Is Coy dark matter really coy?

based on PRL 114 (2015) 011301

in collaboration with E. Del Nobile and P. Panci

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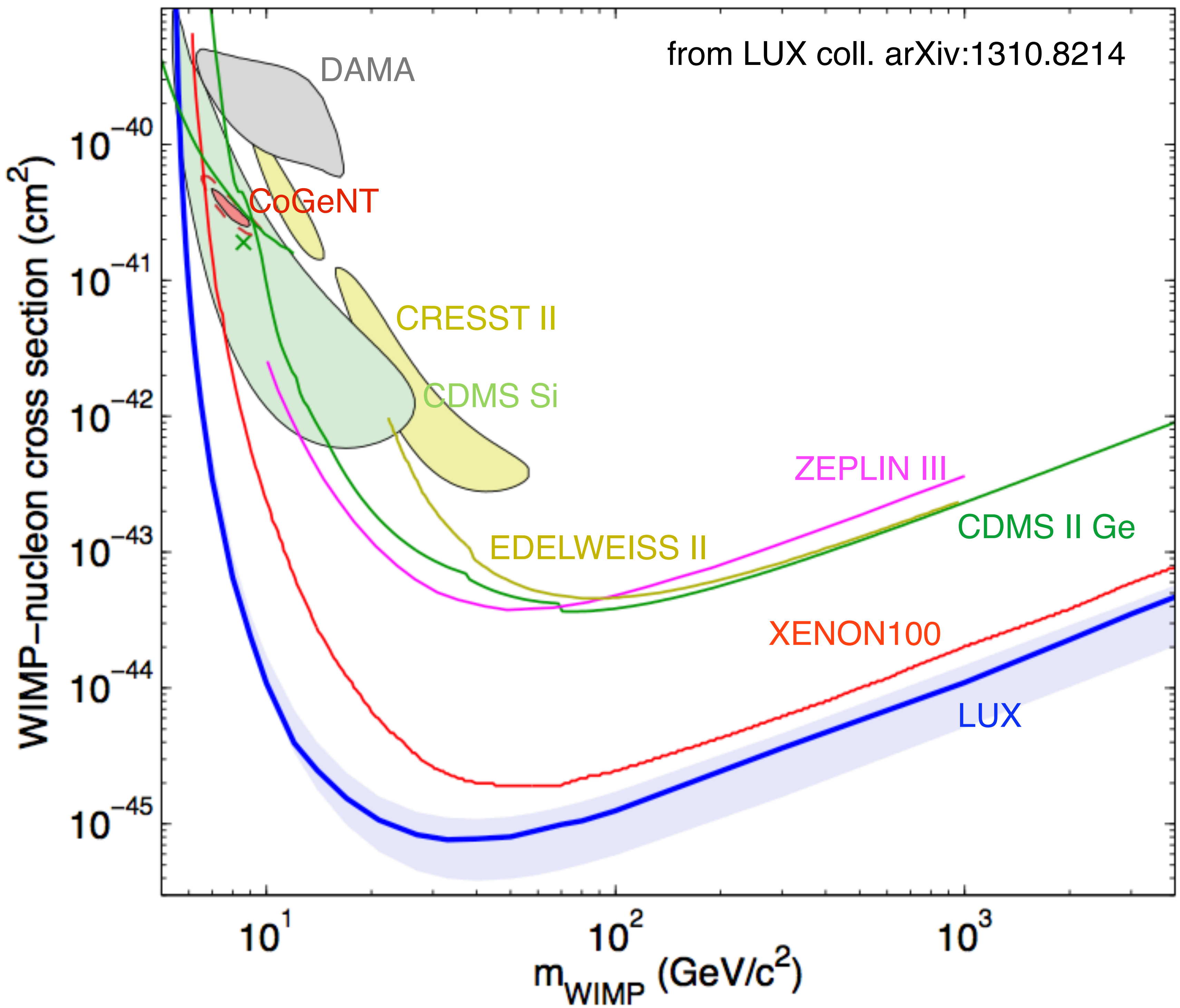
Bolshoi simulation, NASA

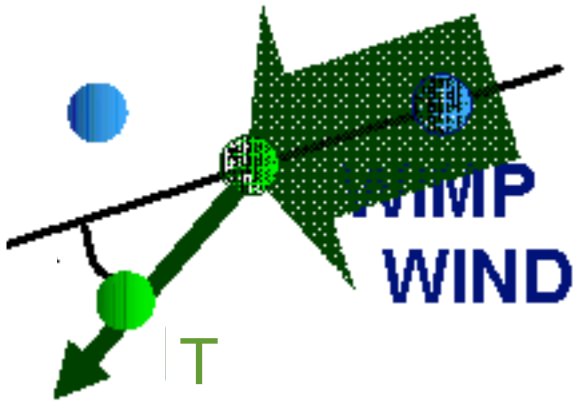
General status of Dark Matter (DM) direct detection



1. Scalar spin-independent (SI) and model independent interaction DM-nucleus

2. Fixed astrophysics in the event rate (DM velocity distribution and astro parameters)

Uncertainties in the event rate



$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}} = \frac{\xi_T}{m_T}\frac{\rho_\odot}{m_\mathrm{DM}}\int_{v\geqslant v_\mathrm{min}} \mathrm{d}^3v\, \frac{f(\vec{v})}{v}\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}}$$

$$v_\mathrm{min} = \sqrt{\frac{m_T E_\mathrm{R}}{2\mu^2}}$$

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}} = \frac{m_T\sigma_n^\mathrm{SI}}{2\mu_n^2}\,\frac{\left(f_p^2 Z + (A-Z)f_n^2\right)^2}{f_n^2}\mathcal{F}^2(E_\mathrm{R})$$

- f_n and f_p can be different!

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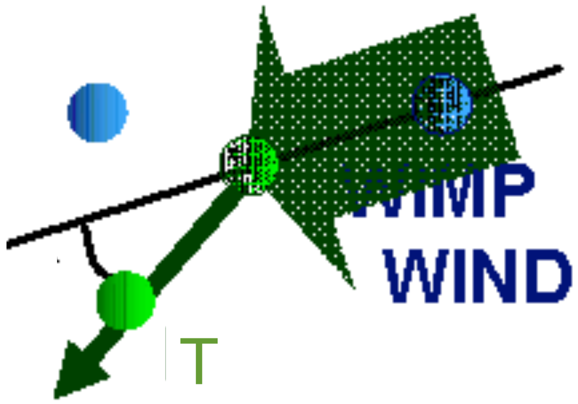

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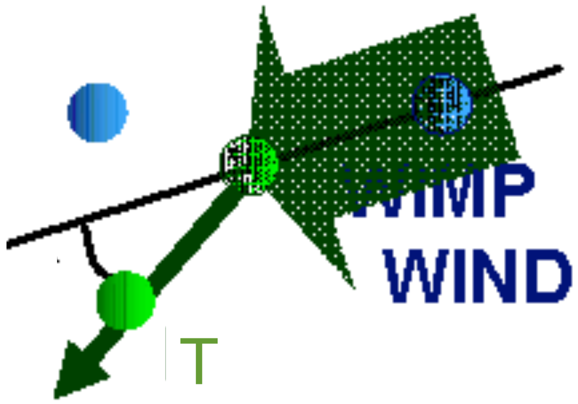

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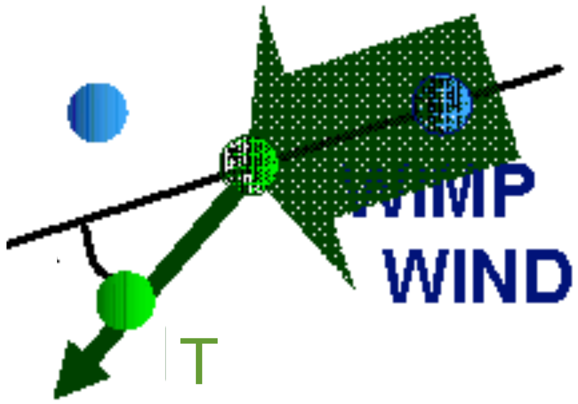

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Depend on DM velocity distribution and astrophysical parameters

- f(v) is not a Maxwell-Boltzmann distribution!

- Astrophysical parameters not well measured

$$v_0^\mathrm{obs} = 230 \pm 24.4 \text{ km s}^{-1}$$
$$v_\mathrm{esc}^\mathrm{obs} = 544 \pm 39 \text{ km s}^{-1}$$
$$\rho_\odot^\mathrm{obs} = 0.4 \pm 0.2 \text{ GeV cm}^{-3}$$

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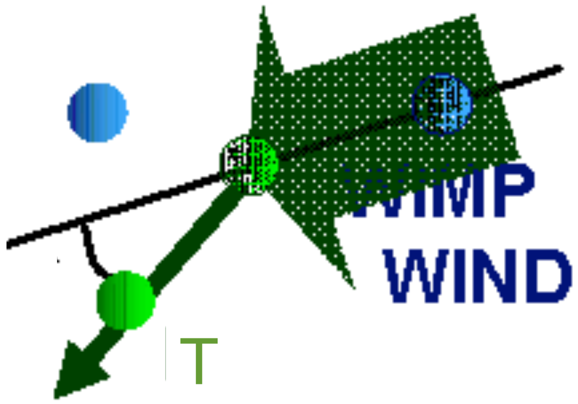

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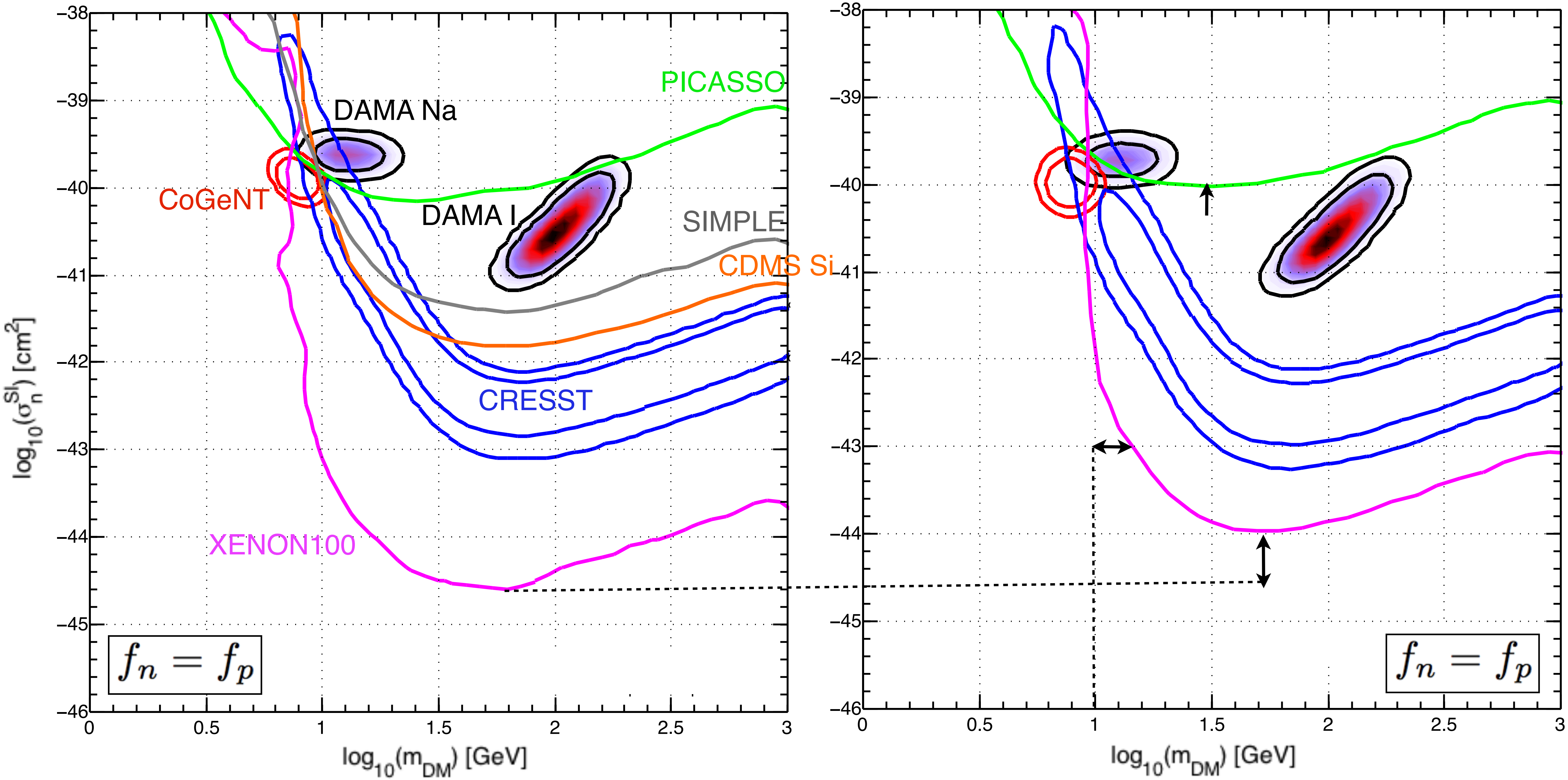
• f_n and f_p can be different!

All these effects can be simultaneously accounted for within Bayesian statistics

Effect of ASTROPHYSICAL uncertainties

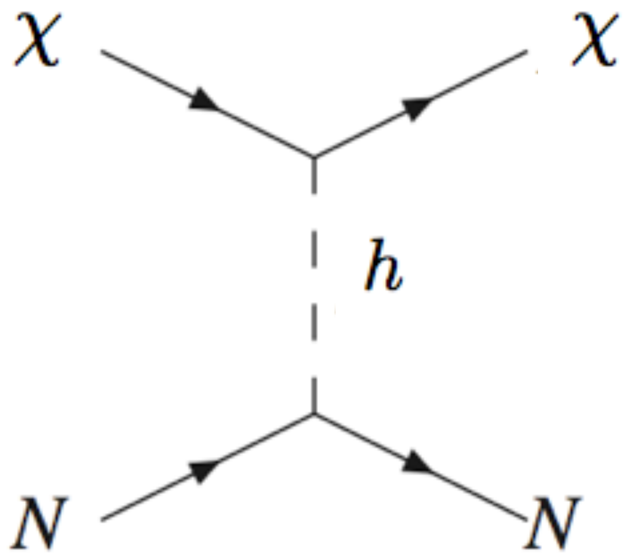
Standard approach: astro FIXED

NFW density profile and marginalized on astro parameters



CA, review for PDU, arXiv:1310.5718

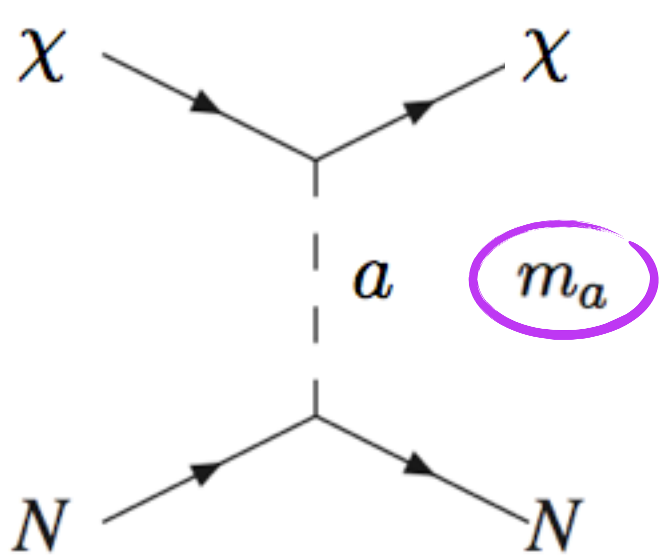
Changing the DM-nucleus interaction



Scalar SI comes from e.g. interaction with Higgs:

$$\mathscr{L}_{\rm int} = -\frac{y_{\rm DM}}{\sqrt{2}} h\bar{\chi}\chi - \sum_f \frac{y_f}{\sqrt{2}} h\bar{f}f$$

$f_n \sim f_p$



Pseudo-scalar interaction (Coy DM):

$$\mathscr{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}} a\bar{\chi}\gamma_5\chi - ig\sum_q \frac{g_q}{\sqrt{2}} a\bar{q}\gamma_5 q$$

1. Flavor-Universal couplings: $g_q = 1$
2. Higgs-like: $g_q = \frac{m_q}{174\,\mathrm{GeV}}$

3 free parameters

Coy DM effective operator I

$$\mathscr{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}} a\bar{\chi}\gamma_5\chi - ig\sum_q \frac{g_q}{\sqrt{2}} a\bar{q}\gamma_5 q$$

Can be written in terms of effective contact operator (DM typical velocity is 10^{-3}c)

$$\mathscr{L}_{\rm eff} = \frac{1}{2\Lambda_a^2}\sum_{N=p,n} g_N\,\bar{\chi}\gamma^5\chi\,\bar{N}\gamma^5 N \qquad \Lambda_a \equiv \frac{m_a}{\sqrt{g_{\rm DM}g}}$$

- The energy scale is the unknown variable instead of the cross-section
- The coefficients g_N are defined to be

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

Flavor-Universal couplings: $g_p/g_n = -16.4$

Higgs-like: $g_p/g_n = -4.1$

NATURAL violation of isospin

Coy DM effective operator II

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}} = \frac{1}{128\pi}\frac{q^4}{\Lambda_a^4}\frac{m_T}{m_\mathrm{DM}^2 m_N^2}\frac{1}{v^2}\sum_{N,N'=p,n} g_N g_{N'} F_{\Sigma''}^{(N,N')}(q^2)$$

See talk by P. Panci for more details on NRO

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- This interaction is SPIN-DEPENDENT (SD) as it comes from this non-relativistic operator:

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

- DAMA: Iodine (Sodium) has an unpaired proton
- LUX: Xenon has an unpaired neutron
- Natural isospin violation implies an strong suppression/enhancement to DM scattering

See talk by P. Panci for more details on NRO

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Nuclear form factor:

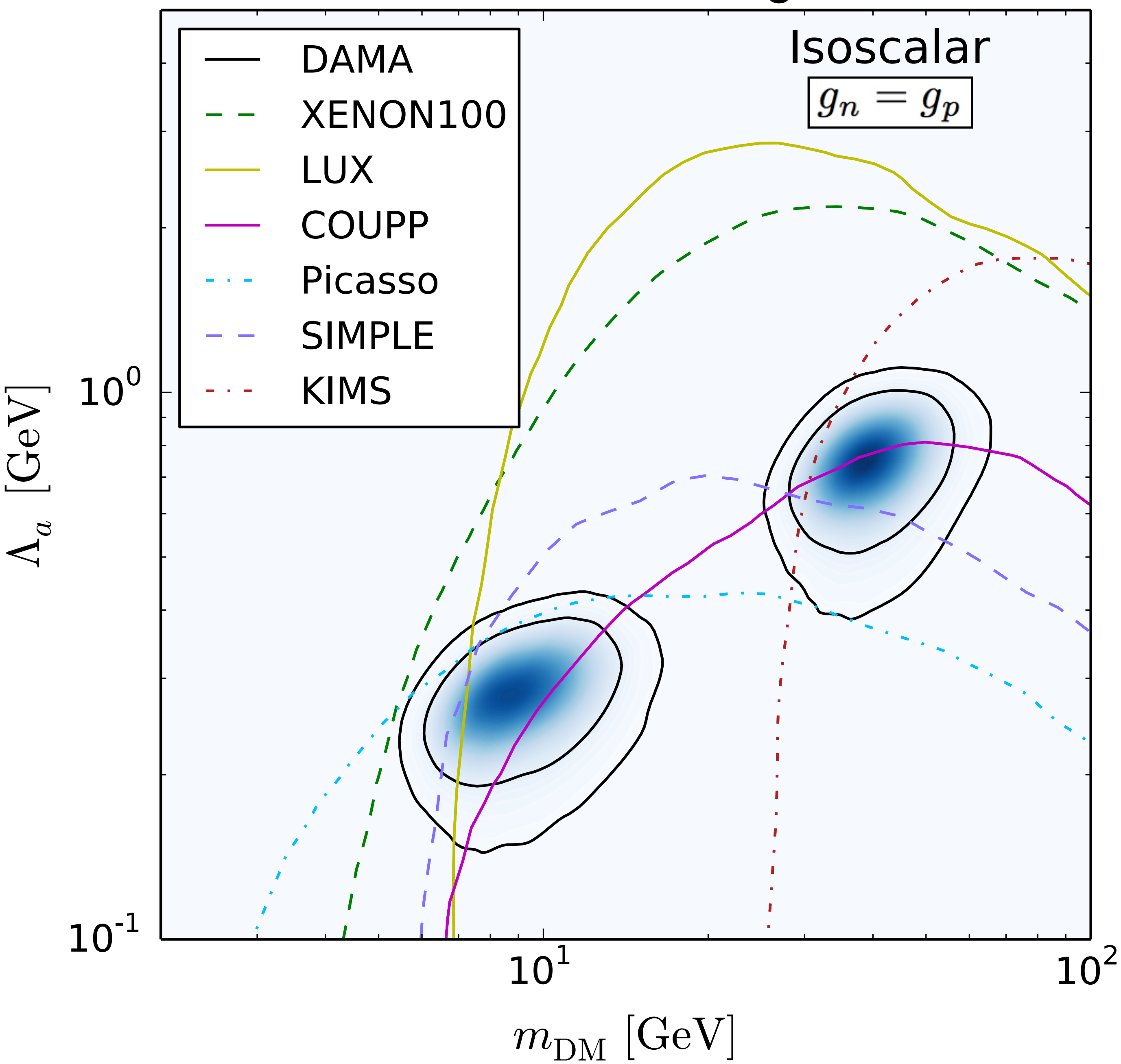
• Source of uncertainties (number of event can change by a factor ~ 3 for standard SD)

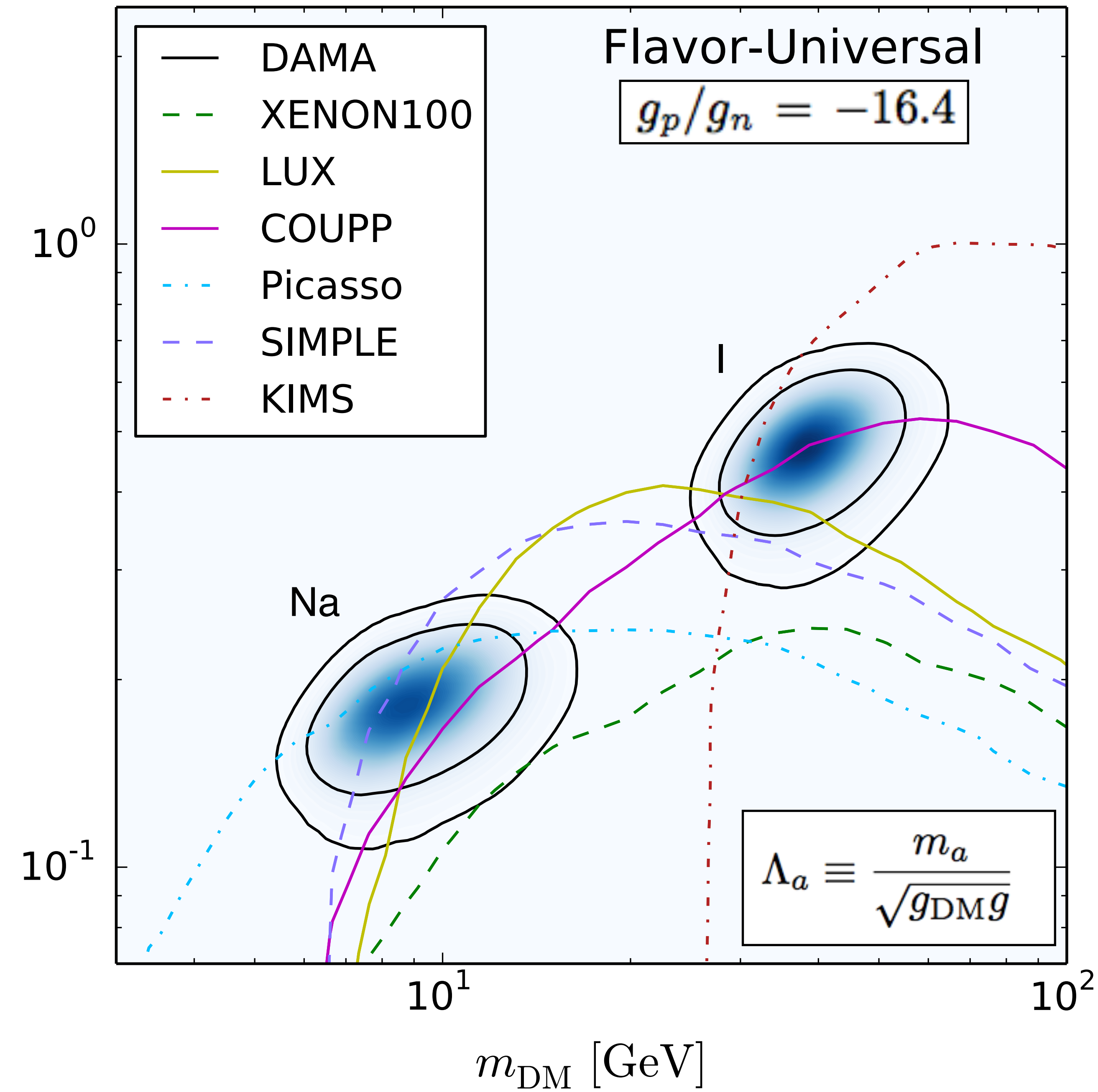
• use of the correct form factor (computed in Fitzpatrick et al. arXiv:1203.3542)

See talk by P. Panci for more details on NRO

Direct detection of Coy DM

marginalized on astro and exp parameters



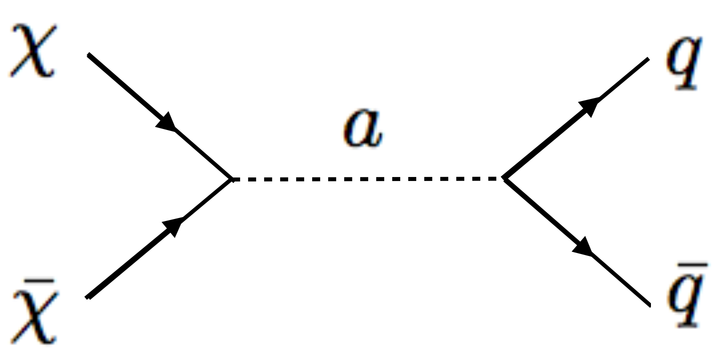


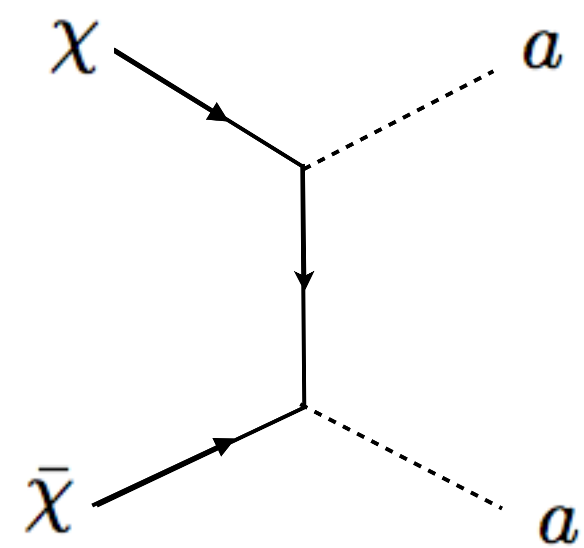
$g\,g_q \sim 10^{-3}$-10^{-2}	$m_a \sim$ 35-60 MeV
$g_{DM} \sim$ 0.5-0.8	$m_{DM} \sim$ 20 - 35 GeV

Relic density & indirect detection I

$$\mathscr{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}} a\bar{\chi}\gamma_5\chi - ig\sum_q \frac{g_q}{\sqrt{2}} a\bar{q}\gamma_5 q$$

Annihilation of Coy DM mediated by two processes





s-wave contribution

p-wave contribution
(dependent on the DM relative velocity)

$$x \equiv \frac{m_{\rm DM}}{T}$$

$$\langle\sigma v\rangle(x) = \sum_q \mathcal{A}_q + \frac{3}{2}\frac{\mathcal{B}}{x} + \mathcal{O}(x^{-2})$$

Relic density & indirect detection I

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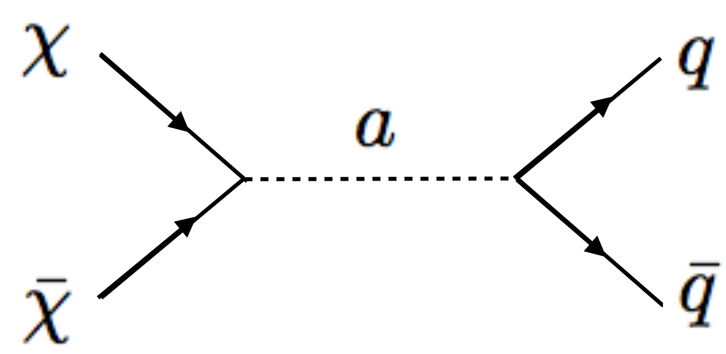

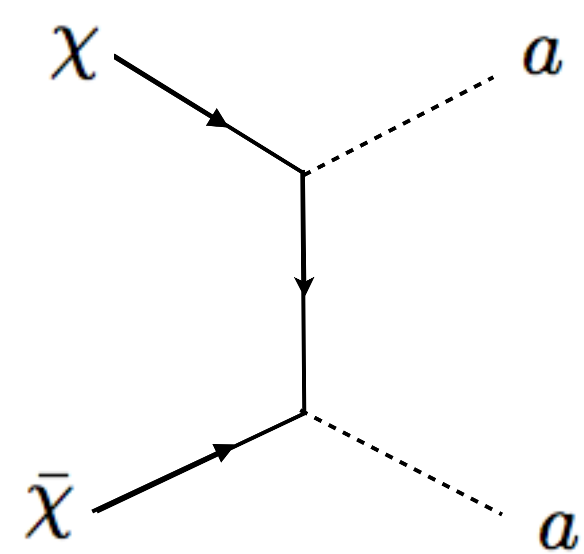

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p-wave contribution
(dependent on the DM relative velocity)

$$x \equiv \frac{m_{\rm DM}}{T} \qquad \langle\sigma v\rangle(x) = \sum_q \mathcal{A}_q + \cancel{\frac{3\mathcal{B}}{2x}} + \mathcal{O}(x^{-2})$$

At present time (x_0>>1) only s-wave contribution is relevant

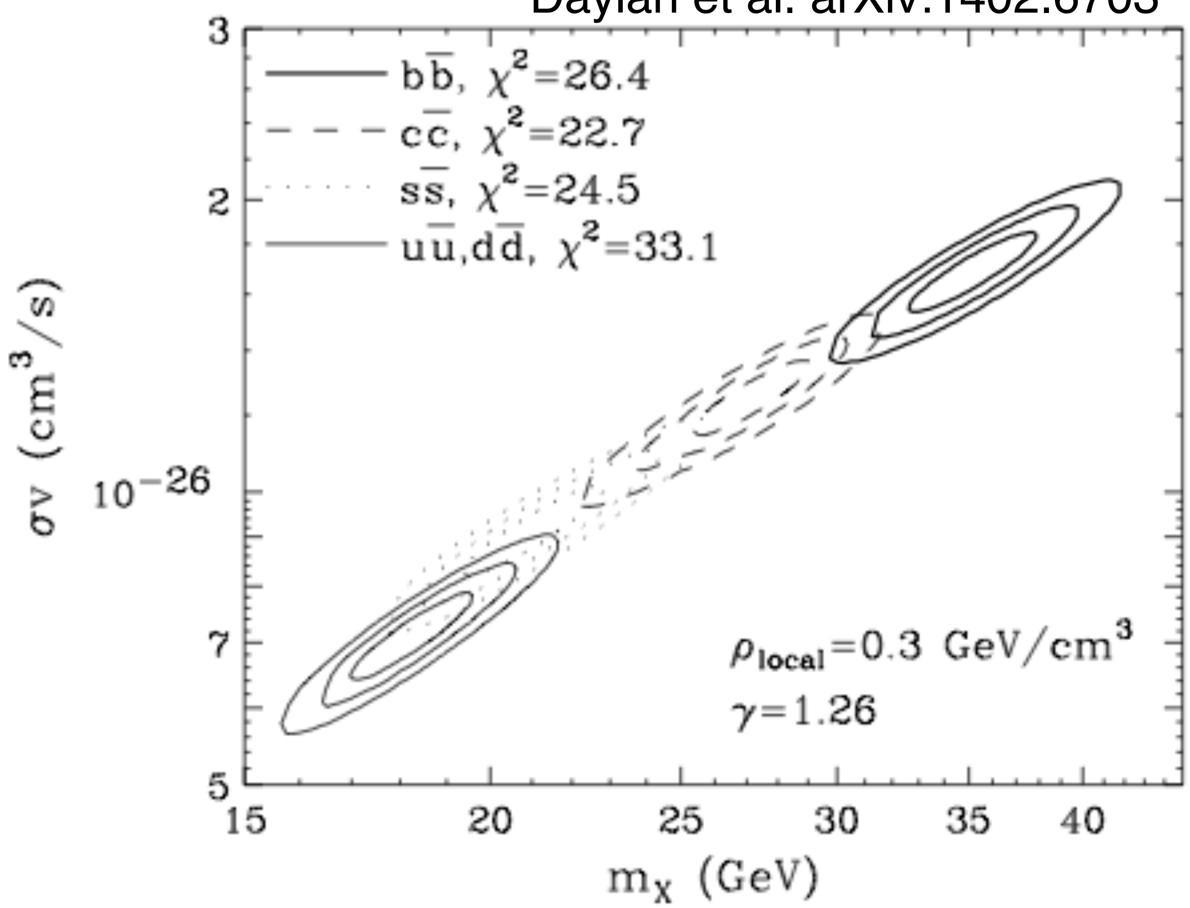
(i.e. for producing gamma ray flux)

Relic density & indirect detection II

- There is an excess in gamma rays from 1-3 GeV around the galactic center (GC)

- If due to DM, it can be explained by a ~ 30 GeV WIMP annihilating into quarks

Daylan et al. arXiv:1402.6703



Coy DM parameters for DAMA (heavy-flavor)

$g\,g_q \sim 10^{-3}$-10^{-2}	$m_a \sim$ 35-60 MeV
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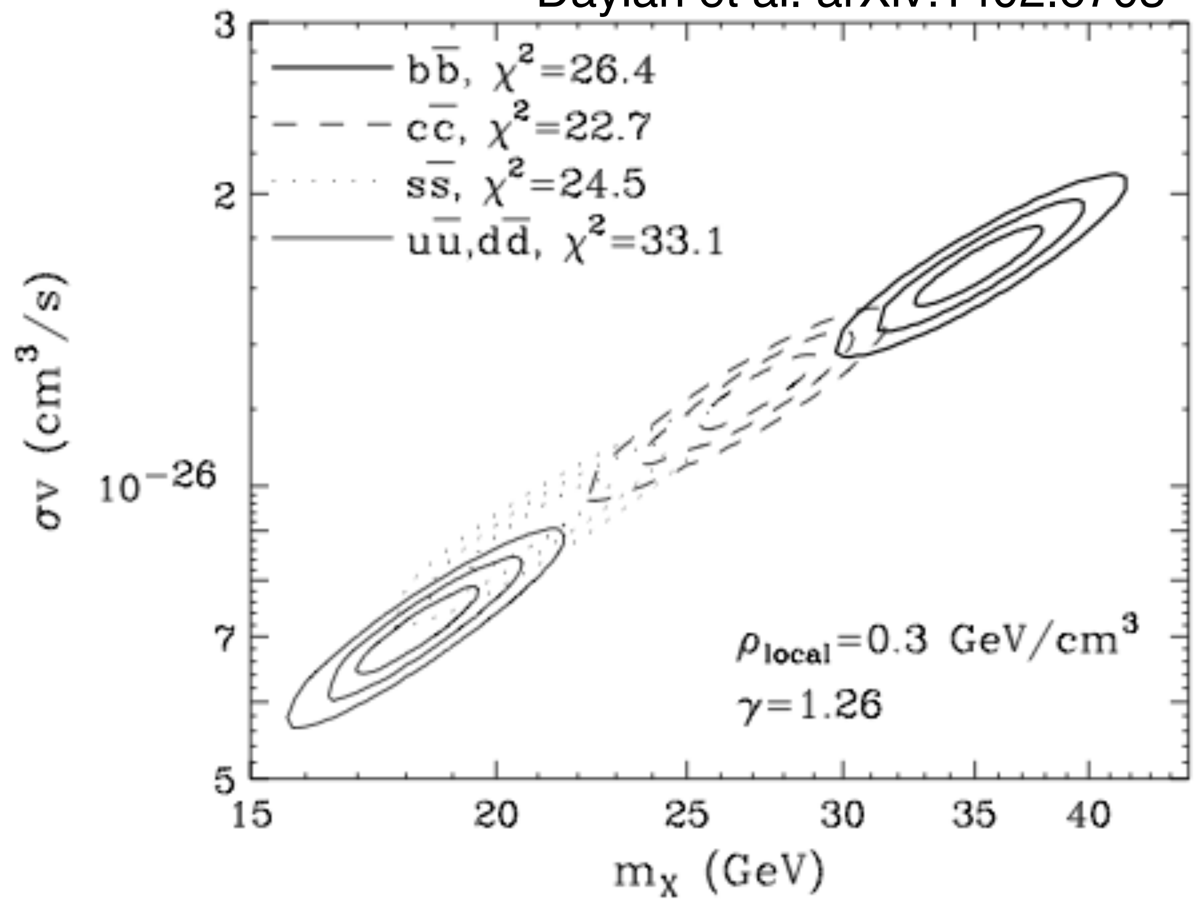

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$$\xrightarrow[\langle\sigma v\rangle(x_0)\sim 1.4\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}]{\langle\sigma v\rangle(x_{\rm fo})\sim 3\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}\left\{\begin{array}{l} g g_q \simeq 1.8\times 10^{-2} \\ g_{\rm DM}\simeq 0.72 \\ m_a \simeq 56\ \mathrm{MeV}\end{array}\right.$$

- Same ballpark of values explains at the same time DAMA and the gamma ray GC excess
- Model completely determined: relic density - gamma ray GC excess and DAMA constraints fix the 3 free parameters

Conclusions

- Difficult to reconcile DAMA with other exclusion bounds with SI (even allowing for all exp and astro uncertainties)
- Coy DM with light pseudo-scalar reconciles DAMA and LUX because it induces naturally isospin violation
- Coy DM explains the GC excess in gamma-rays and has the correct relic density (no free parameters left)
- Interesting phenomenological model
- Flavor constraints on the pseudo-scalar mediator are relevant (see Dolan et al. arXiv:1412.5174)
- Light pseudo-scalar interesting for self-interacting DM

Back up slides

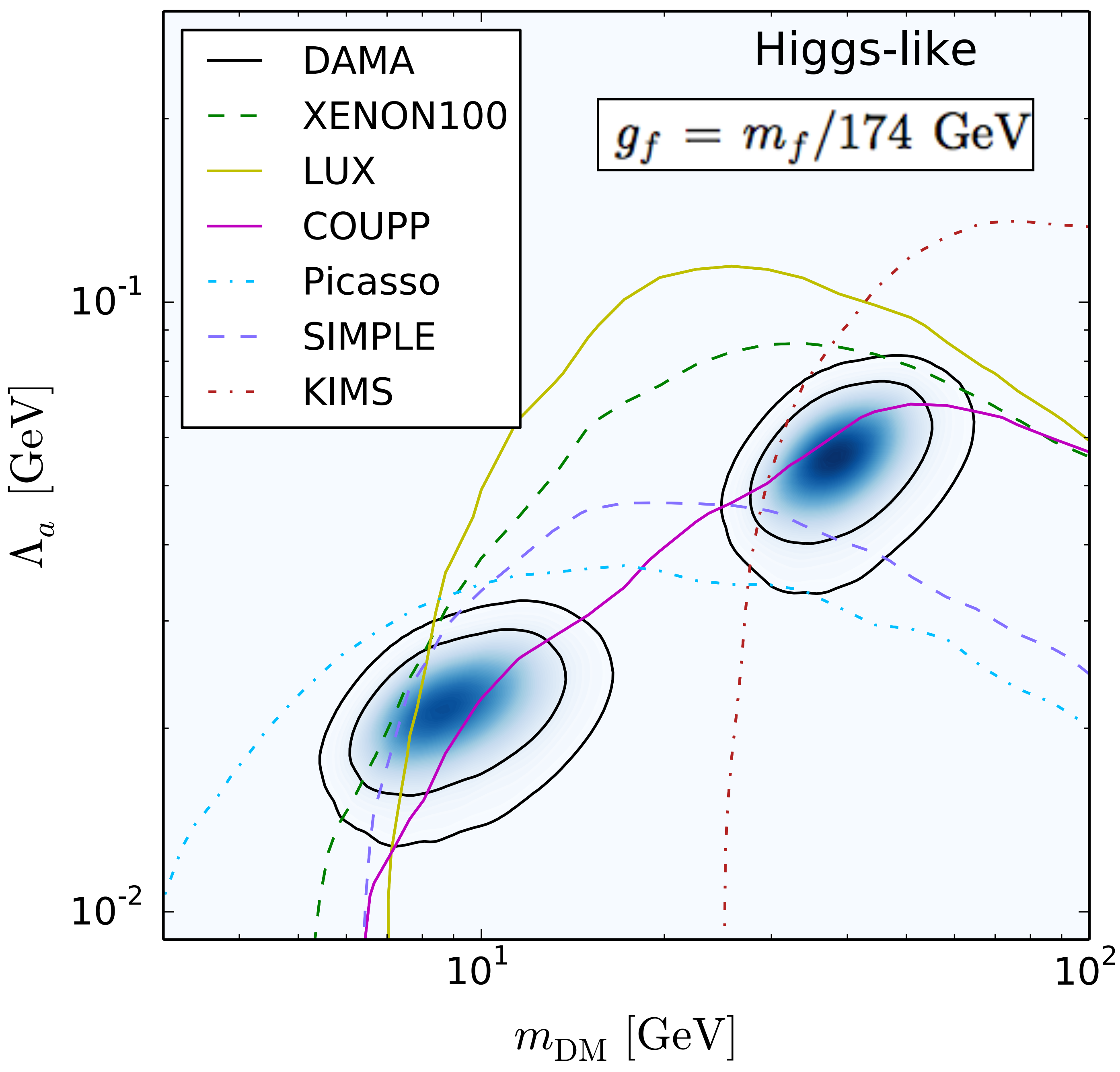
Flavor constraints

The light pseudo scalar mediator can be constrained by rare meson decays.

For $m_a < 100$ MeV, the most constraining channels are:

Channel	Experiment	Mass range [MeV]	Relevant
$K^+ \to \pi^+ + \text{inv}$	E949	0–110	Long lifetime
	E787	0–110 & 150–260	Long lifetime
$K_L \to \pi^0 \gamma\gamma$	KTeV	40–100 & 160–350	Photonic decays
$K^+ \to \pi^+ A$	$K_{\mu 2}$	10–130 & 140–300	All decay modes
$B^0 \to K_S^0 + \text{inv}$	CLEO	0–1100	Long lifetime
$b \to s\, g$	CLEO	$m_A < m_B - m_K$	Hadronic decays
$K, B \to A + X$	CHARM	0–4000	Photonic decays

Coy dark matter with Higgs-like couplings



Quark spin content of the nucleon

Cheng and Chiang, arXiv:1202.1292

$$\boxed{\begin{aligned} \Delta_u^{(p)} &= \Delta_d^{(n)} = +0.84 \\ \Delta_d^{(p)} &= \Delta_u^{(n)} = -0.44 \\ \Delta_s^{(p)} &= \Delta_s^{(n)} = -0.03 \end{aligned}}$$

$$\bar{m} \equiv (1/m_u + 1/m_d + 1/m_s)^{-1}$$

- These are conservative values
- These coefficients are subject to large uncertainties (measured experimentally with e.g. pion scattering)
- For extreme values the natural isospin violation ca be $g_p/g_n = -44.2$
- The value of g_N coefficients does not change if the pseudo-scalar couples only to heavy flavors (s,t,b)
- This makes the pseudo-scalar an axion-like particle

Constraints on the pseudoscalar

1. ok for BaBaR constraints

2. ok for electric (moun) anomalous magnetic moments

electrons' AMM

muons' AMM

electrons' AMM, universal couplings

muons' AMM, universal couplings

Constraints from magnetic moments

electrons' AMM, leptophilic
electrons' AMM, only heavy flavors
muons' AMM, leptophilic
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Details on annihilation cross-section

$$\sigma(\bar{\chi}\chi \to \bar{q}q) = N_c \frac{g^2 g_f^2 g_{\rm DM}^2}{64\pi} \frac{s}{(s-m_a^2)^2} \sqrt{\frac{s-4m_q^2}{s-4m_{\rm DM}^2}}$$

$$\sigma(\bar{\chi}\chi \to aa) = \frac{g_{\rm DM}^4}{256\pi} \frac{h(t_0)-h(t_1)}{s(s-4m_{\rm DM}^2)}$$

$$t_{\substack{0\\1}} = -\frac{1}{4}\left(\sqrt{s-4m_{\rm DM}^2} \mp \sqrt{s-4m_a^2}\right)^2$$

$$h(t) \equiv 4\left(m_{\rm DM}^2 - t\right) + \frac{m_a^4(u-t)}{\left(m_{\rm DM}^2-t\right)\left(m_{\rm DM}^2-u\right)} - \frac{2m_a^4 + \left(s-2m_a^2\right)^2}{s-2m_a^2} \log\left(-\frac{m_{\rm DM}^2-t}{m_{\rm DM}^2-u}\right)$$

$$u = 2m_{\rm DM}^2 + 2m_a^2 - s - t$$

$$\langle\sigma v\rangle(x) = \sum_q \mathcal{A}_q + \frac{3}{2}\frac{\mathcal{B}}{x} + \mathcal{O}(x^{-2})$$

$$\mathcal{A}_q = \frac{N_c}{8\pi} \frac{g^2 g_f^2 g_{\rm DM}^2 m_{\rm DM}^2}{(4m_{\rm DM}^2 - m_a^2)^2} \sqrt{1-\frac{m_q^2}{m_{\rm DM}^2}}$$

$$s \simeq m_{\rm DM}^2\left(4-v^2\right)$$

$$\mathcal{B} = \frac{g_{\rm DM}^4}{96\pi} \frac{m_{\rm DM}^2(m_{\rm DM}^2-m_a^2)^2}{(2m_{\rm DM}^2-m_a^2)^4} \sqrt{1-\frac{m_a^2}{m_{\rm DM}^2}}$$

Flavor constraints

We study a Dirac Dark Matter particle interacting with ordinary matter via the exchange of a light pseudo-scalar, and analyze its impact on both direct and indirect detection experiments. We show that this candidate can accommodate the long-standing DAMA modulated signal and yet be compatible with all exclusion limits at $99_S\%$ CL. This result holds for natural choices of the pseudo-scalar-quark couplings (e.g. flavor-universal), which give rise to a significant enhancement of the Dark Matter-proton coupling with respect to the coupling to neutrons. We also find that this candidate can accommodate the observed $1-3$ GeV gamma-ray excess at the Galactic Center and at the same time have the correct relic density today. The model could be tested with measurements of rare meson decays, flavor changing processes, and searches for axion-like particles with mass in the MeV range.