

# $g_A$ Quenching Information from Neutrino Scattering

Saori Pastore  
 $\nu$ Eclipse Workshop  
Knoxville, TN, August 2017



Open Questions in Fundamental Symmetries and Neutrino Physics

Majorana Neutrinos, Neutrinos Mass Hierarchy,  
CP-Violation in Neutrino Sector, Dark Matter

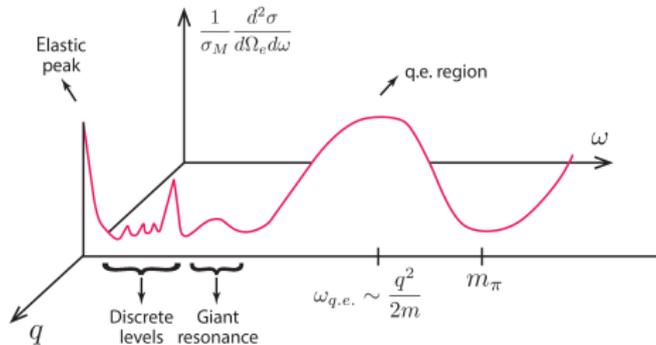
WITH

Carlson & Gandolfi (LANL) - Schiavilla & Baroni (ODU/JLAB) - Wiringa & Piarulli & Pieper (ANL)  
Mereghetti & Dekens & Cirigliano (LANL)

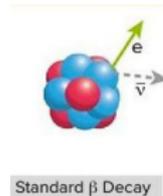
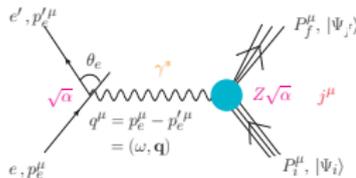
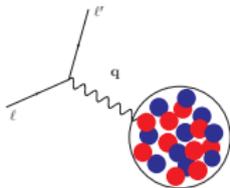
REFERENCES

PRC78(2008)064002 - PRC80(2009)034004 - PRL105(2010)232502 - PRC84(2011)024001 - PRC87(2013)014006  
PRC87(2013)035503 - PRL111(2013)062502 - PRC90(2014)024321 - JPhysG41(2014)123002 - PRC(2016)015501

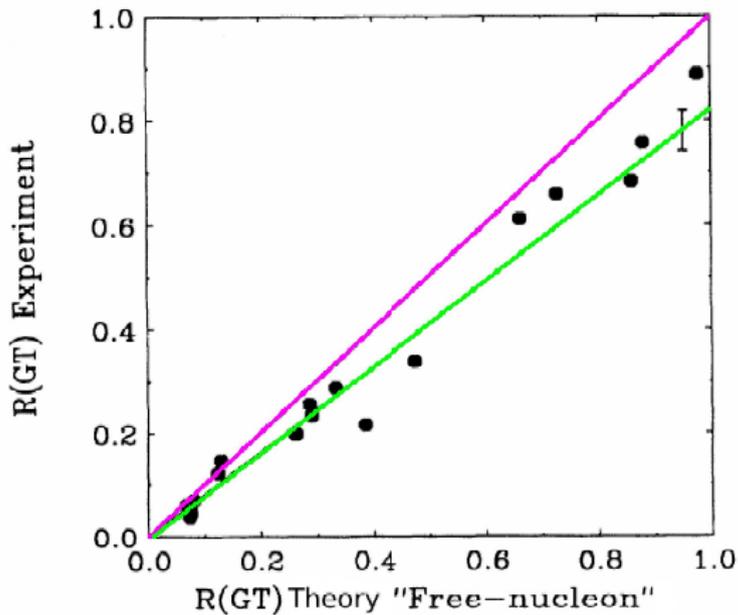
# Electroweak Reactions



- \*  $\omega \sim 10^2$  MeV: Accelerator neutrinos
- \*  $\omega \sim 10^0$  MeV: EM decay,  $\beta$ -decay
- \*  $\omega \lesssim 10^1$  MeV: Astrophysical  $\nu$ 's, Stopped- $\pi$ 's expt



$\omega \sim \text{MeV}$ : single  $\beta$  decay



$$g_A^{\text{eff}} \simeq 0.70 g_A$$

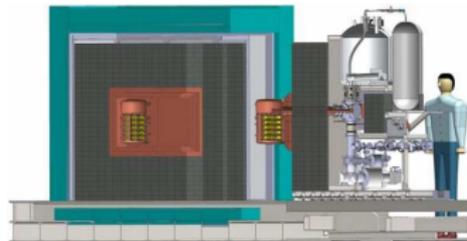
quenching required to bring theory in agreement with expt

$$\text{Rates} \propto g_A^2$$

Fig. from Chou *et al.* [PRC47\(1993\)163](#)

# Neutrinoless Double Beta Decay

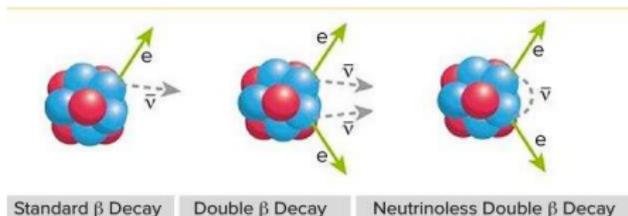
observation of  $0\nu\beta\beta$ -decay  
→  
lepton #  $L = l - \bar{l}$  not conserved  
→  
implications in  
matter-antimatter imbalance



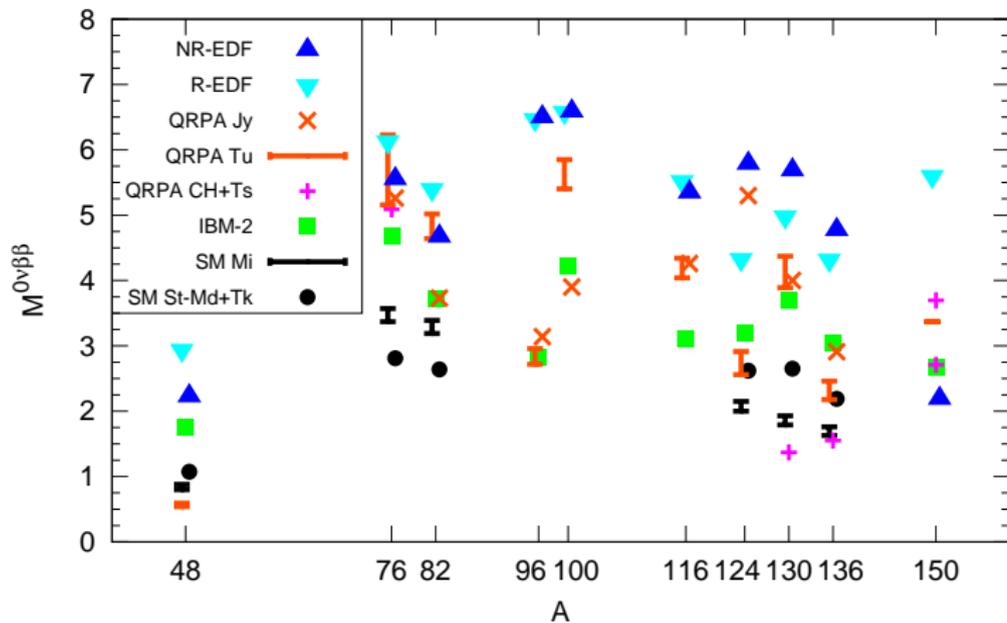
Majorana Demonstrator

- \* detectors' active material  $^{76}\text{Ge}$  \*
- $0\nu\beta\beta$ -decay  $\tau_{1/2} \gtrsim 10^{25}$  years (age of the universe  $1.4 \times 10^{10}$  years)  
1 ton of material to see (if any)  $\sim 5$  decays per year
- \* also, if nuclear m.e.'s are known, absolute  $\nu$ -masses can be extracted \*

$$\text{Rates} \propto g_A^4$$

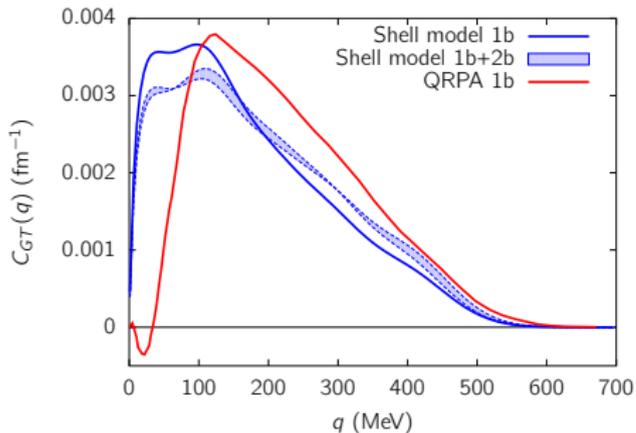


# Neutrinoless Double Beta Decay



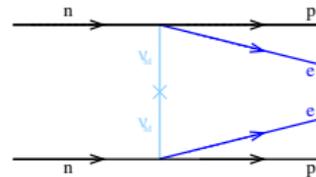
J. Engels & J. Menendez - Rep. on Prog. in Physics 80(2017)046301

# Neutrinoless Double Beta Decay

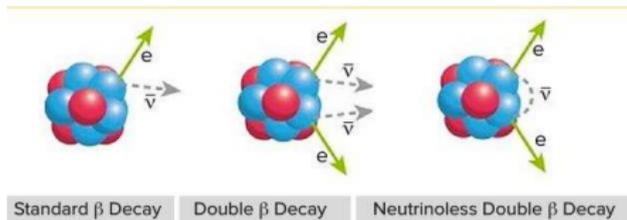


J. Engels & J. Menendez

- \*  $\beta$  decay energy and momentum are set by the Q-value  $\sim$  MeV
- \*  $0\nu\beta\beta$  decay the scales is set by the interparticle distance of the two decay nucleon  $\sim$  100 MeV



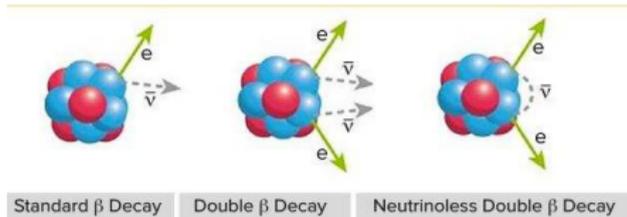
\*  $GT \propto \sigma_1 \cdot \sigma_2 \tau_1^+ \tau_2^+ / r_{12}$



2015 Long Range Plane for Nuclear Physics

## $g_A$ Quenching from Neutrino Scattering

- \* Does the  $g_A$  problem persist at moderate momenta?
- \* How does the  $g_A$ -quenching affect  $0\nu\beta\beta$ -decay matrix elements?
- \* Data at moderate momenta from  $\nu$ -scattering very valuable
- \* LSND (stopped pions) data available on  $^{12}\text{C}$ ;  $C(\nu_e, e^-)\text{N}$ ,  $C(\nu_\mu, \mu^-)\text{N}$



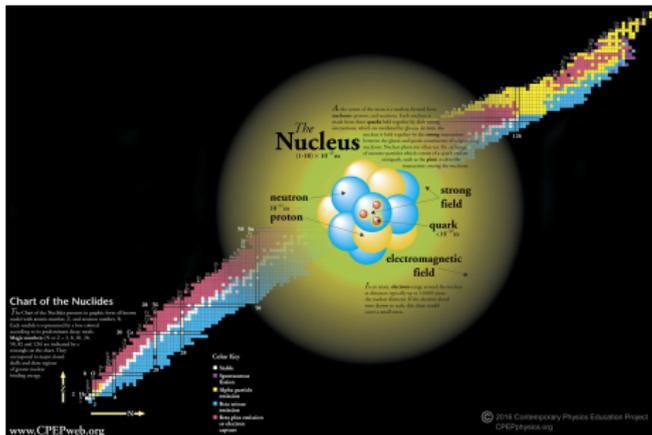
2015 Long Range Plane for Nuclear Physics

# Nuclear Physics

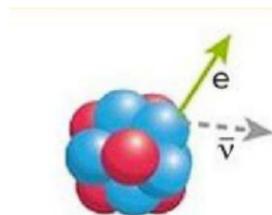
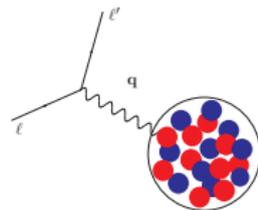
Nuclei used as laboratories for precision tests of the standard model and in searches for beyond the standard model physics



An **accurate understanding** of **nuclear structure and dynamics** is required to **extract new physics from nuclear effects**



<http://www.cpepweb.org>



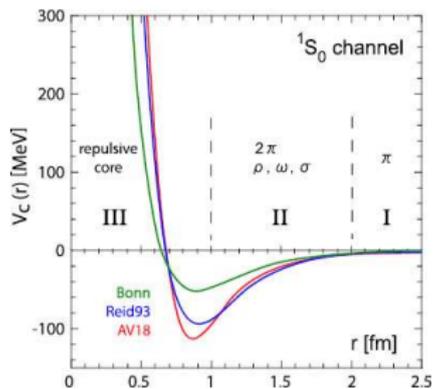
Standard  $\beta$  Decay

## Nuclear Interactions

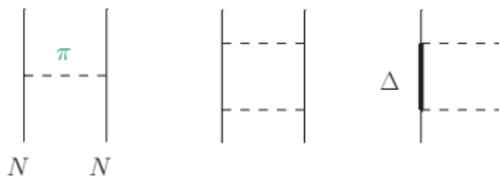
The nucleus is made of  $A$  non-relativistic interacting nucleons and its energy is

$$H = T + V = \sum_{i=1}^A t_i + \sum_{i<j} \mathbf{v}_{ij} + \sum_{i<j<k} V_{ijk} + \dots$$

where  $\mathbf{v}_{ij}$  and  $V_{ijk}$  are **two-** and **three-**nucleon operators based on EXPT data fitting and fitted parameters subsume underlying QCD



Aoki *et al.* *Comput.Sci.Disc.*1(2008)015009

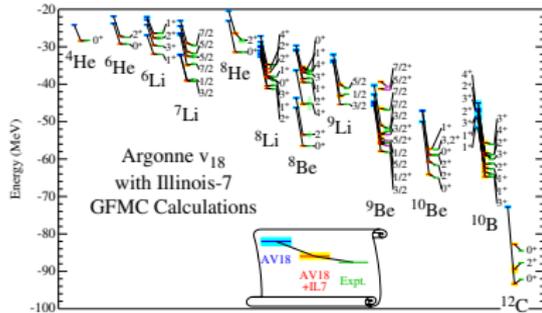


- \* One-pion-exchange: range  $\sim \frac{1}{m_\pi}$
- \* Two-pion-exchange: range  $\sim \frac{1}{2m_\pi}$

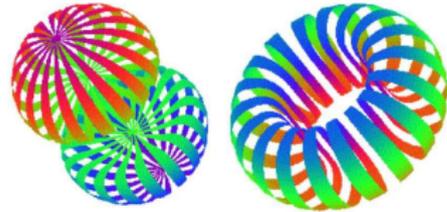
- \* AV18+UIX / AV18+IL7 - QMC
- \* NN(N3LO)+3N(N2LO) - QMC

( $\pi N \Delta$ ) by Maria Piarulli *et al.*  
PRC91(2015)024003

# Energy Spectrum and Shape of Nuclei

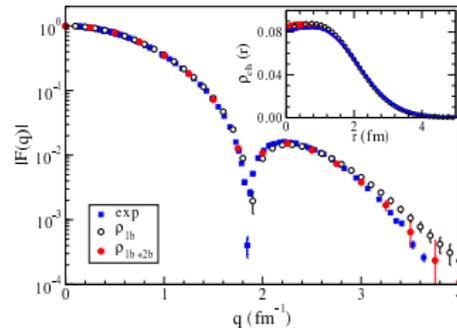
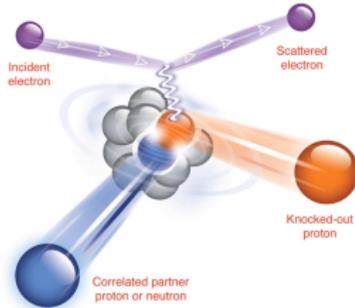


Carlson *et al.* *Rev.Mod.Phys.*87(2015)1067



Constant density surfaces for a polarized deuteron in the  $M = \pm 1$  (left) and  $M = 0$  (right) states

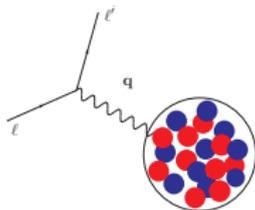
Carlson and Schiavilla *Rev.Mod.Phys.*70(1998)743



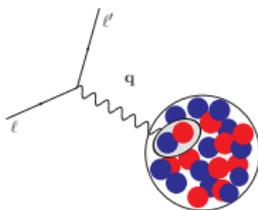
Lovato *et al.* *PRL*111(2013)092501

## Nuclear Currents

1b



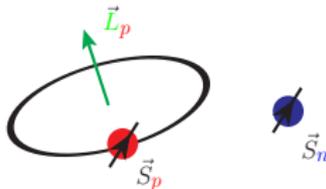
2b



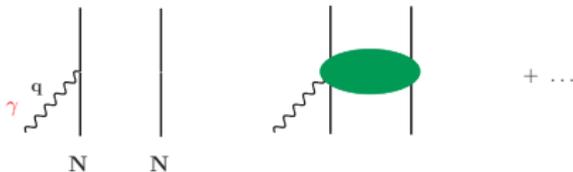
$$\rho = \sum_{i=1}^A \rho_i + \sum_{i<j} \rho_{ij} + \dots,$$

$$\mathbf{j} = \sum_{i=1}^A \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \dots$$

\* In Impulse Approximation **IA** nuclear currents are expressed in terms of those associated with individual protons and nucleons, *i.e.*,  $\rho_i$  and  $\mathbf{j}_i$ , **1b**-operators



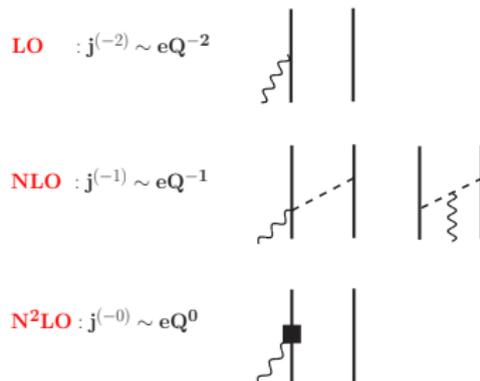
\* Two-body **2b** currents essential to satisfy current conservation



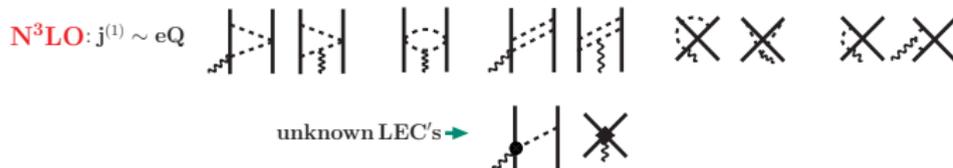
$$\mathbf{q} \cdot \mathbf{j} = [H, \rho] = [t_i + v_{ij} + V_{ijk}, \rho]$$

\* Villars, Myiazawa, Chemtob, Riska, Schiavilla, Marcucci, ...

# Electromagnetic Currents from Chiral Effective Field Theory

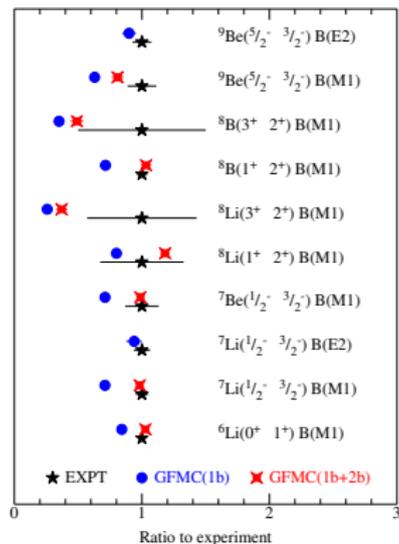
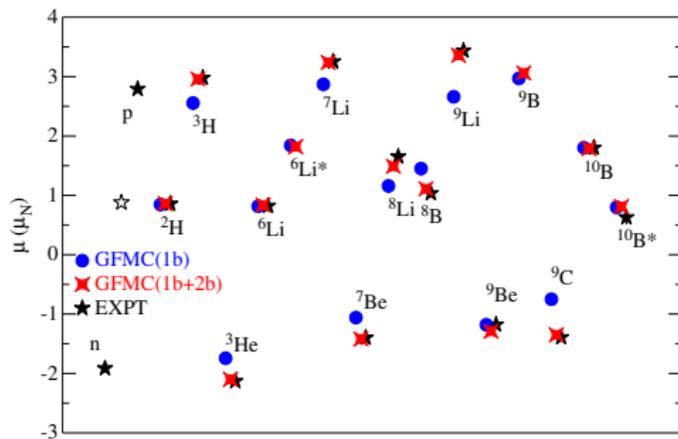


\* 3 unknown Low Energy Constants:  
fixed so as to reproduce  $d$ ,  ${}^3H$ , and  ${}^3He$  magnetic moments



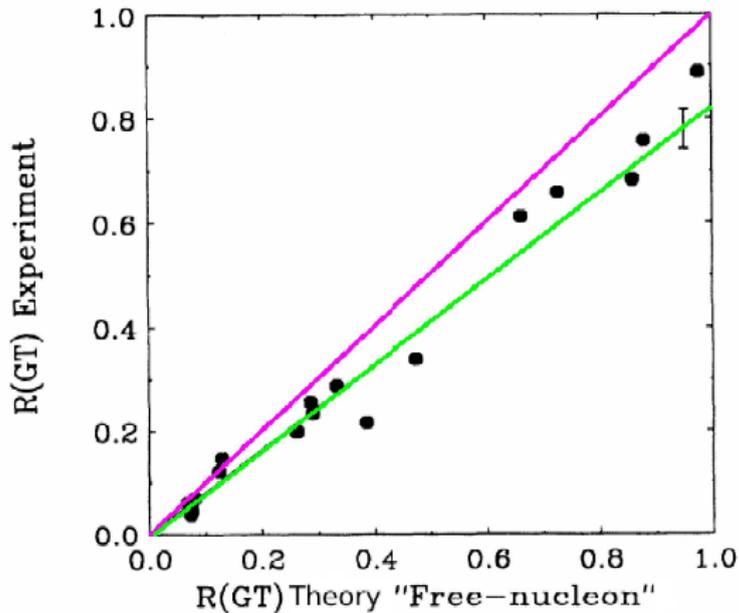
Pastore *et al.* PRC78(2008)064002 & PRC80(2009)034004 & PRC84(2011)024001  
\* analogue expansion exists for the Axial nuclear current - Baroni *et al.* PRC93 (2016)015501 \*

# Magnetic Moments and M1 Transitions



Pastore *et al.* PRC87(2013)035503 & PRC90(2014)024321, Datar *et al.* PRL111(2013)062502

$\omega \sim \text{MeV}$ : single  $\beta$  decay



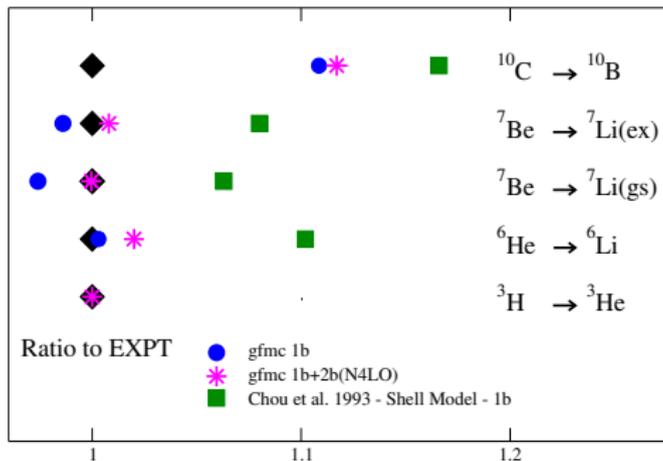
$$g_A^{\text{eff}} \simeq 0.70 g_A$$

quenching required to bring theory in agreement with expt

We use  $g_A = 1.2723$  from PDG

Fig. from Chou *et al.* [PRC47\(1993\)163](#)

## Single beta decay in $A \leq 10$ Nuclei

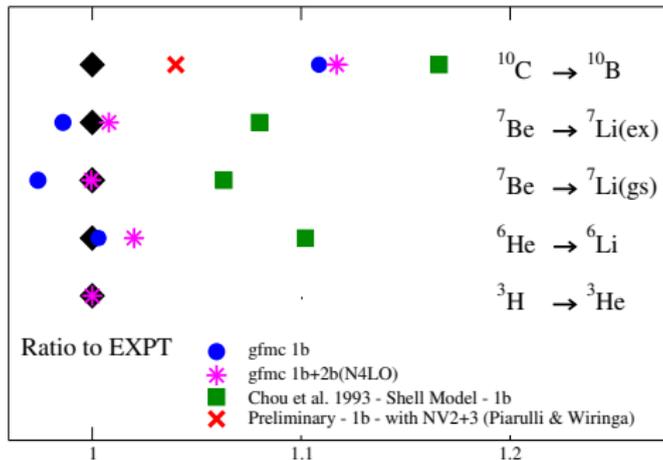


$g_A = 1.2723$  from PDG

in preparation

- \* Two-body currents are found to provide a small (negligible) contribution
  - \* Significant reduction from correlations
  - \* no quenching required - limited to the light systems we studied

## Single beta decay in $A \leq 10$ Nuclei

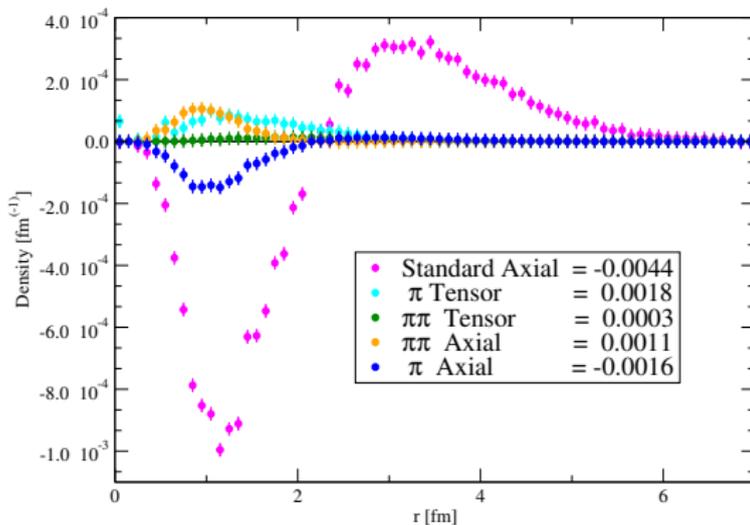


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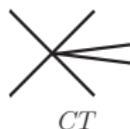
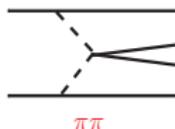
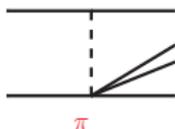
## Double beta-decay m.e.'s in ${}^8\text{He}(0^+;2) \rightarrow {}^8\text{Be}(0^+;0)$ : A test case II



$$\text{Axial} \propto \tau_1^+ \tau_2^+ \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

$$\text{Tensor} \propto \tau_1^+ \tau_2^+ S_{12}$$

\* Preliminary \*



WITH

Emanuele Mereghetti & Dekens & Cirigliano & Graesser & Wiringa *et al.*

## Summary and Outlook

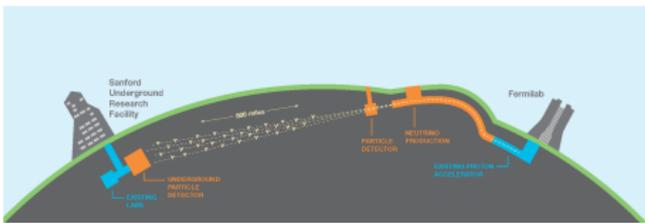
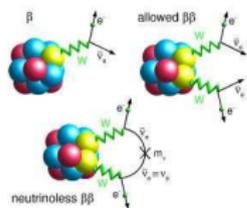
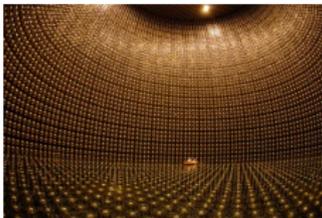
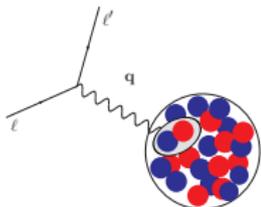
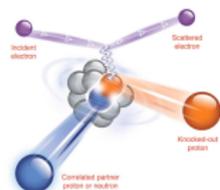
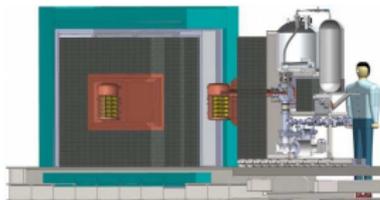
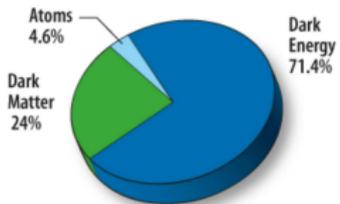
We discussed the role played by **correlations** and **many-body currents** in  $\beta$ - and  $\nu 0\beta\beta$ -decay m.e.'s of  $A \leq 10$  nuclei

- \* Two-body currents provide negligible quenching in the  $\beta$ -decay m.e.'s we studied
- \* Large reduction from correlations found in  $\beta$ -decay m.e.'s
- \*  $\nu 0\beta\beta$ -decay involves different energy scale,  $g_A$ -quenching likely to be different
- \* Data very valuable at moderate momenta
- \* GFMC calculations computationally limited to  $A = 12$  (data on C valuable)
- \* AFDMC pushing microscopic picture to  $A \sim 40$  (data on O, Ca, LAr valuable)

## Outlook

- \* Understand quantitatively and qualitatively  $g_A$  quenching
- \* Benchmark both single- and double-beta decay m.e.'s
- \* Characterize two-body currents entering double-beta decay m.e.'s

# Outlook



$$\langle j_{1a}^{\dagger} j_{1b} \rangle > 0$$

$$\langle j_{1a}^{\dagger} j_{2b} \nu_{\tau} \rangle \propto \langle \nu_{\tau}^2 \rangle > 0$$

Fundamental Physics with Electroweak Probes of Light Nuclei

June 12 - July 13, 2018

S. Bacca, R. J. Hill, S. Pastore, D. Phillips

Contacts

<http://www.int.washington.edu/>

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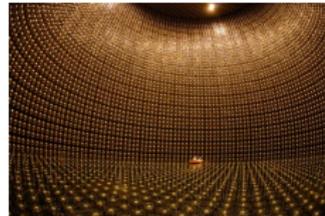
[saori@lanl.gov](mailto:saori@lanl.gov)

## EXTRA SLIDES

# $\omega \sim \text{GeV}$ : Accelerator Neutrinos



LBNF



T2K

neutrinos oscillate  
 $\rightarrow$   
 they have tiny masses  
 =  
 BSM physics  
 Beyond the Standard Model  
 Simplified 2 flavors picture:

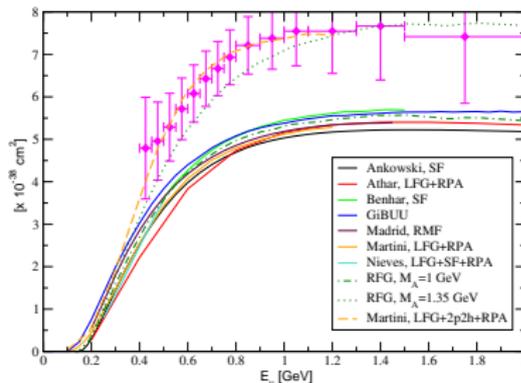
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{2E_\nu} \right)$$

\* Unknown \*

$\nu$ -mass hierarchy, CP-violation,  
 accurate mixing angles

## Neutrino-Nucleus scattering

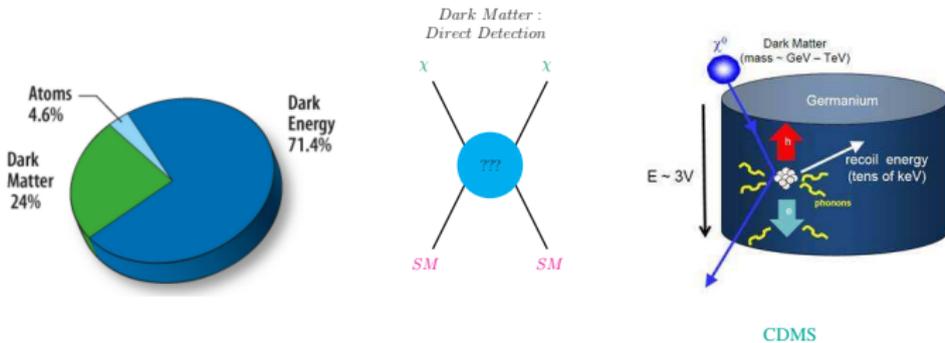
CCQE on  $^{12}\text{C}$



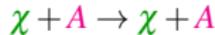
Alvarez-Ruso [arXiv:1012.3871](https://arxiv.org/abs/1012.3871)

DUNE, MiniBoone, T2K, Minerva ... active material \*  $^{12}\text{C}$ ,  $^{40}\text{Ar}$ ,  $^{16}\text{O}$ ,  $^{56}\text{Fe}$ , ... \*

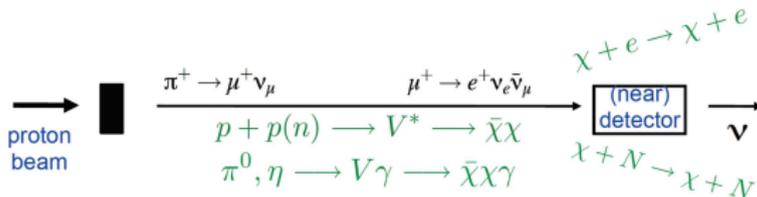
# $\omega \sim \text{GeV}$ : Dark Matter Direct Detection



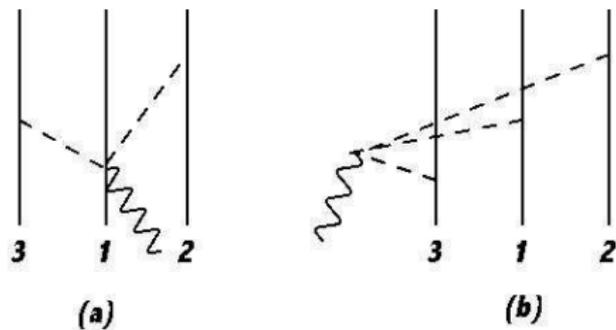
Dark Matter Beam Production and Direct detection:



Dark Matter is detected via scattering on nuclei in the detector  
 Detection of Sub-GeV Dark Matter requires knowledge of nuclear responses

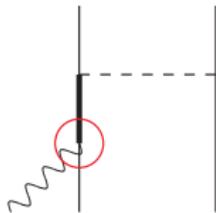


## Three-body Axial Currents from $\chi$ EFT



A. Baroni *et al.* PRC93(2016)015501 & PRC94(2016)024003

## SNPA Two-body Axial Currents

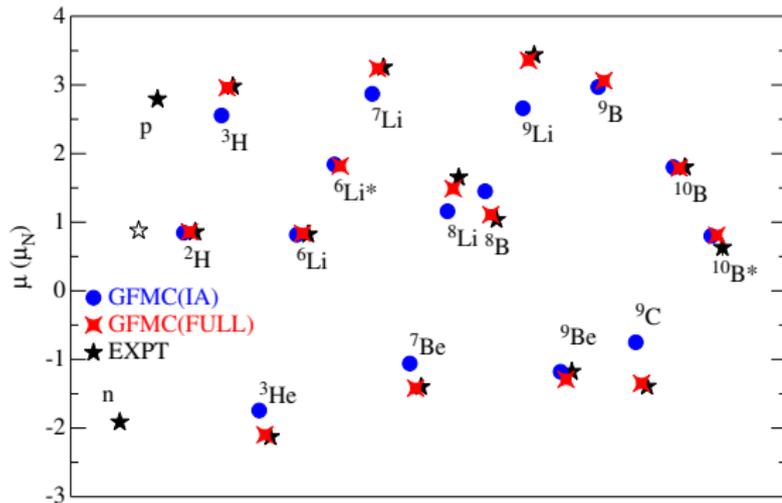


- 1) One body has GT, relativistic corrections, PS from pion-pole diagrams
- 2) Two-body currents
  - 2.a) Major contribution from  $\Delta$ -excitation current
  - 2.b) Negligible contributions from  $A\pi$ ,  $A\rho$ ,  $A\pi\rho$
- 3)  $AN\Delta$  coupling fixed to tritium beta-decay
- 4)  $\sim 3\%$  **additive** correction from  $\Delta$ -current

Chemtob, Rho, Towner, Riska, Schiavilla, Marcucci ...

see, e.g., [Marcucci \*et al.\* PRC63\(2001\)015801](#) and references therein

## Error Estimate



EE *et al.* error algorithm  
Epelbaum, Krebs, and  
Meissner EPJA51(2015)53

$$\delta^{\text{N3LO}} = \max \left[ Q^4 |\mu^{\text{LO}}|, Q^3 |\mu^{\text{LO}} - \mu^{\text{NLO}}|, \right. \\ \left. Q^2 |\mu^{\text{NLO}} - \mu^{\text{N2LO}}|, \right. \\ \left. Q^1 |\mu^{\text{N2LO}} - \mu^{\text{N3LO}}| \right]$$

$$Q = \max \left[ \frac{m_\pi}{\Lambda}, \frac{p}{\Lambda} \right]$$

m.m.	THEO	EXP
<sup>9</sup> C	-1.35(4)(7)	-1.3914(5)
<sup>9</sup> Li	3.36(4)(8)	3.4391(6)

\* 'N3LO-Δ' corrections can be 'large' \*

\* SNPA and  $\chi$ EFT currents qualitatively in agreement,  $\chi$ EFT isoscalar currents provide better description exp data \*

Pastore *et al.* PRC87(2013)035503

## $\chi$ EFT currents: a closer look

$A = 7$  Captures

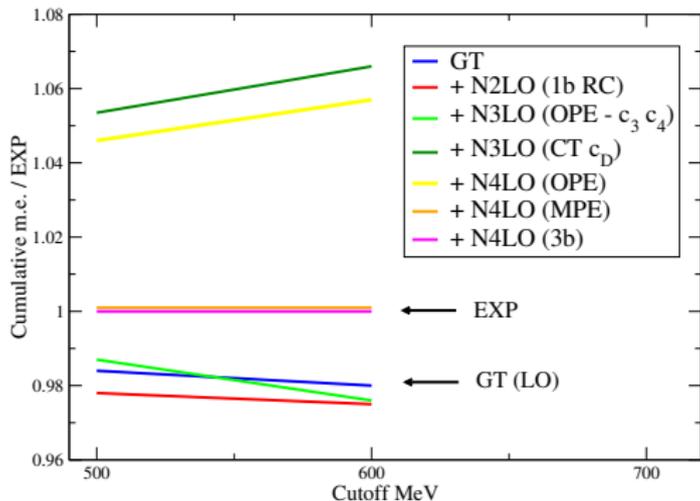
	gs	ex
LO	2.334	2.150
N2LO	$-3.18 \times 10^{-2}$	$-2.79 \times 10^{-2}$
N3LO(OPE)	$-2.99 \times 10^{-2}$	$-2.44 \times 10^{-2}$
N3LO(CT)	$2.79 \times 10^{-1}$	$2.36 \times 10^{-1}$
N4LO(2b)	$-1.61 \times 10^{-1}$	$-1.33 \times 10^{-1}$
N4LO(3b)	$-6.59 \times 10^{-3}$	$-4.86 \times 10^{-3}$
TOT(2b+3b)	0.050	0.046

\* Large cancellations due to positive CT at N3LO with  $c_D$  fixed to GT m.e. of tritium

In preparation

# Convergence and cutoff dependence

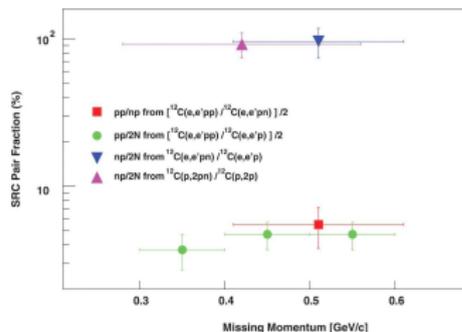
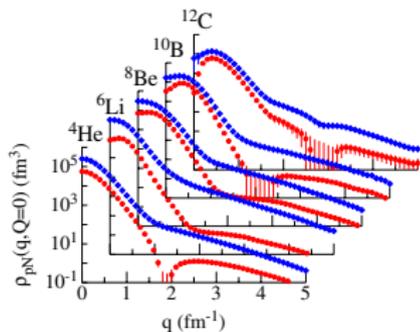
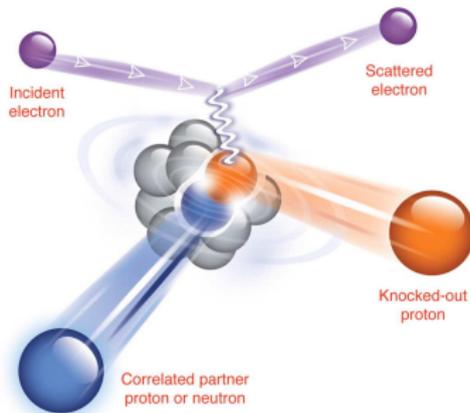
## Tritium $\beta$ -decay



\*  $\sim 2\%$  additive contribution from two-body currents

A. Baroni *et al.* PRC93(2016)015501 & PRC94(2016)024003

## Back-to-back $np$ and $pp$ Momentum Distributions



Wiringa *et al.* [PRC89\(2014\)024305](#)

JLab, Subedi *et al.* [Science320\(2008\)1475](#)

Nuclear properties are strongly affected by **two-nucleon** interactions!

## Electromagnetic Currents from Nuclear Interactions (SNPA currents)

$$\mathbf{q} \cdot \mathbf{j} = [H, \rho] = [t_i + v_{ij} + V_{ijk}, \rho]$$

- 1) Longitudinal component fixed by current conservation
- 2) Plus transverse “phenomenological” terms

$$\mathbf{j} = \mathbf{j}^{(1)} + \mathbf{j}^{(2)}(v) + \mathbf{j}^{(3)}(V)$$

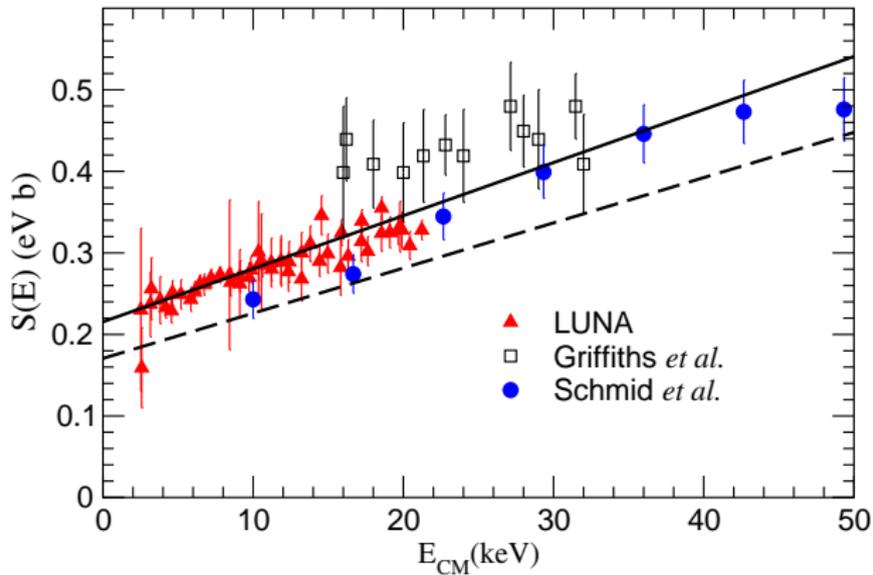
The diagram illustrates the decomposition of the current density  $\mathbf{j}$  into three components. The first component,  $\mathbf{j}^{(1)}$ , is the longitudinal component. The second component,  $\mathbf{j}^{(2)}(v)$ , is the transverse component, shown as a wavy line labeled  $\pi$  and  $\rho\omega$  between two vertical lines labeled  $N$ . The third component,  $\mathbf{j}^{(3)}(V)$ , is the transverse component, shown as a wavy line labeled  $\Delta$  and  $q$  between two vertical lines labeled  $N$ . A horizontal line above the diagram is labeled "transverse".

Villars, Myiazawa (40-ies), Chemtob, Riska, Schiavilla ...  
see, e.g., [Marcucci \*et al.\* PRC72\(2005\)014001](#) and references therein

## Currents from nuclear interactions

Satisfactory description of a variety of nuclear em properties in  $A \leq 12$

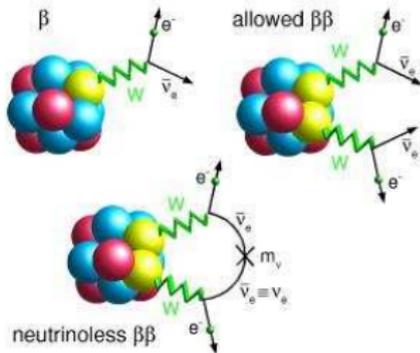
${}^2\text{H}(p,\gamma){}^3\text{He}$  capture



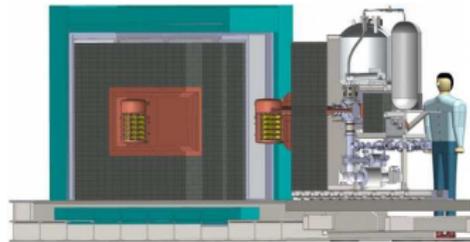
Marcucci *et al.* PRC72, 014001 (2005)

# $0\nu\beta\beta$ -decay

## $0\nu\beta\beta$ -decay matrix elements and the role of two-nucleon correlations



Berna U.

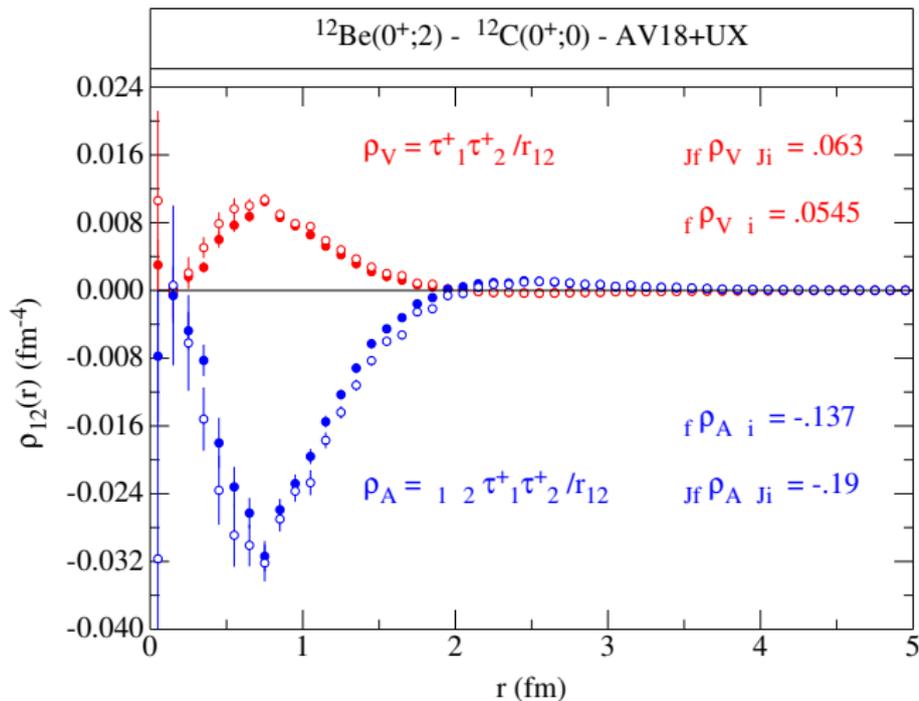


Majorana Demonstrator

\*Preliminary results\*

# Double beta-decay m.e.'s in $^{12}\text{Be}(0^+;2) \rightarrow ^{12}\text{C}(0^+;0)$ : A test case

\*Preliminary\*

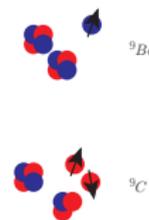
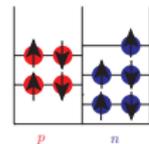
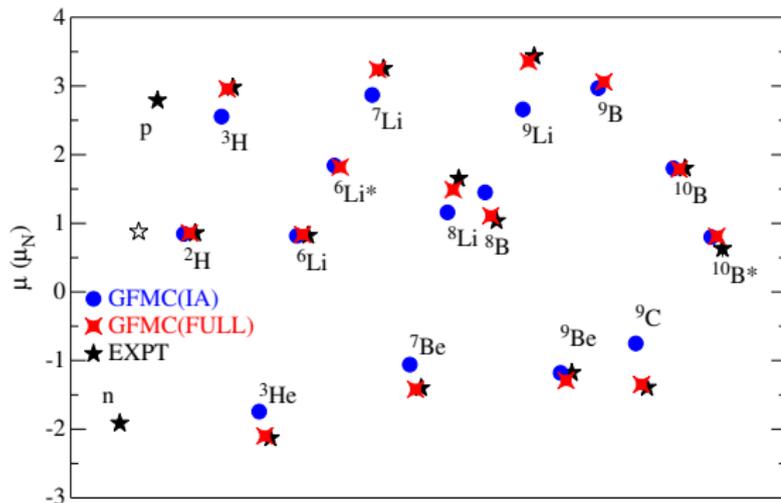


\*  $\frac{\langle \rho_V \rangle_{\text{corr}}}{\langle \rho_V \rangle_{\text{uncorr}}} \sim 0.86$

\*  $\frac{\langle \rho_A \rangle_{\text{corr}}}{\langle \rho_A \rangle_{\text{uncorr}}} \sim 0.72$

# Magnetic Moments in $A \leq 10$ Nuclei - bis

## Predictions for $A > 3$ nuclei



- ▶  $\mu_N(\text{IA}) = \sum_i [(L_i + g_p S_i)(1 + \tau_{i,z})/2 + g_n S_i(1 - \tau_{i,z})/2]$
- ▶  ${}^9\text{C}$  ( ${}^9\text{Li}$ ) dominant spatial symmetry [s.s.] = [432] =  $[\alpha, {}^3\text{He}({}^3\text{H}), pp(nn)] \rightarrow$  Large MEC
- ▶  ${}^9\text{Be}$  ( ${}^9\text{B}$ ) dominant spatial symmetry [s.s.] = [441] =  $[\alpha, \alpha, n(p)]$

PRC87(2013)035503

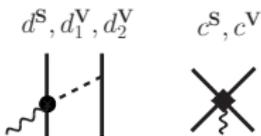
## Outlook

The microscopic description of nuclei successfully reproduces EXPT data provided that many-body effects in nuclear interactions and EM currents are accounted for.

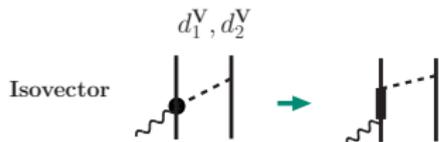
J.Phys.G41(2014)123002 - S.Bacca&S.P.

- \* EM structure and dynamics of light nuclei
  - ▶ Charge and magnetic form factors of  $A \leq 10$  systems
  - ▶ M1/E2 transitions in light nuclei
  - ▶ Radiative captures, photonuclear reactions . . .
  - ▶ Role of  $\Delta$ -resonances in ‘MEC’ (EM current consistent with the chiral ‘ $\Delta$ -full’ NN potential developed by M. Piarulli et al. PRC91(2015)024003)
  - ▶ Fully consistent  $\chi$ EFT calculations with ‘MEC’ for  $A > 4$  (based on, e.g., PRC91(2015)024003)
  - ▶ Zemach moments of light nuclei with ‘MEC’
  
- \* Electroweak structure and dynamics of light nuclei
  - ▶ Test axial currents (chiral and conventional) in light nuclei (A. Baroni et al. PRC93(2016)015501)
  - ▶ Incorporate pion production mechanisms in STA
  
- \* Strong reactions in nuclei
  - ▶ QMC calculations of nuclear reactions

## $\chi$ EFT EM currents at N3LO: fixing the EM LECs



Five LECs:  $d^S$ ,  $d_1^V$ , and  $d_2^V$  could be determined by pion photo-production data on the nucleon



$d_2^V$  and  $d_1^V$  are known assuming  $\Delta$ -resonance saturation

Left with 3 LECs: Fixed in the  $A = 2 - 3$  nucleons' sector

► Isoscalar sector:

\*  $d^S$  and  $c^S$  from EXPT  $\mu_d$  and  $\mu_S(^3\text{H}/^3\text{He})$

► Isovector sector:

\* model I =  $c^V$  from EXPT  $npd\gamma$  xsec.

or

\* model II =  $c^V$  from EXPT  $\mu_V(^3\text{H}/^3\text{He})$  m.m. ← our choice

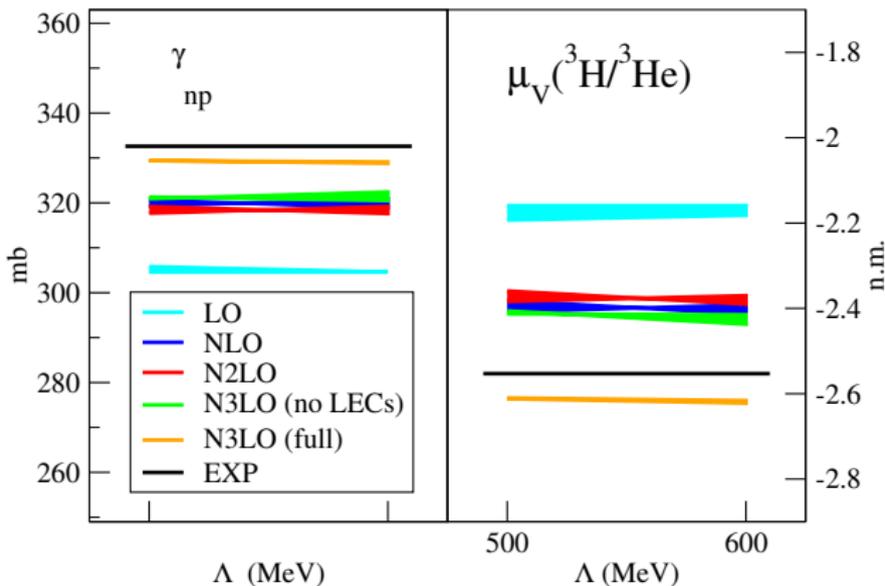
Note that:

$\chi$ EFT operators have a power law behavior  $\rightarrow$  introduce a regulator to kill divergencies at large  $Q$ , e.g.,  $C_\Lambda = e^{-(Q/\Lambda)^n}$ , ...and also, pick  $n$  large enough so as to not generate spurious contributions

$$C_\Lambda \sim 1 - \left(\frac{Q}{\Lambda}\right)^n + \dots$$

## Predictions with $\chi$ EFT EM currents for $A = 2-3$ systems

$np$  capture xsec. (using model II) /  $\mu_V$  of  $A = 3$  nuclei (using model I)  
bands represent nuclear model dependence (N3LO/N2LO – AV18/UIX)



- ▶  $npd\gamma$  xsec. and  $\mu_V(^3\text{H}/^3\text{He})$  m.m. are within 1% and 3% of EXPT
- ▶ Two-body currents important to reach agreement with exp data
- ▶ Negligible dependence on the cutoff entering the regulator  $\exp(-(k/\Lambda)^4)$