Isospin-Violating Dark Matter Beyond Leading Order

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Physics at the interface: Energy, Intensity, and Cosmic frontiers
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w Cirigliano, Graesser **arXiv:1205.2695, JHEP**

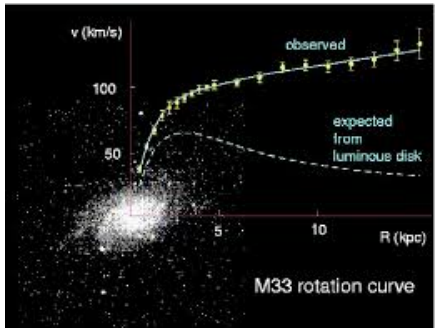
w Cirigliano, Graesser, Shoemaker arXiv:1311.5886

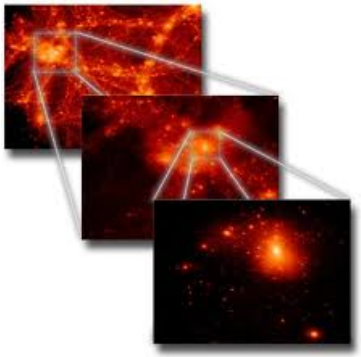
Santa Fe 2014 Summer Workshop, ``LHC After the Higgs'', July 1, 2014

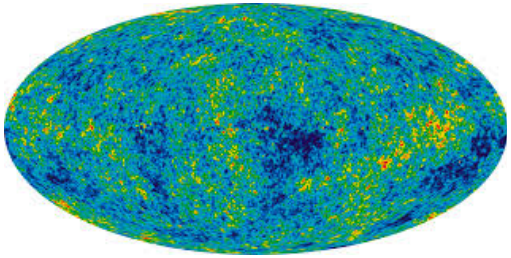
Outline

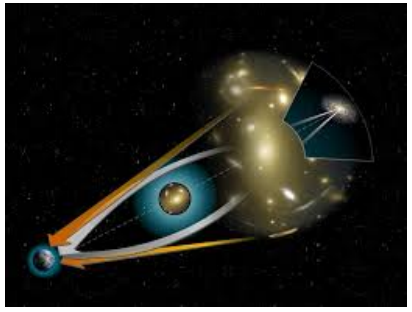
- Motivation
- WIMP-nucleus interaction from EFT
- Phenomenology for Xenon/CDMS-Si
- Conclusions

Motivation



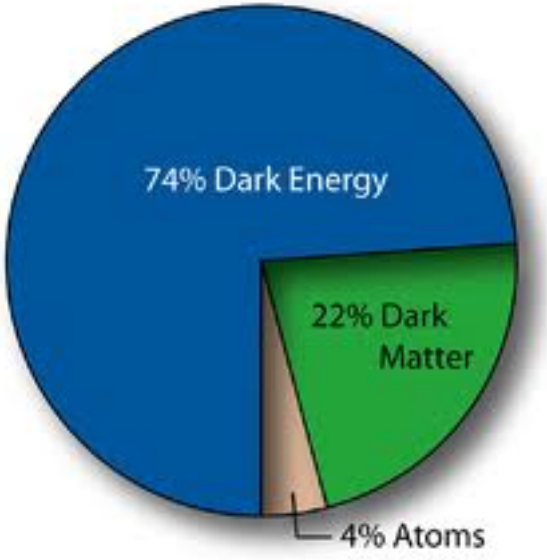






- Overwhelming evidence of dark matter presence in the universe
- All observation based on gravitational interactions only

$$\Omega_{\mathrm{DM}} \approx 0.22$$



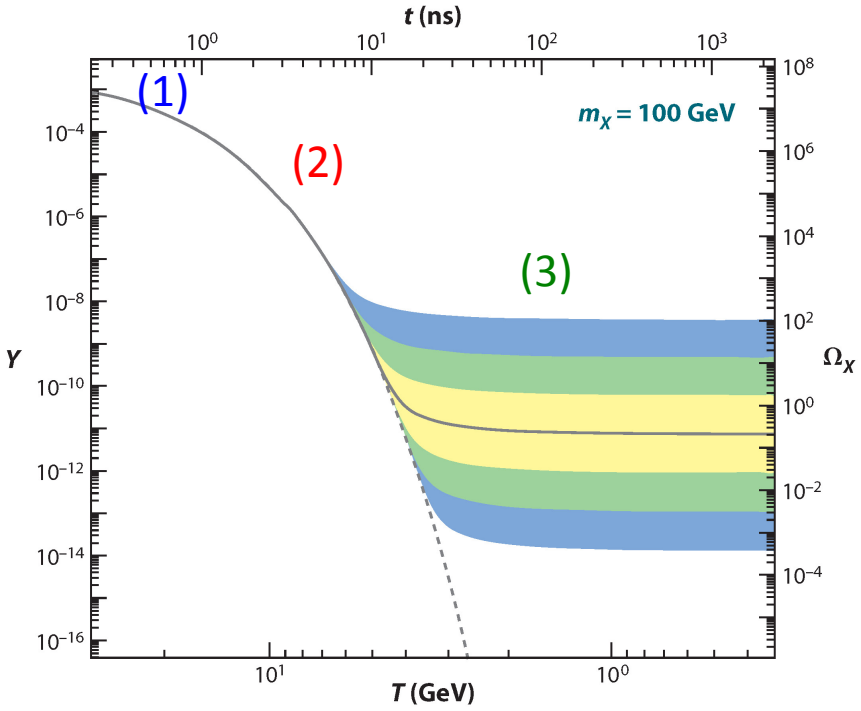
Motivation

- We know that Dark Matter exists through its gravitational interactions
- We do Not know what it is made of

Possible explanations for DM:

- Expand Standard Model with some new particles (SUSY, Extra dimensions, Technicolor, etc)
- Modified gravity laws

The "WIMP miracle"



(1) A new heavy particle is in thermal Equilibrium $\chi\bar{\chi} \leftrightarrow f\bar{f}$

(2) Universe cools down

$$\chi\bar{\chi} \not\rightarrow f\bar{f}$$

(3) Dark matter species freeze out

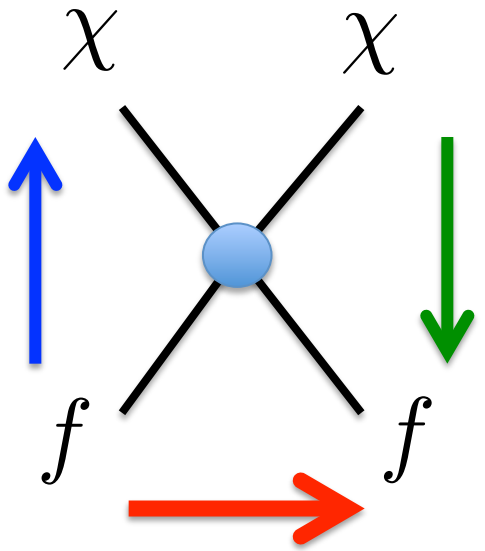
$$\chi\bar{\chi} \not\leftrightarrow f\bar{f}$$

$$\Omega_\chi h^2 \sim \frac{3\times 10^{-26}\mathrm{cm}^3/s}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$$

(for weak scale interactions)

Search for non-gravitational DM interactions

- Produce at LHC
- Indirect detection
- Direct detection

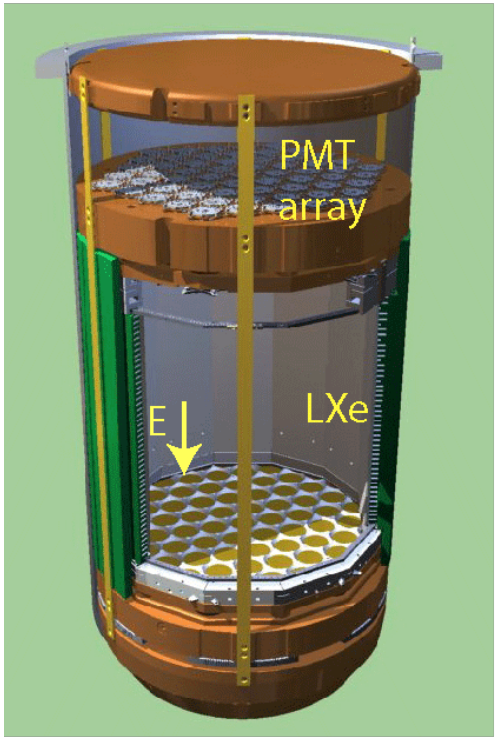


- In this talk we focus on DM scattering off a Nucleus
- WIMP-quark interaction leads to the WIMP-Nucleus interaction

Dark Matter Direct Detection

300 kg, liquid Xe

The Large Underground Xenon Experiment (LUX)



$m_\chi \sim \mathrm{GeV} - \mathrm{TeV}$

$v_\chi \sim 10^{-3}$

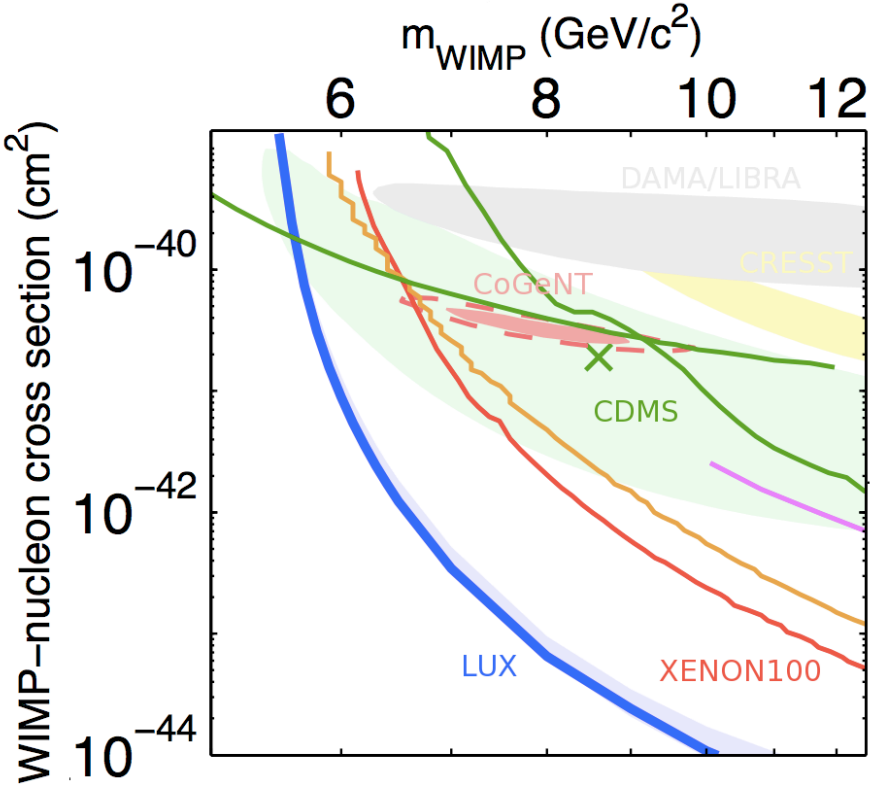
$E_R \sim 10 - 100\mathrm{KeV}$

First data released at the end of 2013

Direct Detection Results

$$\frac{dR}{dE_R}^{\mathrm{LO}} = \frac{\sigma_p \rho_{m_X}}{2\mu^2 m_X} \left| \Big(Z + (A - Z) r \Big) F(E_R) \right|^2 \times \eta(E_R, m_W, m_A)$$

$r = f_n / f_p$



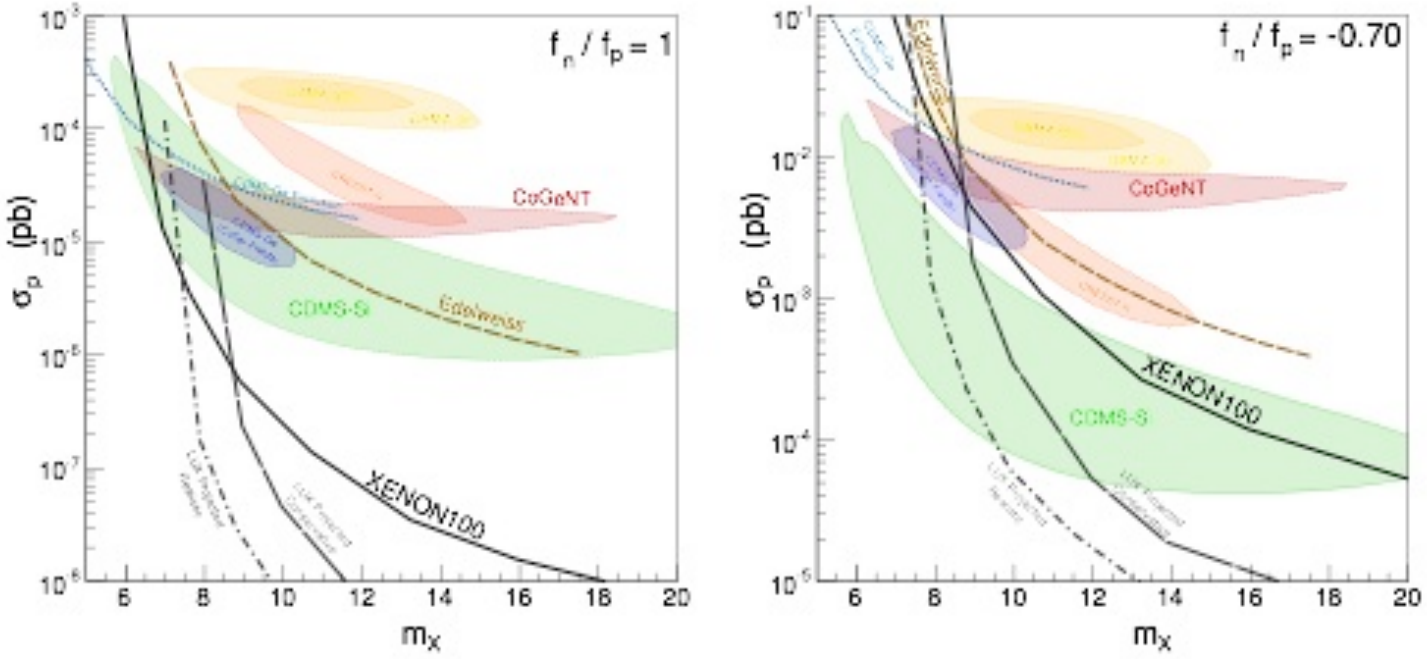
r=1 (Isospin-conserving DM)

Direct Detection Results

$$\frac{dR}{dE_R}^{\mathrm{LO}} = \frac{\sigma_p \rho_{m_X}}{2\mu^2 m_X} \left| \left(Z + (A-Z)r \right) F(E_R) \right|^2 \times \eta(E_R, m_W, m_A)$$

$r=f_n/f_p$

Feng, Kumar, Marfatia, Sanford, 2013



r=1 (Isospin-conserving DM)

r=-0.7 (Isospin-violating DM)

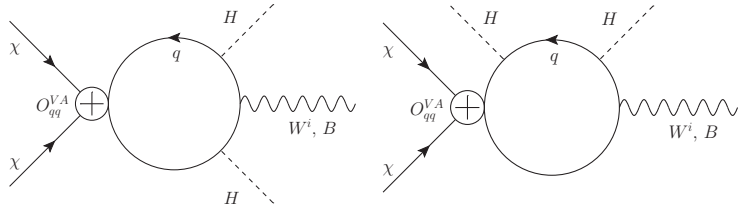
Feng, Kumar, Marfatia, Sanford, 2011

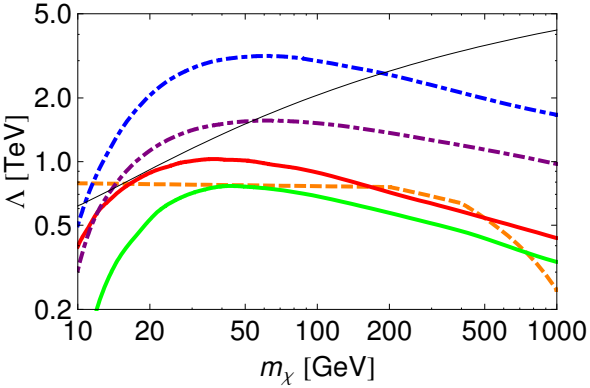
Isospin violation from SM running

Crivellin, D'Eramo, Procura, 2014

$$O^{IJ}_{qq} = \frac{1}{\Lambda^2}\,\bar{\chi}\Gamma^{\mu}_{I}\chi\;\bar{q}\,\Gamma_{J,\mu}\,q\,,$$

$$O^{I}_{HHD} = \frac{i}{\Lambda^2}\bar{\chi}\,\Gamma^{\mu}_{I}\chi\,[H^{\dagger}\overleftrightarrow{D}_{\mu}H\,]\,,$$



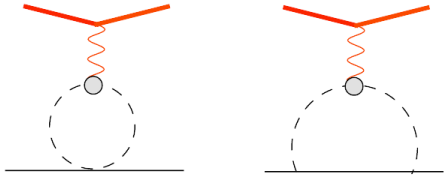


- Because of EW running, the spin-dependent operators mix with spin-independent ones
- Isospin violation is generated at low scale even if UV complete theory is isospin conserving

Our Goal

- Study the phenomenology of long-distance QCD corrections to the leading order WIMP-nucleus interaction

Typical size of chiral corrections in Chiral Perturbation Theory (ChPT) is:



$$f_{\rm NLO}/f_{\rm LO} - 1 \sim \frac{m_\pi}{4\pi f_\pi} \sim 10\%$$

- These corrections can be used for precision fits after discovery of DM in direct detection
- These corrections play significant role for the special case of isospin-violating scenario (generically chiral corrections wash out the tree level cancellation for Xenon)

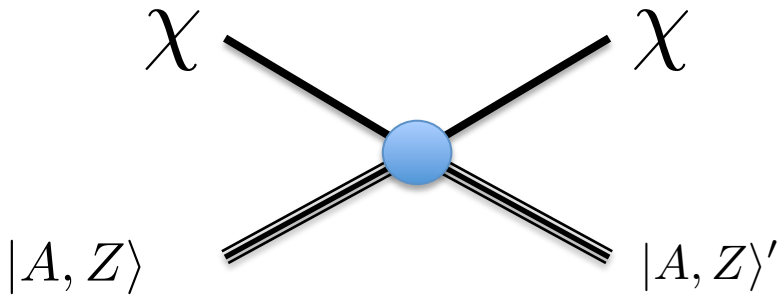
WIMP-nucleus interaction from EFT

WIMP-nucleus scattering

$m_\chi \sim \mathrm{GeV} - \mathrm{TeV}$

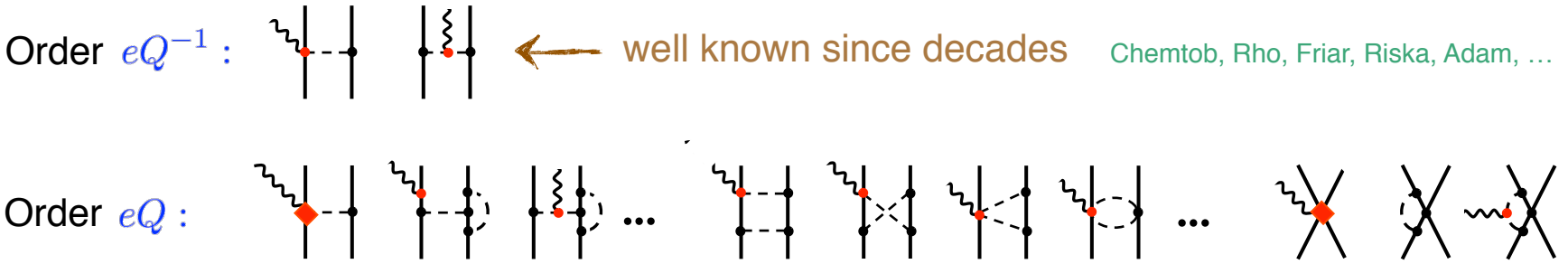
$E_R < 100\,\mathrm{KeV}$

$q \sim \sqrt{2 m_N E_R} < 200\,\mathrm{MeV}$



- Signal for DM direct detection experiments
- WIMP-nucleus interaction can be computed similarly to neutrino-nucleus and electron-nucleus cross sections
- Short distance interaction is unknown

Electromagnetic probes of the nucleus



(From the talk by Epelbaum)

We will use same technology for WIMP-nucleus scattering

Quark level bottom-up approach, i.e. relate the nucleon level coefficients to the short-distance coefficients at the new physics scale

WIMP-quark interaction

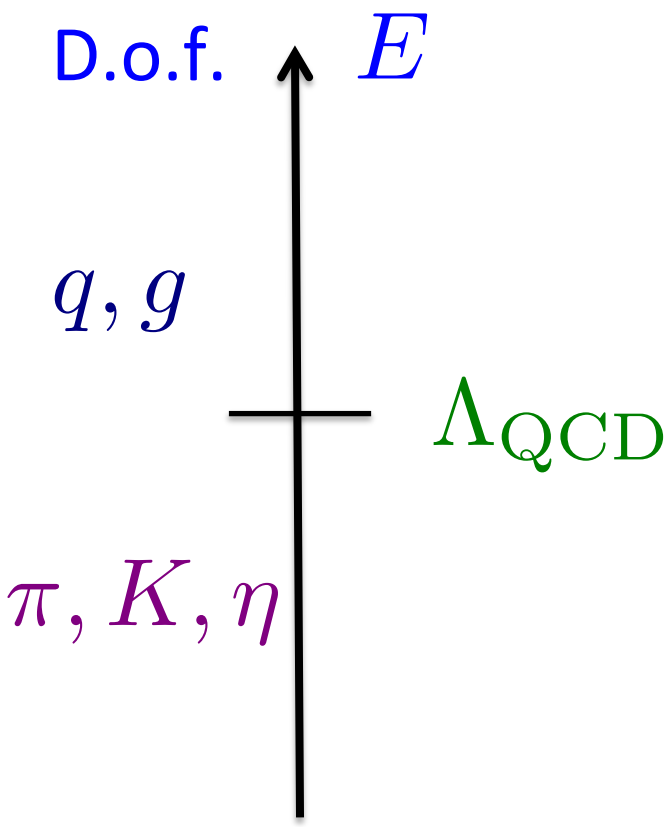
Prezeau, Kurylov, Kamionkowski, Vogel, 2003

$$\mathcal{L}_{\mathcal{X}q} = G_{\rm F} \sum_q [a_1^q \mathcal{S} \bar{q} q + a_2^q \mathcal{P} \bar{q} \gamma_5 q + \mathcal{V}^\mu \bar{q} \gamma_\mu (a_3^q + a_4^q \gamma_5) q + \mathcal{A}^\mu \bar{q} \gamma_\mu (a_5^q + a_6^q \gamma_5) q + a_7^q \mathcal{T}^{\mu\nu} \bar{q} \sigma_{\mu\nu} q]$$

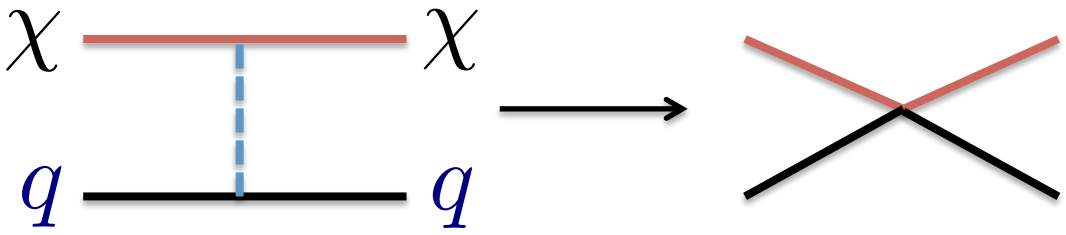
- Model independent approach considering effective WIMP-quark operators
- Bottom-up approach, by keeping connection between the low-energy constants and short-distance coefficients at the new physics scale
- To leading order, only Scalar and Vector operators on the quark side contribute to spin-independent interaction

Chiral perturbation theory (ChPT)

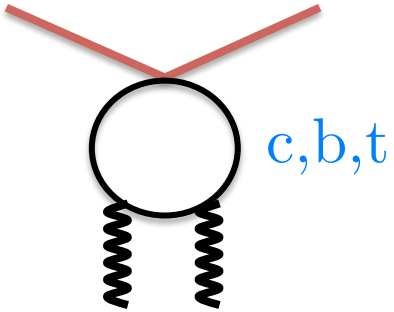
- At low energies QCD becomes non-perturbative
- ChPT is an effective theory for QCD at low energies where hadrons are the fundamental degrees of freedom
- Write down all terms consistent with symmetries of QCD
- Power counting



Short distance Lagrangian



Shifman, Vainshtein, Zakharov, 1978
integrating out heavy quarks:

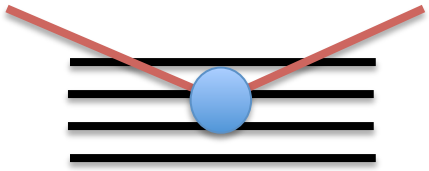


$$L_{\chi q} = \sum_{q=u,d,s,c,b,t} \tilde{\lambda}_q m_q \bar{q} q + \tilde{\lambda}_G \frac{\alpha_s}{\pi} G_{\mu\nu} G^{\mu\nu}$$

$$\mathcal{L}_{\rm eff} = \frac{\bar{\chi}\chi}{v\Lambda^2_{\rm np}} \left(\sum_q \lambda_q \, m_q \, \bar{q} q + \lambda_\Theta \, \Theta^\mu_\mu \right)$$

- We assume a scalar operator for the WIMP-quark interaction
- This involves four short distance parameters: $\lambda_u, \lambda_d, \lambda_s, \lambda_\Theta$
- From ChPT point of view this interaction is equivalent to the quark mass term

Power counting



$\sim p^\nu$

Using Weinberg's general formula:

$$\nu = 4 - A - 2C + 2L + \sum V_i \, \epsilon_i + \epsilon_W$$

atomic number

number of the connected parts

number of loops

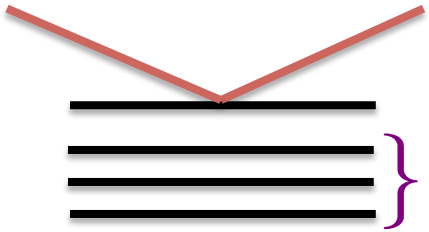
number of vertices of type i

$$\mathcal{L}_M = \mathcal{L}_M^{(2)} + \mathcal{L}_M^{(4)} + \ldots, \quad \mathcal{L}_M^{(n)} \sim p^{2n}$$

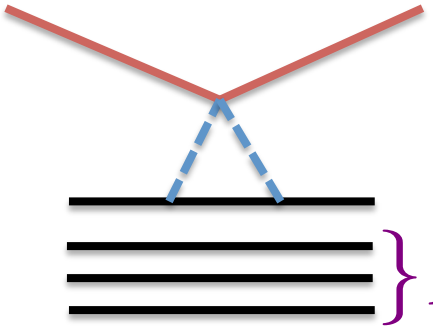
$$\mathcal{L}_{MB} = \mathcal{L}_{MB}^{(1)} + \mathcal{L}_{MB}^{(2)} + \ldots, \quad \mathcal{L}_{MB}^{(n)} \sim p^{n}$$

Effective Lagrangian	d_i	n_i	$\epsilon_i \equiv d_i + \frac{n_i}{2} - 2$
$\mathcal{L}_M^{(2n)}$	$2n$	0	$2(n-1)$
$\mathcal{L}_{MB}^{(n)}$	n	2	$n-1$

Examples



$$\sim p^2 \times (p^{-3})^{A-1} = p^{5-3A}$$

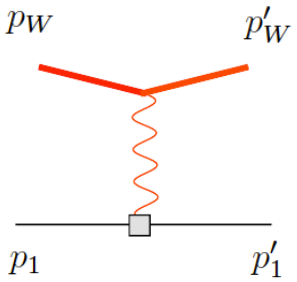


$$\sim p^2 \times p \times p \times p^4 \times \frac{1}{p^2} \times \frac{1}{p^2} \times \frac{1}{p} \times (p^{-3})^{A-1} = p^{6-3A}$$

Same result one gets using our general topological power counting formula from last slide with respectively C=A, L=0 and C=A, L=1 and the corresponding V_i, d_i of the vertices involved

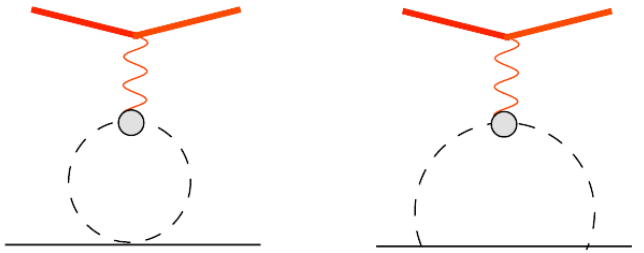
All LO and NLO graphs

LO



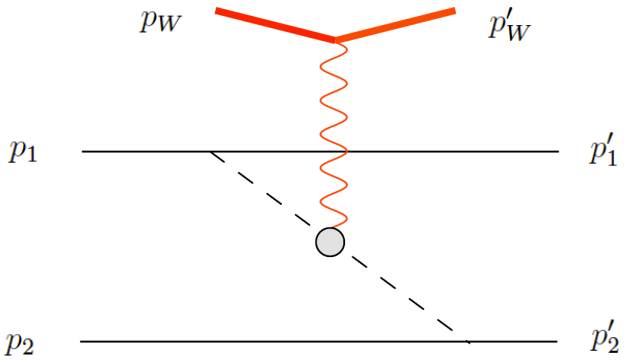
$$\sim p^{\nu_{\rm LO}}$$

NLO



$$\sim p^{\nu_{\rm NLO}}$$

$$\nu_{\rm NLO} = \nu_{\rm LO} + 1$$



Matching to nuclear potentials

Description	D.o.f.
BSM physics	q, g, Φ
SM+effective interaction	q, g
ChPT with WiMP	π, K, η
Quantum mechanics with potentials (one and two body)	$x_1, \ldots, x_A$

E

$\Lambda_{\rm np}$

$\Lambda_{\rm QCD}$

$p \sim m_\pi$

Standard (LO) WIMP analysis

$$\frac{d\,R}{d\,E_R} = \frac{2\rho_W}{\pi\, m_W} |[Z f_p + (A-Z) f_n] F(E_R)|^2\, \eta(E_R, m_W, m_A)$$

Nuclear form-factor

Astrophysical function

- At LO there is a factorization between particle, nuclear and astro-physics
- If WIMP-quark interaction is isospin-conserving, then $f_p = f_n$

Existing literature

Prezeau, Kurylov, Kamionkowski, Vogel, 2003 (Caltech)

Pointed out that the two body operators can be quite large (double-pion exchange).

Fan, Reece, Wang, 2010 (Princeton)

Bottom-up approach of nucleus level operators. A systematic study within EFT

Feng, Kumar, Marfatia, Sanford, 2011 (UC Irvine)

Showed that if one relaxes assumption $f_p=f_n$ and in fact tunes this ratio one can resolve the standard WIMP crisis (Isospin-Violating Dark Matter).

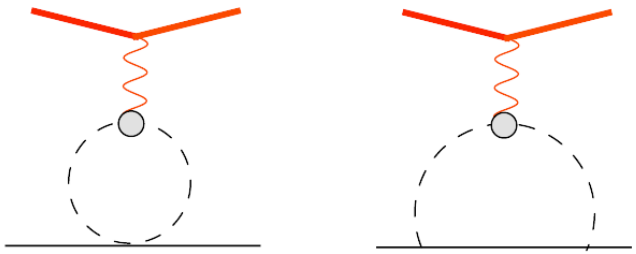
Fitzpatrick, Haxton, Katz, Lubbers, Xu, 2012 (UC Berkeley-Stanford)

Bottom-up approach of nucleon level operators and nuclear responses. A systematic study within EFT, 2-body operators not considered.

Cirigliano, Graesser, GO, 2012 (LANL)

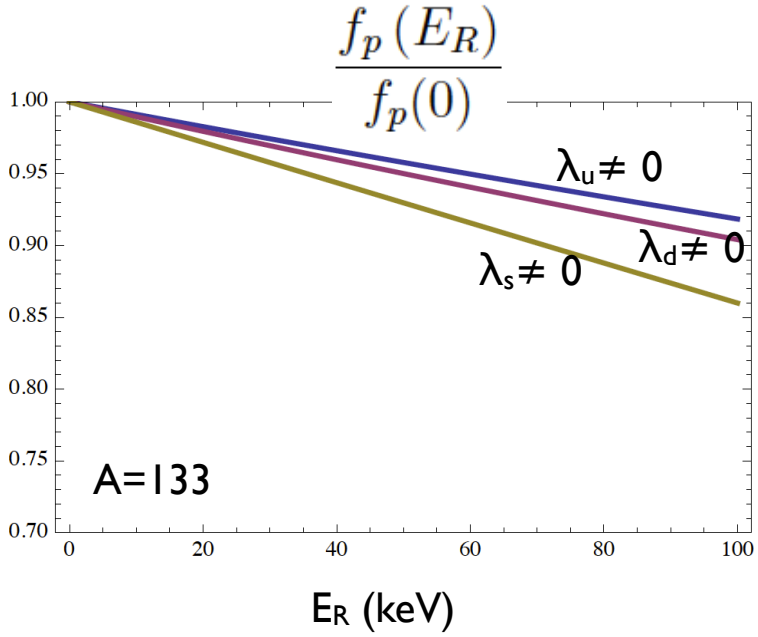
Bottom-up approach of quark level operators (scalar). A systematic study within EFT of All NLO chiral corrections, including 2-body operators.

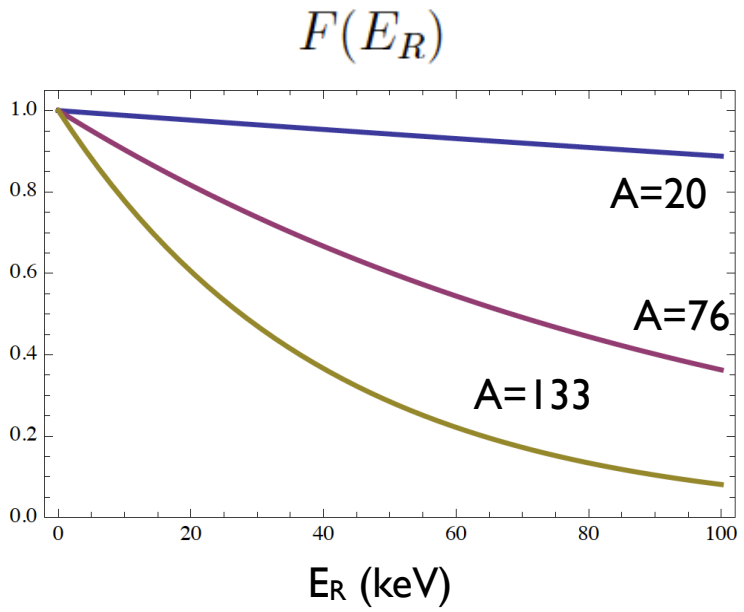
One body corrections



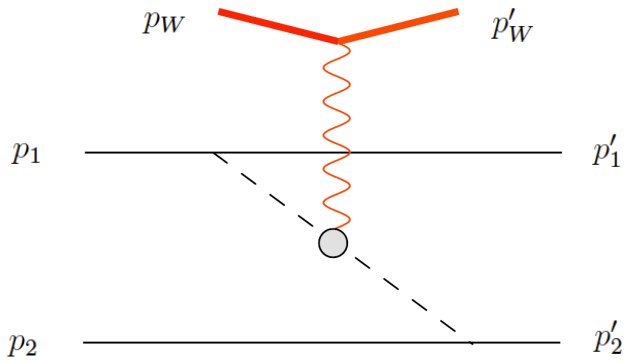
Cirigliano, Graesser, GO, 2012

- These graphs lead to nucleon level form-factors





Two body operators



Cirigliano, Graesser, GO, 2012

$$T_2^{(\pi\pi)} = -\frac{\lambda^{(+)}}{v\,\Lambda_{\rm np}^2}\,\frac{g_A^2 m_\pi^3}{96\,\pi\,F_\pi^2}\,\mathcal{N}_{\pi\pi}$$

$$T_2^{(\eta\eta)} = -\frac{1}{v\,\Lambda_{\rm np}^2}\,\frac{g_A^2 m_\eta}{288\,\pi\,F_\pi^2}\,\left(\frac{4\alpha-1}{\sqrt{3}}\right)^2\left[m_\pi^2\,\lambda^{(+)} + 4\left(M_K^2 - \frac{1}{2}m_\pi^2\right)\lambda_s\right]\mathcal{N}_{\eta\eta}$$

$$\mathcal{N}_{MM} = \langle\psi_0|\sum_{i<j} O_{MM}(i,j)\,|\psi_0\rangle \qquad M = \pi,\eta$$

- We used Nuclear Shell Model to calculate the two body matrix element*
- For pion-pion exchange we agree with Prezeau,Kurylov,Kamionkowski,Vogel,2003
- Eta-eta contribution is new

$$\mathcal{N}_{\pi\pi} \approx -0.91A,$$
$$\mathcal{N}_{\eta\eta} \approx 0.0061A\ .$$

*Special thanks to Joe Ginocchio and Anna Hayes for help!

NLO WIMP-nucleus differential rate

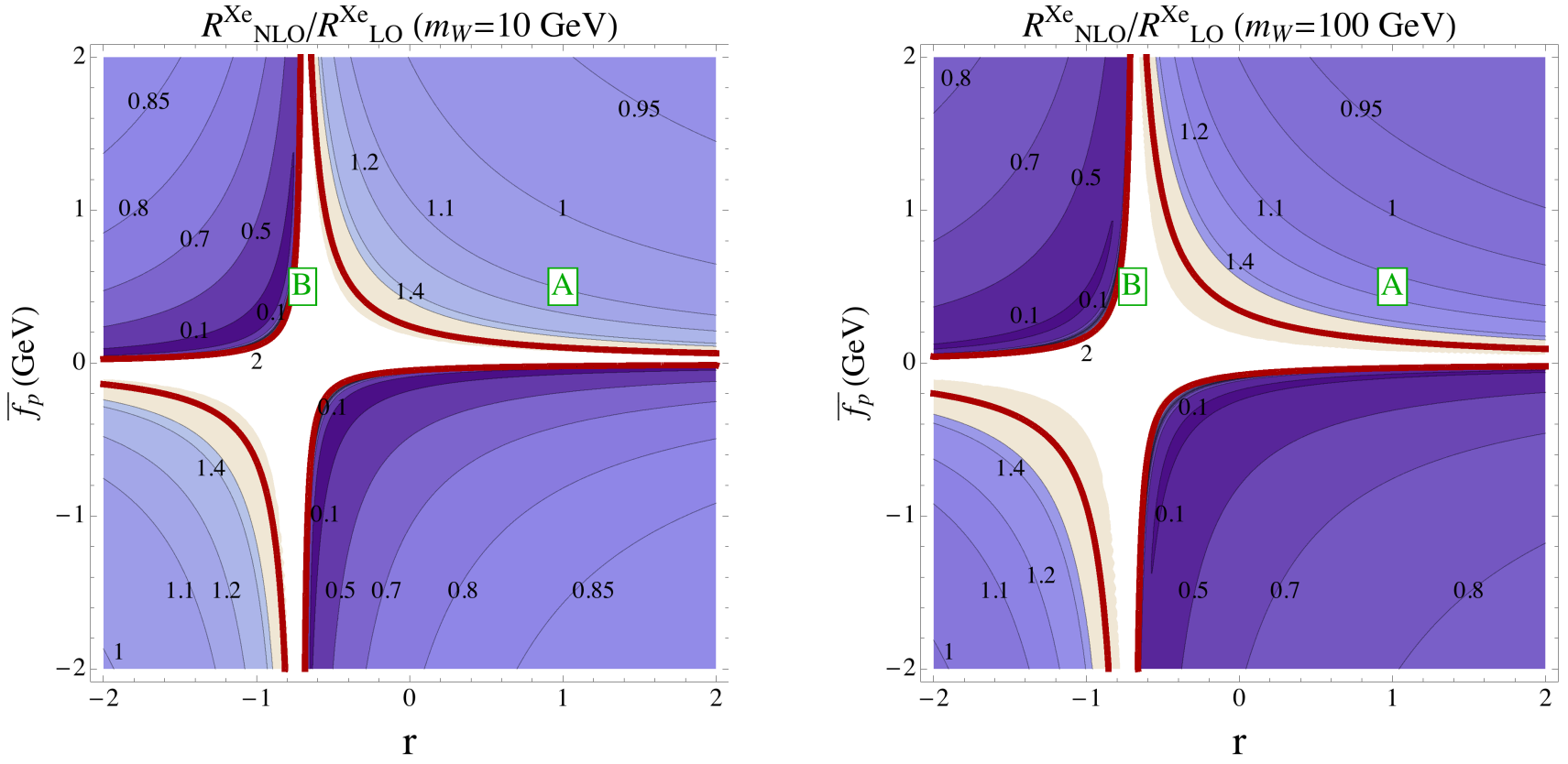
Cirigliano, Graesser, GO, 2012

$$\frac{dR}{dE_R} = \frac{2\rho_W}{\pi\, m_W} \left| \left[Z f_p(E_R) + (A-Z) f_n(E_R) \right] F(E_R) - T_2(E_R, A, Z) \right|^2 \eta\left(E_R, m_W, m_A\right)$$

- At NLO order the couplings of WIMP to proton and neutron become recoil-energy dependent
- The two body interactions lead to a new term T_2
- Simple factorization between particle, nuclear and astro-physics is violated at NLO order
- For Isospin Violating Dark Matter NLO corrections cannot be neglected

Contour plots for R_{NLO}/R_{LO} (Xe)

Cirigliano, Graesser, GO, 2012

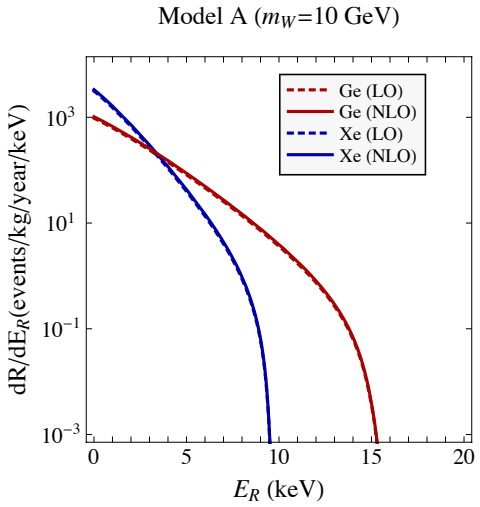


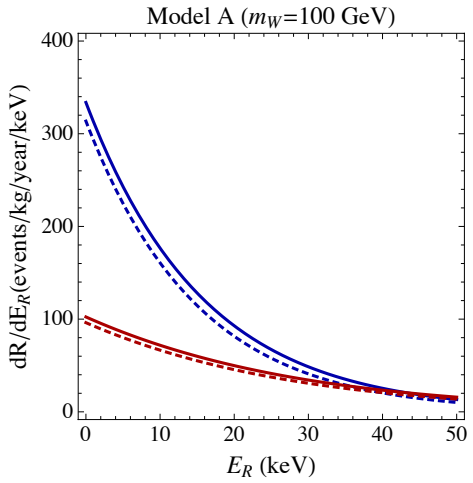
Inside the red line the ratio is bigger than 2

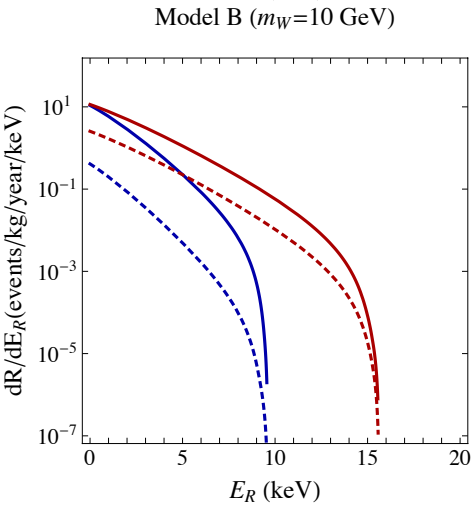
$r=f_n/f_p$

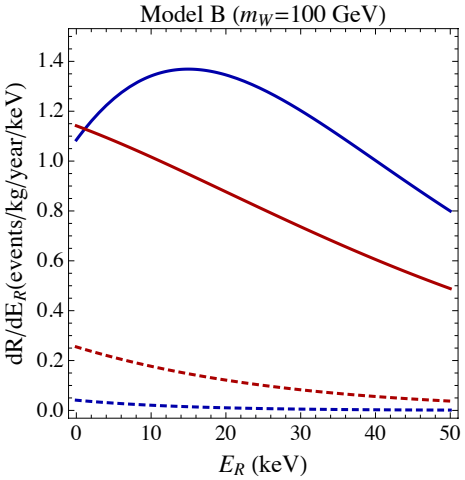
Differential rate for models A,B

Cirigliano, Graesser, GO, 2012







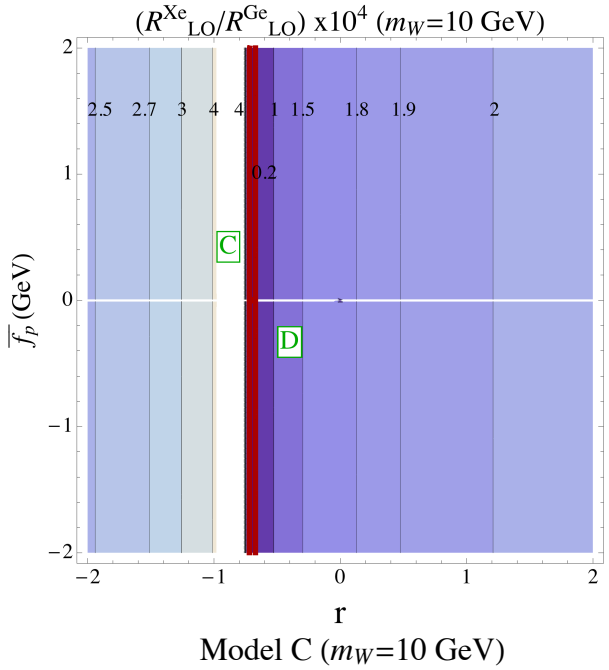


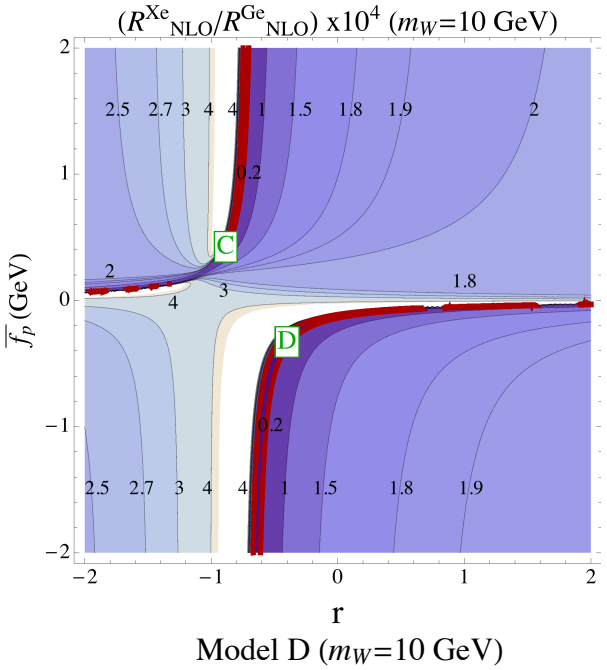
For model A NLO corrections are small

For model B NLO corrections are over an order of magnitude

Shape of the recoil spectrum For heavy WIMP

Cirigliano, Graesser, GO, 2012



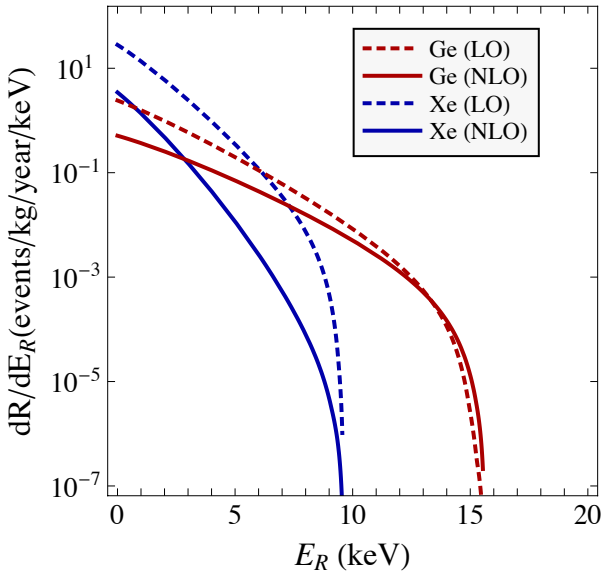


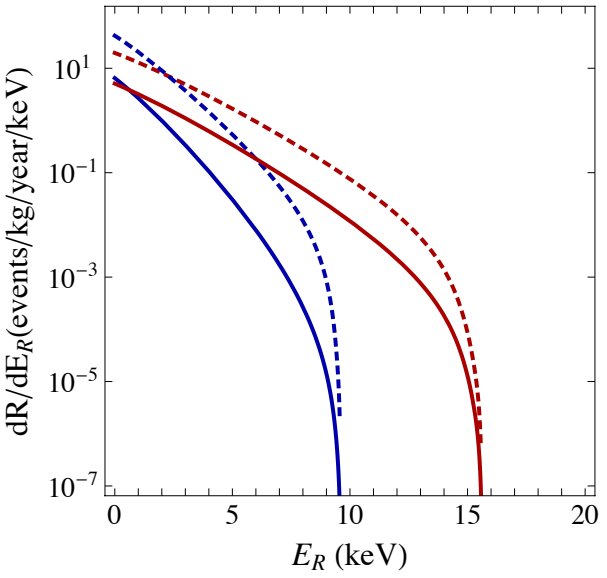
Inside the solid red line we have:

$$R^{\rm Xe}/R^{\rm Ge} < 2\times 10^{-5}$$

which is the condition that insures that CoGeNT signal cannot be observed at Xenon100

$r=f_n/f_p$

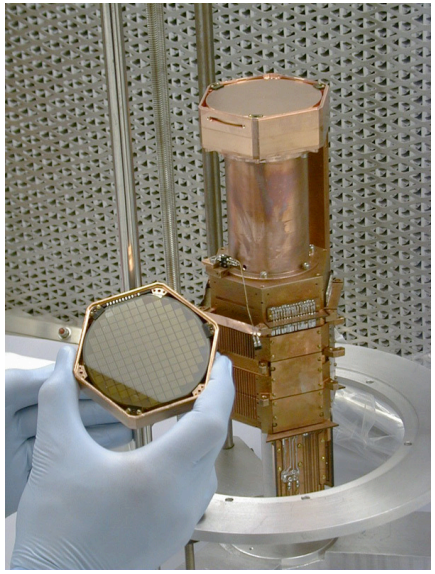




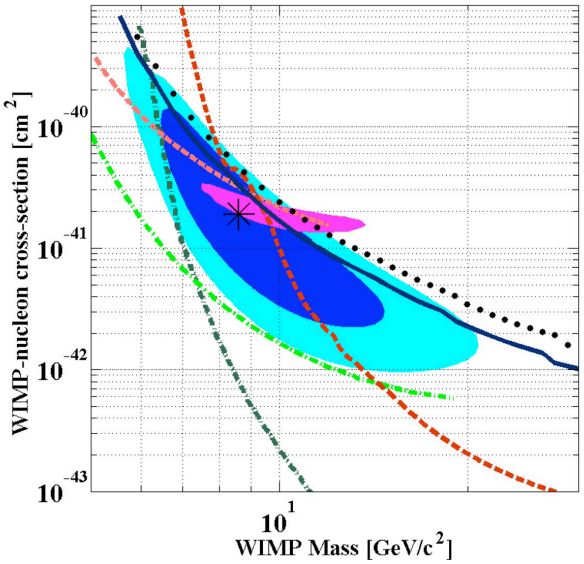
For isospin violating dark matter (Xe):

$Zf_p+(A-Z)f_n=0$

Results for Xenon/CDMS-Si

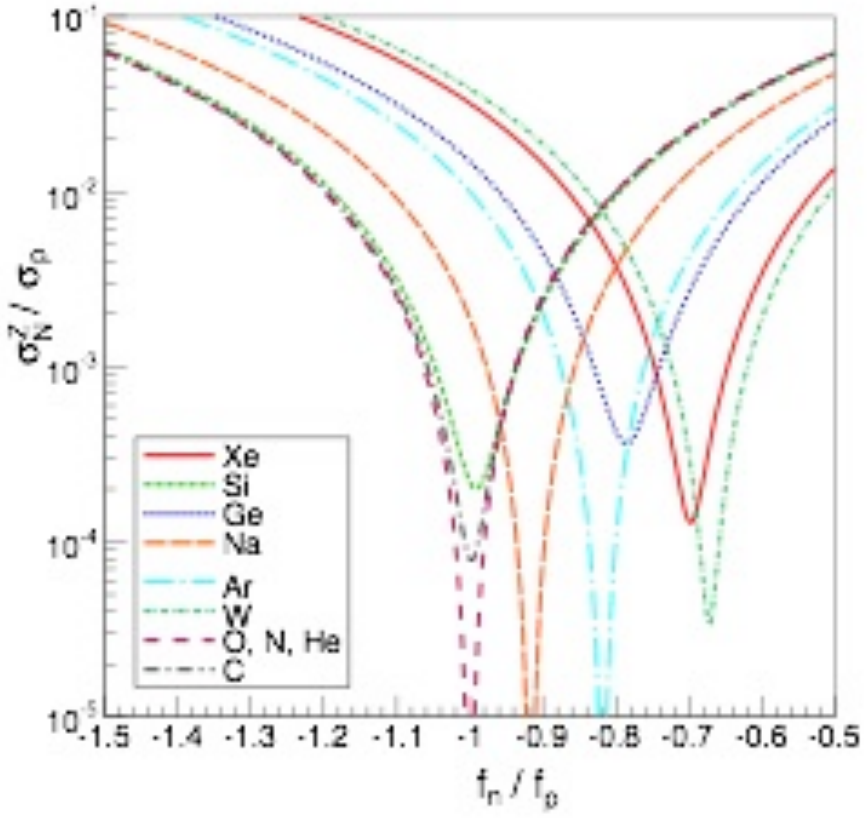


2013



Isospin Violating Dark Matter

$$\frac{dR}{dE_R} = \frac{2\rho_W}{\pi m_W} |[Z f_p + (A-Z) f_n] F(E_R)|^2 \, \eta(E_R, m_W, m_A)$$



$$D_p^Z \equiv \frac{\sigma_N^Z}{\sigma_p} = \frac{\sum_i \eta_i \mu_{A_i}^2 [Z + (f_n/f_p)(A_i - Z)]^2}{\sum_i \eta_i \mu_{A_i}^2 A_i^2}$$

- For Xenon and r=-0.7 the degradation factor is just above 10^{-4}

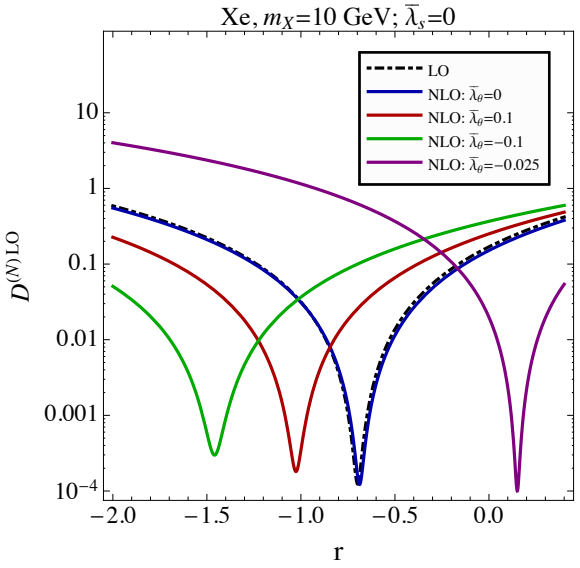
Isospin Violating Dark Matter

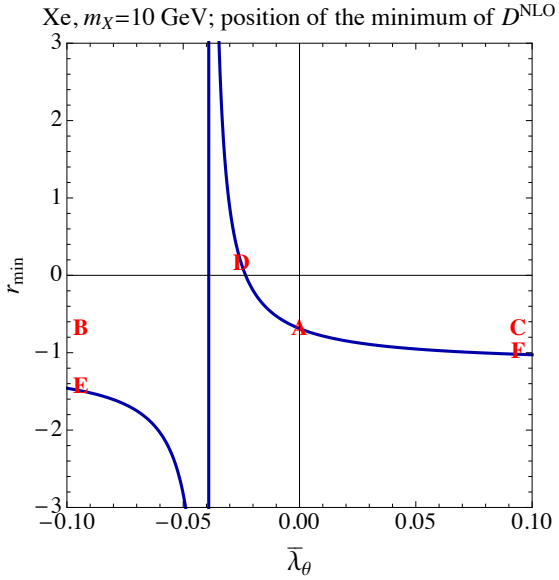
Cirigliano, Graesser, GO, Shoemaker 2013

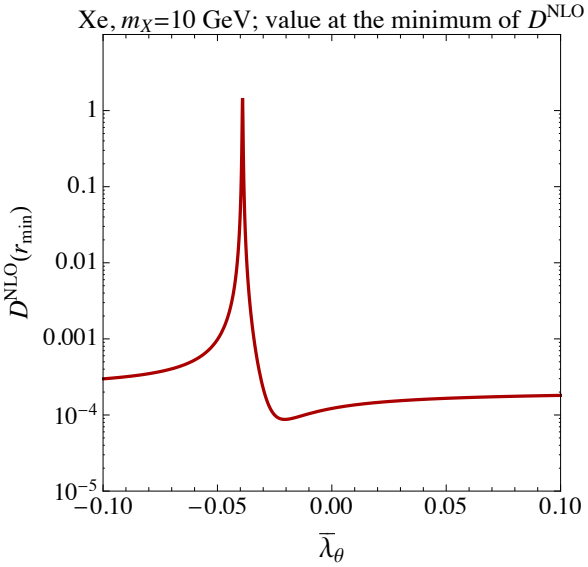
$$\frac{dR}{dE_R} = \frac{2\rho_W}{\pi\, m_W} \left| \left[Z f_p(E_R) + (A-Z) f_n(E_R) \right] F(E_R) - T_2(E_R, A, Z) \right|^2 \eta\left(E_R, m_W, m_A\right)$$

Beyond the leading order:

$$r_{\min} = -\frac{\bar{Z}}{1-\bar{Z}} \cdot \frac{1+\frac{\Delta}{\bar{Z}}}{1-\frac{\Delta}{1-\bar{Z}}} \qquad \bar{Z} = Z/A$$



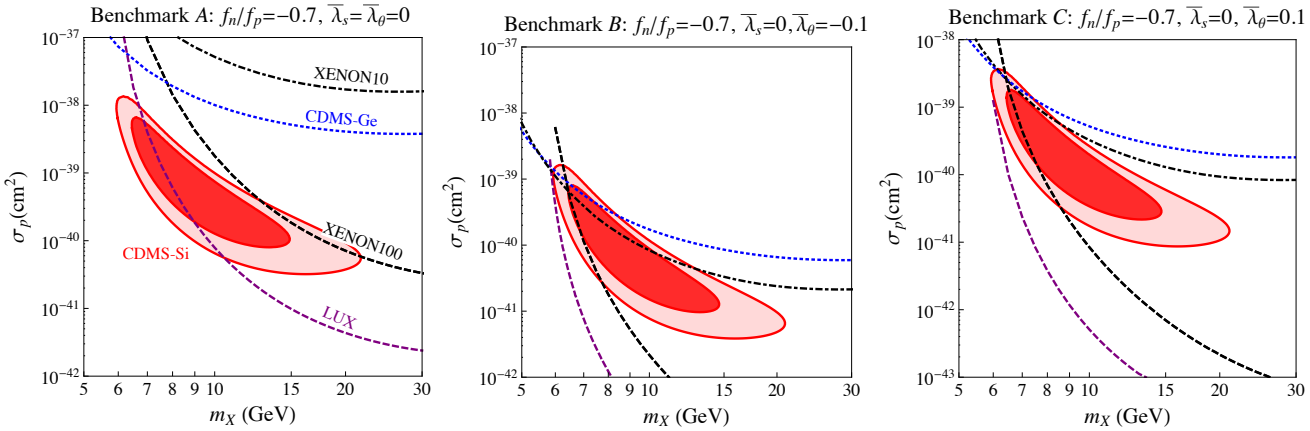




At next-to-leading order qualitative changes in IVDM phenomenology

LUX exclusion vs CDMS signal

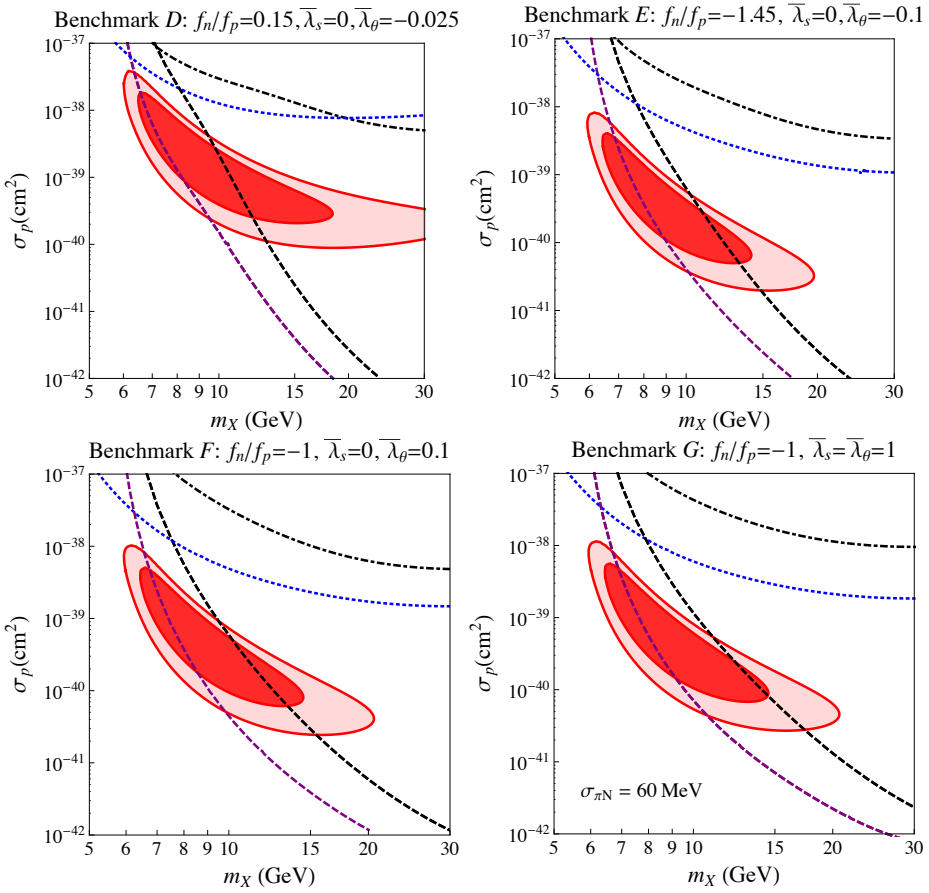
Cirigliano, Graesser, GO, Shoemaker 2013



- At next-to-leading order, depending on extra parameters (λ_s , λ_θ) r=-0.7 works in some cases and does not work in others

LUX exclusion vs CDMS signal

Cirigliano, Graesser, GO, Shoemaker 2013



- At next-to-leading order, new values of r become allowed, even positive ones
- Large degeneracies with unknown hadronic parameters

$$\sigma_{\pi N} = ((m_u + m_d)/2)\langle p|\bar{u}u + \bar{d}d|p\rangle$$

$$= 45 \pm 15\,\mathrm{MeV}$$

Conclusions

- Assuming scalar WIMP-quark interaction we systematically computed all NLO corrections in chiral power counting to WIMP-nucleus scattering cross section
- Qualitative changes for Isospin Violating Dark Matter phenomenology
- Factorization between particle, nuclear and astro-physics is violated by NLO corrections
- Even for just scalar operator we get 4 independent parameters at NLO instead of 2 as at LO
- Maybe the direct detection experiments seem to be in an apparent crisis because of combination of isospin violation and NLO nuclear corrections?