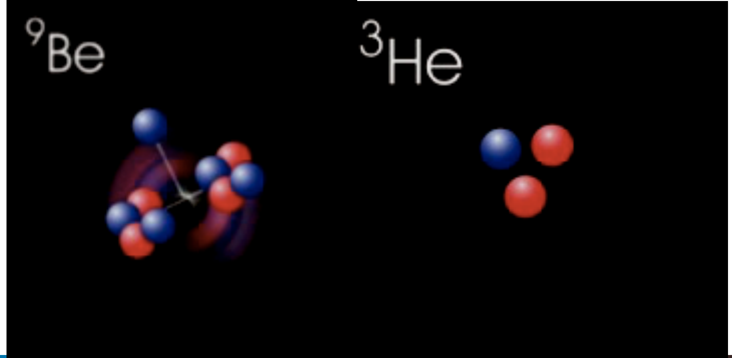
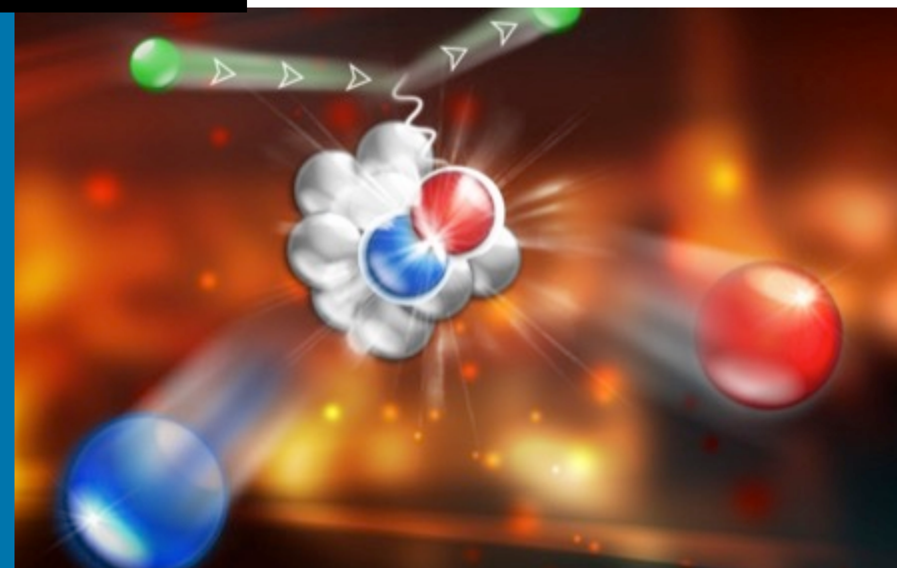
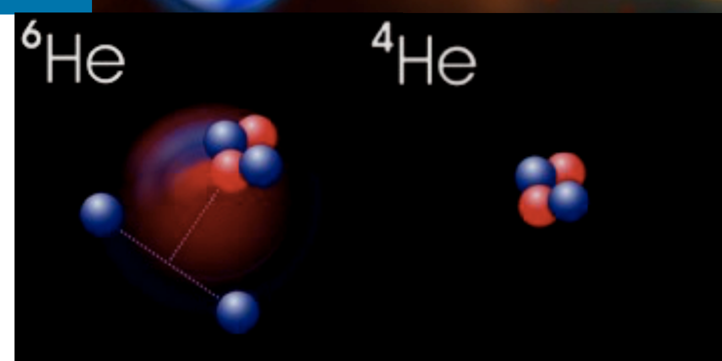


Conveners' Highlights: Nuclear Forces and Structure, Nucleon-Nucleon correlations, and the EMC effect



Paul E Reimer
Physicist
Argonne National Laboratory

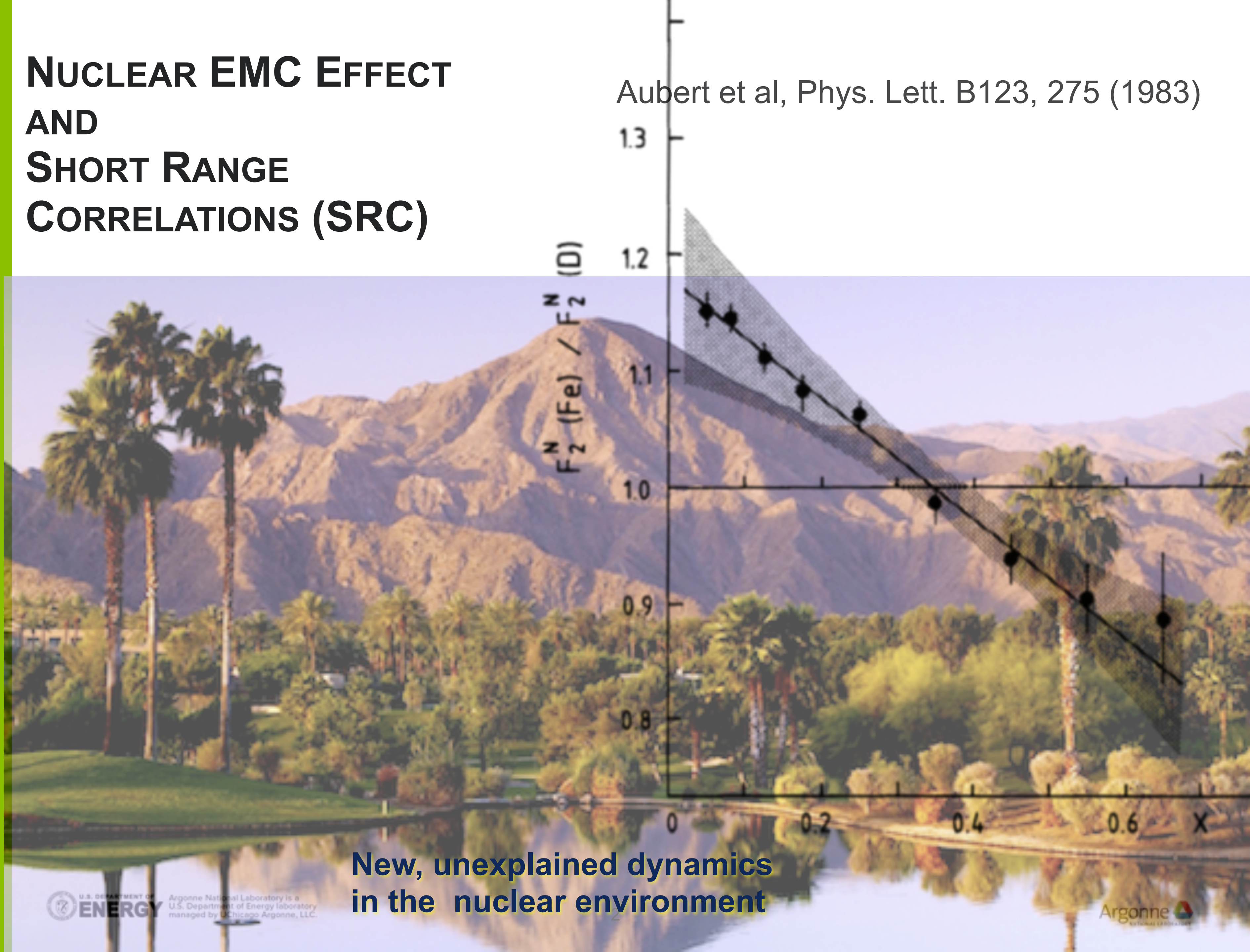


3 June 2018
Indian Wells, CA

This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

Nuclear EMC Effect and Short Range Correlations (SRC)

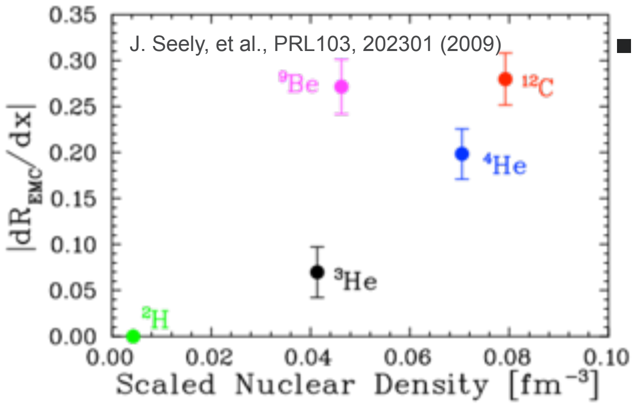
Aubert et al, Phys. Lett. B123, 275 (1983)



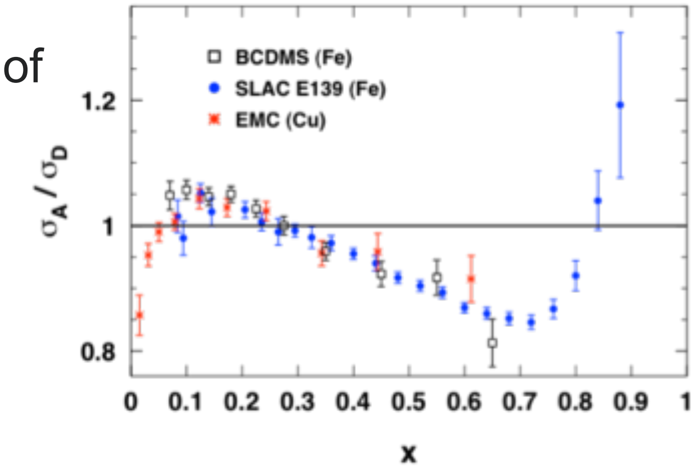
New, unexplained dynamics in the nuclear environment

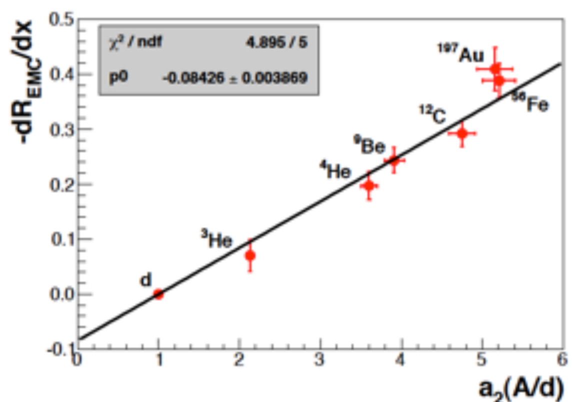
DAVID GASKELL THE EMC EFFECT

- 35 years of inclusive experiments have provided a lot of information about the properties of the EMC Effect
- – No consensus on origin



- New several avenues of investigation
  - Connection with Short Range Correlations
  - Tagged measurements
  - Flavor dependence (valence)
  - EMC effect in polarized quark distributions
  - Sea quarks





O. Hen et al, Phys.Rev. C85 (2012) 047301

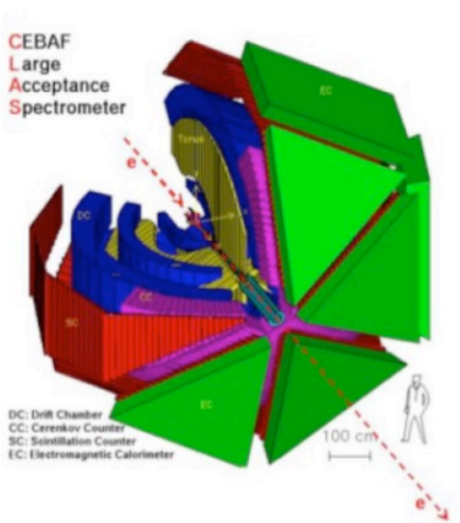
There are a lot of interesting new ideas and there will soon be a lot of new data with which to test these new ideas.

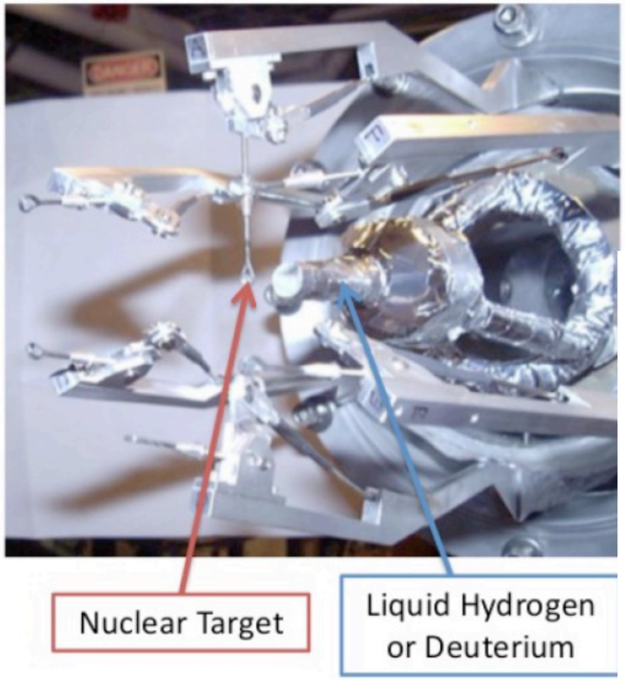
Or Hen - MIT
Barak Schmookler - MIT

NEW RESULTS: SRCS & EMC EFFECT

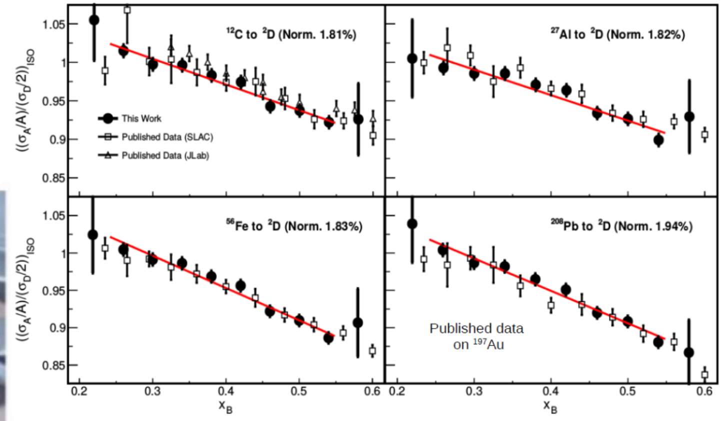
Several results shown from data mining of CLAS eg6 data set (nuclear targets)

Study (e,e') Data from the CLAS6 Detector at JLab

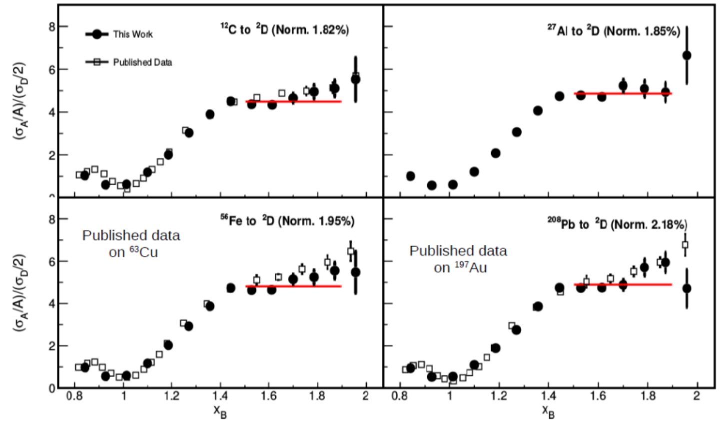




Our New EMC Effect Measurements

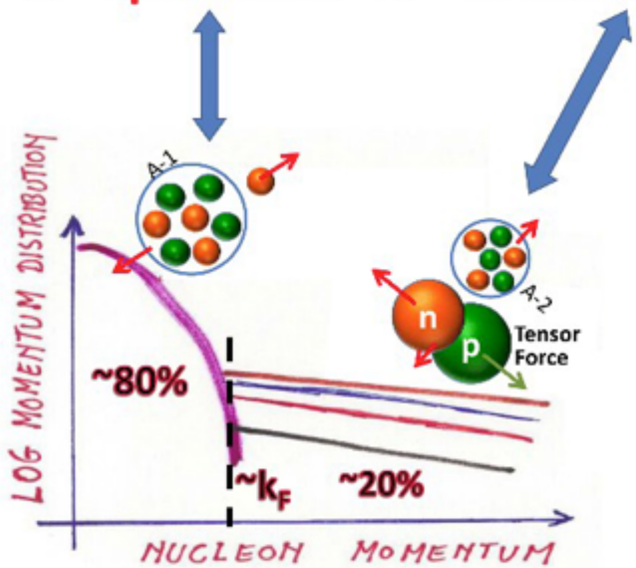


Our New SRC a_2(A/d) Measurements



ASSUME THAT SRC ACTS AS 'MEASURE' OF EMC EFFECT AND THAT SRCS (AND EMC) ARE DOMINATED BY NP PAIRS

Bound = 'quasi Free' + Modified SRCs

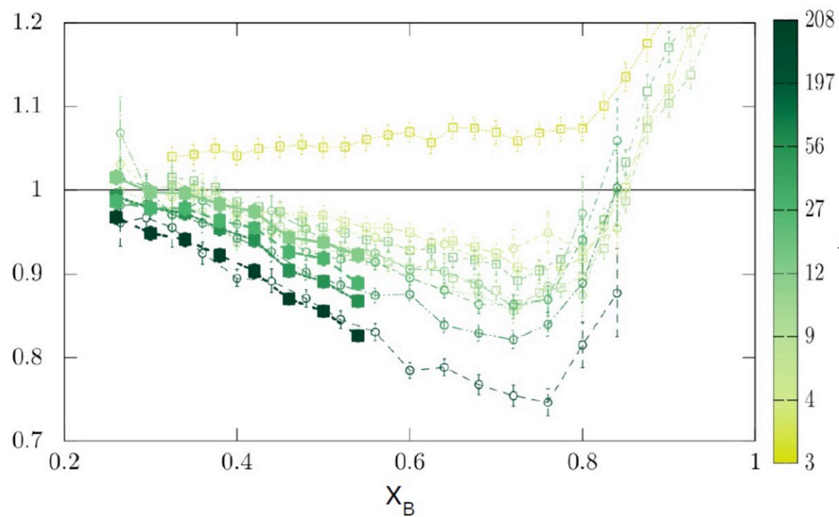


Or Hen - MIT
Barak Schmookler - MIT

Bound = 'quasi Free' + Modified SRCs

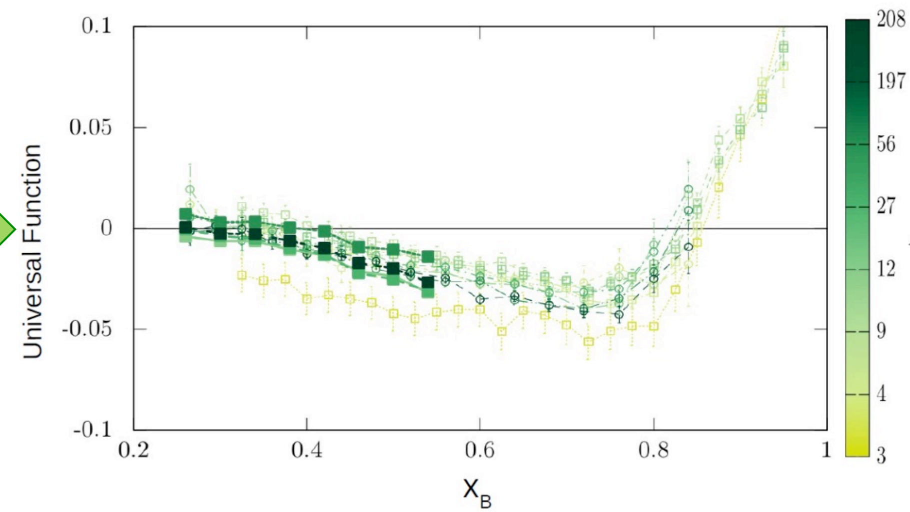
$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n)$$

Measured EMC Ratios



atory

Universal EMC Modification Function



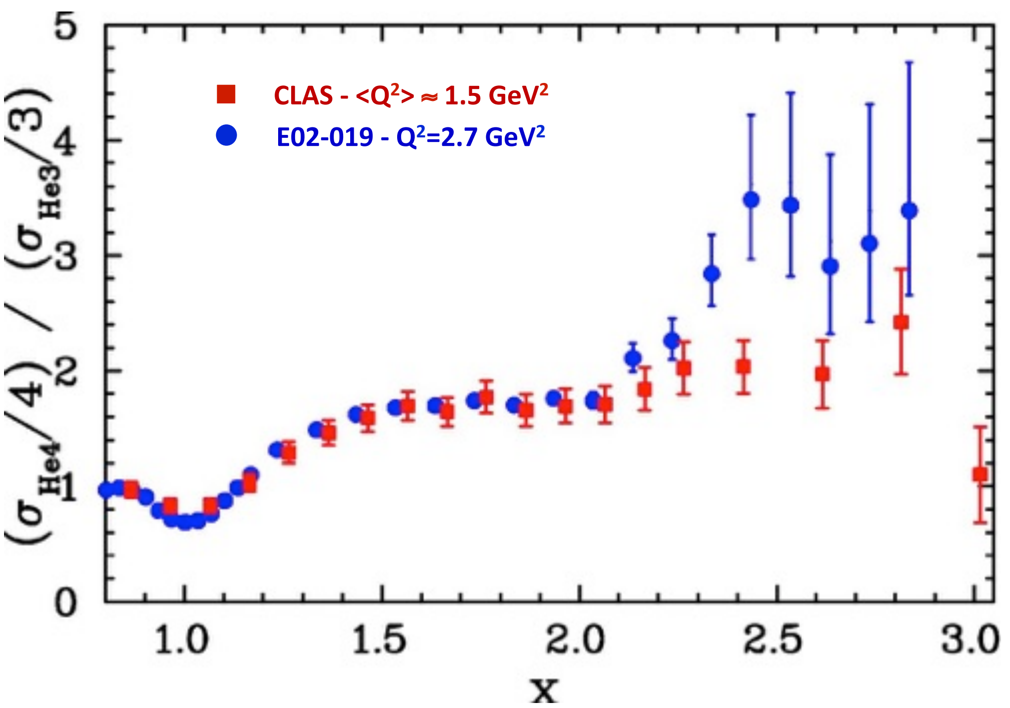
3N-SRCS?

CLAS showed second plateau beyond x=2

•Significant bin migration corrections due to modest momentum resolution

JLab E02-019 [Hall C] – much higher ratio at x>2; higher Q^2

•Poor statistics



No real test for 3N-SRCs in inclusive scattering

John Arrington, Zhihong Ye - ANL

E08-014 RESULTS

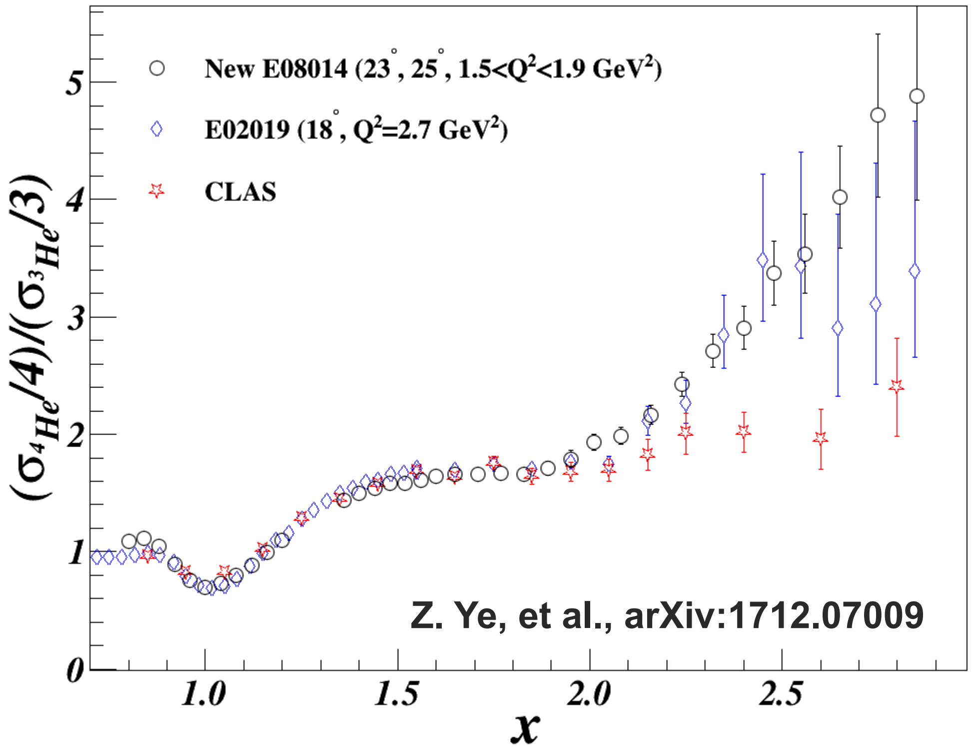
Consistent within uncertainties of E02-019; well above CLAS ratios

- ➢ Q^2 values near CLAS data, so not a Q^2 dependence

Ratio increases above x=2, but does not show plateau

- ➢ Scaling prediction for 3N-SRCs not valid in this x, Q^2 range

Why?



Kinematics (x, Q^2) may not be sufficient to isolate 3N-SRCs

•Don't know what x_{min} is required for plateau to begin at any given Q^2

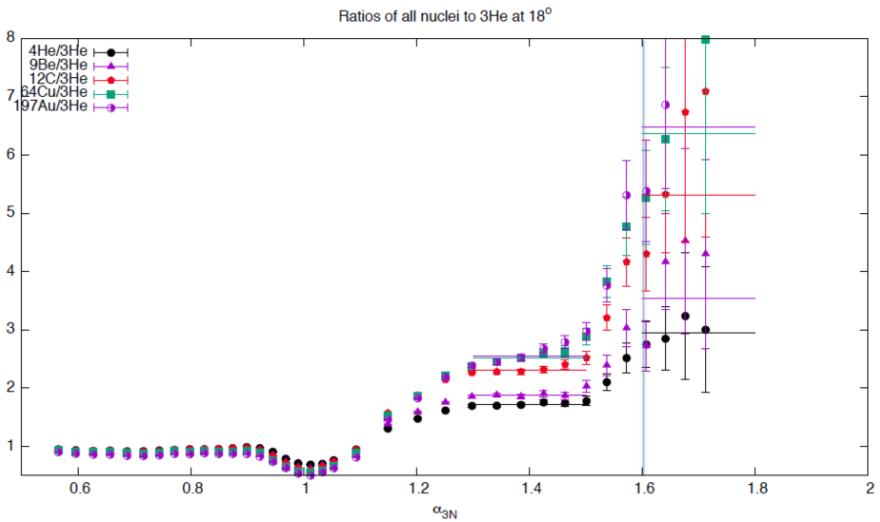
- Don't have a clear momentum threshold for 2N-SRCs to be negligible, as opposed to 2N-SRCs while MF contributions fall dramatically beyond k_{Fermi}

•Motion of 3N-SRCs has large effect near kinematic endpoint ($x \approx 3$); much worse than for deuteron

John Arrington, Zhihong Ye - ANL

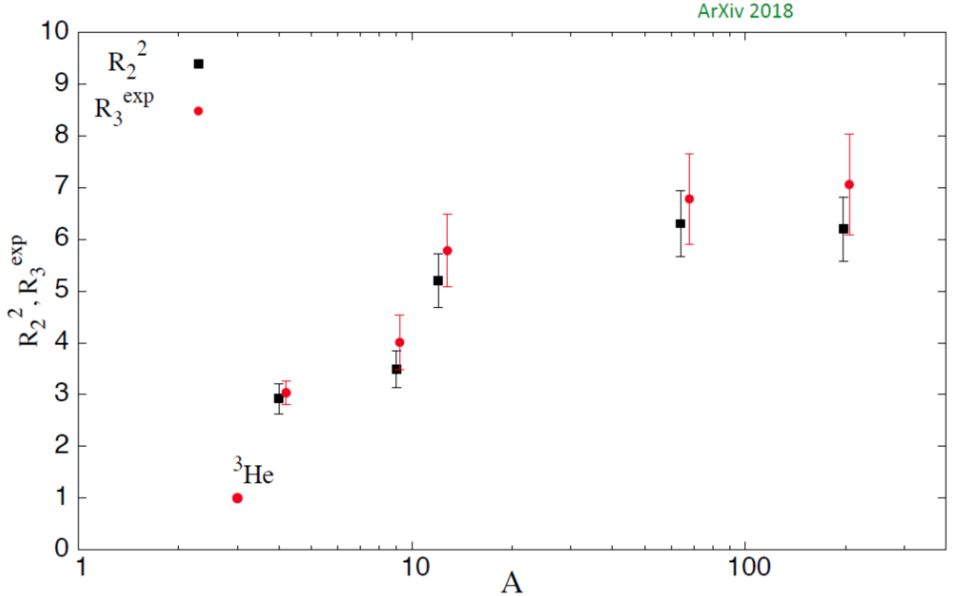
NEW ANALYSIS OF E02-019 DATA

Misak Sargsian - FIU



Assume 3N region shows plateau; extract a_3 (relative contribution of 3N-SRCs)

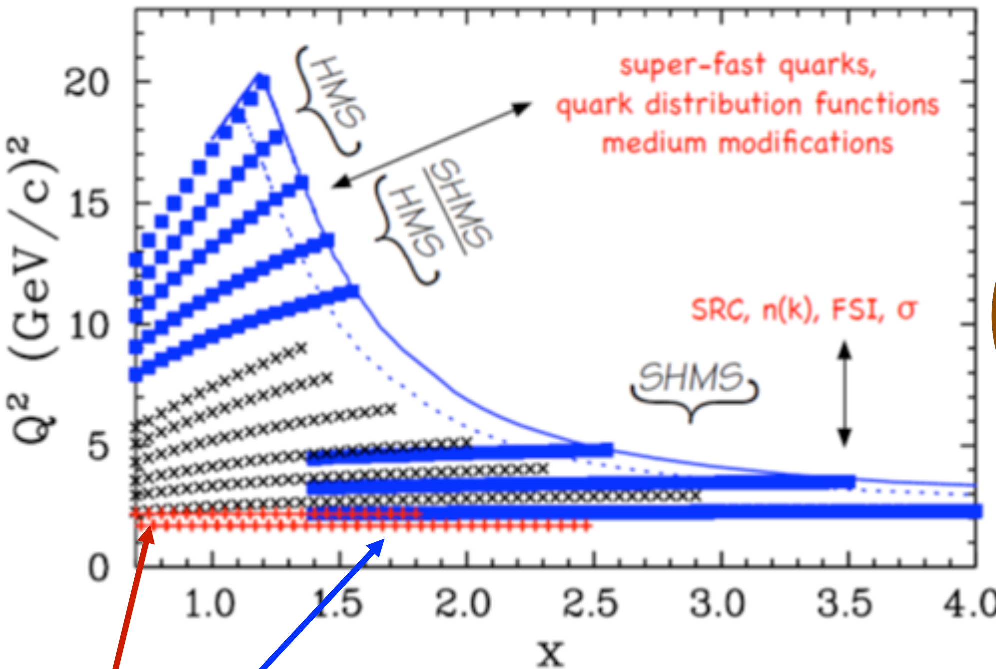
D.Day, L.Frankfurt,M.S, M.Strikman ArXiv 2018



A_3 is proportional to $(a_2)^2$; expected if 2N-SRCs proportional to density and 3N-SRCs proportional to $(density)^2$

a_2=relative likelihood of nucleon to be in a high momentum nucleon pair

INCLUSIVE SRC (AND EMC) MEASUREMENTS: JLAB@12 GEV



SRCs at x>1 at 12 GeV
[E06-105: JA, D. Day, N. Fomin, P. Solvignon]

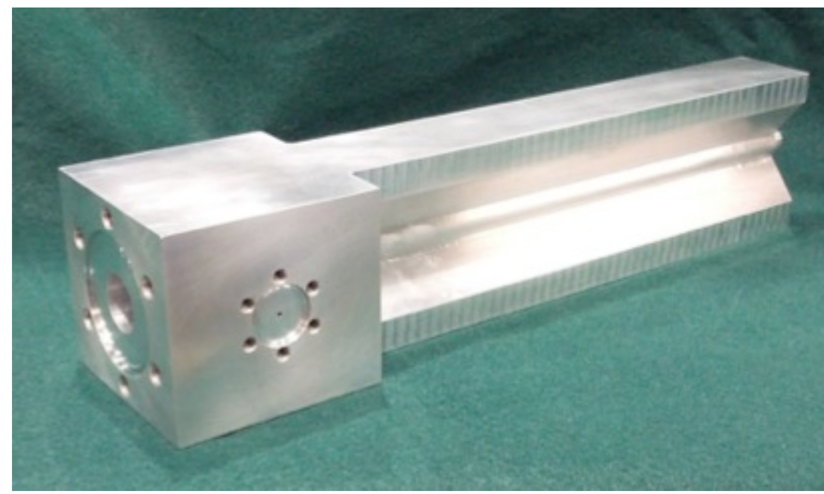
EMC effect at 12 GeV
[E10-008: JA, A. Daniel, D. Gaskell]

Full ^{3}H, ^{3}He program (5 expts) in 2018 (Hall A)

Initial set of light nuclei in 2018 (Hall C)

^{1}H	^{6,7}Li	^{40}Ca
^{2}H	^{9}Be	^{48}Ca
^{3}He	^{10,11}B	Cu
^{4}He	^{12}C	Au

^{3}H
^{3}He

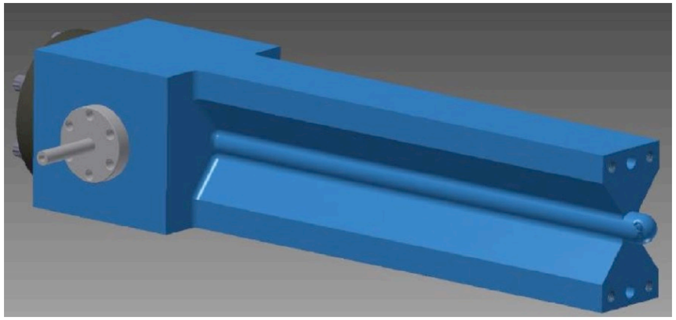


SRC Isospin dependence: ^{3}H vs ^{3}He
E12-11-112 (e,e'), E12-14-011 (e,e' p)
^{3}H, ^{3}*He DIS: EMC effect and d(x)/u(x)*
Charge radius difference: ^{3}He - ^{3}H
Lambda hypernuclei from ^{3}H

Hall A 2018 Spring Tritium Run

Axel Schmidt – MIT

1. MARATHON
   - Inclusive deep-inelastic scattering: d/u ratio
2. $(e, e'p)$ Experiment
   - Coincident quasielastic proton knock-out
3. $x_B < 3$ Experiment
   - Inclusive scattering in the $1 < x_B < 3$



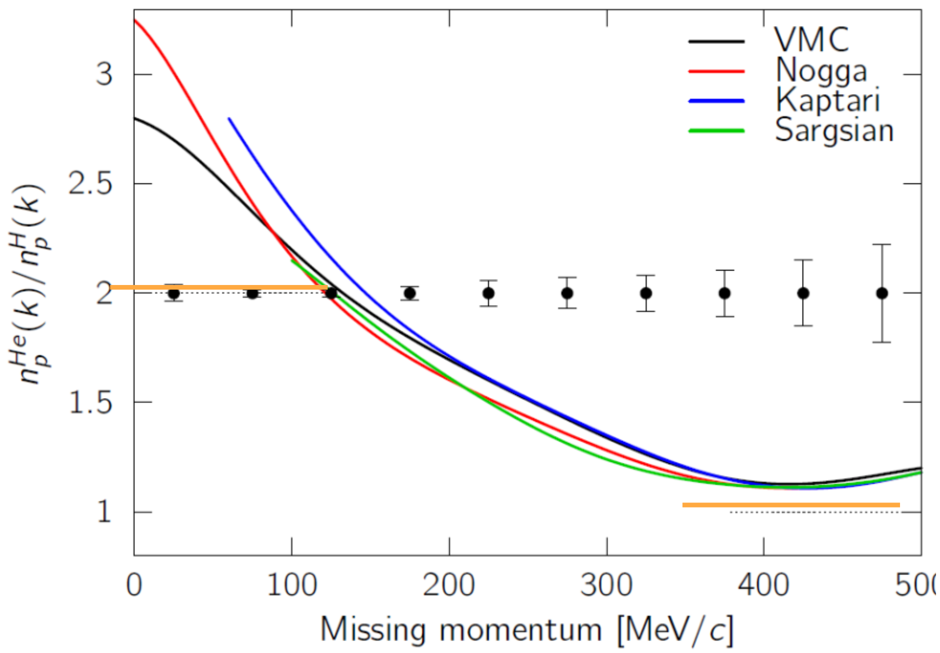
Sealed-cell gas target

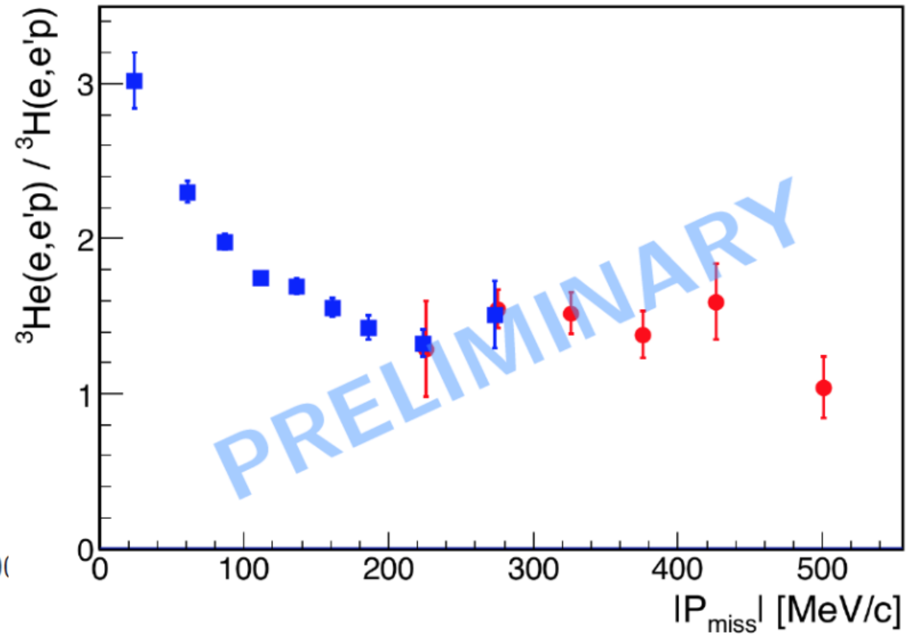
Still to come in Fall Run

1. $x_B < 3$ continued . . .
   - Investigation of $x > 1$ and $x > 2$ regions
2. $x_B = 3$ Experiment
   - Elastic form factors of the triton.
3. Hypernucleus Experiment
   - Λn interaction via $^3\mathrm{H}(e, e'K^+)$

Axel Schmidt – MIT

^{3}He(e,e' p)/^{3}H(e,e' p) ratios





Map out transition from R≈2 (proton counting) at low missing momentum to R≈1 (np-SRC dominance) at high missing momentum

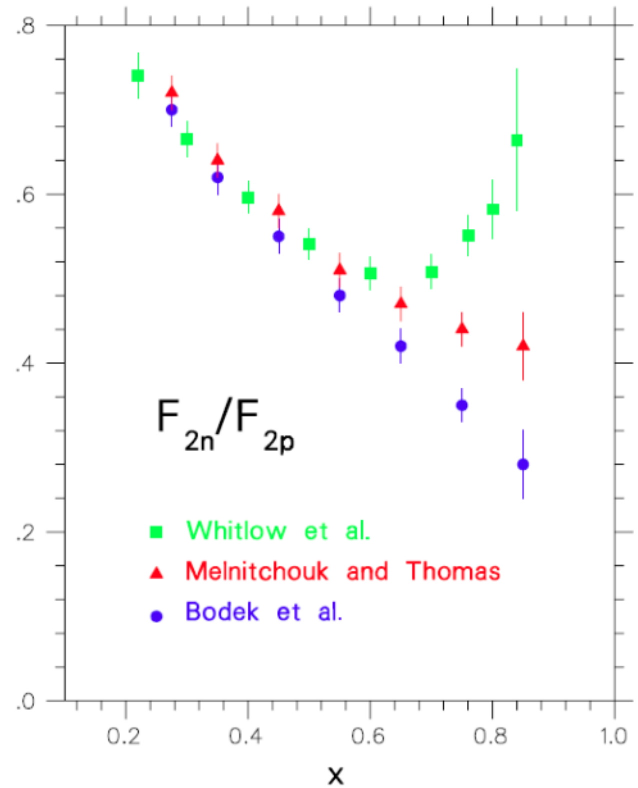
Very preliminary (online) results show accumulated statistics

Axel Schmidt – MIT

MARATHON - D(X)/U(X)

$$\frac{F_2^p}{F_2^n} = \frac{2\mathcal{R} - F_2^{^3\text{He}}/F_2^{^3\text{H}}}{2F_2^{^3\text{He}}/F_2^{^3\text{H}} - \mathcal{R}}$$

Ratio of proton to neutron depends only on **ratio** of nuclear effects in ^{3}He and ^{3}H



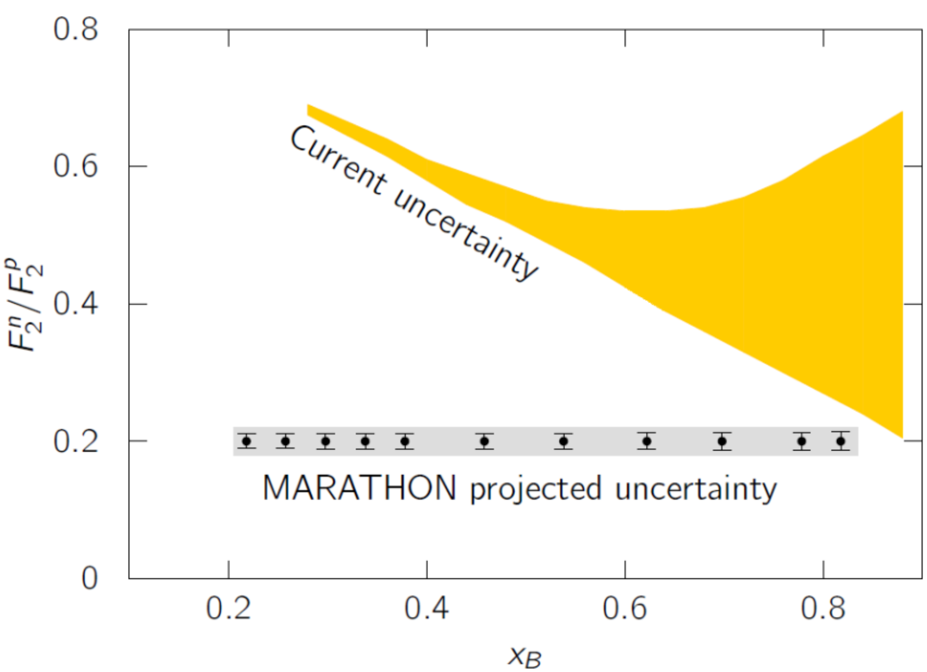
Avoids large model dependence associated with extraction from D/p

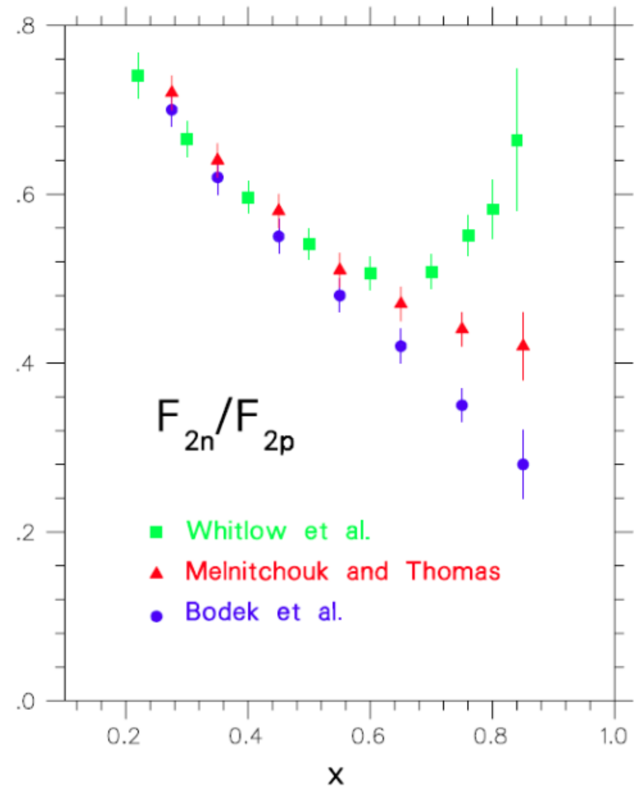
Axel Schmidt – MIT

MARATHON - D(X)/U(X)

$$\frac{F_2^p}{F_2^n} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}}$$

Ratio of proton to neutron depends only on **ratio** of nuclear effects in ^{3}He and ^{3}H





Avoids large model dependence associated with extraction from D/p

Points show statistical uncertainties based on spring 2018 data taking

The ALERT experimental run-group

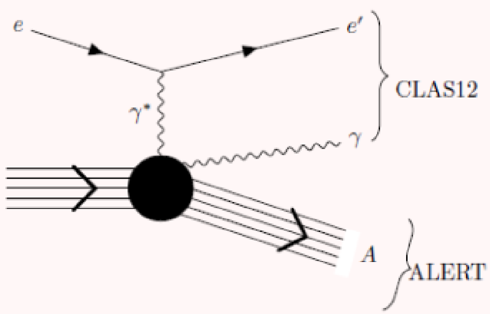
A comprehensive program to study nuclear effects

Whitney Armstrong - ANL

Nuclear GPDs

$^4\mathrm{He}(e, e'\,^4\mathrm{He}\,\gamma)$

$^4\mathrm{He}(e, e'\,^4\mathrm{He}\,\phi)$



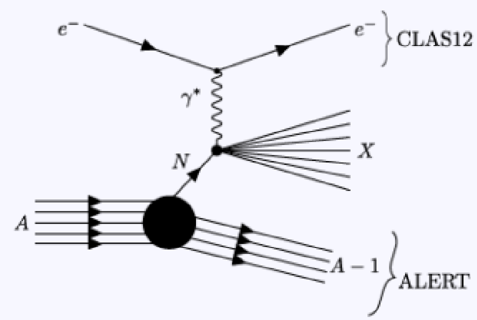
Directly compare quark and gluon radii

Tagged EMC

$^4\mathrm{He}(e, e' + \,^3\mathrm{H}\,)X$

$^4\mathrm{He}(e, e' + \,^3\mathrm{He})X$

$^2\mathrm{H}(e, e' + \,p\,)X$



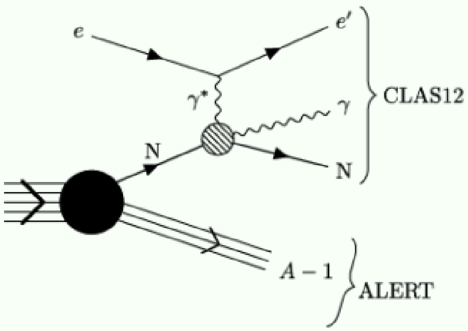
Address key questions about the EMC effect

Tagged DVCS

$^4\mathrm{He}(e, e'\gamma\, p + \,^3\mathrm{H}\,)$

$^4\mathrm{He}(e, e'\gamma\, + \,^3\mathrm{He})n$

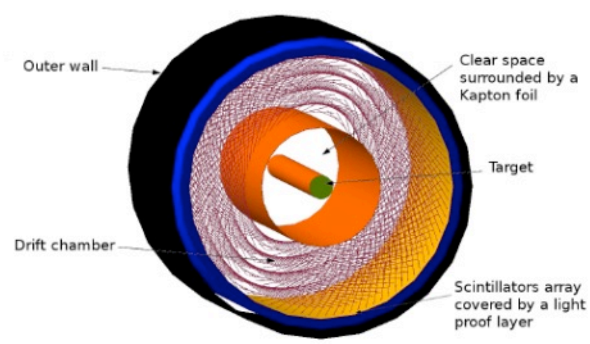
$^2\mathrm{H}(e, e'\gamma\, + \,p\,)n$



Connect partonic and nucleonic modification

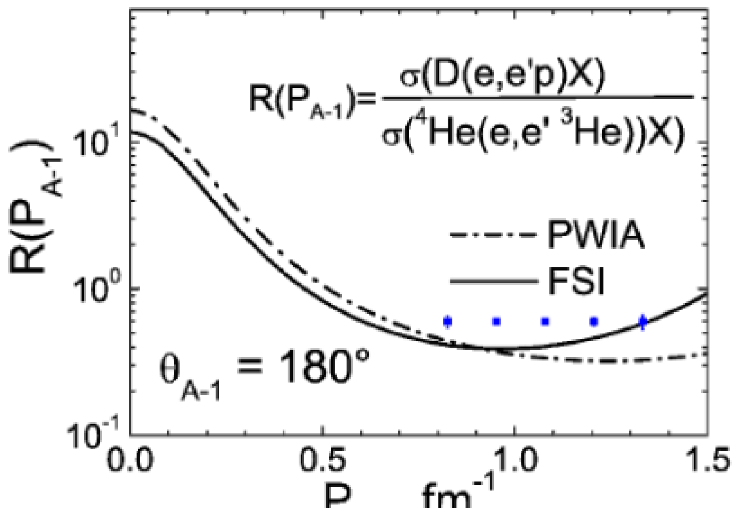
ALERT requirements

- Identify light ions: H, ^{2}H, ^{3}H, ^{3}He, and ^{4}He
- Detect the **lowest momentum** possible (close to beamline)
- Handle **high rates**
- Provide **independent trigger**
- Survive high radiation environment
  → **high luminosity**

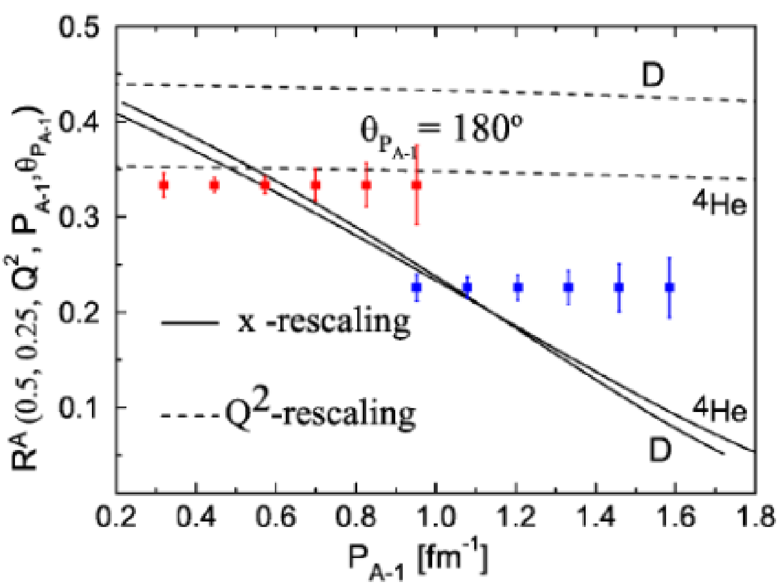


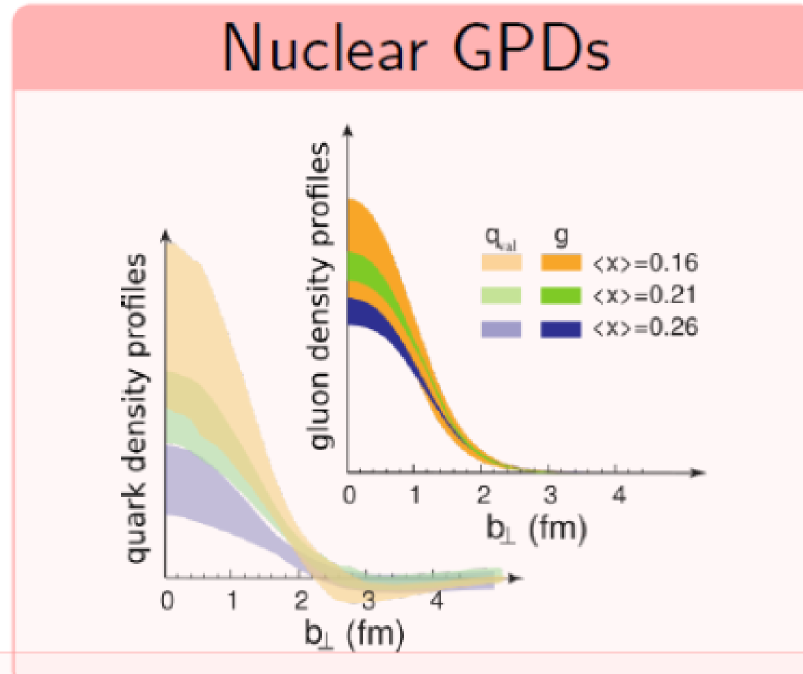
Whitney Armstrong - ANL

Test FSI models for different spectator kinematics with high precision



$Q^2=5\ (GeV/c)^2 \quad E_e=11$ GeV





Directly compare quark, gluon radii

Separate EMC effect from low-momentum (mean-field) nucleons and high-momentum SRCs

Q^2-resclaing and x-rescaling as examples of models with very different dependence on recoil momentum

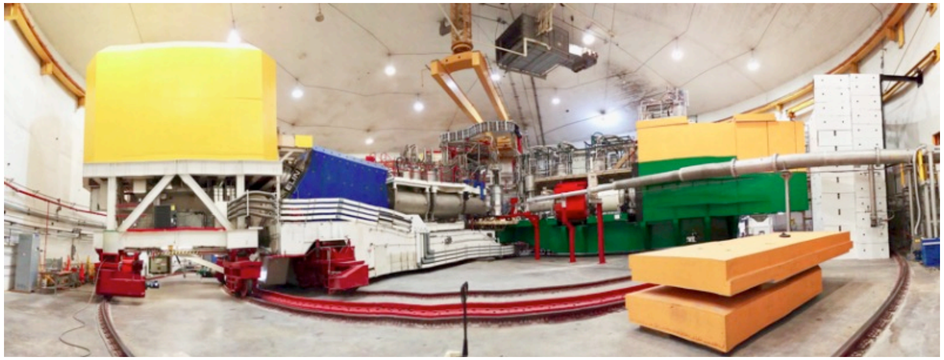
Color Transparency and the EMC effect; overview, plans, and First Hall C data taking

Eric Pooser – JLab
Dipangkar Dutta – MSU
Holly Szumila-Vance – JLab
Dave Gaskell – JLab [plenary]

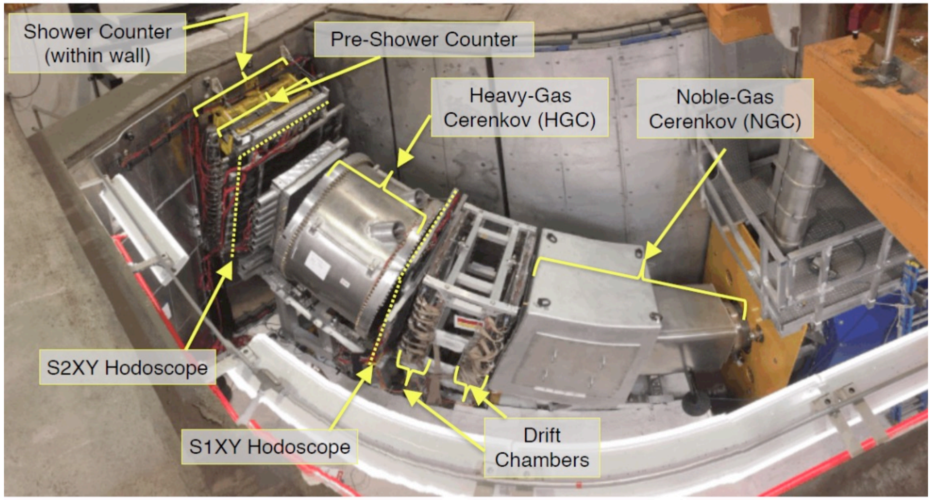
Spring 2018:

- SHMS optics commissioning
- Detector checkout, calibration

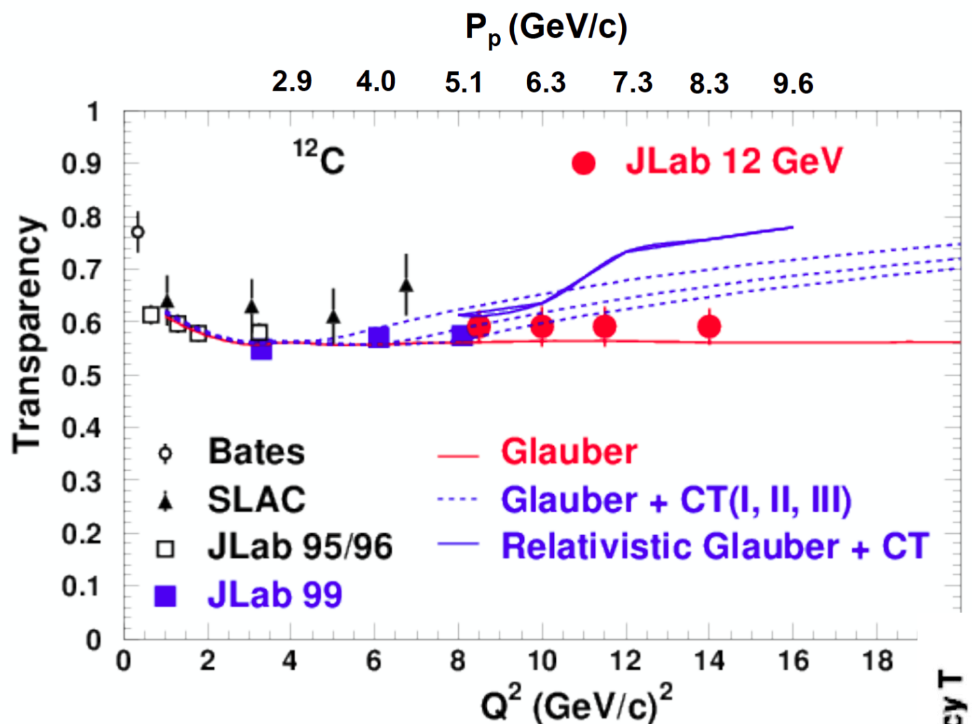
- F2 of proton, deuteron
- Color Transparency in $^{12}C(e,e'p)$
- EMC effect in ^{9}Be, $^{10,11}B$, ^{12}C



SHMS Detector System



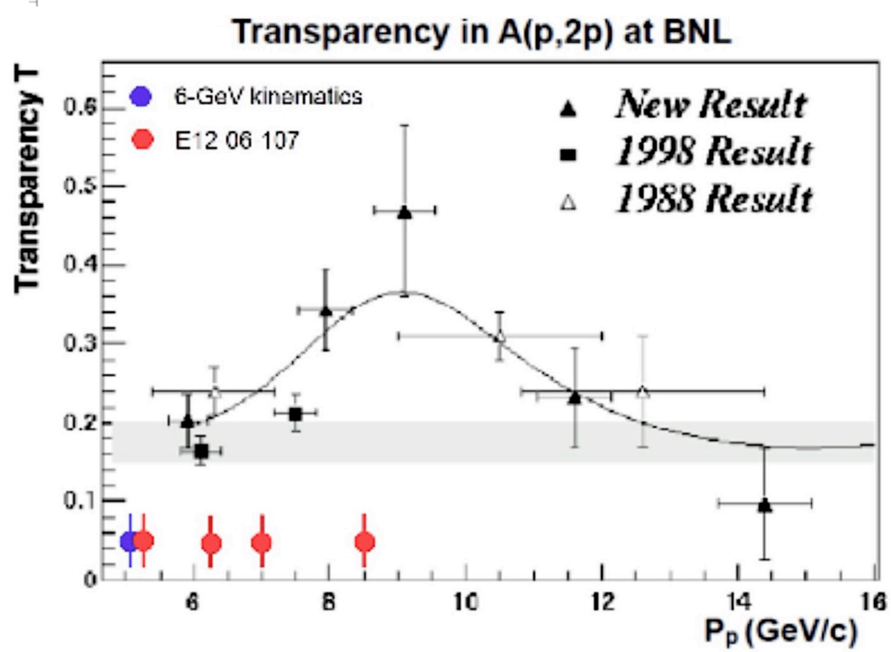
Color Transparency; new Hall C data



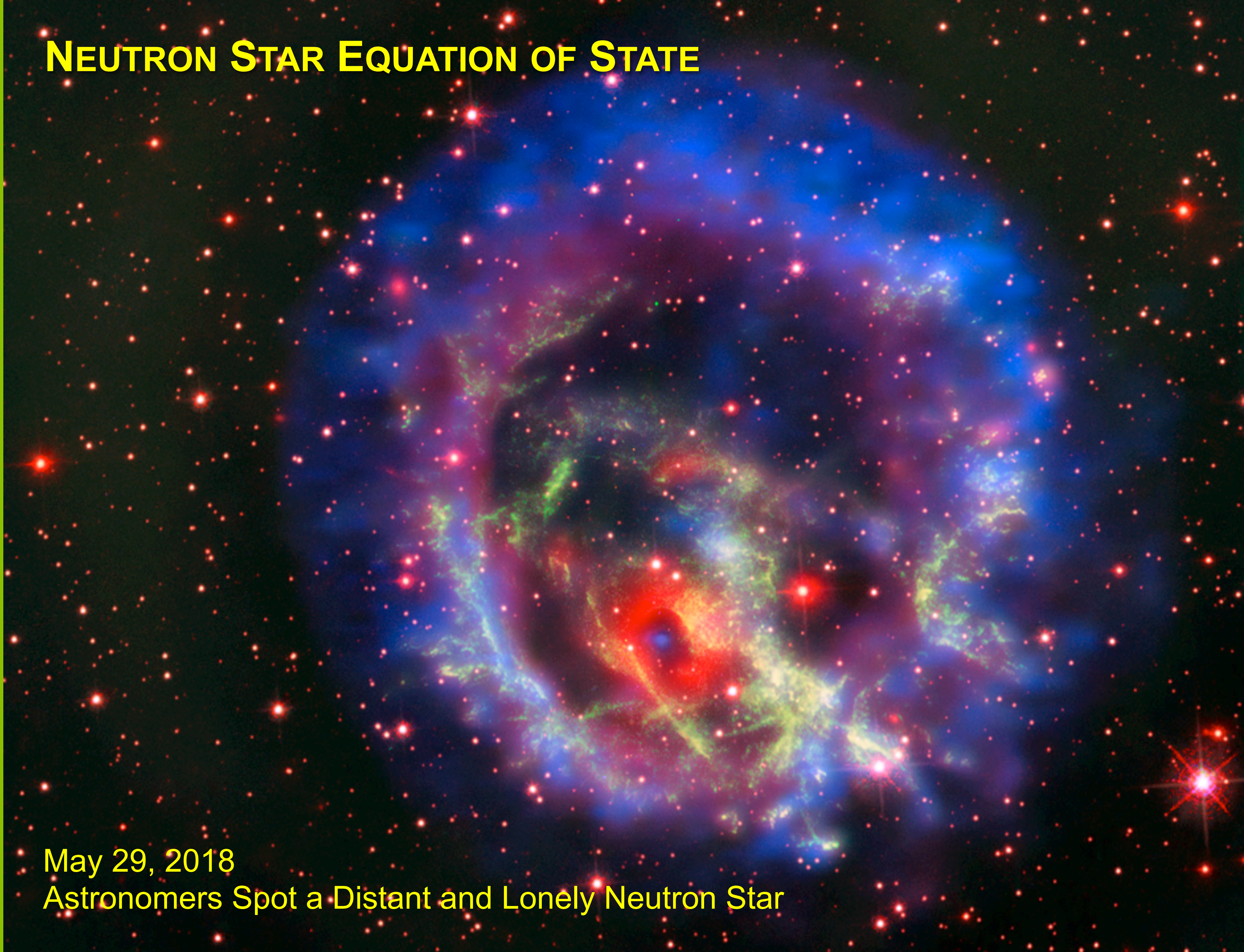
Dipangkar Dutta – MSU
Holly Szumila-Vance – JLab

Kinematics and uncertainties from spring data taking

Reach Proton momenta where BNL saw large effect in (p,2p)



Neutron Star Equation of State



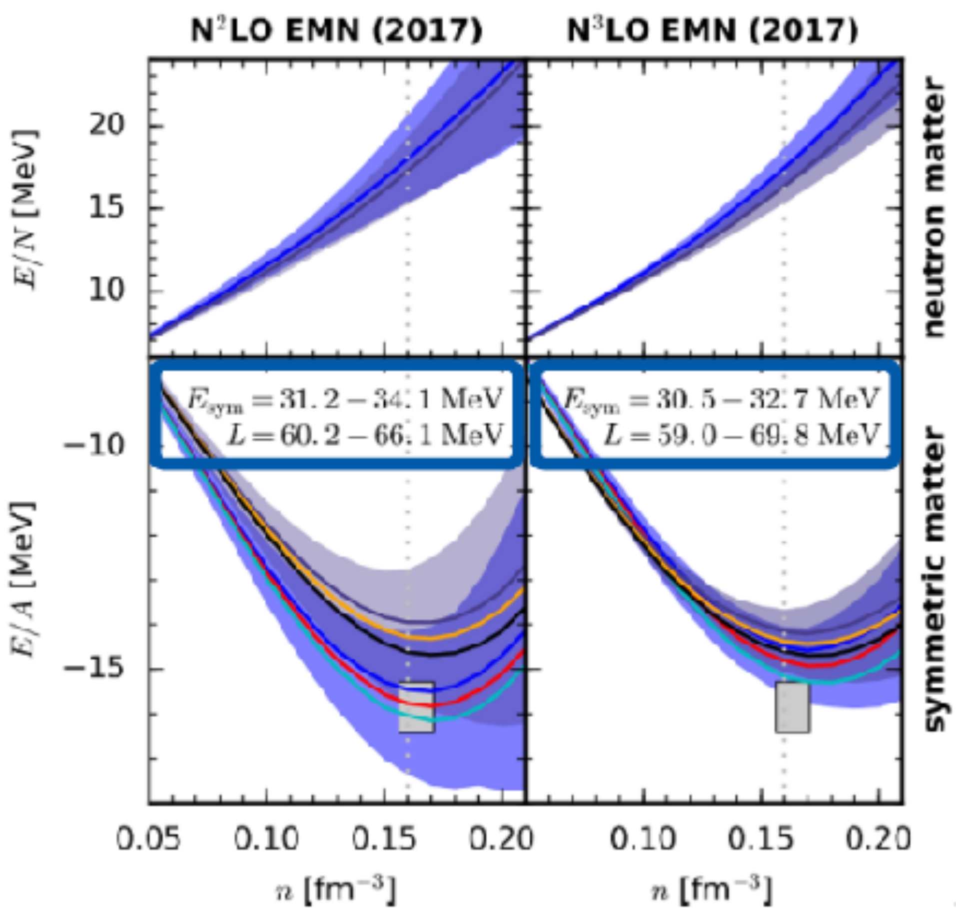
May 29, 2018
Astronomers Spot a Distant and Lonely Neutron Star

Nuclear-Matter Equation of State from Chiral Effective Field Theory

Christian Drischler

Fits to saturation region

CD, Hebeler, Schwenk, arXiv:1710.08220



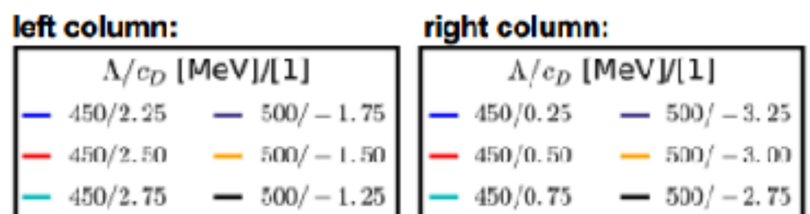
Neutron and symmetric matter with consistent NN + 3N forces

- 4N HF energy ~150 keV @ n_0
- **narrow ranges** for E_{sym} and L
- uncertainties from chiral EFT

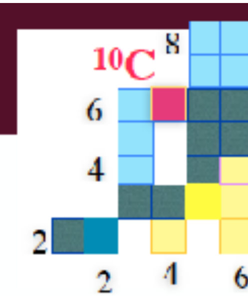
Epelbaum *et al.*, EPJ A **51**, 53

Symmetric matter @ N³LO:

- **reduced cutoff dependence**
- **reduced theo. uncertainties**

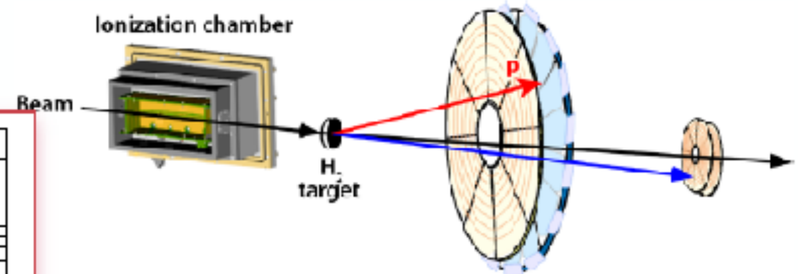


$^{10}C(p,p)$: Constraining the nuclear force via dynamics @ drip-line

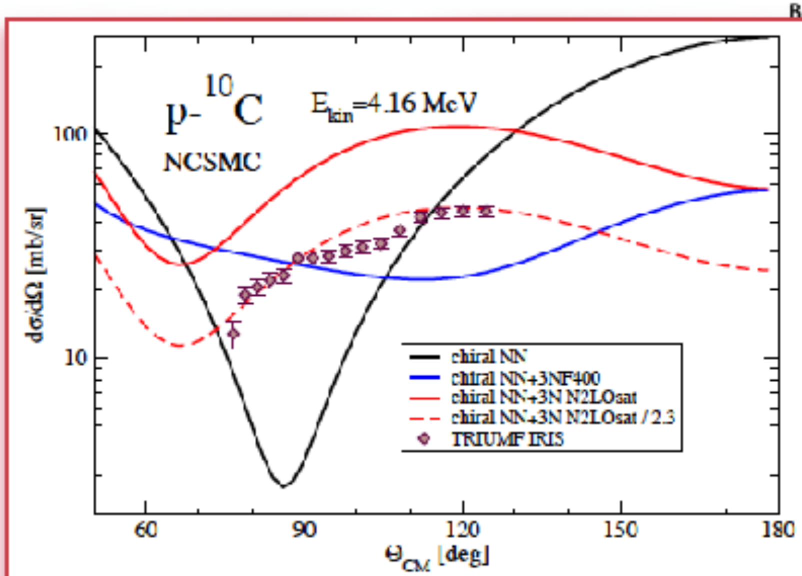


Selected for a Viewpoint in *Physics*
PRL 118, 262502 (2017) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2017

Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with ^{10}C



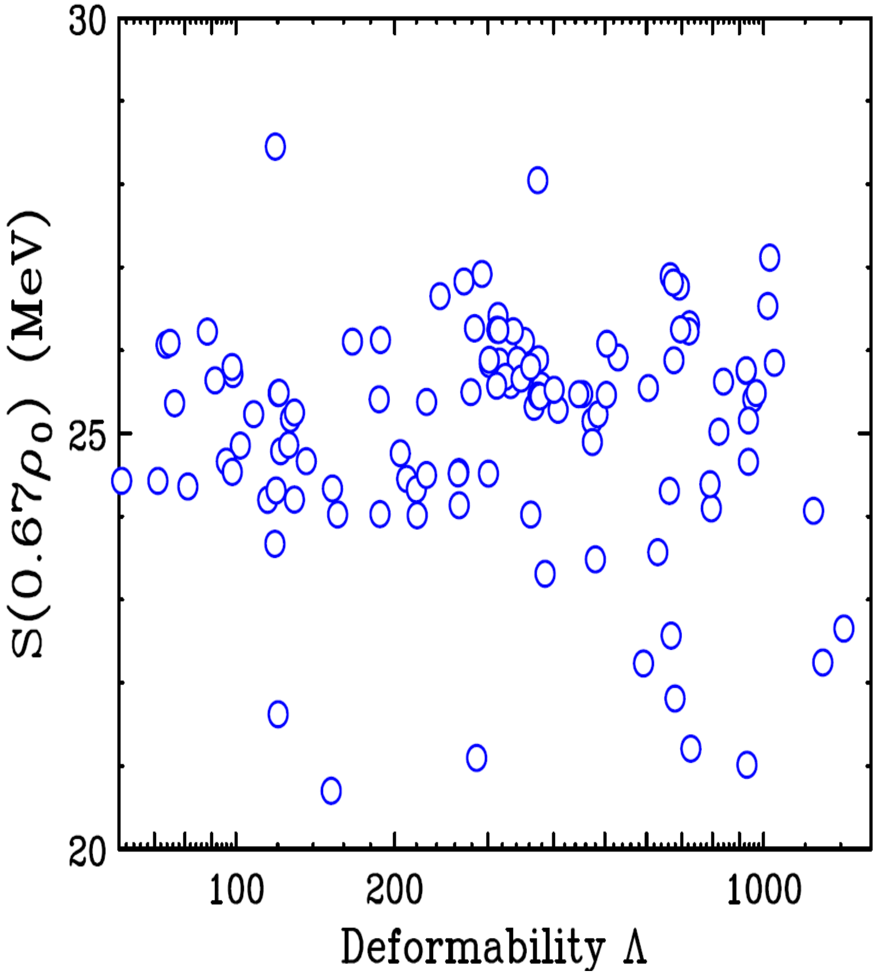
IRIS @ TRIUMF

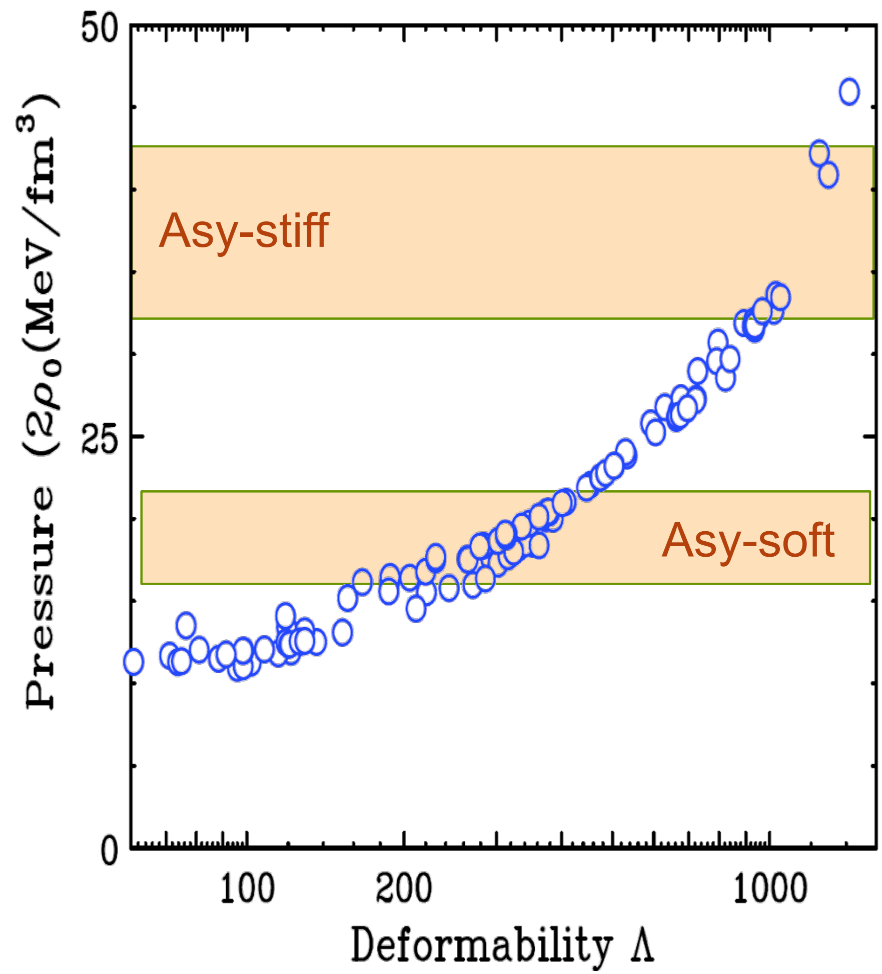


A. Kumar, R.Kanungo, A. Calci, P. Navratil et al.

$^{10}C(p,p)$ elastic scattering angular distribution exhibits strong sensitivity to constrain various prescriptions of the nuclear forces from chiral EFT

BETTY TSANG: LABORATORY PROBES OF THE NEUTRON MATTER EOS





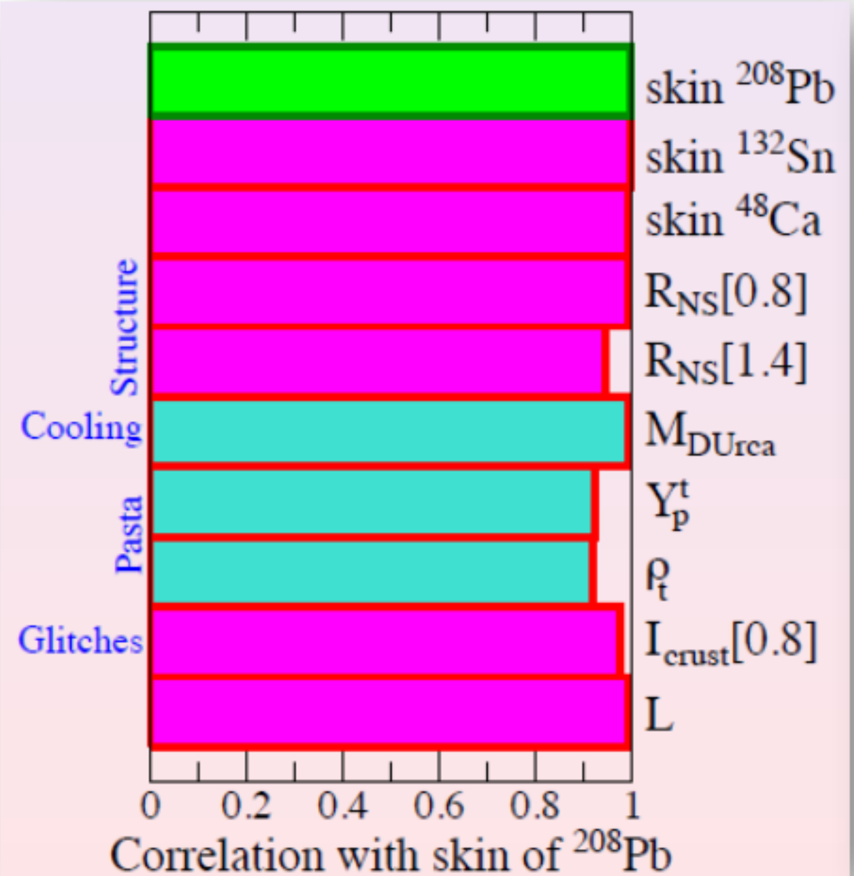
Tidal deformability, Λ, is not sensitive to measured sub-saturation constraints.

At high density, pressure P and Λ are strongly correlated. P can be determined from heavy ion experiments

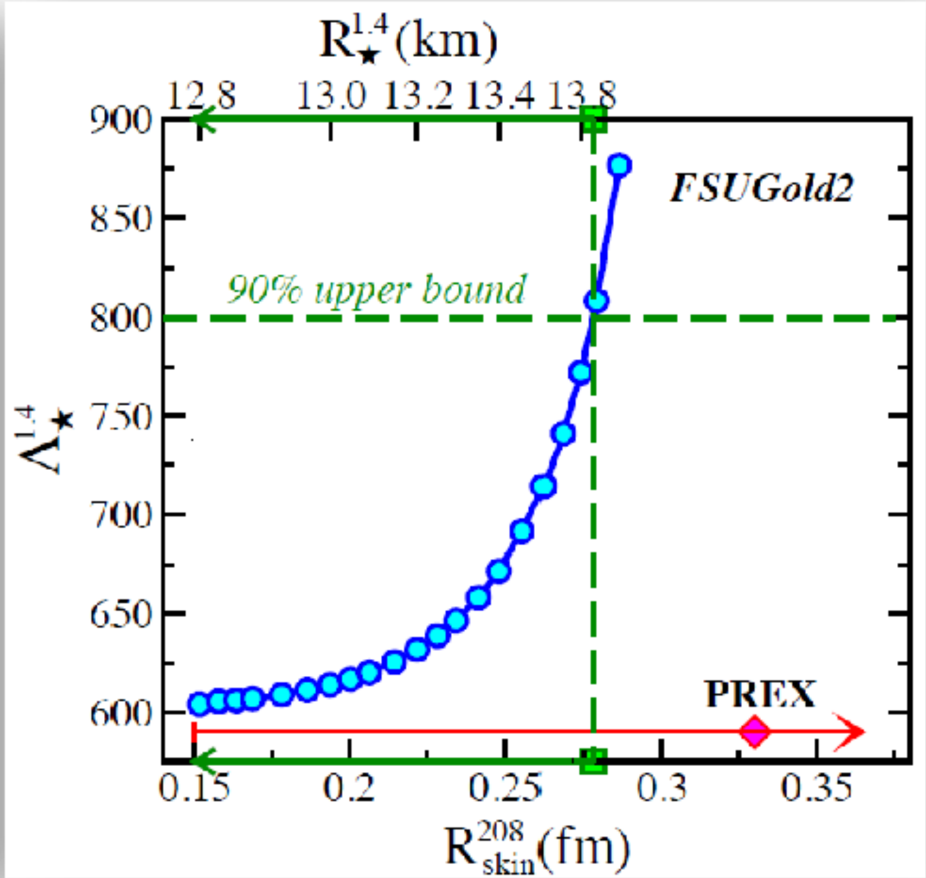
Neutron Skins and Neutron Stars: Farrukh J. Fattoyev

Neutron skin thickness is strongly correlated with a myriad of neutron-star observables:
neutron-star radii, crust-core transition properties, cooling observations, pulsar glitches, moments of inertia, and tidal polarizabilities.

Experimental measurement of the *neutron skin thickness* in conjunction with the astrophysical and gravitational wave observation of *neutron star properties* can be used to constrain the nuclear equation of state under extreme conditions.



Fattoyev & Piekarewicz, PRC86,015802(2012)



Fattoyev, Piekarewicz, Horowitz, Phys. Rev. Lett., 172702 (2018)

NEUTRON SKIN

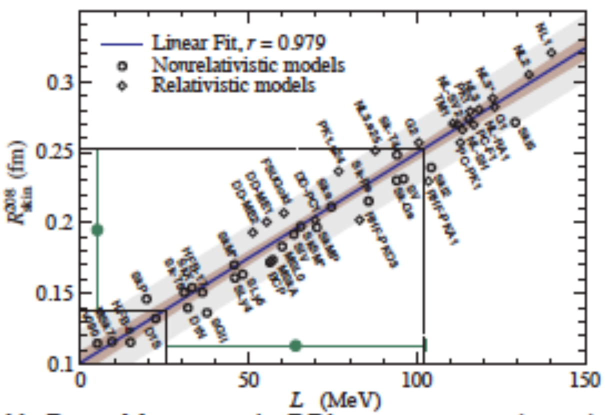
Seamus Riordan—Argonne

PREX-II - ^{208}Pb

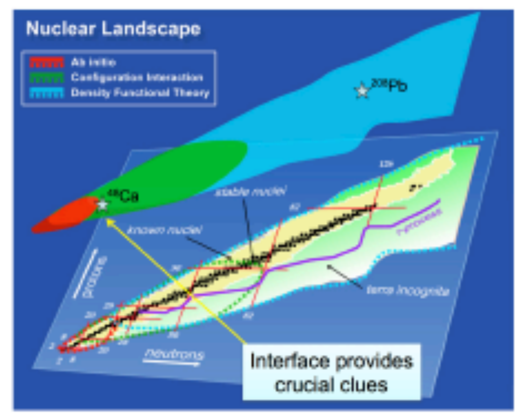
- Aims to each goal of $\delta R_n \sim 0.06$ fm
- Improved shielding and more advanced targets allow for full running
- Will provide reliable constraints on slope of symmetry energy

CREX - ^{48}Ca

- Measurements on ^{48}Ca to 0.02 fm
- Gives broader reach over periodic table
- Contributing systematics slightly different
- $A \sim 40$ now within reach of microscopic calculations

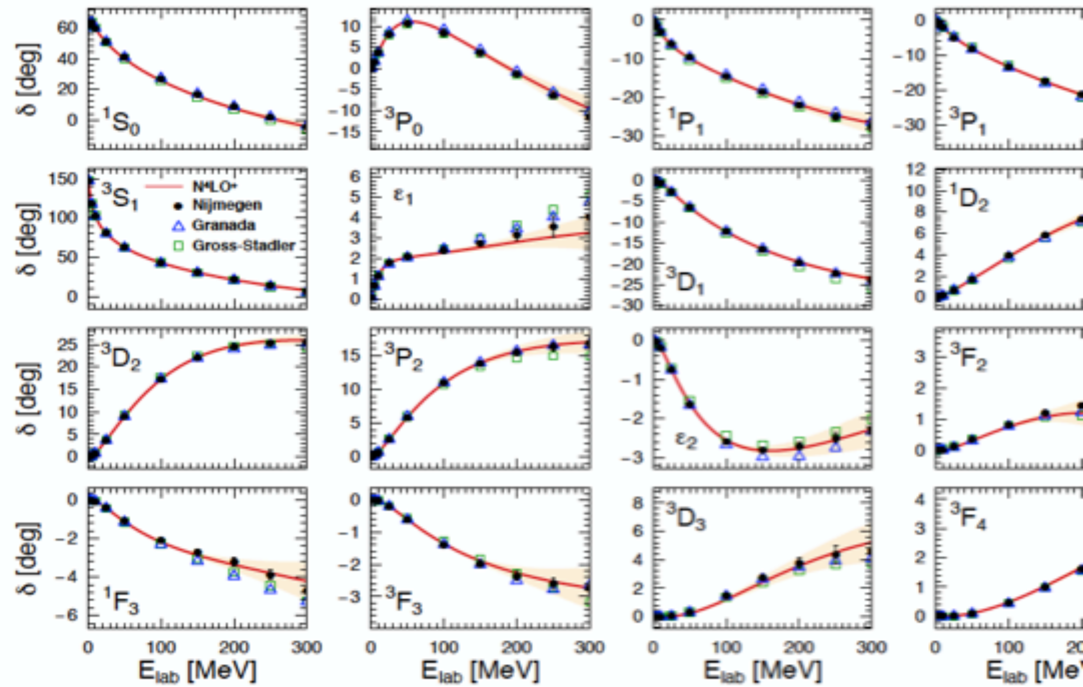


X. Roca-Maza *et al.*, PRL 106 252501 (2011)



Scheduled for Summer 2019

Evgeny Epelbaum: Current status of nuclear forces from Chiral EFT



— N^4LO^+ yields currently the best description of the 2013 Granada data

— 40% less parameters (27+1) compared to high-precision potentials

— Clear evidence of the parameter-free chiral 2π exchange

Nuclear Hamiltonian:

— derivation of contributions up to N^3LO completed already in 2011; derivation of N^4LO corrections done for V_{2N} and almost done for V_{3N} (new LECs…) and V_{4N}

— accurate & precise 2N potentials at N^4LO^+ are available,

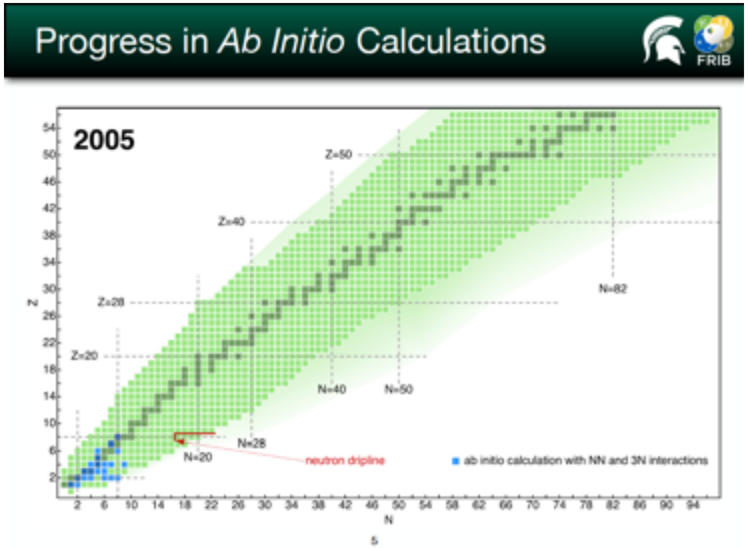
— promising results for few-N systems based on 2NF + 3NF@N^2LO [LENPIC]

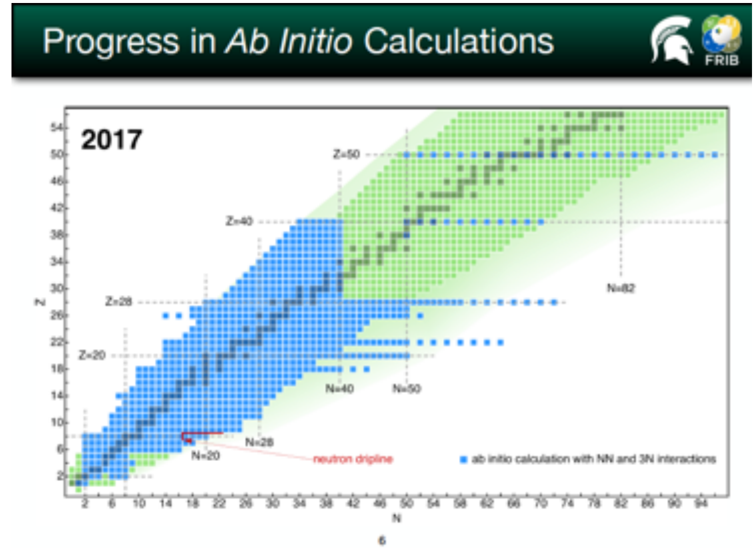
Electroweak current operators:

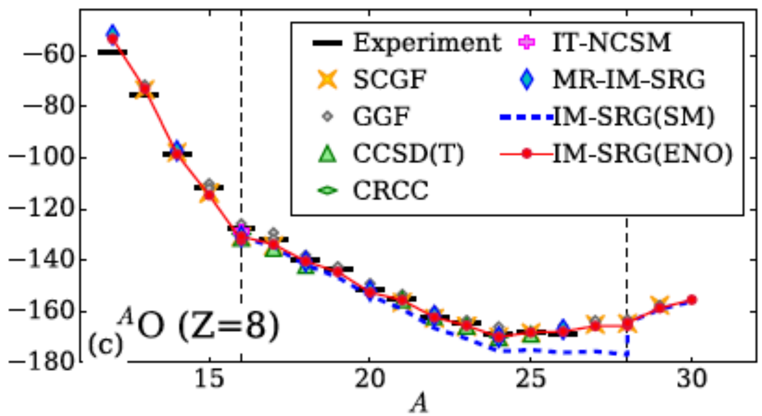
— have been worked out completely to N^3LO

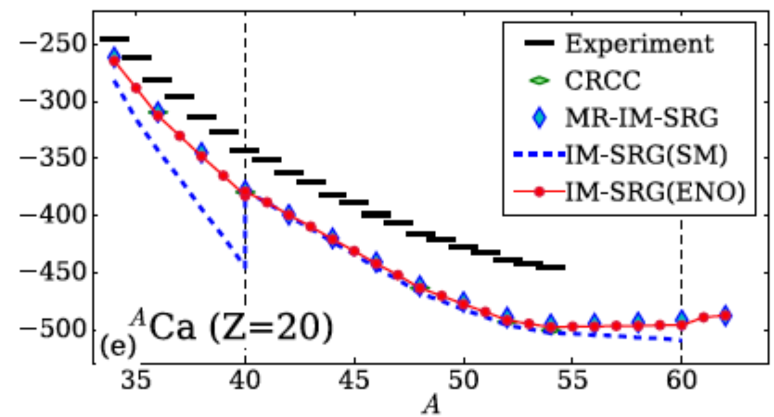
— some πN LECs in 1π axial charge at N^3LO are unknown…
[lattice QCD? ν-induced π-production? resonance saturation? large-N_c?…]

Scott Bogner: Ab-initio shell model interactions and effective operators









Stroberg et al., PRL (2017)

- Tremendous growth of ab-initio progress recent years
- Agreement between different ab-initio methods now possible for medium-mass nuclei
- Poor saturation properties of existing chiral EFT interactions clear in heavier systems

One approach is **diagonalization of the Hamiltonian in a basis.** Modern techniques and computers can handle up to ~ 25 billion basis states (though that is is not the primarily measure of computational burden) and there are many promising techniques for extending the reach and accuracy of *ab initio* calculations (e.g., Machine learning)

-- Machine learning

From Negoita *et al*, arXiv:1803.03215

Extrapolation via Artificial Neural Net (ANN)

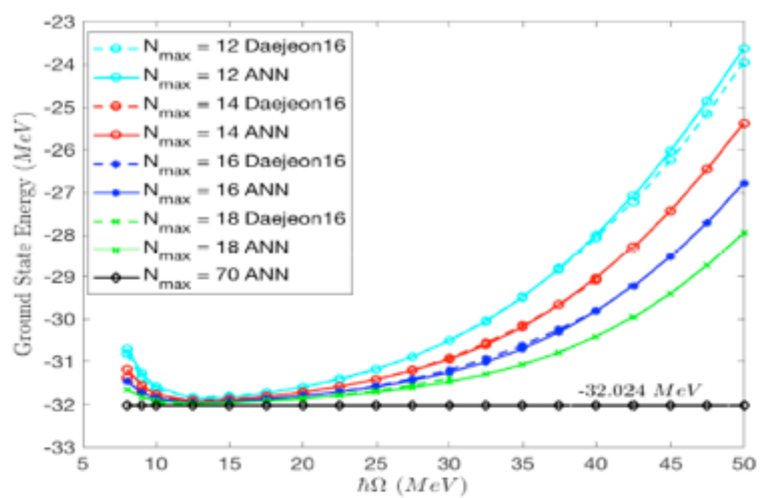


Figure 7. Comparison of the NCSM calculated and the corresponding ANN predicted gs energy values of ^{6}Li as a function of $\hbar\Omega$ at $N_{\max} = 12, 14, 16$, and 18. The lowest horizontal line corresponds to the ANN nearly converged result at $N_{\max} = 70$.

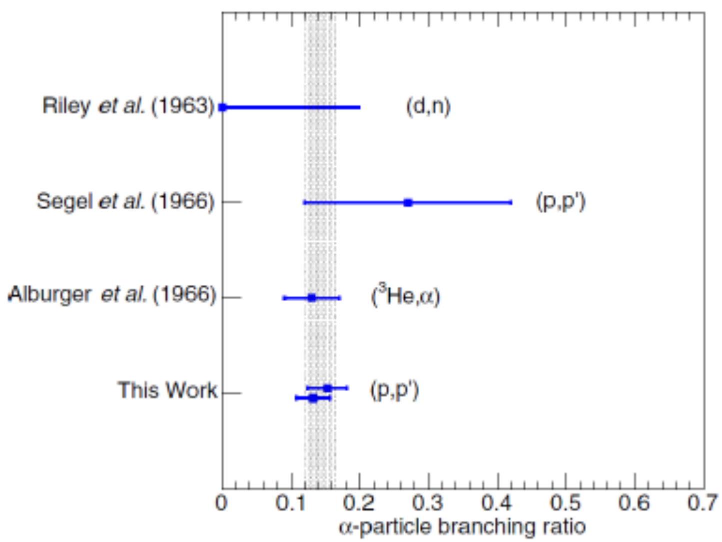
Alan Wuosmaa: Experimental tests of ab-initio structure calculations

- Many Successes
  - Binding and excitation energies
  - Charge and matter radii
  - Spectroscopic overlaps / spectroscopic factors
  - Transition matrix elements
  - Continuum states

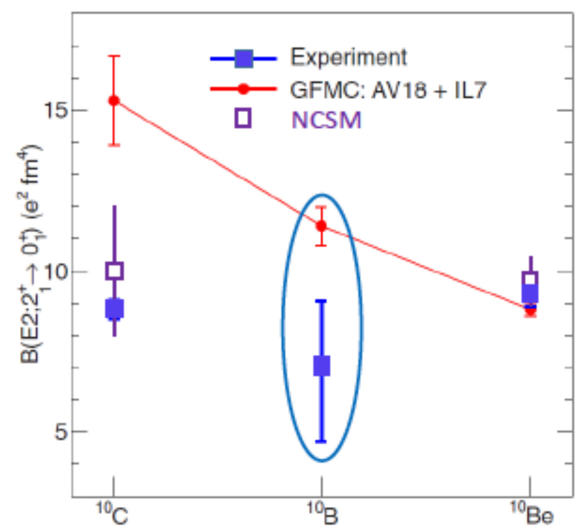
more challenging for theory

$^{10}B(p,p')^{10}B^*$ in HELIOS at ANL

The discrepancy remains for GFMC in ^{10}B



New results favor a smaller α branch, reduce combined uncertainty



Uncertainty in B(E2) now dominated by 0.16% gamma-ray branching ratio

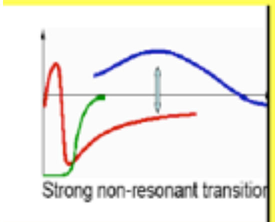
Kuvin et al., PRC 96, 041301(R) (2017)

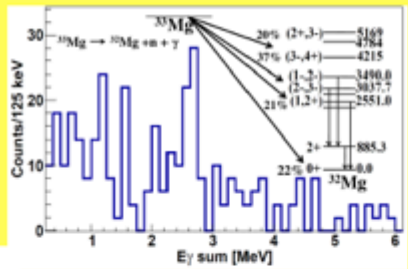
Argonne

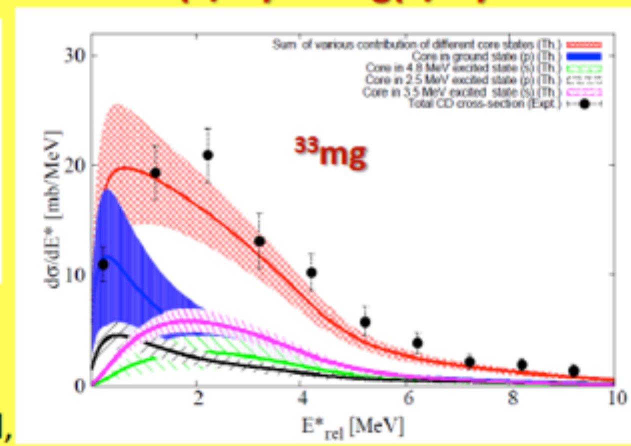
First Direct evidence of multi particle-hole ground state of ^{33}Mg

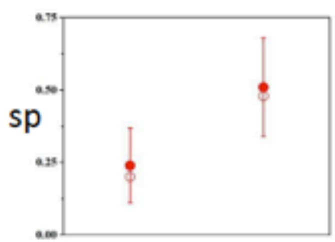
Threshold strength---direct breakup-----quantum numbers with spectroscopic factor

^{41}Ca (7/2-) ^{33}mg(3/2-)









● ➡ Expt.

○ ➡ Sdpf-M

Y.Utsuno et al,

U.Datta et al, PRC 94, 034304 (2016),

^{32}Mg(0, gr) ⊗ν p3/2

^{32}Mg(3.5, 1-) ⊗ν s1/2

^{32}Mg(2.5, 2 +) ⊗ν p3/2

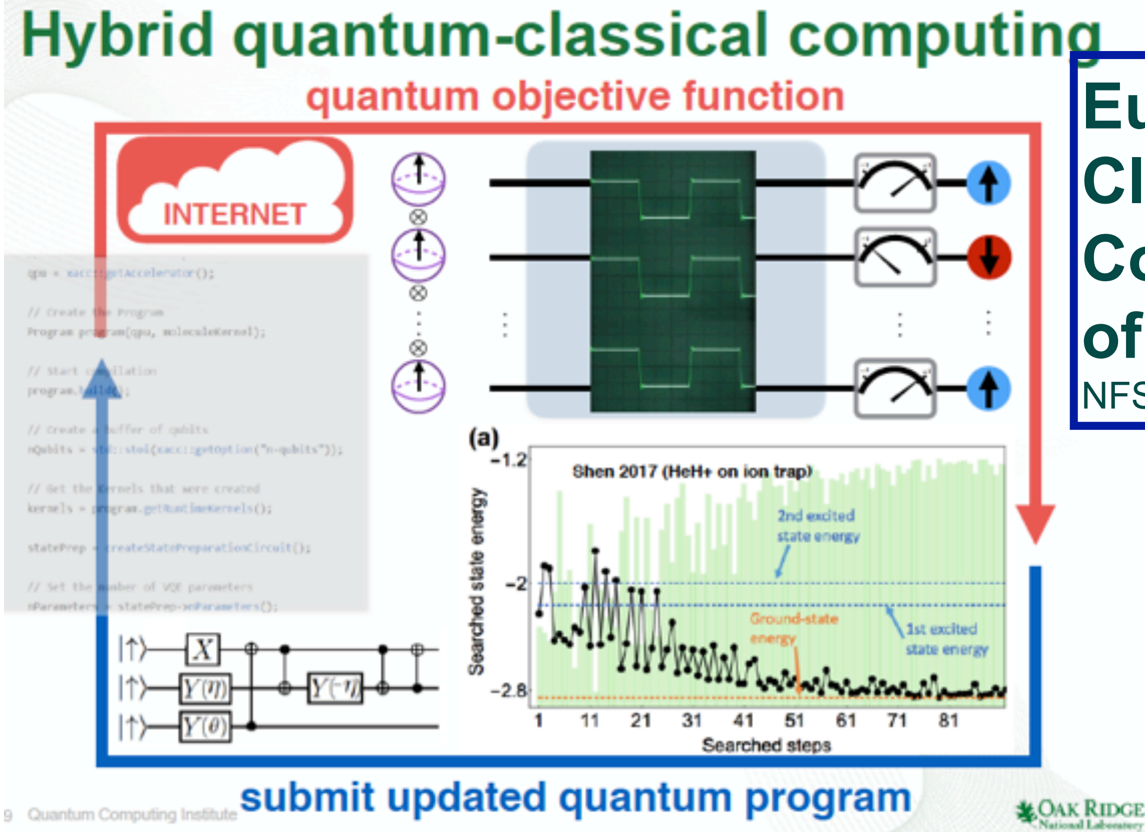
½[200] ~ 60-70% j1/2

Yordanov et al., PRL 104(2010)

magnetic moment~- 0.86 μn, expt.- 0.745 μn

Larry et al, PLB23(1966) explained

similar observation by deformed core



Eugene Dumitresco: Cloud Quantum Computing of an Atomic Nucleus

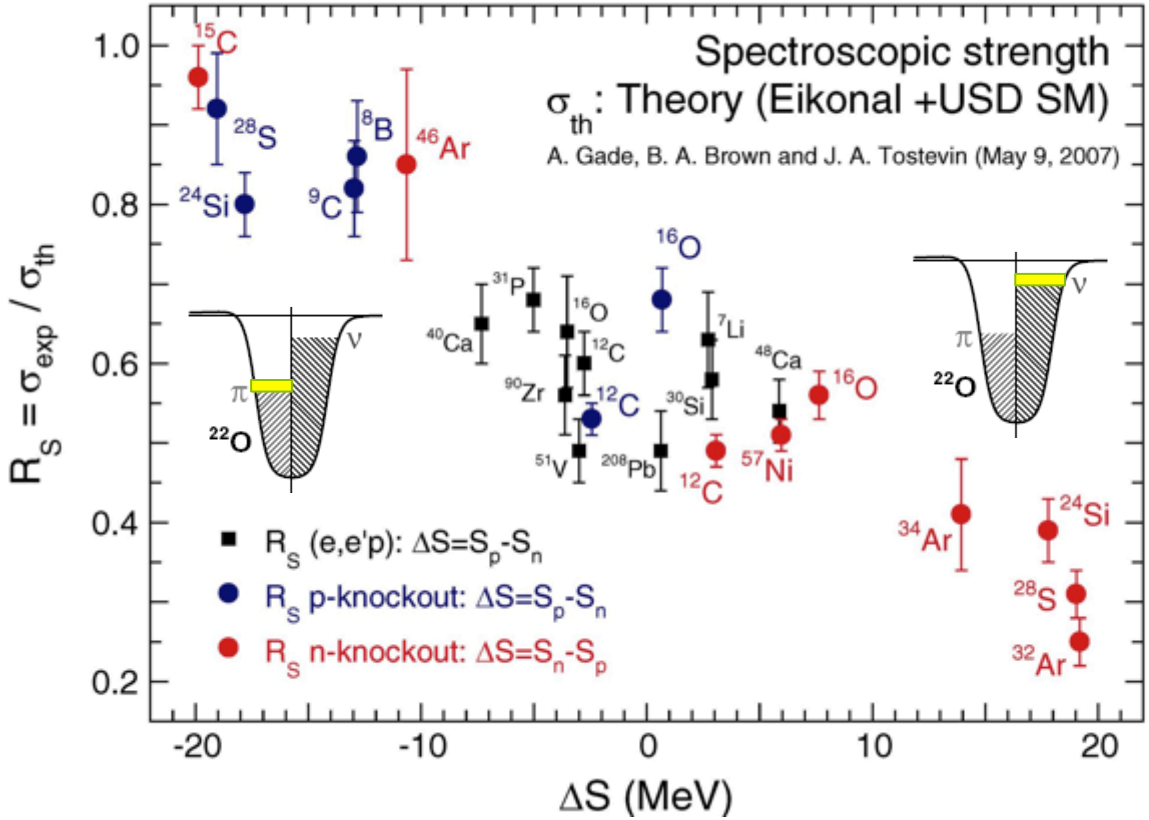
NFS #8

1st quantum computation of the deuteron

E from exact diagonalization				
N	E_N	$\mathcal{O}(e^{-2kL})$	$\mathcal{O}(kLe^{-4kL})$	$\mathcal{O}(e^{-4kL})$
2	-1.749	-2.39	-2.19	
3	-2.046	-2.33	-2.20	-2.21
E from quantum computing				
N	E_N	$\mathcal{O}(e^{-2kL})$	$\mathcal{O}(kLe^{-4kL})$	$\mathcal{O}(e^{-4kL})$
2	$-1.74(3)$	$-2.38(4)$	$-2.18(3)$	
3	$-2.08(3)$	$-2.35(2)$	$-2.21(3)$	$-2.28(3)$

ALEXANDRA GADE: SHORT RANGE CORRELATIONS IN NUCLEI

- The reduction of spectroscopic strength. . .may indicate correlations beyond effective interaction theory and limited model spaces.
  - Minority nucleons are more correlated than the majority species
  - These correlations are not captured in effective shell-model



- From the asymmetry dependence of the reduction and consistent with expectations from some models of nuclei and nuclear matter, the minority nucleons in an asymmetric nucleus are more correlated than the majority nucleon species. This agrees with the large body of work on SRC from JLab by Hen, Weinstein *et al.*