23 October 2014
IFAC/Montpellier

New Directions in Direct DM Searches

Paolo Panci

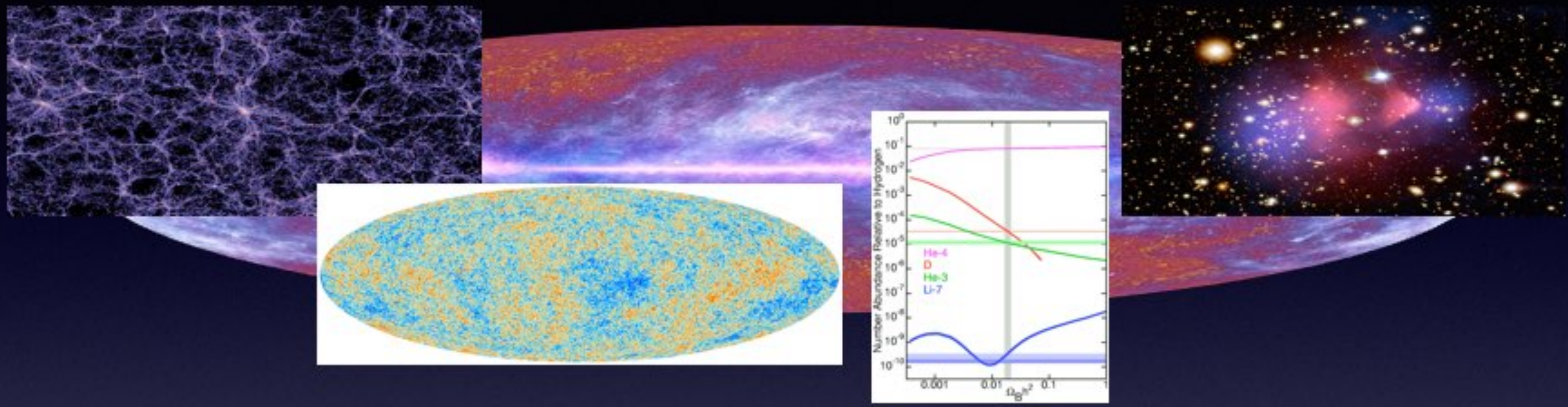
based on:
P. Panci,
Review in Adv.High Energy.Phys. [arXiv: 1402.1507]

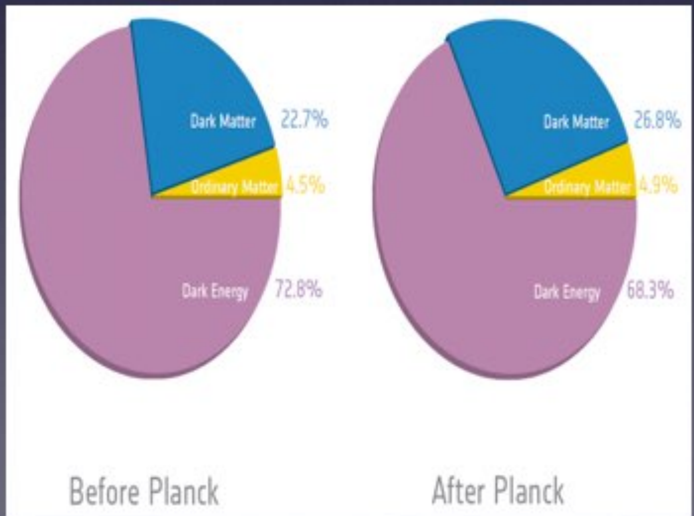
M. Cirelli, E. Del Nobile, P. Panci
JCAP **1310** (2013), **019**, [arXiv: 1307.5955]

and on:
C. Arina, E. Del Nobile, P. Panci,
[arXiv: 1406.5542]

Dark Side: Overview

Precise measurements on CMB, BBN, LSS, etc...





Planck reveals an almost perfect Universe

$$\Omega_{\rm tot} = \Omega_\Lambda + \Omega_{\rm M} + \Omega_{\rm Rad} \simeq 1 \qquad \Omega_{\rm M} = \Omega_{\rm b} + \Omega_{\rm DM}$$

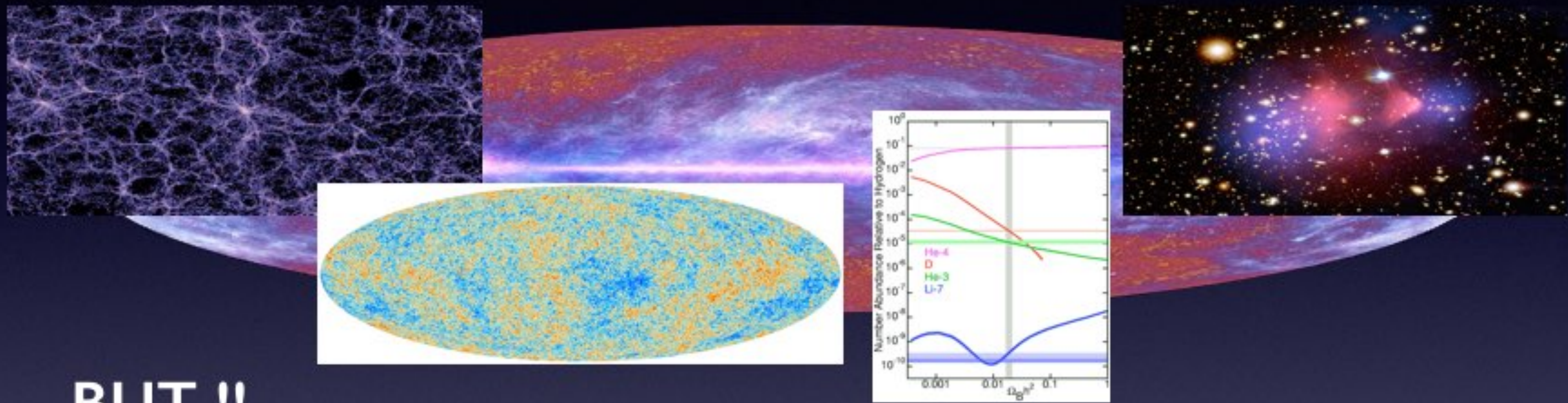
$\Omega_{\rm Rad} \sim 10^{-5}$ $\qquad \Omega_\Lambda \simeq 0.68$

$\Omega_{\rm b} \simeq 0.05$ $\qquad \Omega_{\rm DM} \simeq 0.27$

Dark Sector: $\Omega_{\rm DM} + \Omega_\Lambda = 0.95$

DM Open Questions

There is a compelling and strong evidence of non-baryonic matter in the Universe, ranging from galactic to cosmological scale



BUT !!

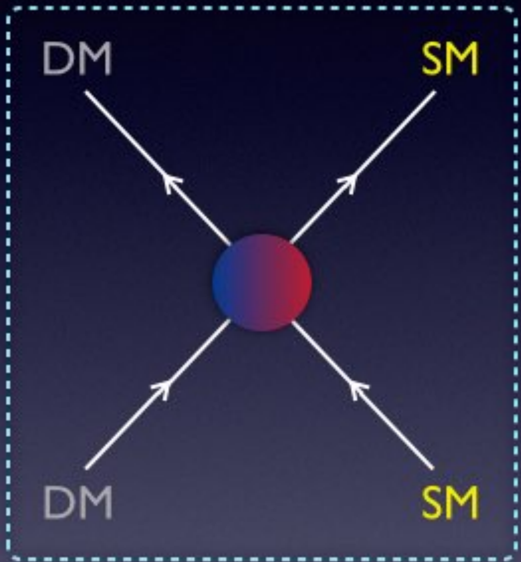
The microphysics of this new kind of matter is unknown yet

- ☑ DM candidate: axions, neutralinos, technicolor particles, wimpzillas, etc...
- ☑ Underlying theory: supersymmetry, technicolor, mirror models, etc...
- ☑ DM density profile: cuspy profile (NFW, Einasto), cored profile (isothermal)
- ☑ Nuclear response of the target nucleus: Helm form factor, etc...

Dark Matter Detection

production at collider

LHC



direct detection

DAMA/Libra, CoGeNT, CRESST.... (Xenon, CDMS, Edelweiss....)

indirect detection

γ from ann/dec in GC or halo and from synchrotron emission

FERMI, radio telescopes....

e^+ from ann/dec in Galactic Center or halo

PAMELA, FERMI, HESS, AMS-II, balloons....

$\bar{p}$ from ann/dec in Galactic Center or halo

PAMELA, AMS-II

$\bar{d}$ from ann/dec in Galactic Center or halo

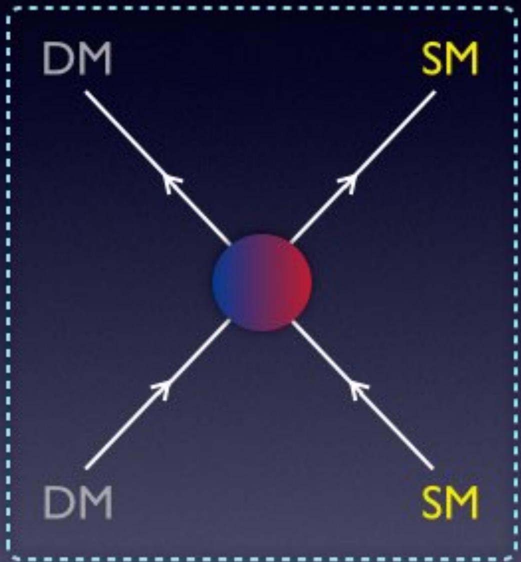
AMS-II, GAPS....

$\bar{\nu}, \nu$ from ann/dec in Galaxy and massive bodies

SuperK, Icecube....

Dark Matter Detection

production at collider
LHC



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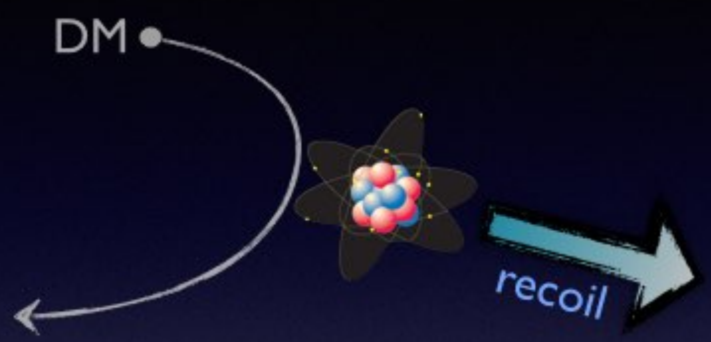
Direct Detection: Overview

Direct searches aim at detecting the nuclear recoil possibly induced by:



- elastic scattering:

$$\chi + \mathcal{N}(A,Z)_{\rm rest} \to \chi + \mathcal{N}(A,Z)_{\rm recoil}$$

- inelastic scattering:

$$\chi + \mathcal{N}(A,Z)_{\rm rest} \to \chi' + \mathcal{N}(A,Z)_{\rm recoil}$$

Direct Detection: Overview

Direct searches aim at detecting the nuclear recoil possibly induced by:

- elastic scattering:
  $\chi + \mathcal{N}(A, Z)_{\text{rest}} \rightarrow \chi + \mathcal{N}(A, Z)_{\text{recoil}}$
- inelastic scattering:
  $\chi + \mathcal{N}(A, Z)_{\text{rest}} \rightarrow \chi' + \mathcal{N}(A, Z)_{\text{recoil}}$

DM signals are very rare events (less then one cpd/kg/keV)

Experimental priorities for DM Direct Detection

- ✔ the detectors must work deeply underground in order to reduce the background of cosmic rays
- ✔ they use active shields and very clean materials against the residual radioactivity in the tunnel (γ, α and neutrons)
- ✔ they must discriminate multiple scattering (DM particles do not scatter twice in the detector)

Direct Detection: Overview

DM local velocity $v_0 \sim 10^{-3}c$ $\Rightarrow$ the collision between $\chi\,\&\,\mathcal{N}$ occurs in deeply non relativistic regime

$$E_R = \underbrace{\frac{1}{2}m_\chi v^2}_{\text{DM kinetic energy}} \underbrace{\frac{4m_\chi m_\mathcal{N}}{(m_\chi + m_\mathcal{N})^2}}_{\text{Kinematics factor}} \left(\frac{1 - \frac{v_t^2}{2v^2} - \sqrt{1 - \frac{v_t^2}{v^2}}\cos\underbrace{\theta}_{\text{scatter angle}}}{2}\right), \quad \begin{cases} v_t = 0 & \text{elastic} \\ \underbrace{v_t}_{\text{threshold velocity}} = \sqrt{\frac{2\delta}{\mu_{\chi\mathcal{N}}}} \neq 0 & \text{inelastic} \end{cases}$$

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Theoretical differential rate of nuclear recoil in a given detector

$$\frac{\mathrm{d}R_{\mathcal{N}}}{\mathrm{d}E_{\rm R}} = N_{\mathcal{N}} \frac{\rho_\odot}{m_\chi} \int_{v_{\rm min}(E_{\rm R})}^{v_{\rm esc}} \mathrm{d}^3 v \, |\vec{v}| \, f(\vec{v}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\rm R}}$$

- ☑ $N_{\mathcal{N}} = N_a / A_{\mathcal{N}}$: Number of target
- ☑ $v_{\rm min}(E_{\rm R}) = \sqrt{\frac{m_{\mathcal{N}} E_{\rm R}}{2\,\mu_{\chi\mathcal{N}}^2}} \left(1 + \frac{\mu_{\chi\mathcal{N}}\,\delta}{m_{\mathcal{N}} E_{\rm R}}\right)$: Minimal velocity
- ☑ $\rho_\odot / m_\chi$: DM number density
- ☑ $v_{\rm esc}$: DM escape velocity (450 - 650 km/s)

DM Velocity Distribution

"Violent relaxation" lead to fast mixing of the DM phase-space elements
DM particles are frozen in high entropy configuration: ~ Maxwell-Boltzmann-like

"Statistical Mechanics of Violent Relaxation in Stellar System", Mon.Not.Roy.Astrom.Soc. (1966) **136**, 101

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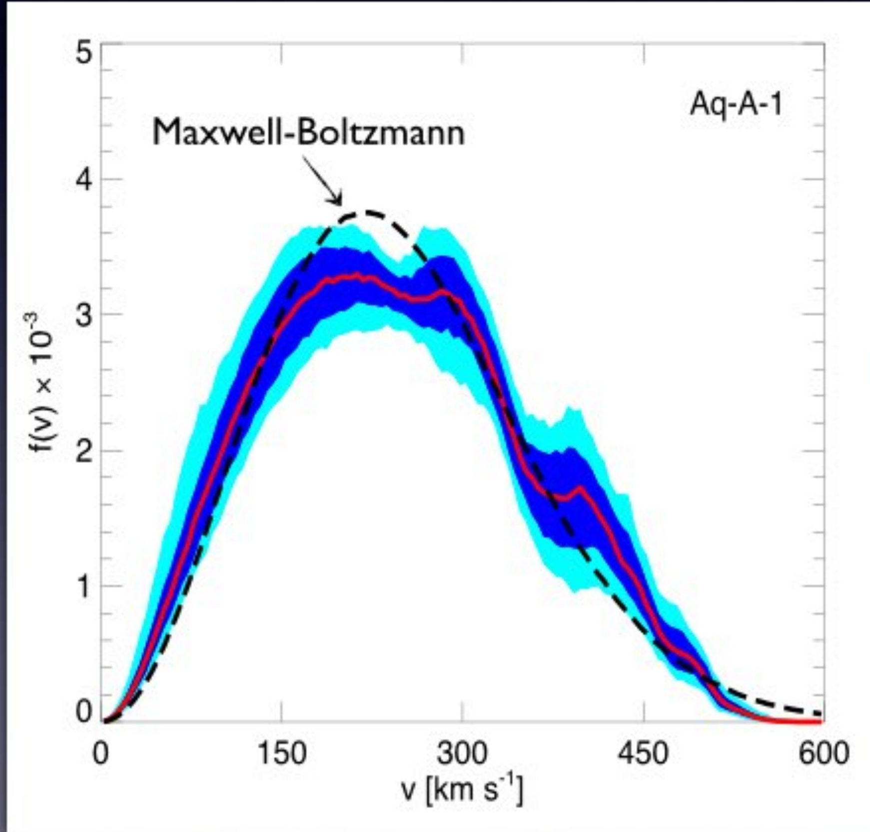
Recent Numerical Simulations

- ☑ This has been roughly confirmed by some numerical simulations
- ☑ There are deviations due to the DM assembly history of the Milky Way
- ☑ The geometry of the halo is not exactly spherical, but tends to a triaxial configuration



"Phase Space Structure in the Local DM Distribution", Mon.Not.Roy.Astrom.Soc. (2009) **395**, 797

DM Velocity Distribution

The velocity distribution (VD) in the Earth frame $f_\oplus$ is related to the VD in the Galactic frame $f_{\rm gal}$ through a Galileian transformation

$$f_\oplus(\vec{v},t) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t))$$

velocity distribution in the Earth's frame

$$f_{\rm gal}(\vec{v}) = \begin{cases} k \exp\left(-\frac{v^2}{v_0^2}\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

e.g: Maxwell-Boltzmann distribution

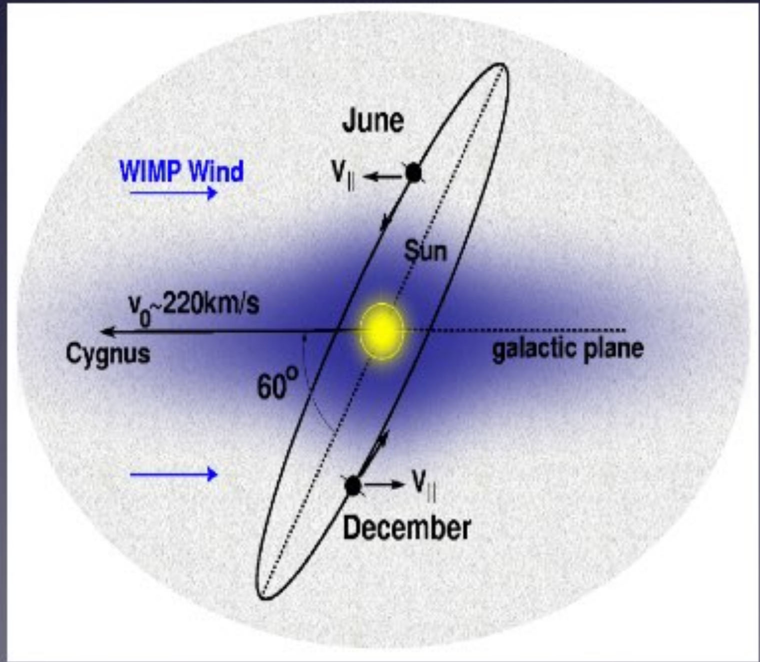
The Earth is moving around the Sun and the Sun around the GC

$$\vec{v}_{\rm obs}(t) = \underbrace{\vec{v}_\odot}_{\text{drift velocity of the Sun}} + \underbrace{v_\oplus\left[\vec{\varepsilon}_1 \cos w(t-t_1) + \vec{\varepsilon}_2 \sin w(t-t_1)\right]}_{\text{time dependent Earth's velocity projected in the GP}}$$

$$\vec{v}_\odot \simeq (0,220,0) + (10,13,7)\ \mathrm{km/s}$$
$$v_\oplus \simeq 29.8\ \mathrm{km/s}$$

$$|\vec{v}_\oplus| / |\vec{v}_\odot| \simeq 0.05$$

$$\vec{\varepsilon}_1 \simeq (0.9931, 0.1170, -0.0103) \qquad t_1 \simeq 21^{\rm st}\ \mathrm{March}$$
$$\vec{\varepsilon}_2 \simeq (-0.0670, 0.4927, -0.8676) \qquad w = 2\pi/\mathrm{year}$$



Looking for annual modulation is very challenge from the exp. point of view

Differential Cross Section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}}(v, E_{\mathrm{R}}) = \frac{1}{32\pi}\frac{1}{m_\chi^2 m_{\mathcal{N}}}\frac{1}{v^2}\boxed{|\mathcal{M}_{\mathcal{N}}|^2} \longrightarrow$$ Matrix Element (ME) for the DM-nucleus scattering

$v \ll c$ $\Rightarrow$ the framework of relativistic quantum field theory is not appropriate

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Non relativistic (NR) operators framework

NR d.o.f. for elastic scattering

- $\vec{v}$: DM-nucleon relative velocity
- $\vec{q}$: exchanged momentum
- $\vec{s}_N$: nucleon spin ($N = (p, n)$)
- $\vec{s}_\chi$: DM spin

The DM-nucleon ME can be constructed from Galileian invariant combination of d.o.f.

$$|\mathcal{M}_N| = \sum_{i=1}^{12} \boxed{\mathfrak{c}_i^N(\lambda, m_\chi)} \, \mathcal{O}_i^{\mathrm{NR}}$$

functions of the parameters of your favorite theory (e.g. couplings, mixing angles, mediator masses), expressed in terms of NR operators

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Contact interaction (q << Λ)

$$\mathcal{O}_1^{\rm NR} = \mathbb{1}\,,$$
$$\mathcal{O}_3^{\rm NR} = i\,\vec{s}_N \cdot (\vec{q} \times \vec{v}^\perp)\,, \quad \mathcal{O}_4^{\rm NR} = \vec{s}_\chi \cdot \vec{s}_N\,,$$
$$\mathcal{O}_5^{\rm NR} = i\,\vec{s}_\chi \cdot (\vec{q} \times \vec{v}^\perp)\,, \quad \mathcal{O}_6^{\rm NR} = (\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q})\,,$$
$$\mathcal{O}_7^{\rm NR} = \vec{s}_N \cdot \vec{v}^\perp\,, \quad \mathcal{O}_8^{\rm NR} = \vec{s}_\chi \cdot \vec{v}^\perp\,,$$
$$\mathcal{O}_9^{\rm NR} = i\,\vec{s}_\chi \cdot (\vec{s}_N \times \vec{q})\,, \quad \mathcal{O}_{10}^{\rm NR} = i\,\vec{s}_N \cdot \vec{q}\,,$$
$$\mathcal{O}_{11}^{\rm NR} = i\,\vec{s}_\chi \cdot \vec{q}\,, \quad \mathcal{O}_{12}^{\rm NR} = \vec{v}^\perp \cdot (\vec{s}_\chi \times \vec{s}_N)\,.$$

Long-range interaction (q >> Λ)

$$\mathcal{O}_1^{\rm lr} = \frac{1}{q^2}\mathcal{O}_1^{\rm NR}\,, \quad \mathcal{O}_5^{\rm lr} = \frac{1}{q^2}\mathcal{O}_5^{\rm NR}\,,$$
$$\mathcal{O}_6^{\rm lr} = \frac{1}{q^2}\mathcal{O}_6^{\rm NR}\,, \quad \mathcal{O}_{11}^{\rm lr} = \frac{1}{q^2}\mathcal{O}_{11}^{\rm NR}\,.$$

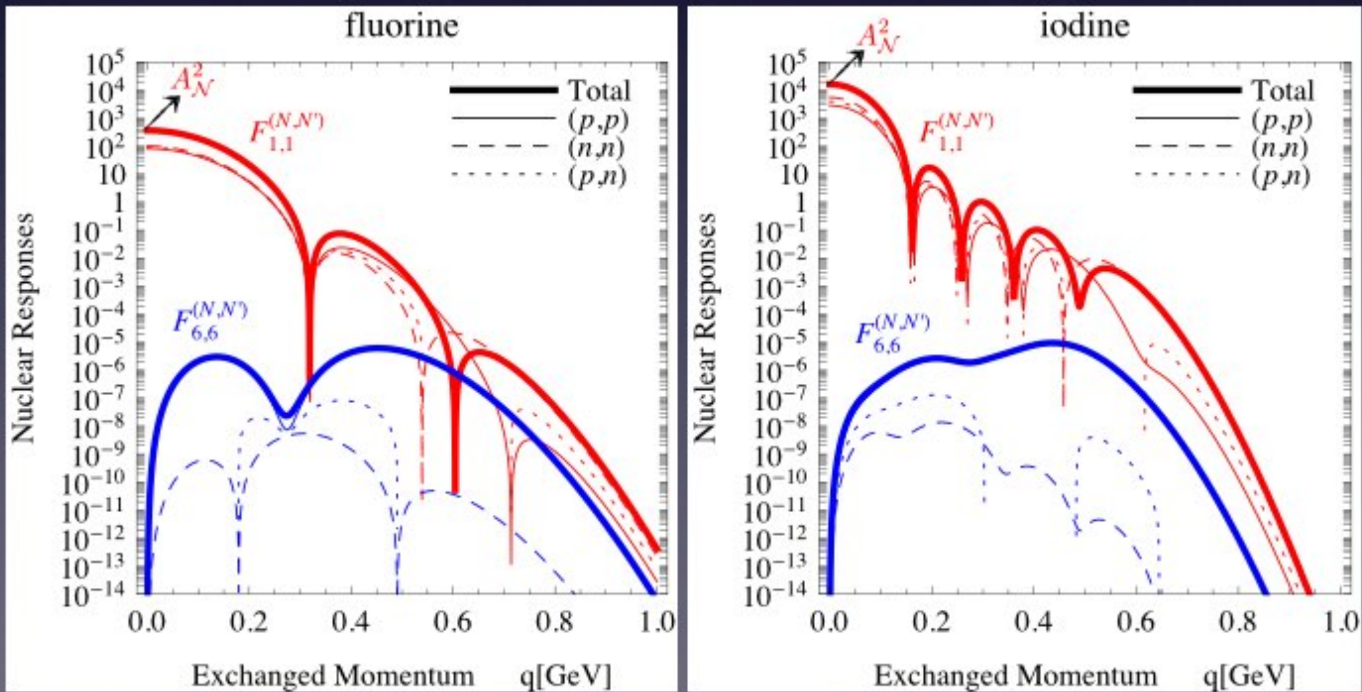
Differential Cross Section

Nucleus is not point-like

There are different Nuclear Responses for any pairs of nucleons & any pairs of NR Operators

$$|\mathcal{M}_{\mathcal{N}}|^2 = \frac{m_{\mathcal{N}}^2}{m_N^2} \underbrace{\sum_{i,j=1}^{12}}_{\text{pairs of NR operators}} \underbrace{\sum_{N,N'=p,n}}_{\text{pairs of nucleons}} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} \underbrace{F_{i,j}^{(N,N')}(v,q^2)}_{\text{Nuclear response of the target nuclei}}$$

Nuclear responses for some common target nuclei in Direct Searches



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$\mathcal{O}_1^{NR} = \mathbb{1}$,

$\mathcal{O}_3^{NR} = i\,\vec{s}_N \cdot (\vec{q} \times \vec{v}^\perp)$, $\mathcal{O}_4^{NR} = \vec{s}_\chi \cdot \vec{s}_N$,

$\mathcal{O}_5^{NR} = i\,\vec{s}_\chi \cdot (\vec{q} \times \vec{v}^\perp)$, $\mathcal{O}_6^{NR} = (\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q})$,

$\mathcal{O}_7^{NR} = \vec{s}_N \cdot \vec{v}^\perp$, $\mathcal{O}_8^{NR} = \vec{s}_\chi \cdot \vec{v}^\perp$,

$\mathcal{O}_9^{NR} = i\,\vec{s}_\chi \cdot (\vec{s}_N \times \vec{q})$, $\mathcal{O}_{10}^{NR} = i\,\vec{s}_N \cdot \vec{q}$,

$\mathcal{O}_{11}^{NR} = i\,\vec{s}_\chi \cdot \vec{q}$, $\mathcal{O}_{12}^{NR} = \vec{v}^\perp \cdot (\vec{s}_\chi \times \vec{s}_N)$.

Long-Range interaction (q >> Λ)

$$\mathcal{O}_1^{lr} = \frac{1}{q^2}\mathcal{O}_1^{NR}, \quad \mathcal{O}_5^{lr} = \frac{1}{q^2}\mathcal{O}_5^{NR},$$

$$\mathcal{O}_6^{lr} = \frac{1}{q^2}\mathcal{O}_6^{NR}, \quad \mathcal{O}_{11}^{lr} = \frac{1}{q^2}\mathcal{O}_{11}^{NR}.$$

"The Effective Field Theory of Dark Matter Direct Detection", JCAP **1302** (2013) 004

Rate of Nuclear Recoil

$$\frac{\mathrm{d}R_{\mathcal{N}}}{\mathrm{d}E_{\mathrm{R}}} = N_{\mathcal{N}} \frac{\rho_{\odot}}{m_{\chi}} \frac{1}{32\pi} \frac{m_{\mathcal{N}}}{m_{\chi}^2 m_N^2} \sum_{i,j=1}^{12} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} \int_{v_{\min}(E_{\mathrm{R}})}^{v_{\mathrm{esc}}} \mathrm{d}^3 v \frac{1}{v} f_{\oplus}(v)\, F_{i,j}^{(N,N')}(v, q^2)$$

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"Standard" Spin Independent (SI) Interaction

Effective Lagrangian

$$\mathcal{L}_{\mathrm{SI}}^N = \lambda_{\mathrm{SI}}^N \cdot \bar{\chi}\chi\, \bar{N}N$$

free parameter expressed in $[1/\mathrm{GeV}^2]$

DM-nucleon Matrix Element in the NR limit

$$\left|\mathcal{M}_{\mathrm{SI}}^N\right| = {}_{\mathrm{out}}\langle N, \chi |\, \mathcal{L}_{\mathrm{SI}}^N \,| N, \chi \rangle_{\mathrm{in}} = \underbrace{4\,\lambda_{\mathrm{SI}}^N m_\chi m_N}_{\mathfrak{c}_1^N} \underbrace{\mathbf{1}}_{\mathcal{O}_1^{\mathrm{NR}}}$$

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Rate of nuclear recoil for the SI Interaction

$$\frac{\mathrm{d}R_{\mathcal{N}}}{\mathrm{d}E_{\mathrm{R}}} = N_{\mathcal{N}} \frac{\rho_{\odot}}{m_{\chi}} \frac{m_{\mathcal{N}}}{2\mu_{\chi p}^2} \sigma_{\mathrm{SI}}^{p} \mathcal{I}(E_{\mathrm{R}}) \sum_{N,N'=p,n} F_{1,1}^{(N,N')}(q^2)$$

Total DM-nucleon Cross Section:

$$\sigma_{\mathrm{SI}}^{p} = \frac{\lambda_{\mathrm{SI}}^2}{\pi} \mu_{\chi p}^2$$

with $\lambda_{\mathrm{SI}} \equiv \lambda_{\mathrm{SI}}^{p} = \lambda_{\mathrm{SI}}^{n}$

"Standard" velocity integral:

$$\mathcal{I}(E_{\mathrm{R}}) = \int_{v_{\min}(E_{\mathrm{R}})}^{v_{\mathrm{esc}}} \mathrm{d}^3 v \, \frac{1}{v} f_{\oplus}(v)$$

Customary Helm Form Factor:

$$\simeq A_{\mathcal{N}}^2 \, F_{\mathrm{Helm}}^2(q^2)$$

Rate of Nuclear Recoil

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Comparison with the Experimental data

exposure

$$N_k^{\mathrm{th}} = w_k \int_{\Delta E_k} \mathrm{d}E_{\mathrm{det}}\, \epsilon(E_{\mathrm{det}}) \int_0^\infty \mathrm{d}E_{\mathrm{R}} \underbrace{\sum}_{\mathcal{N}=\mathrm{Nucleus}} \mathcal{K}_{\mathcal{N}}(q_{\mathcal{N}} E_{\mathrm{R}}, E_{\mathrm{det}}) \frac{\mathrm{d}R_{\mathcal{N}}}{\mathrm{d}E_{\mathrm{R}}}(E_{\mathrm{R}})$$

takes into account the response and energy resolution of the detector

runs over the different species in the detector (e.g. DAMA and CRESST are multiple-target)

quenching factor: accounts for the partial recollection of the released energy

Rate of Nuclear Recoil

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Uncertainties in Direct DM Searches

- ☑ Local DM energy Density & Geometry of the Halo (e.g: spherically symmetric halos with isotropic or not velocity dispersion, triaxial models, co-rotating dark disk and so on......)
- ☑ Nature of the interaction & Nuclear Responses (e.g: SI & SD scattering, long-range or point like character of the interaction and so on......)
- ☑ Experimental uncertainties (e.g: detection efficiency close to the lower threshold, energy dependence of the quenching factors, channeling in crystals and so on......)

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Comparison with the Experimental data

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takes into account the response and energy resolution of the detector

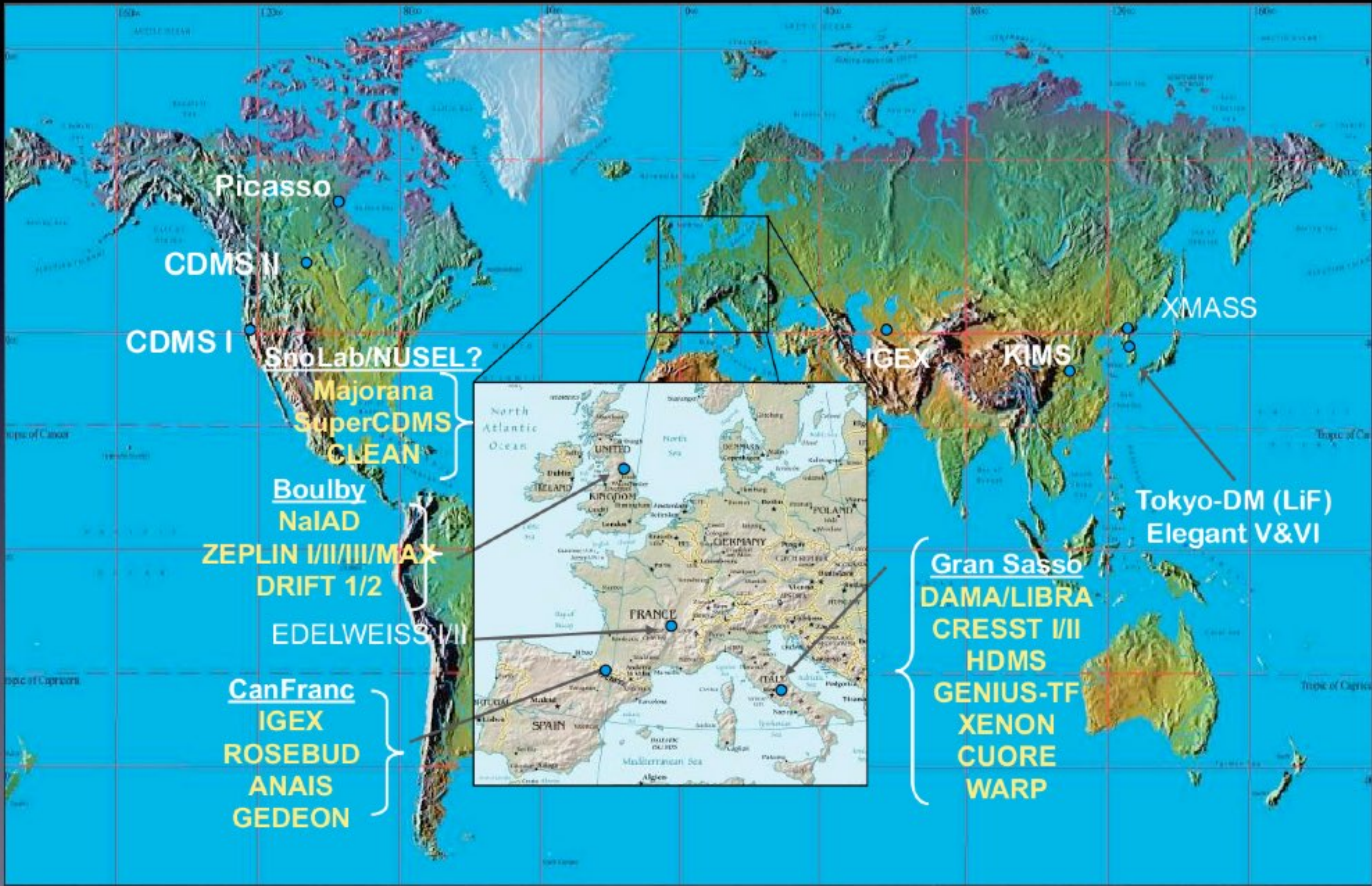
runs over the different species in the detector (e.g. DAMA and CRESST are multiple-target)

quenching factor: accounts for the partial recollection of the released energy

Uncertainties in Direct DM Searches

- Local DM energy Density & Geometry of the Halo (e.g: spherically symmetric halos with isotropic or not velocity dispersion, triaxial models, co-rotating dark disk and so on......)
- Nature of the interaction & Nuclear Responses (e.g: SI & SD scattering, long-range or point like character of the interaction and so on......)
- Experimental uncertainties (e.g: detection efficiency close to the lower threshold, energy dependence of the quenching factors, channeling in crystals and so on......)

World Wide DM Searches



World Wide DM Searches

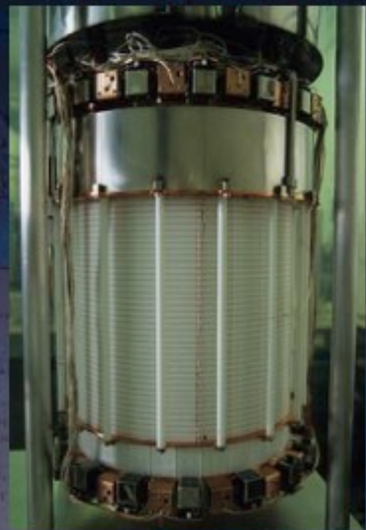
no discrimination between EM and nuclear recoil signals

DAMA

CoGeNT

discrimination between EM and nuclear recoil signals

XENON

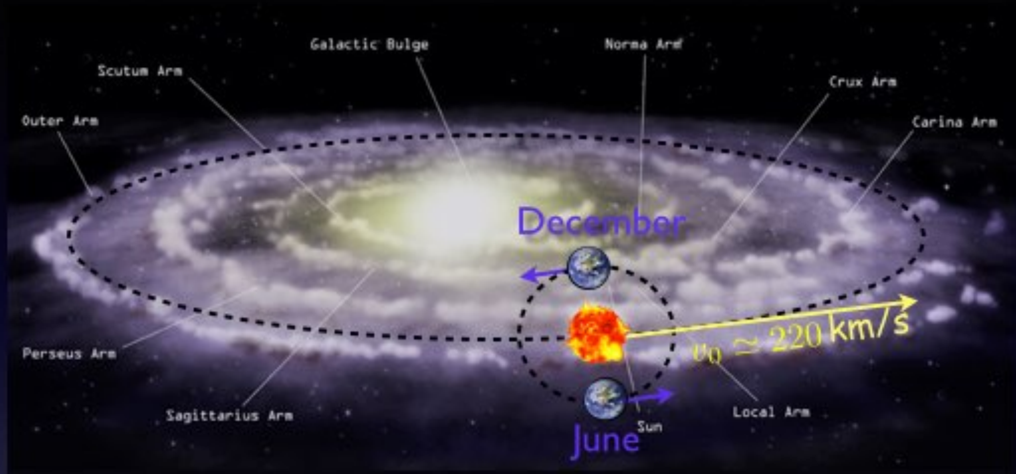


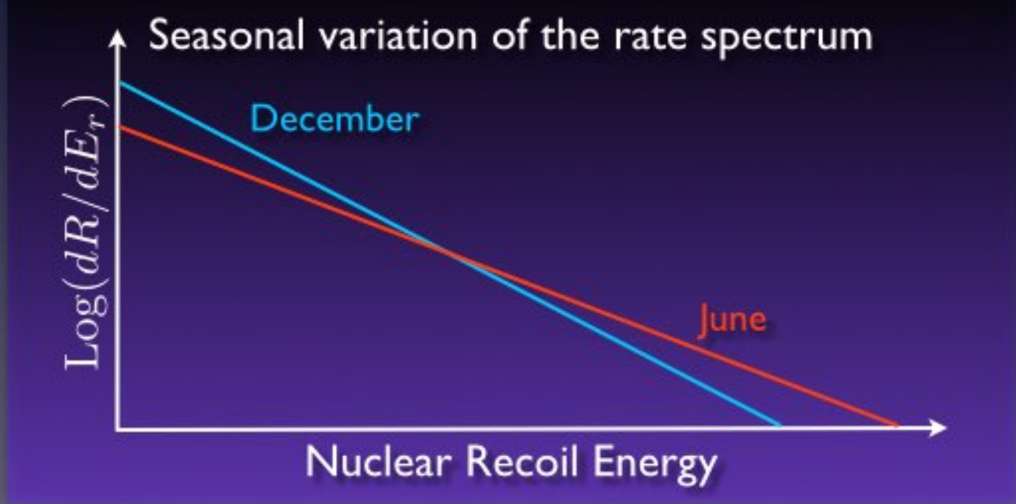
CDMS

CRESST

Model Independent Signature

- if DM exists we expect annual modulation
- DAMA and CoGeNT do not distinguish between EM and nuclear recoil signals, but infer DM from annual modulation





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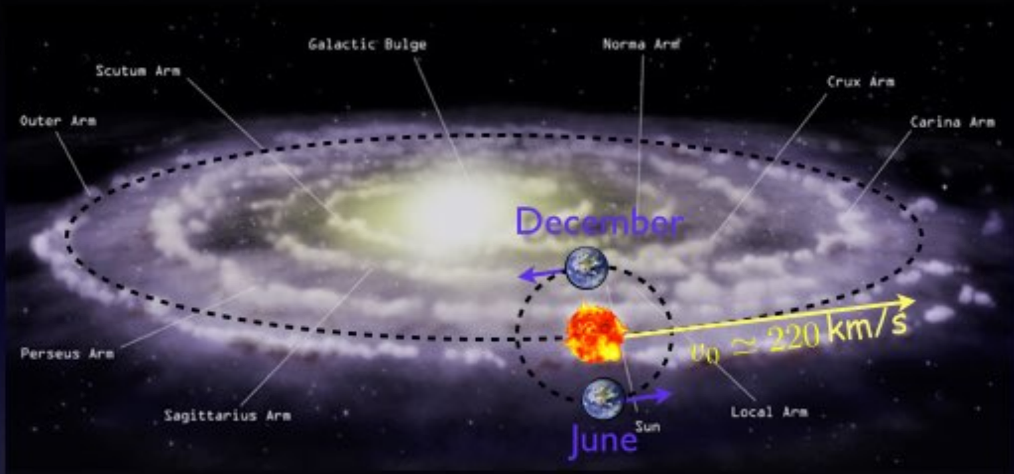
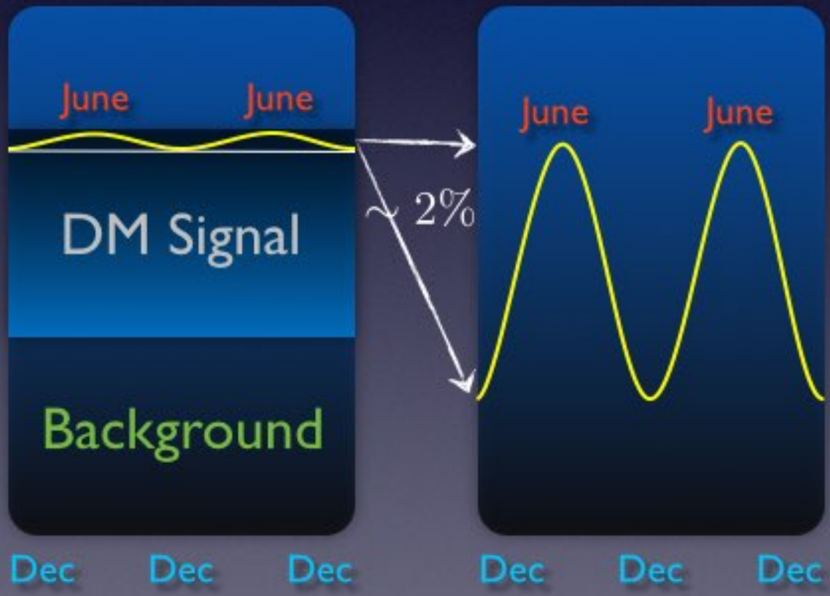
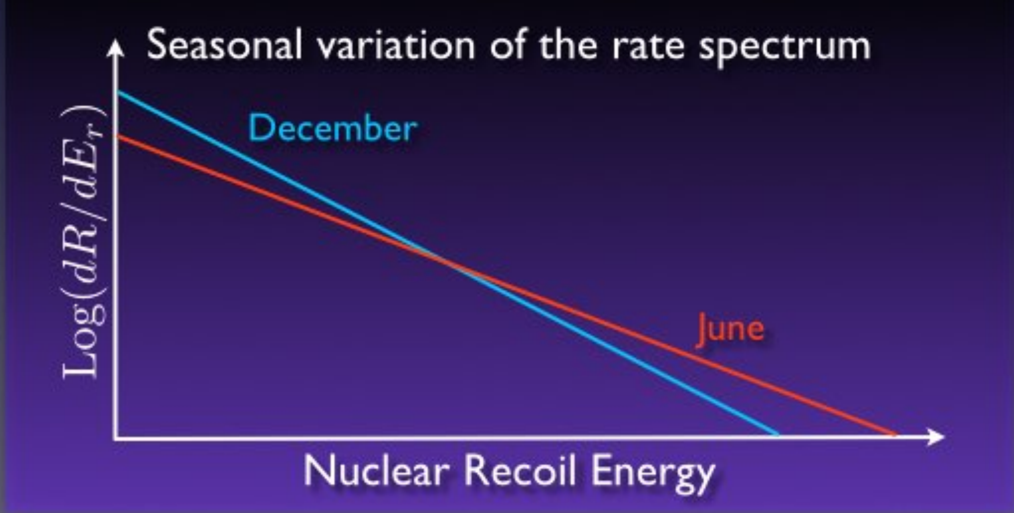


MODULATION

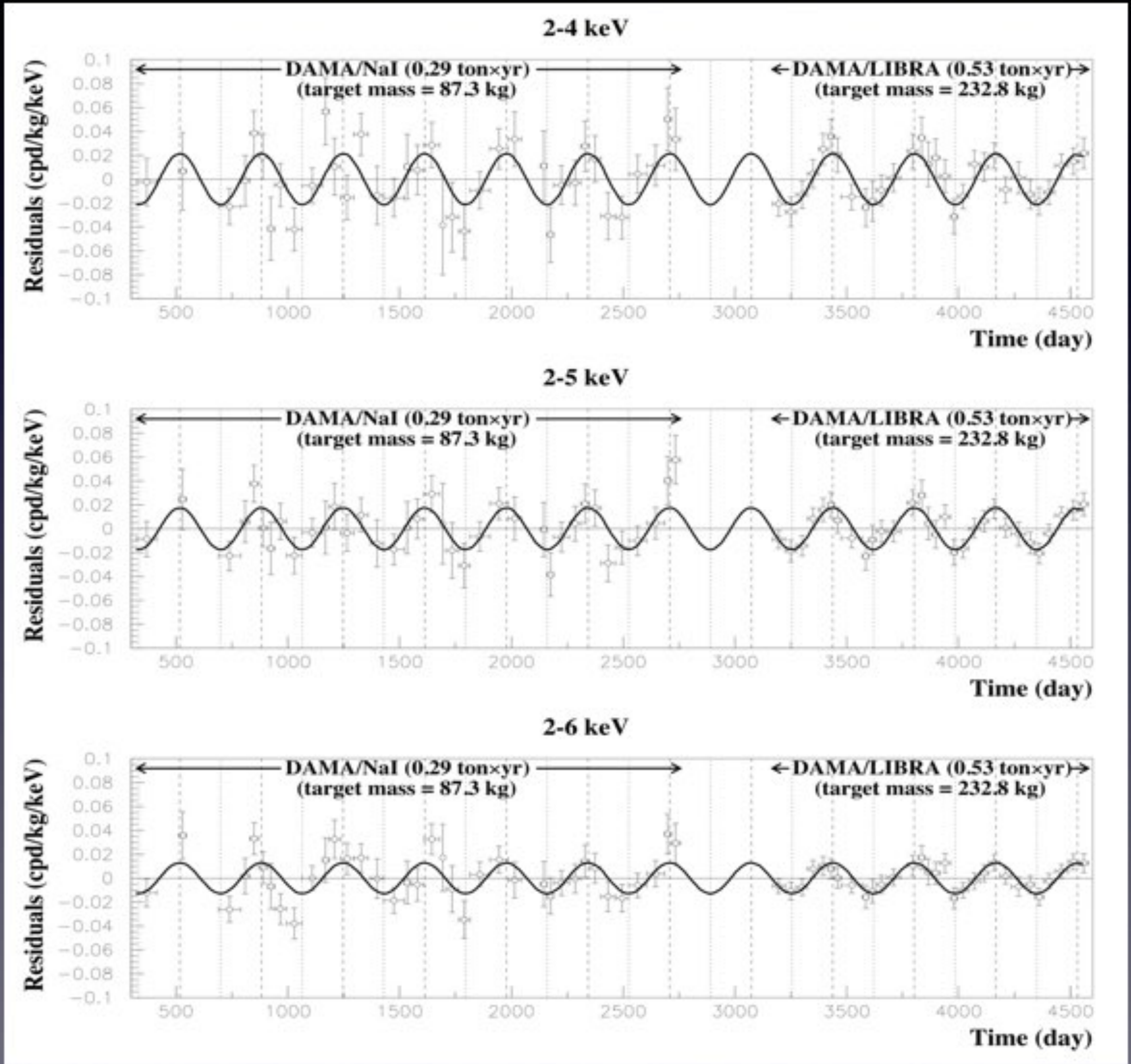




- DAMA and CoGeNT look for the small annual modulation of the sum of the DM signal and the background

DAMA: Results

A clear annual modulation over the course of many years is present !!



Fitted with: $S_m \cos(t/\tau + \phi)$

2-4 keV energy bin

$S_m = 0.0223 \pm 0.0027$ cpd/kg/keV

$\tau = 0.996 \pm 0.002$ year

$\phi = 138 \pm 7$ days $\simeq 2^{nd}$ June

with significance 8.3 σ CL

2-5 keV energy bin

$S_m = 0.0178 \pm 0.0020$ cpd/kg/keV

$\tau = 0.998 \pm 0.002$ year

$\phi = 145 \pm 7$ days $\simeq 2^{nd}$ June

with significance 8.9 σ CL

2-6 keV energy bin

$S_m = 0.0131 \pm 0.0016$ cpd/kg/keV

$\tau = 0.998 \pm 0.003$ year

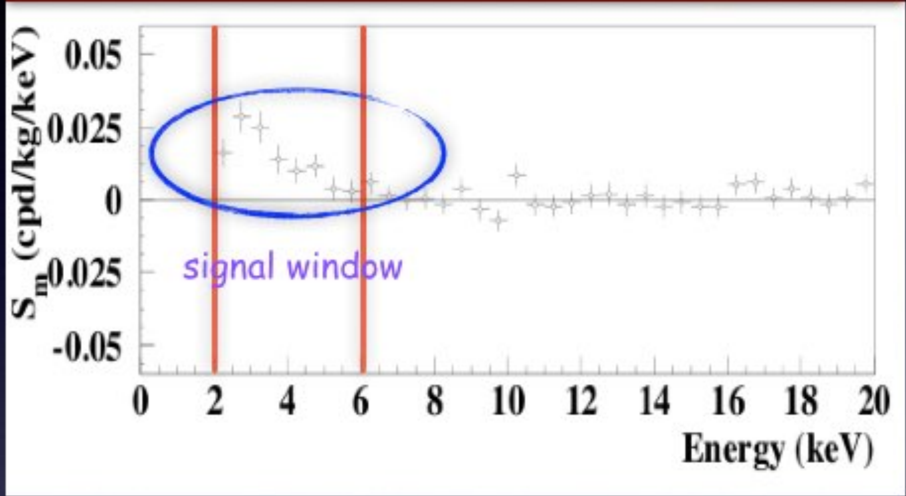
$\phi = 144 \pm 8$ days $\simeq 2^{nd}$ June

with significance 8.2 σ CL

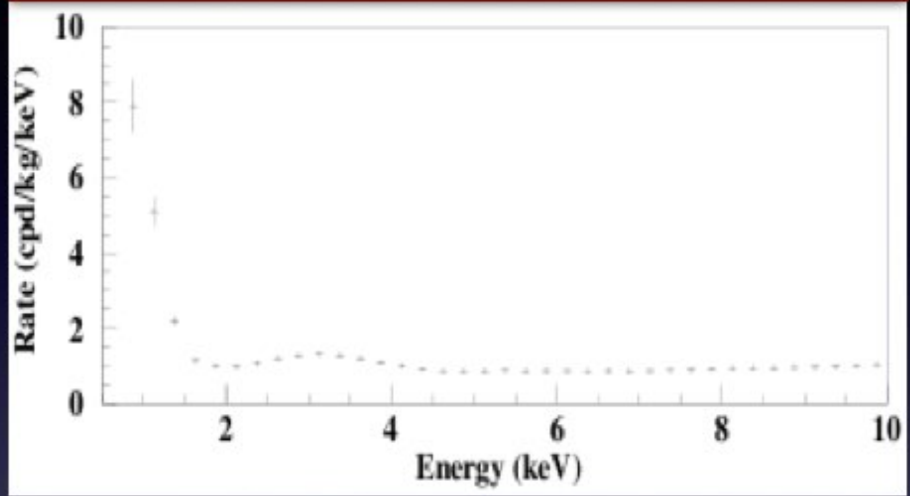
"First results from the DAMA/LIBRA experiments", Eur.Phys.J. **C56** (2008) 333

DAMA: Results

Spectrum of the modulated signal



Spectrum of the total rate

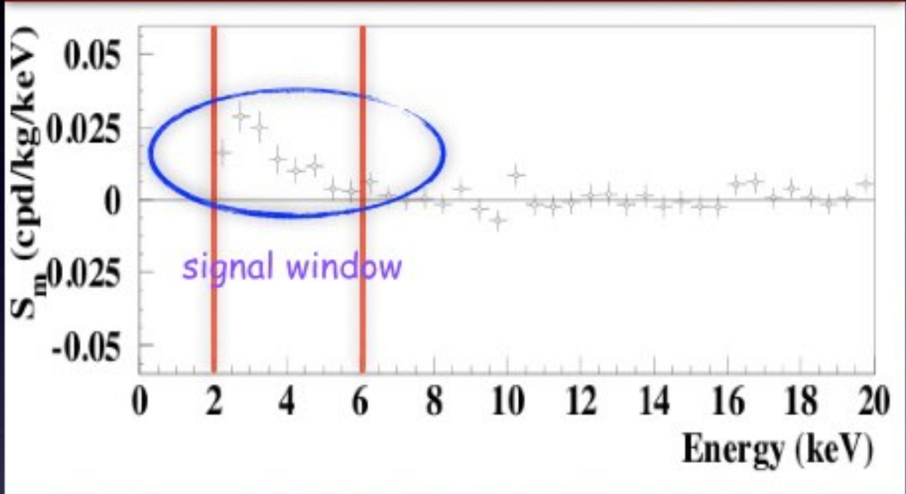


"First results from the DAMA/LIBRA experiments", Eur.Phys.J. **C56** (2008) 333

Bottom line: the modulation is only visible at low energy (from 2 to 6 keVee)

DAMA: Results

Spectrum of the modulated signal



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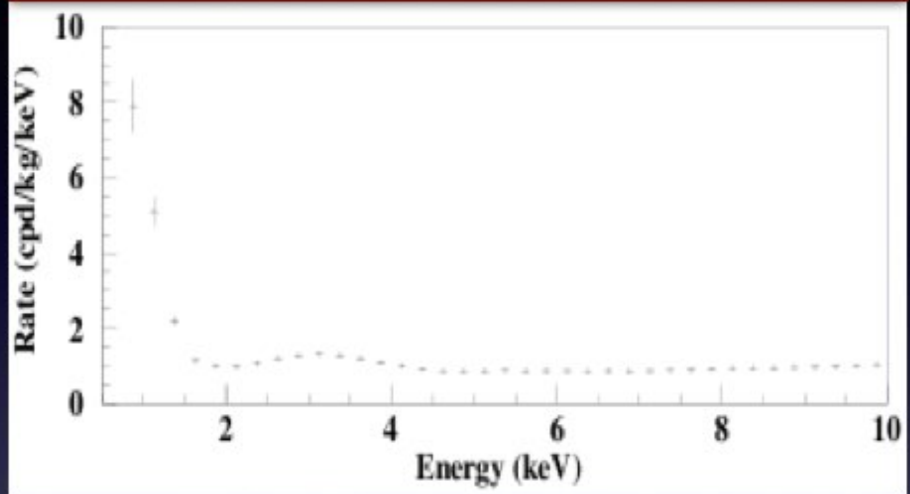


"First results from the DAMA/LIBRA experiments", Eur.Phys.J. **C56** (2008) 333

Bottom line: the modulation is only visible at low energy (from 2 to 6 keVee)

Comparison with the DAMA datasets

- one has to compare the theoretical modulated signal with the experimental one in the energy bins of interest, without exceed the total rate

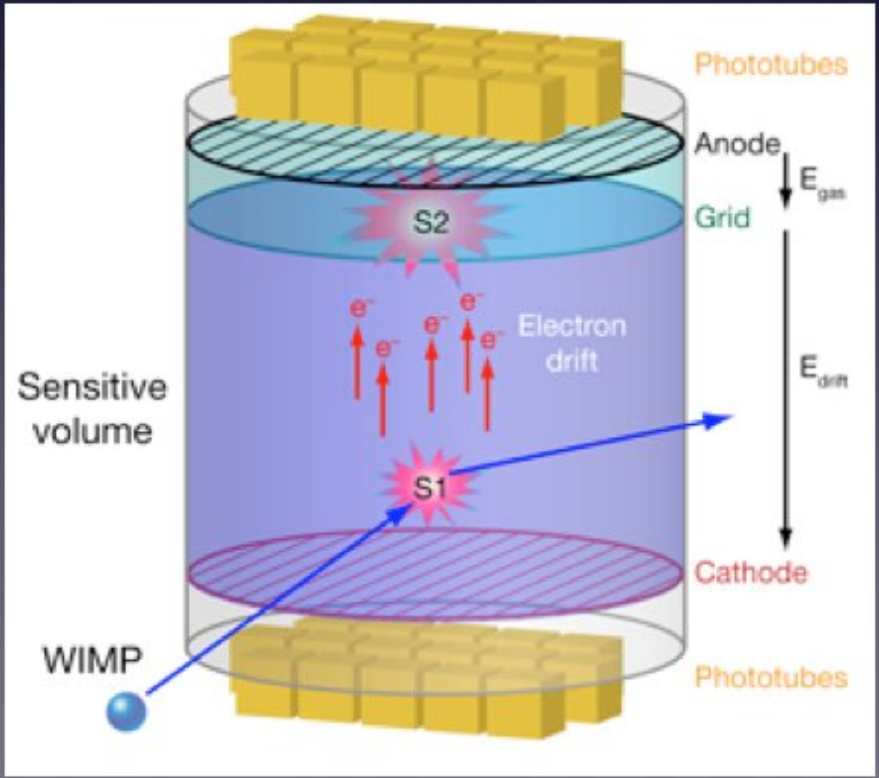
Xenon Experiments

- Nuclear Recoil: $S_{\rm liq} \gg S_{\rm gas}$

the density of ionization is very high, mostly of the ionized electrons promptly recombine, without drift in the gas phase, producing in the liquid the majority of the signal

- Electron Recoil: $S_{\rm liq} \ll S_{\rm gas}$

the density of ionization is very poor, the ionized electrons can drift in the gas phase producing there a scintillation signal



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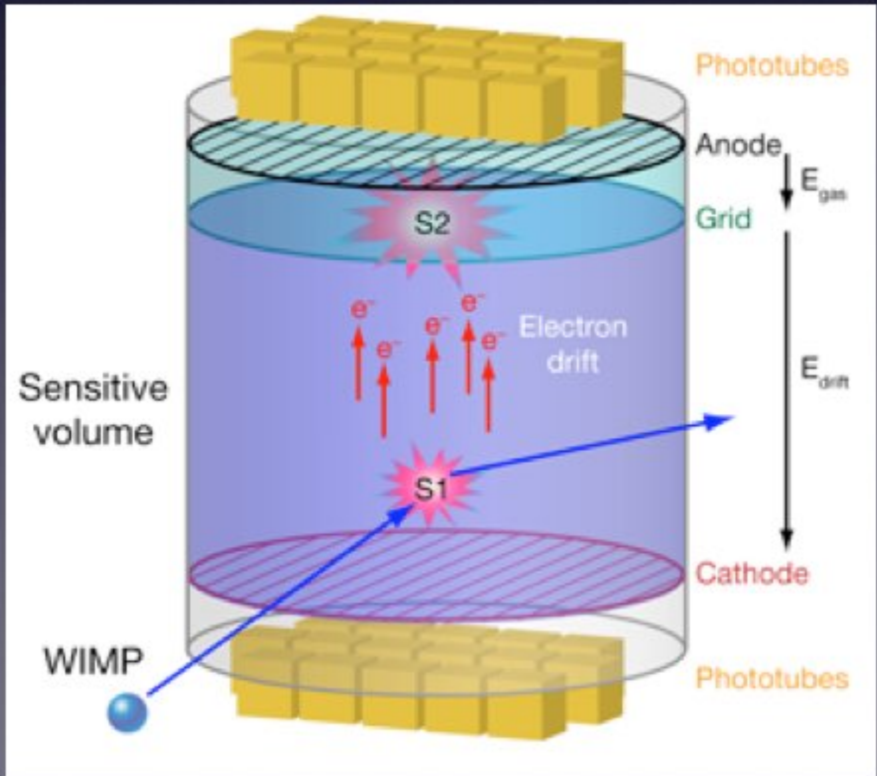
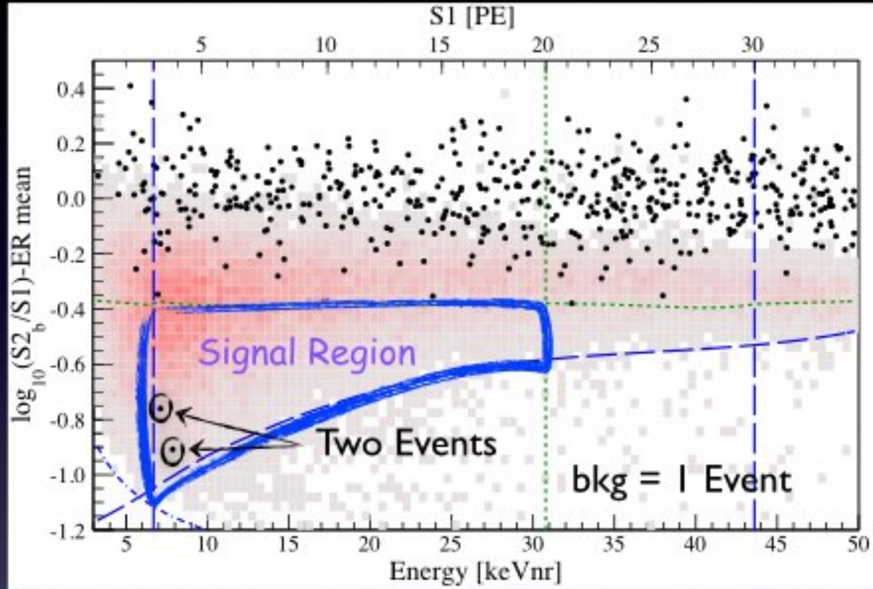
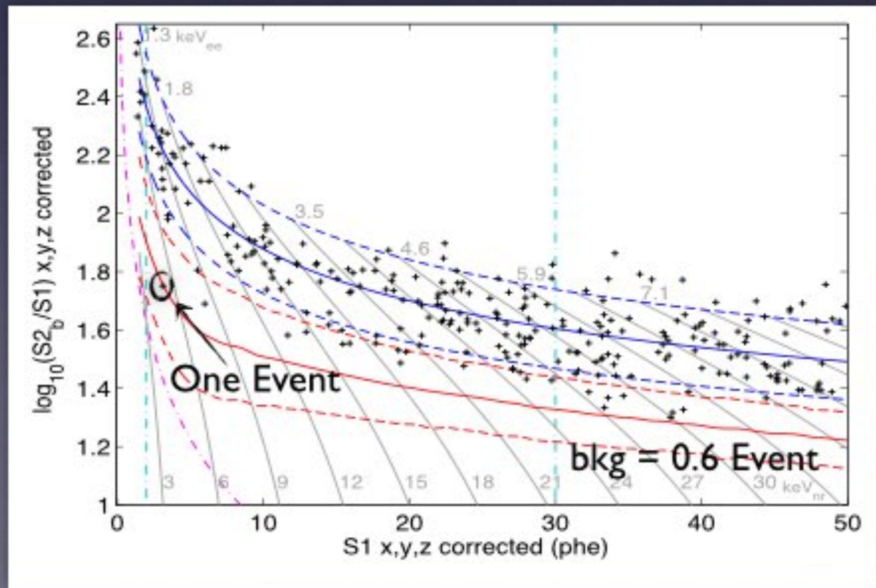


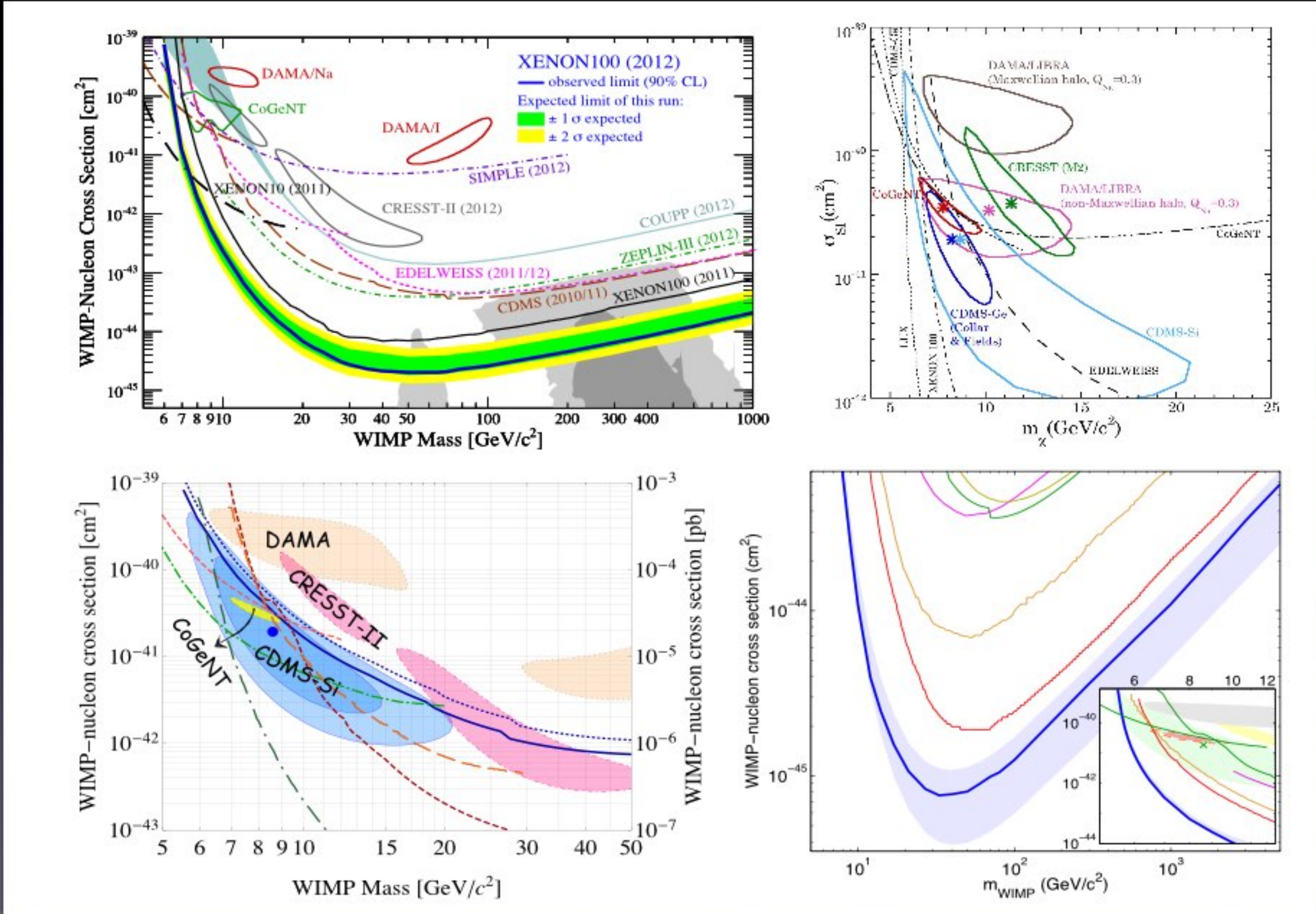


Phys.Rev.Lett. 109 (2012) 18130



LUX results; arXiv: 1310.8214

SI interaction: Current Status



I° Part: Model Independent

Model Independent Bounds in Direct DM Searches

- I'm going to present a new framework for "scaling" a bound given on a certain benchmark interaction to any other kinds of interactions
- For example the model dependent bounds presented by the experimental collaborations can also be applied to other class of models

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Particle physics part

Model independent part

$$N_k^{\rm th}(\lambda, m_\chi) = X \underbrace{\sum_{i,j=1}^{12} \sum_{N,N'=p,n} \mathfrak{c}_i^N(\lambda, m_\chi)\mathfrak{c}_j^{N'}(\lambda, m_\chi)}_{\text{Particle physics part}} \tilde{\mathcal{F}}_{i,j}^{(N,N')}(m_\chi, k)$$

linear combination of integrated form factors

$$X = \frac{\rho_\odot}{m_\chi}\frac{1}{32\pi}\frac{1}{m_\chi^2 m_N^2}$$

$$\tilde{\mathcal{F}}_{i,j}^{(N,N')}(m_\chi, k) = w_k \sum_{\mathcal{N}=\text{Nucleus}} N_\mathcal{N} m_\mathcal{N} \int_{\Delta E_k} \mathrm{d}E_{\rm det}\, \epsilon(E_{\rm det}) \int \mathrm{d}E'\, \mathcal{K}(E_{\rm det}, E') \int_{v_{\rm min}\left(\frac{E'}{q_\mathcal{N}}\right)}^{v_{\rm esc}} \mathrm{d}^3 v \frac{1}{v} f_\oplus(v) F_{i,j}^{(N,N')}(v, q^2)$$

once computed the integrated form factors, one can easily derive the expected number of events for any kinds of interactions, whose particle physics in completely encapsulated in the coefficient $\mathfrak{c}_i^N$

Benchmark interaction

Contact interaction	LR interaction
$\mathcal{O}_1^{\rm NR} = \mathbb{1}$,	$\mathcal{O}_1^{\rm lr} = \frac{1}{q^2}\mathcal{O}_1^{\rm NR}$, $\mathcal{O}_5^{\rm lr} = \frac{1}{q^2}\mathcal{O}_5^{\rm NR}$,
$\mathcal{O}_3^{\rm NR} = i\vec{s}_N \cdot (\vec{q} \times \vec{v}^\perp)$, $\mathcal{O}_4^{\rm NR} = \vec{s}_\chi \cdot \vec{s}_N$,	$\mathcal{O}_6^{\rm lr} = \frac{1}{q^2}\mathcal{O}_6^{\rm NR}$, $\mathcal{O}_{11}^{\rm lr} = \frac{1}{q^2}\mathcal{O}_{11}^{\rm NR}$.
$\mathcal{O}_5^{\rm NR} = i\vec{s}_\chi \cdot (\vec{q} \times \vec{v}^\perp)$, $\mathcal{O}_6^{\rm NR} = (\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q})$,	
$\mathcal{O}_7^{\rm NR} = \vec{s}_N \cdot \vec{v}^\perp$, $\mathcal{O}_8^{\rm NR} = \vec{s}_\chi \cdot \vec{v}^\perp$,	
$\mathcal{O}_9^{\rm NR} = i\vec{s}_\chi \cdot (\vec{s}_N \times \vec{q})$, $\mathcal{O}_{10}^{\rm NR} = i\vec{s}_N \cdot \vec{q}$,	
$\mathcal{O}_{11}^{\rm NR} = i\vec{s}_\chi \cdot \vec{q}$, $\mathcal{O}_{12}^{\rm NR} = \vec{v}^\perp \cdot (\vec{s}_\chi \times \vec{s}_N)$.	

Among all the NR interactions we choose the simplest:
(a model where DM interact with only protons with a constant cross section)

$\mathfrak{c}_1^p = \lambda_{\rm B}$, while $\mathfrak{c}_1^N = 0$

Benchmark DM-nucleon ME

$$|\mathcal{M}_{p,{\rm B}}| = \lambda_{\rm B}\mathcal{O}_1^{\rm NR}$$

Events for the benchmark model

$$N_{k,{\rm B}}^{\rm th} = X\,\lambda_{\rm B}^2\,\tilde{\mathcal{F}}_{1,1}^{(p,p)}(m_\chi, k)$$

benchmark DM constant

Benchmark interaction

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$\mathcal{O}_1^{\rm NR} = \mathbb{1}\,,$ $\mathcal{O}_3^{\rm NR} = i\,\vec{s}_N \cdot (\vec{q} \times \vec{v}^\perp)\,,\quad \mathcal{O}_4^{\rm NR} = \vec{s}_\chi \cdot \vec{s}_N\,,$ $\mathcal{O}_5^{\rm NR} = i\,\vec{s}_\chi \cdot (\vec{q} \times \vec{v}^\perp)\,,\quad \mathcal{O}_6^{\rm NR} = (\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q})\,,$ $\mathcal{O}_7^{\rm NR} = \vec{s}_N \cdot \vec{v}^\perp\,,\quad \mathcal{O}_8^{\rm NR} = \vec{s}_\chi \cdot \vec{v}^\perp\,,$ $\mathcal{O}_9^{\rm NR} = i\,\vec{s}_\chi \cdot (\vec{s}_N \times \vec{q})\,,\quad \mathcal{O}_{10}^{\rm NR} = i\,\vec{s}_N \cdot \vec{q}\,,$ $\mathcal{O}_{11}^{\rm NR} = i\,\vec{s}_\chi \cdot \vec{q}\,,\quad \mathcal{O}_{12}^{\rm NR} = \vec{v}^\perp \cdot (\vec{s}_\chi \times \vec{s}_N)\,.$	$\mathcal{O}_1^{\rm lr} = \frac{1}{q^2}\mathcal{O}_1^{\rm NR}\,,\quad \mathcal{O}_5^{\rm lr} = \frac{1}{q^2}\mathcal{O}_5^{\rm NR}\,,$ $\mathcal{O}_6^{\rm lr} = \frac{1}{q^2}\mathcal{O}_6^{\rm NR}\,,\quad \mathcal{O}_{11}^{\rm lr} = \frac{1}{q^2}\mathcal{O}_{11}^{\rm NR}\,.$

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Determination of the maximal value of $\lambda_{\rm B}$ allowed by the experimental data-set

Likelihood Ratio Test Statistic (TS)

$$\mathrm{TS}(\lambda_{\rm B}, m_\chi) = -2\ln\left(\underbrace{\mathcal{L}(\vec{N}^{\rm obs}\,|\,\lambda_{\rm B})}_{\text{likelihood of obtaining the set of observed data}}/\underbrace{\mathcal{L}_{\rm bkg}}_{\text{bkg. likelihood}}\right)$$

for any given value of m_χ, a 90% CL lower bound on the free parameter can be obtained by solving:

$$\mathrm{TS}(\lambda_{\rm B}, m_\chi) = \chi^2_{90\%\,{\rm CL}} \simeq 2.71$$

Benchmark interaction

Contact interaction

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$$\mathcal{O}_{11}^{\rm NR} = i\,\vec{s}_\chi \cdot \vec{q}\,, \quad \mathcal{O}_{12}^{\rm NR} = \vec{v}^\perp \cdot (\vec{s}_\chi \times \vec{s}_N)\,.$$

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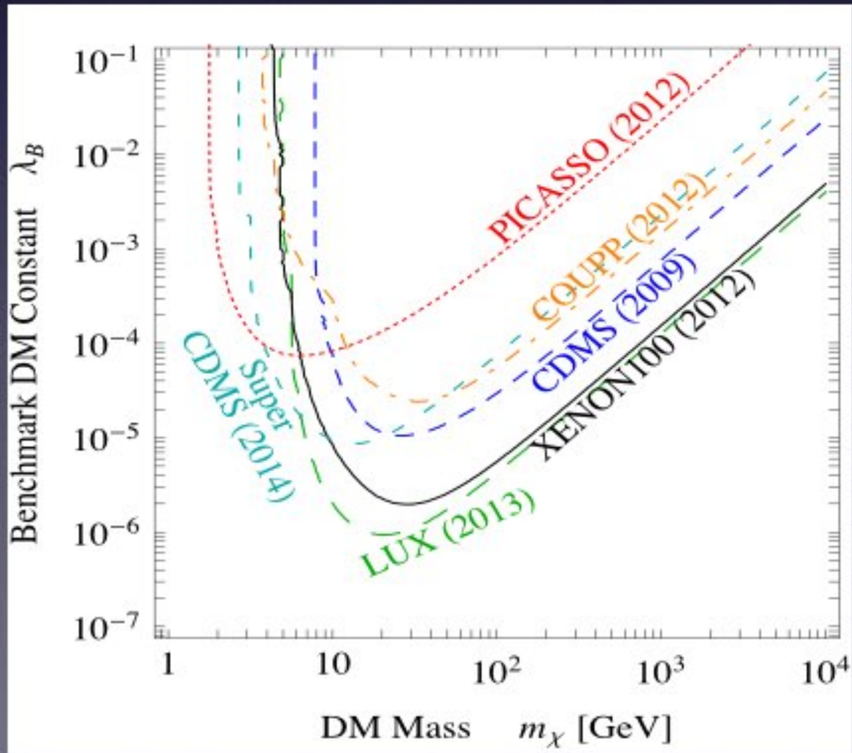
The functions TS that allow the users to compute the bound $\lambda_{\rm B}^{\rm CL}$ at the desired CL are provided here:

http://www.marcocirelli.net/NROpsDD.html



Rescaling Functions

For any model the bound
must be drawn at the same CL:

$$\mathrm{TS}(\lambda, m_\chi) = \mathrm{TS}(\lambda_\mathrm{B}, m_\chi)$$

For null-results Exps. a solution is:

$$\sum_k N_k^{\mathrm{th}}(\lambda, m_\chi) = \sum_k N_{k,\mathrm{B}}^{\mathrm{th}}(\lambda_\mathrm{B}, m_\chi)$$

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$$\sum_{i,j=1}^{12} \sum_{N,N'=p,n} \underbrace{\mathfrak{c}_i^N(\lambda, m_\chi)\mathfrak{c}_j^{N'}(\lambda, m_\chi)}_{\text{Particle physics part}} \underbrace{\tilde{\mathcal{Y}}_{i,j}^{(N,N')}(m_\chi)}_{\text{Model independent}} = \lambda_\mathrm{B}^2$$

$$\tilde{\mathcal{Y}}_{i,j}^{(N,N')}(m_\chi) = \frac{\sum_k \tilde{\mathcal{F}}_{i,j}^{(N,N')}(m_\chi, k)}{\sum_k \tilde{\mathcal{F}}_{1,1}^{(p,p)}(m_\chi, k)}$$

"Scaling" Functions
- nuclear physics
- astrophysics
- experimental details

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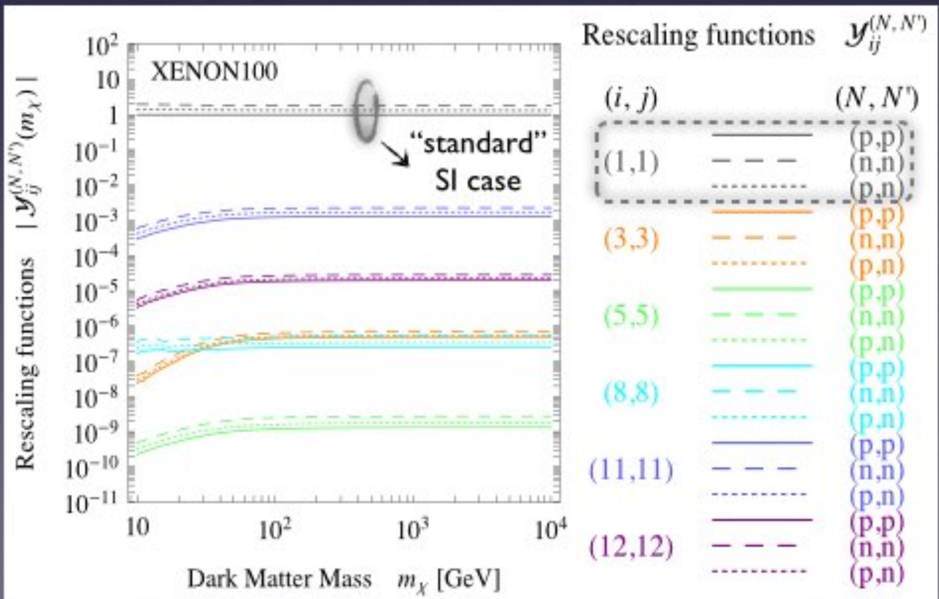

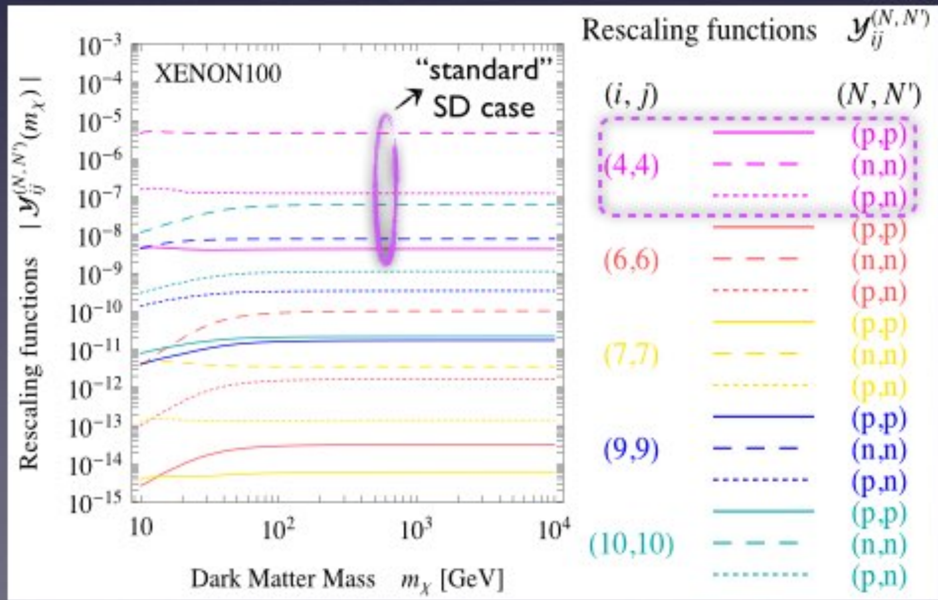

Example: SI & SD Interactions

SI DM-nucleon effective Lagrangian

$$\mathcal{L}_{\rm SI}^{N} = \lambda_{\rm SI} \cdot \bar{\chi}\chi\, \bar{N}N$$

$$\sigma_{\rm SI}^{p} = \frac{\lambda_{\rm SI}^2}{\pi}\mu_{\chi p}^2$$

Total SI DM-nucleon Cross section

SD DM-nucleon effective Lagrangian

$$\mathcal{L}_{\rm SD}^{N} = \lambda_{\rm SD} \cdot \bar{\chi}\gamma^{\mu}\gamma^{5}\chi\, \bar{N}\gamma_{\mu}\gamma^{5}N$$

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Total SD DM-nucleon Cross section

Example: SI & SD Interactions

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Non-relativistic SI DM-nucleon ME

$$\left|\mathcal{M}_{\rm SI}^{N}\right| = \underbrace{4\,\lambda_{\rm SI} m_\chi m_N}_{\mathfrak{c}_1^N}\, \mathbf{1} \rightarrow \mathcal{O}_1^{\rm NR}$$

SD DM-nucleon effective Lagrangian

$$\mathcal{L}_{\rm SD}^{N} = \lambda_{\rm SD} \cdot \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{N}\gamma_\mu\gamma^5 N$$

$$\sigma_{\rm SD}^{p} = 3\frac{\lambda_{\rm SD}^2}{\pi}\mu_{\chi p}^2$$ Total SD DM-nucleon Cross section

Non-relativistic SD DM-nucleon ME

$$\left|\mathcal{M}_{\rm SD}^{N}\right| = \underbrace{16\,\lambda_{\rm SD} m_\chi m_N}_{\mathfrak{c}_4^N}\, \vec{s}_\chi \vec{s}_N \rightarrow \mathcal{O}_4^{\rm NR}$$

Example: SI & SD Interactions

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$$\mathcal{L}^N_{\mathrm{SI}} = \lambda_{\mathrm{SI}} \cdot \bar{\chi}\chi\, \bar{N}N$$

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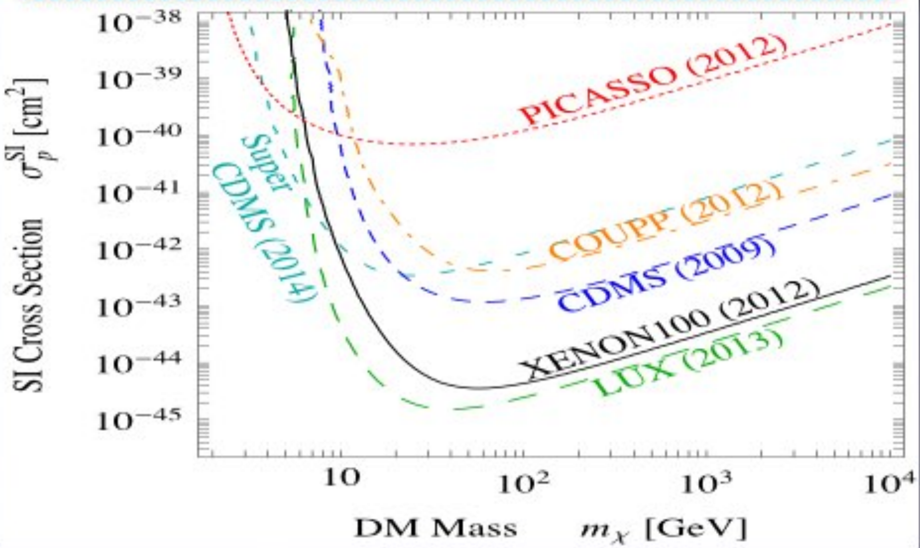
Total SI DM-nucleon Cross section

Non-relativistic SI DM-nucleon ME

$$\left|\mathcal{M}^N_{\mathrm{SI}}\right| = \underbrace{4\,\lambda_{\mathrm{SI}} m_\chi m_N}_{\mathfrak{c}^N_1}\, \underset{\to\,\mathcal{O}^{\mathrm{NR}}_1}{1}$$

$$\lambda^2_{\mathrm{B}} = \sigma^p_{\mathrm{SI}} \sum_{N,N'=p,n} 16\pi\, m^2_\chi \frac{m^2_N}{\mu^2_{\chi p}}\, \tilde{\mathcal{Y}}^{(N,N')}_{1,1}(m_\chi)$$



SD DM-nucleon effective Lagrangian

$$\mathcal{L}^N_{\mathrm{SD}} = \lambda_{\mathrm{SD}} \cdot \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{N}\gamma_\mu\gamma^5 N$$

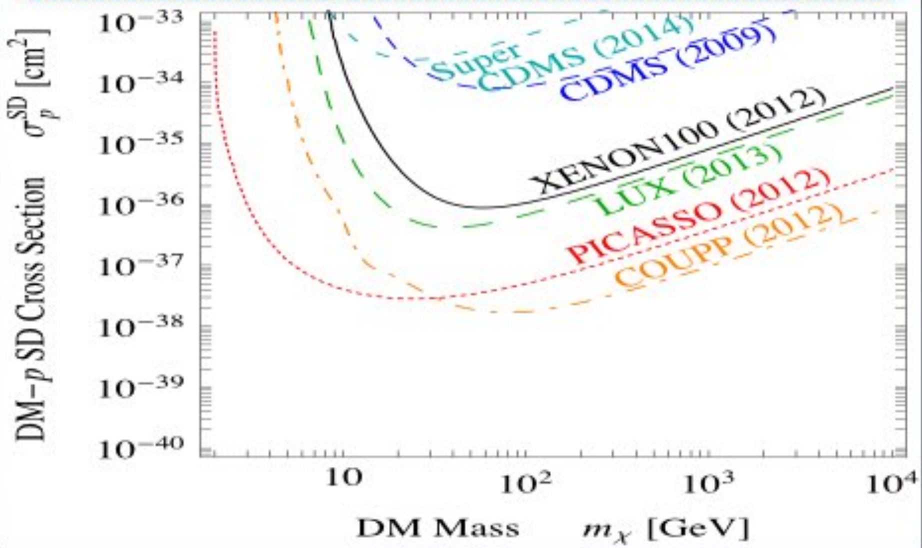
$$\sigma^p_{\mathrm{SD}} = 3\frac{\lambda^2_{\mathrm{SD}}}{\pi}\mu^2_{\chi p}$$

Total SD DM-nucleon Cross section

Non-relativistic SD DM-nucleon ME

$$\left|\mathcal{M}^N_{\mathrm{SD}}\right| = \underbrace{16\,\lambda_{\mathrm{SD}} m_\chi m_N}_{\mathfrak{c}^N_4}\, \underset{\to\,\mathcal{O}^{\mathrm{NR}}_4}{\vec{s}_\chi \vec{s}_N}$$

$$\lambda^2_{\mathrm{B}} = \sigma^p_{\mathrm{SD}} \frac{256}{3}\pi\, m^2_\chi \frac{m^2_N}{\mu^2_{\chi p}}\, \tilde{\mathcal{Y}}^{(p,p)}_{4,4}(m_\chi)$$



Summary of the I° Part

I have described a method and a self-contained set of numerical tools to derive the bounds from some current experiments on virtually any arbitrary models of DM

- The method is based on the formalism of non-relativistic operators
- it incorporates into the nuclear responses all the necessary detector and astrophysical ingredients

Tools for model-independent bounds in direct dark matter searches

Data and Results from 1307.5955 [hep-ph], JCAP 10 (2013) 019.

If you use the data provided on this site, please cite:
M.Cirelli, E.Del Nobile, P.Panci,
"Tools for model-independent bounds in direct dark matter searches",
arXiv 1307.5955, JCAP 10 (2013) 019.

This is **Release 3.0** (April 2014). *Log of changes at the bottom of this page.*

Test Statistic functions:

The TS.m file provides the tables of TS for the benchmark case (see the paper for the definition), for the six experiments that we consider (XENON100, CDMS-Ge, COUPP, PICASSO, LUX, SuperCDMS).

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Sample file:

The Sample.nb notebook shows how to load and use the above numerical products, and gives some examples.

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[23 jul 2013] First Release.
[08 oct 2013] Minor changes in the notations in Sample.nb, to match JCAP version. No new release.
[25 nov 2013] New Release: 2.0. Addition of LUX results. This release corresponds to **version 3** of 1307.5955 (with Addendum).
[03 apr 2014] New Release: 3.0. Addition of SuperCDMS results. This release corresponds to **version 4** of 1307.5955 (with two Addenda).

Contact: Eugenio Del Nobile <delnobile@physics.ucla.edu>, Paolo Panci <panci@iap.fr>

http://www.marcocirelli.net/NROpsDD.html

Summary of the I° Part

I have described a method and a self-contained set of numerical tools to derive the bounds from some current experiments on virtually any arbitrary models of DM

- The method is based on the formalism of non-relativistic operators
- it incorporates into the nuclear responses all the necessary detector and astrophysical ingredients

Tools for model-independent bounds in direct dark matter searches

Data and Results from 1307.5955 [hep-ph], JCAP 10 (2013) 019.

If you use the data provided on this site, please cite:
M.Cirelli, E.Del Nobile, P.Panci,
"Tools for model-independent bounds in direct dark matter searches",
arXiv 1307.5955, JCAP 10 (2013) 019.

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II° Part: Model Dependent

a relativistic model in which the DM particles interact with the SM fermions via the exchange of a pseudo-scalar mediator can:

- ☑ accommodates the DAMA modulated signal while being compatible with all null direct DM searches
- ☑ provides a DM explanation of the GC excess in gamma-rays recently reported by Hooper et al. analysing the FERMI data
- ☑ at the same time achieves the correct today's relic density

OK !!

OK !!

OK !!

II° Part: Model Dependent

Contact interaction (q << Λ)

$$\mathcal{O}_1^{\rm NR} = \mathbb{1}\,,$$
$$\mathcal{O}_3^{\rm NR} = i\,\vec{s}_N \cdot (\vec{q} \times \vec{v}^\perp)\,, \quad \mathcal{O}_4^{\rm NR} = \vec{s}_\chi \cdot \vec{s}_N\,,$$
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DM-nucleon Matrix Element

$$|\mathcal{M}_N| = \sum_{i=1}^{12} \mathfrak{c}_i^N(\lambda, m_\chi)\, \mathcal{O}_i^{\rm NR}$$

NR spin-independent Operators

$$\mathcal{O}_1^{\rm NR} = \mathbf{1}\,, \quad \mathcal{O}_5^{\rm NR} = i\,\vec{s}_\chi \cdot (\vec{q} \times \vec{v}^\perp)\,,$$
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The sodium, iodine and fluorine nuclei have unpaired protons in the nuclear shell

→ sensitive to the DM-p spin dependent

The xenon and germanium nuclei have unpaired neutrons in the nuclear shell

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$$|\mathcal{M}_N| = \sum_{i=1}^{12} \mathfrak{c}_i^N(\lambda, m_\chi)\, \mathcal{O}_i^{NR}$$

Bottom line: the complicated experimental puzzle can probably be solved, if in the NR limit a spin-dependent interaction gives rise in which the coupling $\mathfrak{c}_i^p \gg \mathfrak{c}_i^n$.

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Relativistic Interaction

Relativistic Lagrangian at the quark level

$$\mathcal{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}} a\,\bar{\chi}\gamma_5\chi - ig\sum_f \frac{g_f}{\sqrt{2}} a\,\bar{f}\gamma_5 f\,.$$

Particle Content

χ : DM fermion with mass $m_{\rm DM}$

f : SM fermion with mass m_f

a : pseudo-scalar mediator with mass m_a

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Couplings at the quark level

$g_{\rm DM}$: DM couplings with the mediator

$g\,g_f$: SM fermion couplings with the mediator

flavor-universal:
$g_f = 1$

independent on the fermion type

higgs-like:
$g_f = m_f/v_{\rm H}$

proportional to the fermion mass

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From Rel. Lagrangian to NR DD Observables

In DD, the DM particles interact with the entire nucleus in deeply NR regime:

- ☑ Dress up the quark-operators to the nucleon level
- ☑ Write down the DM-nucleon effective Lagrangian
- ☑ Reduce to NR limit in order to infer the NR operator and its coefficient
- ☑ Account for the composite structure of the nucleus with the nuclear responses

DM-nucleon Lagrangian

Effective Lagrangian for contact interaction

$$\mathcal{L}_{\rm eff} = \frac{1}{2\Lambda_a^2} \sum_{N=p,n} \boxed{g_N}\, \bar{\chi}\gamma^5\chi\, \bar{N}\gamma^5 N\,,$$

Energy Scale of the effective Lagrangian

$\Lambda_a = m_a/\sqrt{g\, g_{\rm DM}}$:

combination of the free parameters of the model (mediator mass and couplings)

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$$g_N = \sum_{q=u,d,s} \frac{m_N}{m_q}\left[g_q - \sum_{q'=u,\ldots,t} g_{q'}\frac{\bar{m}}{m_{q'}}\right]\Delta_q^{(N)}$$

Quark spin content of the nucleons

$$\Delta_u^{(p)} = \Delta_d^{(n)} = +0.84\,,$$
$$\Delta_d^{(p)} = \Delta_u^{(n)} = -0.44\,,$$
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H.-Y. Cheng and C.-W. Chiang, JHEP 1207 (2012) **009**

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"Natural" Isospin Violation

$g_p/g_n = -16.4$: flavor-universal couplings

$g_p/g_n = -4.1$: higgs-like couplings

✔ large isospin violation going from the quark level to the nucleon one

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Important consequences in DD

the pseudo-scalar interaction measures a certain component of the spin content of the nucleus carried by the nucleons.

→ a large g_p/g_n will favor nuclides with a large spin due to their unpaired proton
(e.g. DAMA employs sodium & iodine)

→ nuclides with unpaired neutron will be largely disfavored
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for flavour-universal, the contribution of the light quarks in g_N cancel out

$g_p/g_n = -16.4$: "heavy flavor" couplings

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DM-nucleon Matrix Element in the NR limit

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Longitudinal SD Interaction

$$\mathcal{O}_6^{\rm NR} = (\vec{s}_\chi\cdot\vec{q})(\vec{s}_N\cdot\vec{q})$$

DM-nucleus differential Cross Section

$$\frac{{\rm d}\sigma_{\mathcal{N}}}{{\rm d}E_{\rm R}} = \frac{1}{8\pi}\frac{1}{\Lambda_a^4}\frac{m_{\mathcal{N}}}{m_{\rm DM}^2 m_N^2}\frac{1}{v^2}\sum_{N,N'=p,n} g_N g_{N'} F_{6,6}^{(N,N')}(q^2)$$

Nuclear Responses

$$F_{6,6}^{(N,N')}(q^2) = \frac{q^4}{16}F_{\Sigma''}^{(N,N')}(q^2)$$

Main Properties

- ☑ in the energy window of DD experiments $\propto q^4$
- ☑ measures the spin of the unpaired nucleons in the nuclear shell

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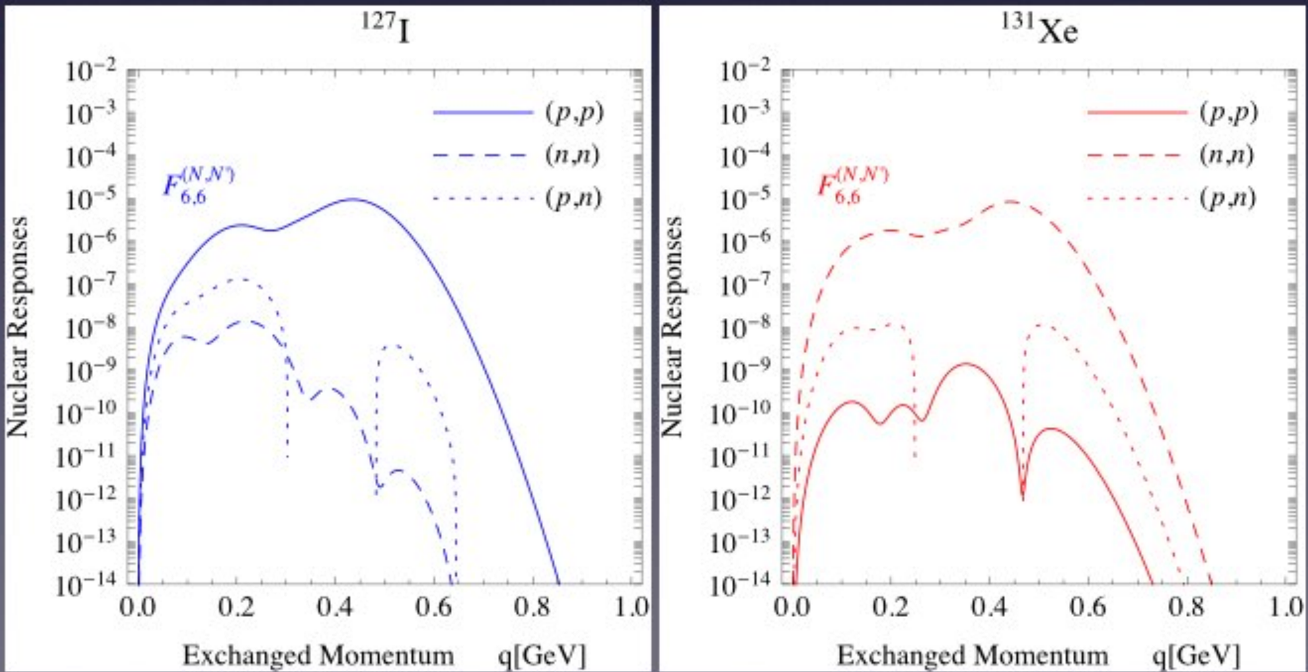
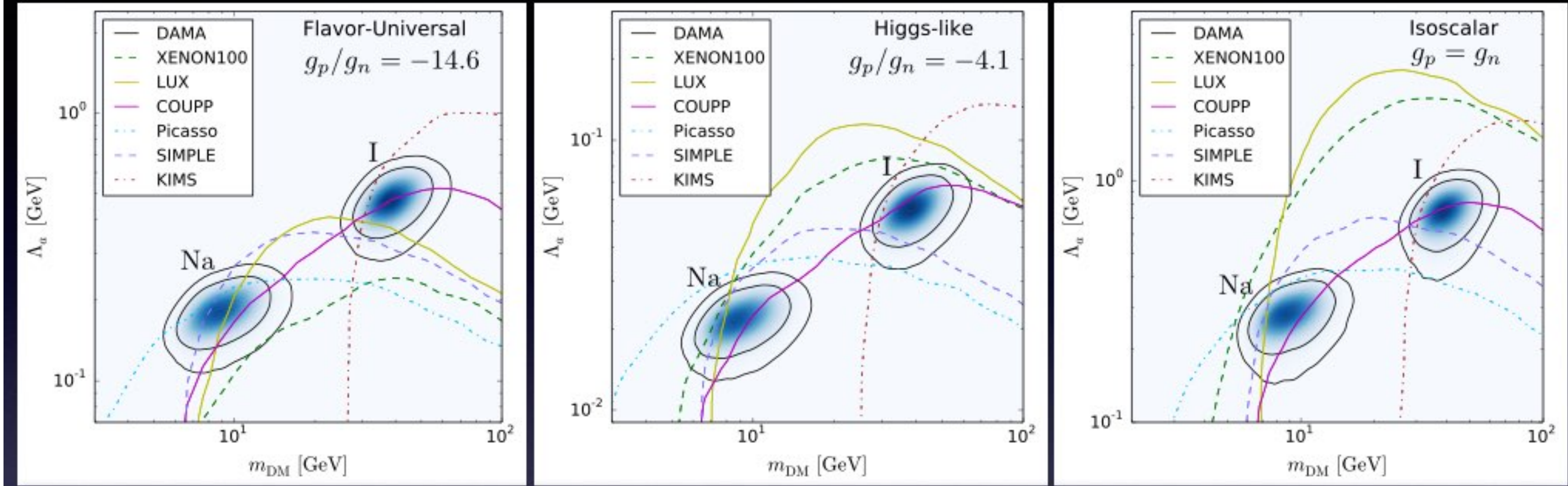


Results



"Not so Coy DM explains DAMA (and the GC excess)", arXiv:1406.5542

Bottom line: the large enhancement of the DM-p coupling with respect to the DM-n coupling suppresses the LUX (solid orange) and XENON100 (dash green) bounds

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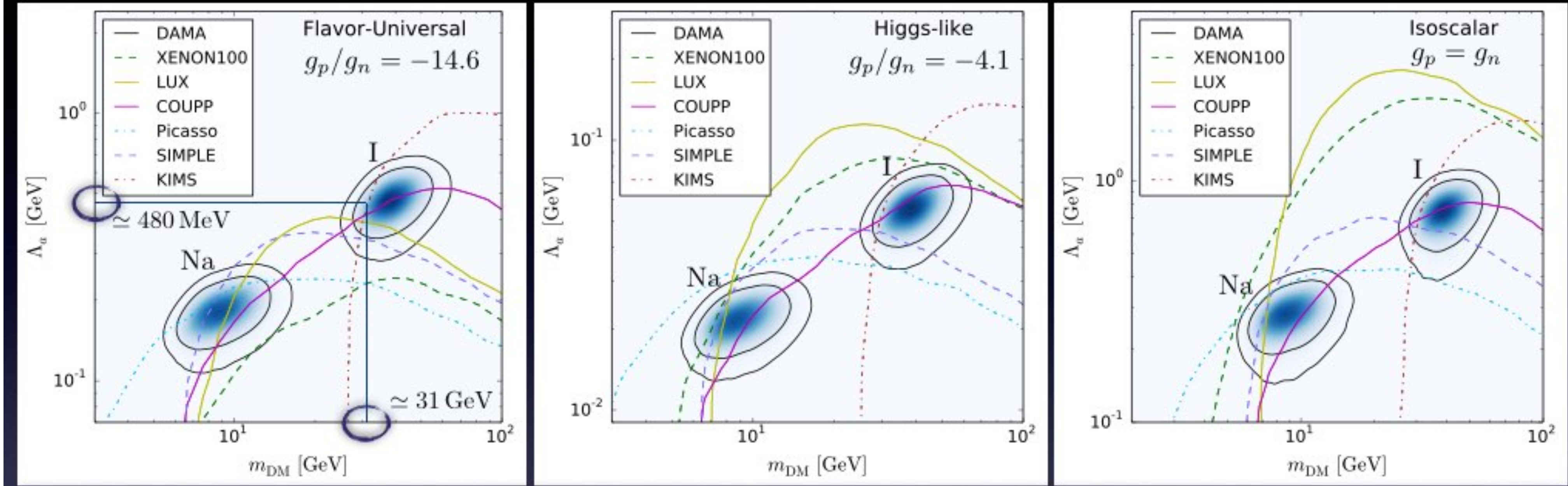

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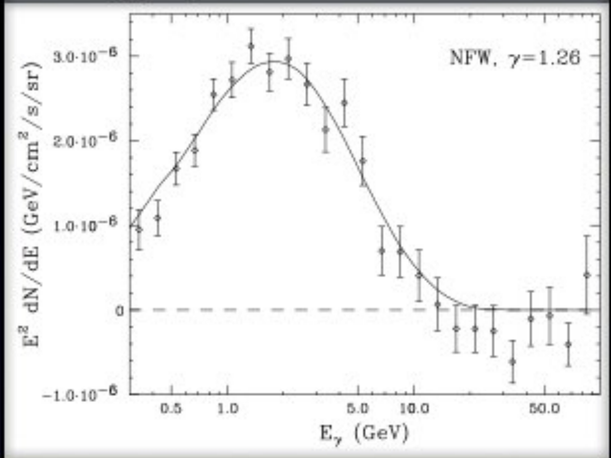
Bottom line: the large enhancement of the DM-p coupling with respect to the DM-n coupling suppresses the LUX (solid orange) and XENON100 (dash green) bounds

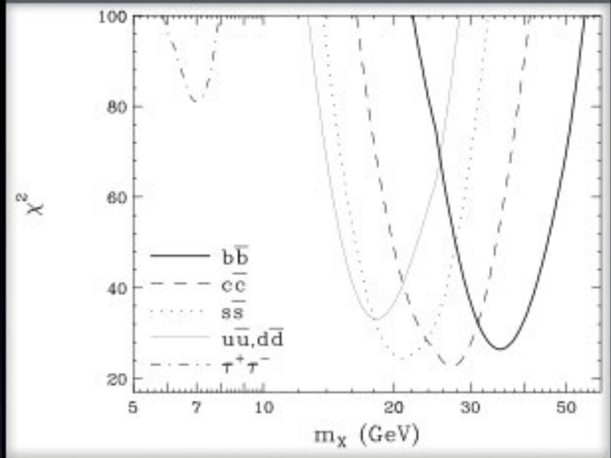
- for flavor-universal couplings: part of the I region is compatible at 90% CL with all null results experiments due to the large isospin violation
- for higgs-like couplings: the LUX and XENON100 bounds are less suppressed due to the reduced g_p/g_n enhancement, and the bounds disfavored both Na and I regions.
- for "isoscalar" couplings (not natural for pseudo-scalar interaction): there is not enhancement and DAMA is largely disfavored (see also e.g. arXiv:1401.3739)

GC Excess in gamma-rays

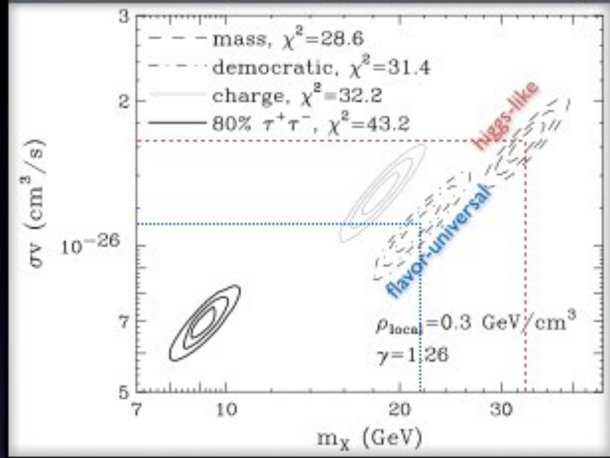
Energy Spectrum of the excess



DM Interpretation of the excess



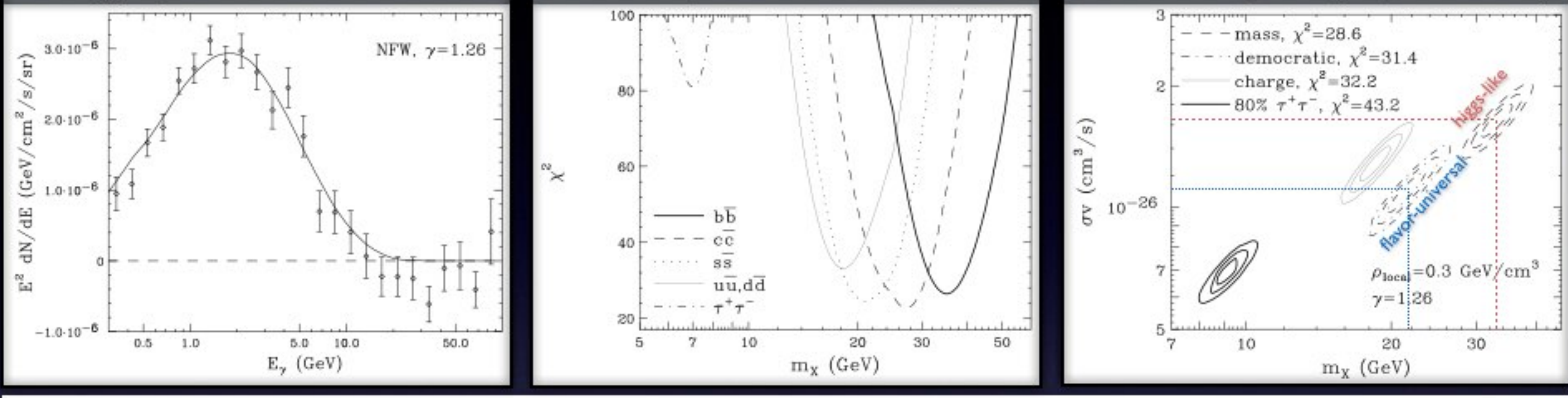
Allowed regions (Majorana DM)



"The Characterization of the gamma-ray signal from the Central Milky Way", arXiv:1402.6703

GC Excess in gamma-rays

Energy Spectrum of the excess | DM Interpretation of the excess | Allowed regions (Majorana DM)



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Best fit values adjusted for our DM model

	$m_{\rm DM}^{\rm best}$	$\langle\sigma v\rangle_{\rm best}$
Universal (*democratic*)	22 GeV	$2.2\times10^{-26}\ {\rm cm}^3/{\rm s}$
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Relativistic Lagrangian at the quark-level

$$\mathcal{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}}a\,\bar\chi\gamma^5\chi - ig\sum_q \frac{g_q}{\sqrt{2}}a\,\bar q\gamma^5 q$$

- ☑ χ is a Dirac Fermions
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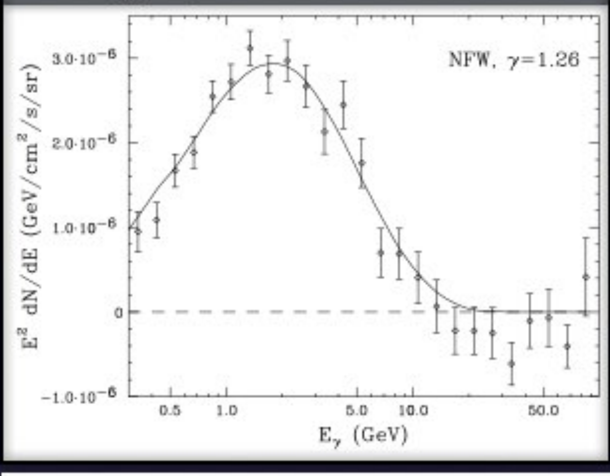

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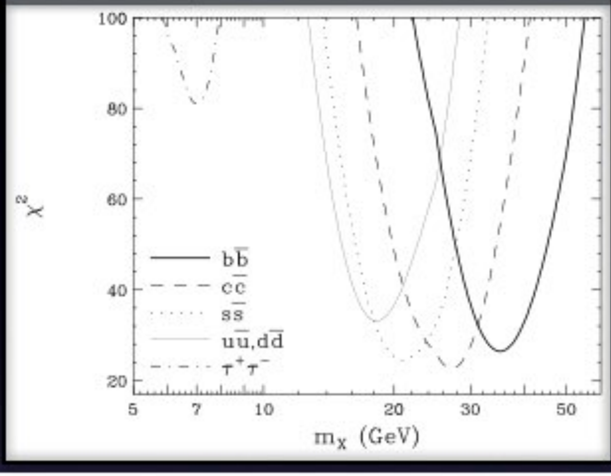

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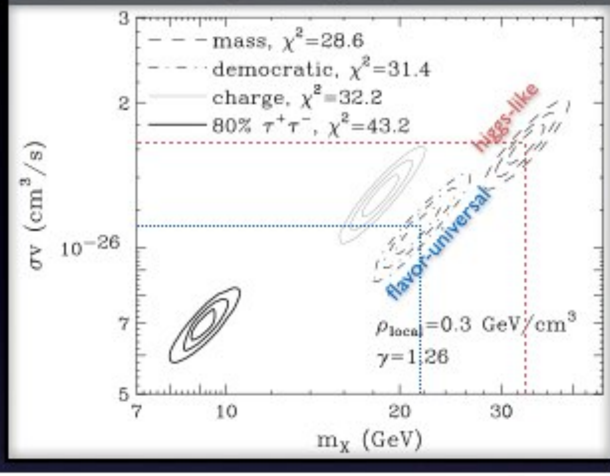

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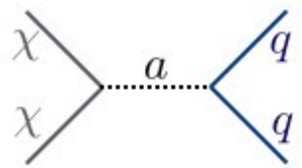
Comparison with the theoretical prediction

χ can annihilate to quarks via s-channel exchange



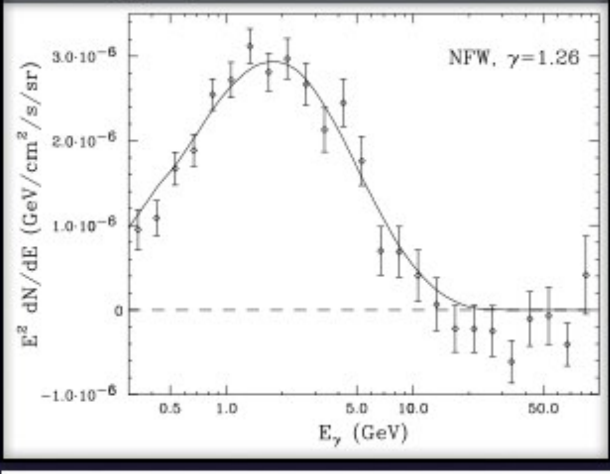
the energy scale of the effective operator constrained by DAMA gives $\Lambda_a = m_a/\sqrt{g\,g_{\rm DM}} \ll m_{\rm DM}$

$$\langle\sigma v\rangle_{qq} \simeq \sum_q \frac{3g_q^2}{8\pi}\frac{g^2 g_{\rm DM}^2}{16 m_{\rm DM}^2}\sqrt{1-\frac{m_q^2}{m_{\rm DM}^2}}$$

the requirement of fitting the excess can be used to disentangle m_a from the product $g\,g_{\rm DM}$ in Λ_a .

GC Excess in gamma-rays

Energy Spectrum of the excess



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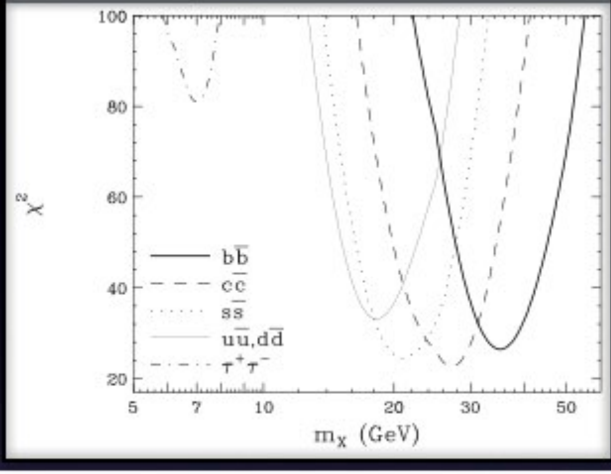

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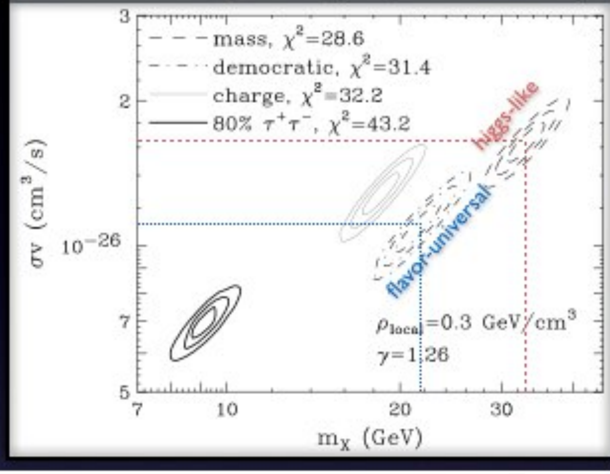

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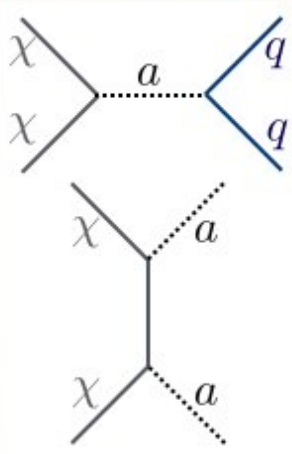
Theoretical prediction for the Relic Abundance



$$\langle\sigma v\rangle_\Omega = \langle\sigma v\rangle_{qq} + \langle\sigma v\rangle_{aa}(x) + \mathcal{O}(x^{-2})$$

s-wave into quarks:
independent on $x = m_{\rm DM}/T$

$$\langle\sigma v\rangle_{qq} \simeq \sum_q \frac{3g_q^2}{8\pi}\frac{g^2 g_{\rm DM}^2}{16 m_{\rm DM}^2}\sqrt{1-\frac{m_q^2}{m_{\rm DM}^2}}$$

p-wave into pseudo-scalars:
only active in the early Universe ($m_{\rm DM}\sim T$)

$$\langle\sigma v\rangle_{aa} \simeq \frac{3}{2x}\cdot\frac{1}{96\pi}\frac{g_{\rm DM}^4}{16 m_{\rm DM}^2}\sqrt{1-\frac{m_a^2}{m_{\rm DM}^2}}$$

$\Omega_{\rm DM}\simeq 0.27$ **breaks the degeneracy between** g & $g_{\rm DM}$

Final Results

Bottom line: from the three observables one can fully determine the free parameters of the model

$$\mathcal{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}}\, a\, \bar{\chi}\gamma^5\chi - ig\sum_q \frac{g_q}{\sqrt{2}}\, a\, \bar{q}\gamma^5 q$$

$\Lambda_a = m_a/\sqrt{g\, g_{\rm DM}}$: energy scale of the EO

- ☑ I-region of DAMA $\Rightarrow (m_{\rm DM},\, \Lambda_a)$
- ☑ GC excess in $\gamma-$rays $\Rightarrow (m_{\rm DM},\, g\, g_{\rm DM})$
- ☑ Correct Relic Density $\Rightarrow g\;\&\; g_{\rm DM}$

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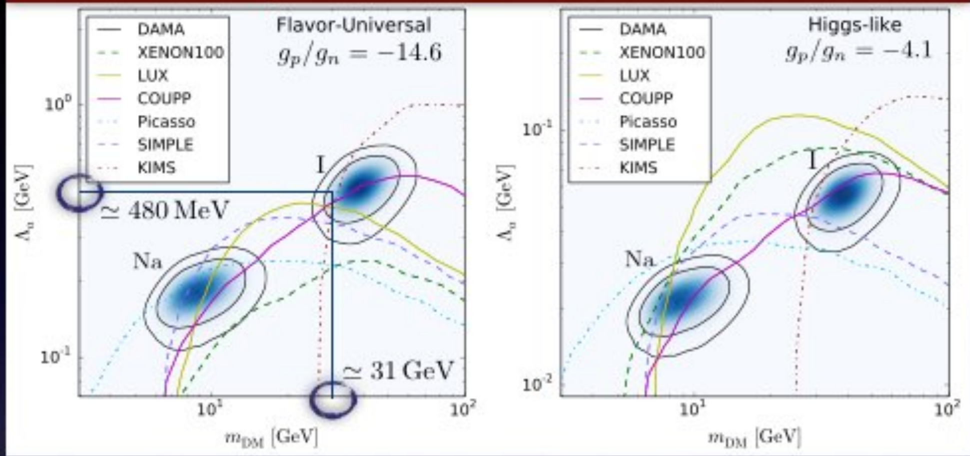

2 Interpretation of the GC excess in gamma-rays

	$m_{\rm DM}^{\rm best}$	$\langle\sigma v\rangle_{\rm best}$
Universal (*democratic*)	22 GeV	$2.2\times10^{-26}\,{\rm cm^3/s}$
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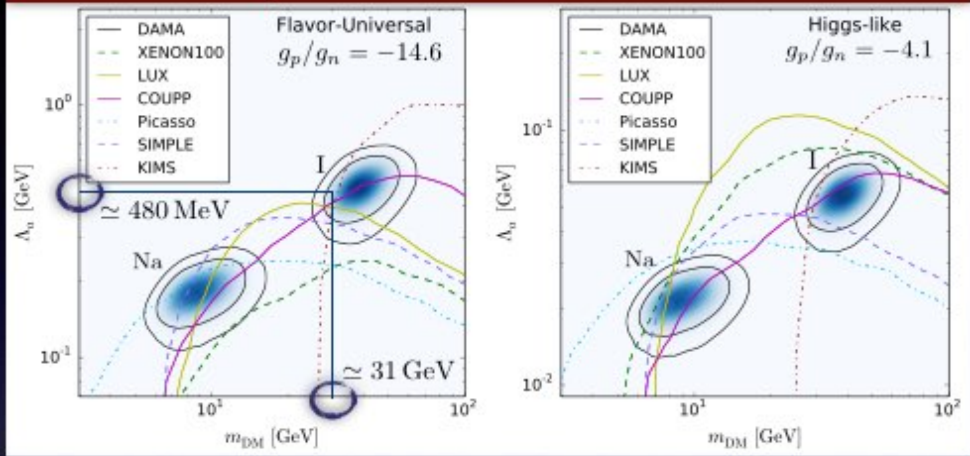

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3 Correct Relic Density

Determination of the free parameters of the relativistic Lagrangian

- ✔ universal (*democratic*): favored by DD, however $m_{\rm DM}^{\rm best}$ is outside the 99% CL of the DAMA I-region
  $g\,g_q \simeq 7.7\times10^{-3}\,,\quad g_{\rm DM}\simeq 0.64\,,\quad m_a \simeq 35\,{\rm MeV}\,.$
- ✔ universal (*heavy-flavors*): best case scenario; $m_{\rm DM}^{\rm best}$ is fully compatible with the DAMA I-region
  $g\,g_q \simeq 1.8\times10^{-2}\,,\quad g_{\rm DM}\simeq 0.72\,,\quad m_a \simeq 56\,{\rm MeV}\,.$
- ✔ higgs-like: $m_{\rm DM}^{\rm best}$ is compatible with DAMA I-region which is however excluded at 99% CL by DD
  $g\,g_q \simeq 1.15\,m_q/v_{\rm H}\,,\quad g_{\rm DM}\simeq 0.69\,,\quad m_a \simeq 52\,{\rm MeV}\,.$

Summary of the II° Part

I have described the phenomenology of a model in which the DM particles interact with the SM fermions via the exchange of a pseudo-scalar mediator

- ✓ this is a viable model that can accommodates the DAMA modulated signal while being compatible with all null direct DM searches
  - the compatibility of DAMA is determined by the large enhancement of the DM coupling with protons with respect to neutrons, occurring for natural choices of the pseudo-scalar coupling with quarks

- ✓ Furthermore, it can provide a DM explanation of the GC excess in gamma-rays and at the same time achieve the correct relic density

The best fit of both direct and indirect signals is obtained when the mediator is much lighter than the DM mass and has universal coupling with heavy quarks

Relativistic Lagrangian

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Free parameters	Best fit values
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