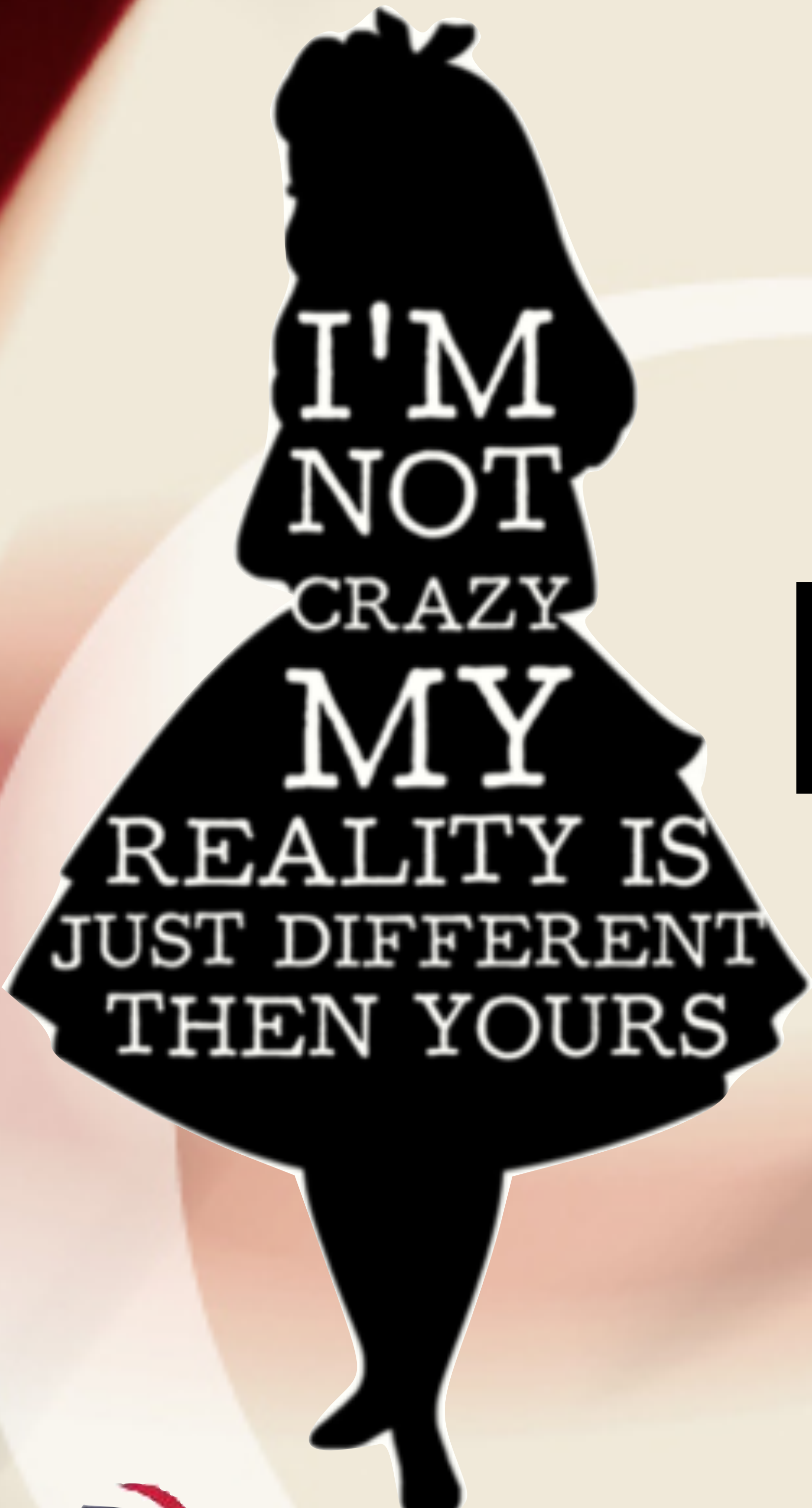
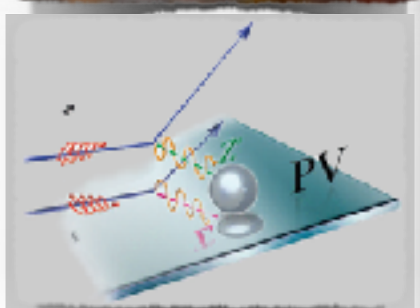
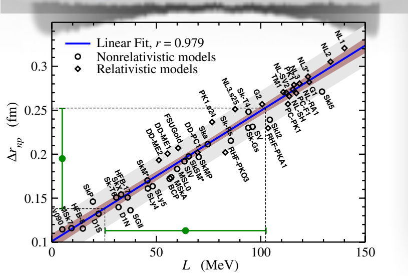



# Neutron Skin in Nuclei

PRiSMA
SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL
JG|U
Concettina Sfienti
Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

# DISCLAIMER




## Monday 30 April 2018

Neutron skin in nuclei - 02.430 (10:00-11:00)

- Presenters: SFIENTI, Concettina

Neutron skins, neutron rich matter and neutron stars - 02.430 (11:30-12:30)

- Presenters: HOROWITZ, Charles

PREX, CREX and MOLLER at Jefferson Lab - 02.430 (14:30-15:30)

- Presenters: KUMAR, Krishna

On potential observables that may further impact on the symmetry energy - 02.430 (16:00-17:00)

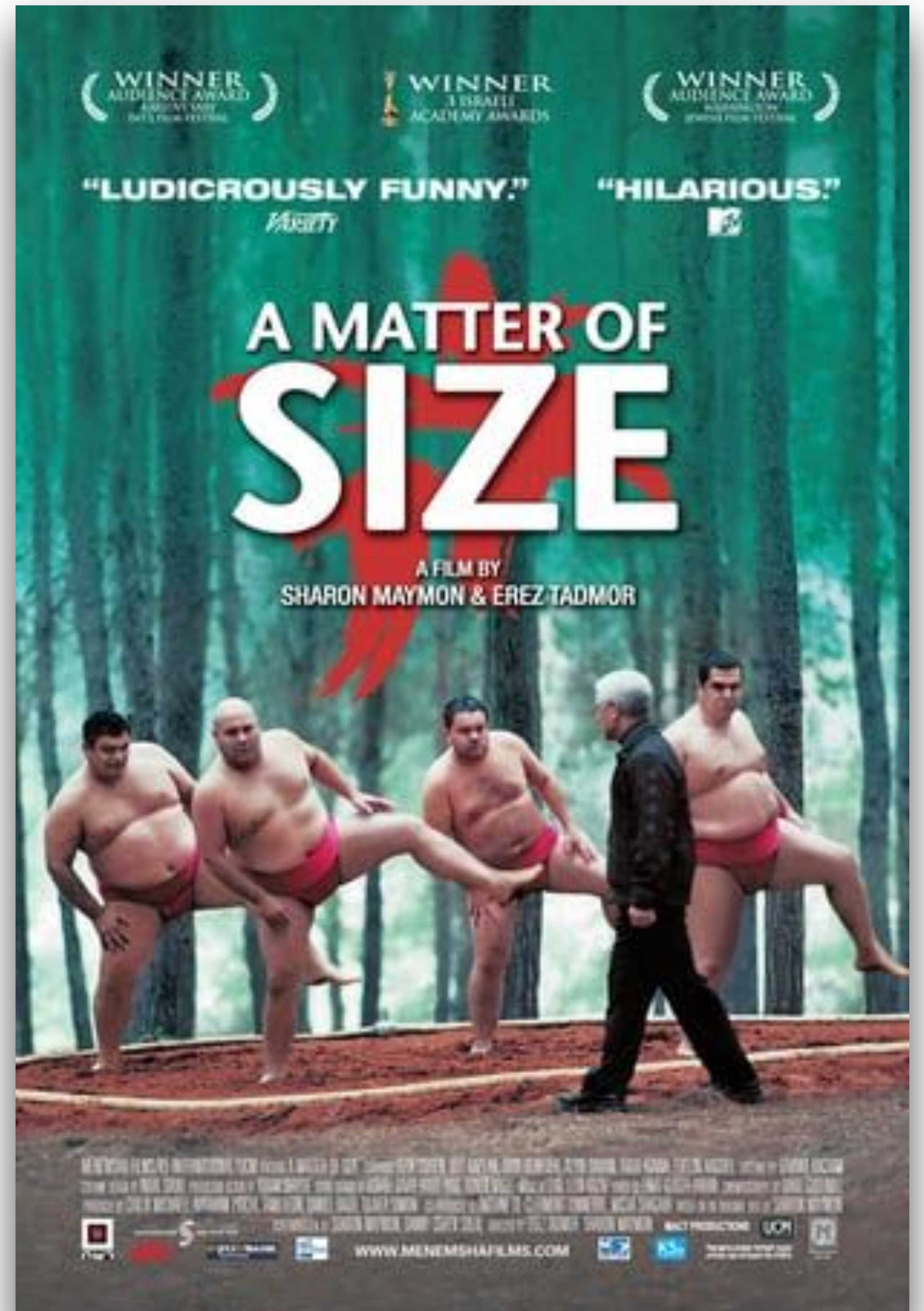
- Presenters: ROCA MAZA, Xavier

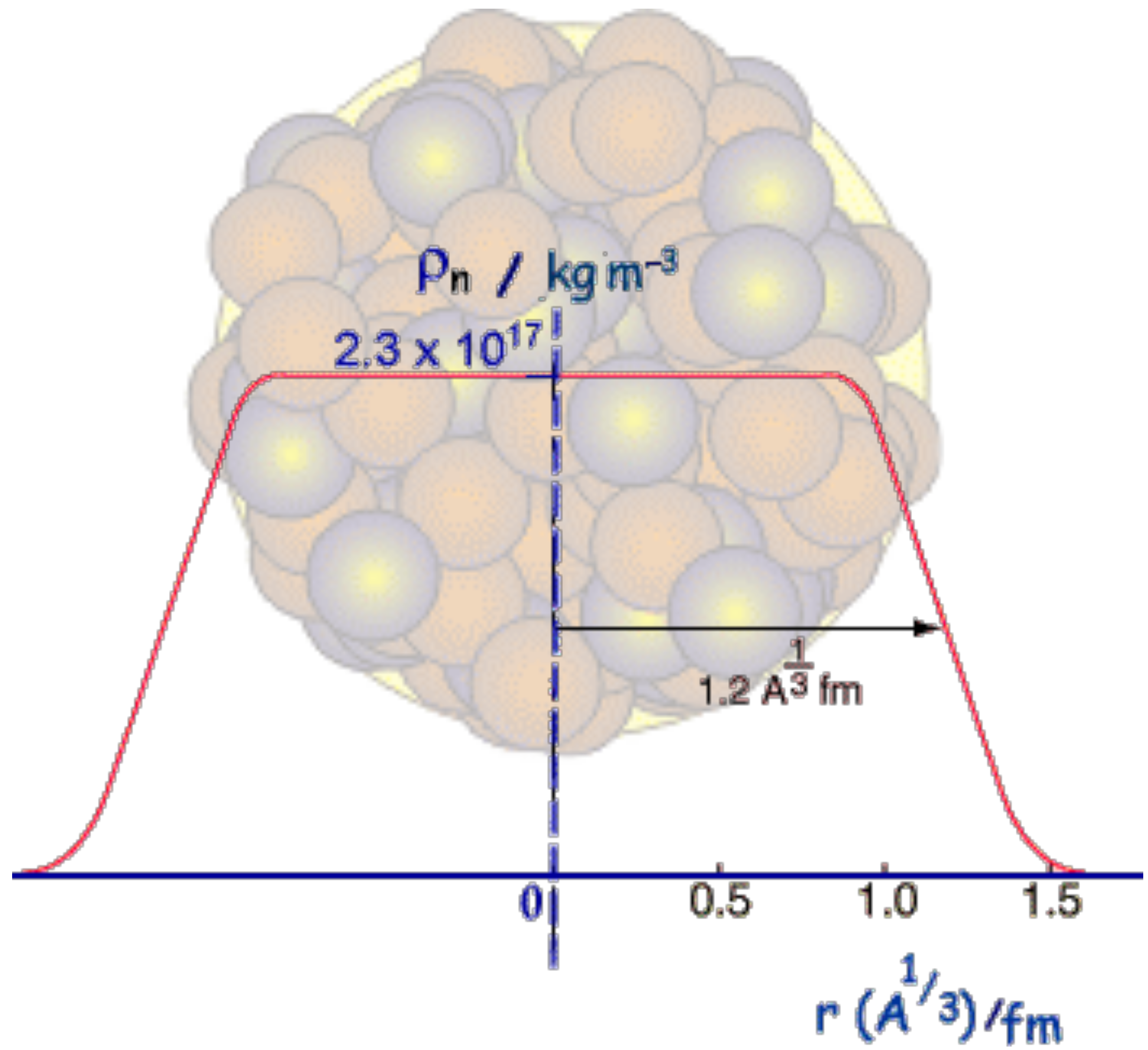
➢ I won't speak about #GW170817 and implications 😢

➢ It will be like beginning SW by watching Episode IV 🤔

➢ It will discuss the connection between neutron skin and symmetry energy

# Nuclear Charge Radius

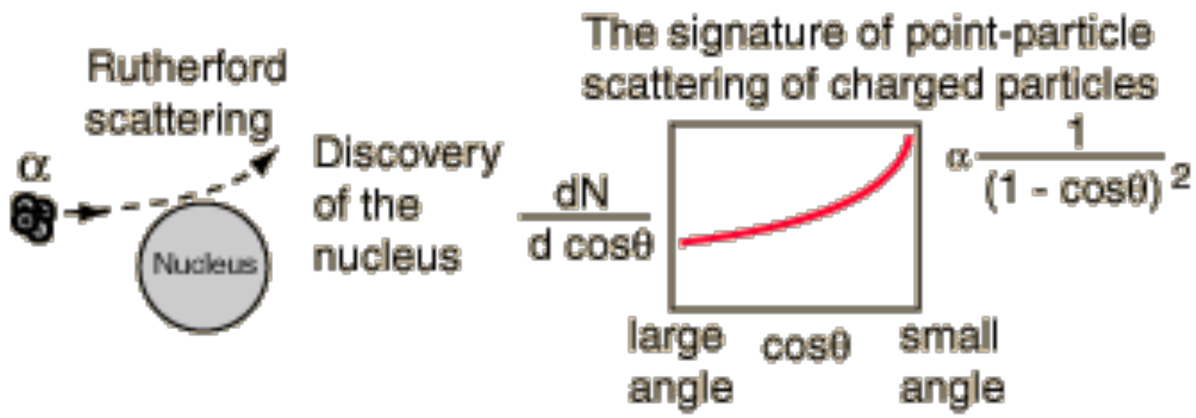


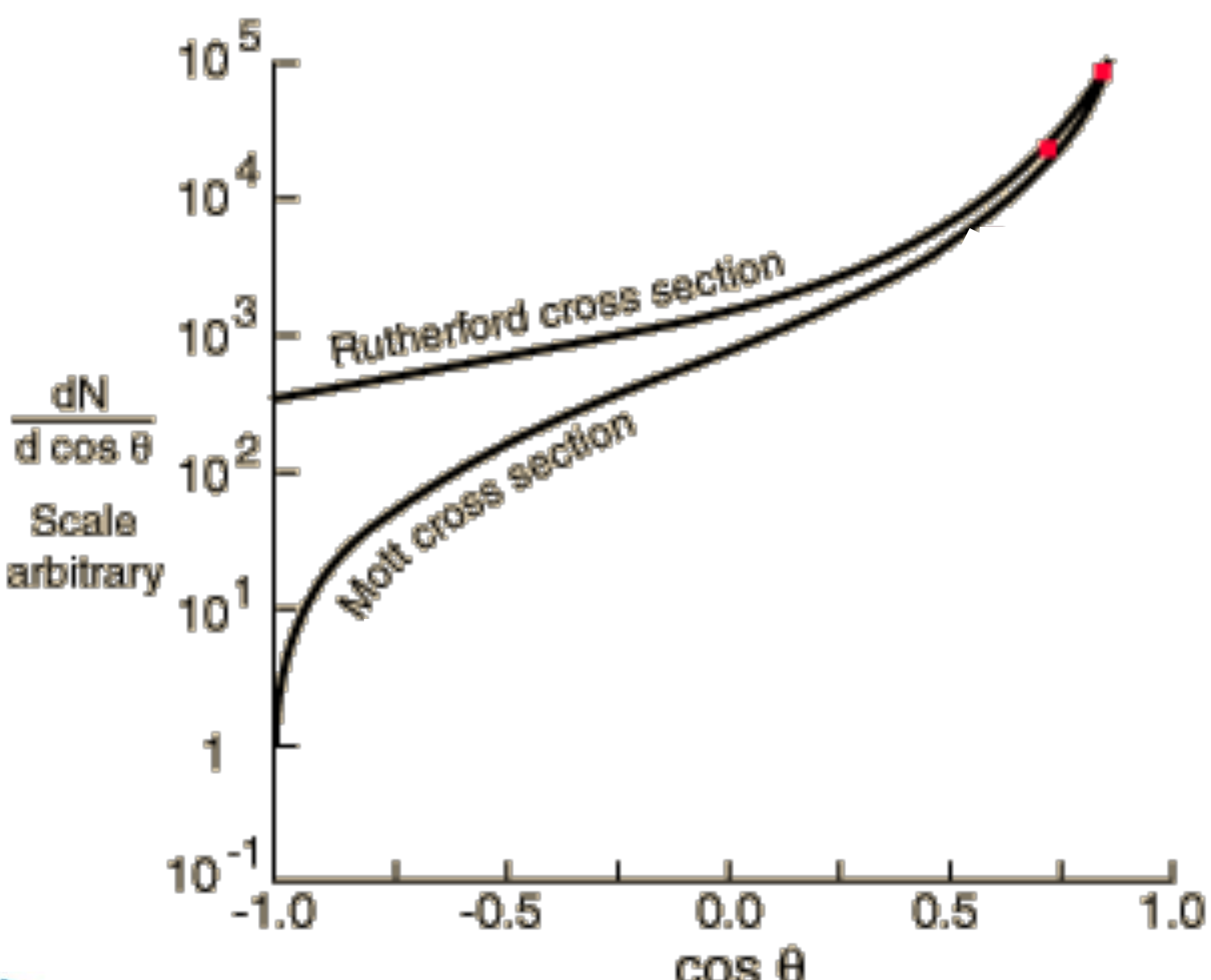



“Diamonds are *for ever*...

# Form Factors are *ethernal*”

http://hyperphysics.phy-astr.gsu.edu/




## Rutherford Scattering

$$\frac{d\sigma}{d\ \cos\theta} = \frac{\pi}{2} z^2 Z^2 \alpha^2 \left(\frac{\hbar c}{KE}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

+ relativistic electrons
+ nuclear recoil
+ magnetic moments
= Mott Scattering

Electron Rutherford formula

Electron magnetic moment effect

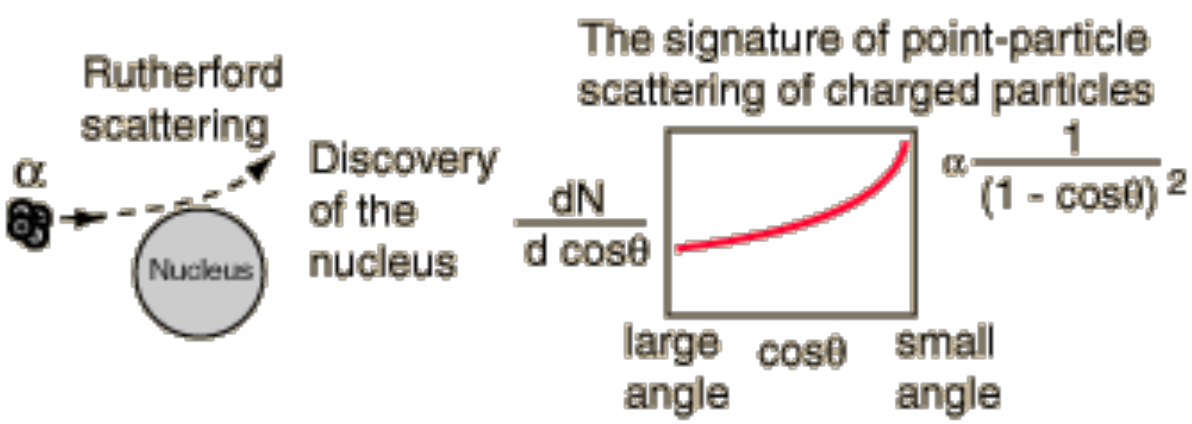
$$\frac{d\sigma}{d\ \cos\theta} = \left(\frac{d\sigma}{d\ \cos\theta}\right)_R \frac{(1+\cos\theta)/2}{\left[1+\frac{(1-\cos\theta)KE}{Mc^2}\right]}$$

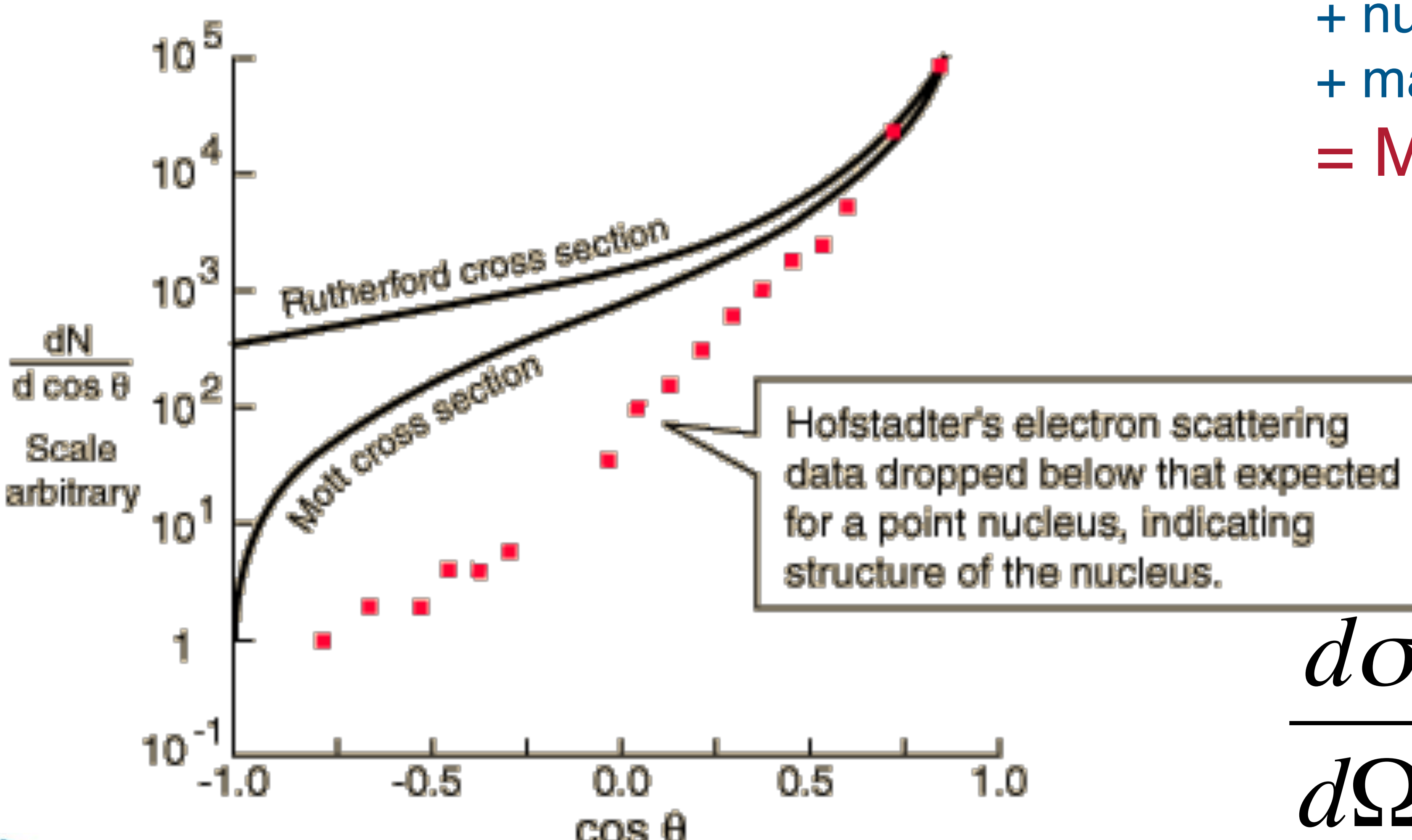
Nuclear recoil effect

“Diamonds are *for ever*…

# Form Factors are *ethernal*”

http://hyperphysics.phy-astr.gsu.edu/




Hofstadter, R., et al., Phys. Rev. 92, 978 (1953).

## Rutherford Scattering

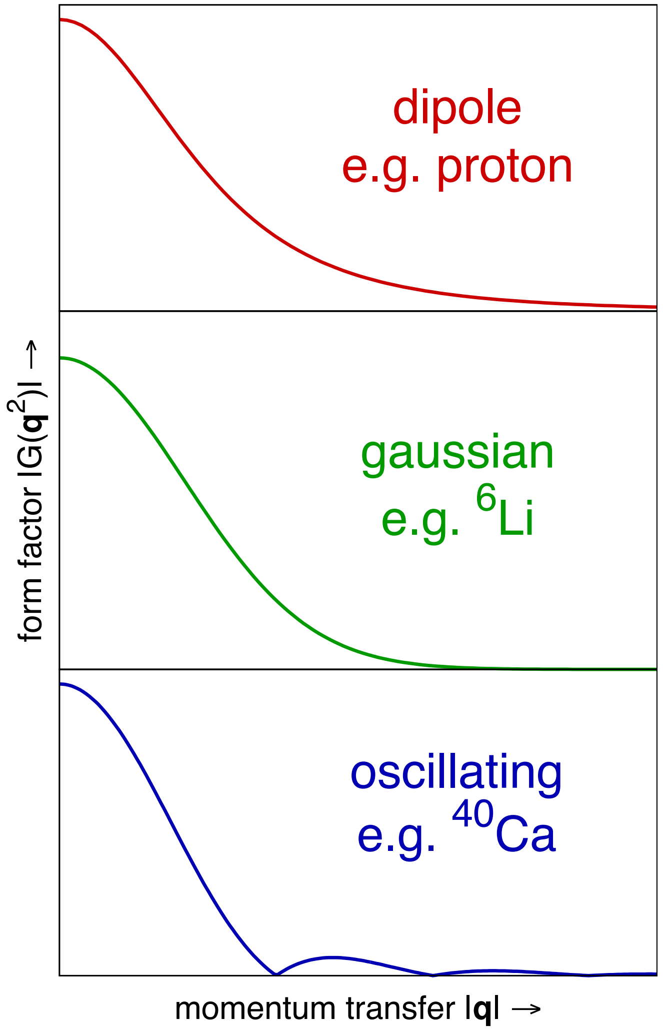
$$\frac{d\sigma}{d\ \cos\theta} = \frac{\pi}{2} z^2 Z^2 \alpha^2 \left(\frac{\hbar c}{KE}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

+ relativistic electrons
+ nuclear recoil
+ magnetic moments
= Mott Scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \left|G(q)\right|^2$$

# Form Factors from Elastic eN scattering

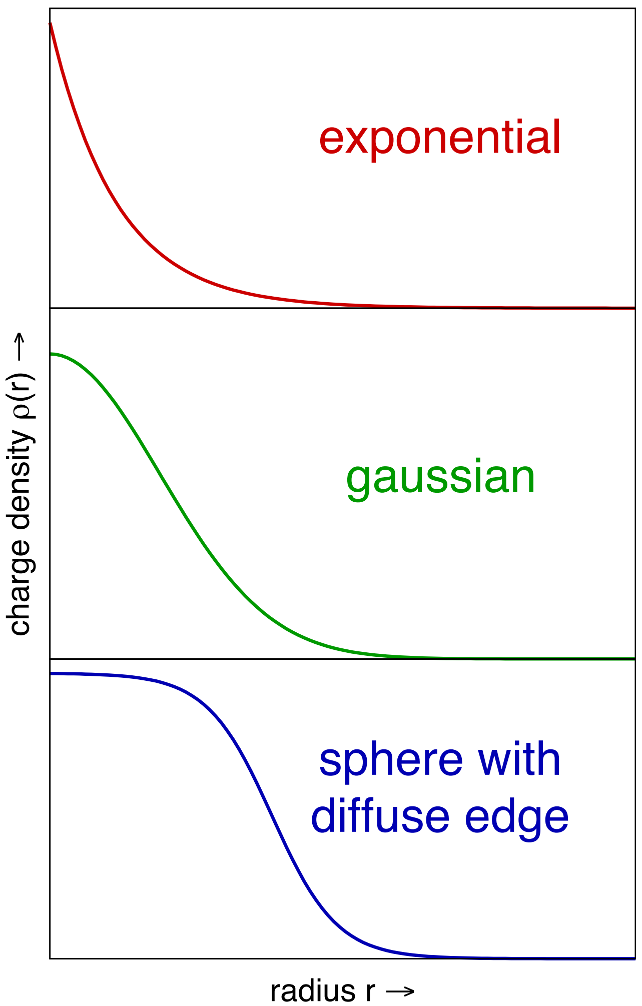
form factor: $G(q^2) = \frac{1}{e} \int_0^\infty \rho(r) \frac{\sin qr}{qr} 4\pi r^2 \, dr$




Fourier

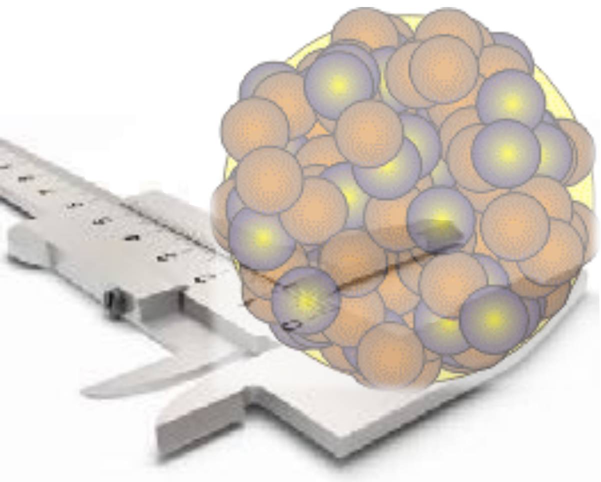
⇔

Transform

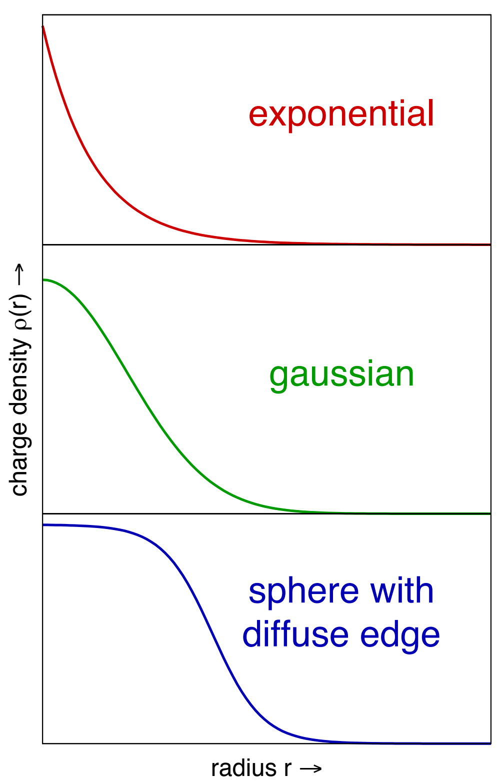



charge distribution: $\rho(r) = \frac{e}{(2\pi)^3} \int_0^\infty G(q^2) \frac{\sin qr}{qr} 4\pi q^2 \, dq$

# Nuclear Charge Radius



- Cross section over **12 orders of magnitude**!
- **THIS** is our picture of the atomic nucleus!



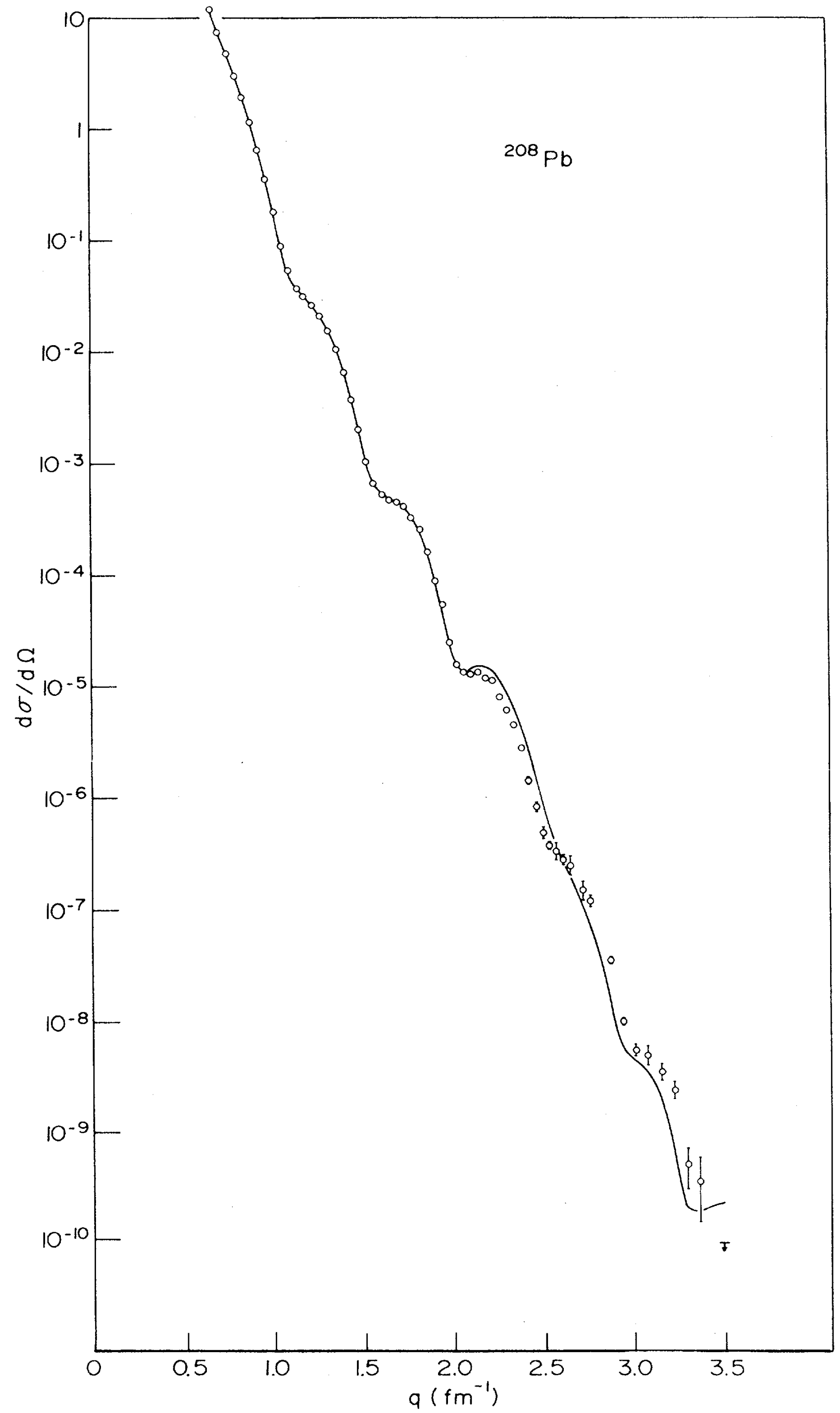




FIG. 10. Cross sections for elastic electron scattering from $^{208}$Pb at 502 MeV compared with DME mean-field theory prediction (solid line).

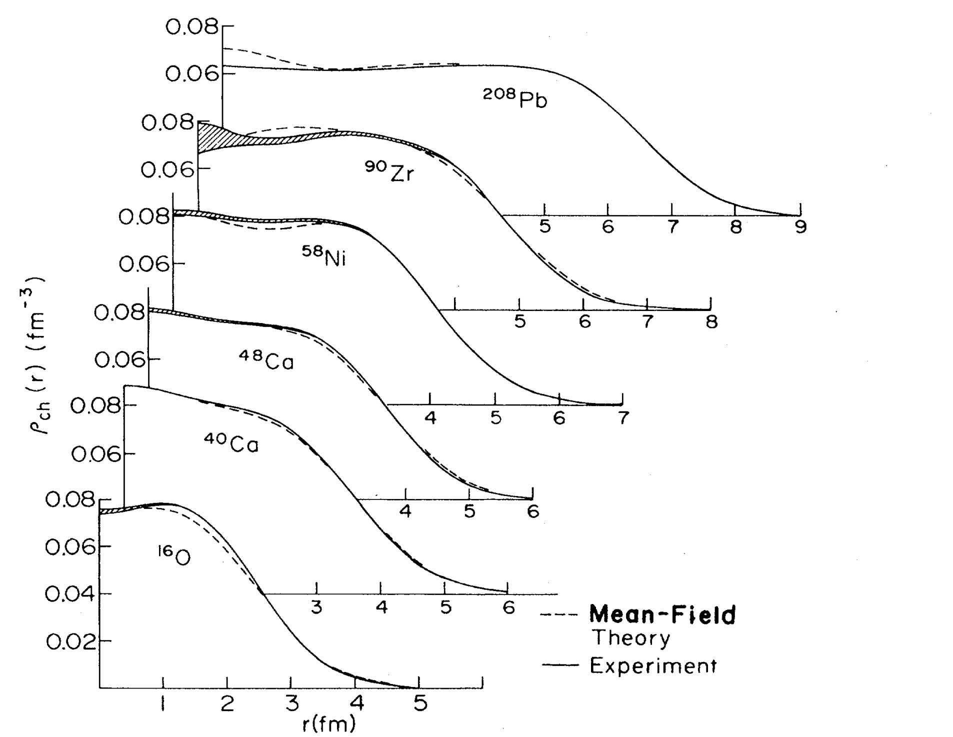
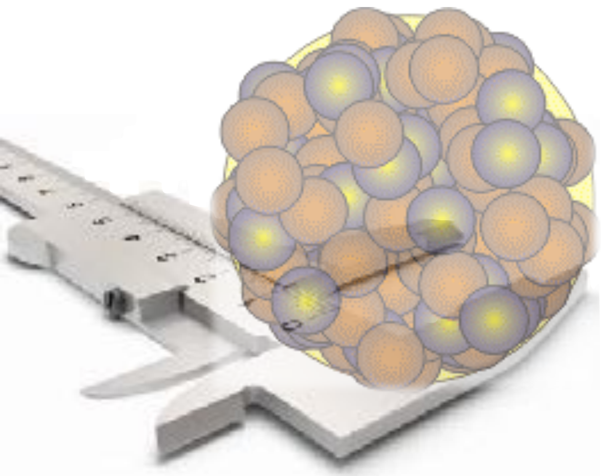
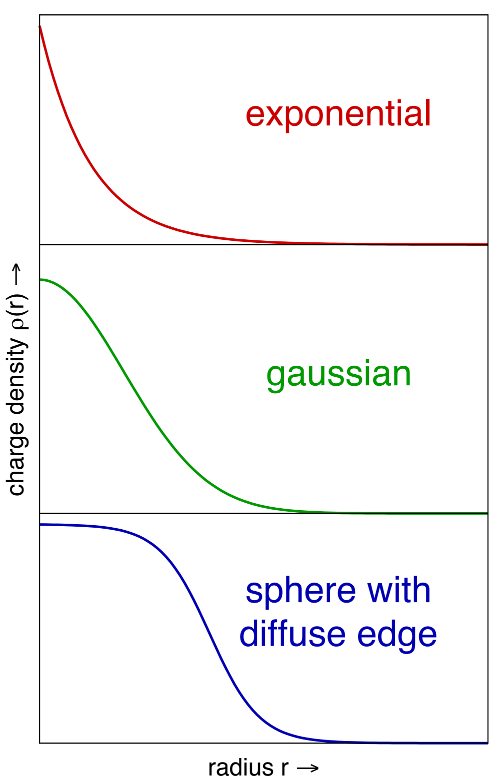



FIG. 11. Comparison of DME mean-field theory charge distributions in spherical nuclei (dashed lines) with empirical charge densities. The solid curves and shaded regions represent the error envelope of densities consistent with the measured cross sections and their experimental uncertainties.

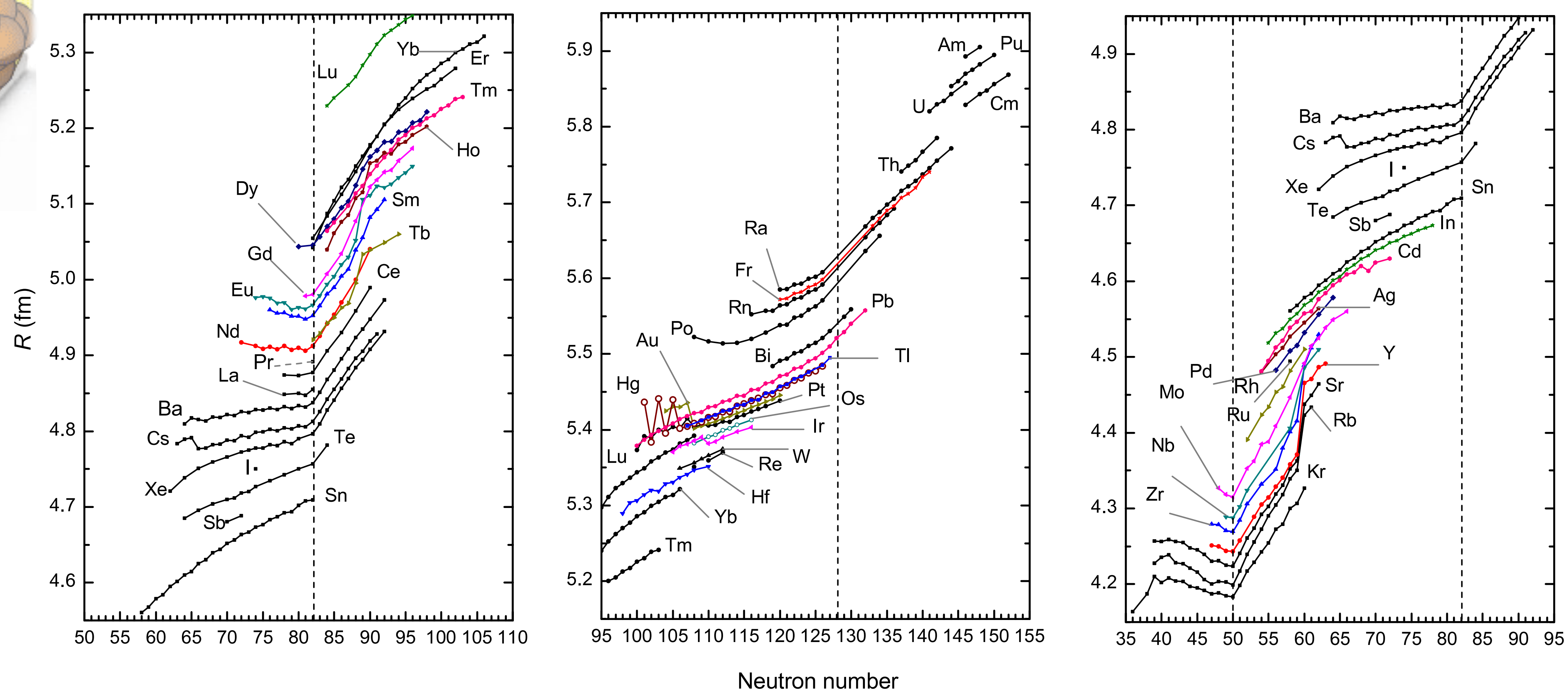
Rev. Mod. Phys., Vol. 54, No. 4, October 1982

# Nuclear Charge Radius





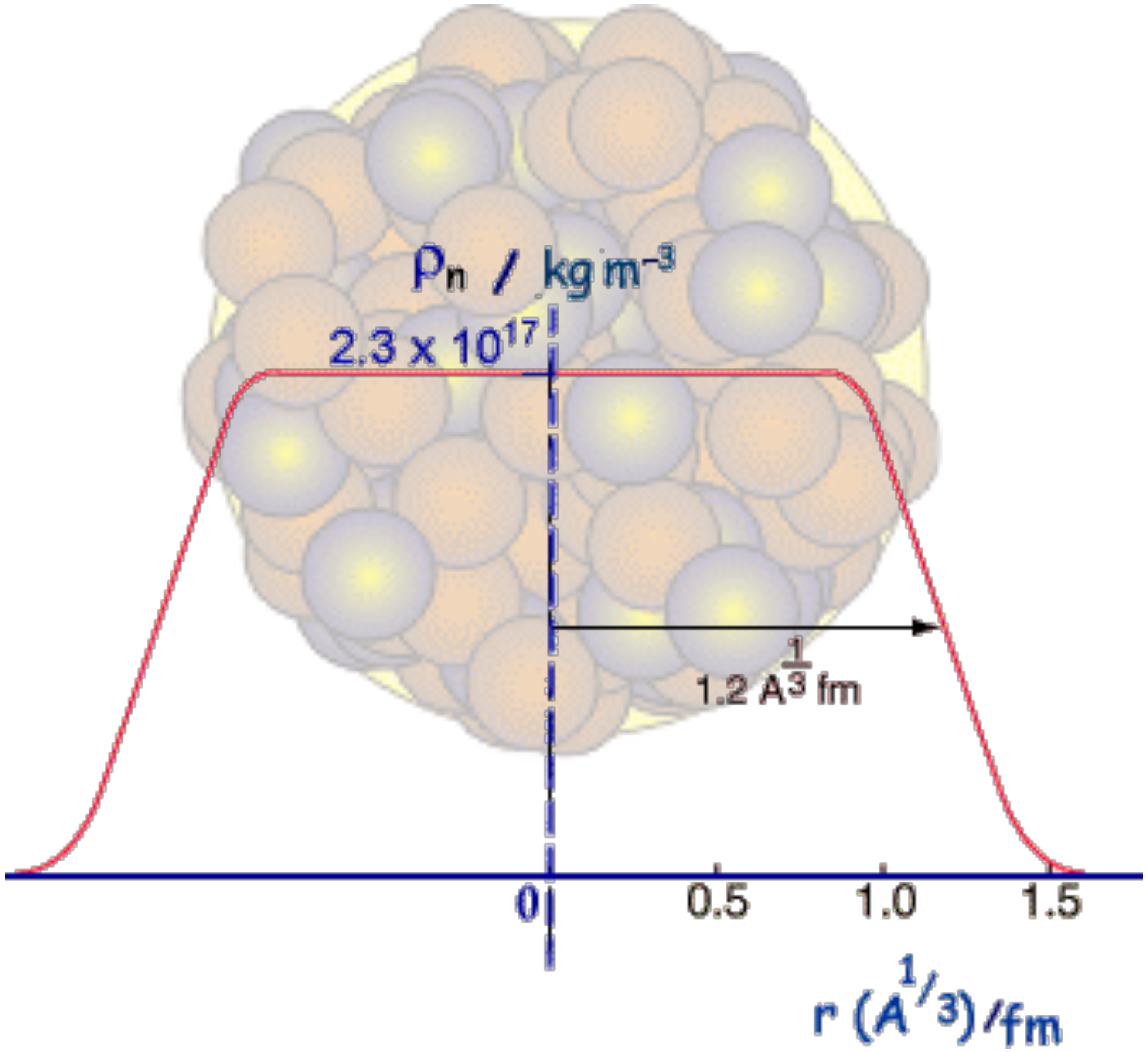

I. Angeli, K.P. Marinova / Atomic Data and Nuclear Data Tables 99 (2013) 69–95




- Kinks at closed neutron shells
- Regular odd-even staggering
- Obvious shape effects
- **Radii of isotopes increase at ~half rate of $1.2A^{1/3}$ !!!**

# Neutron Skin for Beginner

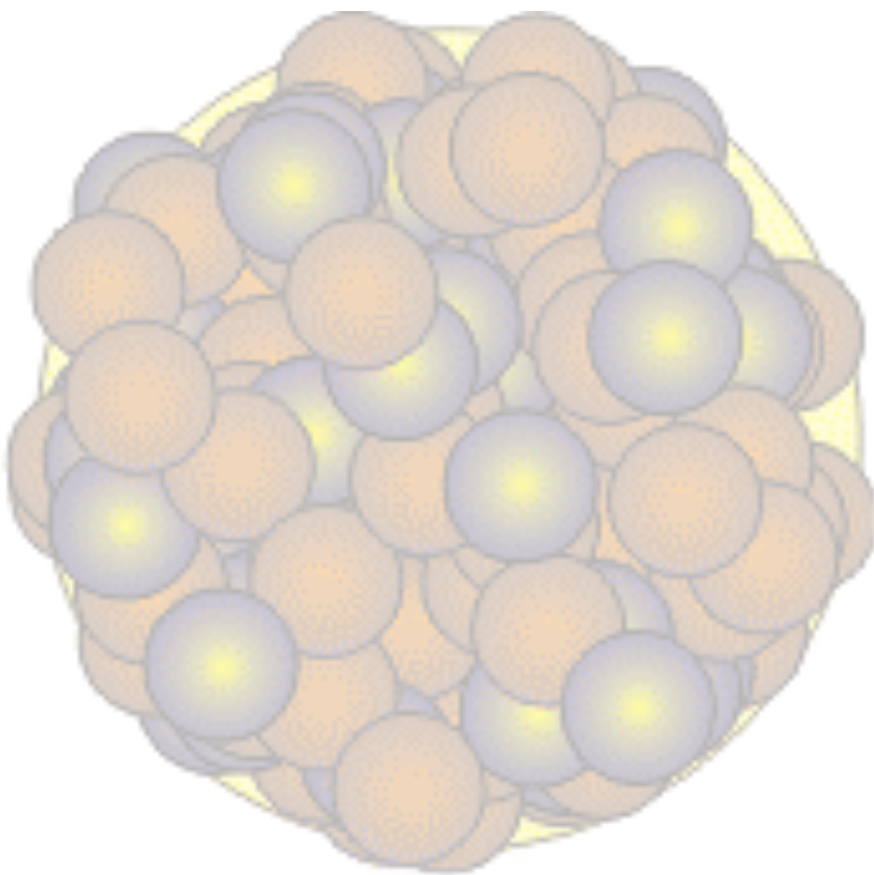
## Nuclear charge radii

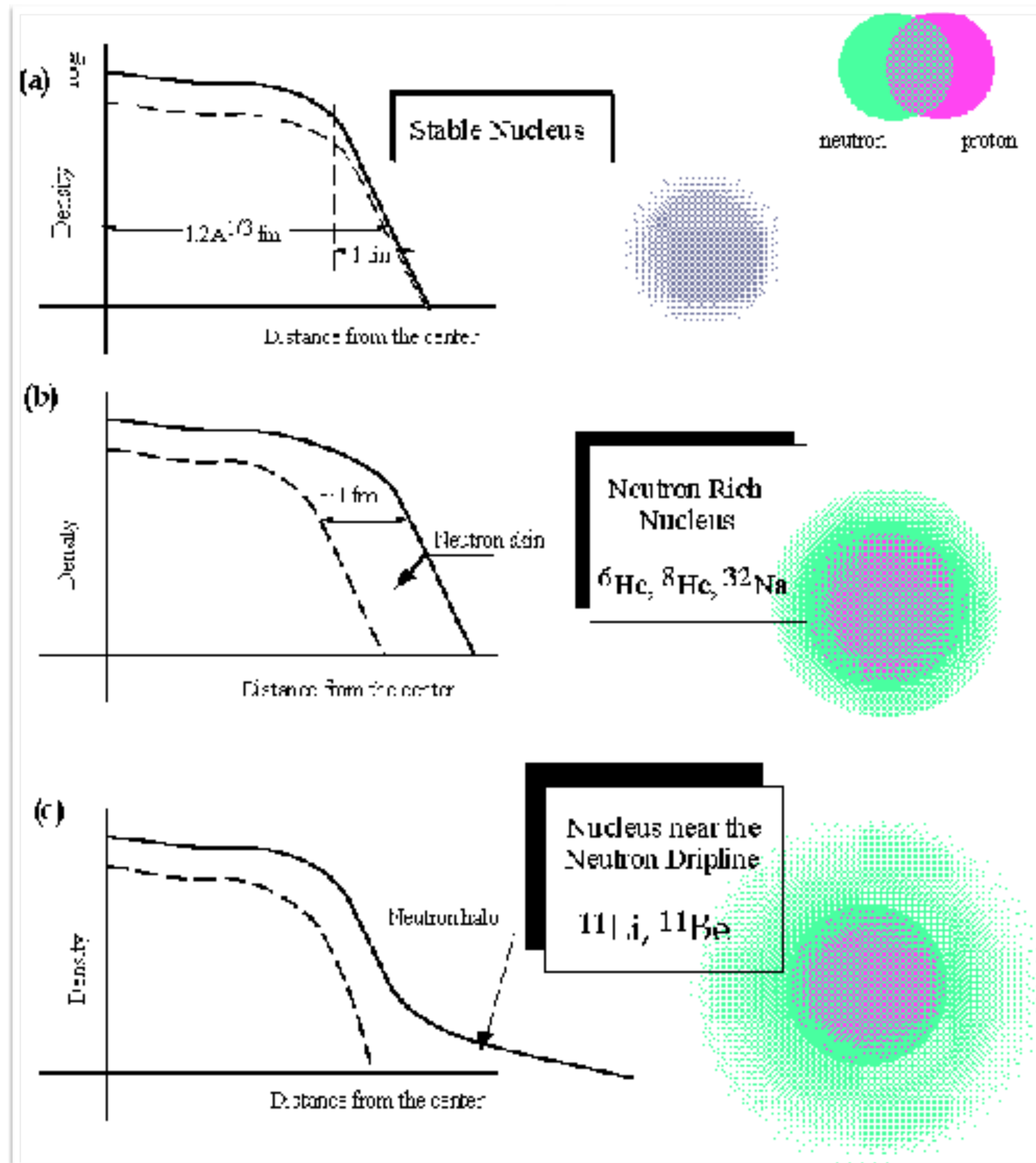



## Where do the neutrons go?

# Neutron Skin for Beginner

## Where do the neutrons go?



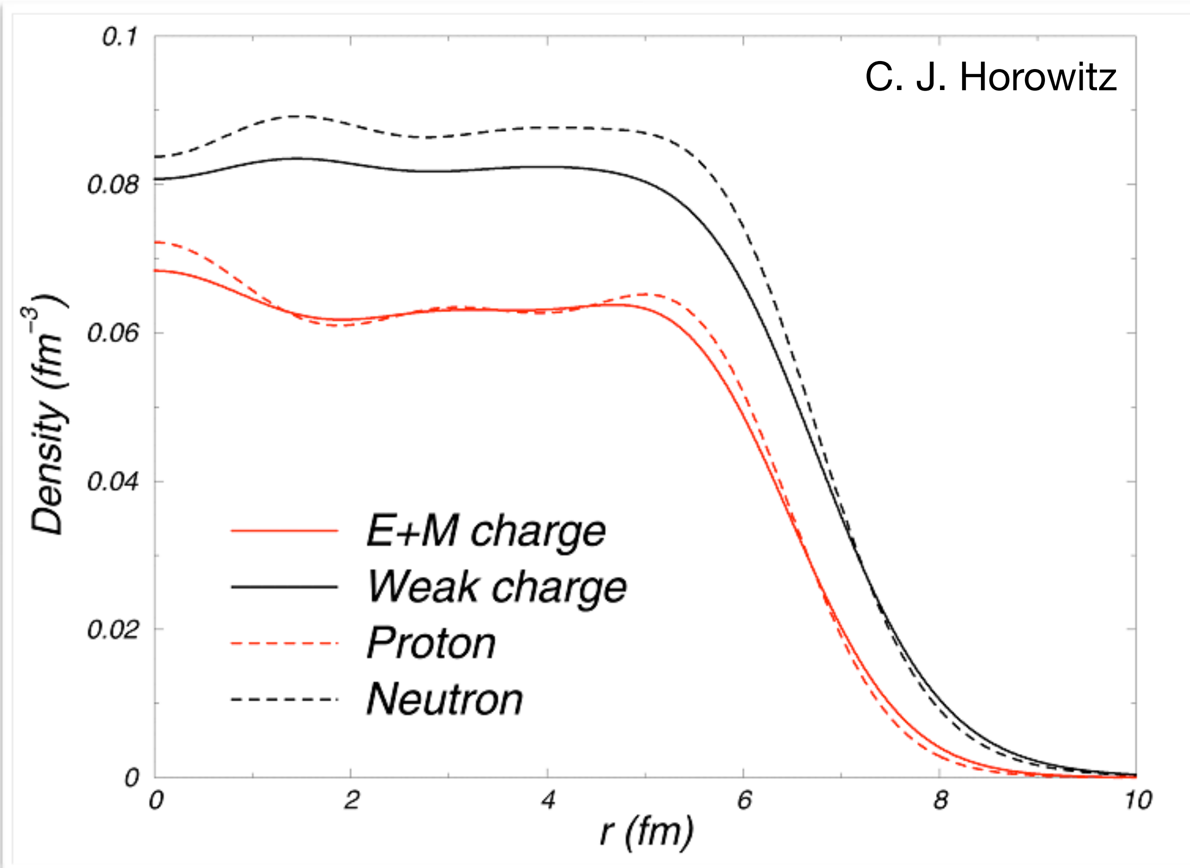


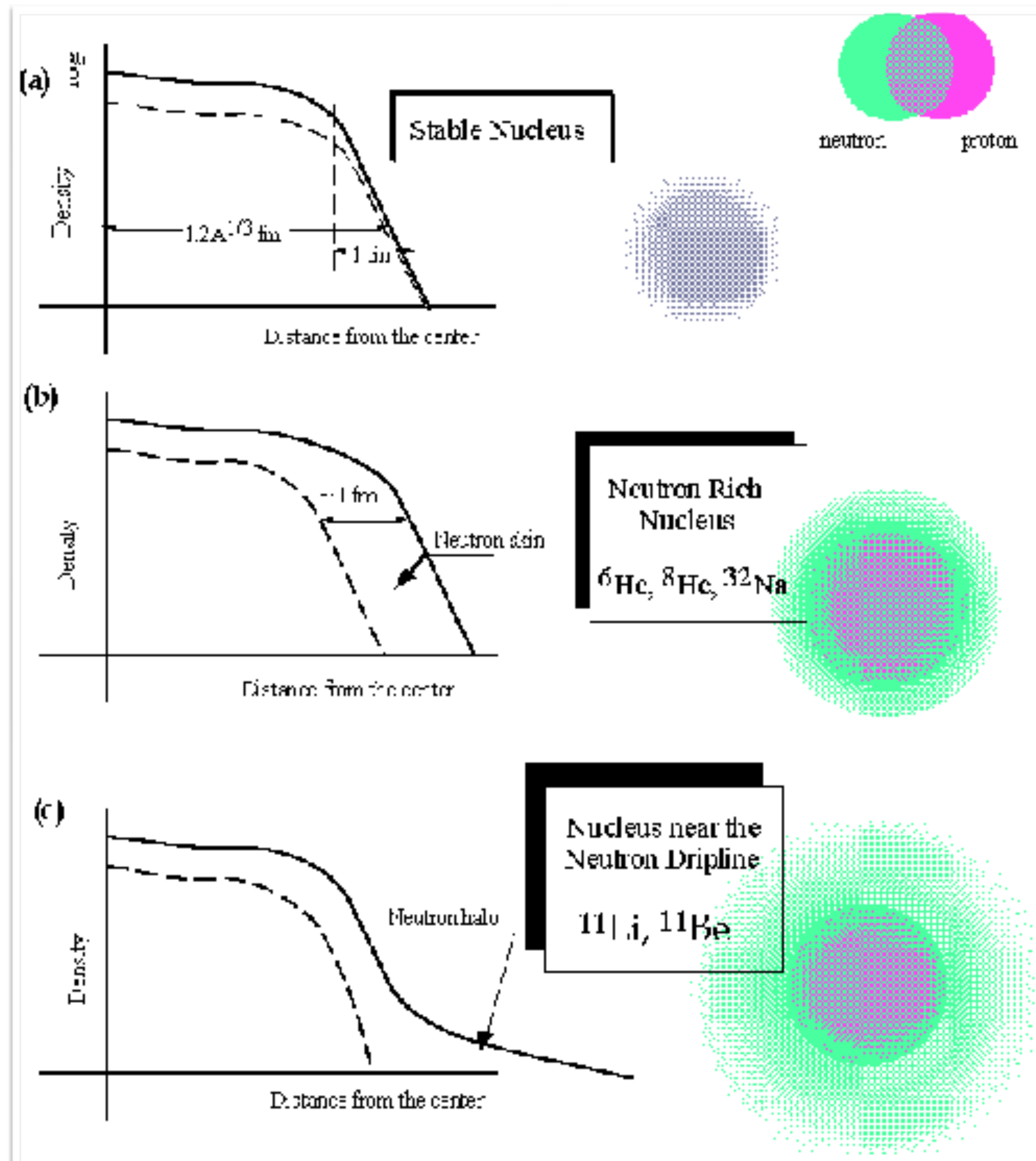

**Pressure forces neutrons out against surface tension**

**Neutron-rich nuclei develop a neutron skin**

# Neutron Skin for Beginner

## Measures how much neutrons stick out past protons

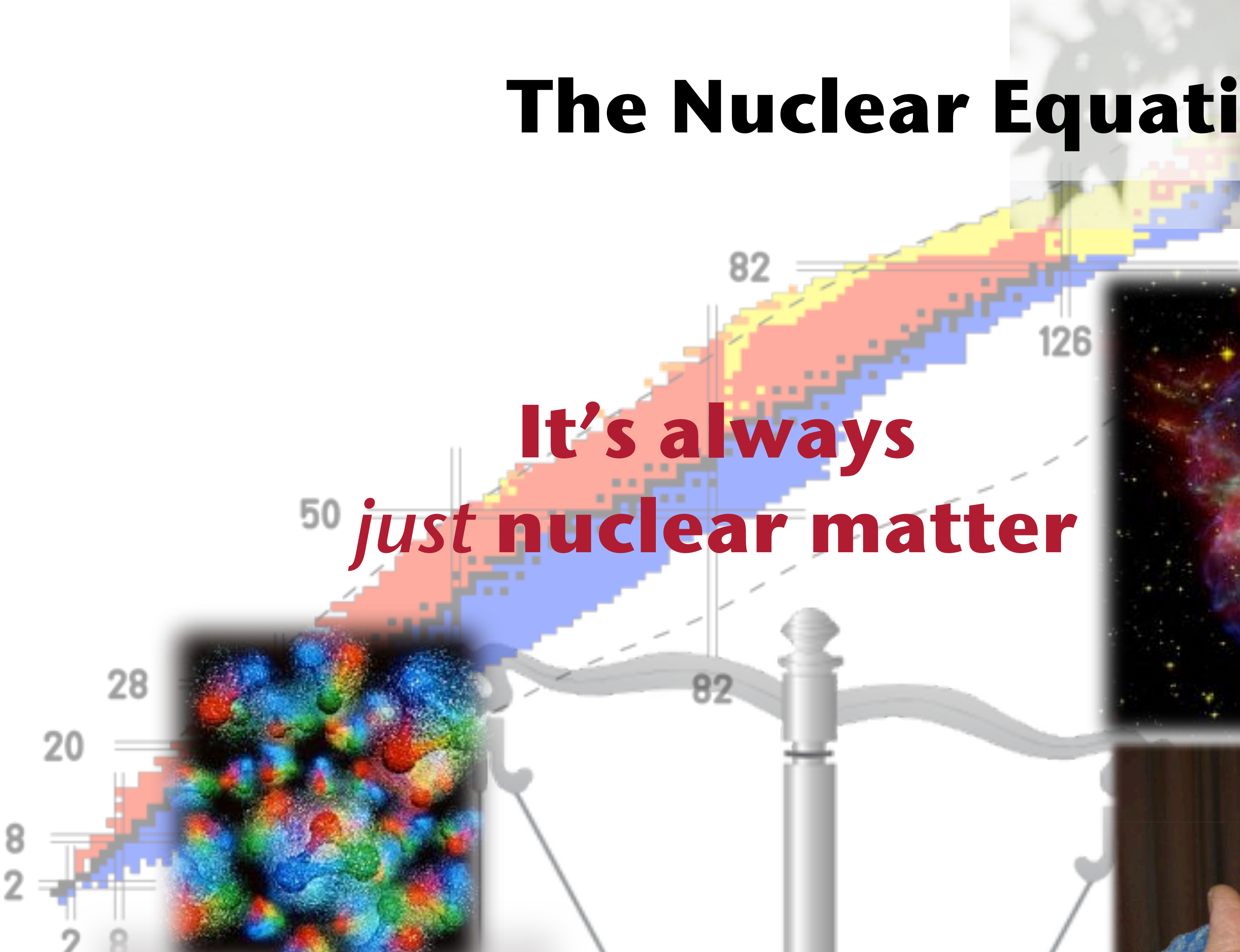


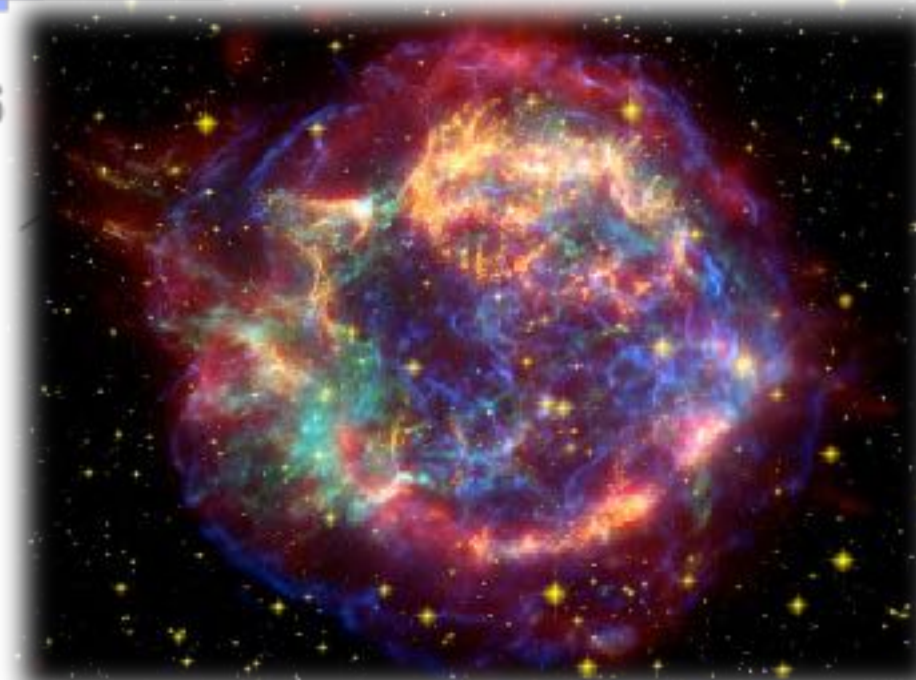

## Pressure forces neutrons out against surface tension

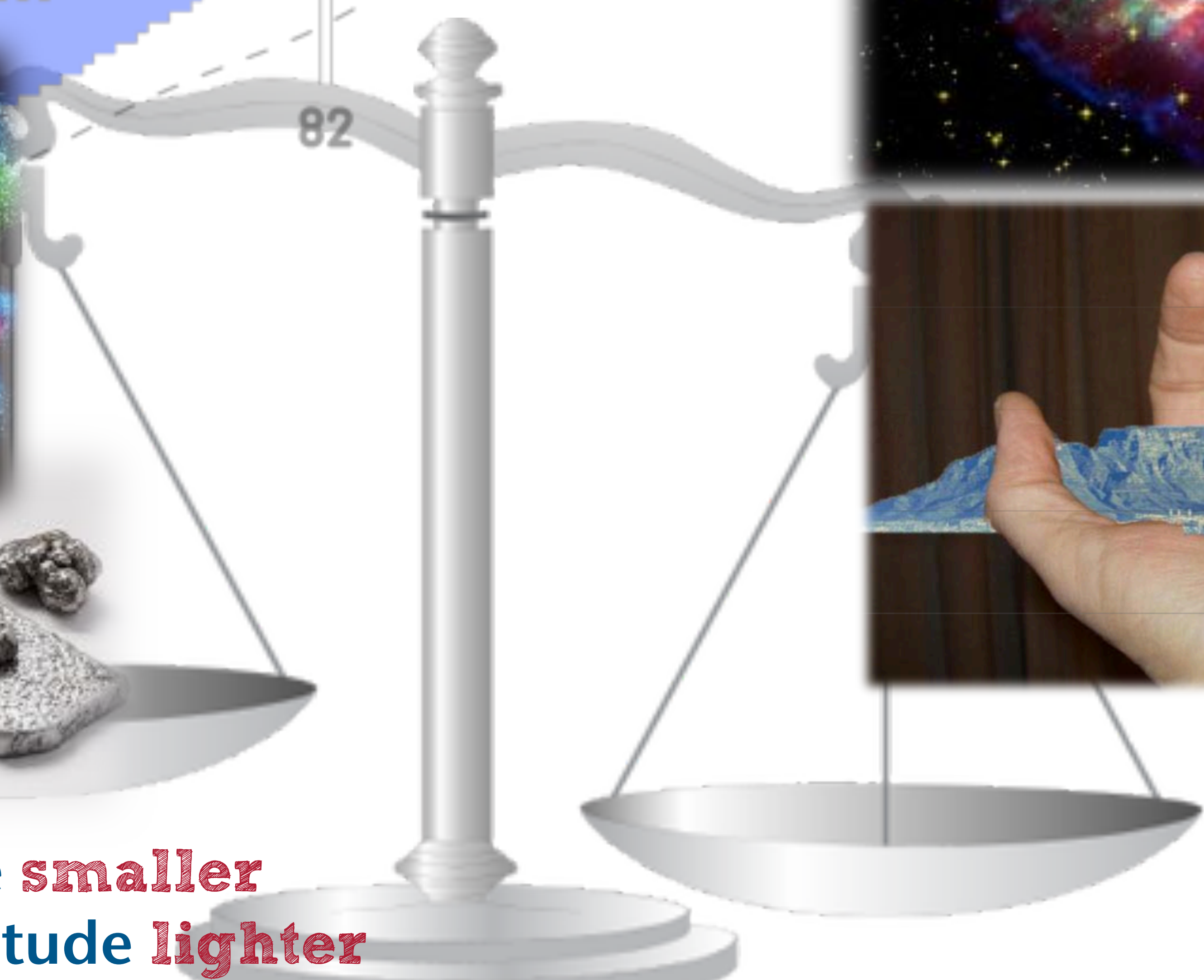
→ **EOS**

# The Nuclear Equation of State




**It's always**
***just* nuclear matter**



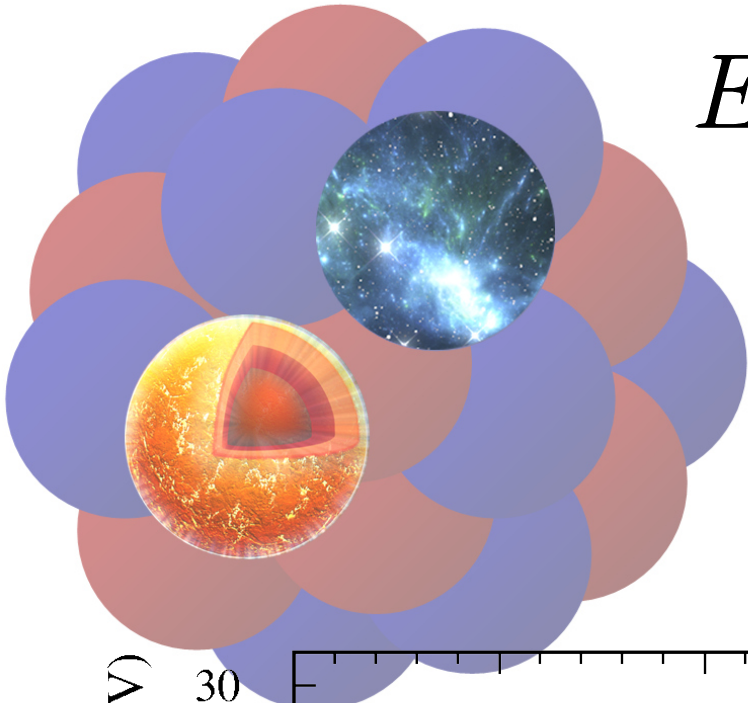


**18** orders of magnitude **smaller**
and **55** orders of magnitude **lighter**

CONCETTINASFIENTI

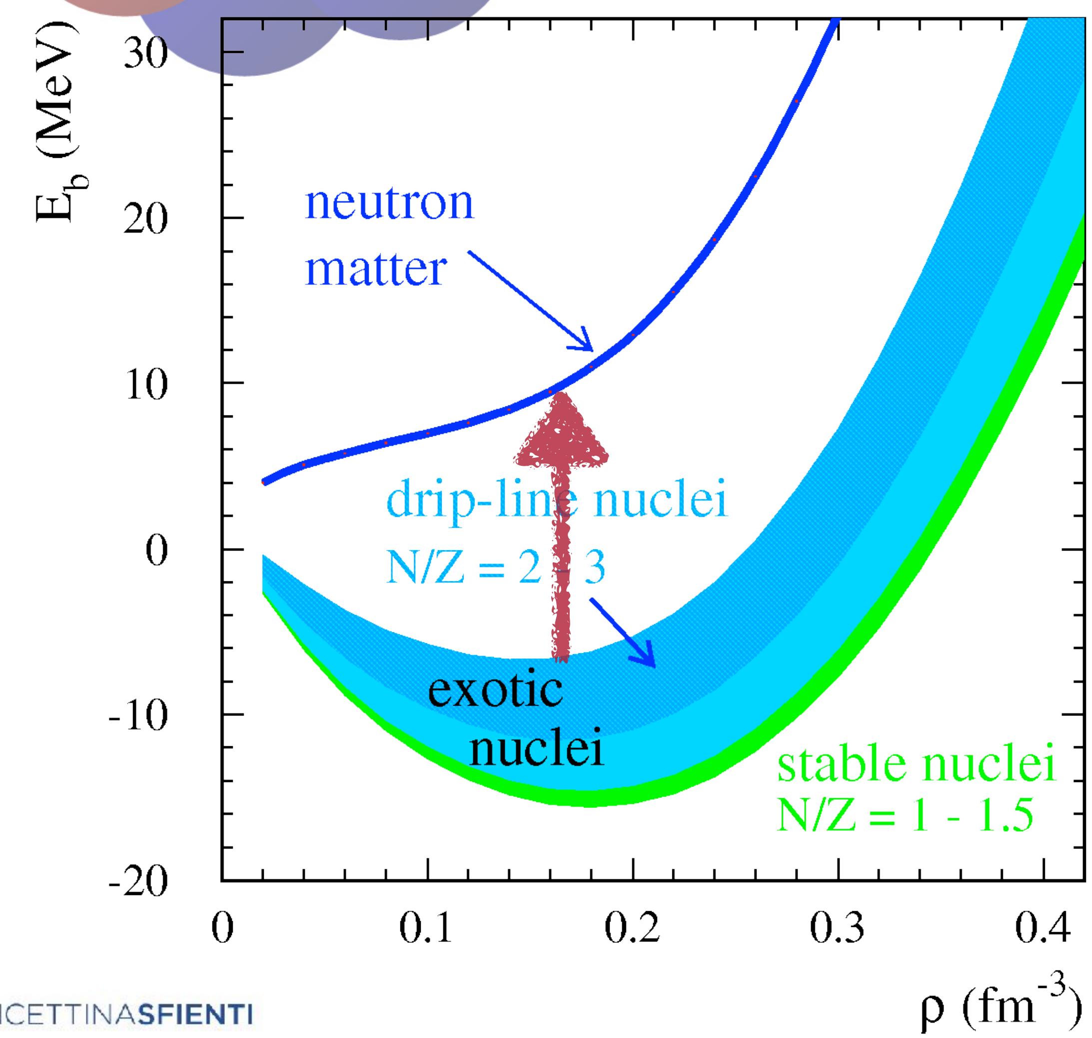
#MakeHumansSmartAgain

# The Search for the Nuclear Symmetry Energy

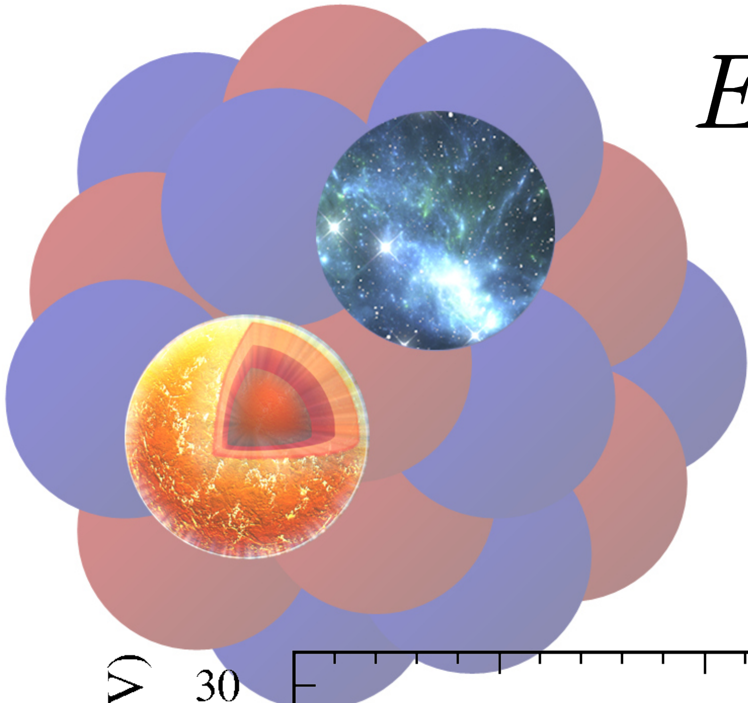


$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + \mathcal{O}(\delta)^4$$

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



# The Search for the Nuclear Symmetry Energy



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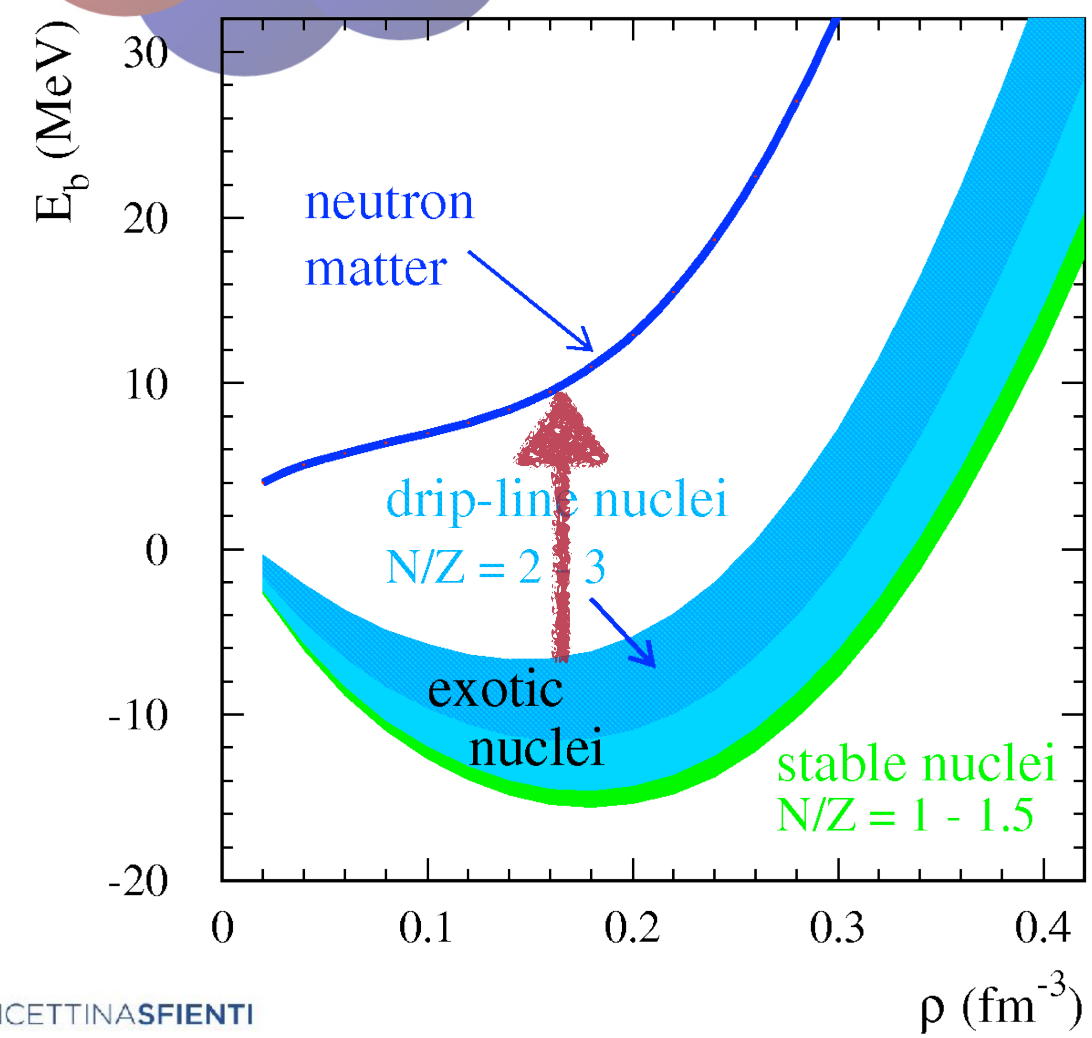


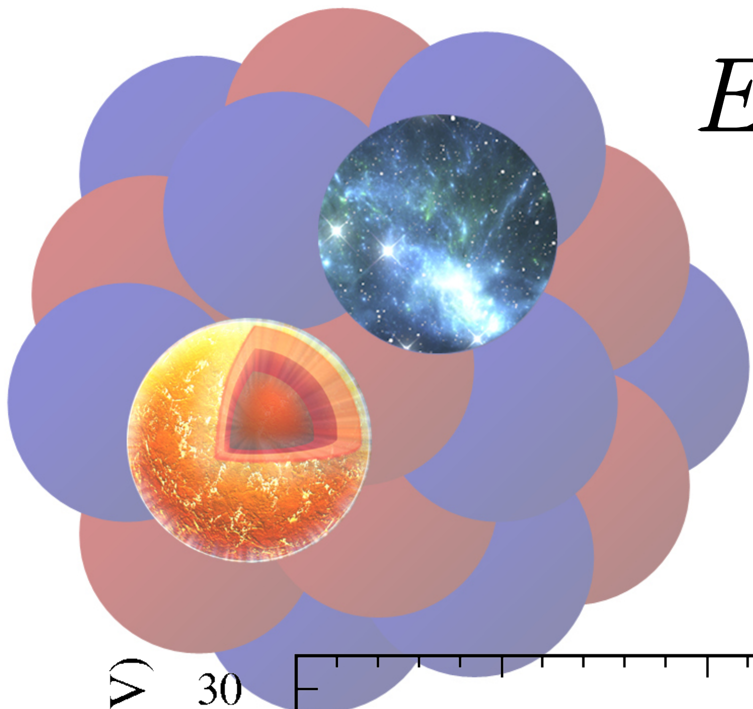

**slope parameter**

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

**curvature parameter**

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

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



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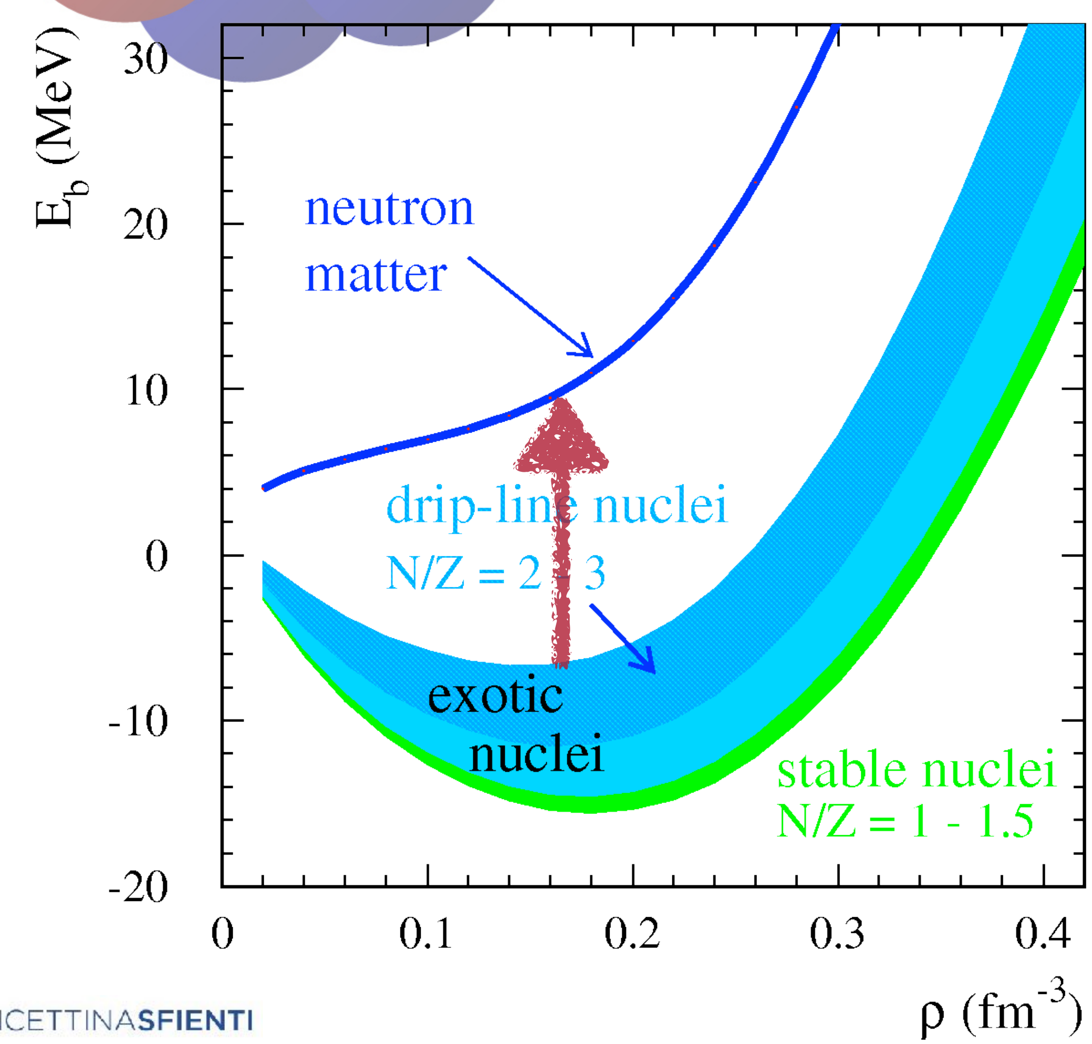


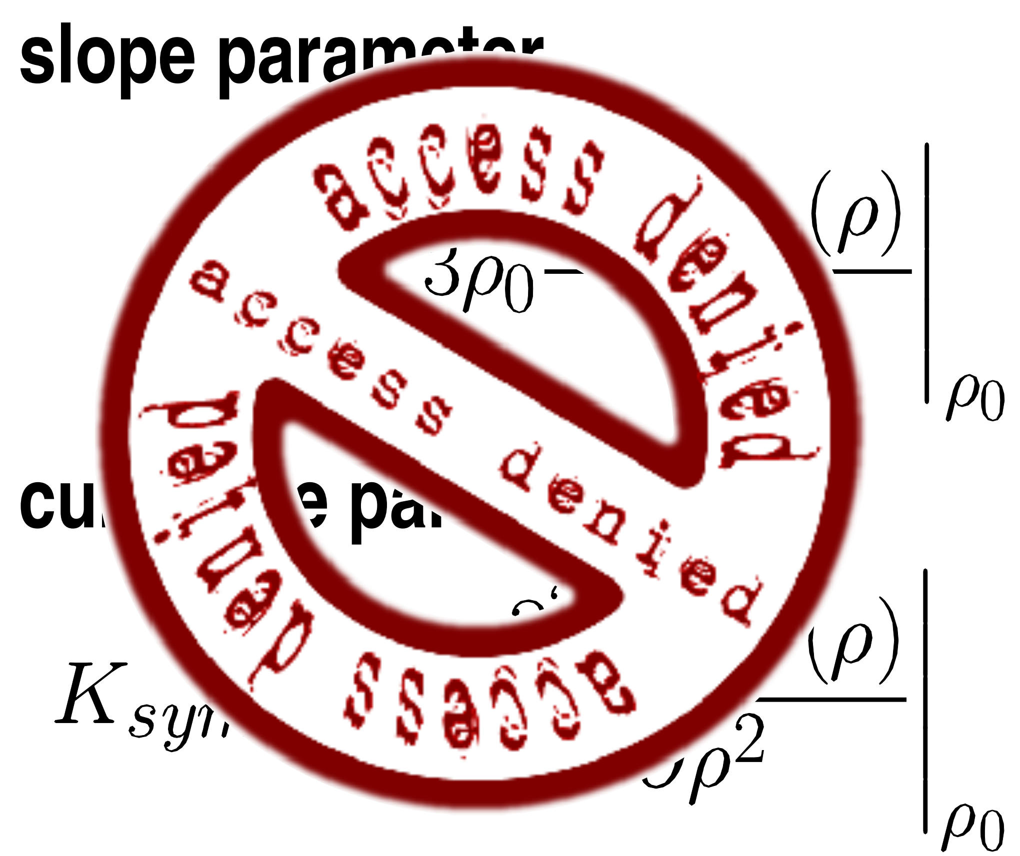

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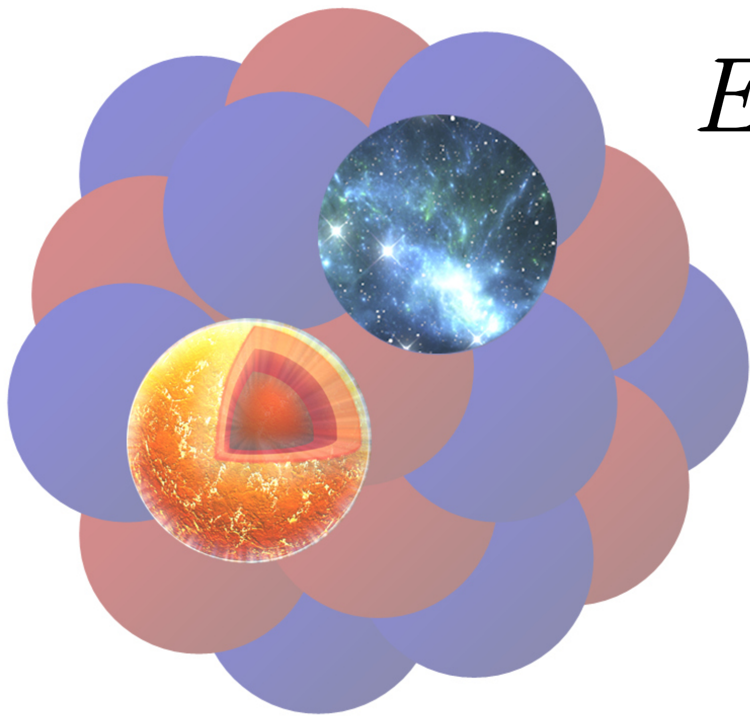

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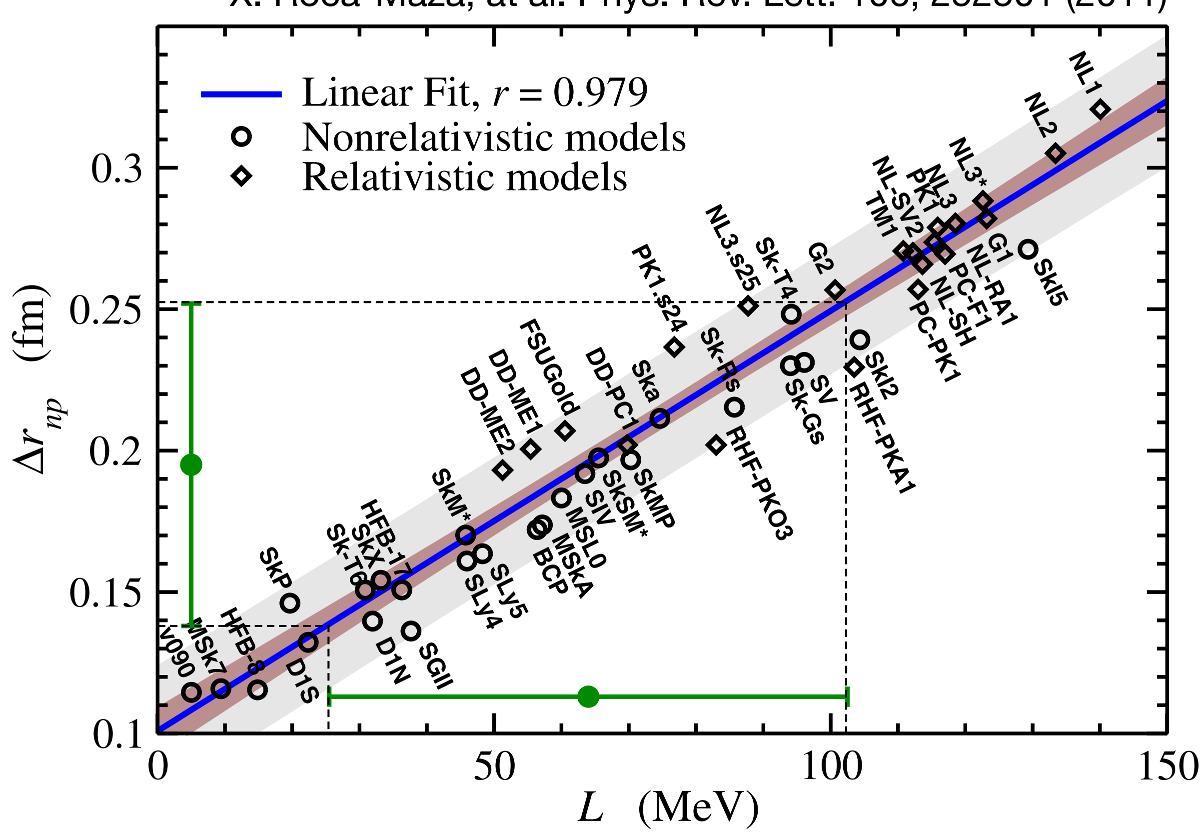
X. Roca-Maza, at al. Phys. Rev. Lett. 106, 252501 (2011)

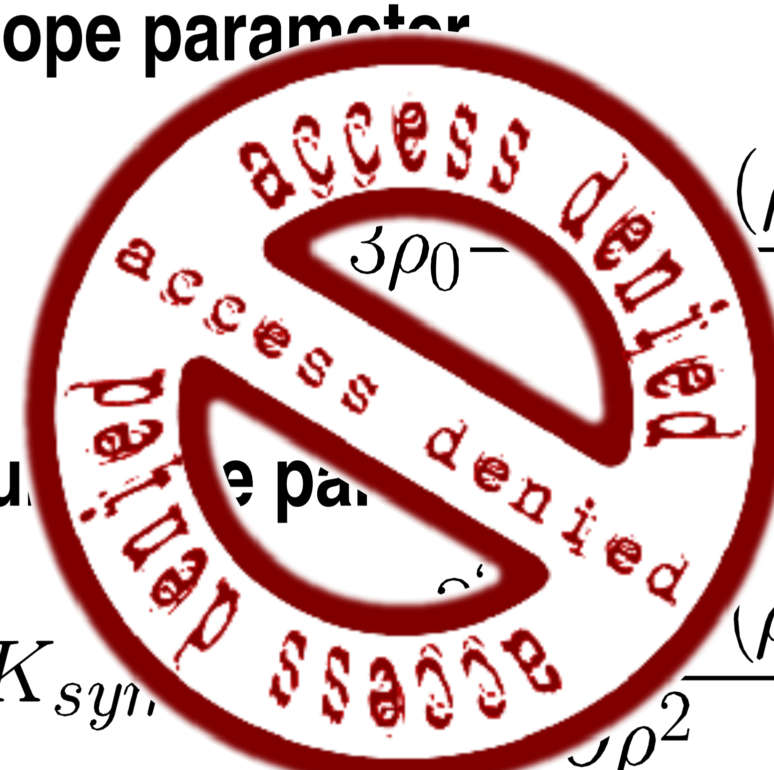



slope paramet

$3\rho_0$ … $(\rho)\Big|_{\rho_0}$

cu… e pa…

$K_{sy}$ … $\partial\rho^2$ … $(\rho)\Big|_{\rho_0}$



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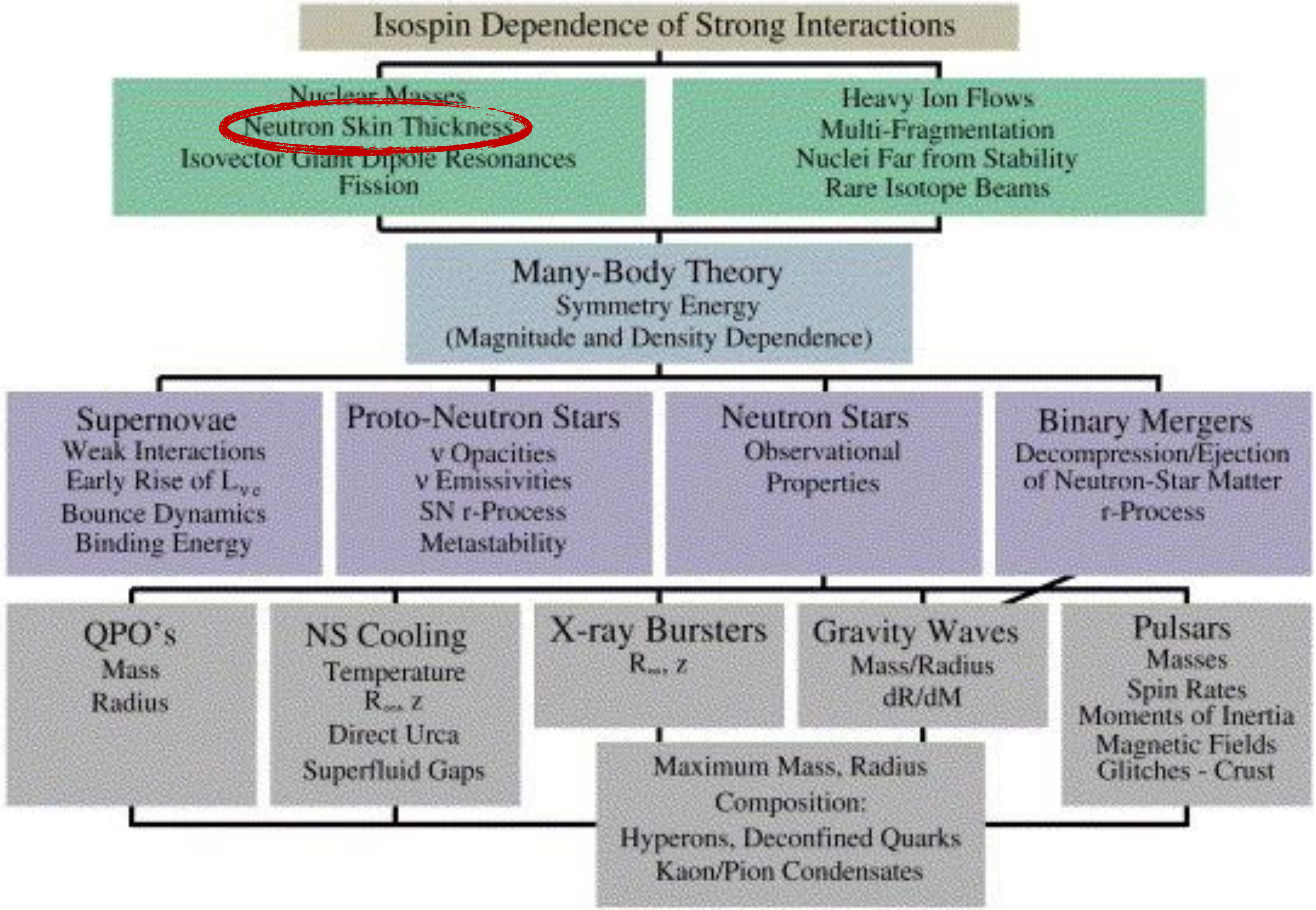
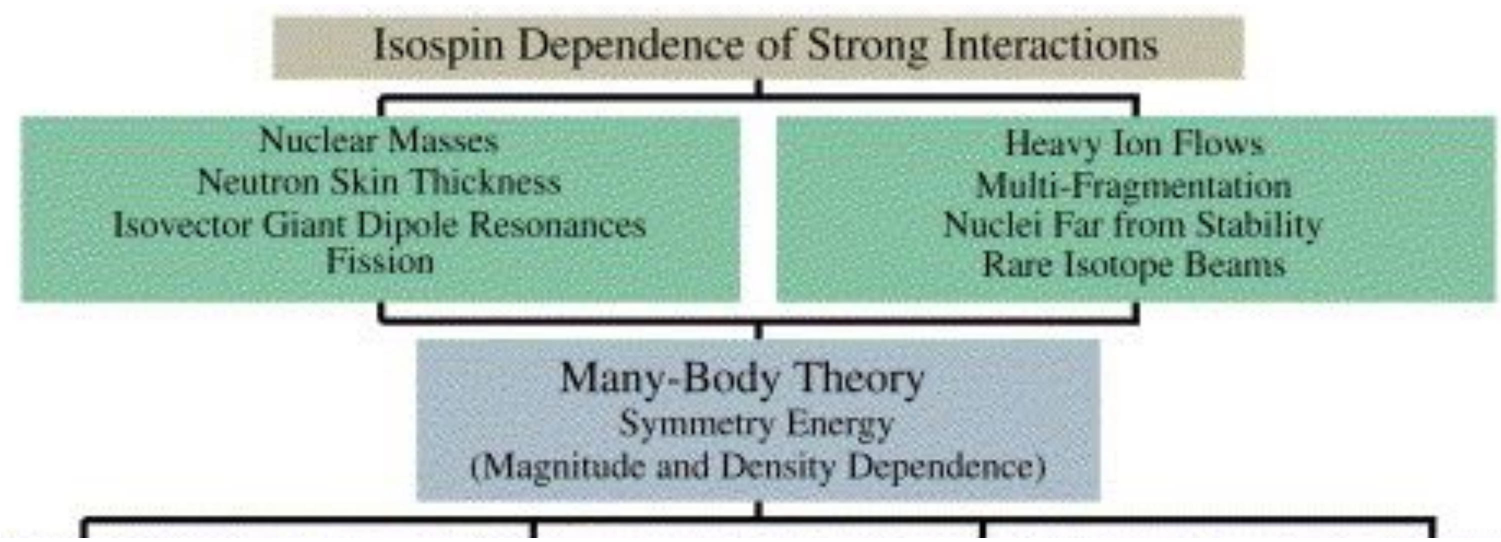
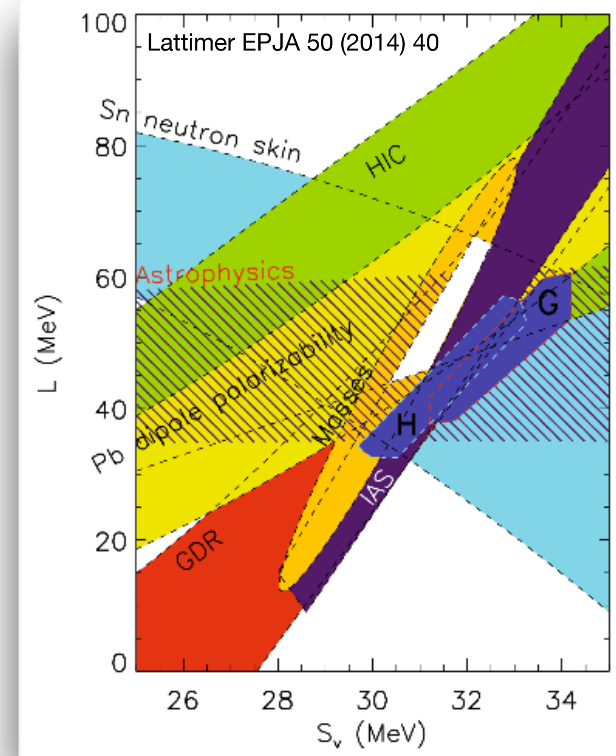



A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, Physics Reports, 411 (2005) 325

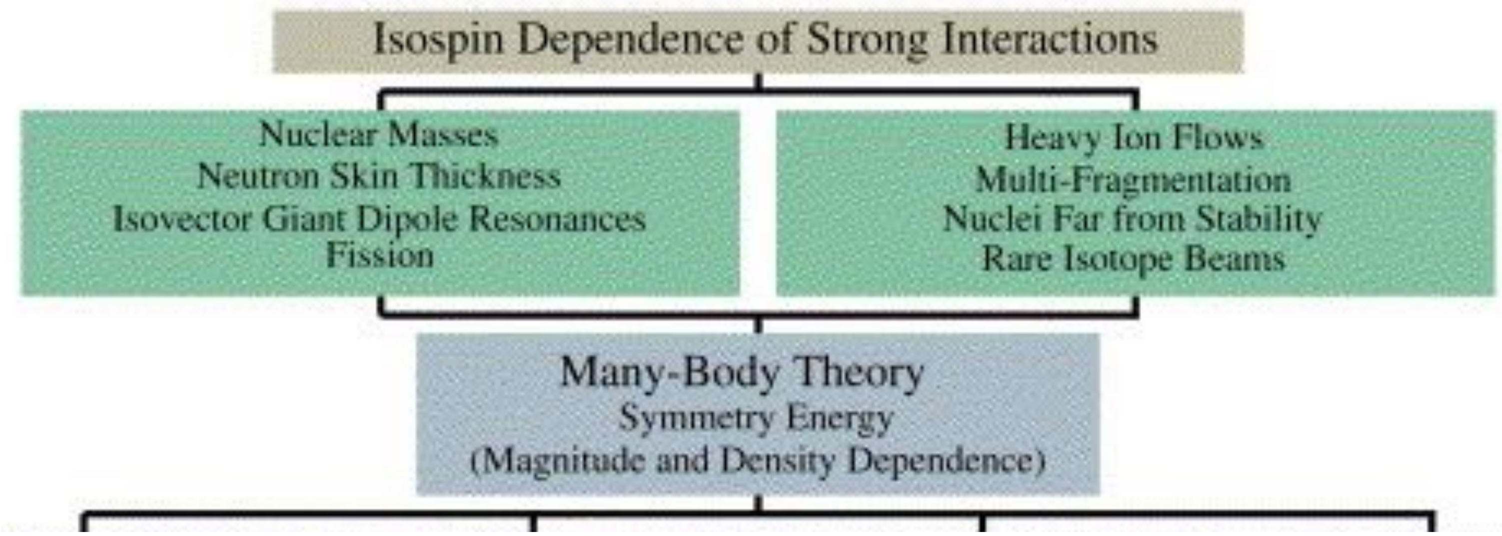
# …the (blind!?) search for the Nuclear Symmetry Energy

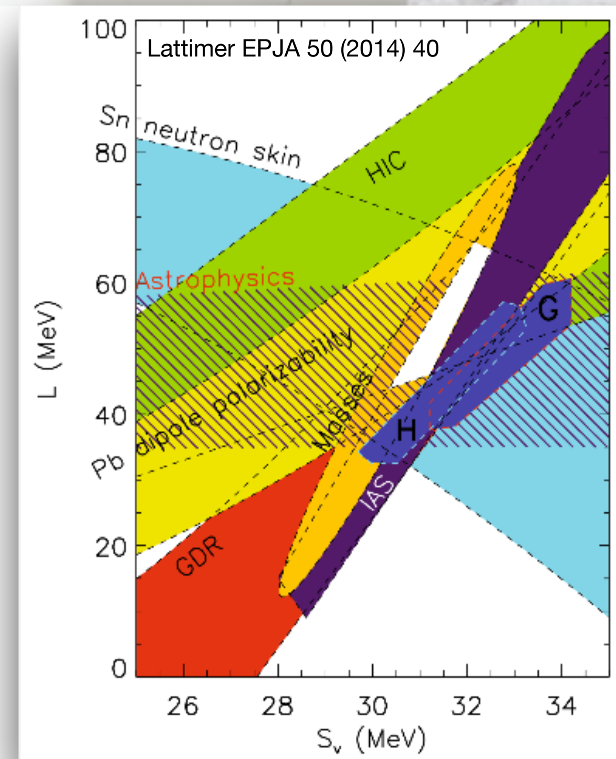



## Observable + Model = $S_v$,L

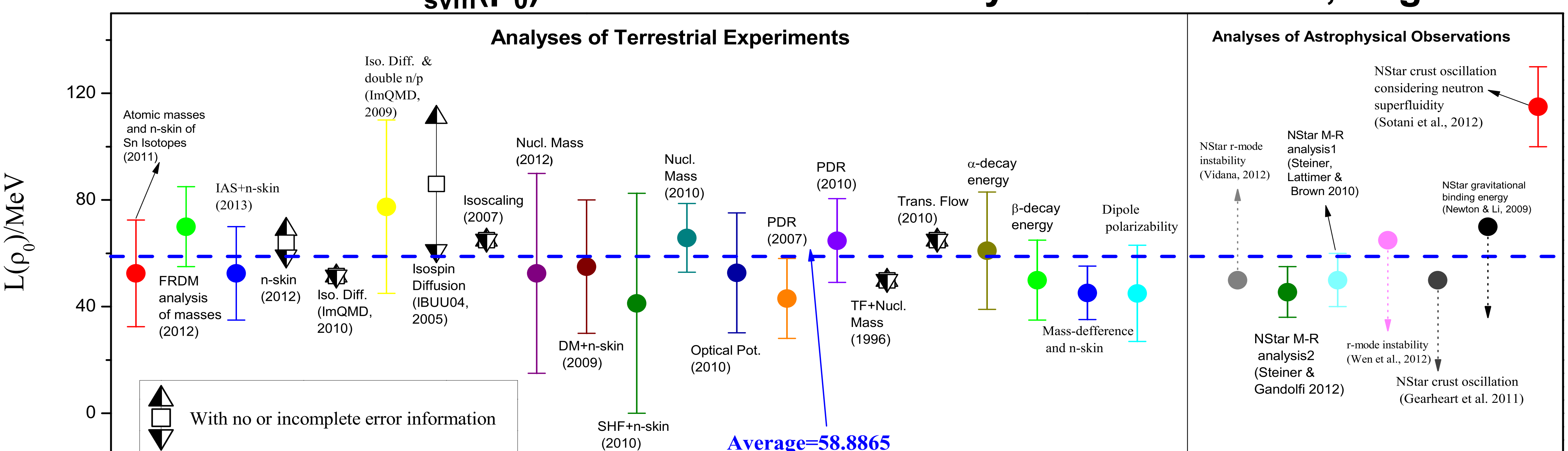
# ...the (blind!?) search for the Nuclear Symmetry Energy



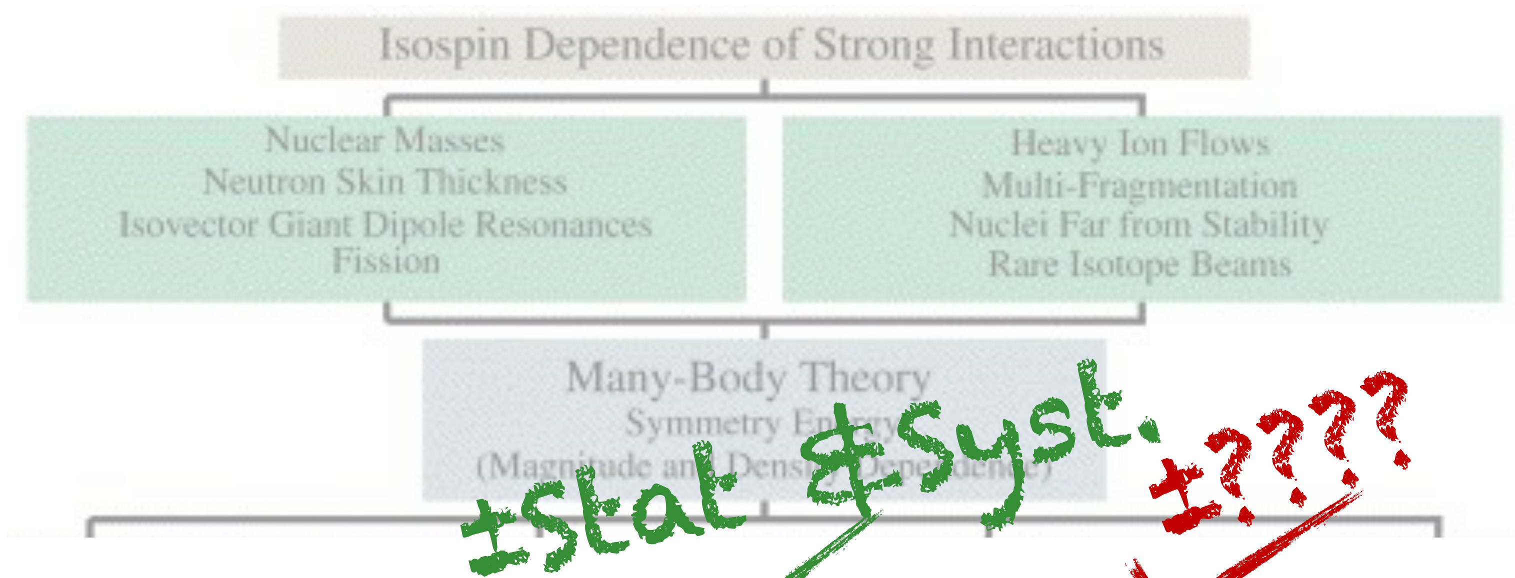

## Observable + Model = $S_v$,L

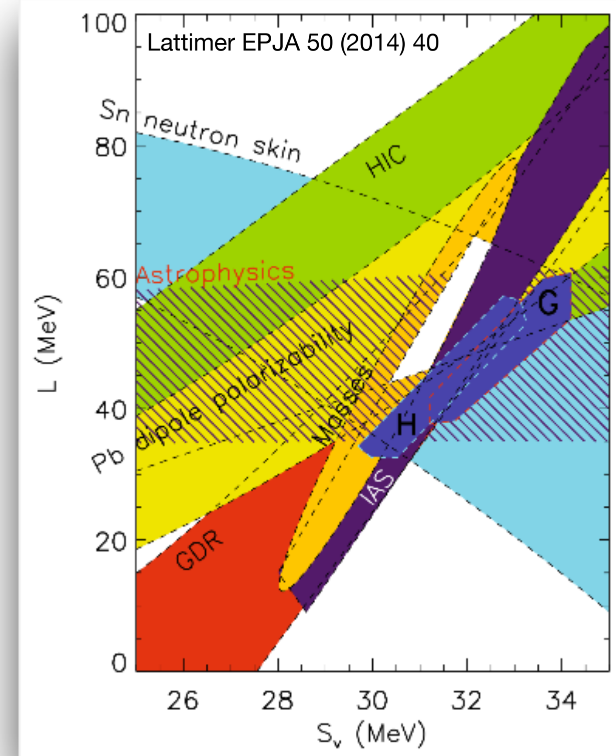
### Constraints on $E_{sym}(\rho_0)$ and L based on 29 analyses of some data, Aug. 2013




Li and Han, PLB 727 (2013)

# …the (blind!?) search for the Nuclear Symmetry Energy

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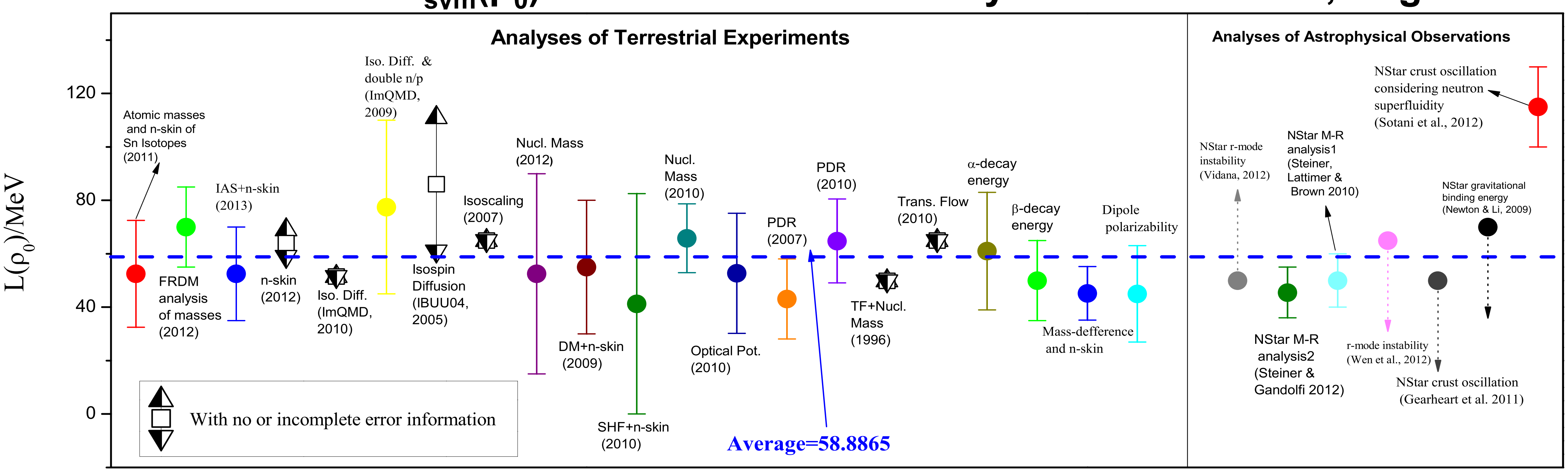


Li and Han, PLB 727 (2013)

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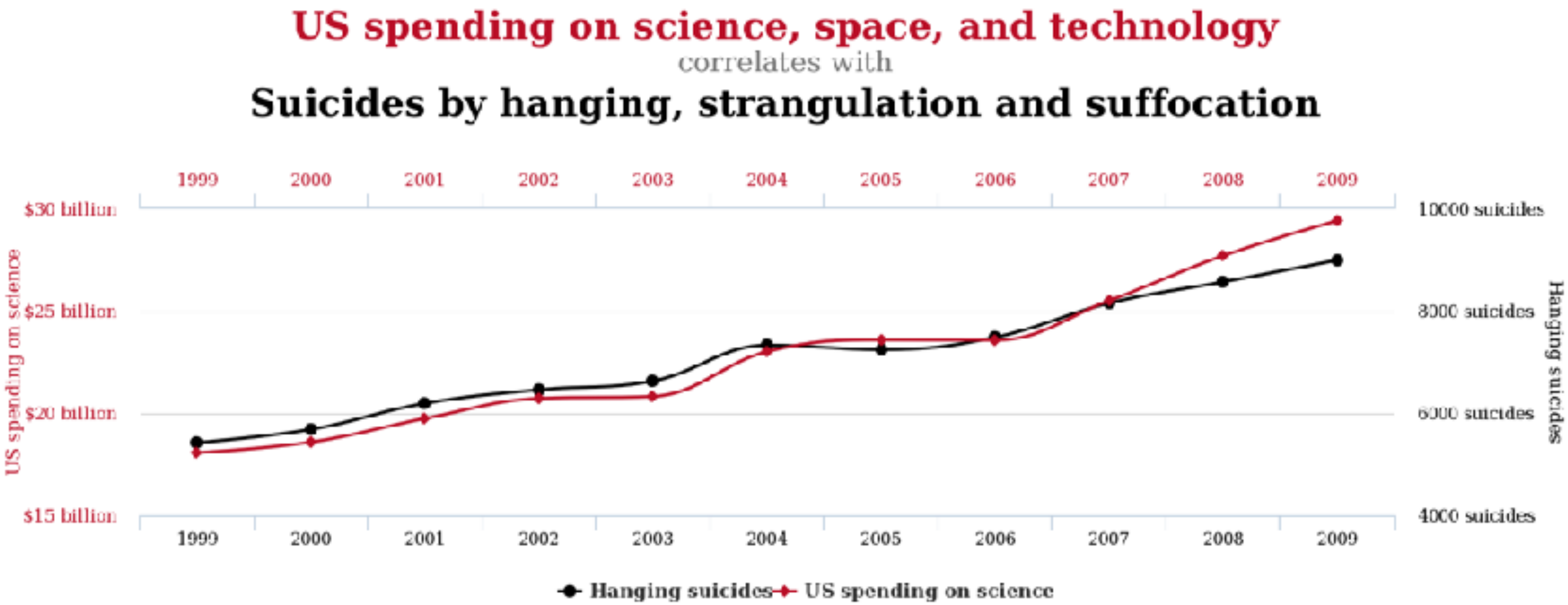
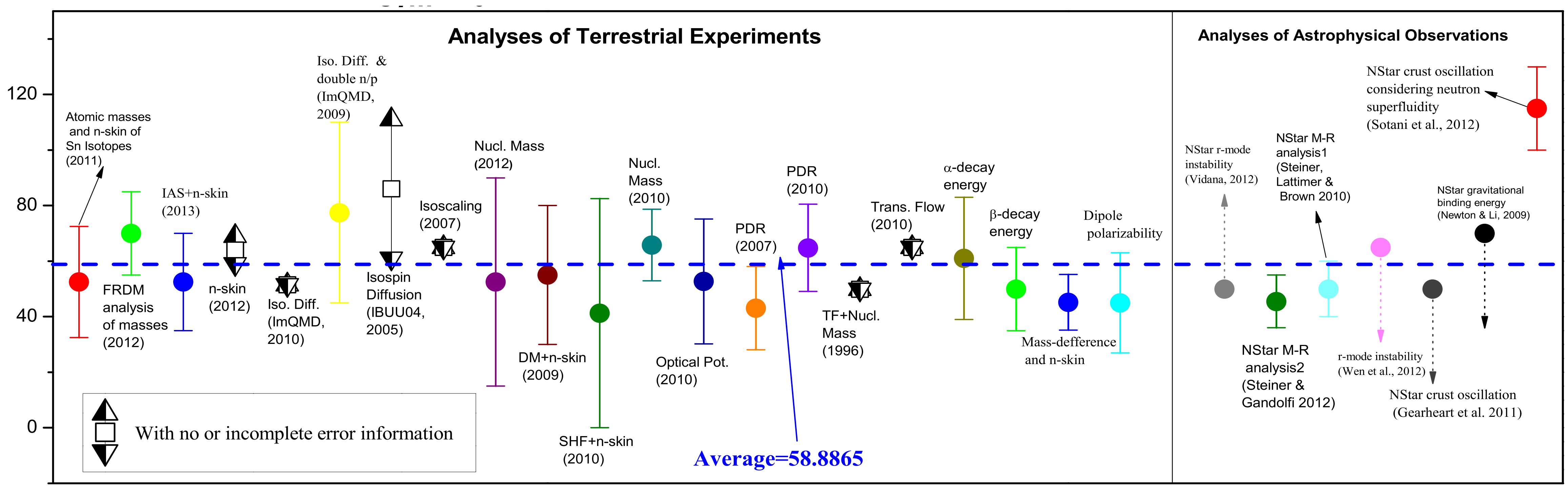
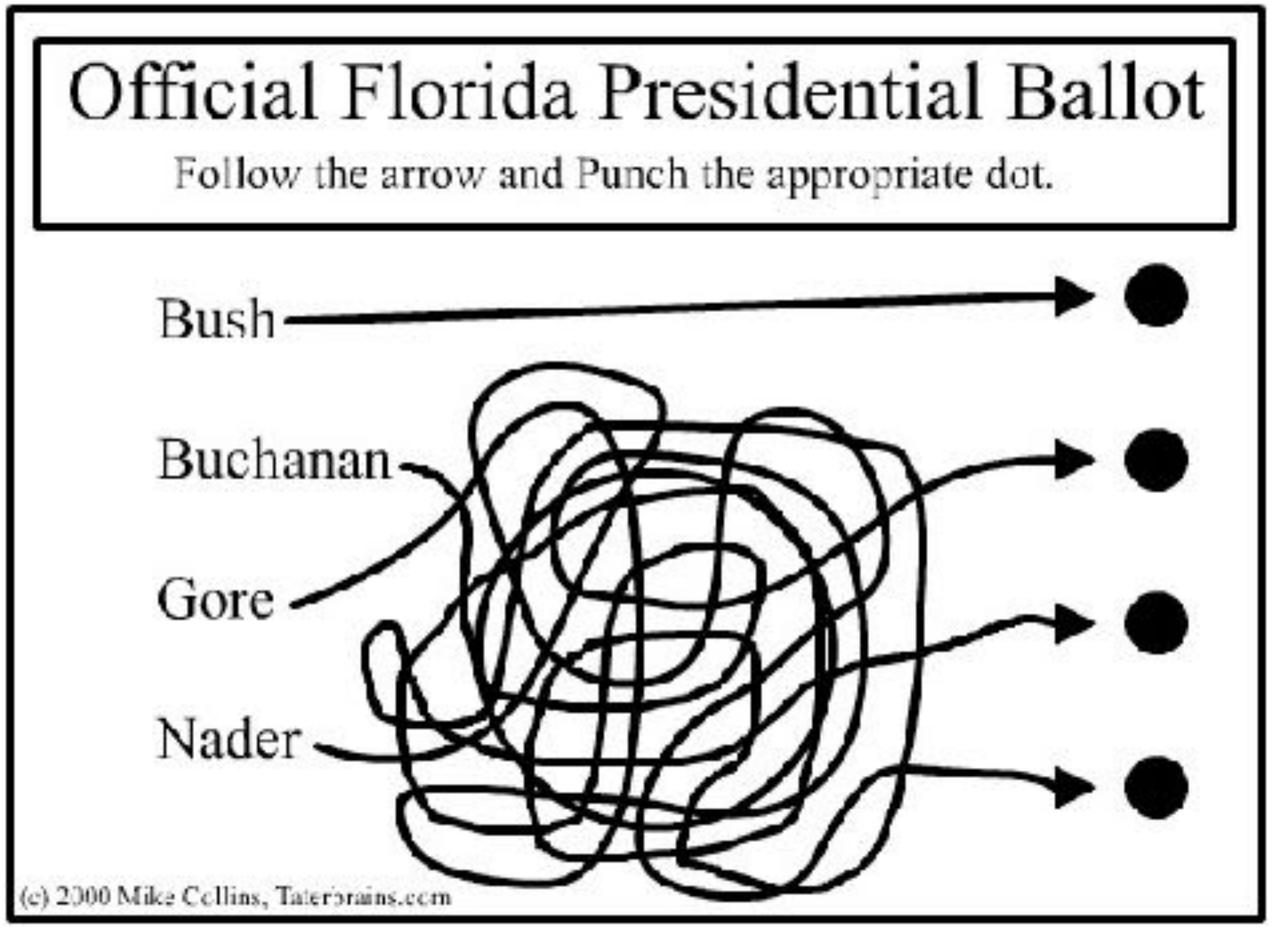



Li and Han, PLB 727 (2013)

# The long winding road ....




## ...FROM MEASURABLE OBSERVABLES TO THE NEUTRON SKIN

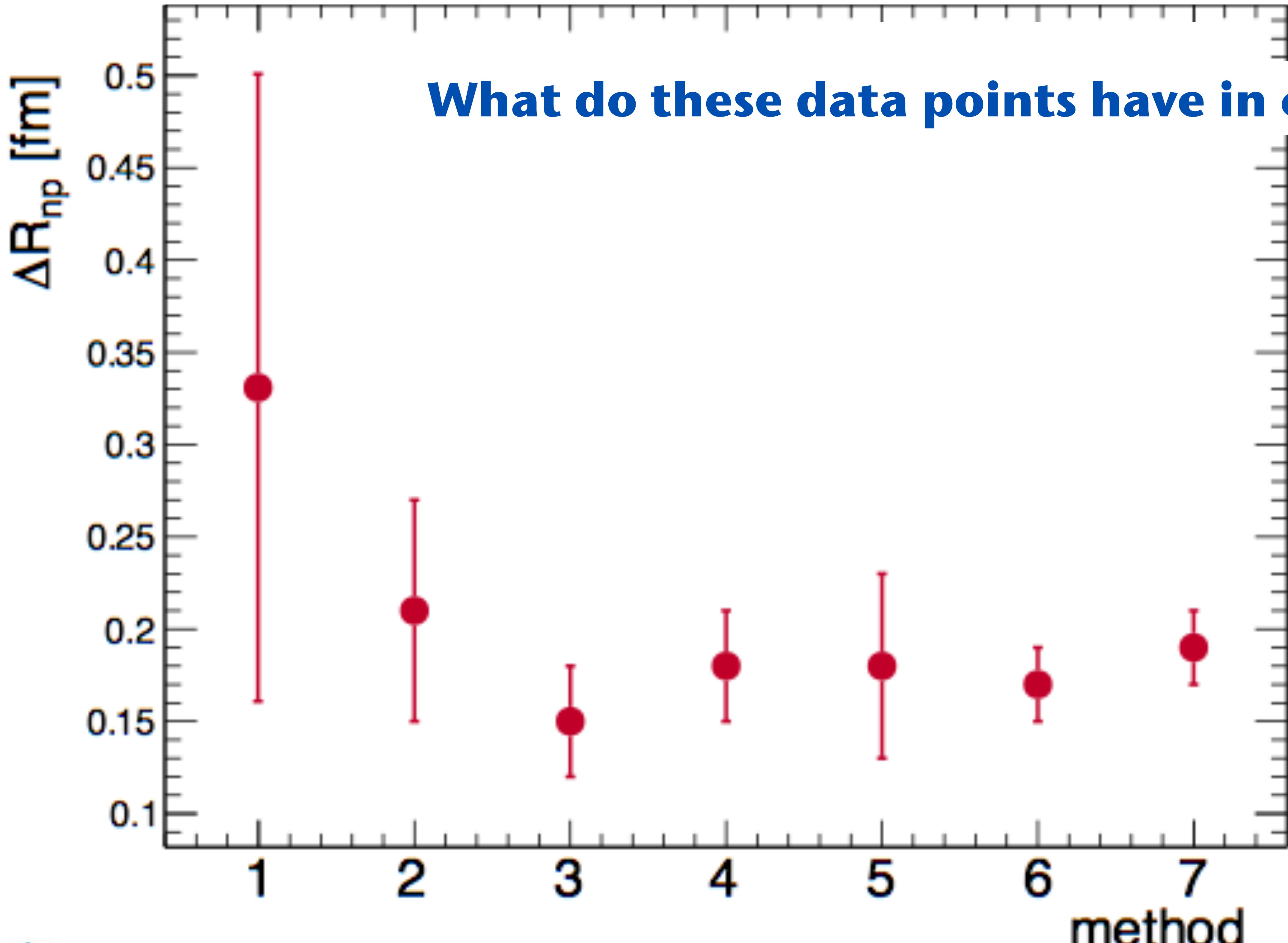
- **What is actually measured?**
  Cross section, asymmetry, spin observables, …

- **How is the measured observable connected to the neutron skin?**
- **What are the assumptions implicit in making this connection?**
  Impulse approximation, off-shell ambiguities, distortion effects, …

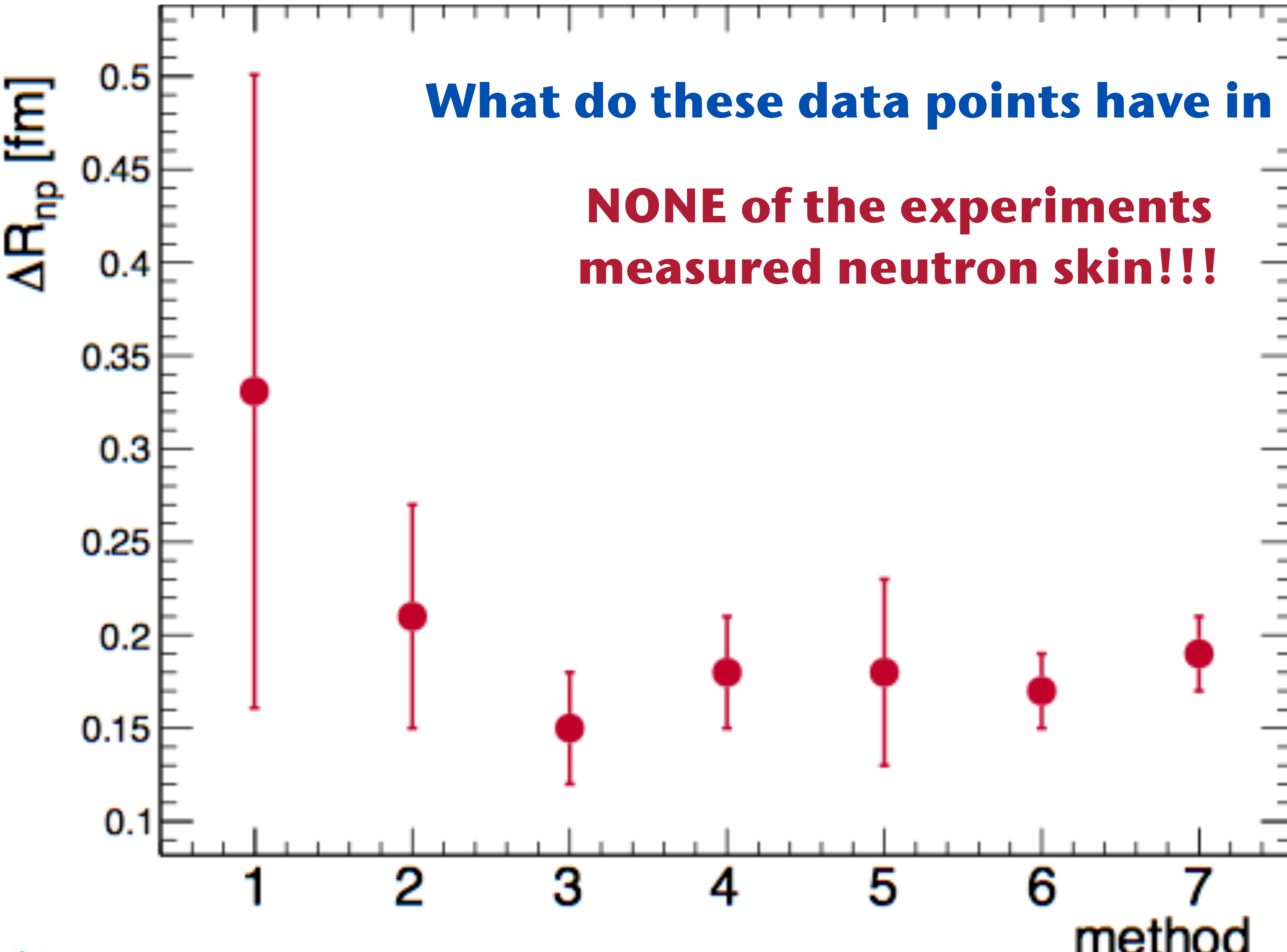
- **How sensitive is the extraction of the neutron radius/skin to these assumptions?**
- **Quantitative assessment of both statistical and systematic errors**

# The answer to the ultimate question

**What do these data points have in common?**



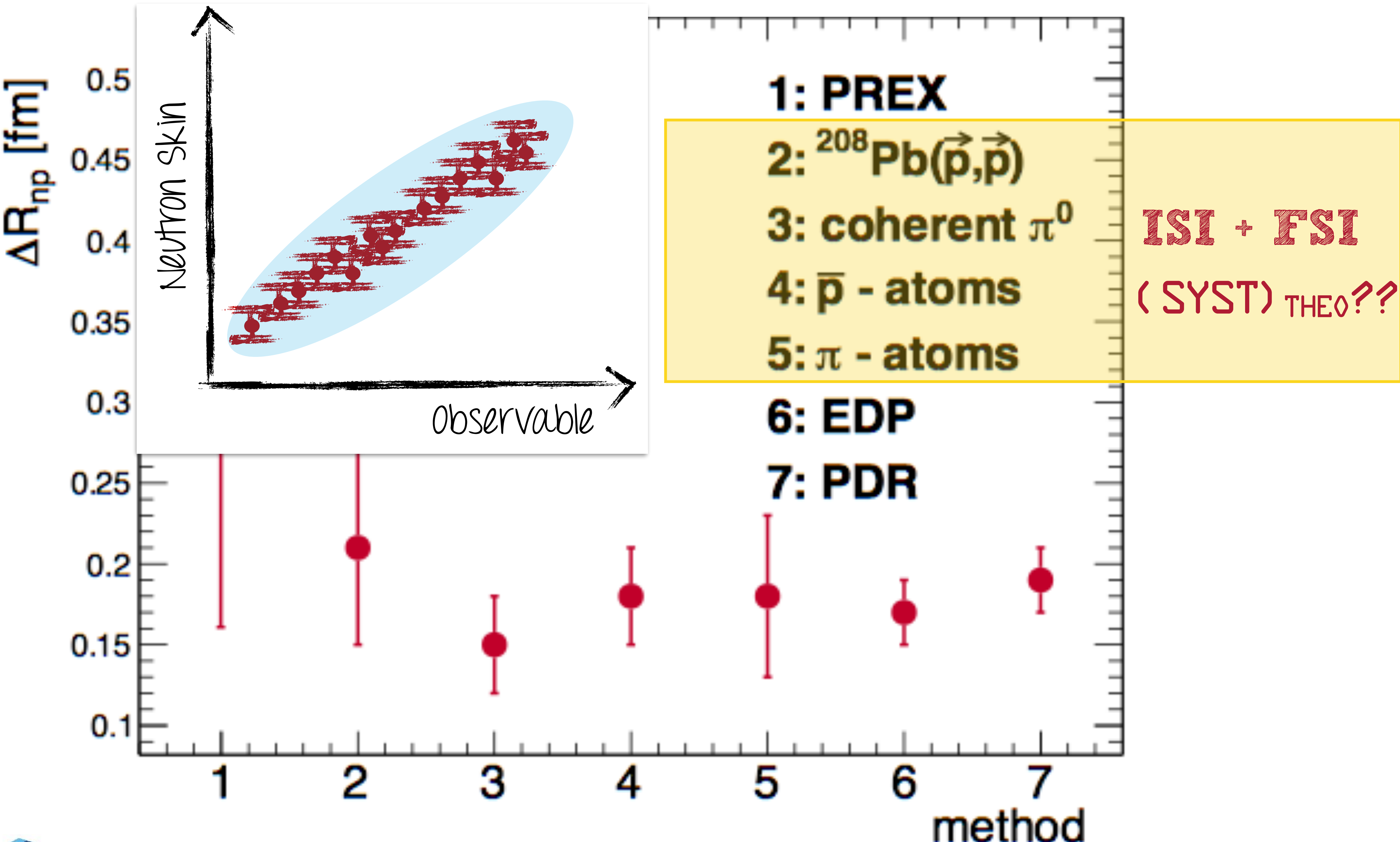
# The answer to the ultimate question




**What do these data points have in common?**

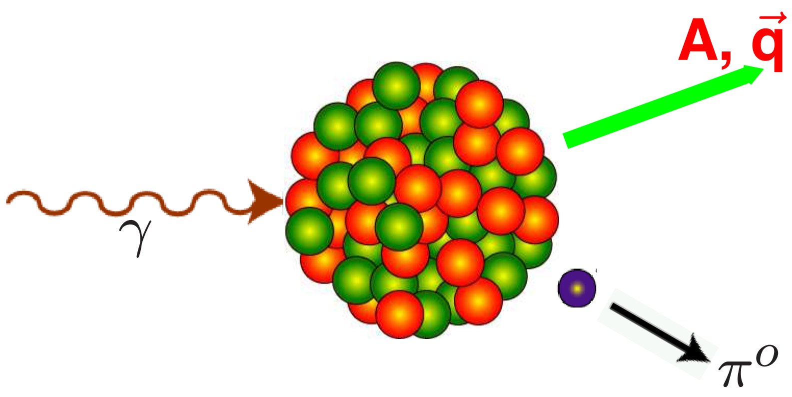
**NONE of the experiments measured neutron skin!!!**

# The answer to the ultimate question



# One MZ-Example

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




**…** ***shine light*** **on the nucleus!**

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

Featured in Physics    Editors' Suggestion

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

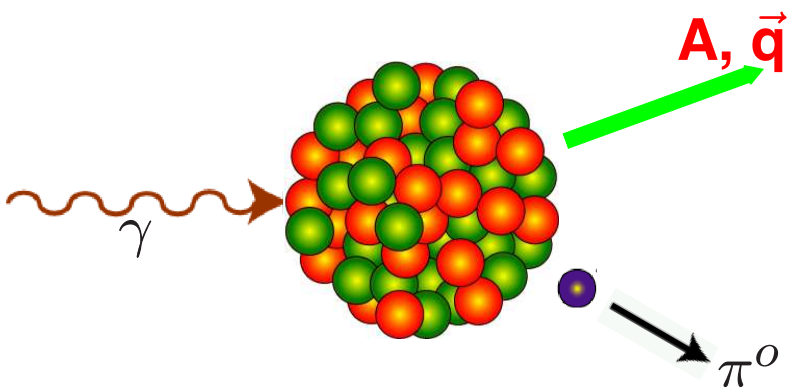
C. M. Tarbert *et al.* (Crystal Ball at MAMI and A2 Collaboration)
Phys. Rev. Lett. **112**, 242502 – Published 18 June 2014

Physics See Synopsis: Neutron Skin Turns Out to Be Soft

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.

# One MZ-Example

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




**…** ***shine light*** **on the nucleus!**

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

Photon probe interaction well understood: No ISI

$\pi^0$ meson produced with ≈ probability on **p AND n**

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

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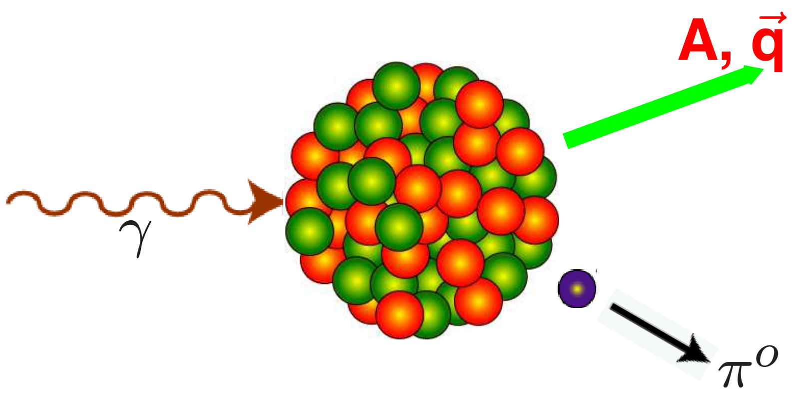


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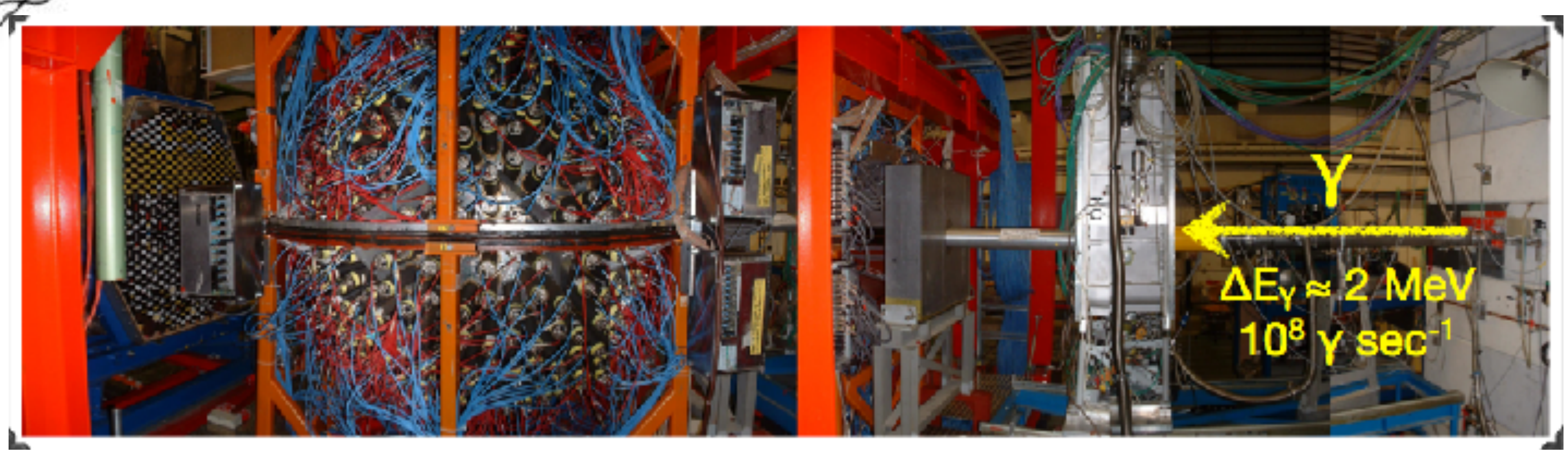

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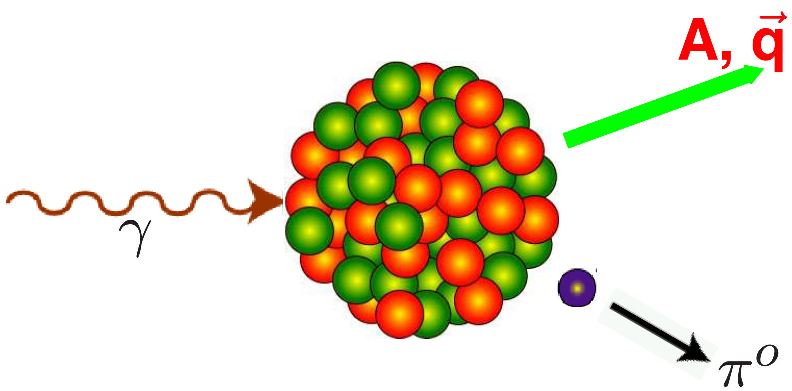


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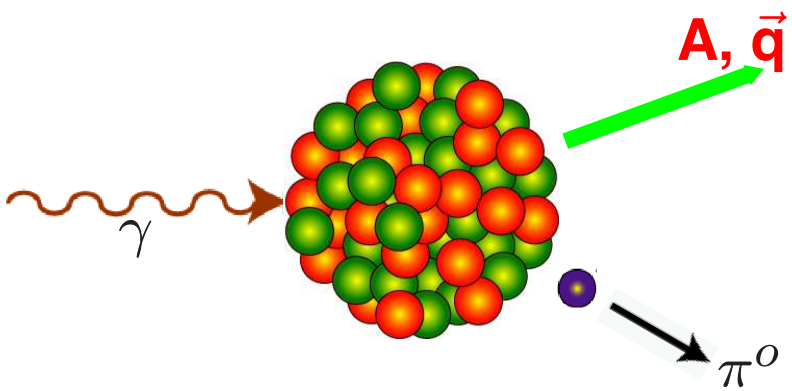


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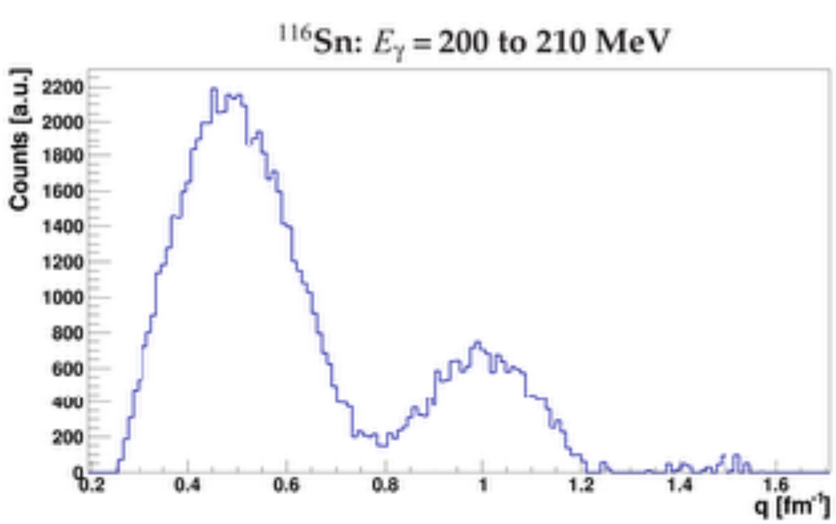
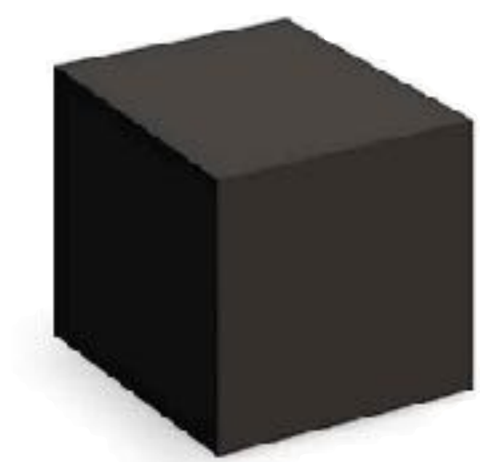
My perspective:




→



→

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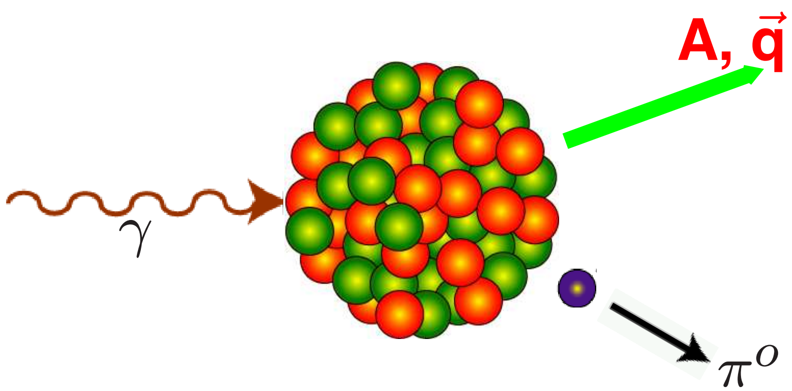
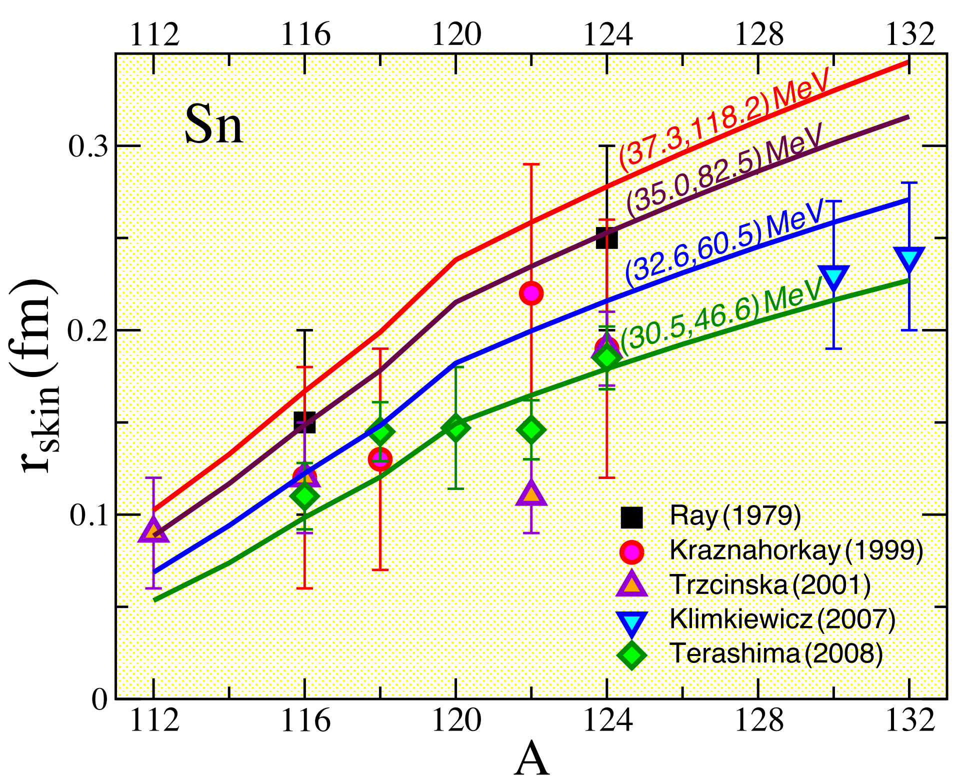






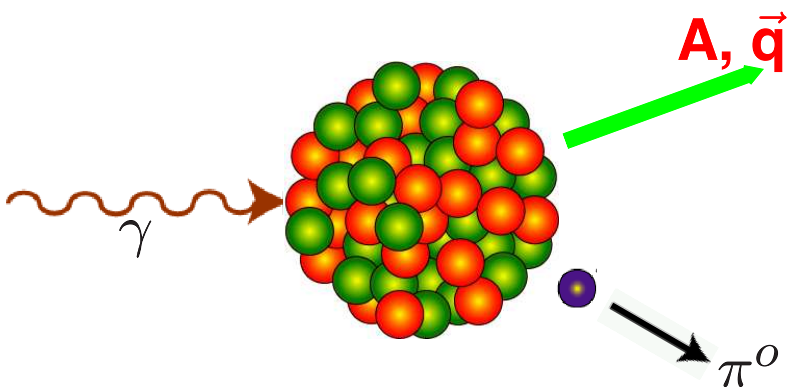

J. Piekarewicz et al.

CONCETTINASFIENTI

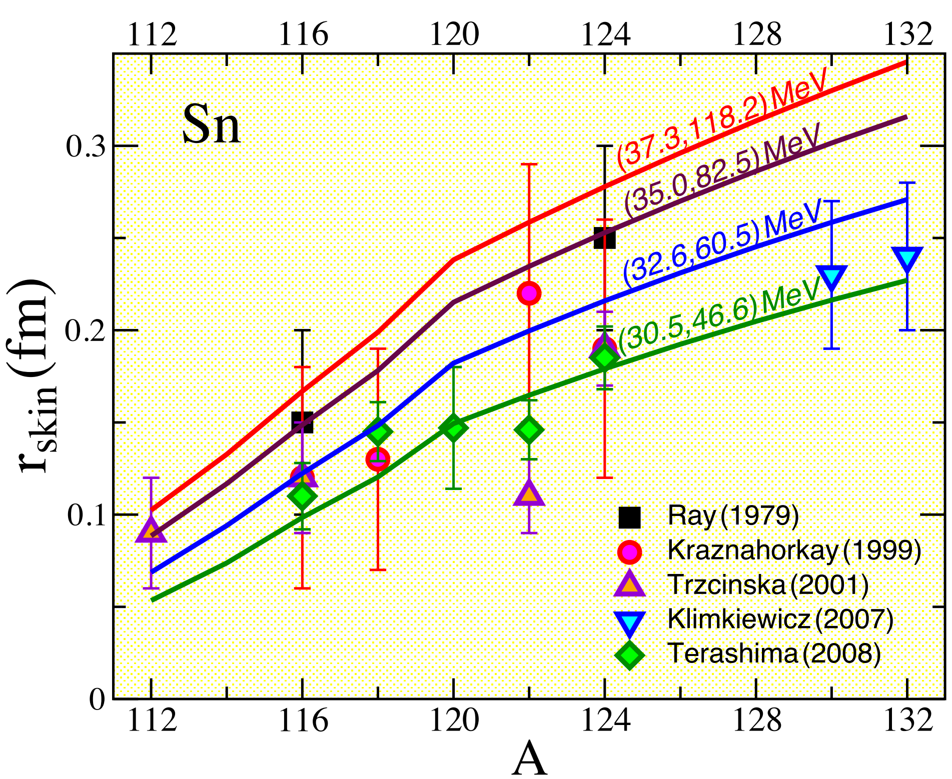
#MakeHumansSmartAgain

# One MZ-Example

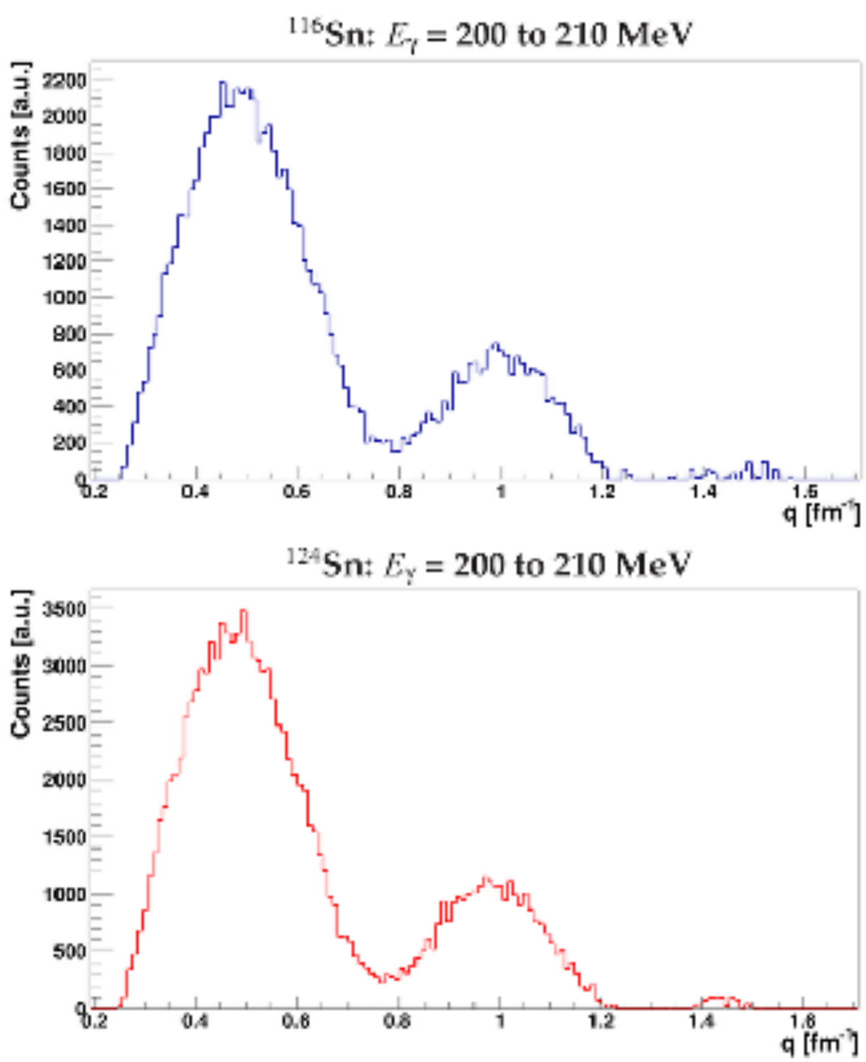
**Coherent π⁰ photoproduction: easy and quick** *(A2 Coll. Phys. Rev. Lett. 112, 242502 )*








J. Piekarewicz et al.



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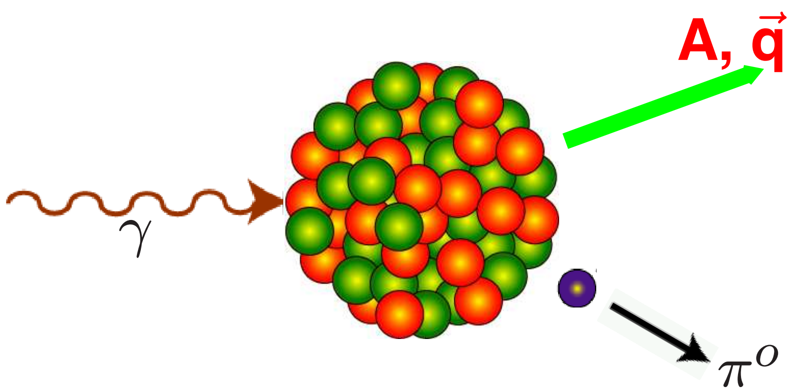
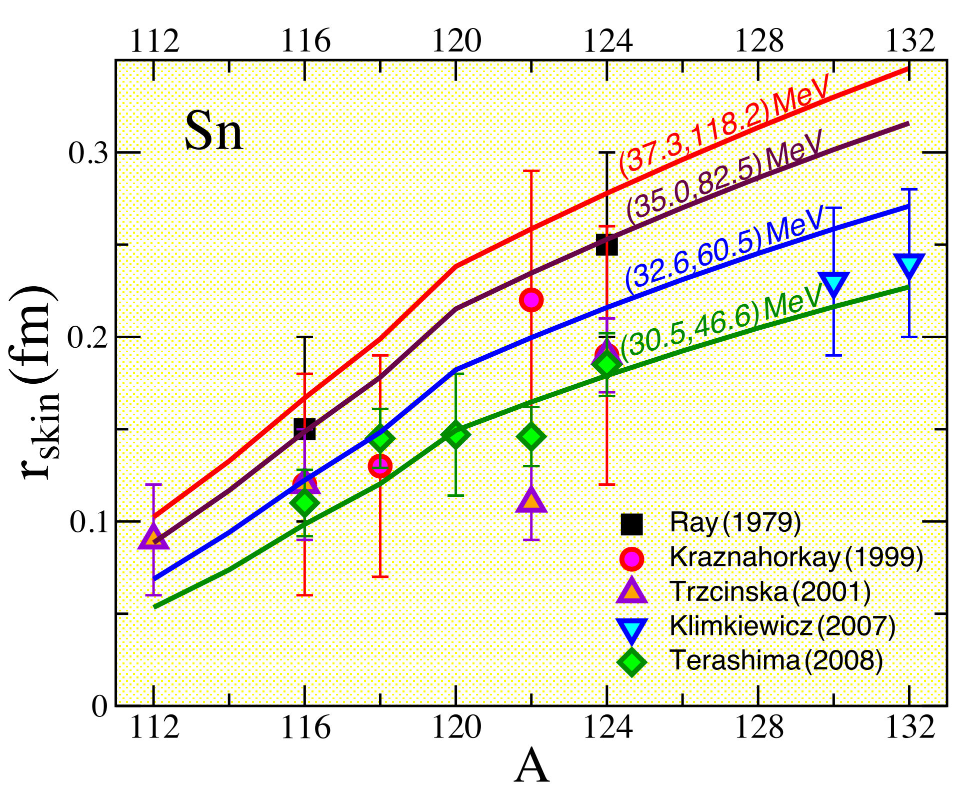
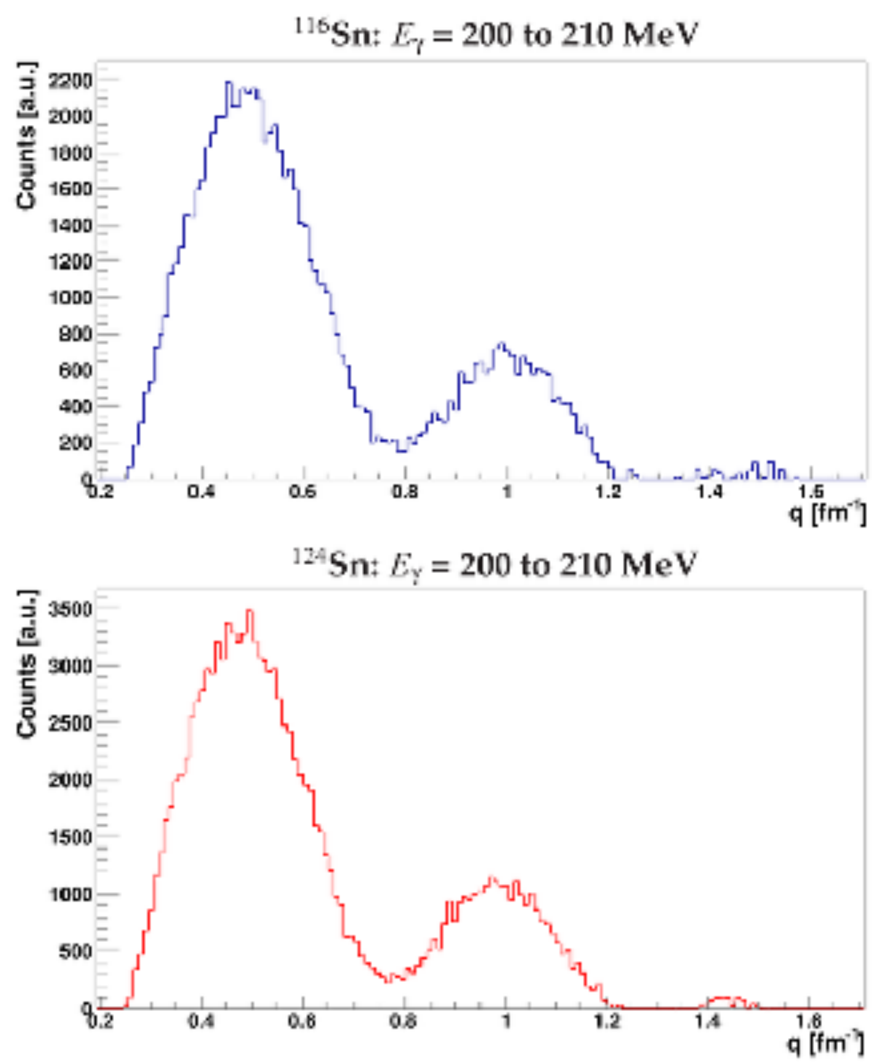




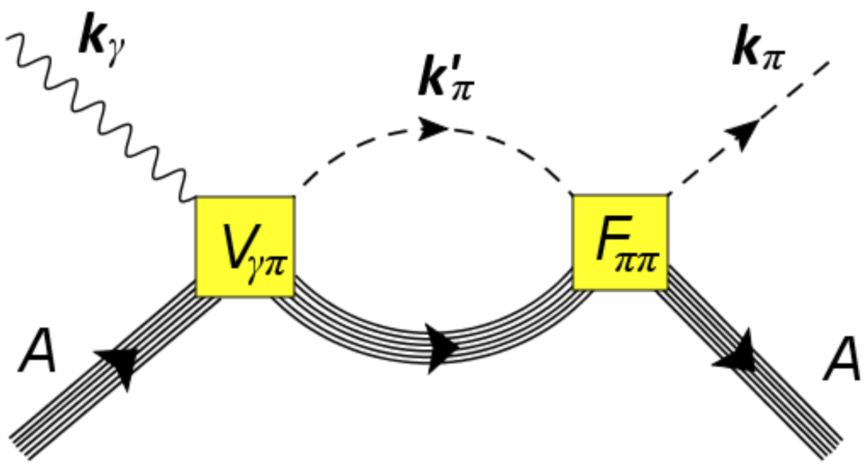



J. Piekarewicz et al.

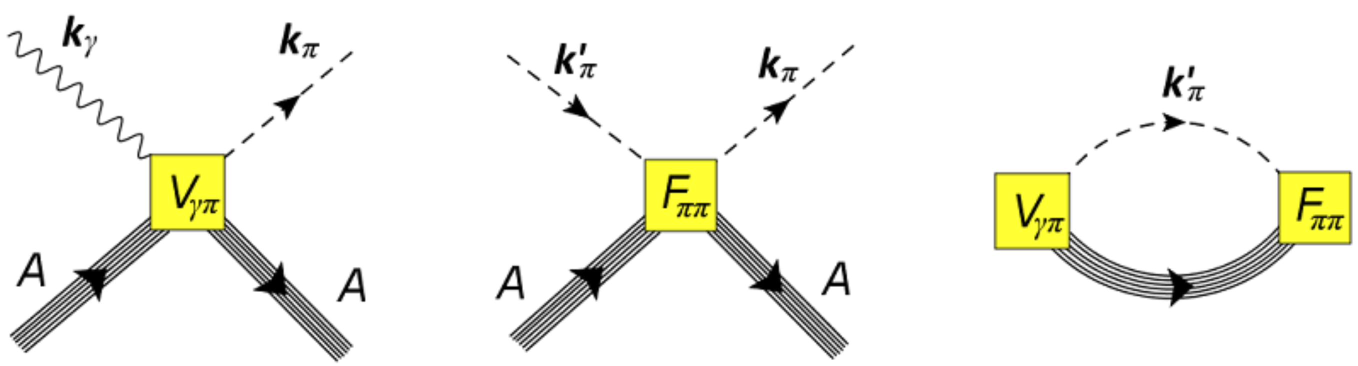



# One MZ-Example

P. Capel, F. Colomer, S. Tsaran, M. Vanderhagen



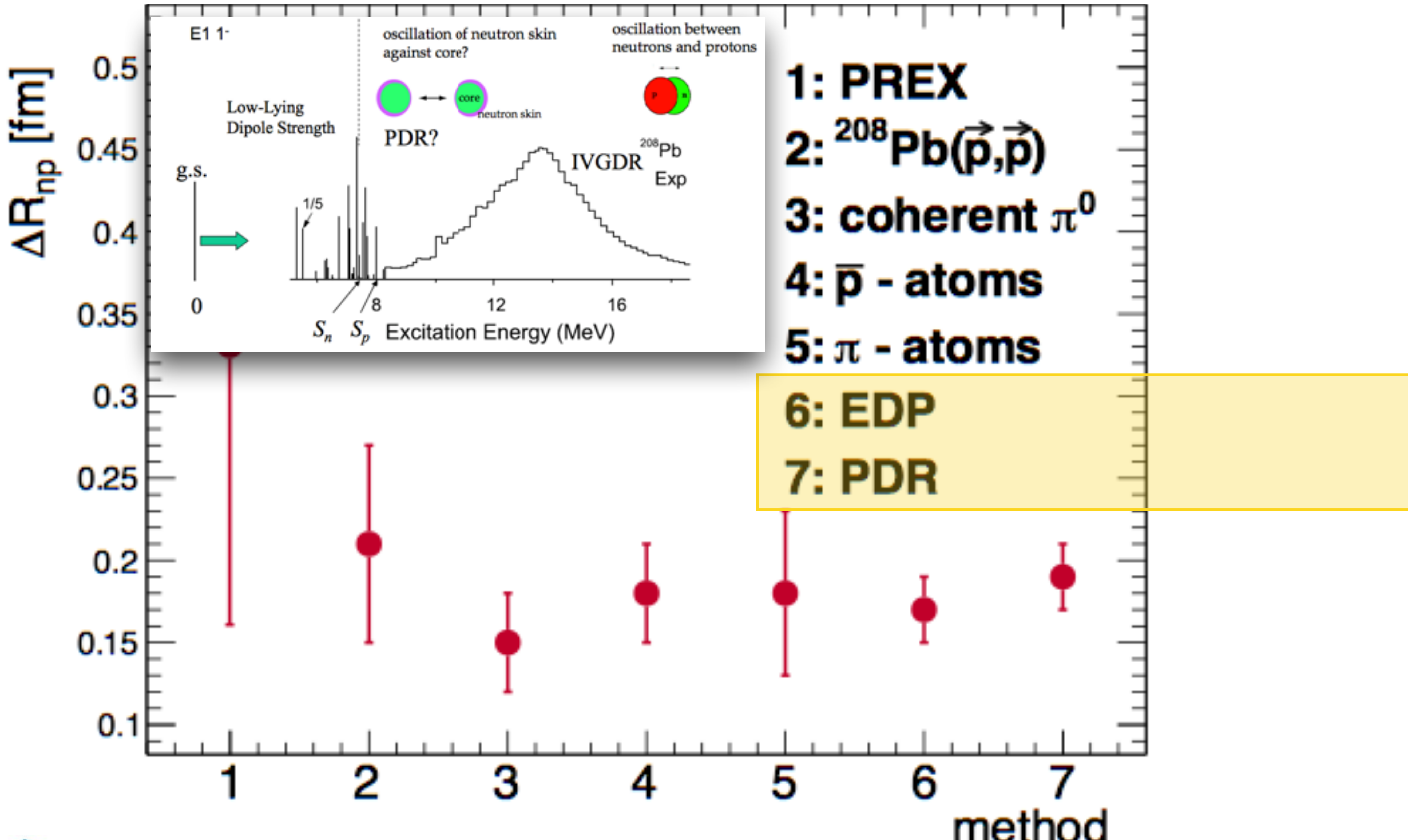

- ■ Working code for PWIA amplitudes for photoproduction $V^{(\lambda)}_{\pi\gamma}(\mathbf{k}_\pi, \mathbf{k}_\gamma)$
- ■ Working code for scattering matrix $F_{\pi A}$ of $\pi^0$
  - Resolution of the Lippmann-Schwinger equation
  - Singularity of Coulomb solved : better constrains on $U^{\mathrm{Nucl}}(k', k)$
- ☐ DWIA amplitudes calculation
  - Off-shell photoproduction amplitudes $V^{(\lambda)}_{\pi\gamma}(\mathbf{k}'_\pi, \mathbf{k}_\gamma)$
- ☐ Devise a better form for $U^{\mathrm{Nucl}}(k', k)$




+ Treatment of Resonances,
+ Use Effective Potentials (J. Piekarewicz)
+ Sensitivity of $\sigma_{\mathrm{coherent}}$ to neutron density
+ Benchmark theory with A/Z and Z variation

**...it is a long way till Rome ...**

# The answer to the ultimate question



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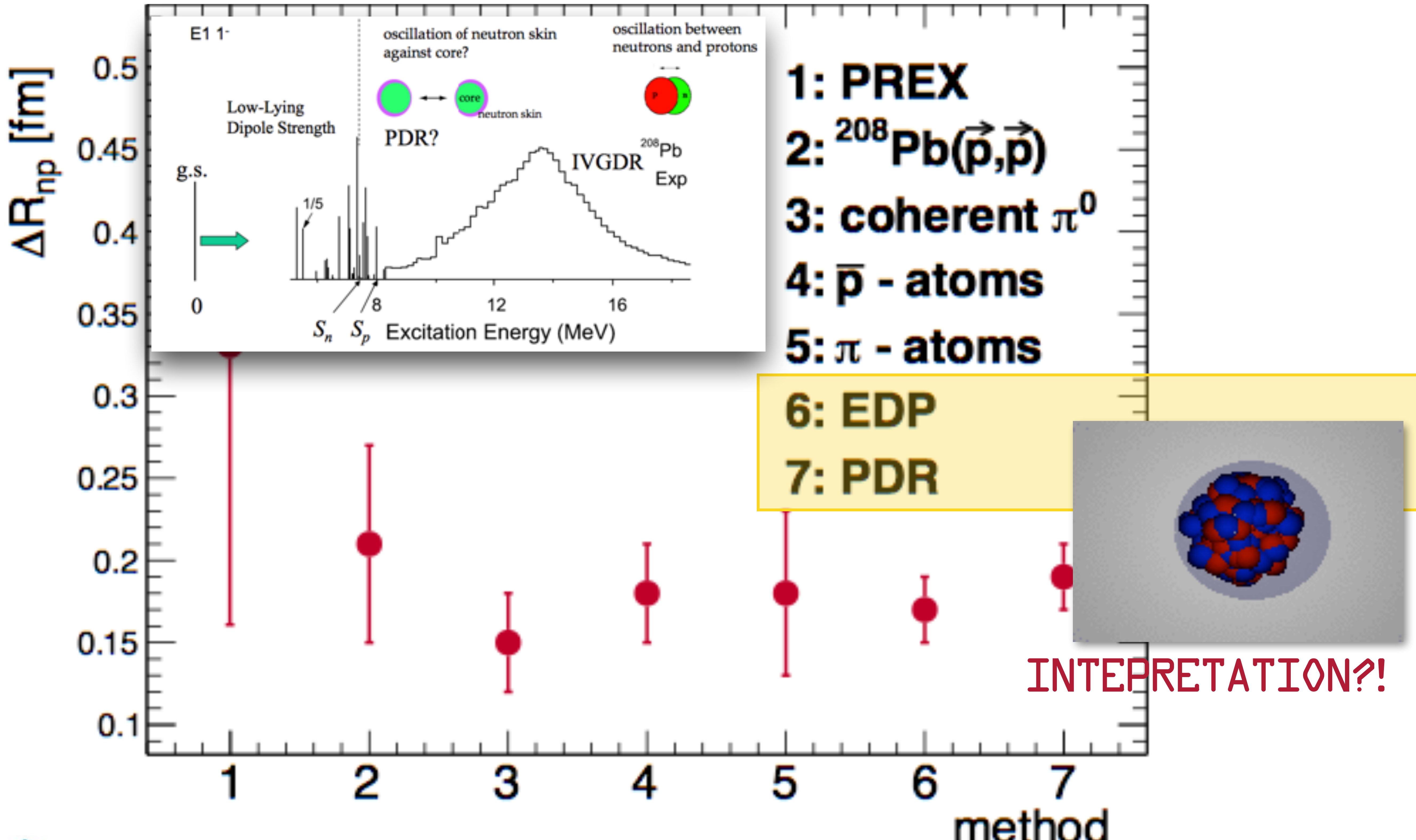

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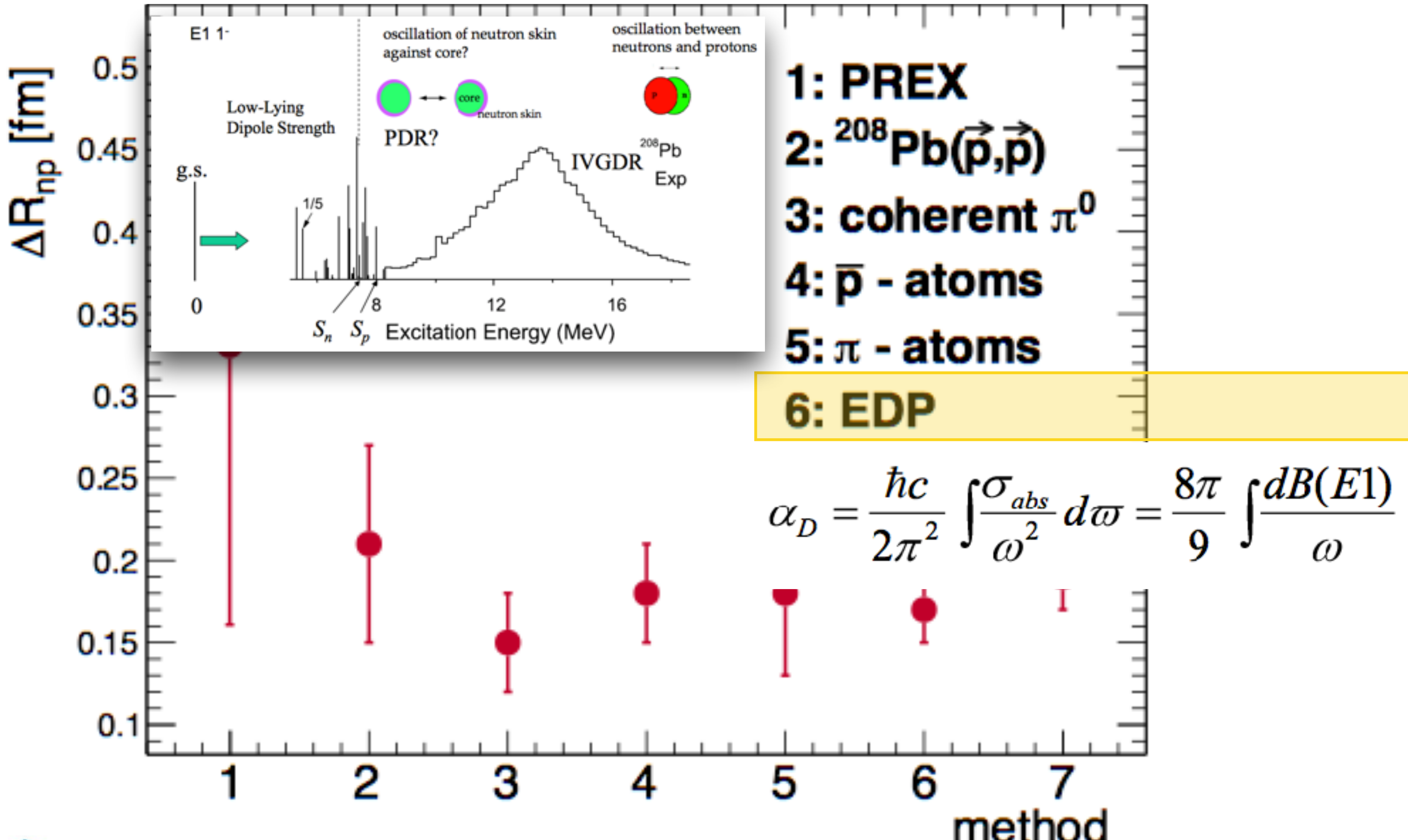


$$\alpha_D = \frac{\hbar c}{2\pi^2}\int\frac{\sigma_{abs}}{\omega^2}d\varpi = \frac{8\pi}{9}\int\frac{dB(E1)}{\omega}$$

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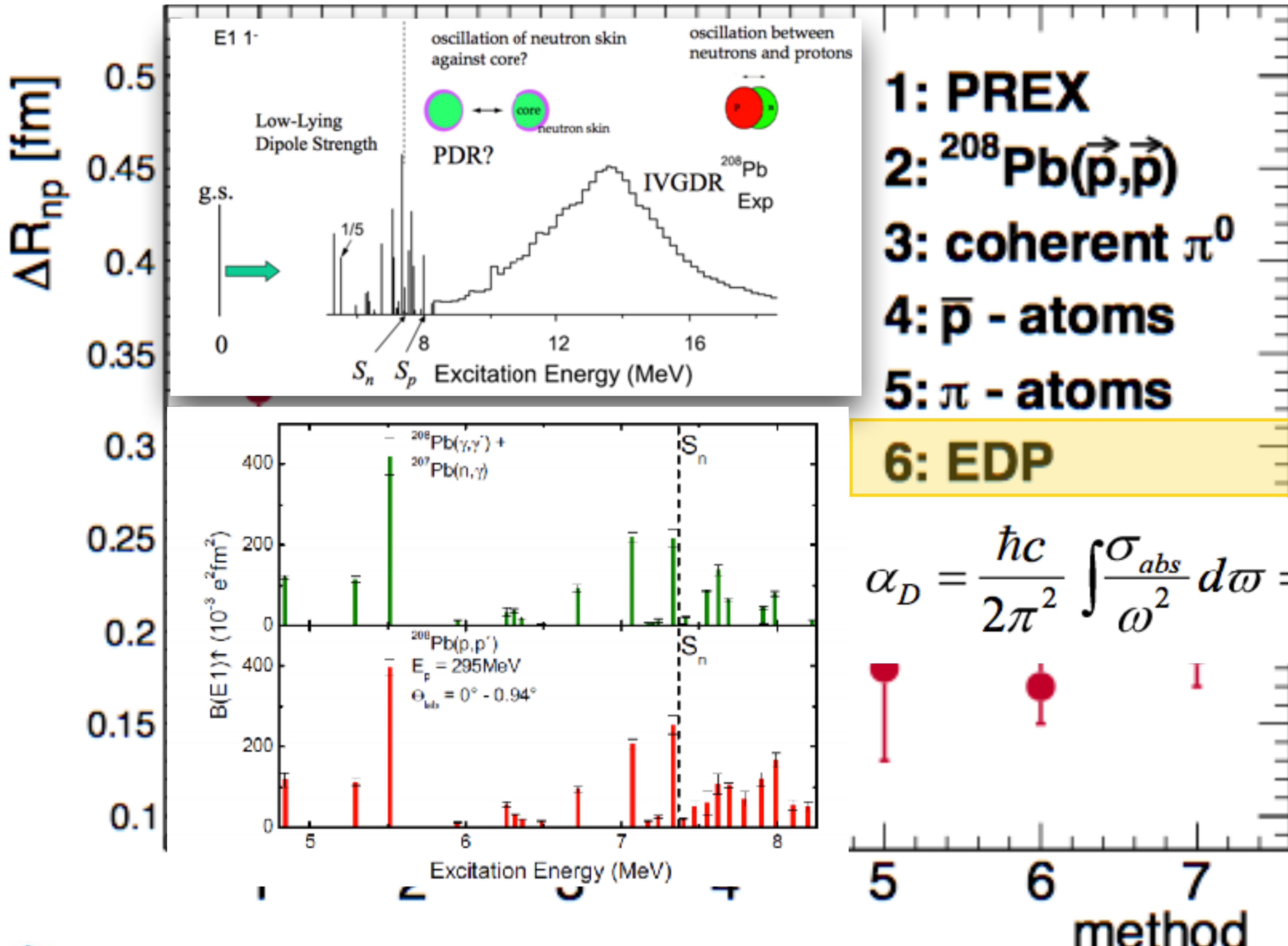


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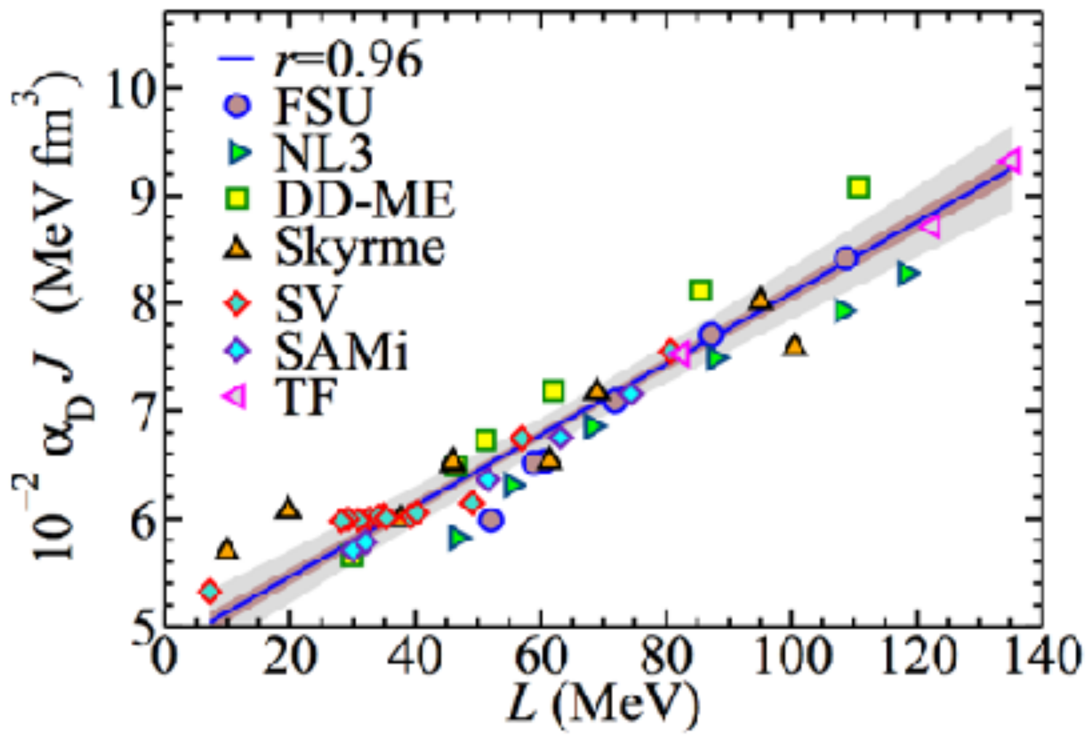
# Electric Dipole Polarizability

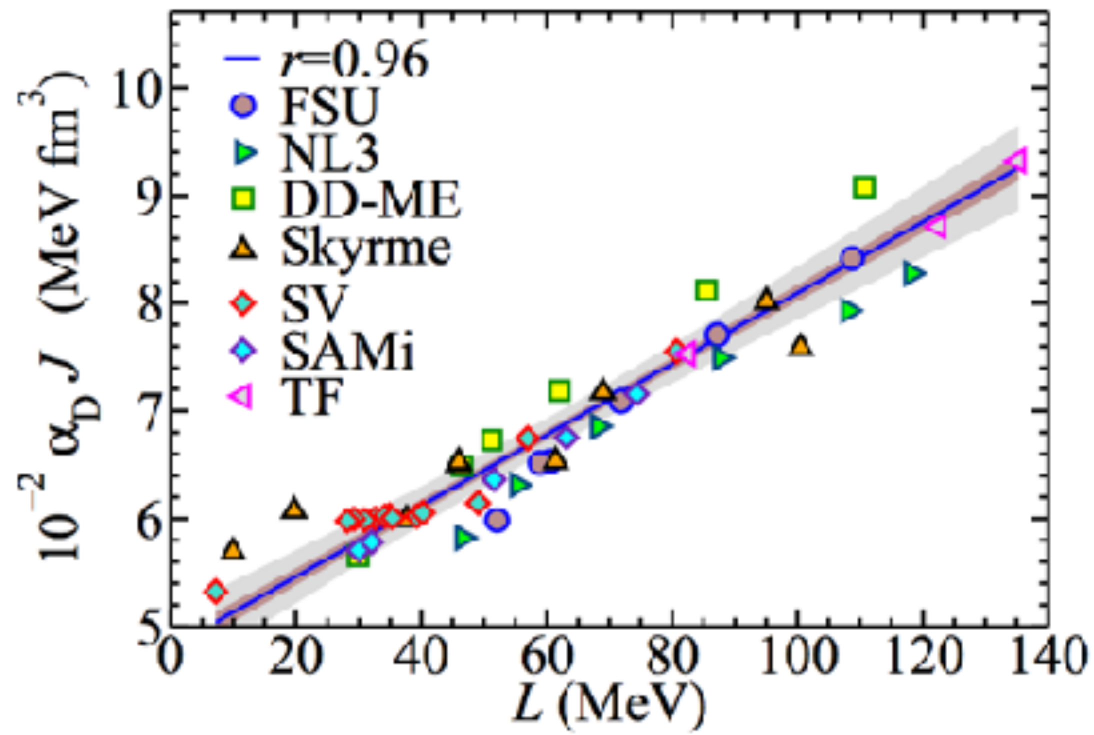



X. Roca-Maza *et al*., PRC**88**, 024316(2013)

*(ask him directly for details 😊)*

$$\alpha_D^{\mathrm{DM}} \approx \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}\left[1+\frac{5}{3}\frac{L}{J}\epsilon_A\right]$$

# Electric Dipole Polarizability

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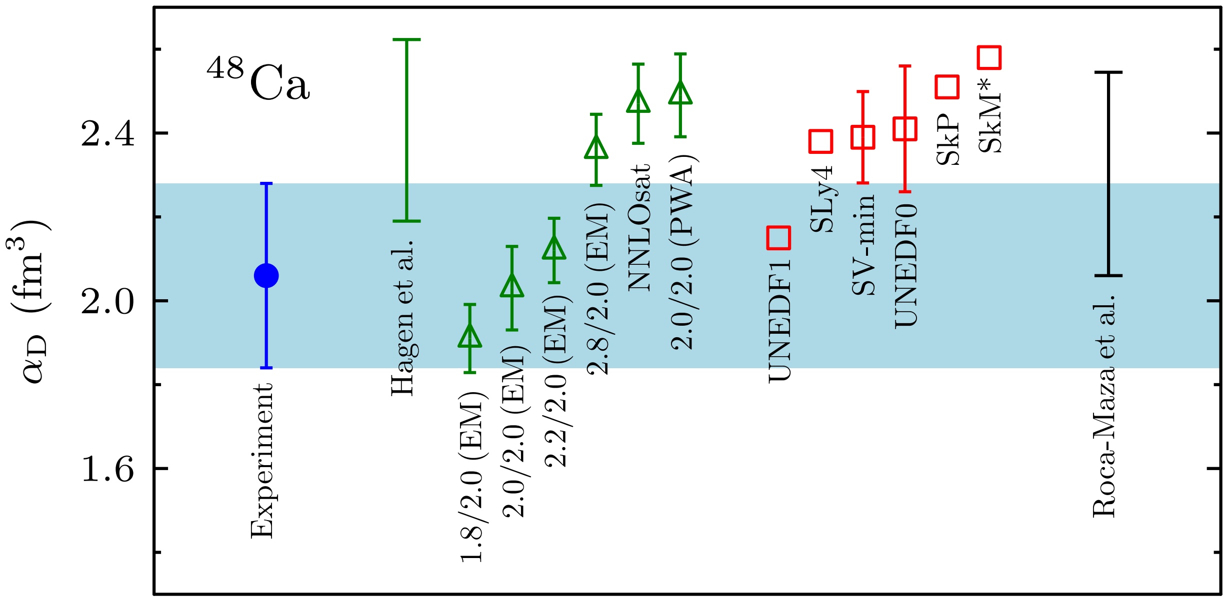



PRL **118,** 252501 (2017)

👍Potentially very useful: RIBs physics

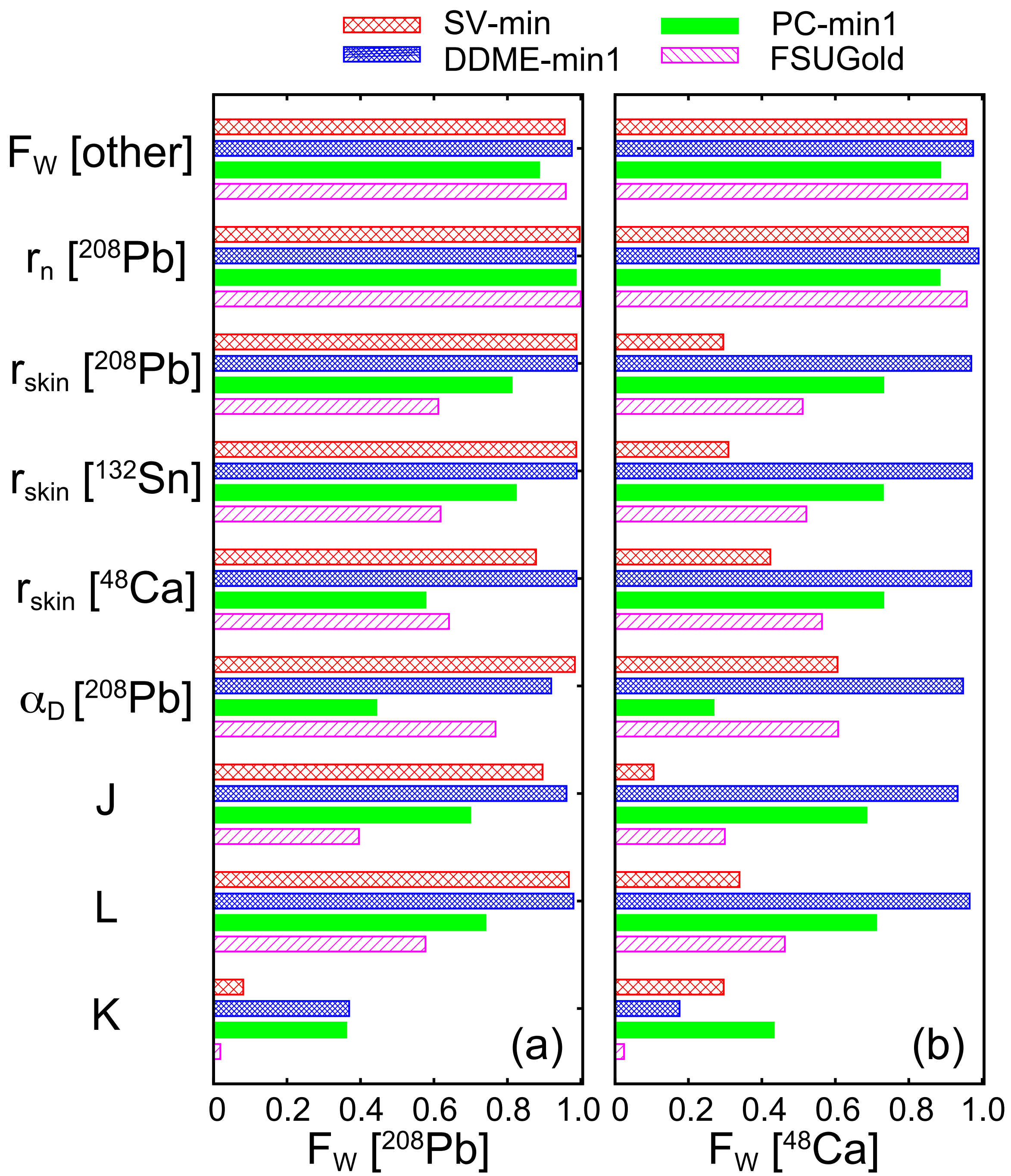
✅High quality data on a variety of nuclei

⚠️Theory: enormous progress in sight

❌K,J,L … ARE NOT experimental observable!

# Correlations et al.

"Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful." (G. E.P. Box)




PHYSICAL REVIEW C88, 034325 (2013)

# Theory informing experiment

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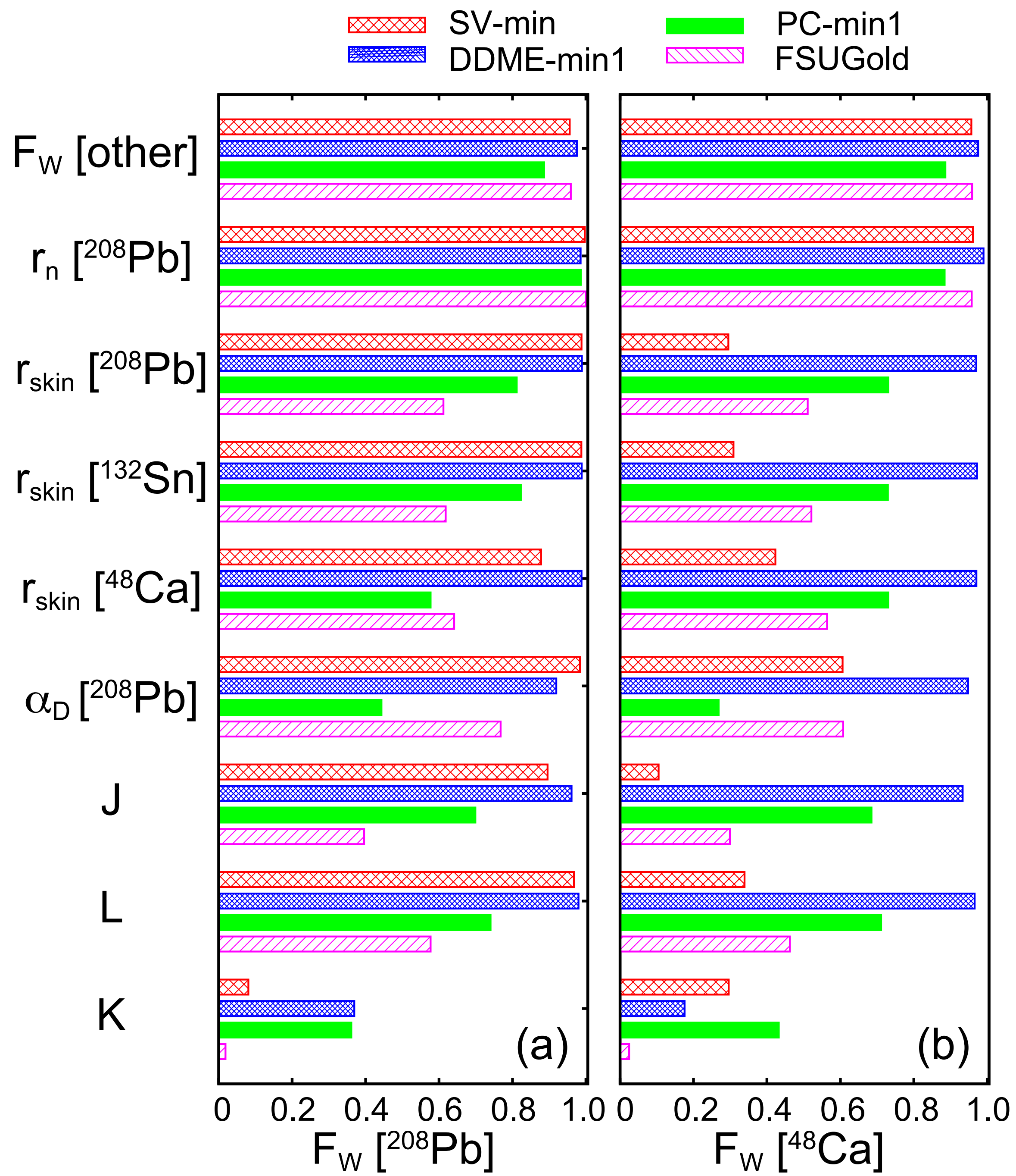


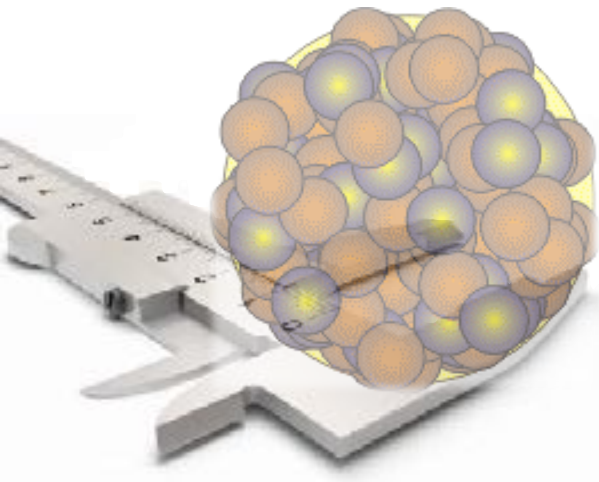

PHYSICAL REVIEW C88, 034325 (2013)

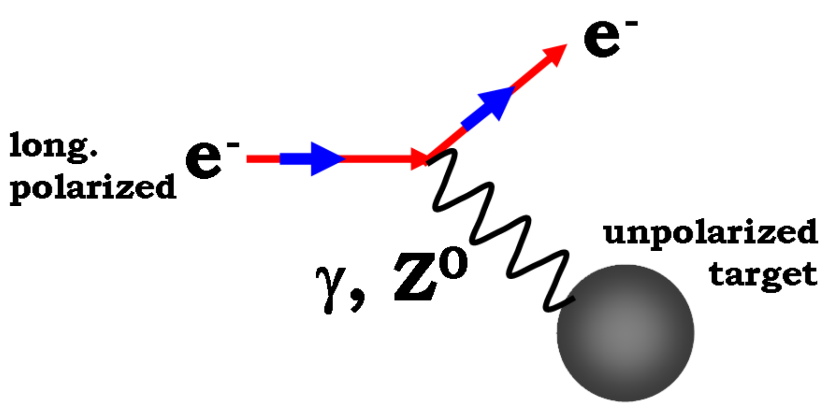
- Quantitative assessment of both statistical and systematic errors; theory must provide error bars!

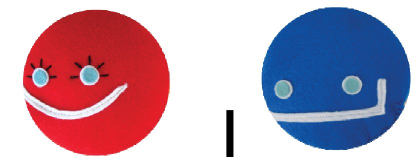
  Uncertainty quantification and covariance analysis (theoretical errors & correlations)

- Precision required in the determination of the neutron radius/skin?
  - As precisely as "humanly possible" - fundamental nuclear structure property
  - To strongly impact Astrophysics?
  - What astrophysical observables to benchmark?

# Trivial? It is a long winding road …





| | | |
|---|---|---|
| electric charge | 1 | 0 |
| weak charge | ≈0.07 | 1 |

Non-PV e-scattering

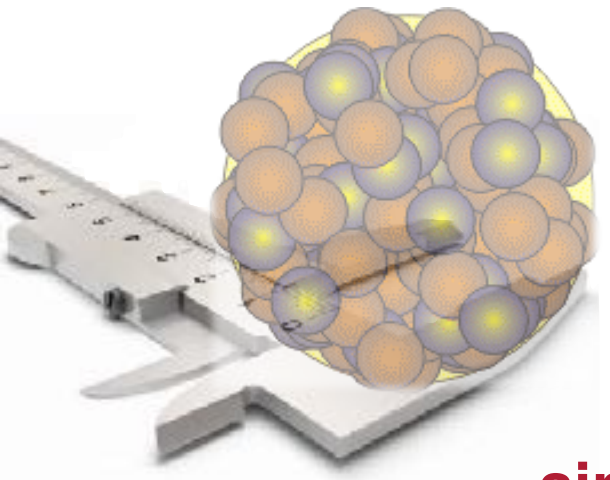
Electron scattering γ exchange provides $R_p$ through nucleus FFs

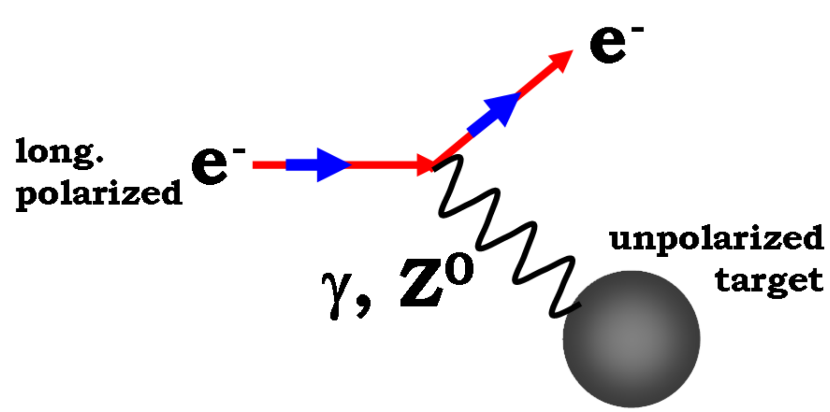
## PV e-scattering

Electron also exchange Z, which is parity violating

Primarily couples to neutron

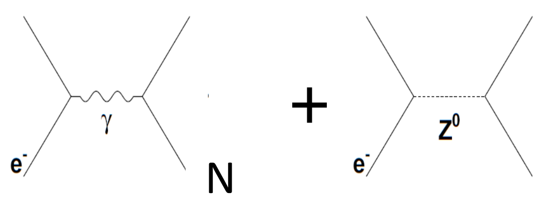
# Trivial? It is a long winding road ...





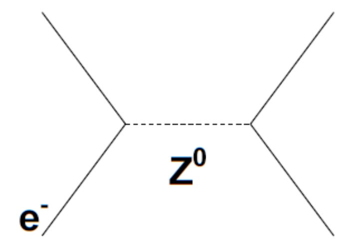

| | (red) | (blue) |
|---|---|---|
| electric charge | 1 | 0 |
| weak charge | ≈0.07 | 1 |

...since...

$\sigma \propto$ $\Big|$  $\Big|^2$



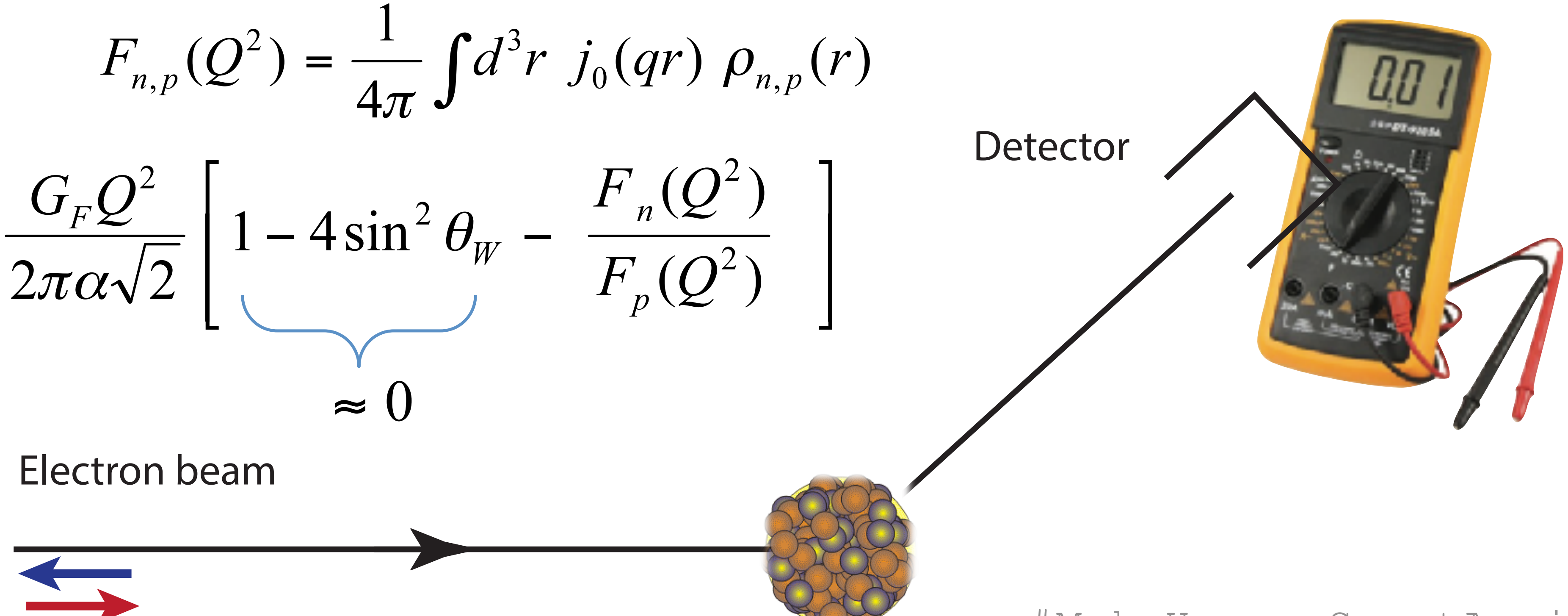
...to measure ...



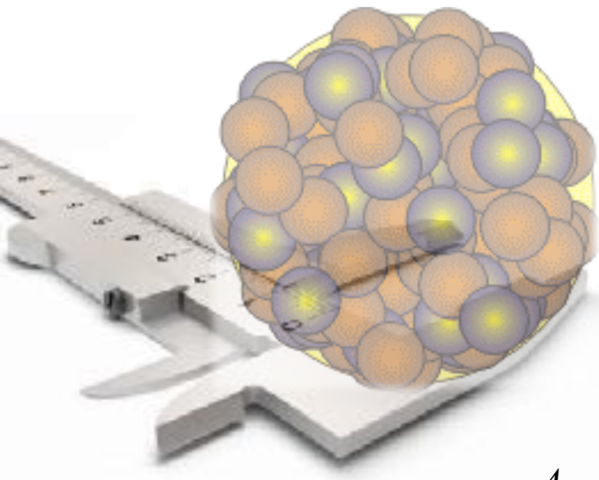

....construct ....

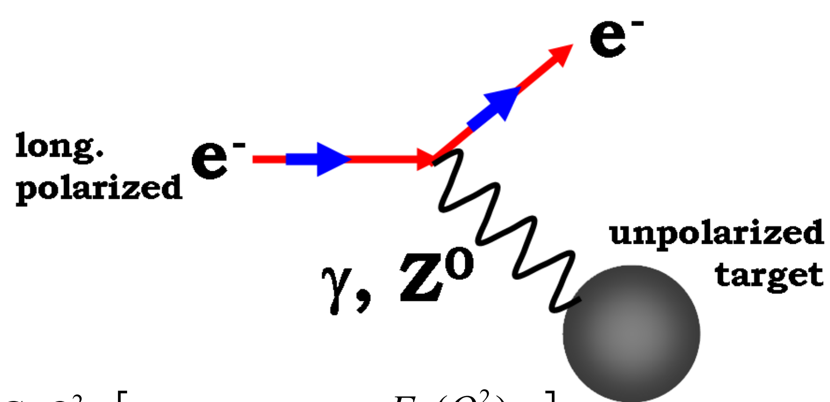
$$F_{n,p}(Q^2) = \frac{1}{4\pi}\int d^3r\; j_0(qr)\,\rho_{n,p}(r)$$

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



# The shortest of the roads …



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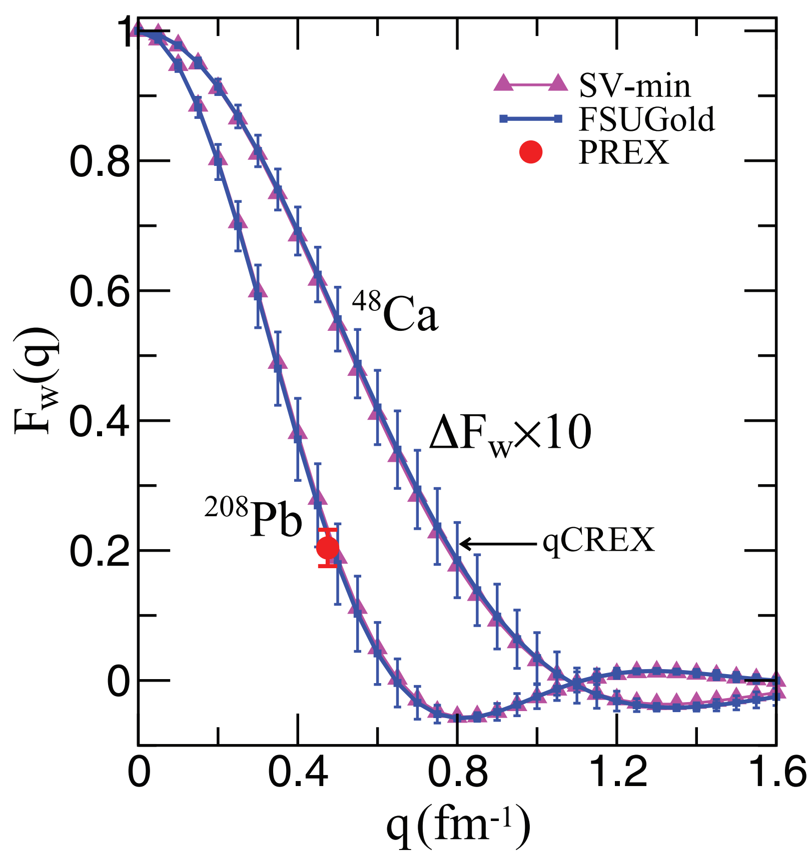
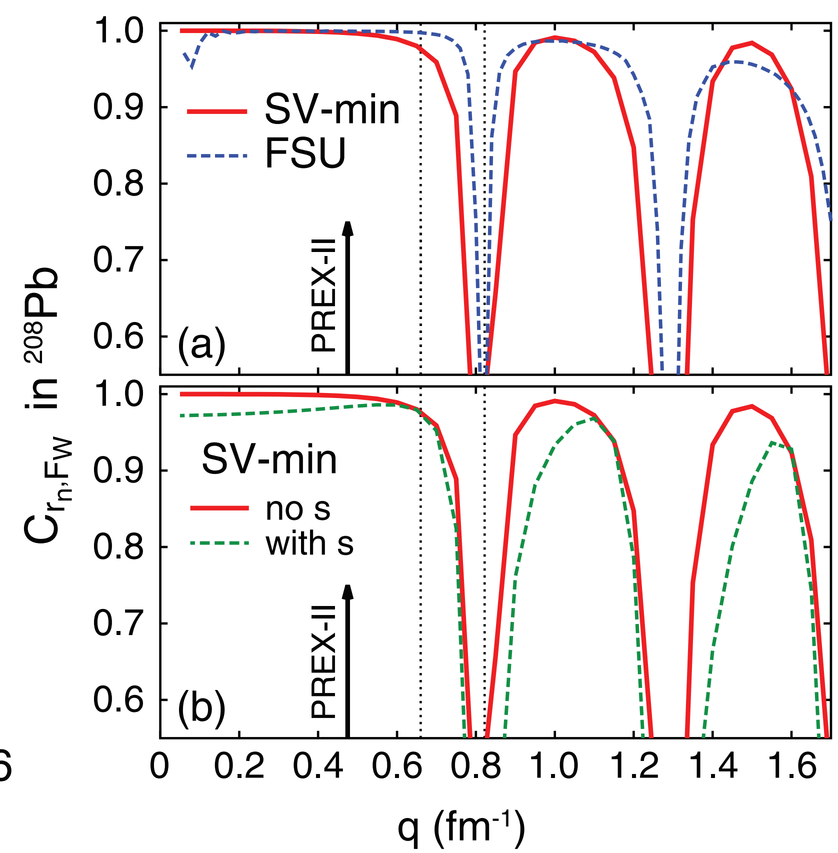
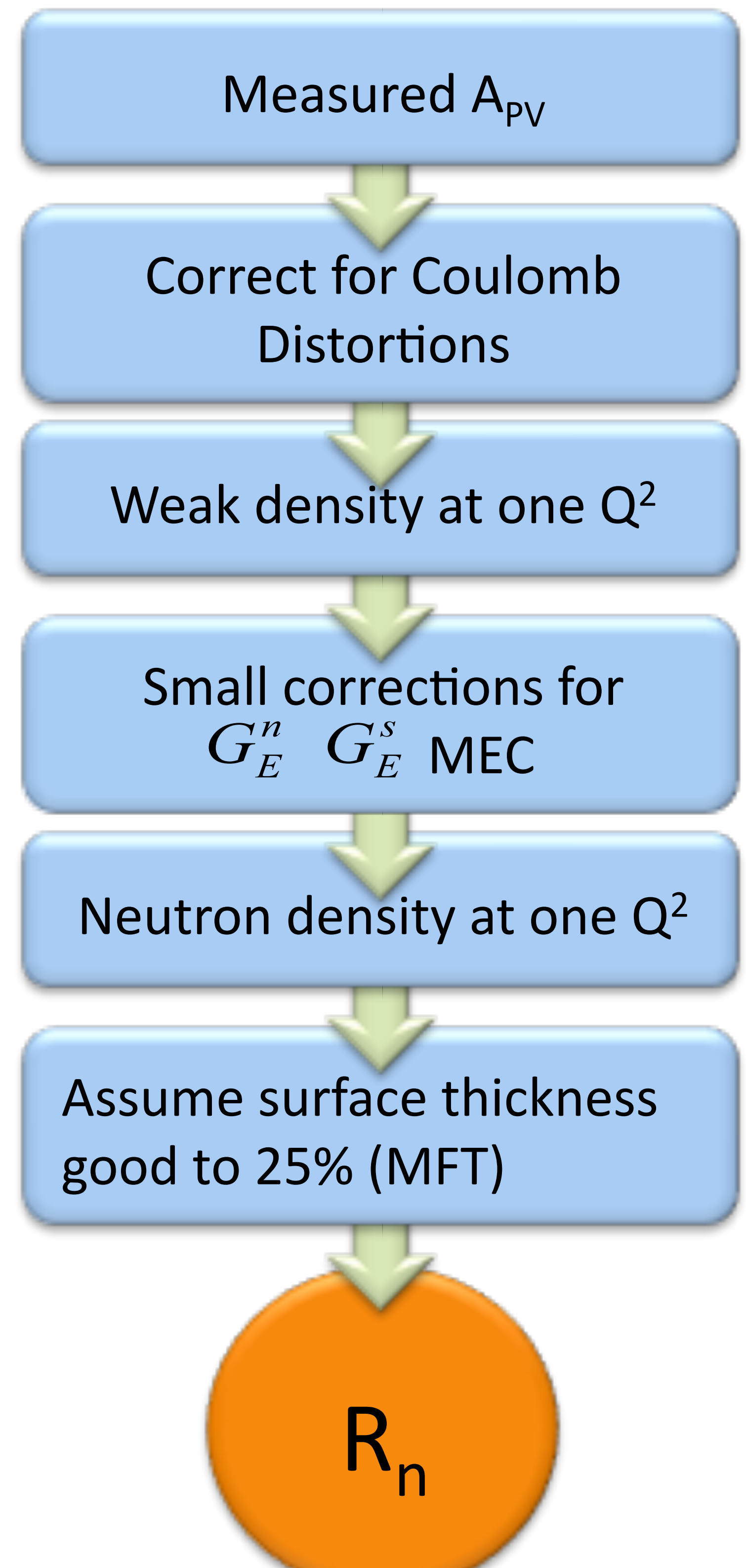


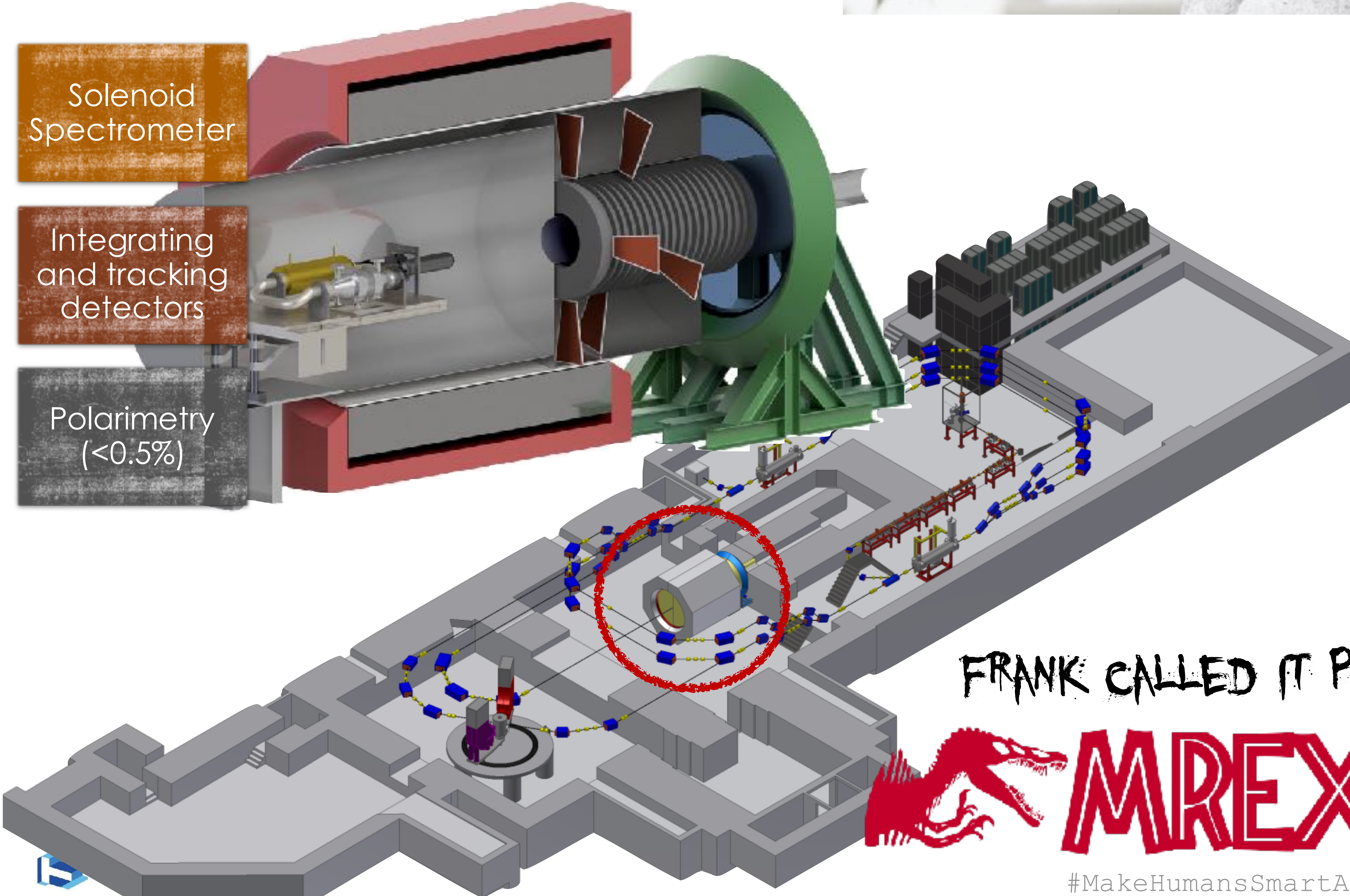

PHYSICAL REVIEW C88, 034325 (2013)

# Neutron Skin@Mainz

Solenoid Spectrometer

Integrating and tracking detectors

Polarimetry (<0.5%)



FRANK CALLED IT P2...

MREX

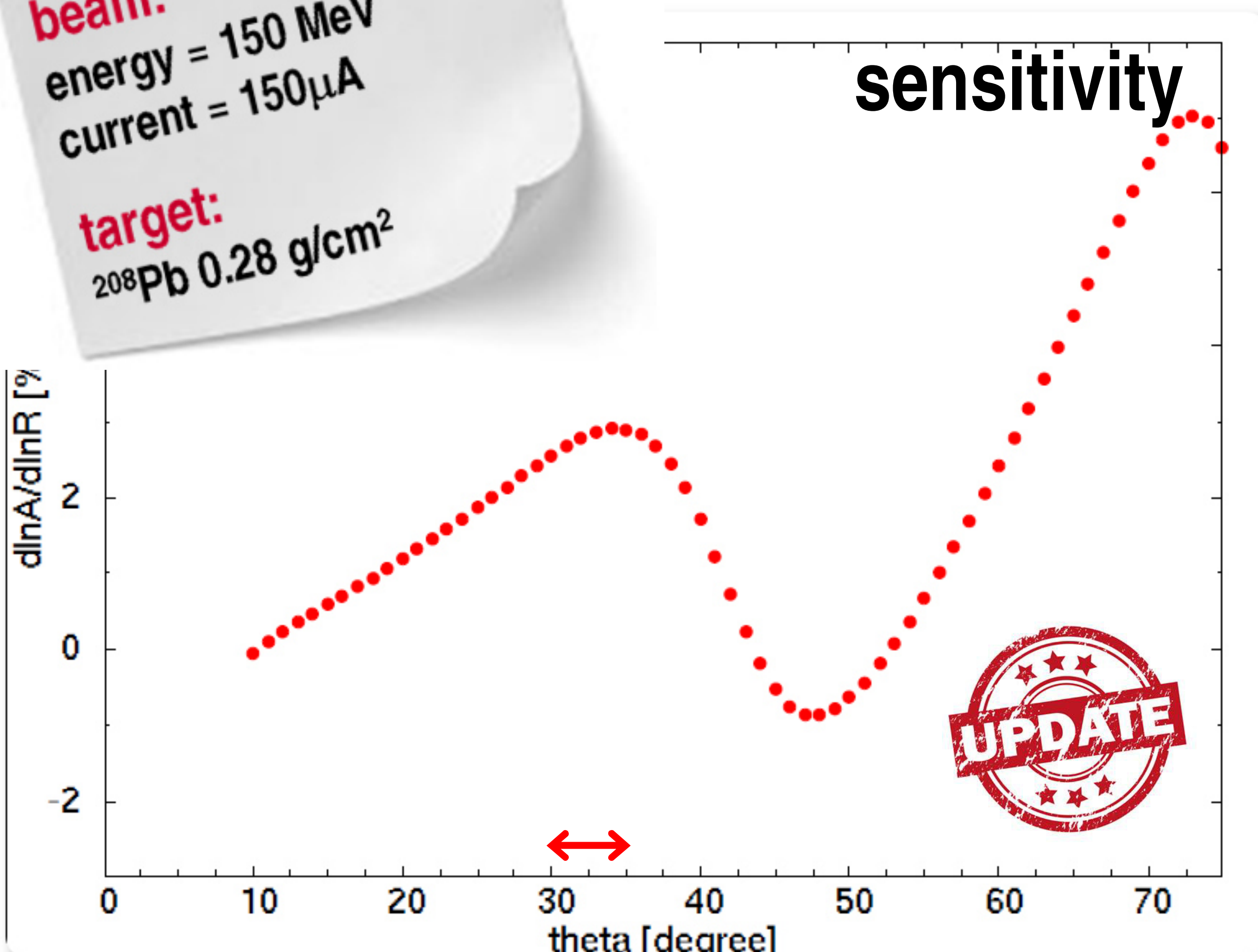
#MakeHumansSmartAgain

**MREX**

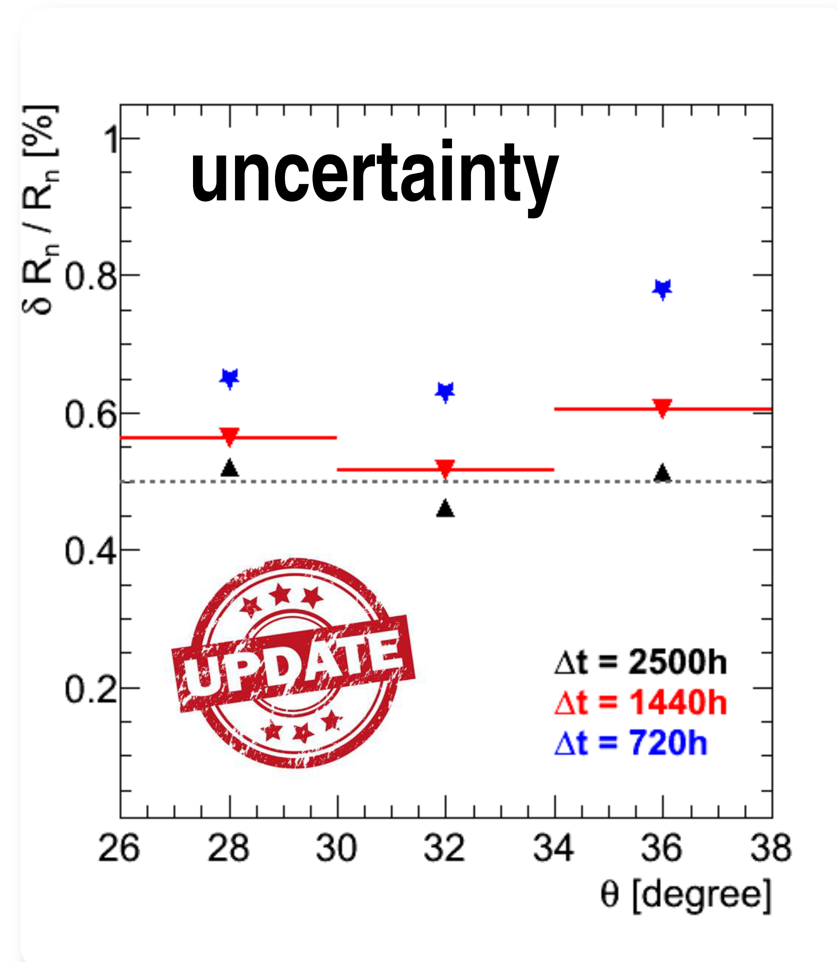
**General condition:**

**beam:**
energy = 150 MeV
current = 150μA

**target:**
$^{208}$Pb 0.28 g/cm$^2$



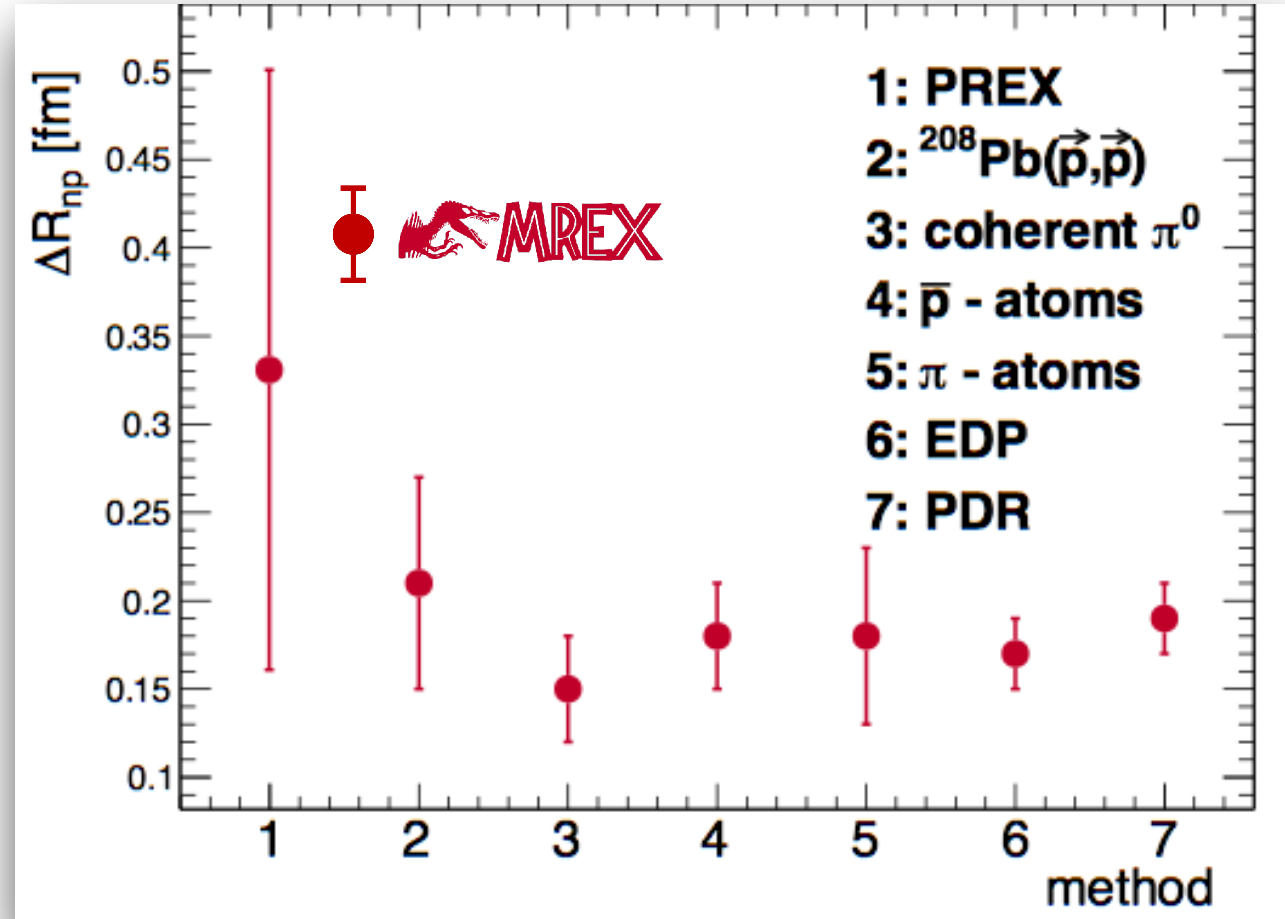

Chuck Horowitz




Michaela Thiel

**$\Delta\theta$=4° : expected rate = 8.25 GHz, $A_{PV}$ = 0.66 ppm, P = 85%, Q ≈ 86 MeV**

## 1440h → $\delta R_n/R_n$ = 0.52% ($^{208}$Pb @ 155 MeV)

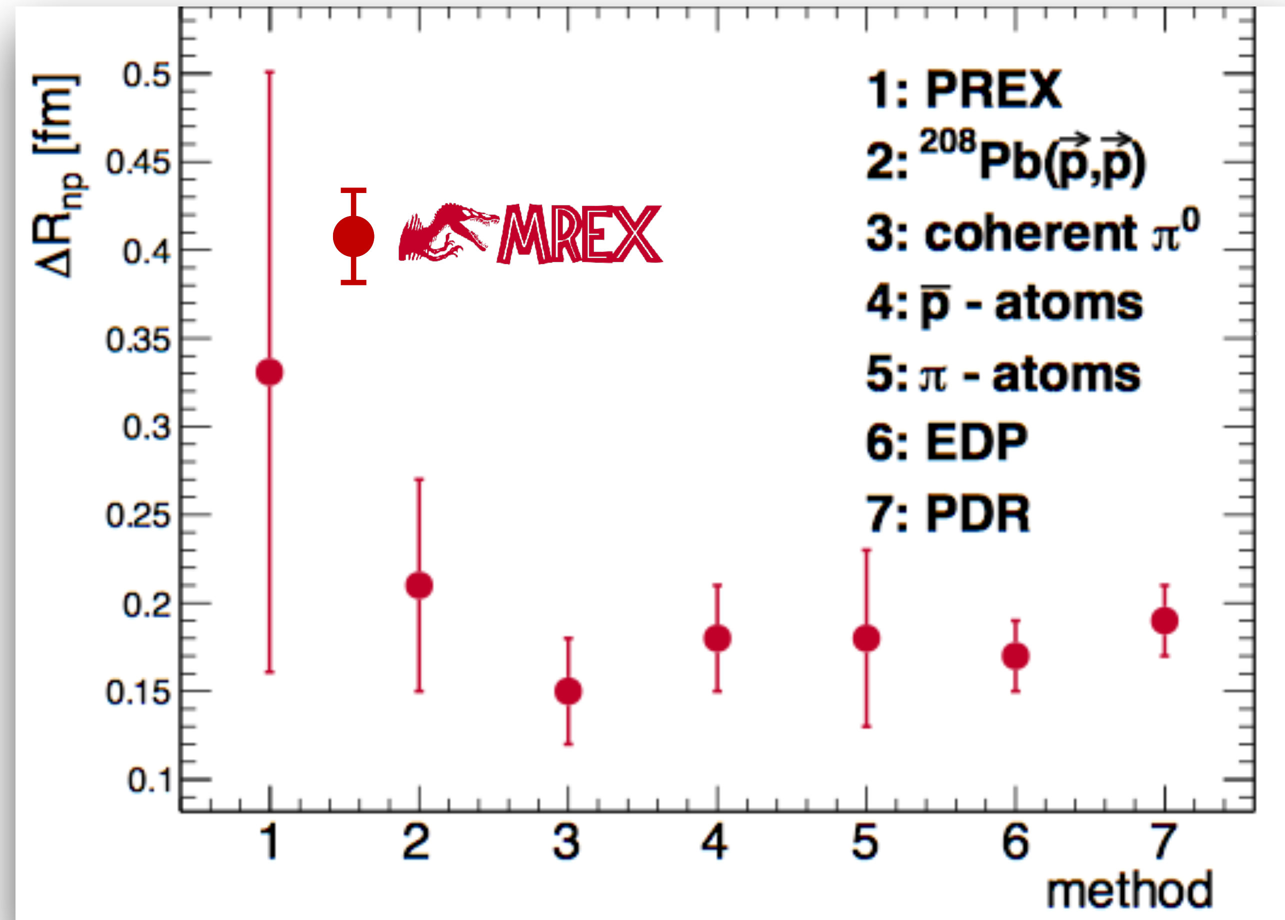



I have a dream too!

- $\delta R_n/R_n = 0.5\%$

→ **L ± 20 MeV**

MREX



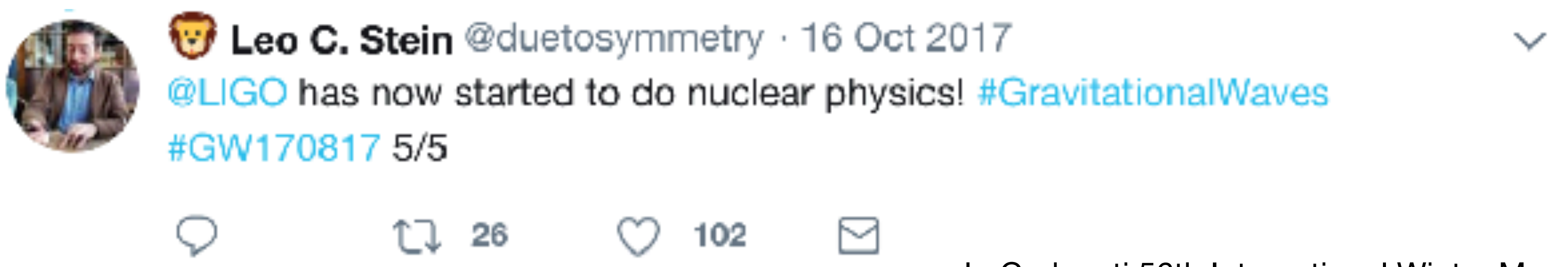

I have a dream too!

➢ $\delta R_n/R_n = 0.5\%$

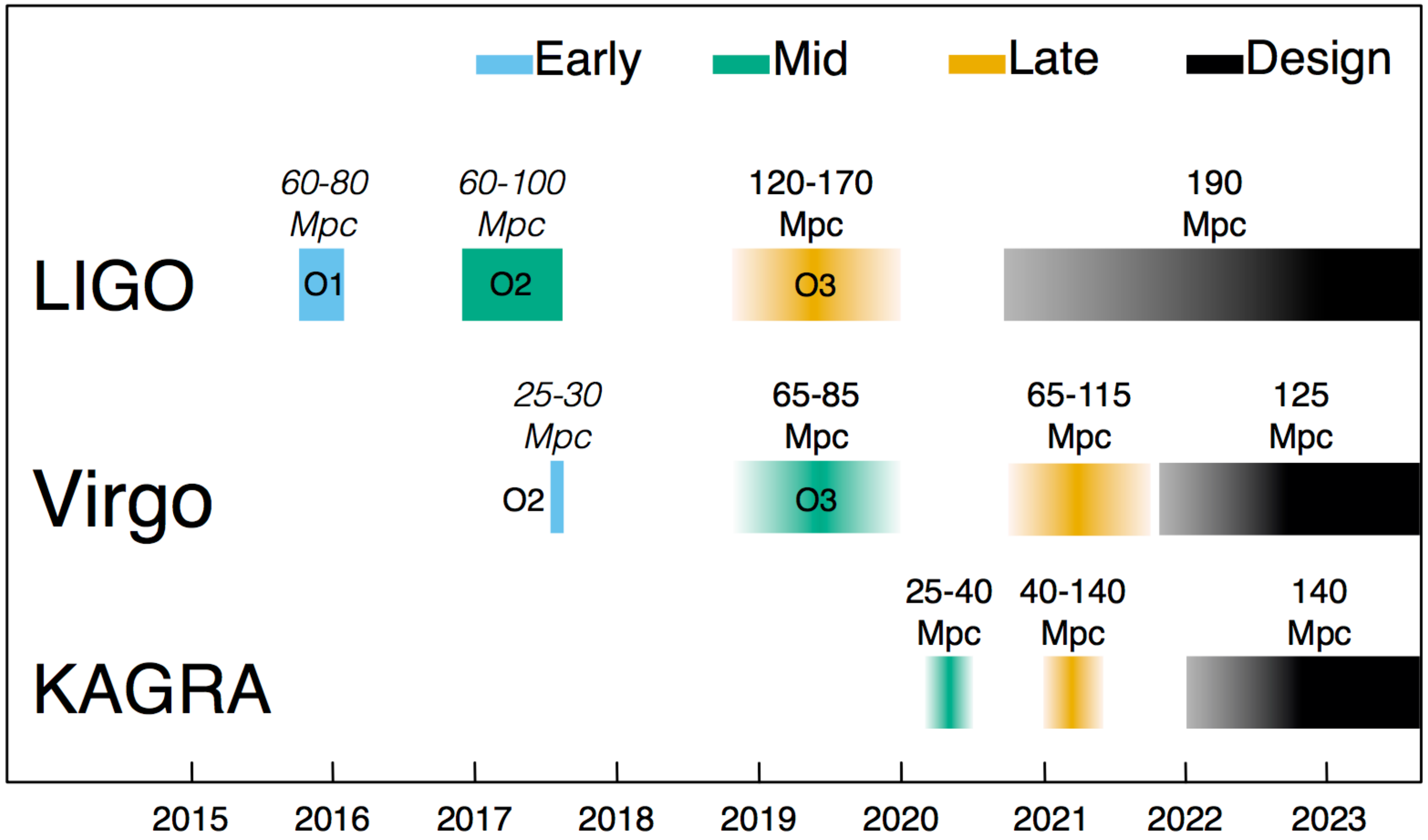
→ L ± 20 MeV

| | $^{208}$Pb @ MREX | $^{48}$Ca @ MREX | PREX-II | CREX |
|---|---|---|---|---|
| $E_{beam}$ | 155 MeV / 105 MeV | 155 MeV / 105 MeV | ≈ 1 GeV | 2.2 GeV |
| Q | 86 MeV / 58 MeV<br>0.44 fm$^{-1}$ / 0.29 fm$^{-1}$ | 143 MeV / 75 MeV<br>0.73 fm$^{-1}$ / 0.38 fm$^{-1}$ | 86 MeV<br>0.44 fm$^{-1}$ | 154 MeV<br>0.78 fm$^{-1}$ |
| $\delta A_{PV}/A_{PV}$ | 1.3% | 1.3% | 3.6% | 2.4% |

# Timeliness: LIGO et al.




L. Cadonati 56th International Winter Meeting on Nuclear Physics, Bormio, 2018




#MakeHumansSmartAgain

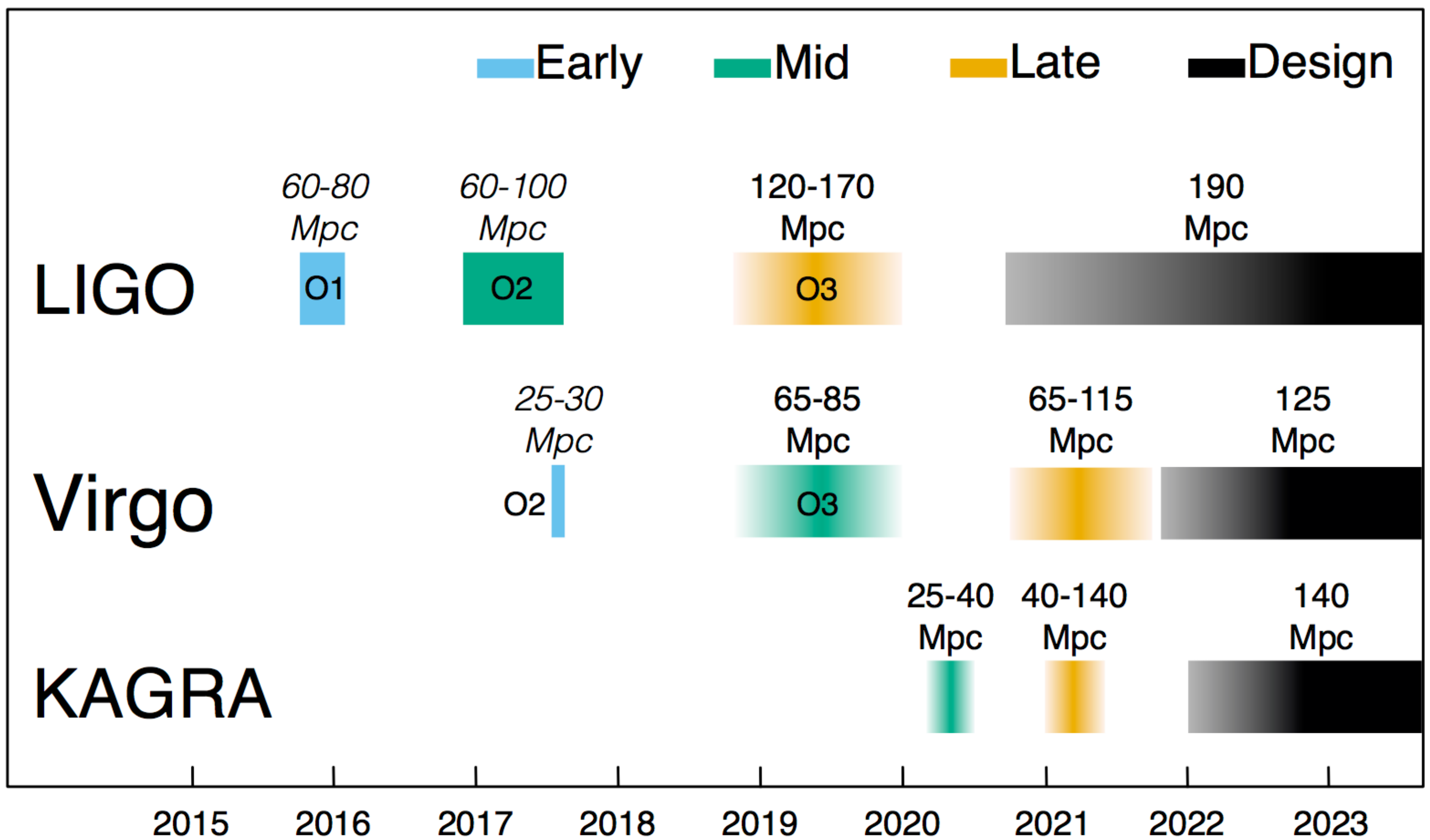
# Timeliness: LIGO et al.

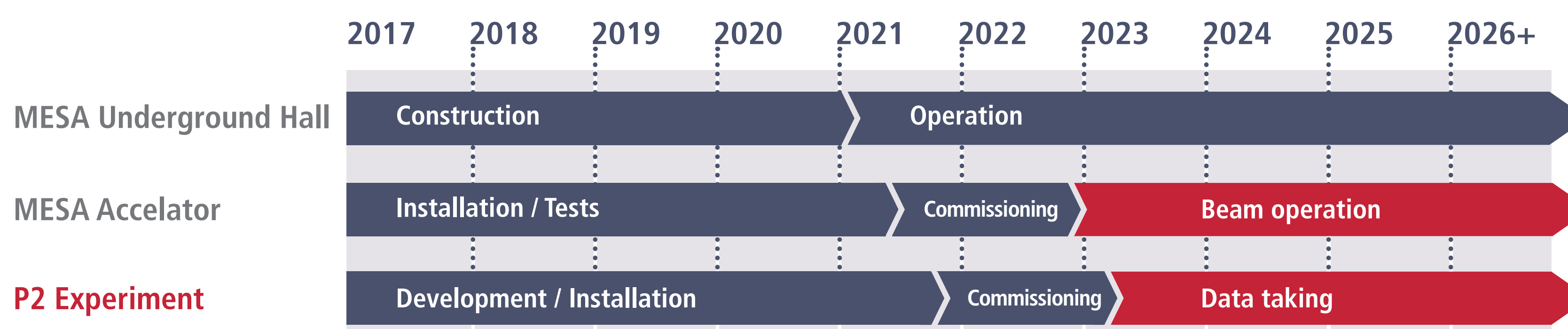
Leo C. Stein @duetosymmetry · 16 Oct 2017

@LIGO has now started to do nuclear physics! #GravitationalWaves #GW170817 5/5

26 102

L. Cadonati 56th International Winter Meeting on Nuclear Physics, Bormio, 2018

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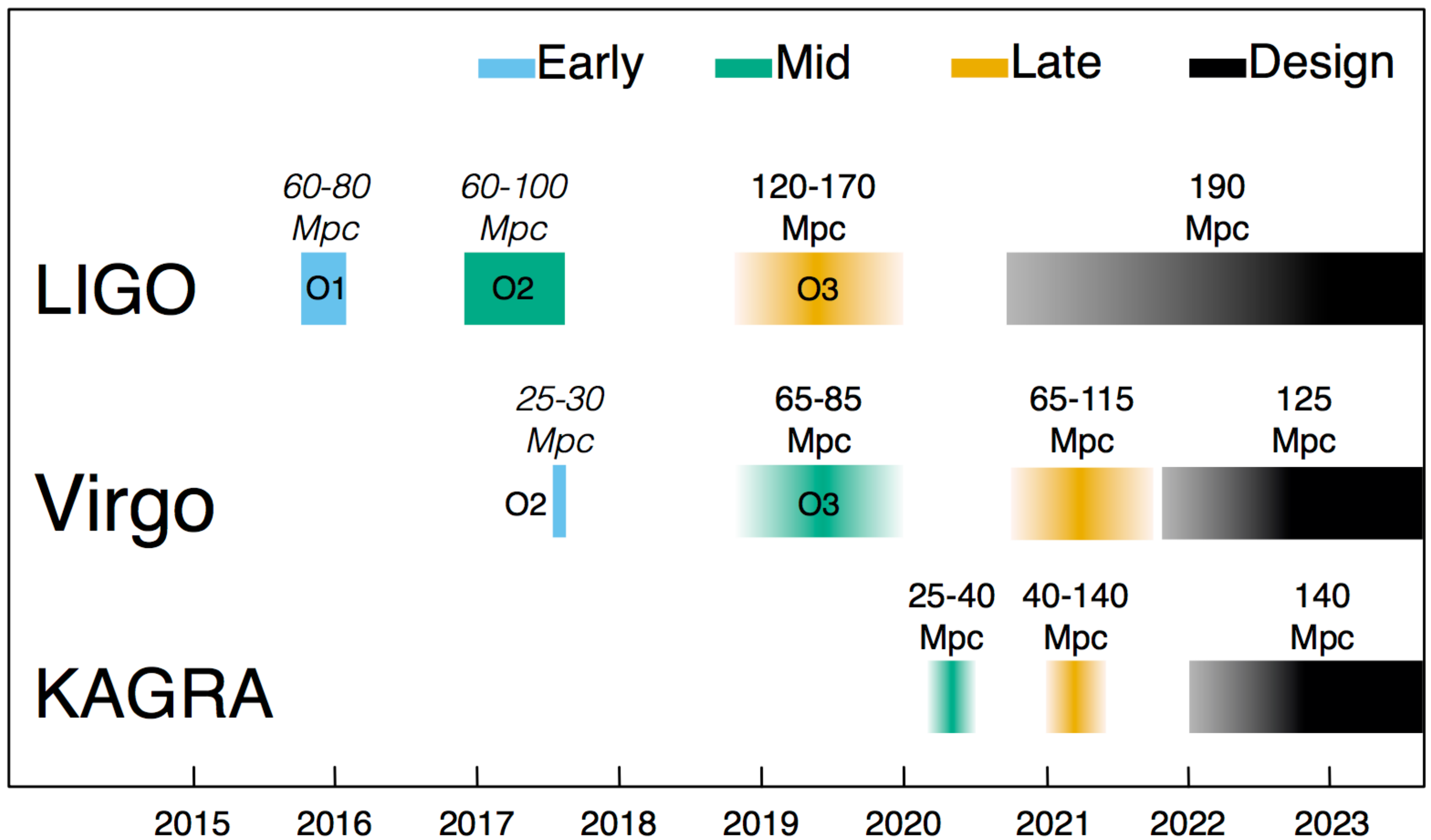
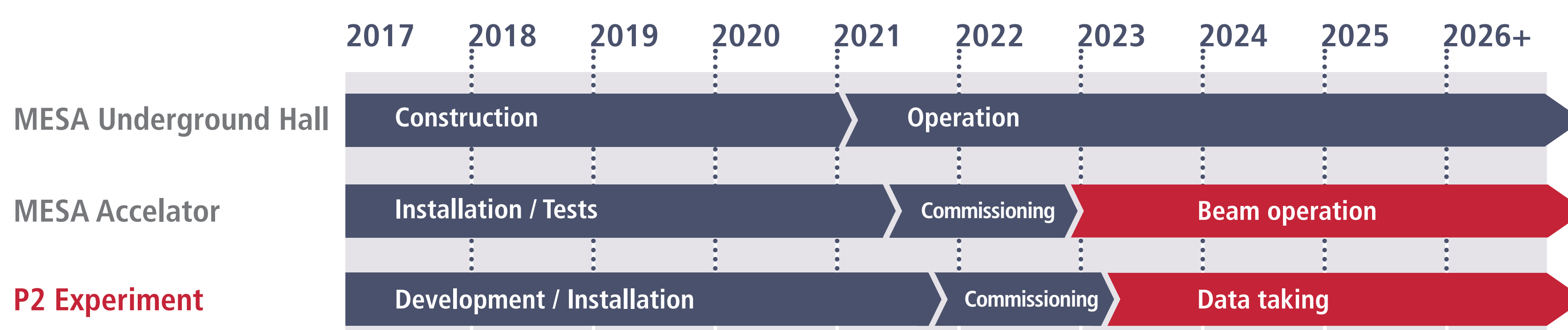
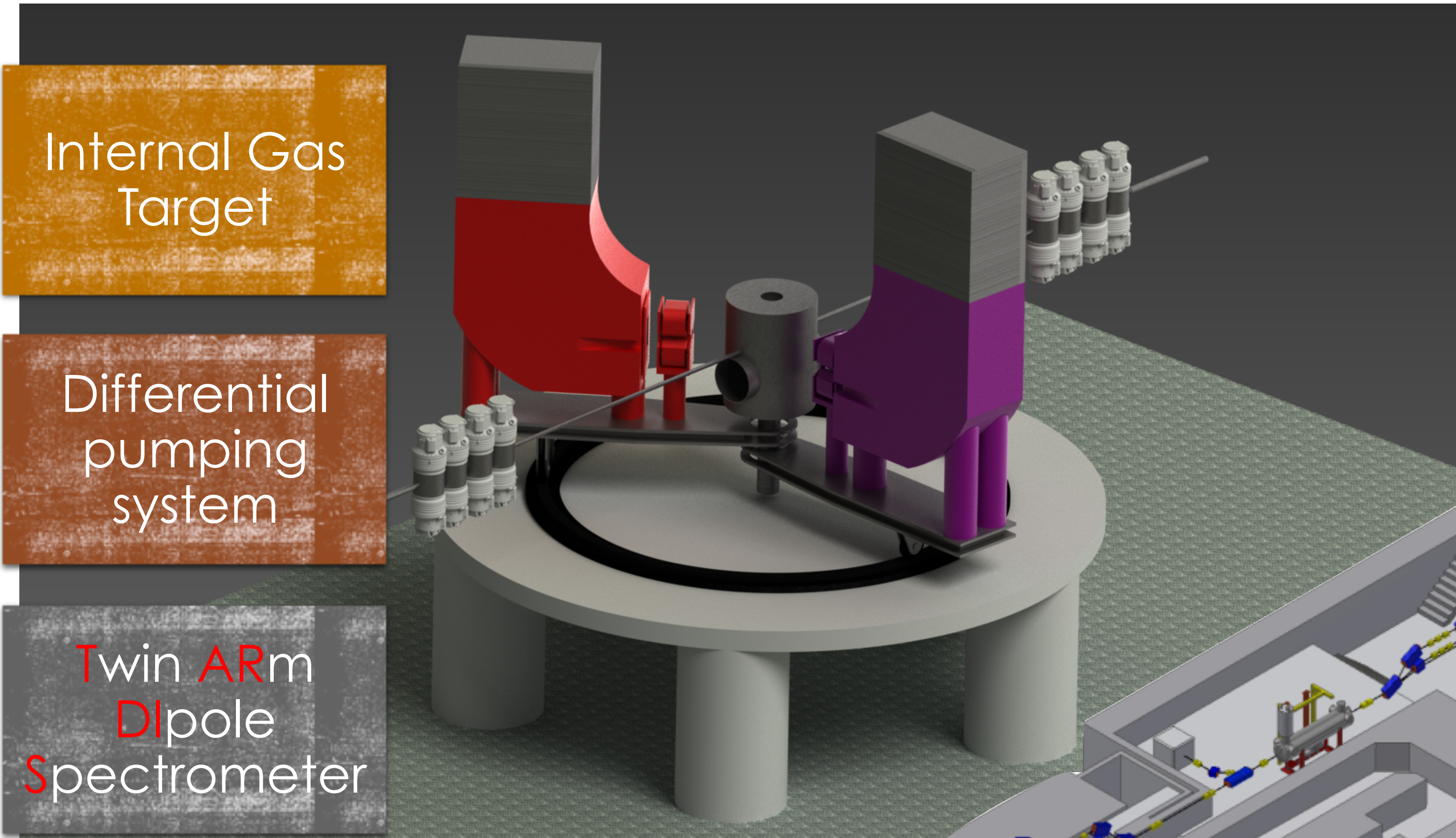


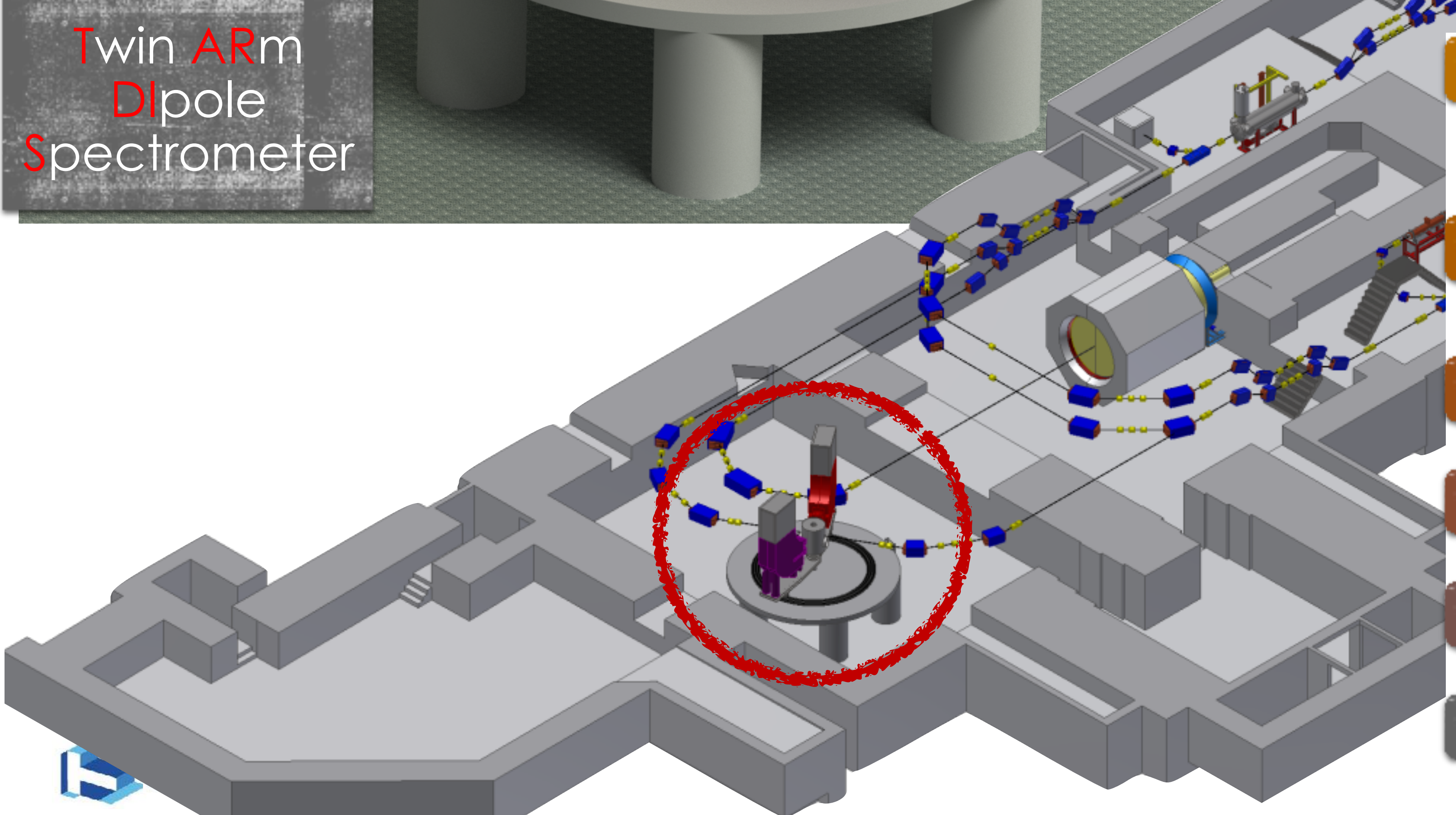

A lot more coming …




#MakeHumansSmartAgain

# The "Dark Side" of MESA



## High resolution on low momentum electrons

- 1 < p < 100 MeV
- $\frac{\Delta p}{p} \approx 10^{-4}$
- $\Delta\theta \cong 5 * 10^{-2}$ °

## Material reduction

- No window before the magnet
- Thin detector

## Large sensitive surface

- $120 * 30\ cm^2$ focal plane surface

## Good point resolution

- $50\ \mu m$ point resolution along the in the dispersive plane

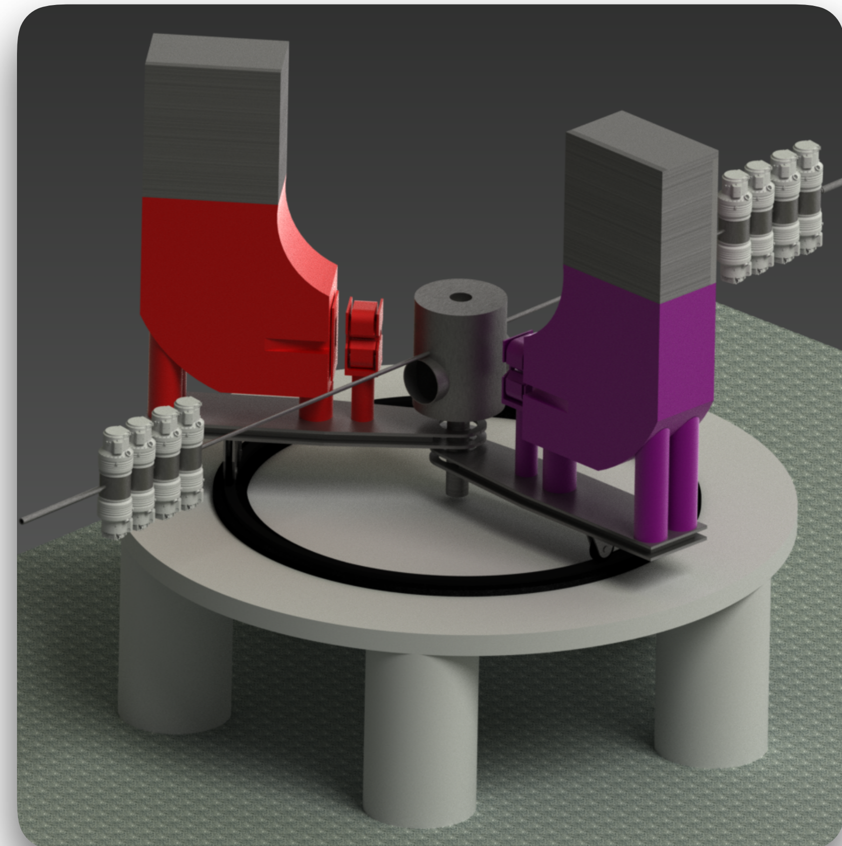
## Multiple samples

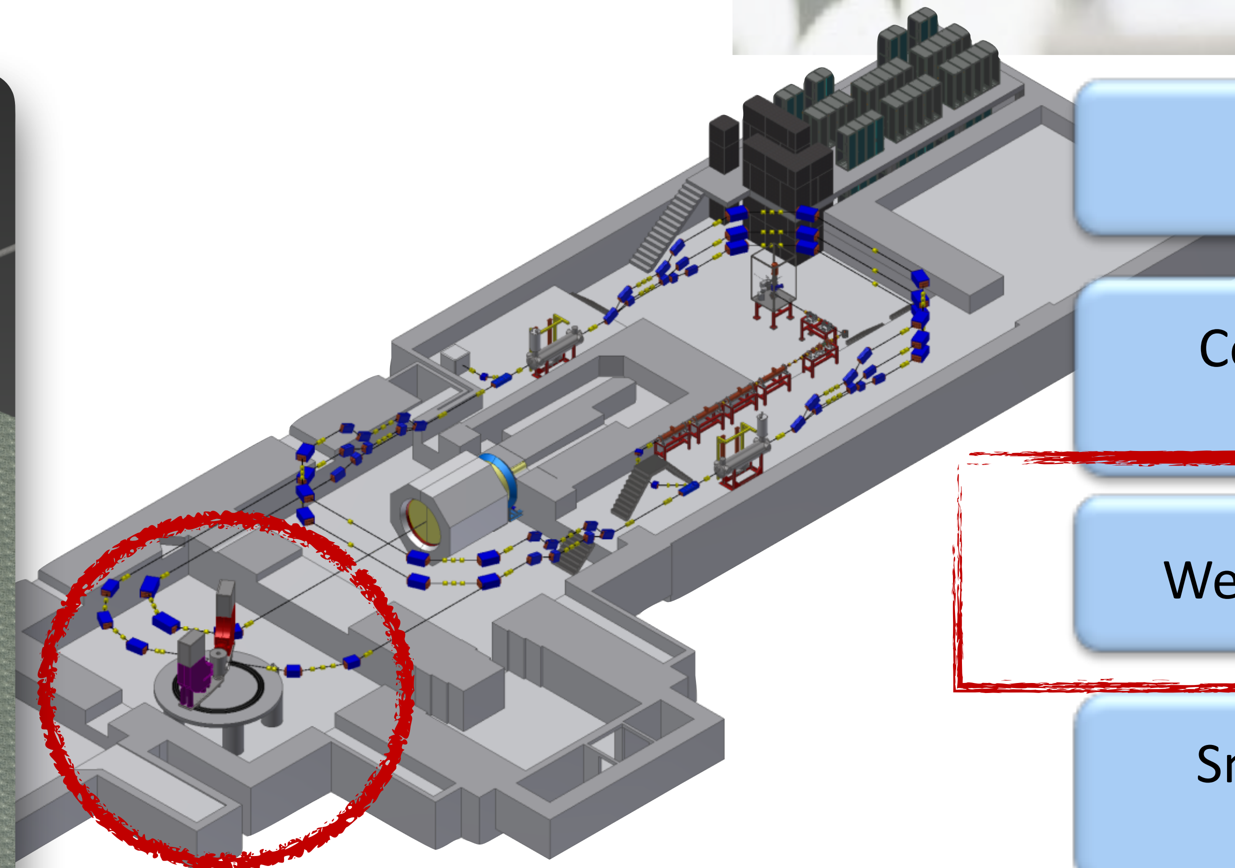
- At least 2 points to reconstruct the full kinematics

## High rate capability

- With a CW operation rates up to $O(1\ MHz)$

# Getting rid of model dependences





Measured $A_{PV}$
↓
Correct for Coulomb Distortions
↓
Weak density at one $Q^2$
↓
Small corrections for $G_E^n$ $G_E^s$ MEC
↓
Neutron density at one $Q^2$
↓
Assume surface thickness good to 25% (MFT)
↓
$R_n$

Addition to the P-C-MREX measurements program
Ex: Measurement of surface thickness (≈15%)

Final estimates ongoing: MAGIX TDR in 2019

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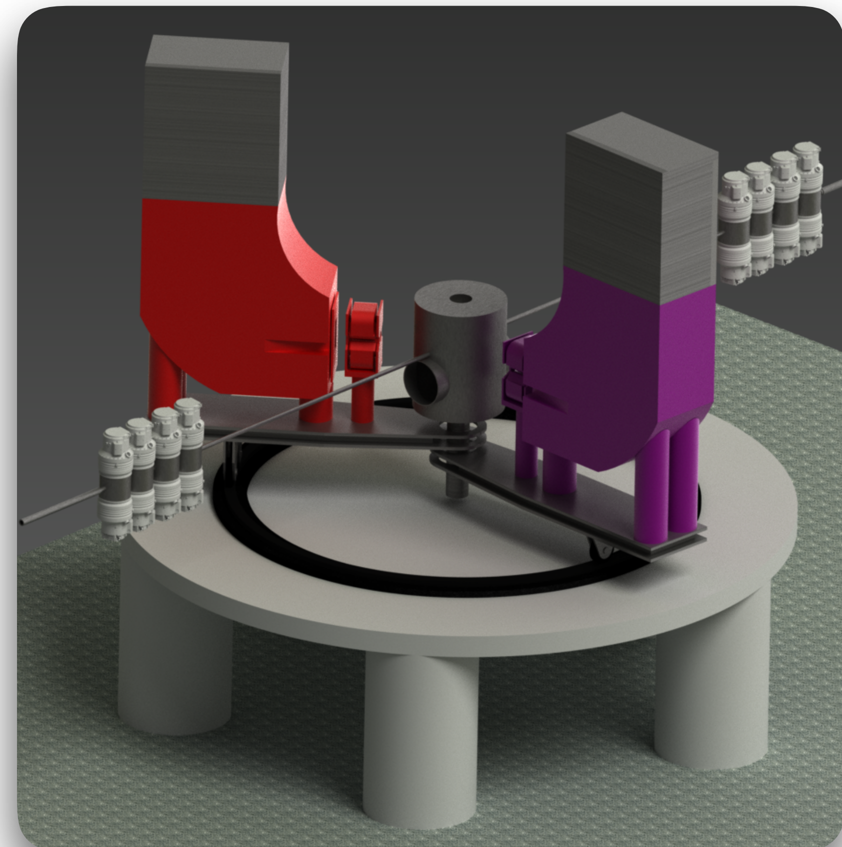

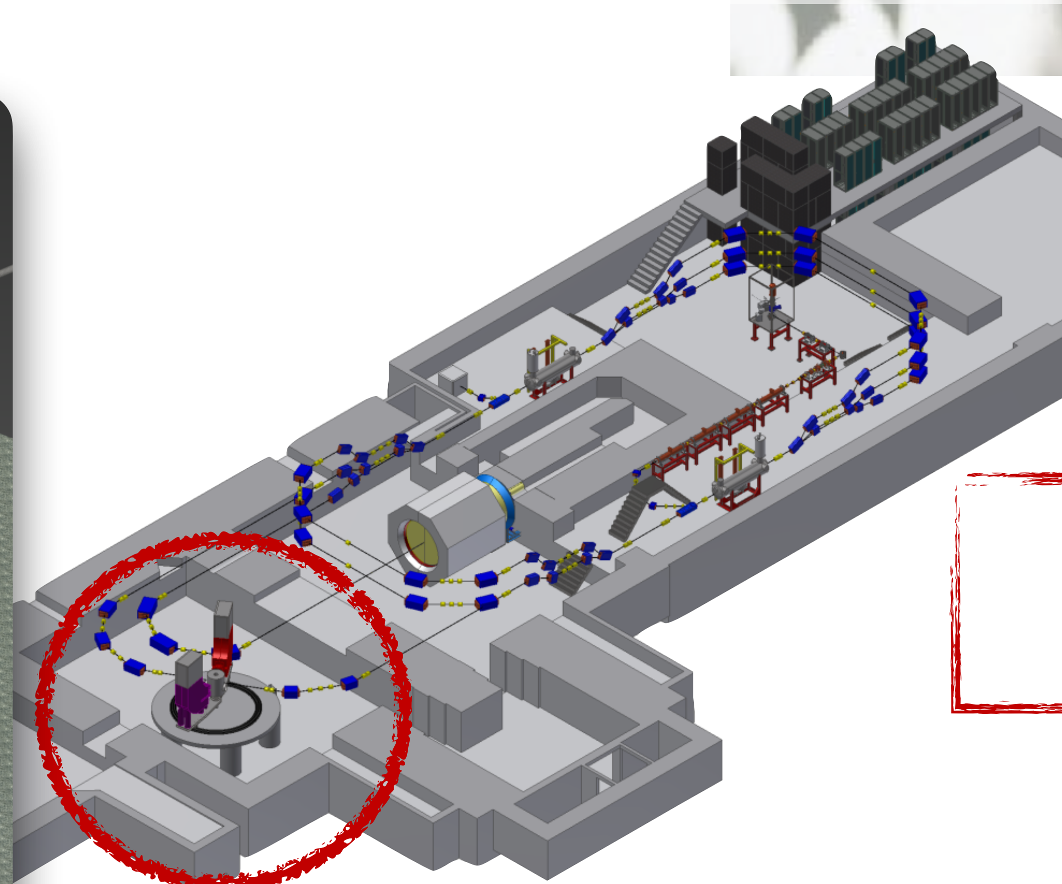

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+ complement A1 Program on beam-normal single spin asymmetries ($A_T$)

*… am I running out of time? (Y/N)*

# “Background” measurements at MAMI

*Beam normal (single-spin) asymmetry*

- Count rate asymmetry in elastic e-scattering for transverse polarisation (normal to scattering plane)
- No PV effects BUT:

➢ Helicity-correlated background contribution in PV experiments caused by transversal polarisation component

➢ Necessary to measure for all targets used in PV experiment

# “Background” measurements at MAMI

*Beam normal (single-spin) asymmetry*

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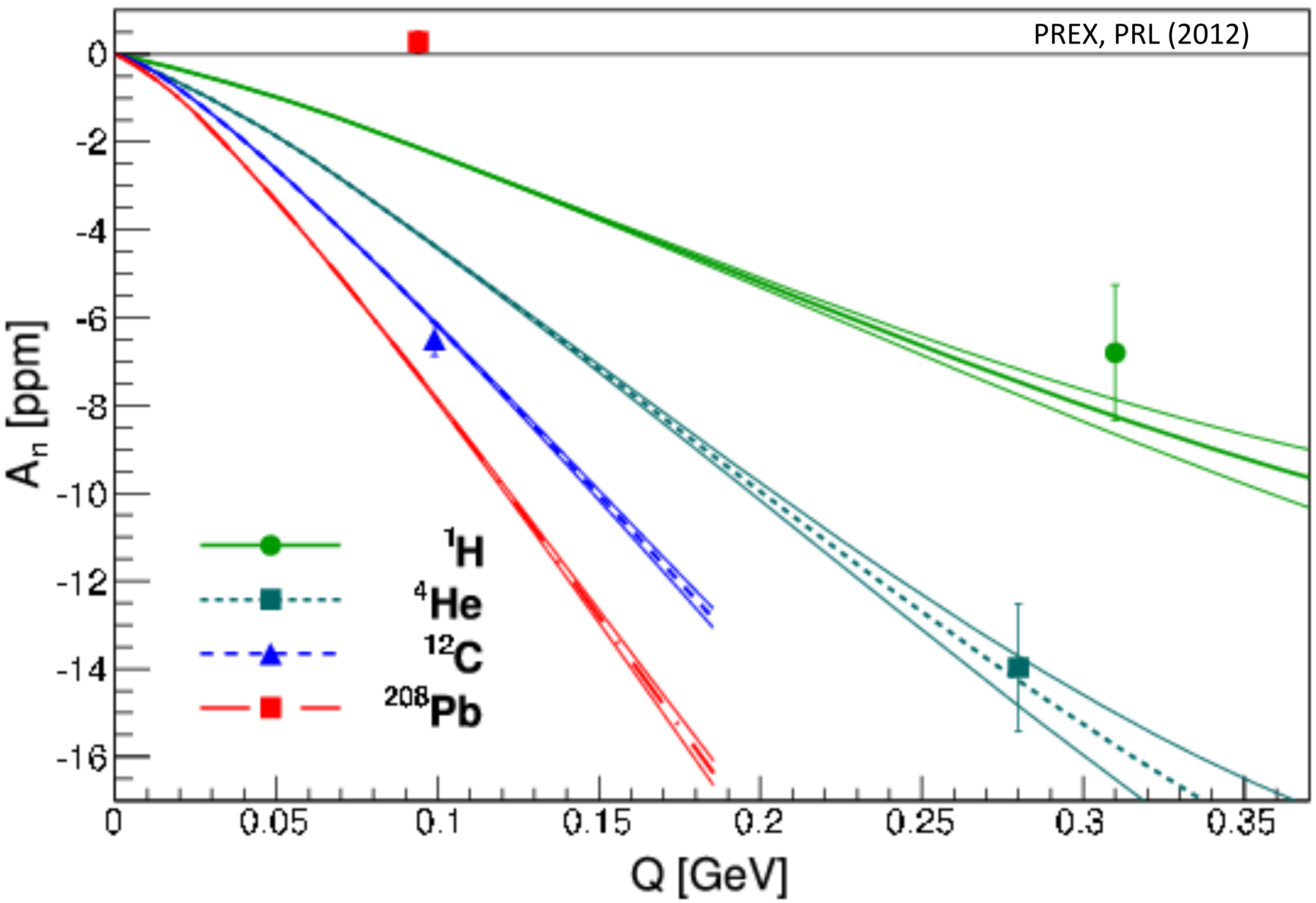
- No PV effects BUT:

  - Interference term between one- and multi-photon exchange

➢ First phase: MAMI



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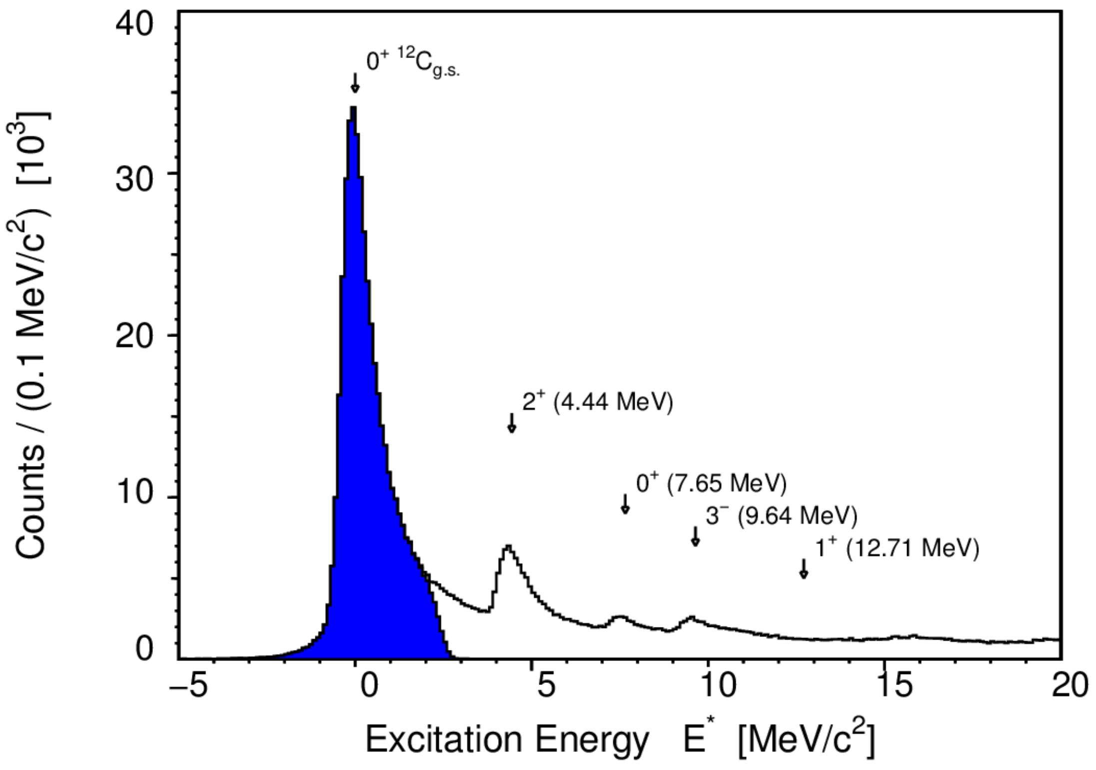
*Beam normal (single-spin) asymmetry*

- Elastic peak is well-separated in precision spectrometers



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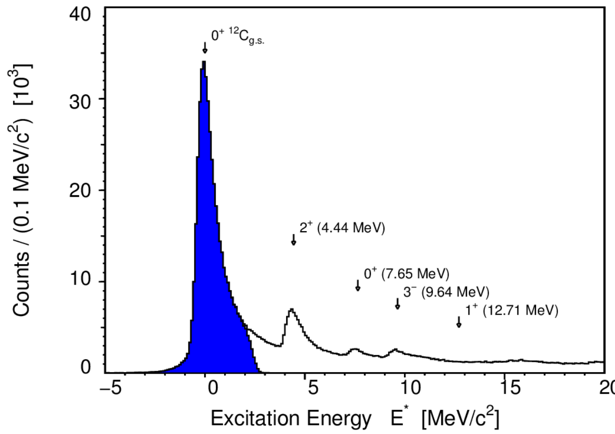
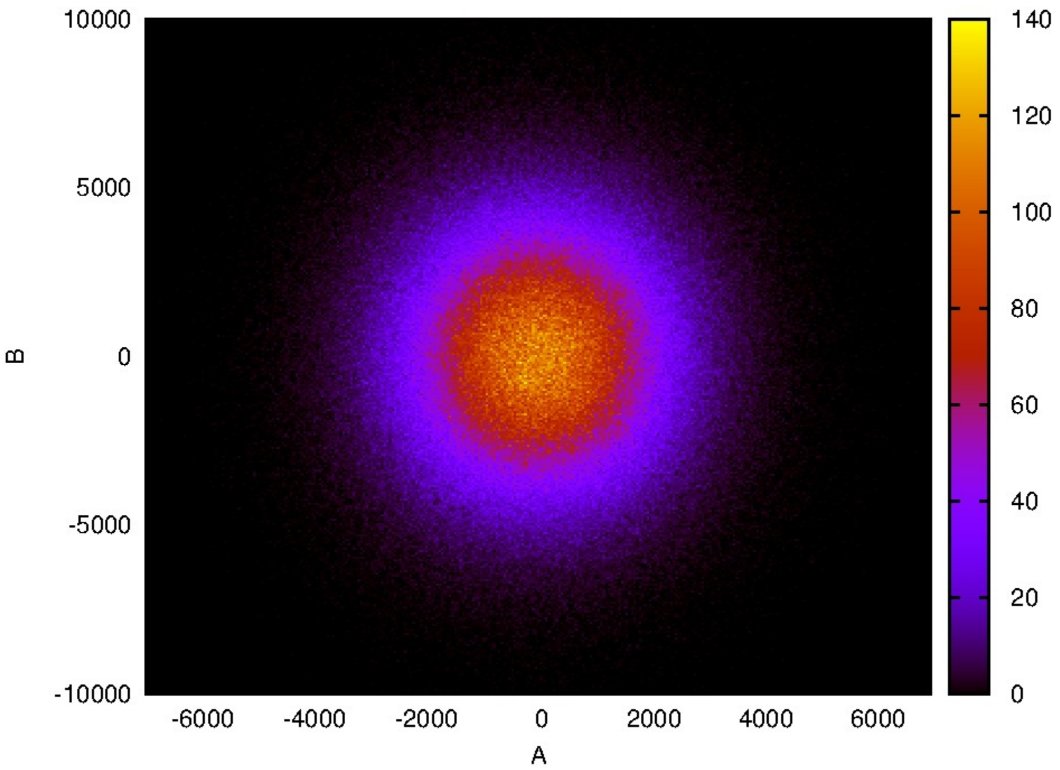



- Raw data is uncorrelated between left/right spectrometers: highly stabilised beam!



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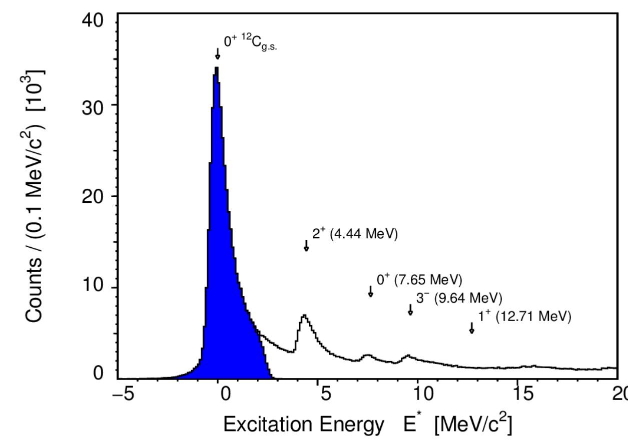


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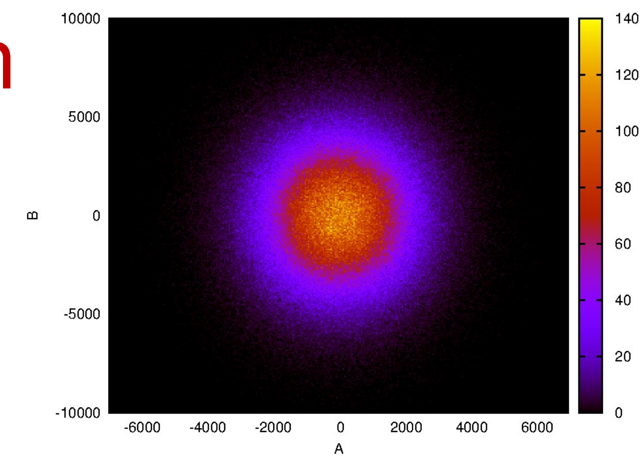
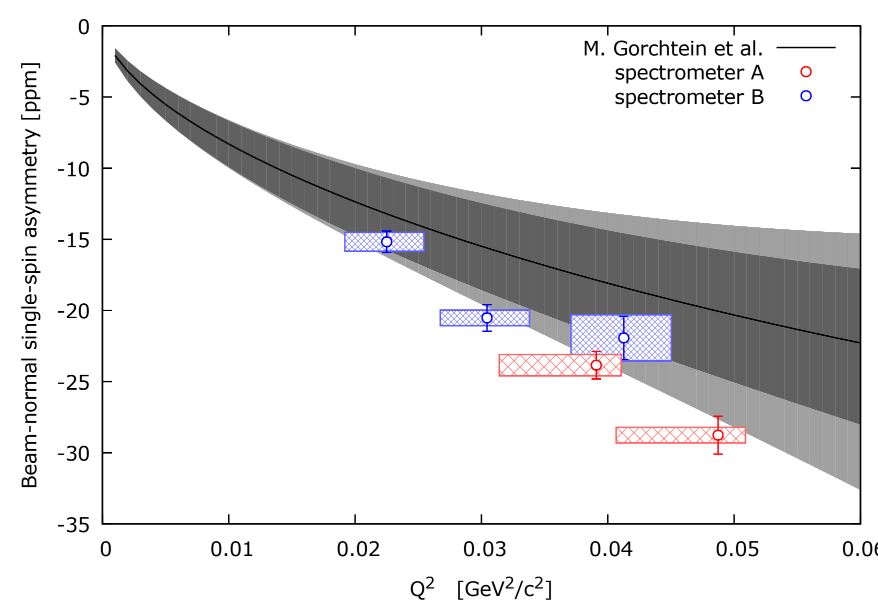



- Systematic study on $^{12}C$: future studies on other targets

➢ Improving theory

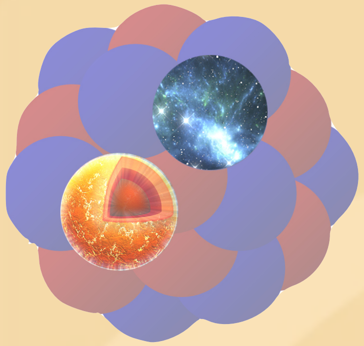
➢ Lowest Q@MAGIX

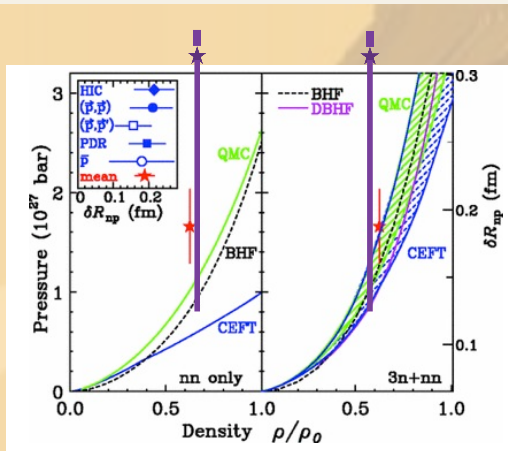



CONCETTINASFIENTI

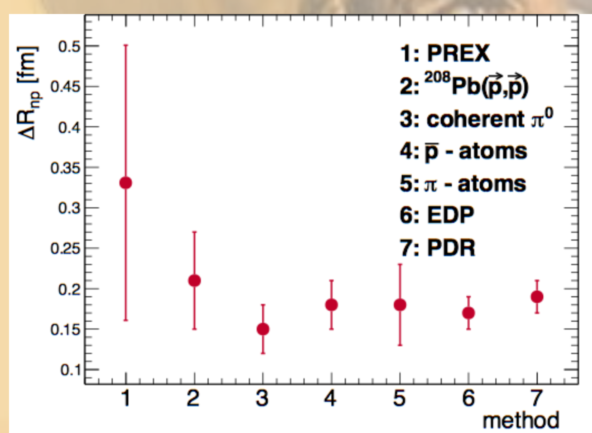
#MakeHumansSmartAgain

# Neutron Skin in Nuclei: a story about…






**the Good…**




**the Bad…**


**AND THE UGLY**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