Jefferson Lab
Thomas Jefferson National Accelerator Facility

OLD DOMINION UNIVERSITY

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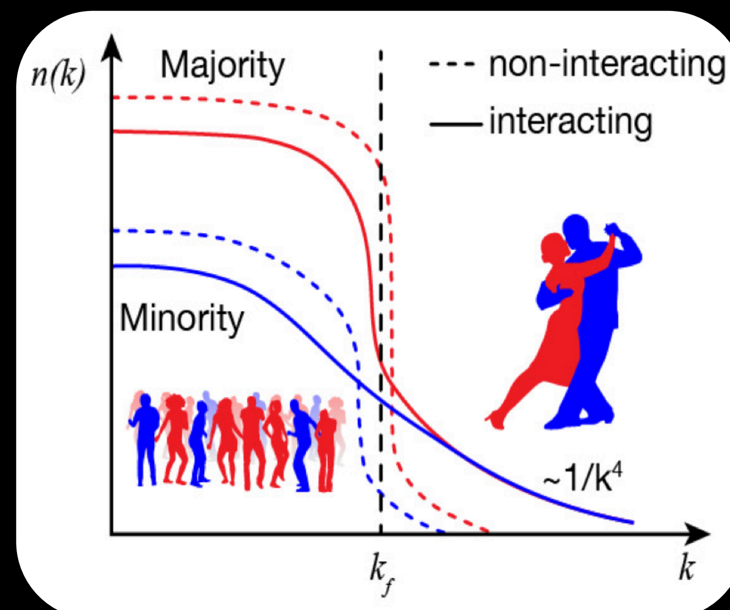
The CaFe Experiment: Short-Range Pairing Mechanisms in Heavy Nuclei

Proposal PR12-16-004

Spokespersons:

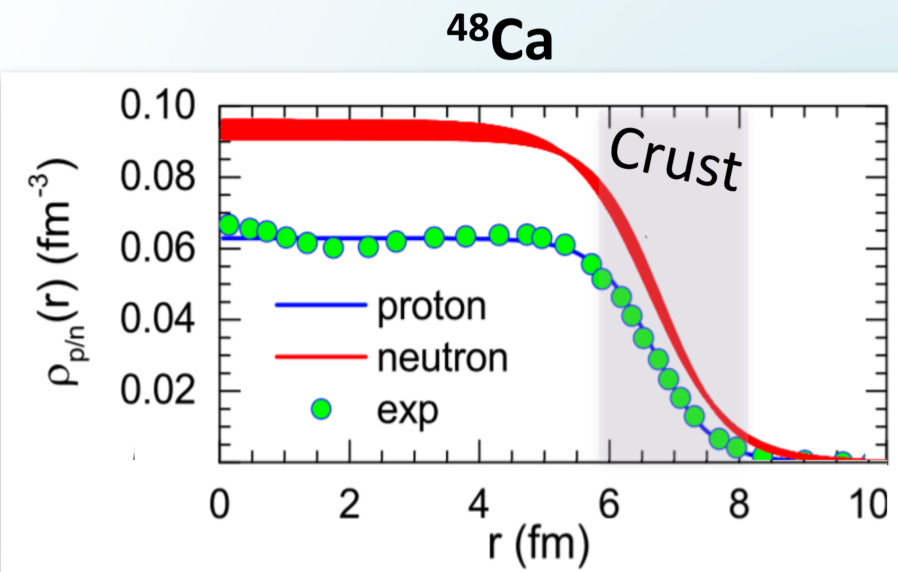
O. Hen (MIT), L. B. Weinstein (ODU),
D. Higinbotham (JLab), E. Cohen (TAU)

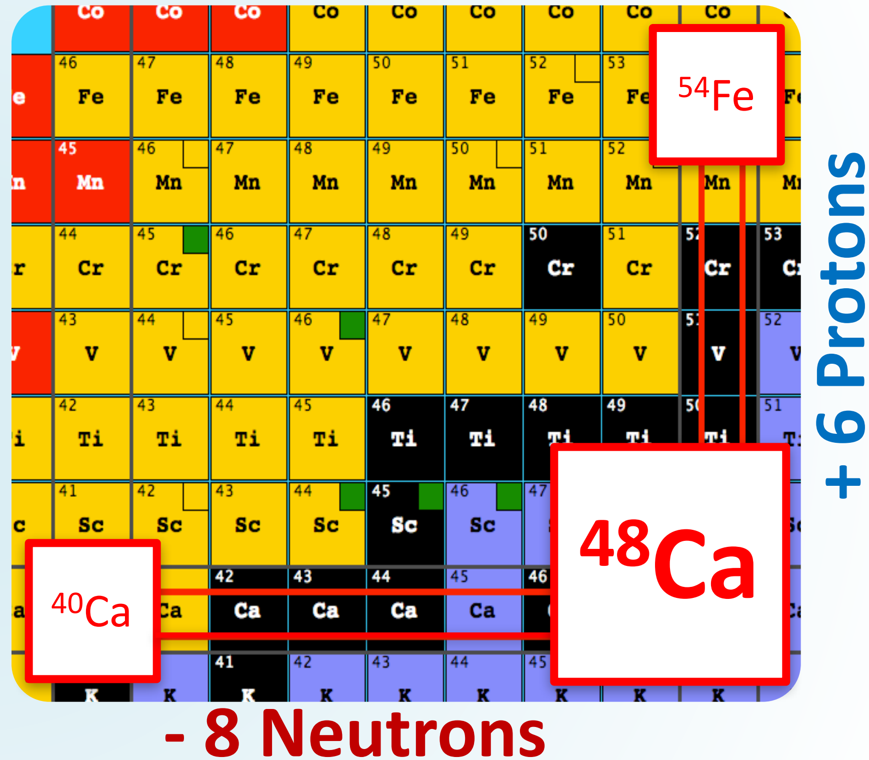


JLab PAC-44, July 27th, 2016.

CaFe: Executive Summary

Focused measurement of <u>short-range pairing</u> in neutron rich nuclei and dynamics of nucleons in the ^{48}Ca crust.





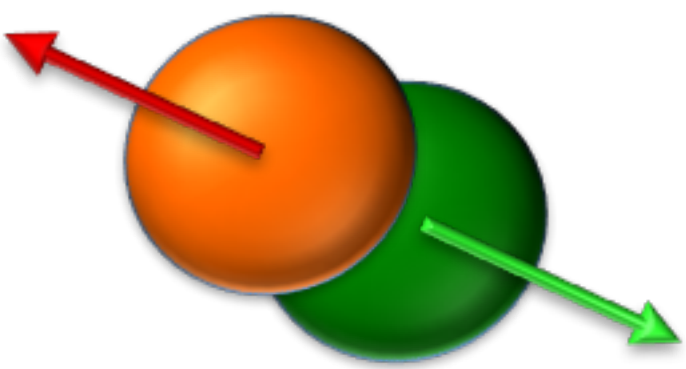
We will measure mean-field and correlated nucleons using the (e,e'p) reaction in ^{2}H, ^{12}C, ^{40}Ca, ^{48}Ca and ^{54}Fe.

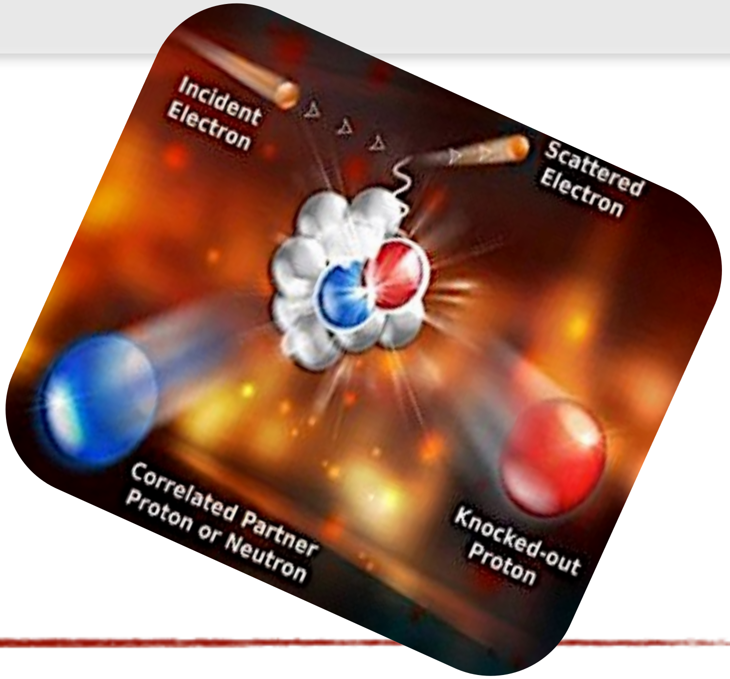
4 days in Hall-C using standard SHMS and HMS setup.

Short-Range Correlations

Nucleon **pairs** that are close together in the nucleus (wave functions overlap)

=> Momentum space: **pairs** with *high relative momentum* and *low c.m. momentum* compared to the Fermi momentum (k_F)

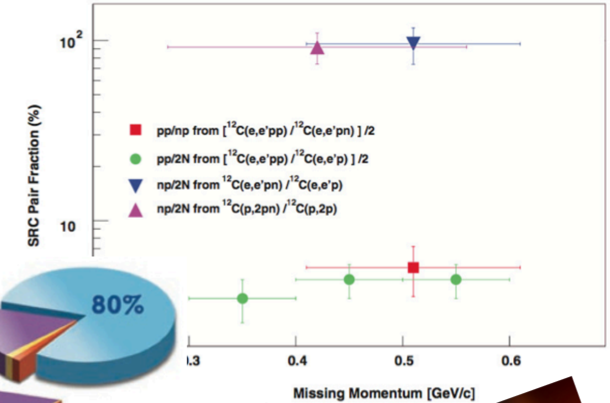


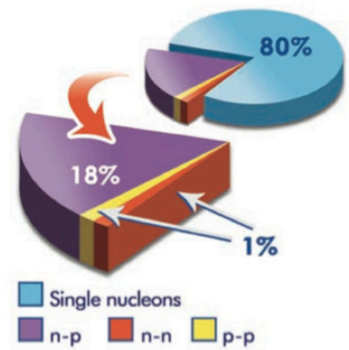


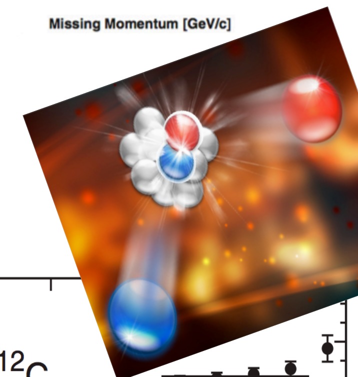
Short-Range Correlations

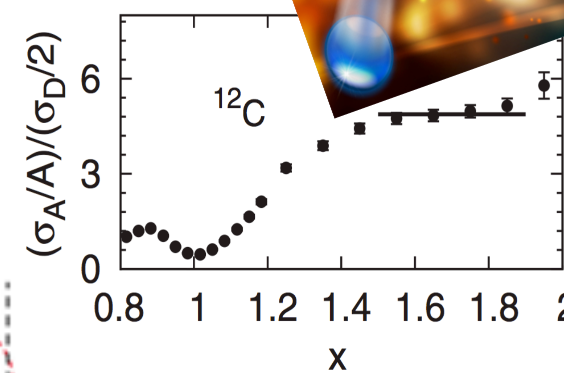
What we've learned so far:

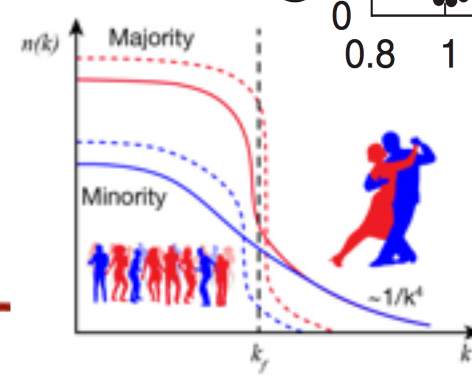
1. 20 - 25 % of nucleons in nuclei (A>12) have high-momentum ($k > k_F \sim 250$ MeV/c).
2. High-momentum nucleons predominantly belong to 2N-SRC pairs.
3. 2N-SRC are dominated by np pairs (tensor interaction).



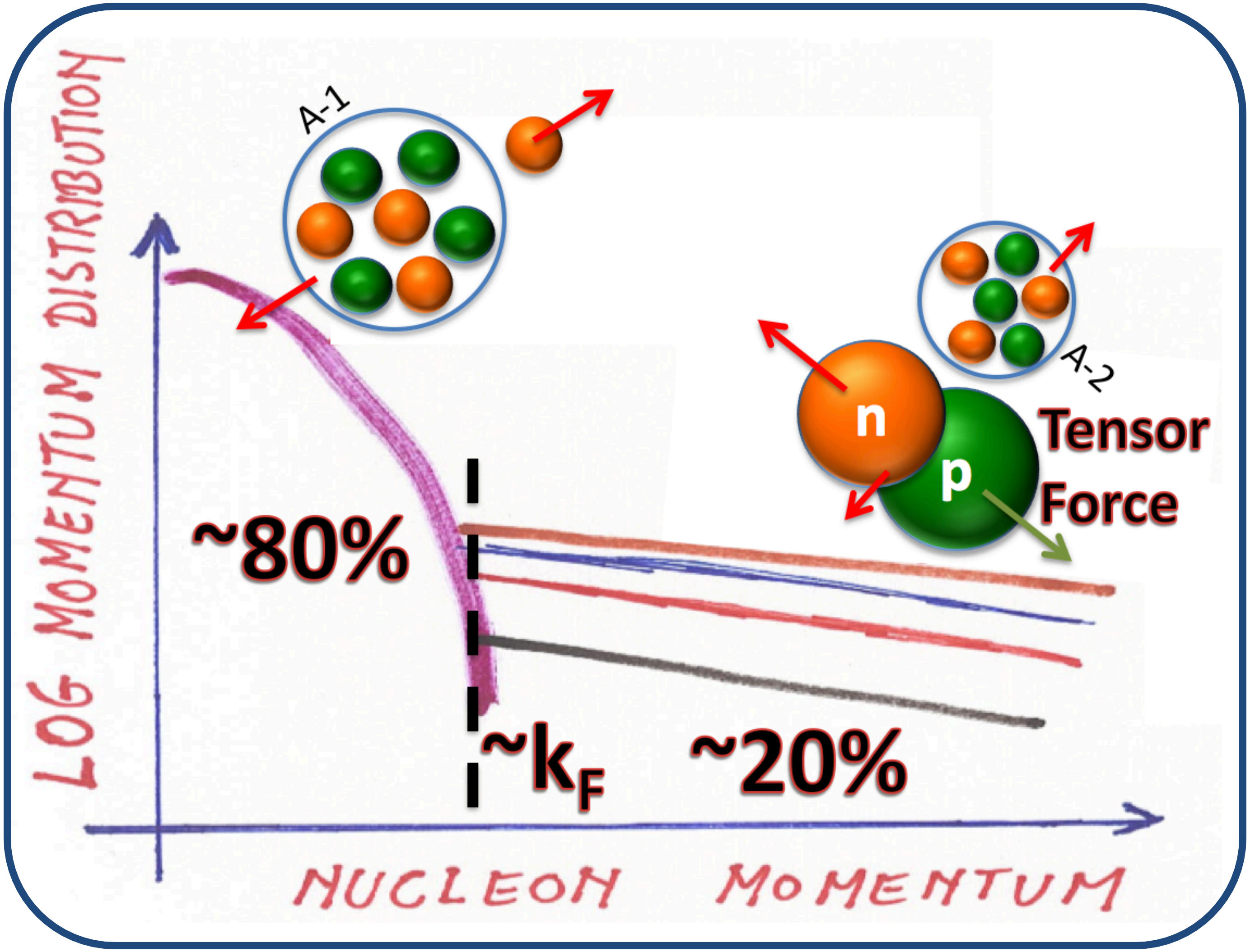








SRC lead to a 'universal' structure of nuclei in momentum space



Important to JLab!

6 GeV experimental SRC results:

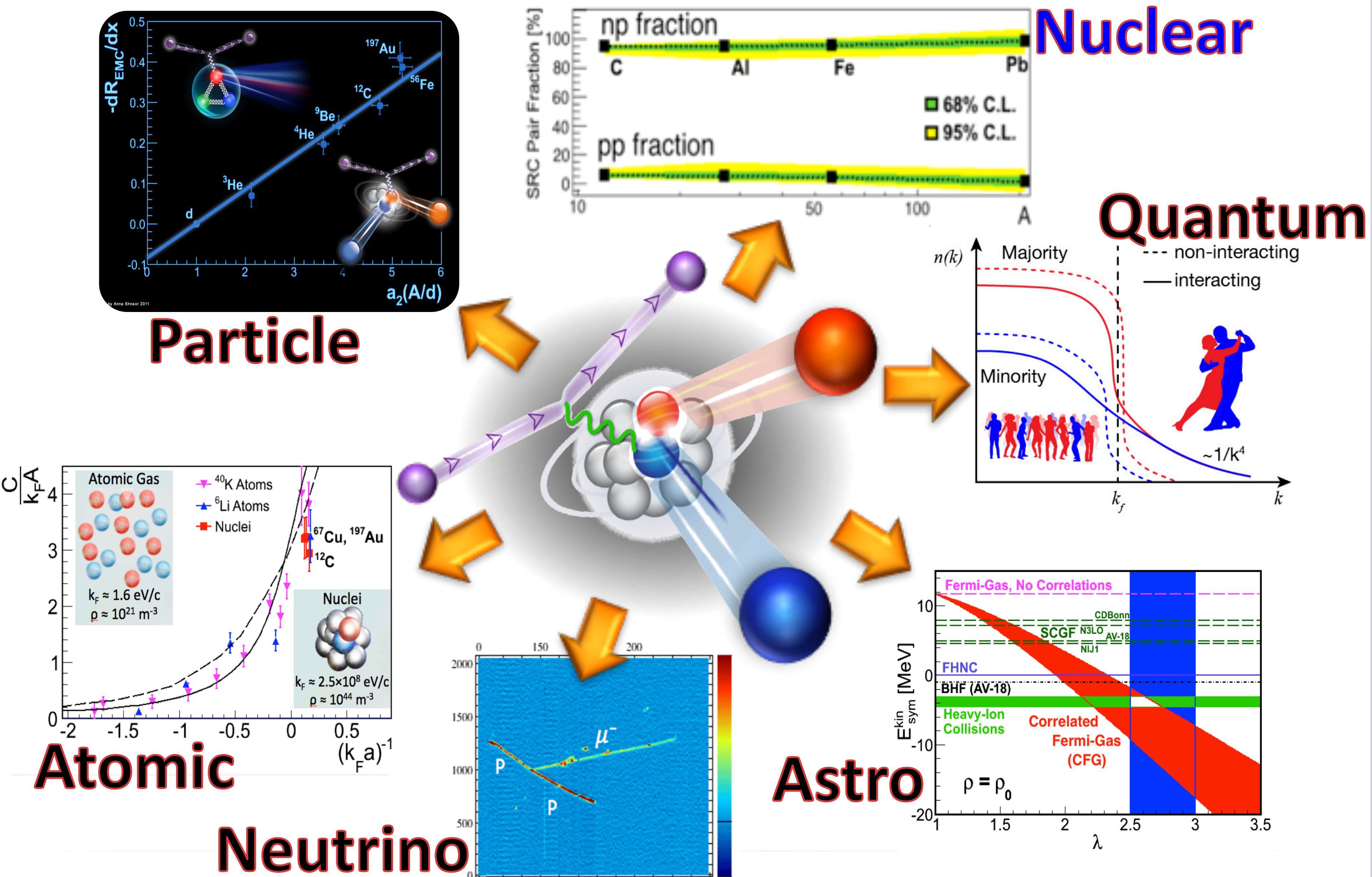
2 Science, 6 PRLs, RMP (forthcoming), and more…

+ LOTS of theoretical / phenomenological work inspired by the experimental results.

"**A highlight of the JLAB 6 GeV program was the discovery that neutron-proton pairs dominate short-range correlations, SRC, in nuclei**. This is a fundamental piece of information important for achieving a comprehensive model of nuclei. Knowledge of short-range correlations and consequently the resulting high-momentum components of the nucleon wave functions is also important information for experiments that use nuclei, for example in neutrino scattering, that rely on accurately known nuclear properties." (JLab PAC 41)

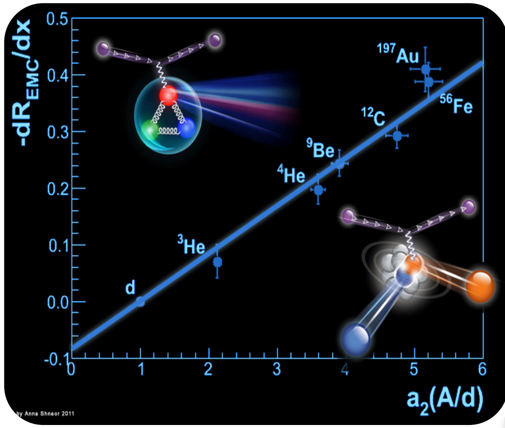
Can 12 GeV Compete?? ☺

Important to Physics! ☺

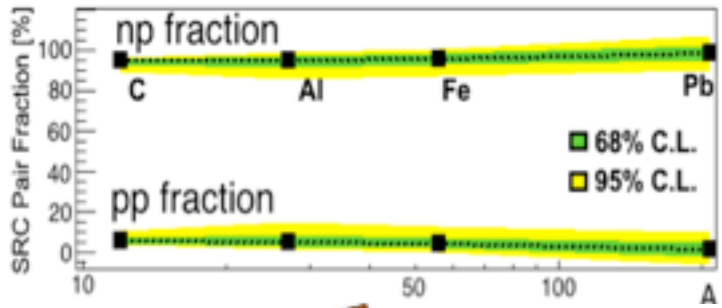


Important to Physics! ☺

Particle



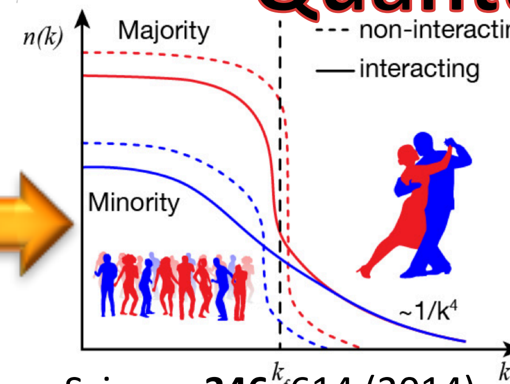
PRL **106**, 052301 (2011),
PRD **84**, 117501(2011),
PRC **85**, 047301(2012),
IJMPE **22**, 1330017 (2013),
arXiv 1607.03065 (2016).



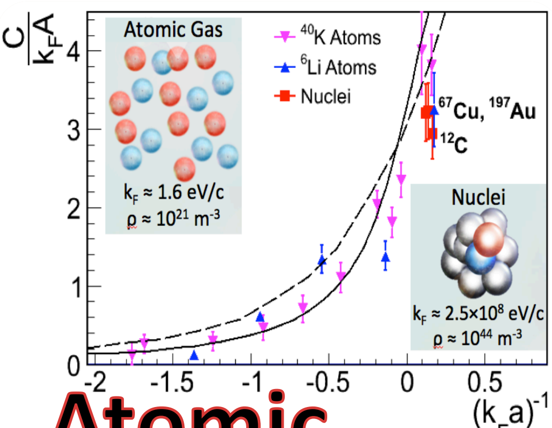
Nuclear

Science **320**, 1476 (2008),
PRL **108**, 092502 (2012),
PLB 772, **63** (2013),
PRL **113**, 022501 (2014),
PRC **92**, 024604 (2015).

Quantum

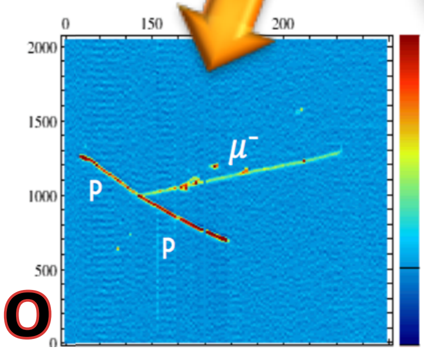


Science **346**, 614 (2014).



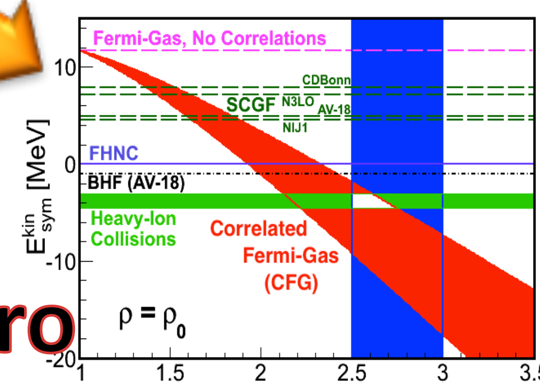
Atomic

PRC **92**, 045205 (2015).



Neutrino

PRD **90**, 012008 (2014); arXiv 1604.02482 (2016)



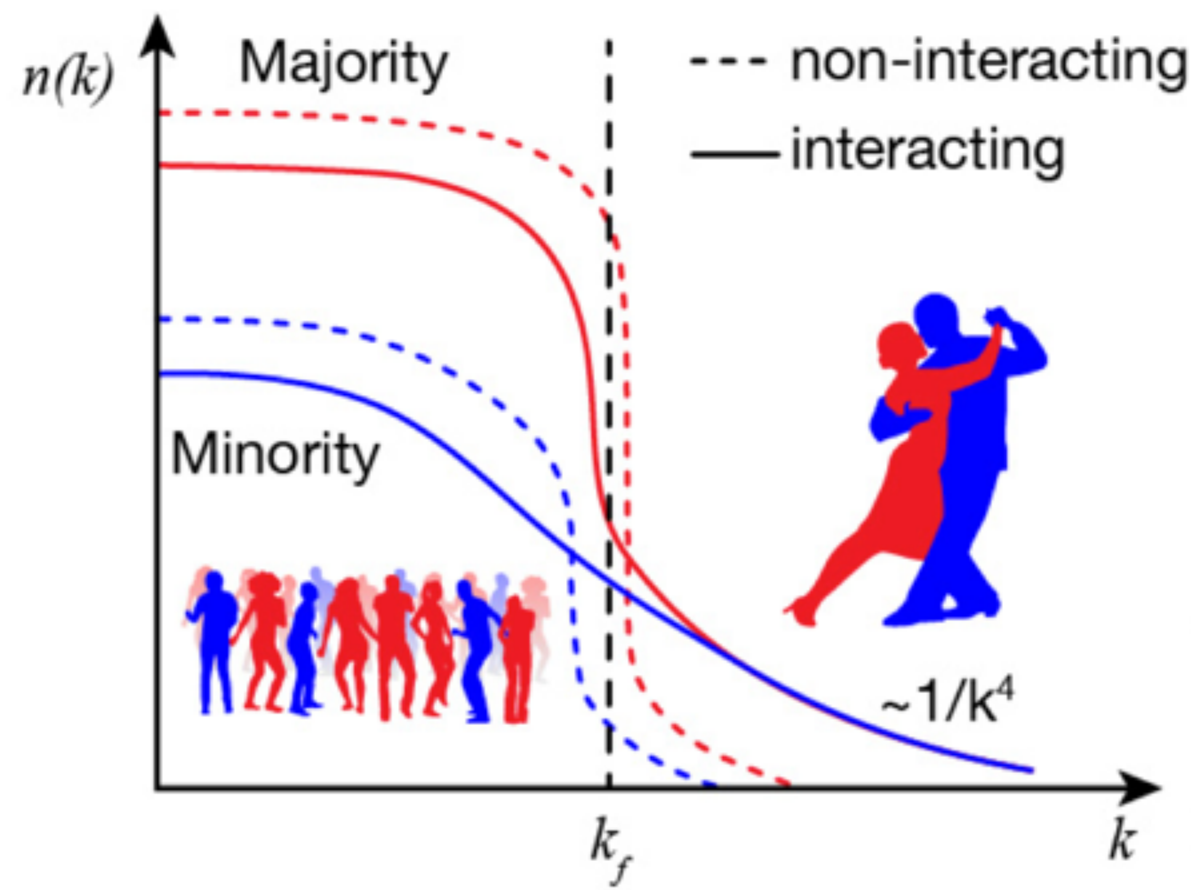
Astro

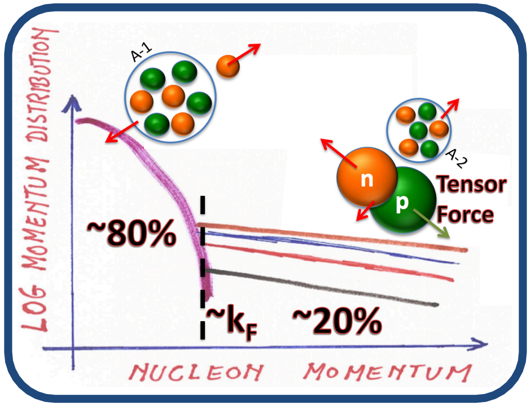
PRC **91**, 025803 (2015), PRC **93**, 044610 (2016),
PRC **91**, 044601 (2015), PRC **93**, 014619 (2016),
PRC **92**, 011601 (2015), PLB **759**, 79 (2016),
Hen and Steiner et al., In Preparation.

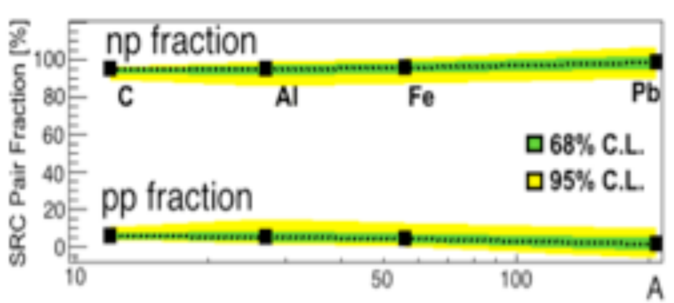
Our focus for today – Correlations in neutron rich nuclei

Asymmetric nuclei

Proton and neutron momentum distribution in imbalanced systems with short-range interactions





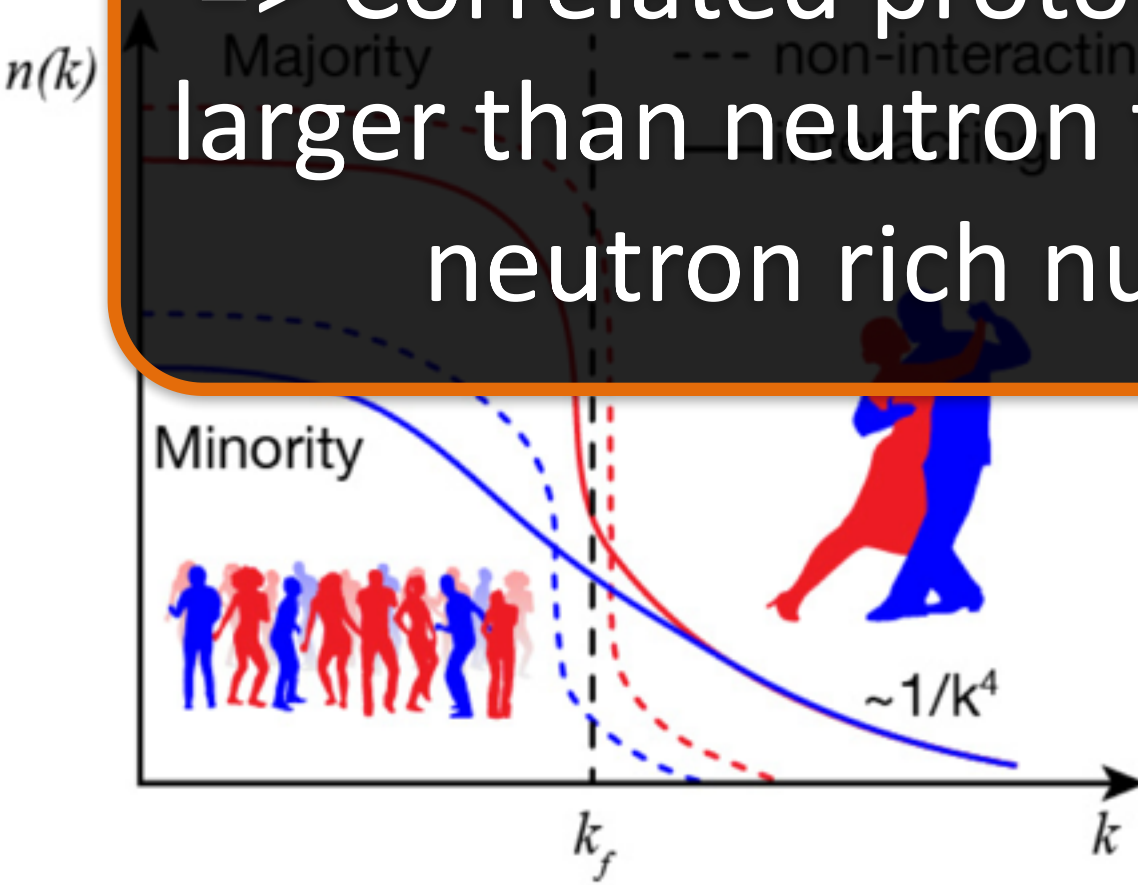


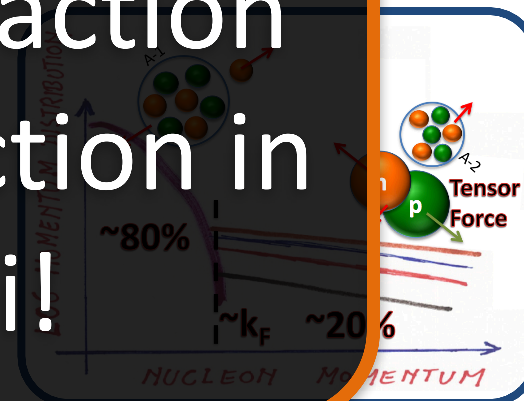
O. Hen et al., Science **346**, 614 (2014).

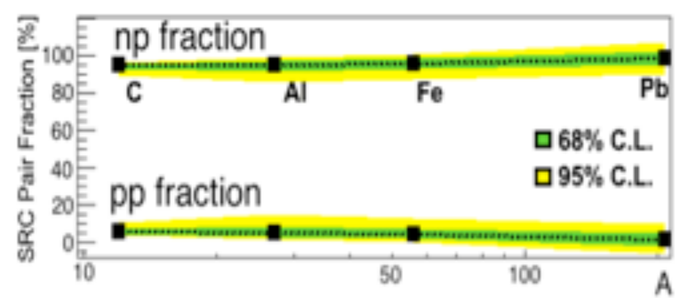
Asymmetric nuclei

Proton and neutron momentum distribution in imbalanced systems with short-range interactions

=> Correlated proton fraction larger than neutron fraction in neutron rich nuclei!







O. Hen et al., Science **346**, 614 (2014).

Kinetic Energy Sharing in Asymmetric Nuclei

Pauli Principle:

higher Fermi momentum

=> Majority (neutrons)

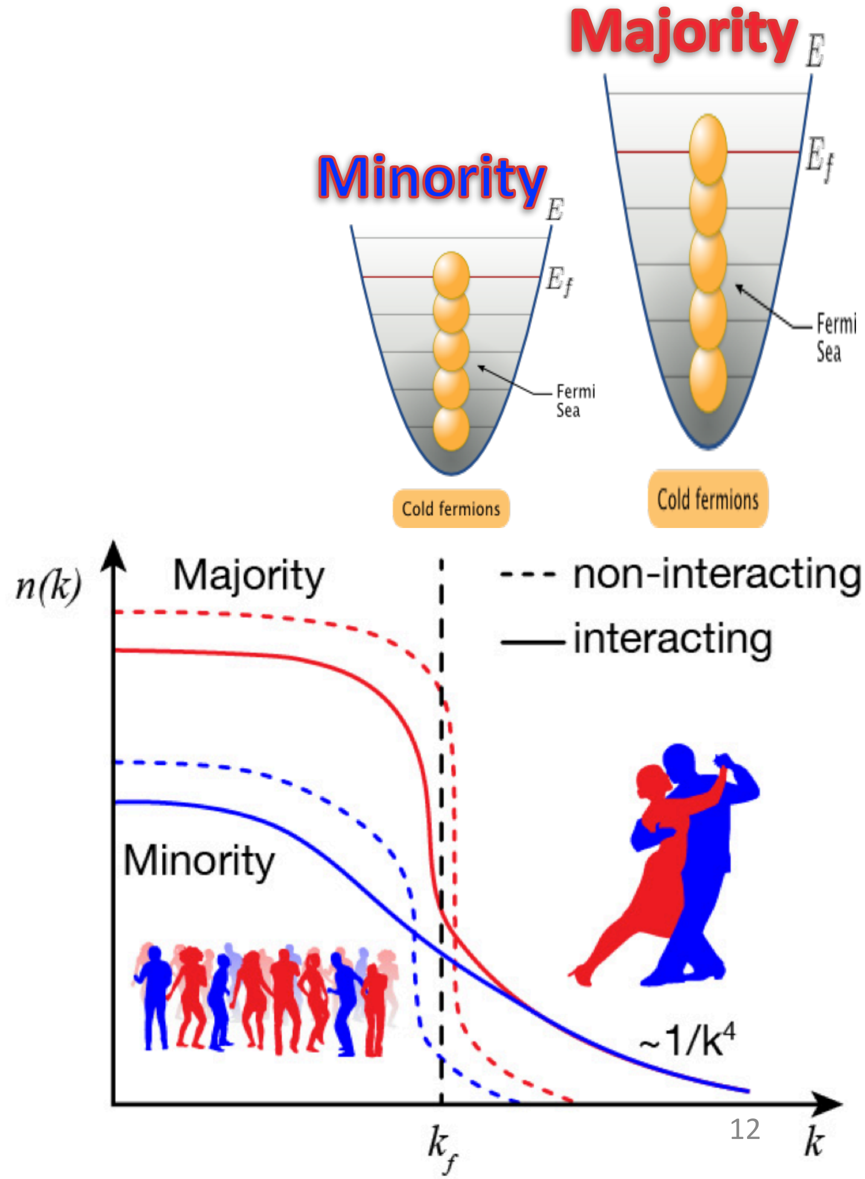
fermions move faster.

np correlations:

greater pairing probability

=> Minority (protons)

fermions move faster



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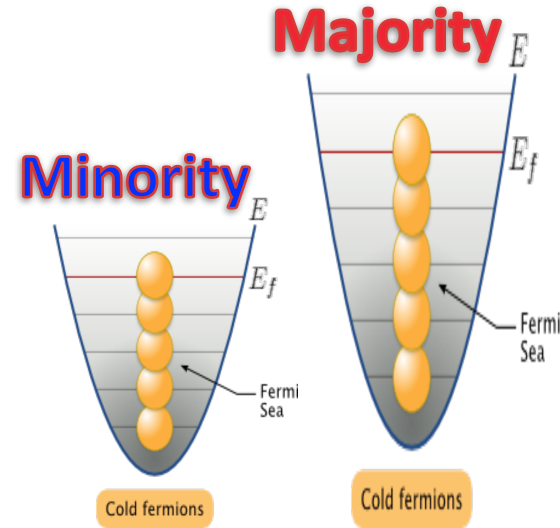

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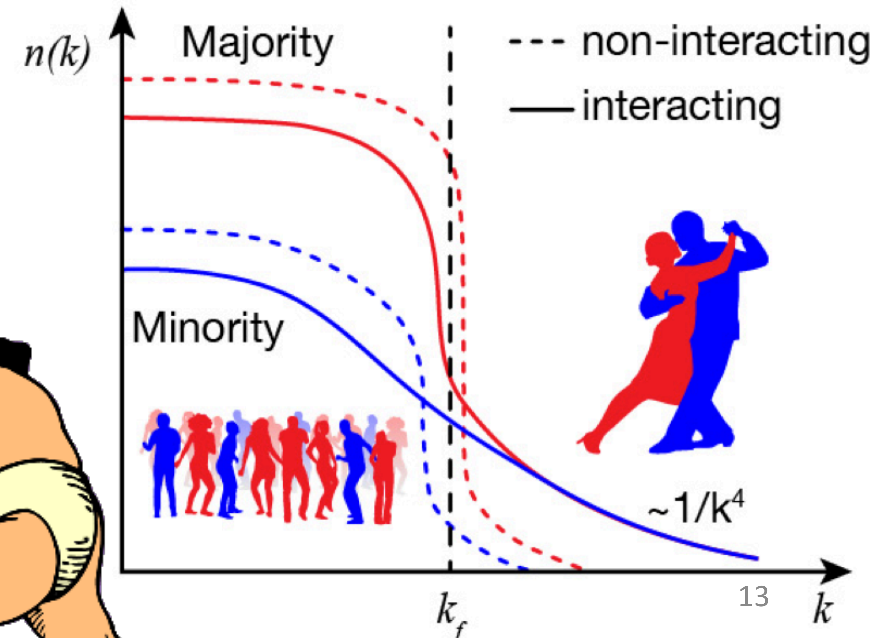
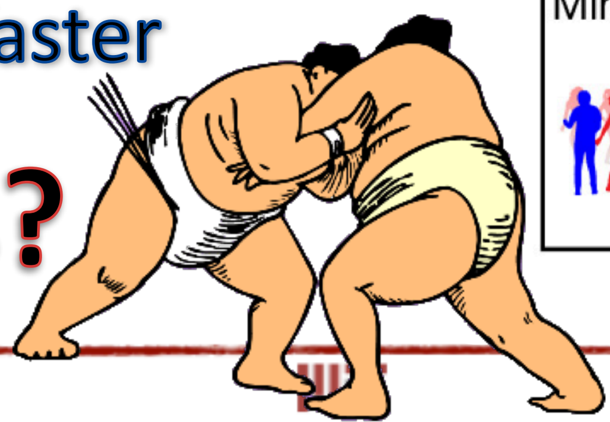
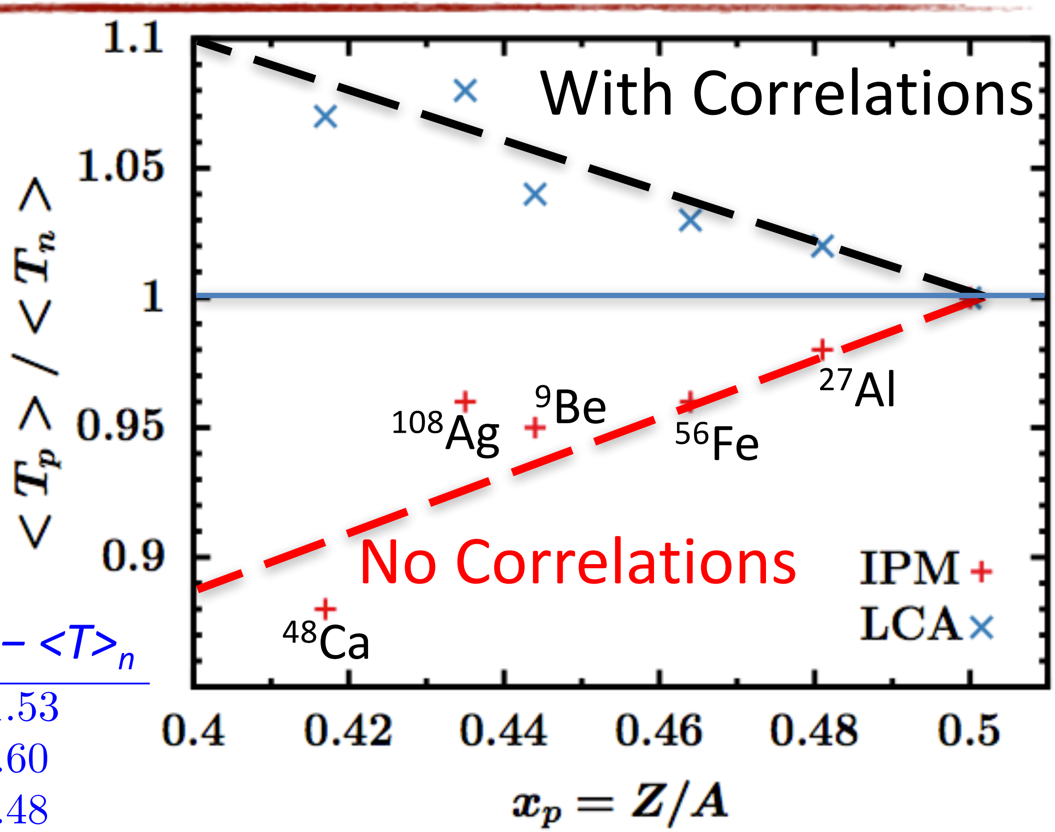


Who wins?



Calculations *Predict* Correlations Win

$\langle T \rangle_{Minority} \geq \langle T \rangle_{Majority}$



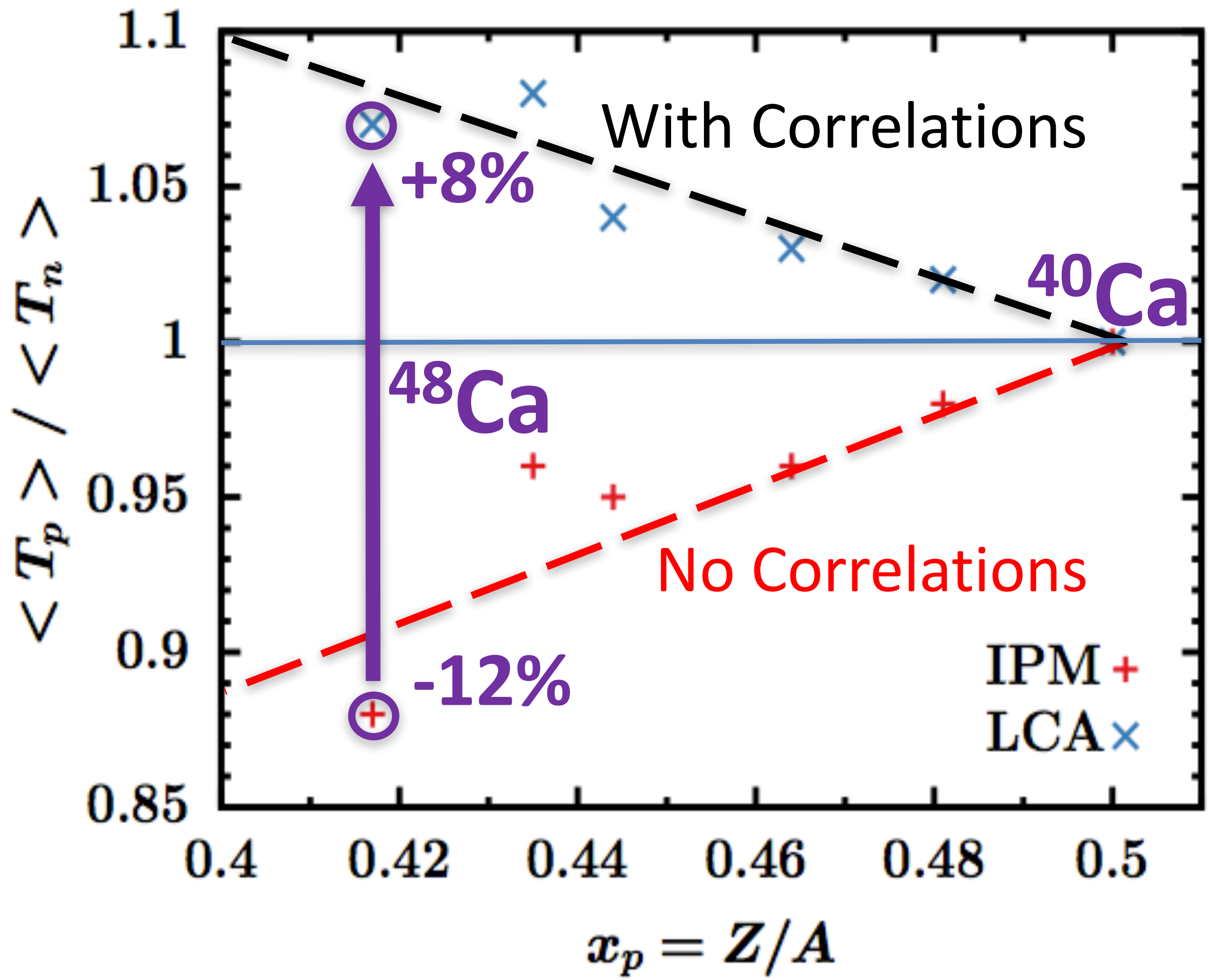
Light Nuclei (A<12)

	$\frac{\lvert N-Z \rvert}{A}$	$\langle T \rangle_p$	$\langle T \rangle_n$	$\langle T \rangle_p - \langle T \rangle_n$
^{8}He	0.50	30.13	18.60	11.53
^{6}He	0.33	27.66	19.06	8.60
^{9}Li	0.33	31.39	24.91	6.48
^{3}He	0.33	14.71	19.35	-4.64
^{3}H	0.33	19.61	14.96	4.65
^{8}Li	0.25	28.95	23.98	4.97
^{10}Be	0.2	30.20	25.95	4.25
^{7}Li	0.14	26.88	24.54	2.34
^{9}Be	0.11	29.82	27.09	2.73
^{11}B	0.09	33.40	31.75	1.65

Heavy Nuclei (27<A<108): M. Vanhalst, W. Cosyn, and J. Ryckebusch, J. Phys. G **42**, 055104 (2015)

VMC Calculations: R. Wiringa et al., Phys. Rev. C **89**, 024305 (2013)

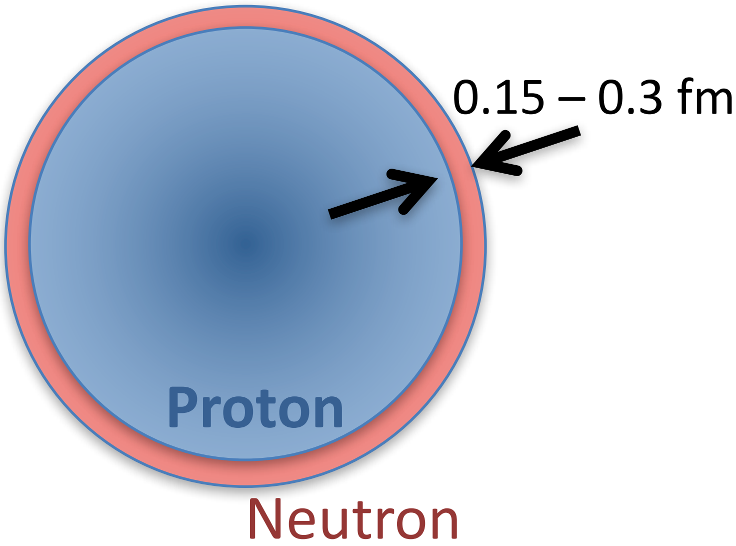
Focusing on ^{48}Ca



Focusing on ^{48}Ca

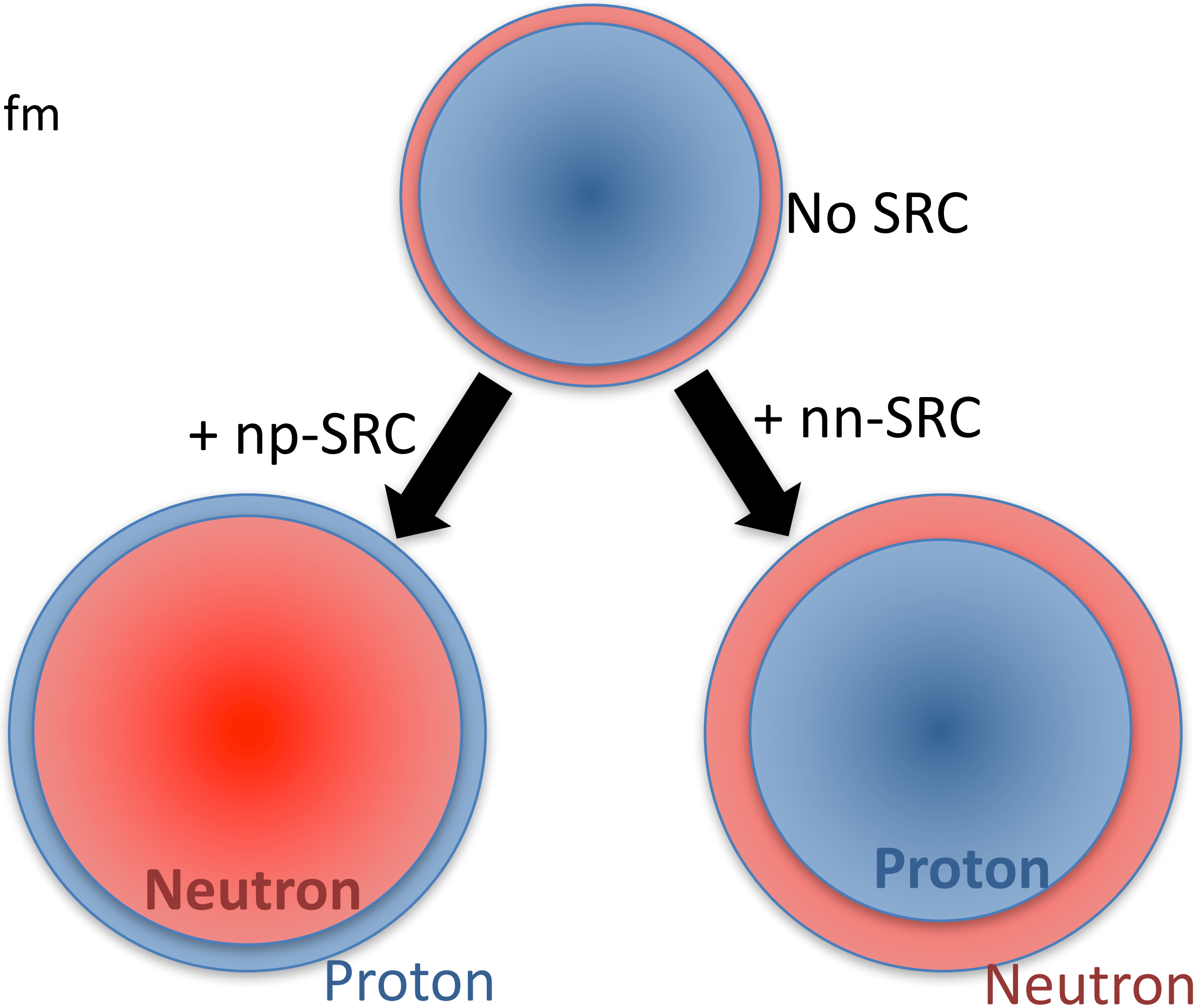
Coordinate space:

[CREX]



Momentum space:

[CaFe]



Adding correlations:

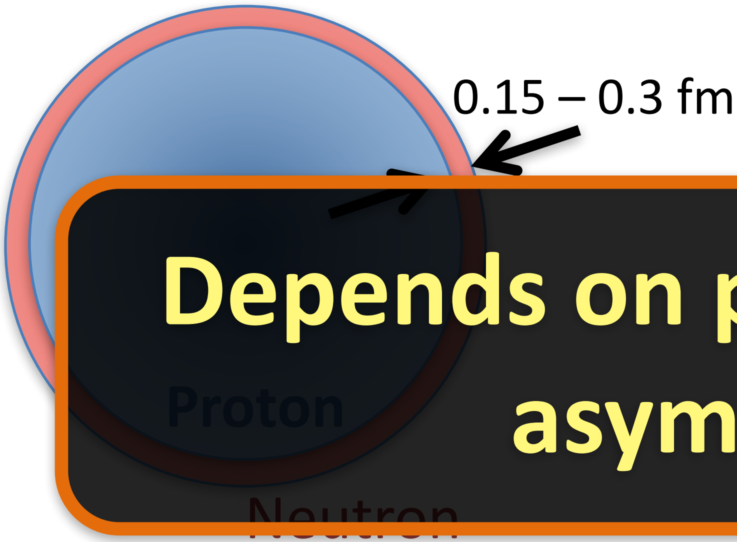
- Reduce the radius.
- Inverts the momentum skin?

M. Vanhalst, et al., J. Phys. G **42**, 055104 (2015)

Focusing on ^{48}Ca

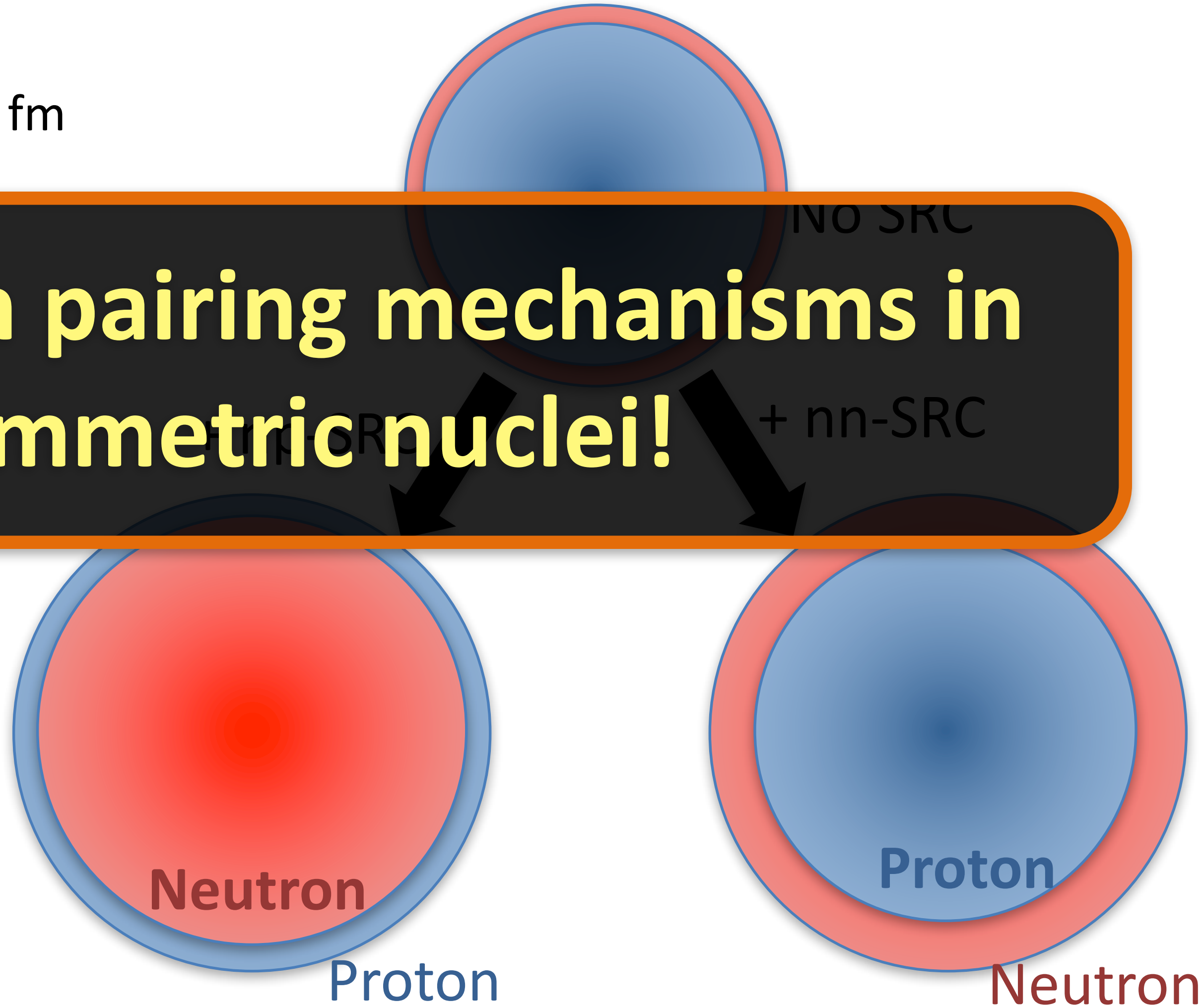
Coordinate space:

[CREX]



Momentum space:

[CaFe]



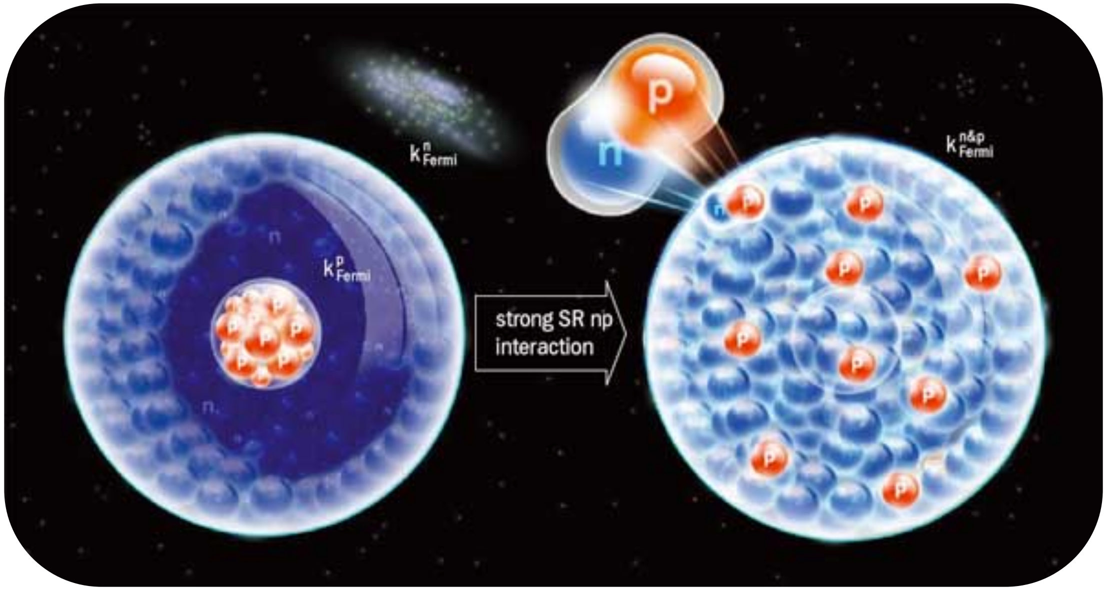
Depends on pairing mechanisms in asymmetric nuclei!

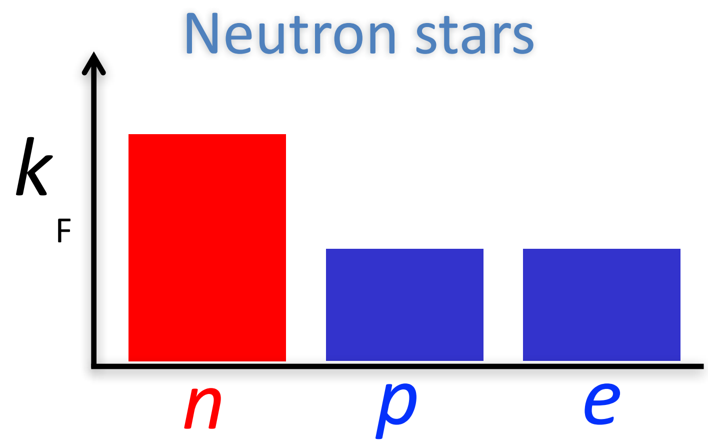
Adding correlations:

- Reduce the radius.
- Inverts the momentum skin?

M. Vanhalst, et al., J. Phys. G **42**, 055104 (2015)

Pairing and…. Neutron Stars





np-SRC pairs

- Create high-momentum protons and open 'holes' in the neutron Fermi sphere.
  - Change the URCA process cooling rate?
  - Change the spatial distribution?
- **Implementing into cooling calculations now!**

A. Steiner, Private com. + Frankfurt, Sargsian and Strikman, Int. J. Mod. Phys. A **23**, 2991 (2008).

Pairing and…. the Symmetry Energy

Relates to the energy change when replacing n with p.

- equation-of-state of neutron stars,
- heavy-ion collisions,
- r-process nucleosynthesis,
- core-collapse supernovae,
- more…

How can JLab help?

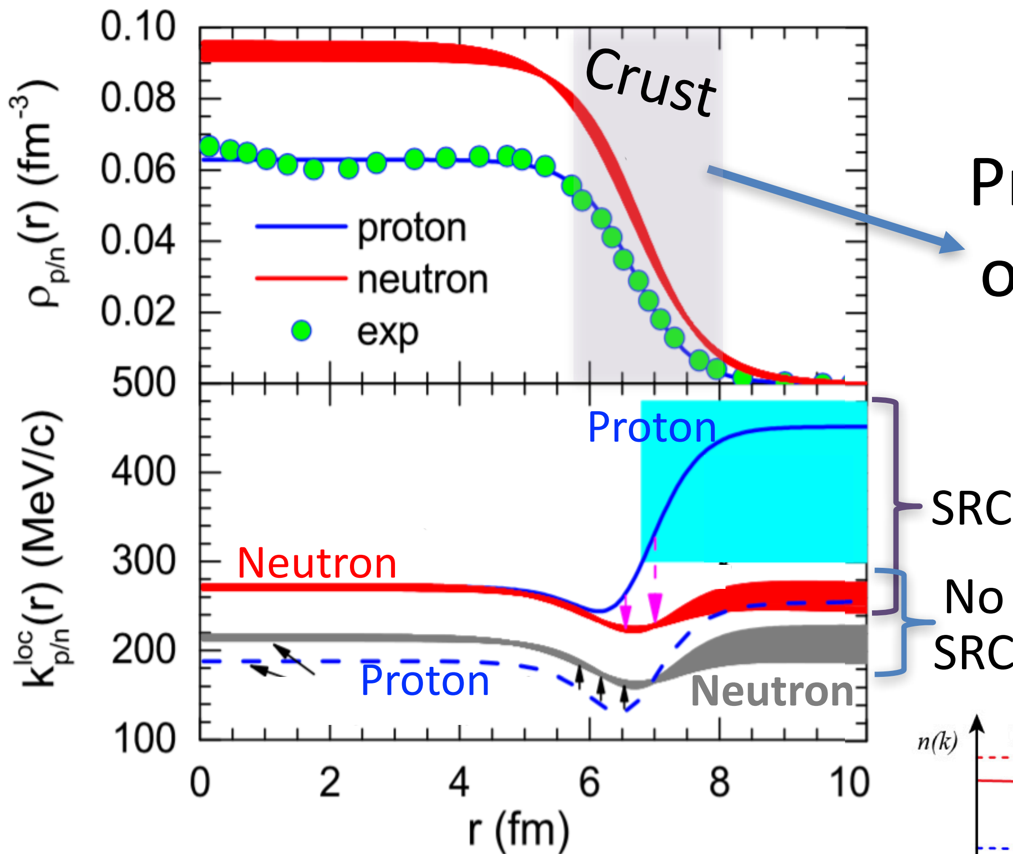
- **CREX / PREX** constrain the slope [$L \propto (dE_{sym}/d\rho)|_{\rho 0}$].
- **Pairing** changes the kinetic / potential balance.

CaFe will measure the pairing mechanism

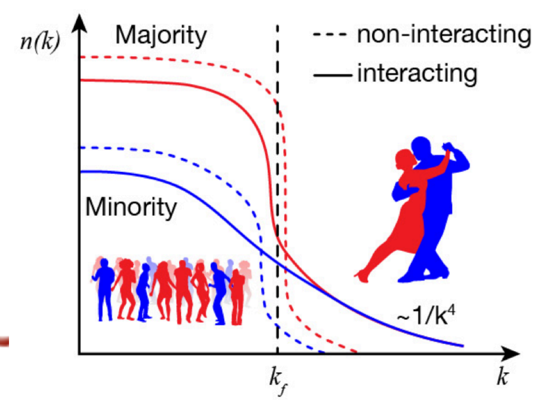
O. Hen et al., PRC 91, 025803 (2015)

O. Hen and A. Steiner et al. (on arXiv soon)

Protons move faster in the neutron skin



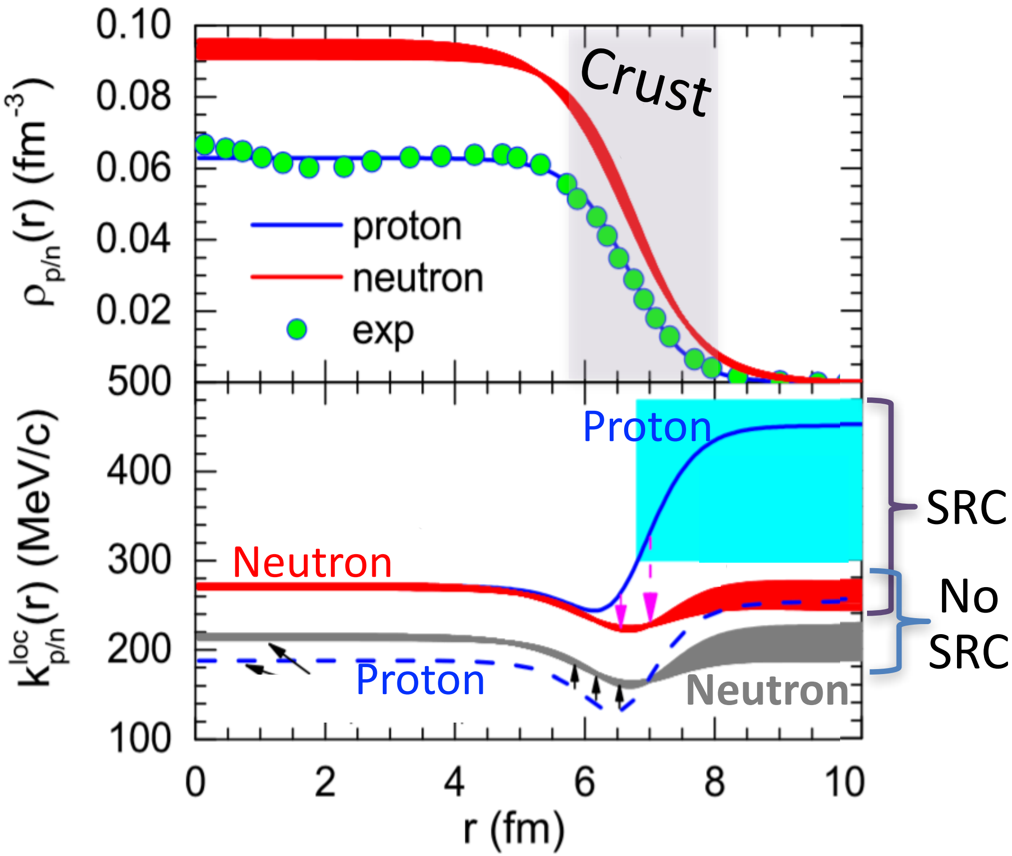
Protons in the **crust** 'feel' one of the largest neutron excess reachable by terrestrial experiments



B.J. Cai et al., arXiv: 1606.08045 (2016).

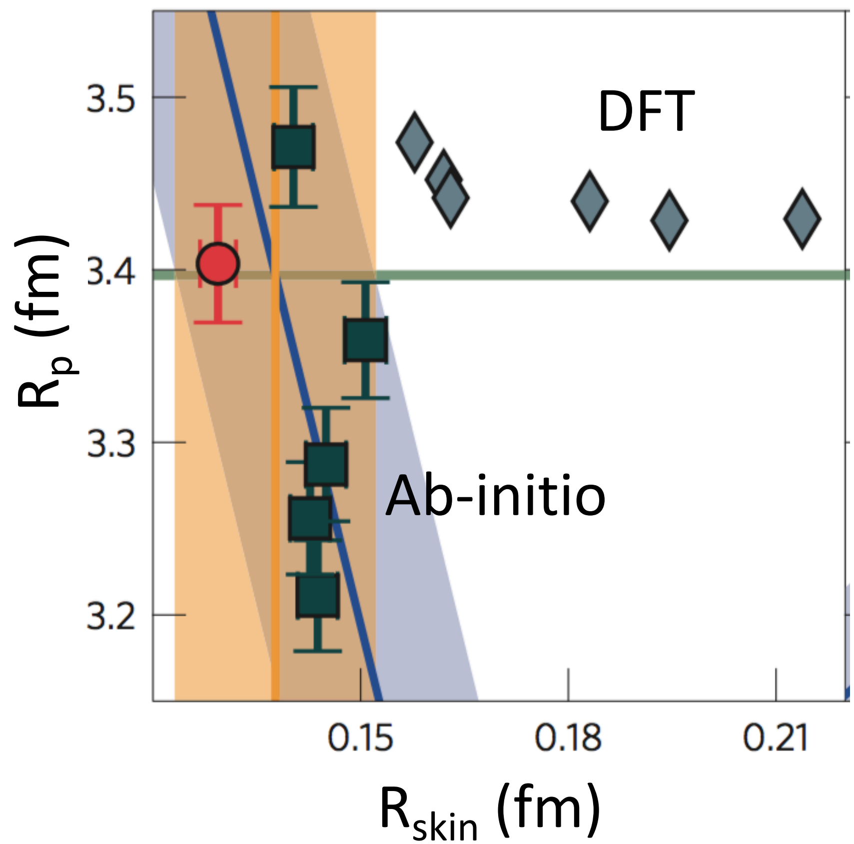
Pairing and…. Neutron Skins

Protons move faster in the neutron skin



B.J. Cai et al., arXiv: 1606.08045 (2016).

Do SRC change the neutron skin?



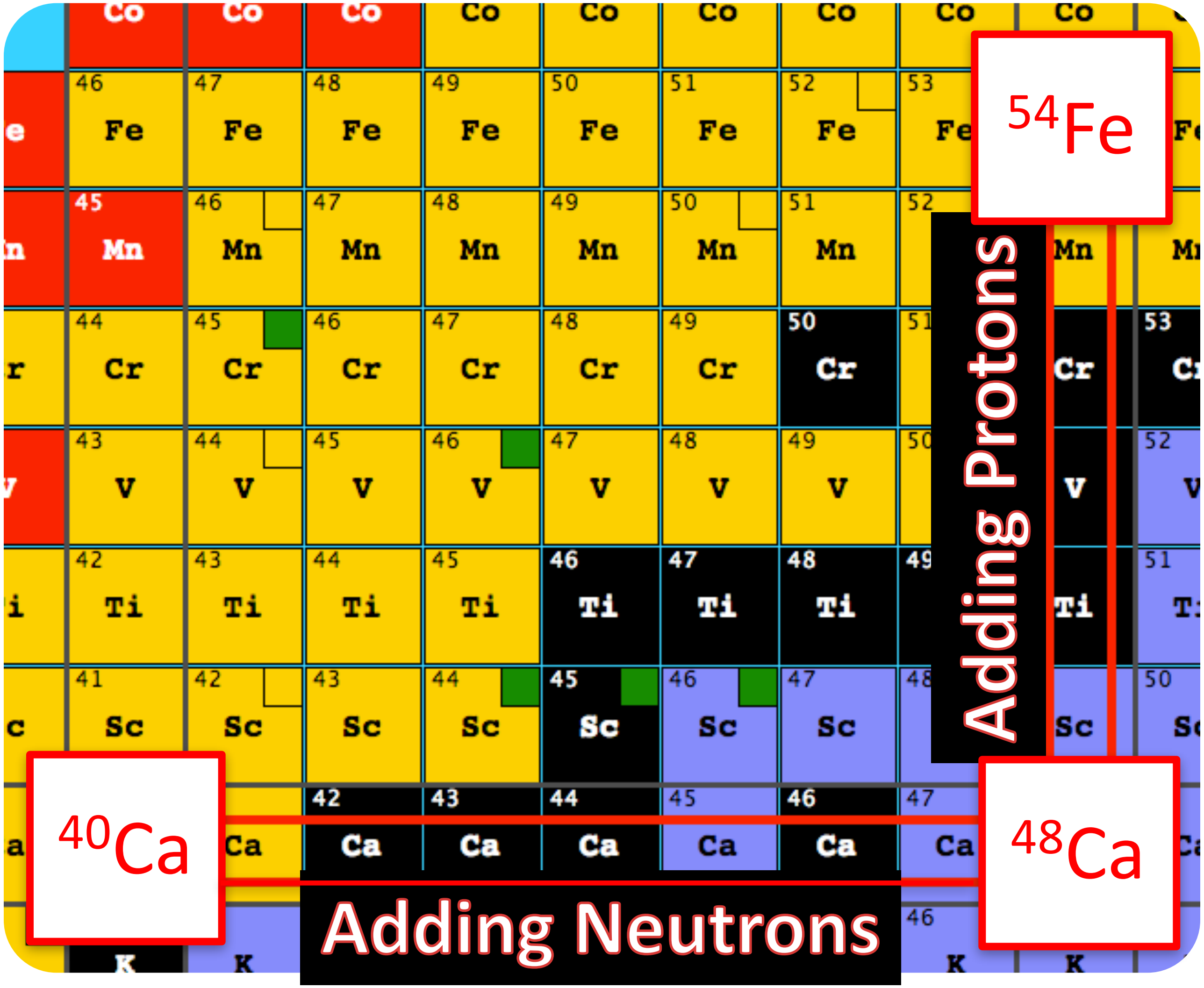
G. Hagen et al., Nature Physics 12, 186 (2016).

what's the Problem?

These effects depend quantitatively on the short-range pairing mechanism in asymmetric nuclei.

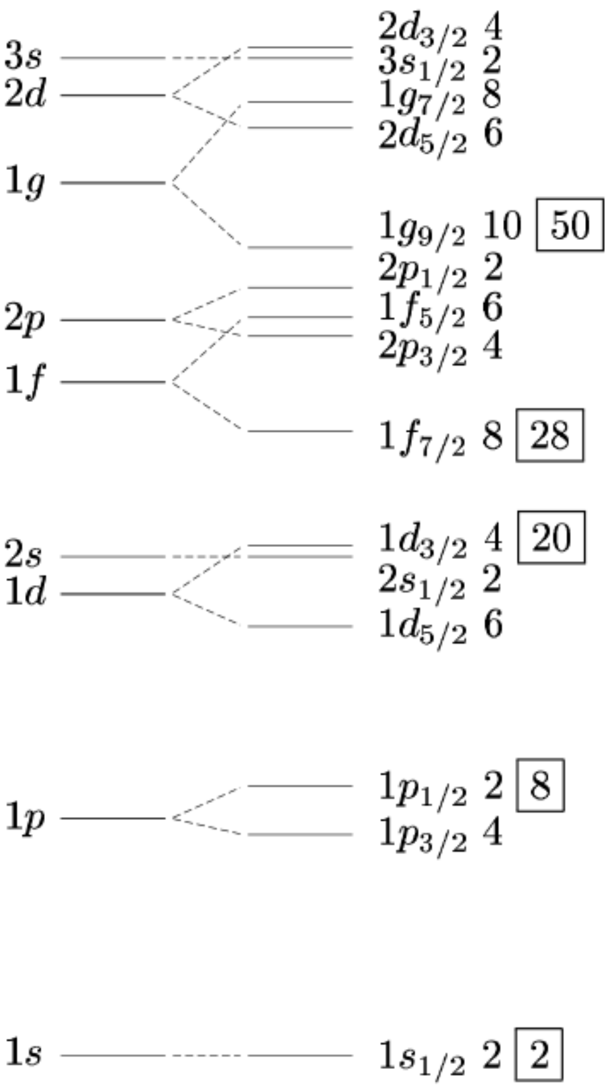
=> In comes CaFe!

The CaFe Triplet:
A Lab for Asymmetric Nuclei



^{48}Ca has a 40% neutron excess!!

The CaFe Triplet:
A Lab for Asymmetric Nuclei

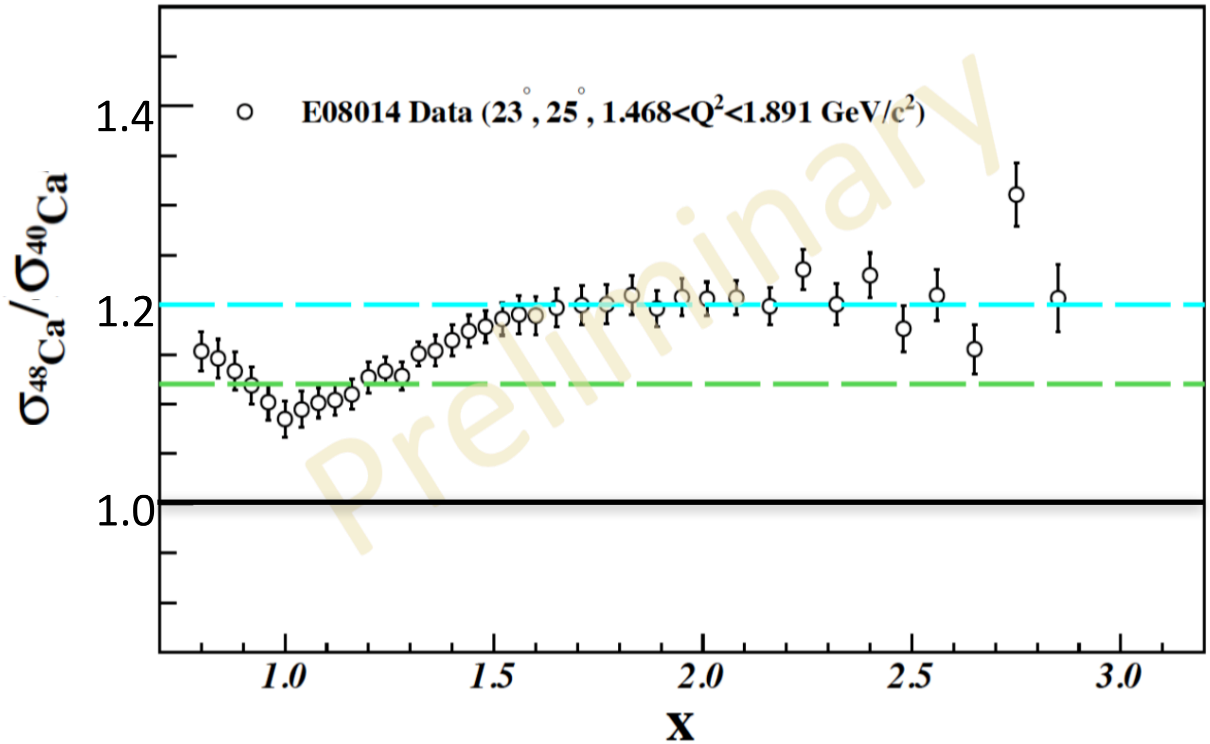


Nucleus	Z	N	
^{40}Ca	20	20	Symmetric double magic
^{48}Ca	20	28	+ Full neutron shell ($1f_{7/2}$)
^{54}Fe	26	28	Almost symmetric double magic

How do the neutrons from the outer $1f_{7/2}$ shell correlate with the ^{40}Ca core?

What do we already know?

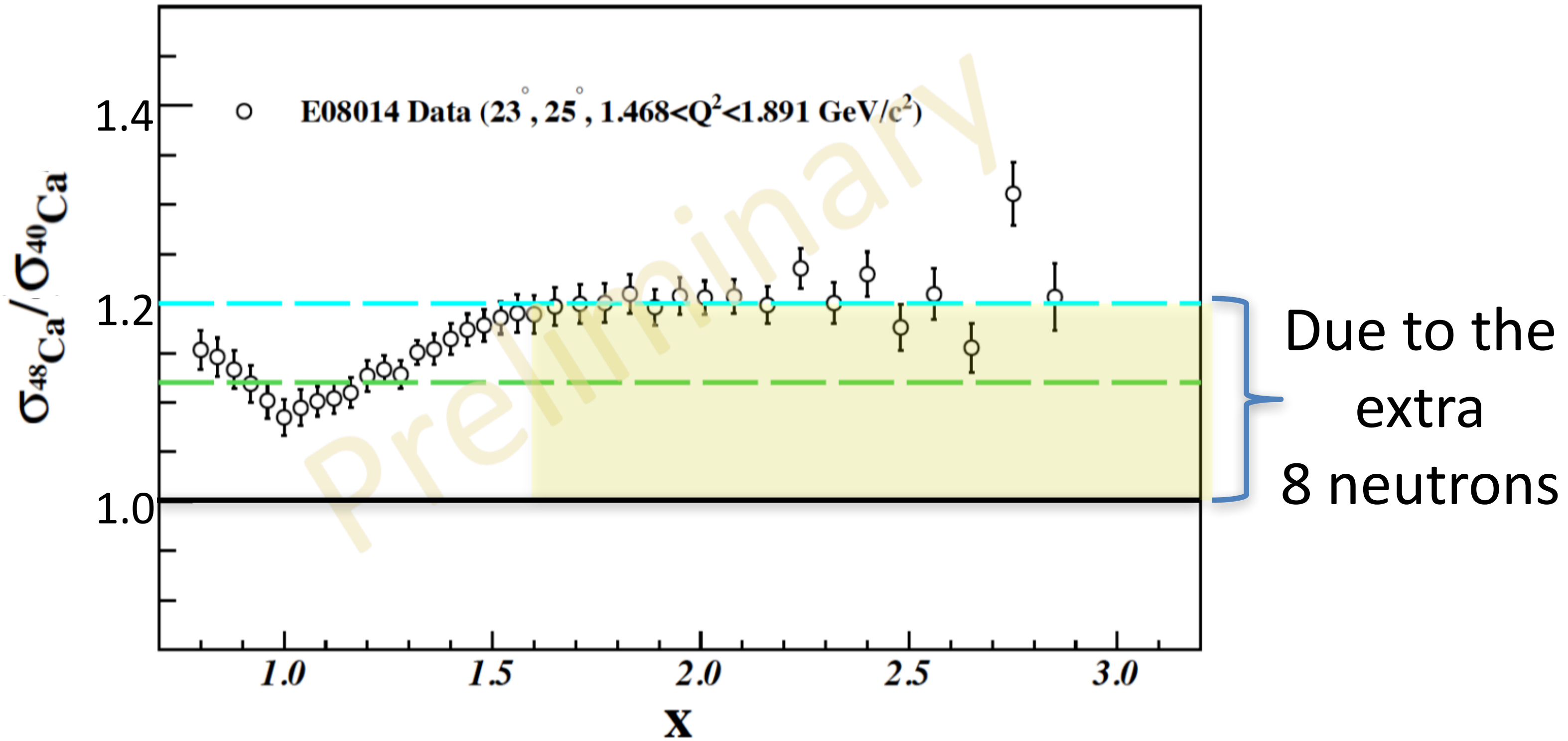
(e,e') cross-section ratios at x_B>1 are sensitive to the TOTAL NUMBER OF SRC PAIRS:



=> ^{48}Ca: + 20% nucleons, +20% SRC pairs!

What do we already know?

(e,e') cross-section ratios at $x_B>1$ are sensitive to the TOTAL NUMBER OF SRC PAIRS:



The neutrons in the outer $1f_{7/2}$ shell (i.e. in the skin) are *equally correlated* as the nucleons in the ^{40}Ca core!

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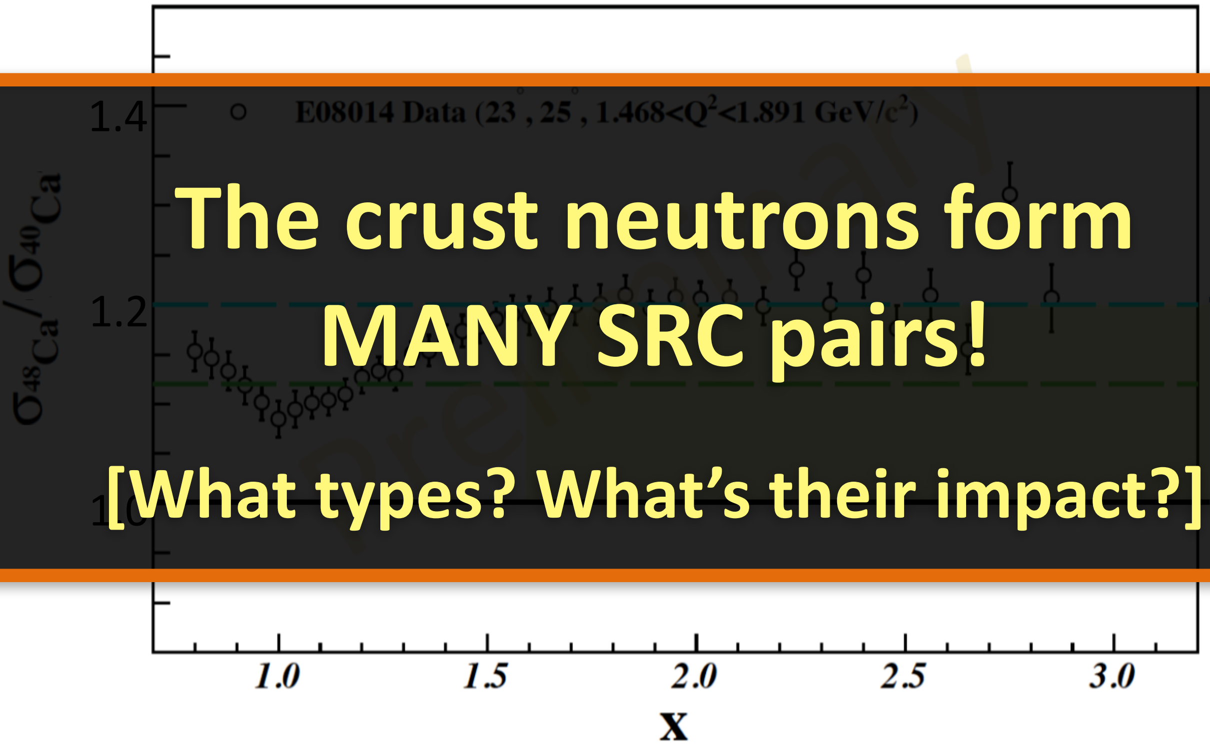

Due to the extra 8 neutrons

The crust neutrons form MANY SRC pairs!

[What types? What's their impact?]

The neutrons in the outer $1f_{7/2}$ shell (i.e. in the skin) are *equally correlated* as the nucleons in the ^{40}Ca core!

Correlations in the skin

Can (e,e') also tell us what type of pairs the $1f_{7/2}$ neutrons create?
Unfortunately No…

Examine two extreme hypothesis:

All pairs can form SRC pairs:

$$\sigma_{(e,e')|x>1} \propto \left(\sigma_p + \sigma_n\right)(NZ) + 2\sigma_p(Z \cdot (Z-1)/2) + 2\sigma_n(N \cdot (N-1)/2)$$

Only np pairs can form SRC pairs:

$$\sigma_{(e,e')|x>1} \propto \left(\sigma_p + \sigma_n\right)(NZ)$$

All-Pairs / np-Pairs = 0.94 → VERY hard to discriminate

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All-Pairs / np-Pairs = 0.94 → VERY hard to discriminate

The (e,e') reaction can not distinguish protons and neutrons → need (e,e'p) !

Correlations in the skin

Can **(e,e'p)** tell us what type of pairs the $1f_{7/2}$ neutrons create? **Yes!**

Ratios of correlated protons in different nuclei

Model	$^{40}Ca/C$	$^{48}Ca/^{40}Ca$	$^{54}Fe/^{48}Ca$	$^{54}Fe/^{40}Ca$
1 – all protons	1.7	1	1.3	1.3
2 – all pairs	11.7	1.23	1.44	1.77
3 – all np pairs	10.1	1.4	1.30	1.82
4 – S and P np pairs	10.4	1.31	1.32	1.73
5 – $l = 0, n = 0$ np pairs	5.3	1.20	1.22	1.47

The sensitivity of the (e,e'p) reaction gives **large effects**!

C. Colle and O. Hen et al., Phys. Rev. C **92**, 024604 (2015)

Correlations in the skin

Can **(e,e'p)** tell us what type of pairs the $1f_{7/2}$ neutrons create? **Yes!**

Ratios of correlated protons in different nuclei

Model	^{40}Ca/C	^{48}Ca/^{40}Ca	^{54}Fe/^{48}Ca	^{54}Fe/^{40}Ca
1 [redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2 [redacted]	[redacted]	[redacted]	[redacted]	[redacted]
3 [redacted]	[redacted]	[redacted]	[redacted]	[redacted]
4 [redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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How can (e,e'p) study the correlated protons?

The sensitivity of the (e,e'p) reaction gives **large effects**!

C. Colle and O. Hen et al., Phys. Rev. C **92**, 024604 (2015)

(e,e'p) - studying the protons

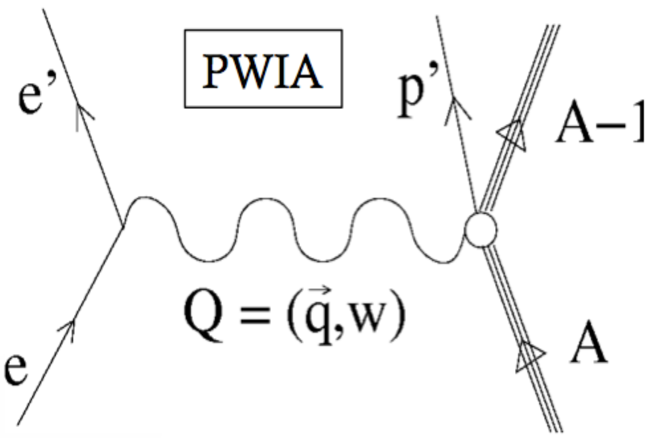
$$\sigma_{(e,e'p)} = k \cdot \sigma_{ep} \cdot S_p(E_{miss}, P_{miss}) \cdot T$$

Kinematical Factor

e-p Cross Section

Spectral Function

"Transparency"



Complications:

- Rescattering of the outgoing proton.
- Off-shell proton cross-section.
- Meson Exchange Currents (MEC).
- Delta production (i.e. IC).

=> Spectral function is not an observable!

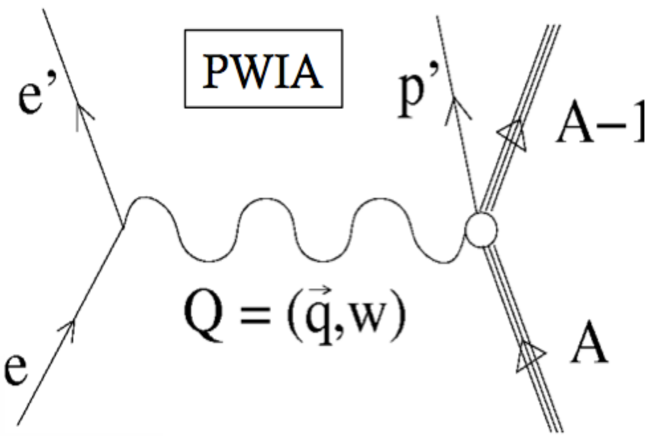
$$E_{\text{miss}} = \omega - T_p - T_{A-1}$$

$$\vec{p}_{miss} = \vec{q} - \vec{p}\,' = -\vec{p}_{init}$$

(e,e'p) - studying the protons

$$\sigma_{(e,e'p)} = k \cdot \sigma_{ep} \cdot S_p(E_{miss}, P_{miss}) \cdot T$$

Kinematical Factor · e-p Cross Section · Spectral Function · "Transparency"



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Solution:

(A) Choosing the 'right' kinematics,
(B) Integrate over a wide P_{miss} range,
(C) Extract cross-section ratios.

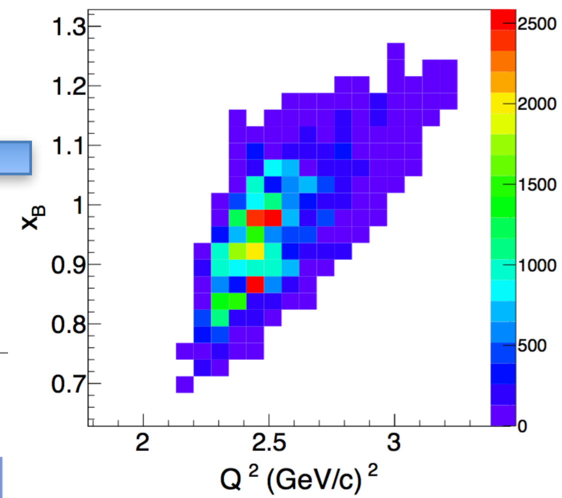
Choosing Kinematics

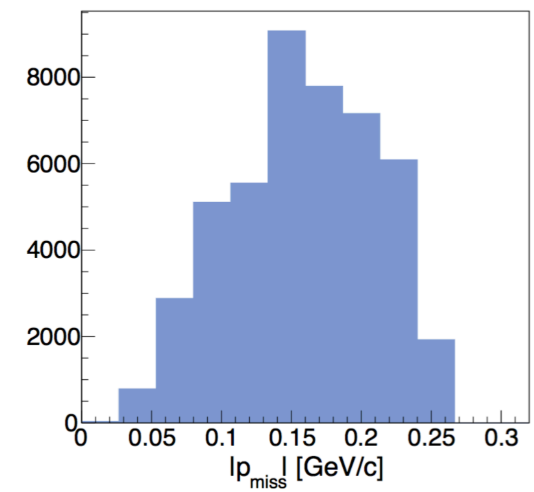
- E_{beam} = **11 GeV** @ 40 uA to maximize rates.
- ^{1}H, ^{2}H, ^{12}C, **^{40}Ca, ^{48}Ca, and ^{54}Fe** targets.
- **$Q^2 \approx 3.5$ GeV^2**
  - Reduces non-nucleonic currents (MEC, IC).
  - Proton energies high enough for Glauber FSI calculations.
- **$x_B = Q^2/2m\omega > 1.2$** to minimize non-nucleonic currents.
- **$\theta_{Pm,q} < 50^o$** to minimize FSI.
- Two Kinematics:
  - **$350 < p_{miss} < 600$ MeV/c ("SRC")**
  - **$p_{miss} < 250$ MeV/c ("Mean-Field")**

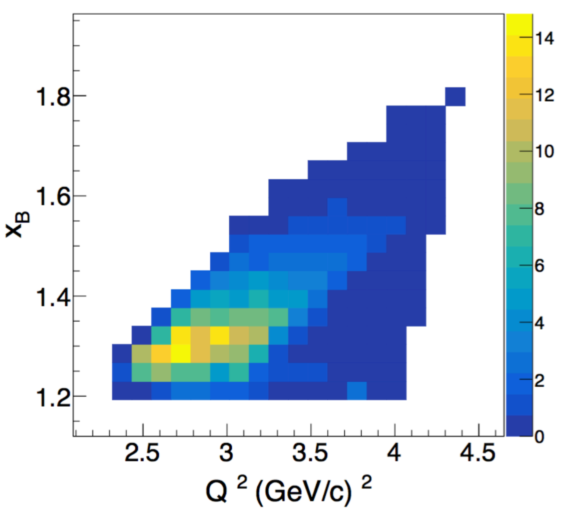
Kinematics and Acceptance

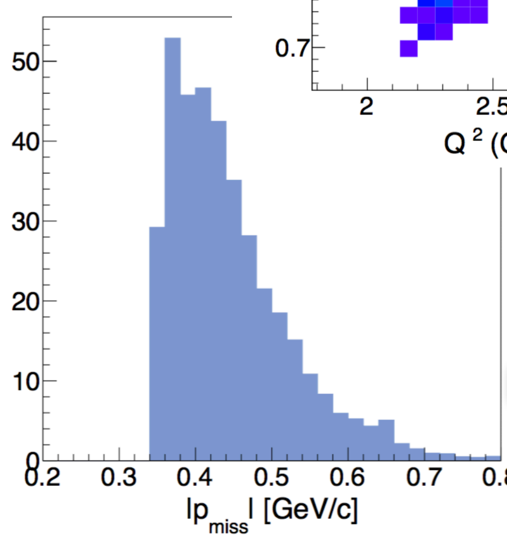
Q^2	E_{Beam}	E'_e	θ_e	$\lvert \mathbf{p}_p \rvert$	θ_p	p_{miss}
GeV^2	GeV	GeV		GeV/c		GeV/c
3.5	11	9.85	10.0°	1.80	43.0°	0.45
3.5	11	9.85	10.0°	1.90	42.5°	0.15

Mean-Field Kinematics









SRC Kinematics

The Final Observable

(e,e'p) Cross-section Ratios for:

$$\frac{A_1(e,e'p)|_{SRC}}{A_1(e,e'p)|_{Mean-Field}} \Big/ \frac{A_2(e,e'p)|_{SRC}}{A_2(e,e'p)|_{Mean-Field}}$$

- Proportional to the relative number of correlated protons with minimal (experimental and theoretical) uncertainties.
- Tells us how many np-SRC pairs the extra $f_{7/2}$ neutrons create!
- Reduced transparency corrections: Hen et al., Phys. Lett. B 722, 63 (2013)
  - $A^{1/3}$ dependence, T(^{48}Ca/^{40}Ca) ~ 6% correction.
  - Mean-field / SRC ratio further reduce the correction.
  - Well understood benchmark for symmetric nuclei (^{2}H, ^{12}C, ^{40}Ca, ^{54}Fe).

Measurement Plan and Beam-Time Request

4 days @ 11 GeV

kinematics	Target	Data-Taking [Hours]	Current [uA]	Expected Number of Events
high p_{miss}	^{2}H	12	40	4000
	^{12}C	10	40	4000
	^{40}Ca	14	40	4000
	^{48}Ca	14	40	4000
	^{54}Fe	14	40	4000
low p_{miss}	All Targets	16	40	10,000/Target
Commissioning and calibrations		12	20–60	
Target and Spectrometer Changes		4	N/A	
Total		96 (4 days)		

Summary

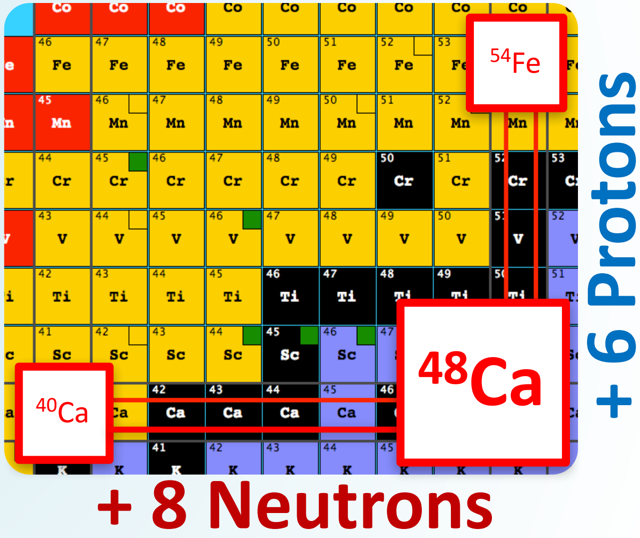
What? CaFe is a focused measurement of <u>short-range pairing</u> in neutron rich nuclei.

Why?

What is the dynamics of the neutron skin in ^{48}Ca?

Do correlations impact:

- Movement of nucleons in the skin?
- Extraction of static properties like the skin size?



Implications include neutron stars, the EMC effect and more…

How?

We will measure mean-field and correlated nucleons using the (e,e'p) reaction in ^{2}H, ^{12}C, ^{40}Ca, ^{48}Ca and ^{54}Fe

We request 4 days at Hall-C using SHMS and HMS in standard configuration.

Additional Observables (Benchmarks)

Using (e,e'p) ratios of symmetric nuclei to validate extraction procedure:

$$\frac{A_1(e,e'p)|_{Mean-Field}}{A_2(e,e'p)|_{Mean-Field}}$$

- 'Traditional' Transparency measurement.
- Well understood for symmetric nuclei ratios.
- Benchmark for Glauber calculations over a wide range of nuclei (from ^{2}H to ^{12}C to ^{40}Ca and ^{54}Fe).

$$\frac{\boldsymbol{A_1(e,e'p)|_{SRC}}}{\boldsymbol{A_2(e,e'p)|_{SRC}}}$$

- 'SRC' Transparency measurement.
- Benchmark against (e,e') for symmetric nuclei ratios.
- Allows to extract physics in ^{48}Ca / ^{40}Ca ratio where FSI corrections are small (~ 6%).

SRC and the Symmetry Energy

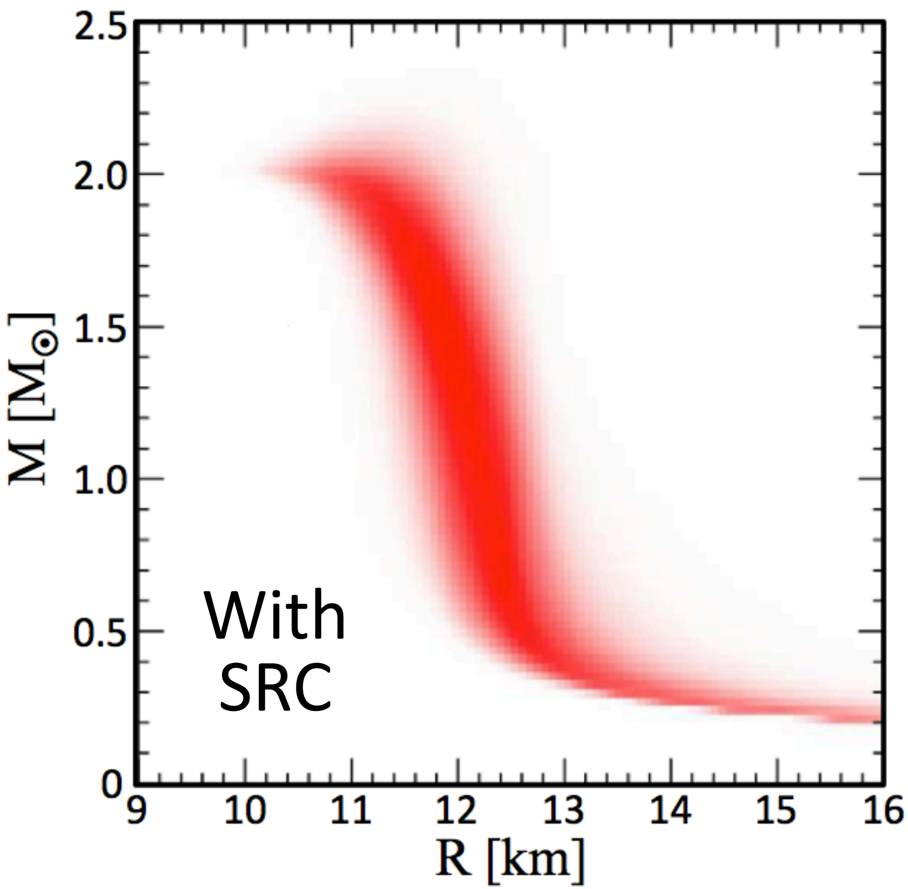
Tensor Correlations:

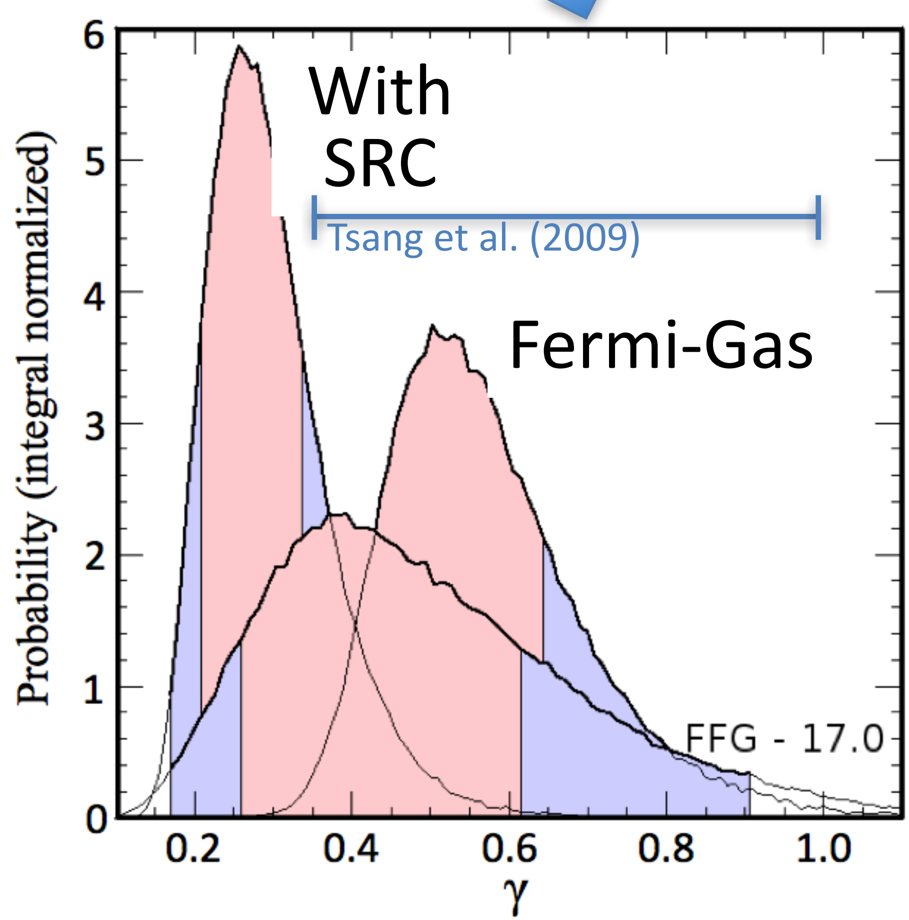
- Break the Fermi-Gas picture
- Reduce the kinetic symmetry energy (at ρ_0)
- Enhance the potential symmetry energy (at ρ_0)
- Softens the potential symmetry density dependence

But…. Still consistent with constrains from neutron stars observations!

SRC and the Symmetry Energy

$$E_{sym}(\rho) = E_{sym}^{kin}(\rho_0) \cdot \left(\frac{\rho}{\rho_0}\right)^{\alpha} + E_{sym}^{pot}(\rho_0) \cdot \left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$





Skin Width and Symmetry Energy