Dark matter

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MULTIDARK
Multimessenger Approach
for Dark Matter Detection

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ift

TALLER DE ALTAS ENERGÍAS – BENASQUE 2104

Outline

1) Motivation for dark matter

2) DM production: Weakly-Interacting Massive Particles (WIMPs)

3) DM (WIMP) detection

   - Indirect searches

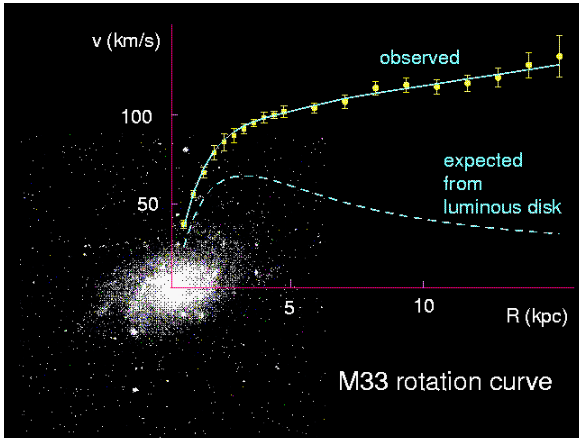
   - direct searches
     - Searches in SuperCDMS)
     - reconstruction of DM parameters

   - collider searches

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

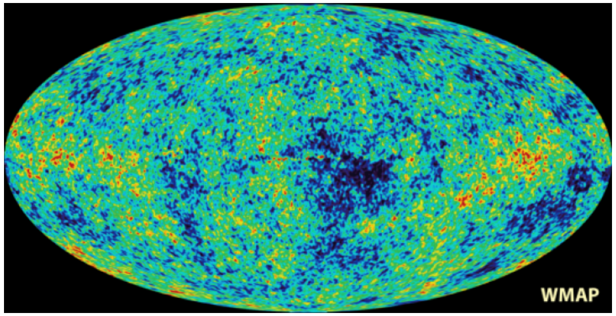
- Peculiar velocities and gas temperature
- Weak lensing
- Dynamics of cluster collision

Cosmological scales

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

$$\Omega_{CDM}\, h^2 = 0.1196 \pm 0.003$$

Planck 2013



Rotation curves of spiral galaxies become flat for large distances

From the luminous matter of the disc one would expect a decrease in the velocity that is not observed

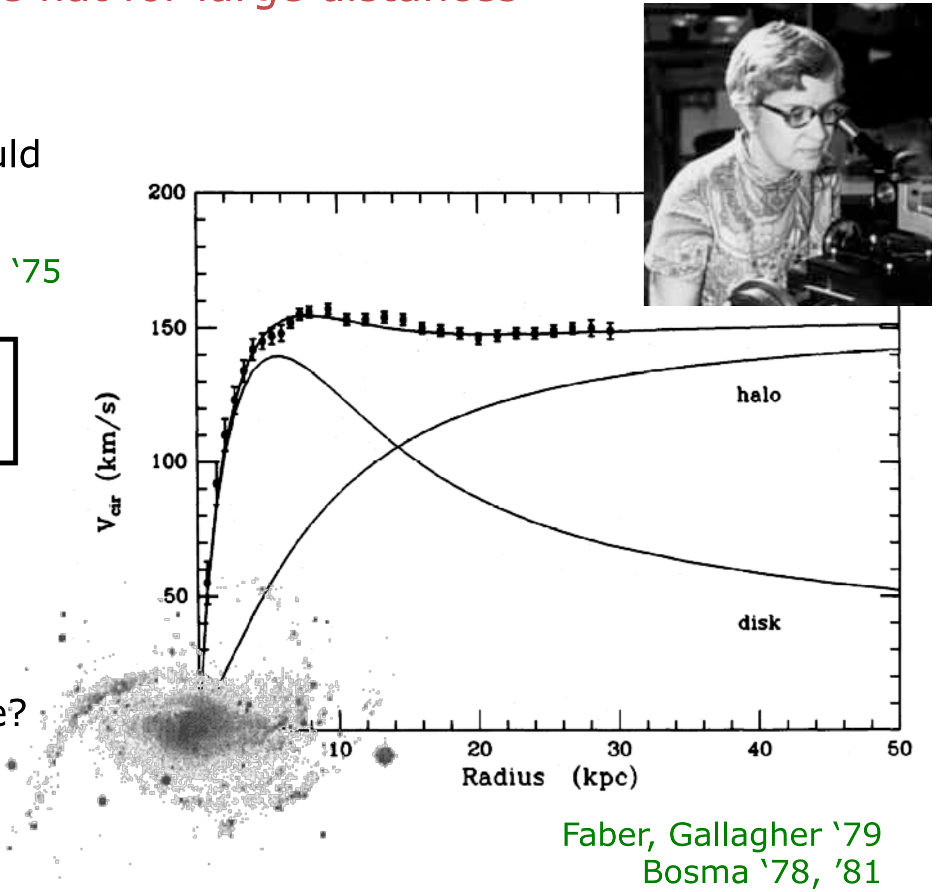
Rubin ‘75

$$\boxed{\frac{v_{\text{rot}}^2}{r} = \frac{G\ M(r)}{r^2}} \rightarrow \boxed{v_{\text{rot}} = \sqrt{\frac{G\ M(r)}{r}}}$$

$$M(r) = cte \rightarrow v_{\text{rot}} \propto \frac{1}{\sqrt{r}}$$

Is there more matter than the one we can see?

Non-luminous (**DARK MATTER**)



Faber, Gallagher ‘79
Bosma ‘78, ’81
van Albada, Bahcall, Begeman, Sancisi ‘84

Measurements of the gas temperature in elliptical galaxies provide further support for the Dark Matter hypothesis

Galaxies contain vast amounts of non-luminous matter $M \gg M_*$

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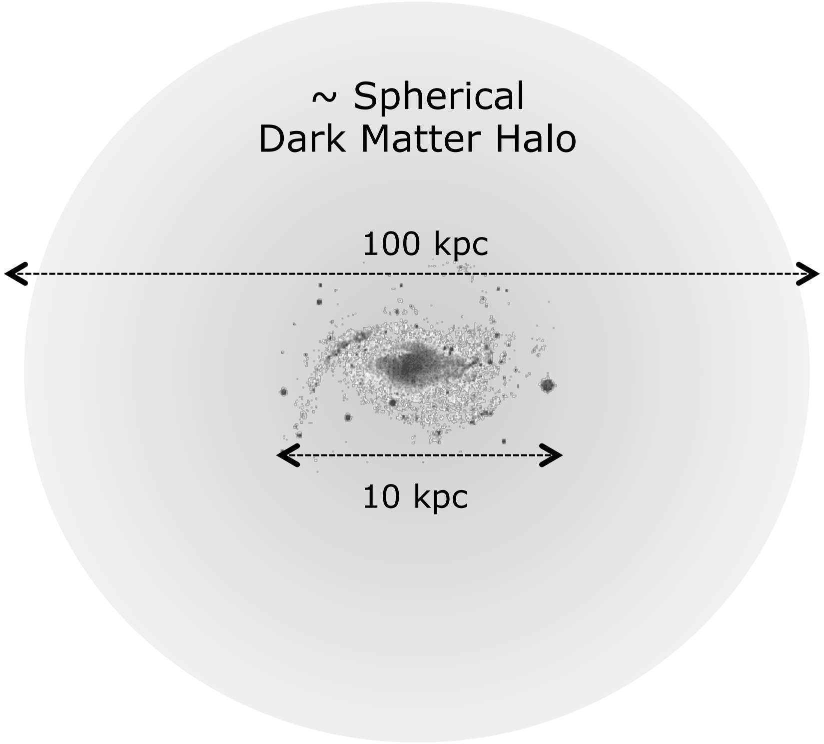

~ Spherical
Dark Matter Halo

100 kpc

10 kpc

Is there more matter than the one we can see?

Non-luminous (**DARK MATTER**)

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Galaxies contain vast amounts of non-luminous matter

$$M \gg M_*$$

Rotation curves have also been measured for a large number of spiral galaxies

The mismatch in the shape cannot be compensated by modifying the contribution from luminous components (disk and bulge)

Faber, Gallagher ‘79
Bosma ‘78, ’81
van Albada, Bahcall, Begeman, Sancisi ‘84

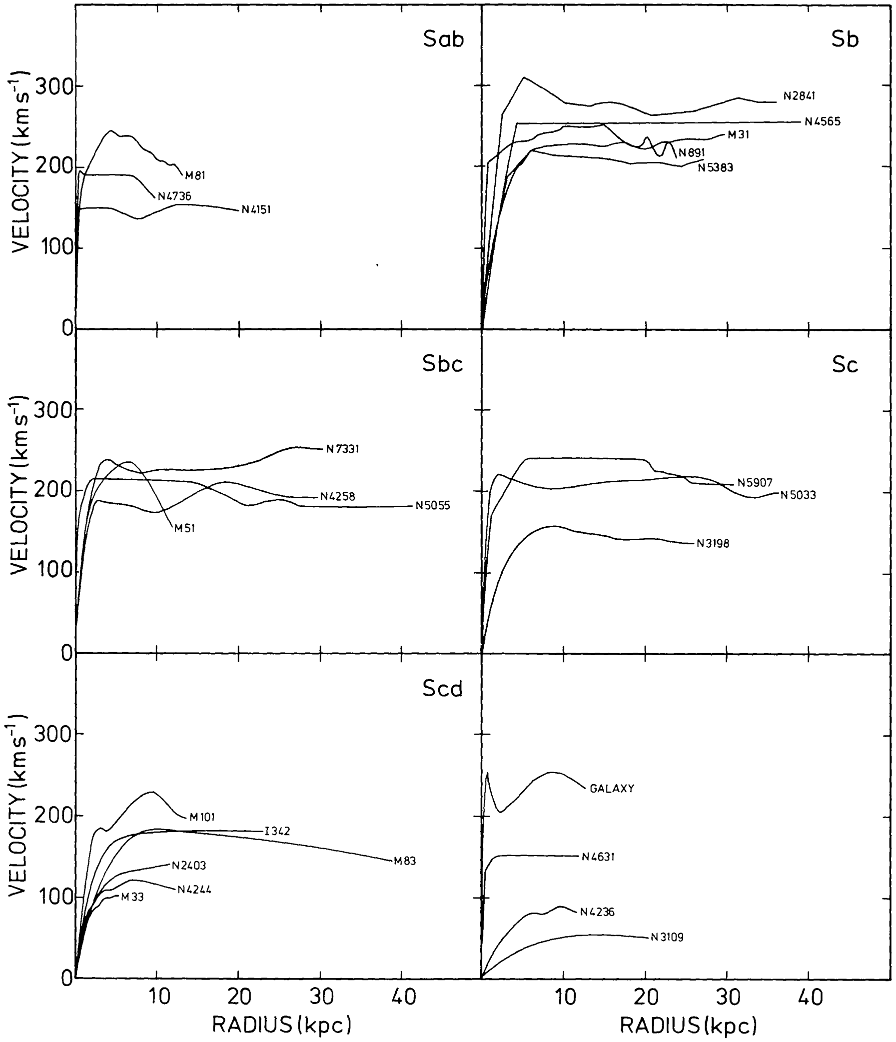
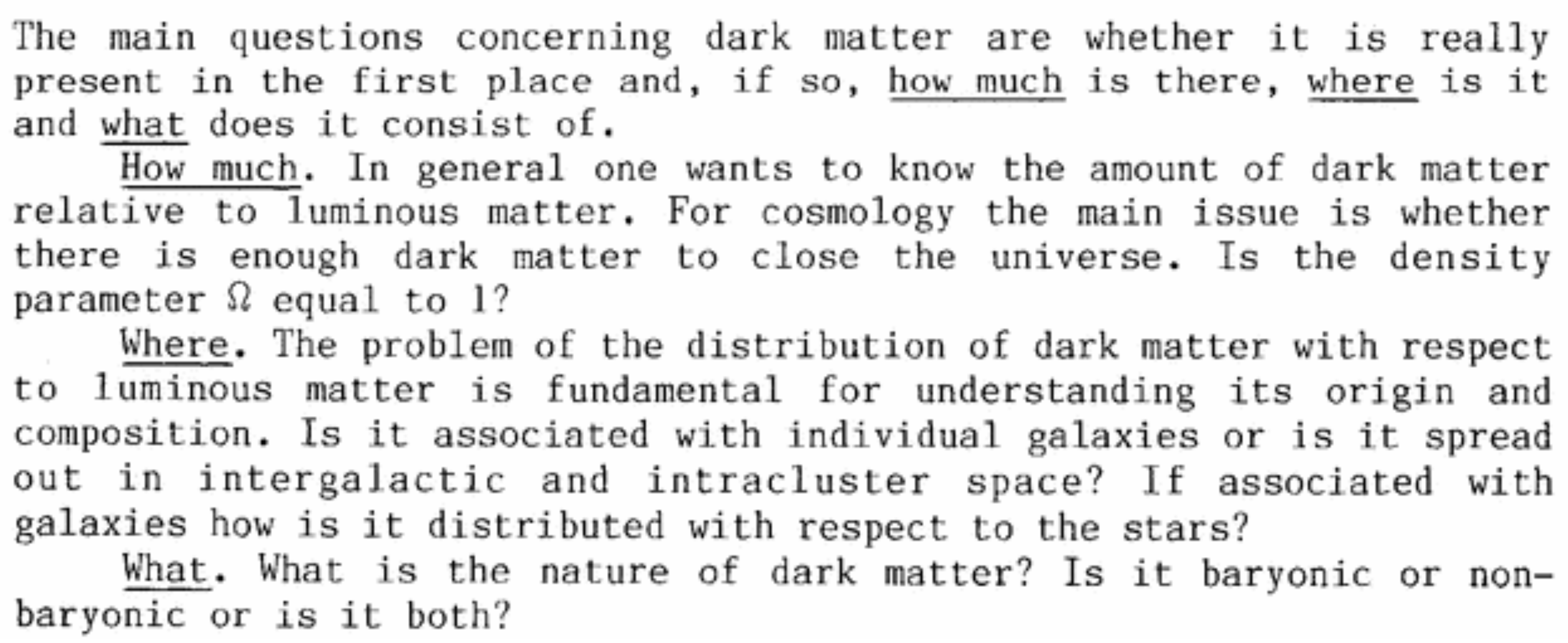


Figure 2 Rotation curves of 25 galaxies of various morphological types from Bosma (1978).



The main questions concerning dark matter are whether it is really present in the first place and, if so, how much is there, where is it and what does it consist of.

How much. In general one wants to know the amount of dark matter relative to luminous matter. For cosmology the main issue is whether there is enough dark matter to close the universe. Is the density parameter Ω equal to 1?

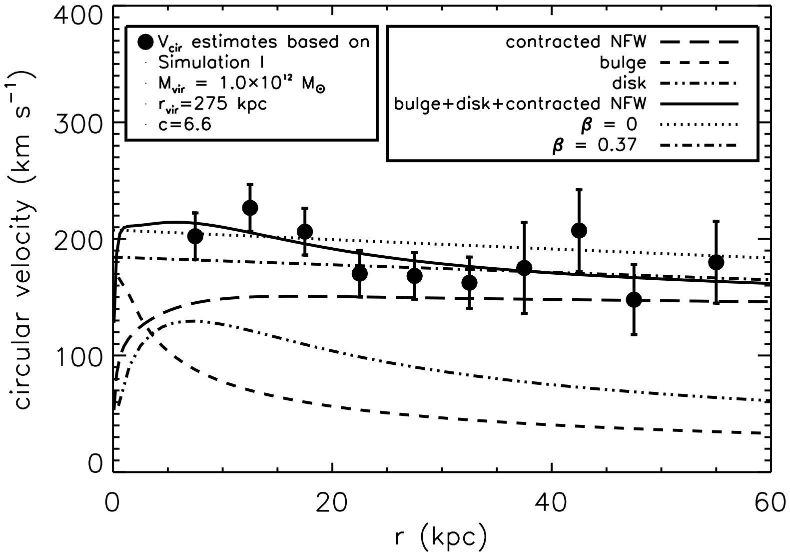
Where. The problem of the distribution of dark matter with respect to luminous matter is fundamental for understanding its origin and composition. Is it associated with individual galaxies or is it spread out in intergalactic and intracluster space? If associated with galaxies how is it distributed with respect to the stars?

What. What is the nature of dark matter? Is it baryonic or non-baryonic or is it both?

van Albada, Sancisi ‘87

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

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

Bovy, Tremaine 2012

Uncertainties in the parameters defining the halo:

- local DM density

$\rho_{DM}(R_0) = 0.43(0.11)(0.10)\,\mathrm{GeV/cm^3}$ Nesti, Salucci 2012

$\rho_{DM}(R_0) = 0.385 \pm 0.027\,\mathrm{GeV\,cm^{-3}}$ Catena, Ullio 2010

$\rho_{DM}(R_0) = 0.32 \pm 0.07\ \mathrm{GeV/cm^3}$ Strigari, Trotta 2009

$\rho_{DM}(R_0) = 0.40 \pm 0.04\,\mathrm{GeV\,cm^{-3}}$ McMilan 2011

$\rho_{DM}(R_0) = 1.3 \pm 0.3\ \mathrm{GeV/cm^3}$ De Boer, Webber 2011 (possible enhancement due to ring-like structures)

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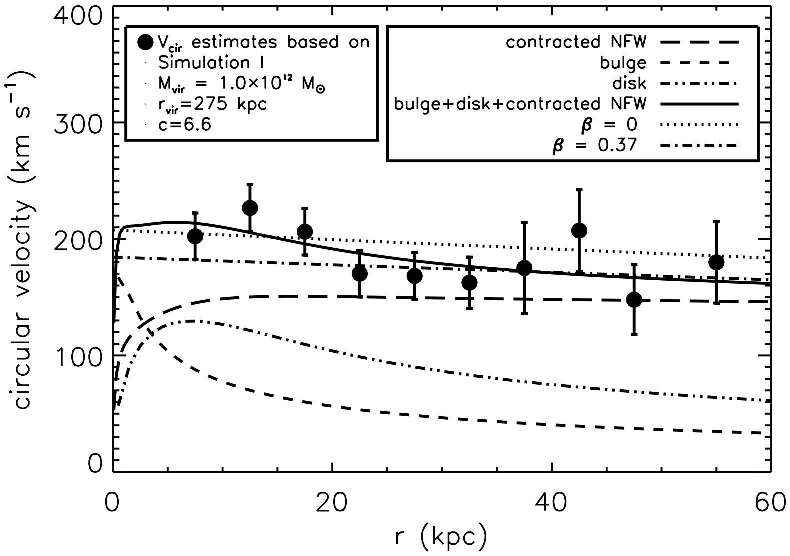
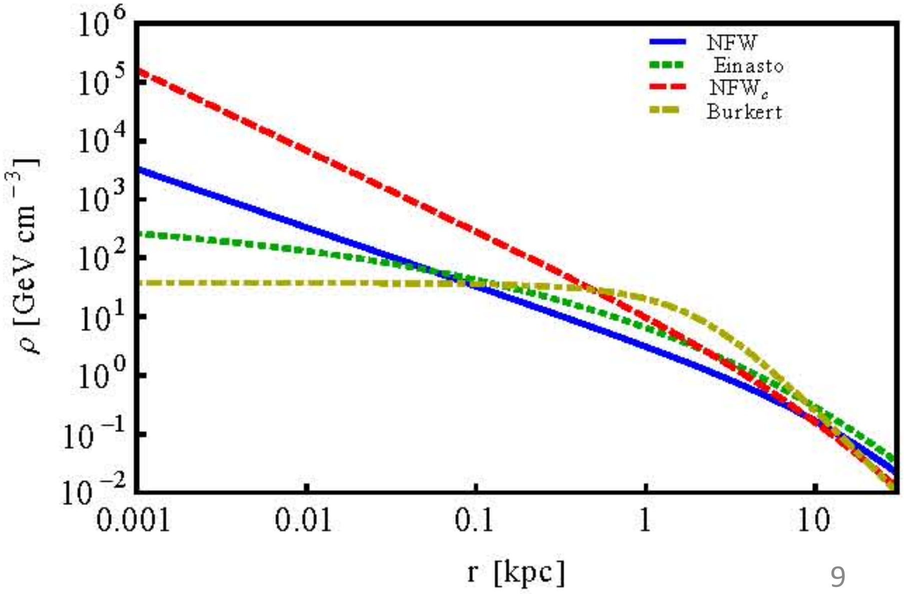


Xue et al. 2008

Uncertainties in the parameters defining the halo:

- local DM density
- DM density profile
  (DM density at the galactic centre)

crucial for indirect detection!



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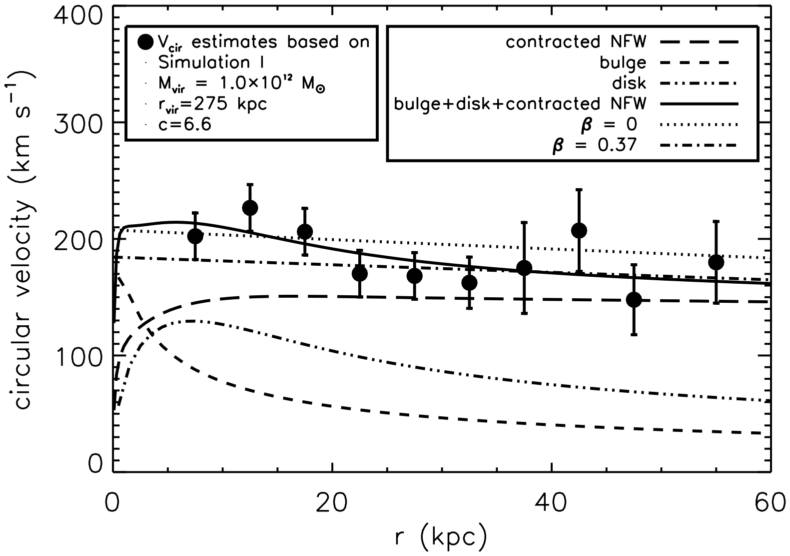
Uncertainties in the parameters defining the halo:

- local DM density
- DM density profile
  (DM density at the galactic centre)
- velocity distribution function

Central and escape velocities
Deviations from Maxwellian distribution



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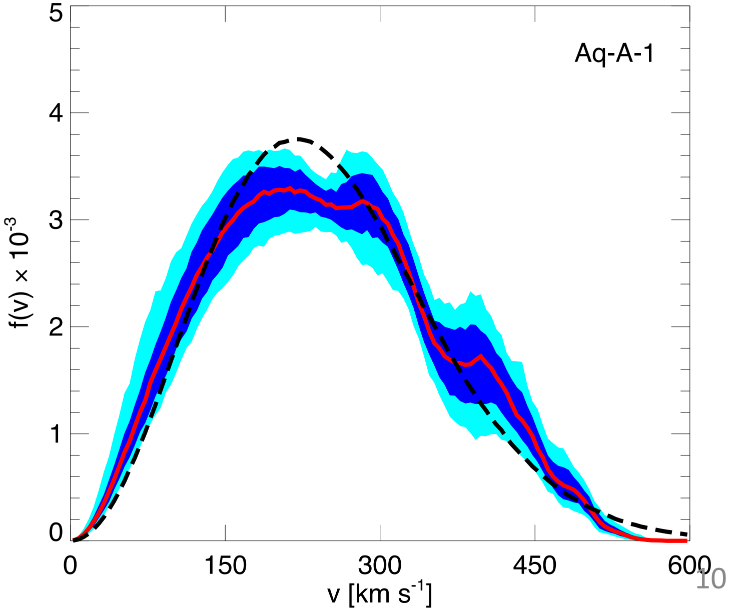
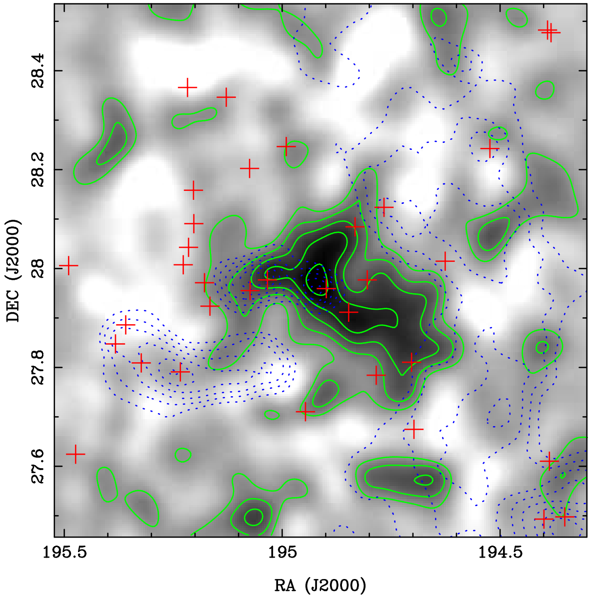


Vogelsberger et al. 2008

Galaxy clusters also contain large amounts of non-luminous matter

Peculiar motions of galaxies in the Coma cluster show that the total mass is much larger than the luminous one

Zwicky 1933, '37

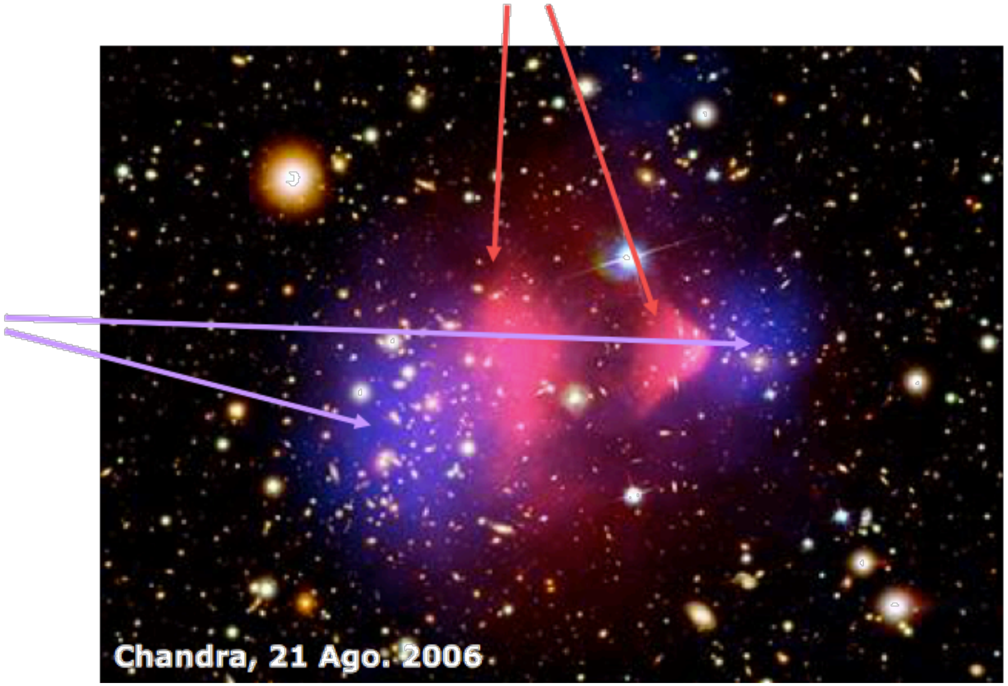


Weak lensing techniques also allow to "weigh" galaxy clusters by measuring the distortion (shear) of distant galaxies behind the cluster.

Gavazzi et al 2009
Kubo et al. 2007

The bullet cluster (a.k.a. merging galaxy cluster 1E0657-56)

Hot gas (luminous matter) observed by Chandra



(Collisionless)
dark matter

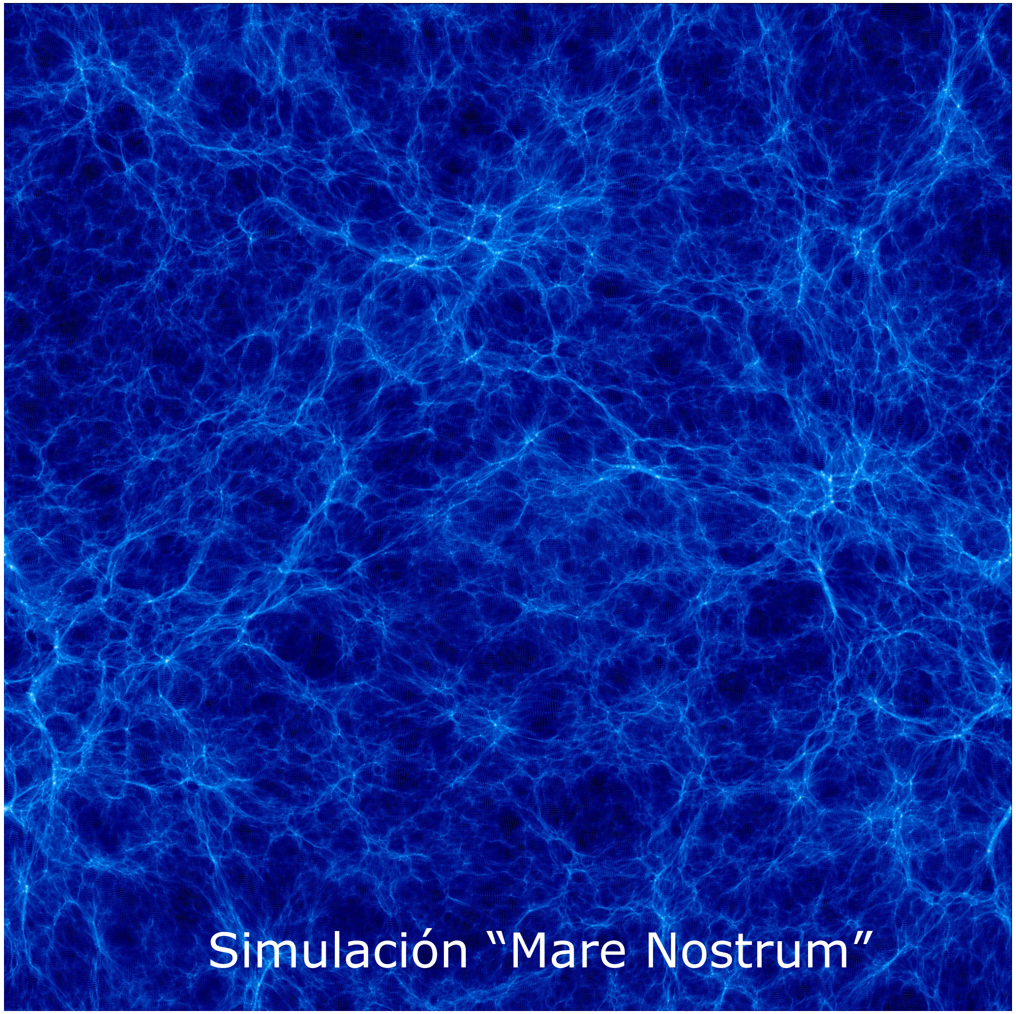
(false colour)

Clowe, González, Markevitch 2003
Clowe et al. 2006
Bradac et al. 2006

The observed displacement between the bulk of the baryons and the gravitational potential favours the dark matter hypothesis versus modifications of gravity.

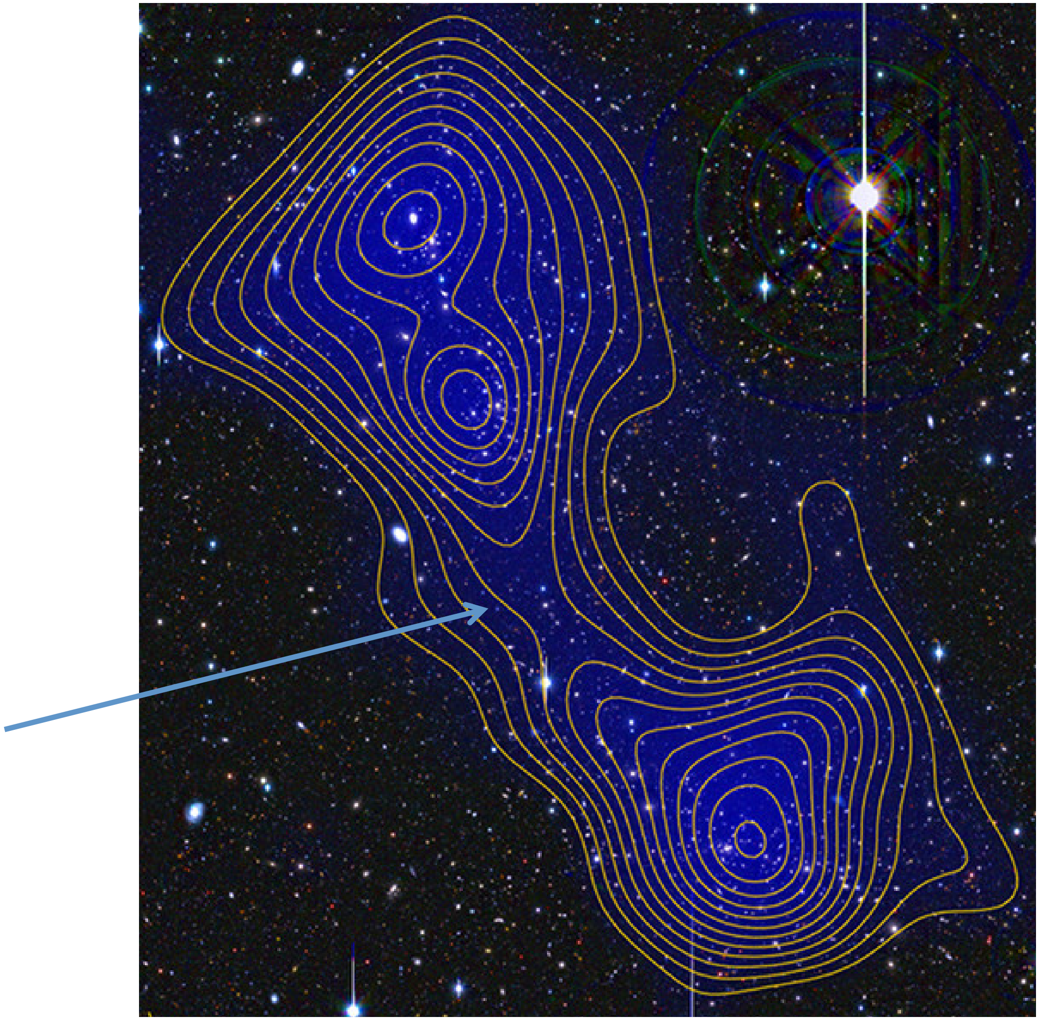
Numerical simulations reproduce the filamentary structure of the Universe at large scale

It provides the gravitational "seeds" for the formation of galaxies



… and in fact dark matter filaments might have been recently observed

Using weak-lensing techniques



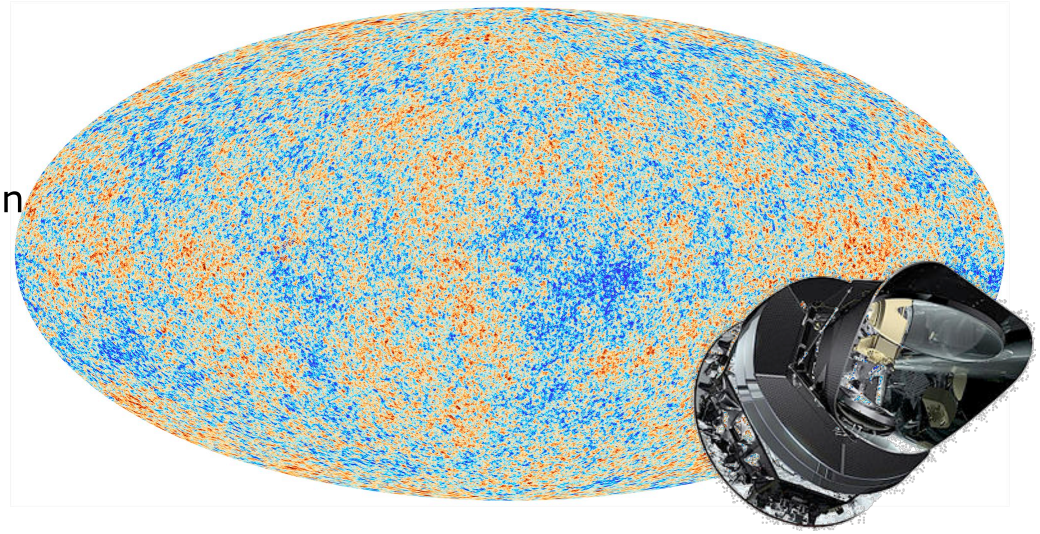
Dark matter filament between two galaxy clusters

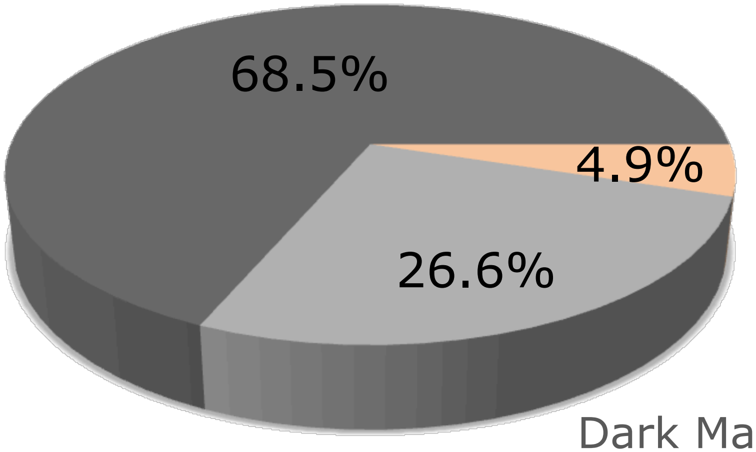
Dietrich et al. 2012

Observations of the Cosmic microwave Background can be used to determine the components of our Universe

WMAP and Planck precision data of the CMB anisotropies allow the determination of cosmological parameters

COBE, WMAP, Planck





The dark matter abundance is measured accurately

$$\Omega_\Lambda h^2 = 0.3116 \pm 0.009$$

$$\Omega_c h^2 = 0.1196 \pm 0.003$$

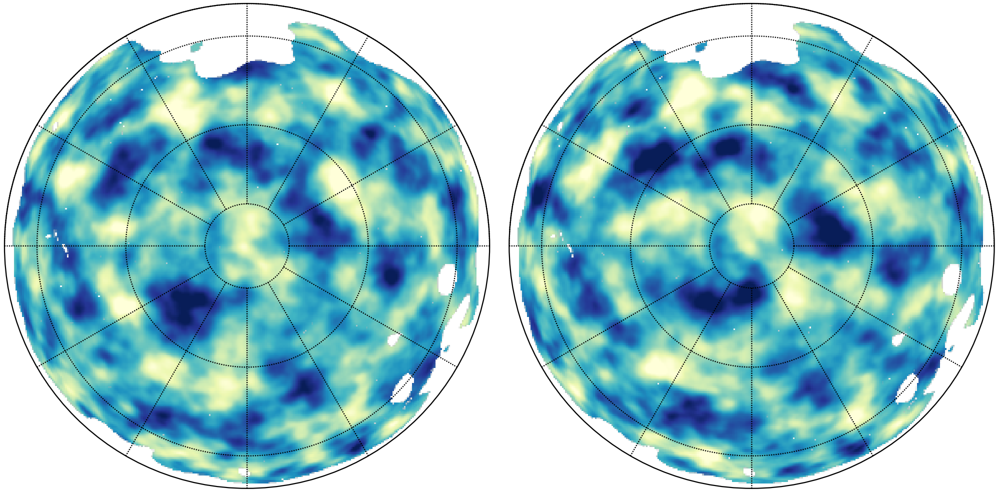
$$\Omega_b h^2 = 0.02207 \pm 0.00033$$

Planck 2013

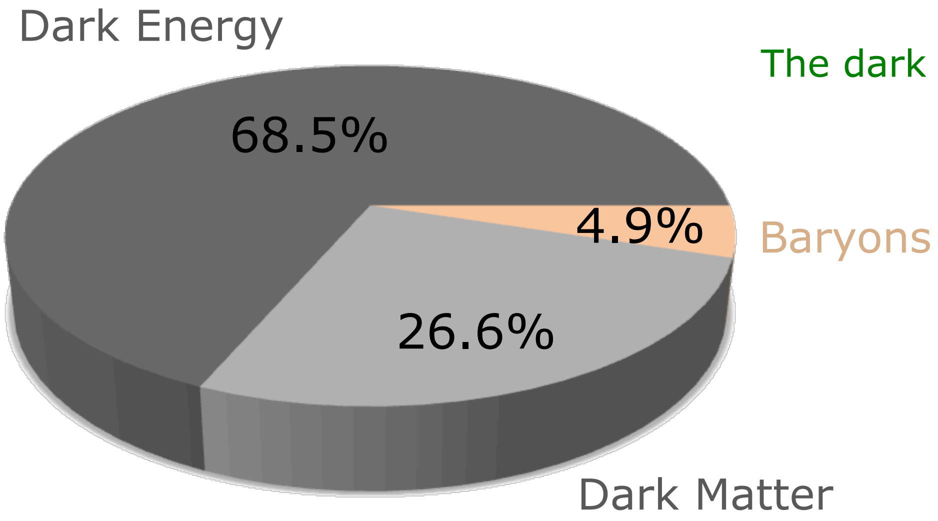
Observations of the Cosmic microwave Background can be used to determine the components of our Universe

The matter distribution can also be determined from lensing measurements on the CMB

Planck 2013



Galactic South - 143 GHz   Galactic South - 217 GHz



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Planck 2013

Dark Baryons and MACHOs

- Part of the budget of dark matter is baryonic, in the form of faint objects which escape astronomical observation

- Hydrogen (frozen, cold gas)
- Low mass stars/Jupiters
- Remnants of massive stars (white dwarfs, neutron stars, black holes)

MACHOS

In almost every case there are theoretical or observational problems

- Microlensing experiments (Alcock et al. MACHO coll. '01; Alfonso et al. EROS coll. '04)
- Effects on the halo and disk distributions
- Acretion on black holes implies emmission of X-rays which cannot exceed the X-ray background. Also metals produced in stars prior to the formation of Black Holes cannot exceed the observed metallicity of the galactic disk.

(Hegyi, Olive '96)

Baryonic dark matter cannot account for the observed amount of dark matter

Non-relativistic at the epoch of structure formation (a.k.a. cold)?

Relativistic (hot) dark matter (with a large free-streaming length) damp the power spectrum of density fluctuations at large scales (for neutrinos this corresponds to the scale of superclusters)

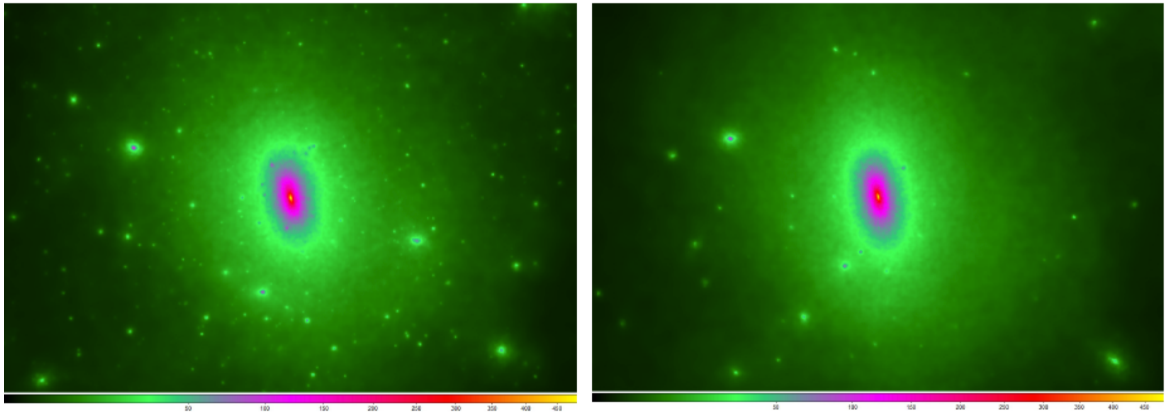
Hot dark matter predicts a top-down hierarchy in structure formation (small structures forming by fragmentation of larger ones). Observation shows that galaxies are older than superclusters.

N-body simulations usually predict many more satellites of galaxies than are observed...

Solutions include strongly interacting DM or warm dark matter with masses around 1 keV.

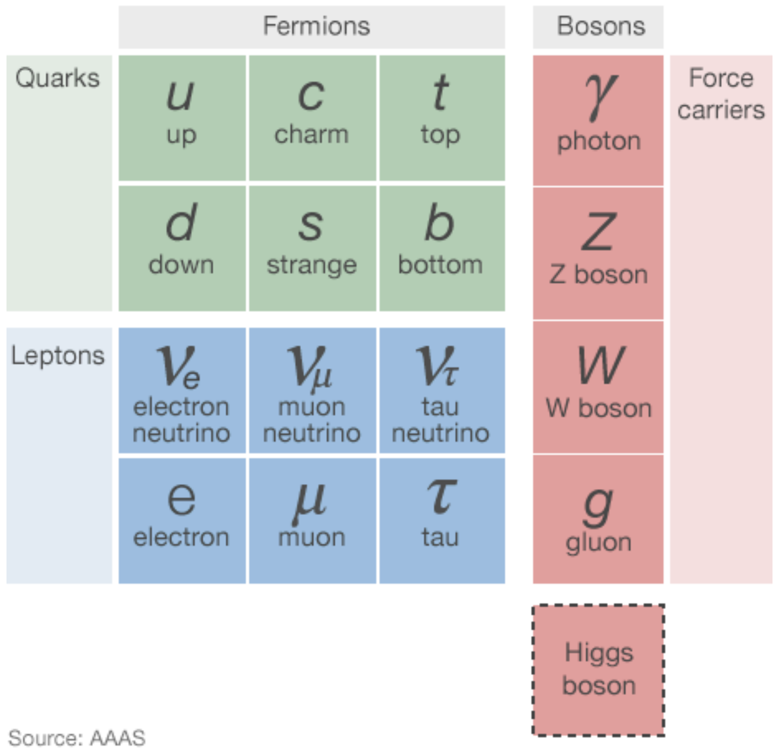
Or maybe subhaloes do not contain enough visible matter

Numerical simulations with warm dark matter show the reduction in the number of subhaloes.



Structure of a DM distribution in a simulated halo comparable to the Milky Way. Left) Halo formed assuming that DM is made of cold, massive particles. Right) The same halo simulated from same initial cosmological parameters and resolution, but assuming that DM is made of warm, light particles with rest mass = 3 keV

The Standard Model does not contain any viable candidate for dark matter



Source: AAAS

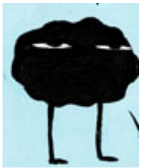
Neutrinos constitute a tiny part of (Hot) dark matter

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{91.5\mathrm{eV}} \lesssim 0.003$$

Hot dark matter not consistent with observations on structure formation.

Dark Matter is one of the clearest hints of Physics Beyond the SM

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

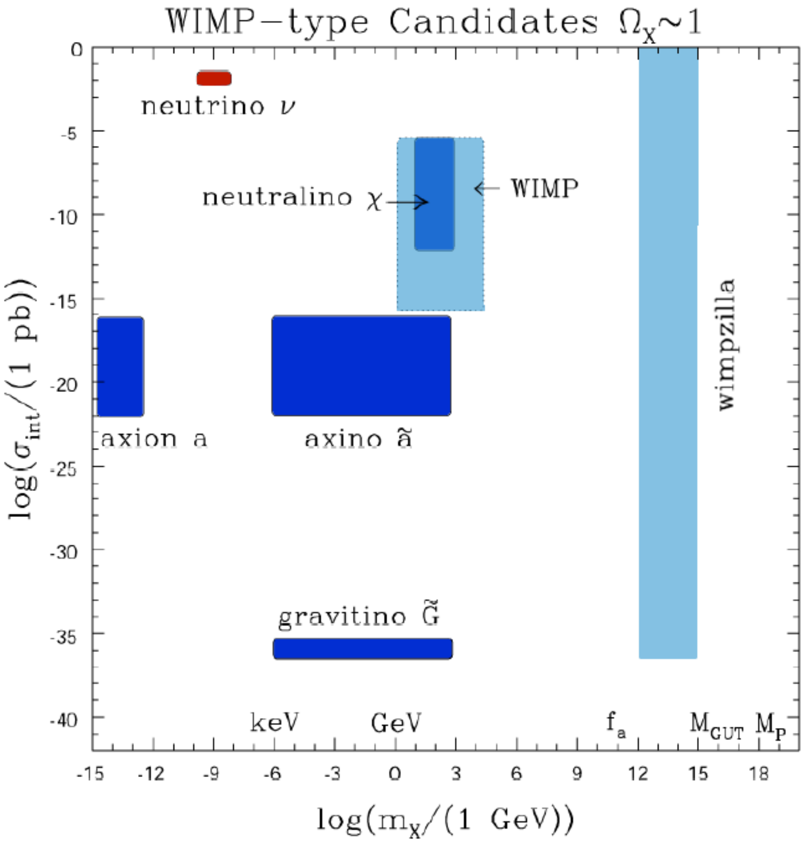


Good candidates for Dark Matter have to fulfil the following conditions

- 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...

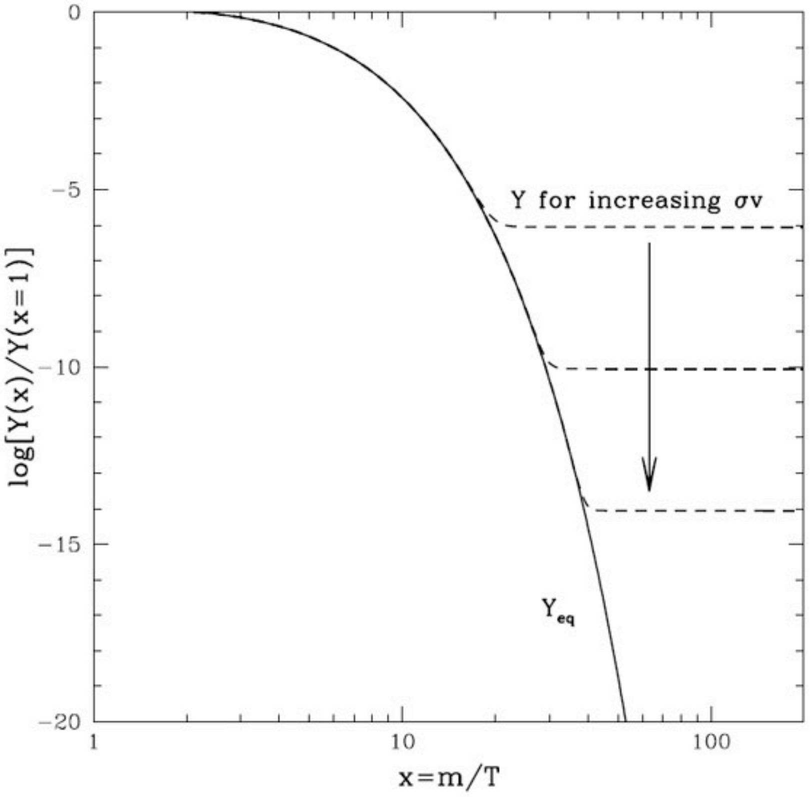


... they have very different properties

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

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



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

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

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

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

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

However....

- Not applicable to non-thermal candidates (for which the relic abundance is calculated differently, such as decays of heavier particles) (e.g., gravitinos and axinos)

- Non-standard Cosmology, e.g.,

  The presence of scalar fields in the Early Universes may induce a period of a much higher expansion rate. WIMPs decouple earlier and have a much larger relic abundance (by several orders of magnitude).

  (Catena, Fornengo, Masiero, Pietroni, Rosati, '04)

  Changes in the cosmology also affect the calculation of relic abundance for non-thermal dark matter. E.g., quintessence-motivated kination models.

  (Gómez, Lola, Pallis, Rodríguez-Quintero '08)

  Late entropy production which dilutes the DM density

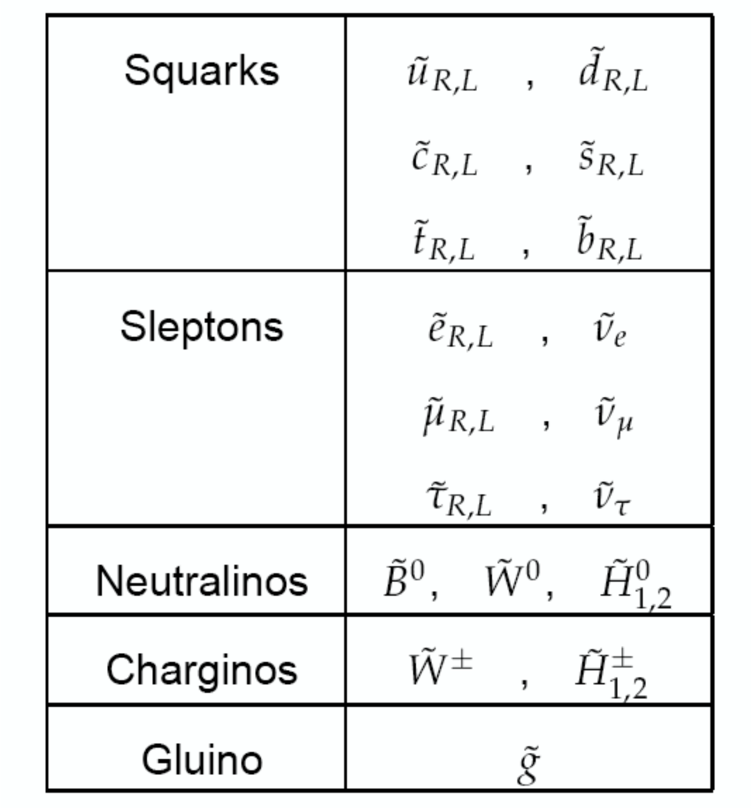
  See, e.g., (Giudice, Kolb, Riotto '01)

  E.g., decay of heavy sterile neutrinos

  (Abazajian,Koushiappas '06)
  (Asaka, Shaposnikov, Kusenko '06)

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

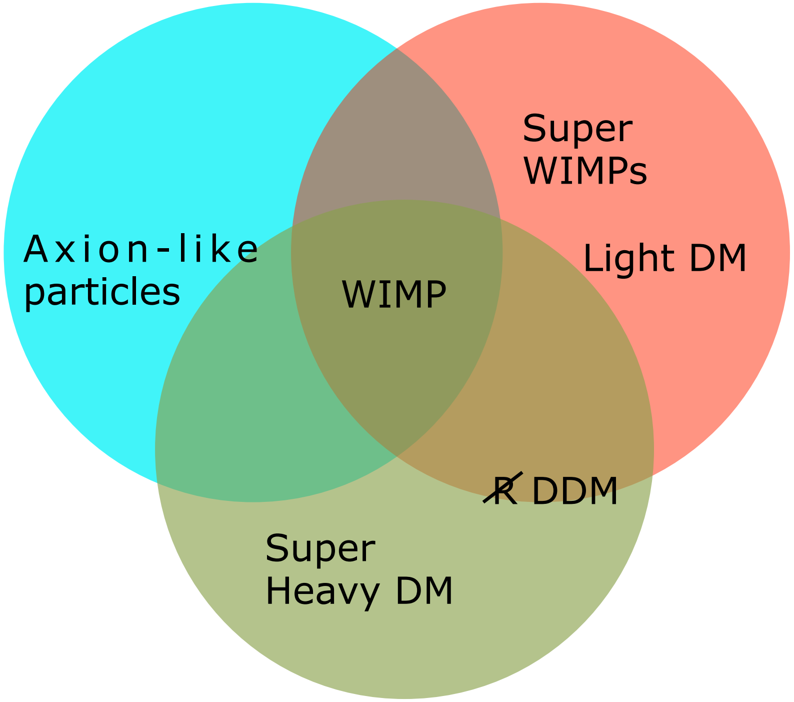
Good annihilation cross section. it is a WIMP

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

Dark matter can be searched for in different ways



Accelerator Searches (DM production) LHC (ILC)

Direct Detection

(DM-nuclei scattering)

DAMA/LIBRA
CDMS, SuperCDMS
XENON
KIMS
COUPP
PICASSO
ZEPLIN
CoGeNT
CRESST
SIMPLE
ZEPLIN
ANAIS
XMASS
...

Axion-like particles

WIMP

Super WIMPs

Light DM

$\not{R}$ DDM

Super Heavy DM

Indirect Detection

(DM annihilation)

PAMELA	ANTARES
Fermi	IceCube
MAGIC	CTA
AMS	...

probing different aspects of the DM interactions with ordinary matter

Accelerator Searches (DM production) LHC (ILC)

Direct Detection

(DM-nuclei scattering)

DAMA/LIBRA
CDMS, SuperCDMS
XENON
KIMS
COUPP
PICASSO
ZEPLIN
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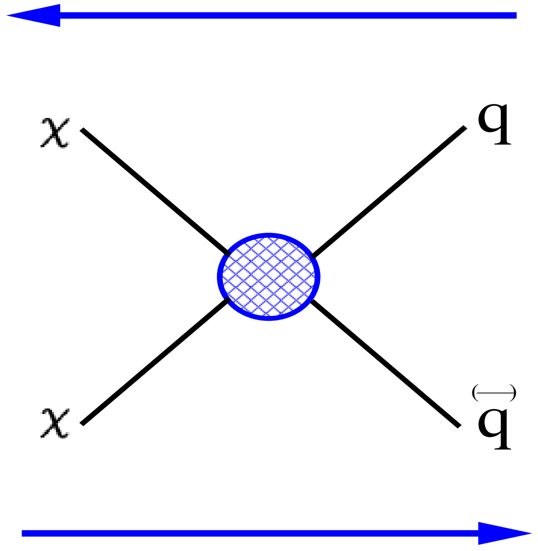
ZEPLIN
ANAIS
XMASS
...



Indirect Detection

(DM annihilation)

PAMELA
Fermi
MAGIC
AMS

ANTARES
IceCube
CTA
...

Many DM models can be probed by the different experimental techniques

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

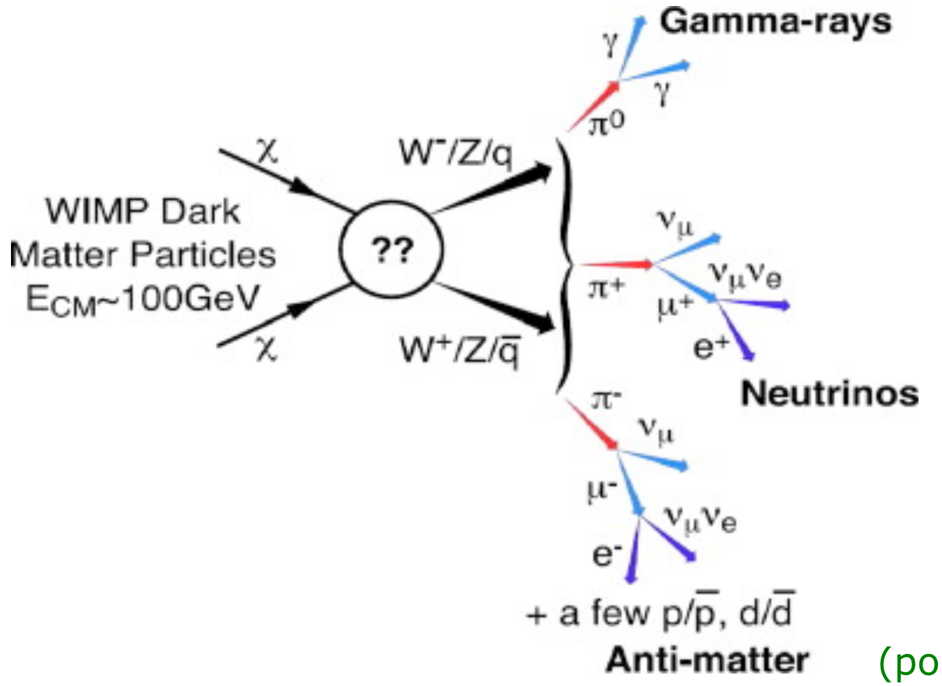
“Redundant” detection can be used to extract DM properties

COMPLEMENTARITY of DM searches

Indirect detection

Indirect detection, signals or backgrounds?

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



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

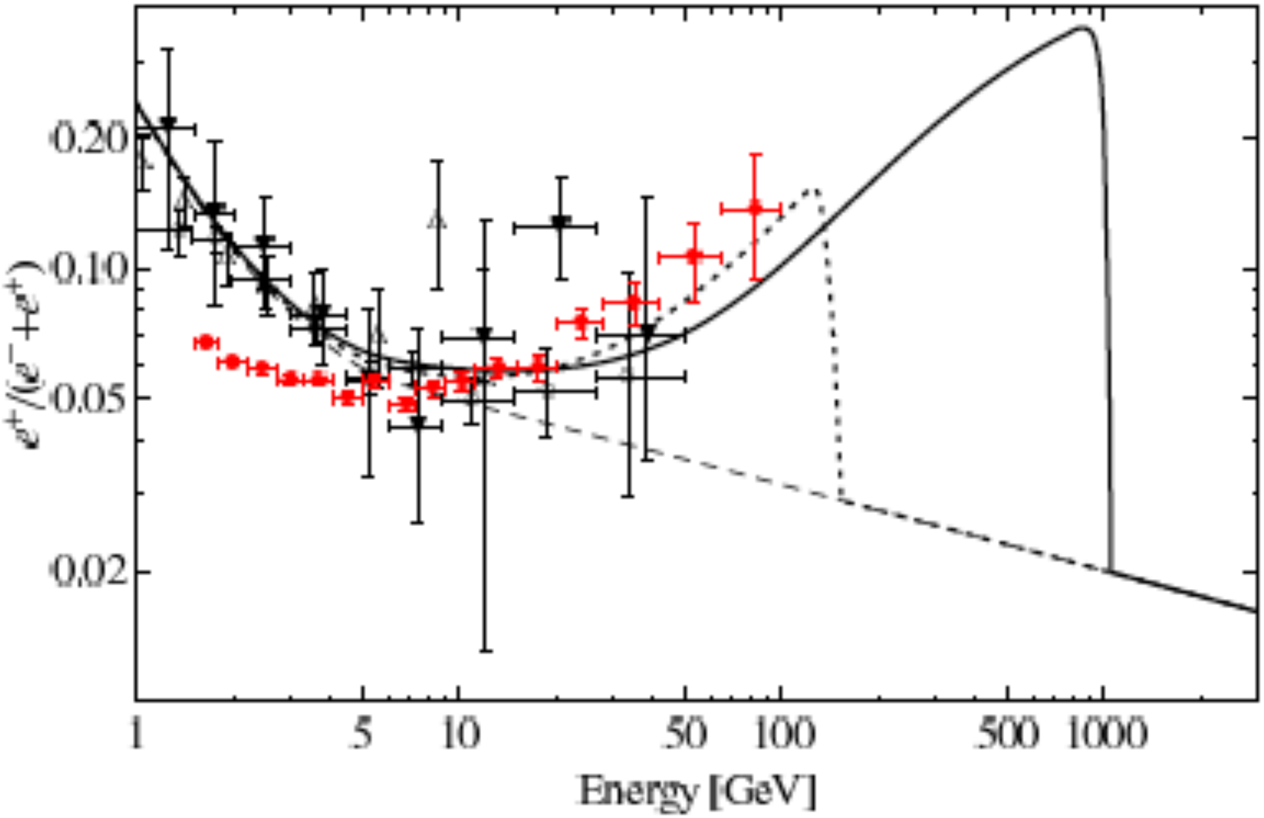
(from the centre of the Sun or the Earth)

(positrons, antiprotons, antideuterons)

Subject to large uncertainties and very dependent on the halo parameters

The antimatter puzzle...

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



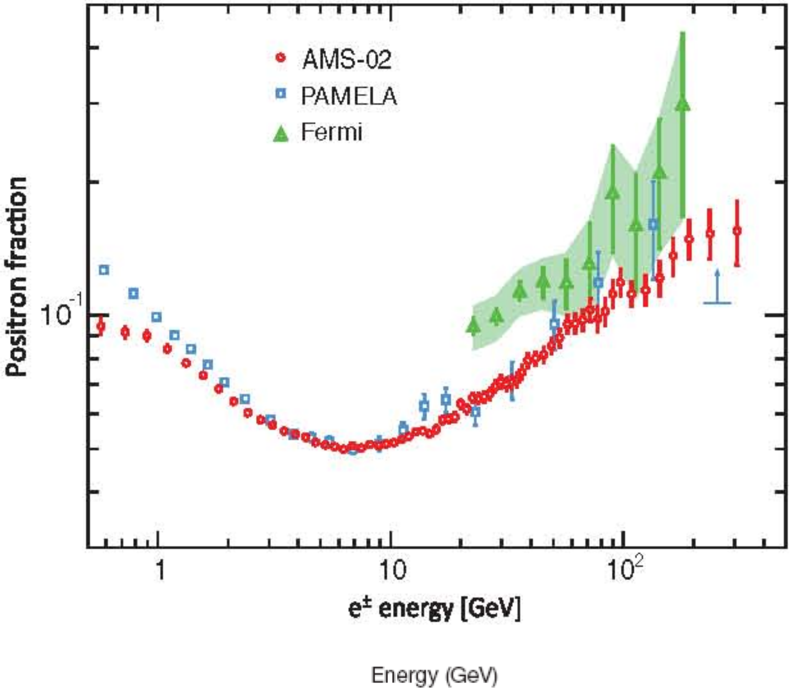
Is this an evidence of DM annihilation?

Even Decaying DM could account for it

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

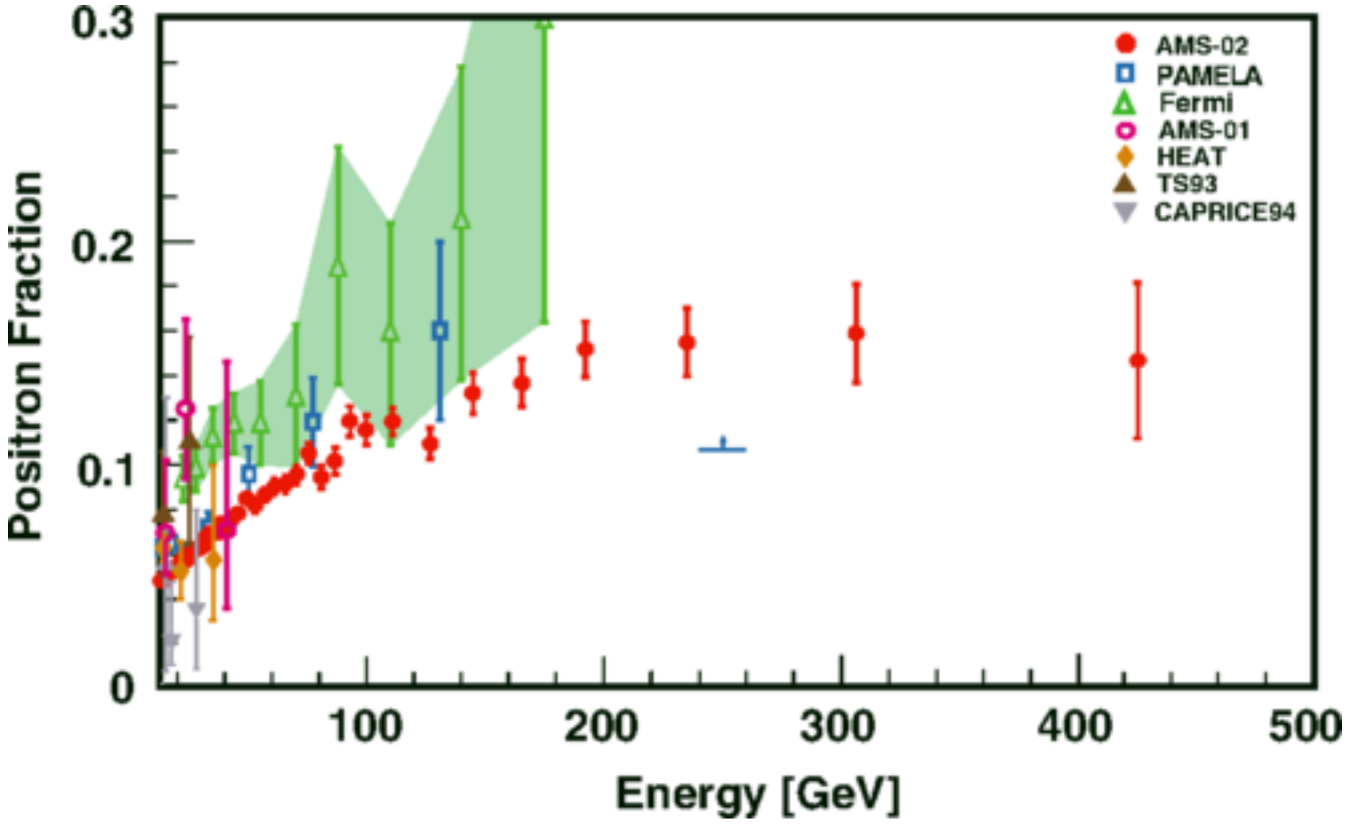
No evidence for associated gamma ray excess

- decaying dark matter

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

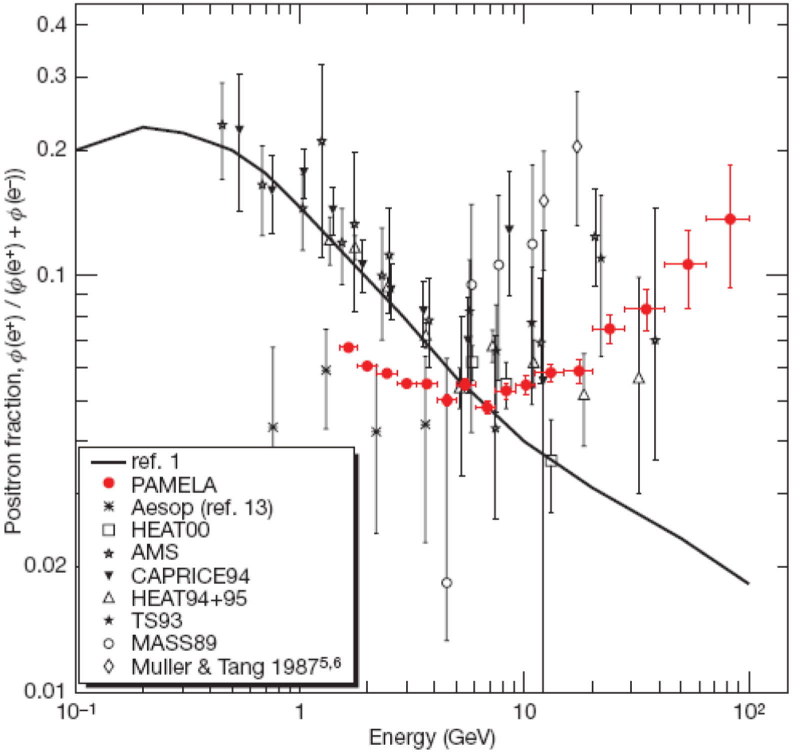
The antimatter puzzle...

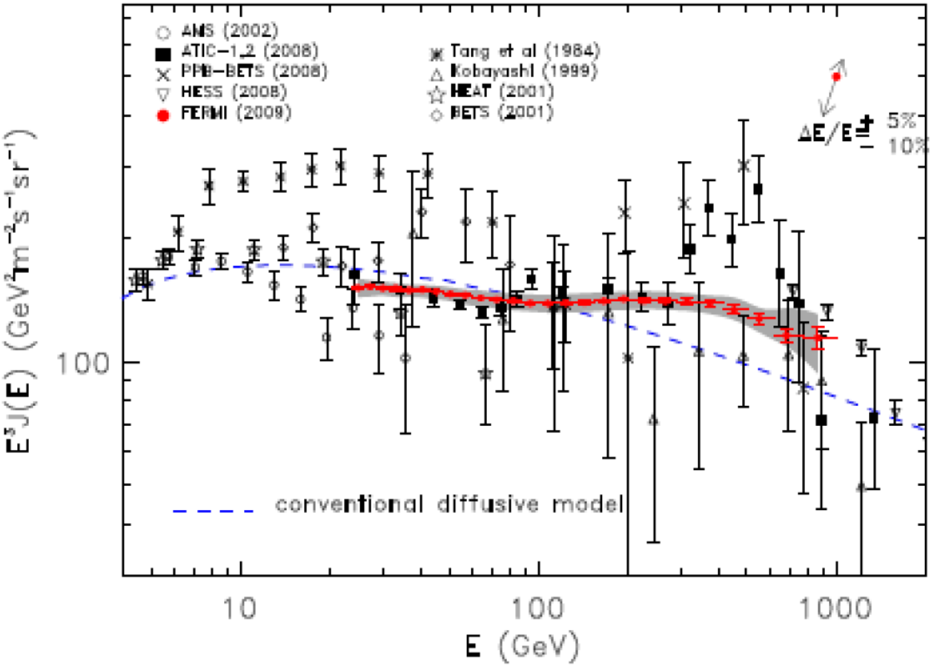
New AMS results up to 500 GeV shows a “plateau” (or is it starting to decrease??)



AMS 2014

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





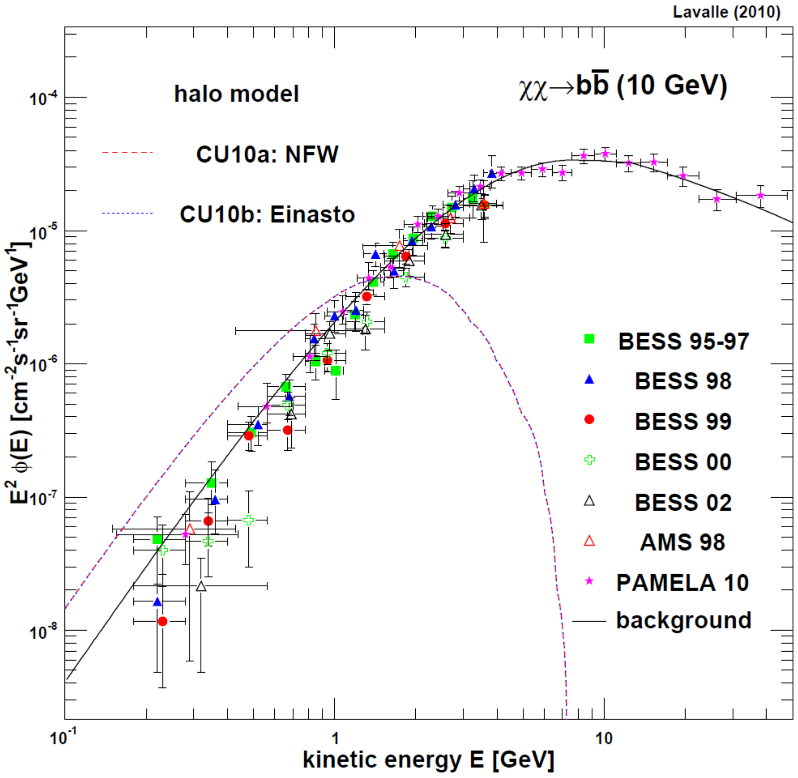
Astrophysical explanation in terms of pulsars is plausible.

See e.g., Delahaye et al. 2010

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?

DGC, Delahaye, Lavalle 2012

See also latest results by BESS-II

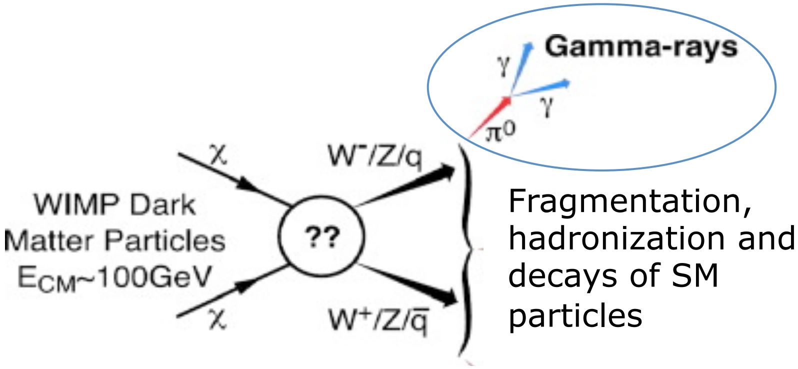
BESS-II '11

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

Donato et al. 2008
Salati, Donato, Fornengo 2010

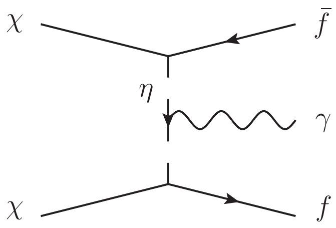
Gamma rays from DM annihilation

Continuum (secondary photons)

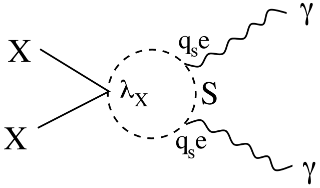


Fragmentation, hadronization and decays of SM particles

Direct gamma emission (features, lines)



Internal bremsstrahlung



Loop processes

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

Theoretical input

DM annihilation cross section IN THE HALO

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

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

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

Astrophysical input

DM Density profile

Region of observation (backgrounds)

Fermi-LAT can provide constraints for light WIMPs

Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT '11

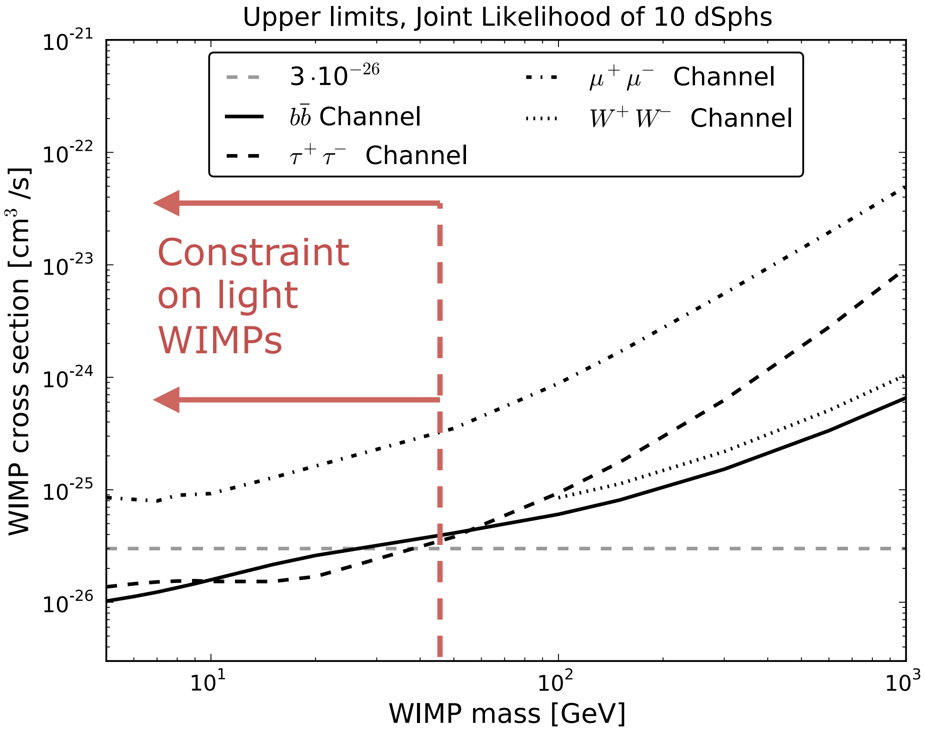
Thermal cross-section excluded for some channels (bb and ττ)

Upper bounds are normally expressed for "pure" annihilation channels.

m>27 GeV for the bb channel

m>37 GeV for the $\tau^+\tau^-$ channel

Fermi-LAT '11



Constraint on light WIMPs

Dwarf spheroidal galaxies are ideal objects to look for dark matter

- They are nearby
- Largely dark matter dominated systems
- Relatively free from gamma-ray emission from other astrophysical sources

Fermi-LAT can provide constraints for light WIMPs

Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT '11

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

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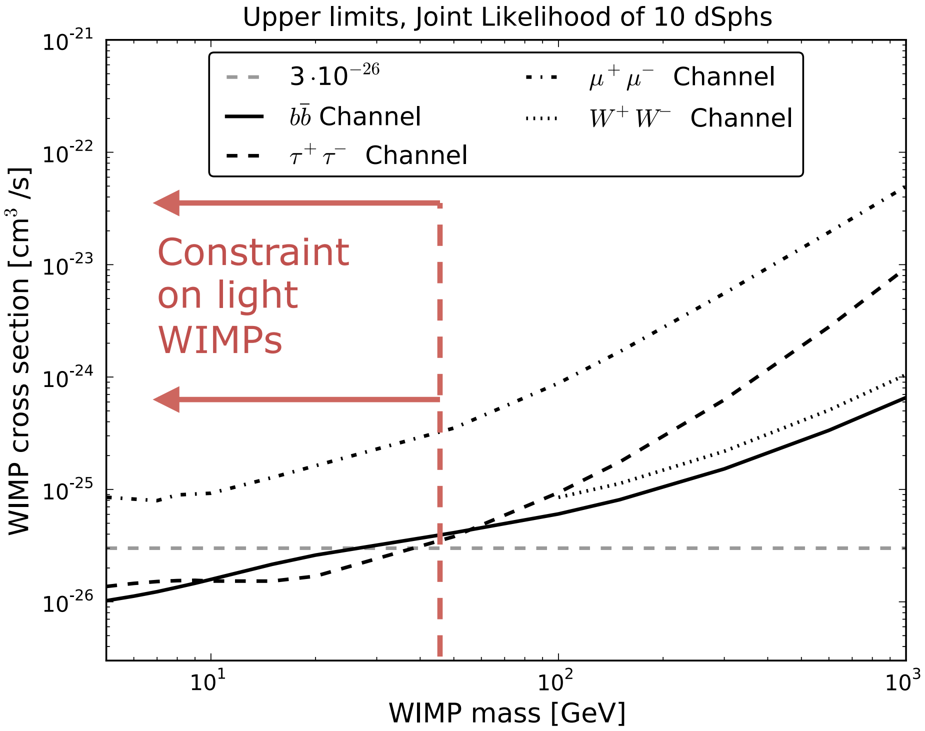
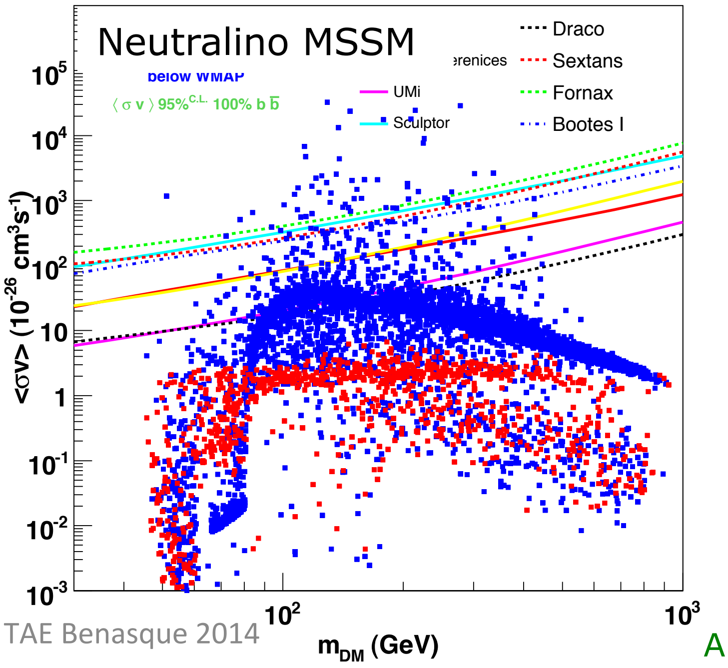
Fermi-LAT '11



Constraint on light WIMPs



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

Coannihilation effects,
velocity-dependent cross-section
resonances

Abdo et al. 1001.4531

No signal from GR in dwarf spheroidals

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

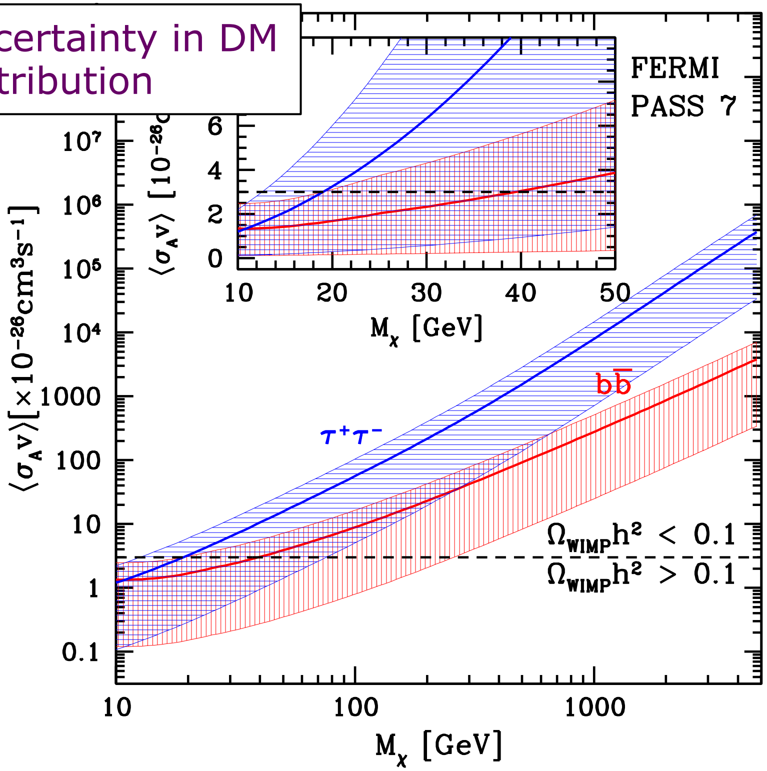
Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT '11

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

Bounds are normally expressed for "pure" annihilation channels.

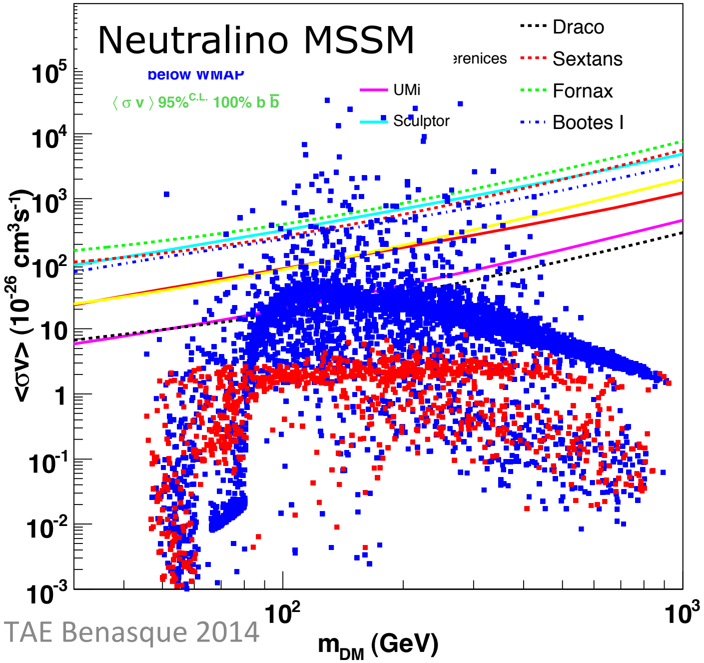
Uncertainty in DM distribution



Geringer-Sameth, Koushiappas '11

"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 with data from the Galactic Centre

Fermi-LAT observation of Dwarf Spheroidals

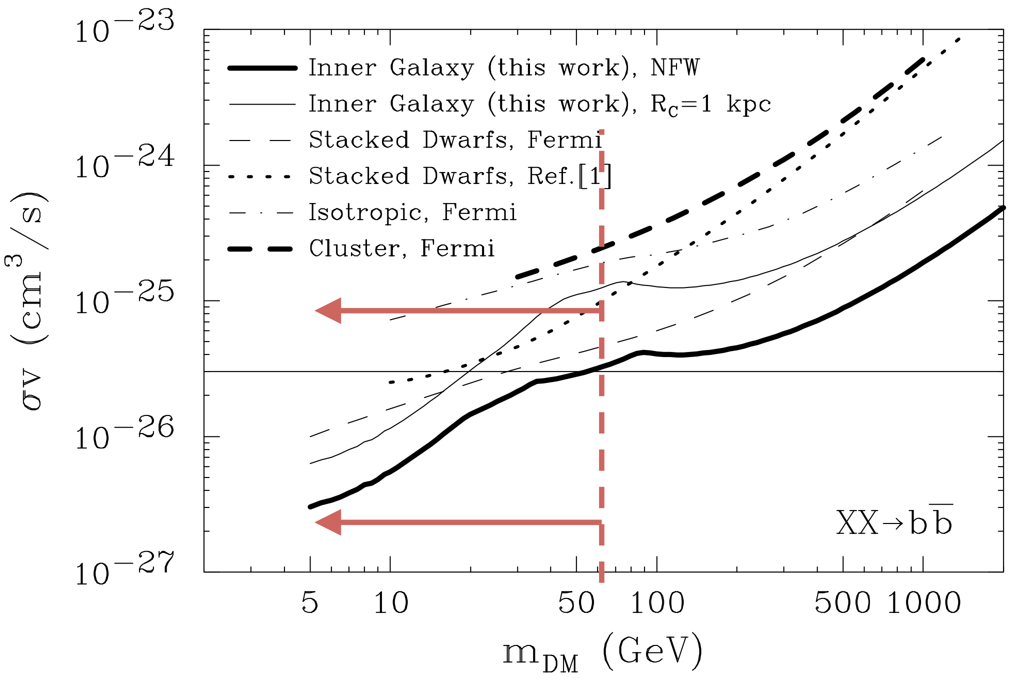
Fermi-LAT ‘11

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

Fermi-LAT data from GC

Similar bounds Hooper et al. `12

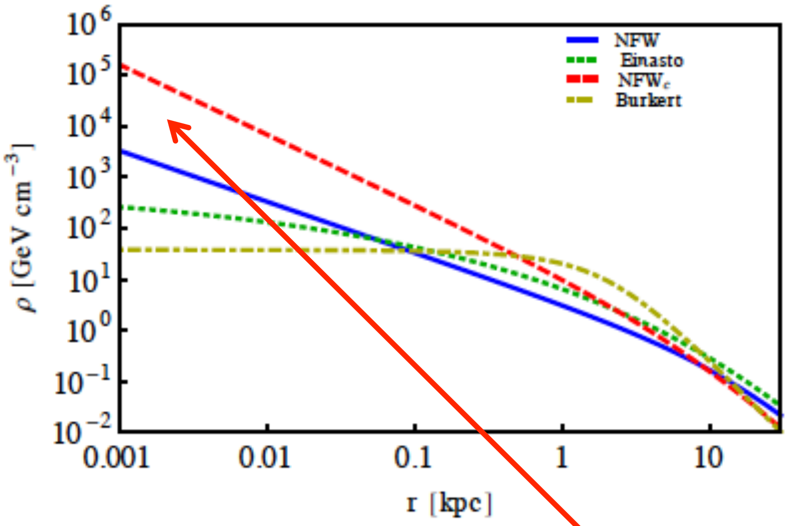
Using a model for the foreground emission to get rid of the astrophysical background.



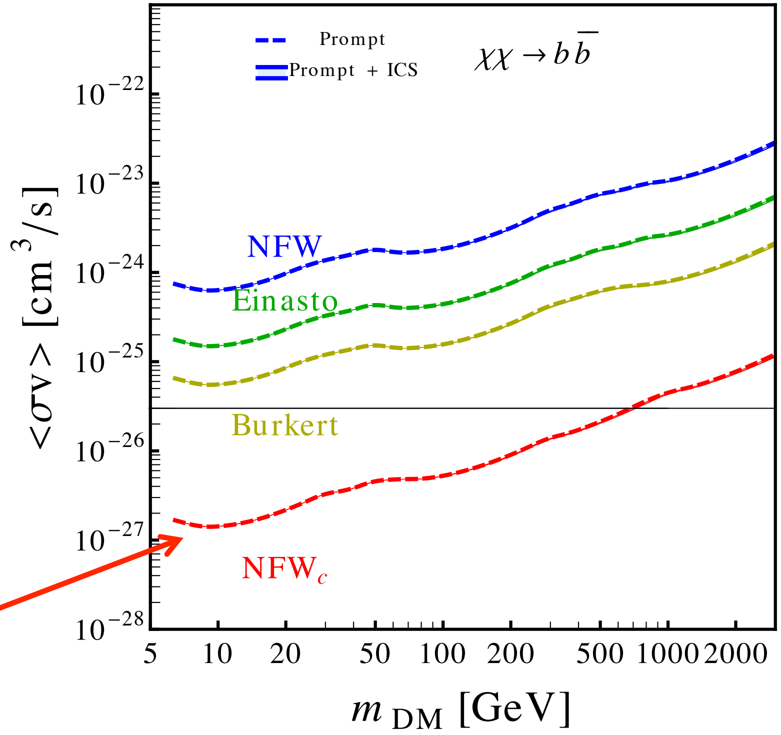
Hooper et al. `12

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

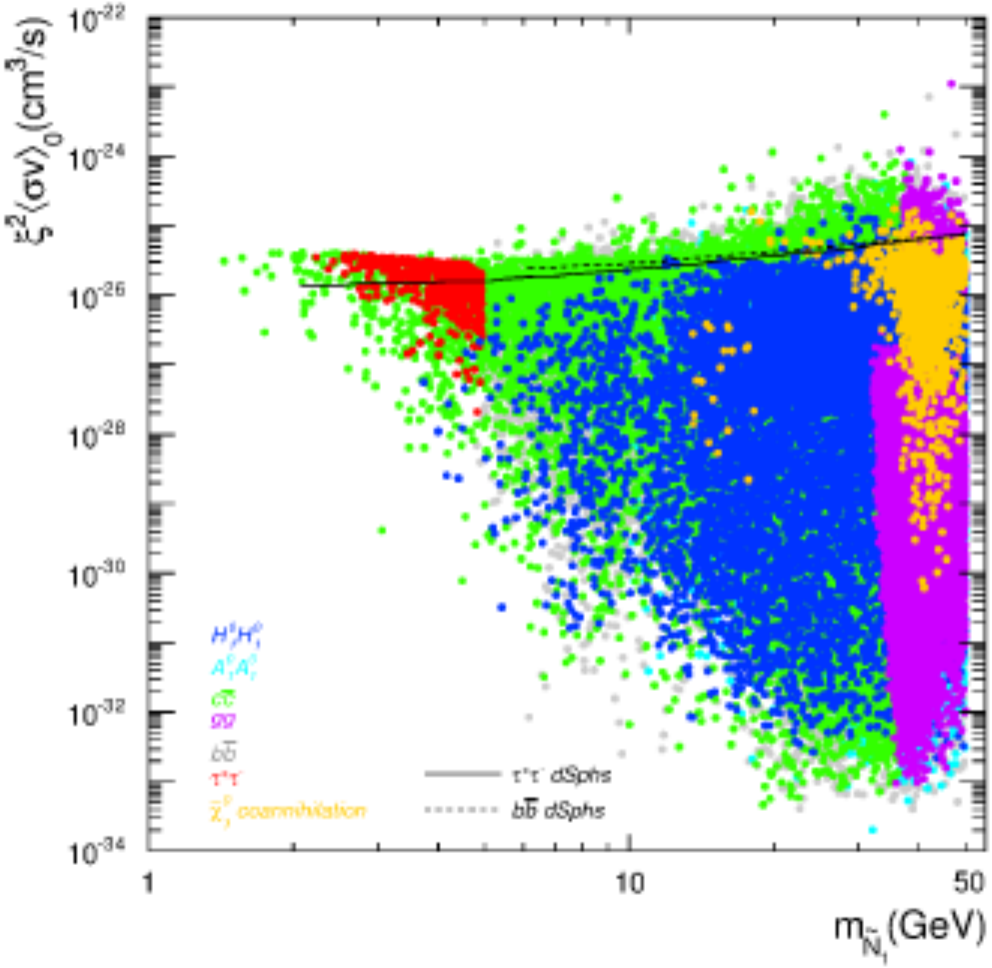


Very strong for COMPRESSED haloes

These bounds are enough to start constraining the parameter space of some very light WIMP models

RH-sneutrino in the NMSSM

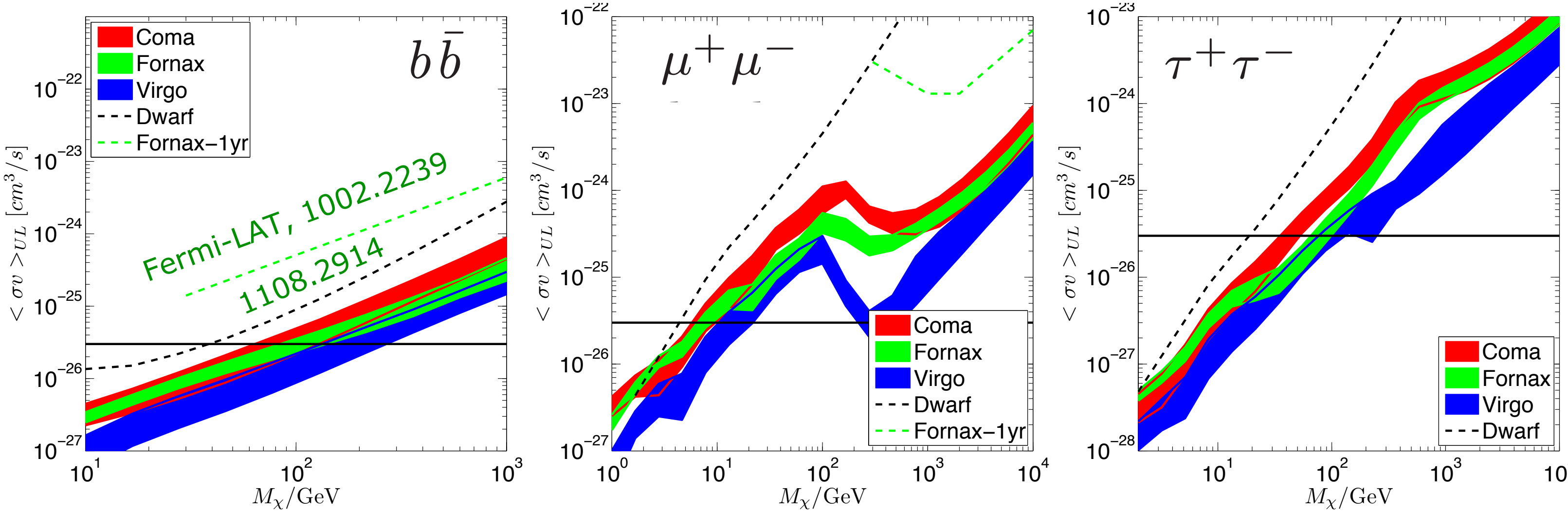
Different colours represent different dominant annihilation channels



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

$$b(M_{200}) = \mathcal{J}_{sub}/\mathcal{J}_{NFW} = 1.6\times10^{-3}(M_{200}/\mathrm{M}_\odot)^{0.39}$$

Gao et al., 1107.1916

A sharp feature in the gamma ray spectrum?

Difficult to attribute to astrophysical background (*)

Gamma-ray line emission (130 GeV)

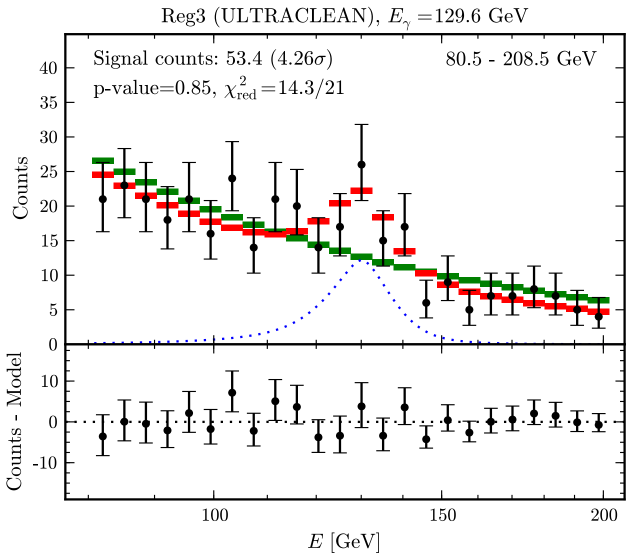
Weniger 1204.2797

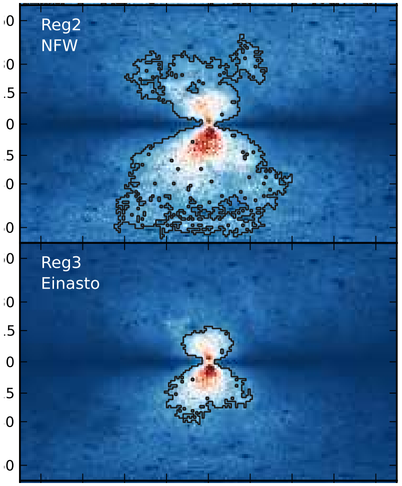
$$E_\gamma = m_\chi \left(1 - \frac{m_P^2}{4m_\chi^2}\right)$$

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

145 GeV WIMP annihil. into γZ^0

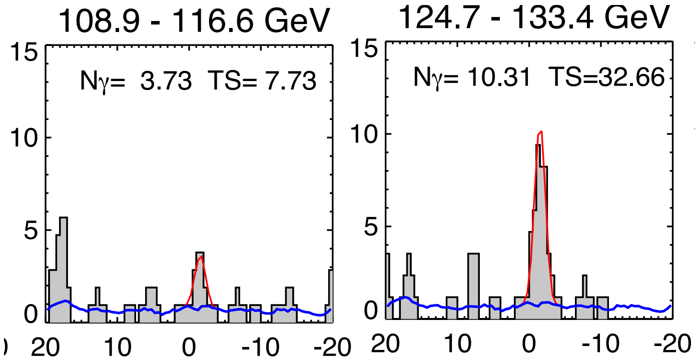
155 GeV WIMP annihil. into $H\gamma$





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.
Power-law fit of the background?

Instrumental effect? (Earth's limb...)

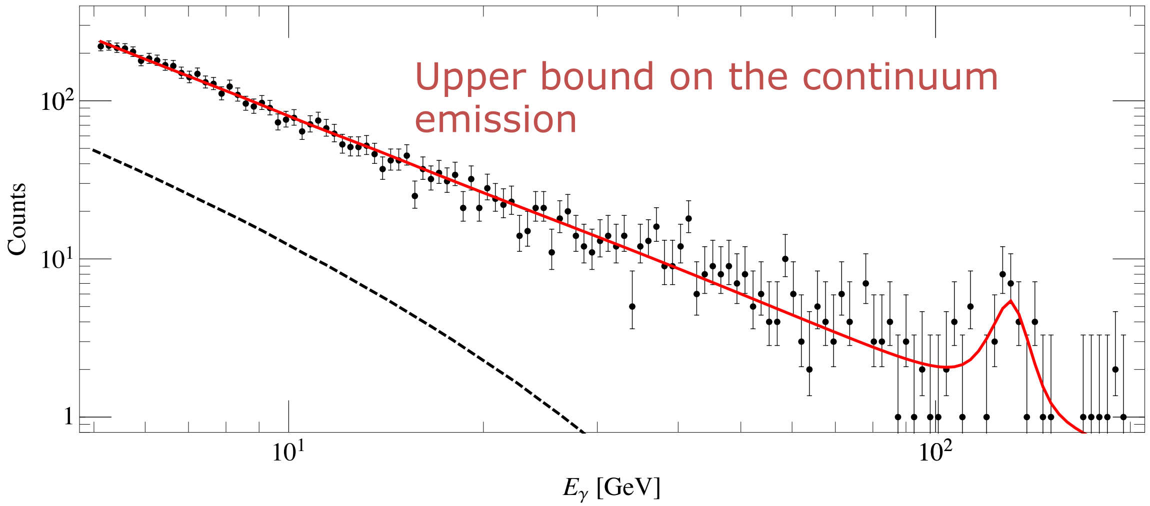
How to explain this with particle DM models?

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

Relatively common channel (at 1 loop)

However, the line emission is very intense

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



Upper bound on the continuum emission

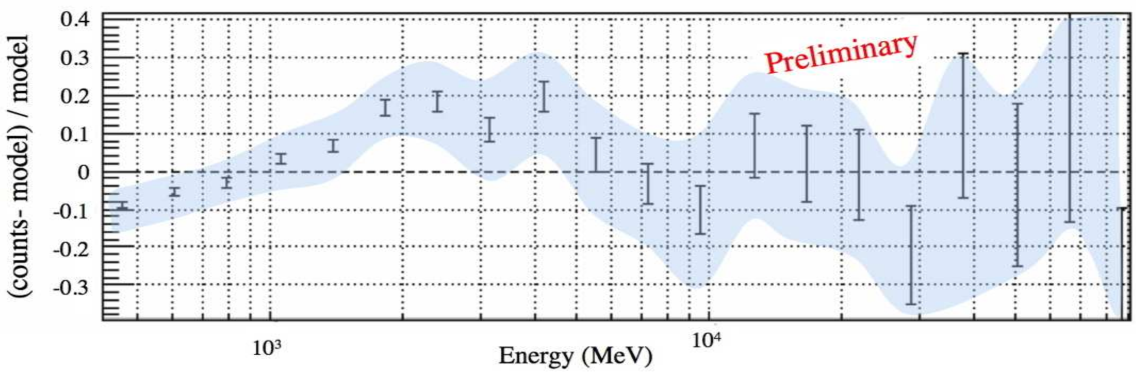
Cohen et al. 1207.0800

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

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

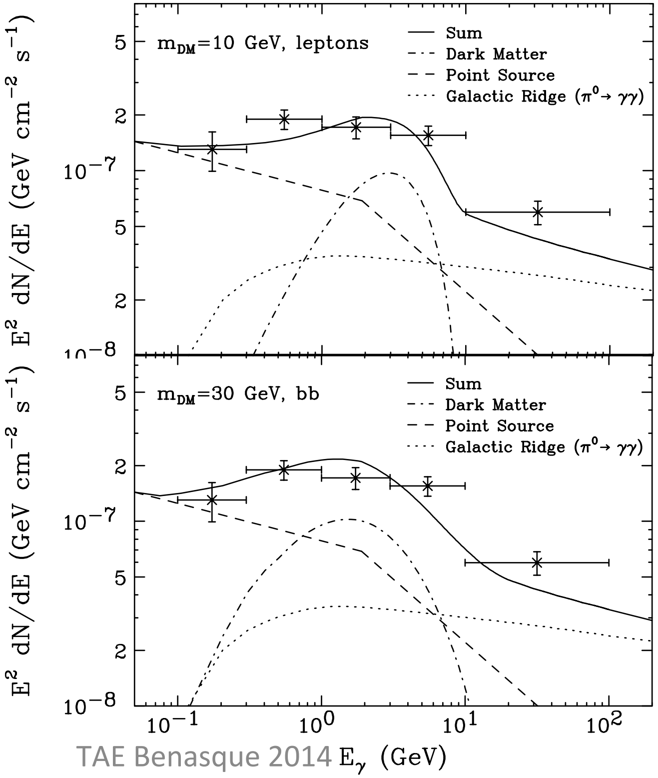
Currently looking for models with “enhanced gamma-lines”

Gamma rays form the Galactic centre also show a "feature" at low energies



If interpreted in terms of WIMPs, it favours light dark matter with an annihilation cross section not far from "thermal"

Cañadas, Morselli, Vitale 2010



$$\sigma v = 7 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$$

Hooper, Goodenough 2010
Hooper, Linden 2011

But there are other possible explanations:

- Consistency of the excess with a millisecond pulsar population

  Abazajian 1011.4275

- Cosmic-ray effects

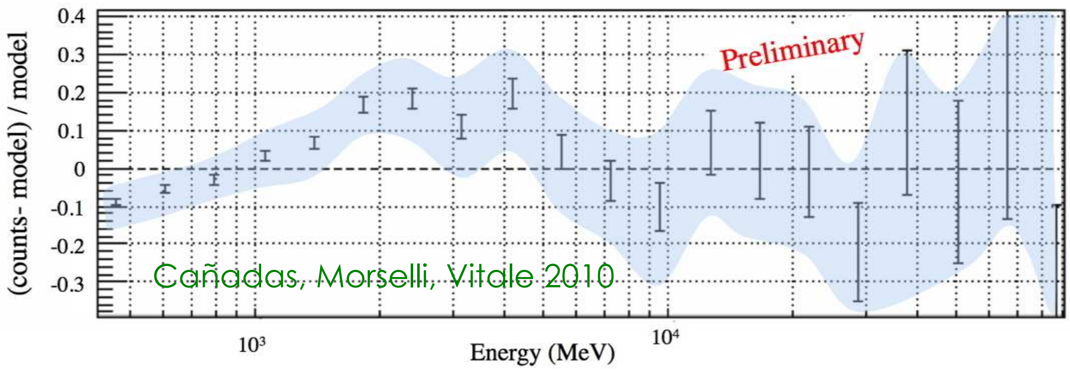
  Chernyakova 1009.2630

- Different spectrum of the point source at the galactic center,

  Boyarsky, Malyshev, Ruchayskiy, 1012.5839

There can also be surprises in Fermi LAT data at low energy

An excess at low masses?



Cañadas, Morselli, Vitale 2010

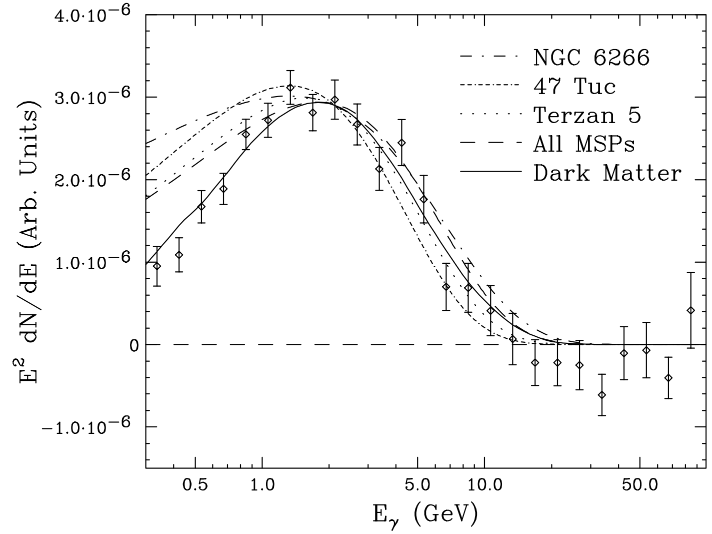
Compatible with the annihilation of a light WIMP ~10 GeV

Hooper, Goodenough 2010
Hooper, Linden 2011

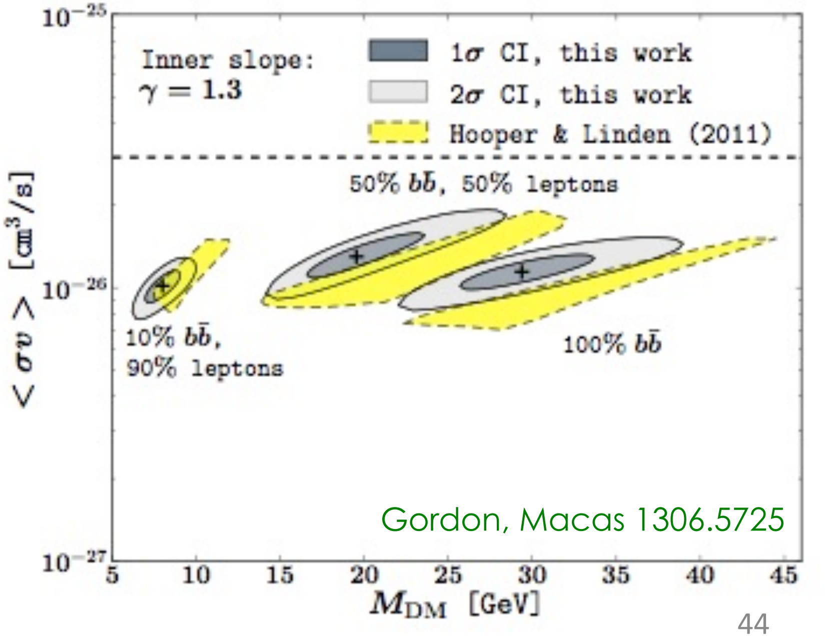
or due to millisecond pulsars, cosmic ray effects or different spectrum at galactic centre.

Abazajian 1011.4275
Chernyakova 1009.2630
Boyarsky, Malyshev, Ruchayskiy, 1012.5839

Millisecond pulsars seem to produce a softer spectrum...



Daylan et al. 1402.6703



Gordon, Macas 1306.5725

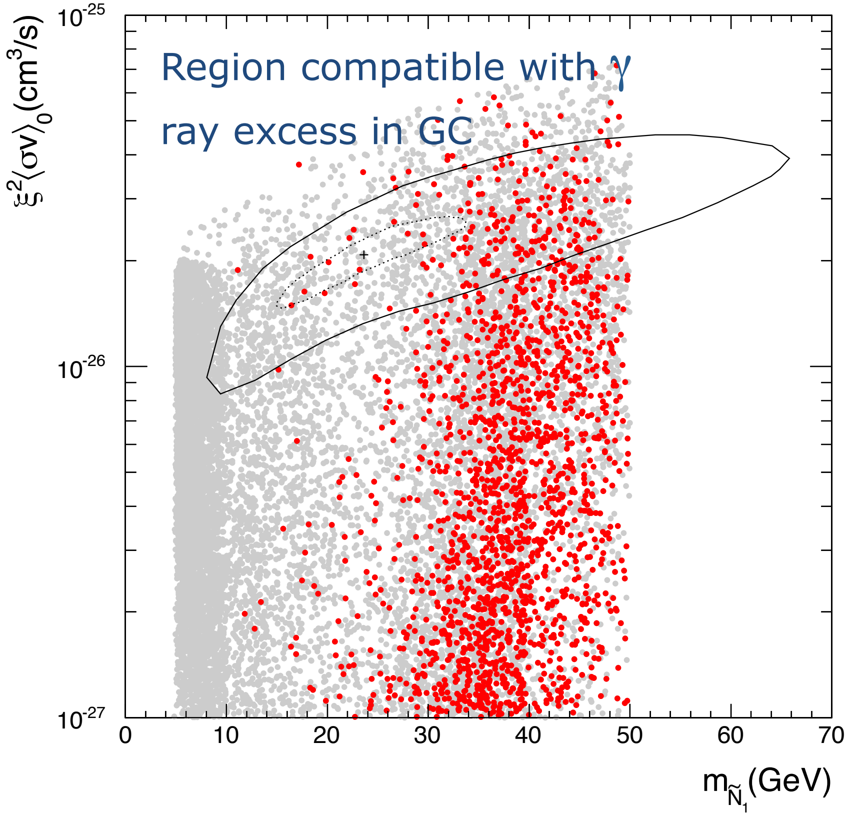
Predictions for indirect detection (gamma-ray searches)

For subdominant DM we assume that the DM haloes preserve the ratio in its abundance

$$\xi = \min[1, \Omega_{\tilde{N}_1} h^2/0.13]$$

Excludes some points for low mass (especially in tau channels)

Some examples could account for the excess in gamma ray in the GC



$m_{\tilde{N}_1}$(GeV)	$\xi^2\langle\sigma v\rangle_0(\mathrm{cm}^3/\mathrm{s})$	$\%b\bar{b}$	$\%\tau^+\tau^-$	$\%c\bar{c}$	$\%gg$	$\xi\sigma^{SI}_{\tilde{N}_1 p}$(pb)
23.60*	2.10×10^{-26}	79.76	6.65	9.20	4.22	6.69×10^{-10}
27.35	1.72×10^{-26}	66.26	4.88	1.86	9.91	5.91×10^{-11}
35.62**	1.71×10^{-26}	90.54	7.70	0.47	1.22	1.05×10^{-10}

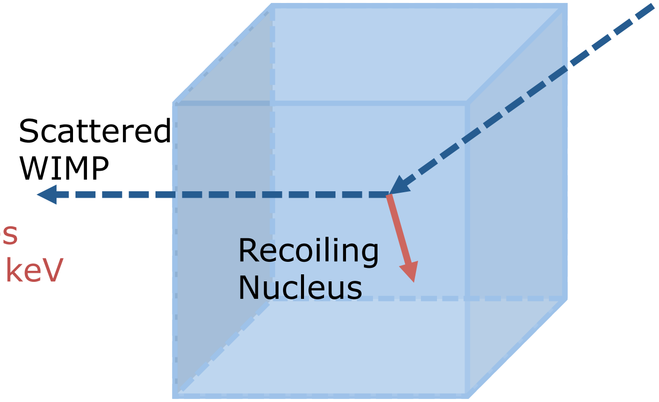

COFFEE
BREAK

Direct Detection of Dark Matter

Direct DM detection, where do we stand?

WIMP scattering with nuclei can be measured through

- Ionization
- Scintillation
- Phonons
- Bubble nucleation



For a 100 GeV WIMP, this implies recoil energies of order $E_R \sim 10$ keV

Detection rate

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

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)

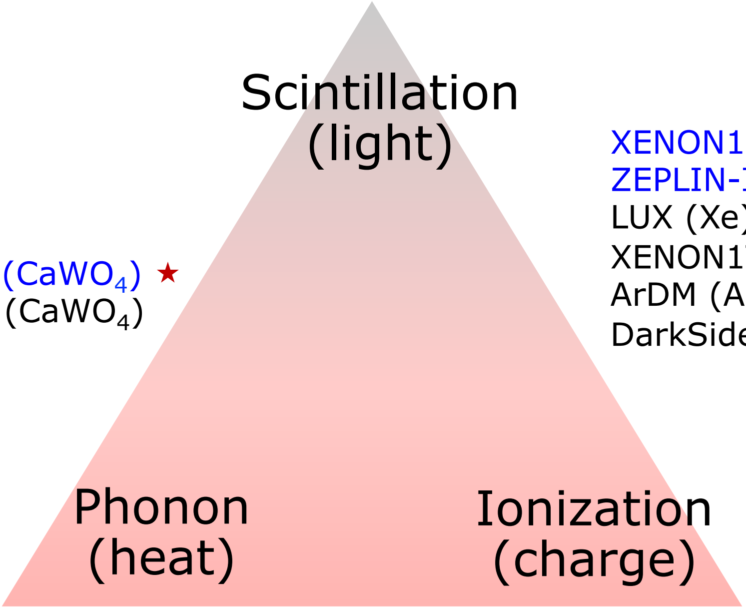
Only present for nuclei with J≠ 0 and WIMPs with spin

The combination of signals is used to discriminate backgrounds

DAMA/LIBRA (NaI) ★
KIMS (CsI)
XMASS (Xe)
ANAIS (NaI)
DM-Ice (NaI)
DEAP3600 (Ar)
MiniCLEAN (Ar)

Superheated liquids (bubble)

PICASSO (C_4F_{10})
SIMPLE (C_2ClF_5)
COUPP (CF_3I)



XENON100 (Xe)
ZEPLIN-III (Xe)
LUX (Xe)
XENON1T (Xe)
ArDM (Ar)
DarkSide (Ar)

CRESST ($CaWO_4$) ★
EURECA ($CaWO_4$)

CUORE (TeO_2)

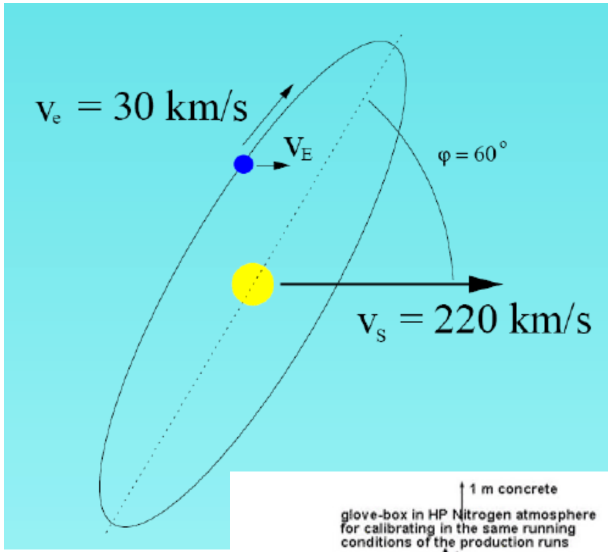
CDMS (Ge, Si★)
EDELWEISS-II (Ge)
SuperCDMS (Ge)
EURECA (Ge)

CoGeNT (Ge) ★
TEXONO-CDEX (Ge)
C-4 (Ge)
DRIFT (CS_2)
DM-TPC (CF_4)
NEWAGE (CF_4)
MIMAC ($^3He/CF_4$)
MAJORANA (Ge)
GERDA (Ge)

Present
Future
★ DM hints

From the thesis of Clara Cuesta Soria

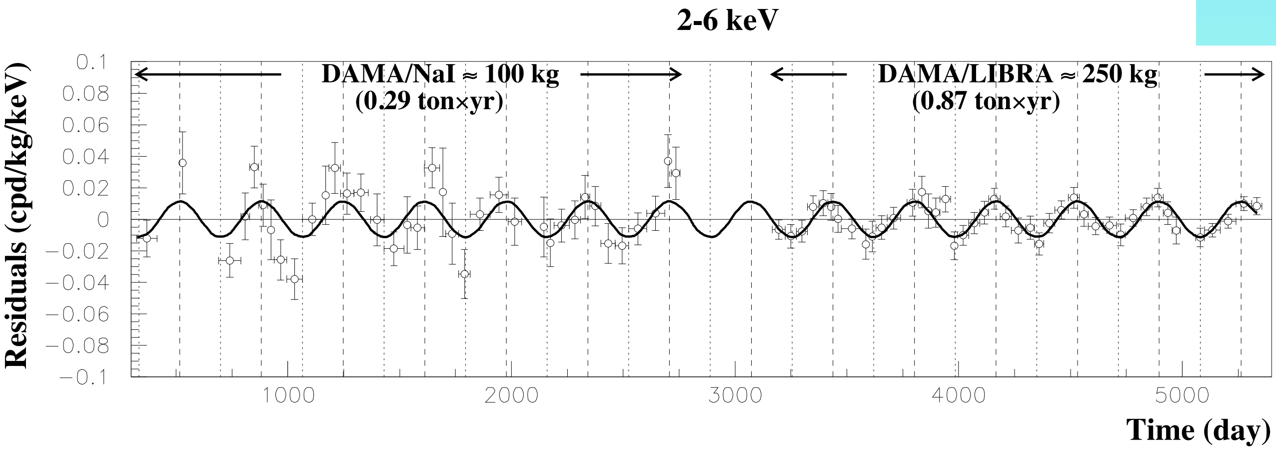
DAMA (DAMA/LIBRA) signal on annual modulation

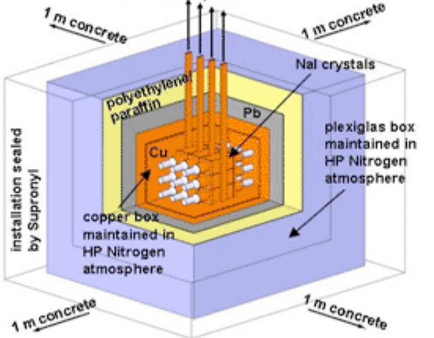


cumulative exposure 427,000 kg x day
(13 annual cycles)

DAMA/LIBRA Coll. '10

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \approx \left(\frac{\mathrm{d}\bar{R}}{\mathrm{d}E_R}\right)[1+\Delta(E_R)\cos\alpha(t)]$$





Simplified schema of ~ 100 kg NaI(Tl) set-up

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

Direct DM detection, where do we stand?

DAMA (DAMA/LIBRA) signal on annual modulation

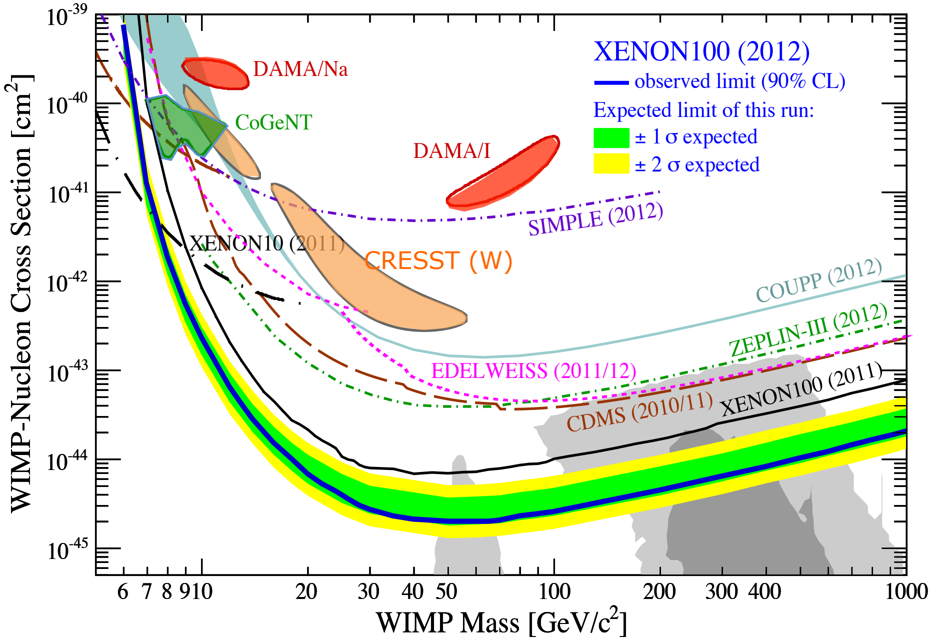
cumulative exposure 427,000 kg x day (13 annual cycles)

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
- Isospin Violating DM



Freese, Lisanti, Savage '12

More hints for very light WIMPs...?

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

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

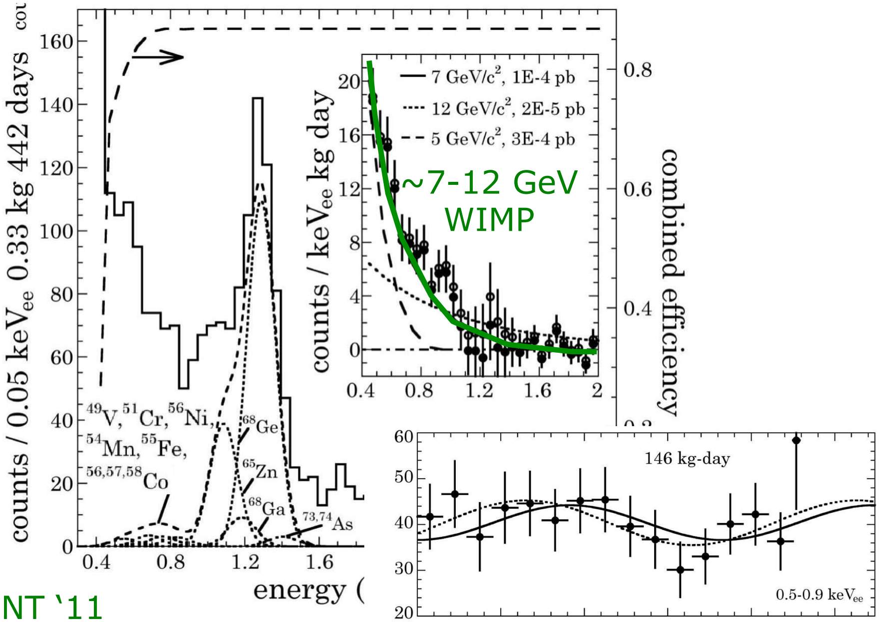
- CoGeNT (Ge) finds irreducible background that can be compatible with 7-12 GeV WIMPs

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

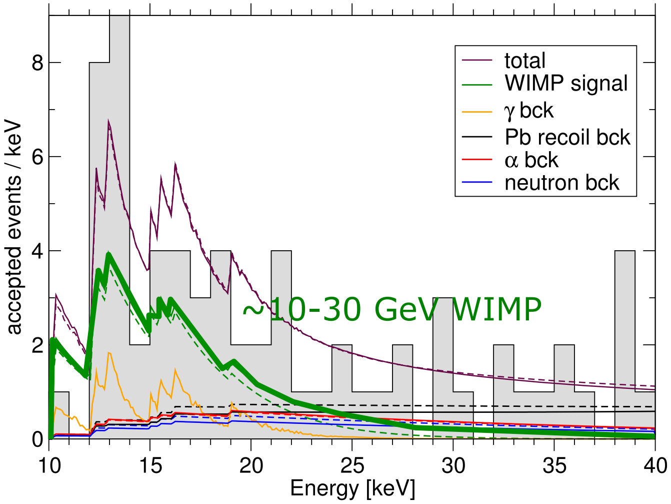
Collar et al. ‘10, ‘11

- CRESST II (CaWO$_4$) (730 kg day) finds a significant excess over the expected background

Angloher et al. ‘11



CoGeNT ‘11



CRESST-II ‘11

More hints for very light WIMPs...?

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

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

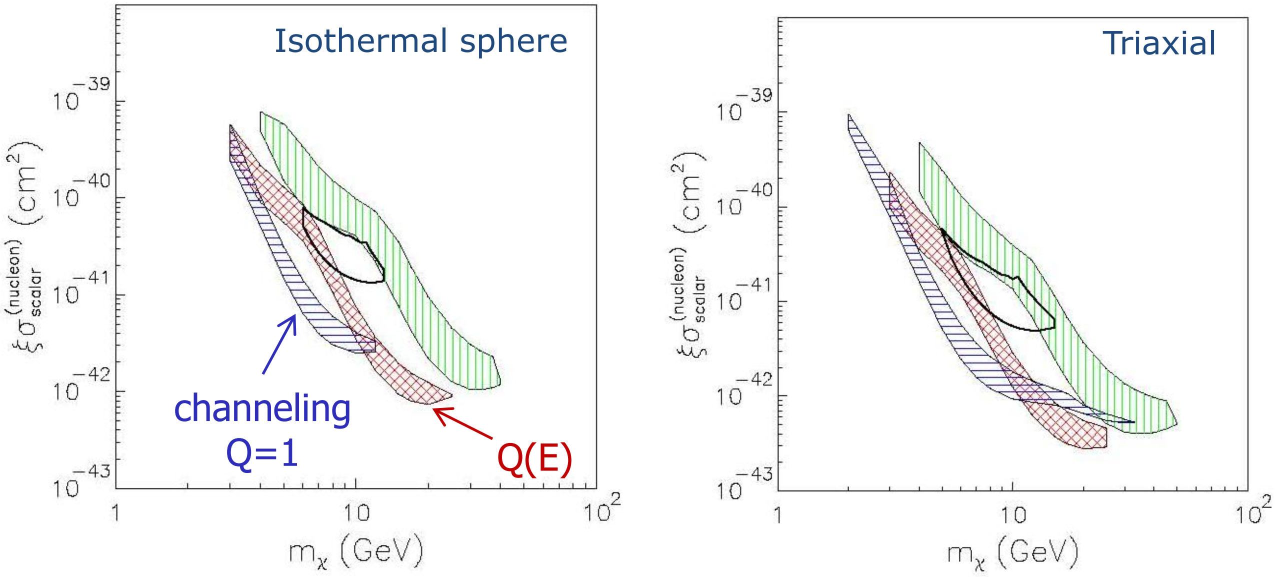
- CoGeNT (Ge) finds irreducible background that can be compatible with 7-10 GeV WIMPs

... 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

However very light WIMPs did not show up in other experiments

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

XENON10, XENON100 '11-12

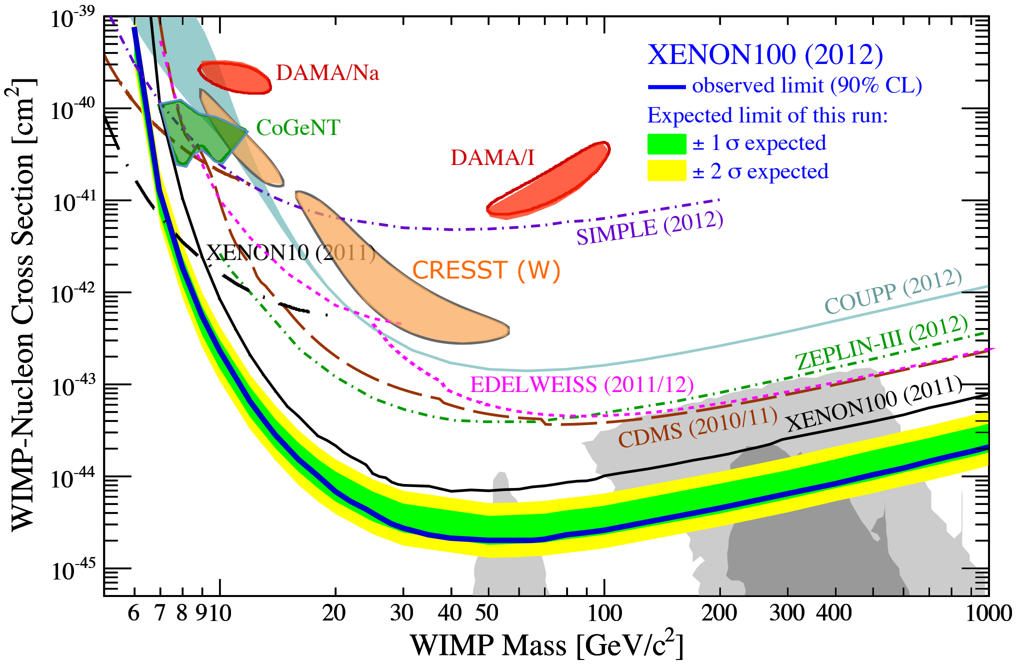
- CDMS II: A low-energy reanalysis of the data is incompatible with CoGeNT region

CDMS '11

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

SIMPLE '11-12

XENON 2012 (224.6 live days)



- DAMA-LIBRA interpretation in terms of channelling is challenged

Gelmini, Gondolo, Bozorgnia, '09 '10

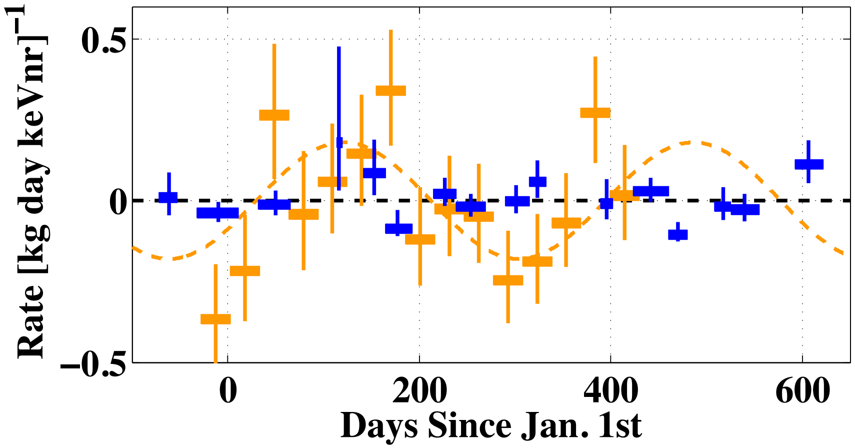
- CRESST: backgrounds from ^{210}Po underestimated?

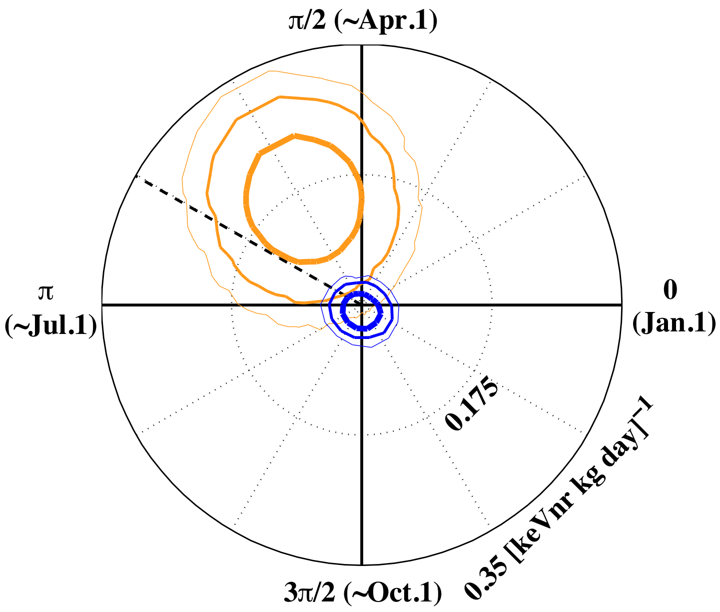
Kuzniak, Boulay, Pollmann '12

CDMS did not see annual modulation

An analysis of CDMS II (Ge) data has shown no evidence of modulation.

This means a further constraint on CoGeNT claims



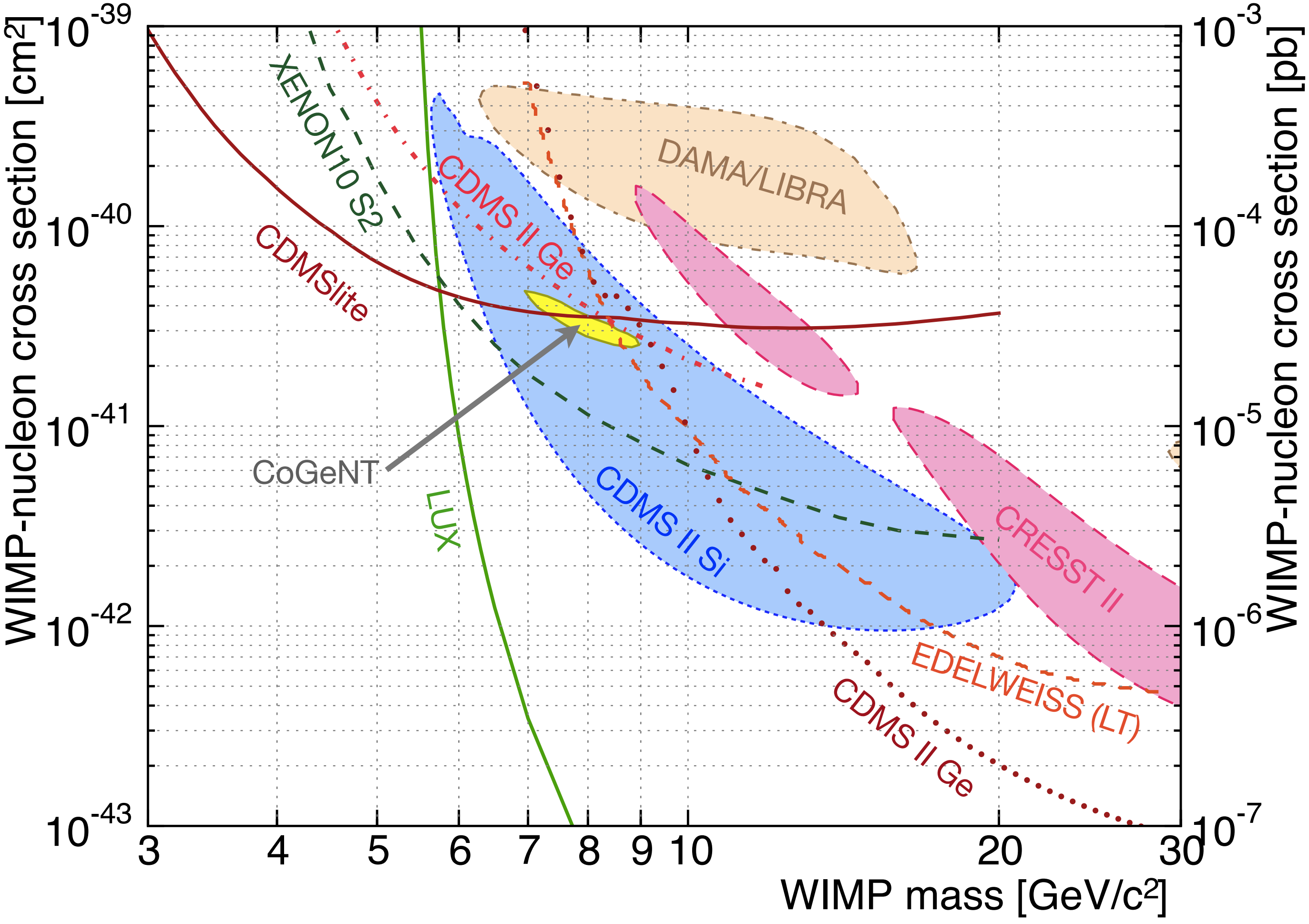


CDMS II 2012

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

Collar in IDM 2012

The light DM puzzle

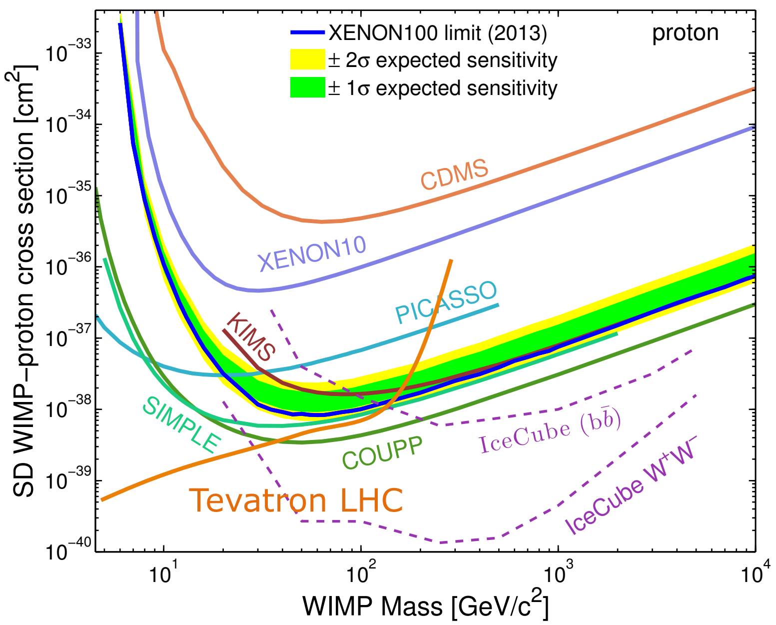


CDMS II Si: Phys.Rev.Lett. 111 (2013) 251301
CDMSlite: Phys.Rev.Lett. 112 (2014) 041302

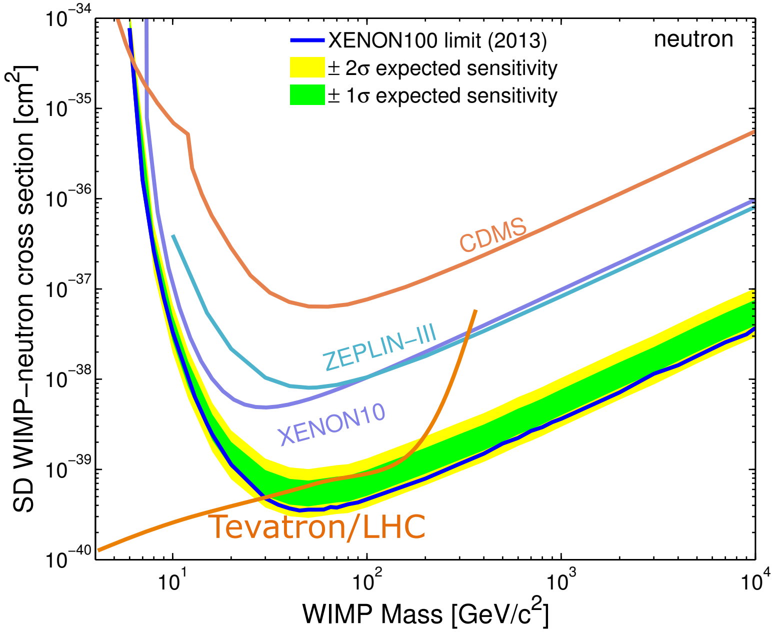
Spin-dependent searches have also become more sensitive

Although they do not impose yet strong constraints on DM models

SD coupling to protons



SD coupling to neutrons

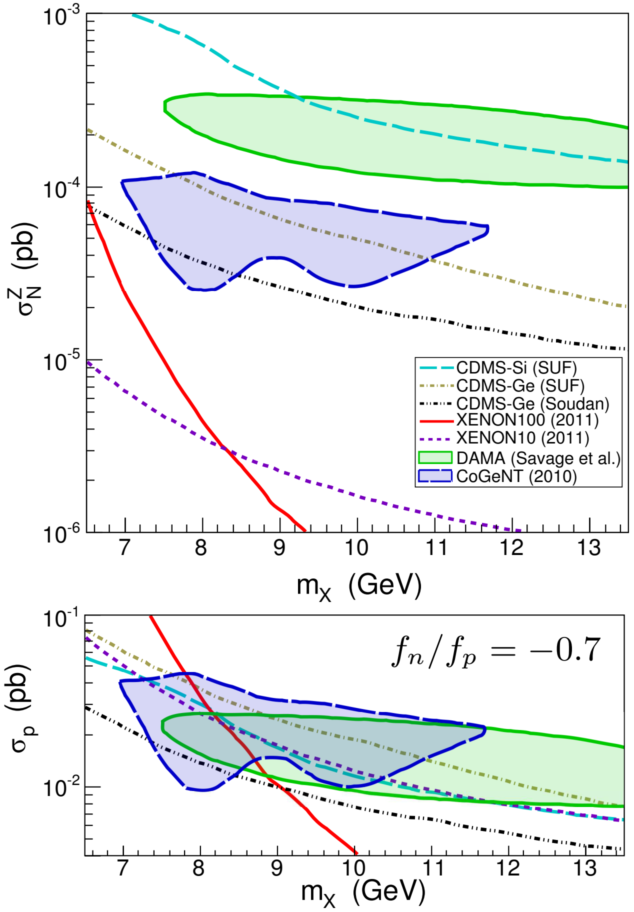


Currently we have also understood how nuclear uncertainties in the form factors affect these constraints

CDGC, Fornasa, Huh, Peiró 2012
Cannoni 2013

Isospin-Violating Dark Matter

Feng, Kumar, Marfatia, Sanford 2011

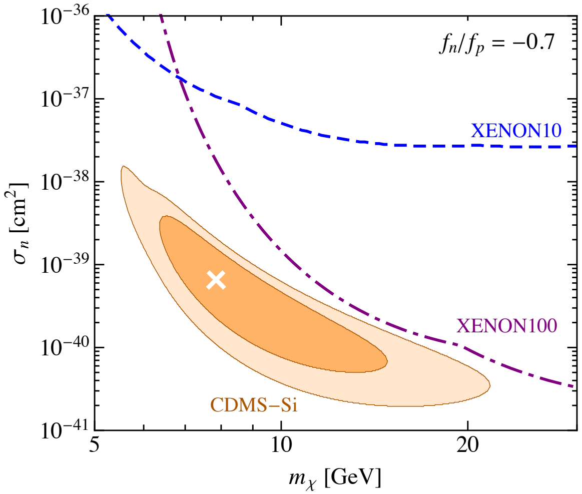


$$R = \sigma_p \sum_i \eta_i \frac{\mu^2_{A_i}}{\mu^2_p} I_{A_i} \left[Z + (A_i - Z) f_n/f_p\right]^2$$

The scattering amplitudes for proton and neutrons may interfere destructively

Complete destructive interaction $\quad f_n/f_p = -Z/(A-Z) \quad$ Target dependent

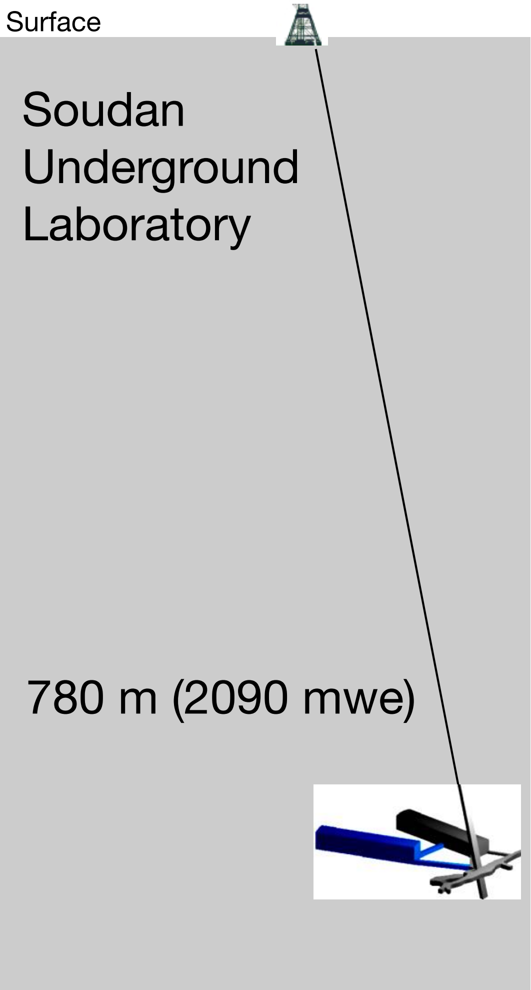
For Xe (Z=54, A~130) → $f_n/f_p = -0.7$



Frandsen et al. 2013

XENON100 (Xe) and CDMS II (Si) results can be “reconciled”

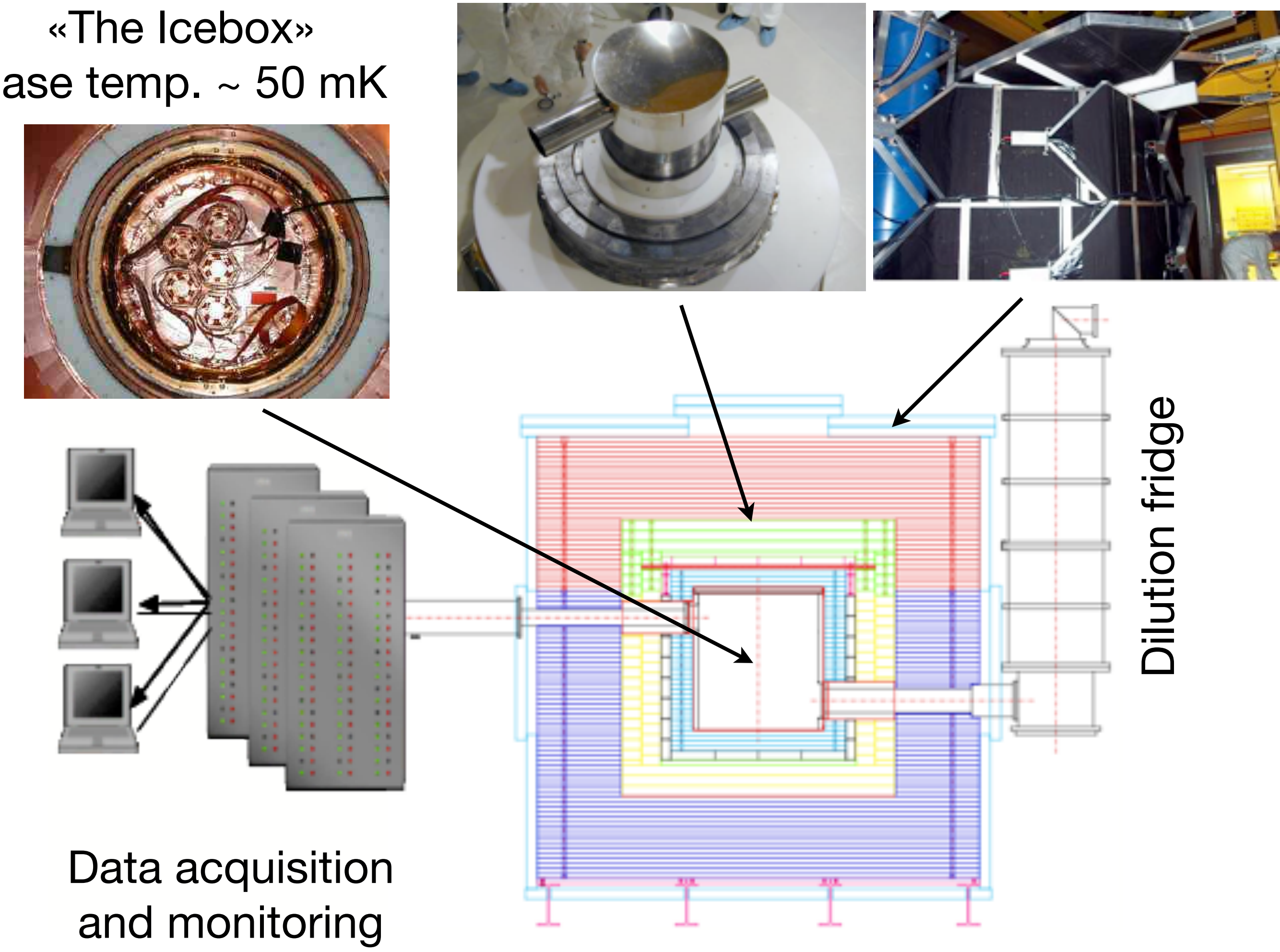
The experimental setup



Surface

Soudan Underground Laboratory

780 m (2090 mwe)



«The Icebox»
base temp. ~ 50 mK

Poly and lead shielding

Muon veto

Dilution fridge

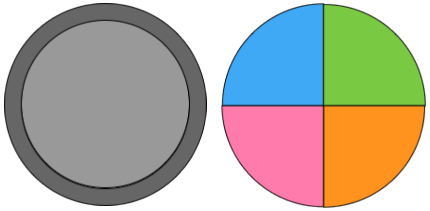
Data acquisition and monitoring

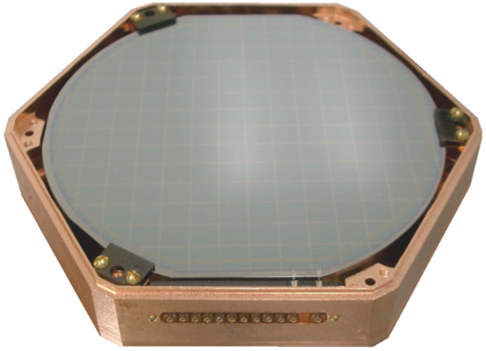
CDMS II

4.6 kg Ge (19 x 240 g)
1.2 kg Si (11 x 106g)

3" Diameter
1 cm Thick

2 charge + 4 phonon



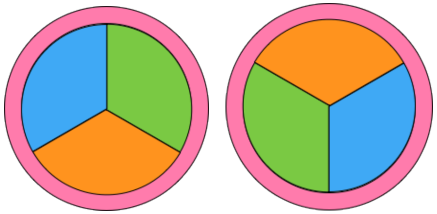


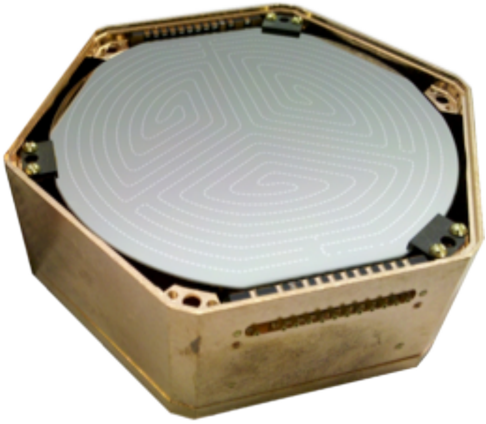
SuperCDMS Soudan

9.0 kg Ge (15 x 600g)

3" Diameter
2.5 cm Thick

2 charge + 2 charge
4 phonon + 4 phonon



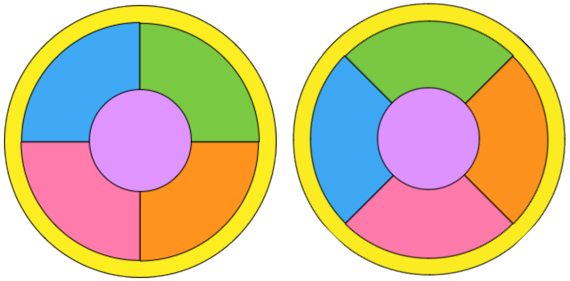


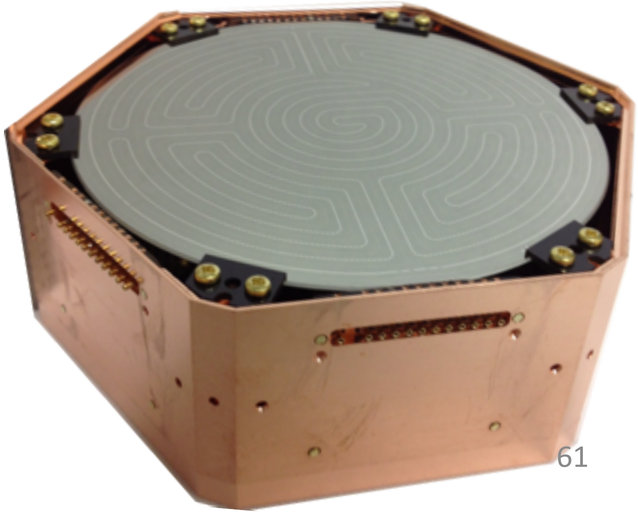
SuperCDMS SNOLAB

100 kg Ge (72 x 1.4 kg)
(also ~10 kg Si)

4" Diameter
3.3 cm Thick

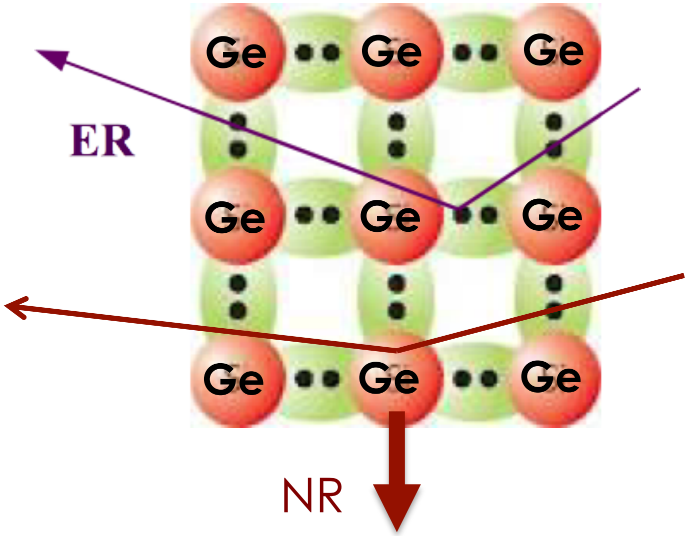
2 charge + 2 charge
6 phonon + 6 phonon





The detection principle in CDMS

The scattering of an incident particle can induce a recoil of a nucleus (neutrons and WIMPs) or an electron (elecrons and gammas)

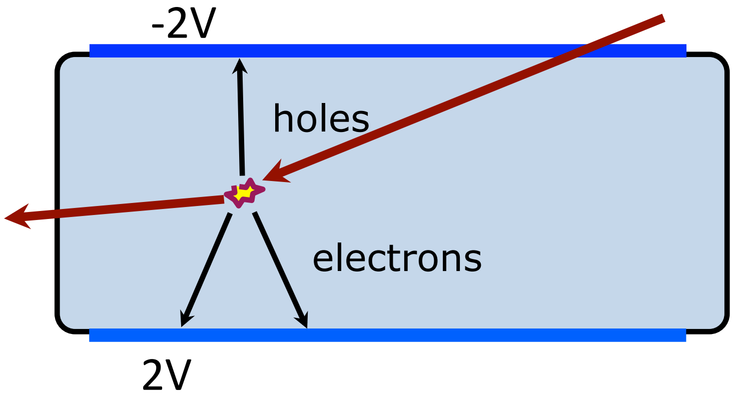


The recoiling particle produces

- Lattice vibrations (Phonons)
- Electron-hole pairs (Ionization)

Charge carriers can propagate inside the crystal volume by applying an external electric field.

Kinetic energy of propagating charge carriers is released into additional phonons (Luke phonons)



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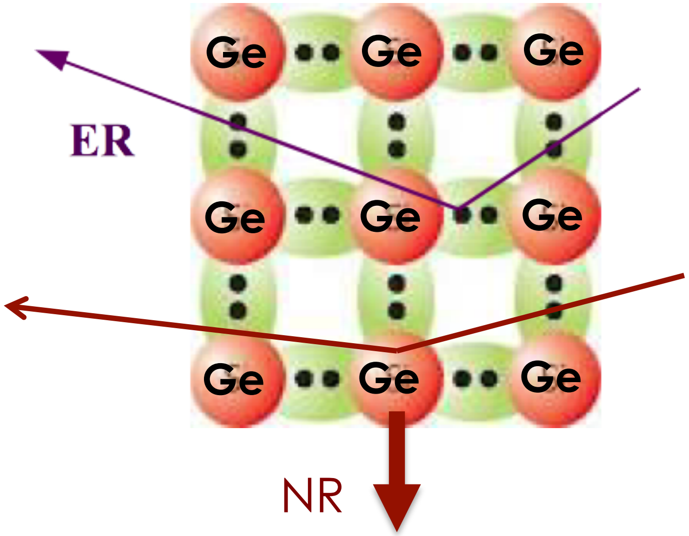

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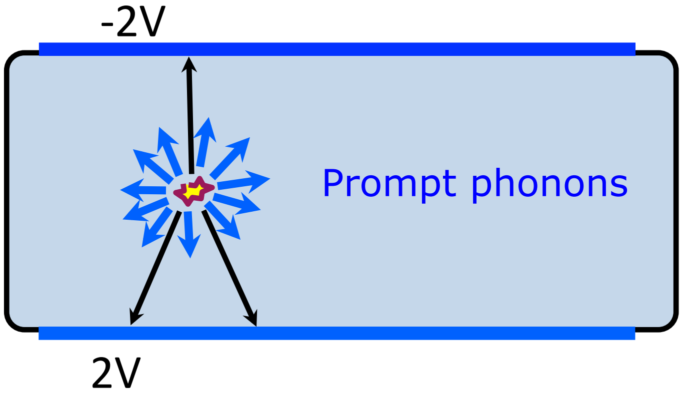

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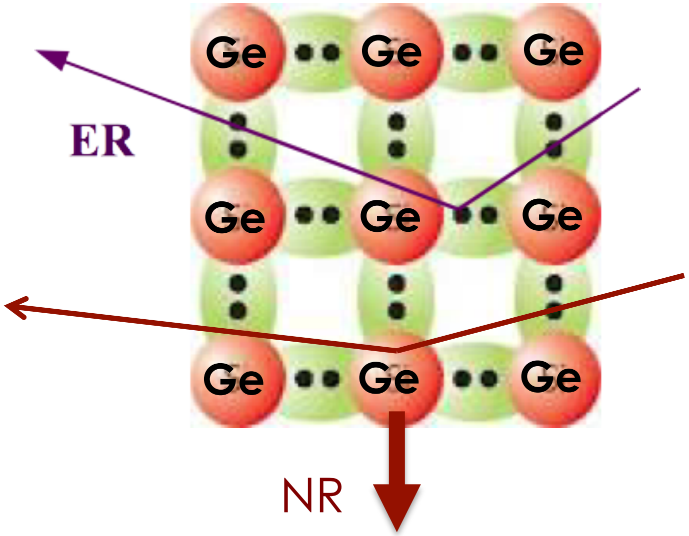

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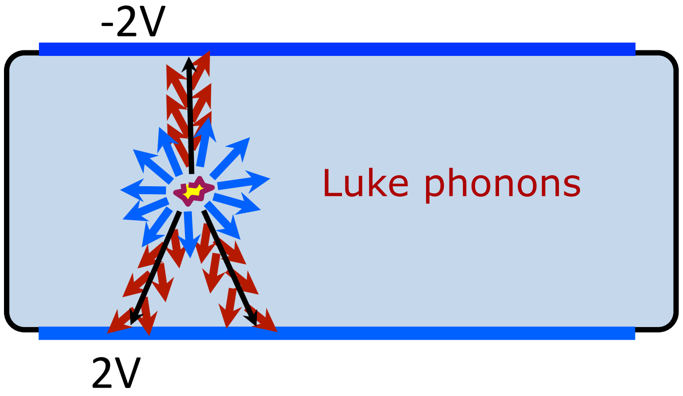
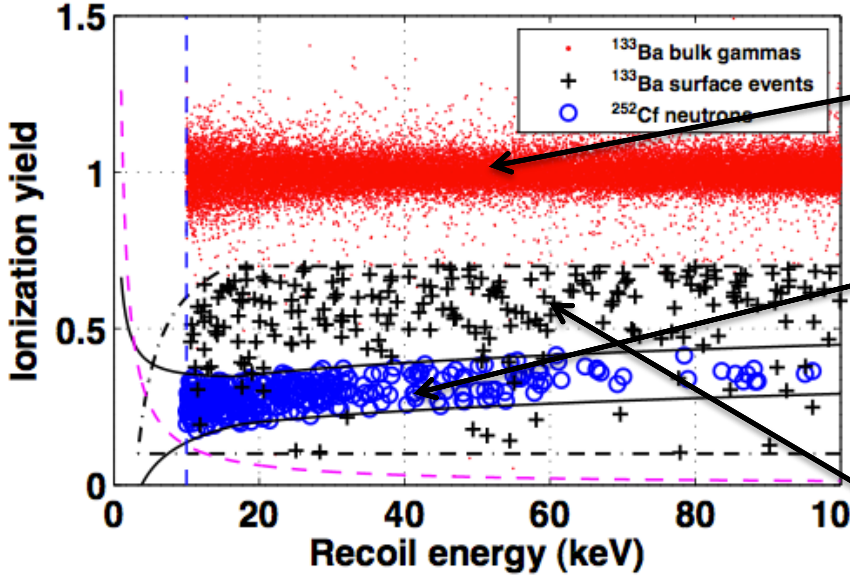


Background rejection in CDMS II (using ionization and phonons)

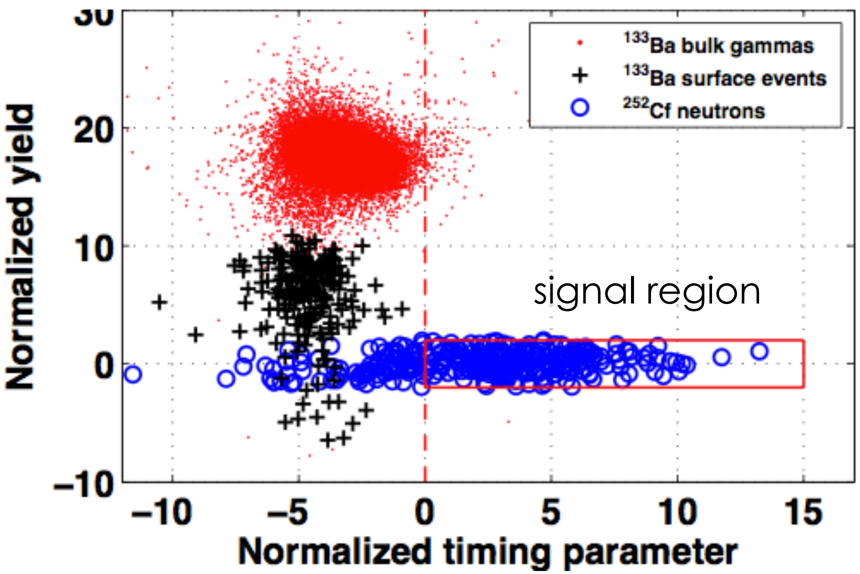


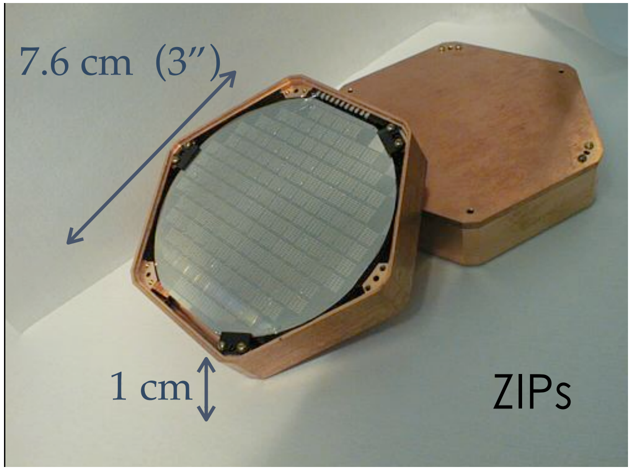
Most backgrounds (e.γ) produce electron recoils with Yield~1

Nuclear recoils produce a lower yield (~0.3) in a known band (from calibration with ^{252}Cf)

For surface events the charge collection is not complete and the yield can be lower.

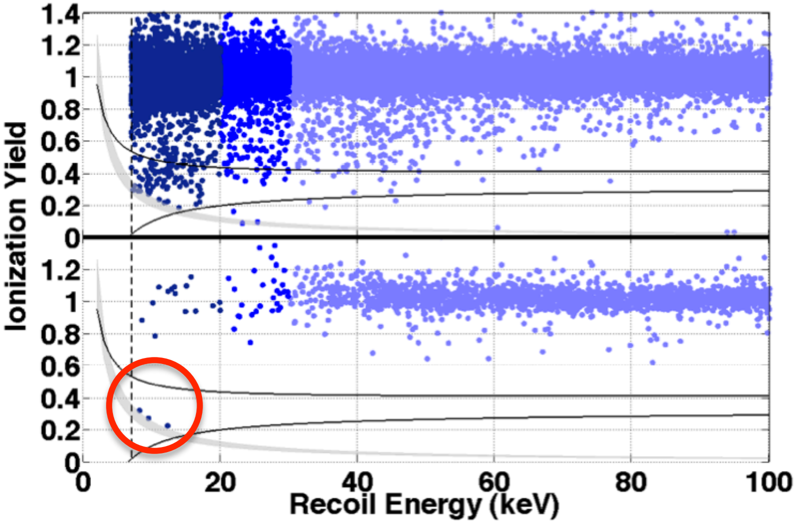
They are distinguished using a timing cut.

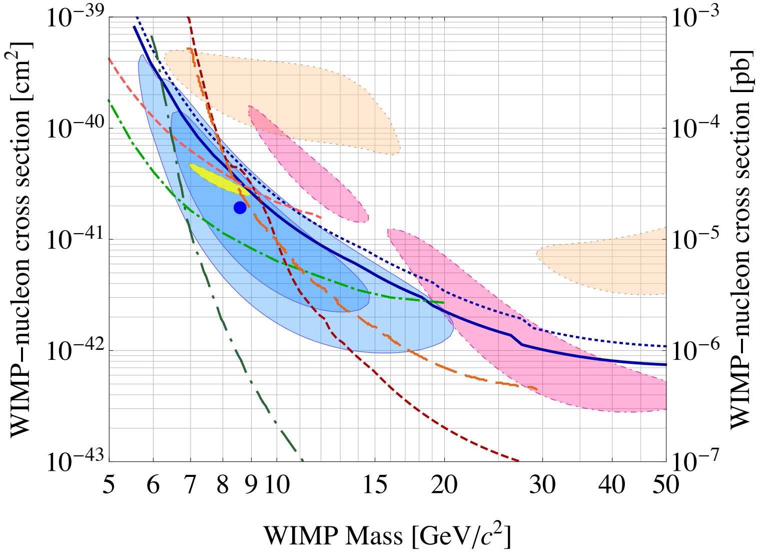




Results from the silicon detectors in CDMS II

Three WIMP-like events in the Si run that could correspond to ~9 GeV WIMP





Results from the last SI data-taking period

Phys.Rev.Lett. 111 (2013) 251301

- Jul. 2007 – Sep. 2008 (8 Si ZIPs, 140.2 kg days) – **3 EVENTS OBSERVED (~0.7 expected)**

WIMP+background hypothesis favoured over the known background estimate at the 99.81% confidence level (~3 σ, p-value: 0.19%).

Can this result be tested with the new Ge detectors?

The search for low-mass WIMPs is challenging

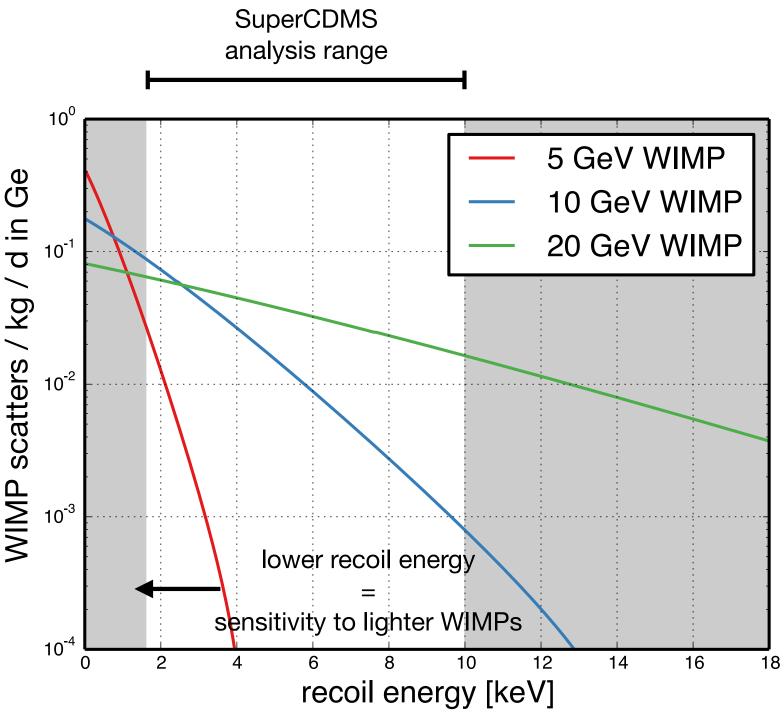
- The signal is expected at very low recoil energies

  Favours light targets

  Low-threshold searches

- Ge is relatively heavy so the threshold has to be just above the noise to be sensitive to 5 GeV WIMPs

  trigger threshold 1.6 keVnr



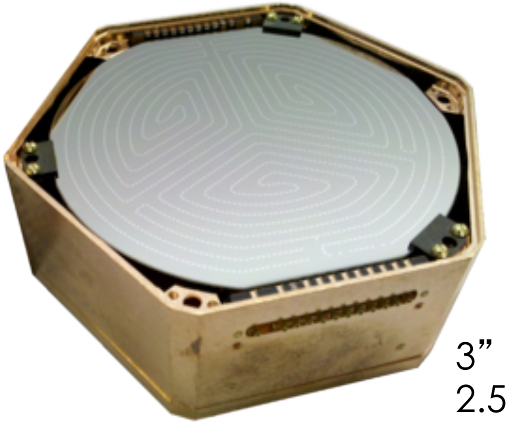
- Backgrounds are more difficult to discriminate due to a degradation in the resolution (this is not a background free search)

SuperCDMS at SOUDAN

Operational since March 2012

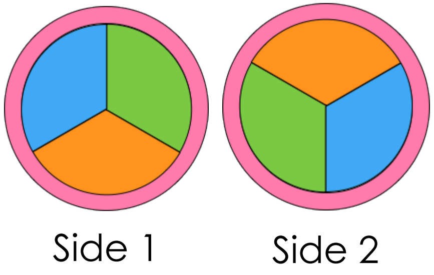
iZIP

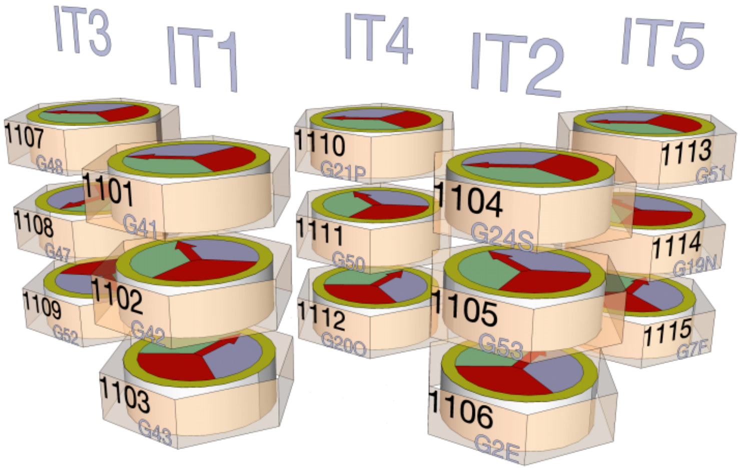
interleaved Z-sensitive
Ionization & Phonon detectors



3” Diameter
2.5 cm Thick

Instrumented on both sides with
2 charge+ 4 phonon sensors





9.0 kg Ge (15 iZIPs x 600g)

Data for this analysis:

577 kg-days
taken from Mar 2012 – July 2013
7 iZIPs with lowest trigger threshold

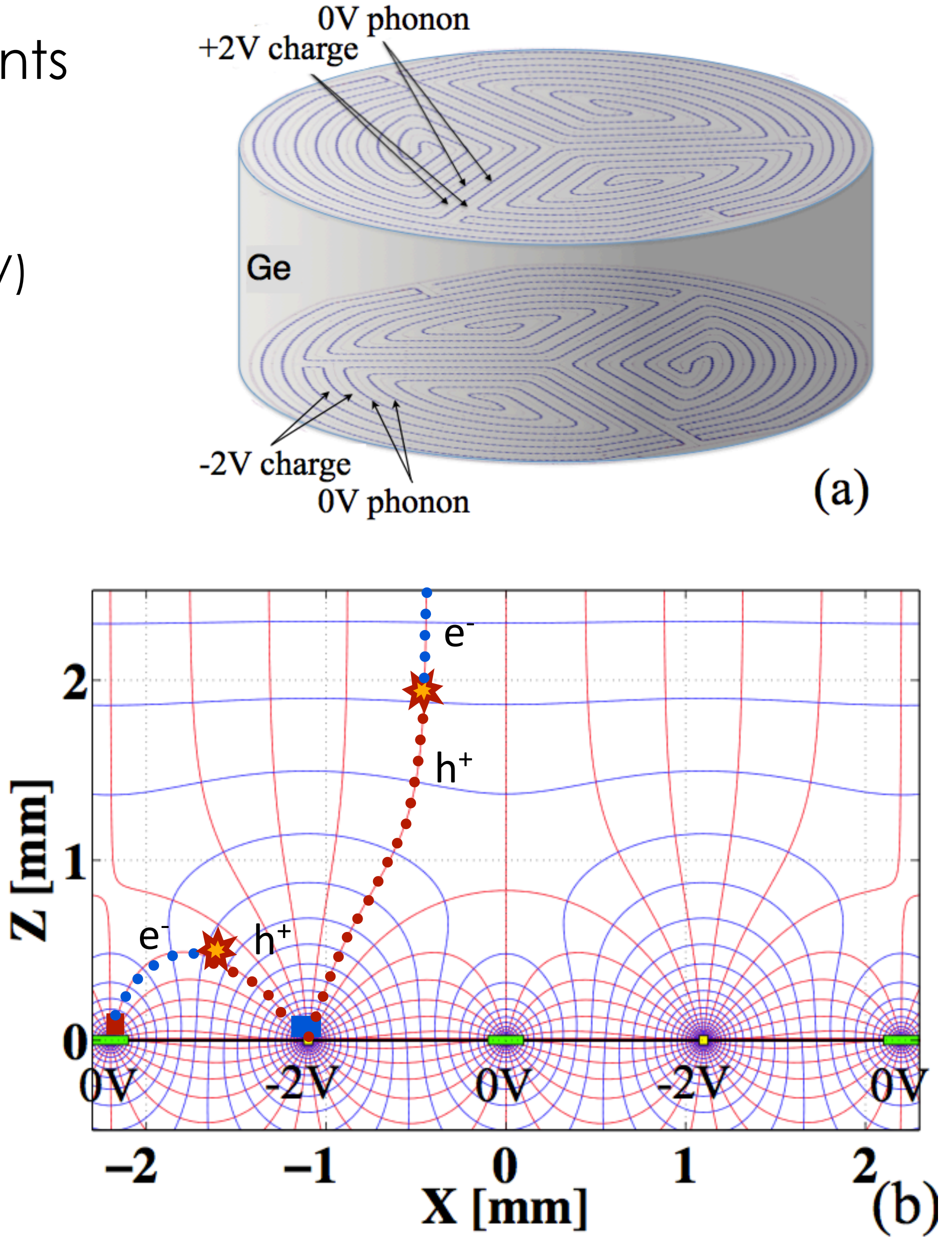
iZIP discrimination of surface events

In the new iZIPs the ionization lines (±2V) are interleaved with phonon sensors (0V) on a ~1mm pitch

Bulk events:
charges (e,h) drift to **both sides** of the crystal

Surface events:
charges (e,h) drift to **only one side** of the crystal

Z-PARTITION:
The resulting **symmetry**/**asymmetry** in charge collection in sides 1 and 2



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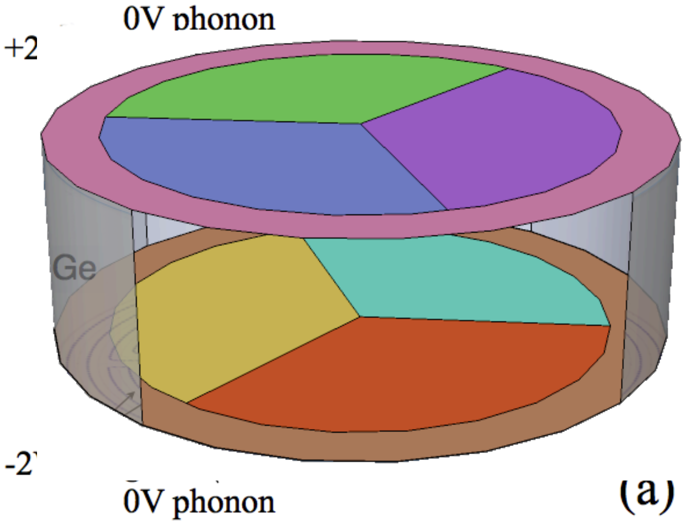

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Surface events:
charges (e,h) drift to **only one side** of the crystal

Z-PARTITION:
The resulting **symmetry**/**asymmetry** in charge collection in sides 1 and 2

Sidewalls

Surface events on the sides of the detector leave more energy in the outer sensors.

RADIAL PARTITION:
division of energy between inner and outer sensors

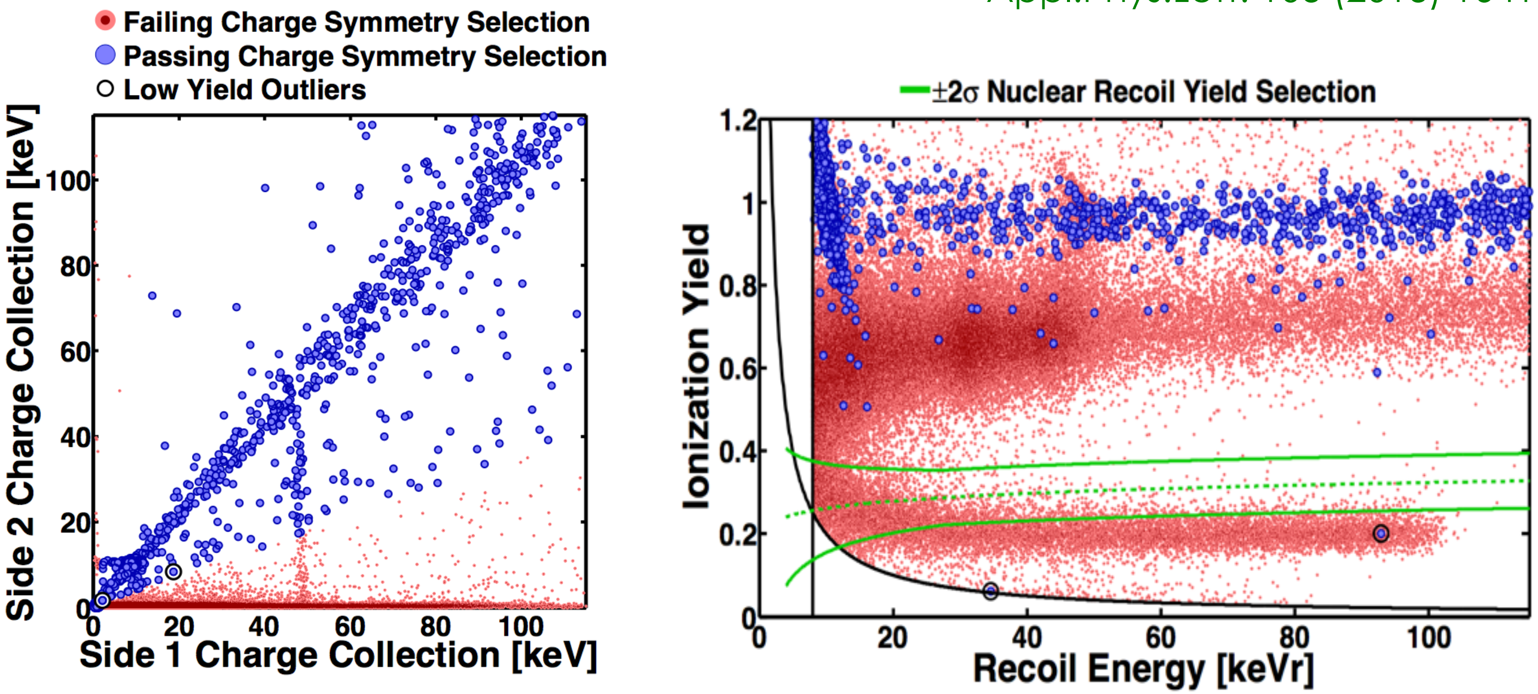
The rejection of surface events with the new iZIPs using Z-partition has been demonstrated with data from exposure to betas from ^{210}Pb sources

In ~800 live hours, no events leaked into the 8-115 keV signal region

Rejection at > 1.7×10^{-5}

This could allow a background free search for 5 yr of operation in SuperCDMS @ SNOLAB (~100 kg)

Appl.Phys.Lett. 103 (2013) 164105



(the low threshold analysis corresponds to smaller energies and some leakage is expected)

Sources of background

- Bulk electron recoils

  Compton background
  1.3 keV activation line

→ Yield = Ionization/phonon helps discriminating NR from ER

- Sidewall & surface events

  betas and x-rays from ^{210}Pb, ^{210}Bi, recoils from ^{206}Pb, outer radial Comptons, ejected electrons from Compton scattering

→ Z-Partition and Radial partition define a fiducial volume

- Neutrons
  (cosmogenic & radiogenic)

→ Use active and passive shielding. Simulation determines remaining irreducible rate

Analysis: Selection criteria and efficiencies

We carry out a blind analysis, with all singles in energy range removed from study, except data following ^{252}Cf calibration due to activation

Data Quality:

Reject periods with poor detector performance
Remove misreconstructed and noisy pulses
Measure efficiency with pulse MC

Trigger and analysis threshold:

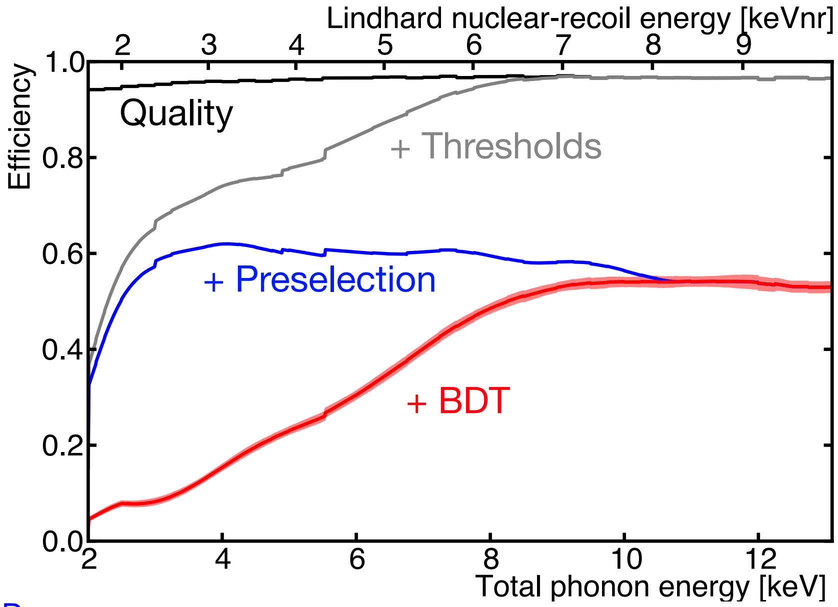
Select periods with stable well-defined trigger threshold
Measure efficiency from ^{133}Ba calibration data

Preselection:

Single-detector scatter
Remove events coincident with muon veto
Ionization fiducial volume
Ionization and phonon partitions consistent with NR

Boosted Decision Tree:

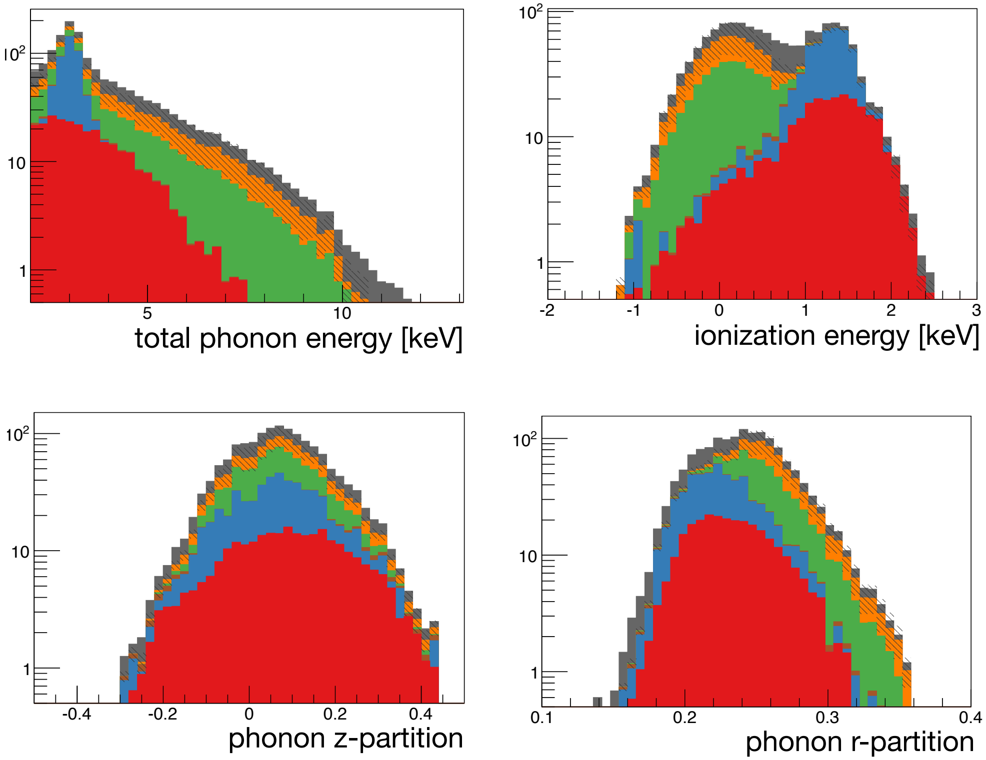
Optimised cut on the phonon fiducial volume and ionization yield at low energy
Efficiency estimated from fraction of ^{252}Cf passing



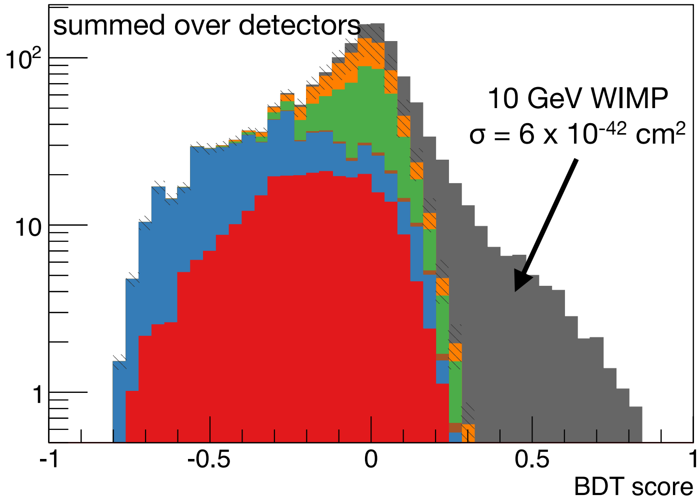
Efficiencies: measured for neutrons from ^{252}Cf. Corrected for multiple scattering with Geant4

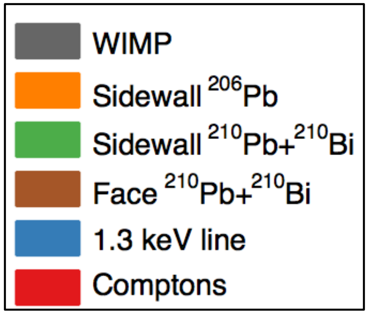
Boosted Decision Tree (BDT)

Inputs (per detector)



Output



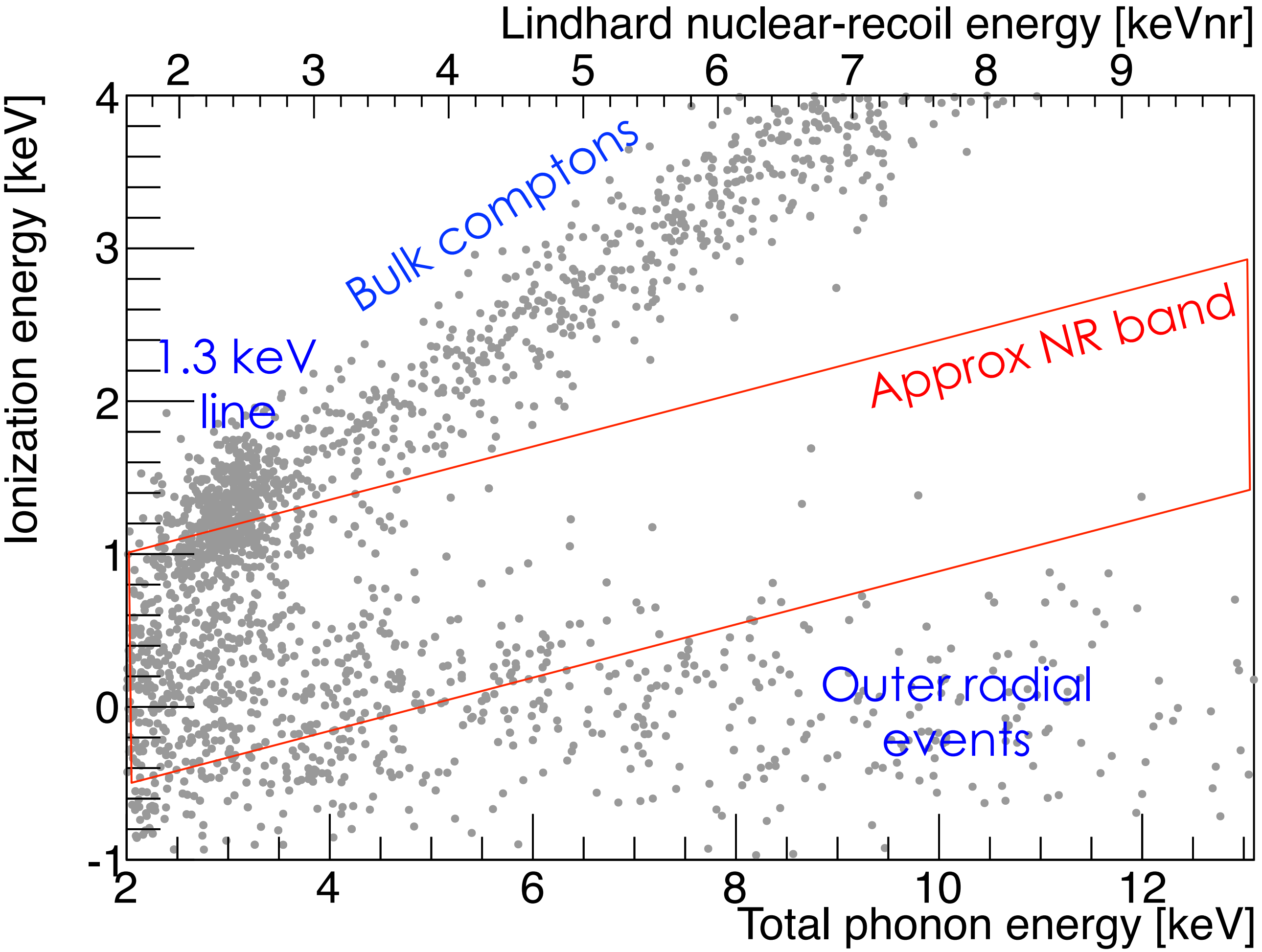


Background: Modelled with simulated data on sidebands and calibration.

WIMP Signal: Modelled with NR data from ^{252}Cf, then rescaled for WIMPs with mass 5, 7, 10, 15 GeV

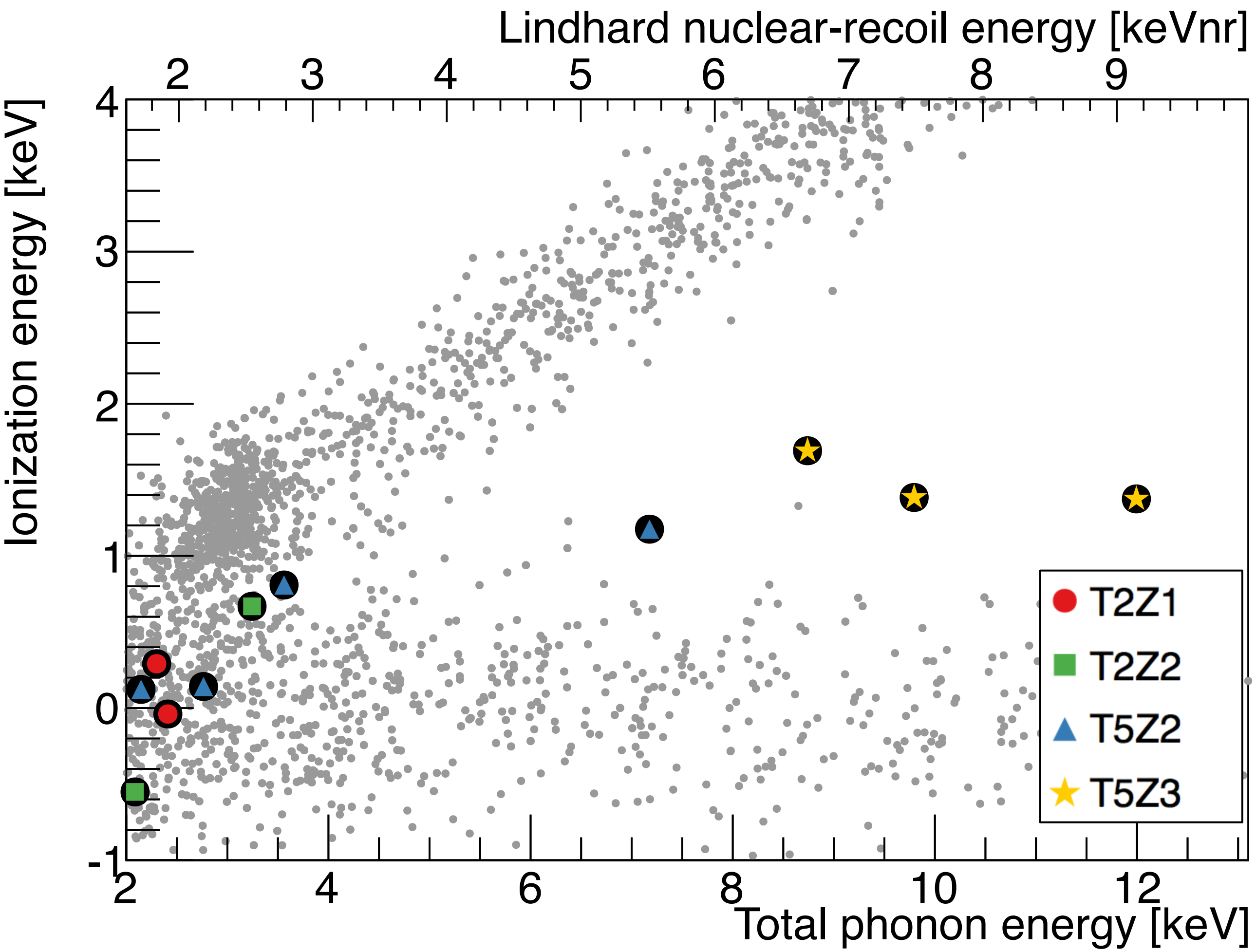
Unblinding: Before BDT cut

Events passing all the cuts prior to applying BDT



Unblinding: After BDT cut

11 candidates (6.2 +1.1 -0.8 expected)



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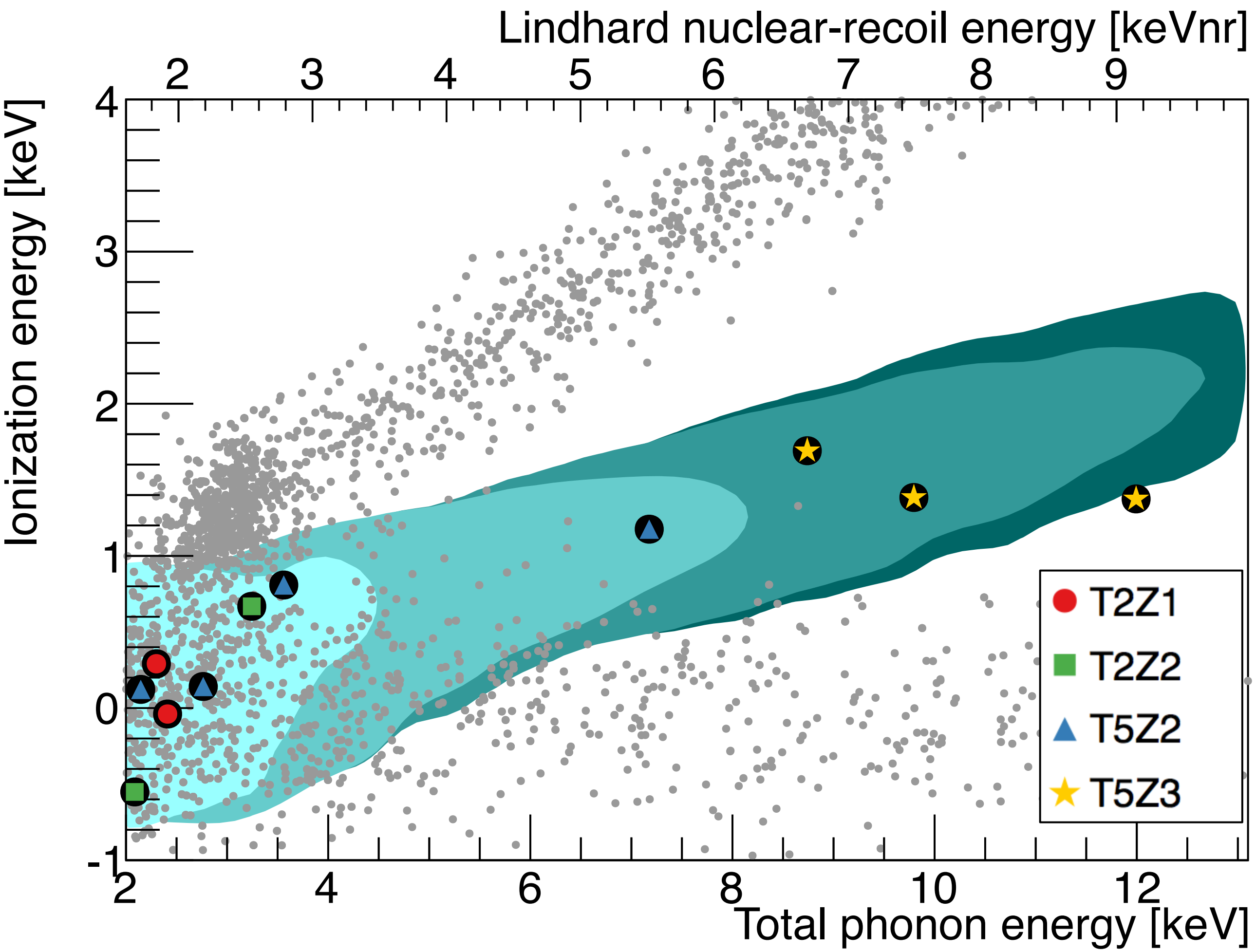
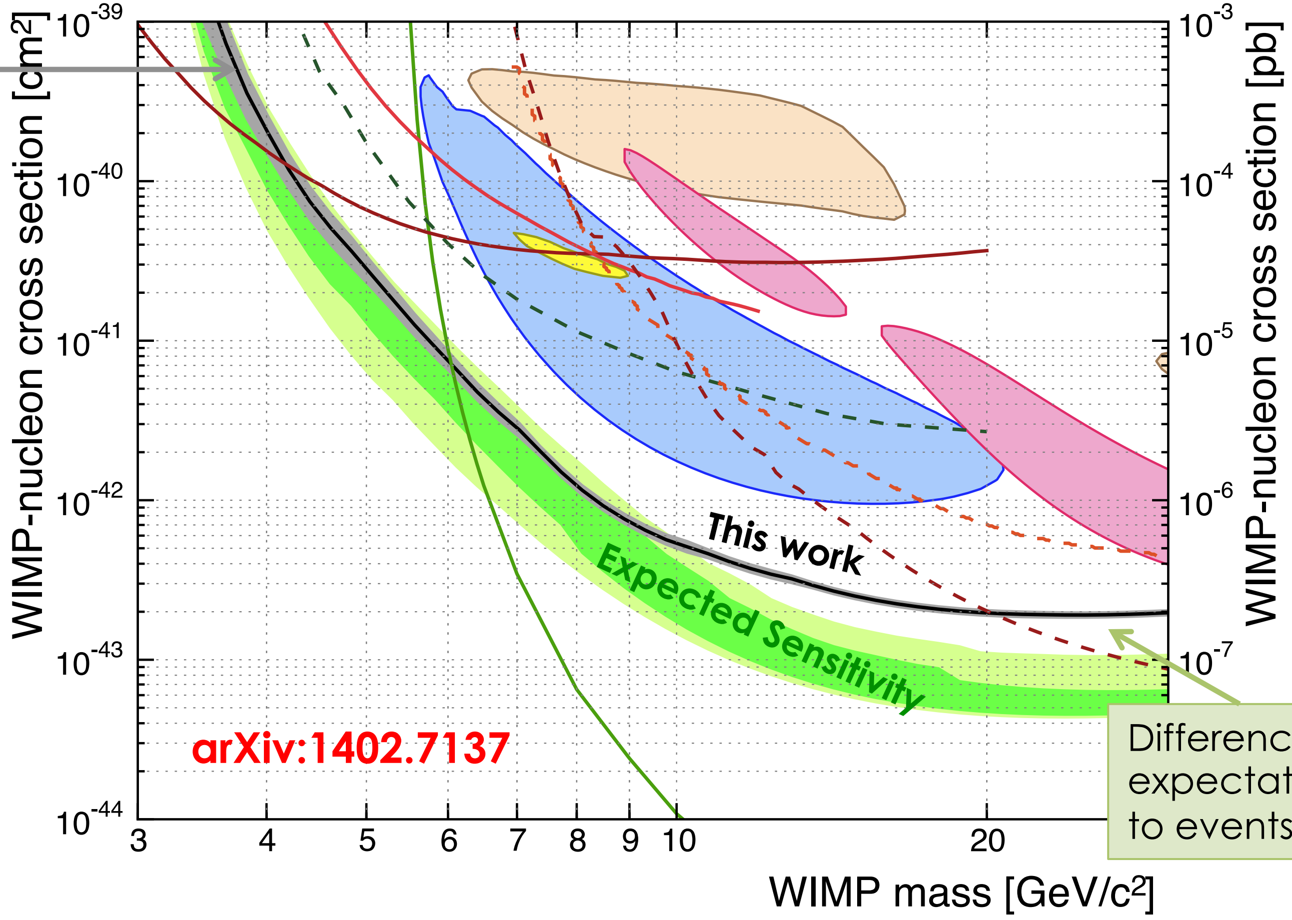


95% CL intervals for WIMPS with

m=5 GeV
m=7 GeV
m=10 GeV
m=15 GeV

New limit for low-mass WIMPs

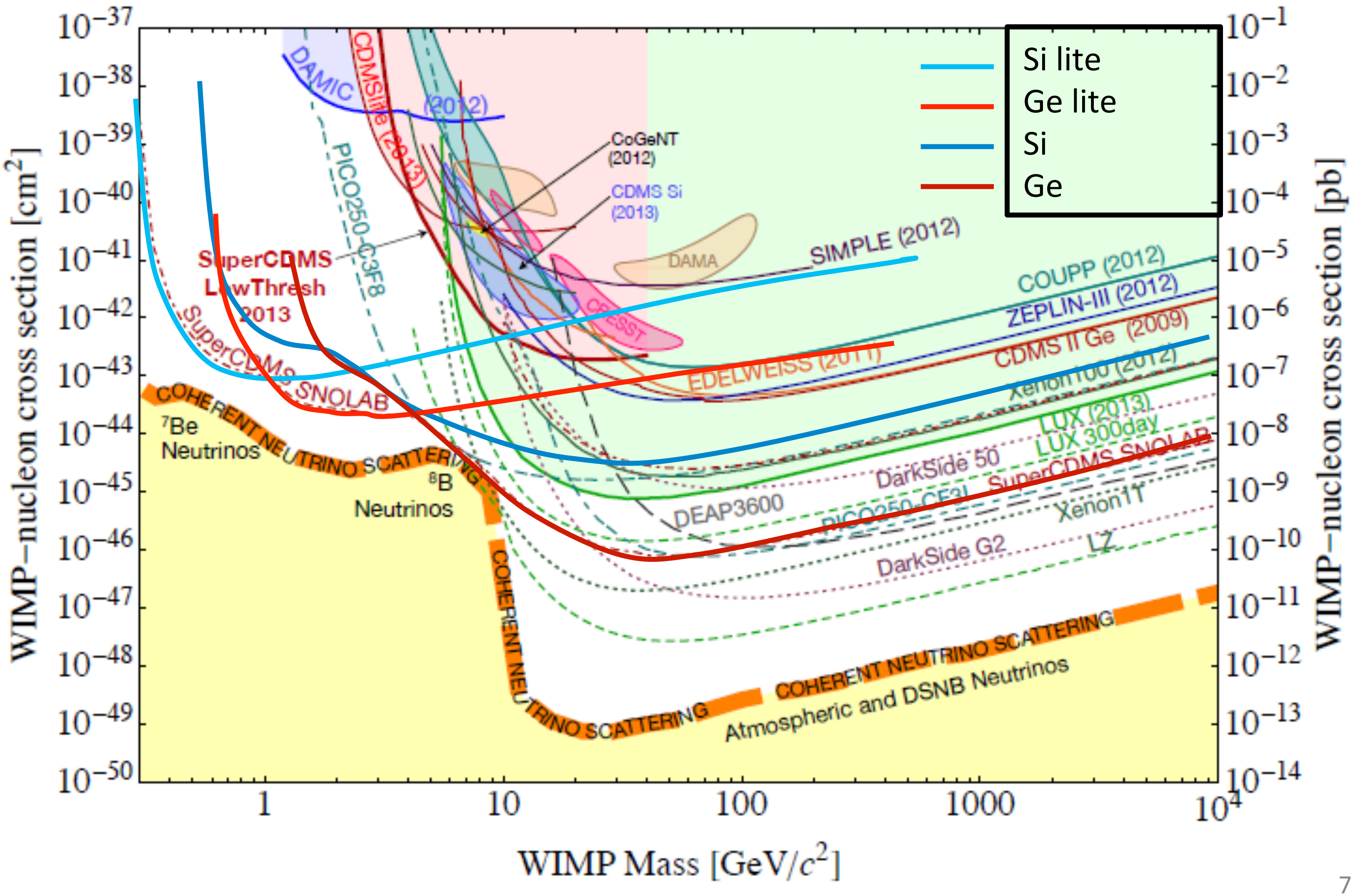
90% C.L. optimal interval method
(no background subtraction)



systematics (efficiency, energy scale, trigger efficiency)

Difference with expectation due to events in T5Z3

- SuperCDMS-SNOLAB (with ~100 kg Ge and ~10kg Si) will extend the sensitivity by over an order of magnitude with an excellent coverage of the light mass window.



Neutralino in the MSSM

Linear Superposition of Bino, Wino and Higgsinos

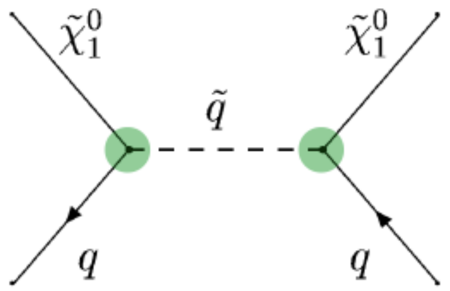
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 \end{pmatrix}$$

Its detection properties depend crucially on its composition

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

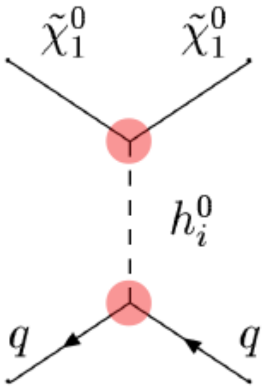
Spin-independent cross section

- Contributions from **squark-** and **Higgs-**exchanging diagrams:



Squark-exchange

$$\sigma_{\tilde\chi_1^0-p} \propto \frac{m_r^2}{4\pi}\left(\frac{g'^2\sin\theta}{m_{\tilde q}^2-m_{\tilde\chi_1^0}^2}\right)^2 |N_{11}|^4$$

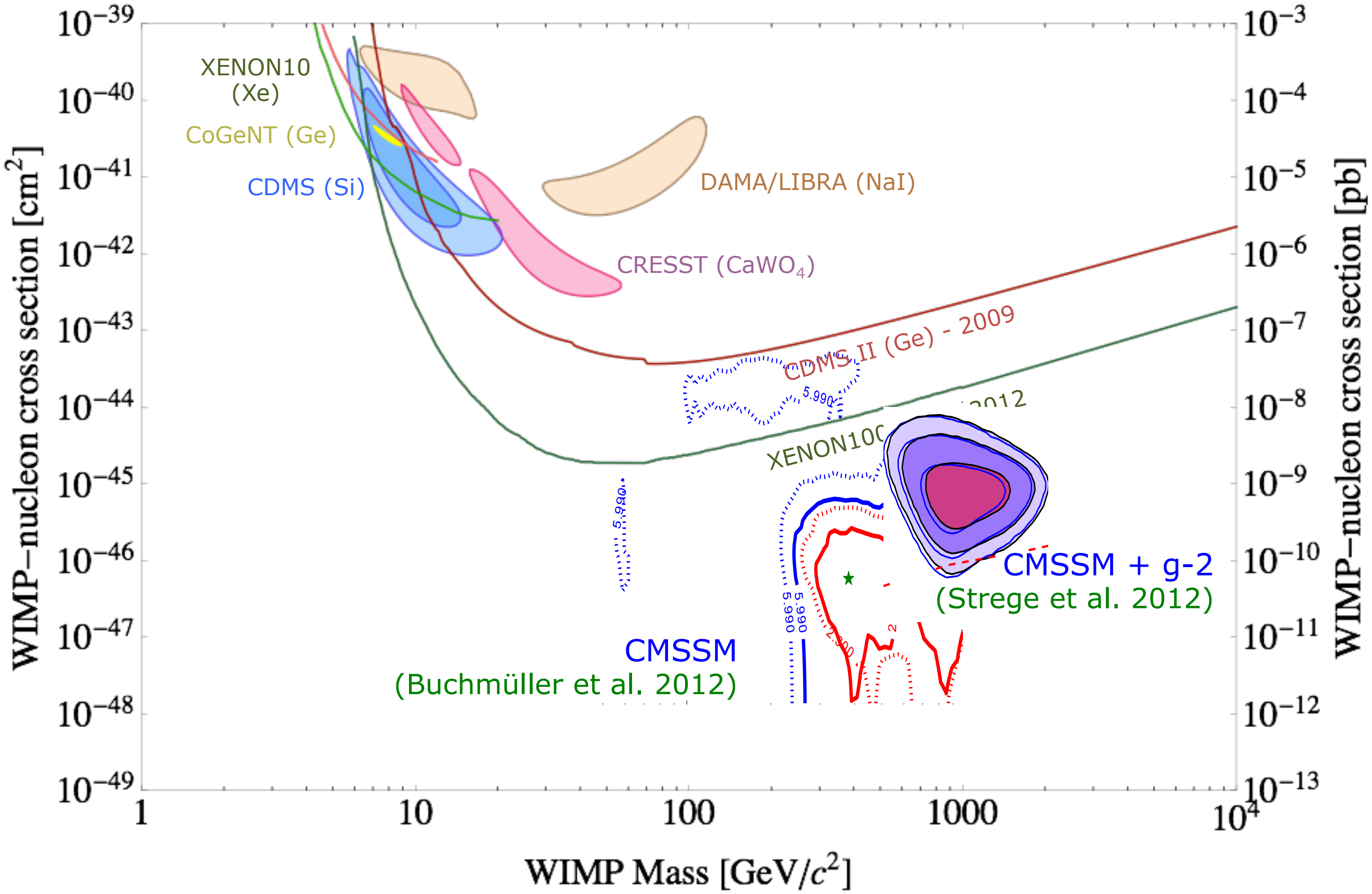


Higgs-exchange It is the leading contribution, and increases when

$$\sigma_{\tilde\chi_1^0-p} \propto \frac{m_r^2}{4\pi}\frac{\lambda_q^2}{m_h^4}|N_{13,14}(g'N_{11}-gN_{12})|^2$$

- The Higgsino components of the neutralino increase $\mu\downarrow$
- The Higgs masses decrease $m_h,\ m_{H^0}\ m_{A^0}\downarrow$

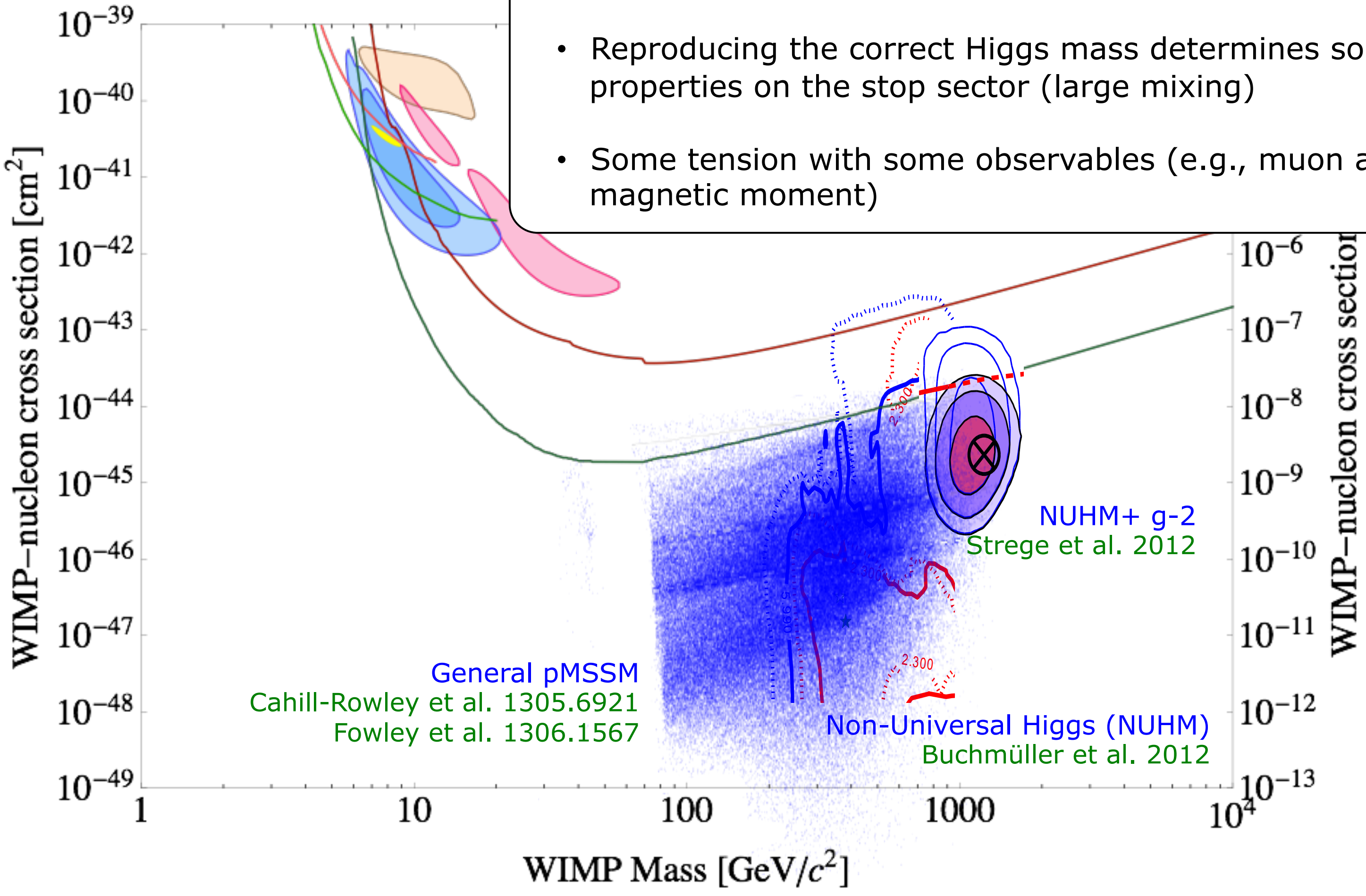
Neutralino in the (Constrained) MSSM



Neutralino in the MSSM

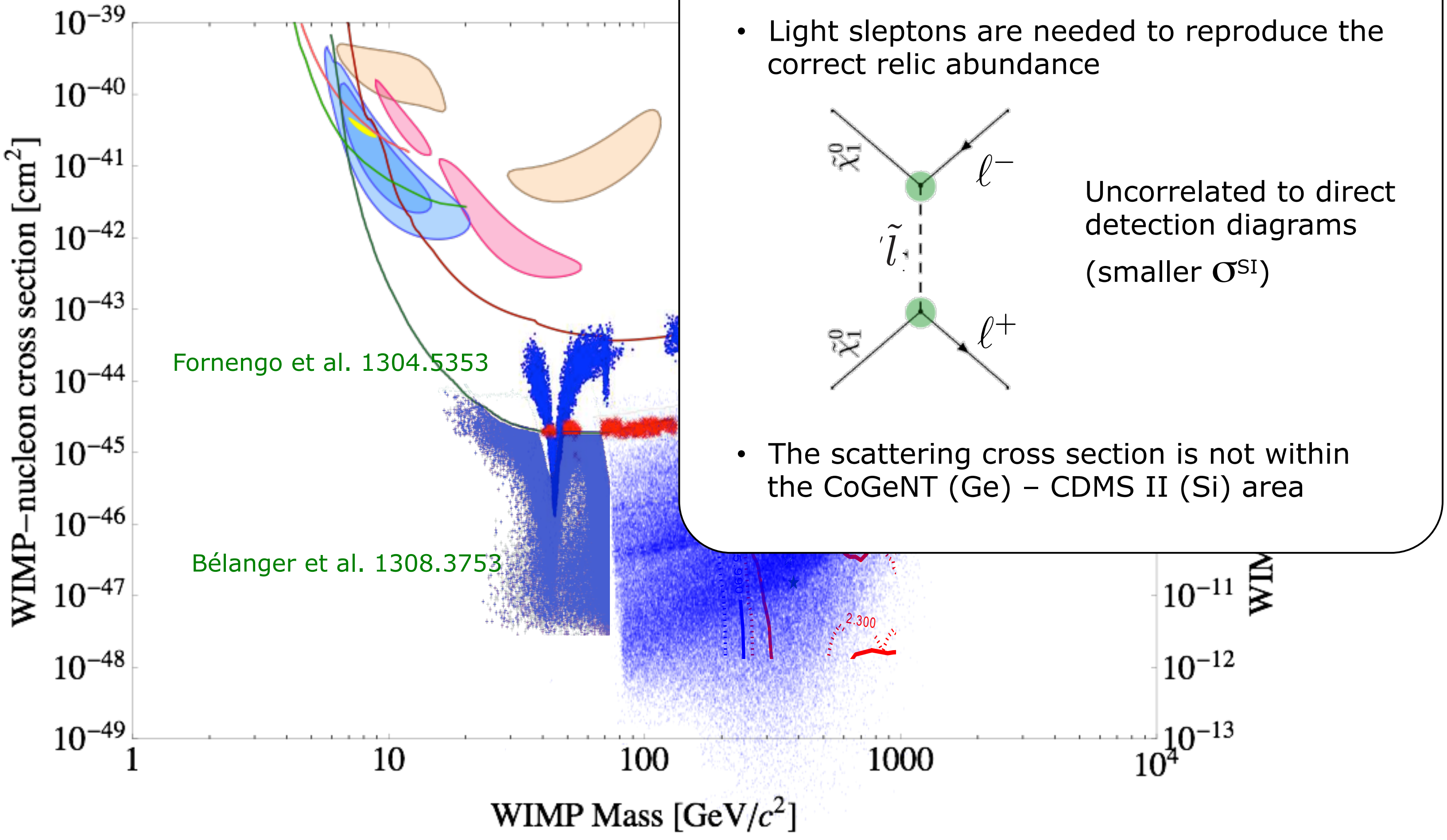
A wide region of the neutralino parameter space is valid

- Large masses appear naturally $m_\chi > 100$ GeV
- Reproducing the correct Higgs mass determines some properties on the stop sector (large mixing)
- Some tension with some observables (e.g., muon anomalous magnetic moment)



The predictions for its scattering cross section still span many orders of magnitude (excellent motivation for more sensitive detectors)

Neutralino in the MSSM



Fornengo et al. 1304.5353

Bélanger et al. 1308.3753

Very light neutralinos are viable in corners of the parameter space

- Light sleptons are needed to reproduce the correct relic abundance

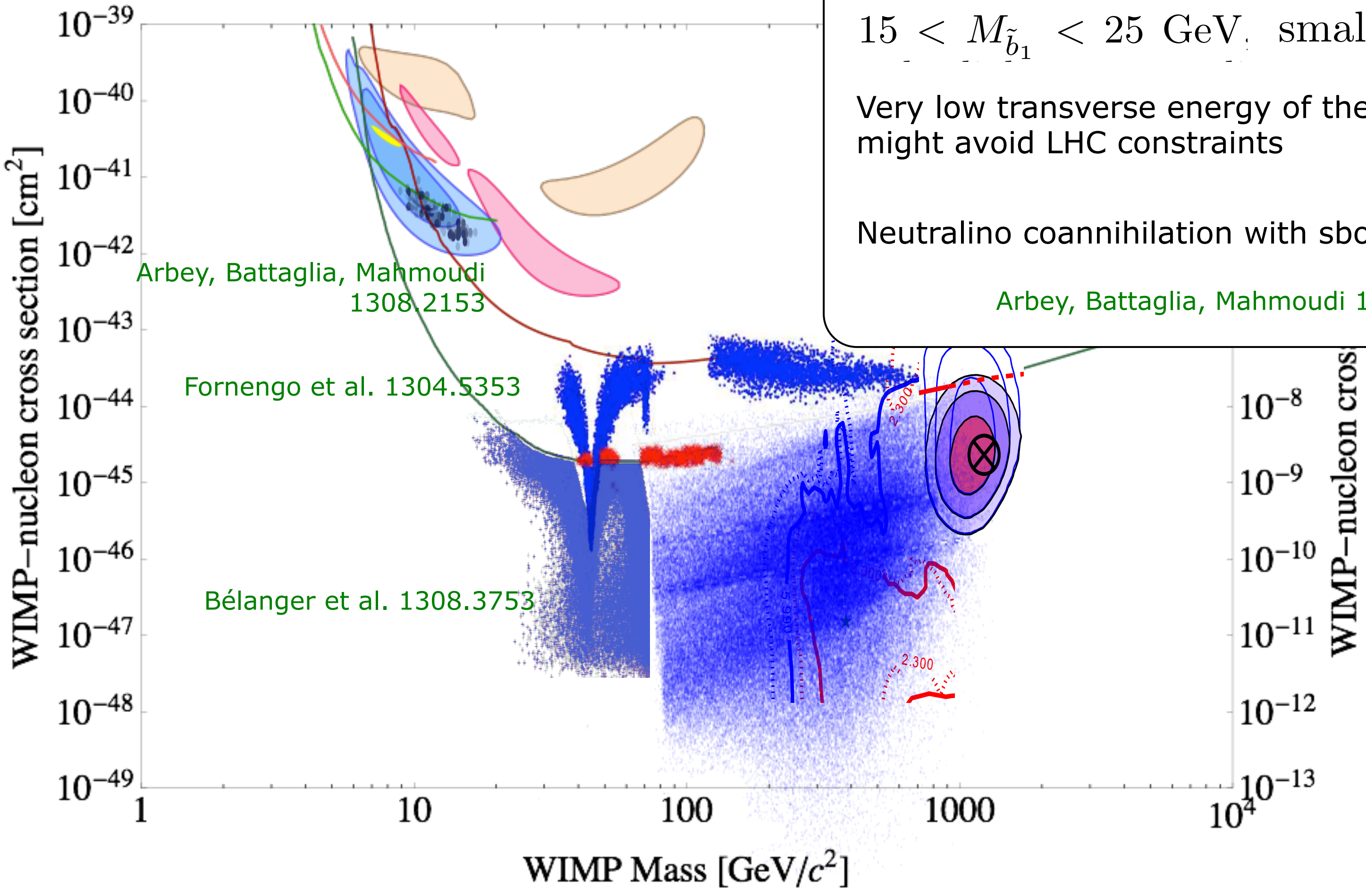
Uncorrelated to direct detection diagrams

(smaller σ^{SI})

- The scattering cross section is not within the CoGeNT (Ge) – CDMS II (Si) area

The predictions for its scattering cross section still span many orders of magnitude (excellent motivation for more sensitive detectors)

Neutralino in the MSSM



Arbey, Battaglia, Mahmoudi 1308.2153

Fornengo et al. 1304.5353

Bélanger et al. 1308.3753

Extremely light sbottom

$15 < M_{\tilde{b}_1} < 25$ GeV, small $\cos\theta_b$

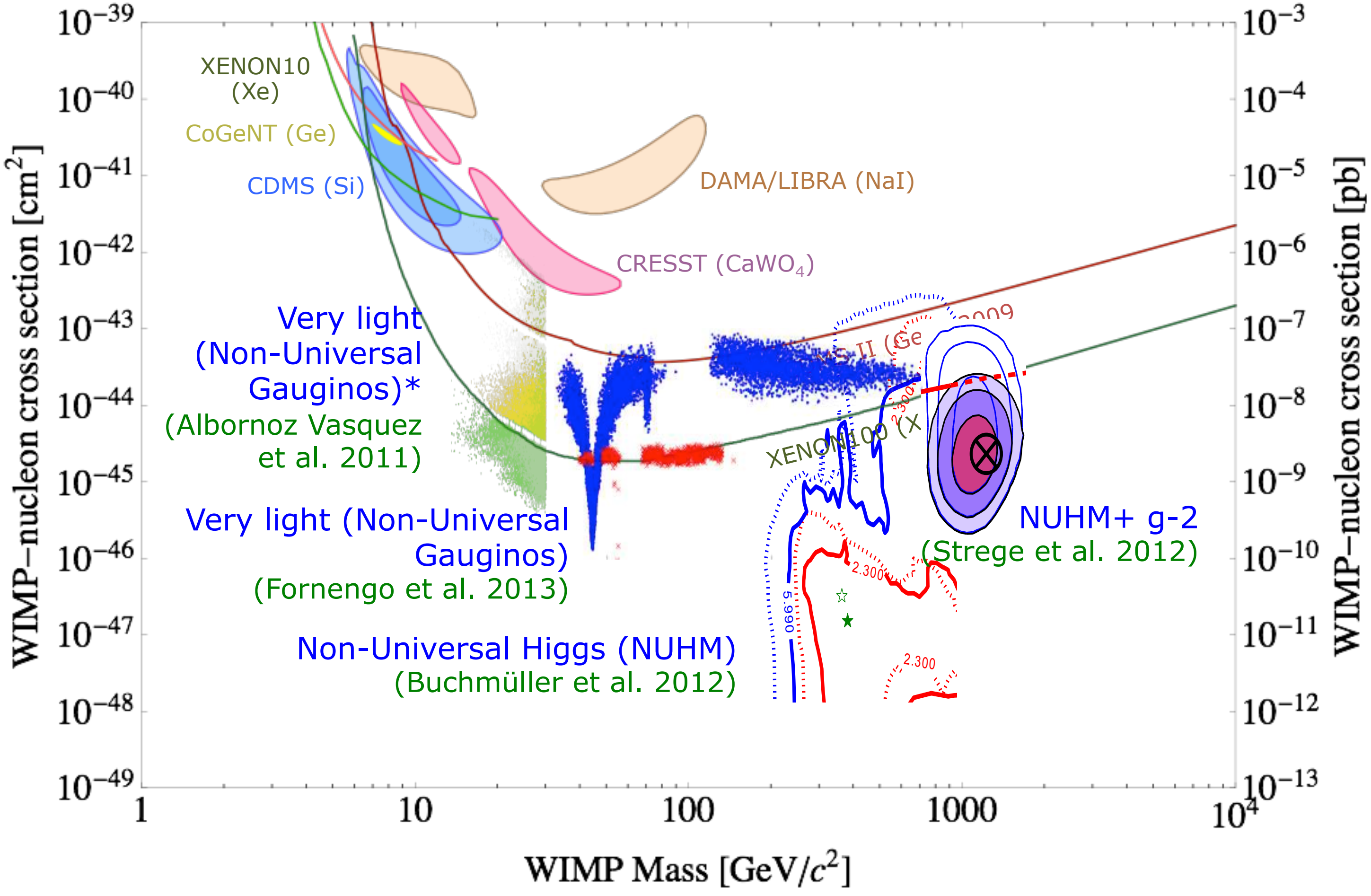
Very low transverse energy of the jets might avoid LHC constraints

Neutralino coannihilation with sbottom

Arbey, Battaglia, Mahmoudi 1308.2153

Very light neutralinos are viable (though quite fine-tuned) in the Minimal Supersymmetric Standard Model.

Neutralino in the MSSM – Unconstrained scenarios



* without constrains on the Higgs sector

Neutralino in the Next-to-MSSM

Extensions of the MSSM are well motivated from the theoretical point of view and potentially very interesting from the point of view of dark matter.

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:

$$\mathrm{NMSSM} \quad = \quad \mathrm{MSSM} + \hat{S} \left\{ \begin{array}{l} 2 \text{ extra Higgs } (\mathrm{CP-even,\ CP-odd}) \\ 1 \text{ additional Neutralino} \end{array} \right.$$

Interesting Collider & DM Phenomenology

- 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

Neutralino in the Next-to-MSSM

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

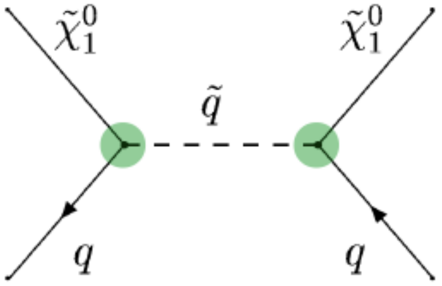
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta & 0 \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta & 0 \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu & -\lambda v_2 \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu &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

Its detection properties depend crucially on its composition

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

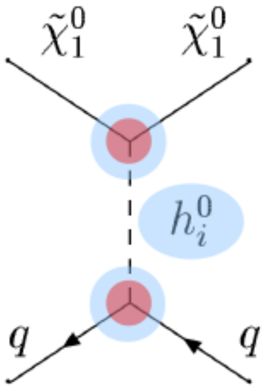
Spin-independent cross section

- Contributions from **squark-** and **Higgs-**exchanging diagrams:



Squark-exchange

$$\sigma_{\tilde{\chi}_1^0-p} \propto \frac{m_r^2}{4\pi}\left(\frac{g'^2\sin\theta}{m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2}\right)^2 |N_{11}|^4$$



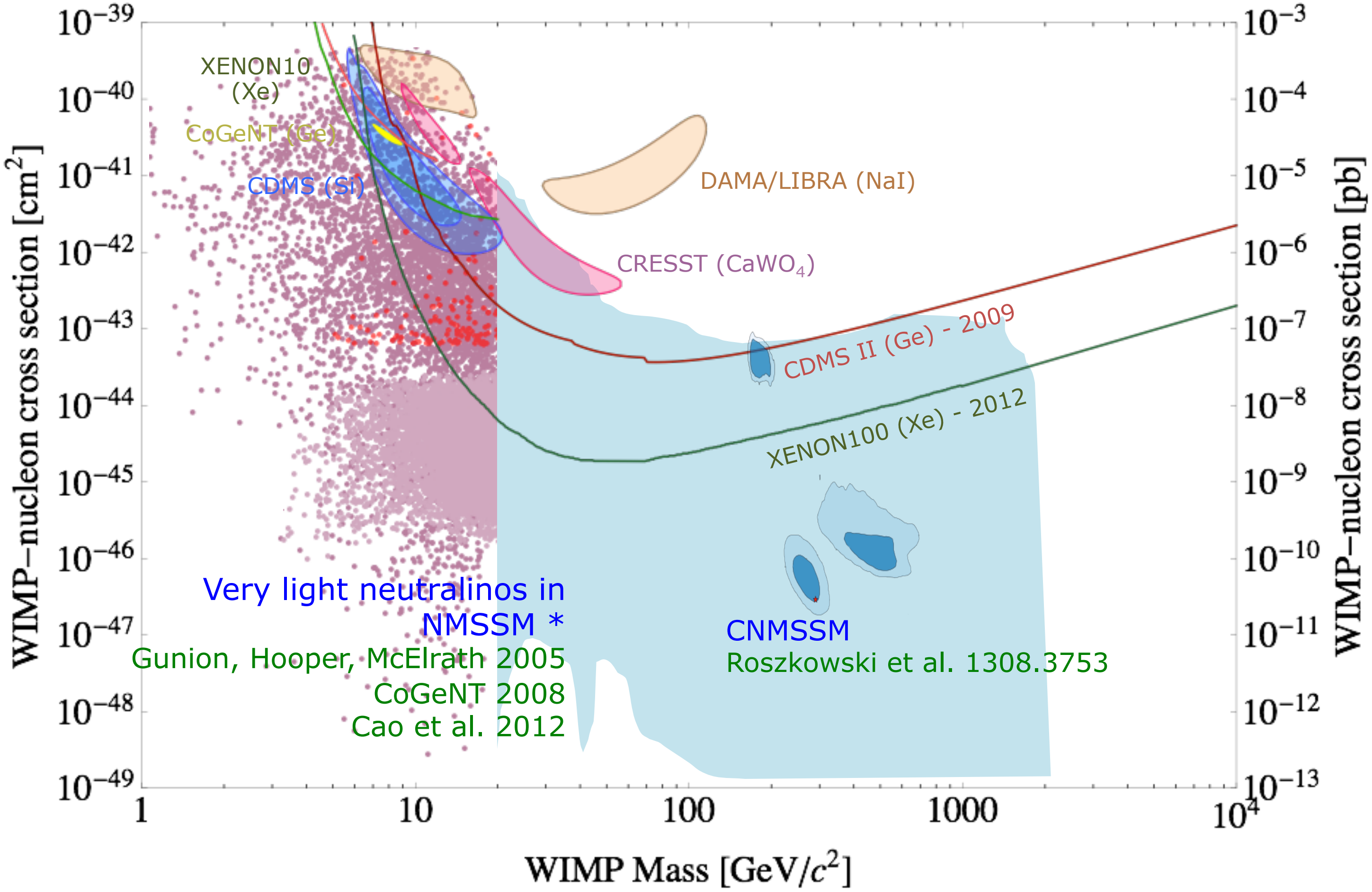
Higgs-exchange It is the leading contribution, and increases when

In the NMSSM very light Higgses ($m_h \geq 20$ GeV) can be obtained in the NMSSM. These have a large singlet component and avoid experimental constraints.

- The Higgs masses decrease $m_h,\ m_{H^0}\ m_{A^0} \downarrow$

Neutralino in the Next-to-MSSM

Predictions more flexible than in the MSSM



Very light neutralinos in NMSSM *

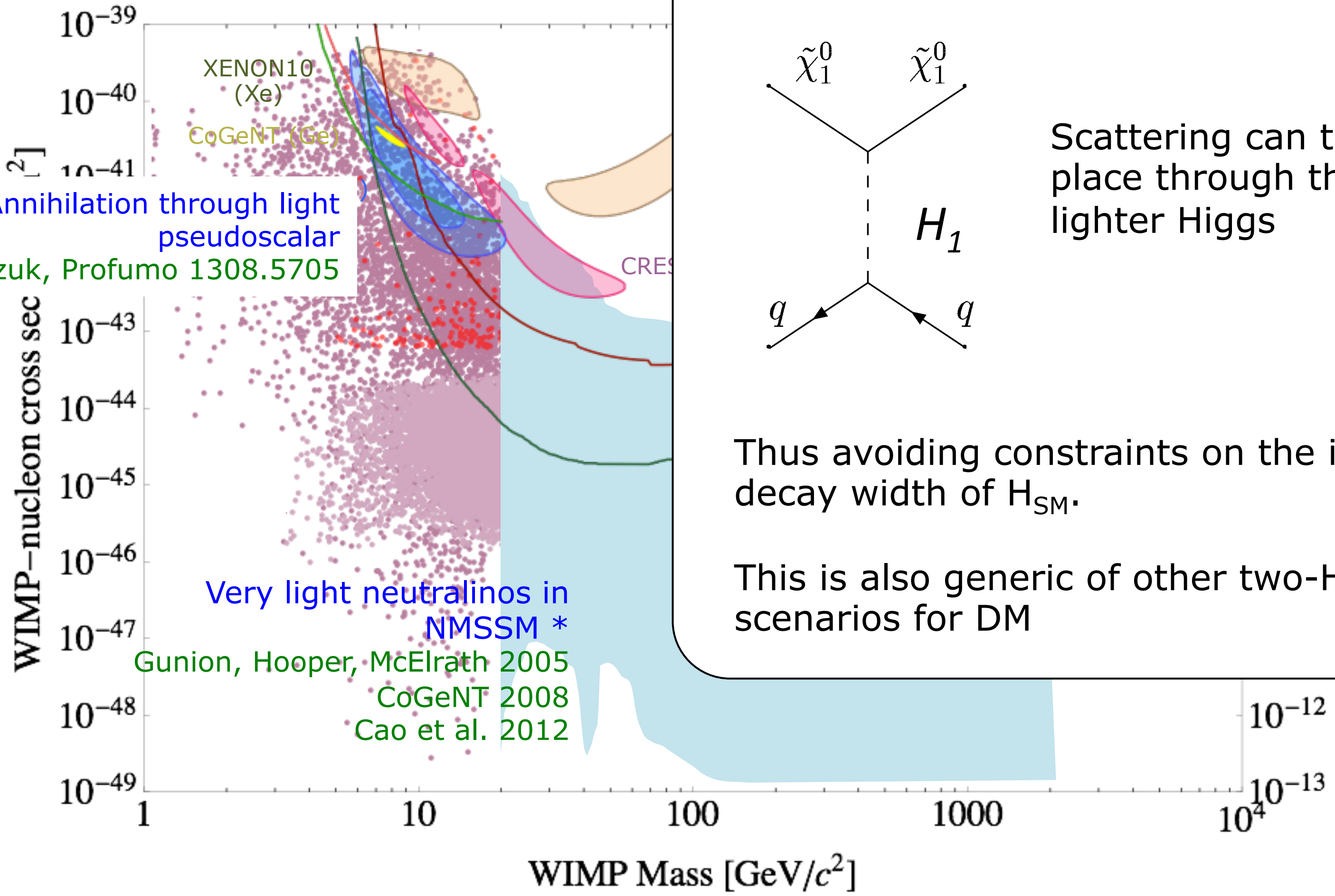
Gunion, Hooper, McElrath 2005
CoGeNT 2008
Cao et al. 2012

CNMSSM

Roszkowski et al. 1308.3753

* without constrains on the Higgs sector

Neutralino in the Next-to-MSSM



Annihilation through light pseudoscalar
Kozaczuk, Profumo 1308.5705

Very light neutralinos in NMSSM *
Gunion, Hooper, McElrath 2005
CoGeNT 2008
Cao et al. 2012

Very light neutralinos are also possible

Scattering can take place through the lighter Higgs

Thus avoiding constraints on the invisible decay width of H_{SM}.

This is also generic of other two-Higgs scenarios for DM

The light WIMP region becomes more populated: an excellent motivation for low-threshold experiments.

Right-handed sneutrino in the NMSSM

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

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

$$+ N \left\{ \begin{array}{l} 1 \text{ additional (right-handed) Neutrino} \\ \text{and sneutrino} \end{array} \right.$$

- New terms in the superpotential

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

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

- After Radiative Electroweak Symmetry-Breaking

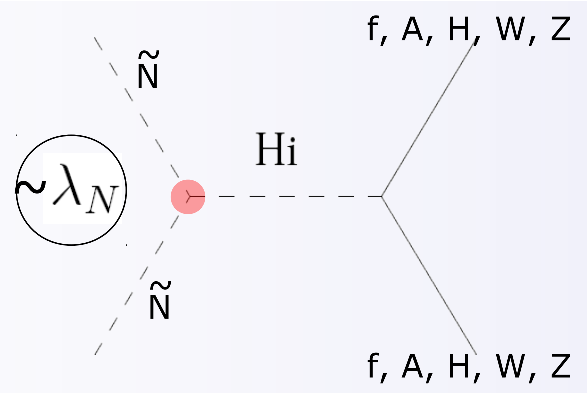
$$\langle H_1^0 \rangle = v_1 \quad ; \quad \langle H_2^0 \rangle = v_2 \quad ; \quad \langle S \rangle = s \qquad \left\{ \begin{array}{l} \mu \, H_1 \, H_2 \\ m_N \, N \, N \end{array} \right.$$

EW-scale
Higgsino-mass
parameter
&
Majorana
neutrino mass

EW-scale see-saw mechanism implies very small yukawa couplings

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

Since this determines the LR mixing of the neutrino/sneutrino sector one is left with pure Right and Left fields



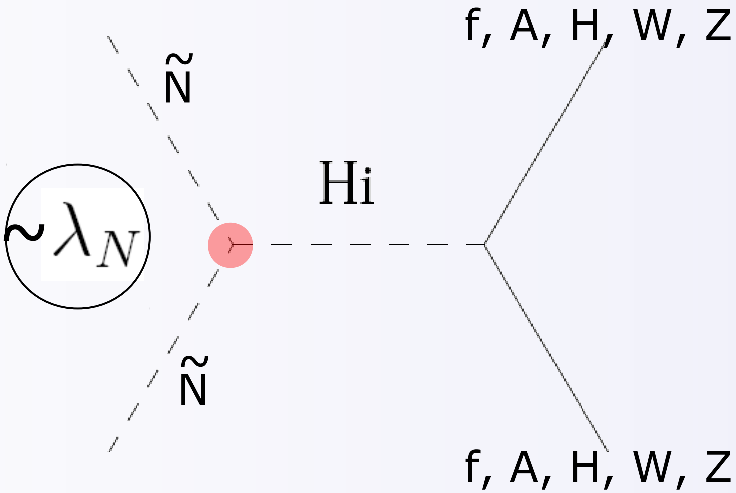
The correct relic density can be obtained for λN~0.1 (it is a WIMP) and a wide range of sneutrino masses

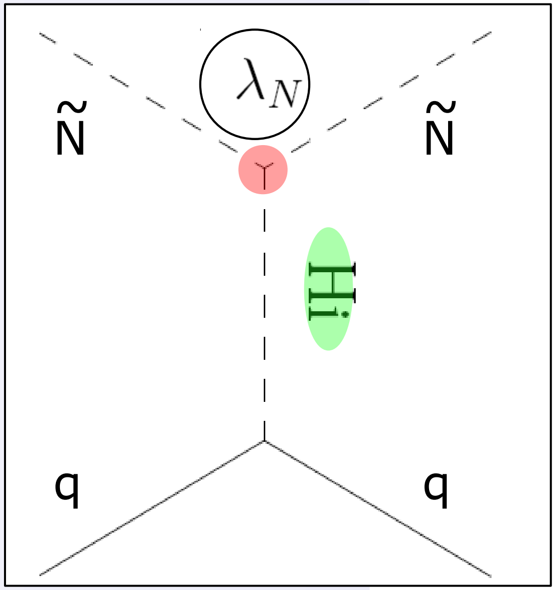
Cerdeño, Muñoz, Seto 0807.3029
Cerdeño, Seto 0903.4677

Other solution for sneutrino dark matter consists in considering LR-sneutrinos

Arina, Fornengo 0709.4477

$\tilde{\nu} = \tilde{N}$ PURE RH-SNEUTRINO (LR mixing proportional to very small Yukawa)

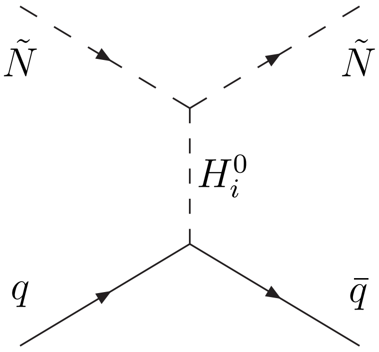


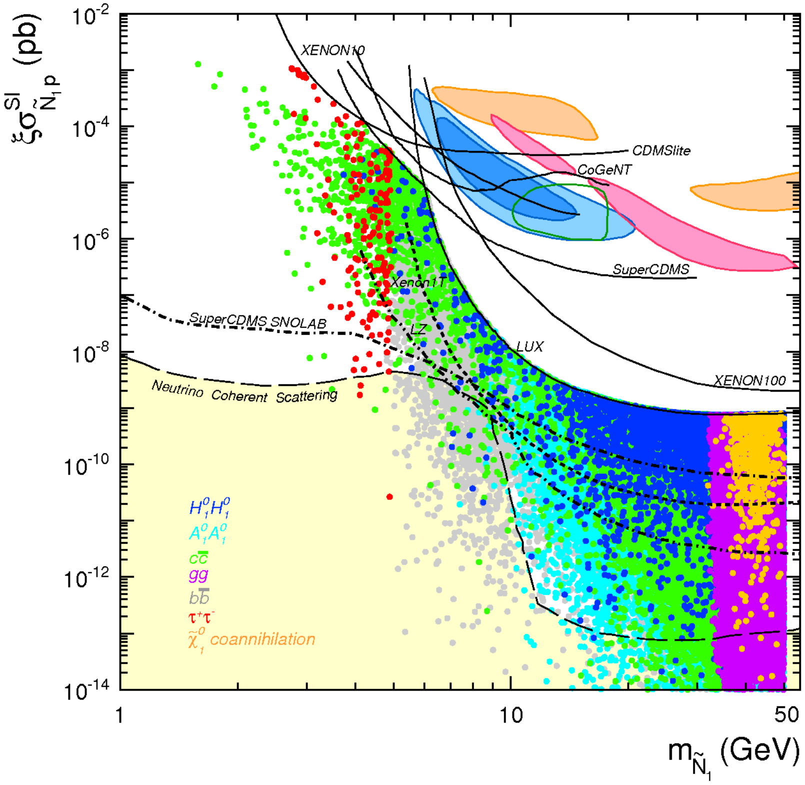


BUT COUPLED TO THE HIGGS (and therefore to SM particles)

Right-handed sneutrino in the NMSSM

The predictions span many orders of magnitude.





Indirect detection constraints remove some areas but have no impact on the lower mass of the RH sneutrino

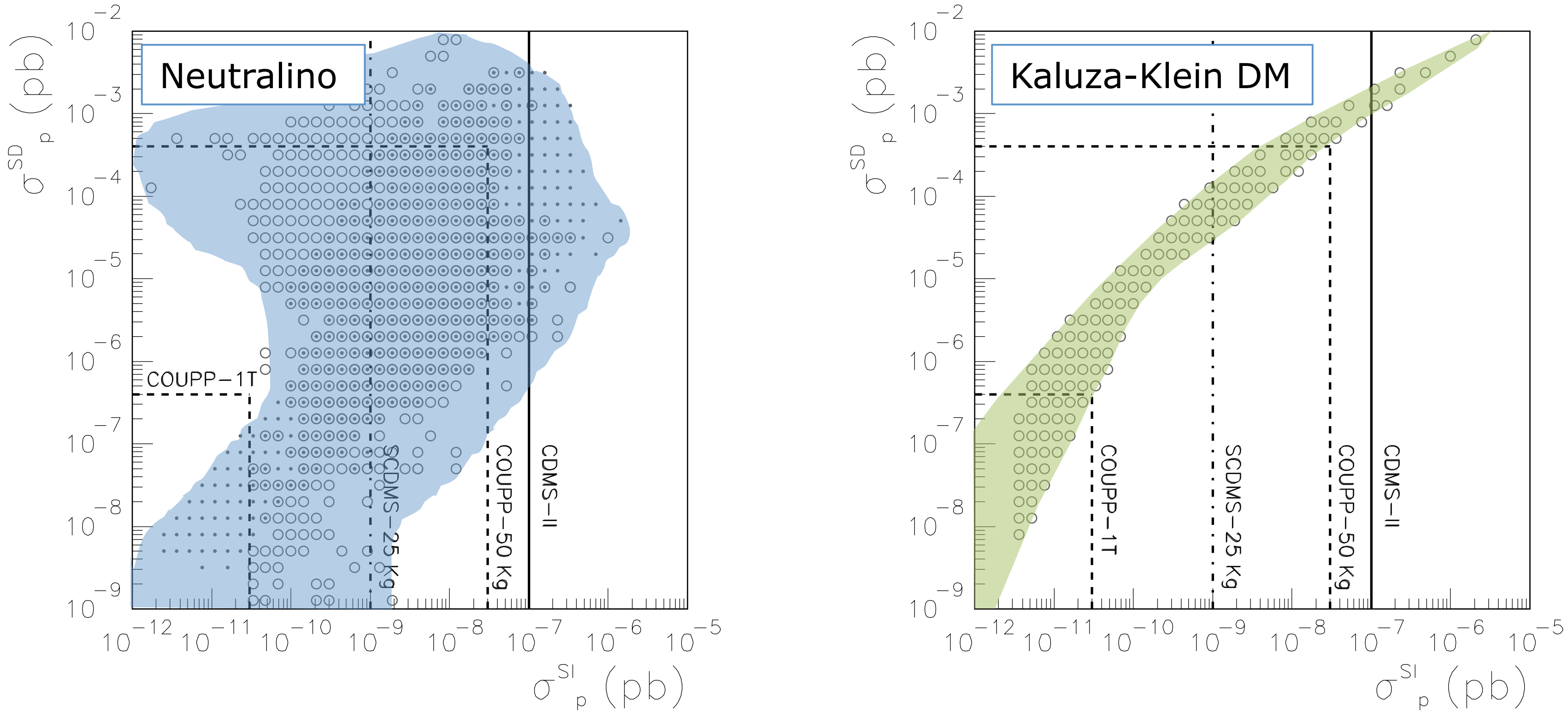
The predictions fill up the whole parameter space with $m_{\tilde{N}}>2$ GeV and a scattering cross section within the reach of second generation experiments.

This is a good motivation for low-threshold detectors.

WIMPs behave very similarly (not surprisingly)

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

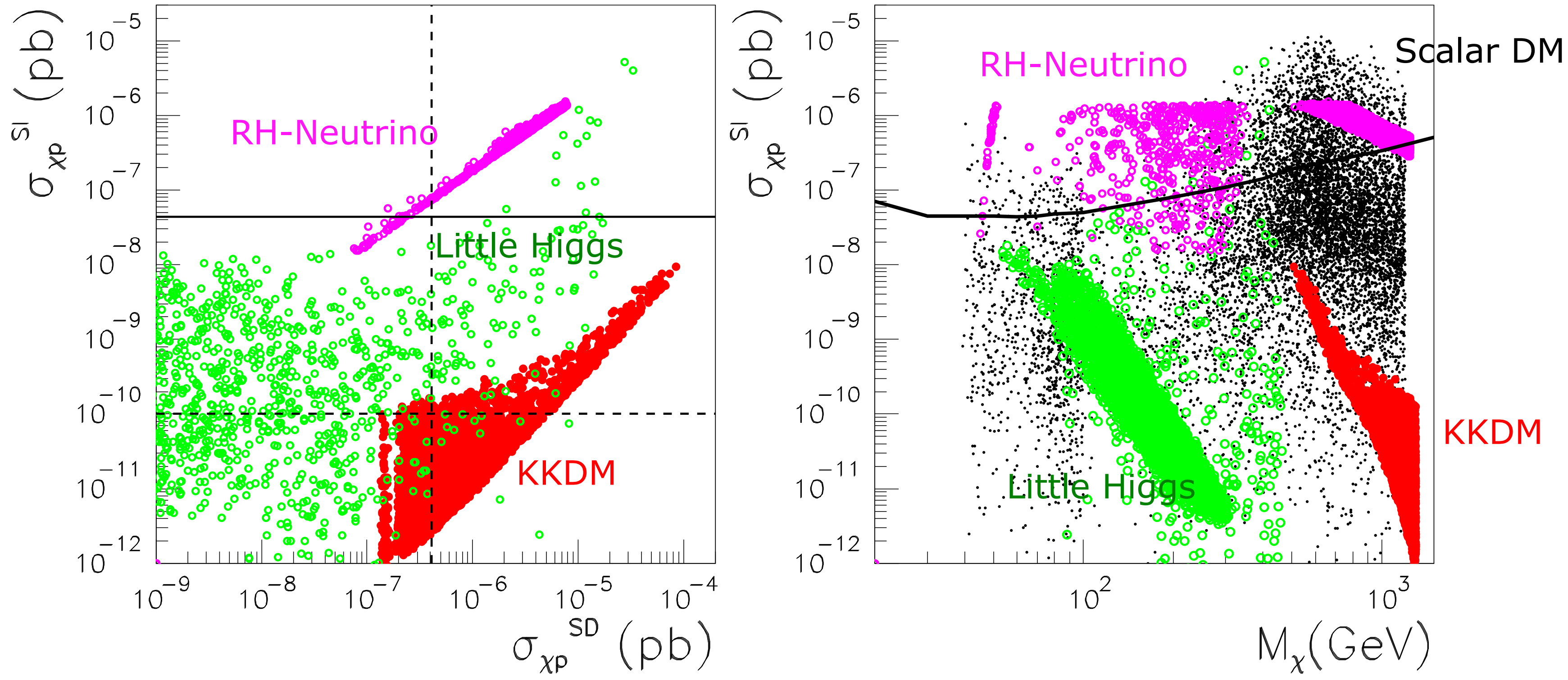
“Advance in both fronts” (spin-dependent and -independent) to gain discriminating power

Can we determine to which DM model it corresponds?

There can be 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

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

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

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

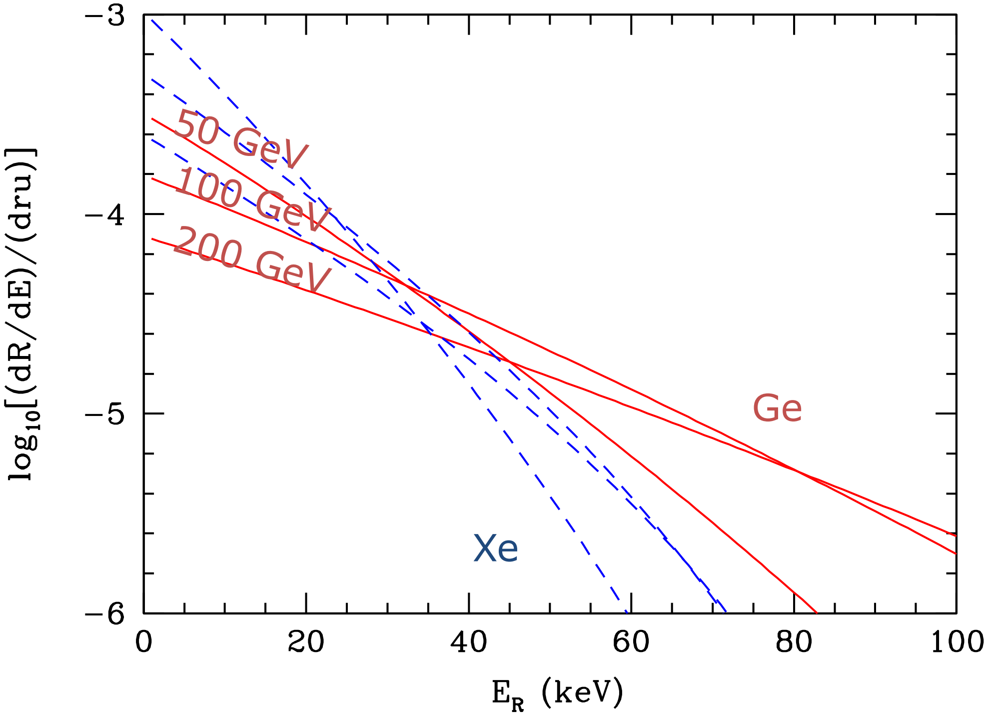
$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

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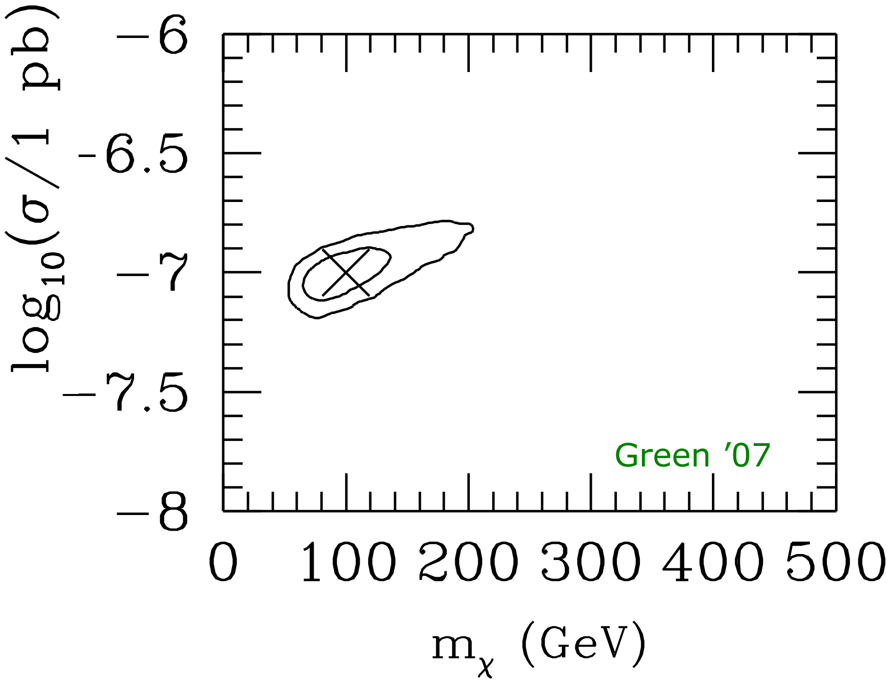
$$E_c = (c_1 2\mu_N^2 v_c^2)/m_N$$

Direct detection can only determine “phenomenological” WIMP parameters

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

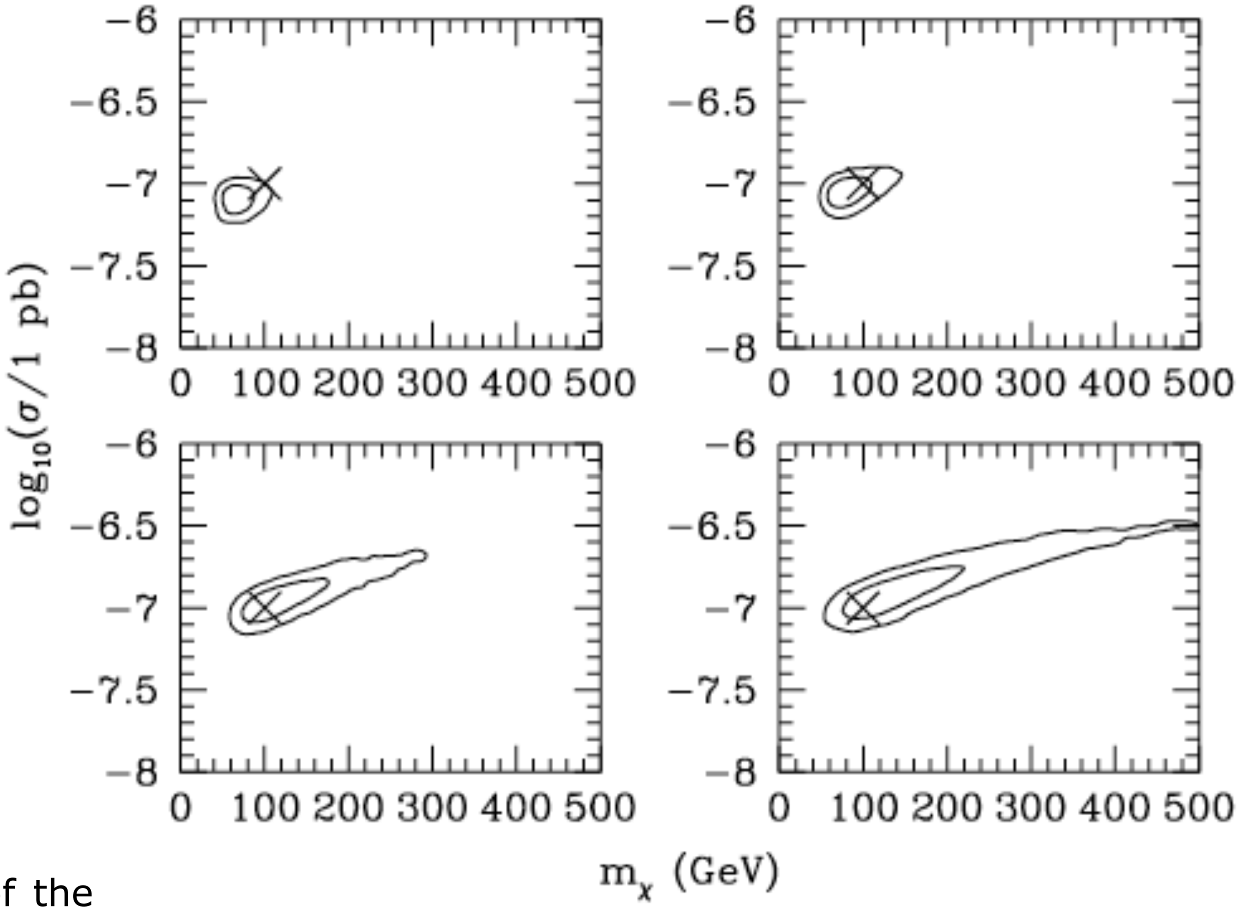


Example: m_X=100 GeV
Exposure: 3000 kg day (Ge target)

The determination is affected by uncertainties

Astrophysical uncertainties in direct DM searches

For example, on the central velocity of the DM halo

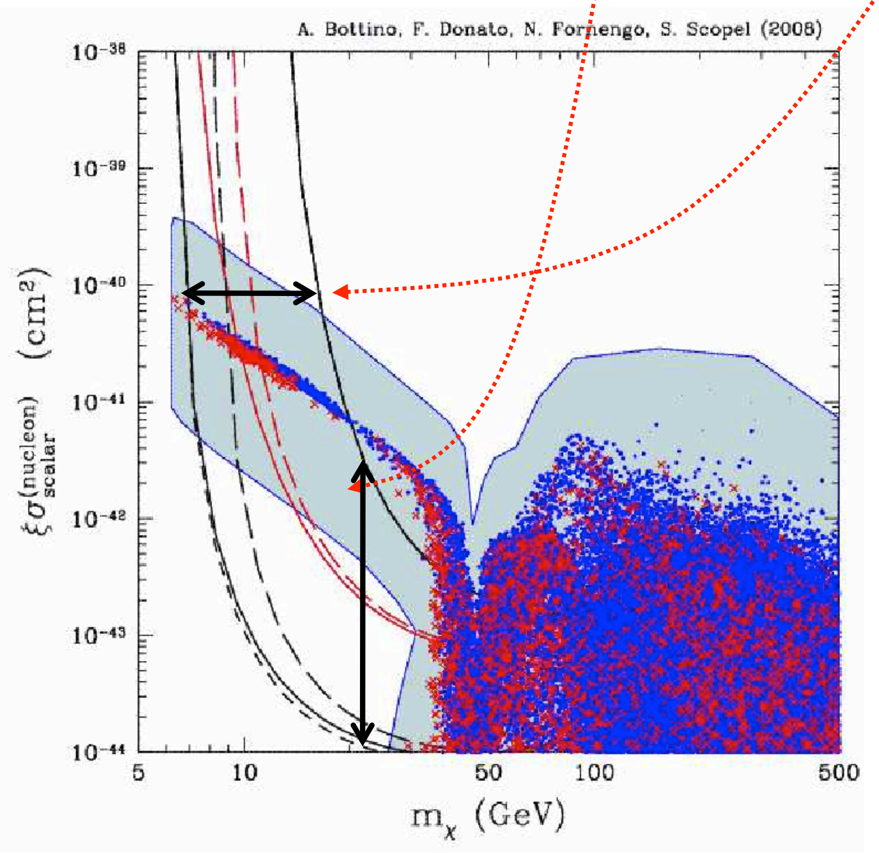


And also on the shape of the DM halo and the velocity distribution function.

Green '07

Astrophysical uncertainties in direct DM searches

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



Bottino, Donato, Fornengo, Scopel 2008

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 can be correlated

Parameterizing astrophysical uncertainties

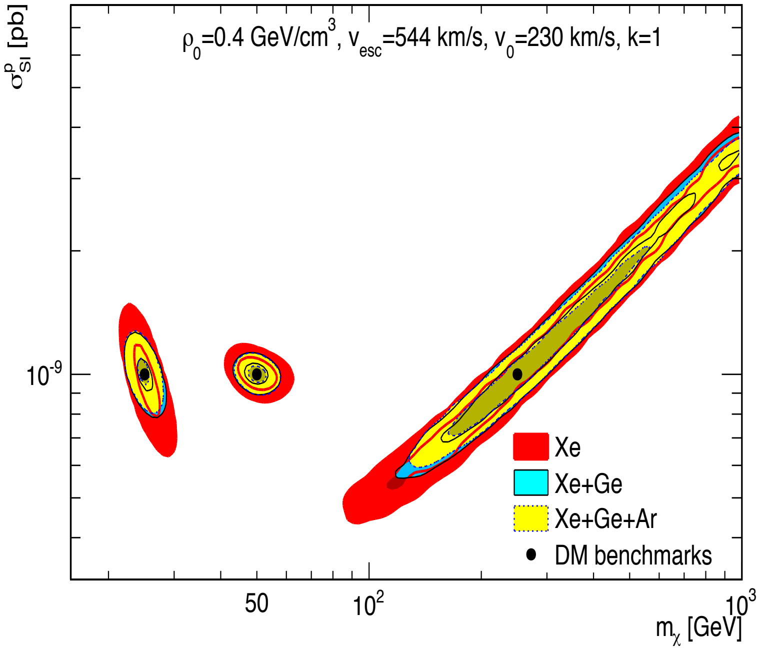
Generalization of the SHM for the velocity distribution function

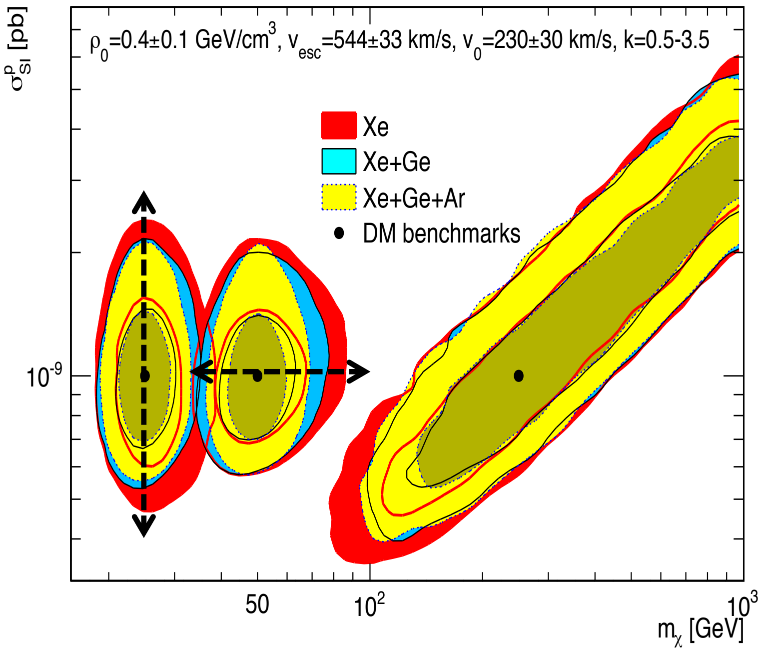
Based on Binney, Tremaine ‘08

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

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





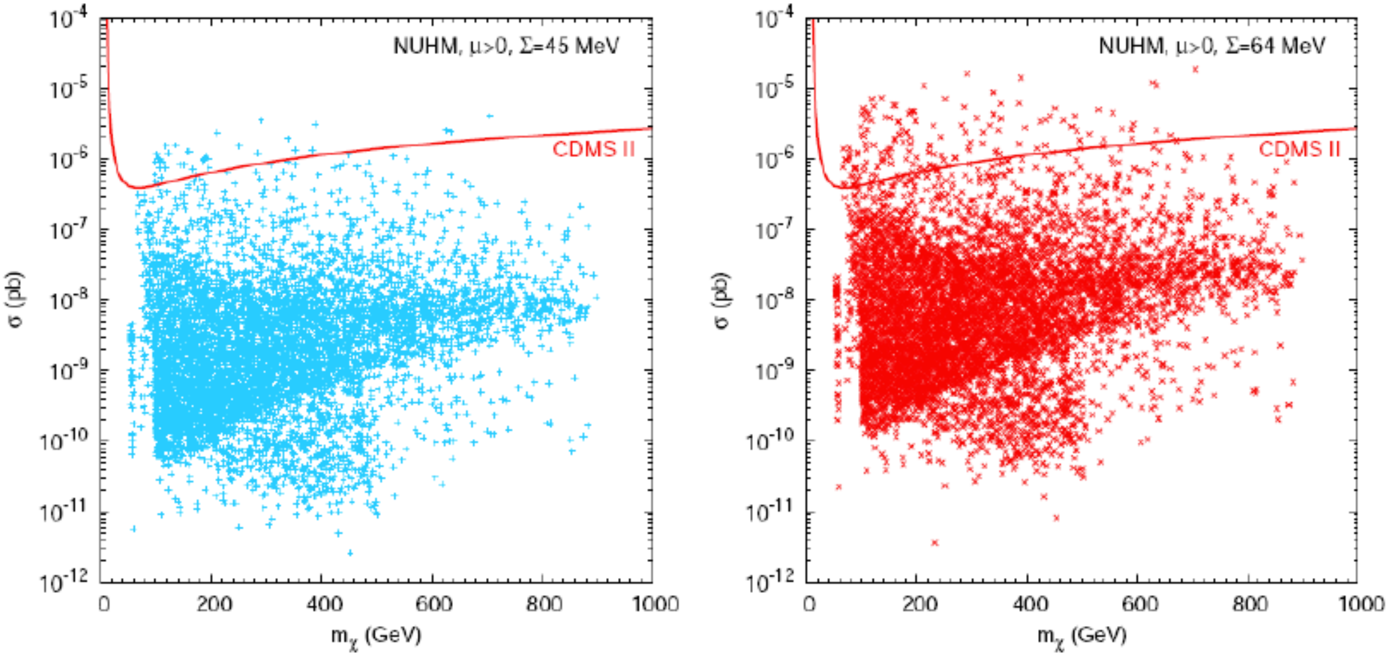
Pato, Baudis et al. 2011

Uncertainties in the hadronic matrix elements can also be responsible for a large uncertainty in the predicted cross-section. E.g., the π-nucleon sigma term

$$\Sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\,\langle N|\bar{u}u + \bar{d}d|N\rangle = (64 \pm 8)\,\mathrm{MeV}$$

Leads to an uncertainty of ~ a factor 4 in the s-quark composition in nucleons

Which implies approx 1 order of magnitude in theoretical predictions!



(Ellis, Olive, Santoso, Spanos '05)

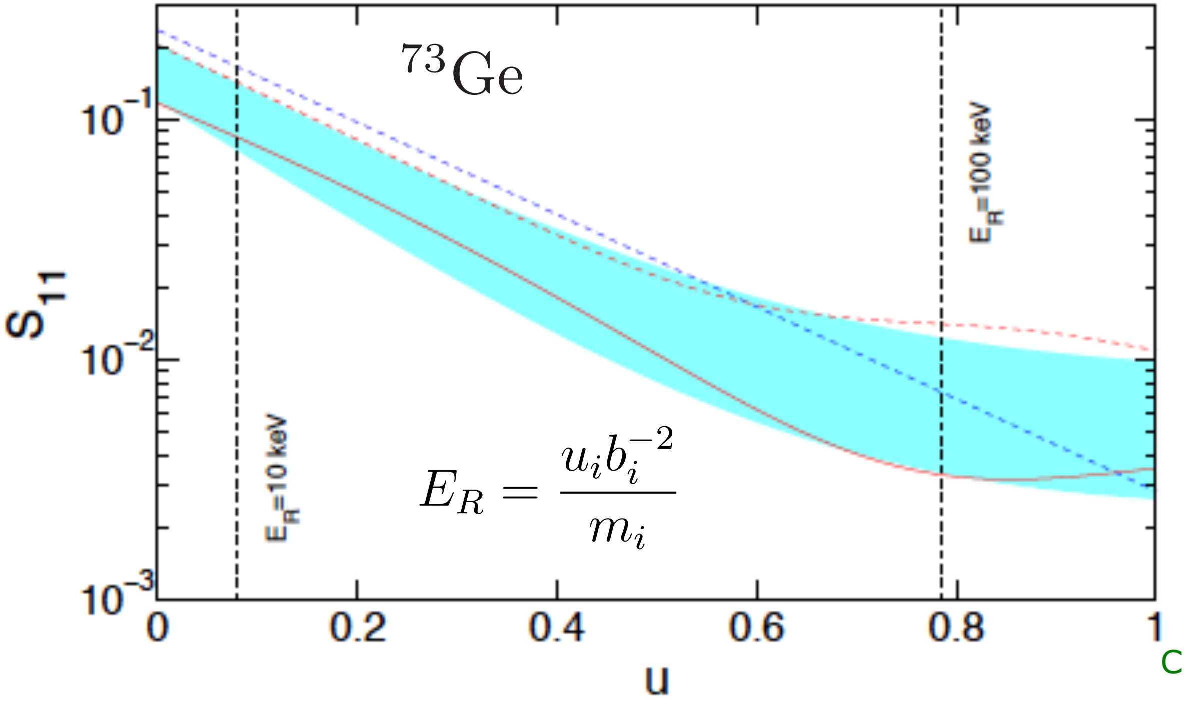
Uncertainties in the spin-dependent form factors

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

$$a_0 = a_p + a_n$$

$$a_1 = a_p - a_n$$

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



ShM COMPUTATIONS:

Ressel, et al. ‘93

Dimitrov, et al. ‘94

Variations in

- Zero-momentum value
- Slope
- Plateau

Cerdeno, Fornengo, Huh, Peiro 2012

Uncertainties in the spin-dependent form factors

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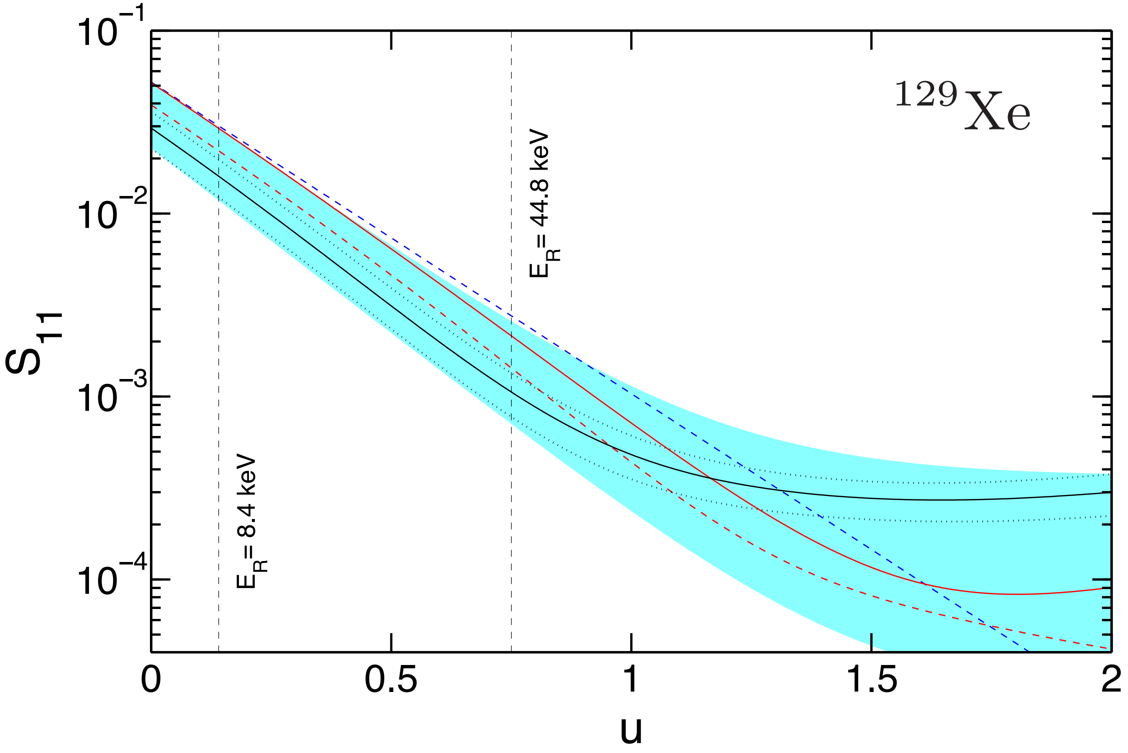


ShM COMPUTATIONS:

Bonn A / Nijmegen II

Ressel, Dean '97

gcn5020 interaction

Menéndez, Gazit, Schwenk '12

Variations in

- Zero-momentum value
- Slope
- Plateau

Cerdeno, Fornengo, Huh, Peiro 2012

There are degeneracies in reconstructing the phenomenological parameters.

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

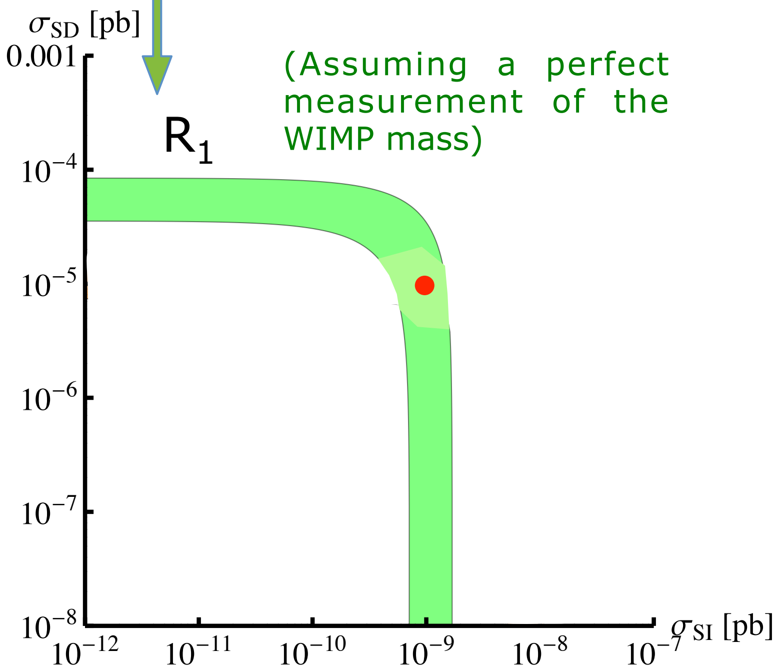
$$R_1 = A_1 \sigma_0^{SI} + \left(B_1^p \sqrt{\sigma_0^{SD,p}} + B_1^n \sqrt{\sigma_0^{SD,n}} \right)^2$$

Target-dependent

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

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

Determination of both SD and SI cross section



(Assuming a perfect measurement of the WIMP mass)

The same rate can be explained by a candidate with

Mostly spin-dependent interactions

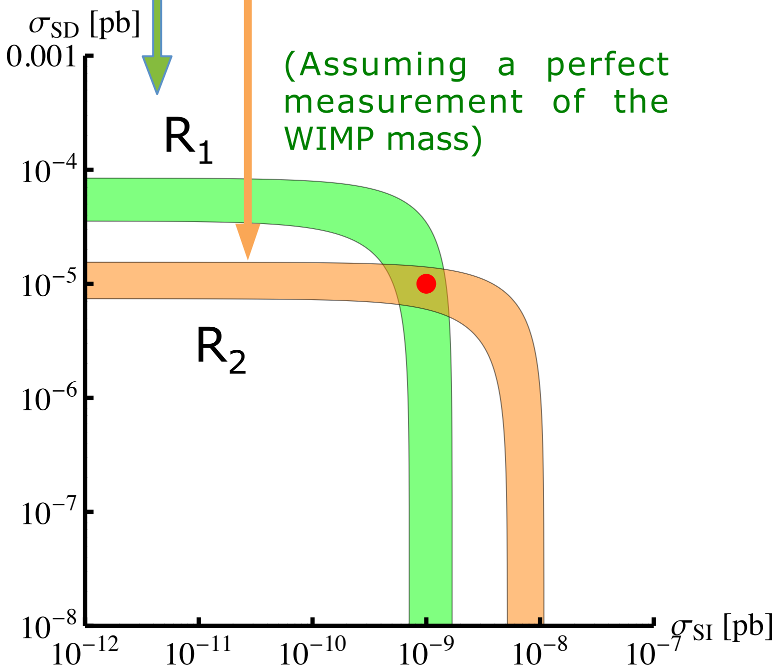
Mostly spin-independent interactions

NB: in fact we should take into account SD-interactions with protons and neutrons separately (i.e. 3D plots) – not in this talk.

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

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

Determination of both SD and SI cross section



(Assuming a perfect measurement of the WIMP mass)

Complementarity of targets

- One target mostly SI and the other mostly SD

Bertone, DGC, Collar, Odom 2007

- Large exposure → smaller area

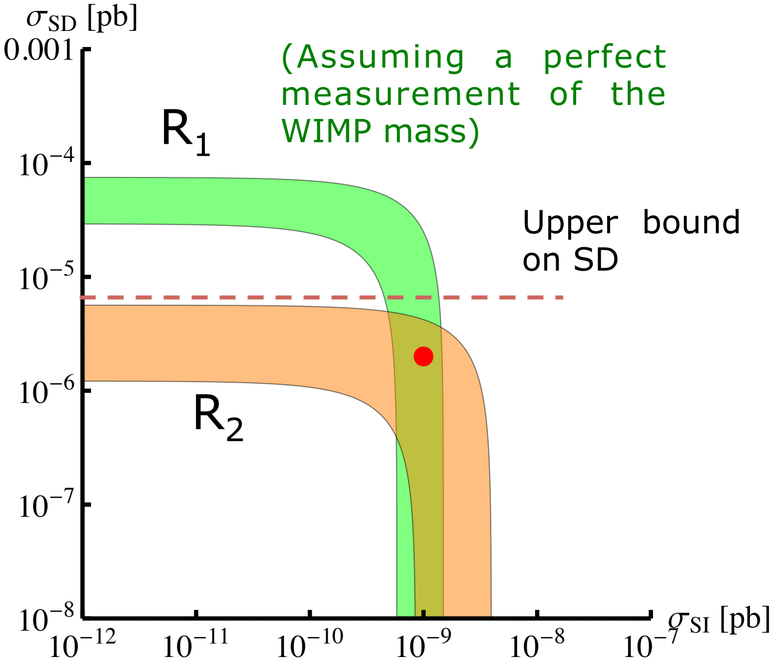
Analytical determination of the parameters without uncertainties (ideal)

Cannoni, Gómez, Vergados 2010
Cannoni 2011

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

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

Determination of only the SI cross section



The most common situation

- Most targets are more sensitive to the SI component
  (e.g. Ge, Xe, I)
- Heavy targets or heavy WIMPs
- Small SD cross section

The inclusion of uncertainties is CRUCIAL

Astrophysical uncertainties

Nuclear uncertainties:
Uncertainties in the Spin-dependent form factor can lead to a misreconstruction of WIMP parameters

D.G.C. Fornasa, Huh, Peiro 2012

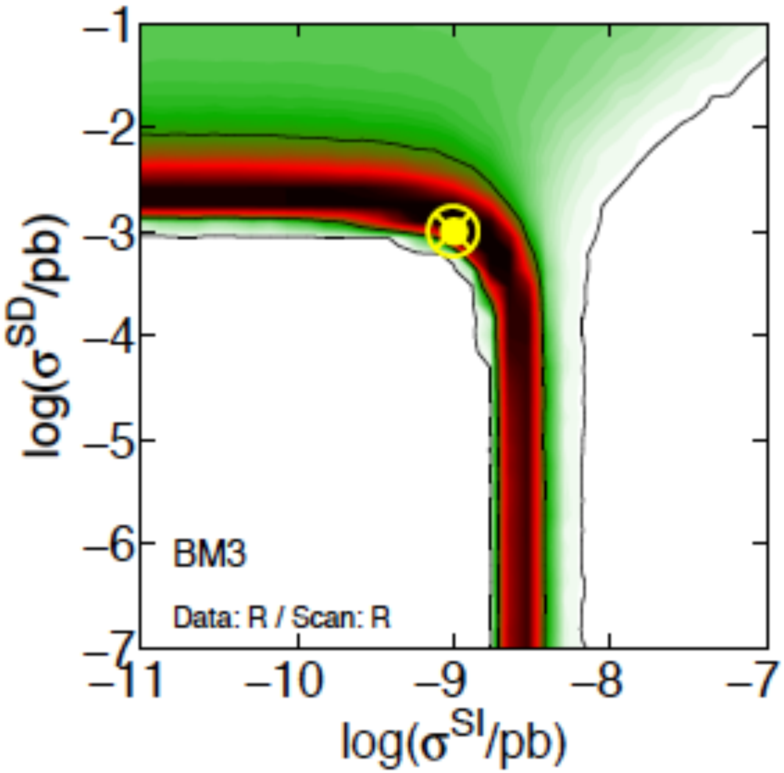
Varitions in

- Zero-momentum value
- Slope
- Plateau

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

$$\sigma_0^{SD} = 10^{-3}\,\mathrm{pb}$$

$$m_W = 100\,\mathrm{GeV}$$



We introduce a 3-dimensional parametrization

$$S_{ij}(u) = N\left((1-\beta)e^{-\alpha u} + \beta\right)$$

	N	α	β
^{73}Ge	$0.12 - 0.21$	$0.020 - 0.042$	$5.0 - 6.0$
^{129}Xe	$0.029 - 0.052$	$4.2 - 4.7$	$1.0 \times 10^{-3} - 7 \times 10^{-3}$
^{131}Xe	$0.017 - 0.027$	$4.3 - 5.0$	$4.2 \times 10^{-2} - 6.1 \times 10^{-2}$

Reconstruction with a fixed model for the SD form factor

Variations in

- Zero-momentum value
- Slope
- Plateau

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

$$\sigma_0^{SD} = 10^{-3}\,\mathrm{pb}$$

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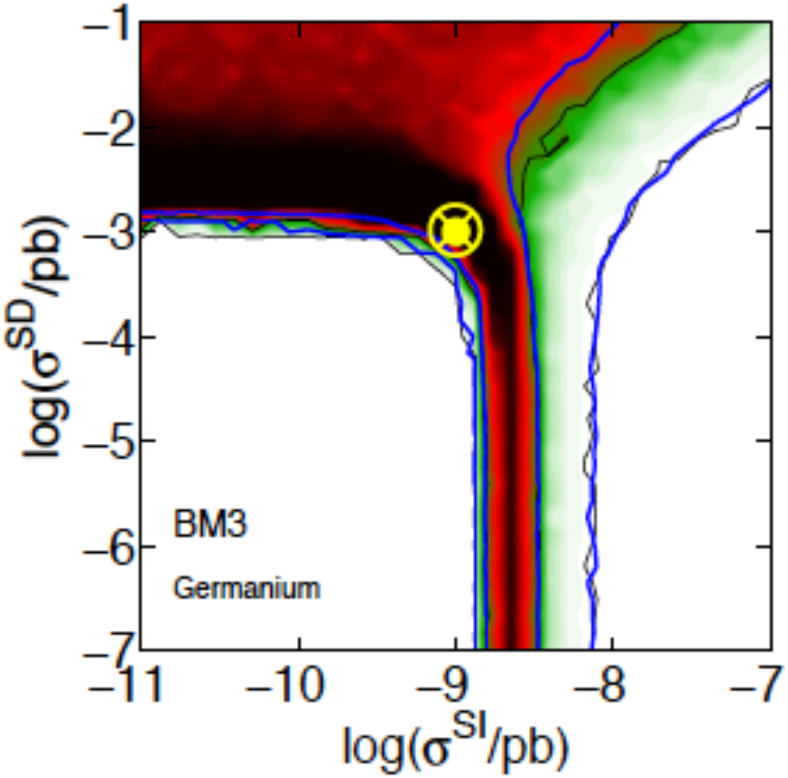

BLACK = Reconstruction with uncertainties in the SD form factor

BLUE = Astrophysical uncertainties

Effects are only important when the SD contribution is sizable

Variations in

- Zero-momentum value
- Slope
- Plateau

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

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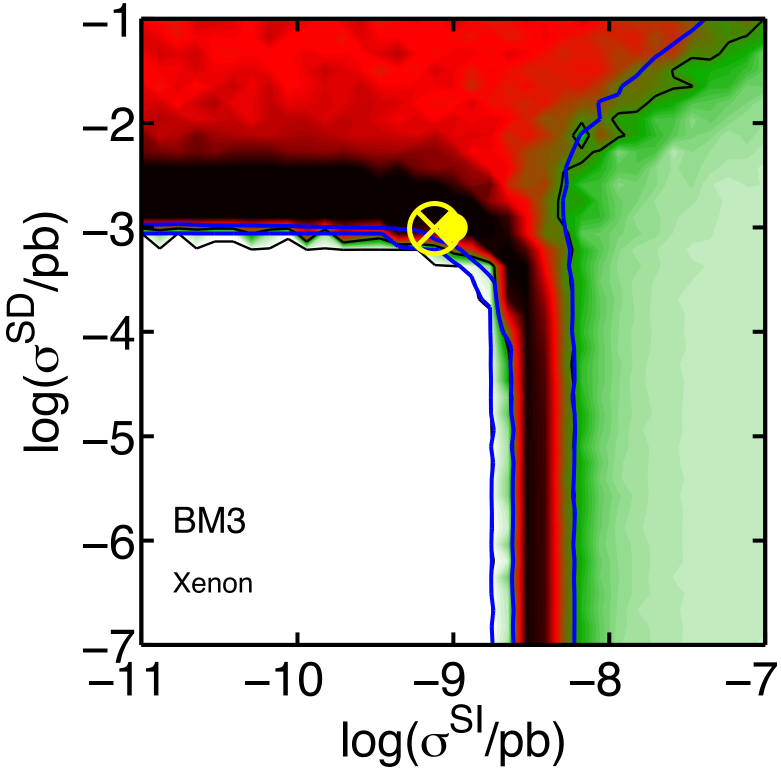


BLACK = Reconstruction with uncertainties in the SD form factor

BLUE = Astrophysical uncertainties

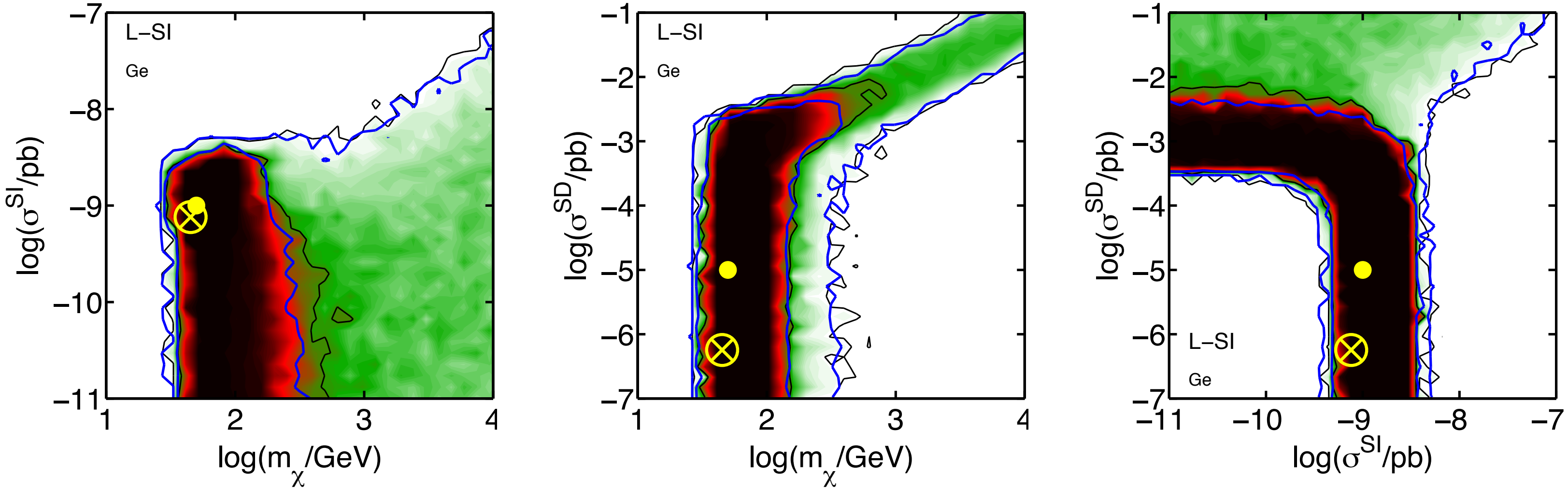
Effects are only important when the SD contribution is sizable

Quantitatively similar for XENON or CDMS

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. SuperCDMS)



$$\boxed{\begin{aligned} \sigma_0^{SI} &= 10^{-9}\,\mathrm{pb} \\ \sigma_0^{SD} &= 10^{-5}\,\mathrm{pb} \\ m_W &= 50\,\mathrm{GeV} \\ \epsilon &= 300\,\mathrm{kg\,yr} \end{aligned}}$$

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

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

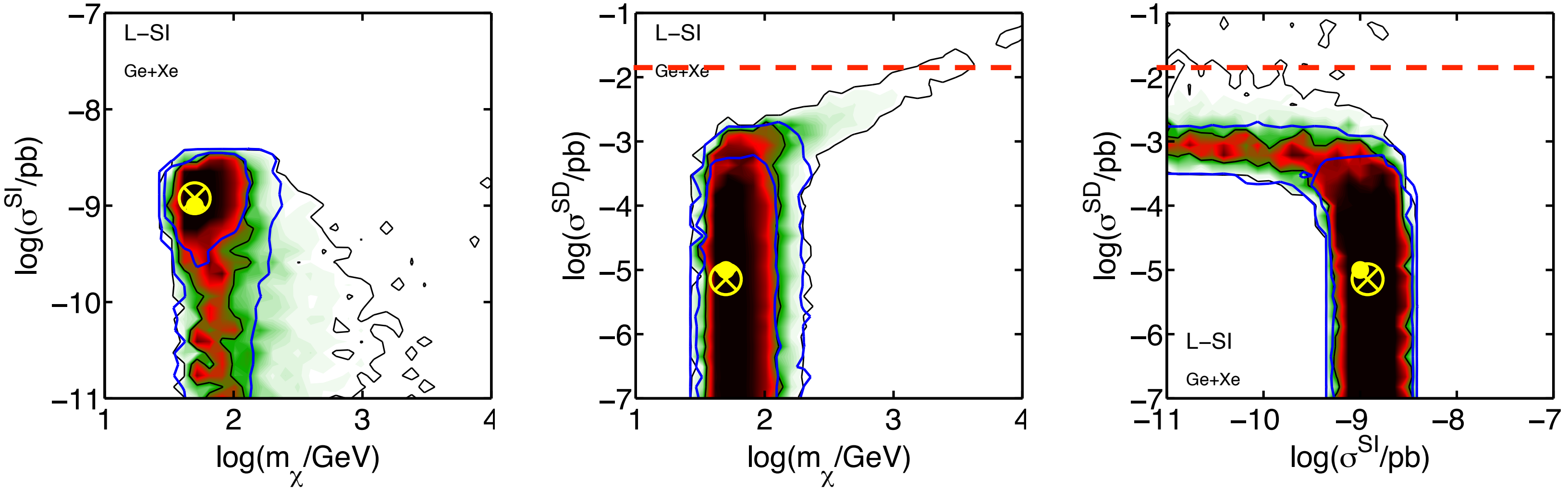
Detection with two experiments

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

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

Ge detector (e.g. SuperCDMS)

Xe detector (e.g. Xenon)



$$\boxed{\begin{aligned} \sigma_0^{SI} &= 10^{-9}\,\mathrm{pb} \\ \sigma_0^{SD} &= 10^{-5}\,\mathrm{pb} \\ m_W &= 50\,\mathrm{GeV} \\ \epsilon &= 300\,\mathrm{kg\,yr} \end{aligned}}$$

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

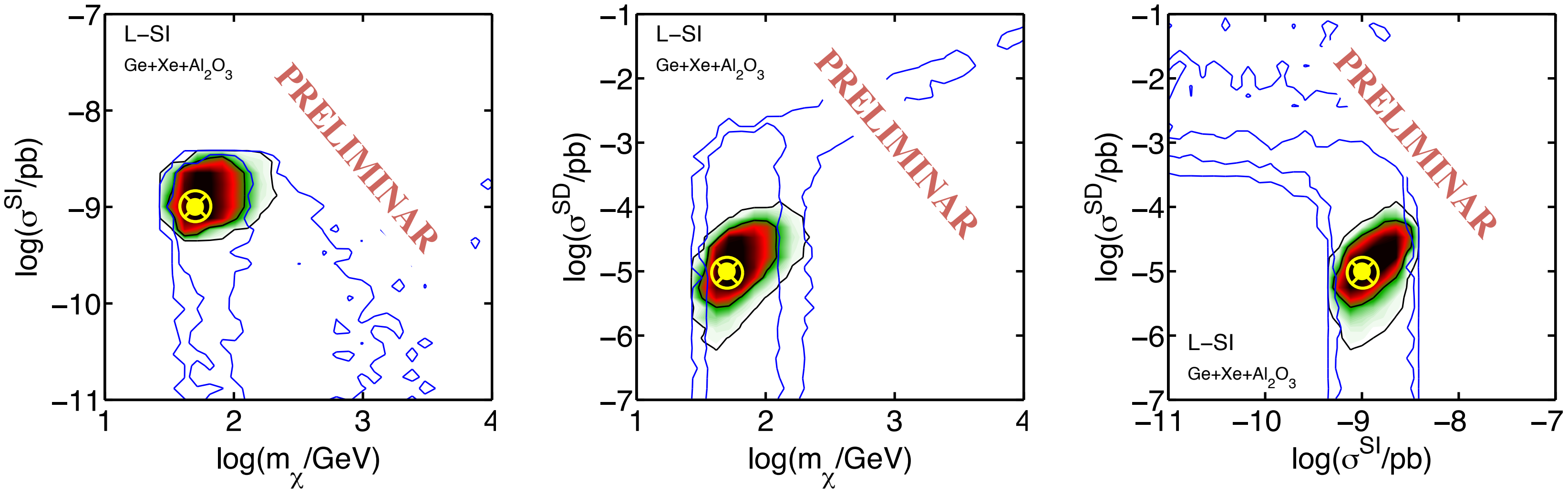
Fluorine? – e.g., used in COUPP

Detection with three experiments

Ge detector (e.g. SuperCDMS)

Xe detector (e.g. Xenon)

+ EURECA (Al_2O_3)
300 kg yr



$$\sigma_0^{SI} = 10^{-9}\,\mathrm{pb}$$
$$\sigma_0^{SD} = 10^{-5}\,\mathrm{pb}$$
$$m_W = 50\,\mathrm{GeV}$$
$$\epsilon = 300\,\mathrm{kg\,yr}$$

Degeneracies can be removed and the phenomenological parameters determined

The needed exposure depends on the actual point in the parameter space

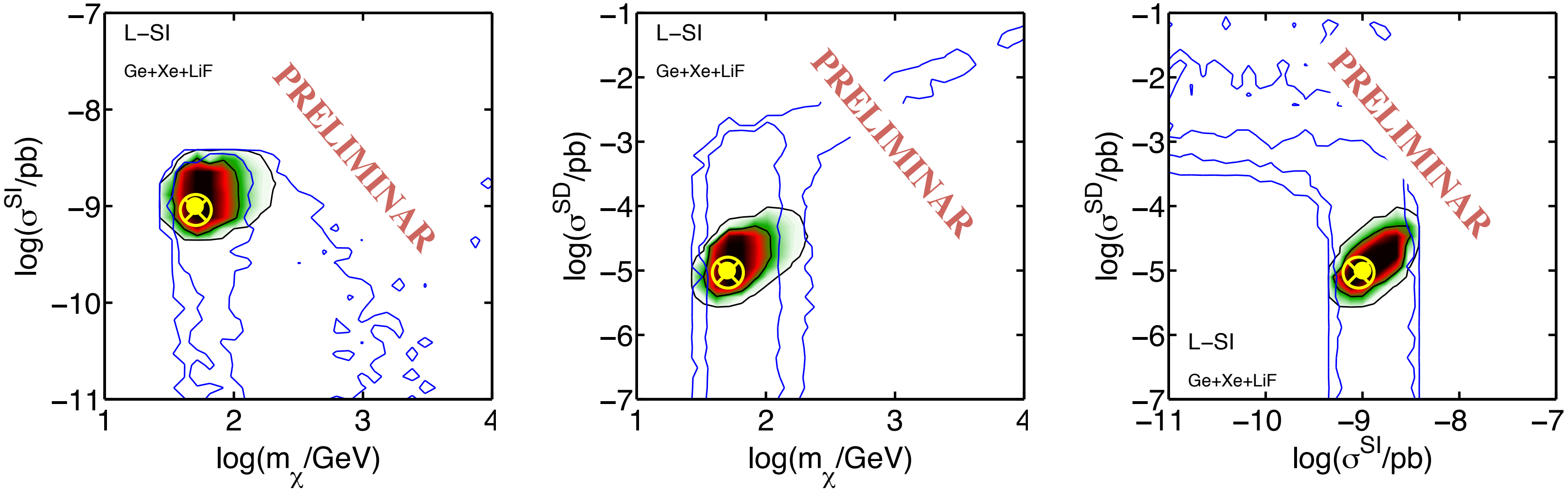
In progress: testing other possible targets and the whole parameter space

Detection with three experiments

Ge detector (e.g. SuperCDMS)

Xe detector (e.g. Xenon)

+ EURECA (LiF)
300 kg yr



$$\sigma_0^{SI} = 10^{-9}\,\text{pb}$$
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$$\epsilon = 300\,\text{kg yr}$$

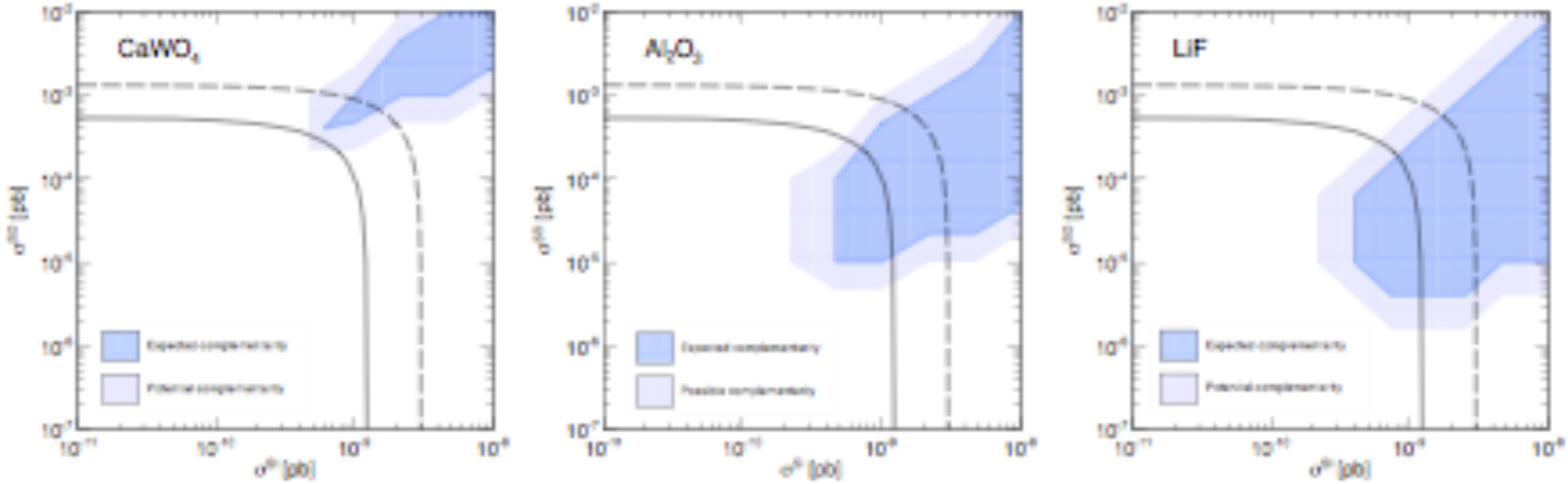
Degeneracies can be removed and the phenomenological parameters determined

The needed exposure depends on the actual point in the parameter space

In progress: testing other possible targets and the whole parameter space

We have scanned the parameter space looking for the regions in which each target provides complementarity

300 kg yr of Ge + 300 kg yr of Xe + 300 kg yr of (LiF, Al_2O_3 or $CaWO_4$)
m_{WIMP} = 50 GeV



$CaWO_4$ is more sensitive to the SI contribution

It provides more information in those points in which the scattering in Ge or Xe is mostly SD

Al_2O_3 and LiF are more sensitive to the SD contribution

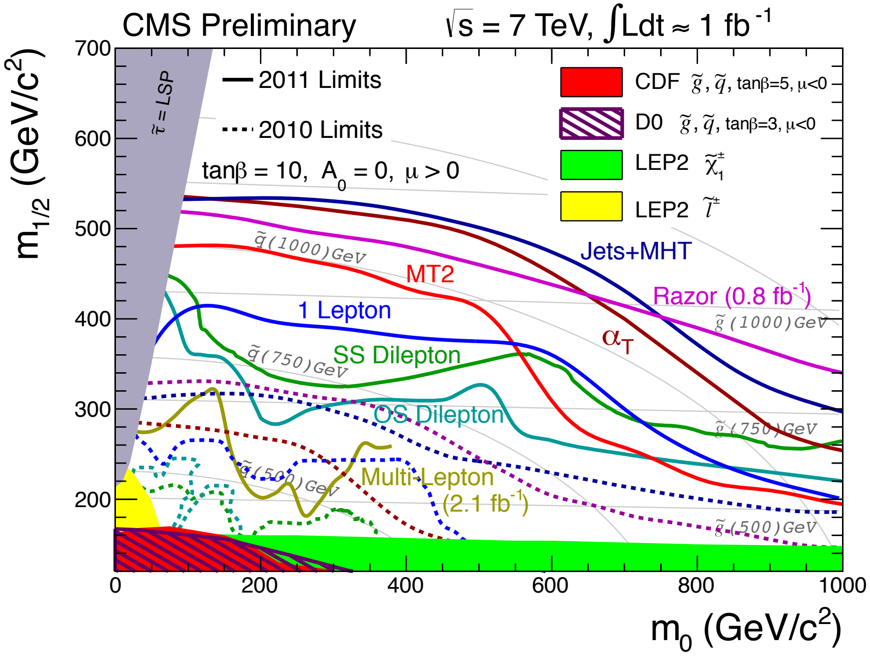
They are ideal in points in which the scattering in Ge or Xe is mostly SI (more often)

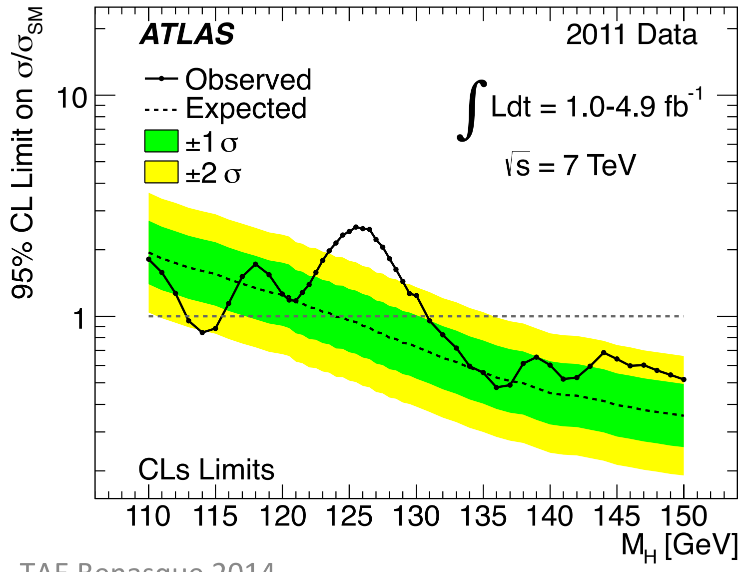
Dark matter in colliders

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

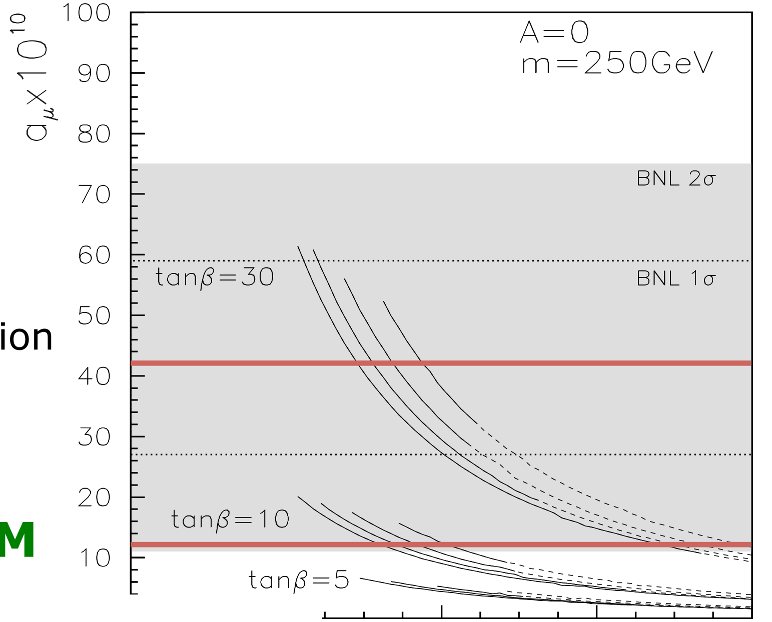
A determination of the Higgs mass also has implications for the DM annihilation and detection processes

Muon anomalous magnetic moment

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

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

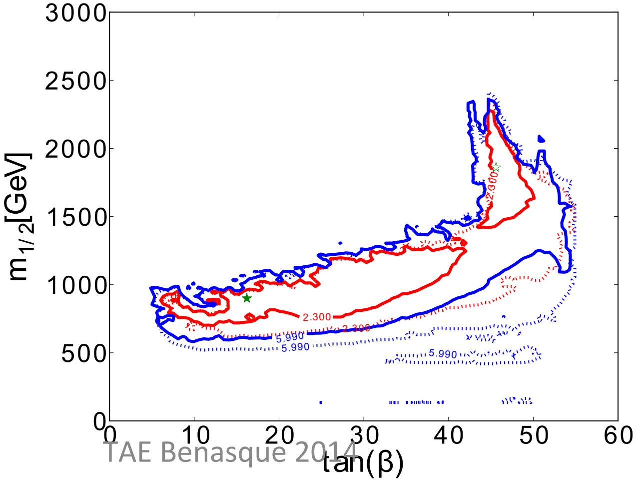
$$2.9 \times 10^{-10} < a_\mu^{SUSY} < 36.1 \times 10^{-10}$$

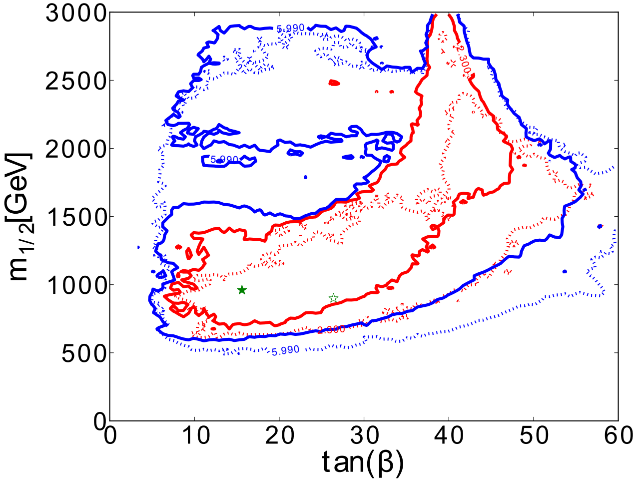


LHC lower bounds on SUSY masses imply some tension for specific models: large tanβ preferred

CMSSM

NUHM





Buchmuller et al. '12

Muon anomalous magnetic moment

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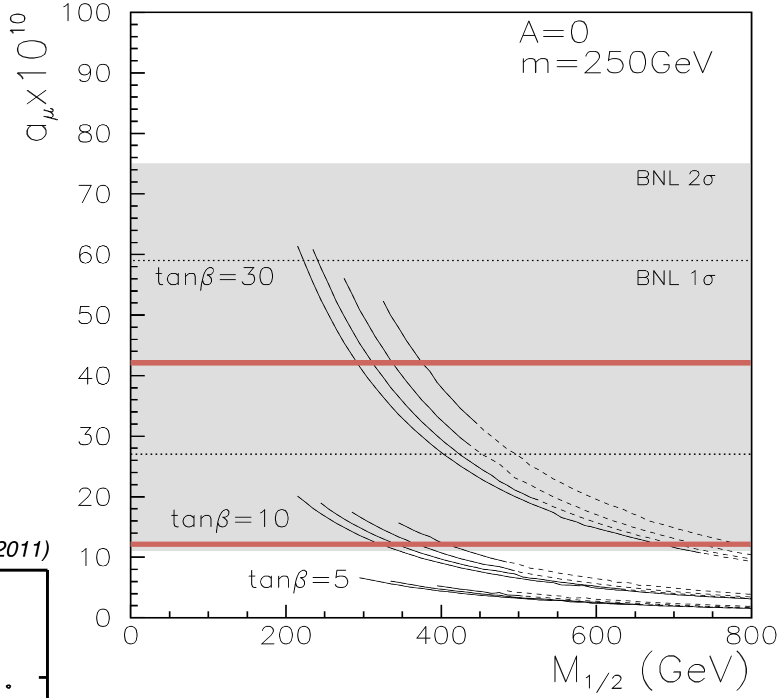
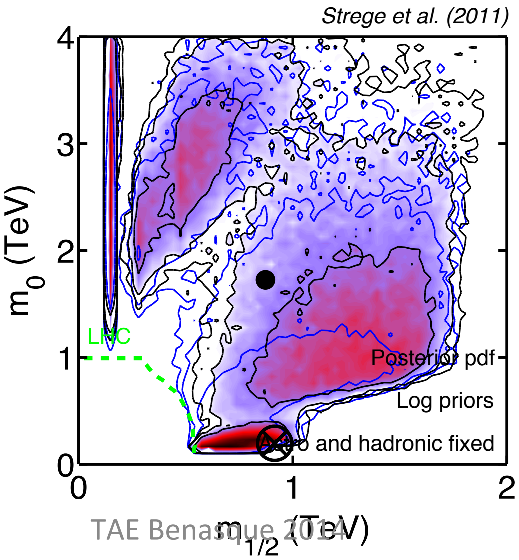
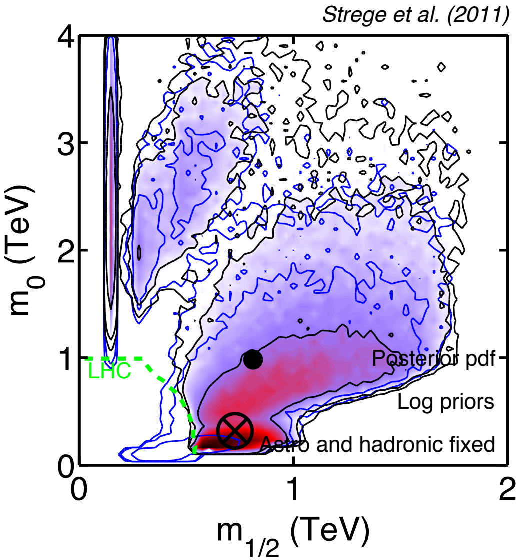


IF DM relic density is also imposed only a few regions of the parameter space survive... Heavier points are also disfavoured

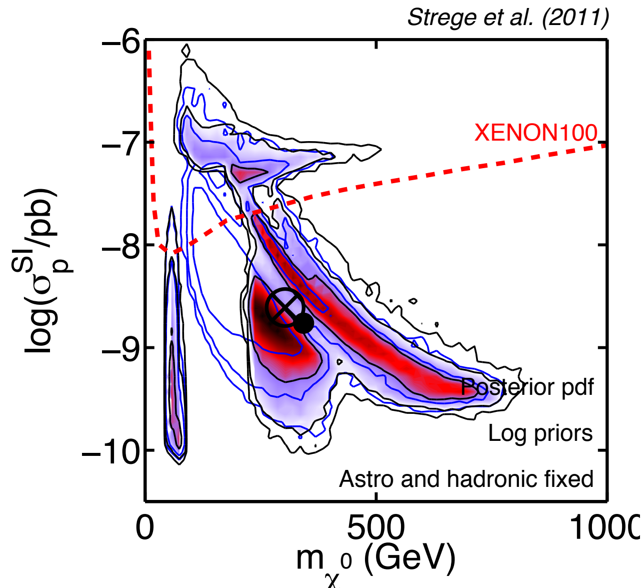


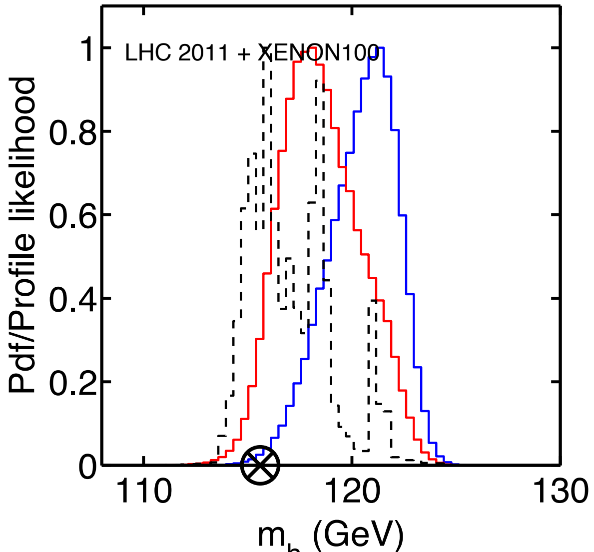


Strege et al. '11

Implications for dark matter

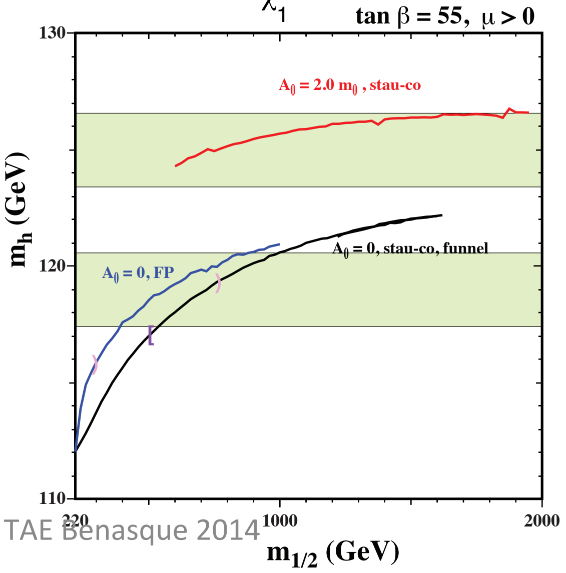
LHC constraints INDIRECTLY lead to constraints on the DM model

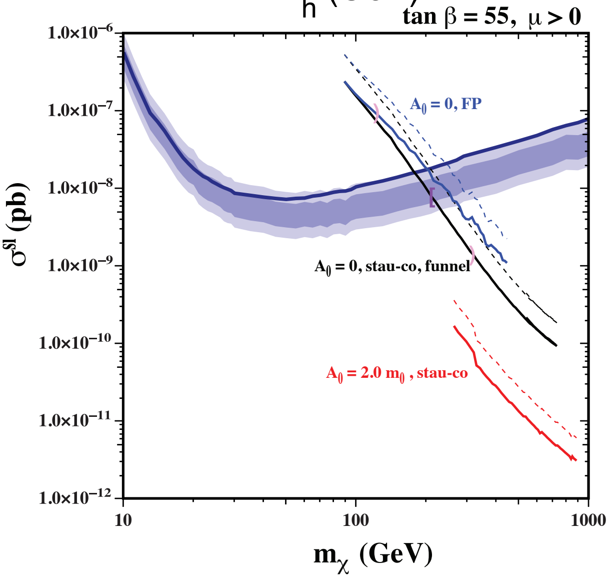




A lower bound in the neutralino mass is found that excludes some regions with large scattering cross-section IN THE CMSSM

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

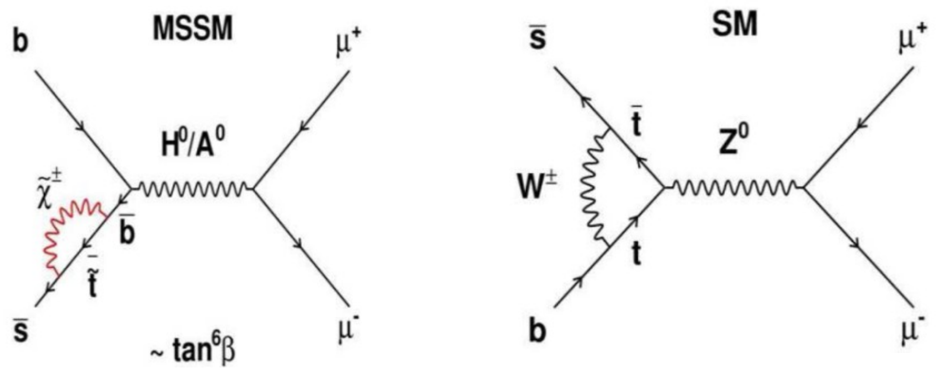
Ellis, Olive 2012

Constraints from rare decays

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

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

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



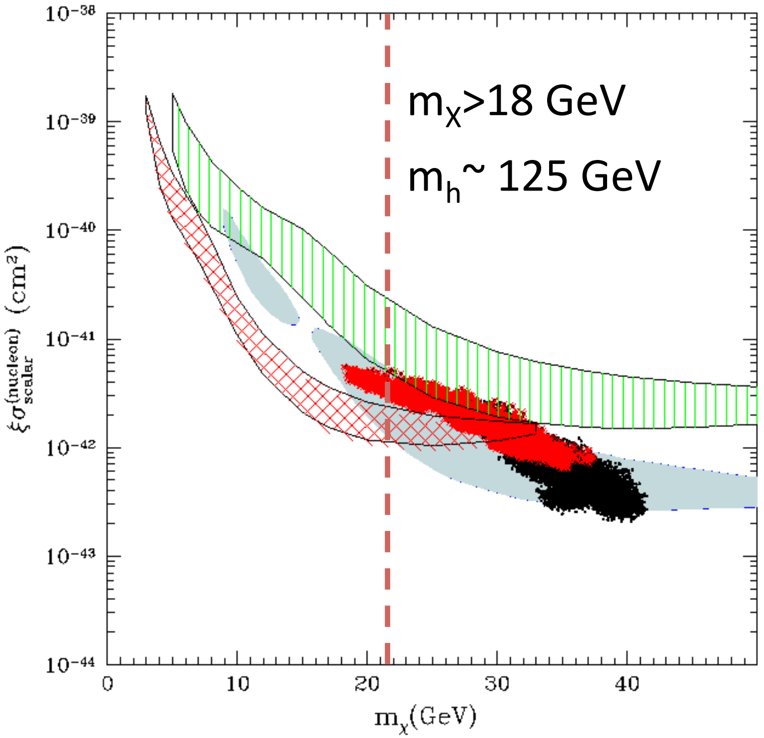
$$\mathrm{B}(B_s^0 \to \mu^+\mu^-) \propto \frac{\tan^6\beta}{m_A^4}\left(\frac{\mu A_t}{m_{\tilde{t}_L}^2}\right)^2$$

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

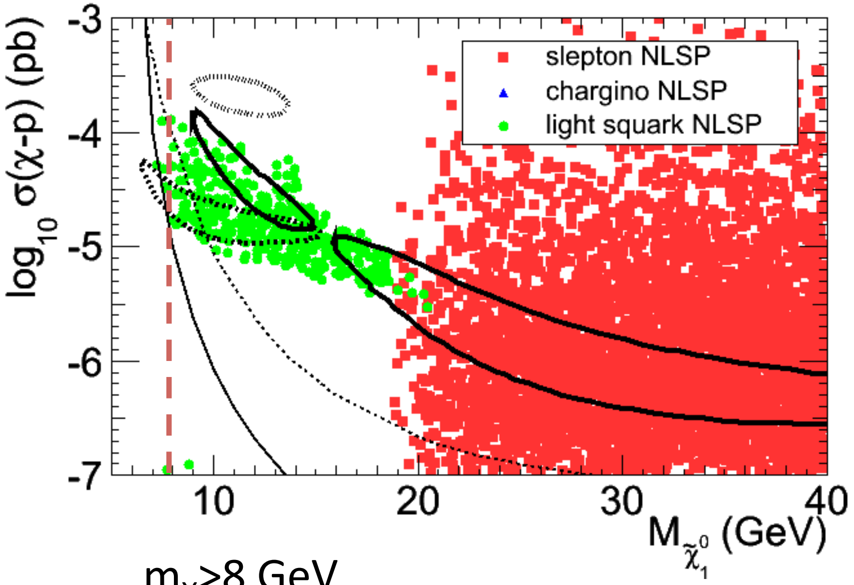
- Models for very light neutralino dark matter (small m_A, large tanb)



m_χ>18 GeV

m_h~ 125 GeV

Bottino, Fornengo, Scopel 2011

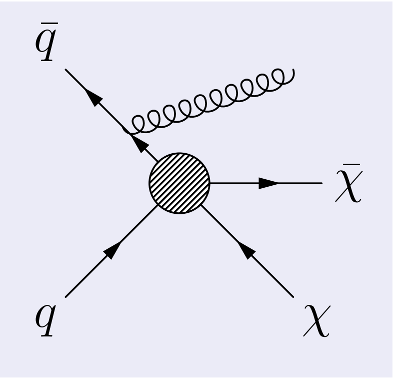


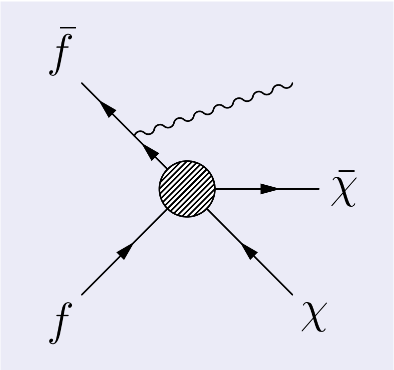
m_χ>8 GeV

Arbey, Battaglia, Mahmoudi 2012

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

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

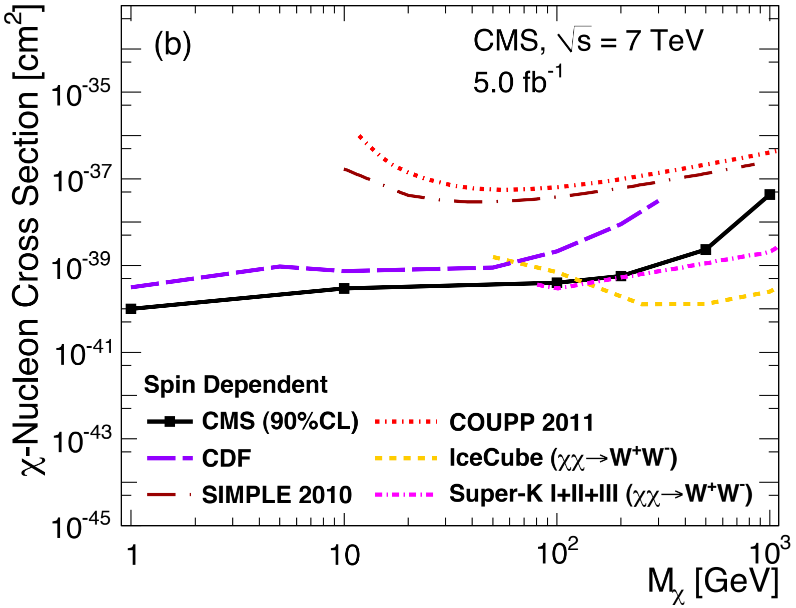


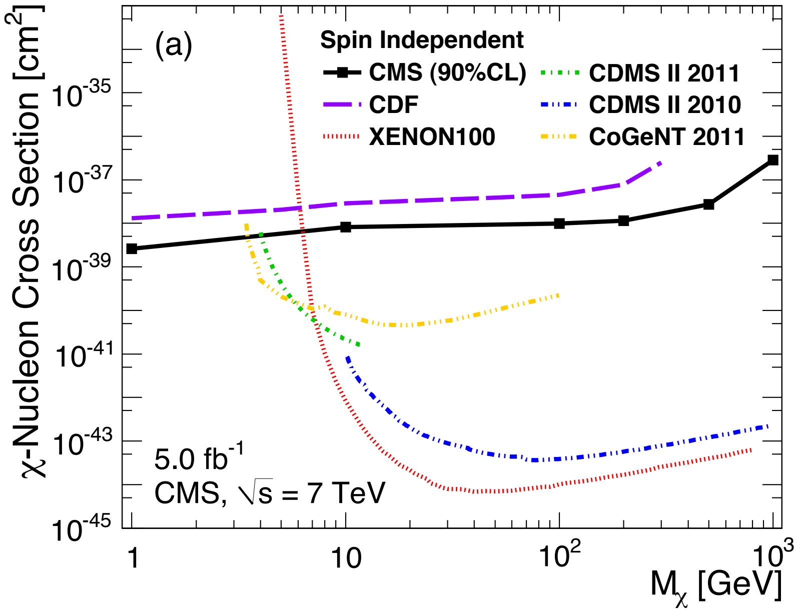


Dark matter production with initial state radiation

Bounds depend on the DM effective operators to fermions

LHC data (see also previous results from Tevatron)





(CMS-PAS-EXO-11-096)

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) (DAMA/LIBRA, CoGeNT, CRESST, CDMS-II)

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

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

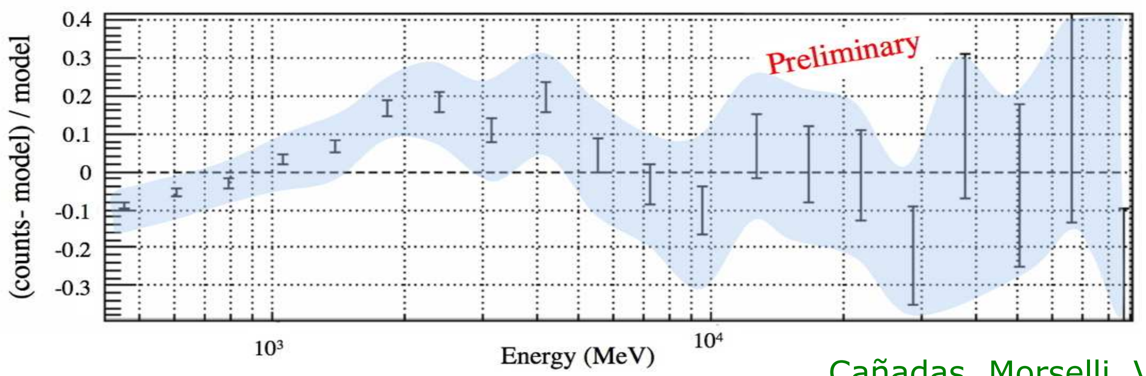
LHC alone cannot determine the DM properties (or if it is the DM at all), need combination with direct or/and indirect searches

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

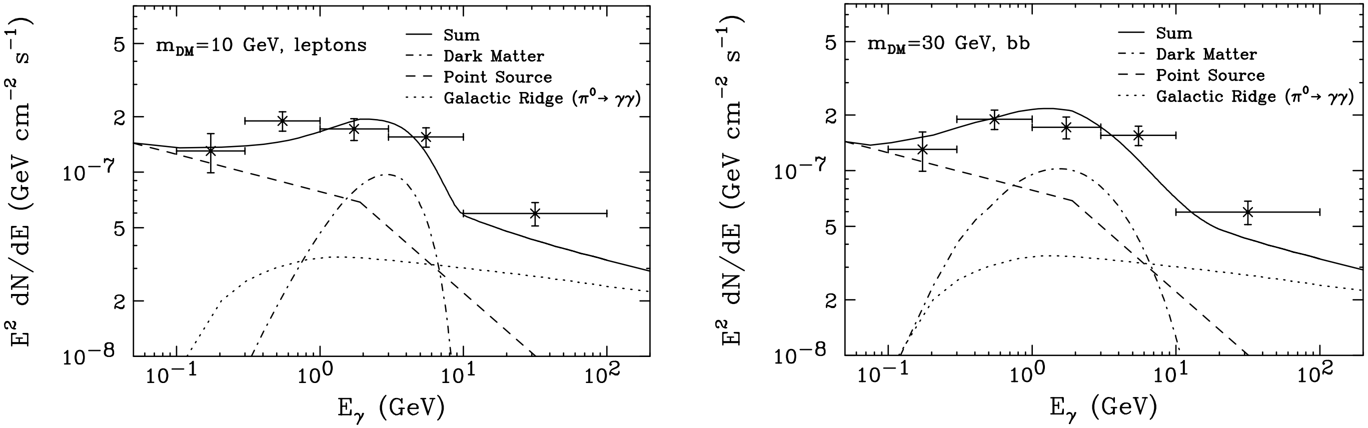
Hints for very light DM?

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



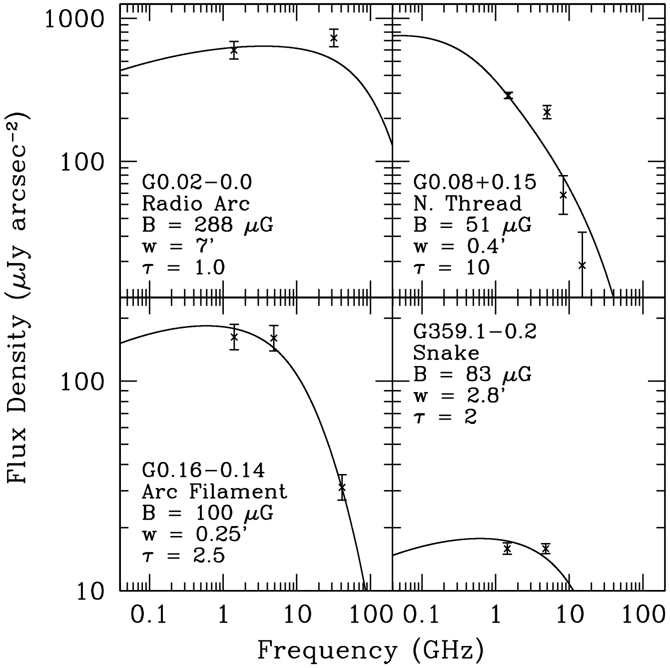
Hooper, Goodenough 2011; Hooper, Linden 2011

Hints for very light DM?

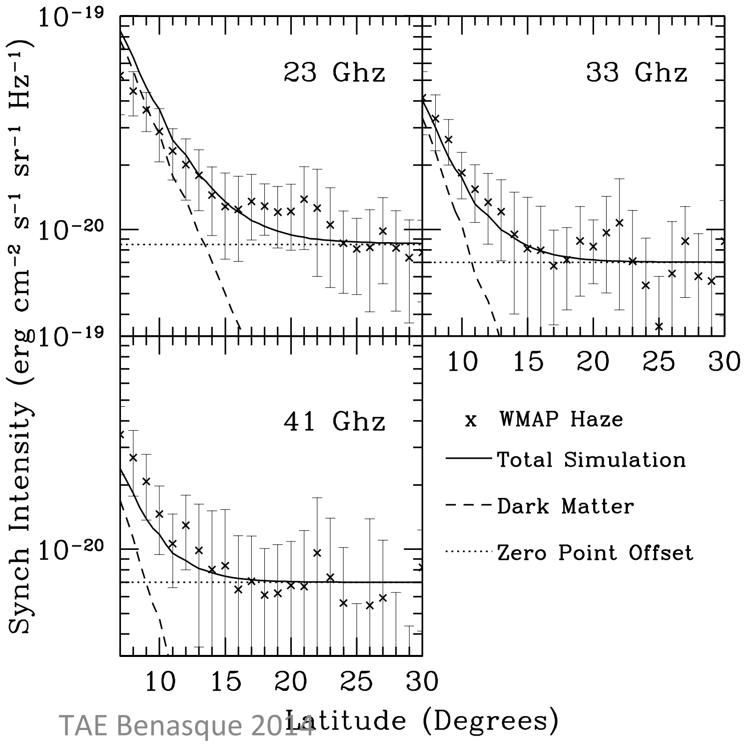
Synchrotron emission from radio filaments in the inner galaxy

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

Consistent with thermal very light WIMPs?



Linden, Hooper, Yusuf-Zadeh 2011

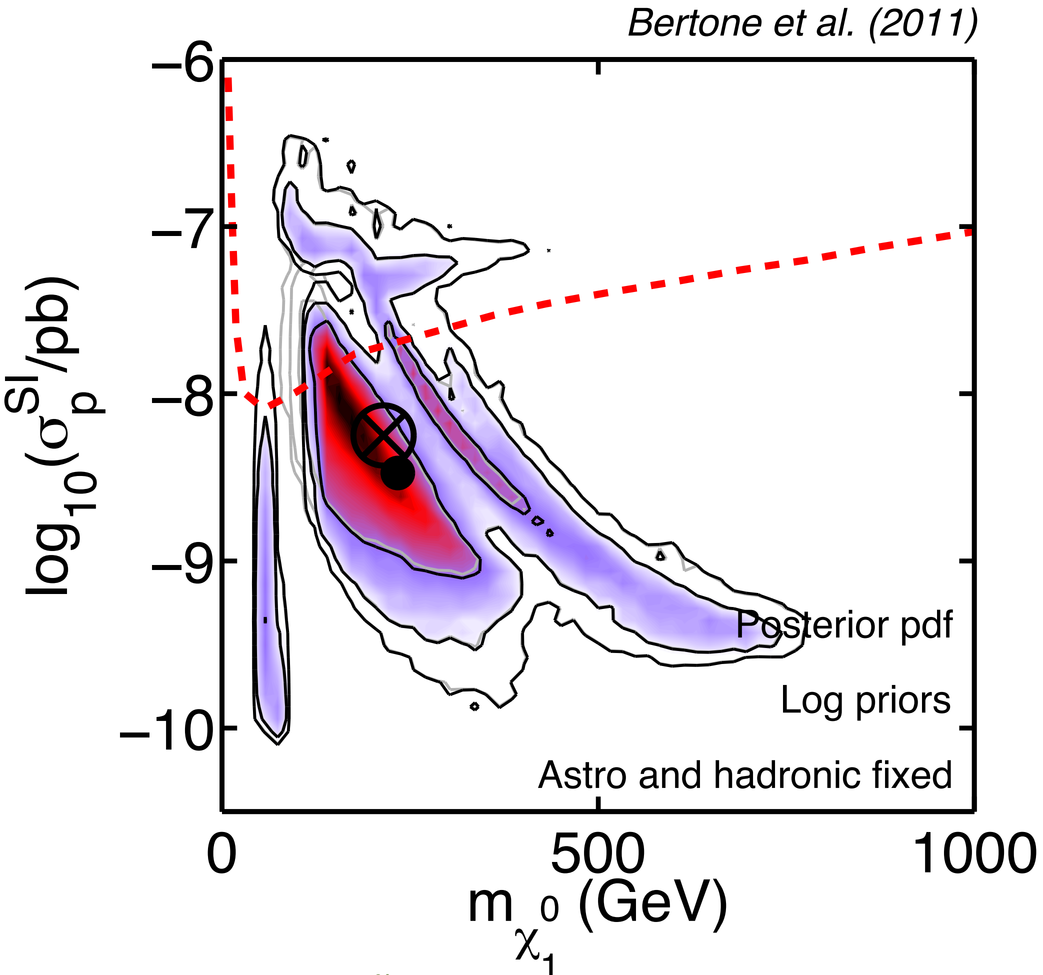


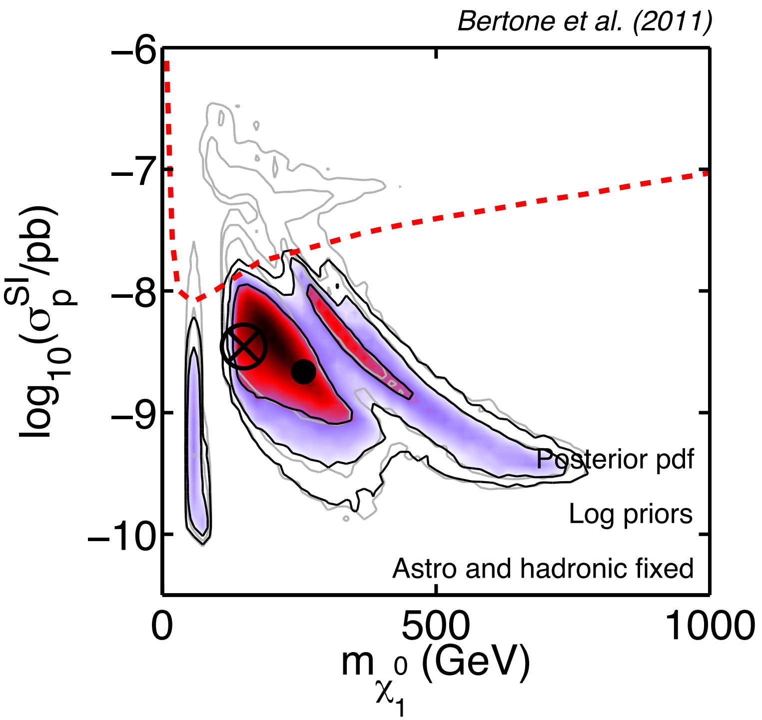
WMAP Haze

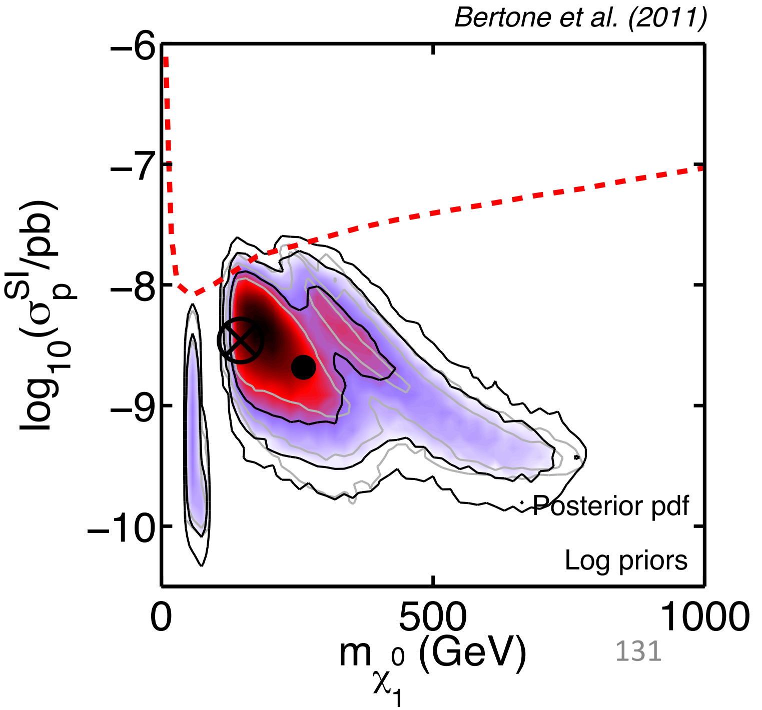
Could be further evidence of light (thermally produced) DM (m~10 GeV) annihilating mostly into leptons.

Impact of Xenon100 results

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


Bertone et al. (2011)

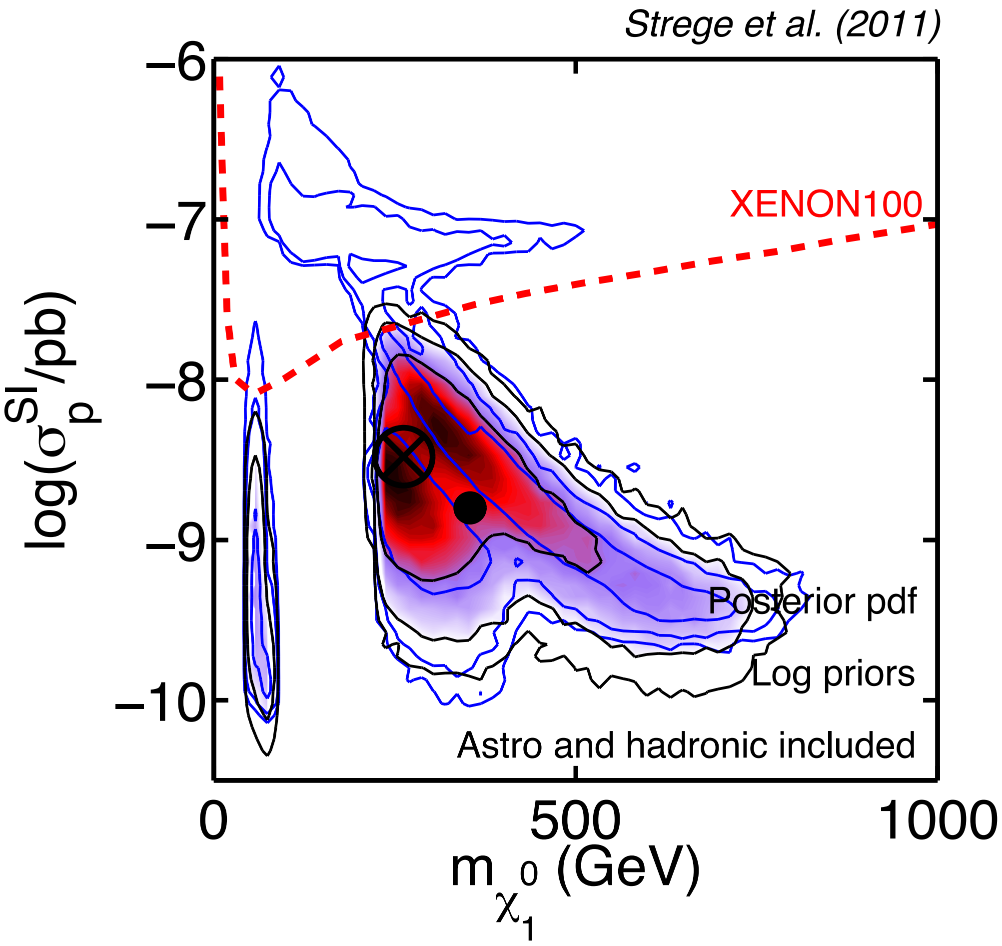

Bertone et al. (2011)

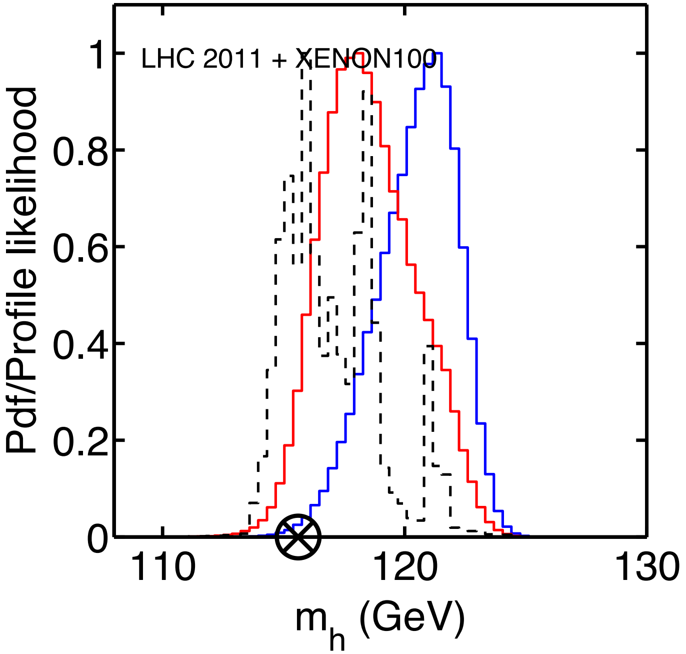

Bertone et al. (2011)

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

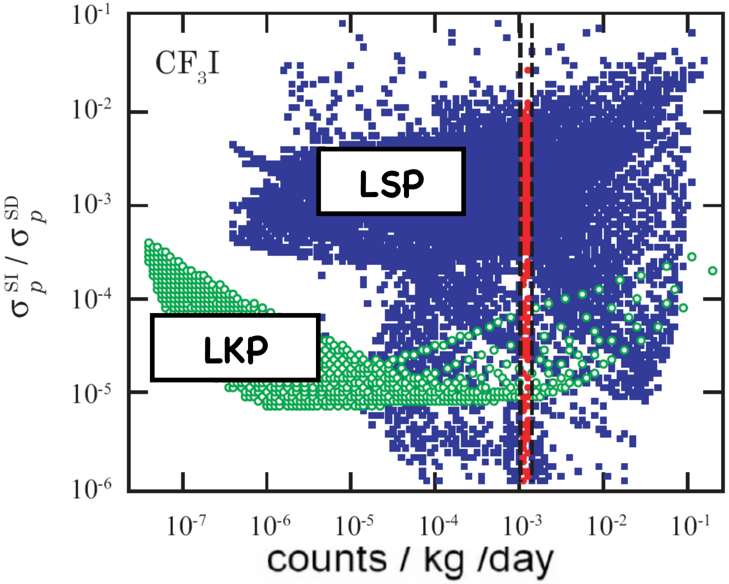
$$R_1 \sim A_1\, \sigma^{SI}_p + B_1\, \sigma^{SD}_p$$

(use WIMP relation among 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



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

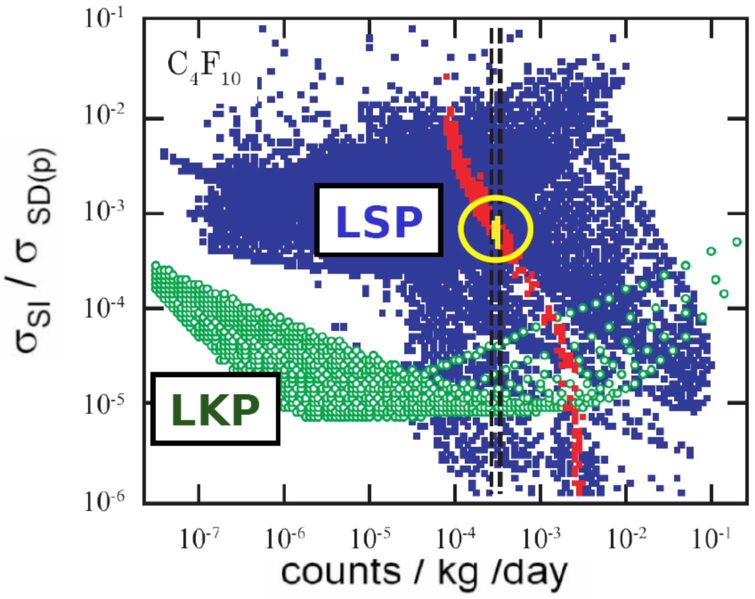
$$R_1 \sim A_1\, \sigma^{SI}_p + B_1\, \sigma^{SD}_p$$
$$R_2 \sim A_2\, \sigma^{SI}_p + B_2\, \sigma^{SD}_p$$

(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}

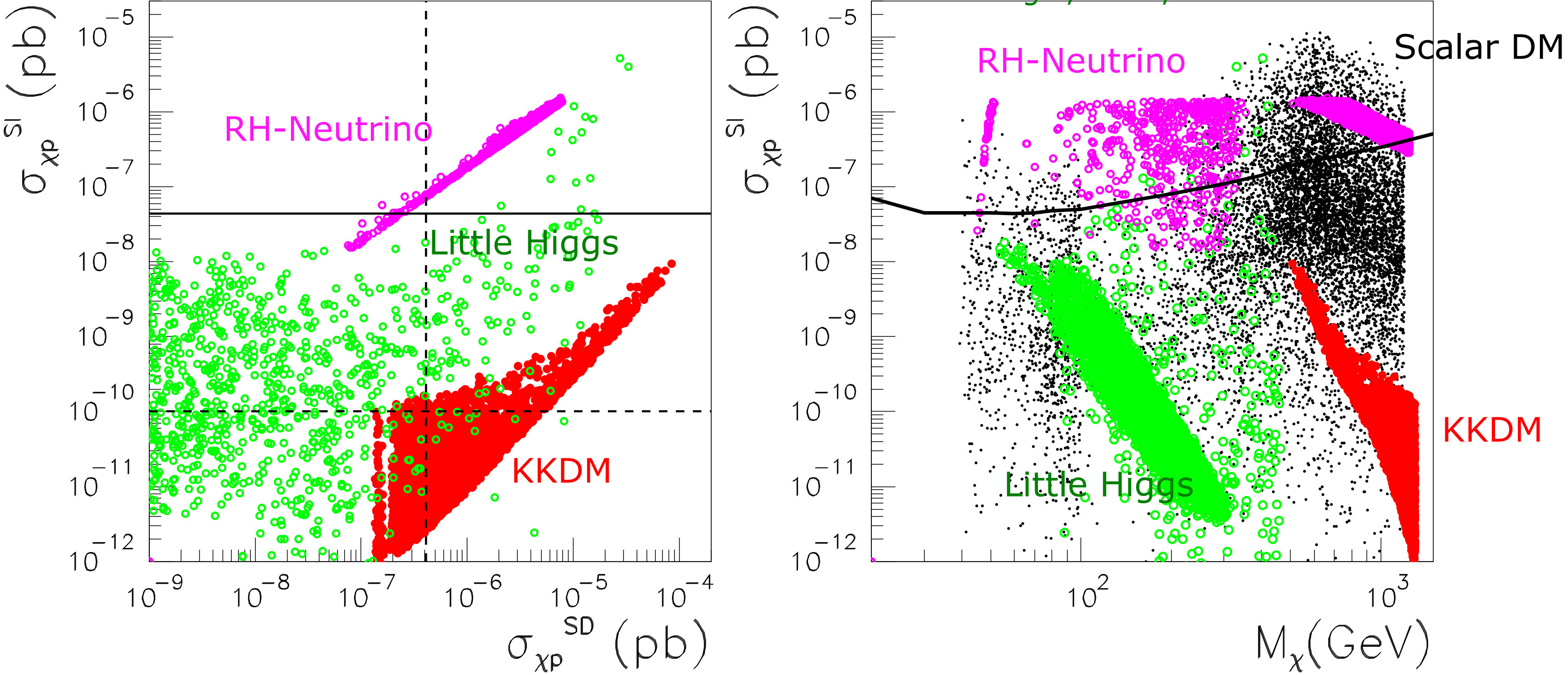


(See also Belanger, Nezri, Pukhov ‘08)

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

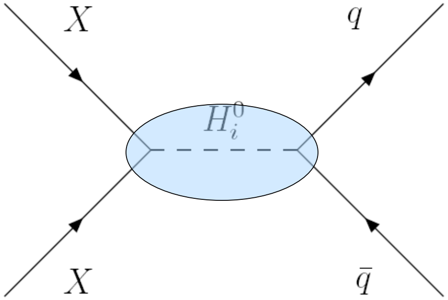
Determining the full set of parameters provides crucial information

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

DM signals in colliders (LHC)

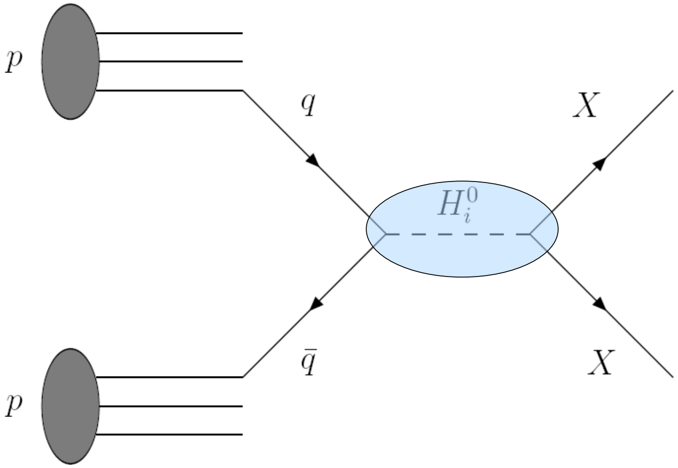
Direct DM production (pp → XX) does not leave a good signal

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

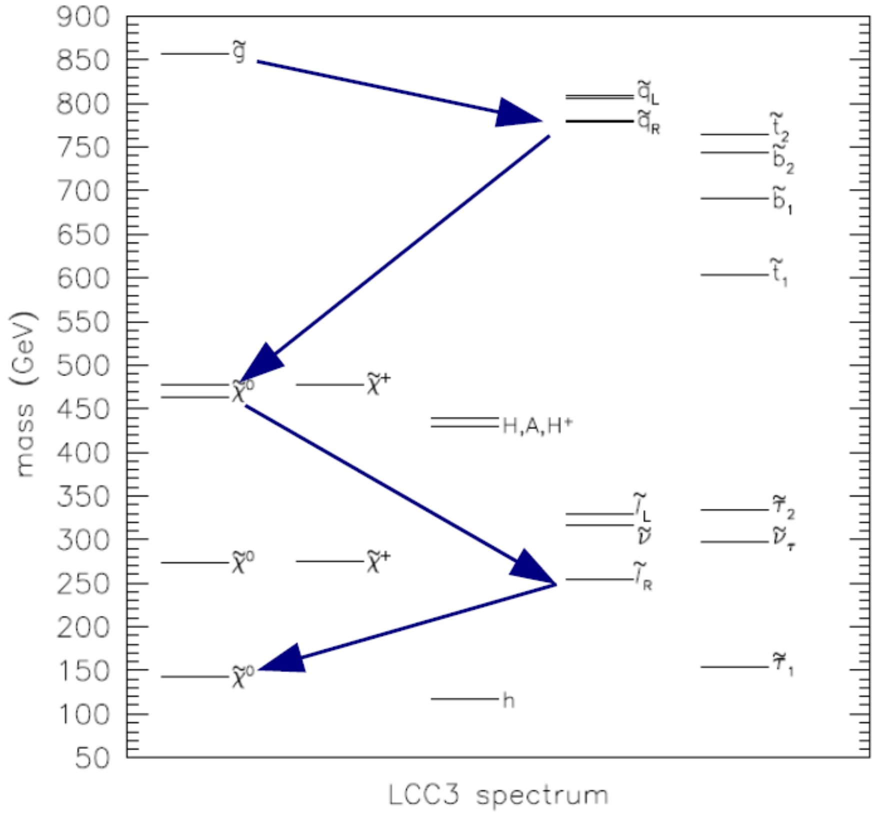
Look for jets + extra leptons

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

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

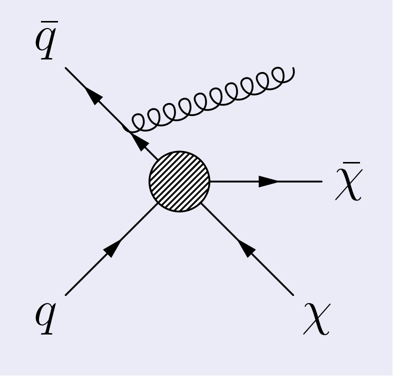
Matrix element of the axial-vector current

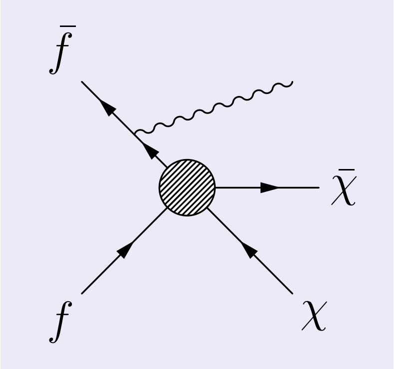
Parametrization of the form factor

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

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

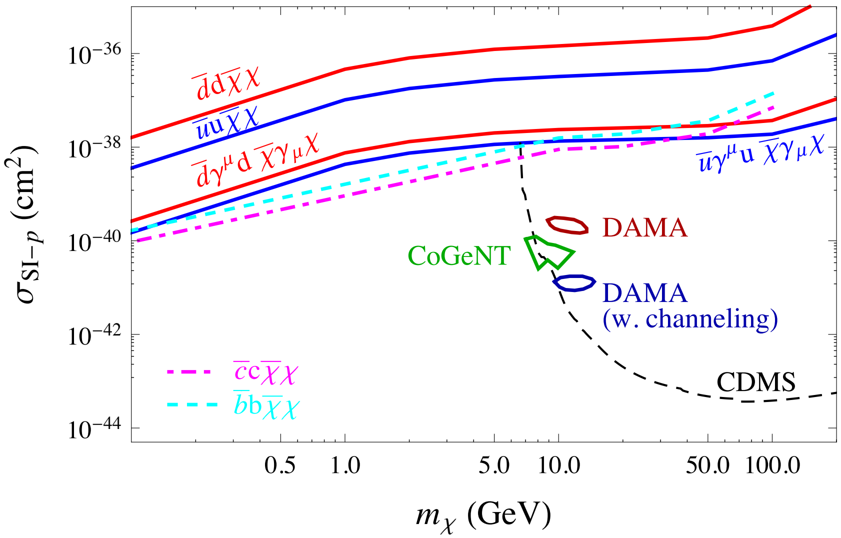
Mono-jet and Mono-γ (plus MET) searches constrain the region of light WIMPs



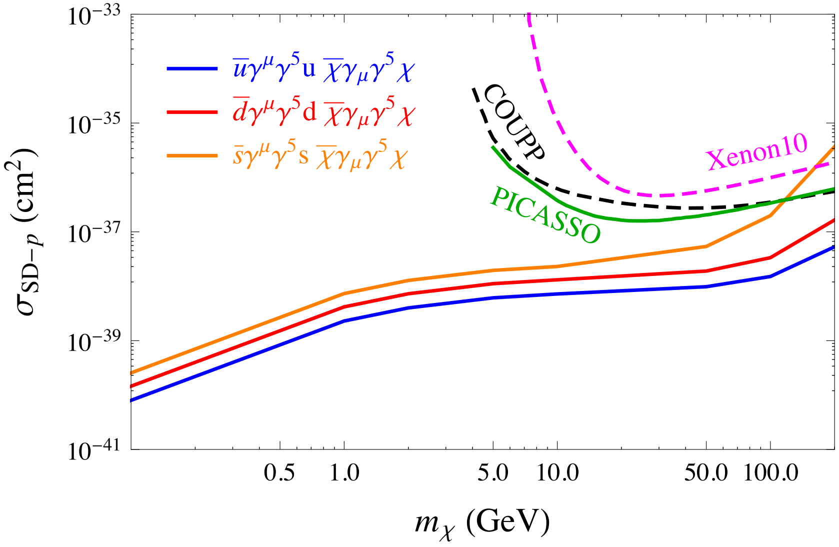


Dark matter production with initial state radiation

Bounds depend on the DM effective operators to fermions

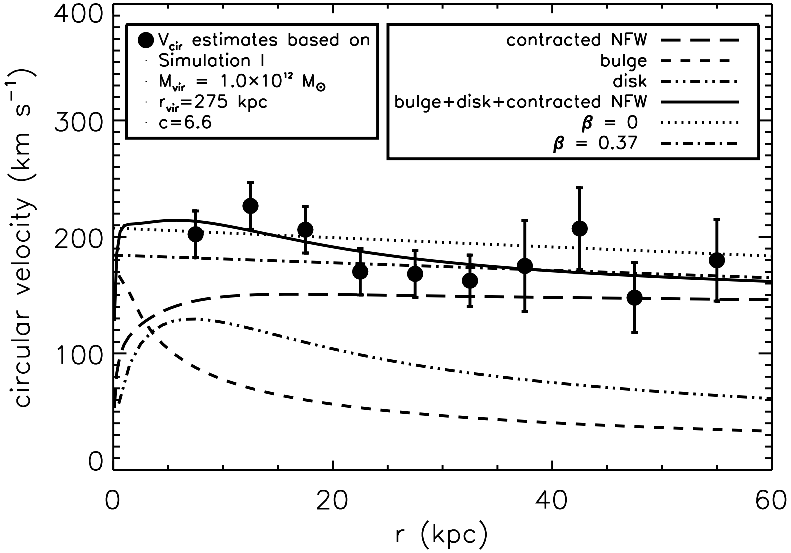


Tevatron data

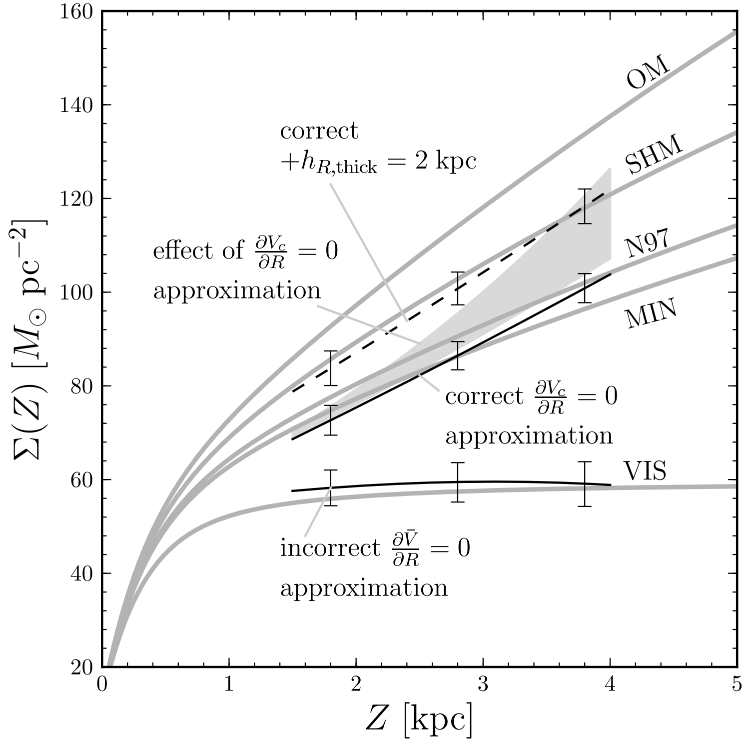


Observations of the Milky way are also consistent with the existence of DM at our position in the Galaxy

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

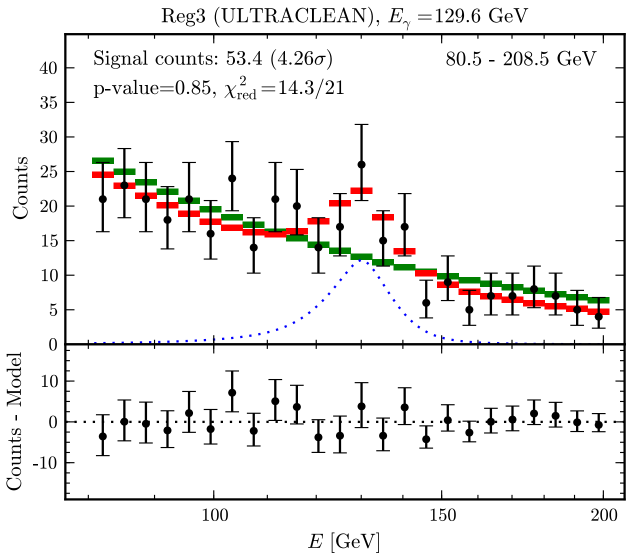
130 GeV WIMP annihil. into $\gamma\gamma$

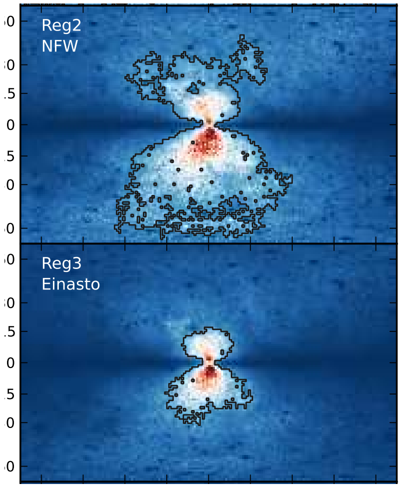
145 GeV WIMP annihil. into γZ^0

155 GeV WIMP annihil. into $H\gamma$

Internal bremsstrahlung

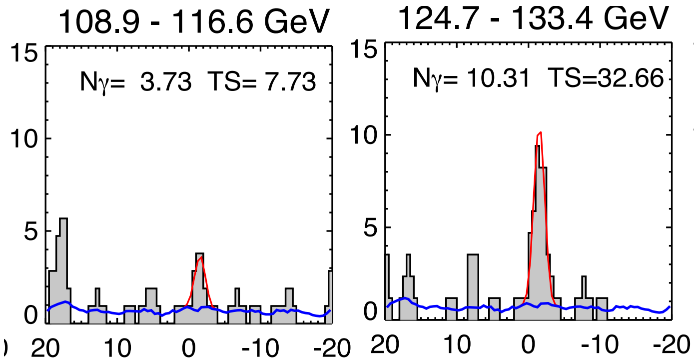
Bringmann et al. 1203.1312





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

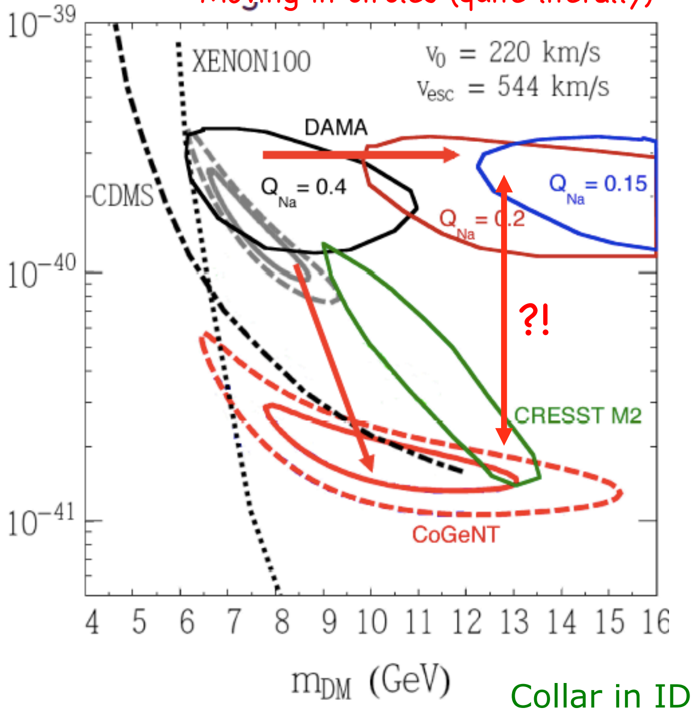
- CDMS II: A low-energy reanalysis of the data is incompatible with CoGeNT region

CDMS '11

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

SIMPLE '11-12

Moving in circles (quite literally)



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

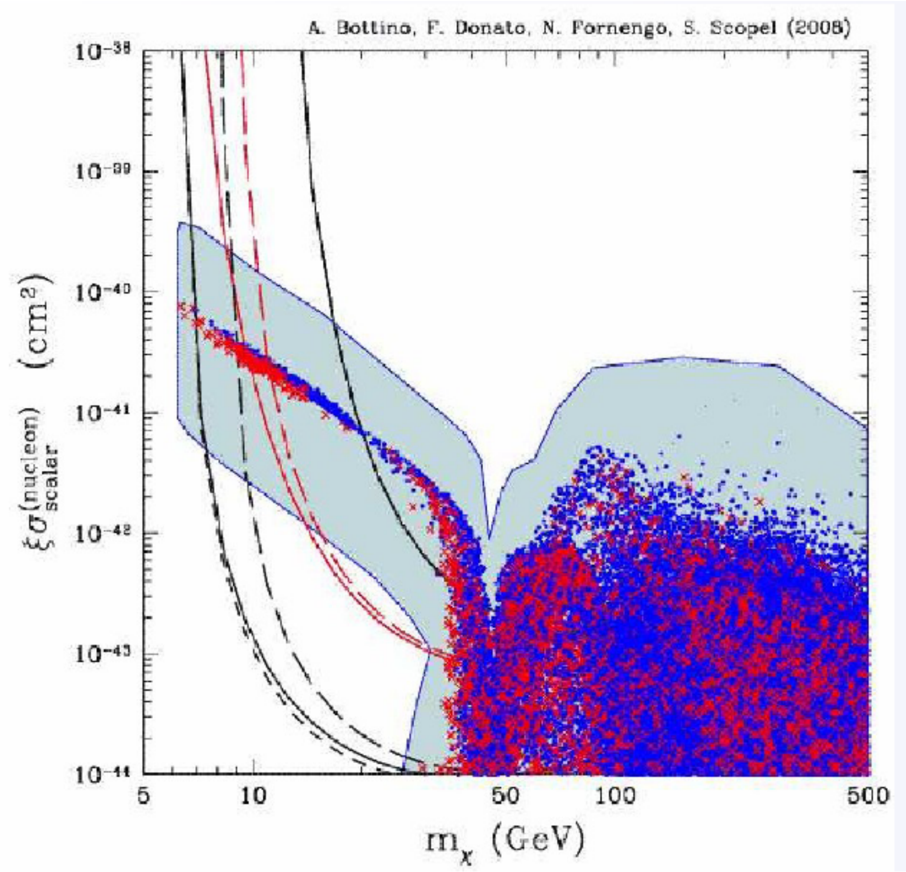
Very light Bino-like neutralinos with masses ~10 GeV could account for the DAMA signal

Bottino, Donato, Fornengo, Scopel 2008

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

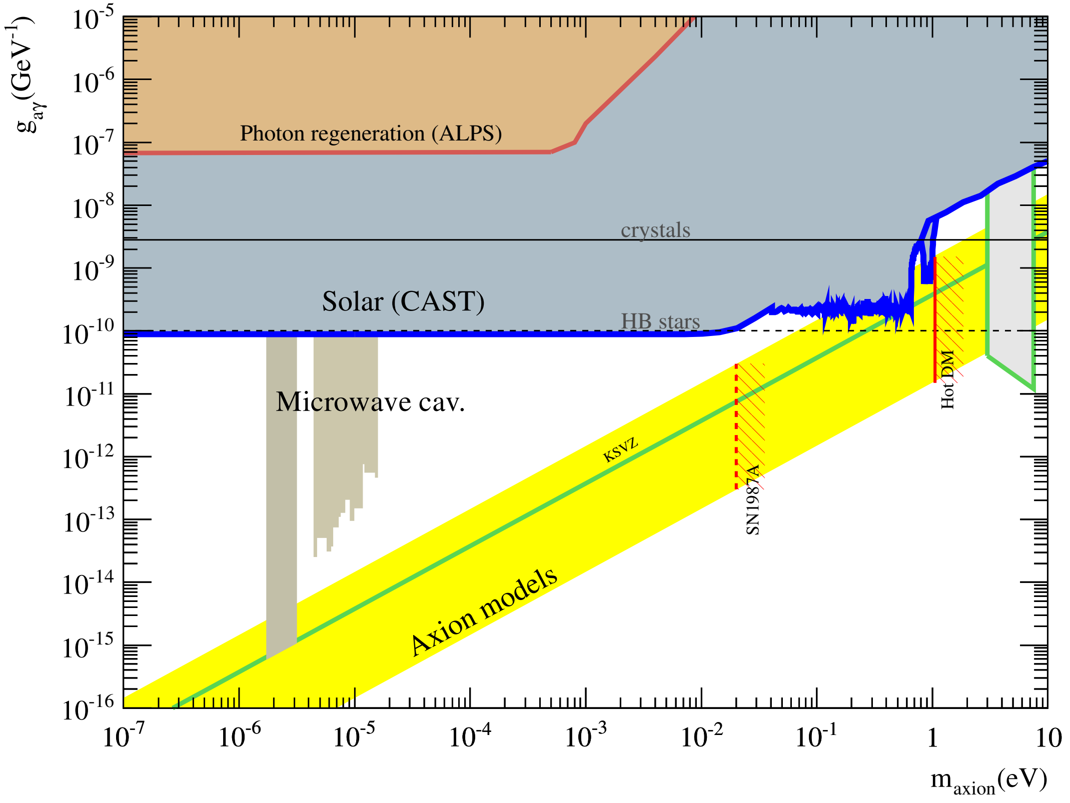
LHCb 2012

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



Axions

- Spin 0 pse
global U(1) Pe



reaking of a
roblem.

lczek '78; Kim '79)

The axion c

Axions with a mass of order $m_a = 10^{-5}\, eV$ can reproduce the correct relic density

Very weakly interacting, can only be detected through conversion into photons in large magnets (e.g., CAST experiment)