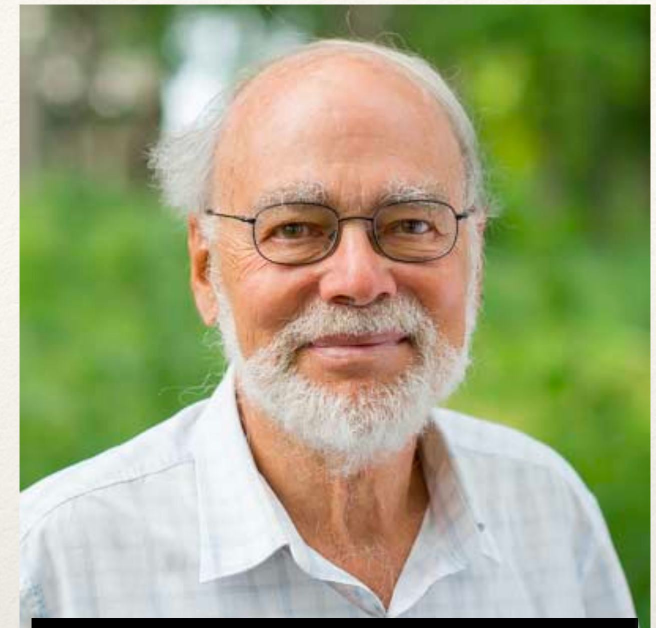
Quantum Monte Carlo and Nuclear Physics:
Steven C. Pieper

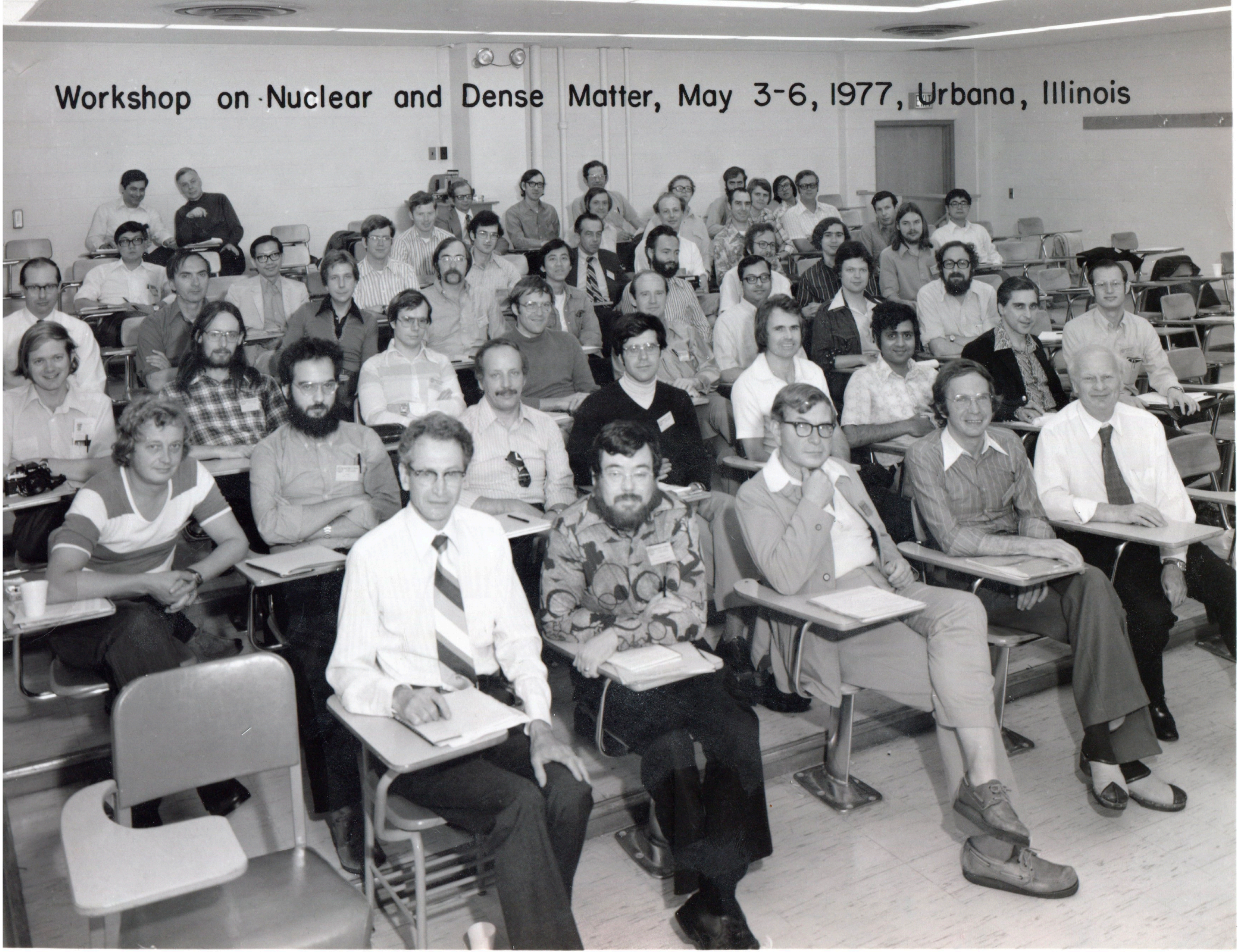
- Early days of Nuclear QMC
- Ground States
- EM form factors and transitions
- Excited States and Low Energy Scattering
- Neutron Matter and Drops
- Electron and Neutrino Scattering
- Outlook



Argonne NATIONAL LABORATORY

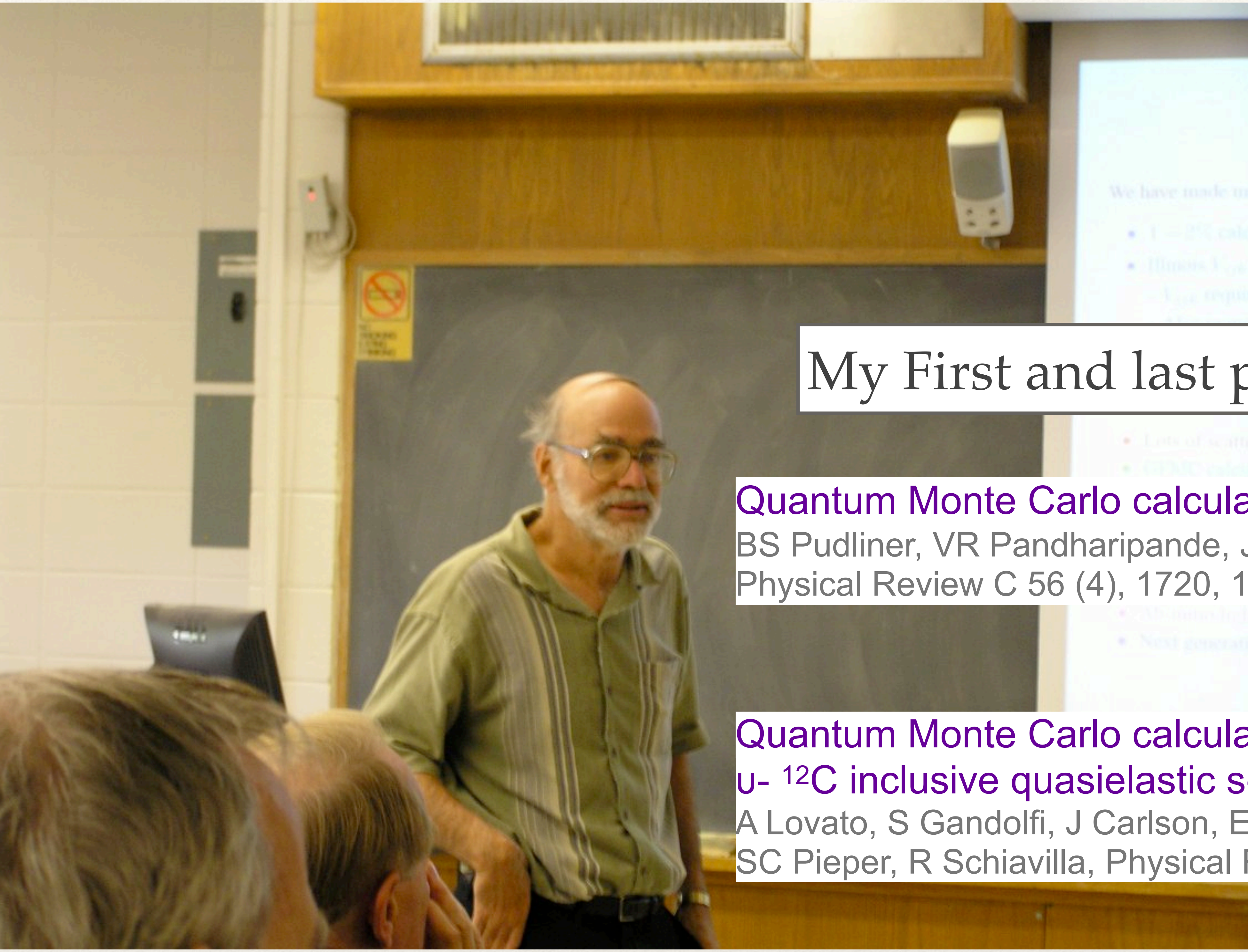


AV18 celebration


Workshop on Nuclear and Dense Matter, May 3-6, 1977, Urbana, Illinois

Find in the picture

- Nobel Prize Winner
- Director of INT
- Former Secretary of DOE
- Professors from:
  Cornell, Illinois, MIT, Minnesota,
  Pisa, Stony Brook, …
- Several other past, current
  leading scientists in NP



My First and last papers w/ Steve

Quantum Monte Carlo calculations of nuclei with A≦7
BS Pudliner, VR Pandharipande, J Carlson, SC Pieper, RB Wiringa
Physical Review C 56 (4), 1720, 1997.

Quantum Monte Carlo calculation of neutral-current υ- ^{12}C inclusive quasielastic scattering
A Lovato, S Gandolfi, J Carlson, E Lusk,
SC Pieper, R Schiavilla, Physical Review C 97 (2), 022502, 2018

~26 Papers w/ S.C. Pieper

Nuclear Spectra with A≤7
Pion exchange and three-nucleon forces
A=8 nuclei
Benchmark of A=4
Excited states in A=6,8
RMP 2015. (QMC methods for Nuclear Physics)
Tensor Forces and the Ground State of Nuclei
Neutron-alpha scattering
Nucleon and Pair-momentum distributions
Neutron Drops and Skyrme density Functionals
Cold neutrons trapped in external fields
Charge Form Factor and Sum Rules in 12C
Neutral Weak currents in inclusive scattering from 12C
EM and neutral-weak response functions of 12C
Isovector spin-longitudinal and transverse response of nuclei
EM response of 12C
Neutron Matter: A superfluid Gas

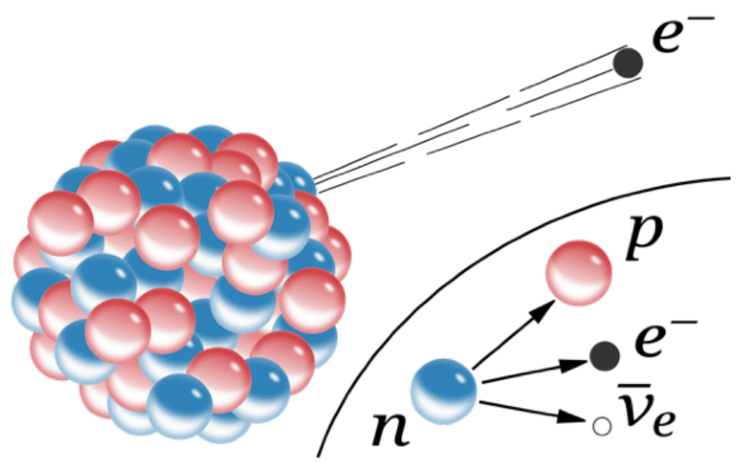
I was Vijay's Graduate Student at Urbana
(VMC of A=3,4; quark models)
visited Bob at ANL to work with advanced computers
Mal gave QMC lectures at Urbana
…
Bob and Vijay recruited Steve to QMC work
I went to Courant (NYU) to work with Mal Kalos and Kevin Schmidt

Excellent combination of ingredients:

Good physics problem: interacting nucleons to nuclei
Rapidly advancing tools: from very primitive to very advanced computers
Excellent Collaborators: Steve Pieper

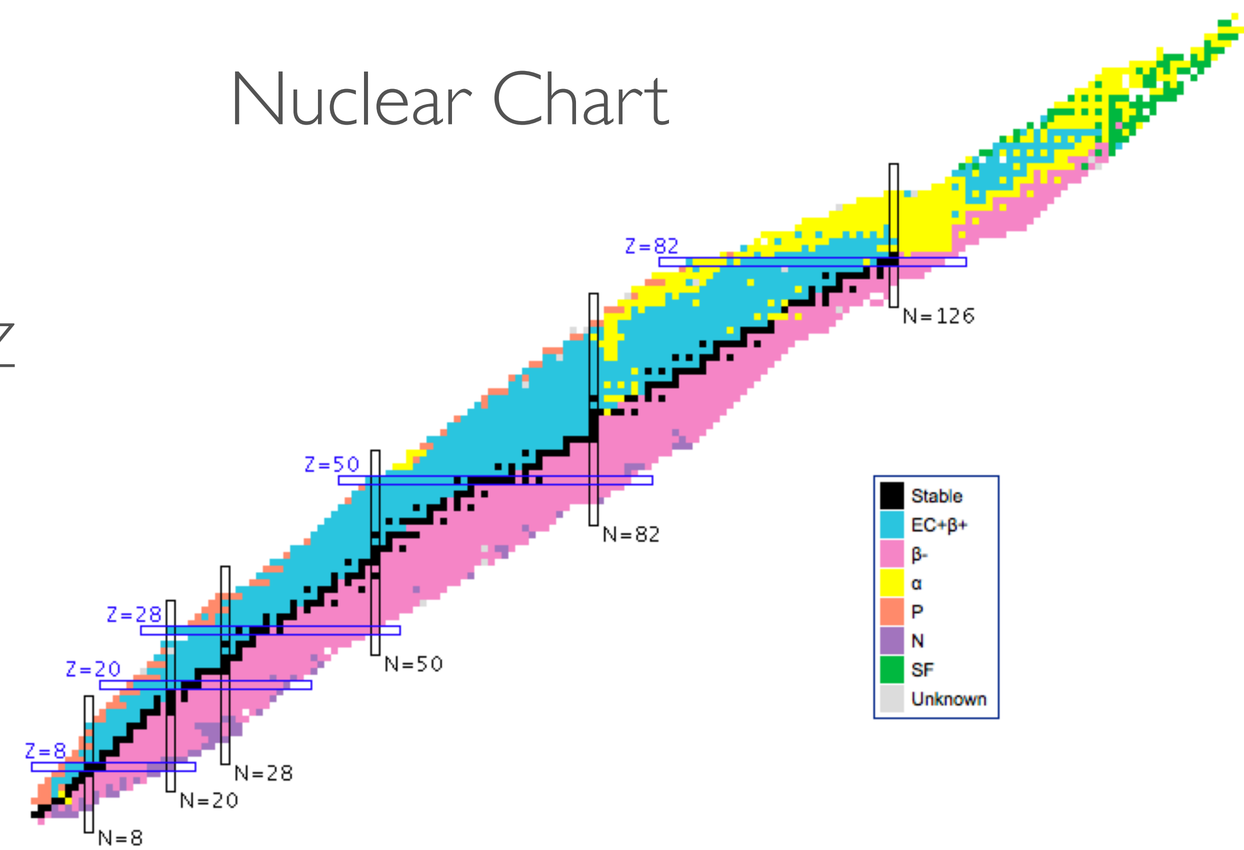
Nuclei are a strongly correlated many-body systems

- nuclear binding, Equation of State
- Superfluidity, Beta Decay, …



Nuclear Chart

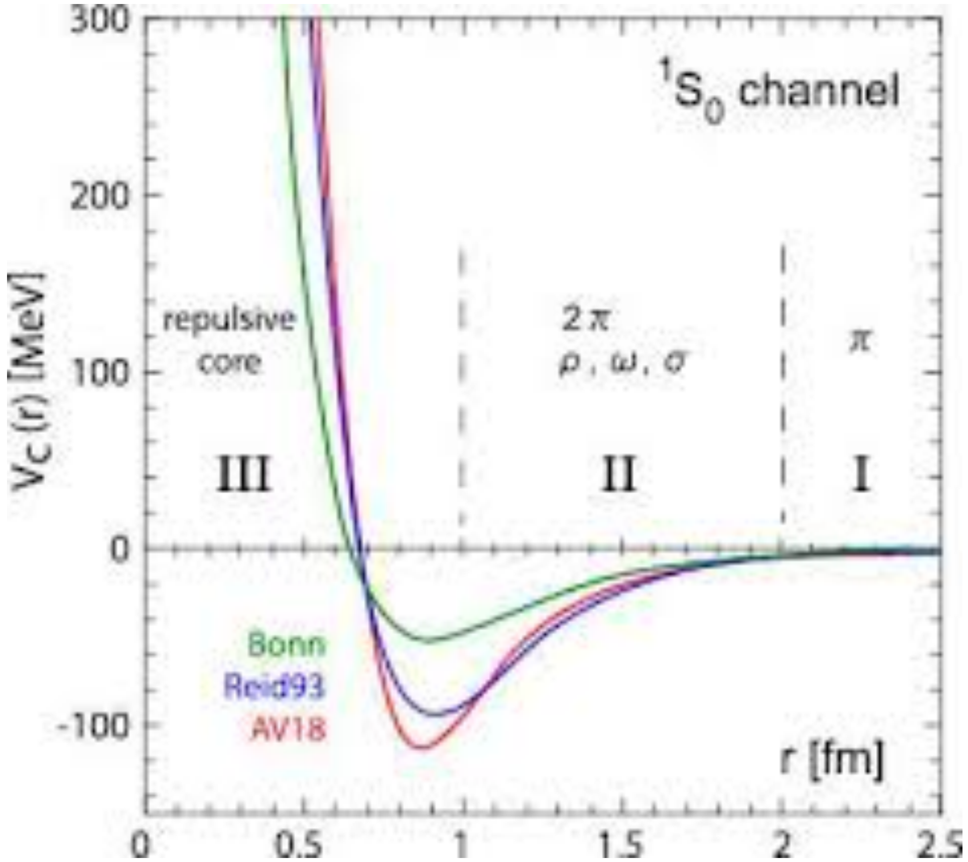
Z



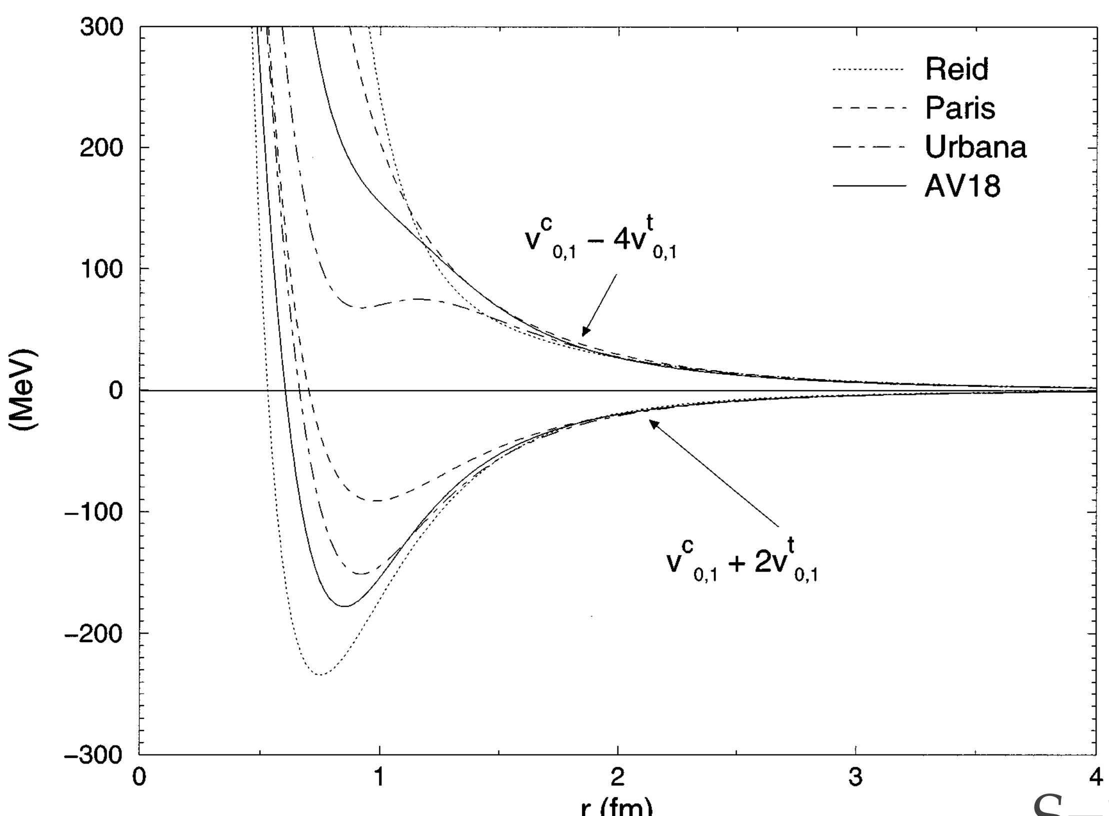
N

- nucleosynthesis (r-process)
- beta decays
- electron and neutrino scattering
- neutron stars
- fundamental symmetries (EDM, beta decay, etc.)

Nuclei and Nuclear Interactions

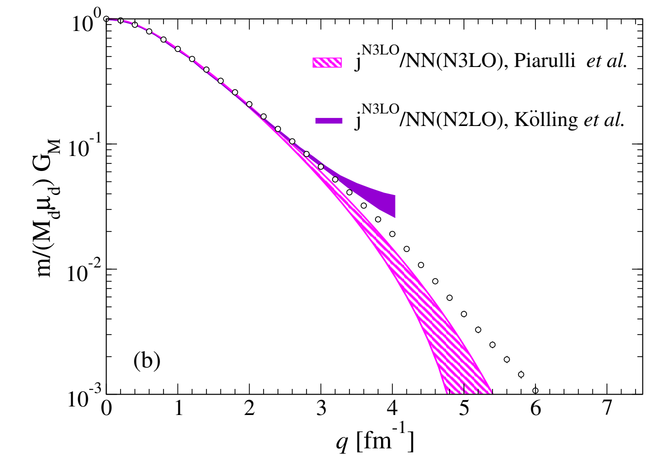


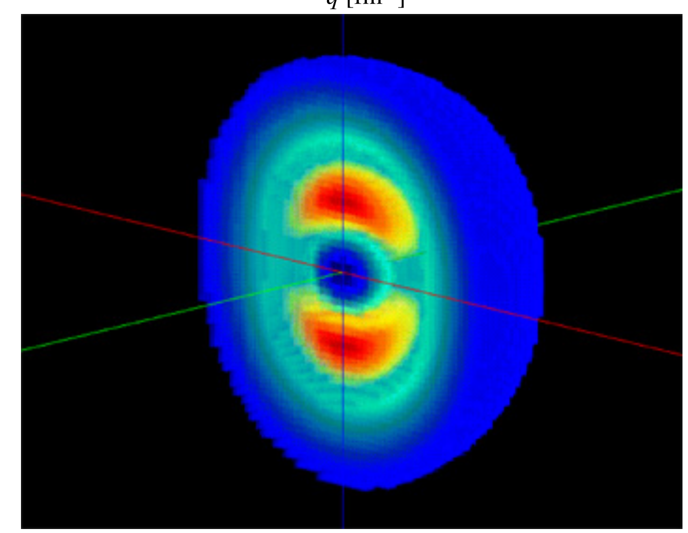
S=0 T=1 channel

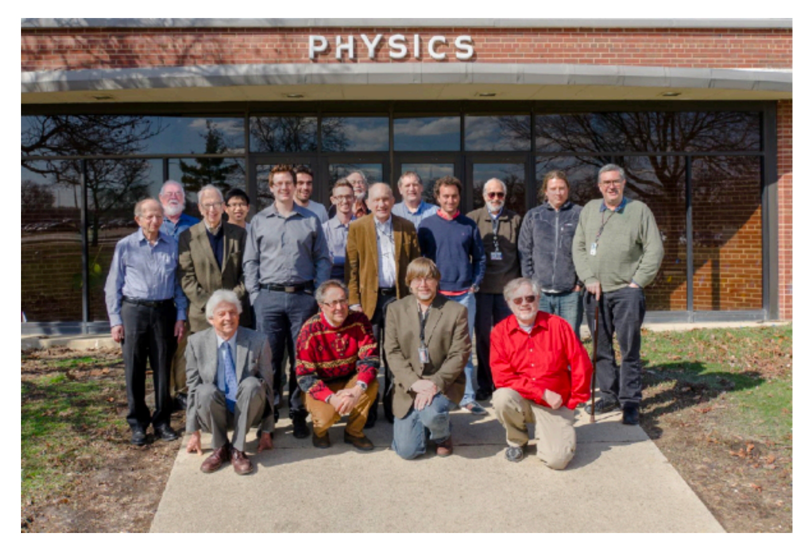


S=1 T=0 channel

Deuteron form factors







Strongly Correlated Quantum Many-Body Physics

Must solve the quantum many-body problem: structure & dynamics

cautions:

The Schrodinger equation cannot be solved accurately when the number of particles exceeds about 10. No computer existing, or that will ever exist, can break this barrier because it is a catastrophe of dimension ...
Pines and Laughlin (2000)

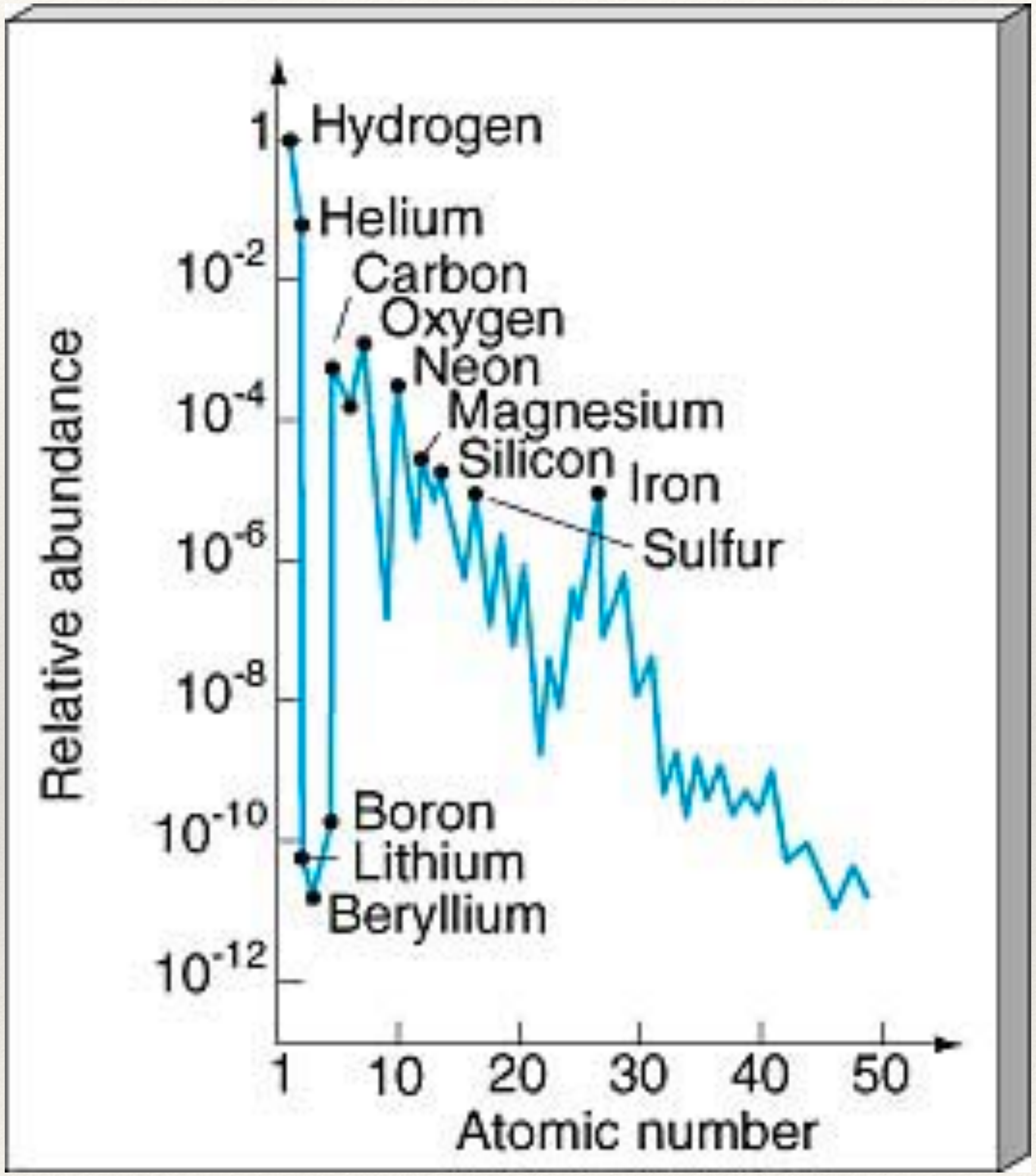
In general the many electron wave function Ψ ... for a system of N electrons is not a legitimate scientific concept [for large N]
Kohn (Nobel lecture, 1998)

but often we do not need a complete description of the system: thermal properties, samples of path integral, cluster expansions,…

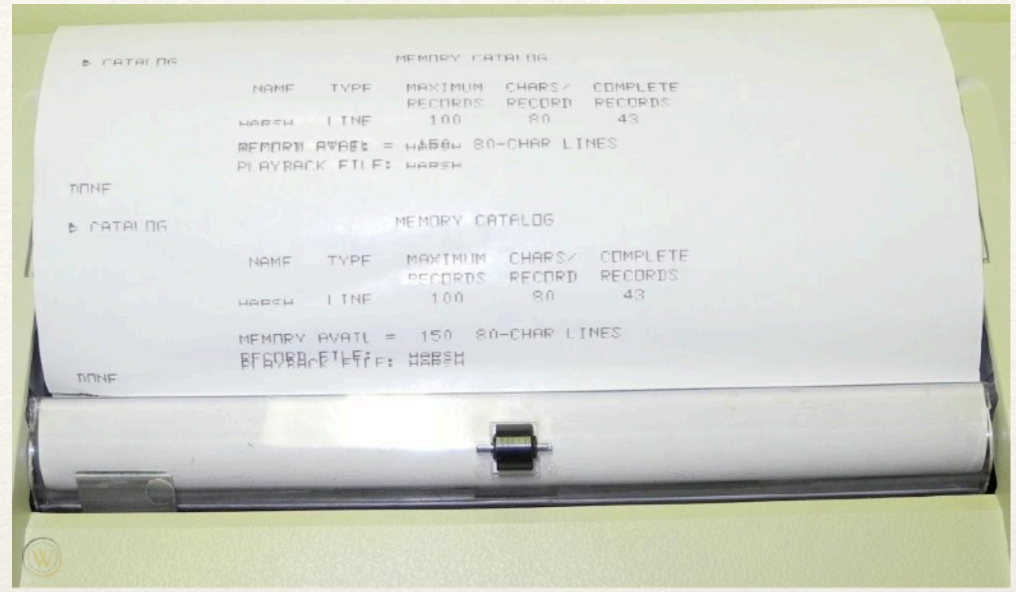
Quantum Monte Carlo, Coupled Cluster and other many-body methods

Abudance of the Elements in the Galaxy

Z	Element	Mass fraction (ppk)
1	Hydrogen	739
2	Helium	240
8	Oxygen	10
6	Carbon	5
	Total	99.4%



TI Silent 700 terminals



Apple II for a terminal

Cyber 175

THE VAST COMPUTATIONAL power of the large-scale Control Data CYBER 176 computer system in the company's Houston Data Center is monitored from this control console. The system is used primarily to run petroleum industry applications.

Courant Institute

1980s:
The Ultracomputer

Design Underway:
Mal Kalos, Allan Gottlieb,
and Jack Schwartz

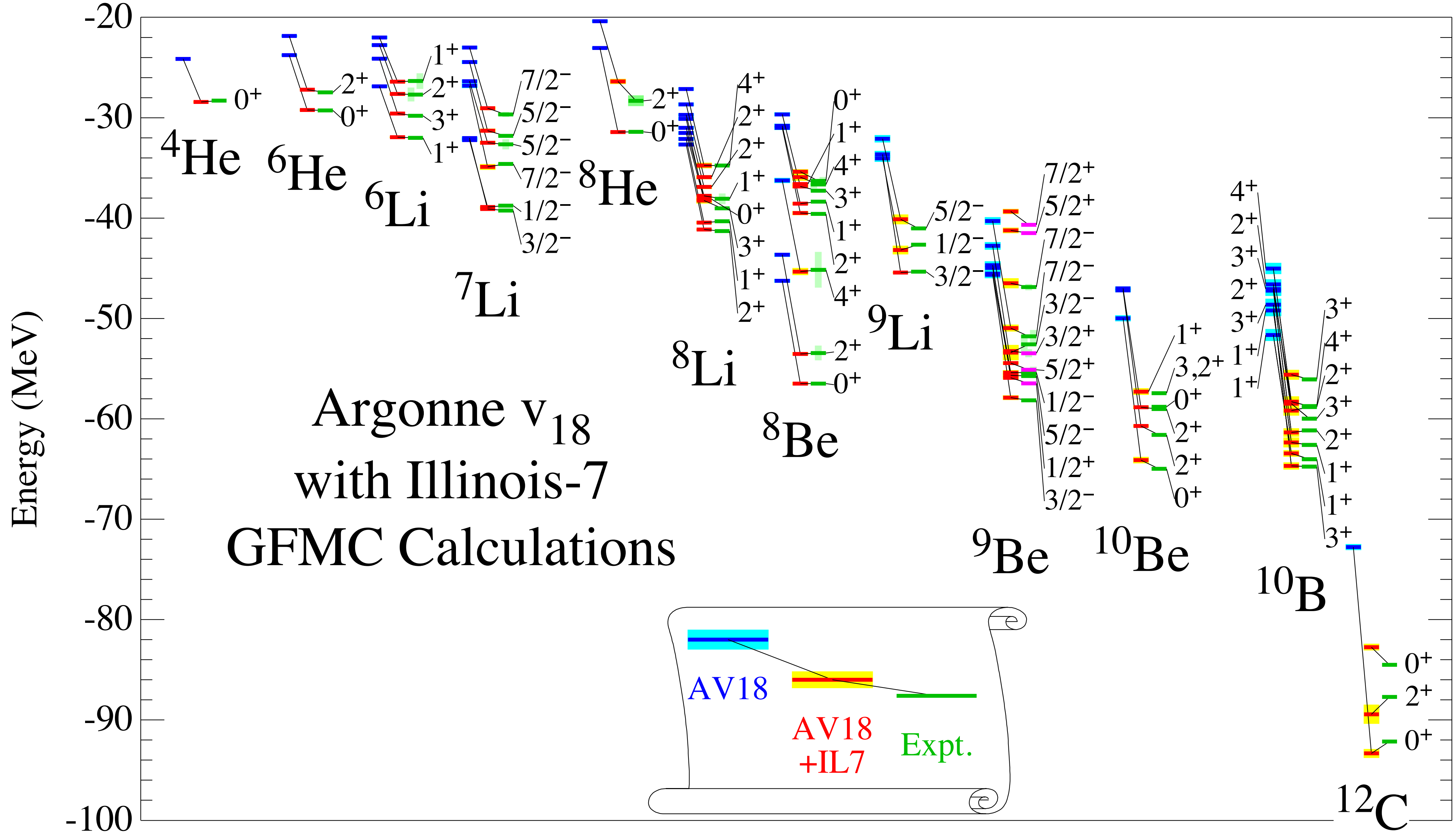
my time as a PD at Courant, with the group of Mal, Paula Whitlock, Jules Moskowitz, w/ frequent visitor Geoffrey Chester around this time

Kevin Schmidt returned to NYU as a chemistry professor

- work on Liquid Helium, nuclear VMC calculations, low-energy nuclear scattering

Over the years, much bigger and faster computers
and the software to use them effectively

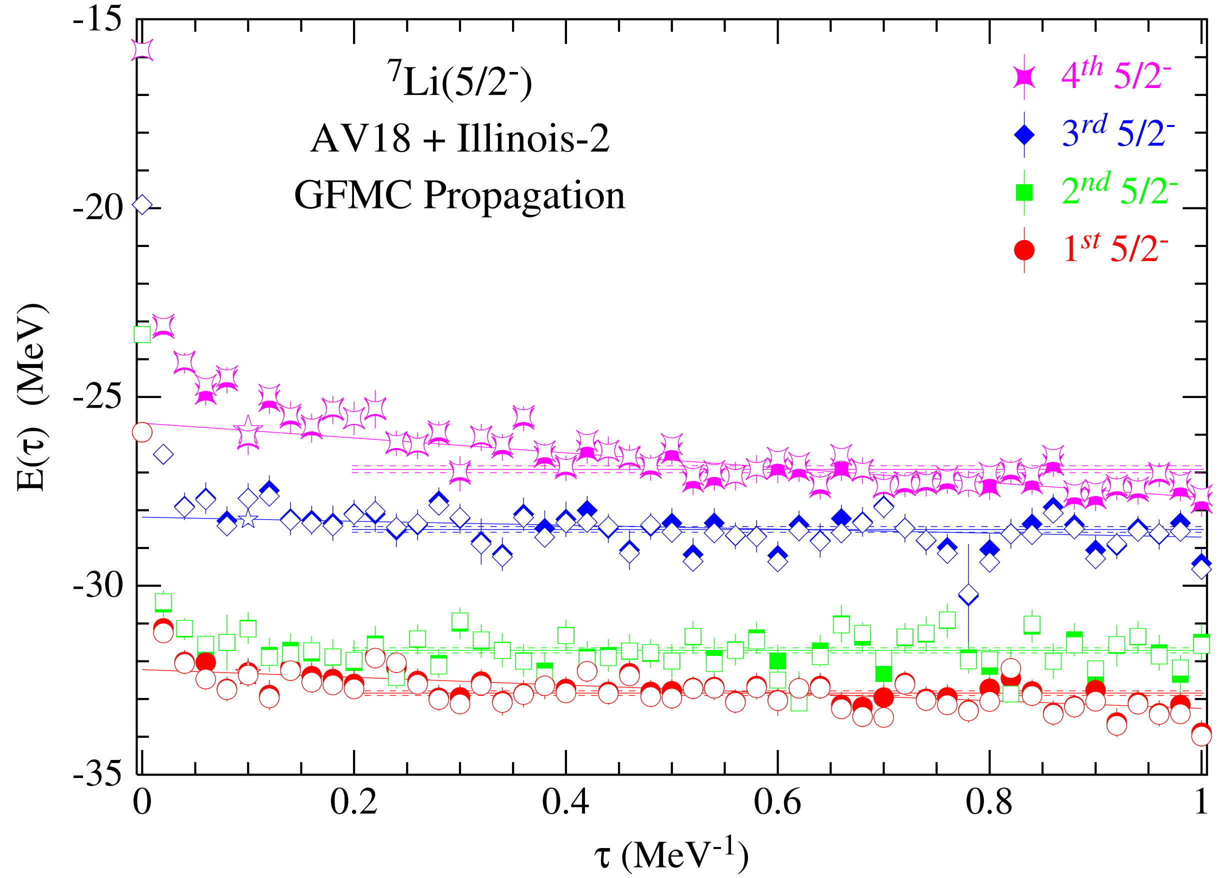
One 'Solution' to problem of dimension:
solve up to A~12



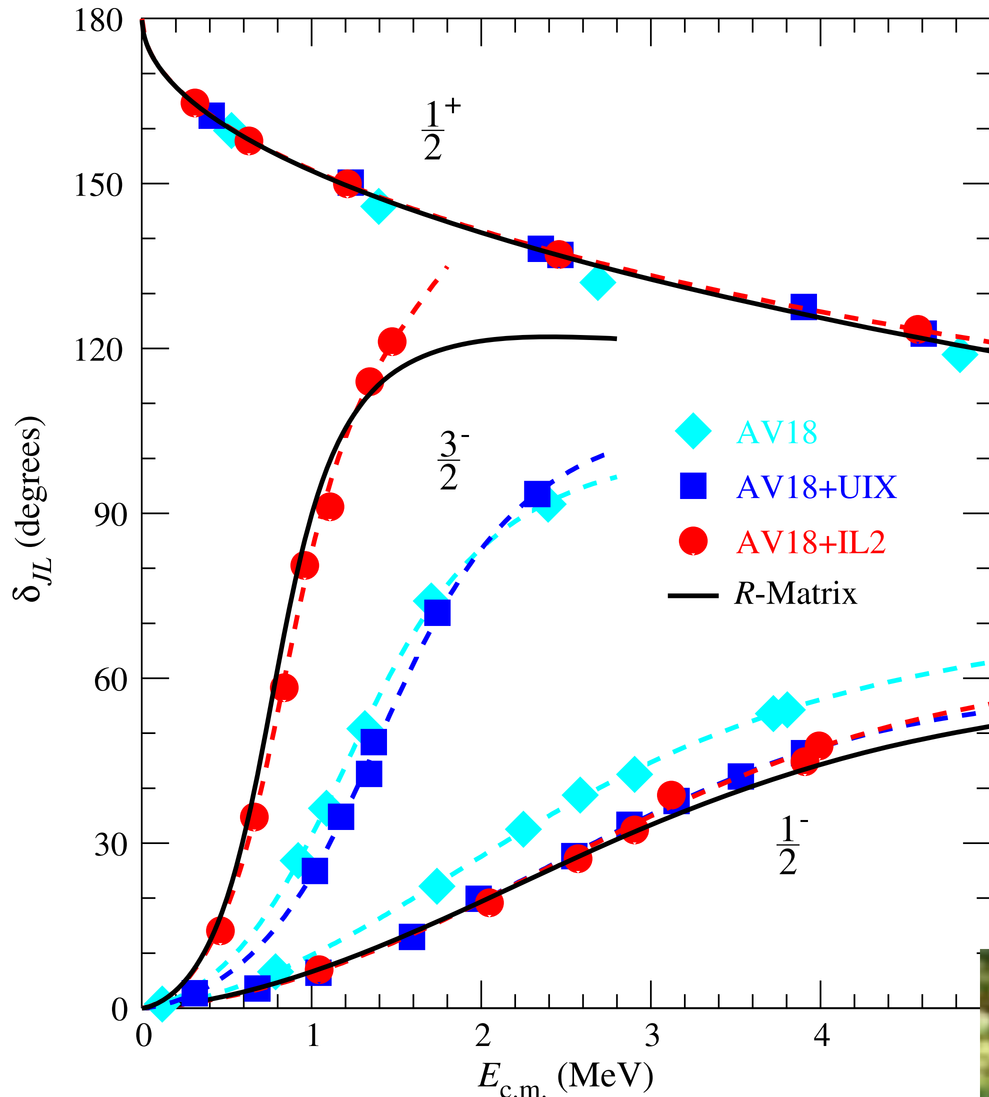
Pieper, Wiringa, Carlson, Schiavilla, …

Carlson, et al, RMP 2015

Low Energy Scattering



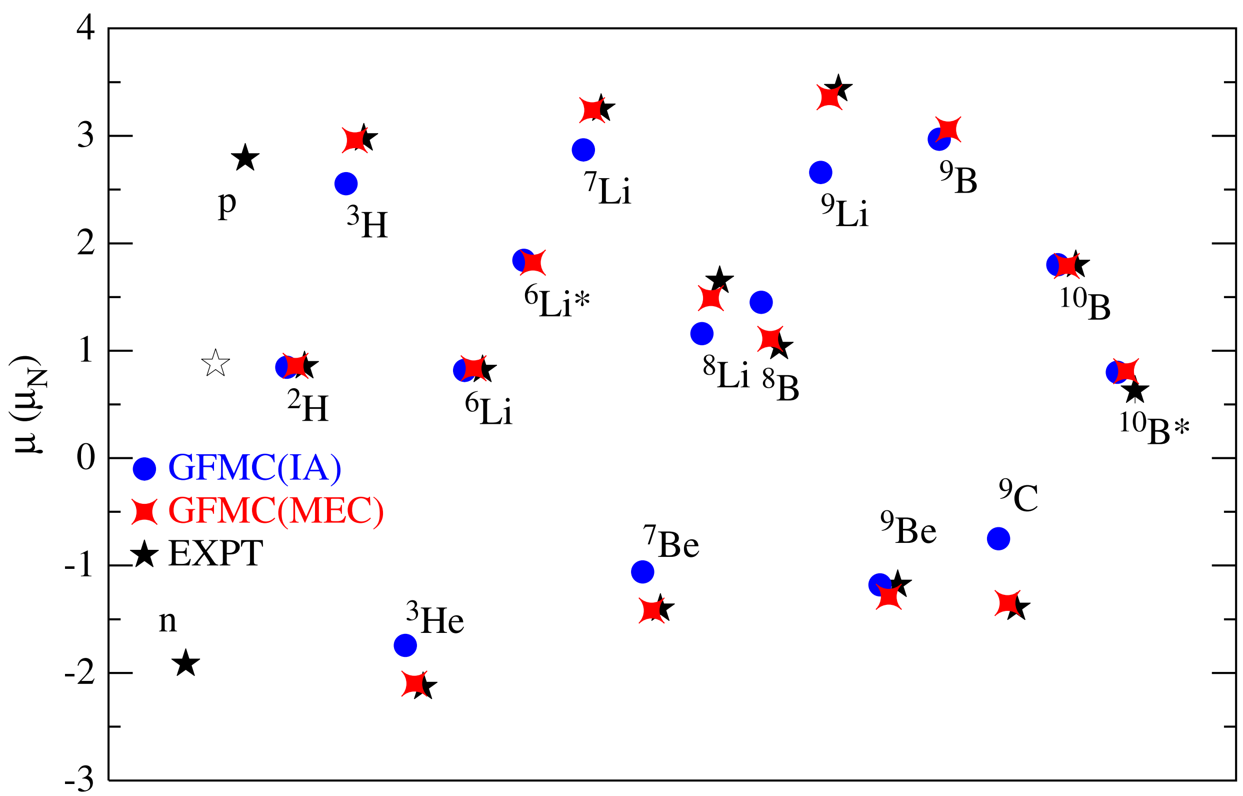
States in ^{7}Li
width of resonance
correlated to E vs. tau
Pieper, et al, 2004



Neutron-alpha scattering
Nollett, et al., 2007

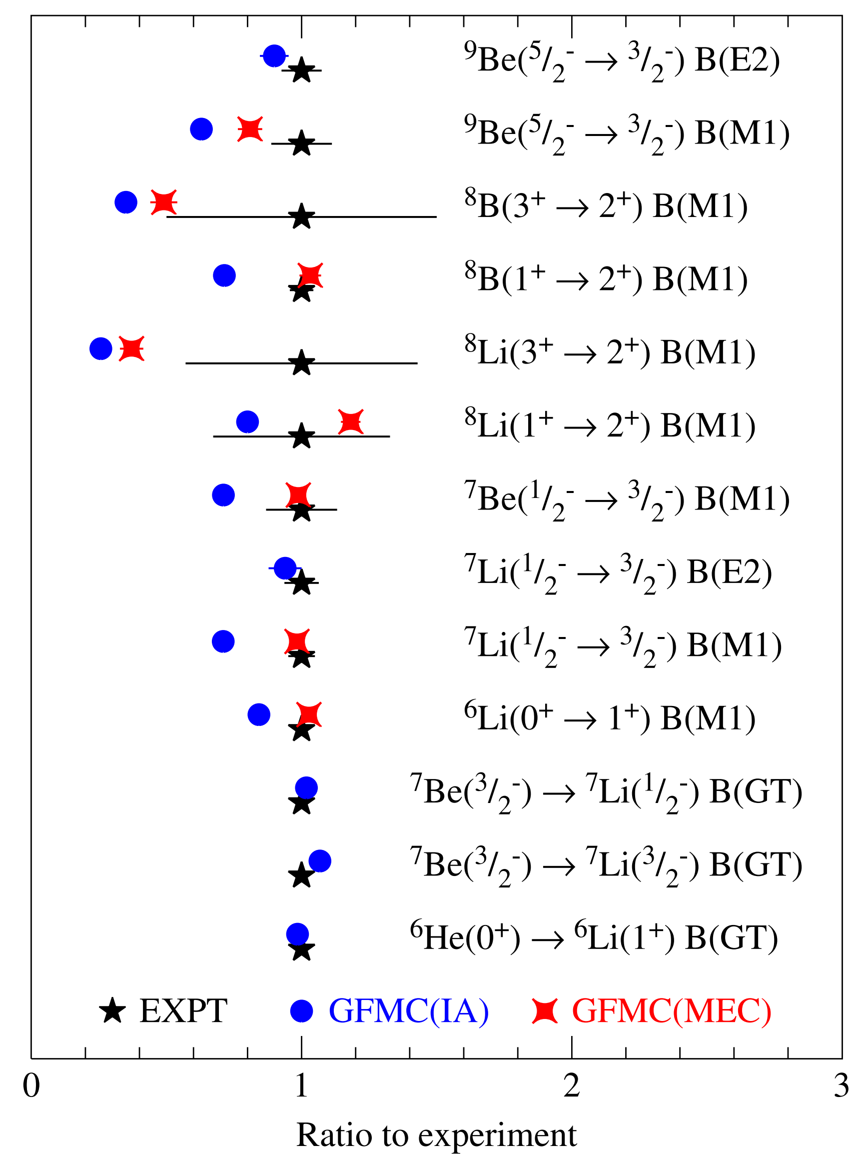
Electroweak Observables: Transitions

Magnetic Moments

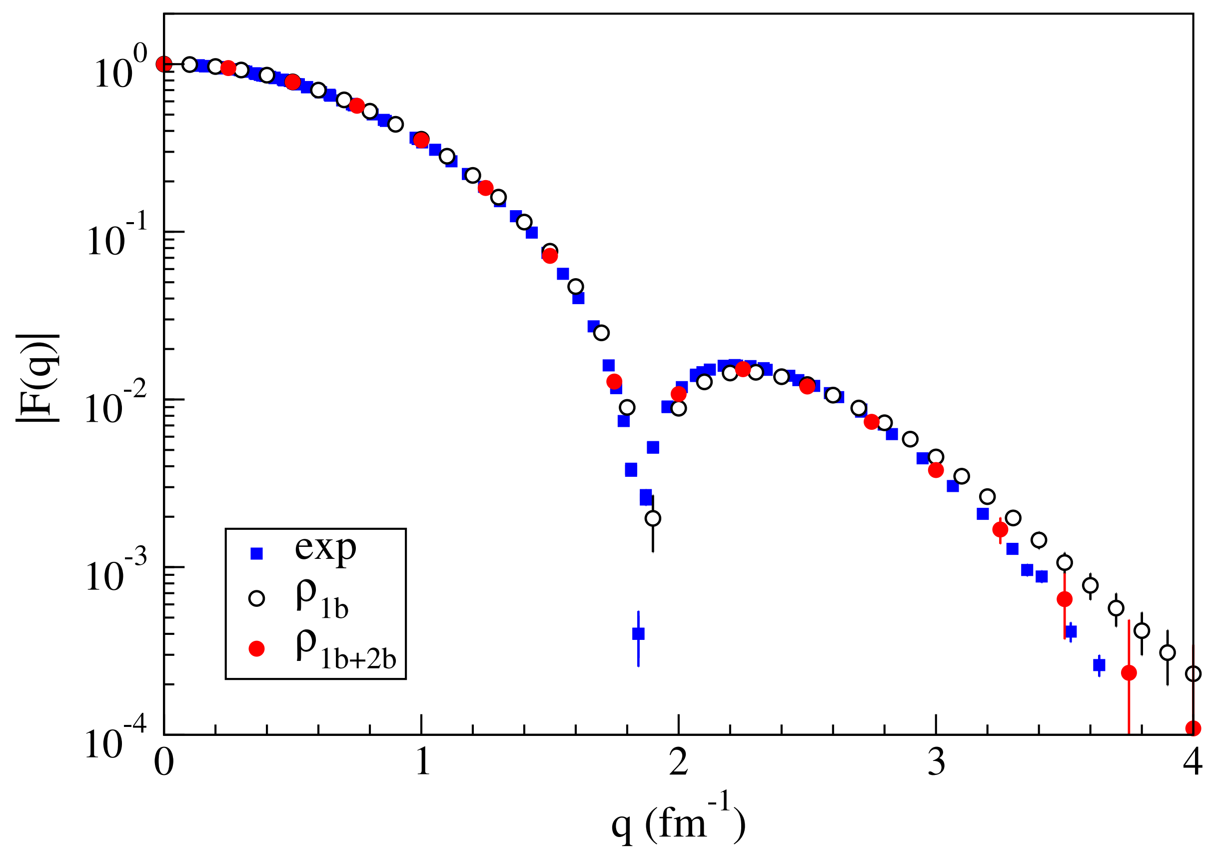


Pastore, et al., 2013 and 2014

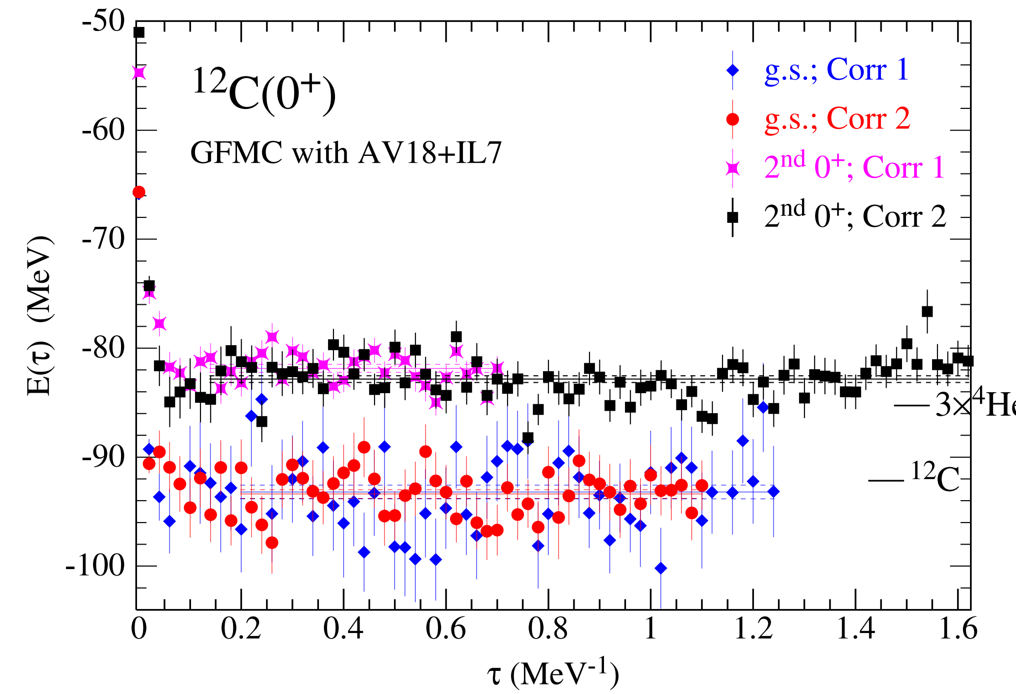
EM transitions



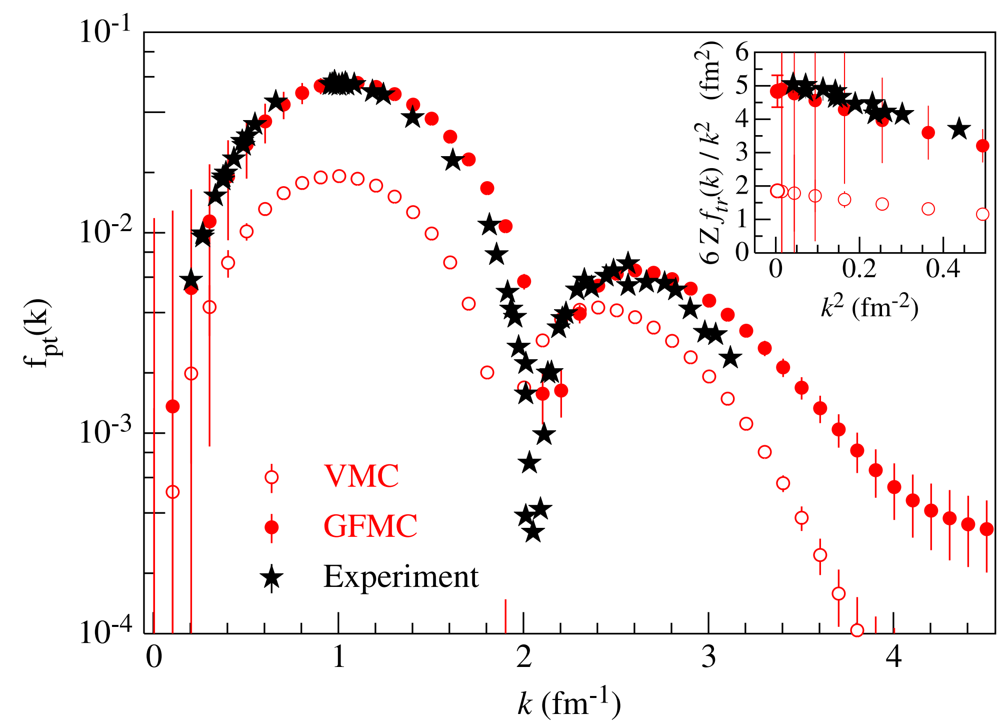
Nuclear Properties: A=12 Ground and Hoyle States



^{12}C charge form factor
Lovato, et al., 2013



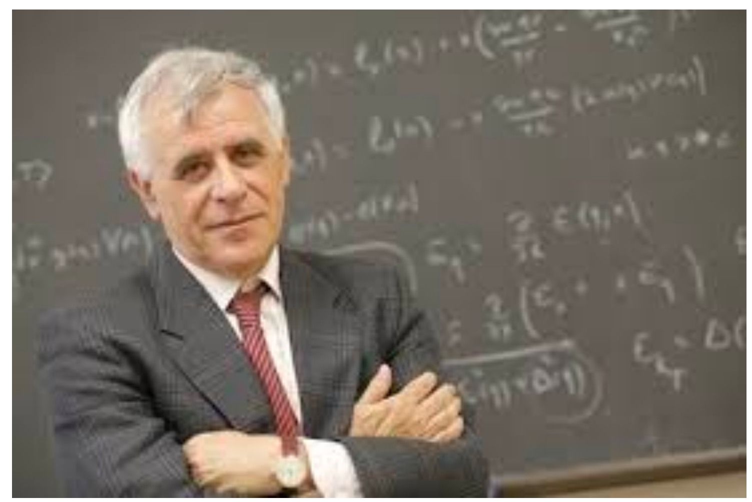
Hoyle State; Chernykh et al, 2010

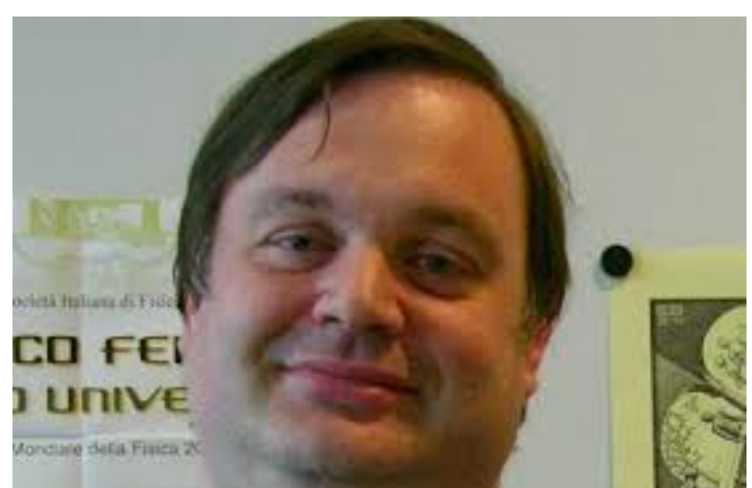


Auxiliary Field QMC: Monte Carlo also for spins/isospins

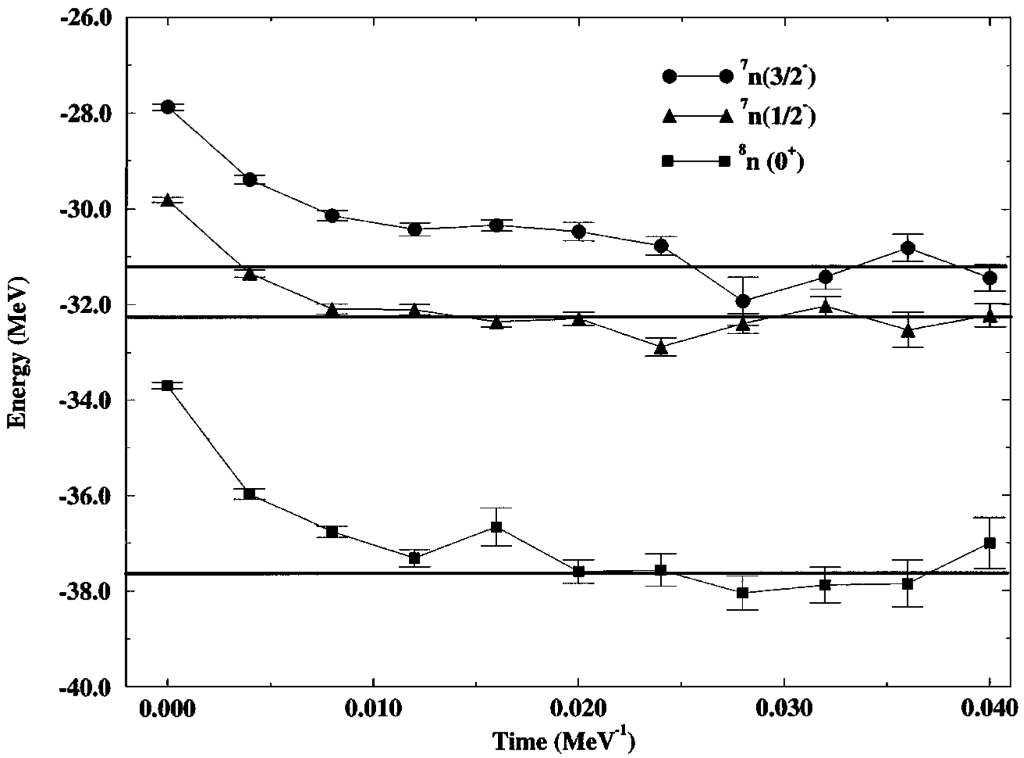
Applications to larger nuclei: ^{16}O,… to neutron matter and stars

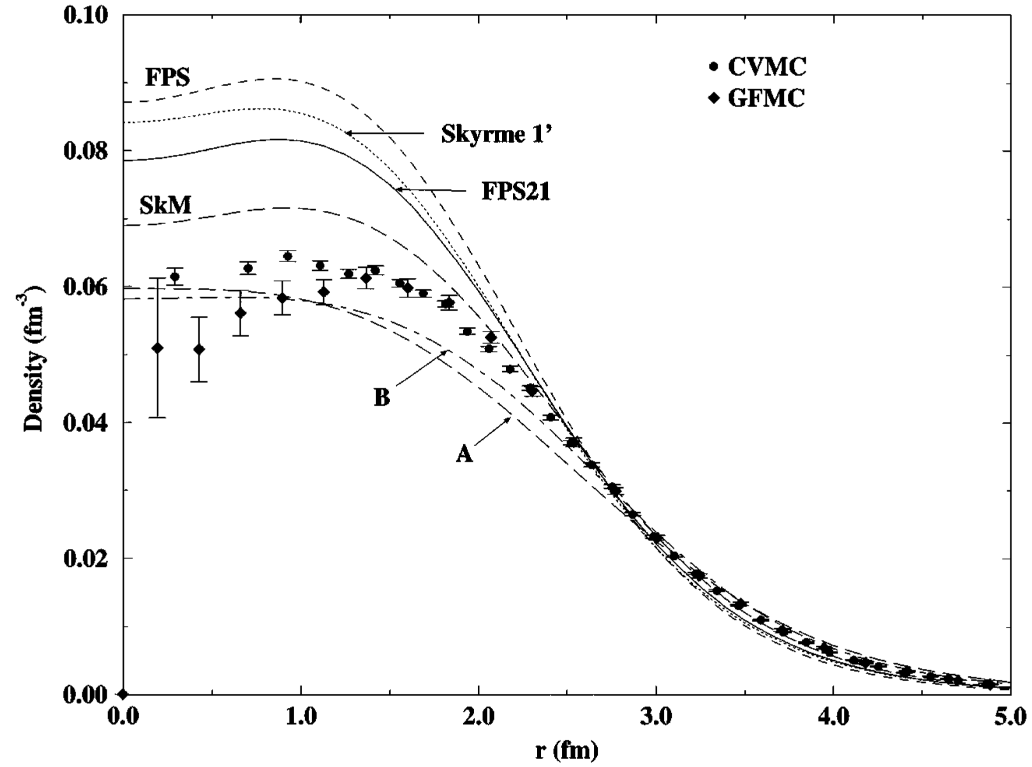
hyperons in neutron star matter



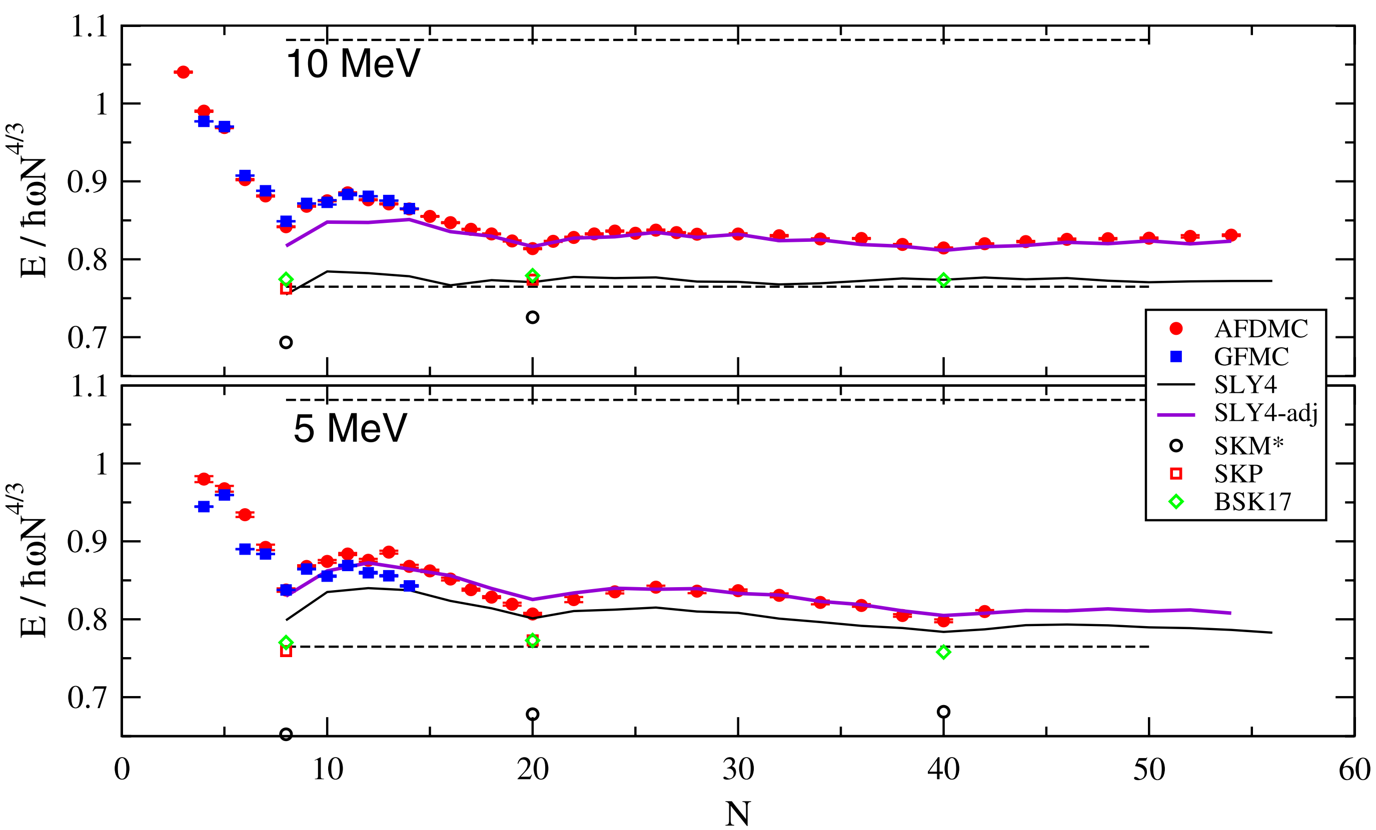


Neutron Drops and Inhomogeneous Neutron Matter





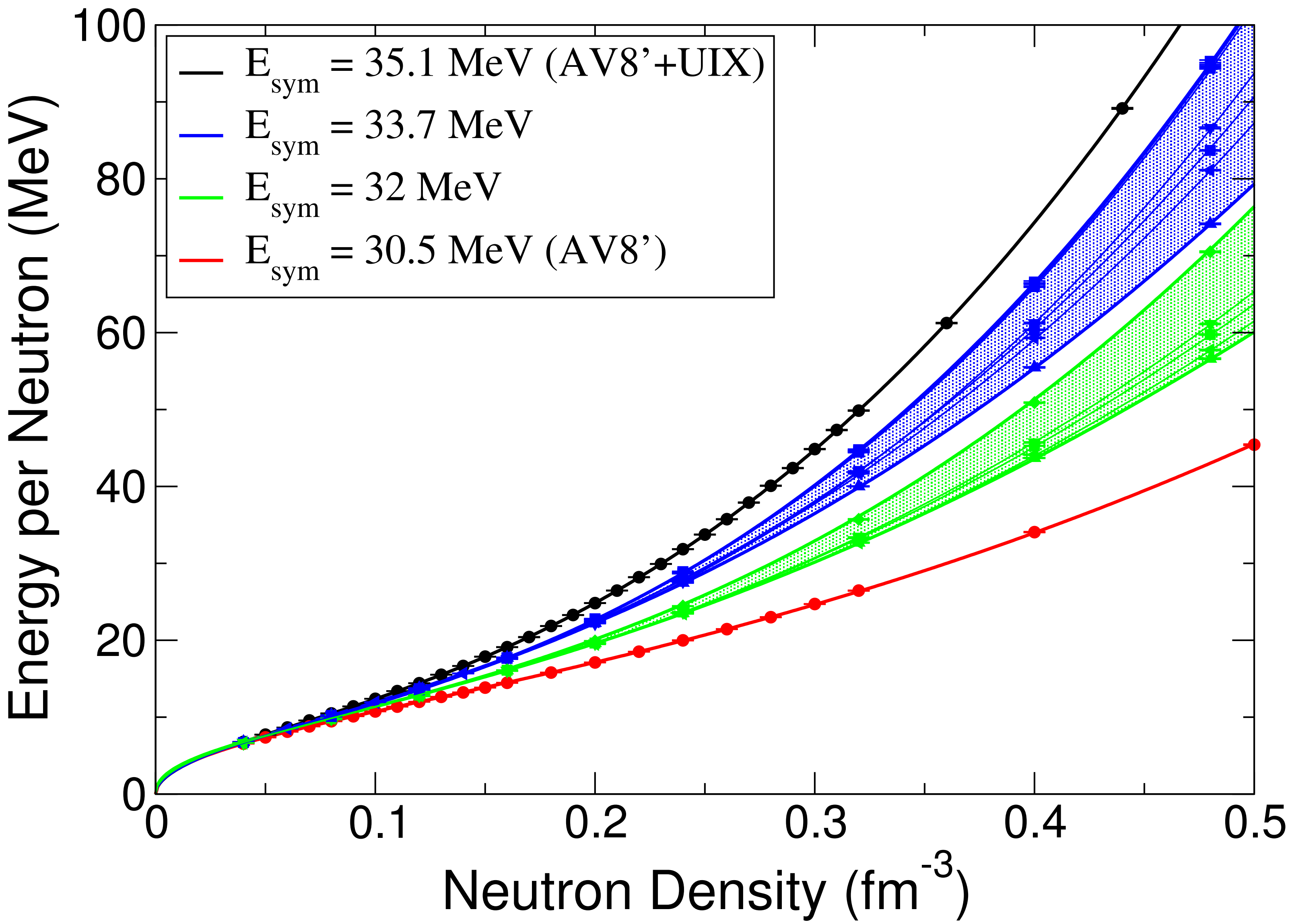
n = 7,8; Pudliner, et al, PRL, 1996

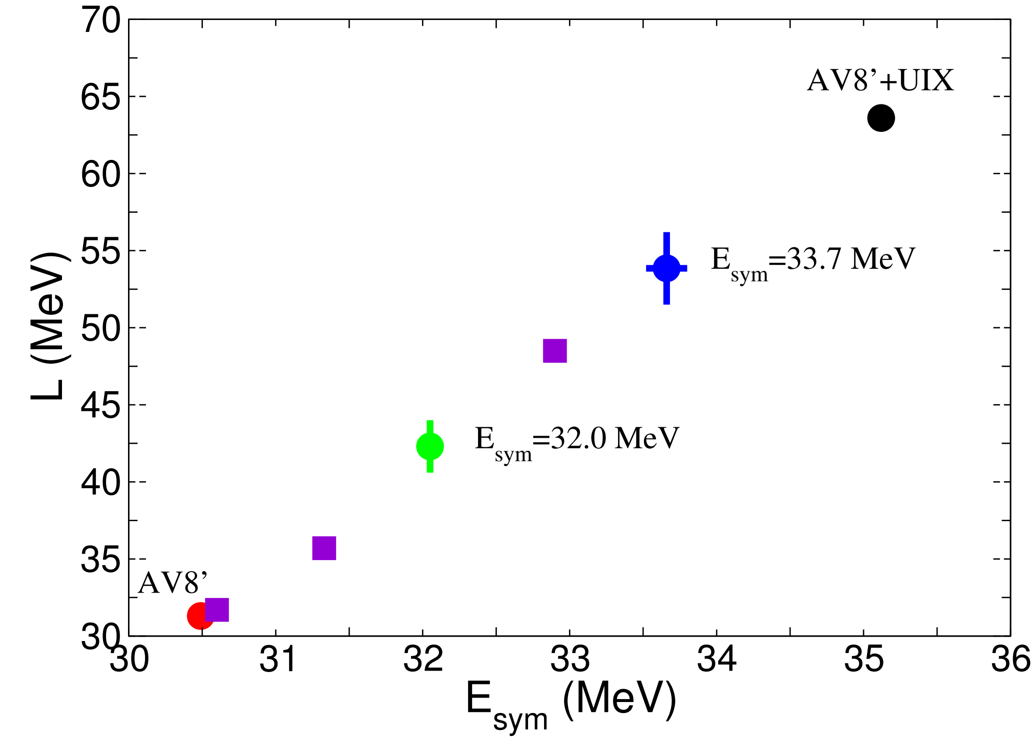


Cold Neutrons Trapped in External Fields; Gandolfi, et al, PRL 2011

Neutron Matter at higher density and the Three Neutron Interaction

S.

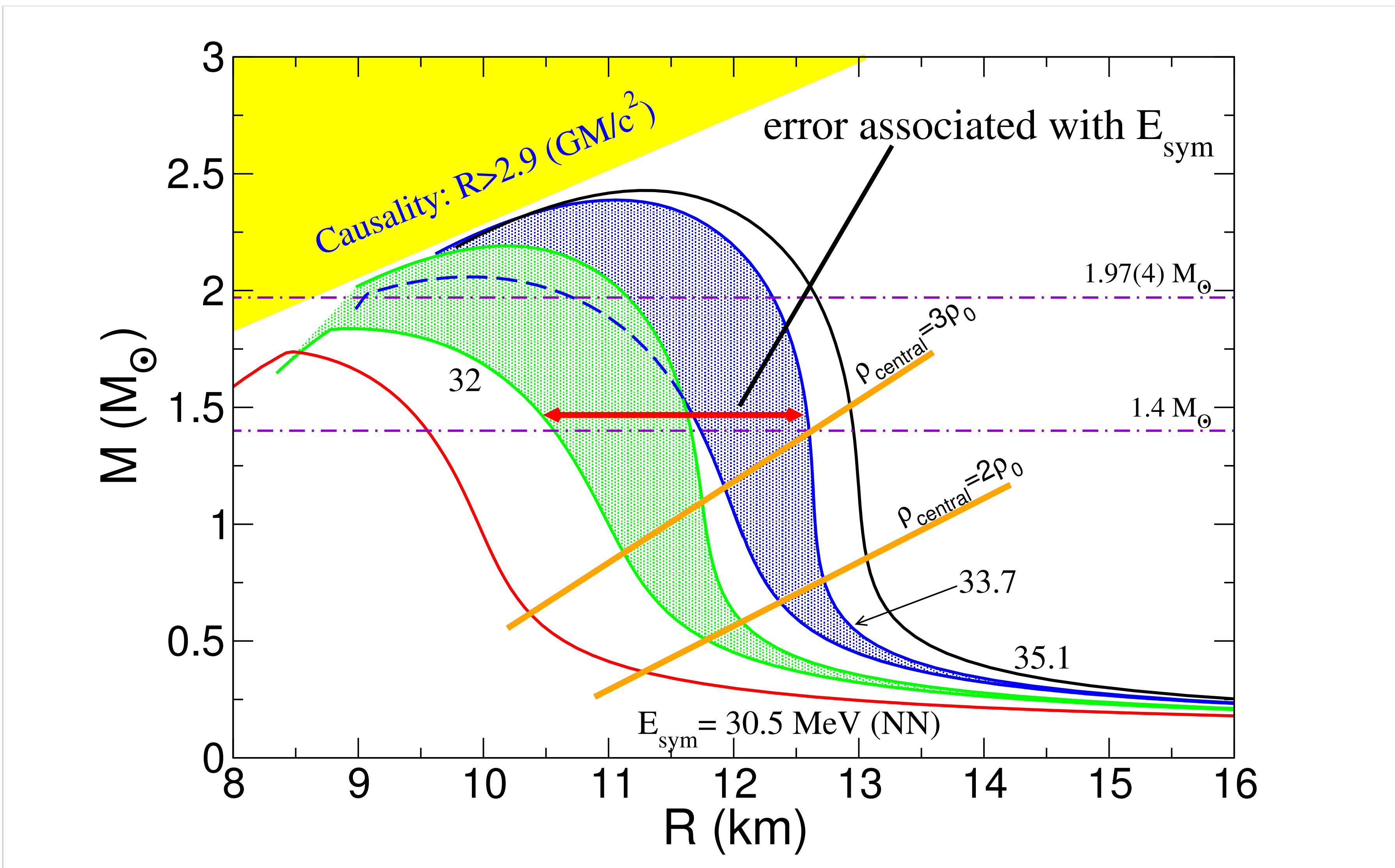


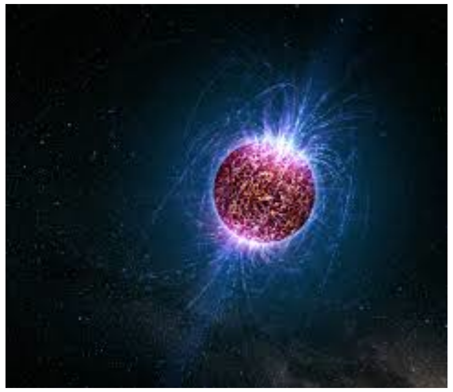


Gandolfi, JC, and Reddy (2012):
arXiv 1101.1921

Strong Correlation between symmetry energy
at saturation density and its slope

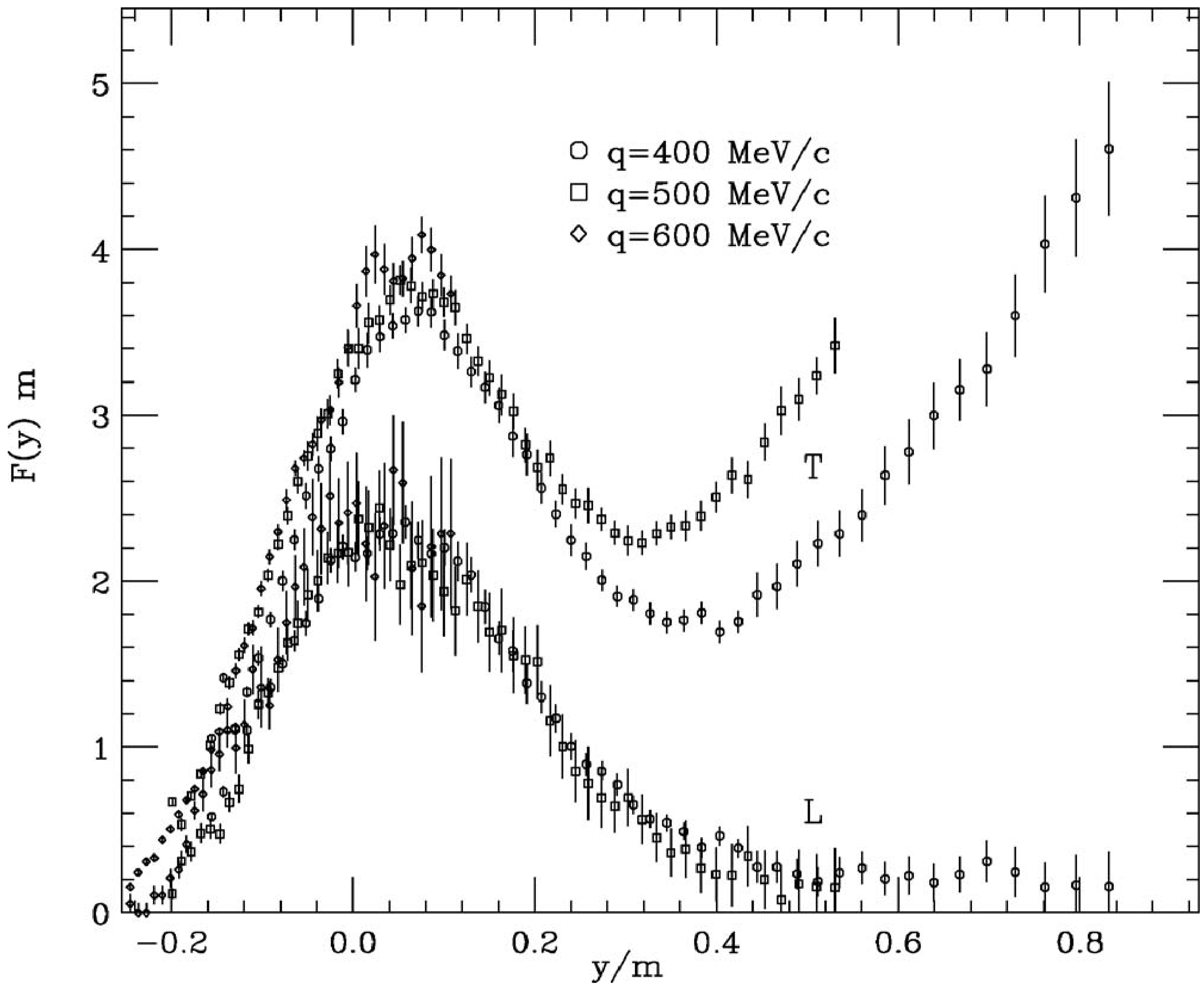
Neutron Star Mass-Radius Relations
testable with neutron star observations, advanced LIGO





How to further reduce uncertainty at 1-4 times saturation density?
Where is the phase transition ?

Electron and Neutrino Scattering in the QuasiElastic Regime



Benhar, Day, Sick; RMP 2007

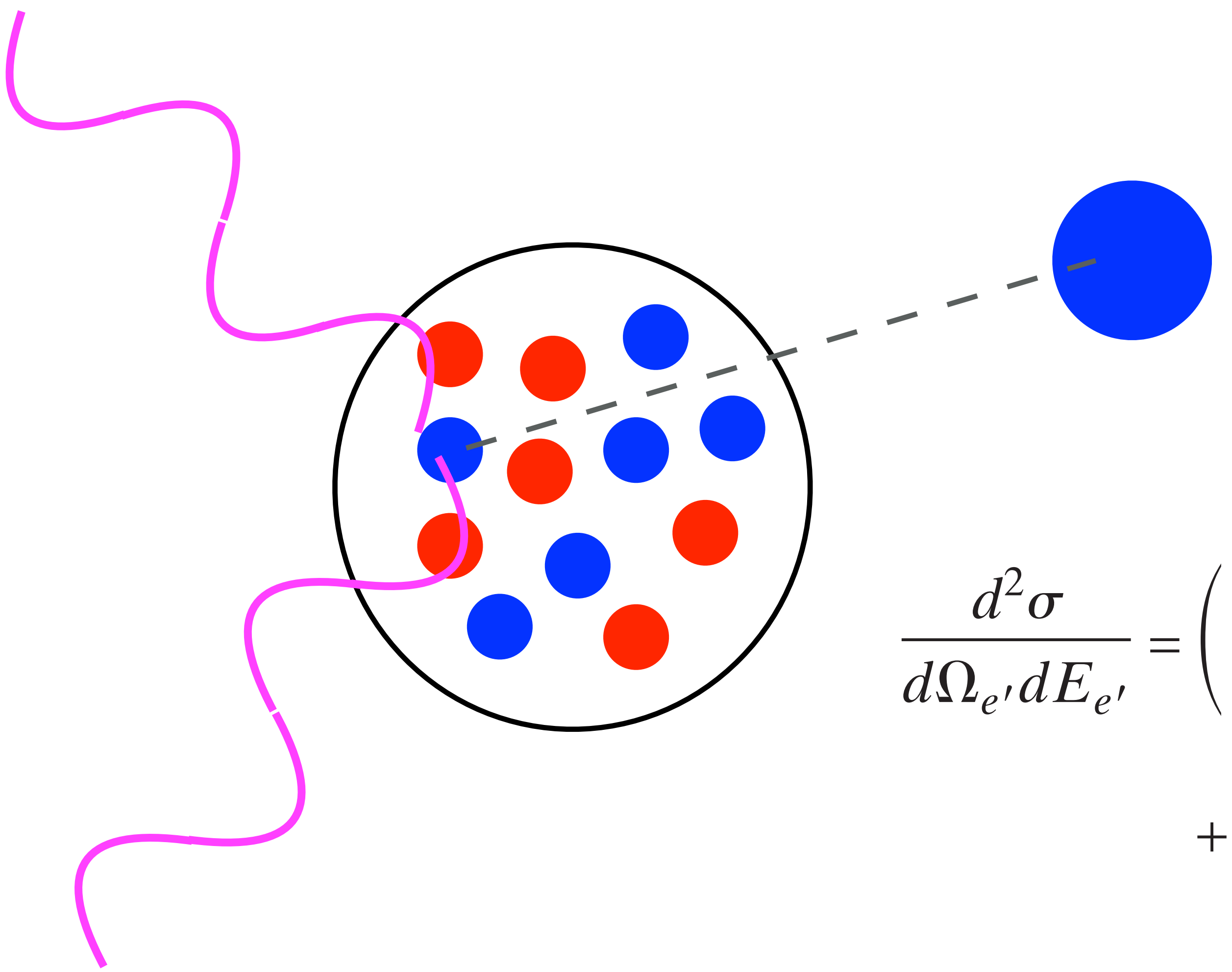
Observations:

- Scaling with momentum transfer - ‘y’ scaling
- Scaling w/ number of nucleons

But Longitudinal and Transverse Response are very different

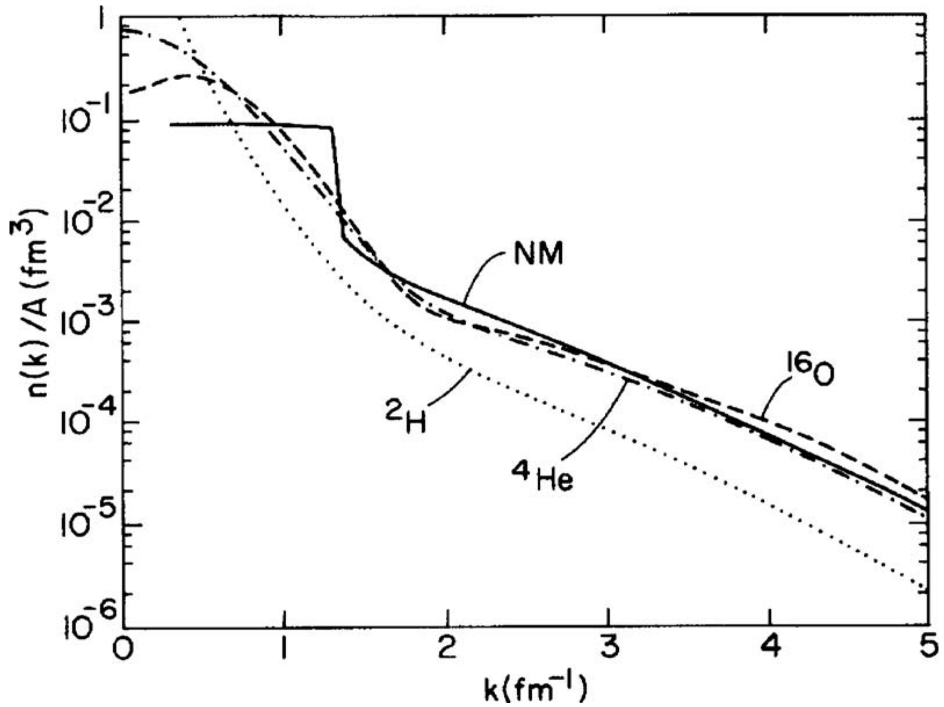
Quasi-elastic scattering: higher q, E

Scaling with momentum transfer: 'y'-scaling
incoherent sum over scattering from single nucleons
- scaling of 1st kind-

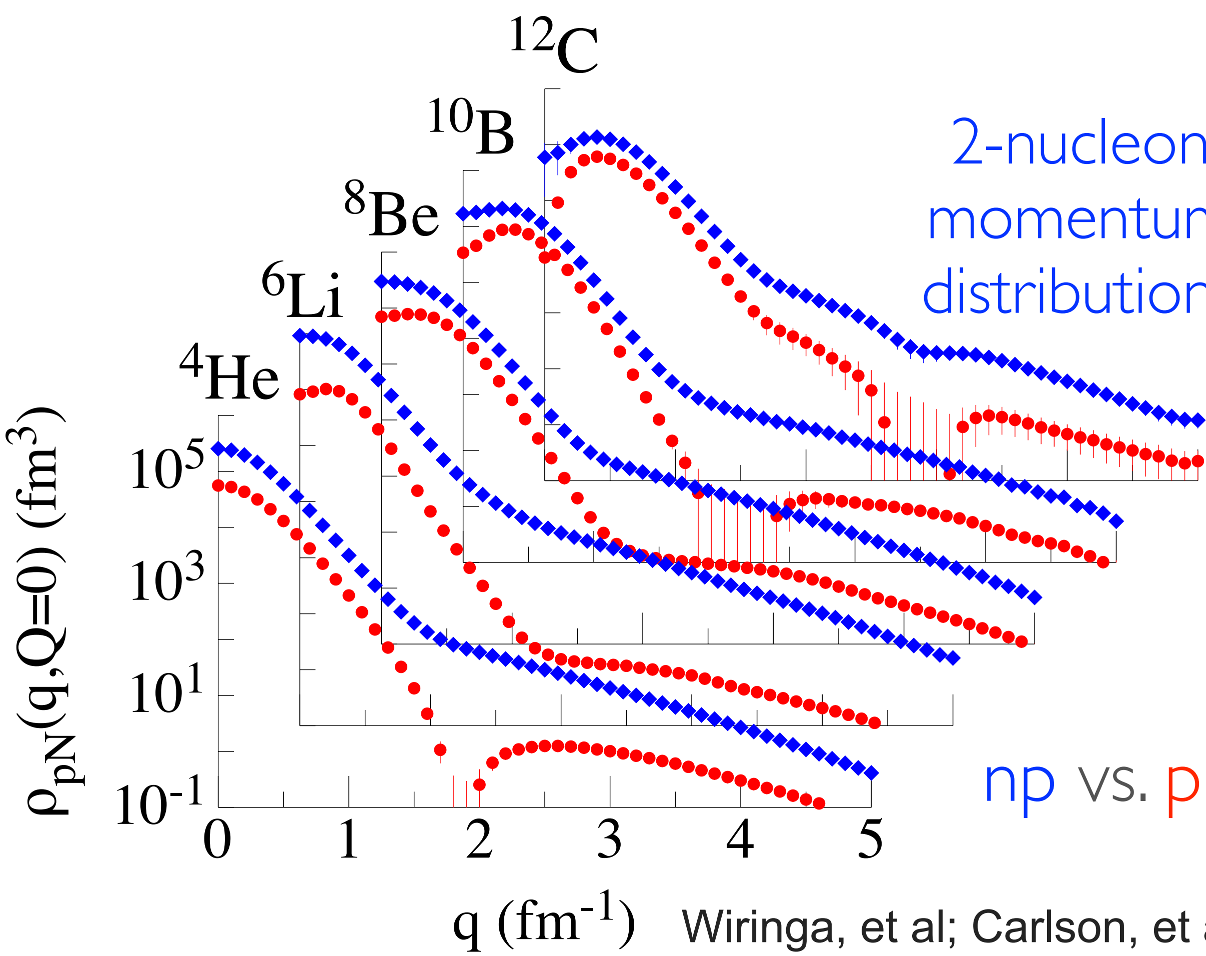


$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4} R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega)\right]$$

Nuclei: 1- and 2-nucleon momentum distributions



Schiavilla, et al 1986, Benhar, et al 1993

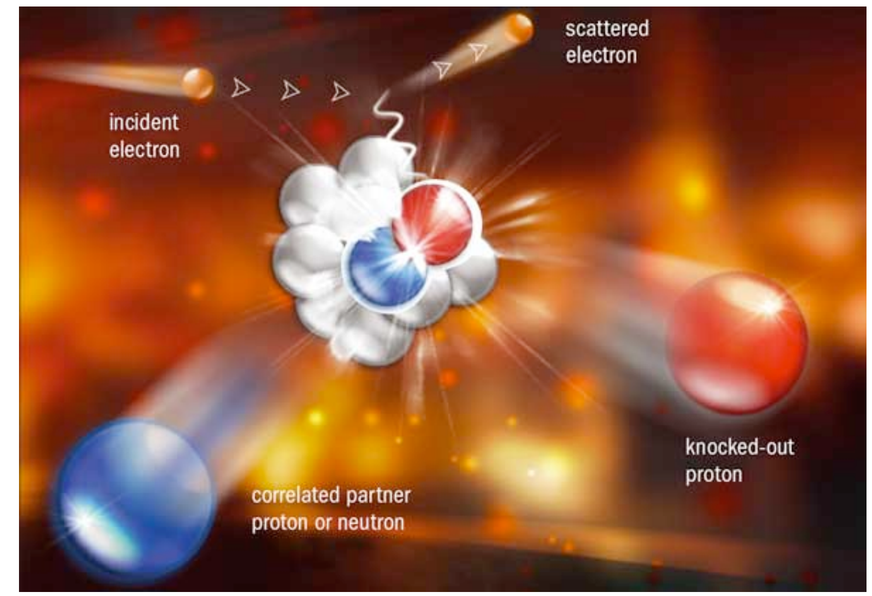


2-nucleon momentum distributions

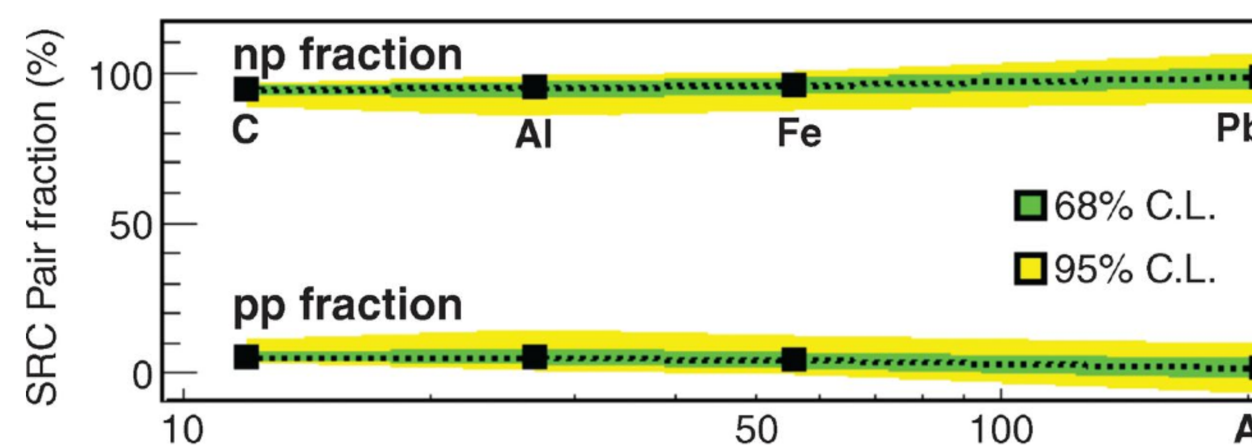
np vs. pp

Wiringa, et al; Carlson, et al, RMP 2015

Experimental measurement of back-to-back nucleons dominance of np pairs



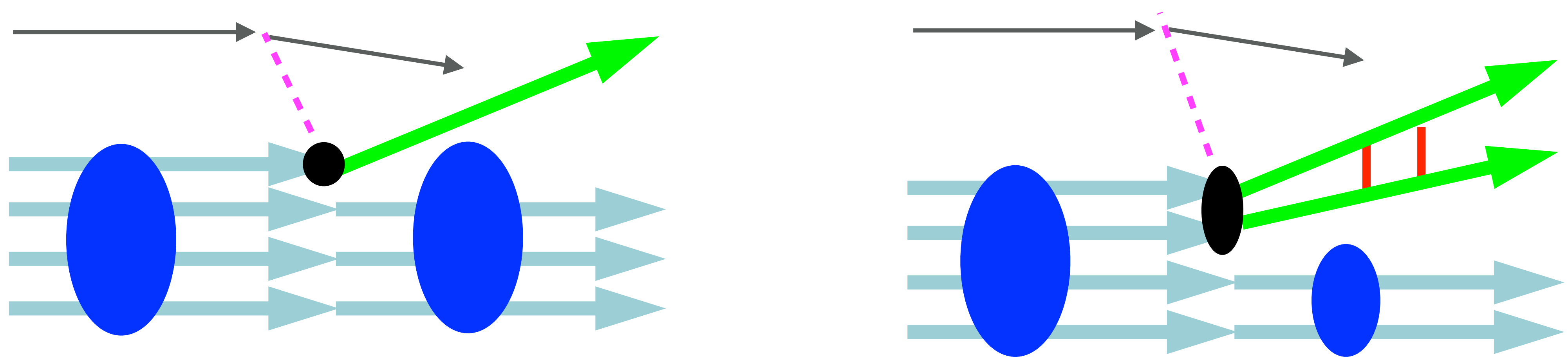
Subedi, et al, Science, 2008, …
relation to EMC effect



Hen, et al., Science, 2014

Quasi-elastic electron and neutrino scattering: 1- and 2-nucleon processes

Both correlations and currents are important



Single Nucleon Scattering
plus scattering from correlated pairs

Euclidean Response

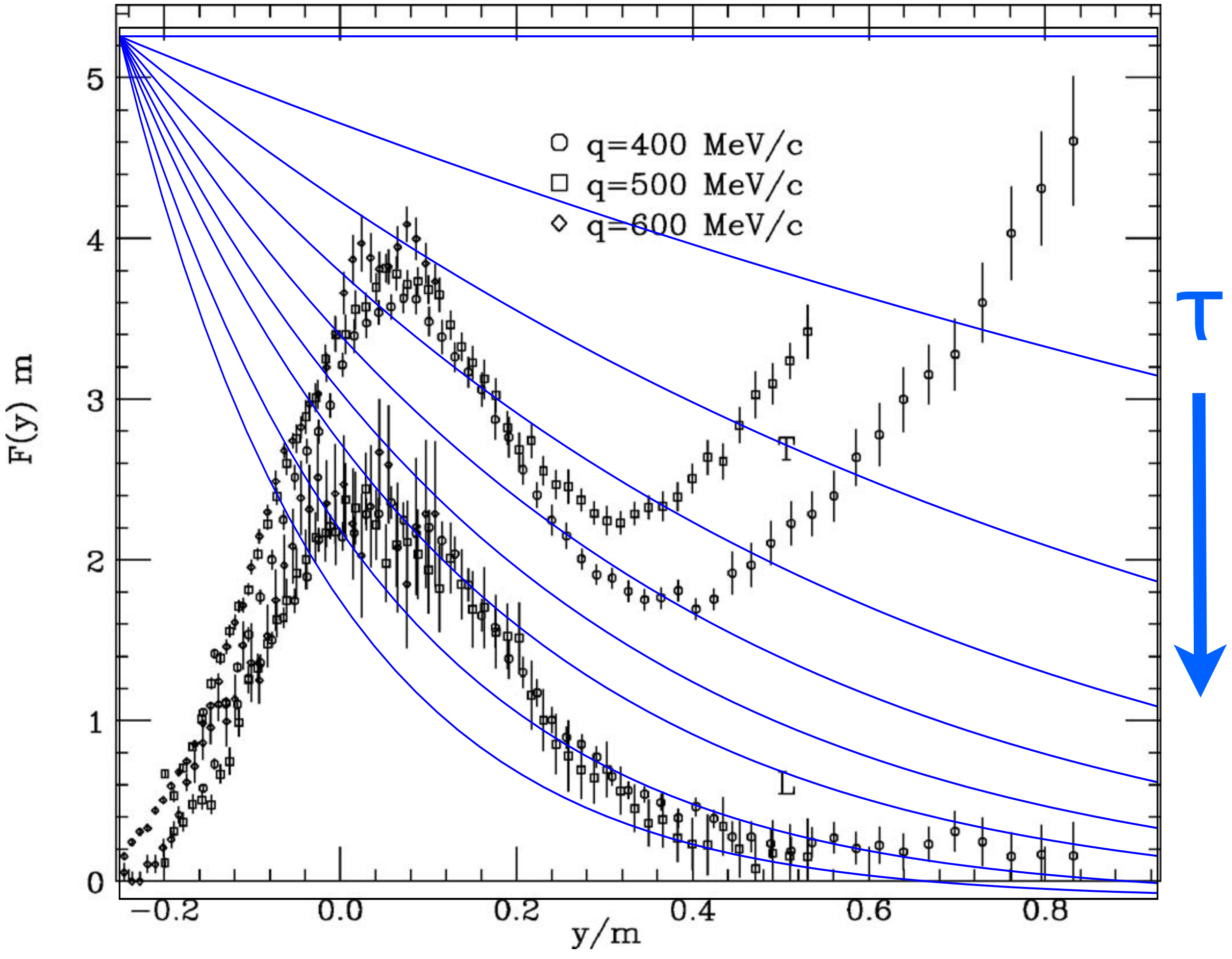
Want to calculate

$$R(q,\omega) \;=\; \int dt\; \langle 0|\; \mathbf{j}^\dagger \exp[i(H-\omega)t]\; \mathbf{j}\; |0\rangle$$

Can calculate

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

- Exact given a model of interactions, currents
- \`Thermal' statistical average
- *Full final-state interactions*
- *All contributions included - elastic, low-lying states, quasi elastic, …*

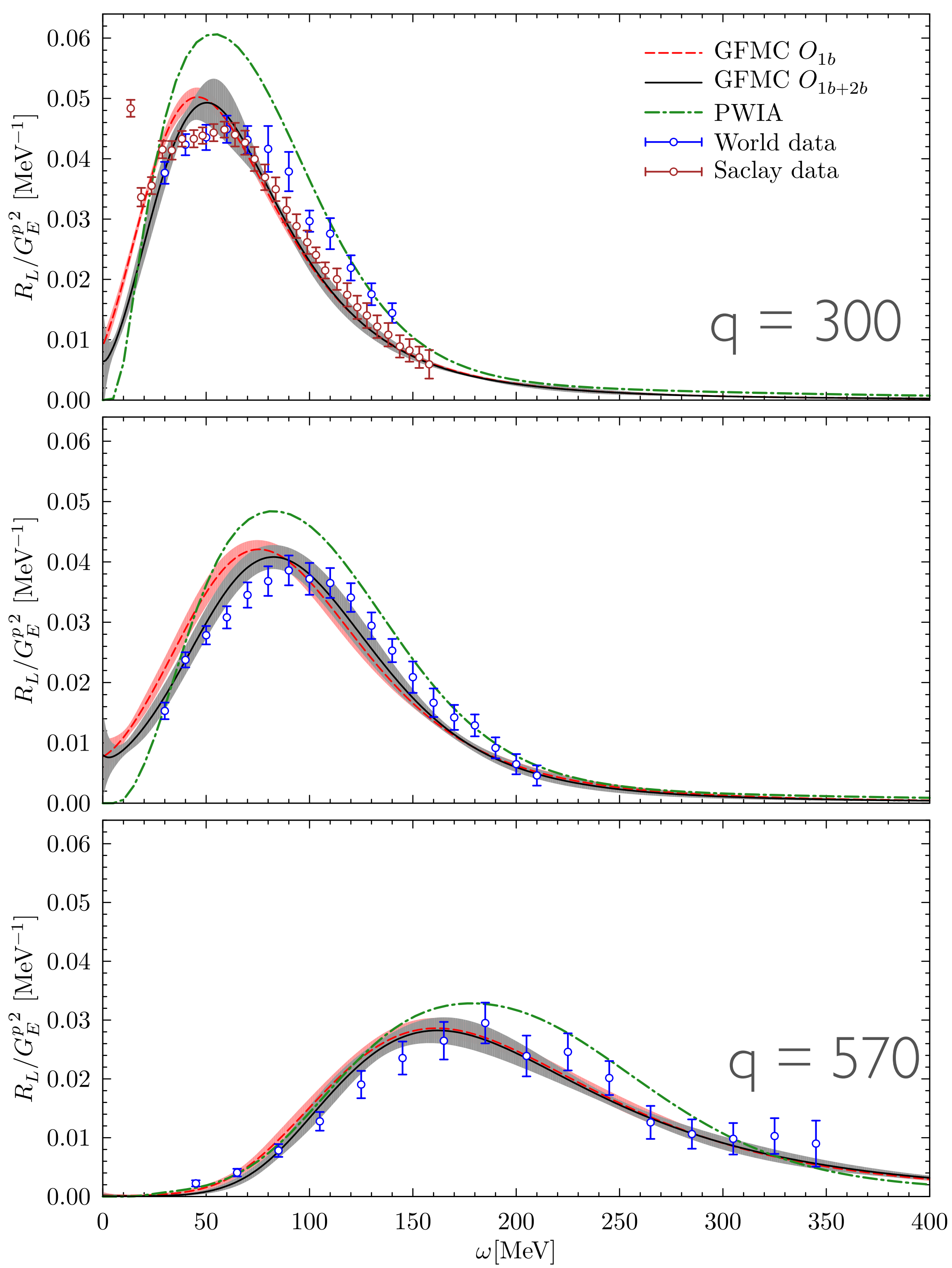


Excellent agreement w/ EM (L & T) response in A=4,12
Lovato, 2015, PRL 2016

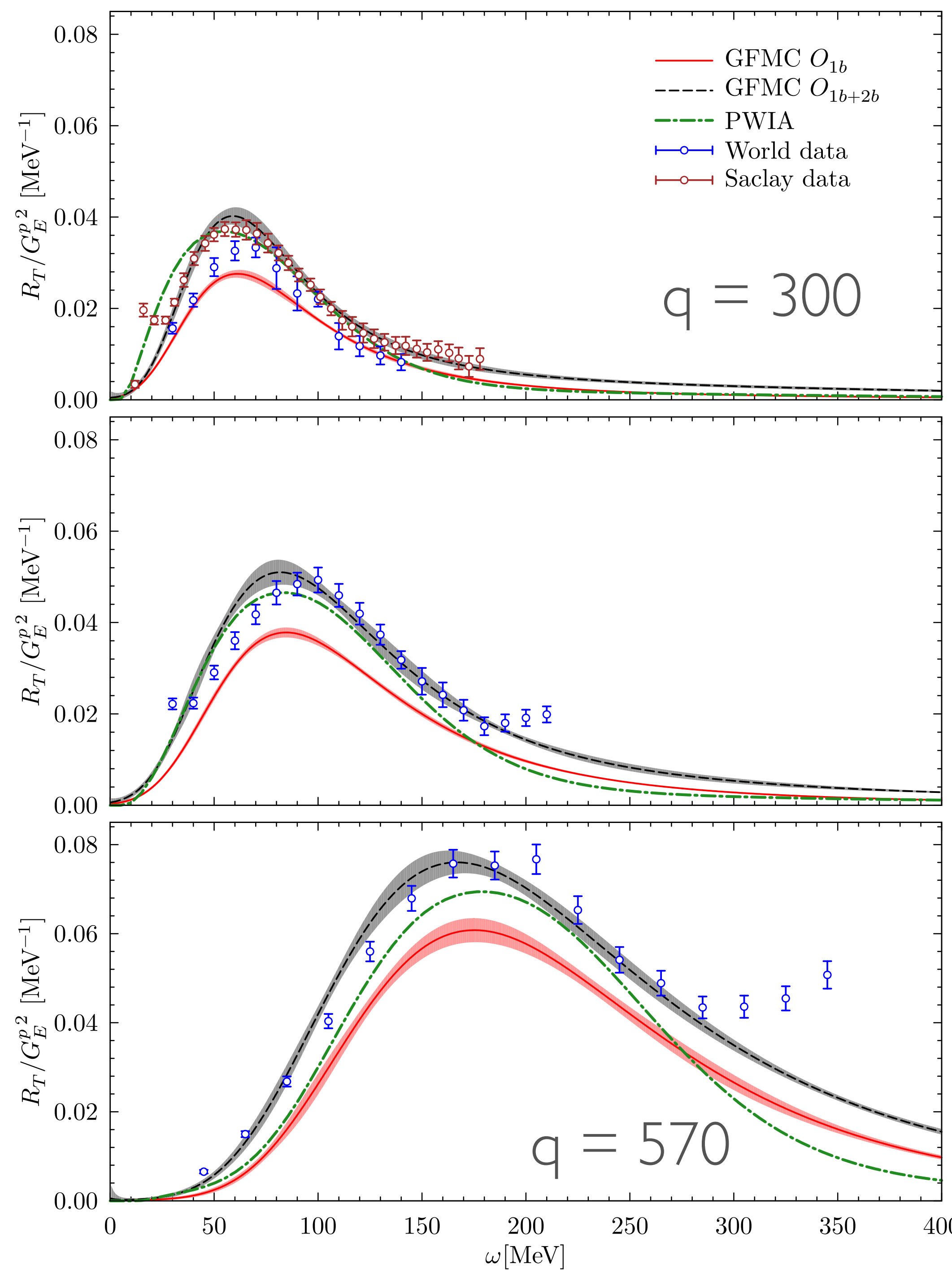
Sum rule → elastic FF^2 w/ increasing

Nuclei: inclusive electron scattering: Carbon

Longitudinal (charge) Response



Transverse (curent) Response

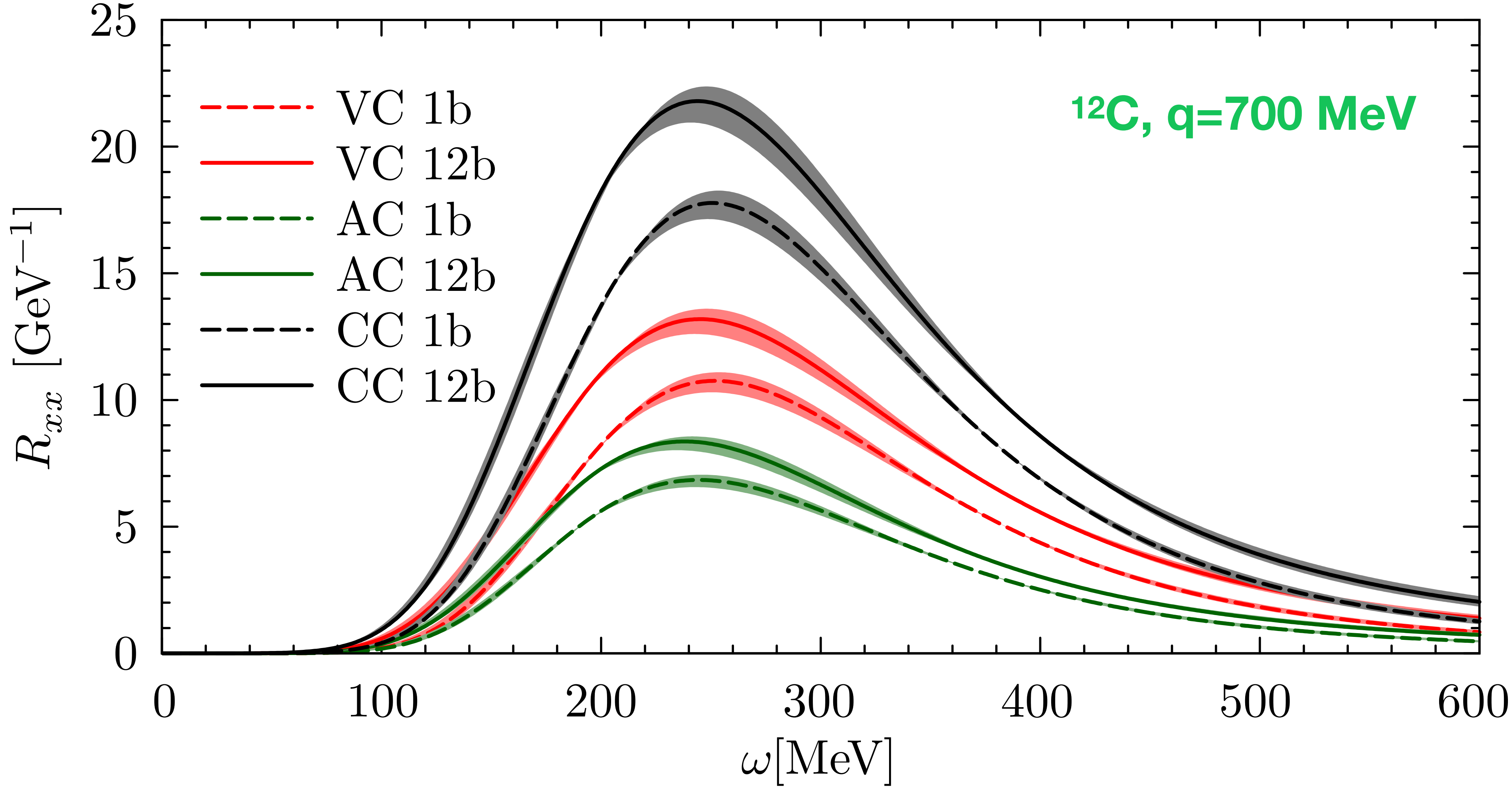


PWIA dashed lines
One-nucleon currents: red band
Full result: gray band

Lovato, et al, PRL 2016

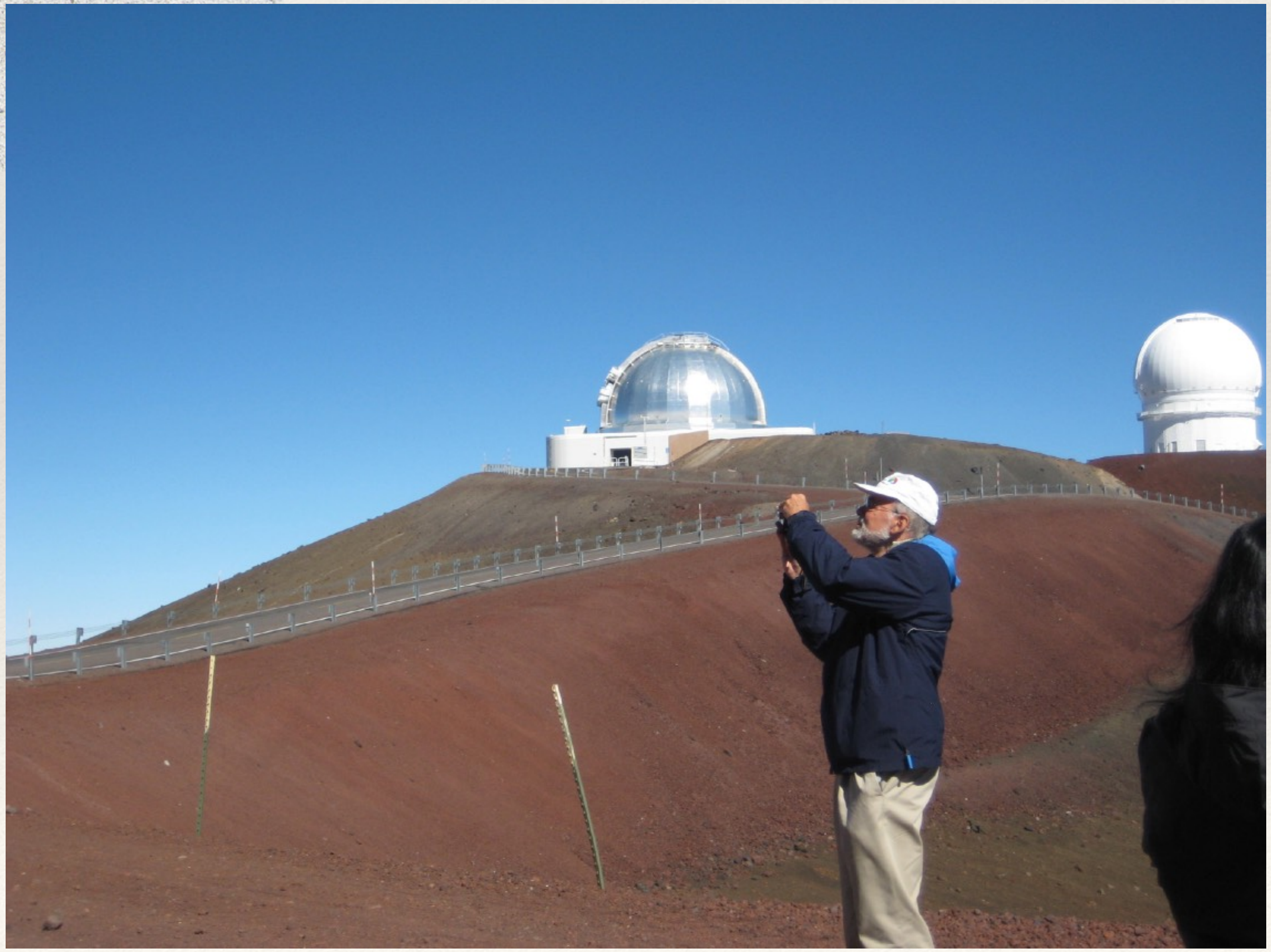
similar calculations for ^{4}He

charged current neutrino scattering from ^{12}C



Alessandro Lovato, 2019

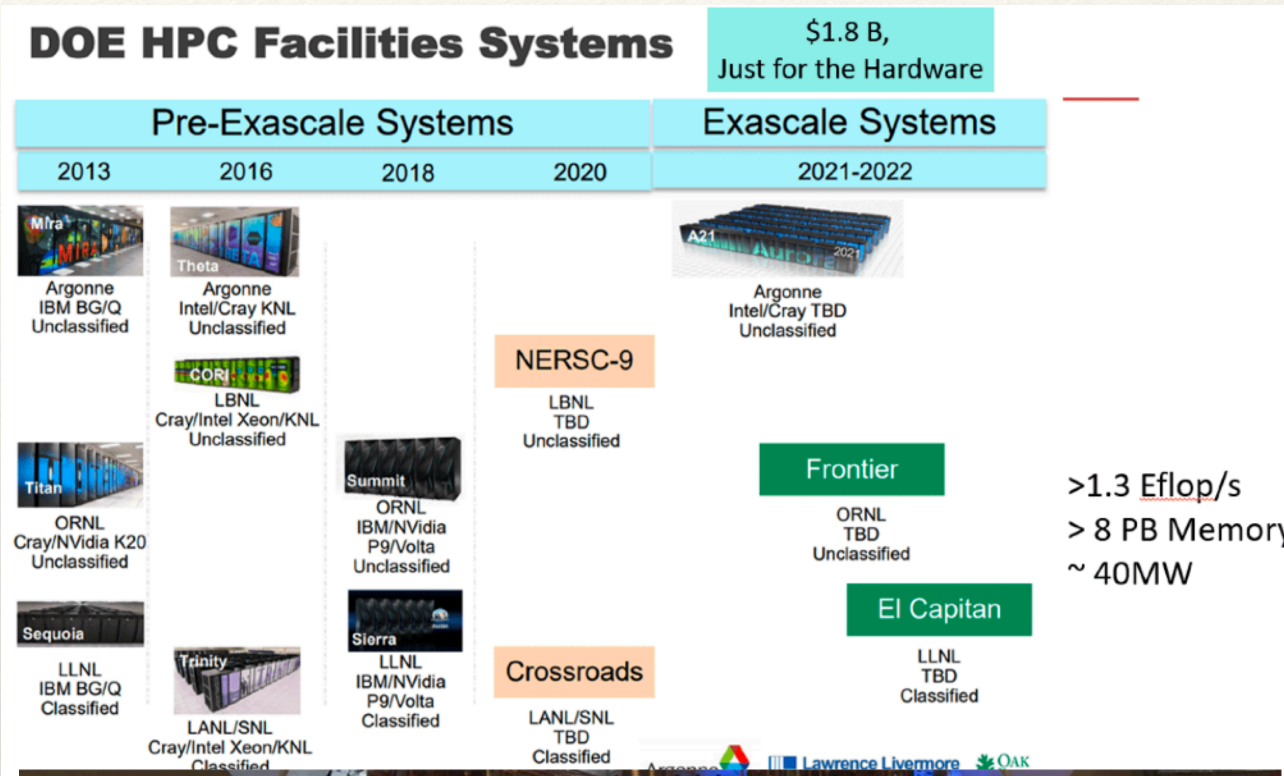
Some time for Fun
DNP in Hawaii



Present status : Outstanding combination of ingredients:

Many important physics problems:

- electron and neutrino scattering - accelerators
- astrophysical neutrinos
- double beta decay
- neutron star structure and mergers
- larger and neutron rich nuclei
- tests of BSM physics
- connections to other areas:
  - cold atoms, ...
- Quantum (Nuclear) Dynamics



Rapidly advancing tools:

- Exascale Computers (Cray, Intel, AMD)
- Quantum Computers (IBM, Google, Microsoft, ...)












Thank you for many wonderful years working together: Steve Pieper