DARK MATTER
STATUS OF DIRECT SEARCHES

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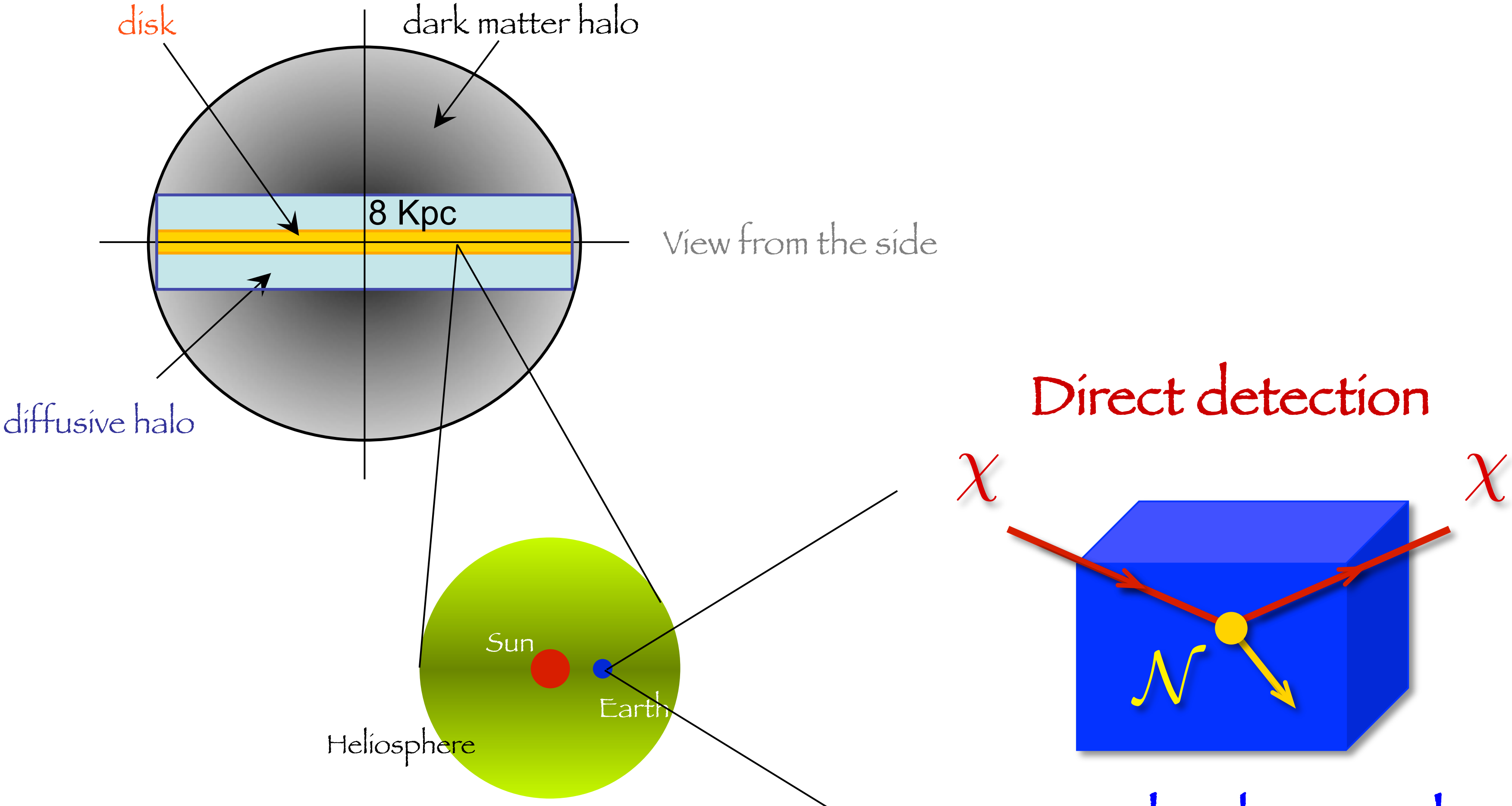
INFN
Torino

Dark Workshop @ GGI
Firenze (Italy) – 26.10.2011

Direct detection of galactic dark matter



Low-background underground detector

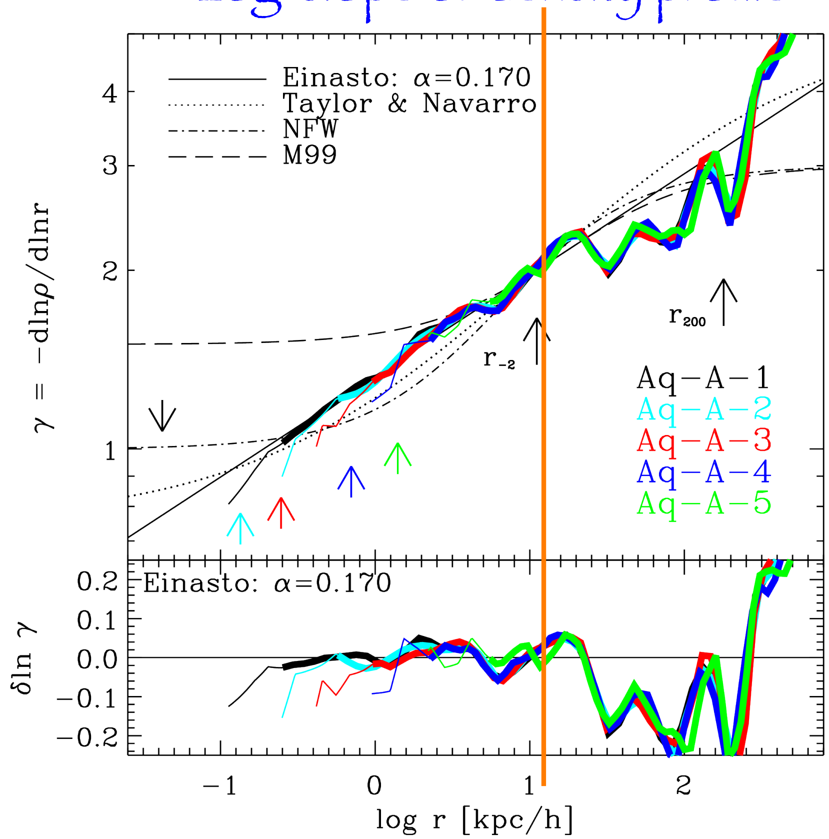
Key elements of Direct Detection

- How DM is locally distributed
- How DM scatters with nuclei
- What kind of signal and signature we can target
- What kind of backgrounds we need to confront with
- How detectors respond to DM scattering

Dark matter phase space (for CDM)

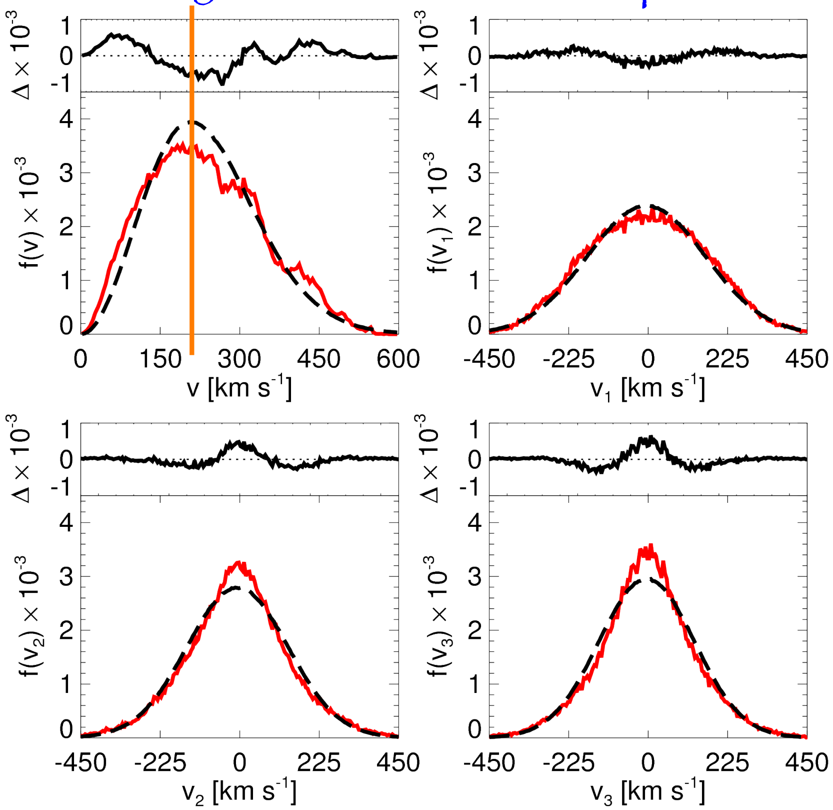
$\rho(r)$

Log-slope of density profile



$f(v)$

Velocity distribution at Sun position

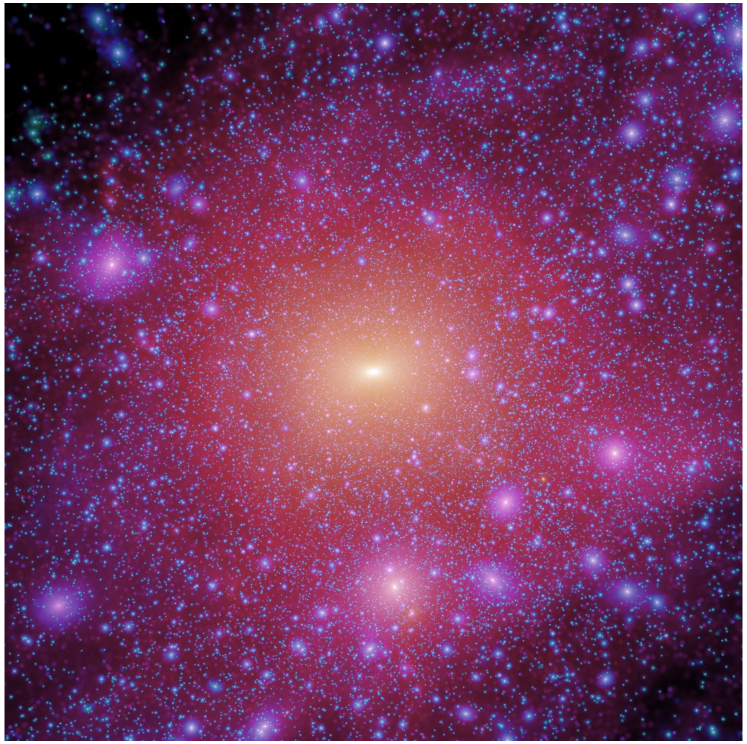


From numerical simulations

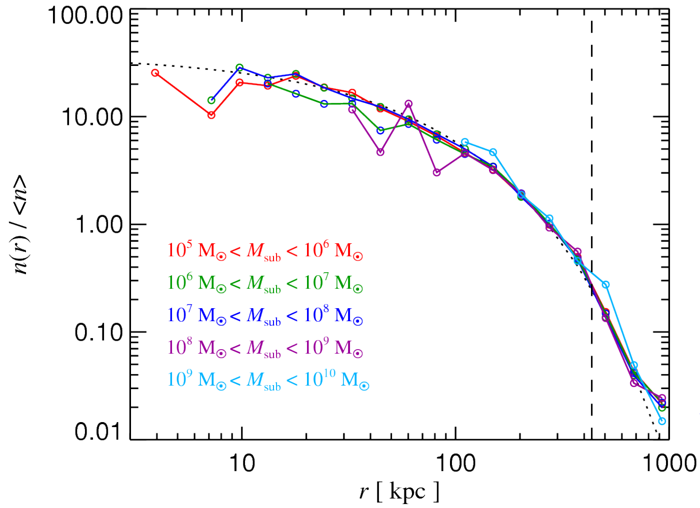
Navarro et al., arXiv:0810.1522

Vogelsberger et al., arXiv:0812.0362

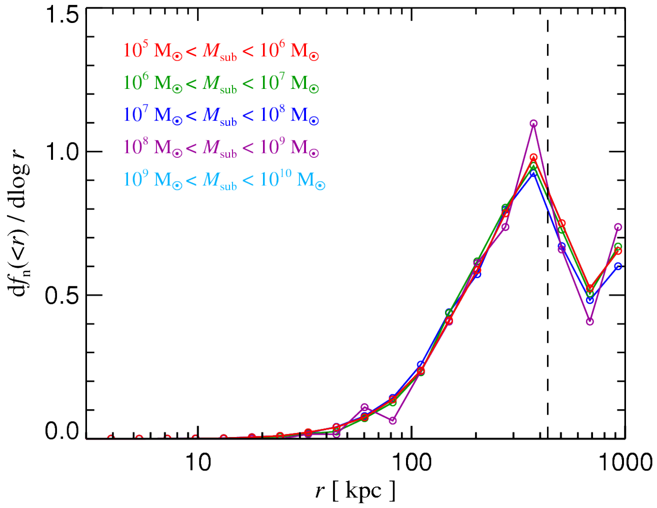
Subhalos



The Aquarius Project



Subhalo number density

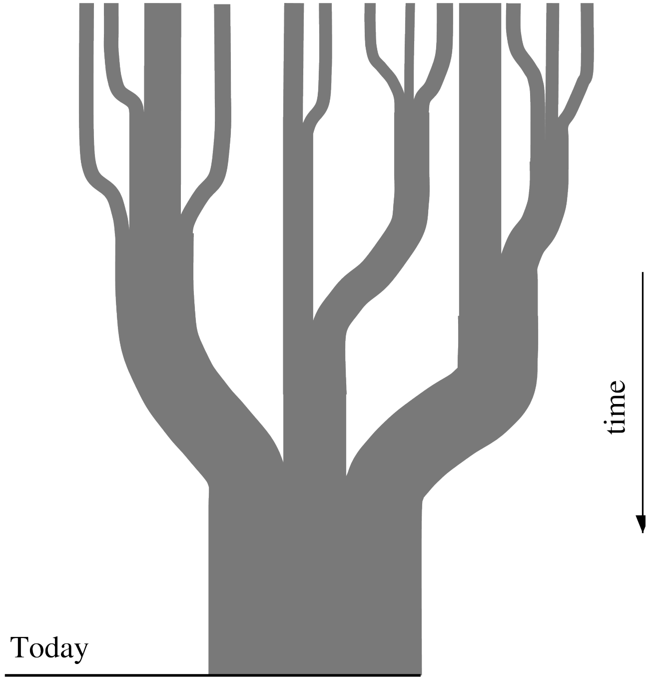


Subhalo fraction

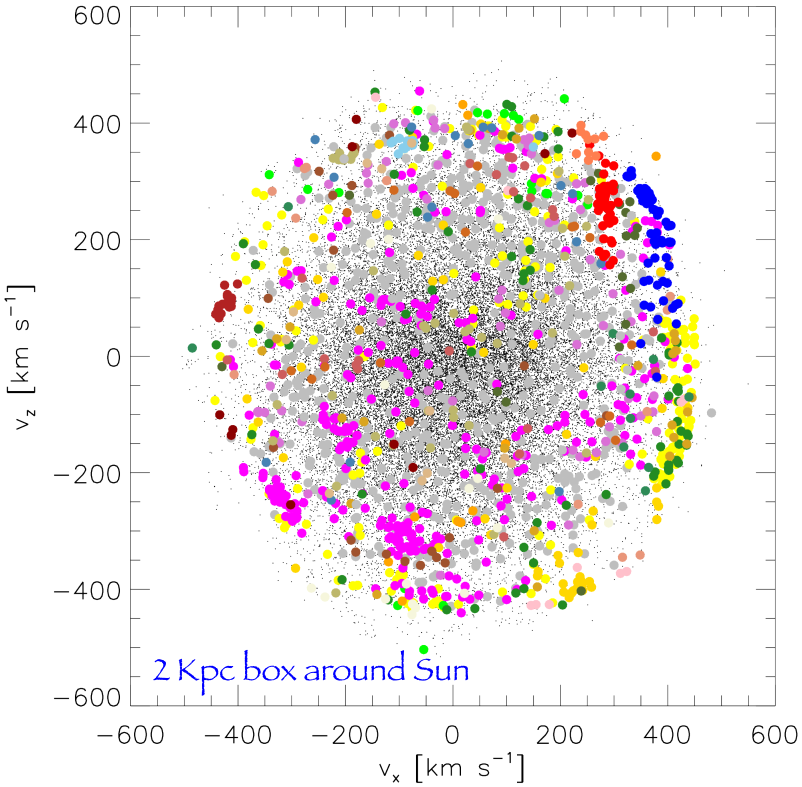
Springel et al., MNRAS 391 (2008) 1685

Velocity streams

Merger tree



"Particles" from common branch



Vogelsberger et al., arXiv:0812.0362

"Canonical" halo for direct detection

$$\rho(r) \longrightarrow \rho_0 = 0.3\ \mathrm{GeV\ cm^{-3}}$$

Some recent determinations [1-3]

[1] $\rho_0 = 0.385 \pm 0.027\ \mathrm{GeV\ cm^{-3}}$ (Einasto)
$\rho_0 = 0.389 \pm 0.025\ \mathrm{GeV\ cm^{-3}}$ (NFW)

[2] $\rho_0 = 0.43(11)(10)\ \mathrm{GeV\ cm^{-3}}$
[4] $\rho_0 = (0.20 \div 0.55)\ \mathrm{GeV\ cm^{-3}}\ [1\sigma]$

$$f(\vec{v}) = N \exp\left(-v^2/v_0^2\right)|_{v_{\rm esc}}$$

$$v_0 = (220 \pm\ 50)\mathrm{km\ s^{-1}}$$

$$v_{\rm esc} = (450 \div 650)\ \mathrm{km\ s^{-1}}$$

Anisotropies may be present
Profile may not be gaussian
Tails are relevant for DD

Streams may have (even relevant) impact

[1] Catena, Ullio, arXiv:0907.0018
[2] Salucci et al. arXiv:1003.3101
[3] Pato et al., arXiv:1006.1322
[4] Iocco et al., arXiv:1107.5810

Interaction mechanisms - WIMPs

- Elastic scattering with nuclei
  - Ex.: Neutralino, Sneutrinos, KK

$$\chi\,\mathcal{N} \longrightarrow \chi\,\mathcal{N}$$

$$E_R = \mu_{\mathcal{N}}^2 v^2 (1-\cos\theta)/m_{\mathcal{N}}$$

E_R > few KeV

- Inelastic scattering with nuclei

Tucker-Smith, Weiner, PRD 64 (2001) 043502

  - Ex.: Sneutrinos

$$\chi\,\mathcal{N} \longrightarrow \chi'\,\mathcal{N}$$

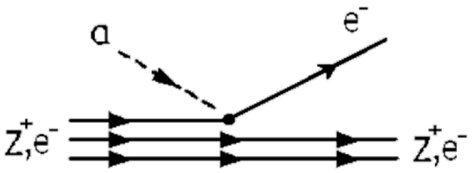
Scatter if: $\Delta m < \dfrac{\beta^2 m_1 m_{\mathcal{N}}}{2(m_1 + m_{\mathcal{N}})}$

about 1-100 KeV

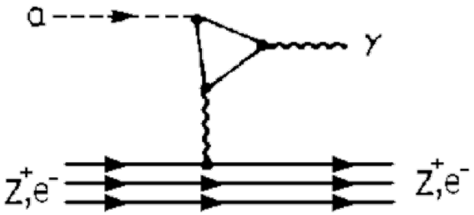
Interaction mechanisms – non WIMPs

- Inelastic, scatter on electrons
  - Ex.: Light (KeV) [pseudo]scalars

Compton-like

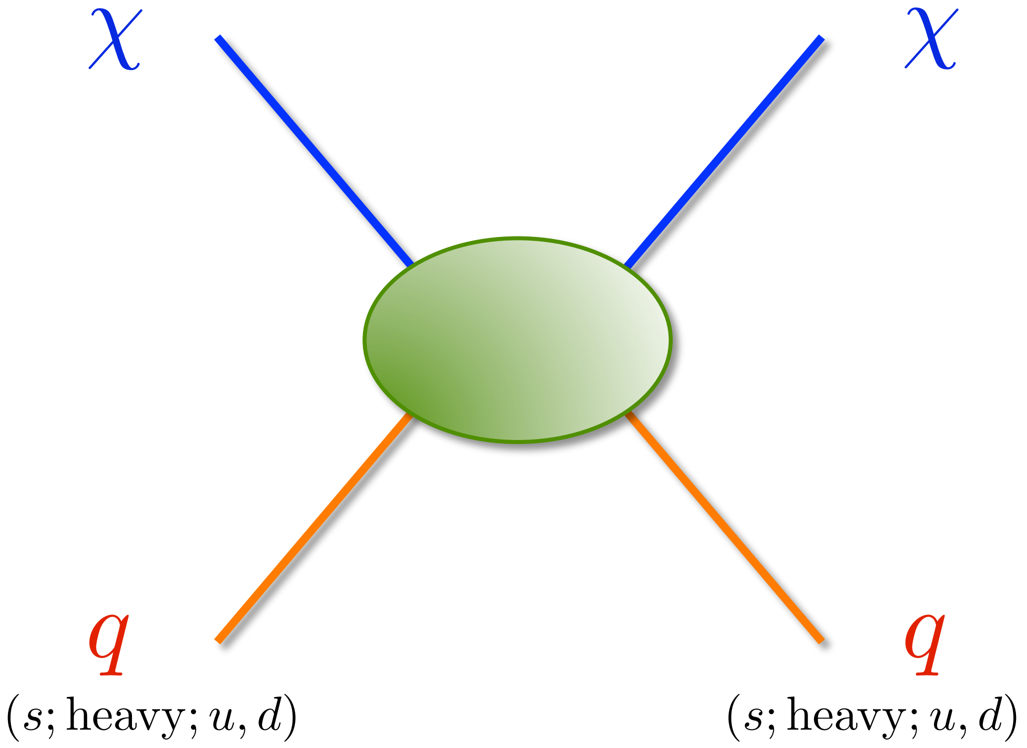


Axioelectric
or Photoelectric-like



Primakoff

Interaction mechanisms - WIMPs



$$\mathcal{L}_{\text{eff}} = \sum_i \alpha_i (\bar{q}\mathcal{O}q)(\bar{\chi}\mathcal{O}\chi)$$

$$\mathcal{L}_{\text{eff}} \underset{\text{nucleon}}{\longrightarrow} < N|\bar{q}\mathcal{O}q|N > \sim \bar{\psi}_N \mathcal{O} \psi_N \underset{\text{nucleus}}{\longrightarrow} < \mathcal{N}|\bar{\psi}_{\mathcal{N}} \mathcal{O} \psi_{\mathcal{N}}|\mathcal{N} >$$

WIMPs - Scattering cross section

- Spin-independent
  - Cross section proportional to the (mass number)^2 of the nucleus, more generally:

$$[f_p Z + f_n(A-Z)]^2$$

  - Nuclear form factors F(E_R)

- Spin-dependent
  - Cross section proportional to the (spin)^2 of the nucleus
  - Spin form factors S(E_R)

Interaction rate (WIMP ; scalar interaction)

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{m_N}{2\mu_1^2} A^2 \left[\xi \sigma_{\rm scalar}^{\rm (nucleon)}\right] F^2(E_R)\, \mathcal{I}(v_{\rm min})$$

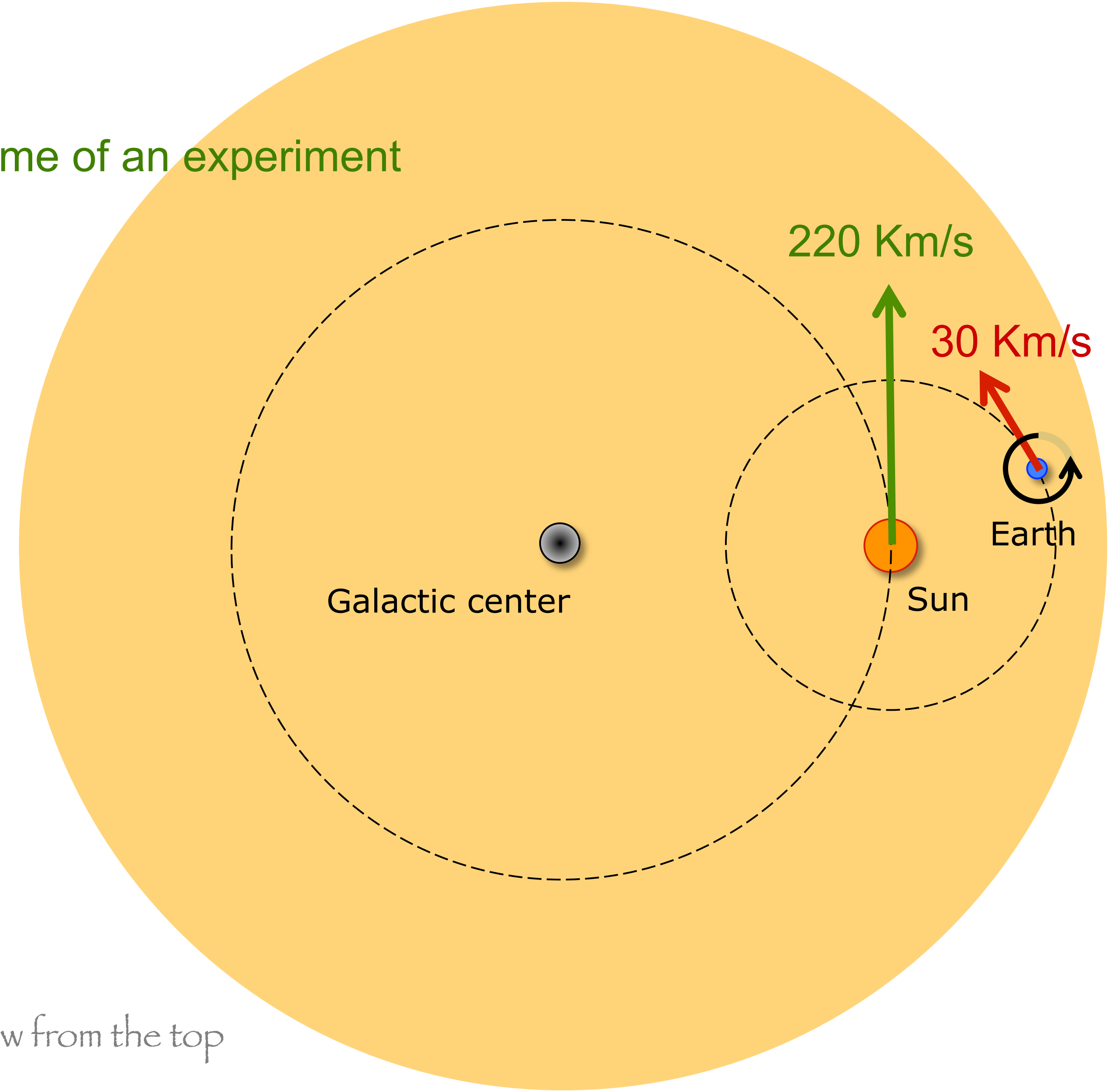
$$\mathcal{I}(v_{\rm min}) = \int_{w \geq v_{\rm min}} d^3 w \; \frac{f_{\rm ES}(\vec{w})}{w}$$

$$f_{\rm ES}(\vec{w}) = f(\vec{w} + \vec{v}_\oplus)|_{[v_{\rm rot}\,;v_{\rm esc}]}$$

$$v_{\rm min} = [m_N E_R/(2\mu_A^2)]^{1/2}$$

Local motions

- Stationary over the lifetime of an experiment
  Directional boost



View from the top

Interaction rate (WIMP ; scalar interaction)

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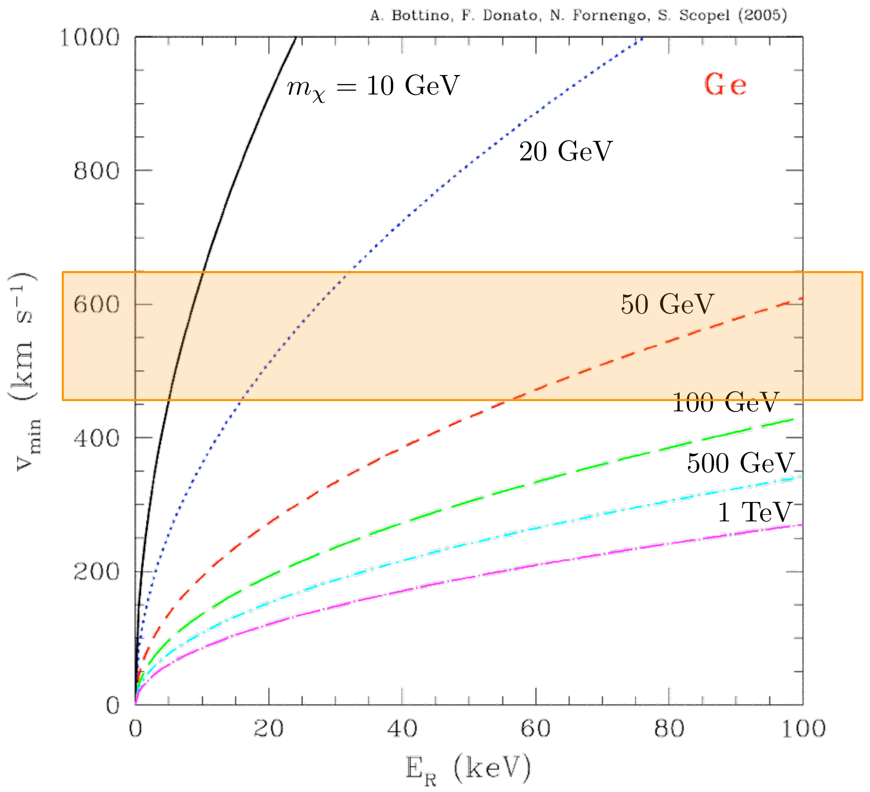
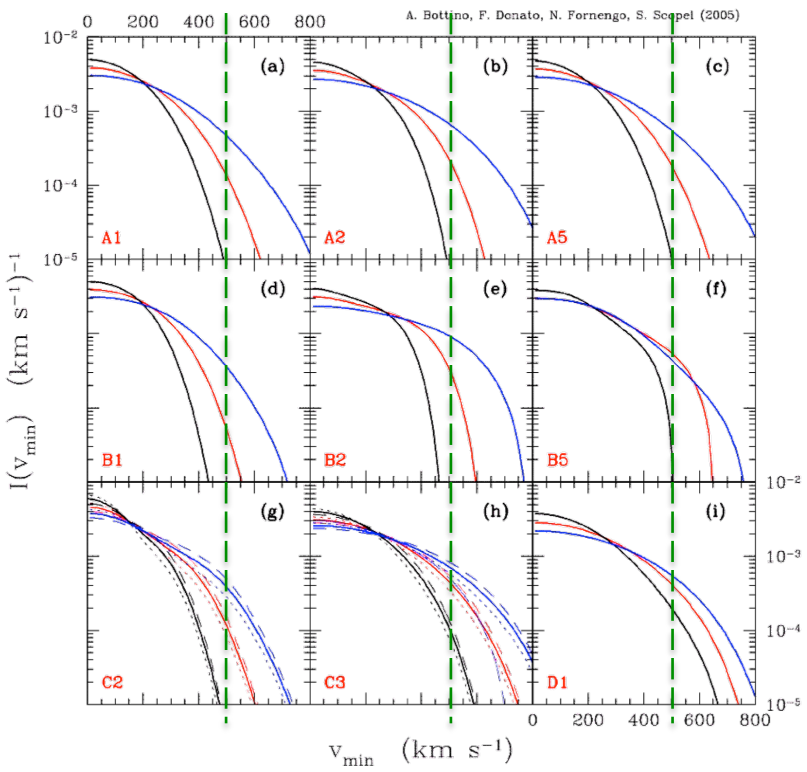
Response function





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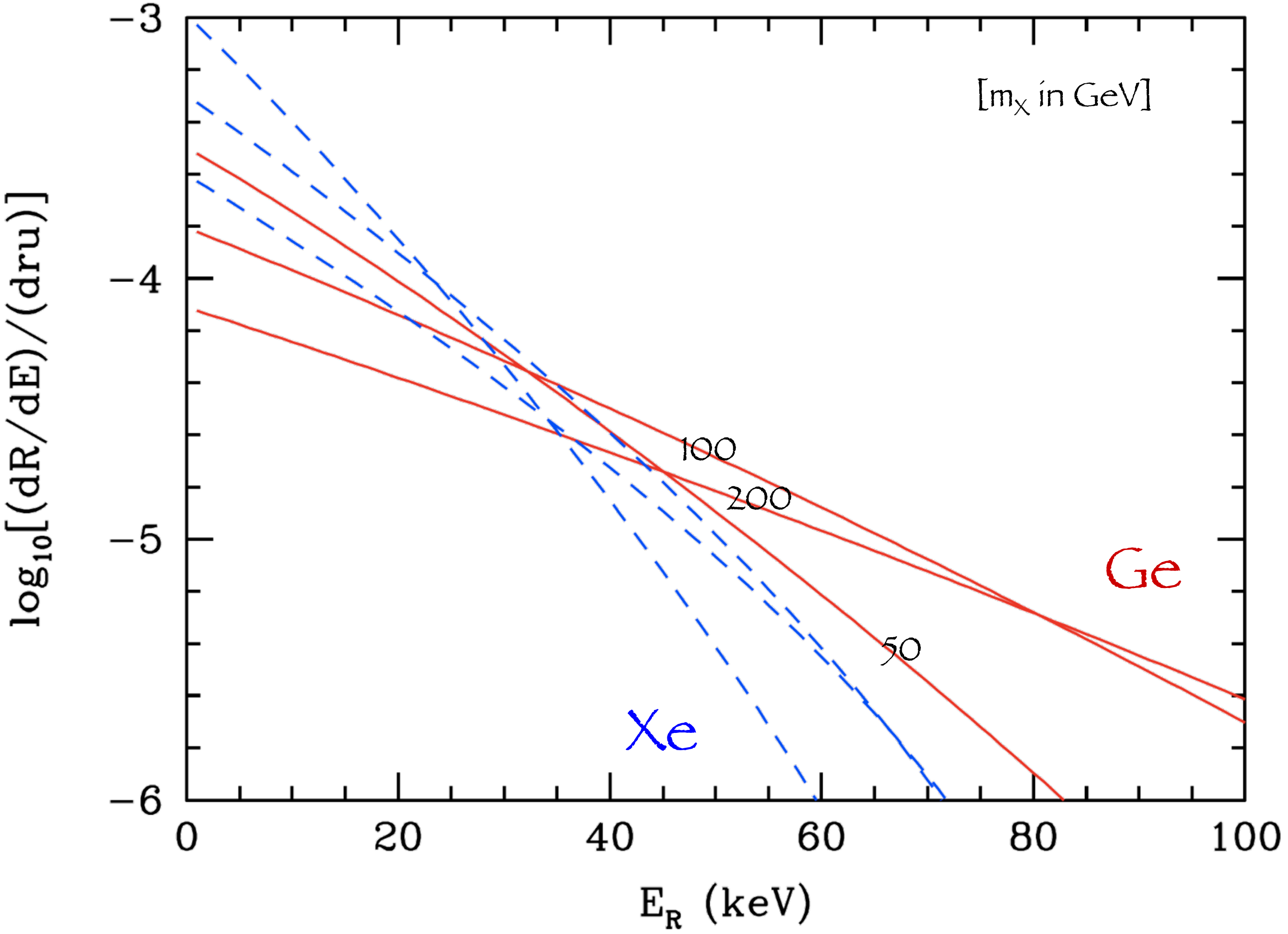
A. Bottino, F. Donato, NF, S. Scopel, PRD 72 (2005) 083521

Differential Rate – Energy Dependence

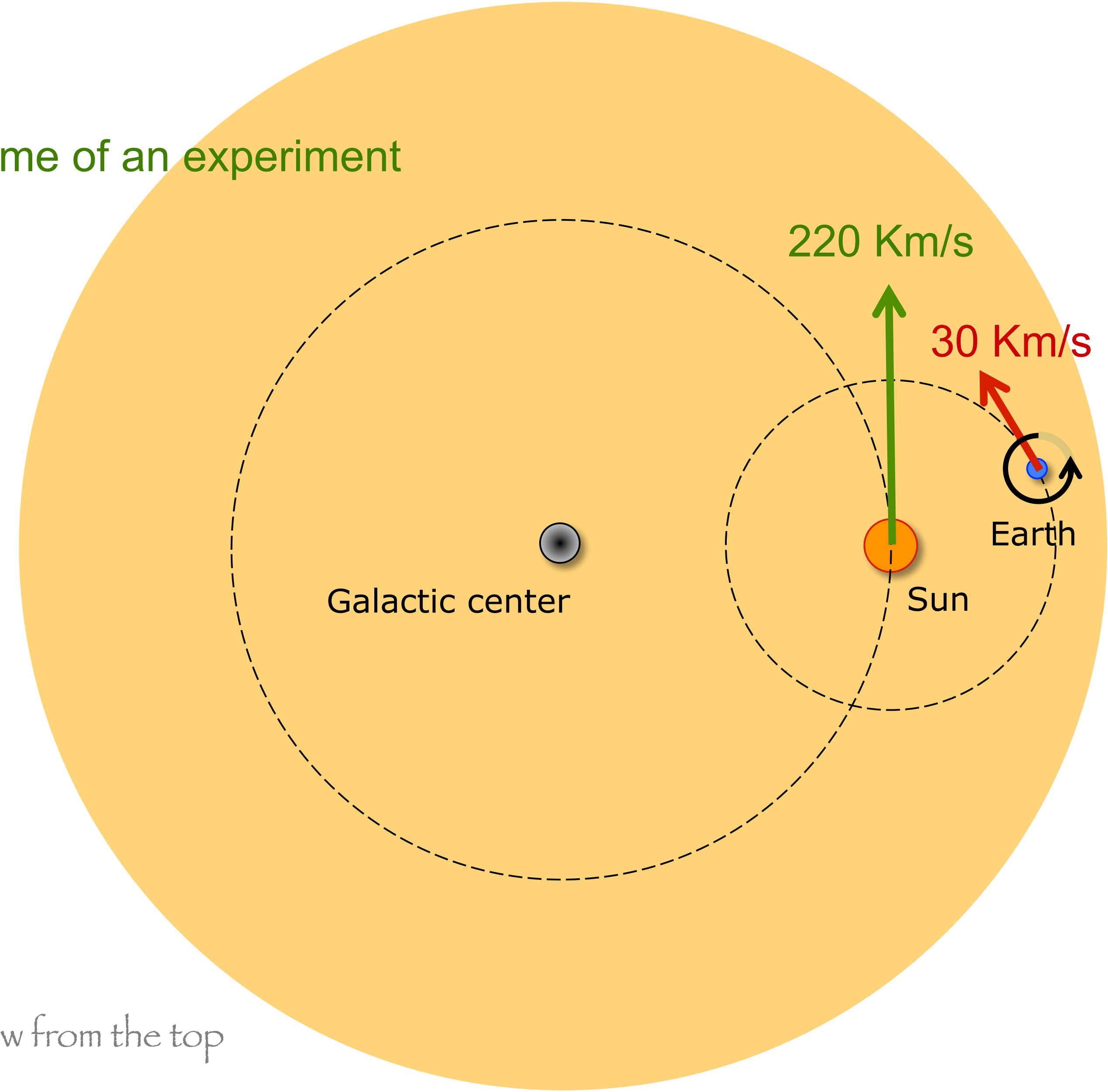


Local motions

- Stationary over the lifetime of an experiment
  Directional boost

- Period: 1 year

- Period: 1 day



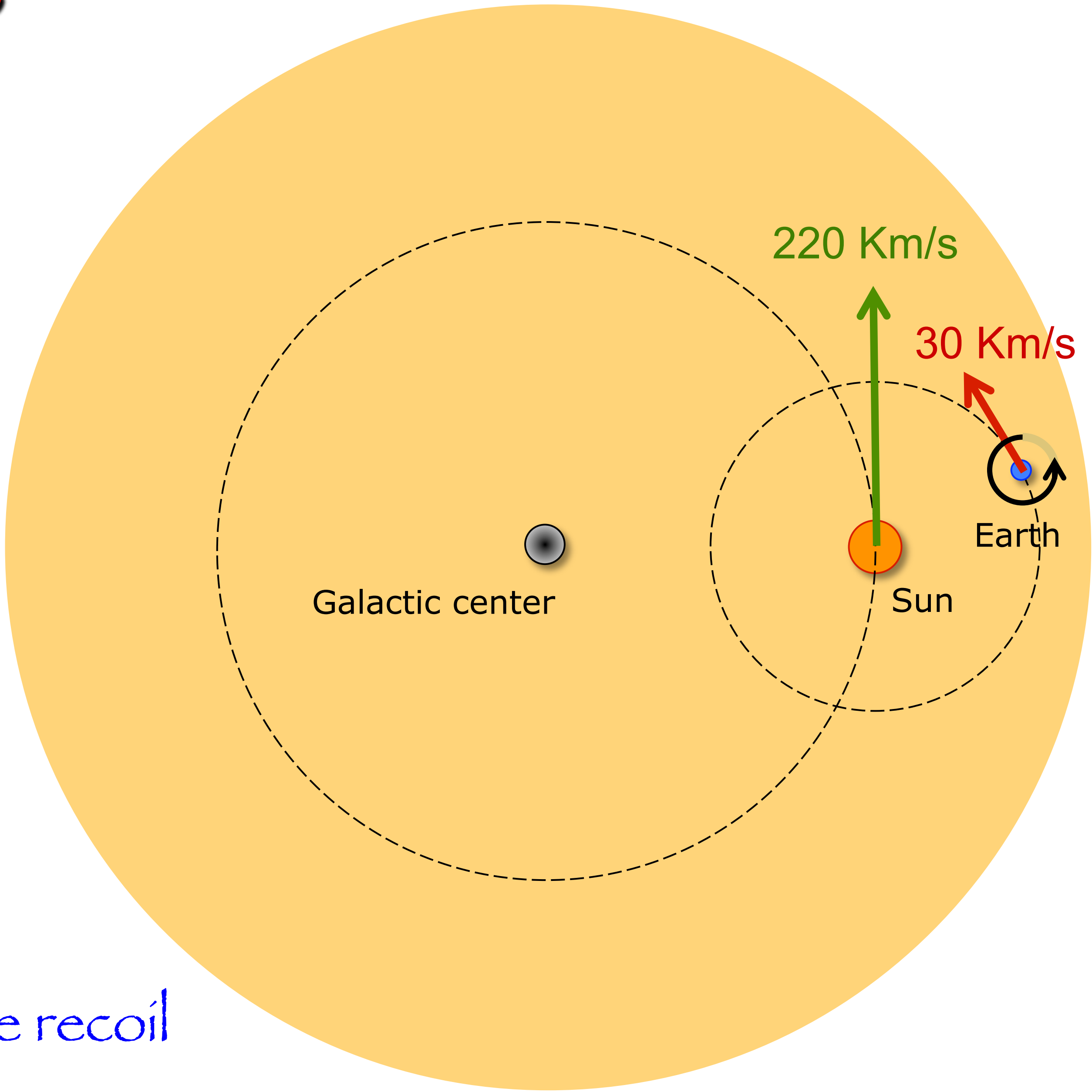
View from the top

Typical signatures of direct detection

- 🔴 Annual modulation

- ● Diurnal modulation

- 🟢 Directionality of the recoil



From the galactic RF to the Earth RF

$$\begin{aligned} \vec{v} &\rightarrow \vec{w} = \vec{v} - \vec{v}^E(t), \\ f(\vec{v}) &\rightarrow f_{\mathrm{ES}}(\vec{w}) = f(\vec{w} + \vec{v}^E(t)) \end{aligned}$$

Earth's velocity
wrt. galactic rest frame

$$\begin{aligned} v_x^E &= v_x^G + v_x^S + u^E(\lambda) \cos\beta_x \cos[\omega(t - t_x)] \\ v_y^E &= v_y^G + v_y^S + u^E(\lambda) \cos\beta_y \cos[\omega(t - t_y)] \\ v_z^E &= v_z^G + v_z^S + u^E(\lambda) \cos\beta_z \cos[\omega(t - t_z)] \end{aligned}$$

Galactic rotational velocity $\vec{v}^G = (0, v_0, 0)$ Km s^{-1}

Sun's proper motion $\vec{v}^S = (-9, 12, 7)$ Km s^{-1}

Earth's orbital motion $u^E(\lambda) = \langle u^E \rangle [1 - e \sin(\lambda - \lambda_0)]$ $\langle u^E \rangle = 29.79$ Km s^{-1}

$$v_E(t) \equiv |\vec{v}_E| = (233.5 + 14.4 \ \cos[\omega(t - t_0)]) \ \text{Km s}^{-1}$$

$$t_0 = 152 \text{ days} = \text{June } 2^{\text{nd}}$$

$$\omega = 2\pi/(365 \text{ days})$$

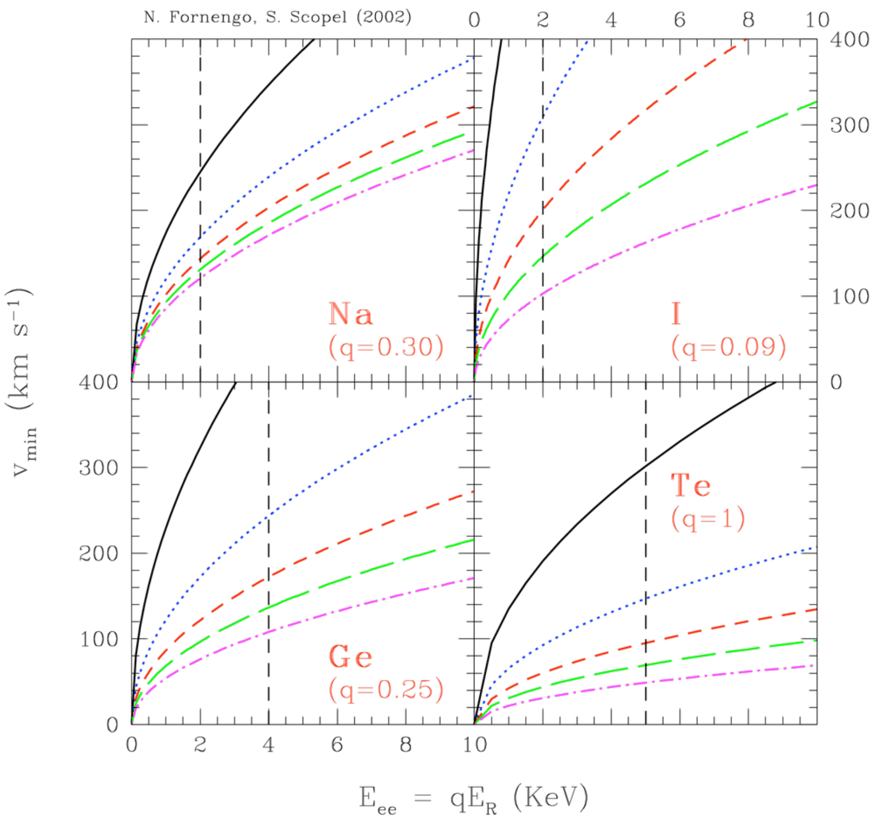
Annual Modulation of the rate

$$\frac{dR}{dE_R}[\eta(t)] = \frac{dR}{dE_R}[\eta_0] + \frac{\partial}{\partial\eta}\left(\frac{dR}{dE_R}\right)_{\eta=\eta_0} \Delta\eta \; \cos[\omega(t-t_0)]$$

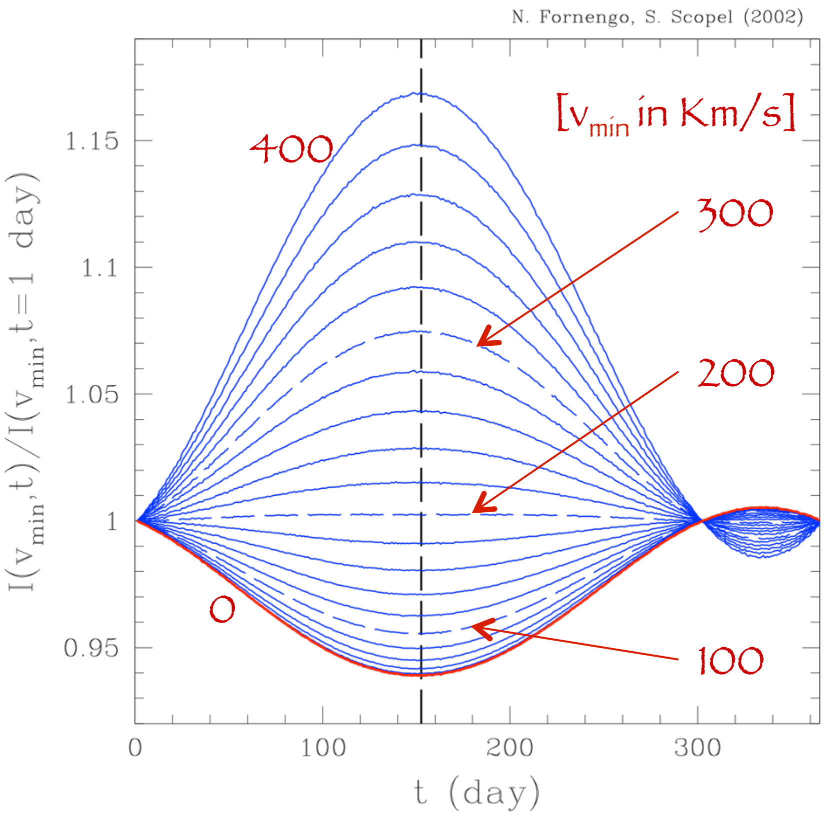
$$= S_0(E_R) + S_m(E_R) \; \cos[\omega(t-t_0)]$$

$$\eta(t) = v(t)/v_0$$

Annual modulation



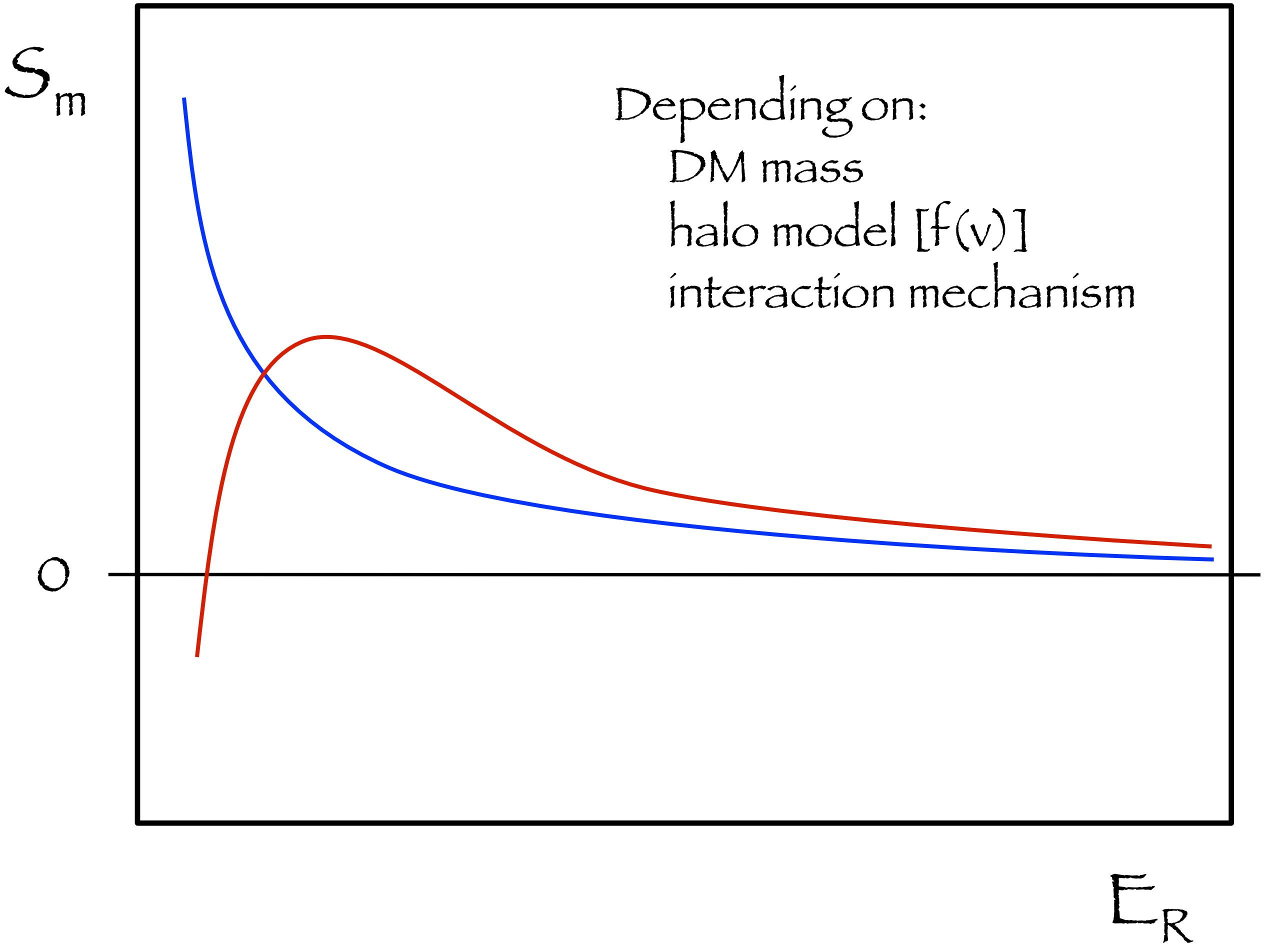
$E_{ee} = q\, E_R$



f(v) : isotropic maxwellian

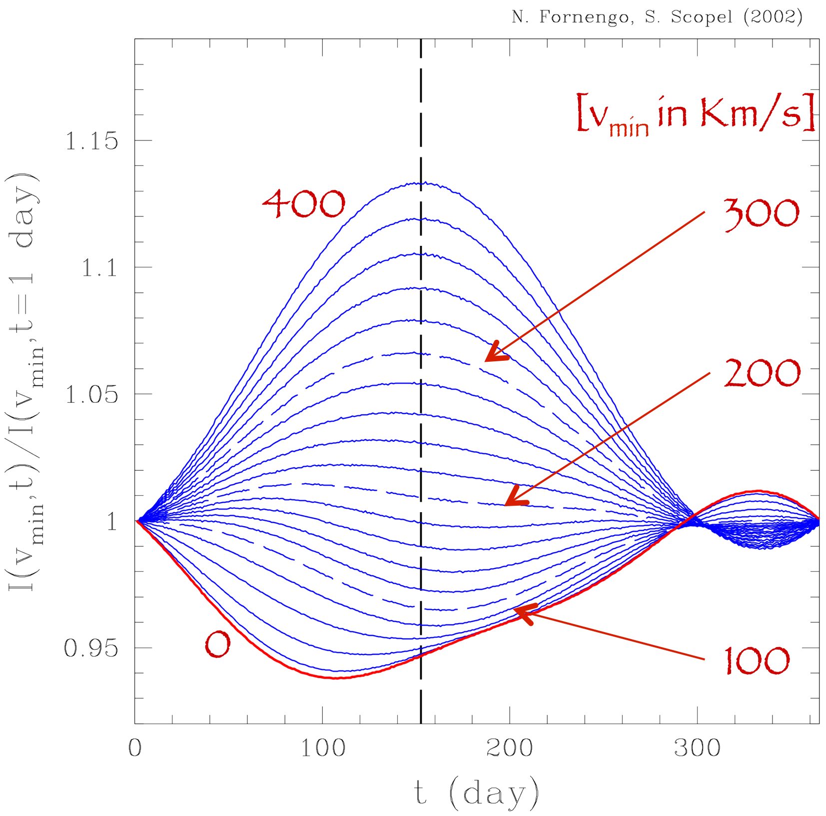
NF , S. Scopel, PLB 576 (2003) 189

Modulation amplitude - energy dependence



Depending on:
- DM mass
- halo model [f(v)]
- interaction mechanism

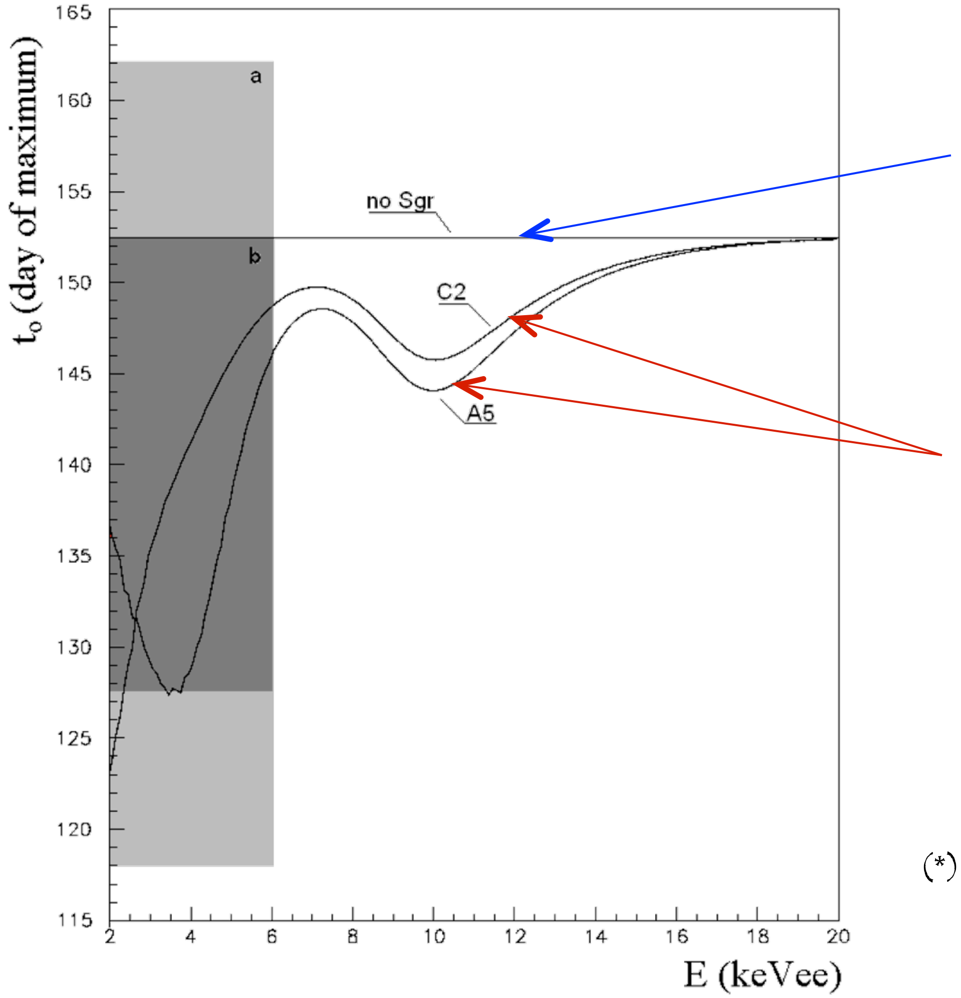
Annual modulation



f(v): anisotropic maxwellian

NF, S. Scopel, PLB 576 (2003) 189

Effect of DM streams



Standard halo

Including Sagittarius$^{(*)}$

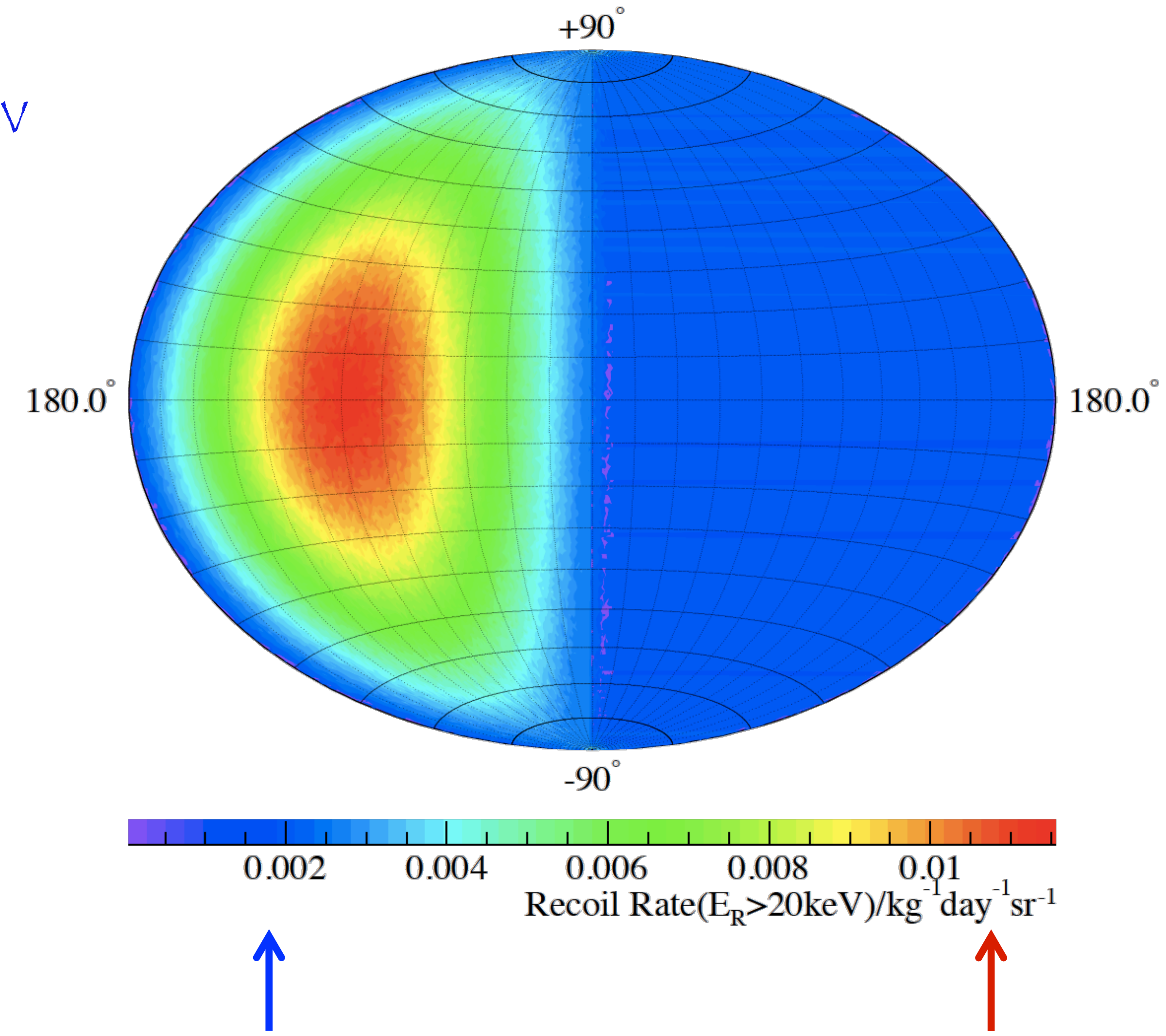
$^{(*)}$ satellite dwarf galaxy

$E_{ee} \approx q\, E_R$

Bernabei et al., astro-ph/0501412

Directionality of the recoil

$m_\chi \simeq 100$ GeV



Summarizing

- Scattering of DM WIMPs on the detector induces a recoil spectrum for the nuclei dR/dE_R
- DM-nucleus interactions may couple to the nucleus mass (coherent scattering)or to the nucleus spin (spin-dependent scattering)
- Local motions in the Galaxy induce a time-dependence of the recoil, which (if experimentally accessible) can help to disentangle a true signal from radioactive backgrounds:
  - Annual modulation
  - Diurnal modulation
  - Directionality

Current experimental status

Current direct detection experiments

- Background-rejection experiments (CDMS, XENON, CRESST)
  - Do not exploit a specific signature of the signal
  - Rely on reduction/interpretation of background

- Annual modulation experiments (DAMA, CoGeNT)
  - Exploit a specific signature
  - Required to be highly stable over long periods

DAMA/NaI and DAMA/LIBRA

Target: NaI

Annual modulation observed
Effect at 8.9 σ C.L.

Single-hit events in the signal energy-window
Stability parameters do not modulate

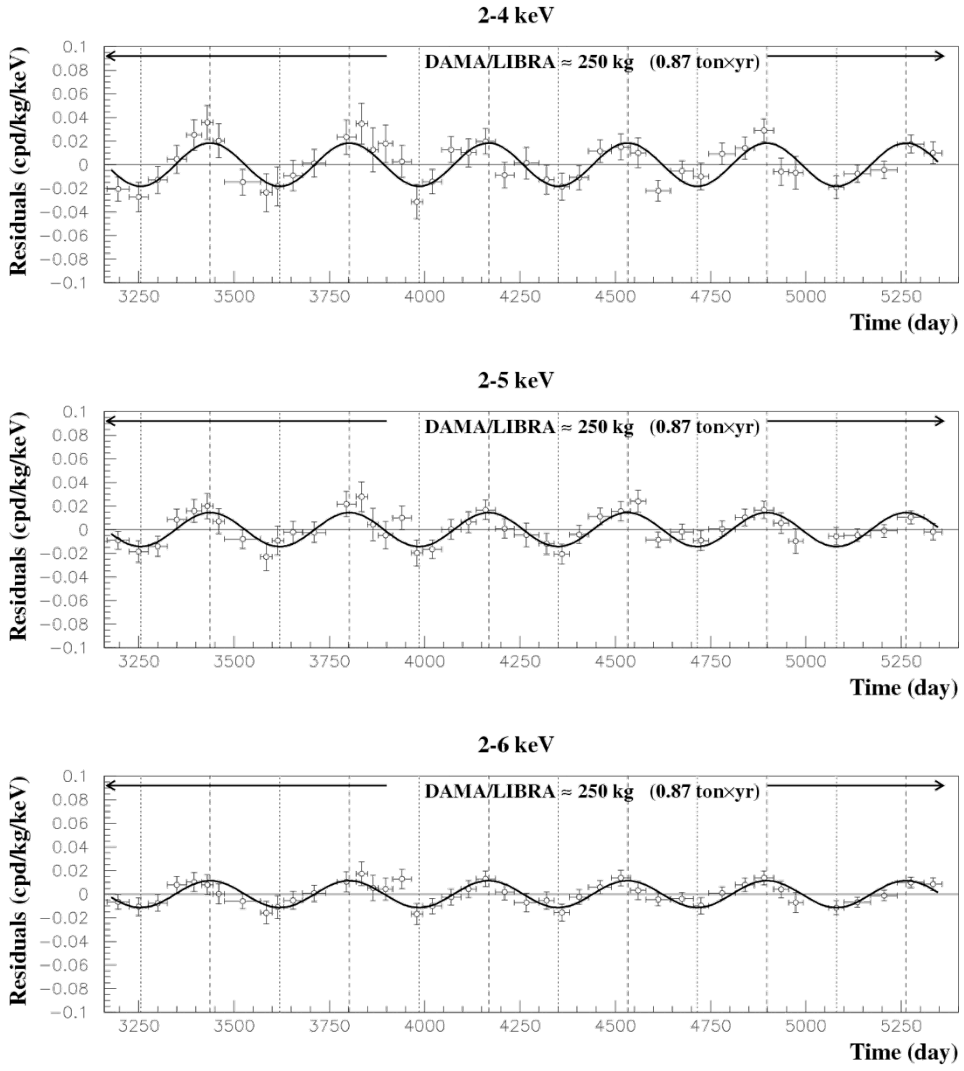
Compatible to DM scatter
- off nuclei
- on electrons

Cumulative exposure: 1.17 ton x yr (13 annual cycles)
(i.e. 427050 Kg x day)

S_m[2-6 KeV] ≈ (0.0116 ± 0.0013) cpd/kg/keV

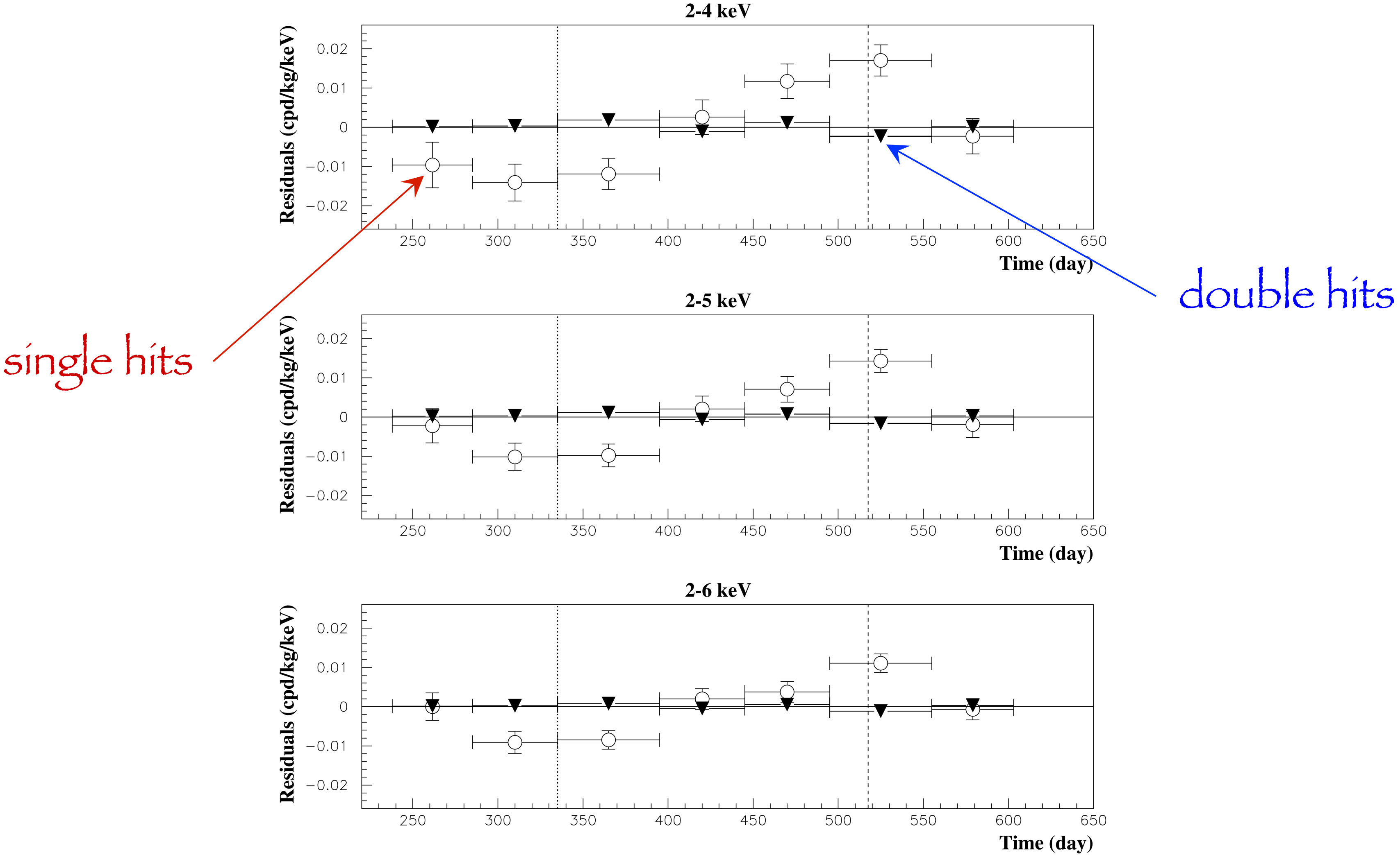
Phase ≈ (146 ± 7) days

Period ≈ (0.999 ± 0.002) years



R. Bernabei et al. (DAMA Collab.), Eur. Phys. J. C (2010) 67

DAMA annual modulation



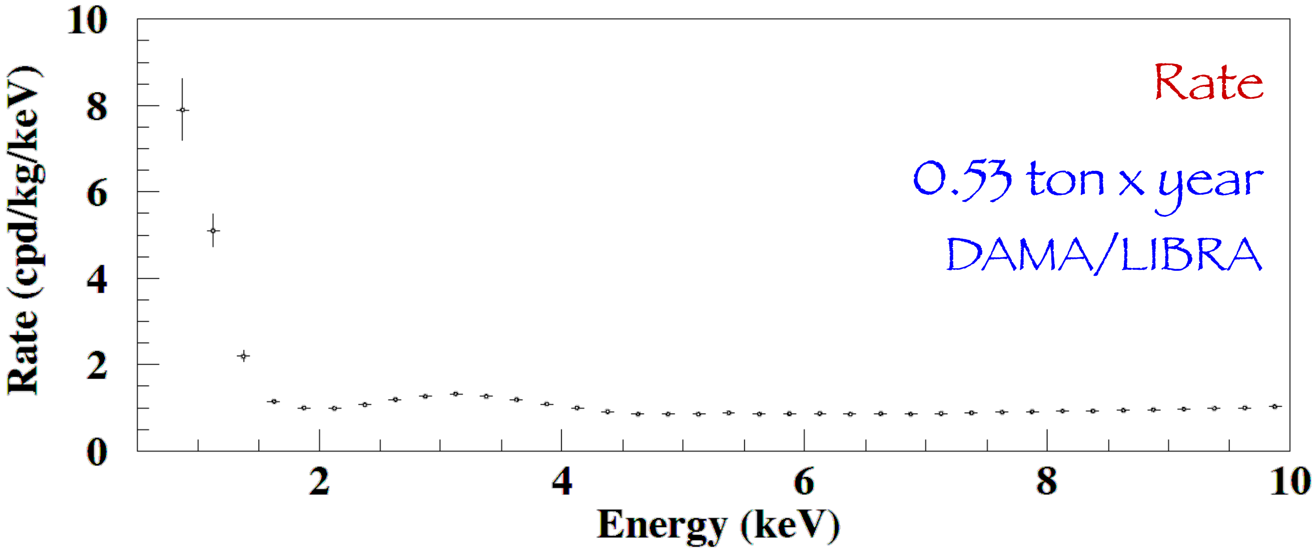
single hits

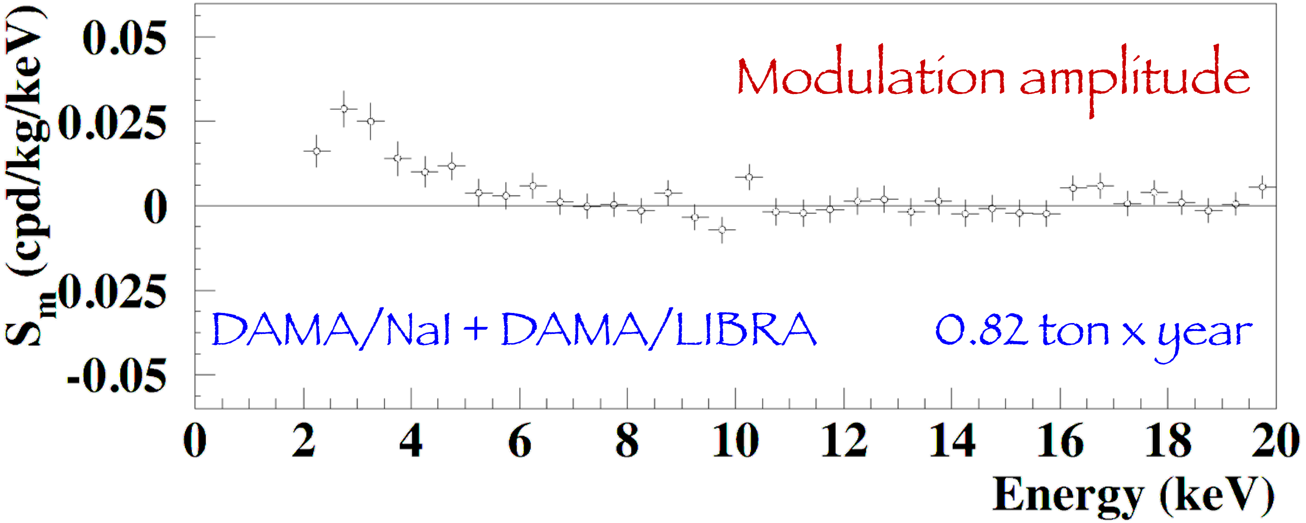
double hits

Rate above 90 KeV does not modulate

R. Bernabei et al. (DAMA Collab.), Eur. Phys. J. C (2010) 67

Differential rate and modulation amplitude





Interaction rate (WIMP ; scalar interaction)

$$\frac{dR}{dE_R} = N_T \, \frac{\rho_0}{m_\chi} \, \frac{m_N}{2\mu_1^2} \, A^2 \, [\xi \sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}}] \, F^2(E_R) \, \mathcal{I}(v_{\mathrm{min}})$$

$$\mathcal{I}(v_{\mathrm{min}}) = \int_{w \geq v_{\mathrm{min}}} d^3 w \; \frac{f_{\mathrm{ES}}(\vec{w})}{w}$$

$$f_{\mathrm{ES}}(\vec{w}) = f(\vec{w} + \vec{v}_{\oplus})|_{[v_{\mathrm{rot}};v_{\mathrm{esc}}]}$$

$$v_{\mathrm{min}} = [m_N E_R/(2\mu_A^2)]^{1/2}$$

$$E_R \to E_{\mathrm{det}}$$

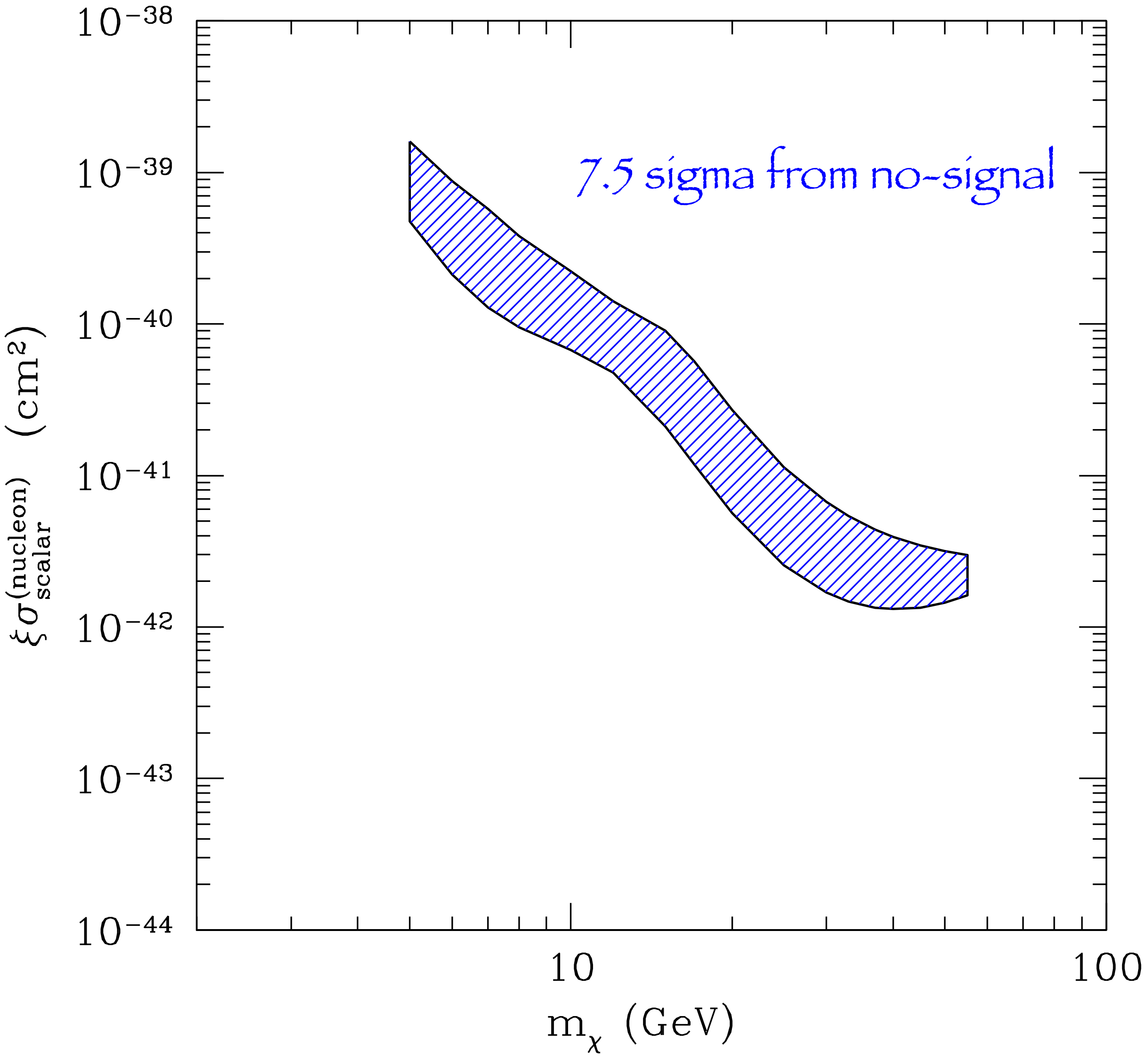
$$E_{\mathrm{ee}} = q(E)\, E_R$$

DAMA annual modulation regions

“Canonical” halo

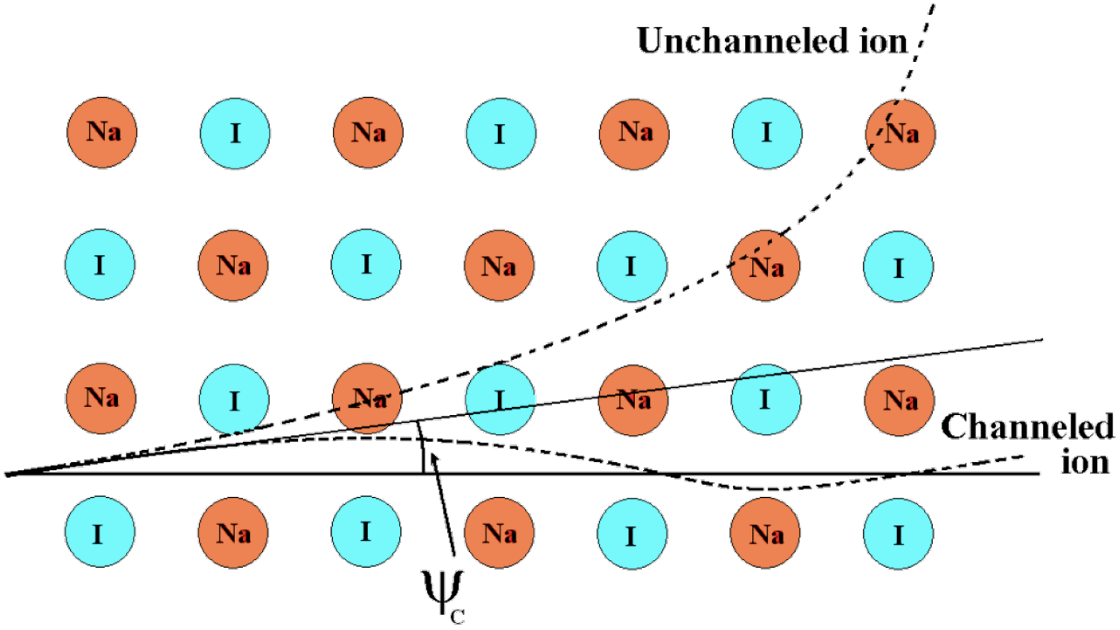
Fixed quenching
$q_{Na} \simeq 0.30$
$q_I \simeq 0.09$

No channeling

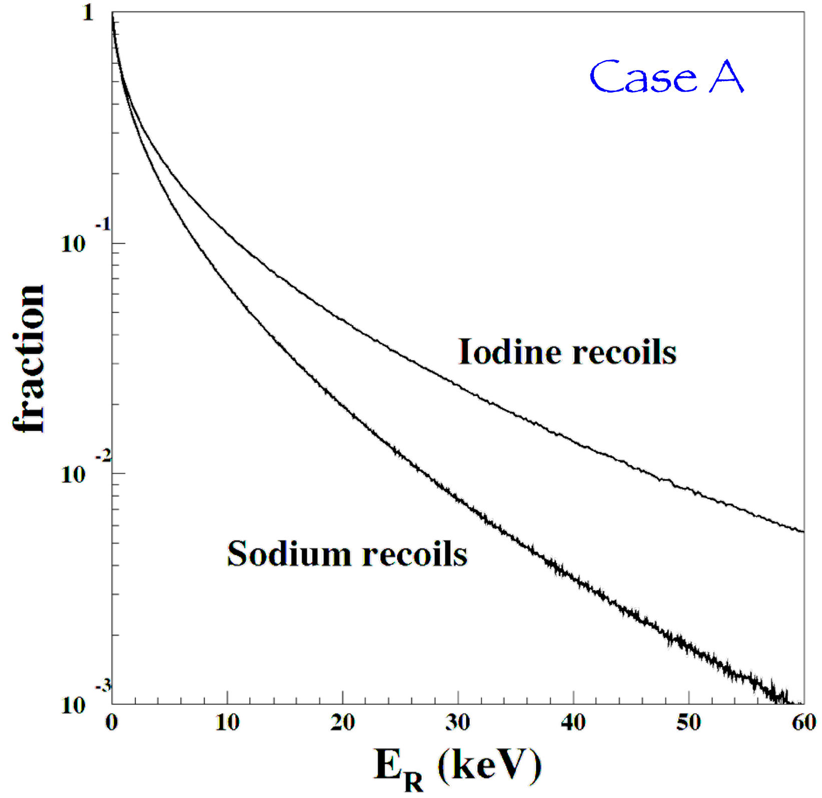


Belli et al., PRD 84 (2011) 055014

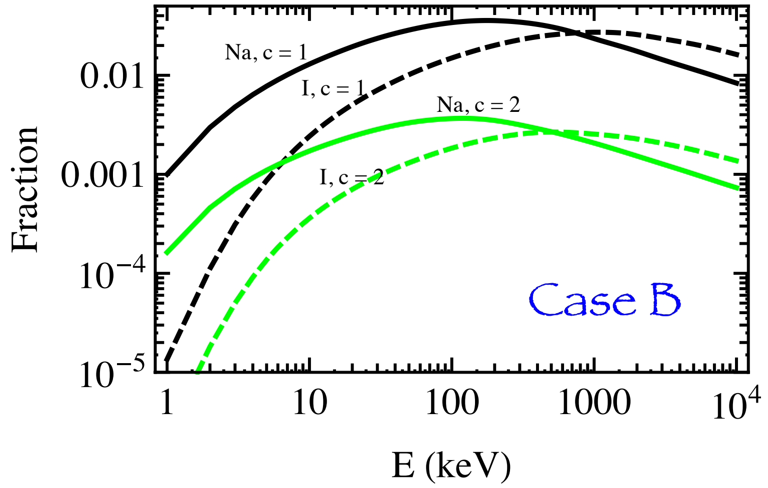
Ion channeling in NaI crystals

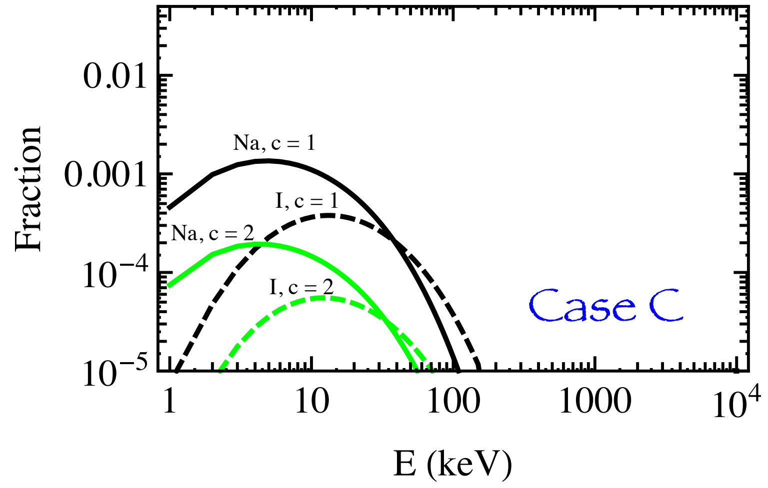


Ion channeling in NaI crystals



R. Bernabei et al. (DAMA Collab.), arXiv:0710.0288 [astro-ph]





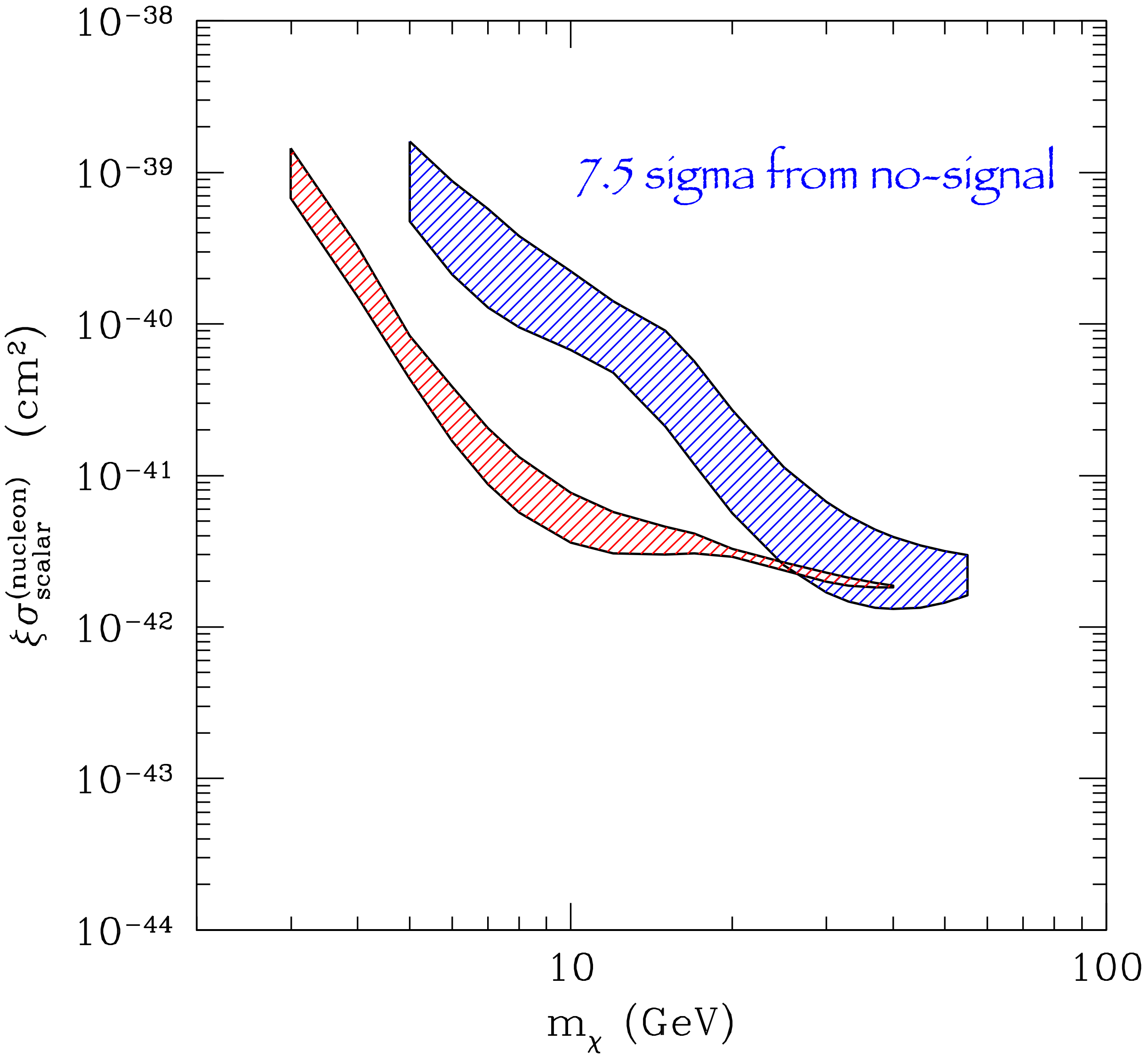
See also: Borzorgnia, Gelmini, Gondolo, JCAP 1011 (2010) 019

See also: Matyukhin, Technical Physics 53 (2008) 1578 - predicts larger fraction of channeling

DAMA annual modulation regions

"Canonical" halo

Channeling fraction according to Case A



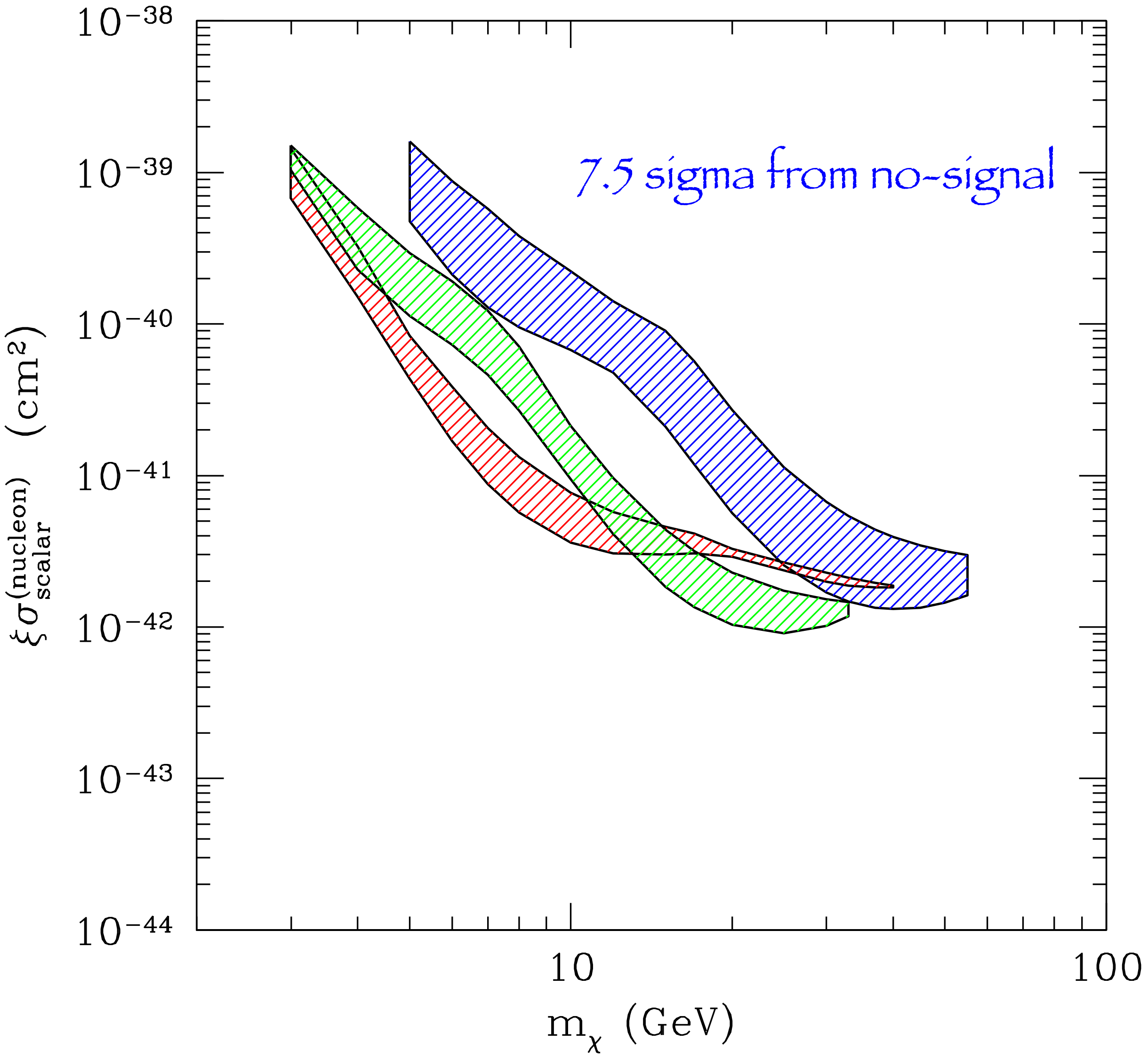
Belli et al., PRD 84 (2011) 055014

DAMA annual modulation regions

"Canonical" halo

E-dep. quenching(*)

No channeling



(*) Tretyak, Astrop. Phys. 33 (2010) 40

Belli et al., PRD 84 (2011) 055014

CoGeNT annual modulation

Target: Ge

COGeNT 2010

Aalseth et al. (COGeNT Collab.), PRL 106 (2011) 131301

Irreducible excess of bulk-like events

Cumulative exposure: 18.48 Kg x day

COGeNT 2011

Aalseth et al. (COGeNT Collab.), PRL 107 (2011) 141301

Annual modulation of the recoil rate

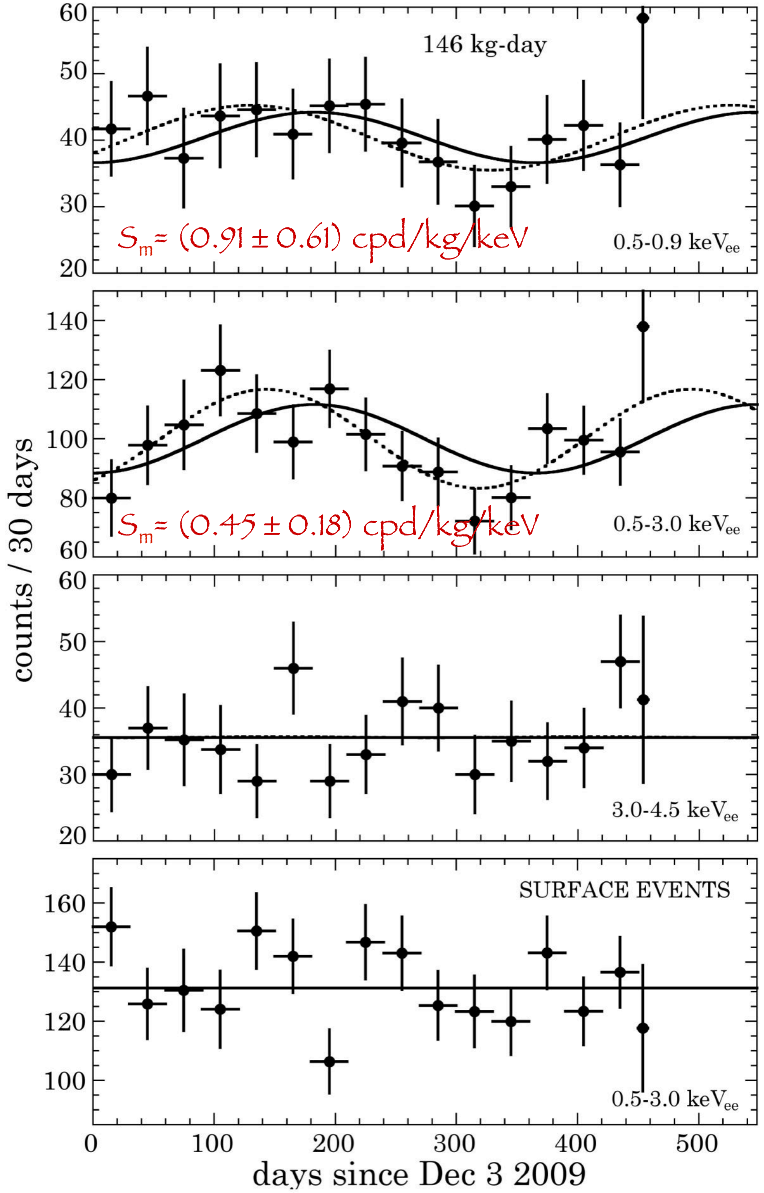
Effect at 2.8 σ C.L.

Cumulative exposure: 145.89 Kg x day (1 annual cycle)

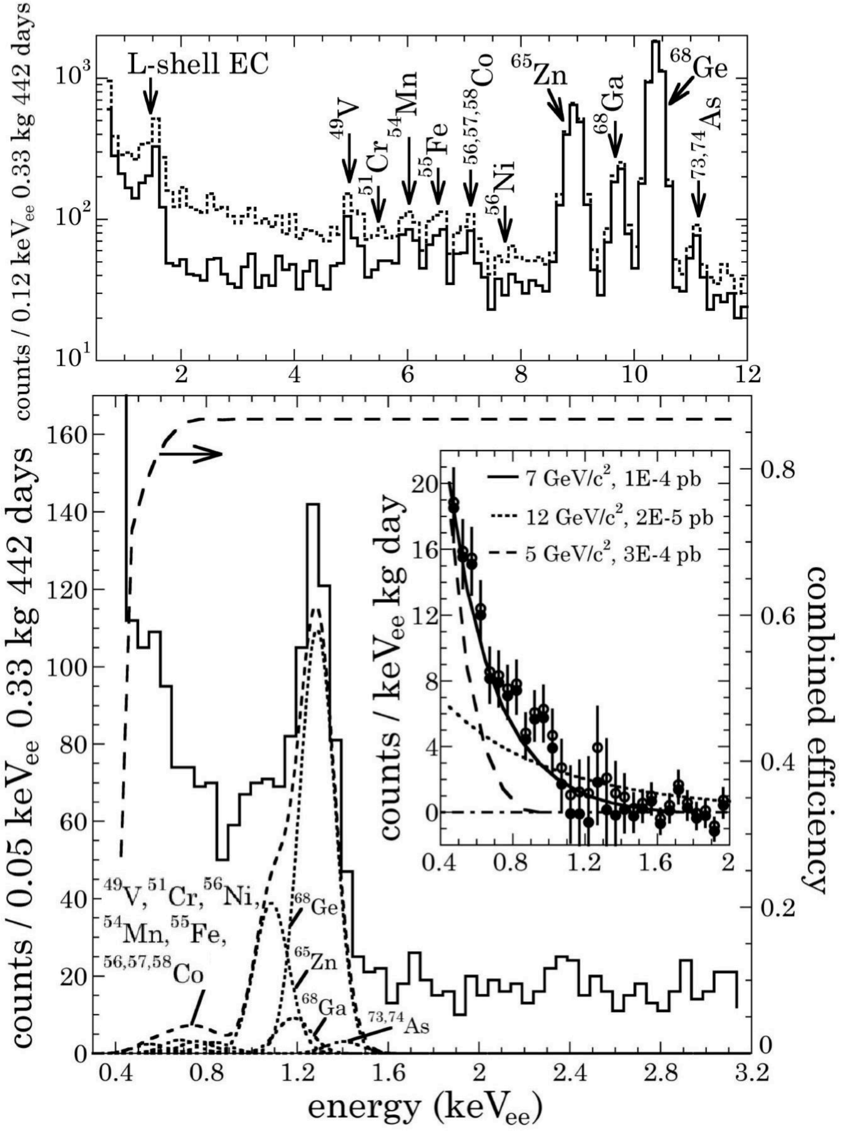
S_m[0.5-3 KeV] = (16.6 ± 3.8) %

Phase = (106 ± 12) days

Period = (0.951 ± 0.079) years



CoGeNT total rate

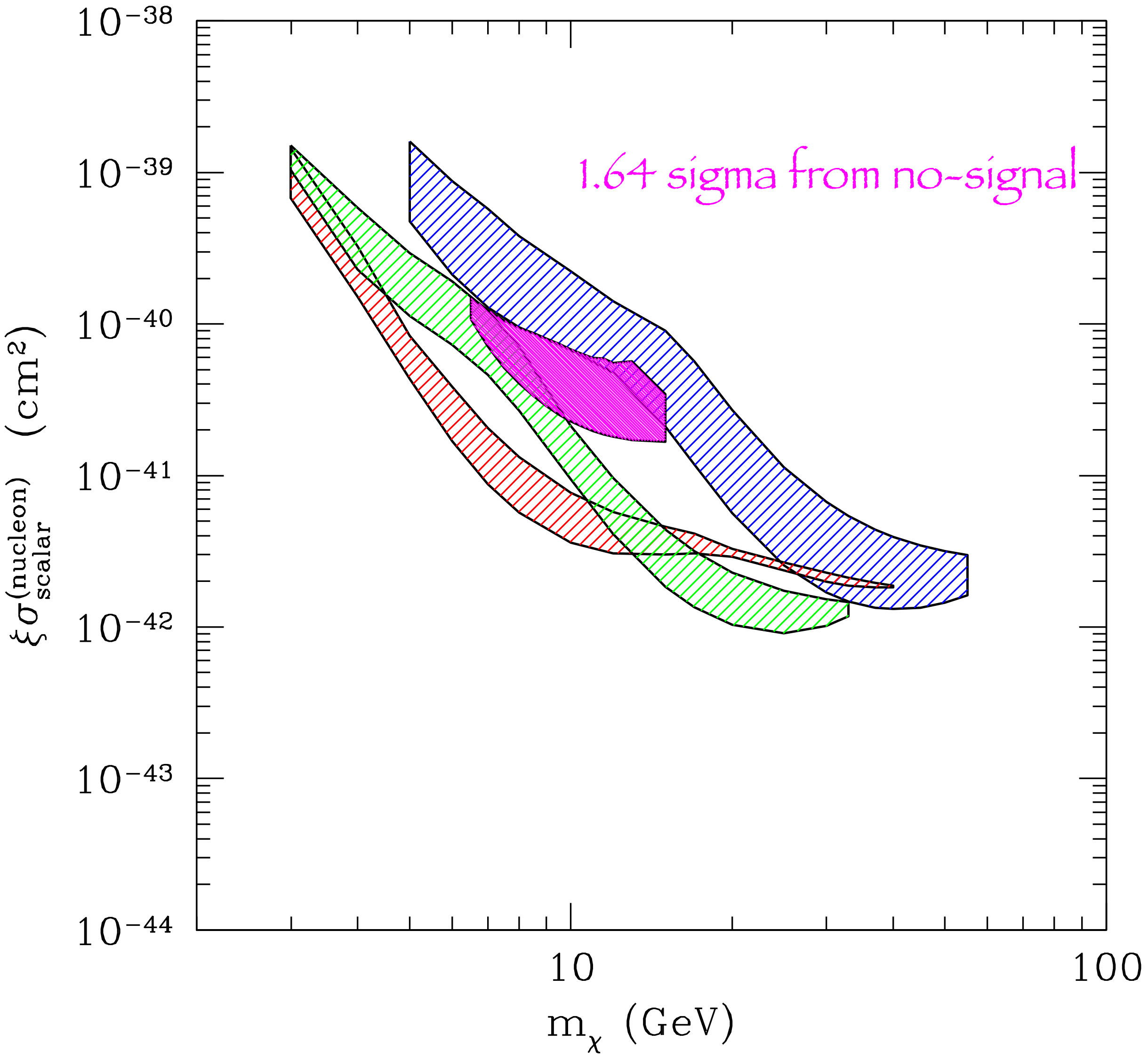


Aalseth et al. (COGeNT Collab.), PRL 107 (2011) 141301

CoGeNT annual modulation region

"Canonical" halo

Fixed quenching

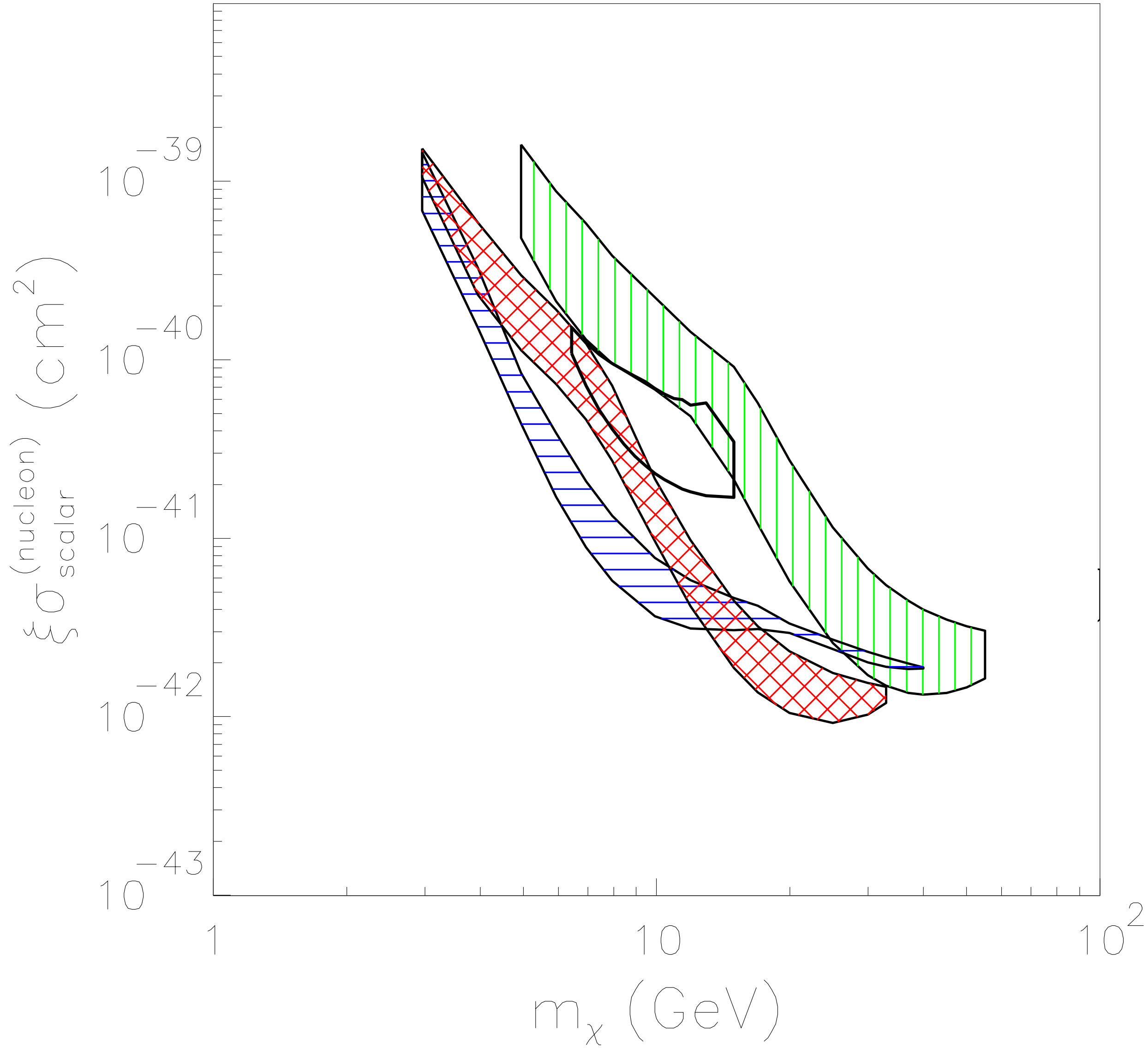


Belli et al., PRD 84 (2011) 055014

Changing galactic halo properties

"Canonical" halo

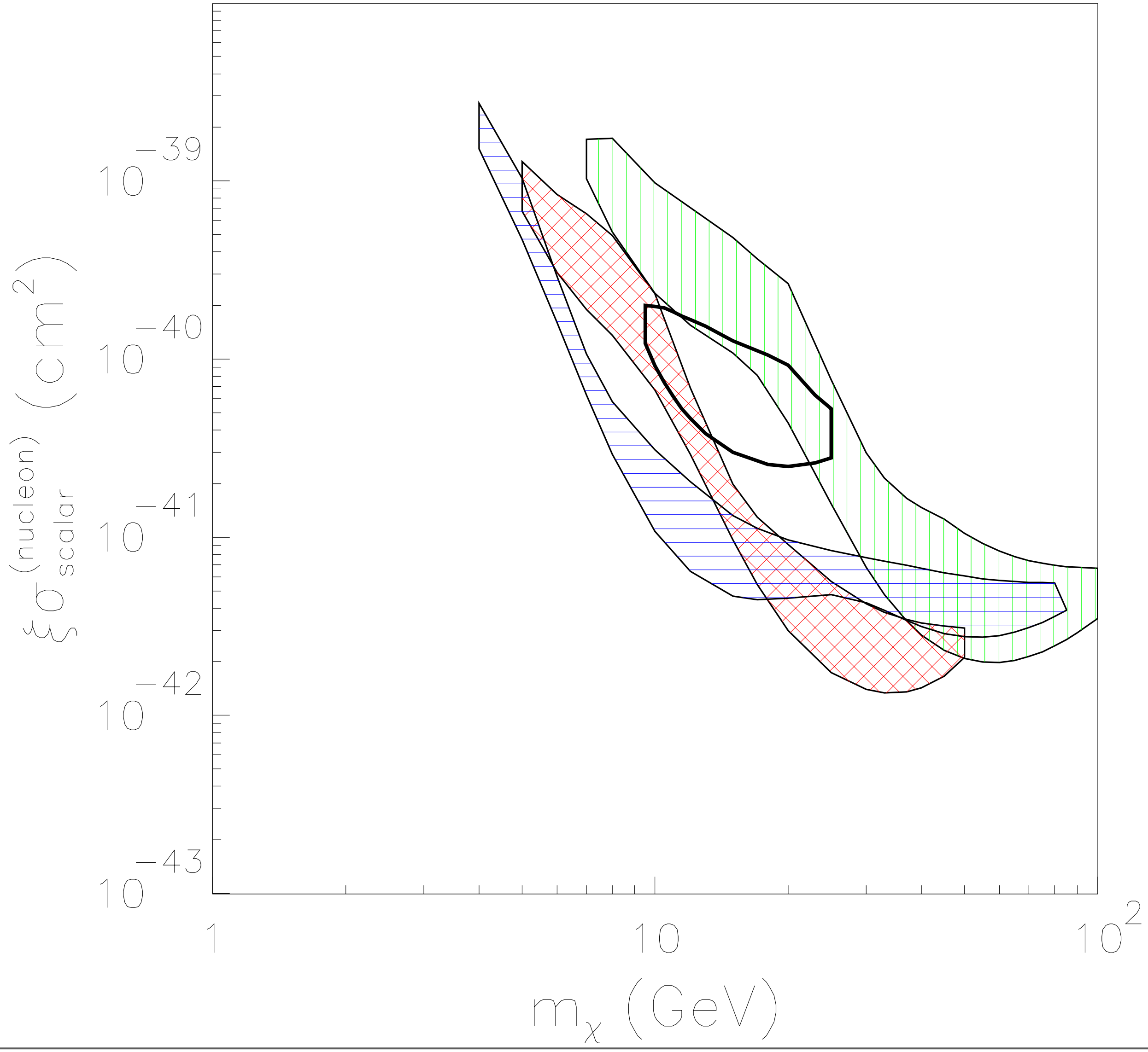
Isotropic MB f(v)
$V_0 = 220$ km s^{-1}
$\rho_0 = 0.34$ GeV cm^{-3}



Belli et al., PRD 84 (2011) 055014

Changing galactic halo properties

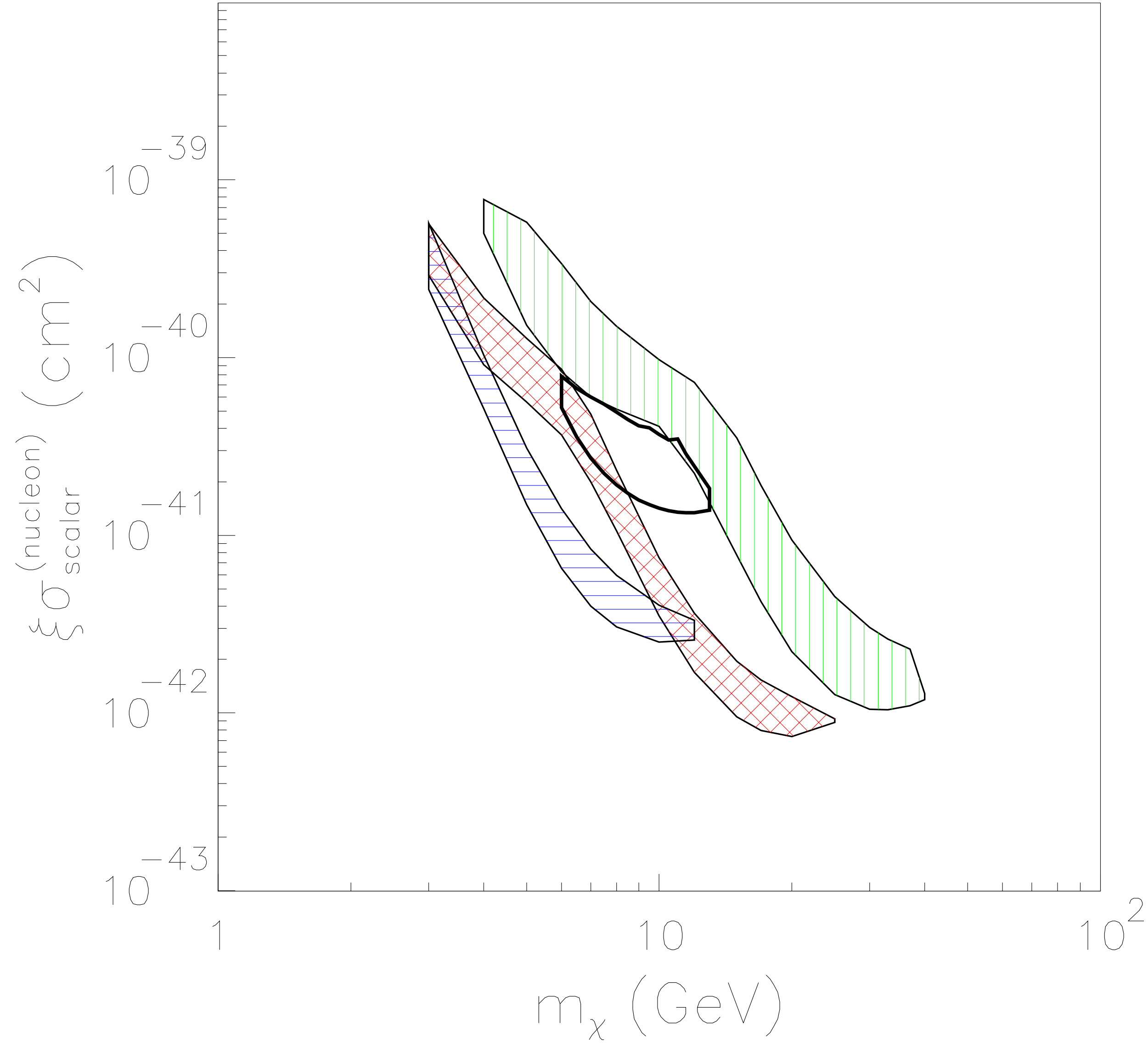
Isotropic MB f(v)
$V_0 = 170$ km s^{-1}
$\rho_0 = 0.18$ GeV cm^{-3}



Belli et al., PRD 84 (2011) 055014

Changing galactic halo properties

Isotropic MB f(v)
V_0 = 270 km s^{-1}
ρ_0 = 0.45 GeV cm^{-3}

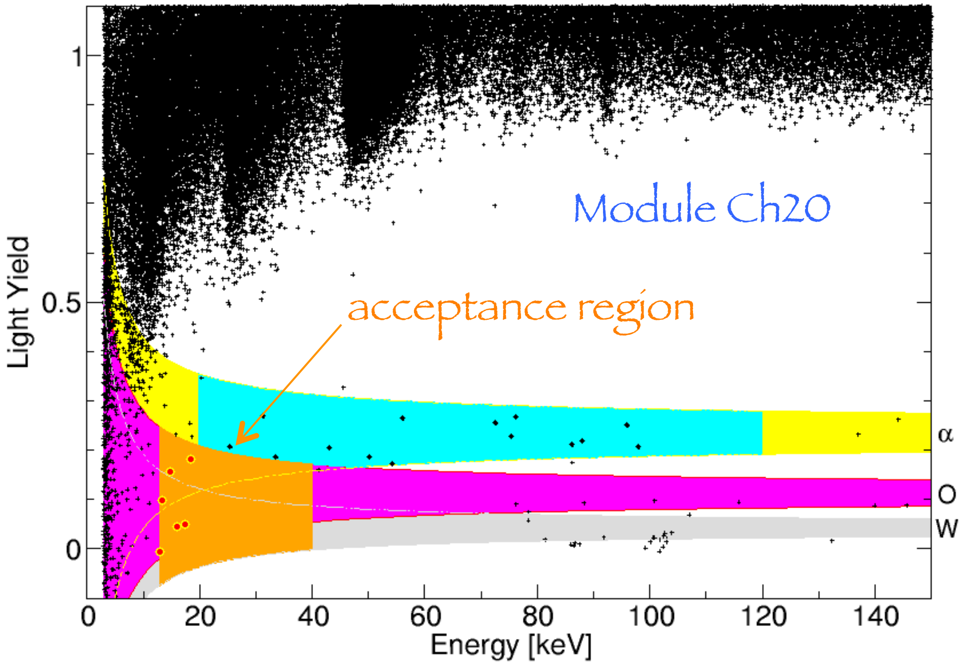


Belli et al., PRD 84 (2011) 055014

CRESST

Target: $CaWO_4$

Irreducible excess over background
Effect at > 4 σ C.L.



Cumulative exposure: 730 Kg x day

67 events in the acceptance region

Max likelihood analysis: bakgrounds unable to account for all the events

- leakage from e/gamma band
- leakage from alpha band
- neutrons
- ^{206}Pb recoils from ^{210}Po decay

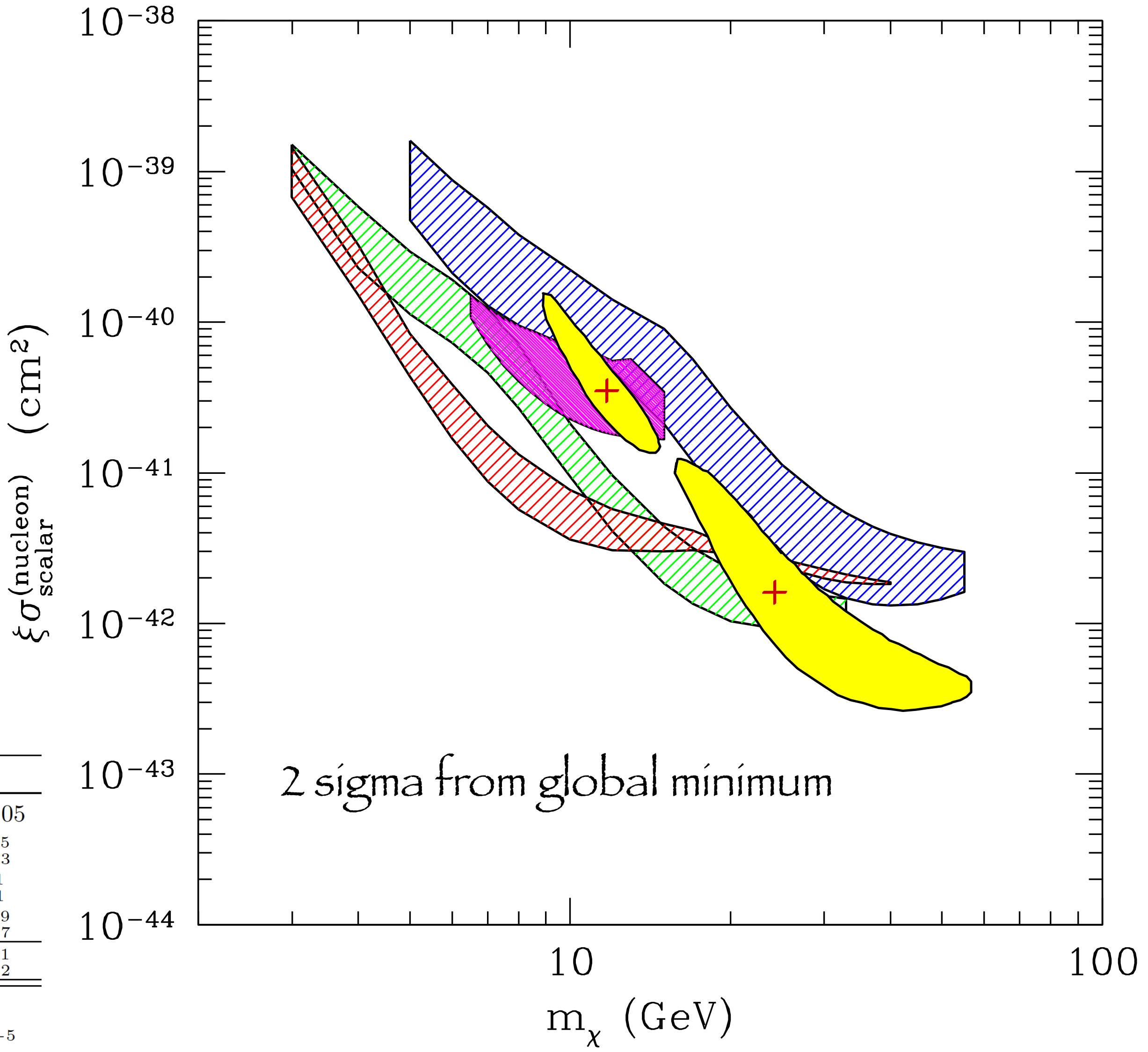
module	$E_{\rm acc}^{\rm min}$ [keV]	acc. events
Ch05	12.3	11
Ch20	12.9	6
Ch29	12.1	17
Ch33	15.0	6
Ch43	15.5	9
Ch45	16.2	4
Ch47	19.0	5
Ch51	10.2	9
total	-	**67**

Angloher et al. (CRESST Collab.), arXiv:1109.0702 [astro-ph.CO]

CRESST regions

“Canonical” halo

Fixed quenching

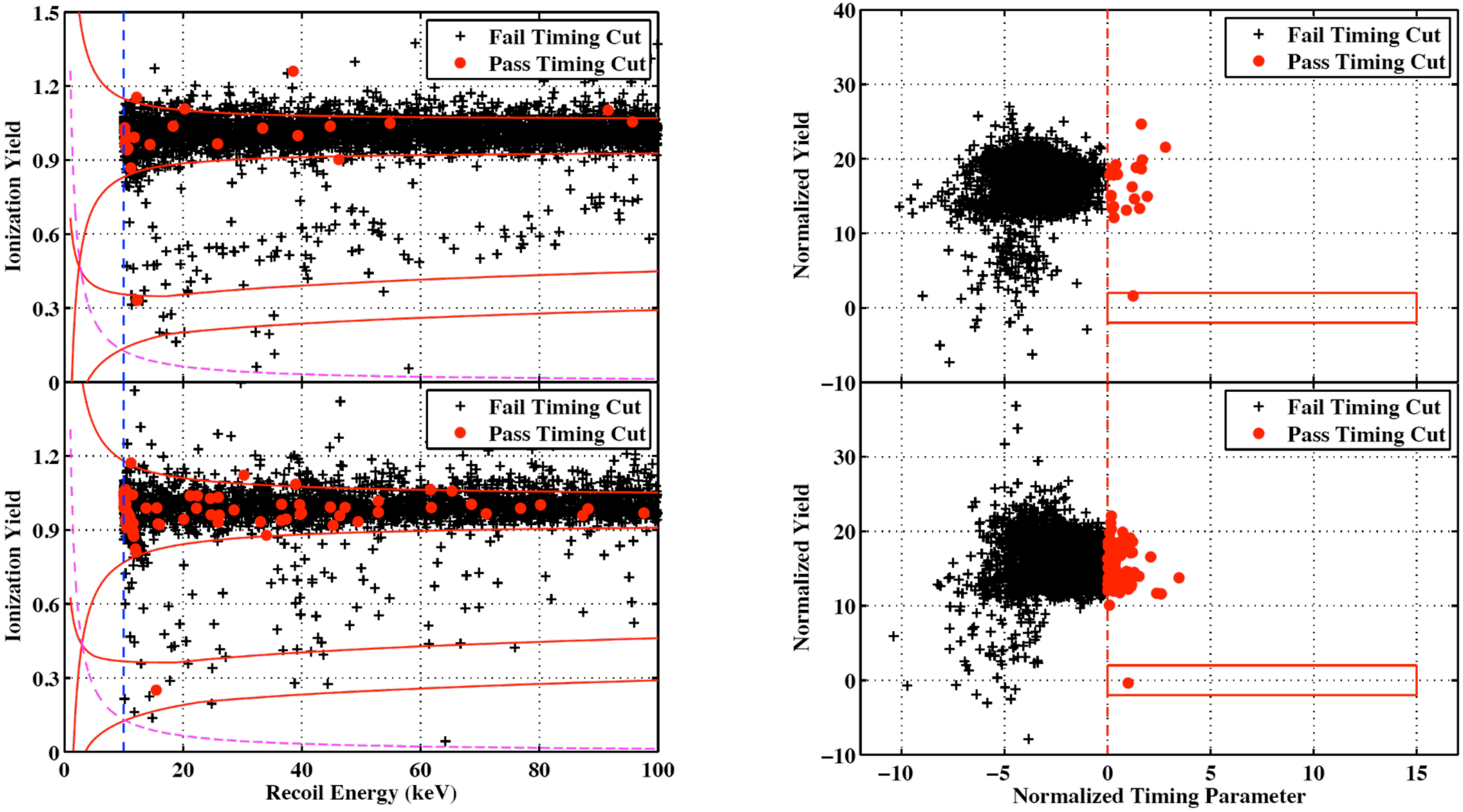


2 sigma from global minimum

	$4.7\,\sigma$	$4.2\,\sigma$
	M1	M2
e/γ-events	8.00 ± 0.05	8.00 ± 0.05
α-events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

Angloher et al. (CRESST Collab.) arXiv:1109.0702 [astro.ph.CO]

CDMS II



Target: Ge, Si

Cumulative exposure: 612 kg x day

2 candidate events

Z. Ahmed (CDMS Collab.), arXiv:0912.3592 [astro-ph.CO]

CDMS II

2 signal events

(0.04 ± 0.04) : cosmogenic background

(0.03 ± 0.06) : neutrons from contaminants

$(0.8 \pm 0.1_{stat} \pm 0.2_{syst})$: misidentified surface events

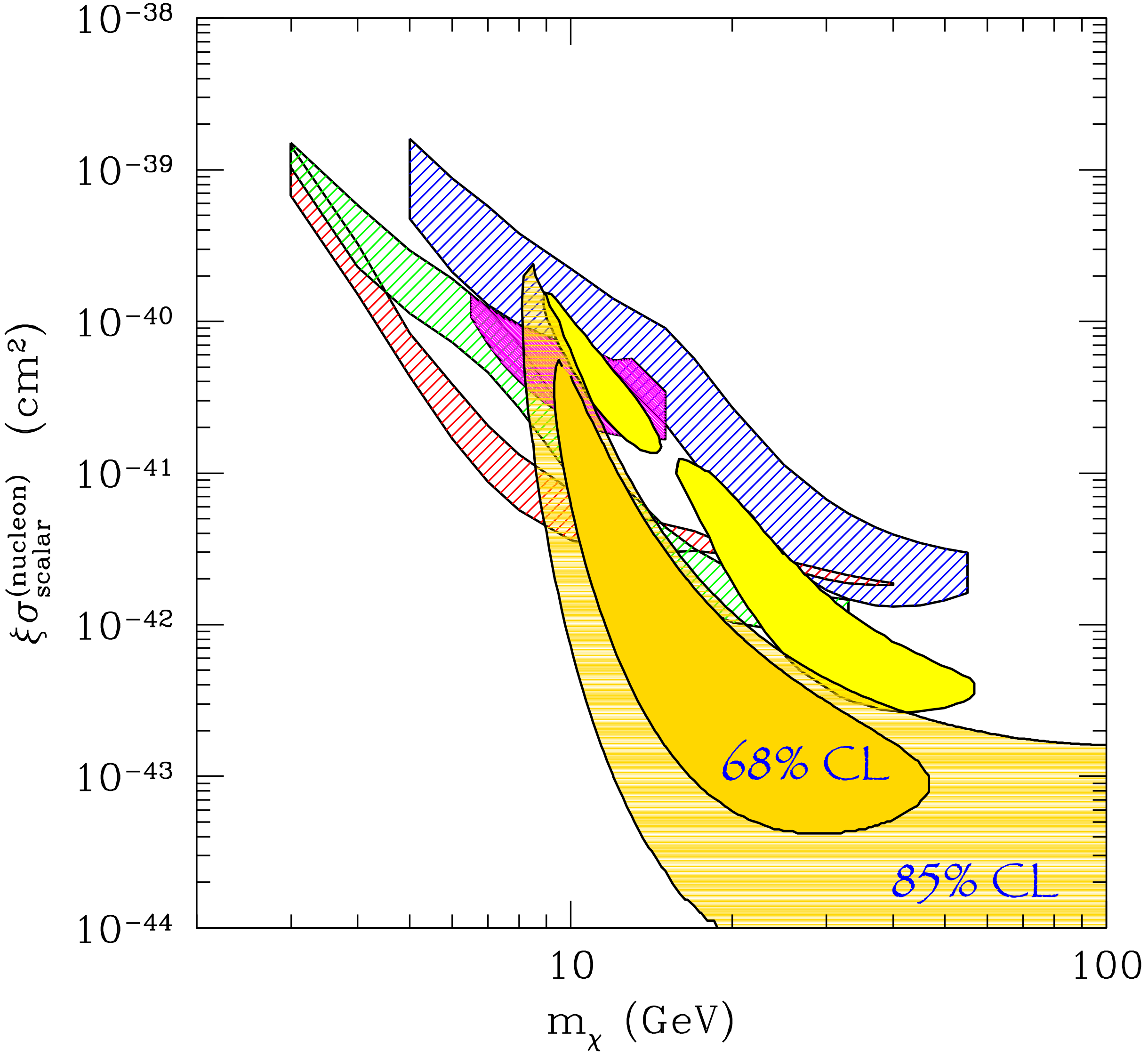
"No significant evidence of a signal, but cannot be rejected" [*]

Ahmed (CDMS Collab.), arXiv:0912.3592 [astro-ph.CO]

CDMS II interpreted as a signal

“Canonical” halo

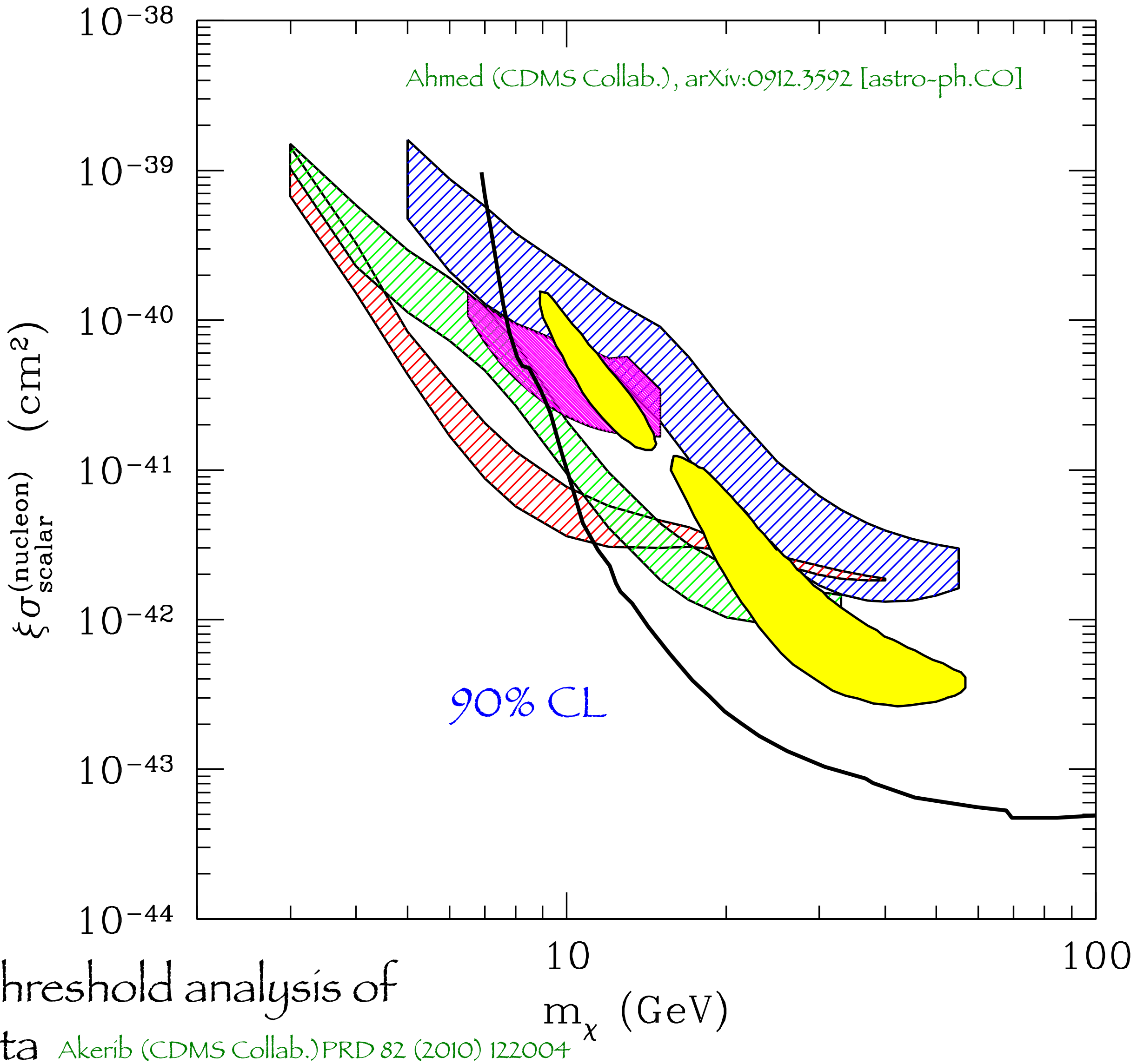
Fixed quenching



CDMS Soudan combined

“Canonical” halo

Fixed quenching



Also: attempt of low-threshold analysis of CDMS shallow site data Akerib (CDMS Collab.) PRD 82 (2010) 122004

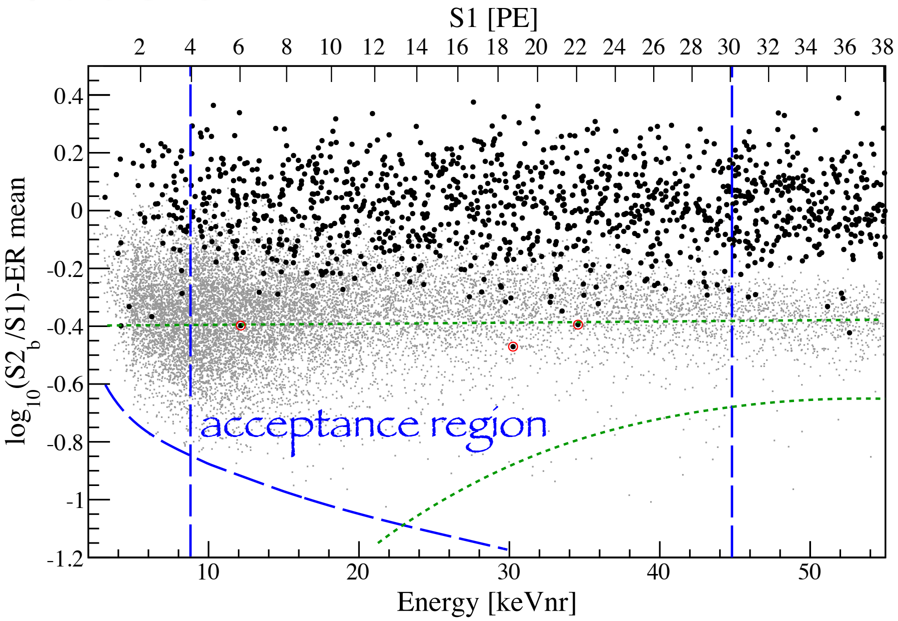
XENON 100

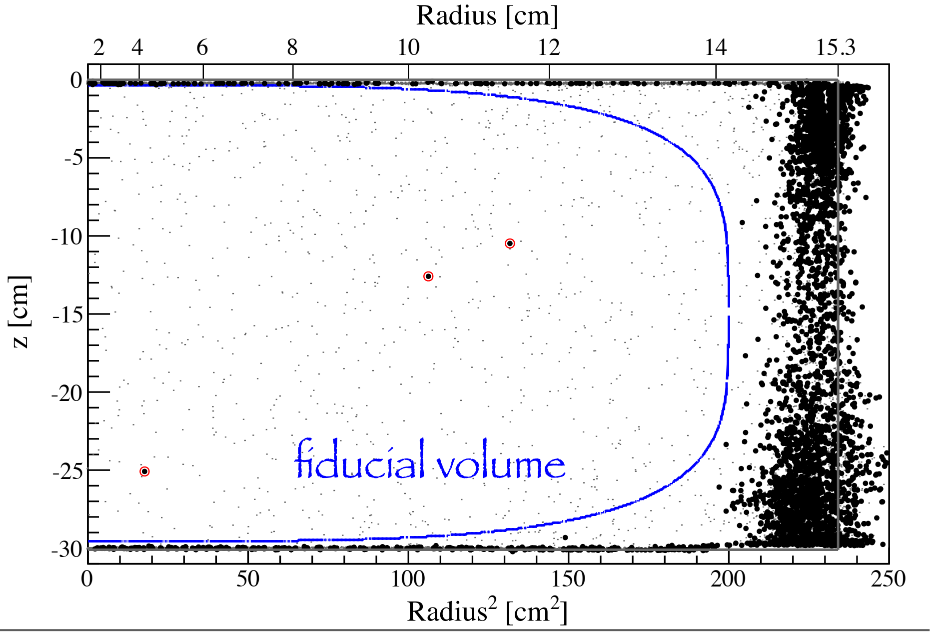
Target: liquid Xe

3 candidate events

(1.8 ± 0.6) expected background

Cumulative exposure: 4843.2 Kg x day





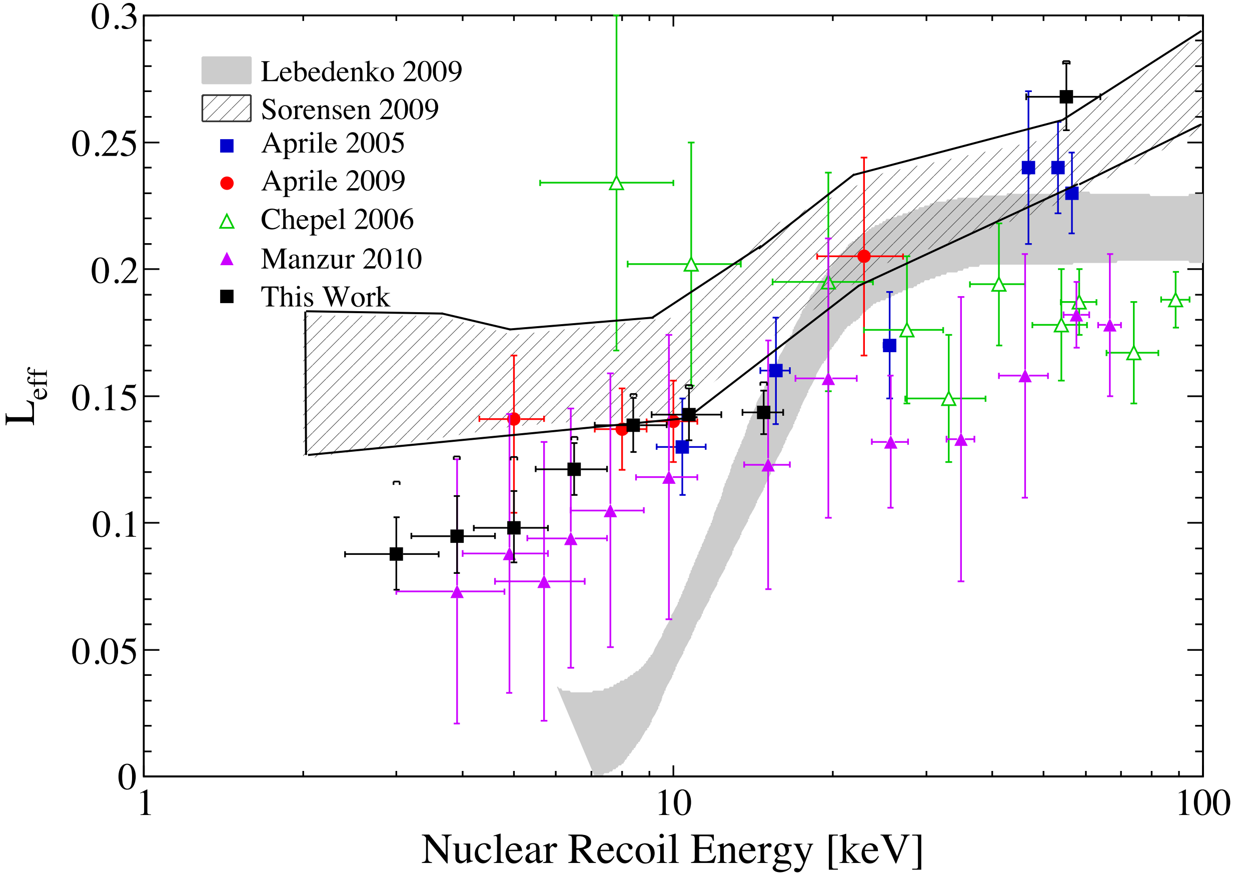
Aprile et al. (XENON 100 Collab.), arXiv:1104.2549 [astro-ph.CO]

Scintillation efficiency

$$E_{\rm nr} = \frac{S1}{\mathcal{L}_y} \, \frac{1}{\mathcal{L}_{\rm eff}} \, \frac{S_{\rm ee}}{S_{\rm nr}}$$

$L_{\rm eff}$: scintillation efficiency of nuclear recoils relative to that of 122 KeV gamma-rays at zero electric field

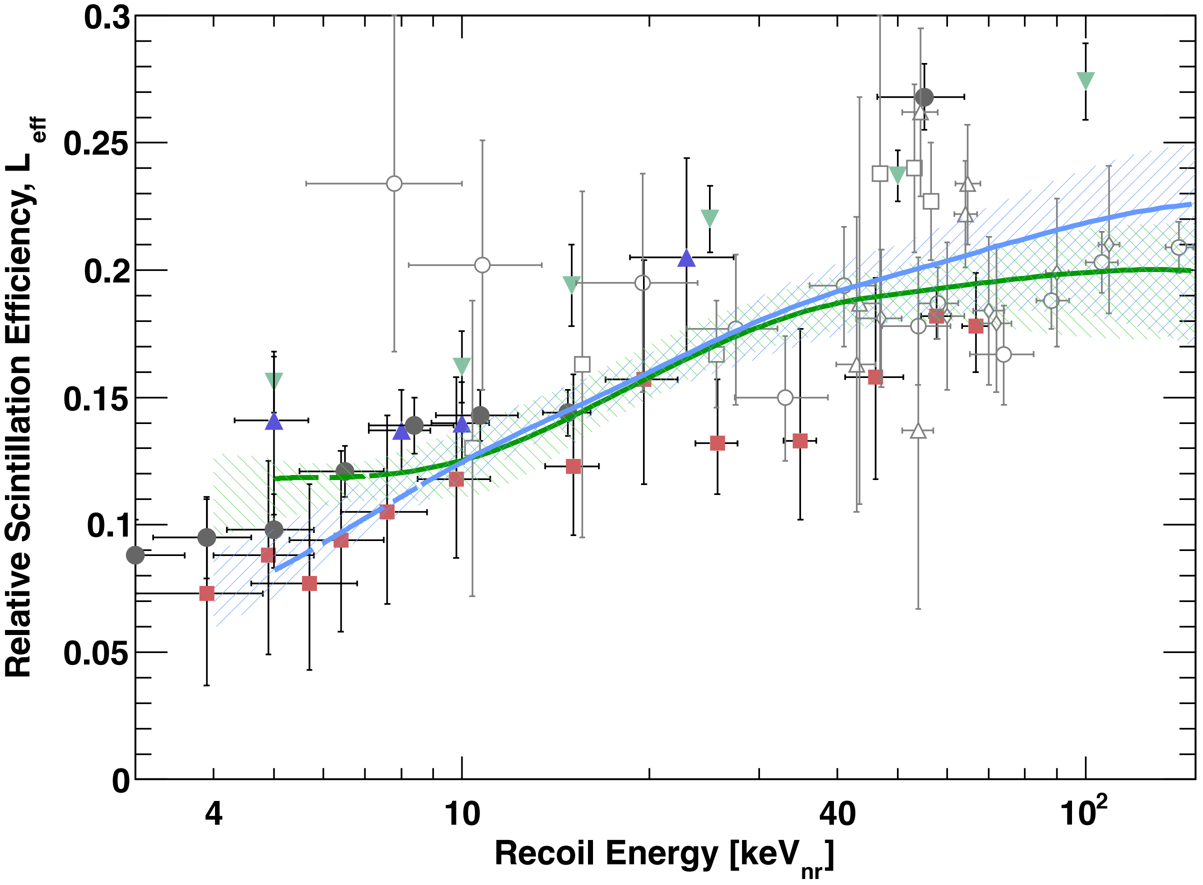
Plante et al. (XENON 100 Collab.), arXiv:1104.2587 [nucl-ex]



S1 : prompt scintillation light (PE)

$L_y \simeq (2.20 \pm 0.09)$: light yield at 122 KeV

$S_{ee} \simeq 0.58$, $S_{nr} \simeq 0.95$: electric field scintillation quenching factors

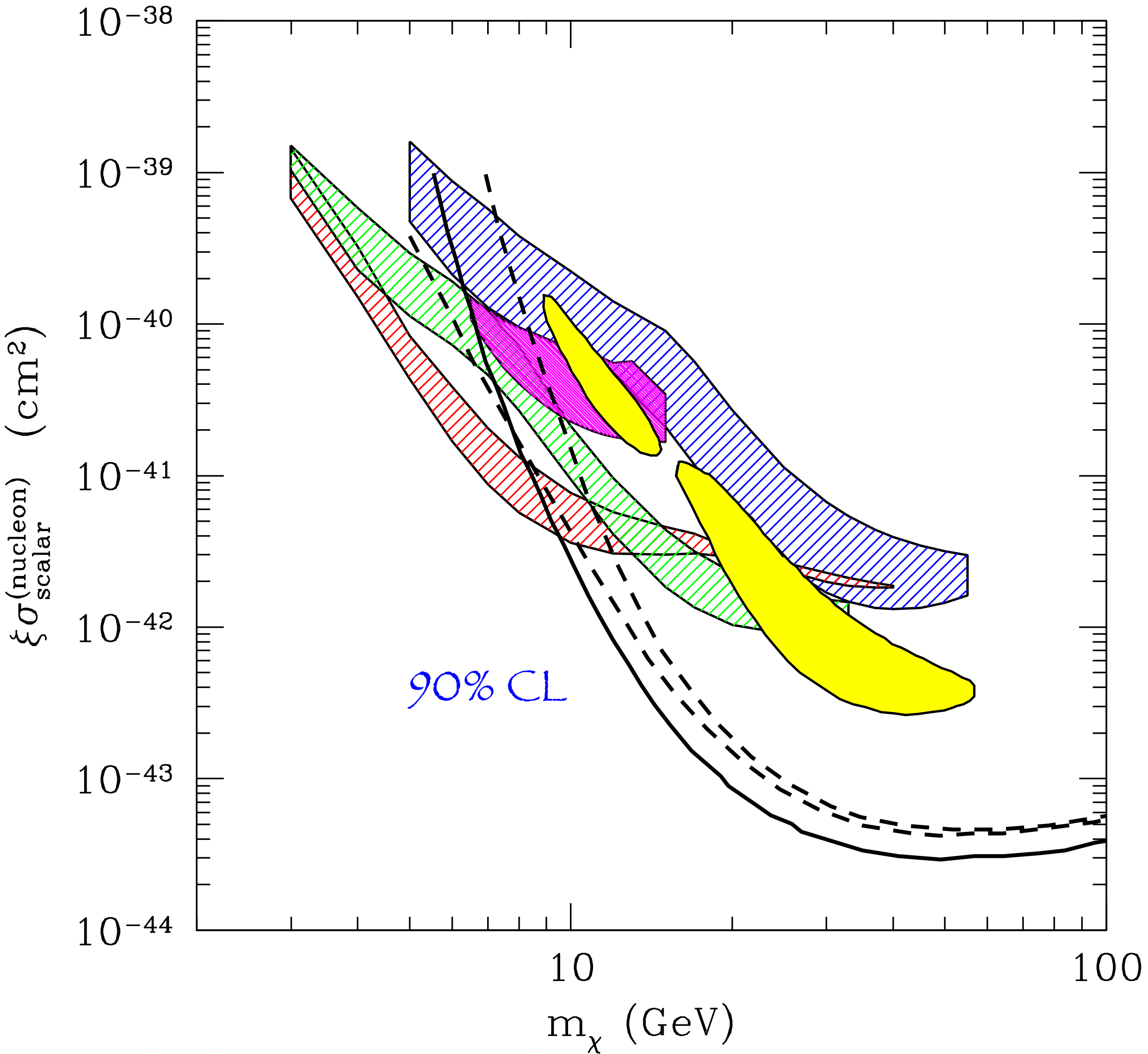


Horn et al., arXiv:1106.0694 [physics.ins-det]

XENON 100

“Canonical” halo

Fixed quenching



Aprile et al. PRL 105 (2011) 131302; Aprile et al. PRD 84 (2011) 052003

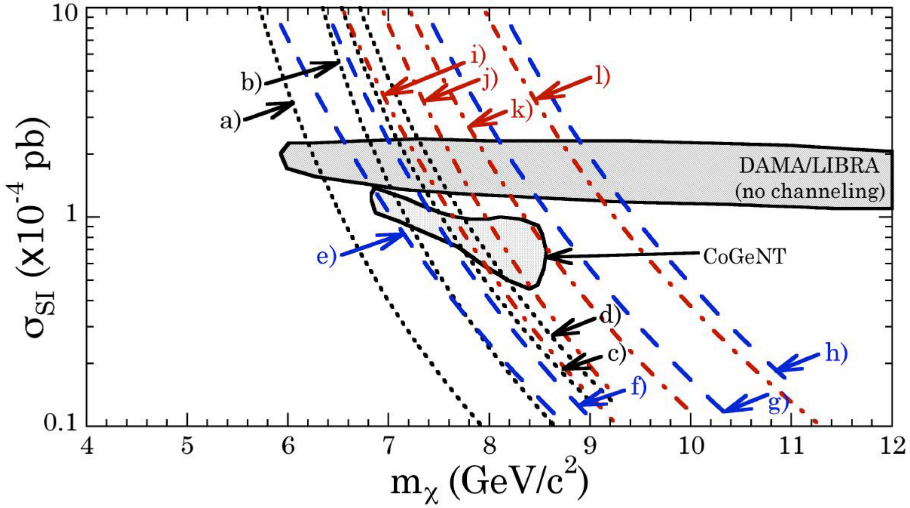
Light DM range

For light WIMPs, knowledge of L_{eff} at low energies is crucial

Extrapolation down to $E \approx 0$ necessary

Statistical tail of low number of PE has impact

Collar, arXiv:1106.0653



Dashed: Leff from Manzur et al.

Dotted: Leff from Plante et al.

Collar, 1005.0838; 1005.2615; 1006.2031; 1010.5187; 1106.0653

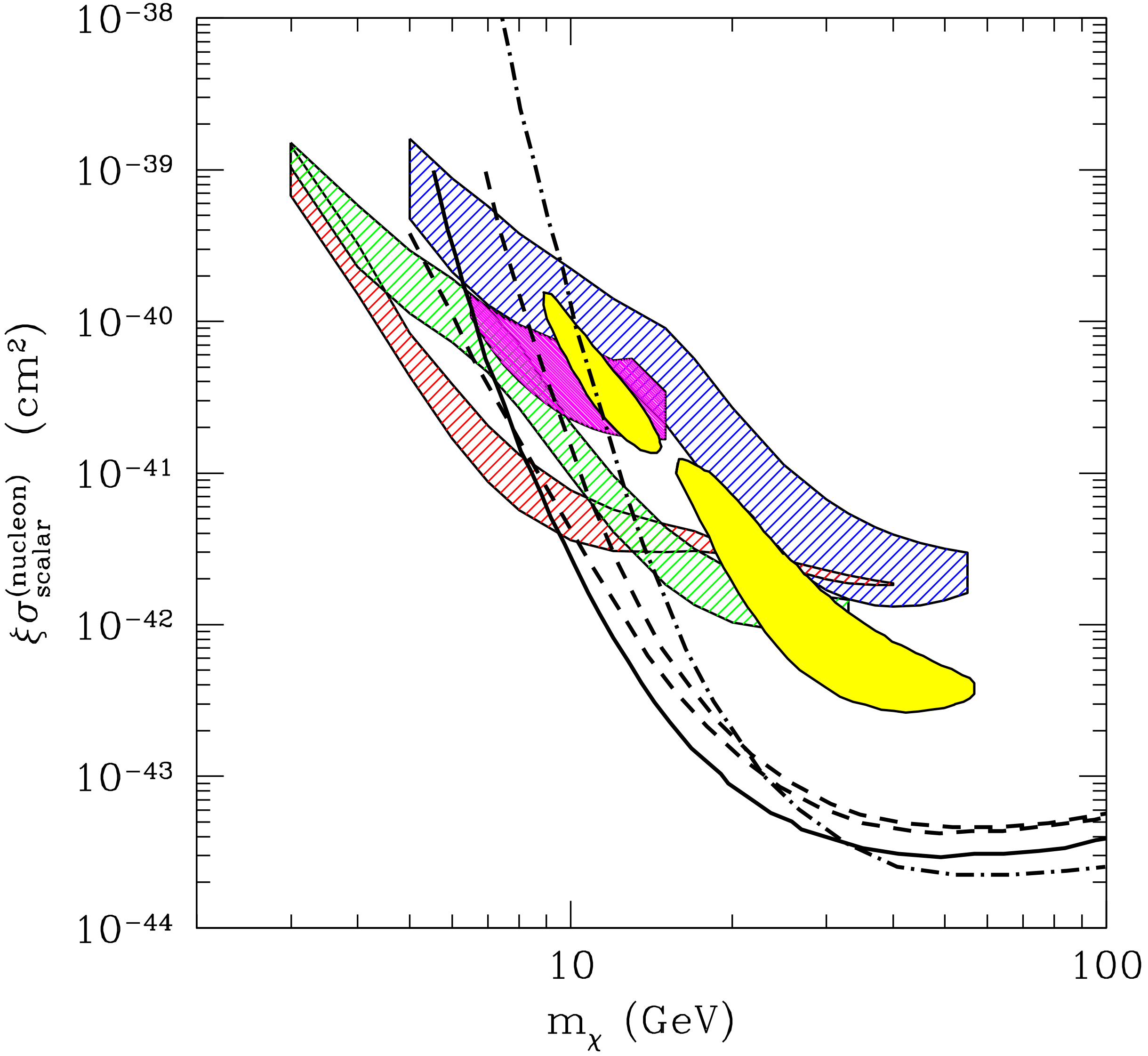
XENON 100 Collab. 1005.2615

Savage et al. 1006.0972

XENON 100

"Canonical" halo

Fixed quenching



For light WIMPs, see also:

- Kopp, Schwetz, Zupan, JCAP 1002:014,2010
- Fairbairn, Schwetz, JCAP 0901:037,2009
- Savage, Gelmini, Gondolo, Freeze, JCAP 0904:010 (2009)
- Gondolo, Gelmini, PRD 71:123520,2005
- Andreas, Arina, Hambye, Ling, Tytgat, arXiv:1003.2595 [hep-ph]
- Fitzpatrick, Hooper, Zurek, arXiv:1003.0014 [hep-ph]
- Petriello, Zurek, JHEP 0809:047,2008
- Foot, arXiv:1004.1424 [hep-ph]
- Schwetz et al., arXiv:1011.5432
- Farina et al. ,arXiv:1107.0715
- Fox et al., arXiv:1107.0717

(...)

Comparison with theoretical models

Coherent (scalar) cross sections

On nucleon:

$$\sigma_0^{SI} = \frac{8G_F^2}{\pi} M_Z^2 \, \mu_1^2 \, \left[F_h I_h P_h^t + F_H I_H P_H^t + F_{\tilde{q}} I_{\tilde{q}} (P_{\tilde{q}}^s + P_{\tilde{q}}^u)\right]^2$$

$F_{h,H}$: coupling $(h,H)\chi\chi$

$$I_{h,H} = \sum_q k_q^{h,H} \, m_q < N|\bar{q}q|N >$$

$k_q^{(h,H)}$: coupling $(h,H)qq$

$$I_{\tilde{q}} = \sum_q C_q^2 \, m_q < N|\bar{q}q|N >$$

C_q : coupling $\tilde{q}q\chi$

On nucleus: $$\sigma_{\mathcal{N}}^{SI} = \frac{\mu_{\mathcal{N}}^2}{\mu_1^2} \, \sigma_0^{SI} \, A_N^2$$

Hadronic matrix elements

Light quarks

$$\sigma_{\pi N} = \frac{1}{2}(m_u + m_d) < N|(\bar{u}u + \bar{d}d)|N >$$

Pion-nucleon sigma term

$$\Sigma_0 = \frac{1}{2}(m_u + m_d) < N|(\bar{u}u + \bar{d}d - 2\bar{s}s)|N >$$

$$R = 2m_s/(m_u + m_d)$$

Octet baryon masses
Chiral perturb. Theory
Lattice

Heavy quarks

$$m_N = \sum_q m_q < N|\bar{q}q|N > + \frac{\beta(\alpha_S)}{4\alpha_S} < N|G^a_{\mu\nu}G^{\mu\nu}_a|N >$$

Nucleon mass

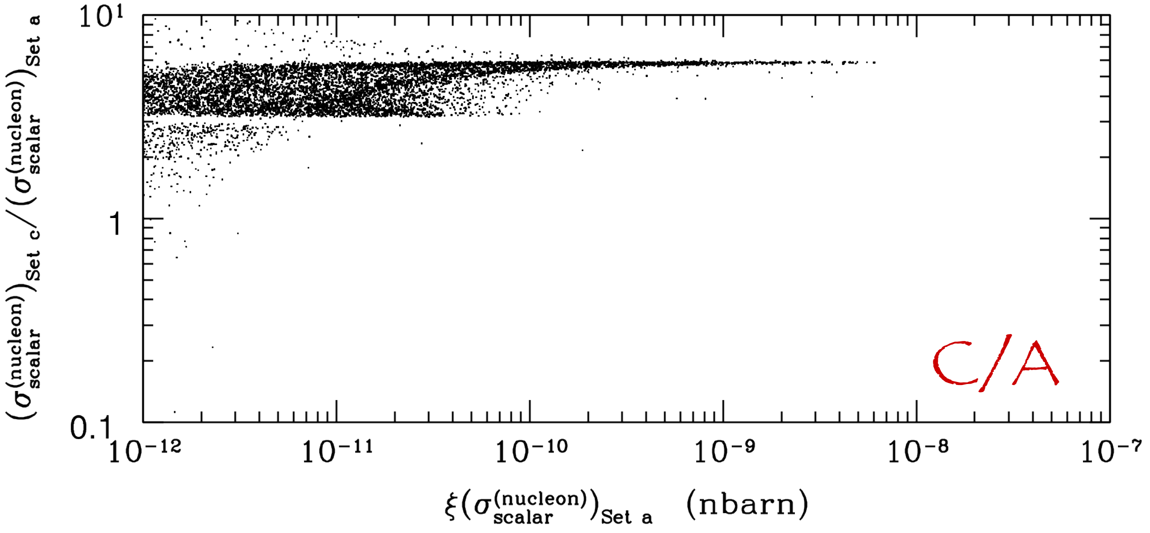
$$m_h < N|\bar{h}h|N > = -\frac{\alpha_S}{12\pi} < N|G^a_{\mu\nu}G^{\mu\nu}_a|N > + \mathcal{O}(\Lambda^3/m_h^3)$$

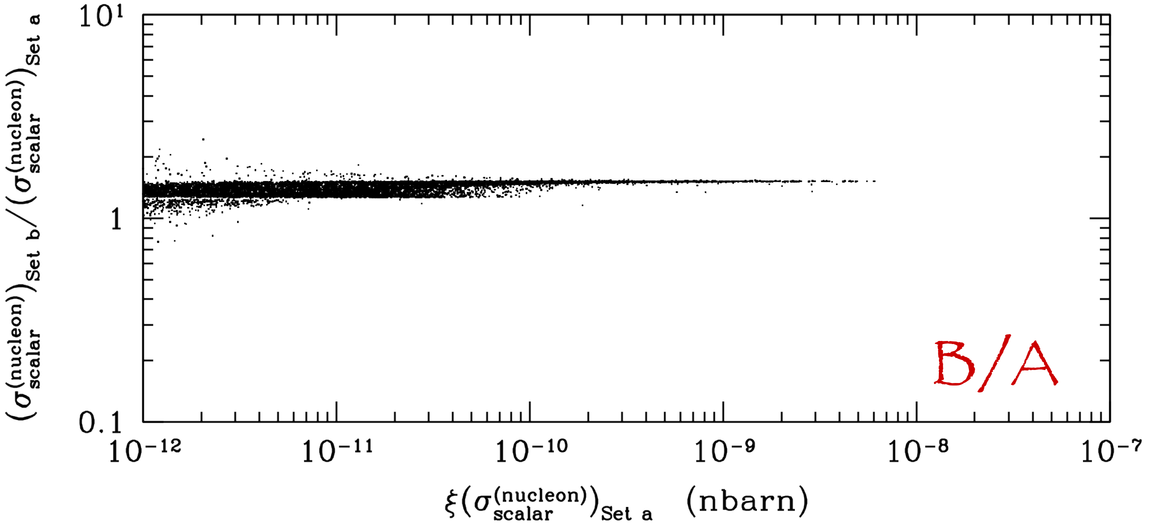
Heavy-q expansion

$$m_h < N|\bar{h}h|N > = \frac{2}{27}[m_N - \sum_{q=u,d,s} m_q < N|\bar{q}q|N >]$$

(in MeV)	$m_l < N\|\bar{q}_l q_l\|N >$	$m_s < N\|\bar{s}s\|N >$	$m_h < N\|\bar{h}h\|N >$	g_u	g_d
Set A	27	131	56	139	214
Set B	28	186	52	132	266
Set C	37	456	30	97	523

Effect of hadronic uncertainties

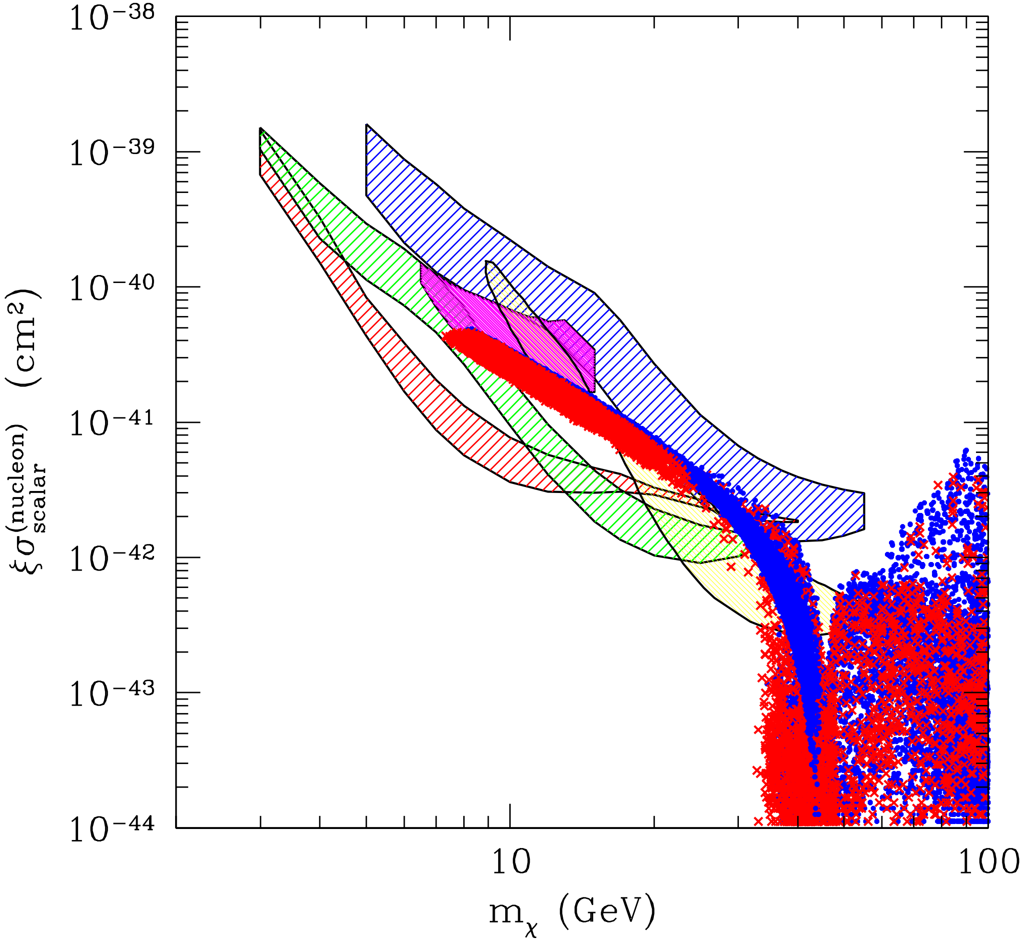




A. Bottino, F. Donato, NF, S. Scopel, Astrop. Phys. 18 (2002) 205

Light neutralinos in the MSSM

MSSM (8 params) with gaugino non universality
Light neutralinos, light pseudoscalar higgs, medium tanbeta



A. Bottino et al., PRD 67 (2003) 063519; PRD 78 (2008) 083520; PRD 83 (2011) 015001; PRD 84 (2011) 055014

COSMOLOGY

Light neutralinos
Light A higgs

$$\boxed{\chi\chi \longrightarrow \bar{b}b}$$

$$\Omega_\chi h^2 \simeq \frac{4.8\cdot 10^{-6}}{\mathrm{GeV}^2}\,\frac{x_f}{g_\star(x_f)^{1/2}}\,\frac{1}{a_1^2 a_3^2 \tan^2\beta}\, m_A^4\, \frac{[1-(2m_\chi)^2/m_A^2]^2}{m_\chi^2\ [1-m_b^2/m_\chi^2]^{1/2}}\,\frac{1}{(1+\epsilon_b)^2}$$

$$m_\chi \frac{[1-m_b^2/m_\chi^2]^{1/4}}{[1-(2m_\chi)^2/m_A^2]} \gtrsim 7.4\ \mathrm{GeV}\left(\frac{m_A}{90\ \mathrm{GeV}}\right)^2\left(\frac{35}{\tan\beta}\right)\left(\frac{0.12}{a_1^2 a_3^2}\right)^{\frac{1}{2}}\left(\frac{0.12}{(\Omega_{CDM}h^2)_{\max}}\right)^{\frac{1}{2}}$$

$$\boxed{m_\chi \gtrsim 7-8\ \mathrm{GeV}}$$

Mass lower bound from Cosmology

Higgs A needs to be light
$\tan\beta$ nees to be relatively large
Bino-higgsino mixing needs to be "sizeable"

$$\boxed{\begin{aligned} m_A &\sim (90-200)\ \mathrm{GeV} \\ \tan\beta &\sim 20-45 \\ |\mu| &\simeq (100-200)\ \mathrm{GeV}\quad [*] \end{aligned}}$$

LIGHT$_\chi$ DM SIGNALS - DIRECT DETECTION

From the relic abundance bound:

$$\boxed{\begin{array}{r} m_A \sim (90 - 200)\ \text{GeV} \\ \tan\beta \sim 20 - 45 \\ |\mu| \simeq (100 - 200)\ \text{GeV} \end{array}}$$

$\longrightarrow$ Light h higgs $(m_h \sim m_A)$

$\longrightarrow$ Fix couplings $a_1^2 a_3^2$

$$\sigma_{\text{scalar}}^{(\text{nucleon})} \simeq 5.3 \times 10^{-41}\ \text{cm}^2 \left(\frac{a_1^2 a_3^2}{0.13}\right) \left(\frac{\tan\beta}{35}\right)^2 \left(\frac{90\ \text{GeV}}{m_h}\right)^4 \left(\frac{\enclose{circle}{g_d}}{290\ \text{MeV}}\right)^2$$

× 3 ↑

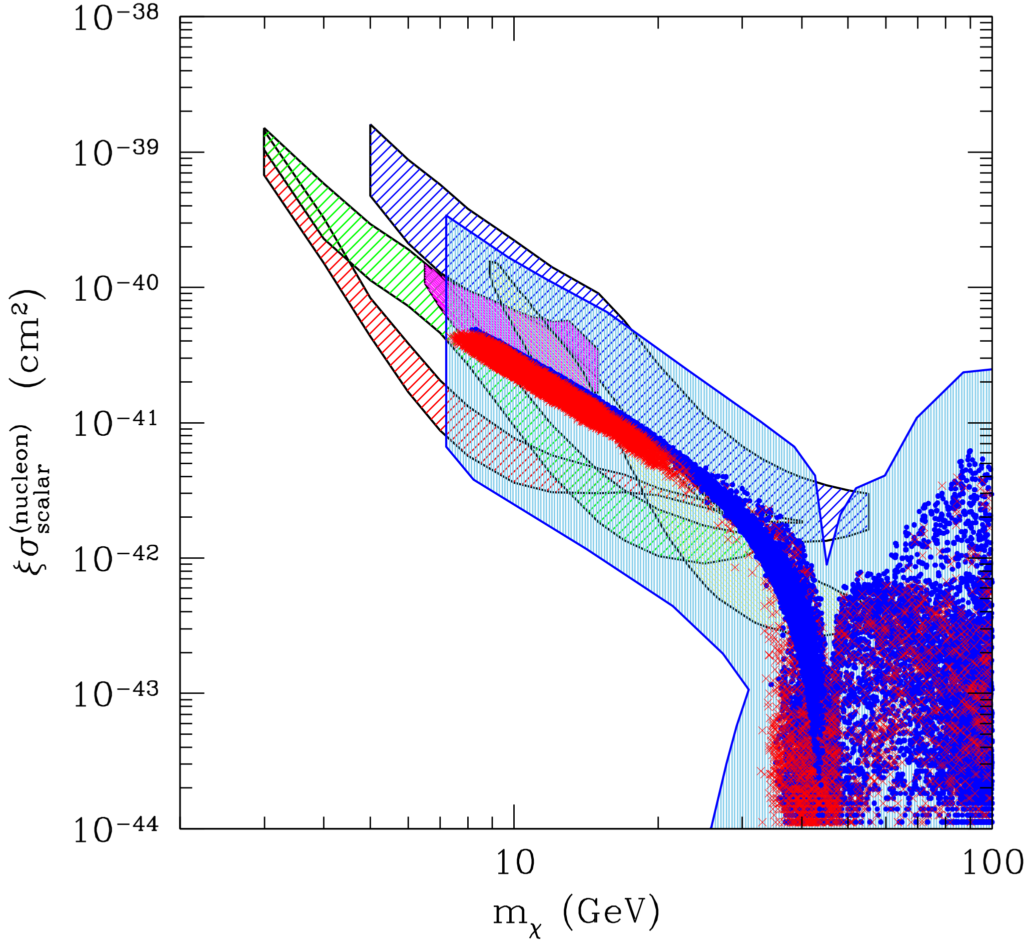
× 0.12 ↓

$$\underbrace{(\Omega_\chi h^2)}_{0.098 - 0.12}\ \sigma_{\text{scalar}}^{(\text{nucleon})} \simeq 3.3 \times 10^{-39}\ \text{cm}^2\ g_d^2\ \frac{[1 - (2m_\chi)^2/m_A^2]^2}{m_\chi^2\ [1 - m_b^2/m_\chi^2]^{1/2}}\ \frac{1}{(1+\epsilon_b)^2}$$

$$\sigma_{\text{scalar}}^{(\text{nucleon})} \simeq (2.7 - 3.4) \times 10^{-41}\ \text{cm}^2 \left(\frac{g_d}{290\ \text{MeV}}\right)^2 \frac{[1 - (2m_\chi)^2/m_A^2]^2}{\underbrace{(m_\chi/(10\ \text{GeV})^2}_{m_\chi^{-2}}\ [1 - m_b^2/m_\chi^2]^{1/2}}$$

Light neutralinos in the MSSM

MSSM (8 params) with gaugino non universality
Light neutralinos, light pseudoscalar higgs, medium tanbeta



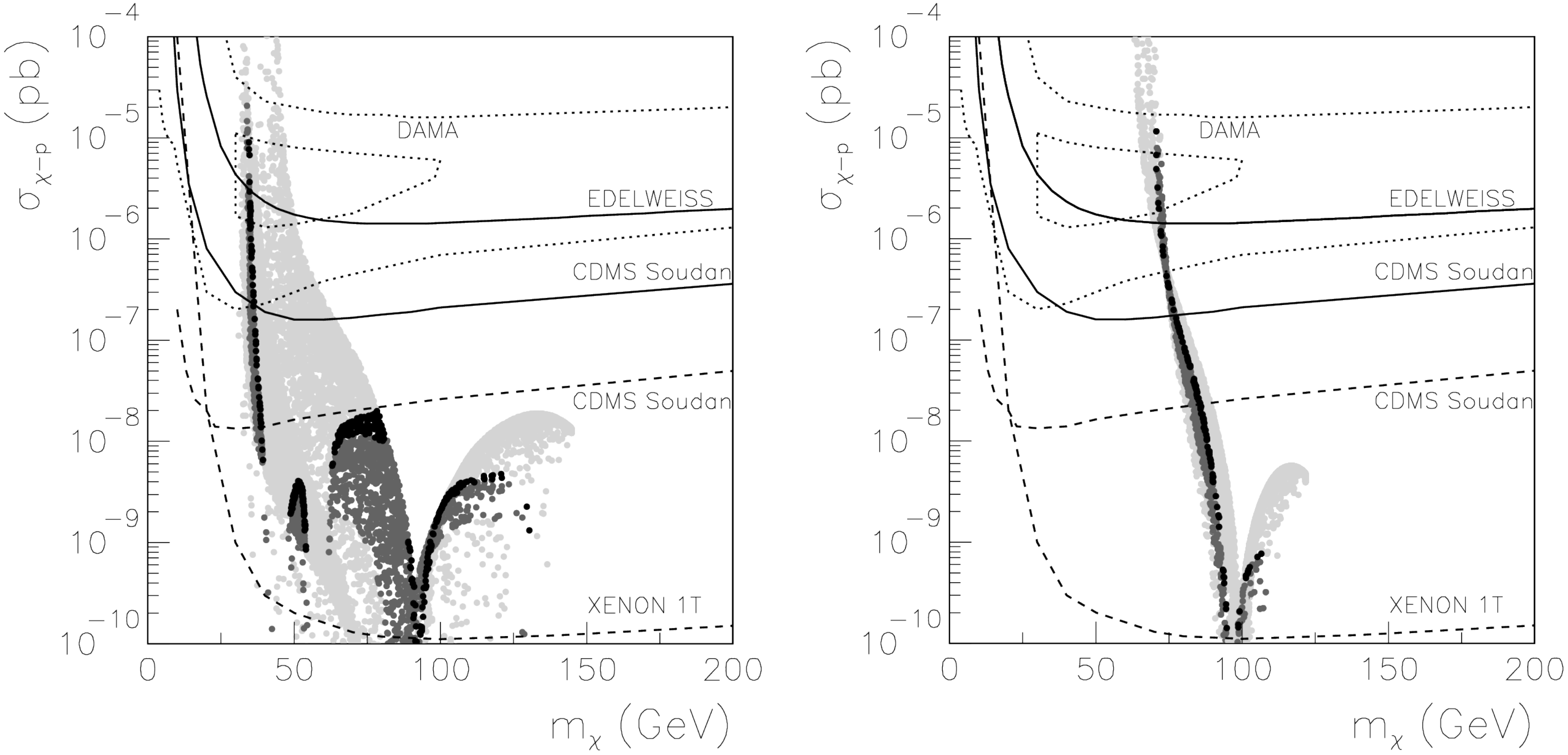
A. Bottino et al., PRD 67 (2003) 063519; PRD 78 (2008) 083520; PRD 83 (2011) 015001; PRD 84 (2011) 055014

Next-to-Minimal MSSM (NMSSM)

NMSSM = MSSM + singlet superfield

Addresses naturally the mu-problem

Higgs and neutralinos may be light

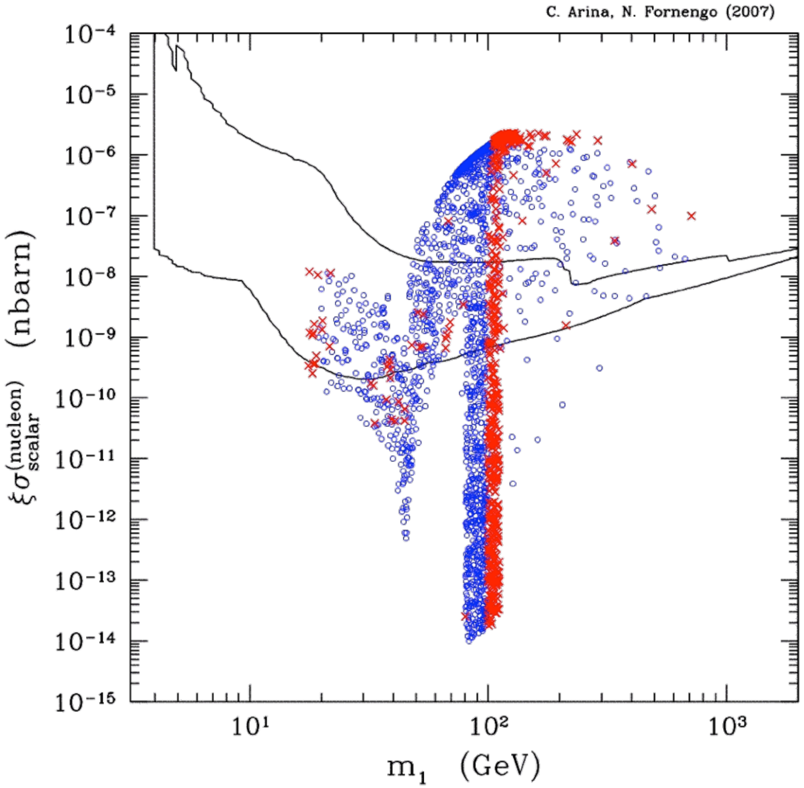


Cerdeno, Gabrielli, Lopez-Fogliani, Munoz, Teixeira, JCAP0706:008,2007

Sneutrinos

MSSM + right-handed neutrino superfields

Addresses DM + neutrino mass in the same sector

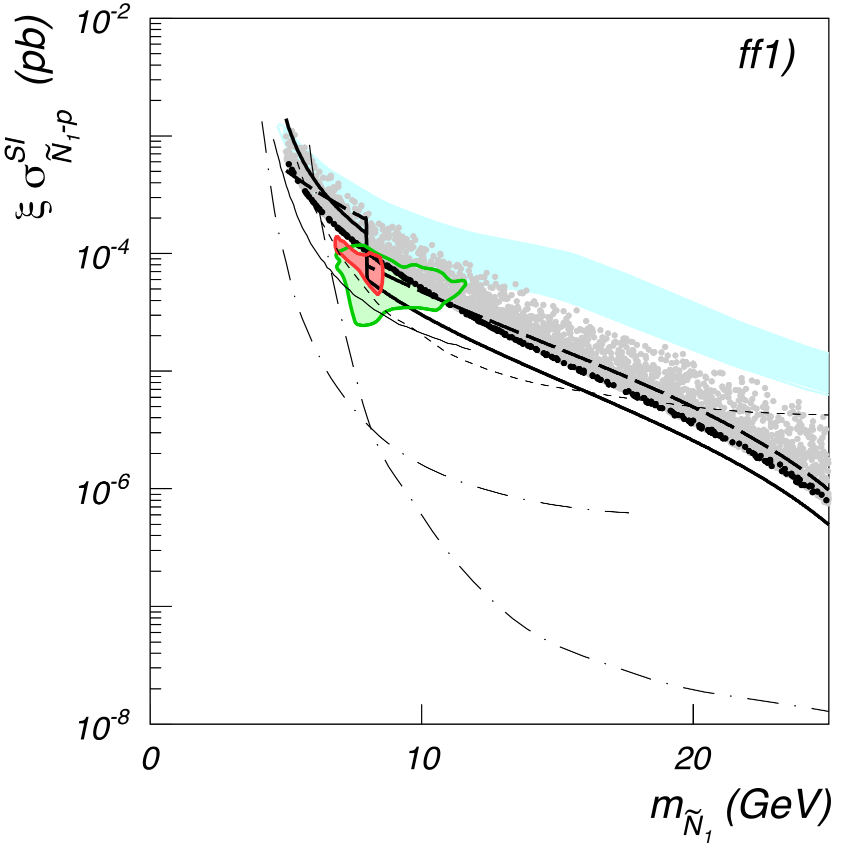


C. Arina, NF, JHEP 0711 (2007) 029

Sneutrinos in the NMSSM

NMSSM + right-handed neutrino superfield

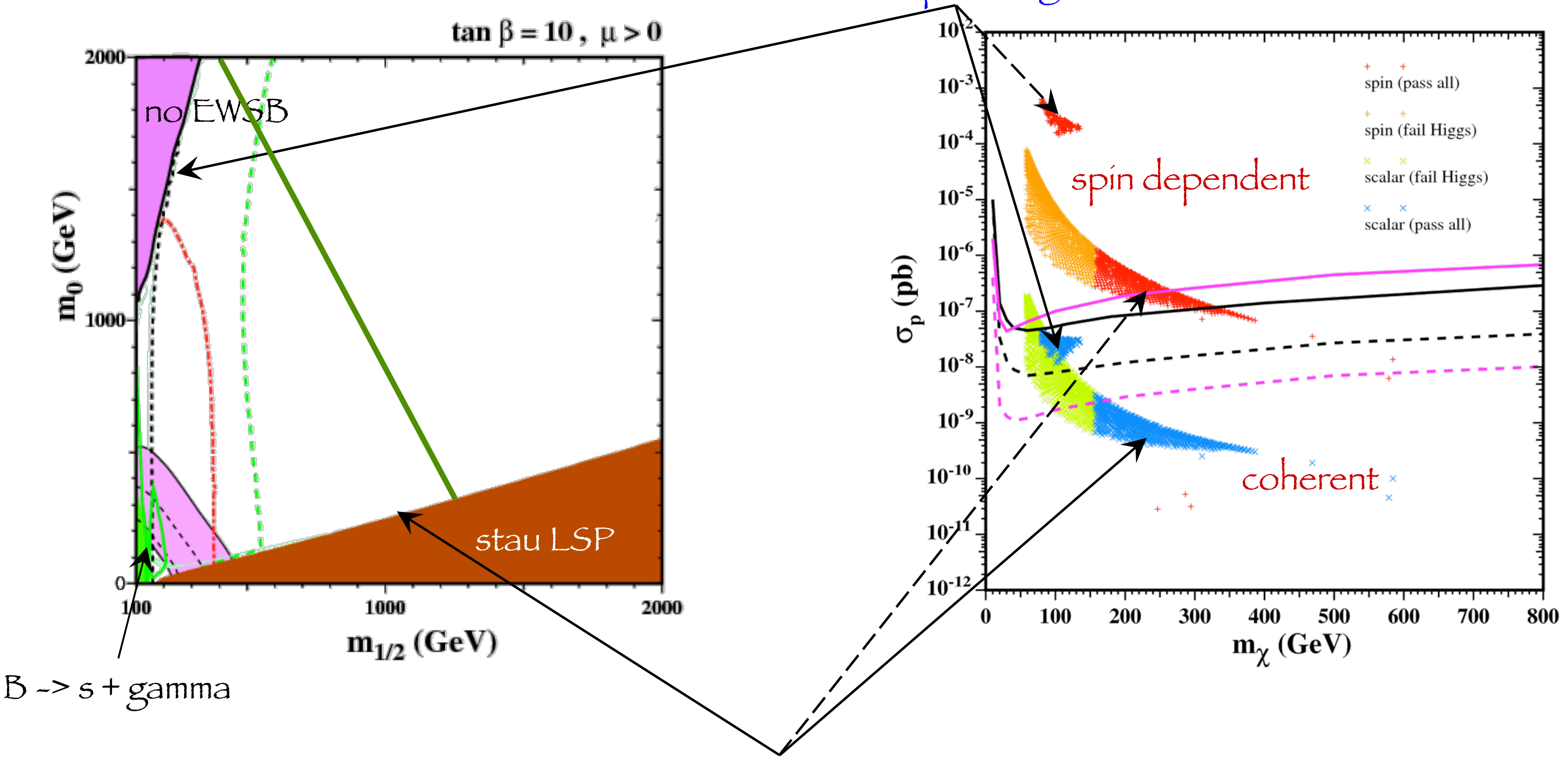
Light sneutrinos and psedoscalar higgs



Cerdeno, Seto, JCAP 0908 (2009) 032

Minimal Supergravity

“focus point region”



B -> s + gamma

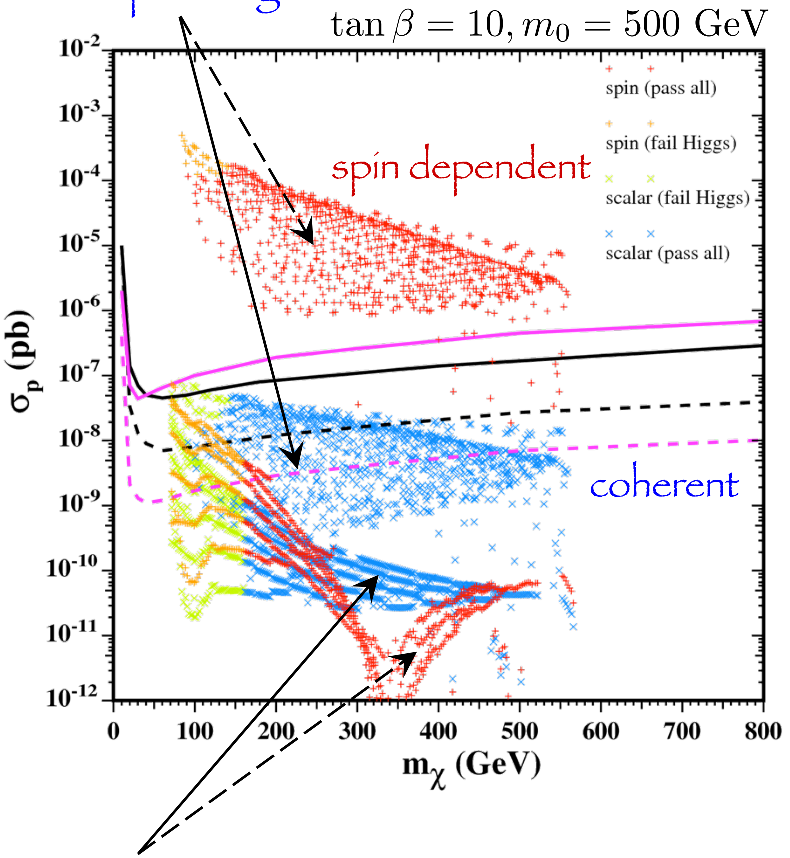
“coannhilation strip”

Ellis, Olive, Sandik, New J.Phys.11:105015,2009

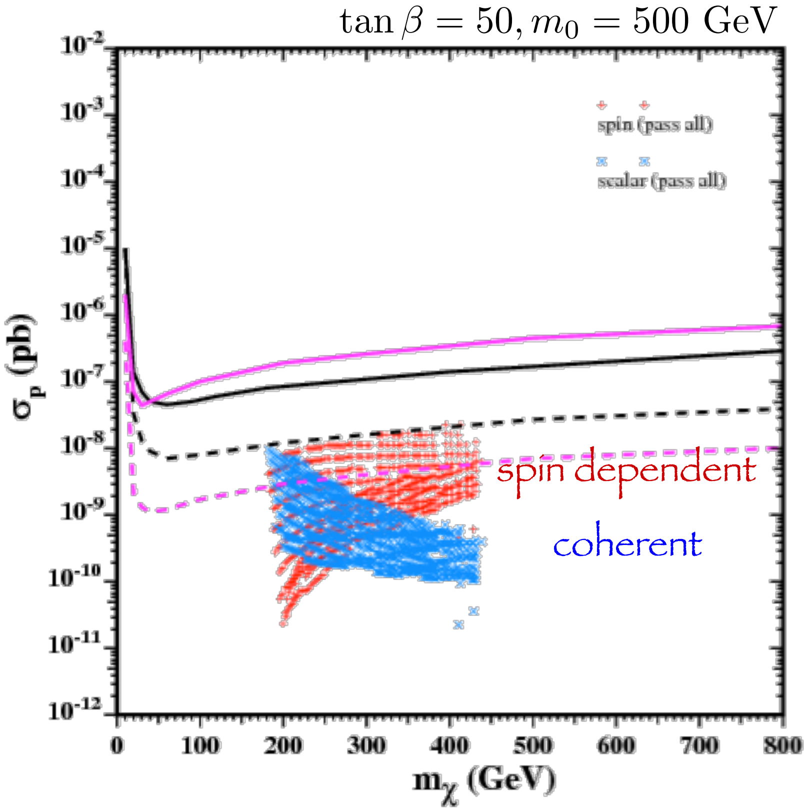
Non-minimal Supergravity

Non-universality in the Higgs sector

“focus point region”

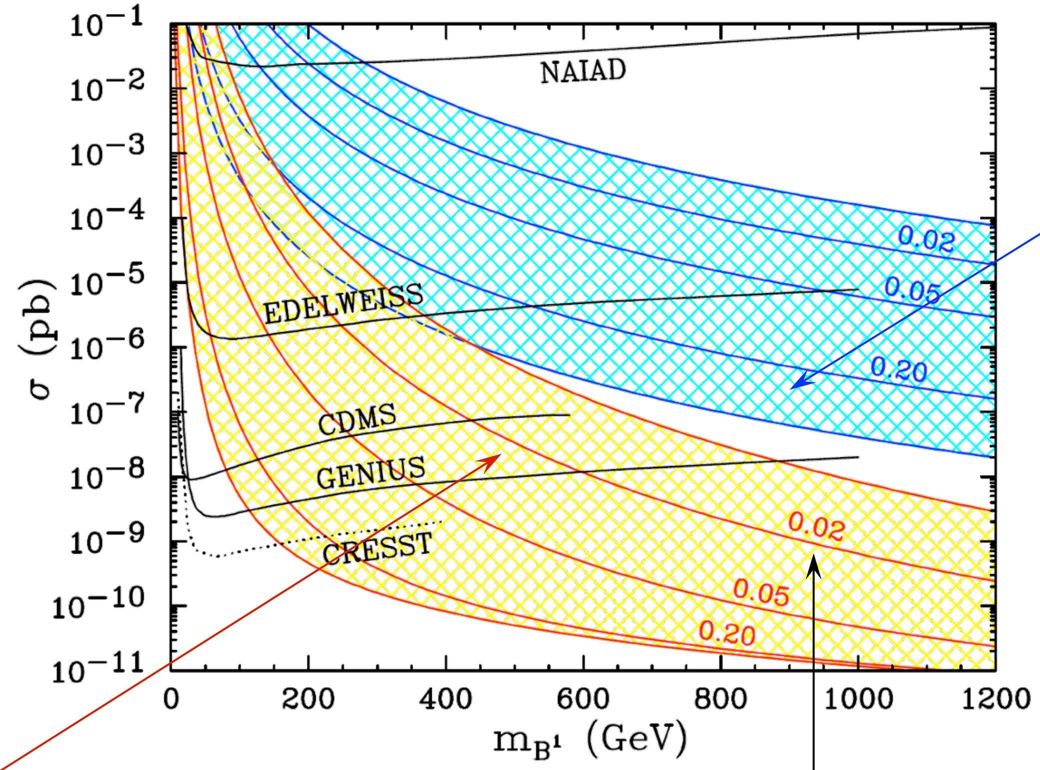


“funnel region”



Ellis, Olive, Sandik, New J.Phys.11:105015,2009

Universal extra-dimensions



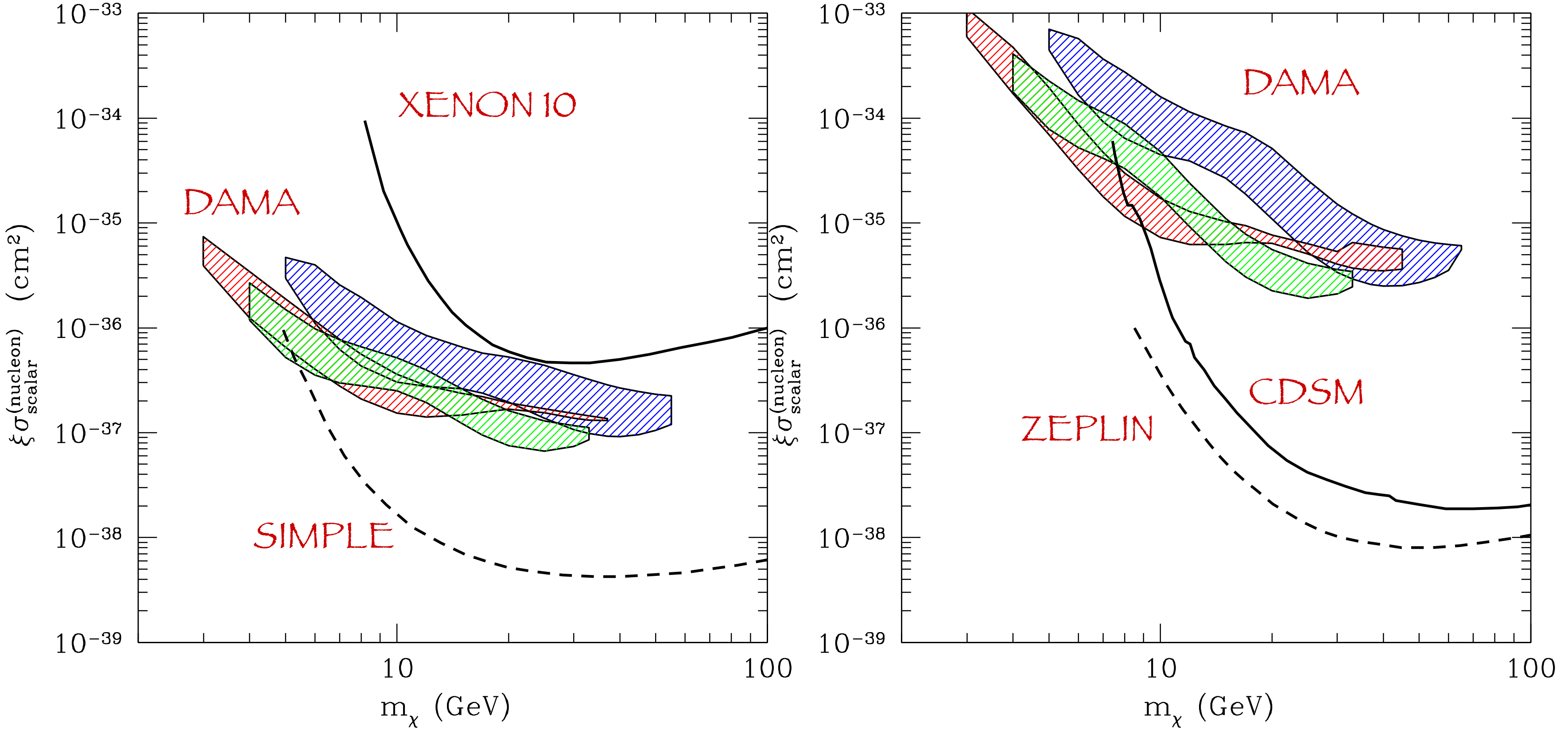
spin dependent

spin independent

$r = (m_{q^1} - m_{B^1})/m_{B^1}$

Cheng, Feng, Matchev, PRL 89 (2002) 211301

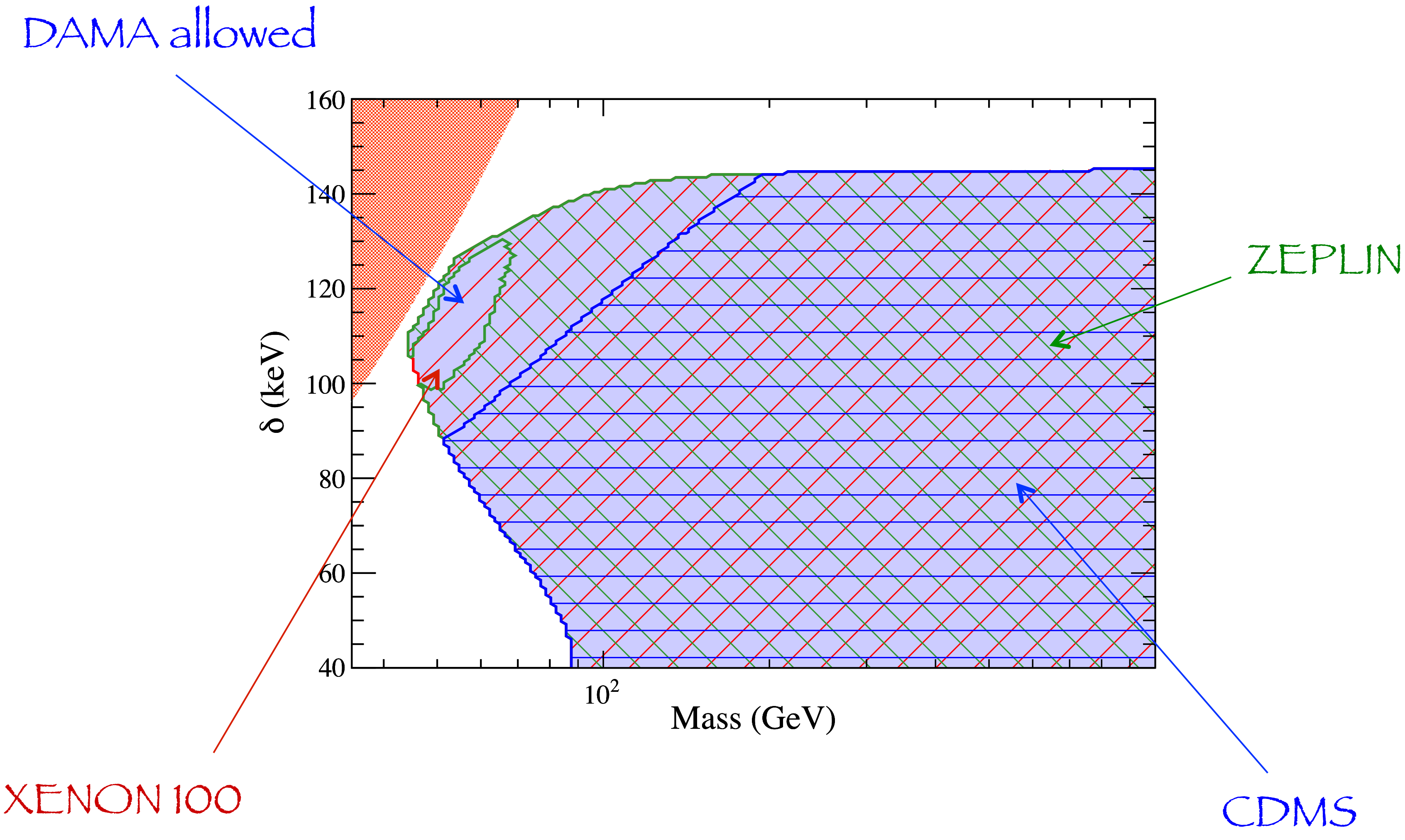
Spin dependent



scattering on protons

scattering on neutrons

Inelastic



Aprile et al. RD84 (2011) 061101

Additional mechanism

- Isospin violation: $f_p \neq f_n$

  Kurylov, Kamionkowski, PRD 69 (2004) 063503
  Giuliani, PRL 95 (2005) 101301
  Cotta, Gainer, Hewett, Rizzo, New J. Phys. 11 (2009) 105026
  Chang, Liu, Pierce, Weiner, Yavin, JCAP 1008 (2010) 018
  Kang, Li, Liu, Tong, Yang, JCAP 1101 (2011) 028
  Feng, Kumar, Marfatia, Sanford arXiv:1102.4331
  Farina, Pappadopulo, Strumia, Volansky, arXiv:1107.0715
  (...)

- Long-range interactions

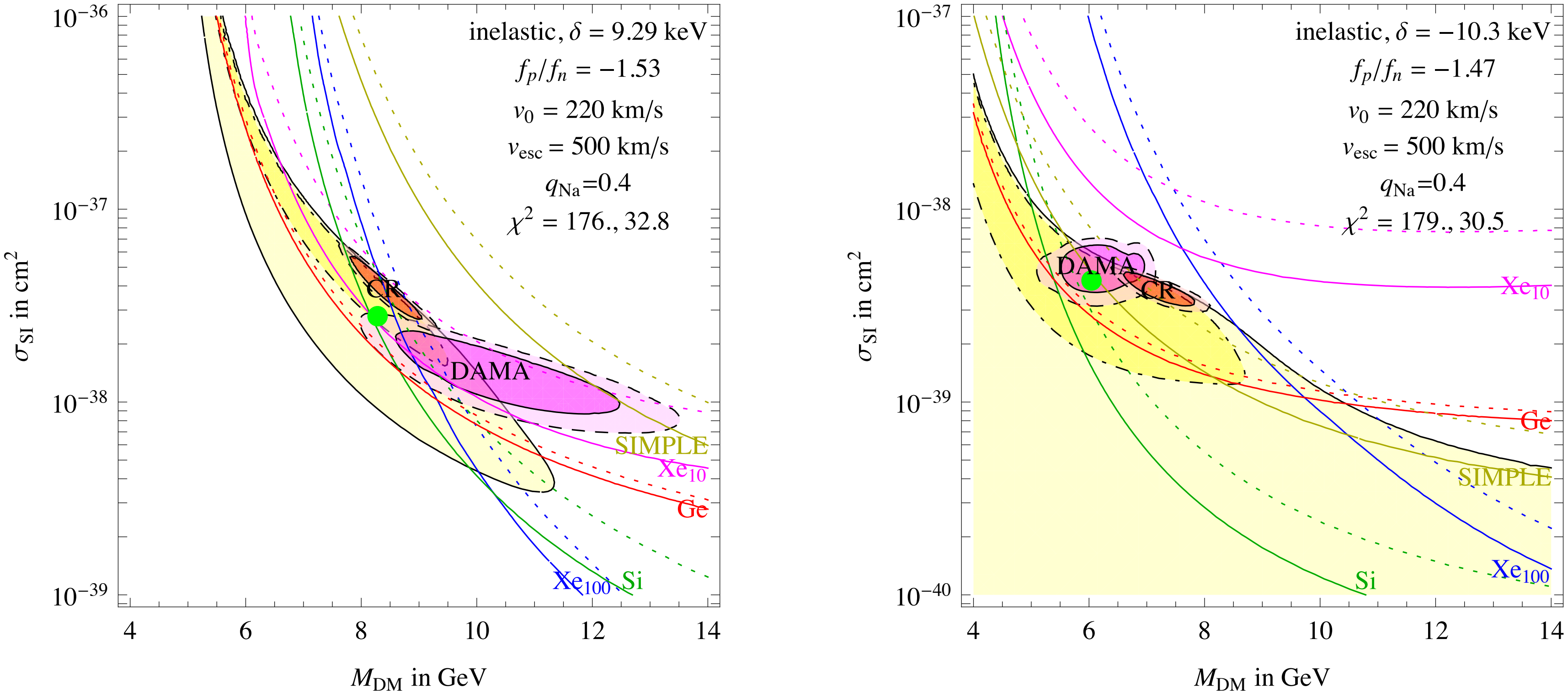
  NF, Panci, Regis, arXiv:1108.4461
  (...)

- Energy or momentum dependent interactions

  Feldstein, Fitzpatrick, Katz, JCAP 1001 (2010) 020
  Chang, Pierce, Weiner, JCAP 1001 (2010) 006
  Farina, Pappadopulo, Strumia, Volansky, arXiv:1107.0715
  (...)

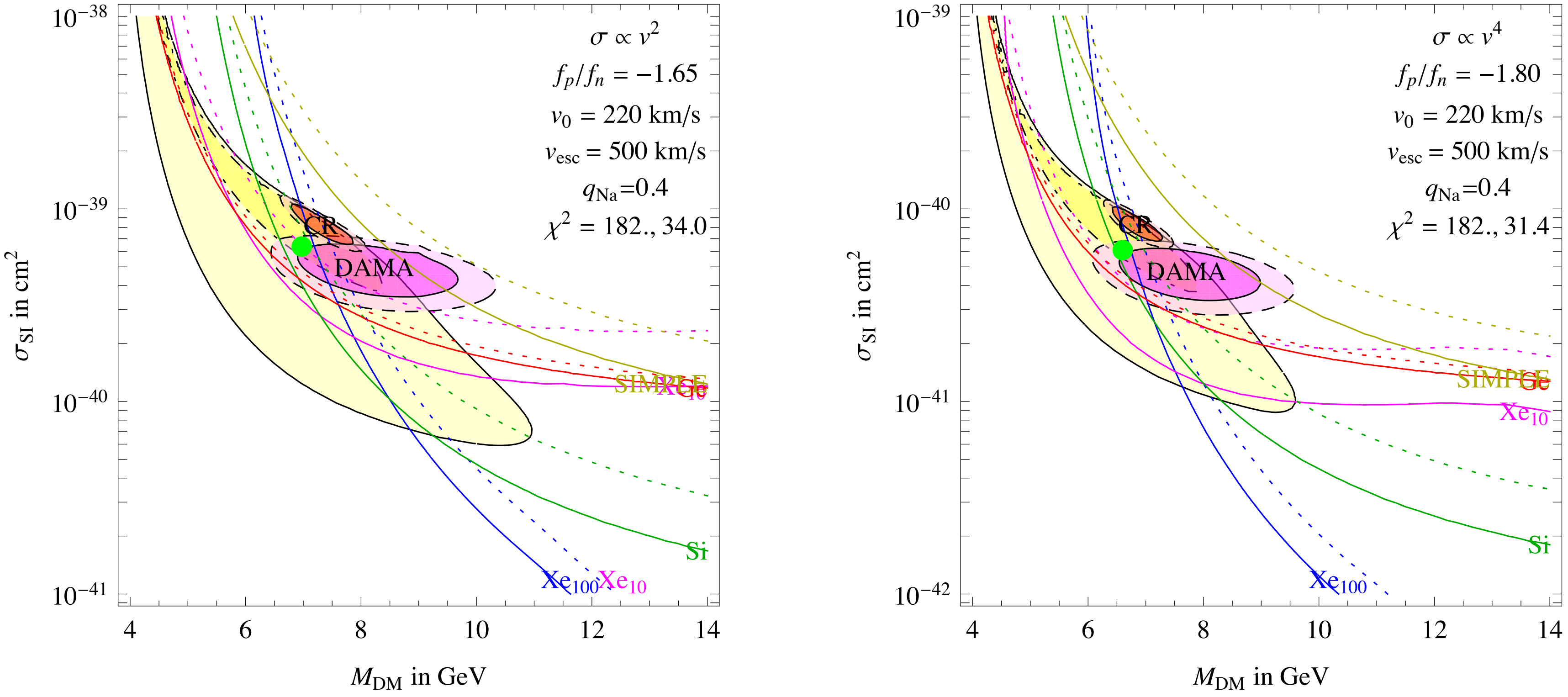
(...)

Inelastic + isospin violation



Farina et al., arXiv:1107.0715

Isospin violating + v dependence



Farina et al., arXiv:1107.0715

Conclusions

- Experimentally, a preference toward light DM (few GeV few tens of GeV) is growing: DAMA, CRESST, CoGeNT
- The impact of bounds from null-experiments (CDMS, XENON) is debated. It might not be easy to improve much on Leff at low energies (critical for light DM)
- If tension between null/positive results stated, it may point toward:
  - Alternative interaction mechanisms
  - Alternative galactic halo modeling

Conclusions

- Some worthwhile developments:
  - Reduce energy threshold in DAMA: recently achieved
  - Address diurnal modulation with DAMA: 1 ton?
  - Increase mass and exposure in COGeNT: (?)
  - Reduce background sources in CRESST: under development

  - Other modulation experiments? ANAIS, DM-ICE, KIMS (?)
  - Directionality

Conclusions

- Theoretically, well motivated models (MSSM, NMSSM, ...) are able to account for light DM (+ many models studied ad hoc)

- The request to explain light DM (correct relic abundance + DD results) singles out specific sectors of parameter space (worthwhile a data-driven model-building approach?)

- Keep open eyes on alternative modelling (inelastic, isospin violation, long-ranges, ...)