from outer space to deep inside: exploring neutron skins

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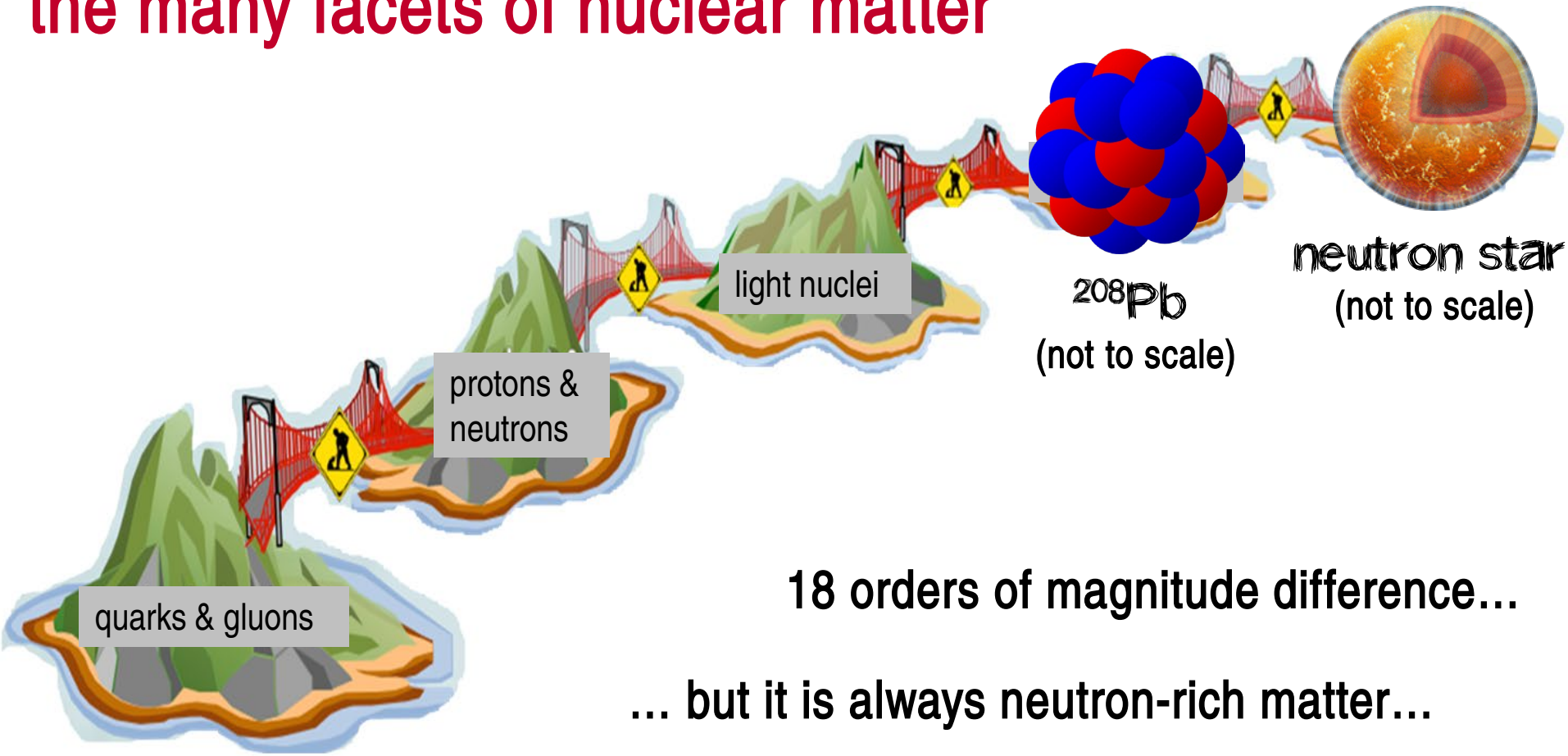
on behalf of the A1 and P2 collaborations
Institut für Kernphysik, Johannes Gutenberg-Universität Mainz

QNP2022
the 9th International Conference
on Quarks and Nuclear Physics
September 5-9, 2022
online conference

the many facets of nuclear matter

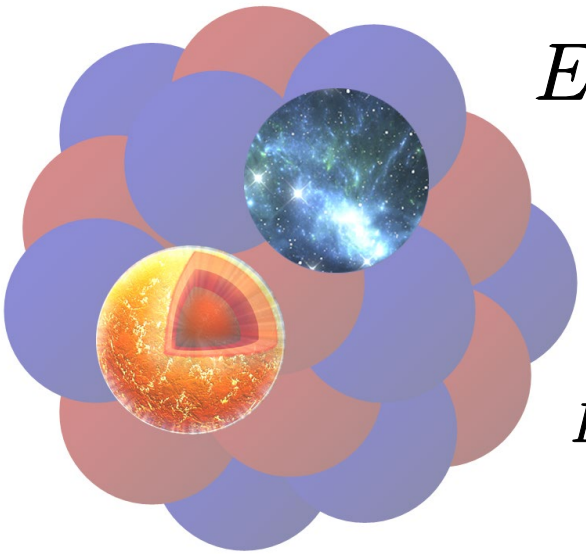


18 orders of magnitude difference…

… but it is always neutron-rich matter…

…described by the same nuclear Equation Of State

Equation Of State



$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + \mathcal{O}(\delta)^4$$

with $\boldsymbol{\delta} = \frac{\rho_n - \rho_p}{\rho}$

symmetry energy

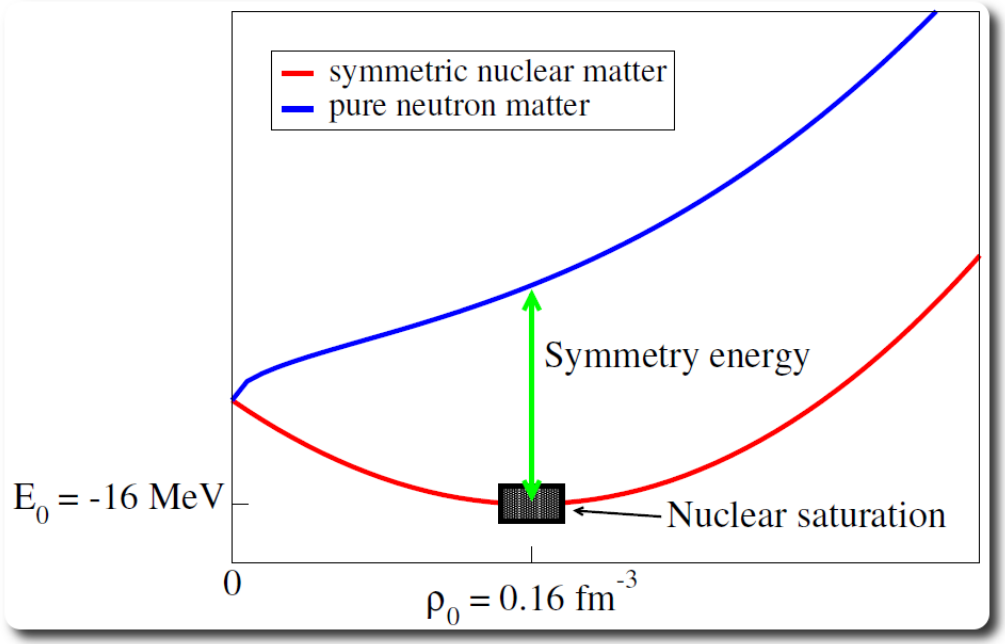
$$E_{sym}(\rho) = \left[S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2\right] + \ldots$$

slope parameter

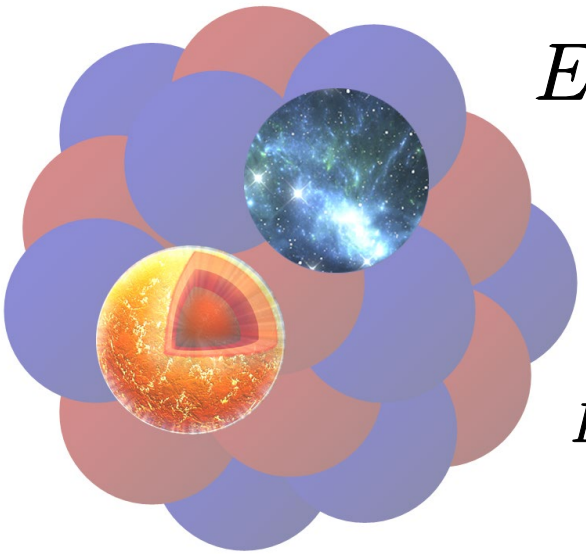
$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\bigg|_{\rho_0}$$

curvature parameter

$$K_{sym} = 9\rho_0^2 \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\bigg|_{\rho_0}$$



Equation Of State



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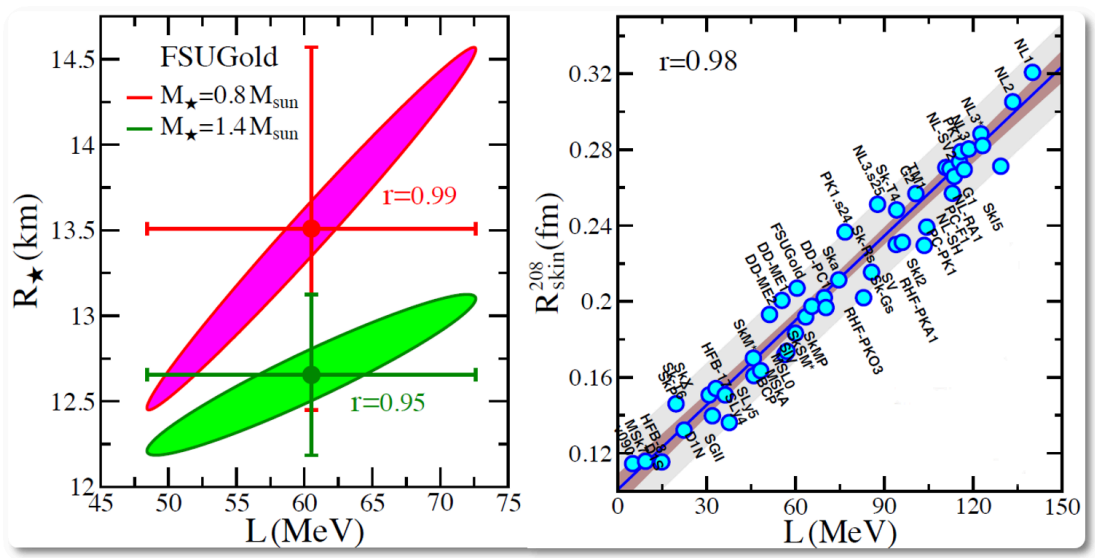
slope parameter

$L =$

cu

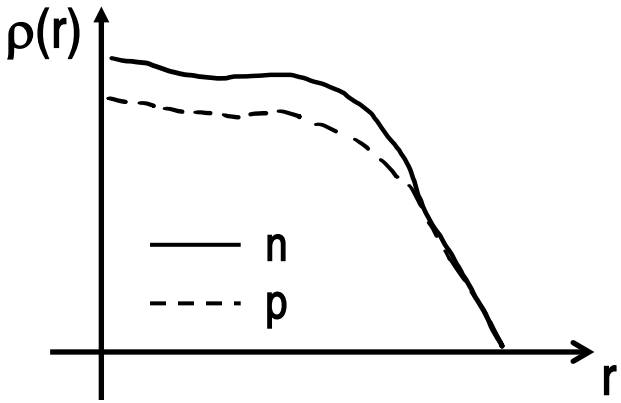
K_{sy} $\Big|_{\rho_0}$

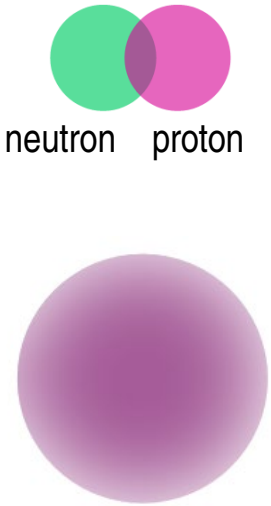


J. Piekarewicz and F.J. Fattoyev, Physics Today 72, 7, 30 (2019)

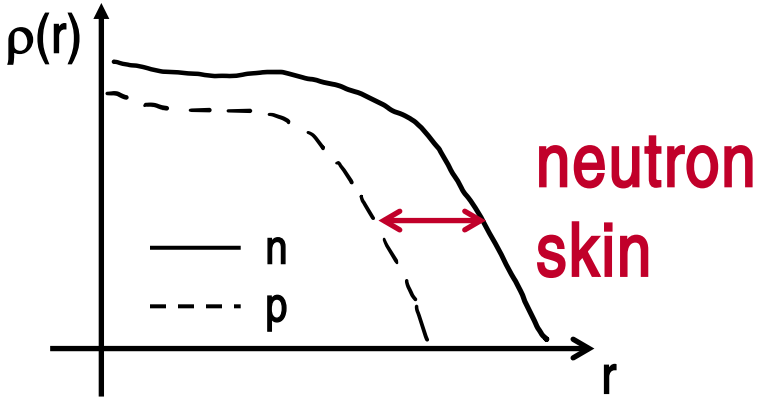
neutron skin

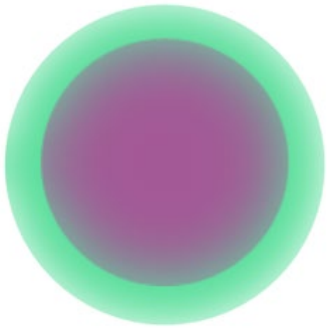
stable nuclei (N≈Z)





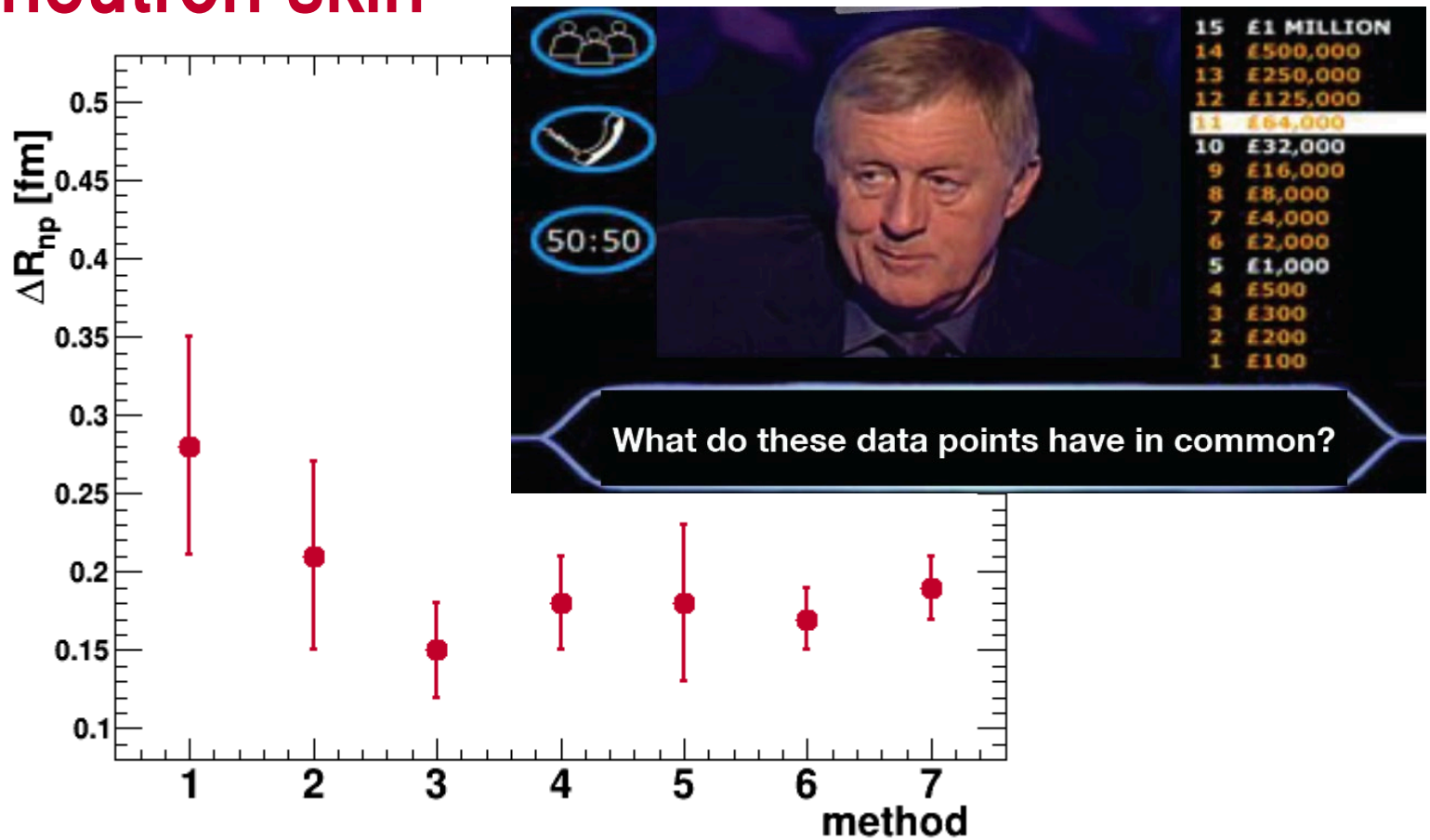
neutron rich nuclei (N>>Z)



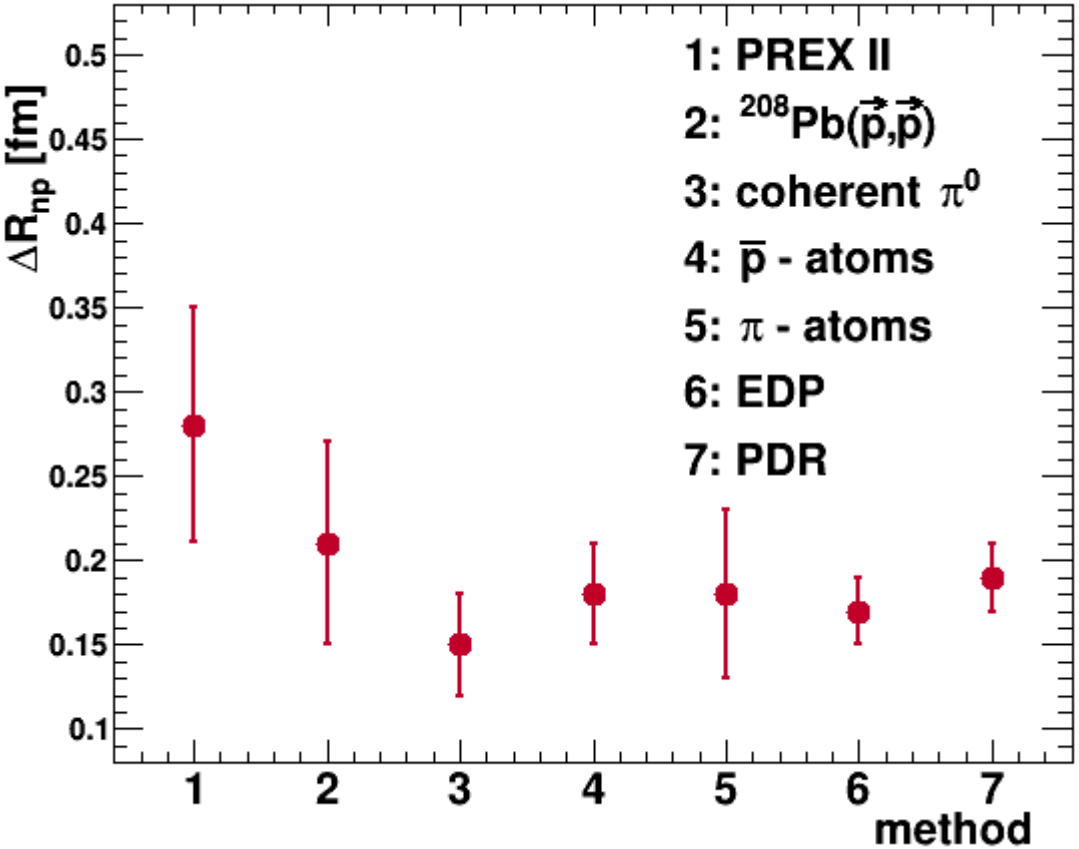


pressure forces neutrons out against surface tension

neutron skin

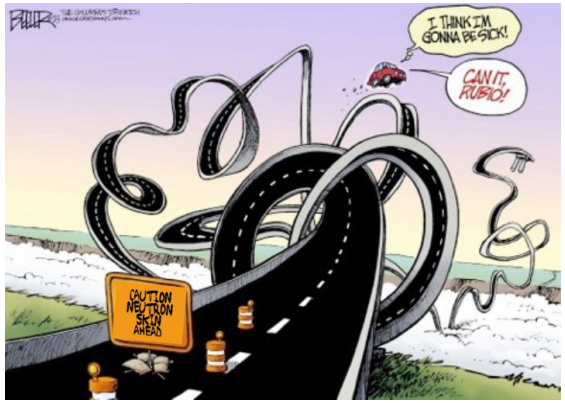


neutron skin



none

is an actual measurement of neutron skin!



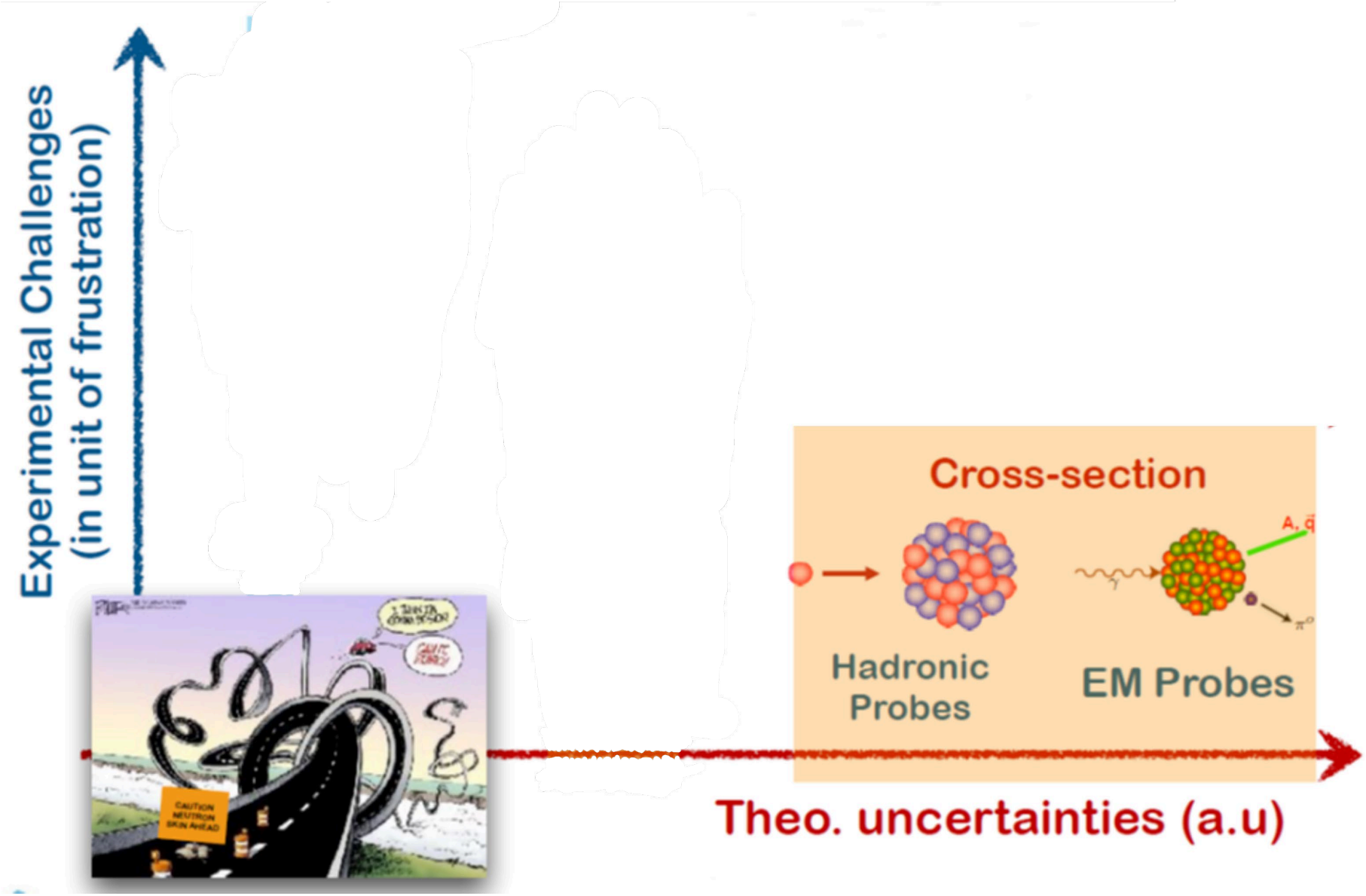
from measurable observables to neutron skin

highway to hell or stairway to heaven?

Experimental Challenges
(in unit of frustration)

Theo. uncertainties (a.u)

highway to hell or stairway to heaven?



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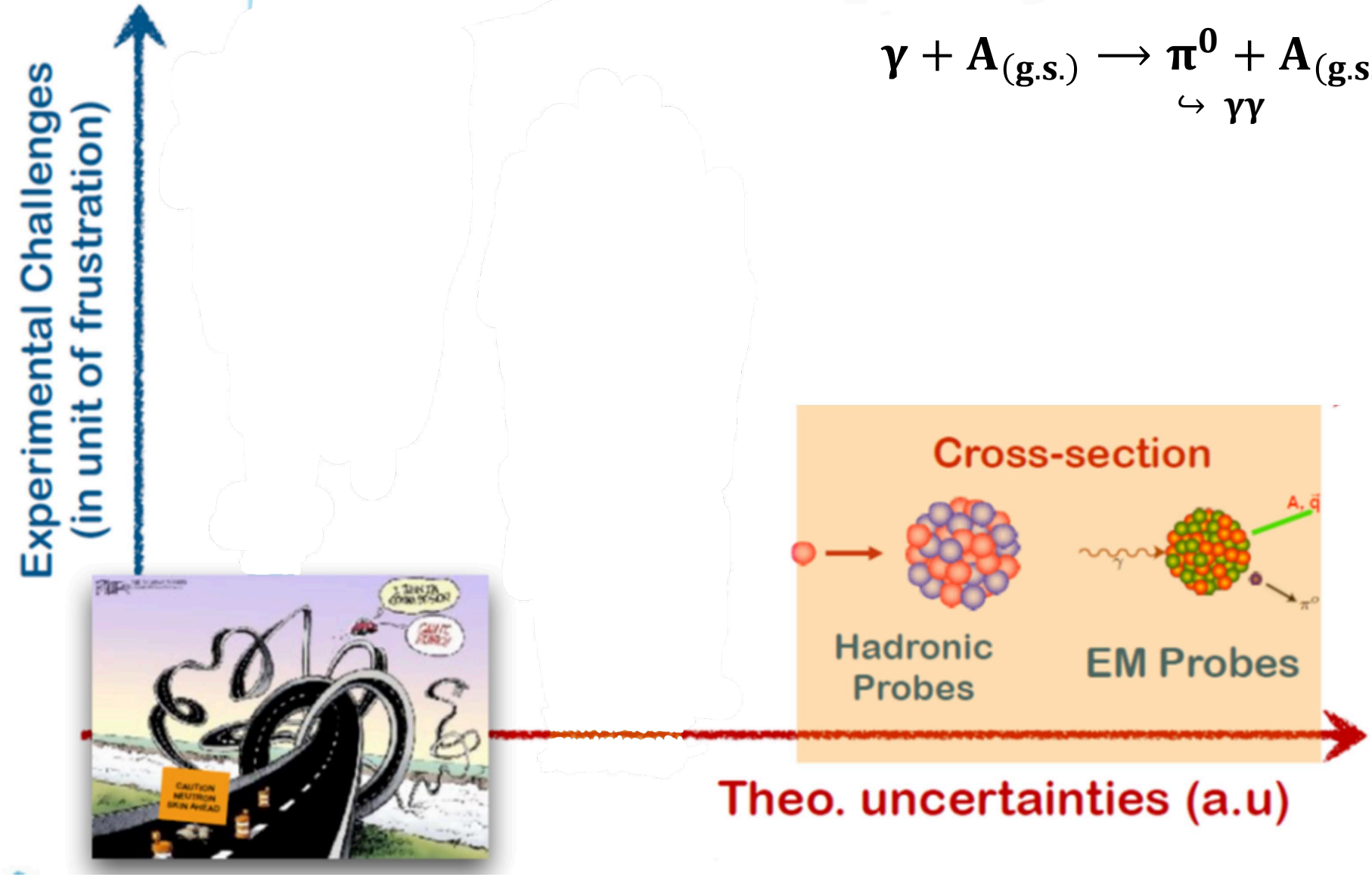
$$\gamma + A_{(g.s.)} \longrightarrow \pi^0 + A_{(g.s.)}$$
$$\hookrightarrow \gamma\gamma$$



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Featured in Physics | Editors' Suggestion

Neutron Skin of ^{208}Pb from Coherent Pion Photoproduction

C. M. Tarbert *et al.* (Crystal Ball at MAMI and A2 Collaboration)
Phys. Rev. Lett. **112**, 242502 – Published 18 June 2014

Physics See Synopsis: Neutron Skin Turns Out to Be Soft

$$\Delta r_{np} = 0.15 \pm 0.03(\text{stat.})^{+0.01}_{-0.03}(\text{sys.})\,\text{fm}$$

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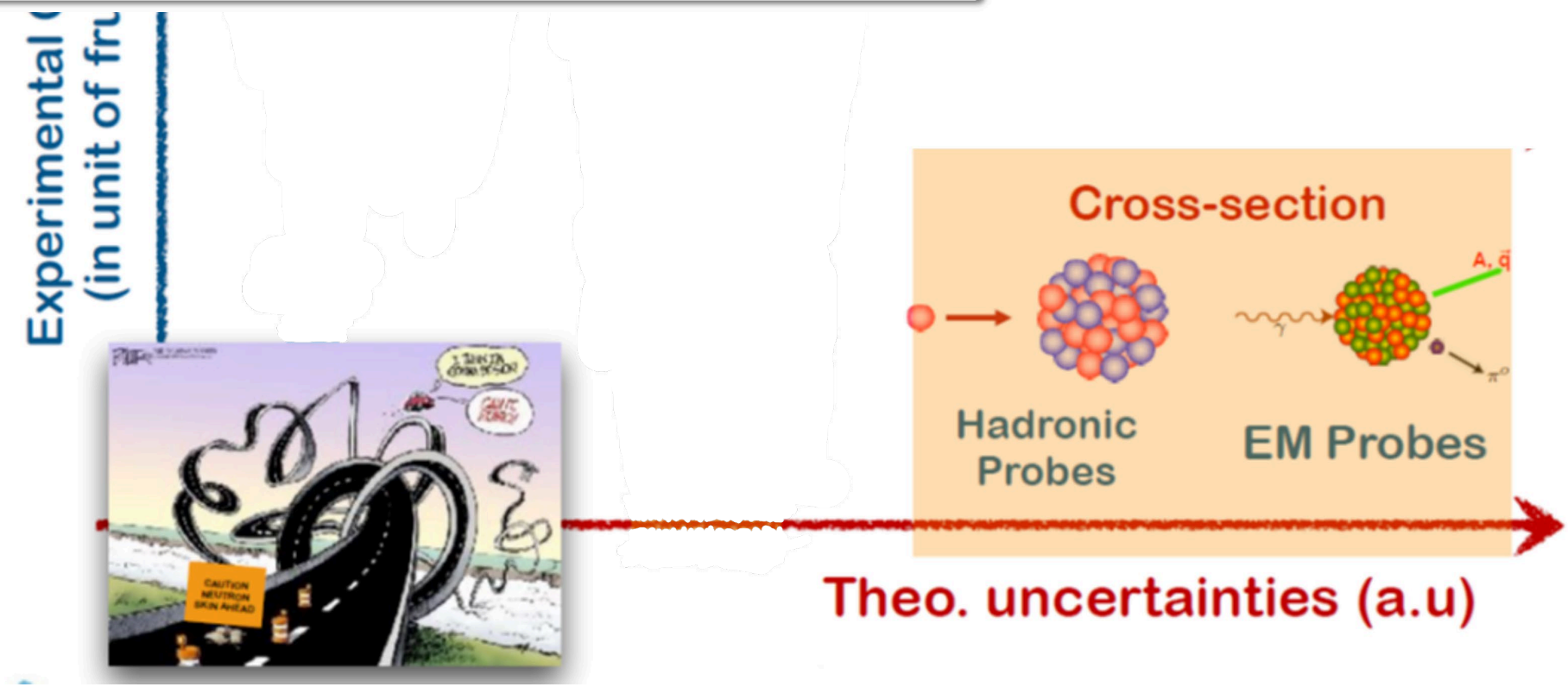

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Theoretical analysis of the extraction of neutron skin thickness from coherent π^0 photoproduction off nuclei

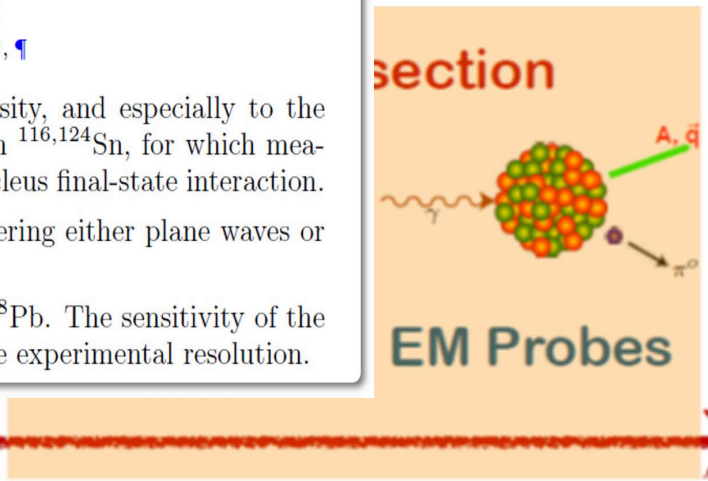
arXiv:2204.13395

F. Colomer,[1,2] P. Capel,[2,1,*] M. Ferretti,[2] J. Piekarewicz,[3,†]
C. Sfienti,[2,‡] M. Thiel,[2,§] V. Tsaran,[2] and M. Vanderhaeghen[2,¶]

Purpose: We analyze the sensitivity of that reaction process to the nucleonic density, and especially to the neutron skin thickness, for ^{12}C, ^{40}Ca and ^{208}Pb, for which reliable data exist, and on ^{116,124}Sn, for which measurements have been performed in Mainz. We study also the role played by the π^0-nucleus final-state interaction.

Method: A model of the reaction is developed at the impulse approximation considering either plane waves or distorted waves to describe the π^0-nucleus scattering in the outgoing channel.

Results: Our calculations are in good agreement with existing data, especially for ^{208}Pb. The sensitivity of the theoretical cross sections to the choice of the nucleonic density is small, and below the experimental resolution.



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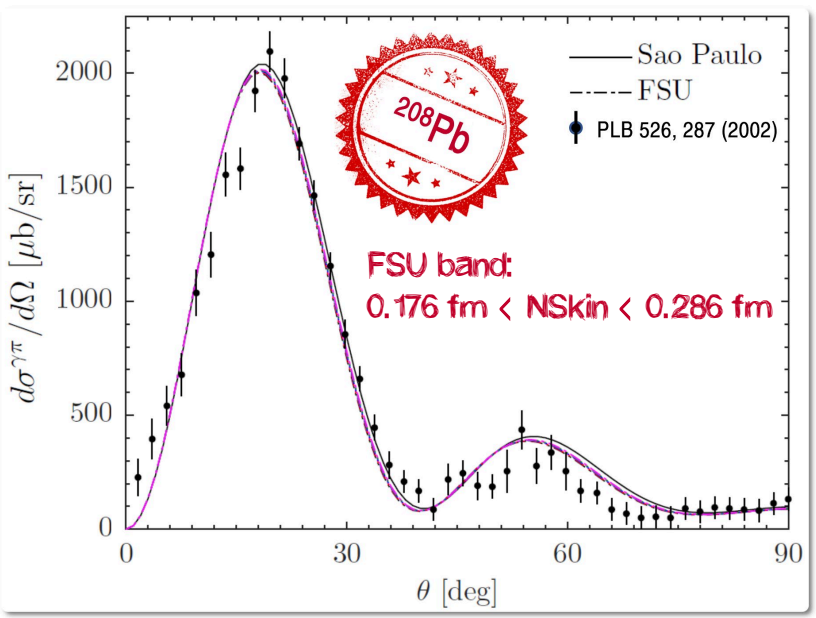

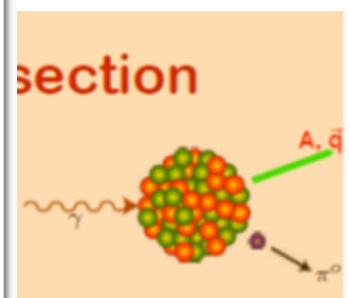

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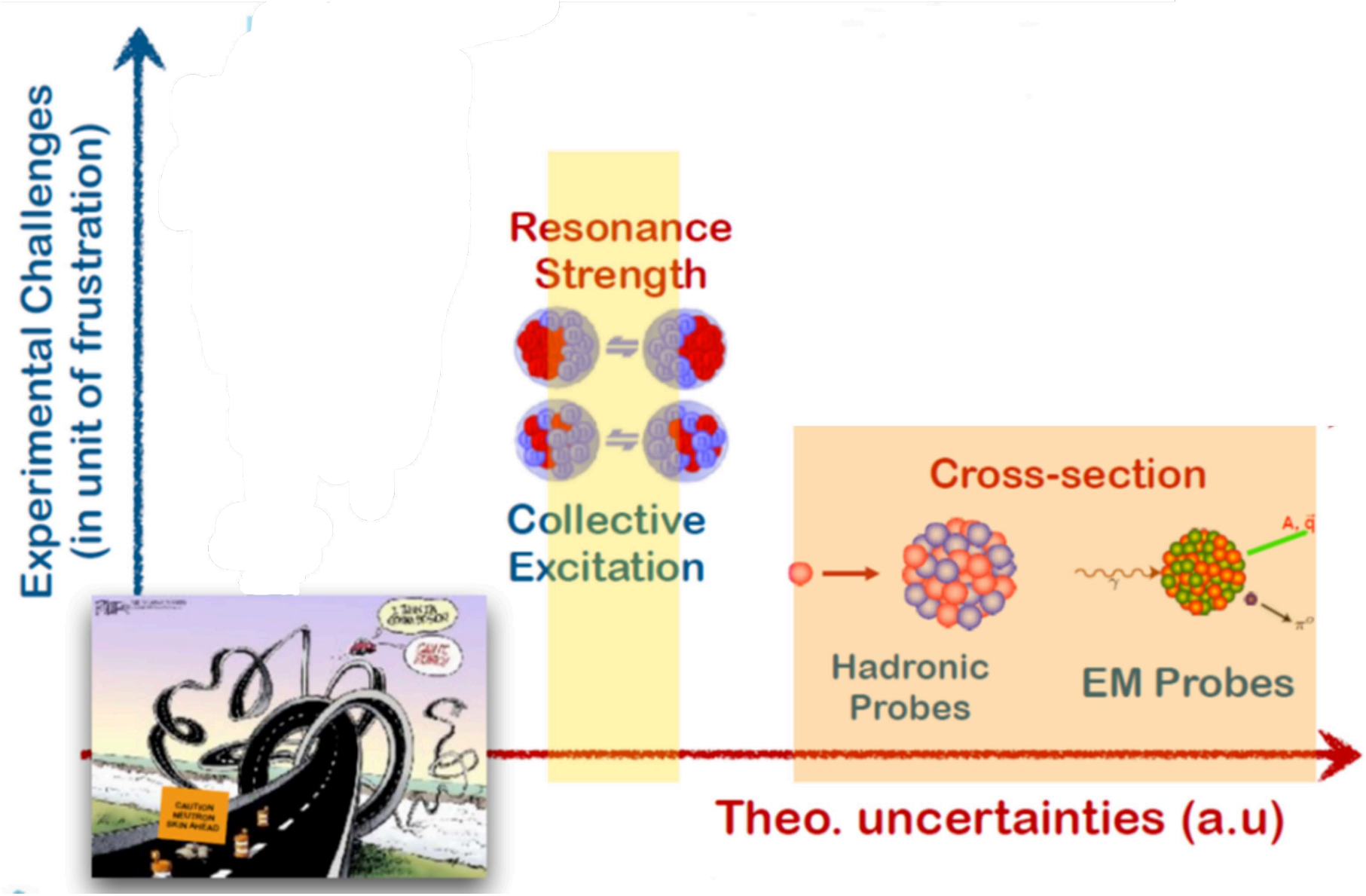
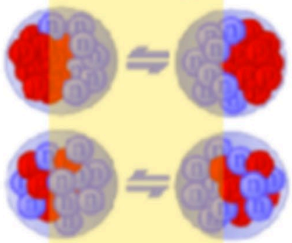


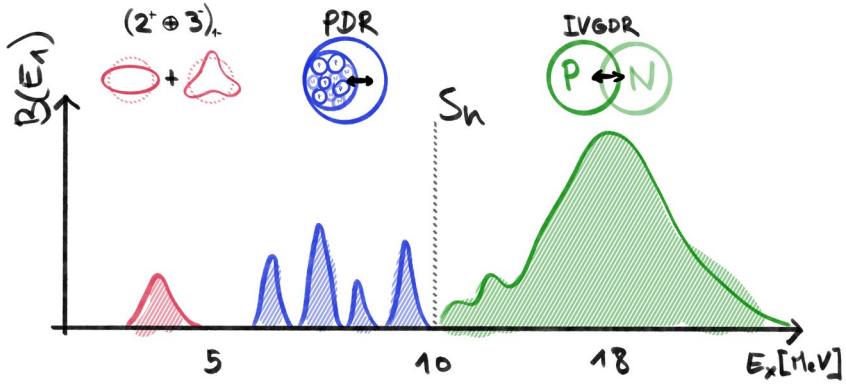
highway to hell or stairway to heaven?

Experimental Challenges
(in unit of frustration)

Resonance
Strength

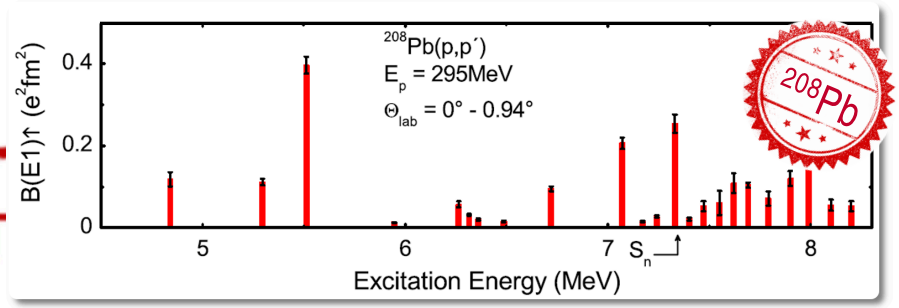


Collective
Excitation



$$\alpha_D = \frac{8\pi}{9}\int \frac{B(E_1, E_x)}{E_x} dE_x = \frac{\hbar c}{2\pi^2}\int \frac{\sigma_{abs}(E_x)}{E_x^2} dE_x$$

A. Tamii et al., PRL 107 (2011) 062502



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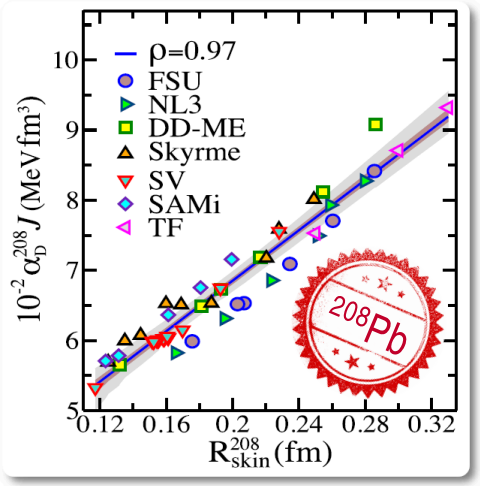
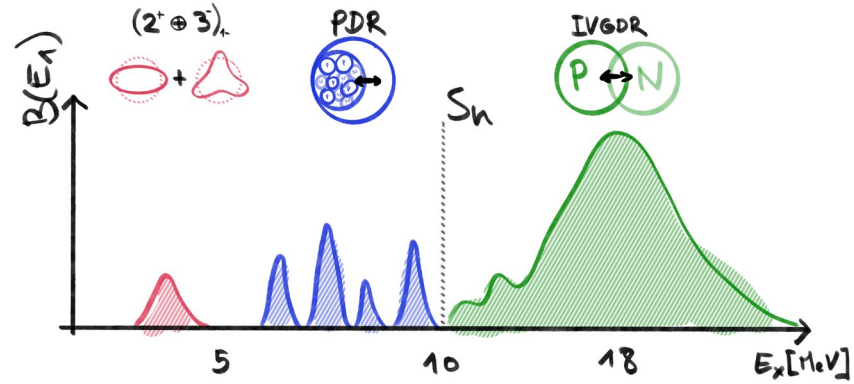


X. Roca-Maza et al., PRC 88 (2013) 024316)



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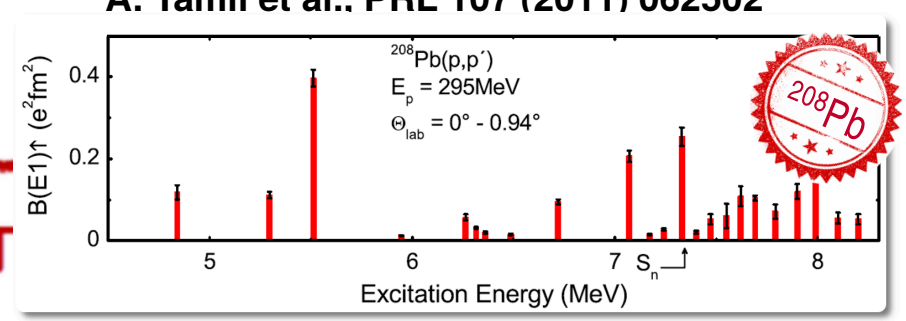

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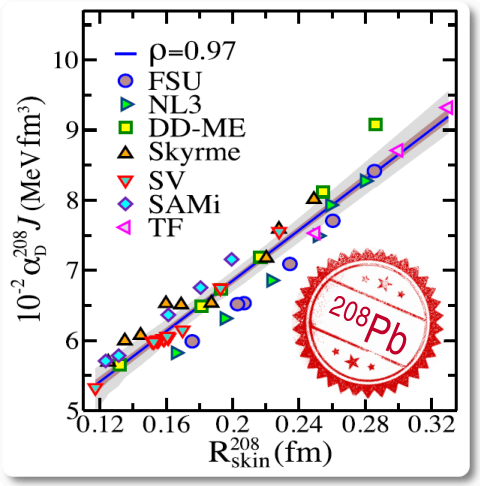

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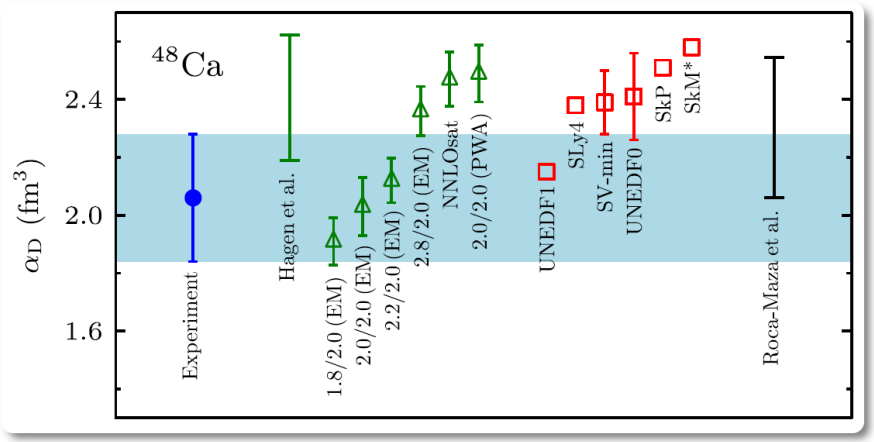
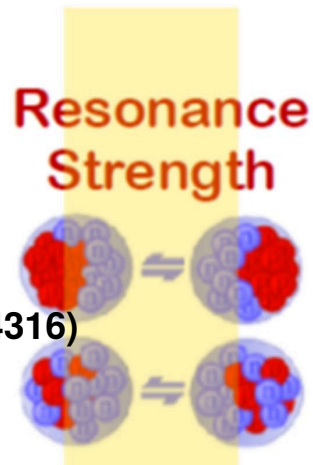
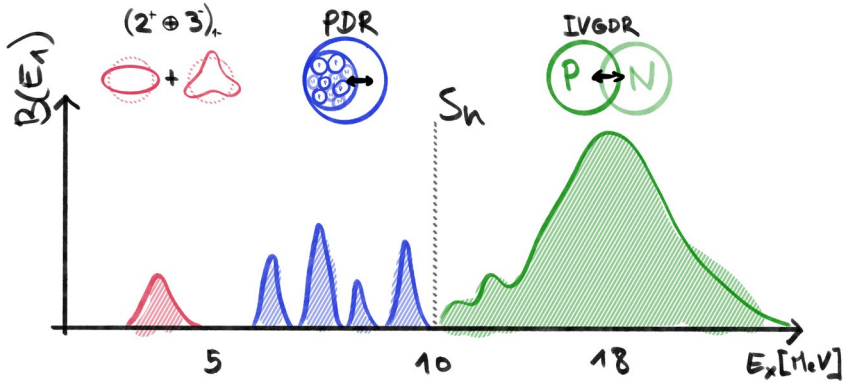
G. Hagen et al., Nature Physics 12 (2016) 186

J. Birkhan et al., PRL 118 (2017) 252501







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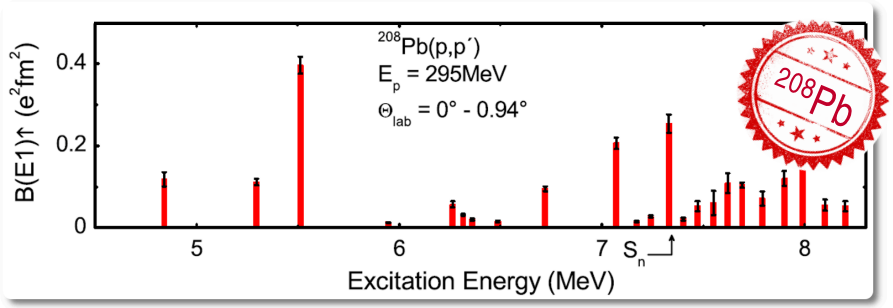

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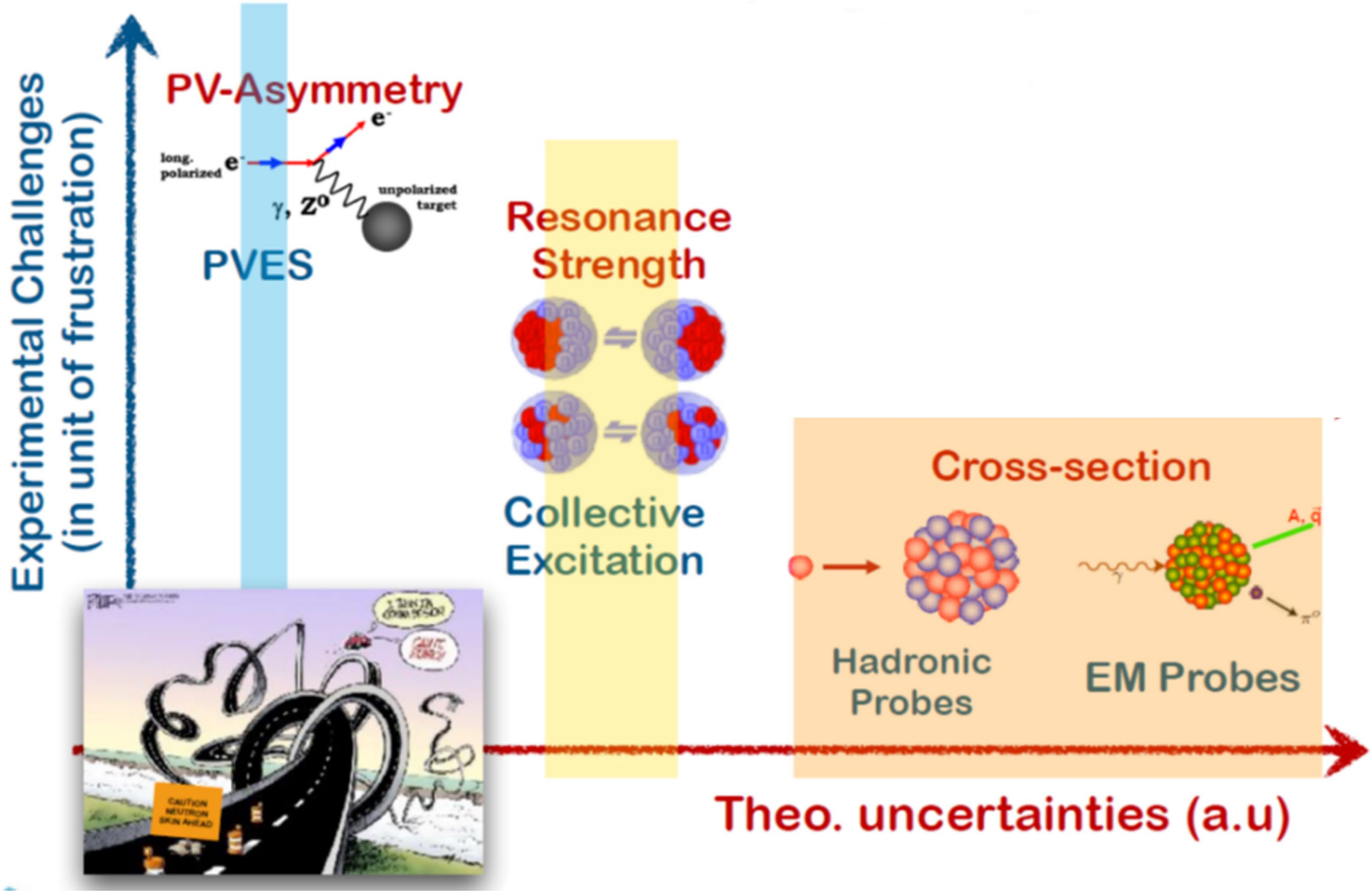
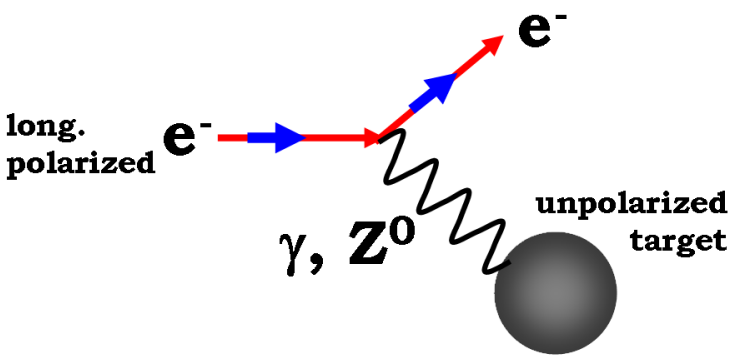
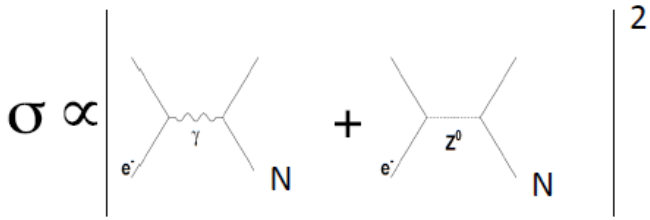


Parity-Violating Electron Scattering (PVES)

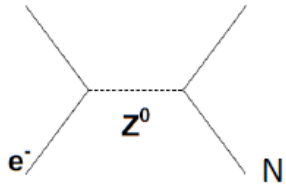


electric charge	1	0
weak charge	≈0.07	-1

...since...



...to measure ...

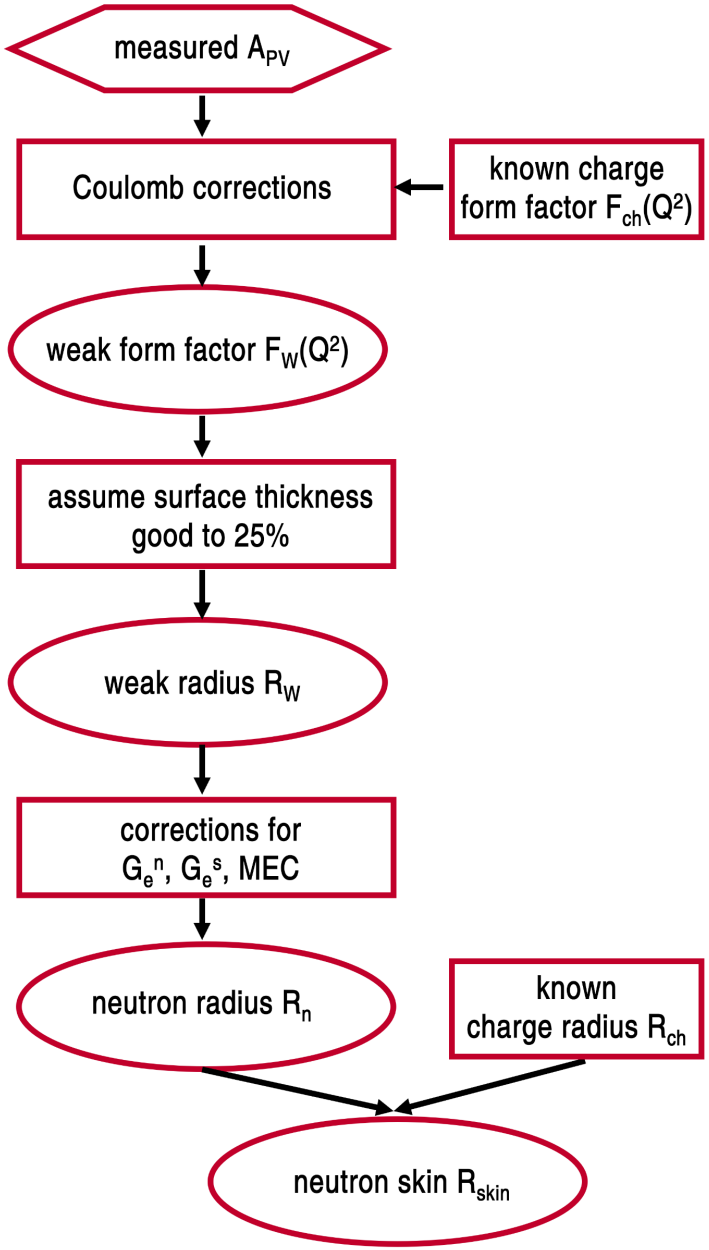


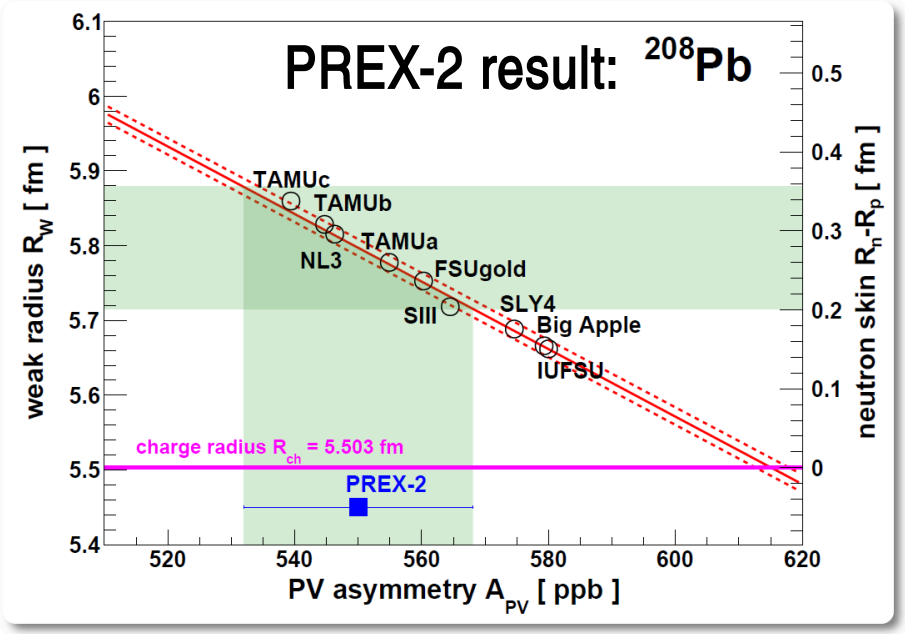
....construct ....

$$A_{PV} = \frac{\sigma^R - \sigma^L}{\sigma^R + \sigma^L}$$

$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[1 - 4\sin^2(\theta_w) - \frac{F_w(Q^2)}{F_{ch}(Q^2)}\right]$$

PVES: extraction of neutron skin



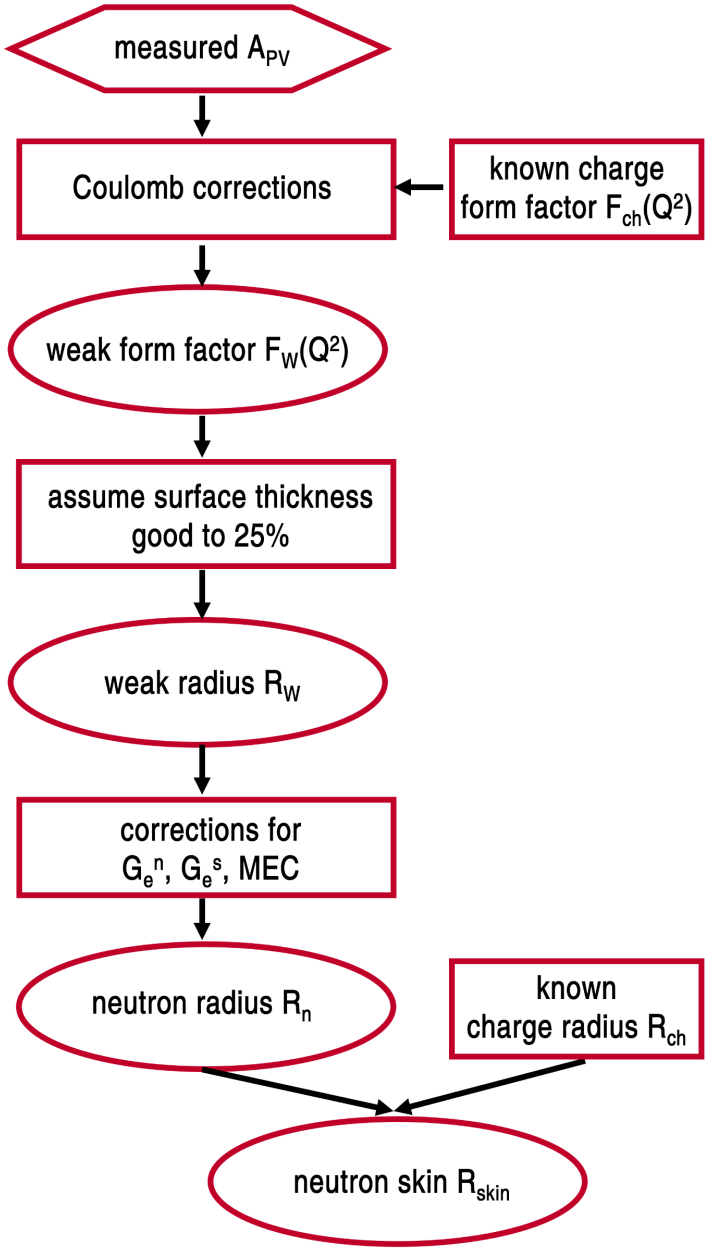


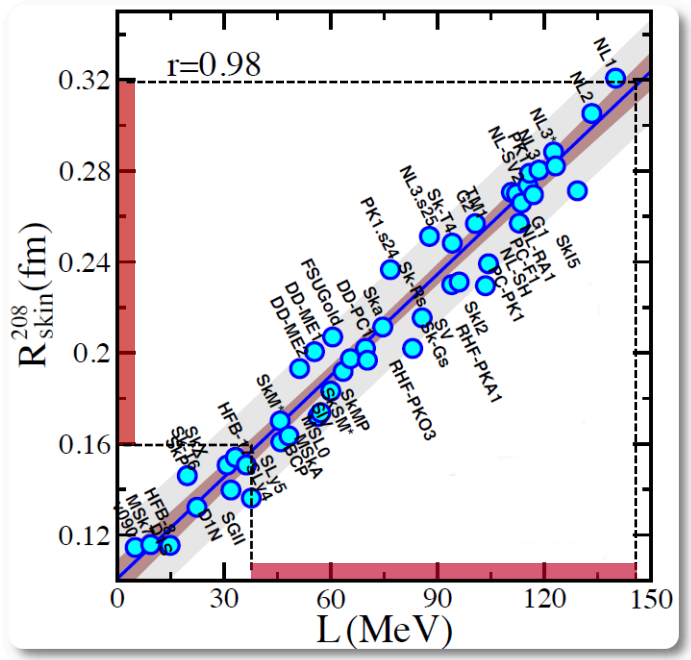
D. Adhikari et al., PRL 126 (2021) 172502

A_{PV} = 550 ± 16 (stat) ± 8 (sys) ppb

R_{skin} = 0.278 ± 0.078 fm

PVES: extraction of neutron skin





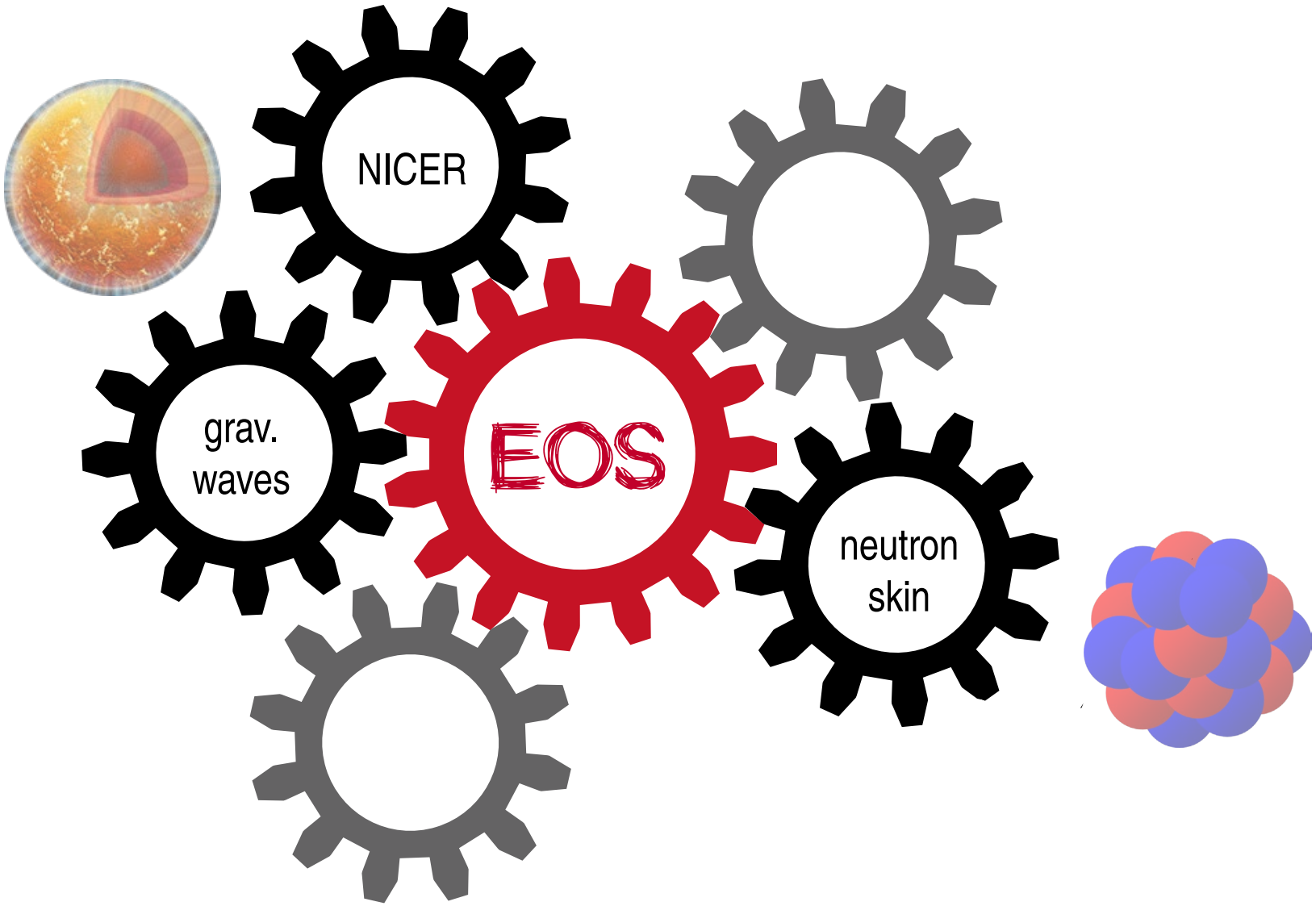
J. Piekarewicz, F.J. Fattoyev, Physics Today 72, 7, 30 (2019)

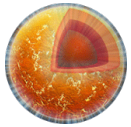
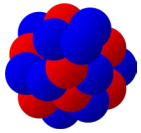
A_{PV} = 550 ± 16 (stat) ± 8 (sys) ppb

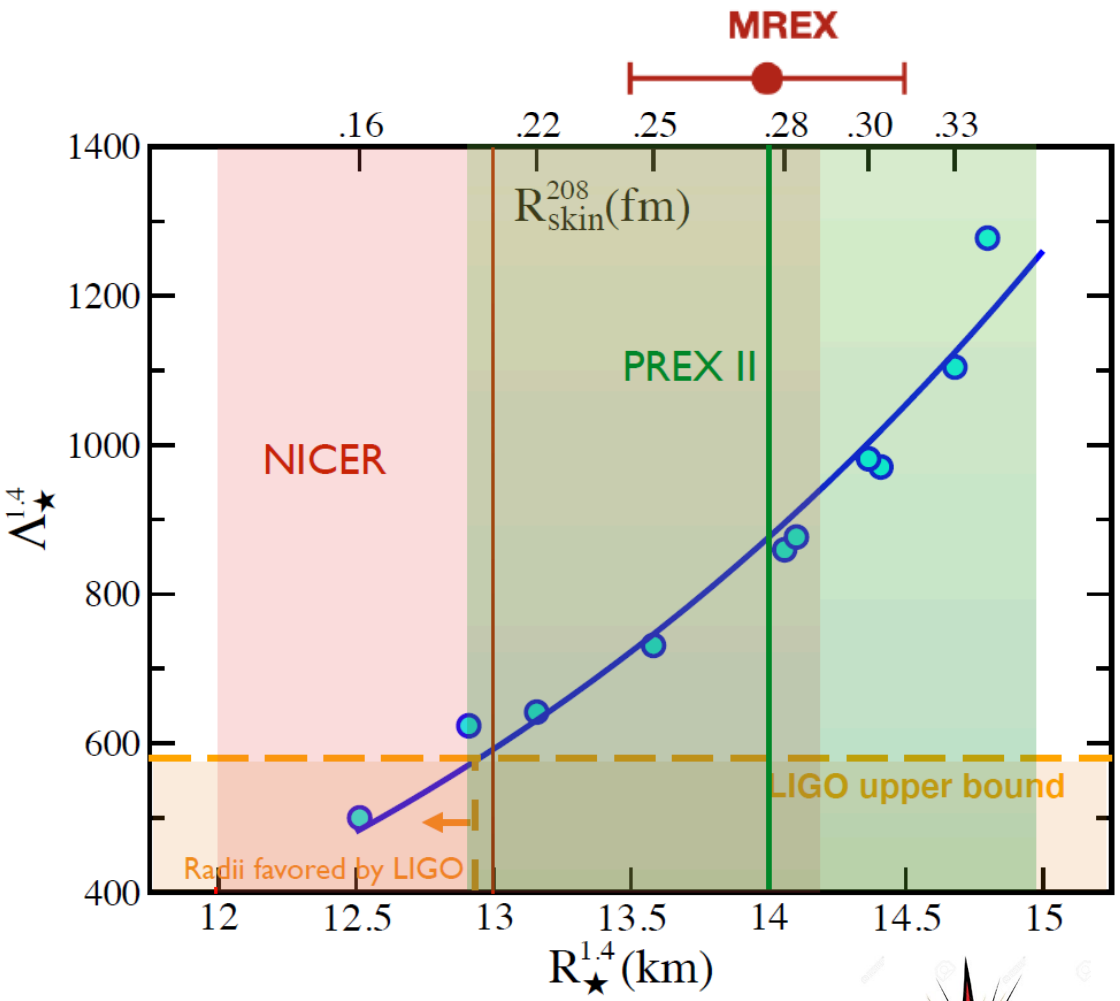
R_{skin} = 0.278 ± 0.078 fm

→ L = ± 50 MeV

it is all connected



from outer space  to deep inside 

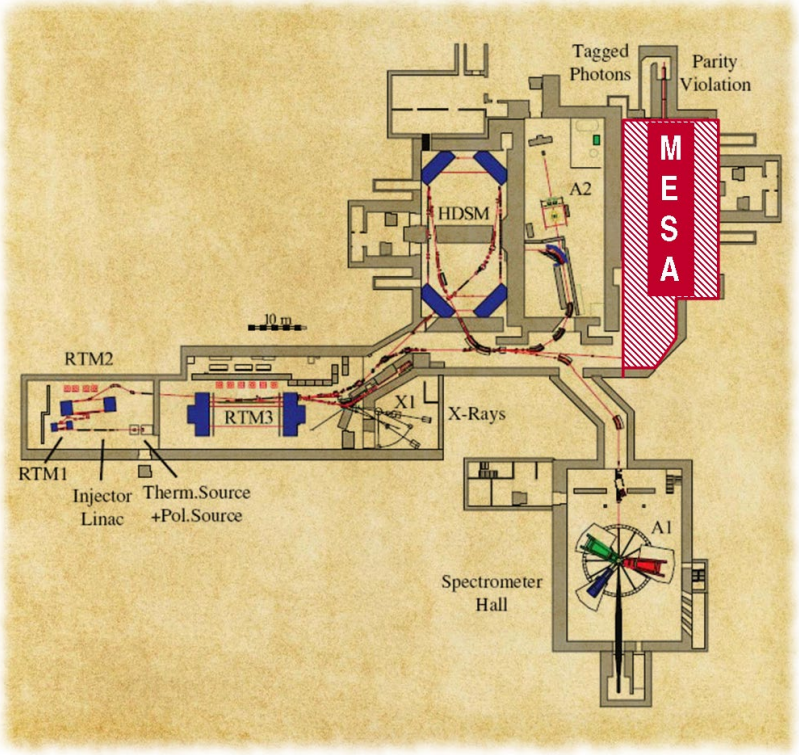


soft EOS vs. stiff EOS 

ultimate determination of the neutron-skin thickness of ^{208}Pb

MREX @ MESA

(Mainz Radius Experiment)



the new stage:

Mainz **E**nergy recovering **S**uperconducting **A**ccelerator

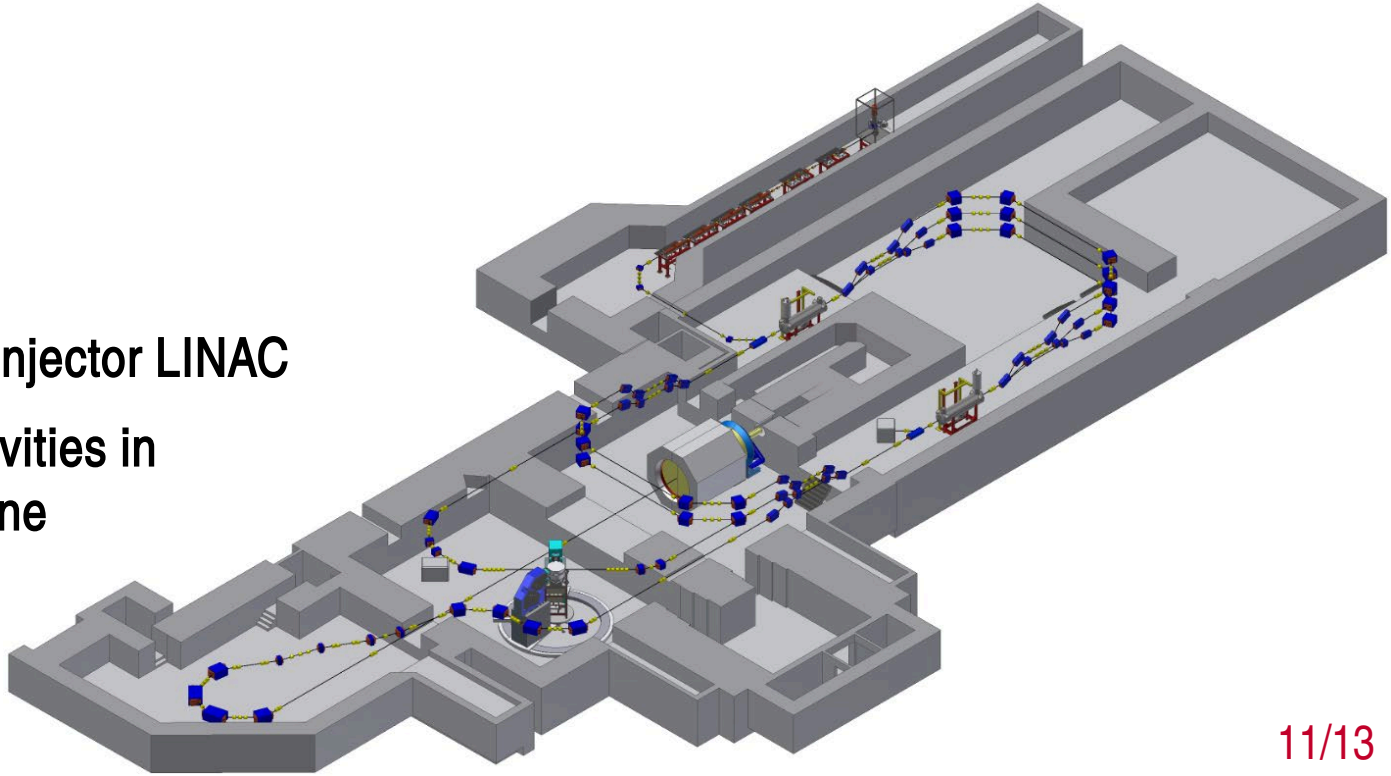
ultimate determination of the neutron-skin thickness of ^{208}Pb

MREX

(Mainz Radius Experiment)

MESA:

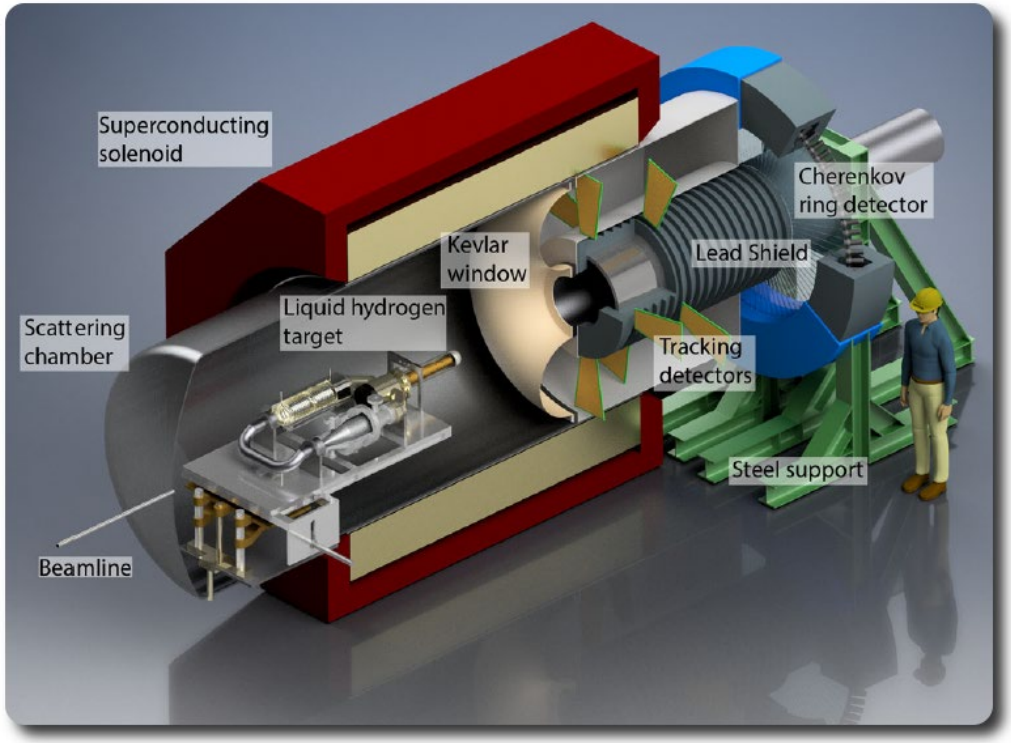
- 1.3 GHz c.w. beam
- normal conducting injector LINAC
- superconducting cavities in recirculation beamline

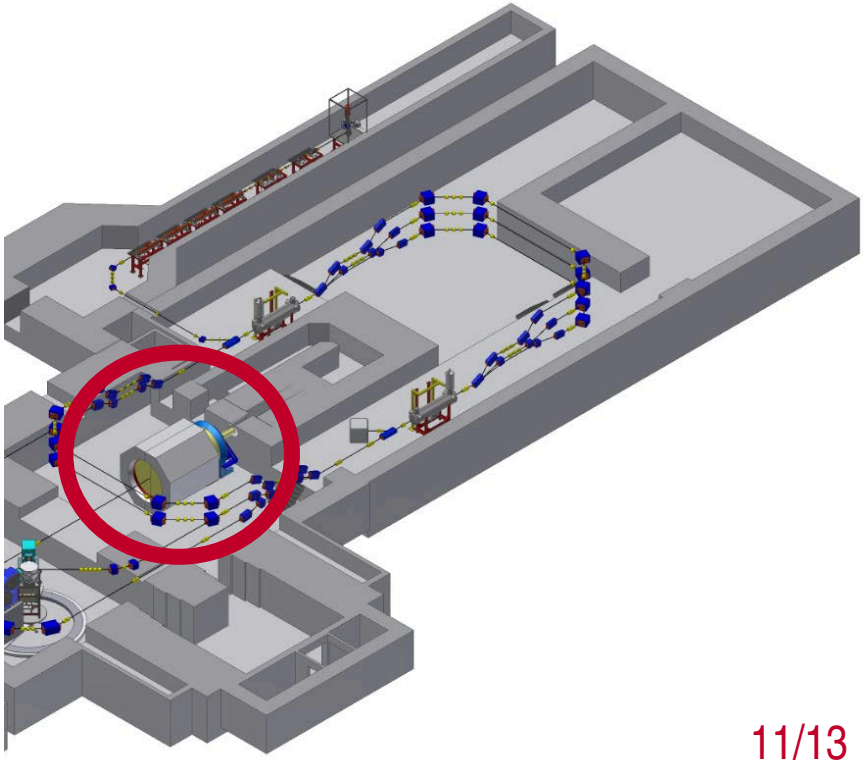


ultimate determination of the neutron-skin thickness of ^{208}Pb

MREX

(Mainz Radius Experiment)





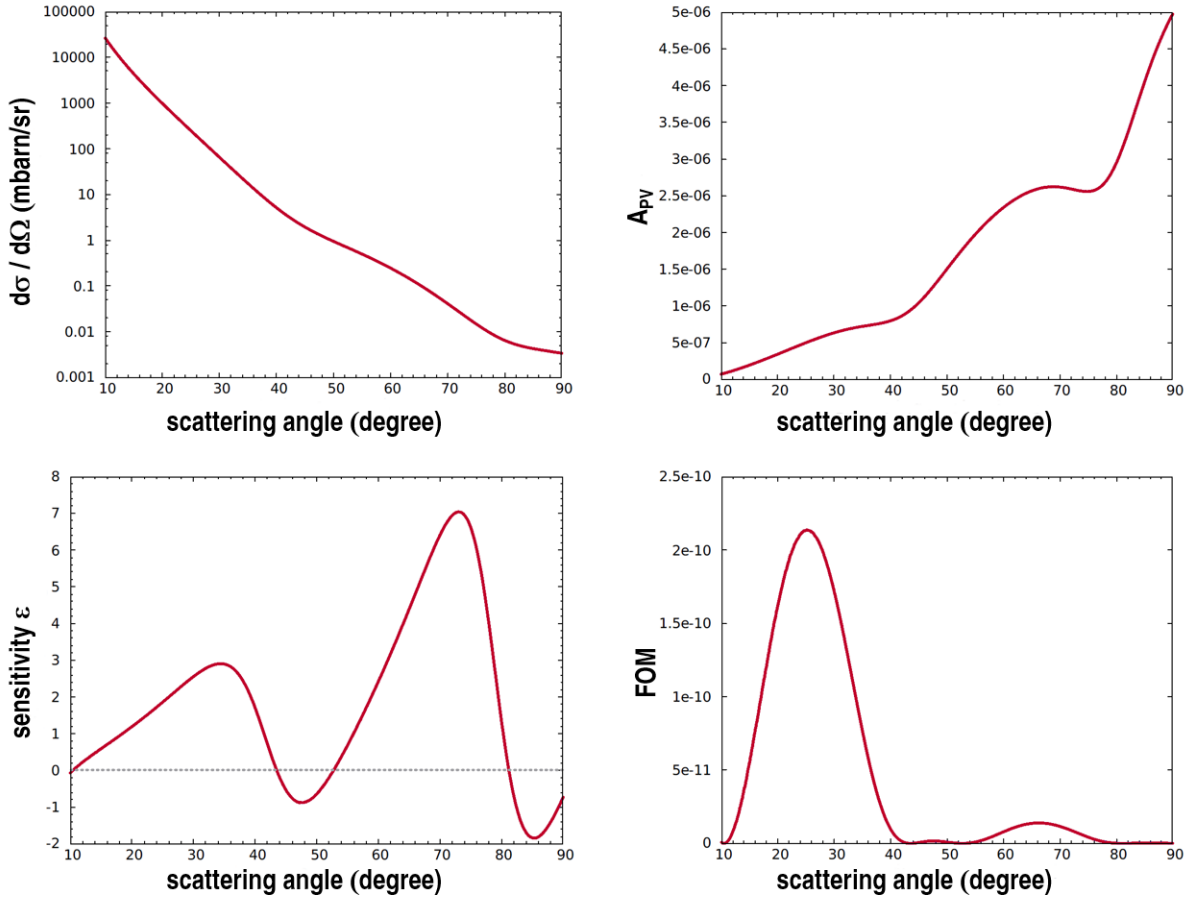
MREX: Figure Of Merit

beam
energy: 155 MeV
current: 150μA

target
^{208}Pb 0.56 g/cm^2

A_{PV}: 0.66 ppm
$\Delta\theta = 4°$
polarization: 85%
q: 86 MeV/c

Chuck Horowitz



±0.03 fm determination of neutron-skin thickness (60 days)

summary (exciting times are ahead)