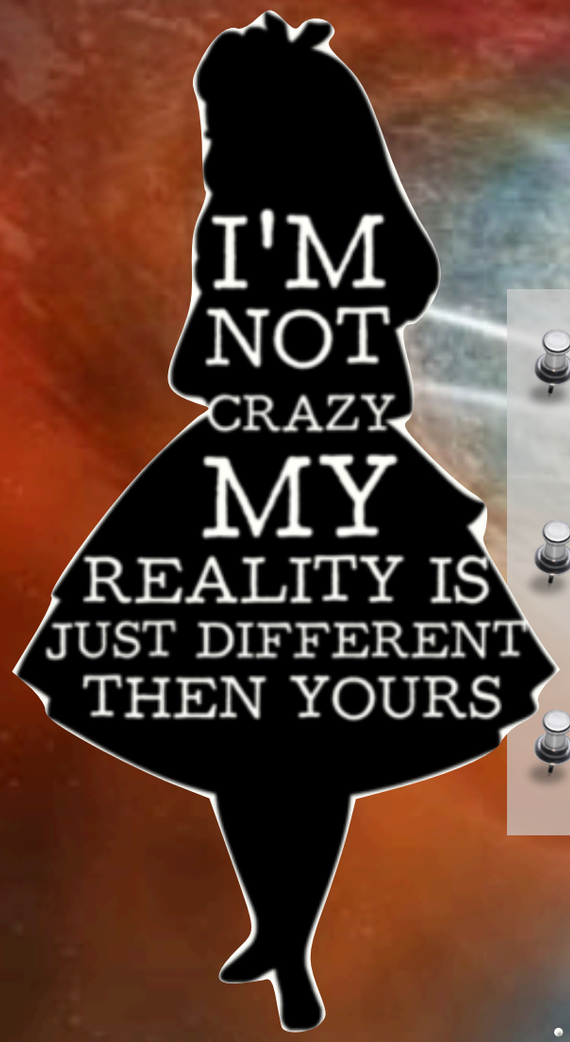
Per aspera ad astra ...

The future of the Neutron-Skin Program at MESA

Concettina Sfienti
Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

Per aspera ad astra ...

Neutron Skin: Quo vadis?



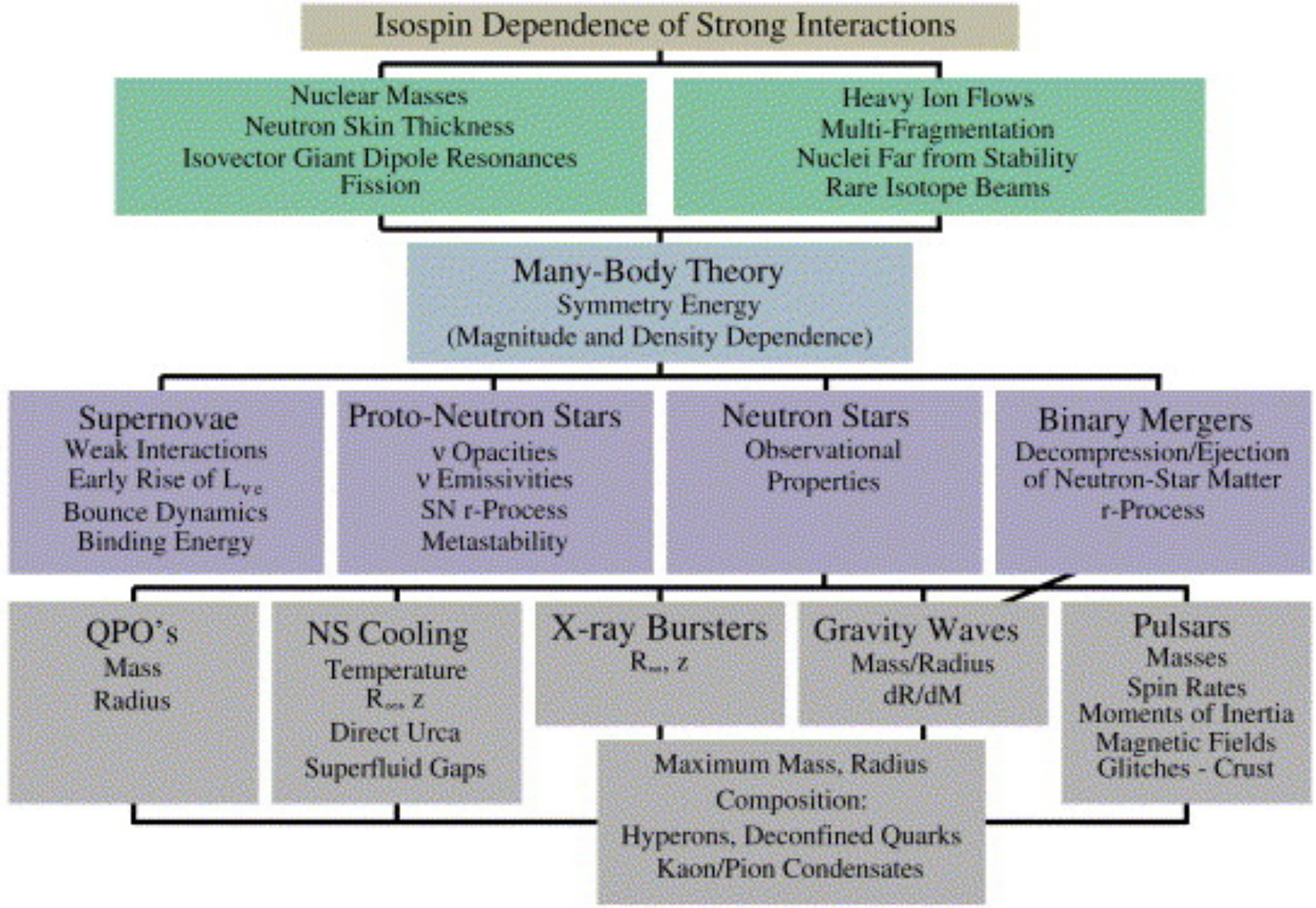
- Heaven and Earth
- Stairway or Highway?
- The next decade

Bad news isn't wine. It doesn't improve with age.

(Colin Powell)

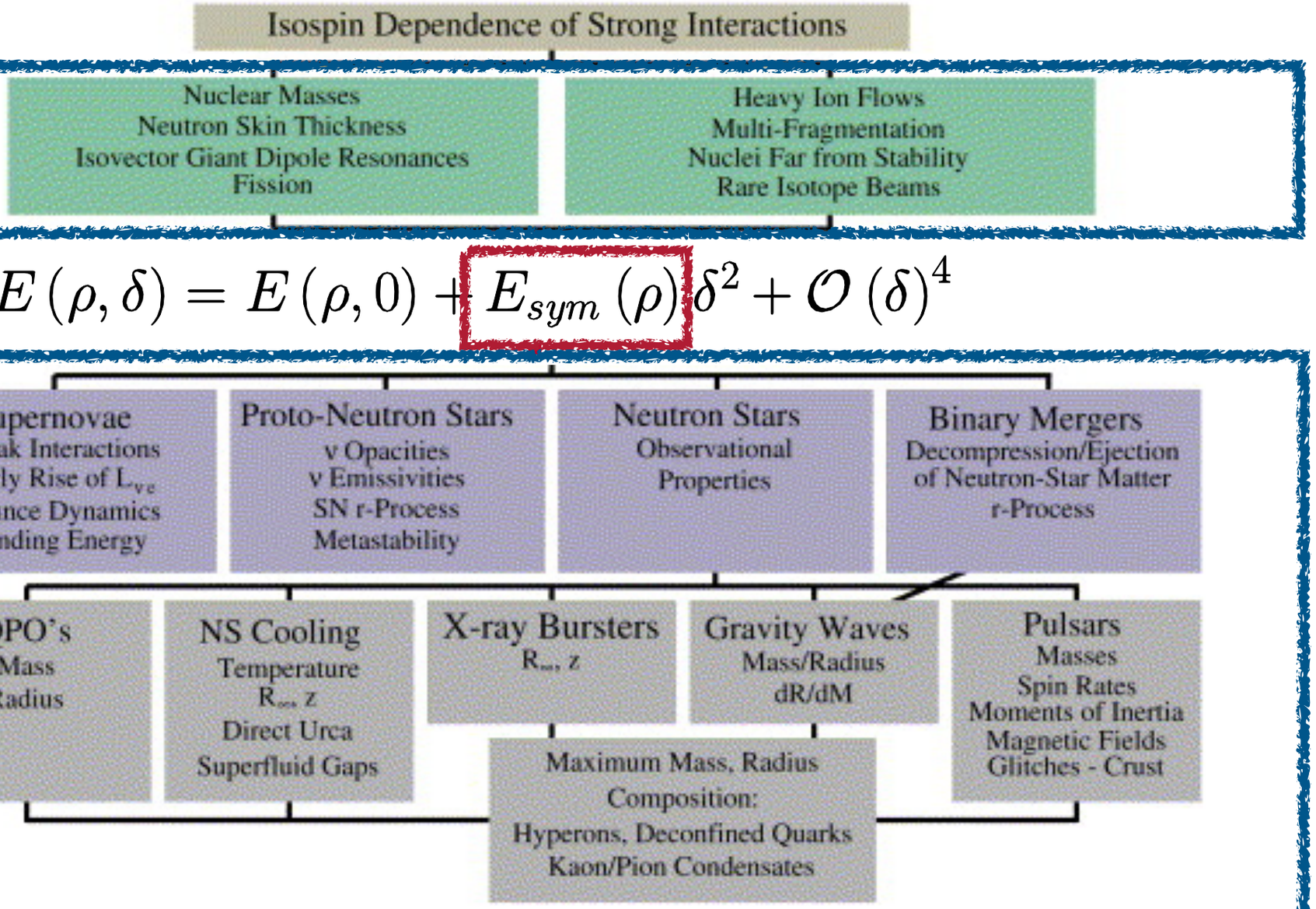
Concettina Sfienti
Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

Once upon a time...



A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, Physics Reports, 411 (2005) 325

“Multi-messengers Physics”



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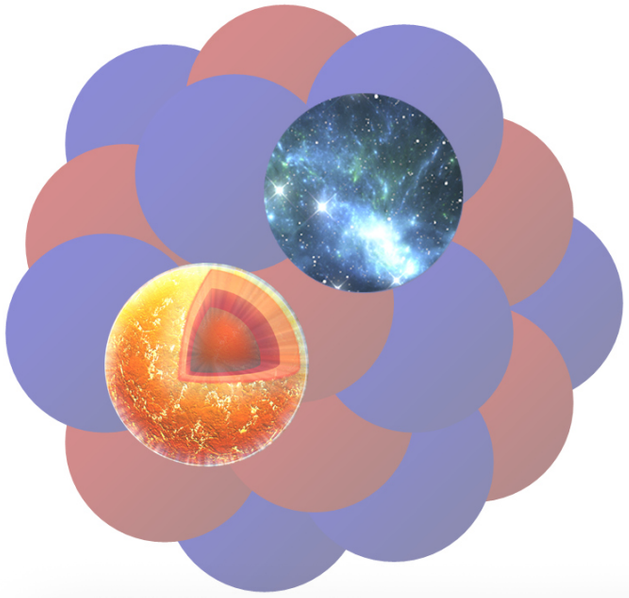
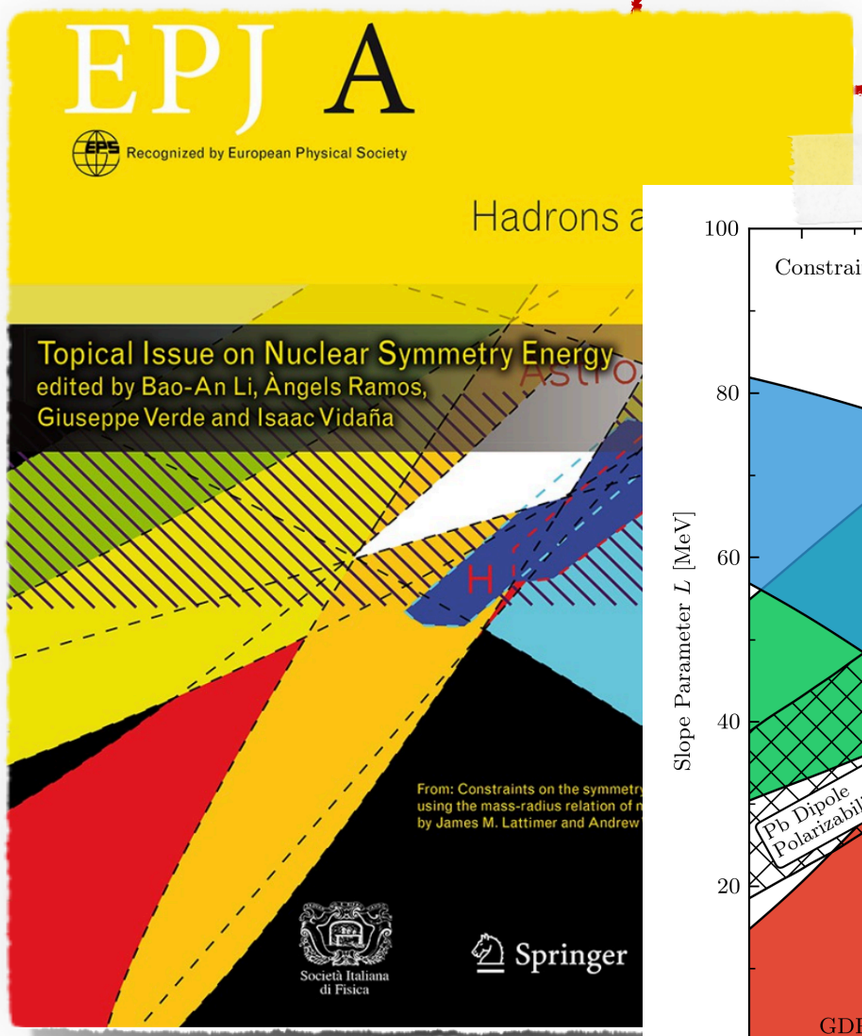
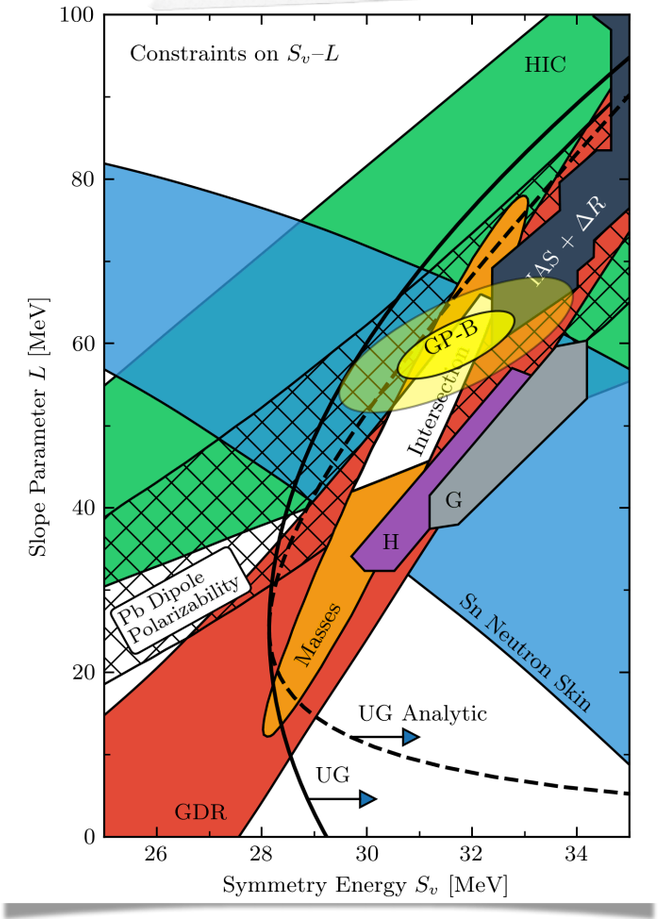
...that which binds us!



$$\mathcal{E}(\rho,\alpha) = \mathcal{E}(\rho,\alpha=0) + S(\rho)\,\alpha^2 + \ldots$$

$$S(\rho) = J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{1}{2}K_{\text{sym}}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \ldots$$





slope parameter

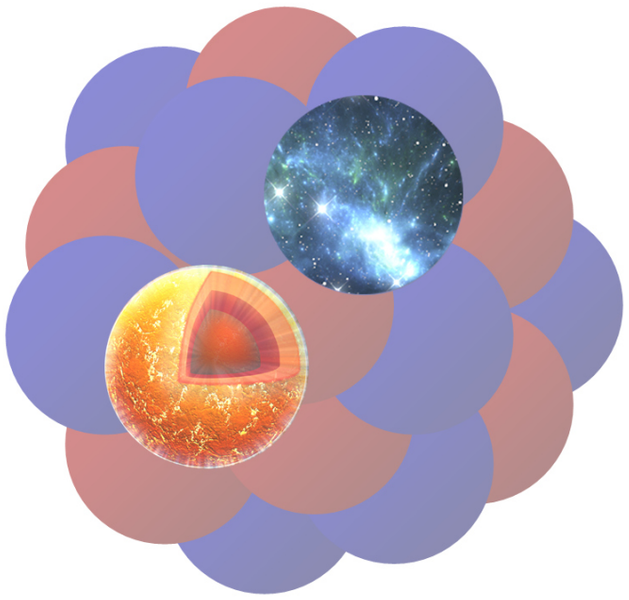
$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\bigg|_{\rho_0}$$

curvature parameter

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

C. Drischler, et al.
Phys. Rev. Lett. **125**, 202702

The spoiler: reality!



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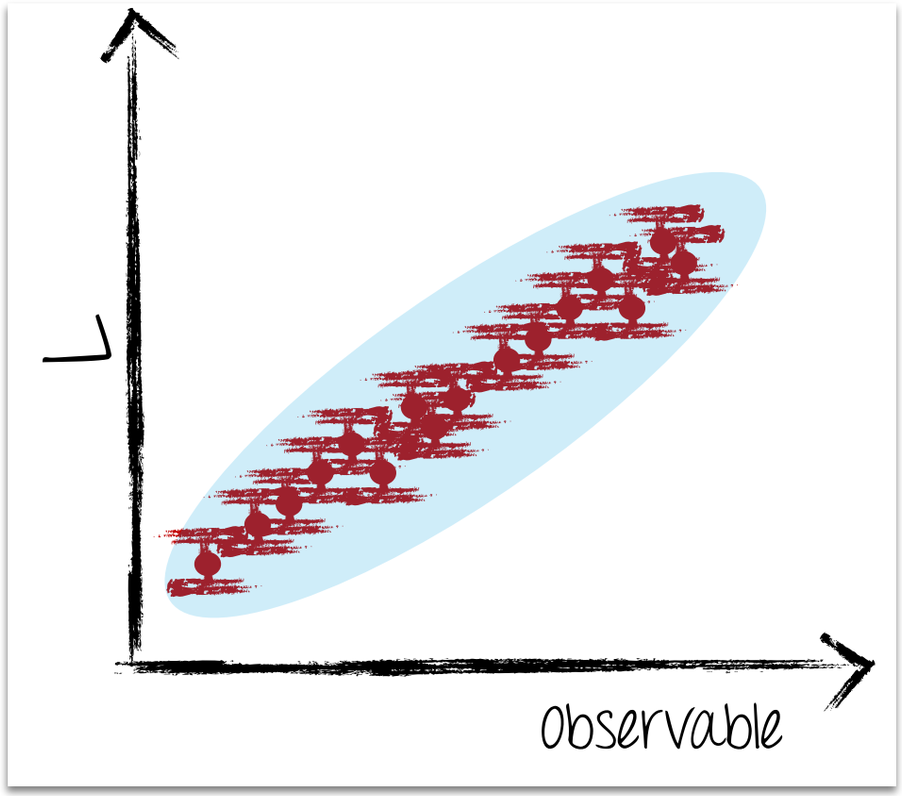

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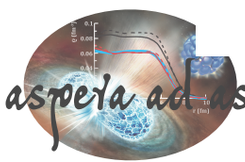
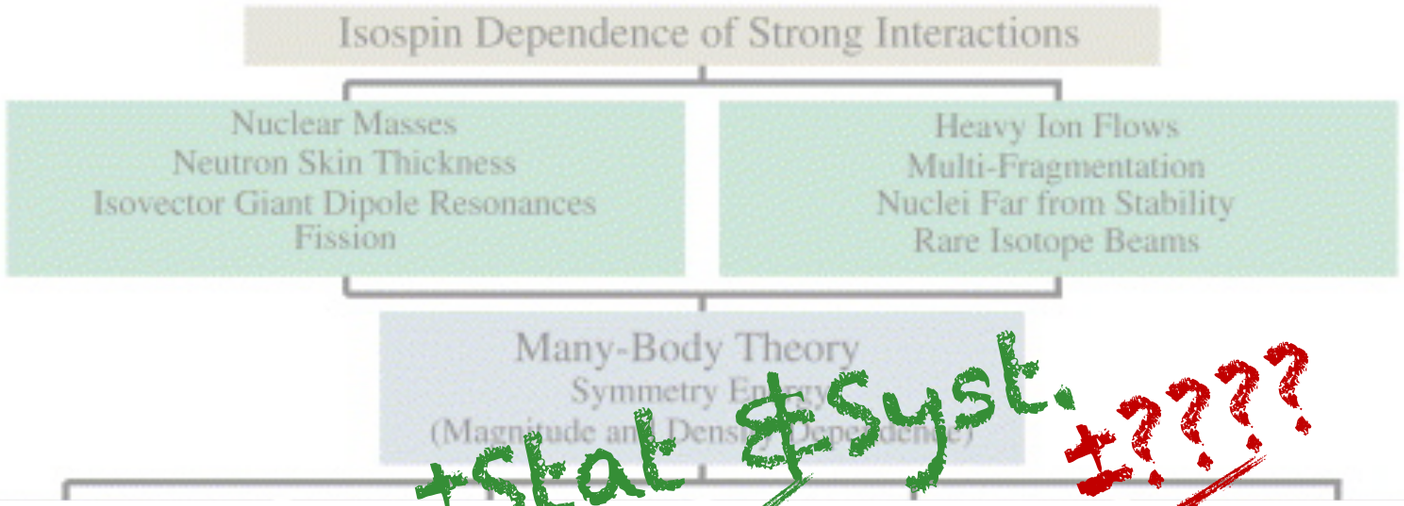
access denied



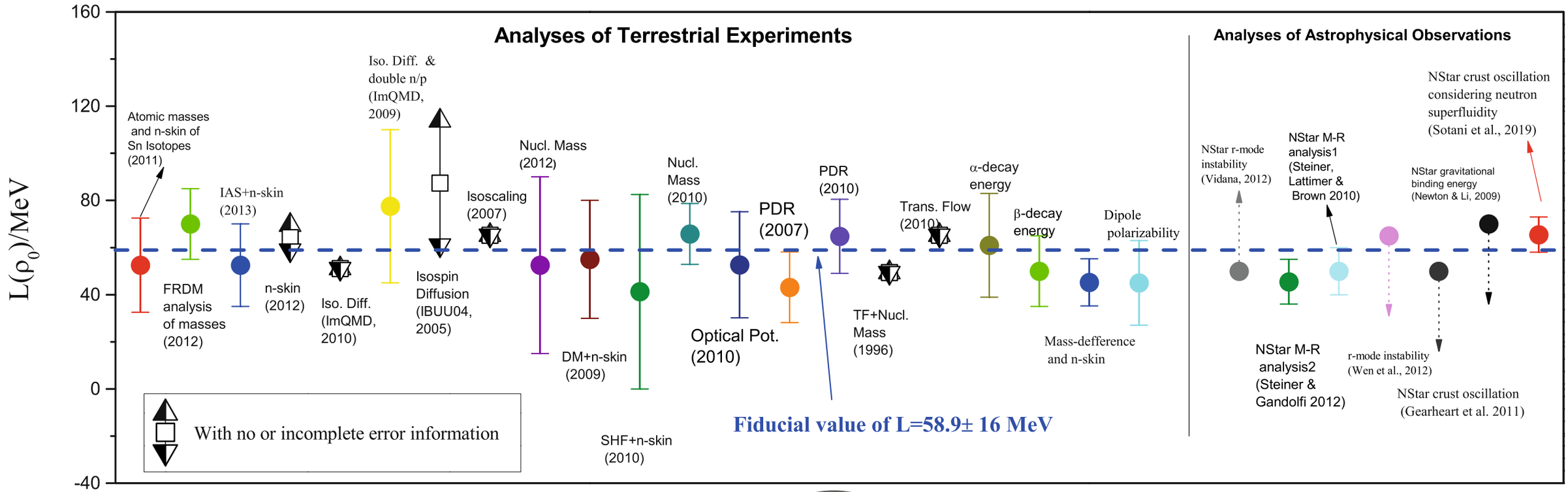
... per aspera ad astra ...

...the (blind!?) search for the Nuclear Symmetry Energy



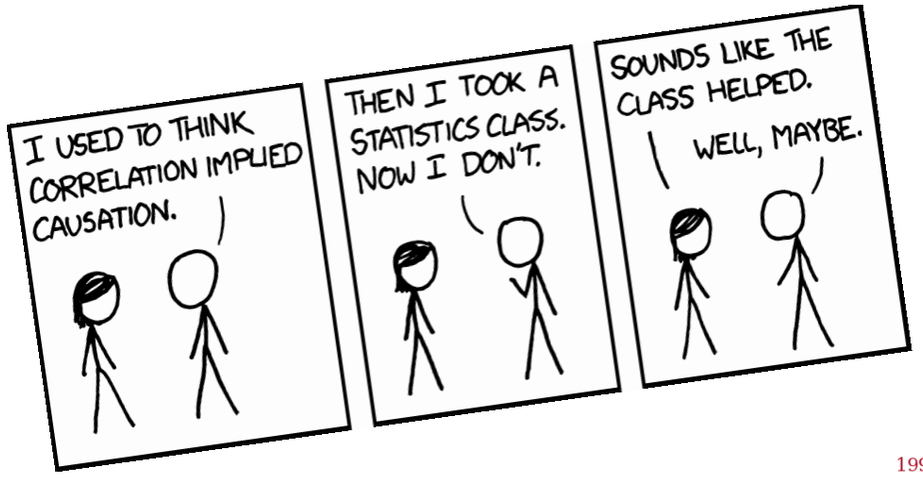
±stat & Syst. ±????

Observable + Model = S_v,L



Bao-An Li et al., Eur. Phys. J. A (2019) 55: 117

... per aspera ad astra ...



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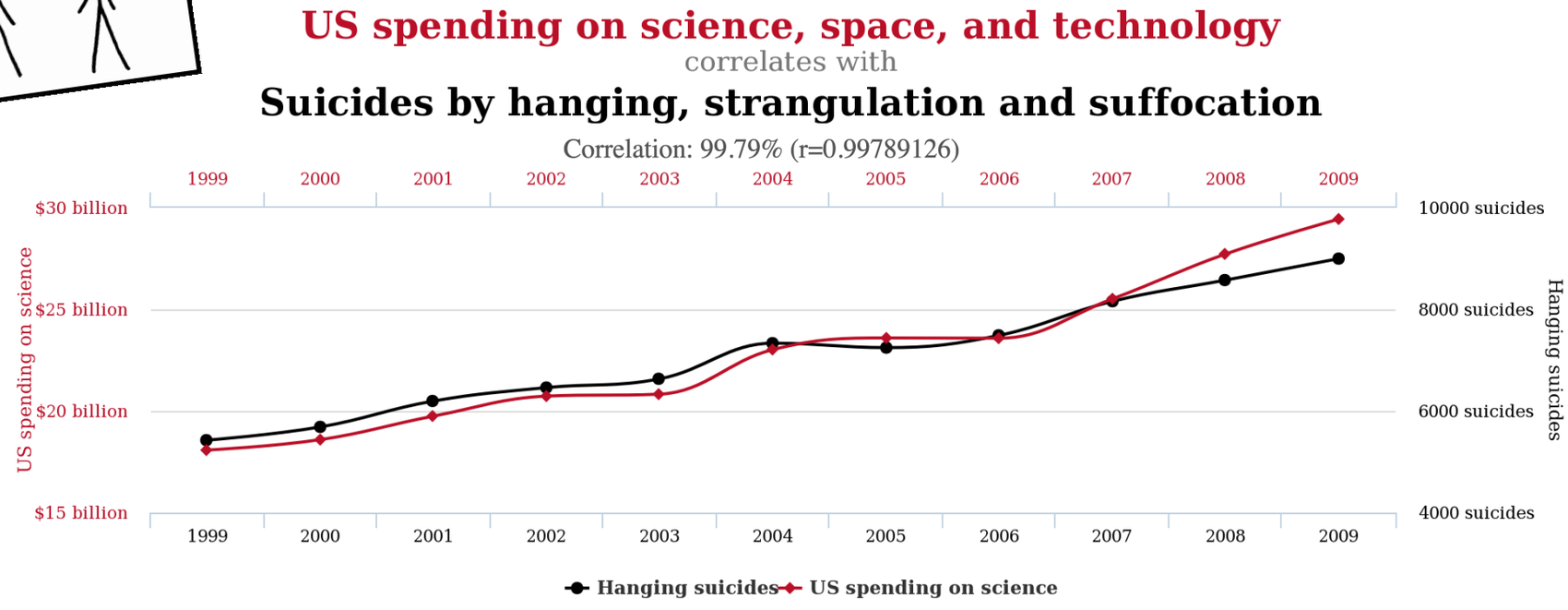

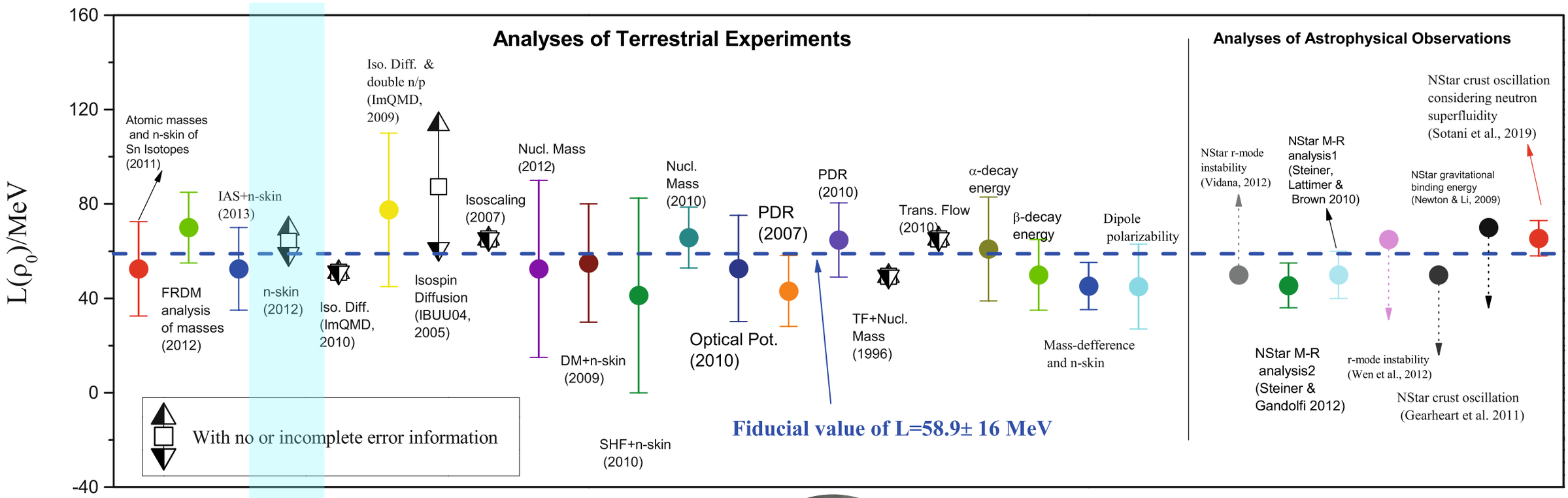

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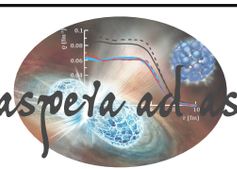


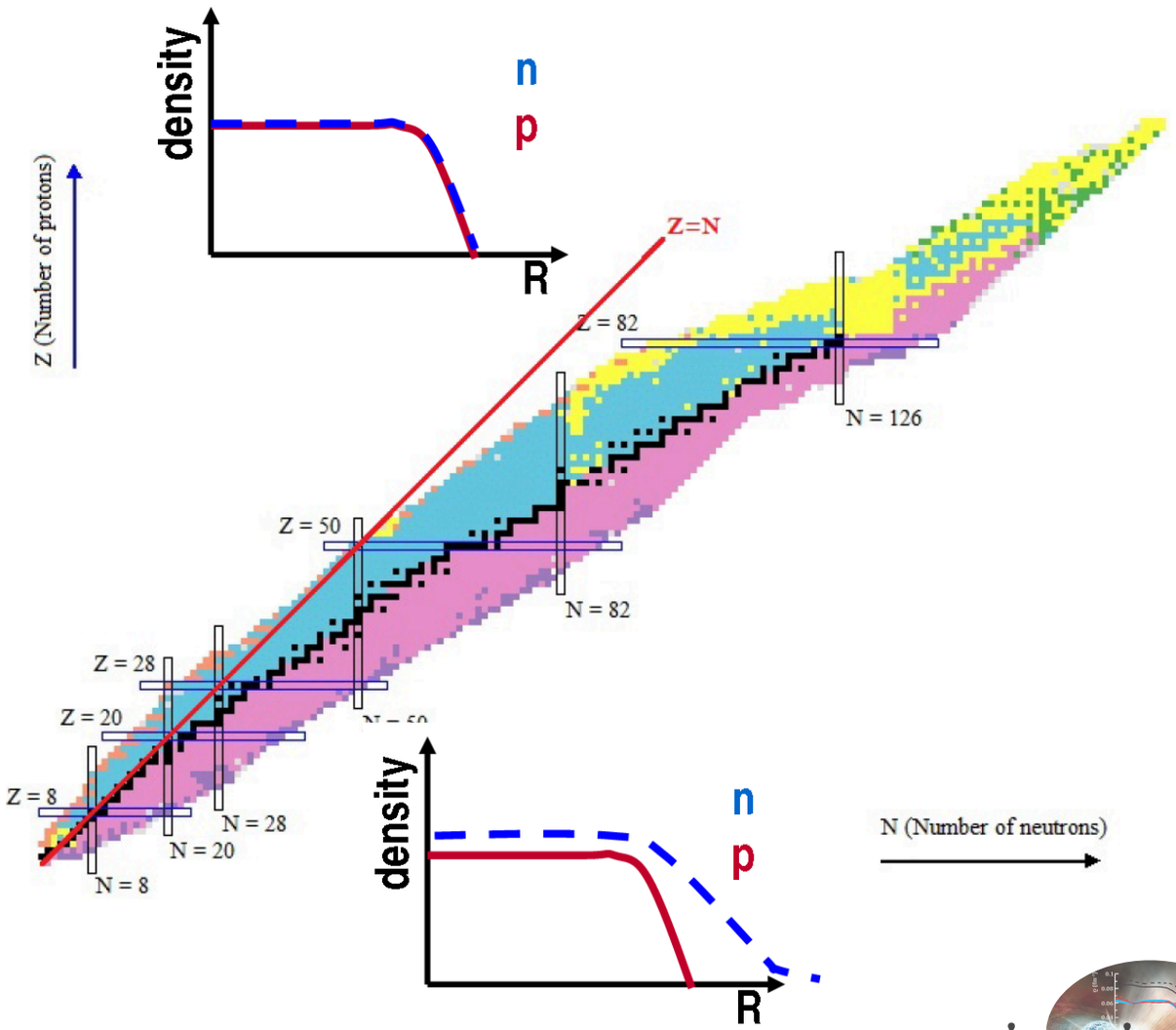
... per aspera ad astra ...

CONCETTINASFIENTI

#MakeHumansSmartAgain

...did somebody already mentioned neutron-skin to you?

The neutron skin measures how much neutrons stick out past protons



... per aspera ad astra ...

CONCETTINASFIENTI

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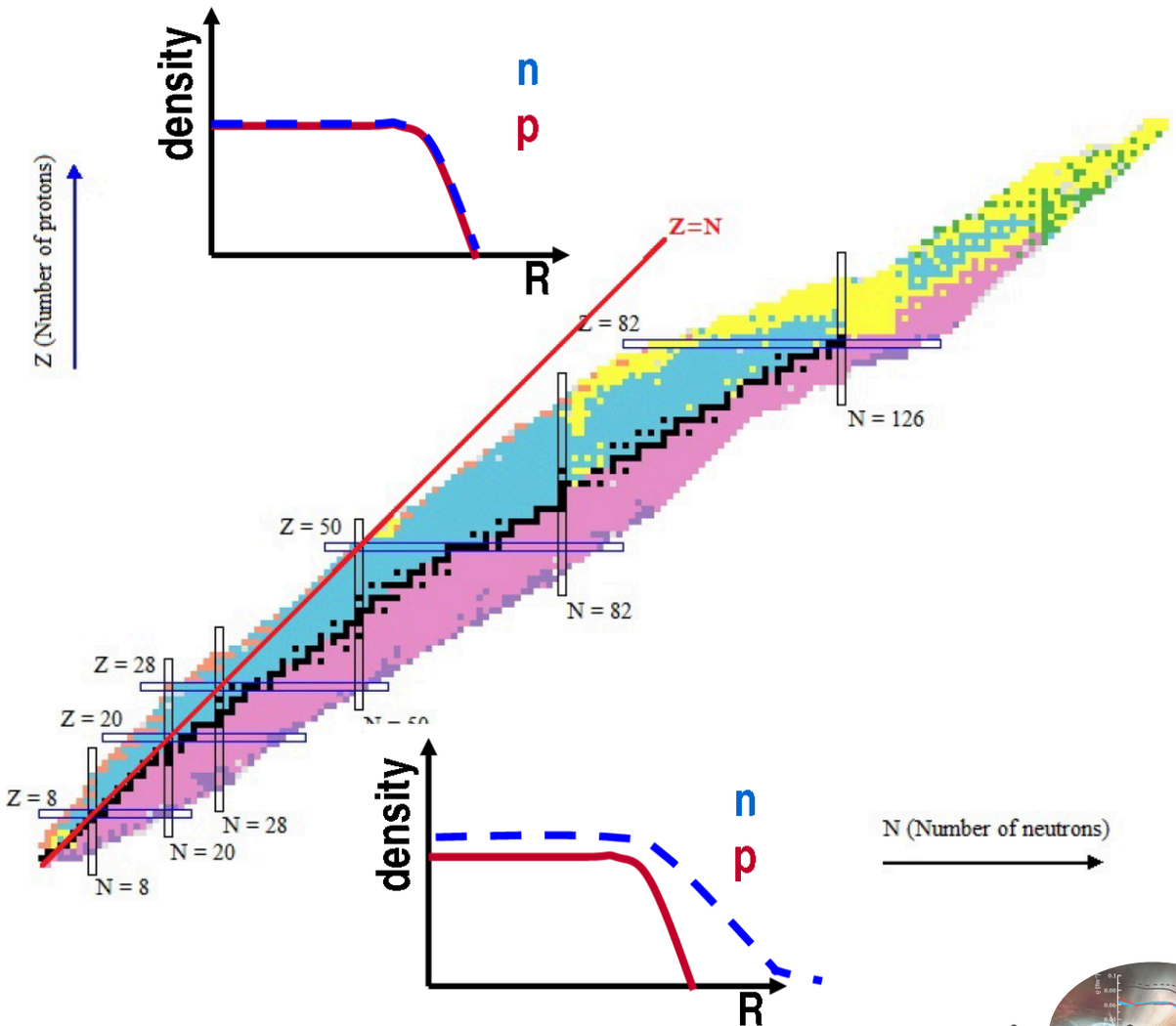
Symmetry energy favours moving them to the surface

Surface tension favours spherical drop of uniform equilibrium density



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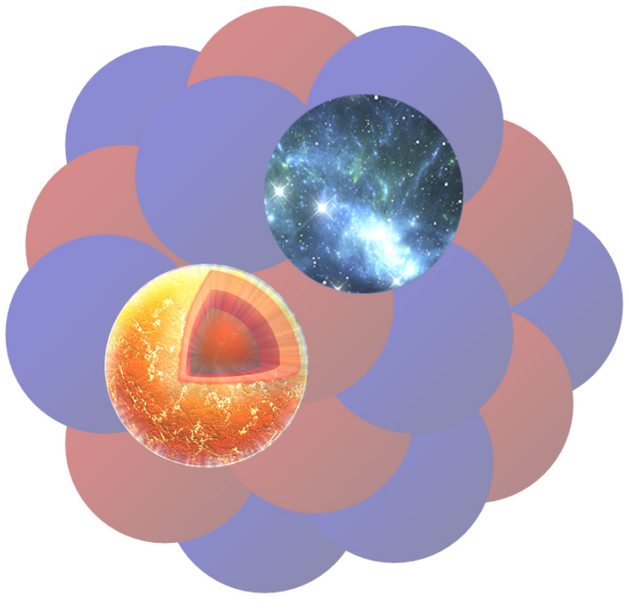

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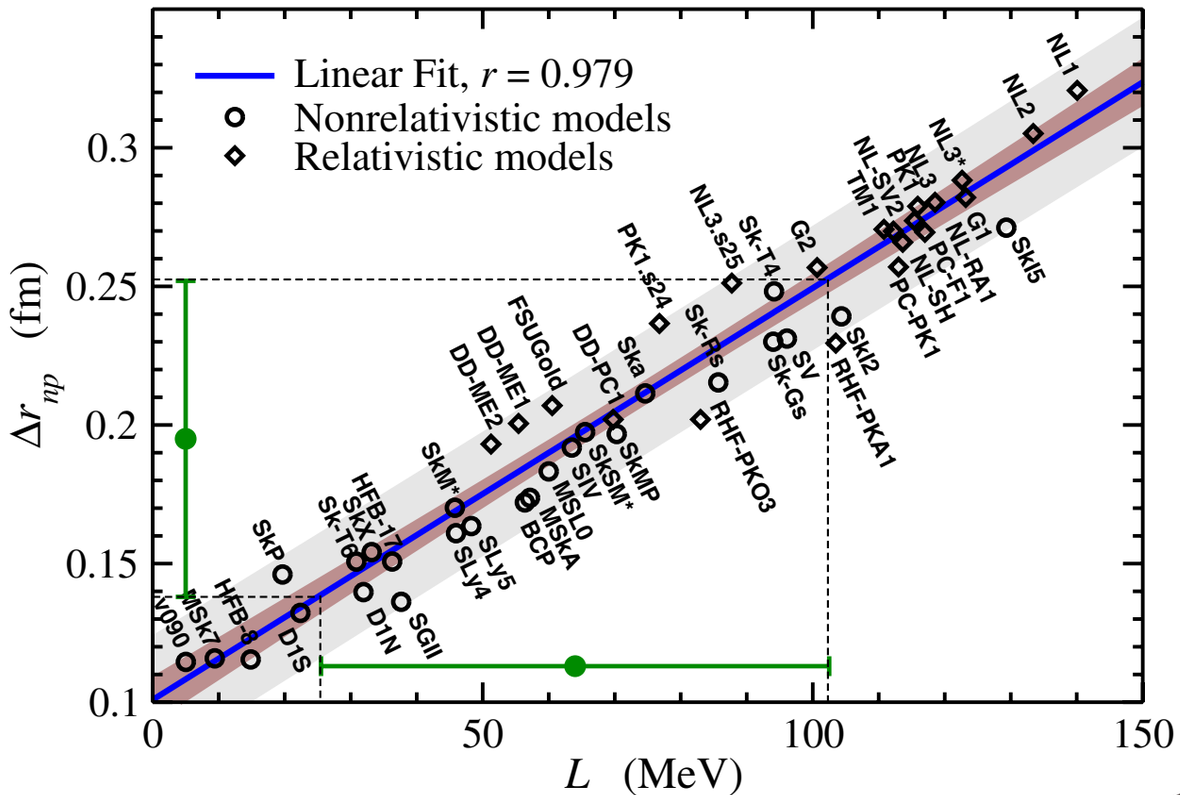
X. Roca-Maza, at al. Phys. Rev. Lett. 106, 252501 (2011)



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Access denied

The stairway to heaven

The answer to the ultimate question

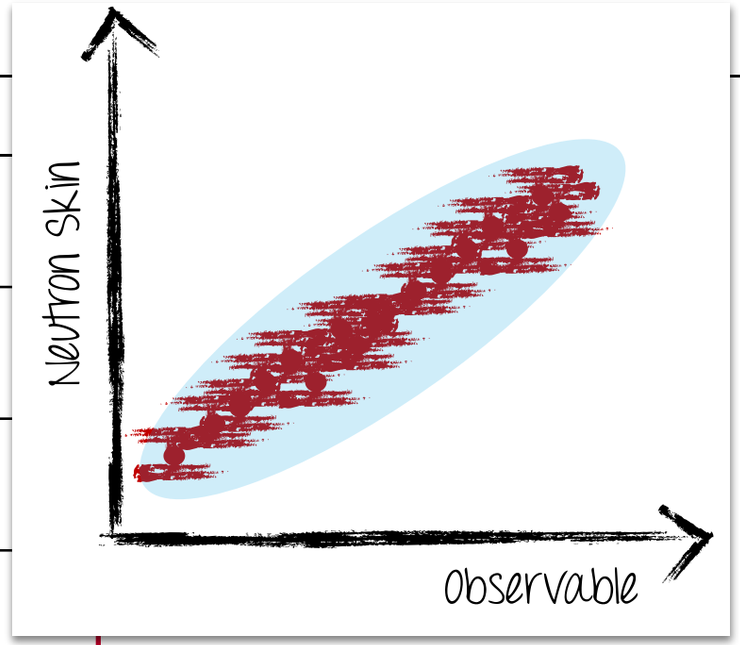
... per aspera ad astra ...

CONCETTINASFIENTI

#MakeHumansSmartAgain

The stairway to heaven

NONE is an actual MEASUREMENT of neutron skin!



... per aspera ad astra ...

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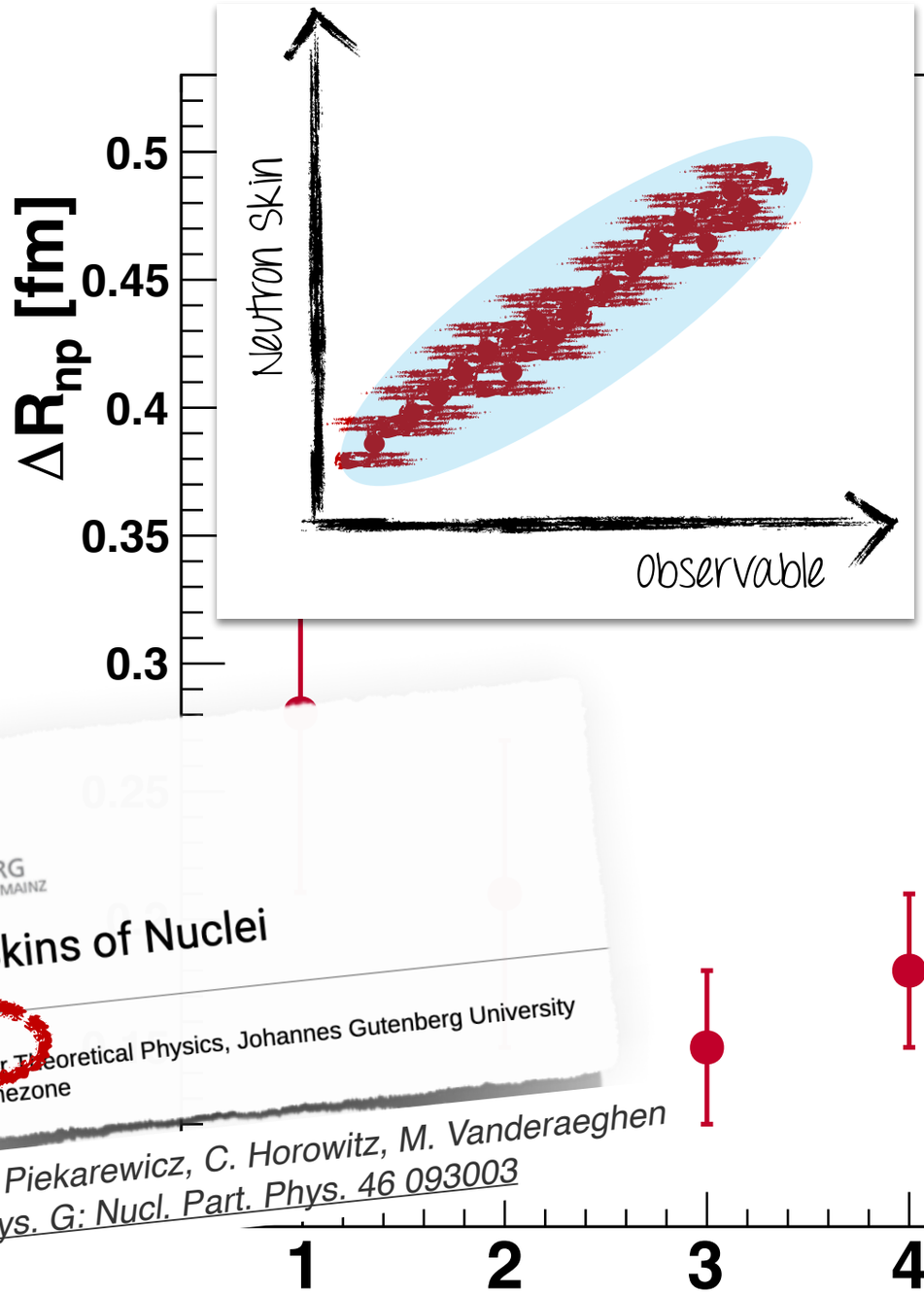
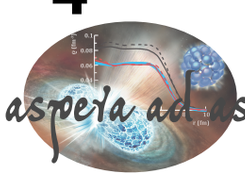


M. Thiel, CS, J. Piekarewicz, C. Horowitz, M. Vanderaeghen
J. Phys. G: Nucl. Part. Phys. 46 093003

... per aspera ad astra ...

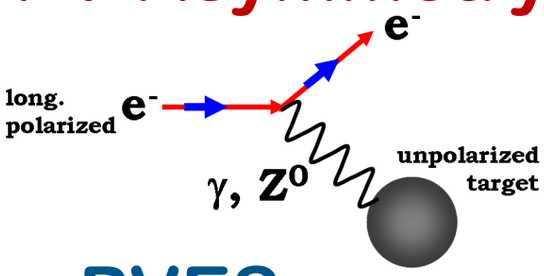


The stairway to heaven

(or the highway to hell, depending on your level of optimism)

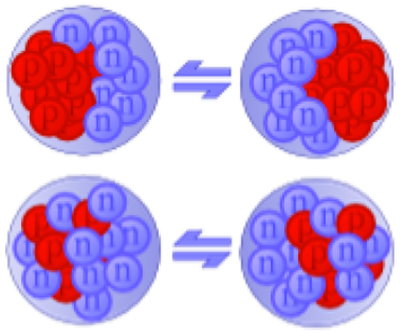
(Personal selection)

PV-Asymmetry



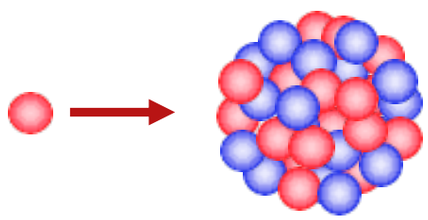
PVES

Resonance Strength

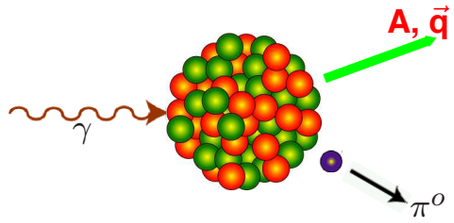


Collective Excitation

Cross-section



Hadronic Probes



EM Probes

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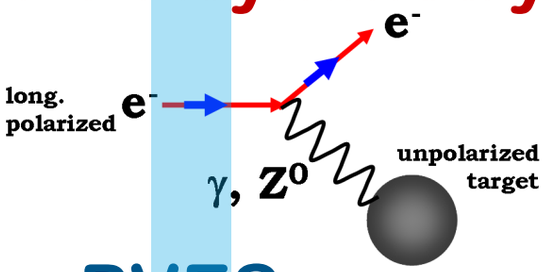
PV-Asymmetry



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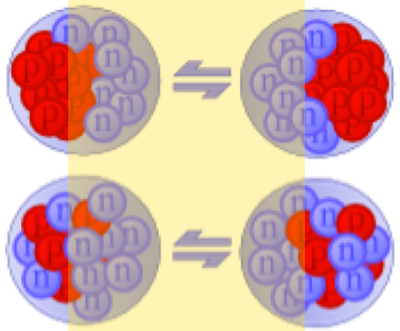

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????..

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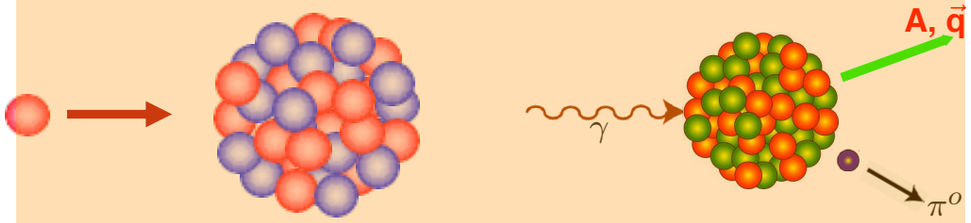
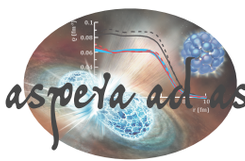


Hadronic Probes

EM Probes

Theo. uncertainties (a.u)

... per aspera ad astra ...



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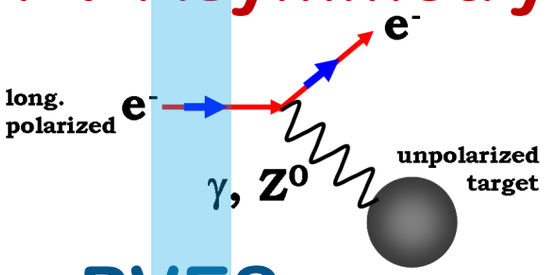
Experimental Challenges
(in unit of frustration)

PV-Asymmetry



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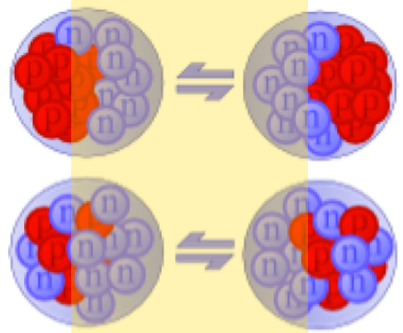

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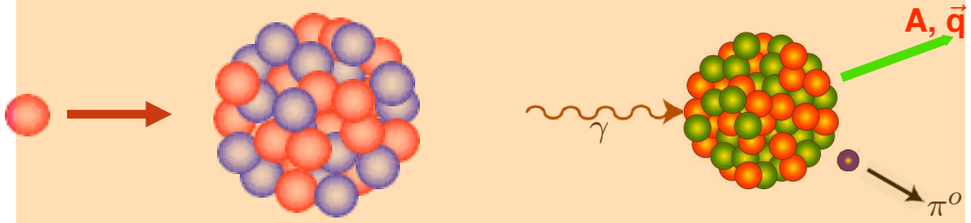

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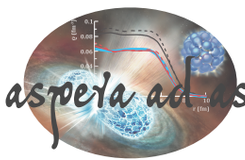
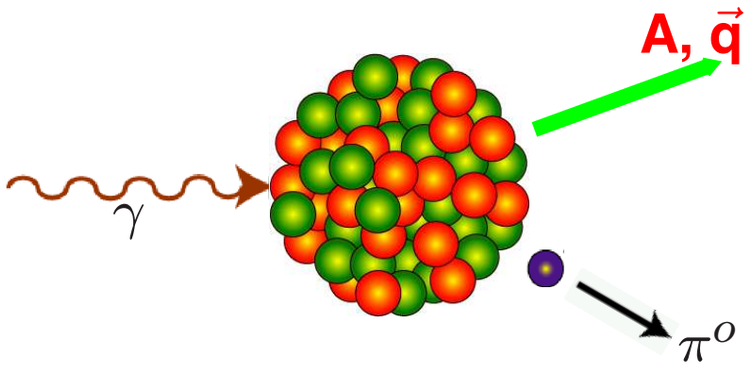


One MZ-Example

Coherent π^0 photoproduction: easy and quick *(A2 Coll. Phys. Rev. Lett. 112, 242502)*



... *shine light* on the nucleus!

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

Advantages:

- Same amplitude for n and p
  - $\rightarrow$ Sensitivity to nucleon dist.
- Photon is neutral
  - $\rightarrow$ Whole volume is probed
- Quick measurement

Drawbacks:

- Final state interactions
  - $\rightarrow$ Model dependence
- Delta resonance region
  - $\rightarrow$ Model dependence

One MZ-Example

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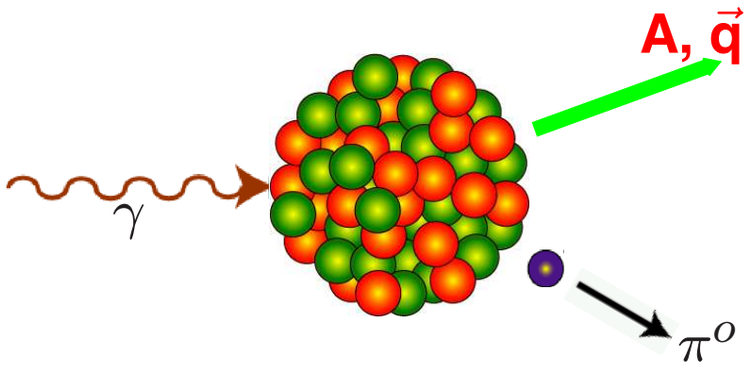

Featured in Physics Editors' Suggestion

... *shine light* on the nucleus!

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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

tagger at the MAMI electron beam facility. On exploitation of an interpolated fit of a theoretical model to the measured cross sections, the half-height radius and diffuseness of the neutron distribution are found to be $c_n = 6.70 \pm 0.03(\text{stat.})$ fm and $a_n = 0.55 \pm 0.01(\text{stat.})^{+0.02}_{-0.03}(\text{sys.})$ fm, respectively, corresponding to a neutron skin thickness $\Delta r_{np} = 0.15 \pm 0.03(\text{stat.})^{+0.01}_{-0.03}(\text{sys.})$ fm. The results give the first successful extraction of a neutron skin thickness with an electromagnetic probe and indicate that the skin of ^{208}Pb has a halo character. The measurement provides valuable new constraints on both the structure of nuclei and the equation of state for neutron-rich matter.

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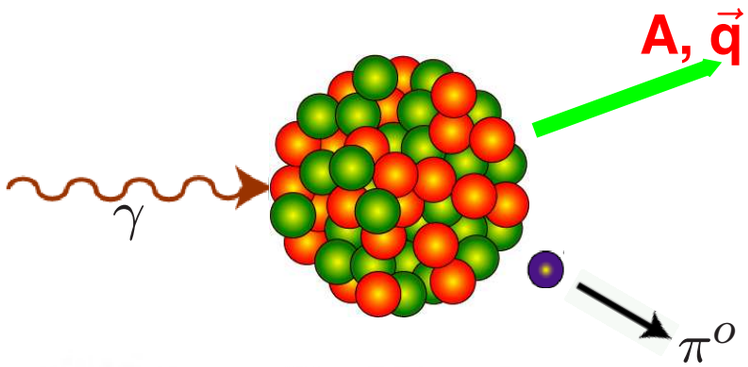

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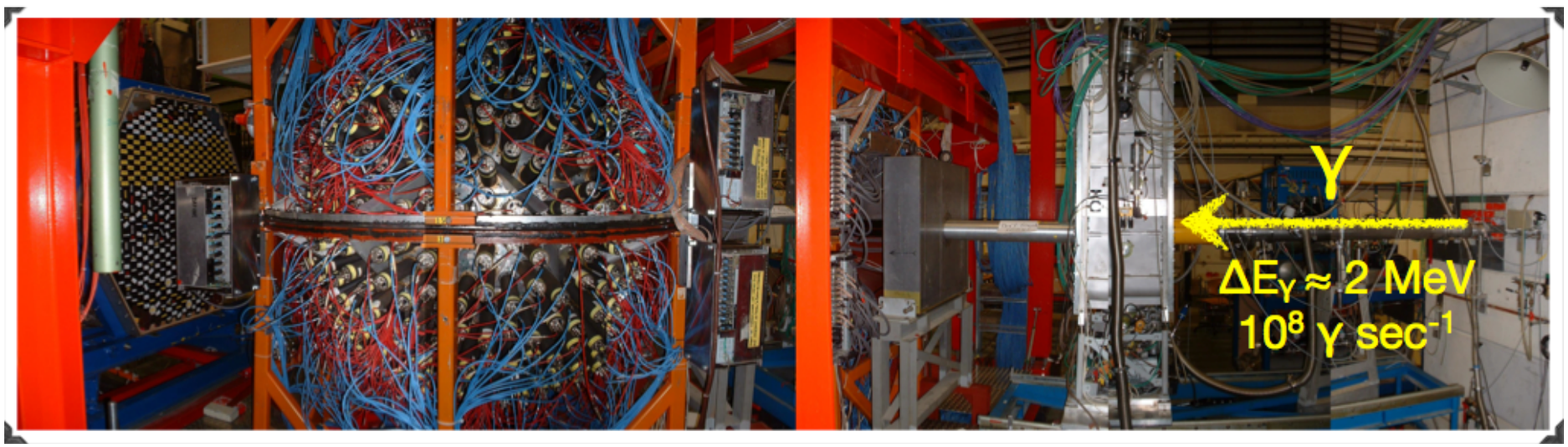
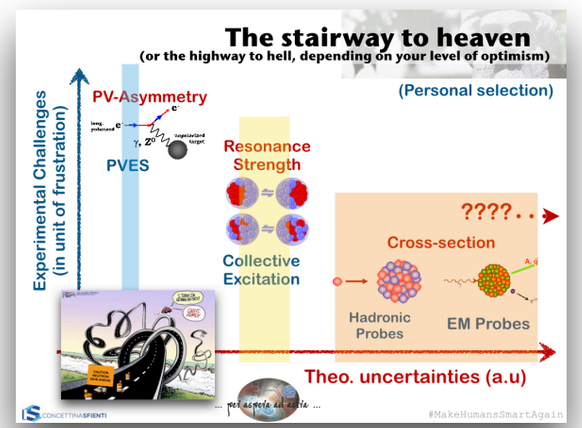
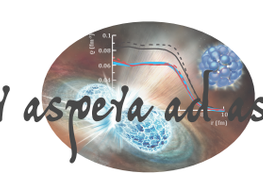
TO DO: Reconstruct π^0 from $\pi^0 \rightarrow 2\gamma$ decay







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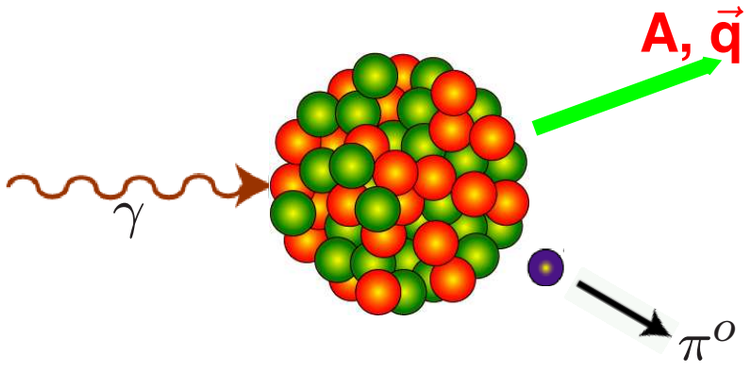

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$$\frac{d\sigma}{d\Omega}(\mathrm{PWIA}) \propto sin^2\left(\theta_\pi^*\right) A^2 F^2\left(q\right)$$

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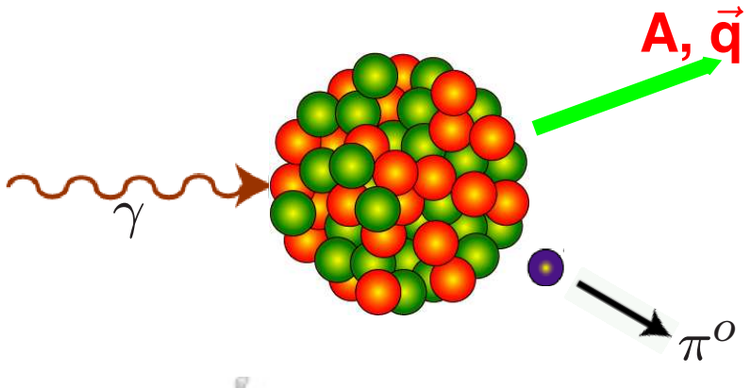

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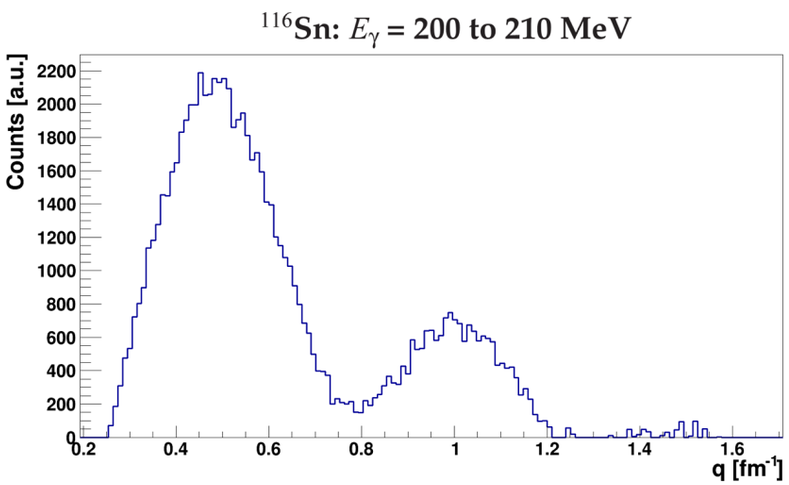
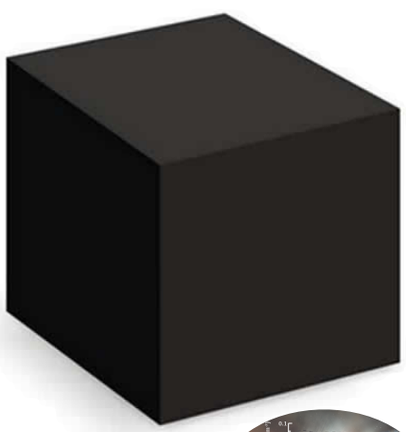
My perspective:

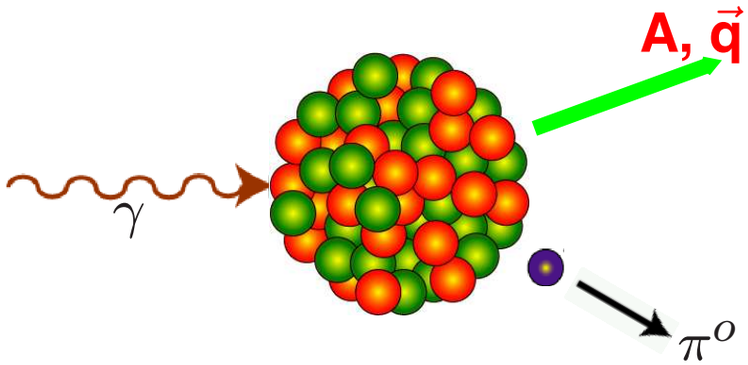




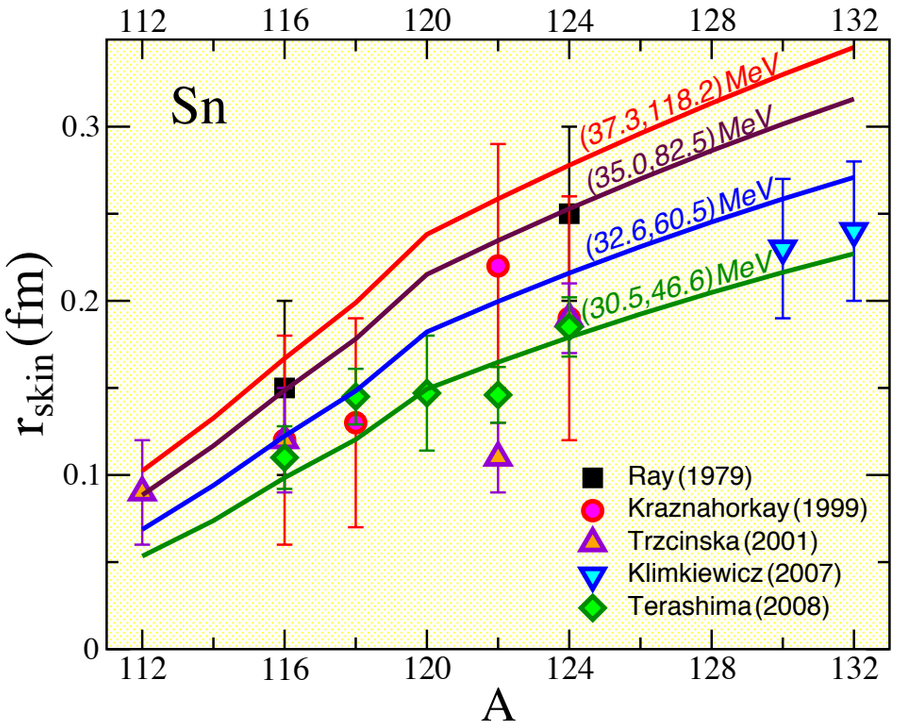
... per aspera ad astra ...

One MZ-Example

Coherent π⁰ photoproduction: easy and quick *(A2 Coll. Phys. Rev. Lett. 112, 242502)*



PhD M. Ferretti-Bondy (exp), F. Colomer (theo), S. Tsaran (theo)



J. Piekarewicz et al.

One MZ-Example

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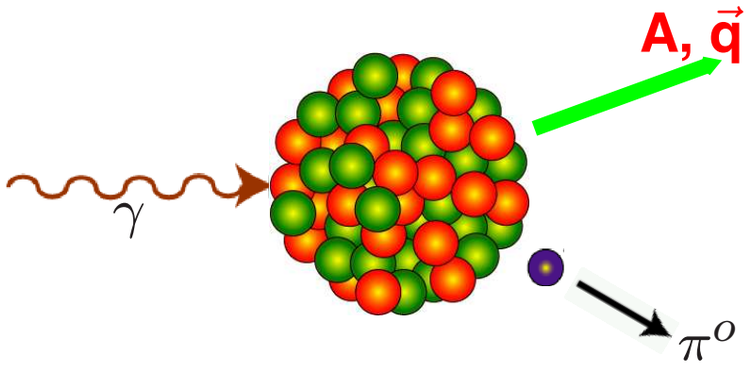

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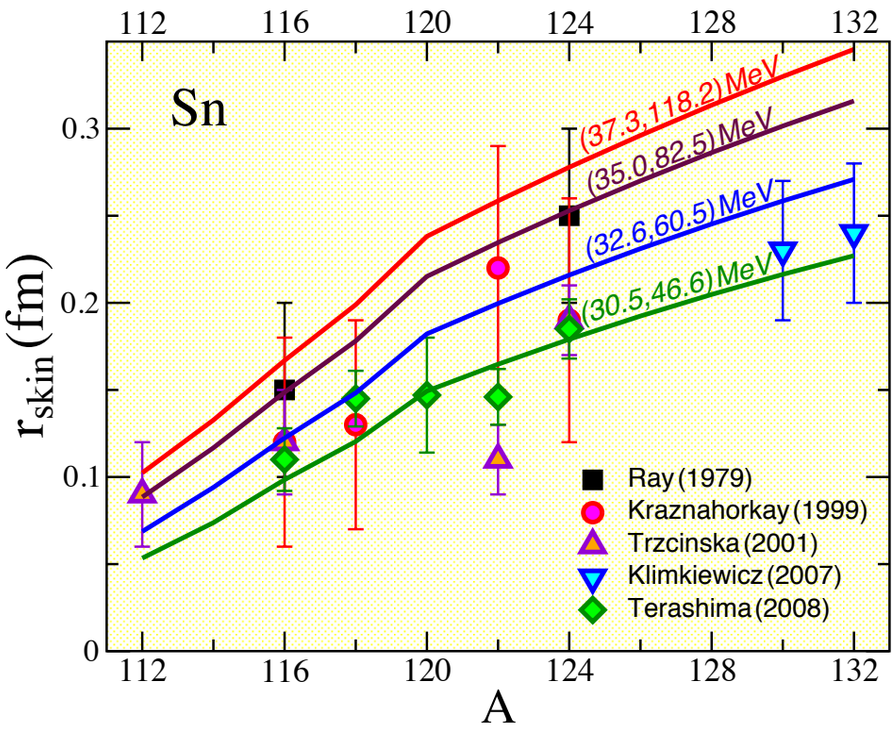
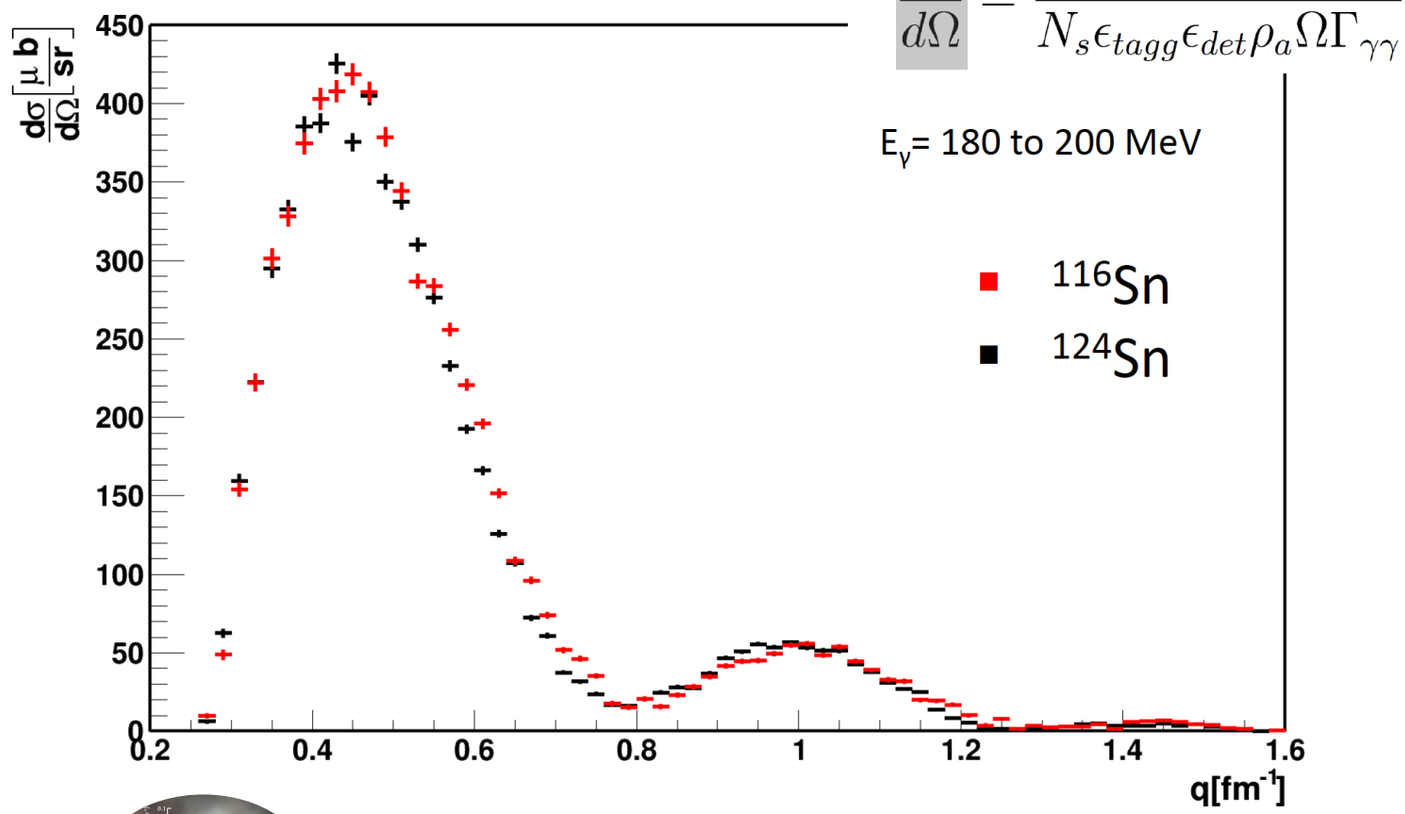


J. Piekarewicz et al.

Differential cross section

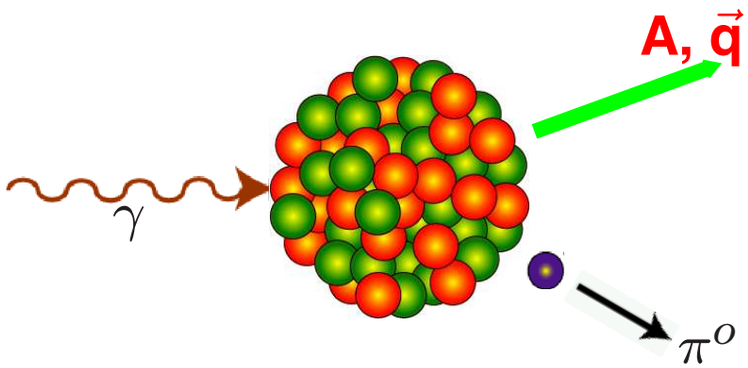
$$\frac{d\sigma}{d\Omega} = \frac{N_{\pi^0}}{N_s \epsilon_{tagg} \epsilon_{det} \rho_a \Omega \Gamma_{\gamma\gamma}}$$



... per aspera ad astra ...

One MZ-Example

Coherent π^0 photoproduction: easy and quick *(A2 Coll. Phys. Rev. Lett. 112, 242502)*



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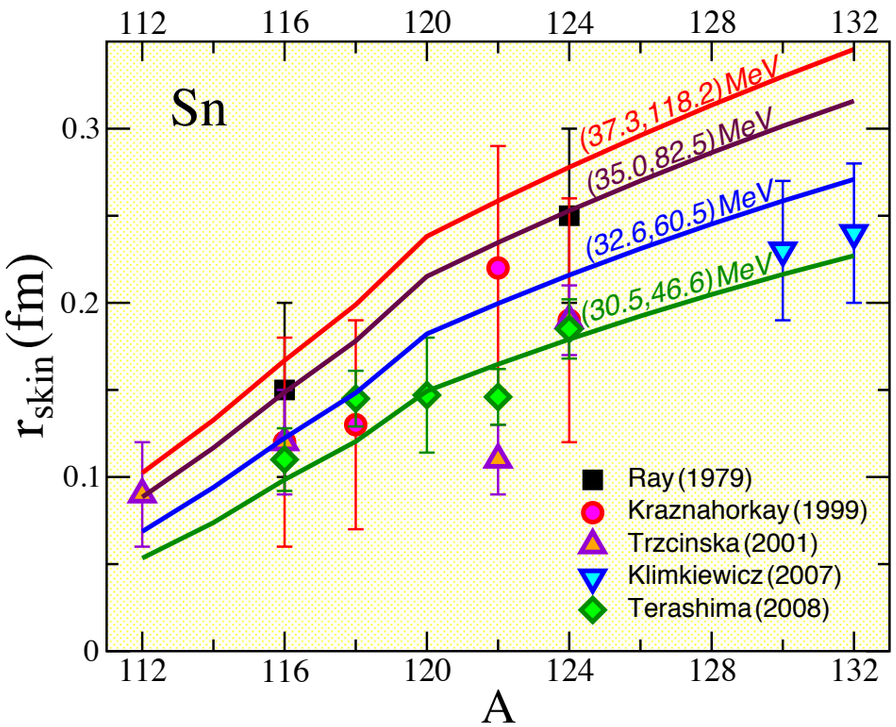
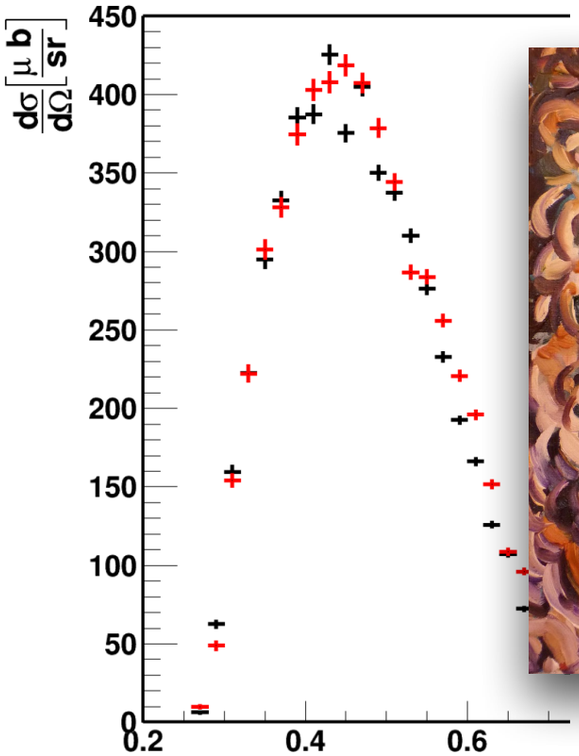
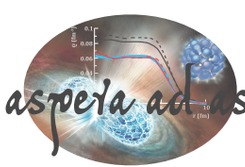


J. Piekarewicz et al.

Differential cross section



... per aspera ad astra ...



...when not all roads lead to Rome

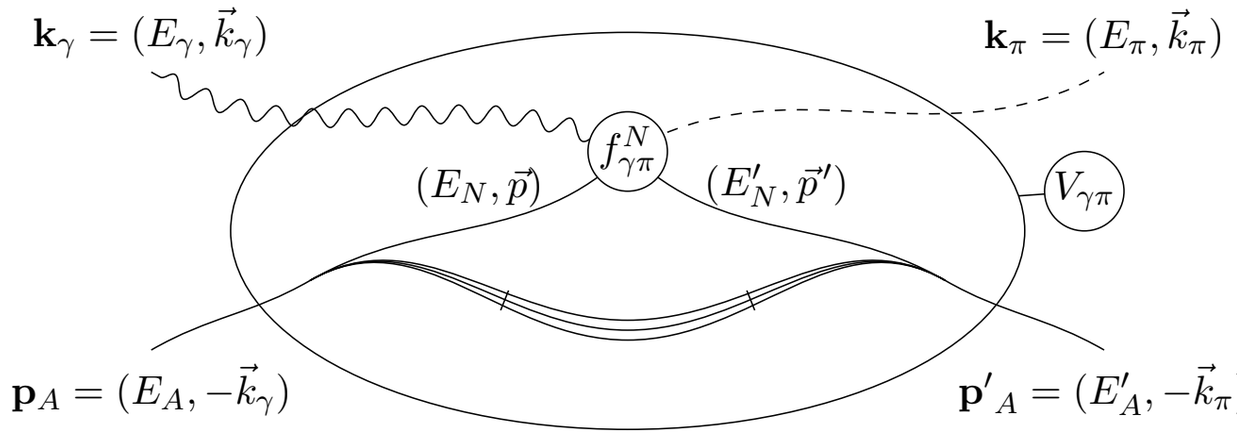
Theoretical analysis of the extraction of neutron skin thickness from coherent π^0 photoproduction off nuclei

arXiv:2204.13395v1

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*

$$\gamma + \mathrm{A} \rightarrow \mathrm{A} + \pi^0$$



Plane Wave : No FSI in exit chanel π^0-A

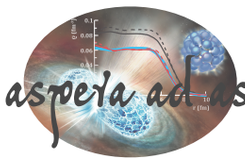
At the Impulse Approximation :
production of π^0 on one single nucleon
$\Rightarrow$ coherent sum on each nucleon

$$\frac{d\sigma}{d\Omega} \propto \left| f_2(\vec{k}_\pi, \vec{k}_\gamma)\, \rho_{\mathrm{A}}(q) \right|^2$$

- f_2 : CGLN amplitudes from MAID [Drechsel *et al.* EPJA 34, 69 (2007)]
- ρ_{A} : nucleus form factor

$\Rightarrow$ Should give access to nuclear density, but

Slide stolen from Pierre 😊



...reality is distorted though ...

...and it also has higher-order effects *Miller PRC 100,044608 (2019)*

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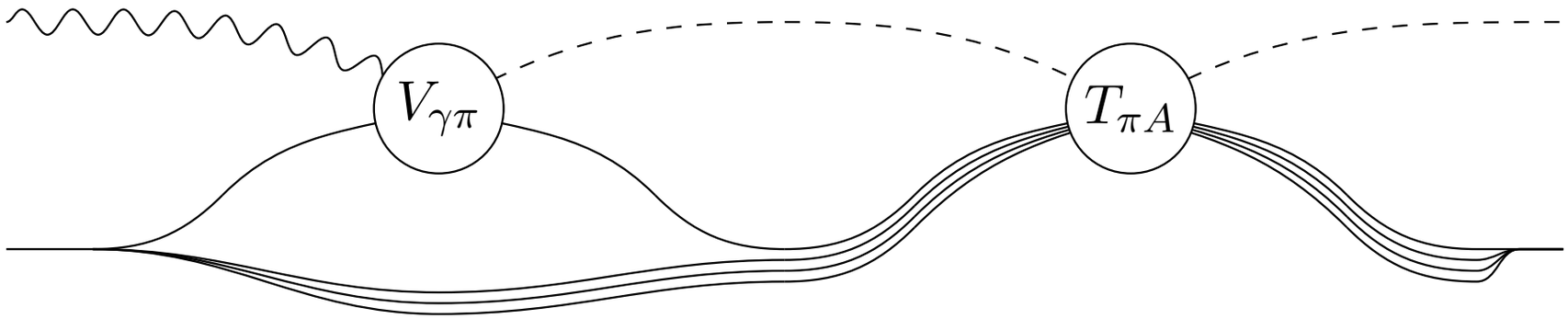
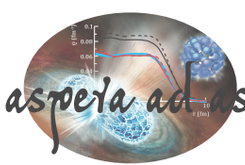


After its production, the π^0 undergoes π-A scattering
$\rightarrow$ Cross section of photoproduction in DWIA (NPA 660, 423):

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

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

Slide stolen from Frederic 😊



...when not all roads lead to Rome

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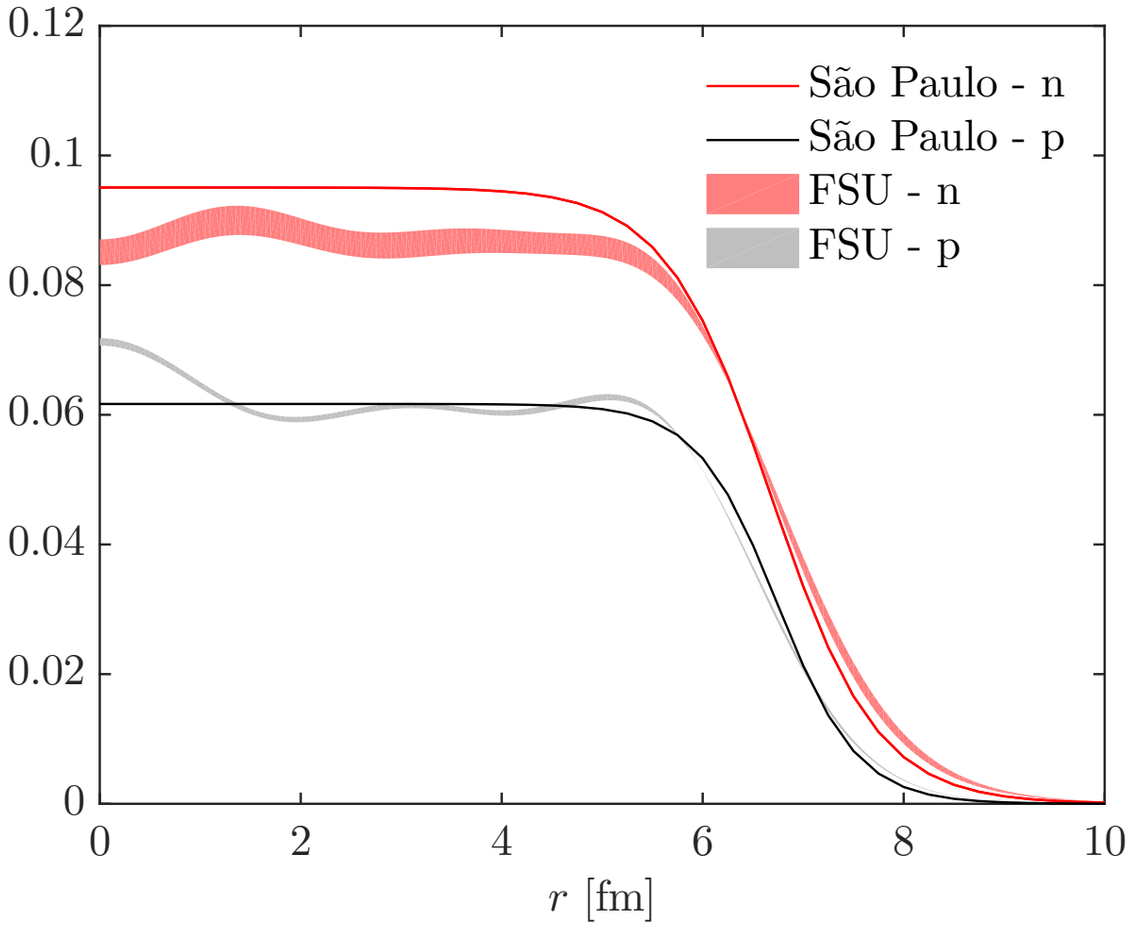
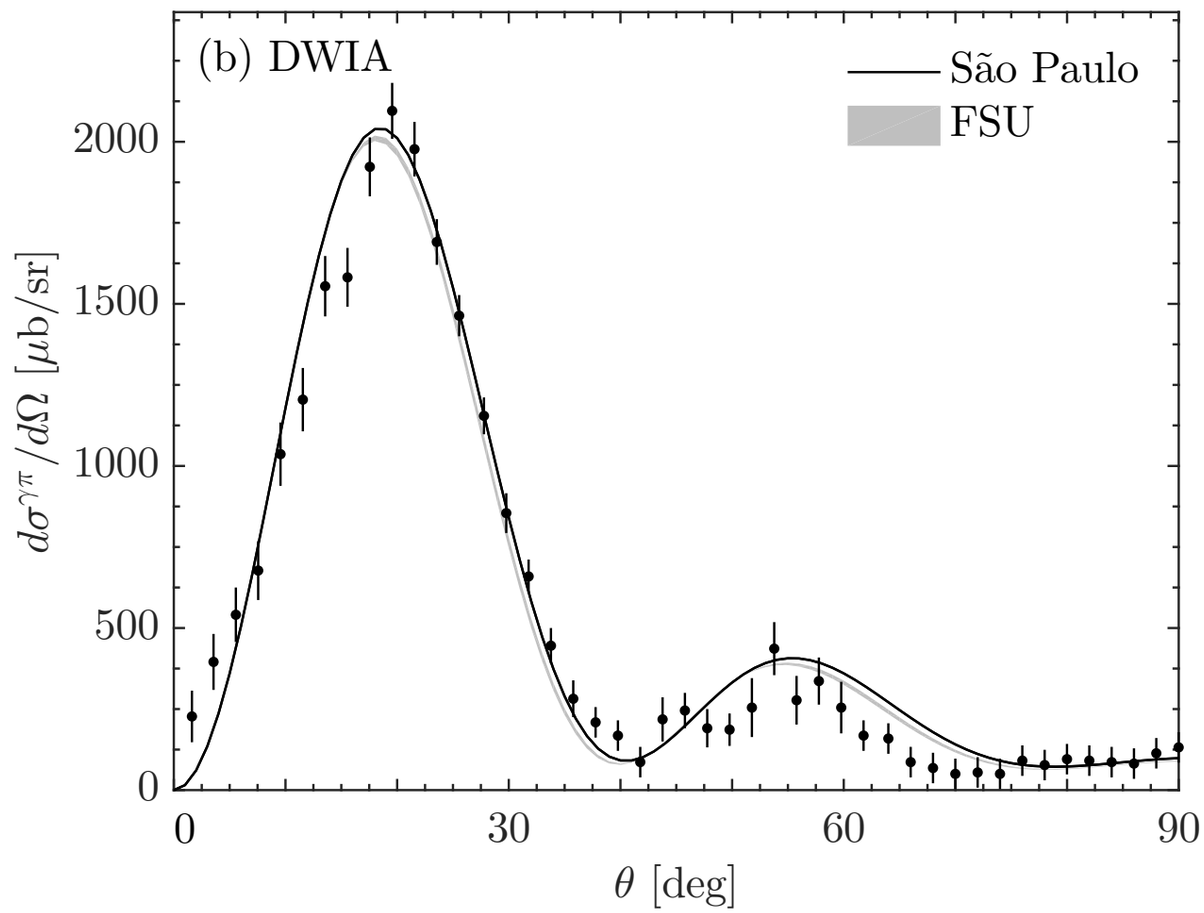
^{208}Pb





...definitely not leading to Rome!

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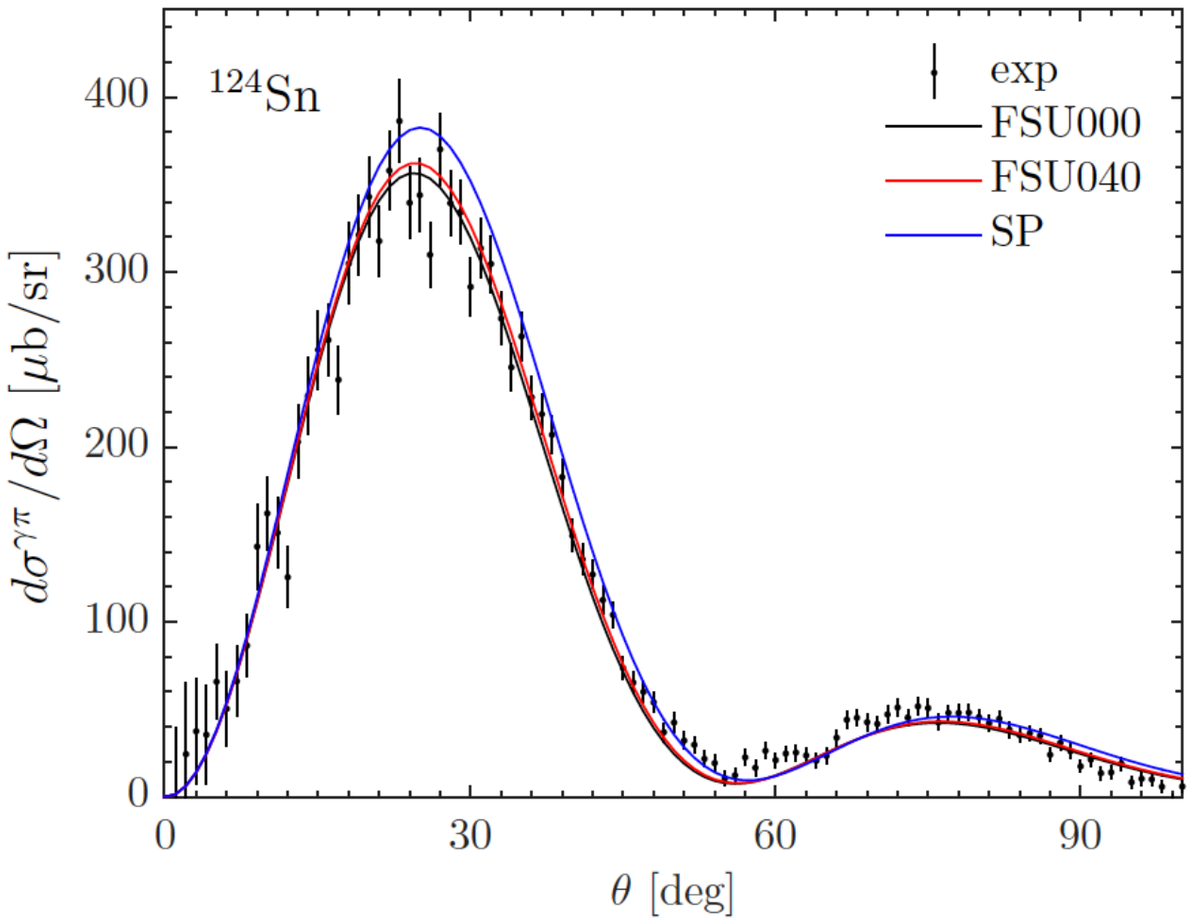
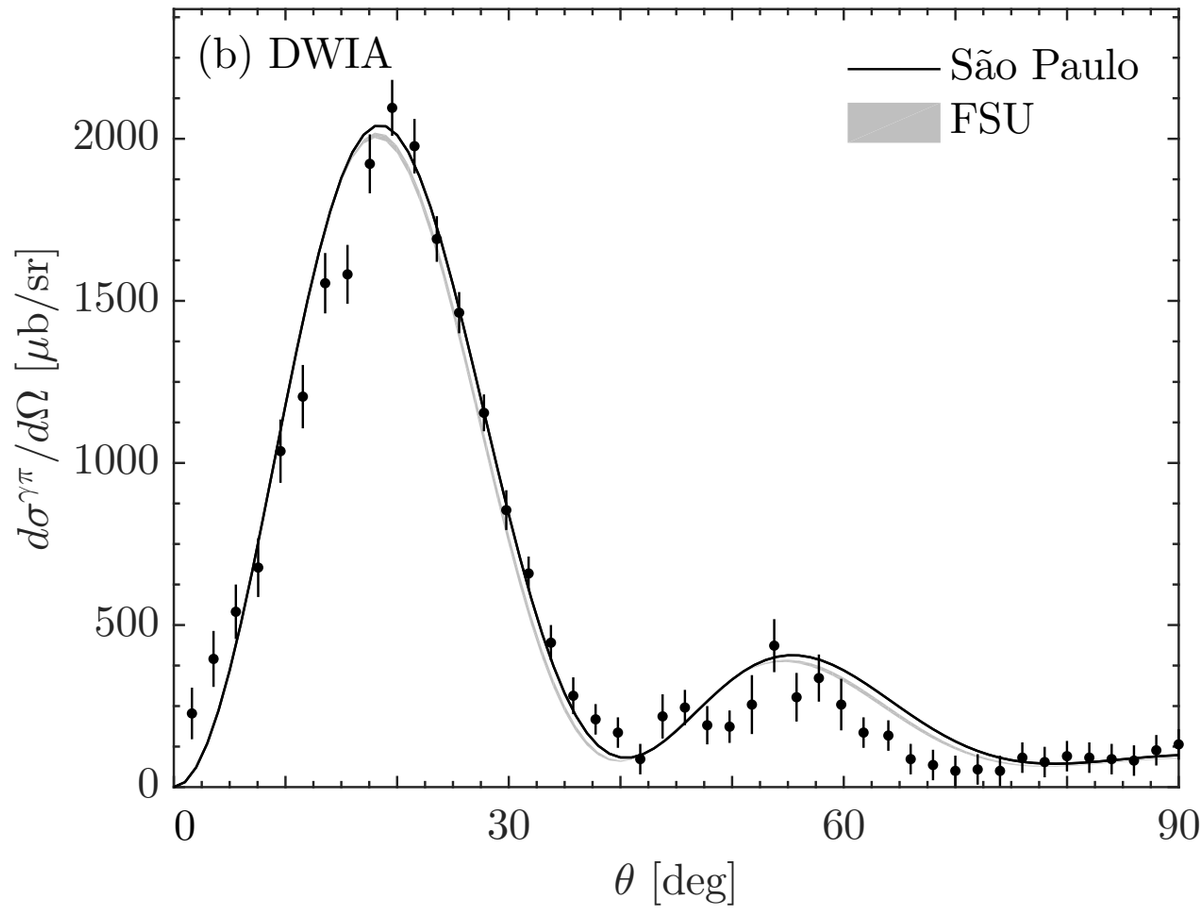
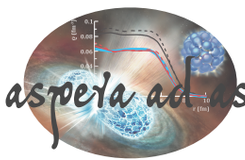
^{208}Pb







... per aspera ad astra ...

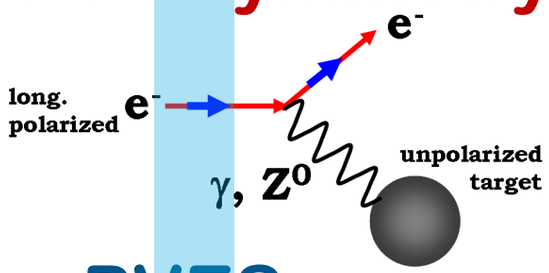
CONCETTINASFIENTI

#MakeHumansSmartAgain

...back to the (high-)stairway

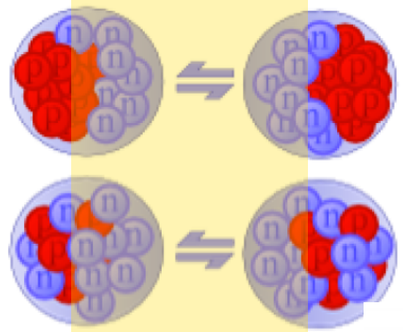
Experimental Challenges
(in unit of frustration)

PV-Asymmetry

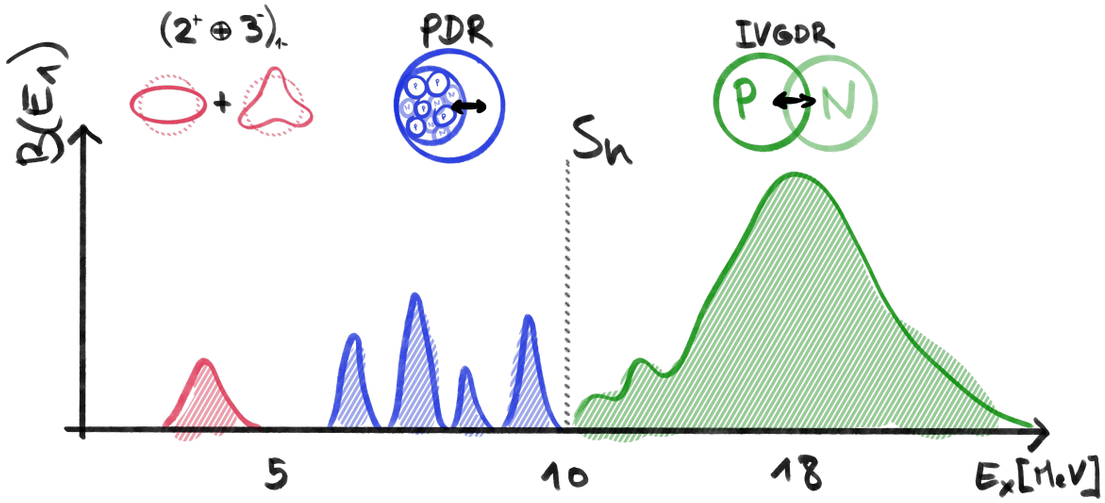


PVES

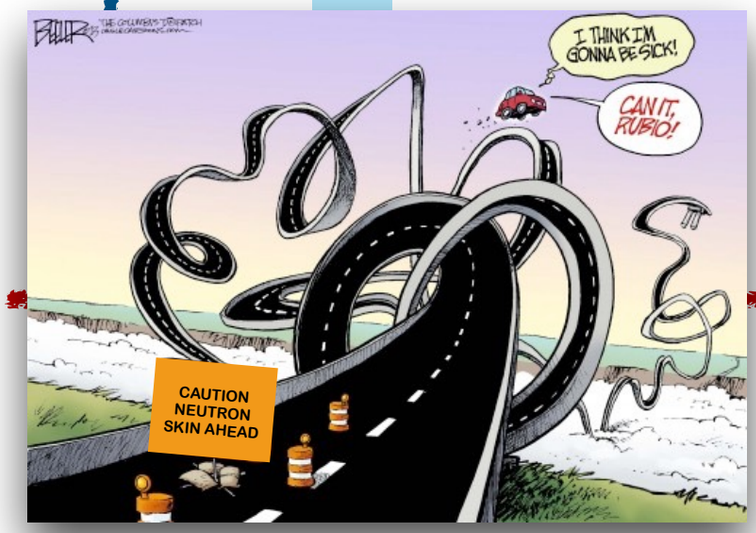
Resonance Strength

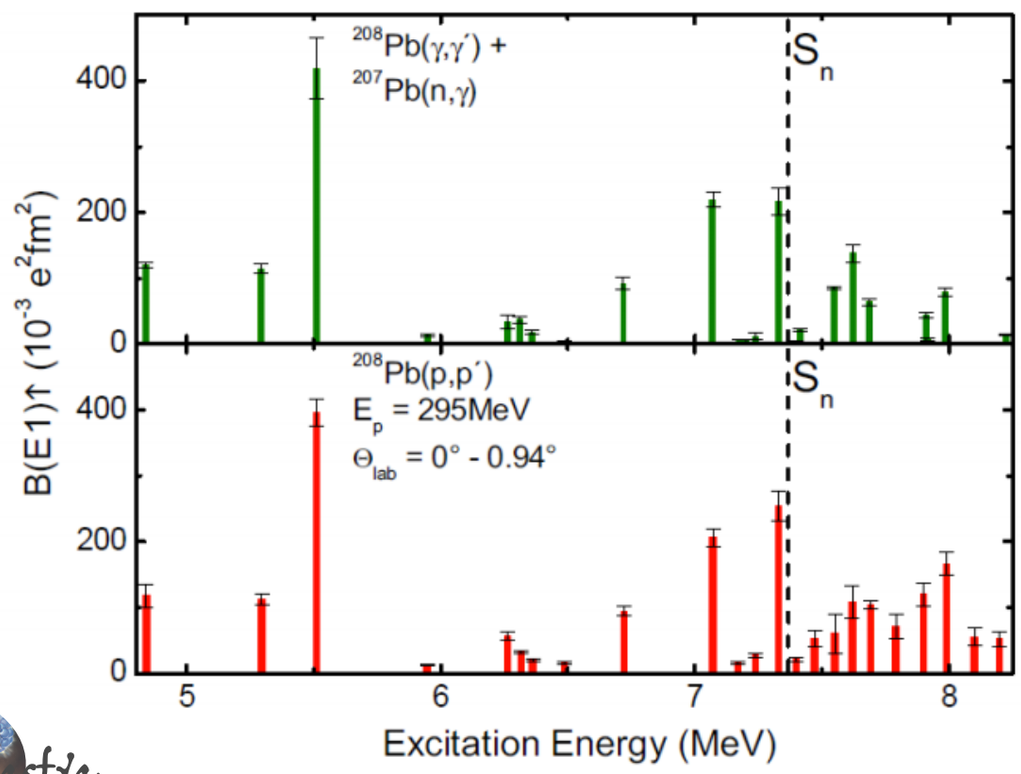


Collective Excitation

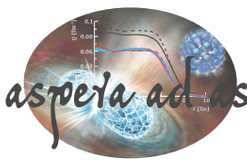


A. Klimkiewicz et al., PRC 76 (2007) 051603(R)
A. Carbone et al., PRC 81 (2010) 041301(R)
P.-G. Reinhard, W. Nazarewicz, PRC 81 (2010) 051303(R)
A. Tamii et al., Phys. Rev. Lett. 107 (2011) 062502.





... per aspera ad astra ...



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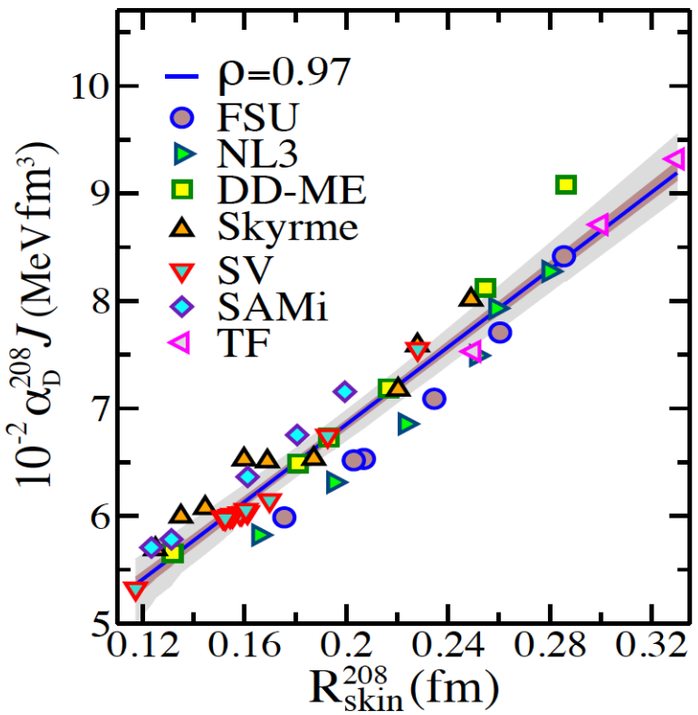
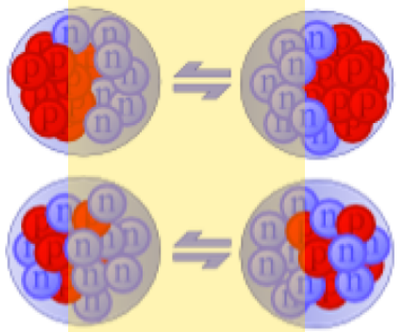
#MakeHumansSmartAgain

...back to the (high-)stairway

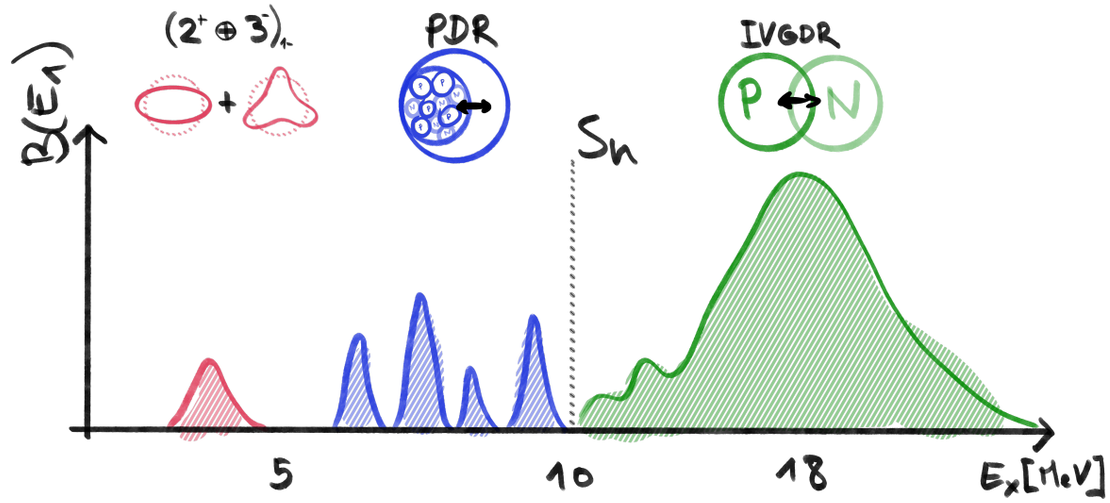
X. Roca-Maza, et al., Phys. Rev. , C88:024316



Resonance Strength

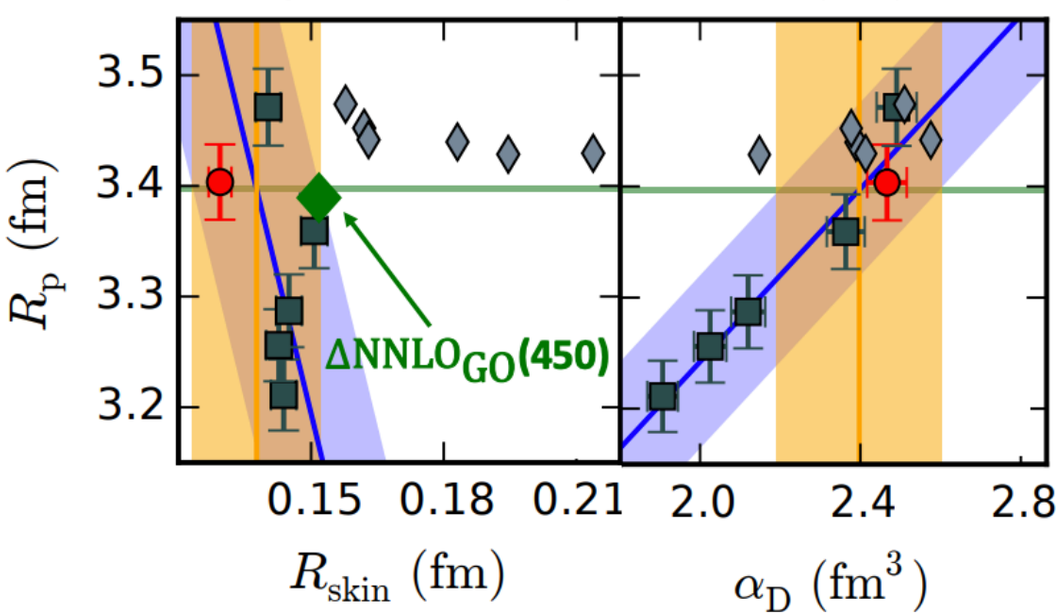


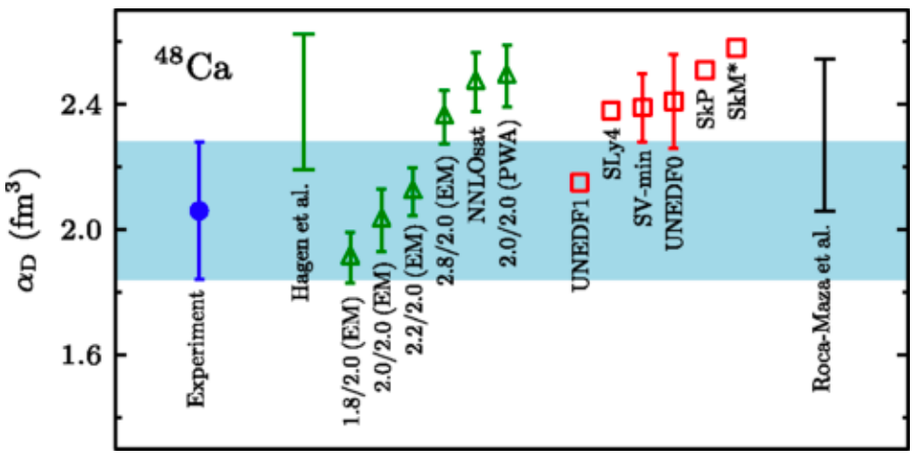
Collective excitation



$$\alpha_D = \frac{\hbar c}{2\pi^2}\int\frac{\sigma_{abs}}{\omega^2}d\varpi = \frac{8\pi}{9}\int\frac{dB(E1)}{\omega}$$

G. Hagen et al., Nature Physics 12, 186-190 (2016)

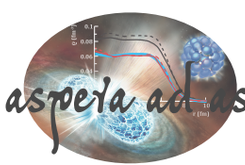




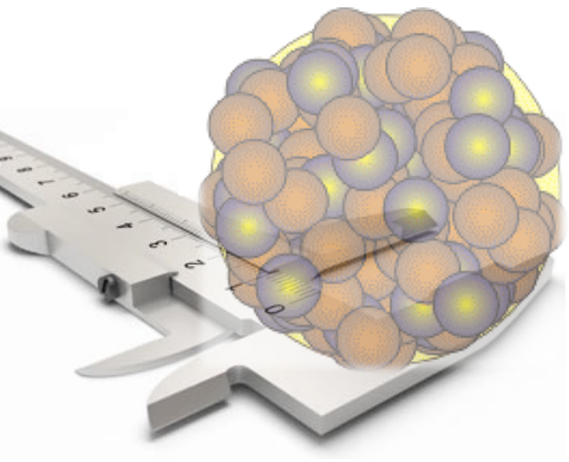
✅High quality data on a variety of nuclei

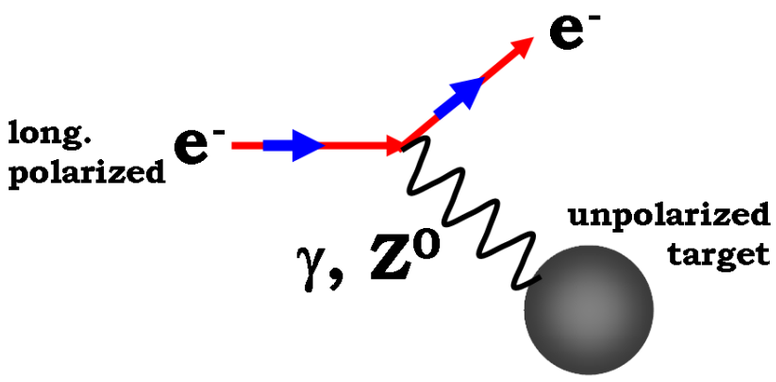
👍Theory: enormous steady progress

... per aspera ad astra ...



The shortest of the roads …





electric charge	1	0
weak charge	≈0.07	1

Non-PV e-scattering

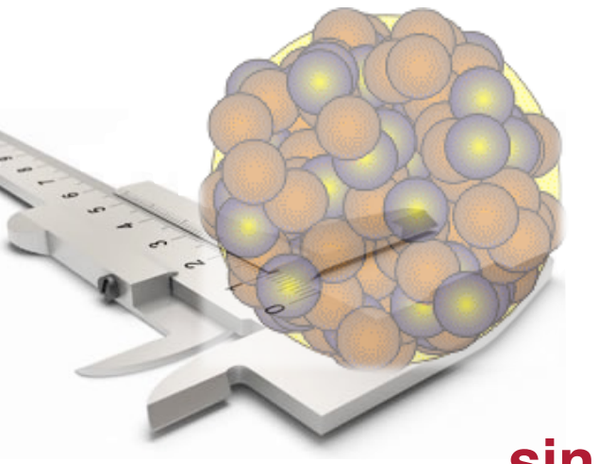
Electron scattering γ exchange provides R_p through nucleus FFs

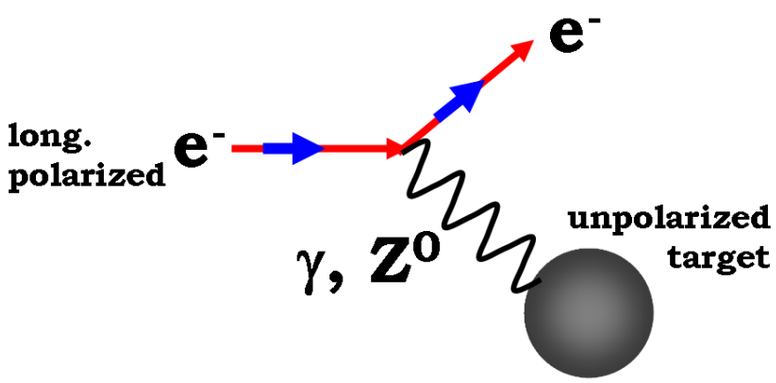
PV e-scattering

Electron also exchange Z, which is parity violating

Primarily couples to neutron

The shortest of the roads ...



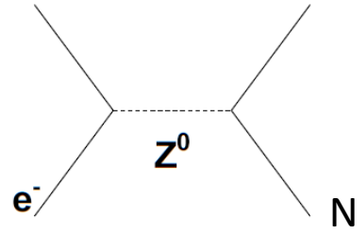


electric charge	1	0
weak charge	≈0.07	1

...since...

$$\sigma \propto \left| \begin{array}{c} \gamma \\ e^- \quad\quad N \end{array} + \begin{array}{c} Z^0 \\ e^- \quad\quad N \end{array} \right|^2$$

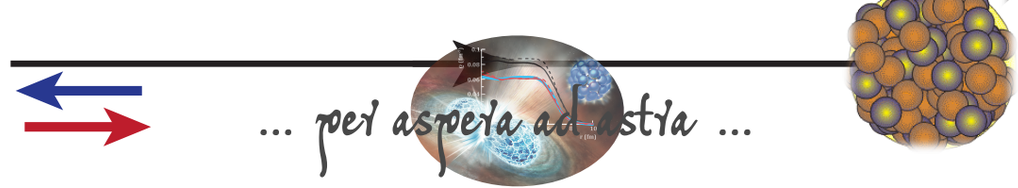
...to measure ...



....construct ....

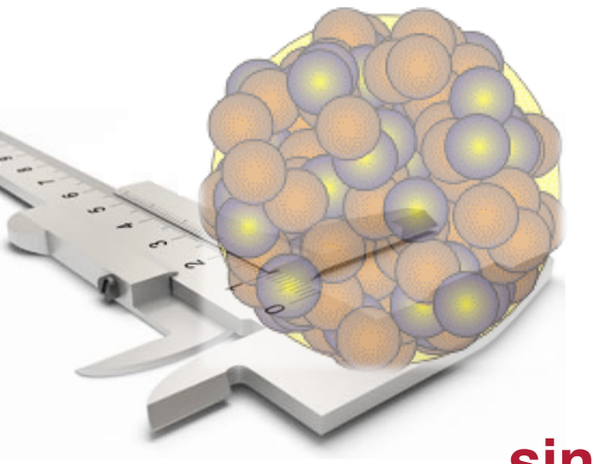
$$A_{PV} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_+ - \left(\frac{d\sigma}{d\Omega}\right)_-}{\left(\frac{d\sigma}{d\Omega}\right)_+ + \left(\frac{d\sigma}{d\Omega}\right)_-}$$

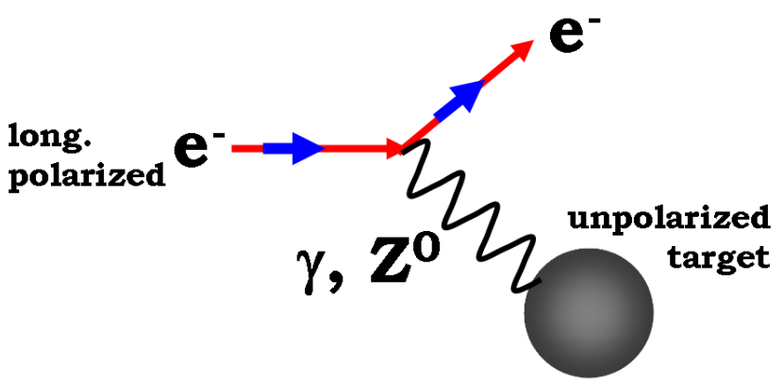
Electron beam



... per aspera ad astra ...

The shortest of the roads ...





electric charge	1	0
weak charge	≈0.07	1

...since...

$$\sigma \propto \left| \; e^- \xrightarrow{\gamma} N \; + \; e^- \xrightarrow{Z^0} N \; \right|^2$$

...to measure ...

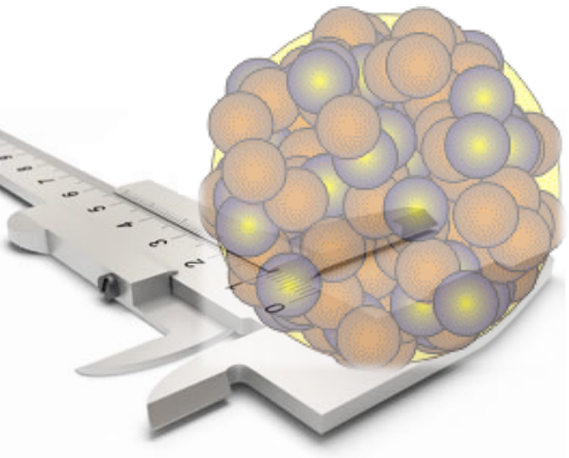
....construct ....

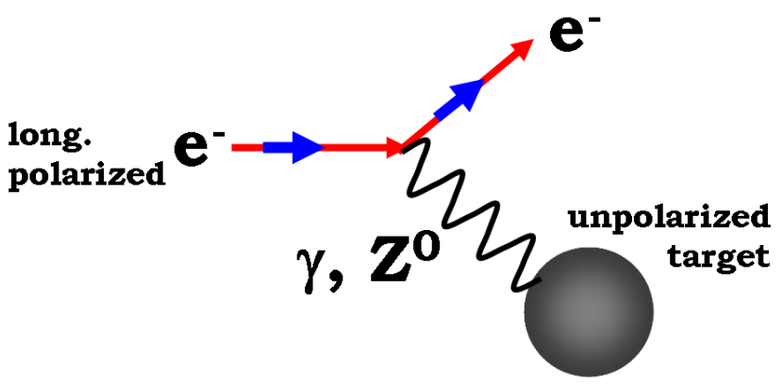
$$A_{PV} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_+ - \left(\frac{d\sigma}{d\Omega}\right)_-}{\left(\frac{d\sigma}{d\Omega}\right)_+ + \left(\frac{d\sigma}{d\Omega}\right)_-} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)} \right]$$

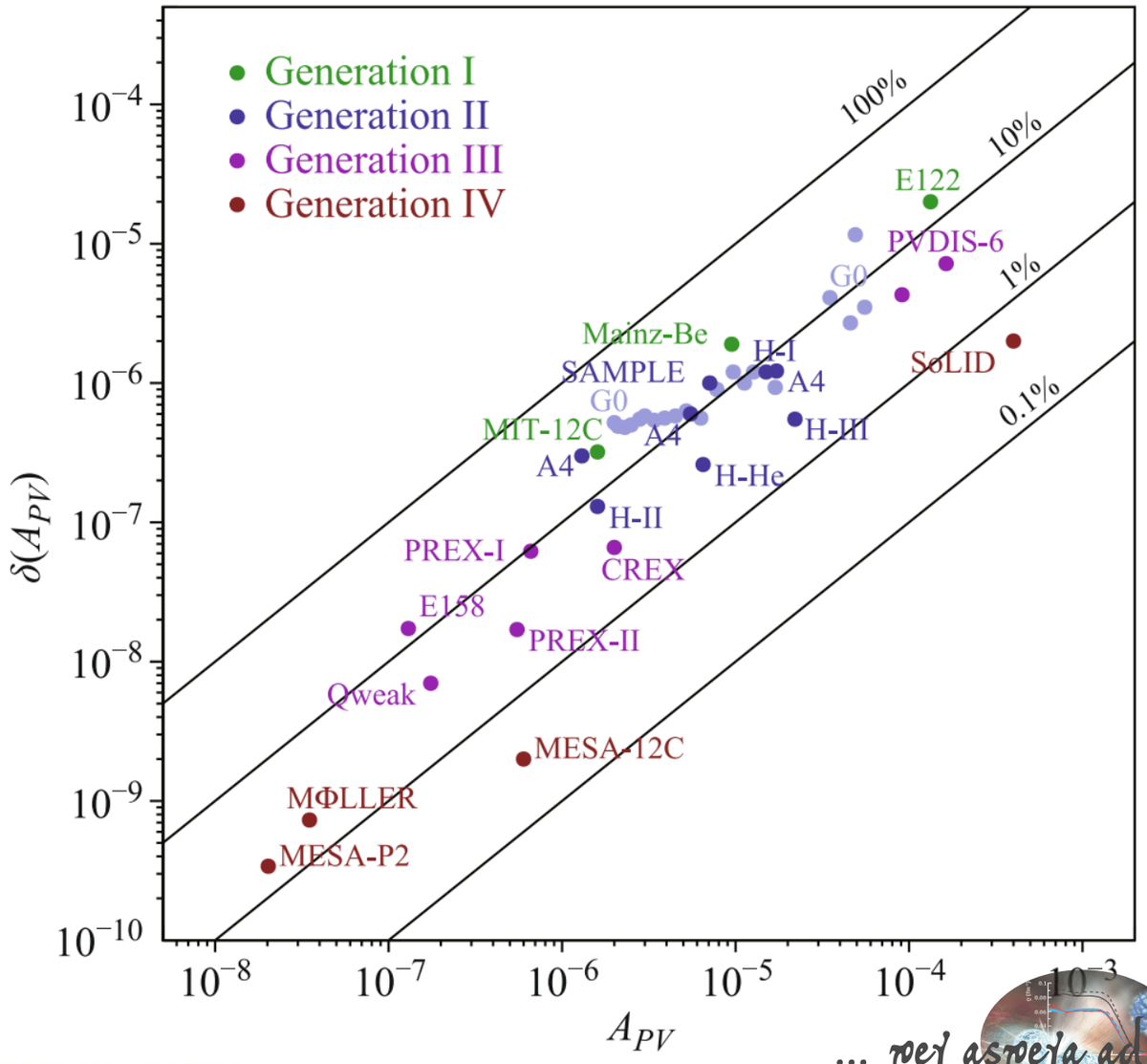
$$F_{n,p}(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_{n,p}(r)$$

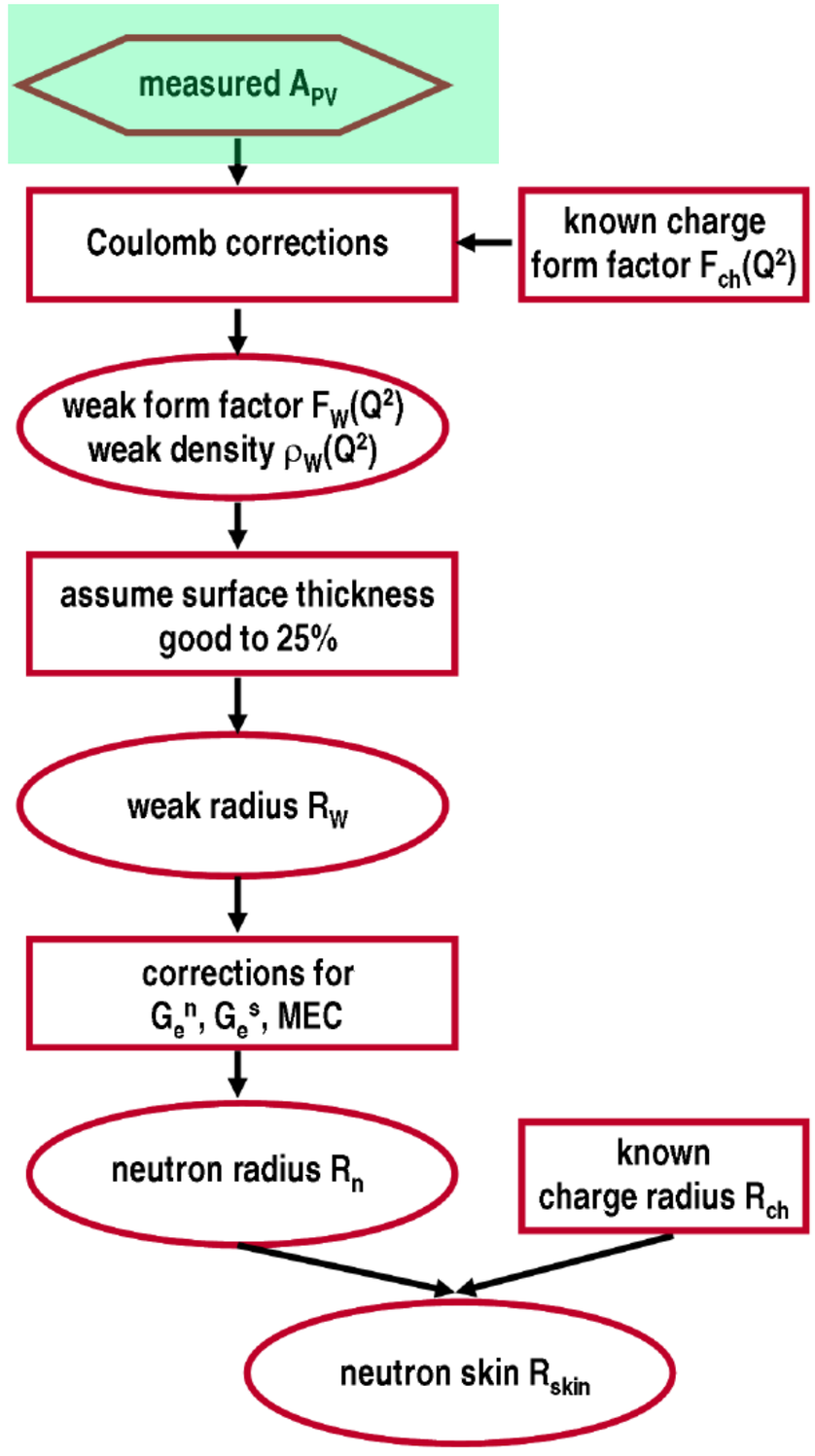
Electron beam

The shortest of the roads ...







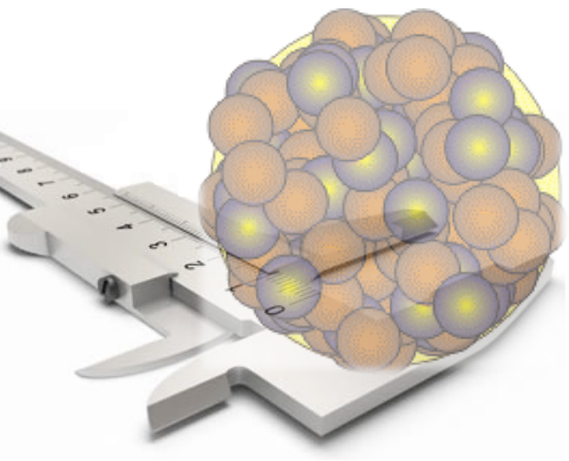


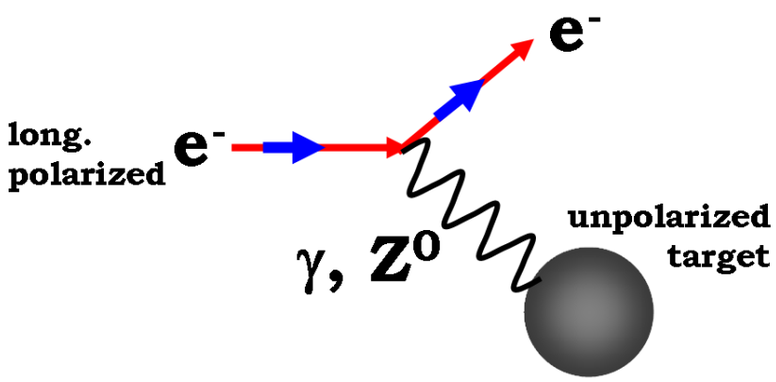
... per aspera ad astra ...

CONCETTINASFIENTI

#MakeHumansSmartAgain

Welcome to Hell!



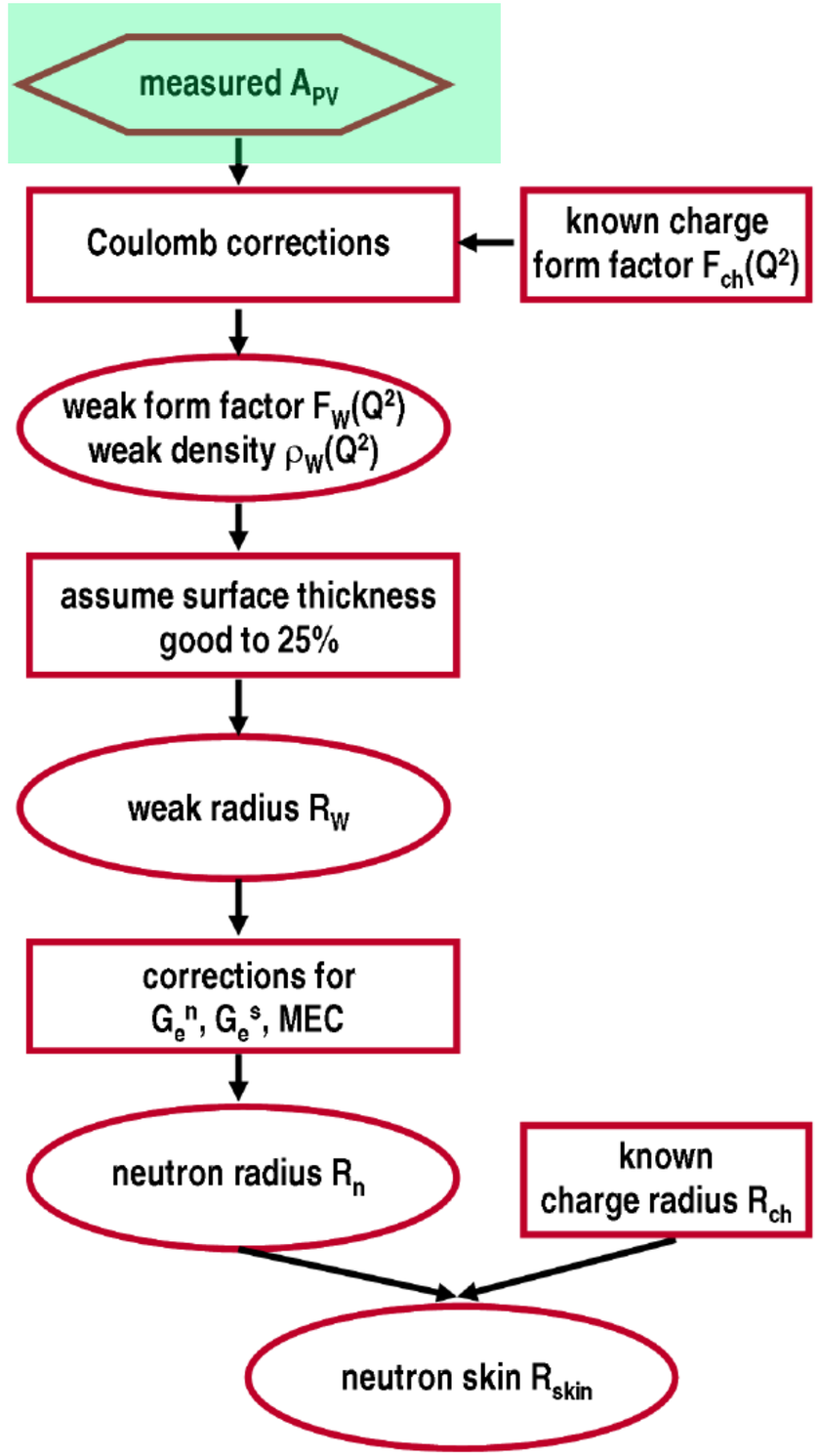


- Essentially means 1.5% on A_{PV}

- A_{PV} is 40 parts per billion

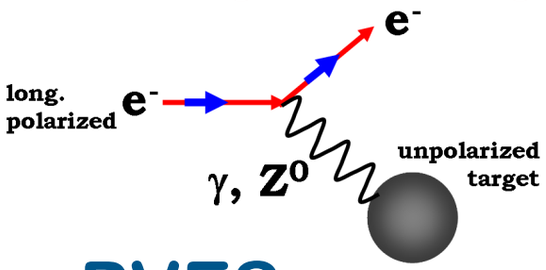
- $\delta(A_{PV})$ is 0.6 parts per billion

$$\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}$$



Welcome to Hell!

PV-Asymmetry

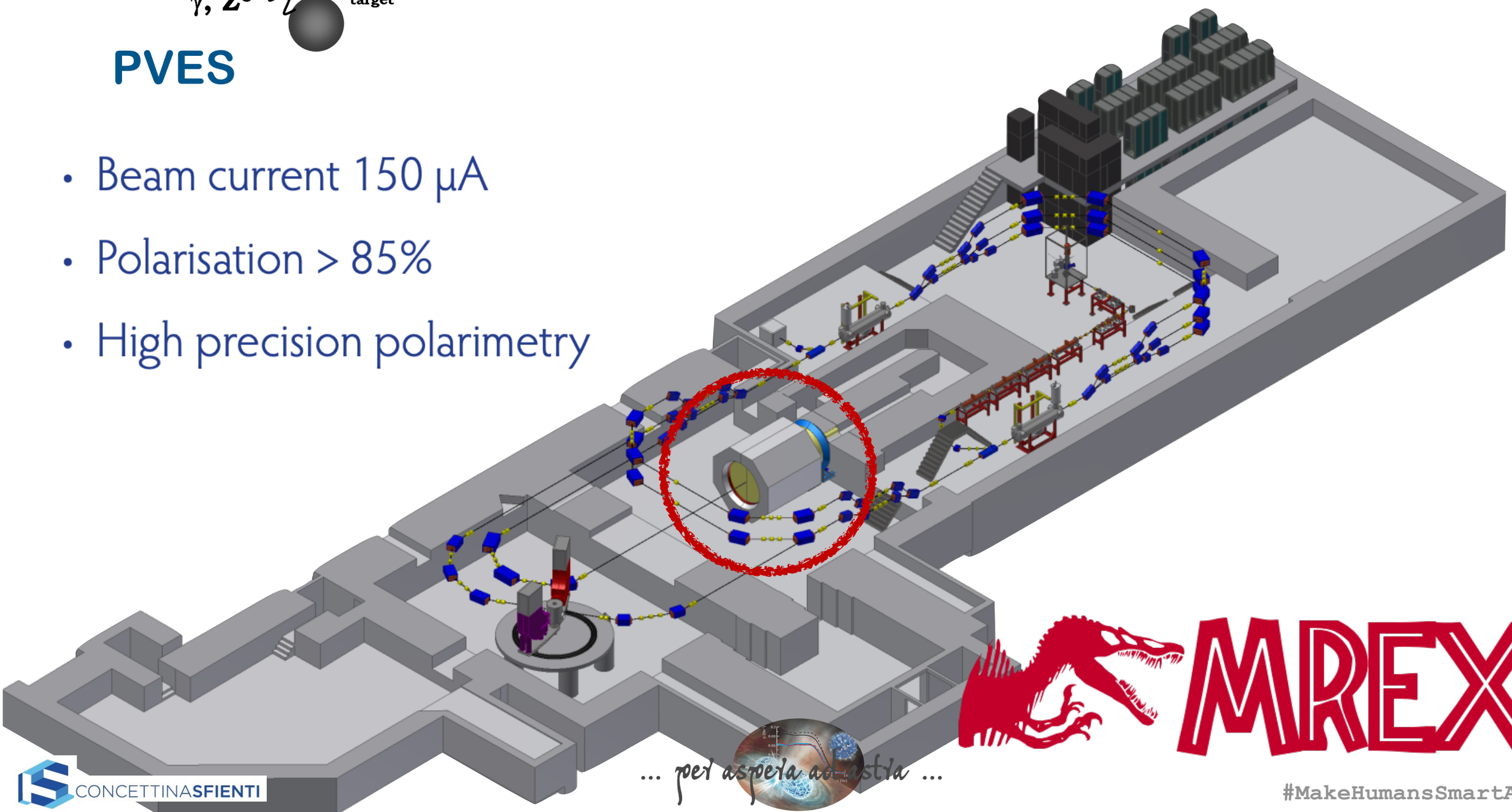


PVES

…. need a few N=10^{18} electrons!

… close to 10^{11} electrons/s

- Beam current 150 μA
- Polarisation > 85%
- High precision polarimetry



MREX

… per aspera ad astra …

beam

energy: 155 MeV

current: 150μA

target

^{208}Pb 0.56 g/cm^2

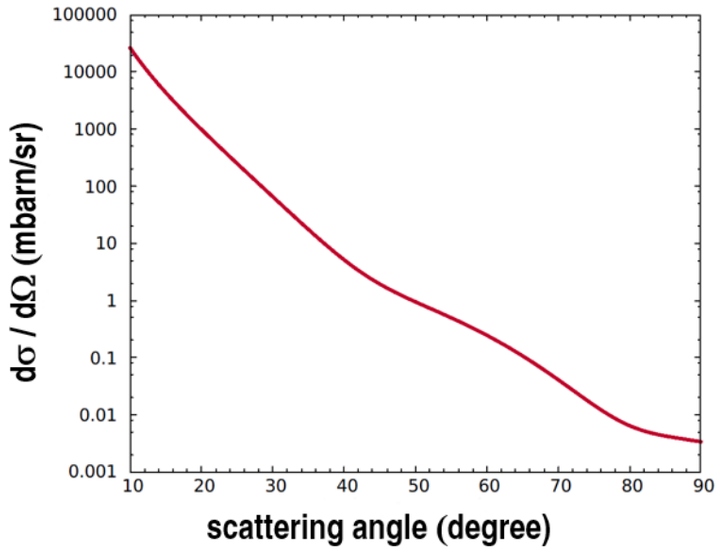
A_{PV}: 0.66 ppm

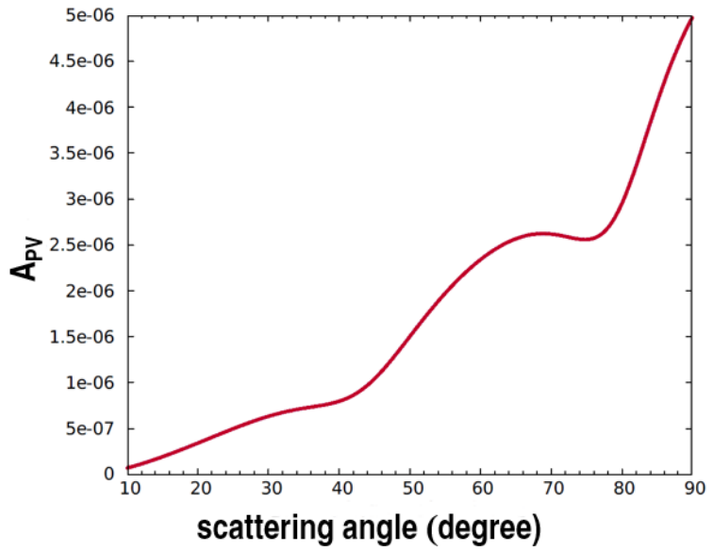
$\Delta\theta = 4°$

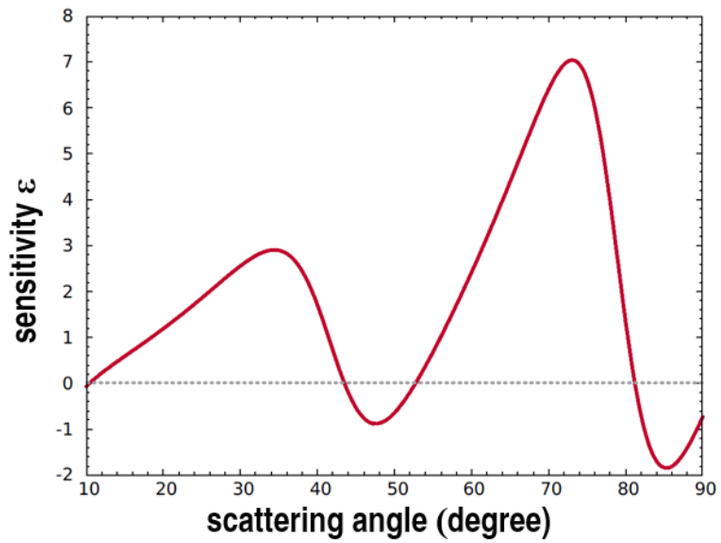
polarization: 85%

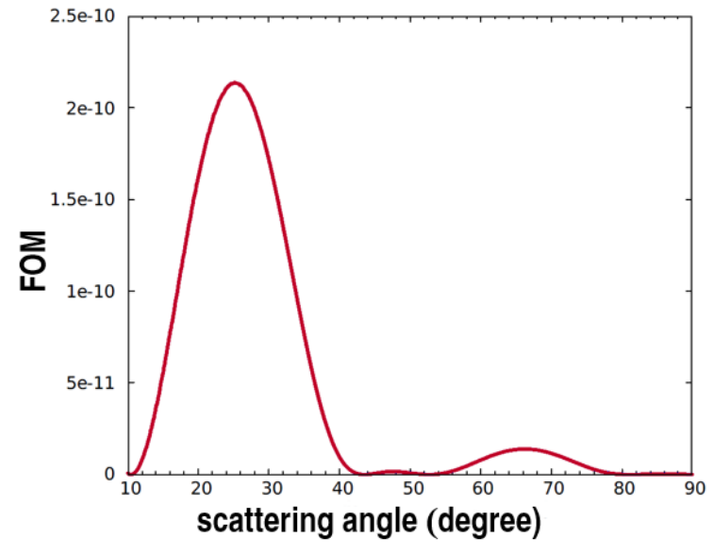
q: 86 MeV/c

Chuck Horowitz

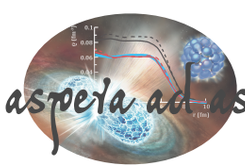








±0.03 fm determination of neutron-skin thickness (🕓 60 days)



... per aspera ad astra ...

CONCETTINASFIENTI

#MakeHumansSmartAgain

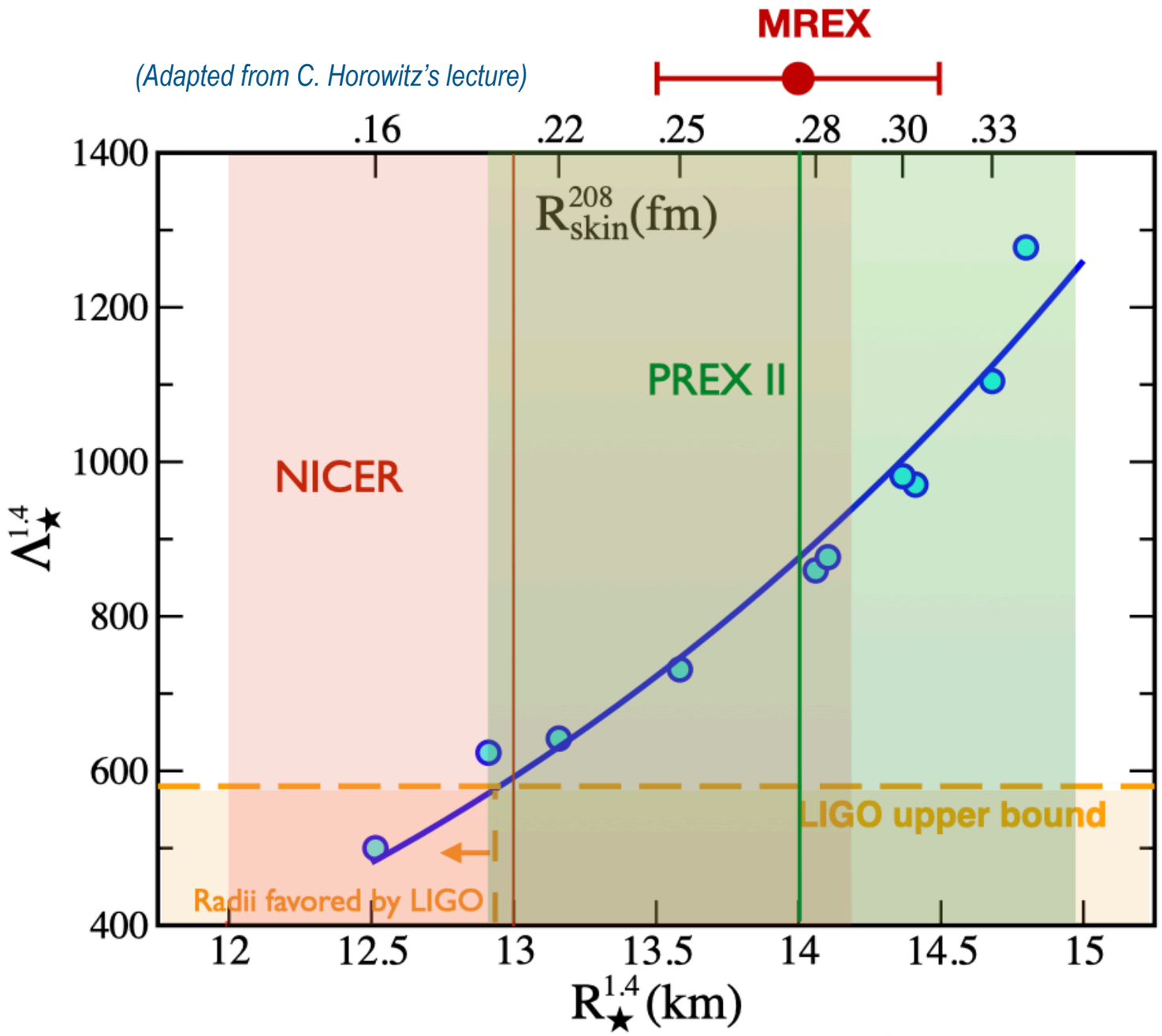
MREX

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

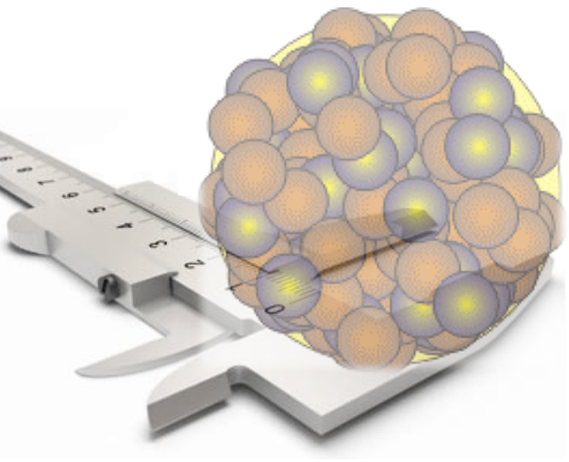
(Adapted from C. Horowitz's lecture)

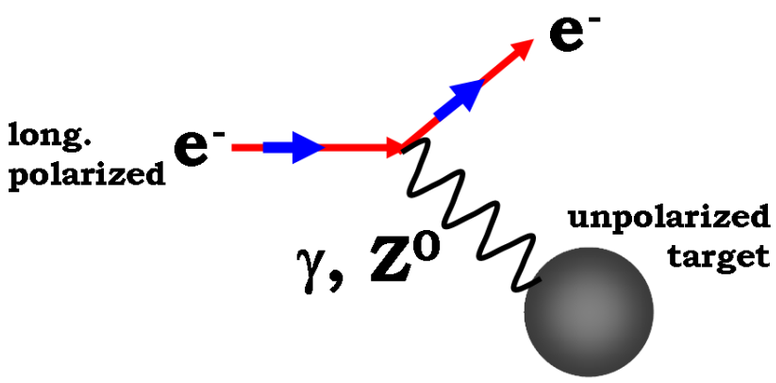


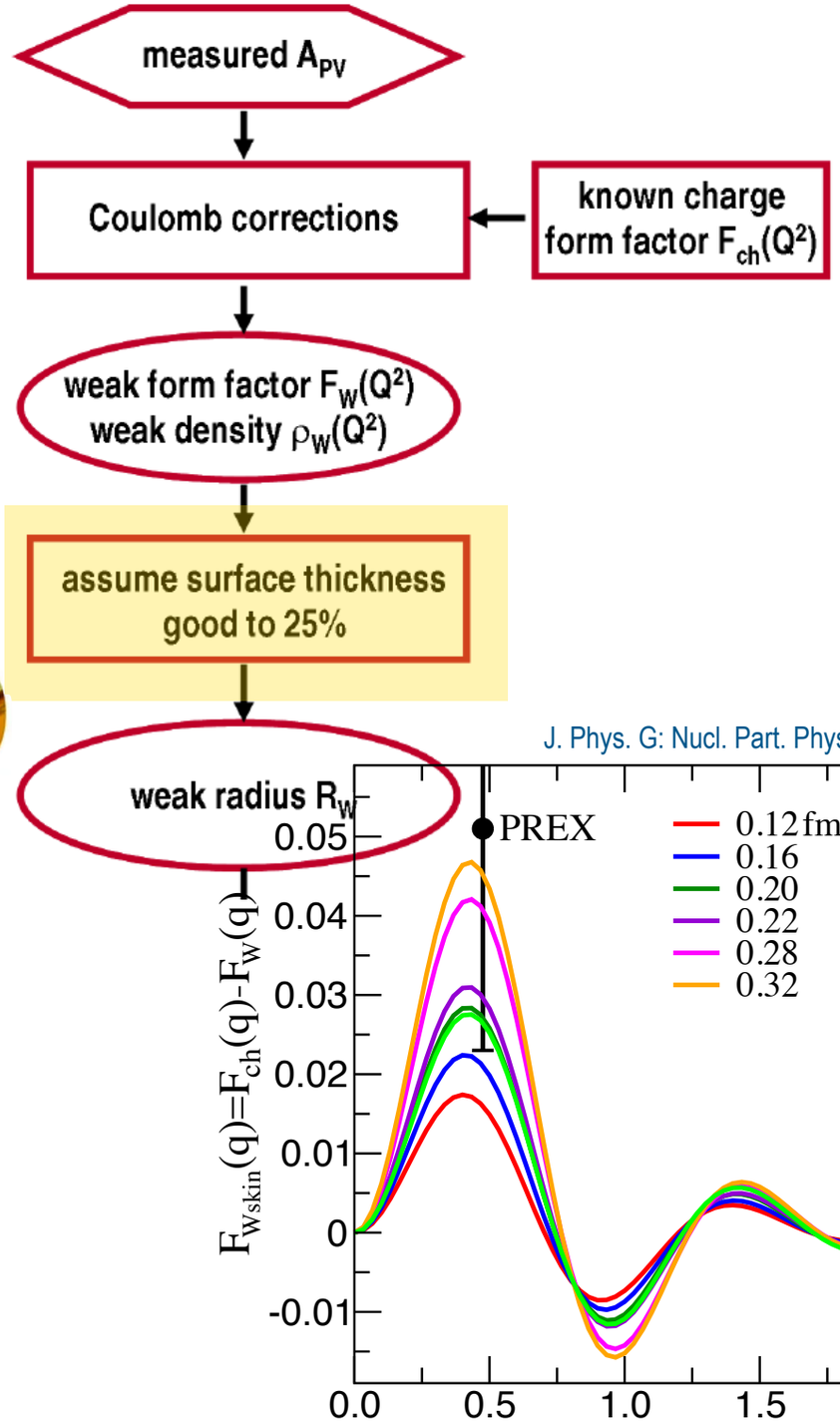
±0.03 fm determination of neutron-skin thickness (🕒 60 days)

... per aspera ad astra ...

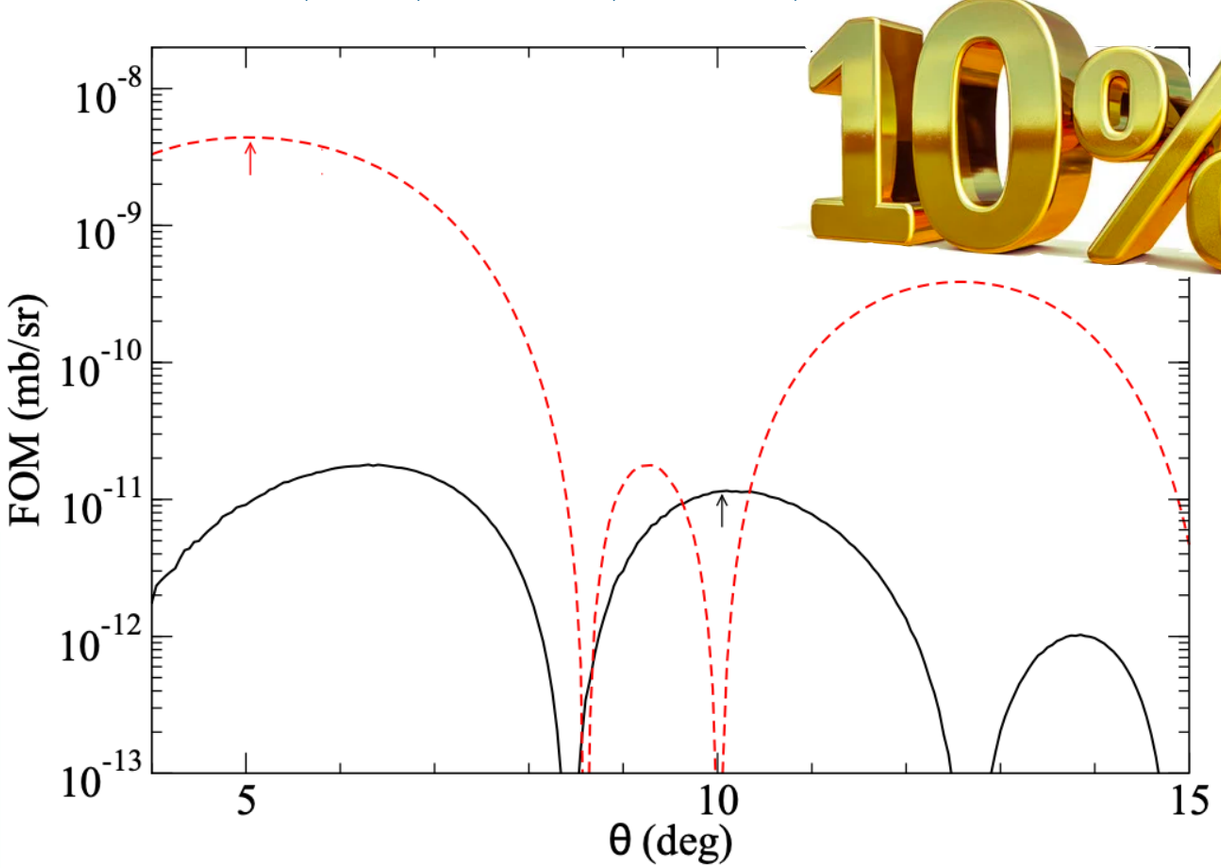
The shortest of the roads ...



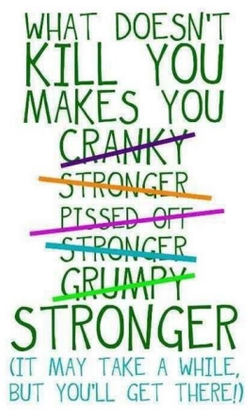


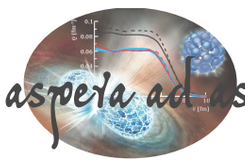


Brendan T. Reed, Z. Jaffe, C. J. Horowitz, CS PRC **102**, 064308



J. Phys. G: Nucl. Part. Phys. 46

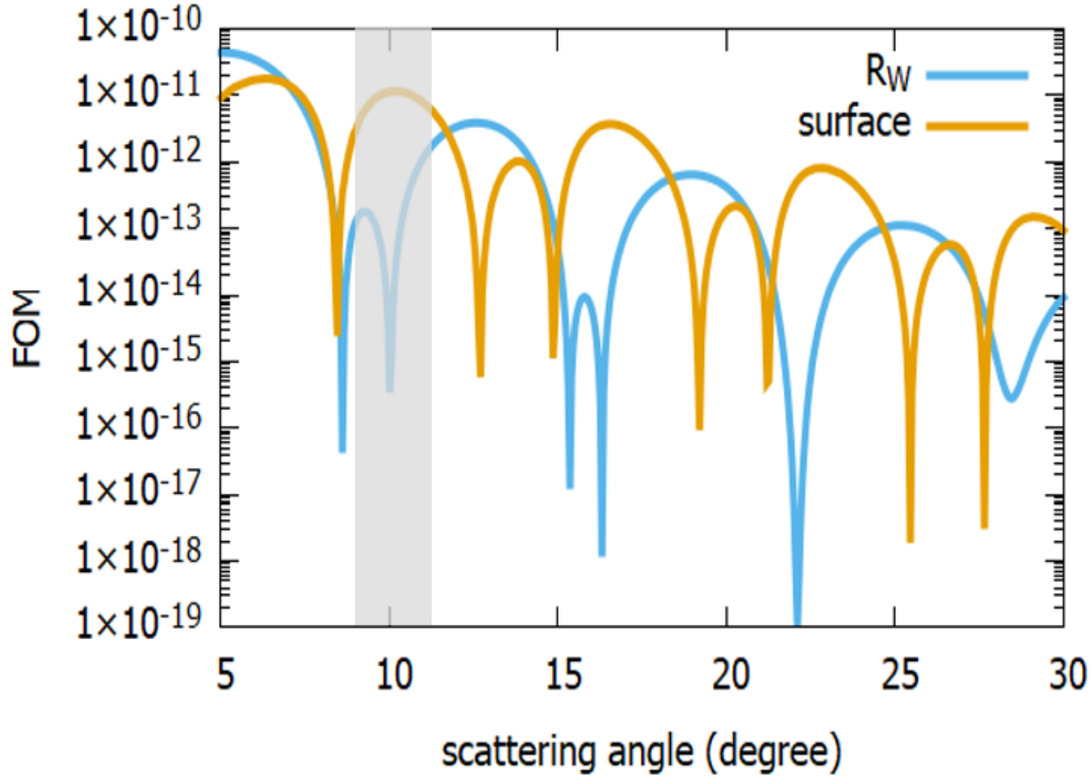




CONCETTINASFIENTI

#MakeHumansSmartAgain

Welcome to Hell! (Part II)

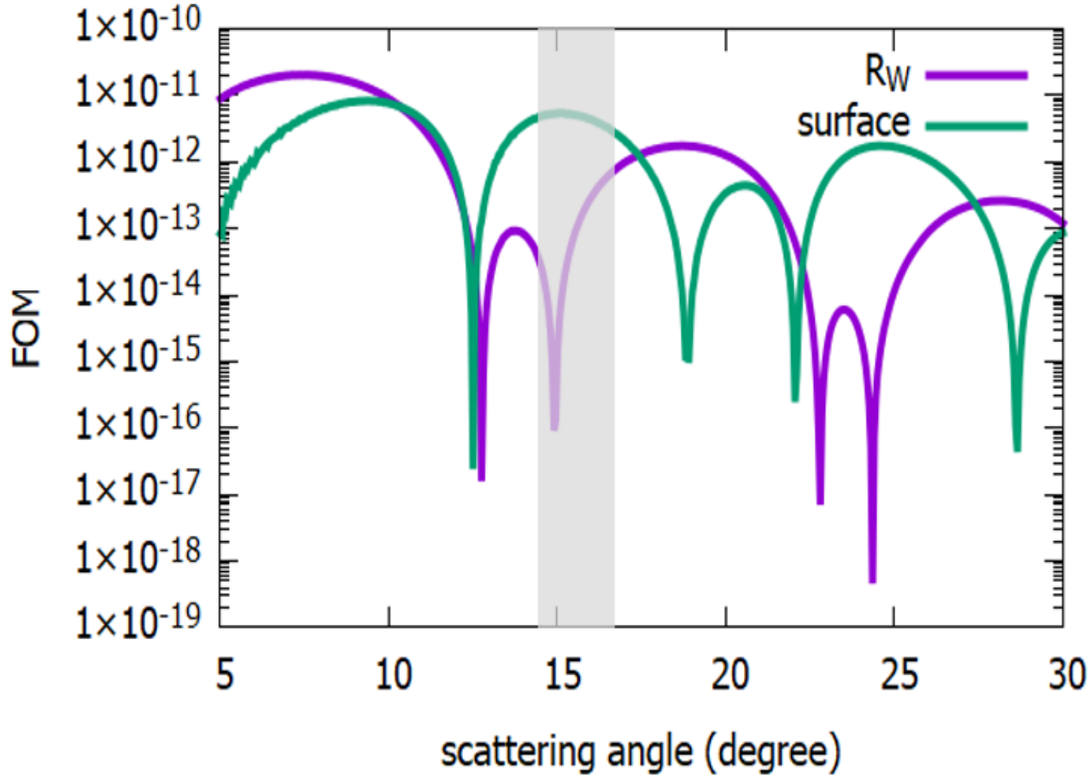


855 MeV

specB: 10.35°
Q^2: 0.02 GeV^2/c^2
I_{beam}: 20μA

running time: 78 days

☺ time, 😐 modified setup

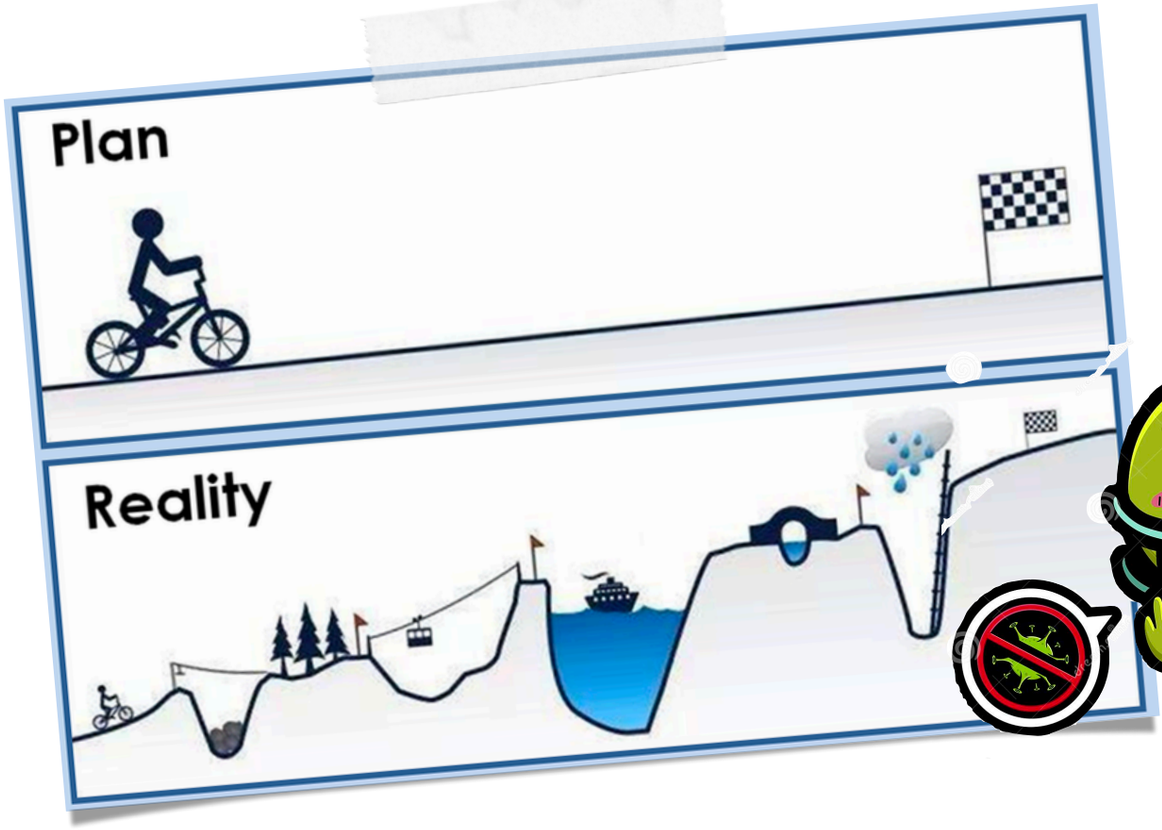


570 MeV

specB: 15.2°
Q^2: 0.02 GeV^2/c^2
I_{beam}: 20μA

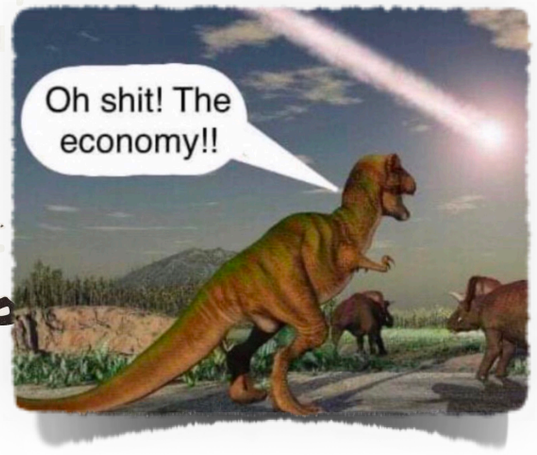
running time: 166 days

😐 time, ☺ well tested setup

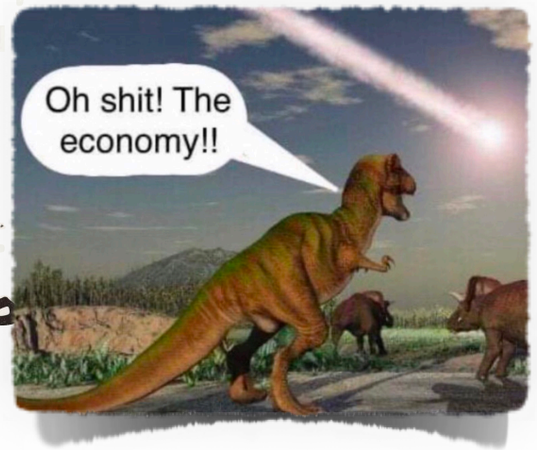

Plan
Reality


ROAR


MREX


Oh shit! The economy!!

MREX



	2024-2027	2028-2031	2032-2035

...per astra da astra ....

Neutron Skin: Quo vadis?

Bad news isn't wine. It doesn't improve with age.

(Colin Powell)

... per aspera ad astra ...

CONCETTINASFIENTI

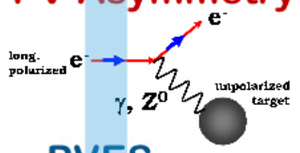
JG|U

The first principle is that you must not fool yourself and you are the easiest person to fool.

— Richard P. Feynman —

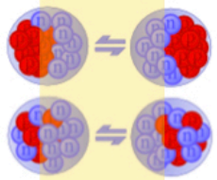
Experimental Challenges (in unit of frustration)

PV-Asymmetry



PVES

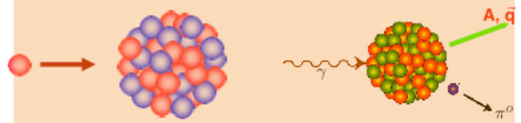
Resonance Strength



Collective Excitation

????..

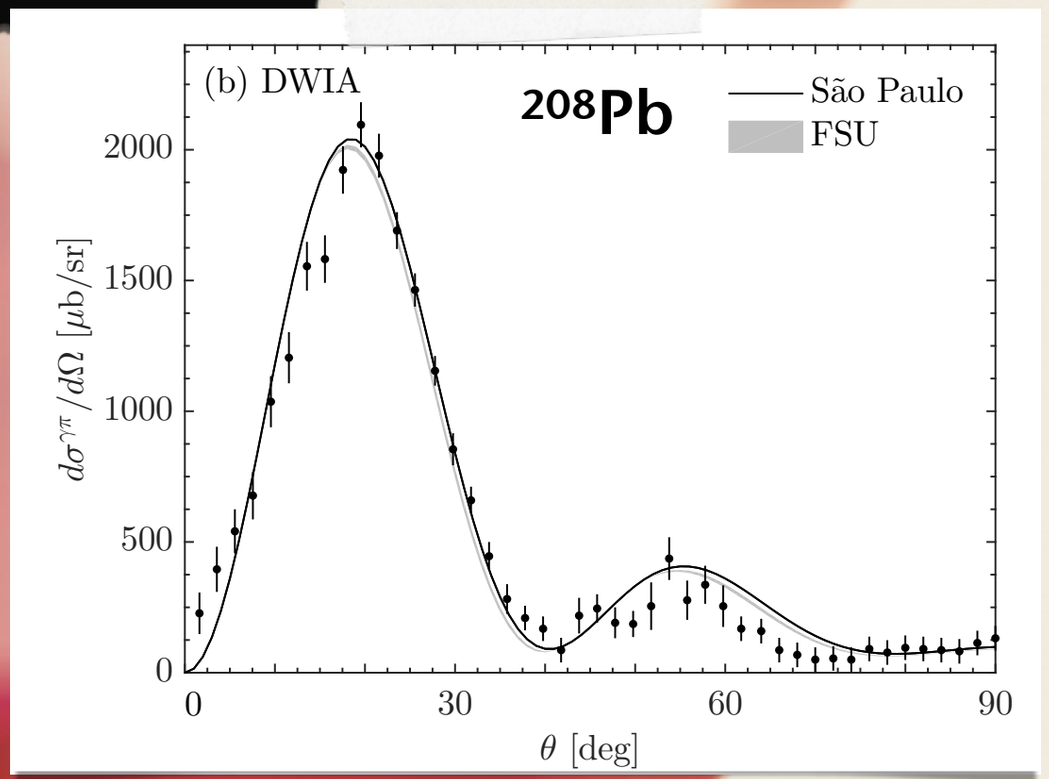
Cross-section

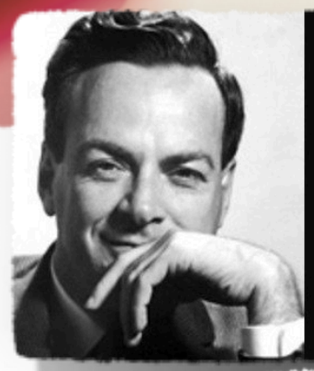


Hadronic Probes

EM Probes

Theo. uncertainties (a.u)





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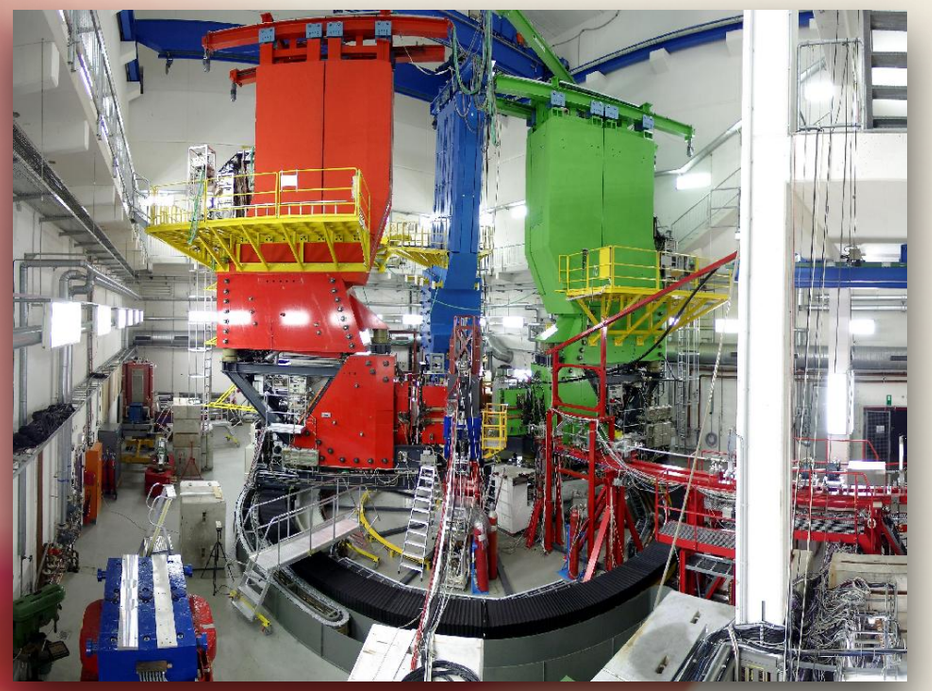
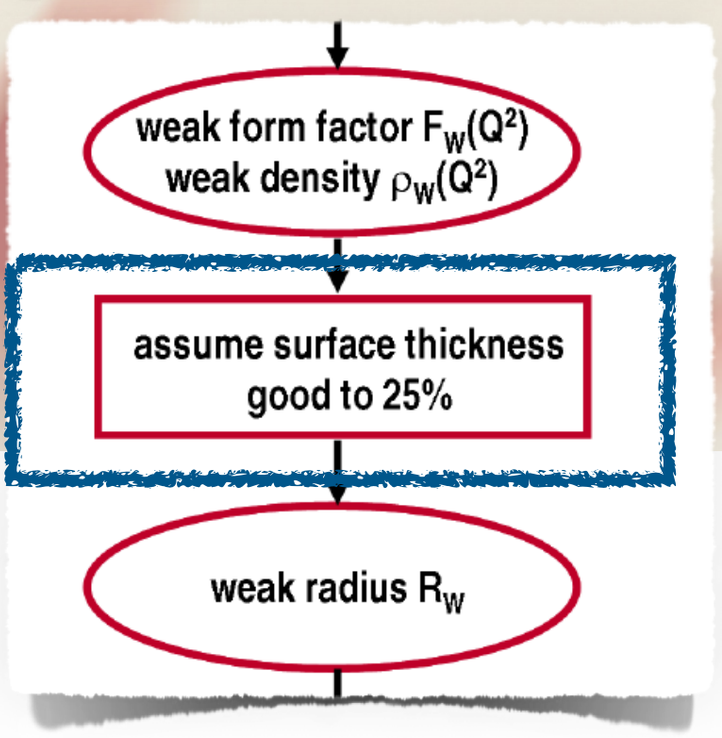
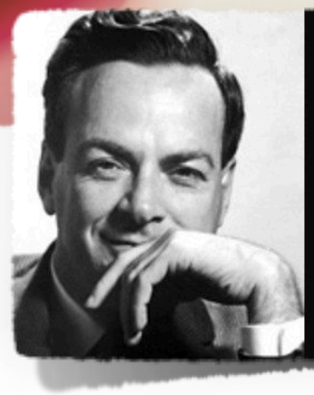
> — Richard P. Feynman —





Exploring different options at A1 to measure the surface thickness of ^{208}Pb

...per astra da astra ....



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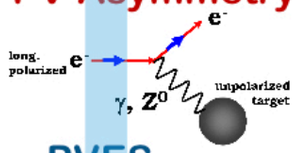
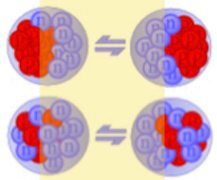
Experimental Challenges (in unit of frustration)

PV-Asymmetry



PVES

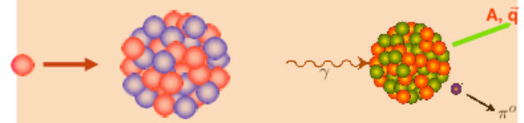
Resonance Strength



Collective Excitation

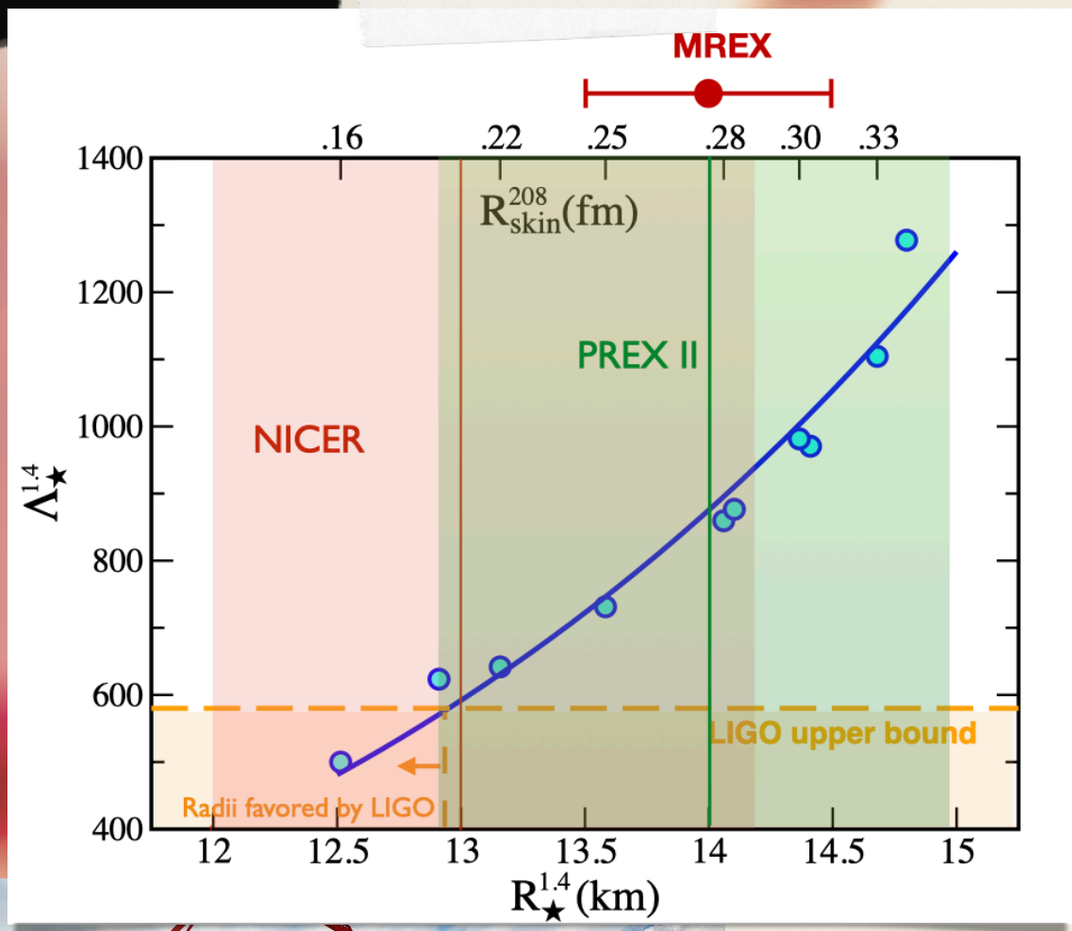
????..

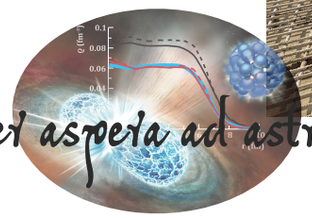
Cross-section



Hadronic Probes | **EM Probes**

Theo. uncertainties (a.u)





... per aspera ad astra ...

CONCETTINASFIENTI

Stand April 2021

JG|U