(Some) problems of (my/our) current interest

Suppose we can accurately solve the nuclear many-body problem for ground- and low-lying states; certain low-energy scattering/reaction problems and inclusive high-energy scattering.

What physics can we address?

- Larger nuclei with chiral interactions
- Low energy scattering and reactions
- β decay
- υ and electron scattering
- β β decay
- dense matter and neutron stars

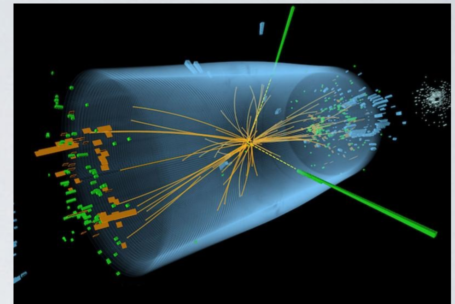
Nuclear Physics Scales

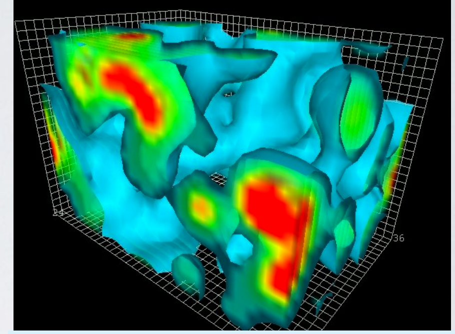
Physics
input
output

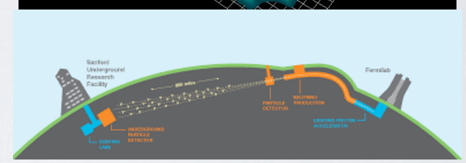
Energy

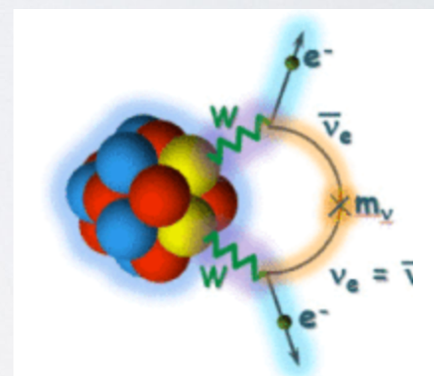
Distance

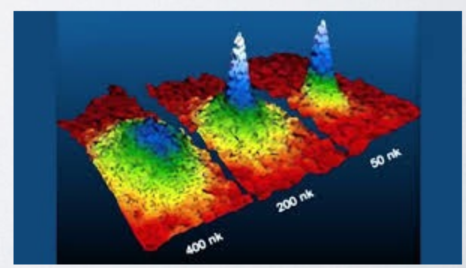
>10 (?) GeV	BSM Physics
0.1 - 10	QCD
10-100 MeV	Nuclear Interactions
10 MeV	Typical Energies / A in nuclei, dense matter
1 MeV	Light Nucleus Excitations
0.01- 1 MeV	Heavy Nuclei
eV	AMO, condensed matter









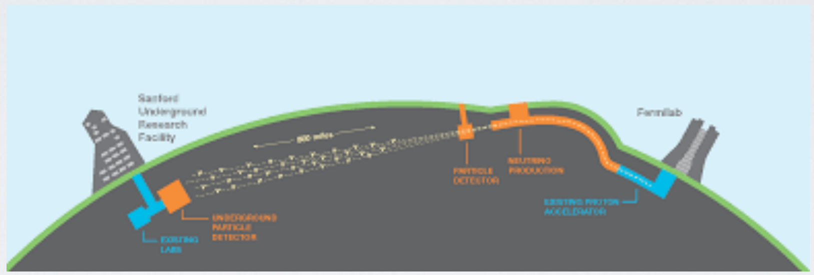


New Large-Scale Experiments and Facilities in Nuclear and High-Energy Physics

FRIB

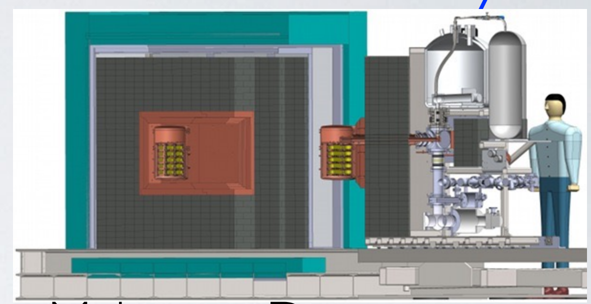
FRIB construction, Jan 2016

DUNE

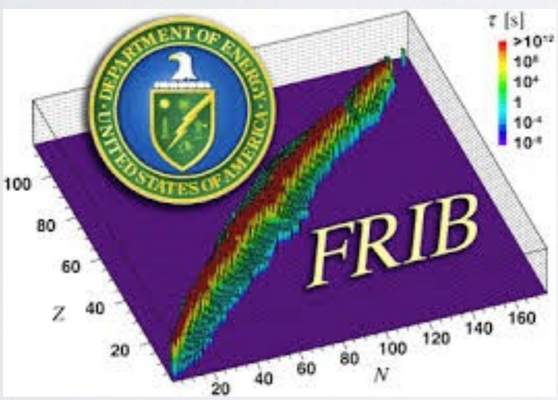


Sanford Lab FNAL

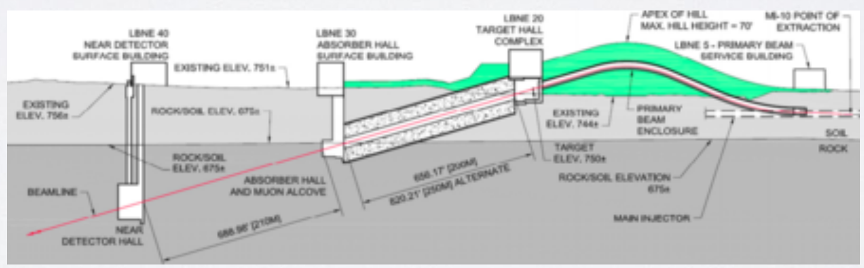
Double Beta Decay



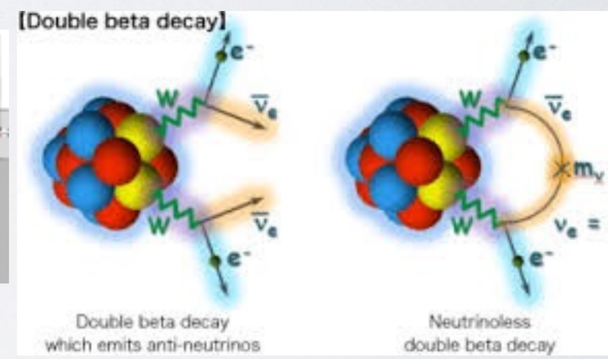
Majorana Demonstrator



Neutron-rich Nuclei
Nucleosynthesis



Neutrino CP violation
Hierarchy
Supernovae Neutrions



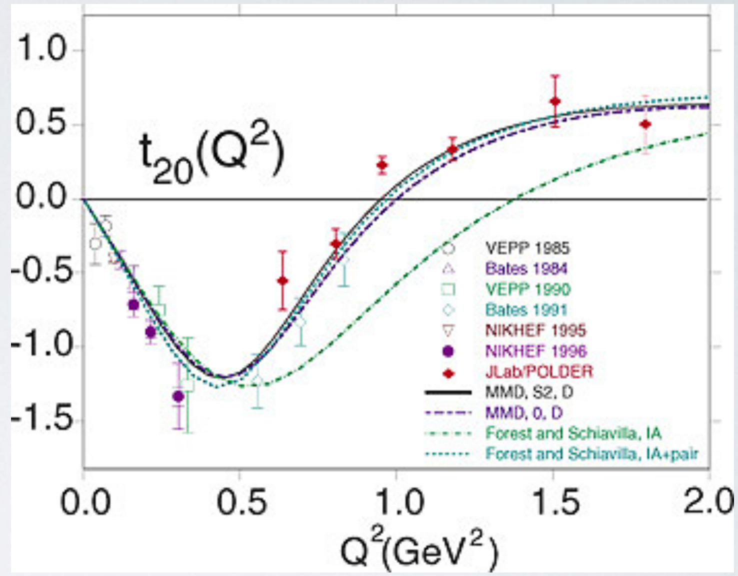
Lepton Flavor Violation
Majorana Neutrinos
Absolute mass

Nuclear Interactions and Currents

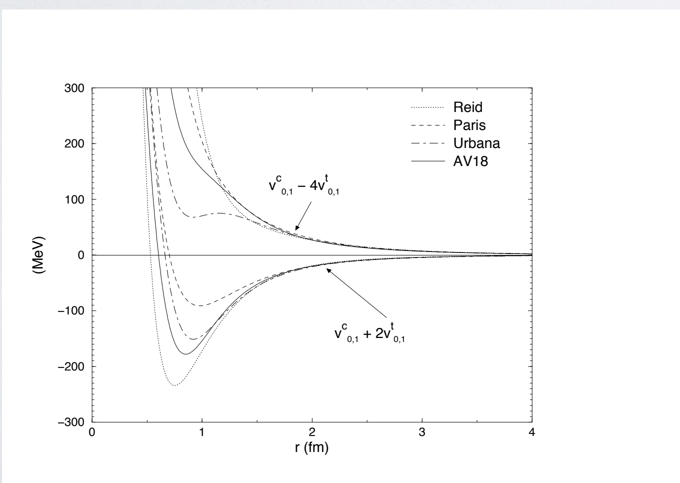
Non-relativistic nucleons w/ 2, 3-body interactions, currents

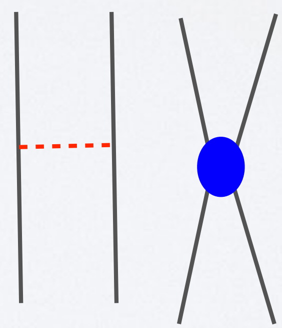
$$
\begin{aligned}
H &= \frac{1}{2m}\sum_i p_i^2 + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} \\
V_{ij} &= \sum_k V_{ij}^k(r_{ij})\, O_{ij}^k \\
O_{ij}^k &= [1, \sigma_i\cdot\sigma_j, \sigma_i\cdot r_{ij}\sigma_j\cdot r_{ij}, L\cdot S_{ij}] \times [1, \tau_i\cdot\tau_j]
\end{aligned}
$$

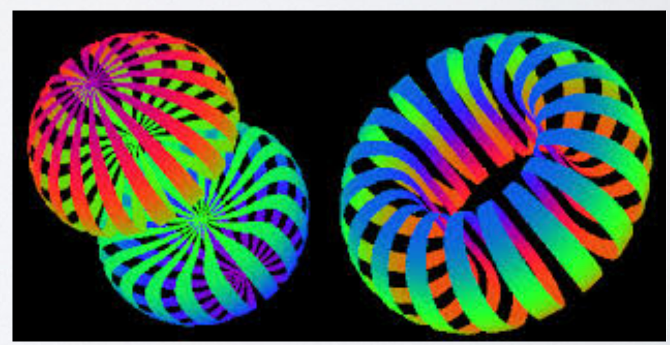
$$
\mathbf{J} = \sum_i \mathbf{j}_{1;i} + \sum_{i<j} \mathbf{j_{2;ij}} + \ldots
$$



t20 experiment Jlab R. Holt







Deuteron Potential Models with Different Spin Orientations

Forrest, et al, PRC 1996

Configuration Interaction
Coupled Cluster
IMSRG
QMC
DFT

NUCLEI

Nuclear Computational Low-Energy Initiative

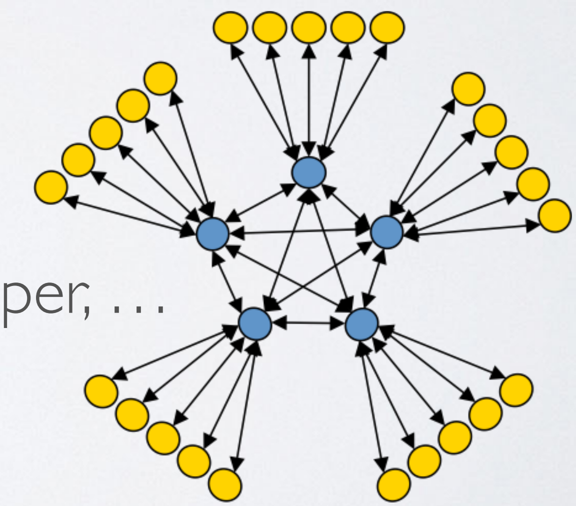
computingnuclei.org

^{12}C calculations:

$2^A = 4096$ spin amplitudes x
$12!/(6!6!) = 924$ isospin amplitudes
(charge basis) for each sample

~ 45 M core-hours/run
GFMC scaling to ~1M cores
AFDMC scaling to ~200K cores

ADLB
Lusk, Pieper, …



SciDAC Scientific Discovery through Advanced Computing

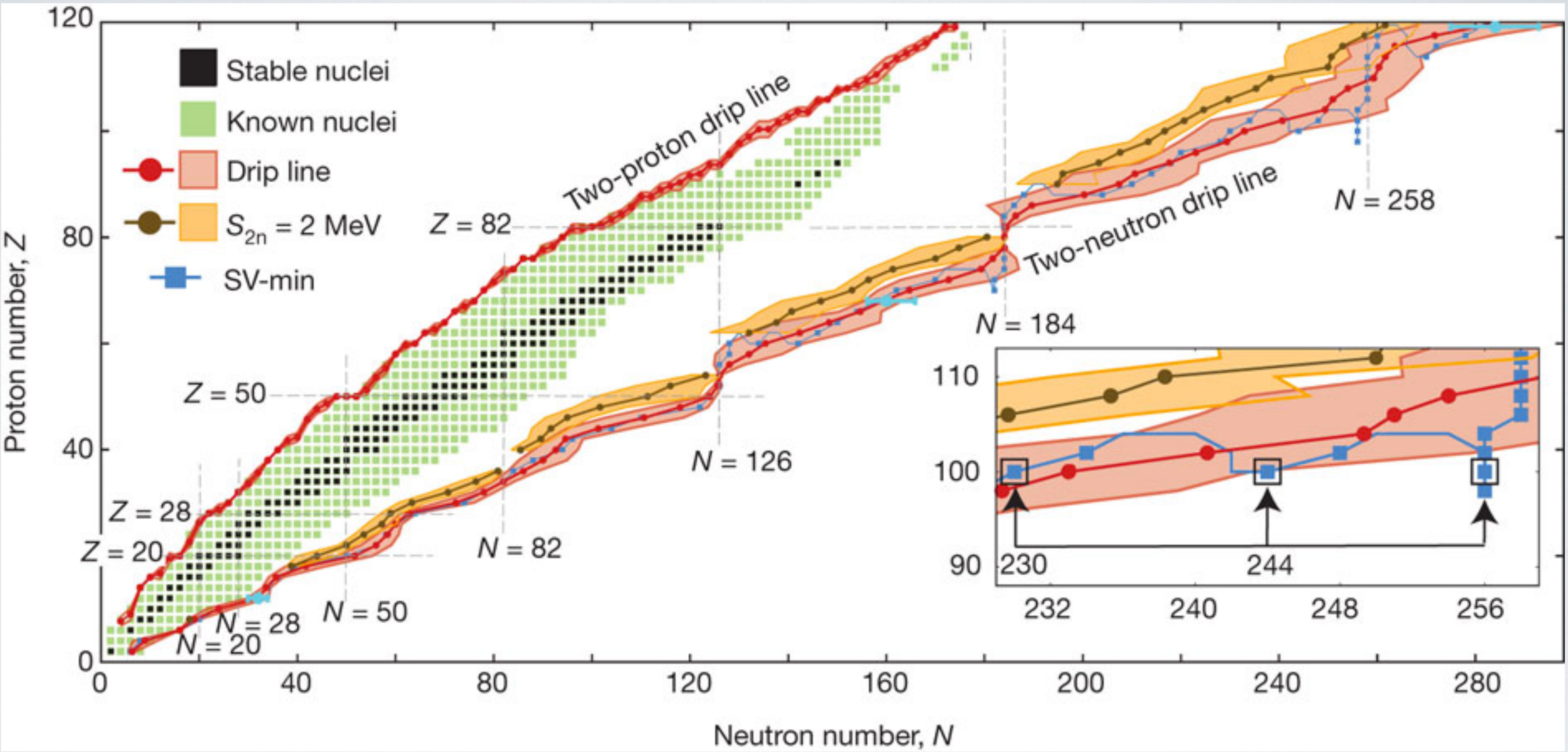
U.S. DEPARTMENT OF ENERGY Office of Science

U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

NNSA National Nuclear Security Administration

http://www.mcs.anl.gov/project/adlb-asynchronous-dynamic-load-balancer

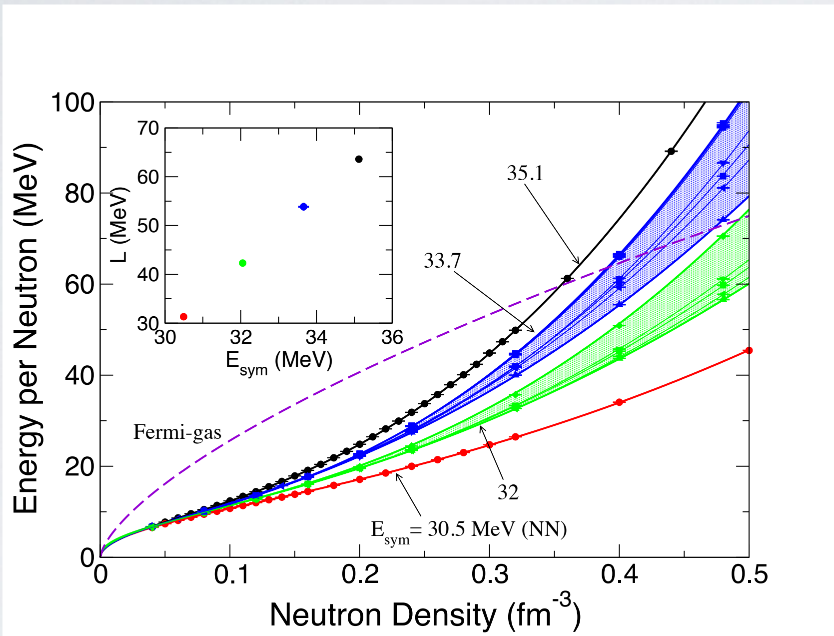
FRIB:
How accurate can we predict drip lines? shell closures?…



What about weak reaction rates for these nuclei?

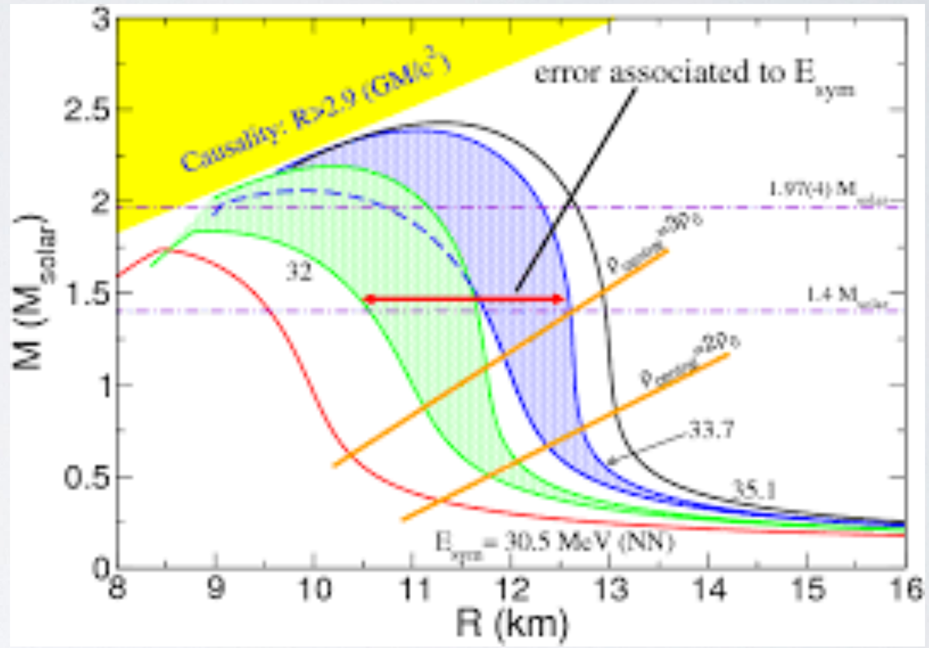
FRIB: High Density Neutron Matter
Can we determine EOS up to/beyond saturation density?

Neutron Matter Equation of State



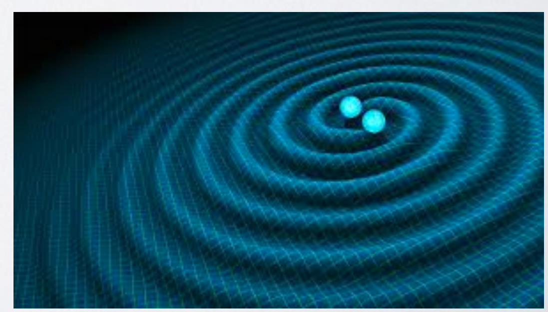
Periodic Boundary Conditions
~50 to 150 neutrons

Mass Radius Relationship



Exploring implications of different
3 Nucleon Interactions

- Important consequences for gravitational waves from neutron star mergers!
- Talking with lattice QCD at high densities



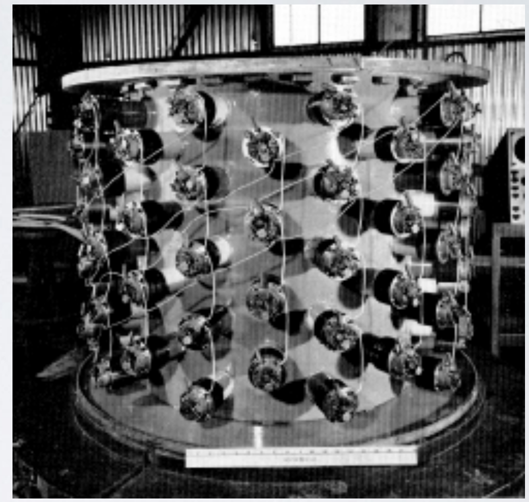
Neutrinos

Neutrinos proposed by Pauli in 1930 to conserve energy, momentum, and angular momentum in nuclear beta decay.

$$n \rightarrow p + e^- + \bar{\nu}_e$$

In 1956 Reines and Cowan detected anti-neutrinos from Savannah River reactors:

$$\bar{\nu}_e + p \rightarrow n + e^+$$



through coincidence of e+e- gamma rays and neutron capture.

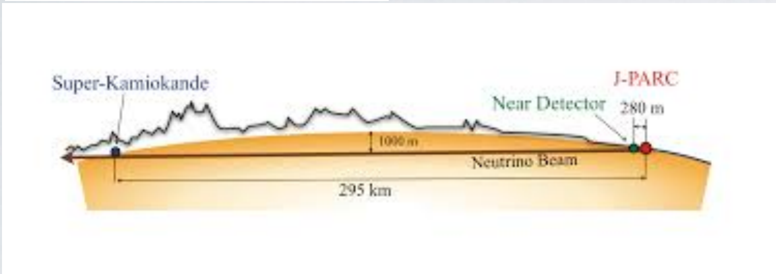
Reines was a LANL employee at the time.

Reines and Cowan were awarded the Nobel Prize in 1995.

Reines and Cowan discovered the electron (anti-) neutrino. Lederman, Schwartz and Steinberger detected the muon neutrino, receiving the Nobel Prize in 1988.

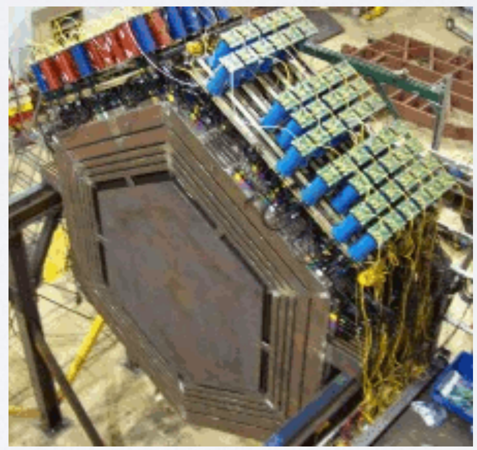
Accelerator Neutrinos and Electrons

T2K

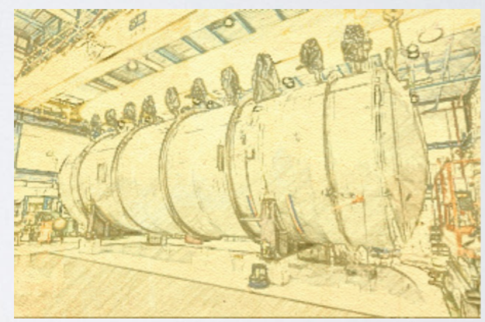


MINOS

SuperK



MINERva



MicroBooNE

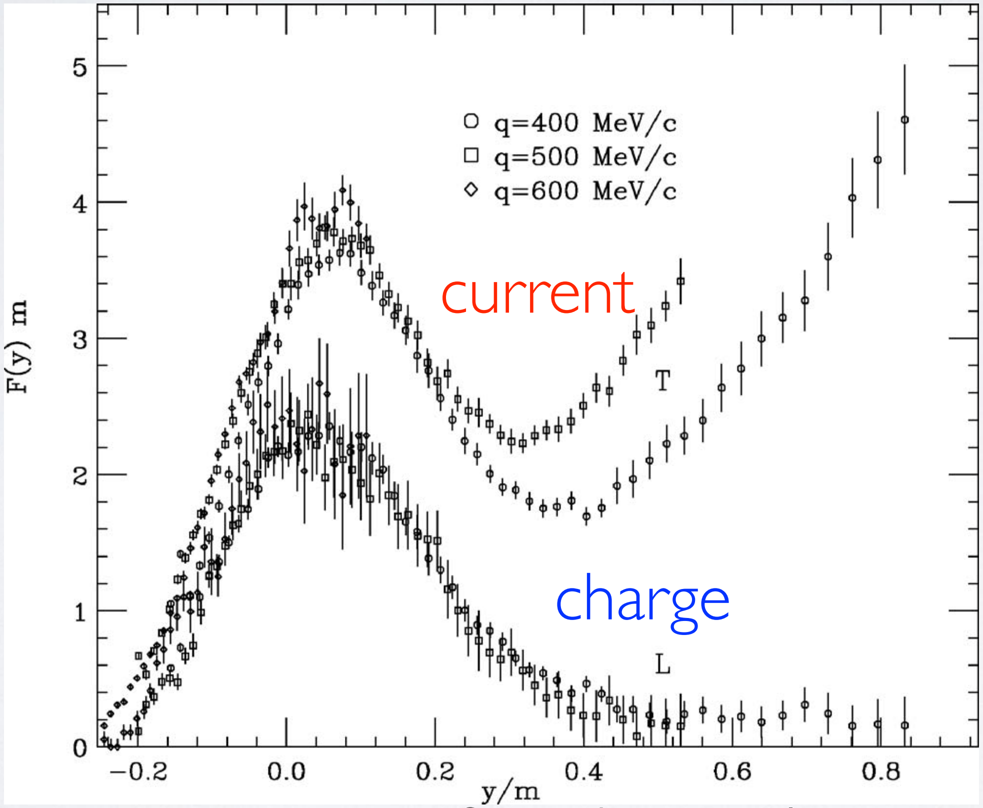
Advantages: Control over Energy, flux
neutrino 'beams' can be sent over long distances

Electron Scattering

Longitudinal (charge) and Transverse (current) response:

$$R_O(q,\omega) = \sum_f \langle 0 \mid O^\dagger(q) \mid f \rangle \langle f \mid O(q) \mid 0 \rangle \, \delta(\omega - (E_f - E_0))$$

For single-nucleon physics charge and current response are proportional

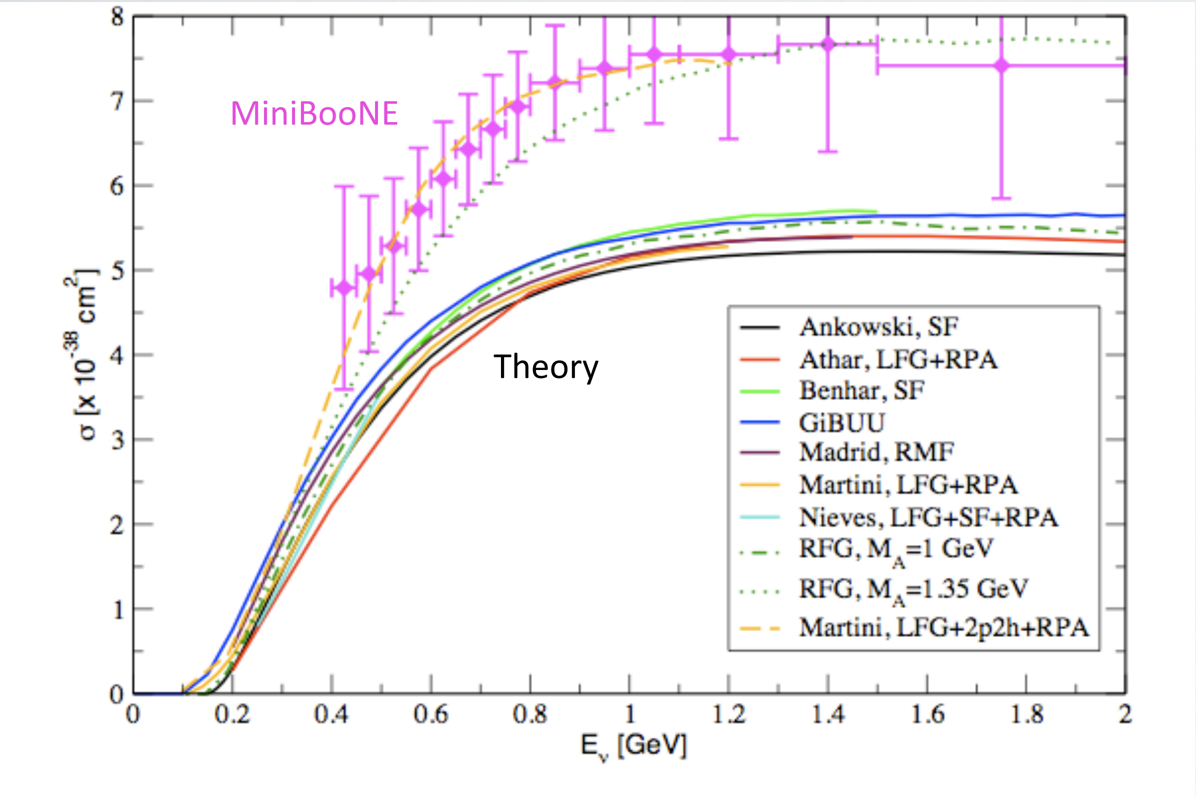


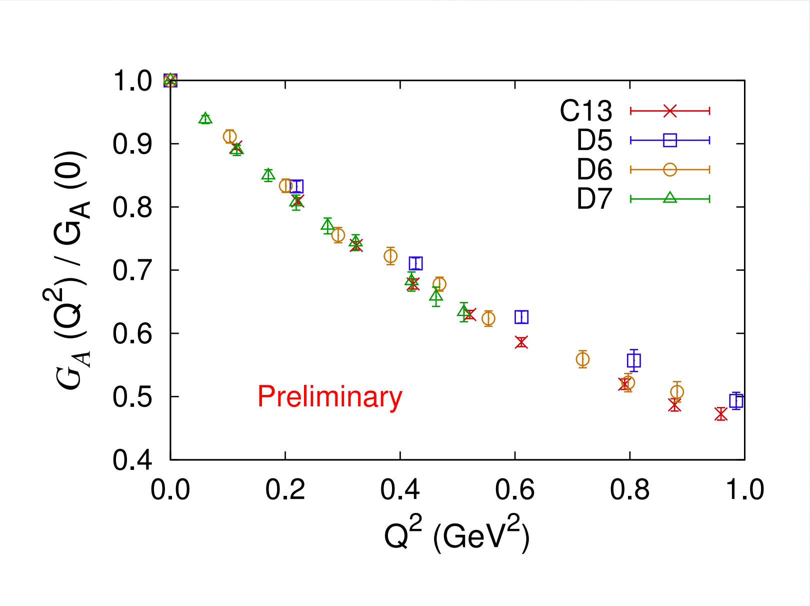
energy transferred to nucleus

from Benhar, Day, Sick, RMP 2008
data Finn, et al 1984

Beyond single-nucleon physics is critical!

Neutrino Scattering

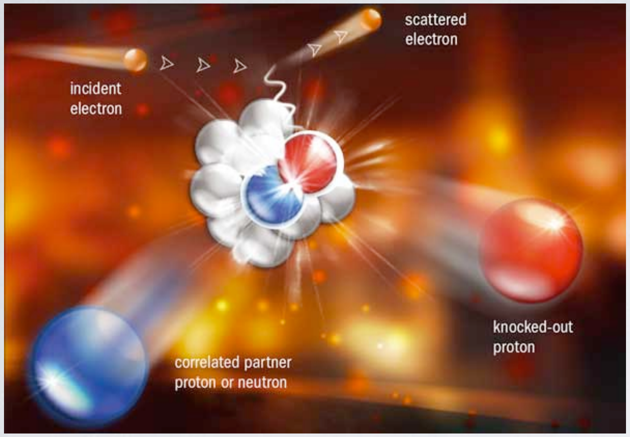




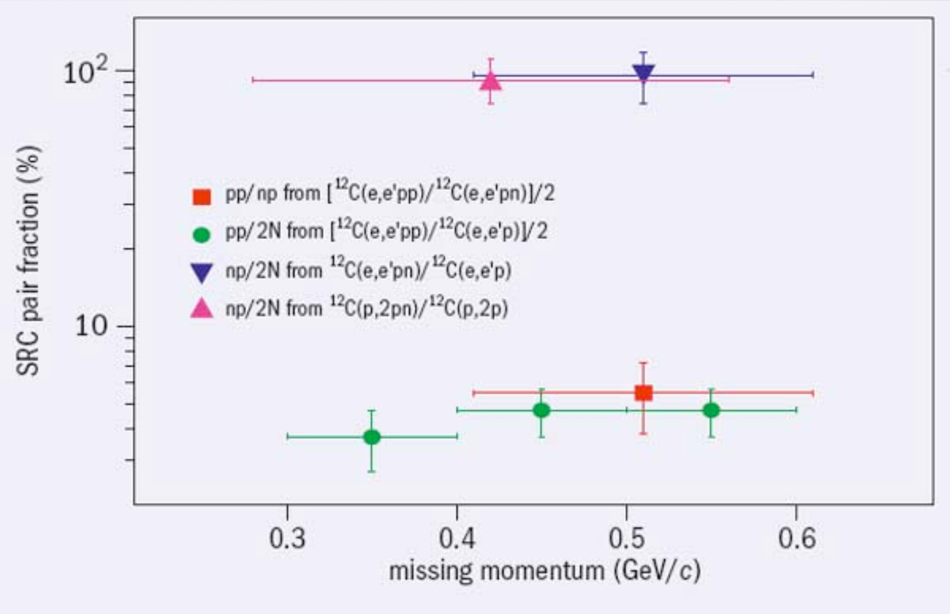
Significant Enhancement required, calculations show enhancement in Vector, Axial, and Interference Terms

Single-nucleon form factors from experiment or LQCD (LANL)

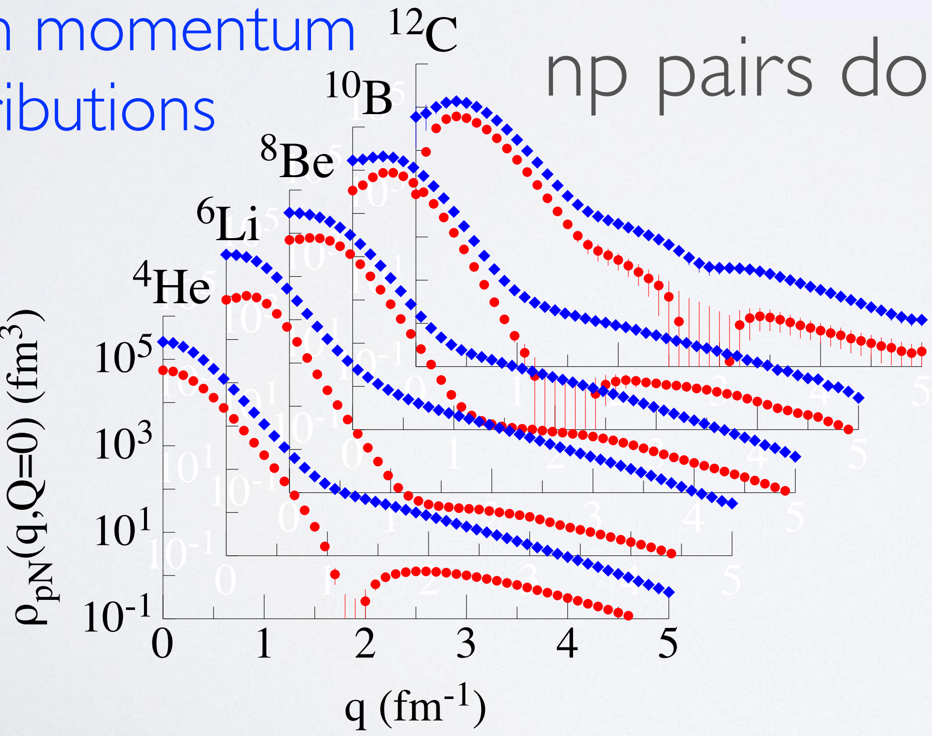
Back to Back Nucleons: Jlab experiments



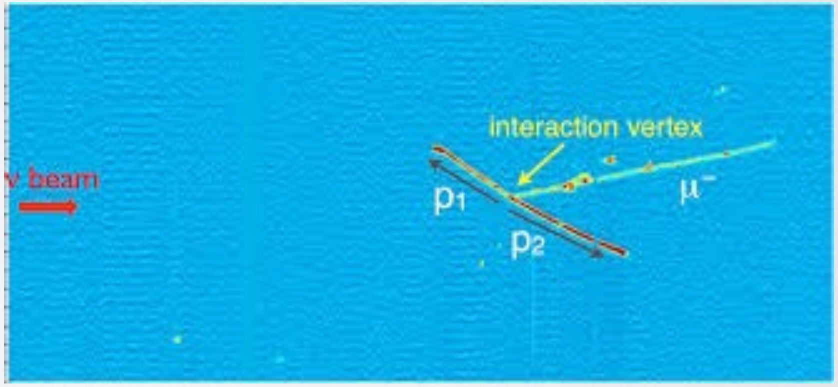
E Piasetzky *et al.* 2006 **Phys. Rev. Lett. 97** 162504.
M Sargsian *et al.* 2005 **Phys. Rev. C 71** 044615.
R Schiavilla *et al.* 2007 **Phys. Rev. Lett. 98** 132501.
R Subedi *et al.* 2008 **Science 320** 1475.



2-nucleon momentum distributions



np pairs dominate over nn and pp



Argoneut

np vs. pp

Carlson, et al, arXiv:1412.3081

^{12}C electron scattering: Quantum Monte Carlo

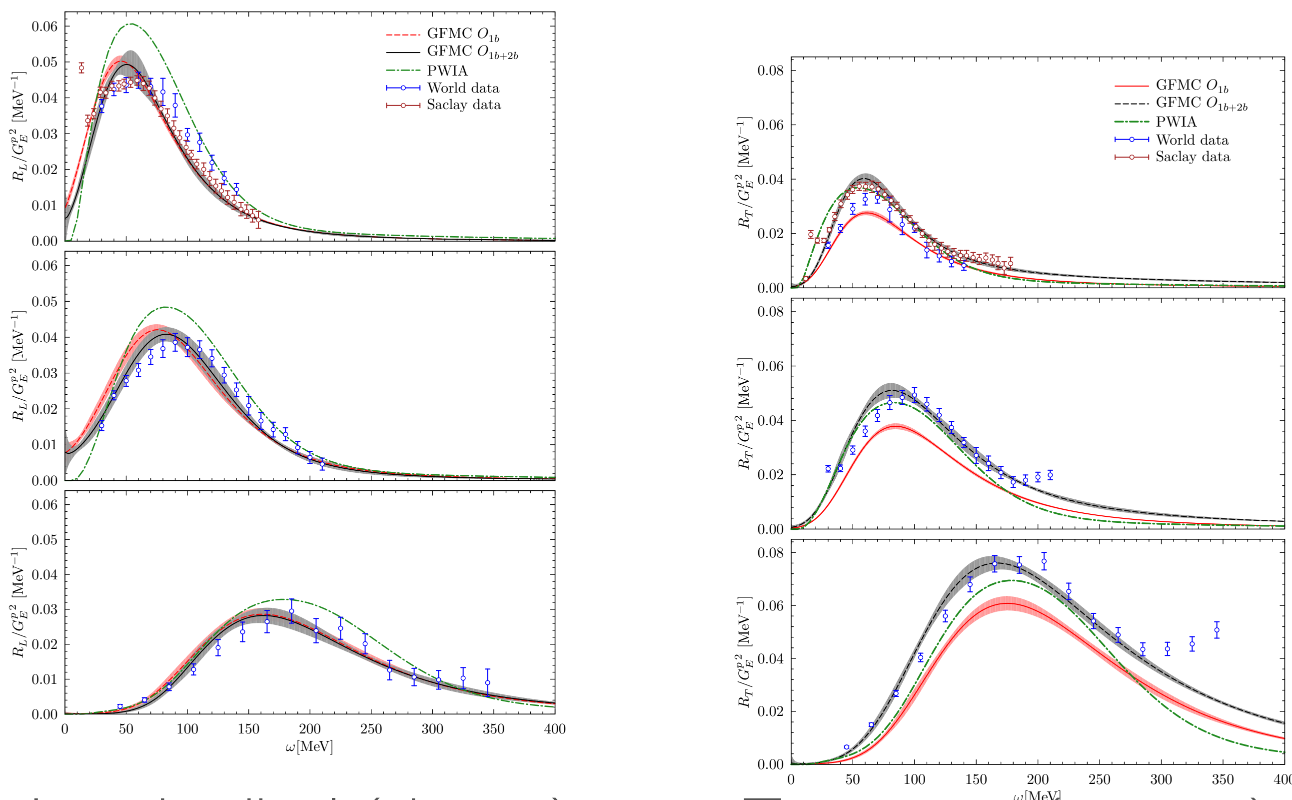
Imaginary Time (Euclidean) Response w/ Maximum Entropy

$$\tilde{R}(q,\tau) \;=\; \langle 0|\; \mathbf{j}^\dagger \;\exp[-(\mathbf{H}-\mathbf{E_0}-\mathbf{q^2}/(\mathbf{2m}))\tau]\;\; \mathbf{j}\;|\mathbf{0}\rangle >$$

Full treatment of initial and final state and 2N currents

q=300

q=570

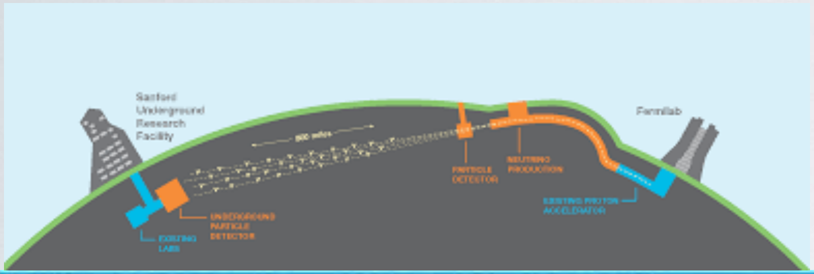


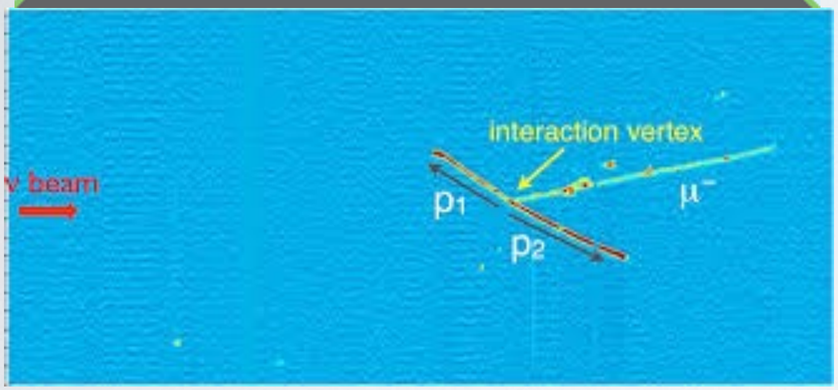
Longitudinal (charge)

Transverse (current)

Lovato, et al., PRL 2016

Neutrino scattering in Argon





- AFDMC of sum rules and imaginary time response
- Factorization at neutrino vertex
- Quantum / classical transition implemented in generators

GENIE (classical MC) used for data analysis

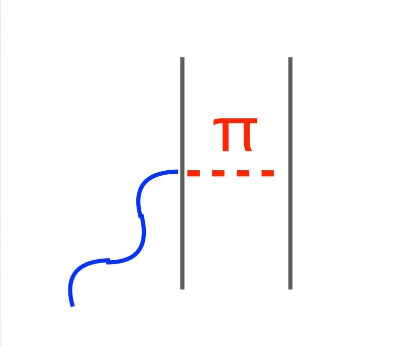
- *at present at single-nucleon level*
- *incorporating two-nucleon physics at quantum level*

genie-mc.org

Electromagnetic Moments and Transitions

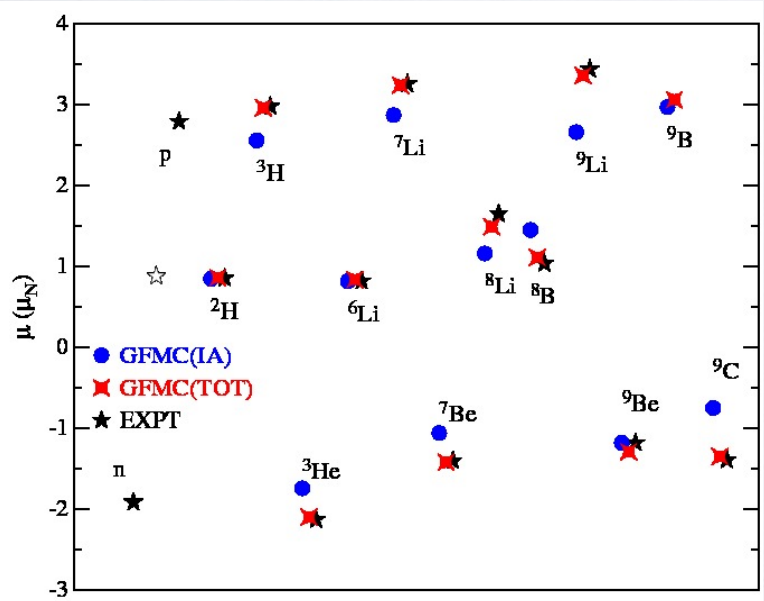
Beyond single-nucleon currents

$$\mathbf{j} = \sum_i \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$

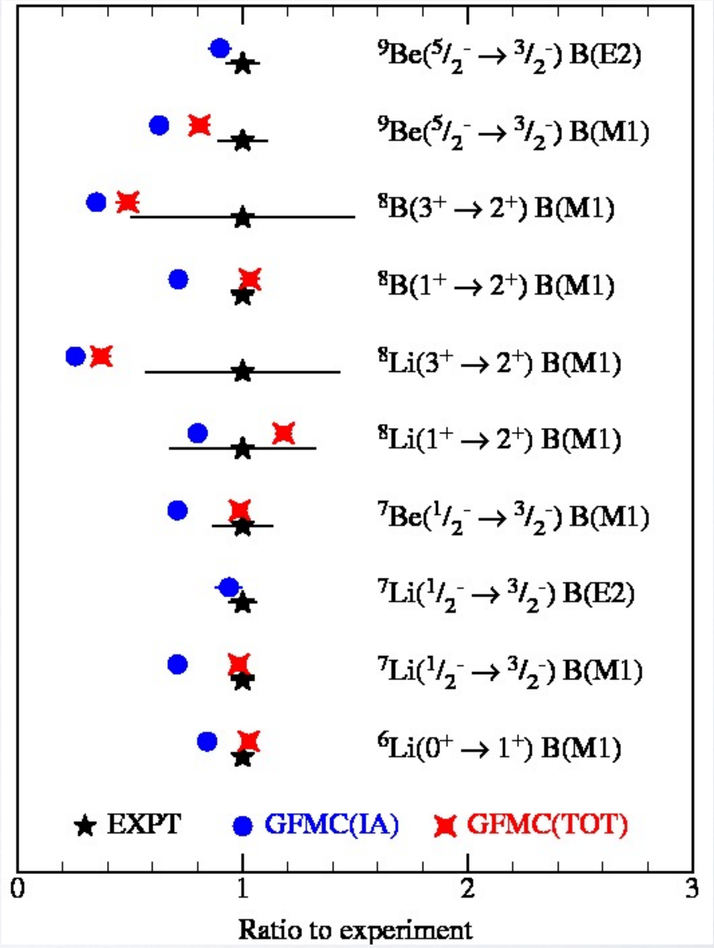


Two-nucleon currents required by current conservation

Input from expt and lattice QCD



magnetic moments

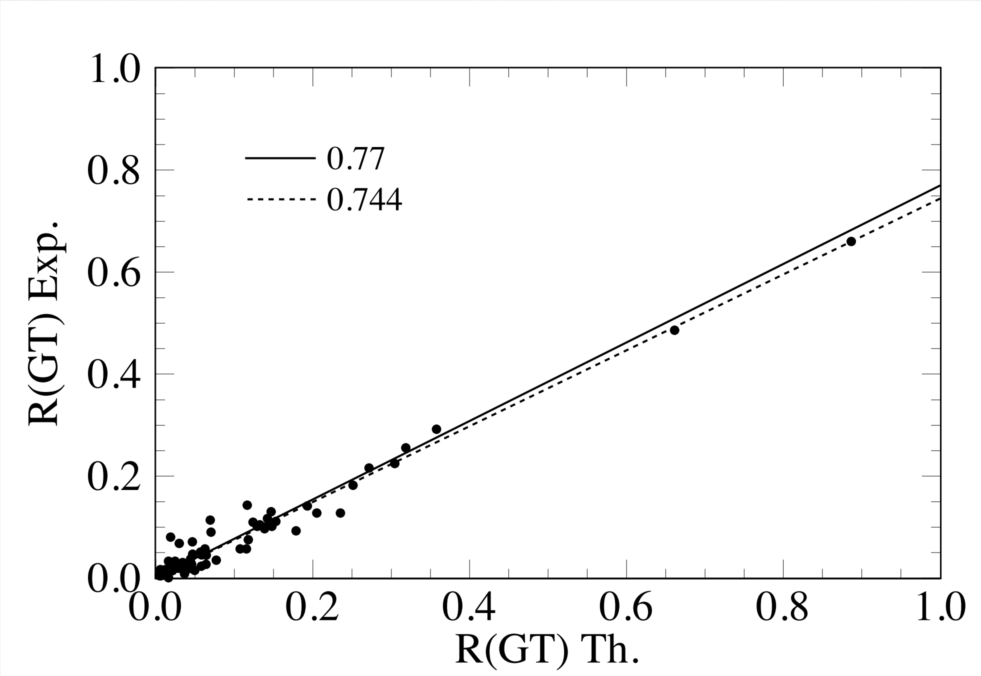


EM transitions

Single Beta Decay

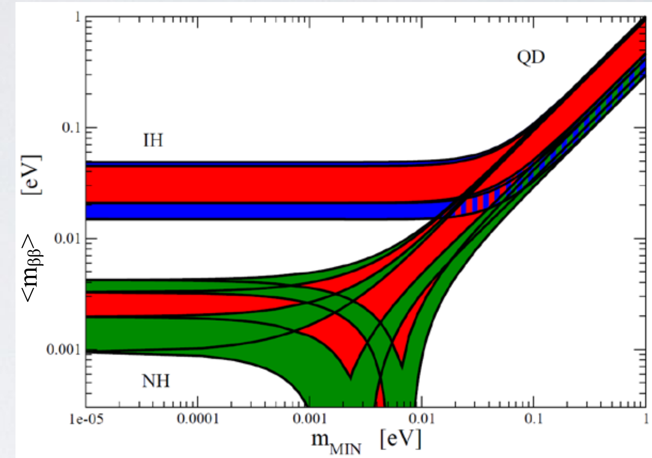
Very light nuclei (A<11) fit reasonably well with realistic currents and interactions. Modest suppression due to correlations (few % to ~10% w/ increasing A)

Note the sign of the two-nucleon effects (reduction) is opposite to quasi-elastic scattering (enhancement). Similar ~30-40% magnitude of the effect.

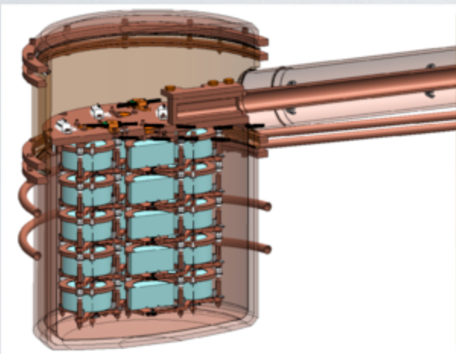


Neutrinoless Double Beta Decay
What is the role of two-nucleon correlations/currents?

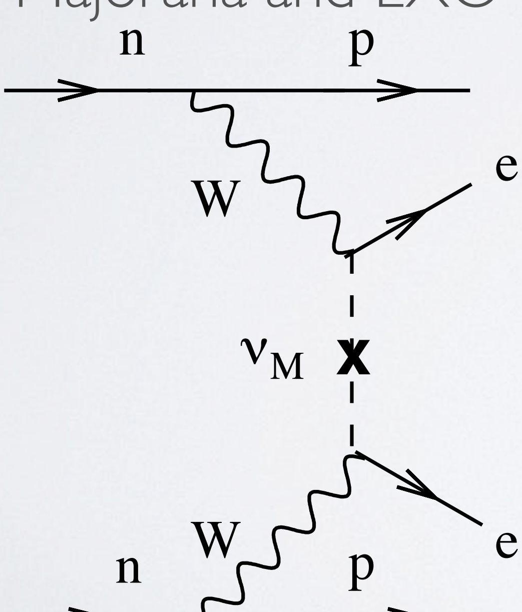
Absolute mass scale



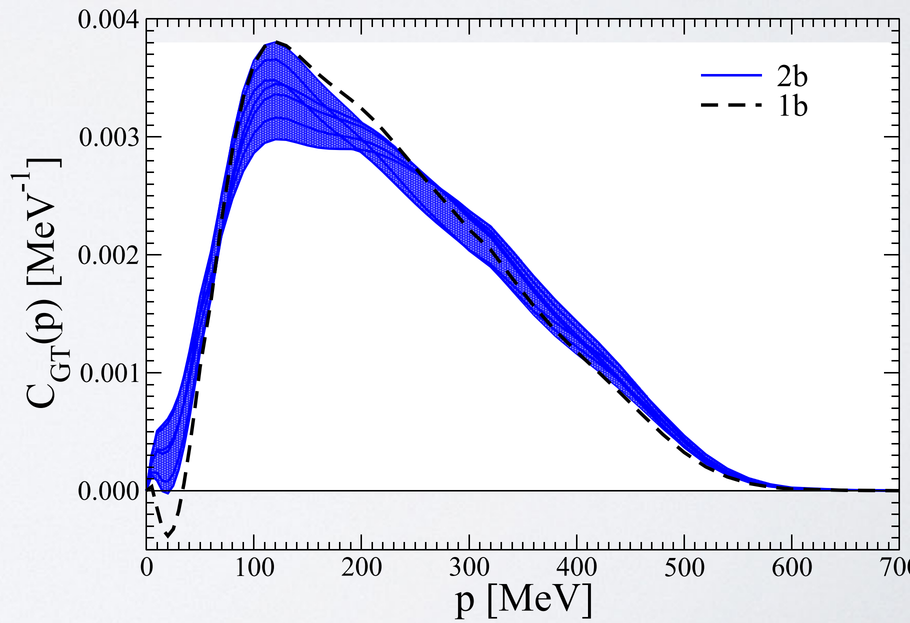
Rate g_A^4 : big impact



Majorana and EXO



Double Beta Decay (?)



Momentum transfer comparable to QE

Exciting Time for Nuclear Many-Body Theory

- Many connections to important experiments in NP:
  FRIB, JLAB, Double-beta decay
- Many important connections to experiments beyond NP
  HEP (neutrinos), Gravitational Waves, Cold Atoms, …
- Important ties to Theory over a wide range of scales:
  Lattice QCD
  Supernovae, Neutron Star Merger Simulation
- Rapidly advancing algorithms and computers
- Outstanding young people

Thanks to NC State,
Dean, Joaquin,
Stefano
and all of you.