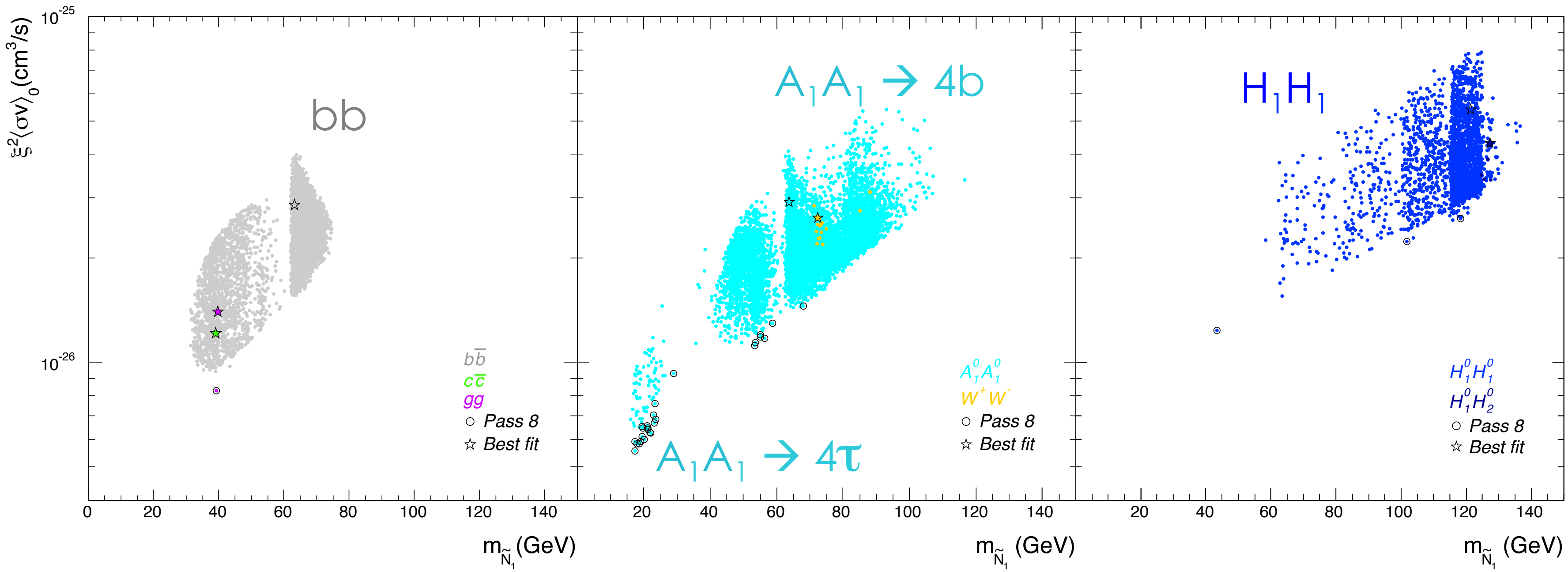
The presence of four-body decays with two or four photons in the final state gives rise to box-shaped features and lines.





This improves the fit at high energy

Best fit points often correspond to mixed final states



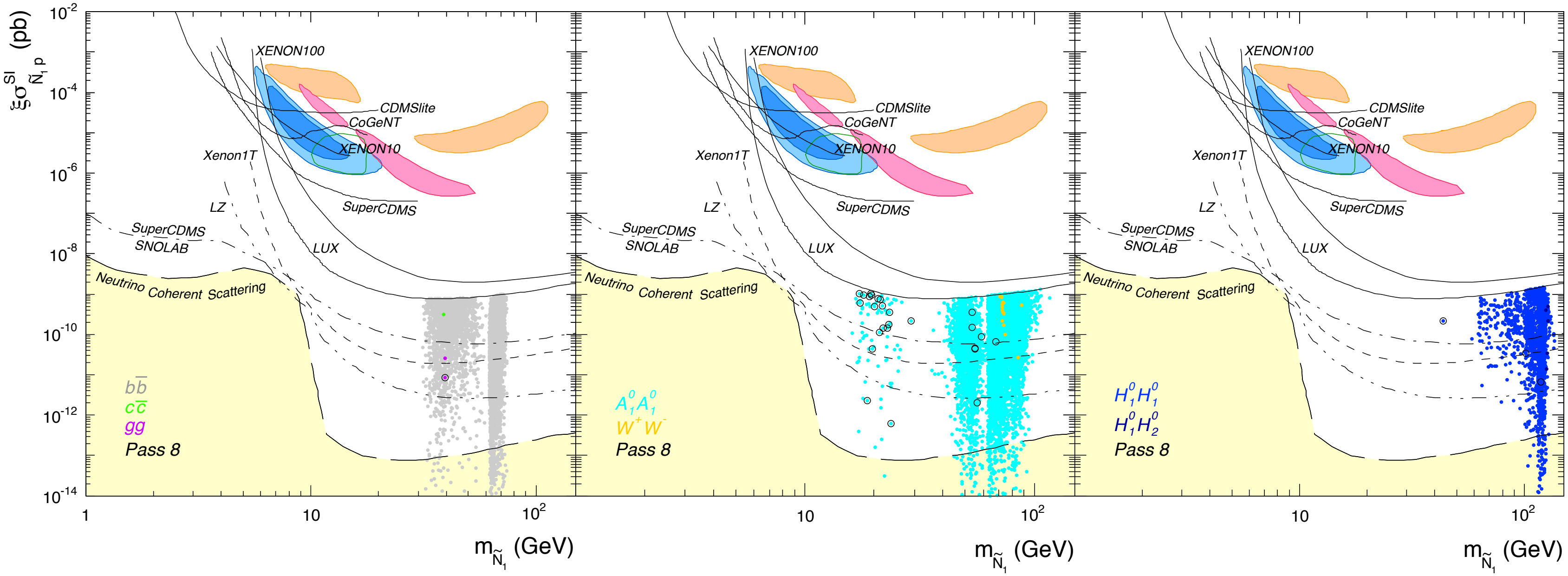
Pure final states

Final state	$m_{\tilde{N}_1}$ (GeV)	$\xi^2\langle\sigma v\rangle_0$ (cm^3/s)	$\Omega_{\tilde{N}_1}h^2$	χ^2
$H_1^0H_1^0$ (91.8%)	119.8	5.1×10^{-26}	0.094	21.9
$A_1^0A_1^0$ (90.6%)	65.0	2.7×10^{-26}	0.109	22.3
$b\bar{b}$ (90.2%)	46.1	1.9×10^{-26}	0.038	22.6

Mixed final states

Final state	$m_{\tilde{N}_1}$ (GeV)	$\xi^2\langle\sigma v\rangle_0$ (cm^3/s)	$\Omega_{\tilde{N}_1}h^2$	χ^2
$A_1^0A_1^0$ (44.7%)	63.8	2.9×10^{-26}	0.061	20.8
$b\bar{b}$ (42.1%)	63.2	2.9×10^{-26}	0.042	21.0
$H_1^0H_1^0$ (71.4%)	121.4	5.4×10^{-26}	0.075	21.6
gg (38.8%)	39.6	1.4×10^{-26}	0.071	23.7
$c\bar{c}$ (33.0%)	39.0	1.2×10^{-26}	0.099	25.4
$H_1^0H_2^0$ (44.5%)	127.4	4.3×10^{-26}	0.054	25.9
$A_1^0A_1^0$ (4τ) (67.5%)	25.5	1.5×10^{-26}	0.068	27.4
W^+W^- (28.0%)	72.4	2.6×10^{-26}	0.104	29.2

Some of these models can be explored in direct detection



There is no correlation among the signatures and the predictions span many orders of magnitude.

The comparison of signatures in direct and indirect searches could be used to test this model.

SUSY eWIMPs

Gravitino (very weakly-interacting) Dark Matter

The spin 3/2 superpartner of the graviton can also be the Lightest Supersymmetric Particle

It interacts only gravitationally → Processes such as decays, annihilation, scattering are gravitationally suppressed

- Not a thermal relic:
  It would decouple extremely early, leading to an overdensity or relativistic (hot) DM.

- Late decays into gravitinos might create problems with BBN (if these take place after ~1s.

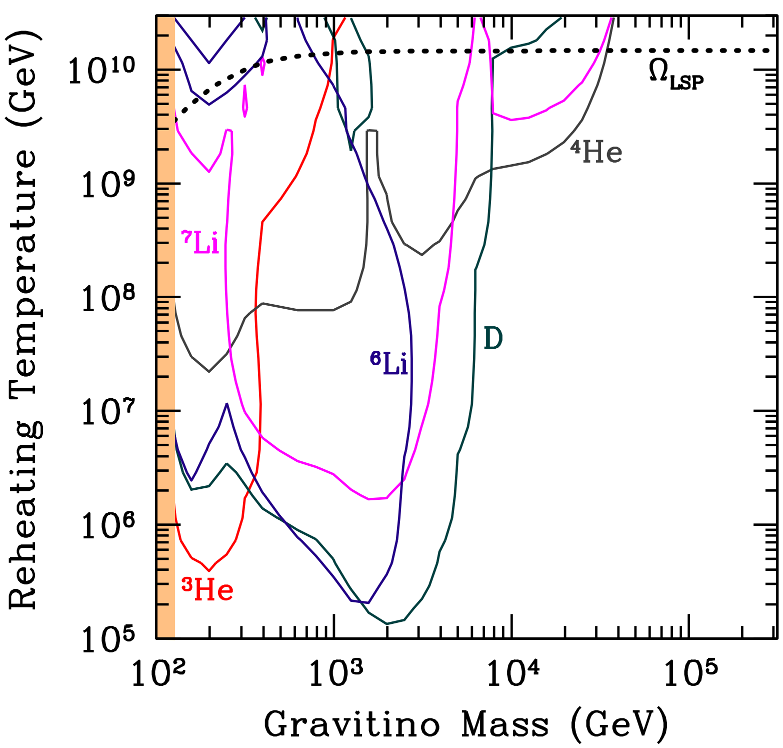
- Stability is not necessary (it could decay very late)

- The gravitino mass is related to the mechanism of Supersymmetry breaking

Gravitino not LSP

If the gravitino is NOT the LSP, it still has influence on the computation of the relic abundance of the WIMP (e.g., the neutralino).

Kawasaki et al. 2008



Late gravitino decays into LSP

$$\Omega_{\rm LSP} h^2 = \Omega_{\tilde{G}} h^2 \frac{m_{\rm LSP}}{m_{\tilde{G}}}$$

Non-termal production of neutralino/ sneutrino, fixing underabundance

$$\Omega_{\rm LSP} h^2 \simeq 2.8 \times 10^{10} \times Y_{3/2} \left(\frac{m_{\chi_1^0}}{100 \text{ GeV}} \right)$$

Requires either very heavy gravitinos or too small reheating temperatures

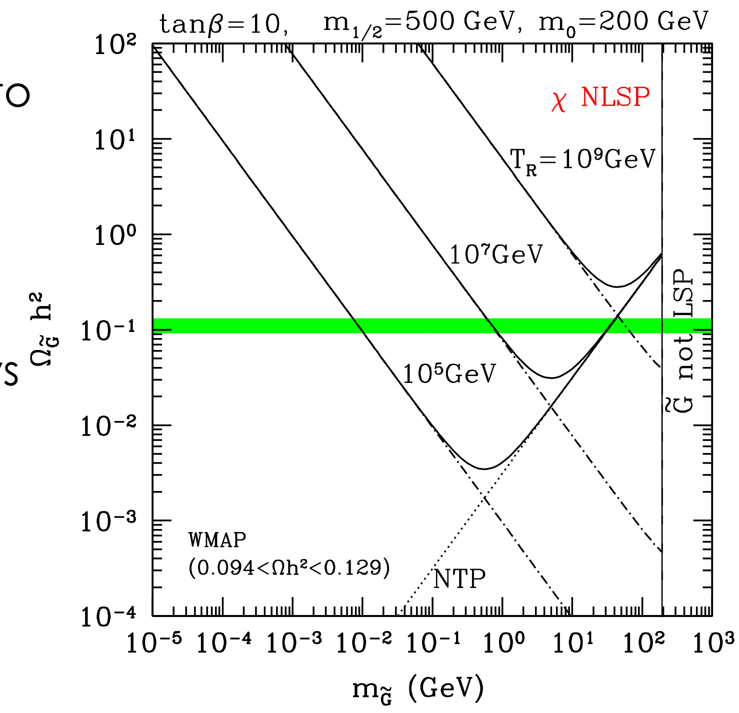
Gravitino LSP

- **Thermal production**: through scatterings with the gauge sector

$$\Omega_{\widetilde{G}}^{\rm TP} h^2 \simeq 0.27 \left(\frac{T_{\rm R}}{10^{10}\,{\rm GeV}}\right)\left(\frac{100\,{\rm GeV}}{m_{\widetilde{G}}}\right)\left(\frac{m_{\tilde{g}}(\mu)}{1\,{\rm TeV}}\right)^2$$

Sensitive to the reheating temperature and to the scale of SUSY breaking

E.g., light gravitinos require smaller T_R



- **Non-Thermal production**: through NLSP decays

$$\Omega_{\widetilde{G}}^{\rm NTP} h^2 = \frac{m_{\widetilde{G}}}{m_{\rm NLSP}} \Omega_{\rm NLSP} h^2$$

Sensitive to the properties of the NLSP (e.g., neutralino, stau, sneutrino...)

Stringent constraints from BBN (if lifetime is long)

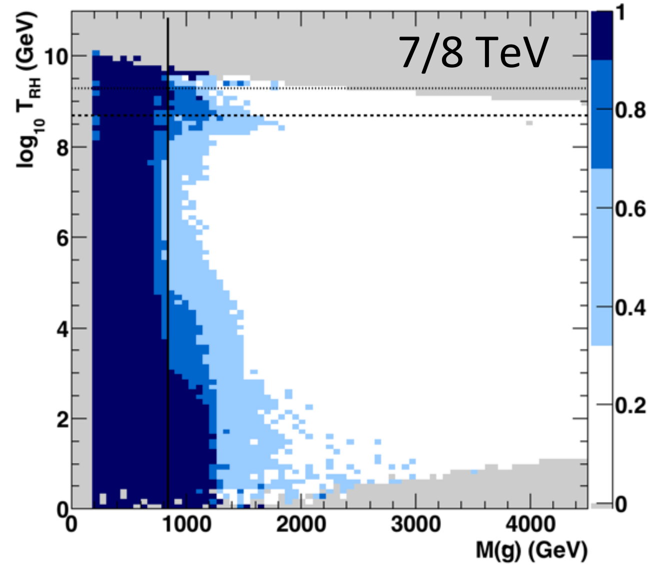
Arbey et al 2015

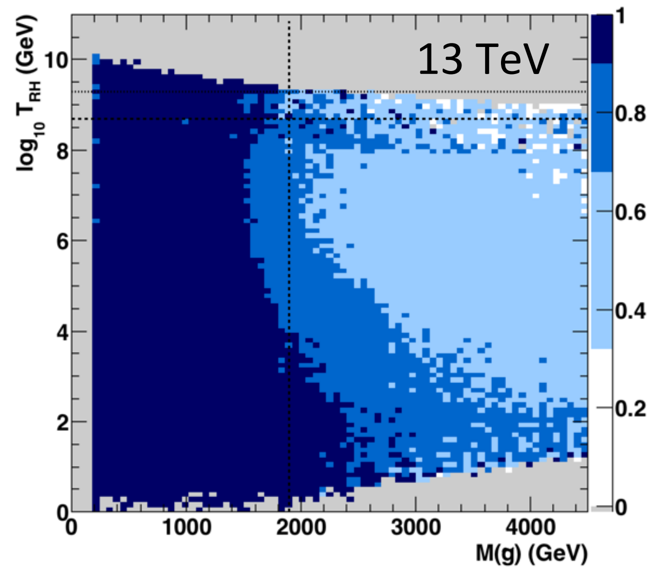
Collider constraints therefore limit the value of the reheat temperature.

E.g., constraints on the gluino mass affects the reheating temperature and gravitino mass

Using data from monojet searches on the NLSP (neutralino)

LHC already constraining the viable values of the reheating temperature, might be able to probe the region for leptogenesis.





Arbey et al 2015

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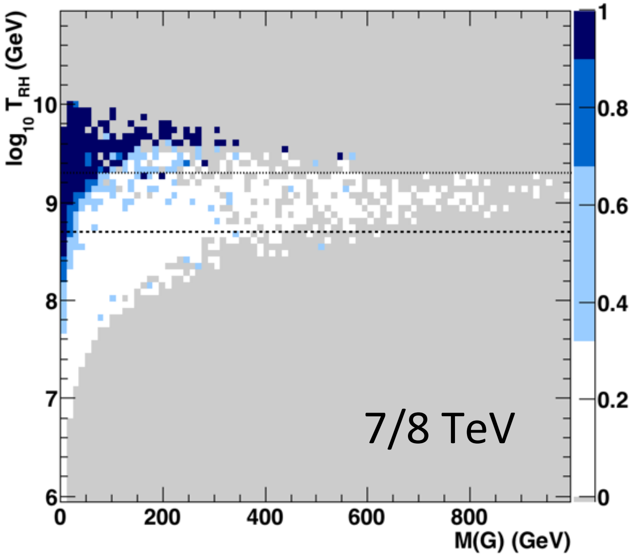
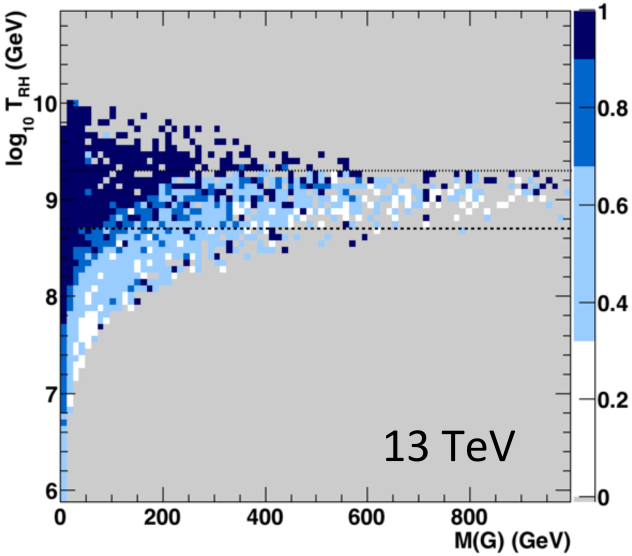
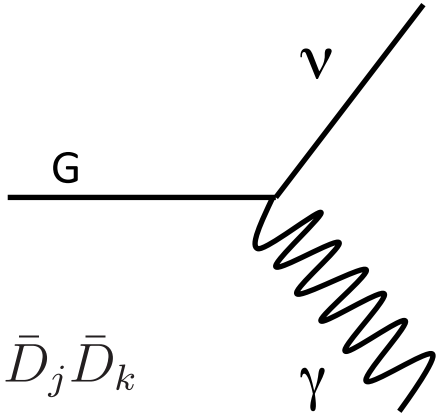




Gravitino decay in indirect searches

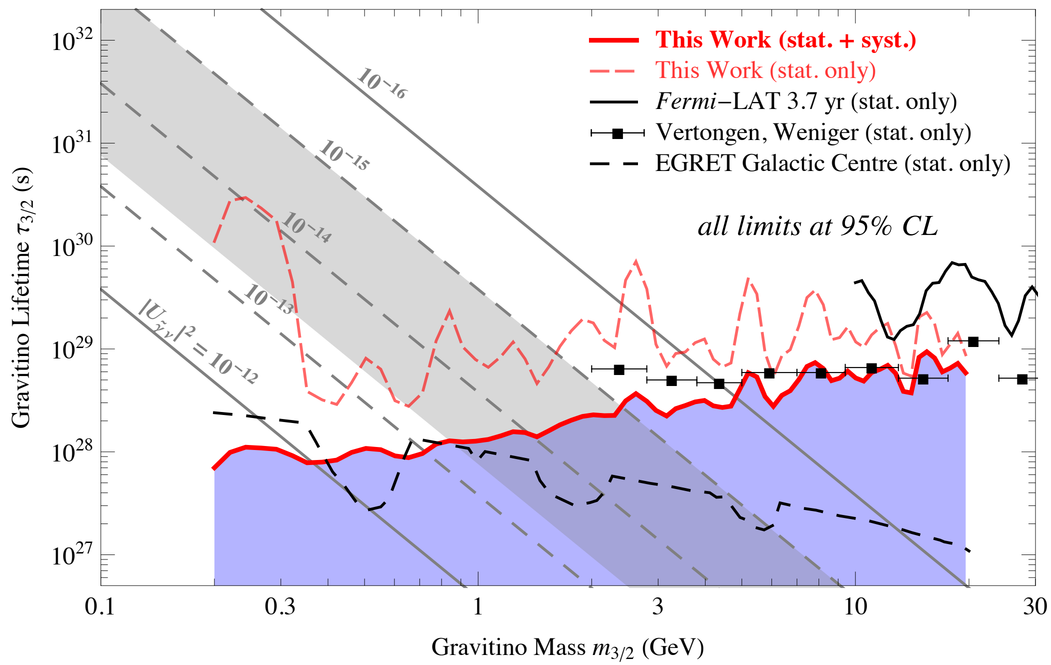
The gravitino can be unstable in models with R-parity breaking.



$$\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \mu_i H_1 L_i + \lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$$

Since its lifetime is very long, it is still a viable DM candidate

The gamma rays produced by gravitino decay can be searched for in indirect detection experiments

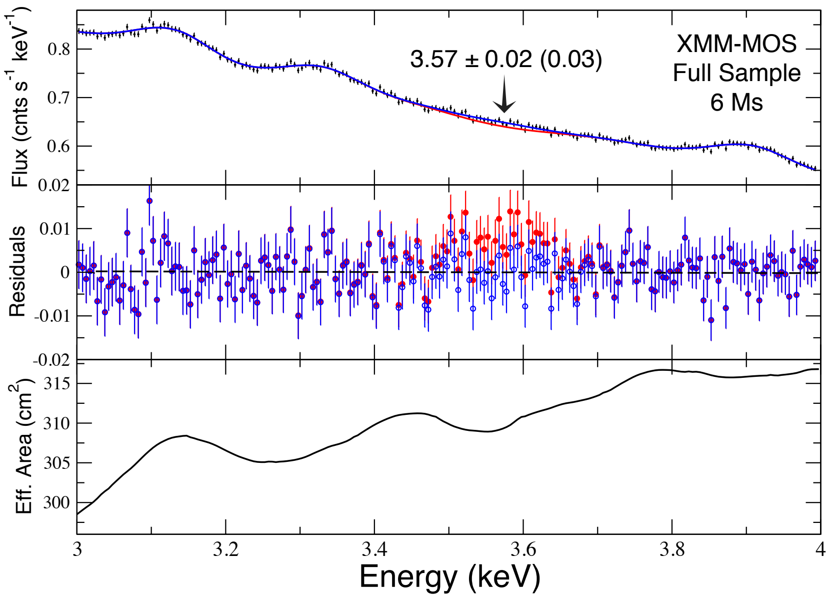


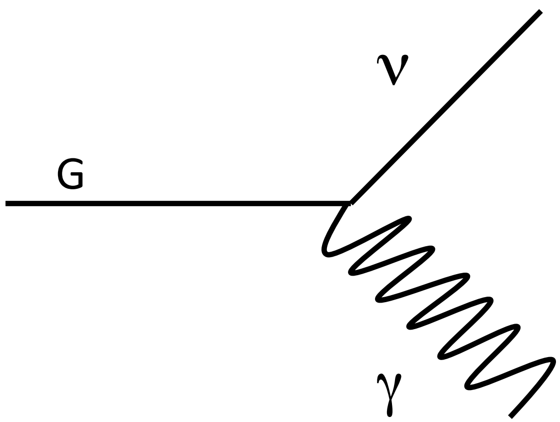
Albert et al. 2014

Gravitino DM and the 3.5 keV line

A (small) excess was observed at 3.5 keV in the emission spectrum of galaxy clusters and M31

Bulbul et al. 2014
Boyarsky et al. 2014





Tensions for DM interpretations:

No corresponding signal has been detected from the Milky Way or from Draco .

Riemer-Sorensen 2014

Gravitino DM and the 3.5 keV line

The best fit to the signal would imply

$$m_{\rm DM} \simeq 7 \text{ keV}, \quad \tau_{\rm DM} \simeq 10^{28} \text{ s}.$$

Bilinear couplings result in a too large lifetime
(also ruled out by Fermi-LAT searches)

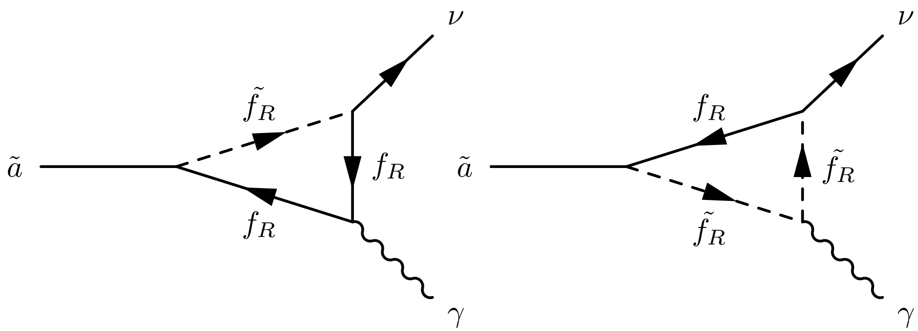
$$\tau_{\tilde{G}} \approx 4 \times 10^{11} \text{ s } |U_{\nu\tilde{\gamma}}|^{-2} \left(\frac{m_{\tilde{G}}}{10 \text{ GeV}}\right)^{-3}$$

- Must include trilinear R-parity violation
- Thermal relic abundance is too large (given the bounds on the gluinos) thereby requiring very low T_R = 100 GeV – 1 TeV
- Potential problem with thermal leptogenesis

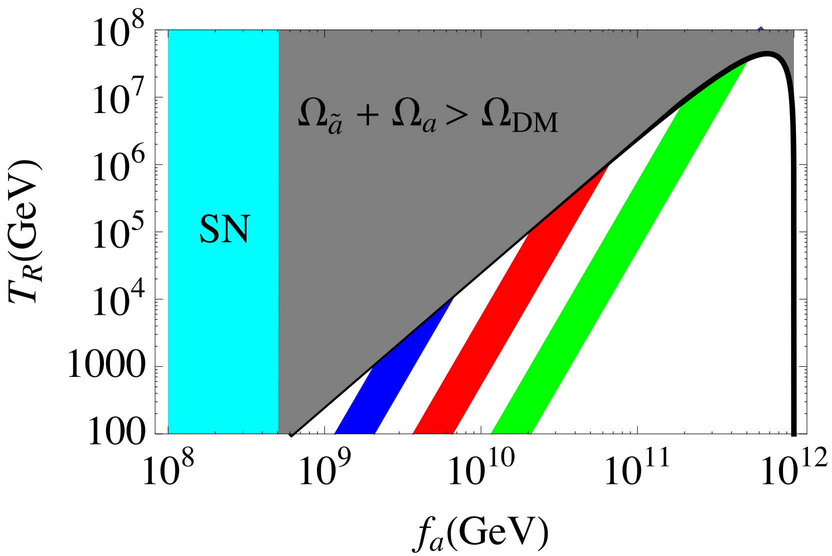
Roszkowski et. al 2015

Axino DM and the 3.5 keV line

Also in R-parity violating $W = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k + \mu_i L_i H_u$



Liew 2014
Kong et al. 2014
Choi et al. 2014



$$\Gamma_{\tilde{a}\to\gamma\nu_i} = \frac{m_{\tilde{a}}^3}{128\pi^3 f_a^2} \alpha_{em}^2 C_{a\gamma\gamma}^2 |U_{\nu_i\tilde{\gamma}}|^2$$

Reproducing the correct relic abundance leads to bounds on the reheating temperature.

Interestingly, this requires a very light (100 MeV-10 GeV) bino-like neutralino (NLSP) so as to avoid BBN constraints

Colucci et al. 2015

- **The DM paradigm is in good health**

  Future experiments + different techniques will probe new regions of the parameter space

- **The connection with SUSY is still extremely attractive**

  SUSY WIMPs (e.g., neutralinos and sneutrinos) can still show up in future experiments (LHC, direct, indirect) or be responsible for some potential hints (GCE).

  SUSY eWIMPs (gravitinos and axinos) might seem more exotic but also provide a window to cosmological parameters of the Early Universe (e.g., the reheating temperature)

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Identify some basic features from a positive observation

(Galactic Centre Emission)

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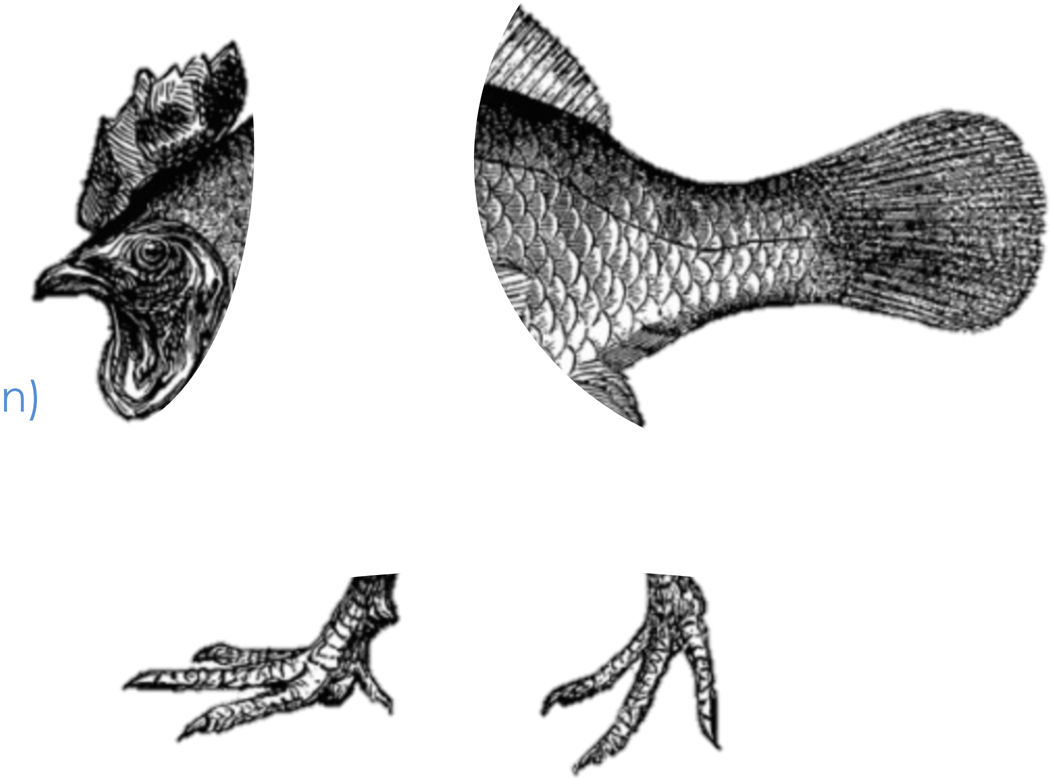

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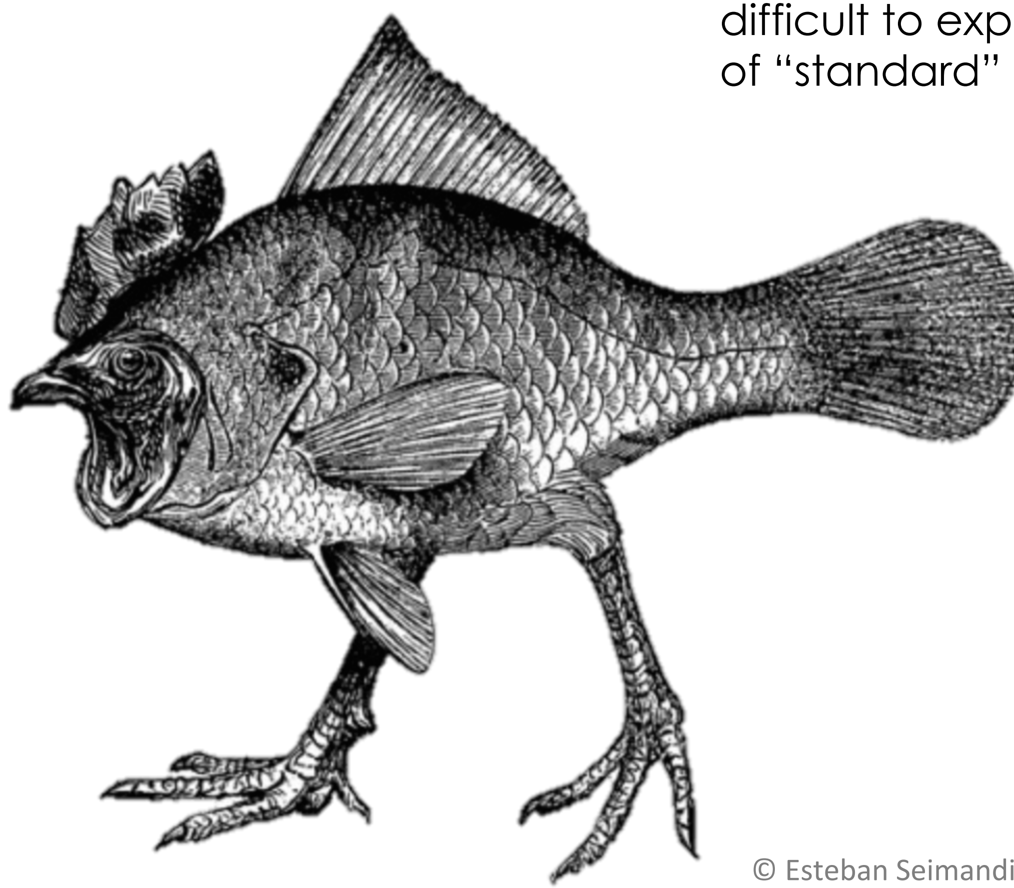

Perform a complementary measurement with other search technique

This motivates working with general frameworks, where little or nothing is assumed for the DM particle