



# Probing open quantum systems with open questions using rare isotopes along the dripline at high energies

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MICHIGAN STATE  
UNIVERSITY



U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science

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# Outline

- Human & Nature: two sides of the same coin
- Open Quantum Systems
  - A brief introduction
  - Two examples:  $^{31}\text{Ne}$  &  $^{11}\text{B}$
- Short detour to electron scattering
  - One-photon approximation issue
  - Duality
- FRIB and MoNA-LISA
- What else can't we "see"?
- Summary



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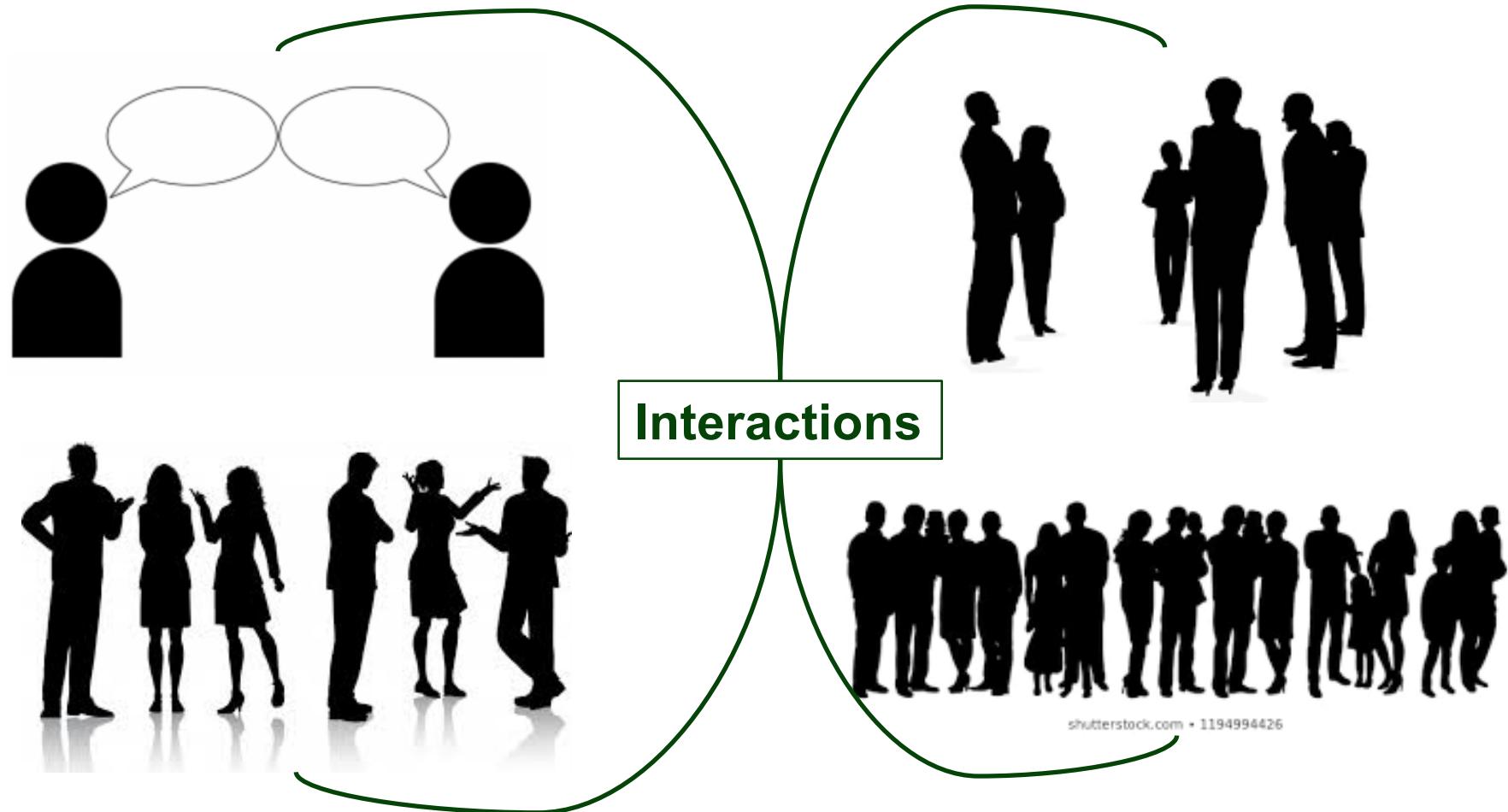
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# 2, 3, 4 ... Too Many



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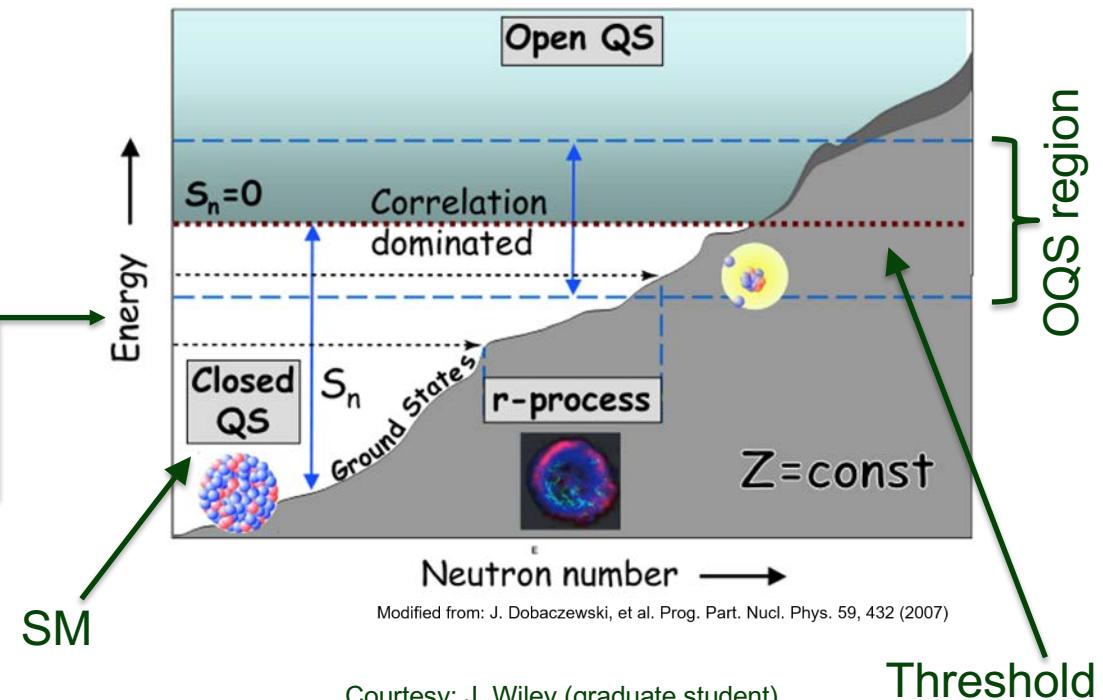
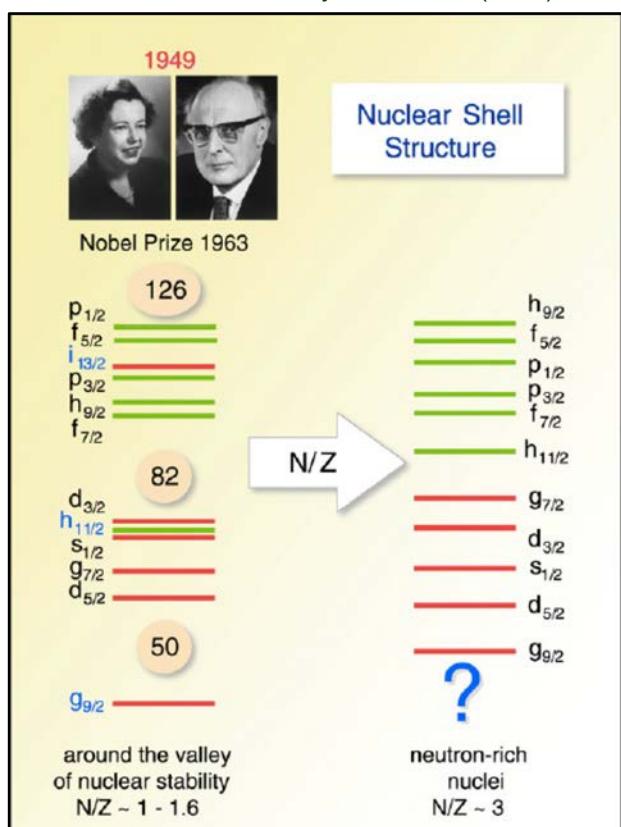
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# Open Quantum Systems – 1

Wikipedia – An open quantum system is a quantum system which is found to be in interaction with an external quantum system or the environment.

J. Dobaczewski et al., Phys. Rev. Lett. **72** (1994) 981  
J. Dobaczewski et al., Phys. Rev. **C53** (1996) 2809



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# Open Quantum Systems – 2

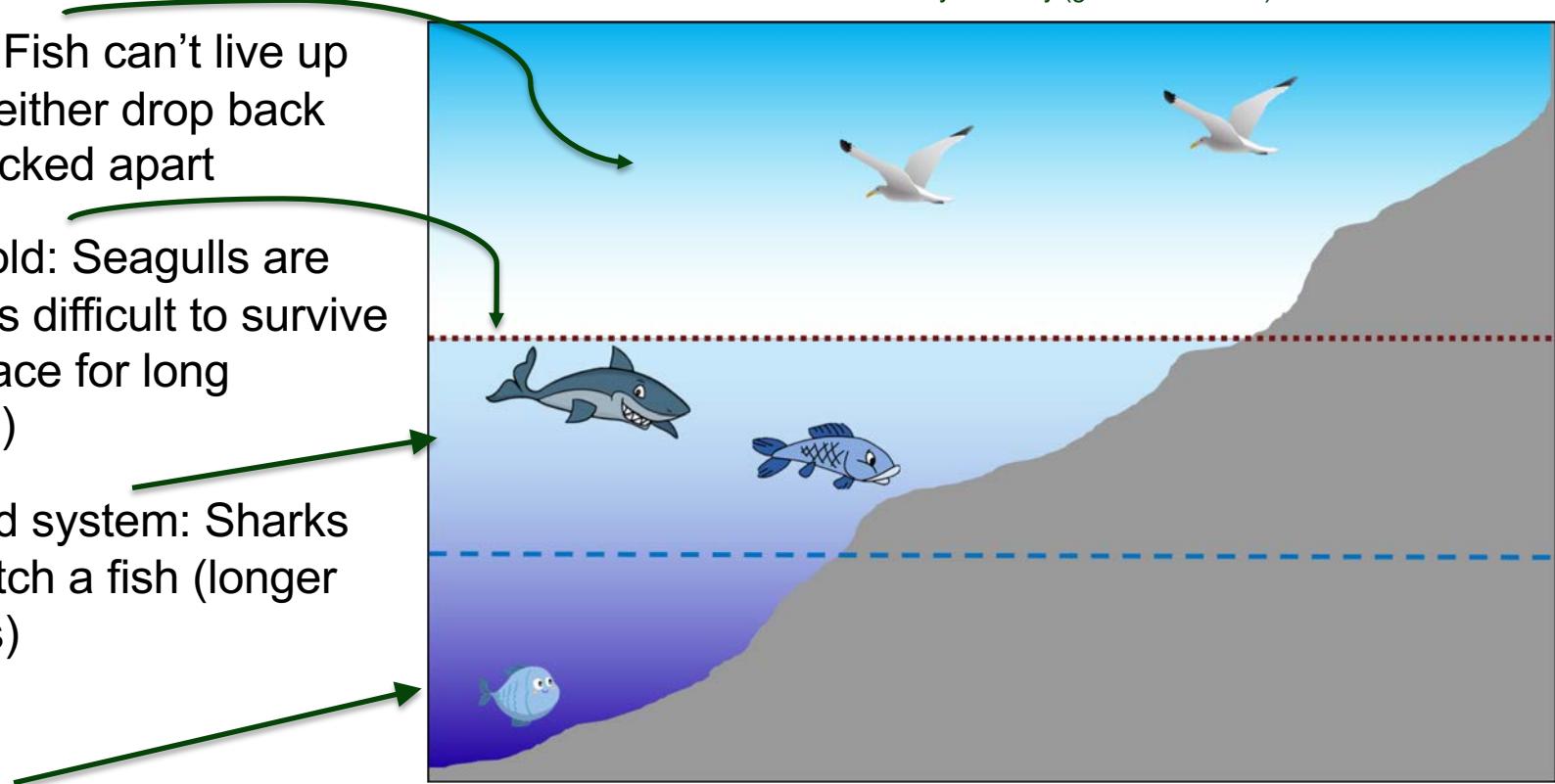
Fun analogy: fish in the ocean

Courtesy: J. Wiley (graduate student)

Above water: Fish can't live up here and will either drop back down or be picked apart

Near Threshold: Seagulls are hostile and it's difficult to survive near the surface for long (Resonances)

Weakly-bound system: Sharks eventually catch a fish (longer lived isotopes)



Closed System: Trench where fish experience little change from the environment (no light, constant temperature, etc.)



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# Reconstructing the Invisible

Decay of Unstable Nuclei



Reconstruction: **Invariant/Missing Mass**

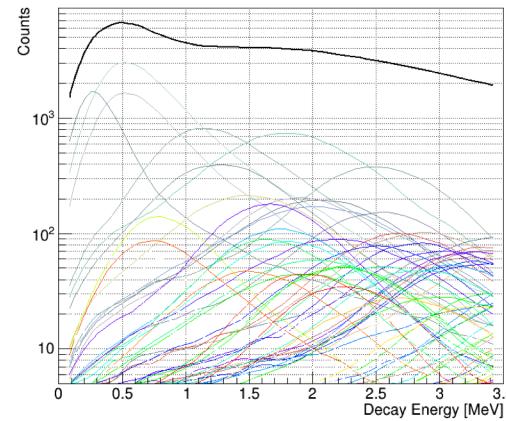
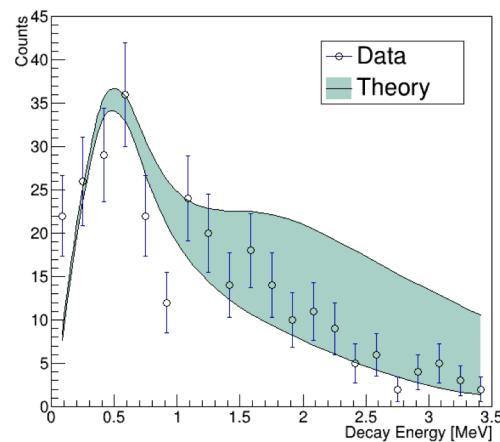
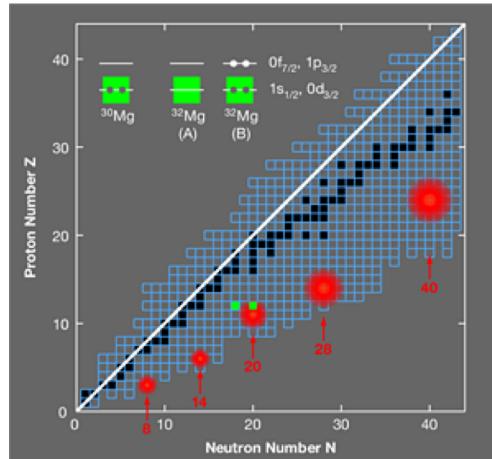
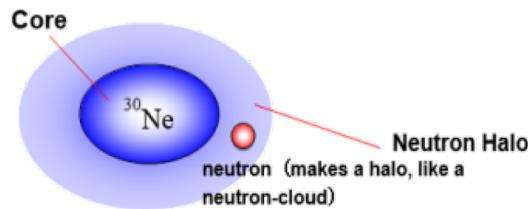


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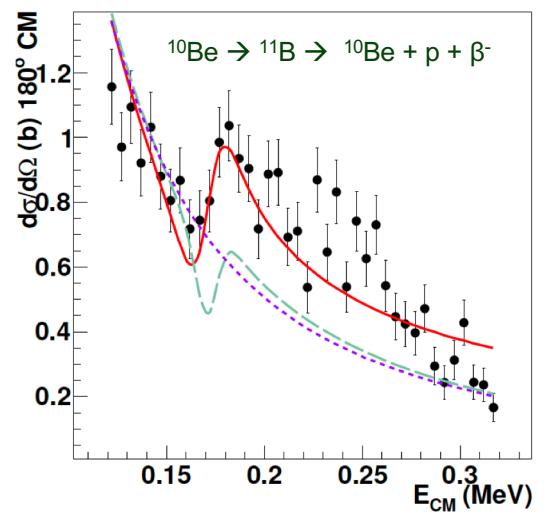
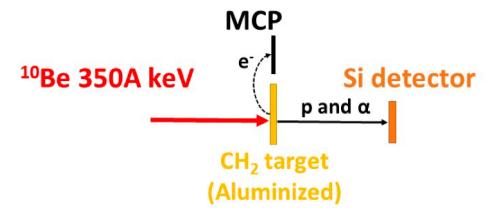
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# 31Ne & 11B cases

$^{31}\text{Ne}$  - D. Chrisman et al., PR C104, 034313 (2021)



$^{11}\text{B}$  - Y. Assad, accepted in PRL (06/24/22)



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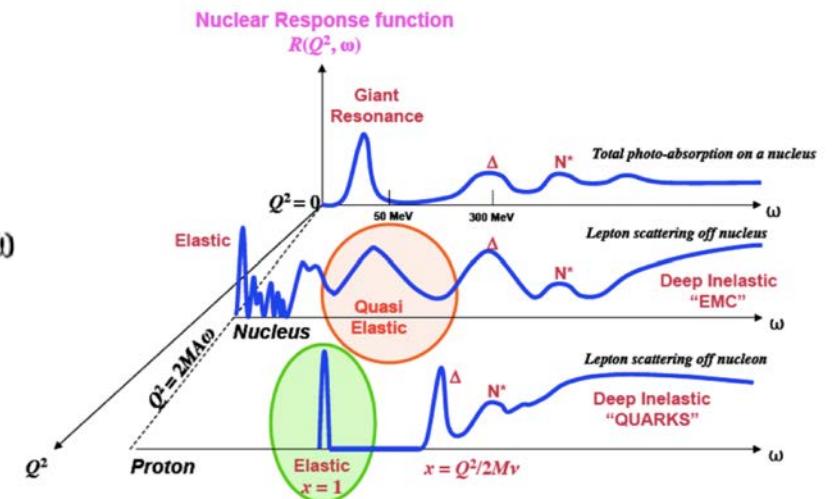
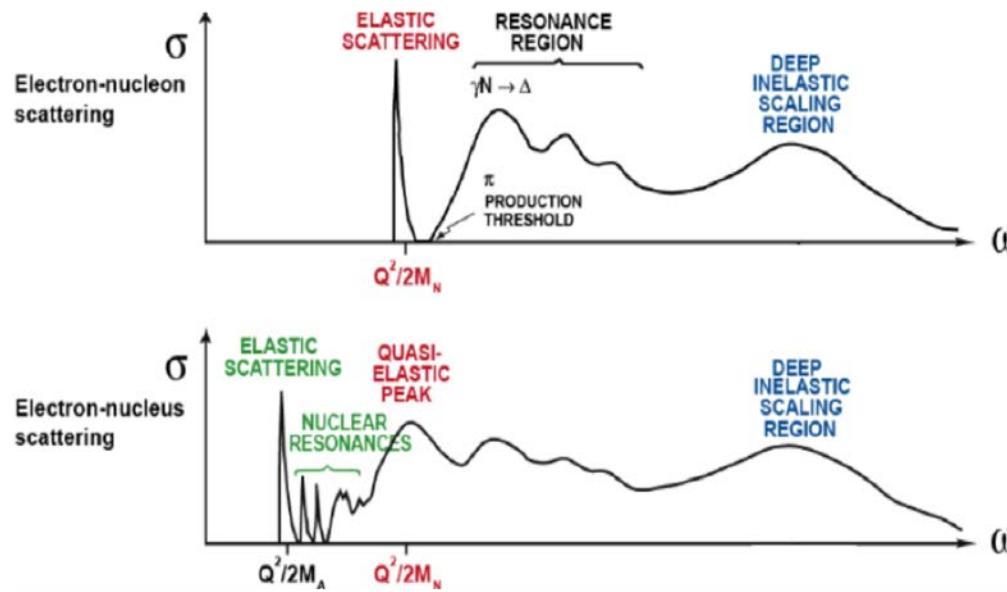


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# Probing nuclei and nucleons with electrons

The power of (electron) scattering experiments as a microscope

- A [beam] + B [target] = inside view of the nuclear matter!!
- **Invariant mass** technique probing **new particles/states**
- **Missing mass** technique probing **reaction mechanisms**

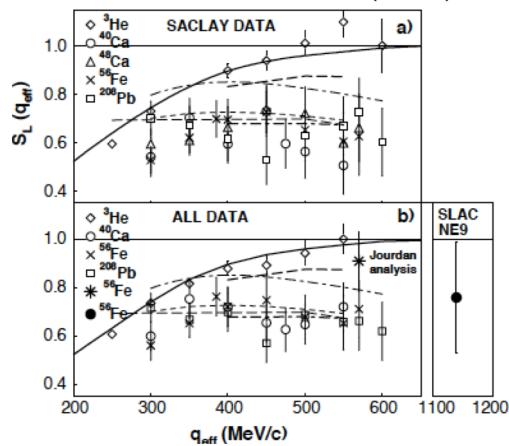


# What's going on with $>1\gamma$ ?

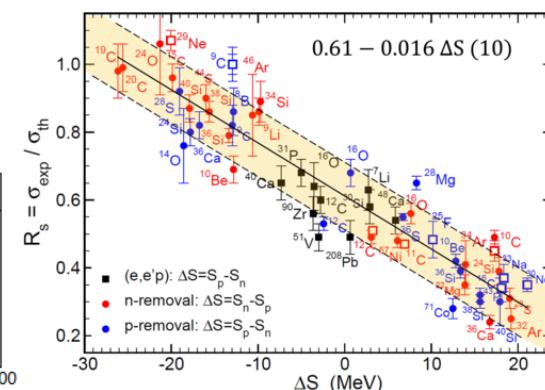
## In-medium nucleons & the Coulomb Sum Rule (CSR)

$$S_L(|\mathbf{q}|) = \int_{\omega>0}^{|q|} \frac{R_L(\omega, |\mathbf{q}|)}{ZG_{E_p}^2(Q^2) + NG_{E_n}^2(Q^2)} d\omega$$

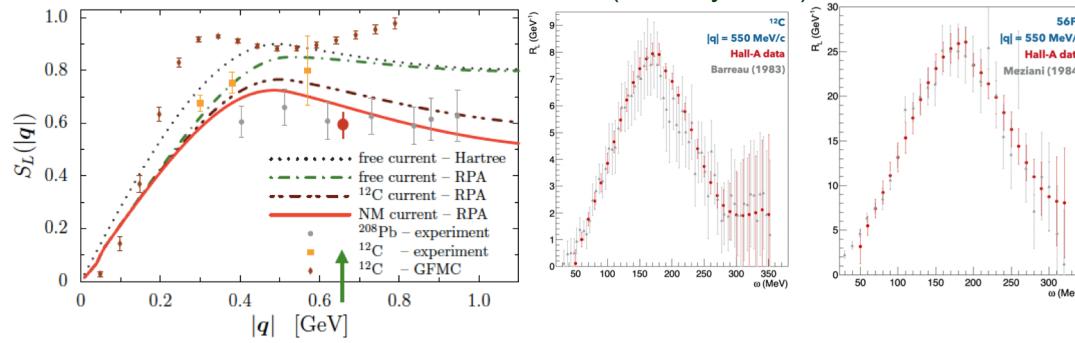
J. Morgenstern & Z. Meziani.  
EPJ, **A17**, 451–455, (2003)



J. A. Tostevin and A. Gade  
Phys. Rev. C **103**, 054610 (2021)

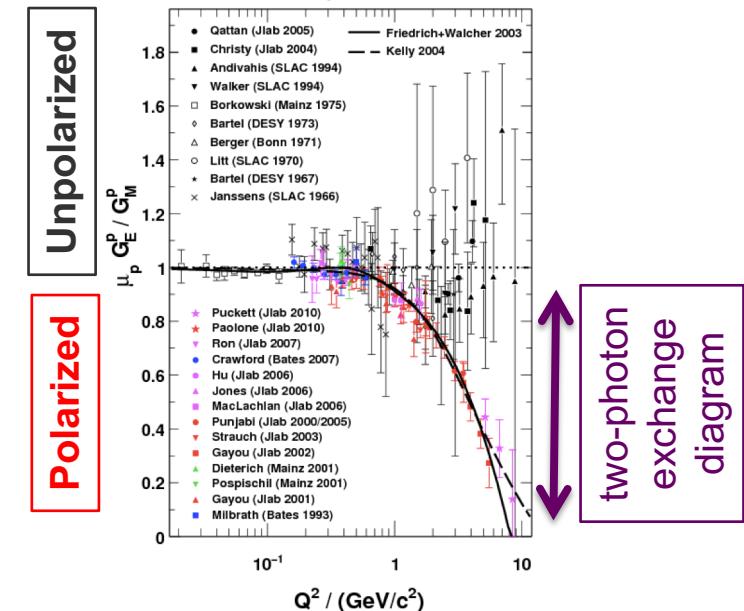


M. Paolone, JLab e05-110; CSR quenching?  
Hall A/C Collaboration (January 2022)

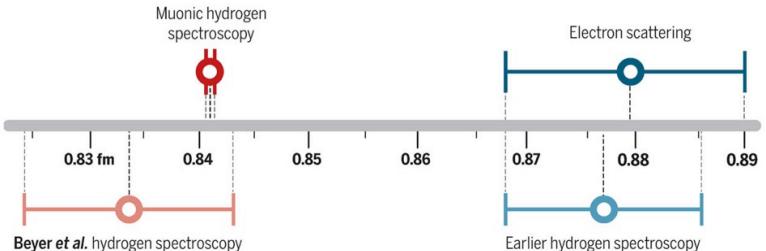


## Proton radius

M. Kohl, NSTAR2017  
Columbia, SC, August 20-23, 2017



W. Vassen, Science, **358**, 6359, pp. 39-40 (2017)  
R. Pohl, Nature, **466** (2010)



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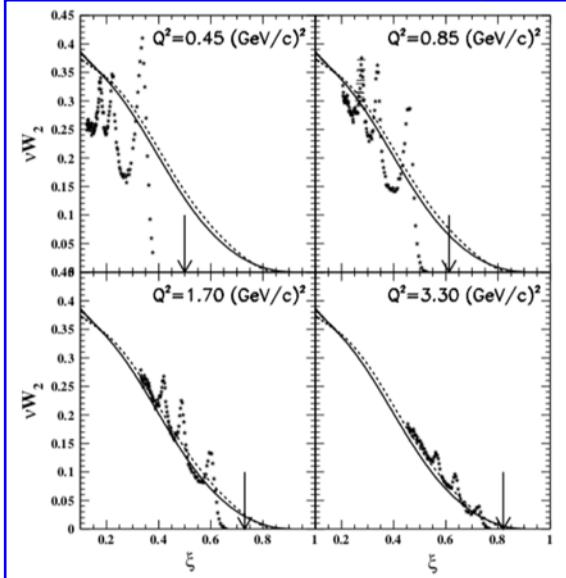
# Validation of Duality

Low Energy  
Nuclear Physics  
(nuclei)

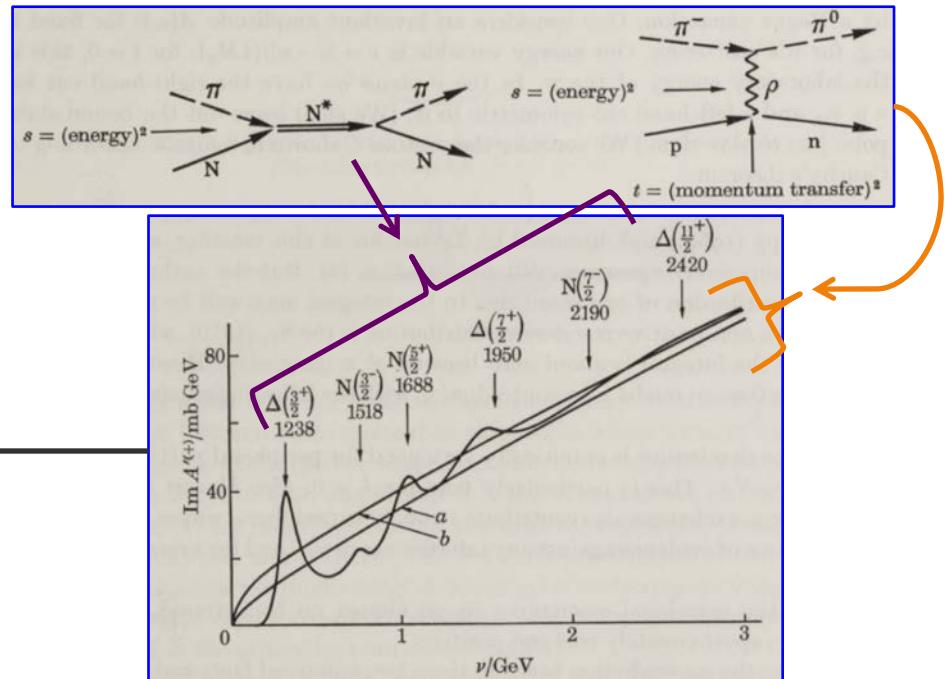
Intermediate Energy  
Nuclear Physics  
(nucleons)

High Energy  
Physics  
(quarks)

I. Niculescu, PRL 85, 1186 (2000)



C. Schmid, Proc. Roy. Soc. Lond., A318, 257 (1970)

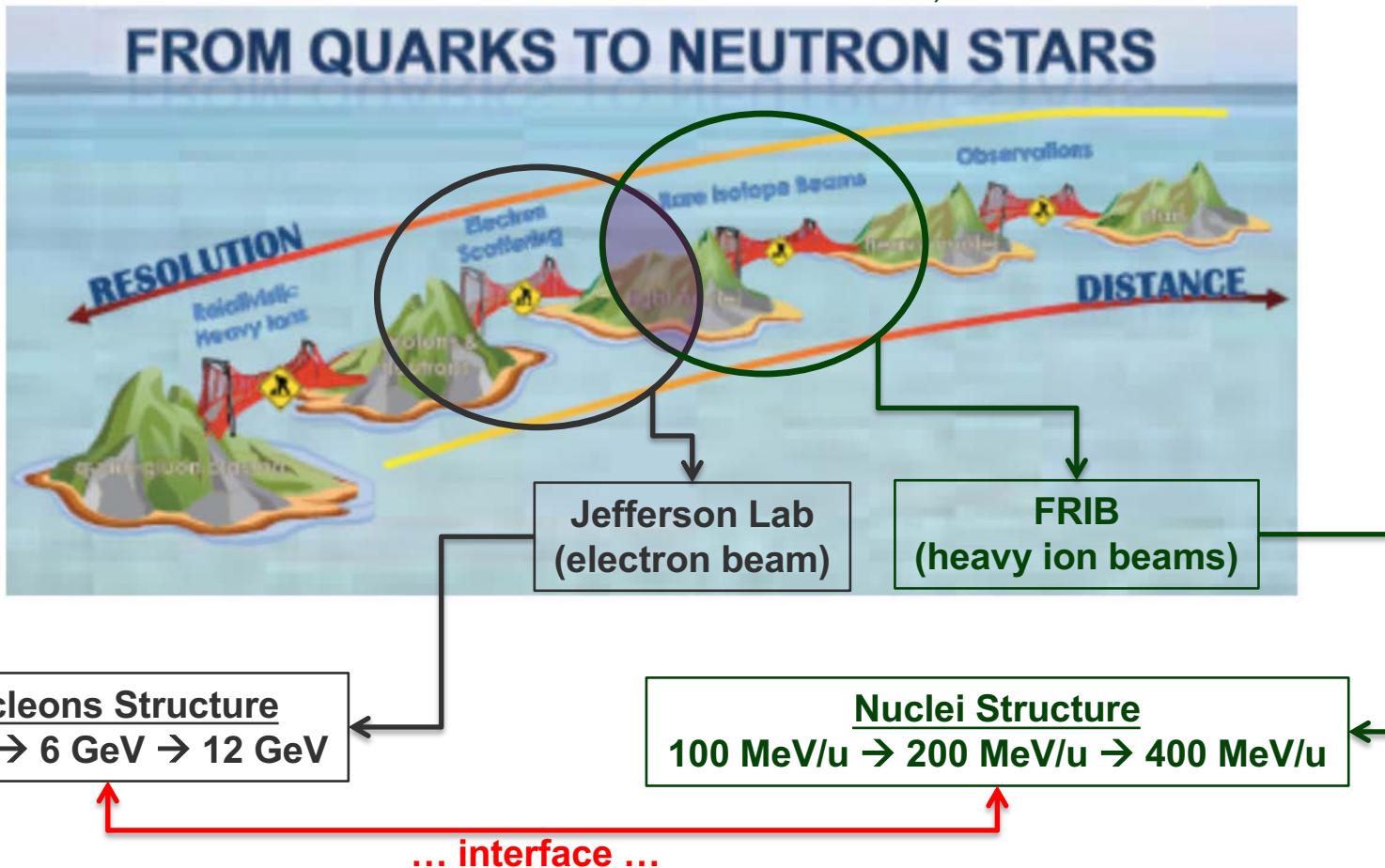


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# Two Probes + One Target = Scaling

The National Academies of Science, 2013



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# Outline

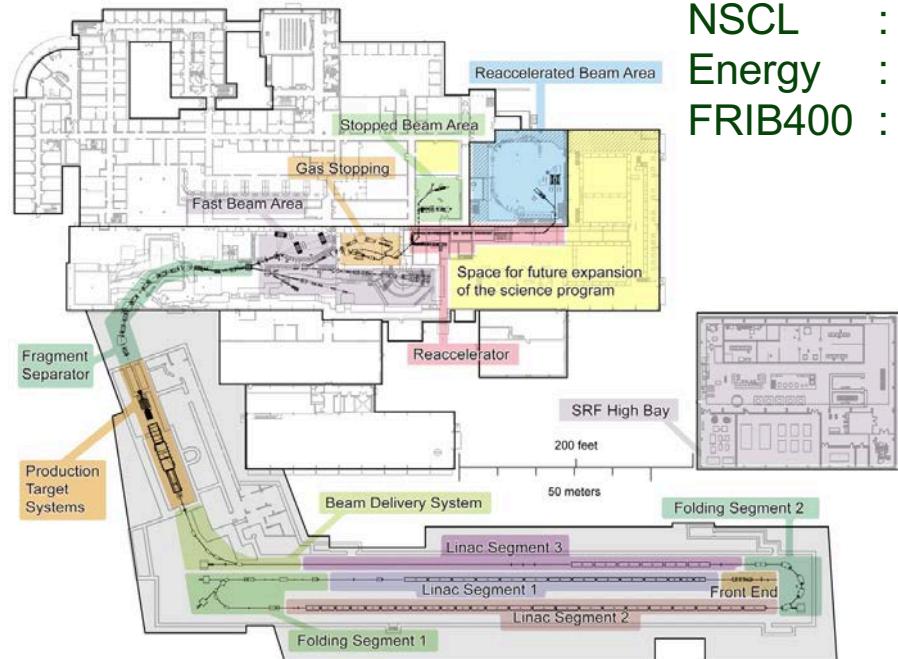
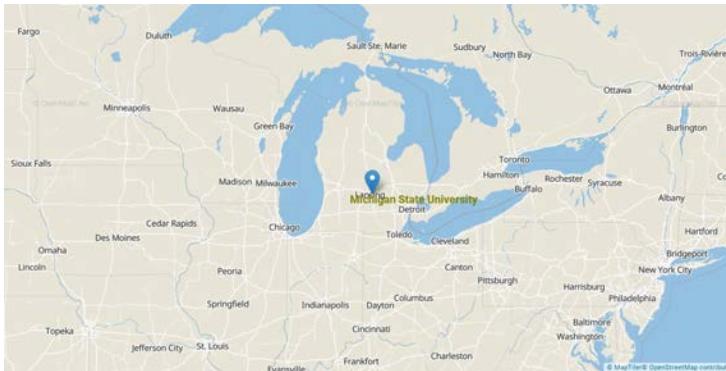
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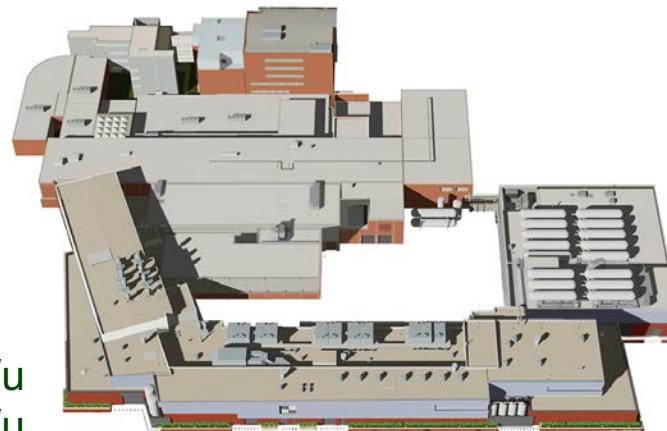
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# Facility for Rare Isotope Beams

([www.frib.msu.edu](http://www.frib.msu.edu); start: May 10, 2022!)



NSCL : ~100 MeV/u  
Energy : ~200 MeV/u  
FRIB400 : ~400 MeV/u

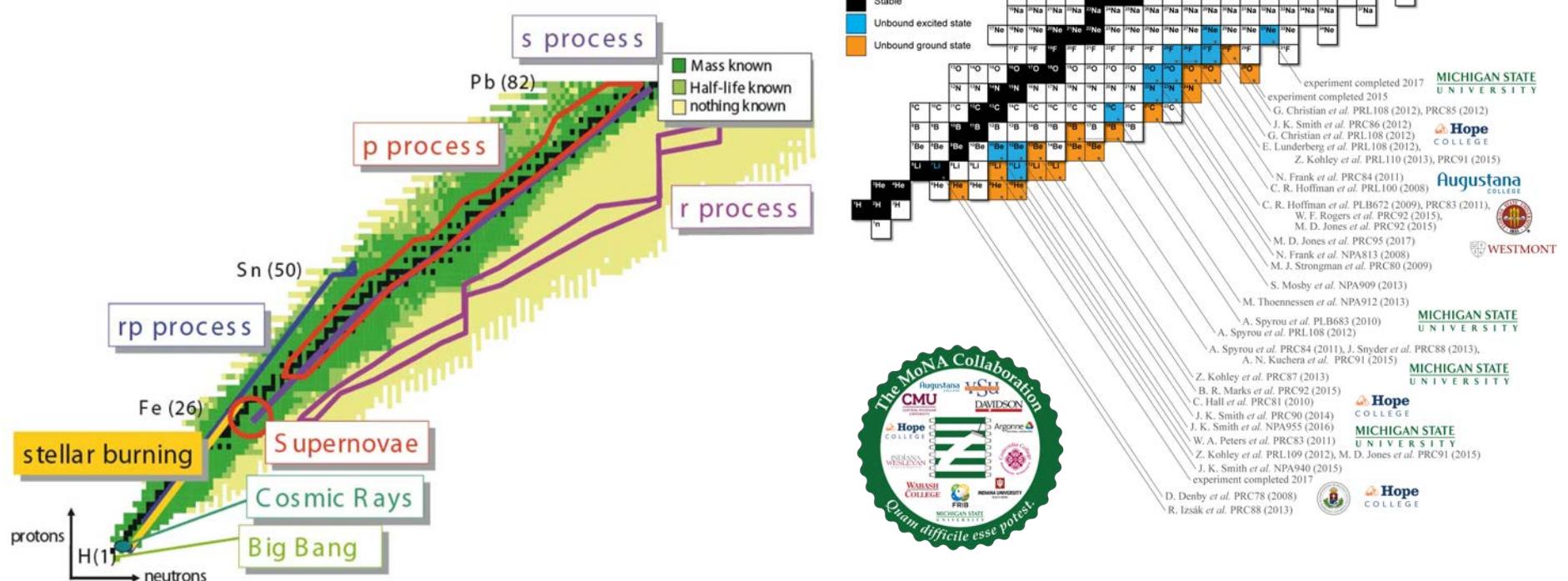


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# Nuclear Chart & Nuclear Science

~3,000 different isotopes to be enabled with FRIB



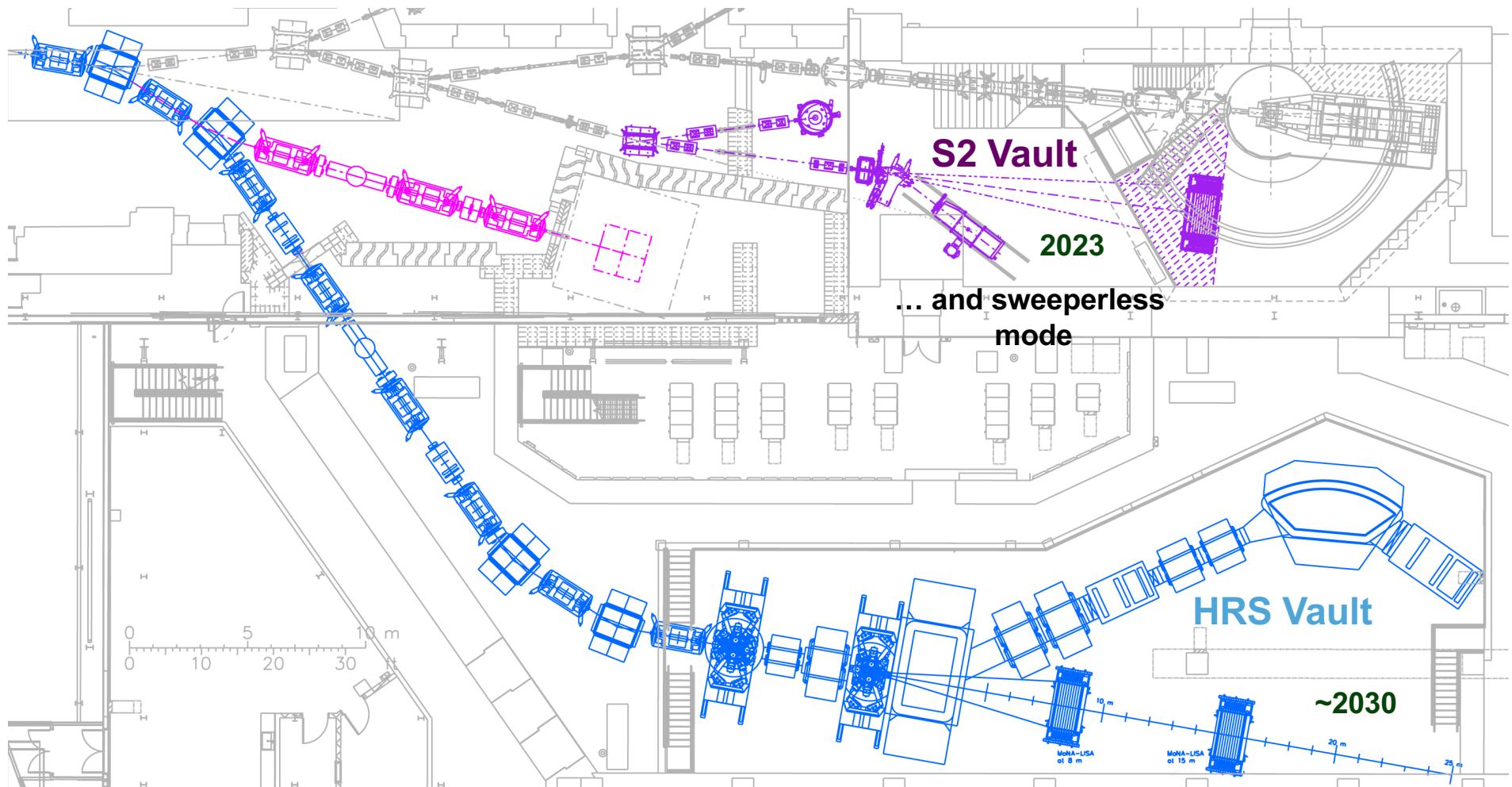
K.Blaum et al., Contemporary Physics, 51, 149-175 2010



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# The Facility for Rare Isotope Beams (and the MoNA-LISA System)

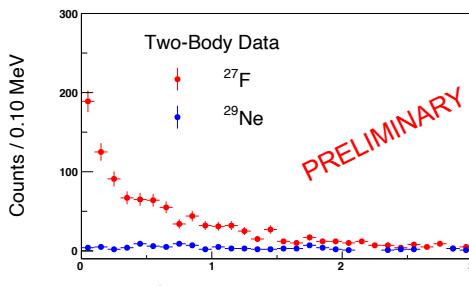
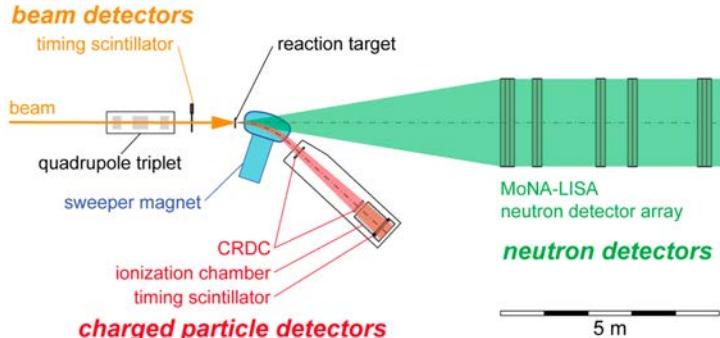


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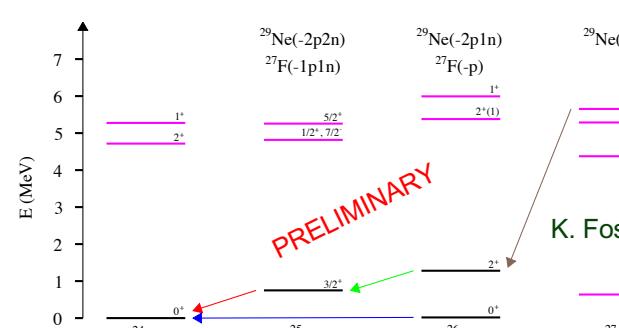
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# Invariant Mass Technique – 1

Beam + Target → Unbound(\*) → Fragments +  $[1..N_n]n$  ( $[1..N_\gamma]\gamma$ )



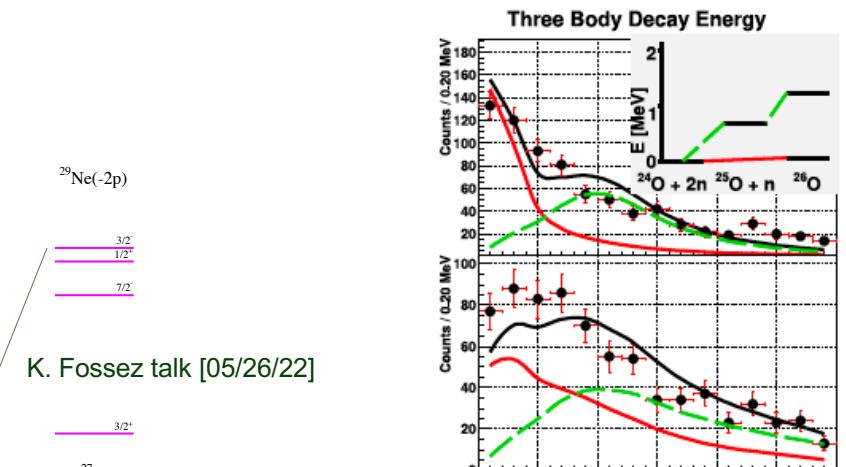
P. Gueye, in progress (2022)



**Invariant Mass Technique**  
Beam + Target → Unst. Isotope: X[n-rich]  
X[n-rich] → Fragment + neutron(s)

$$\begin{aligned} E_U &= E_F + E_n \\ \vec{P}_U &= \vec{P}_F + \vec{P}_n \end{aligned} \} \rightarrow M_U = \sqrt{E_U^2 - \vec{P}_U^2}$$

$$E_{decay} = \sqrt{M_F^2 + M_n^2 + 2(E_F E_n - \vec{P}_F \cdot \vec{P}_n)} - (M_F + M_n)$$



T. Redpath et al, NIMA (2020)



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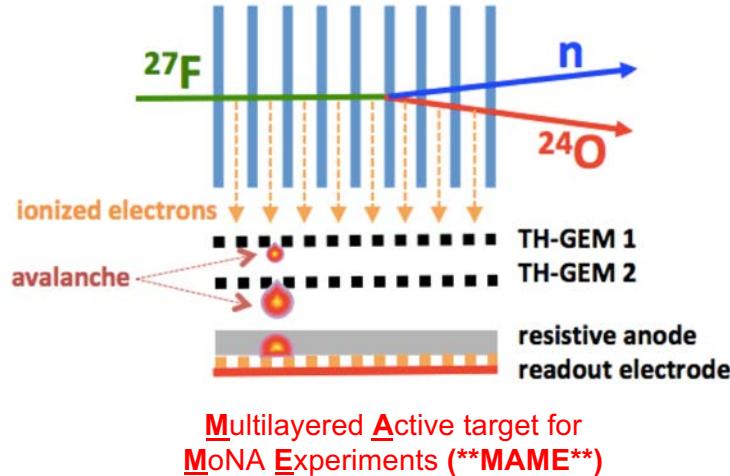


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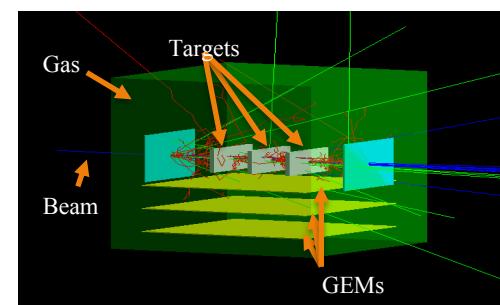
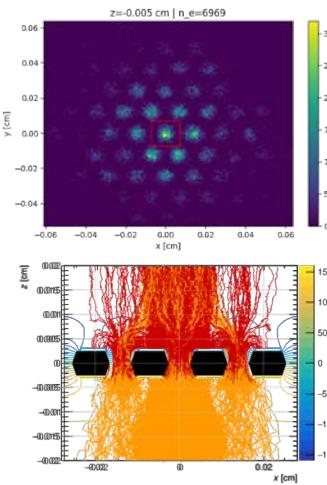
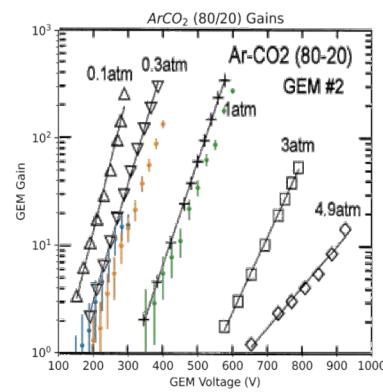
# Senegalese Main Dish!! (... and seasonings)



# From Invariant Mass to Missing Mass (enabling reaction mechanisms)



- beam + target  $\rightarrow$  unbound + [X]
- Missing mass capability
  - MoNA targets: 3-9 mm thick
  - Be foils: 18 x 0.5 mm
  - Box: 10 cm x 10 cm x 15 cm
  - Gas filled TH-GEM
  - Detect low energy species (fragments, n, p, recoil)



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# Nuclear (femto)Tomography? What About Polarization?

Meson electro-production

$$\begin{aligned} \frac{d\sigma_v}{d\Omega_\eta} = & \frac{|\mathbf{k}|}{k_{\gamma}^{cm}} P_\alpha P_\beta \{ R_T^{\beta\alpha} + \varepsilon_L R_L^{\beta\alpha} \\ & + [2\varepsilon_L(1+\varepsilon)]^{1/2} ({}^cR_{TL}^{\beta\alpha} \cos \phi_\eta + {}^sR_{TL}^{\beta\alpha} \sin \phi_\eta) \\ & + \varepsilon ({}^cR_{TT}^{\beta\alpha} \cos 2\phi_\eta + {}^sR_{TT}^{\beta\alpha} \sin 2\phi_\eta) \\ & + h [2\varepsilon_L(1-\varepsilon)]^{1/2} ({}^cR_{TL'}^{\beta\alpha} \cos \phi_\eta + {}^sR_{TL'}^{\beta\alpha} \sin \phi_\eta) \\ & + h(1-\varepsilon^2)^{1/2} R_{TT'}^{\beta\alpha} \}, \end{aligned} \quad (12)$$

G. Knöchlein, D. Drechsel, L. Tiator  
Z. Phys. **A352**, 327-343 (1995)

**3D nucleon tomography!!  
(DVCs, parton distributions ...)**

**Table 1.** Polarization observables in pseudoscalar meson electroproduction. A star denotes a response function which does not vanish but is identical to another response function via a relation in App. A

		Target			Recoil			Target + Recoil								
$\beta$	$\alpha$	-	-	-	$x'$	$y'$	$z'$	$x'$	$x'$	$x'$	$y'$	$y'$	$y'$	$z'$	$z'$	$z'$
$T$	$R_T^{00}$	0	$R_T^{0y}$	0	0	$R_T^{y'0}$	0	$R_T^{x'x}$	0	$R_T^{x'z}$	0	*	0	$R_T^{z'x}$	0	$R_T^{z'z}$
$L$	$R_L^{00}$	0	$R_L^{0y}$	0	0	*	0	$R_L^{x'x}$	0	$R_L^{x'z}$	0	*	0	*	0	*
${}^cTL$	${}^cR_{TL}^{00}$	0	${}^cR_{TL}^{0y}$	0	0	*	0	${}^cR_{TL}^{x'x}$	0	*	0	*	0	${}^cR_{TL}^{z'x}$	0	*
${}^sTL$	0	${}^sR_{TL}^{0x}$	0	${}^sR_{TL}^{0z}$	${}^sR_{TL}^{x'0}$	0	${}^sR_{TL}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^cTT$	${}^cR_{TT}^{00}$	0	*	0	0	*	0	*	0	*	0	*	0	*	0	*
${}^sTT$	0	${}^sR_{TT}^{0x}$	0	${}^sR_{TT}^{0z}$	${}^sR_{TT}^{x'0}$	0	${}^sR_{TT}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^cTL'$	0	${}^cR_{TL'}^{0x}$	0	${}^cR_{TL'}^{0z}$	${}^cR_{TL'}^{x'0}$	0	${}^cR_{TL'}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^sTL'$	${}^sR_{TL'}^{00}$	0	${}^sR_{TL'}^{0y}$	0	0	*	0	${}^sR_{TL'}^{x'x}$	0	*	0	*	0	${}^sR_{TL'}^{z'x}$	0	*
$TT'$	0	$R_{TT'}^{0x}$	0	$R_{TT'}^{0z}$	$R_{TT'}^{x'0}$	0	$R_{TT'}^{z'0}$	0	*	0	*	0	*	0	*	0



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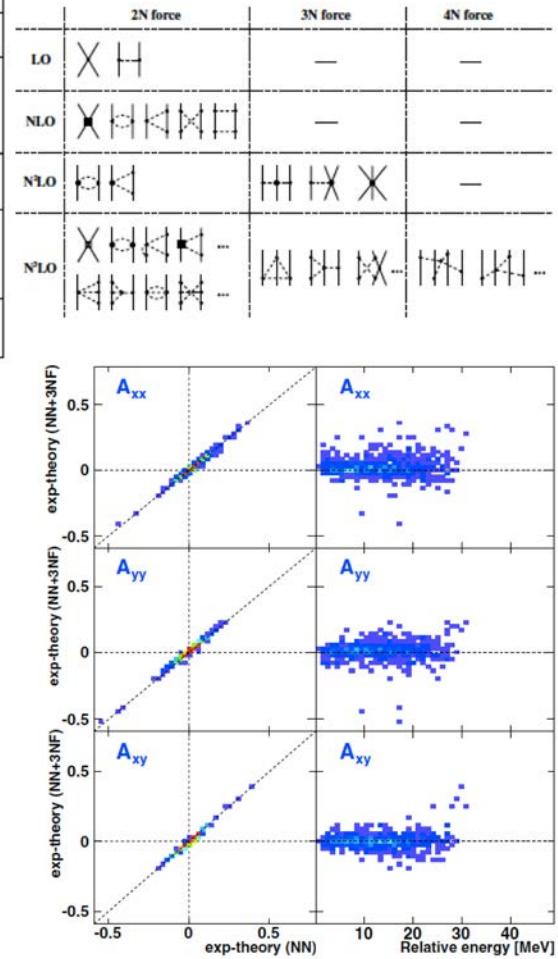
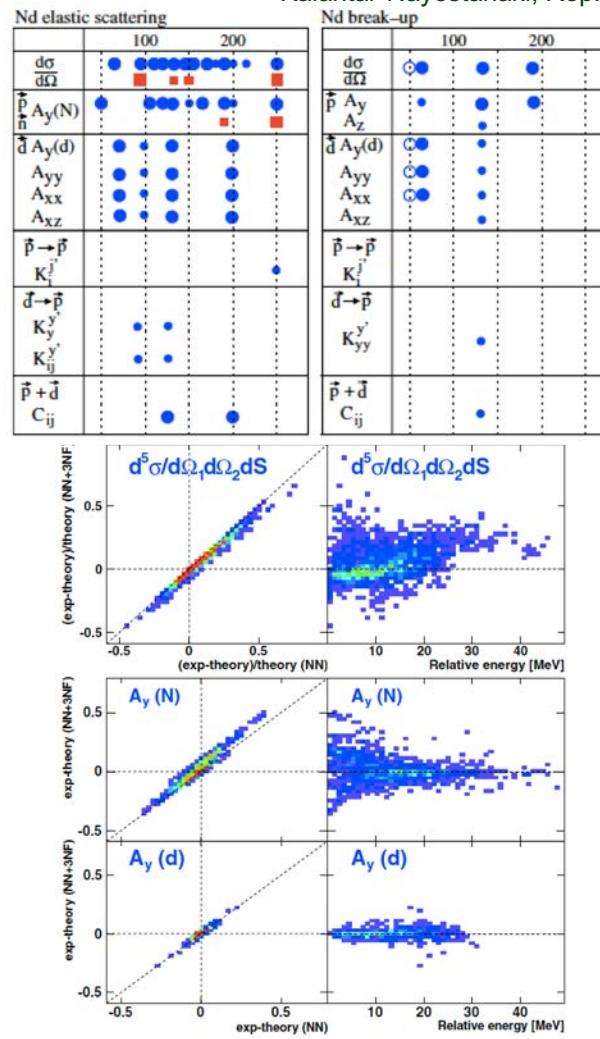
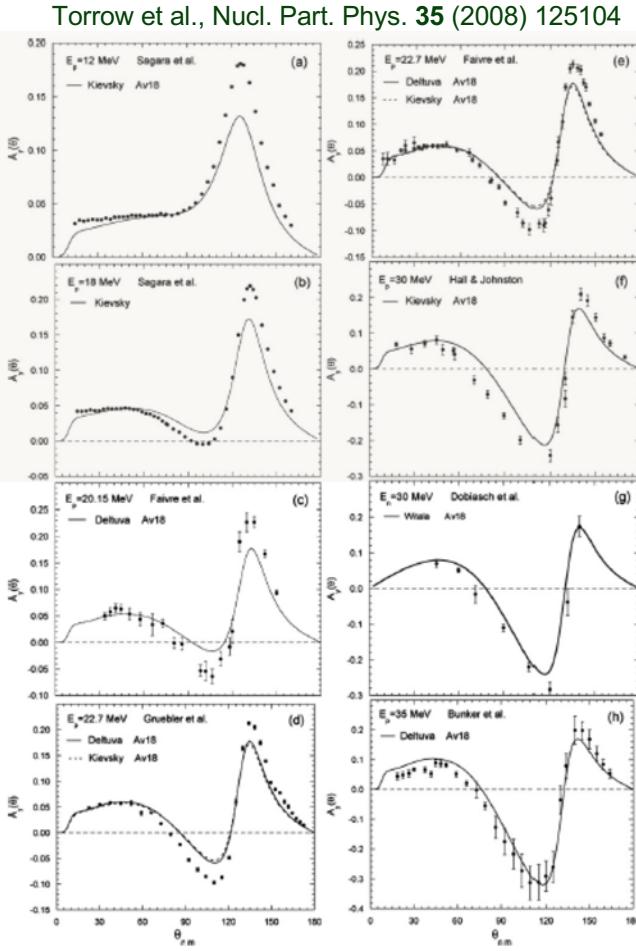
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# Polarization in Heavy Ion Physics

## See Talk from Emiko Hiyama (RIKEN) [06/24/22]

Kalantar-Nayestanaki, Rep. Prog. Phys. **75** (2012) 016301

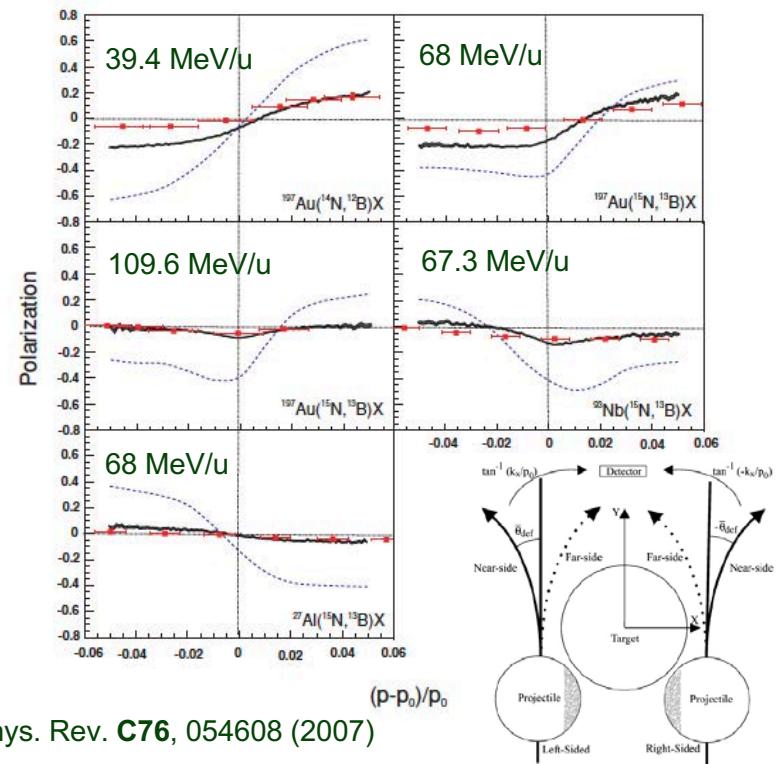


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# Measuring Polarized Observables with Rare Isotopes – 1

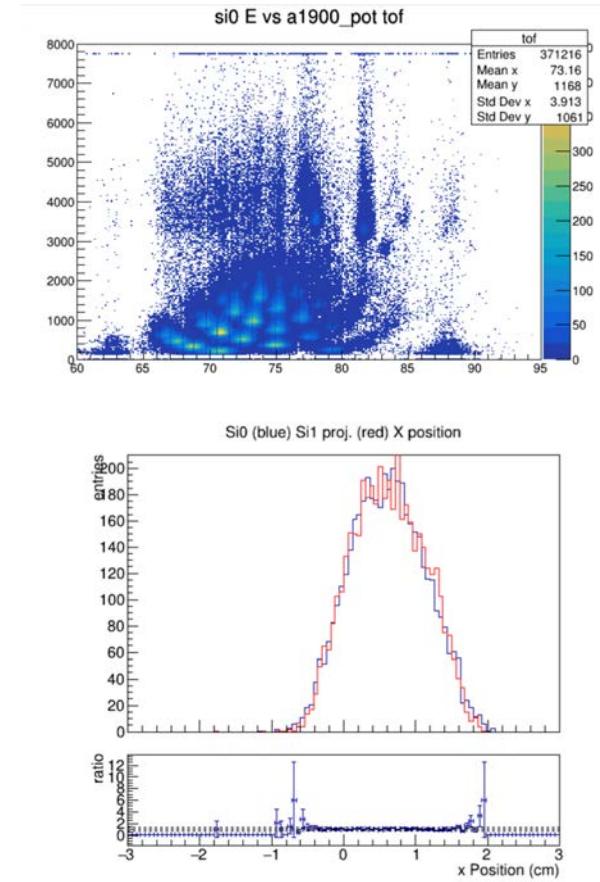
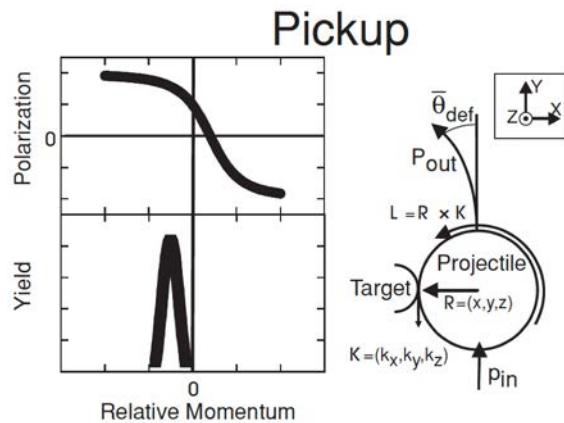
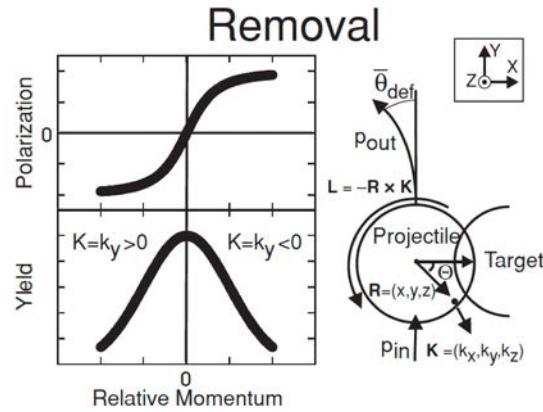
- Another “nitch” @ FRIB
- Beam polarization
  - ✓ Spin polarization in nuclear structure: allows spin-parity assignment
  - ✓ Fragments are (always) longitudinally polarized:  
spin flip (polarized  $^{31}\text{Na}^+$  @ TRIUMF)
  - ✓ Some good references
    - P. Mantica *et al.*, Phys. Rev. **C55**, 2501 (1997)
    - D. Hoff *et al.*, PRL **119**, 232501 (2017);
    - D. Hoff *et al.*, Phys. Rev. **C97**, 054605 (2018)
- Target polarization
  - ✓ The  $A_y$  puzzle (n-d scattering)
  - ✓ Asymmetry in  $<30$  MeV
  - 3N & 4N forces



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# Measuring Polarized Observables with Rare Isotopes – 2

- [Another] monitoring of (fast) beam polarization



# Polarized $e^\pm$ -RIBs

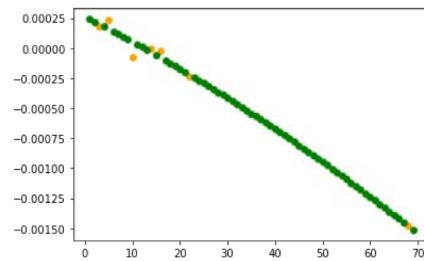
## RIBs Radii

M. Wallach

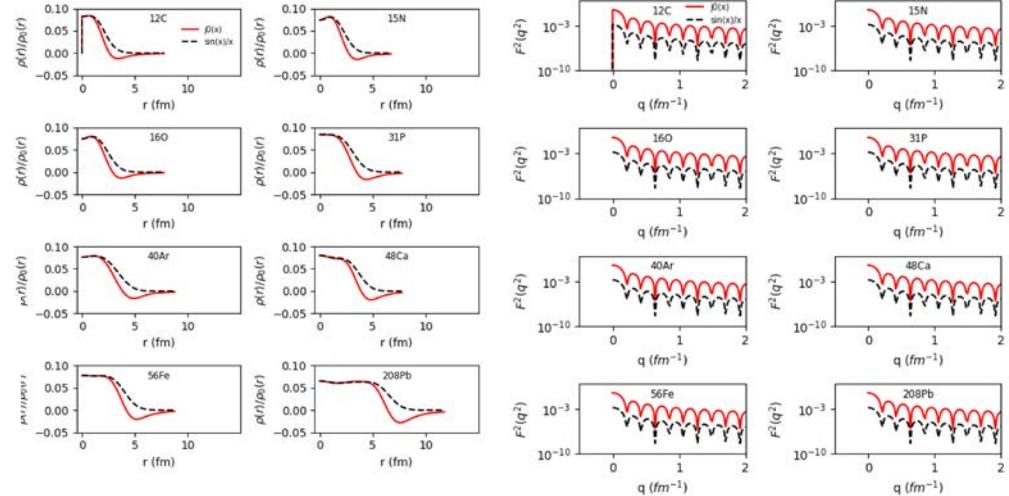
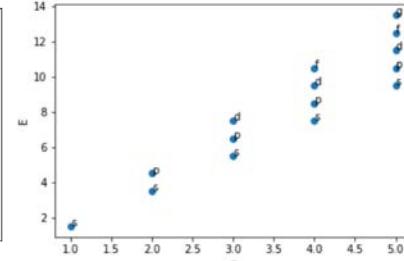
- Nuclear charge distributions
- Bessel function parameterization
  - ✓ Extrapolation of Bessel coefficients
  - ✓ Expansion to unstable isotopes



## Interpolation/extrapolation of Bessel a1



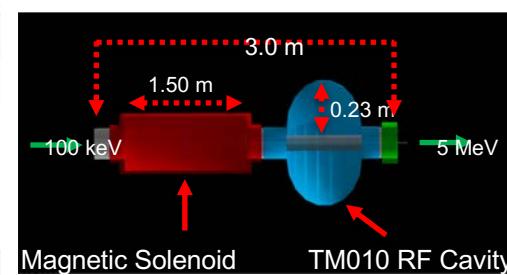
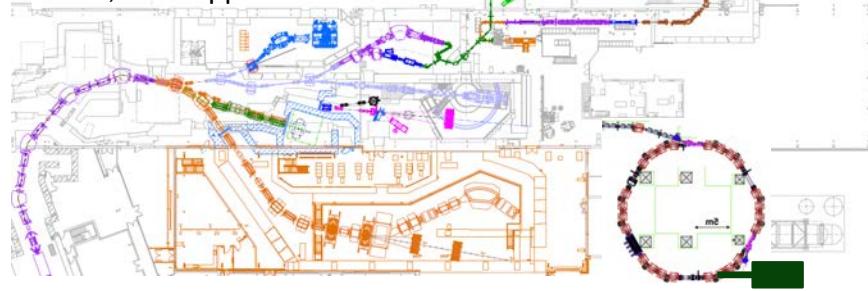
## Shel model Harmonic oscillator



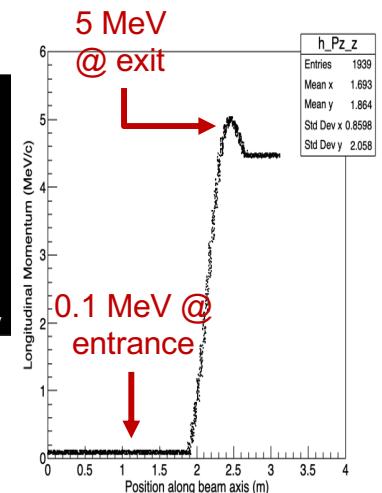
## Compact $e^\pm$ linac/RIBs

L. Harris, M. Wallach

- Polarized  $e^\pm$  scattering off rare isotopes
- Coupling to storage ring FRIB project
- Nuclear radii, Born approximation



Had two brainstorming meetings  
03/25/22 & 04/01/22



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Michigan State University

# Outline

- Human & Nature: two sides of the same coin
- Open Quantum Systems
  - A brief introduction
  - Two examples:  $^{31}\text{Ne}$  &  $^{11}\text{B}$
- Short detour to electron scattering
  - One-photon approximation issue
  - Duality
- FRIB and MoNA-LISA
- What else can't we “see”?
- Summary



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# Summary

- **Exciting time ...**

- Start of FRIB producing RIBs from  $^{235}\text{U}$  with up to 200 MeV/u
- Push our understanding of nuclear matter in completely new regime
- Access new neutron/proton-rich nuclei
- Test location of the n-dripline
- ... and accelerator, isotopes harvesting for basic (targetry)/applied nuclear science

- **Even more ...**

- Unexpected physics, behaviors in the data
- New thinking on how nuclei behave/nucleon interactions
- New ideas (theories and techniques) to model/probe nuclei



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# Research Group (Spring 2022)

**Thomas Baumann**  
MoNA device physicist  
Experimental Physics (2020)



**Thomas Redpath**  
MSU grad, 2019  
MSI Fellow (2020)  
Virginia State Ass. Prof. (2021)



**Belen Monteagudo Godoy**  
Postdoc (2020)  
Hope Faculty Fellow/FRIB  
[Ass. Prof.] (2021)



**Clémentine Santamaria**  
Postdoc [W. Mittig] (2021)  
MSI Fellow (2021)  
Morgan State, Ass. Prof. (2021)



**Dayah Chrisman**  
(Spring 2022)



**Xinyi Wang**  
(3<sup>rd</sup> year)



**Andrew Wantz**  
(2<sup>nd</sup> year)



**Georgia Votta**  
(1<sup>st</sup> year)



**Nicholas Mendez**  
(1<sup>st</sup> year)



**Lettrell Harris**  
(1<sup>st</sup> year)



## Graduate Students +2 (Fall 2022)

**Sokhna Bineta Lo Amar**  
Postdoc, MSU/AAP  
(2021)



**Pierre Nzabahimana**  
(4<sup>th</sup> year)  
Advisor: Pawel Danielewicz



**Tracy Edwards**  
(2<sup>nd</sup> year)  
Advisor: Greg Severin



**Undergraduate/high school students**  
**MSU:** Phuonganh Pham, Paige Lyons, Maya Wallach, Jared Bloch, Anna Brandl, Emily Holman, Emma Benedek, Turuu Ariunbold, Justin Schmitz, Miles Klapthor, Sara Tatreau, Thomas Webb – **MSI:** Toni Trail, Isaiah Marshall, Joi Malone – **Africa:** Faith Cherop , Yoann Gueye, Ngono Afefa Reine De Lima (Lumière), Ange Ntivuguruzwa + NSF/DoE Programs (PING [NSF], INSIGHT [DoE] ...)



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# Thank You!

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