Dark Matter:

Th

David G. Cerdeño

Dark Matter:

a Thrilling present

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Dark Matter:
a Thrilling present
¿Are we There yet?

David G. Cerdeño

MULTIDARK
Multimessenger Approach for Dark Matter Detection

UNIVERSIDAD AUTONOMA DE MADRID

Outline

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

1) Dark Matter can be detected

- Direct DM detection
- Indirect Searches
- Collider implications

2) Particle Dark Matter Models

- WIMPs?
- Very light DM

3) Dark Matter in the (near?) future

- Identification of DM
- Complementarity of DM searches

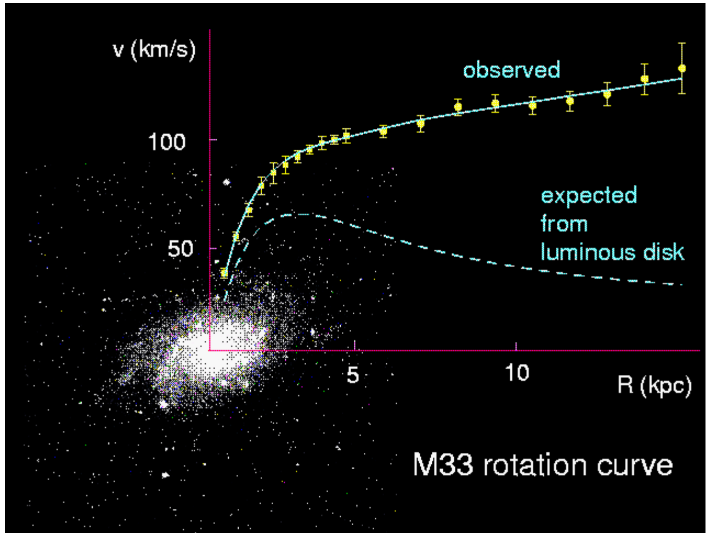
4) End (probably late)

Motivation for dark matter

The evidence for Dark Matter is present in all scales of the Universe

Galaxies

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

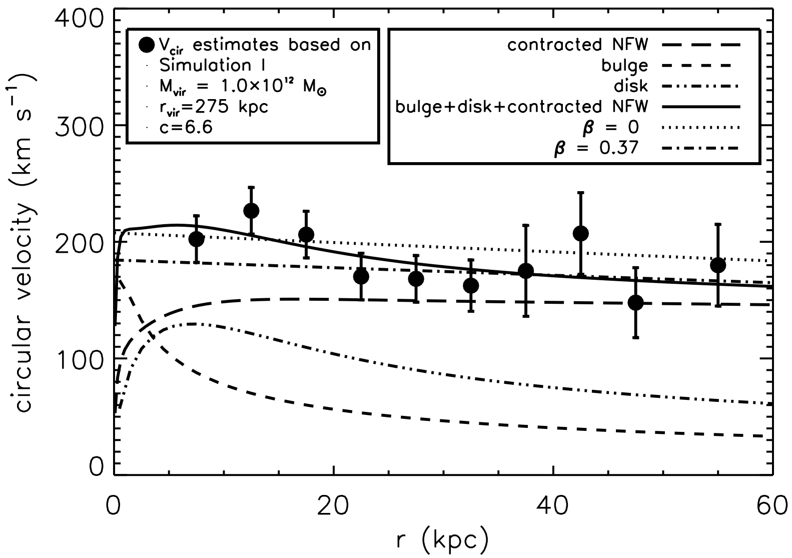


Clusters of galaxies

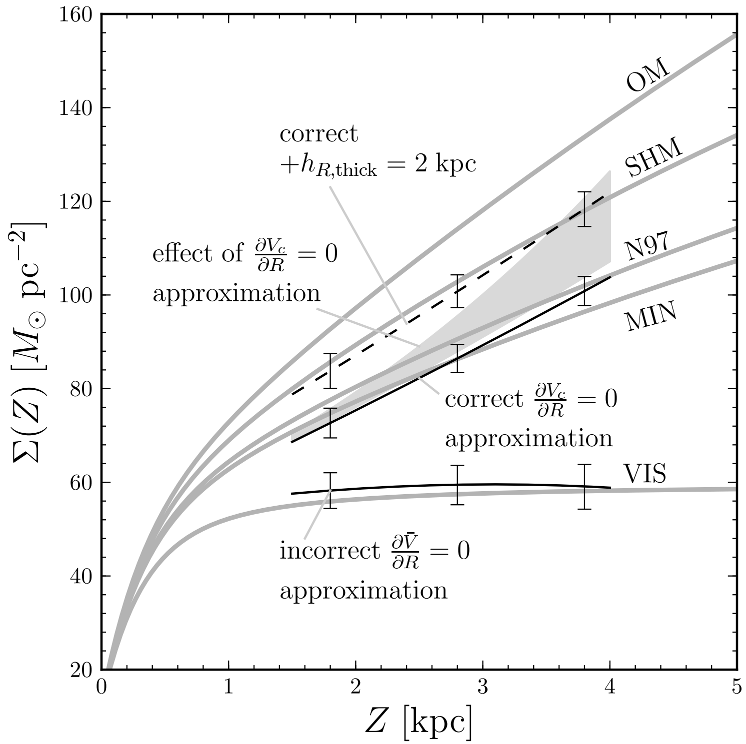
- Peculiar velocities and gas temperature
- Weak lensing

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

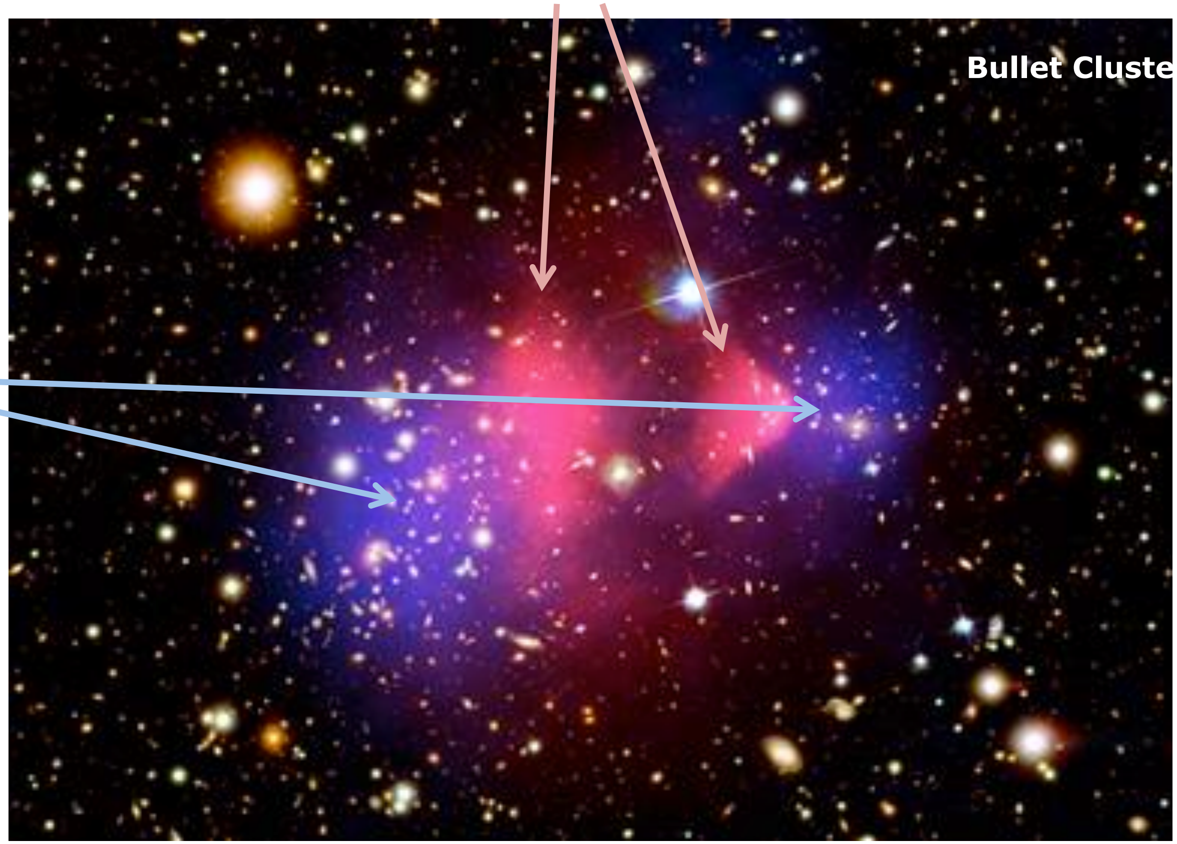
Motivation for dark matter

Hot gas (luminous matter) observed by Chandra

Components with different behaviour observed through X-ray emission and weak lensing

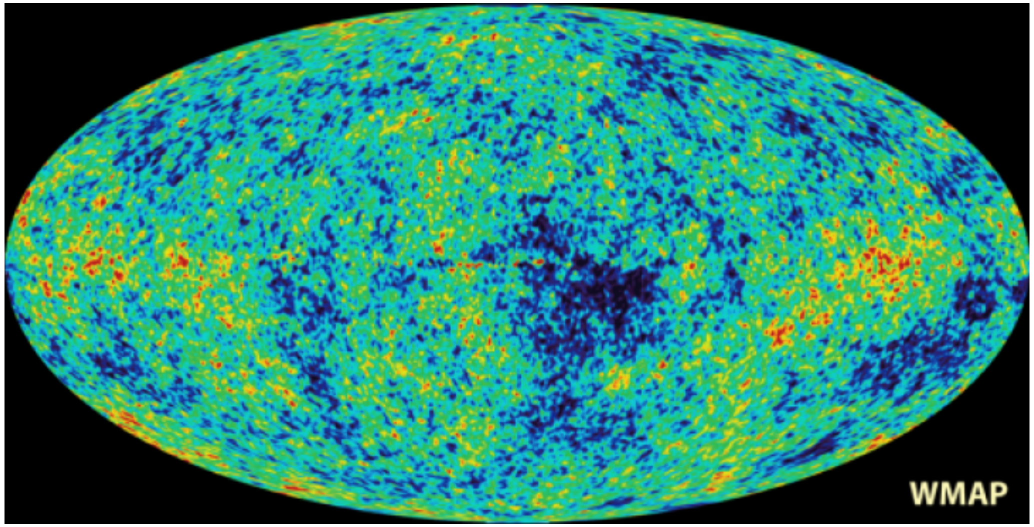
(Collisionless) dark matter

(false colour)



Chandra, 21 Ago. 2006

Motivation for dark matter

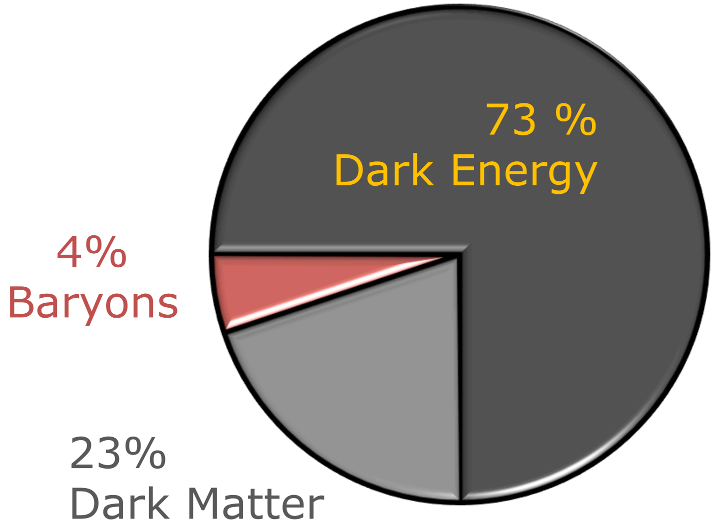


WMAP – 7yr

The results from the WMAP satellite have allowed to measure the amount of DM

Dark Matter differs from known matter (is non-baryonic)

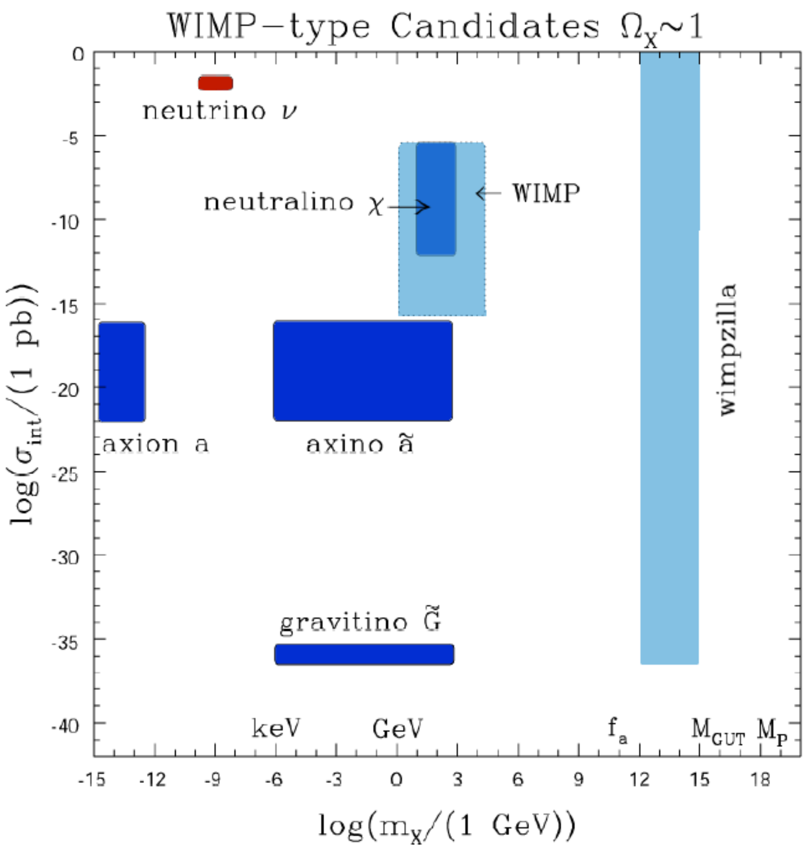
$$\Omega_{CDM}\, h^2 = 0.110 \pm 0.006$$



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

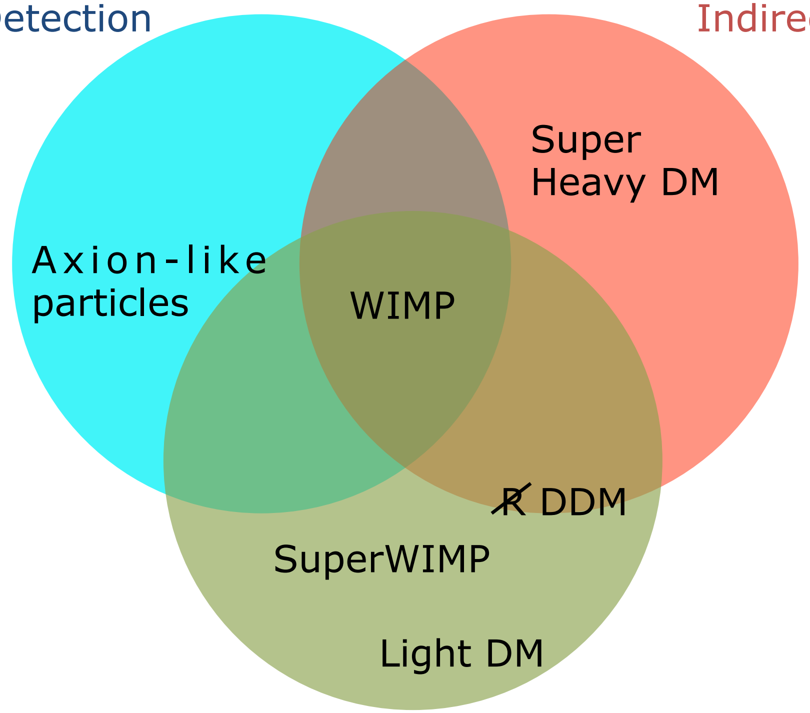
- Axions
- Weakly Interacting Massive Particles (WIMPs)
- SuperWIMPs and Decaying DM
- WIMPzillas
- Asymmetric DM
- SIMPs, CHAMPs, SIDMs, ETCs...

... they have very different properties

Complementarity of DM searches

Direct Detection

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



Indirect Detection

PAMELA
Fermi
MAGIC
AMS
ANTARES
IceCube
CTA
WMAP
...

Accelerator searches

LHC (ILC)

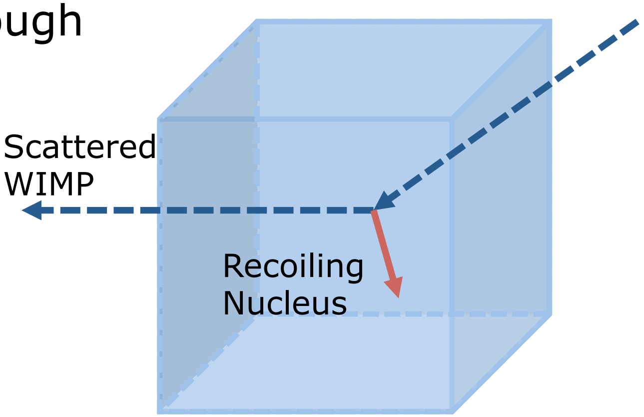
Many DM models can be probed by the different experimental techniques

"Redundant" detection can be used to extract DM properties

Direct detection, where do we stand?

WIMP scattering with nuclei can be measured through

- Ionization
- Scintillation light
- 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

The WIMP-nucleus cross section has two components

$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

Spin-independent contribution: scalar (or vector) coupling of WIMPs with quarks

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q + \alpha_q^V \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

Total cross section with Nucleus scales as A^2

Present for all nuclei (favours heavy targets) and WIMPs

Spin-dependent contribution: WIMPs couple to the quark axial current

$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

Total cross section with Nucleus scales as J/(J+1)

Only present for nuclei with J≠ 0 and WIMPs with spin

An exciting experimental situation

DAMA/NaI (DAMA/LIBRA) signal on annual modulation

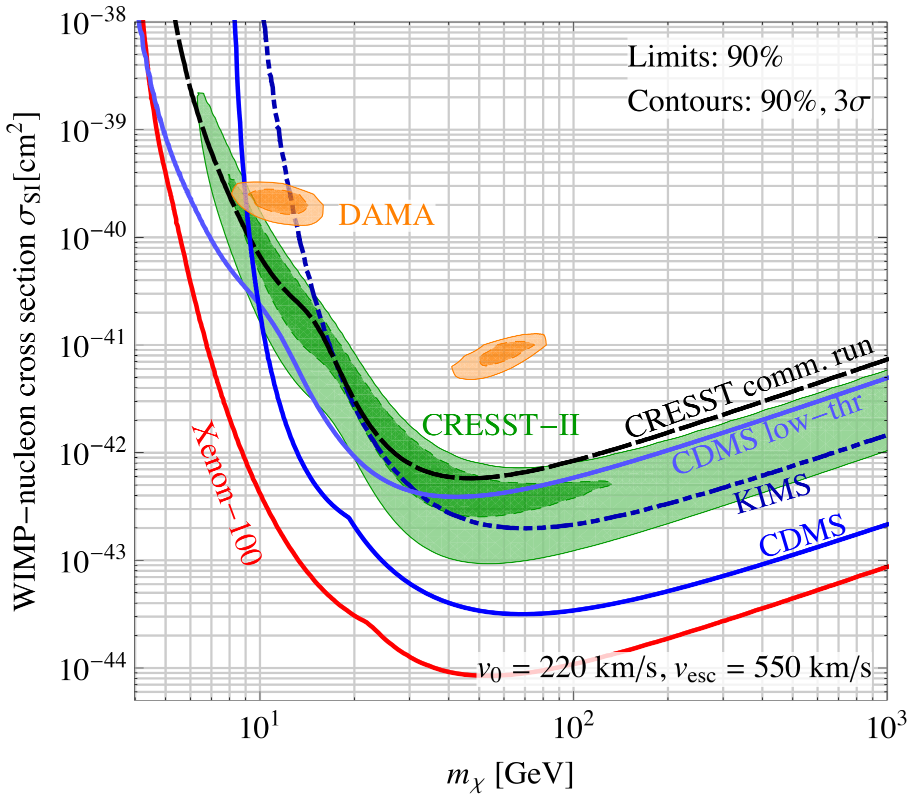
cumulative exposure 427,000 kg x day (13 annual cycles)

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
- None of the above...?



Kopp, Schwetz, Zupan ‘11

Hints of light WIMPs in recent experimental results...?

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

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

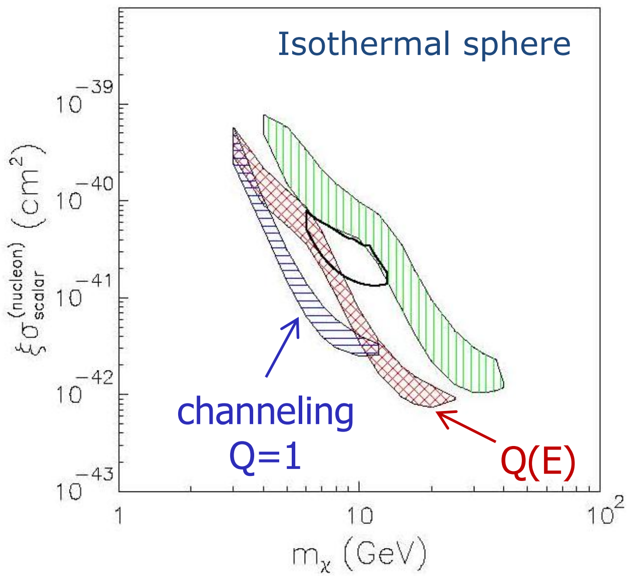
- CoGeNT finds irreducible background that can be compatible with 7-10 GeV WIMPs

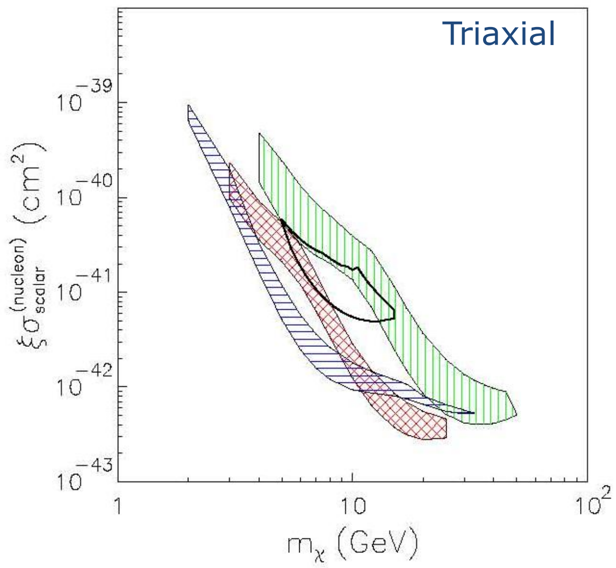
  ... annual modulation (2.8 in 15 months data) in CoGeNT

  Collar et al. '10, '11

- CRESST finds an excess over the expected background

  CRESST '11





Belli et al. '11

Many efforts in reconciling these results

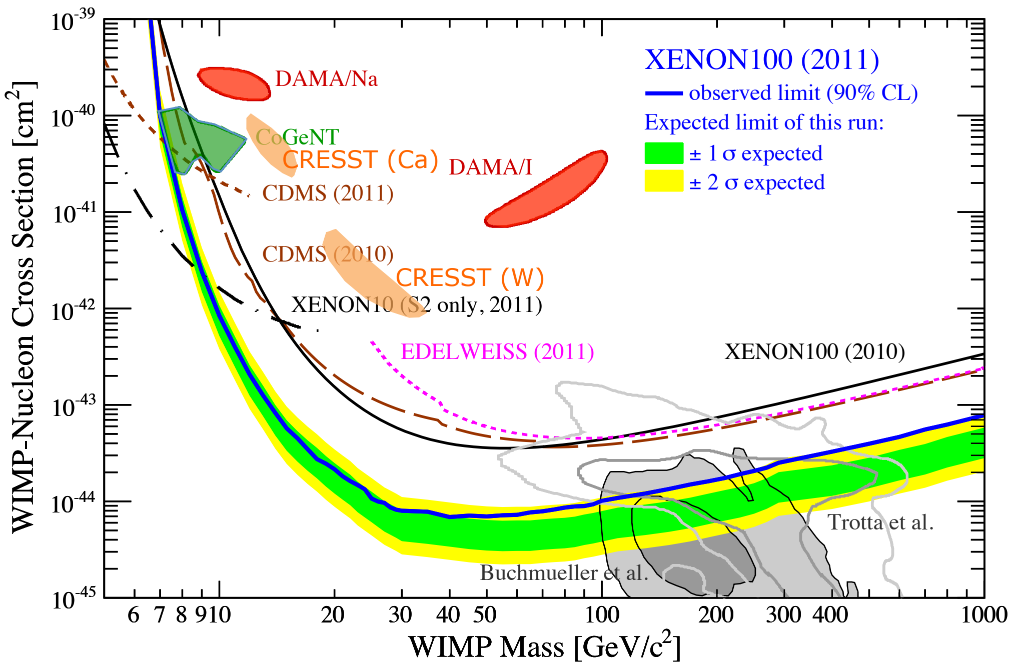
See, e.g., Schwetz, Zupan '11;
Hooper, Kelso '11;
Farina et al. '11;
McCabe '11;
Arina et al. '11;
...

Uncertainties in determination of DM parameters

However very light WIMPs have not shown up in other experiments

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

Xenon10, Xenon100 2011



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

CDMS 2011

• SIMPLE: Further constraints on the CoGeNT region

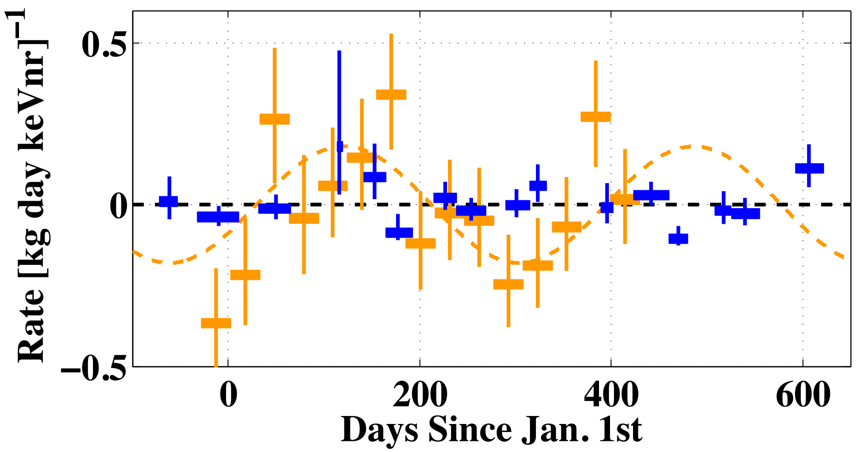
• DAMA-LIBRA interpretation in terms of channelling is challenged

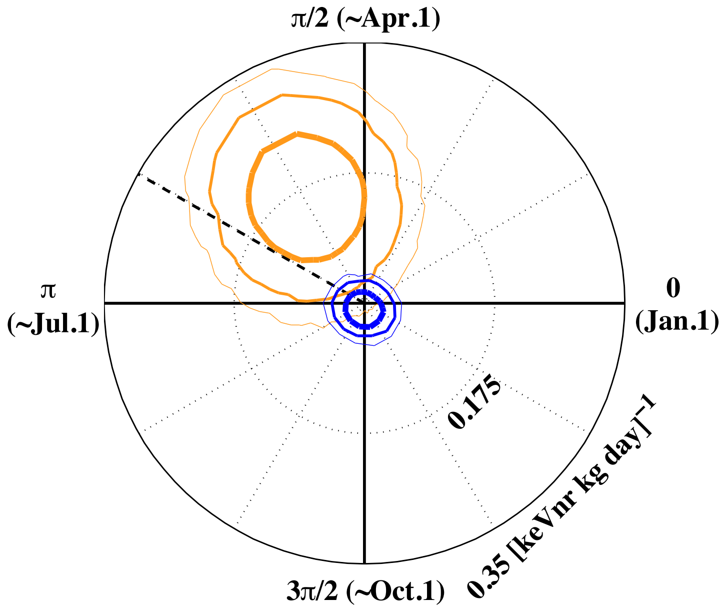
Gelmini, Gondolo, Bozorgnia, 2009 2010

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 observation



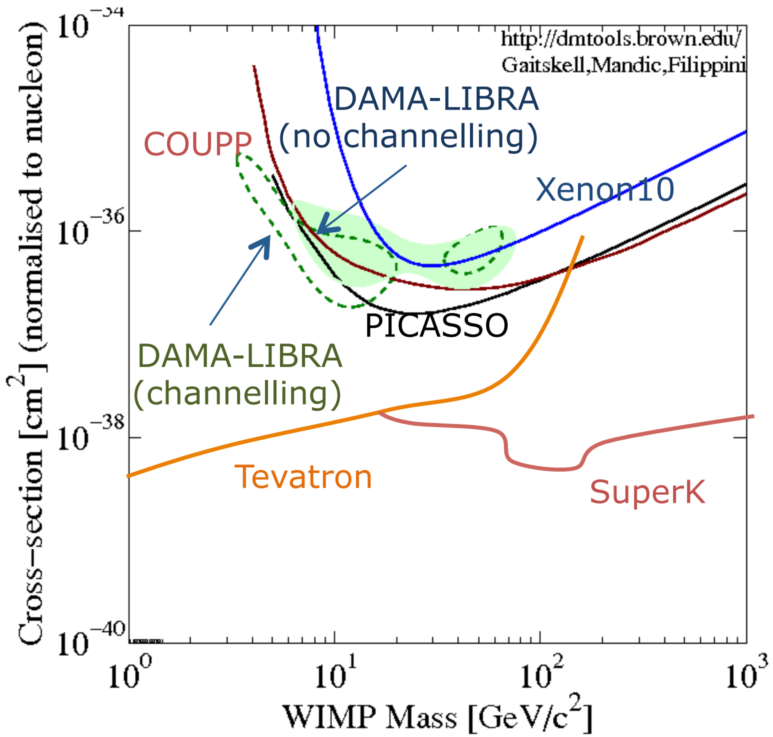


CDMS II 2012

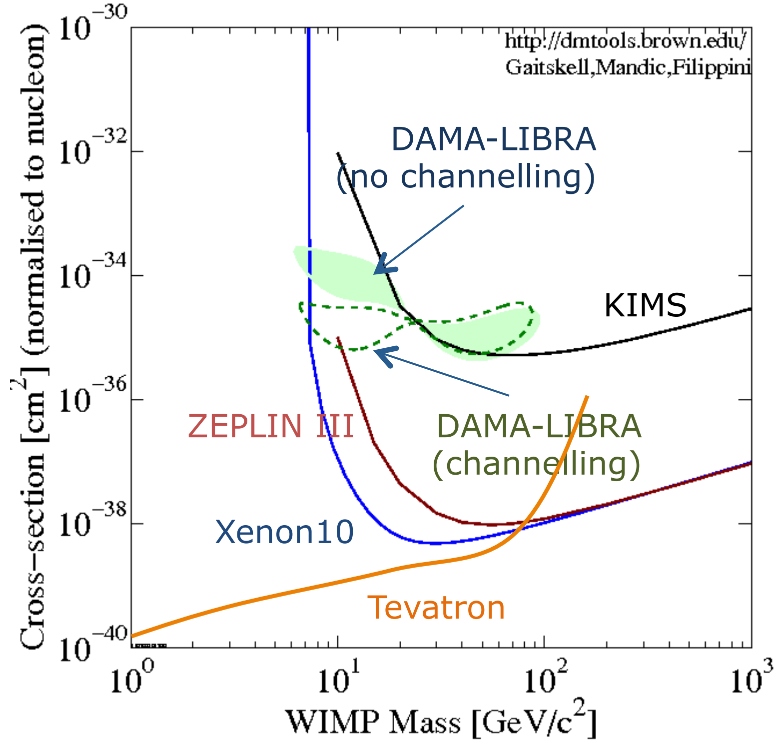
Spin-dependent searches have also become more sensitive

Dedicated experiments with targets sensitive to spin-dependent WIMP couplings

SD coupling to protons



SD coupling to neutrons



The DAMA-LIBRA interpretation in terms of spin-dependent couplings is not consistent with other detectors

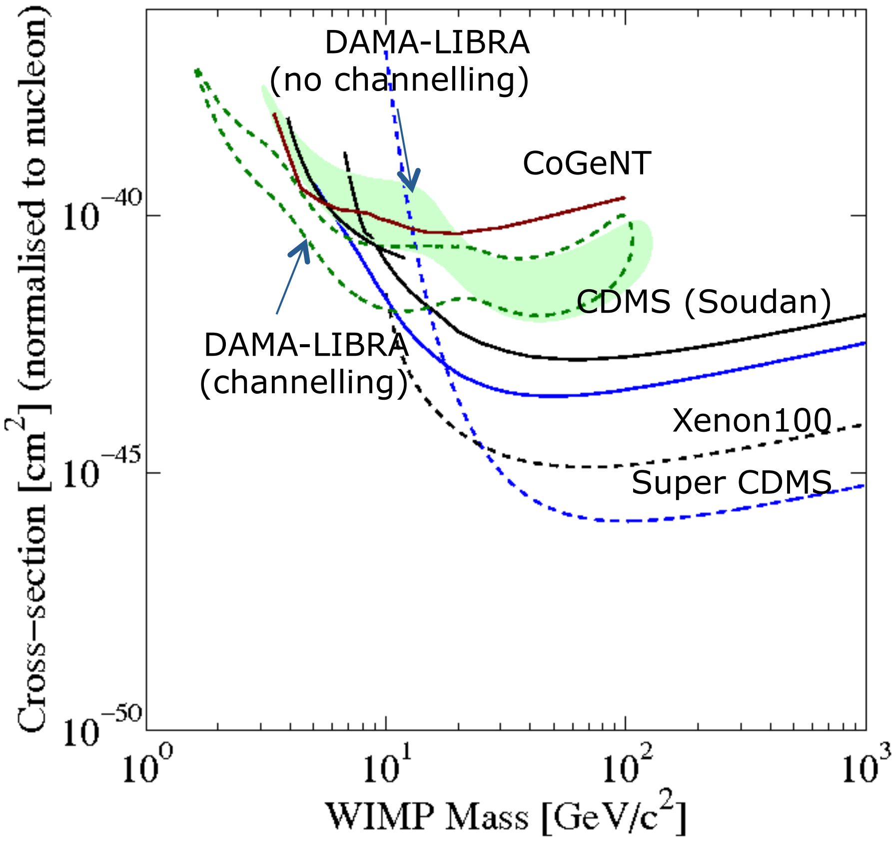
Spin-independent searches in the future...

Future experiments (or upgrades of existing ones) will reach sensitivities ~ $10^{-9\ -10}$ pb

Advances in the light WIMP window are subject to improvements in low threshold experiments

(e.g., CDMS, CRESST or CoGeNT?)

How do these sensitivities compare with theoretical predictions for WIMP models?

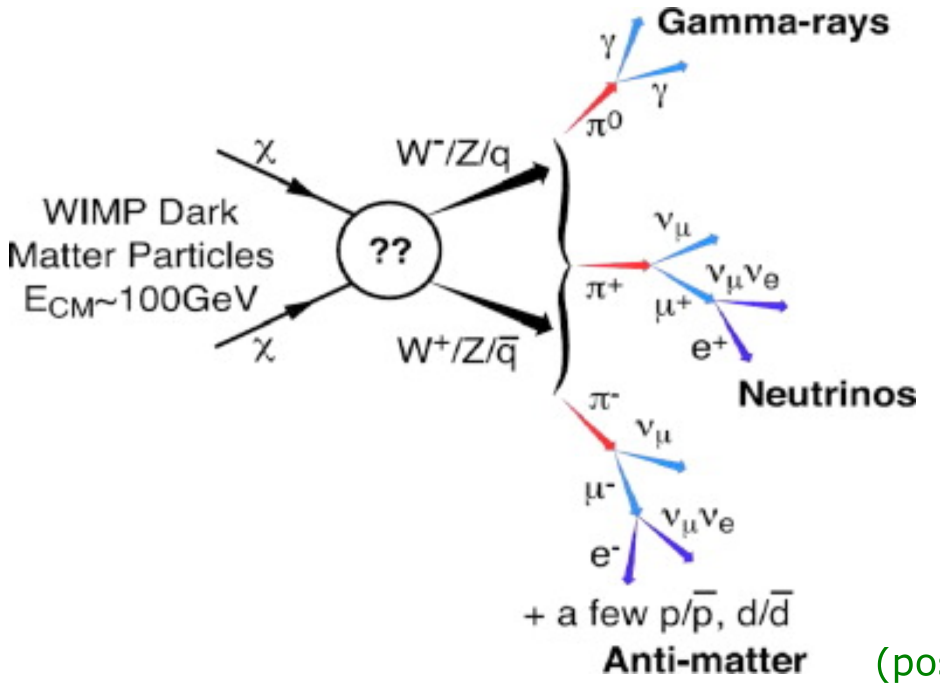


Plotted with DMTools

In case of a detection... (how well) can we determine the DM parameters?

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

Recently there are potential indirect hints for DM annihilation

Difficult to disentangle these from possible astrophysical components

Excess in the positron flux (PAMELA)

- Heavy DM (~300 GeV) annihilating mostly into leptons
- Large boost factor (non-thermal relic density?)

Gamma rays from the Galactic centre (Fermi LAT data)

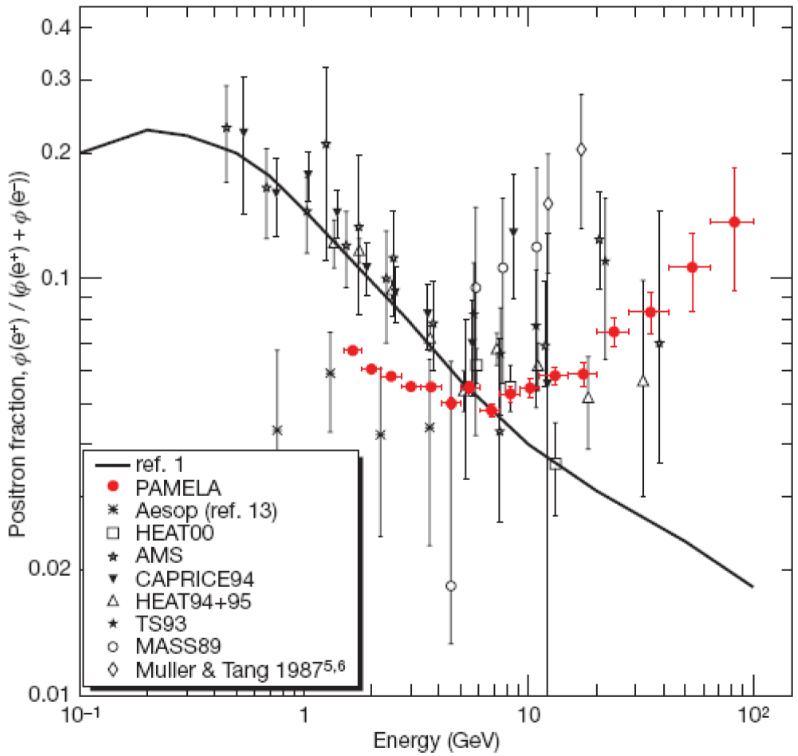
Synchrotron emission from radio filaments in the inner galaxy

Synchrotron emission from the inner galaxy (WMAP haze)

- Vely light DM (~10GeV) annihilating mostly into leptons
- Thermal relic density

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 was complicated

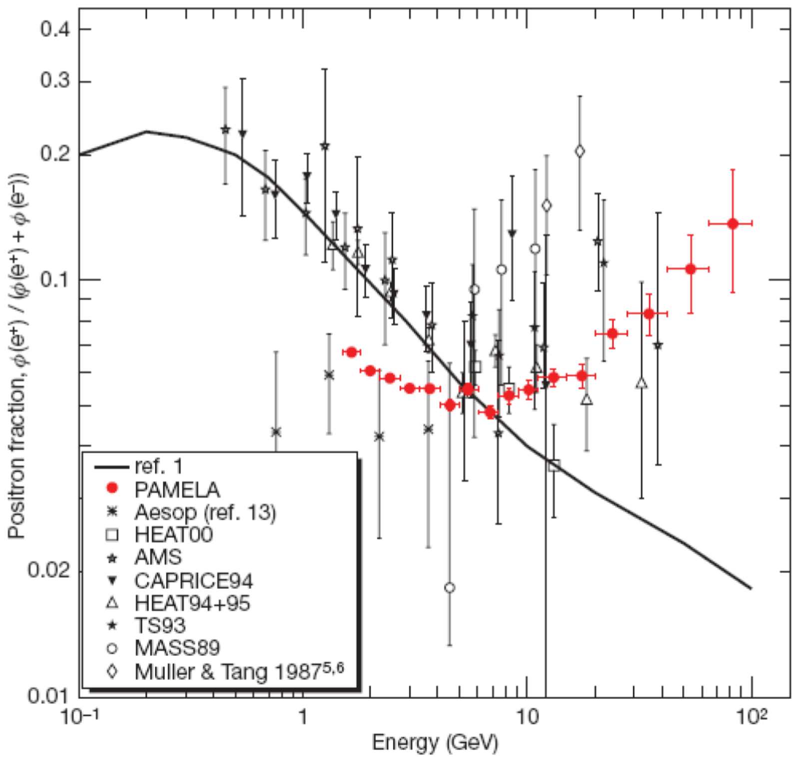
Too small signals in canonical models (WIMP)

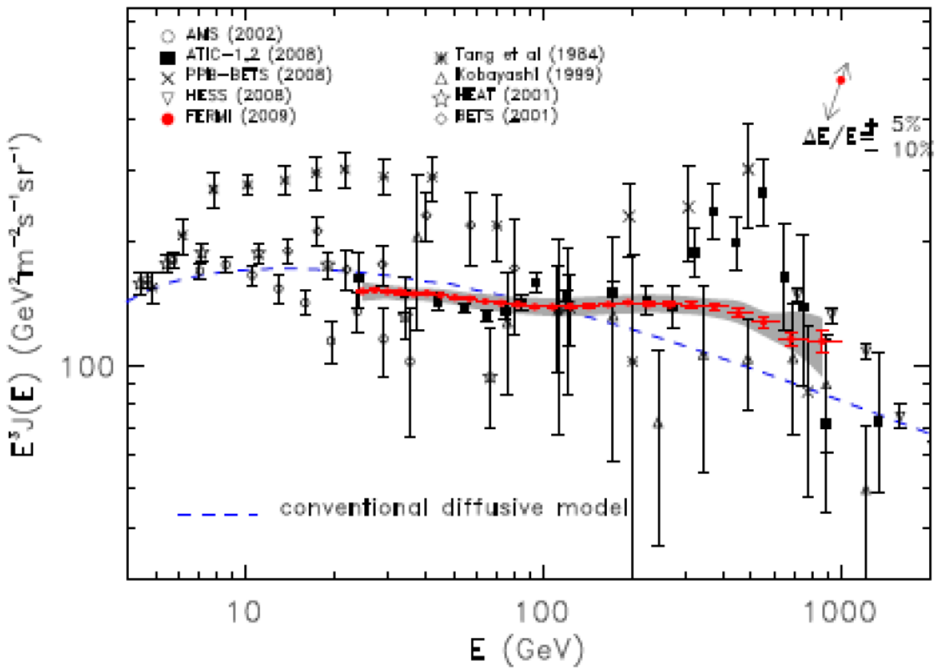
- boost factors (inhomogeneities? IMBH?)
- play with propagation parameters
- non-thermal DM
- decaying dark matter

Why are there no antiprotons?

- Majorana fermions disfavoured (neutralino)
- Leptophilic dark matter

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



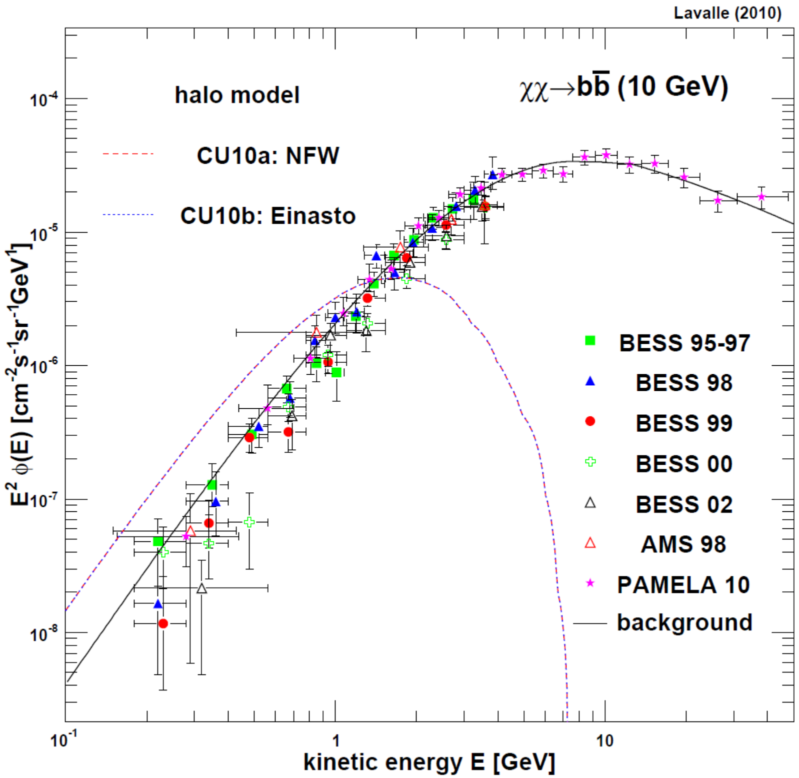


Astrophysical explanation in terms of pulsars is plausible.

See e.g., Delahaye et al. 2010

Still, antimatter searches might be good to constrain DM models

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?

DGC Delahaye, Lavalle 2012

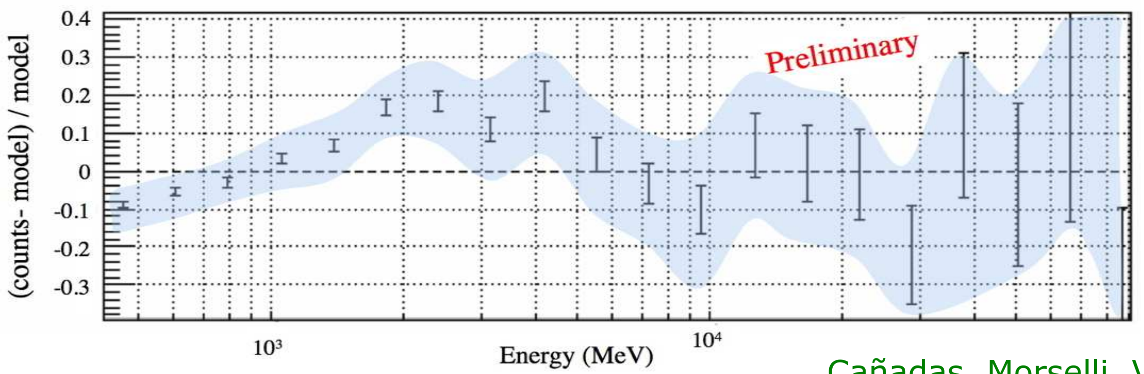
... also a potentially promising future in antideuteron searches...

Donato et al. 2008
Salati, Donato, Fornengo 2010

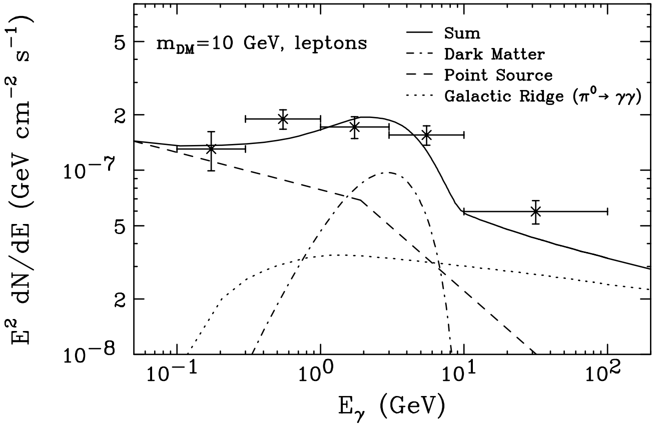
Hints for very light DM?

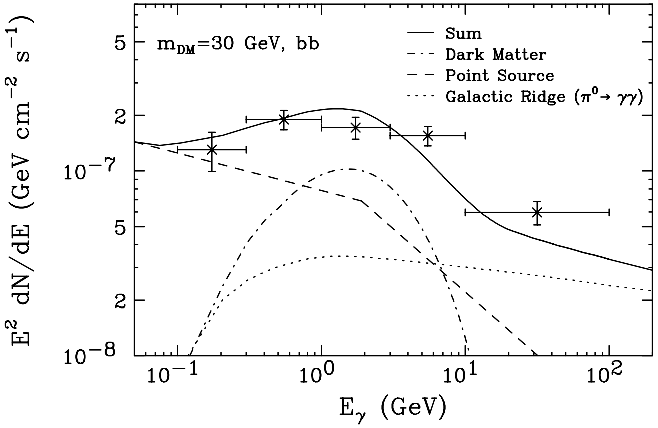
Gamma rays from the Galactic centre (Fermi LAT data)

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



Cañadas, Morselli, Vitale 2010





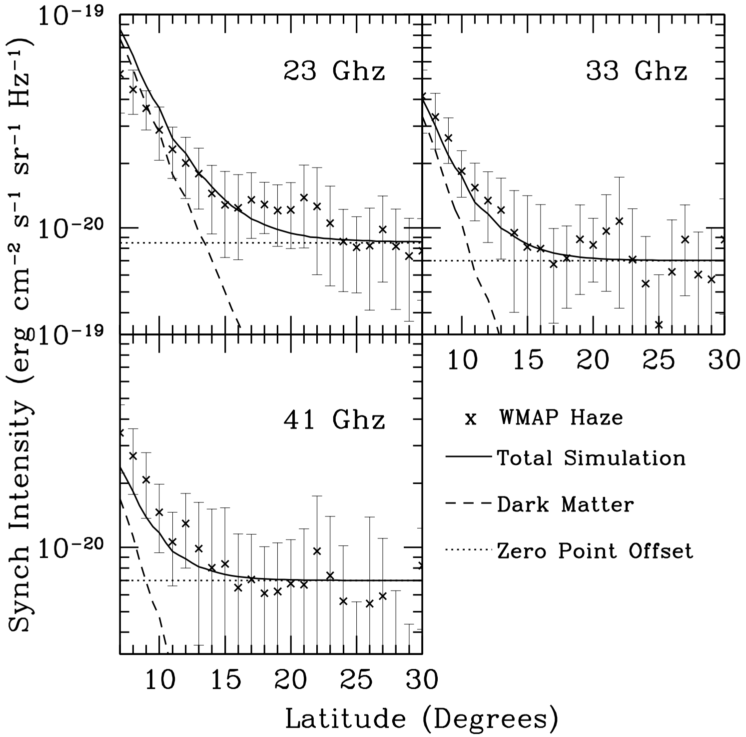
Hooper, Goodenough 2011; Hooper, Linden 2011

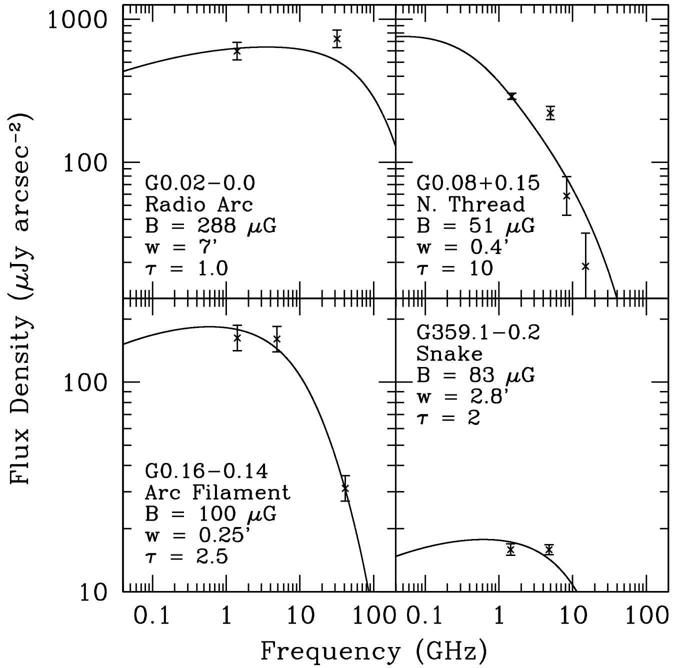
Hints for very light DM?

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?





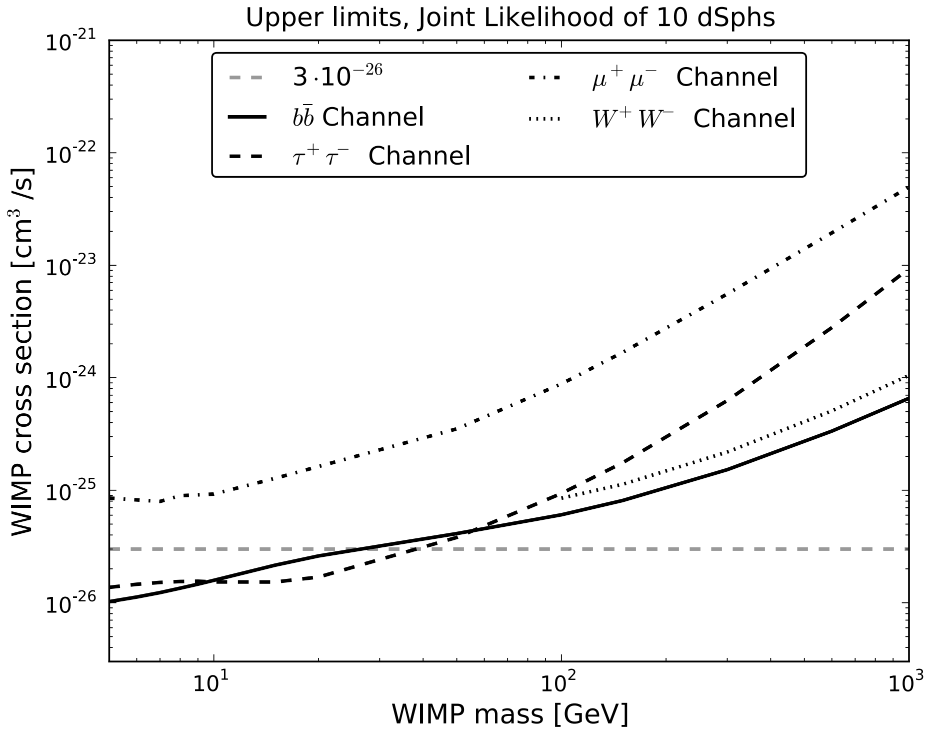
Linden, Hooper, Yusuf-Zadeh 2011

WMAP Haze

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

Very light DM can be further constrained, however.

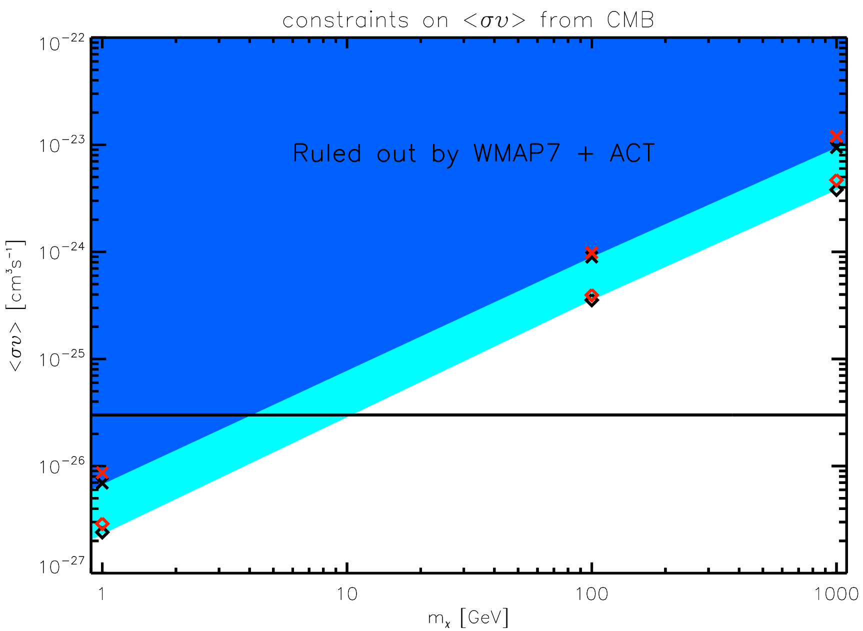
Fermi-LAT '11



Fermi-LAT observation of Dwarf Spheroidals

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

Current bounds are still higher than what needed to account for Gamma ray and synchrotron hints.



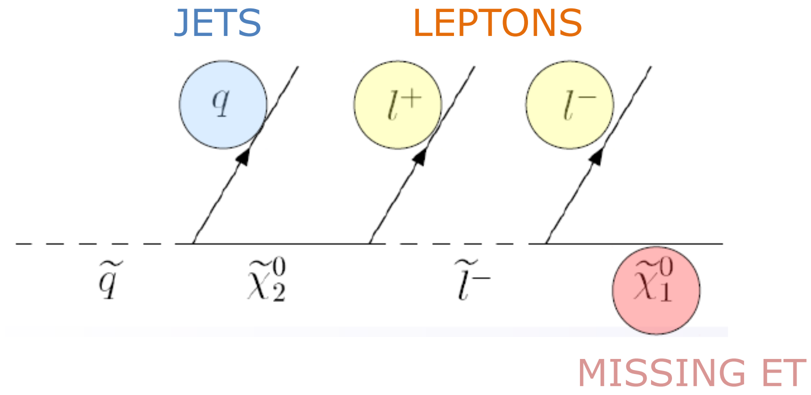
Planck constraints on the CMB

Also more important for light WIMPs

Dark matter at the LHC

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

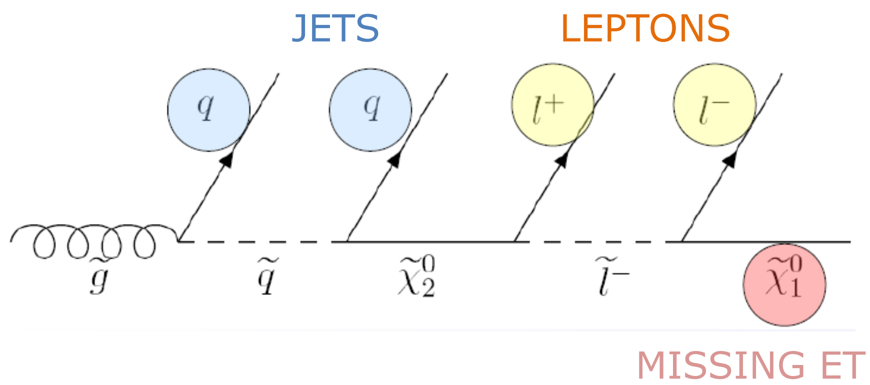
Look for jets + extra leptons



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

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

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

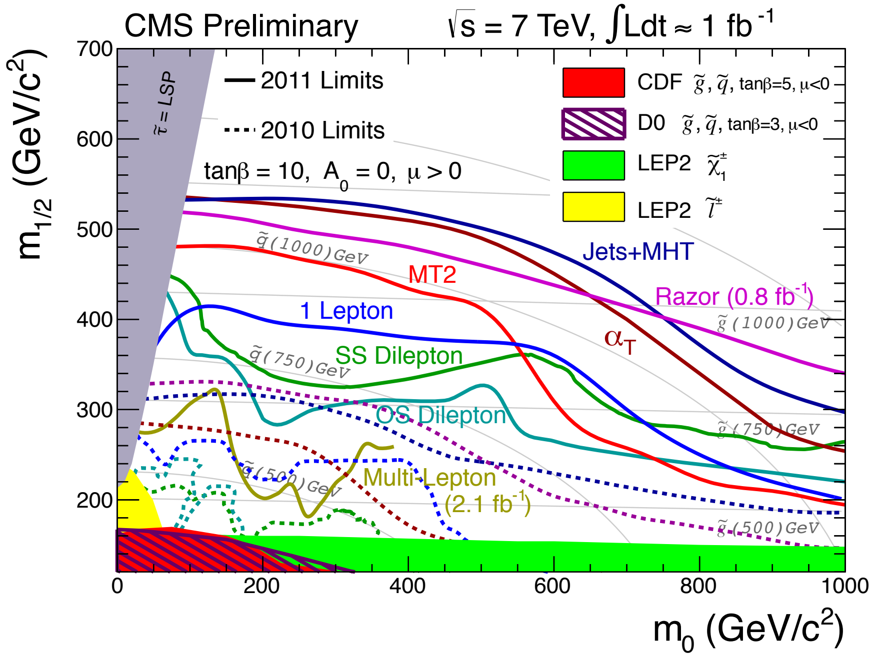


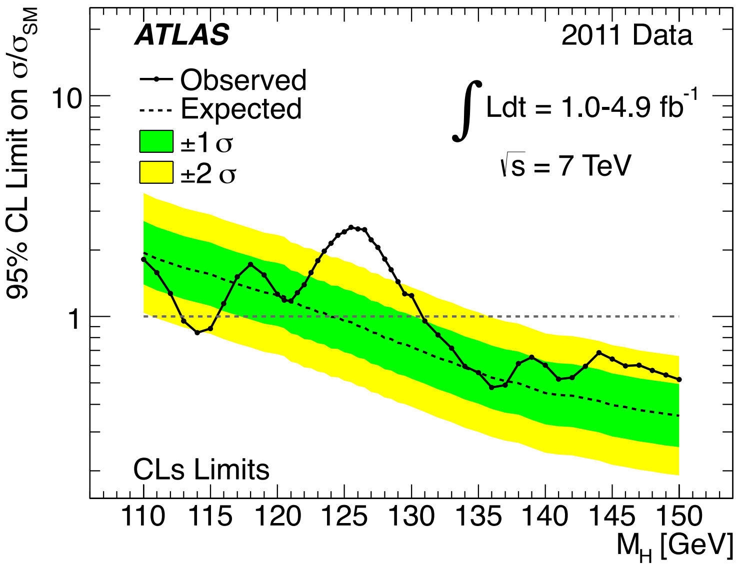
These subsequently decay in lighter particles and eventually in the LSP

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





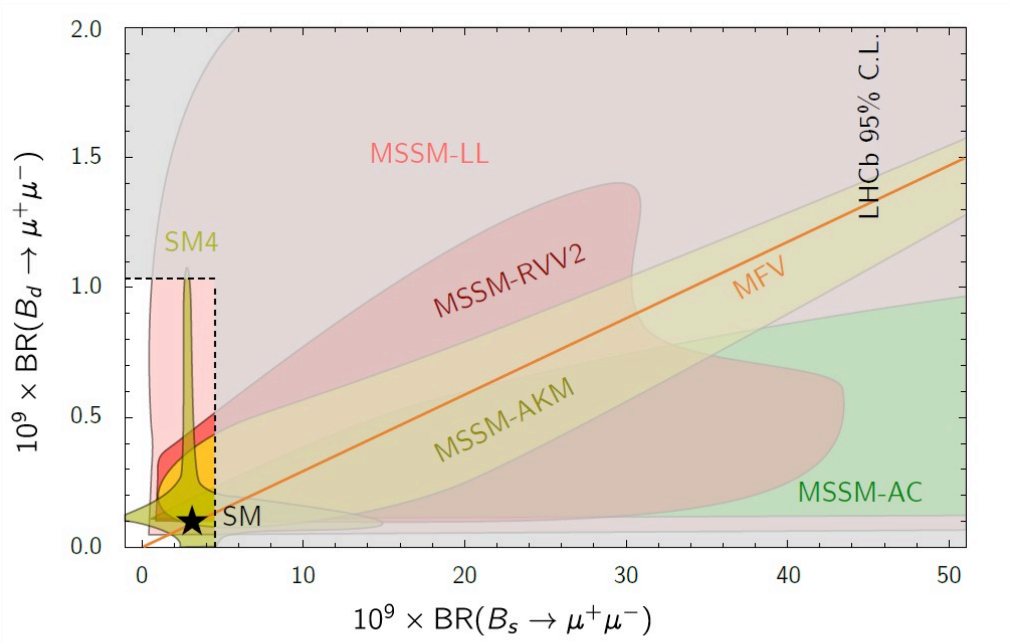
Higgs searches

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

Current BSM-specific searches help constrain some DM candidates

Constraints on low energy observables

Also constrain the parameter space. Indirectly also constrain DM models



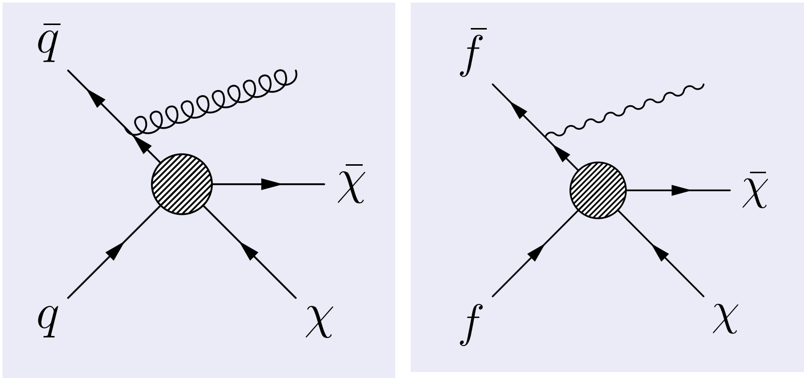
Mode	Limit	at 90% CL	at 95% CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	6.3×10^{-9}	7.2×10^{-9}
	Exp. bkg	2.8×10^{-9}	3.4×10^{-9}
	Observed	3.8×10^{-9}	4.5×10^{-9}
$B^0 \to \mu^+\mu^-$	Exp. bkg	0.91×10^{-9}	1.1×10^{-9}
	Observed	0.81×10^{-9}	1.0×10^{-9}

For example, rare B decays

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

LHCb March 2012

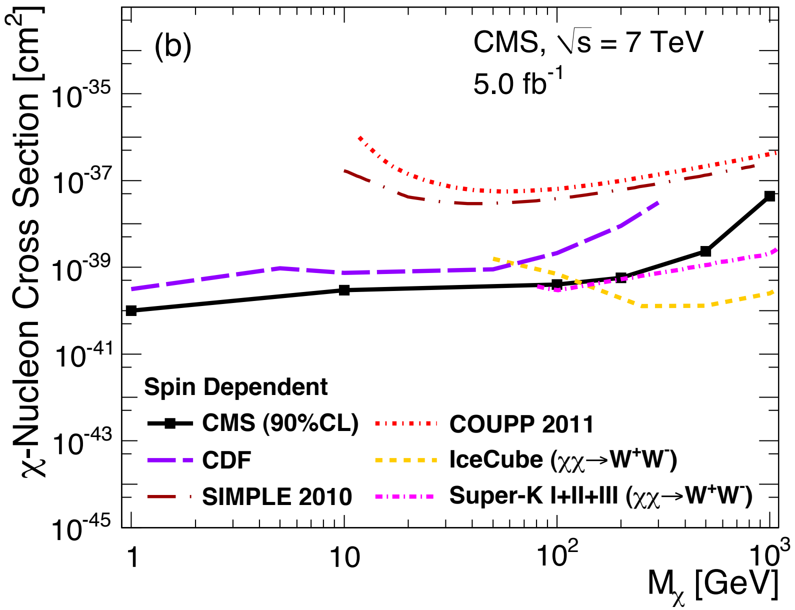
Mono-jet and Mono-γ (plus MET) searches constrain the region of light WIMPs

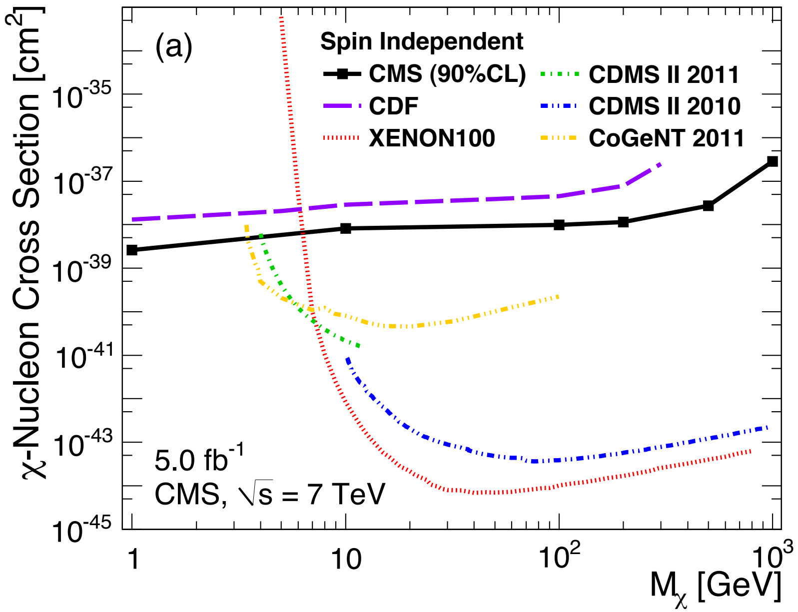


Dark matter production with initial state radiation

Bounds depend on the DM effective operators to fermions

LHC data 2011 (see also previous results from Tevatron)



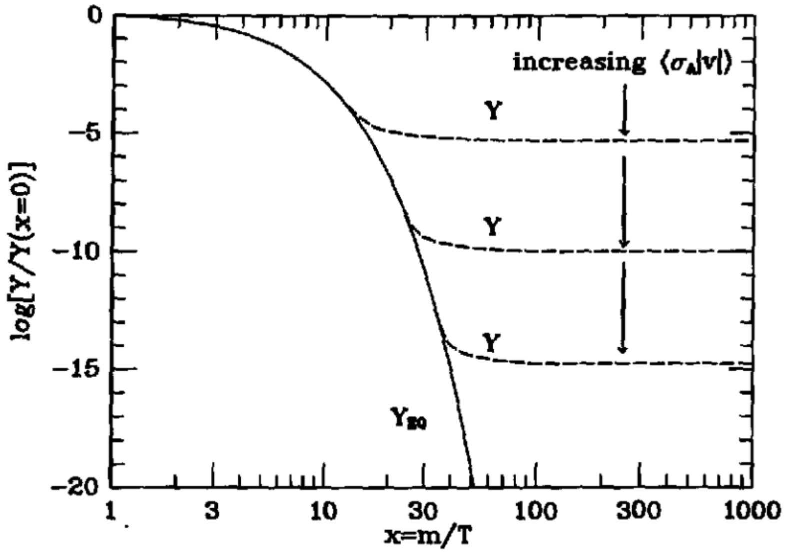


(CMS-PAS-EXO-11-096)

Particle dark matter models

The WIMP miracle ("survival of the weakest")

A (stable) particle with Electroweak-scale interactions can be thermally produced in the early Universe in the right amount to account for WMAP data



Present in many models for Physics Beyond the SM

- Supersymmetry
- Theories with extra dimensions
- Little Higgs models
- Phenomenological scenarios

... but WIMPs are not the only "natural" possibility.

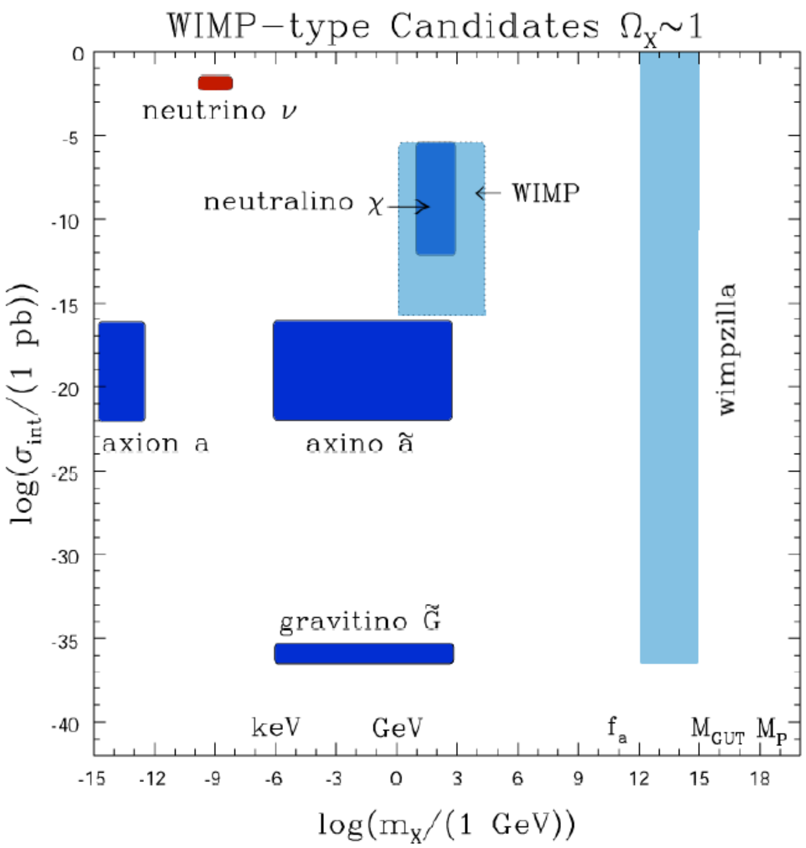
Dark Matter

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

Supersymmetric dark matter

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	$\tilde{g}$

Sneutrino

They annihilate very quickly and the regions where the correct relic density is obtained are already experimentally excluded

Ibáñez '84
Hagelin, Kane, Rabi '84

Neutralino

Good annihilation cross section. it is a WIMP

Goldberg '83
Ellis, Hagelin, Nanopoulos, Olive, Srednicki '83
Krauss '83

Gravitino (Superpartner of the graviton)
Axino (Superpartner of the axion)

Extra-weakly interacting massive particles

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

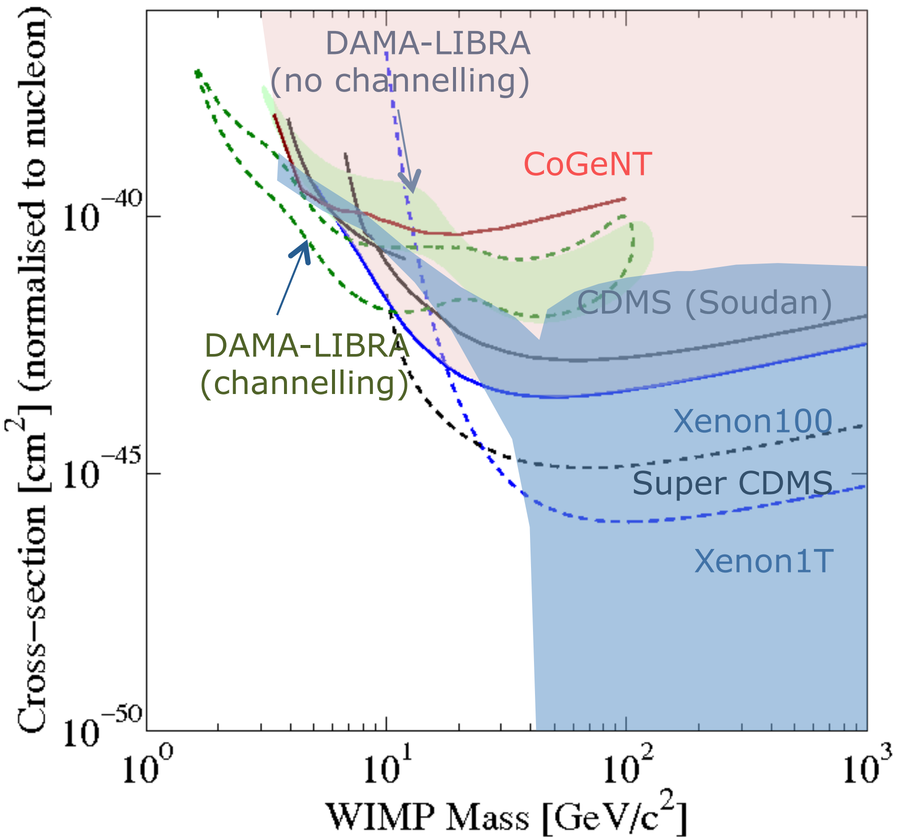
$$\tilde{\chi}_1^0 = \underbrace{N_{11}\,\tilde{B}^0 + N_{12}\,\tilde{W}_3^0}_{\text{Gaugino content}} + \underbrace{N_{13}\,\tilde{H}_d^0 + N_{14}\,\tilde{H}_u^0}_{\text{Higgsino content}}$$

Neutralino in the MSSM

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



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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

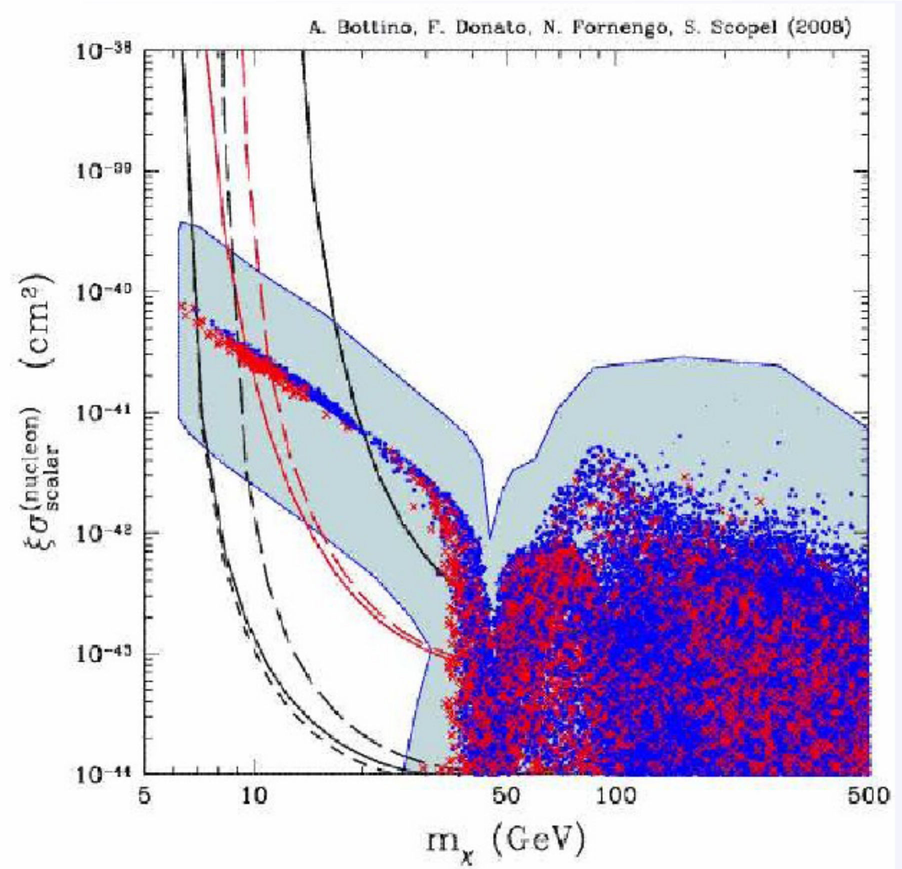
Very light Bino-like neutralinos with masses ~10 GeV could account for the DAMA signal

Bottino, Donato, Fornengo, Scopel 2008

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

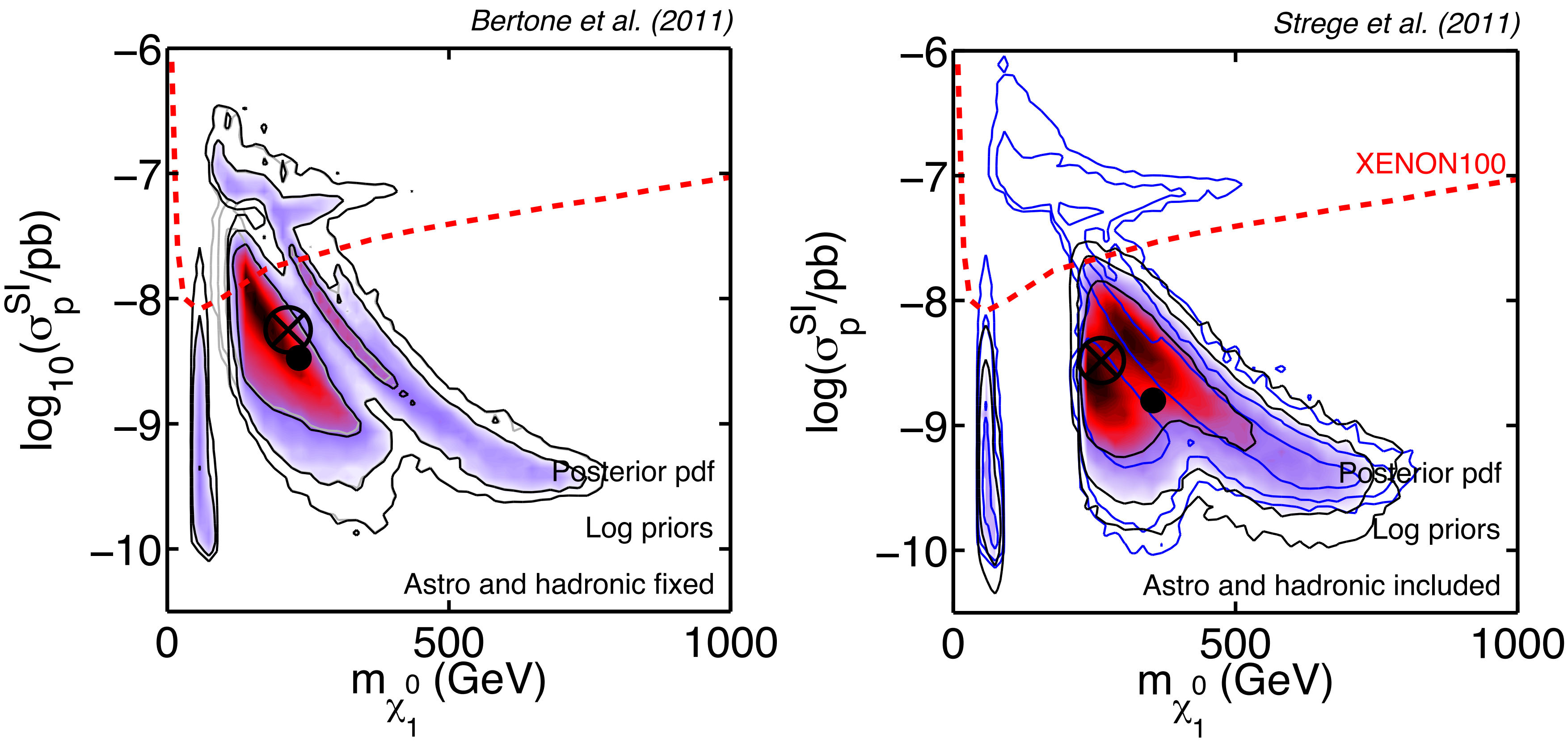
LHCb 2012

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



Impact of Xeon 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

Linear Superposition of Bino, Wino and Higgsinos with a singlino component

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta & 0 \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta & 0 \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu & -\lambda v_2 \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2\kappa \frac{\mu}{\lambda} \end{pmatrix}$$

Its detection properties depend crucially on its composition

$$\tilde{\chi}_1^0 = \underbrace{N_{11}\,\tilde{B}^0 + N_{12}\,\tilde{W}_3^0}_{\text{Gaugino content}} + \underbrace{N_{13}\,\tilde{H}_d^0 + N_{14}\,\tilde{H}_u^0}_{\text{Higgsino content}} + \underbrace{N_{15}\,\tilde{S}}_{\text{Singlino content}}$$

Neutralino in the Next-to-MSSM

The theoretical predictions differ from those in the MSSM

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

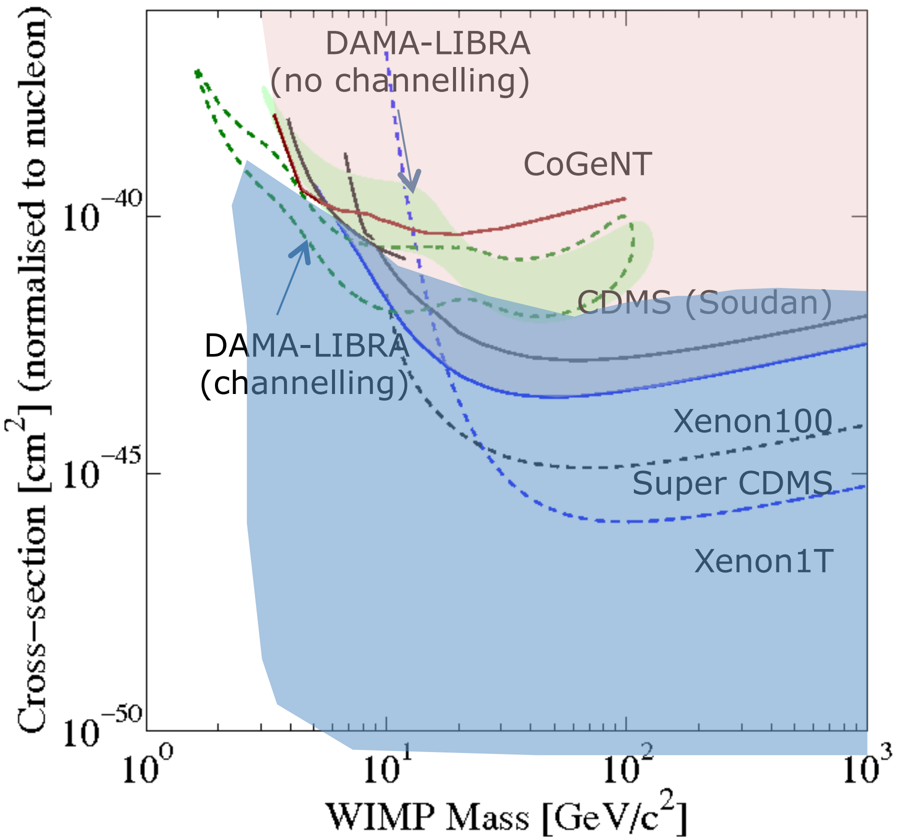
DGC, Gabrielli, Fogliani Muñoz, Teixeira 2007

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

Gunion, Hooper, McElrath 2005

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

DGC with CoGeNT 2008



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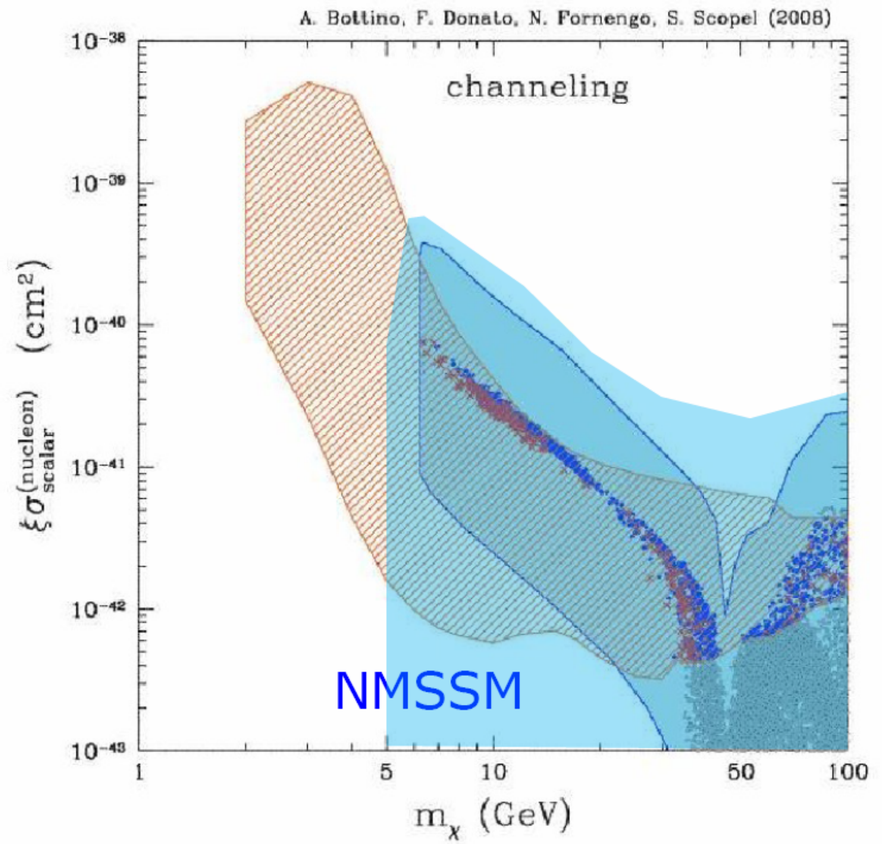
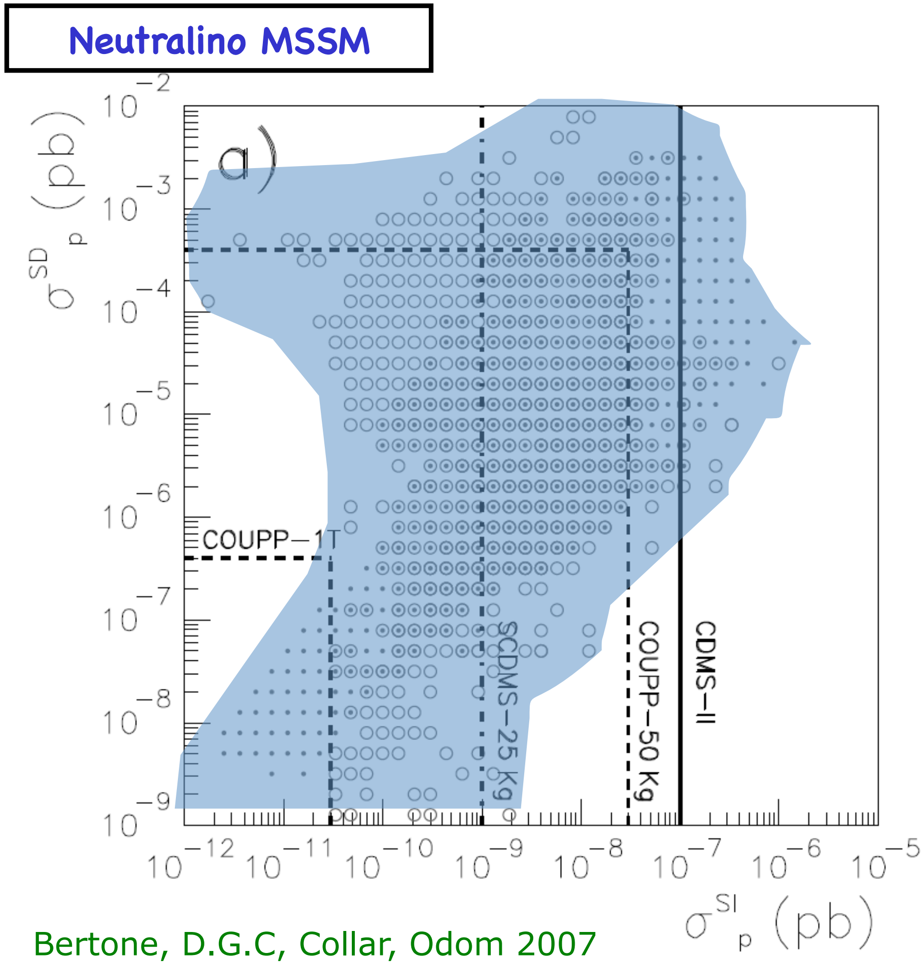


Neutralino spin-dependent cross section

About one order of magnitude below current sensitivities



Bertone, D.G.C, Collar, Odom 2007

Regions where both SI and SD cross sections are large

"Fine tuned" cases in which SD contribution can dominate

RH Sneutrino in the MSSM

The theoretical predictions differ from those in the MSSM

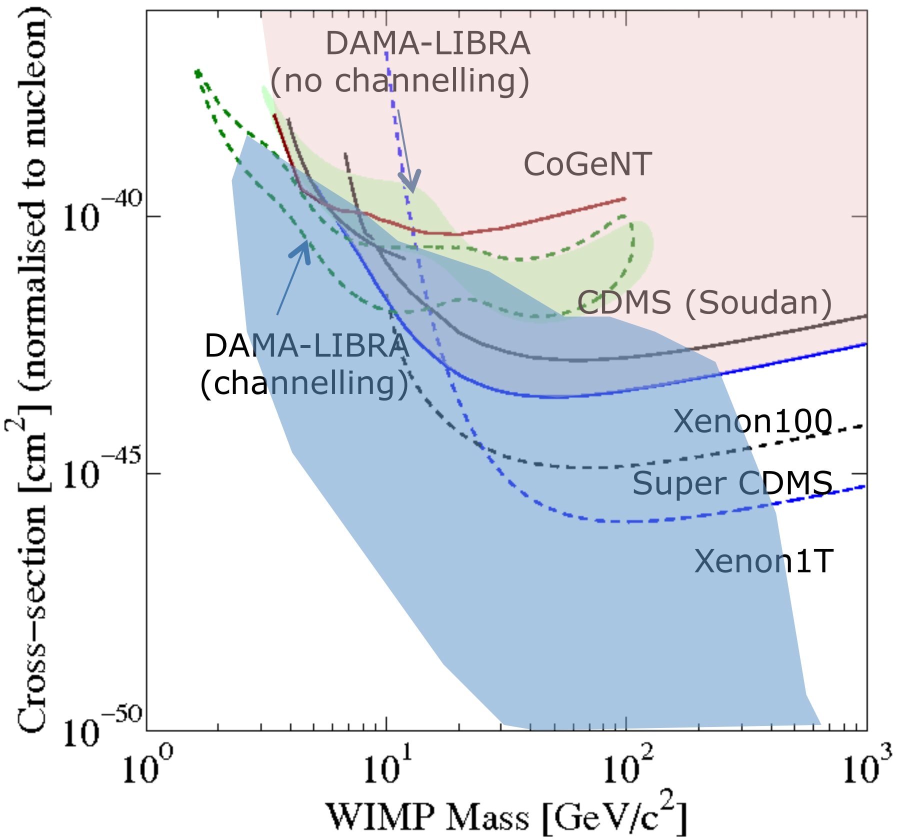
The RH Sneutrino is a viable WIMP candidate in the NMSSM

It can be detectable in future experiments

DGC, Munoz, Seto 2007; DGC, Seto 2008

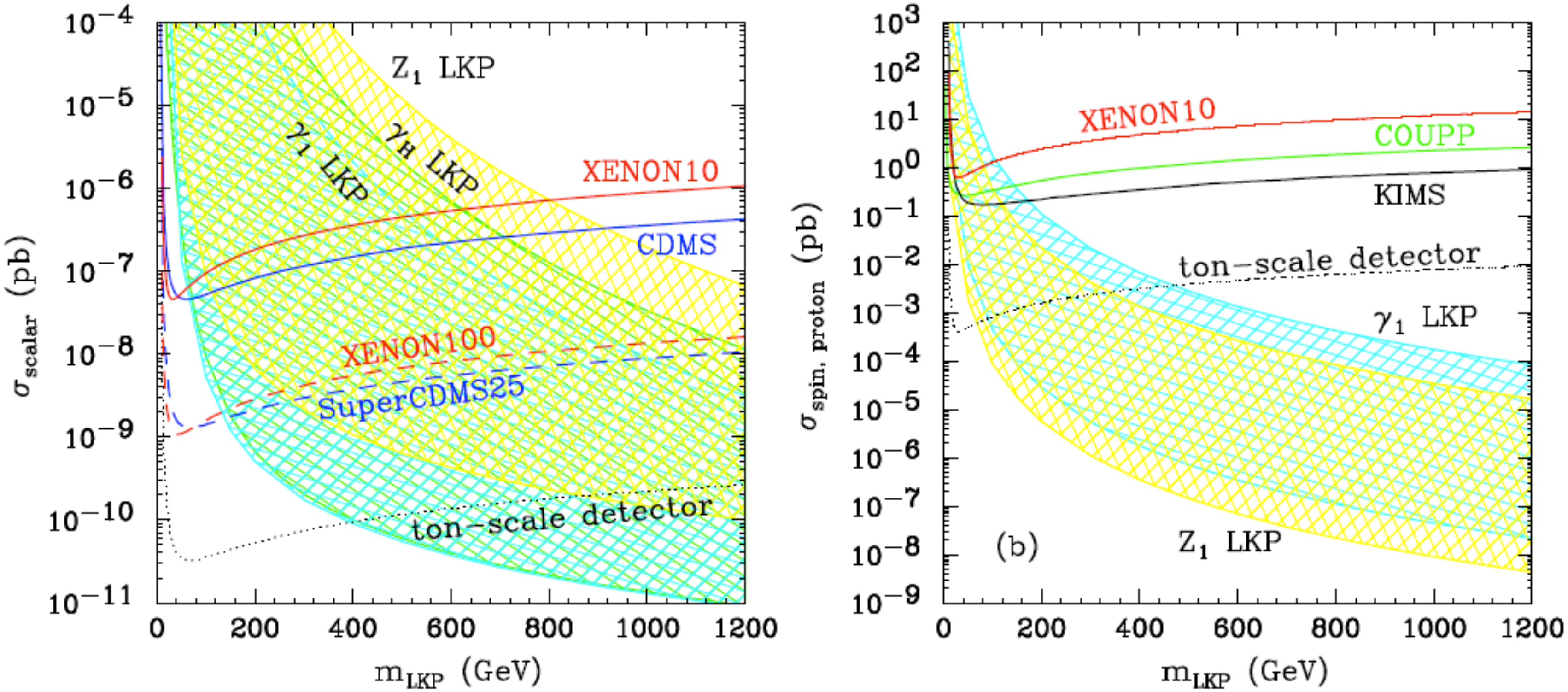
Very light sneutrinos are possible and potentially distinguishible from Neutralino DM

DGC, Huh, Seto, Peiro 2011



Dark matter in models with Universal Extra Dimension

Kaluza-Klein dark matter can have similar interaction cross section



Arrenberg, Baudis, Kong, Matchev, Yoo '08

Complementarity of dark matter searches

If there is a positive detection the DM parameters can be determined

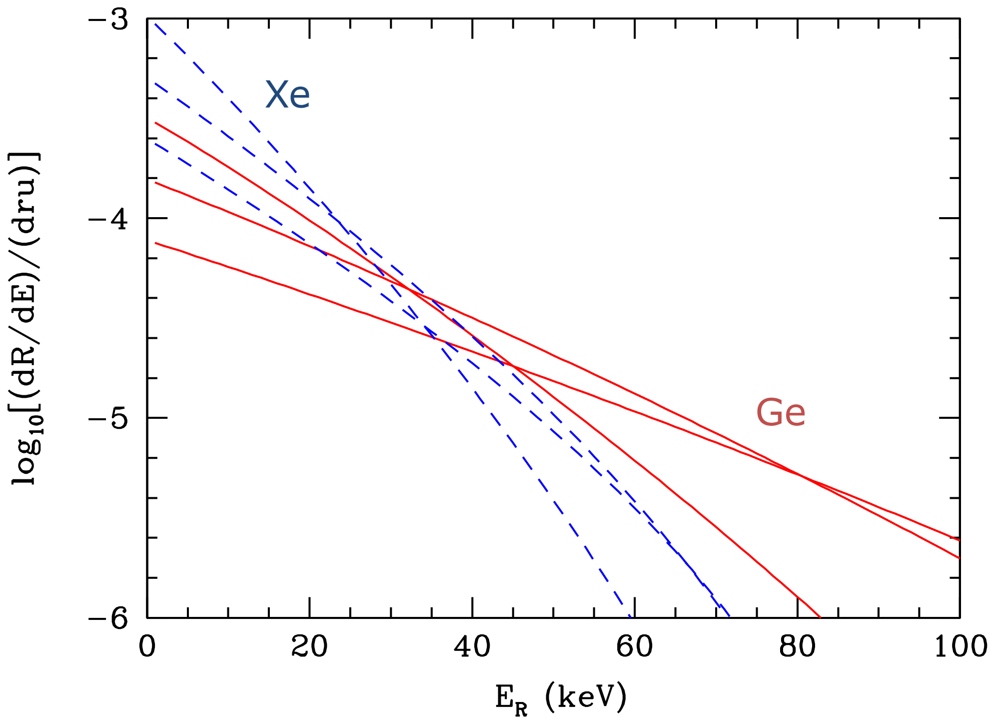
$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

From the observed rate and differential rate the cross section and mass of the WIMP can be determined

Green '07-10; Drees et al. '08'09

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \approx \left(\frac{\mathrm{d}R}{\mathrm{d}E_R}\right)_0 F^2(E_R) \exp\left(-\frac{E_R}{E_c}\right)$$

$$E_c = (c_1 2\mu_N^2 v_c^2)/m_N$$



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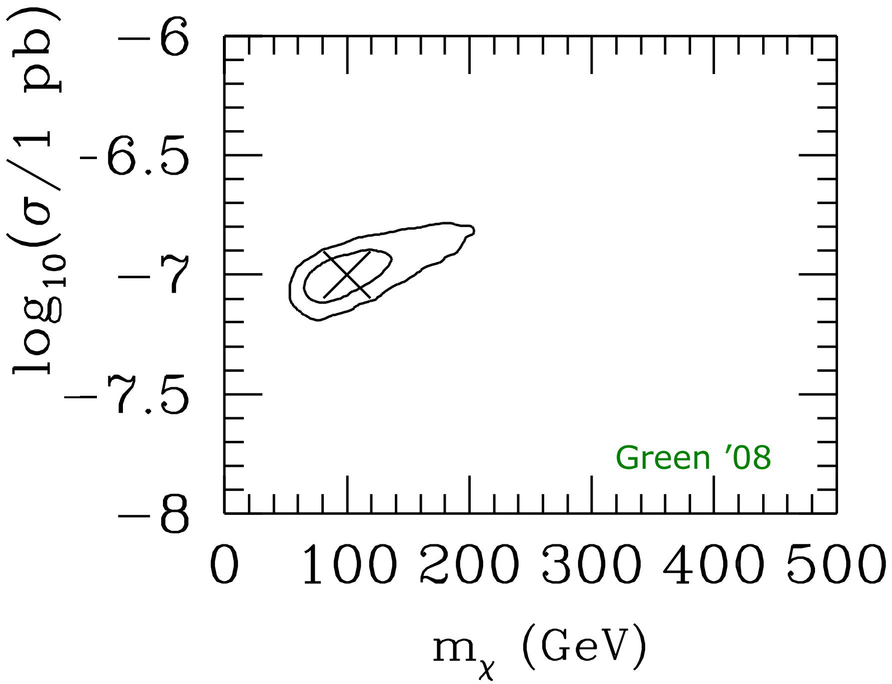


Direct detection can only determine "phenomenological" WIMP parameters

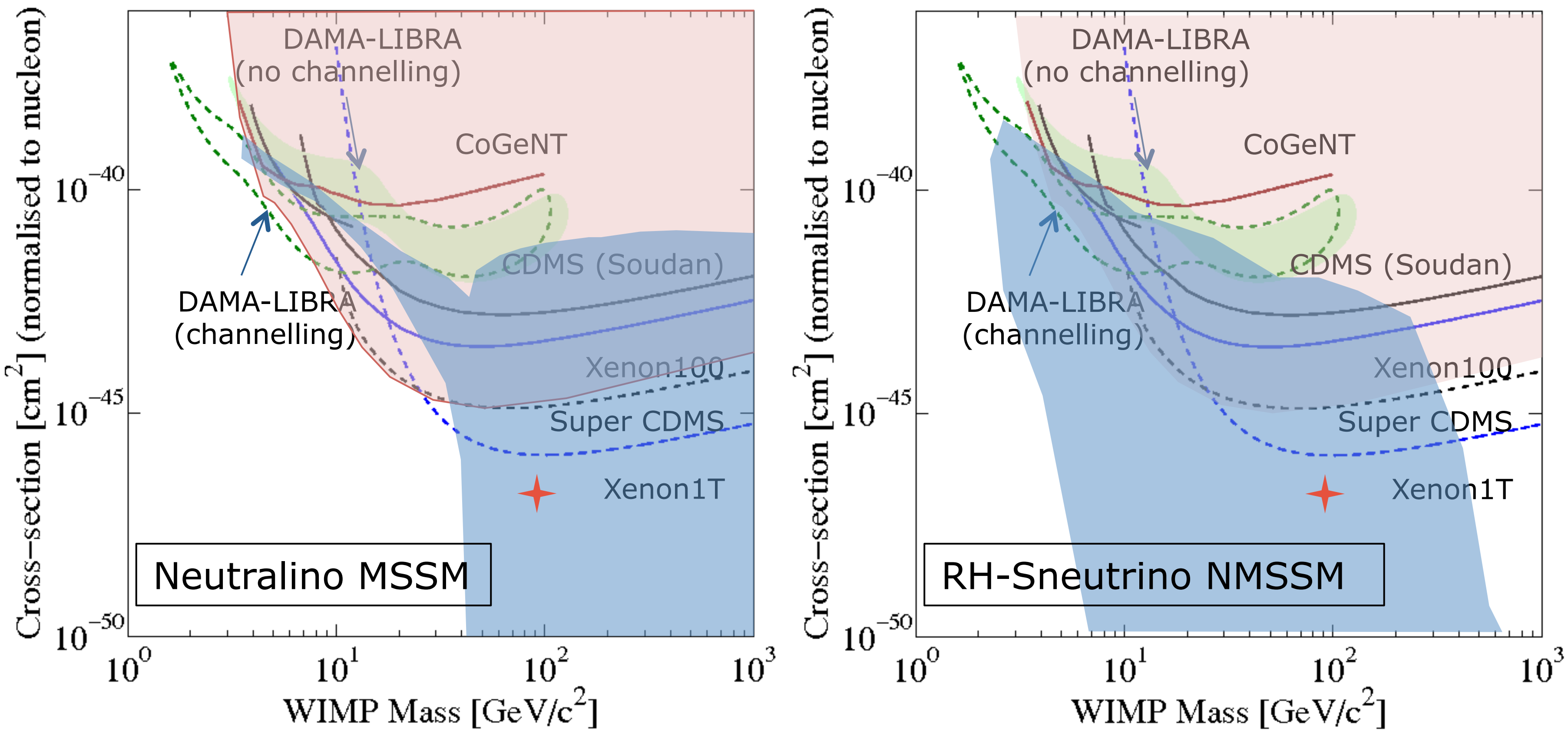
$$m_X \quad \sigma^{SI}{}_p \quad \sigma^{SD}{}_p \quad \sigma^{SD}{}_n$$

Example: m_χ=100 GeV
Exposure: 3000 kg day (Ge target)

Can we determine to which DM model it corresponds?

In general WIMPS... all seem to be alike

Supersymmetric WIMP Dark Matter:



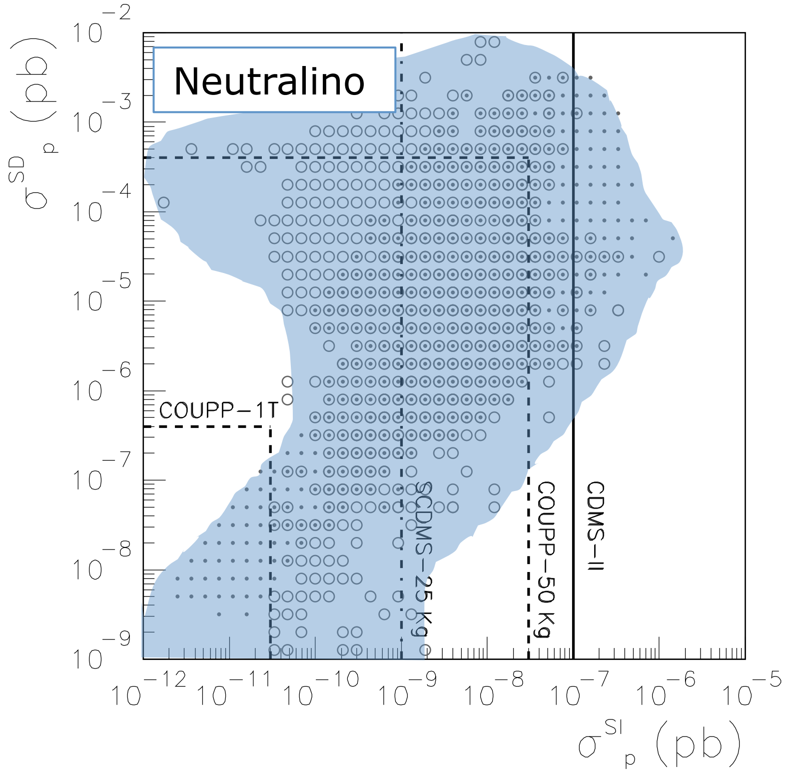
Bottino, Donato, Fornengo '04-'11

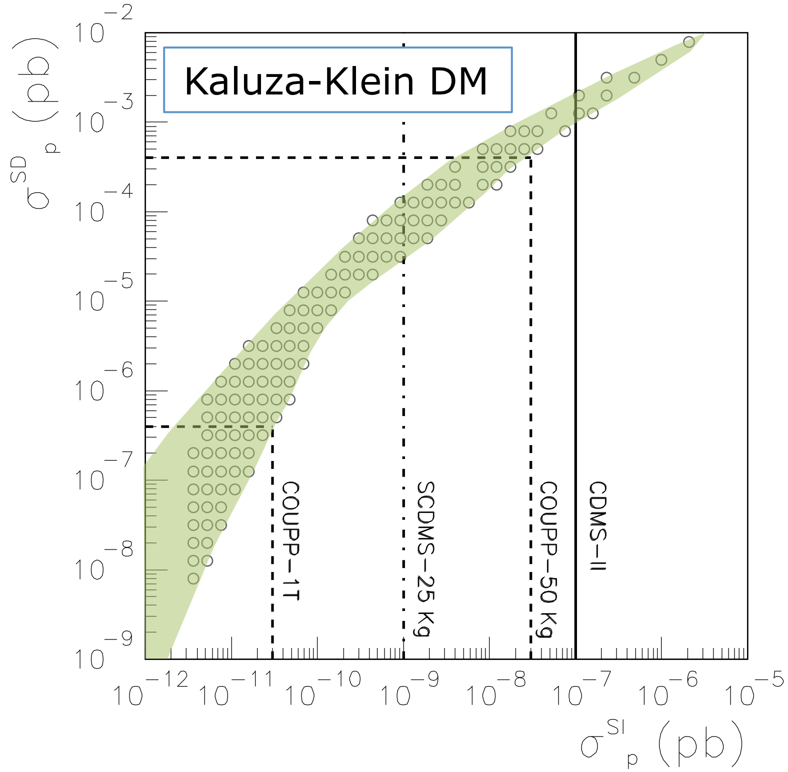
DGC, Seto '08

Not really if we look at the whole parameter space...

There can be correlations in the "phenomenological parameters"

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





Bertone, DGC, Collar, Odom '07

"Advance in both fronts" (spin-dependent and -independent) to gain discriminating power

Can we determine the DM model from future data?

All WIMPs behave very similarly (not surprisingly)

The complete identification of the WIMP may not be possible from just the phenomenological parameters

Combination direct/indirect searches with LHC results

Determining the full set of phenomenological parameters

$$m_X \qquad \sigma^{SI}_p \qquad \sigma^{SD}_p \qquad \sigma^{SD}_n$$

Is nevertheless important to distinguish between different WIMP models

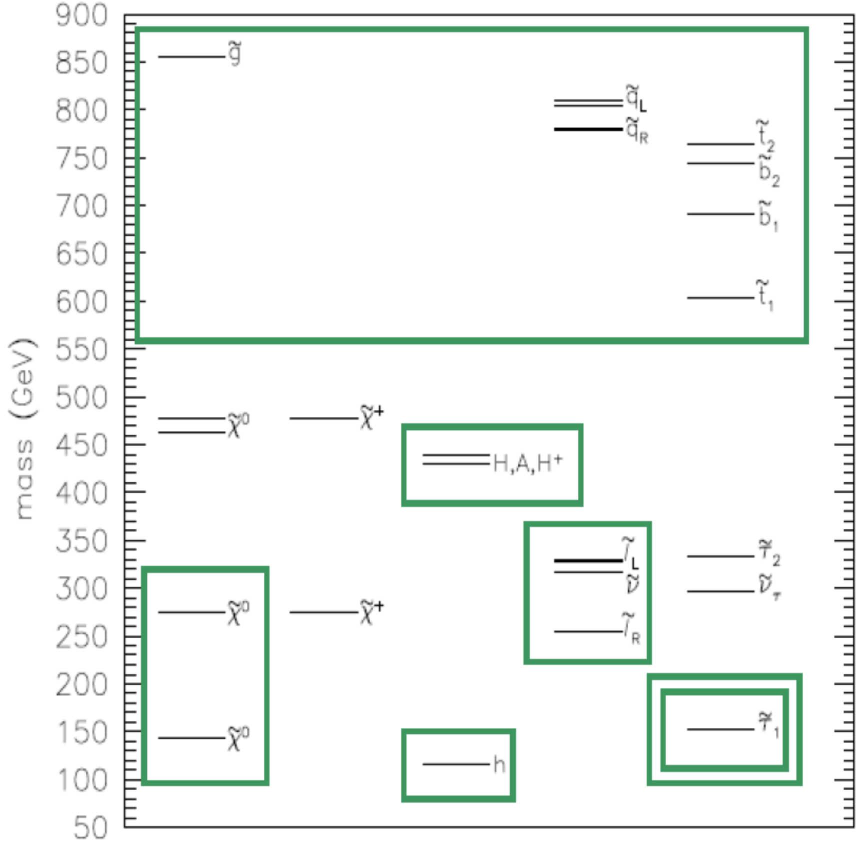
Direct searches with different targets

Combination from different experiments

Example 1: Complementarity of direct detection and collider searches

Some DM (WIMP) properties can be determined in a collider ...but its relic density might be difficult to determine

For example, assuming detection at the LHC (i.e., a set of measurements of the SUSY spectrum)



Some DM (WIMP) properties can be determined in a collider

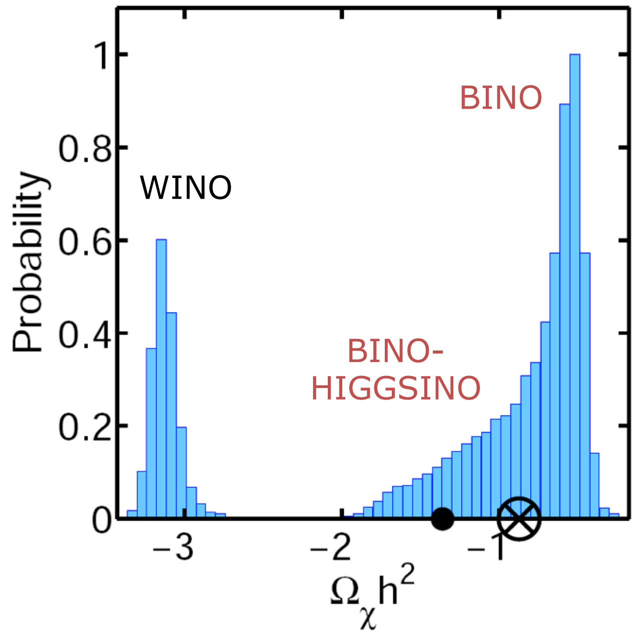
...but its relic density might be difficult to determine

LCC3 point
LHC @ 14 TeV, 100 fb-1

For example, assuming detection at the LHC (i.e., a set of measurements of the SUSY spectrum)

The neutralino relic density can be extracted (from the most likely configurations)

This determination can be inconclusive due to incomplete knowledge of the WIMP couplings



Bertone, D.G.C., Fornasa, Ruiz de Austri Trotta 2010

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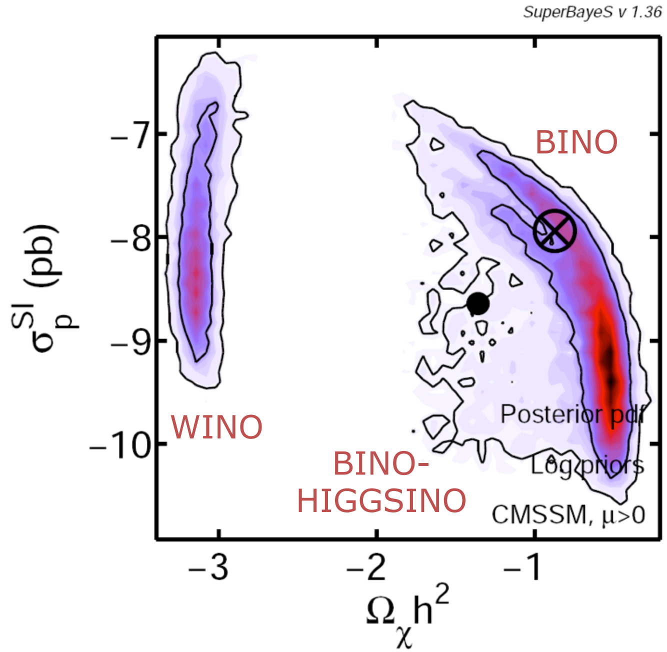
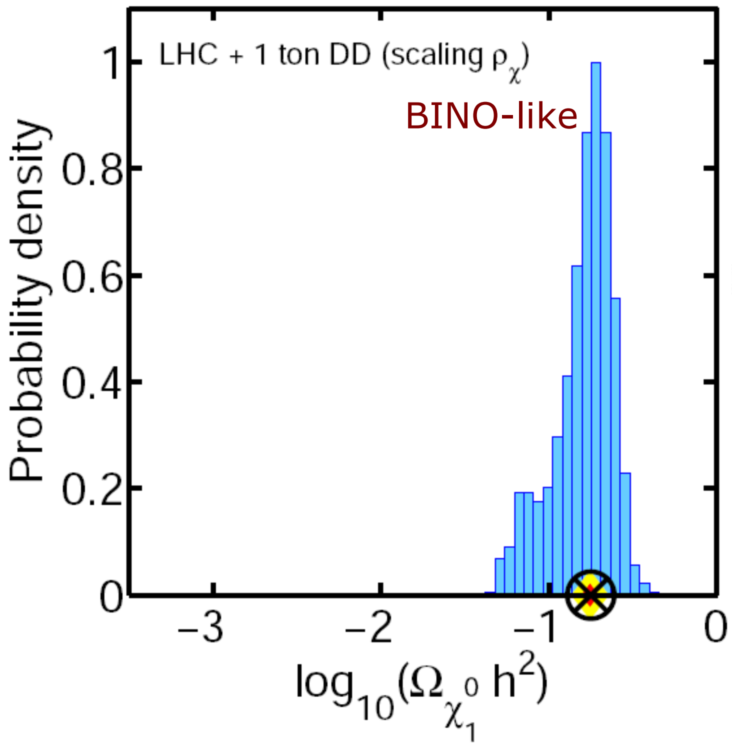


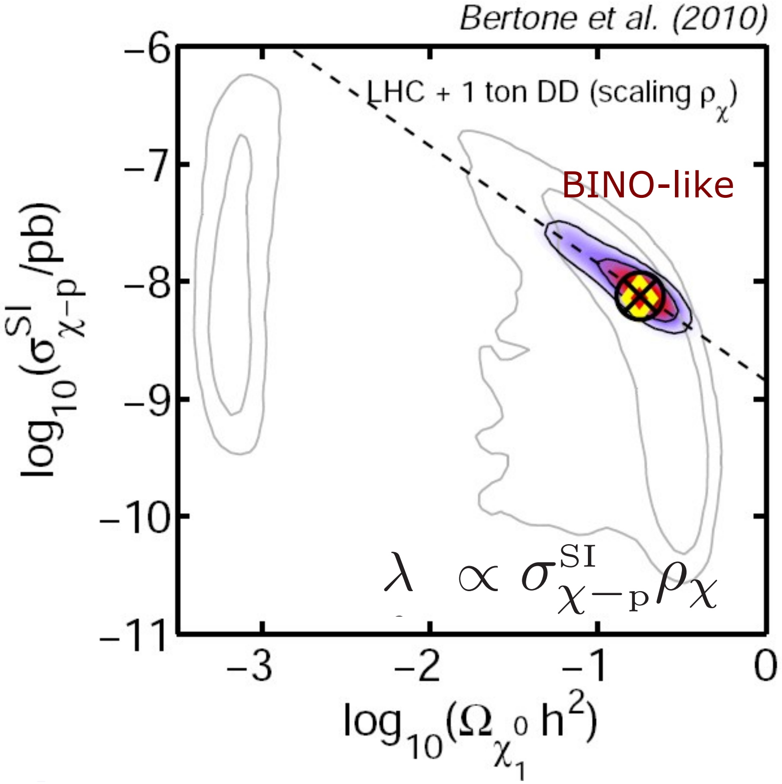
Bertone, D.G.C., Fornasa, Ruiz de Austri Trotta 2010

Combination of collider searches with DD removes the degeneracies

Scaling ansatz: The local dark matter density scales as the cosmological abundance

$$\rho_{\tilde{\chi}_1^0}/\rho_{\rm DM} = \Omega_{\tilde{\chi}_1^0}/\Omega_{\rm DM}$$





LCC3 point LHC @ 14 TeV, 100 fb-1

Bertone, D.G.C., Fornasa, Ruiz de Austri Trotta 2010

Example 2: Combination with Indirect detection can also remove degeneracies

For the same (LCC3) point, we determine the gamma ray flux that could be observed in dwarf Spheroidal galaxies

Imposing Fermi-LAT bound from the non-observation

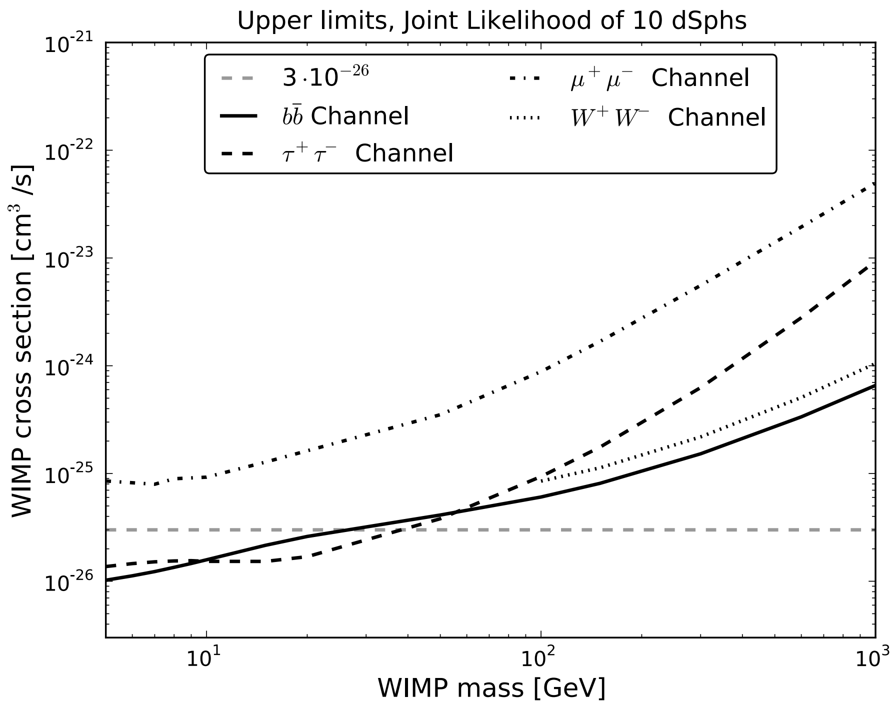
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Psi) = \frac{d\Phi_{PP}}{dE_\gamma}(E_\gamma) \times \mathrm{los}(\Psi, \Delta\Omega)$$

Particle Physics-dependent terms

$$\frac{d\Phi_{PP}}{dE_\gamma}(E_\gamma) = \frac{1}{4\pi}\frac{(\sigma v)}{2m^2_{\tilde{\chi}^0_1}} \sum_f \frac{dN^f_\gamma}{dE_\gamma} B_f$$

Astrophysical factor

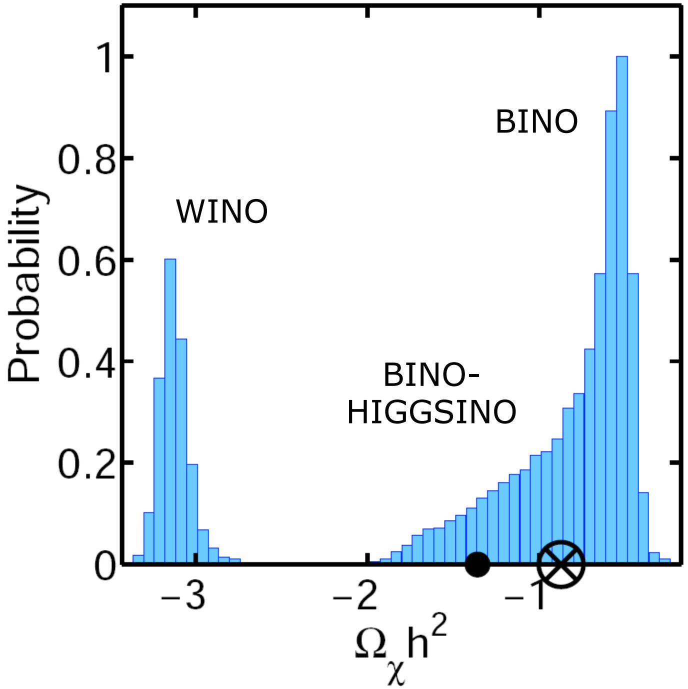
$$\mathrm{los}(\Psi, \Delta\Omega) = \int_{\Delta\Omega}\int \frac{\rho^2(r(s, R_\odot, \Psi))}{s^2} ds\, d\Omega$$



Fermi-LAT '11

Combination with Indirect detection can also remove degeneracies

For the same (LCC3) point, we determine the gamma ray flux that could be observed in dwarf Spheroidal galaxies

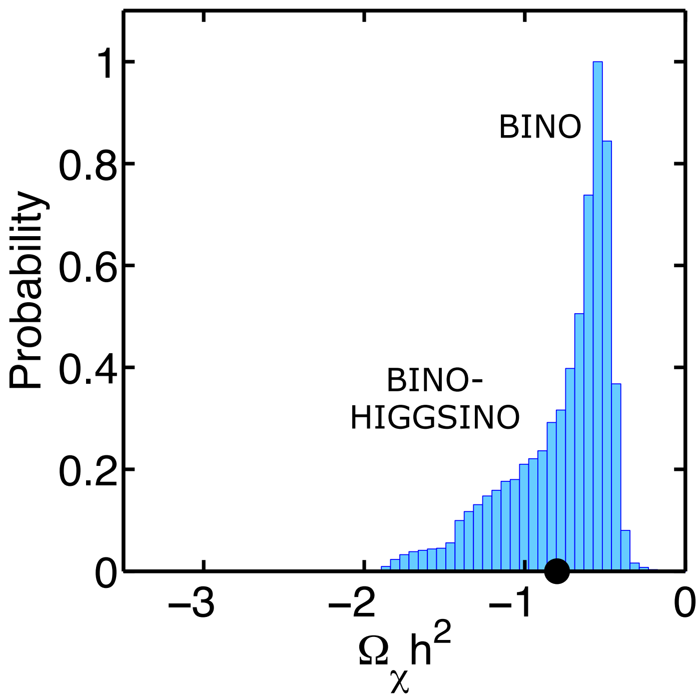


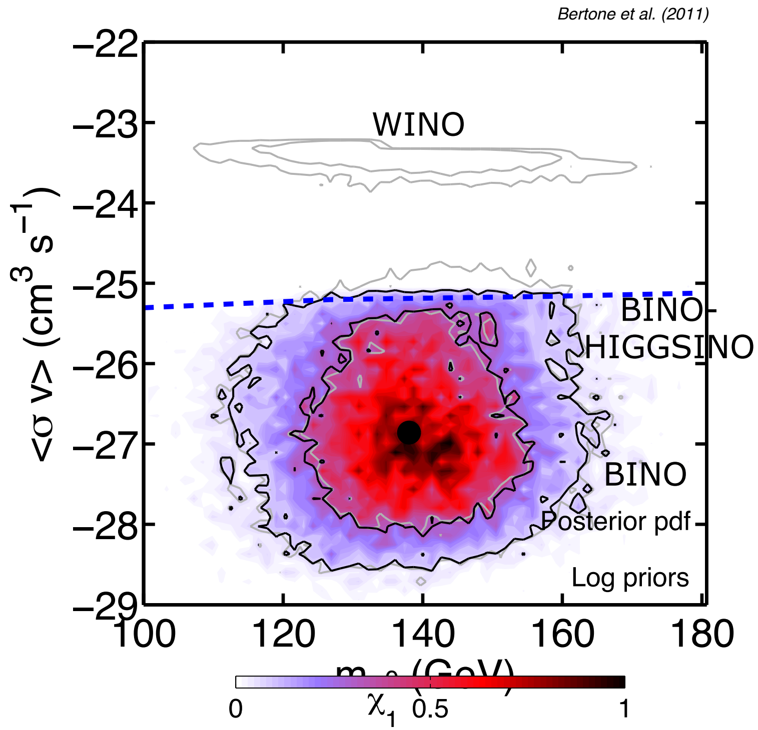
Once more, we start from the reconstruction of DM parameters form LHC

Combination with Indirect detection can also remove degeneracies

For the same (LCC3) point, we determine the gamma ray flux that could be observed in dwarf Spheroidal galaxies

Imposing Fermi-LAT bound from the non-observation (Wino-like cases are disfavoured)





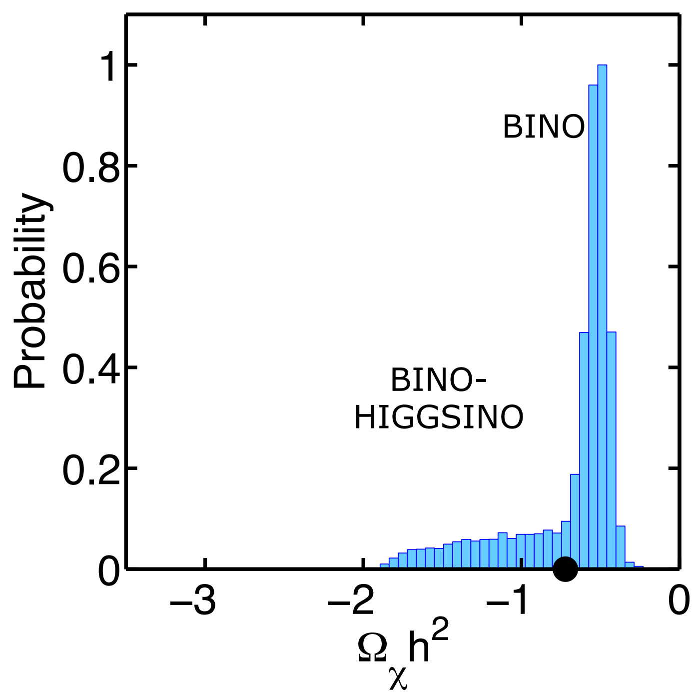
Not yet unambiguous but excludes spurious maxima

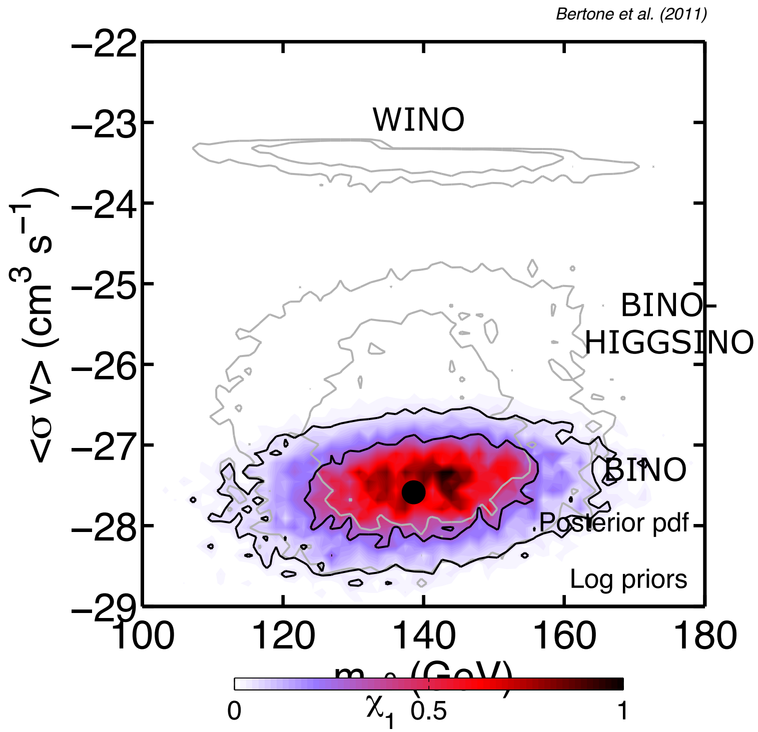
Bertone, D.G.C., Fornasa, Pieri, Ruiz de Austri, Trotta 2011

In case of a future detection the relic density reconstruction improves

Hypothetical future CTA observation of Draco

Assuming E_{TH} = 20 GeV and effective area 10^4 m^2





Once more, the relic density is better reconstructed and the spurious maxima disappear

Bertone, D.G.C., Fornasa, Pieri, Ruiz de Austri, Trotta '11

Example 3: Combination of Direct Detection experiments

The same detected rate can be due to different combinations of SI-SD interactions

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

$$\frac{d\sigma_{WN}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2} \left(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right)$$

Nuclear form factors

Integrating in energies and velocities

$$R_1 = A_1 \sigma_0^{SI} + \left(B_1^p \sqrt{\sigma_0^{SD,p}} + B_1^n \sqrt{\sigma_0^{SD,n}}\right)^2$$

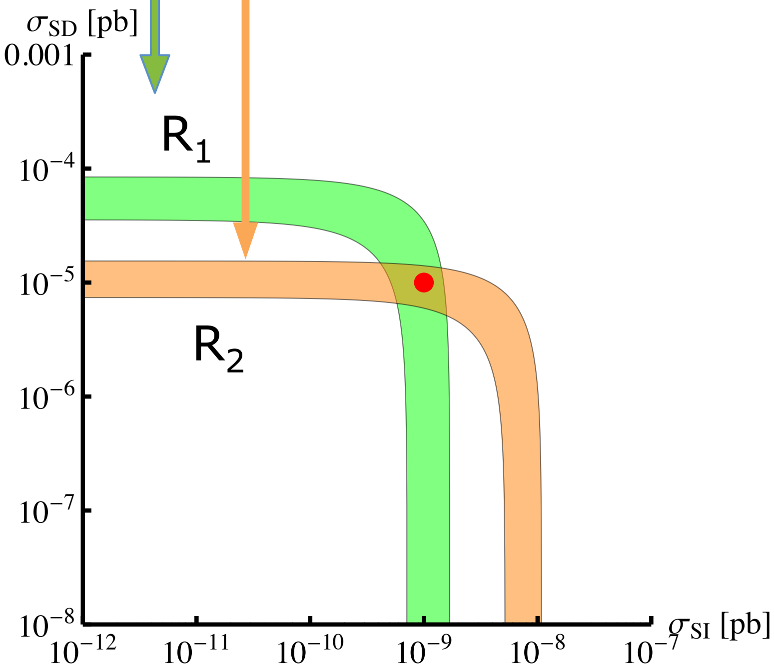
Target-dependent

A single experiment cannot determine the three WIMP couplings (the shape of the differential rate allows a determination of the WIMP mass)

$$R_1 = A_1\sigma_0^{SI} + \left(B_1^p\sqrt{\sigma_0^{SD,p}} + B_1^n\sqrt{\sigma_0^{SD,n}}\right)^2$$

$$R_2 = A_2\sigma_0^{SI} + \left(B_2^p\sqrt{\sigma_0^{SD,p}} + B_2^n\sqrt{\sigma_0^{SD,n}}\right)^2$$

Determination of both SD and SI cross section



Complementarity of targets

- One target mostly SI and the other mostly SD
- WIMP SD coupling has to be large (for enough statistics in the SD target)
- Large exposure → smaller area

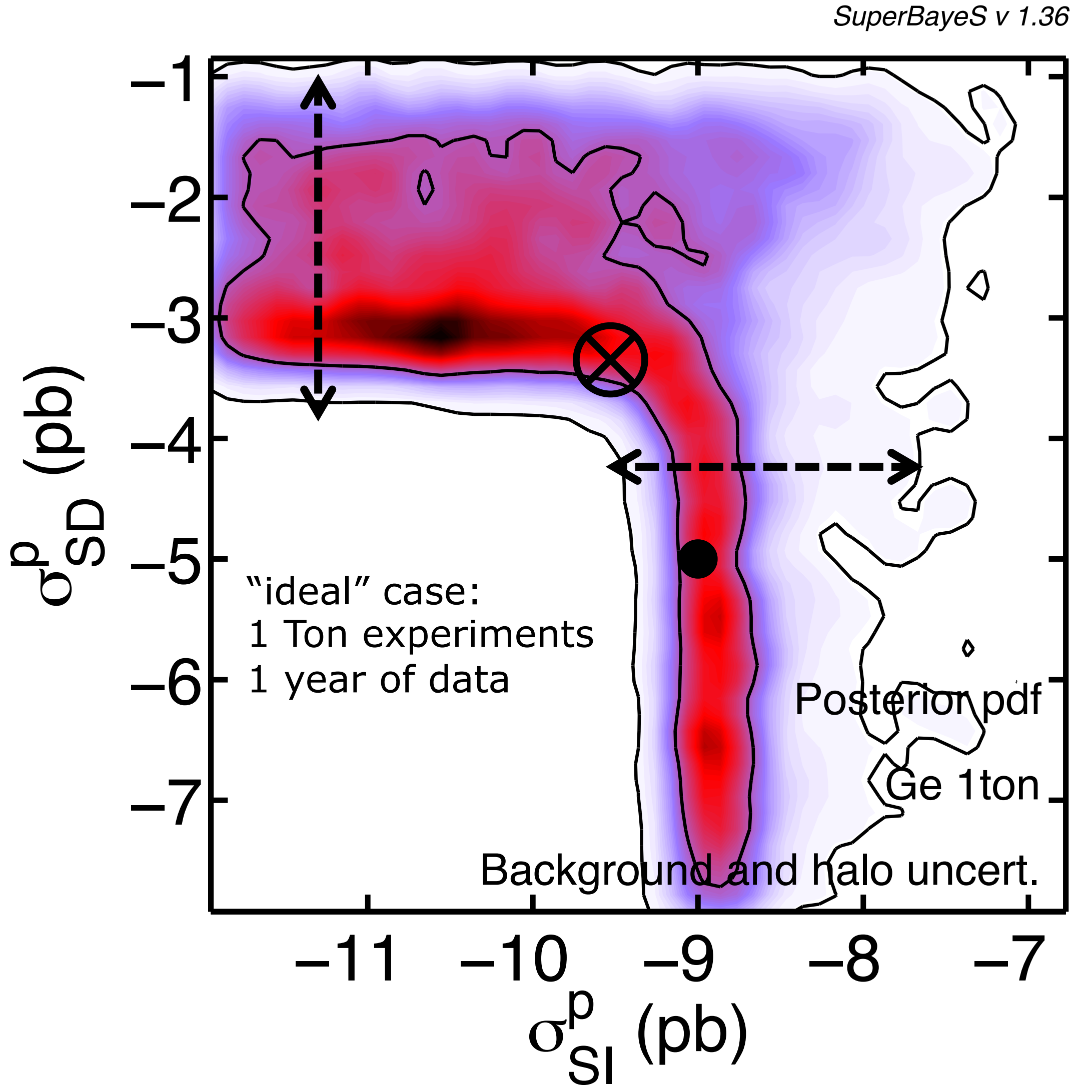
Analytical determination of the parameters without uncertainties (ideal)

Cannoni, Gómez, Vergados '10
Cannoni '11

Detection with one experiment

$$R_1 = A_1\sigma_0^{SI} + \left(B_1^p\sqrt{\sigma_0^{SD,p}} + B_1^n\sqrt{\sigma_0^{SD,n}}\right)^2$$

Ge detector (e.g. Super CDMS)



$$\sigma_0^{SI} = 10^{-9}\,\mathrm{pb}$$
$$\sigma_0^{SD} = 10^{-5}\,\mathrm{pb}$$
$$m_W = 50\,\mathrm{GeV}$$
$$\epsilon = 333\ \mathrm{kg\ yr}$$

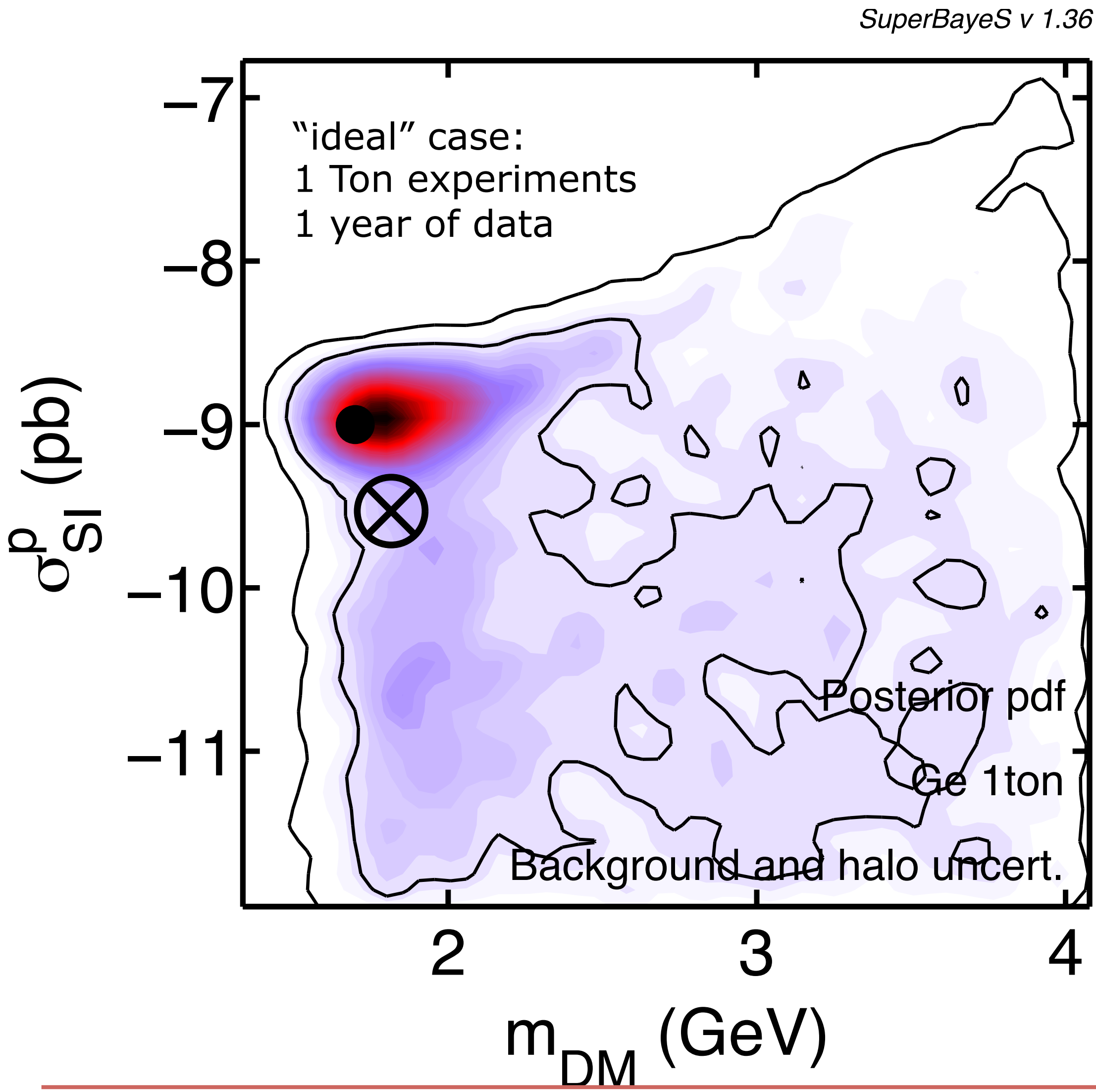
The degeneracy cannot be fully removed unless assumptions are made on the WIMP model

Uncertainties lead to a poorer reconstruction of parameters

Detection with one experiment

Ge detector (e.g. Super CDMS)

$$R_1 = A_1\sigma_0^{SI} + \left(B_1^p\sqrt{\sigma_0^{SD,p}} + B_1^n\sqrt{\sigma_0^{SD,n}}\right)^2$$



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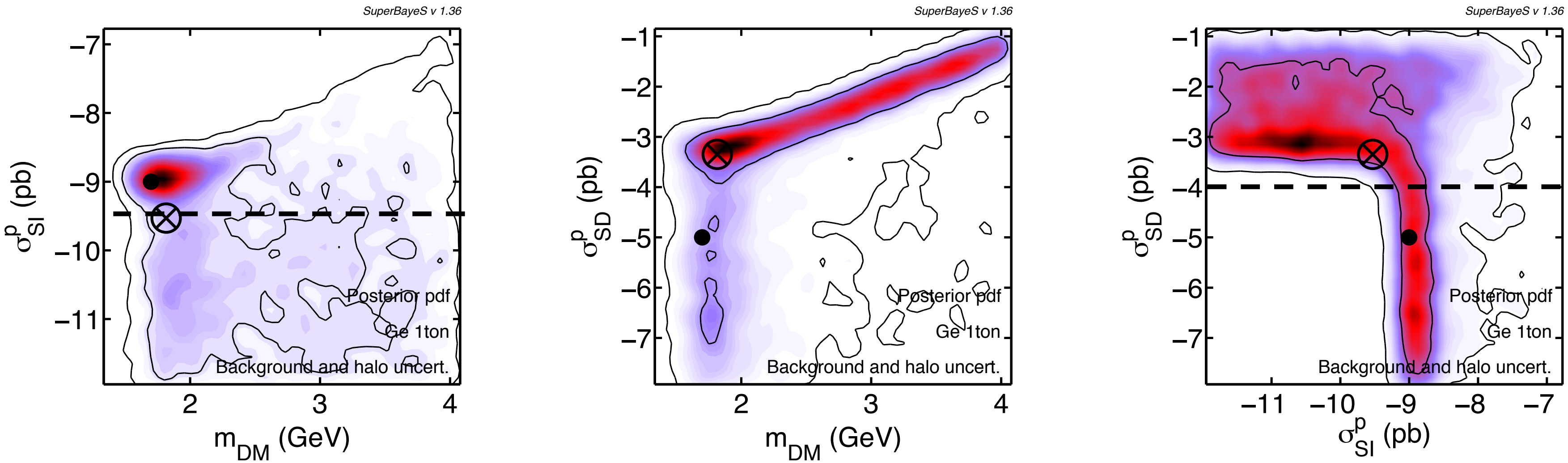

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The degeneracy cannot be fully removed unless assumptions are made on the WIMP model

(e.g., usually the SD contribution is considered negligible)

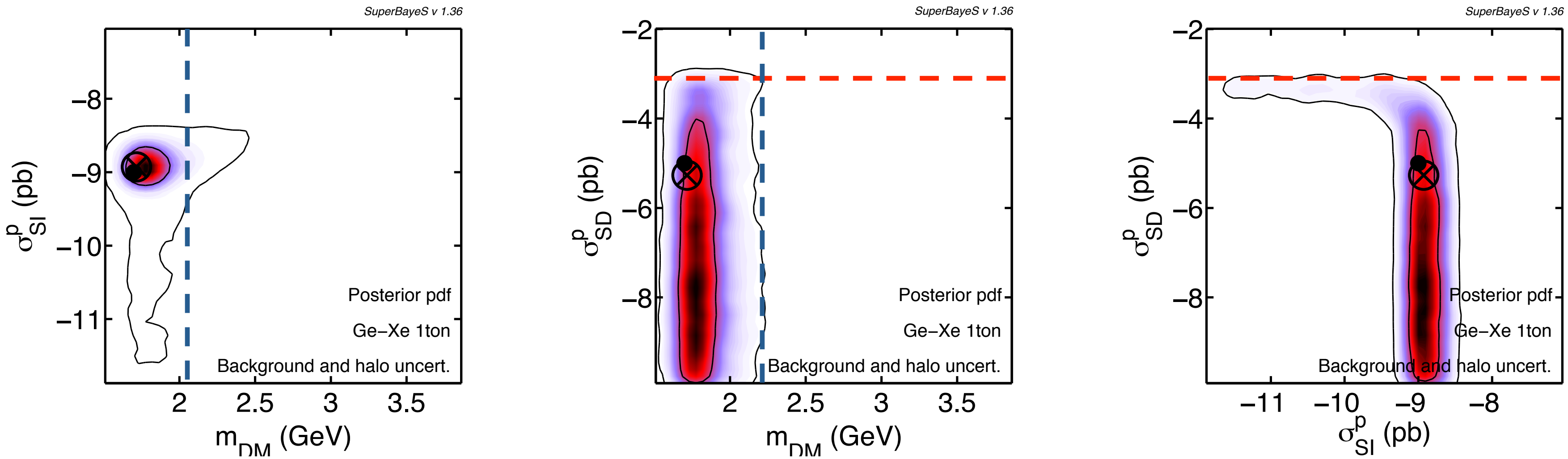
Detection with two experiments

Ge detector (e.g. Super CDMS)

Xe detector (e.g. Xenon)

$$R_1 = A_1\sigma_0^{SI} + \left(B_1^p\sqrt{\sigma_0^{SD,p}} + B_1^n\sqrt{\sigma_0^{SD,n}}\right)^2$$

$$R_2 = A_2\sigma_0^{SI} + \left(B_2^p\sqrt{\sigma_0^{SD,p}} + B_2^n\sqrt{\sigma_0^{SD,n}}\right)^2$$



$$\sigma_0^{SI} = 10^{-9}\,\mathrm{pb}$$
$$\sigma_0^{SD} = 10^{-5}\,\mathrm{pb}$$
$$m_W = 50\,\mathrm{GeV}$$

$$\epsilon = 333\ \mathrm{kg\ yr}$$

Both experiments are mostly sensitive to the spin-independent component

Degeneracies cannot be completely removed but the upper bound on the spin-dependent component is more stringent

Better determination of the WIMP mass

Ideal for complementarity: targets which have large spin content

	^{3} He	^{19}F	^{29}Si	^{23}Na	^{73}Ge	^{127}I*	^{127}I**	^{207}Pb$^+$
$\Omega_0(0)$	1.244	1.616	0.455	0.691	1.075	1.815	1.220	0.552
$\Omega_1(0)$	-1.527	1.675	-0.461	0.588	-1.003	1.105	1.230	-0.480
$\Omega_p(0)$	-0.141	1.646	-0.003	0.640	0.036	1.460	1.225	0.036
$\Omega_n(0)$	1.386	-0.030	0.459	0.051	1.040	0.355	-0.005	0.516
μ_{th}		2.91	-0.50	2.22				
μ_{exp}		2.62	-0.56	2.22				
$\frac{\mu_{th}(spin)}{\mu_{exp}}$		0.91	0.99	0.57				

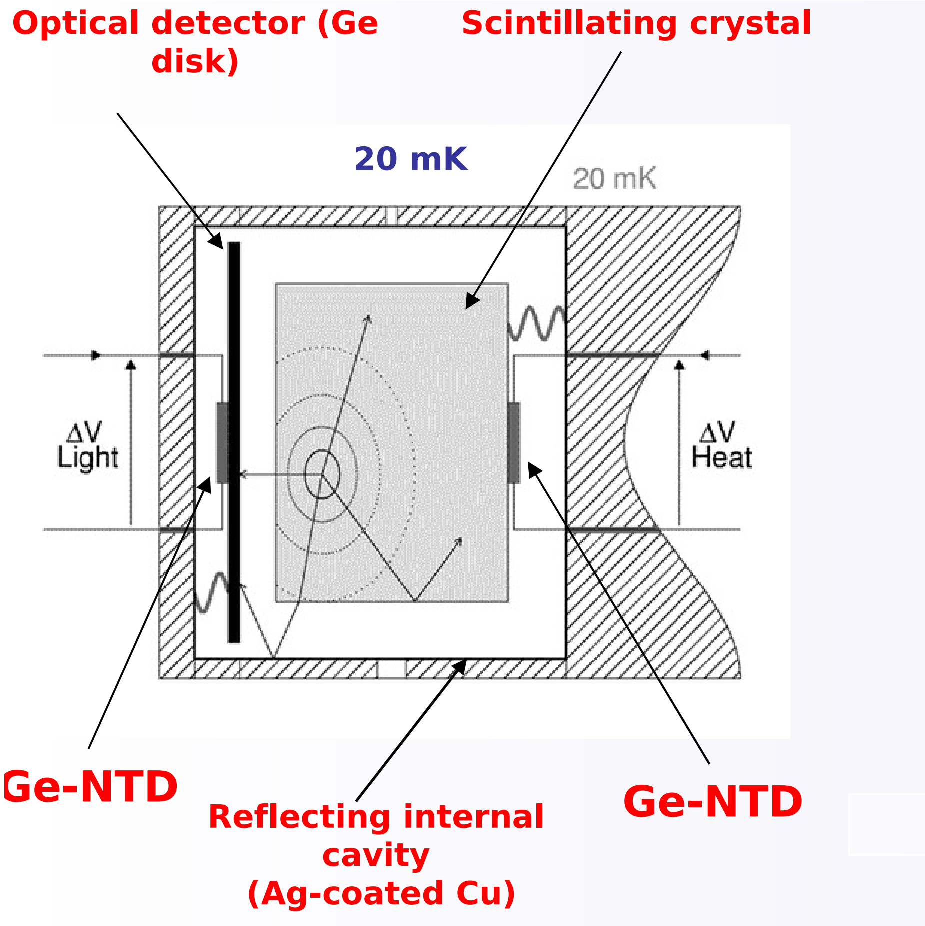
From Vergados '09

Ideally one also wants to further discriminate SD-proton and SD-neutron

Fluorine? – e.g., used in COUPP

How large do we need the target to be to obtain complementarity?

We studied scintillating-bolometric targets for the ROSEBUD collaboration

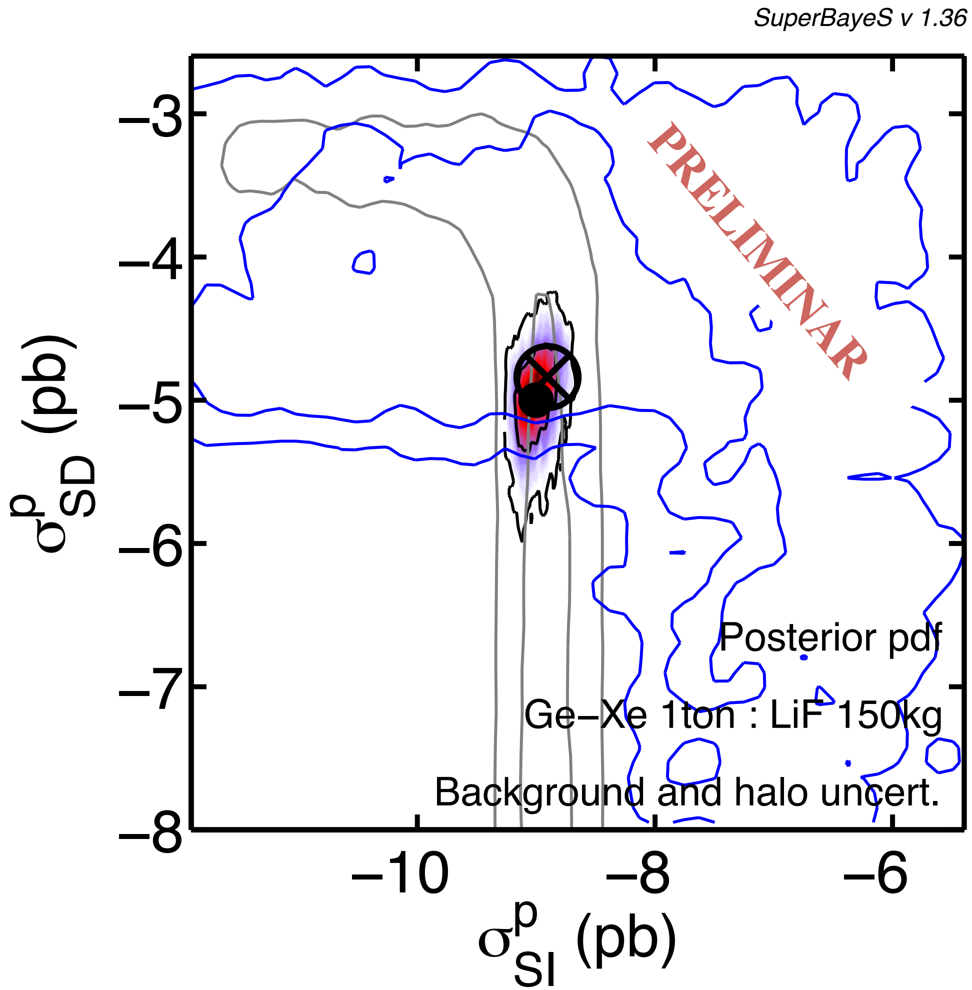


The signal is heat (phonons) and scintillation light

LiF
CaF
CaWO
Al_2O_3
BGO (Bi, Ge, O)
...

CDMS + Xenon + ROSEBUD/EURECA

A relatively "small" spin-dependent target can provide good discrimination potential



$$\sigma_0^{SI} = 10^{-9}\,\mathrm{pb}$$
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$$m_W = 50\,\mathrm{GeV}$$

Ge detector (e.g. Super CDMS)

Xe detector (e.g. Xenon 1T)

$$\epsilon = 333 \text{ kg yr}$$

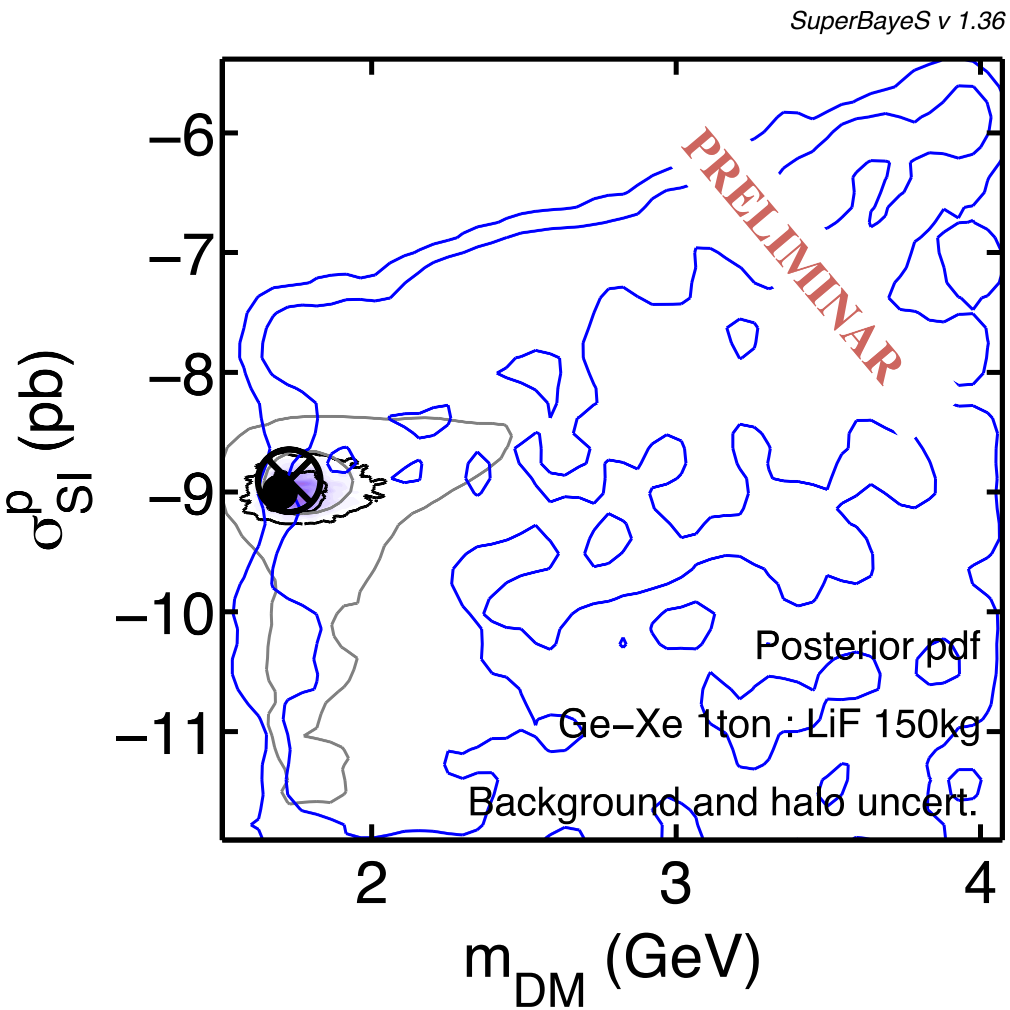
ROSEBUD targets:

Al_2O_3 ~ 400 kg

Li F ~ 150 kg

CDMS + Xenon + ROSEBUD/EURECA

A relatively “small” spin-dependent target can provide good discrimination potential



$$\sigma_0^{SI} = 10^{-9}\,\mathrm{pb}$$
$$\sigma_0^{SD} = 10^{-5}\,\mathrm{pb}$$
$$m_W = 50\,\mathrm{GeV}$$

Ge detector (e.g. Super CDMS)

Xe detector (e.g. Xenon 1T)

$$\epsilon = 333 \text{ kg yr}$$

ROSEBUD targets:

Al_2O_3 ~ 400 kg

Li F ~ 150 kg

Conclusions

Advances in direct DM detection leave room for OPTIMISM:

direct detection experiments are getting more sensitive
possible hints in indirect searches
LHC further constraining the parameter space for new physics

In all these UNCERTAINTIES play an important role:

To conclusively determine claim DM detection we will need observation using different experimental techniques.
Direct detection is needed

Dark matter IDENTIFICATION requires combination of data from different sources

LHC alone cannot determine the DM properties (or if it is the DM at all), need combination with direct or/and indirect searches

Combination of Direct Detection experiments seems promising to determine DM phenomenological parameters

Thank you