Nuclear structure for $\beta\beta$ decay and dark matter searches

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日本学術振興会 Japan Society for the Promotion of Science

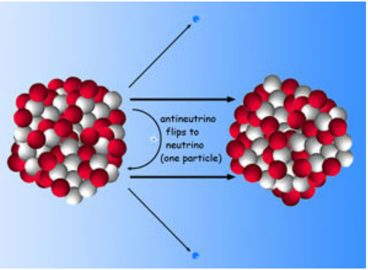
東京大学 THE UNIVERSITY OF TOKYO

Nuclear physics, $\beta\beta$ decay, dark matter detection

Nuclear structure crucial for design
and interpretation of experiments

Neutrinos, dark matter studied in
low-energy experiments using nuclei

Abundant material, long observation time
with very low background sensitive to
rarest decays and tiny cross-sections!



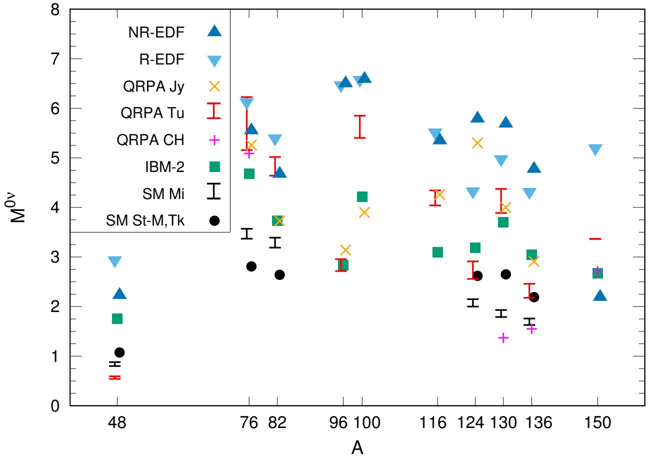
$0\nu\beta\beta$ decay: $\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$

Dark matter: $\frac{d\sigma_{\chi\mathcal{N}}}{d\mathbf{q}^2} \propto \left|\sum_i c_i\,\zeta_i\,\mathcal{F}_i\right|^2$

$M^{0\nu\beta\beta}$: Nuclear matrix element
$\mathcal{F}_i$: Nuclear structure factor

$0\nu\beta\beta$ decay nuclear matrix elements

Large difference in nuclear matrix element calculations: factor $\sim 2-3$

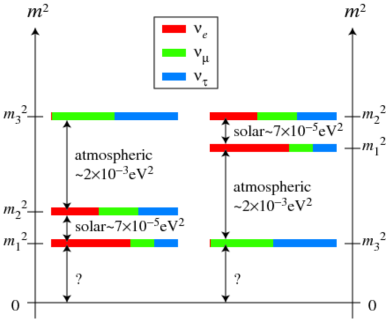


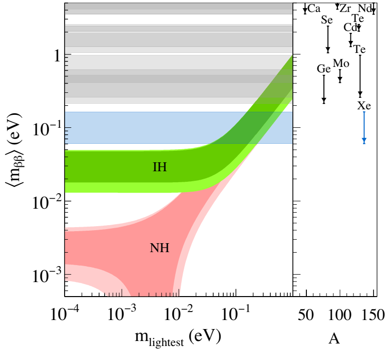
Engel, JM, arXiv: 1610.06548

Application to experiment: inverted hierarchy

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

sensitive to absolute neutrino masses, $m_{\beta\beta} = |\sum U_{ek}^2 m_k|$, and hierarchy

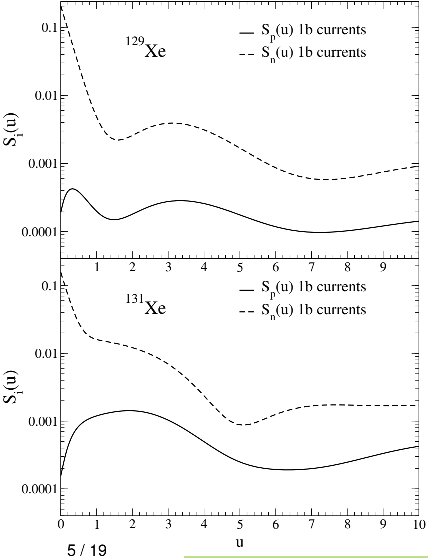


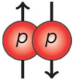


Matrix elements needed to make sure next generation ton-scale experiments fully explore "inverted hierarchy"

KamLAND-Zen, PRL117 082503(2016)

Spin-dependent scattering: 1b+2b currents



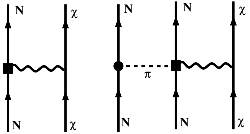


In $^{129,131}_{54}$Xe $\langle S_n \rangle \gg \langle S_p \rangle$,
Neutrons carry most nuclear spin

1b current: couple to proton or neutron

$$S(q=0) \propto \left| a_p \langle S_p \rangle + a_n \langle S_n \rangle \right|^2$$

2b current: involve neutrons + protons



Dramatic $S_p(u)$ increase due to neutrons

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

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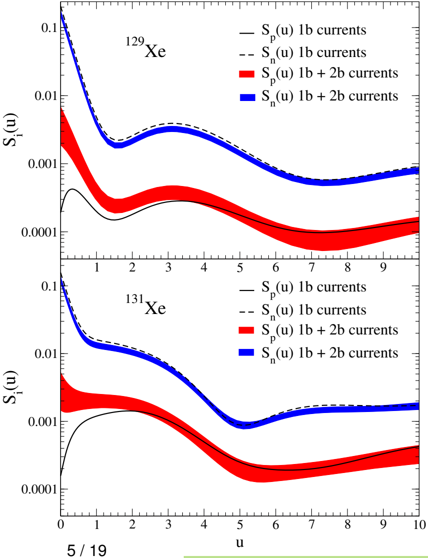

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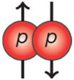

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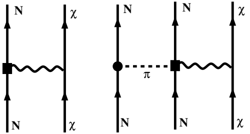


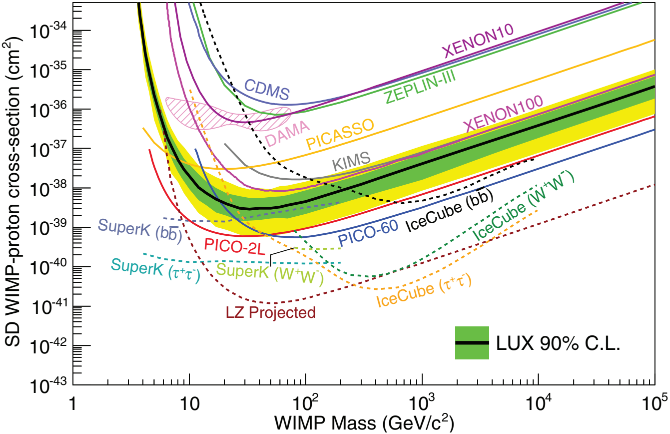
Dramatic $S_p(u)$ increase due to neutrons

JM, Gazit, Schwenk, PRD86 103511(2012)

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

Application to experiment: LUX SD analysis

2b contributions make LUX results (xenon, more sensitive to neutrons) competitive also for the spin-dependent WIMP-proton cross-section



LUX Collaboration, PRL116 161302 (2016)

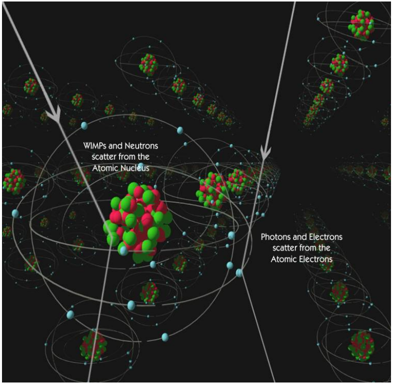
Nuclear matrix elements and structure factors

Nuclear matrix elements needed to study fundamental symmetries

$$\langle \text{Final} \,|\mathcal{L}_{\text{leptons}-\text{nucleons}}|\, \text{Initial} \,\rangle = \langle \text{Final} \,|\, \int dx\, j^{\mu}(x) J_{\mu}(x) \,|\, \text{Initial} \,\rangle$$

- Nuclear structure calculation of the initial and final states:
  Ab initio, shell model, energy density functional...

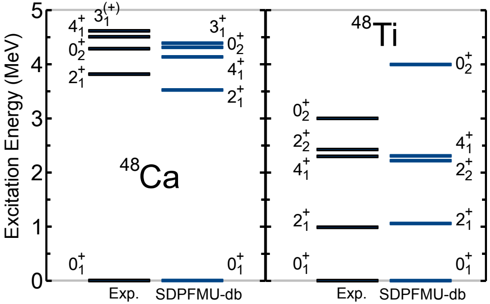
- Lepton-nucleus interaction:
  Evaluate (non-perturbative) hadronic currents inside nucleus: phenomenology, effective theory



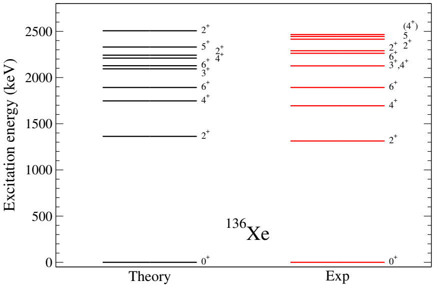
CDMS Collaboration

Test of initial and final nuclear states

Relevant nuclear states spectra very good agreement with experiment
Electromagnetic transitions, knockout data... also good agreement



Iwata et al. PRL116 112502 (2016)



Vietze et al. PRD91 043520 (2015)

Single-β decay Gamow-Teller, need quenching of transition operator

Phenomenological calculations, uncertainties difficult to quantify

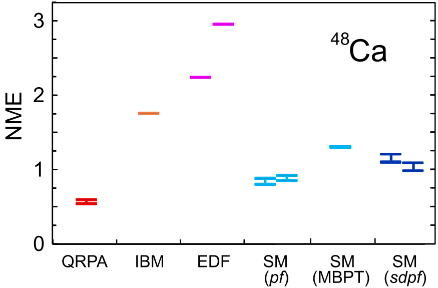
Improving nuclear matrix element calculations

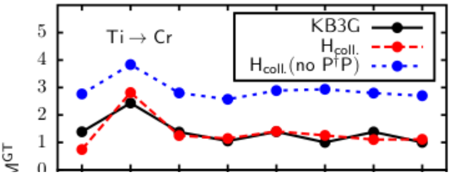
For ^{48}Ca enlarge configuration space from *pf* to *sdpf* (4 to 7 orbitals) increases matrix element but only moderately $\sim$ 30%

Iwata et al. PRL116 112502 (2016)

Enlarge further configuration space with Monte Carlo shell model

Togashi et al. PRL117 172502 (2016)





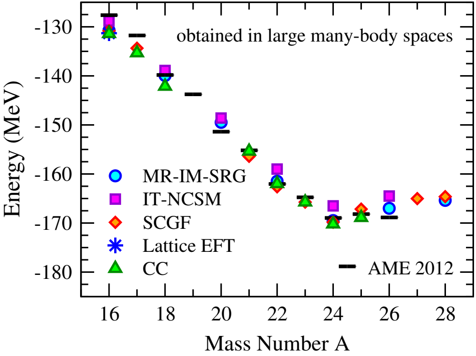
$0\nu\beta\beta$ decay very sensitive to proton-neutron (isoscalar) pairing

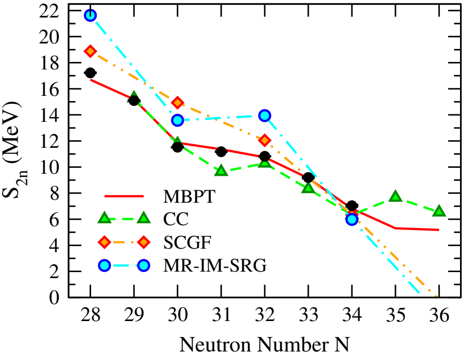
Matrix element too large if neglect proton-neutron correlations: density functional, IBM values

JM et al. PRC93 014305 (2016)

Nuclear structure *ab initio* calculations

Great sucess prediction of oxygen dripline, calcium separation energies





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

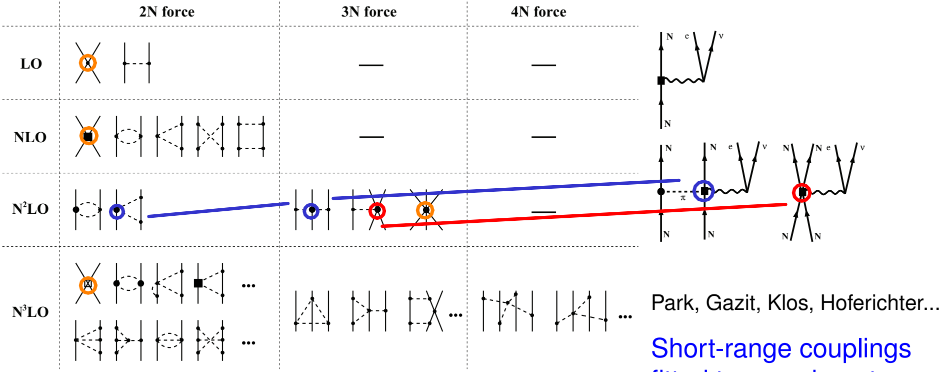
Gallant et al. PRL 109 032506 (2012)
Wienholtz et al. Nature 498 346 (2013)
Hagen et al. PRL 109 032502 (2012)
Somà et al. PRC 89 061301 (2014)
Hergert et al. PRC 90 041302 (2014)

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



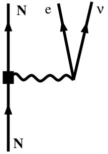
Park, Gazit, Klos, Hoferichter...

Short-range couplings fitted to experiment once

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

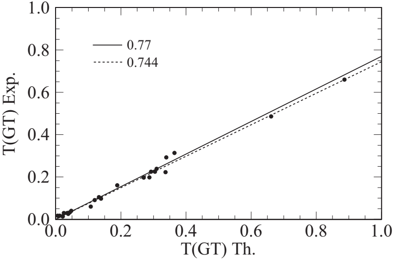
Gamow-Teller decay: "quenching" and 2b currents

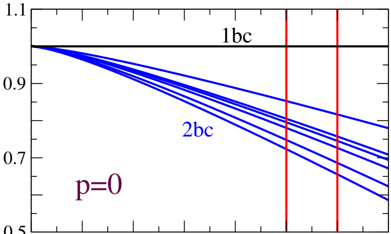
Single-β decays well described by nuclear theory (shell model),
but need to “quench“ $\sigma\tau$ operator to predict Gamow-Teller half-lives

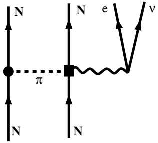


$$\langle F | \sum_i g_A^{\mathrm{eff}} \boldsymbol{\sigma}_i \tau_i^- | I \rangle$$

$$g_A^{\mathrm{eff}} = (0.7 - 0.8) g_A$$



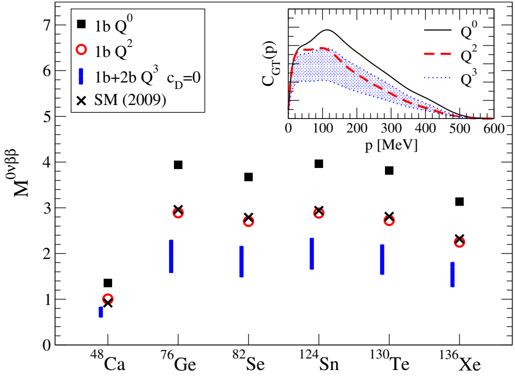




Anything missing
in transition operator?

2b currents predict quenching
$g_A^{\mathrm{eff}} = (0.66 \ldots 0.85) g_A$

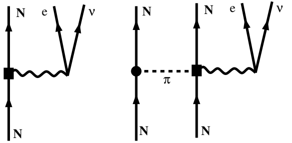
Nuclear matrix elements with 1b+2b currents

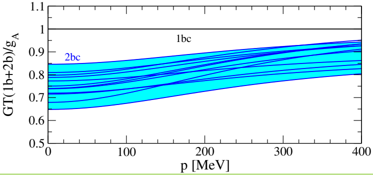


JM, Gazit, Schwenk PRL107 062501 (2011)

JM arXiv:1605.05059, updated 2b currents

2b currents
reduce matrix elements
$\sim$ 20% – 50%





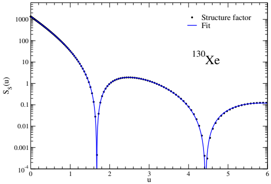
Quenching reduced in $0\nu\beta\beta$ decay
large momentum transfer $p \sim m_\pi$ $\Longrightarrow$

WIMP scattering off nuclei: standard analysis

Standard direct detection analyses consider two very different cases

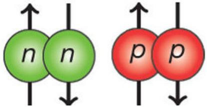
Spin-Independent (SI) interaction:
WIMPs couple to the nuclear density ($\mathbb{1}_\chi \mathbb{1}_N$)

Coherent sum over neutrons and protons
Cross section enhancement by factor
$|\sum_A \langle \mathcal{N} \| \mathbb{1}_N | \mathcal{N} \rangle|^2 = A^2$



Spin-Dependent (SD) interaction:
WIMP spins couple to the nuclear spin ($\boldsymbol{S}_\chi \cdot \boldsymbol{S}_N$)

Pairing interaction: spins couple to $S = 0$
Cross section scale set by
single-proton/neutron spin expectation value
$|\sum_A \langle \mathcal{N} \| \boldsymbol{S}_N | \mathcal{N} \rangle|^2 = \langle \boldsymbol{S}_n \rangle^2, \langle \boldsymbol{S}_p \rangle^2 \sim 0.1$



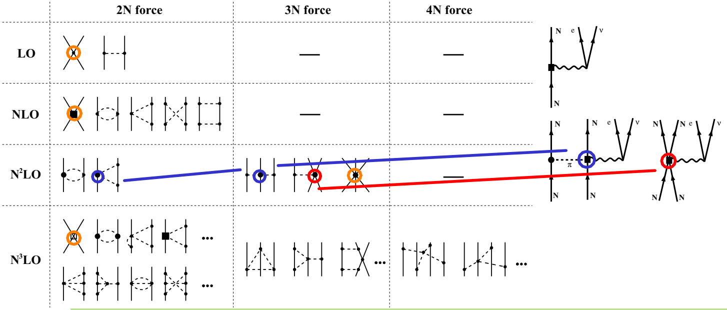
$$\frac{d\sigma^{SI}_{\chi\mathcal{N}}}{d\mathbf{q}^2} \propto \left| \sum_i c_i \, \zeta_i \, \mathcal{F}_i \right|^2$$

How can direct detection analyses be generalized?

Non-relativistic / Chiral effective field theory

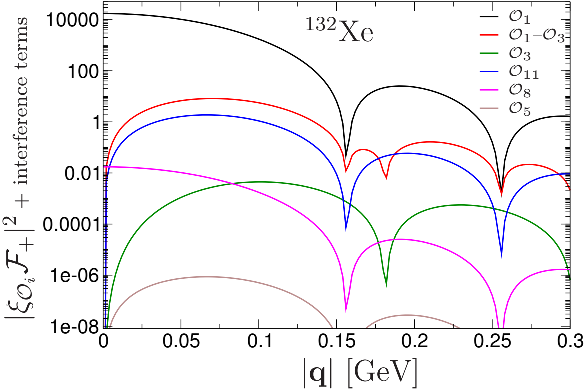
Non-relativistic effective field theory: set of operators $\mathcal{O}_i$
in the non-relativistic basis spanned by $\mathbb{1}_\chi$, $\mathbb{1}_N$, $\boldsymbol{S}_N$, $\boldsymbol{S}_\chi$, $\mathbf{q}$, $\mathbf{v}^\perp$
All terms taken to be independent $\Rightarrow$ nucleon (hadronic) physics missing
Fitzpatrick et al. JCAP02 004(2013), Anand et al. PRC89 065501 (2014)

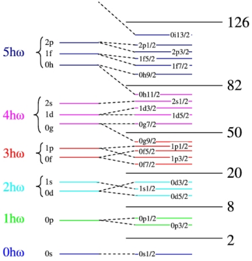
Chiral EFT: low energy approach to QCD, includes hadronic physics
Set hierarchy on $\mathcal{O}_i$ operators, and incorporate 2b effects



1b corrections: $\mathcal{O}_3$ operator

In addition to standard spin-independent operator $\mathcal{O}_1$,
contribution from coherent $\mathcal{O}_{11,8,5}$, quasi-coherent $\mathcal{O}_3$ operator





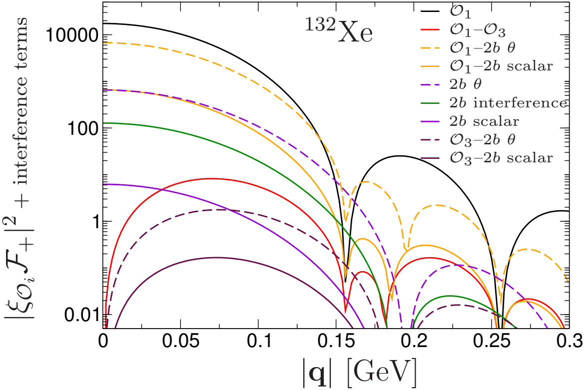
Hoferichter, Klos, JM, Schwenk
PRD94 063505 (2016)

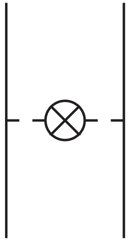
$\mathcal{O}_3 \to \Phi''$ response $\sim$ nucleon spin orbit operator, interference with $\mathcal{O}_1$

$\mathcal{O}_{11,8,5}$ suppressed by $1/m_\chi$ or $v \sim 10^{-3}$, no $\mathcal{O}_1$ interference

2b contributions to coherent scattering

Two coherent contributions from 2b currents:
π coupling via scalar current, energy-momentum trace anomaly (θ^{μ}_{μ})





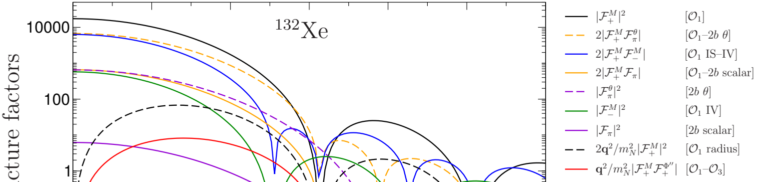
Hoferichter, Klos, JM, Schwenk
PRD94 063505 (2016)

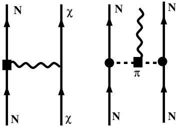
2b structure factors more important than leading 1b corrections ($\mathcal{O}_3$)

Minimal extension of spn-independent analyses

The hierarchy in structure factors suggests a minimal extension:

$$\frac{d\sigma^{\mathrm{SI}}_{\chi\mathcal{N}}}{d\mathbf{q}^2} = \frac{1}{4\pi\mathbf{v}^2}\left| c_+^M \mathcal{F}_+^M(\mathbf{q}^2) + c_-^M \mathcal{F}_-^M(\mathbf{q}^2) + c_\pi \mathcal{F}_\pi(\mathbf{q}^2) + c_\pi^\theta \mathcal{F}_\pi^\theta(\mathbf{q}^2) \right|^2$$





Hoferichter, Klos, JM, Schwenk PRD94 063505 (2016)

Constrain each c_i, 4 combinations of new-physics parameters

All structure factors for xenon available, other nuclei (argon...) very soon

Summary

Nuclear matrix elements and structure factors key for
fully exploiting $\beta\beta$ decay and direct dark matter detection experiments

Neutrinoless $\beta\beta$ decay:

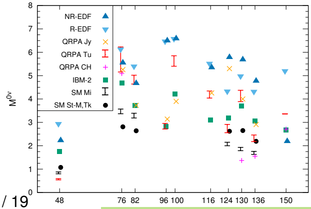
Improved matrix elements
in larger configuration spaces
with all relevant correlations
and 2b current contributions

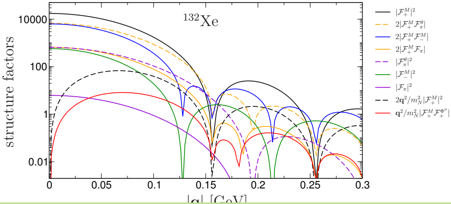
Outlook: *ab initio* calculations
with controlled uncertainties

Direct dark matter detection:

Coupling to protons and neutrons
can be same (usual) or different
2b currents (scalar, θ coupling)
1b corrections ($\mathcal{O}_3$) subleading

Each contribution constrains
new-physics models differently





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