Non-collider constraints on new physics:

Dark matter searches

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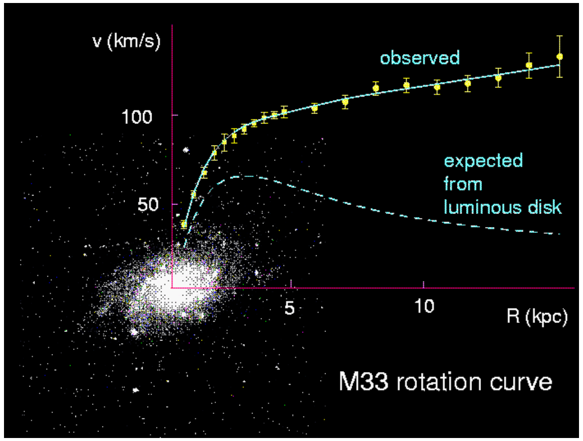
Dark Matter is a necessary (and abundant) ingredient in the Universe

Galaxies

- Rotation curves of spiral galaxies
- Gas temperature in elliptical galaxies



It is also one of the clearest hints to look for Physics Beyond the SM

Clusters of galaxies

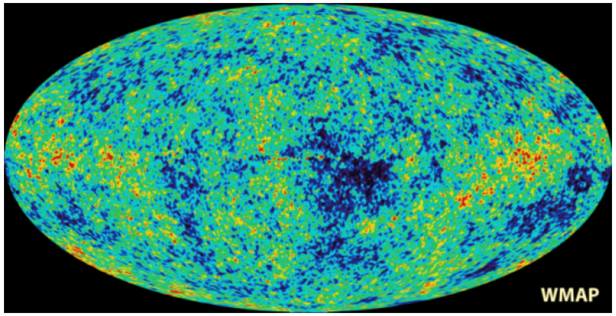
- Peculiar velocities and gas temperature
- Weak lensing
- Dynamics of cluster collision

Cosmological scales

Through the study of the anisotropies in the Cosmic Microwave Background the fundamental components of the Universe can be determined

$$\Omega_{CDM}\, h^2 = 0.110 \pm 0.006$$

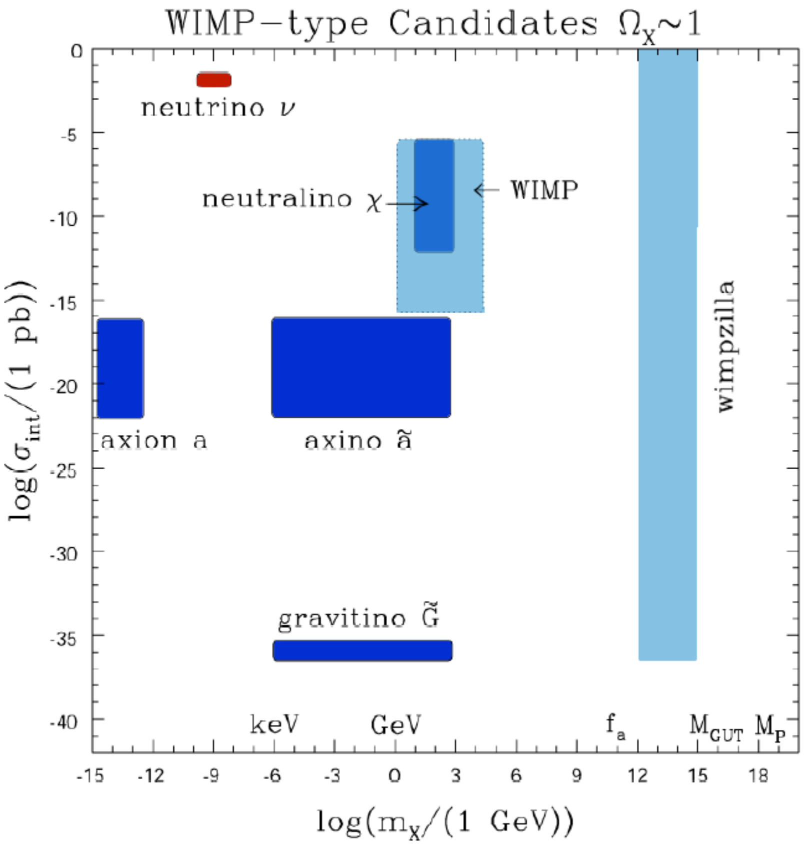
WMAP 7 yr



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

Good candidates for Dark Matter have to fulfil the following conditions

- Neutral
- Stable on cosmological scales
- Reproduce the correct relic abundance
- Not excluded by current searches
- No conflicts with BBN or stellar evolution



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

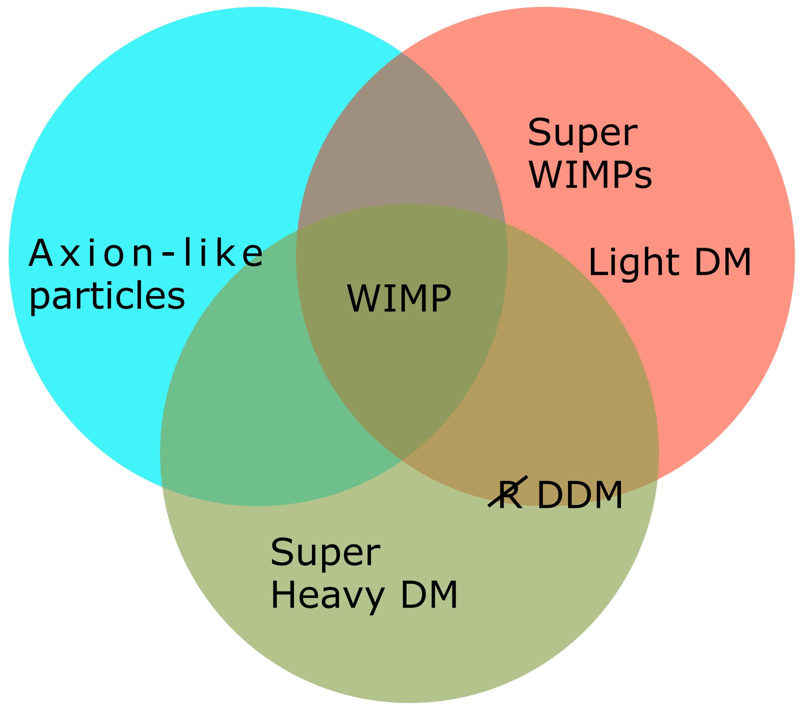
Dark matter can be searched for in different ways

Accelerator Searches (DM production) LHC (ILC)

Direct Detection

(DM-nuclei scattering)

DAMA/LIBRA
CDMS
XENON
KIMS
COUPP
ZEPLIN
CoGeNT
CRESST
ANAIS
SIMPLE
...



Indirect Detection

(DM annihilation)

PAMELA
Fermi
MAGIC
AMS

ANTARES
IceCube
CTA
...

probing different aspects of the DM interactions with ordinary matter

Accelerator Searches (DM production) LHC (ILC)

Direct Detection

(DM-nuclei scattering)

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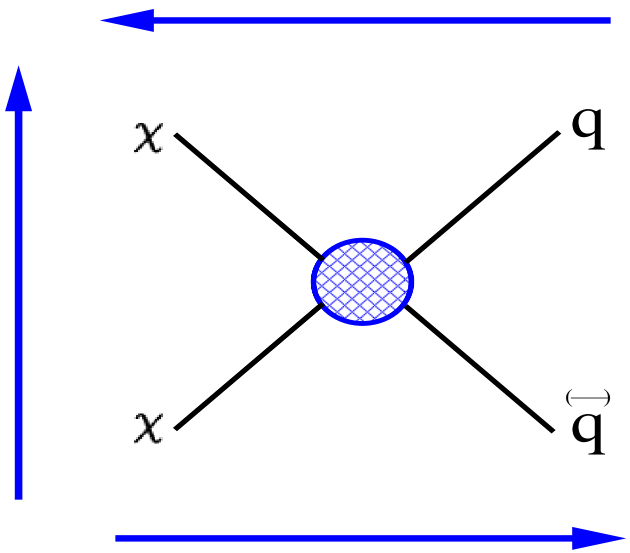


Many DM models can be probed by the different experimental techniques

Constraints in one sector might affect observations in the other two.

"Redundant" detection can be used to extract DM properties

Indirect Detection

(DM annihilation)

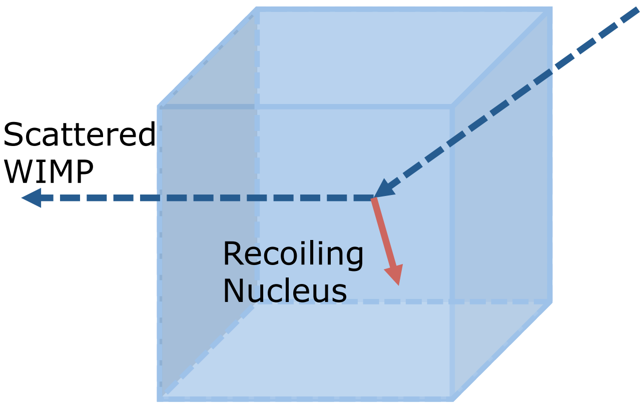
PAMELA	ANTARES
Fermi	IceCube
MAGIC	CTA
AMS	...

COMPLEMENTARITY of DM searches

Direct DM detection, where do we stand?

WIMP scattering with nuclei can be measured through

- Ionization
- Scintillation
- Increase of temperature (phonons)
- Bubble nucleation



Detection rate

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

Experimental setup

Target material (sensitiveness to spin-dependent and –independent couplings)

Detection threshold

Astrophysical parameters

Local DM density

Velocity distribution factor

Theoretical input

Differential cross section

(of WIMPs with quarks)

Nuclear uncertainties

Direct DM detection, where do we stand?

DAMA (DAMA/LIBRA) signal on annual modulation

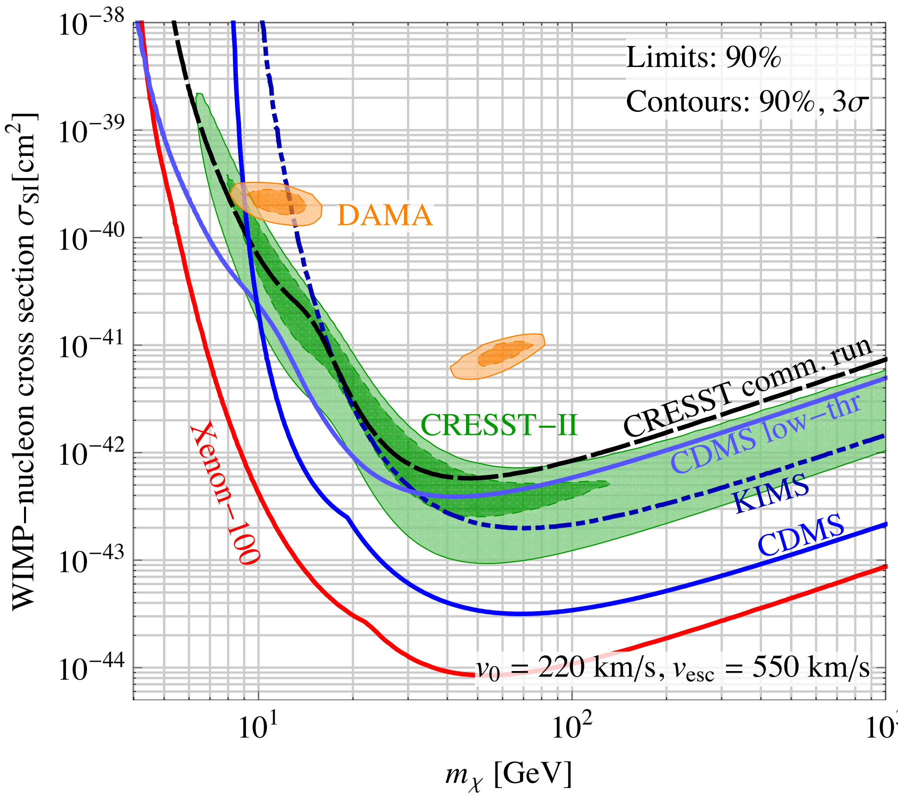
cumulative exposure 427,000 kg x day (13 annual cycles)

DAMA/LIBRA Coll. '10

... however other experiments (CDMS, Xenon, CoGeNT, ZEPLIN, Edelweiss, ...) did not confirm (its interpretation in terms of WIMPs).

Possible explanations in terms of "exotic" dark matter also constrained

- Spin-dependent WIMP couplings
- Pseudoscalar DM
- Inelastic Dark Matter
- Very light WIMPs
- ...



Kopp, Schwetz, Zupan '11

Hints of light WIMPs in recent (2011) experimental results...?

- DAMA/LIBRA (NaI) region extended to very light WIMPs (channelling, quenching factors, ...)

  Bottino, Fornengo, Scopel '09, DAMA/LIBRA '11

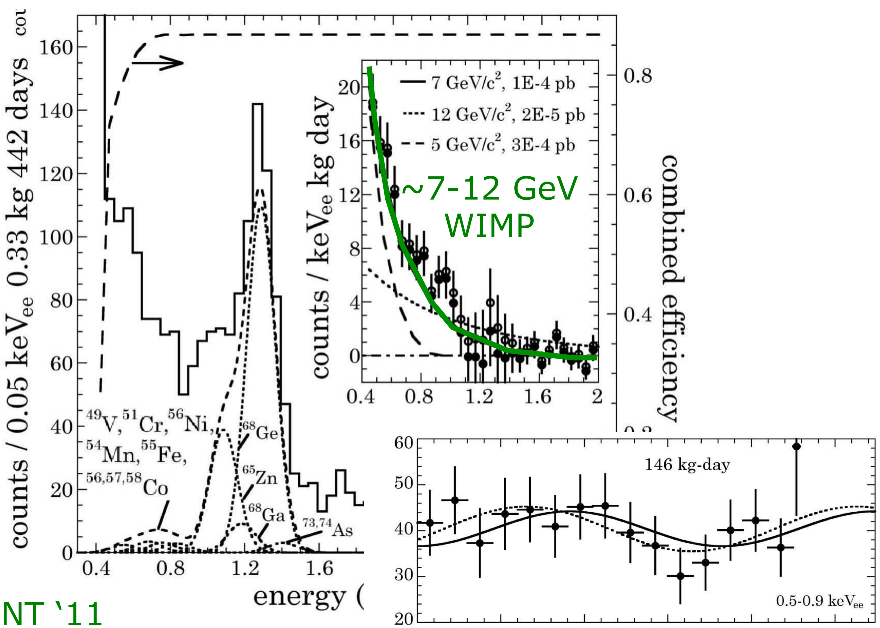
- CoGeNT (Ge) finds irreducible background that can be compatible with 7-12 GeV WIMPs

  ... annual modulation (2.8σ in 15 months data) in CoGeNT

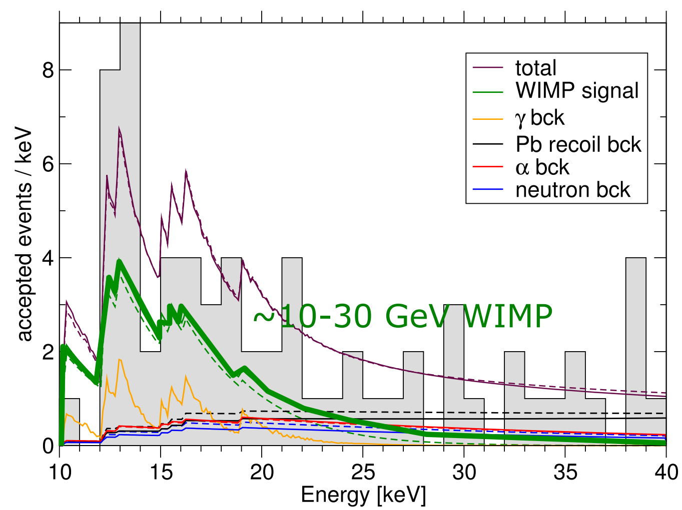
  Collar et al. '10, '11

- CRESST II ($CaWO_4$) (730 kg day) finds a significant excess over the expected background

  Angloher et al. '11



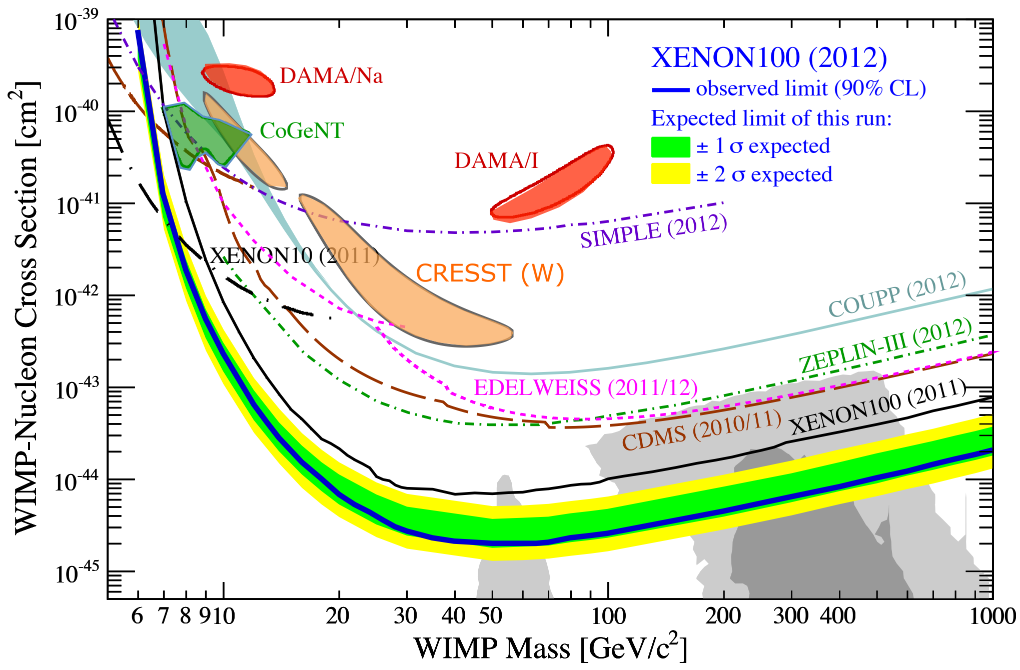
CoGeNT '11



CRESST-II '11

However very light WIMPs have not shown up in other experiments

XENON 2012 (224.6 live days)



- XENON finds no light WIMPs: issues with scintillation efficiency (L_{eff})?

XENON10, XENON100 '11-12

- CDMS II: A low-energy reanalysis of the data is incompatible with CoGeNT region

CDMS '11

- SIMPLE: (C_2ClF_5) Further constraints on DAMA/LIBRA and CoGeNT regions

SIMPLE '11-12

- DAMA-LIBRA interpretation in terms of channelling is challenged

Gelmini, Gondolo, Bozorgnia, '09 '10

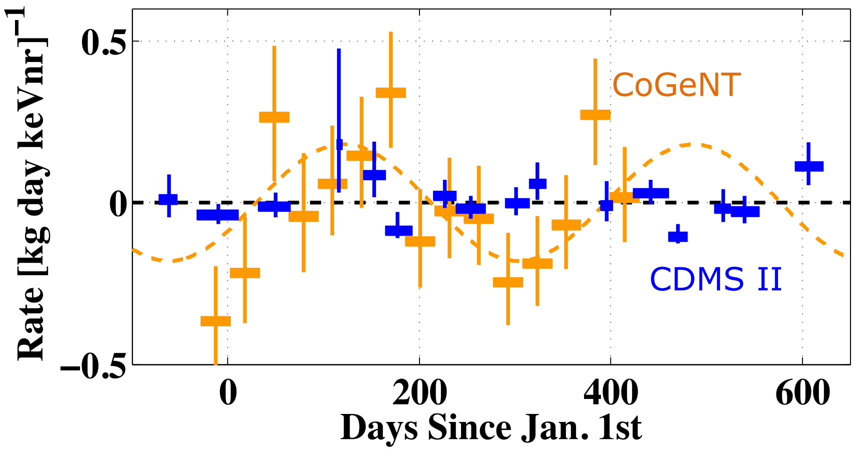
- CRESST: backgrounds from ^{210}Po underestimated?

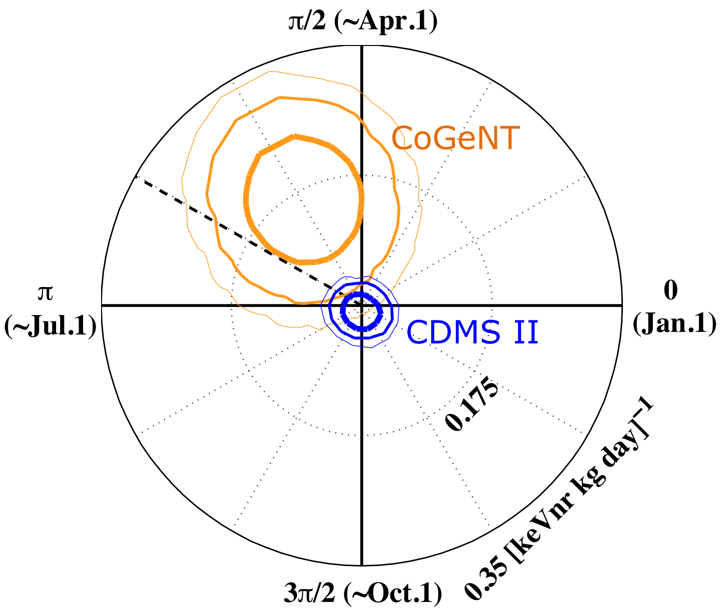
Kuzniak, Boulay, Pollmann '12

CDMS does not see annual modulation

A recent analysis of CDMS II data has shown no evidence of modulation.

This means a further constraint on CoGeNT claims





CDMS II 2012

- CoGeNT: smaller amplitude of the DM modulation signal in second year of data

Collar in IDM 2012

Direct detection experiments set bounds on particle DM models

Example: Lightest neutralino in the Minimal Supersymmetric Standard Model

Large cross section for a wide range of masses

Ellis, Ferstl, Olive 2005
Baek, D.G.C., Kim, Ko, Muñoz 2005

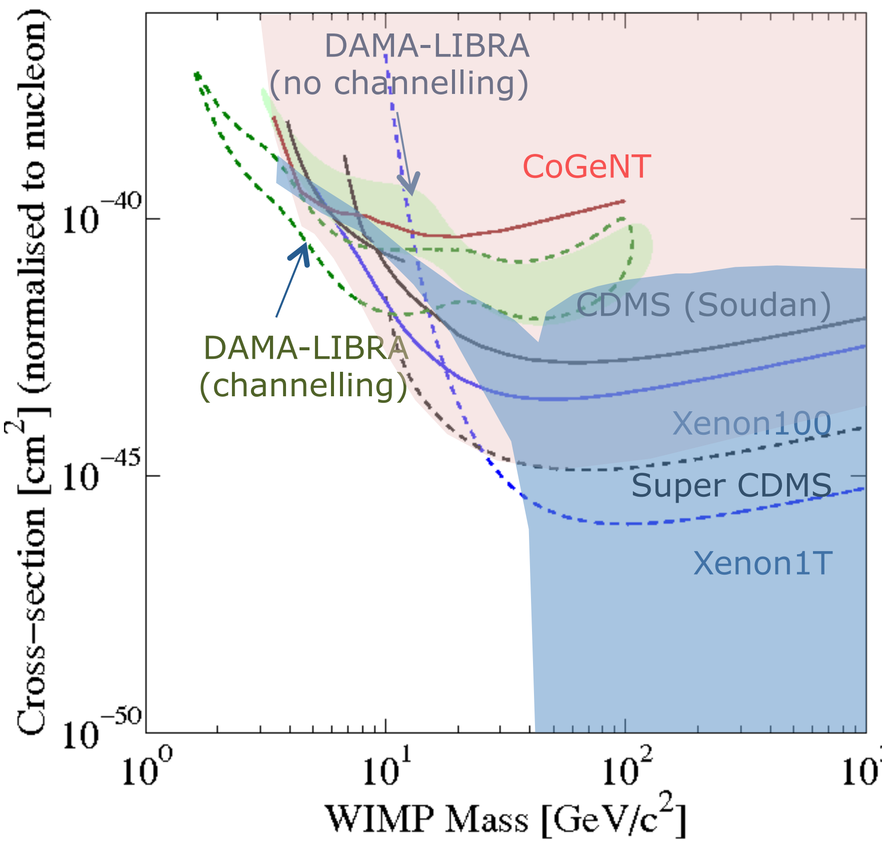
Very light Bino-like neutralinos with masses ~10 GeV could account for the DAMA signal

Bottino, Donato, Fornengo, Scopel 2008

This region is currently extremely constrained (if not ruled out) by current LHC bounds

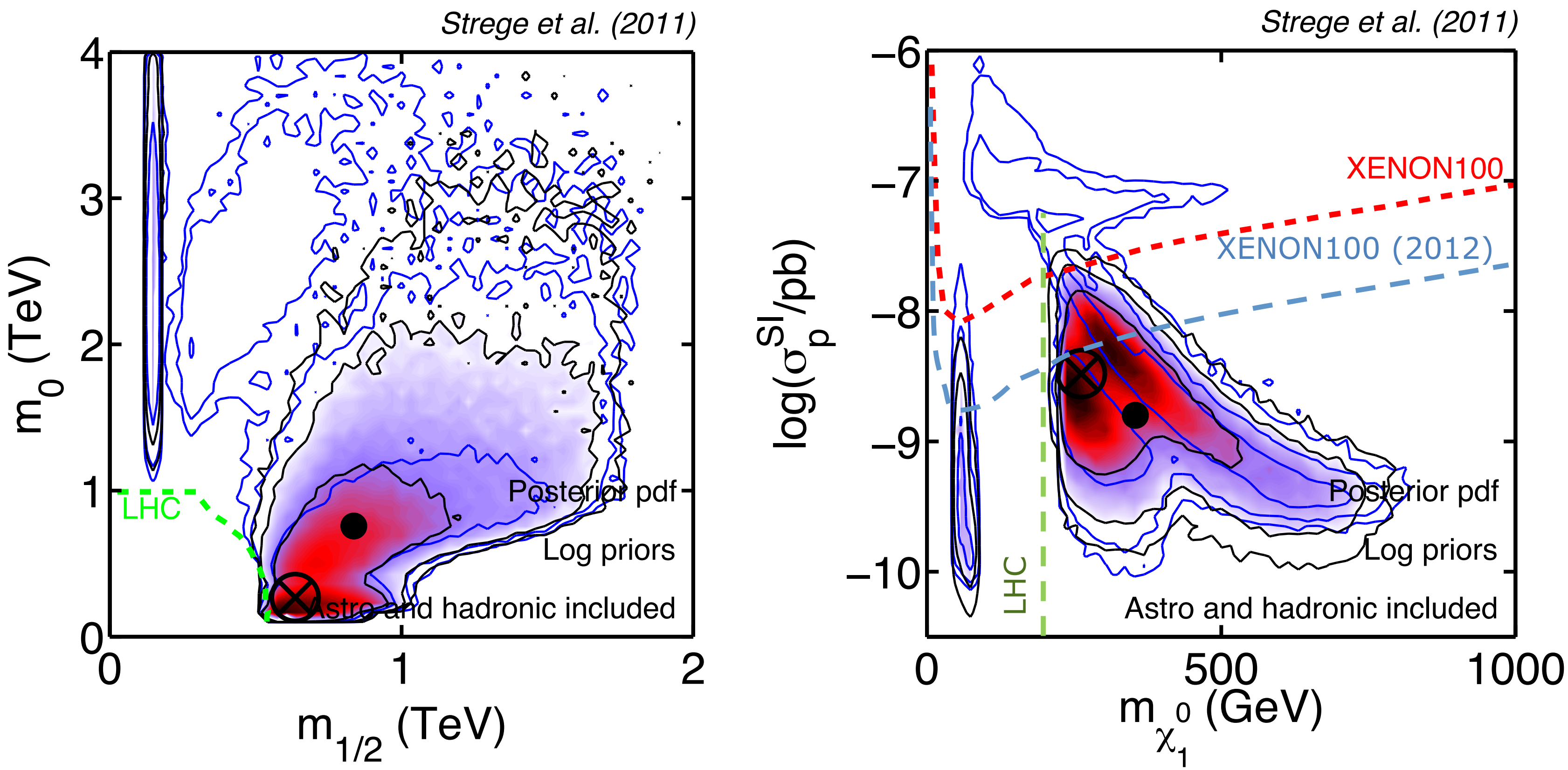
LHCb 2012

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.5 \times 10^{-9}$$



Impact of Xenon 100 (and LHC) results on the CMSSM

The negative results allow to exclude the Focus Point region, even with Astrophysical and Hadronic Uncertainties, and constrain neutralino masses below 250 GeV



Bertone, Cerdeño., Fornasa, Ruiz de Austri, Trotta 2011

Neutralino in the Next-to-MSSM (extended with a singlet field)

The theoretical predictions are more flexible than those in the MSSM

The detection cross section can be larger (due to light Higgses)

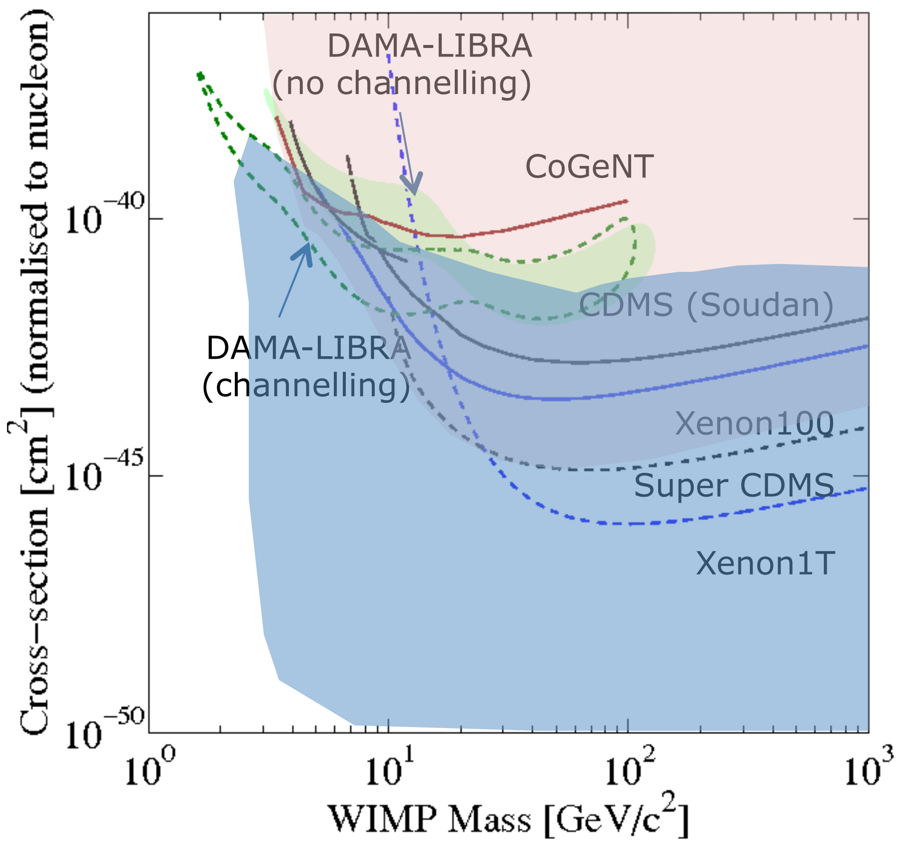
DGC, Gabrielli, Fogliani Muñoz, Teixeira 2007

Very light **Bino-singlino** neutralinos are possible

Gunion, Hooper, McElrath 2005

And their detection cross section significantly differs from that in the MSSM

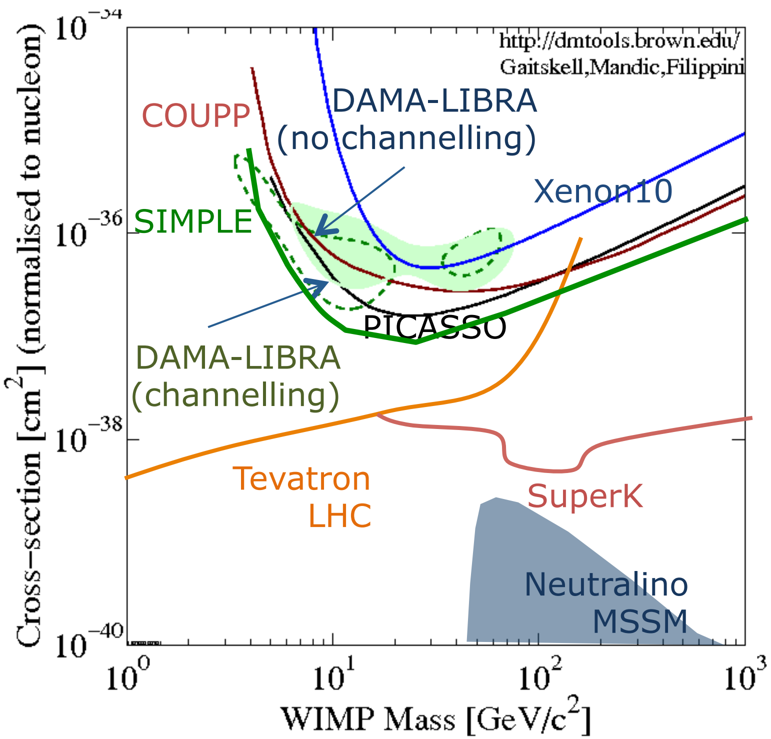
Aalseth et al. 2008



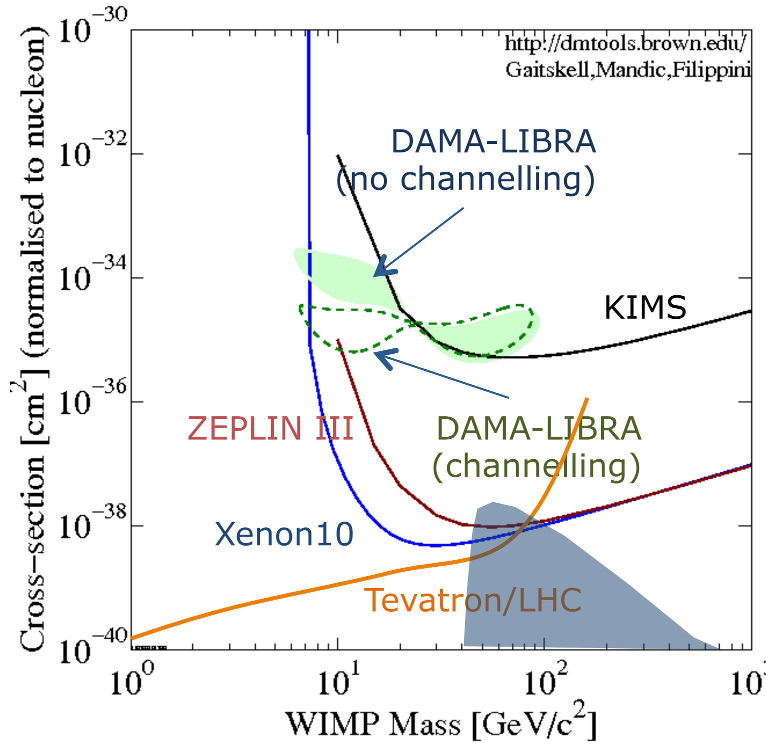
Spin-dependent searches have also become more sensitive

Do not impose yet strong constraints on DM models (notice however collider bounds)

SD coupling to protons



SD coupling to neutrons

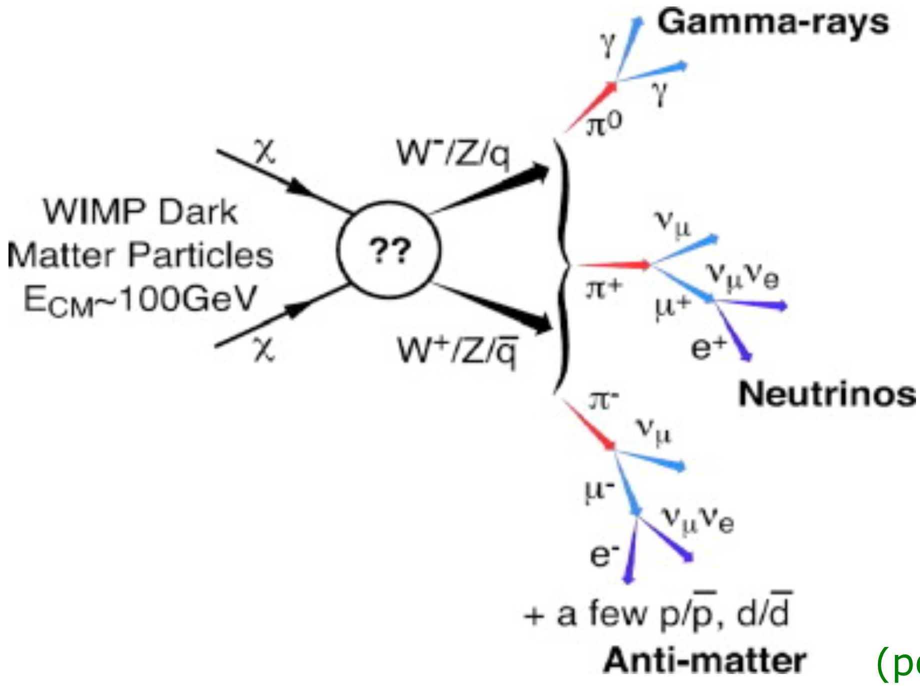


Currently we have also understood how nuclear uncertainties in the form factors affect these constraints

CDGC, Fornasa, Huh, Peiró '12

Indirect detection, signals or backgrounds?

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



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

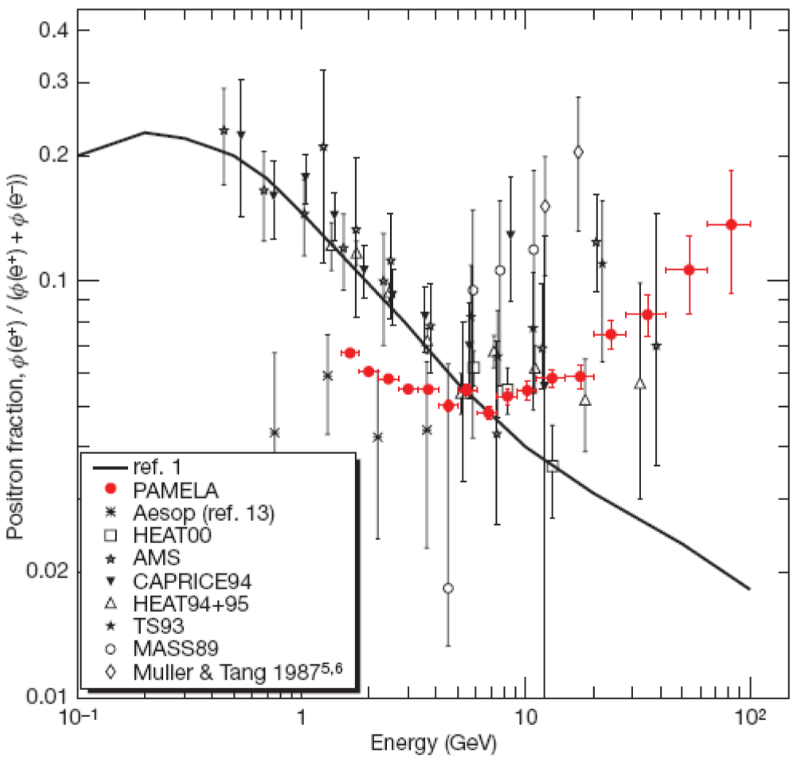
(from the centre of the Sun or the Earth)

(positrons, antiprotons, antideuterons)

Subject to larger uncertainties and very dependent on the halo parameters

The antimatter puzzle...

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



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

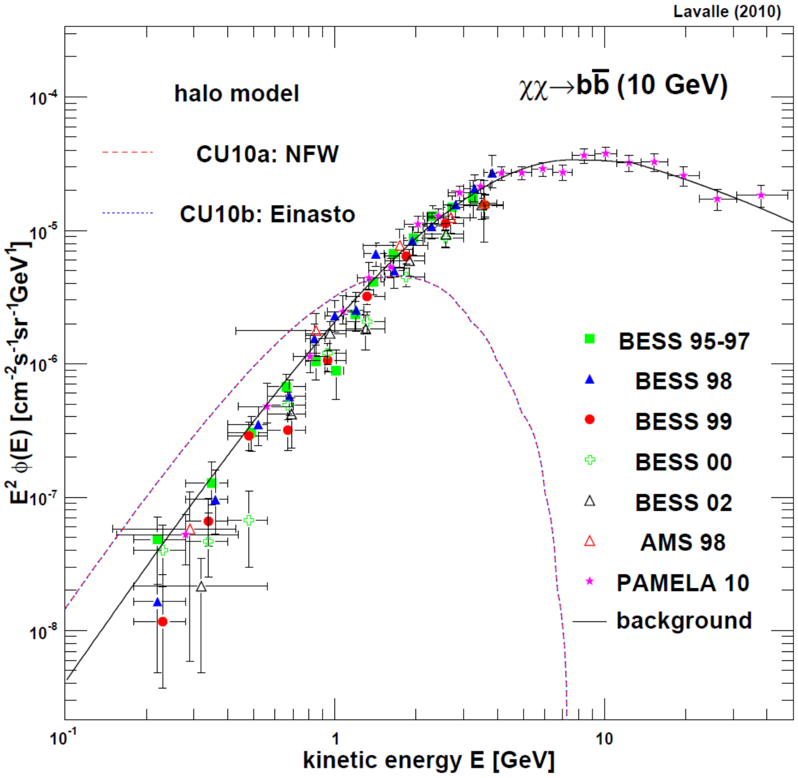
- decaying dark matter

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

Antiproton searches show no hint for DM

The antiproton data is good enough to constrain very light WIMPs

Bottino, Donato, Fornengo, Salati 2005
Salati, Donato, Fornengo 2010



The predicted flux for a very light WIMP annihilating into quarks may exceed observations

Lavalle 2010

Light WIMPs annihilating in scalar particles still viable

DGC Delahaye, Lavalle 2012

See also latest results by BESS-II

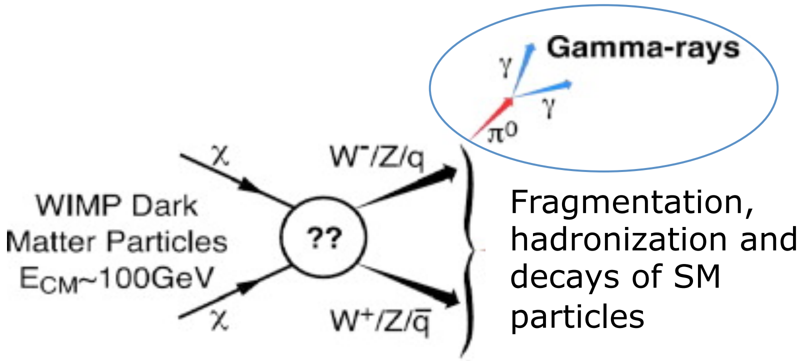
BESS-II '11

... also a potentially promising future in antideuteron searches...

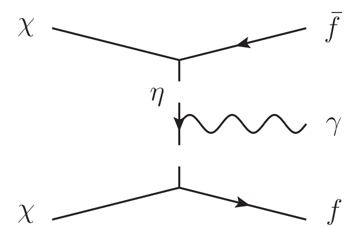
Donato et al. 2008
Salati, Donato, Fornengo 2010

Gamma rays from DM annihilation

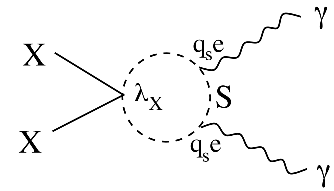
Continuum (secondary photons)



Direct gamma emission (features, lines)



Internal bremsstrahlung



Loop processes

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

Theoretical input

DM annihilation cross section IN THE HALO

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

$$v_{Decoupling}^2 \approx 1/20$$

$$v_{halo}^2 \approx 10^{-7}$$

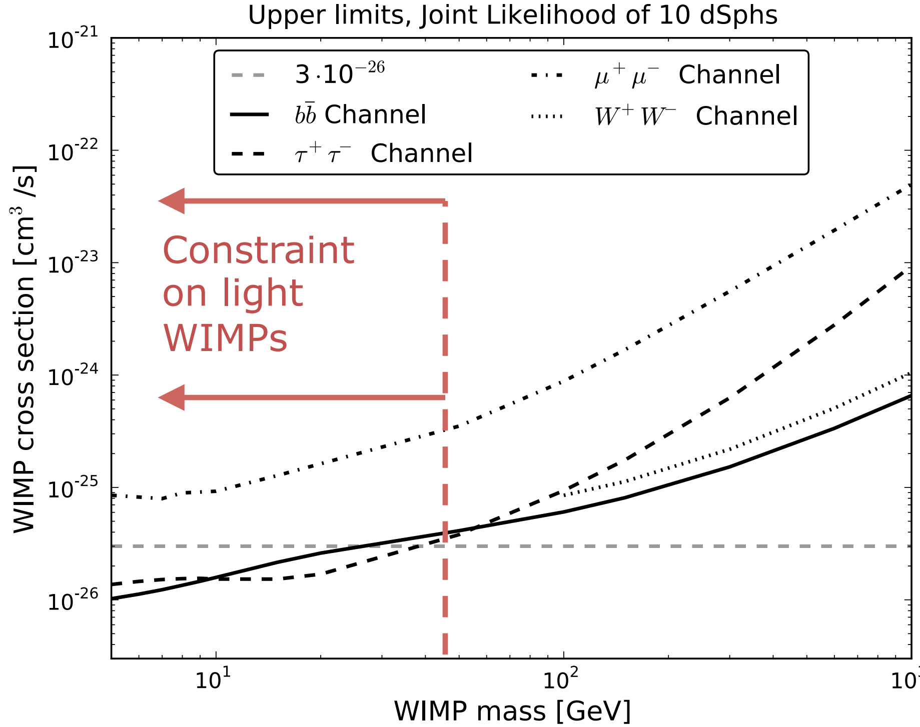
Astrophysical input

DM Density profile

Region of observation (backgrounds)

No signal from GR in dwarf spheroidals

Fermi-LAT '11

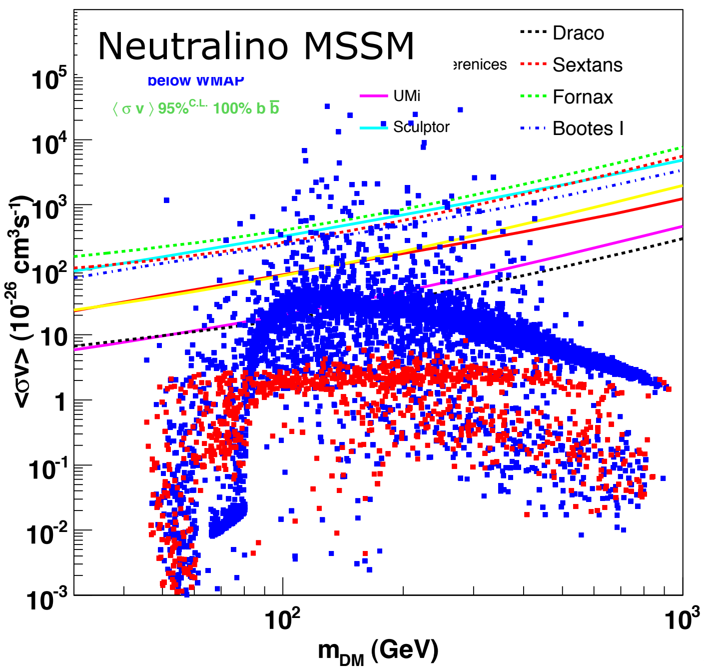


Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT '11

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

Bounds are normally expressed for "pure" annihilation channels.



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

Coannihilation effects,
velocity-dependent cross-section
resonances

Abdo et al. 1001.4531

Very light DM can be further constrained

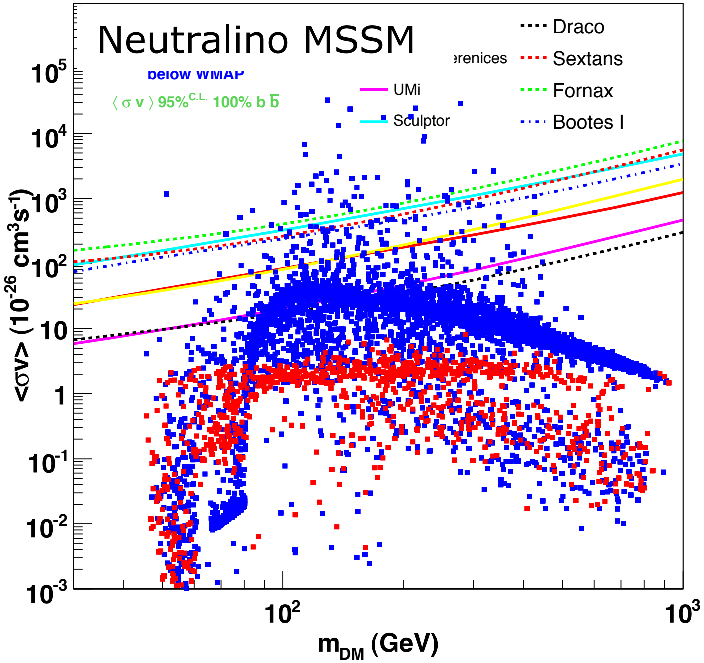
Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT '11

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

Fermi-LAT data from GC

Similar bounds Hooper et al. '12



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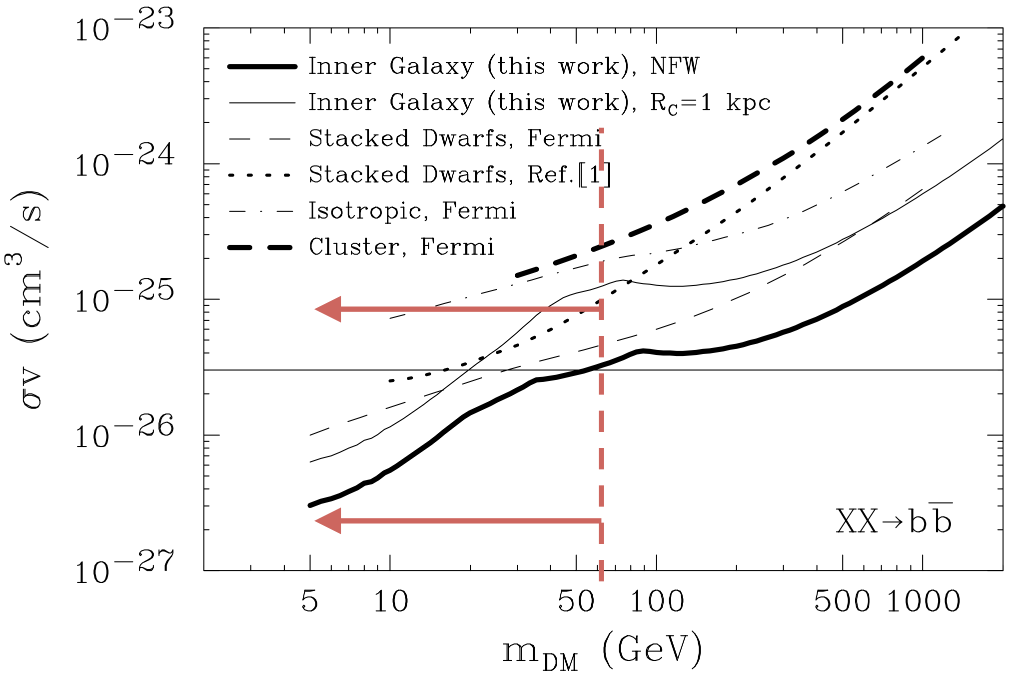


Hooper et al. '12

"Thermal" DM might have a smaller <σv>

Coannihilation effects,
velocity-dependent cross-section
resonances

A sharp feature in the gamma ray spectrum?

Difficult to attribute to astrophysical background (*)

Gamma-ray line emission (130 GeV)

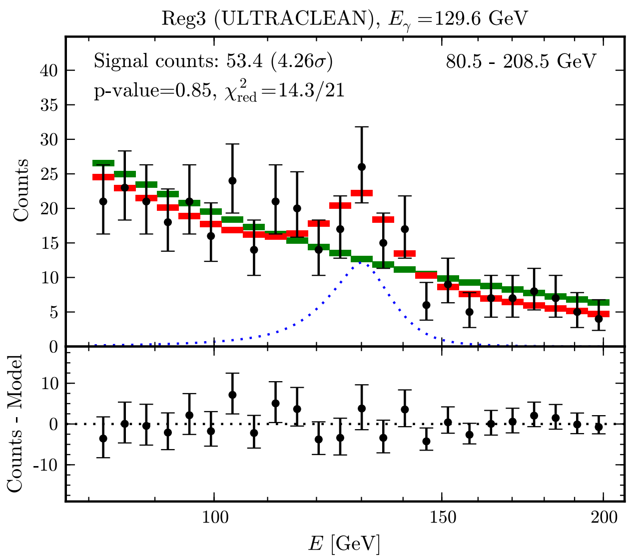
Weniger 1204.2797

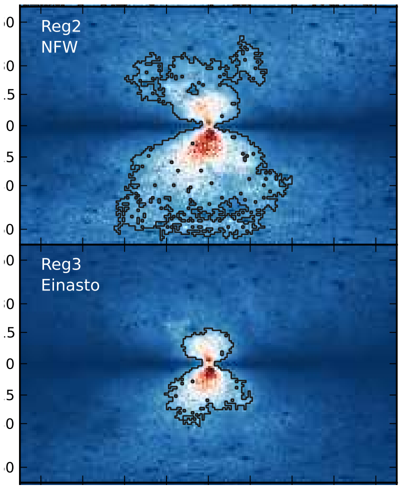
$$E_\gamma = m_\chi \left(1 - \frac{m_P^2}{4m_\chi^2}\right)$$

130 GeV WIMP annihil. into $\gamma\gamma$

145 GeV WIMP annihil. into γZ^0

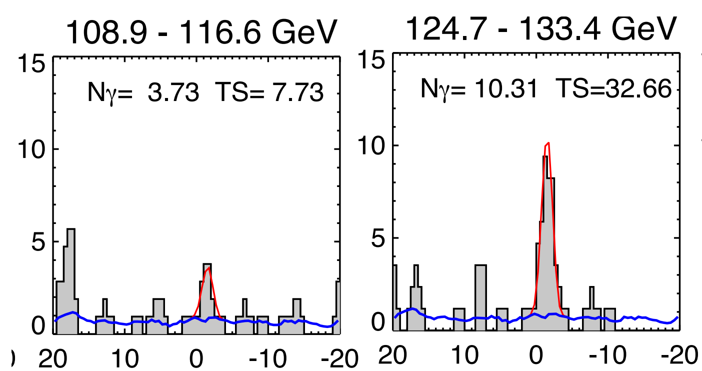
155 GeV WIMP annihil. into $H\gamma$





Internal bremsstrahlung

Bringmann et al. 1203.1312



Possible hints of a second line at ~110 GeV consistent with annihilation into γZ^0

Finkbeiner '12

Not easy to fit with "ordinary" models (e.g., the neutralino does not work)

Cohen et al. '12

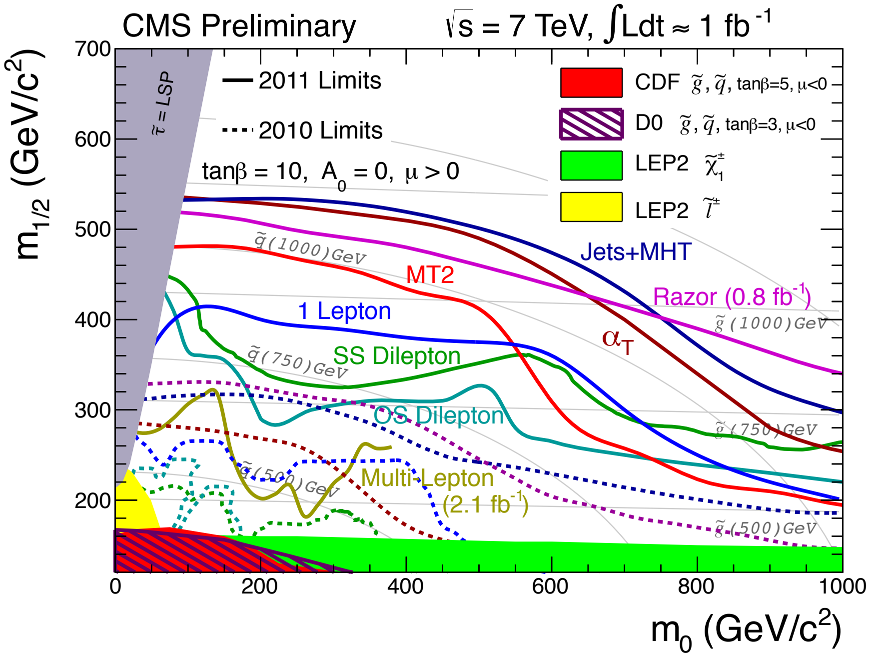
(*) Possible background from Fermi bubbles
Instrumental effect?
Power-law fit of the background?

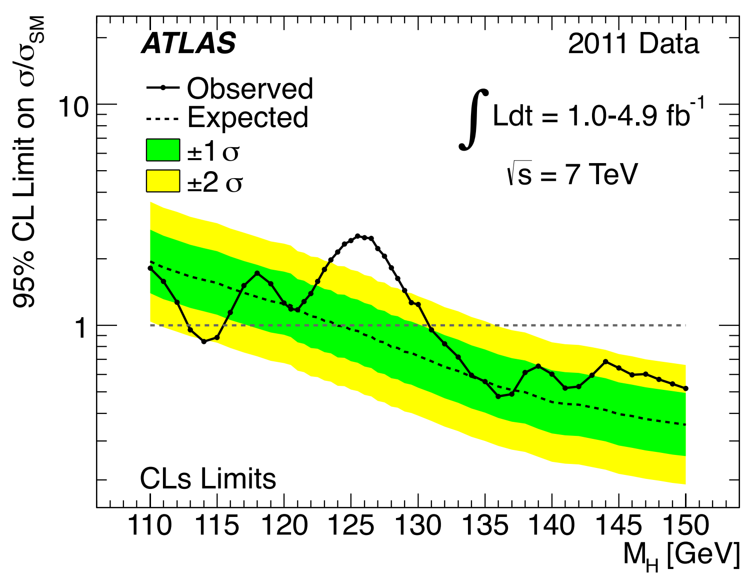
Dark matter in colliders

Current BSM-specific searches help constrain some DM candidates

Searches for BSM physics

(e.g., SUSY) constrain the parameter space and have implications on the nature of the DM





Higgs searches

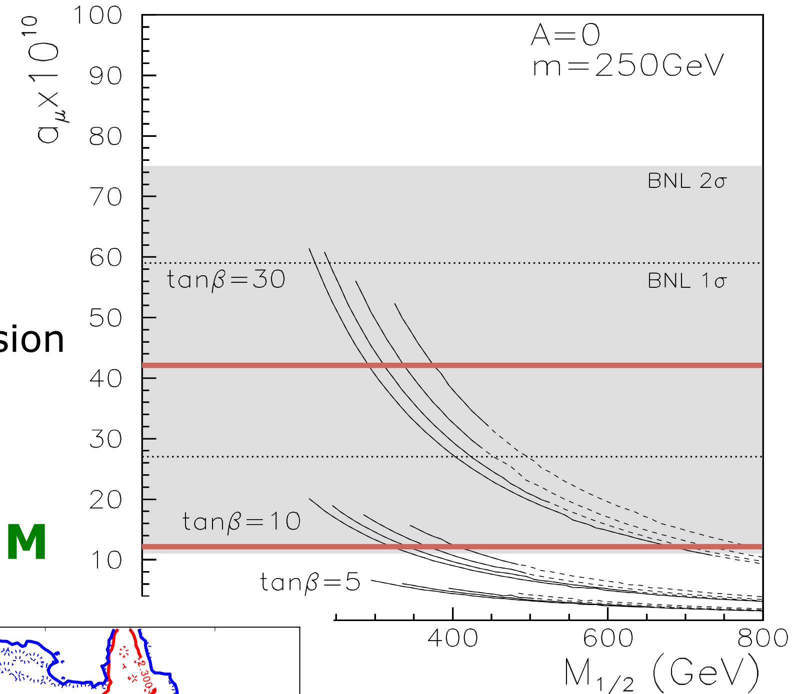
A determination of the Higgs mass also has implications for the DM annihilation and detection processes

Muon anomalous magnetic moment

The SUSY contribution to the muon (g-2) decreases if the spectrum is heavy

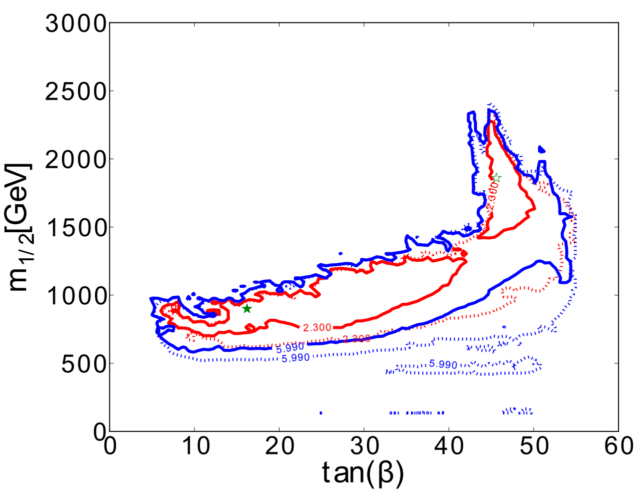
$$10.1 \times 10^{-10} < a_\mu^{SUSY} < 42.1 \times 10^{-10}$$

$$2.9 \times 10^{-10} < a_\mu^{SUSY} < 36.1 \times 10^{-10}$$

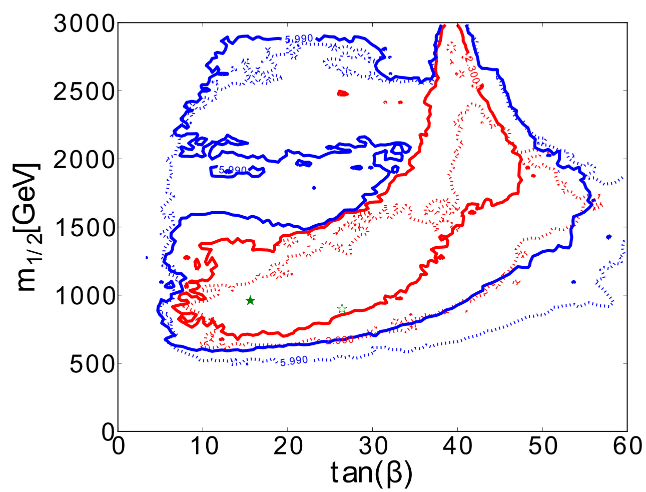


LHC lower bounds on SUSY masses imply some tension for specific models: large tanβ preferred

CMSSM



NUHM



Buchmuller et al. '12

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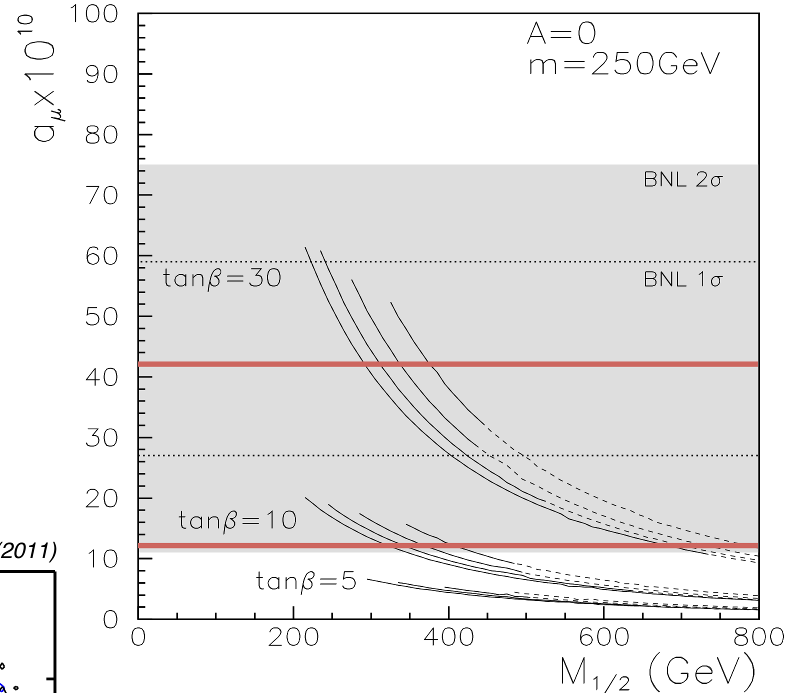
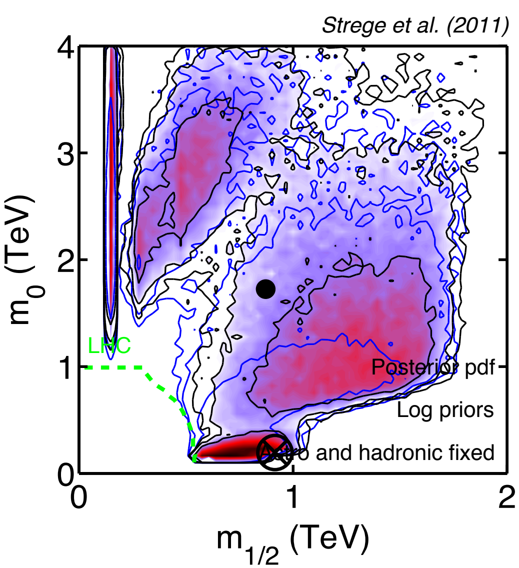
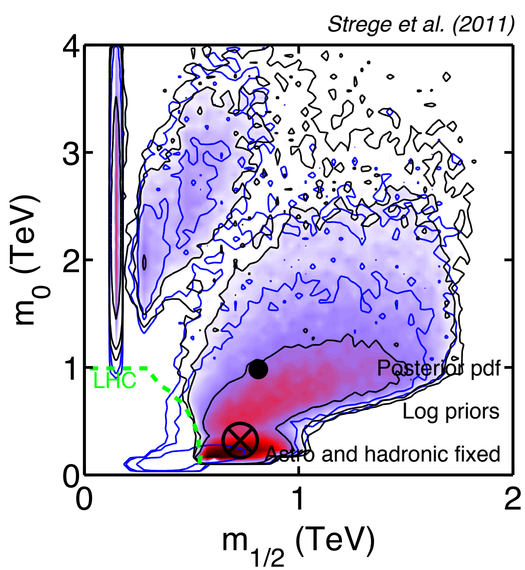


IF DM relic density is also imposed only a few regions of the parameter space survive... Heavier points are also disfavoured

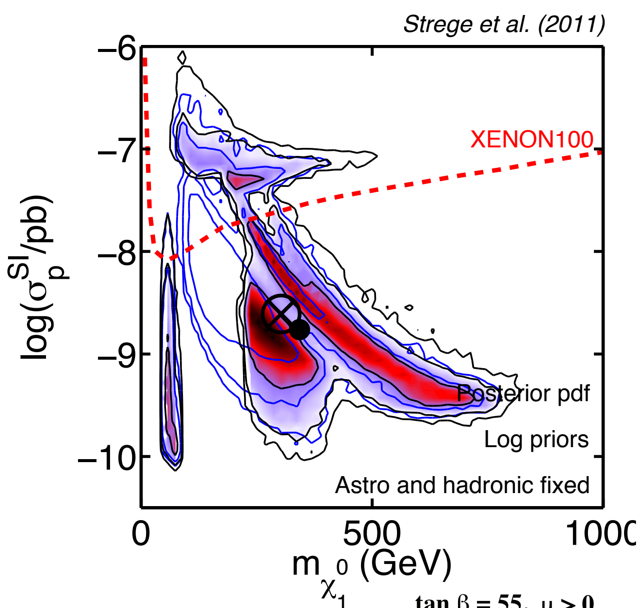


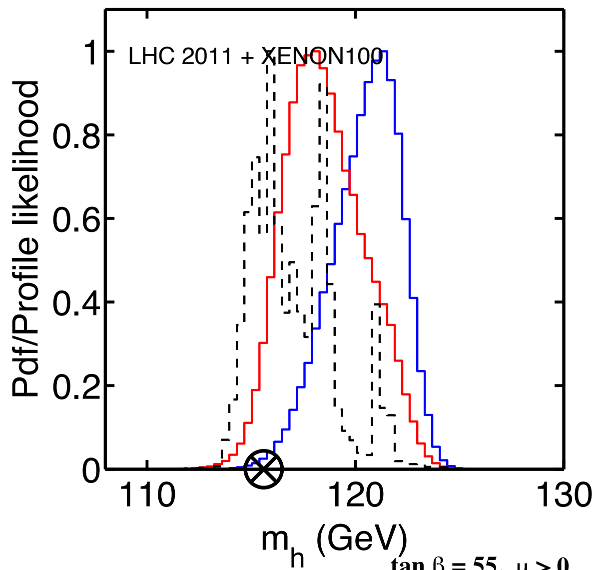


Strege et al. '11

Implications for dark matter

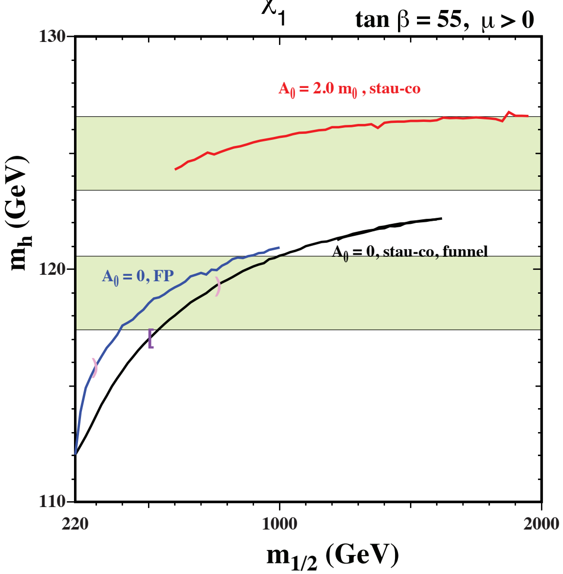
LHC constraints INDIRECTLY lead to constraints on the DM model

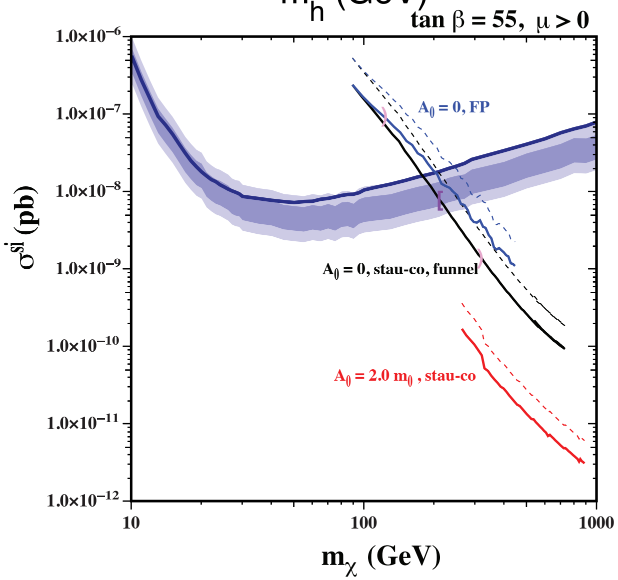




A lower bound in the neutralino mass is found that excludes some regions with large scattering cross-section IN THE CMSSM

Bertone et al. 2012





If mh~125 GeV is imposed, the scattering cross section for neutralinos is generally beyond the reach of direct DM detection IN THE CMSSM

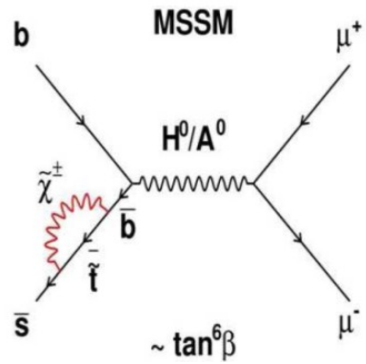
Ellis, Olive 2012

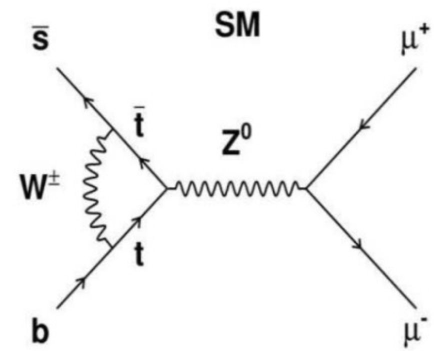
Constraints from rare decays

LHCb has obtained an unprecedented upper bound on the rare decay of Bs into muons

$$\mathrm{BR}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu\mu)_{SM} = (3.2 \pm 0.2) \times 10^{-9}$$





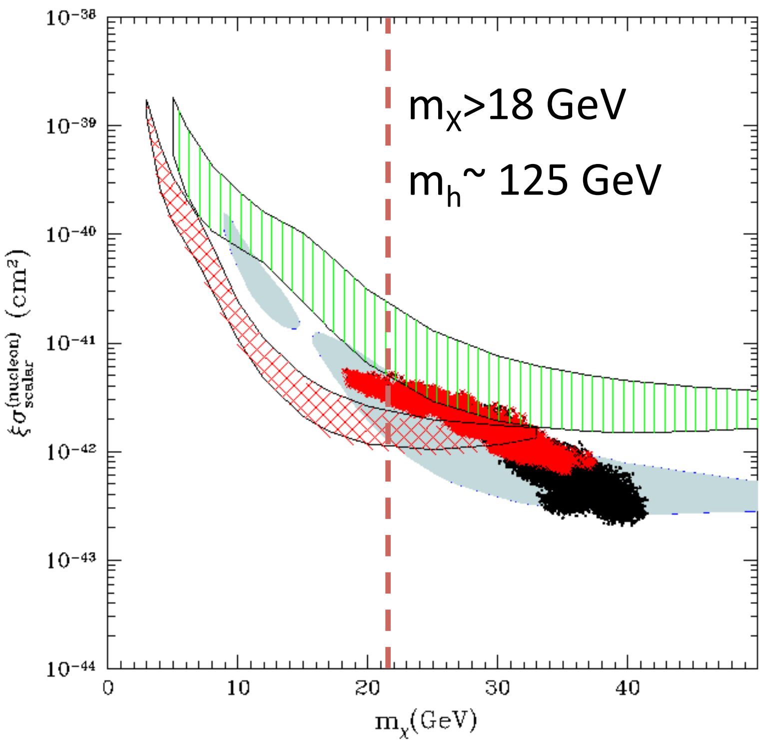
$$\mathrm{B}(B_s^0 \to \mu^+\mu^-) \propto \frac{\tan^6\beta}{m_A^4}\left(\frac{\mu A_t}{m_{\tilde{t}_L}^2}\right)^2$$

This constrains regions with small pseudoscalar mass and large tanb, but also those in which the stop mixing is sizable. This affects:

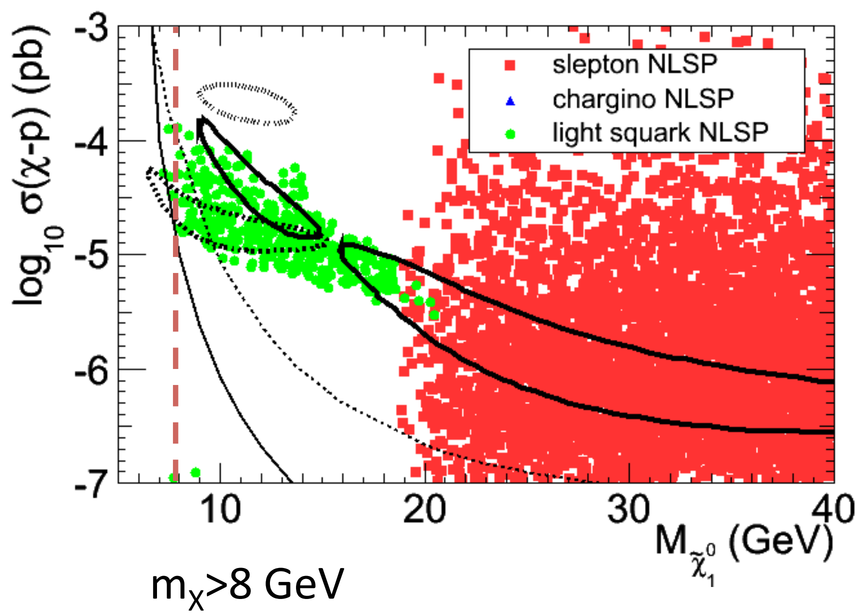
- Regions with heavy Higgs mass (typically maximal stop mixing – normally large tanb)
- Models for very light neutralino dark matter (small m_A, large tanb)

Constraints from rare decays

- Models for very light neutralino dark matter (small m_A, large tanb)



Bottino, Fornengo, Scopel 2011



Arbey, Battaglia, Mahmoudi 2012

No more annihilation mediated by the pseudoscalar – now the relic density is obtained by light-squark exchange

Conclusions

Direct DM searches

No detection of WIMP DM lead to upper bounds on the WIMP-nucleus cross-section

Hints for very light WIMPs (7-10 GeV) remain unconfirmed

Indirect DM searches

Gamma ray searches:

- No clear evidence of DM from the continuum emission in the Galactic Centre or Dwarf Spheroidals
- Hints for a 130 GeV gamma “line”

Antimatter searches:

- Compatible with astrophysical background – constrain very light WIMPs

However...

- Possible hints for very light DM in the study of the WMAP Haze and synchrotron emission from radio filaments in the inner galaxy.

Low energy observables

The muon (g-2) and rare decays set further constraints on physics BSM and affect the predictions for DM detection (so does the Higgs mass, if confirmed)

Backup material

Hints of light WIMPs in recent (2011) experimental results...?

• DAMA/LIBRA (NaI) region extended to very light WIMPs (channelling, quenching factors, ...)

Bottino, Fornengo, Scopel '09, DAMA/LIBRA '11

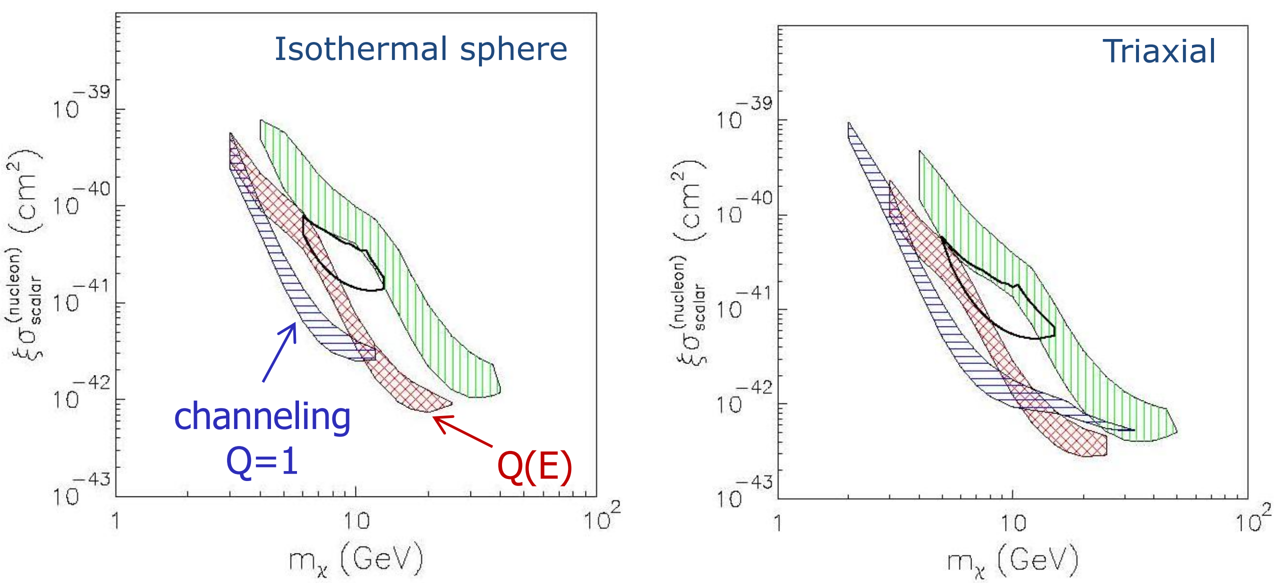
• CoGeNT (Ge) finds irreducible background that can be compatible with 7-10 GeV WIMPs

... annual modulation (2.8σ in 15 months data) in CoGeNT

Collar et al. '10, '11

• CRESST II ($CaWO_4$) (730 kg day) finds a significant excess over the expected background

Angloher et al. '11



Belli et al. '11

Many efforts in reconciling these results

See, e.g., Andreas et al. '10;
Schwetz, Zupan '11;
Hooper, Kelso '11;
Farina et al. '11;
McCabe '11;
Arina et al. '11;
...

Uncertainties in determination of DM parameters

RH Sneutrino in the MSSM (another possible SUSY WIMP)

All WIMPs look alike (the constraints on the actual parameters of the model differ)

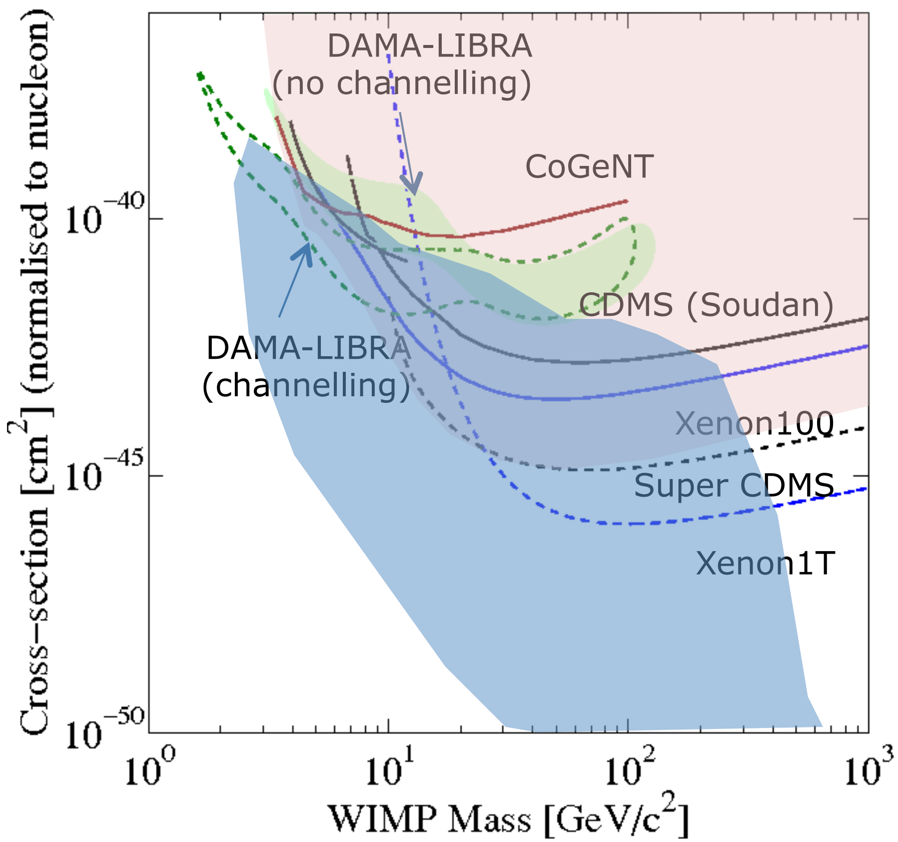
The RH Sneutrino is a viable WIMP candidate in the NMSSM

It can be detectable in future experiments

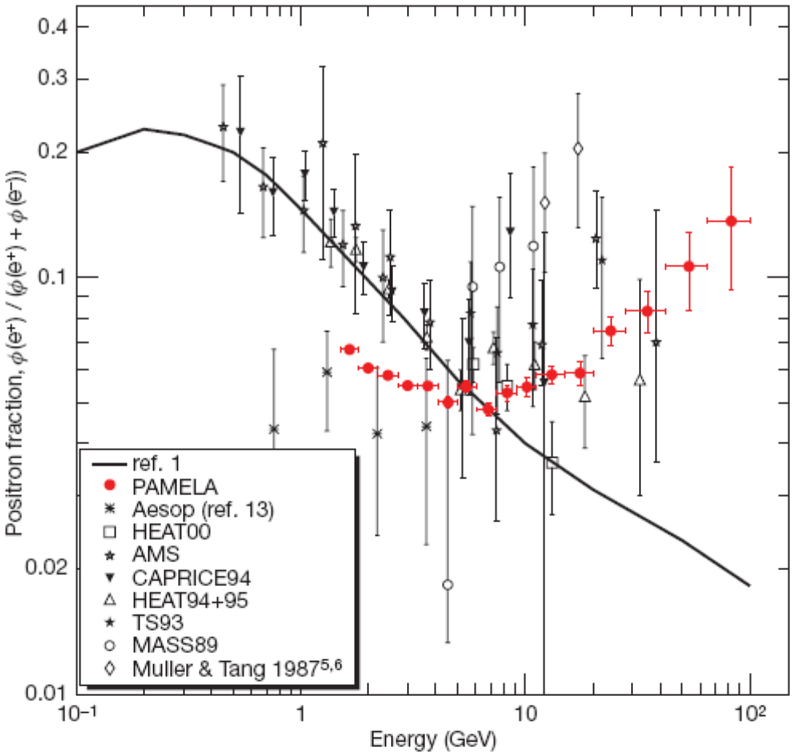
DGC, Munoz, Seto 2007; DGC, Seto 2008

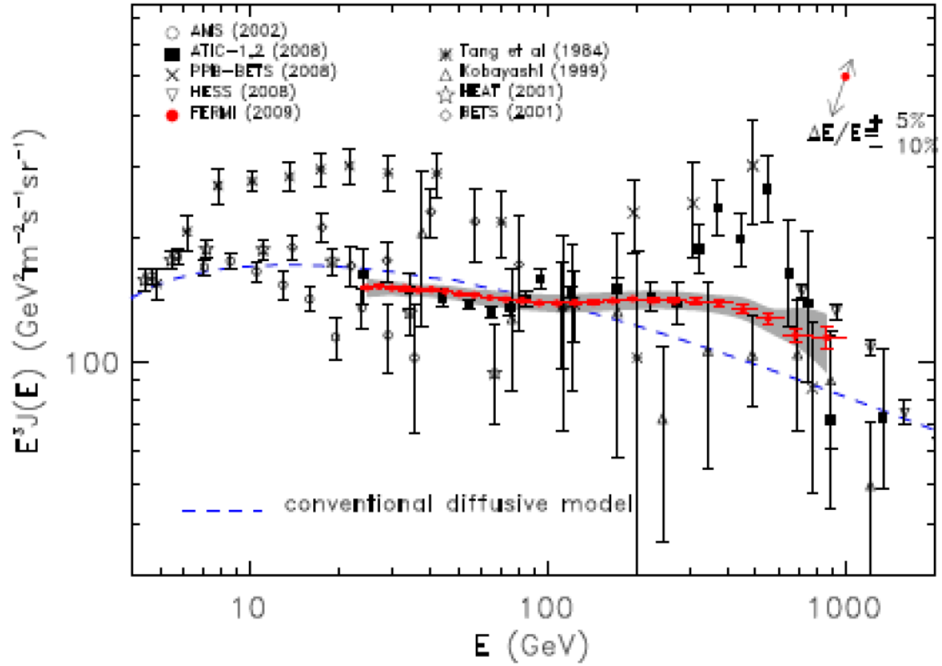
Very light sneutrinos are possible and potentially distinguishible from Neutralino DM

DGC, Huh, Seto, Peiro 2011



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

Very light DM can be further constrained, however.

Fermi-LAT '11

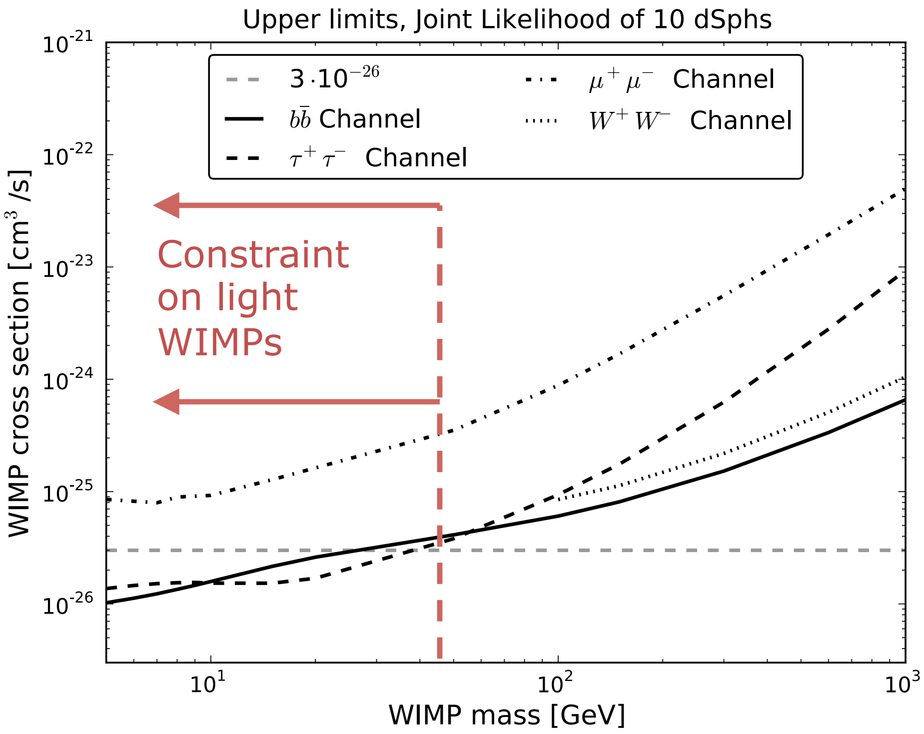
Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT '11

Thermal cross-section excluded for some channels (bb and $\tau\tau$)

Bounds are normally expressed for "pure" annihilation channels.

"Thermal" annihilation cross-section



$$J \equiv \int_{\Delta\Omega(\psi)} \int_{\ell} [\rho(\ell,\psi)]^2 \, d\ell \, d\Omega(\psi)$$

Very light DM can be further constrained, however.

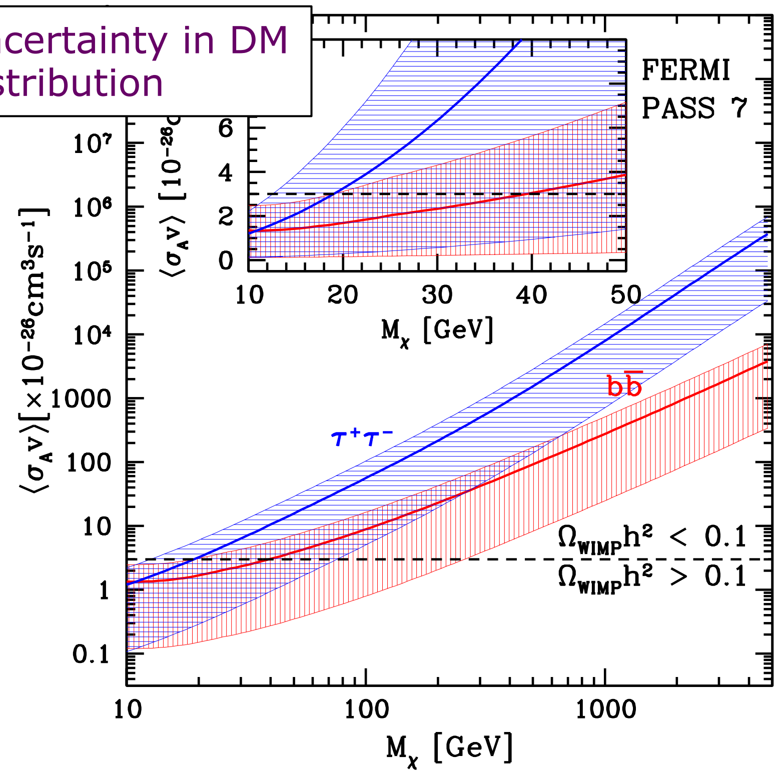
Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT ‘11

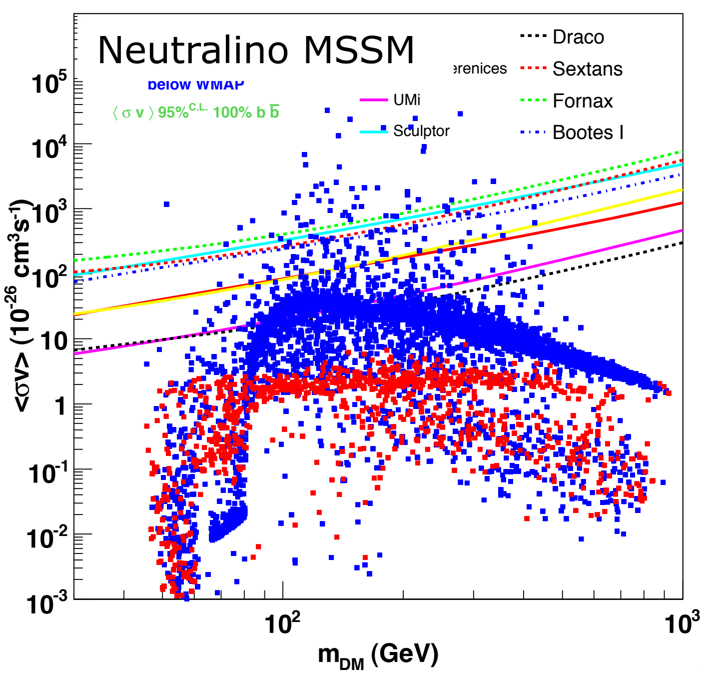
Thermal cross-section excluded for some channels (bb and ττ)

Bounds are normally expressed for “pure” annihilation channels.

Uncertainty in DM distribution



Geringer-Sameth, Koushiappas ‘11



Abdo et al. 1001.4531

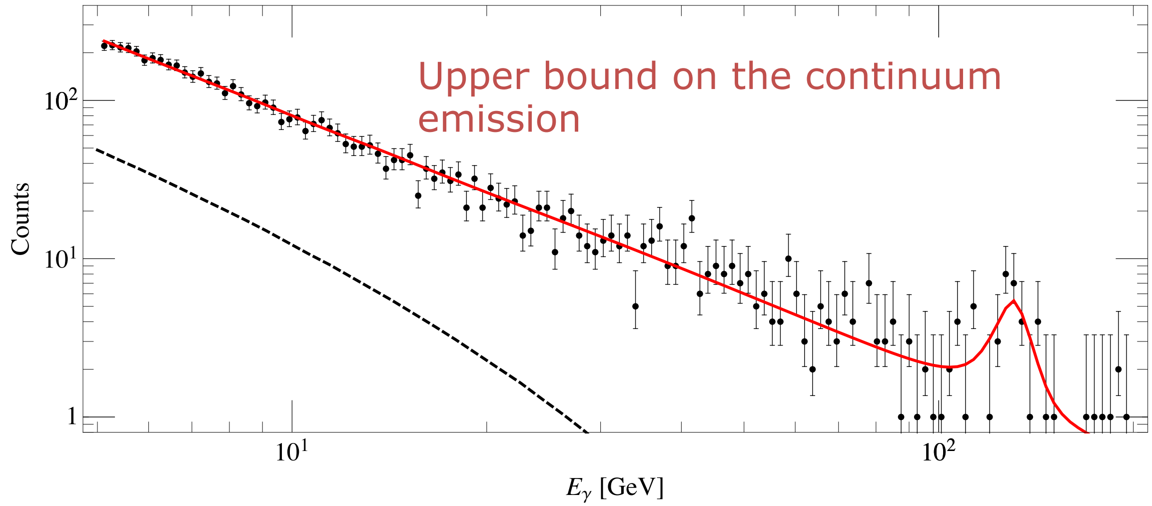
“Thermal” DM might have a smaller $<\sigma v>$ in the halo

Coannihilation effects,
velocity-dependent cross-section
resonances

How to explain this with particle DM models?

130 GeV WIMP annihil. into $\gamma\gamma \quad \gamma Z^0$

Relatively common channel (at 1 loop)



Cohen et al. 1207.0800

However, the line emission is very intense

$$R^{ob} \equiv \frac{1}{n^{\gamma}_{ann}} \frac{N_{ann}}{N_{\gamma\gamma} + N_{\gamma Z}} \quad \leq 90$$

Some common models cannot account for this (e.g. neutralino)

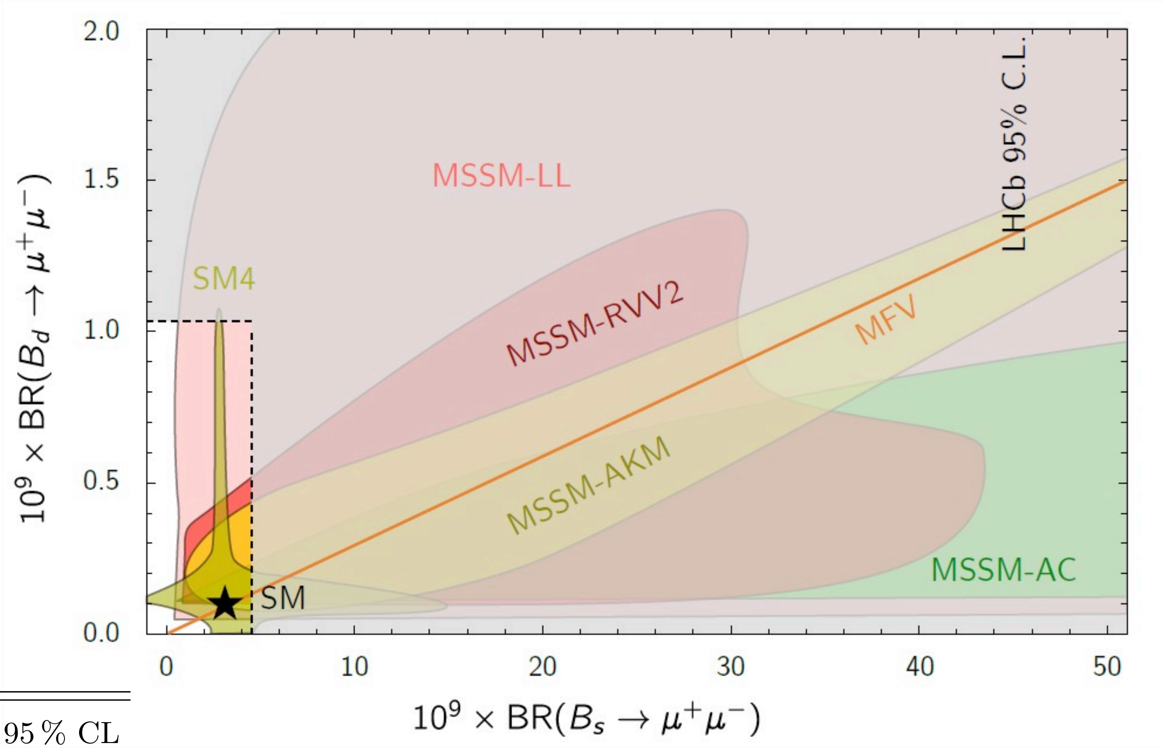
$$R^{\rm th}_{\rm wino} \simeq 200 \text{ and } R^{\rm th}_{\rm Higgsino} \simeq 700.$$

Currently looking for models with “enhanced gamma-lines”

Constraints from rare decays

Constraints on low energy observables

Also constrain the parameter space. Indirectly also constrain DM models



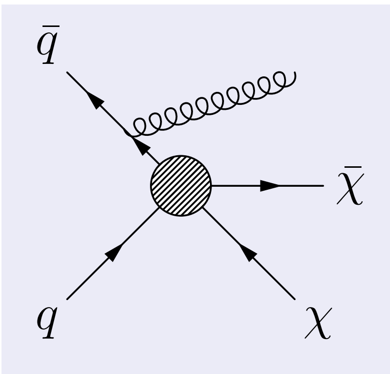
Mode	Limit	at 90 % CL	at 95 % CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	6.3×10^{-9}	7.2×10^{-9}
	Exp. bkg	2.8×10^{-9}	3.4×10^{-9}
	Observed	3.8×10^{-9}	4.5×10^{-9}
$B^0 \to \mu^+\mu^-$	Exp. bkg	0.91×10^{-9}	1.1×10^{-9}
	Observed	0.81×10^{-9}	1.0×10^{-9}

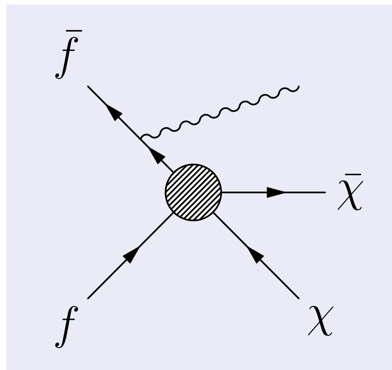
Rare B decays

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.5 \times 10^{-9}$$

LHCb March 2012

Mono-jet and Mono-γ (plus MET) searches constrain the region of light WIMPs

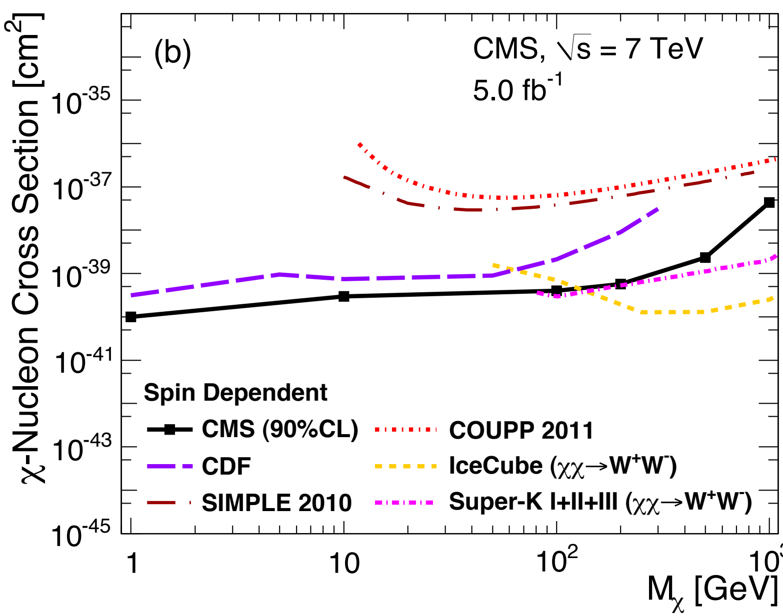


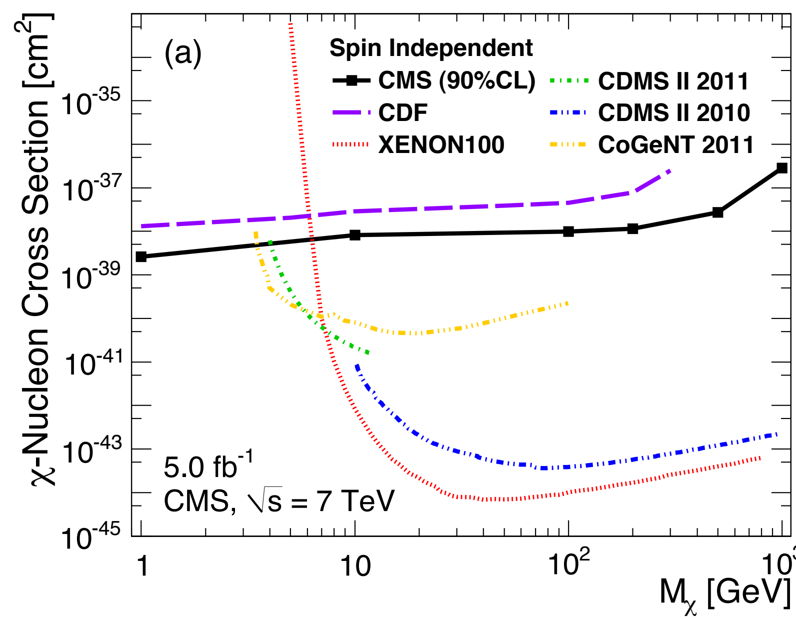


Dark matter production with initial state radiation

Bounds depend on the DM effective operators to fermions

LHC data 2011 (see also previous results from Tevatron)



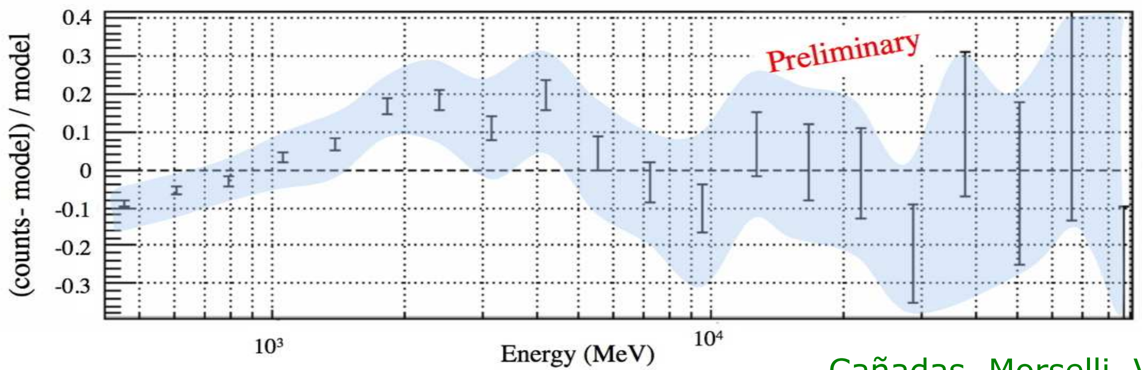


(CMS-PAS-EXO-11-096)

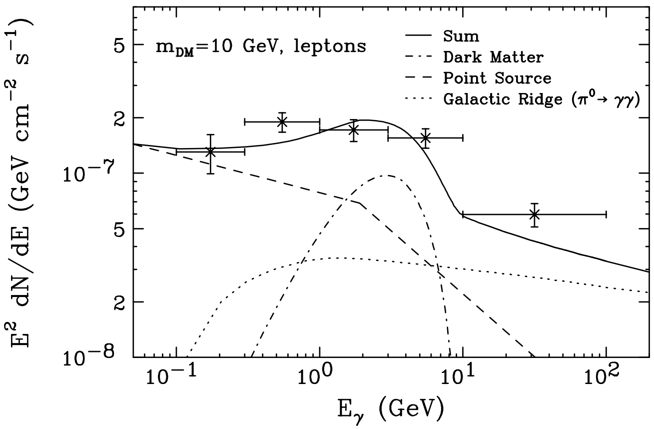
Hints for very light DM?

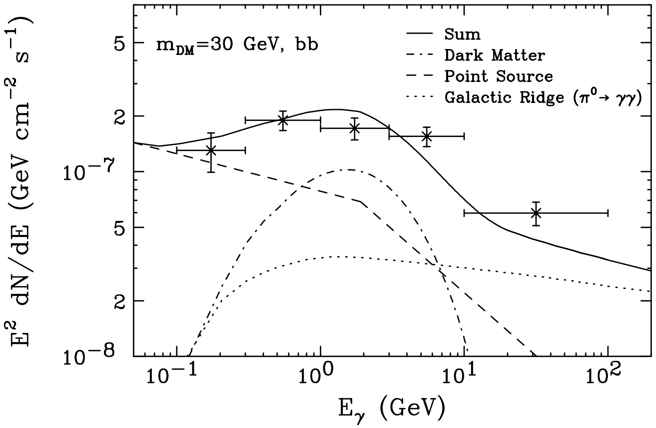
Gamma rays from the Galactic centre (Fermi LAT data)

Favours light dark matter: $\sigma v = 7 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$



Cañadas, Morselli, Vitale 2010





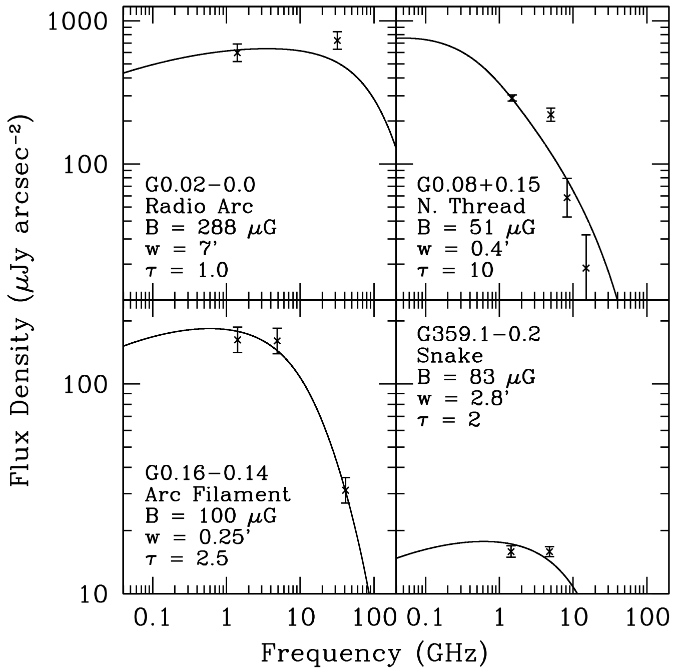
Hooper, Goodenough 2011; Hooper, Linden 2011

Hints for very light DM?

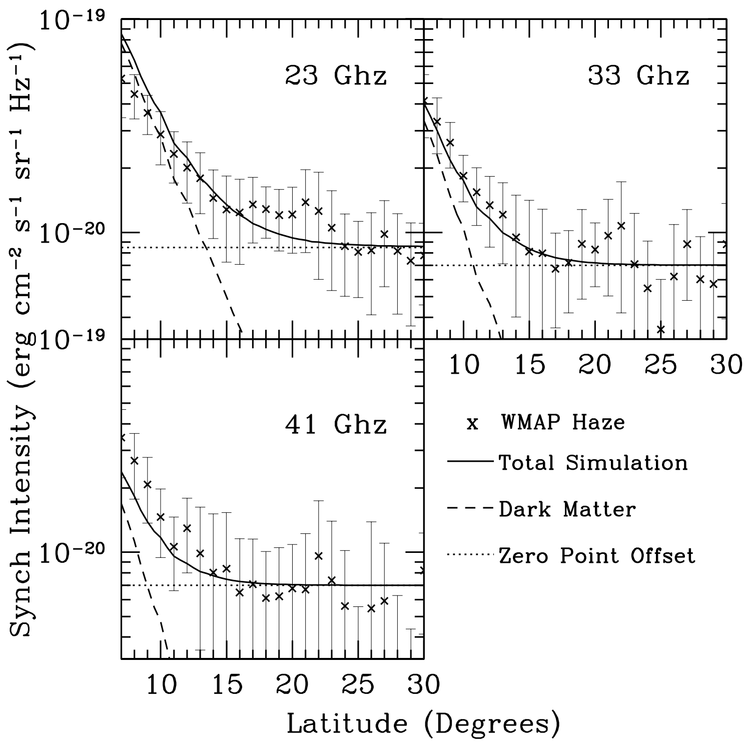
Synchrotron emission from radio filaments in the inner galaxy

Seem to contain spectrum of e^+e^- peaked at 10 GeV

Consistent with thermal very light WIMPs?



Linden, Hooper, Yusuf-Zadeh 2011

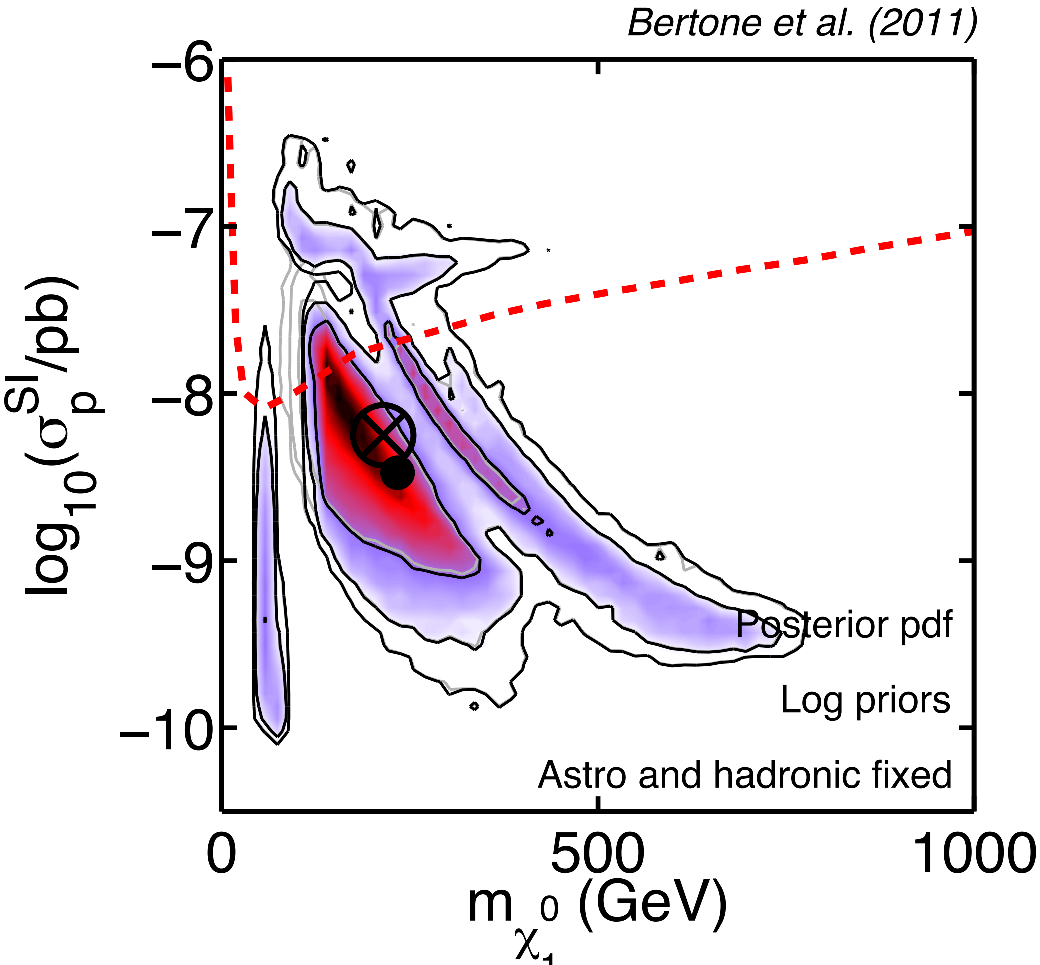


WMAP Haze

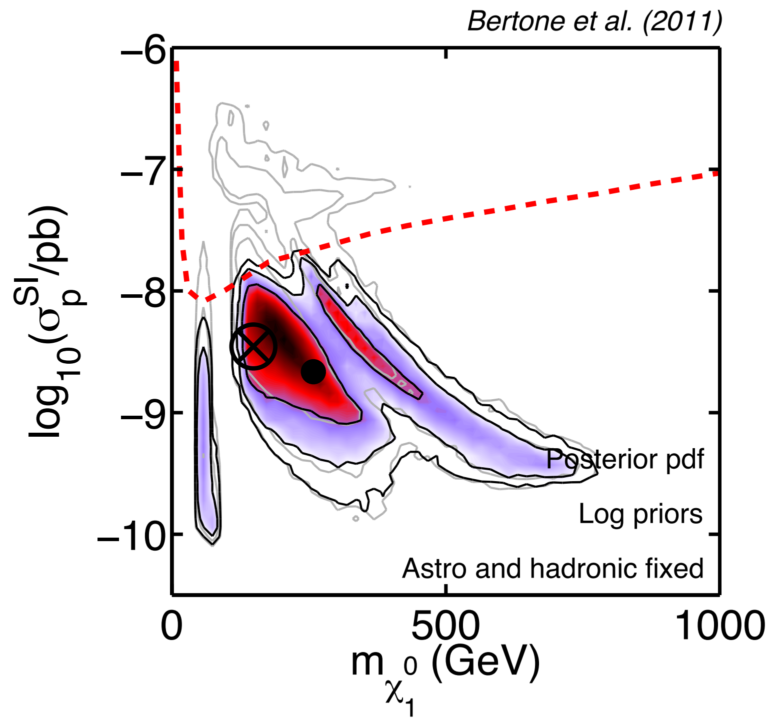
Could be further evidence of light (thermally produced) DM (m~10 GeV) annihilating mostly into leptons.

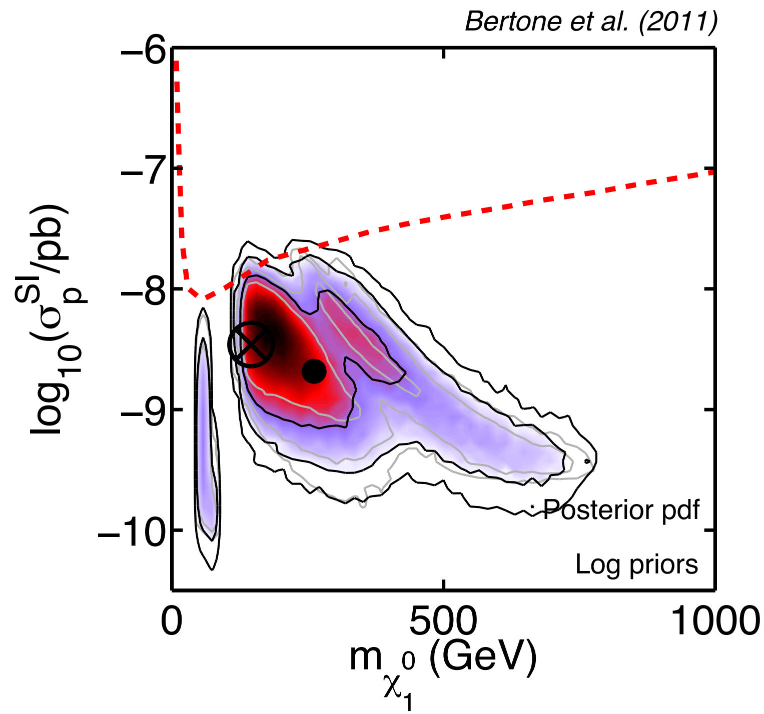
Impact of Xenon100 results

The negative results allow to exclude the Focus Point region, even with Astrophysical and Hadronic Uncertainties.



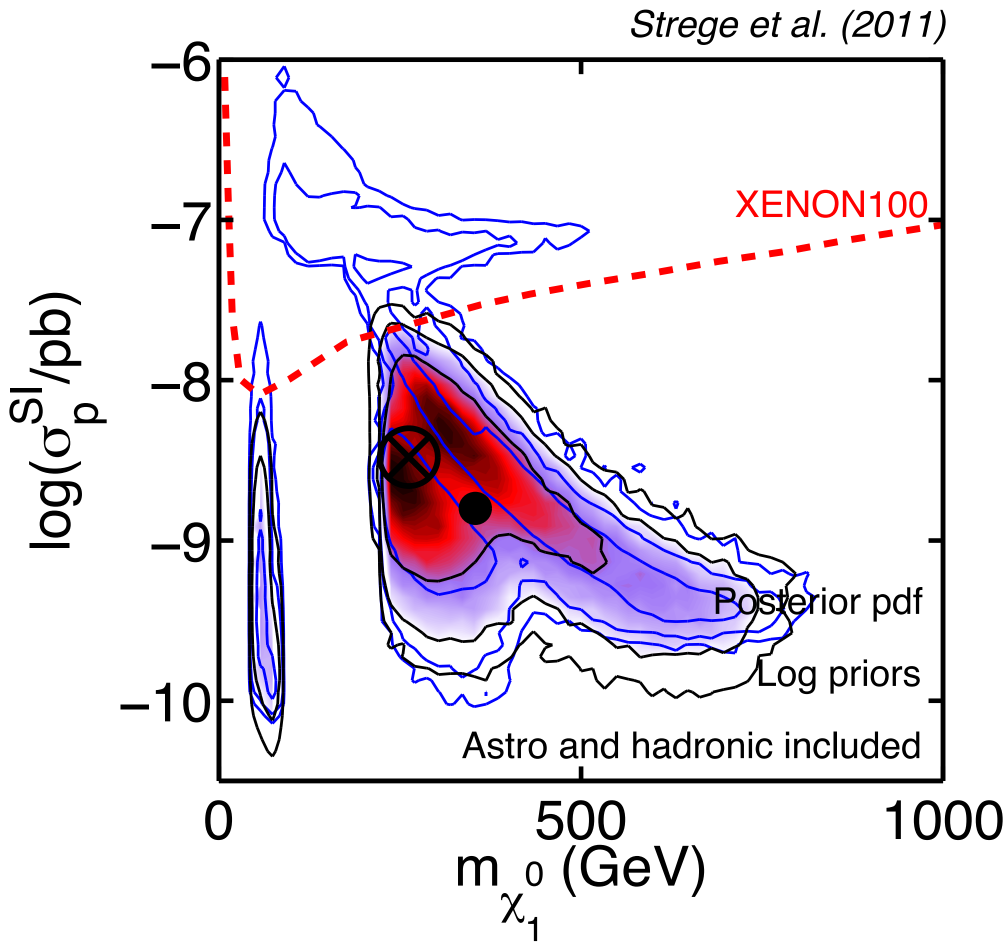
Bertone, Cerdeño., Fornasa, Ruiz de Austri, Trotta ‘1

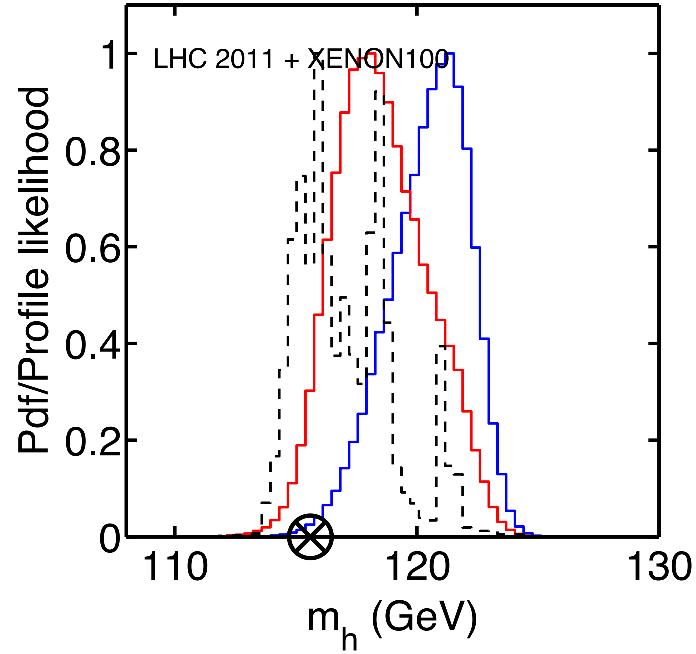




Impact of LHC and Xenon100 results

Including the recent LHC results on SUSY searches...





Strege, Bertone, Cerdeño., Fornasa, Ruiz de Austri, Trotta '11

Conclusions

- LHC alone might be unable to determine the nature of the dark matter

    Failing to unambiguously reconstruct the relic density

  Combination with Dark Matter experiments provides complementary information

    Results from 1 tonne experiments can be combined with LHC data to determine the DM relic abundance

- Spin-dependent sensitive targets can provide complementary information to determine the WIMP phenomenological parameters

    The inclusion of uncertainties (especially those in spin form factors) is important to assess complementarity of targets

    Relatively small targets ~50-100 kg (LiF, Sapphire) can be complementary to 1 tonne (Ge, Xe) experiments

Example: Two targets in COUPP

The detection rate for a given target is a function of the spin-dependent and independent couplings of the WIMP

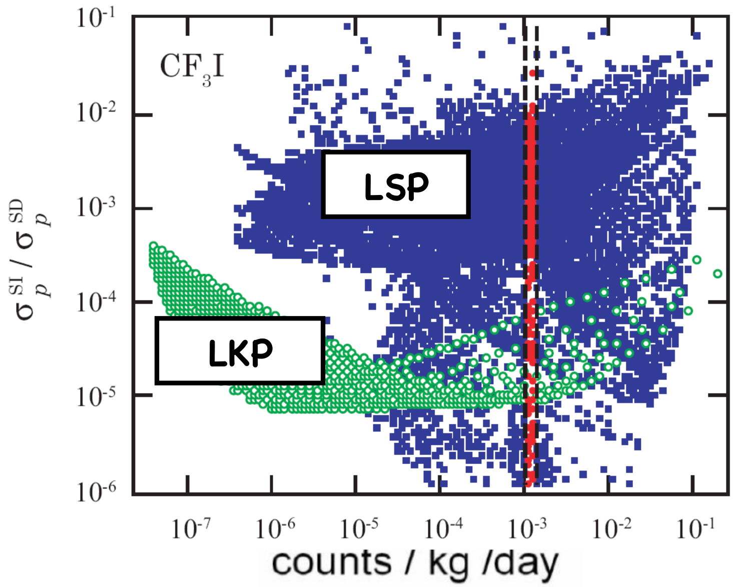
$$R_1 \sim A_1\, \sigma^{SI}{}_p + B_1\, \sigma^{SD}{}_p$$

(use WIMP relation among $\sigma^{SD}{}_n$ and $\sigma^{SD}{}_p$)

WIMP detection in two complementary targets can be used to discriminate WIMP models

Bertone, D.G.C, Collar, Odom '07

E.g., for COUPP with CF_3I



Example: Two targets in COUPP

The detection rate for a given target is a function of the spin-dependent and independent couplings of the WIMP

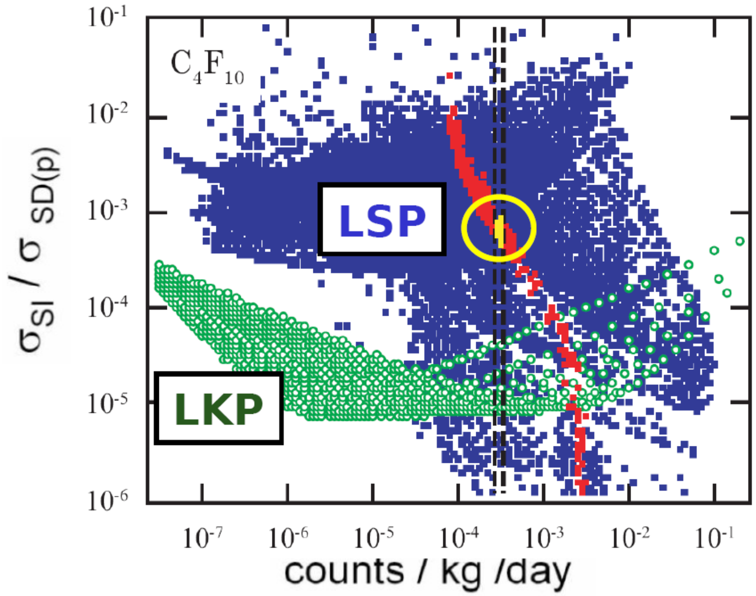
$$R_1 \sim A_1\, \sigma^{SI}_p + B_1\, \sigma^{SD}_p$$
$$R_2 \sim A_2\, \sigma^{SI}_p + B_2\, \sigma^{SD}_p$$

(use WIMP relation among σ^{SD}_n and σ^{SD}_p)

WIMP detection in two complementary targets can be used to discriminate WIMP models

Bertone, D.G.C, Collar, Odom '07

E.g., for COUPP with CF_3I and C_4F_{10}



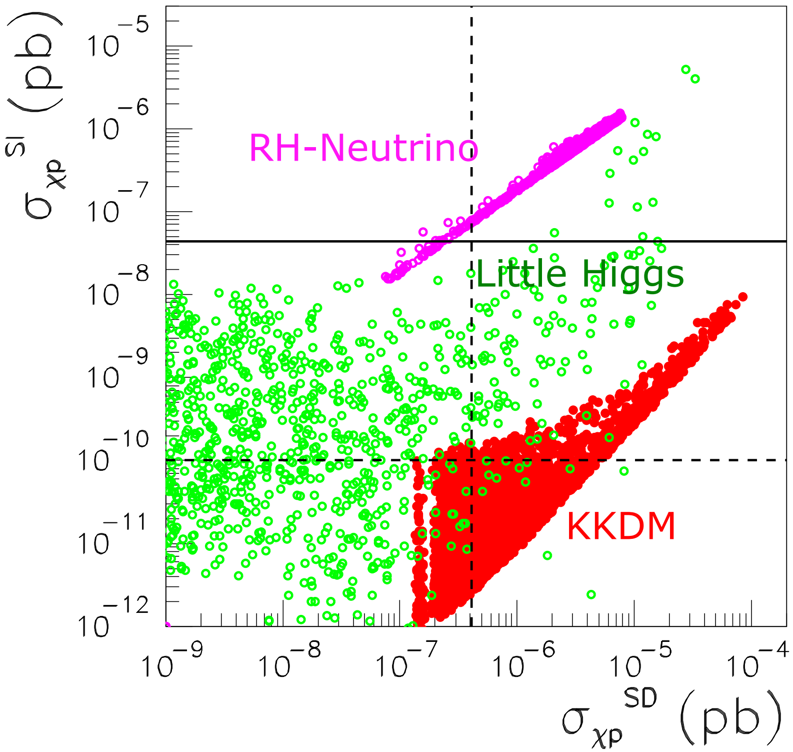
(See also Belanger, Nezri, Pukhov '08)

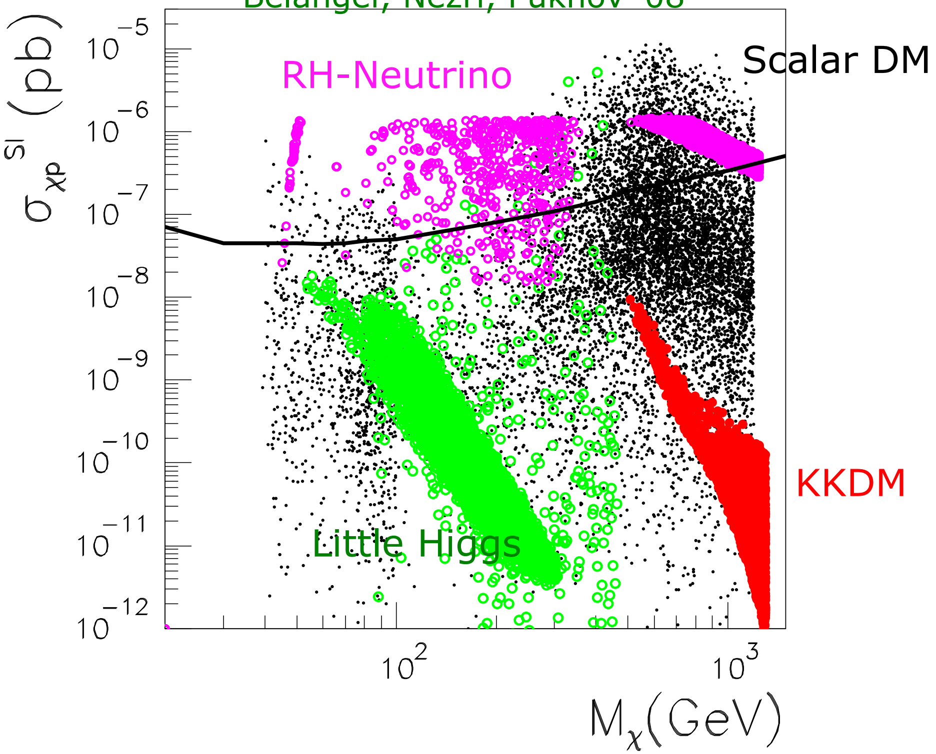
Can we determine to which DM model it corresponds?

There can be, however, correlations in the "phenomenological parameters"

Information on spin-dependent WIMP couplings can prove important to distinguish models

Belanger, Nezri, Pukhov '08





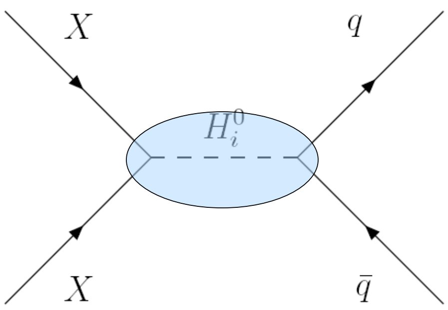
Determining the full set of parameters provides crucial information

m_X σ^{SI}_p σ^{SD}_p σ^{SD}_n

DM signals in colliders (LHC)

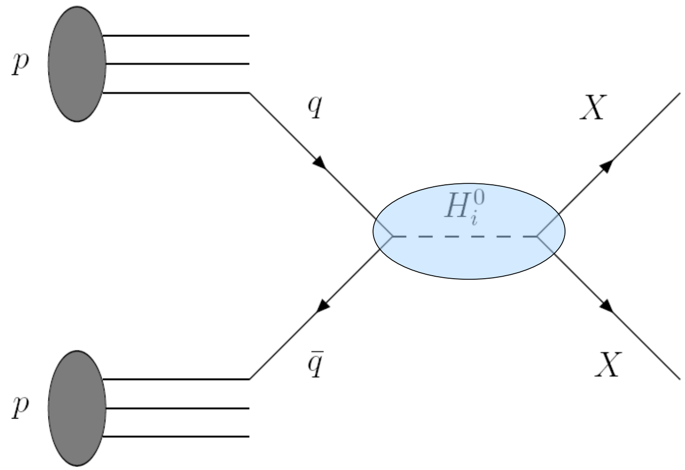
Direct DM production (pp → XX) does not leave a good signal

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

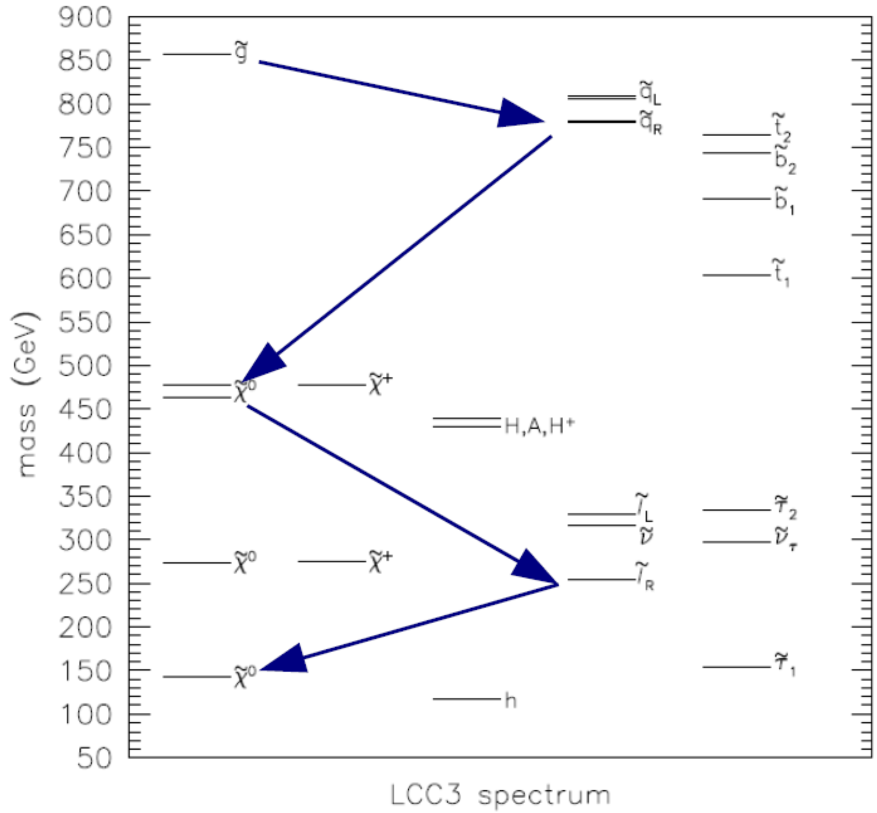
Look for jets + extra leptons

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



Spin-dependent WIMP-nucleus interaction

$$\left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD} = \frac{16\, G_F^2 m_N}{\pi v^2} \frac{(J+1)}{J} \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle\right)^2 \frac{S(E_R)}{S(0)}$$

Form factor

WIMP model

$$a_p = \sum_{q=u,d,s} \frac{\alpha_q^A}{\sqrt{2} G_F} \Delta_q^p \, ; \quad a_n = \sum_{q=u,d,s} \frac{\alpha_q^A}{\sqrt{2} G_F} \Delta_q^n$$

WIMP couplings

Nuclear Physics

$$\langle S_{p,n} \rangle = \langle N | S_{p,n} | N \rangle$$

Expectation value of the spin content of the proton (neutron) group in the Nucleon

$$\langle n | \bar{q} \gamma_\mu \gamma_5 q | n \rangle = 2 s_\mu^{(n)} \Delta_q^{(n)}$$

Matrix element of the axial-vector current

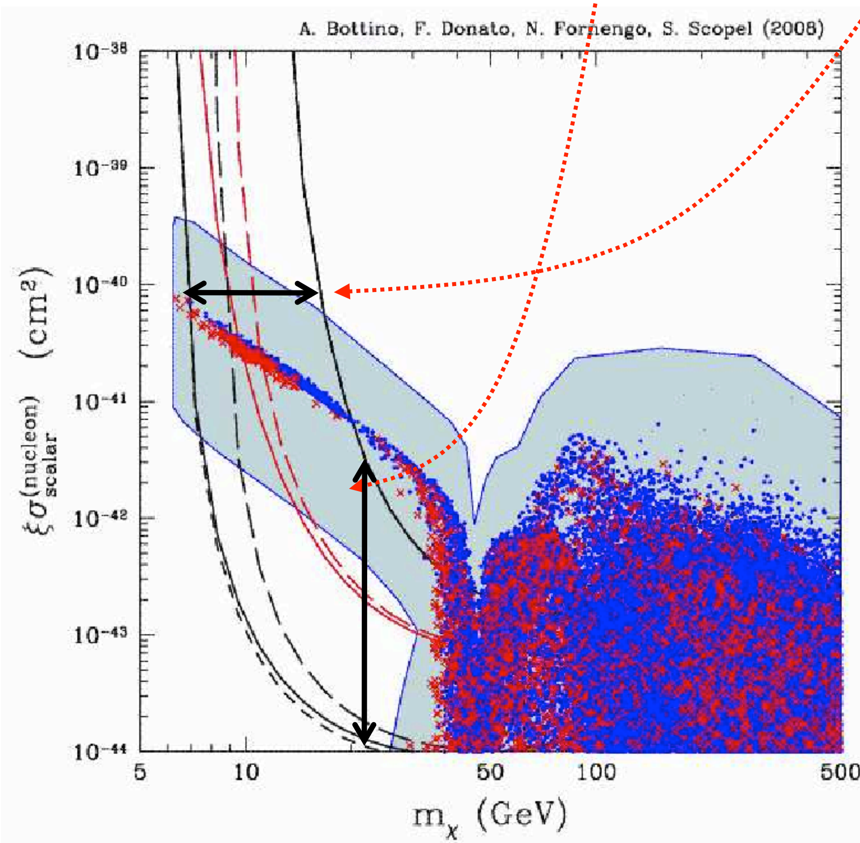
Parametrization of the form factor

$$S(q) = a_0^2 S_{00}(q) + a_0 a_1 S_{01}(q) + a_1^2 S_{11}(q)$$

$$a_0 = a_p + a_n$$
$$a_1 = a_p - a_n$$

Astrophysical uncertainties in direct DM searches

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$



Uncertainty in the local density parameter lead to an indetermination of the total scattering cross section

Variations in the velocity distribution factor affect the potential reach for low mass WIMPs and the reconstruction of WIMP mass

Both effects are correlated

Parameterizing astrophysical uncertainties

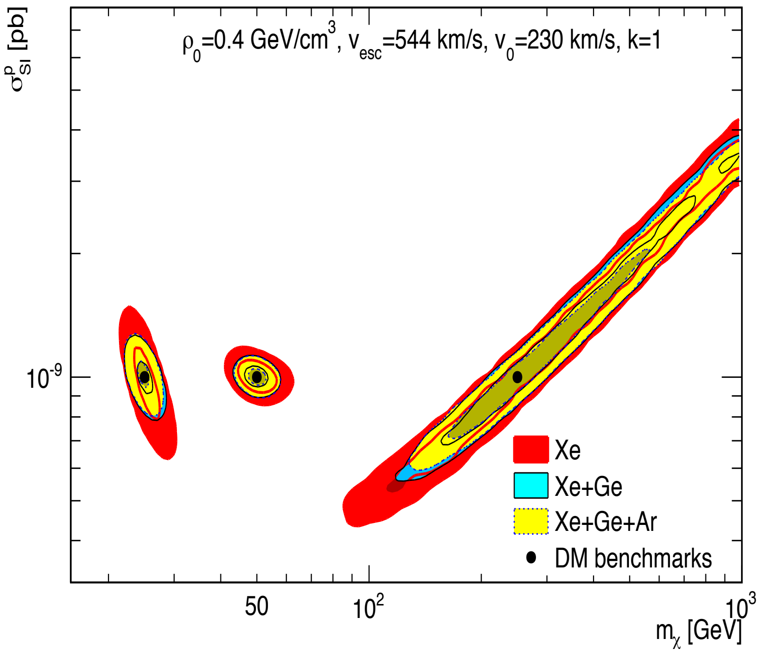
Generalization of the SHM for the velocity distribution function

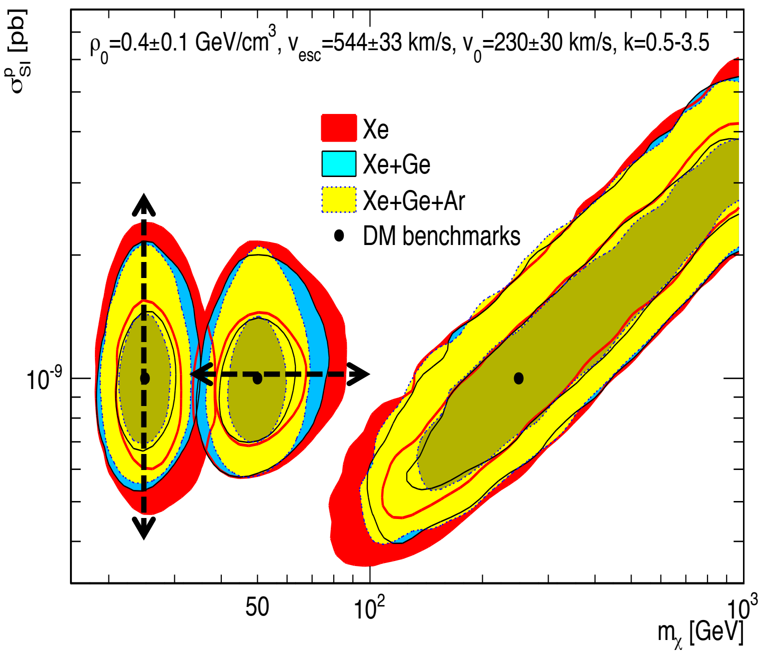
Based on Binney, Tremaine '08

$$f(w) = \begin{cases} \frac{1}{N_f}\left[\exp\left(\frac{v_{esc}^2 - w^2}{k v_0^2}\right) - 1\right]^k & \text{if } w \leq v_{esc} \\ 0 & \text{if } w > v_{esc} \end{cases}$$

Nuisance parameter	Range
$\rho_{\mathrm{WIMP},\odot}$	$[0.2,\ 0.6]$ GeV cm^{-3}
v_{esc}	$[478,\ 610]$ km s^{-1}
$v_{\odot}$	$[170,\ 290]$ km s^{-1}
k	$[0.5,\ 3.5]$

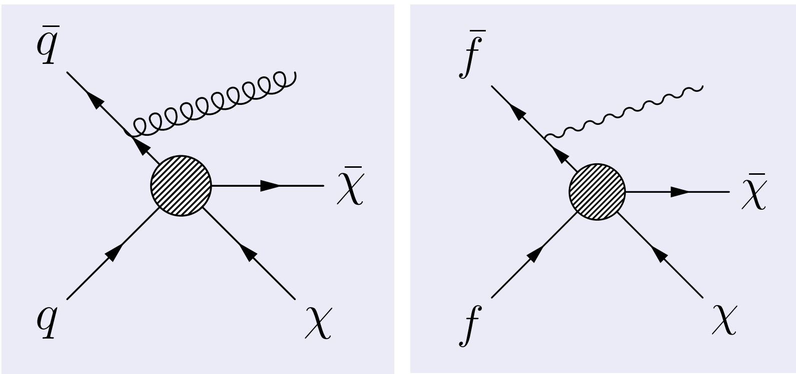
Lisanti et al. '10





Pato, Baudis et al. '11

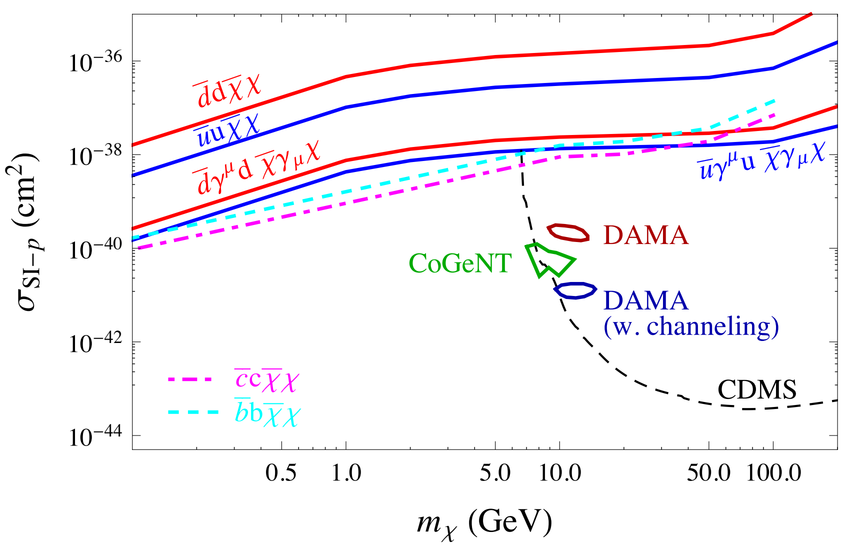
Mono-jet and Mono-γ (plus MET) searches constrain the region of light WIMPs

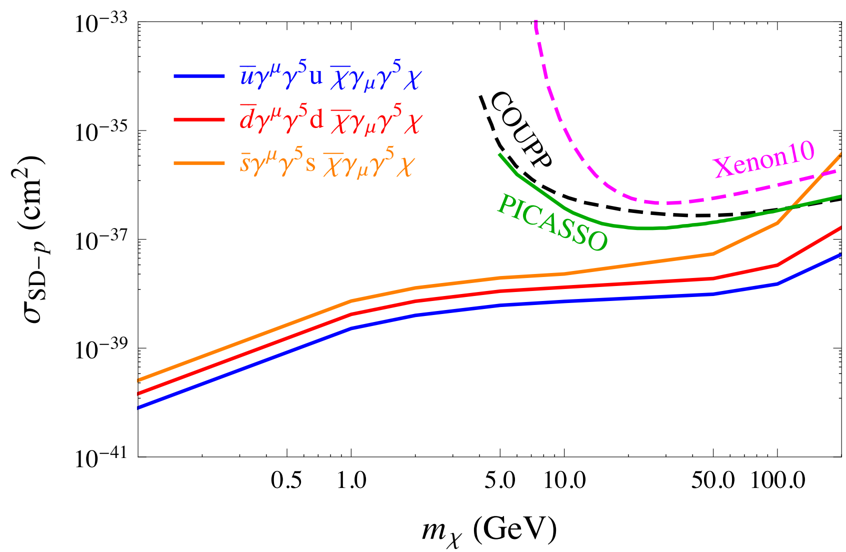


Dark matter production with initial state radiation

Bounds depend on the DM effective operators to fermions

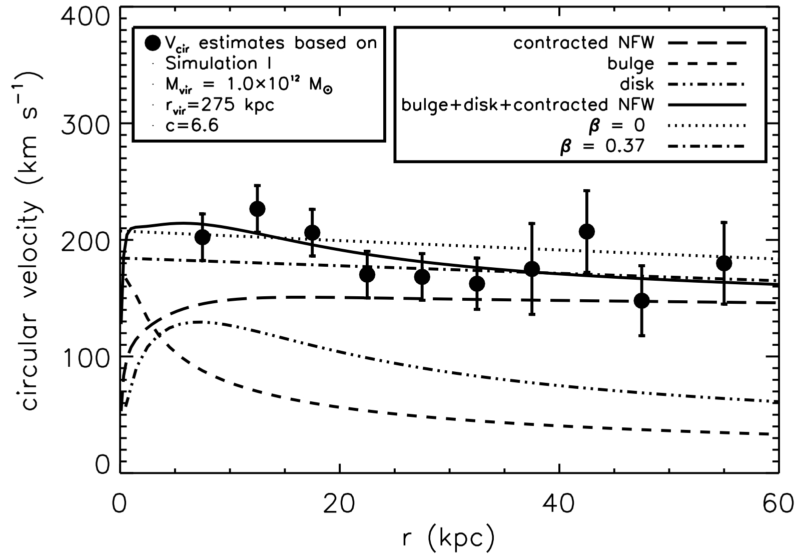
Tevatron data



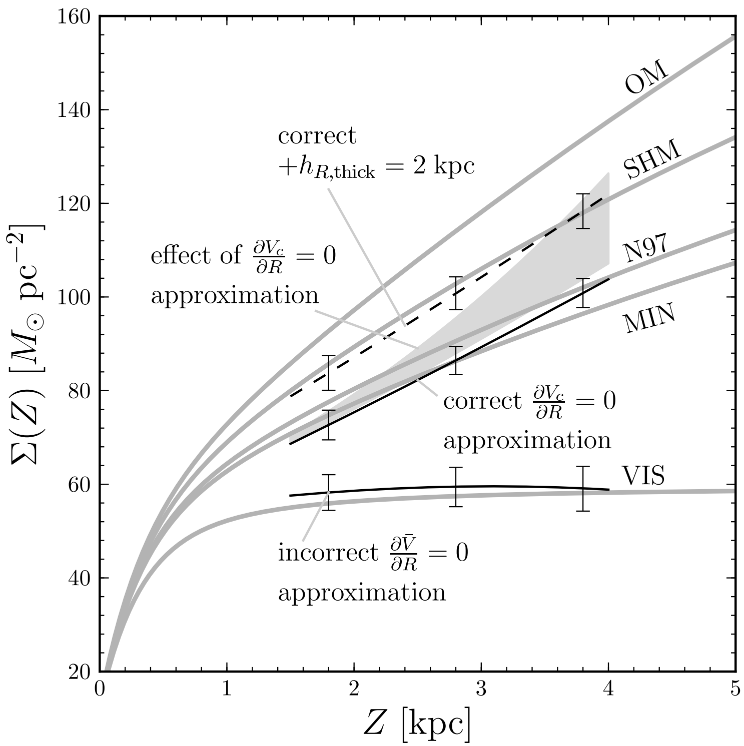


Observations of the Milky way are also consistent with the existence of DM at our position in the Galaxy

The rotation curve is known up to large distances



Xue et al. 2008



And, despite some recent flawed analysis

Bidin, Carraro, Méndez, Smith 2012

Observations show that there is need for dark matter in the solar neighbourhood

Bovy, Tremaine 2012

A sharp feature in the gamma ray spectrum?

Difficult to attribute to astrophysical background (*)

Gamma-ray line emission

Weniger 1204.2797

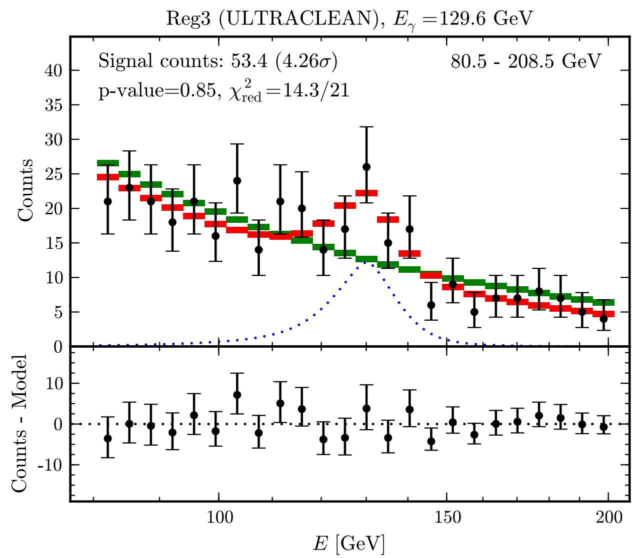
130 GeV WIMP annihil. into $\gamma\gamma$

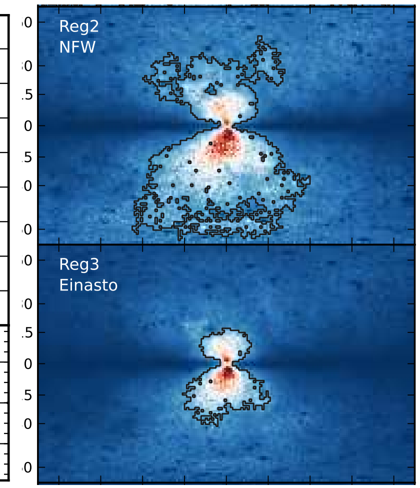
145 GeV WIMP annihil. into γZ^0

155 GeV WIMP annihil. into $H\gamma$

Internal bremsstrahlung

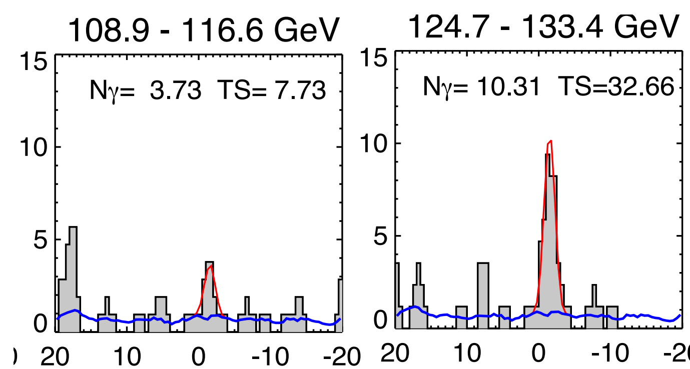
Bringmann et al. 1203.1312





Possible hints of a second line at ~110 GeV consistent with annihilation into γZ^0

Finkbeiner '12



Can it be explained by a particle DM model?

Difficult: need small continuum contribution

Neutralino in the MSSM ruled out

Cohen et al. 1207.0800

(*) Possible background from Fermi bubbles
Instrumental effect?
Power-law fit of the background?

However very light WIMPs have not shown up in other experiments

• XENON finds no light WIMPs: issues with scintillation efficiency (L_{eff})?

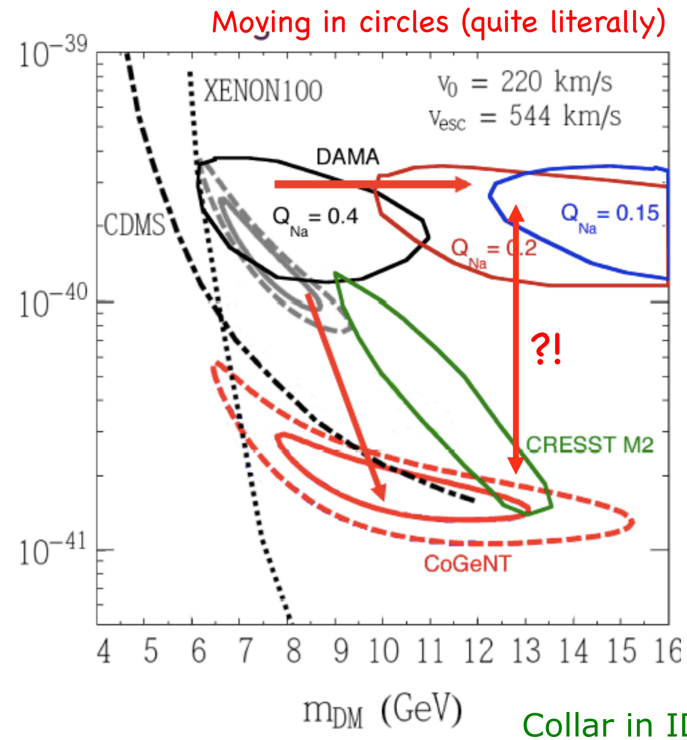
XENON10, XENON100 ‘11-12

• CDMS II: A low-energy reanalysis of the data is incompatible with CoGeNT region

CDMS ‘11

• SIMPLE: Further constraints on DAMA/LIBRA and CoGeNT regions

SIMPLE ’11-12



Collar in IDM 2012

• DAMA-LIBRA interpretation in terms of channelling is challenged

Gelmini, Gondolo, Bozorgnia, ‘09 ‘10

• CoGeNT: smaller amplitude of the DM modulation signal in second year of data

Collar in IDM 2012

• CRESST: backgrounds from ^{210}Po underestimated?

Kuzniak, Boulay, Pollmann ‘12

Neutralino in the MSSM

The theoretical predictions can be within the range of future experiments

Large cross section for a wide range of masses

Ellis, Ferstl, Olive 2005
Baek, D.G.C., Kim, Ko, Muñoz 2005

Very light Bino-like neutralinos with masses ~10 GeV could account for the DAMA signal

Bottino, Donato, Fornengo, Scopel 2008

This region is currently extremely constrained (if not ruled out) by current LHC bounds

LHCb 2012

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.5 \times 10^{-9}$$