WIMP scattering off Xenon: nuclear structure insights

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"Effective Theories and Dark Matter"

Mainz Institute for Theoretical Physics (MITP)
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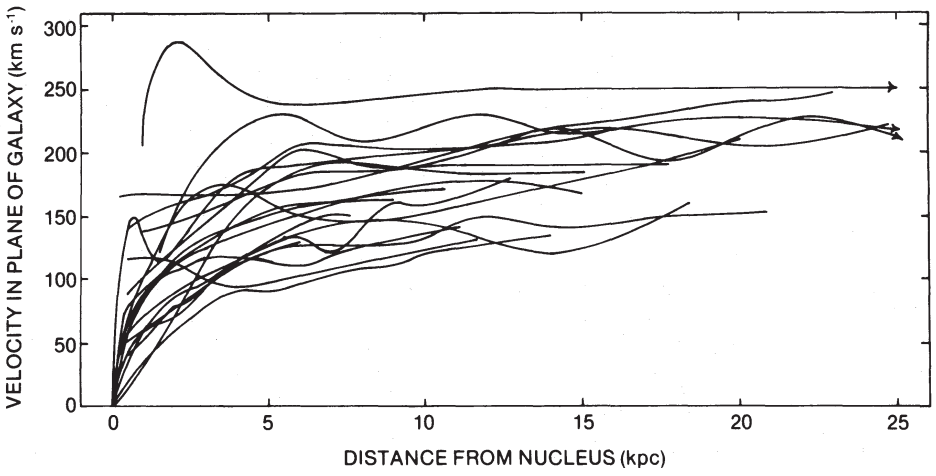
日本学術振興会
Japan Society for the Promotion of Science

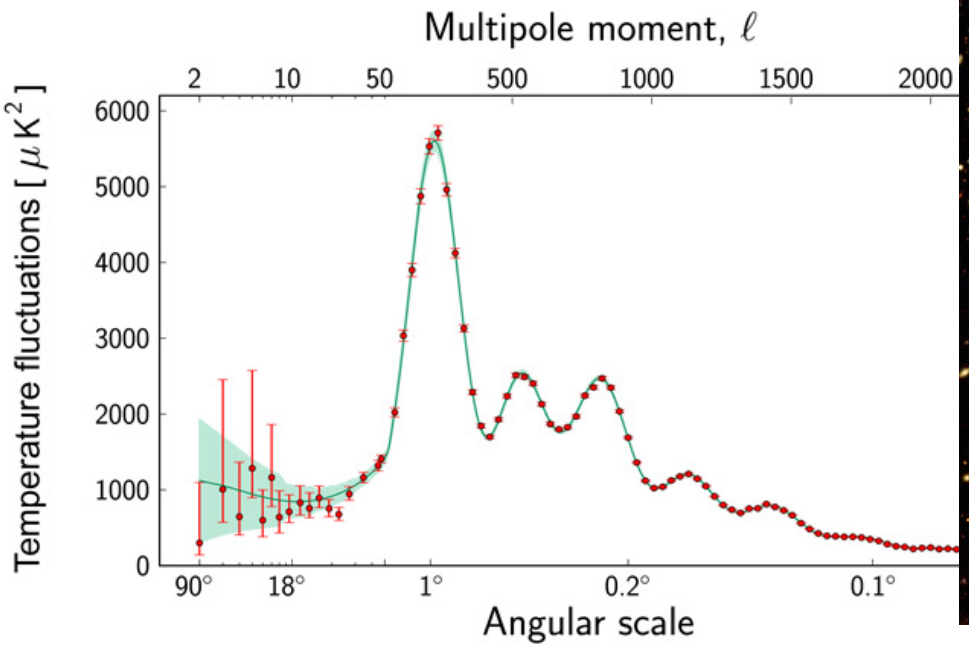
東京大学
THE UNIVERSITY OF TOKYO

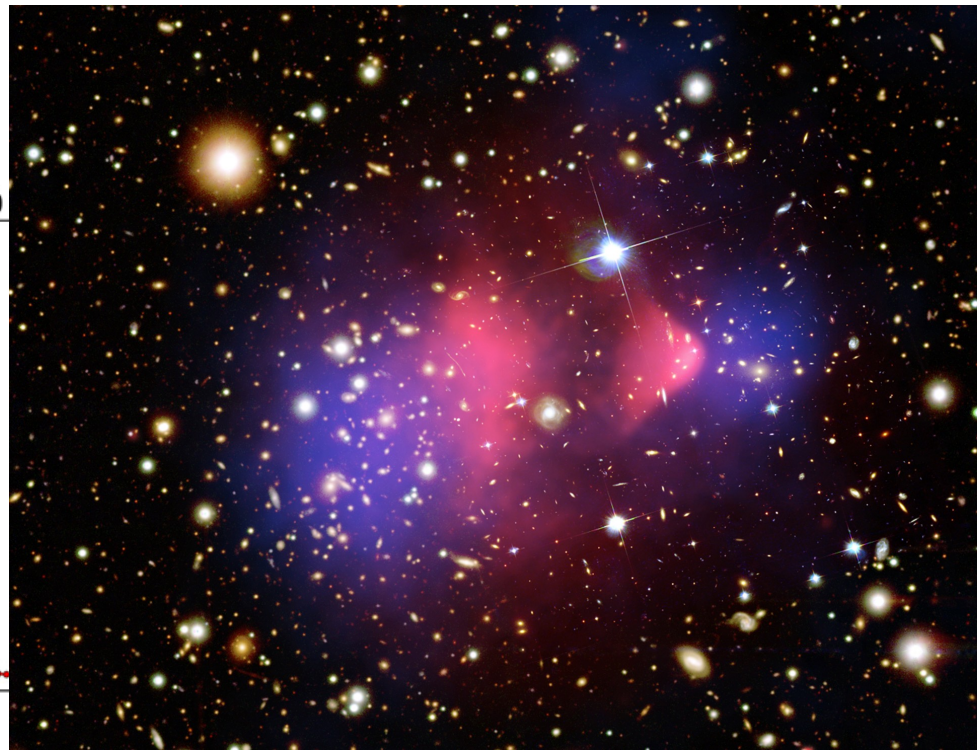
Dark Matter: evidence



Solid evidence of Dark Matter in very different observations:

Rotation curves, Lensing, CMB...
Zwicky 1930's, Rubin 1970's,..., Planck (2013)

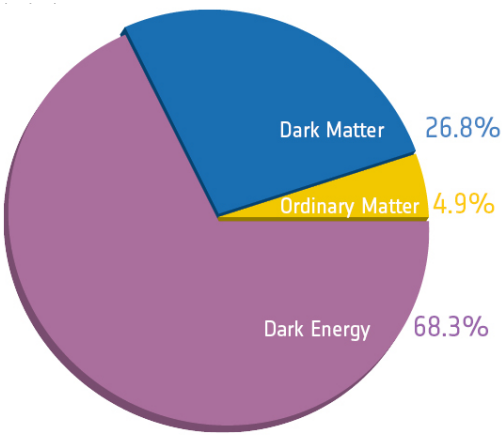




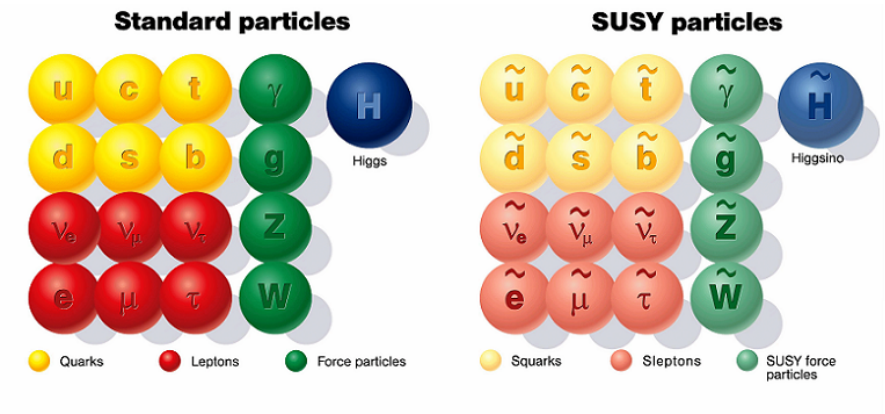
What is Dark Matter made of?

The composition of Dark Matter is unknown

New particles: To be detected

- Weakly interacting massive particles (WIMPs)
- Sterile neutrinos
- Axions
- Gravitons
- 

Lightest supersymmetric particles (usually neutralino) predicted in SUSY extensions of the Standard Model

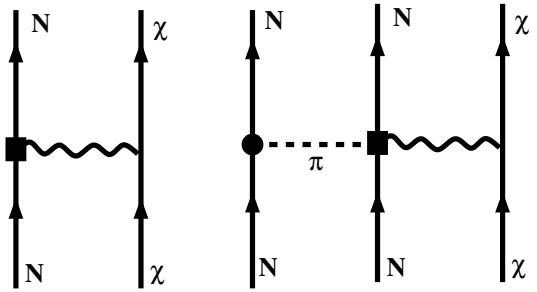


Expected WIMP-density naturally accounts for observed Dark Matter density

WIMP scattering off nuclei

WIMPs interact with quarks $\Rightarrow$ nuclei

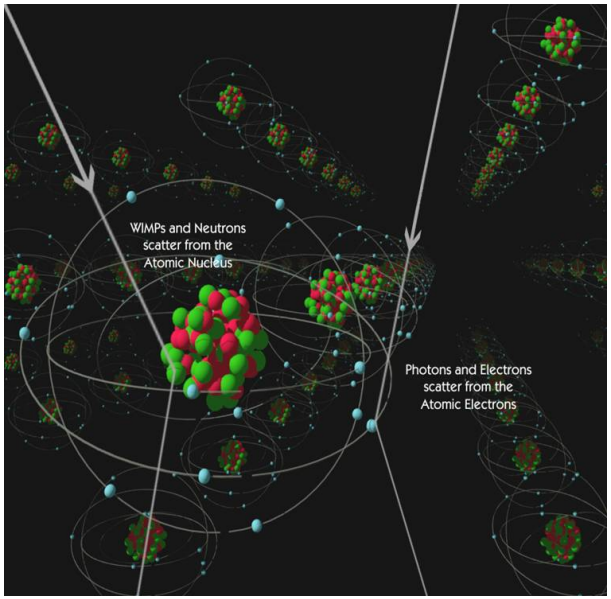
Direct detection experiments: XENON100, LUX
nuclear recoil from WIMP scattering off nuclei
sensitive to Dark Matter masses $\gtrsim$ 1 GeV



Assume spin 1/2 non-relativistic WIMPs
couple to nuclear density or spin

$$\langle \text{Initial} \,|\, \int dx\, j^{\mu}(x) J_{\mu}(x) \,|\, \text{Final} \rangle$$

- WIMP-nucleus interaction:
  - isoscalar spin-independent
  - isoscalar spin-dependent
  - isovector spin-dependent:
    correspond to axial weak neutral currents
    1b + 2b currents predicted by chiral EFT
- Nuclear structure calculation:
  initial and final states

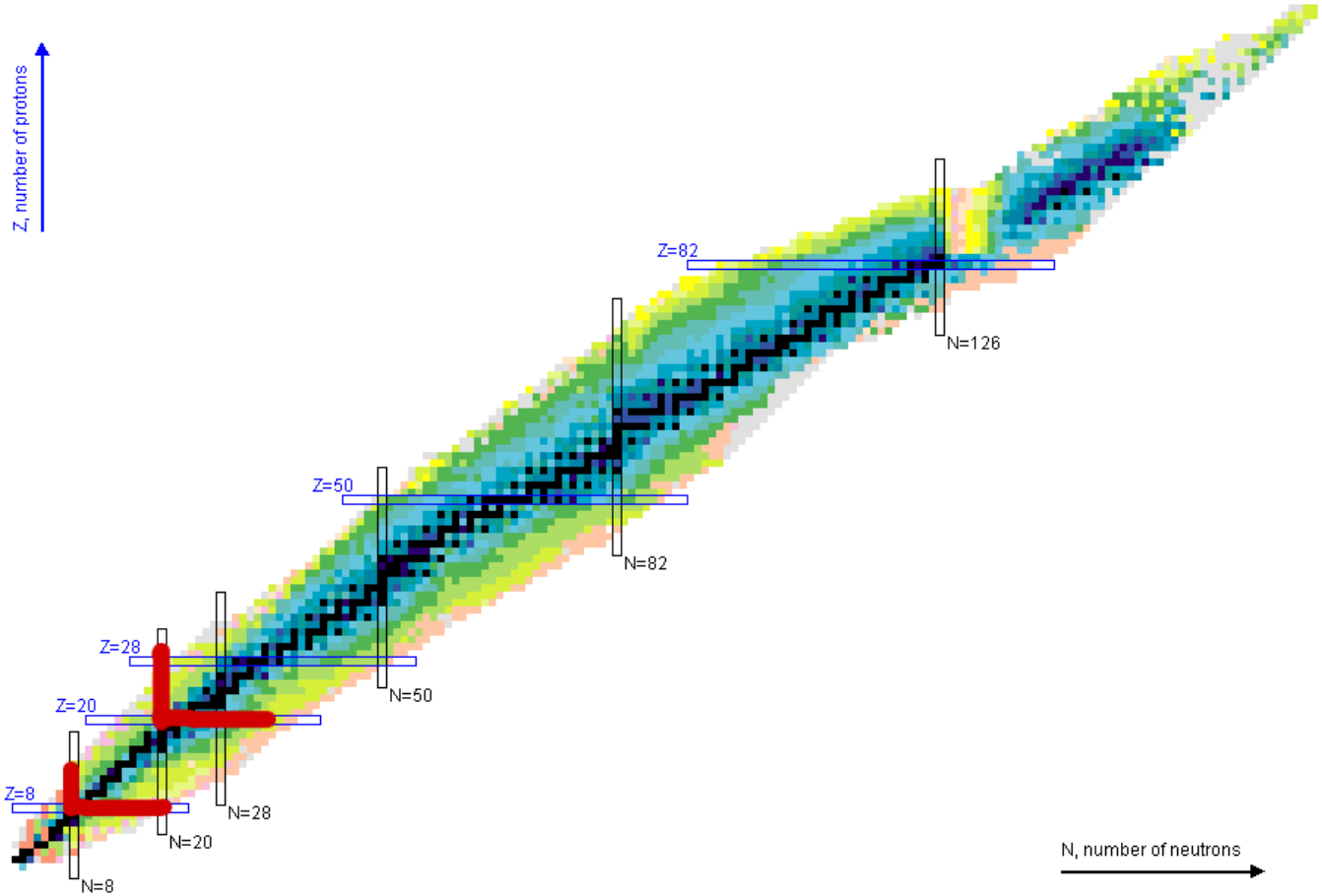


CDMS Collaboration

Outline

Outline

Nuclear landscape



Big variety of nuclei in the nuclear chart, $A \sim 2...300$

Hard many-body problem: approximate methods suited for different regions

Ab initio methods remarkable success in selected medium-mass nuclei: Coupled-Cluster (CC), In-medium Similarily Renormalization Group (IMSRG), Self-Consistent Green's Function (SCGF)...

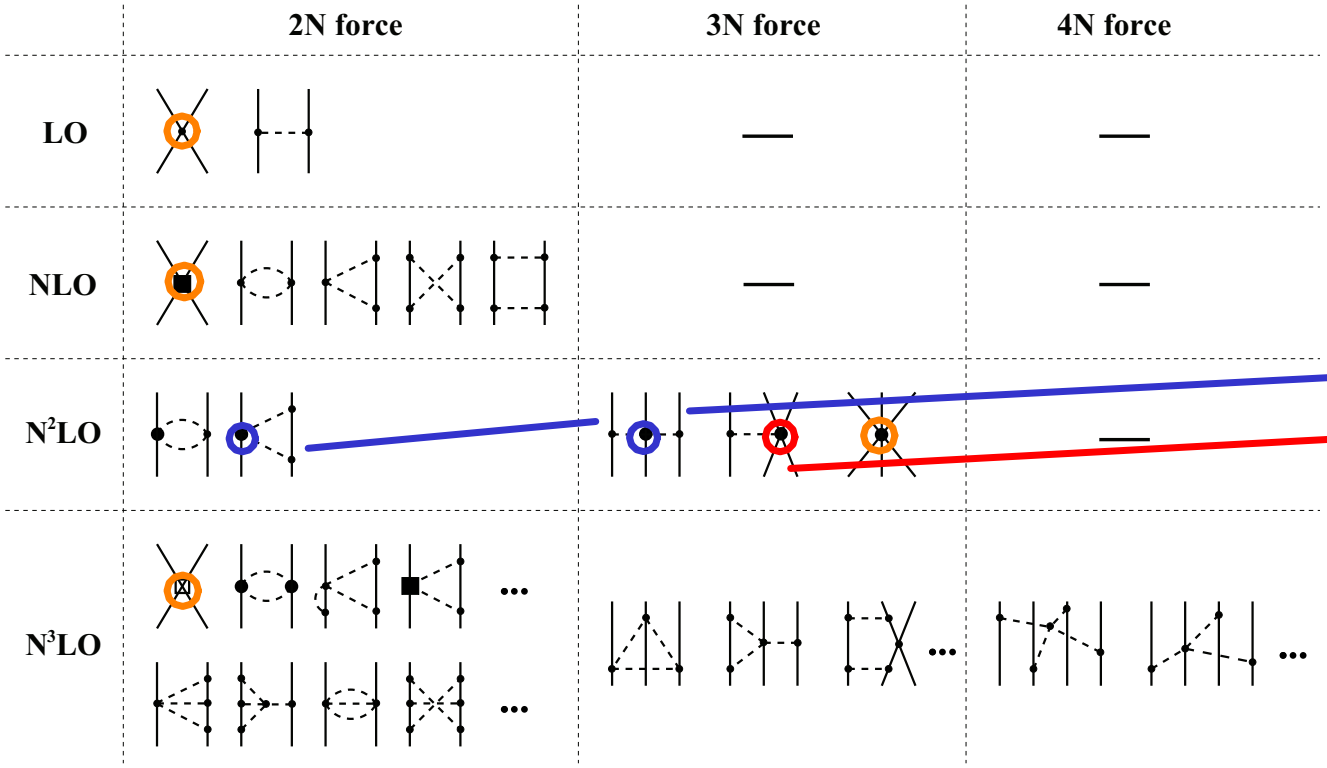
Microscopic shell model: reduced degrees of freedom (valence space), cover wider range range of medium-mass nuclei

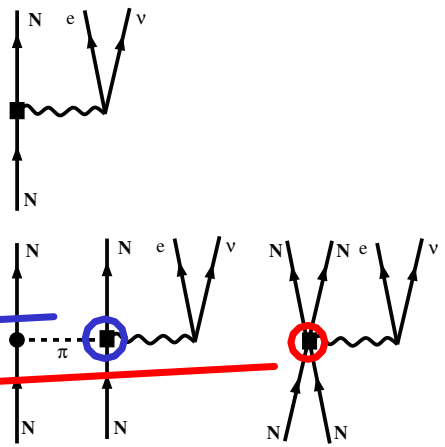
Chiral effective field theory

Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents





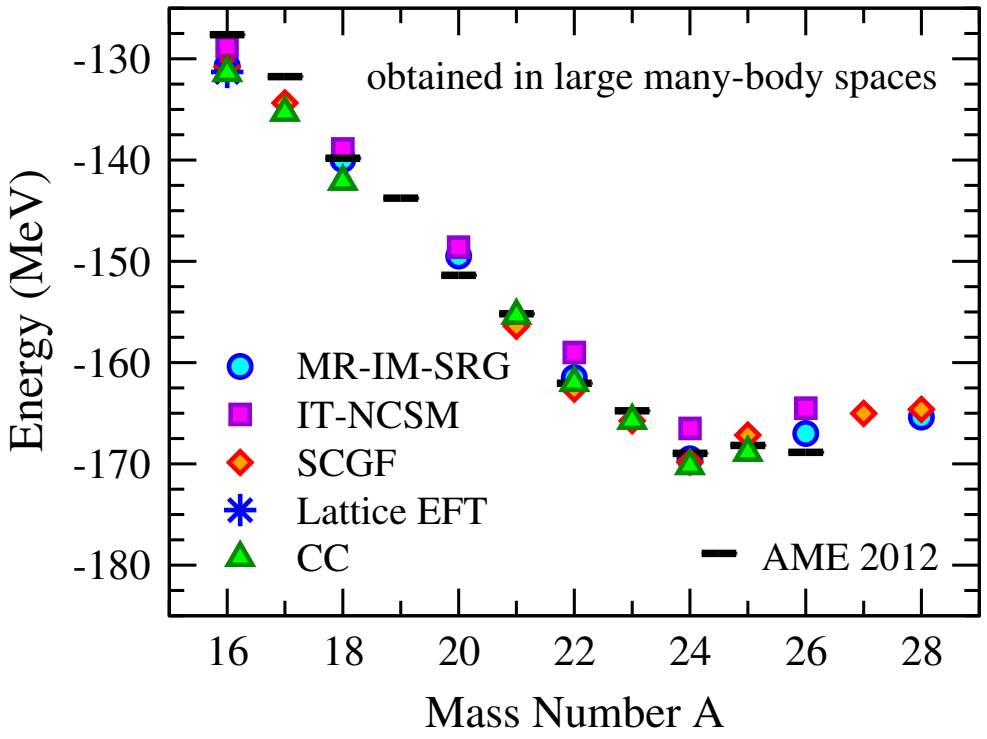
Park et al.
PRC67 055206(2003)

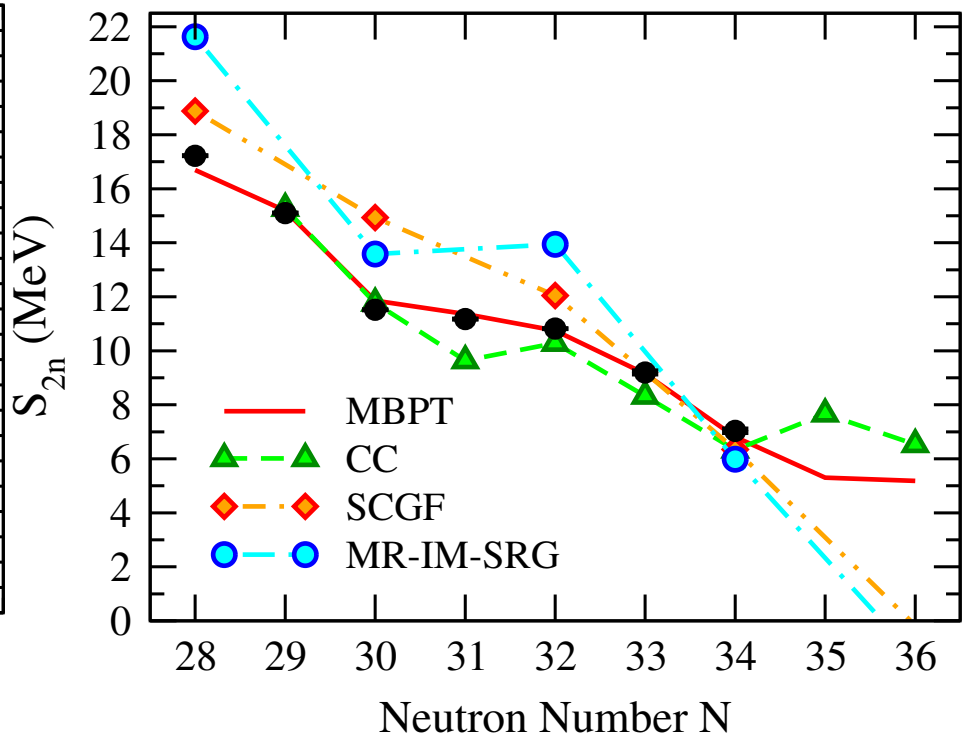
Weinberg, van Kolck, Kaplan, Savage, Weise, Epelbaum, Meißner...

Short-range couplings fitted to experiment once

Nuclear structure wich chiral EFT forces

Great sucess prediction of oxygen dripline and calcium separation energies





Hergert et al. PRL110 242501 (2013)
Cipollone et al. PRL111 062501 (2013)
Jansen et al. PRL113 142502 (2014)

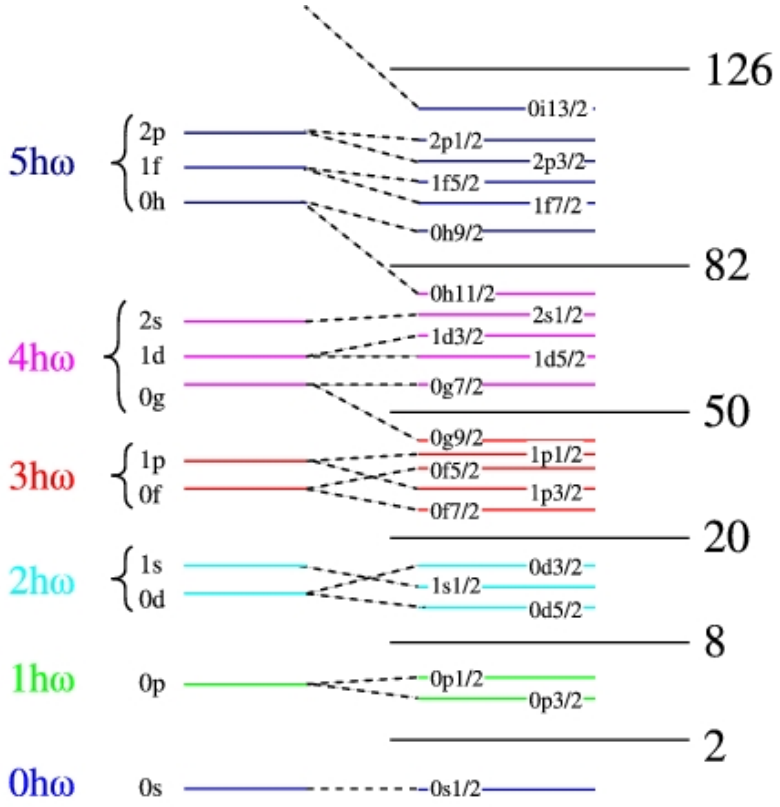
Gallant et al. PRL 109 032506 (2012)
Wienholtz et al. Nature 498 346 (2013)
Hagen et al. PRL 109 032502 (2012)
Somà et al. PRC 89 061301 (2014)
Hergert et al. PRC 90 041302 (2014)

Stable Xenon isotopes

Xenon isotopes beyond present efforts with ab-initio calculations

Seven stable isotopes: ^{128,129,130,131,132,134,136}Xe, $Z = 54$, $N = 74 - 82$

Solve with phenomenological shell model



Configuration space divided into

- Inner core: filled orbits up to $Z = 50$, $N = 50$ (^{100}Sn)
- Valence space: active orbits $0g_{7/2}$, $1d_{3/2}$, $1d_{5/2}$, $2s_{1/2}$ and $0h_{11/2}$
- Outer orbits: empty orbits

$$\mathrm{Dim} \sim \begin{pmatrix} (p+1)(p+2)_\nu \\ N \end{pmatrix} \begin{pmatrix} (p+1)(p+2)_\pi \\ Z \end{pmatrix}$$

Solving the nuclear many-body problem

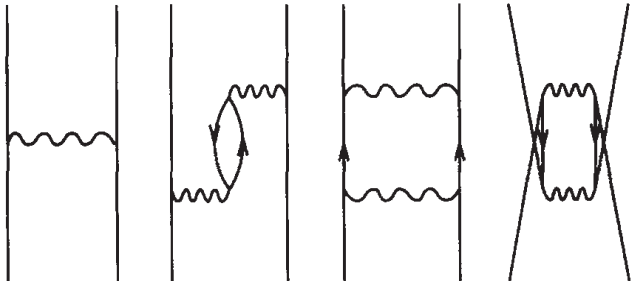
Solve the nuclear many-body problem in the valence space:

$$H\,|\Psi\rangle = E\,|\Psi\rangle \rightarrow H_{eff}\,|\Psi\rangle_{eff} = E\,|\Psi\rangle_{eff}$$

with H_{eff} based on NN forces,

many-body perturbation theory
include effects of core and high-energy orbits

phenomenological modifications needed to compensate for absence of 3N forces



Many body states are linear combination of Slater Determinants

$$|\phi_\alpha\rangle = a^+_{i1}a^+_{i2}...a^+_{iA}\,|0\rangle \qquad |\Psi\rangle_{eff} = \sum_\alpha c_\alpha\,|\phi_\alpha\rangle$$

The ISM code Antoine diagonalizes up to 10^{10} Slater determinants

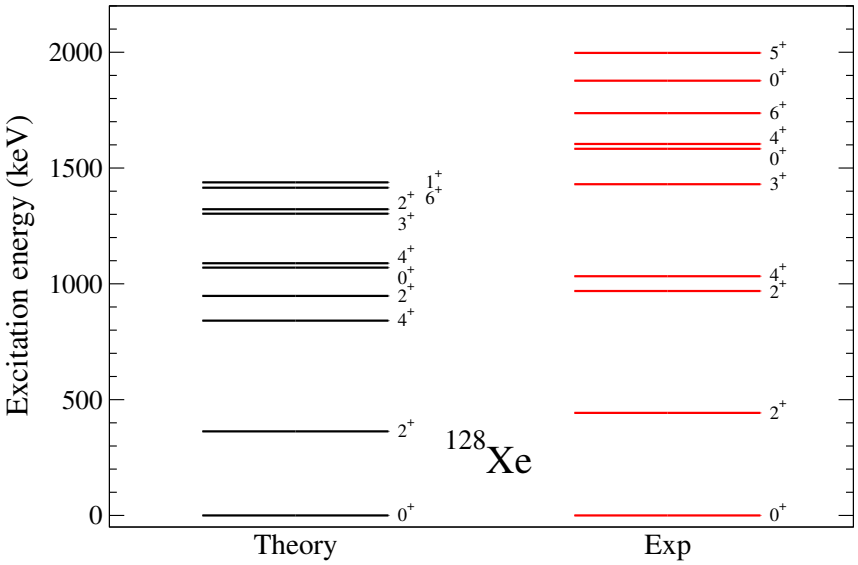
Caurier *et al.* RMP 77 (2005)

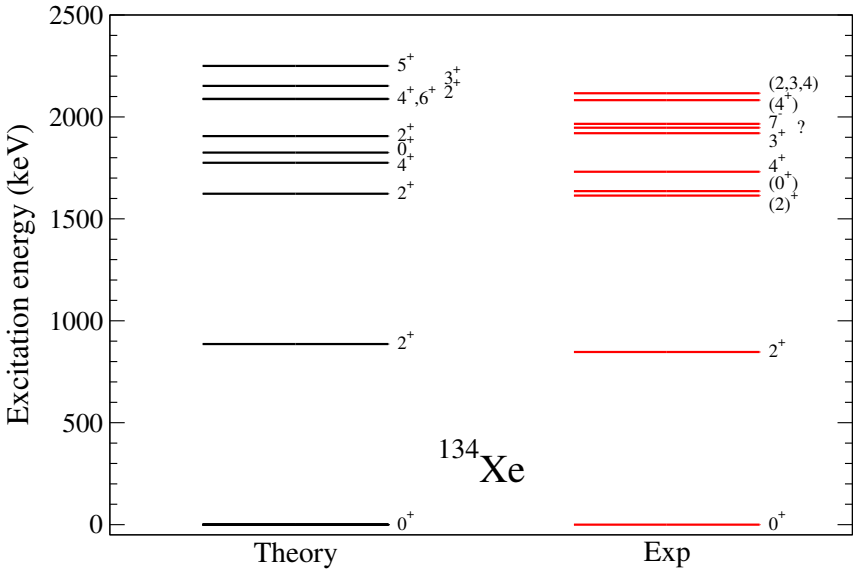
Valence space and interaction tested in nuclear structure, β, $\beta\beta$ decay studies

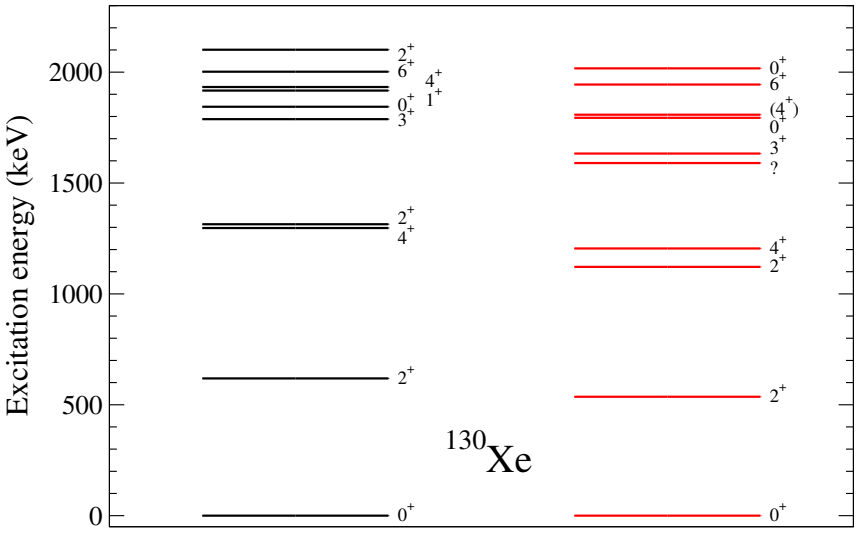
Even-mass Xe spectra

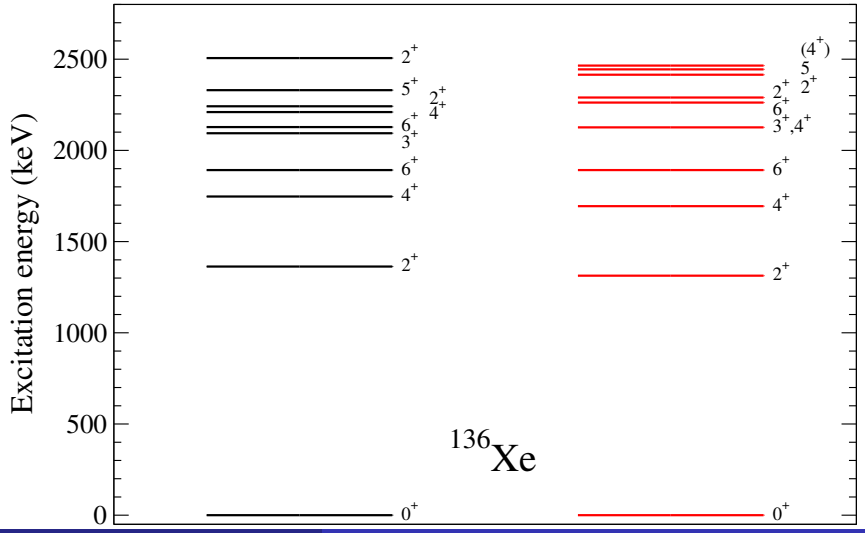
Low-lying excitation spectra in good agreement to experiment in all cases

Vietze, Klos, JM, Haxton, Schwenk PRD91 043520 (2015)



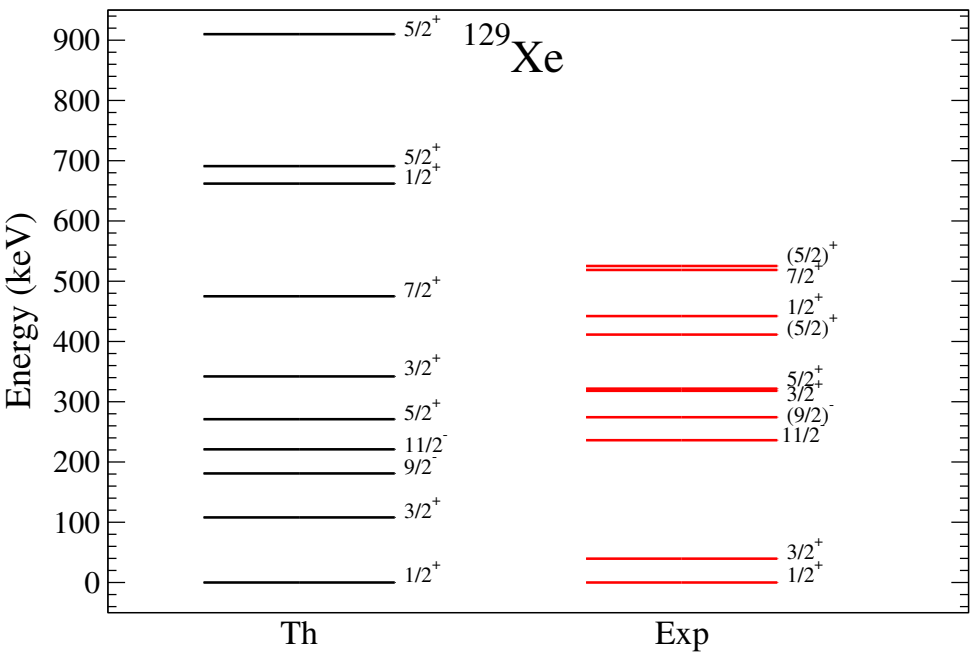


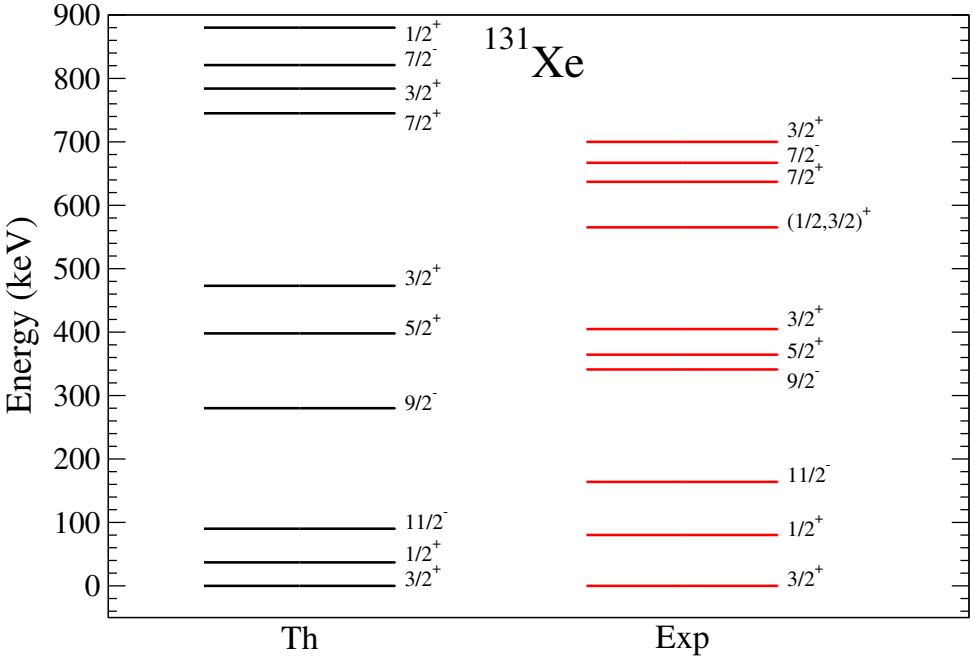




^{129,131}Xe spectra

For odd-mass Xenon isotopes also very good agreement with experiment





JM, Gazit, Schwenk PRD86 103511(2012)

Very low-lying first-excited states $\sim 40, 80$ keV

If WIMPs have enough kinetic energy, inelastic scattering allowed

$$p_{\pm} = \mu v_i \left(1 \pm \sqrt{1 - \frac{2E^*}{\mu v_i^2}}\right)$$

See talk by P. Klos on Tuesday 24!

Outline

Spin-Independent scattering

Spin-Independent (SI) interaction: WIMPs couple to the nuclear density

The interaction Lagrangian at low-energies is given by the scalar leptonic $j(\mathbf{r})$ and scalar hadronic $S(\mathbf{r})$ currents:

$$\mathcal{L}_\chi^{\rm SI} = \frac{G_F}{\sqrt{2}} \int d^3\mathbf{r}\, j(\mathbf{r})\, S(\mathbf{r})$$

The scattering cross-section is proportional to the structure factor $S_S(q)$:

$$\frac{d\sigma}{dq^2} = \frac{2}{(2J_i+1)\pi v^2} \sum_{s_f,s_i} \sum_{M_f,M_i} \left|\langle f|\mathcal{L}_\chi^{\rm SI}|i\rangle\right|^2 = \frac{8G_F^2}{(2J_i+1)v^2}\, S_S(q)$$

Only 1 body currents considered in SI scattering: $S(\mathbf{r}) = c_0 \sum_{i=1}^{A} \delta^{(3)}(\mathbf{r}-\mathbf{r}_i)$

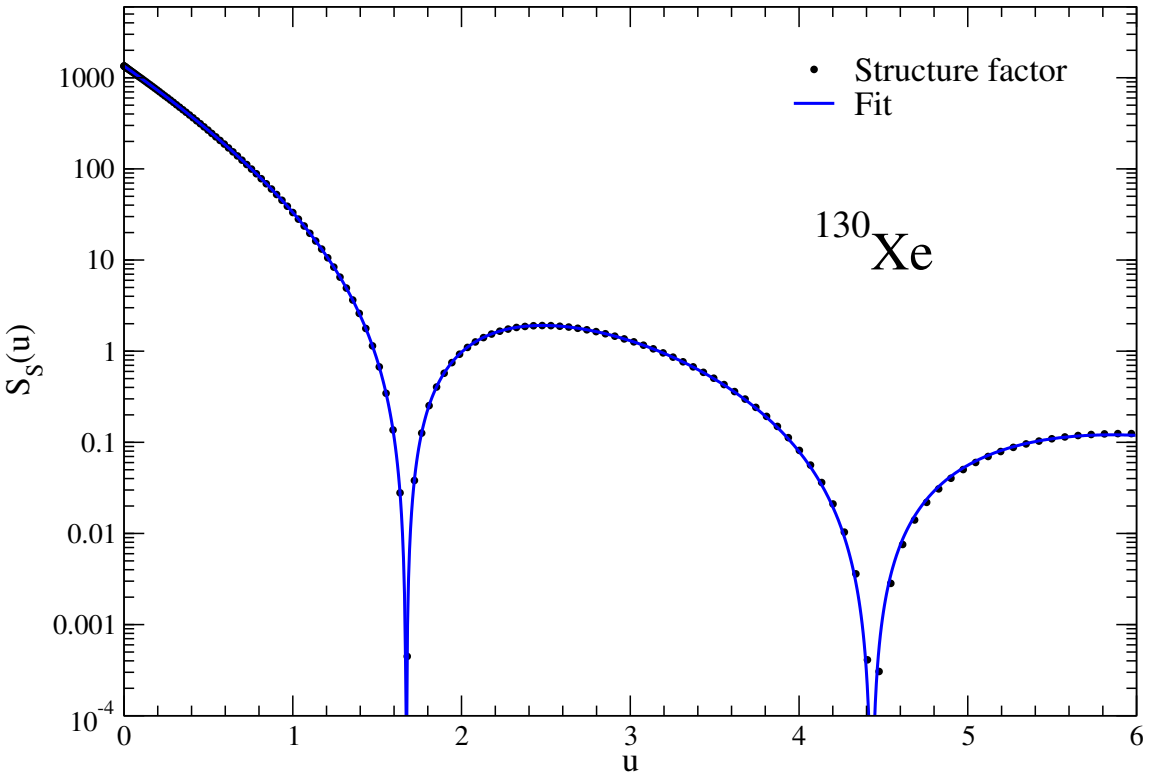
Their impact is under discussion, but could be relevant

Prezeau et al. PRL91 231301 (2003), Cirigliano et al. JHEP10 025 (2012), Beane et al. PRD89 074505 (2014)

SI structure factors: coherence

Structure factor decomposed in multipole expansion

$$S_S(q) = \sum_{L=0,2,4\ldots} \left| \langle J \| c_0 \sum_{i=1}^{A} j_L(qr_i) Y_{LM}(\mathbf{r}_i) \| J \rangle \right|^2 ,$$



Vietze, Klos, JM, Haxton, Schwenk PRD91 043520 (2015)

Plot as function of dimensionless $u = p^2 b^2/2$

Coherent response at $p = 0$:

$$\frac{S_S(0)}{2J+1} = A^2 \frac{c_0^2}{4\pi}$$

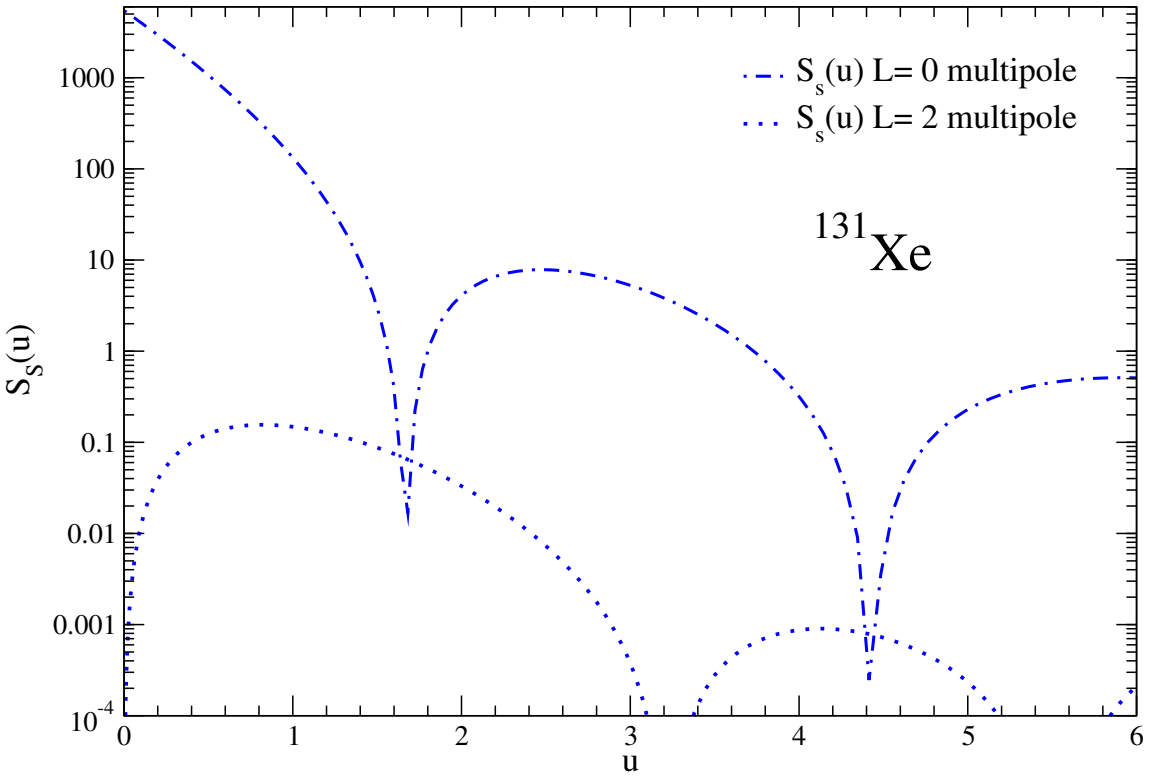
Lost at $p > 0$

With similar couplings for different responses, SI scattering always dominant

SI structure factors: multipole decomposition

Structure factor decomposed in multipole expansion

$$S_S(q) = \sum_{L=0,2,4\ldots} \left| \langle J \| c_0 \sum_{i=1}^{A} j_L(qr_i) Y_{LM}(\mathbf{r}_i) \| J \rangle \right|^2 ,$$



Vietze, Klos, JM, Haxton, Schwenk PRD91 043520 (2015)

Plot as function of dimensionless $u = p^2 b^2/2$

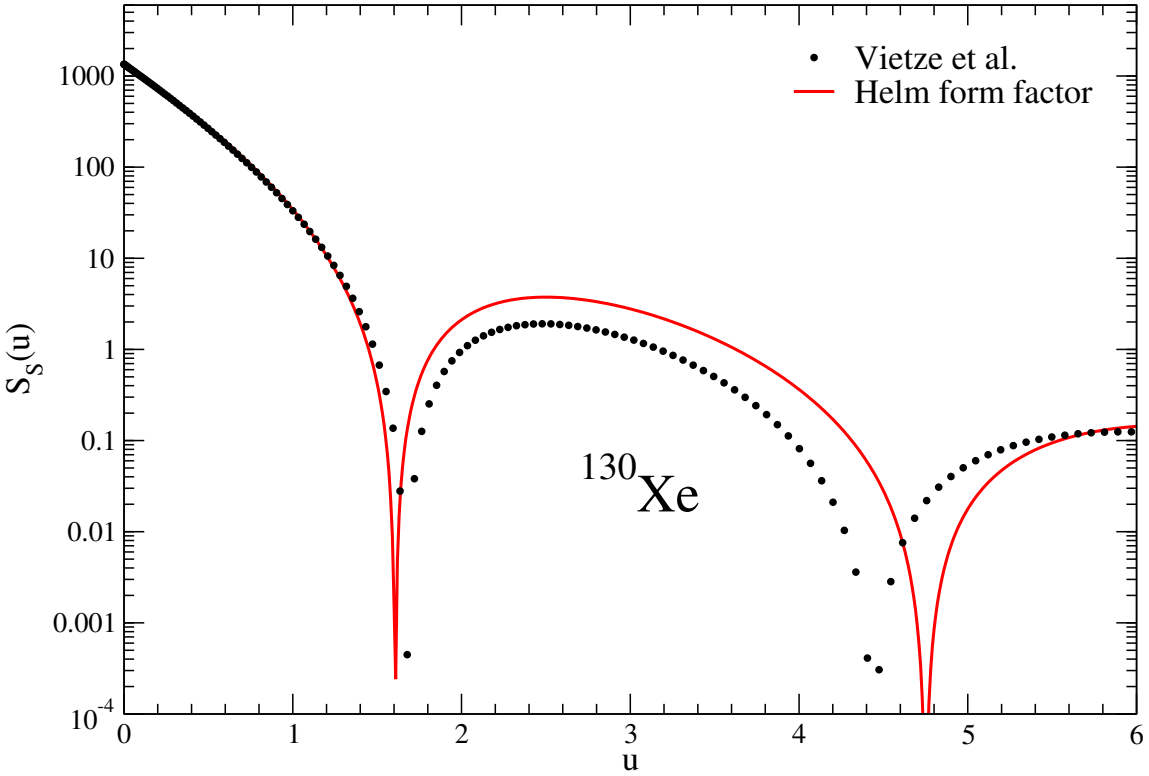
For ^{131}Xe, $J = 3/2$, $L = 0, 2$ multipoles allowed

SI scattering completely dominated by $L = 0$, except at its minima

Comparison to Helm form factor

Phenomenological Helm form factors,
based on a model of constant nuclear density with Gaussian surface,
are used in experimental data analysis of SI scattering

$$S_S^{\text{Helm}}(q) = S_S(0) \left(\frac{3\, j_1(qr)}{qr} \right)^2 e^{-(qs)^2}$$



At low momentum transfers good agreement between state-of-the-art calculation and Helm form factor

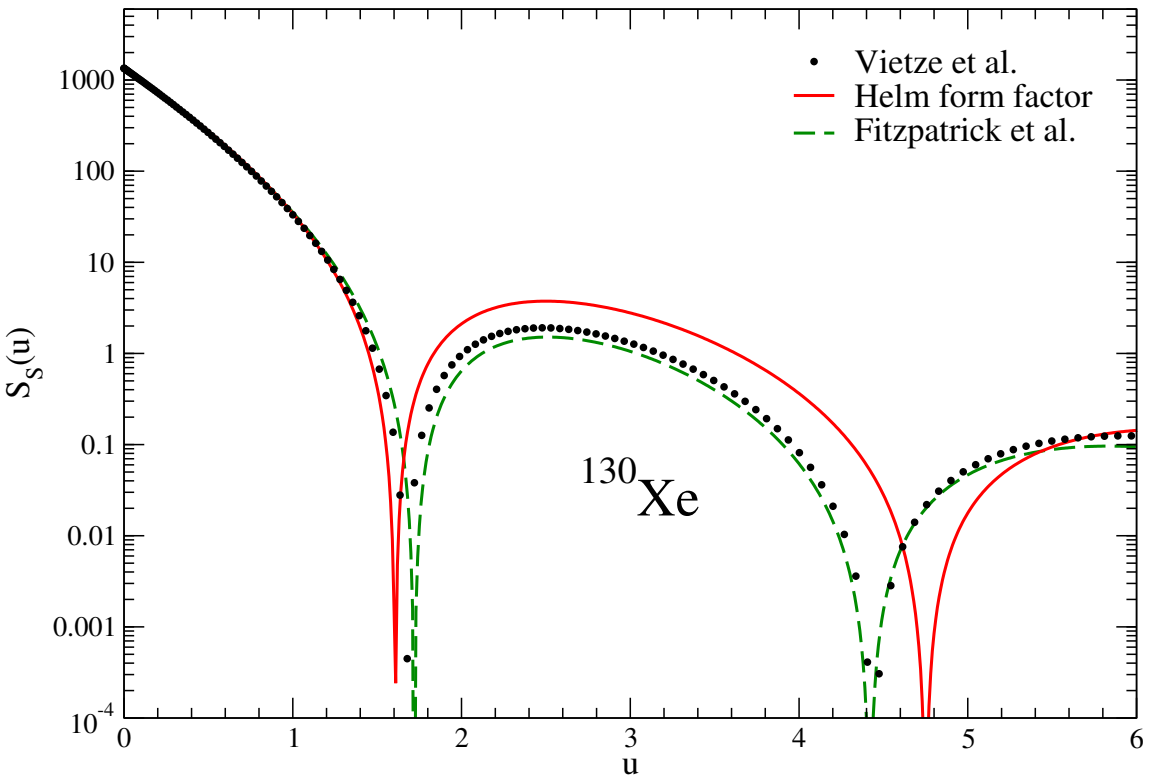
Small differences in amplitude and location of minima appear at higher momentum transfers

SI scattering not very sensitive to nuclear structure details

Vietze, Klos, JM, Haxton, Schwenk PRD91 043520 (2015)

Comparison to Fitzpatrick et al.

Fitzpatrick et al. JCAP02 004 (2013) also calculated Xe with the shell model but using older shell model calculations and larger valence space truncations



Vietze, Klos, JM, Haxton, Schwenk PRD91 043520 (2015)

Shell model calculations by Vietze et al., Fitzpatrick et al. give almost identical SI structure factors

SI scattering not very sensitive to nuclear structure details

Outline

Spin-Dependent scattering

Spin-Dependent (SD) interaction: WIMPs couple to the nuclear spin

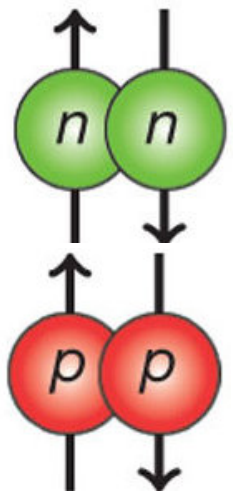
The interaction Lagrangian at low-energies is given
by the axial-vector leptonic $j_\mu(\mathbf{r})$ and axial-vector hadronic $J^A_\mu(\mathbf{r})$ currents:

$$\mathcal{L}^{\rm SD}_\chi = \frac{G_F}{\sqrt{2}} \int d^3\mathbf{r}\, j_\mu(\mathbf{r})\, J^A_\mu(\mathbf{r})$$

Pairing interaction: pairs of spins couple to $S = 0$
No coherence for SD scattering

Only stable nuclei with odd neutrons/protons
relevant for experiment searches:
for Xenon ^{129}Xe and ^{131}Xe

Specially sensitive to nuclear structure,
distribution of spin among nucleons

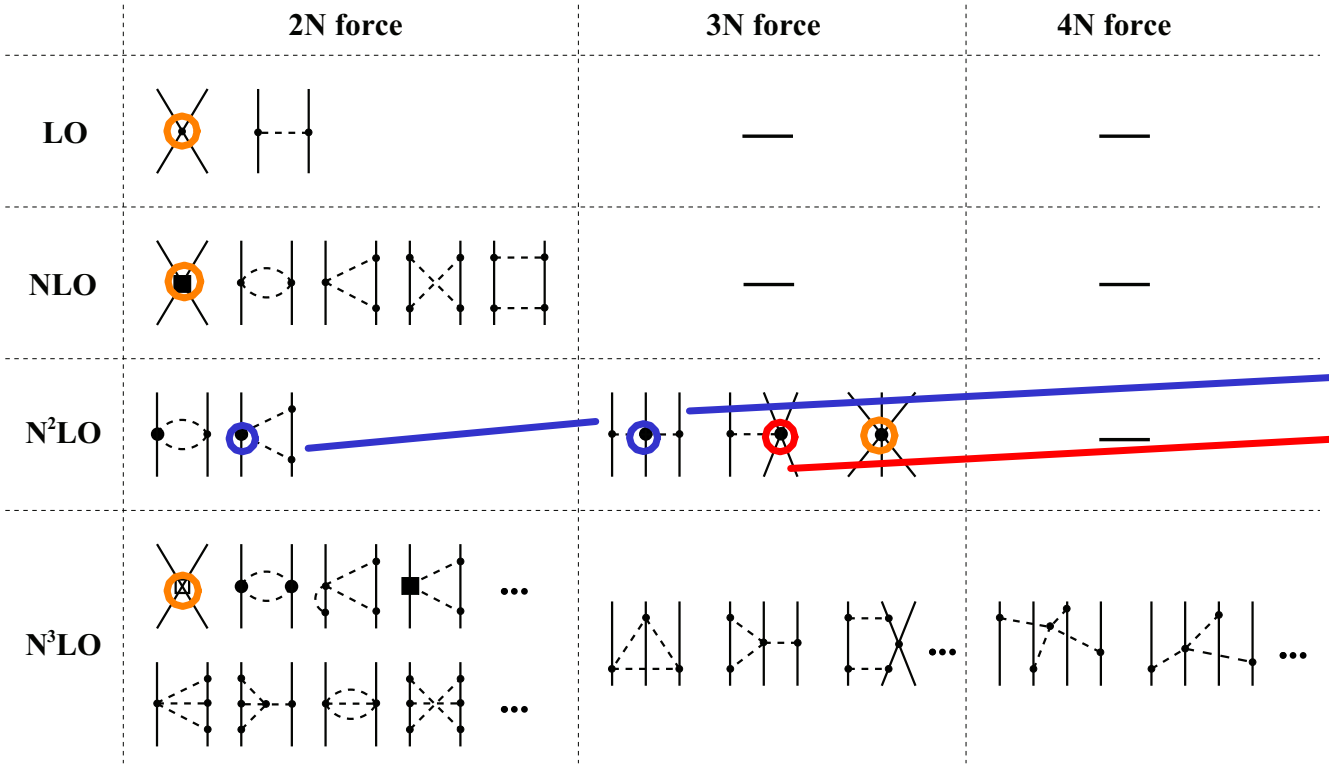


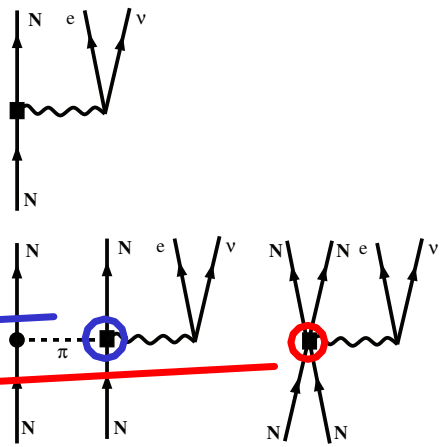
Chiral effective field theory

Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents





Park et al.
PRC67 055206(2003)

Weinberg, van Kolck, Kaplan, Savage, Weise, Epelbaum, Meißner...

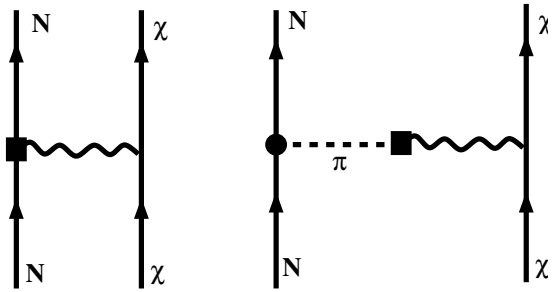
Short-range couplings fitted to experiment once

SD scattering: 1b currents

At lowest orders in chiral EFT, 1b current agrees with phenomenological derivation Engel et al. IJMPE1 1(1992)

$$Q^0: \quad \sum_{i=1}^{A} \mathbf{J}_{i,1\mathrm{b}} = \sum_{i=1}^{A} \frac{1}{2}\left[a_0\sigma_i + a_1\tau_i^3\sigma_i\right],$$

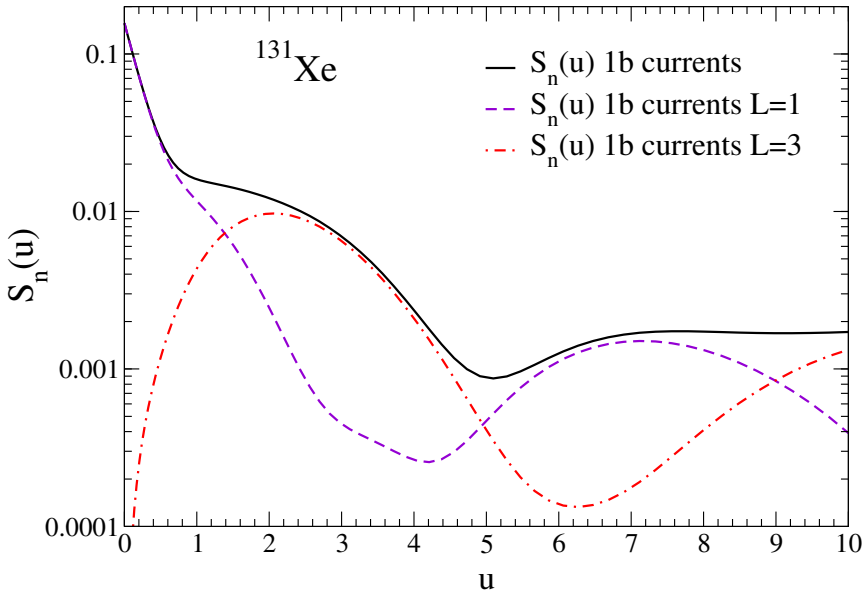
$$Q^2: \quad \sum_{i=1}^{A} \mathbf{J}_{i,1\mathrm{b}} = \sum_{i=1}^{A} \frac{1}{2}\left[a_0\sigma_i + a_1\tau_i^3\left(\frac{g_A(p^2)}{g_A}\sigma_i - \frac{g_P(p^2)}{2mg_A}(\mathbf{p}\cdot\sigma_i)\mathbf{p}\right)\right],$$



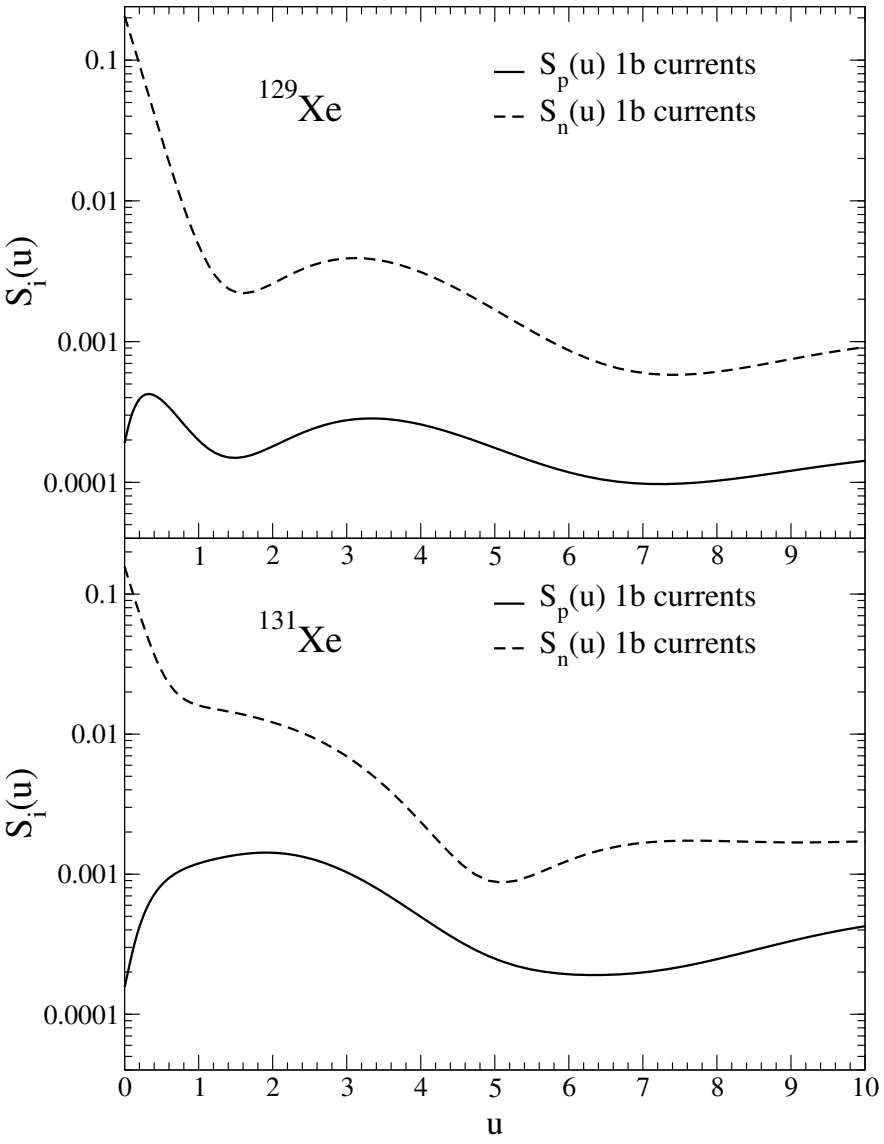
Multipole decomposition of structure factor:

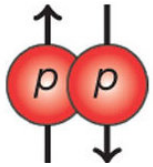
$$S_A(p) = \sum_{L\geqslant 0} \left|\langle J_f \| \mathcal{L}_L^5 \| J_i\rangle\right|^2 + \sum_{L\geqslant 1} \left|\langle J_f \| \mathcal{T}_L^{\mathrm{el}5} \| J_i\rangle\right|^2$$

$L = 1$ multipole dominates at low p, then various multipoles contribute



SD Structure Factors with 1b currents





In $^{129,131}_{54}$Xe $\langle \boldsymbol{S}_n \rangle \gg \langle \boldsymbol{S}_p \rangle$,
Neutrons carry most nuclear spin

$$\boldsymbol{S}_n = \sum_{i=1}^{N} \boldsymbol{\sigma}_i/2,\ \boldsymbol{S}_p = \sum_{i=1}^{Z} \boldsymbol{\sigma}_i/2$$

$$\frac{S_A(0)}{2J+1} = \frac{(J+1)}{\pi J} \left| a_p \langle \boldsymbol{S}_p \rangle + a_n \langle \boldsymbol{S}_n \rangle \right|^2$$

$$a_{n/p} = (a_0 \mp a_1)/2,$$

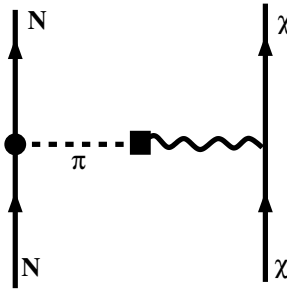
$$S_n(0) \propto \left| \langle \boldsymbol{S}_n \rangle \right|^2 \ S_p(0) \propto \left| \langle \boldsymbol{S}_p \rangle \right|^2.$$

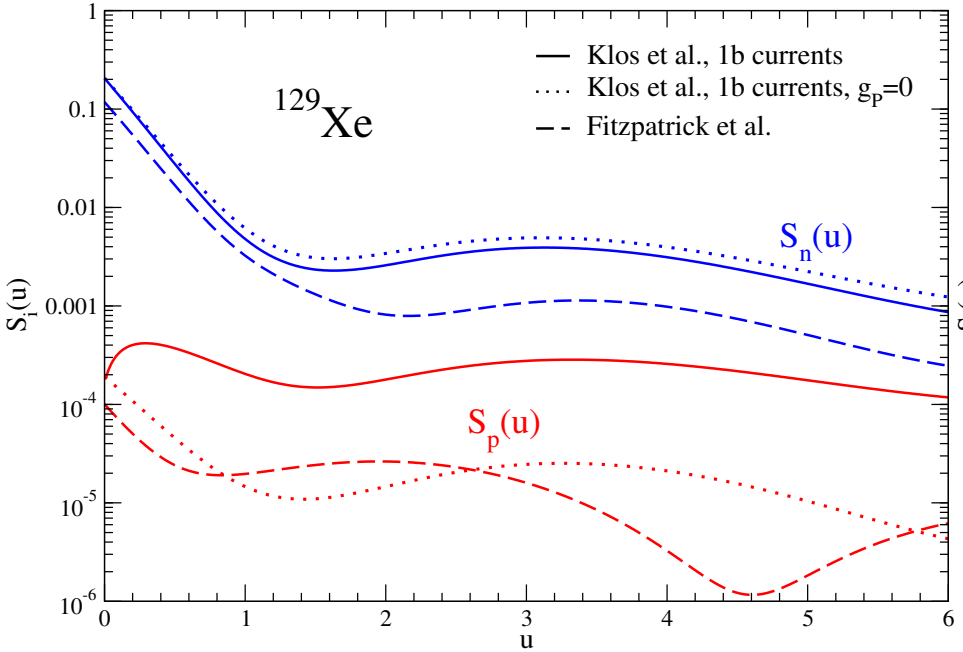
Couplings more sensitive to protons ($a_0 = a_1$) or neutrons ($a_0 = -a_1$)

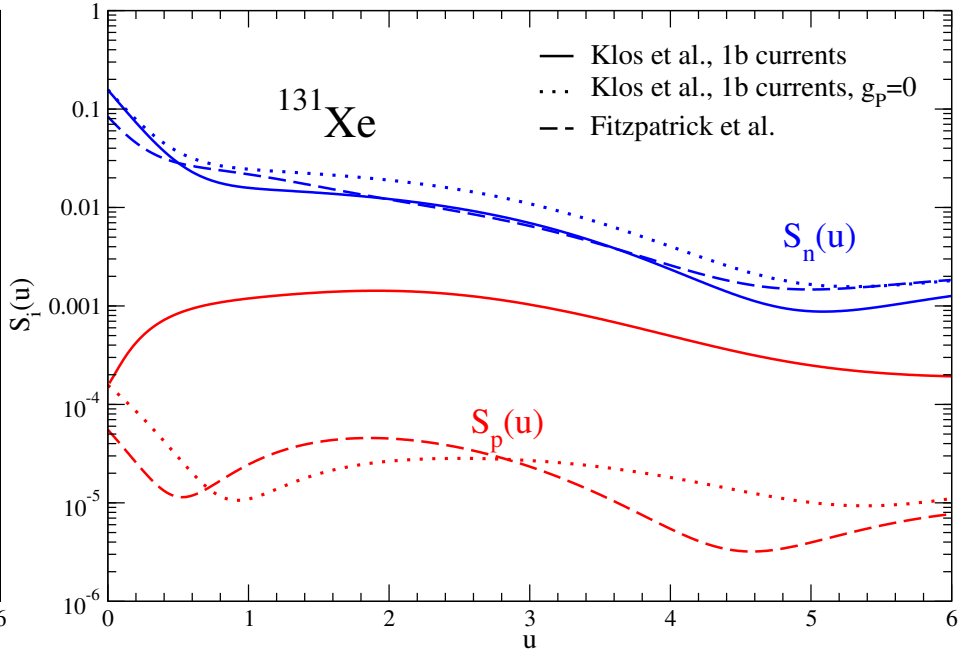
JM, Gazit, Schwenk, PRD86 103511(2012)
Klos, JM, Gazit, Schwenk, PRD88 083516(2013)

Comparison to Fitzpatrick et al.

SD structure factor compared to Fitzpatrick et al. JCAP02 004 (2013) at the level of 1b currents, with no pseudoscalar term, in JCAP02 004 (2013) coupling independent (O_6) to axial term (O_4)







Differences between shell model calculations larger than in SI case: SD scattering sensitive to nuclear structure details: $\langle \boldsymbol{S}_n \rangle, \langle \boldsymbol{S}_p \rangle$

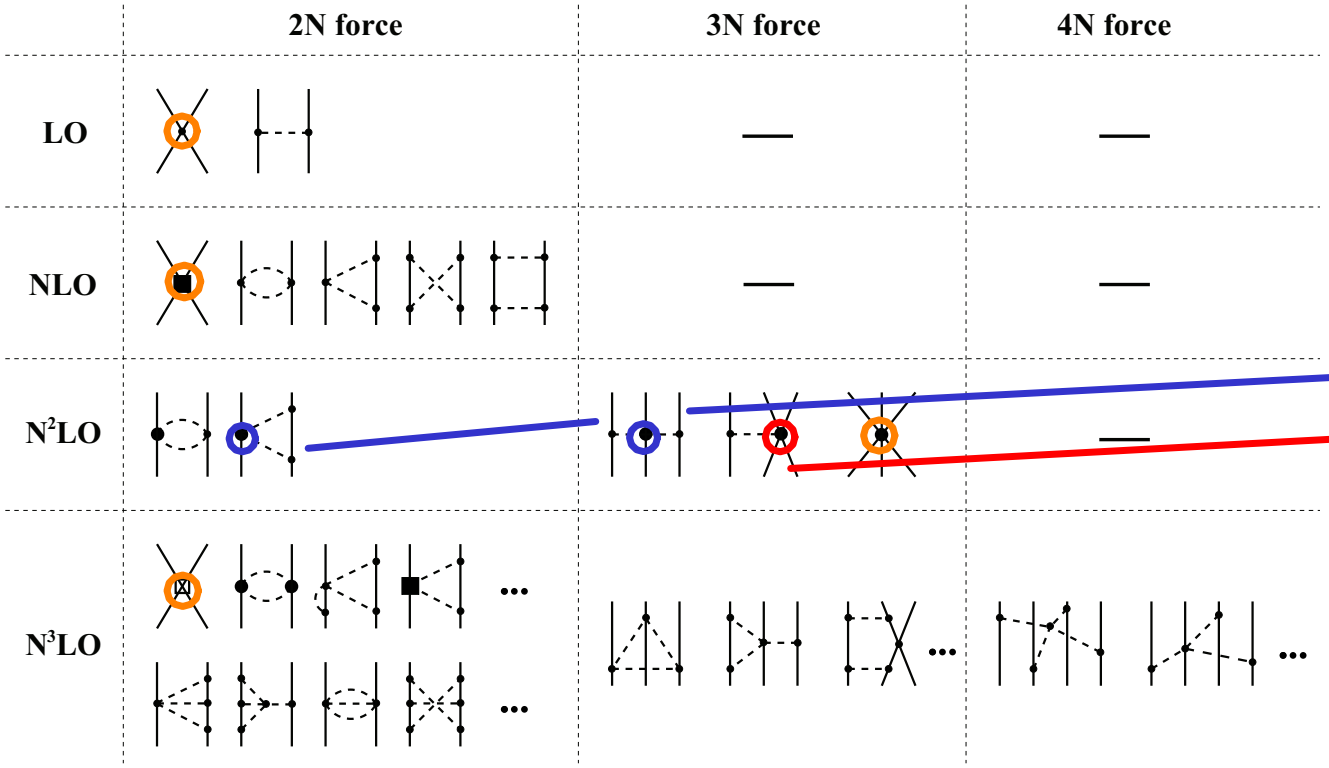
Reasonable agreement between different calculations: nuclear structure not limiting in extracting of relevant physics from WIMP scattering data

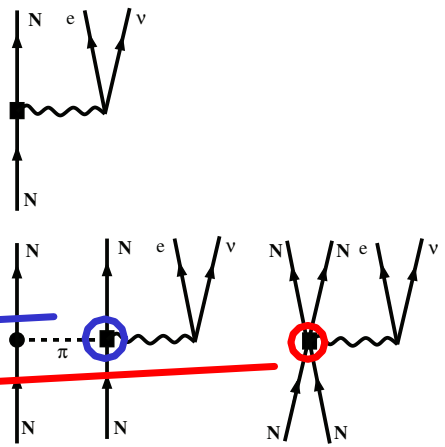
Chiral effective field theory

Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents





Park et al.
PRC67 055206(2003)

Weinberg, van Kolck, Kaplan, Savage, Weise, Epelbaum, Meißner...

Short-range couplings fitted to experiment once

2b currents and light nuclei

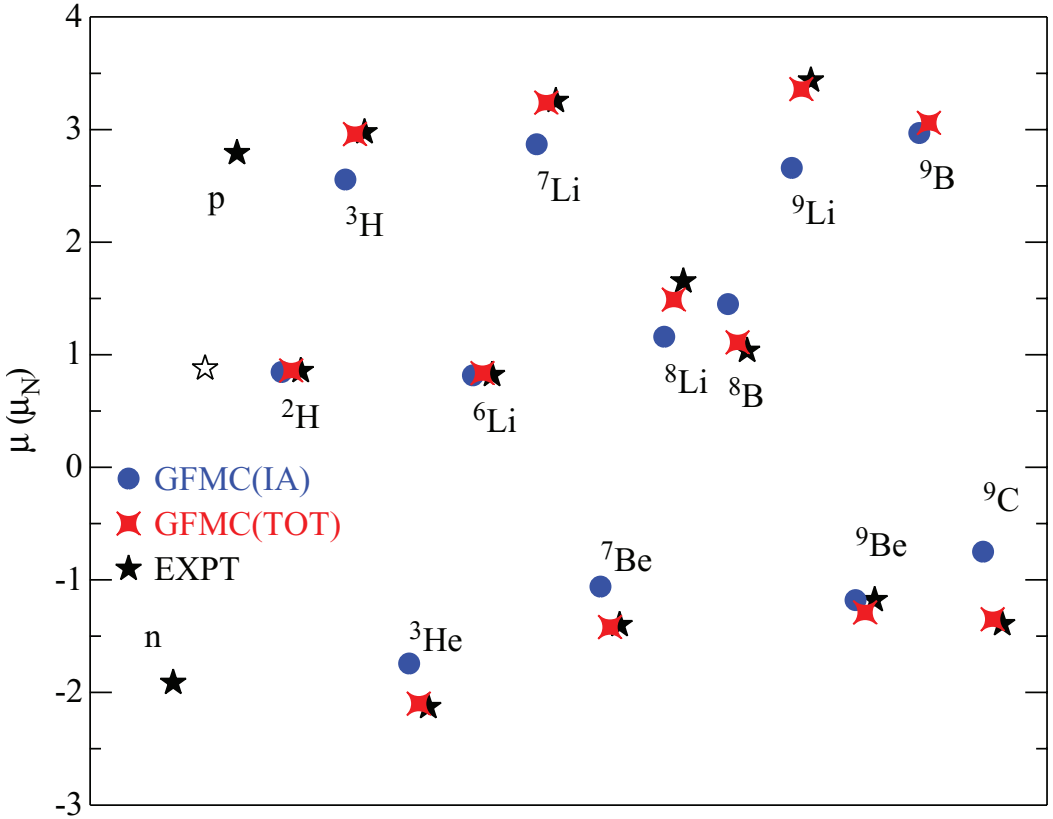
2b currents (meson-exchange currents) tested in light nuclei:

^{3}H β decay
Gazit, Quaglioni, Navrátil
PRL103 102502(2009)

$A \leq 9$ magnetic moments
Pastore et al. PRC87 035503(2013) $\Longrightarrow$

^{8}Be EM transitions
Pastore et al. PRC90 024321(2014)

^{3}H μ capture
Gazit PLB666 472(2008)
Marcucci et al. PRC83 014002(2011)



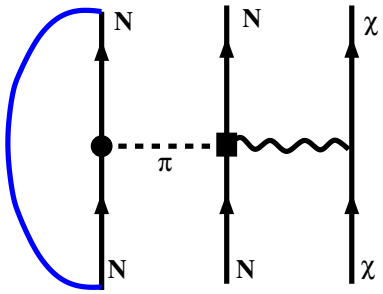
2b currents studied in electromagnetic and weak sectors

Chiral EFT 2b currents

Leading correction: 2b currents
Approximate in medium-mass nuclei: normal-ordered 1b part with respect to spin/isospin symmetric Fermi gas

$$\mathbf{J}^3_{12} = -\frac{g_A}{2F_\pi^2}(\tau_1\times\tau_2)^3\left(\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{m_\pi^2+k_2^2}\left[c_4(\boldsymbol{\sigma}_1\times\mathbf{k}_2)+\frac{\hat{c}_6}{12m}(\boldsymbol{\sigma}_1\times\mathbf{q})-(1\leftrightarrow 2)\right]\right)$$
$$-\frac{g_A}{F_\pi^2}c_3\left[\tau_1^3\frac{(\boldsymbol{\sigma}_1\cdot\mathbf{k}_1)\,\mathbf{k}_1}{m_\pi^2+k_1^2}+\tau_2^3\frac{(\boldsymbol{\sigma}_2\cdot\mathbf{k}_2)\,\mathbf{k}_2}{m_\pi^2+k_2^2}\right]$$

Normal-ordered long-range two-body currents:

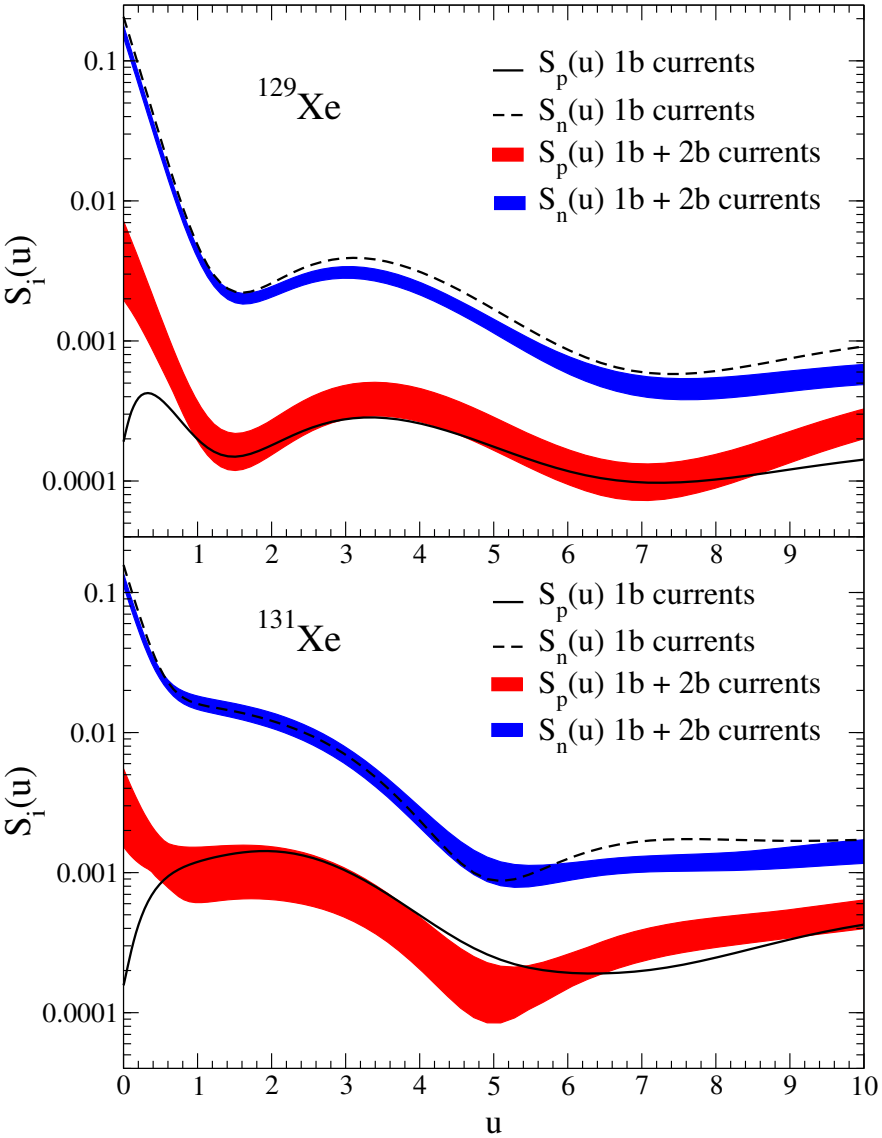


$$\mathbf{J}^{\rm eff}_{i,2b} = -g_A\frac{\tau_i^3}{2}\frac{\rho}{3F_\pi^2}\left[c_4\hat{I}^\sigma_{12}(\rho,p)-c_3 I^\sigma_1(\rho,p)-\frac{\hat{c}_6}{4m}I_{c6}(\rho,p)\right]\Big)\sigma_i = -g_A\frac{\tau_i^3}{2}\delta a_1\sigma_i$$

$$\mathbf{J}^{{\rm eff},\,P}_{i,2b} = -g_A\frac{\tau_i^3}{2}\frac{\rho}{F_\pi^2}\left[\frac{-2c_3p^2}{m_\pi^2+p^2}+\frac{c_3+c_4}{3}I^P(\rho,p)-\frac{\hat{c}_6}{12m}I_{c6}(\rho,p)\right](\mathbf{p}\cdot\sigma_i)\mathbf{p} = -g_A\frac{\tau_i^3}{2}\frac{\delta a_1^P(p^2)}{p^2}(\mathbf{p}\cdot\sigma_i)\mathbf{p}$$

2b currents renormalize isovector couplings:
axial (reduction $\sim 20\%$, $p=0$), pseudoscalar (enhancement $\sim 40\%$, $p=m_\pi$)

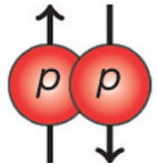
SD Structure Factors with 1b+2b currents



JM, Gazit, Schwenk, PRD86 103511(2012)

Klos, JM, Gazit, Schwenk, PRD88 083516(2013)

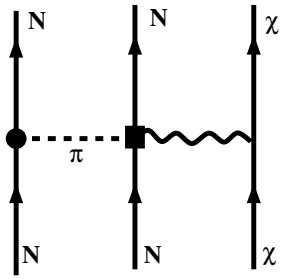
In $^{129,131}_{54}$Xe $\langle S_n \rangle \gg \langle S_p \rangle$,



Neutrons carry most nuclear spin

Couplings more sensitive to protons ($a_0 = a_1$) or neutrons ($a_0 = -a_1$)

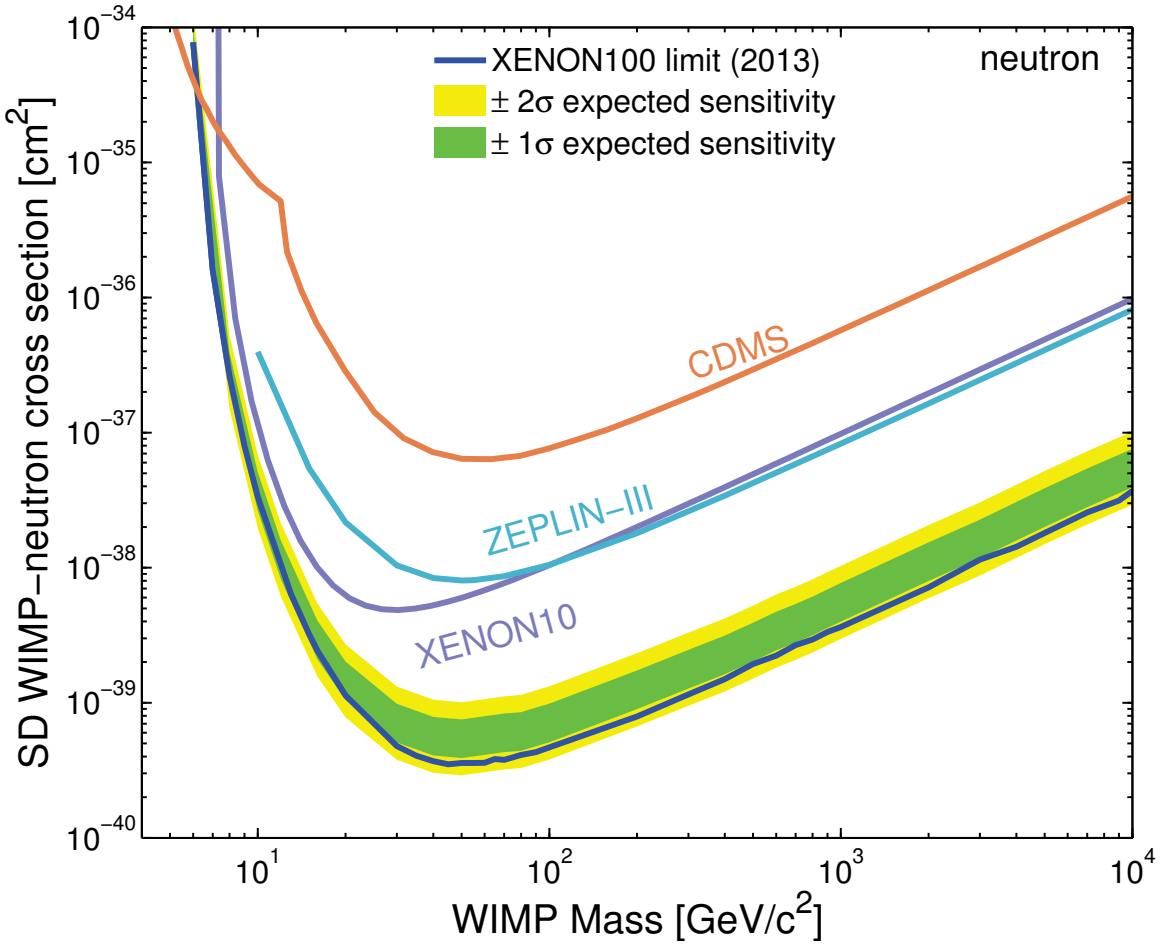
2b currents naturally involve both neutrons and protons:



Neutrons always contribute with 2b currents, dramatic increase in $S_p(u)$

See talk by P. Klos on Tuesday 24!

Application to experiment: XENON100



Our calculations used by XENON100 Collaboration to set limits on WIMP-nucleus cross-sections

XENON100 obtained world best limits for spin-dependent scattering with “neutron” couplings

Soon will be improved by LUX when they complete their spin-dependent analysis

Aprile et al. PRL111 021301 (2013)

Summary

WIMP scattering off Xenon for direct dark matter detection experiments

- State-of-the-art large-scale nuclear structure calculations
  with tested valence spaces and nuclear interactions,
  very good agreement with experimental spectra for all Xe isotopes
  outlook: ab initio calculations based on chiral EFT forces
- Spin-Independent scattering: coherent enhancement
  good agreement to phenomenological Helm form factor
  not very sensitive to nuclear structure details
  possible impact of SI 2b currrents to be explored
- Spin-Dependent scattering:
  more sensitive to nuclear structure: spin expectation values
  2b currents predicted by chiral EFT
  - Reduce the isovector structure factor at low p, $\sim 20\%$ at $p = 0$
  - Smaller reduction/enhancement at $p \sim m_\pi$,
    depending on dominant multipoles (longitudinal enhanced)
  - Large increase in "proton" $S_A(p)$ (subleading species)