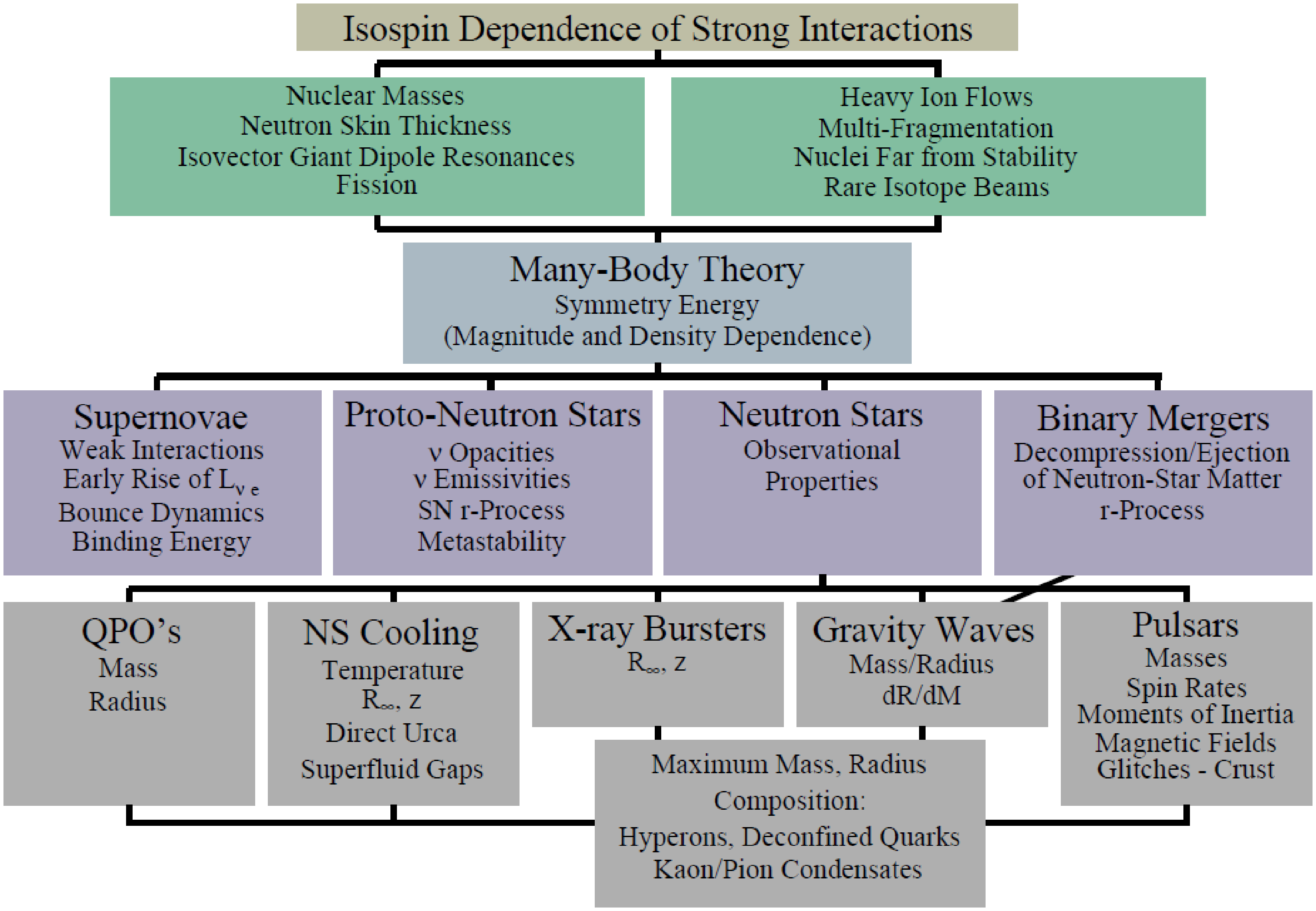
nuclear physics experiments

Michaela Thiel
Institut für Kernphysik, Johannes Gutenberg-Universität Mainz

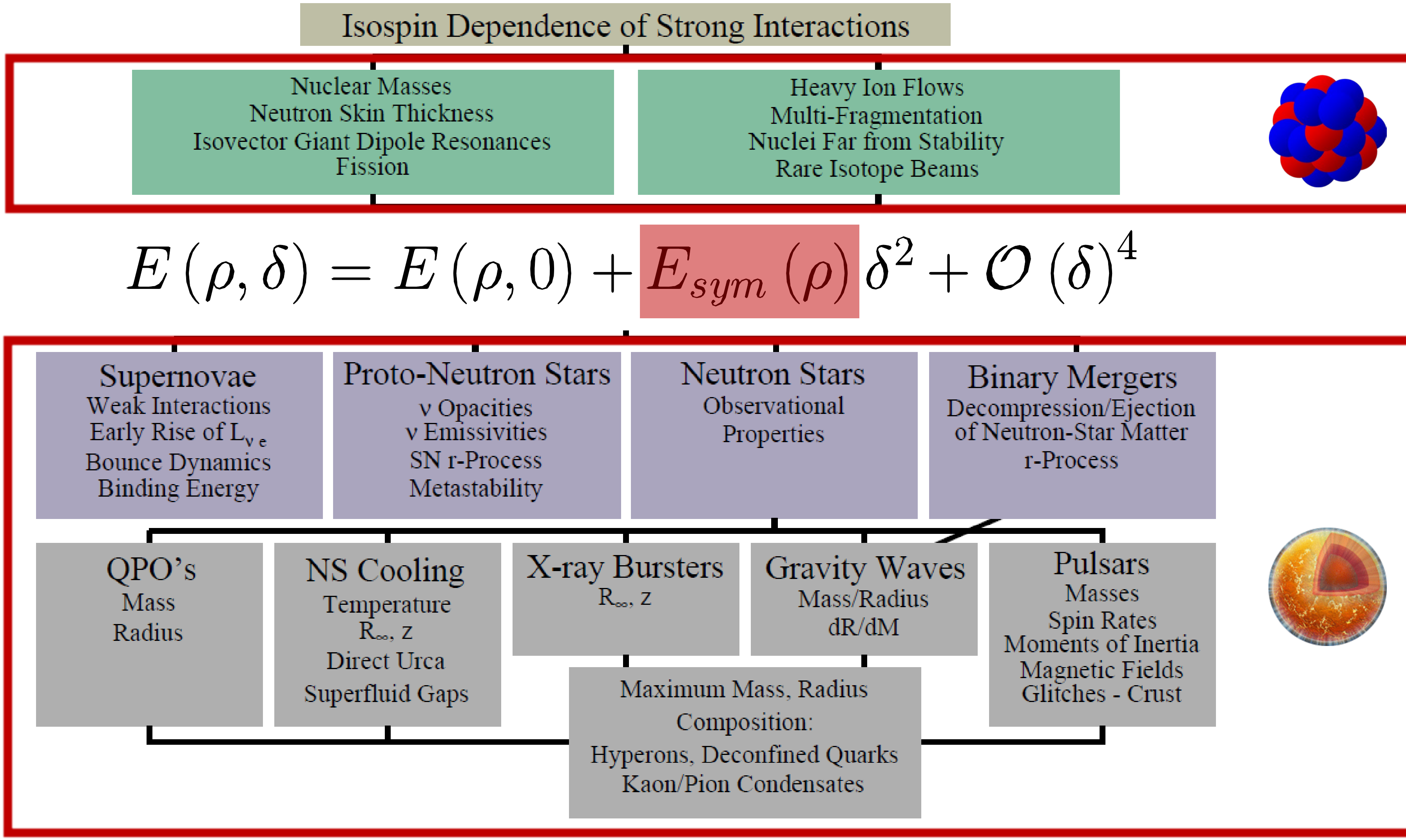
JG|U SFB 1044 PRiSMA

multi-messenger physics



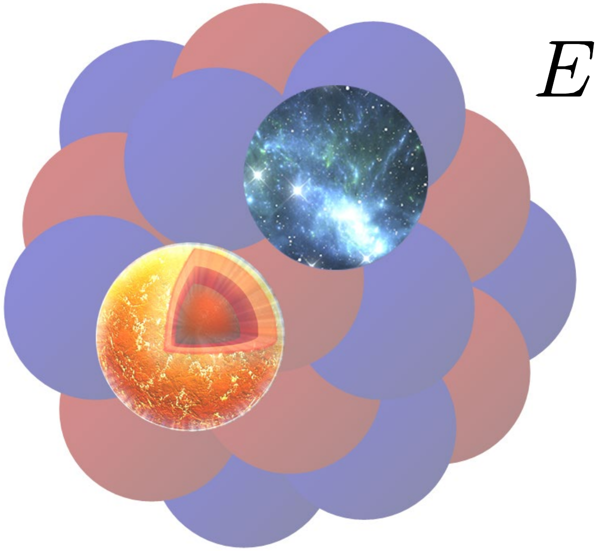
A.W. Steiner et al., Physics Reports, 411 (2005) 325

multi-messenger physics



A.W. Steiner et al., Physics Reports, 411 (2005) 325

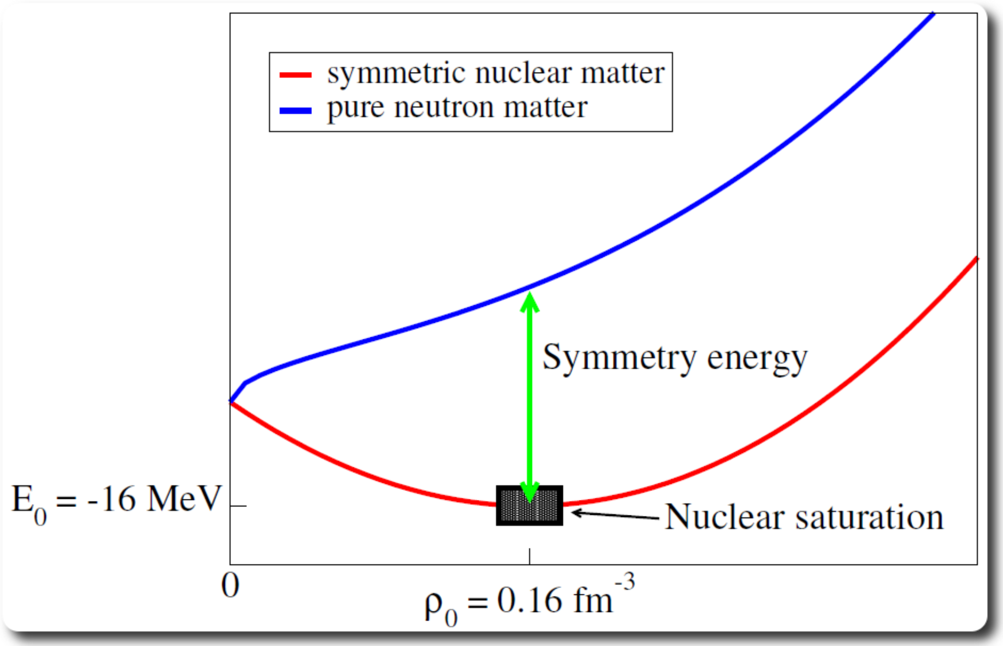
Equation Of State



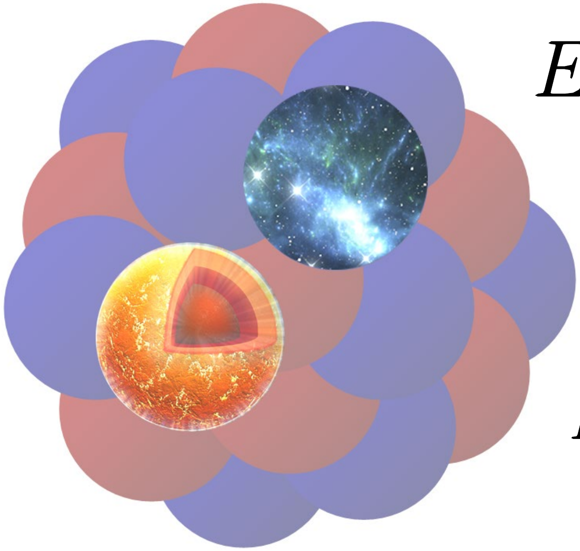
$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + \mathcal{O}(\delta)^4$$

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

symmetry energy



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

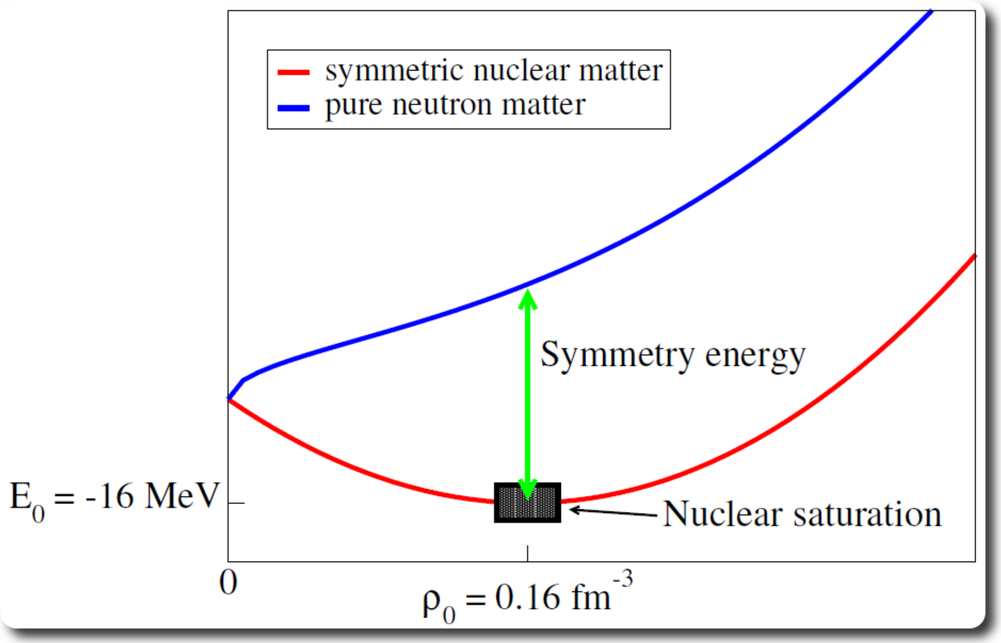
$$E_{sym}(\rho) = \left[S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2\right] + \ldots$$

slope parameter

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

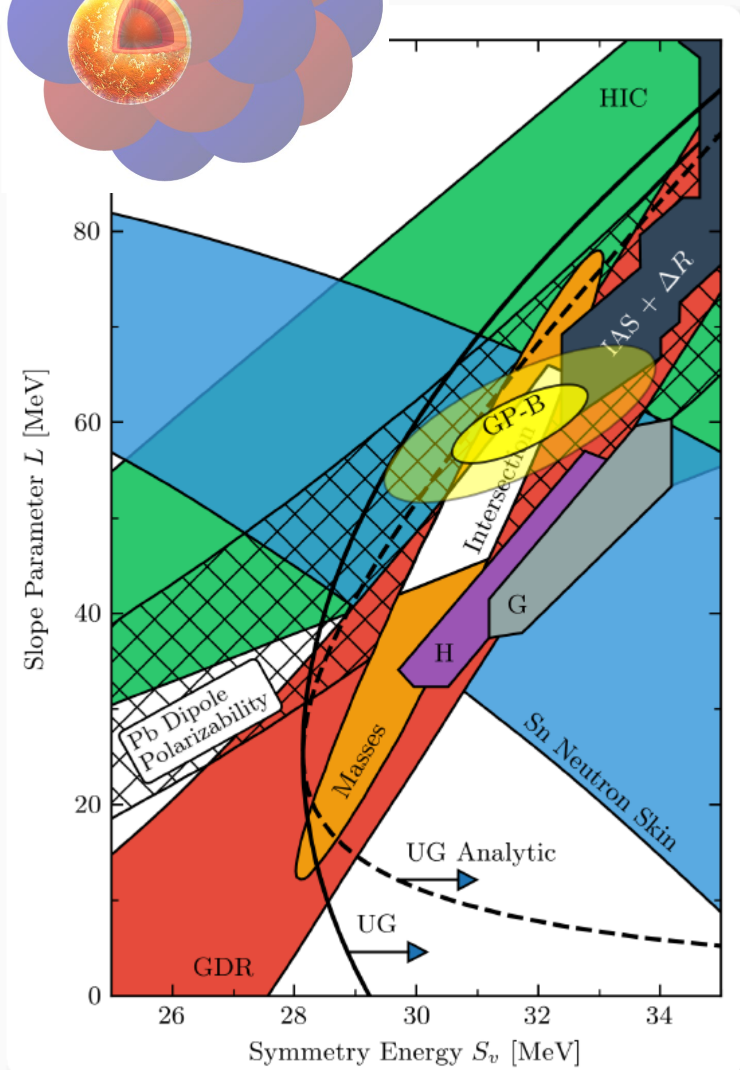
curvature parameter

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



constraining the symmetry energy parameters

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



Heavy Ion Collisions

Nuclear Masses

Giant Dipole Resonances

Dipole Polarizabilities

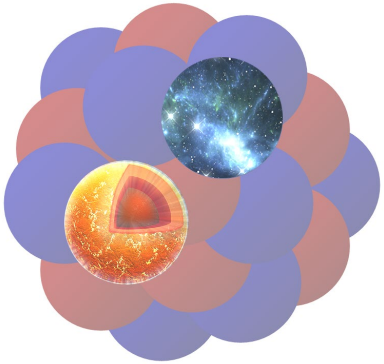
Neutron Skin

Theory

...

C. Drischler et al., PRL 125 (2020) 202702

constraining the symmetry energy parameters



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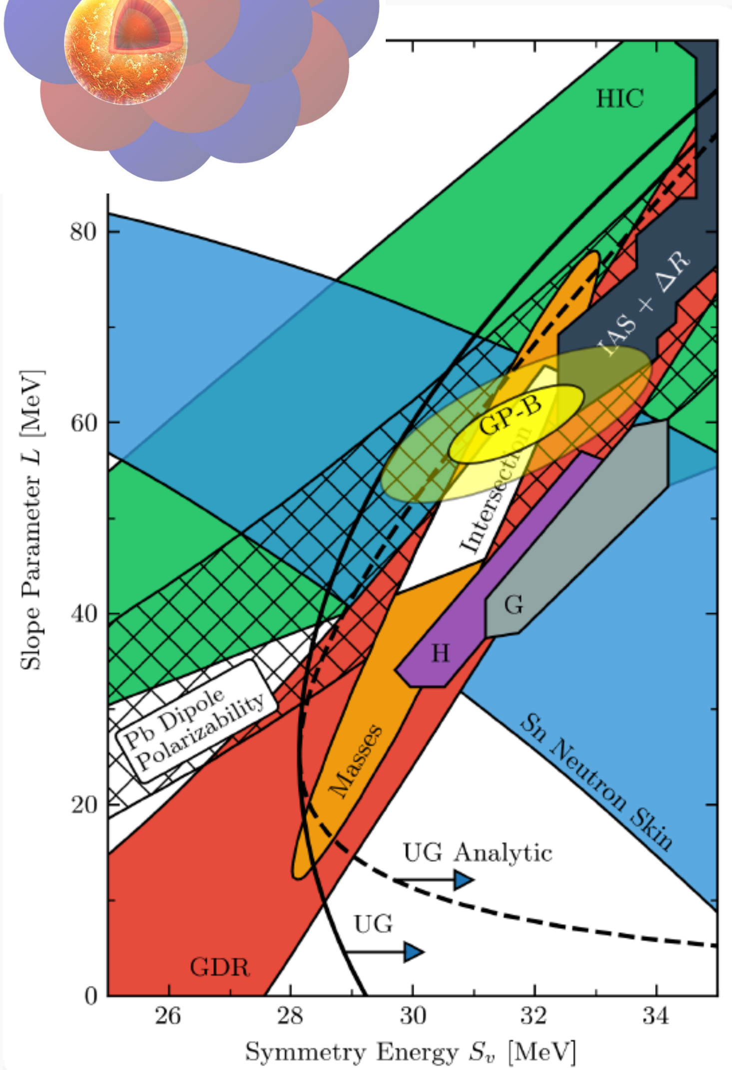
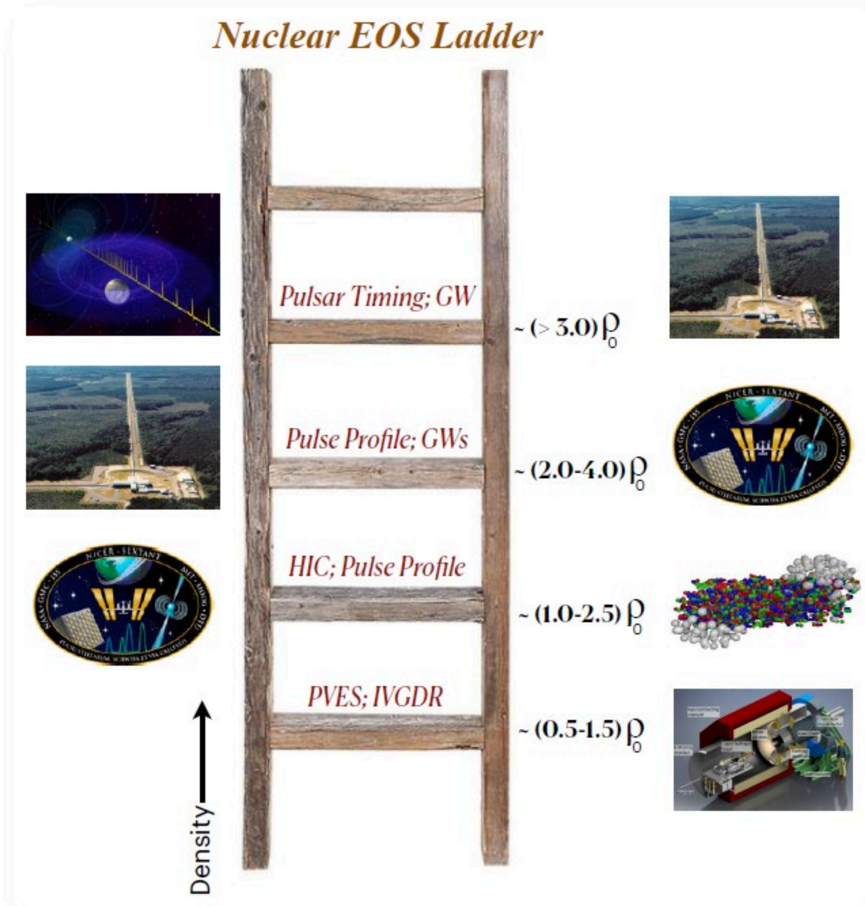
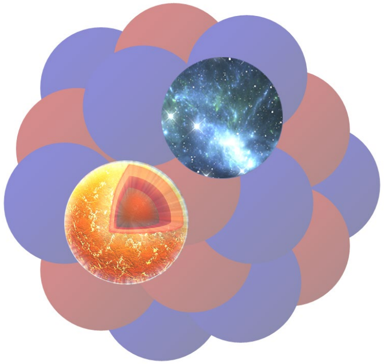




courtesy of J. Piekarewicz

C. Drischler et al., PRL 125 (2020) 202702

constraining the symmetry energy parameters



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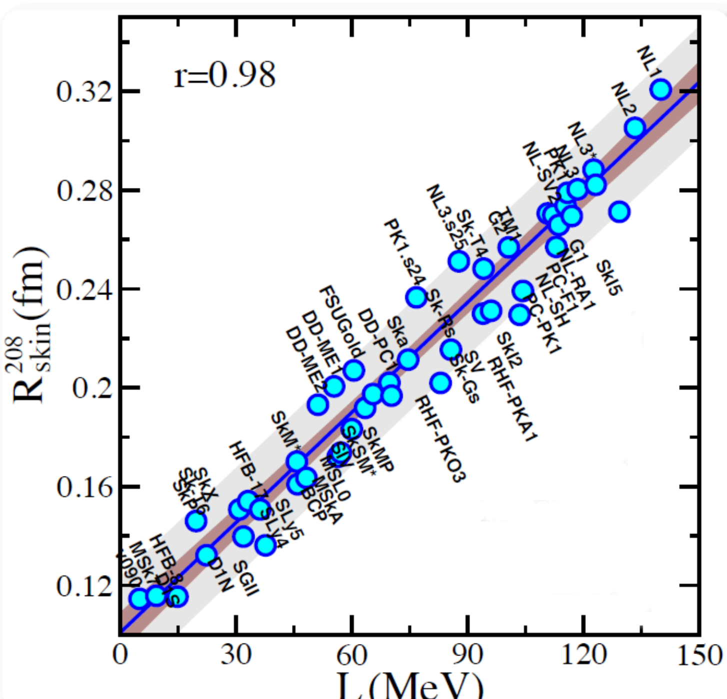
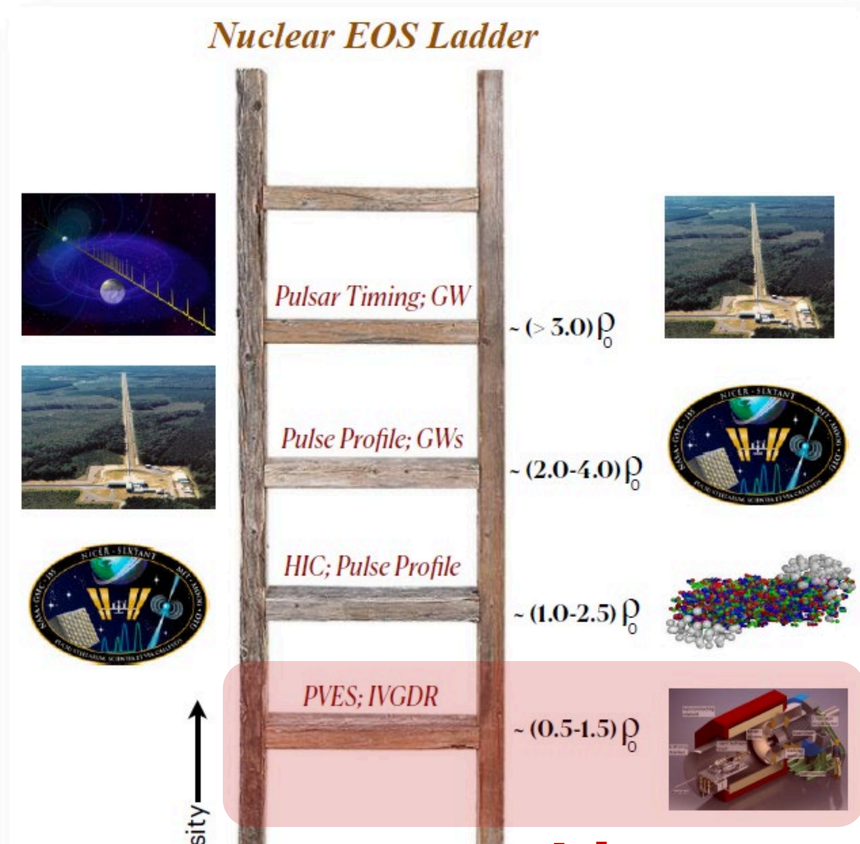


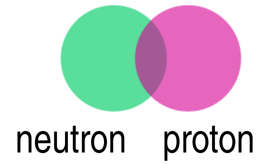
J. Piekarewicz, F.J. Fattoyev, Physics Today 72, 7, 30 (2019)



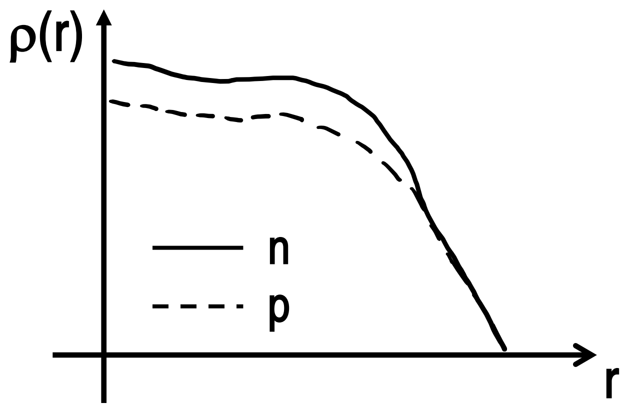
neutron skin: R_{skin}

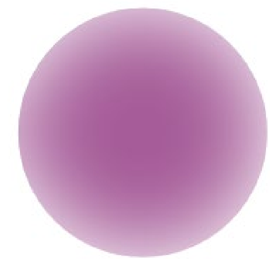
courtesy of J. Piekarewicz

neutron skin

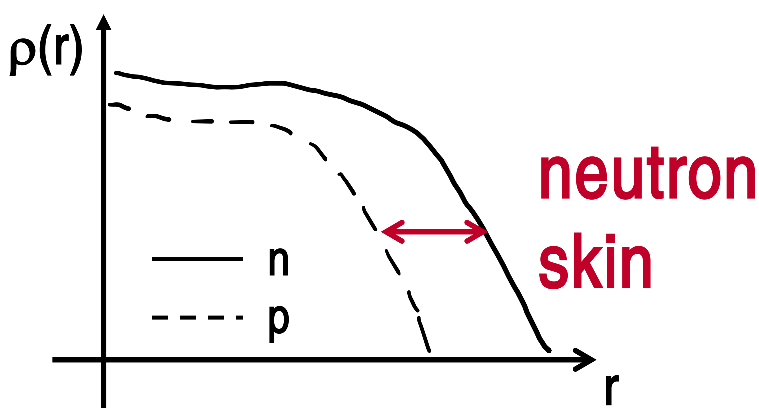


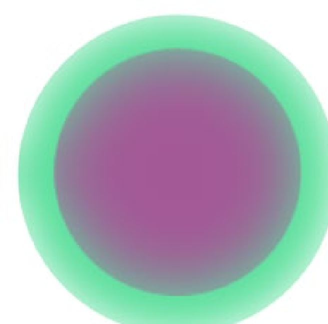
stable nuclei (N≈Z)





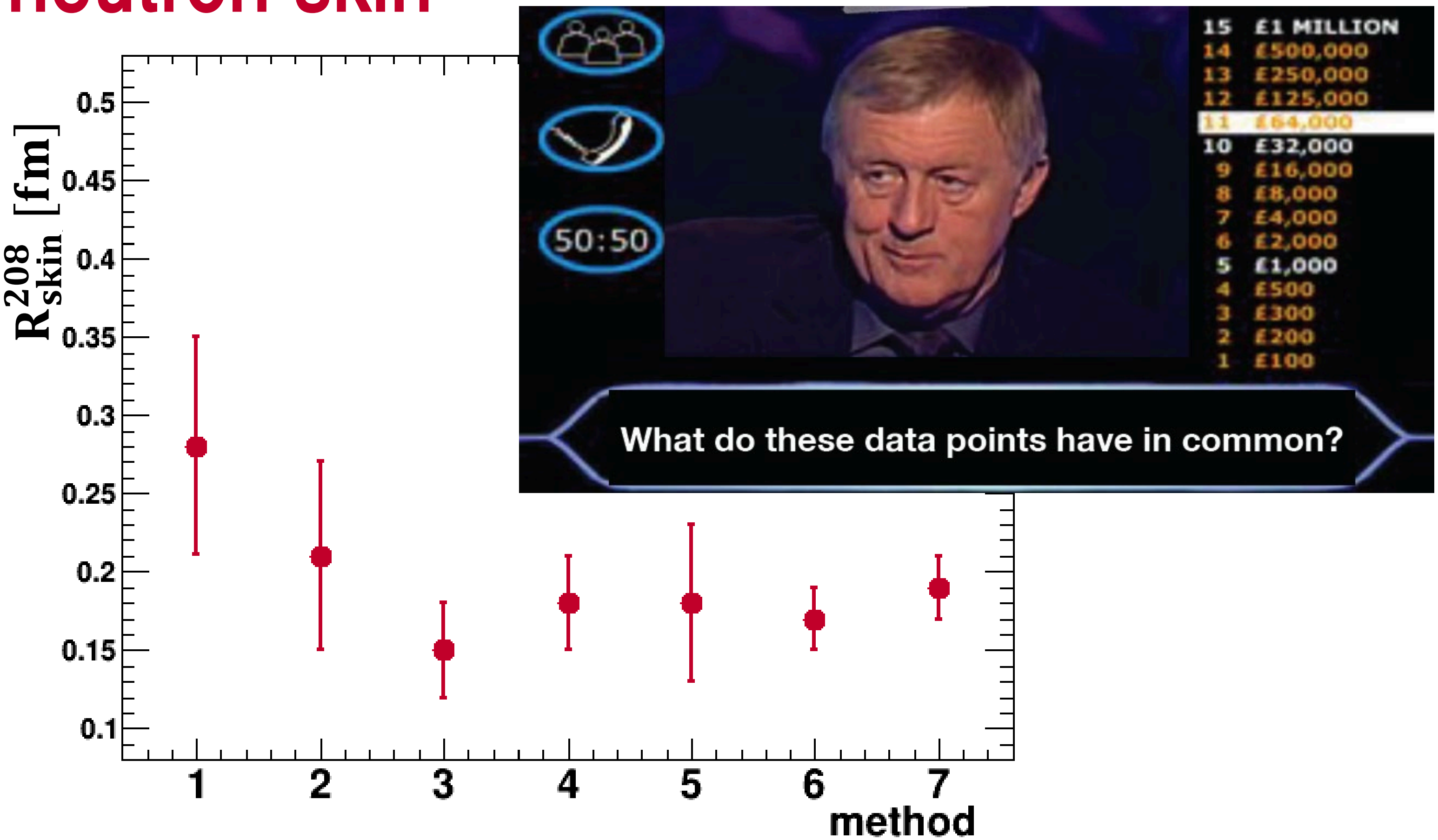
neutron rich nuclei (N>>Z)



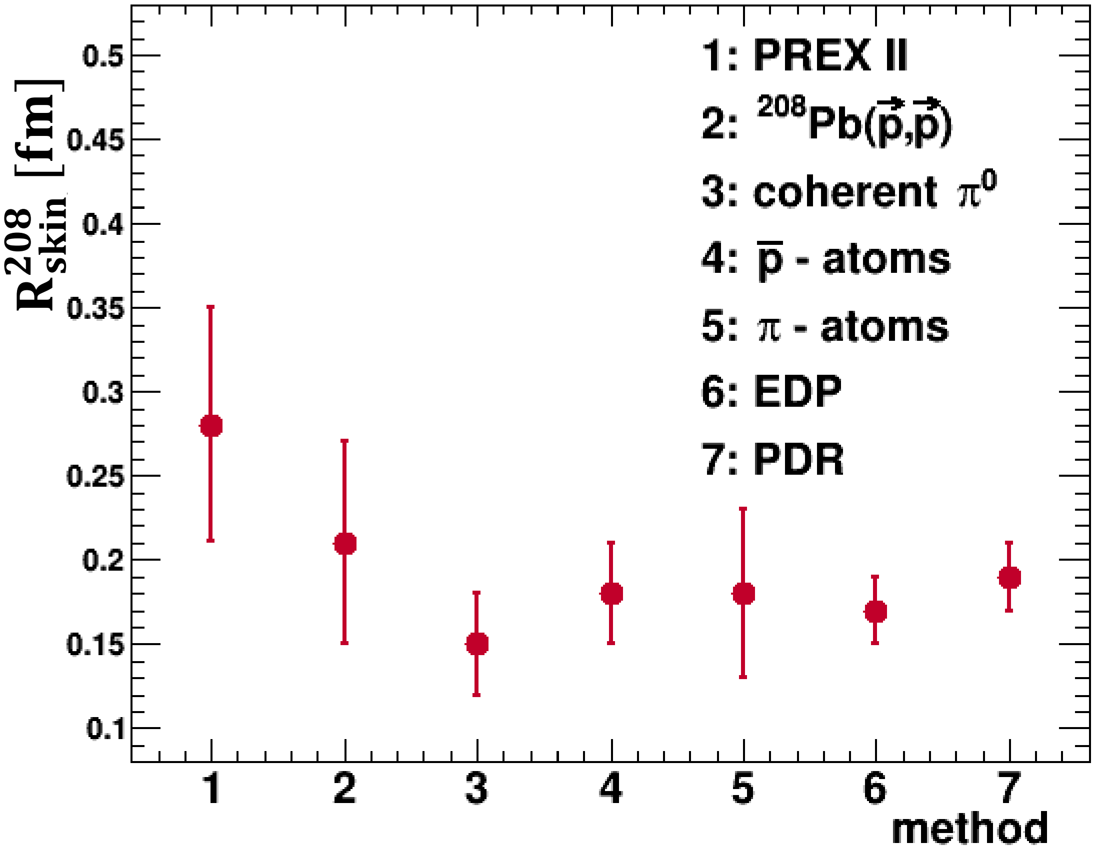


pressure forces neutrons out against surface tension

neutron skin

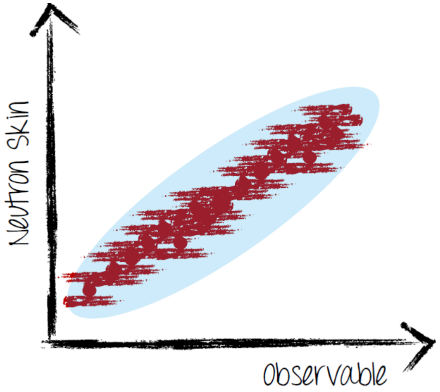


neutron skin

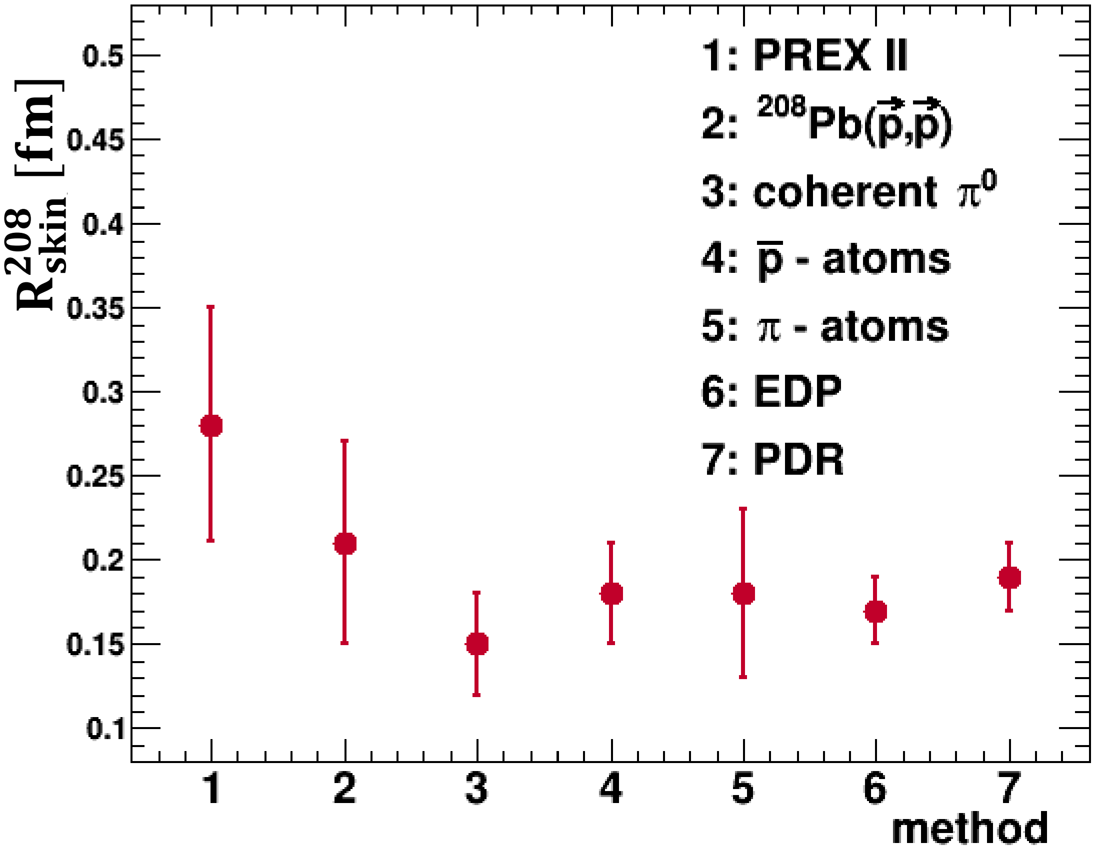


none

is an actual measurement of neutron skin!



neutron skin



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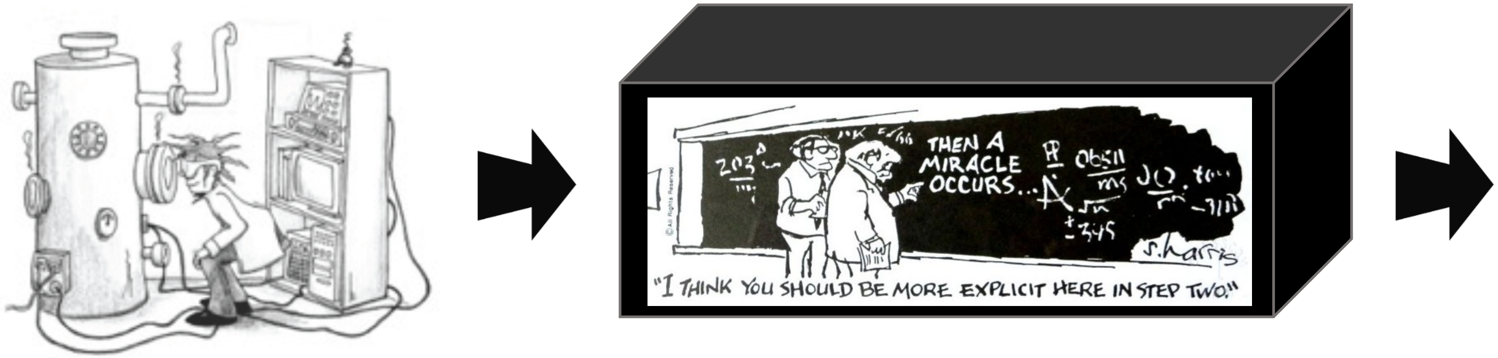
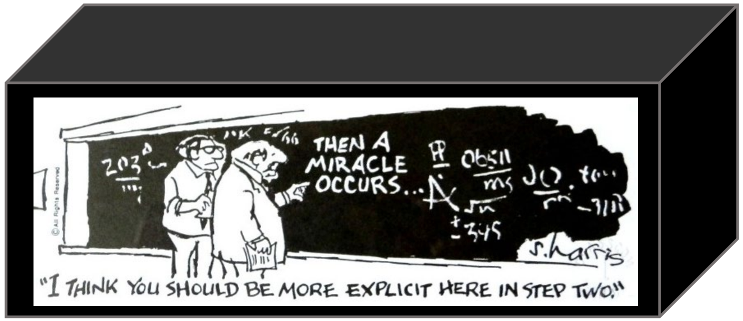
from measurable observables
to neutron skin

from observables to neutron skin



neutron skin

from observables to neutron skin



neutron skin

Experimental Challenges (in unit of frustration)

What is actually measured?

How is the measured observable connected to the neutron skin?

What are the assumptions implicit in making this connection?

How sensitive is the extraction of the neutron skin to these assumptions?

...

Theo. uncertainties (a.u)

from observables to neutron skin

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

2016 Mainz Institute for Theoretical Physics

Neutron Skins of Nuclei

… documenting the relative merits of each experimental approach and to provide a realistic estimate of systematic errors, including theoretical uncertainties associated with the extraction of the neutron skin from the measured experimental observable.

MT, C. Sfienti, J. Piekarewicz, C. Horowitz, M. Vanderhaeghen,
J. Phys. G: Nucl. Part. Phys. 46 (2019) 093003

neutron skin

Experimental Challenges (in unit of frustration)

What is actually measured?

How is the measured observable connected to the neutron skin?

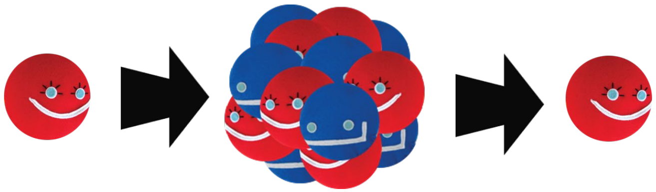
What are the assumptions implicit in making this connection?

How sensitive is the extraction of the neutron skin to these assumptions?

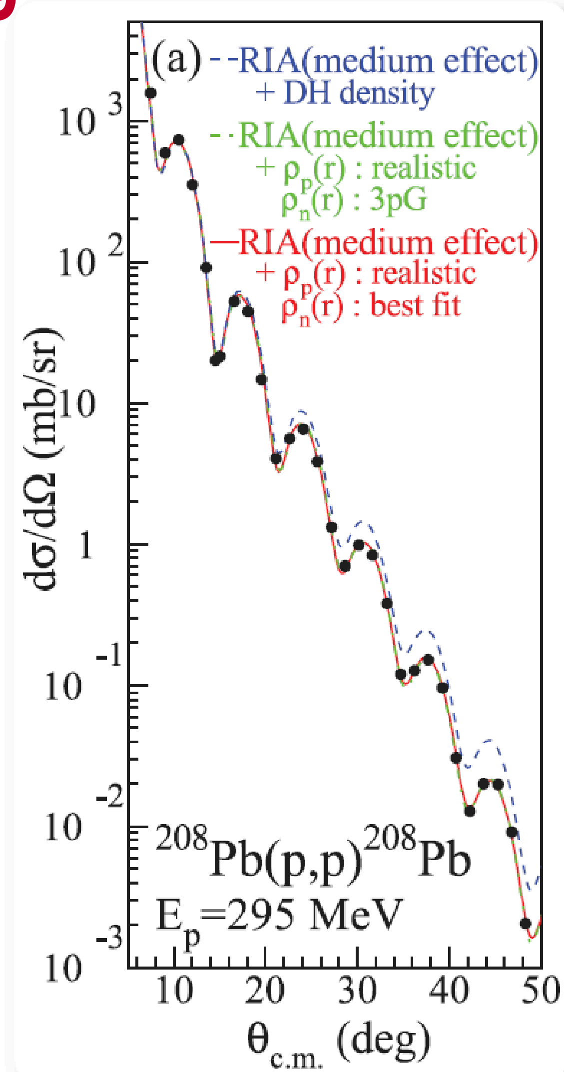
…

Theo. uncertainties (a.u)

hadronic probes: proton scattering



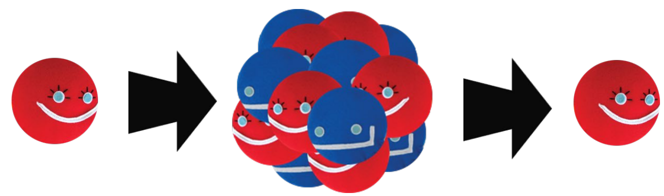
^{208}Pb(p,p)^{208}Pb



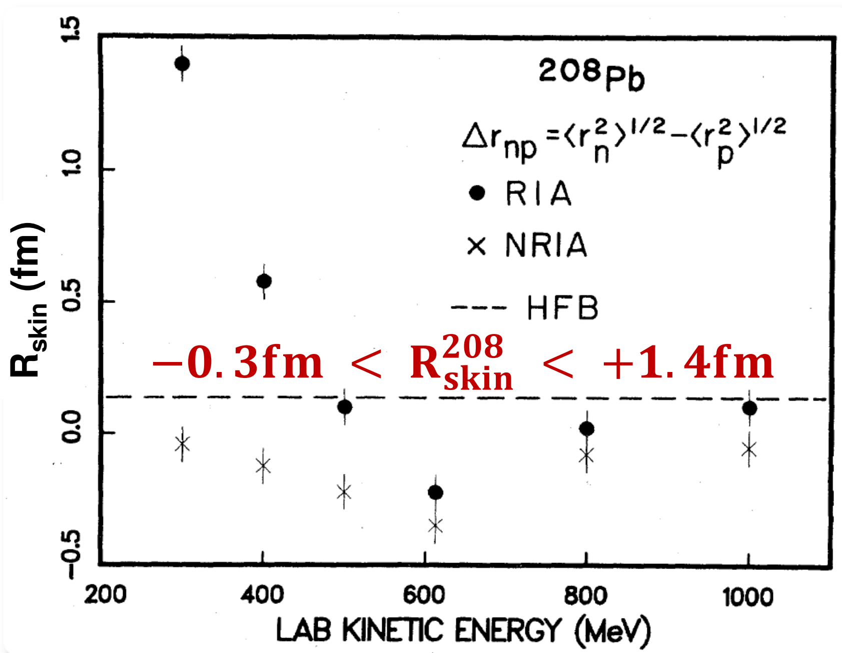
$R^{208}_{skin} = 0.211^{+0.054}_{-0.063}$ fm

J. Zenihiro et al., PRC 82 (2010) 044611

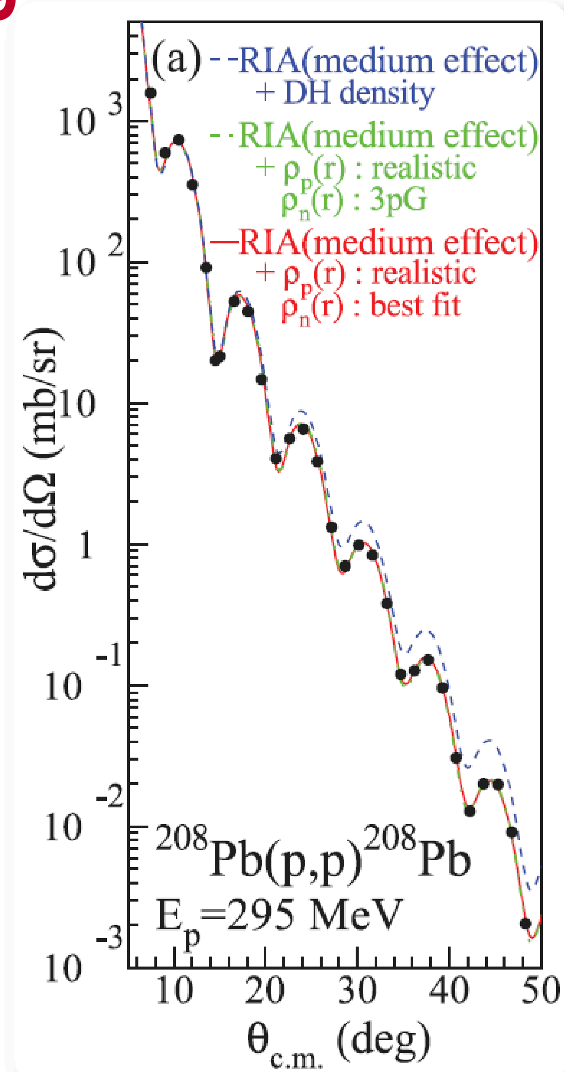
hadronic probes: proton scattering



$^{208}Pb(p,p)^{208}Pb$



$-0.3\text{fm} < R_{skin}^{208} < +1.4\text{fm}$



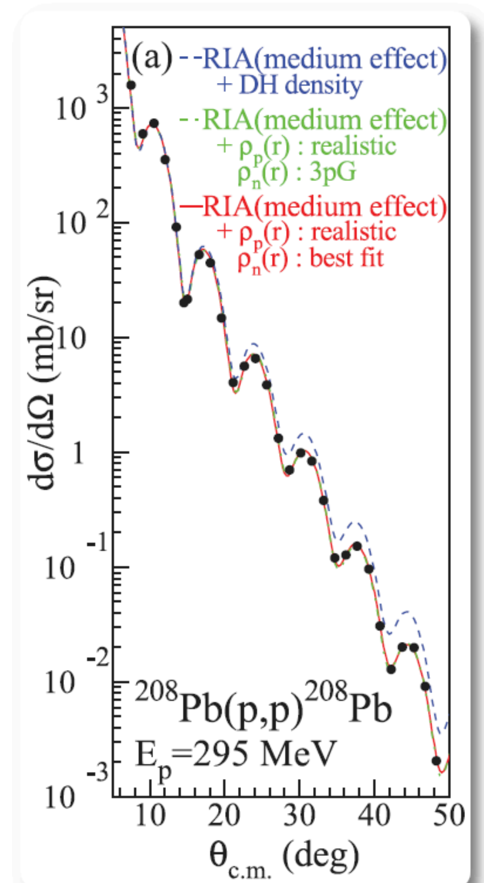
$R_{skin}^{208} = 0.211^{+0.054}_{-0.063}\text{fm}$

J. Zenihiro et al., PRC 82 (2010) 044611

R_{skin} depends strongly on energy!

hadronic probes: proton scattering

incomplete knowledge of the nucleon-nucleon (NN) scattering amplitude inside the nuclear medium!



J. Zenihiro et al., PRC 82 (2010) 044611

L. Ray, G.W. Hoffmann, PRC 31 (1985) 538
D.P. Murdock, C.J. Horowitz, PRC 35 (1987) 1442
V.E. Starodubsky, N.M. Hintz, PRC 49 (1994) 2118
S. Terashima et al., PRC 77 (2008) 024317
J. Zenihiro et al., arXiv 1810.1179 (2018)

hadronic probes: proton scattering

incomplete knowledge **of the nucleon-nucleon (NN) scattering amplitude inside the nuclear medium!**

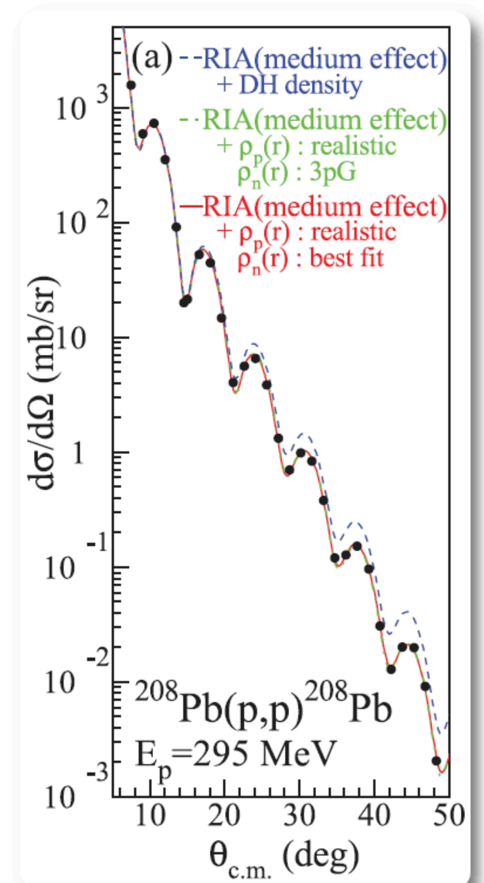
➡ **reduce uncertainties associated with the reaction mechanism!**

TO DO:

theory: choose the best energy range

- **pion production should be suppressed**
- **Impulse Approximation is valid**

experiment: measurements in that energy range



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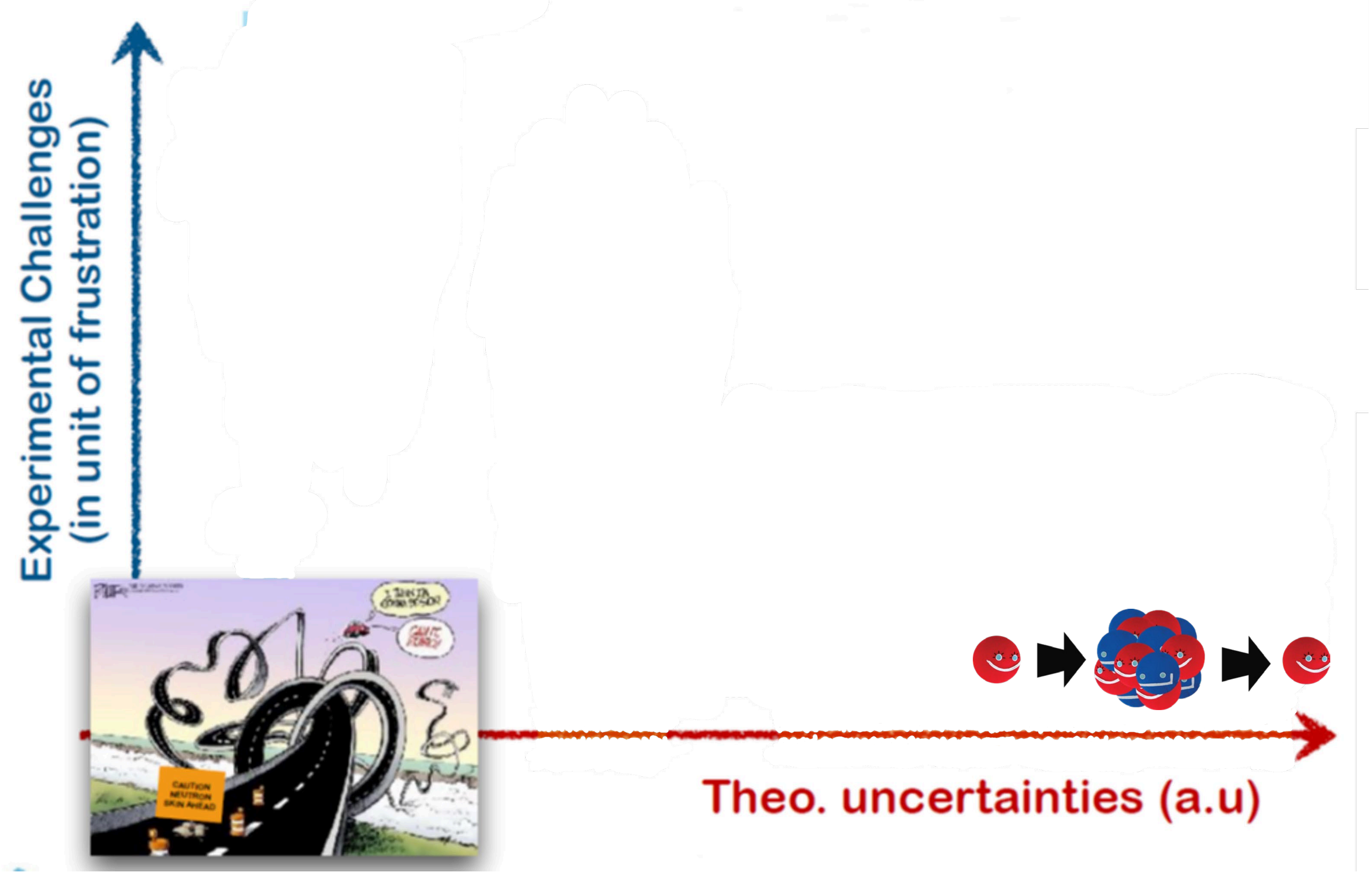
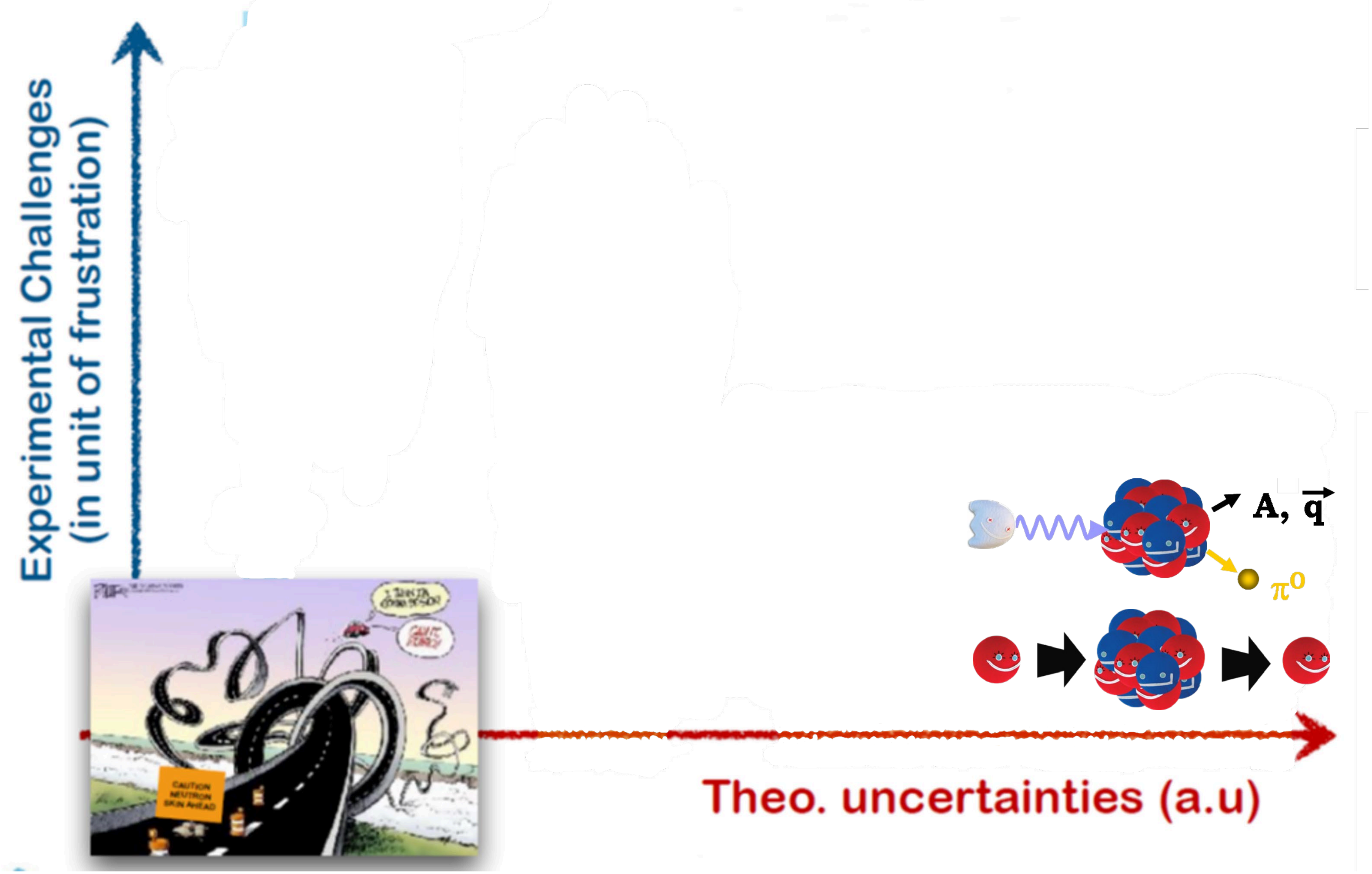


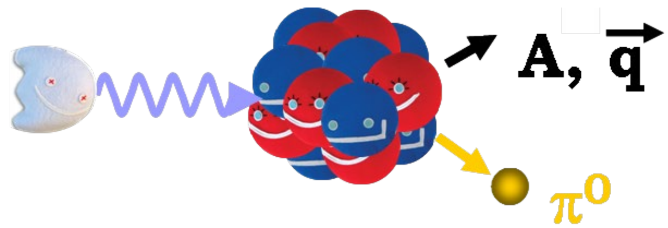
- large cross section
  many nuclei
- initial state interaction (ISI) and final state interaction (FSI)
  Optical Potential

coherent π^0 photoproduction

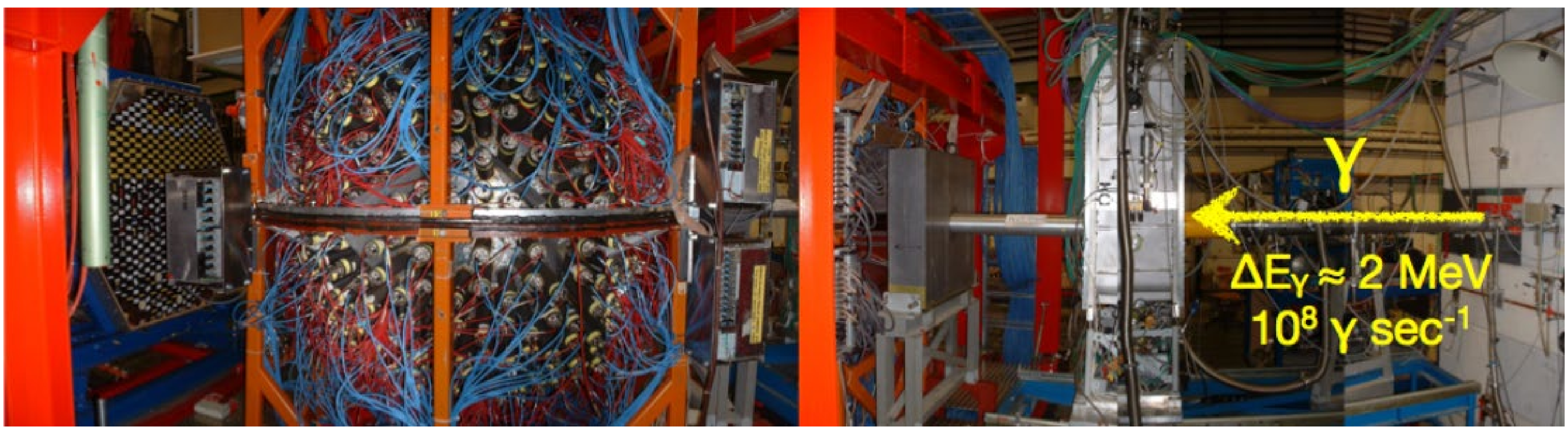


- NO initial state interaction
- theoretical interpretation?

coherent π^0 photoproduction

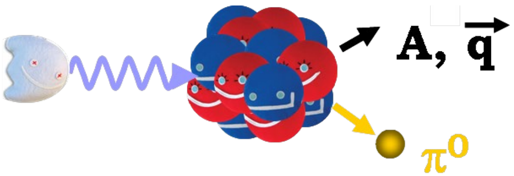


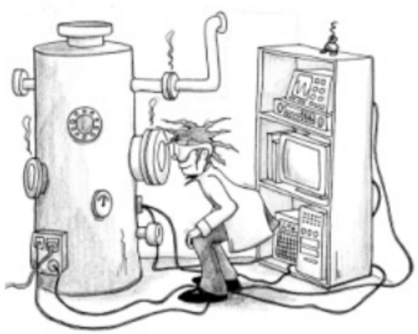
$$\gamma + A_{(g.s.)} \longrightarrow \pi^0 + A_{(g.s.)}$$
$$\hookrightarrow \gamma\gamma$$

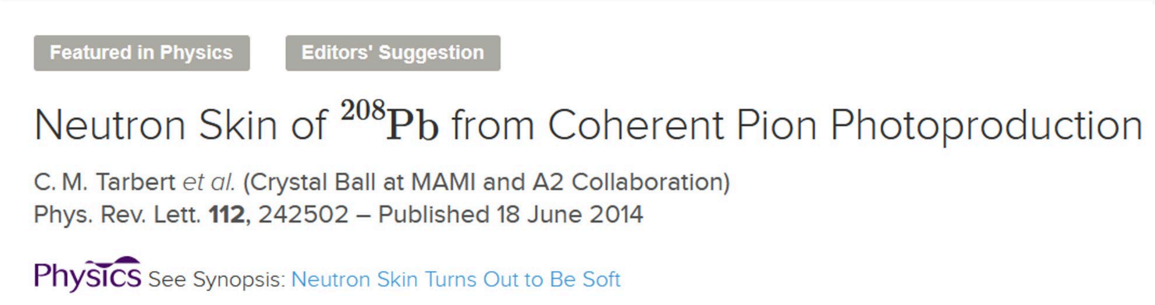


Crystal Ball + TAPS detector @ MAMI

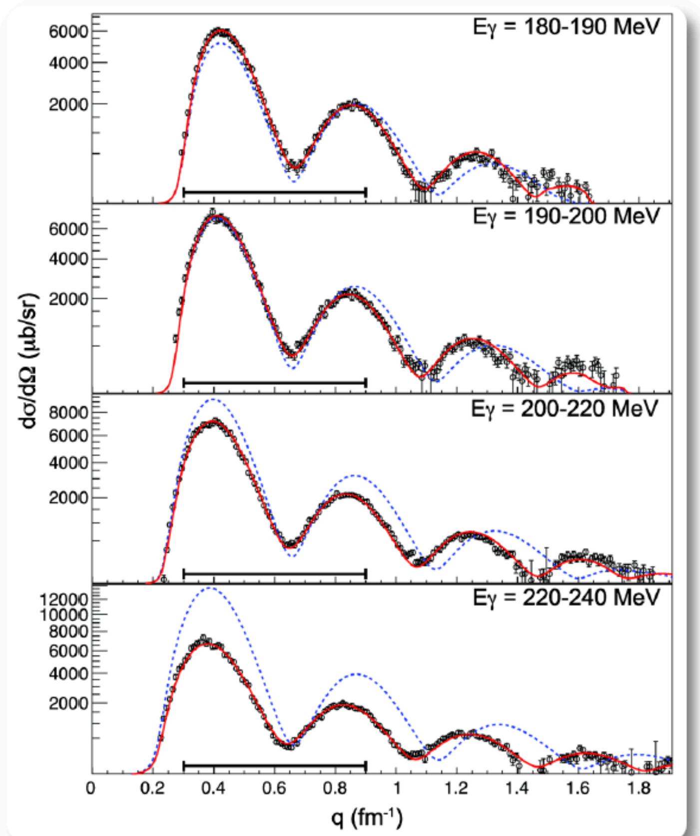
coherent π^0 photoproduction





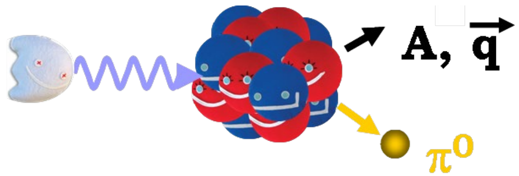


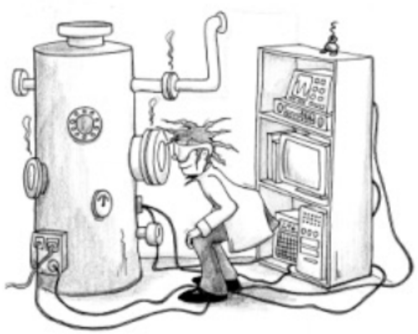
$$R^{208}_{skin} = 0.15 \pm 0.03(\text{stat.})^{+0.01}_{-0.03}(\text{sys.})\text{fm}$$



D. Drechsel et al., Nucl. Phys. A 660 (1999) 423
B. Krusche et al., Phys. Lett. B 526 (2002) 287
D. Drechsel et al., EPJA 34 (2007) 69
G.A. Miller, PRC 100 (2019) 044608

coherent π^0 photoproduction





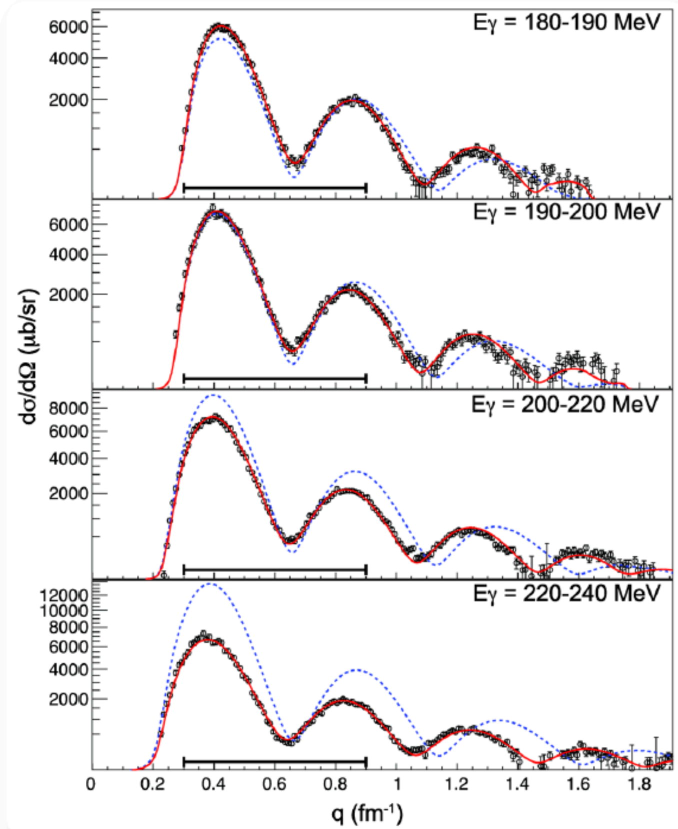
Featured in Physics | Editors' Suggestion

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

$$R_{skin}^{208} = 0.15 \pm 0.03(stat.)^{+0.01}_{-0.03}(sys.)fm$$



is this small systematic uncertainty realistic?

D. Drechsel et al., Nucl. Phys. A 660 (1999) 423
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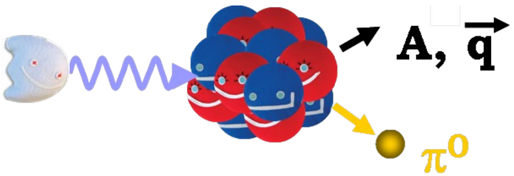


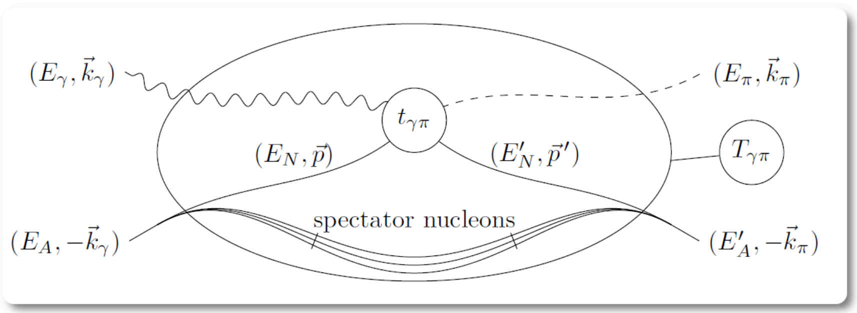
Theoretical analysis of the extraction of neutron skin thickness from coherent π^0 photoproduction off nuclei

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,¶]

[1] *Physique Nucléaire et Physique Quantique, Université Libre de Bruxelles (ULB), B-1050 Brussels*
[2] *Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
[3] *Department of Physics, Florida State University, Tallahassee, FL 32306, USA*

arXiv: 2204.13395v2 (accepted for publication in PRC)

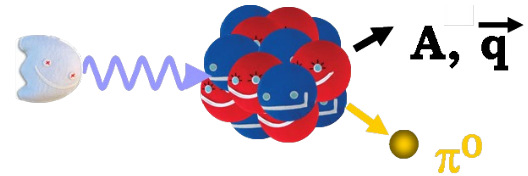
F. Colomer



Plane Wave:
no FSI of the pion with the nucleus

Impulse Approximation:
π^0 production on one single nucleon

coherent π^0 photoproduction



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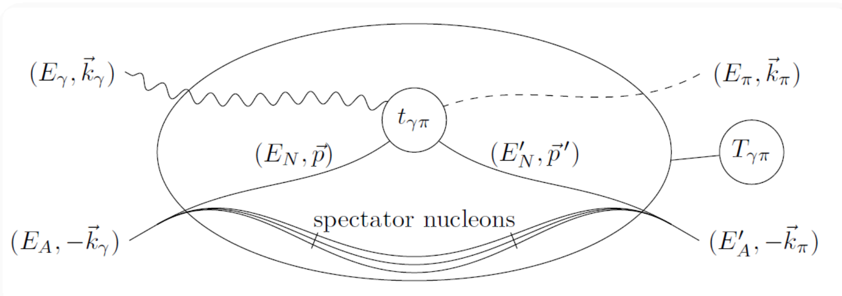


Plane Wave:
no FSI of the pion with the nucleus

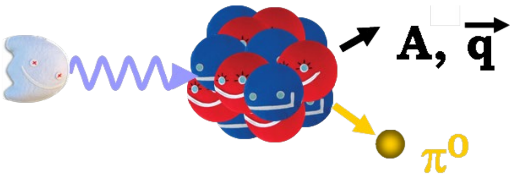
Impulse Approximation:
π^0 production on one single nucleon

➧ **coherent sum on each nucleon:** $\frac{d\sigma}{d\Omega}(\mathrm{PWIA}) \propto \left| f_2\left(\vec{k}_\pi, \vec{k}_\gamma\right) \rho_A(q) \right|^2$

- **f_2: CGLN amplitudes from MAID** (https://maid.kph.uni-mainz.de/maid2007/helic.html)
- **ρ_A: nucleus density**

➧ **should give access to nuclear density, BUT…**

coherent π^0 photoproduction



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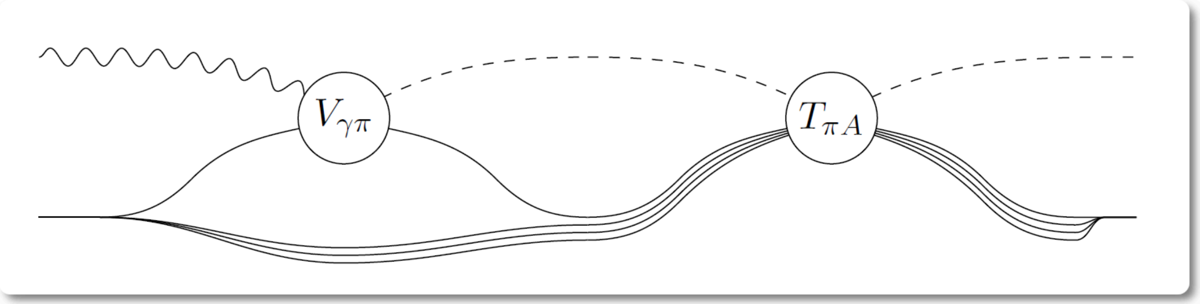
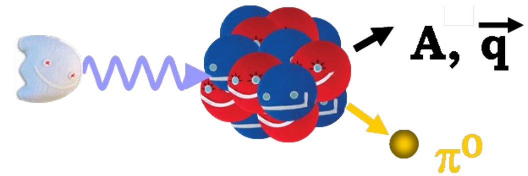


… after its production, the π^0 undergoes

π-A scattering

coherent π^0 photoproduction



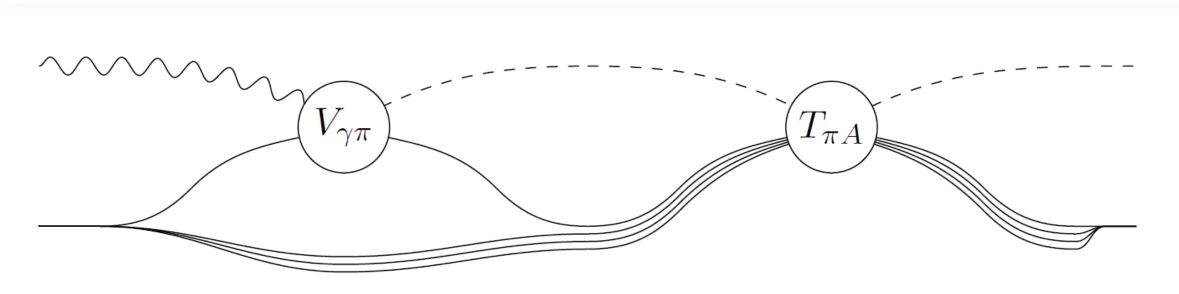
Theoretical analysis of the extraction of neutron skin thickness from coherent π^0 photoproduction off nuclei

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,¶]

[1] *Physique Nucléaire et Physique Quantique, Université Libre de Bruxelles (ULB), B-1050 Brussels*
[2] *Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
[3] *Department of Physics, Florida State University, Tallahassee, FL 32306, USA*

arXiv: 2204.13395v2 (accepted for publication in PRC)

F. Colomer



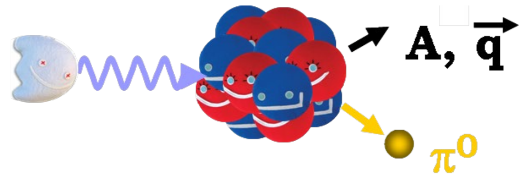
… after its production, the π^0 undergoes **π-A scattering**

Distorted Wave Impulse Approximation

$$F_{\gamma\pi}\left(\vec{k}_\pi,\vec{k}_\gamma\right) = V_{\gamma\pi}\left(\vec{k}_\pi,\vec{k}_\gamma\right) + \frac{A-1}{A}\int \frac{d\vec{k'}_\pi}{2\mathcal{M}(k'_\pi)}\frac{T_{\pi A}\left(\vec{k}_\pi,\vec{k'}_\pi\right)V_{\gamma\pi}\left(\vec{k'}_\pi,\vec{k}_\gamma\right)}{E(k_\pi)-E(k'_\pi)+i\varepsilon}$$

$\frac{d\sigma}{d\Omega}(\mathrm{DWIA}) \propto \left|F_{\gamma\pi}\right|^2$ loses its proportionality to $\rho(q)$!

coherent π^0 photoproduction



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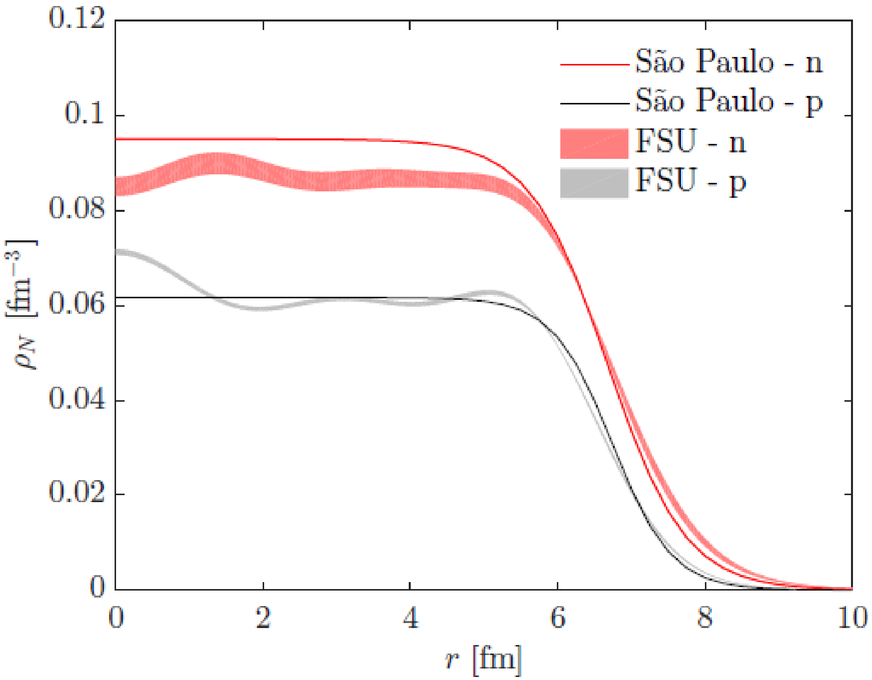

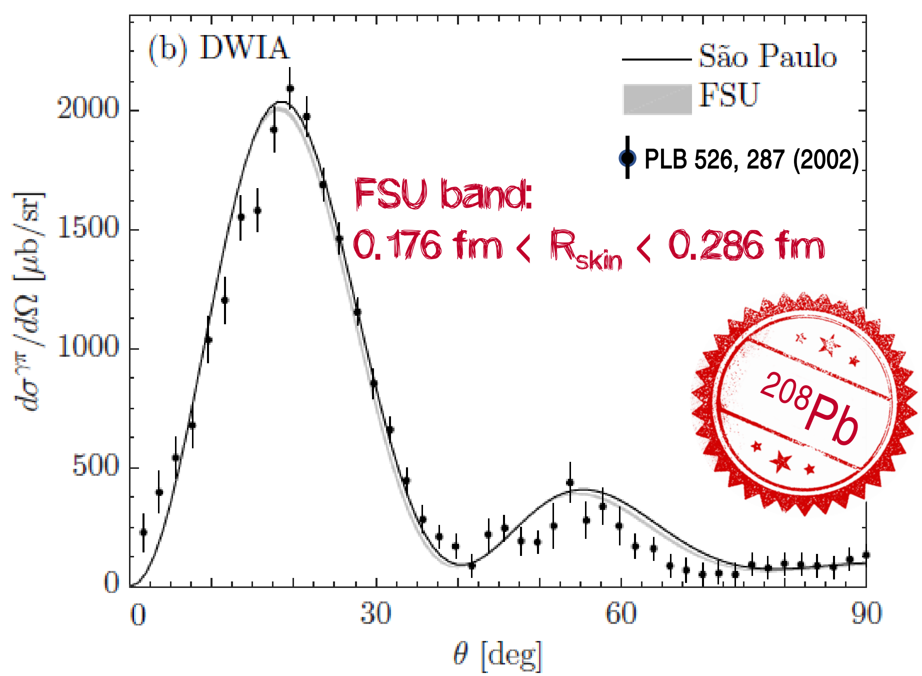

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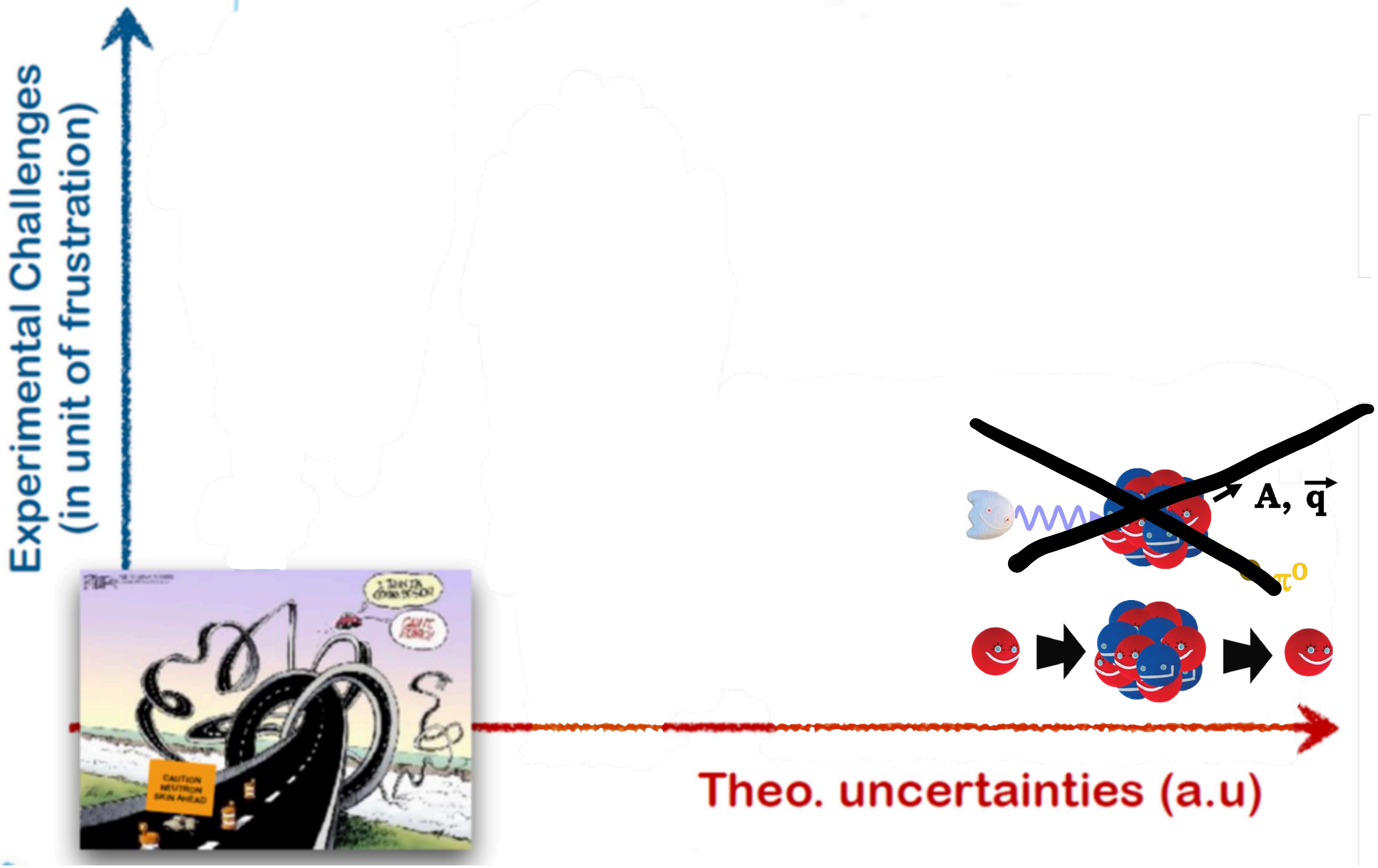
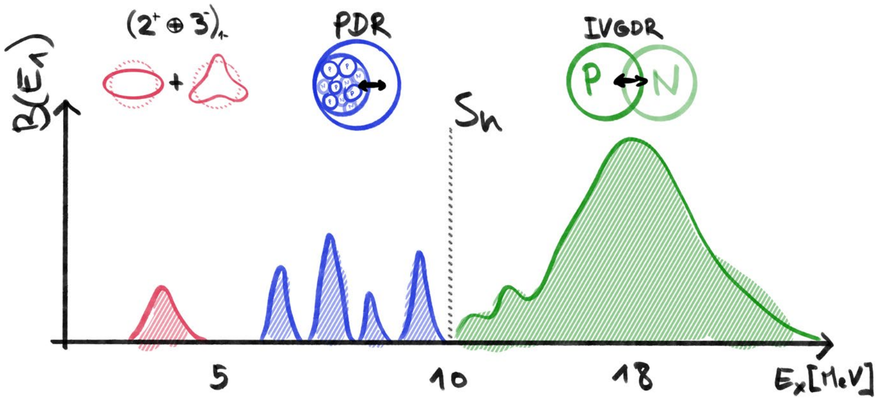


NOT sensitive to R_{skin}!

electric dipole polarizability



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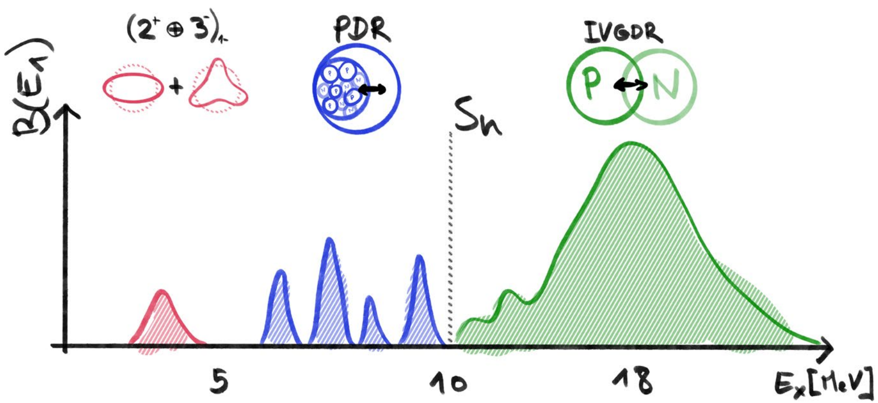
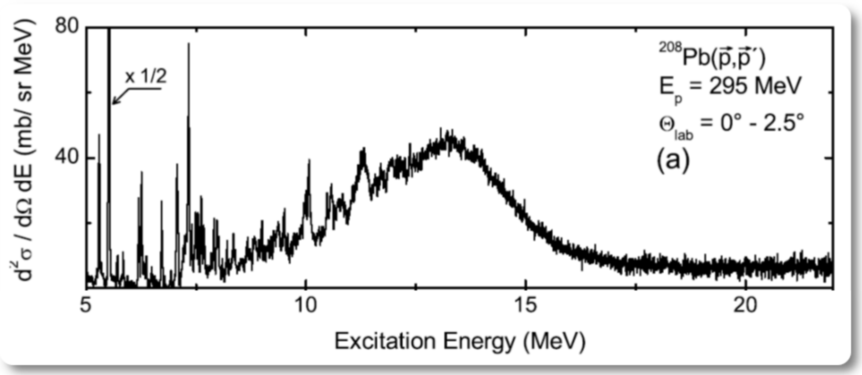
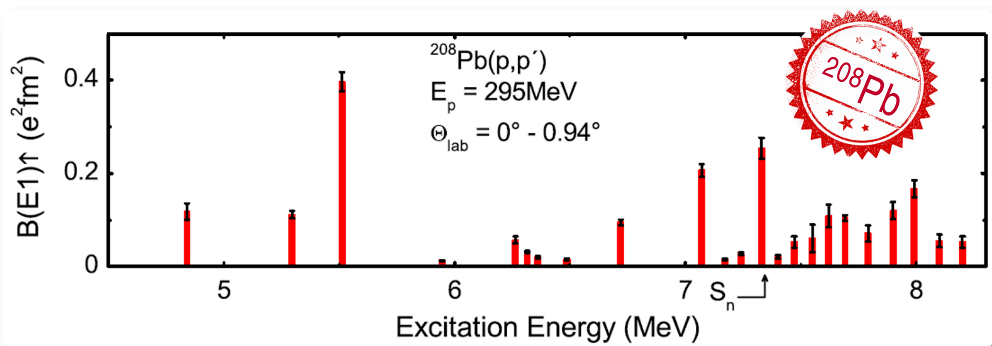


proton inelastic scattering measurements at very forward angles:

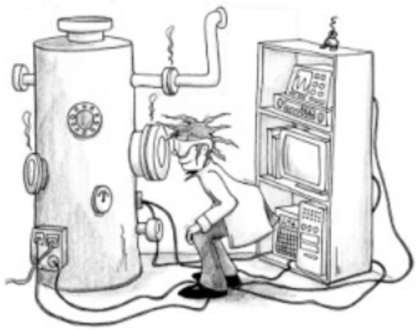
measure cross section and determine the electric dipole E1 response

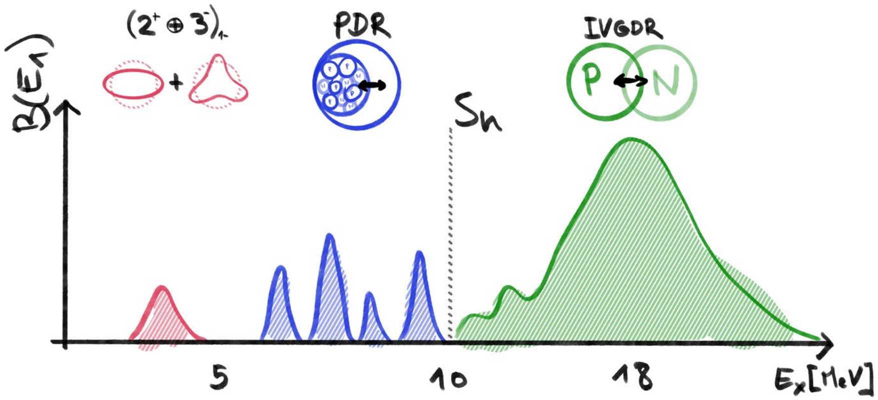




A. Tamii et al., PRL 107 (2011) 062502

electric dipole polarizability





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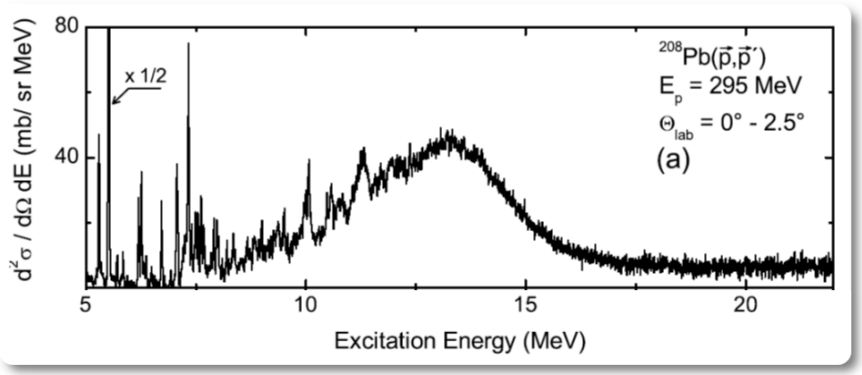
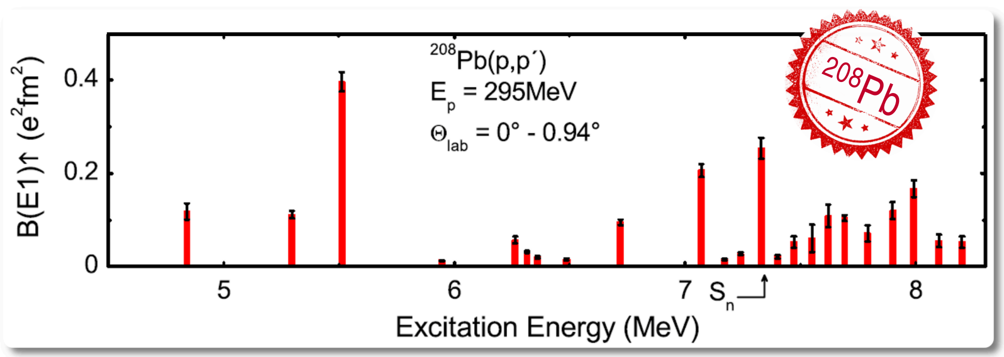
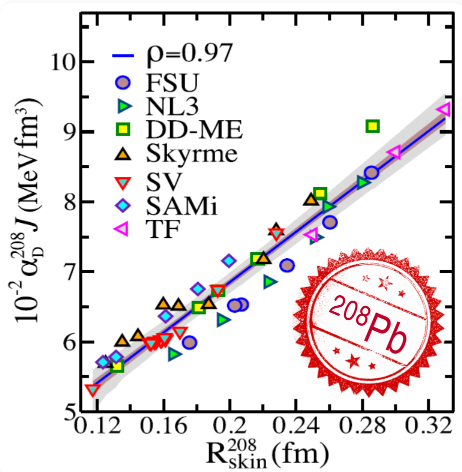




A. Tamii et al., PRL 107 (2011) 062502

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

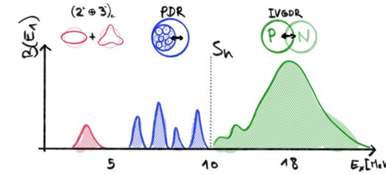
electric dipole polarizability



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

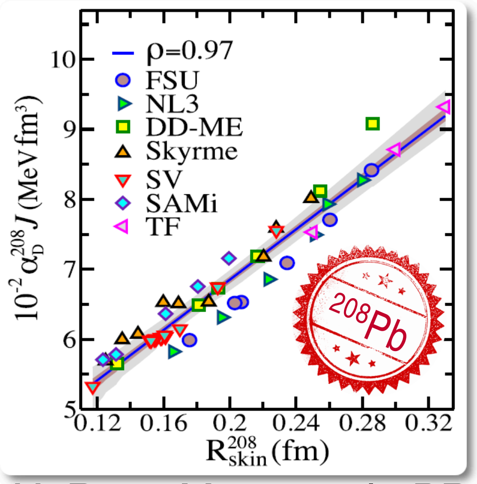
$$\mathrm{R}_{\mathrm{skin}}^{208} = 0.156_{-0.021}^{+0.025}\,\mathrm{fm}$$

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



A. Klimkiewicz et al., PRC 76 (2007) 051603(R)
A. Carbone et al., PRC 81 (2010) 041301(R)
T. Hashimoto et al., PRC 92 (2015) 031305
J. Birkhan et al., PRL 118 (2017) 252501

electric dipole polarizability



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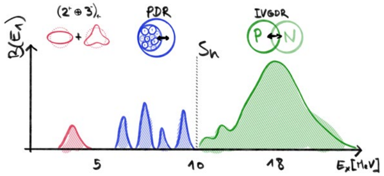
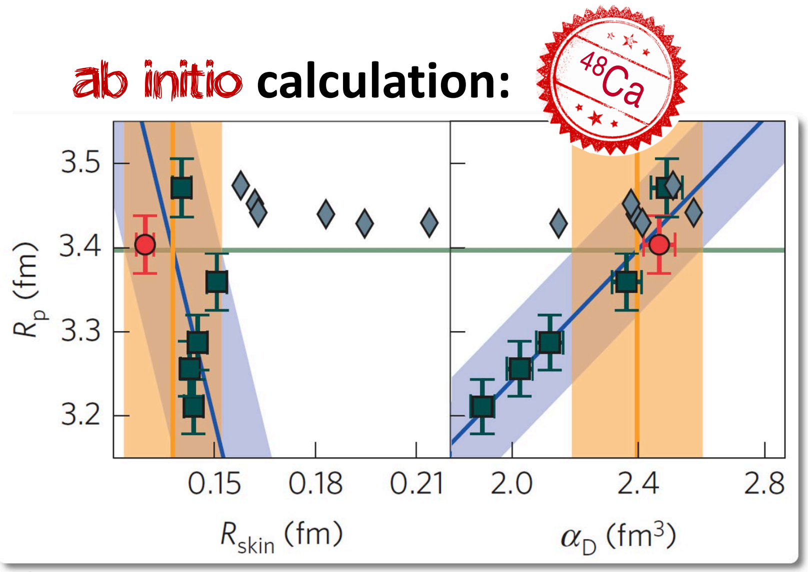


ab initio **calculation:**



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

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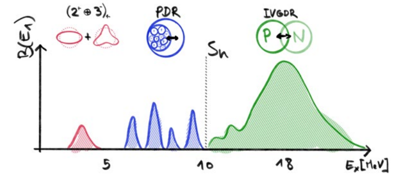
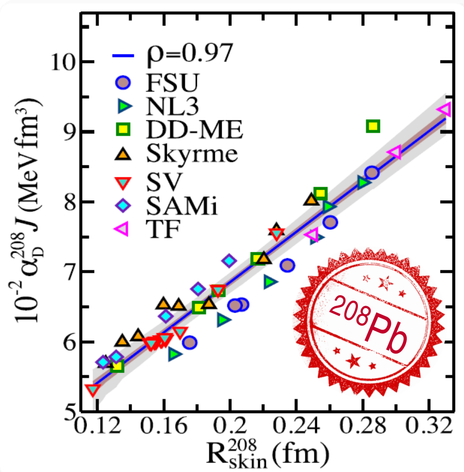
electric dipole polarizability





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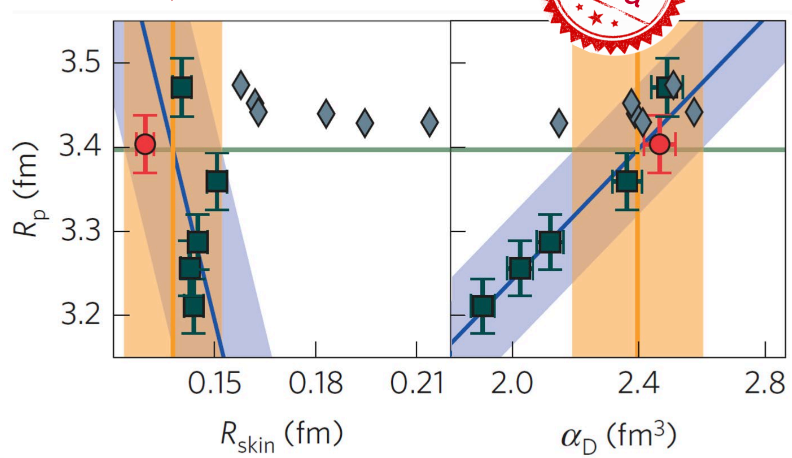

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Friday:
Jorge Piekarewicz

A. Klimkiewicz et al., PRC 76 (2007) 051603(R)
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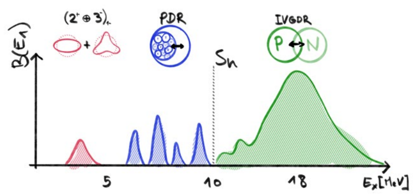
electric dipole polarizability

Experimental Challenges
(in unit of frustration)

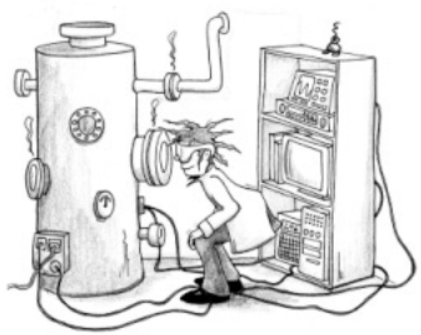


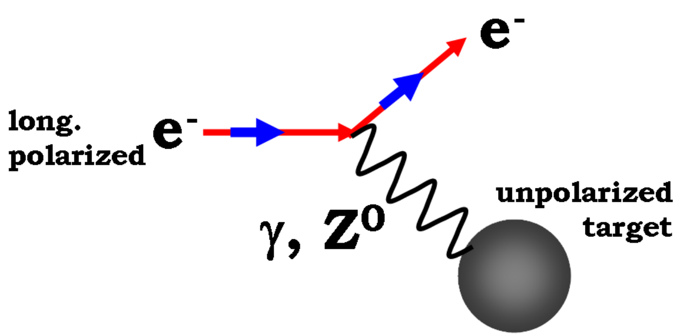
Theo. uncertainties (a.u)

experiment: high quality data on a variety of nuclei
theory: enormous steady progress

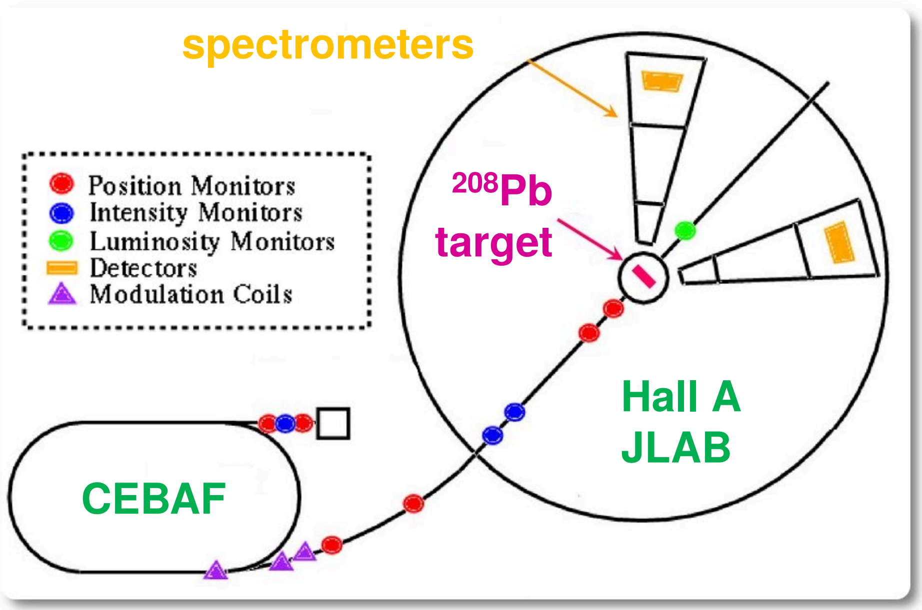
model dependent

Parity-Violating Electron Scattering (PVES)

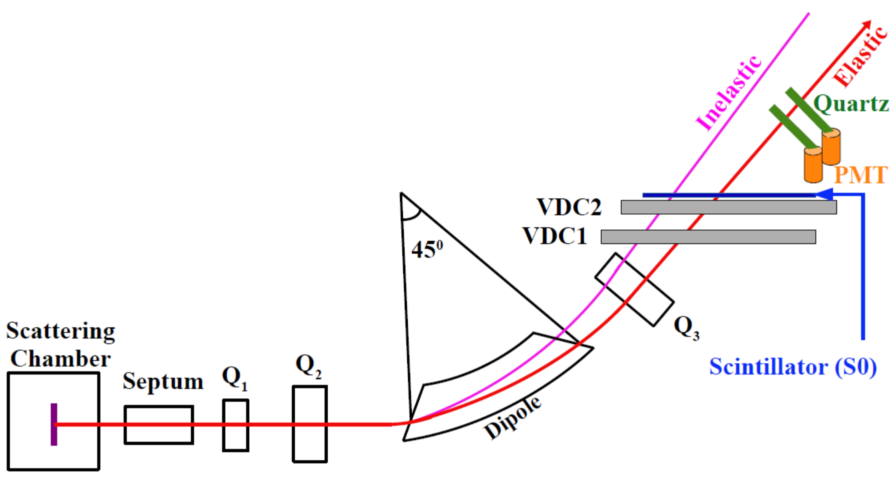




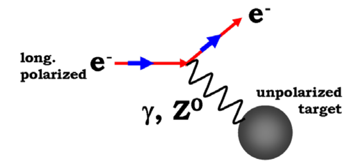
PREX setup

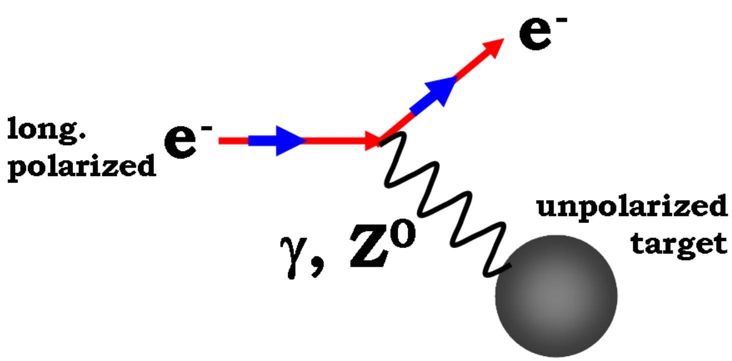


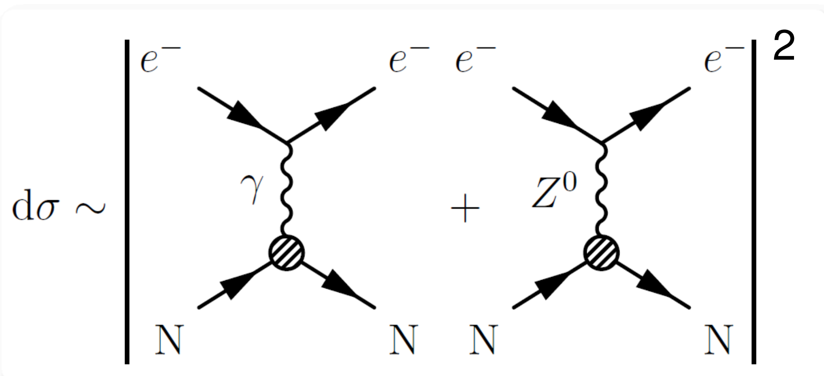
side view spectrometer



PVES

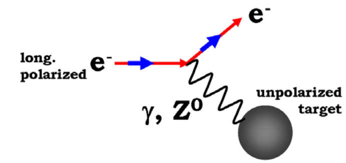


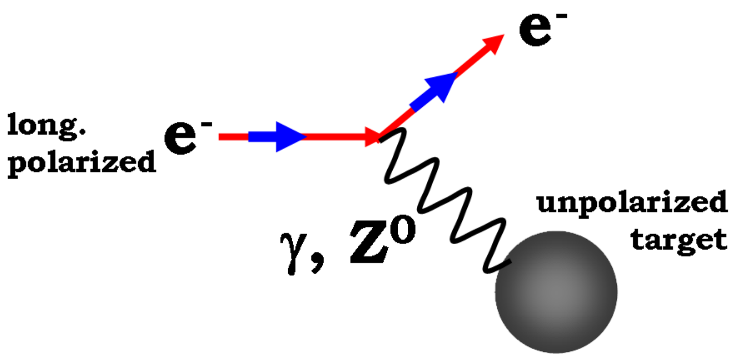




		
electric charge	1	0
weak charge	≈0.07	-1

PVES



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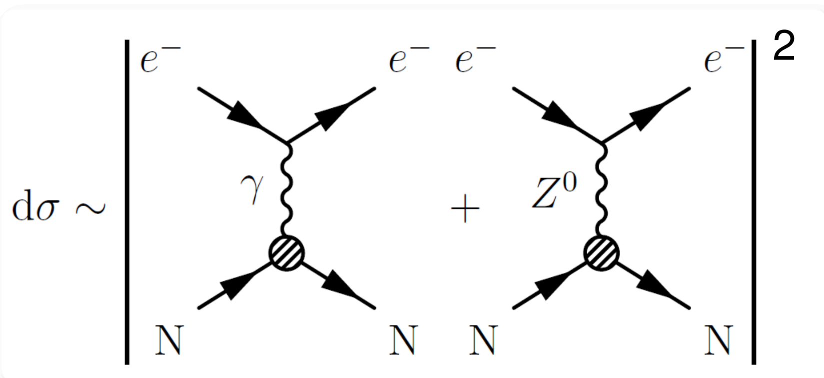
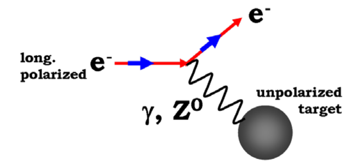
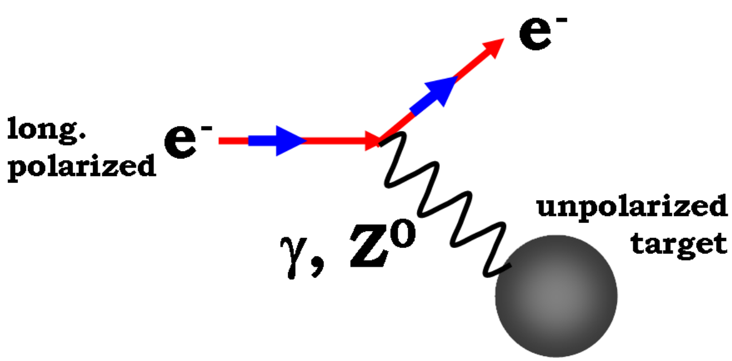


$$A_{PV} = \frac{\sigma^R - \sigma^L}{\sigma^R + \sigma^L}$$

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

PVES





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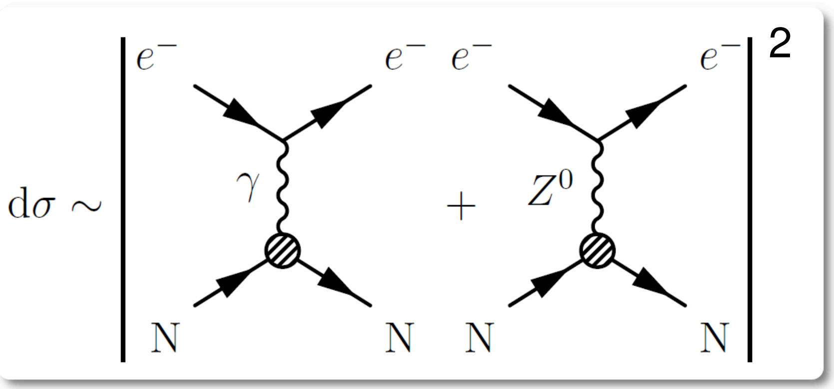

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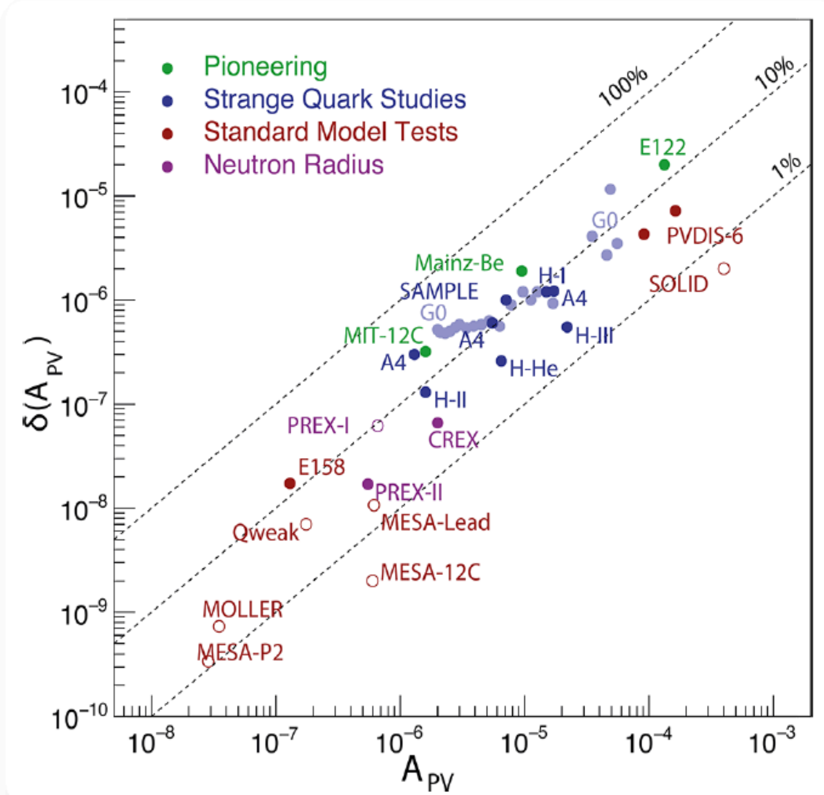
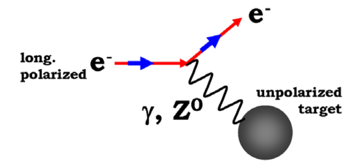
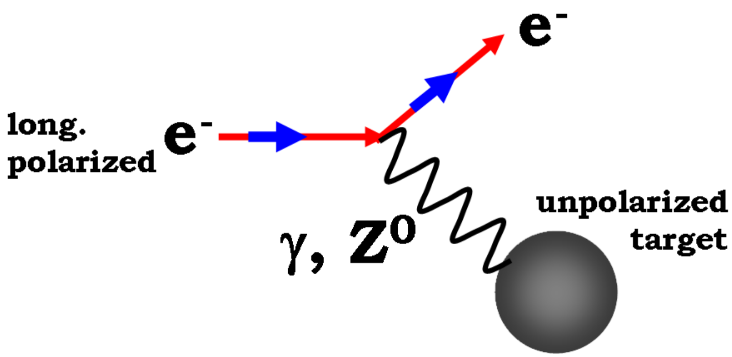


D. Becker et al., EPJA 54 (2018) 208

PVES





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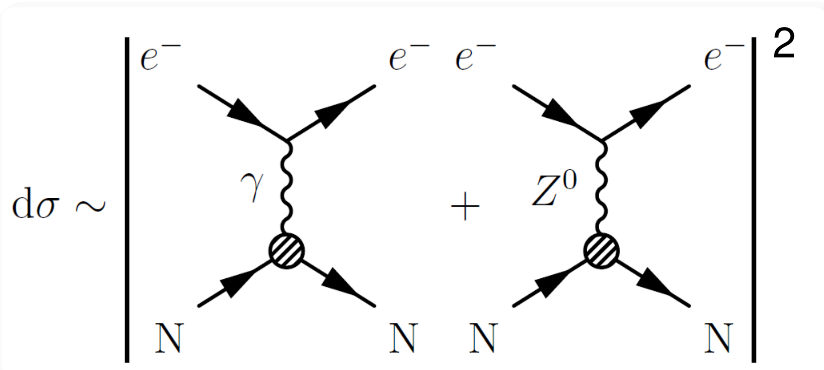

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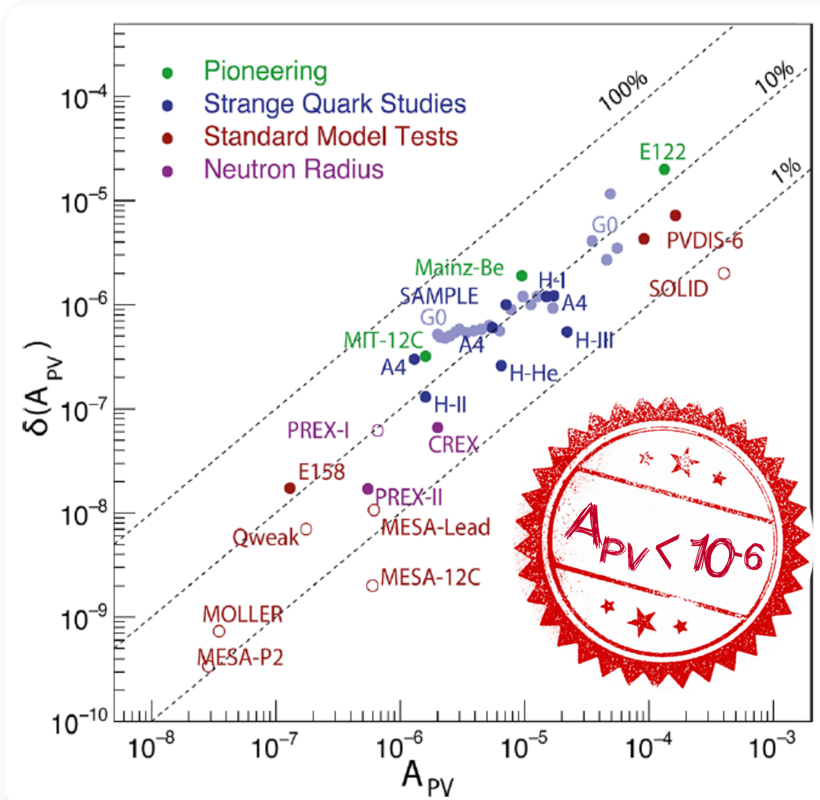

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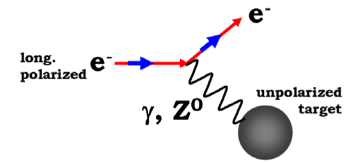
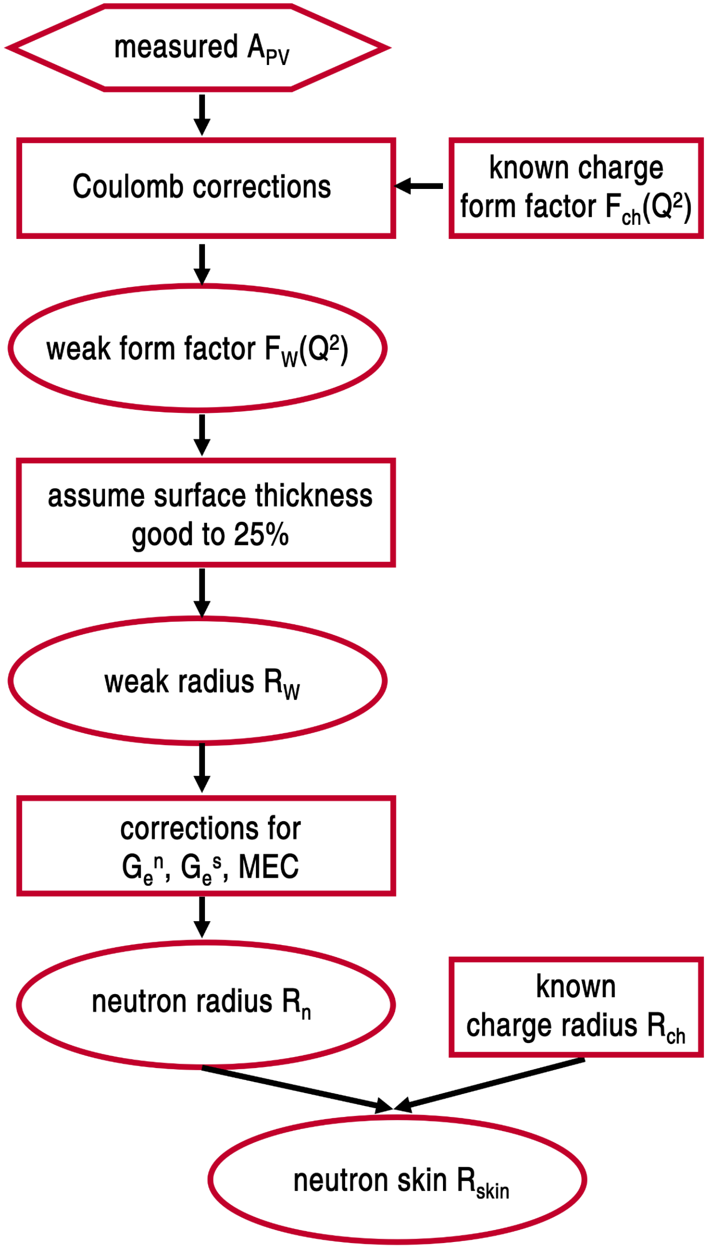
PVES: extraction of neutron skin





C.J. Horowitz, PRC 57 (1998) 3430
S. Abrahamyan et al., PRL 108 (2012) 112502
C.J. Horowitz et al., PRC 85 (2012) 032501(R)
D. Adhikari et al., PRL 129 (2022) 042501

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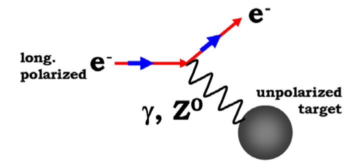

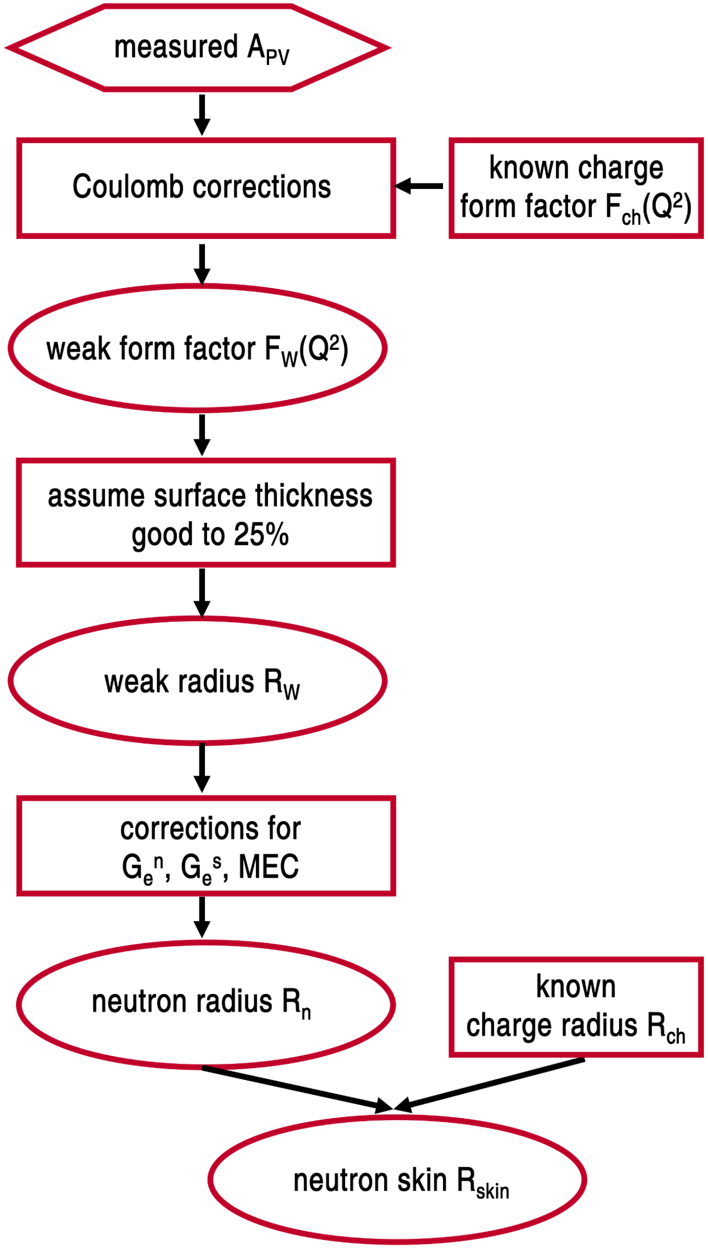

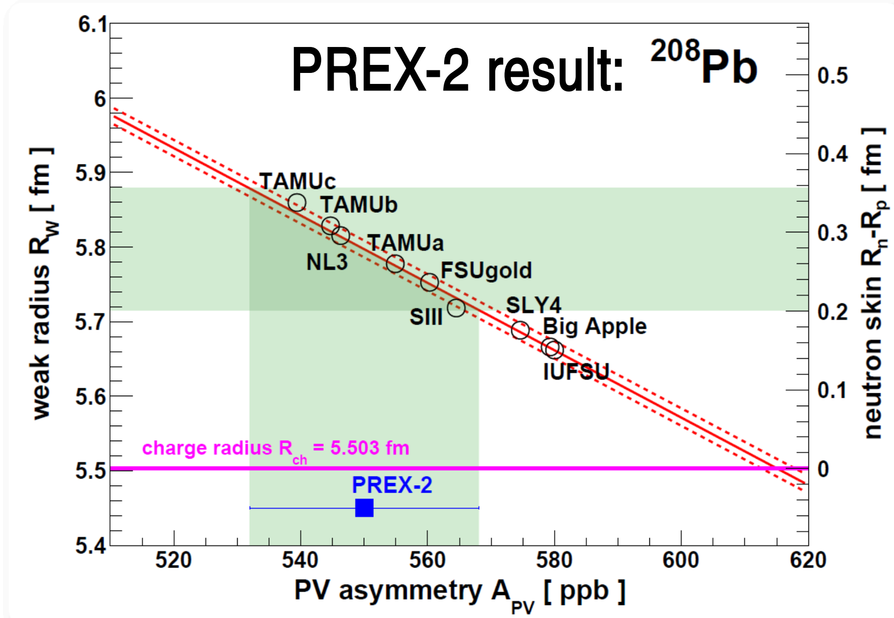

D. Adhikari et al., PRL 126 (2021) 172502

$$A_{PV} = 550 \pm 16\ (\text{stat}) \pm 8\ (\text{sys})\ \text{ppb}$$

$$R_{skin} = 0.278 \pm 0.078\ \text{fm}$$

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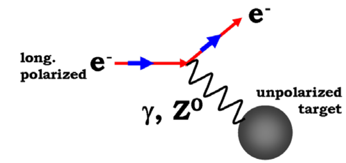
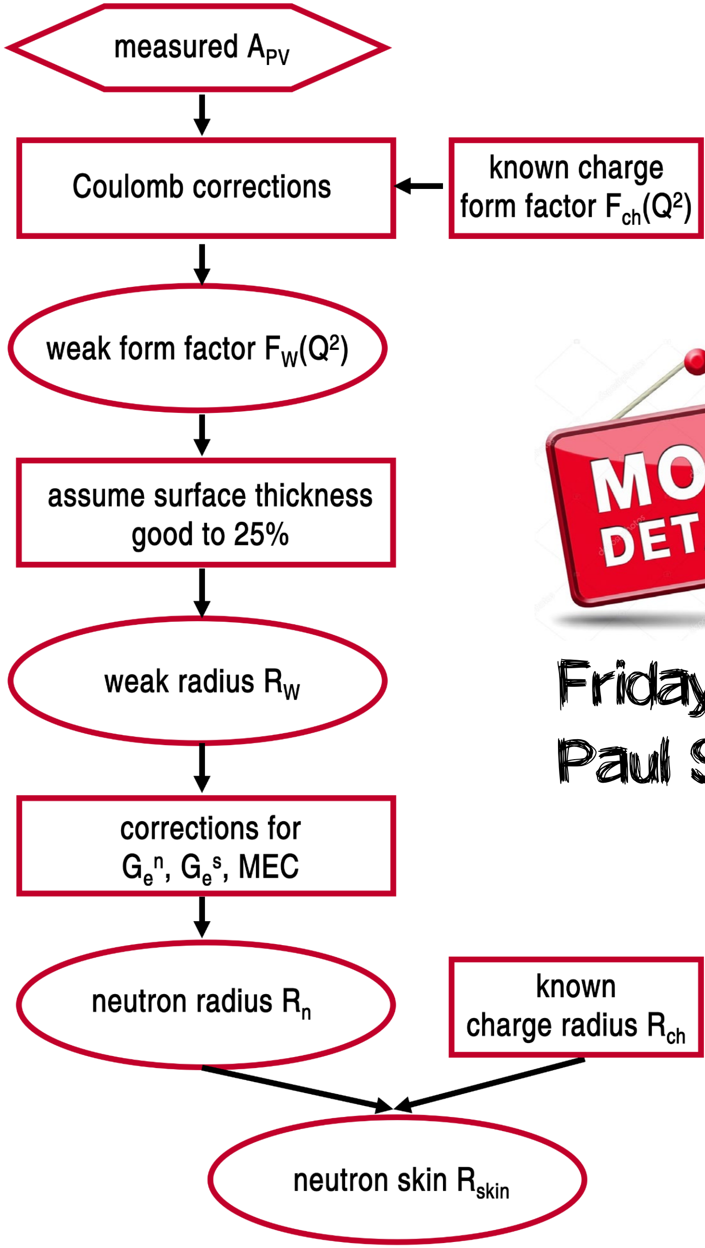
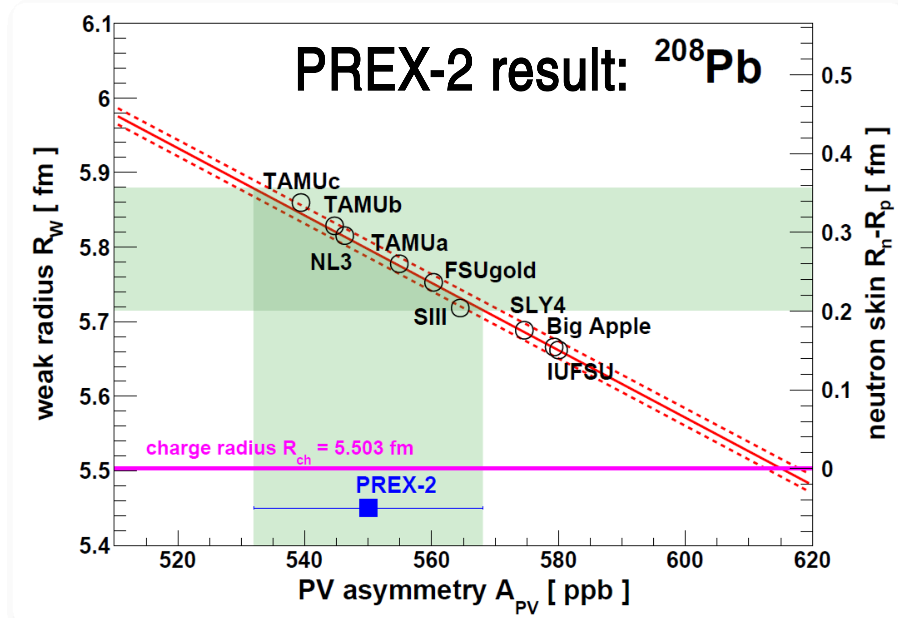




MORE DETAILS

Friday:
Paul Souder



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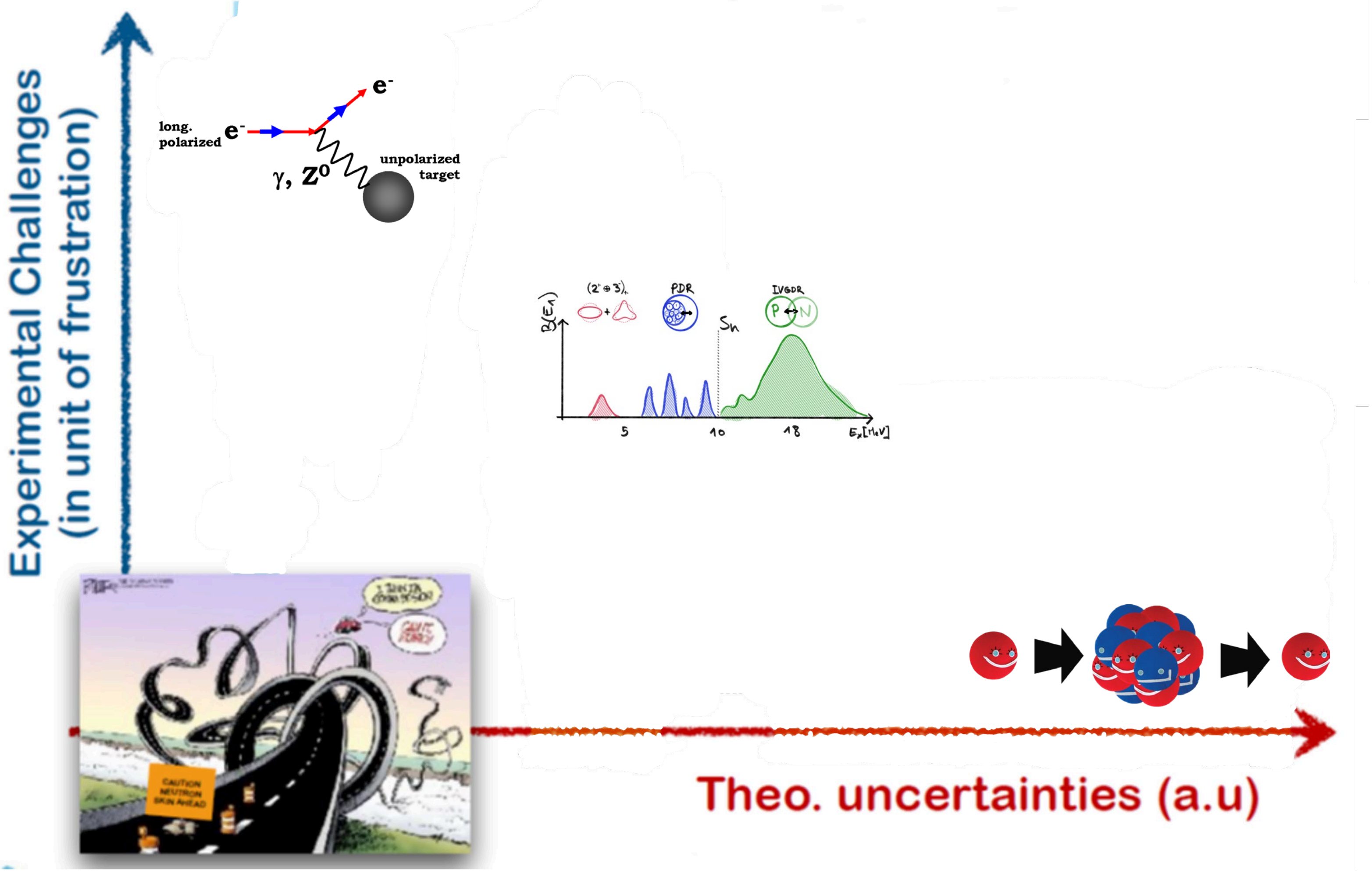
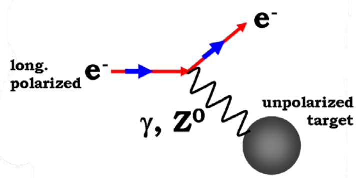
PVES

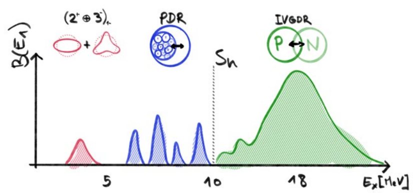


- **least model dependent method to determine R_{skin}**
- **long, challenging experiments**

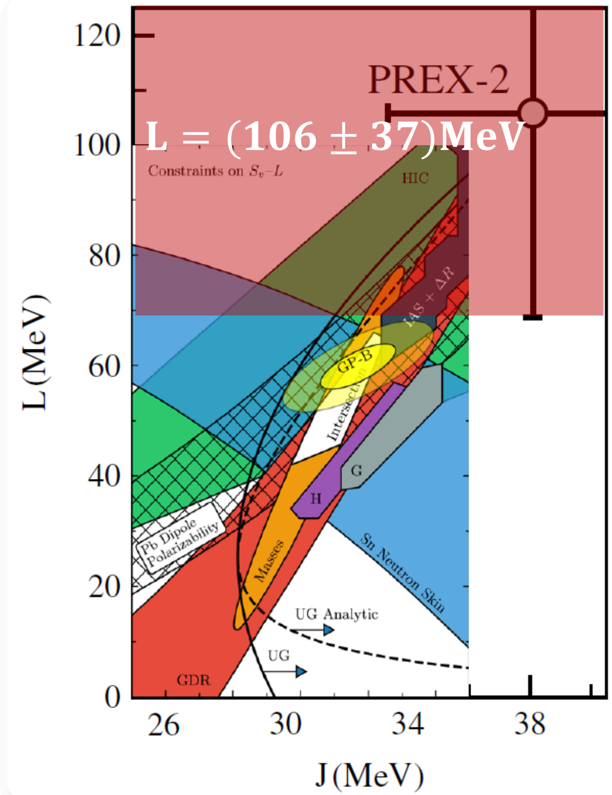
PVES

Experimental Challenges (in unit of frustration)





B.T. Reed et al., PRL 126 (2021) 172503

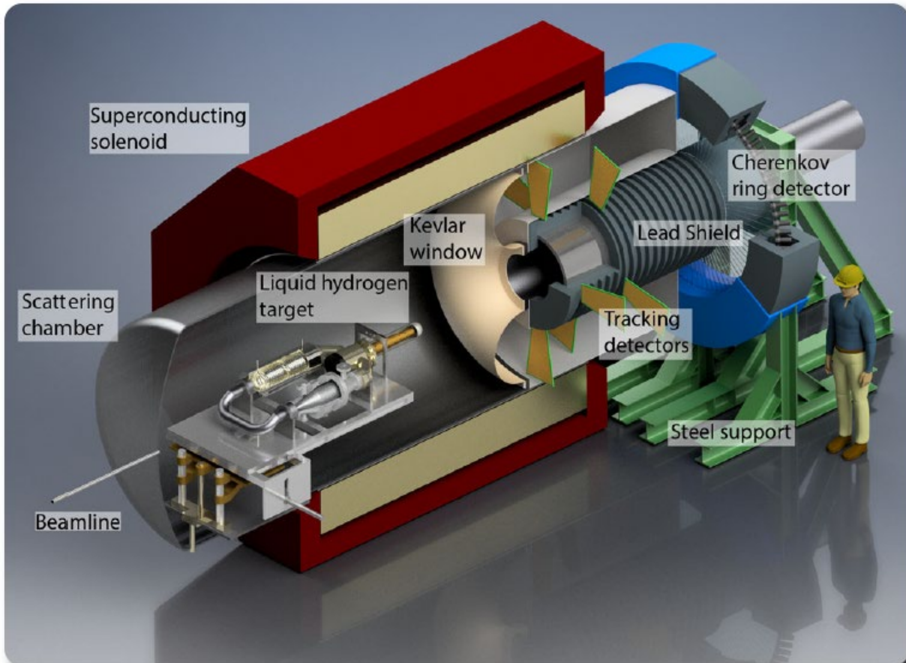


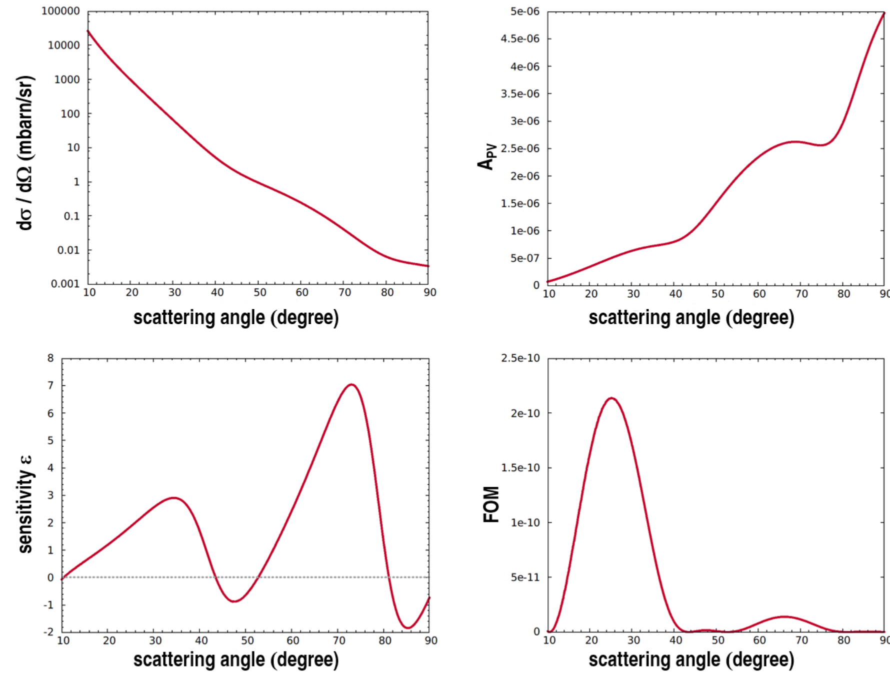
Theo. uncertainties (a.u)

- least model dependent method to determine R_{skin}
- long, challenging experiments

future PVES experiment: MREX @MESA

(Mainz Radius Experiment)





±0.03 fm determination of ^{208}Pb–R_{skin} (60 days)

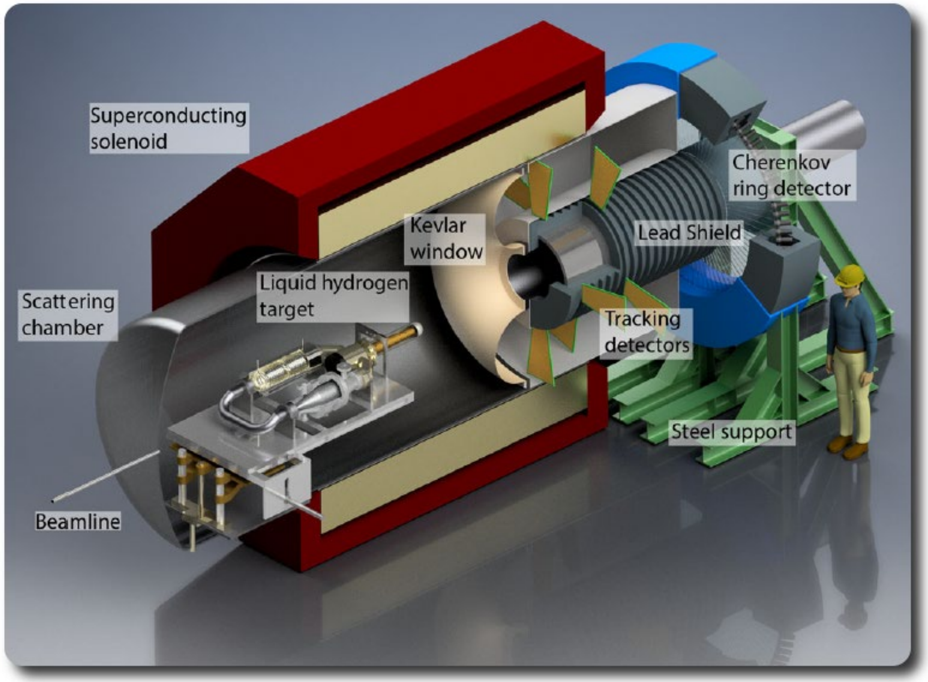
beam
energy: 155 MeV
current: 150μA

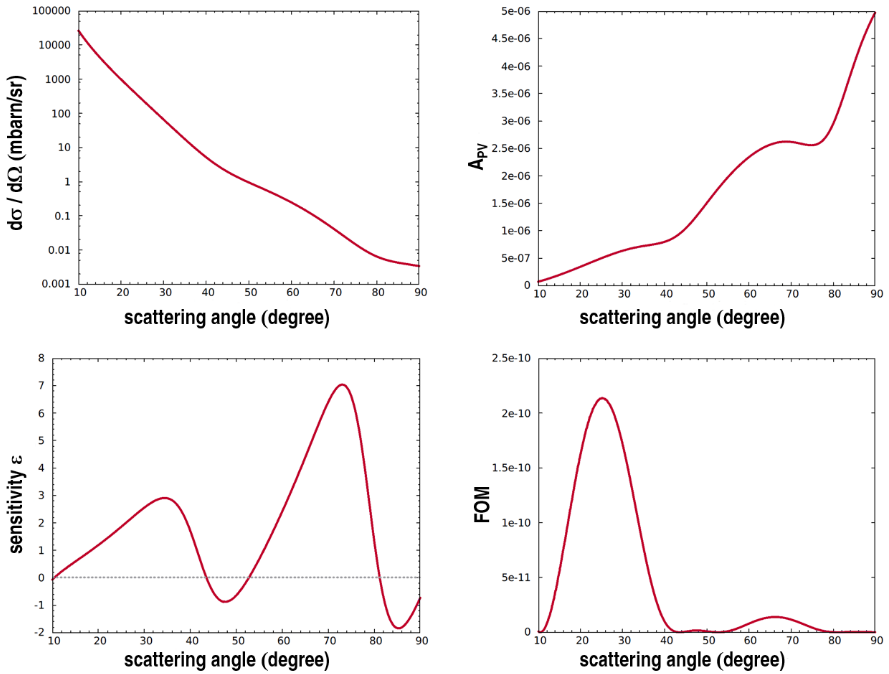
target
^{208}Pb 0.56 g/cm²

A_{PV}: 0.66 ppm
polarization: 85%

future PVES experiment: MREX @MESA

(Mainz Radius Experiment)





± 0.03 fm determination of ^{208}Pb–R_{skin} (60 days)

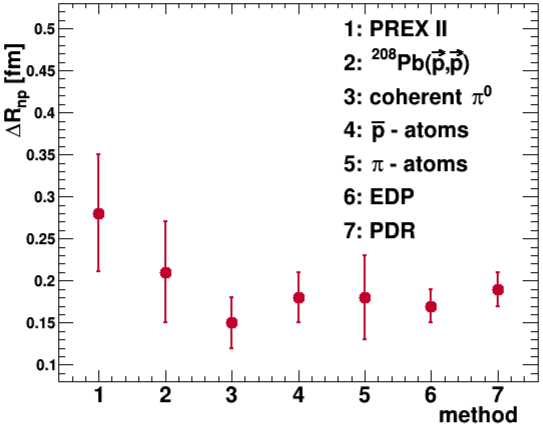
Friday:
Kent Paschke

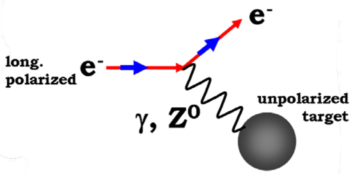
beam
energy: 155 MeV
current: 150μA

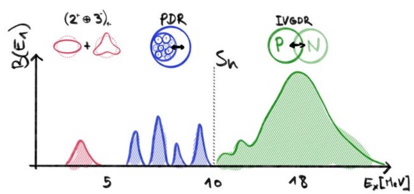
target
^{208}Pb 0.56 g/cm^2

A_{PV}: 0.66 ppm
polarization: 85%

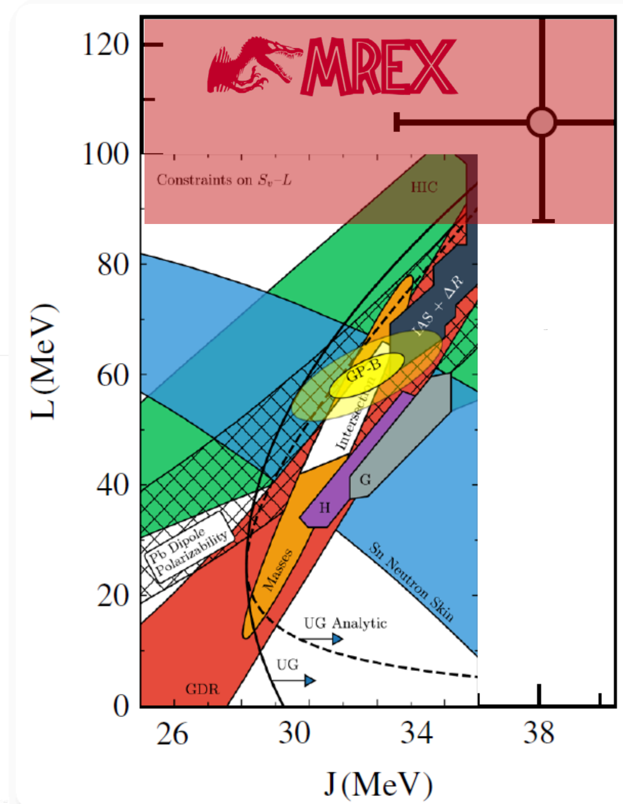
summary

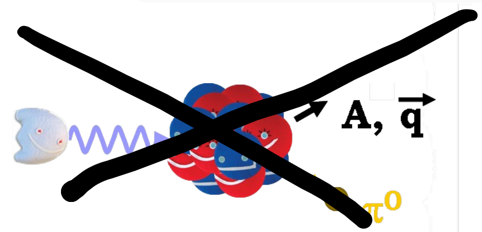






B.T. Reed et al., PRL 126 (2021) 172503

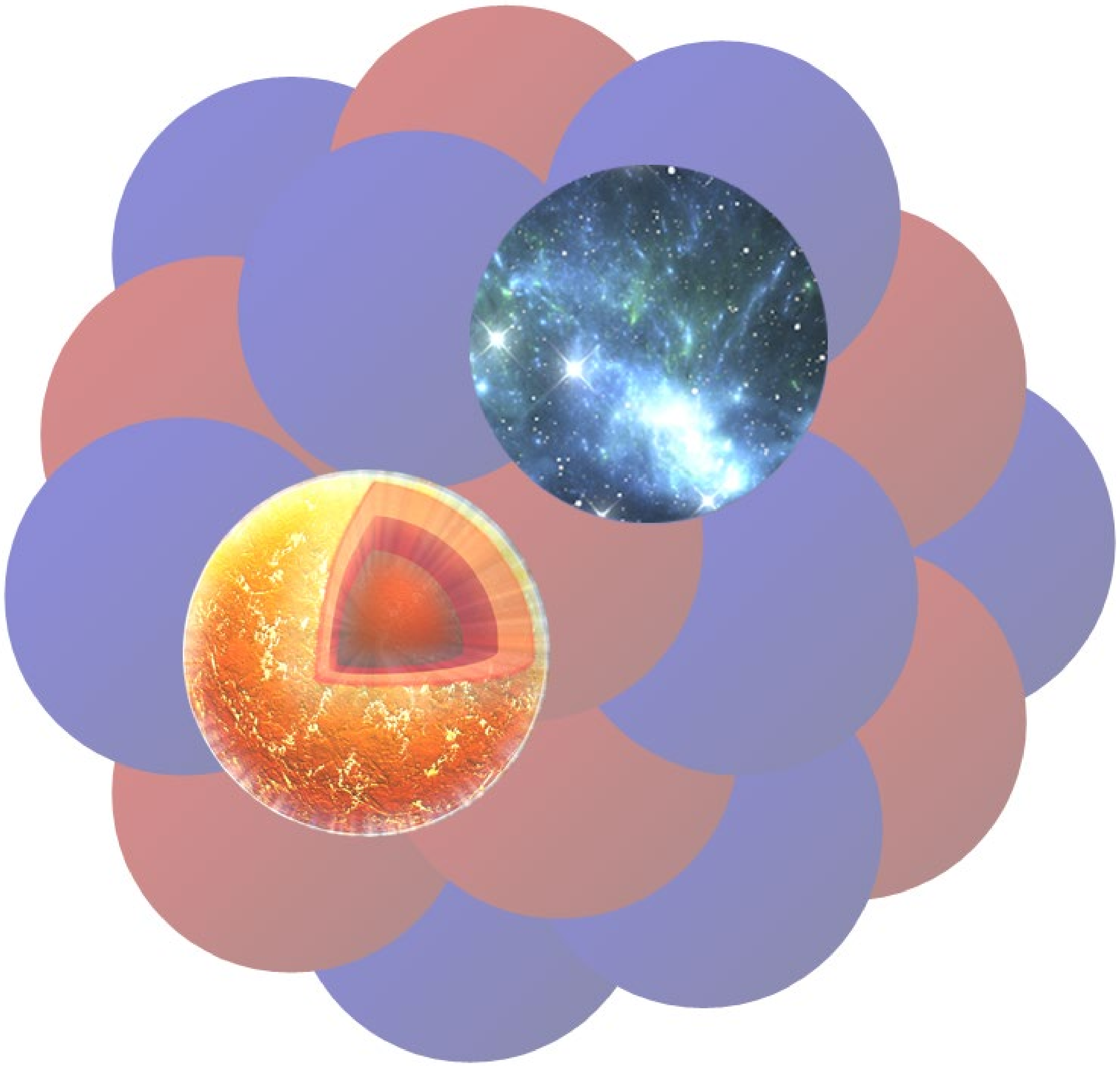




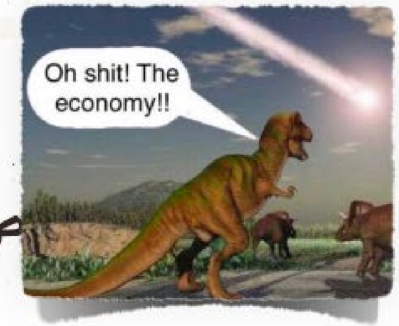
Experimental Challenges (in unit of frustration)

Theo. uncertainties (a.u)

backup



MREX



	2024-2027	2028-2031	2032-2035
MREX DARKMESA			

... per aspera ad astra ...

CONCETTINASFIENTI

#MakeHumansSmartAgain