There's (still) something about light WIMPs

David G. Cerdeño

IPPP, Department of Physics
Durham University

Based on recent works with M. Peiró and S. Robles

Cooking up light WIMPs

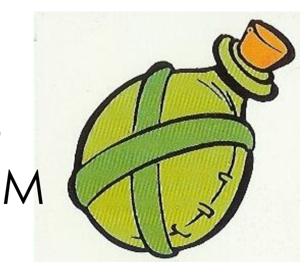
Direct detection

Indirect detection

a pinch of LHC constraints...

... do not forget the Higgs boson

The RH sneutrino
in the Next-to-MSSM

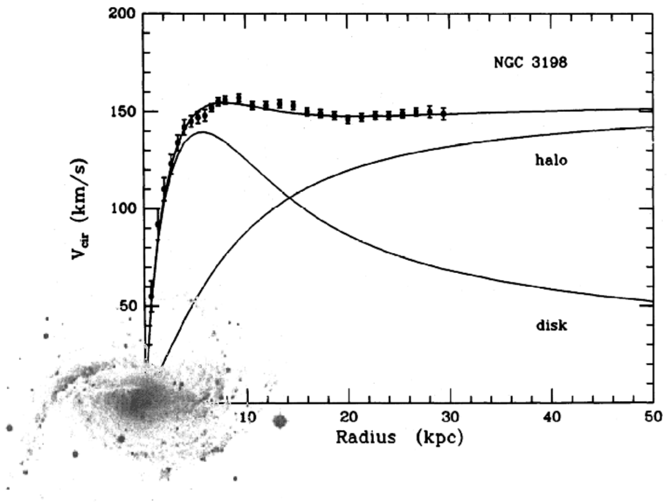


Dark Matter is a necessary (and abundant) ingredient in the Universe

It is one of the clearest hints of
Physics Beyond the SM

Galaxies

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



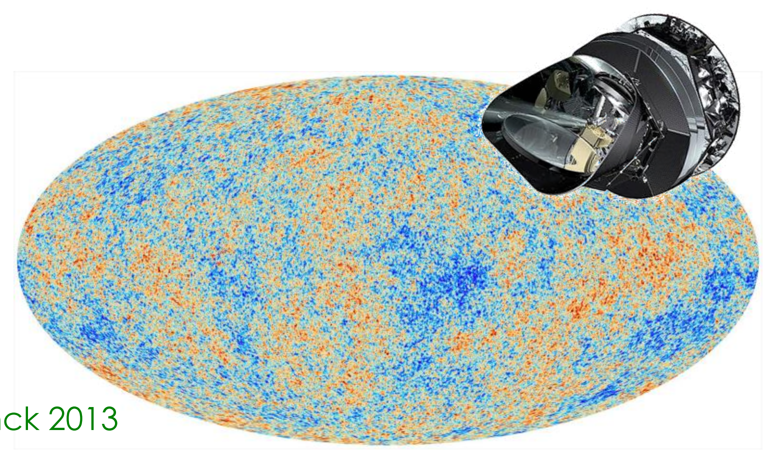
Clusters of galaxies

- Peculiar velocities and gas temperature
- Weak lensing
- Dynamics of cluster collision
- Filaments between galaxy clusters

Cosmological scales

Anisotropies in the Cosmic Microwave Background

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



Planck 2013

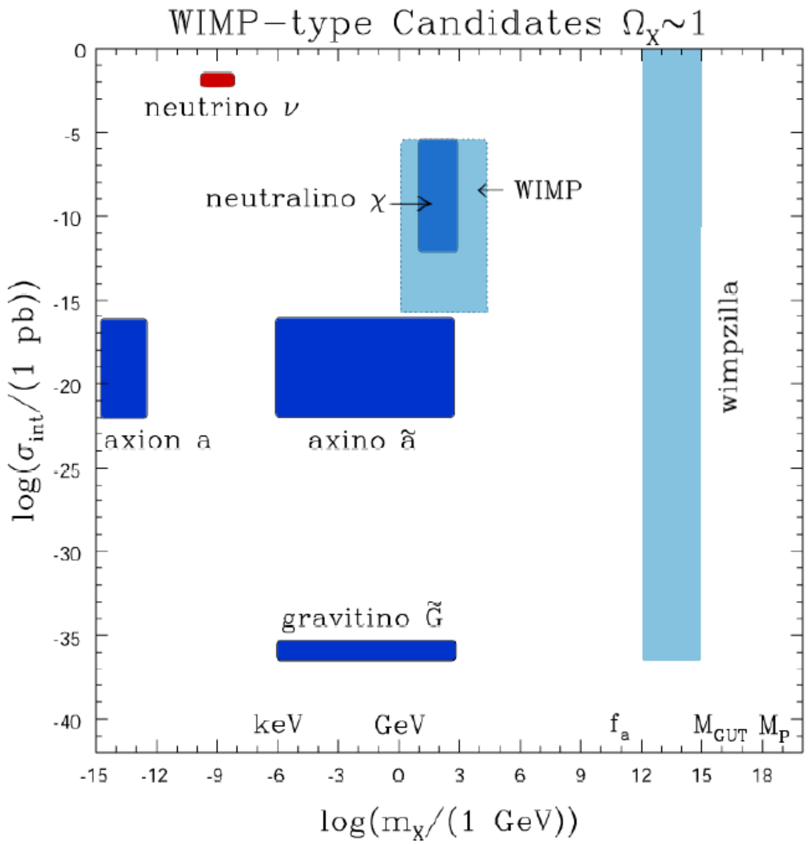
We don't know yet what DM is... but we do know many of its properties

Good candidates for Dark Matter have to fulfil the following conditions

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

Many candidates in Particle Physics

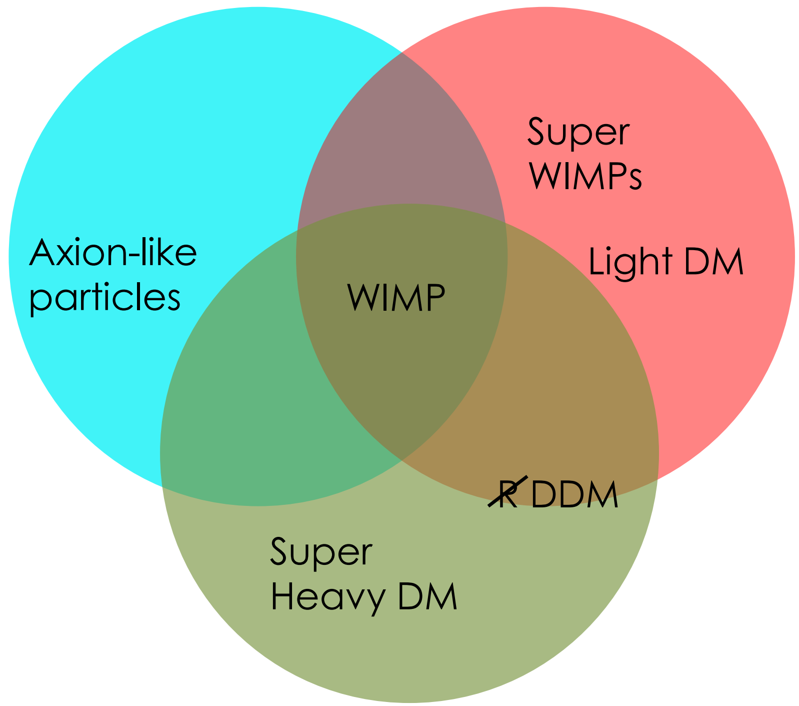
- Axions
- Weakly Interacting Massive Particles (WIMPs)
- SuperWIMPs and Decaying DM
- WIMPzillas
- Asymmetric DM
- SIMPs, CHAMPs, SIDMs, ETCs...



... they have very different properties

Dark Matter can be searched for in different ways…

Accelerator Searches (DM production) LHC (ILC)



Direct Detection

(DM-nuclei scattering)

DAMA/LIBRA
SuperCDMS
XENON
LUX
CoGeNT
DarkSide
KIMS
COUPP
PICASSO
ZEPLIN
CRESST
SIMPLE
ZEPLIN
ANAIS
XMASS
…

Indirect Detection

(DM annihilation)

PAMELA
Fermi
MAGIC
AMS

ANTARES
IceCube
CTA
…

... probing different aspects of the DM interactions with ordinary matter

Accelerator Searches (DM production) LHC (ILC)

Direct Detection

(DM-nuclei scattering)

DAMA/LIBRA
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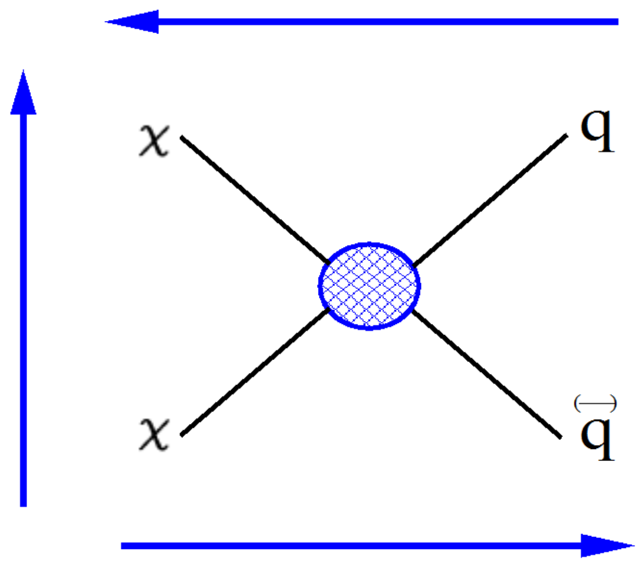


Constraints in one sector might affect observations in the other two.

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

COMPLEMENTARITY
of DM searches

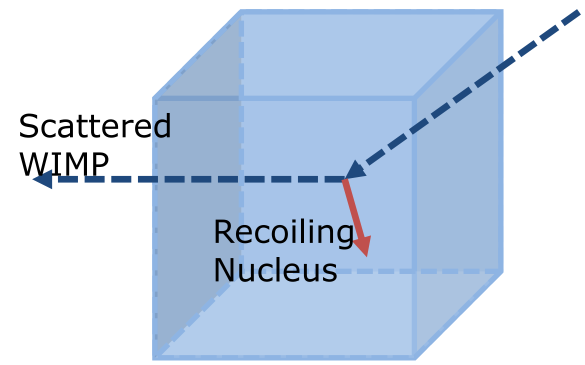
Indirect Detection

(DM annihilation)

PAMELA
Fermi
MAGIC
AMS

ANTARES
IceCube
CTA
...

The direct search for low-mass WIMPs is very challenging



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

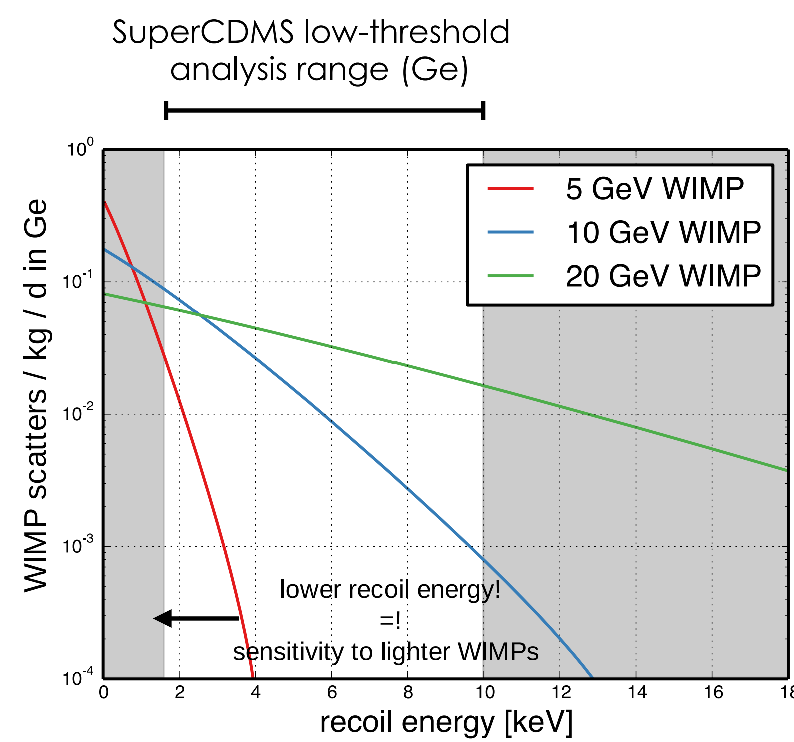
$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

- The signal is expected at very low recoil energies

Favours light targets (e.g., Si, F)

Low-threshold searches

(see talk by Julien Billard)



Possible hints of light WIMPs (m_χ~10-50 GeV)

• DAMA/LIBRA (NaI) Annual modulation signal (cumulative exposure 427,000 kg day)

DAMA/LIBRA Coll. '10

• CoGeNT (Ge) Irreducible background compatible with m~12 GeV
... with annual modulation ... (maybe (?))

Collar et al. '10- '13

• CRESST II ($CaWO_4$) (730 kg day) Excess over the known background

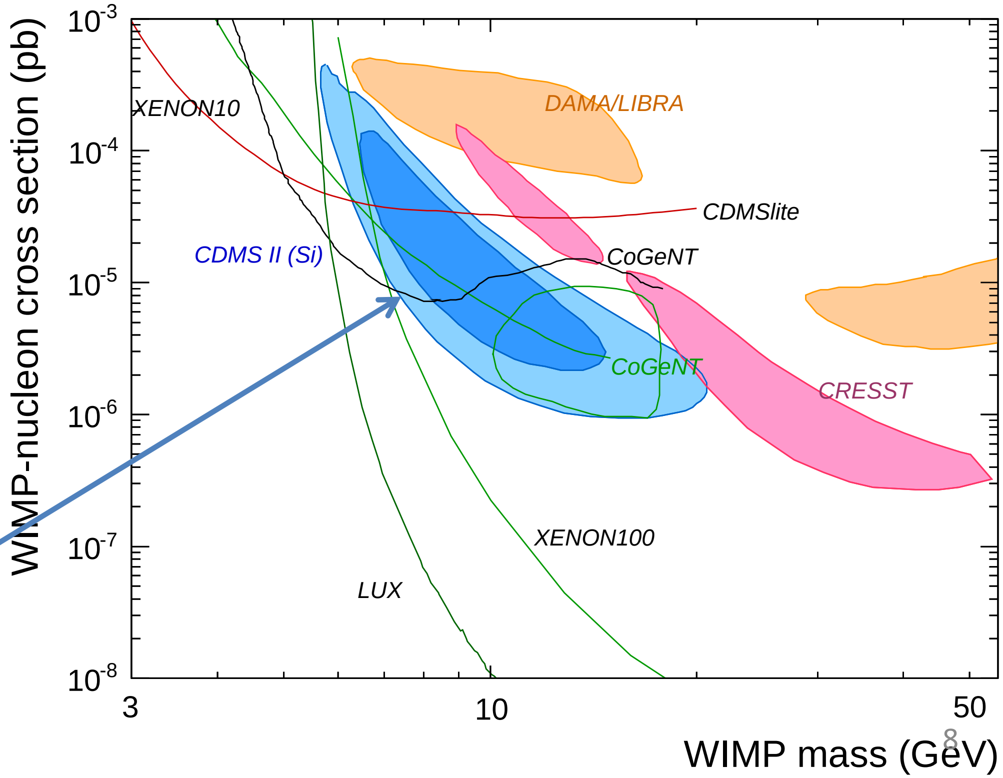
Angloher et al. '11

• CDMS II (Si) (140.2 kg days)

3 events (expected ~0.7)

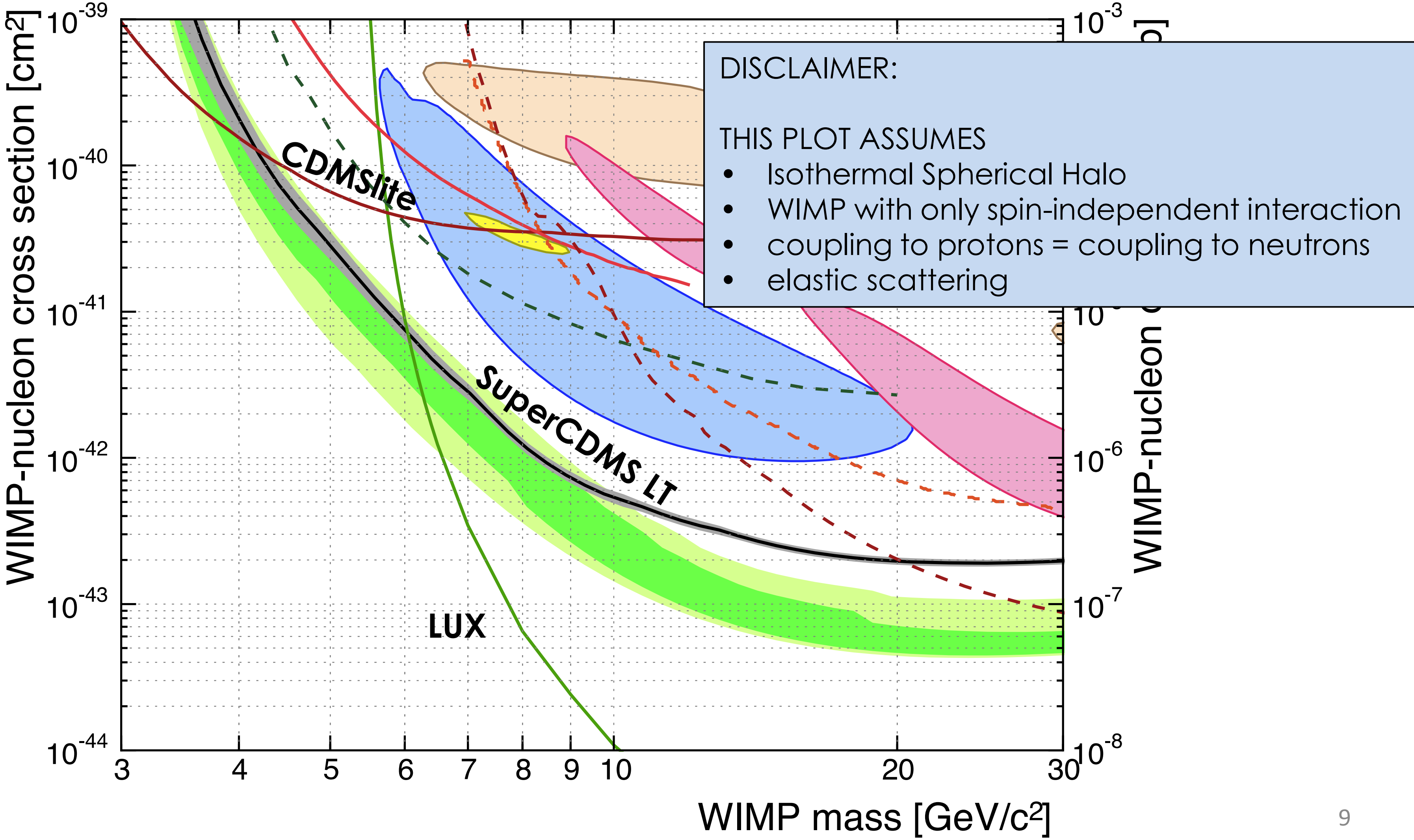
Agnese et al. PRL 111 (2013)
Agnese et al. PRD 88 (2013)

Reconstruction of the compatible regions in the WIMP Spin-independent cross section vs mass



Non-observation in other experiments set upper bounds on the cross section

XENON10, XENON100, LUX (Xe), CDMSlite, SuperCDMS, Edelweiss (Ge), COUPP (CF_3I) have not observed any DM signal, which constrains the scattering cross section



Isospin-Violating Dark Matter can ease this discrepancy

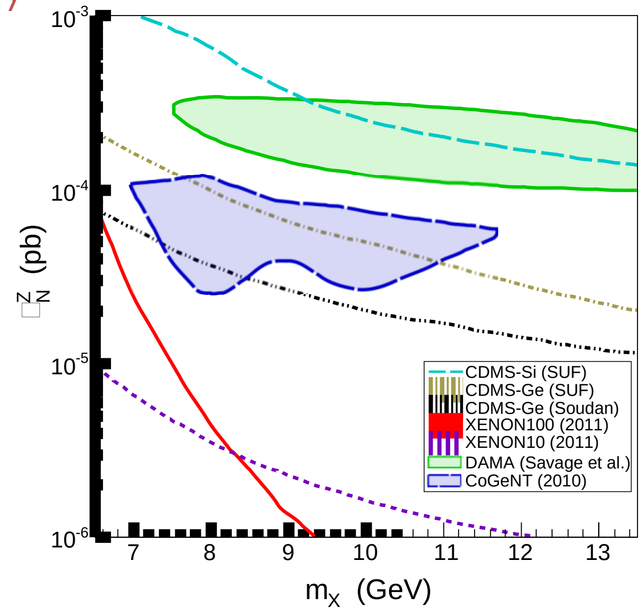
Feng, Kumar, Marfatia, Sanford 2011

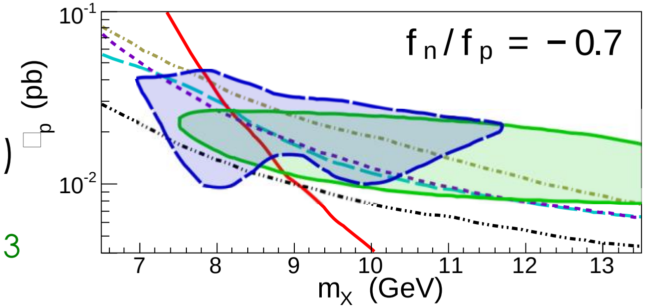
$$R = \sigma_p \sum_i \eta_i \frac{\mu_{A_i}^2}{\mu_p^2} I_{A_i} \left[Z + (A_i - Z) f_n / f_p\right]^2$$

The scattering amplitudes for proton and neutrons may interfere destructively

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

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





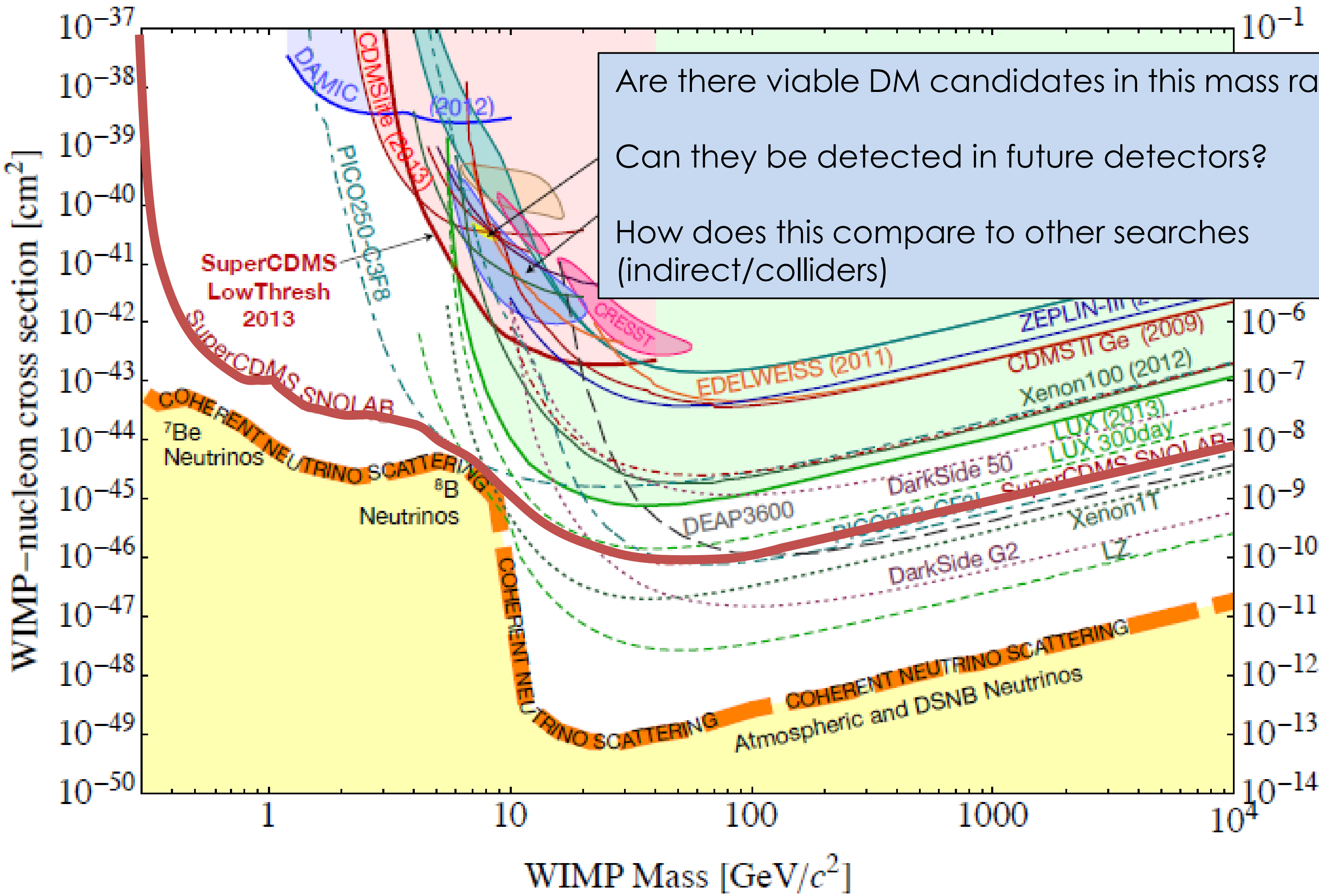
XENON100 (Xe) and CDMS II (Si) results can be "reconciled"

Frandsen et al. 2013

The effective interaction of DM particles with nuclei can be more diverse than previously considered

Fitzpatrick, Wick et al. 2012-2014

Future detectors will extend the sensitivity by over an order of magnitude.
SuperCDMS @ SNOLAB will have an excellent coverage of the light mass window.



Are there viable DM candidates in this mass range?

Can they be detected in future detectors?

How does this compare to other searches (indirect/colliders)

Theoretical models for low-mass WIMPs face some complications

1) Reproducing (thermally) the correct relic abundance

2) Satisfying constraints from DM searches

3) Collider bounds on low-energy observables and from the Higgs sector

4) Naturalness of the small mass

For concreteness I will concentrate on the case of a Right-Handed sneutrino in the Next-to-Minimal Supersymmetric Standard Model (NMSSM)

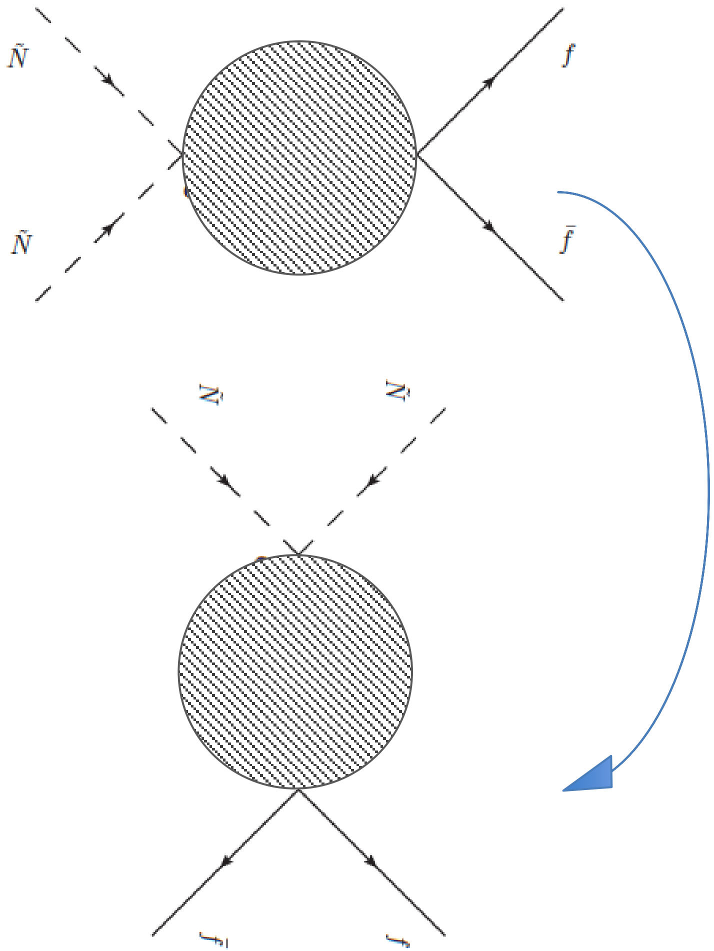
DGC, Muñoz, Seto 2007
DGC, Huh, Peiro, Seto 2011

Theoretical models for low-mass WIMPs face some complications

1) Reproducing (thermally) the correct relic abundance

SM annihilation products: $f\bar{f}$ (generally $b\bar{b}$)

Annihilation into other SM particles kinematically forbidden



This diagram is related to the direct detection scattering cross section off quarks

Fixing the relic abundance also fixes the direct detection rate

Theoretical models for low-mass WIMPs face some complications

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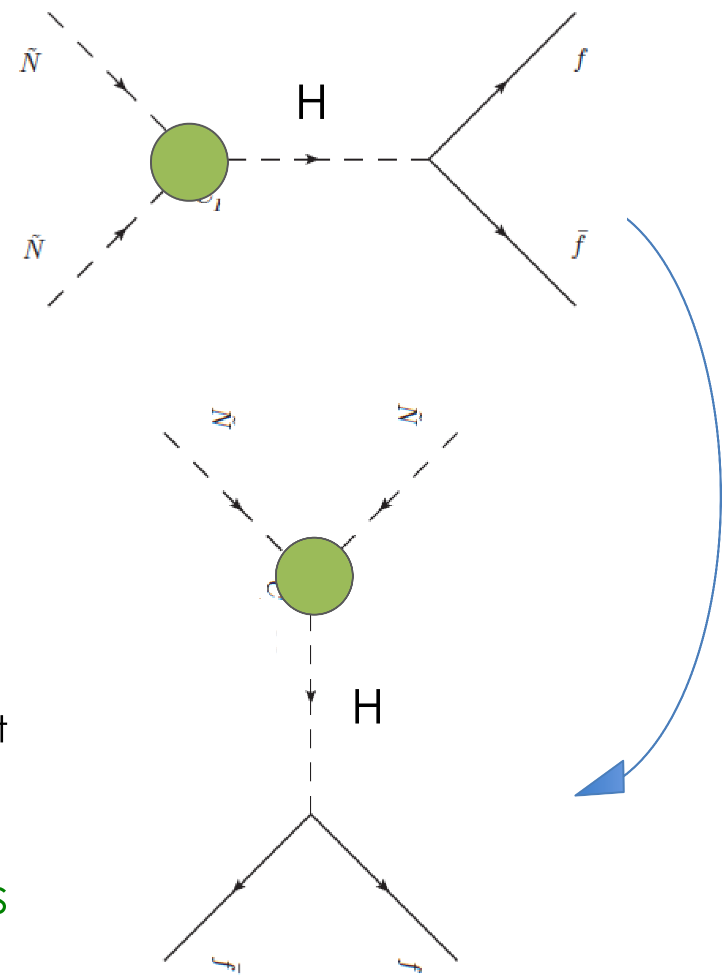

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Fixing the relic abundance also fixes the direct detection rate

If the only mediator is the SM Higgs boson, there is only one coupling to fix

Right-handed sneutrino in the NMSSM

DGC, Muñoz, Seto 2007 , DGC, Seto 2009

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

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

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

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

$$\mu\, H_1\, H_2$$

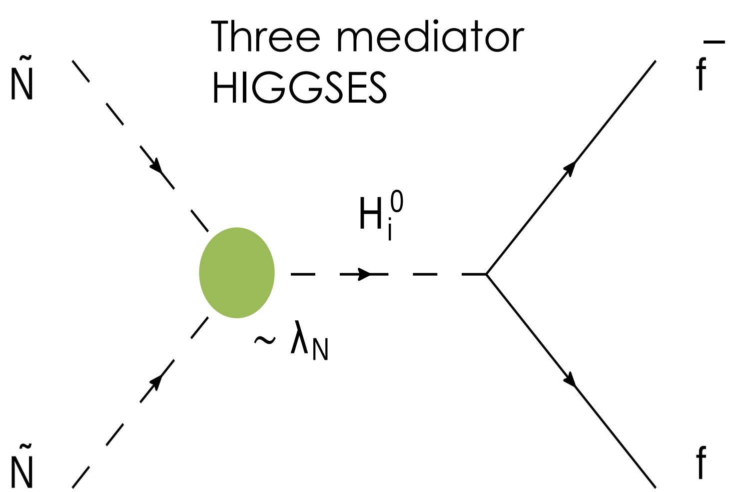
EW-scale Higgsino-mass parameter & Majorana neutrino mass

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

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

small LR mixing of the neutrino/sneutrino sector

Pure Right and Left-handed fields

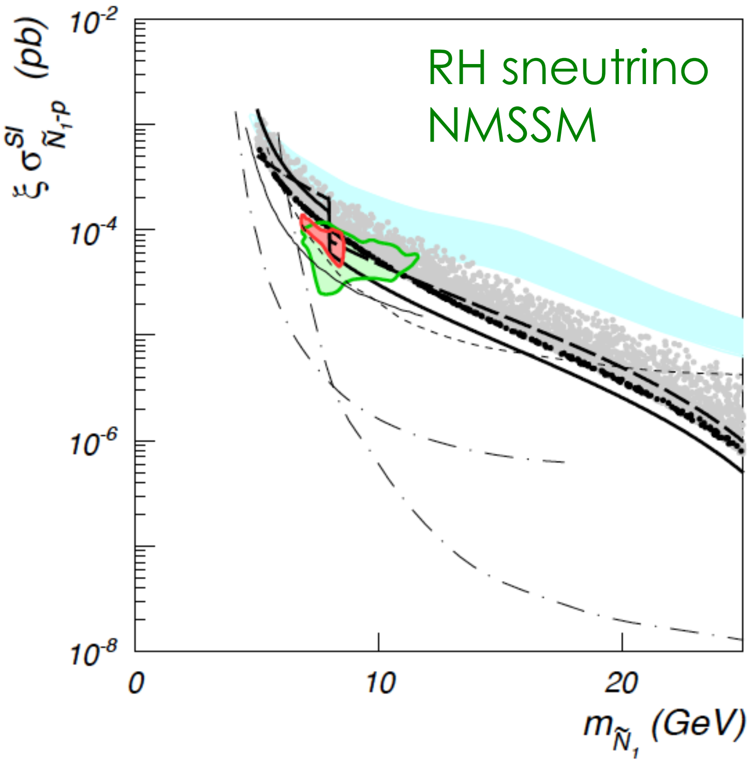


The correct relic density can be obtained for λ_N~0.1 (it is a WIMP) and a wide range of sneutrino masses

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

Light Higgs-portal models predict a large scattering cross section

The predicted scattering cross-section is remarkably close to some of the "hints" from direct detection searches



DGC. Huh, Peiro, Seto, 2011

E.g., RH sneutrino in the Next-to-MSSM

Similar to the neutralino in the MSSM (before experimental constraints ruled out this region)

And the same as in generic Higgs portal models.

However, these results are inconsistent with LUX, XENON, SuperCDMS...

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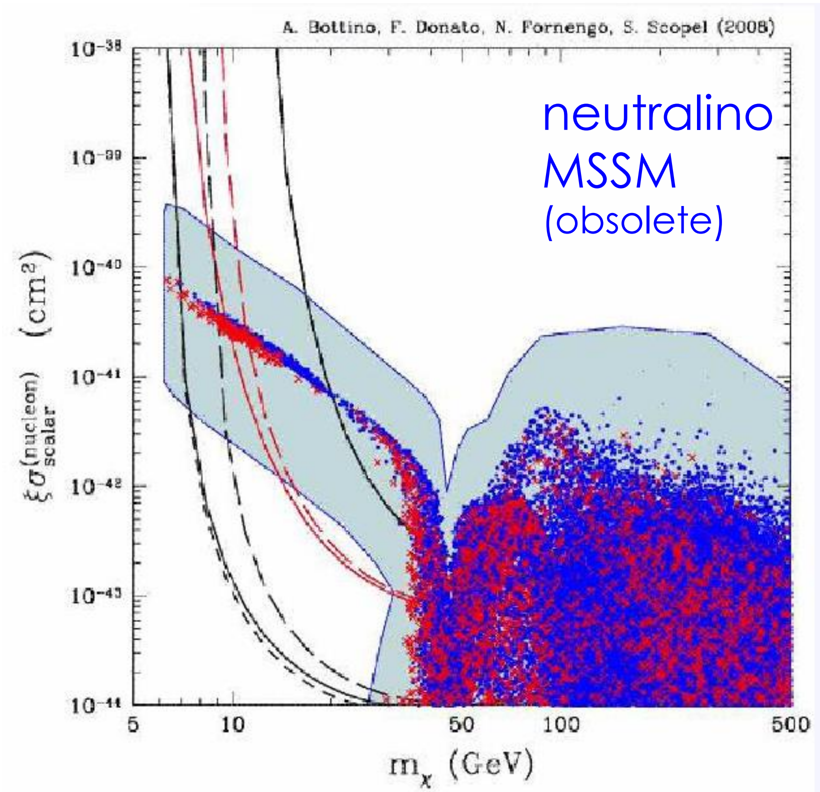

Bottino, Donato, Fornengo, Scopel 2008

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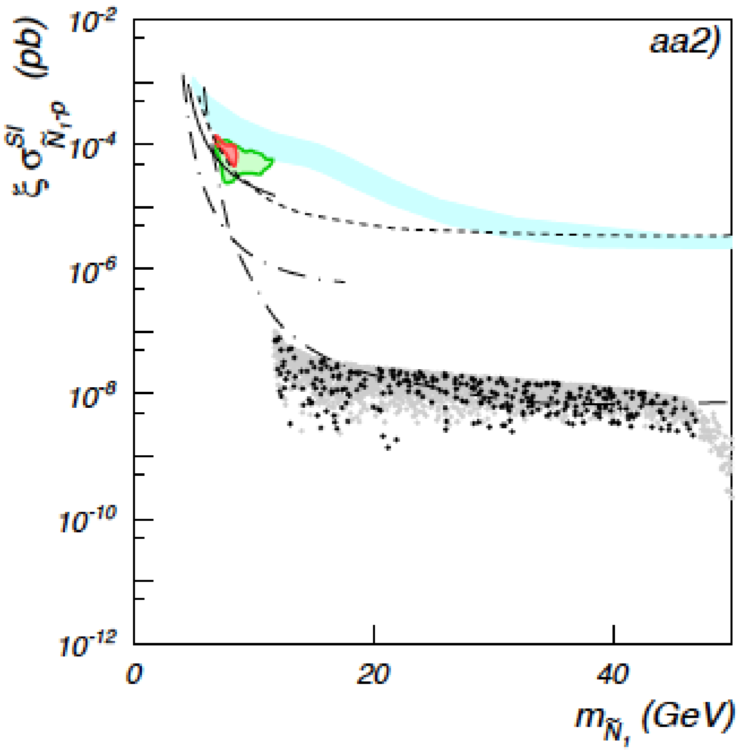
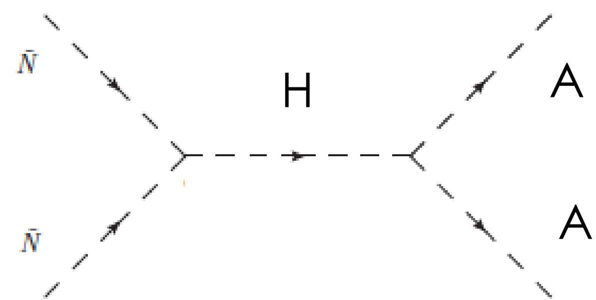
Lower scattering cross section is also possible

The correlation between the annihilation cross section and the direct detection rate can be broken in the presence of **new light particles**

E.g., light scalar and pseudoscalar (singlet-like) Higgses in the NMSSM



DGC. Huh, Peiro, Seto, 2011



If these channels dominate, the interaction with fermions is smaller.

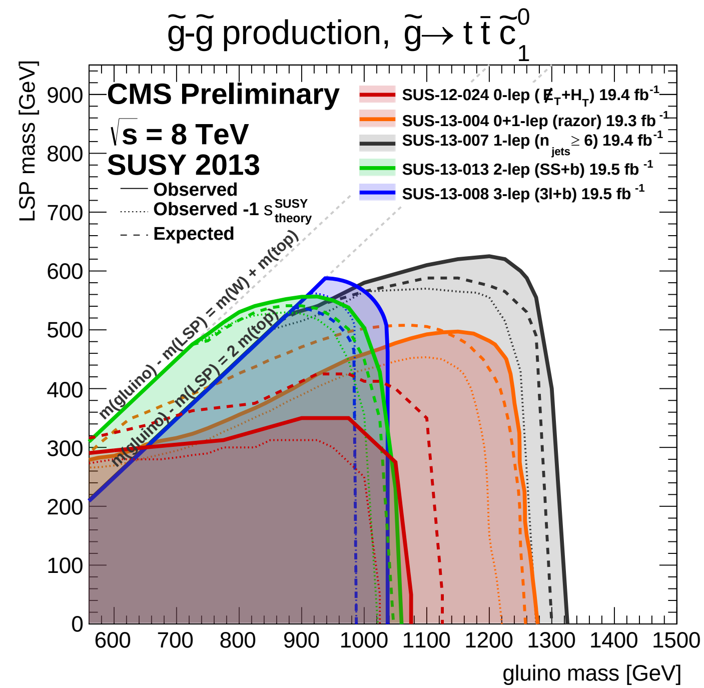
LHC searches constrain DM models

Constraints on SUSY particles and low-energy observables

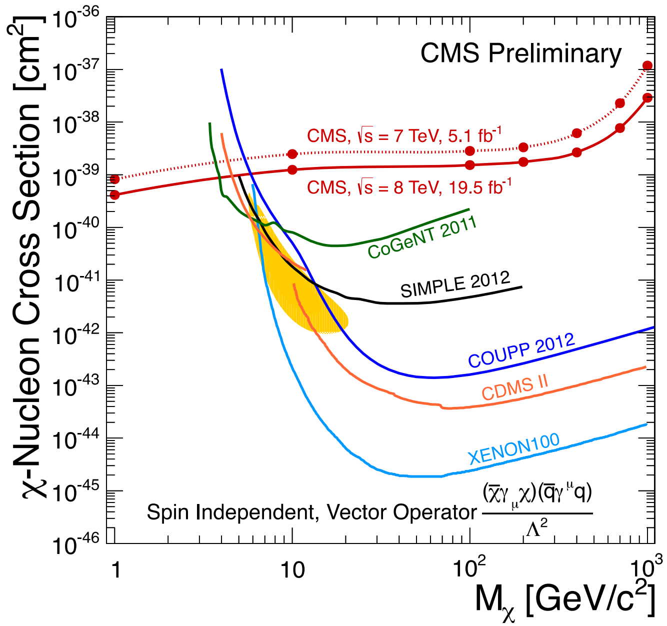
$$B(B_s \to \mu^+ \mu^-) = 2.9 \pm 1.4 \times 10^{-9}$$

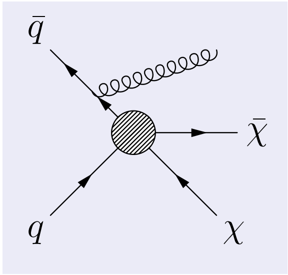
LHCb 2012, 2013

Set INDIRECT bounds on SUSY dark matter (mass and interactions)



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





Dark matter production with initial state radiation

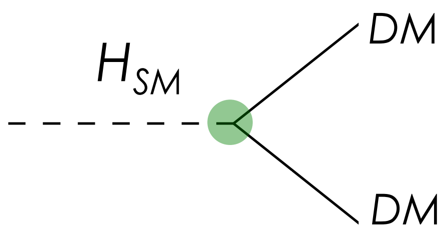
Bounds depend on the DM effective operators to fermions (significantly relaxed for light mediators)

(remember previous talk by O. Buchmueller)

Observation of a SM-like Higgs boson with m_H~125.5 GeV

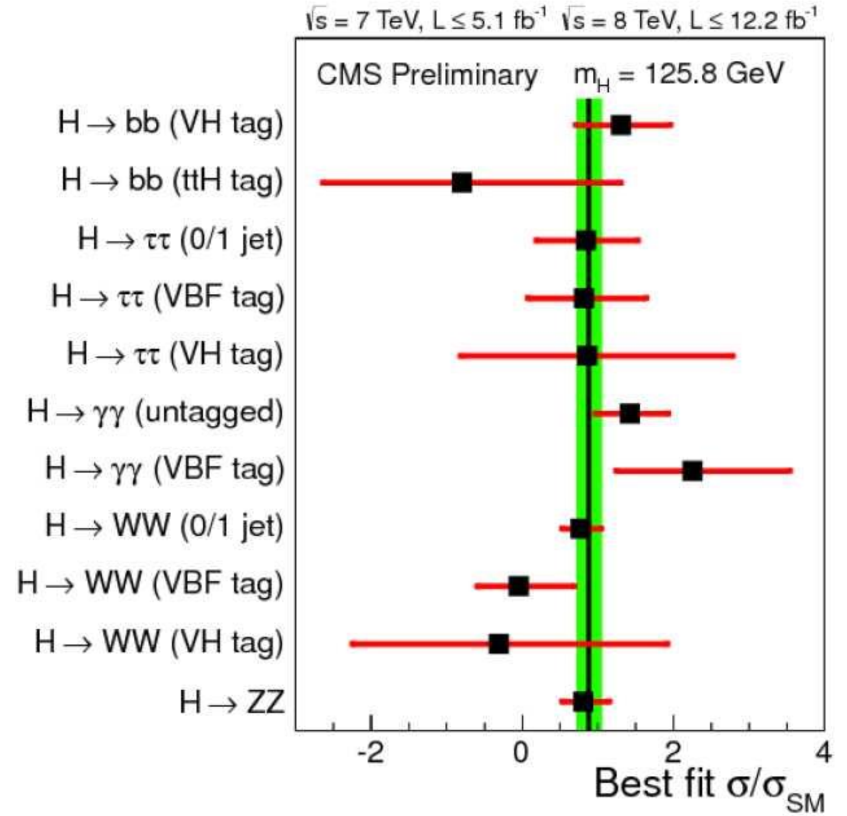
Bound on the invisible decay width of the Higgs

e.g., Djouadi et al. 2013



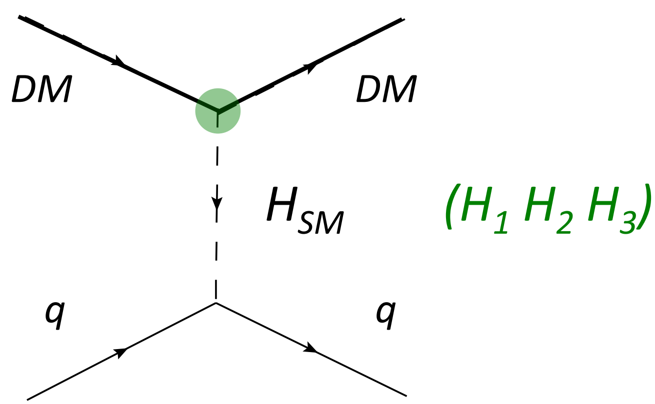
$$BR(h^0_{SM} \to inv) \lesssim 0.20$$

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

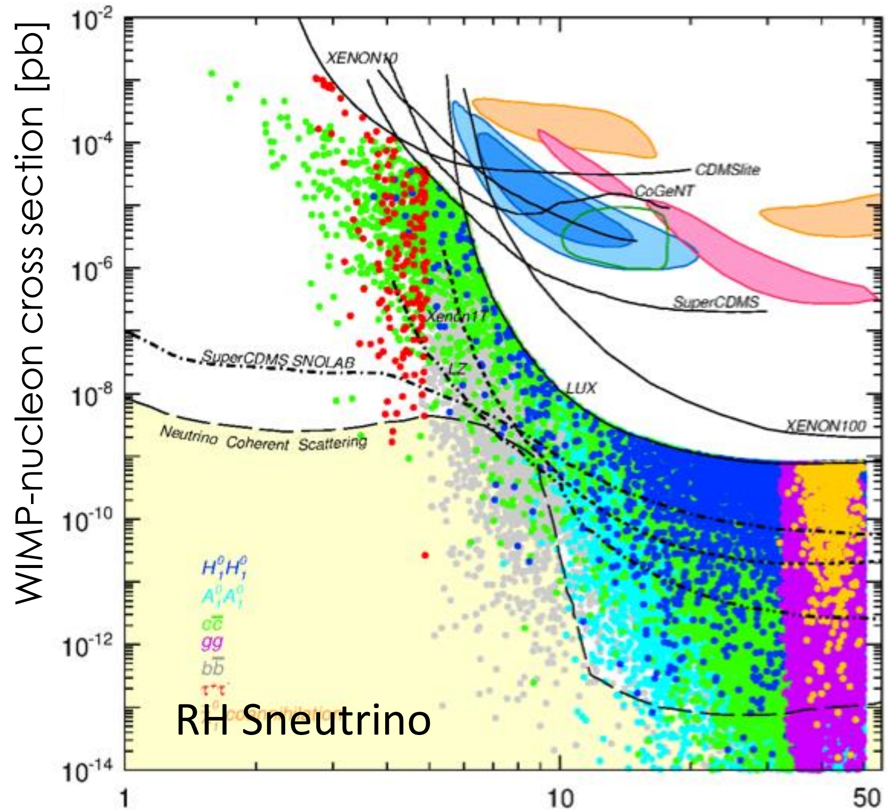


This has implications for the scattering cross section of DM particles

An extended Higgs sector helps avoiding these bounds (NMSSM)



After imposing all these constraints the predictions for direct detection span many orders of magnitude



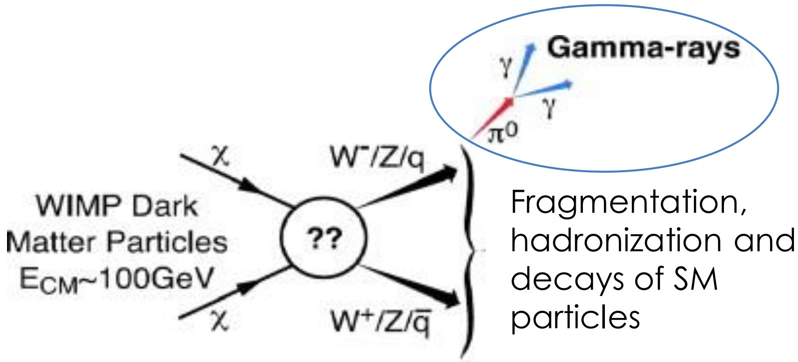
DGC, Peiró, Robles
JCAP 08 (2014) 005

WIMP mass [GeV/c^2]

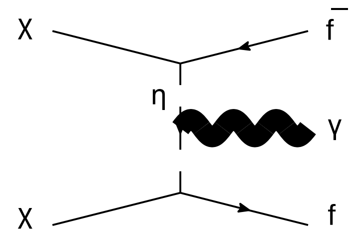
Excellent motivation for direct searches at low masses (preferably with various targets)

Light WIMPs in indirect searches: Gamma rays from DM annihilation

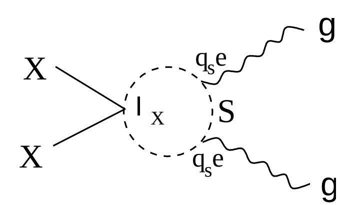
Continuum (secondary photons)



Direct gamma emission (features, lines)



Internal bremsstrahlung



Loop processes

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

Theoretical input

Astrophysical input

DM annihilation cross section IN THE HALO

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

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

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

DM Density profile

Region of observation (backgrounds)

Fermi-LAT can provide constraints for light WIMPs

Fermi-LAT '11

Fermi-LAT observation of Dwarf Spheroidals

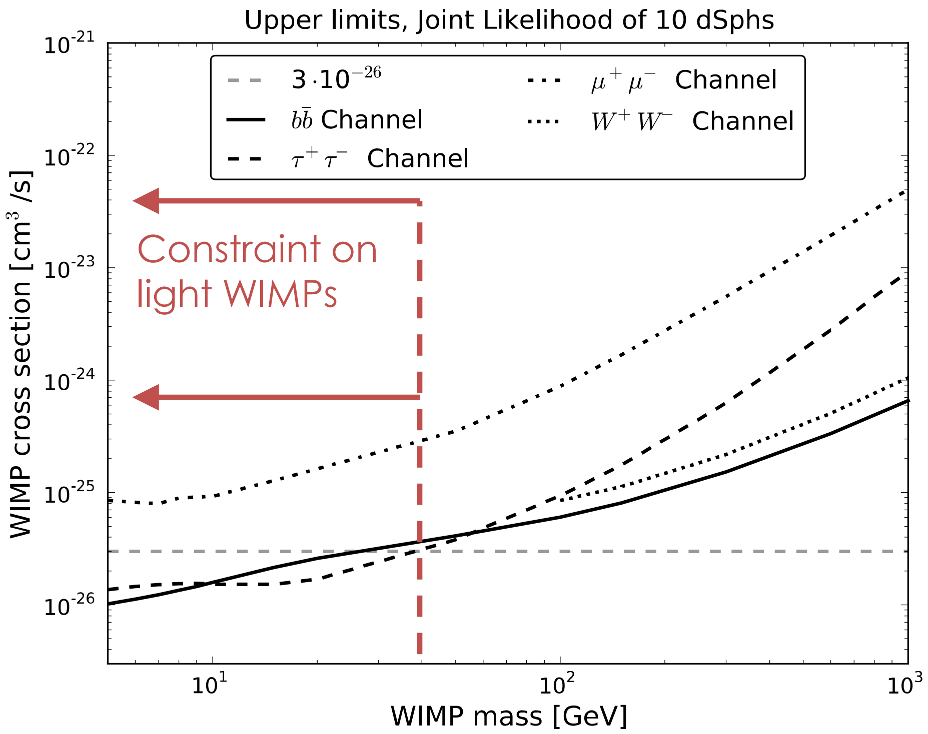
Fermi-LAT '11

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

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

m>27 GeV for the bb channel

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

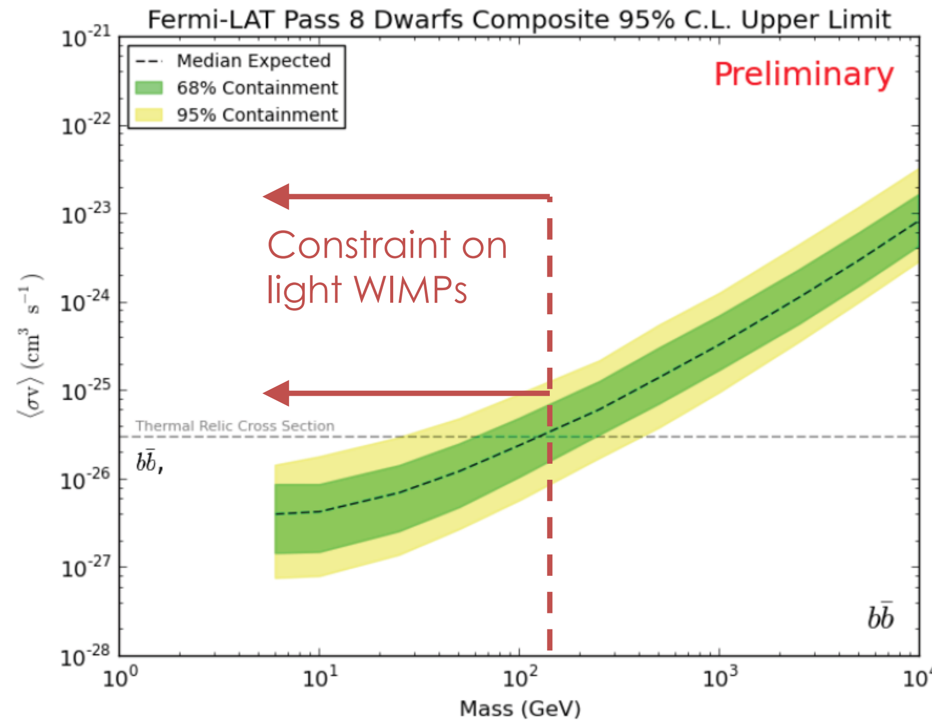


Dwarf spheroidal galaxies are ideal objects to look for dark matter

- 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 '14

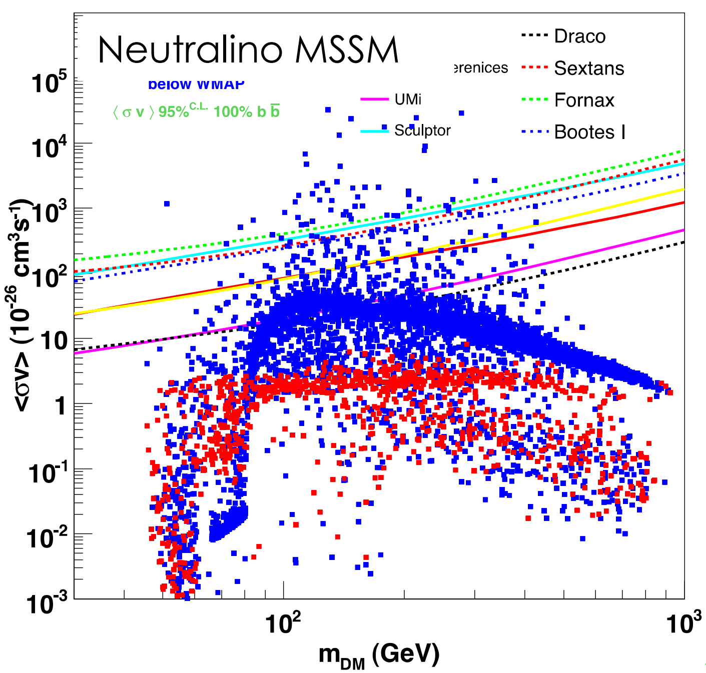


Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT '11

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

m>100 GeV for the bb channel

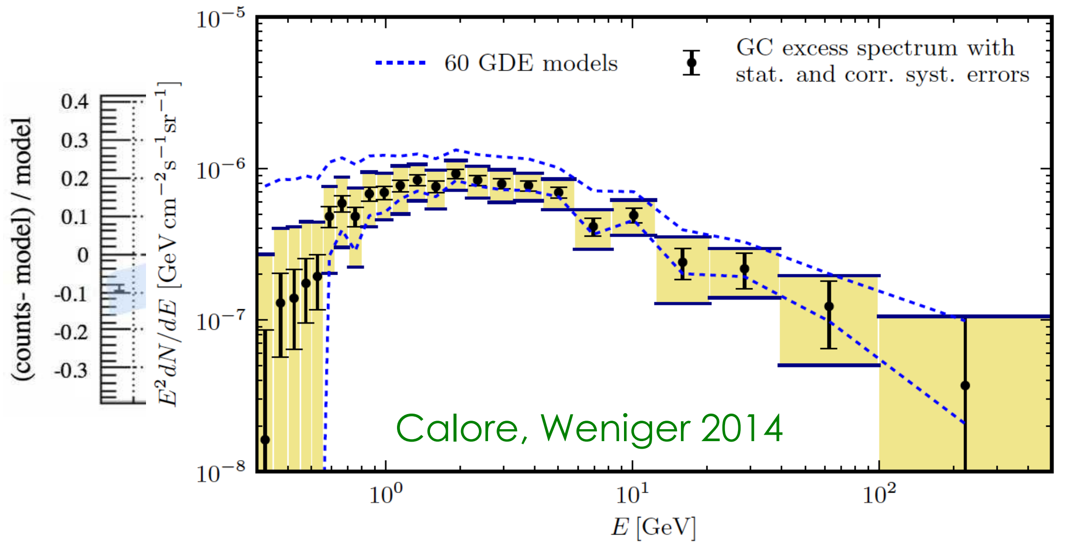


Abdo et al. 1001.4531

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

Coannihilation effects,
velocity-dependent cross-section
resonances

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



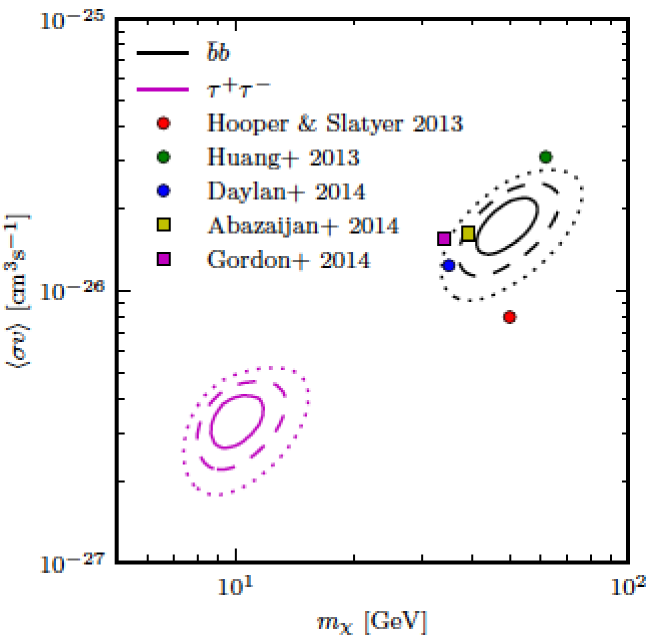
Compatible with the annihilation of a light WIMP ~10-50 GeV

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

Pulsars do not have the right morphology
Hooper, linden 2012



Fits normally done for pure annihilation channels

Compatible with WIMP DM

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

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

Conclusions

Low-mass WIMPs are still an very attractive possibility

The excess in the GCE emission observed by Fermi-LAT is nowadays the best experimental motivation

From the theoretical point of view, Direct, indirect detection and LHC constraints imply

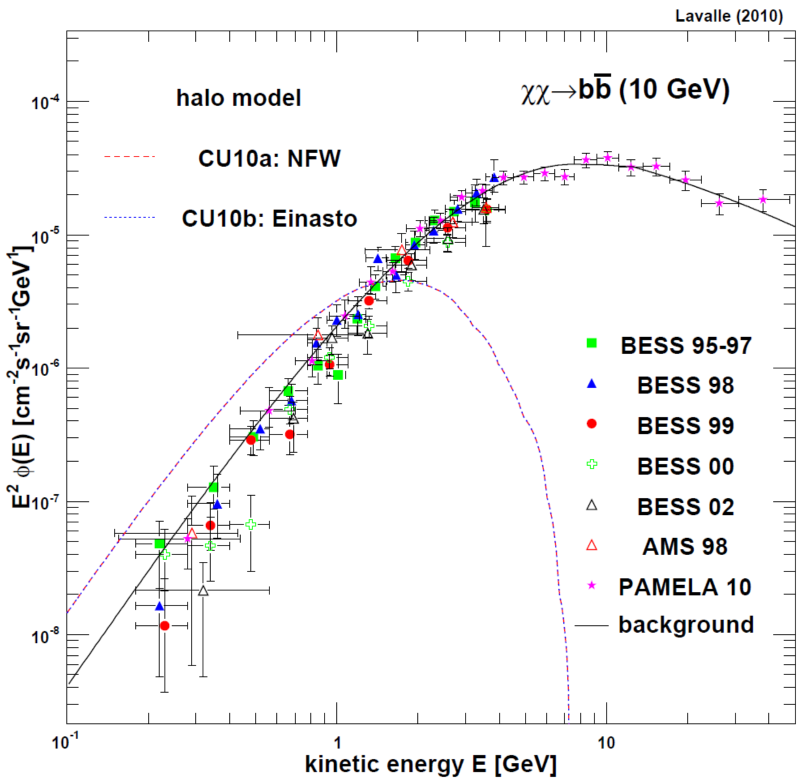
- extra light particles
- extended Higgs sectors

The RH sneutrino in the NMSSM is an excellent example of a complete model with these properties.

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

These bounds are very sensitive to the DM halo properties

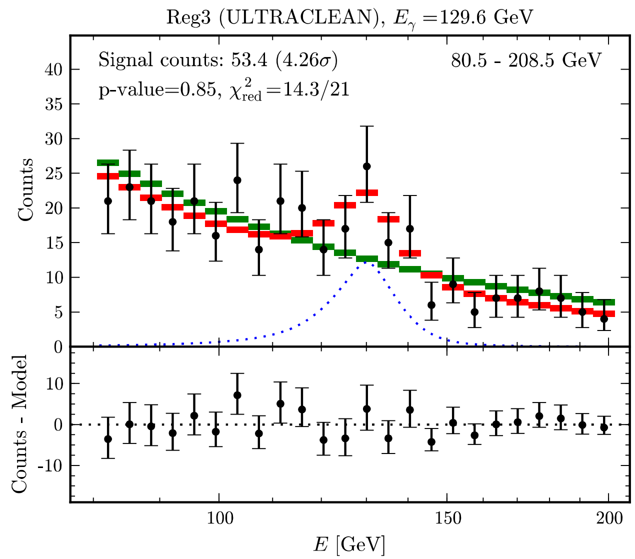
130 GeV WIMP annihilation into $\gamma\gamma$

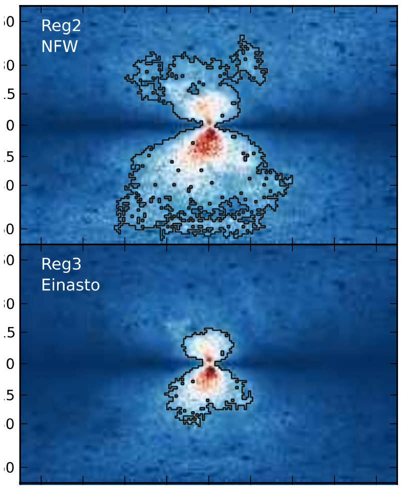
Weniger 1204.2797

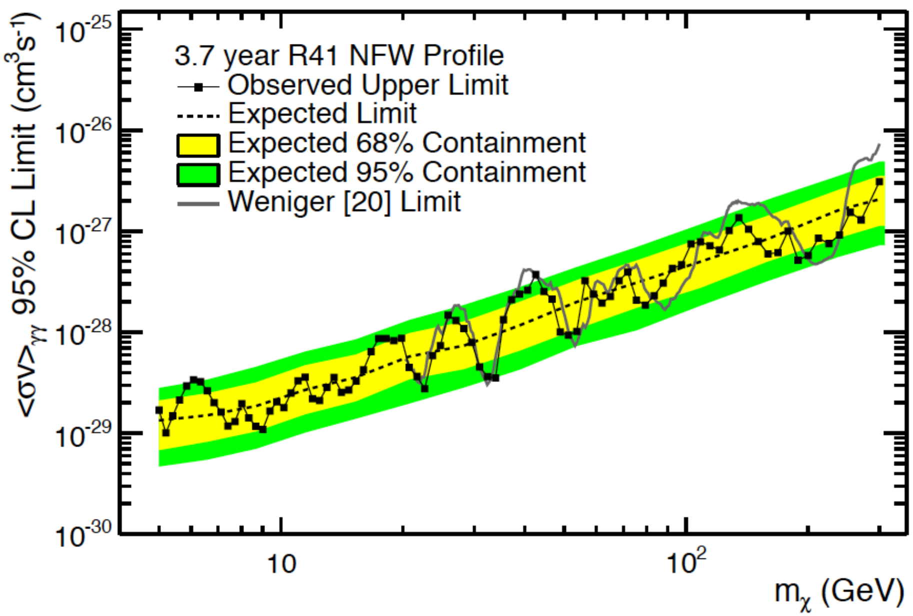
Internal bremsstrahlung

Bringmann et al. 1203.1312

Instrumental effect?
(it appears in data from Earth's limb)



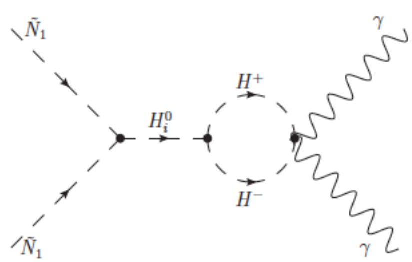




The search for "features" also sets constraints on low-mass WIMPs

Ackerman et al. 1305.5597

Bound on loop-suppressed processes



Very light DM can be further constrained with data from the Galactic Centre

Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT '11

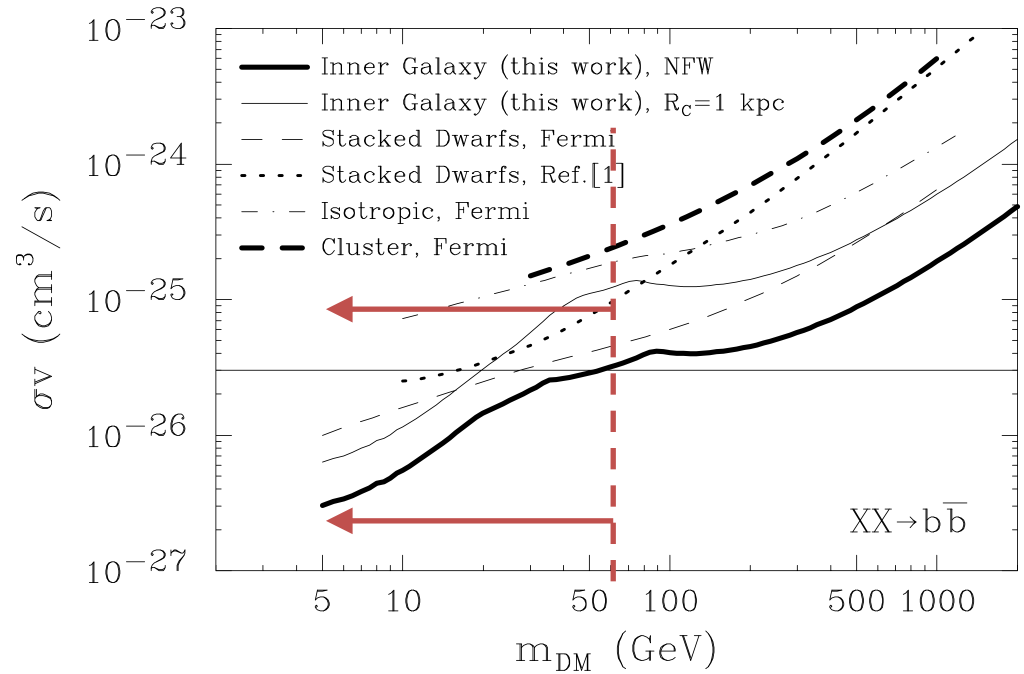
Thermal cross-section excluded for some channels (bb and tt)

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 are very sensitive to the DM halo properties

Fermi-LAT observation of dSph

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

Fermi-LAT bounds from Galactic Centre

Very strong for COMPRESSED haloes

Gómez-Vargas et al. [with Fermi Coll.]
JCAP 10 (2013)