MITP Workshop on Effective Theories and Dark Matter, Mainz, March 16-27 2015

Chiral EFT for direct detection

Vincenzo Cirigliano
Los Alamos National Laboratory

Los Alamos NATIONAL LABORATORY EST. 1943

Outline

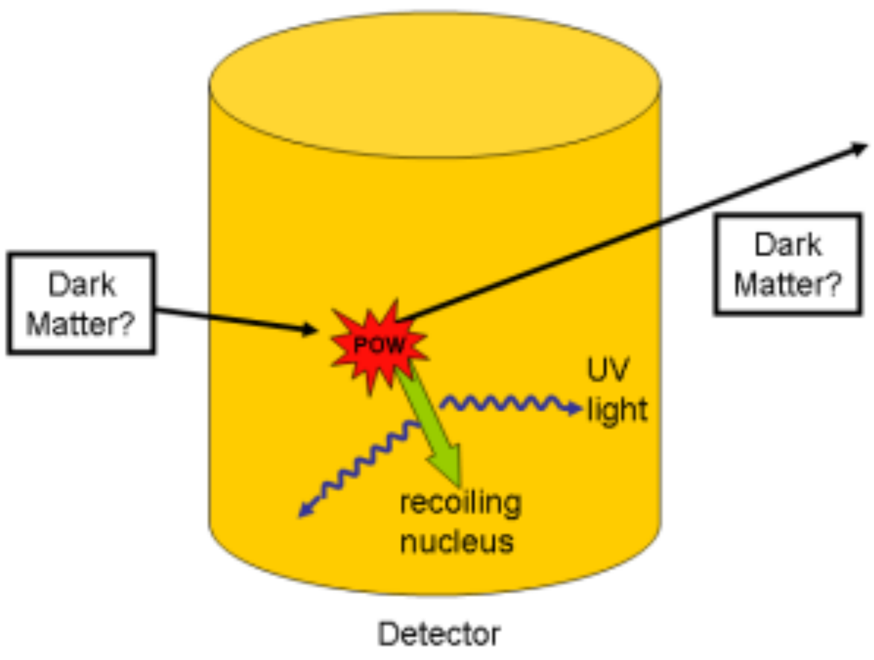
- Introduction: EFT framework for direct detection
- Chiral EFT for scalar quark-WIMP interactions
    - Matching to NLO
    - Phenomenology
- Conclusions

Based on:
VC, M. Graesser, G. Ovanesyan, JHEP 1210 (2012) 025, arXiv:1205.2695 [hep-ph]
VC, M. Graesser, G. Ovanesyan, I. Shoemaker, PLB 739 (2014) 293, arXiv:1311.5886 [hep-ph]

Introduction

WIMP direct detection (1)

- Typical scales involved in direct detection process:



$$\boxed{\begin{array}{c} |\vec{q}|_{\max} = 2\,\mu\, v_{\mathrm{rel}} < 2\, m_A\, v_0 \sim 200\mathrm{MeV} \\ E_R < \dfrac{|\vec{q}|^2_{\max}}{2 m_A} \sim 200\mathrm{KeV} \end{array}}$$

$m_A \sim 100\,\mathrm{GeV}$ $\qquad$ $v_0 \sim 10^{-3}$

"Right" kinematics for (chiral) expansion in $p \sim q/m_N \sim m_\pi / m_N$

WIMP direct detection (II)

- Event rate $$\boxed{\frac{dN}{dE_R} \propto \Phi \otimes \frac{d\sigma}{dE_R}}$$

$$\boxed{\Phi \sim n\, v\, f(v)}$$

Flux factor:
DM local density and velocity distribution

$$\boxed{d\sigma \sim \sigma_p \otimes R_{\rm nucl}}$$

WIMP-nucleus cross section:
particle physics × hadronic x nuclear physics

- Here focus on hadronic / nuclear physics effects, using chiral EFT power counting as organizing principle

EFT framework for direct detection

E

Λ_{BSM}
(?)

Quarks, gluons

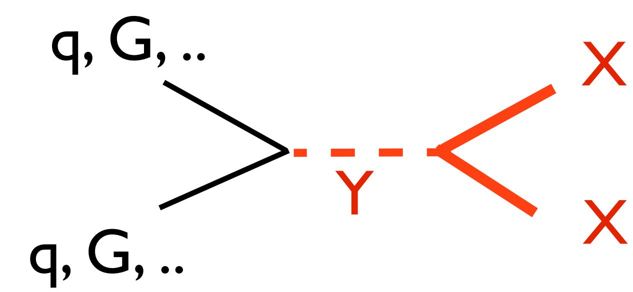
Λ_H
(~GeV)

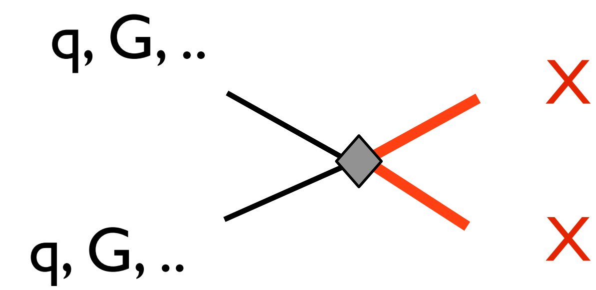
$$\mathcal{L}_{BSM}$$

Perturbative matching

$$\mathcal{L}_{SM} + \sum_{k,i} \frac{c_i^{(k)}}{\Lambda^k} O_i^{(k)}[X^{(\dagger)}, X; q, G, ...]$$

BSM dynamics includes WIMP candidate "X", and other particles "Y", eg:





EFT framework for direct detection

E

Λ_{BSM}
(?)

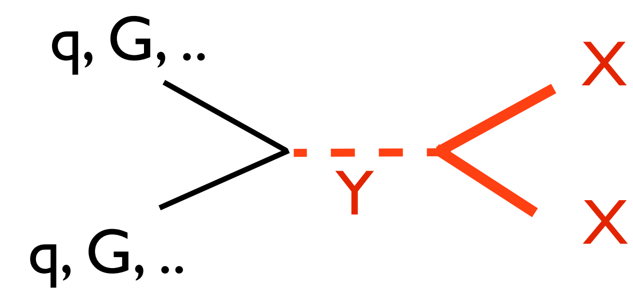
Quarks, gluons

Λ_H
(~GeV)

Nucleons, pions

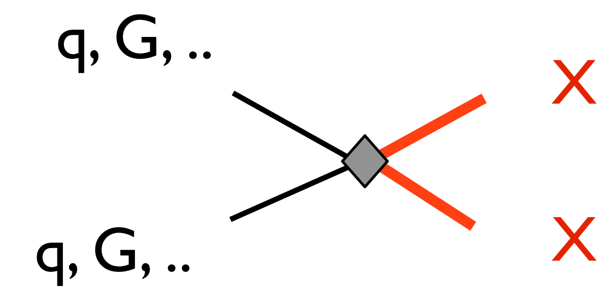
$$\boxed{\mathcal{L}_{\rm BSM}}$$

BSM dynamics includes WIMP candidate "X", and other particles "Y", eg:



Perturbative matching

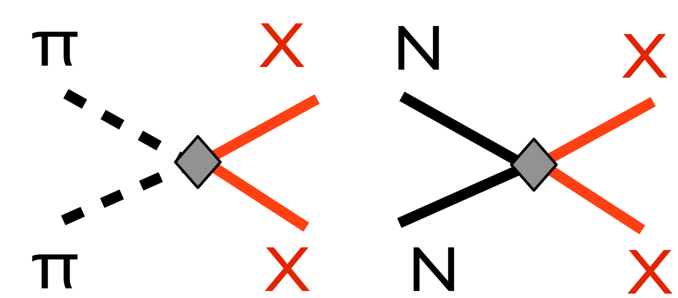
$$\boxed{\mathcal{L}_{\rm SM} + \sum_{k,i} \frac{c_i^{(k)}}{\Lambda^k} O_i^{(k)}[X^{(\dagger)}, X; q, G, ...]}$$



Non-perturbative matching

q << M_N : use chiral EFT

$$\boxed{\mathcal{L}_{\rm ChPT}[X; N, \pi, ...] \;\rightarrow\; H_I = V_{XN} + V_{XNN} + \;\ldots}$$



EFT framework for direct detection

E

Λ_{BSM} (?)

Quarks, gluons

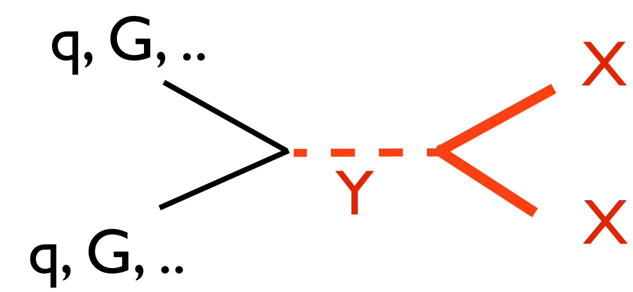
Λ_H (~GeV)

Nucleons, pions

Nuclei

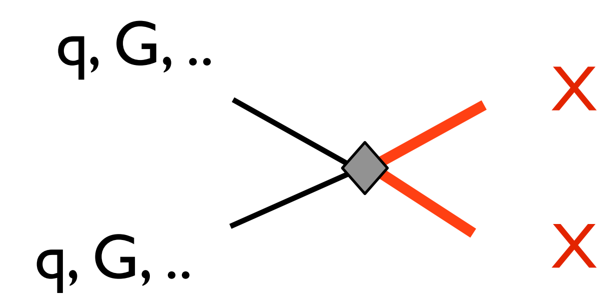
$$\mathcal{L}_{\mathrm{BSM}}$$

BSM dynamics includes WIMP candidate “X”, and other particles “Y”, eg:



Perturbative matching

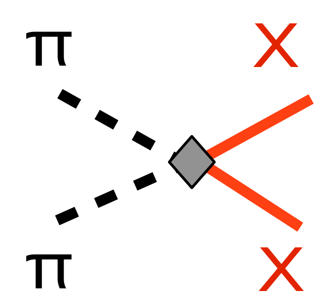
$$\mathcal{L}_{\mathrm{SM}} + \sum_{k,i} \frac{c_i^{(k)}}{\Lambda^k} O_i^{(k)}[X^{(\dagger)}, X; q, G, ...]$$

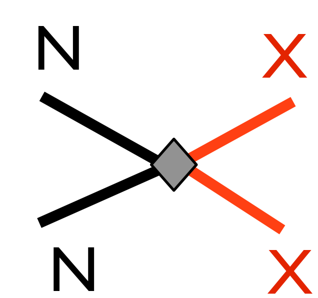


Non-perturbative matching

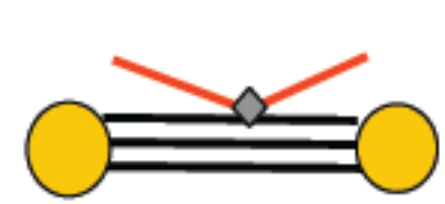
q << M_N : use chiral EFT

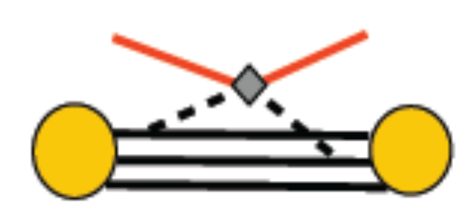
$$\mathcal{L}_{\mathrm{ChPT}}\,[X; N, \pi, ...] \;\rightarrow\; H_I = V_{XN} + V_{XNN} + \;\ldots$$





$$\langle \Phi'_{(A,Z)} X' \mid H_I \mid \Phi_{(A,Z)} X \rangle$$



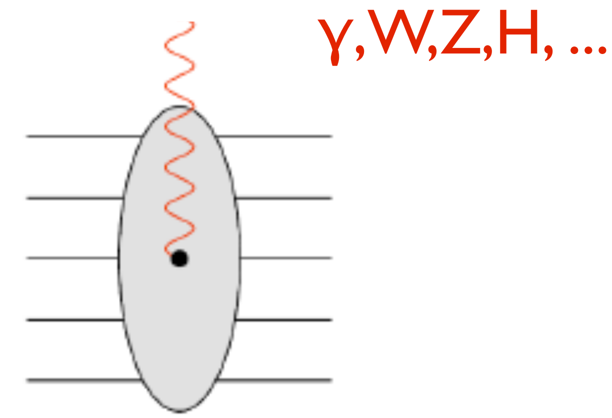


Strategy

- For a given quark-level operator:

1. Chiral symmetry → WIMP couplings to π, N at small q
2. Chiral power counting for $XN_1 \ldots N_A \to XN_1 \ldots N_A$ amplitudes ⇒ $V_{XN}, V_{XNN}, \ldots$ to a given order in $p \sim q/m_N \sim m_\pi/m_N$
3. Nuclear matrix elements

Same strategy as in electron-nucleus or neutrino-nucleus scattering
(difference is in the operator structure, kinematic regime, target nuclei)



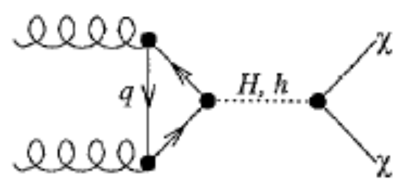
Chiral EFT for scalar interactions

For a discussion of other operators, see Hoferichter-Klos-Schwenk 1503.04811
and references therein

Scalar interactions

- GeV-scale effective Lagrangian* involves 4 short-distance couplings

$$\mathcal{L}_{\rm SM} + \frac{1}{v}\frac{XX}{\Lambda^{[XX]-1}}\left[\sum_{q=u,d,s} \lambda_q\, m_q\, \bar{q}q + \lambda_\theta\, \theta^\mu_\mu\right] + \ldots$$

* After integrating out heavy quarks 

and trading GG operator for trace of energy-mom. tensor: $\theta^\mu_\mu = \sum_q m_q \bar{q}q - \frac{9}{8}\frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{a\mu\nu}$

1. WIMP couplings to π, N

- Hadronic realization of $$\boxed{\mathcal{L}_{\rm QCD} + \sum_{q=u,d,s} s_q\,\bar{q}q \;+\; s_\theta\,\theta^\mu_\mu}$$

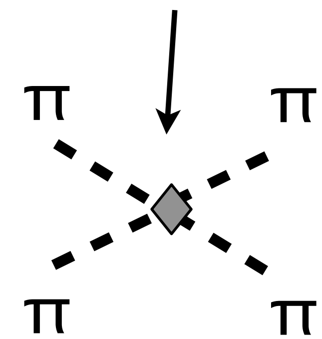
1. WIMP couplings to π, N

- Hadronic realization of

$$\mathcal{L}_{\rm QCD} + \sum_{q=u,d,s} s_q\, \bar{q} q \; + \; s_\theta\, \theta^\mu_\mu$$

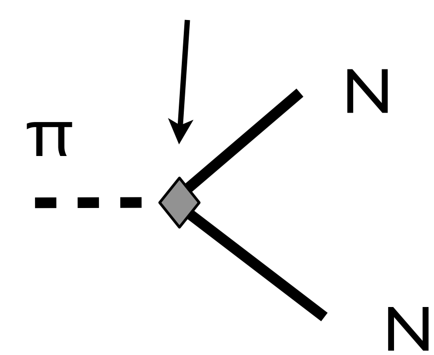
- Usual chiral Lagrangian, organized as expansion in derivatives ∂~O(p) and chiral symmetry breaking m_q~O(p^2)

$$\mathcal{L}_M = \mathcal{L}_M^{(2)} + \mathcal{L}_M^{(4)} + \ldots$$



$$\sim \frac{p_i \cdot p_j}{F_\pi^2}$$

$$\mathcal{L}_{MB} = \mathcal{L}_{MB}^{(1)} + \mathcal{L}_{MB}^{(2)} + \ldots$$



$$\sim \frac{g_A}{F_\pi}\, p_\pi \cdot S_N$$

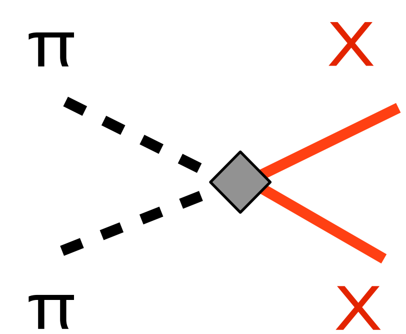
1. WIMP couplings to π, N

- Hadronic realization of

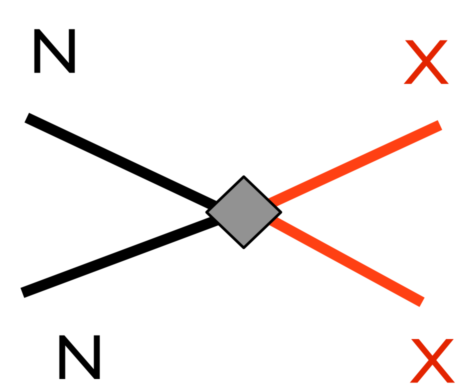
$$\boxed{\mathcal{L}_{\rm QCD} + \sum_{q=u,d,s} s_q\, \bar{q}q + s_\theta\, \theta^\mu_\mu}$$

$$s_q = \lambda_q \frac{m_q}{v} \frac{XX}{\Lambda^{[XX]-1}}$$

- Scalar source appears in chiral effective Lagrangian in the same way as quark mass matrix



$$\longleftrightarrow \quad B_0 F^2 = -\langle 0|\bar{q}q|0\rangle$$



$$\longleftrightarrow \quad \langle N|\bar{q}q|N\rangle$$

1. WIMP couplings to π, N

- Hadronic realization of

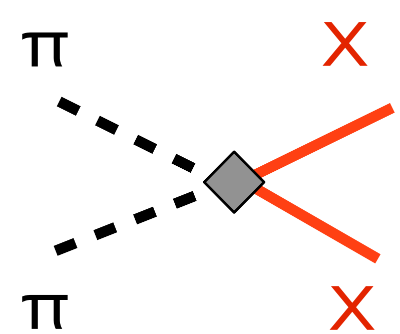
$$\boxed{\mathcal{L}_{\mathrm{QCD}} + \sum_{q=u,d,s} s_q\, \bar{q} q + s_\theta\, \theta^\mu_\mu}$$

$$s_\theta = \lambda_\theta \frac{1}{v} \frac{XX}{\Lambda^{[XX]-1}}$$

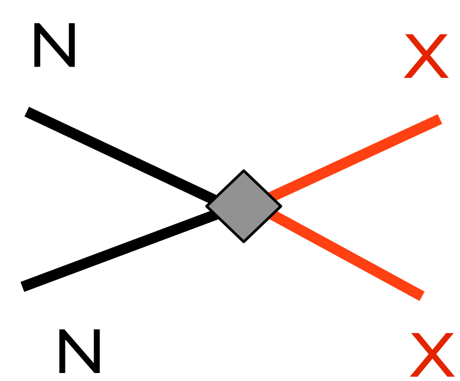
- Energy-momentum tensor operator identified by coupling chiral EFT to external metric

Donoghue-Leutwyler 1991

....



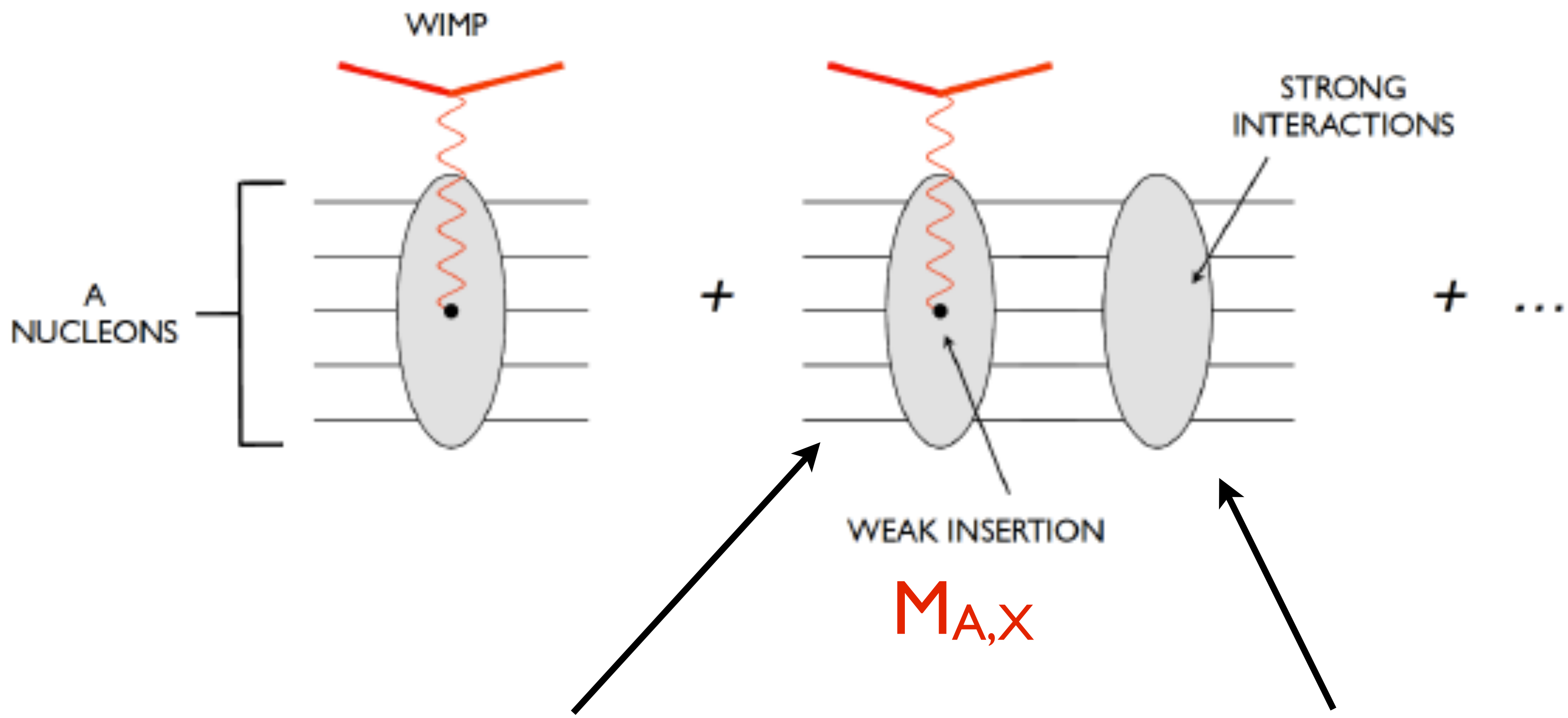
$$\longleftrightarrow \quad O(p^2) + O(p^4) + \ldots$$



$$\longleftrightarrow \quad m_N + O(p) + \ldots$$

2. Power counting and V_{XN}, V_{XNN}, ...

- Non-perturbative amplitude T: sum of ladder diagrams



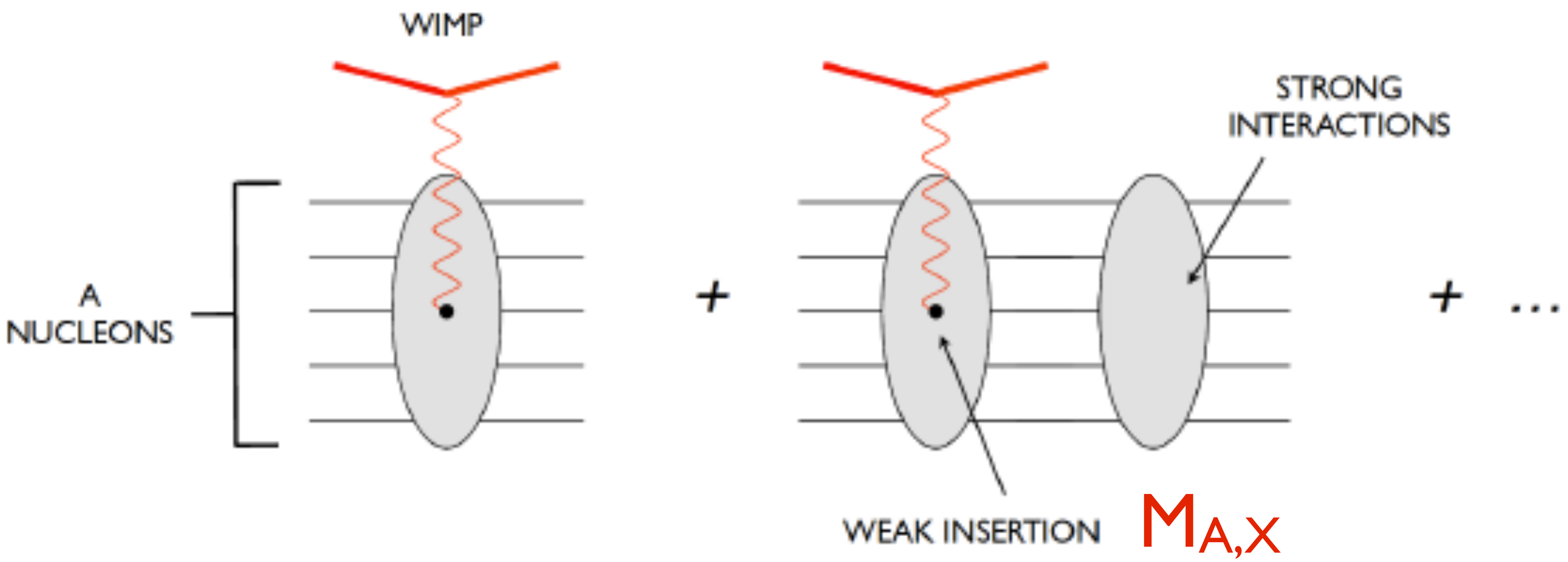
- <u>One insertion</u> of A-nucleon irreducible amplitude with external probe attached

- Has well defined power counting (no IR enhancements ~ M_n/q)

- <u>Arbitrary many insertions</u> of A-nucleon irreducible amplitude with only strong vertices

2. Power counting and $V_{XN}, V_{XNN}, \ldots$

- Non-perturbative amplitude T: sum of ladder diagrams



- Match T to non-rel. Lippmann-Schwinger description

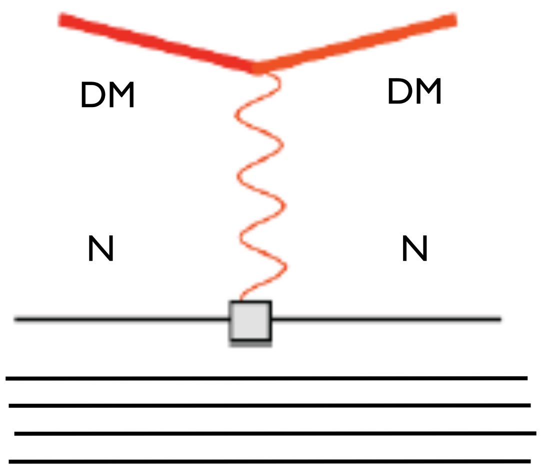
Fourier Transform

$$M_{A,X}(\vec{q}_1, \ldots, \vec{q}_A, \vec{q}_X) \quad \longleftrightarrow \quad H_I(\vec{x}_1, \ldots, \vec{x}_A, \vec{x}_X) = V_{XN} + V_{XNN} + \ \ldots$$

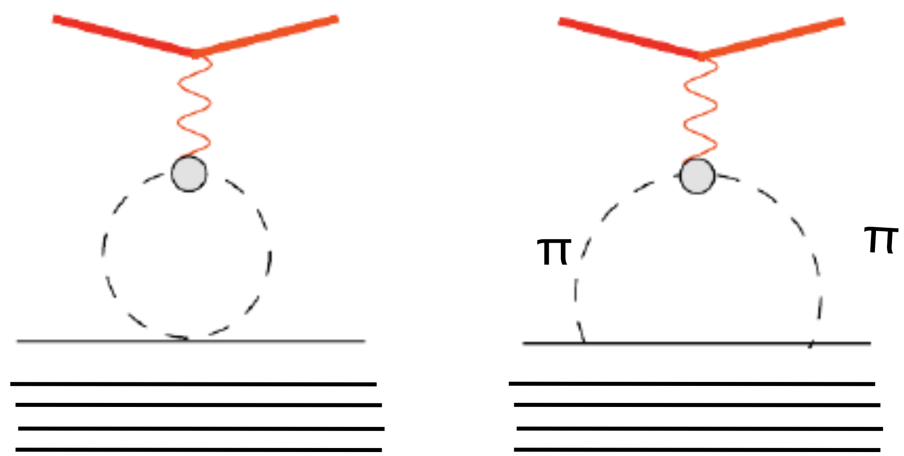
Leading terms in H_I (potentials) determined by power counting of $M_{A,X}$

2. Power counting and $V_{XN}, V_{XNN}, \ldots$

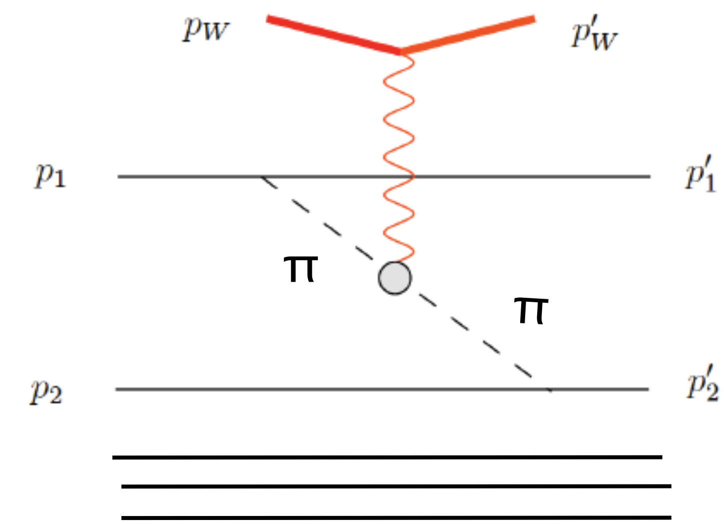
- Scalar density:



LO: contact WIMP-nucleon interaction



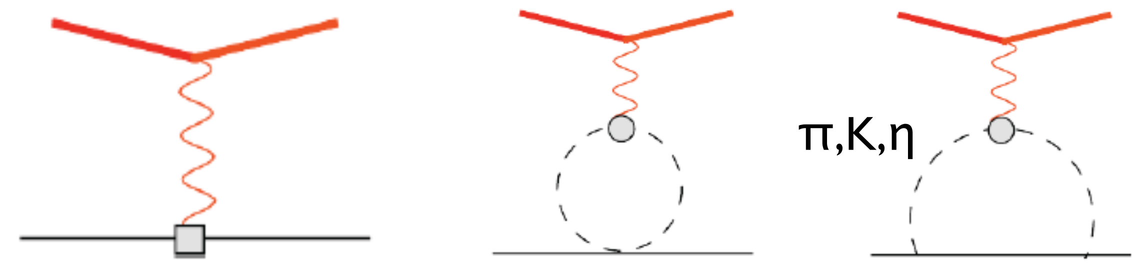
NLO: Single nucleon form factor



NLO: Two-nucleon contribution

- Energy-momentum tensor: first corrections arise in principle to NNLO

- NLO amplitude: 1-nucleon



$$M_{1,X} = f_N(q^2)\, X X\ \bar{N} N \qquad\qquad N = p, n$$

$$\boxed{f_{p/n}(q^2) = \frac{1}{v\,\Lambda_{\rm np}^2}\left[\sum_{q=u,d,s} \lambda_q\, \sigma_q^{(p/n)} + \lambda_\Theta\, m_{p/n} - \frac{g_A^2}{64\pi\, F_\pi^2}\Big(A(q^2) \pm B(q^2)\Big)\right]}$$

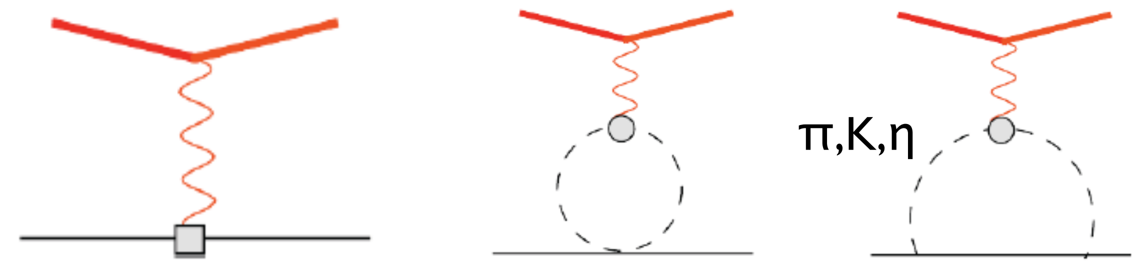
Usual q=0 term,
controlled by sigma terms:

$$\boxed{\langle i|\, m_q q\bar{q}\, |i\rangle = \sigma_q^{(i)} \bar{\psi}_i \psi_i}$$

Giedt-Thomas-Young 0907.4177 Kronfeld 1203.1204

Crivellin-Hoferichter-Procura 1312.4951

- NLO amplitude: 1-nucleon



$$M_{1,X} = f_N(q^2)\, XX\ \bar{N}N \qquad\qquad N = p, n$$

$$\boxed{f_{p/n}(q^2) = \frac{1}{v\,\Lambda_{\rm np}^2}\left[\sum_{q=u,d,s} \lambda_q\, \sigma_q^{(p/n)} \ +\ \lambda_\Theta\, m_{p/n} \ -\ \frac{g_A^2}{64\pi\, F_\pi^2}\Big(A(q^2) \pm B(q^2)\Big)\right]}$$

Usual q=0 term,
controlled by sigma terms:

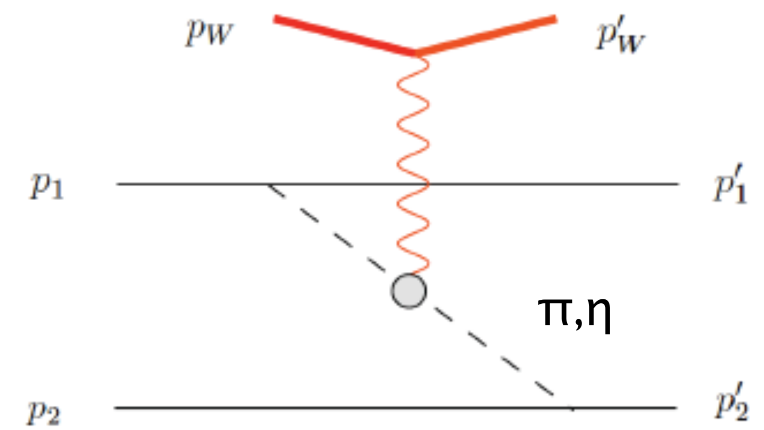
Slope term: no new couplings

$$\boxed{\langle i|\, m_q q\bar{q}\,|i\rangle = \sigma_q^{(i)}\,\bar{\psi}_i\psi_i}$$

Giedt-Thomas-Young 0907.4177 Kronfeld 1203.1204

Crivellin-Hoferichter-Procura 1312.4951

- NLO amplitude: 2-nucleons



$$M_{2,X} = \mathcal{M}_{\pi\pi} + \mathcal{M}_{\eta\eta}$$

$$\mathcal{M}_{\pi\pi} = -\frac{1}{v\,\Lambda_{\mathrm{np}}^2}\,\frac{g_A^2}{F_\pi^2}\,\frac{m_\pi^2\,\lambda_+}{(q_1^2 - m_\pi^2)(q_2^2 - m_\pi^2)}\,\boxed{\bar{N} q_1 \cdot S\,\boldsymbol{\tau}_1^k N\;\bar{N} q_2 \cdot S\,\boldsymbol{\tau}_2^k N}\,\bar{\chi}\chi\,,$$

$$\mathcal{M}_{\eta\eta} = -\frac{1}{v\,\Lambda_{\mathrm{np}}^2}\,\frac{g_A^2}{3\,F_\pi^2}\left(\frac{4\alpha - 1}{\sqrt{3}}\right)^2 \frac{m_\pi^2\,\lambda_+ + 4\left(M_K^2 - \frac{1}{2}m_\pi^2\right)\lambda_s}{(q_1^2 - m_\eta^2)(q_2^2 - m_\eta^2)}\,\boxed{\bar{N} q_1 \cdot S N\;\bar{N} q_2 \cdot S N}\,\bar{\chi}\chi$$

$$\lambda_\pm \equiv (m_u\lambda_u \pm m_d\lambda_d)/(m_u + m_d)$$

$$g_A = D + F = 1.27$$
$$\alpha = F/(D + F) \approx 0.4$$

ππ contribution first considered in
Kamionkoski-Kurylov-Prezeau-Vogel, 2003

3. Nuclear matrix elements

$$\langle f|\hat{T}|i\rangle \;=\; (2\pi)^3\delta^{(3)}\left(\vec{q}_X + \vec{q}_A\right) T(\vec{q}_X) \qquad\qquad T(\vec{q}_X) = T_1 + T_2$$

$$\boxed{\begin{aligned} T_1 &= \sum_{i=1,A} \int d\vec{x}_i \;\; \rho_1(\vec{x}_i) \otimes \tilde{V}_1(\vec{q}_X;\vec{x}_i) \\ T_2 &= \sum_{i<j} \int d\vec{x}_i \, d\vec{x}_j \;\; \rho_2(\vec{x}_i,\vec{x}_j) \otimes \tilde{V}_2(\vec{q}_X;\vec{x}_i,\vec{x}_j) \end{aligned}}$$

3. Nuclear matrix elements

$$\langle f|\hat{T}|i\rangle = (2\pi)^3\delta^{(3)}(\vec{q}_X + \vec{q}_A)\, T(\vec{q}_X) \qquad T(\vec{q}_X) = T_1 + T_2$$

$$\boxed{\begin{aligned} T_1 &= \sum_{i=1,A} \int d\vec{x}_i \;\; \rho_1(\vec{x}_i) \otimes \tilde{V}_1(\vec{q}_X; \vec{x}_i) \\ T_2 &= \sum_{i<j} \int d\vec{x}_i \, d\vec{x}_j \;\; \rho_2(\vec{x}_i, \vec{x}_j) \otimes \tilde{V}_2(\vec{q}_X; \vec{x}_i, \vec{x}_j) \end{aligned}}$$

q-dependent "potentials", related to momentum-space amplitudes

$$\tilde{V}_1(\vec{q}_X; \vec{x}_i) = -\int \frac{d\vec{q}_i}{(2\pi)^3} e^{-i\vec{q}_i\cdot\vec{x}_i}\; (2\pi)^3\delta^{(3)}(\vec{q}_i + \vec{q}_X)\; \overline{M}_{1,X}(\vec{q}_i, \vec{q}_X)$$

$$\tilde{V}_2(\vec{q}_X; \vec{x}_i, \vec{x}_j) = -\int \frac{d\vec{q}_i}{(2\pi)^3} \frac{d\vec{q}_j}{(2\pi)^3} e^{-i\vec{q}_i\cdot\vec{x}_i} e^{-i\vec{q}_j\cdot\vec{x}_j}\; (2\pi)^3\delta^{(3)}(\vec{q}_i + \vec{q}_j + \vec{q}_X)\; \overline{M}_{2,X}(\vec{q}_i, \vec{q}_j, \vec{q}_X)$$

3. Nuclear matrix elements

$$\langle f|\hat{T}|i\rangle \;=\; (2\pi)^3\delta^{(3)}\,(\vec{q}_X+\vec{q}_A)\,T(\vec{q}_X) \qquad\qquad T(\vec{q}_X)=T_1+T_2$$

$$\boxed{\begin{aligned} T_1 &= \sum_{i=1,A}\int d\vec{x}_i\;\rho_1(\vec{x}_i)\otimes\tilde{V}_1(\vec{q}_X;\vec{x}_i) \\ T_2 &= \sum_{i<j}\int d\vec{x}_i\,d\vec{x}_j\;\rho_2(\vec{x}_i,\vec{x}_j)\otimes\tilde{V}_2(\vec{q}_X;\vec{x}_i,\vec{x}_j)\end{aligned}}$$

Nuclear structure input: one- and two-body densities in the ground state

$$\rho_1(\vec{x}) = \int d\vec{x}_1\ldots d\vec{x}_{A-1}\;\;|\psi_0(\vec{x}_1,\ldots,\vec{x}_{A-1},\vec{x})|^2$$

$$\rho_2(\vec{x},\vec{y}) = \int d\vec{x}_1\ldots d\vec{x}_{A-2}\;\;|\psi_0(\vec{x}_1,\ldots,\vec{x}_{A-2},\vec{x},\vec{y})|^2$$

- One-body: factorization of nucleon and nuclear effects

$$\boxed{T_1 = -F(|\vec{q}_X|^2)\left(Z\, f_p(|\vec{q}_X|^2) \;+\; (A-Z)\, f_n(|\vec{q}_X|^2)\right)}$$

Nuclear form factor
(Fourier transform of one-body density)

Nucleon form factors

- One-body: factorization of nucleon and nuclear effects

$$T_1 = -F(|\vec{q}_X|^2)\left(Z\, f_p(|\vec{q}_X|^2)\ +\ (A-Z)\, f_n(|\vec{q}_X|^2)\right)$$

Nuclear form factor
(Fourier transform of one-body density)

Nucleon form factors

- Two-body: use shell model to get first rough estimate

$$T_2^{(\pi\pi)} = -\frac{\lambda_+}{v\,\Lambda_{\rm np}^2}\,\frac{g_A^2 m_\pi^3}{96\,\pi\,F_\pi^2}\,\mathcal{N}_{\pi\pi}\ \times \exp\left(-\frac{|\vec{q}_X|^2 R^2(A)}{6}\right)$$

$$\mathcal{N}_{\pi\pi} = -1.19\,A$$

Phenomenology: scalar interactions

Differential rate

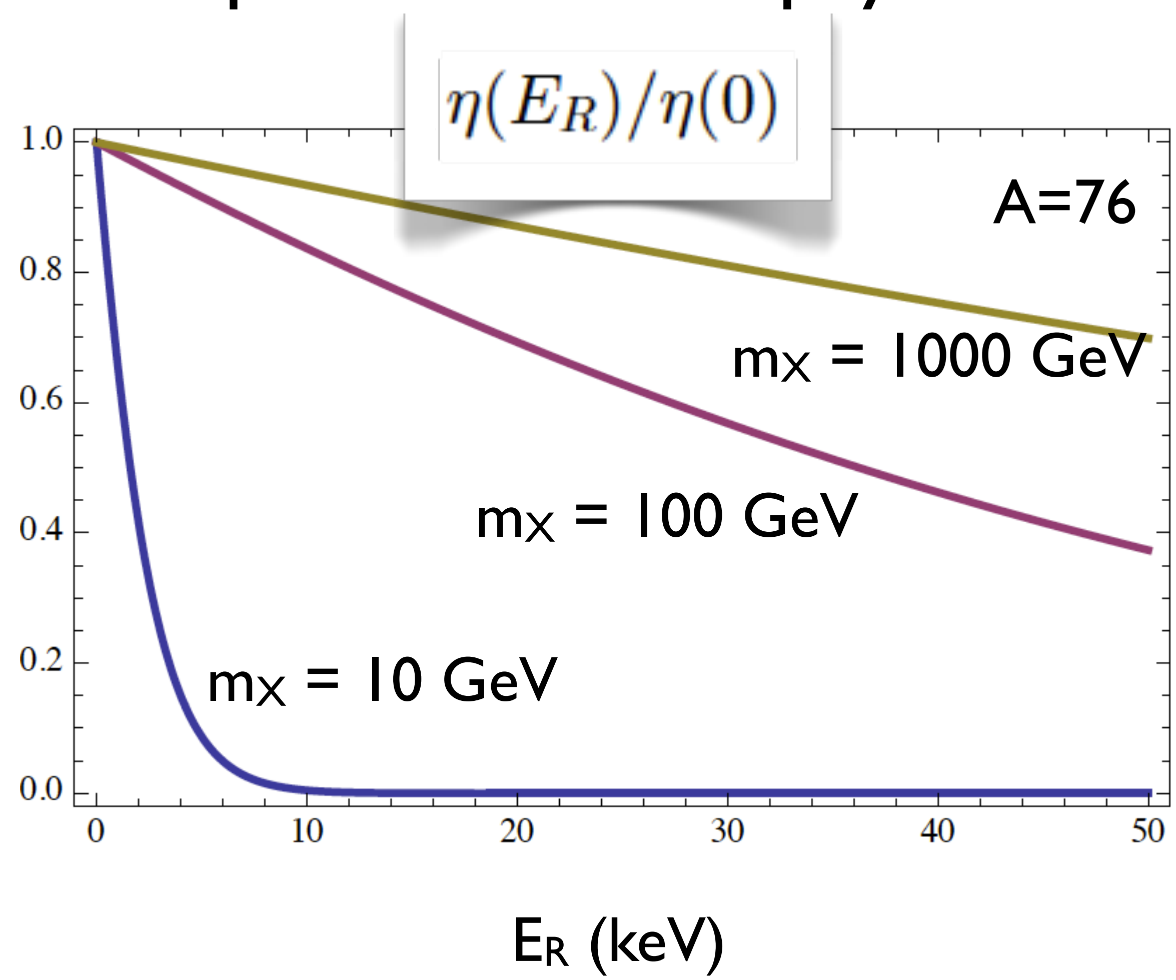
$$\frac{dR}{dE_R} = \frac{\kappa_X \rho_X}{\pi\, m_X} \left| \Big[Z f_p(E_R) + (A - Z) f_n(E_R) \Big] F(E_R) - T_2(E_R, A, Z) \right|^2 \eta\,(E_R)$$

The stuff in red is absent in the LO analysis

Differential rate

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

- Anatomy of recoil spectrum: “astrophysics” factor



$$\eta\,(E_R) = \int_{u_{\min}}^{u_{\rm esc}} \frac{f(u)}{u} \mathrm{d}^3\mathbf{u}$$

Differential rate

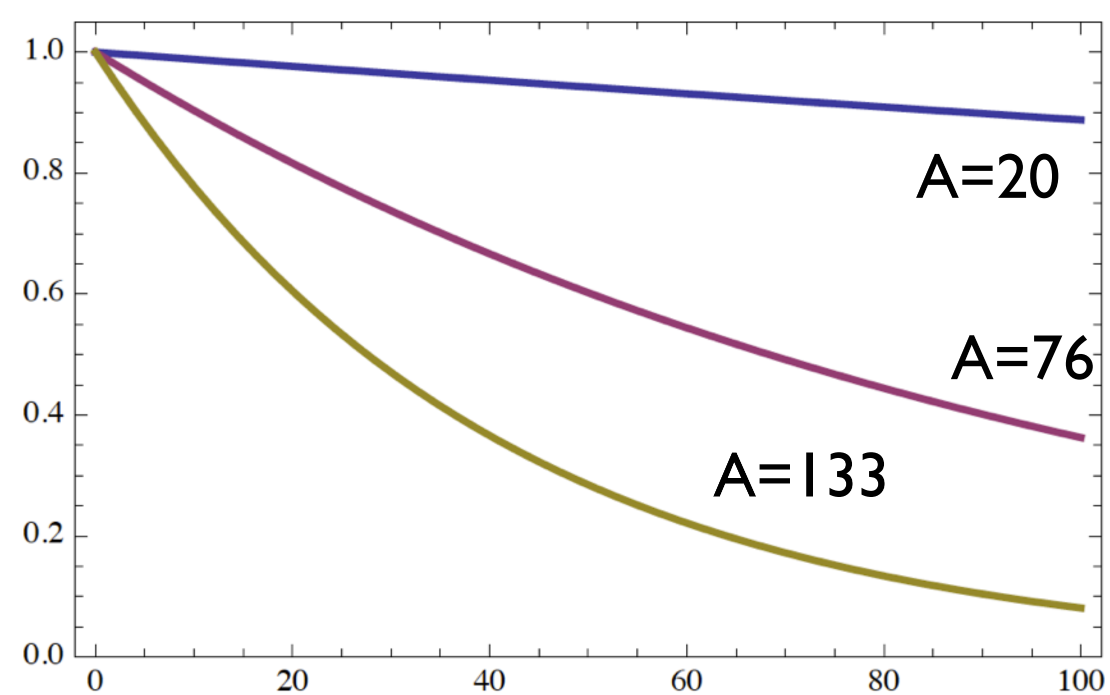
$$\frac{dR}{dE_R} = \frac{\kappa_X \rho_X}{\pi\, m_X} \left| \left[Z f_p(E_R) + (A-Z) f_n(E_R) \right] F(E_R) - T_2(E_R, A, Z) \right|^2 \eta(E_R)$$

- Anatomy of recoil spectrum: hadronic / nuclear effects at LO

$f_{p,n}\ (E_R) = f_{p,n}\ [\lambda_{q,\theta}]$

sigma-terms ⊗ short distance λ's

$F(E_R)$



E_R (keV)

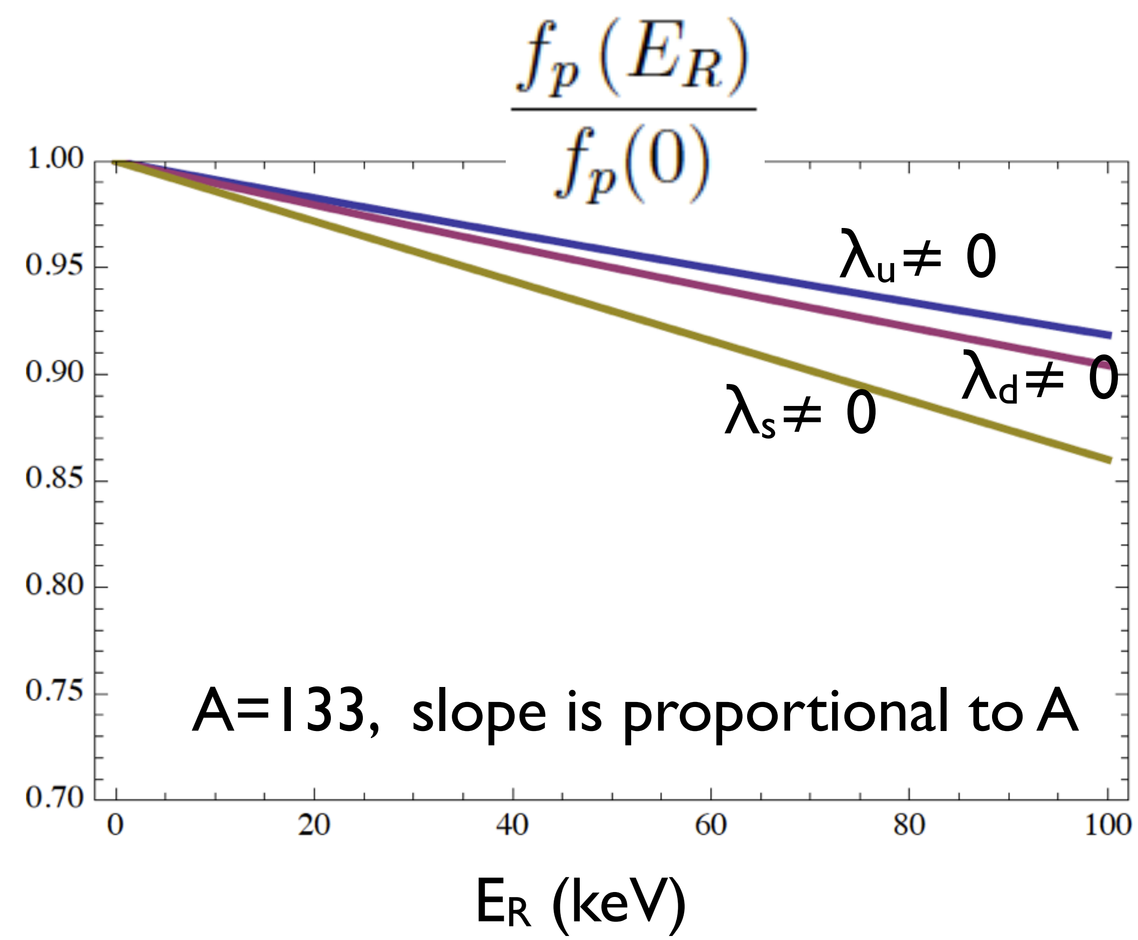
Differential rate

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

- Anatomy of recoil spectrum: hadronic / nuclear effects at NLO

- $f_{p,n}(E_R) = f_{p,n}[\lambda_{q,\theta}] + k_{n,p}[\lambda_q]\ A\ E_R$

Different linear combinations of λ's



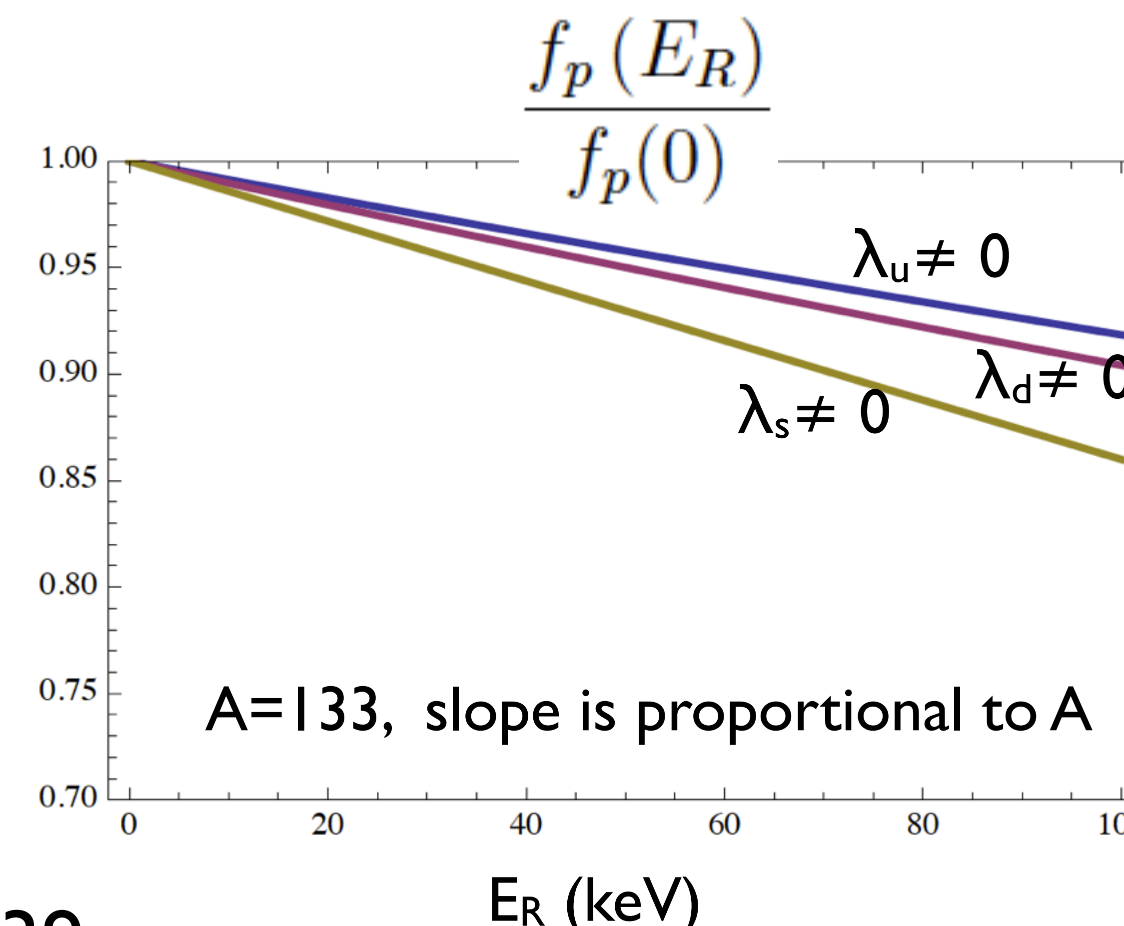
Differential rate

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

- Anatomy of recoil spectrum: hadronic / nuclear effects at NLO

- $f_{p,n}(E_R) = f_{p,n}[\lambda_{q,\theta}] + k_{n,p}[\lambda_q]\ A\ E_R$

Different linear combinations of λ's



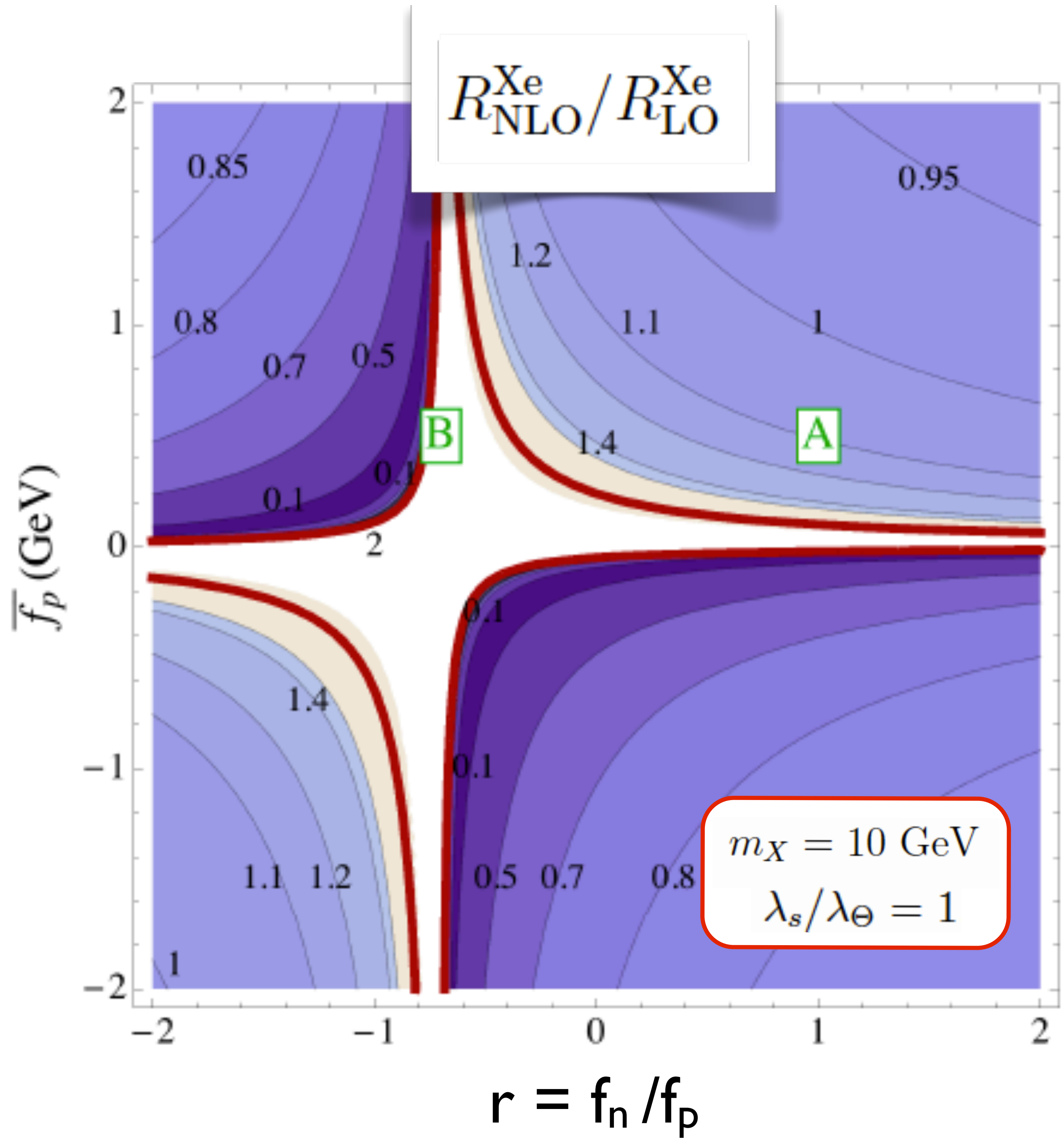
- $T_2(0,A,Z)/(A\, f_p(0)) \sim$ 5%

Similar to LQCD* estimate 1306.6939

NLO vs LO: integrated rates

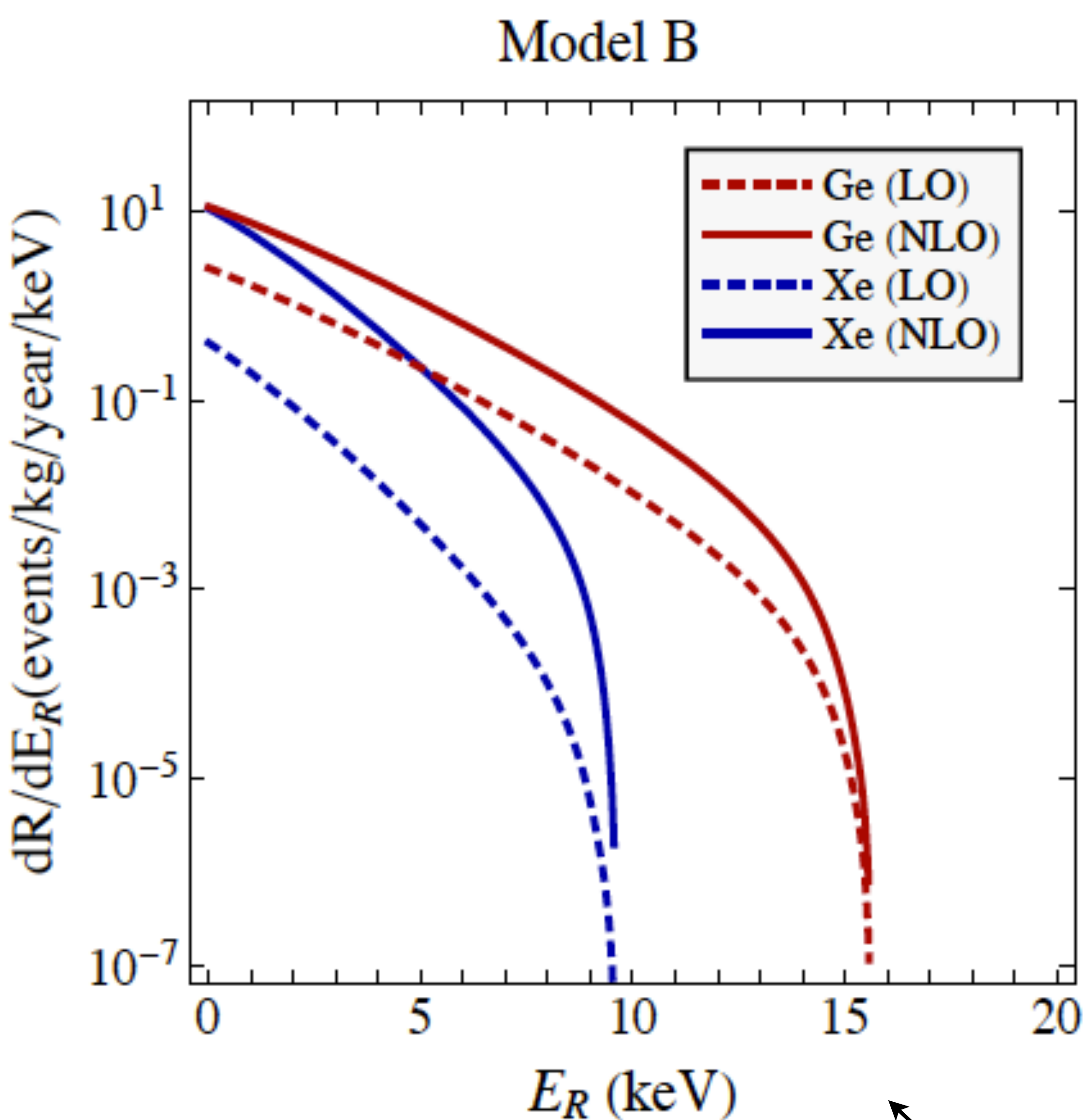
$$R = \left\langle \frac{dR}{dE_R} \right\rangle_{E_R}$$

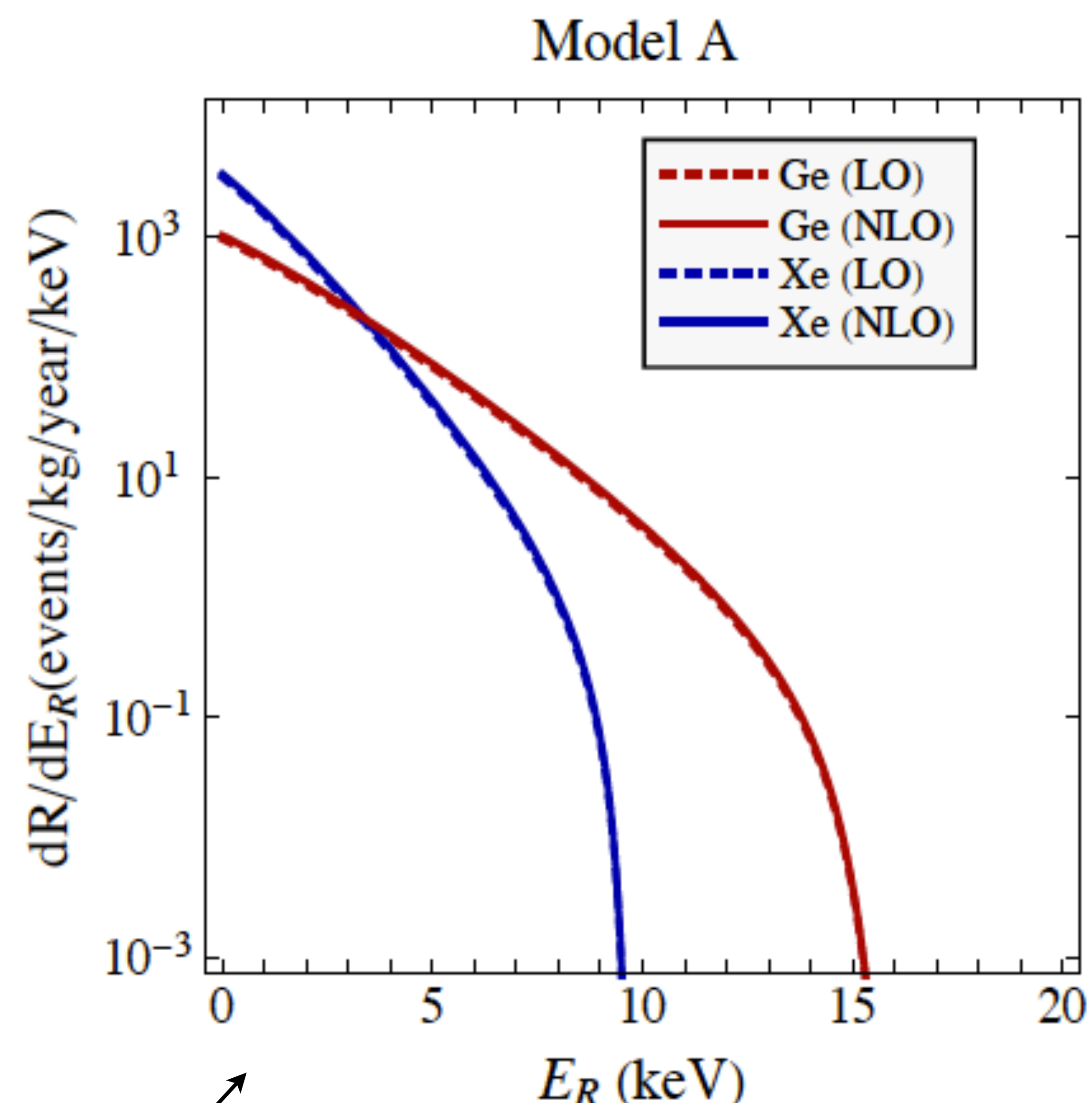
- Huge effects along "singular" lines where LO is suppressed: $f_p \to 0$ (at finite r) and $Z + (A-Z)\, r = 0$
- Similar features for different targets and λ_s/λ_θ, m_X

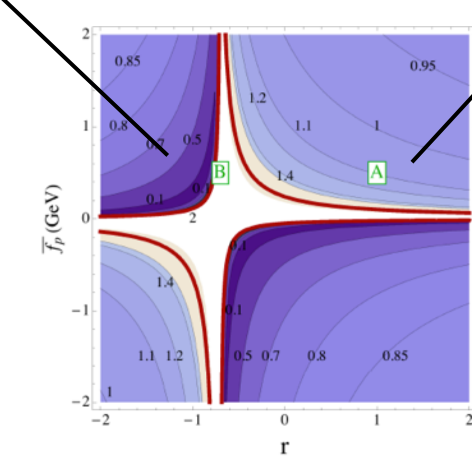


NLO vs LO: spectra

$m_X = 10\ \mathrm{GeV}$

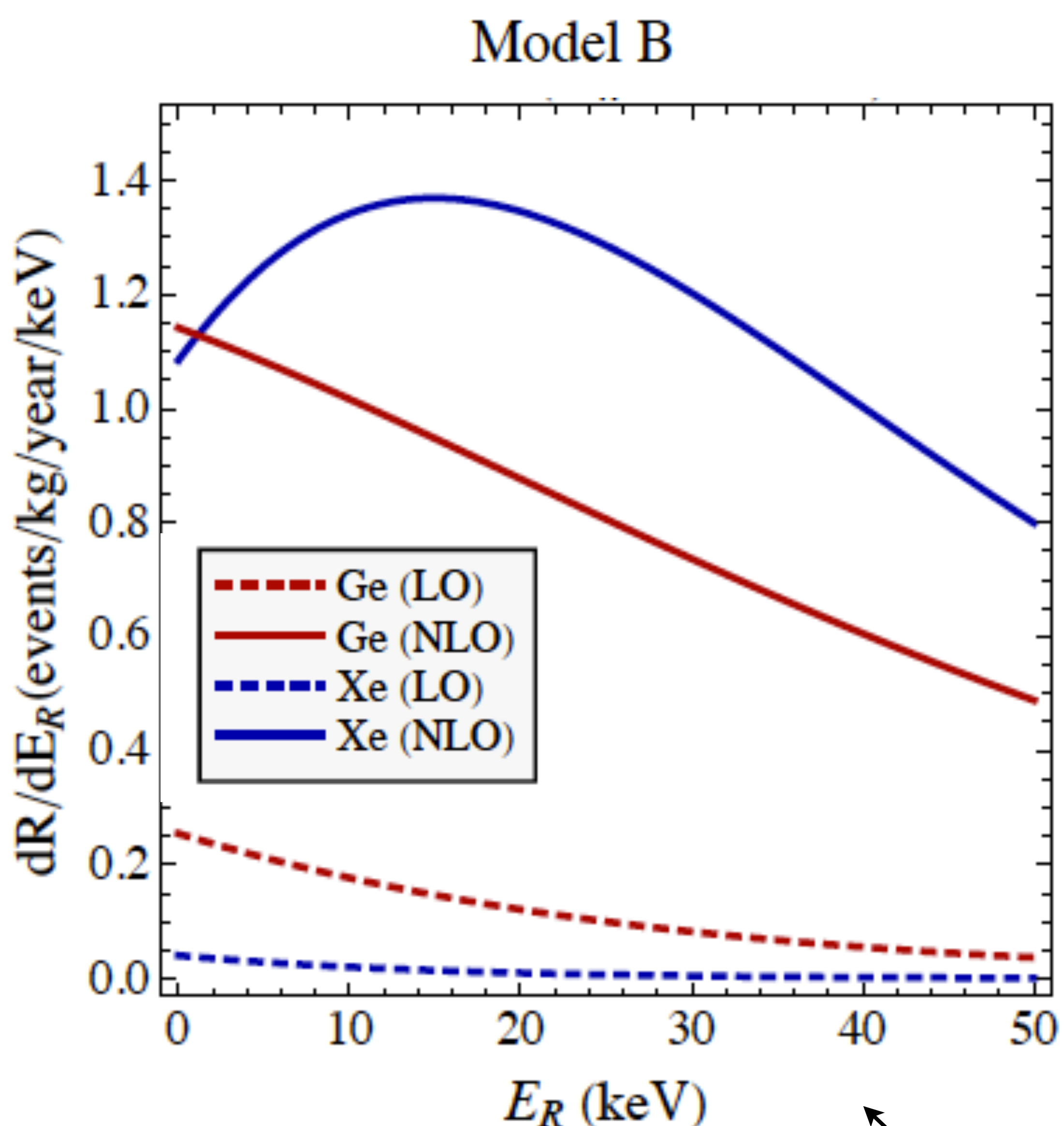


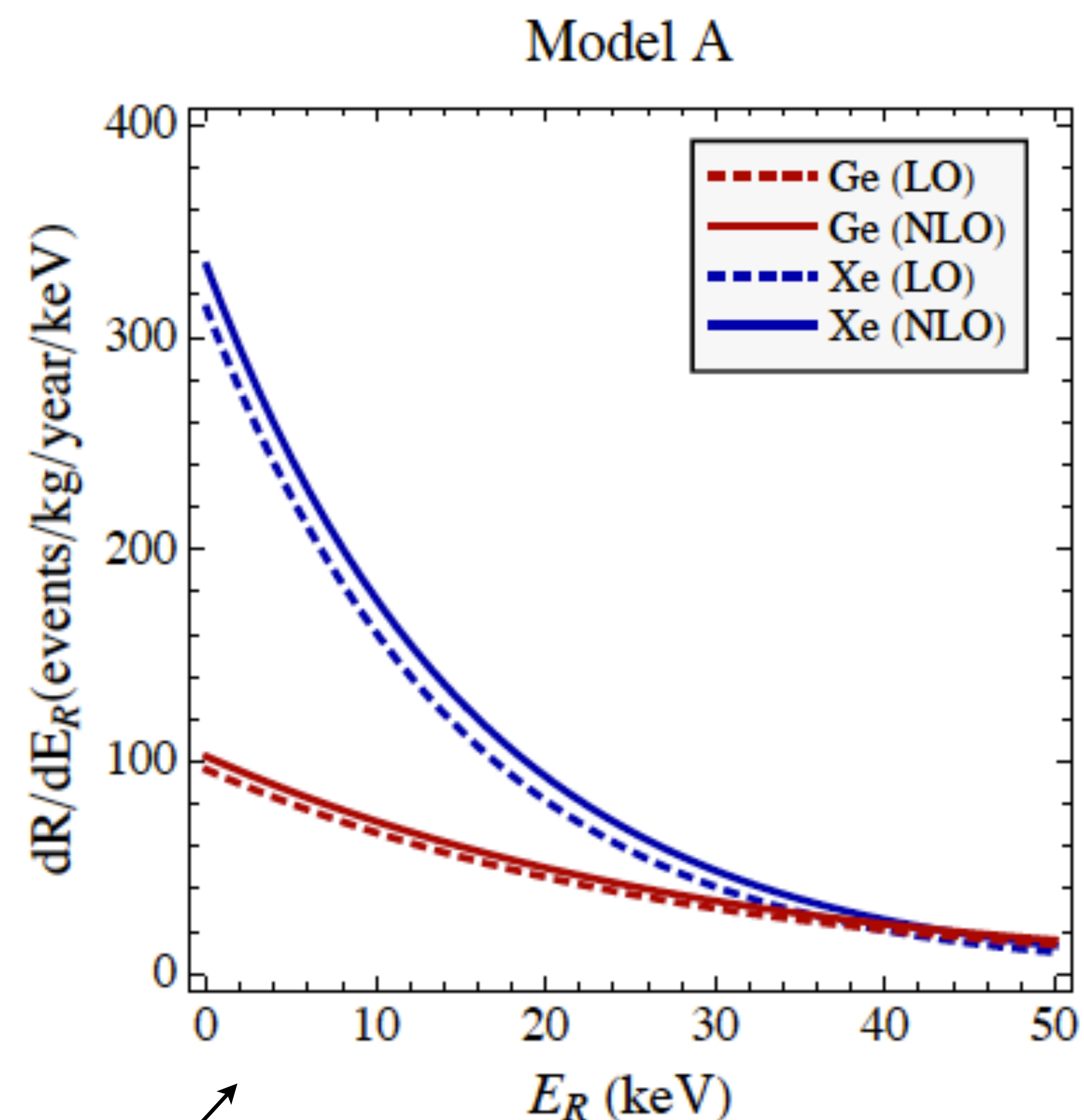


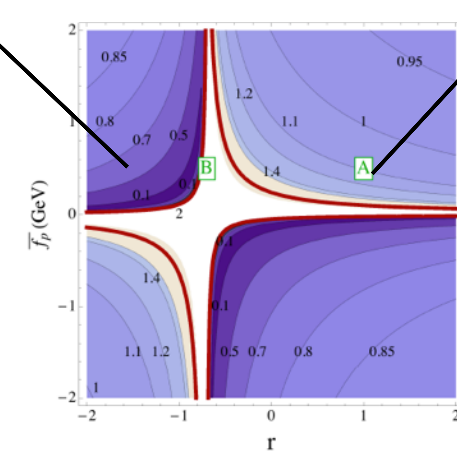


$m_X = 100\ \mathrm{GeV}$

NLO vs LO: spectra







- Large distortion: $f_{n,p}(E_R)$ vs $\eta(E_R)$

Impact of NLO corrections

- While consistent with power counting, NLO effects can have significant impact

  - Description of scalar-mediated WIMP-nucleus scattering involves 4 parameters ($\lambda_{u,d,s,\theta}/\Lambda^2$) rather than 2 ($\sigma_p$ and $r = f_n / f_p$)

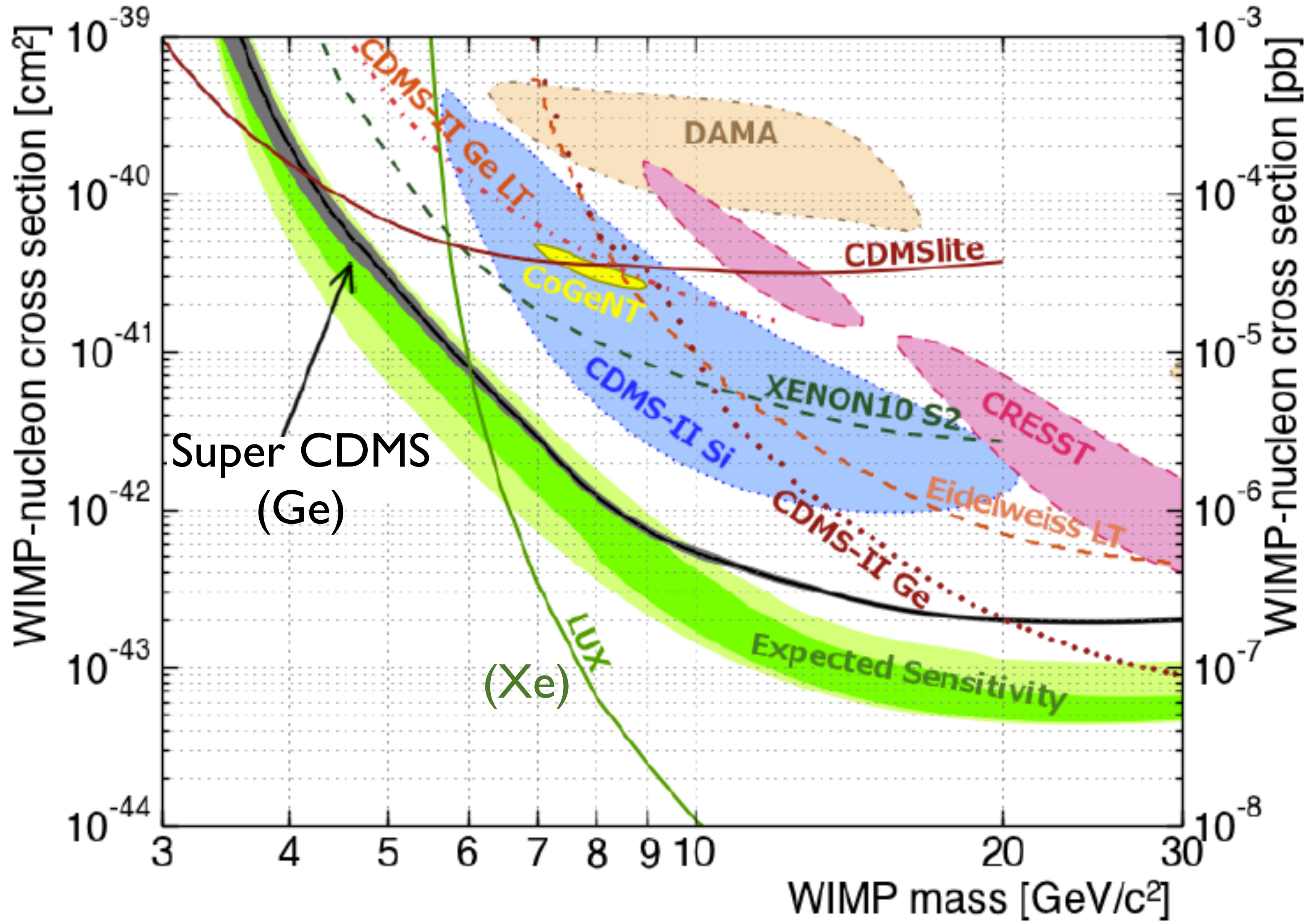
  - LO and NLO contributions depend differently on λ's $\rightarrow$ corrections to amplitude can be larger than what expected by power counting, for certain choices of λ's, <u>especially along LO "blind spot" directions</u>

"Isospin-violating dark matter"

- n and p do not have to couple to DM in the same way

Kurylov-Kamionkowski 2003
Giuliani 2005
Chang-Liu-Pierce-Weiner-Yavin 2010
Feng-Kumar-Marfatia-Sanford 2011

- Idea revived by conflicts in searches using different nuclei, when interpreted at LO with $r = f_n/f_p = 1$



- Can one reconcile experiments by having $f_n \neq f_p$? (i.e. destructive interference in Xe, Ge but not-so-destructive for other nuclei, eg. Si?)

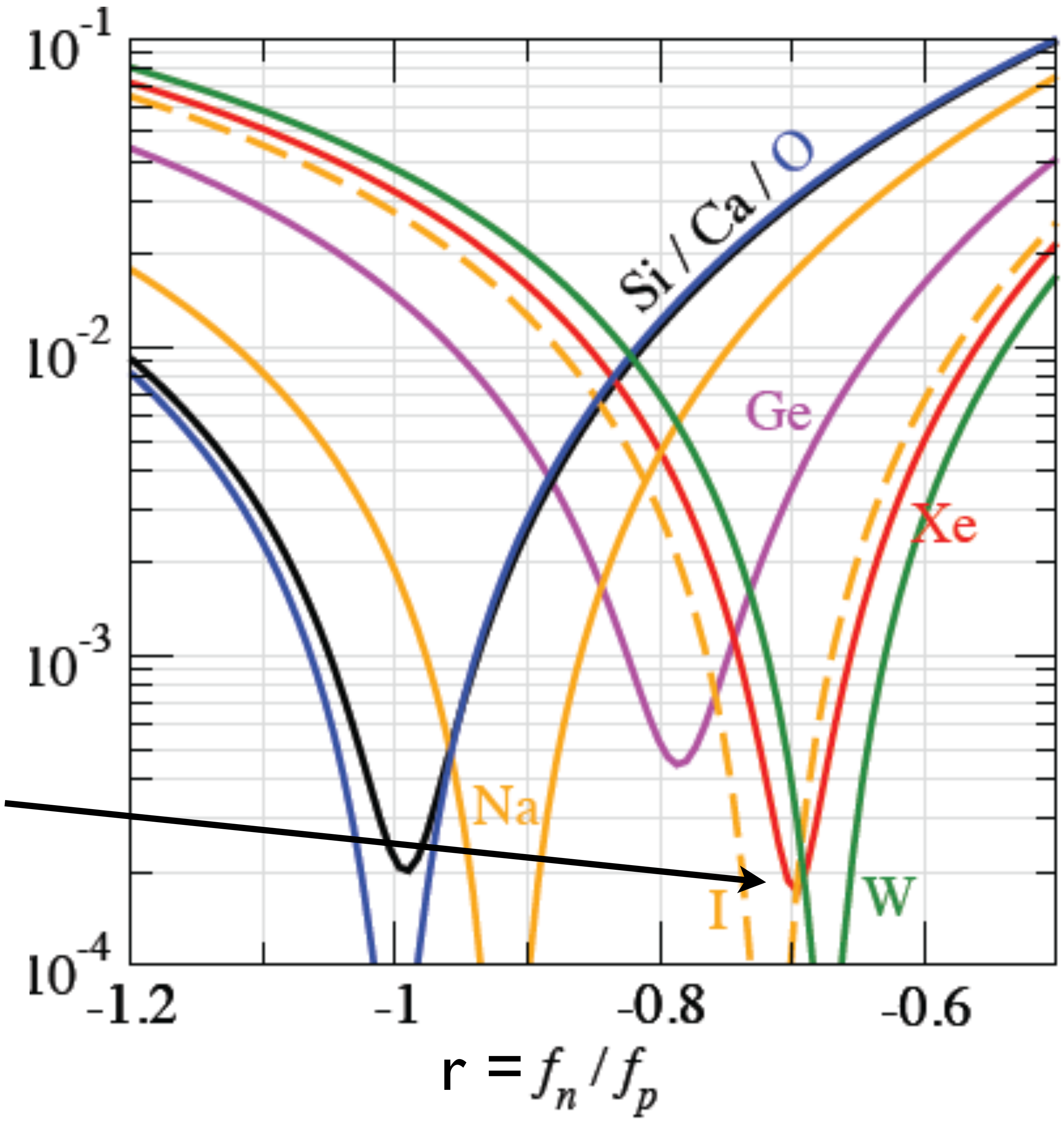
Degradation factors: LO

$$D^{LO}(r) = \frac{\overline{R}^{LO}\left(r, \sigma_p\right)}{\overline{R}^{LO}\left(1, \sigma_p\right)}$$

$$D^{\mathrm{LO}}(r) = \frac{(Z + (A - Z)r)^2}{A^2}$$

“Xe-phobic” region r=-0.7

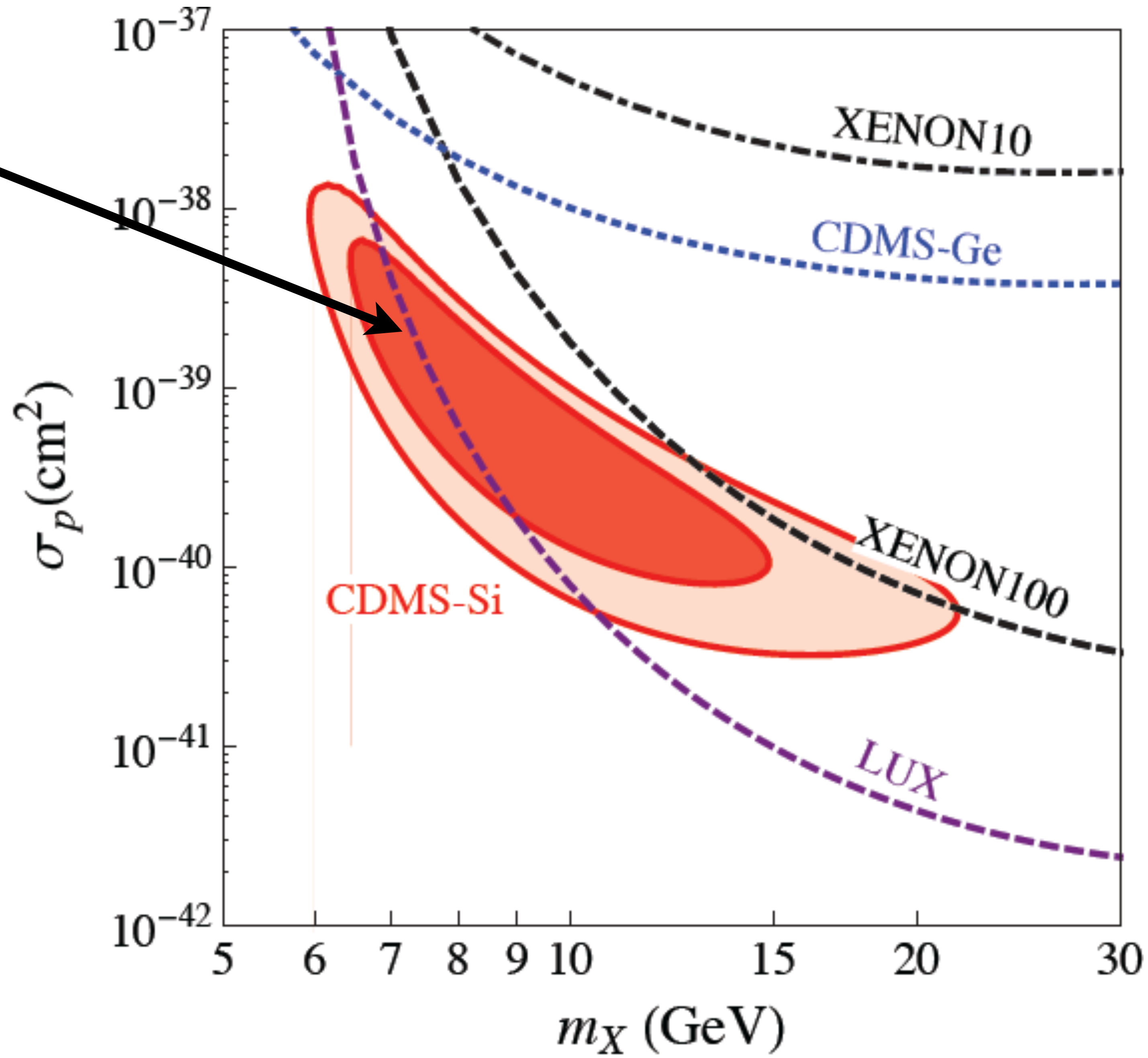
Kopp-Schwetz-Zupan 1110.2721



LO fit to data

- LO fit with r = -0.7 shows compatibility between CMDS-Si and LUX
- But it relies on large suppression of LO Xe cross-section
- What about NLO chiral corrections?

1311.5886



Fits use 2013 input from CDMS-Si and LUX.
Super CDMS (Ge) 2014 input not included

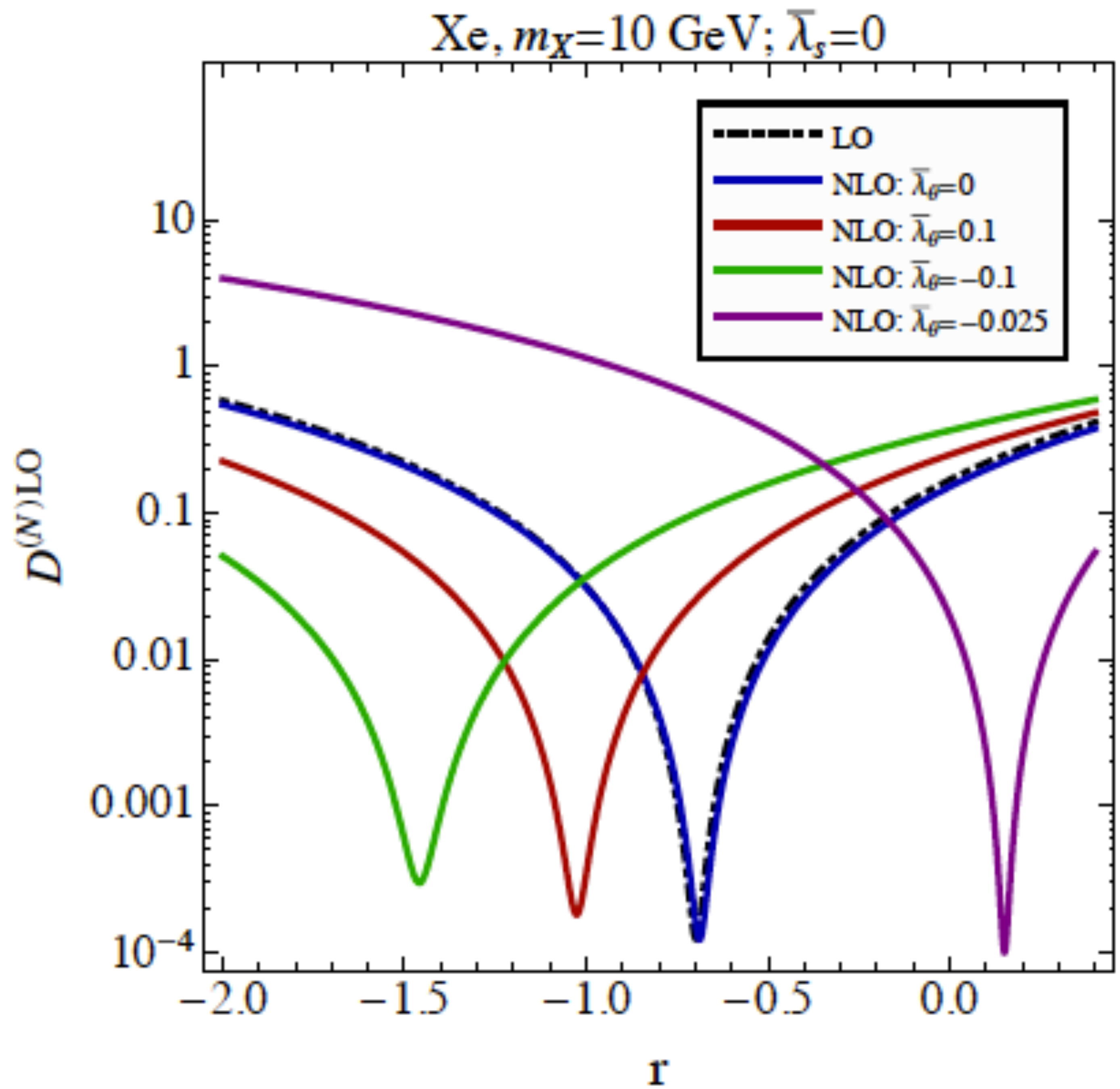
Degradation factors: NLO

$$D^{NLO}(r, \overline{\lambda}_s, \overline{\lambda}_\theta) = \frac{\overline{R}^{NLO}\left(r, \sigma_p, \overline{\lambda}_s, \overline{\lambda}_\theta\right)}{\overline{R}^{LO}\left(1, \sigma_p\right)}$$

- D^{NLO} still quadratic in r
- Location of the minimum shifts, depending on

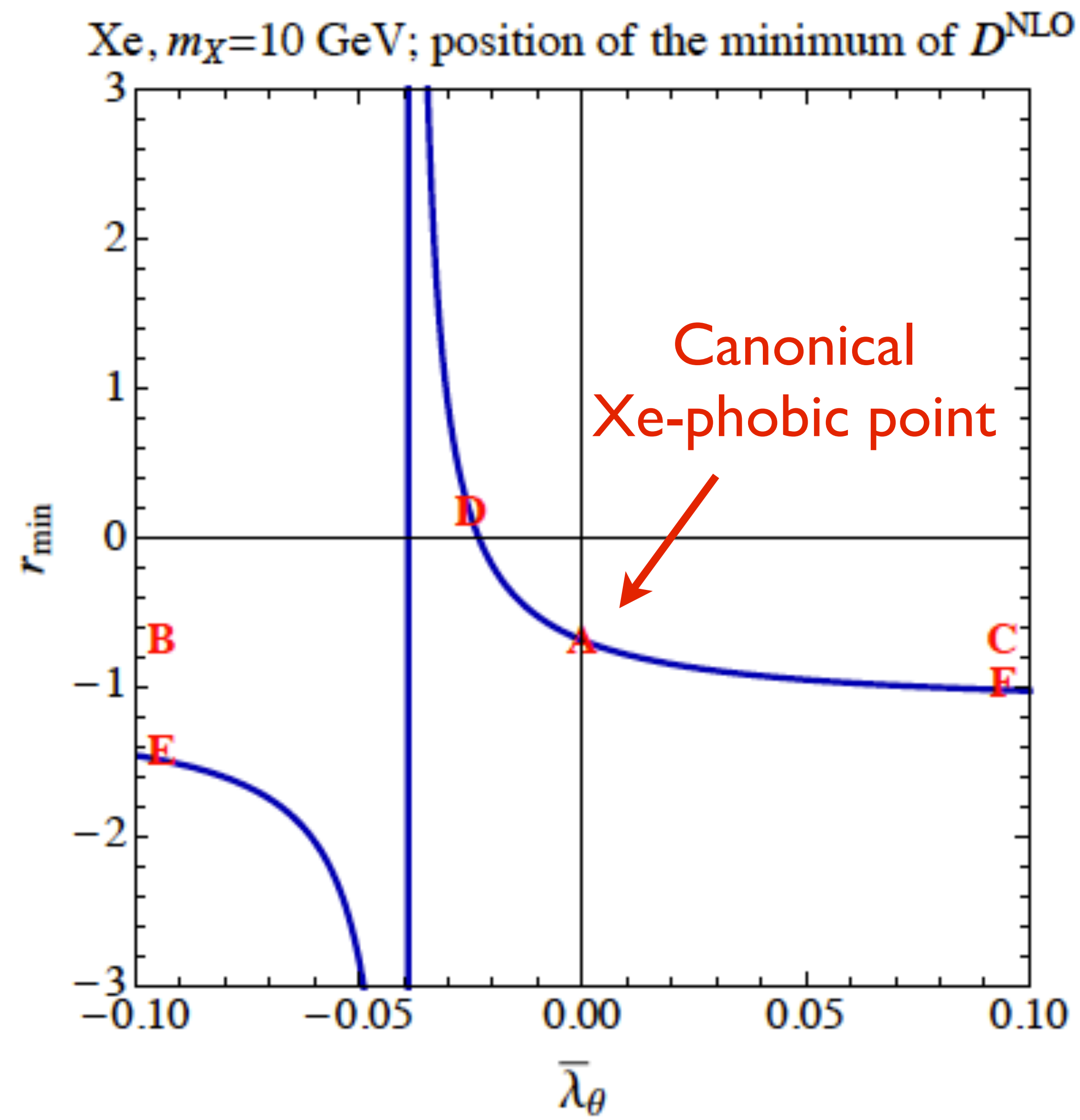
$$\bar{\lambda}_{s,\theta} \equiv \frac{\lambda_{s,\theta}}{\lambda_u}$$

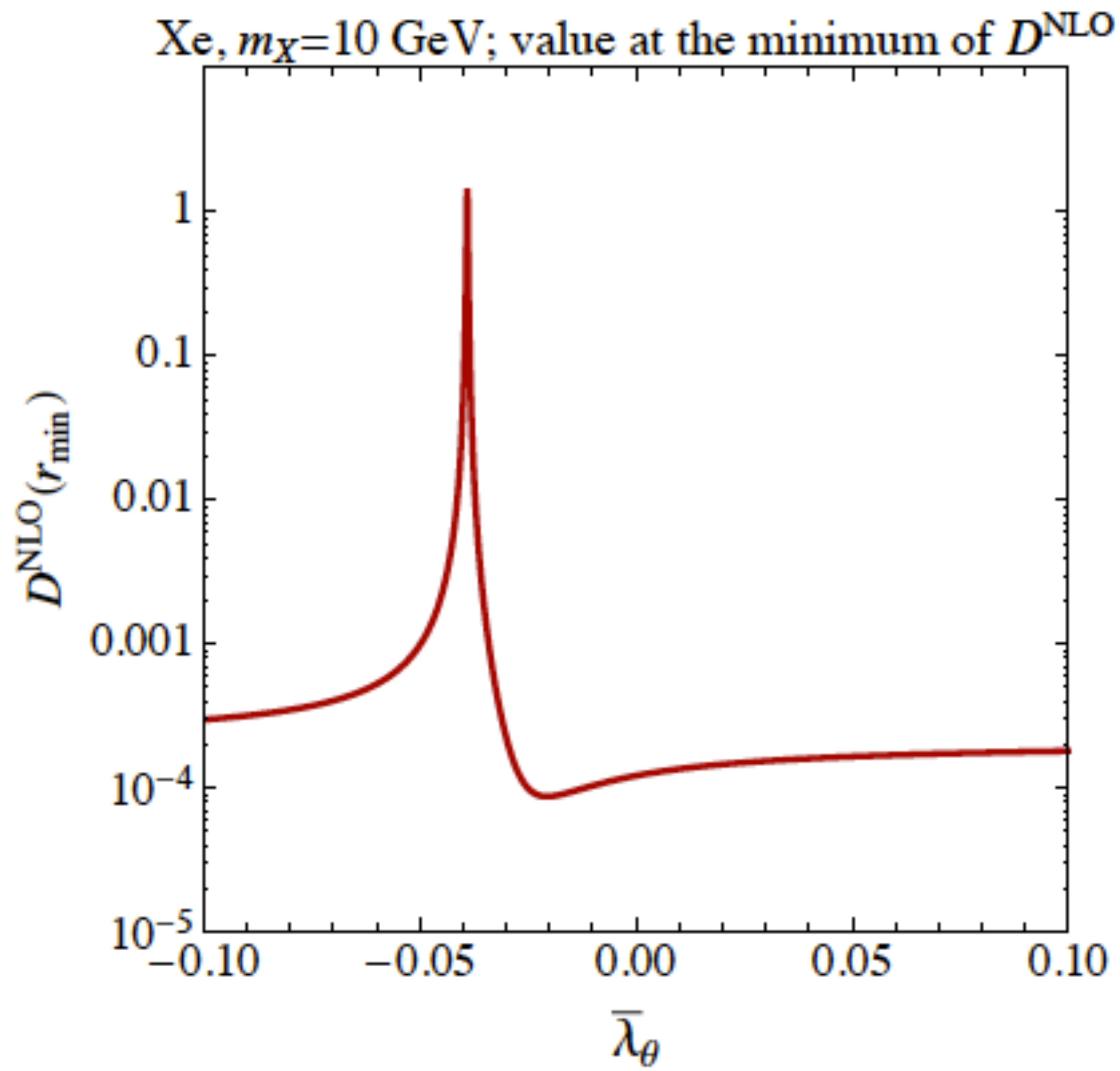
(couplings to heavy quarks)



1311.5886

- Location and depth of the "dip" vs heavy-quark coupling:





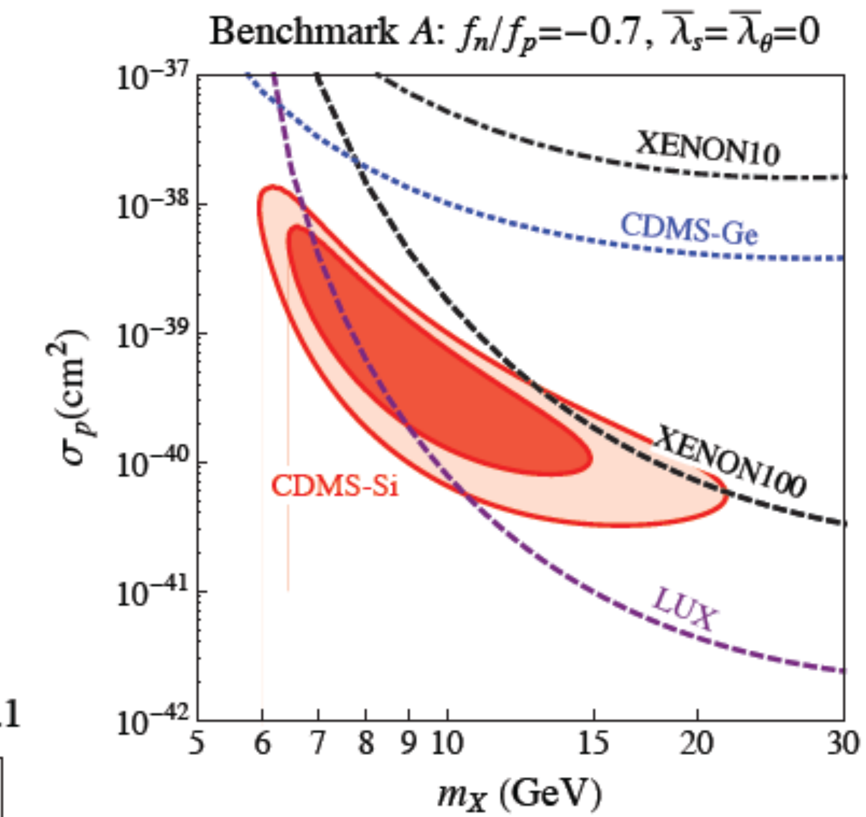
r_{MIN} can take any value

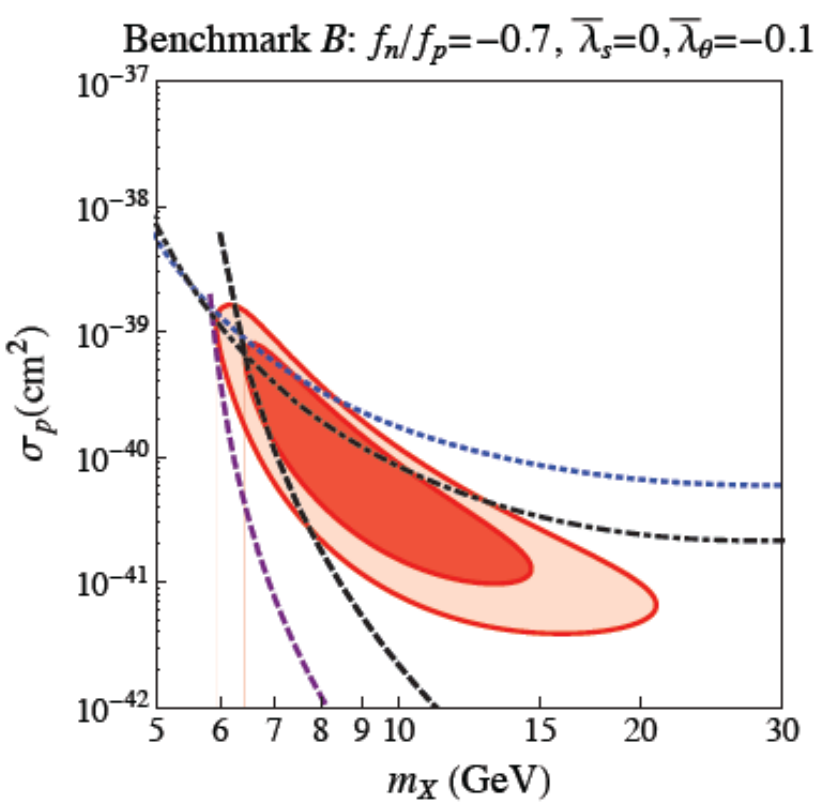
In most cases "degradation"

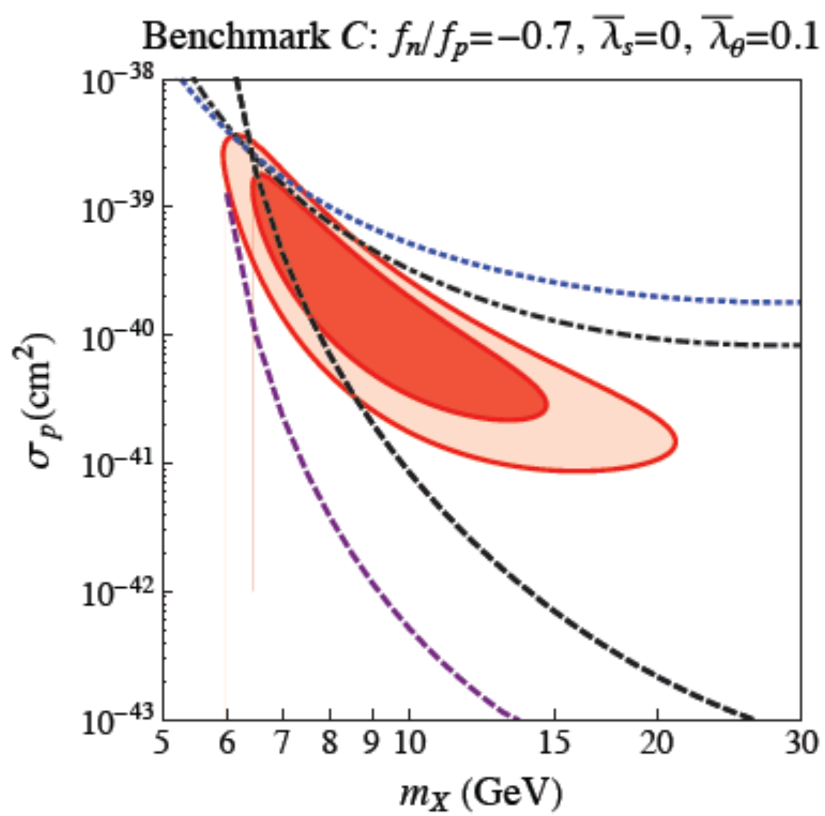
- This points to a manifold of "Xe-phobic" couplings (beyond r=-0.7)

NLO fit to data (I)

- r=-0.7 leads to good compatibility or full exclusion, depending on the values of $\lambda_{s,\theta}$

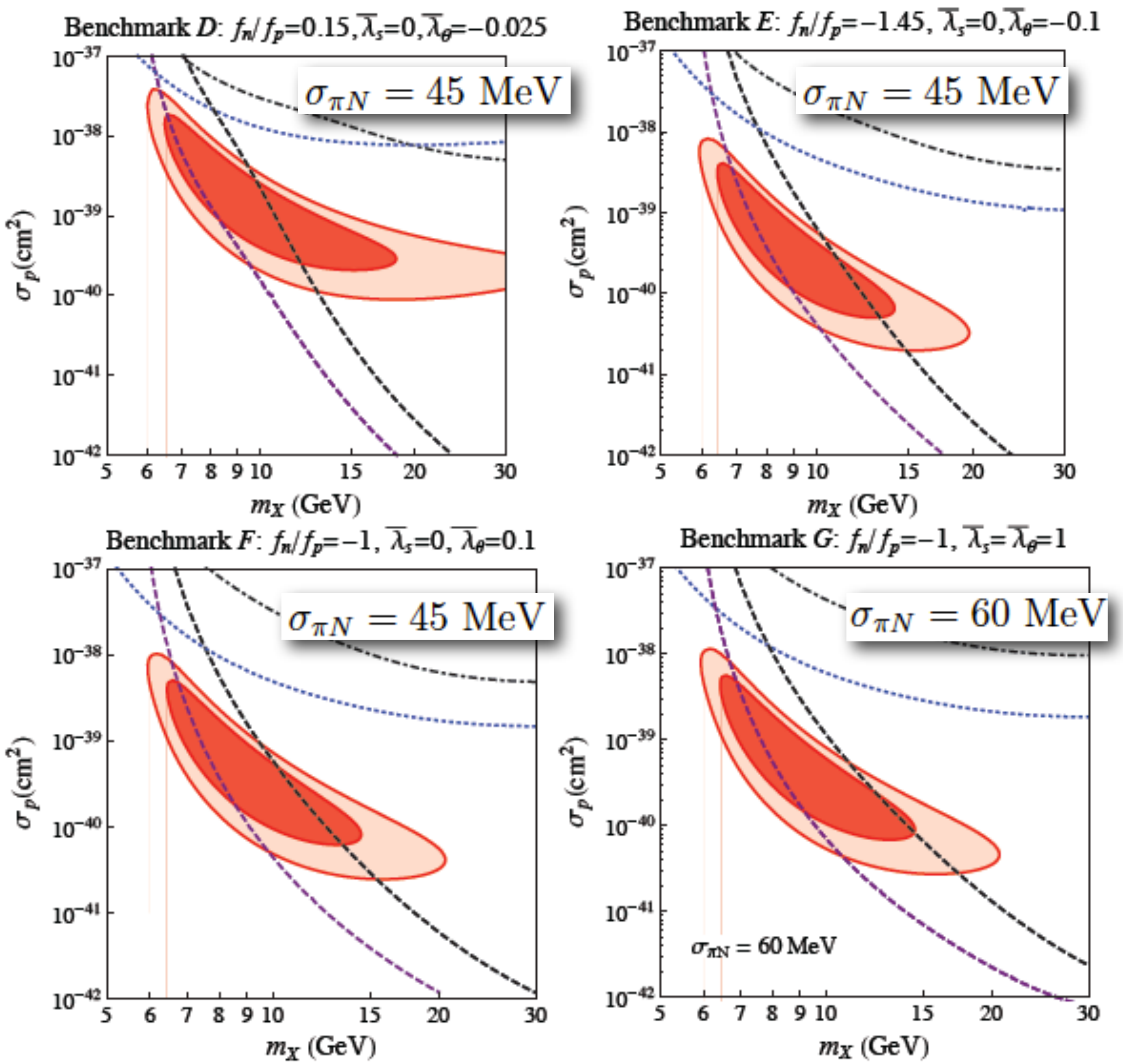






NLO fit to data (II)

- New compatibility regions at r $\neq$-0.7
- Characterized by quite different values of $\lambda_{u,d,s,\theta}$
- Different collider and indirect-detection signatures:
  richer structure!



What about N²LO, ... ?

- At small recoil energy, to all orders in χEFT

$$dR \sim \Big(Z + \Delta_\chi + r\,(A - Z - \Delta_\chi)\Big)^2$$

$$r_{\min} = \frac{\bar{Z}}{1-\bar{Z}} \cdot \frac{1 + \frac{\Delta_\chi}{\bar{Z}}}{1 - \frac{\Delta_\chi}{1-\bar{Z}}}$$

$$\bar{Z} = \frac{Z}{A}$$

What about N²LO, ... ?

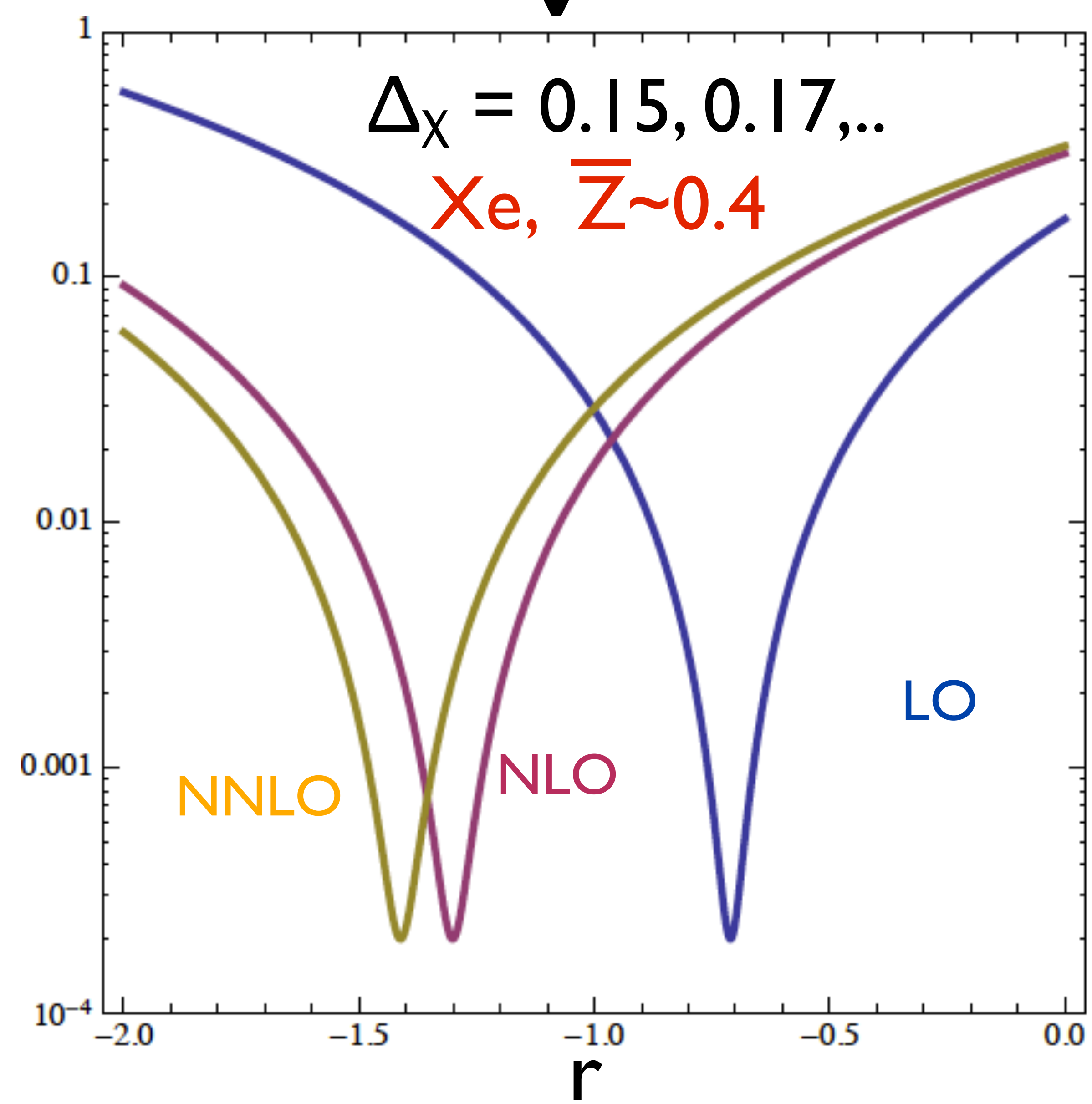
- At small recoil energy, to all orders in χEFT

$$dR \sim \Big(Z + \Delta_\chi + r\,(A - Z - \Delta_\chi)\Big)^2$$

$$r_{\min} = \frac{\bar{Z}}{1-\bar{Z}} \cdot \frac{1+\frac{\Delta_\chi}{\bar{Z}}}{1-\frac{\Delta_\chi}{1-\bar{Z}}}$$

$$\bar{Z} = \frac{Z}{A}$$

- As long as Δ_χ has well behaved expansion, $r_{\min}$ and $dR(r)$ are stable against higher order corrections



Conclusions

- Chiral EFT: systematic tool to analyze WIMP-Nucleus scattering and reconstruct or bound WIMP-quark couplings

- Impact of chiral corrections
  - Quantitative: precision DM phenomenology (post discovery)
  - Qualitative: sizable effects possible through interplay of short-distance parameters and hadronic effects. Dramatic effects on “blind spots”, such as IVDM