11 December 2014
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New Directions in Direct DM Searches

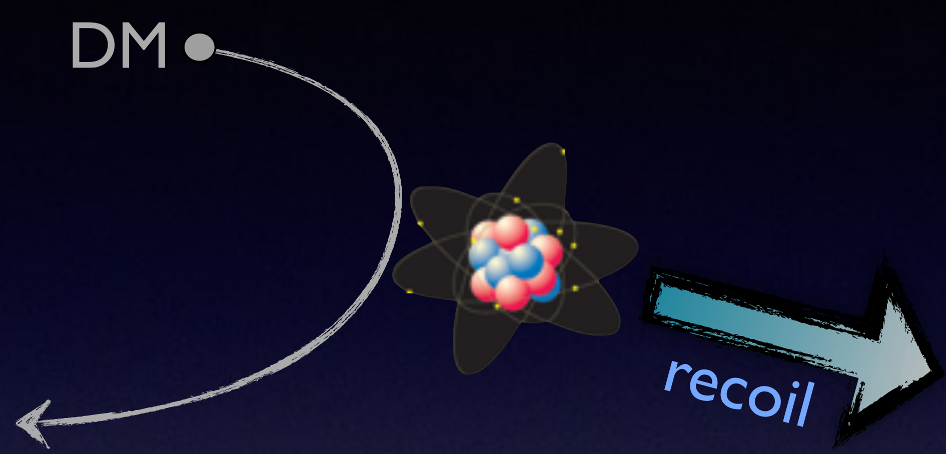
Paolo Panci

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

the second on:
C. Arina, E. Del Nobile, P. Panci,
Published in PRL [arXiv: 1406.5542]

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

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 χ & $\mathcal{N}$ occurs in deeply non relativistic regime

$$E_\mathrm{R} = \frac{1}{2}m_\chi v^2 \frac{4 m_\chi m_\mathcal{N}}{(m_\chi + m_\mathcal{N})^2}\left(\frac{1 - \frac{v_\mathrm{t}^2}{2v^2} - \sqrt{1-\frac{v_\mathrm{t}^2}{v^2}}\cos\theta}{2}\right),$$

$$\begin{cases} v_\mathrm{t} = 0 & \text{elastic} \\ v_\mathrm{t} = \sqrt{\frac{2\delta}{\mu_{\chi\mathcal{N}}}} \neq 0 & \text{inelastic} \end{cases}$$

DM kinetic energy — Kinematics factor — scatter angle — threshold velocity

Theoretical differential rate of nuclear recoil in a given detector

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

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

Differential Cross Section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}}(v, E_{\mathrm{R}}) = \frac{1}{32\pi}\frac{1}{m_\chi^2 m_{\mathcal{N}}}\frac{1}{v^2}|\mathcal{M}_{\mathcal{N}}|^2 \longrightarrow$$

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.

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

$\swarrow$ 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)

$$\mathcal{O}_1^{NR} = \mathbb{1} ,$$
$$\mathcal{O}_3^{NR} = i\, \vec{s}_N \cdot (\vec{q} \times \vec{v}^\perp) , \quad \mathcal{O}_4^{NR} = \vec{s}_\chi \cdot \vec{s}_N ,$$
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Long-range interaction (q >> Λ)

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

Differential Cross Section

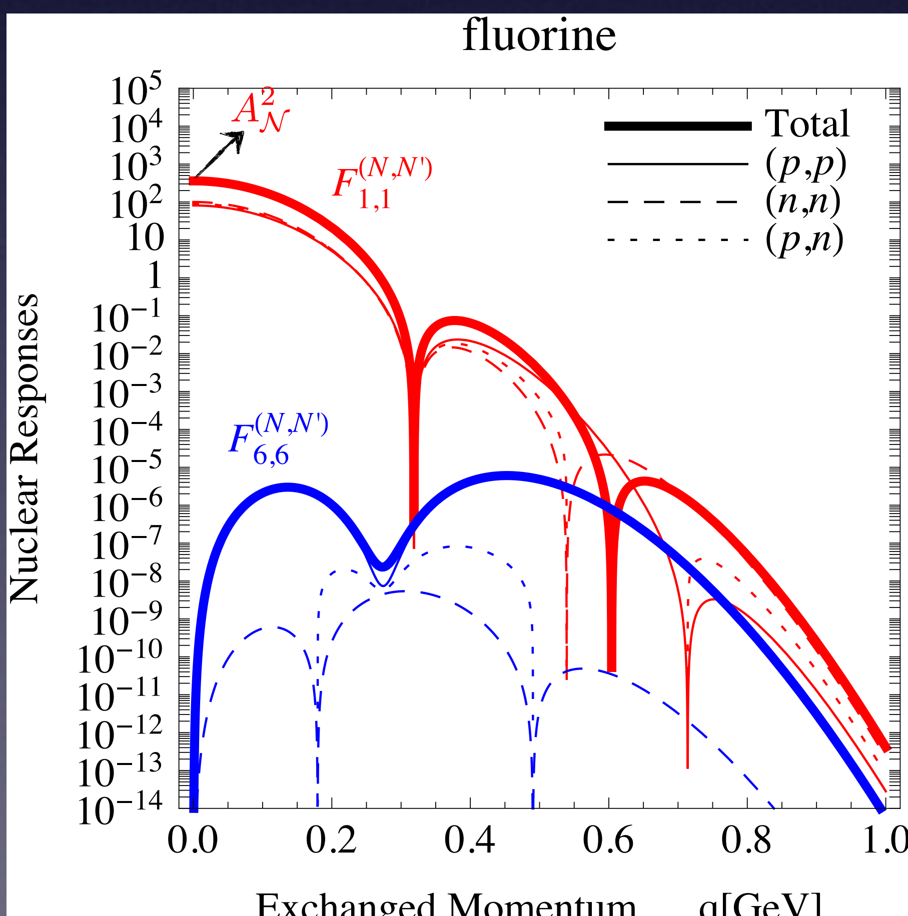
Nucleus is not point-like

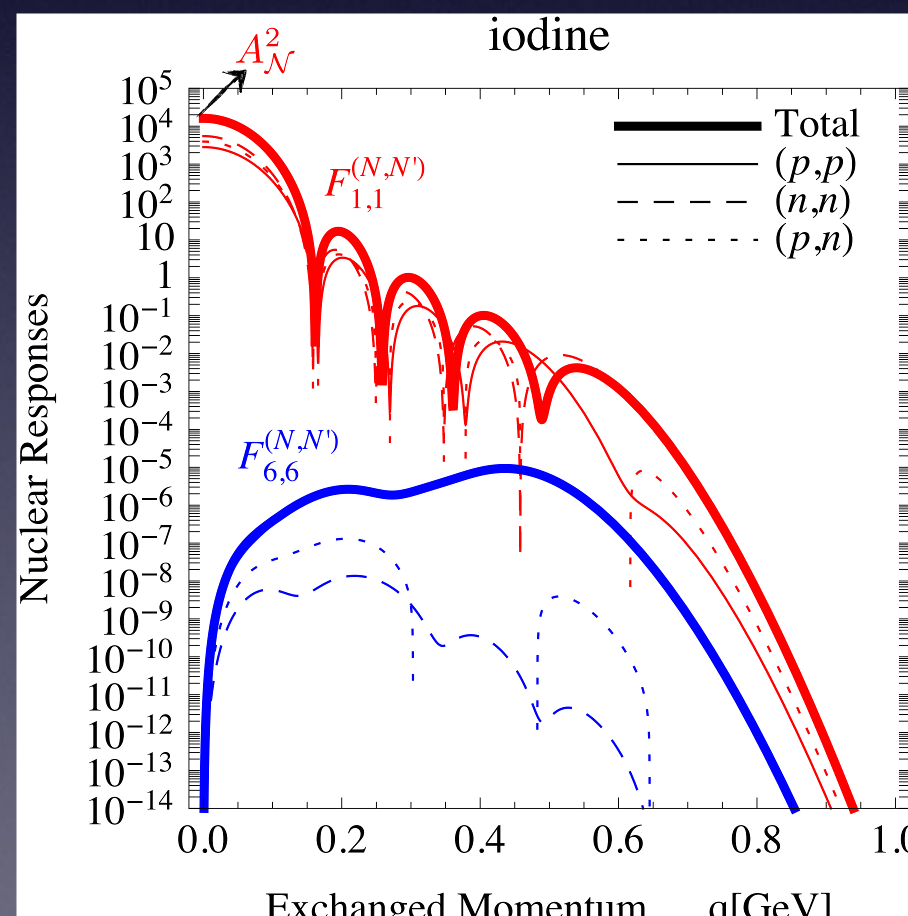
There are different Nuclear Responses for any pairs of nucleons & any pairs of NR Operators

$$|\mathcal{M}_{\mathcal{N}}|^2 = \frac{m_{\mathcal{N}}^2}{m_N^2} \sum_{i,j=1}^{12} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} F_{i,j}^{(N,N')}(v, q^2)$$

pairs of NR operators — pairs of nucleons — Nuclear response of the target nuclei

Nuclear responses for some common target nuclei in Direct Searches





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Long-Range interaction (q >> Λ)

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

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

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

Rate of Nuclear Recoil

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

Comparison with the Experimental data

exposure

$$N_k^{\rm th} = w_k \int_{\Delta E_k} dE_{\rm det}\, \epsilon(E_{\rm det}) \int_0^\infty dE_R \sum_{\mathcal{N}} \mathcal{K}_{\mathcal{N}}(q_{\mathcal{N}} E_R, E_{\rm det}) \frac{dR_{\mathcal{N}}}{dE_R}(E_R)$$

$\mathcal{N}$=Nucleus

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......)

II° Part: Model Dependent

Contact interaction (q << Λ)

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

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

NR spin-independent Operators

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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

→ blind to the DM-p spin dependent

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

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

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

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)

DM-nucleon effective couplings

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

Values of quark spin content of the nucleons

$$\Delta_u^{(p)} = \Delta_d^{(n)} = +0.84 \, ,$$
$$\Delta_d^{(p)} = \Delta_u^{(n)} = -0.44 \, ,$$
$$\Delta_s^{(p)} = \Delta_s^{(n)} = -0.03$$

H.-Y. Cheng and C.-W. Chiang, JHEP 1207 (2012) **009**

DM-nucleon Lagrangian

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DM-nucleon effective couplings

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

Values of quark spin content of the nucleons

$$\Delta_u^{(p)} = \Delta_d^{(n)} = +0.84 \,,$$
$$\Delta_d^{(p)} = \Delta_u^{(n)} = -0.44 \,,$$
$$\Delta_s^{(p)} = \Delta_s^{(n)} = -0.03$$

H.-Y. Cheng and C.-W. Chiang, JHEP 1207 (2012) **009**

"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

Gross, Treiman, Wilczek, Phys. Rev. **D19** 2188, (1979)

DM-nucleon Lagrangian

Effective Lagrangian for contact interaction

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

Energy Scale of the effective Lagrangian

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

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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
  (e.g. XENON100 and LUX employ xenon)

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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

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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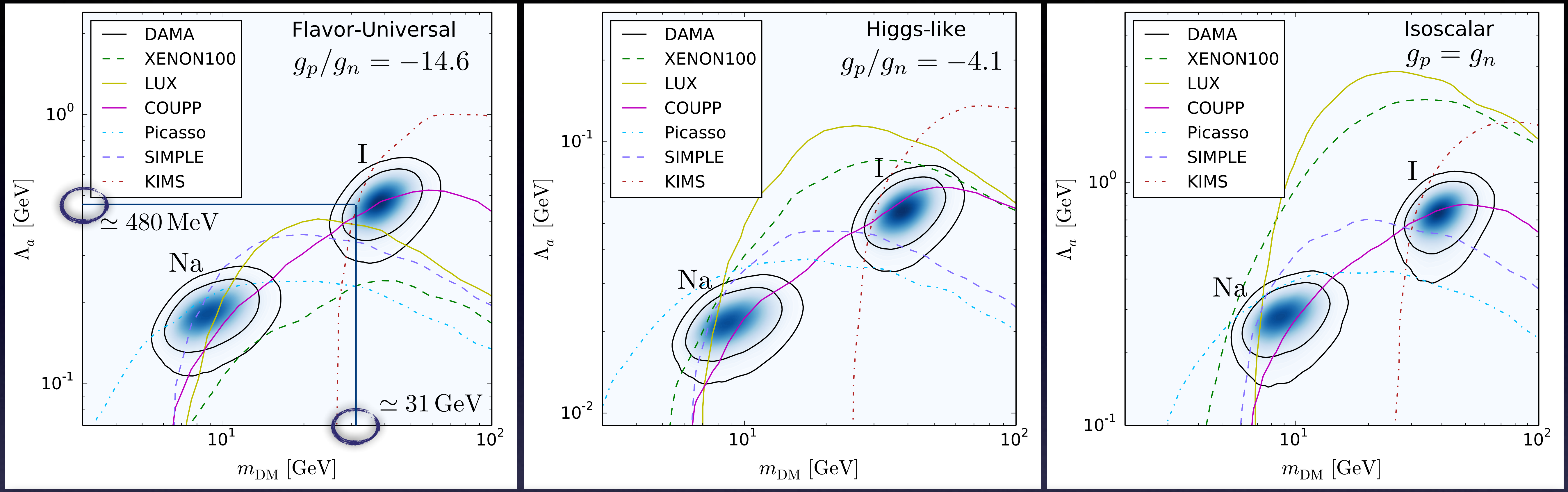
Results (DAMA is still alive !!)



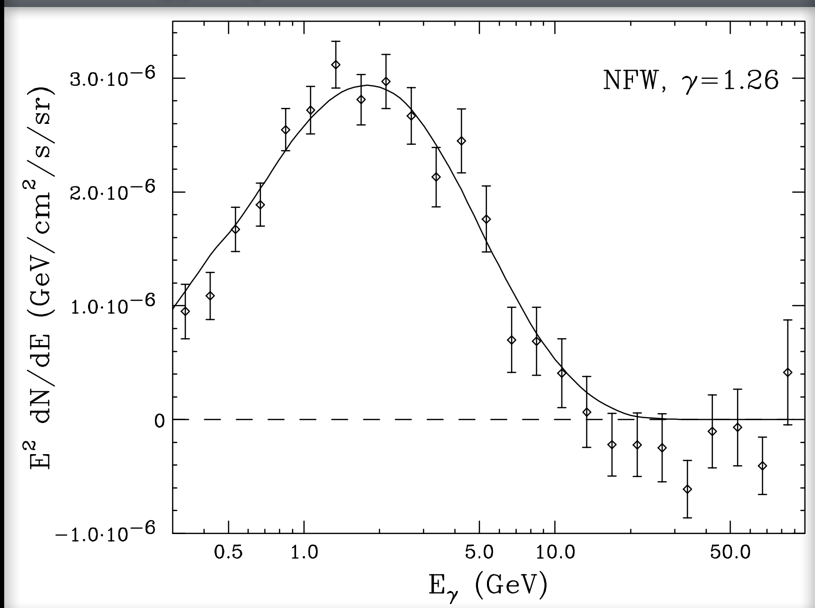
"Not so Coy DM explains DAMA (and the GC excess)", Published in PRL, arXiv:1406.5542

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

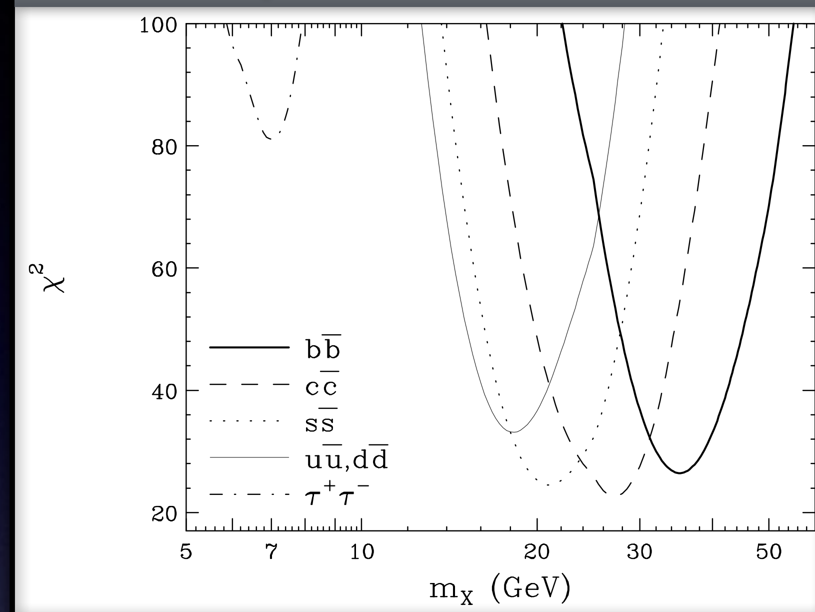
- ✔ for flavor-universal couplings: part of the I region is compatible at 99% CL with all null results experiments due to the large isospin violation
- ✔ for higgs-like couplings: the LUX and XENON100 bounds are less suppressed due to the reduced g_p/g_n enhancement, and the bounds disfavored both Na 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

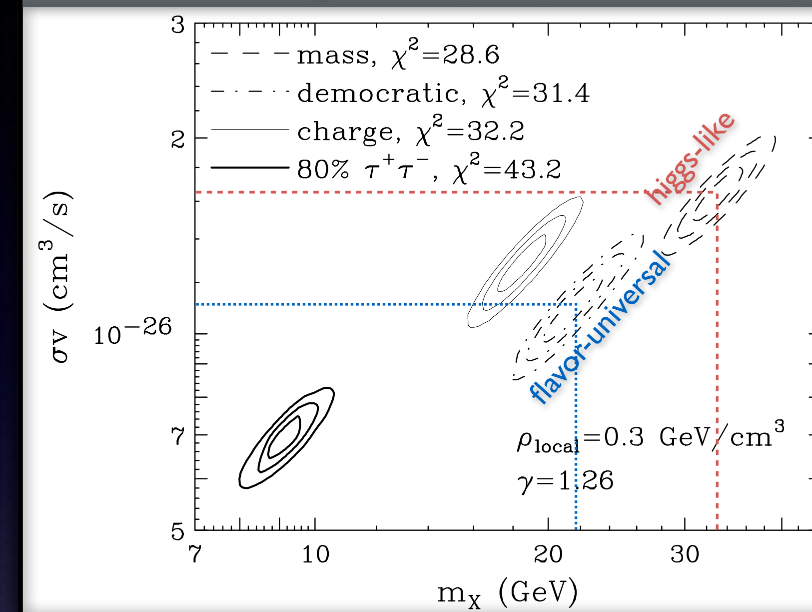
Energy Spectrum of the excess



DM Interpretation of the excess



Allowed regions (Majorana DM)



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

Best fit values adjusted for our DM model

	$m_{\rm DM}^{\rm best}$	$\langle\sigma v\rangle_{\rm best}$
Universal (*democratic*)	22 GeV	$2.2\times10^{-26}\,{\rm cm}^3/{\rm s}$
Universal (*heavy-flavors*)	31 GeV	$2.8\times10^{-26}\,{\rm cm}^3/{\rm s}$
Higgs-like	33 GeV	$3.2\times10^{-26}\,{\rm cm}^3/{\rm s}$

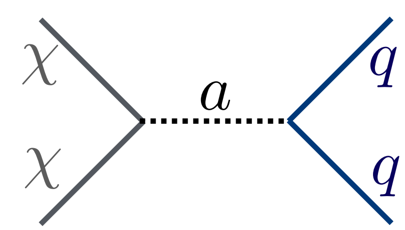
Relativistic Lagrangian at the quark-level

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

- ☑ χ is a Dirac Fermions
- ☑ unlike DD, the gamma-rays fluxes are different if the DM particles couple "democratically" with all quarks or just with the heavy ones.

Comparison with the theoretical prediction

χ can annihilate to quarks via s-channel exchange



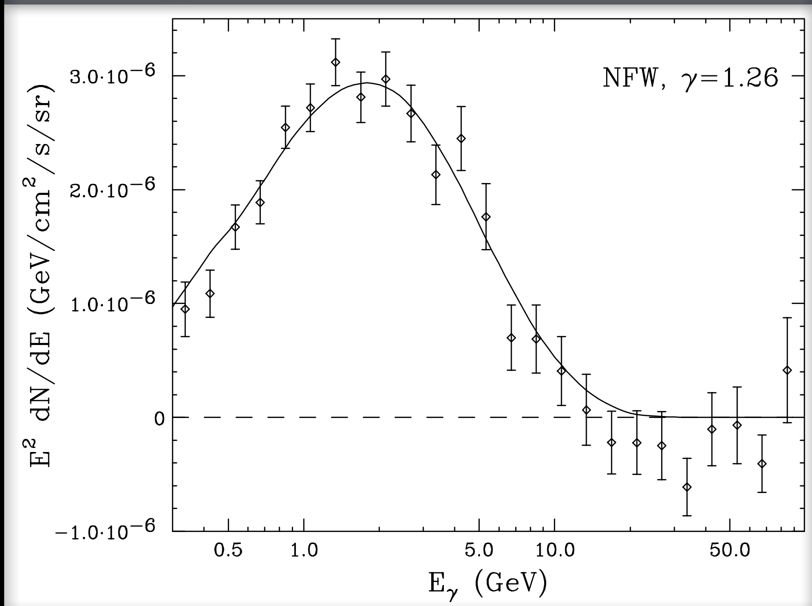
the energy scale of the effective operator constrained by DAMA gives $\Lambda_a = m_a/\sqrt{g\,g_{\rm DM}} \ll m_{\rm DM}$

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

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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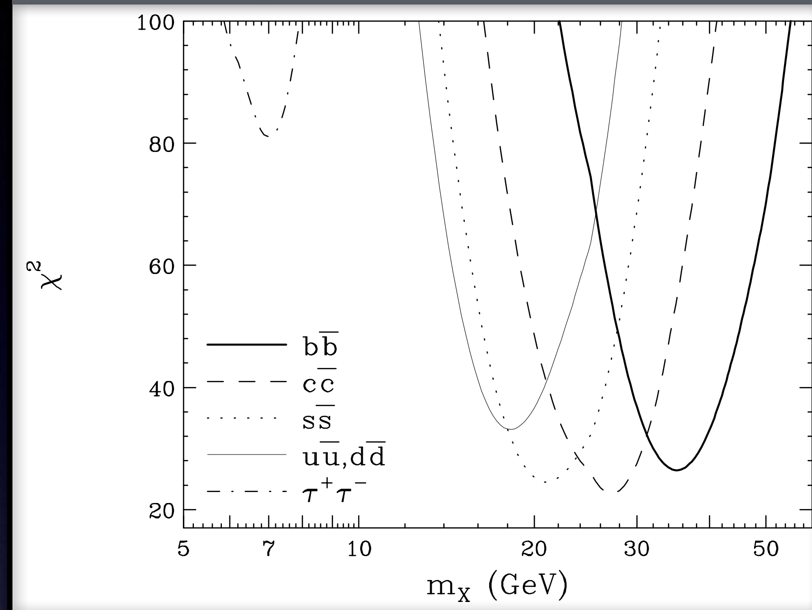

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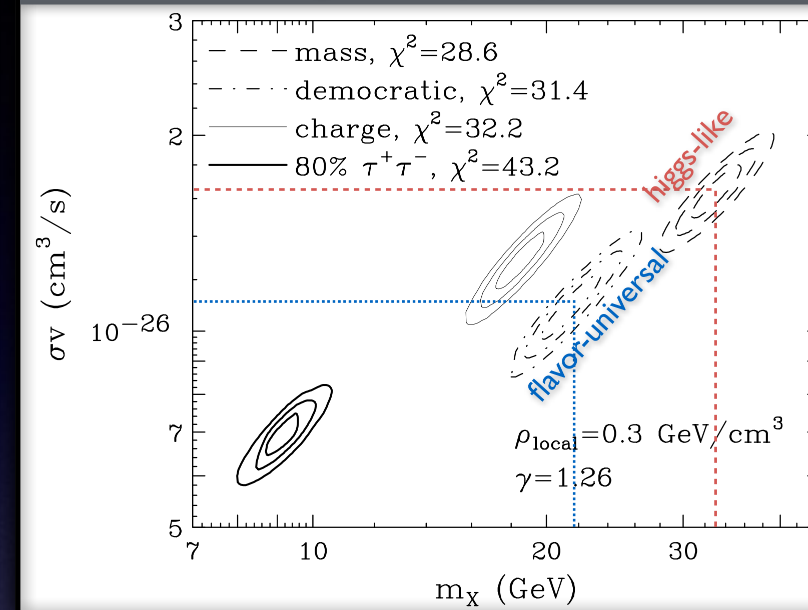

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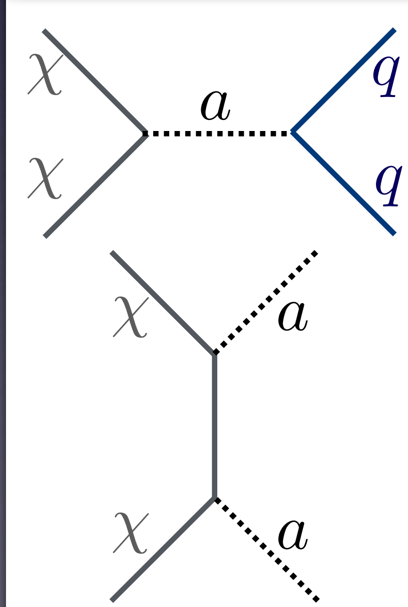
Theoretical prediction for the Relic Abundance



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

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

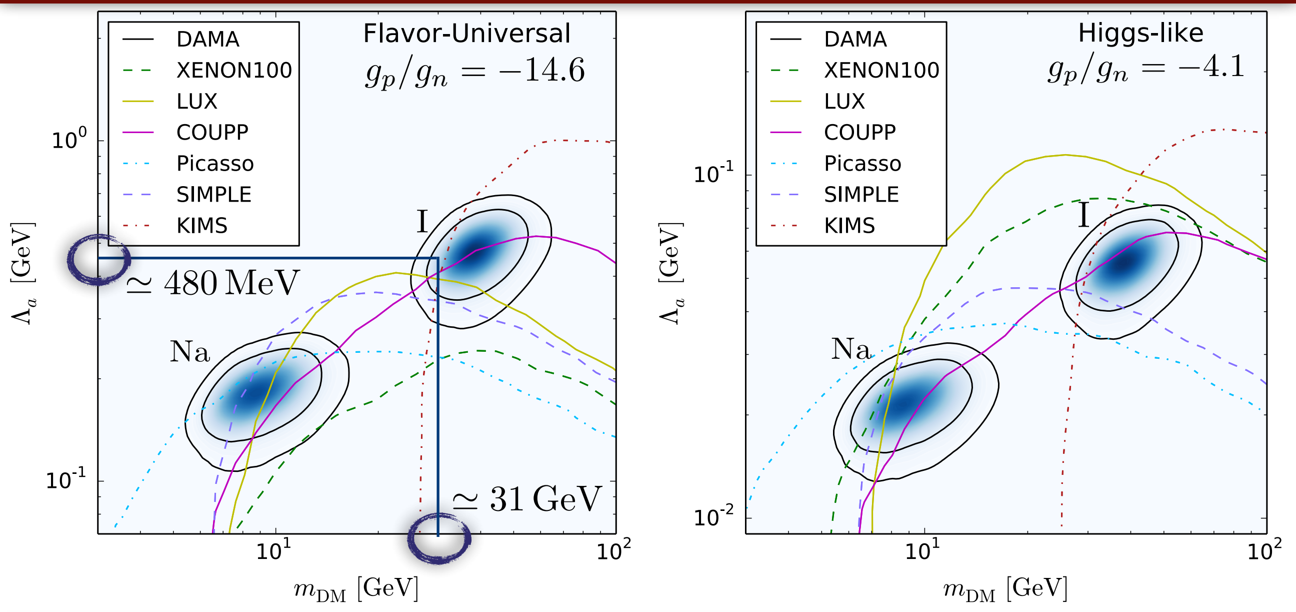
Bottom line: from the three observables one can fully determine the free parameters of the model

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

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

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

1 Interpretation of the DAMA results



2 Interpretation of the GC excess in gamma-rays

	$m_{\rm DM}^{\rm best}$	$\langle\sigma v\rangle_{\rm best}$
Universal (*democratic*)	22 GeV	2.2×10^{-26} cm^3/s
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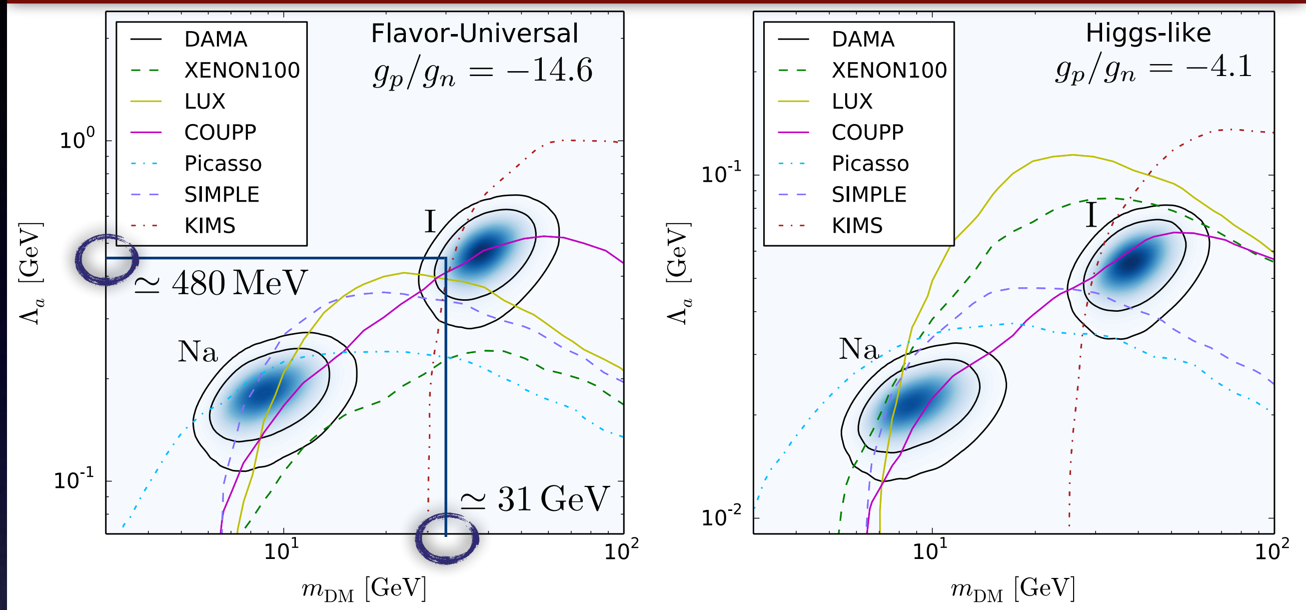

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3 Correct Relic Density

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 & Conclusions

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
  signal
  - 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
  gamma-rays and at the same time

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
$g\,g_q$	$(g\,g_q)^{\rm best} \simeq 1.8\times10^{-2}$
$g_{\rm DM}$	$g_{\rm DM}^{\rm best} \simeq 0.72$
$m_{\rm DM}$	$m_{\rm DM}^{\rm best} \simeq 31$ GeV
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