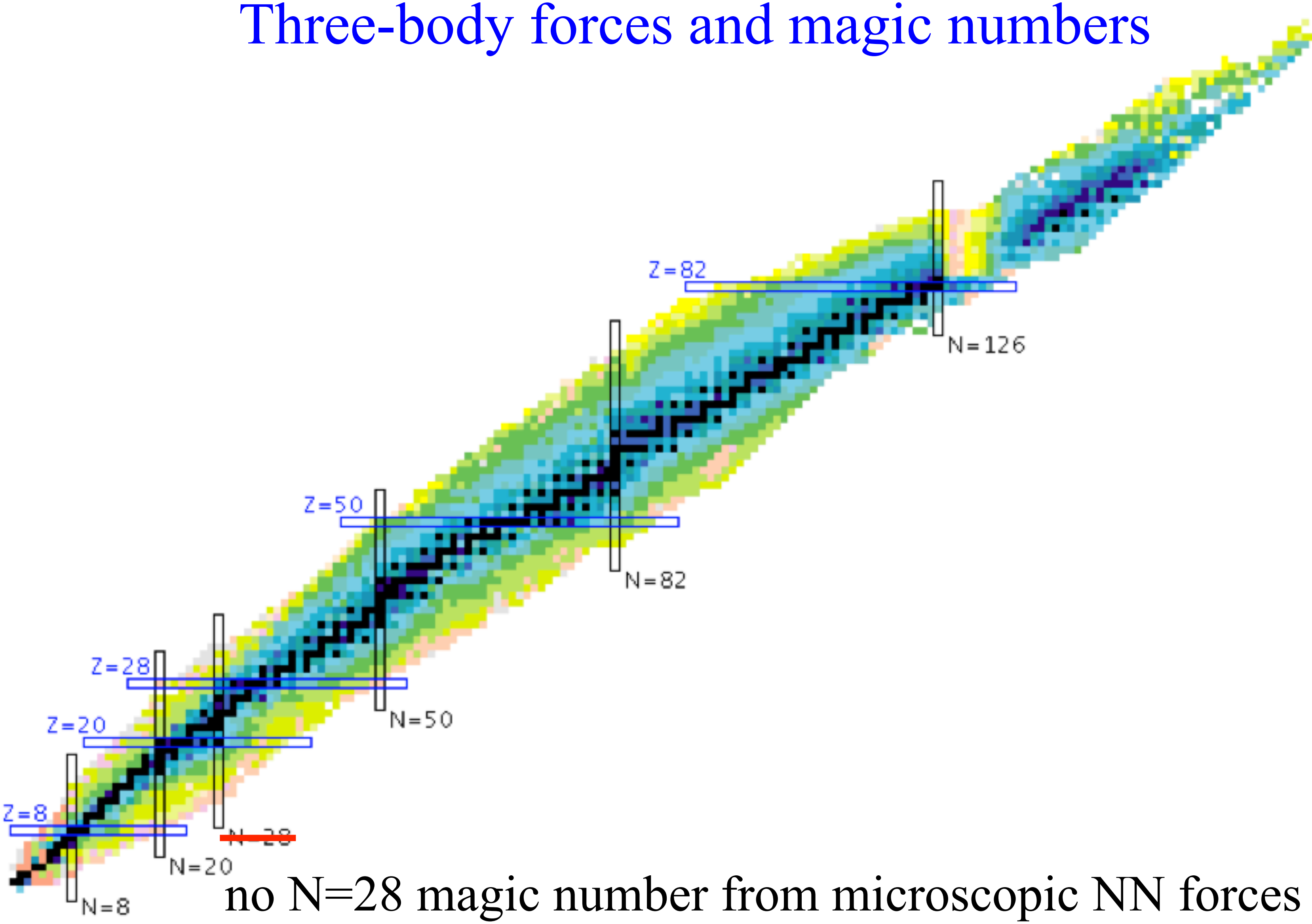
# Outline

3N forces and exotic nuclei

Nuclear physics for direct dark matter detection

Nuclear physics for neutrinoless double-beta decay

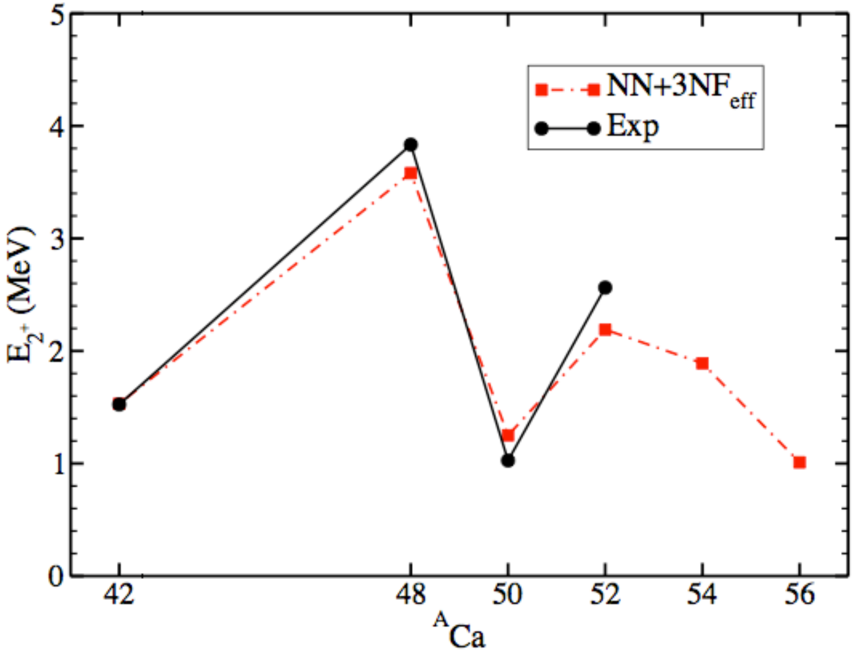
# Three-body forces and magic numbers



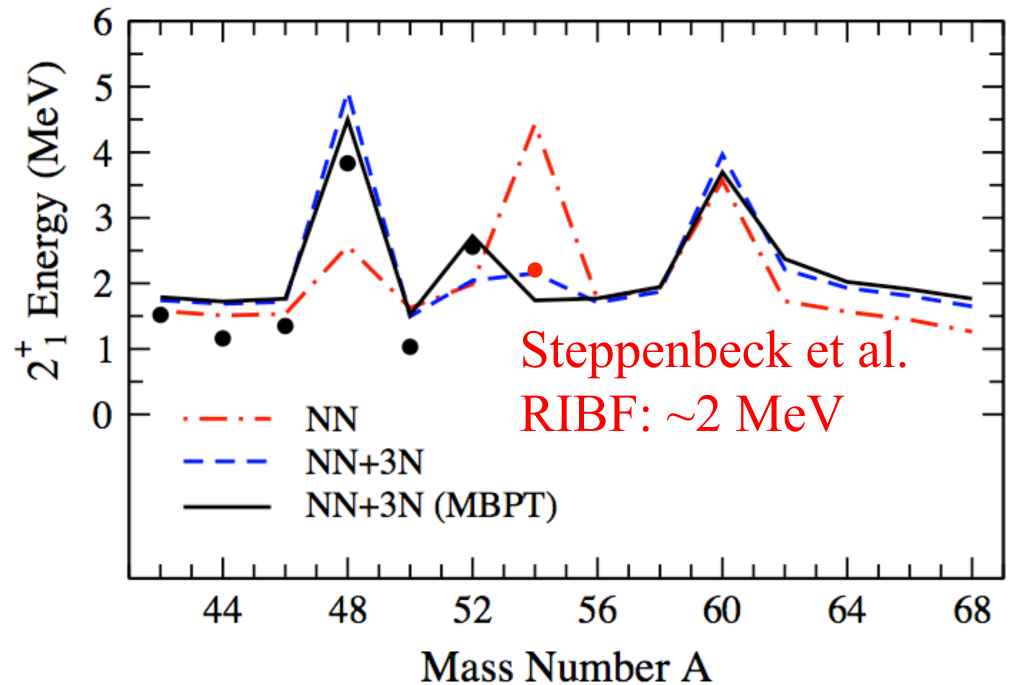

no N=28 magic number from microscopic NN forces

Zuker, Poves,…

# Three-body forces and magic numbers

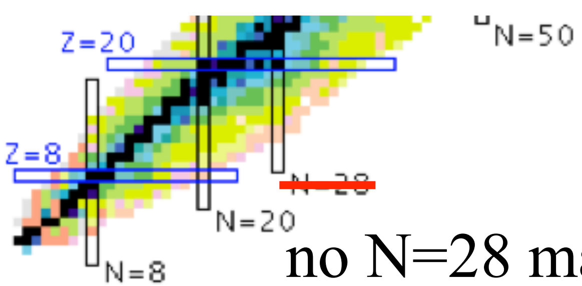



Hagen et al. (2012)




Holt et al. (2012, 2013)

without 3N forces to 3rd order, $2^+$ is higher in $^{54}$Ca




no N=28 magic number from microscopic NN forces

Zuker, Poves,…

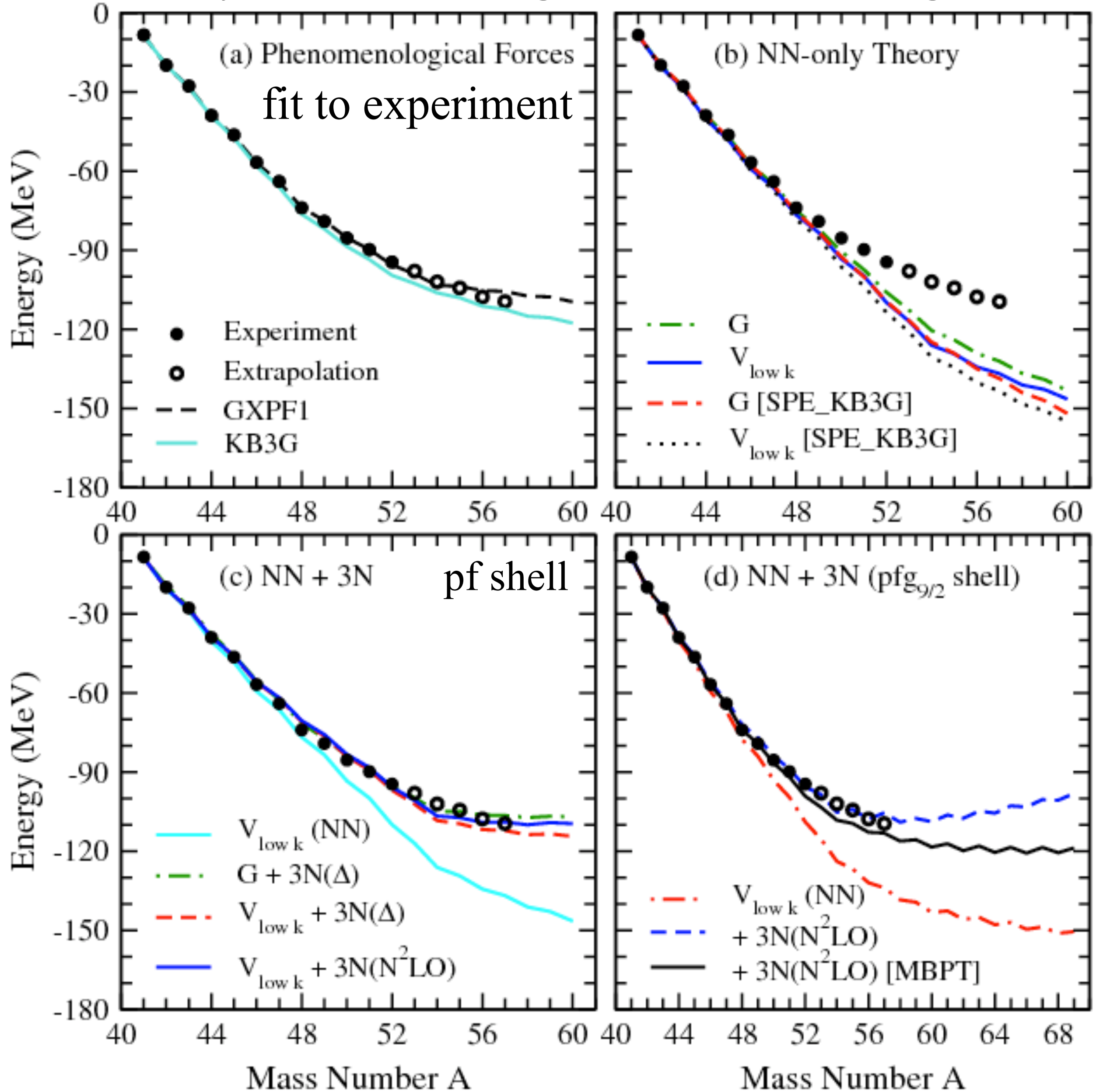
# Evolution to neutron-rich calcium isotopes

repulsive 3N contributions also key for calcium ground-state energies

Holt, Otsuka, AS, Suzuki (2012)

mass measured to $^{52}$Ca
shown to exist to $^{58}$Ca

gs energy flat with N,
continuum important
for dripline location

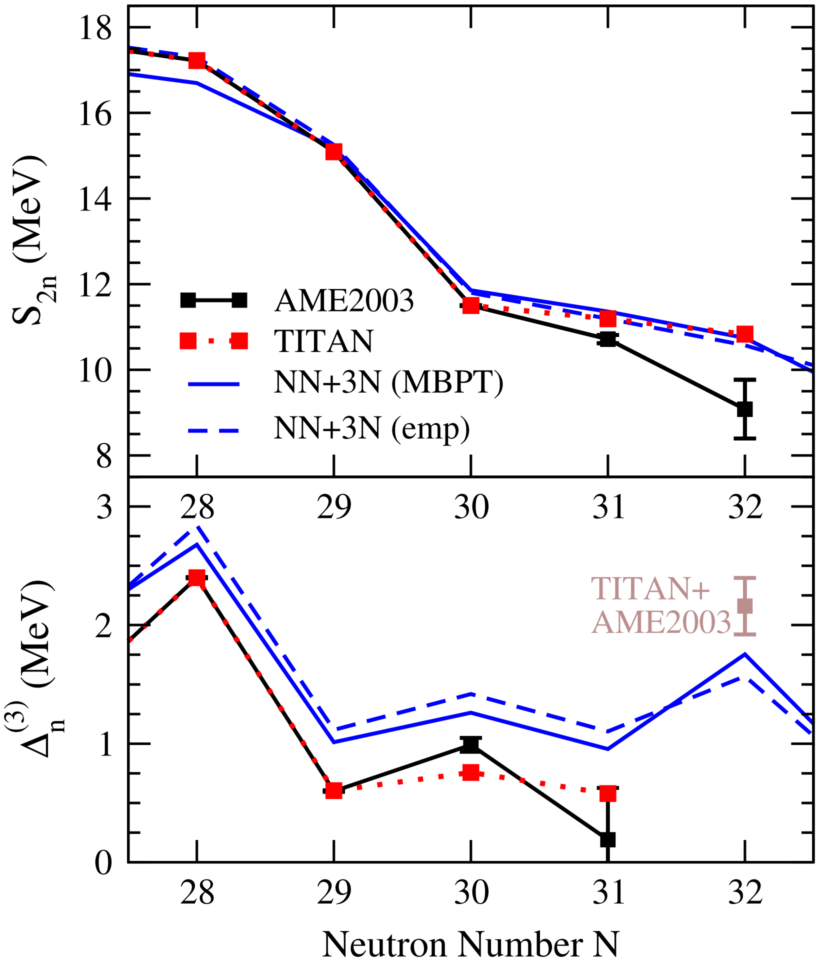


# new $^{51,52}$Ca TITAN measurements

$^{52}$Ca is 1.75 MeV more bound compared to atomic mass evaluation

Gallant et al. (2012)

behavior of 2n separation energy $S_{2n}$ agrees with NN+3N predictions



doi:10.1038/nature12226

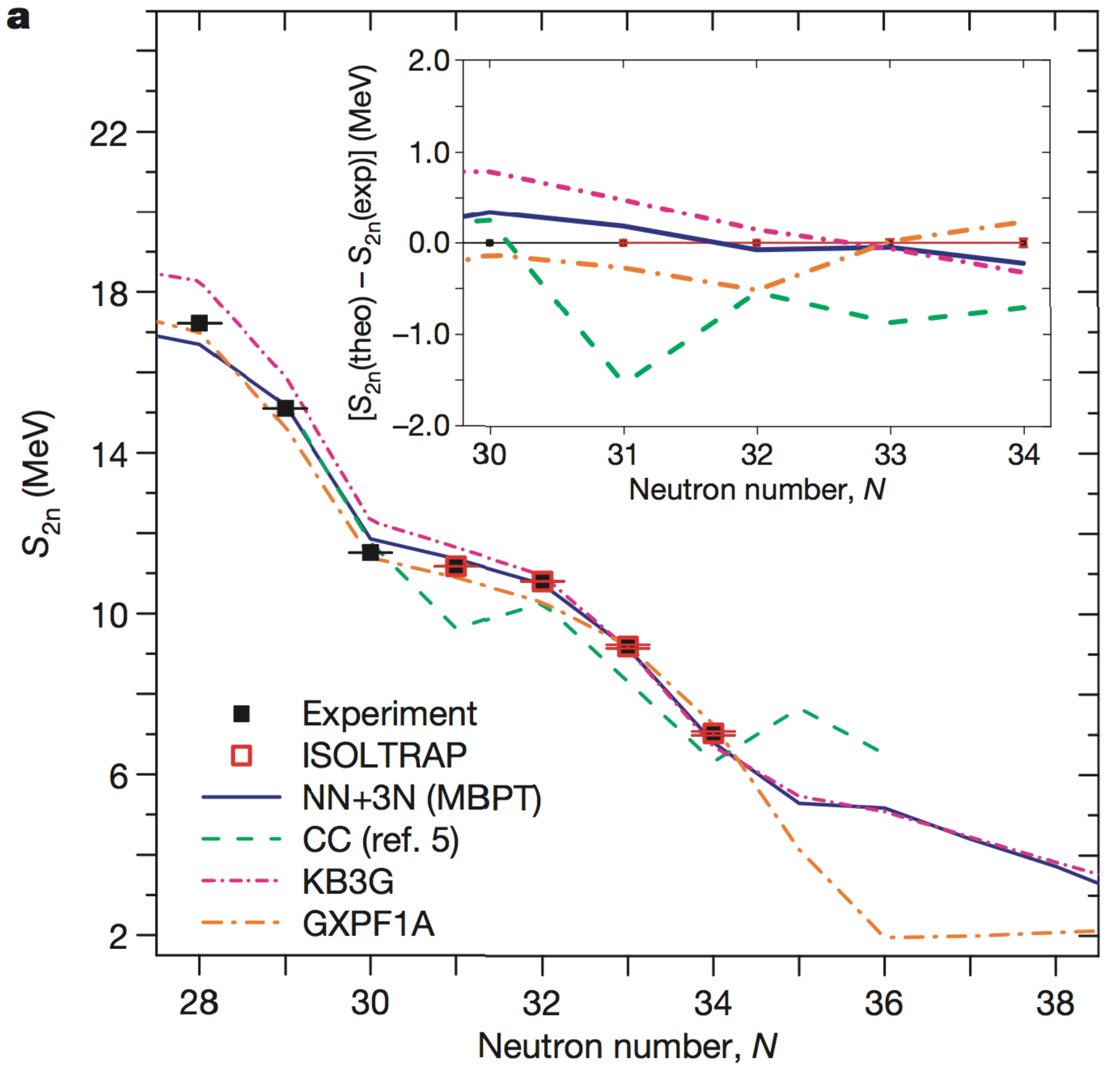
# Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

$^{53,54}$Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer

establish prominent N=32 shell closure in calcium

excellent agreement with theoretical predictions



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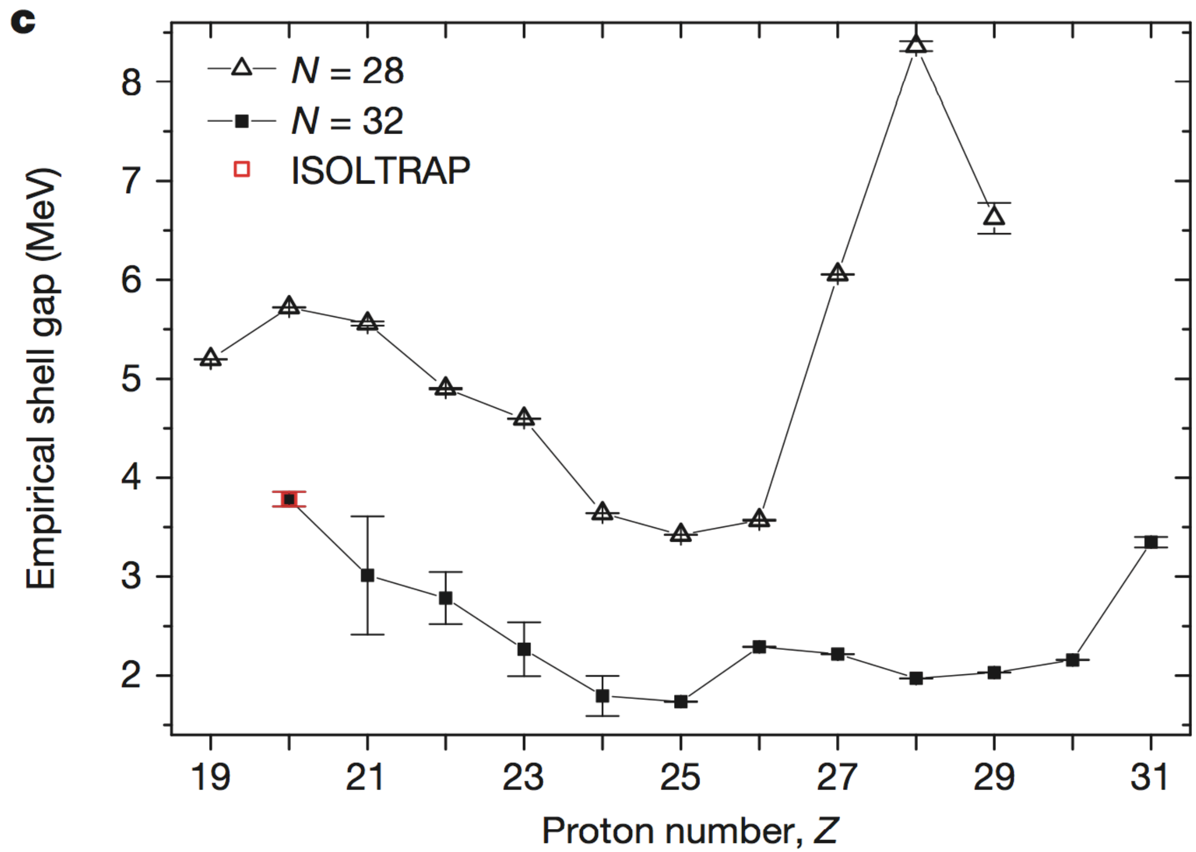
shell gap of 4 MeV

evolution to Z=20
similar for N=28 and 32



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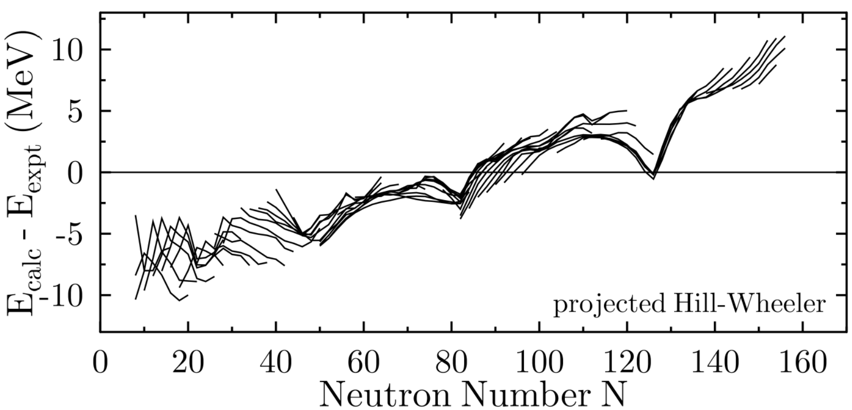
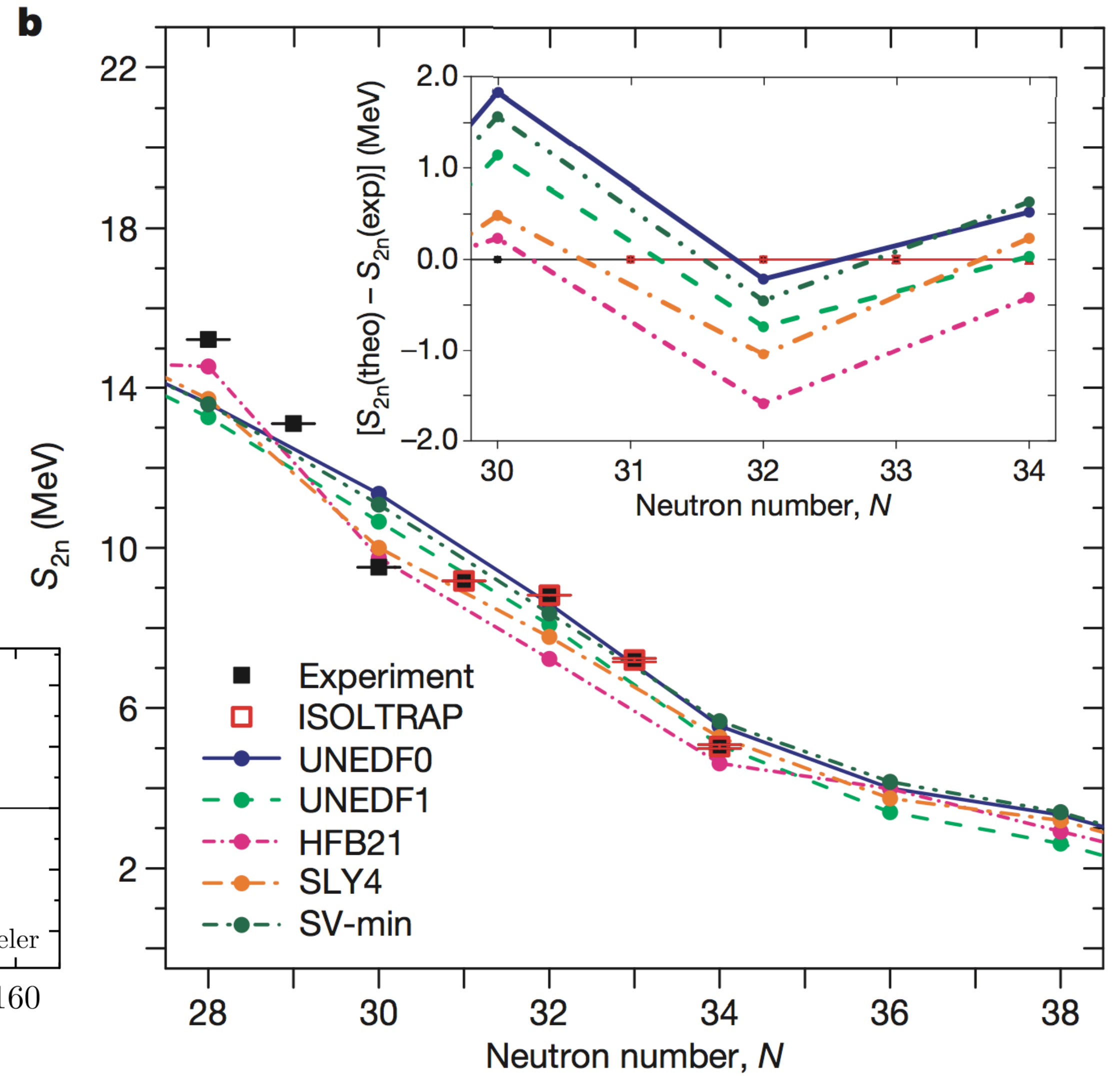
overall good agreement with density functional predictions

but DF’s do not reproduce shell closures

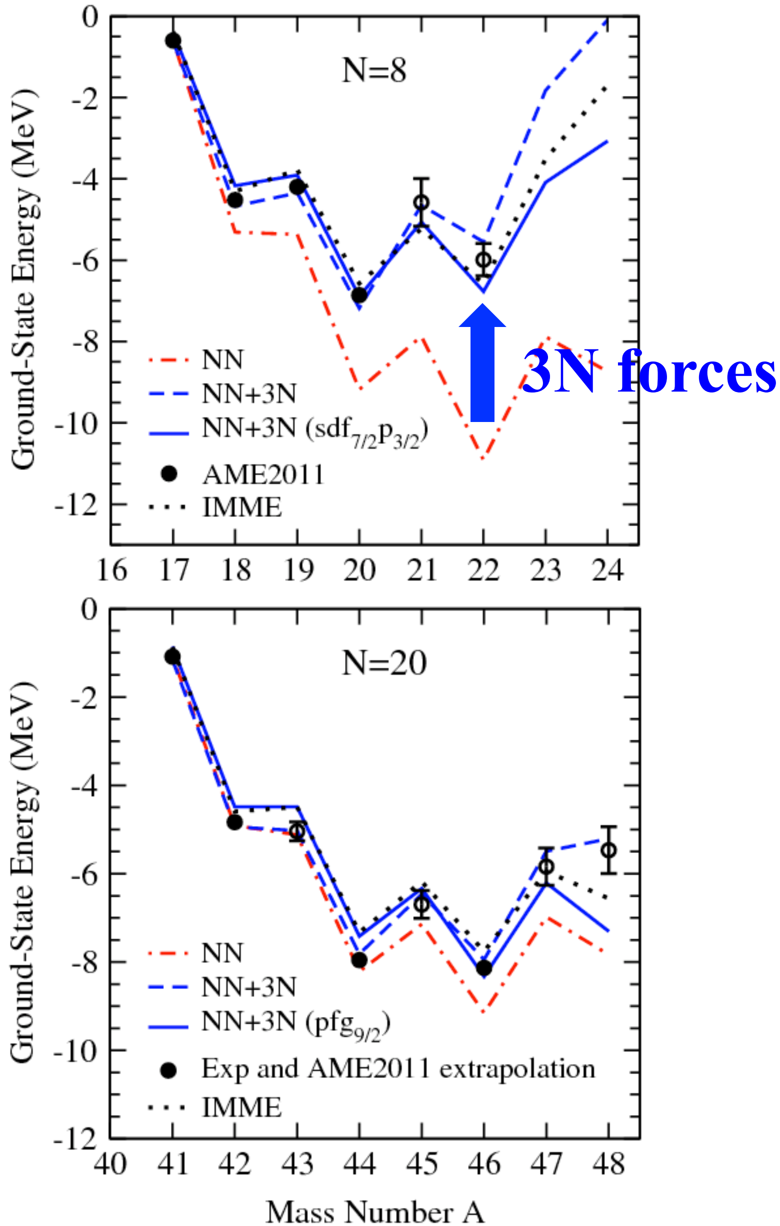
cf. N=50, 82, 126 “arches”
Bender et al. (2005)

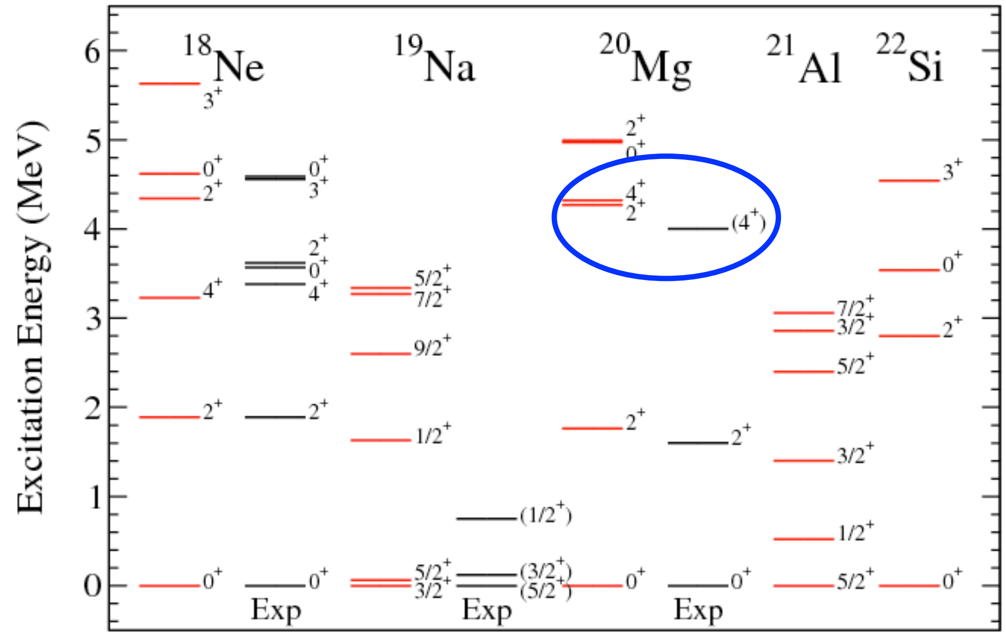


# 3N forces and proton-rich nuclei Holt, Menendez, AS (2013)

first results with 3N forces for ground and excited states of N=8, 20

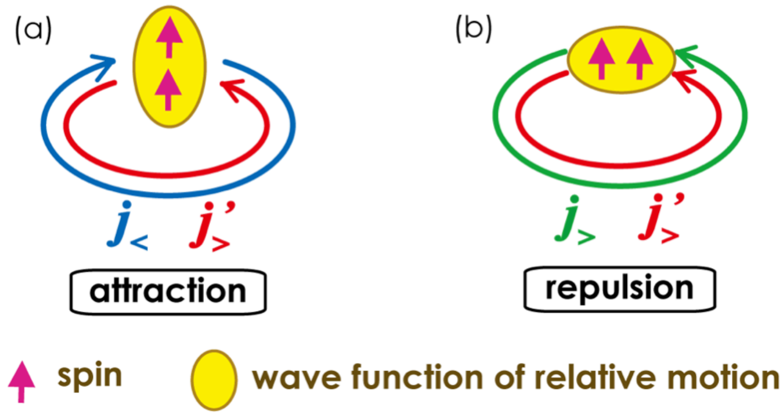



prediction for $^{20}$Mg agrees with new state observed at GSI Mukha, private comm.

# Tensor forces and exotic nuclei Otsuka et al.

attractive tensor force decreases spin-orbit splitting of protons with N



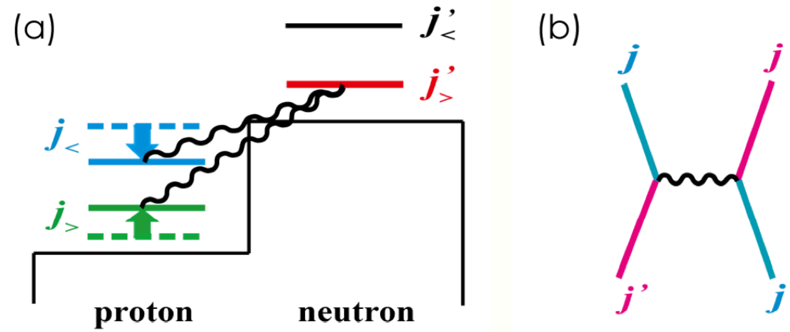
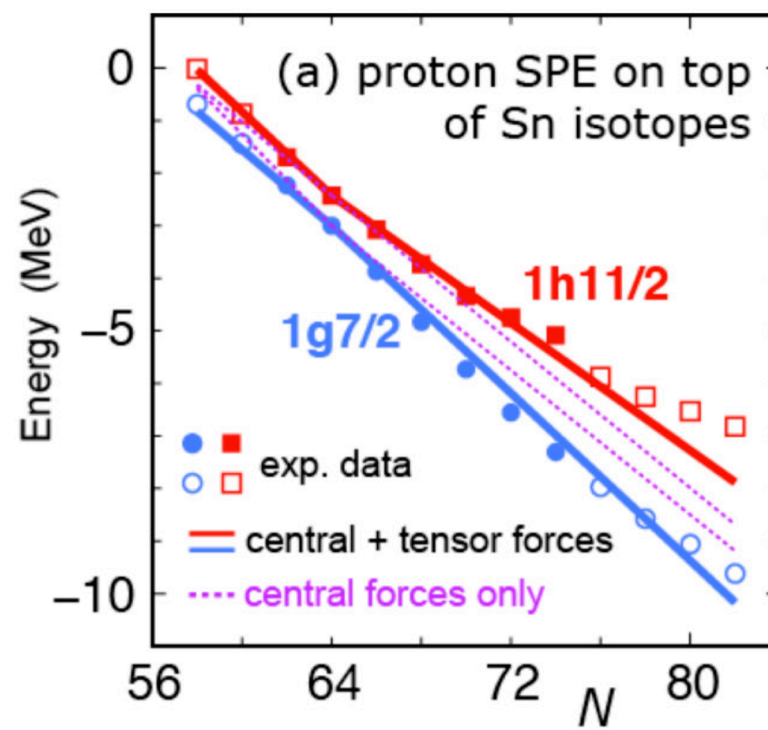



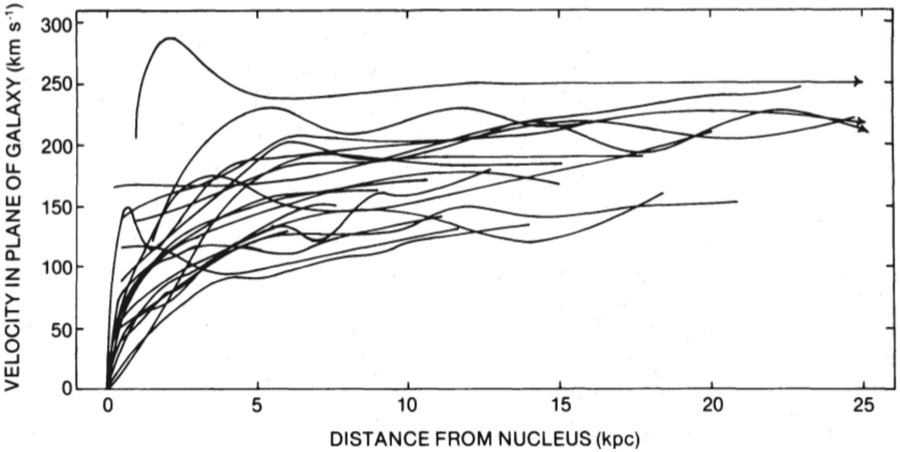

**Figure 2.** *(a) Change of spin-orbit splitting by the tensor force. (b) Diagram causing the change in (a). Wavy line stands for the tensor force. Modified from Ref. [6].*

larger relative momentum decreases horizontal overlap: attractive




figures from Otsuka, AS, Nuclear Physics News (2012)

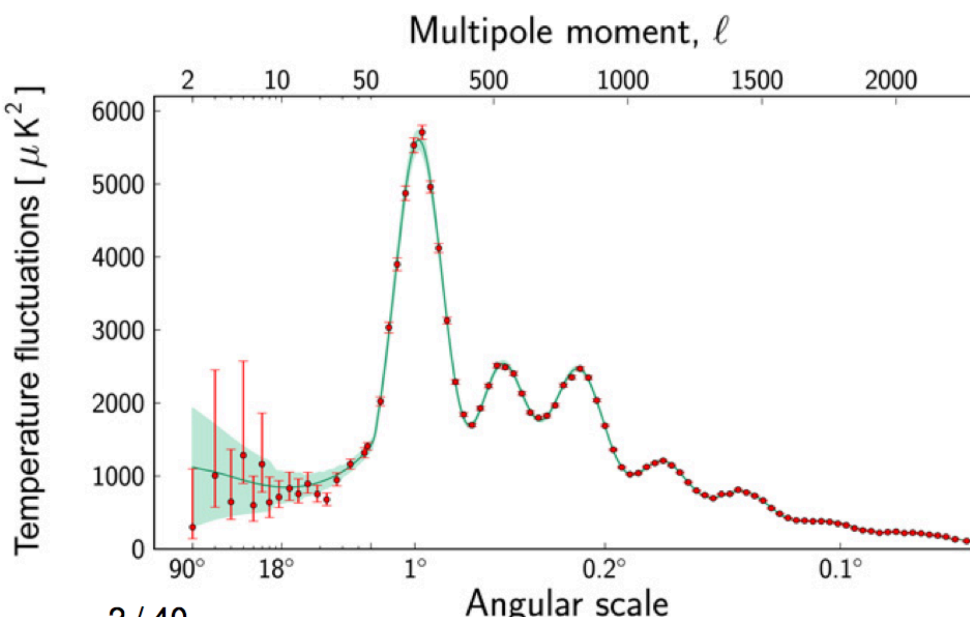
# Dark Matter: evidence

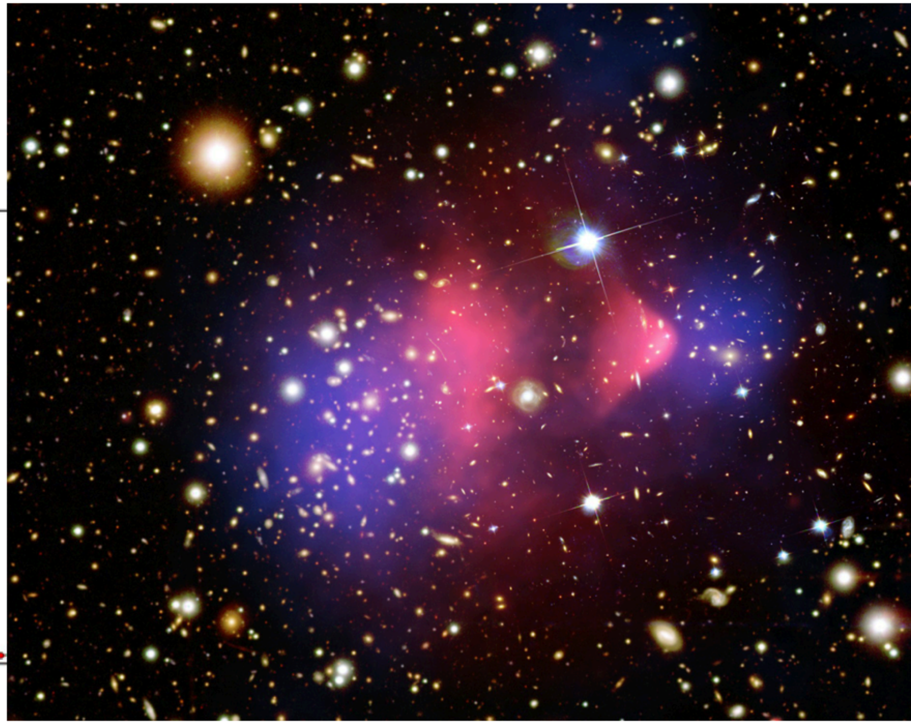



Solid evidence of Dark Matter in very different observations:

Rotation curves, Lensing, CMB...

Zwicky 1930's, Rubin 1970's,..., Planck (2013)



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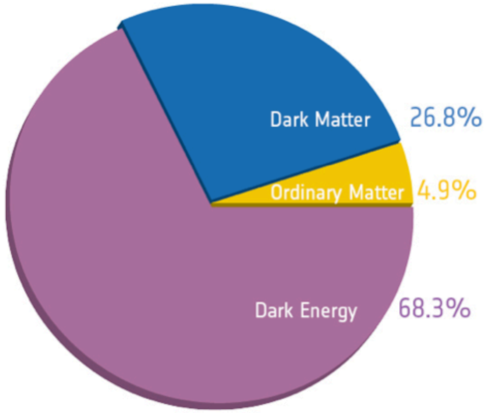
# What is Dark Matter?: WIMPs

We don't know the component of Dark Matter

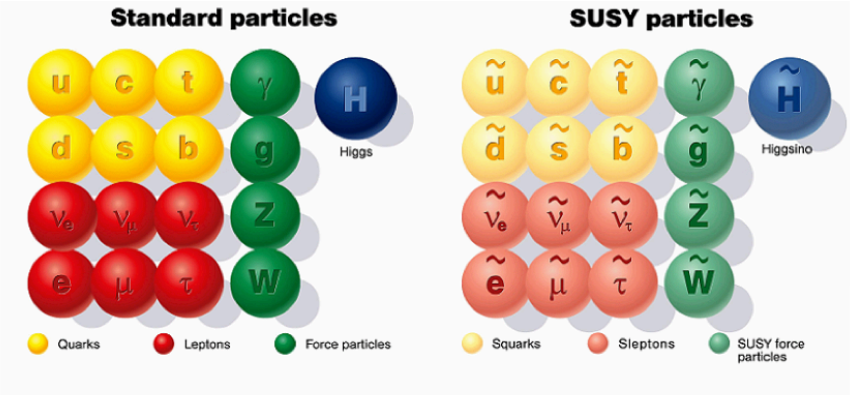
Many very different candidates have been proposed:

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

# Direct dark matter detection

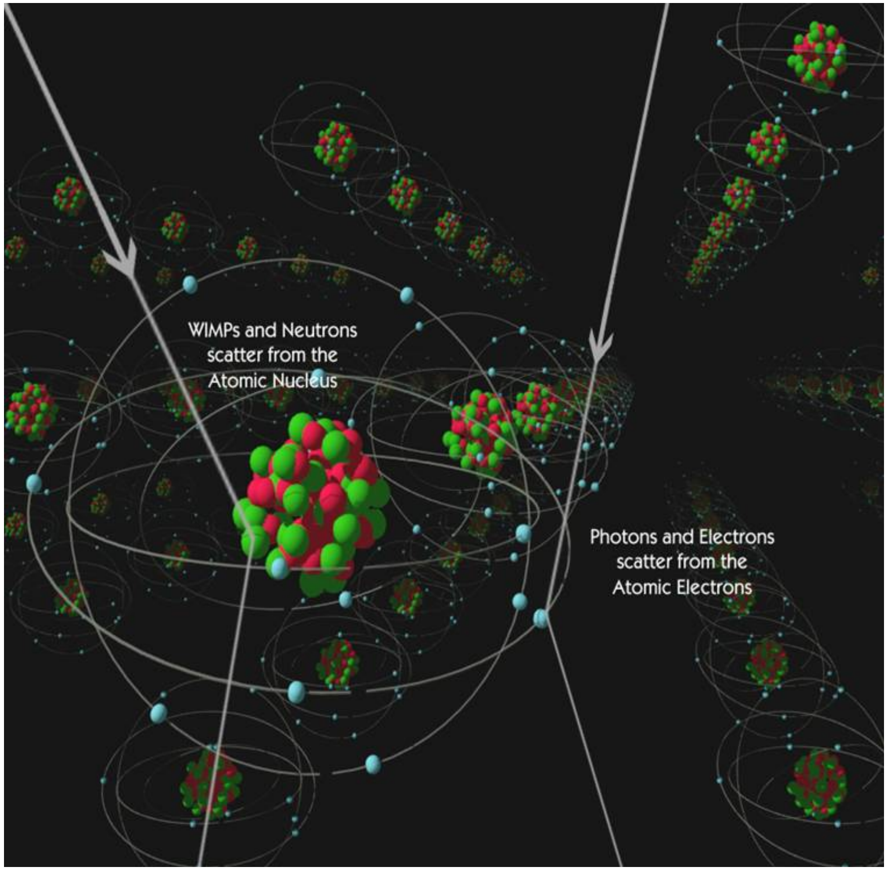
WIMP scattering off nuclei needs **nuclear structure factors** as input

particularly sensitive to nuclear physics for **spin-dependent** couplings

relevant momentum transfers ~ $m_\pi$

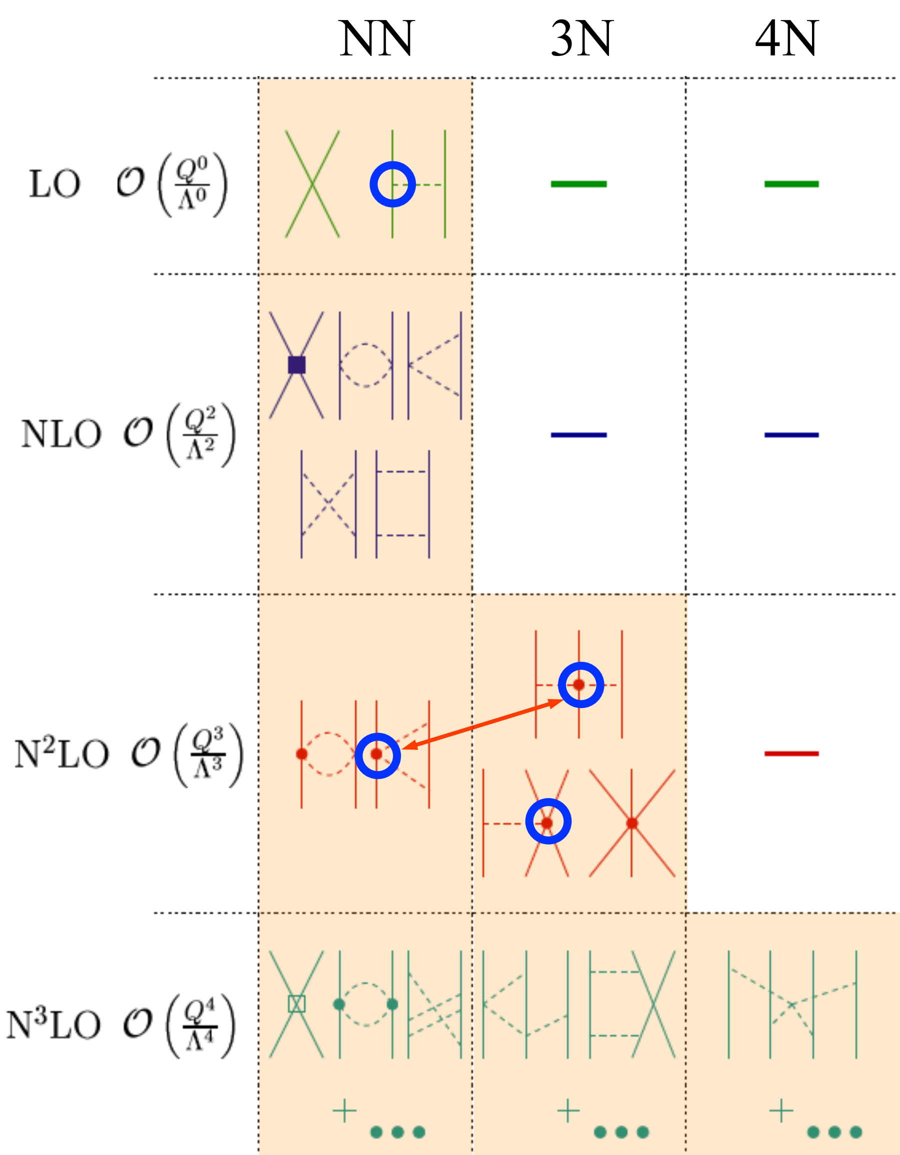
**calculate systematically**
**with chiral effective field theory**
Menendez, Gazit, AS, PRD **86**, 103511 (2012),
Klos, Menendez, Gazit, AS, 1304.7684.

dark matter response may have
more complex couplings in nuclei
Liam Fitzpatrick, Haxton et al. (2012)

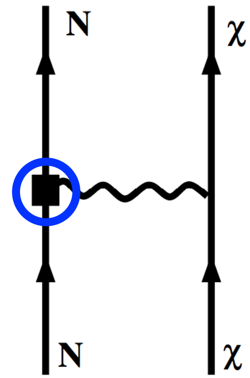



from CDMS collaboration

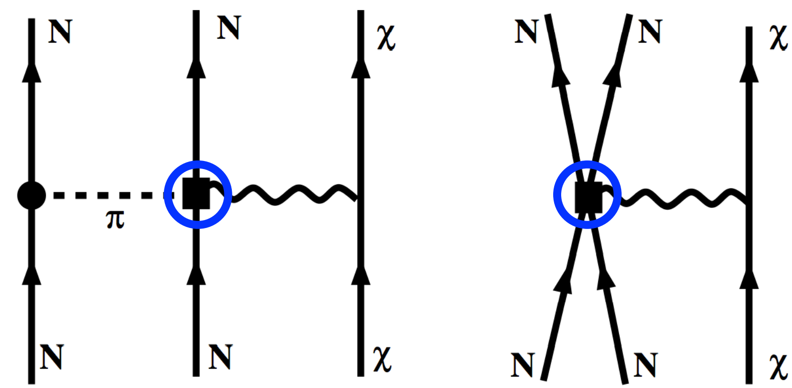
# Chiral EFT for WIMP currents in nuclei




one-body currents at $Q^0$ and $Q^2$




+ two-body currents at $Q^3$



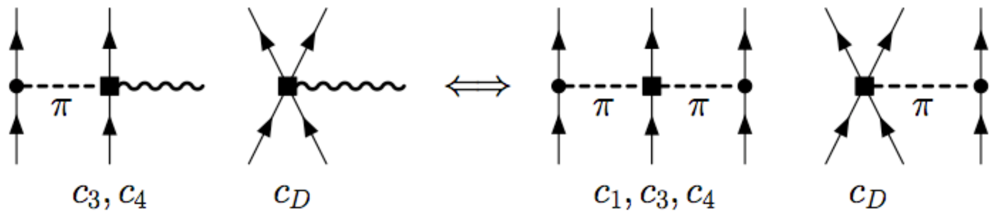

same couplings in forces and currents
for spin-dependent interactions!

# Two-body currents and 3N forces

weak axial currents and WIMP currents couple to spin, similar to pions
spin-dep. WIMP-nucleon int. = isospin rotation of weak axial current

two-body currents predicted by πN, NN, 3N couplings to $N^3LO$

Park et al., Phillips,…




two-body analogue of Goldberger-Treiman relation

explored in light nuclei, but not for larger systems

dominant contribution to Gamow-Teller transitions,
important in nuclei (Q~100 MeV)

3N couplings predict quenching of $g_A$ (dominated by long-range part)
and predict momentum dependence (weaker quenching for larger p)
Menendez, Gazit, AS (2011)

# WIMP currents in nuclei and uncertainties

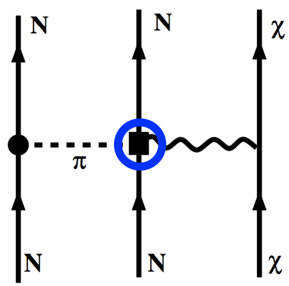
one-body currents with isoscalar/isovector couplings $a_{0/1}$

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

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

$Q^2$ similar to phenomenological currents, but slightly different p-dep.

two-body currents at $Q^3$ predicted by $c_3$, $c_4$ couplings from πN, NN, 3N




$$\mathbf{J}_{12}^3 = -\frac{g_A}{4F_\pi^2}\frac{1}{m_\pi^2+k^2}\left[2\left(c_4+\frac{1}{4m}\right)\mathbf{k}\times(\sigma_\times\times\mathbf{k})\tau_\times^3 \right.$$
$$\left. +4c_3\mathbf{k}\cdot(\sigma_1\tau_1^3+\sigma_2\tau_2^3)\mathbf{k} - \frac{i}{m}\mathbf{k}\cdot(\sigma_1-\sigma_2)\mathbf{q}\tau_\times^3\right]$$

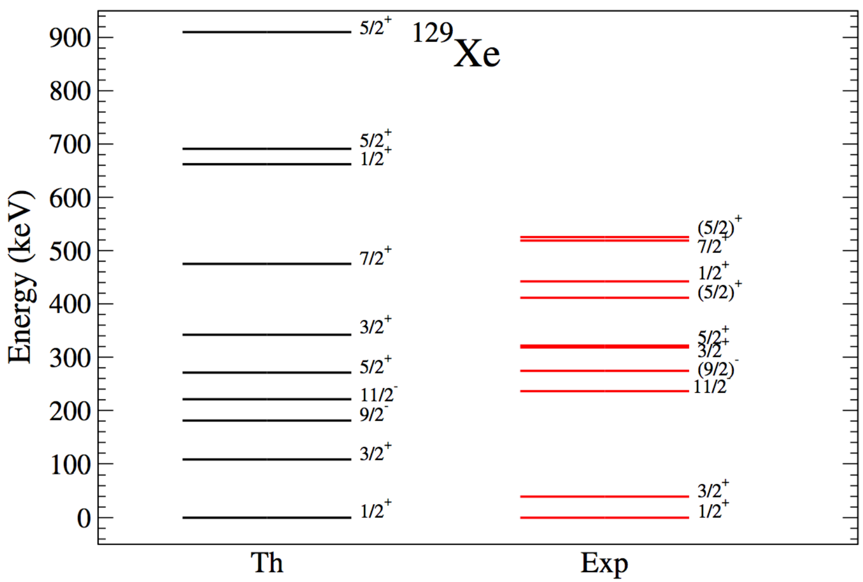
due to interactions among nucleons, dominated by long-range part

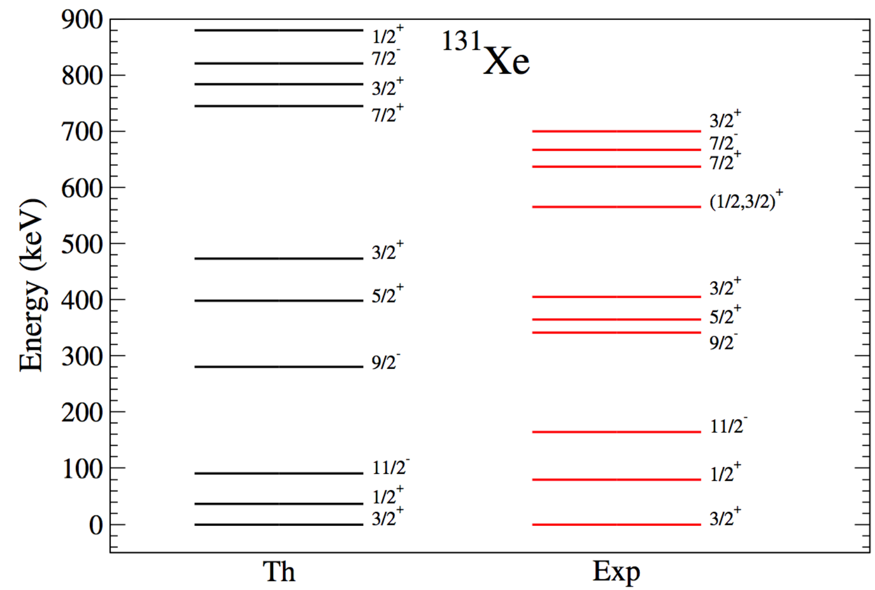
include as density-dependent one-body currents (normal ordering),
uncertainties due to leading-order two-body currents reflected in $c_3$, $c_4$

# Nuclear structure for direct detection

valence-shell Hamiltonian calculated from NN interactions + corrections to compensate for not including 3N forces (will improved in the future)

valence spaces and interactions have been tested successfully in nuclear structure calculations, largest spaces used




very good agreement for spectra; ordering and grouping well reproduced

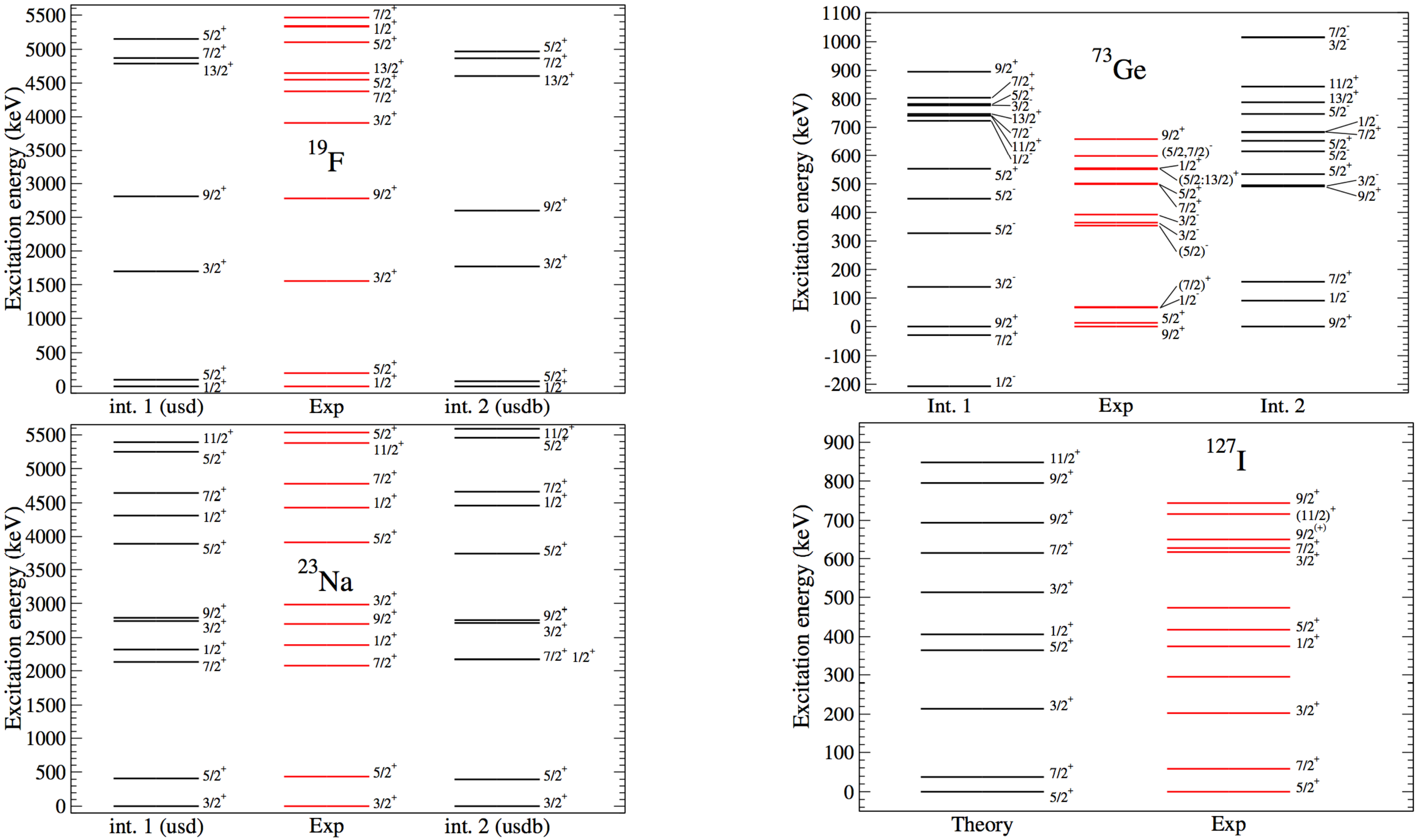
Menendez, Gazit, AS (201)

connects WIMP direct detection with double-beta decay

# Nuclear structure II

## similar agreement for other nuclei relevant to direct detection

Menendez, Klos, Gazit, AS (2013)



# Nuclear structure factors

differential cross section for spin-dependent WIMP scattering
~ axial-vector structure factor $S_A(p)$

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

decompose into longitudinal, transverse electric and transverse magnetic

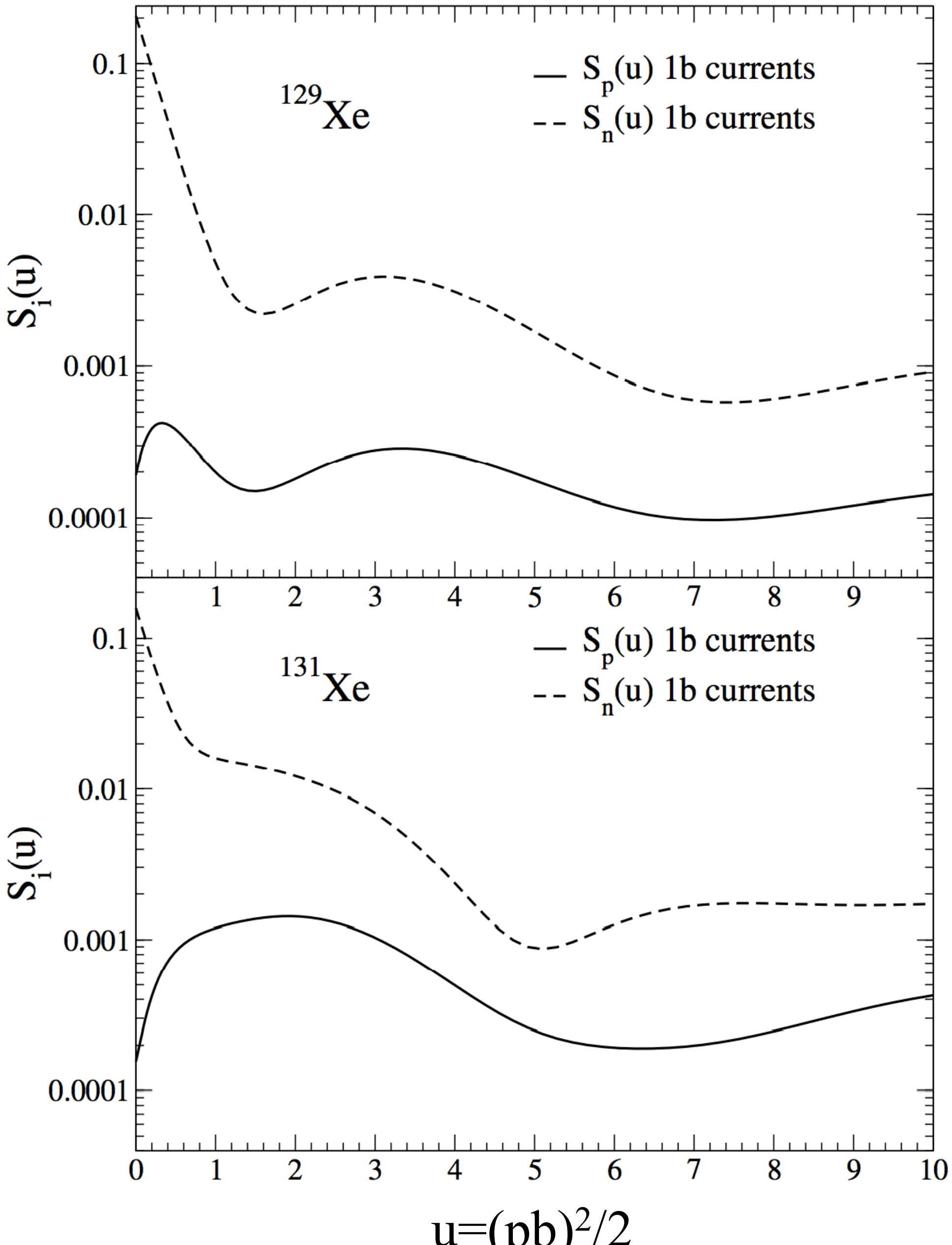
$$S_A(p) = \sum_{L\geqslant 0} \left| \langle J_f || \mathcal{L}_L^5 || J_i \rangle \right|^2 + \sum_{L\geqslant 1} \left( \left| \langle J_f || \mathcal{T}_L^{\rm el5} || J_i \rangle \right|^2 + \left| \langle J_f || \mathcal{T}_L^{\rm mag5} || J_i \rangle \right|^2 \right)$$

transverse magnetic multipoles vanish for elastic scattering

can also decompose into isoscalar/isovector structure factors $S_{ij}(p)$

$$S_A(p) = a_0^2\, S_{00}(p) + a_0 a_1 S_{01}(p) + a_1^2\, S_{11}(p)$$

# Xenon response with one-body currents




$^{129,131}$Xe are even Z, odd N, spin is carried mainly by neutrons

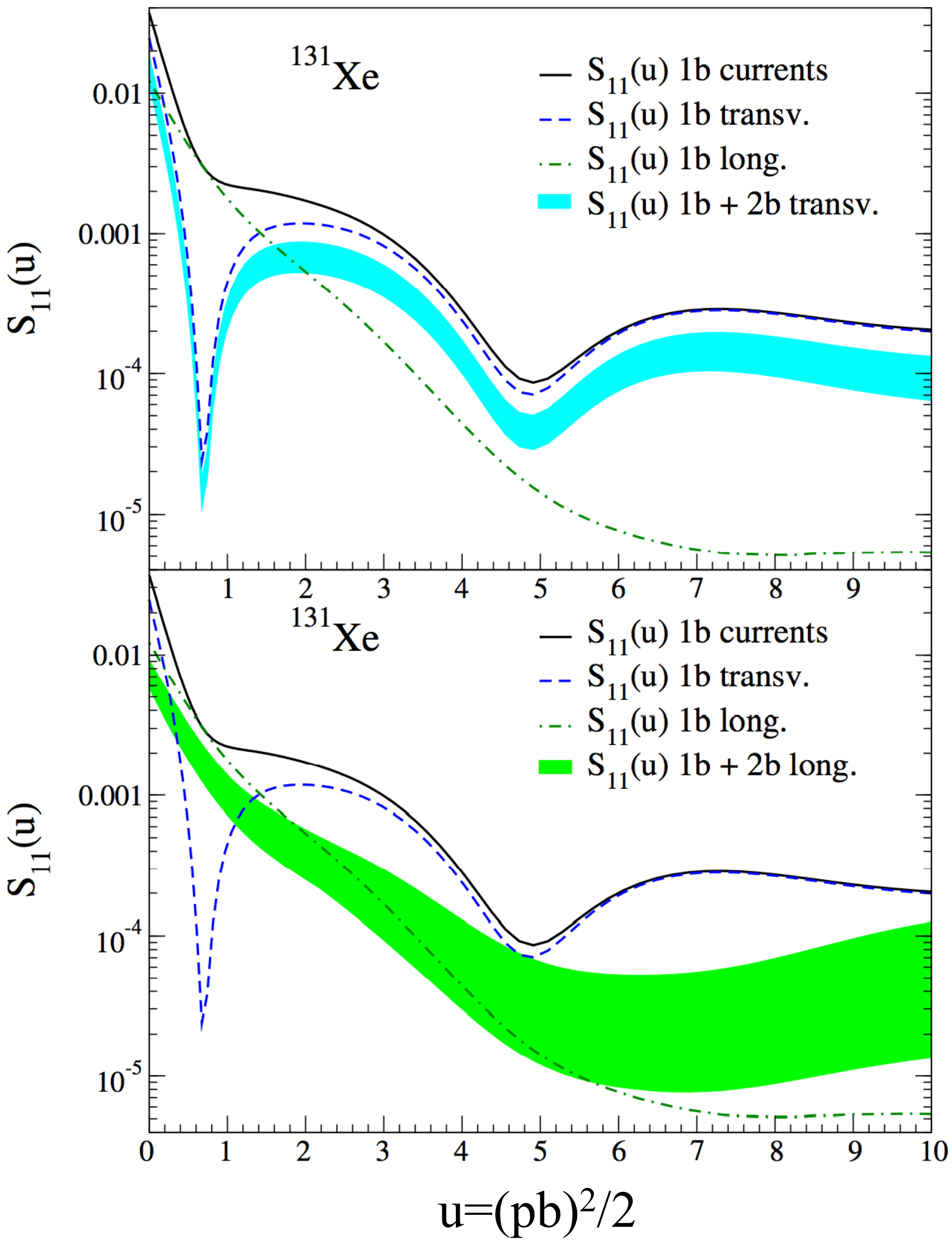
at p=0 structure factors at the level of one-body currents dominated by “neutron”-only

$$S_A = \frac{(2J+1)(J+1)}{\pi J} \left| a_p \langle S_p \rangle + a_n \langle S_n \rangle \right|^2,$$

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

$$S_n(0) \propto \left|\langle S_n \rangle\right|^2 \; S_p(0) \propto \left|\langle S_p \rangle\right|^2.$$

# Xenon response with 1+2-body currents



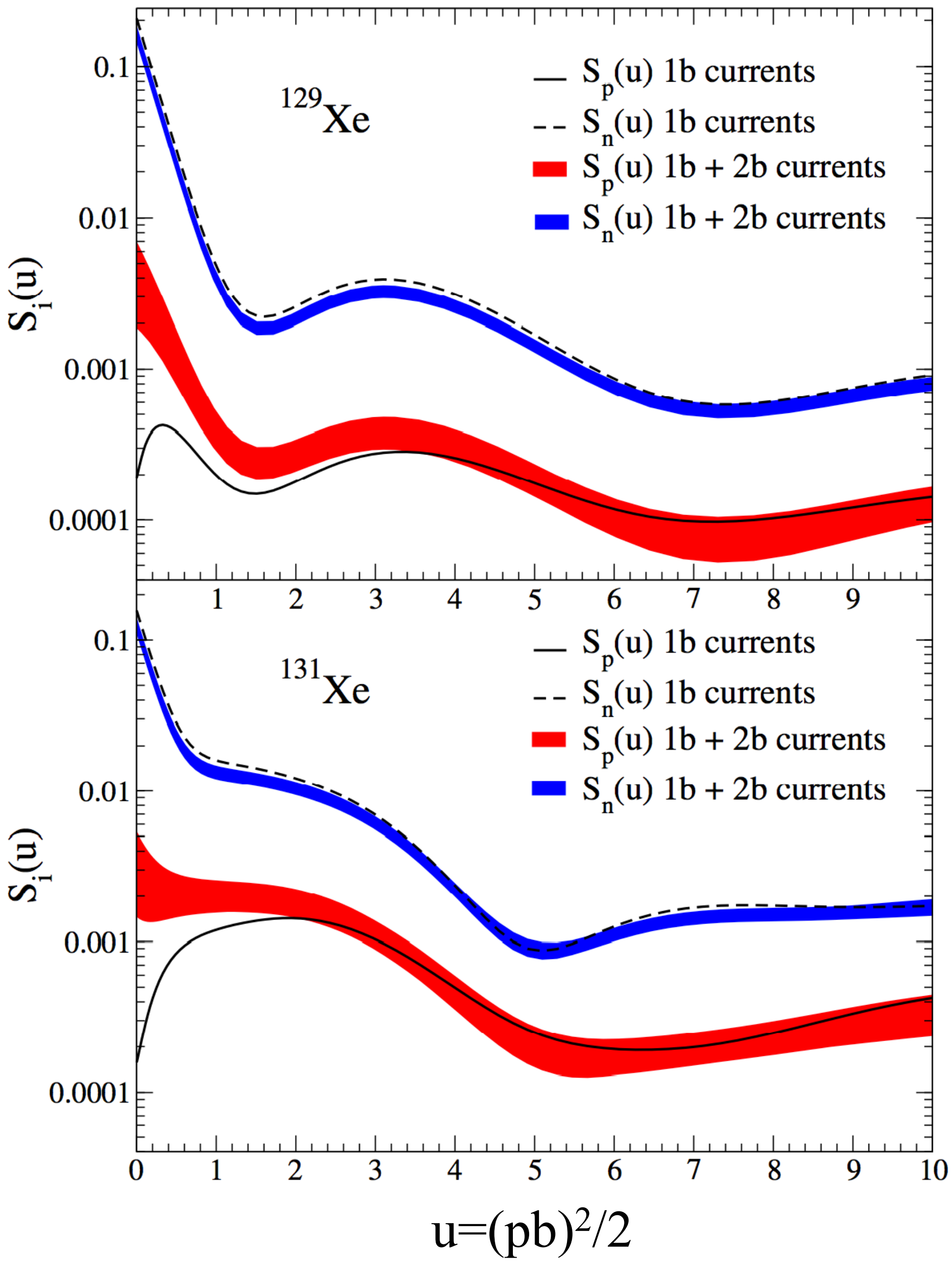

leading two-body currents renormalize isovector coupling: not "neutron"/"proton" only

lead to reduction of axial current enhancement of pseudoscalar curr.

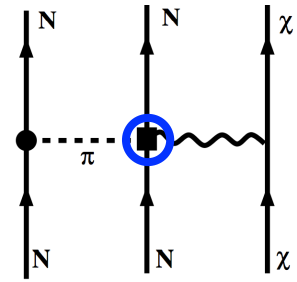
transverse multipoles reduced; longitudinal reduced at low p, but enhanced at high p

uncertainty band due to $c_3$, $c_4$ and normal-ordering

# Xenon response with 1+2-body currents




two-body currents due to strong interactions among nucleons




WIMPs couple to neutrons and protons at the same time

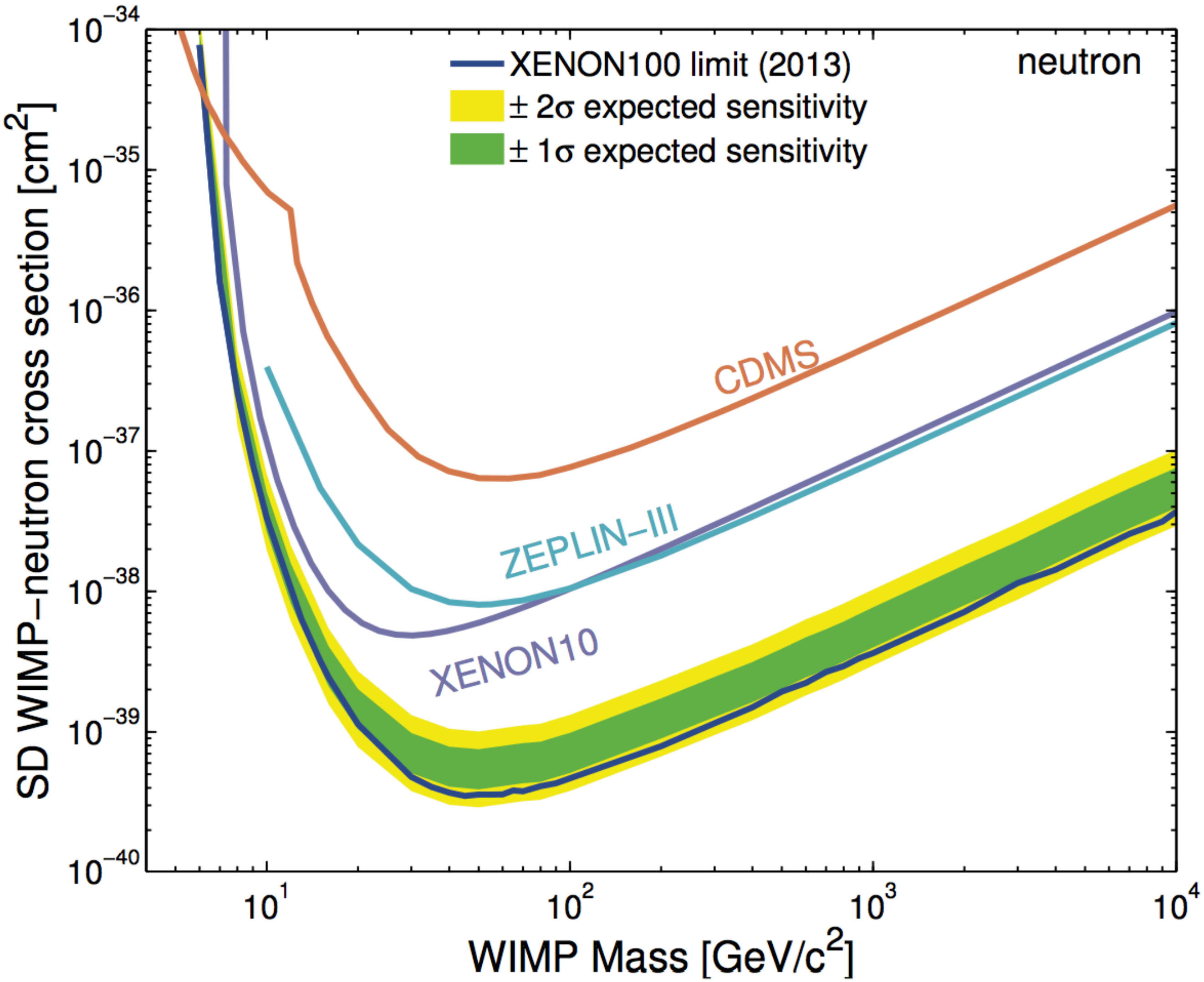
enhances coupling to even species in all cases

first calculations with chiral EFT currents and state-of-the-art nuclear interactions

# Limits on SD WIMP-neutron interactions

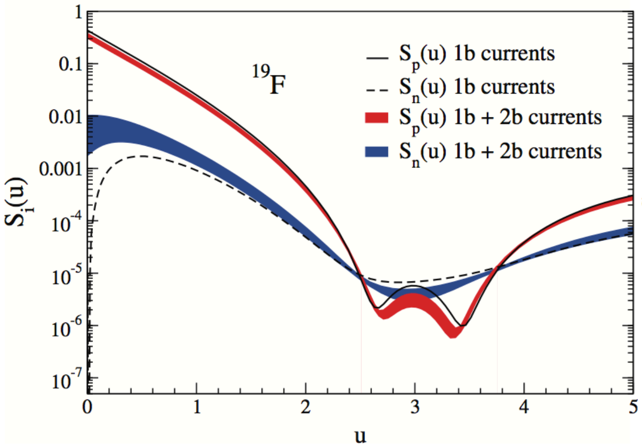
best limits from XENON100 Aprile et al., PRL (2013)

used our calculations with uncertainty bands for WIMP currents in nuclei

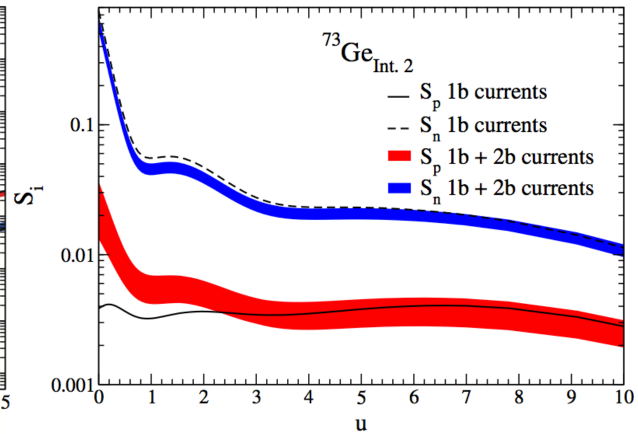


# Spin-dependent WIMP-nucleus response for $^{19}F$, $^{23}Na$, $^{27}Al$, $^{29}Si$, $^{73}Ge$, $^{127}I$

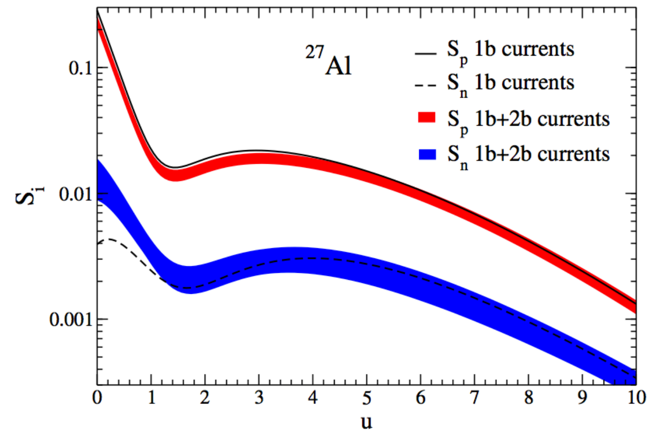
Klos, Menendez, Gazit, AS (2013)




PICASSO, COUPP, SIMPLE




CDMS, EDELWEISS, EURECA

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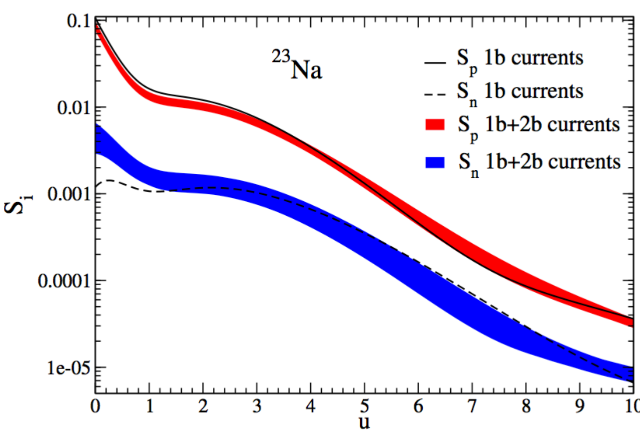
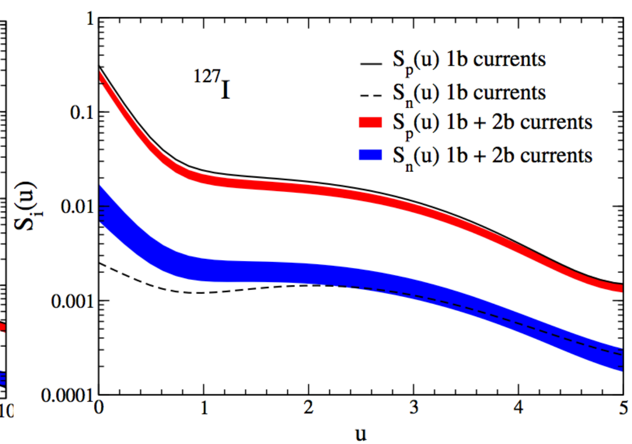
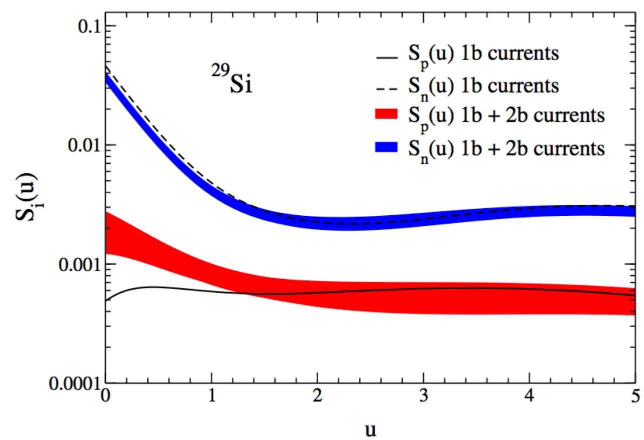



DAMA, ANAIS, DM-Ice




DAMA, ANAIS, DM-Ice, KIMS



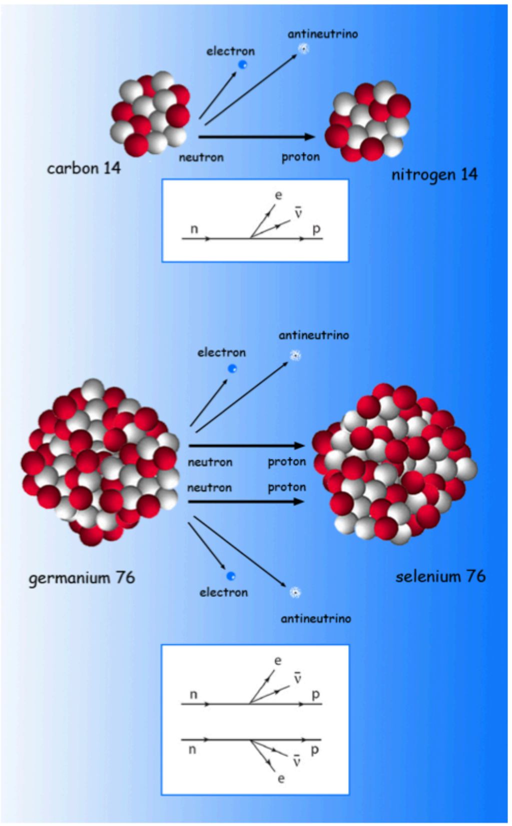

CDMS-II

slide from J. Menendez



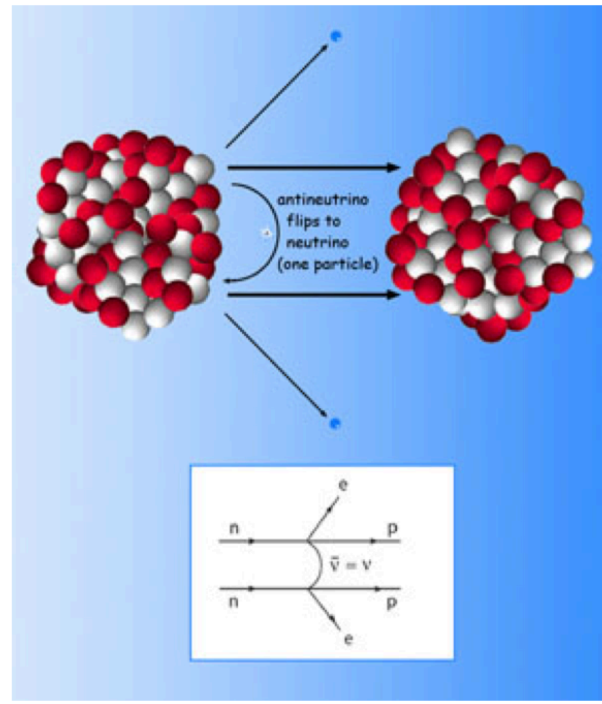
# Neutrinoless Double beta decay

Lepton number conserved in all processes observed so far:




$\beta$ decay, $\beta\beta$ decay...

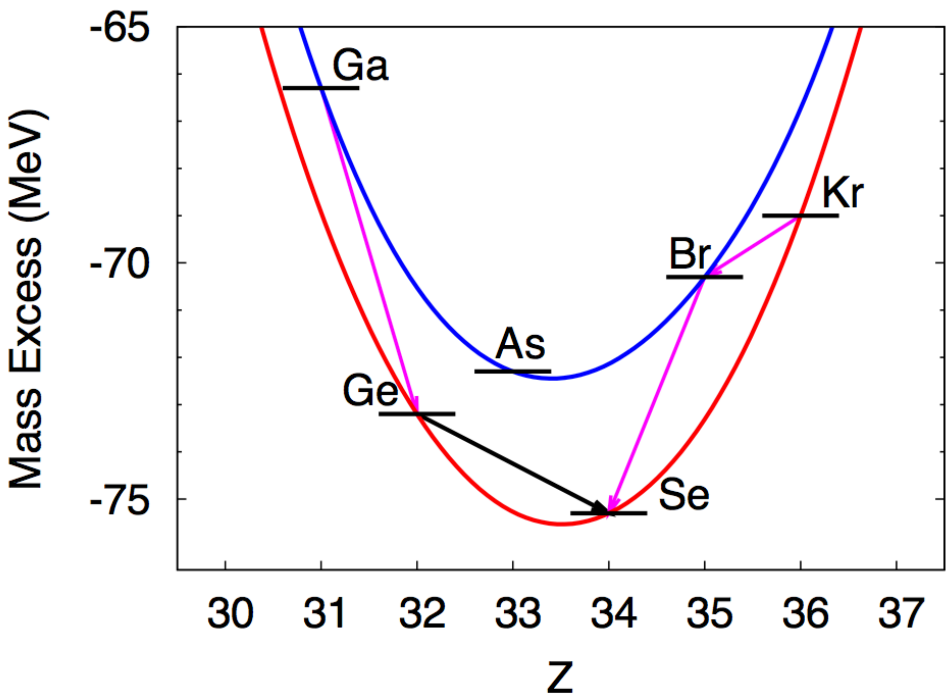
Uncharged massive particles like Majorana neutrinos ($\nu$) theoretically allow L violation




Neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay

# Double beta decay: origin

- Double beta decay is a rare second-order weak process
- It only appears when single $\beta$ decay is energetically forbidden or hindered by large $J$ difference



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# Nuclear Matrix Elements (NMEs)

$0\nu\beta\beta$ process needs massive Majorana neutrinos ($\nu = \bar{\nu}$)
$\Rightarrow$ detection would proof Majorana nature of neutrinos

$$\left(T_{1/2}^{0\nu\beta\beta}\left(0^+ \to 0^+\right)\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$M^{0\nu\beta\beta}$ necessary to identify best candidates for experiment and to obtain neutrino masses and hierarchy with $m_{\beta\beta} = \left|\sum_k U_{ek}^2 m_k\right|$

$$M^{0\nu\beta\beta} = \langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_X H^X(r)\,\Omega^X \,|0_i^+\rangle$$

- Many-body method to describe initial and final nuclear states (ISM)
- Transition operator, appropriate for this decay (chiral EFT)

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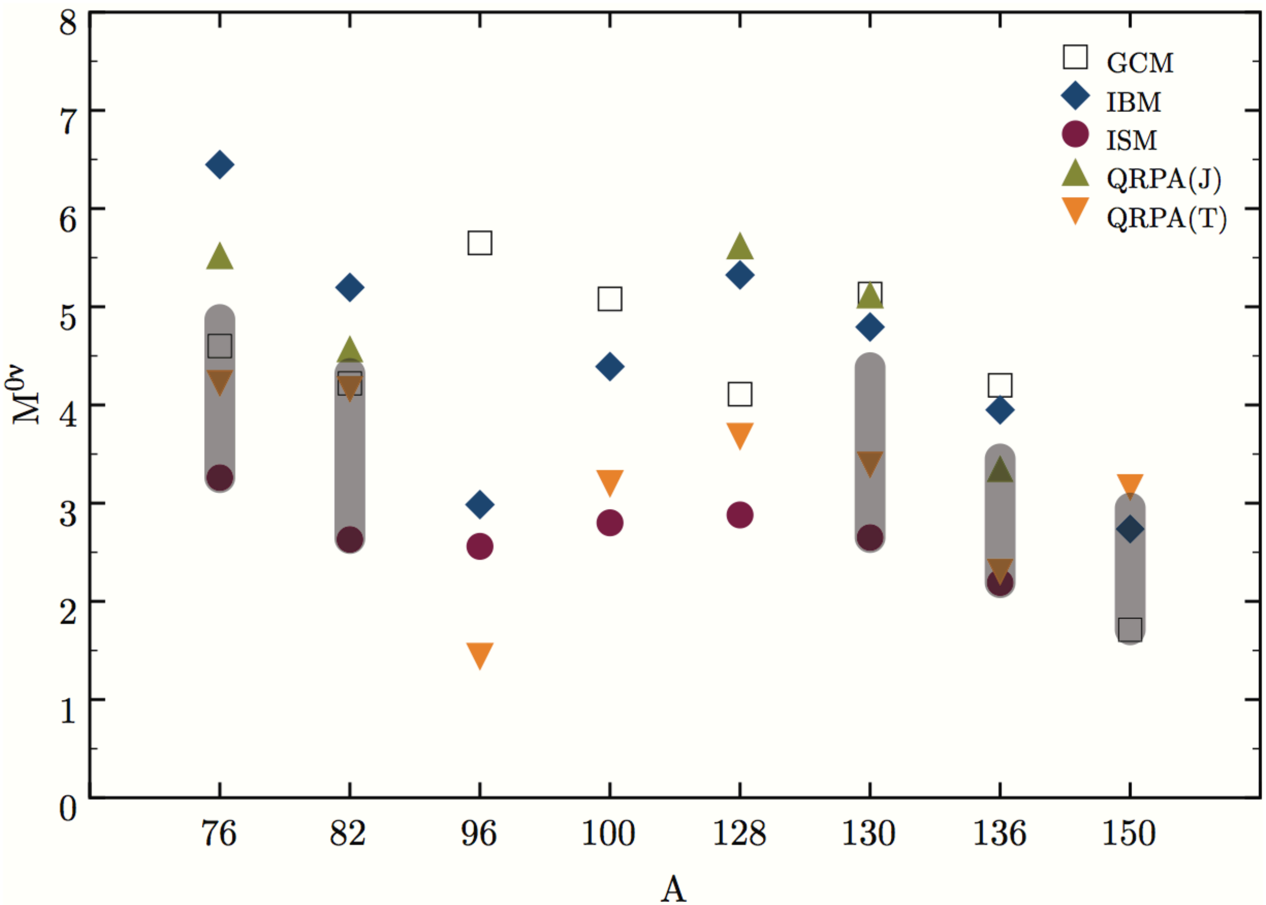
# $M^{0\nu\beta\beta}$ uncertainty: nuclear structure




Gomez-Cadenas et al., JCAP06 007(2011)

Different calculations differ factor $\sim 2$

Work in progress to:
improve calculations
understand differences

# Results from GERDA Phase I Agostini et al., 1307.4720

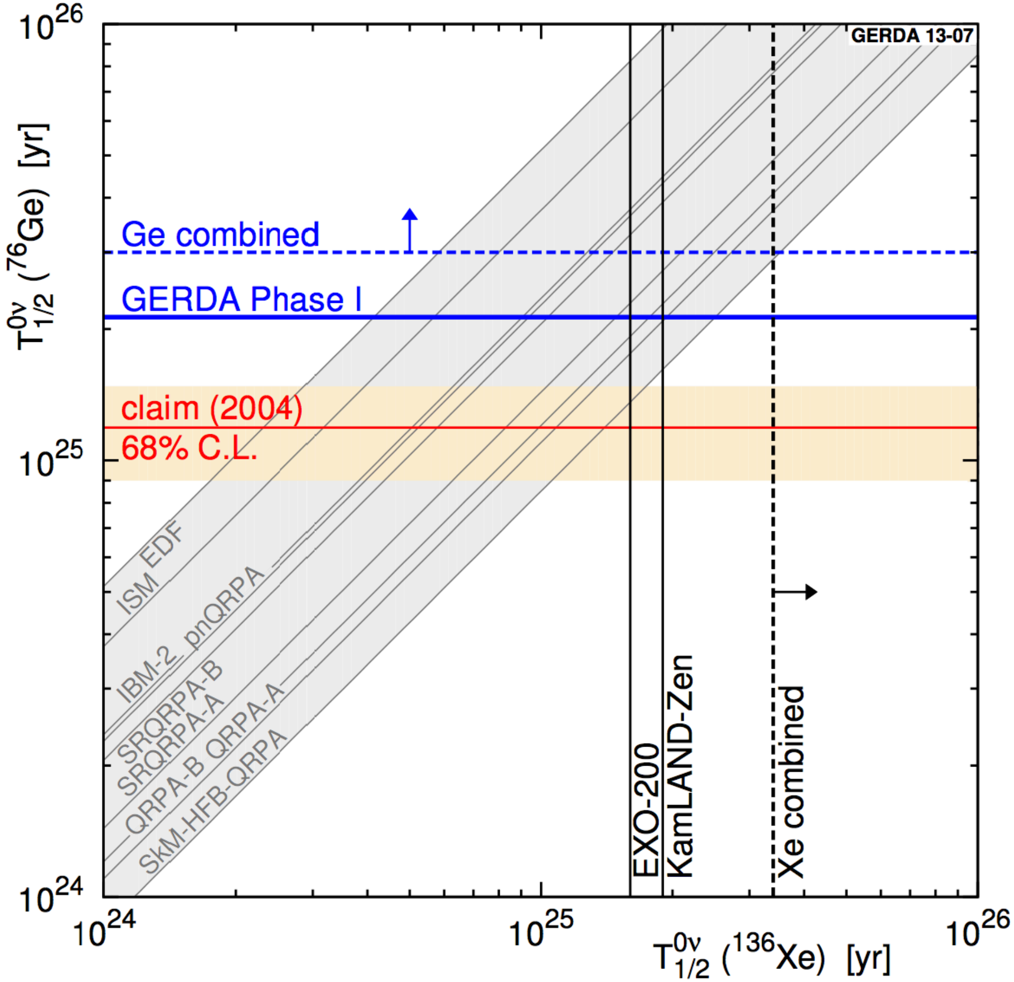



FIG. 2. Limits (90 % C.L.) on $T^{0\nu}_{1/2}$ of $^{76}$Ge (this work) and $^{136}$Xe [14, 15] compared with the signal claim for $^{76}$Ge of Ref. [11] (68 % C.L. band). The lines in the shaded gray band are the predictions for the correlation of the half-lives in $^{136}$Xe and in $^{76}$Ge according to different NME calculations [27–33]. The selection of calculations and the labels are taken from Ref. [34].

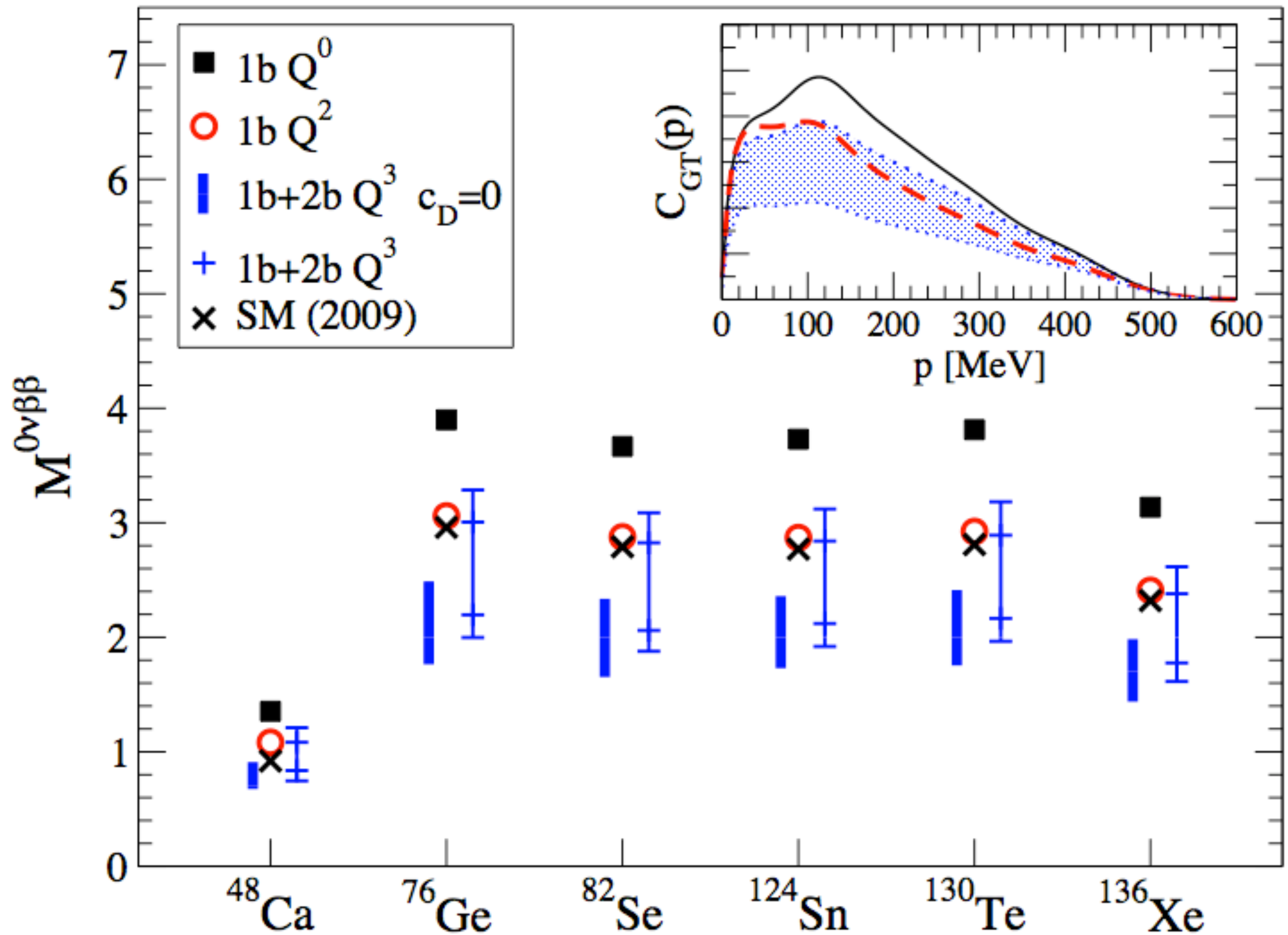
In conclusion, due to the unprecedented low background counting rate and the good energy resolution intrinsic to HPGe detectors, GERDA establishes after only 21.6 kg·yr exposure the most stringent $0\nu\beta\beta$ half-life limit for $^{76}$Ge. The long-standing claim for a $0\nu\beta\beta$ signal in $^{76}$Ge is strongly disfavored, which calls for a further exploration of the degenerate Majorana mass scale. This will be pursued by GERDA Phase II aiming for a sensitivity increased by a factor of about 10.

# Chiral EFT and 0νββ decay

Nuclear matrix elements for 0νββ decay based on chiral EFT operator

Menendez, Gazit, AS (2011)

Modest quenching because 0νββ decay probes higher momentum transfer



# Thank you for a great 3 weeks!!