Weak and rare low energy nuclear processes

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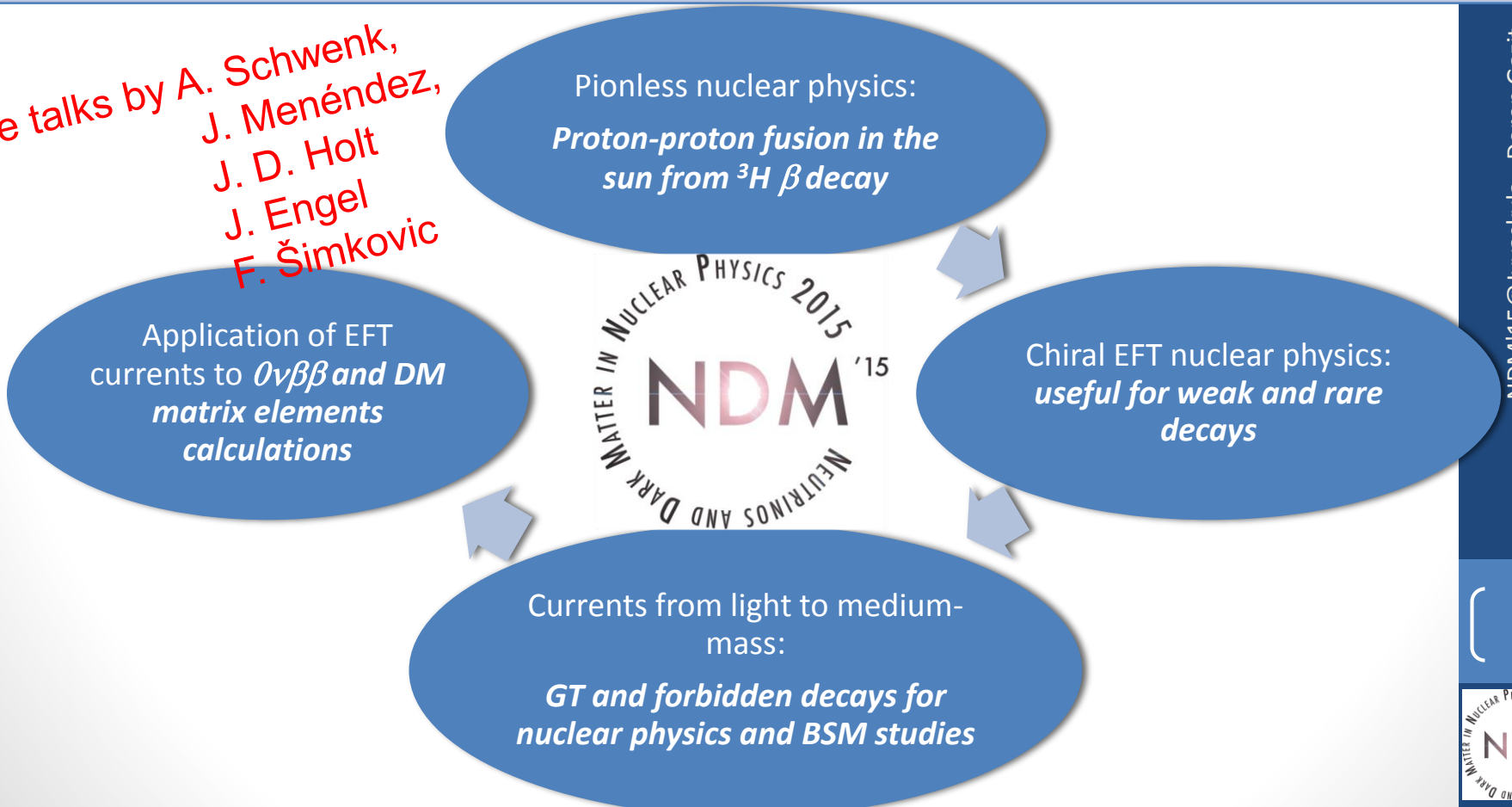
Take home message and outline

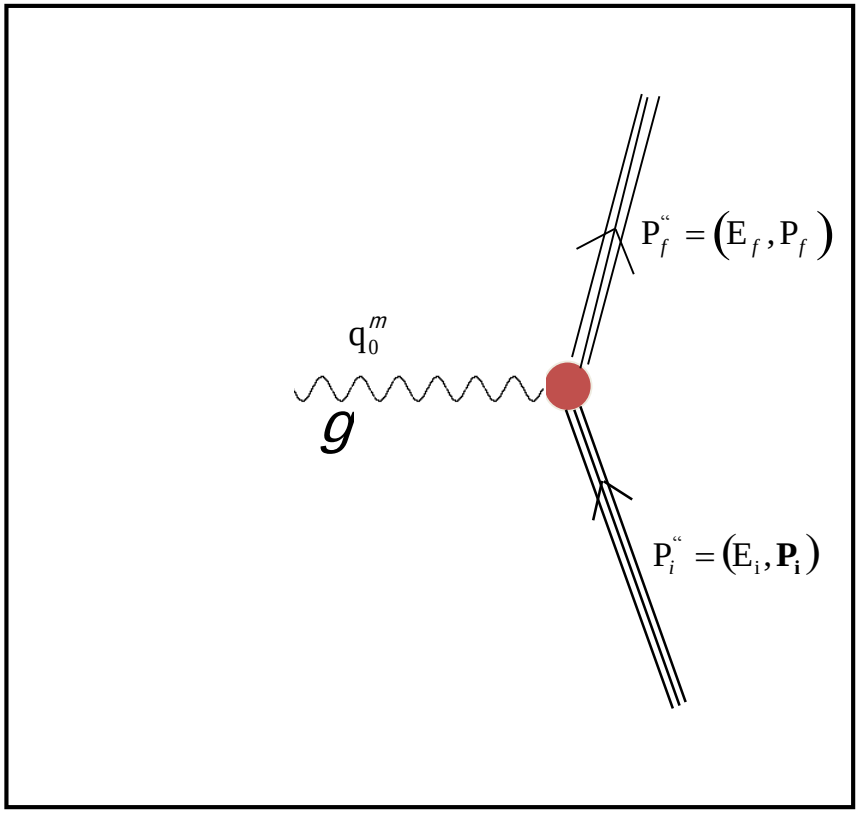
Nuclear theory is ***building a unified fundamental understanding of reactions and structure*** *from* ***Effective Field Theories*** *of low energy QCD,*
intended to help ***solving and identifying fundamental physics problems*** *by reducing the uncertainty coming from nuclear physics in the calculations of weak and rare reactions*

See talks by A. Schwenk, J. Menéndez, J. D. Holt, J. Engel, F. Šimkovic



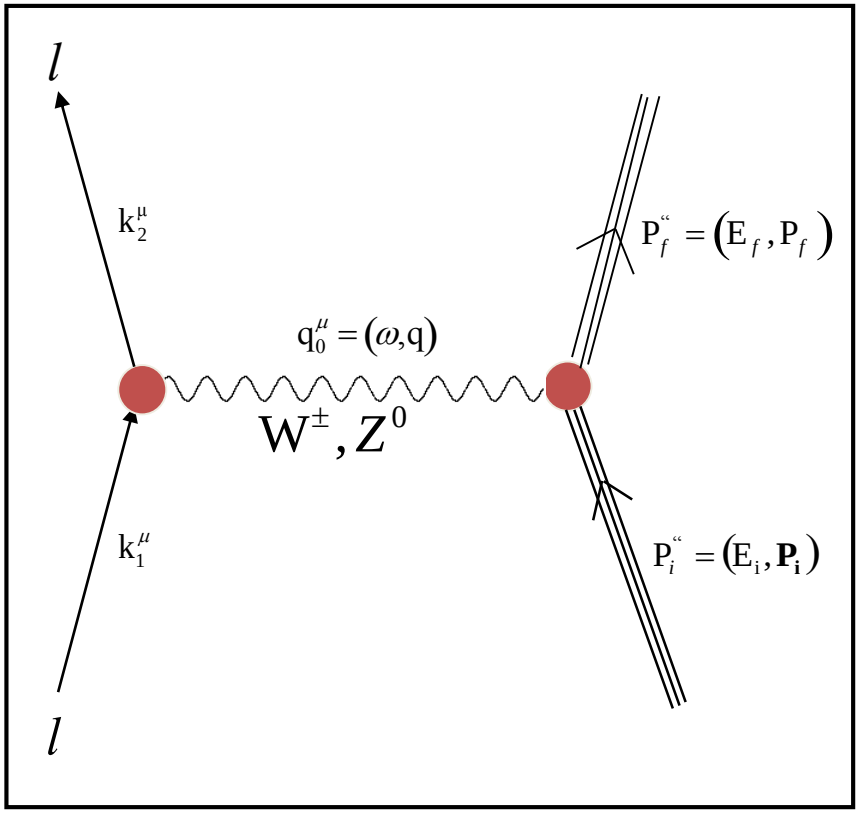
Nucleus interaction with a probe:

- ***Low energy electromagnetic reaction***



Nucleus interaction with a probe:

- ***Low energy weak reaction***



Nucleus interaction with a probe:

- ***Neutrino-less double beta-decay***

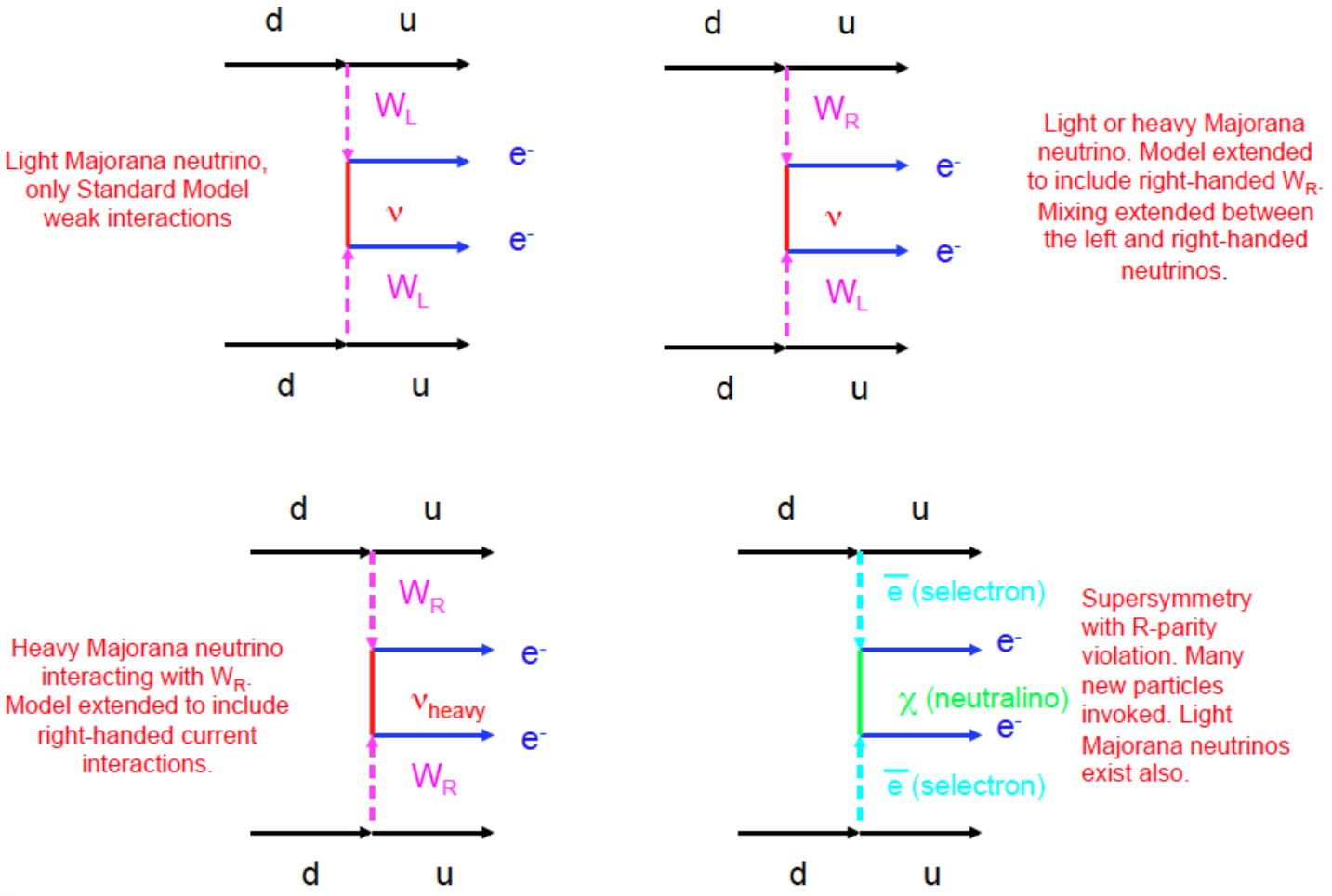
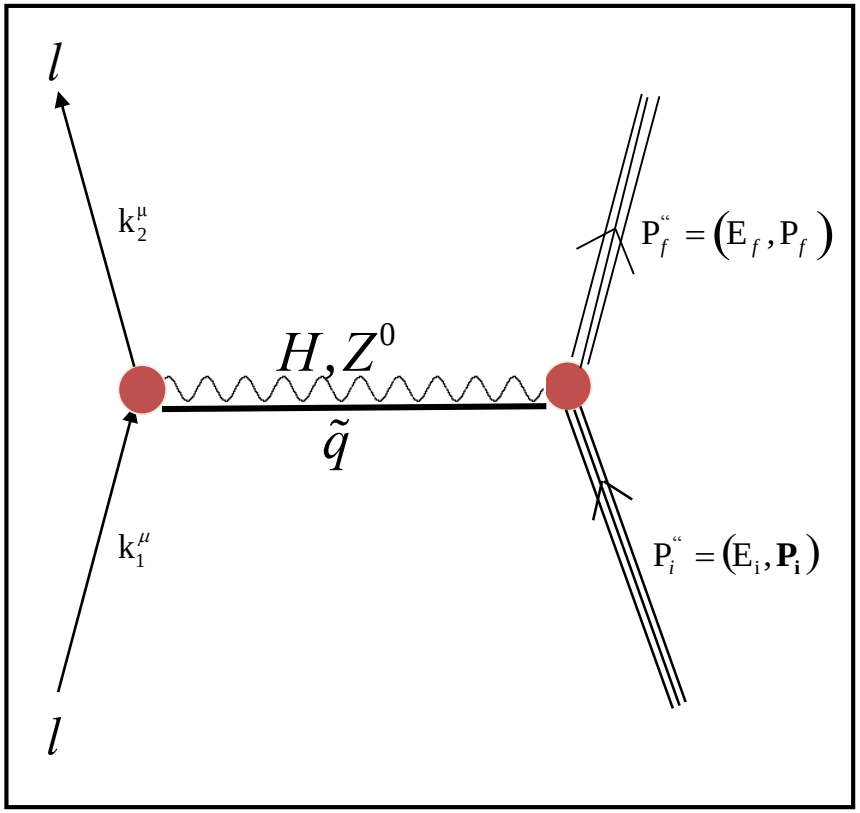


Figure taken from P. Vogel

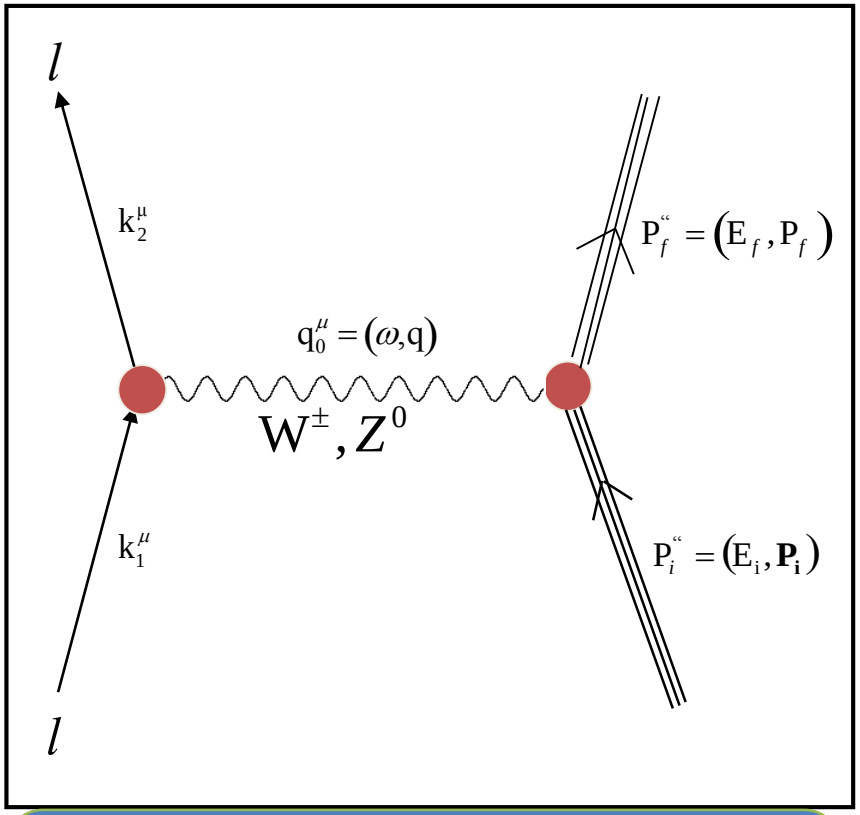
Nucleus interaction with a probe:

- ***Neutralino (WIMP candidate) scattering off a nucleus***



"All happy families are alike, every unhappy family is unhappy in its own way"

- ***Low energy reactions***



$$propagator = \frac{g_{mn} + \frac{q_m q_n}{M^2}}{q^2 + M^2}$$

"All happy families are alike, every unhappy family is unhappy in its own way"

- ***Low energy reactions***

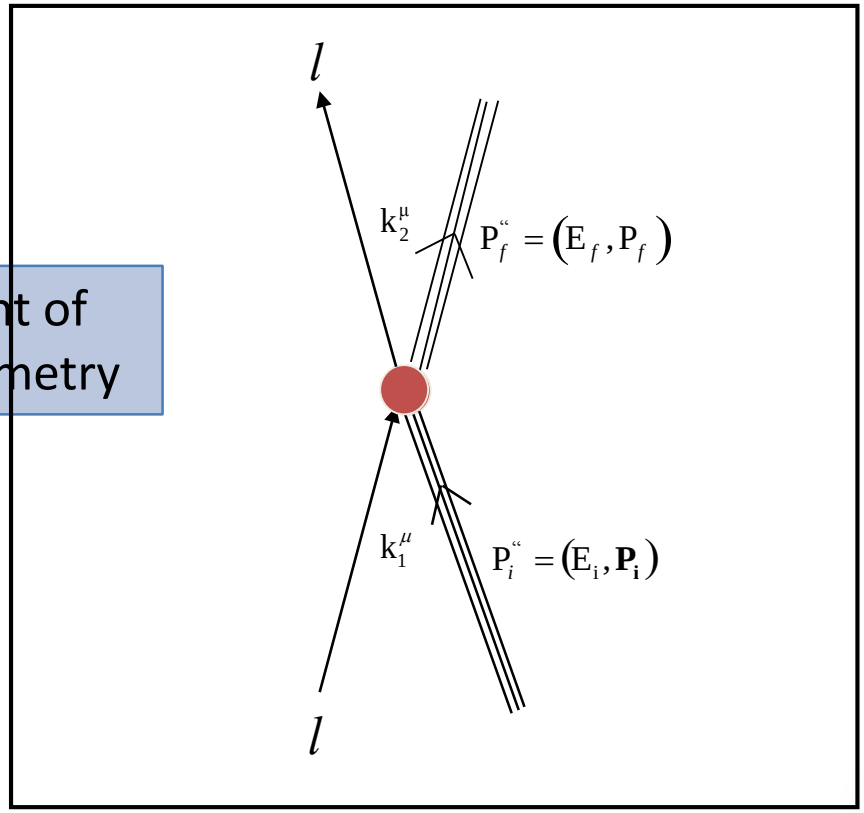
$$\hat{H}_W \sim \int d^3\vec{x}\, \hat{j}^{+}_{m}(\vec{x})\, \hat{J}^{m-}(\vec{x})$$

Probe current of known symmetry

Nuclear current of the same symmetry

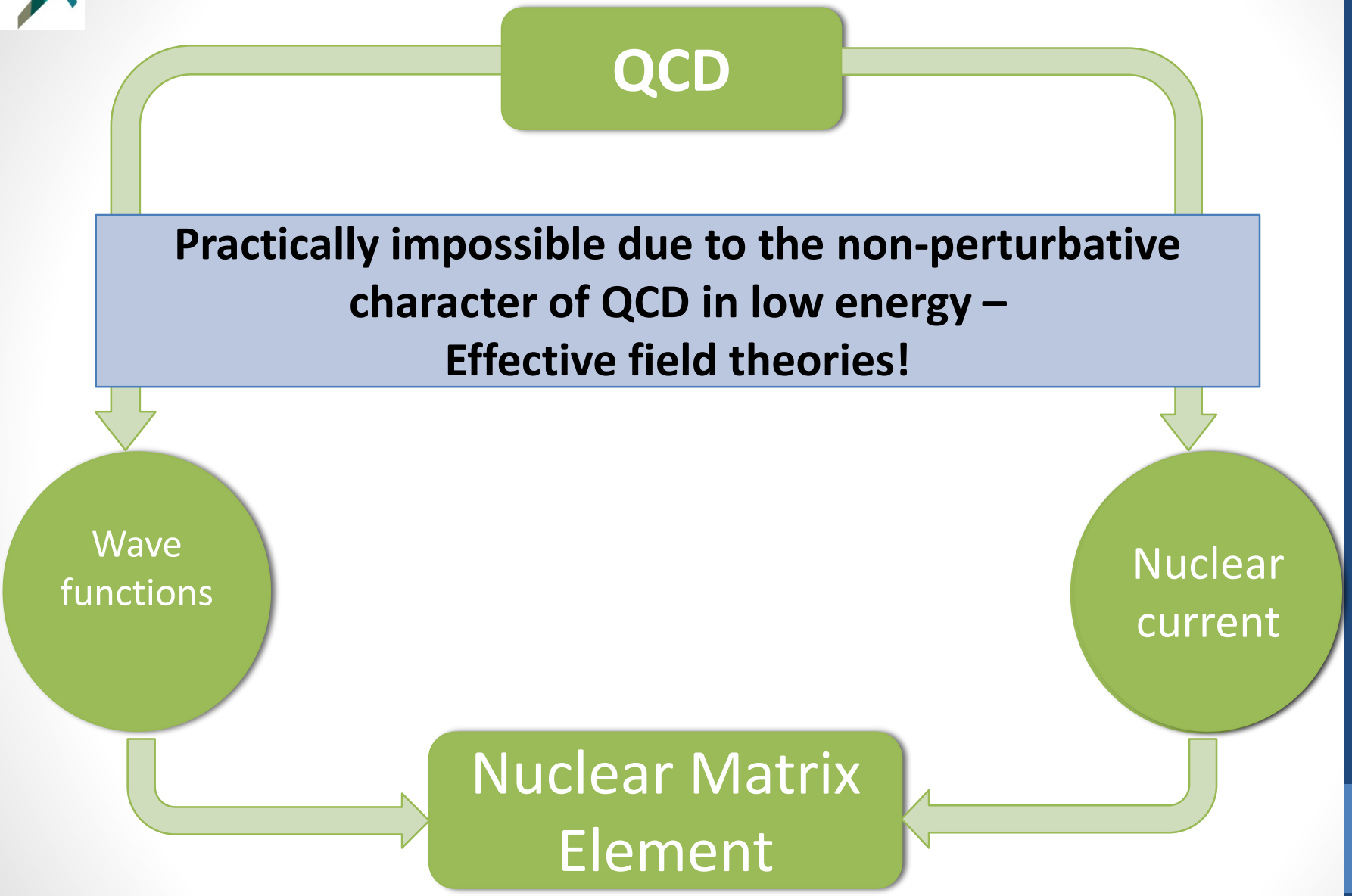
$$\mathcal{O} \sim \left\langle \psi_i \left| \hat{J}^{\mu} \right| \psi_f \right\rangle$$

Scattering operator



Currents in the nucleus – "decoupled" from fund. theory

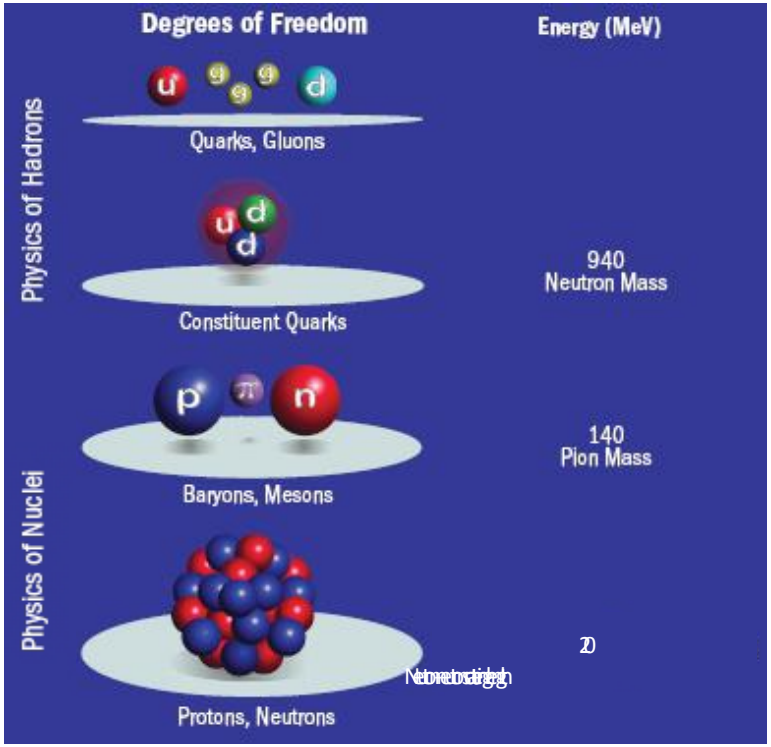
Nucleus interaction with a probe:



Low energy scales in nuclear physics

Chiral Effective Field Theory

Pionless Effective Field Theory



Nucleus interaction with a probe, EFT point of view:

Low energy QCD has (accidental) scale separation

Low energy EFT –
Cutoff $\Lambda >> Q$ dictates viable deg. of freedom

EFT Lagrangian

Nuclear potential

Nöther current

Theoretical uncertainty quantification:

- ***Power Counting***: systematic expansion
- ***RG invariance***: cutoff variation

Wave functions

Nuclear current

Nuclear Matrix Element of characteristic momentum Q

Leutwyler, Gasser, Weinberg, Kaplan, Savage, Wise, van-Kolck, Birse, Meissner, Epelbaum, Machleidt, Chen, Park, Rho,…

Pionless EFT

Kaplan, Savage, van Kolck, Rupak, Chen,…

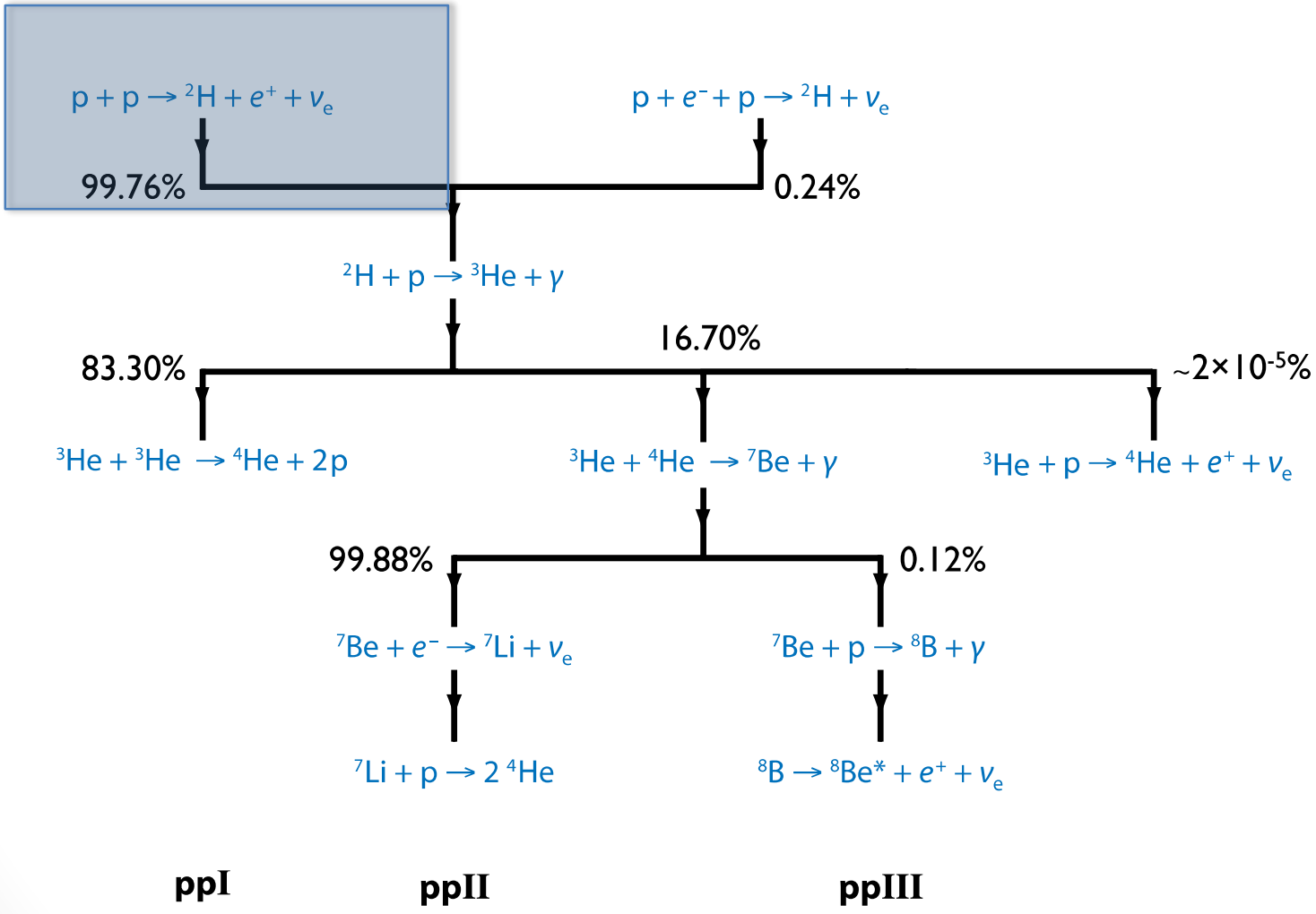
- QCD is non-perturbative at low energies.
- Few body nuclear physics is close to the "unitarity", a→∞, fixed point:
  - Analogous to current experiment in cold atoms.
  - Nucleons interact via contacts: ***Fully renormalizable!***
  - Large (nn) (np) scattering lengths compared to effective ranges – unitary fixed point.
  - For "few-body" nuclei, typical momentum is safely smaller than pion production threshold, e.g., for A=3,

$$q_{\rm typ} \approx \sqrt{\tfrac{2}{3} m_N B(^3{\rm He})} \approx 70 \text{ MeV}$$

- ***Ideal for the calculation of light nuclei and their reactions – where there exists a scale separation between typical reaction momentum and the lightest meson (pion) excitation.***

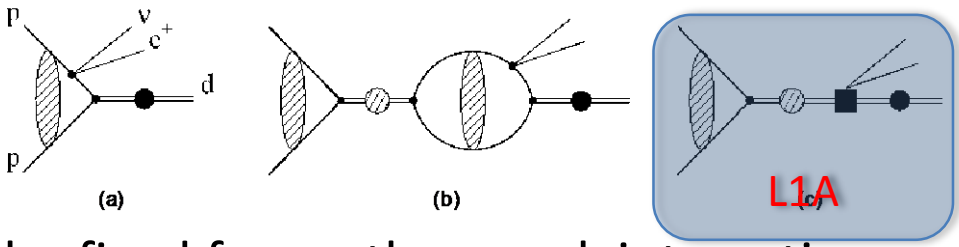
Ideal for stellar "p-p chain" reactions calculations, especially p-p fusion!
Kong, Ravndall, Chen, Butler, Ando et al.

Proton-proton fusion in pionless EFT

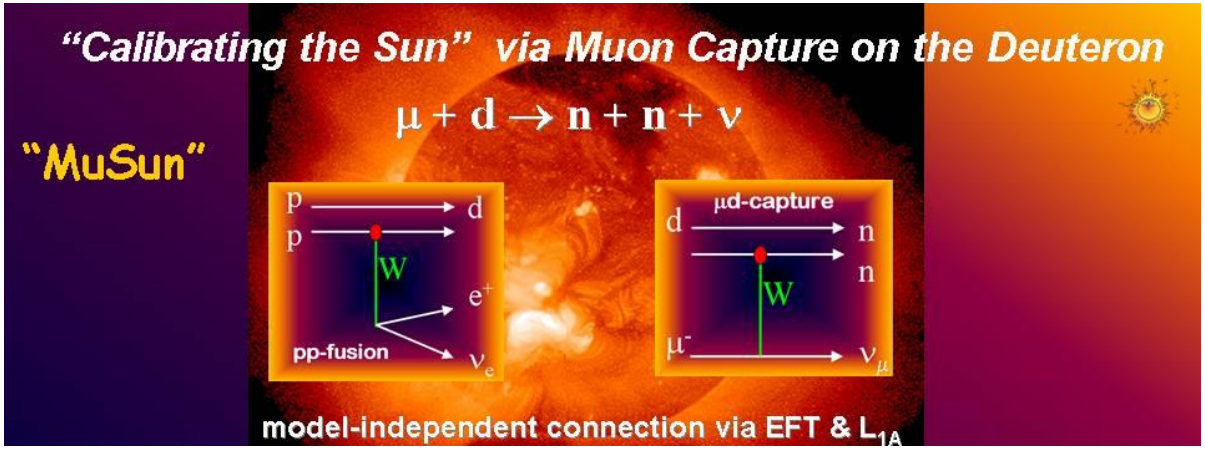


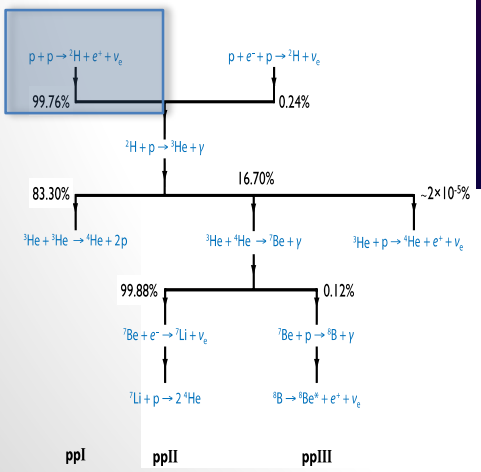
Proton-proton fusion in pionless EFT

- Very low proton-proton relative momentum (keV).
- Needed accuracy: <1%.
- To NLO:



- L1A should be fixed from other weak interaction.

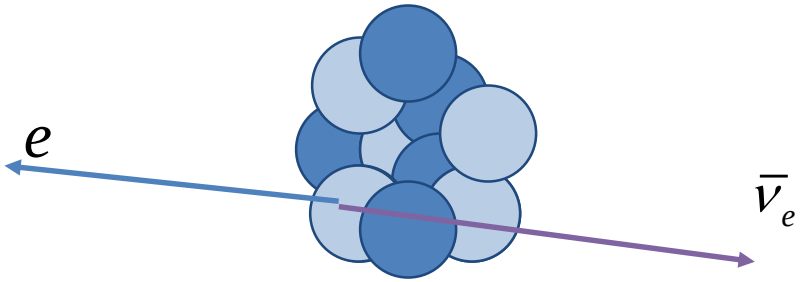




"MuSun" – 1.5% @ mucap ➔ 2% @ pp fusion!

Our plan: Fix L1A from ^{3}H decay

ALLOWED (GAMOW TELLER) BETA DECAYS



$$M_A^2 \propto \left\langle \psi_i \left| GT \right| \psi_f \right\rangle^2$$

$$GT\Big|_{LO} = \sum_{i=1}^{A} \sigma_i \tau_i^{\pm}$$

$$M_V^2 \propto \left\langle \psi_i \left| F \right| \psi_f \right\rangle^2$$

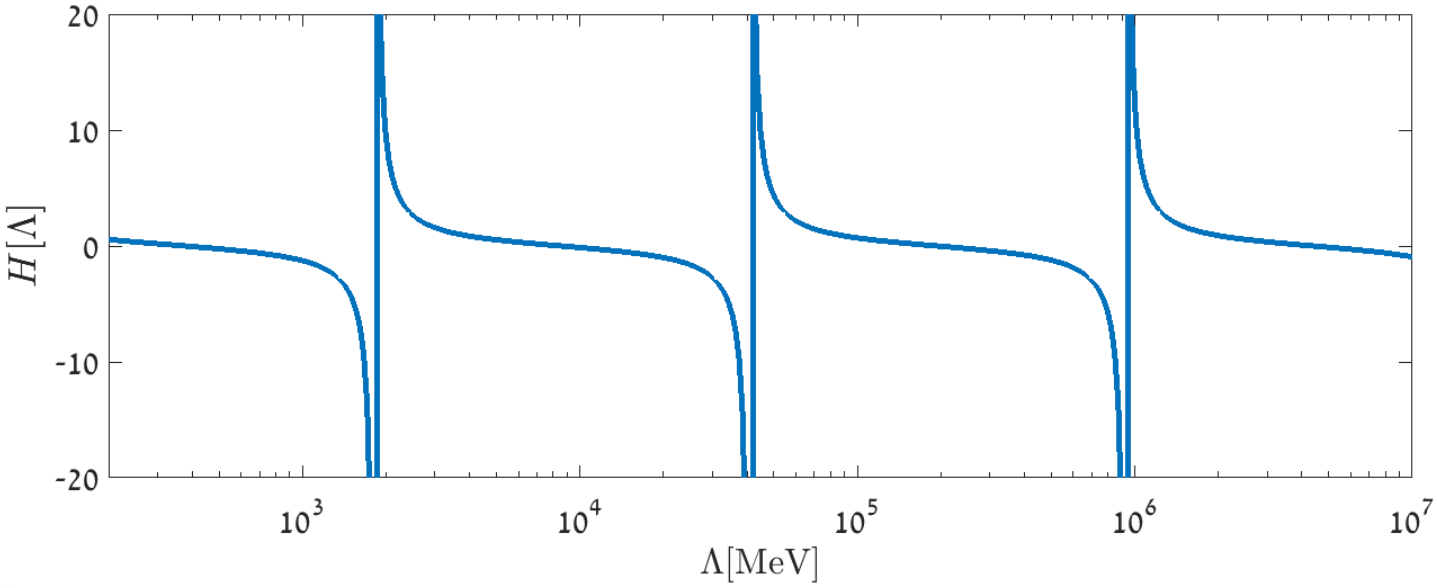
$$F\Big|_{LO} = \sum_{i=1}^{A} \tau_i^{\pm}$$

$$ft = \frac{K}{G_F^2 V_{ud}^2 \left(\left| M_V \right|^2 + g_A^2 \left| M_A \right|^2 \right)}$$

Our plan: Fix L1A from ^{3}H decay

Calibrating L1A from ^{3}H decay

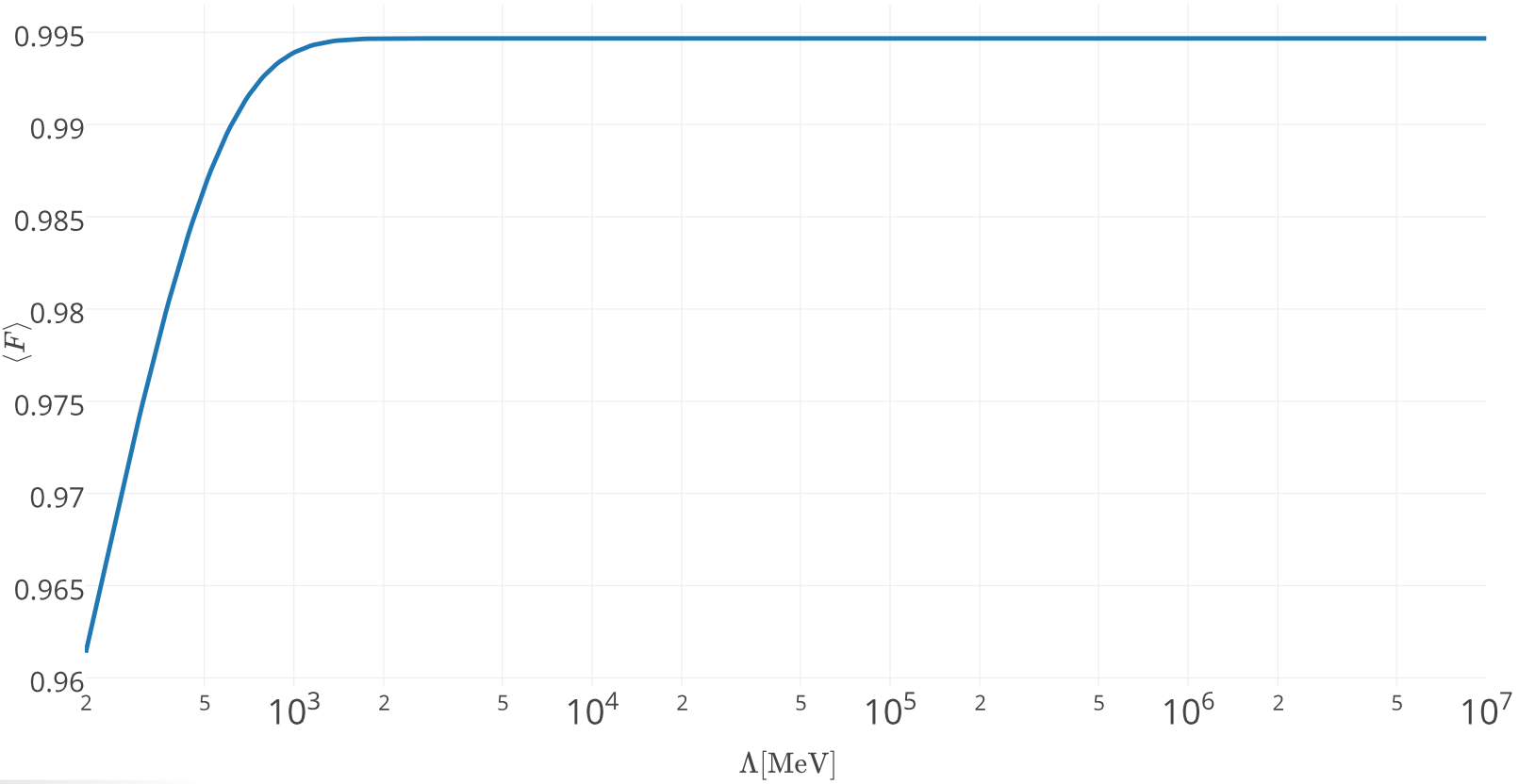
- ^{3}H decay into ^{3}He is very well measured!
- A=3 Efimov effect: *triton at LO has strong cutoff dependence* ➔*add 3-body contact at LO.*
- 3He introduces new complications… [Konig, Hammer, Vanasse,…]



Hammer, Bedaque, van Kolck (1999)

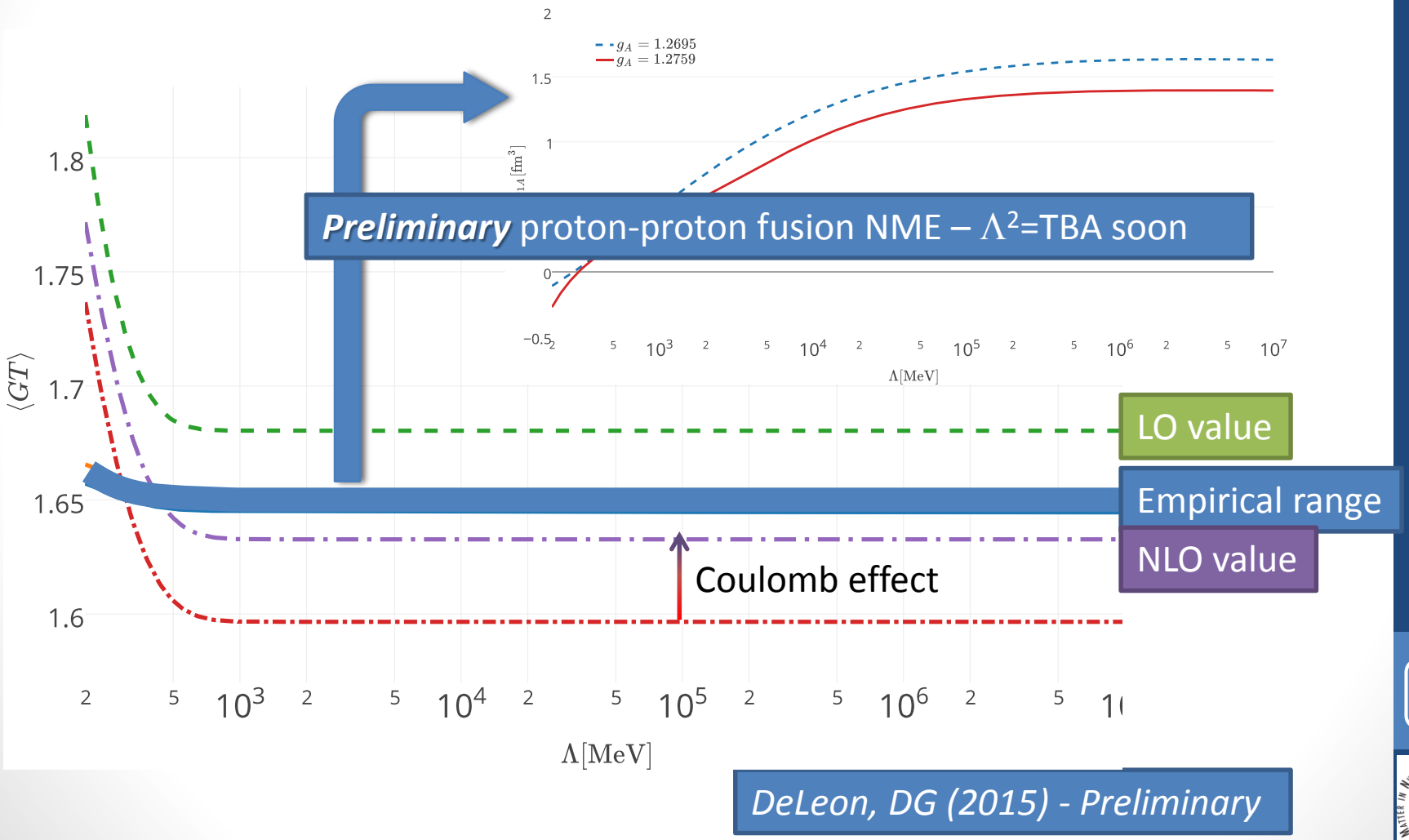
Pionless EFT – ^{3}H decay to next-to leading order

DeLeon, DG (2015) - Preliminary



Pionless EFT – ^{3}H decay to next-to leading order

L1A fixed up to ≈±0.5 – stringent calibration!



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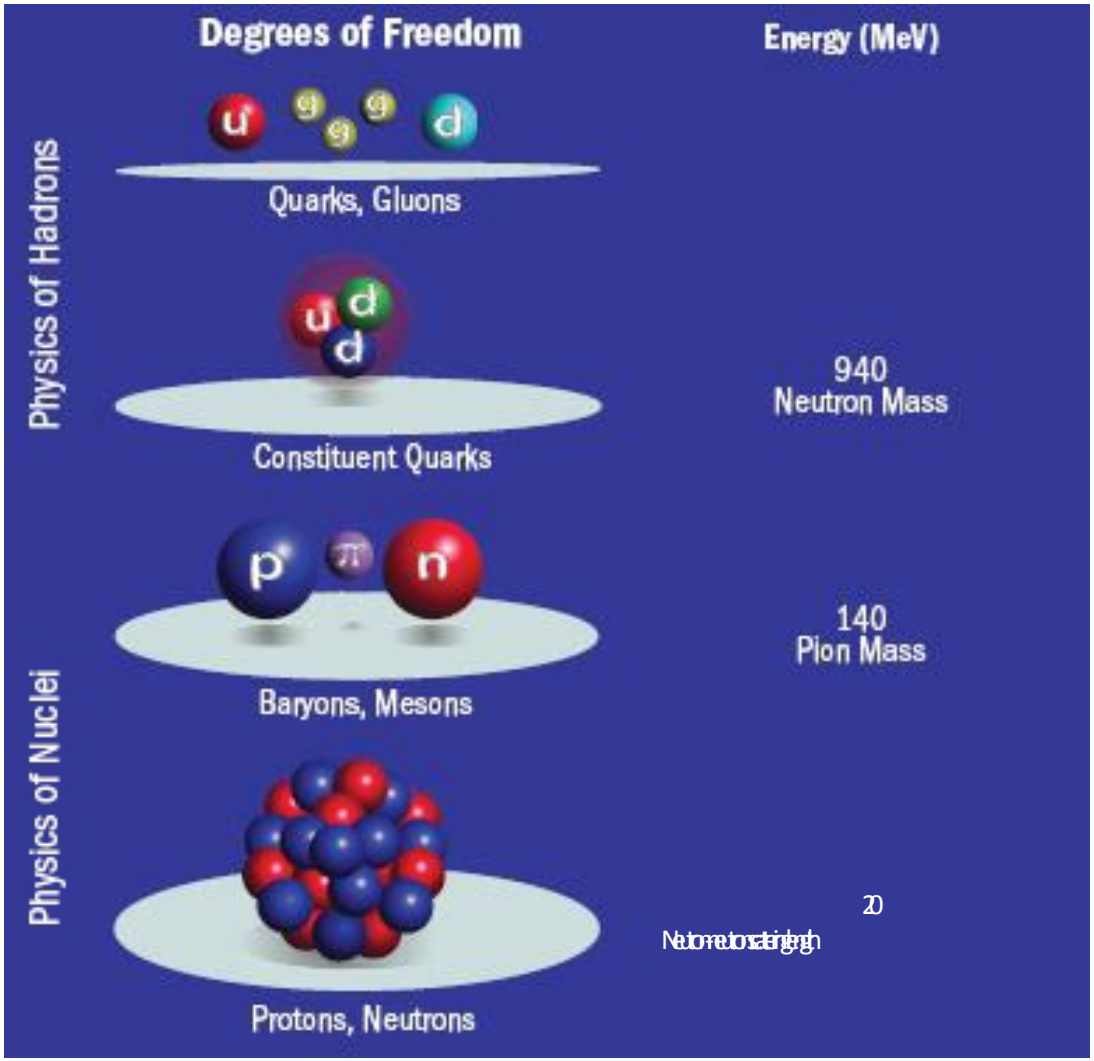
Scales in nuclear physics



Chiral Effective Field Theory

- In QCD – an approximate chiral symmetry:
  - The *u* and *d* quarks are (almost) massless (~5-10 MeV).

$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$$

  - The $SU(2)_V$ symmetry is the isospin symmetry.
  - The **pions** are the **Nambu-Goldstone bosons** of the spontaneous chiral symmetry breaking.
  - The order-parameter is the pion-decay constant:

$$\Lambda_{QCD} = 4\pi f_\pi$$

Chiral Effective Field Theory

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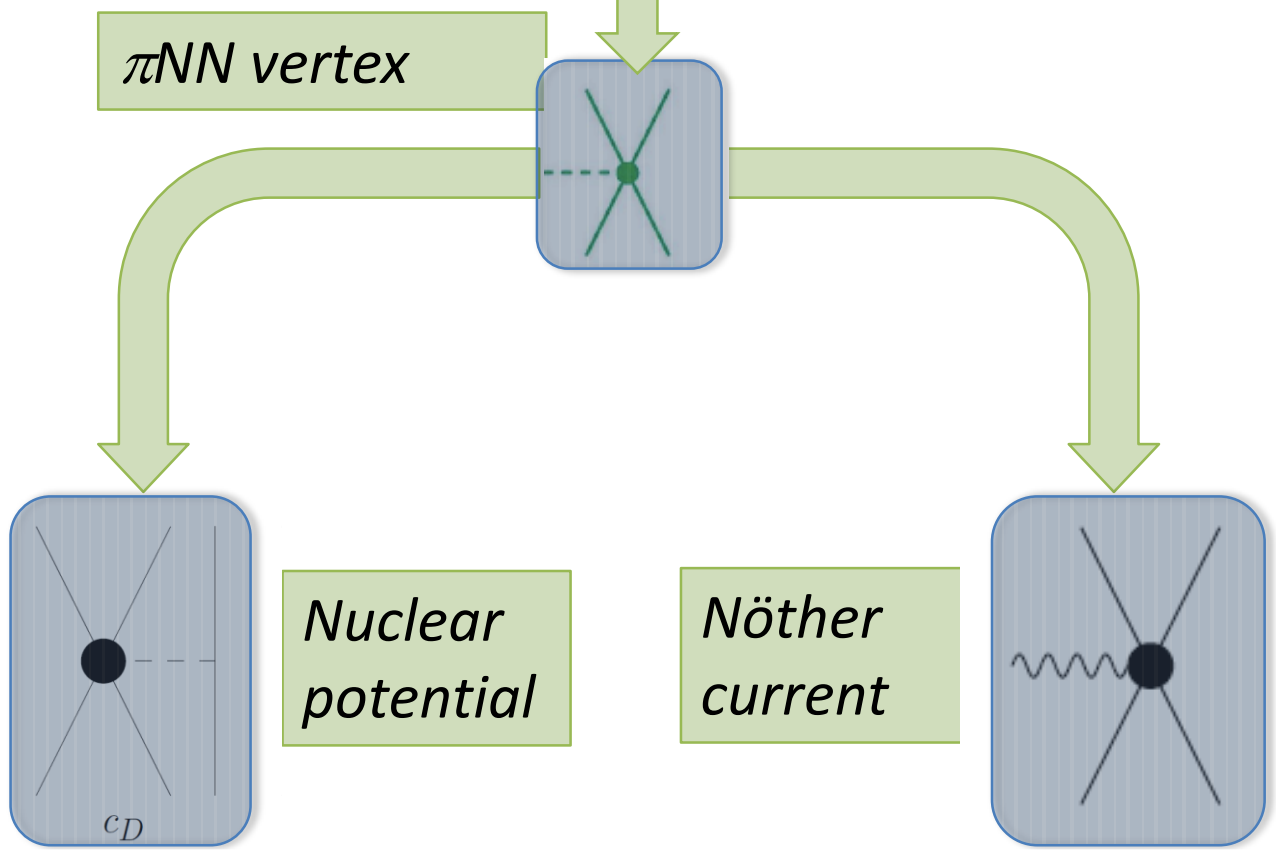
$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \rightarrow \mathrm{SU}(2)_V$$

  - Chiral EFT Lagrangian is built of all terms with chiral symmetry, with ***nucleons*** and ***pions*** as explicit dof.
- ***Why is it useful***:
  - Chiral symmetry is equivalent to the electro-weak gauging!
  - Thus, Nöther currents of the chiral symmetry will couple to the electro-weak probe!

Ideal for reactions calculations with momentum transfer (smaller than) 100 Mev/c: GT transitions, 0νββ, DM…

Unites phenomena: 3 body forces and reactions

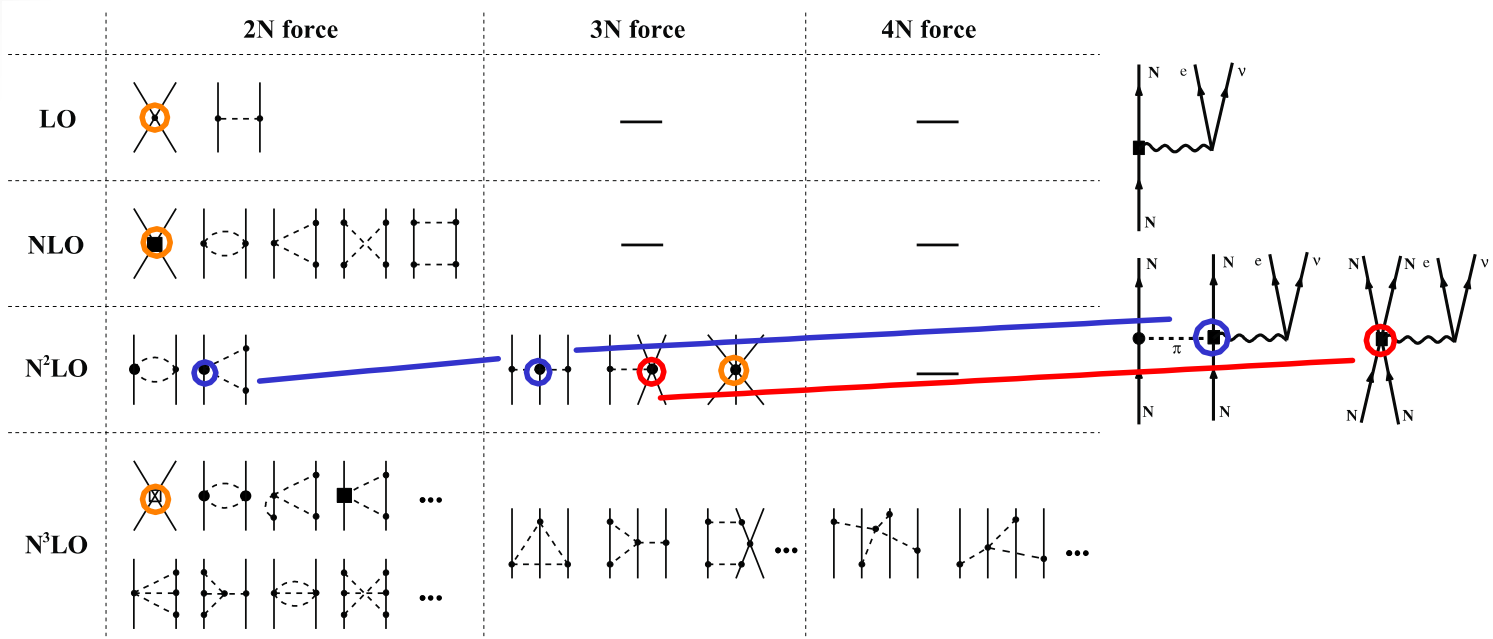
$\mathcal{L}_4 \sim \bar{N}\gamma_\mu\gamma_5 a_\mu N\bar{N}N$



Same LEC appears in the potential and in the axial current!

van Kolck (1995); van Kolck, Ordonez (1995); Gårdestig, Phillips (2006); DG, Quaglioni, Navratil (2009)

Systematic construction of Forces and currents in χEFT



Strategy:

(1) use plethora of nucleon-nucleon and π-nucleon scattering to fix 2N force and long-range axial currents.

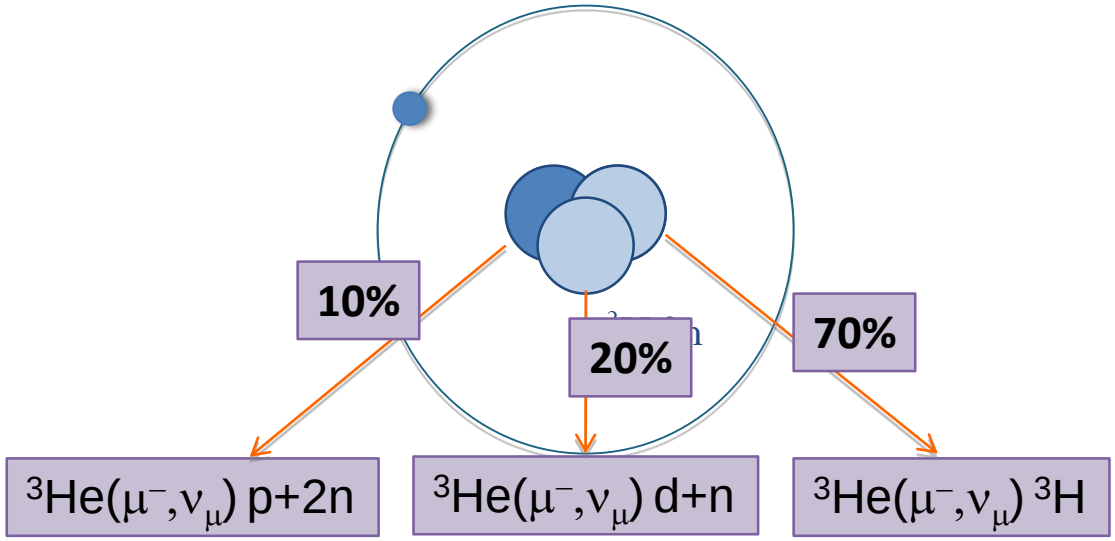
(2) use triron (^{3}H) β-decay and binding energy to fix consistently 3N Force and short range axial currents. [DG, Quaglioni, Navratil (2009)]

Resulting fixing is very accurate (within a specific regularization)

DG, Quaglioni, Navratil, Phys. Rev. Lett. 103, 102502 (2009)

Ab Initio parameter free calculations of weak reactions – LECs from ^{3}H b.e and decay

- ✓ pp fusion – [Marcucci et al (2012)] ~1% MEC contribution.
- ✓ μ Cap. on ^{3}He – [high momentum transfer] - ~10% MEC contribution
  - ✓ Exp. [Eckerbauer et al (1998)] – Γ_{exp}=1496±4 Hz
  - ✓ Thy. [DG (2008)] Γ_{thy}=1499±16 Hz; [Marcucci (2011) Γ_{thy}=1494±21 Hz



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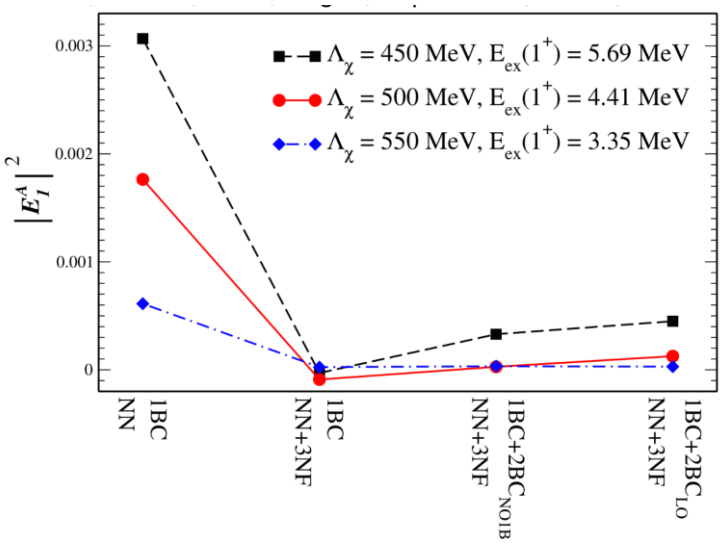
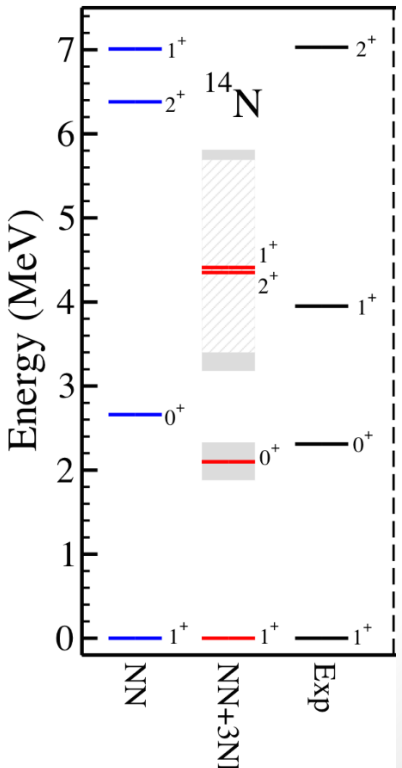
  - ✓ Hybrid calculation - 1.5% off experiment.
- ✓ Anomalously long half-life of ^{14}C
  - ✓ Major role for χEFT 3N Forces – [Holt et al, Maris et al]
  - ✓ [Ekstrom, DG, et al (2014)] – unusual MEC contribution





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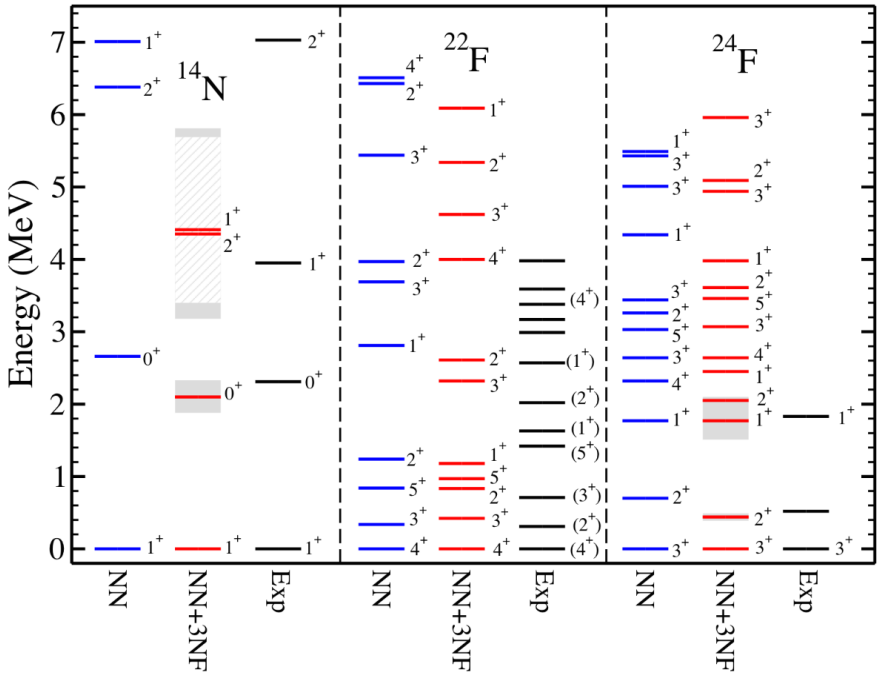

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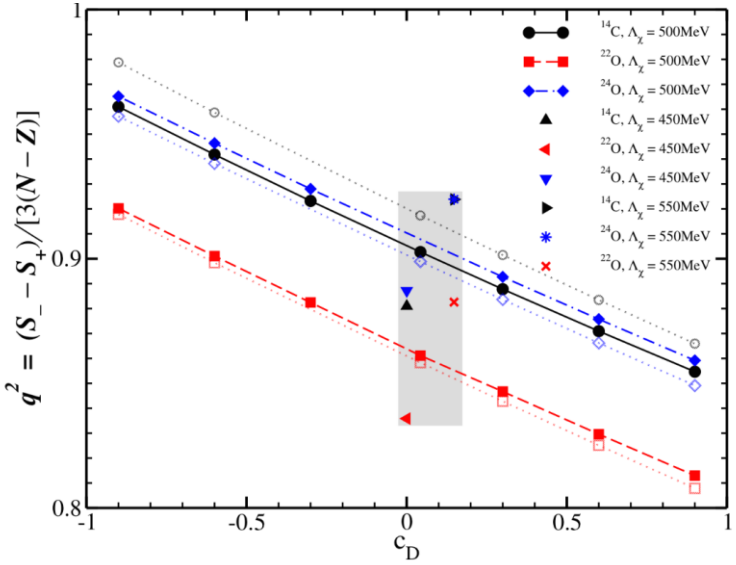
  - ✓ Sum rules quenched by 0.82-0.92 (-5% to -10% "g_A" quenching) in a consistent normal ordering.



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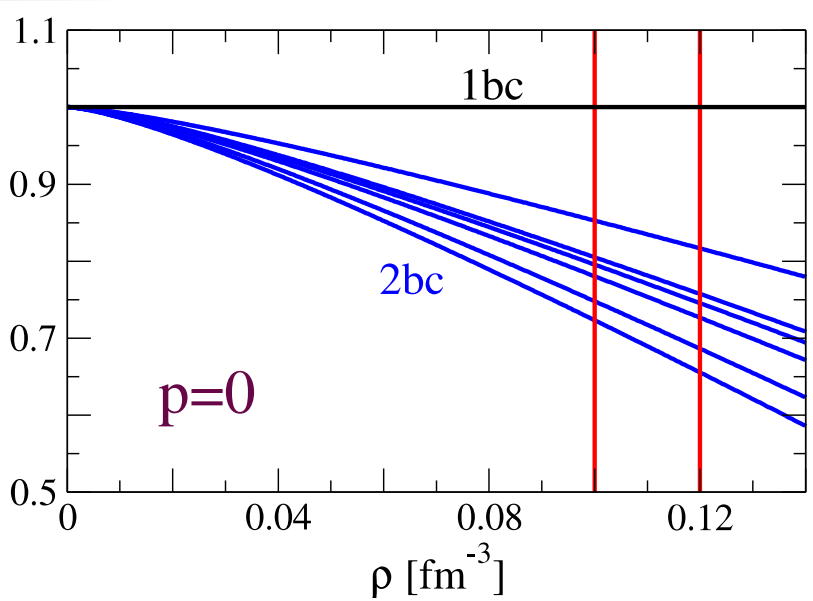
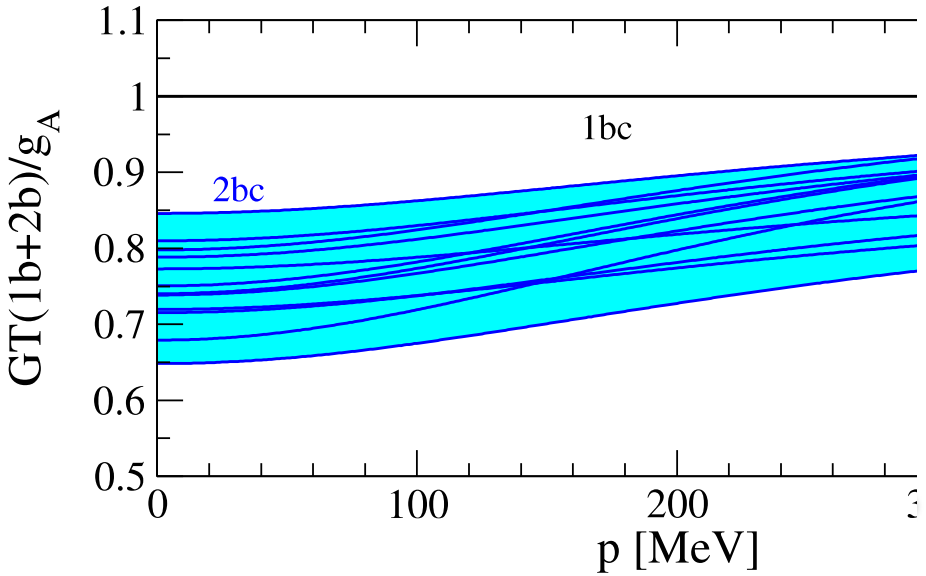
- ? 2B MEC currents induce GT quenching.
  - ? Quenching grows with mass number
  - ? Quenching depends on momentum transfer.
  - ? If MEC induce quenching – expect different quenching to different reactions – origin of "small quenching found in ^{90}Zr?

2B current contributions ~ few % in light nuclei ($Q \sim \sqrt{BEm}$)
2B currents order Q^3 ⇒ larger effect in medium-mass nuclei ($Q \sim k_F$)

Why do 2-body currents lead to GT quenching?





2b currents predict g_A quenching $q = 0.85...0.66$

Quenching reduced at $p > 0$, relevant for $0\nu\beta\beta$ decay where $p \sim m_\pi$

Menendez, DG, Schwenk, Phys. Rev. Lett. **107**, 062501 (2011)

Different reactions → different quenching

M1 transitions

$$\vec{\mathcal{V}}_{1b} = \frac{1}{2m_p}\left[Q\vec{P} + i\mu\vec{\sigma}\times\vec{p}\right] \Rightarrow \hat{\mu}_{1B}(k) = \sum_i \frac{1}{2m_p}\left[\vec{\sigma}_i\mu_i + Q_i\hat{l}_i\right]$$

O(Q)

$$\vec{\mathcal{V}}_{1\pi} = i(\vec{\tau}_1\times\vec{\tau}_2)^3\frac{g_A^2}{4f_\pi^2}\left[\vec{\sigma}_2\frac{\vec{\sigma}_1\cdot\vec{q}_1}{m_\pi^2+\vec{q}_1^2} - \vec{\sigma}_1\frac{\vec{\sigma}_2\cdot\vec{q}_2}{m_\pi^2+\vec{q}_2^2} - 2\vec{q}\frac{\vec{\sigma}_1\cdot\vec{q}_1}{m_\pi^2+\vec{q}_1^2}\frac{\vec{\sigma}_2\cdot\vec{q}_2}{m_\pi^2+\vec{q}_2^2}\right]$$

Gamow-Teller

$$\mathbf{J}^3_{i,1b} = \frac{1}{2}\tau_i^3\left(\frac{g_A(p^2)}{g_A}\boldsymbol{\sigma}_i - \frac{g_P(p^2)}{2mg_A}(\mathbf{p}\cdot\boldsymbol{\sigma}_i)\mathbf{p}\right)$$

O(Q³)

$$\mathbf{J}^3_{12} = -\frac{g_A}{2F_\pi^2}(\tau_1\times\tau_2)^3\left(\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{m_\pi^2+k_2^2}\left[\left(c_4+\frac{1}{4m}\right)(\boldsymbol{\sigma}_1\times\mathbf{k}_2)\right.\right.$$
$$\left.+ i\frac{\mathbf{p}_1+\mathbf{p}_1'}{4} - \left(\frac{1+\hat{c}_6}{12m}\right)(\boldsymbol{\sigma}_1\times\mathbf{q}) - (1\leftrightarrow 2)\right]\Bigg)$$
$$-\frac{g_A}{F_\pi^2}c_3\left[\tau_1^3\frac{(\boldsymbol{\sigma}_1\cdot\mathbf{k}_1)\mathbf{k}_1}{m_\pi^2+k_1^2} + \tau_2^3\frac{(\boldsymbol{\sigma}_2\cdot\mathbf{k}_2)\mathbf{k}_2}{m_\pi^2+k_2^2}\right], \qquad (8)$$

^{A}X(n,p)^{A}X' with a spin flip

Symmetry allows an operator structure

However, completely different origin!

Systematic study of operator needed

$$\vec{J}_{i,1b} = \vec{\sigma}_i\tau_i^+$$

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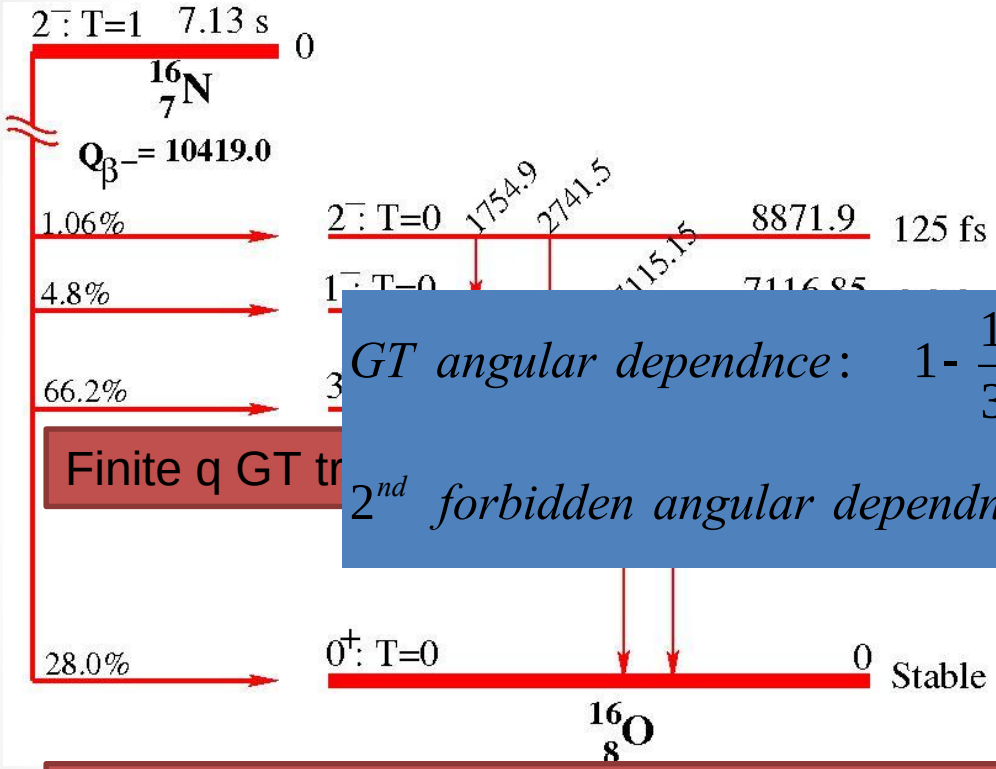
  - ? Quenching grows with mass number
  - ? Quenching depends on momentum transfer.
  - ? If MEC induce quenching – expect different quenching to different reactions!
  - ? If MEC induce significant part of the quenching – different multipoles should have different quenching.

^{16}N β decay to ^{16}O as a test-case



measurements of ^{16}N in 2017

Finite q GT tr

$$GT\ angular\ dependnce: \quad 1 - \frac{1}{3} b \cos q$$

$$2^{nd}\ forbidden\ angular\ dependnce: \quad 1 - \frac{1}{5} b \cos q + \frac{1}{10} \frac{x \sin^2 q}{1 + x \cos q}$$

Second forbidden:

1. Pure E2A transition – suppressed MEC contribution – ***pinpointing suppression origin***
2. Different β–ν correlation properties – ***BSM test***

Hass, Vaintraub, Mishnayot, DG, in prep.

APPLICATIONS:

-NEUTRINOLESS DOUBLE BETA DECAYS NME
-SPIN DEPENDENT WIMP SCATTERING OFF NUCLEI

- Klos, Menéndez, Schwenk, DG.

WIMP-nucleus scattering

- Presents a challenging problem, because even if the coupling of to quarks is known, it needs to be evaluated at the nucleus level in the nonperturbative regime of quantum chromodynamics
- Chiral EFT provides an ideal theoretical framework since the typical momentum transfers in direct dark matter detection are of the order of 100 MeV/c.
- At low energies:

Spin dependent

$$\mathcal{L} = \chi\gamma_\mu\gamma_5\chi\mathcal{J}_5^\mu(x) + \chi\chi\mathcal{S}(x)$$

Spin independent

- Spin dependent:

$$\mathcal{L} = -\frac{G_F}{\sqrt{2}}\overline{\chi}\gamma\gamma_5\chi\cdot\sum_q A_q\overline{\psi}_q\gamma\gamma_5\psi_q$$

- When moving to the nucleon level:

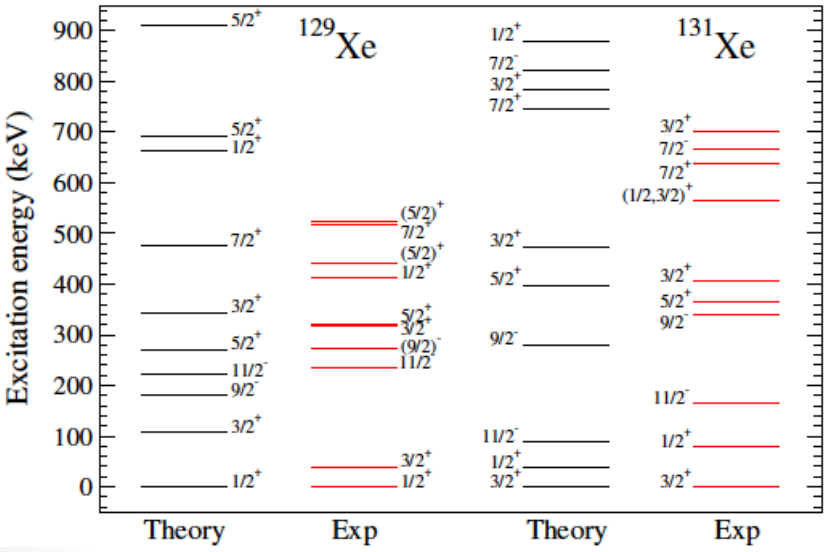
$$\sum_q A_q\overline{\psi}_q\gamma\gamma_5\psi_q \longrightarrow \sum_{i=1}^{A}\mathbf{J}_{i,1\mathrm{b}} = \sum_{i=1}^{A}(\mathbf{J}^0_{i,1\mathrm{b}} + \mathbf{J}^3_{i,1\mathrm{b}})$$

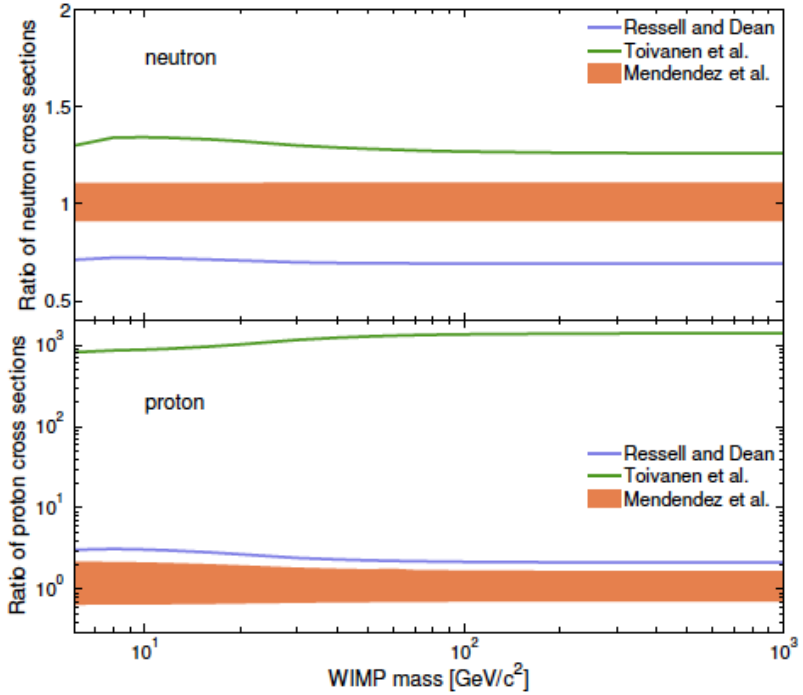
$$= \sum_{i=1}^{A}\frac{1}{2}\left[a_0\,\boldsymbol{\sigma}_i + a_1\tau_i^3\left(\boldsymbol{\sigma}_i - \frac{g_P(p^2)}{2mg_A}(\mathbf{p}\cdot\boldsymbol{\sigma}_i)\mathbf{p}\right)\right],$$

Isoscalar Isovector

- In the nucleus level the isovector part has 2b corrections – **identical to the neutral weak axial current!**

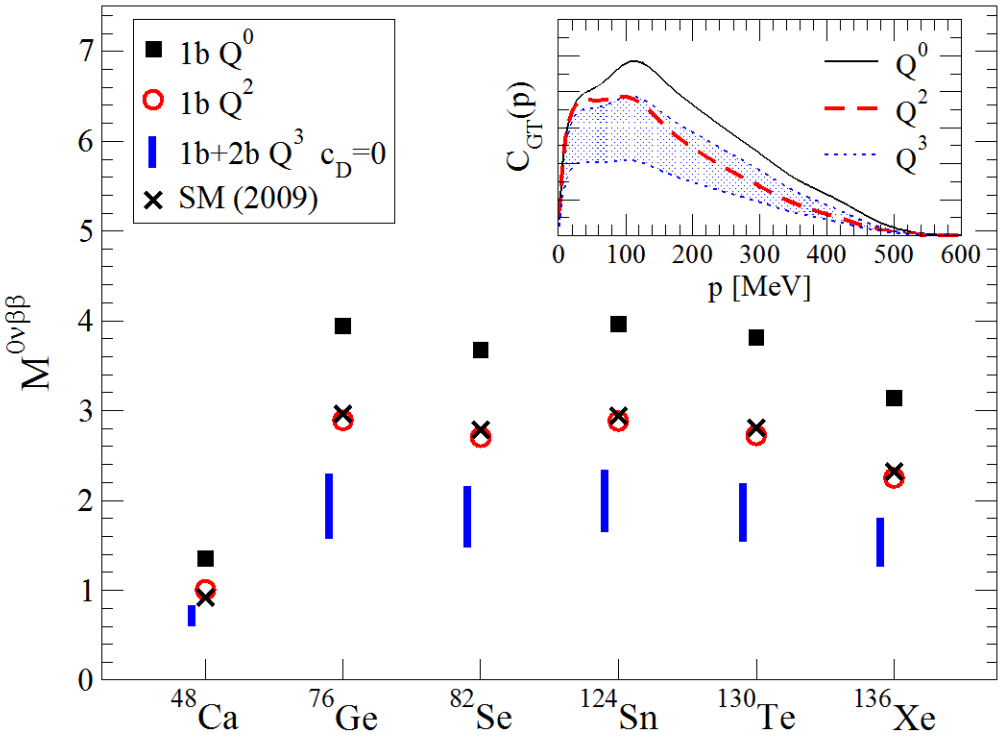
Comparison between nuclear calculations





		Ressell and Dean [14]		Toivanen *et al.* [16]		Menendez *et al.* [17]	
Nucleus	J^P	$\langle S_n \rangle$	$\langle S_p \rangle$	$\langle S_n \rangle$	$\langle S_p \rangle$	$\langle S_n \rangle$	$\langle S_p \rangle$
^{129}Xe	$\left(\frac{1}{2}\right)^+_{g.s.}$	0.359	0.028	0.273	−0.0019	0.329	0.010
^{131}Xe	$\left(\frac{3}{2}\right)^+_{g.s.}$	−0.227	−0.009	−0.125	−0.00069	−0.272	−0.009

$0\nu\beta\beta$ NME predictions



Menéndez, DG, Schwenk, PRL **107**, 062501 (2011)

Similar □ 15% − 25% reduction observed in QRPA with same 2b currents

Engel, Šimkovic, Vogel PRC89 064308 (2014)

Summary

Constrains the Nuclear interaction and structure.

Extract microscopic information about the fundamental theory and its symmetries, and probe the limits of the standard model.

Using EFTs to calculate reactions with nuclei is useful:

Predicts in-medium evolution of nuclear properties.

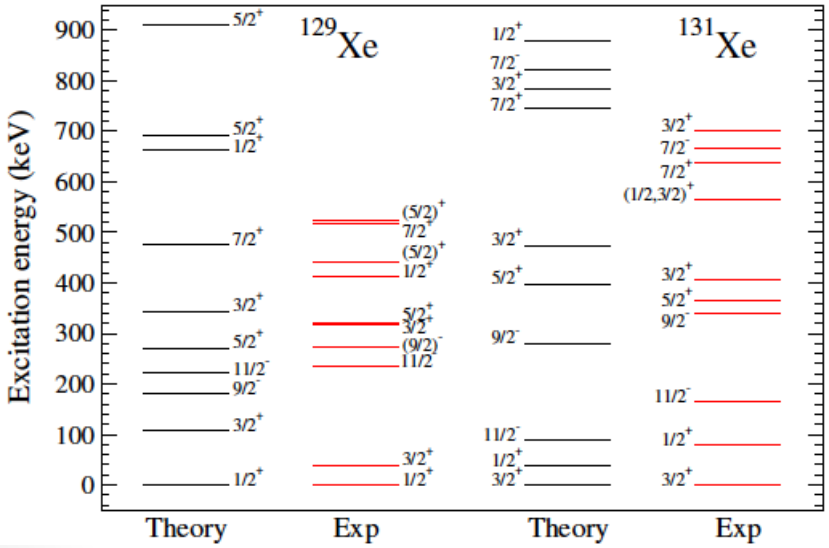
Predict reactions of astrophysical importance.

Nuclear theory is in the process of building a unified fundamental understanding of reactions and structure, which can shed light on many mysteries in physics.

Spin dependent WIMP scattering

For spin-dependent WIMP scattering off nuclei

$$\frac{d\sigma}{dp^2} = \frac{8G_F^2}{(2J+1)v^2} S_A(p), \quad S_A(p) = \sum_L \left(|\langle J||\mathcal{T}^{el5}_L(p)||J\rangle|^2 + |\langle J||\mathcal{L}^5_L(p)||J\rangle|^2 \right)$$



Isotopes ^{129}Xe and ^{131}Xe for liquid Xenon detectors, which provide most stringent experimental limits

Calculations in the $0g_{7/2}$, $1d_{3/2}$, $1d_{5/2}$, $2s_{1/2}$ and $0h_{11/2}$ valence space using the gcn.5082 interaction

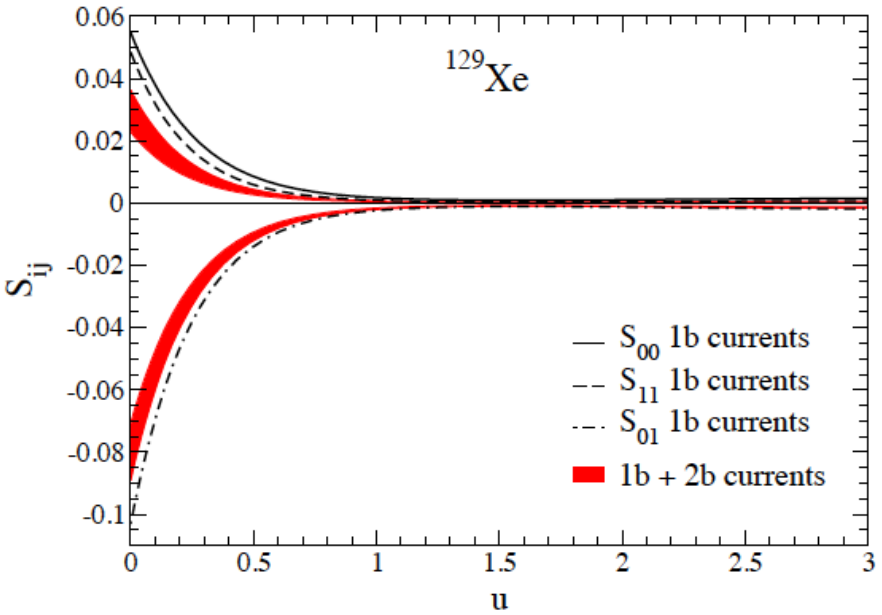
Menendez, DG, Schwenk (2012); Klos, Menendez, DG, Schwenk (2013)

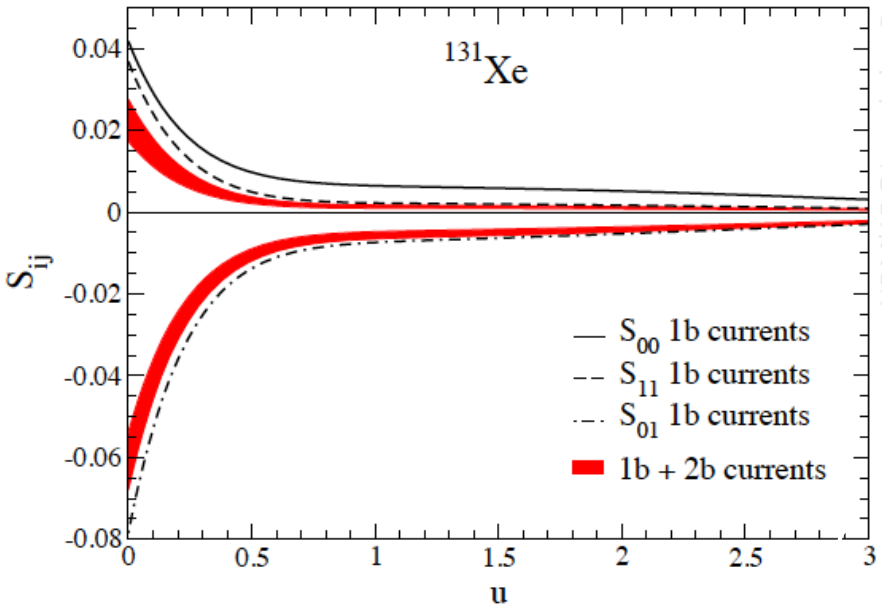
Spin dependent WIMP scattering

$$S_A(p) = \sum_{L\,\mathrm{odd}} \left(\left| \langle J || \mathcal{T}^{\mathrm{el}\,5}_L(p) || J \rangle \right|^2 + \left| \langle J || \mathcal{L}^5_L(p) || J \rangle \right|^2 \right)$$

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

$$u = p^2 b^2 / 2$$

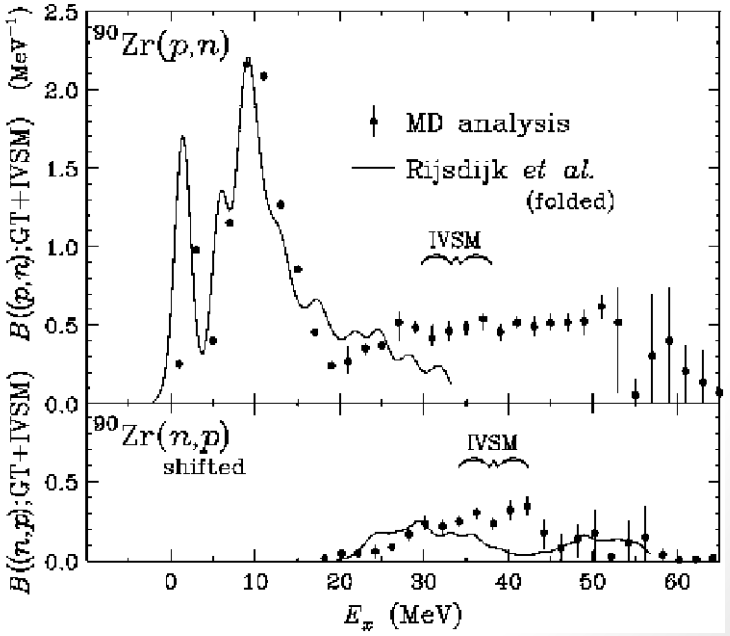




Klos, Menendez, DG, Schwenk (2013)

Gamow-Teller Quenching in heavier nuclei

- Measurements of Ikeda sum-rule in ^{90}Zr up to high energies, show little quenching!

Sesano *et al*, Phys. Rev. **C79**, 024602 (2009); Yako *et al*, Phys. Lett. **B615**, 193 (2005)

$$q^2 = \frac{S_{\beta-} - S_{\beta+}}{3(N-Z)} = 0.92 \pm 0.11 \Rightarrow q = 0.96 \pm 0.06$$