Dark Matter
Theory (biased) overview

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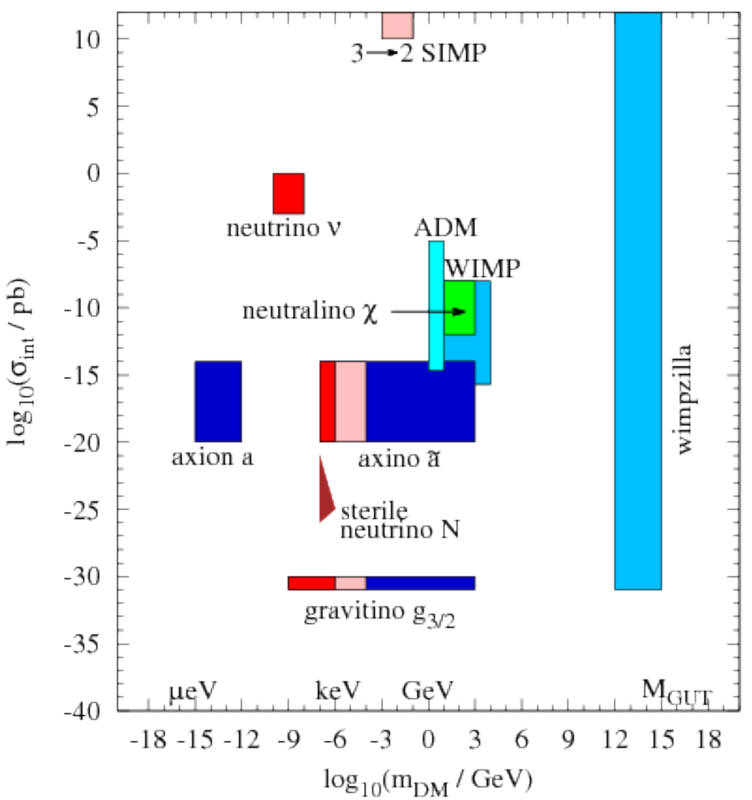
We don't know yet what DM is... but we do know many of its properties

Good candidates for Dark Matter have to fulfil the following conditions

Baer et al. 2014

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



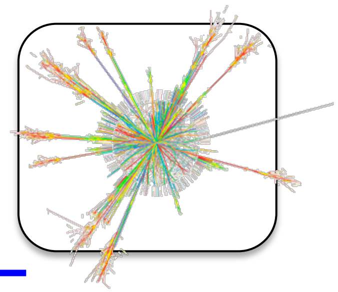
Many candidates in Particle Physics

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

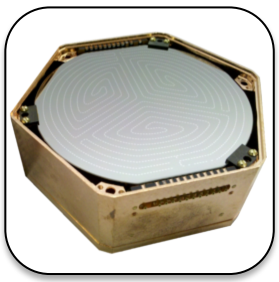
... they have very **different** properties

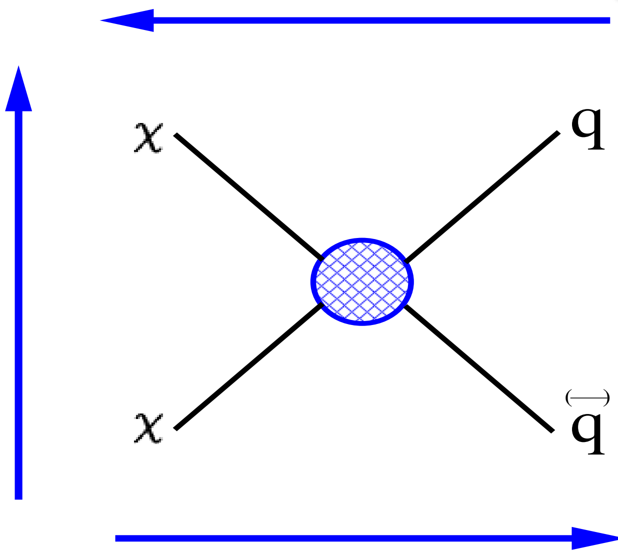
... probing **DIFFERENT** aspects of their interactions with ordinary matter

Accelerator Searches (production)



Direct Detection (scattering)

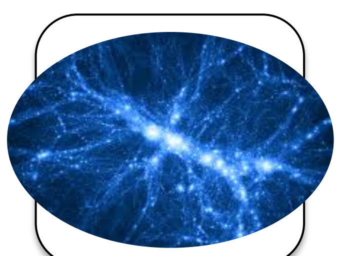


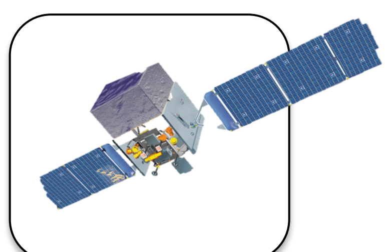


Constraints in one sector affect observations in the other two.

“**Redundant**” detection can be used to extract DM properties.

Indirect Detection (annihilation or decay)





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

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

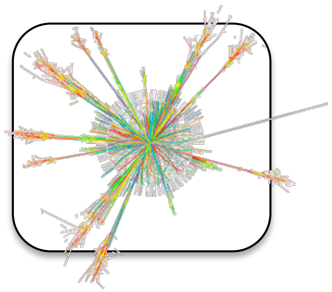
Astro/Cosmo Probes

Warm DM (Simulations)

Self-interacting DM

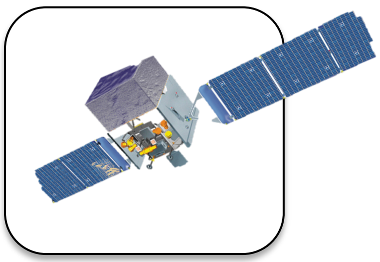
3.5 keV line

LHC



Diphoton at 750 GeV

Indirect Detection

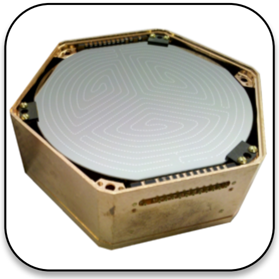


PAMELA-AMS

Fermi-LAT:
- Galactic Centre
- 135 gamma line

511 eV emission

Direct Detection



DAMA annual modulation

Low-mass craze (CDMS, CoGeNT, CRESST)

The role of theorists

Identify some basic features from a positive observation

(Galactic Centre Emission)

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Perform a complementary measurement with other search technique

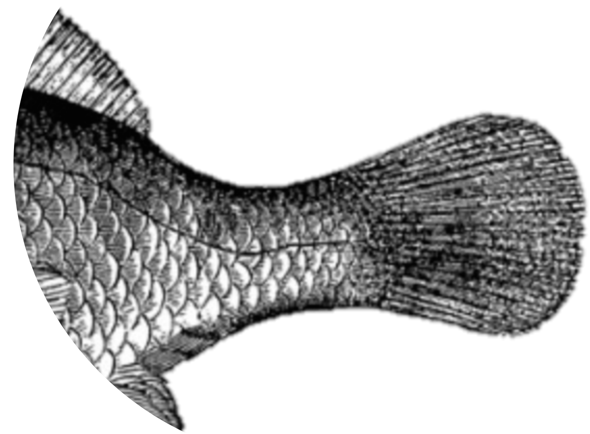
(Signal in various direct detection targets or at the LHC)

The role of theorists

Some data might be more difficult to explain in terms of “standard” DM models

Identify some basic features from a positive observation

(Galactic Centre Emission)



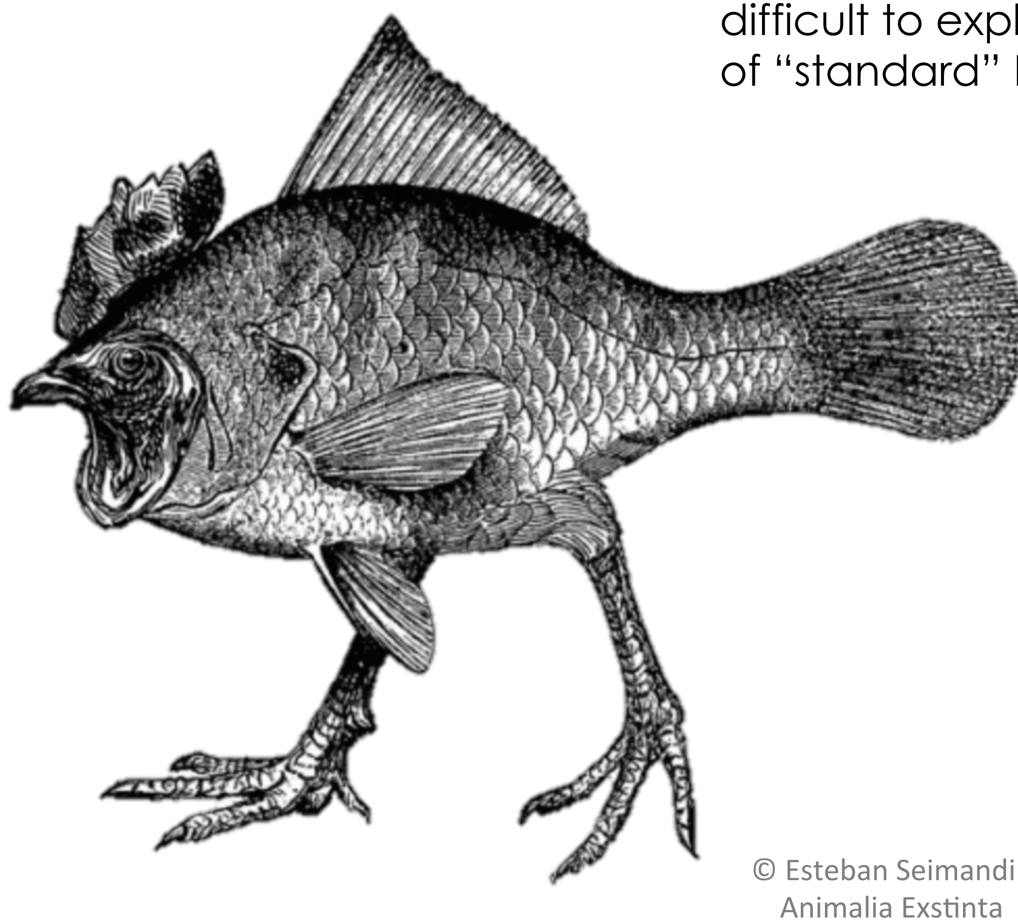
Perform a complementary measurement with other search technique

(Signal in various direct detection targets or at the LHC)

The role of theorists

Some data might be more difficult to explain in terms of "standard" DM models

Identify some basic features from a positive observation

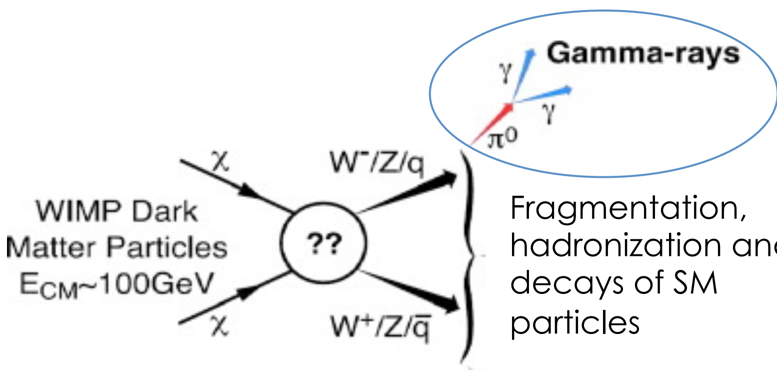


Perform a complementary measurement with other search technique

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

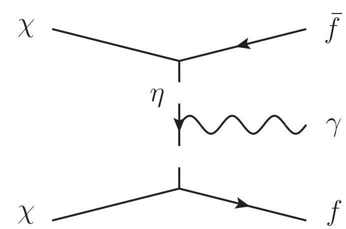
Gamma Rays searches

Continuum (secondary photons)

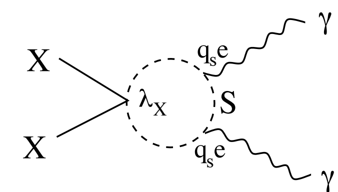


Fragmentation, hadronization and decays of SM particles

Direct gamma emission (features, lines)



Internal bremsstrahlung



Loop processes

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

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

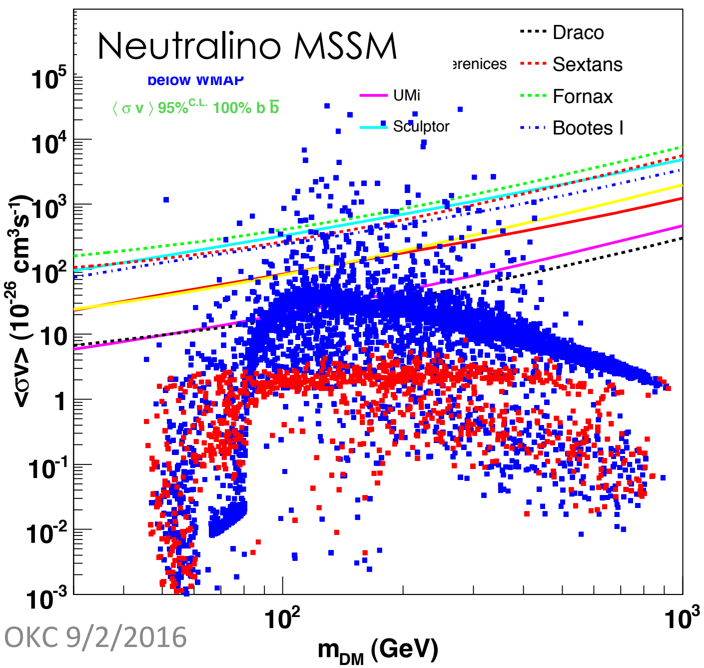
Fermi-LAT '14

Fermi-LAT observation of Dwarf Spheroidals

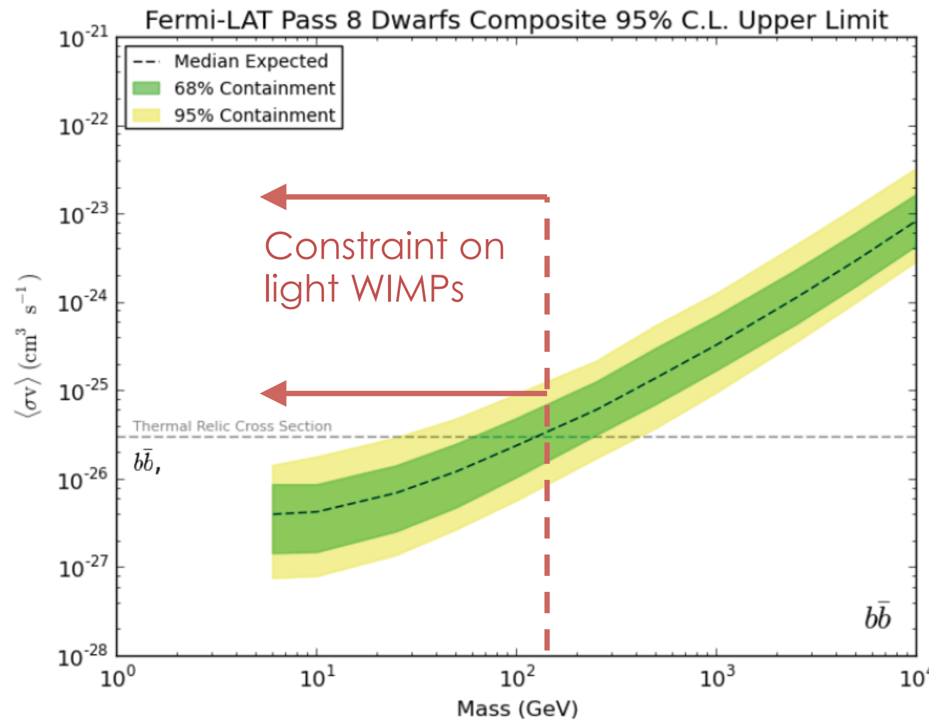
Fermi-LAT

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

m>100 GeV for the bb channel



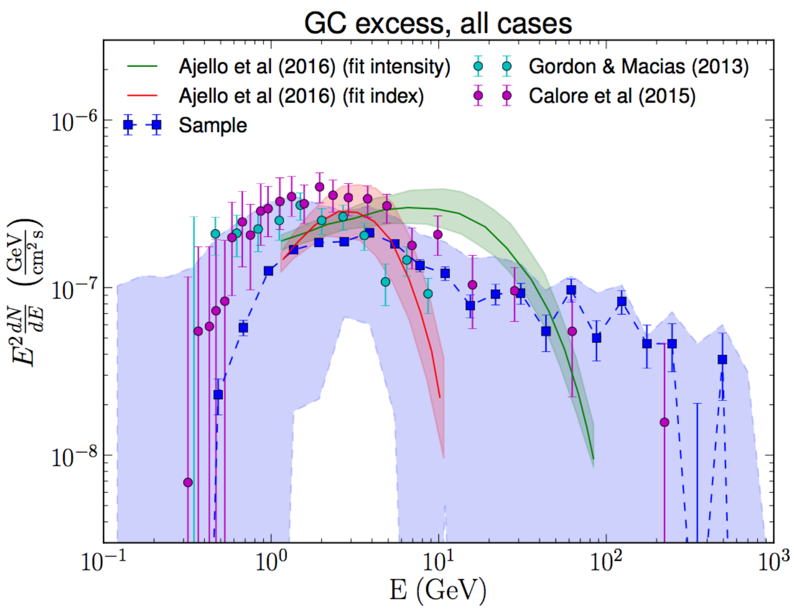
Abdo et al. 1001.4531



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

Coannihilation effects,
velocity-dependent cross-section
resonances

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



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

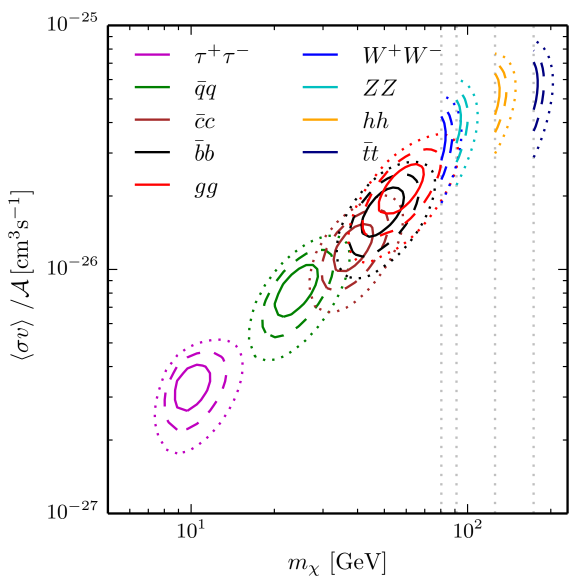
Hooper, Goodenough 2010
Hooper, Linden 2011

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

Abazajian 1011.4275
Chernyakova 1009.2630
Boyarsky, Malyshev, Ruchayskiy, 1012.5839

Most recent analysis by Fermi-LAT confirms the excess

Fermi-LAT 1704.03910



Fits normally done for pure annihilation channels

Compatible with WIMP DM

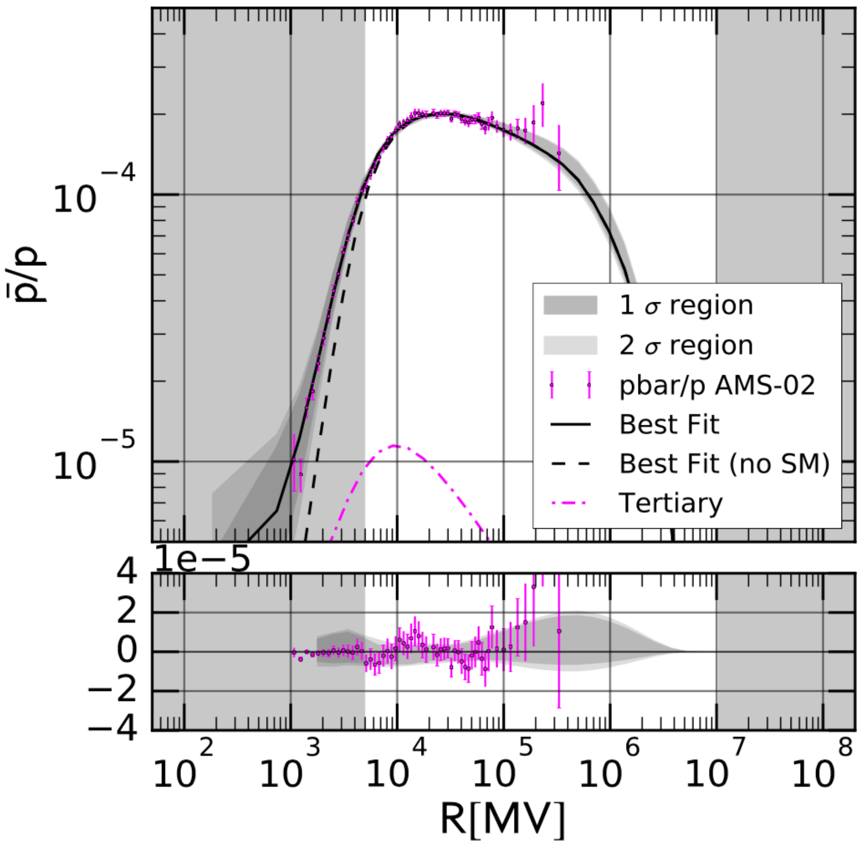
$$m_{DM} \sim 20 - 100 \text{ GeV}$$

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

Calore et al. 1411.4647

Antimatter searches (antiprotons)

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

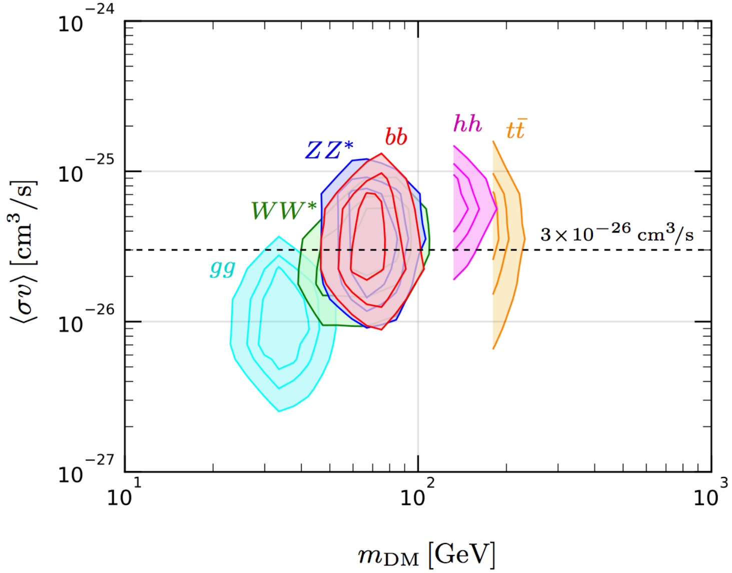


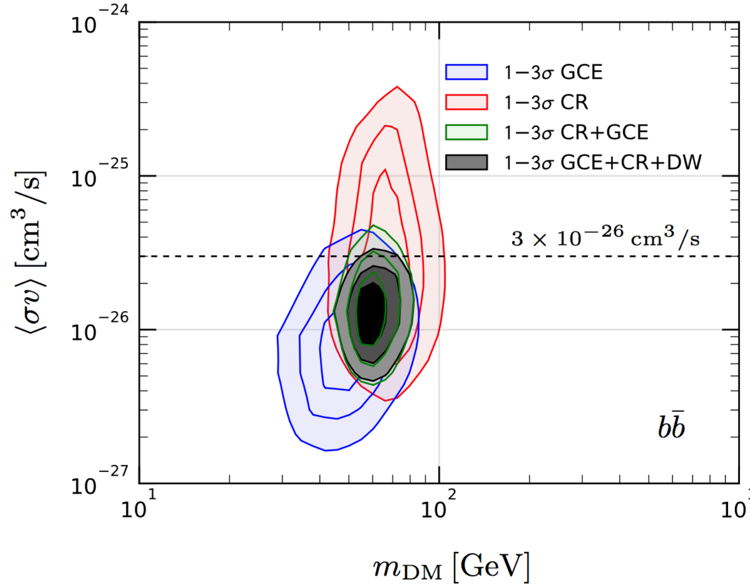
Cuoco et al. 1610.03071
Cui, Yuan, Tsai, Fan 1610.03840

Care must be taken with the treatment of the propagation parameters

The AMS excess is compatible with the Fermi-LAT excess

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





Cuoco et al. 1704.08258

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

Direct dark matter direct detection

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

Experimental setup

Target material (sensitiveness to different couplings)

Detection threshold

Astrophysical parameters

Local DM density

Velocity distribution factor

Theoretical input

Differential cross section

(of WIMPs with quarks)

Nuclear uncertainties

Experimental challenges:

- Increment Target Size
- Low Energy threshold
- Reduction of backgrounds
- Discriminating WIMP events

WIMP expected fingerprint:

- Exponential spectrum
- Annual Modulation of the signal
- Directionality

Conventional direct detection approach

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

Experimental setup

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Differential cross section

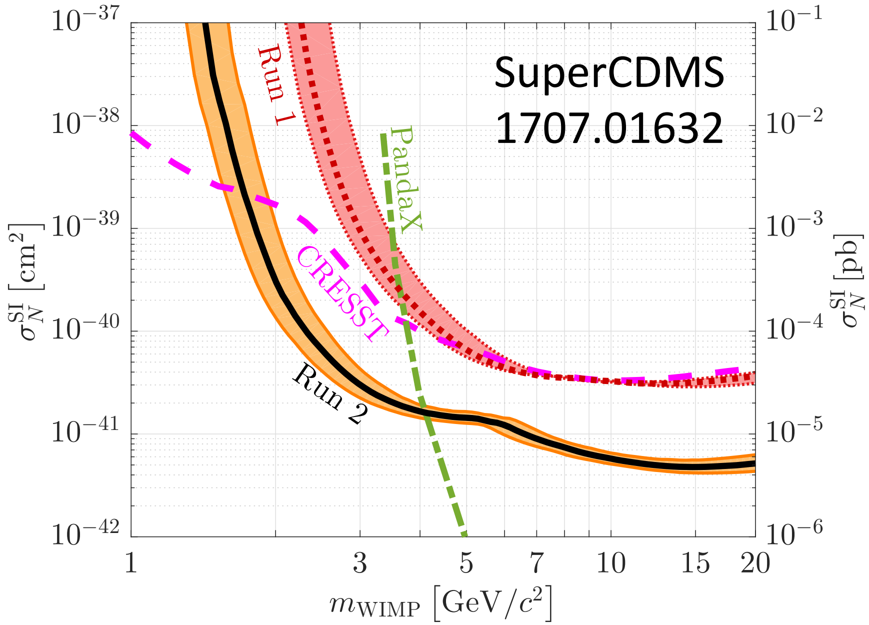
(of WIMPs with quarks)

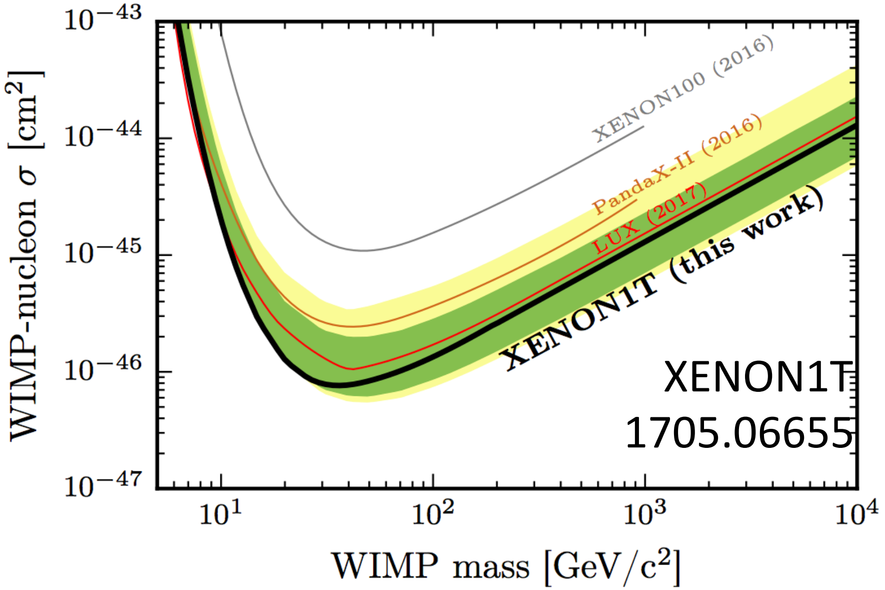
Nuclear uncertainties

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

Spin-independent and **Spin-dependent** components, stemming from different microscopic interactions leading to different coherent factors

Current searches (spin-independent scattering)





DISCLAIMER: THIS PLOT ASSUMES

- Isothermal Spherical Halo
- WIMP with only spin-independent interaction
- coupling to protons = coupling to neutrons
- elastic scattering

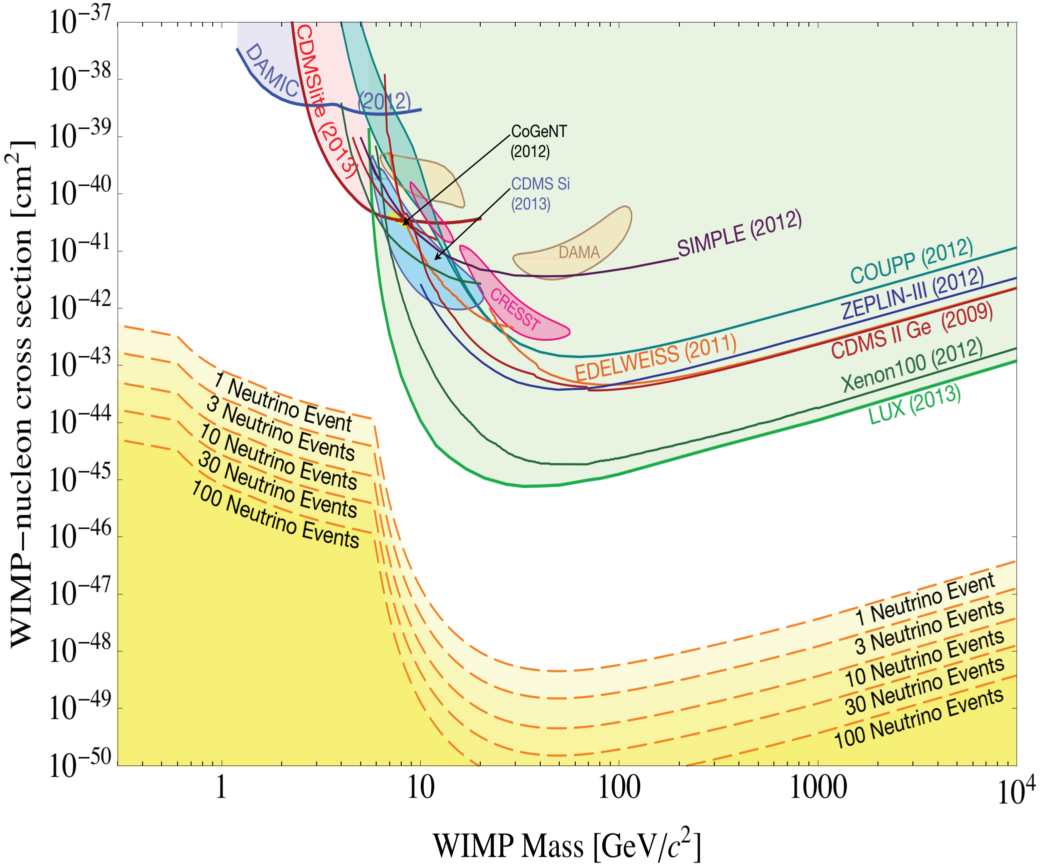
Coherent Neutrino Scattering

Future dark matter experiments will be sensitive to this SM process, limiting the reach for DM searches (Neutrino Floor)

Going beyond the neutrino floor:

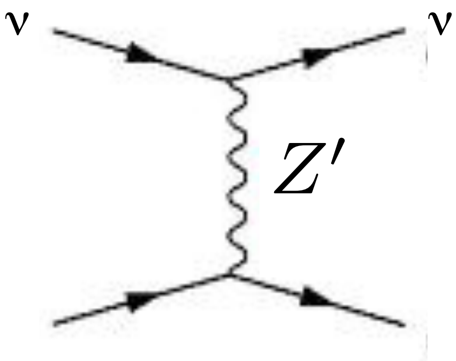
- Spectral analysis
- Annual modulation
  Billard et al. 1307.5458
  Davis 1412.1475
- Combination of complementary targets
  Ruppin et al. 1408.3581
- Directional detection

  Grothaus et al. 1406.5047
  O'Hare et al. 1505.08061



New Physics in the neutrino sector?

$$\mathcal{L} = g_{\nu,Z'} Z'_\mu \bar{\nu}_L \gamma^\mu \nu_L + Z'_\mu \bar{\ell} \gamma^\mu g_{\ell,v} \ell + Z'_\mu \bar{q} \gamma^\mu g_{q,v} q$$



Contributions from new physics to Electron and Nuclear recoils

$$d\sigma\ /dE_R - d\sigma^{\mathrm{SM}}/dE_R$$

ER:

$$\frac{\sqrt{2} G_F m_e g_v g_{\nu,Z'} g_{e,v}}{\pi\left(2E_R m_e + m_{Z'}^2\right)} + \frac{m_e g_{\nu,Z'}^2 g_{e,v}^2}{2\pi\left(2E_R m_e + m_{Z'}^2\right)^2}$$

NR:

$$-\frac{G_F m_N Q_v Q'_v (2E_\nu^2 - E_R m_N)}{2\sqrt{2}\pi E_\nu^2\left(2E_R m_N + m_{Z'}^2\right)} + \frac{Q'^2_v m_N (2E_\nu^2 - E_R m_N)}{4\pi E_\nu^2\left(2E_R m_N + m_{Z'}^2\right)^2}$$

There are interference terms with the SM contribution for NR that can actually suppress the SM prediction for CNS.

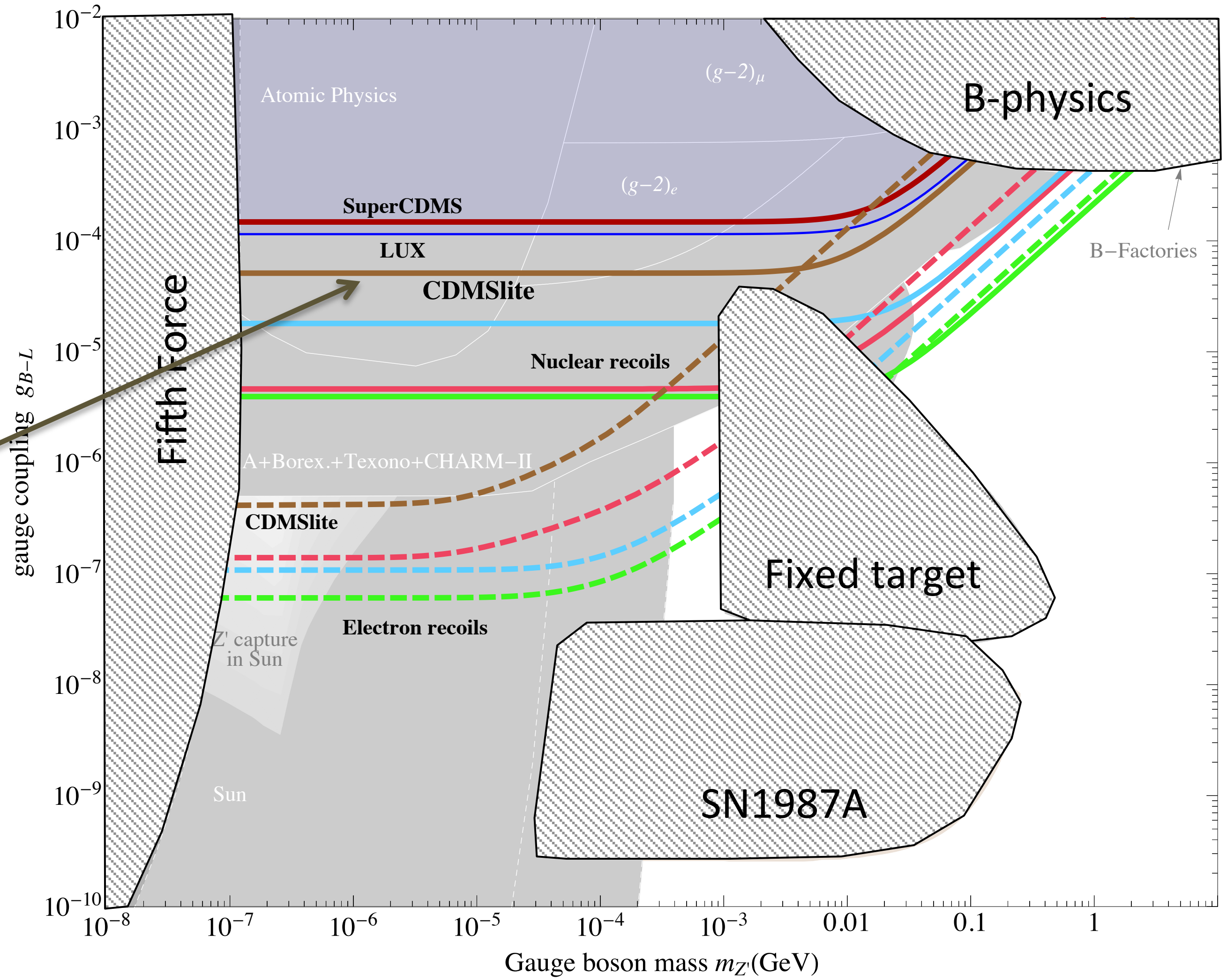
Current bounds on $U(1)_{B-L}$ models

Ge, Xe, Ne

Bounds from NR

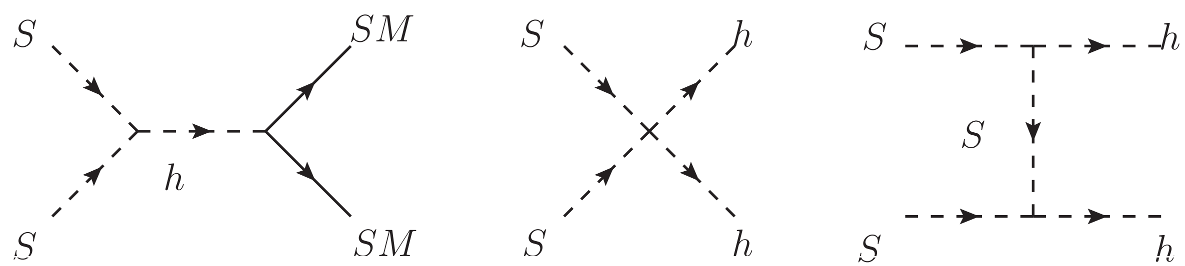
Current bounds probe a new region (only tested previously by electron scattering)

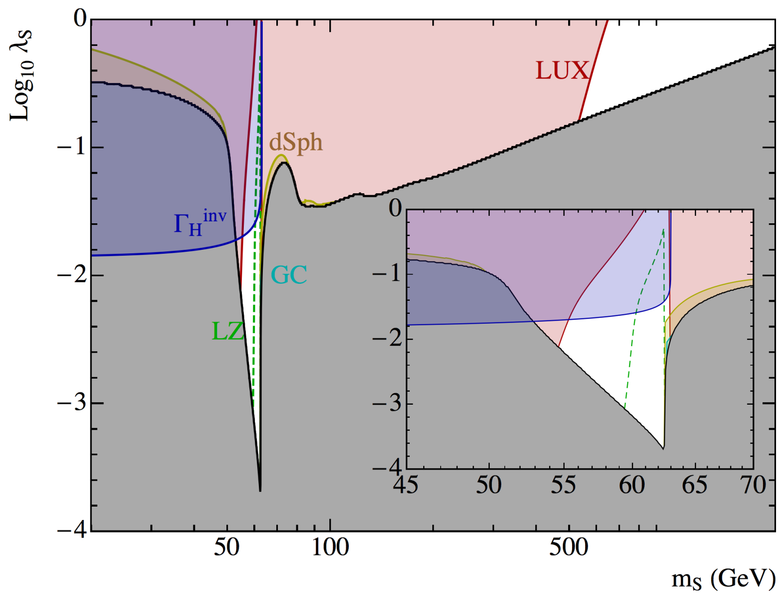
Low-threshold experiments excel in these searches



Tension in some simplified models

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



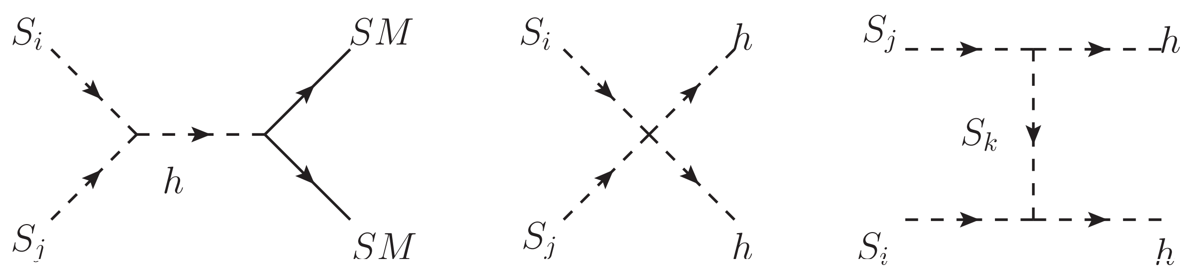


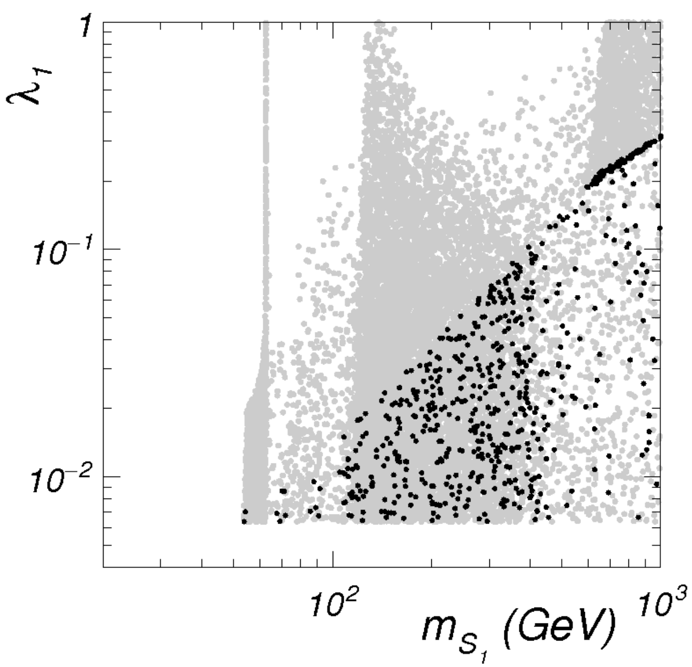
Casas, DGC, Moreno, Quilis 1701.08134
See also GAMBIT 1705.07931

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

Tension in some simplified models

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





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

Casas, DGC, Moreno, Quilis 1701.08134

Effective Field Theory approach

The most general effective Lagrangian contains up to 14 different operators that induce **6 types of response functions and two new interference terms**

Haxton, Fitzpatrick 2012-2014

$$\mathcal{L}_{\rm int}(\vec{x}) = c\ \Psi_\chi^*(\vec{x})\mathcal{O}_\chi\Psi_\chi(\vec{x})\ \Psi_N^*(\vec{x})\mathcal{O}_N\Psi_N(\vec{x})$$

Spin-Indep.

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

Spin-Dep.

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$

$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$

$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

(x2) if we allow for different couplings to protons and neutrons (isoscalar and isovector)

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Haxton, Fitzpatrick 2012-2014

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1. **COMPLETENESS:**
   To accommodate (within reason) all possible WIMP models
   Some of these operators exist even for the simplest DM models

2. **MODELLING OF THE SIGNAL:**
   We might miss (unconventional) DM signatures

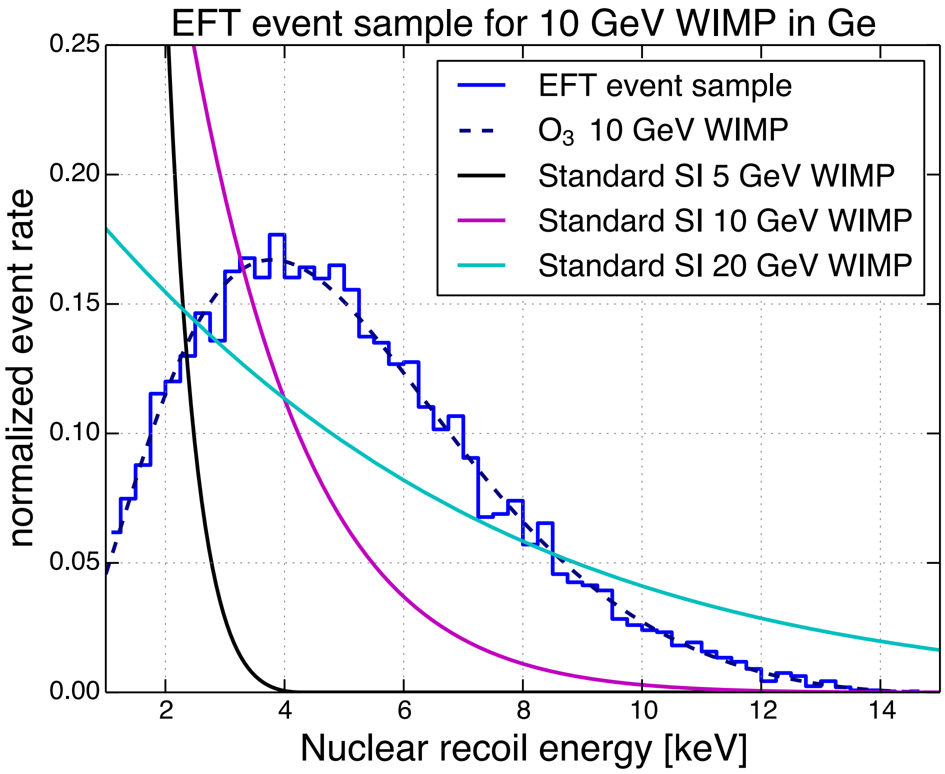
3. **RECONSTRUCTION** of DM parameters:

   COMPLEMENTARITY:
   Different targets are more sensitive to different operators
   Discrimination of DM interactions might be possible

We might MISS a DM signature

The spectrum from some interactions (momentum dependent) differs from the standard exponential signature

We might **misinterpret** a DM signature (if we reconstruct it with the usual templates)



Schneck et al. 1503.03379

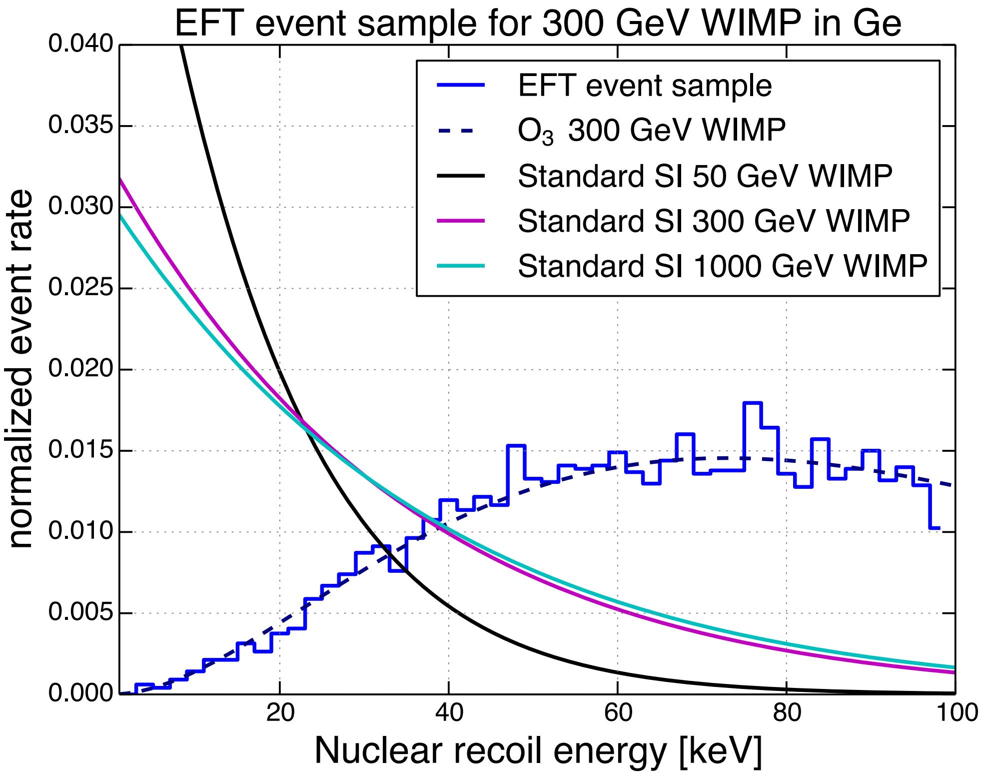
A low threshold is extremely beneficial

We might MISS a DM signature

The spectrum from some interactions (momentum dependent) differs from the standard exponential signature

We might **misinterpret** a DM signature (if we reconstruct it with the usual templates)

We might **miss** a signature (if we misidentify it as a background)



Schneck et al. 1503.03379

A low threshold is extremely beneficial

Reconstruction of Dark Matter Parameters

Given a detection, how well can we determine the DM parameters?

Problems:

- It is a large parameter space
- Degenerate solutions (as in the simpler SI-SD case)
- Mis-reconstruction of parameters if the wrong assumptions (couplings) are used
- Uncertainties in parameters (astrophysical + nuclear)

Solution:

- Combine data with other targets (Ge + Si) o experiments (Xe)
- Look for other effects (e.g., annual modulation)

Example: $\{m_\chi, c_3^0, c_3^1\} = \{8.0\ \text{GeV}, 16, -6.4\}$

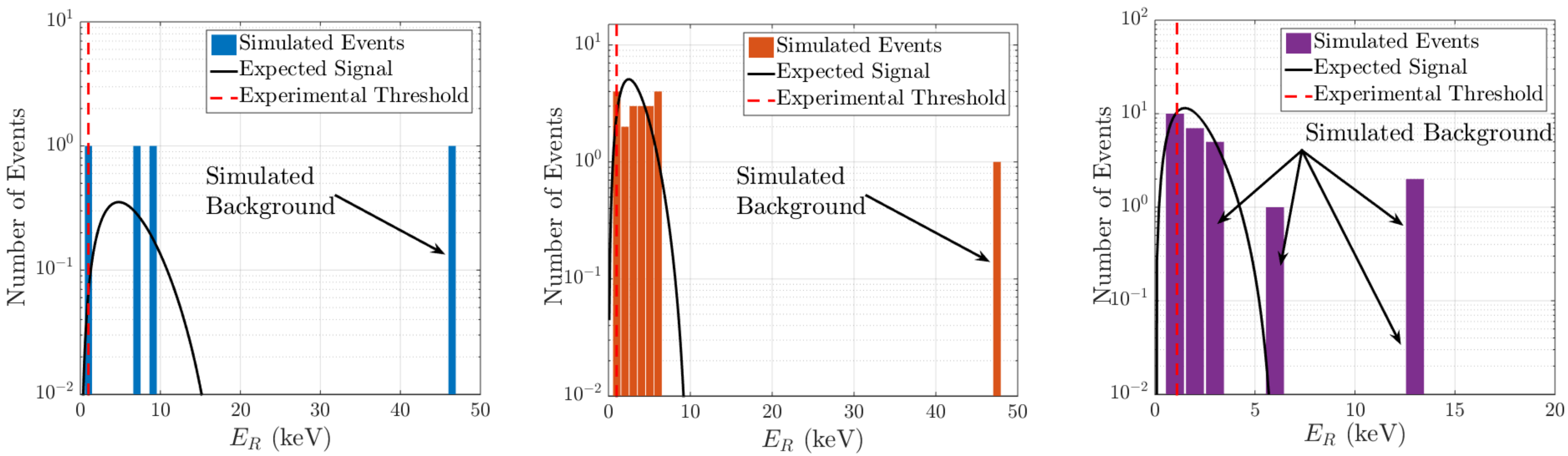
Rogers, Cushman, DGC, Livet, Mandic 1612.09038

Consider reconstruction in future G2 experiments

Target	Live time (kg days)	Total Background (counts)
Si	63000	0.86±0.93
Ge	145000	1±1
LXe	33500	3.5±0.4

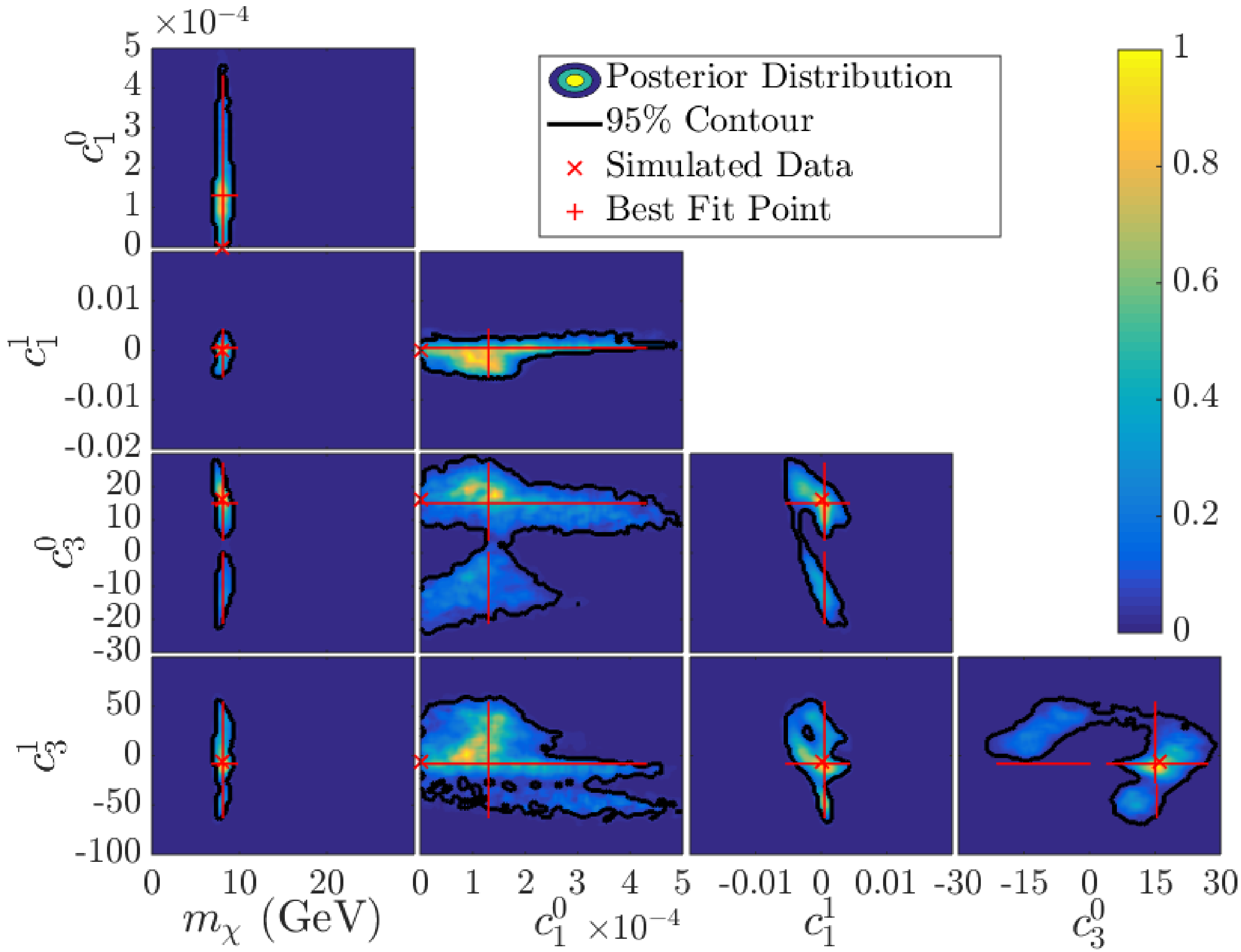
The reconstruction is subject to statistical limitations Strege, et al. 1201.3631

We simulate all possible background configurations (within 2σ of the expected background) and adopt the one that maximises the Likelihood.



(a) Si (b) Ge (c) LXe

Reconstruction in 5D (mass, O1, O3 using Si, Ge, Xe detectors)



Rogers, Cushman, DGC, Livet, Mandic 1612.09038

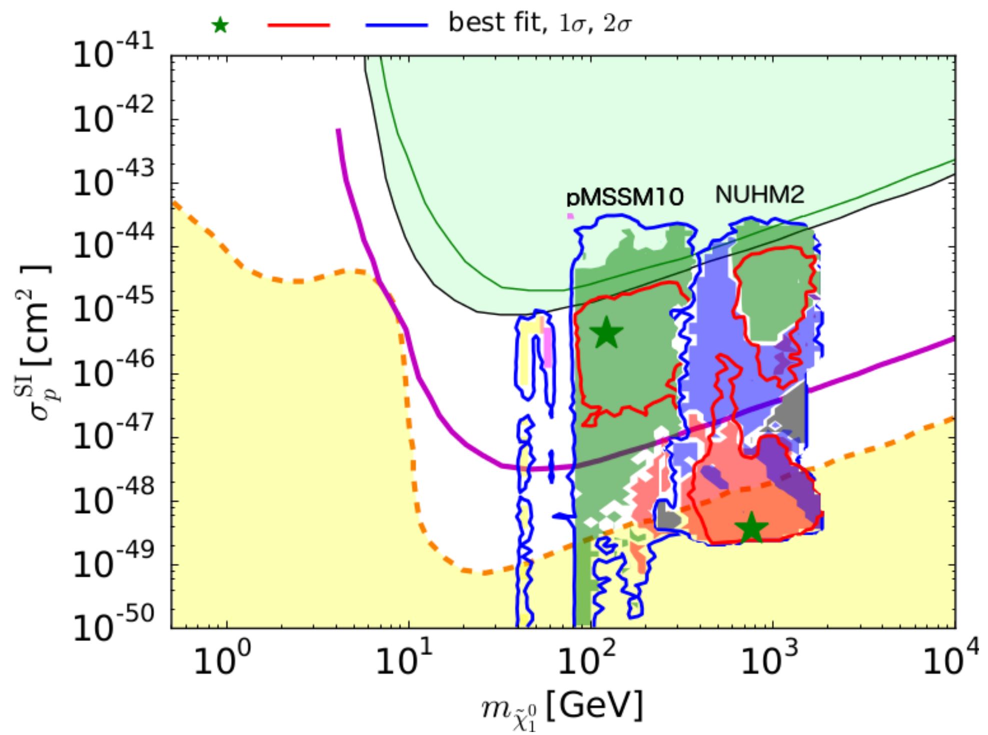
Neutralino in the MSSM

Impose LHC1 bounds and explore the predictions of MSSM parameter space

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

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

(excellent motivation for more sensitive detectors)



MSSM after LHC1
Bagnaschi et al. 2015

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

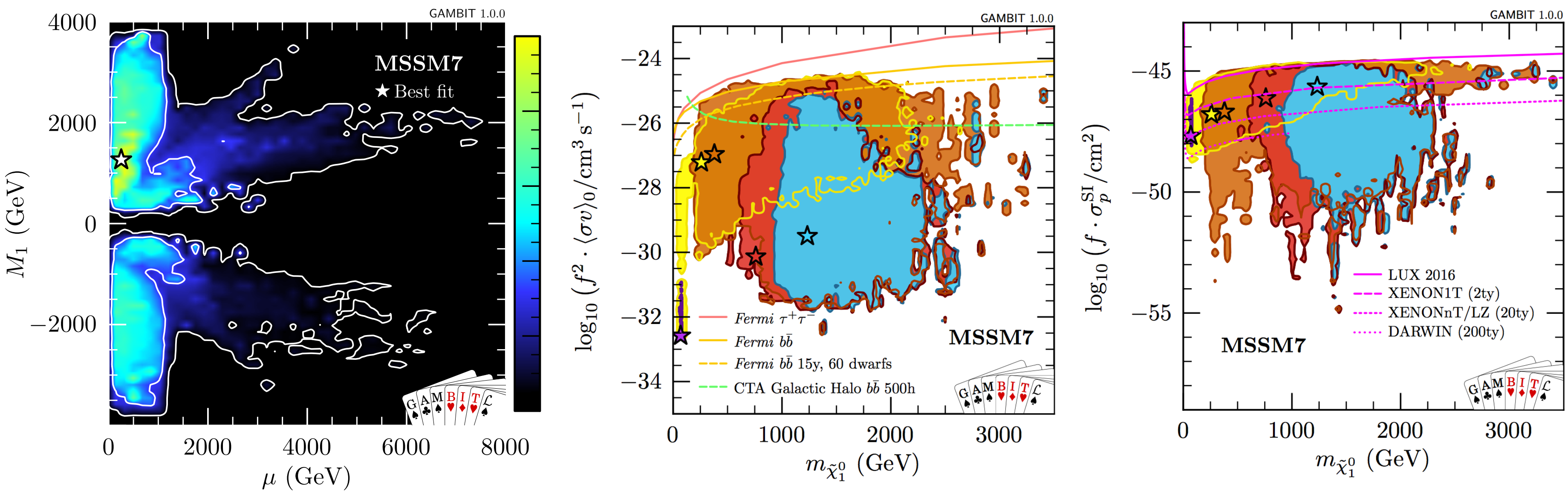
Neutralino in the MSSM

Update on the constraints on the MSSM using GAMBIT

MSSM7

Parameter	Minimum	Maximum
$A_{u_3}(Q)$	-10 TeV	10 TeV
$A_{d_3}(Q)$	-10 TeV	10 TeV
$M^2_{H_u}(Q)$	$-(10\,\text{TeV})^2$	$(10\,\text{TeV})^2$
$M^2_{H_d}(Q)$	$-(10\,\text{TeV})^2$	$(10\,\text{TeV})^2$
$m^2_{\tilde{f}}(Q)$	0	$(10\,\text{TeV})^2$
$M_2(Q)$	-10 TeV	10 TeV
$\tan\beta(m_Z)$	3	70

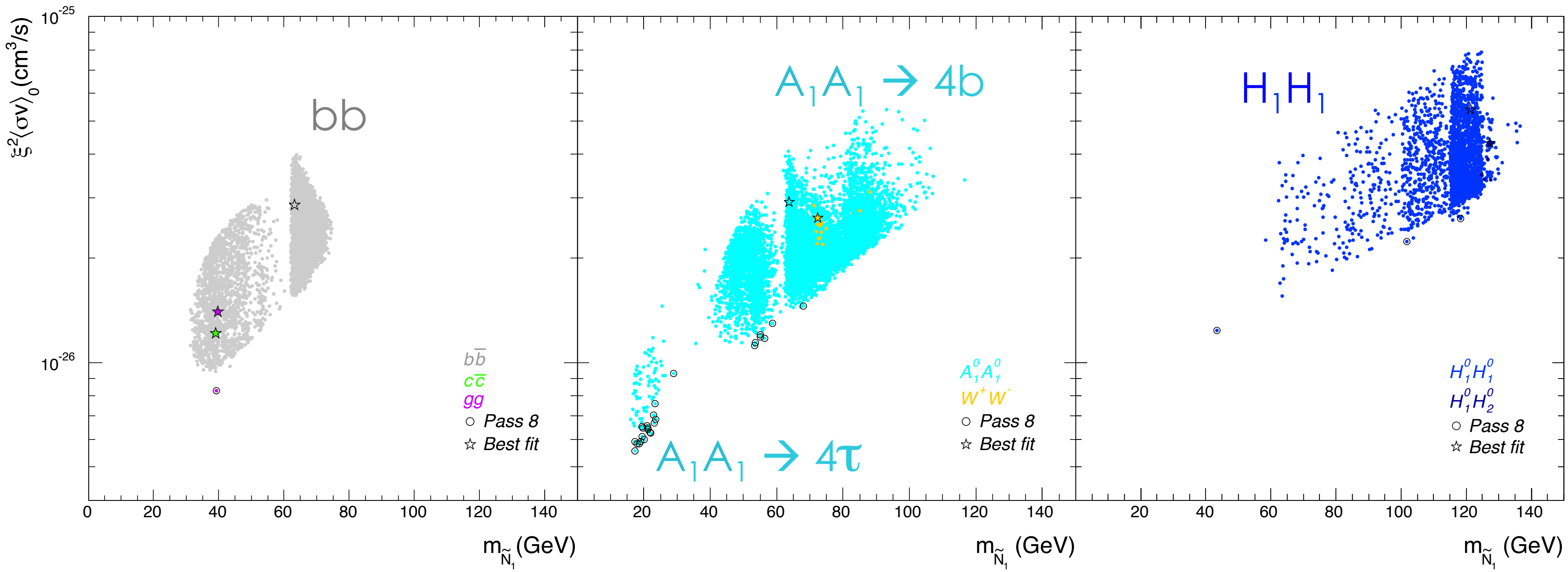
- $\tilde{t}_1$ co-annihilation
- A/H funnel
- $\tilde{\chi}_1^\pm$ co-annihilation
- $\tilde{b}_1$ co-annihilation
- h/Z funnel



GAMBIT 1705.07935

The neutralino can be a viable DM candidate for masses up to 2 TeV, but in some regions of the parameter space, it might not be detected by indirect or direct methods

Light WIMPs can account for Fermi-LAT excess

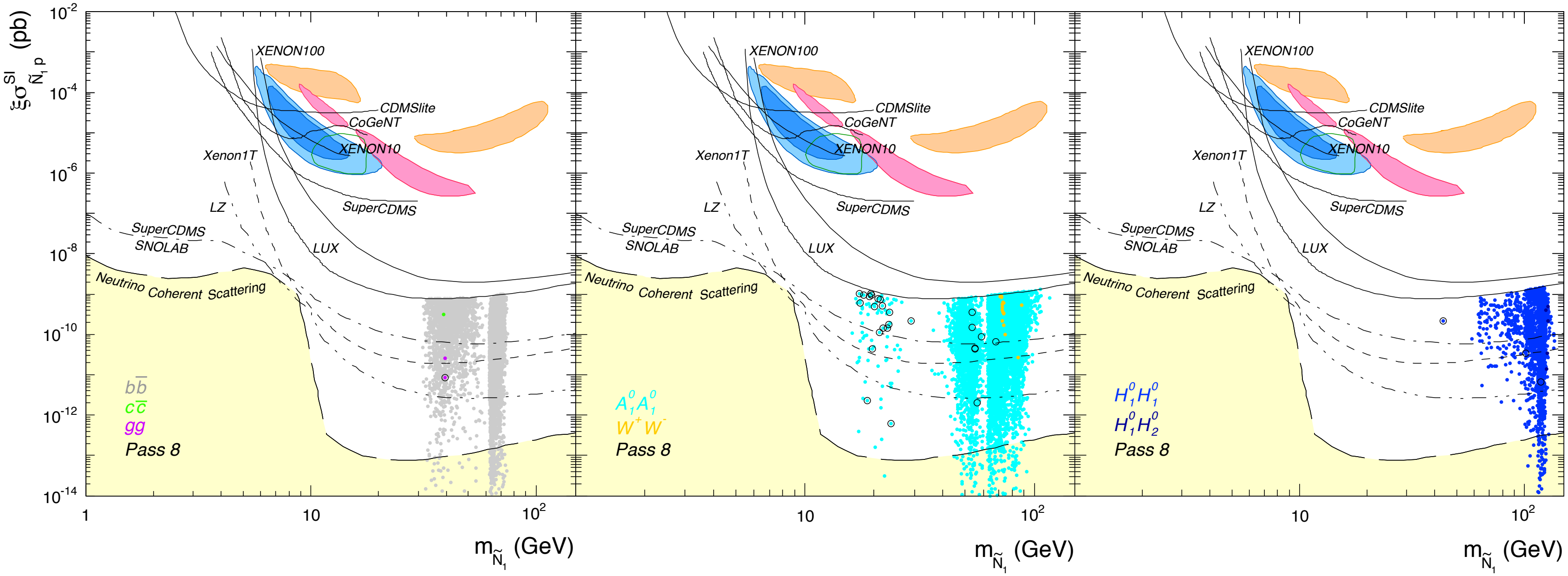


DGC, Robles, Peiro 2015

Working with complete models allows looking for correlations with other search strategies

- What are the predictions for indirect searches/colliders?
- Are these results compatible with other “hints”?

Light WIMPs are viable in extensions of the MSSM



DGC, Robles, Peiro 2015

Working with complete models allows looking for correlations with other search strategies

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Summary

Current experiments have done an excellent job in not detecting Dark Matter (yet)

- Experimental results set **stringent constraints** on simplified models (e.g. Higgs portal) and complete ones (e.g. Supersymmetry)

Interesting "hints" being explored (some point in different directions)

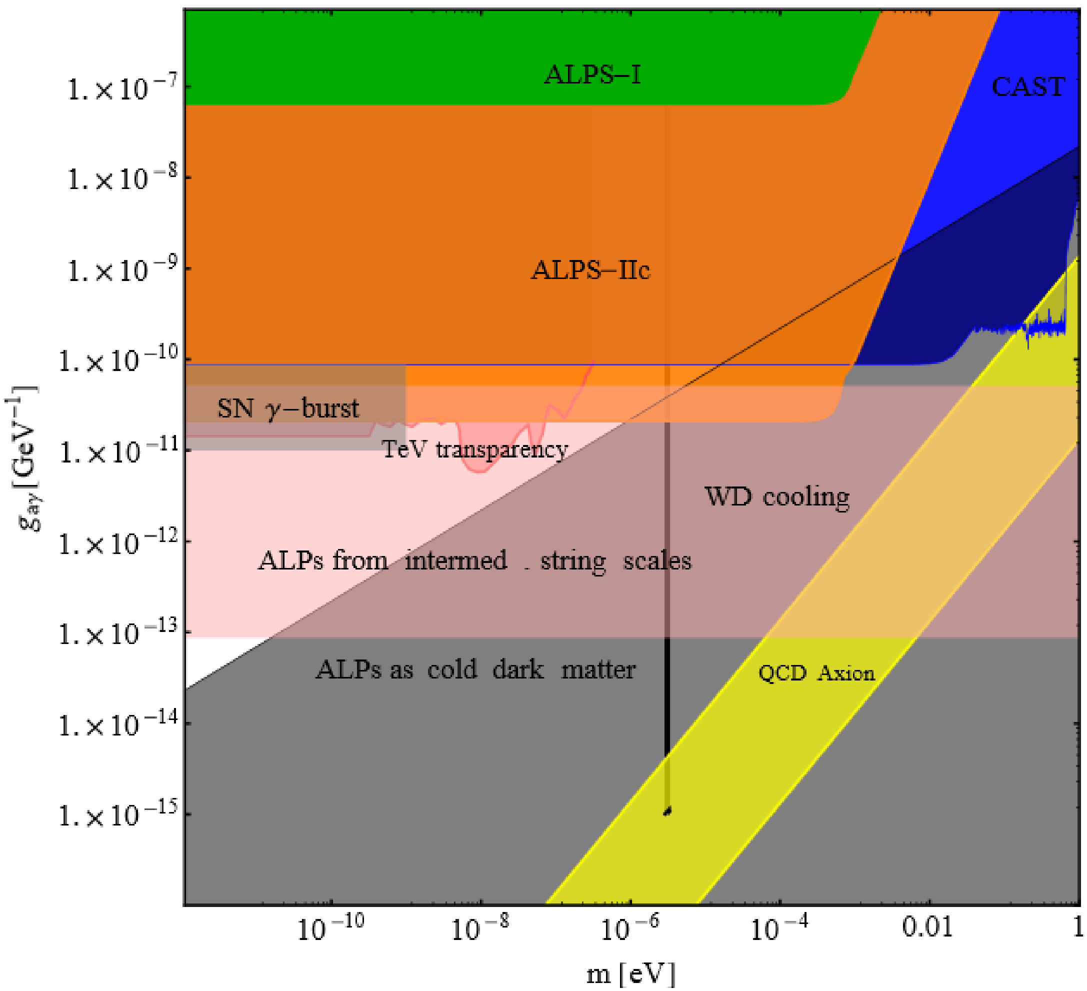
- Fermi-LAT and AMS excesses compatible with WIMPs (m~100 GeV)
- Potential cooling effects in stars point towards Axion-like DM
- keV scale DM explains lines in astrophysical observations

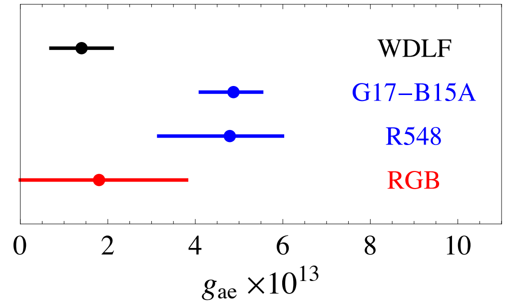
Next generation DM experiments will explore the DM paradigm with increased sensitivity.

- **Complementarity** of experiments is crucial to determine DM parameters

Astrophysical observations (Can also be considered "indirect searches")

Hints of overcooling in various astrophysical objects have been interpreted in terms of Axion-like particles or a neutrino dipole moment



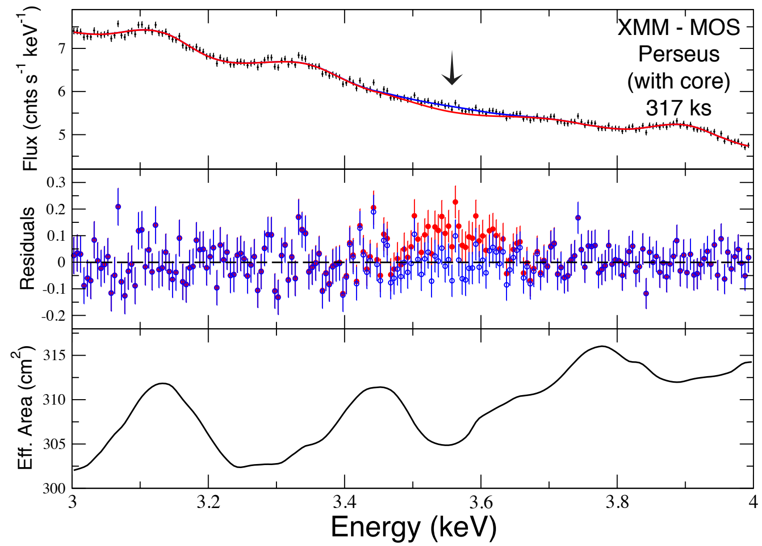


Very severe bounds from helioscopes, cavity searches, and light-shining through the wall experiments

A hint of a 3.5 keV line in astrophysical galaxies and clusters

Apparent 3.5 keV excess in stacked observation of galaxy clusters

Bulbul et al. 1402.2301
Boyarsky et al. 1402.4119



And in the centre of the Milky Way

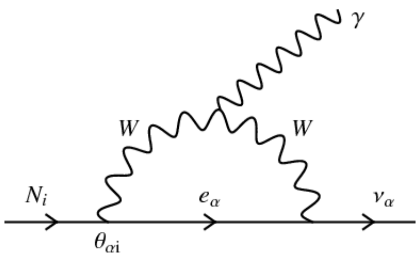
Boyarsky et al. 1408.2503

This line has NOT been observed in other objects

Stacked galaxies: Anderson et al. 1408.4115
Dwarf galaxies: Malyshev et al. 1408.3531
Blank sky areas in Milky Way: Sekiya et al. 1504.02826
X-ray galaxy clusters: Urban et al. 1411.0050
Milky way centre: Riemer Sorensen et al. 1405.2943

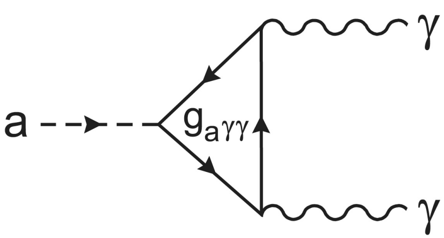
Can this be a hint of decaying 7 kev dark matter?

Sterile neutrinos



Dodelson, Widrow 1994
Shi, Fuller 1999

Axion-like particles



Jaeckel, Redondo, Ringwald

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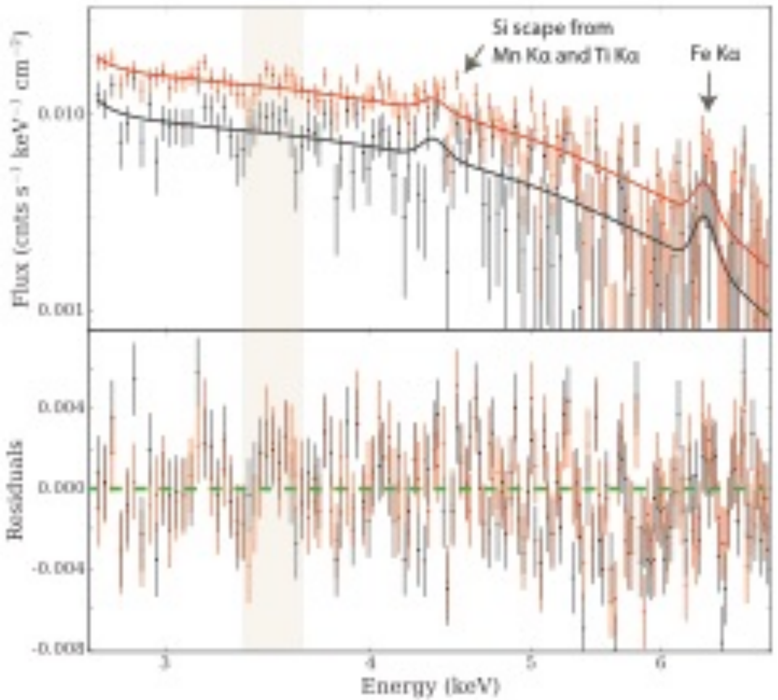
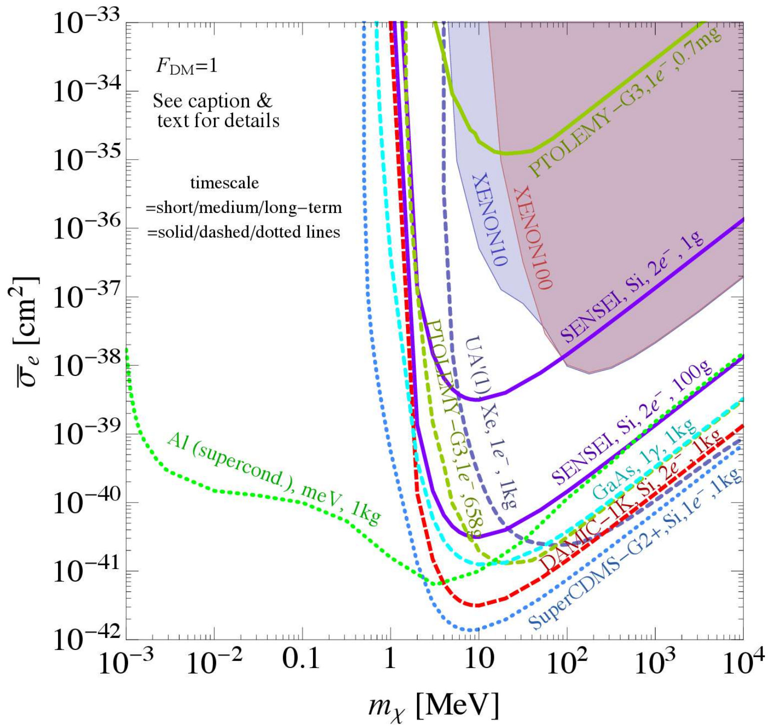


The same feature seems to be observed in the Cosmic X-ray background

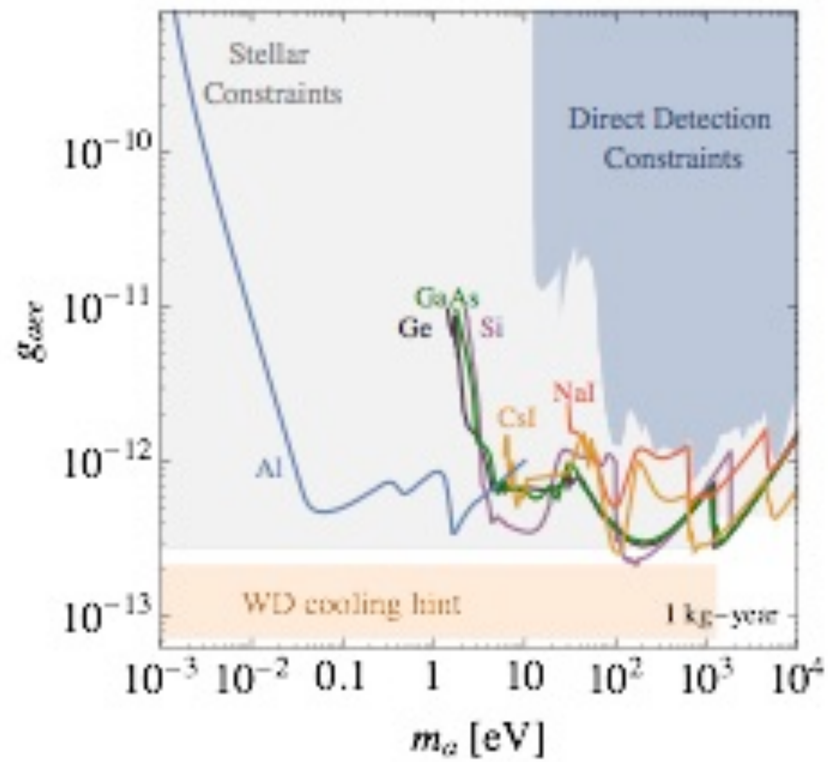
Bulbul et al. 1701.07932

Direct detection can also prove less conventional scenarios

DM-e (momentum independent) scattering



Axion-like particles

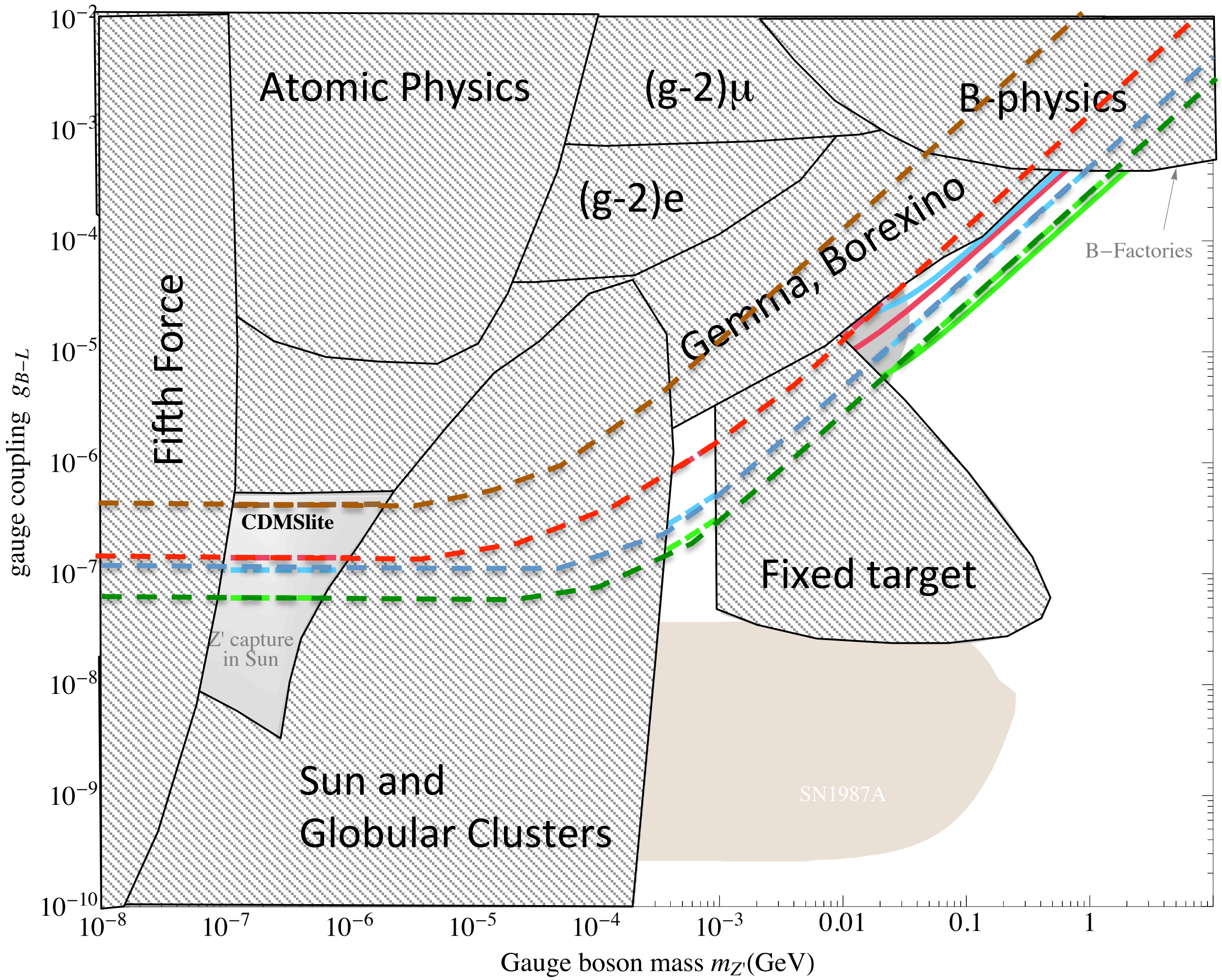


Current bounds on $U(1)_{B-L}$ models

Ge, Xe, Ne

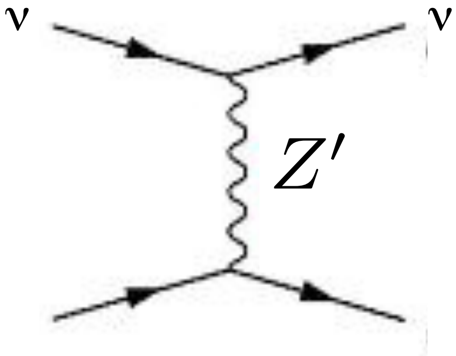
Bounds from ER

New unexplored regions at large mediator masses

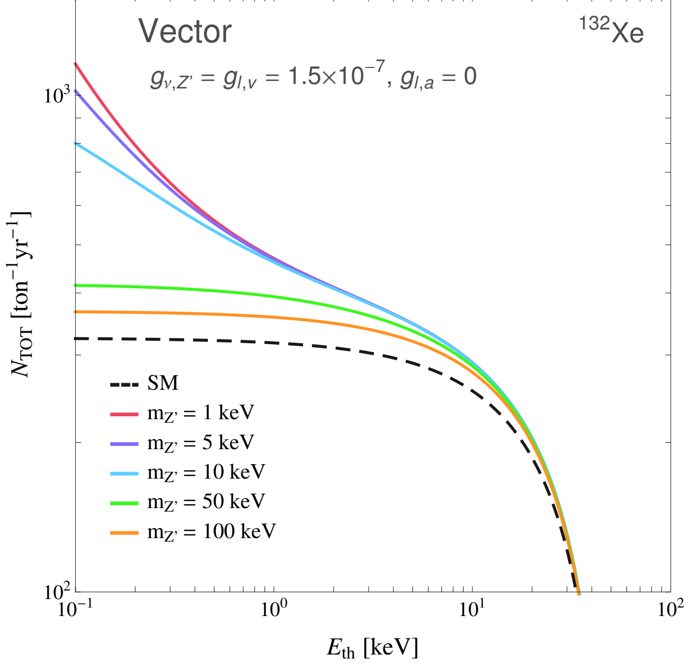


New VECTOR mediator

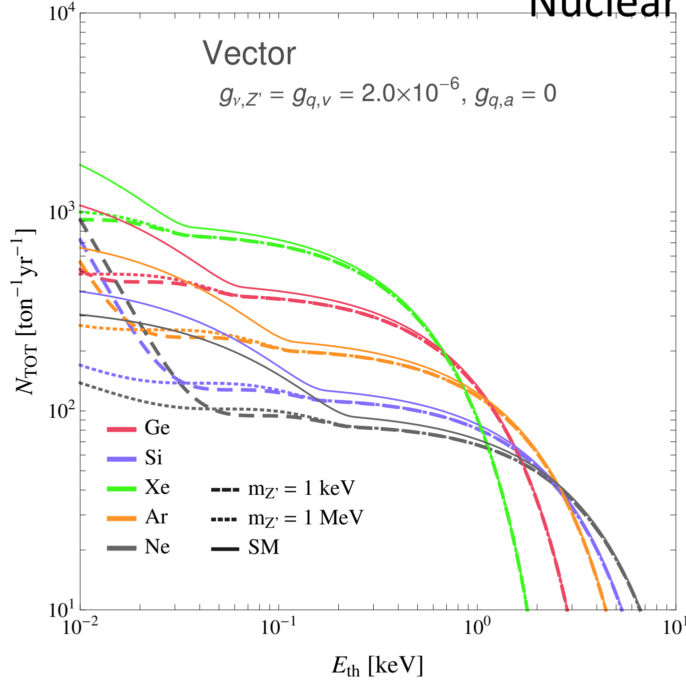
$$\mathcal{L} = g_{\nu,Z'} Z'_\mu \bar{\nu}_L \gamma^\mu \nu_L + Z'_\mu \bar{\ell} \gamma^\mu g_{\ell,v} \ell + Z'_\mu \bar{q} \gamma^\mu g_{q,v} q$$



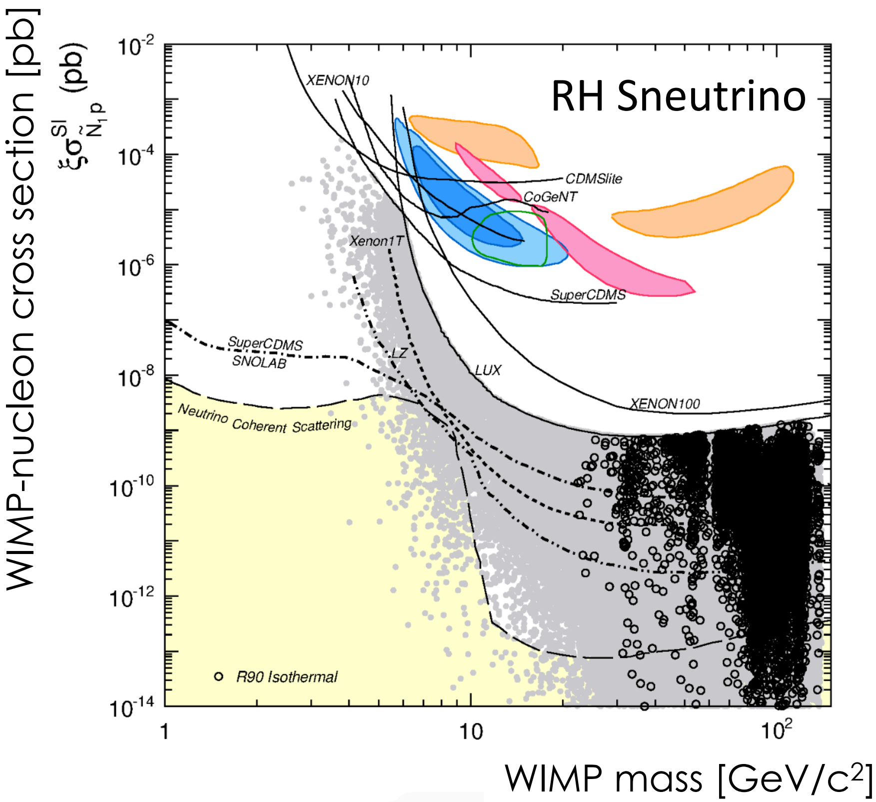
Electron recoils

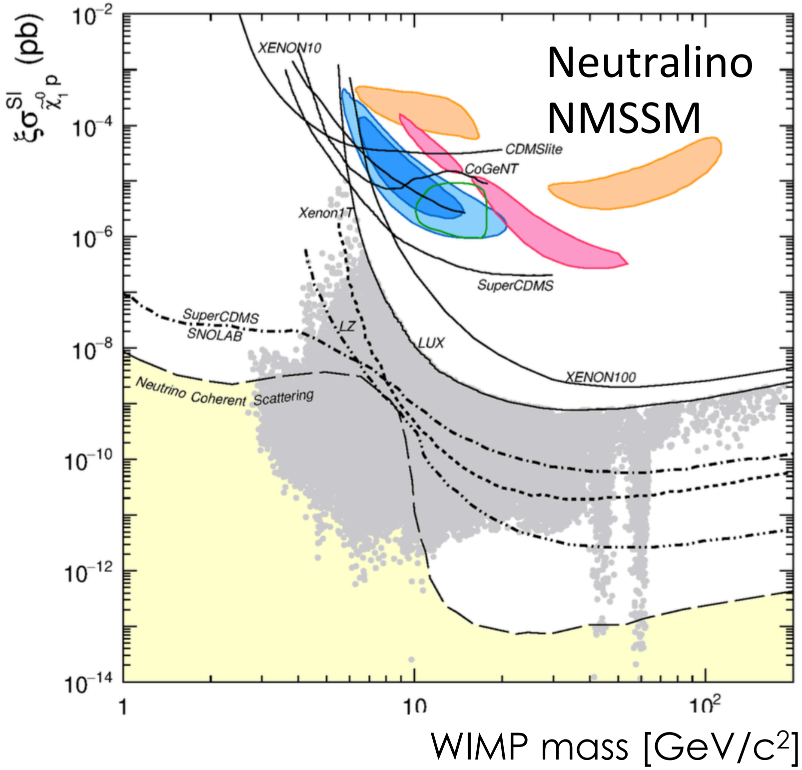


Nuclear recoils



Light WIMPs are viable in extensions of the MSSM





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

Excellent motivation for low-mass WIMP searches

Neutrino scattering in a DM experiment

$$\frac{dR}{dE_R} = \frac{\epsilon}{m_T} \int dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_\nu}{dE_R}$$

Neutrino-Electron scattering (ER)

$$\frac{d\sigma_{\nu e}}{dE_R} = \frac{G_F^2 m_e}{2\pi} \left[(g_v + g_a)^2 + \quad (g_v - g_a)^2 \left(1 - \frac{E_R}{E_\nu}\right)^2 + (g_a^2 - g_v^2) \frac{m_e E_R}{E_\nu^2} \right]$$

for muon and tau only charged current $g_{v;\mu,\tau} = 2\sin^2\theta_W - \frac{1}{2}; \quad g_{a;\mu,\tau} = -\frac{1}{2}.$

for electrons, charged and neutral currents $g_{v;e} = 2\sin^2\theta_W + \frac{1}{2}; \quad g_{a;e} = +\frac{1}{2}$

Coherent Neutrino-Nucleus scattering (NR)

$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_v^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

$$Q_v = N - (1 - 4\sin^2\theta_W) Z$$

The form factor is the same as in WIMP-nucleus scattering.

The spectrum differs as it depends on neutrino flux.