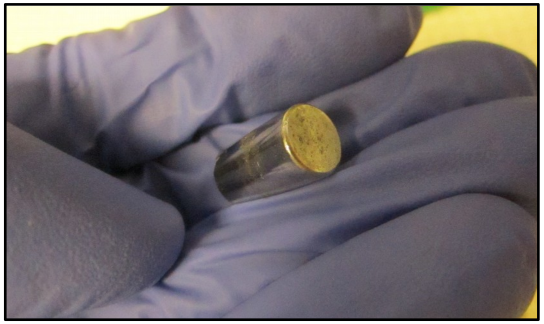
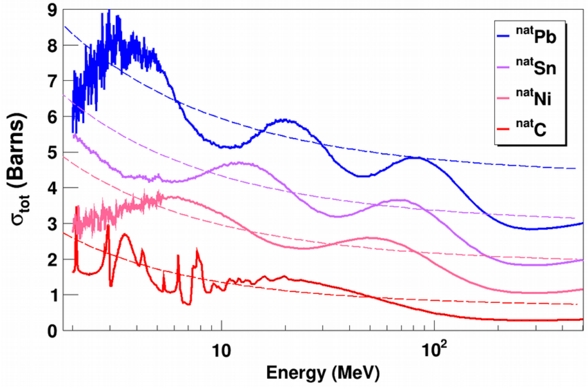
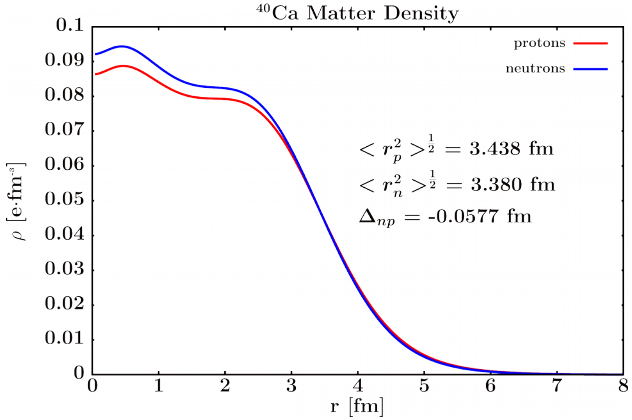
Neutron Total Cross Sections and Neutron Skins







"What do the nucleons do in the nucleus?" - Sir Denys Wilkinson
(proton and neutron matter distribution, neutron skin)

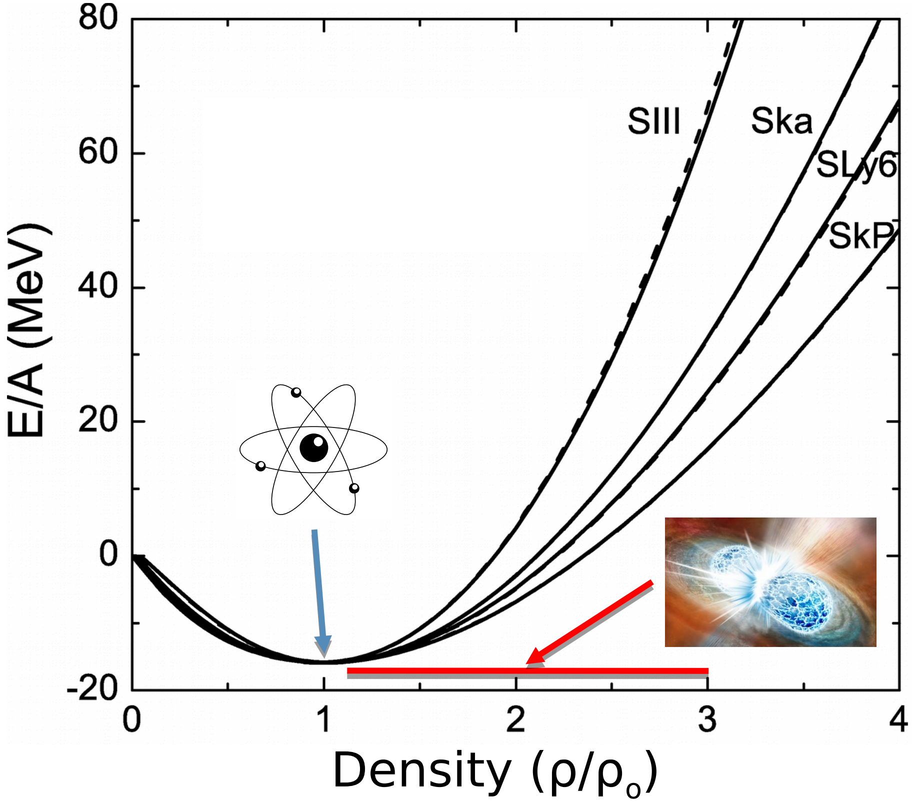
How does the nucleus "look" to an incident neutron, compared to a proton?
(isovector components of potential)

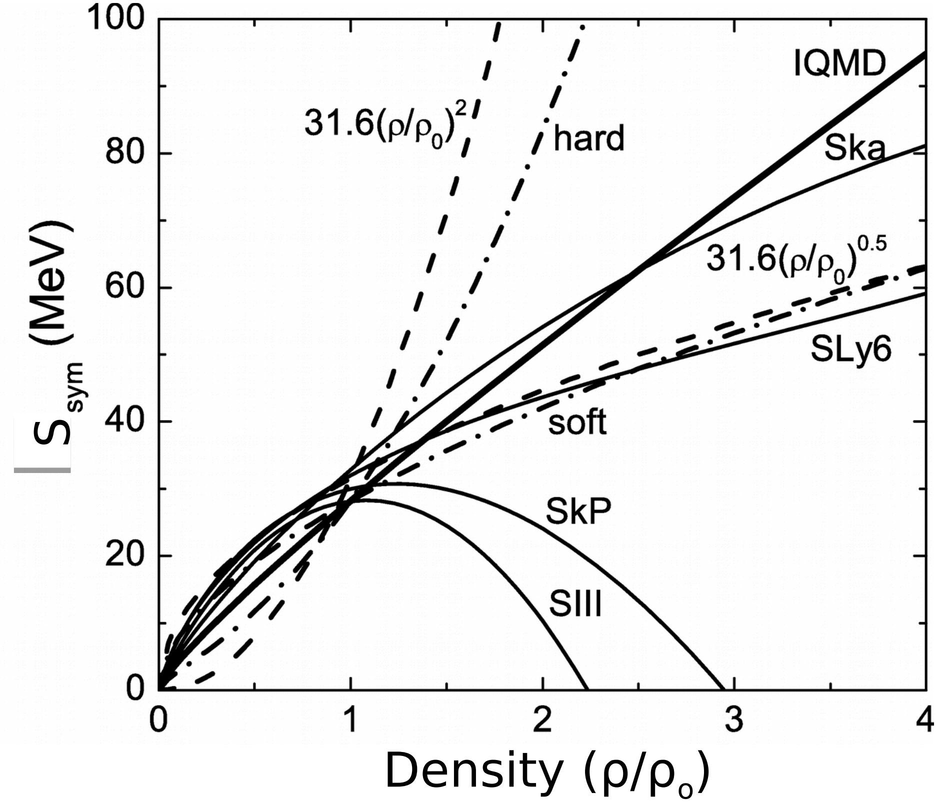
How do reaction and structure inform each other?
(connecting data > ε_F ↔ data < ε_F by applying a dispersion relation)

Cole D. Pruitt
PhD candidate in Chemistry
Washington University in St Louis

Density Dependence of the Symmetry Energy

$$E\left(\rho,\frac{N-P}{N+P}\right) = E(\rho,0) + S_{sym}(\rho)\left[\frac{N-P}{N+P}\right]^2$$





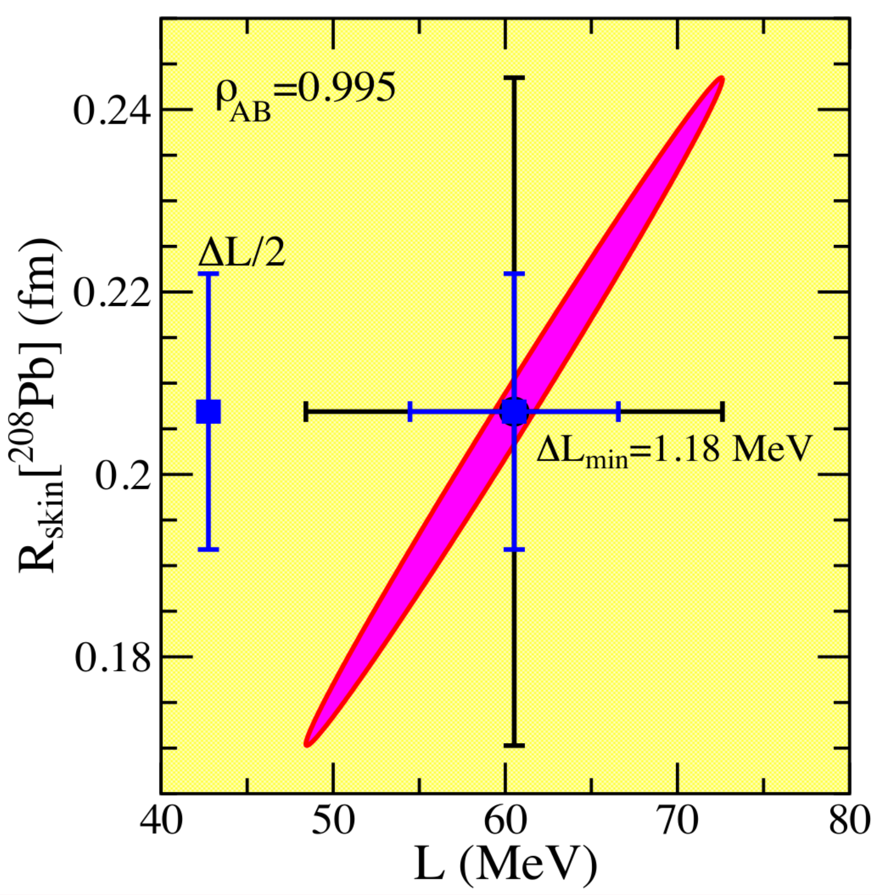
Z.Q. Feng *et al.* Phys Lett B 683 (2010)

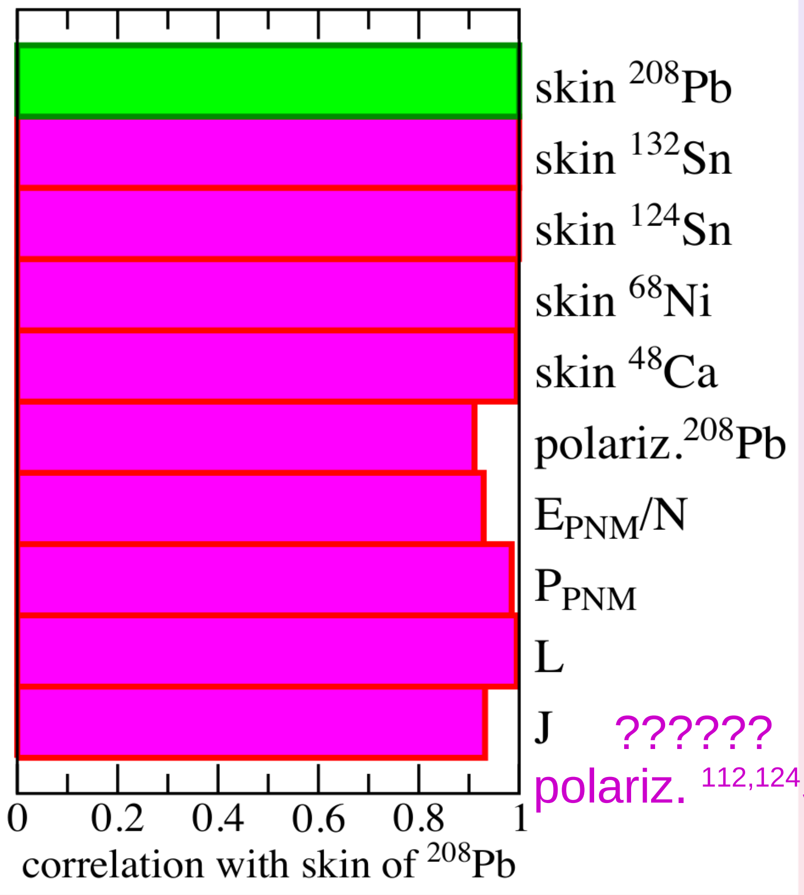
Slide courtesy J. Silano

Neutron star EOS $\Leftrightarrow$ $S(\rho) \simeq S(\rho_0) - L\left(\frac{\rho_0 - \rho}{3\rho_0}\right) + \frac{1}{2} K_{sym}\left(\left(\frac{\rho_0 - \rho}{3\rho_0}\right)^2\right)$

???

"The correlation between **neutron radius of ^{208}Pb and the slope of the symmetry energy L** is by now very well established..."
- F. J. Fattoyev and J. Piekarewicz, PRC 86 015802 (2012)





?????? polariz. ^{112,124}Sn

PREX, PREX II, and CREX

Neutron weak charge is ~12x proton weak charge. *REX measures the weak charge distribution directly via parity-violating election scattering ↔ neutron skin

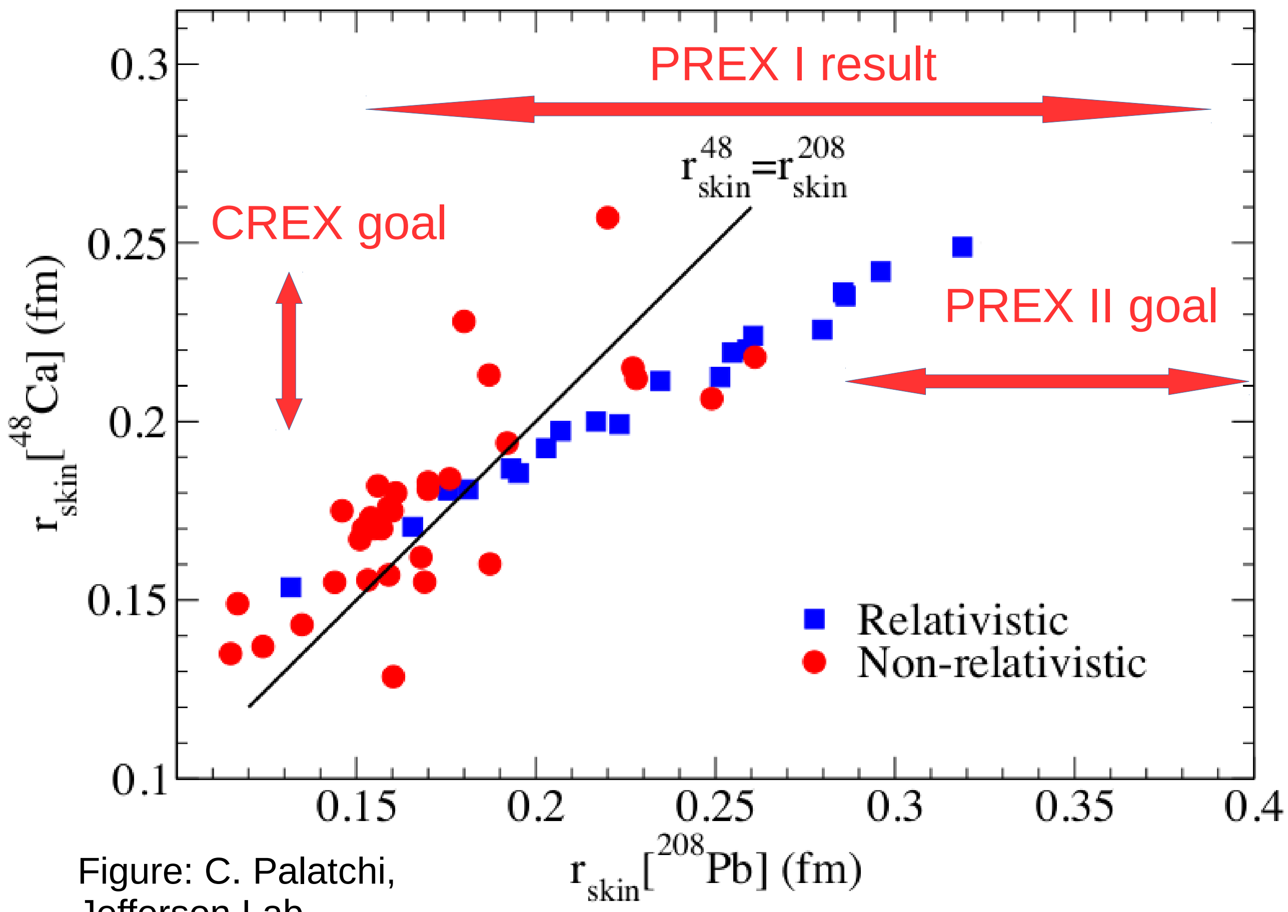


Figure: C. Palatchi, Jefferson Lab

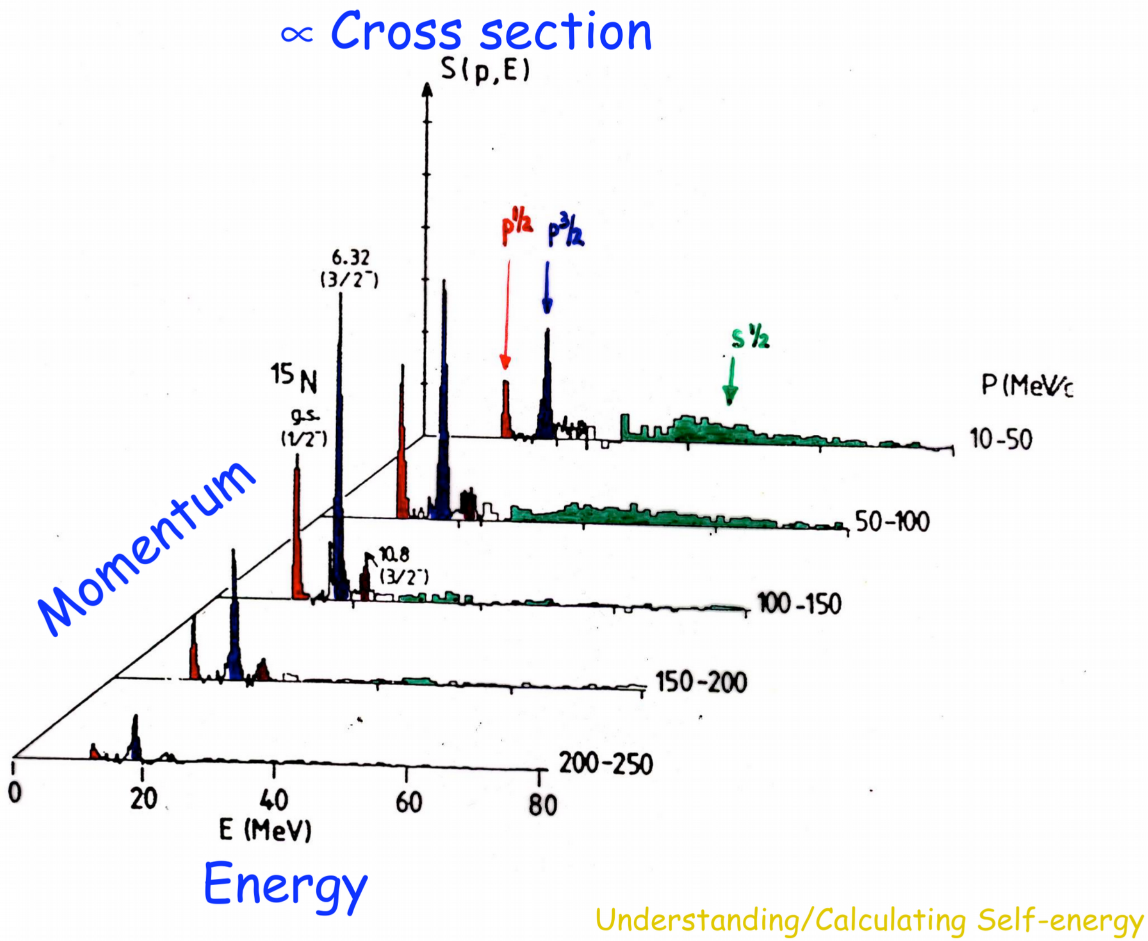
Results from PREX I:
Δ_{np} = 0.33 + 0.16 – 0.18 fm

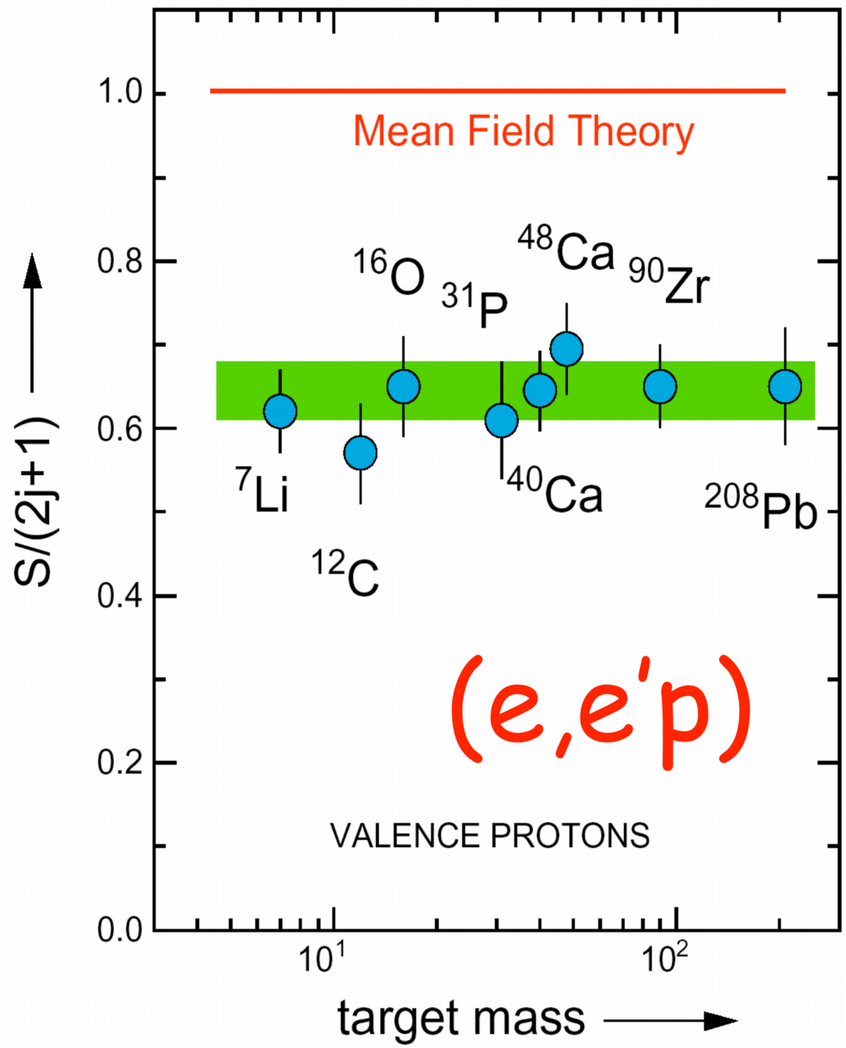
Upcoming run PREX II:
Δ_{np} within 0.06 fm

Upcoming run CREX:
Δ_{np} within 0.02 fm

How can we access this physics from “traditional” nuclear data?

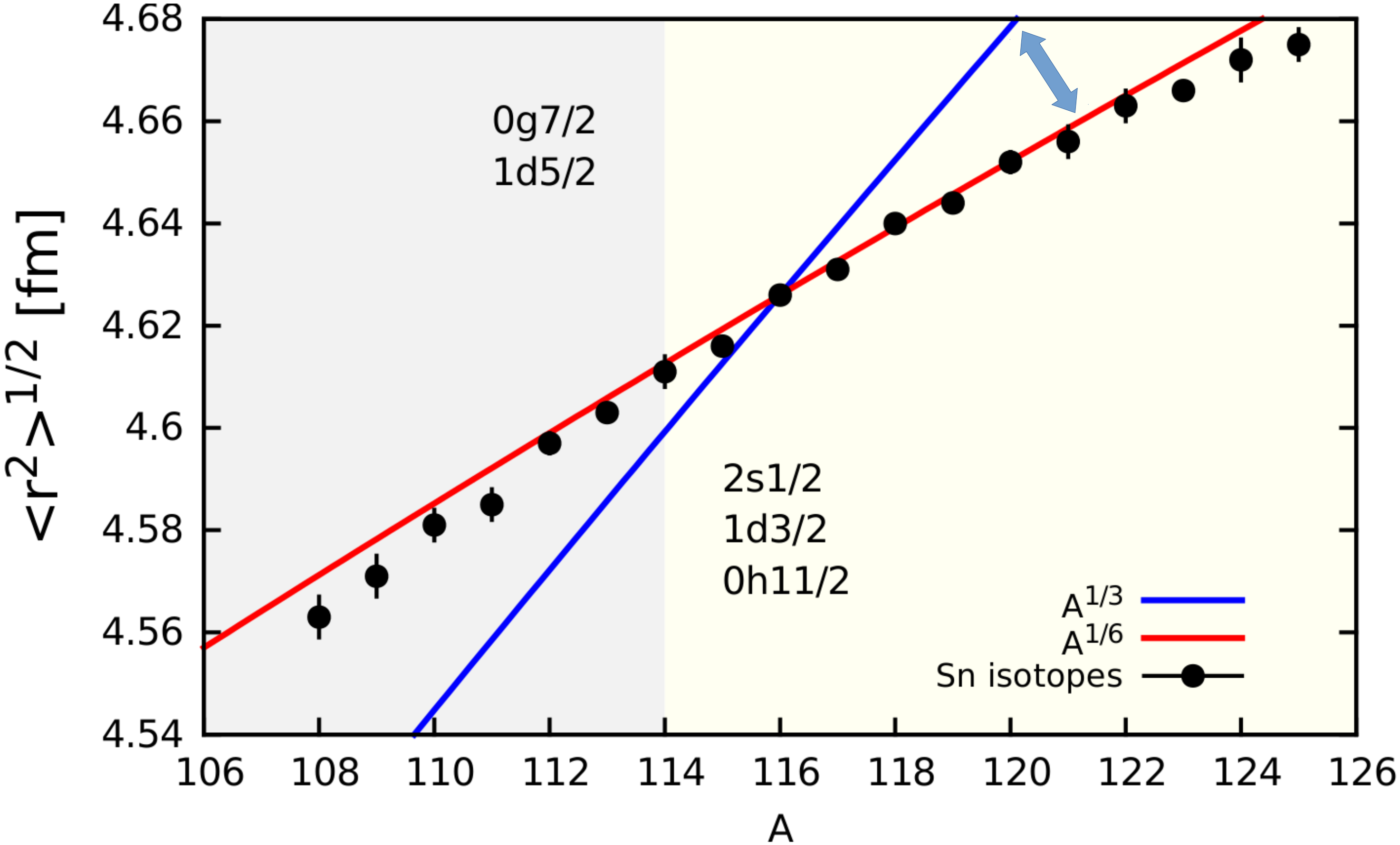
(e,e'p): depletion from MF below ε_F





Figures courtesy W. Dickhoff (WUSTL)

The symmetry energy and the isotope shift in Sn



Anselment et al., PRC **34** 1052 (1986); Berdichevsky et al., Z. Physik A **329** 393 (1988)

Shift in atomic s, p transitions with laser spectroscopy → nuclear charge radius

Slope deviation from $A^{1/3}$ ↔ bulk properties:

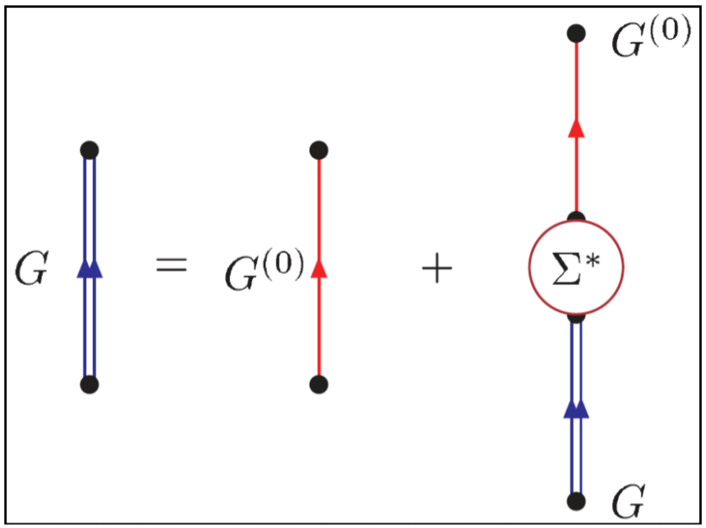
- S (symmetry energy)
- L (density dep. of S)
- Q (surface stiffness)

Non-linearity: microscopic effects. Surprisingly small, despite traversing 18 neutrons and multiple subshells!

What if we looked across ALL scattering data to extract structure information? → DOM

Dispersive Optical Model Formalism

Dyson Equation for SP propagator



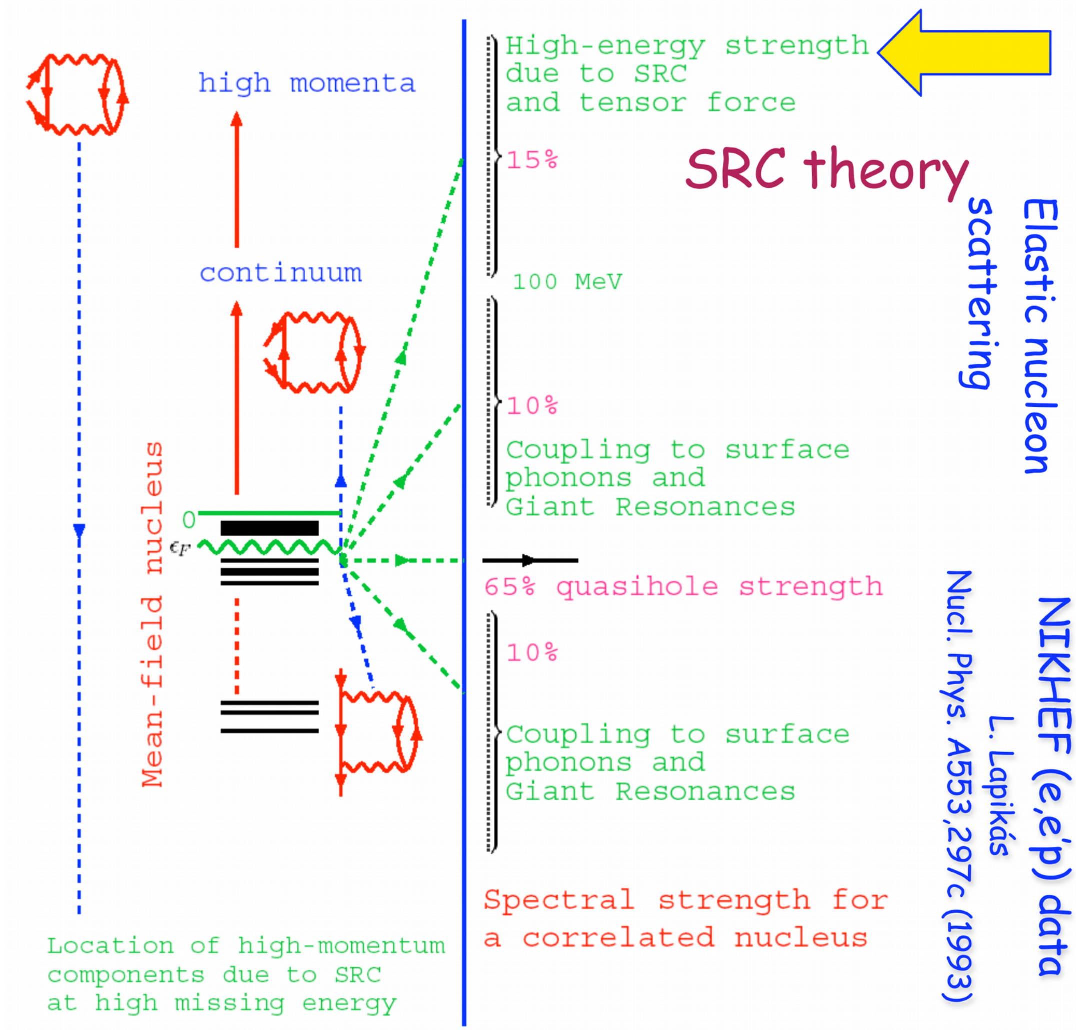
Equivalent to …

Schrödinger-like equation with: $E_n^- = E_0^A - E_n^{A-1}$

Self-energy: non-local, energy-dependent potential

With energy dependence: spectroscopic factors < 1

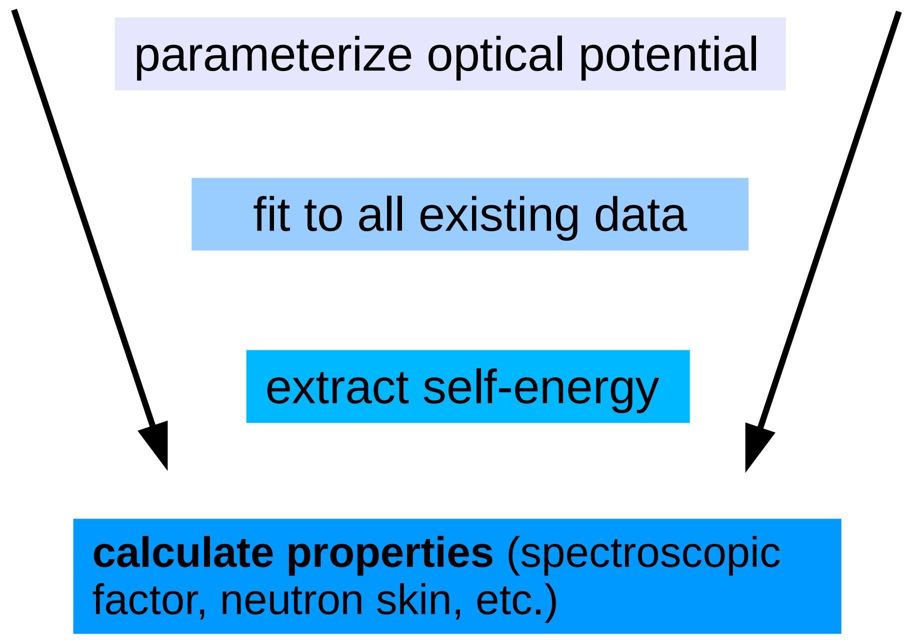
⇒ as observed in (e,e'p)



Figures courtesy W. Dickhoff (WUSTL)

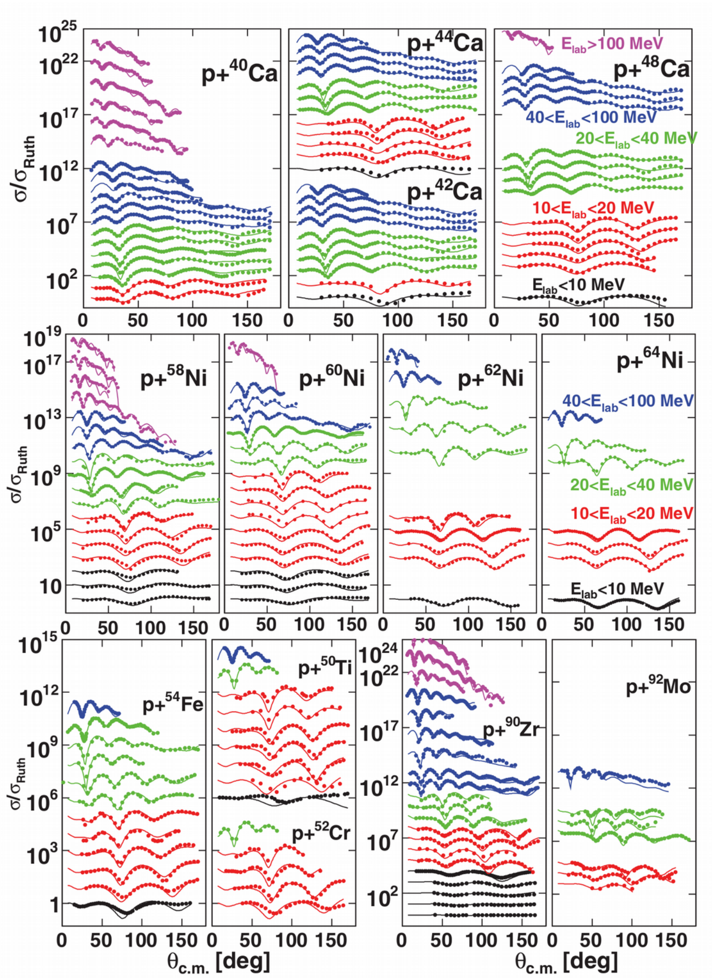
DOM construction and procedure

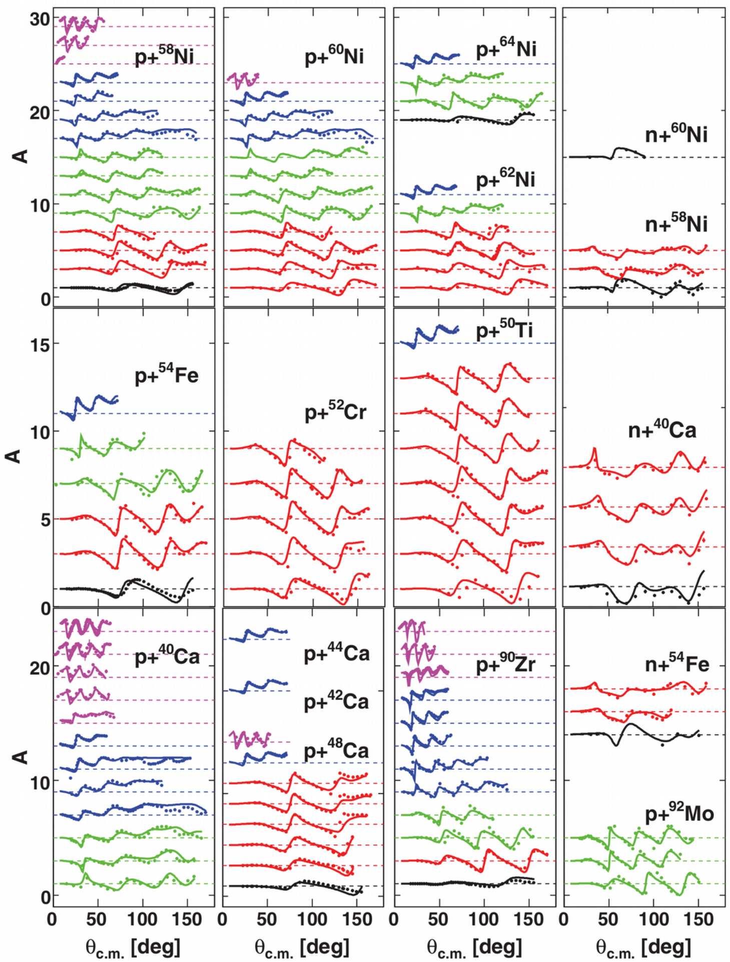
- Construct a ***complex optical potential*** for nucleon-nucleus interaction (with analogy to optical scattering).
- In the DOM, ***real part*** *(elastic scattering) and* ***imaginary part*** *(inelastic scattering) of potential* ***are inextricably coupled***, via Kramers-Kronig relations, just as in optical case.
- Need ***orthogonal data*** to constrain different parameters
- Not a global OM (like KD), but ***regional***

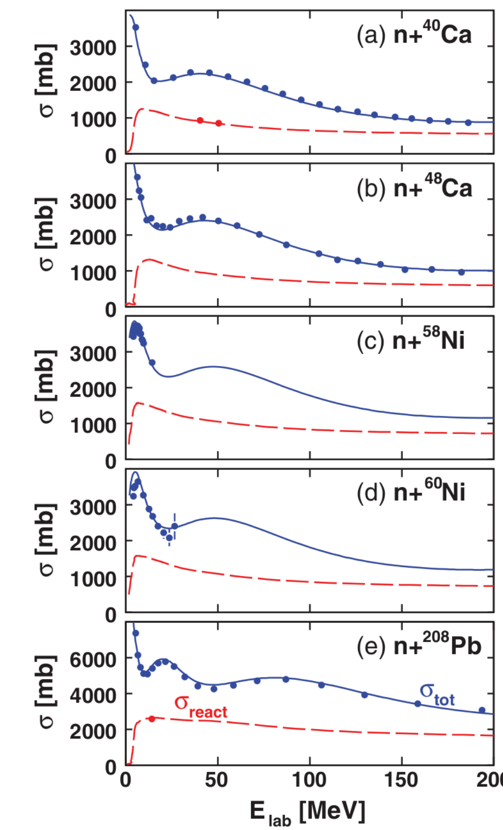


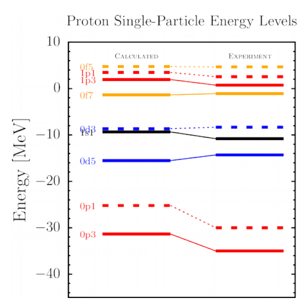
Self-energy/OP is **NON-local**, **dispersively correct**, applied far **below and above ε_F:**

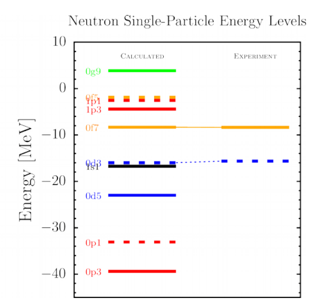
$$\mathrm{Re}\ \Sigma(E) = \Sigma^{HF} - \frac{1}{\pi}\mathcal{P}\int_{E_T^+}^{\infty} dE' \frac{\mathrm{Im}\ \Sigma(E')}{E - E'} + \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{E_T^-} dE' \frac{\mathrm{Im}\ \Sigma(E')}{E - E'}$$

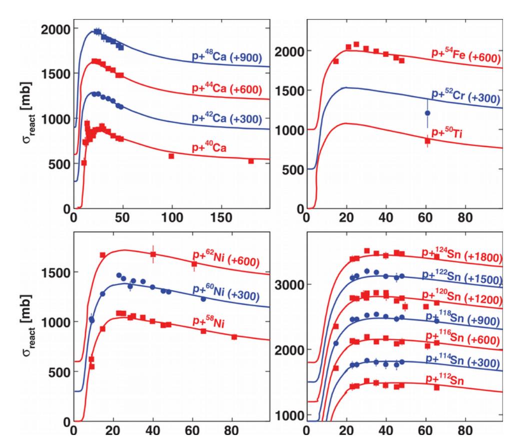








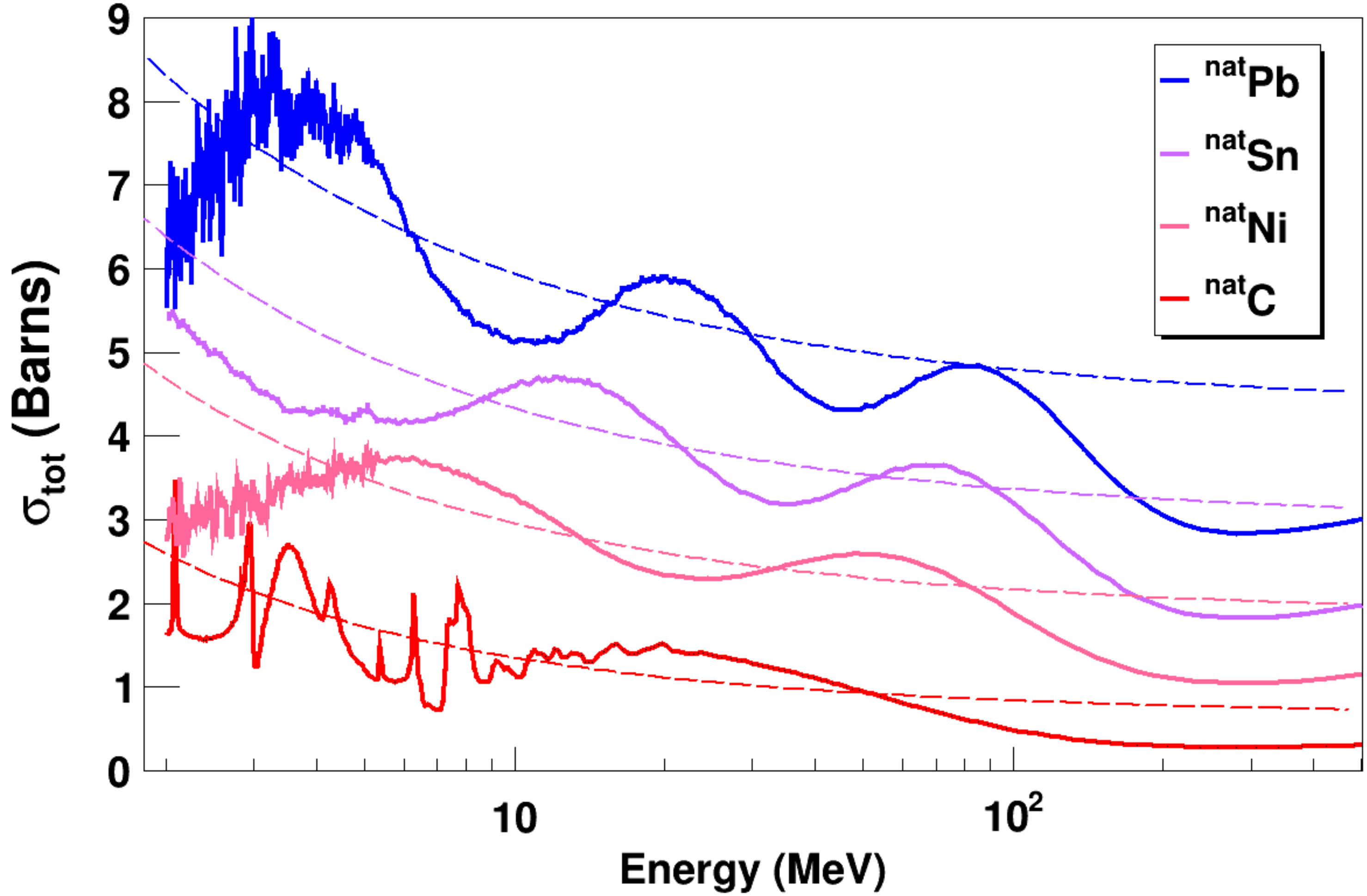




Fitted data from 2011 DOM treatment:

ECS, A Power, TCS, RCS, SP levels

Data Type	Typical E range (protons)	Typical E range (neutrons)	Importance + connection to potential
$\left[\frac{d\sigma_{el}}{d\omega}\right]$	0-200 MeV	0-100 MeV	Historically the best-measured. Sensitive to Re-WS term
A. Power	0-200 MeV	0-100 MeV	Similar to ECS but not as well-measured; sensitive to spin-orbit strength, Re-WS
σ_{rxn}	0-100 MeV	14.1 MeV	Protons: data often lacking >50 MeV. Neutrons: *almost no data except 14.1 MeV* ($d+^3H$)
σ_{tot}	N/A	0-100 MeV	Isotopic targets poorly known! *Strongly tied to Re-WS, Im strength above* ε_F*!*
e(A,A)e	q-range: 0.5-3.5 fm^{-1}	N/A	Can get charge density by Fourier transform: *Critically connected to proton SP occupations*
A(e,e’p)A-1	p-range: 10-200 MeV/c	N/A	Can extract S(E): *Direct demonstration of depletion from MF, peak broadening*



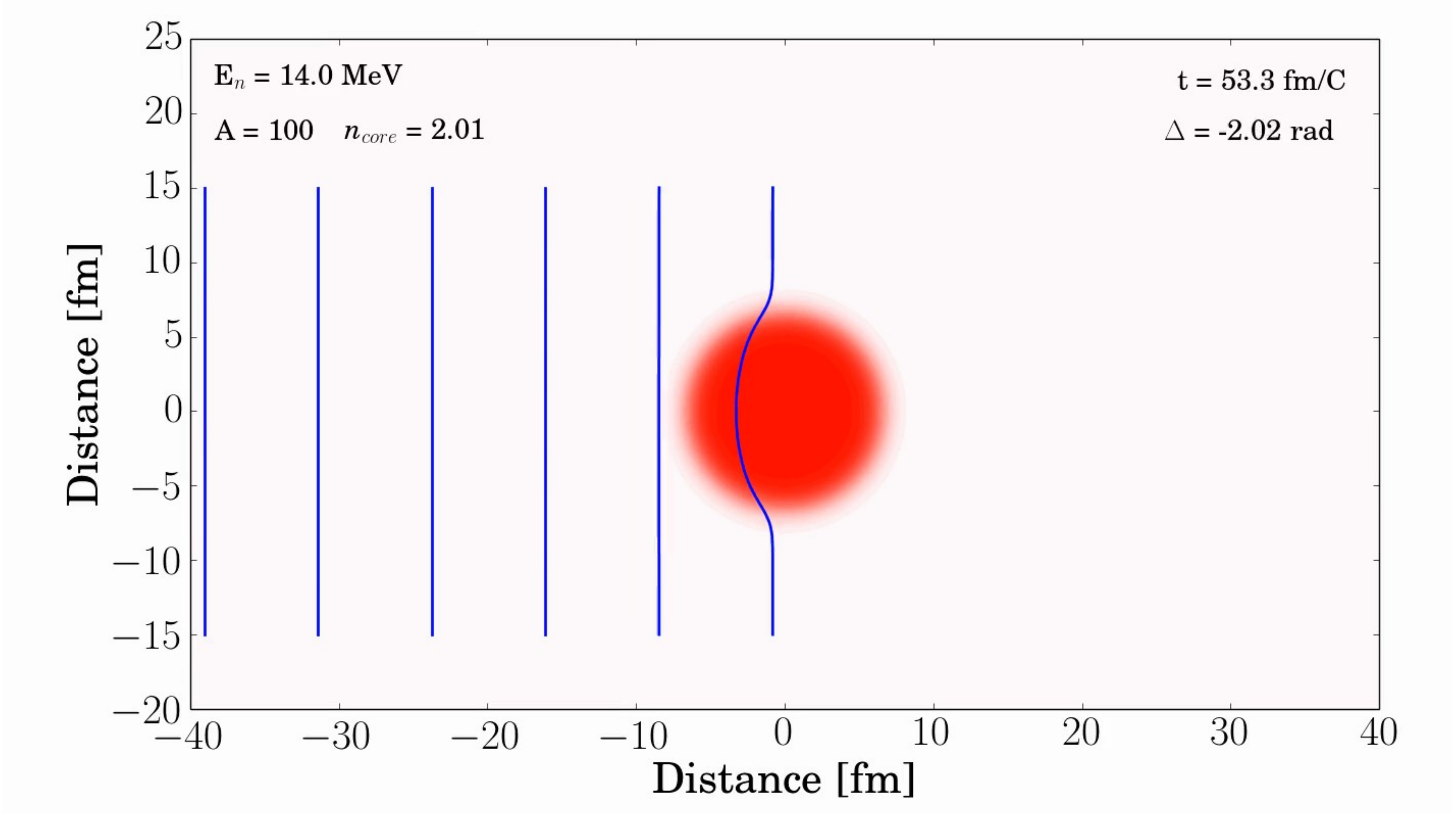
$$\sigma_{tot}(E) = 2\pi(R + \lambdabar)^2[1 - \rho\cos(\delta)]$$

"SAS": $r_0A^{1/3}$, $E^{-1/2}$

"Nuclear Ramsauer Effect": $e^{-\mathrm{Im}(\boldsymbol{\Delta})}$, $\mathrm{Re}(\boldsymbol{\Delta})$

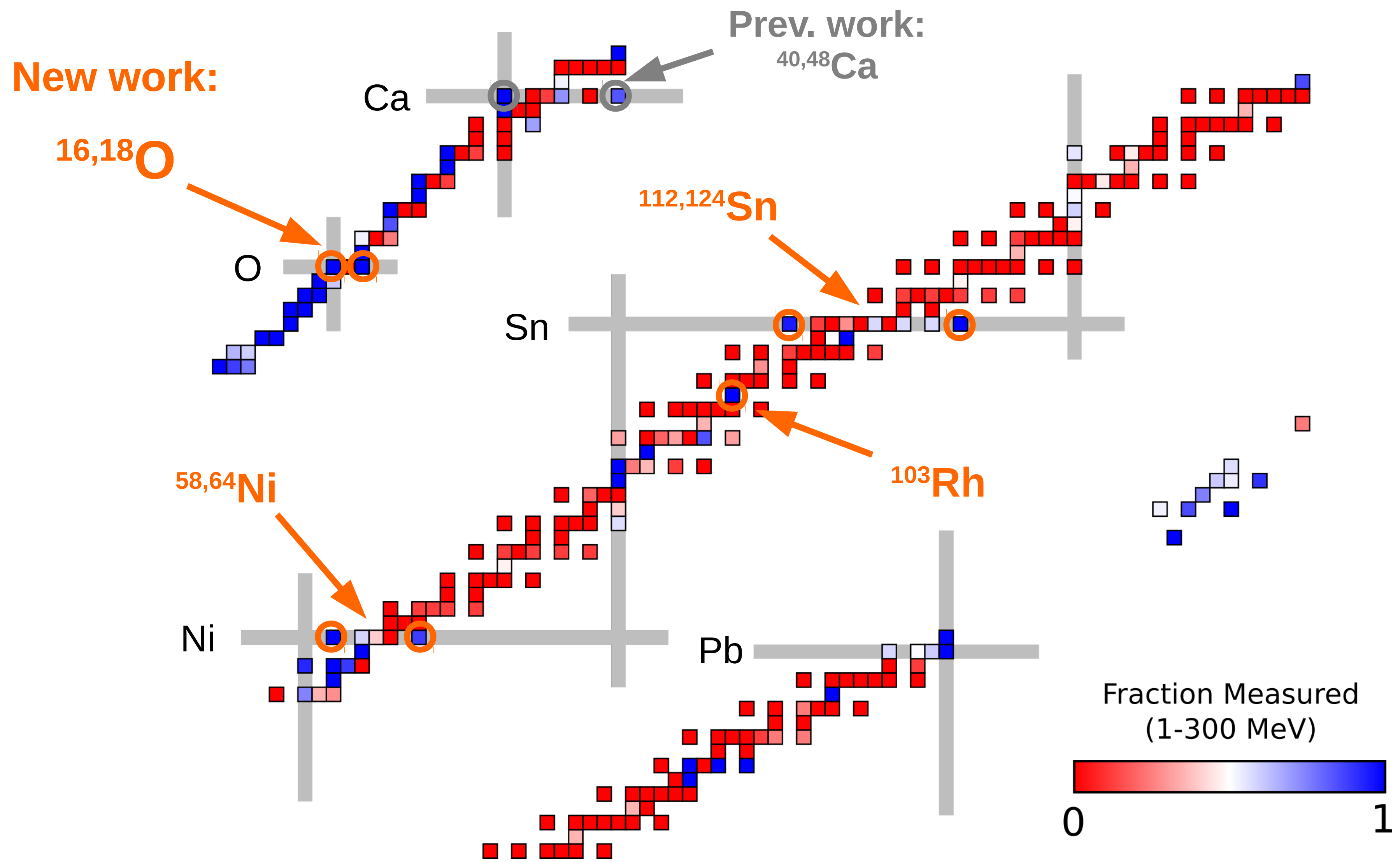
Angeli and Csikai, *Nucl. Phys. A* **158**, 389 (1970)

σ_{tot} oscillations: “nuclear Ramsauer effect”

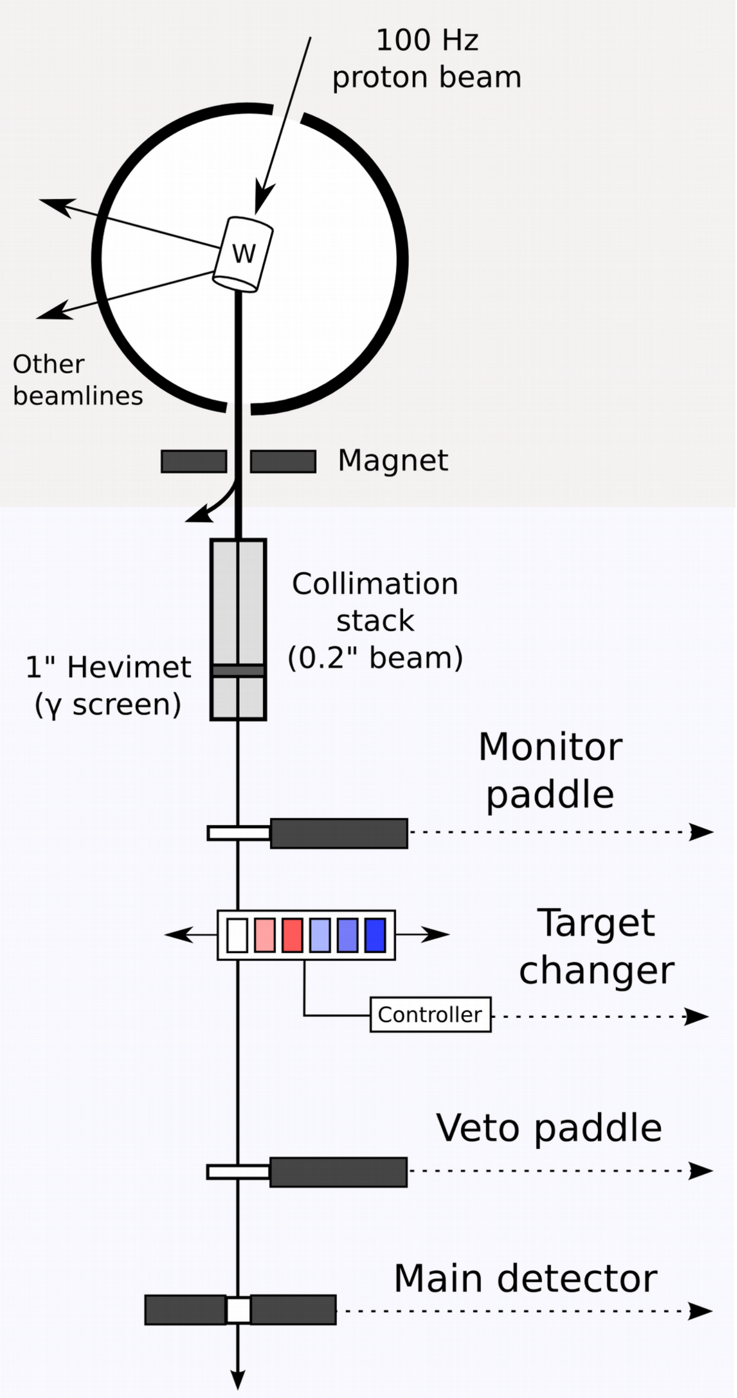


σ_{tot} provides *Re(Σ) and Im(Σ) constraints* and *isovector information* (when compared with proton σ_{rxn} data)

Intermediate-energy σ_{tot}(E)



Takeaway: tons of missing σ_{tot} data, especially isotopically resolved!



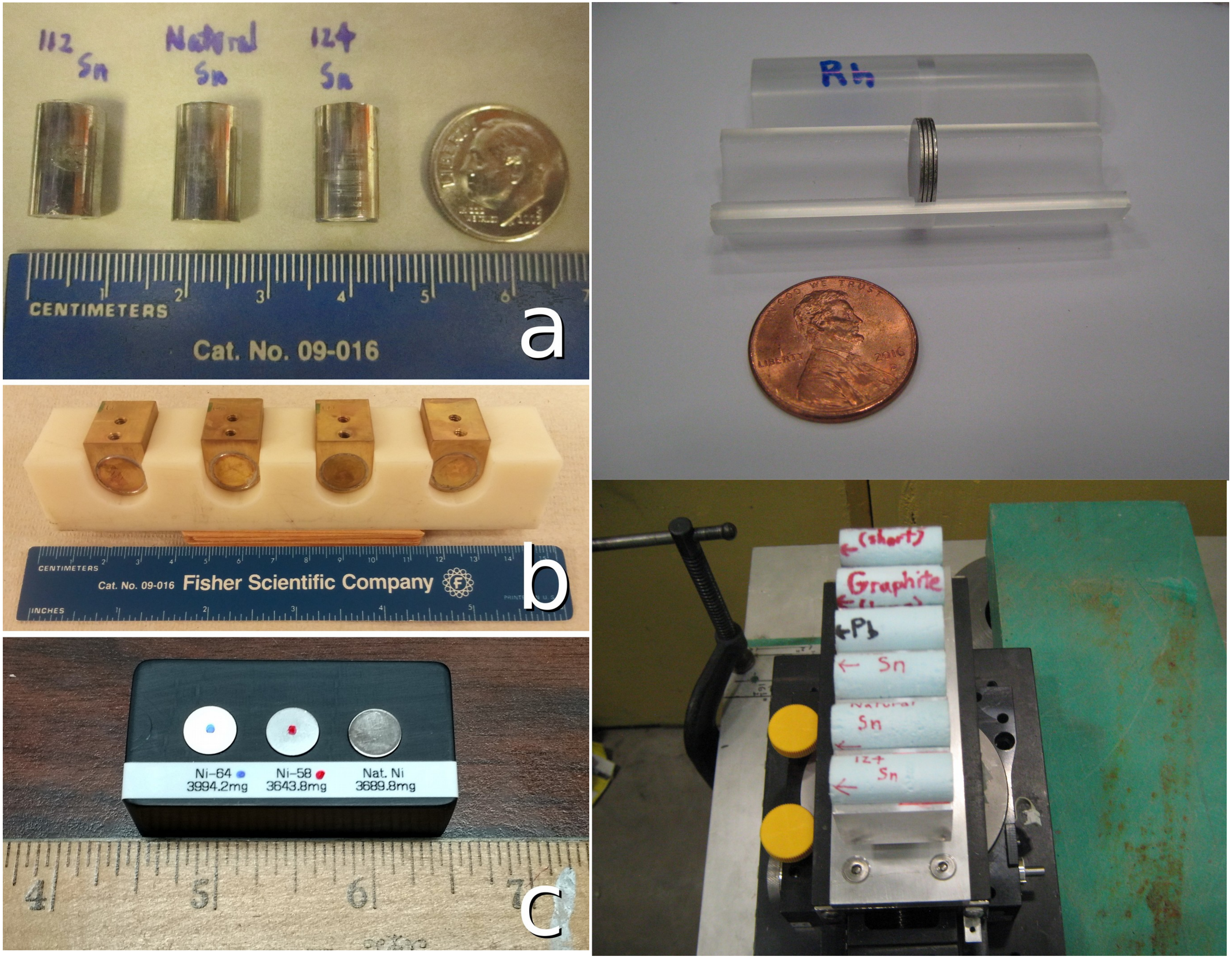
Measuring σ_{tot} for isotopically-enriched targets

Targets: $^{16,18}O$ (as H_2O), $^{58,64}Ni$, ^{103}Rh, $^{112,124}Sn$

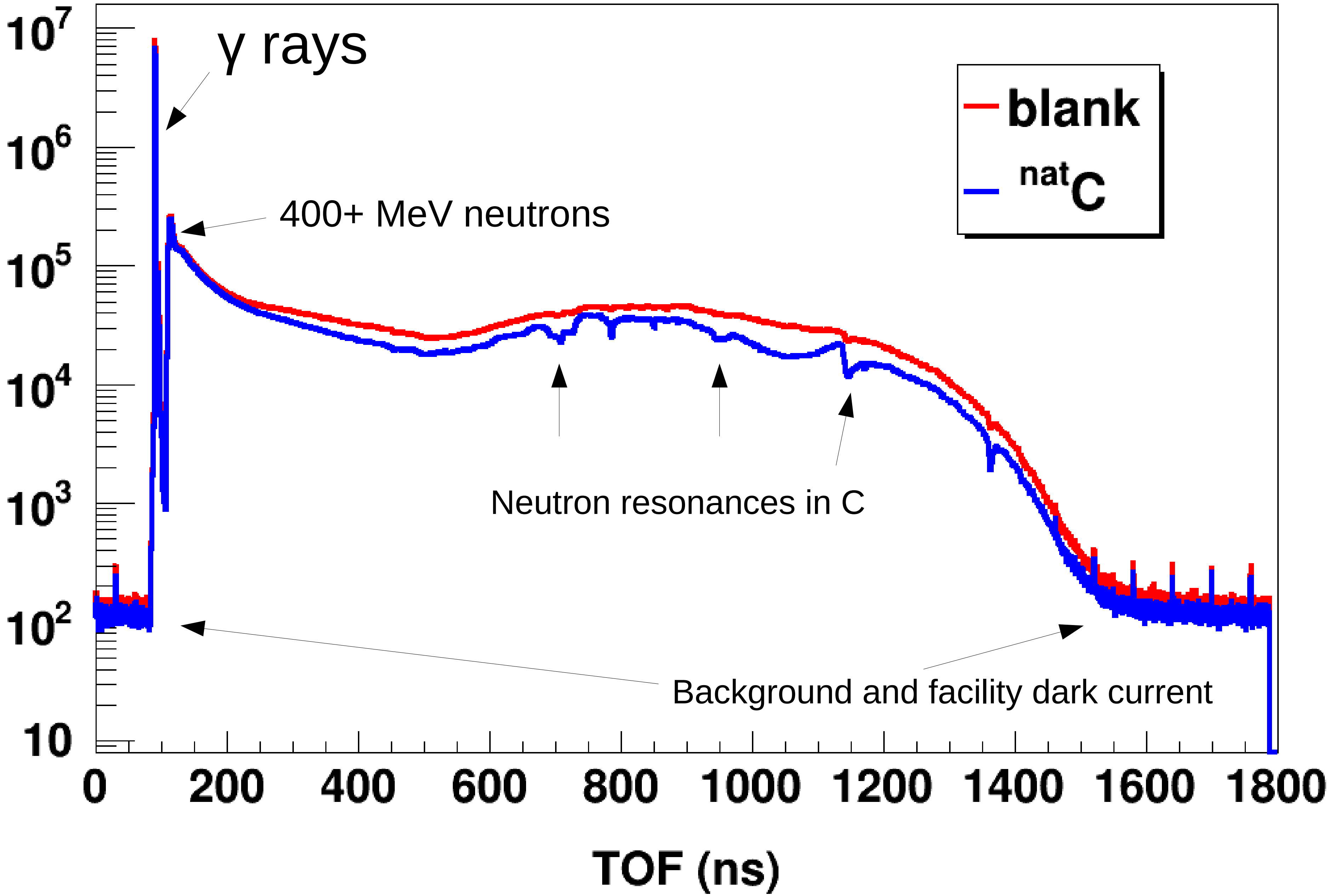
Goal: achieve 1% statistical accuracy for each of 50 energy bins, 3-300 MeV

Time: 50+ hours beam per target
x 10^4 neutrons/sec =
~10^9 neutrons per target

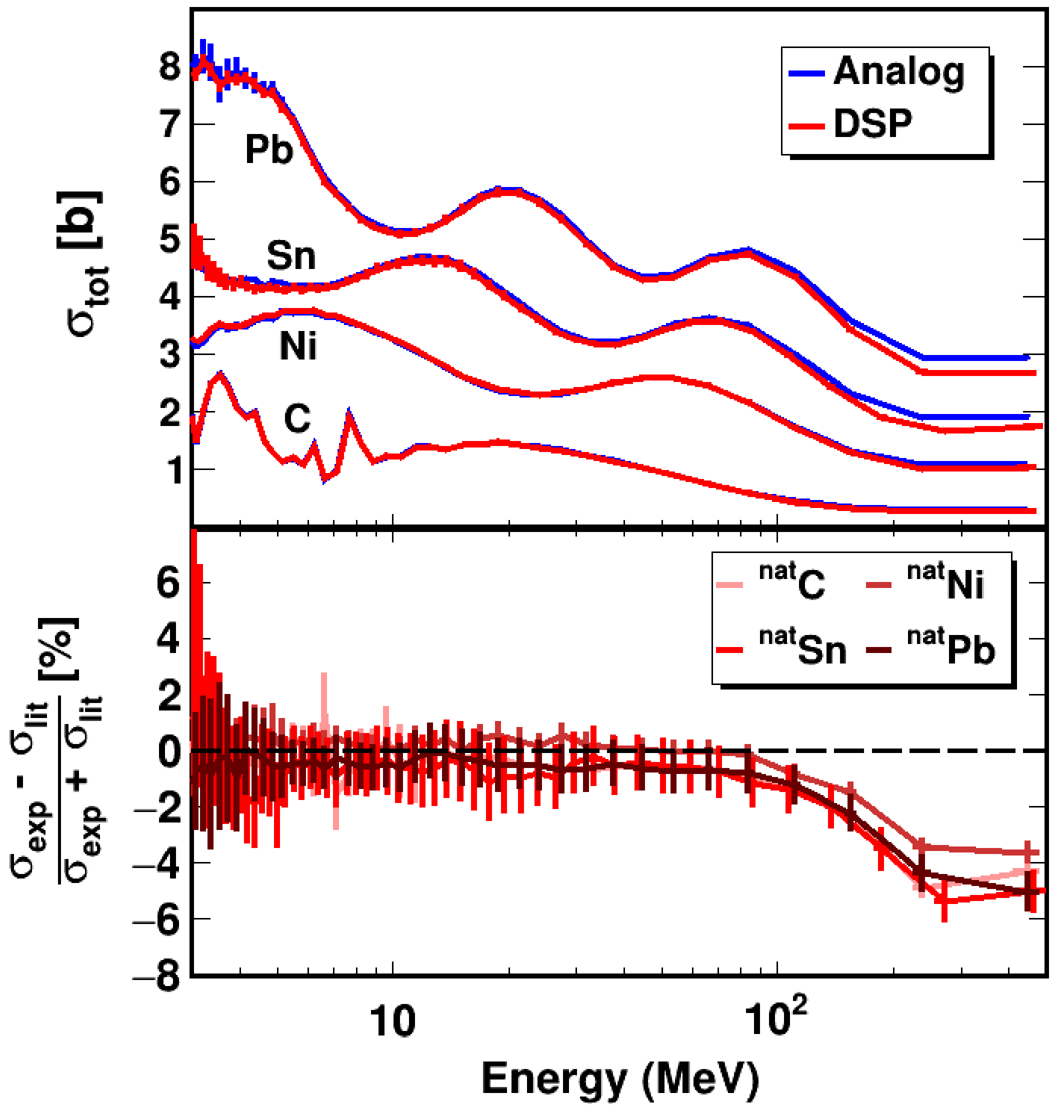
Leverage digitizer technology:
reduce deadtime 10x → reduce sample by 10x



112 Sn
Natural Sn
124 Sn
CENTIMETERS
Cat. No. 09-016
a
CENTIMETERS
Cat. No. 09-016
Fisher Scientific Company
INCHES
b
Ni–64 3994.2mg
Ni–58 3643.8mg
Nat. Ni 3689.8mg
c
Rh
(short)
Graphite
Pb
Sn
Sn
124 Sn


γ rays
400+ MeV neutrons
Neutron resonances in C
Background and facility dark current
blank
natC
10
10^2
10^3
10^4
10^5
10^6
10^7
0
200
400
600
800
1000
1200
1400
1600
1800
TOF (ns)

Benchmarking: literature results on natural samples



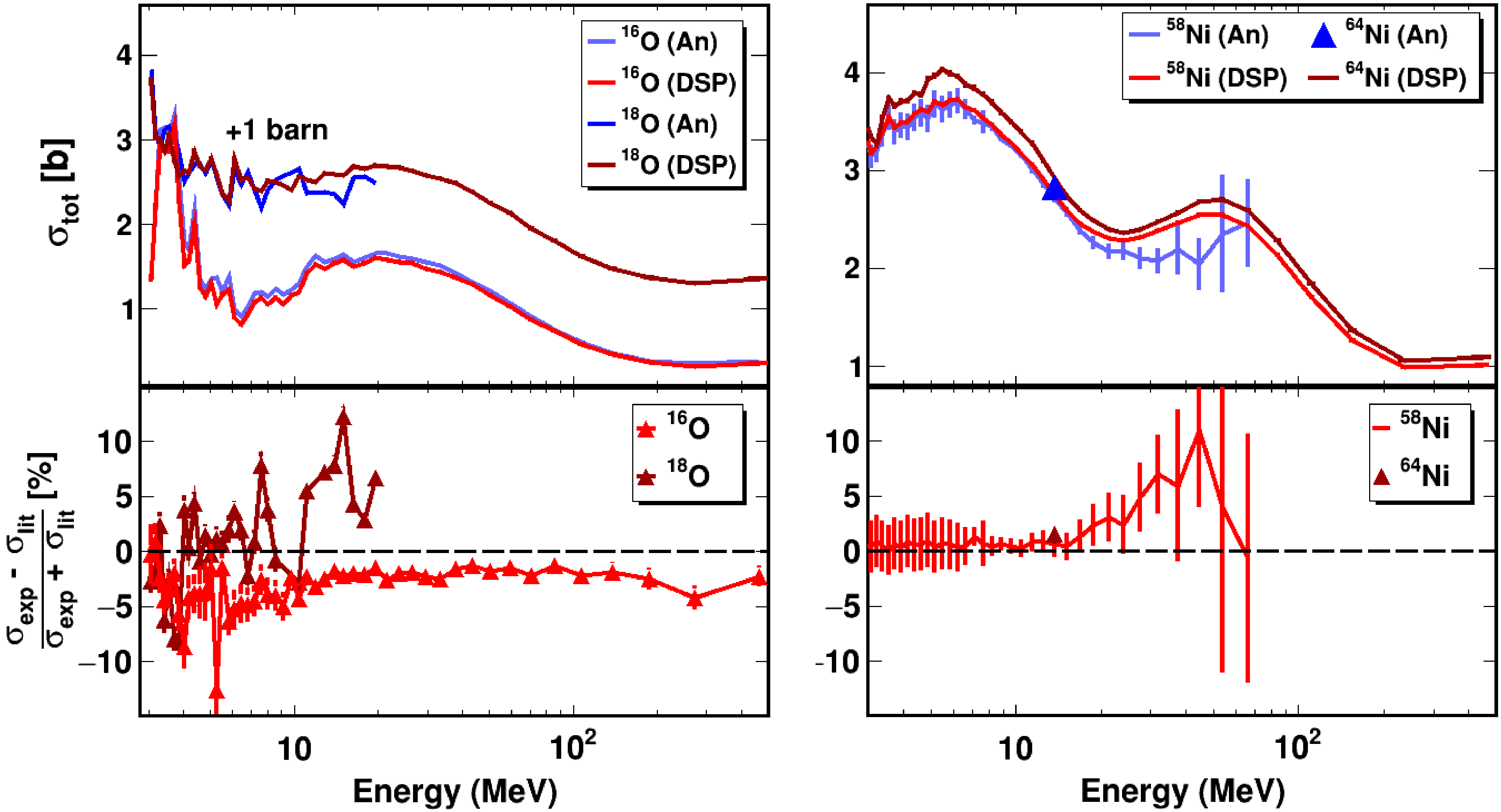
→ *Analog and DSP methods give identical results up to 100 MeV* (within statistical errors)

→ Above, 100 MeV, systematic difference of up to 10%

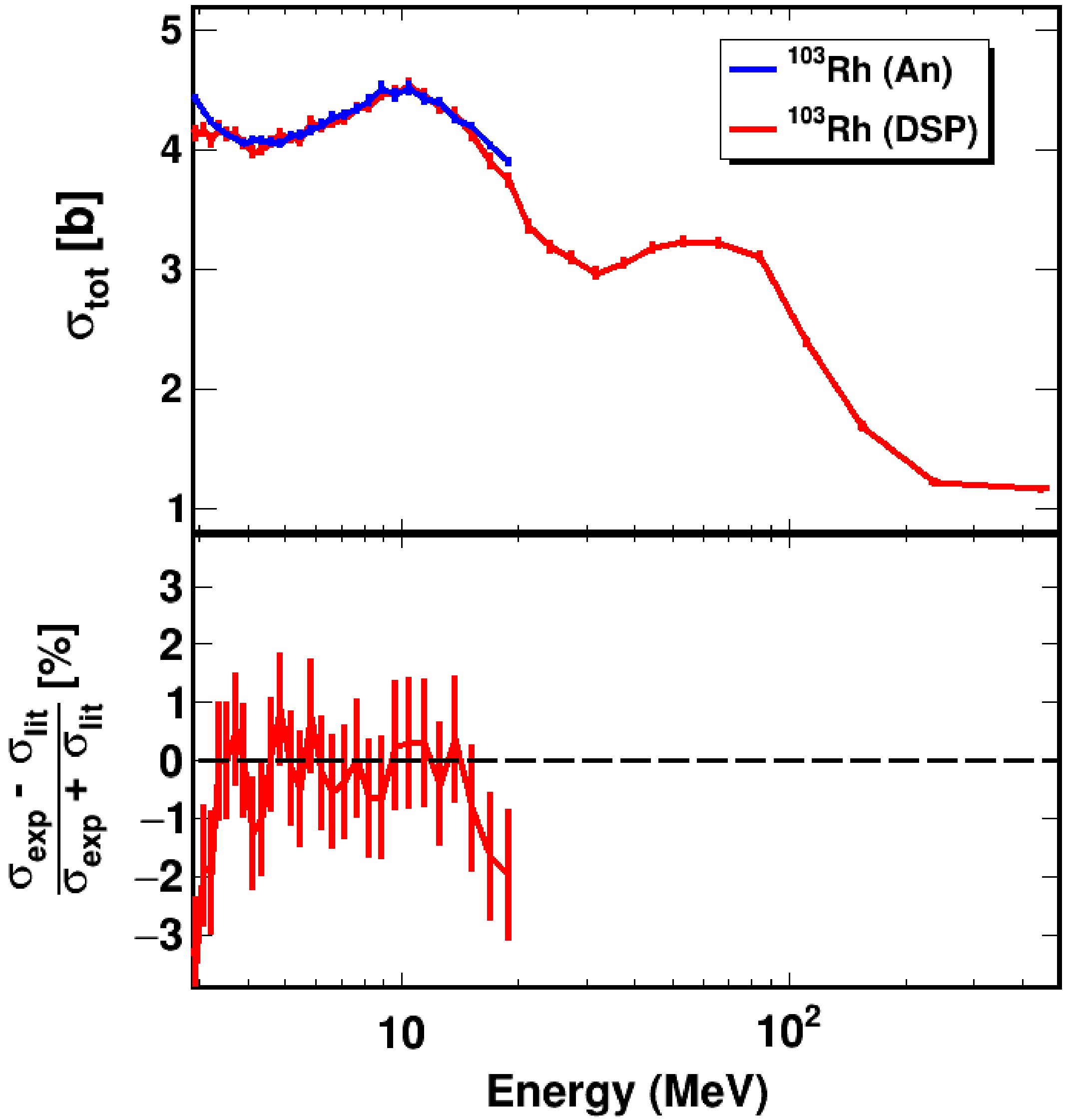
Isotopic relative differences are insensitive to systematic results

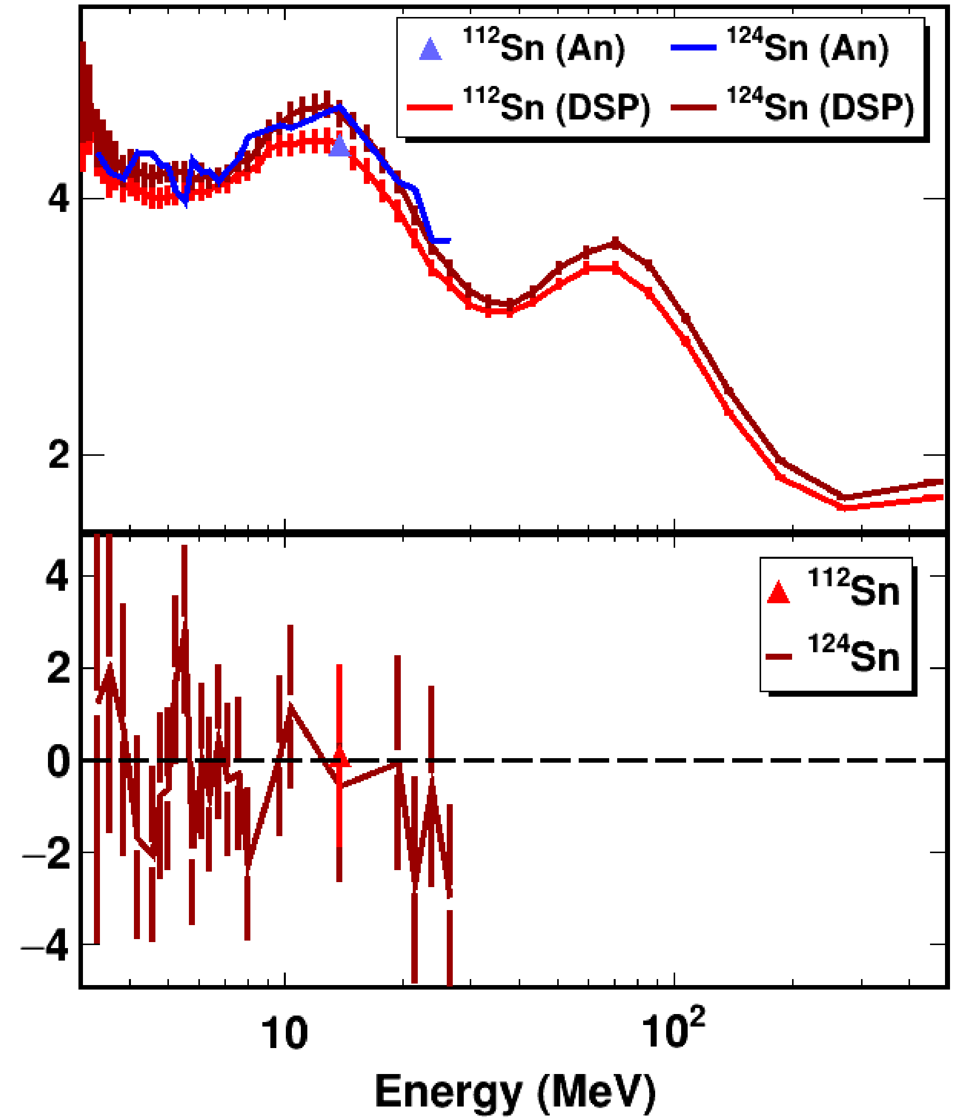
For relative differences, achieved ± 1% error over 50 energy bins from 3 to 500 MeV

^{16,18}O and ^{58,64}Ni

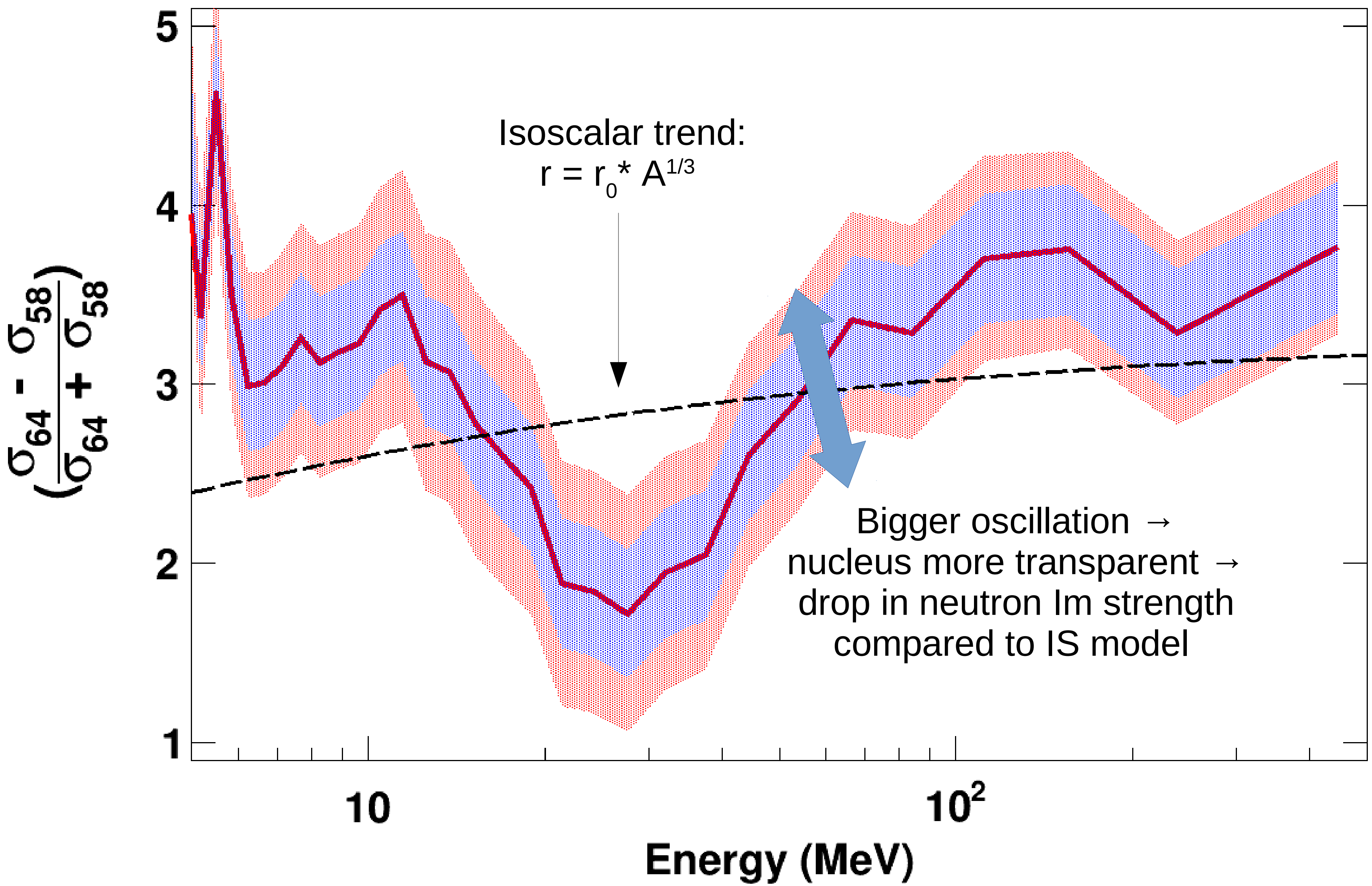


^{103}Rh and ^{112,124}Sn

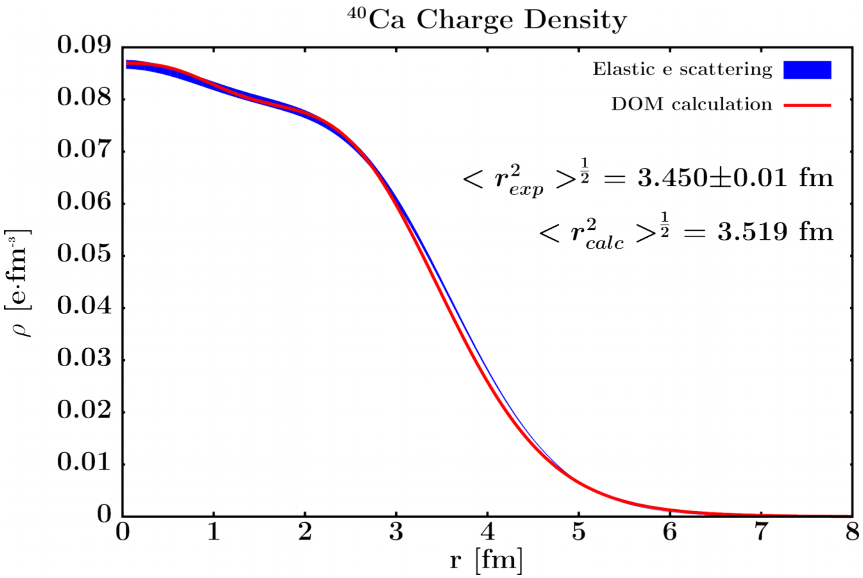




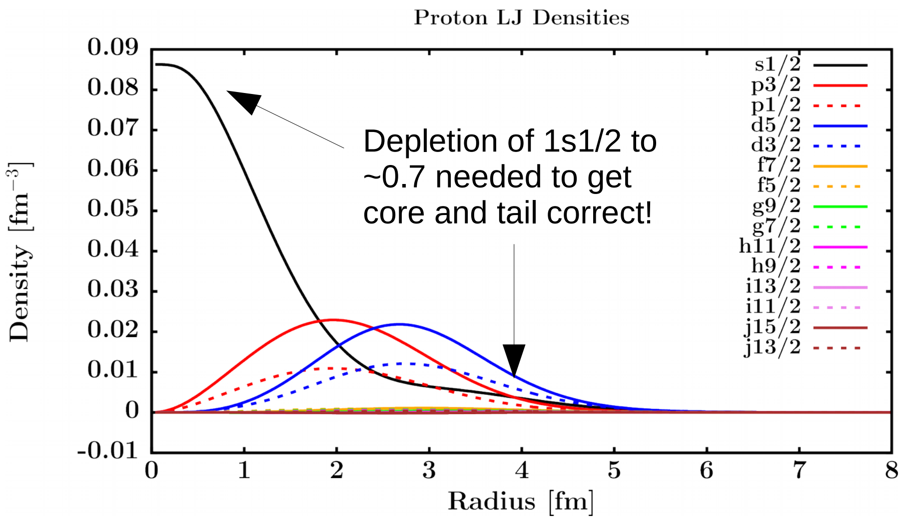
^{58,64}Ni relative difference: isovector information

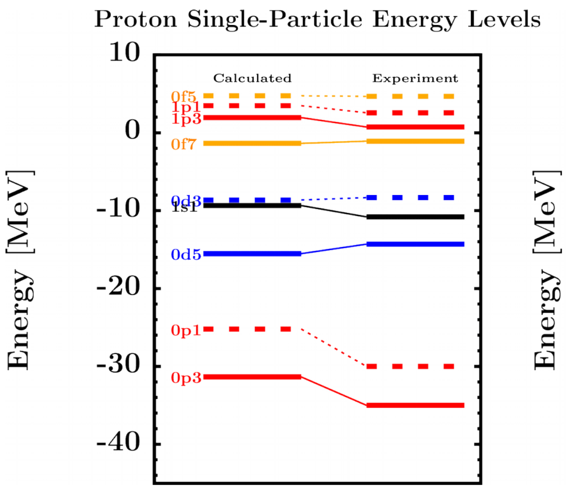


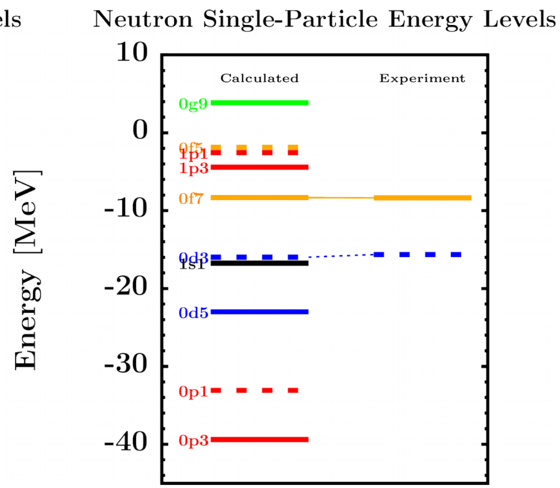
DOM results: ^{40}Ca

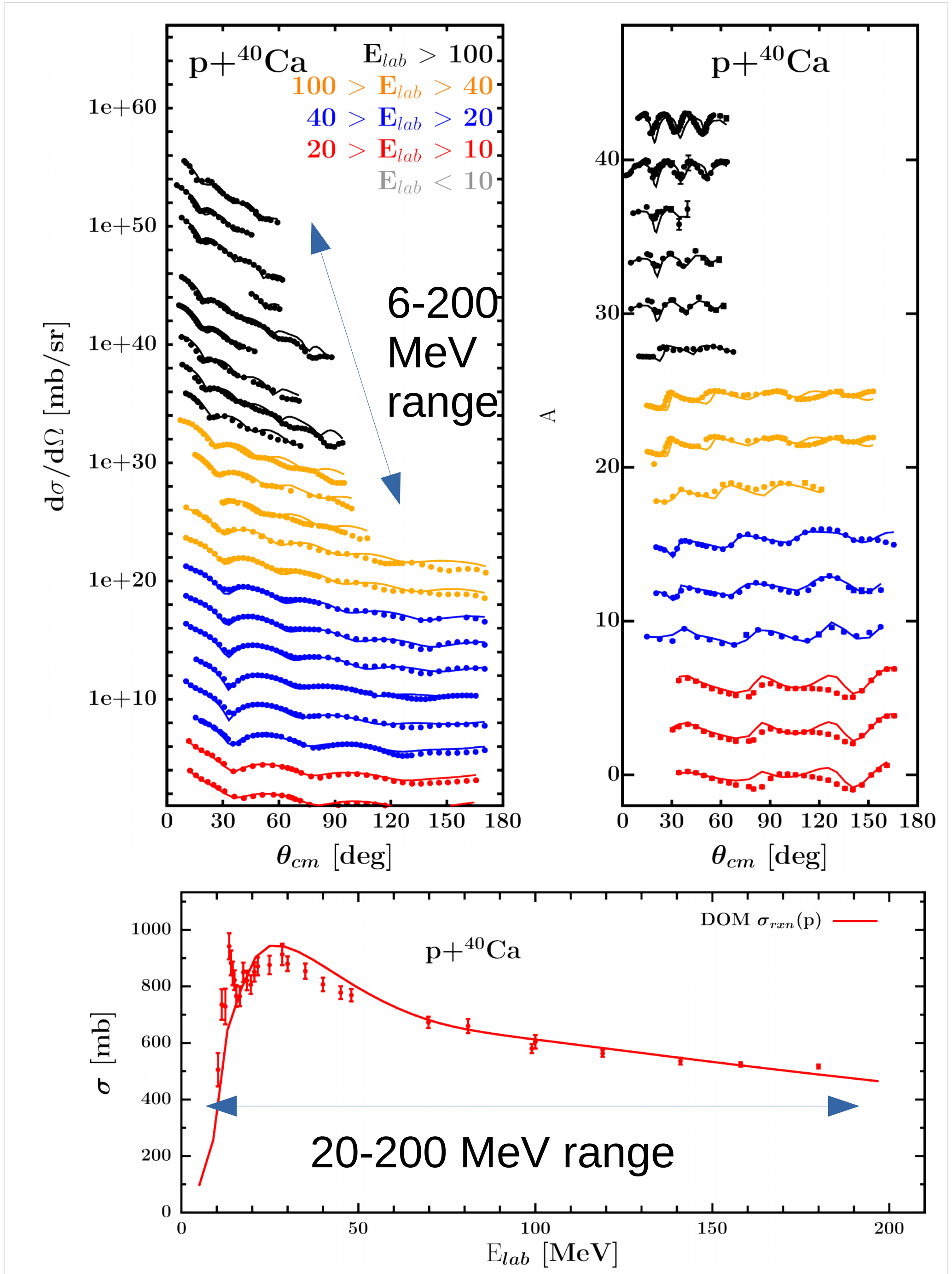


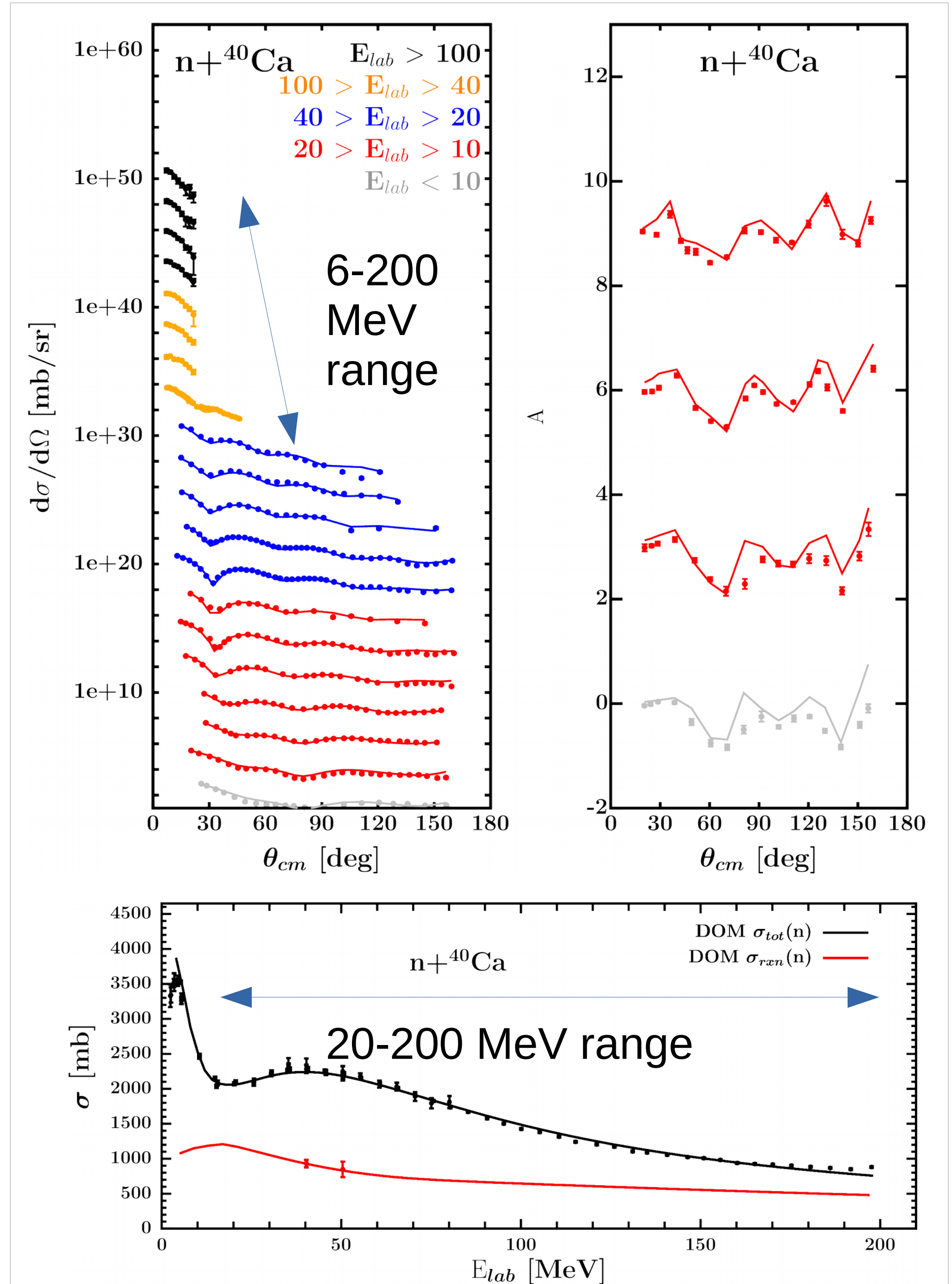
- Recover the charge density distribution to within a few %
- Recover RMS charge radius within 2%
- **Nonlocality critical** to recovering particle number and getting core of charge density correct





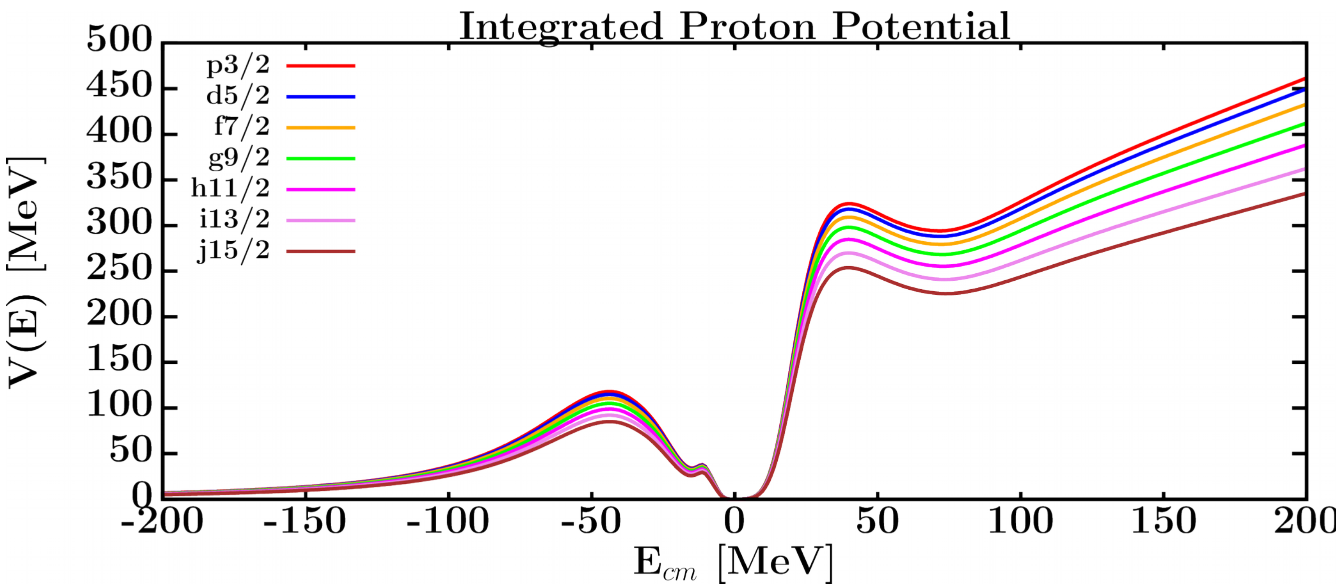



p+40Ca
Elab > 100
100 > Elab > 40
40 > Elab > 20
20 > Elab > 10
Elab < 10
6-200 MeV range
dσ/dΩ [mb/sr]
θcm [deg]
A
DOM σrxn(p)
20-200 MeV range
σ [mb]
Elab [MeV]

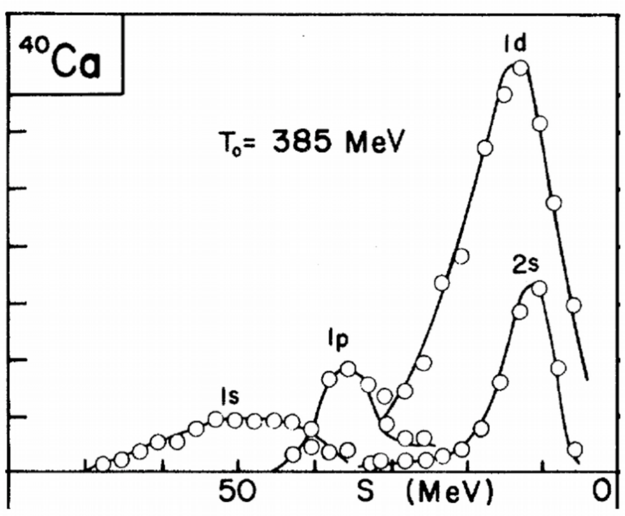

n+40Ca
Elab > 100
100 > Elab > 40
40 > Elab > 20
20 > Elab > 10
Elab < 10
6-200 MeV range
dσ/dΩ [mb/sr]
θcm [deg]
A
DOM σtot(n)
DOM σrxn(n)
20-200 MeV range
σ [mb]
Elab [MeV]

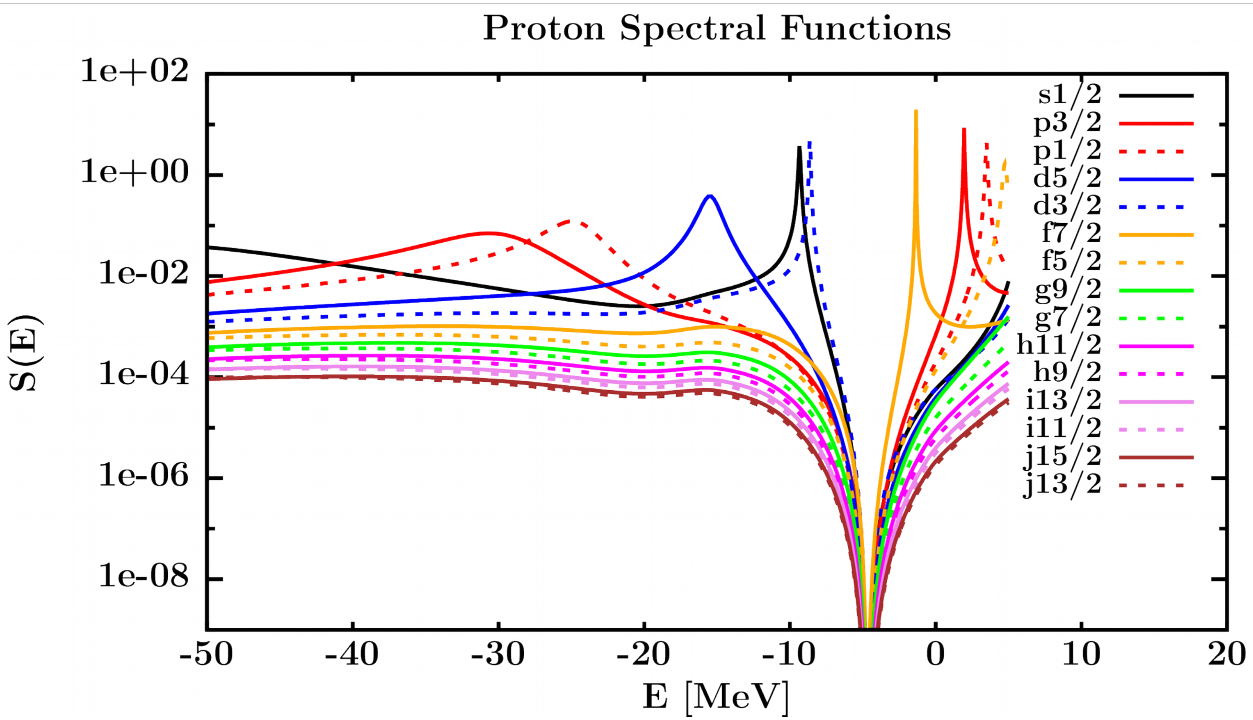
Is potential integral reasonable?

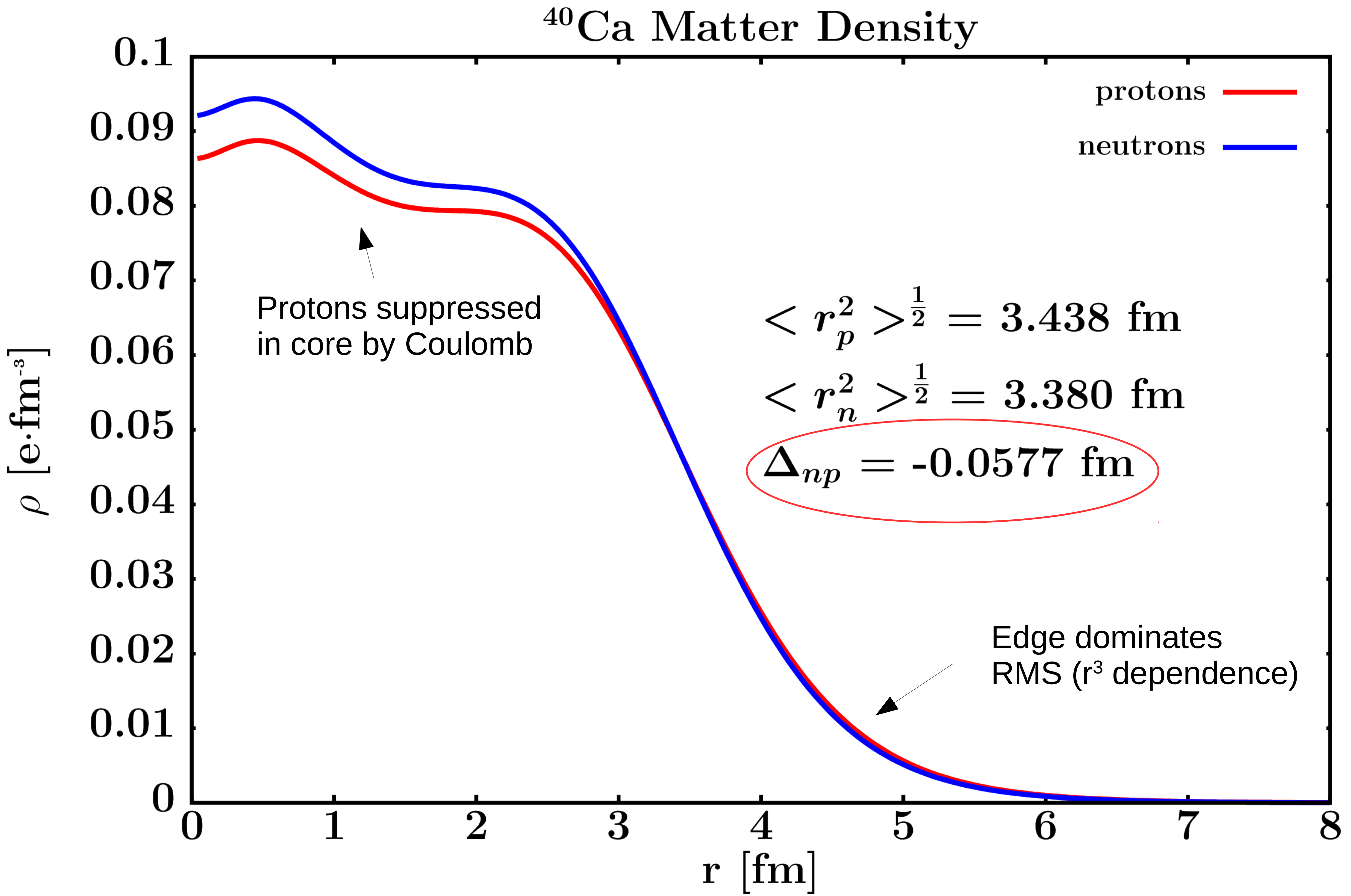
- Asymmetric far from ε_F? YES
- Symmetric near ε_F? SOME
- Surface ~ 20-30 MeV? YES
- Volume > 50 MeV? YES

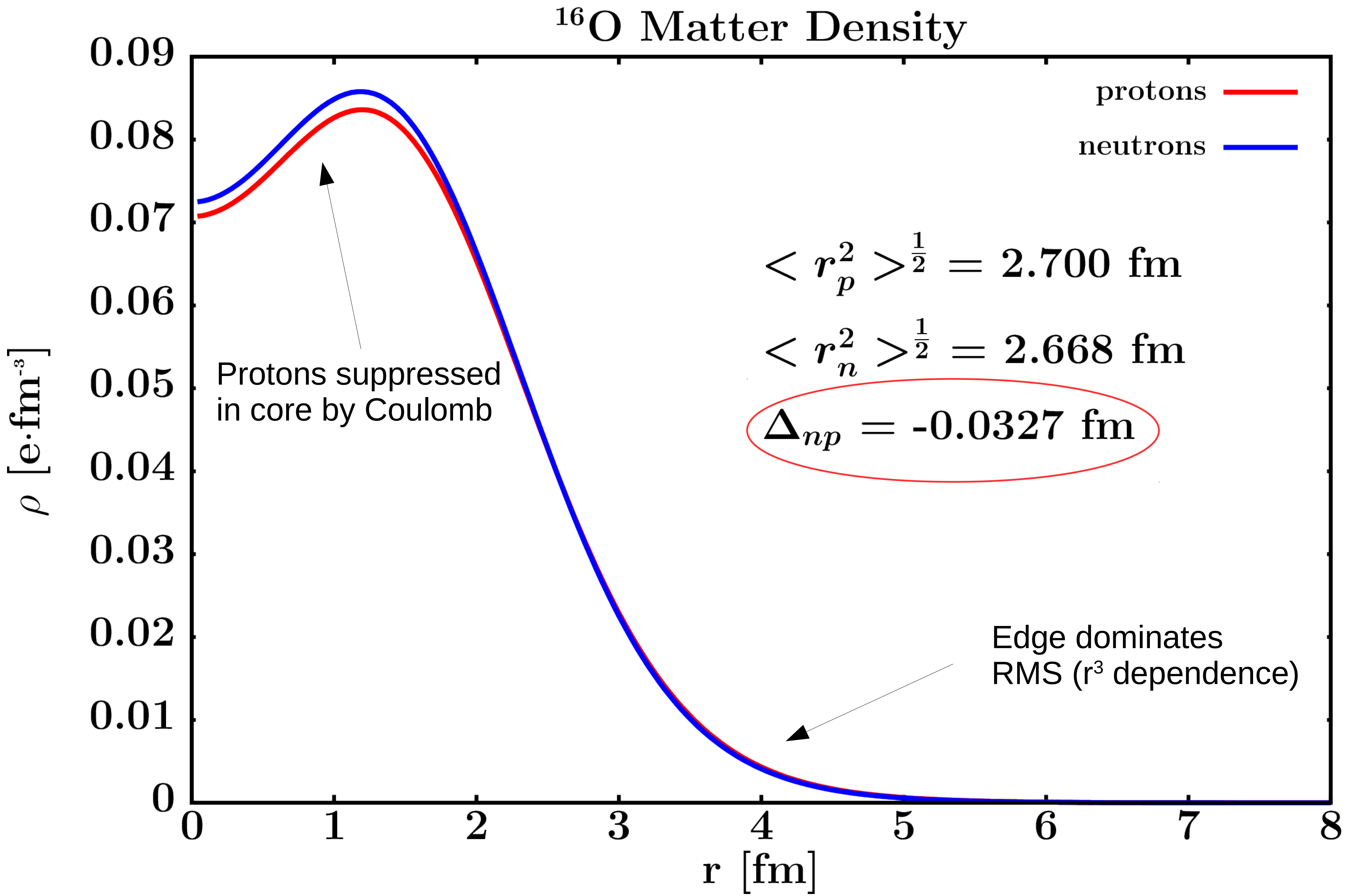


Old (p,2p) data from Liverpool

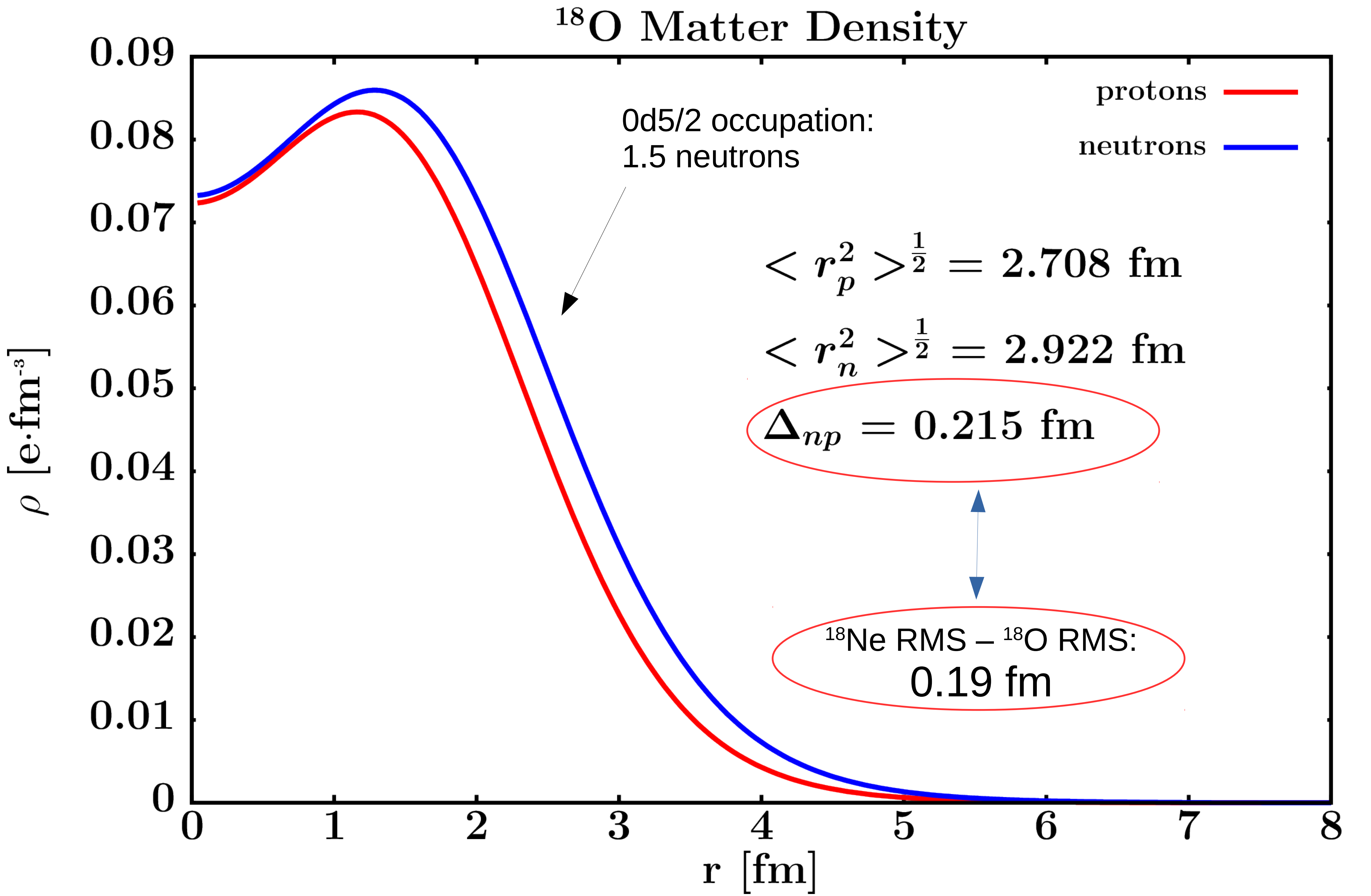


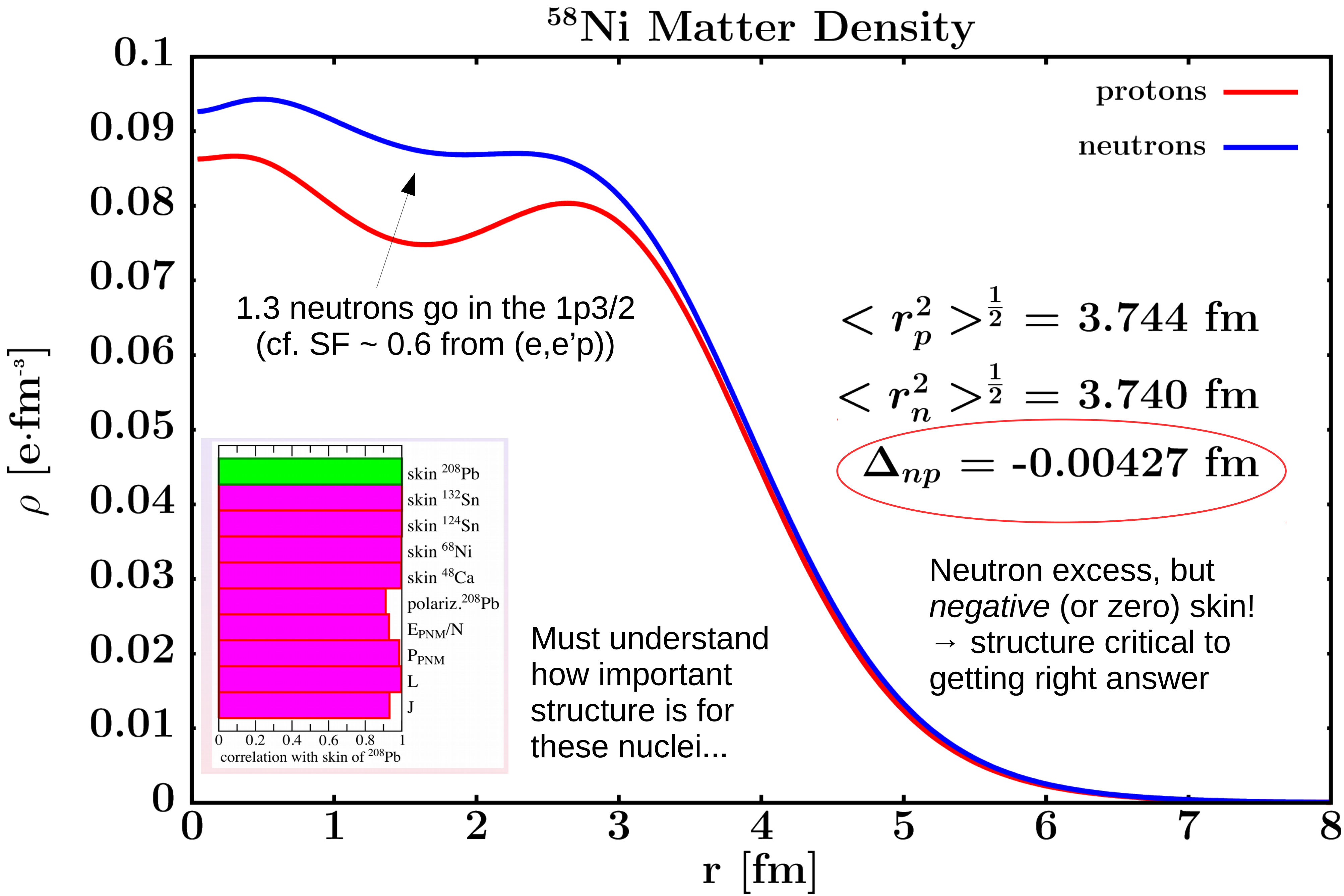



^{40}Ca Matter Density
protons
neutrons
Protons suppressed
in core by Coulomb
$< r_p^2 >^{\frac{1}{2}} = 3.438$ fm
$< r_n^2 >^{\frac{1}{2}} = 3.380$ fm
$\Delta_{np} =$ -0.0577 fm
Edge dominates
RMS (r^3 dependence)
ρ [e·fm^{-3}]
r [fm]
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 1 2 3 4 5 6 7 8

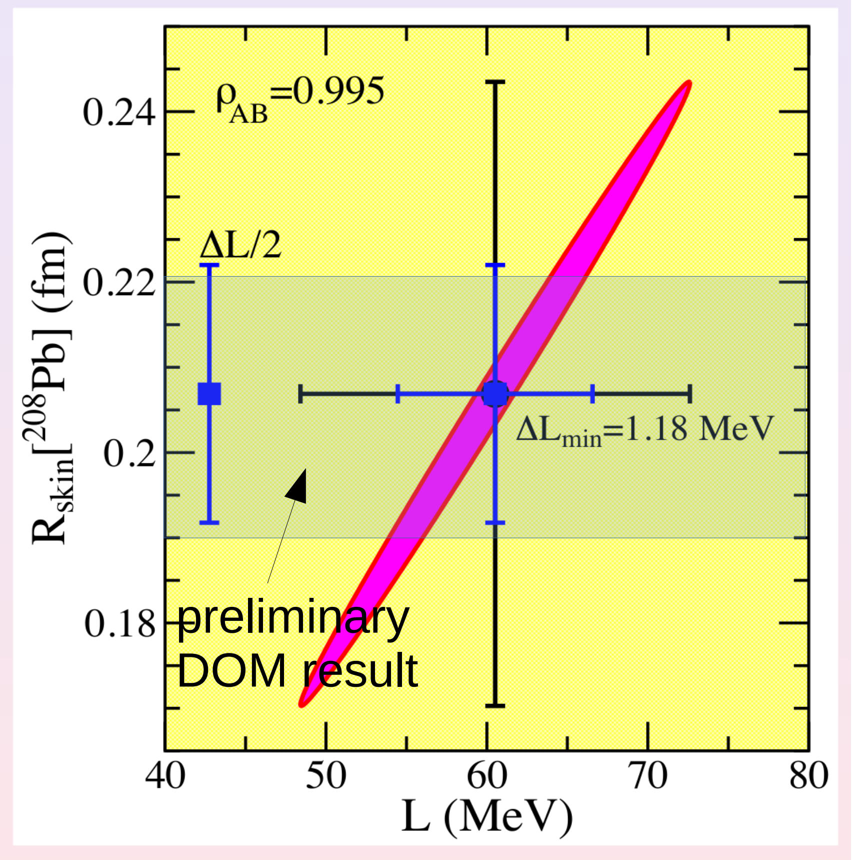


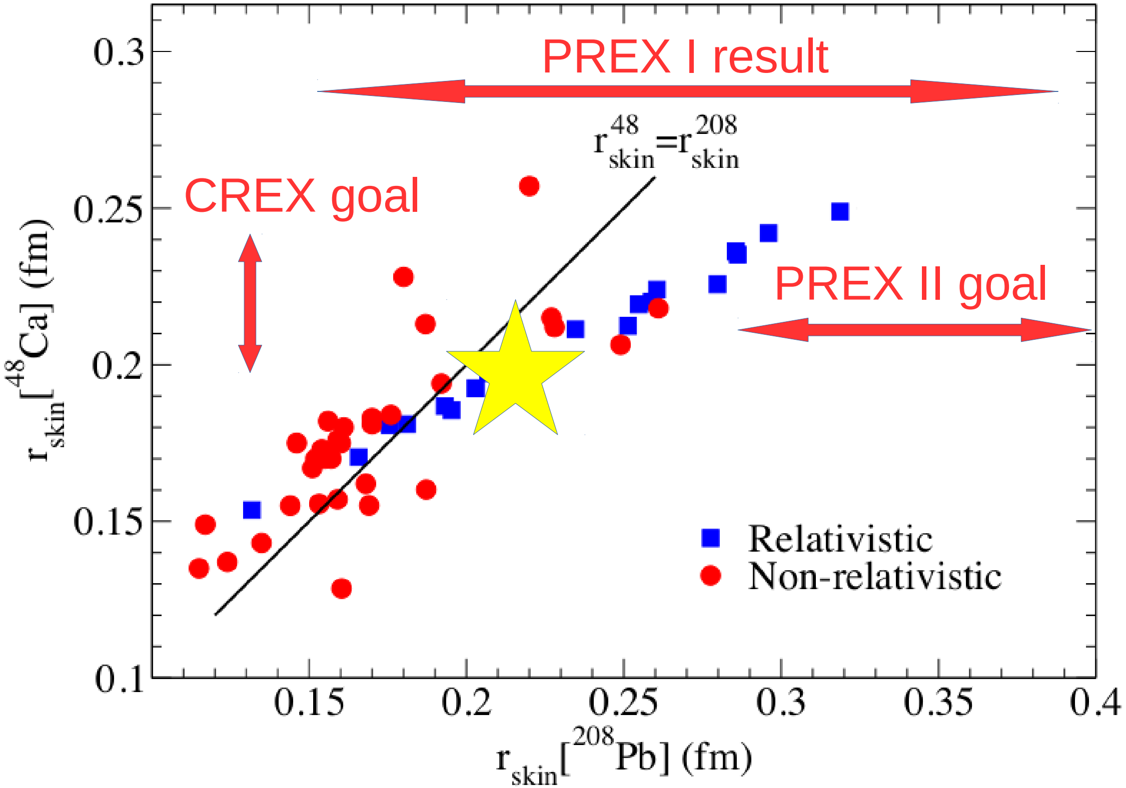
^{16}O Matter Density
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
ρ [e·fm^{-3}]
0 1 2 3 4 5 6 7 8
r [fm]
protons
neutrons
$< r_p^2 >^{\frac{1}{2}} = 2.700$ fm
$< r_n^2 >^{\frac{1}{2}} = 2.668$ fm
Δ_{np} = -0.0327 fm
Protons suppressed in core by Coulomb
Edge dominates RMS (r^3 dependence)


^{18}O Matter Density
protons
neutrons
0d5/2 occupation:
1.5 neutrons
$< r_p^2 >^{\frac{1}{2}} = 2.708$ fm
$< r_n^2 >^{\frac{1}{2}} = 2.922$ fm
$\Delta_{np} = 0.215$ fm
^{18}Ne RMS – ^{18}O RMS:
0.19 fm
ρ [e·fm^{-3}]
r [fm]
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
1
2
3
4
5
6
7
8


^{58}Ni Matter Density
protons
neutrons
ρ [e·fm^{-3}]
r [fm]
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
5
6
7
8
1.3 neutrons go in the 1p3/2
(cf. SF ~ 0.6 from (e,e'p))
$< r_p^2 >^{\frac{1}{2}} = 3.744$ fm
$< r_n^2 >^{\frac{1}{2}} = 3.740$ fm
Δ_{np} = -0.00427 fm
Neutron excess, but
negative (or zero) skin!
→ structure critical to
getting right answer
Must understand
how important
structure is for
these nuclei...
skin ^{208}Pb
skin ^{132}Sn
skin ^{124}Sn
skin ^{68}Ni
skin ^{48}Ca
polariz.^{208}Pb
E_{PNM}/N
P_{PNM}
L
J
0.2
0.4
0.6
0.8
correlation with skin of ^{208}Pb

Large neutron skin ↔ large L ↔ large neutron star radius





Urgent task: generate covariance matrix to understand sensitivity of extracted values to underlying data/parameter choices!

Takeaways

- Must go beyond the mean field to get p/n distribution!
  - In ^{16}O, ~10% p/n density is missing from mean-field occupations!
  - Depletion mandatory to get charge density correct

- **σ_{rxn}(p)** and **σ_{tot}(n)** tell you the isoscalar/isovector Im strength above ε_F

- **(e,e)** and quasi-free scattering **(e,e'p; p,2p)** tell you the *isoscalar* Im strength below ε_F

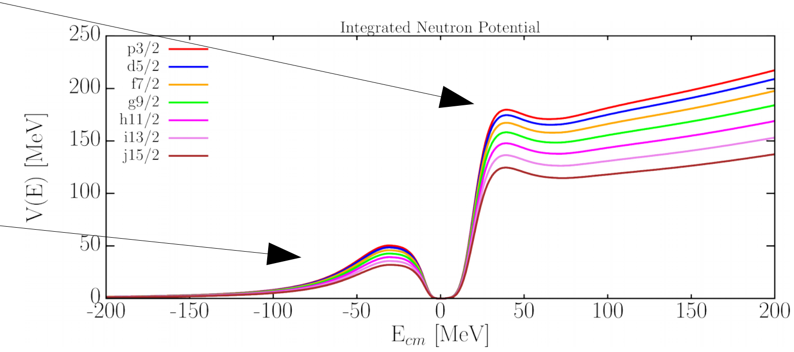
- **all data together, coupled with dispersion relation**, constrains *isovector* Im strength below ε_F

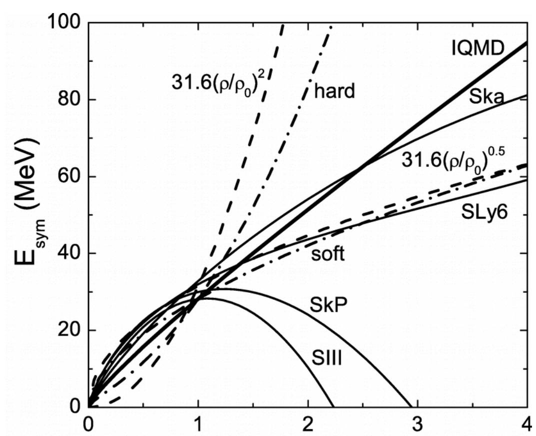
- Need a complete covariance analysis on DOM to generate theoretical error bars → *ongoing project*

- Need covariance analysis on *beyond-mean-field models* to see how it affects bulk properties!

^{16}O SP particle number from DOM

0s1/2	0p3/2	0p1/2	sum
1.858	3.617	1.772	7.247





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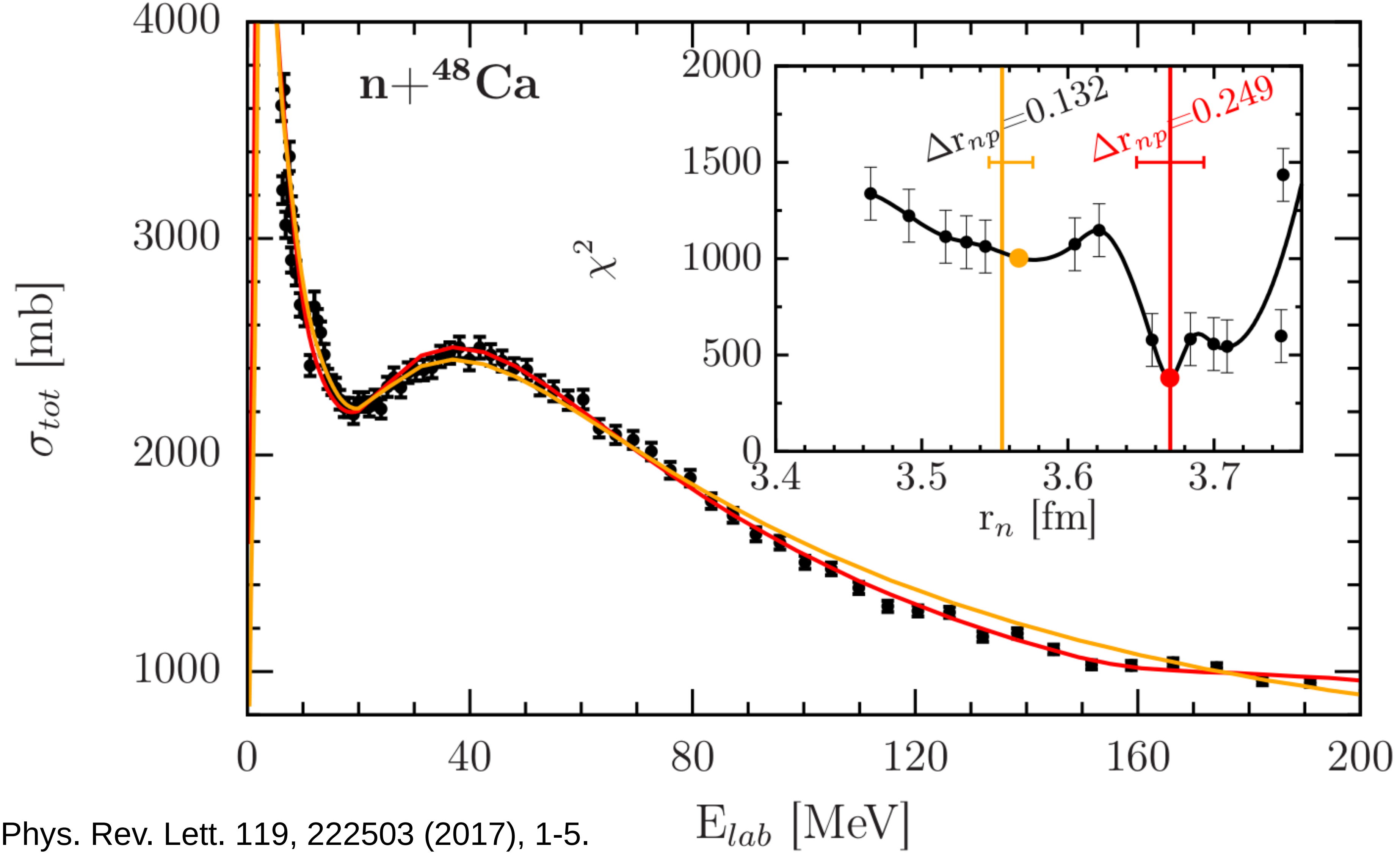
^{40,48}Ca σ_{tot}(E): Shane et al, NIM Sect. A **614**, 468 (2010)

DOM fitting: an overview



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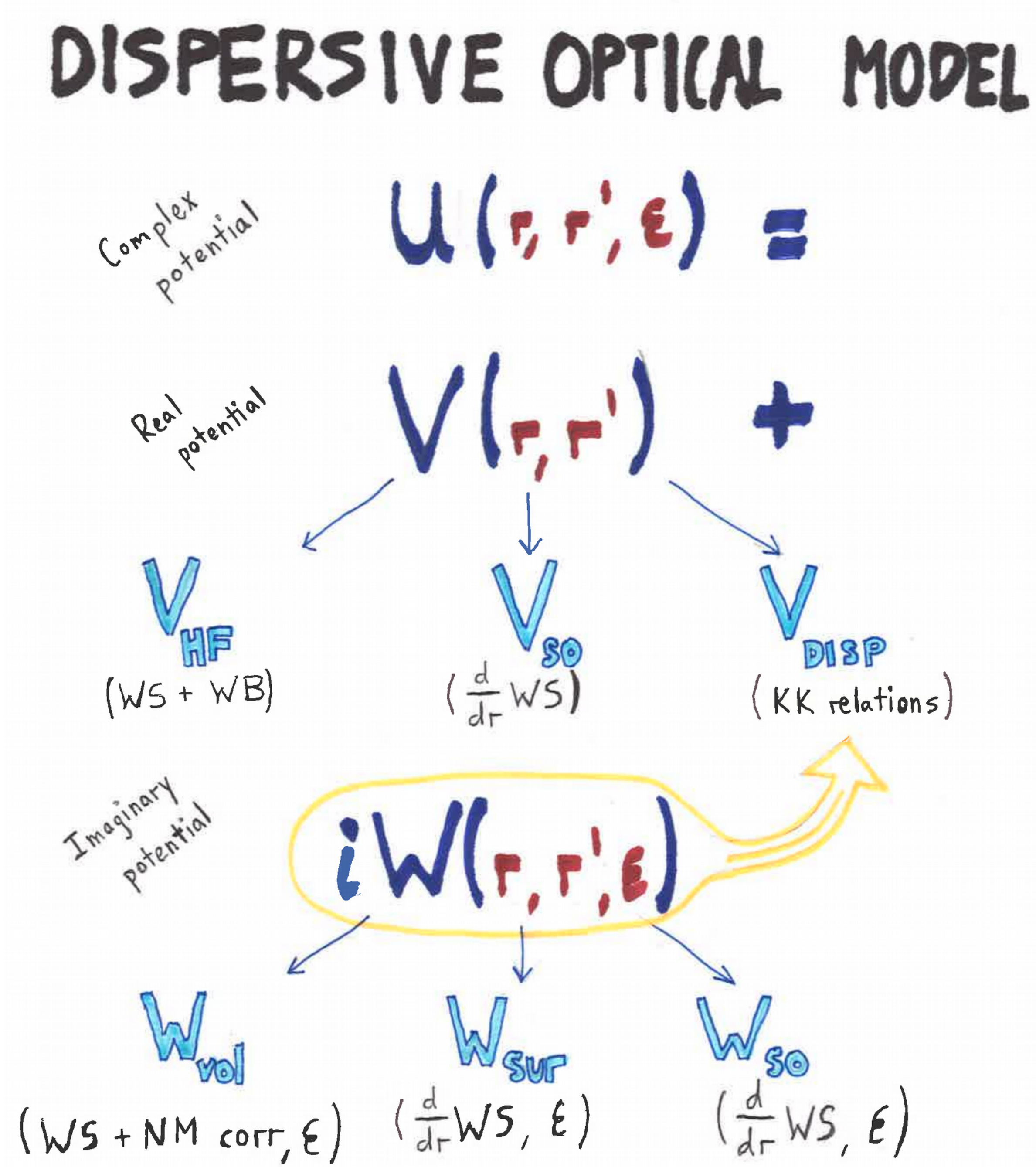
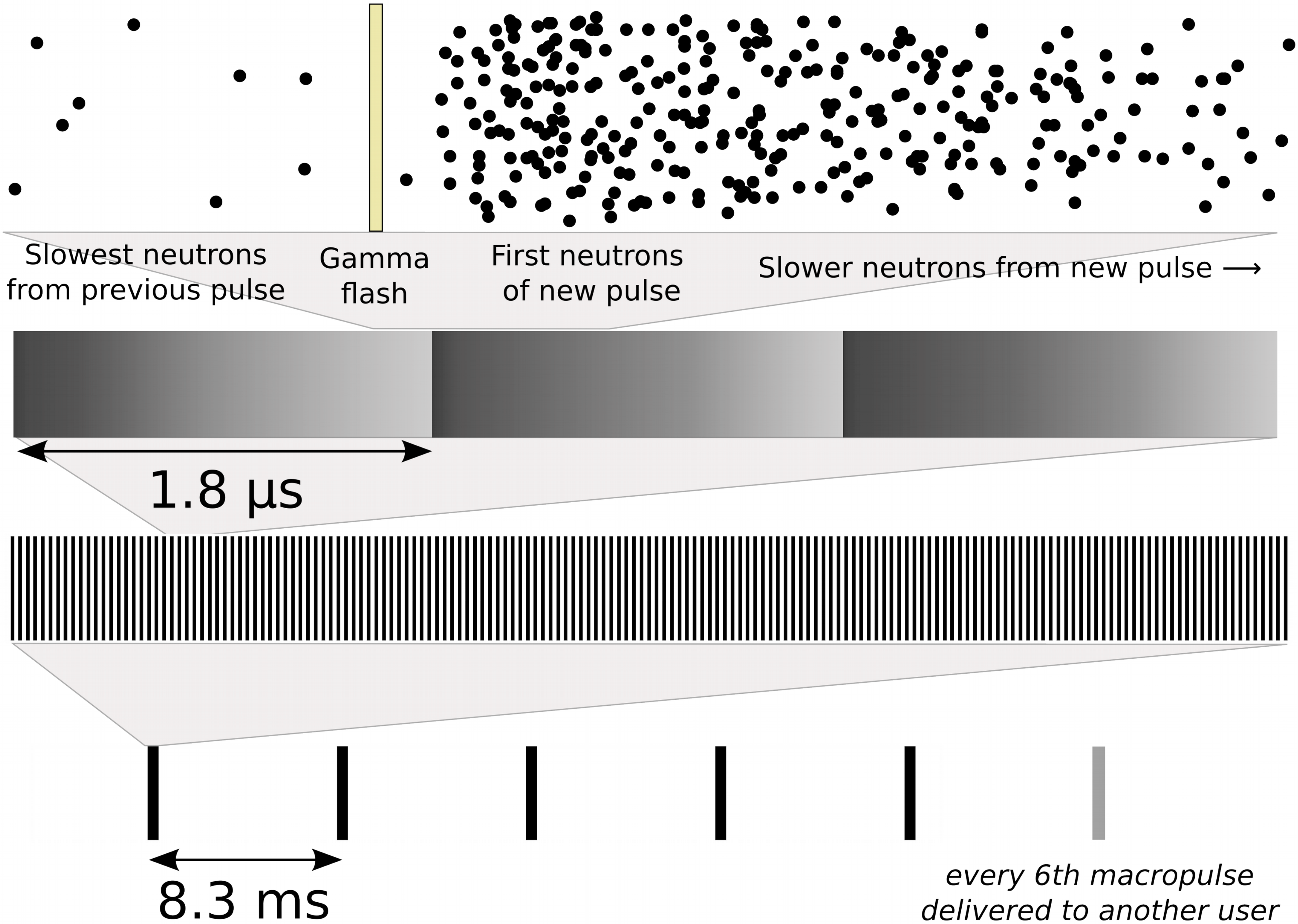

DISPERSIVE OPTICAL MODEL
Complex potential
U(r, r', ε) =
Real potential
V(r, r') +
V_HF
(WS + WB)
V_SO
(d/dr WS)
V_DISP
(KK relations)
Imaginary potential
iW(r, r', ε)
W_vol
(WS + NM corr, ε)
W_sur
(d/dr WS, ε)
W_SO
(d/dr WS, ε)


Slowest neutrons
from previous pulse
Gamma
flash
First neutrons
of new pulse
Slower neutrons from new pulse ⟶
1.8 µs
8.3 ms
every 6th macropulse
delivered to another user