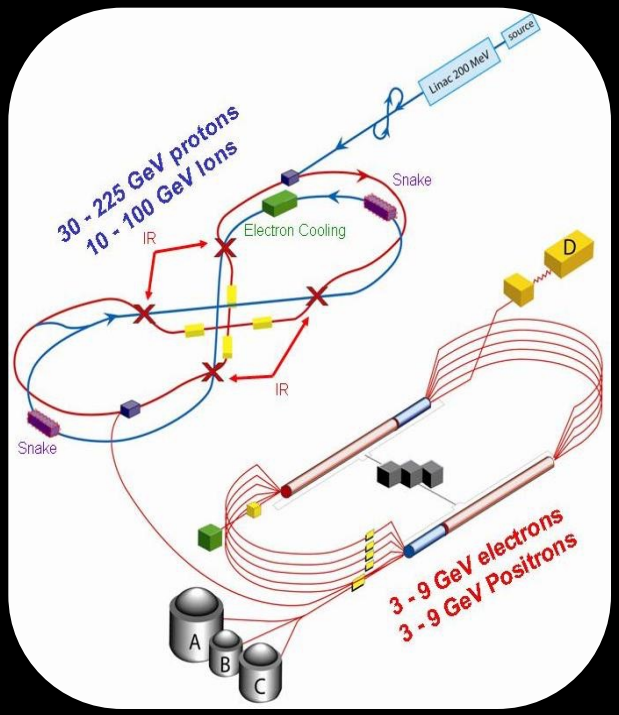
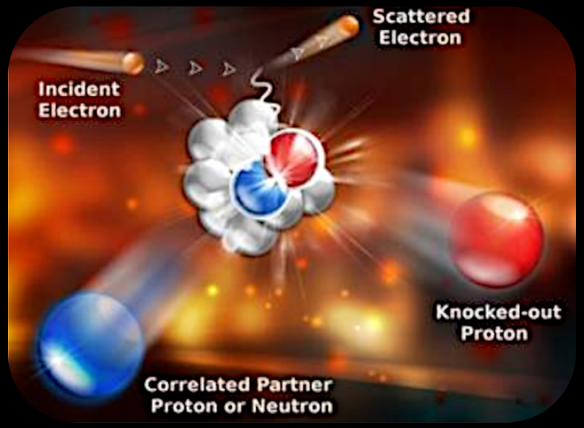
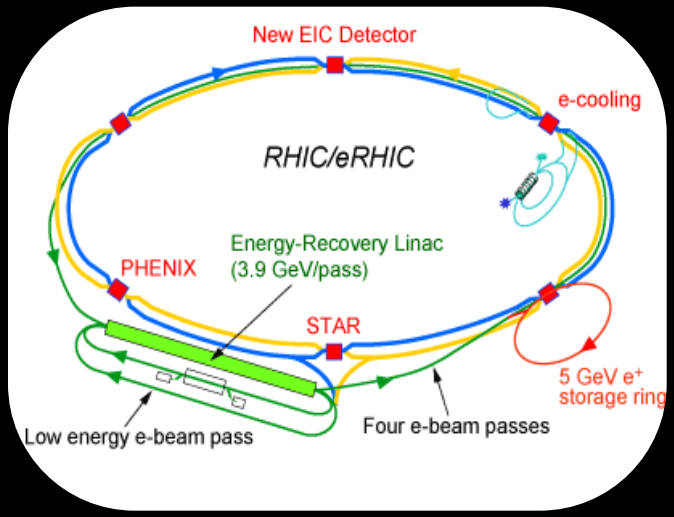
Bound Nucleon Structure Studies with an EIC

Or Hen
MIT



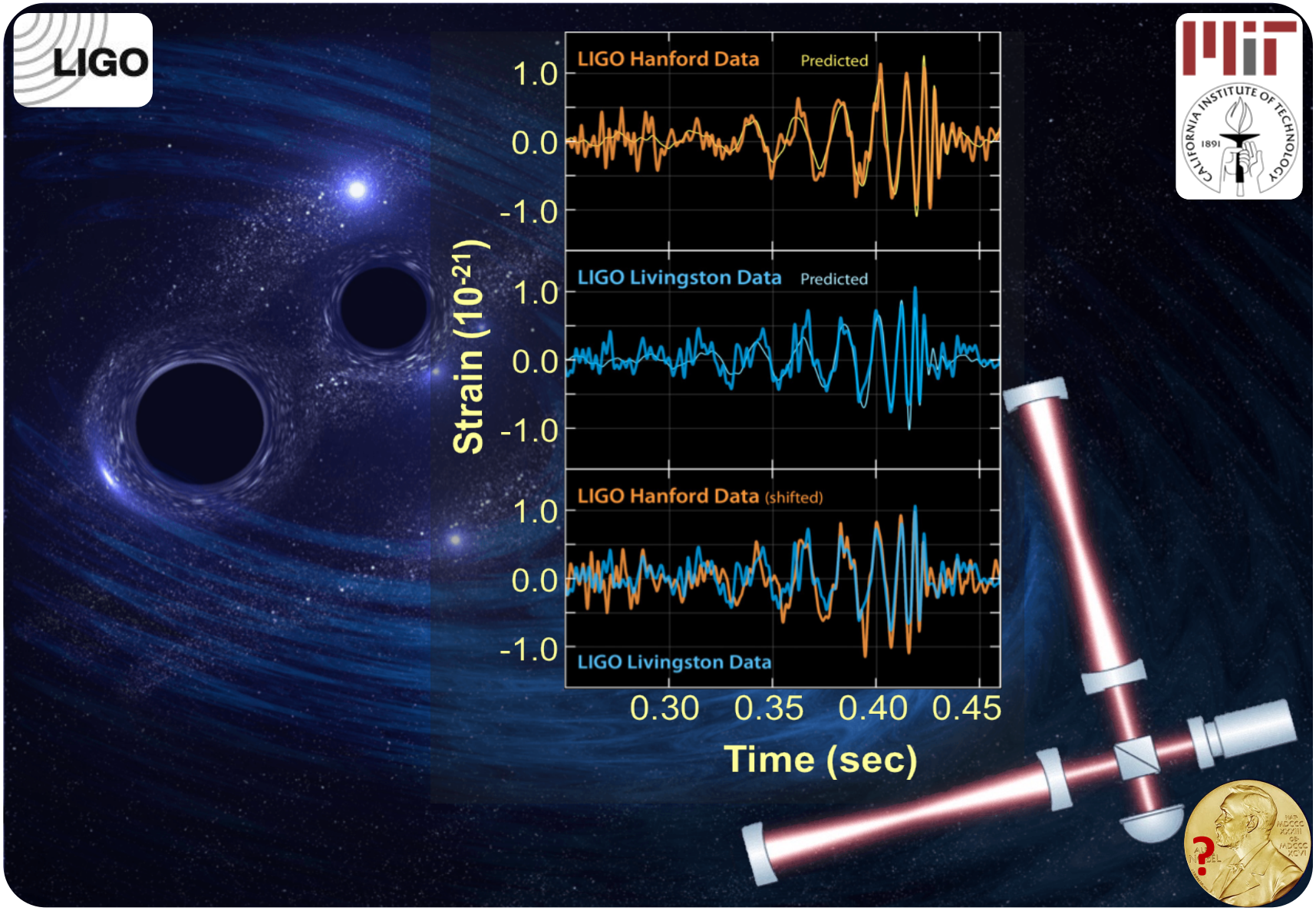




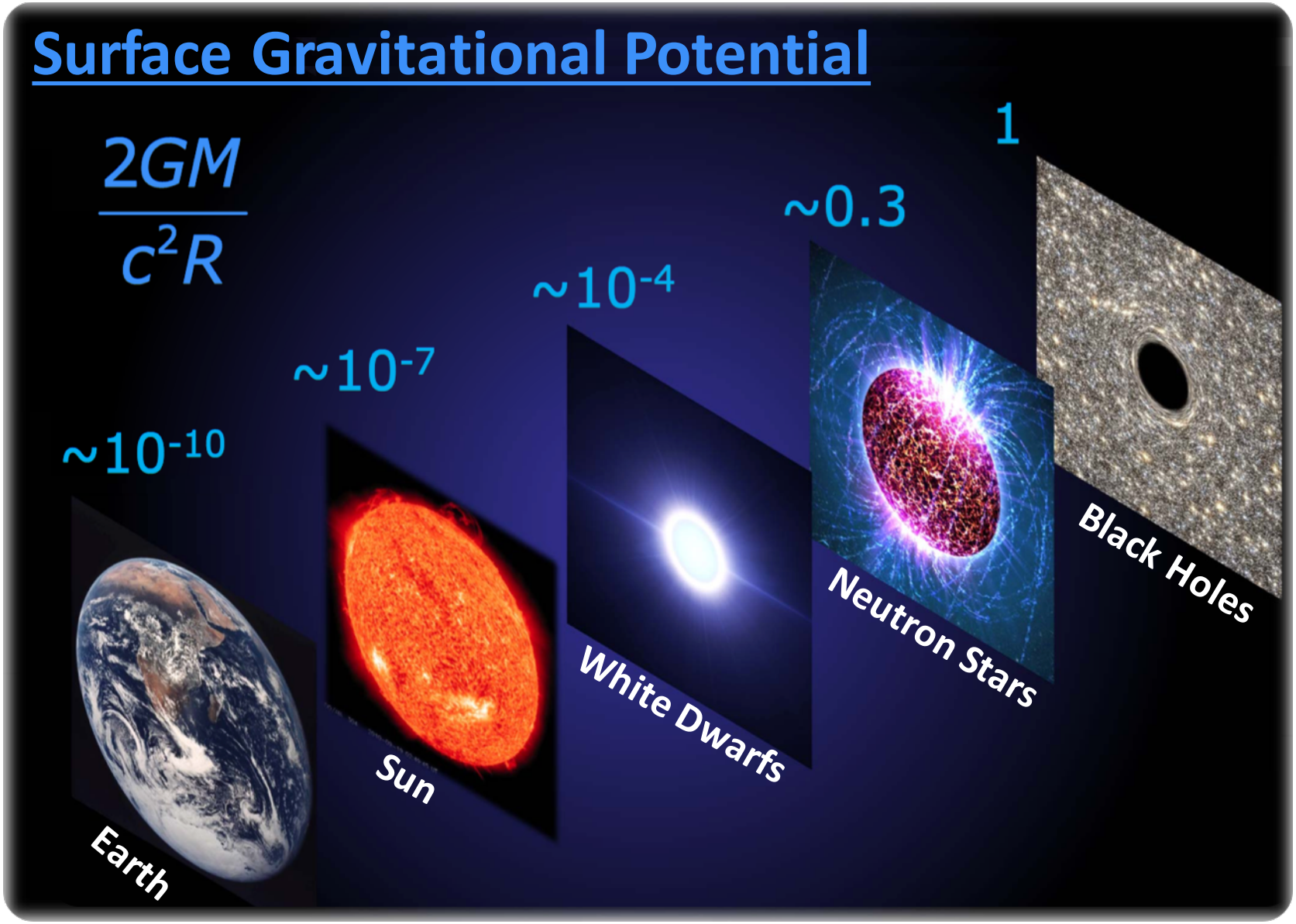
Electron Ion Collider

EIC Users Group Meeting, ANL, July 8th, 2016

2016: Year of Gravity



From Black Holes to Neutron Stars



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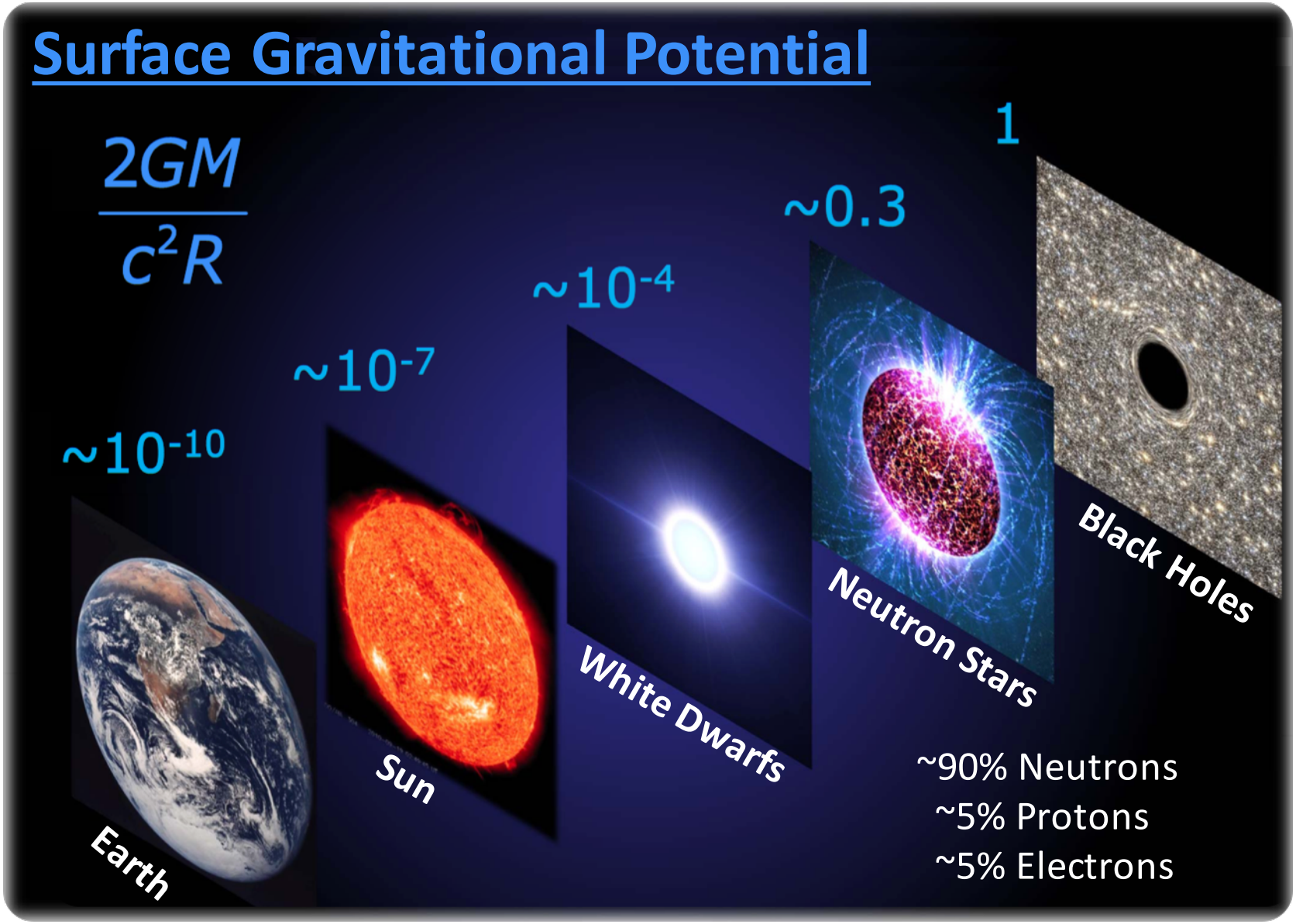

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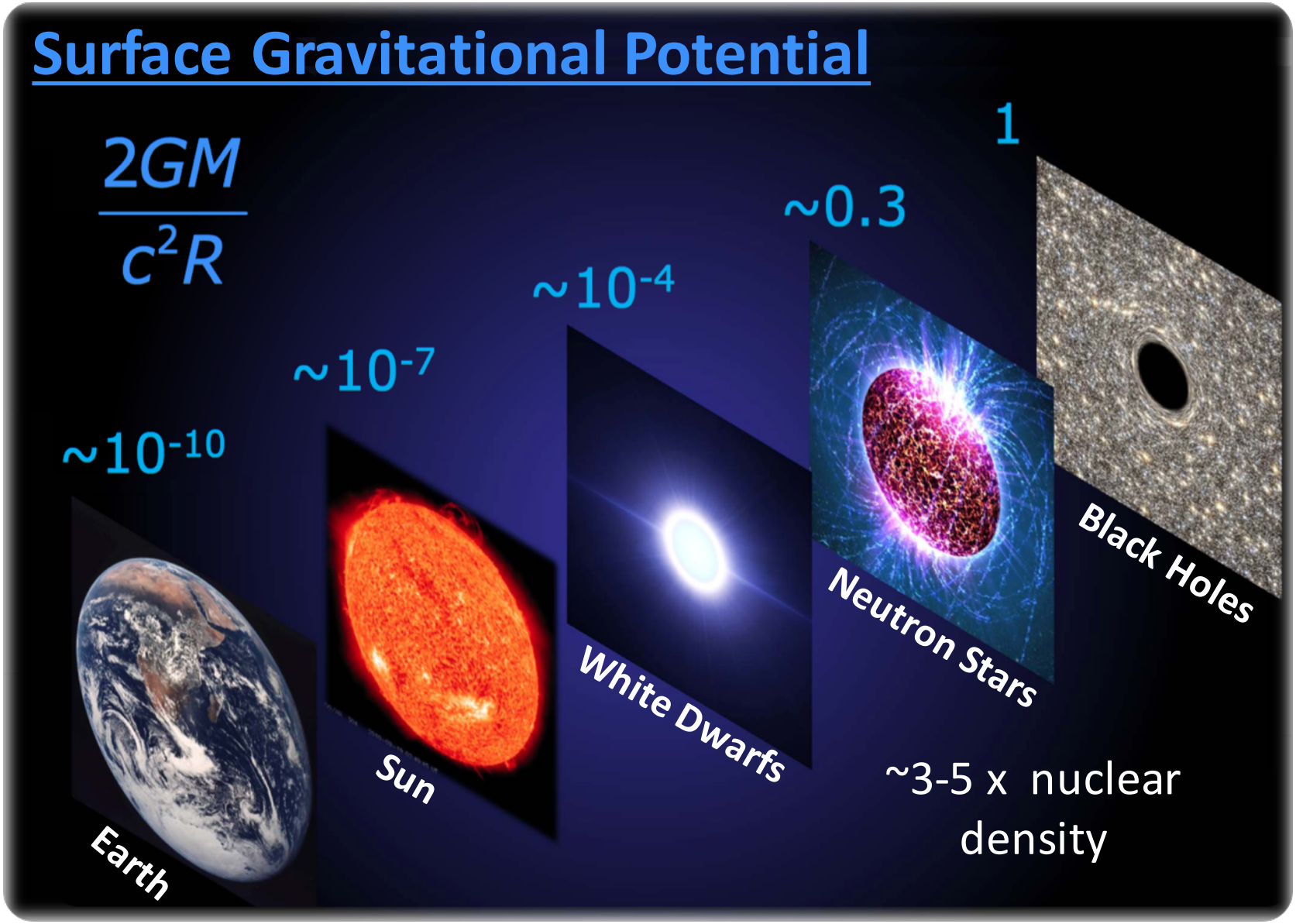

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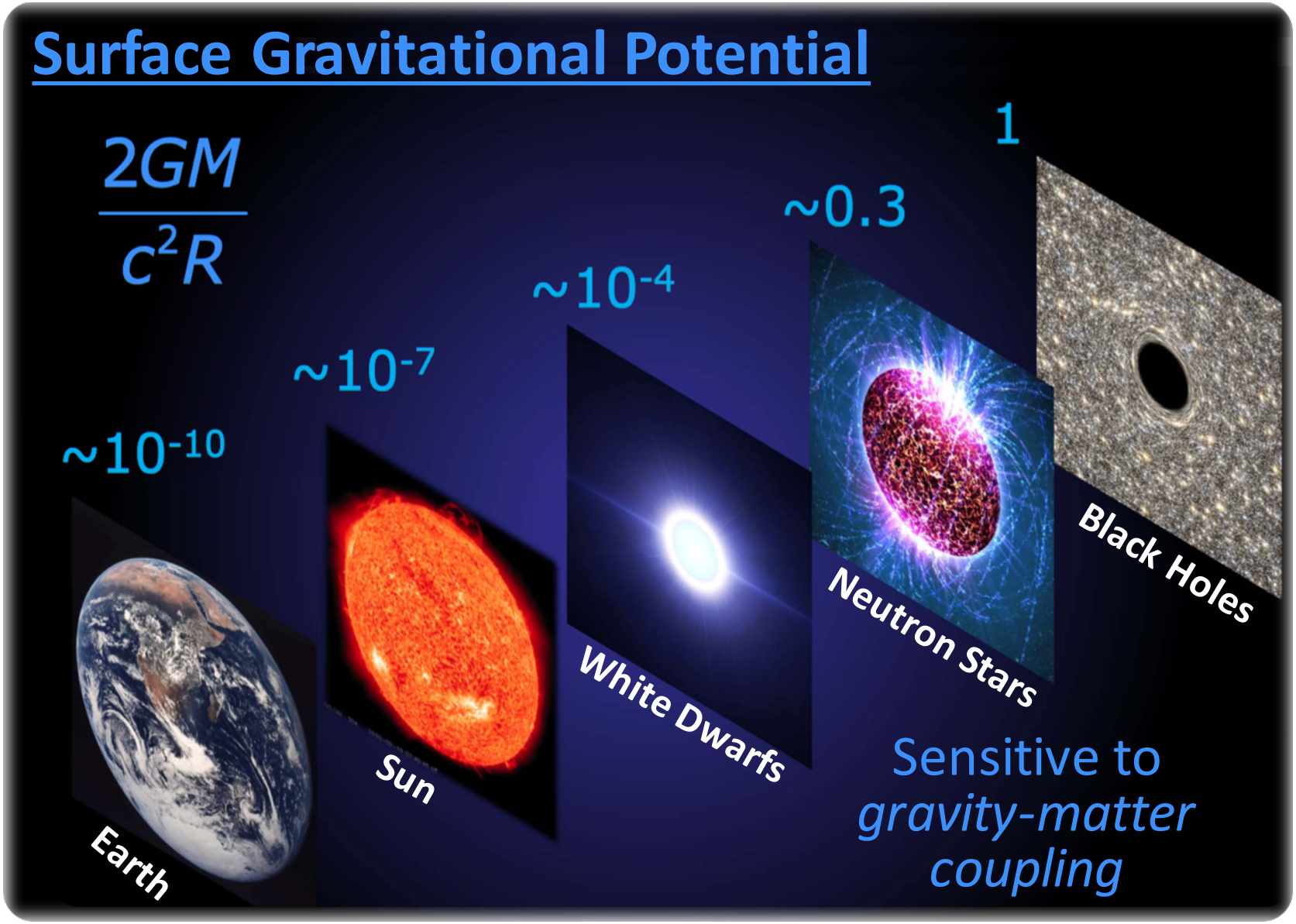

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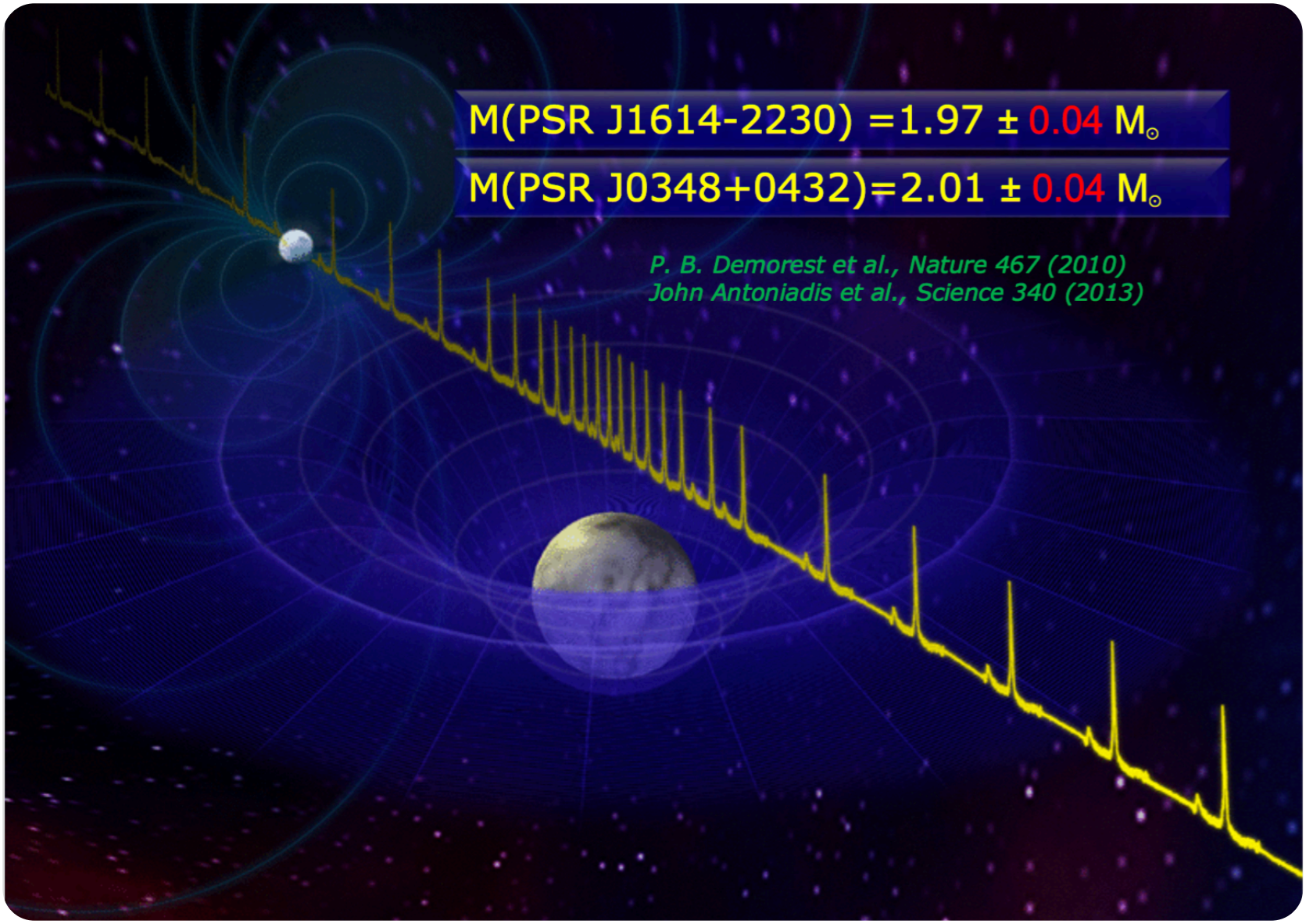

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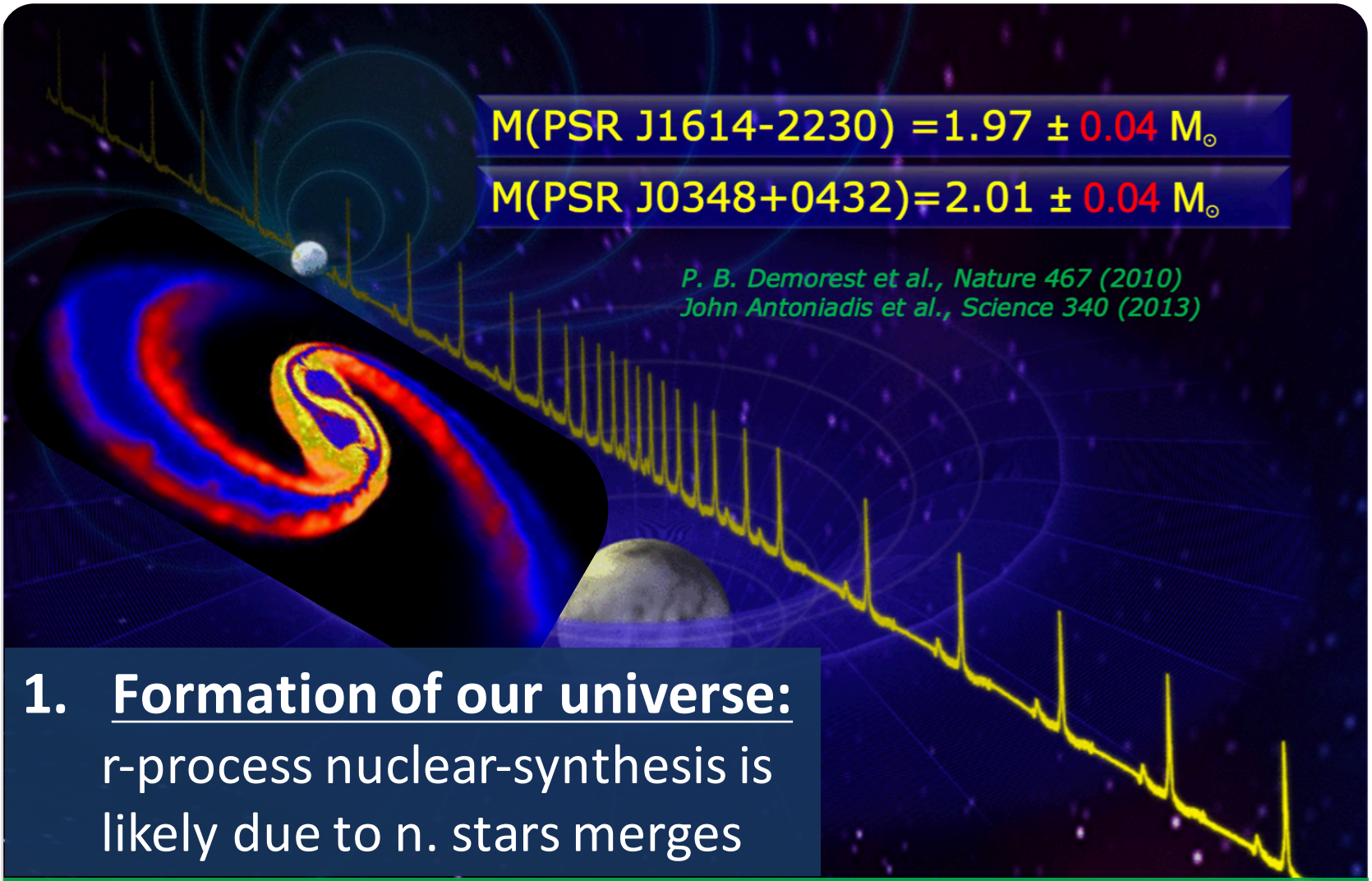

1. **Formation of our universe:**
   r-process nuclear-synthesis is likely due to n. stars merges

=> Requires input on COLD dense nuclear matter.

From Black Holes to Neutron Stars

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2. **Fundamental nature of gravity:**
   n. stars are a unique lab for testing models of gravity-matter couplings in the strong-field regime.

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From Black Holes to Neutron Stars

M(PSR J1614-2230) =1.97 ± 0.04 $M_\odot$

M(PSR J0348+0432)=2.01 ± 0.04 $M_\odot$

P. B. Demorest et al., Nature 467 (2010)
John Antoniadis et al., Science 340 (2013)

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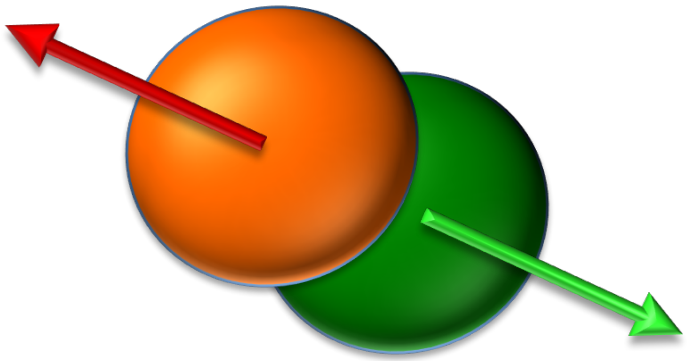
So… How do we probe the heighest densities in the universe using experiments done on earth?

“The Universe in a Lab”

(Our Approach) Look for Density Fluctuations!

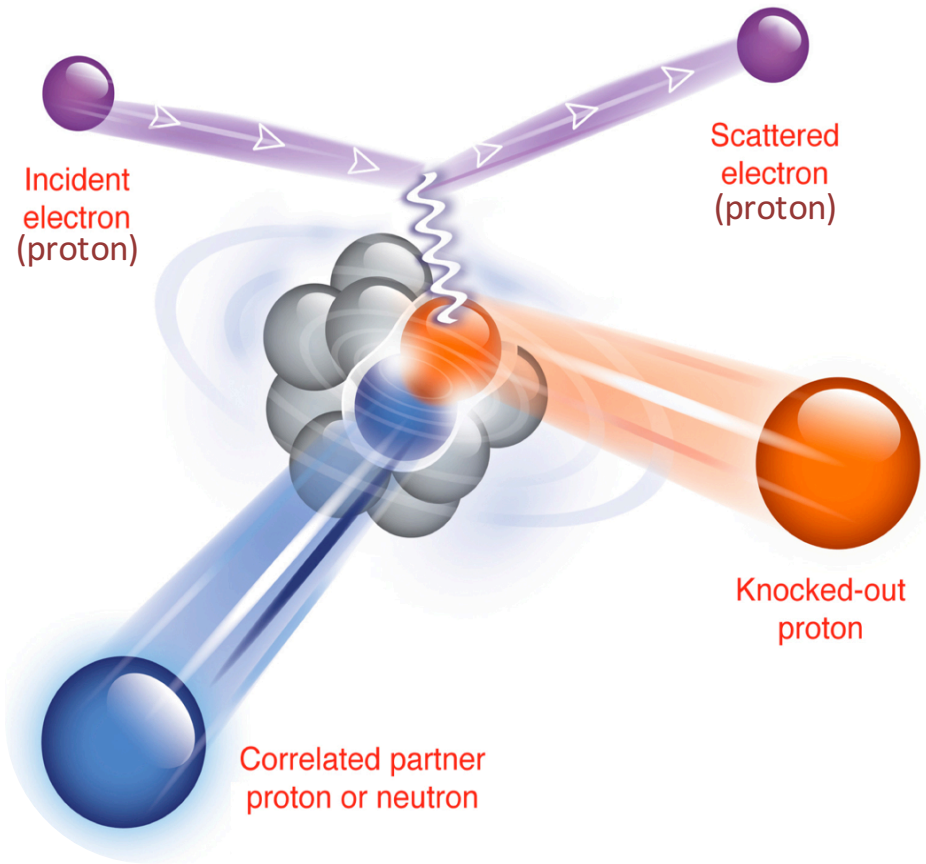
Looking for nucleon pairs that are close together in the nucleus (wave functions overlap)

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



Exclusive 2N-SRC Studies

Breakup the pair =>
Detect both nucleons =>
Reconstruct 'initial' state



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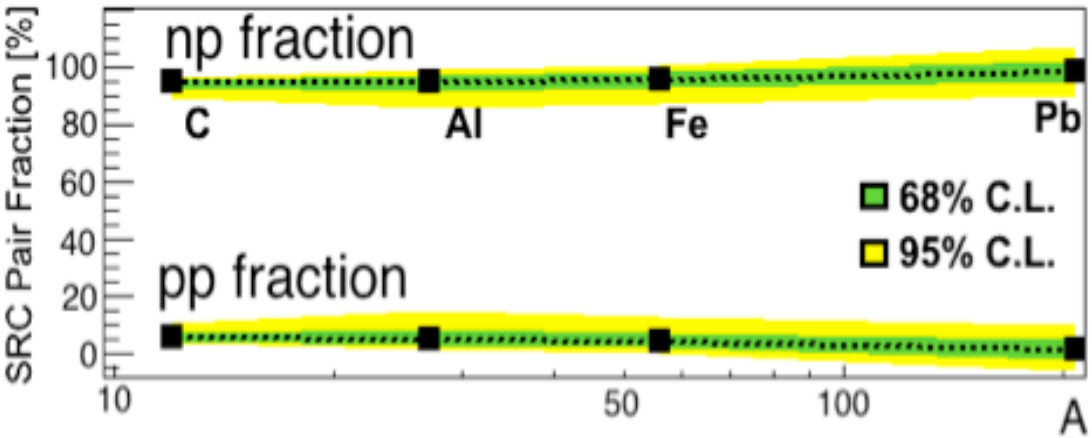
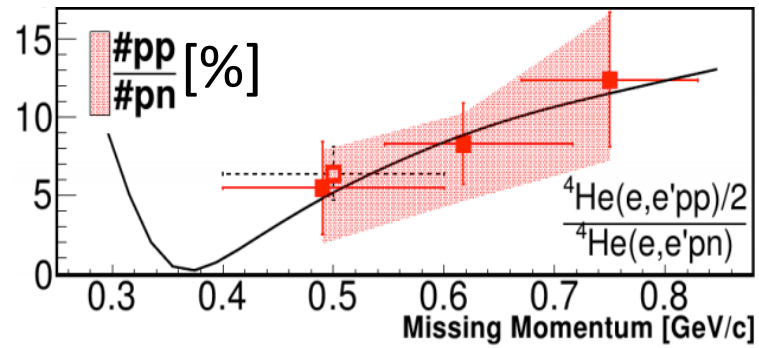
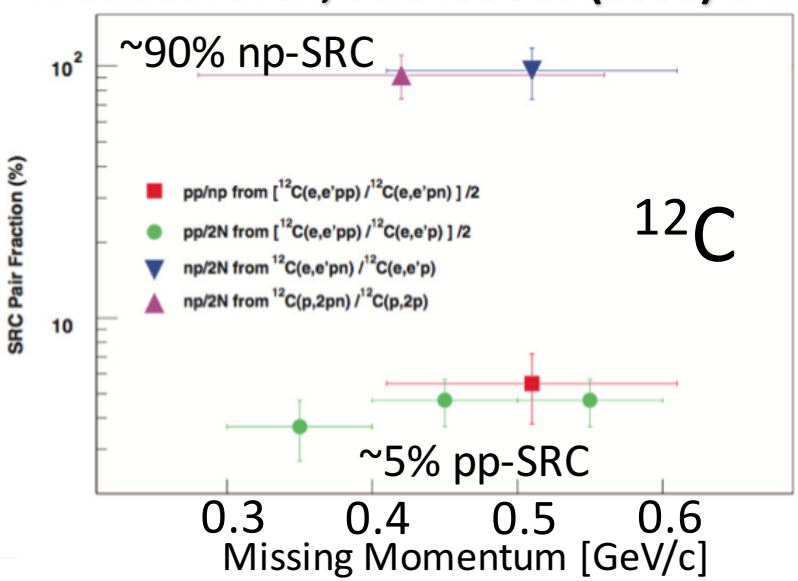
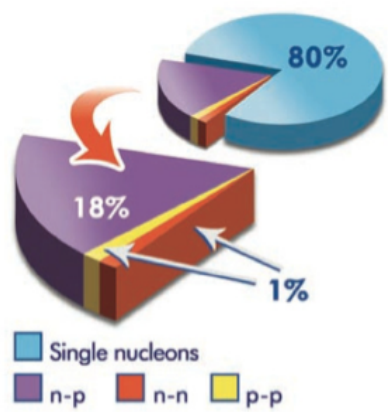


O. Hen et al., Science 364 (2014) 614

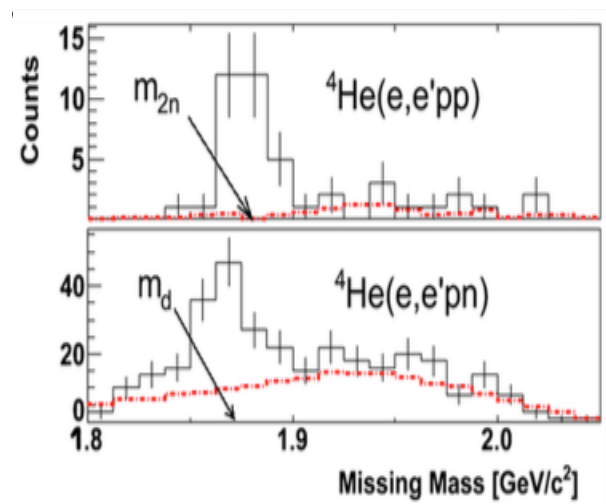


R. Subedi et al., Science 320 (2008) 1476





Korover, Navaphon and Hen et al., PRL 113 (2014) 022501



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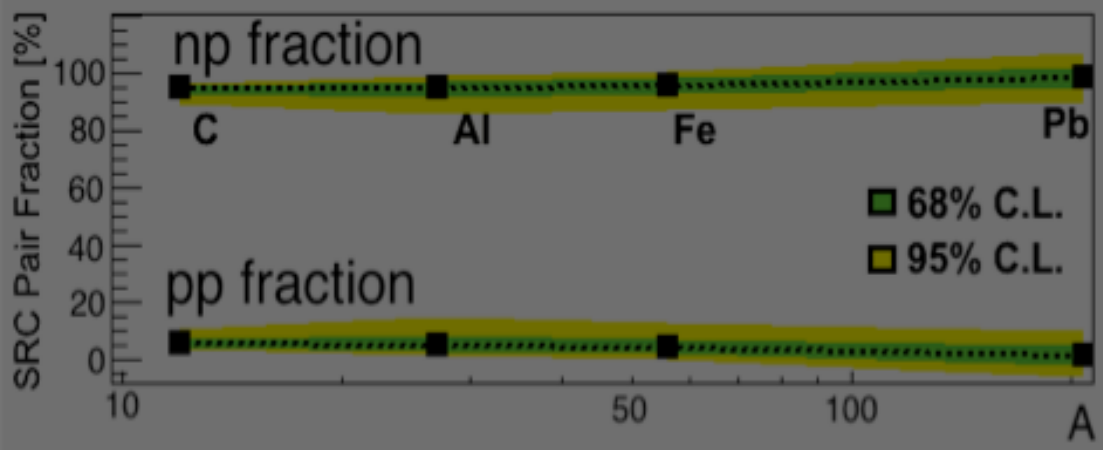

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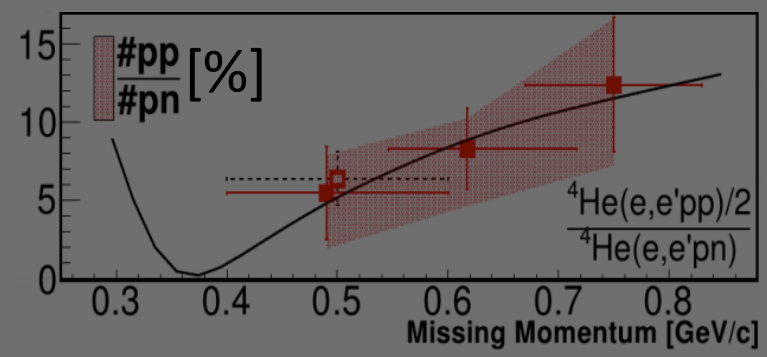

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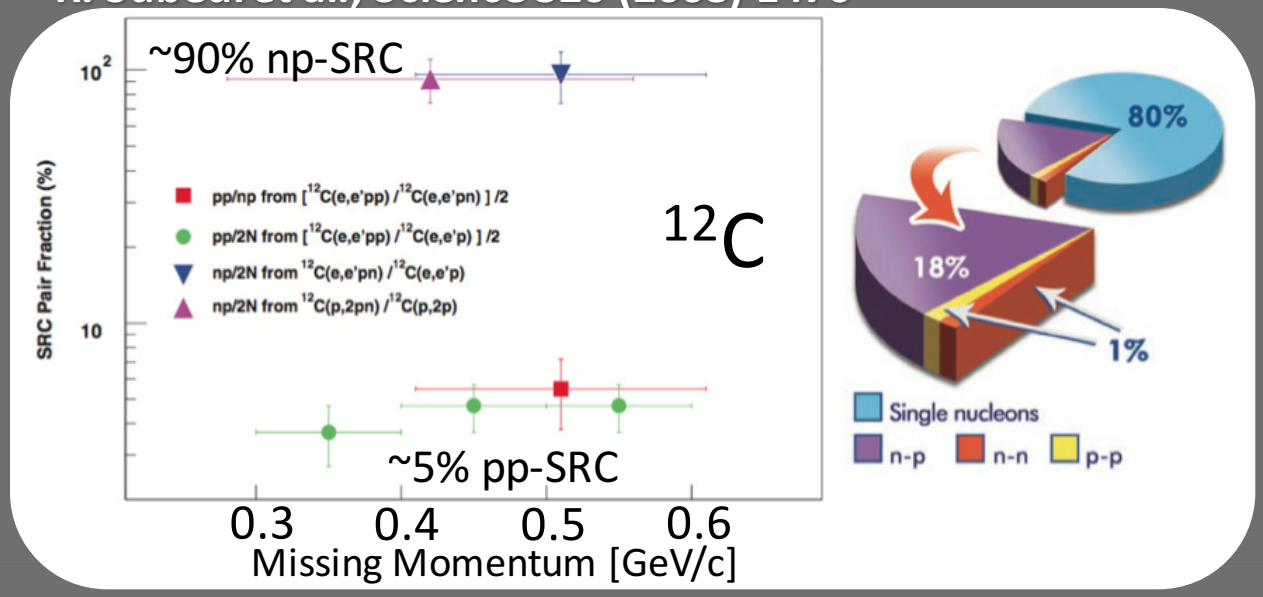

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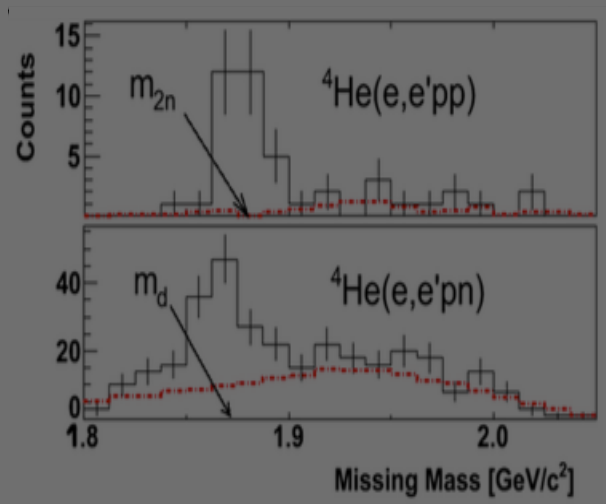

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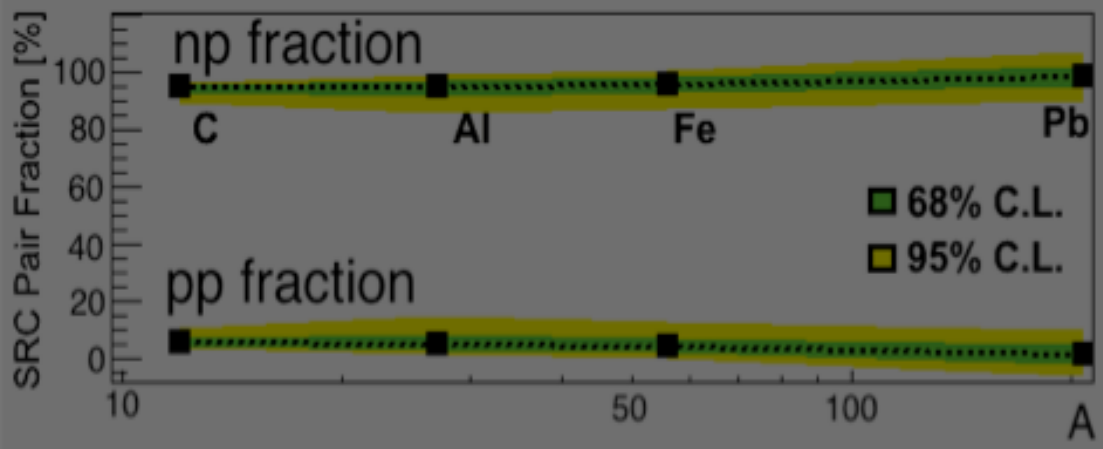
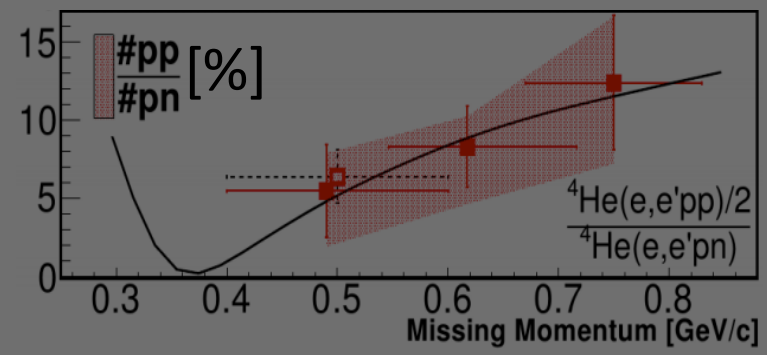


O. Hen et al., Science 364 (2014) 614



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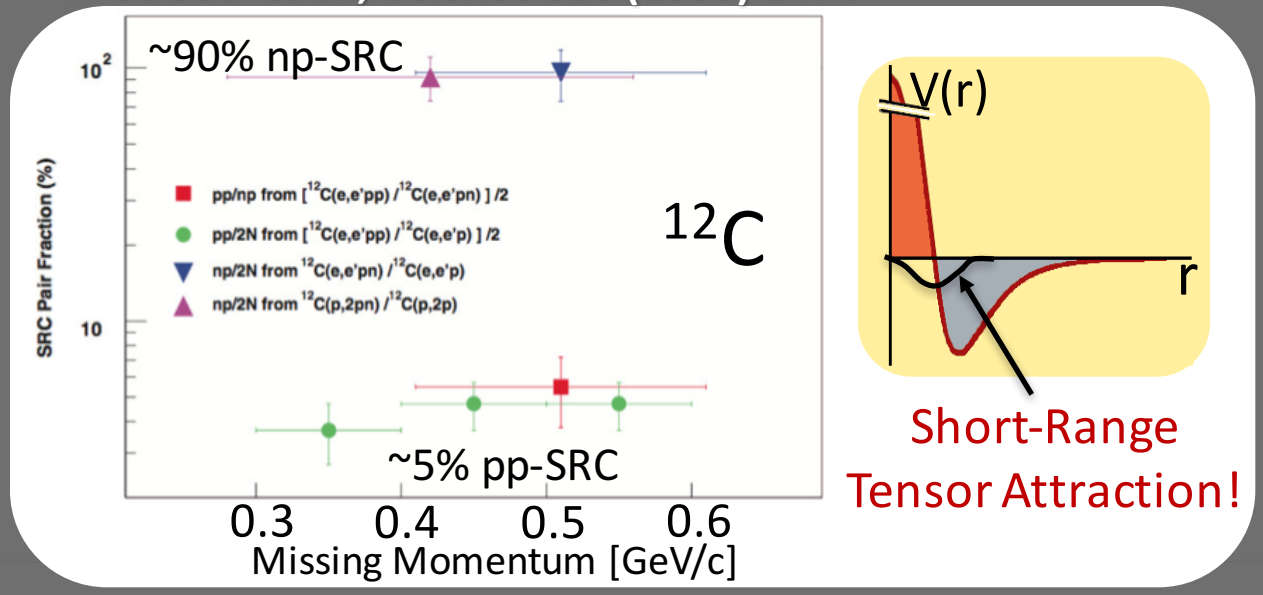
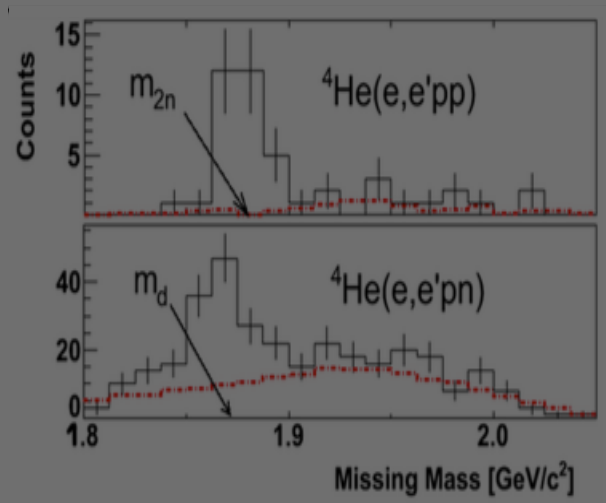


Short-Range Tensor Attraction!

Korover, Navaphon and Hen et al., PRL 113 (2014) 022501



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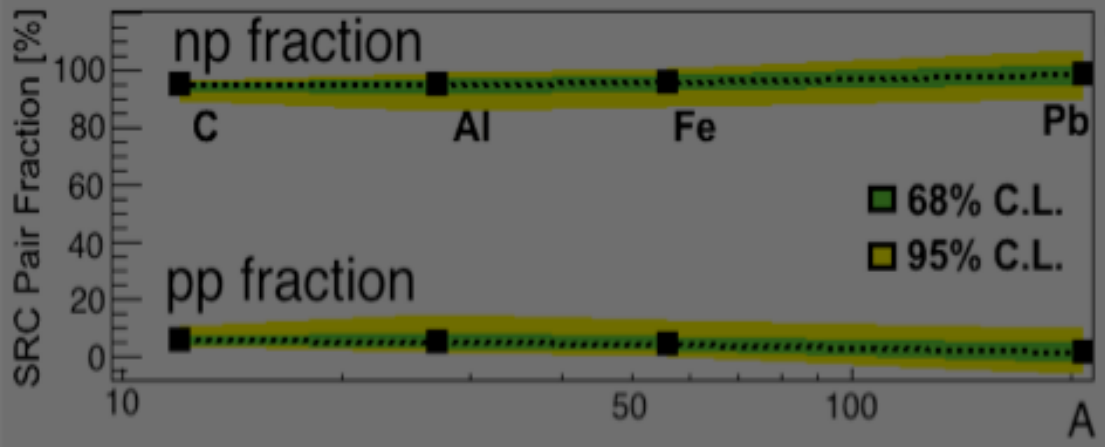

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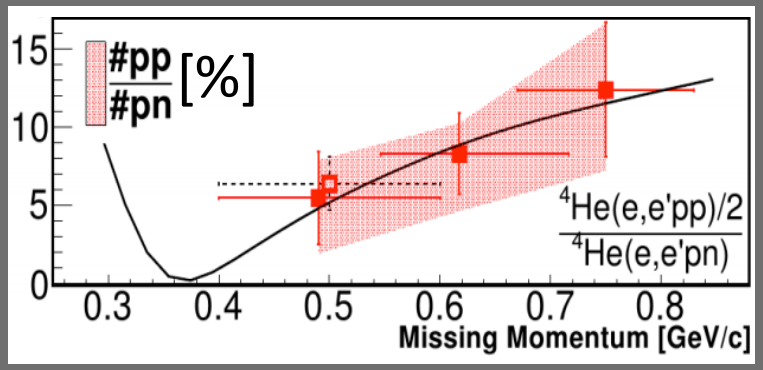

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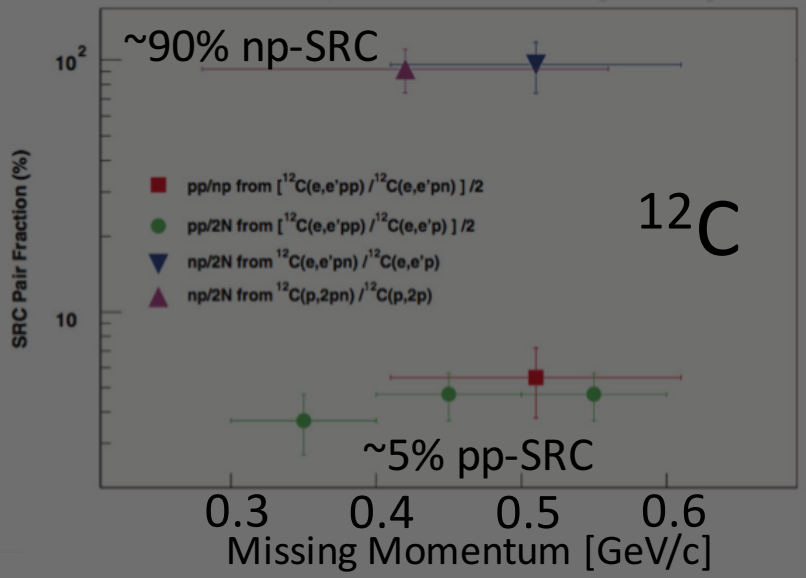

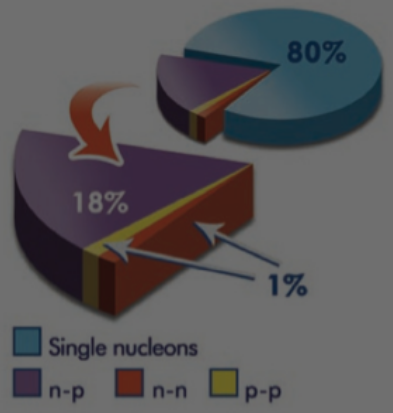

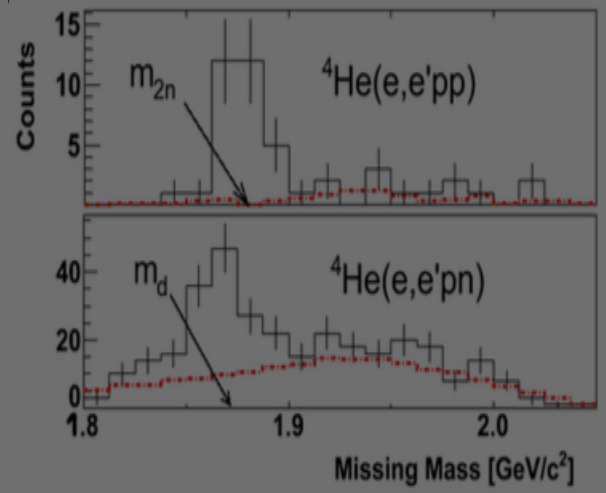

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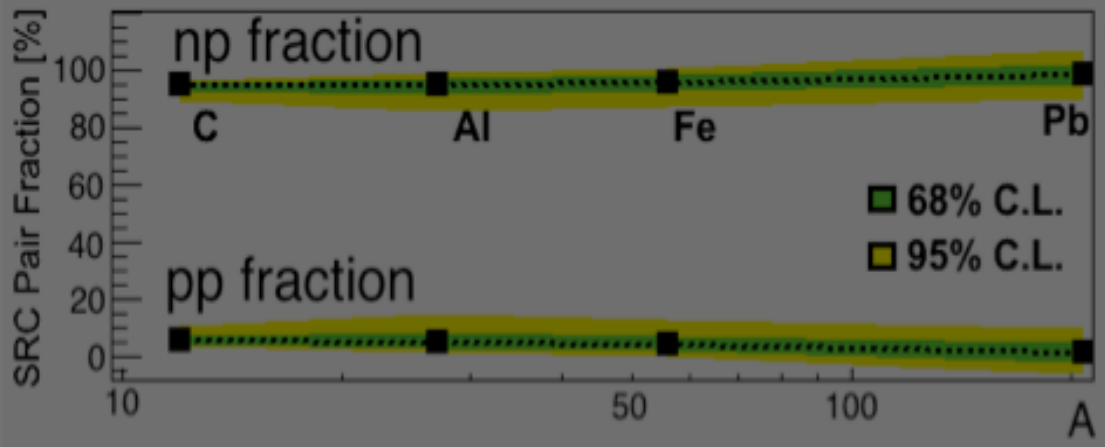

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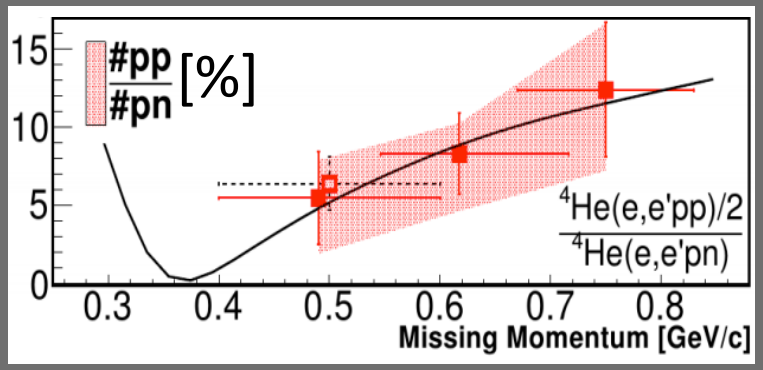

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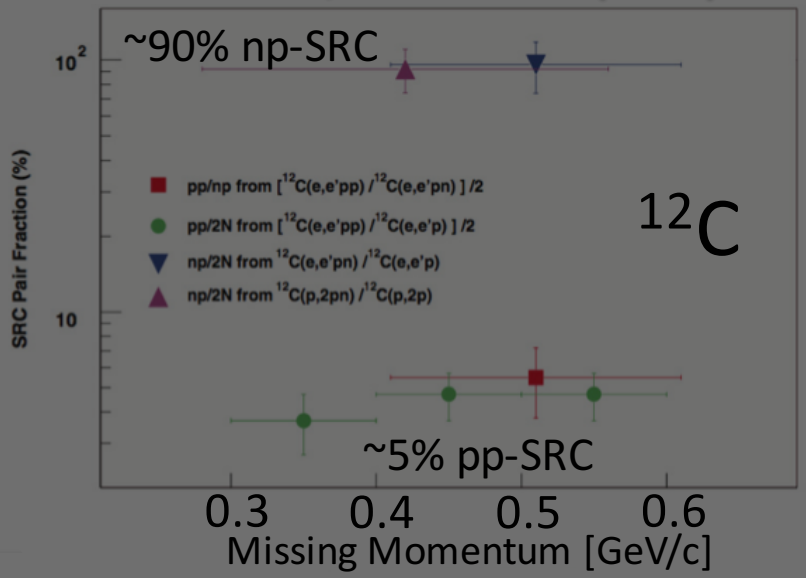

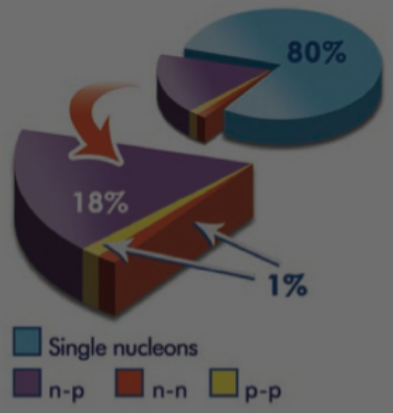

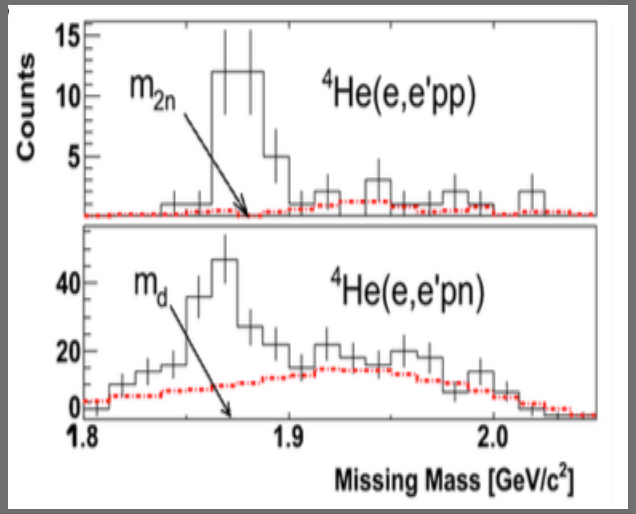

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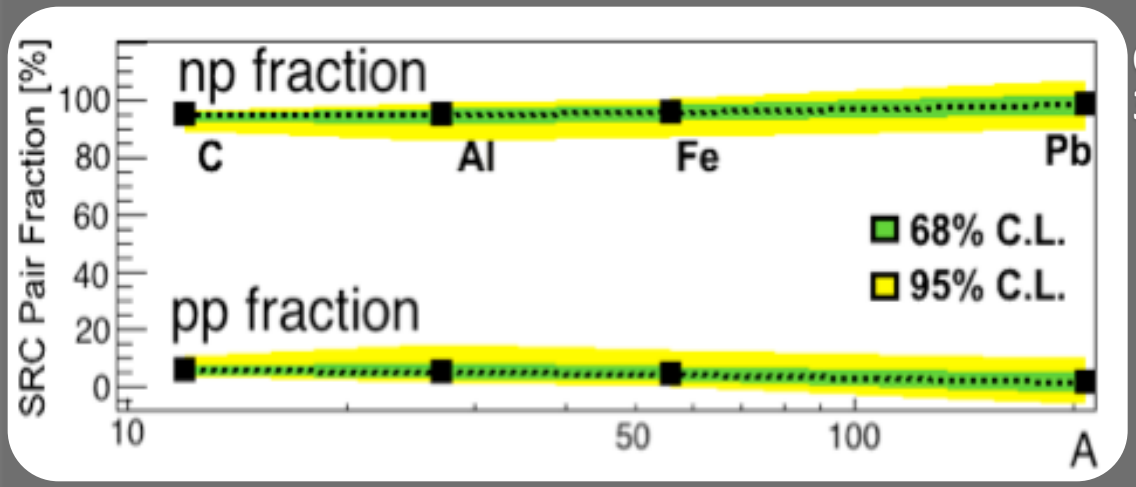

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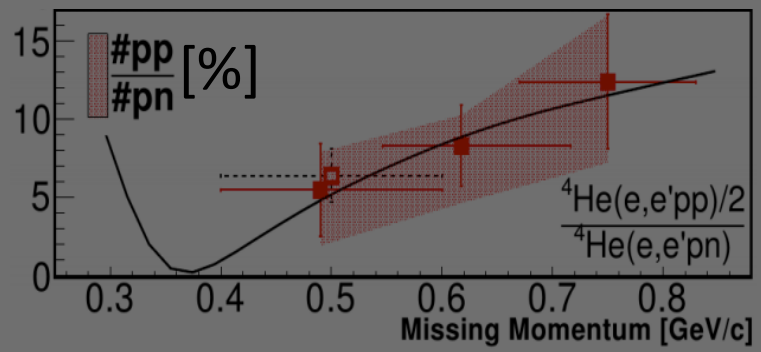

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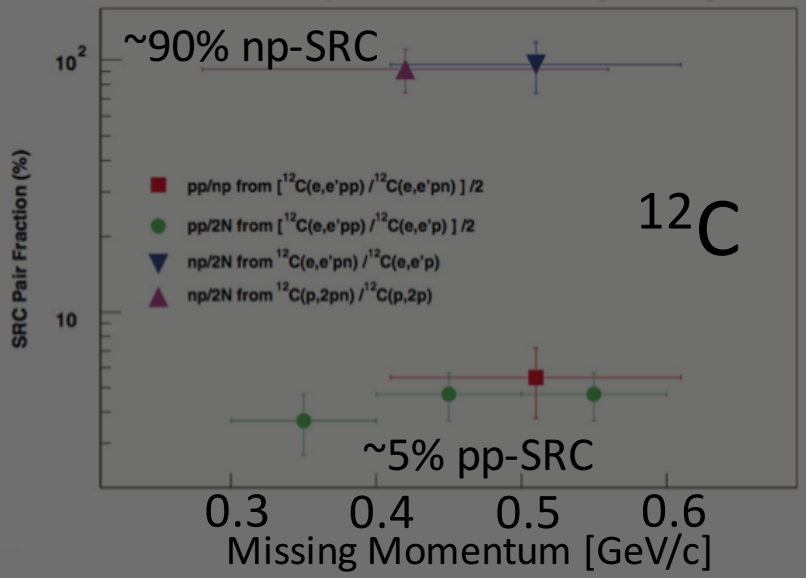
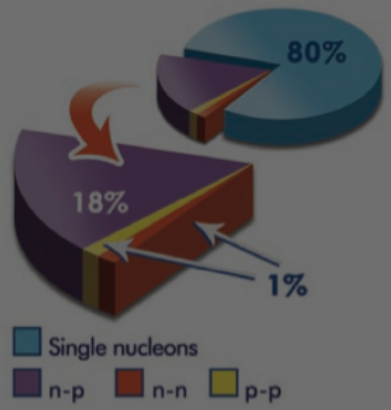
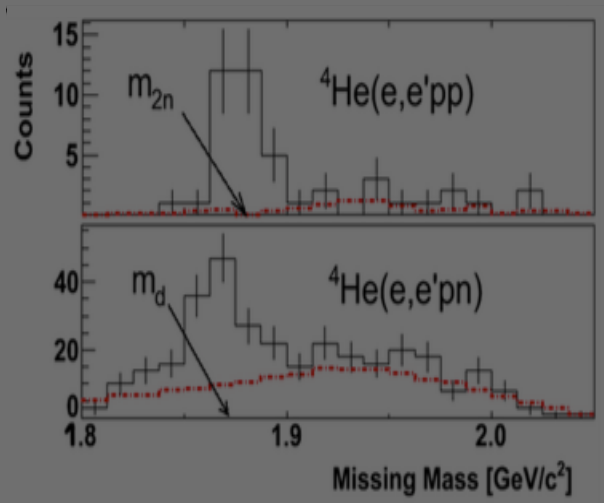




Korover, Navaphon and Hen et al., PRL 113 (2014) 022501



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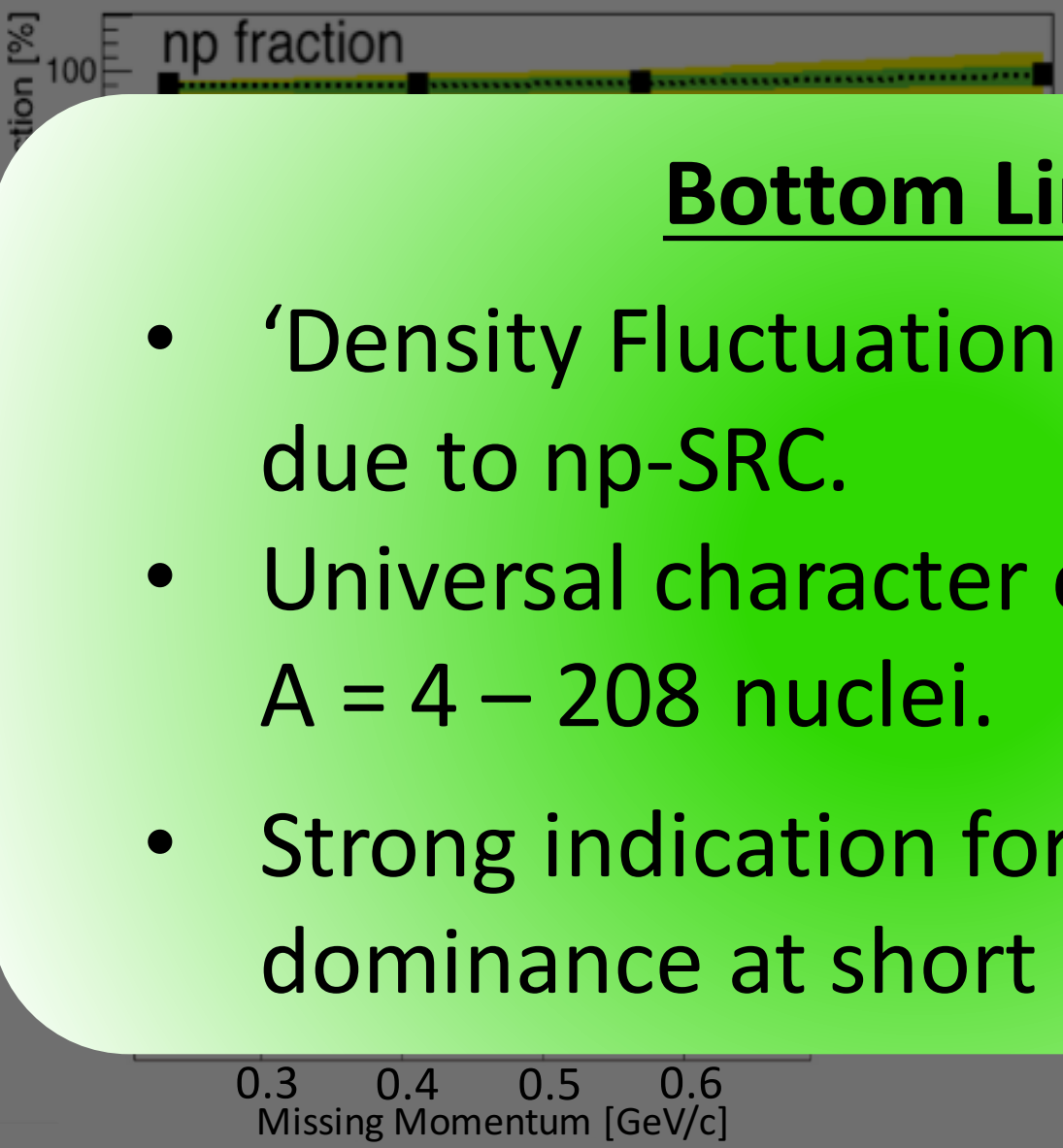


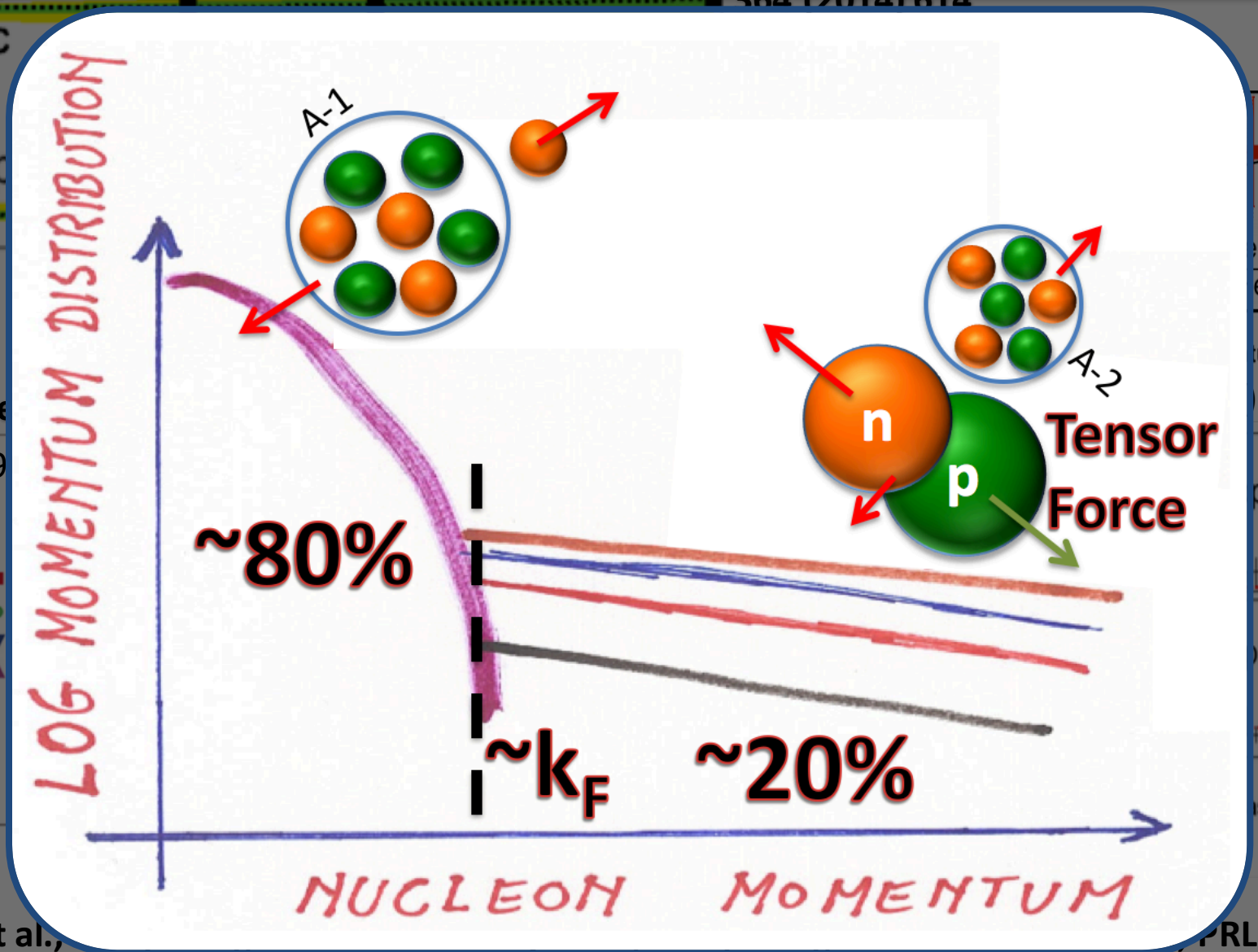
O. Hen et al., Science 364 (2014) 614

Bottom Line:

- 'Density Fluctuations' predominantly due to np-SRC.
- Universal character observed in A = 4 – 208 nuclei.
- Strong indication for Tensor force dominance at short distance

A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

Universal structure of nuclear momentum distributions

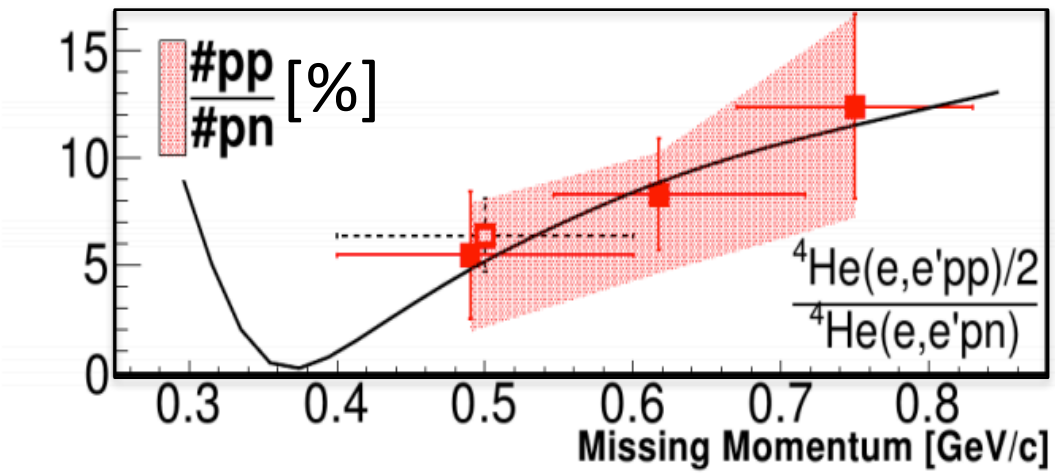


A. Tang et al., PRL (2007)

Fundamental Importance:

- NN Interaction at short distances.
- Pairing mechanisms in nuclei.
- Interplay between 'local 2N dynamics' and the many body problem.
- Nuclear spectral functions and energy sharing.
- Neutron stars, Gravity, Neutrino Physics, more....

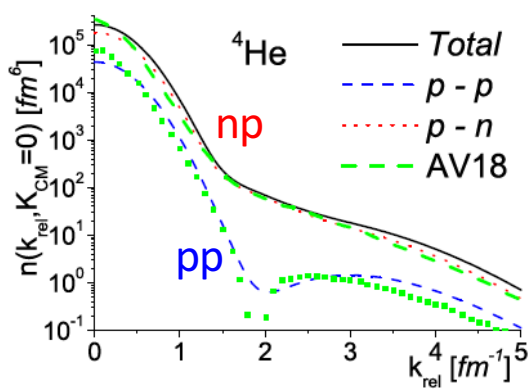
pp/np ratio increase with P_{miss}

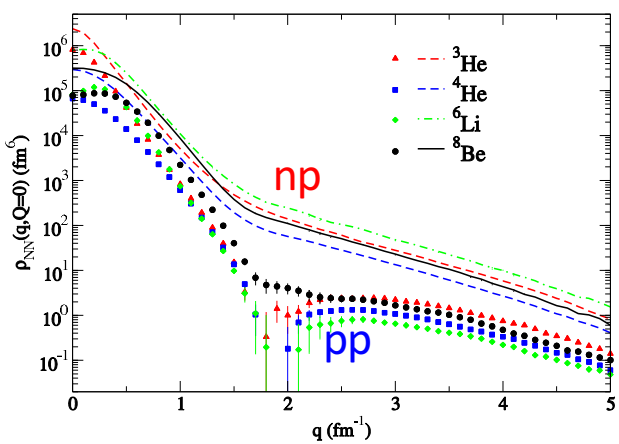


I. Korover, N. Muangma, and O. Hen et al., Phys. Rev. Lett 113, 022501 (2014).

Pair density calculations:

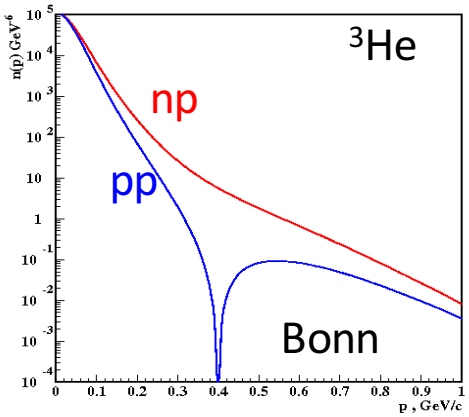
Ciofi and Alvioli PRL 100, 162503 (2008)





Schiavilla et al., PRL 98,132501 (2007)

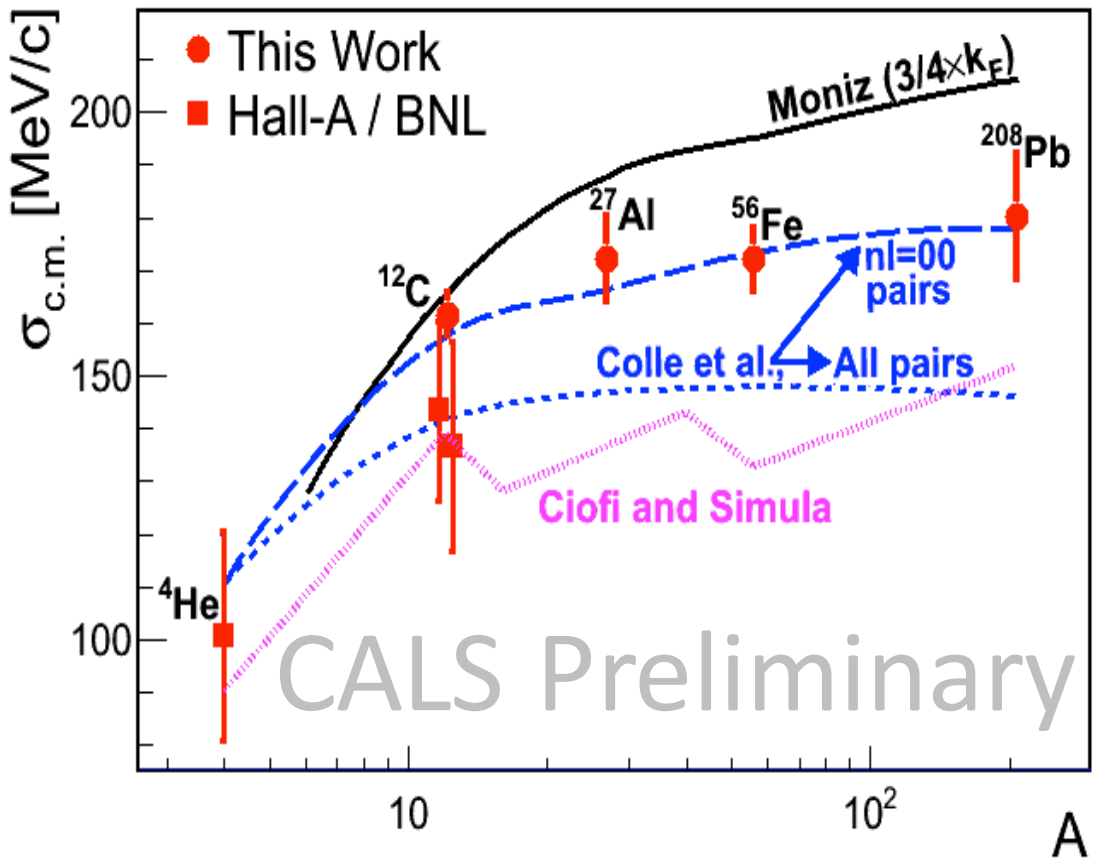
Sargsian et al., PRC 71 044615 (2005)



Pair c.m. motion

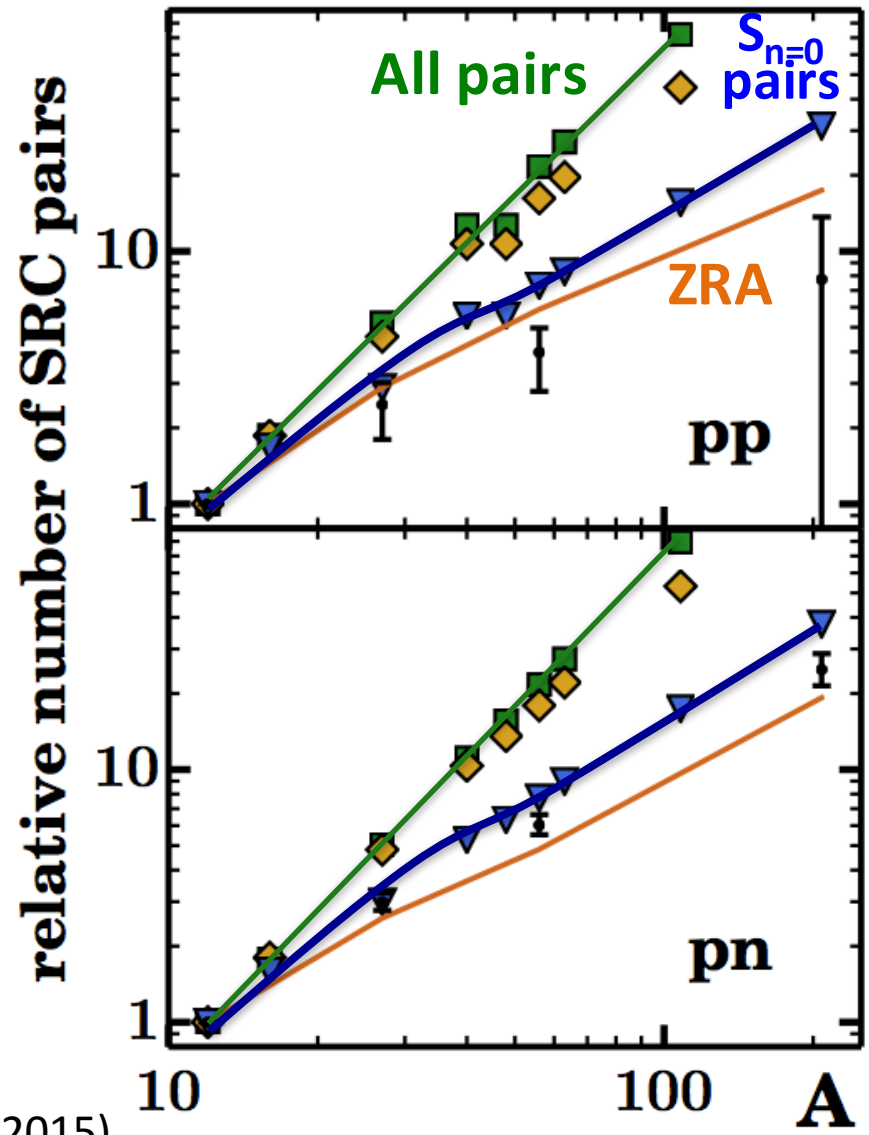
"… high relative momentum and *low c.m. momentum* compared to the Fermi momentum (k_F)"

- Reconstructed total (c.m) pair momentum insensitive to FSI in the pair.
- Observed to be Gaussian in each direction.
- Small width, consistent with calculations.



Selectivity of SRC Pairs

- Extract the number of pp (np) SRC pairs in nuclei relative to ^{12}C.
- Pair number increases very slowly with A
- consistent with $^1S_0$ ($^3S_0$) pairs creating SRCs.



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

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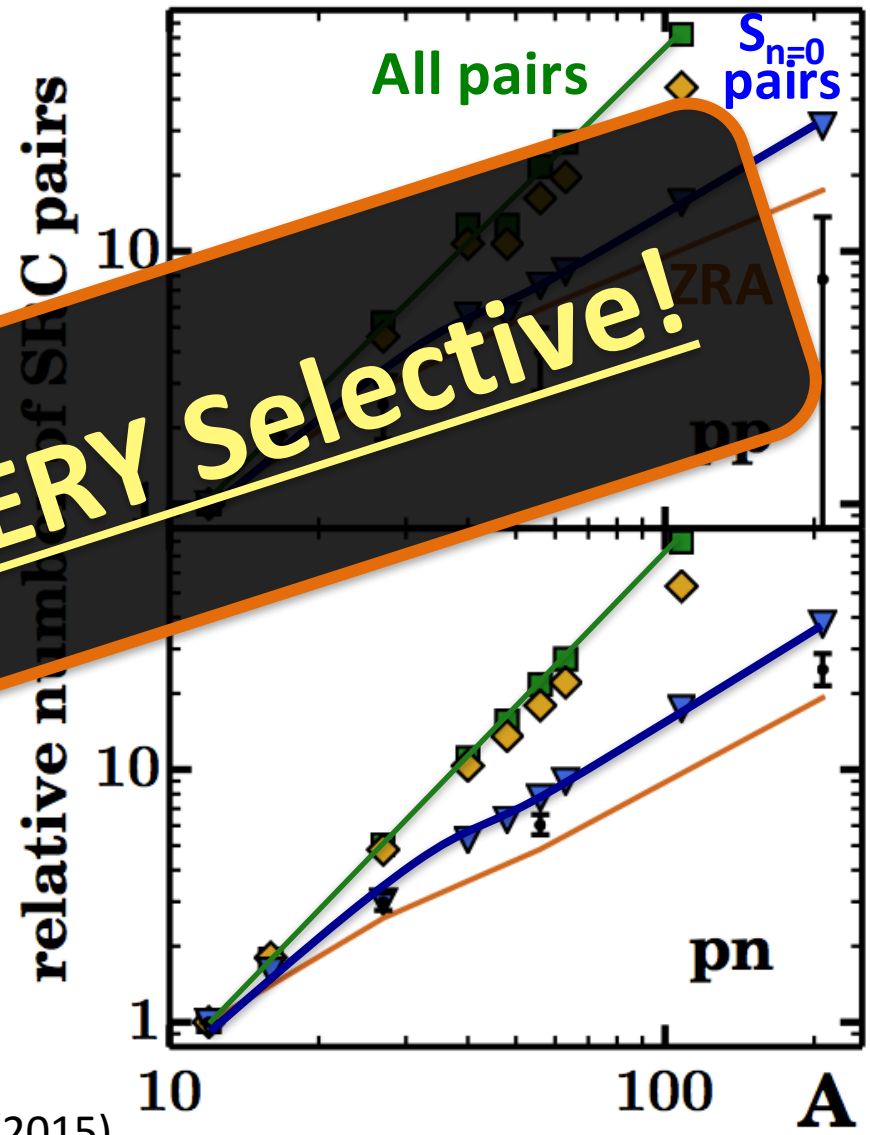
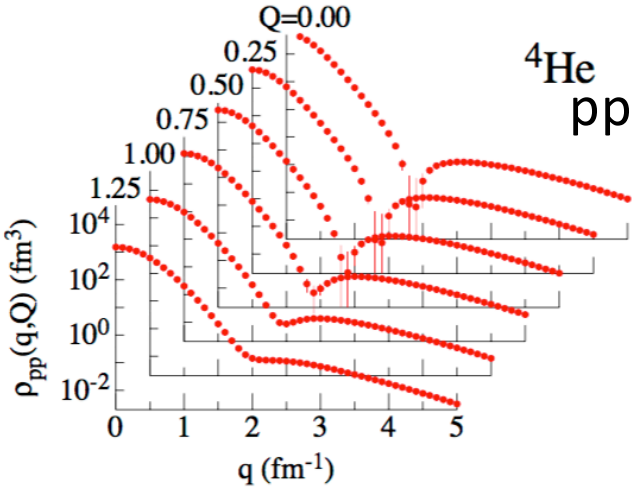
- consistent with $^1S_0$ ($^3S_0$) pairs creating SRCs.

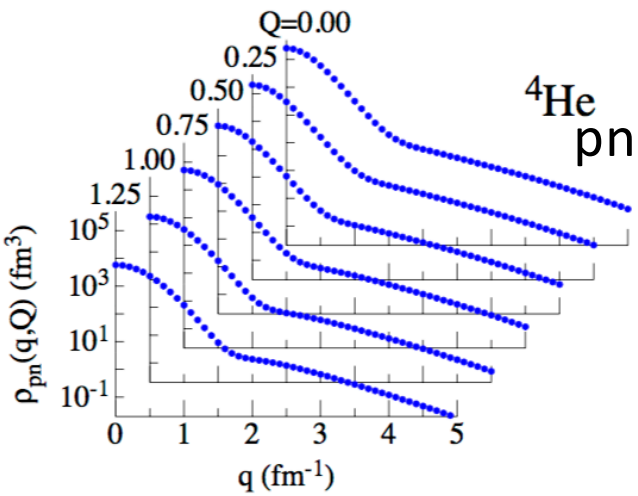
SRC Pairs are VERY Selective!

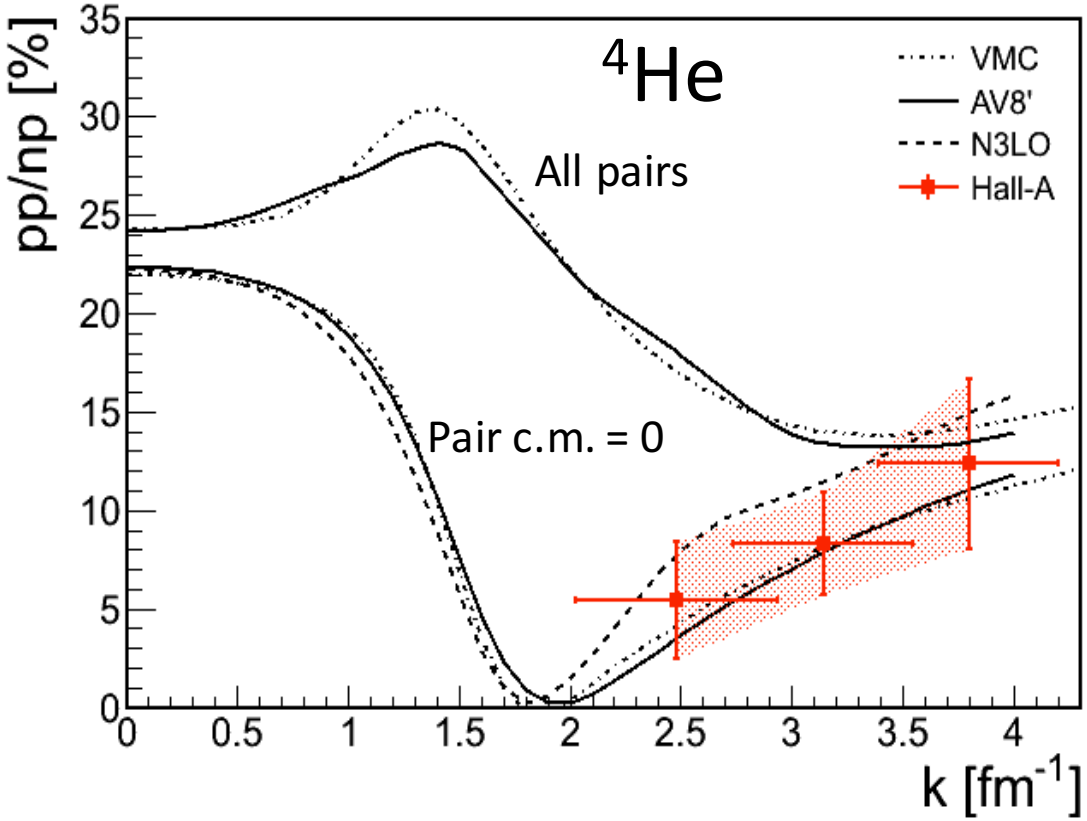


C. Colle and O. Hen et al., Phys. Rev. C **92**, 024604 (2015)

Selectivity in Light Nuclei



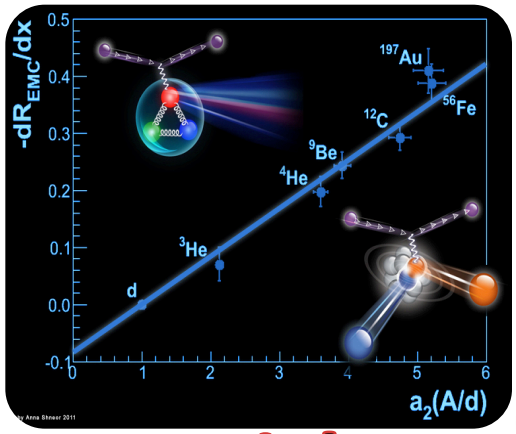




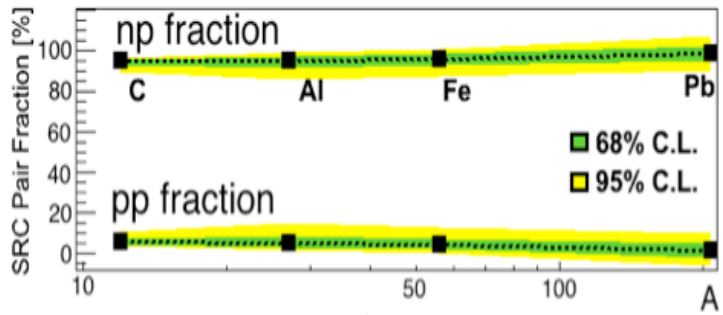
SRC pairs are consistent with Q = 0
back-to-back pairs

R. Wiringa et al., Phys. Rev. C 89, 024305 (2014).
T. Neff, H. Feldmeier and W. Horiuchi, Phys. Rev. C 92, 024003 (2015).
I. Korover, N. Muangma, and O. Hen et al., Phys. Rev. Lett 113, 022501 (2014).

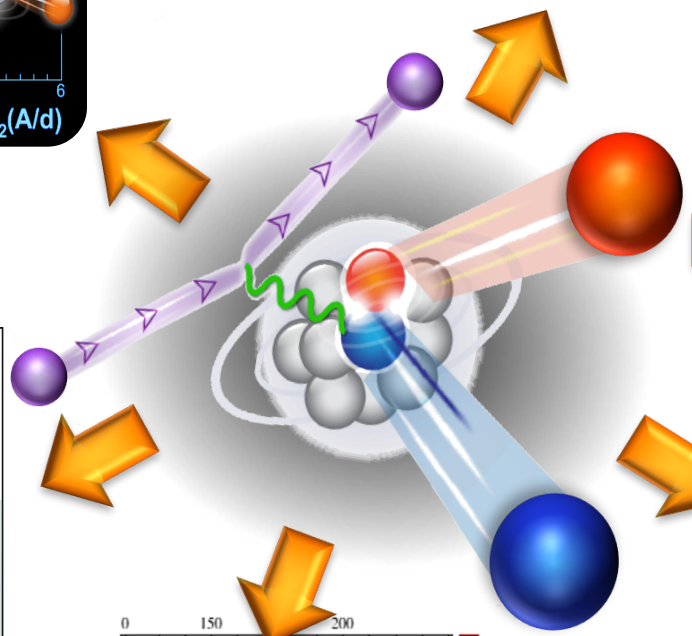
Importance of SRC Properties

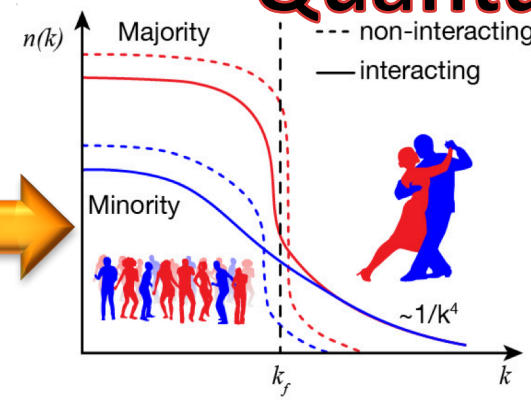


Particle

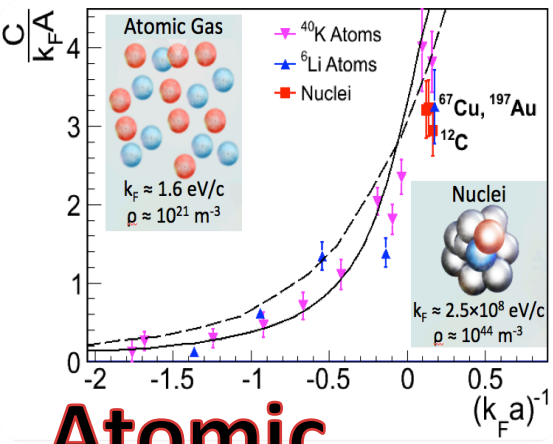


Nuclear

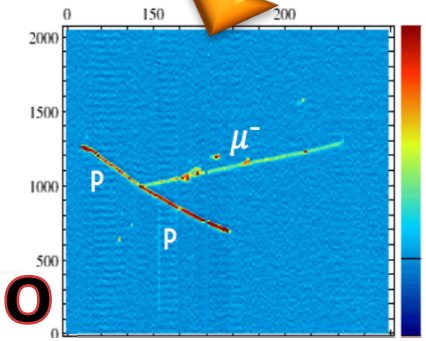




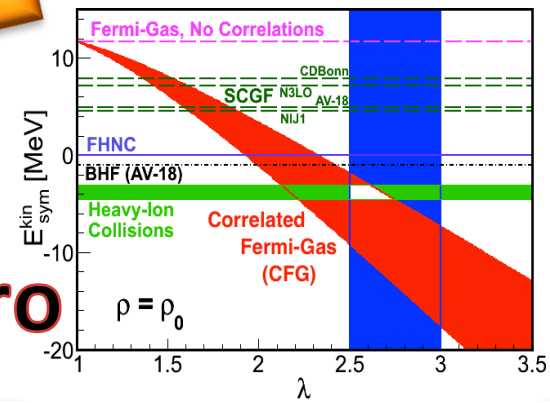
Quantum



Atomic



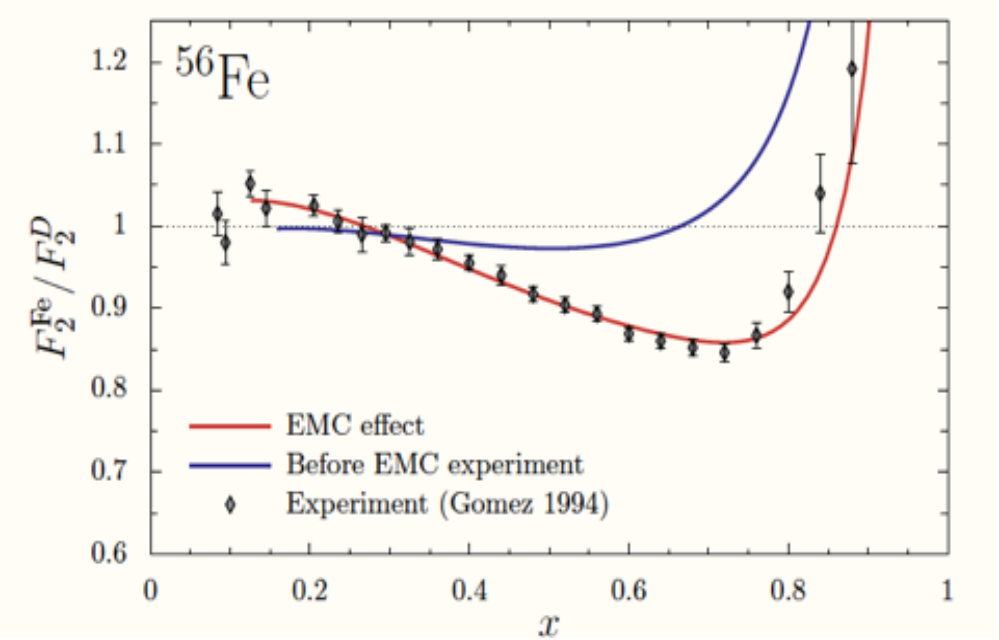
Neutrino



Astro

EMC Effect

- Deviation of the per-nucleon DIS cross section ratio of nuclei relative to deuterium from unity.
- Universal shape for 0.3<x<0.7 and 3<A<197.
- ~Independent of Q^2.
- Overall increasing as a function of A.
- No fully accepted theoretical explanation.



$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_A = \frac{4\alpha^2 E'^2}{Q^4}\left[2\frac{F_1}{M}\sin^2\left(\frac{\theta}{2}\right) + \frac{F_2}{\nu}\cos^2\left(\frac{\theta}{2}\right)\right] \qquad F_2\left(x,Q^2\right) = \sum_i e_i^2 \cdot x \cdot f_i(x)$$

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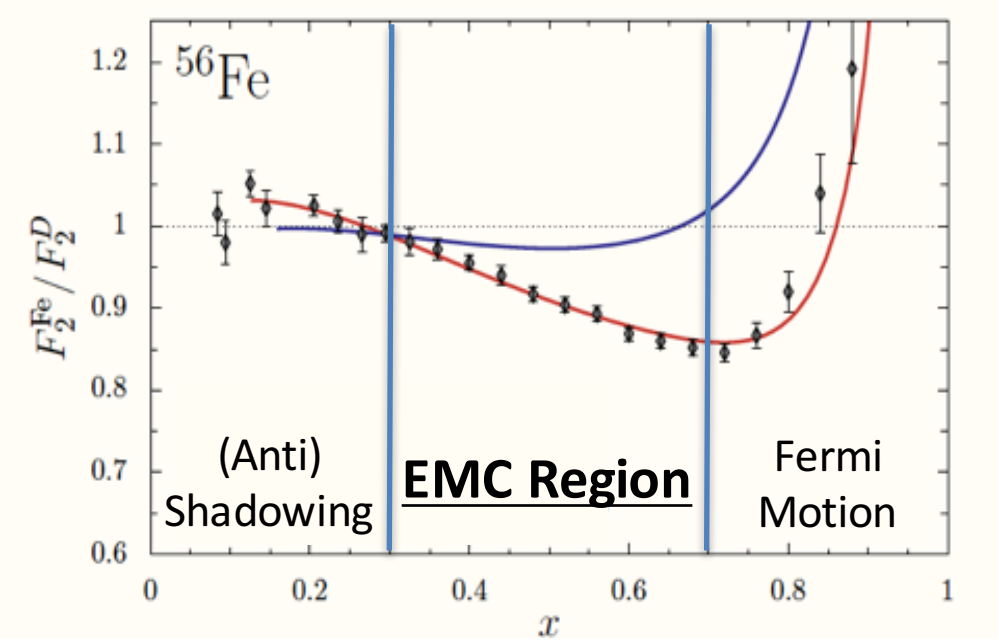

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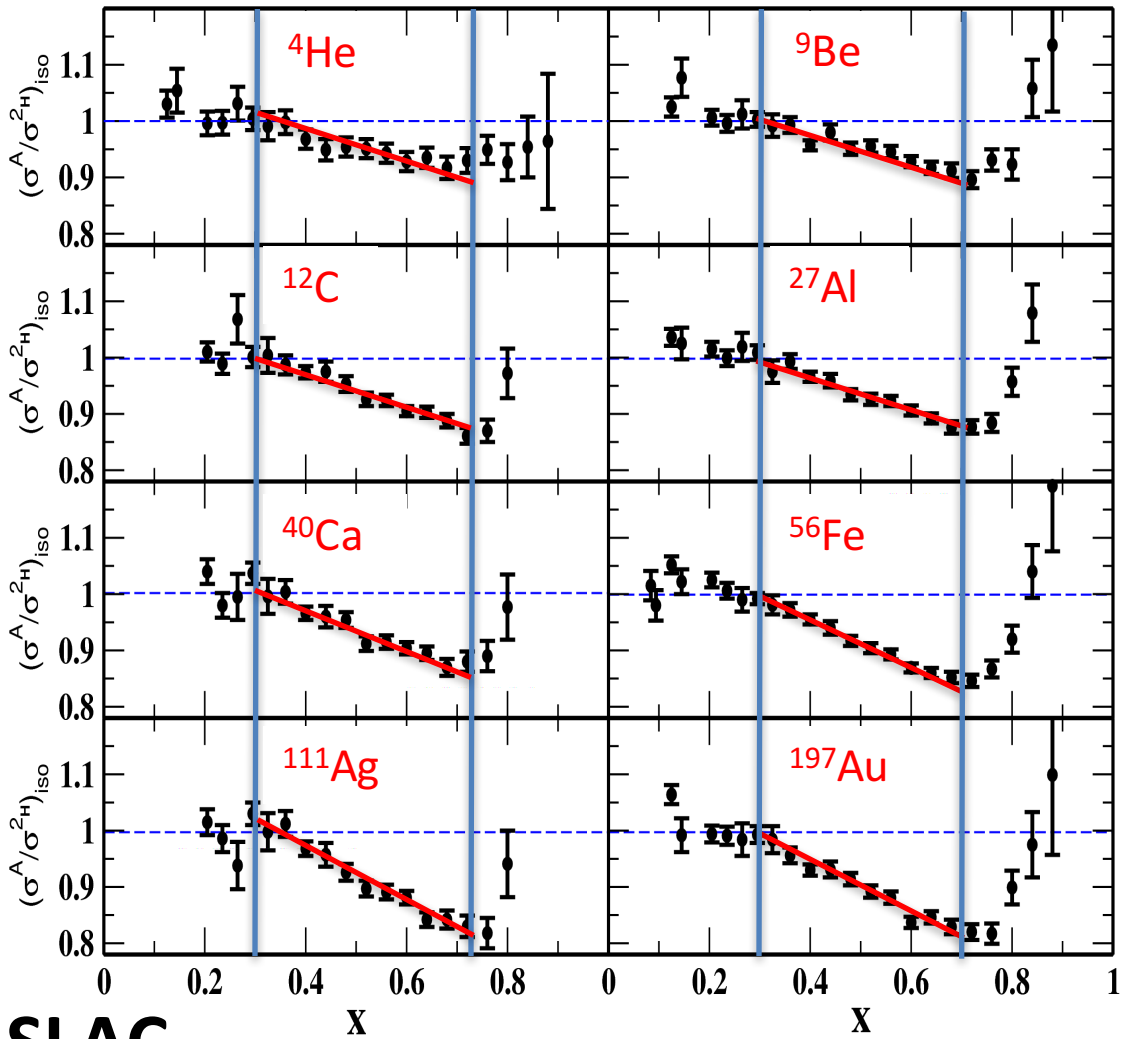
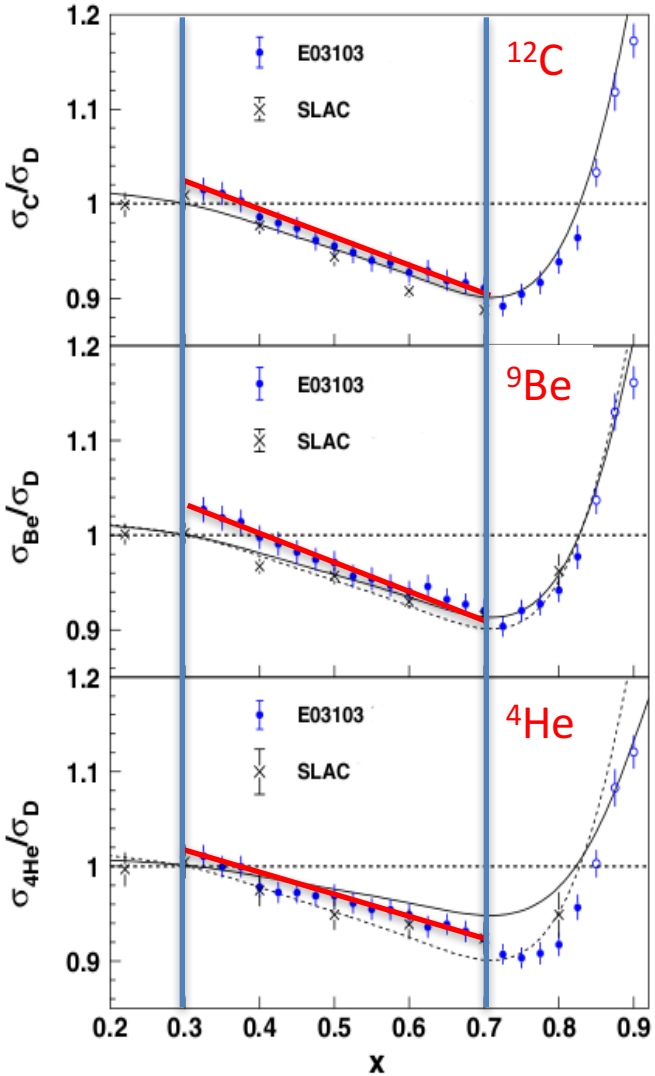
Universality of the EMC Effect



SLAC

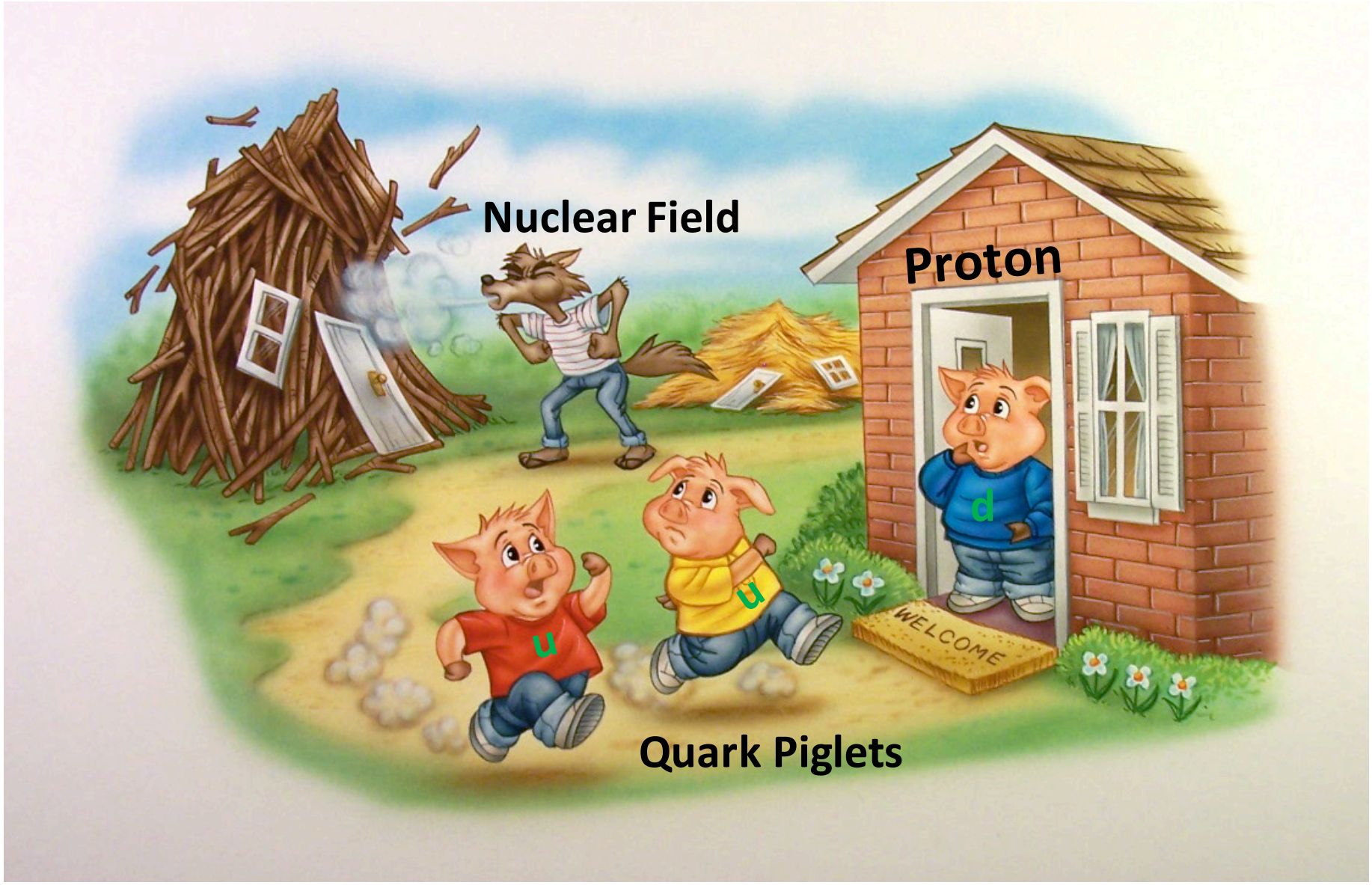
J. Gomez et al., Phys. Rev. D **49**, 4348 (1994).

JLab



J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

EMC Challenge: Scales in Physics



EMC Theory

- Standard nuclear effects that contribute:
  [explain some of the effect, up to x≈0.5]
  - Nuclear Binding and Fermi motion
  - Coulomb Field
- Various theoretical models:
  [Most incorporate modification of the bound nucleon structure]
  - Dynamical rescaling
  - Point-like configuration suppression
  - Structure function modification in the nuclear mean-field
  - 6 quark clusters
  - More….

EMC – Everyone's Model is Cool (G. A. Miller)

EMC Theory

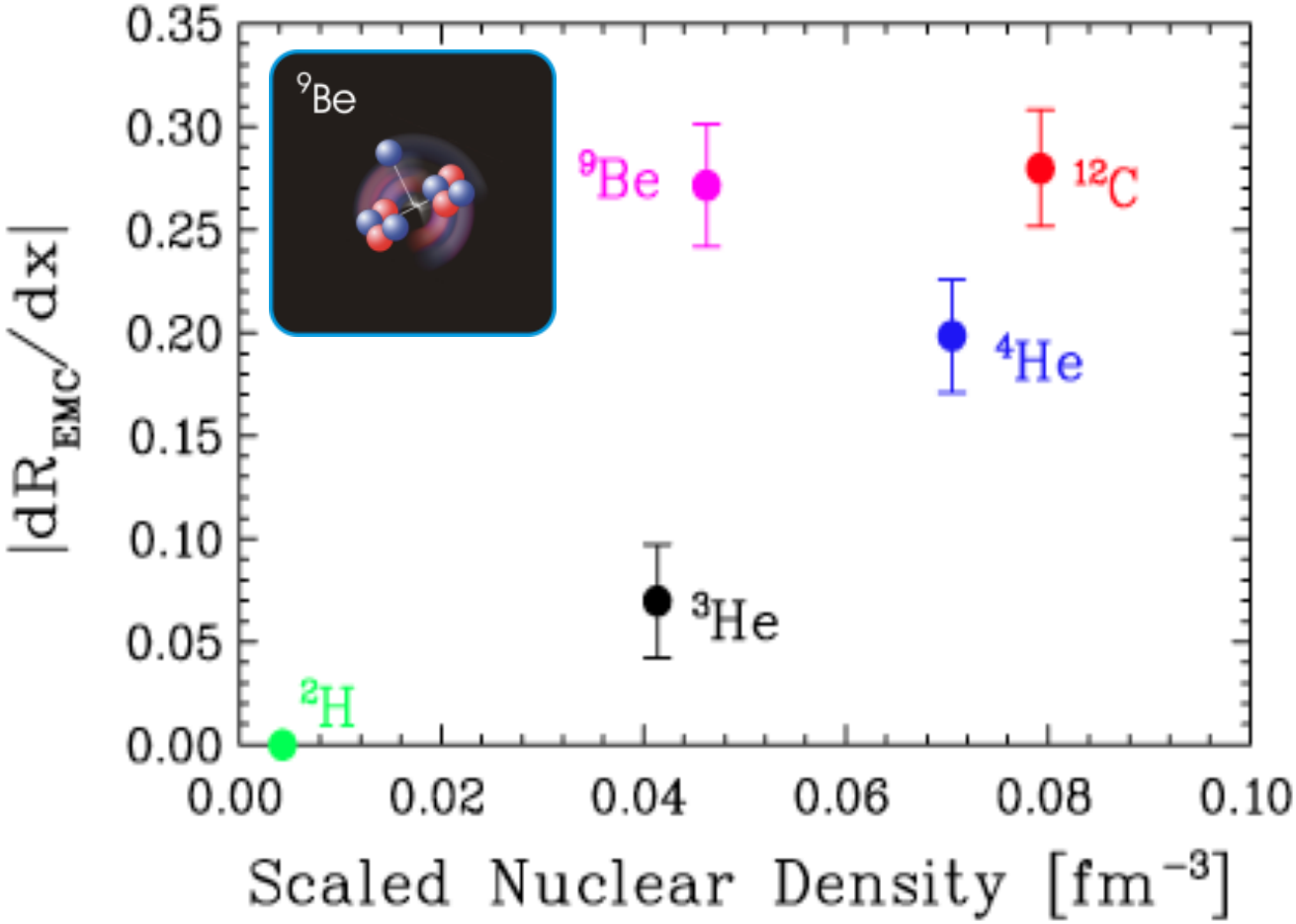
- Standard nuclear effects that contribute:
  [explain some of the effect, up to x≈0.5]
  - Nuclear Binding and Fermi motion
  - Coulomb Field
- Vari

One Model Isn't Cool: "No Bound-Nucleon Structure Modification"

  - [illegible] function modification in the nuclear mean-field
  - 6 quark clusters
  - More….

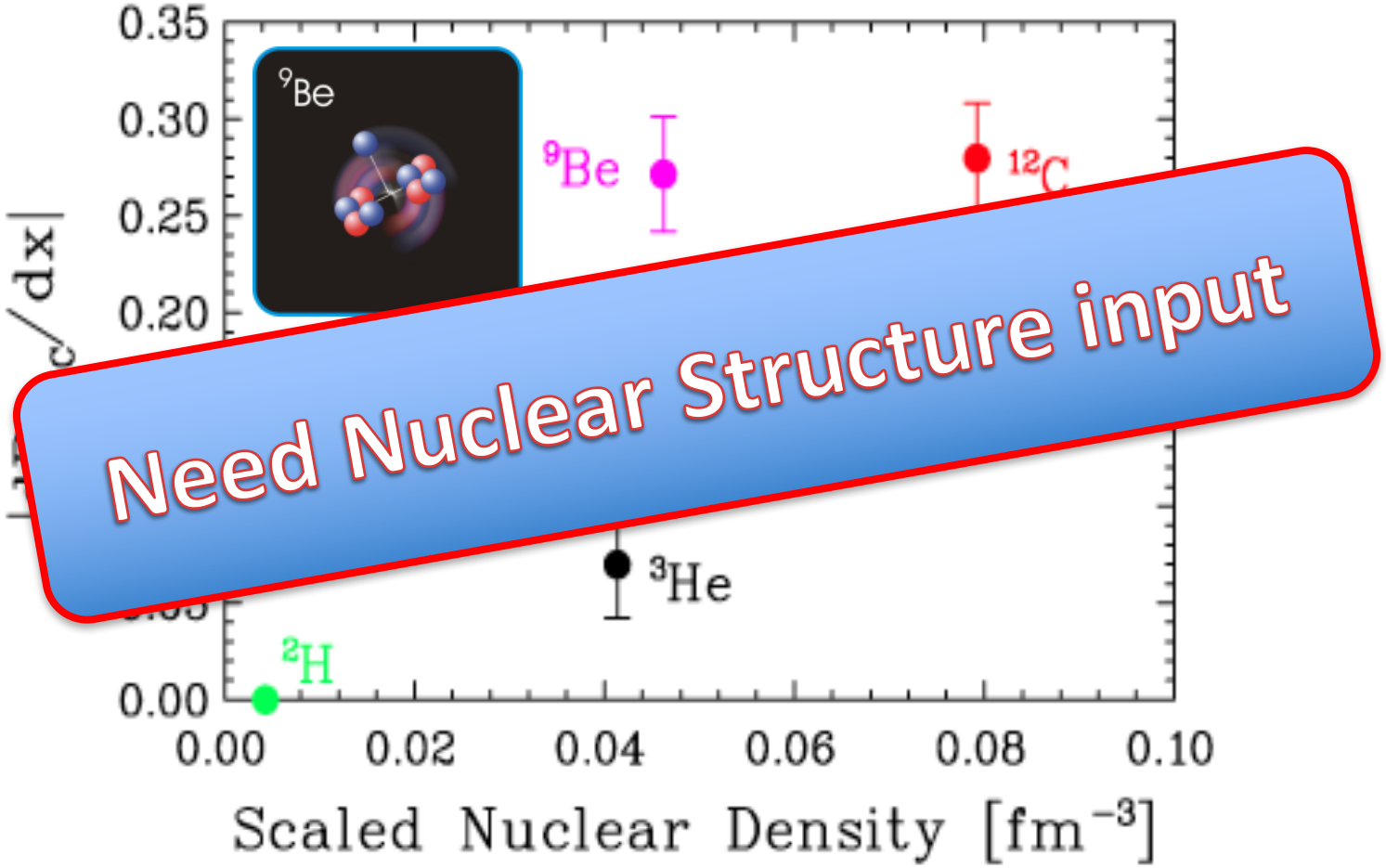
EMC – Everyone's Model is Cool (G. A. Miller)

Non Trivial Nuclear Dymanics



J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

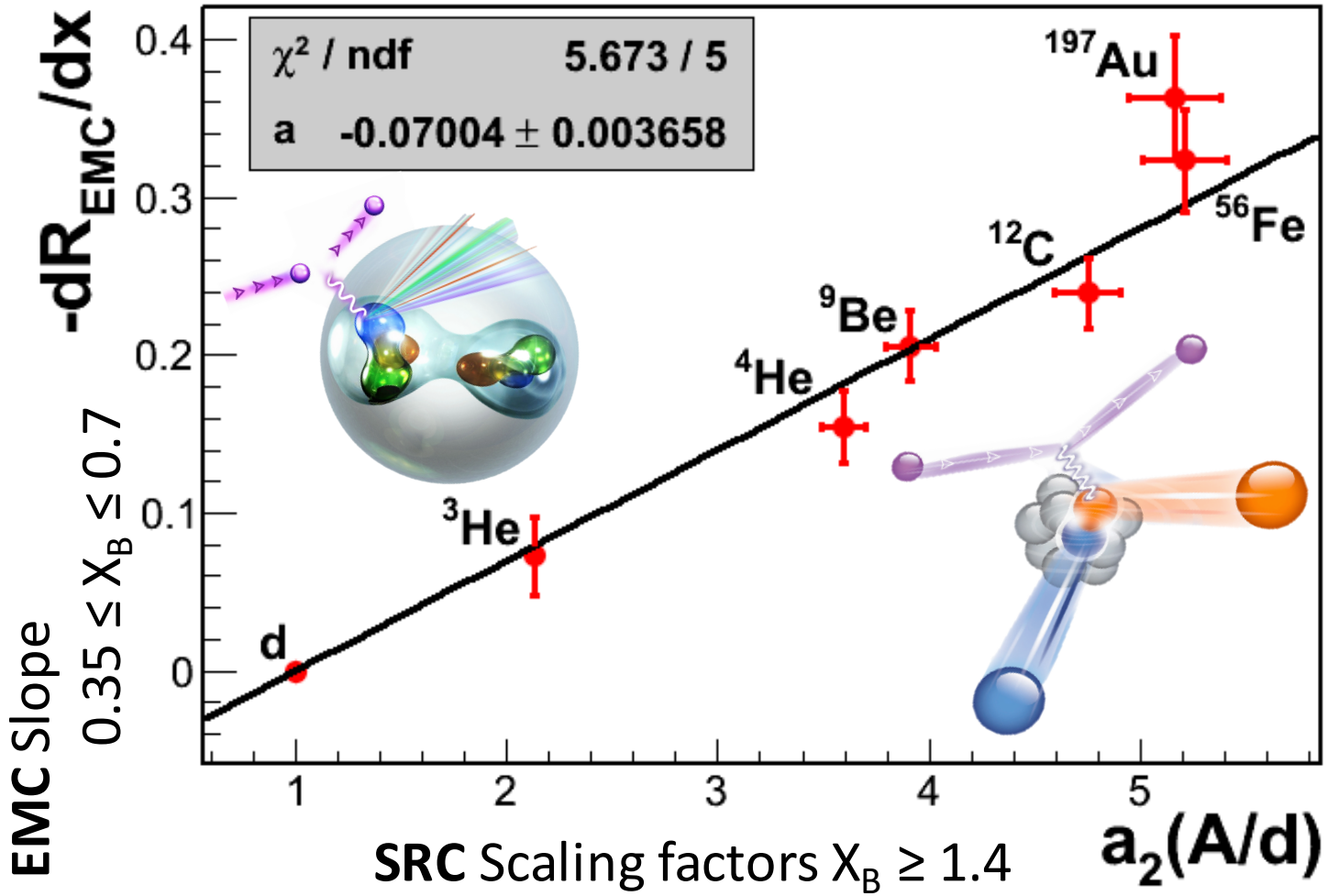
Non Trivial Nuclear Dymanics



Need Nuclear Structure input

J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

From QE to DIS



O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).

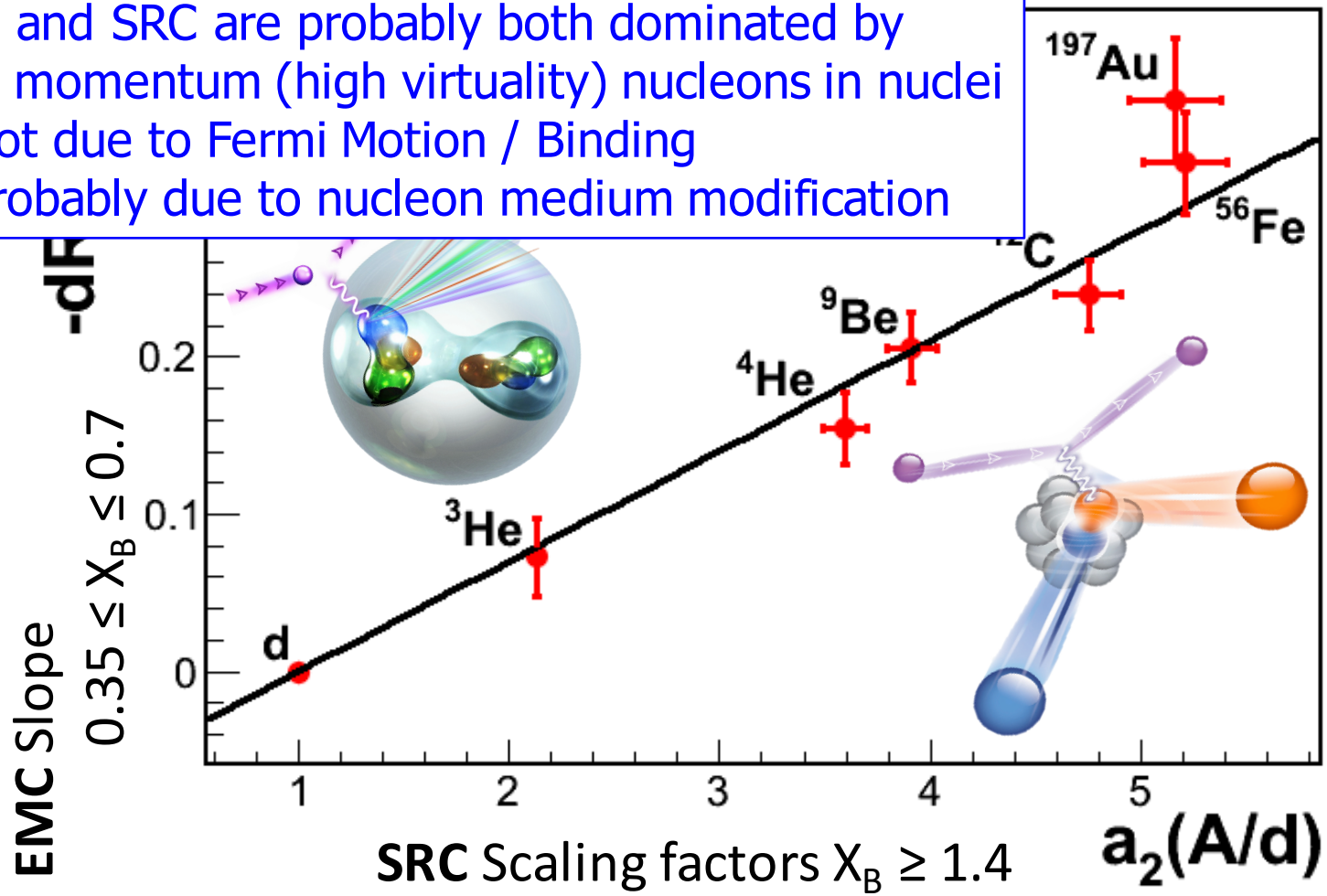
O. Hen et al., Phys. Rev. C **85** (2012) 047301.

L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, R. Shneor, Phys. Rev. Lett. **106** (2011) 052301.

From QE to DIS

EMC and SRC are probably both dominated by high momentum (high virtuality) nucleons in nuclei

- Not due to Fermi Motion / Binding
- Probably due to nucleon medium modification



O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).

O. Hen et al., Phys. Rev. C **85** (2012) 047301.

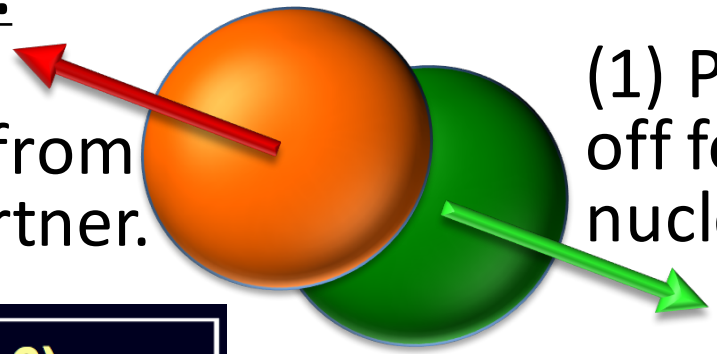
L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, R. Shneor, Phys. Rev. Lett. **106** (2011) 052301.

Tagged Structure Functions (JLab12)

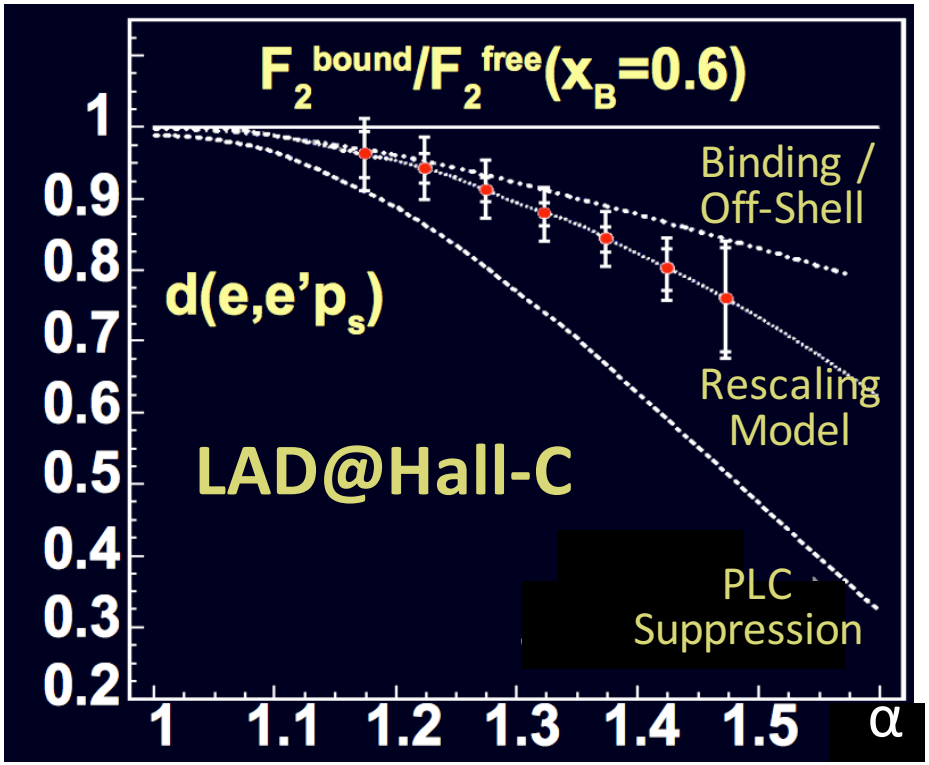
Internal structure of SRC nucleons?

Focus on the deuteron:

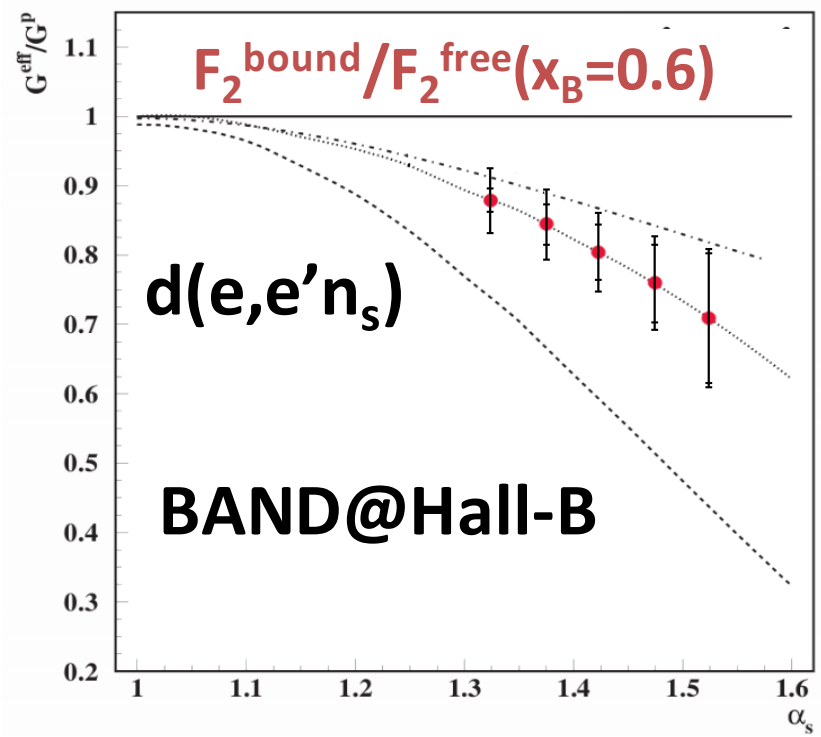
(2) Infer its momentum from the recoil partner.



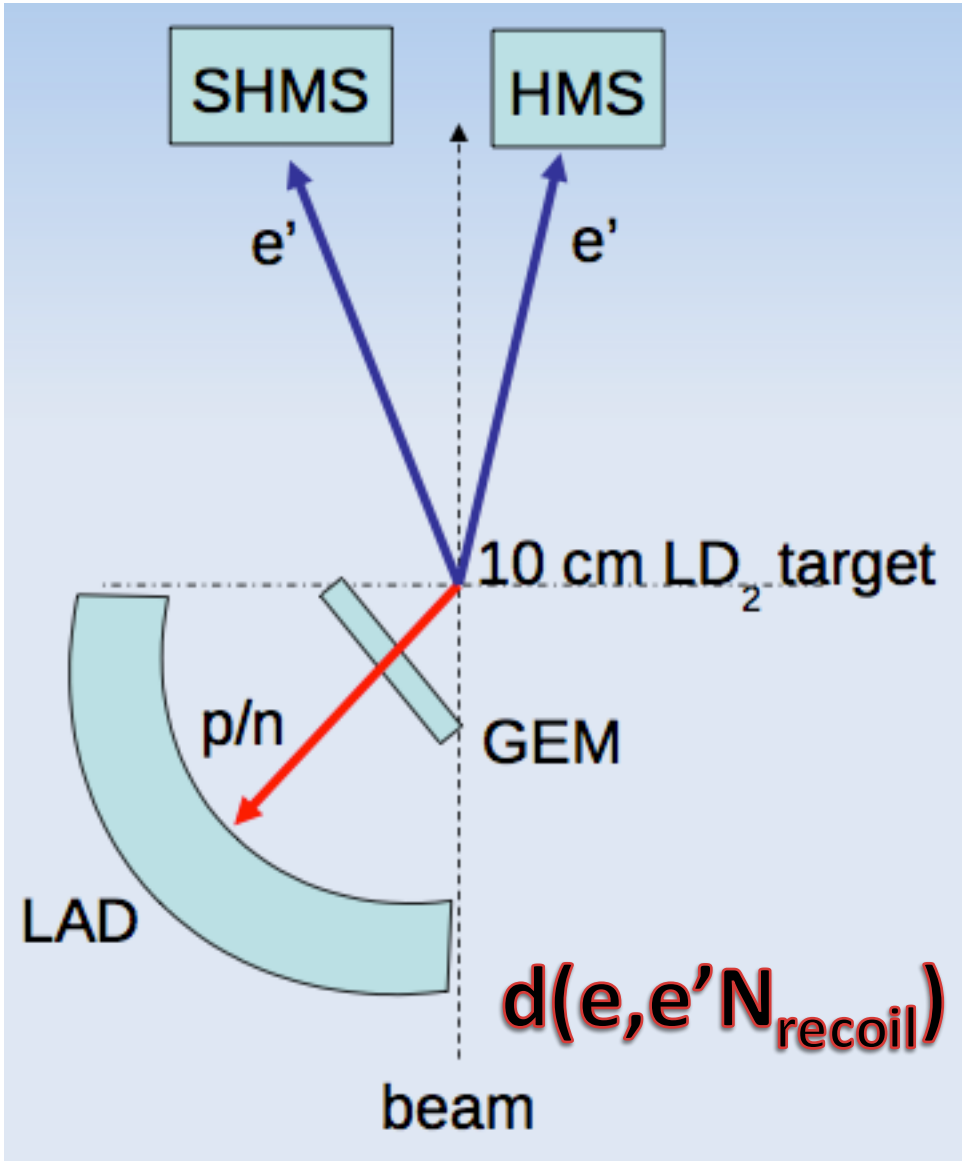
(1) Perform DIS off forward going nucleon.



Melnitchouk et al., Z. Phys. A **359**, 99-109 (1997)



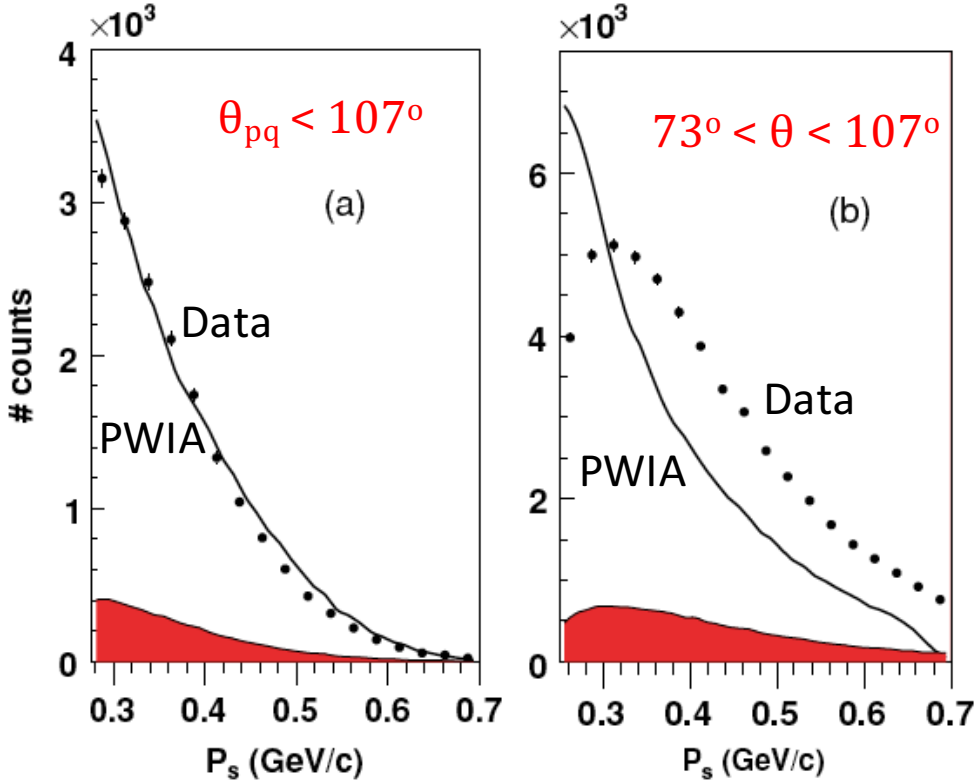
Fixed Target Concept…



- High resolution spectrometers for d(e,e') measurement in DIS kinematics
- Large acceptance recoil proton \ neutron detector
- Long target + GEM detector – reduce random coincidence

Backward Kinematics: Minimize Re-Scattering

D(e,e'p_S)

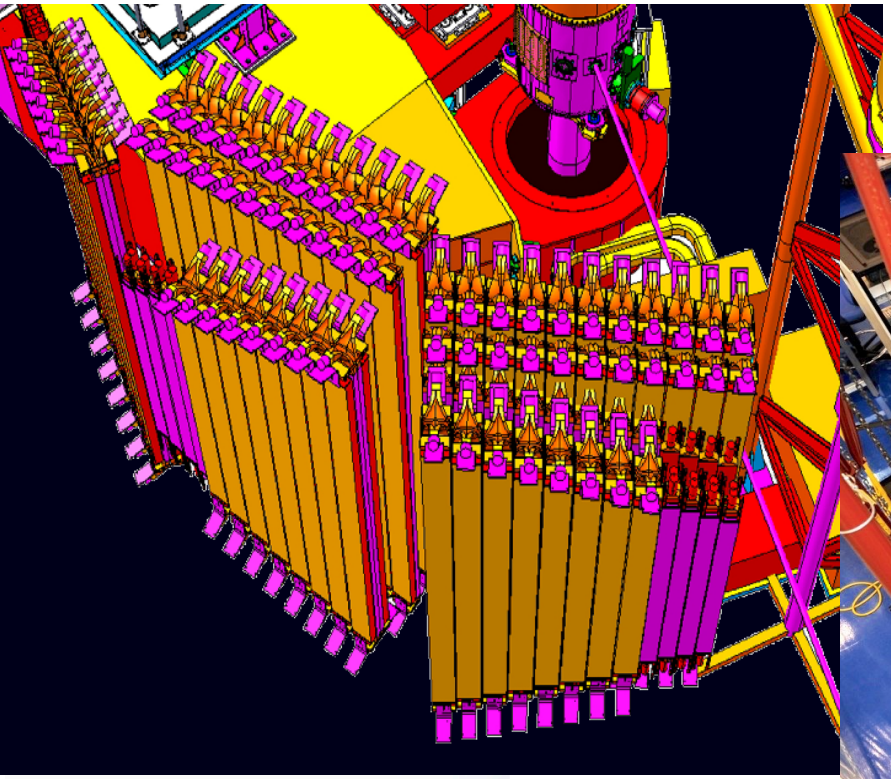


A. V. Klimenko *et al.*, PRC **73**, 035212 (2006)

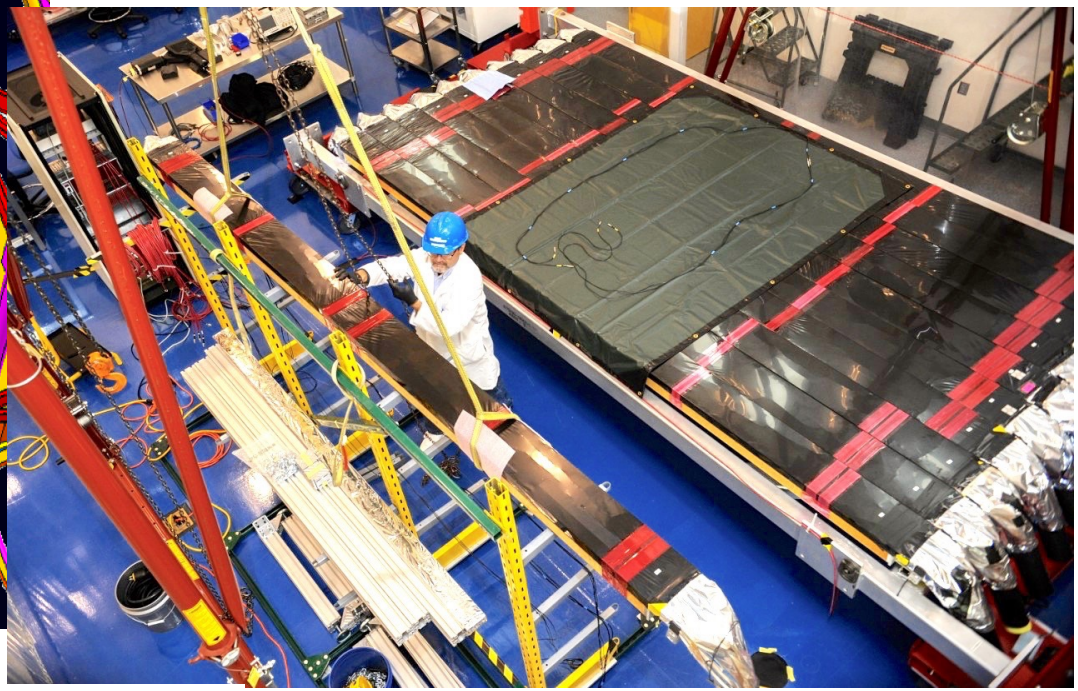
FSI:

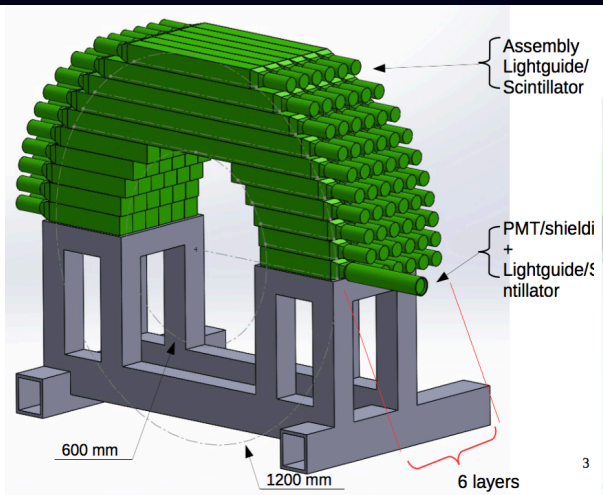
- Decrease with Q^2
- Increase with W'
- Not sensitive to x'
- Small for $\theta_{pq} > 107°$

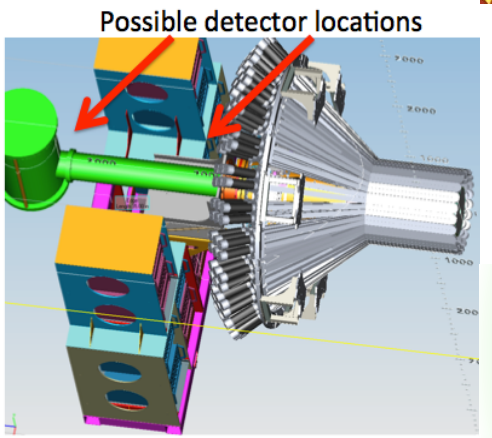
Next Generation Experiments



Large Acceptance Detector (LAD@Hall-C)





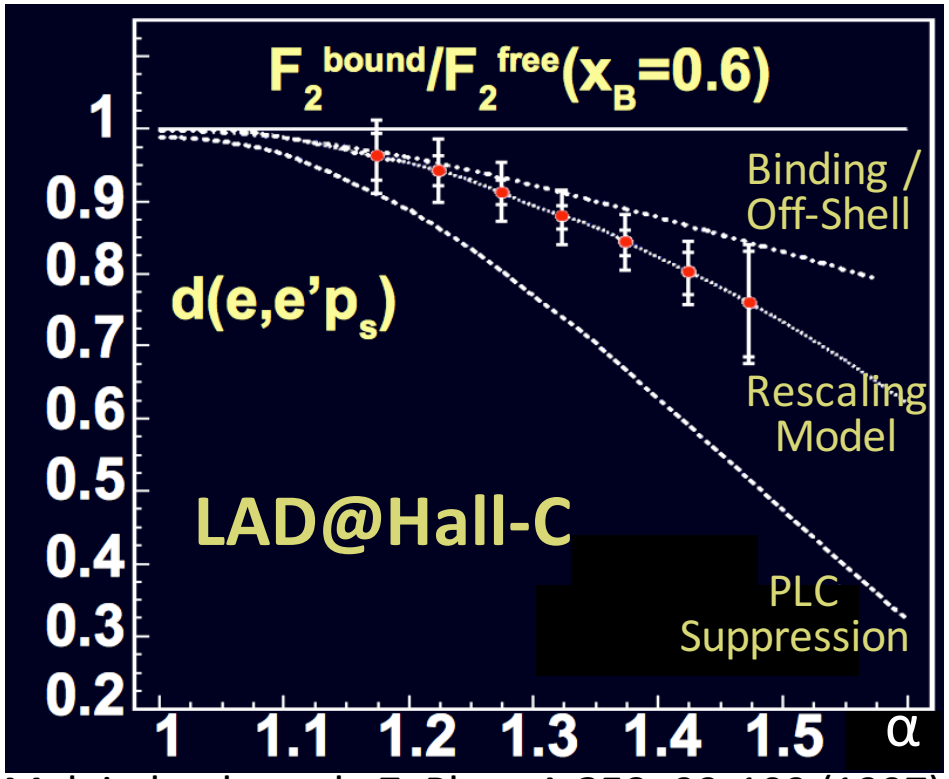


Backward Angle Neutron Detector (BAND@Hall-B)

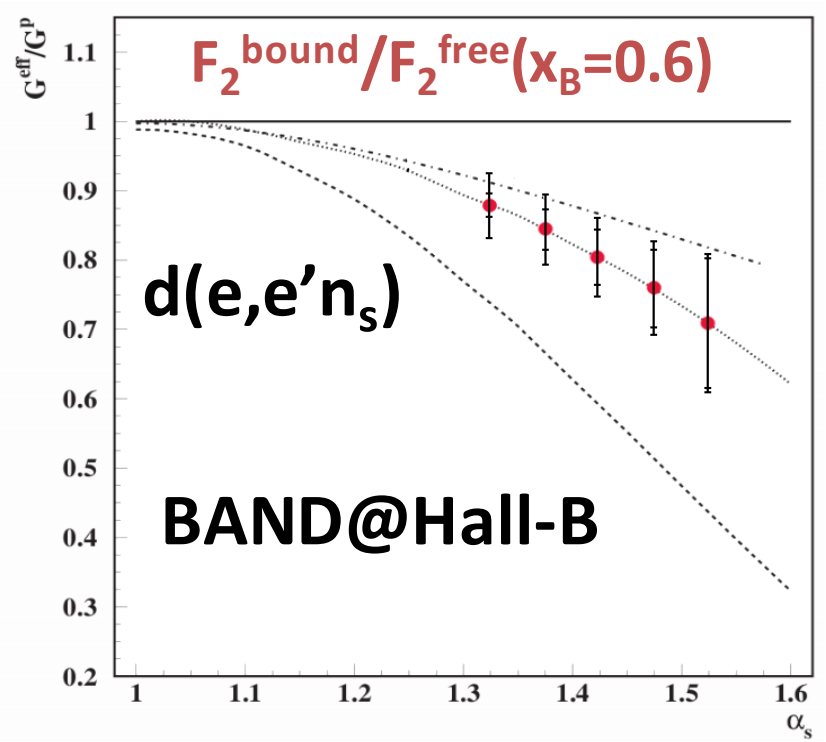
R&D @ MIT / Construction @ BATES

Kinematics and Uncertainties

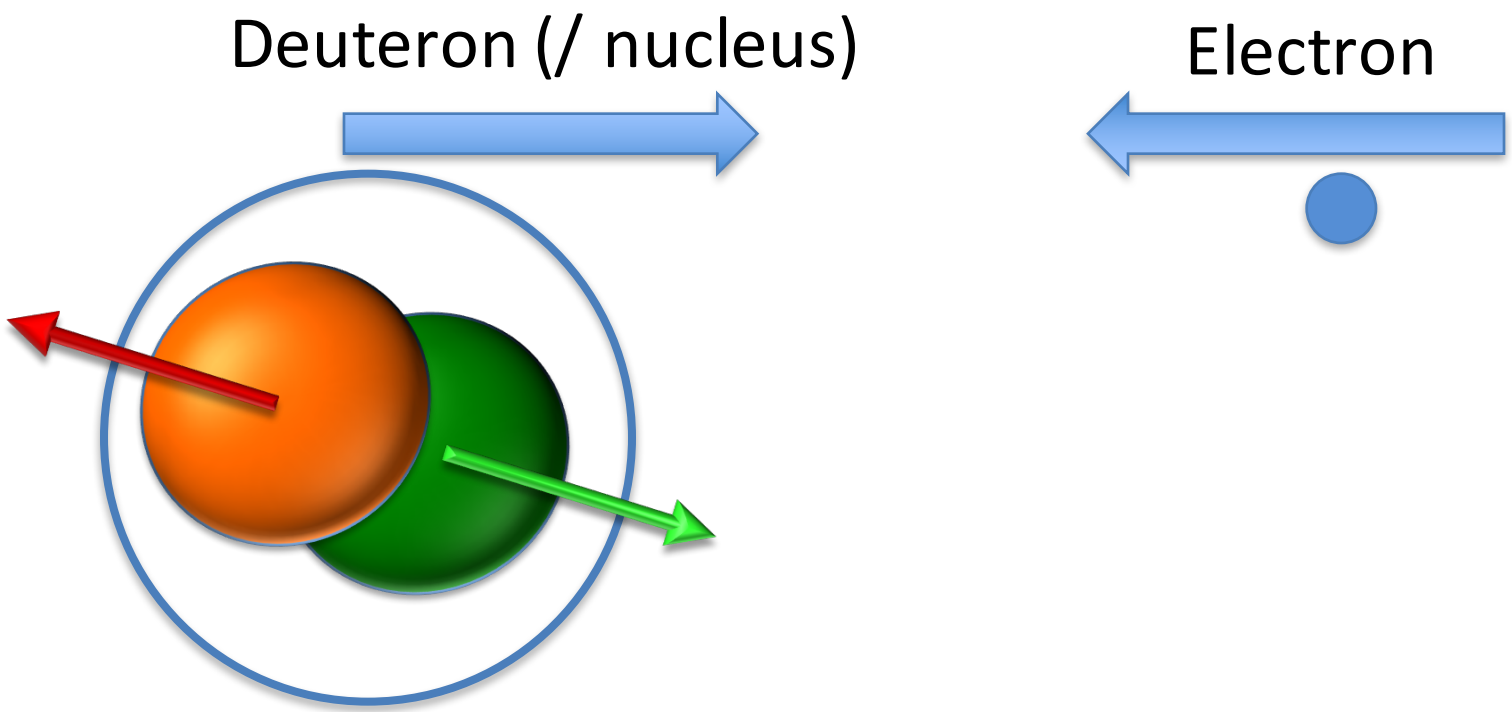
- Tagging allows to extract the structure function in the nucleon reference frame: $x' = \frac{Q^2}{2(\bar{q}\cdot\bar{p})}$
- Expected coverage: x' ~ 0.3 & 0.45(0.5) < x' < 0.55(0.7) @ $W^2 > 4$ [GeV/c]^2



Melnitchouk et al., Z. Phys. A **359**, 99-109 (1997)

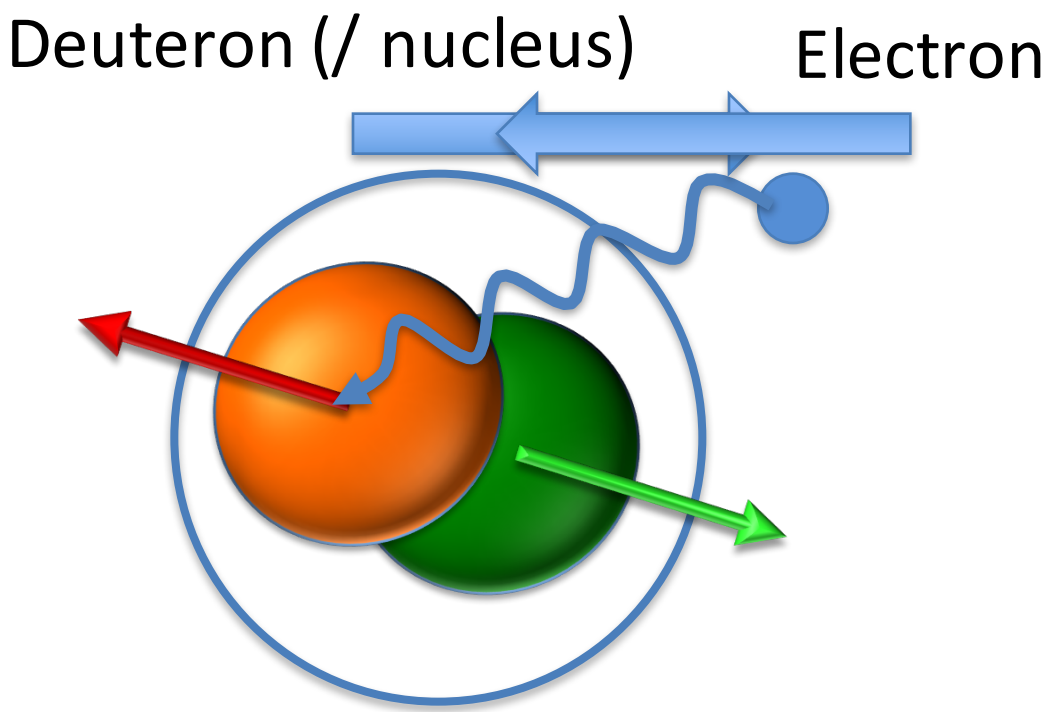


Collider Concept…



See C. Hyde talk for experimental details

Collider Concept…



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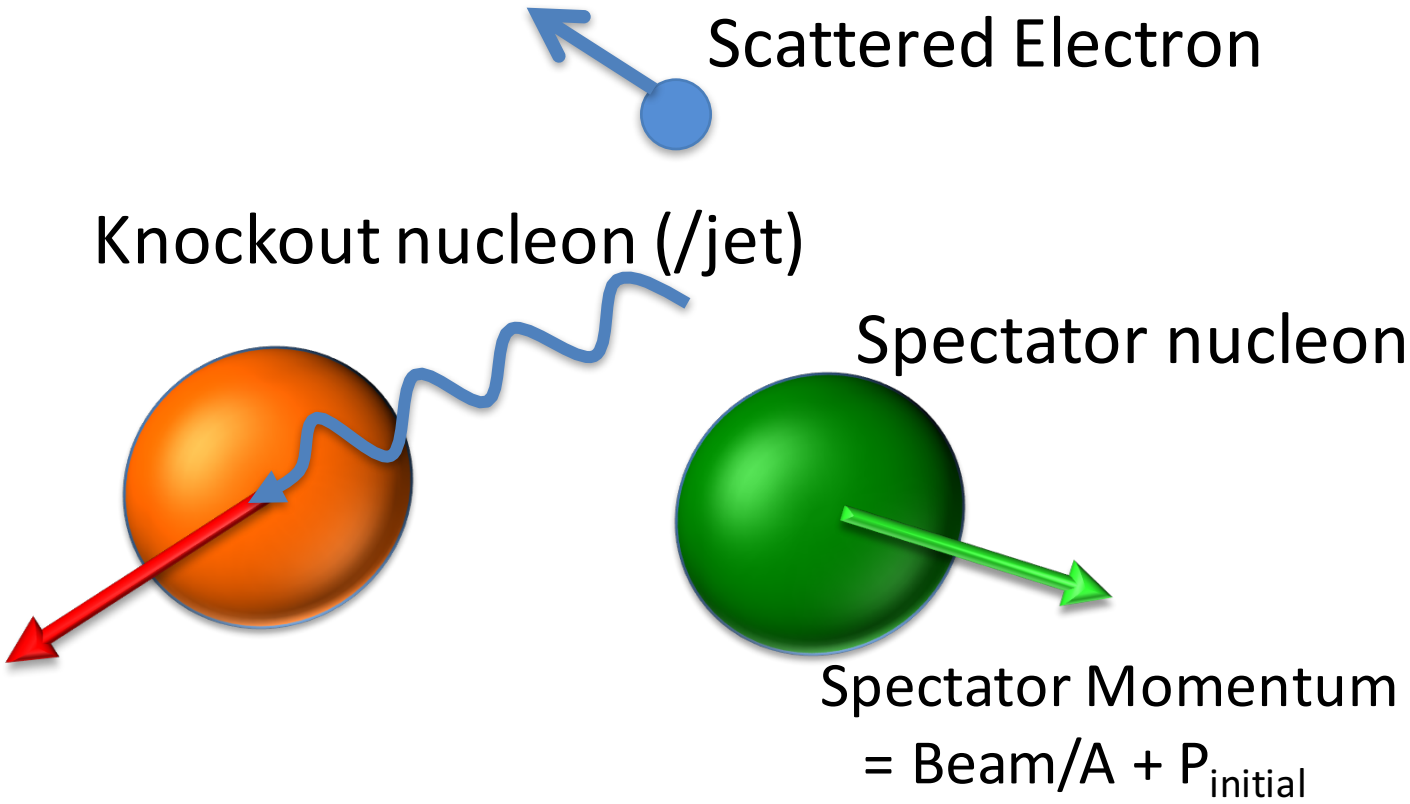

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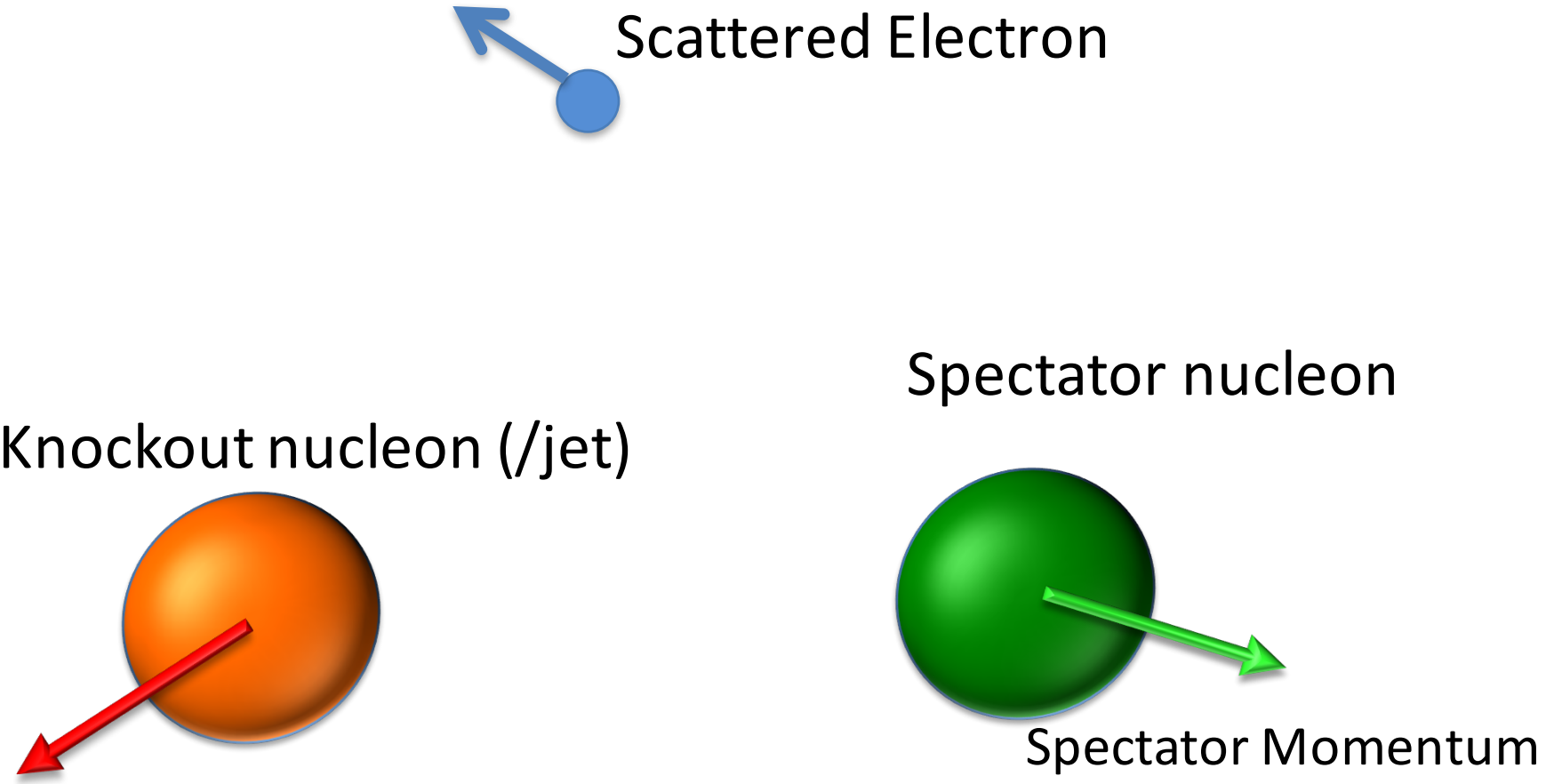
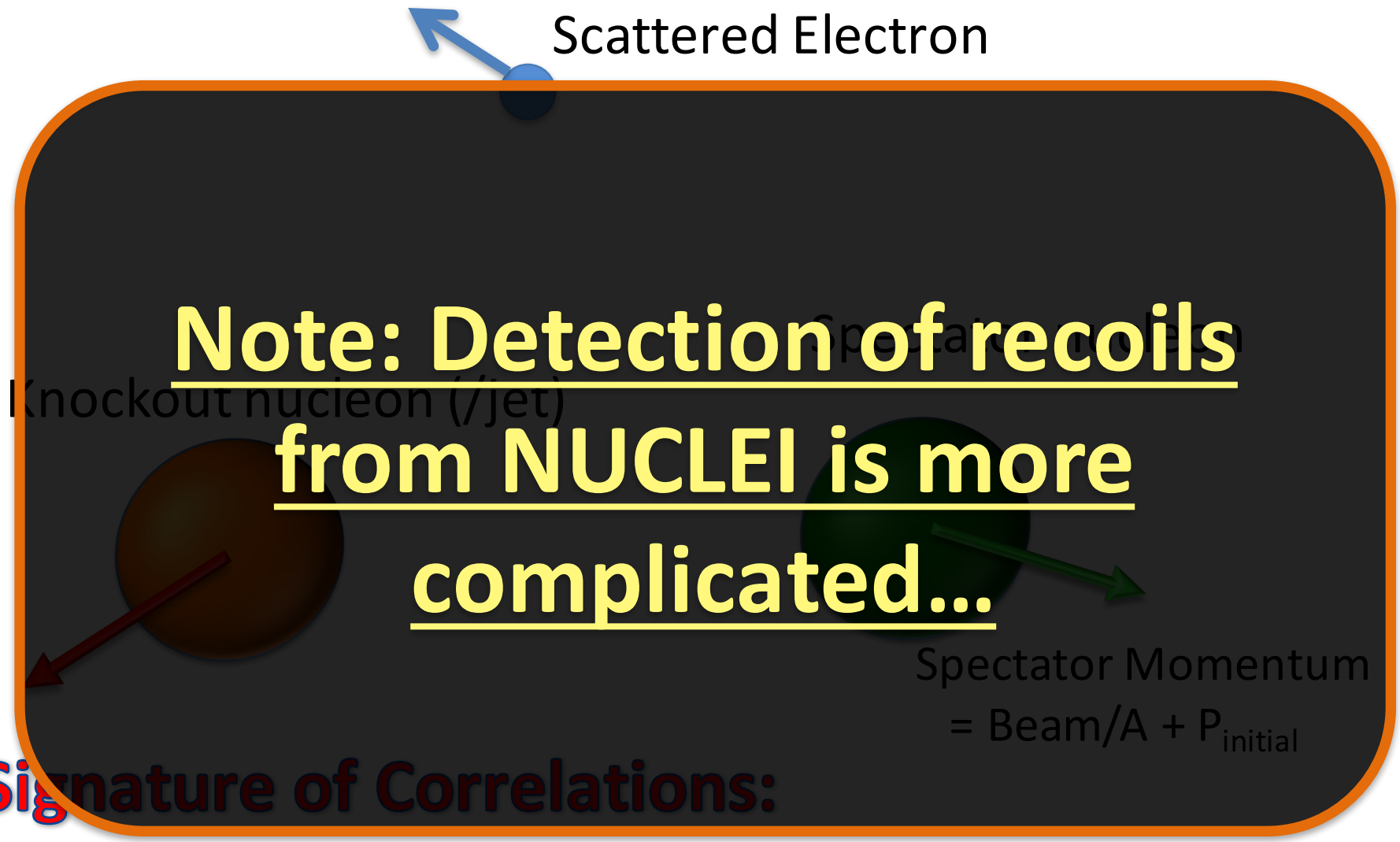


Signature of Correlations:

Spectator momentum > beam momentum

Collider Concept…

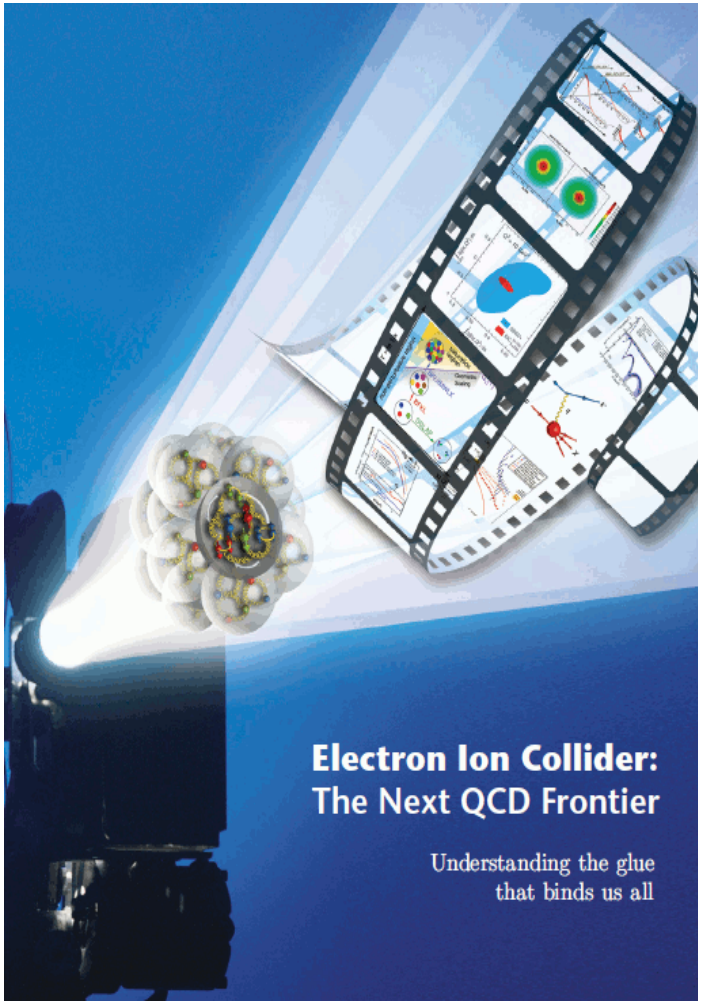


Note: Detection of recoils from NUCLEI is more complicated…

Signature of Correlations:

Spectator momentum > beam momentum

Collider Tagging Kinematics



Spectator Momentum

100 GeV d: $\gamma = 50$

Center of Mass		Lab	
P_z (CM) GeV/c	P_{perp} (CM) GeV/c	P_z (Lab) GeV/c	θ_p (Lab)
0	0	50	0
0.2	0	41	0
0.4	0	34	0
0.6	0	28	0
0.6	0.2	29	0.007
0.6	0.6	36	0.02

EIC/SRC Physics Shopping List?

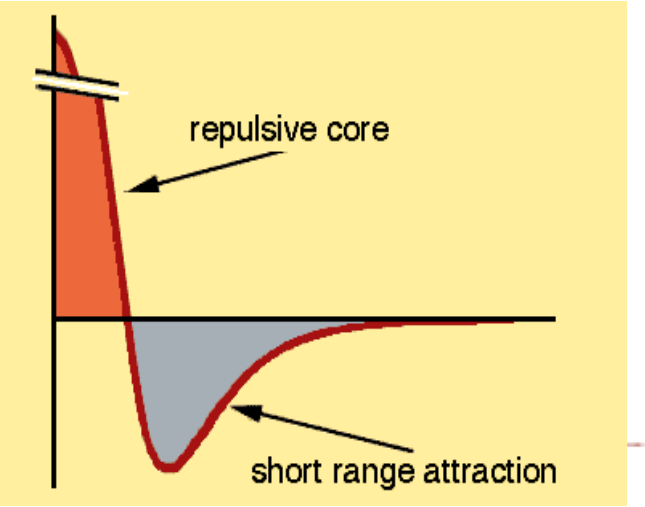
- Proton / Neutron structure functions – from low to high vitruality.
- NN Interactions at short distance (see Matt's talk).
- Polarization of SRC pairs.
- 2N-SRC IsoSpin structure at very high P_{miss}
- 2N-SRC dymanics in heavy, asymmetry, nuclei.
- 3N-SRC, #N-SRC ???
- Your ideas here!

Need very versatile detectors!!

"What holds the nucleons of the atom together? In the past quarter century physicists have devoted a huge amount of experimentation and mental labor to this problem, probably more man hours than have been given to any other scientific question in the history of man kind" – Hans Bethe, Scientific American 1953

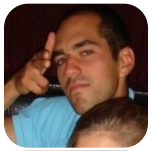
63 years later….

Did we solve the nuclear problem??
How about the 'partonic' problem??

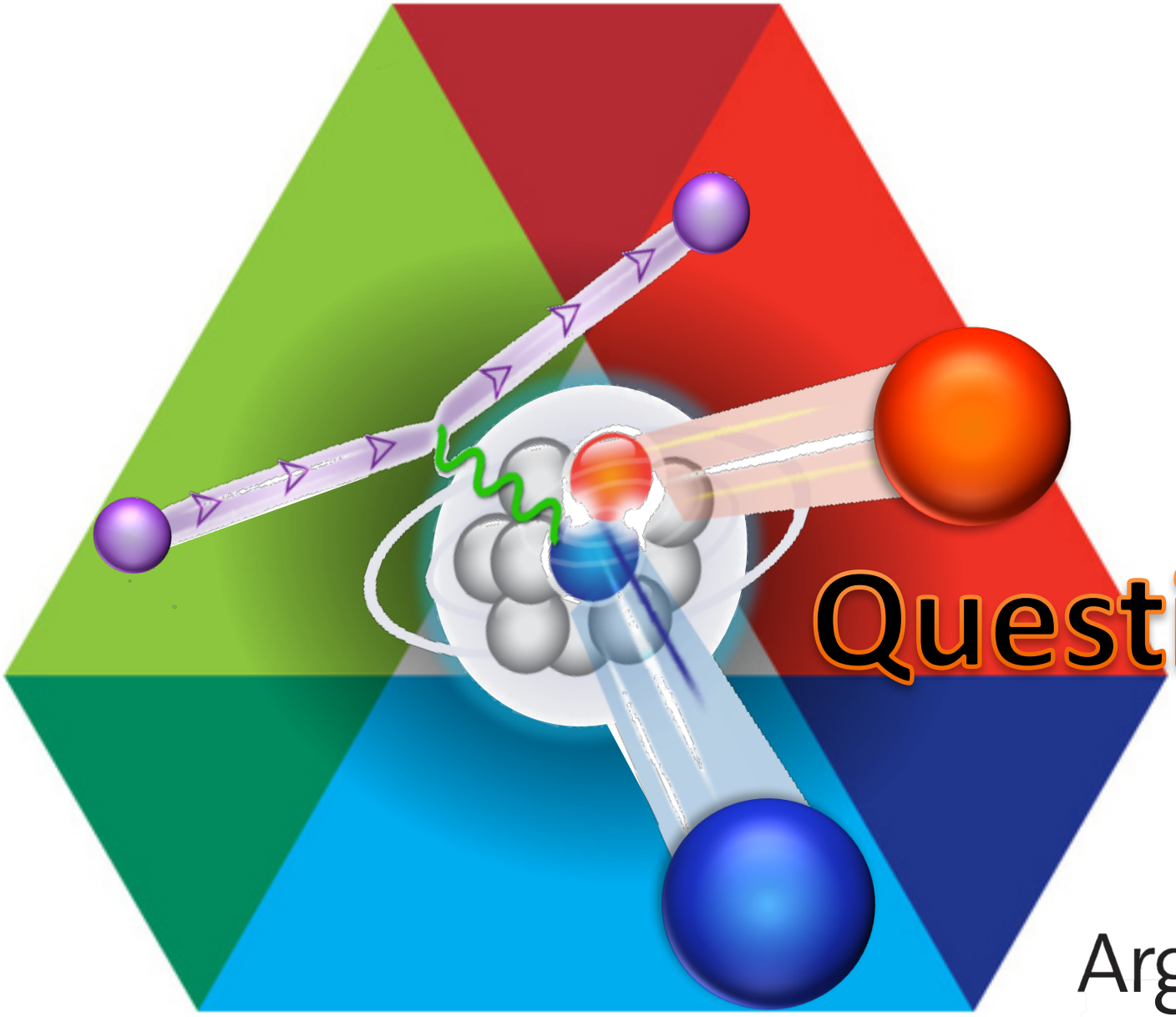


The Correlations group

- **MIT:**
  - **Barak Schmookler**
  - **Navaphon (Tai) Muangma**
  - **Reynier Torres**
  - **Efrain Segarra**
  - **Afroditi Papadopoulou**
  - Or Hen
  - Shalev Gilad

  [+Axel Schmidt and George Laskaris to join as postdocs]
- **ODU:**
  - **Mariana Khachatryan**
  - Larry Weinstein
- **Tel-Aviv:**
  -  **Erez Cohen**
  - **Meytal Duer**
  - **Igor Korover**
  - Eli Piasetzky
- Many theory friends ☺

Thank You!



Questions?

Argonne NATIONAL LABORATORY