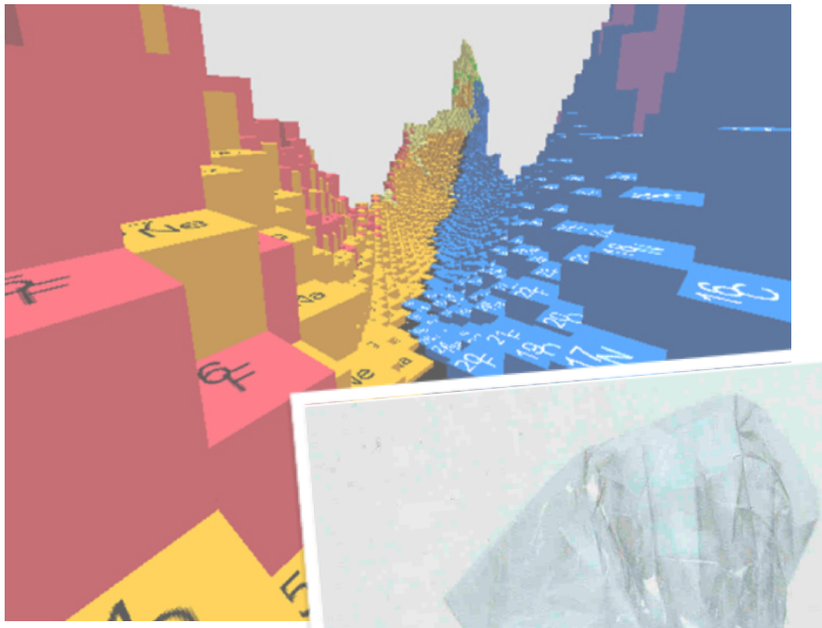
Per Aspera ad Astra ...

Frontiers in precision nuclear physics

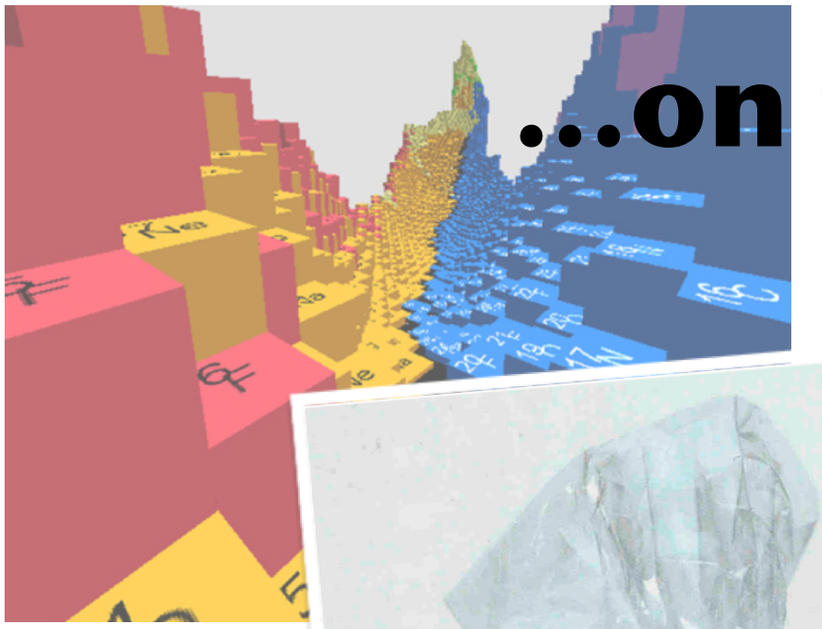
Concettina Sfienti
Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

Aiming at simplicity...



Ursus Wehrli, Noch mehr Kunst aufräumen

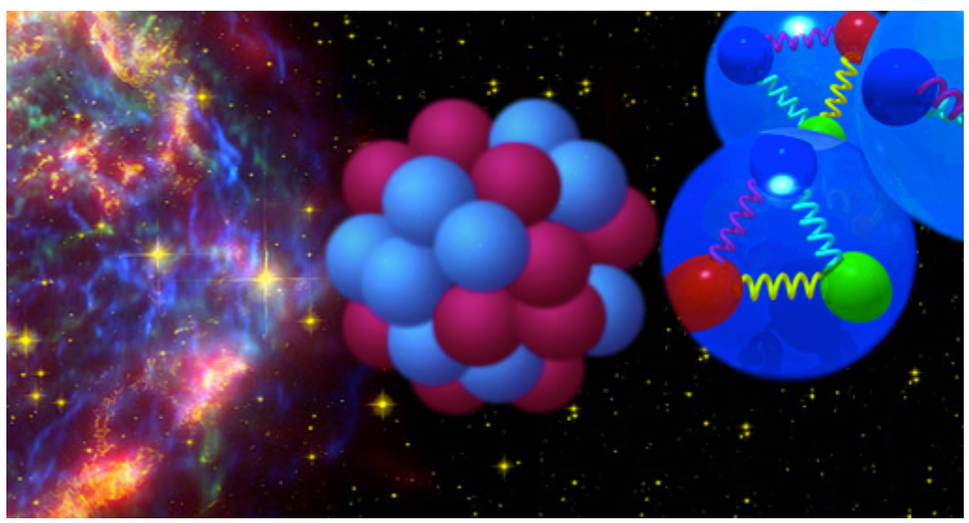
...on the far side of complexity!



Ursus Wehrli, Noch mehr Kunst aufräumen

Seurat, Les Poseuses

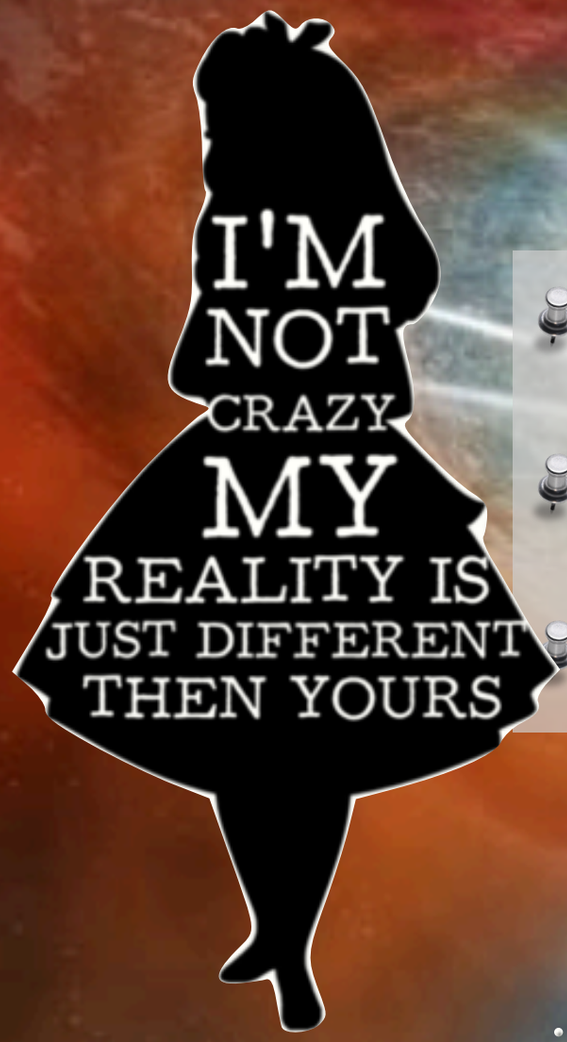
...connecting quarks with stars ...



Courtesy R.F.Carsten (WNSL)

Per Aspera ad Astra ...

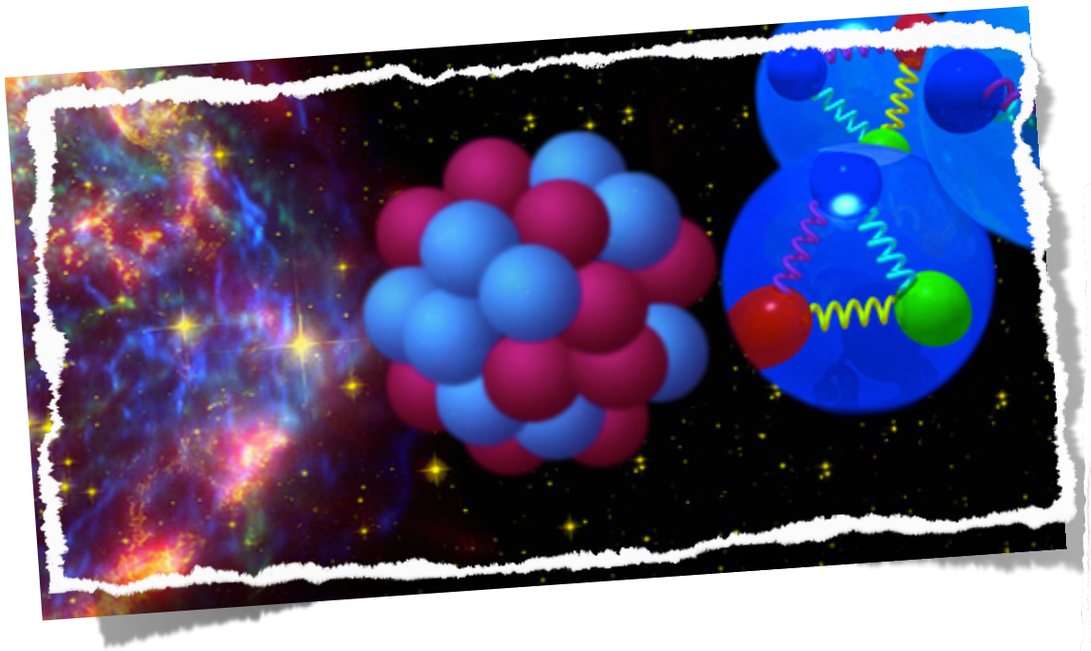
A romance in three acts with 4, 208 and (*for all practical purposes*) ∞ performers!

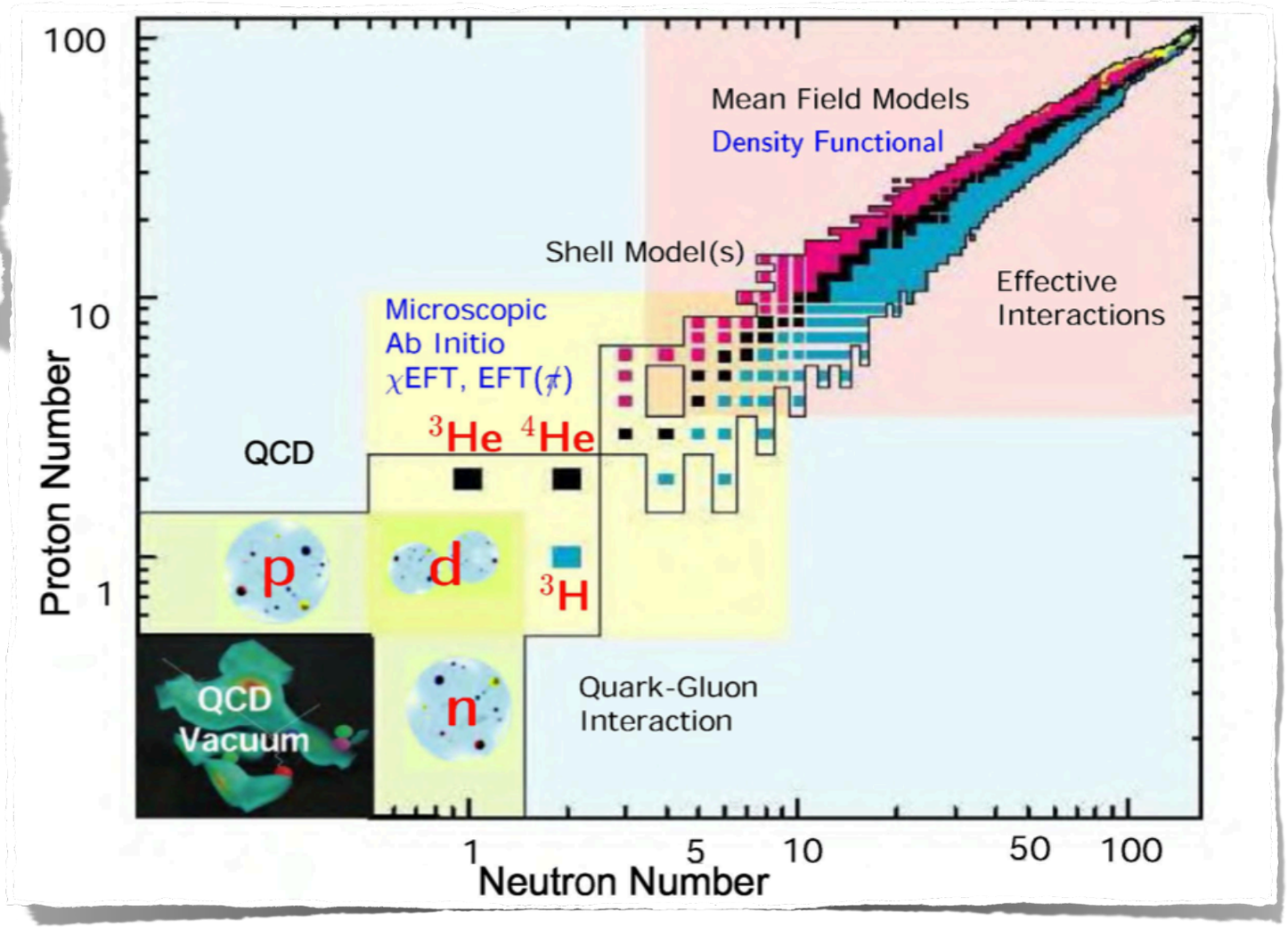


- **The 4-horsemen of the Apocalypse**
- **Rebellious skins**
- **...to infinity and beyond**

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

“Scales”: First constraint

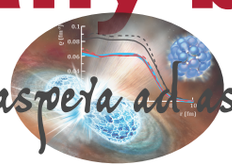




Modern nuclear physics is about…

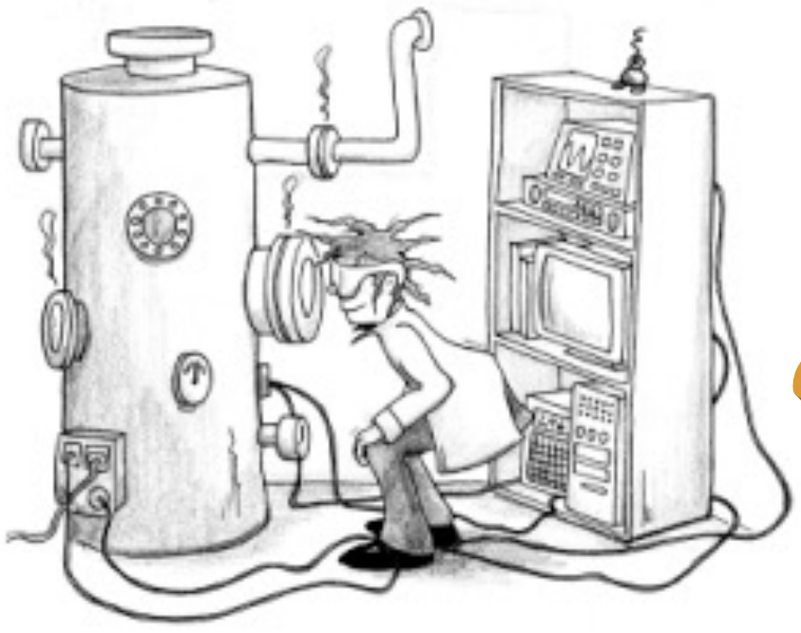
UNEDF SciDAC Collaboration
Universal Nuclear Energy Density Functional

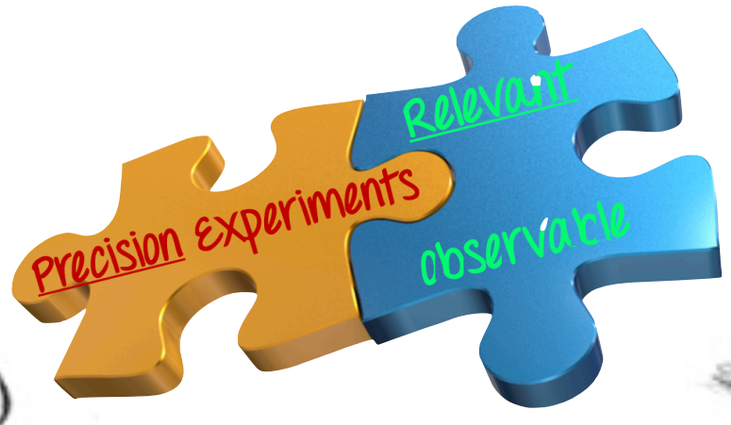
→Linking QCD to many body systems

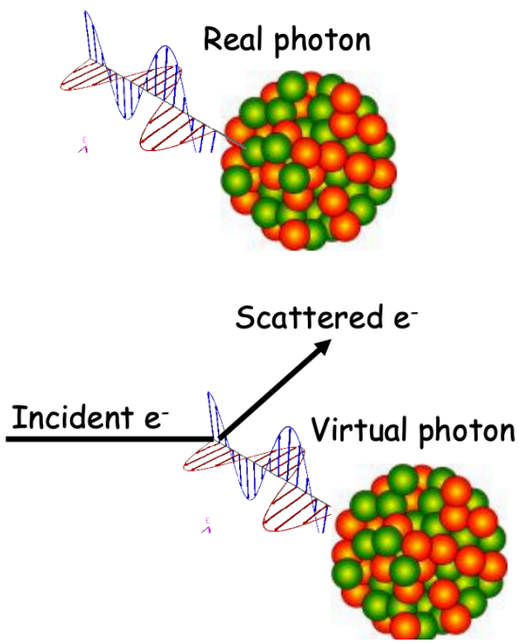


… per aspera ad astra …

A scientific... tango





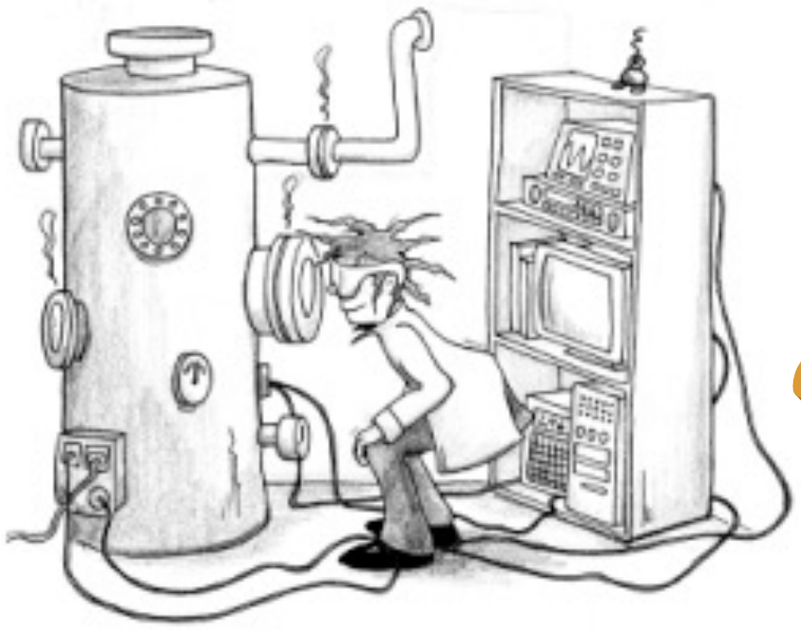


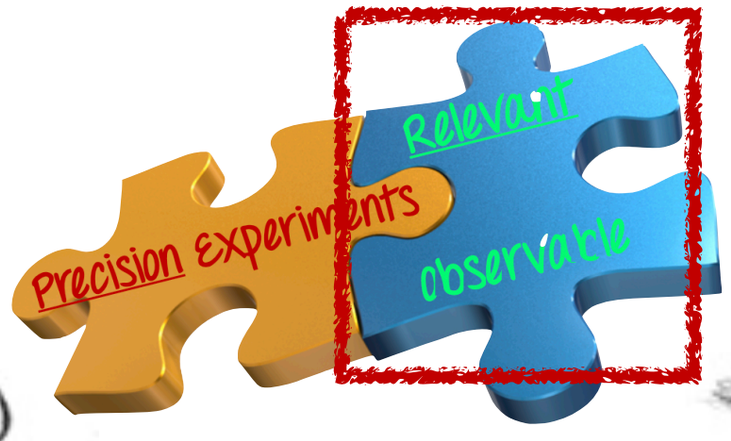
"With the electro-magnetic probe, we can immediately relate the cross section to the matrix element of the current operator, thus to the structure of the target itself"

(De Forest-Walecka, Ann. Phys. 1966)

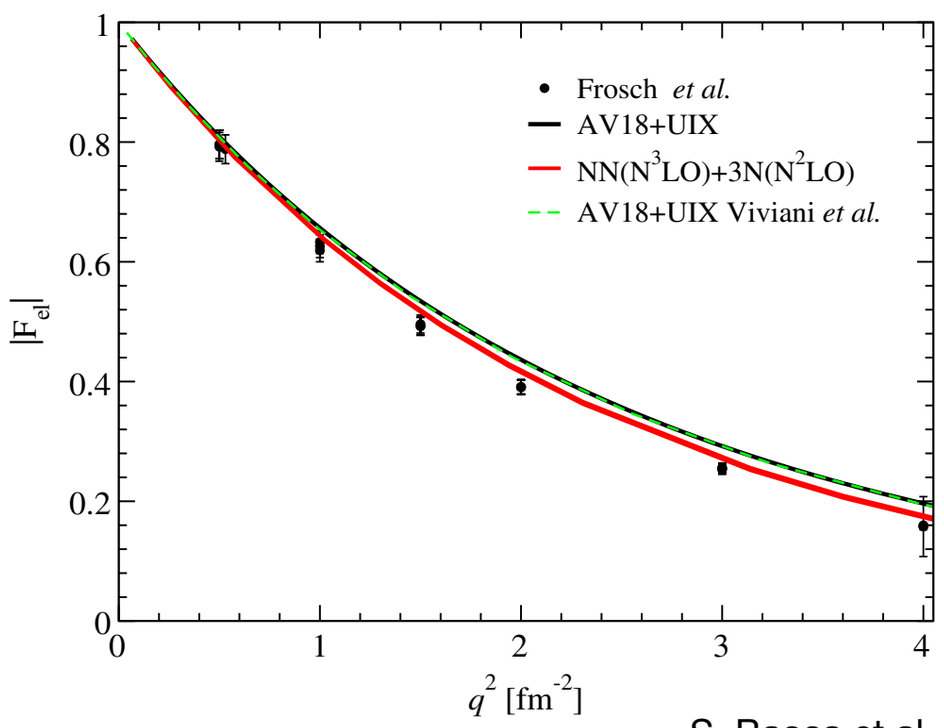
$$\sigma \propto \left| \langle \Psi_f | J^\mu | \Psi_0 \rangle \right|^2$$

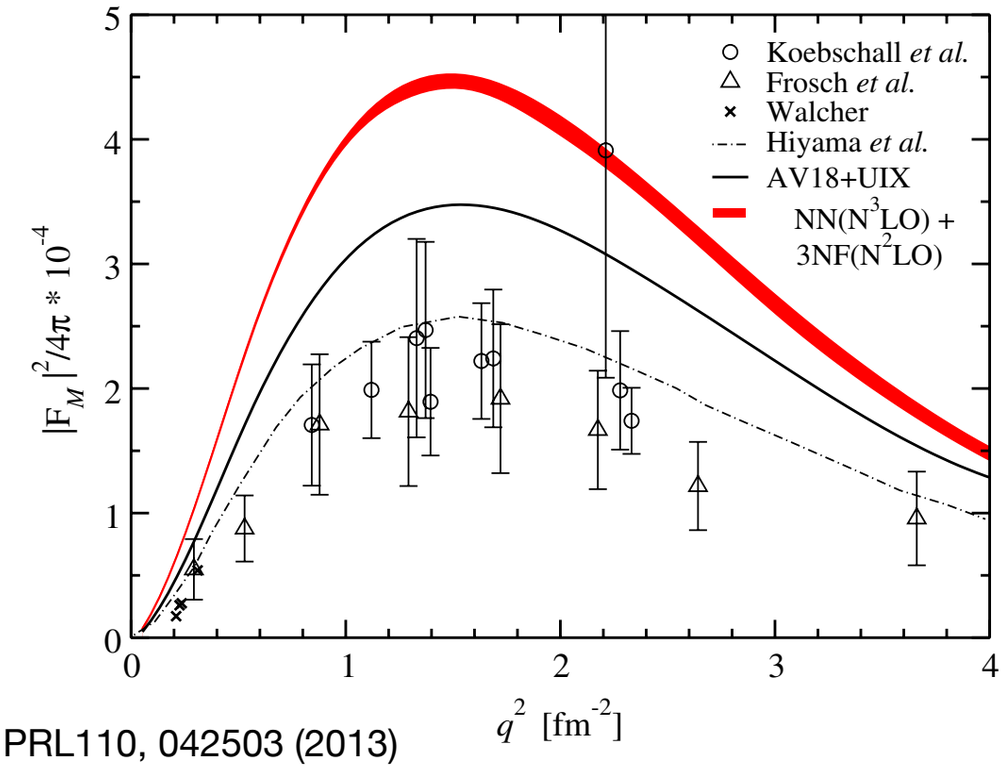
A scientific... tango





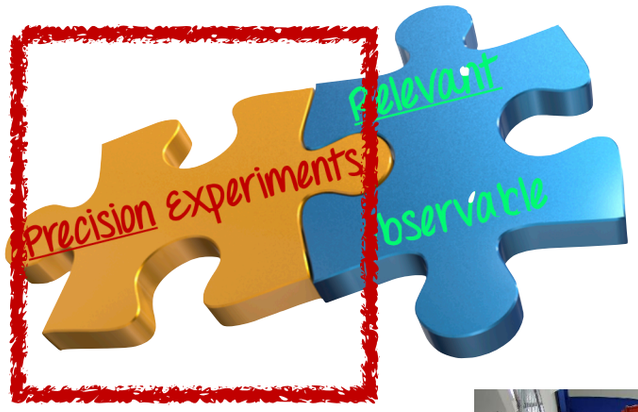
- Exact calculations both for bound and scattering states
- Energy and momentum transfer MUST be consistent with ChEFT predictions!



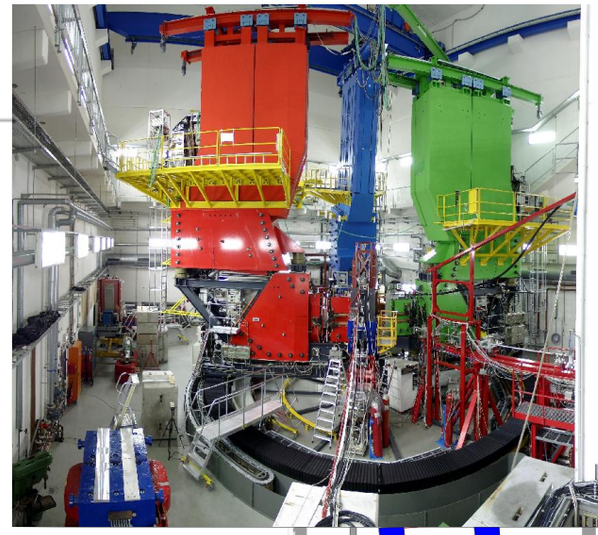


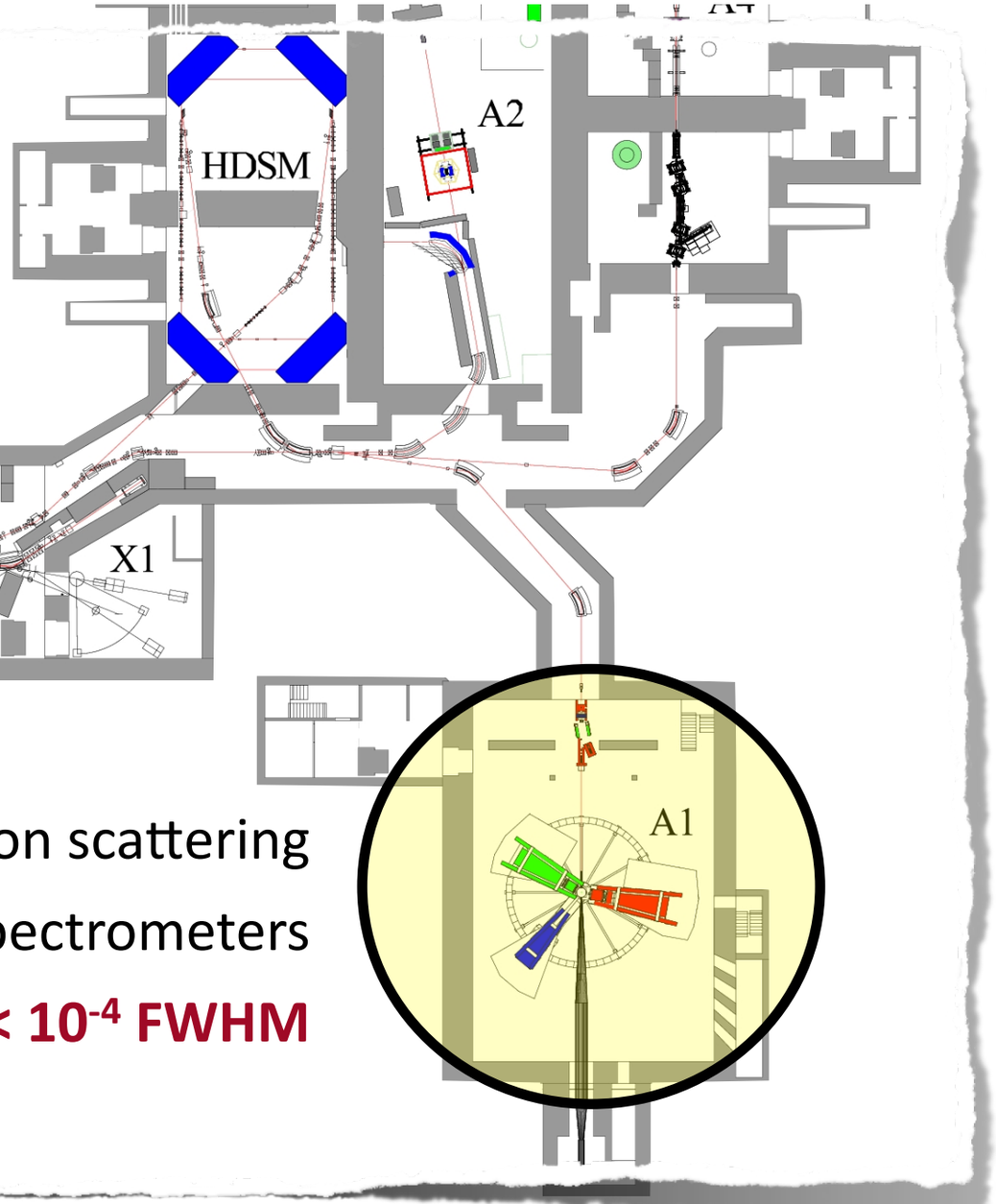
S. Bacca et al, PRL110, 042503 (2013)

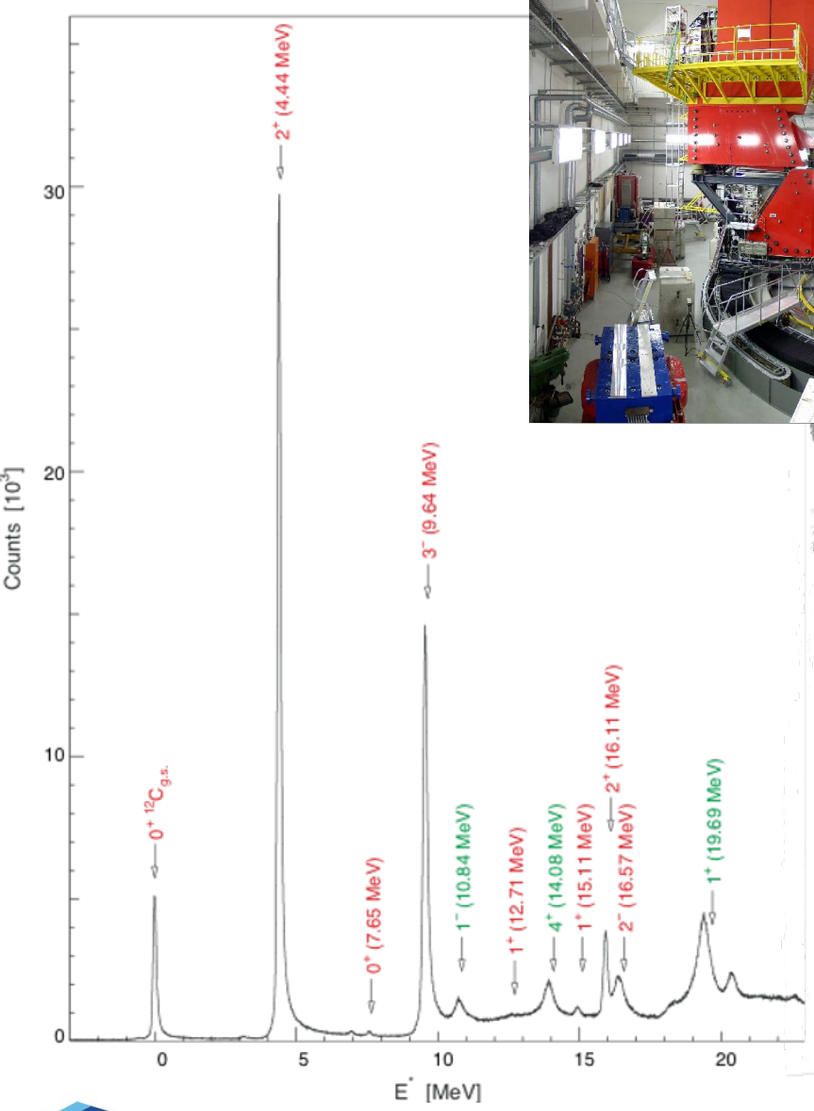
Precision experiment



ToDo: Define highest precision achievable (HM: “A1 kann alles”)



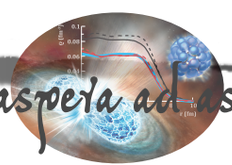




A1: Electron scattering

Three **High Resolution** Spectrometers

$\Delta p/p < 10^{-4}$ FWHM



... per aspera ad astra ...

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#MakeHumansSmartAgain

The four horsemen of the Apocalypse

Theory and experiment disagree on alpha particles

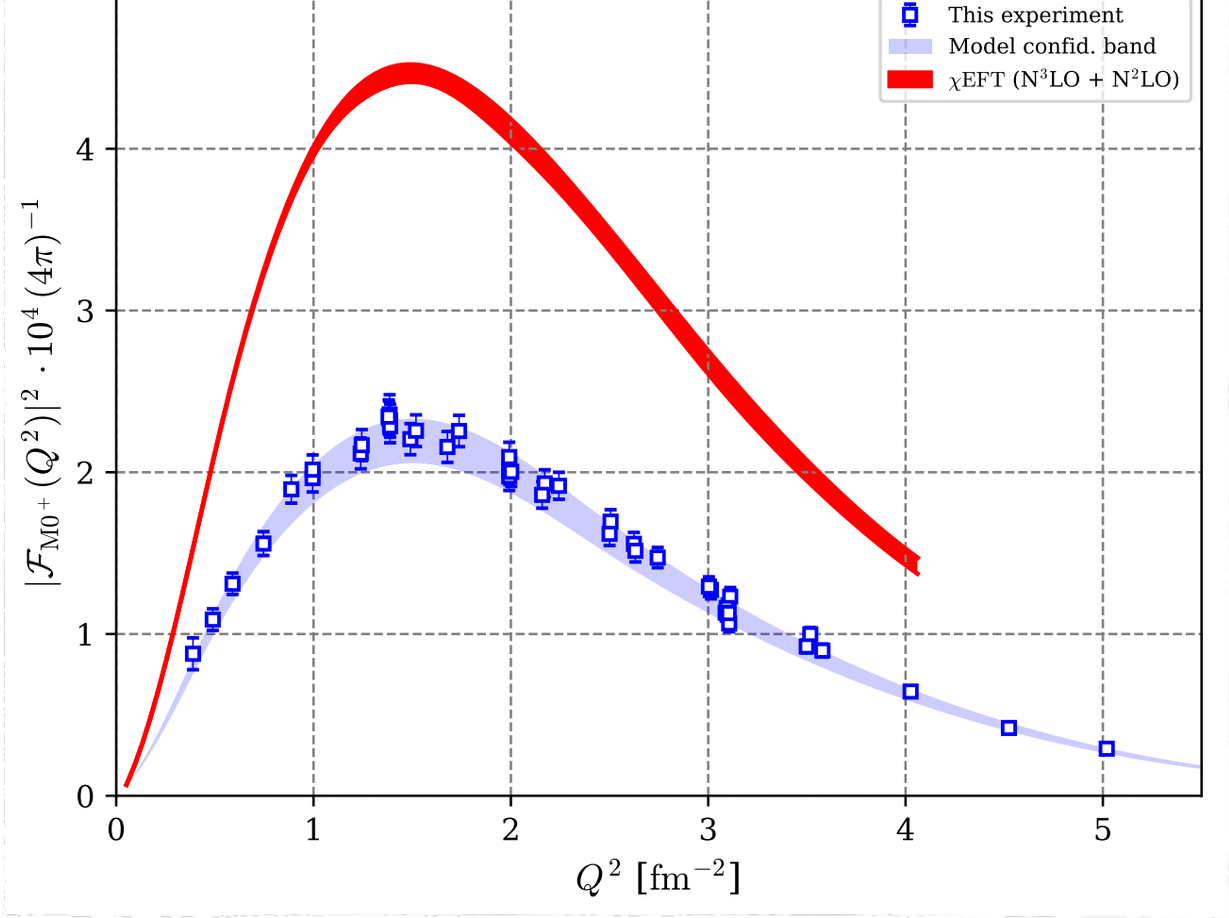
Electron-scattering experiments on excited helium nuclei open questions about the accuracy and sensitivity of state-of-the-art nuclear models.

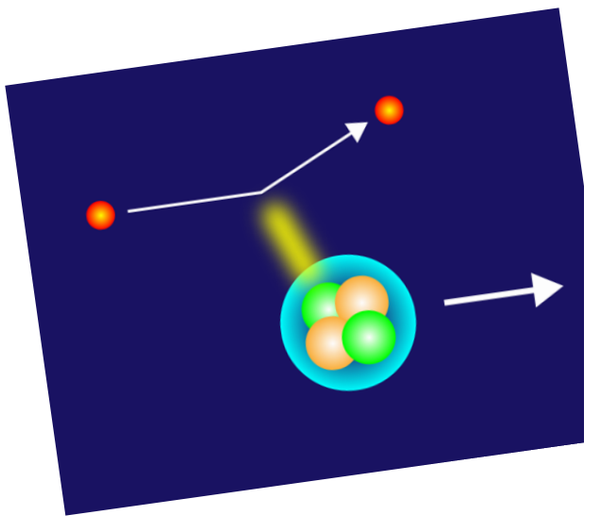
Although the helium nucleus has just four nucleons—two neutrons and two protons—theoretical models fail to replicate some of its properties.

ter. The researchers' calculations of a quantity related to how the nucleons are arranged in the alpha particle's first excited state didn't match the values inferred from electron-scattering experiments. The experiments were primarily from t
the uncertaint
intervening d
and technolog
tor sensitivity
ically, but that

tween theory and expe
and her colleagues deci
and improve experime
tion was warranted. Nov
theory collaborators hav
disagreement and char

PRL **130**, 152502 (2023)





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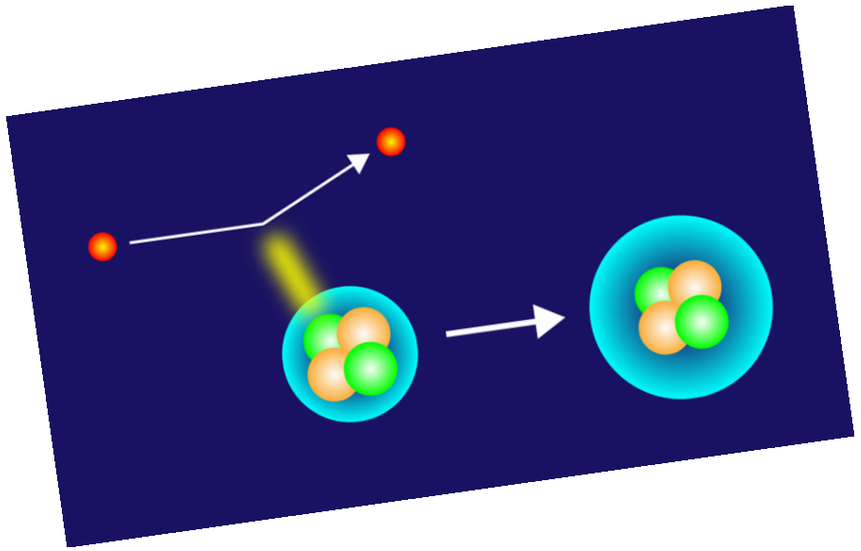
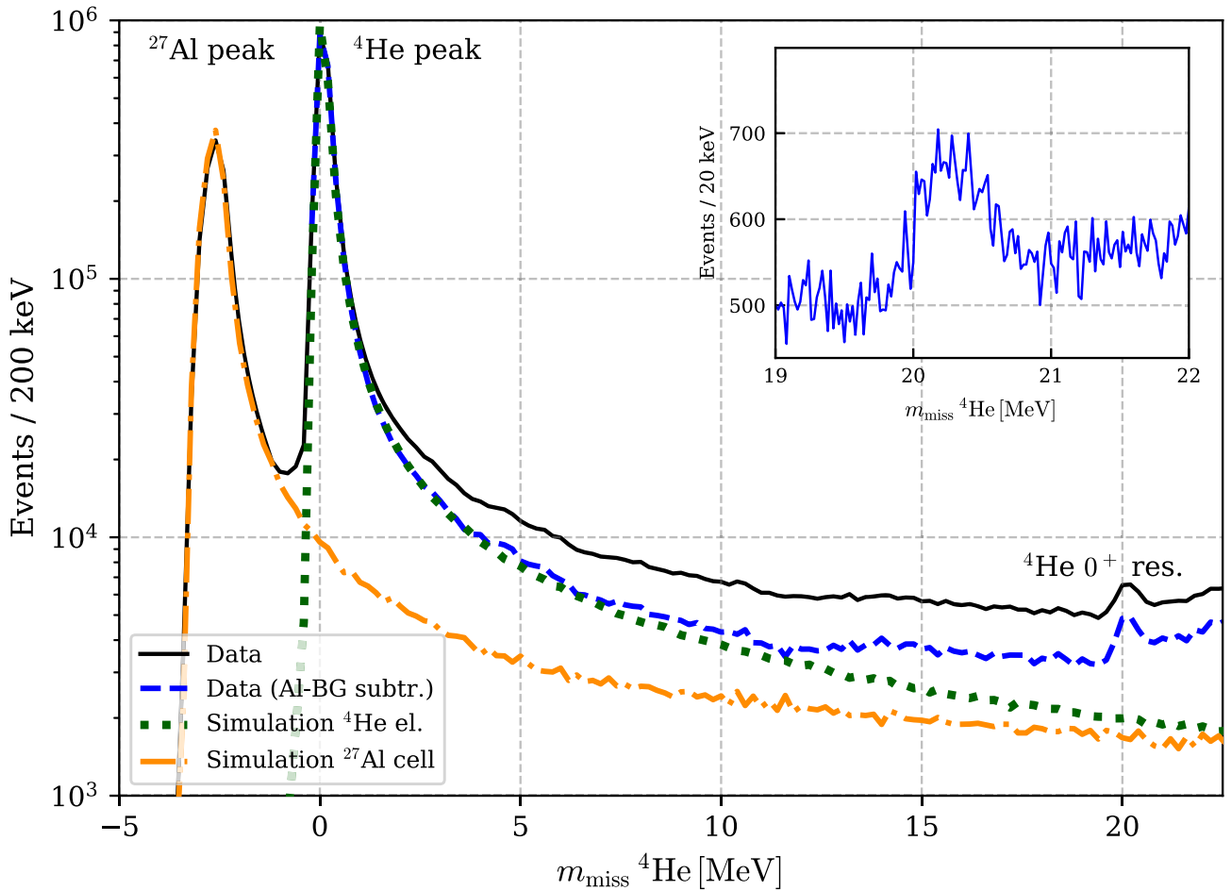
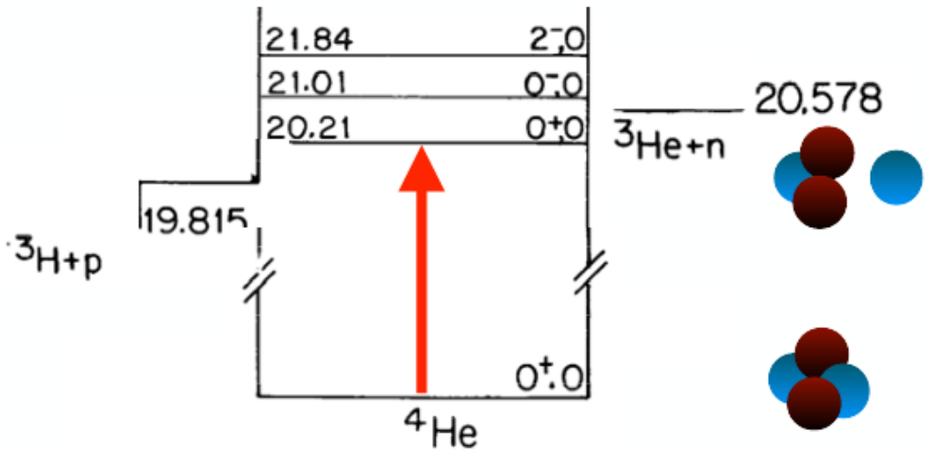
The four horsemen of the Apocalypse



The transition form factor describes the dynamics of excitation between resonance and ground state depending on Q^2



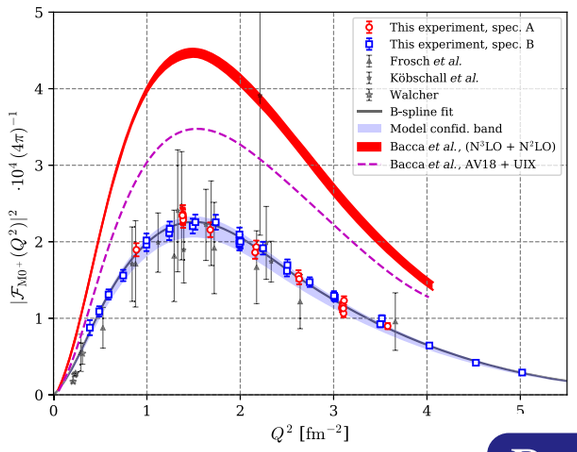


^{4}He TRANSITION FORM FACTOR

$$\mathcal{F}_{M0+}(Q^2) \propto | < 0_2^+ | \mathcal{M}(Q^2) | 0_1^+ > |$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{exp}} \propto |\mathcal{F}_{M0+}(Q^2)|^2 \propto \mathbf{Events}$$

The four horsemen of the Apocalypse



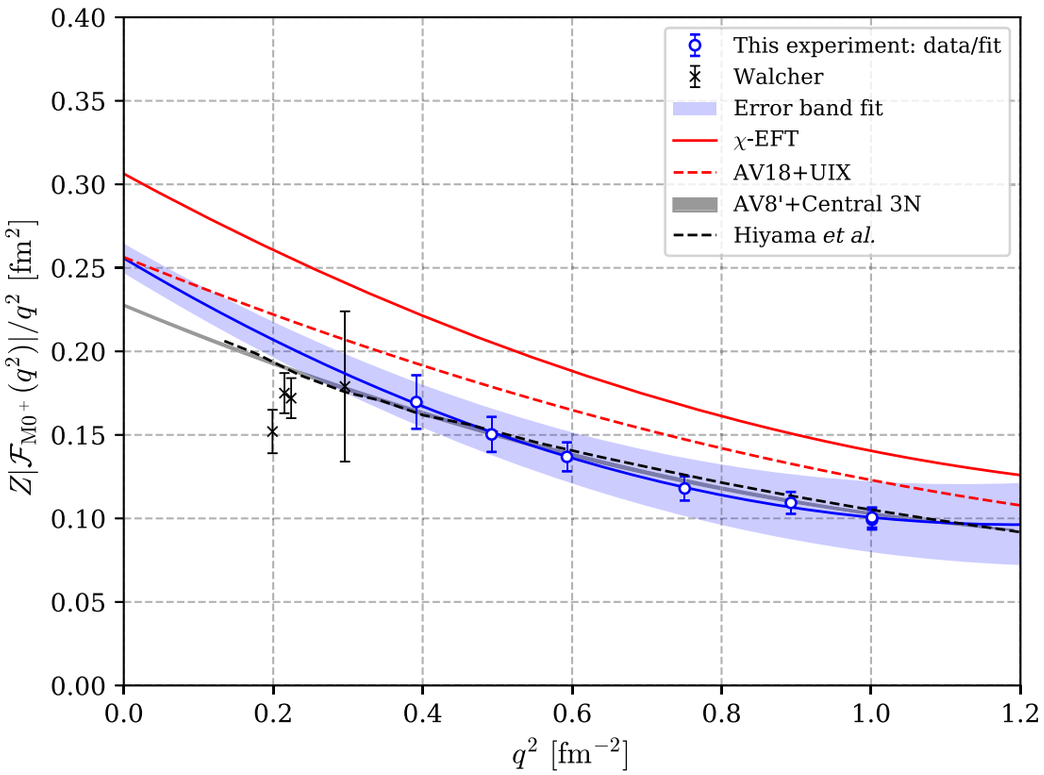
Low Q^2-data of F_{M0+} (Q^2) used to determine Monopole Matrix Element ME and transition radius R_{tr}

→ Information about the **spatial structure** of the resonance

Pol. Expansion

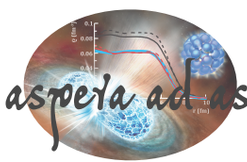
$$\frac{\sqrt{Z^2\cdot|\mathcal{F}_{M0+}(Q^2)|^2}}{Q^2} = \frac{ME}{6}\left[1-\frac{Q^2}{20}\mathcal{R}_{tr}+\frac{Q^4}{840}\frac{\langle r^6\rangle_{tr}}{\langle r^2\rangle_{tr}}+\mathcal{O}(Q^6)\right] \text{ with } ME=\langle r^2\rangle_{tr} \;\&\; \mathcal{R}_{tr}=\frac{\langle r^4\rangle_{tr}}{\langle r^2\rangle_{tr}}$$

M. Chernykh, PhD Thesis, Darmstadt (2008)



R_{tr} ≈10% larger than the calculation with chiral EFT: hard core of the interaction too weak?

- Lower energy data needed!
- Extension to other nuclei (^{12}C?)



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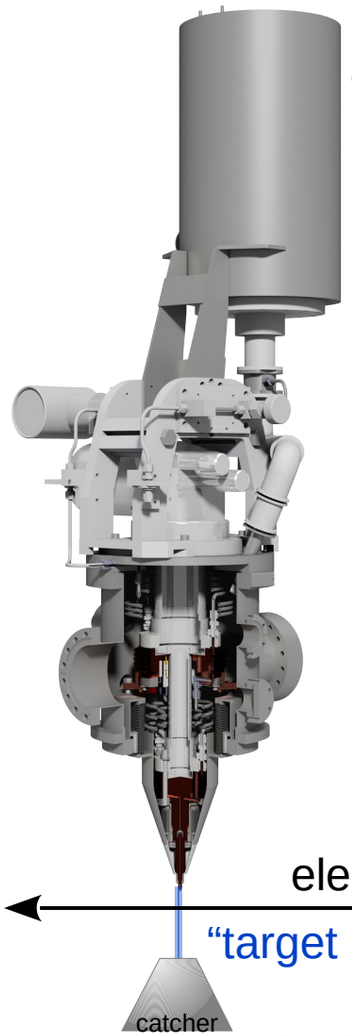
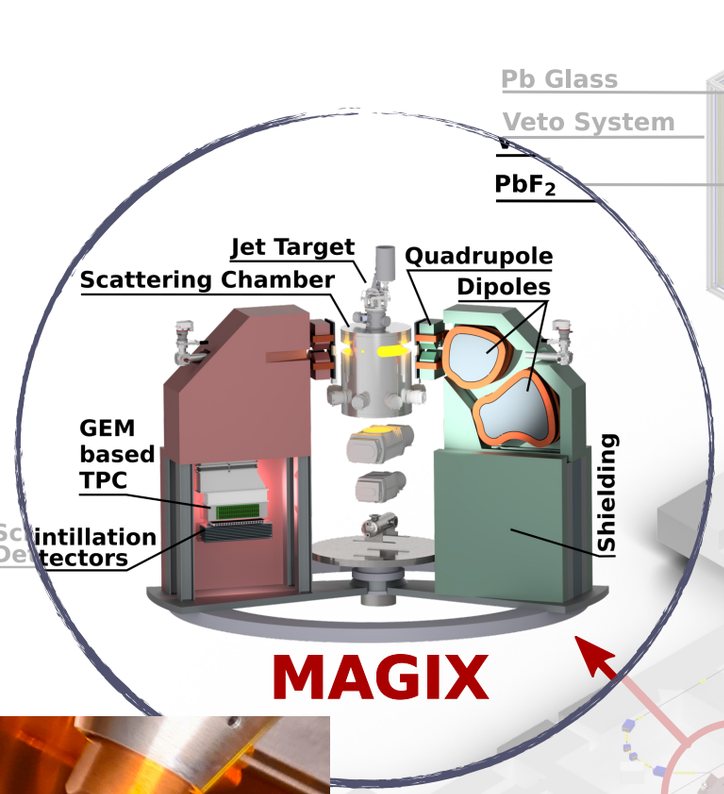
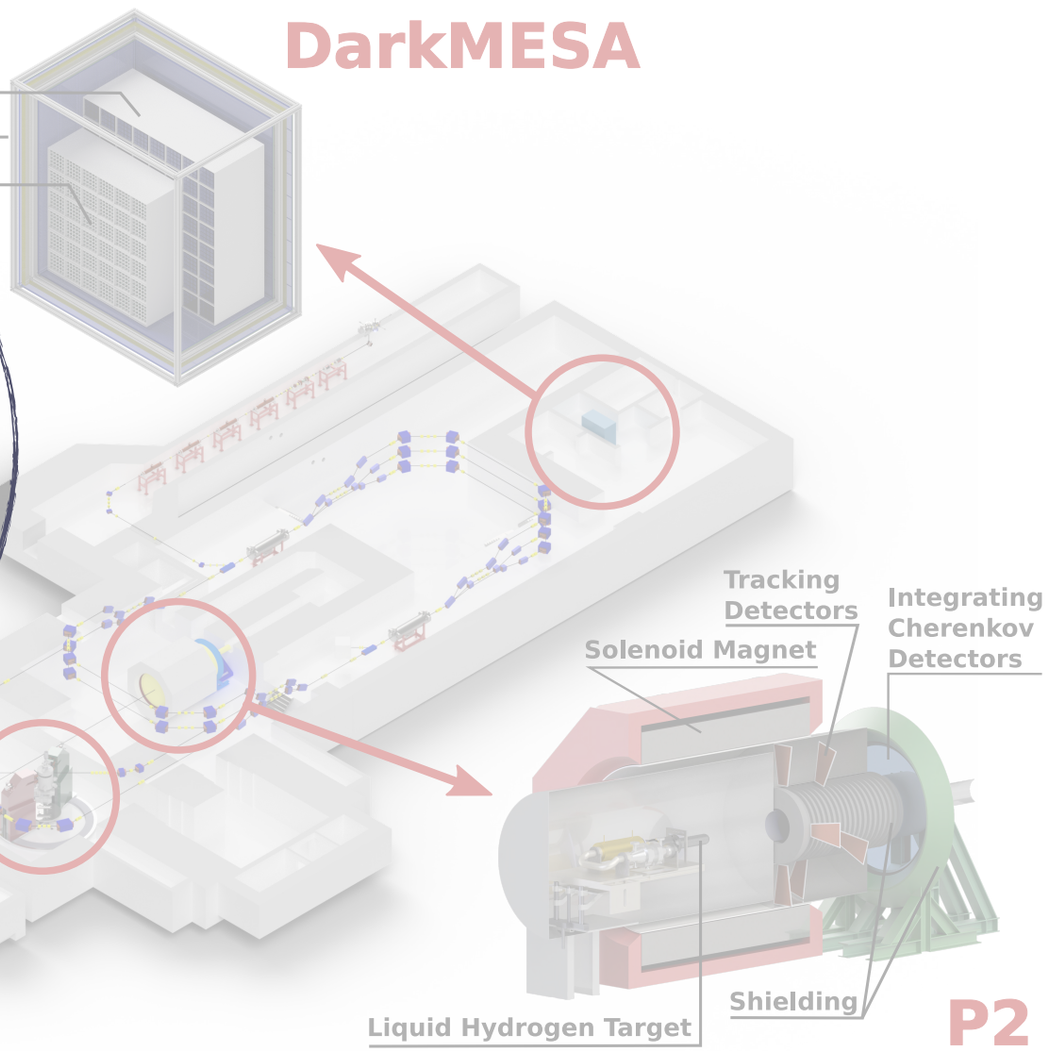
New Experimental Opportunities



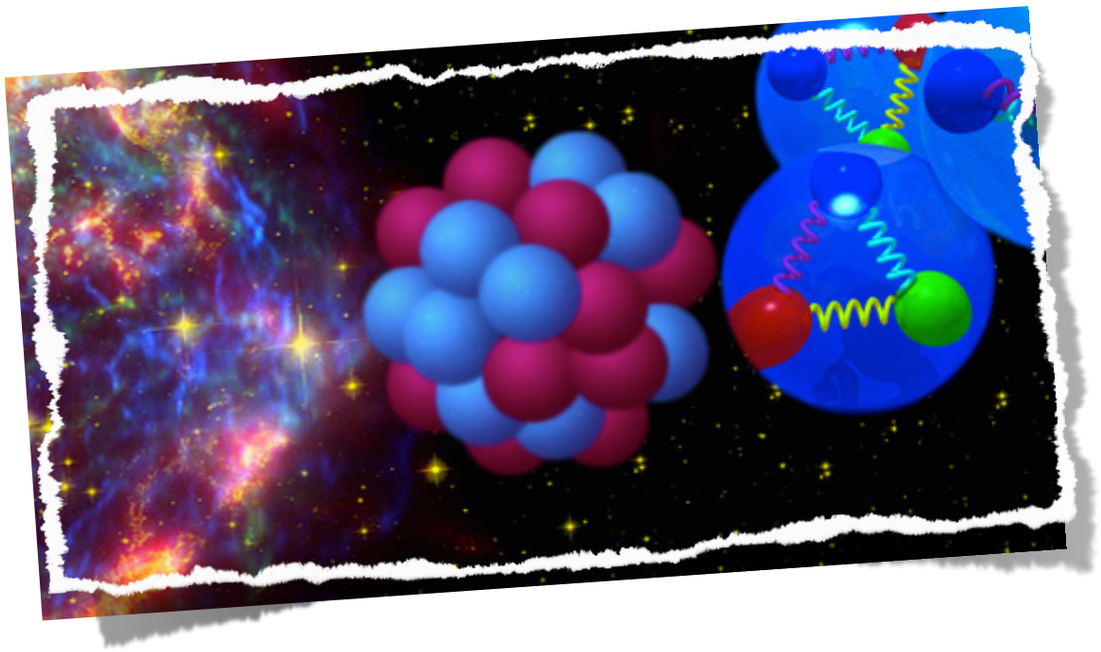
NO background, energy loss or multiple scattering from target foils and ice layer and re-scattering from frame, and target length acceptance issues!

windowless,
thin, point-like



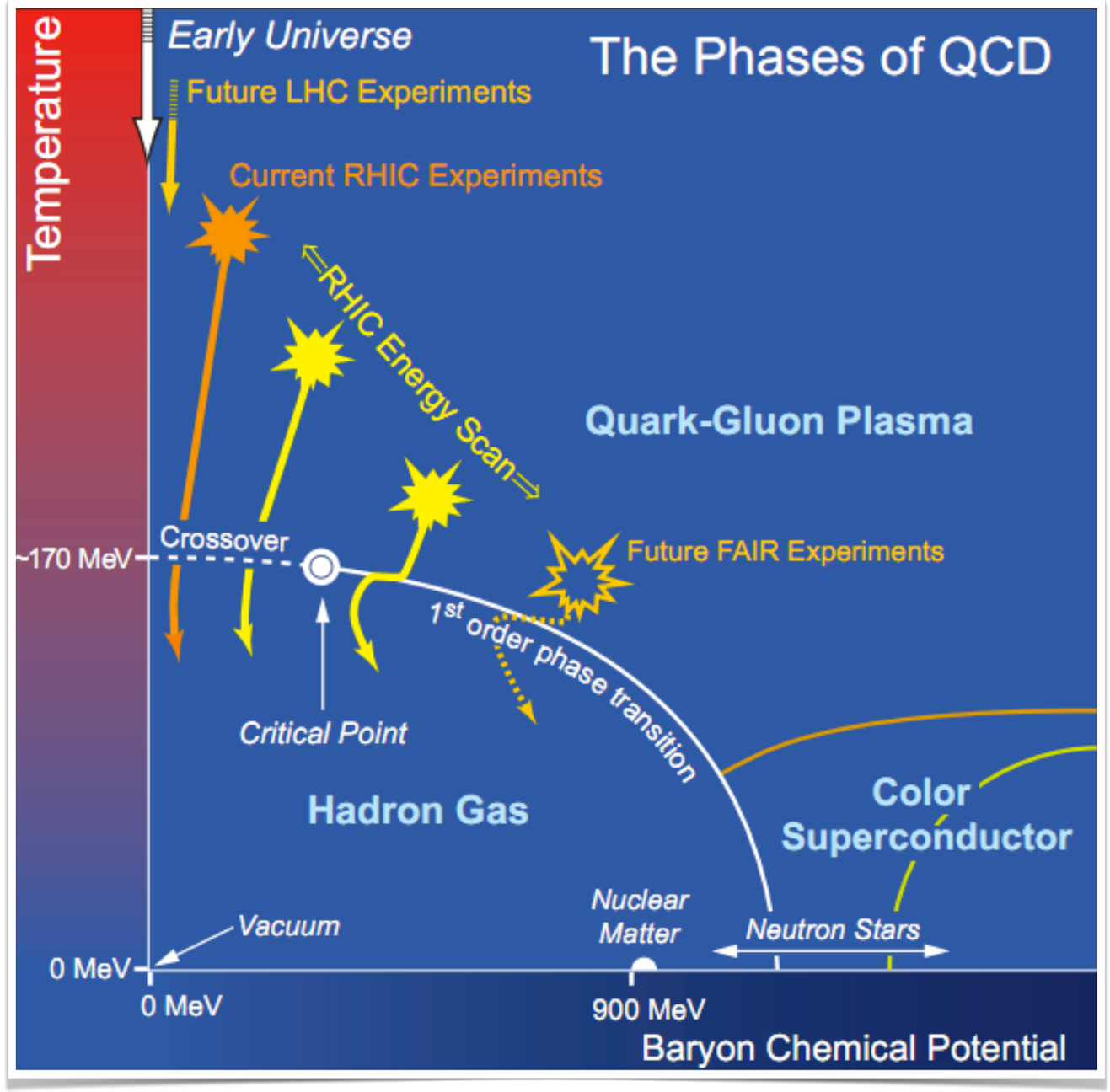


The phases: second constraint



Modern nuclear physics is about…

→ Unravelling the phases of nuclear matter

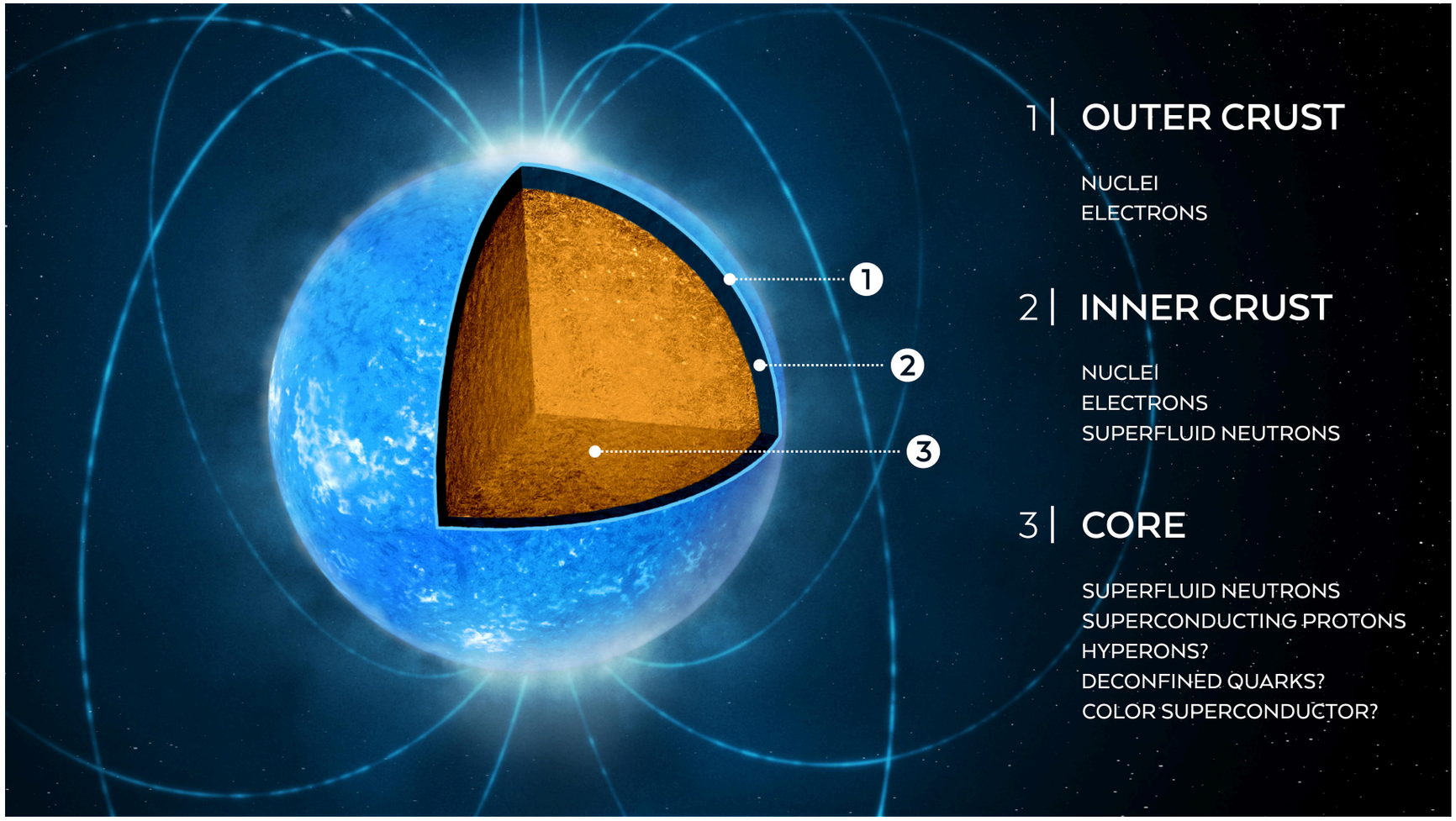


LRP Nuclear Science Advisory Committee(2008)

Neutron Stars & Nuclear Matter

- NS are bound by gravity **NOT** by the strong force

A. Watts et al., Rev. Mod. Phys. **88**, 021001



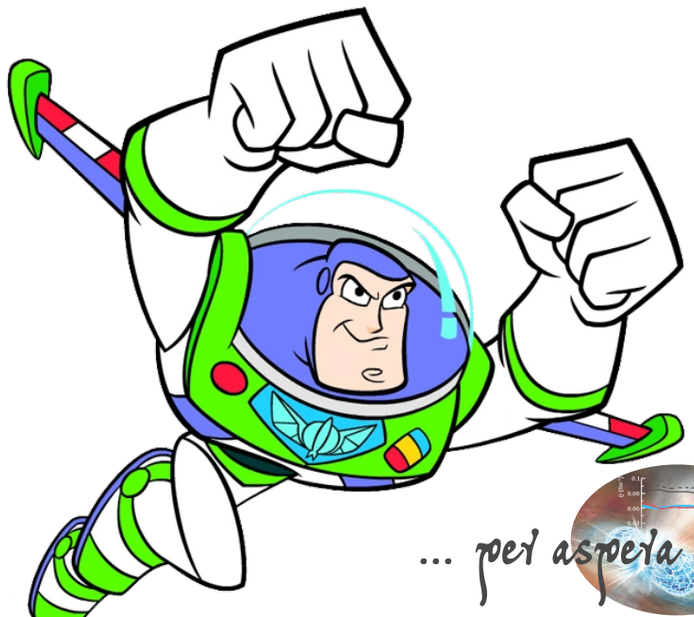
…to infinity and beyond!

- NS are bound by gravity **NOT** by the strong force
- NS satisfy the **Tolman-Oppenheimer-Volkoff** equation ($v_{esc}/c \approx 1/2$)

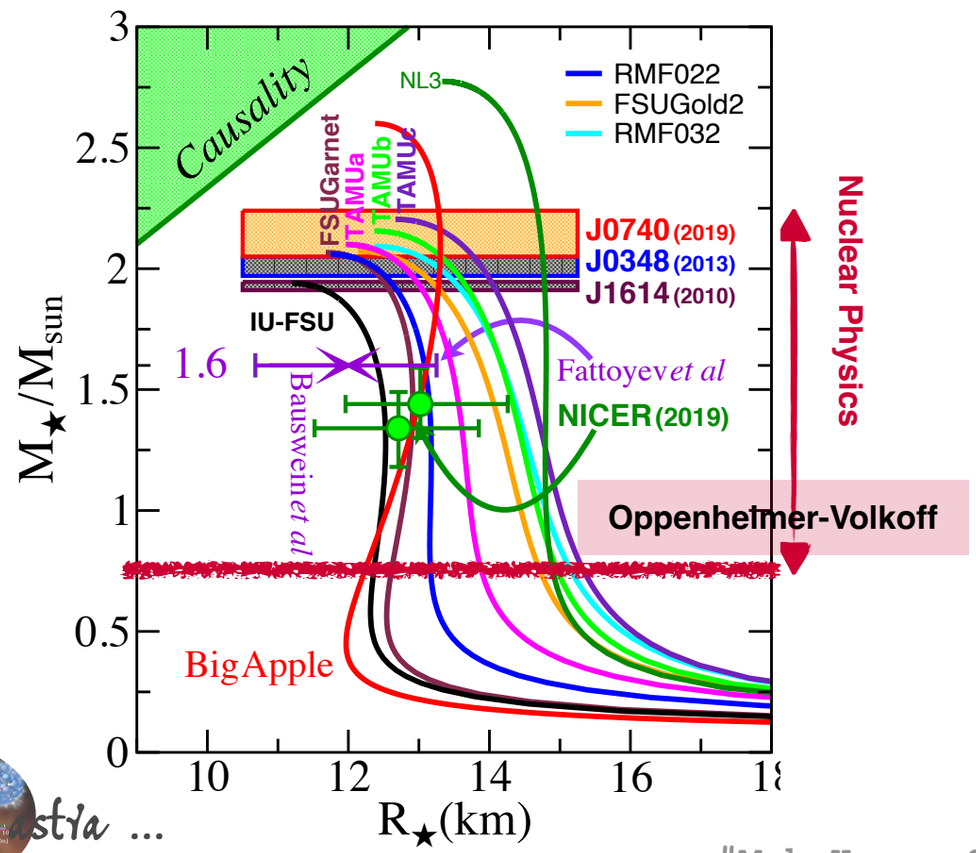
$$\frac{dP}{dr} = -G\frac{(\varepsilon/c^2 + P/c^2)(M + 4\pi r^3 P/c^2)}{r^2(1 - 2GM/rc^2)}$$

$$\frac{dM}{dr} = 4\pi r^2 \varepsilon/c^2, \quad P = P(\varepsilon) \quad \text{(EOS)}$$

- Only Physics that the TOV equation is sensitive to: **Equation of State**
- Increase from 0.7 to 2 M_{Sun} transfer ownership to **Nuclear Physics**

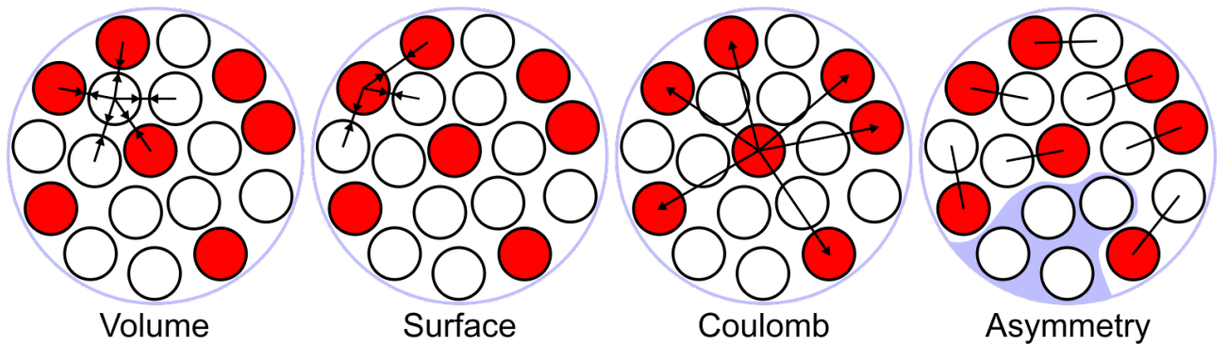


… per aspera ad astra …



How to build an EOS

Take an incompressible quantum liquid-drop…



How to build an EOS

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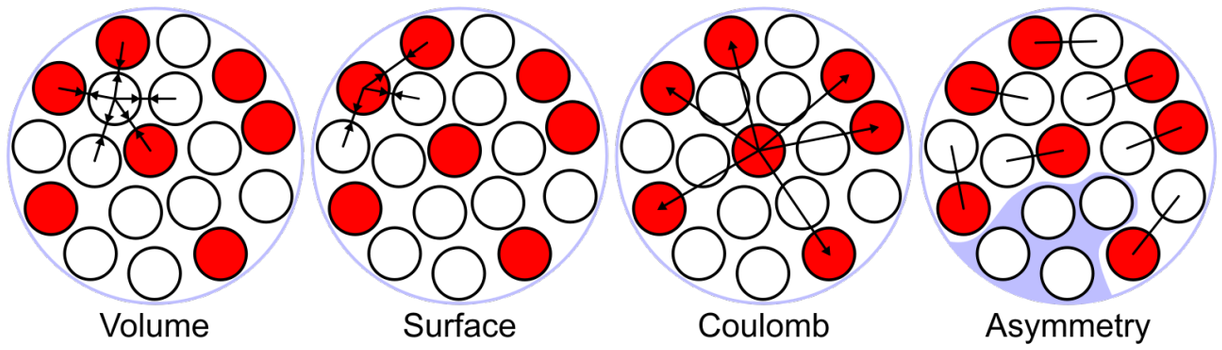
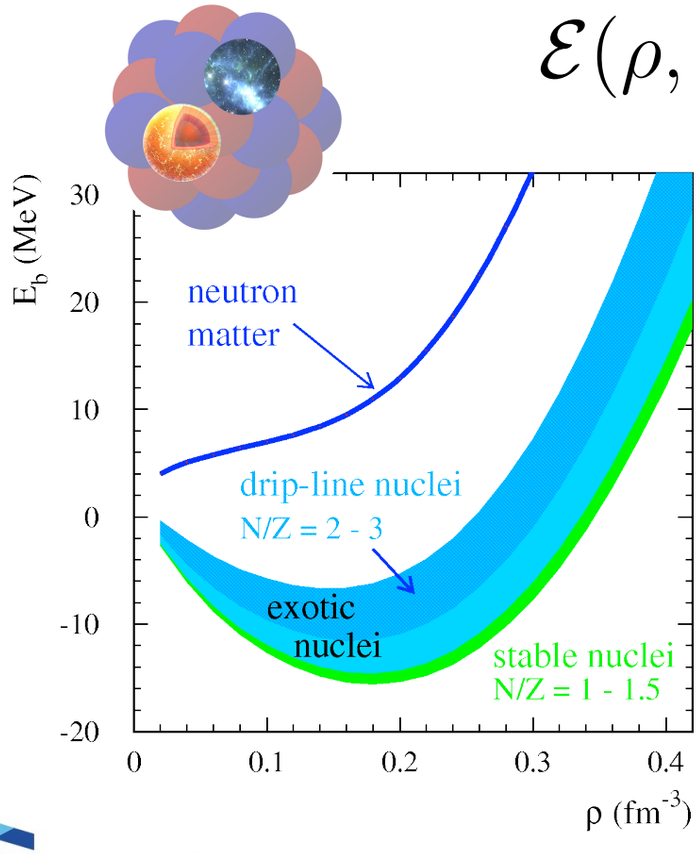


…make it compressible and bring it to thermodynamic limit

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}(\rho,\alpha=0) + \mathcal{S}(\rho)\alpha^2 + \mathcal{O}(\alpha^4) \qquad \alpha = \frac{N-Z}{A}$$



How to build an EOS

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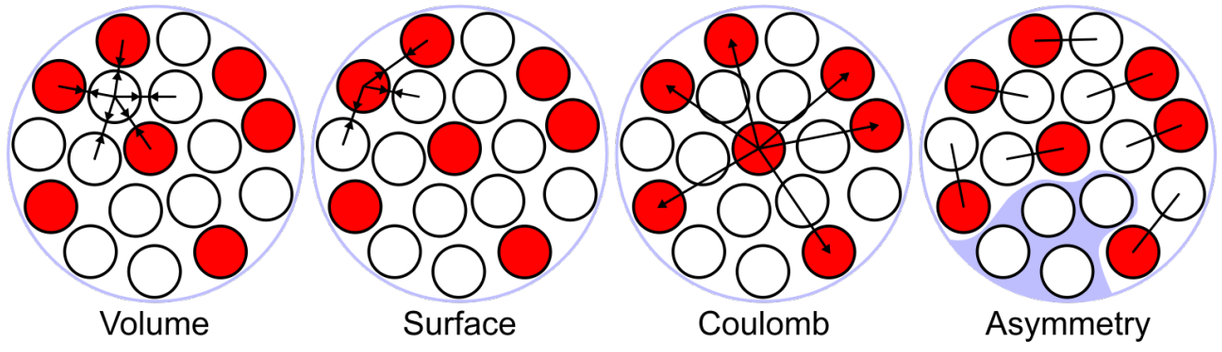

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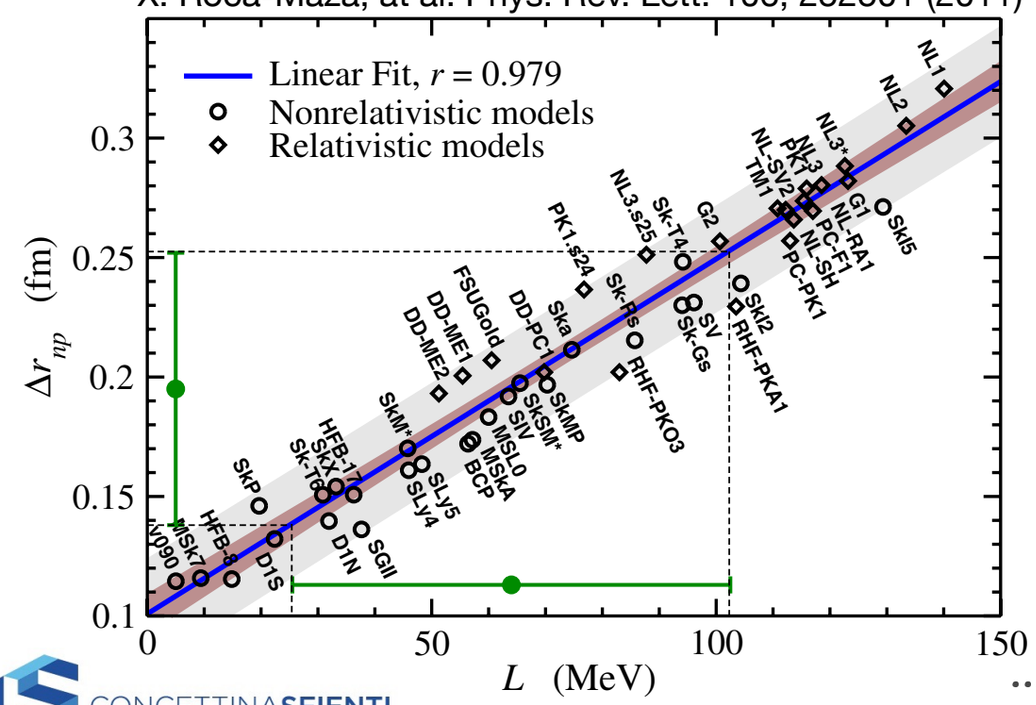
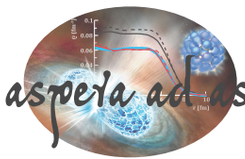
X. Roca-Maza, at al. Phys. Rev. Lett. 106, 252501 (2011)



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

..neither L nor K_{sym} are experimentally accessible!

… per aspera ad astra …



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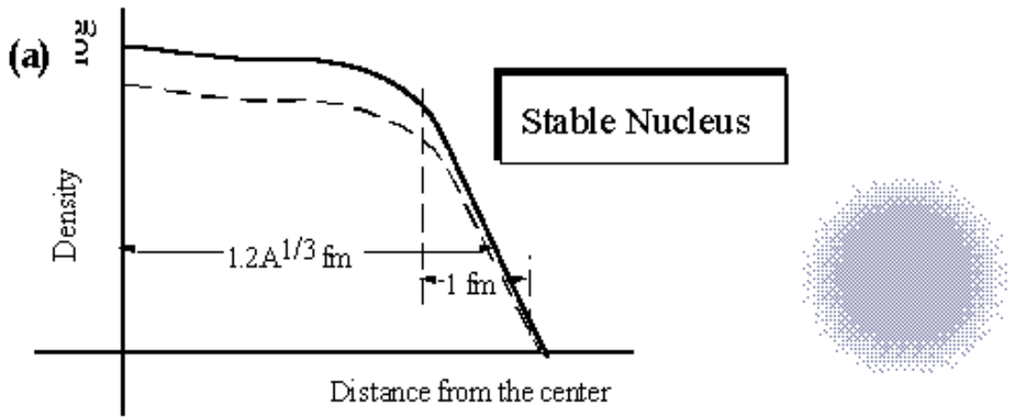
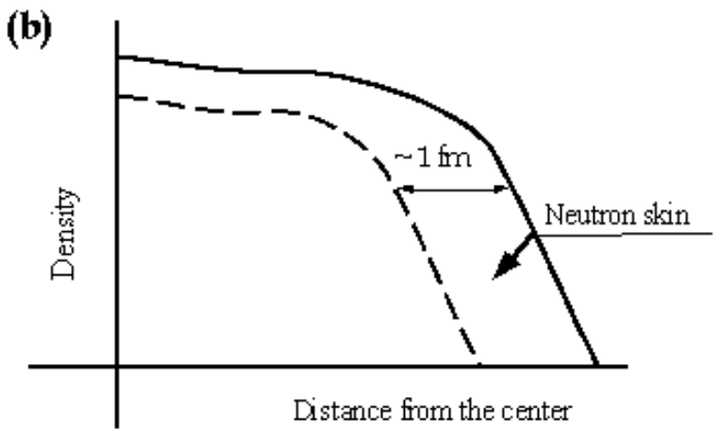
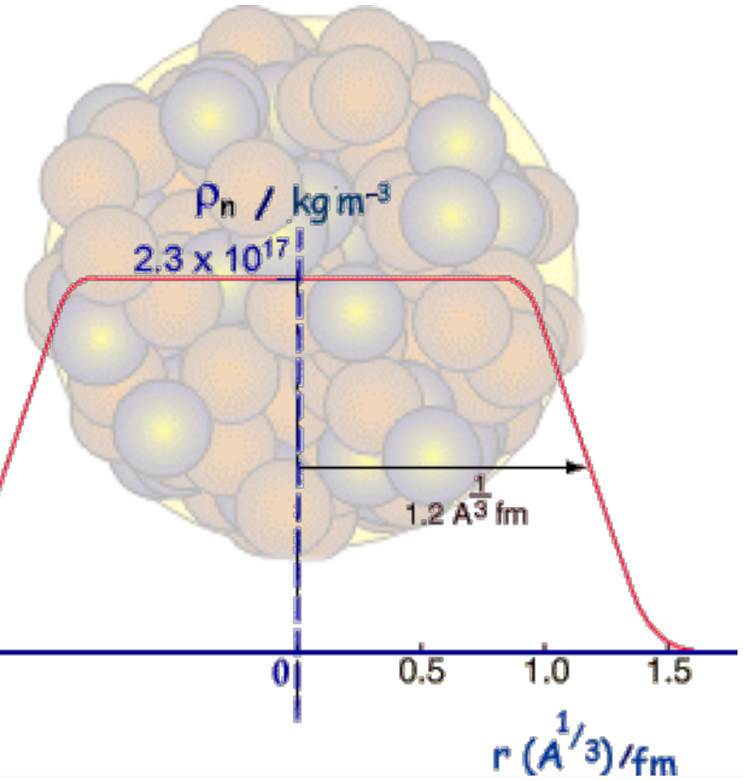
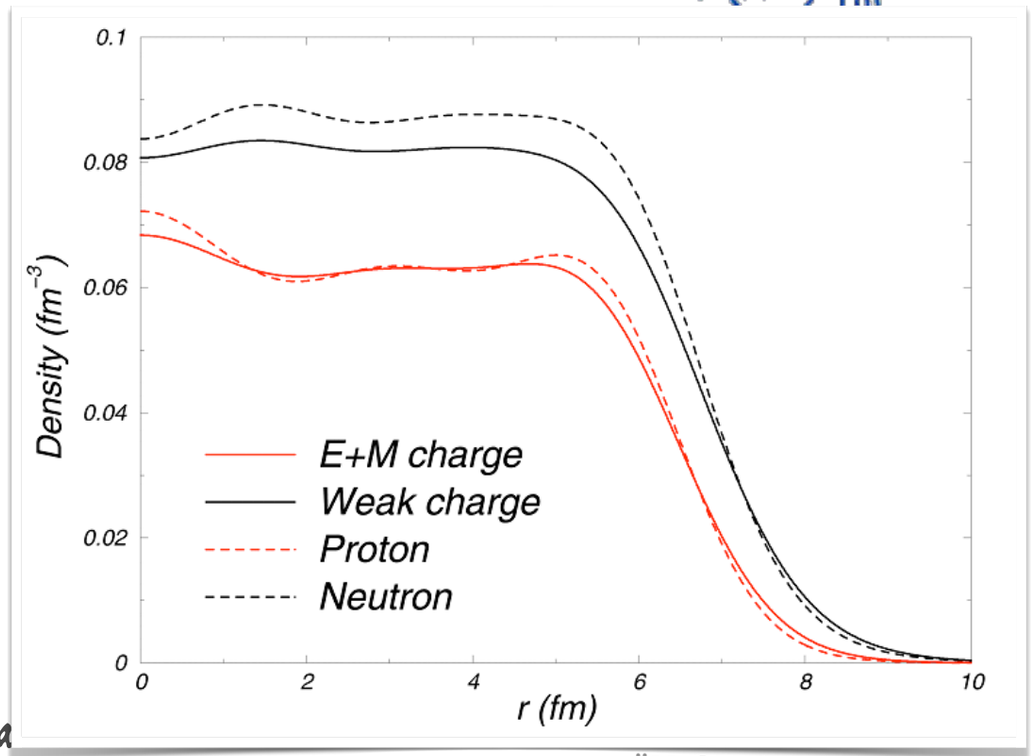
#MakeHumansSmartAgain

Where do the neutrons go?



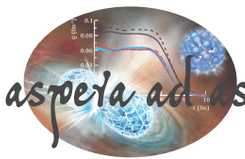




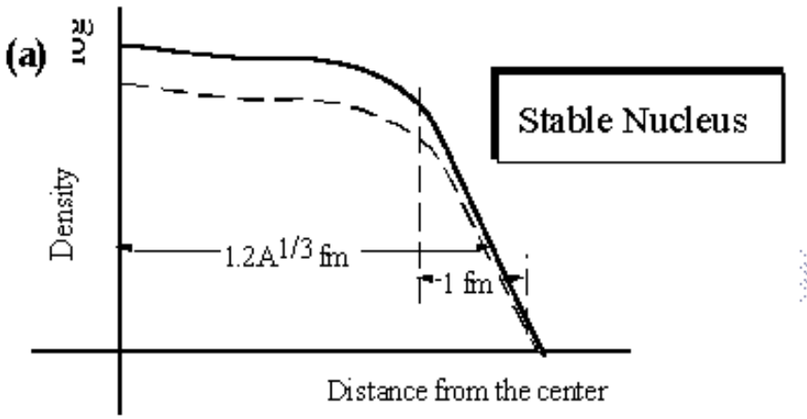


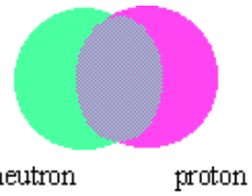
Pressure forces neutrons out against surface tension

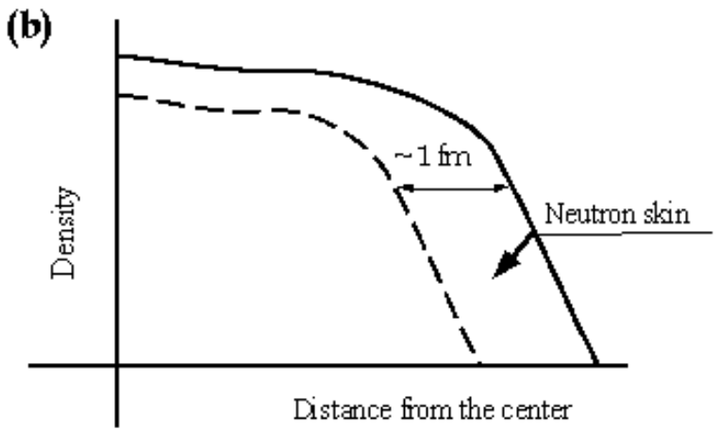
The neutron skin measures how much neutrons stick out past protons

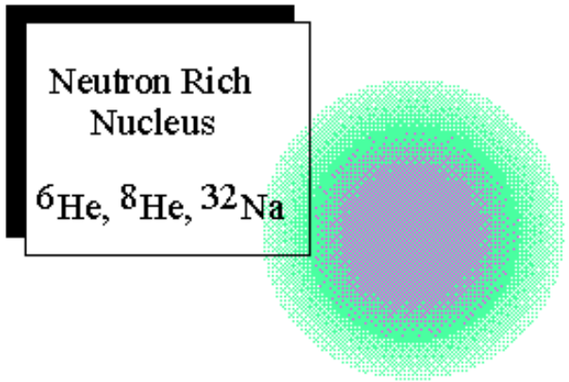


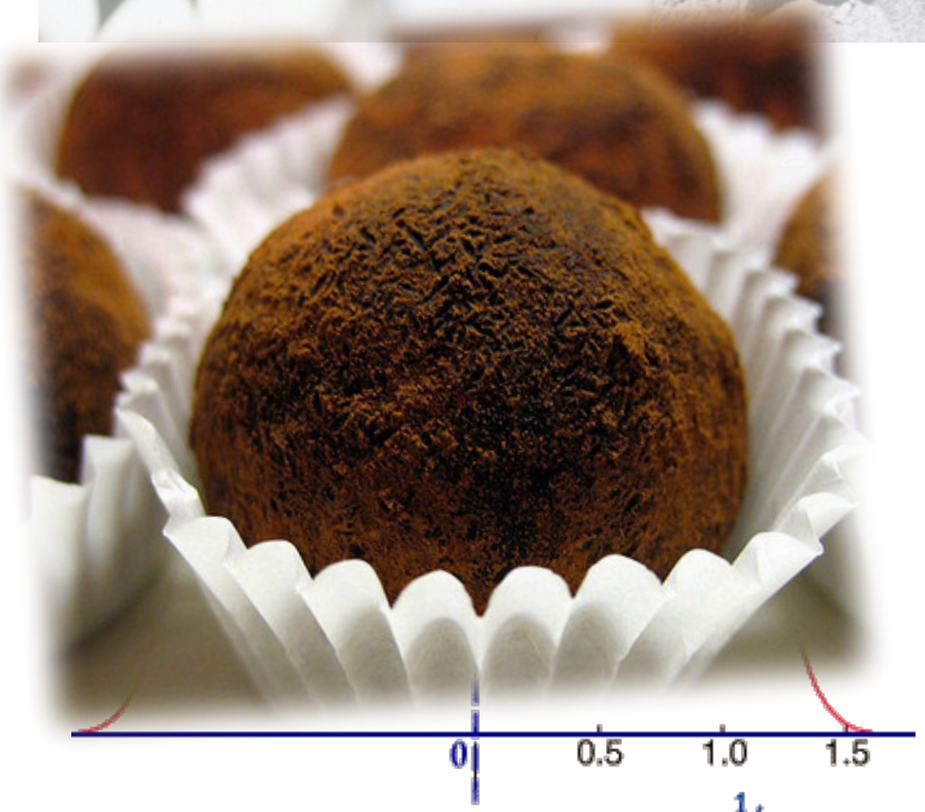
Where do the neutrons go?

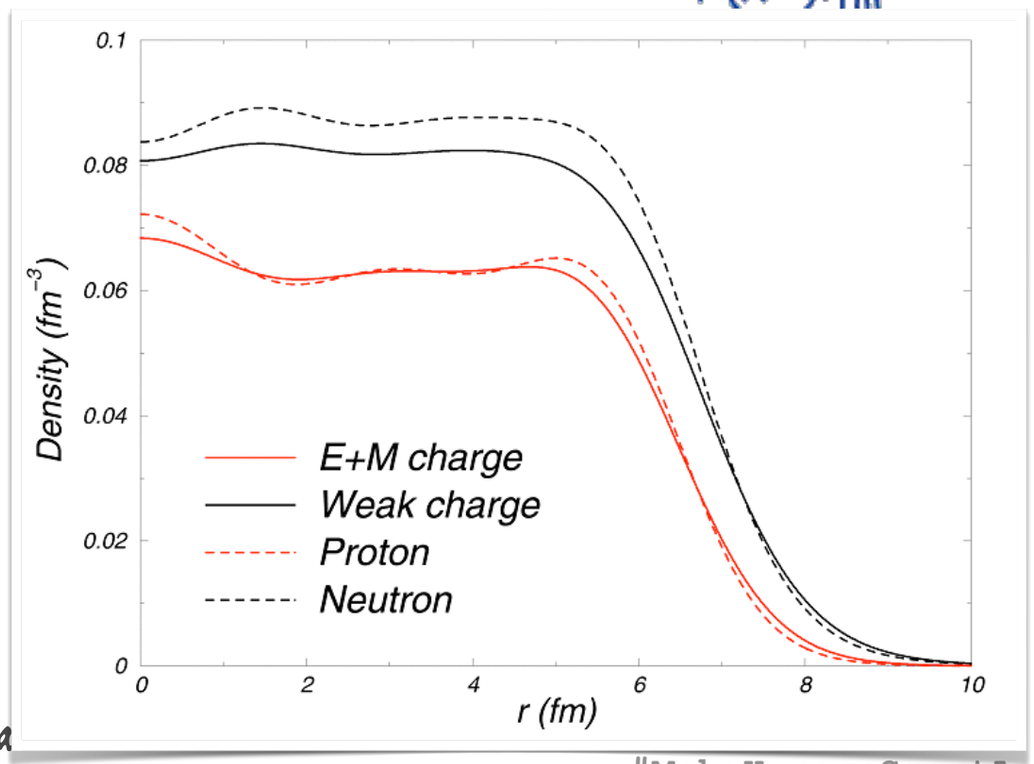












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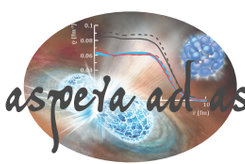


... per aspera ad astra

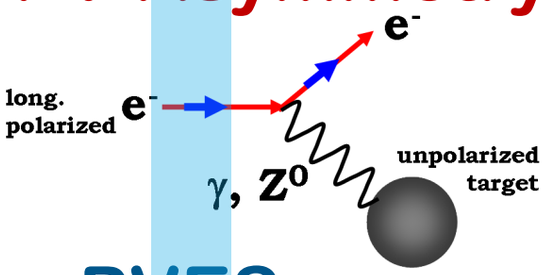
The stairway to heaven

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

(Personal selection)

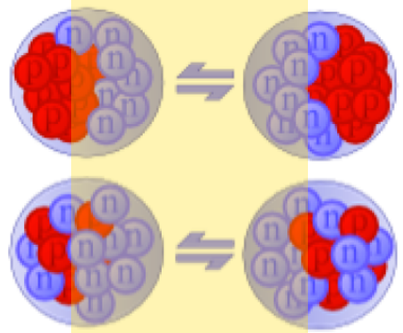
Experimental Challenges
(in unit of frustration)

PV-Asymmetry



PVES

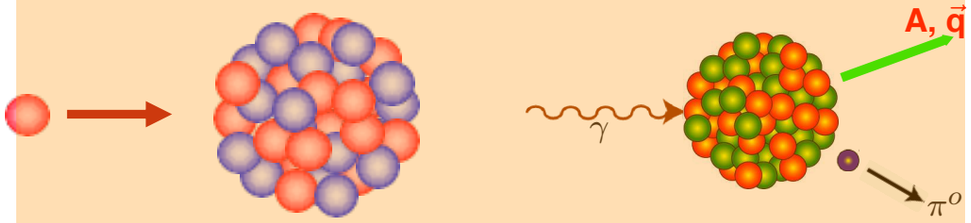
Resonance Strength



Collective Excitation

????..

Cross-section

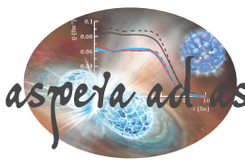


Hadronic Probes

EM Probes

Theo. uncertainties (a.u)

... per aspera ad astra ...



How hellish is hell?

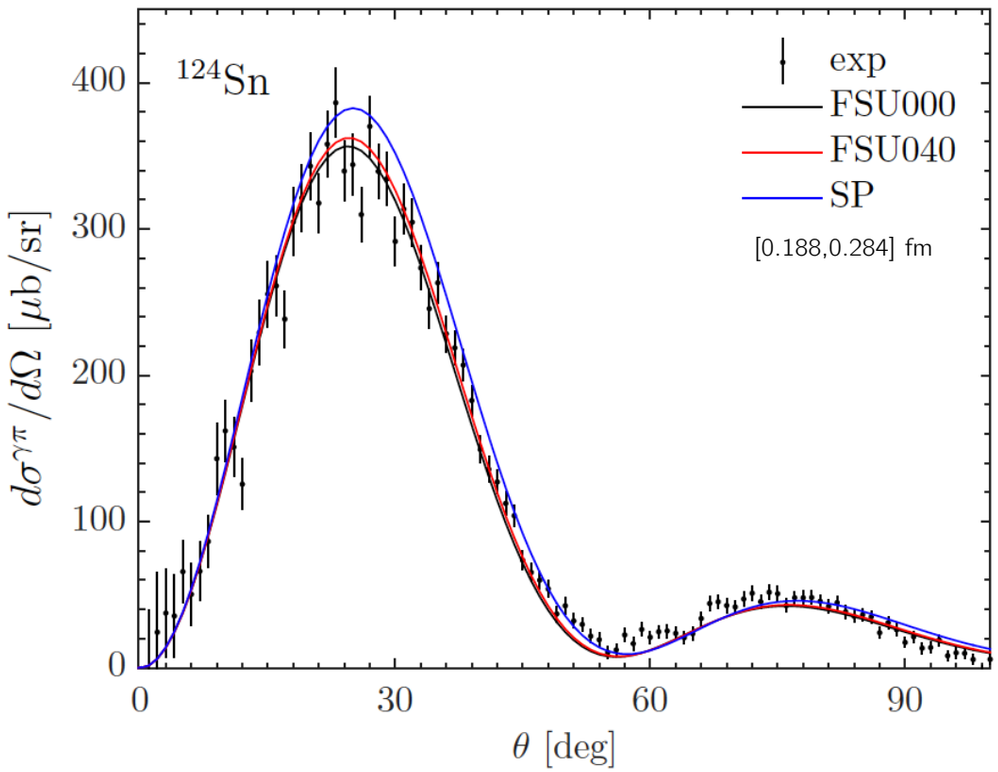
Featured in Physics Editors' Suggestion

Neutron Skin of $^{208}\mathrm{Pb}$ 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

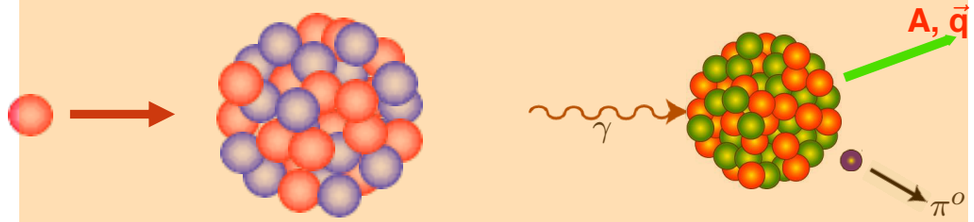
PHYSICS See Synopsis: Neutron Skin Turns Out to Be Soft

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 $^{208}\mathrm{Pb}$ 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.



????..

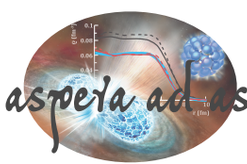
Cross-section



Hadronic Probes

EM Probes

Theo. uncertainties (a.u)

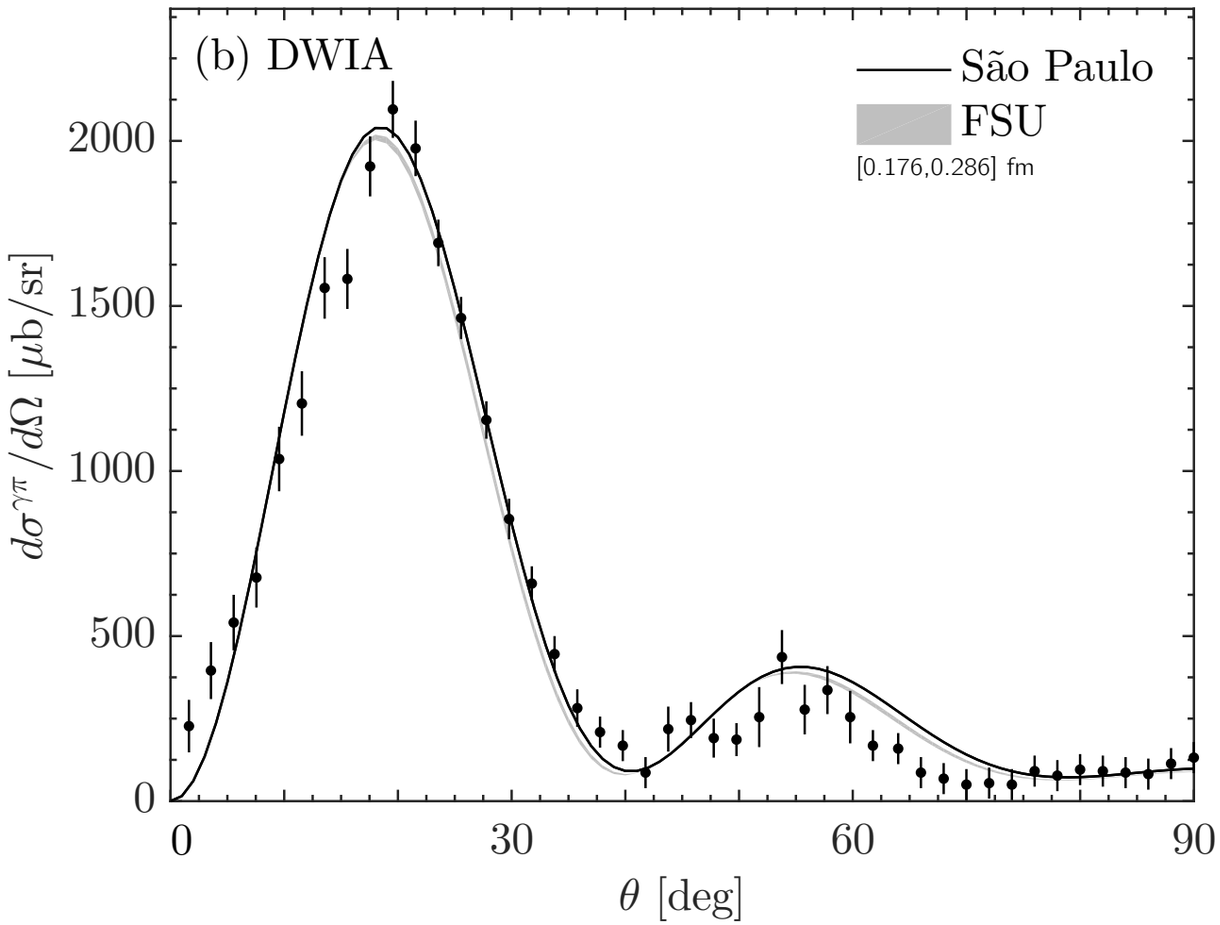


... per aspera ad astra ...

How hellish is hell?

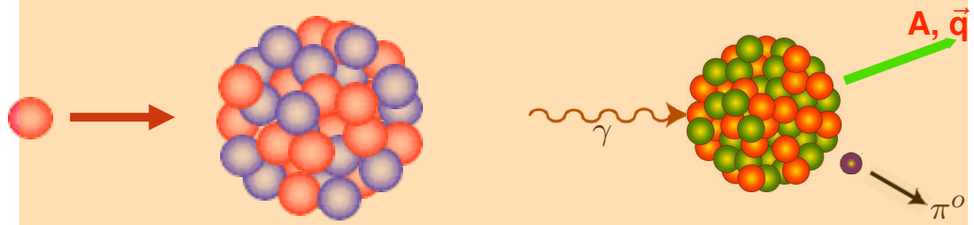
Theoretical analysis of the extraction of neutron skin thickness from coherent π^0 photoproduction off nuclei

F. Colomer, P. Capel, M. Ferretti, J. Piekarewicz, C. Sfienti, M. Thiel, V. Tsaran, and M. Vanderhaeghen
Phys. Rev. C **106**, 044318 – Published 18 October 2022



????..

Cross-section



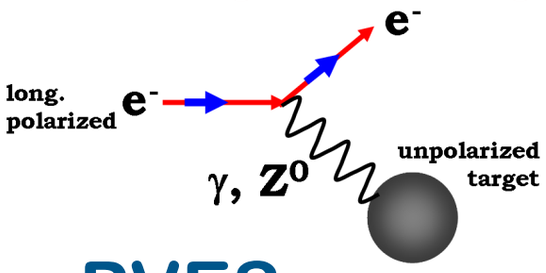
Hadronic Probes

EM Probes

Theo. uncertainties (a.u)

The shortest of the roads ...

PV-Asymmetry



PVES

electric charge	**1**	**0**
weak charge	**≈0.07**	**1**

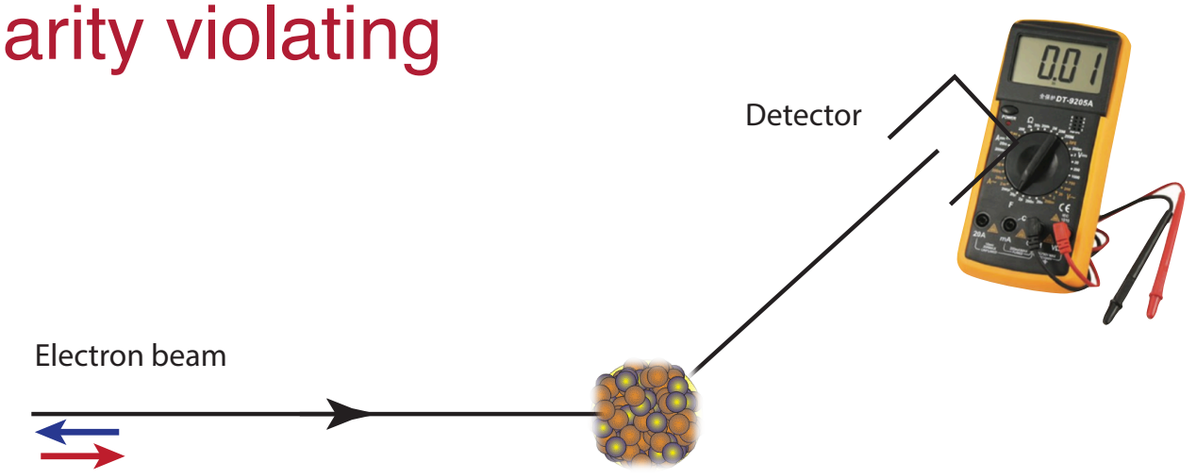
Non-PV e-scattering

Electron scattering γ exchange provides R_p through nucleus FFs

PV e-scattering

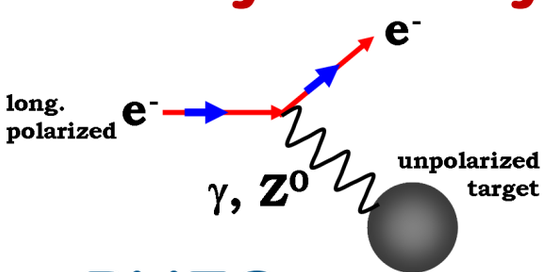
Electron also exchange Z, which is parity violating

Primarily couples to neutron



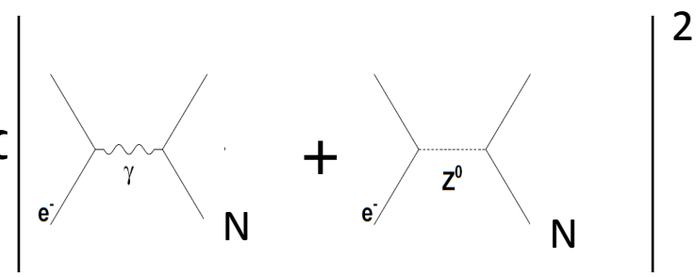
The shortest of the roads ...

PV-Asymmetry

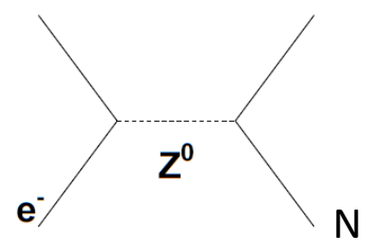


PVES

$\sigma \propto$

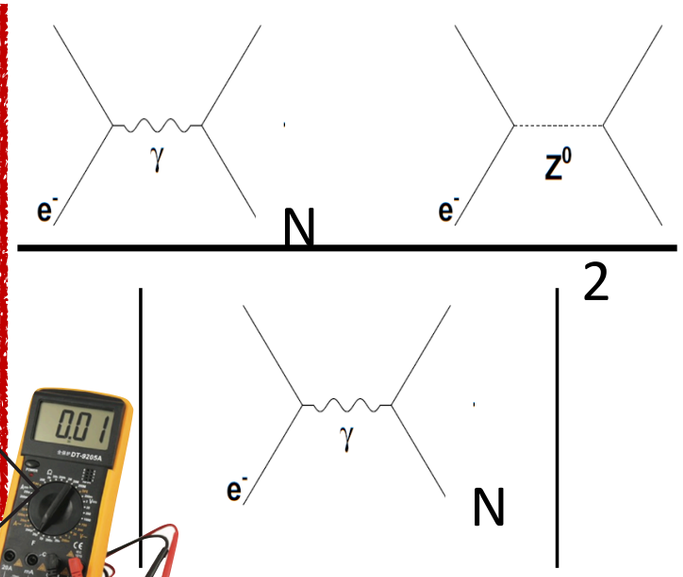


...to measure ...



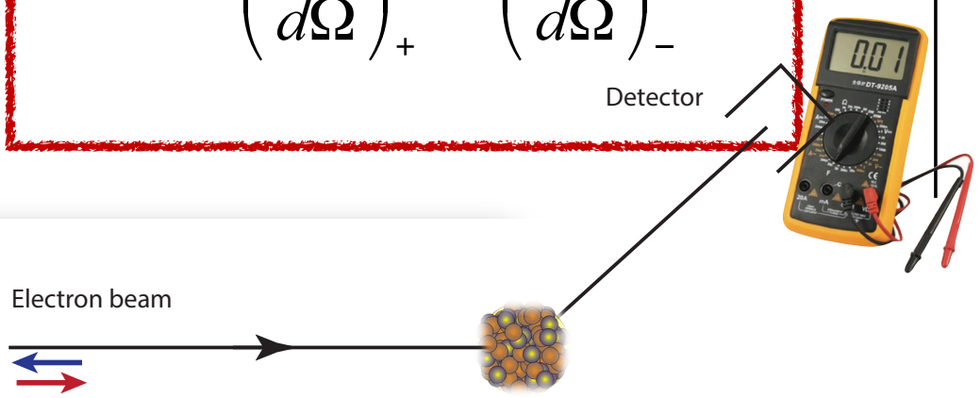
....construct ....

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



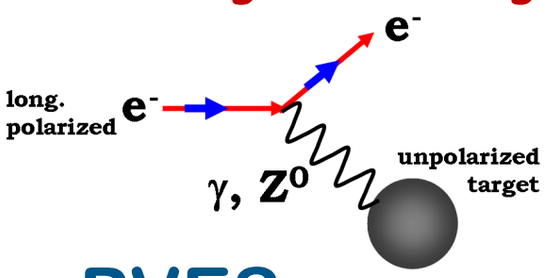
$$N = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

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



...we call it: MREX

PV-Asymmetry

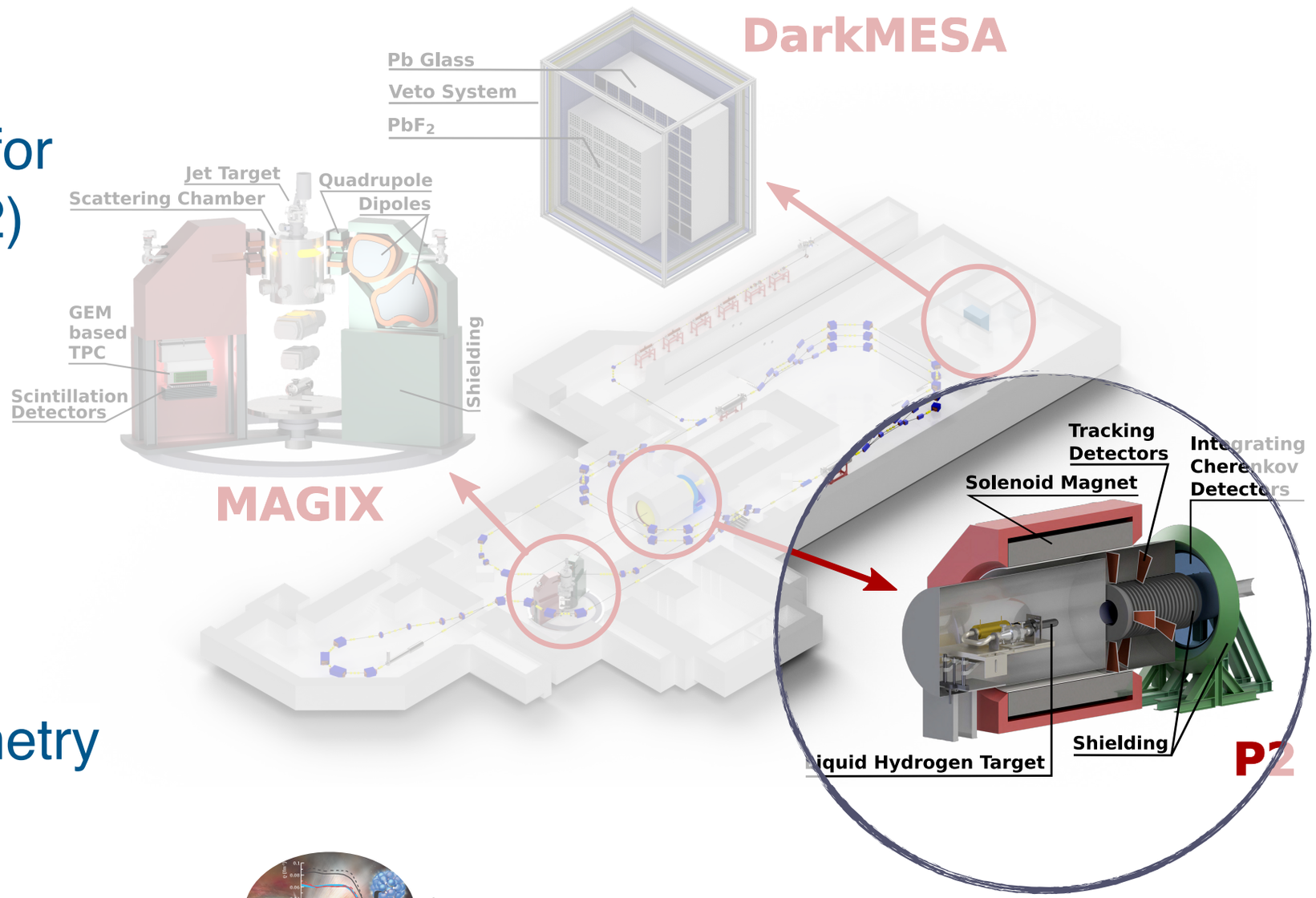


PVES

.... need a few N=10^{18} electrons!

... close to 10^{11} electrons/s

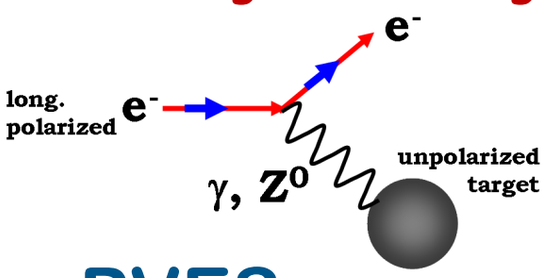
- External-beam mode for **high polarisation** (P2)



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

...we call it: MREX

PV-Asymmetry



PVES

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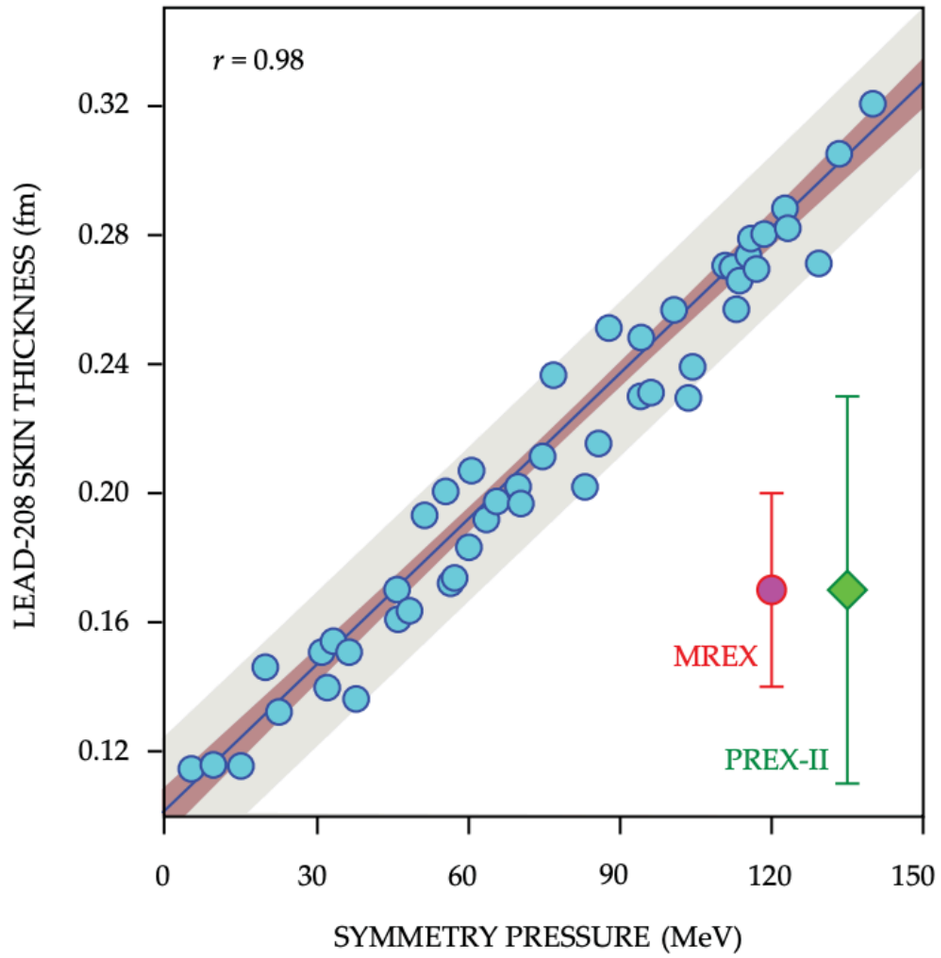
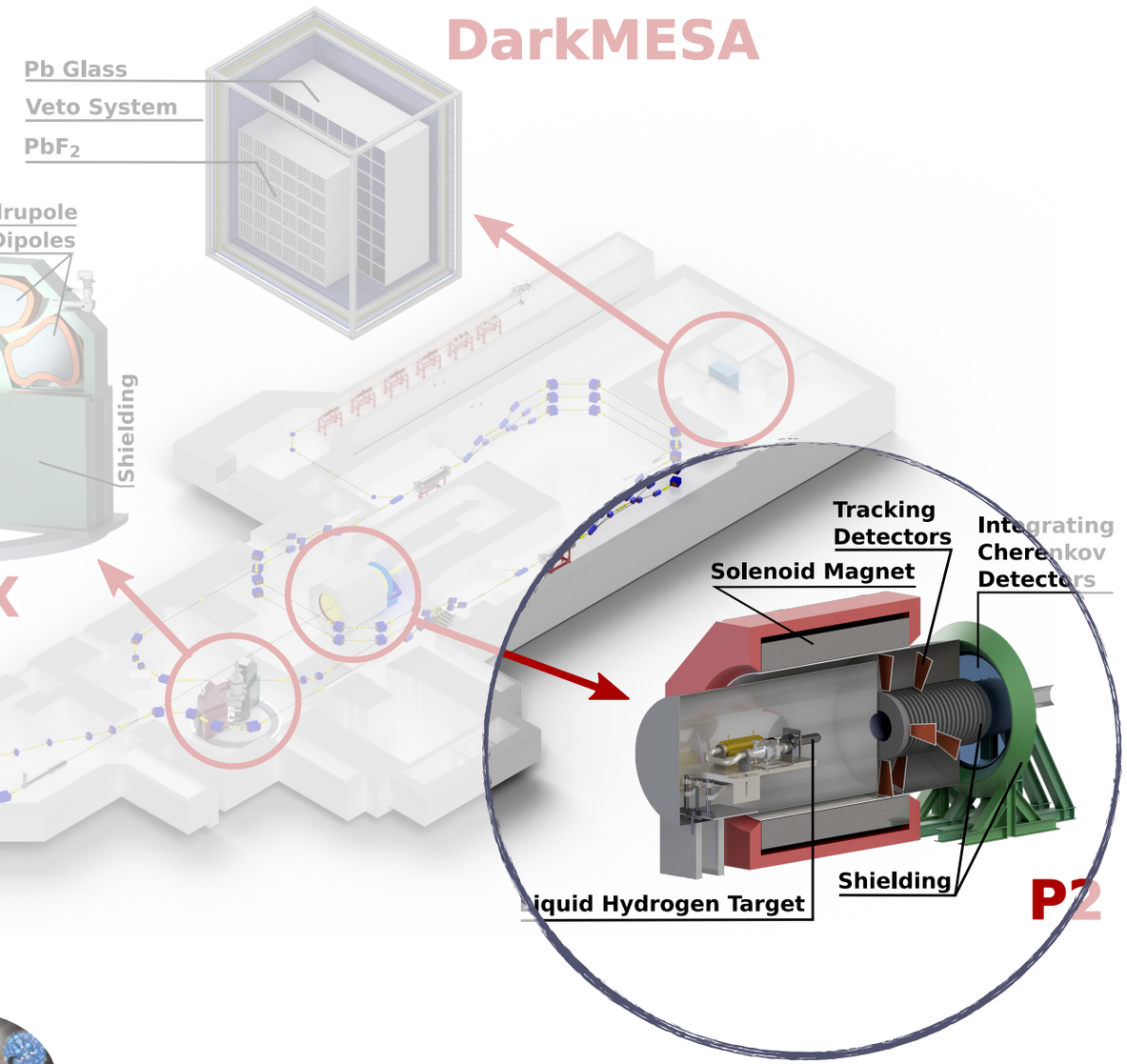
J. Piekarewicz et al. Physics Today 72, 7, 30 (2019)



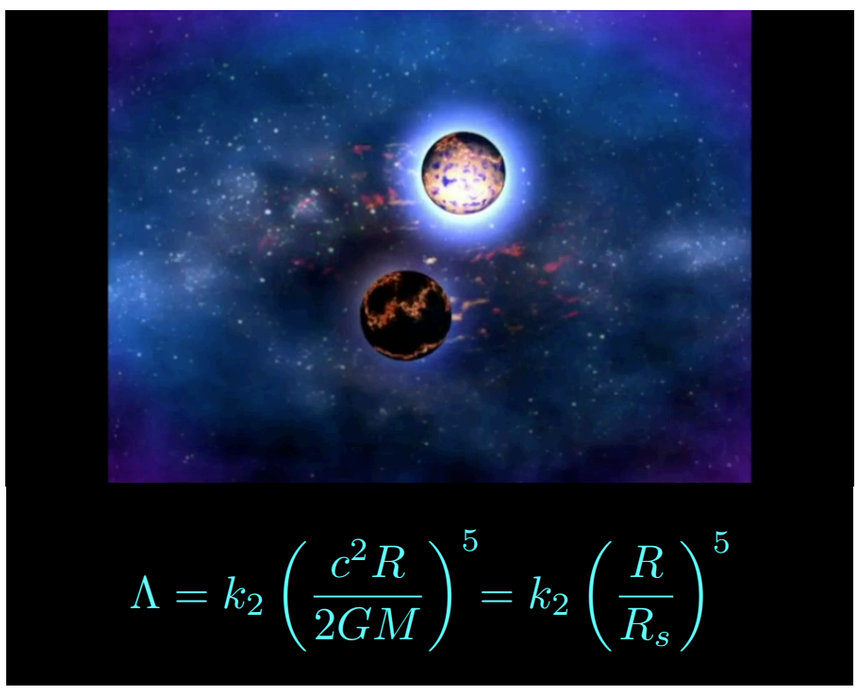


CONCETTINASFIENTI

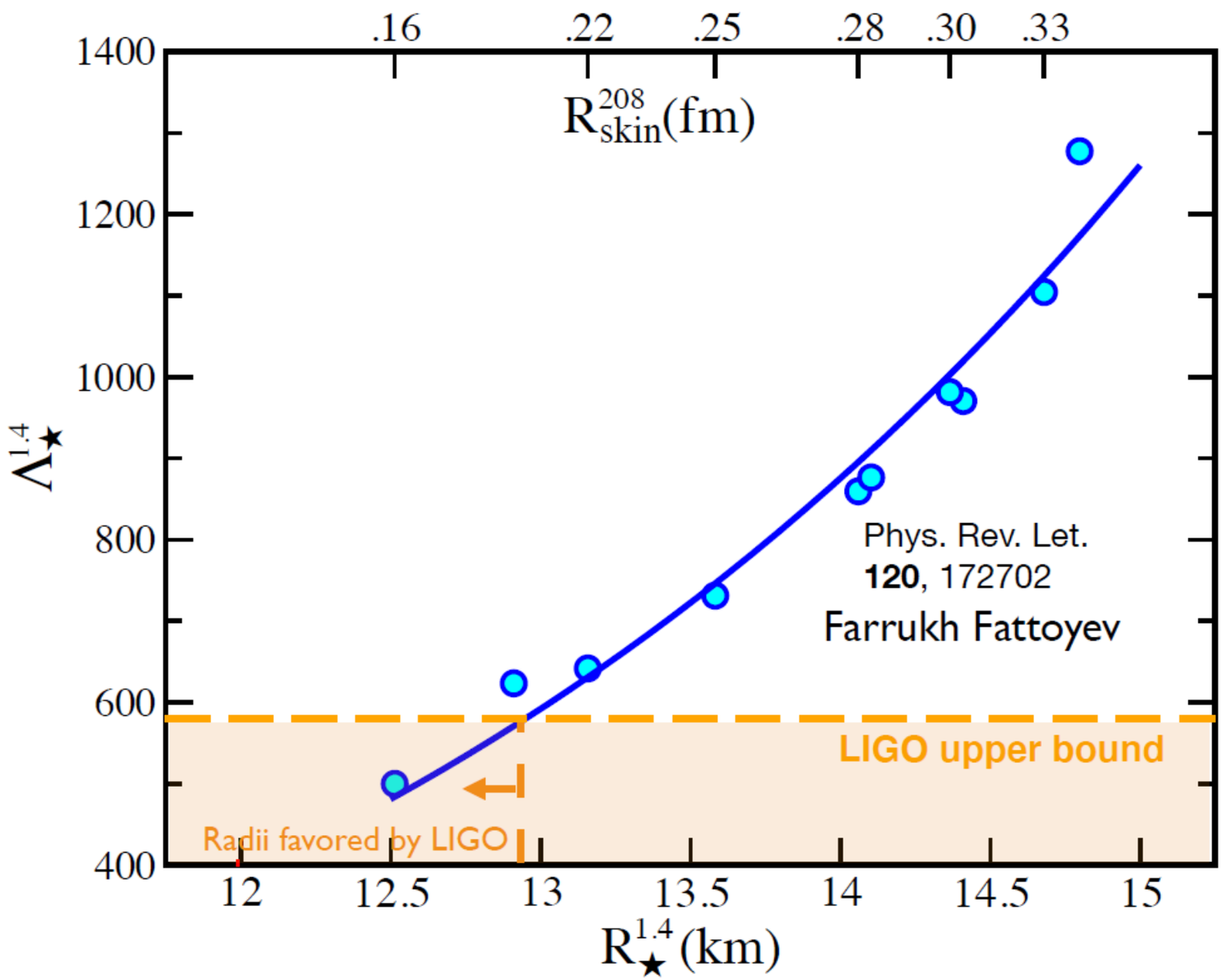
... per aspera ad astra ...

#MakeHumansSmartAgain

Bringing it all together



$$\Lambda = k_2 \left(\frac{c^2 R}{2GM}\right)^5 = k_2 \left(\frac{R}{R_s}\right)^5$$



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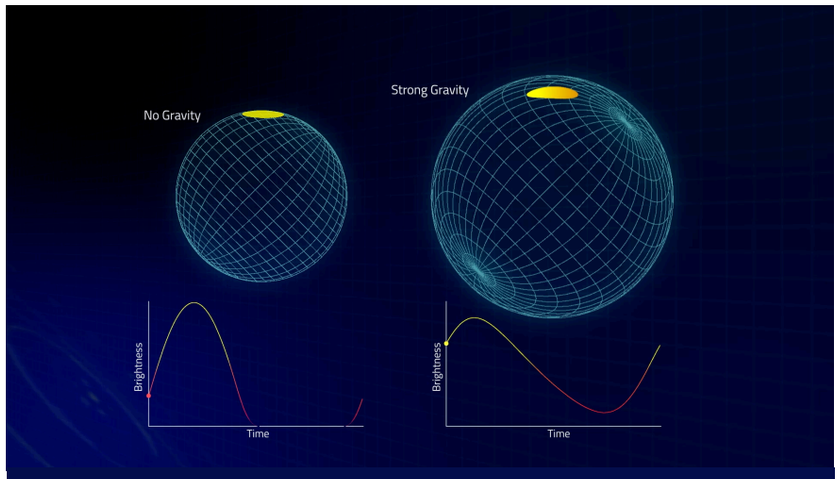
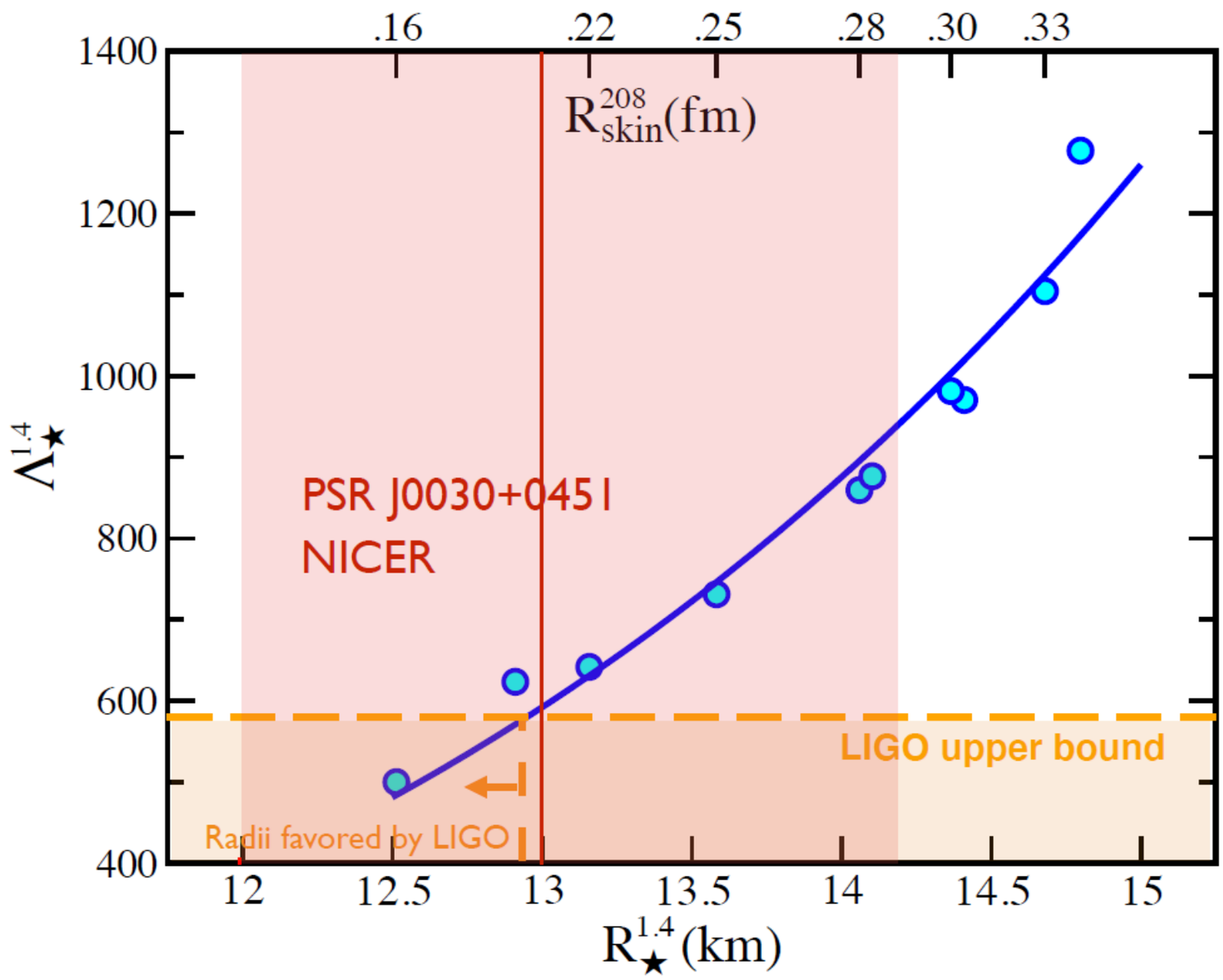
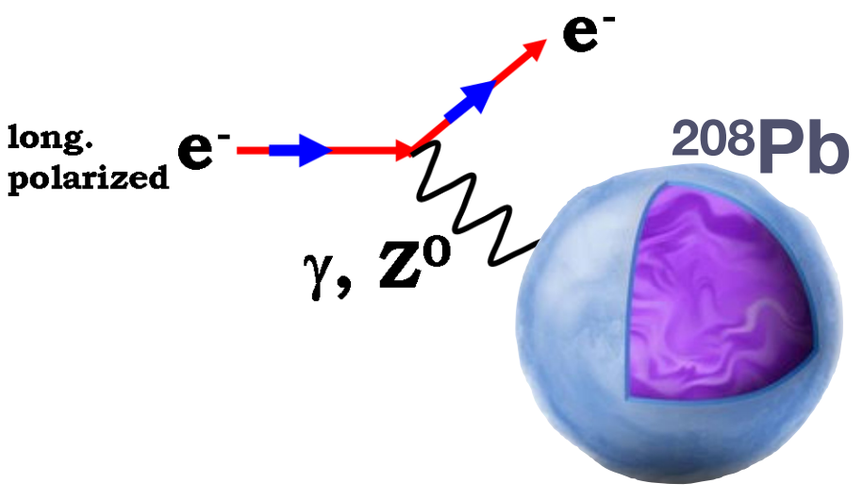
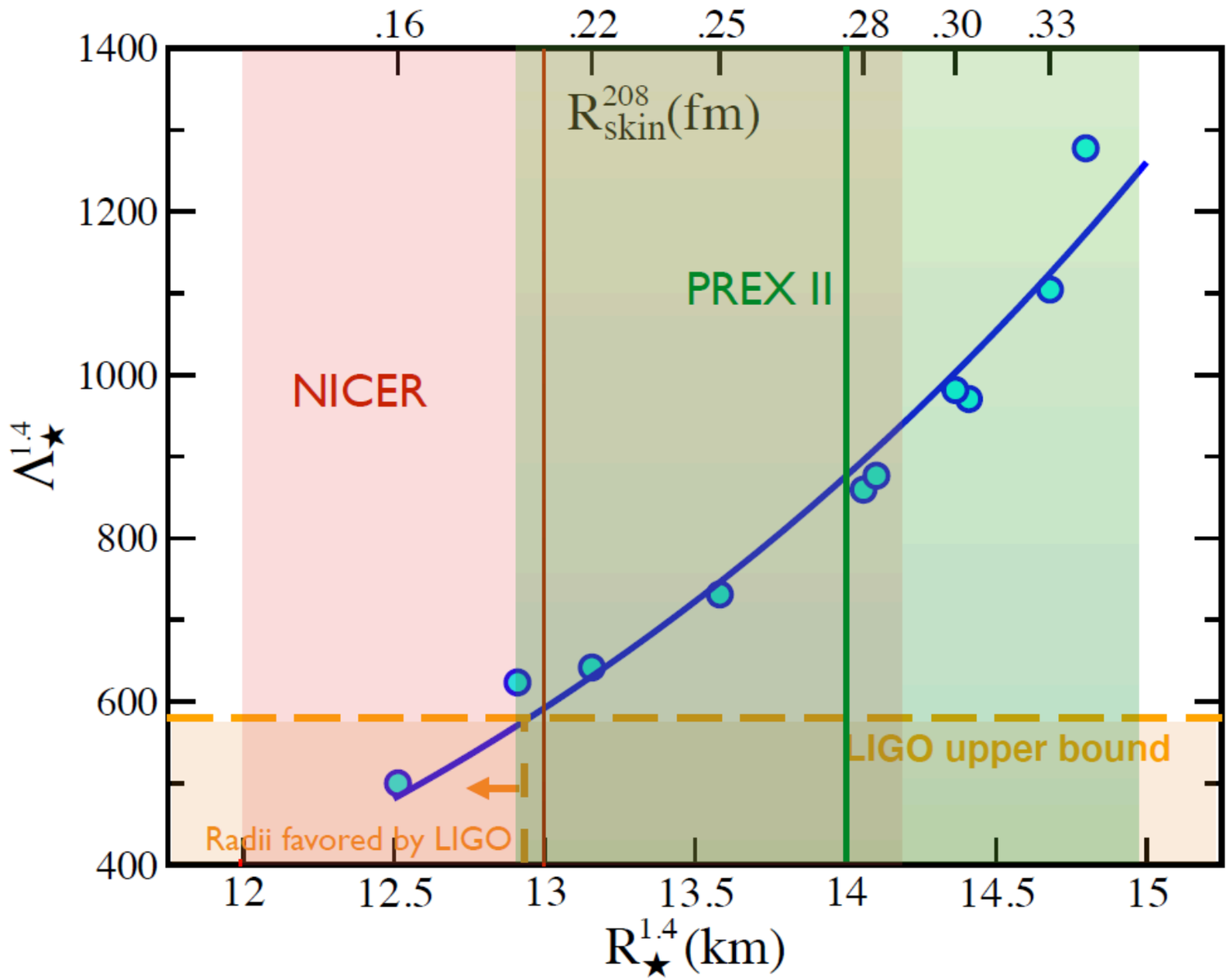


$$\xi = \frac{2GM}{c^2 R} = \frac{R_S}{R}$$



Bringing it all together

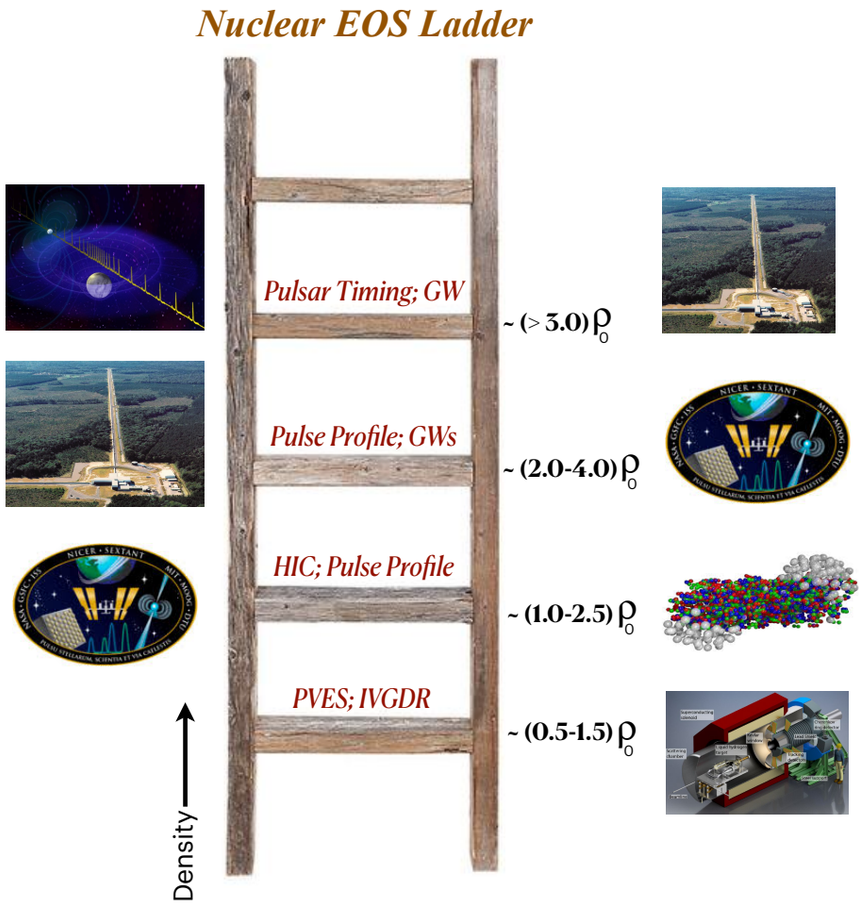


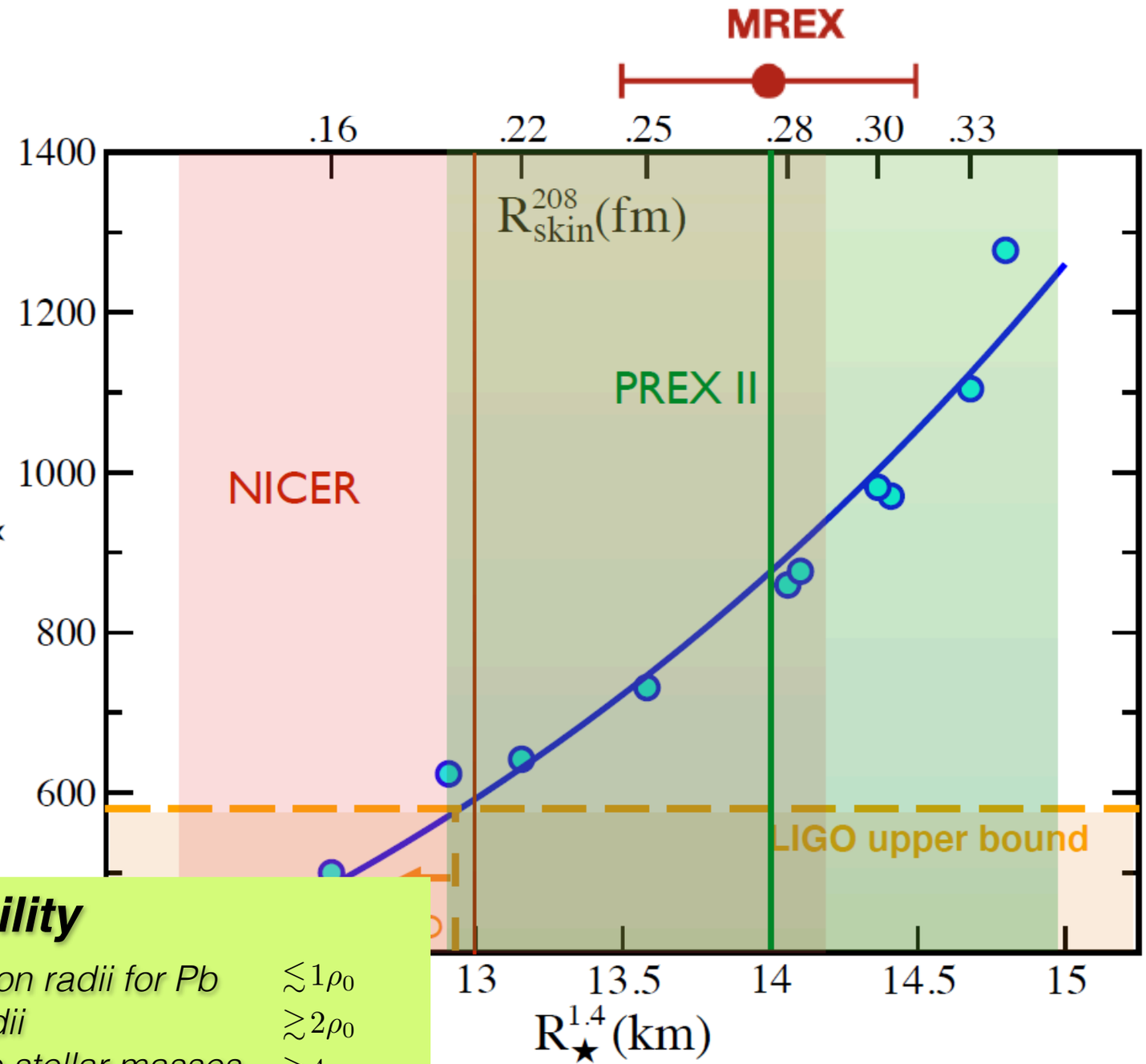


... per aspera ad astra ...

Bringing it all together

Jorge Piekarewicz (2020)





Tantalizing Possibility

- *Laboratory Experiments suggest large neutron radii for Pb* $\lesssim 1\rho_0$
- *Gravitational Waves suggest small stellar radii* $\gtrsim 2\rho_0$
- *Electromagnetic Observations suggest large stellar masses* $\gtrsim 4\rho_0$

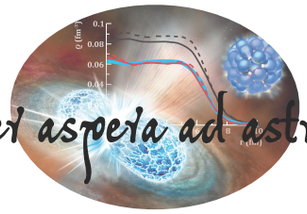
Exciting possibility: If all are confirmed, this tension may be evidence of a softening/stiffening of the EOS (phase transition?)

...per astra da astra ....

Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.

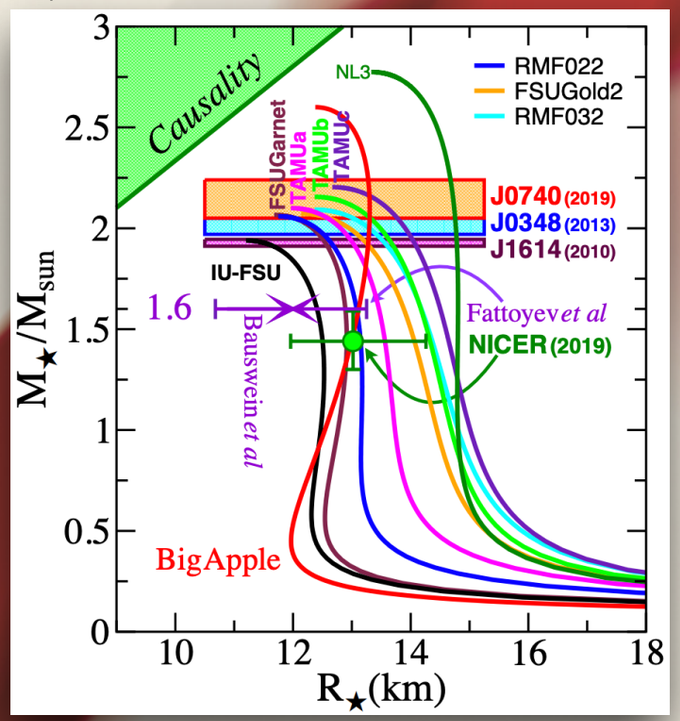
(Winston Churchill)

CONCETTINASFIENTI



... per aspera ad astra ...

JG|U



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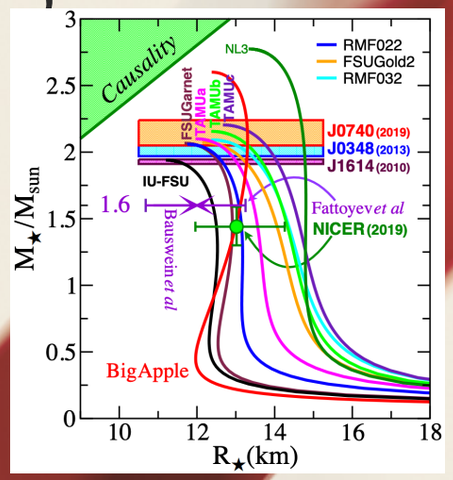
(Winston Churchill)

The Good...

...there is a way of bridging Earth and heaven...



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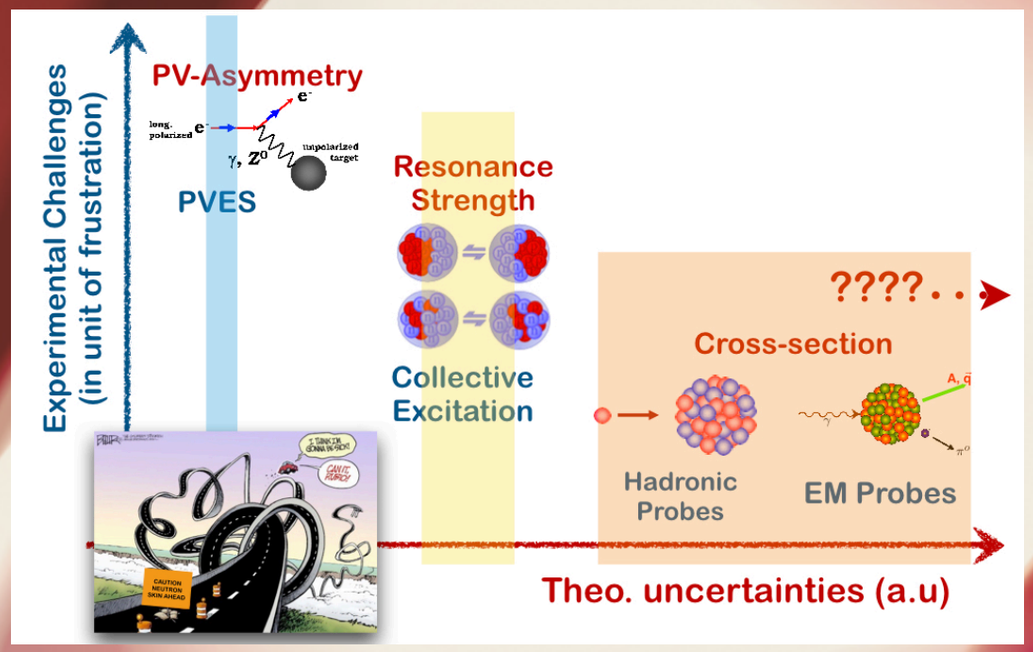
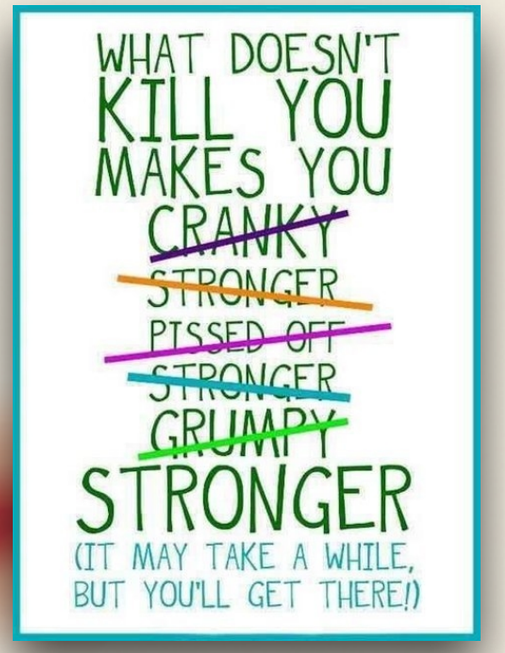
(Winston Churchill)

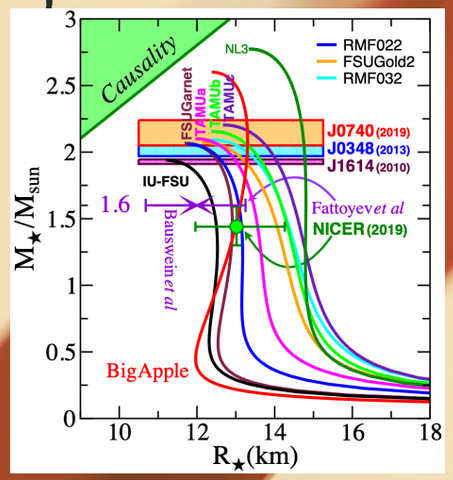
The Good...

...the bad...





...per astra da astra ....



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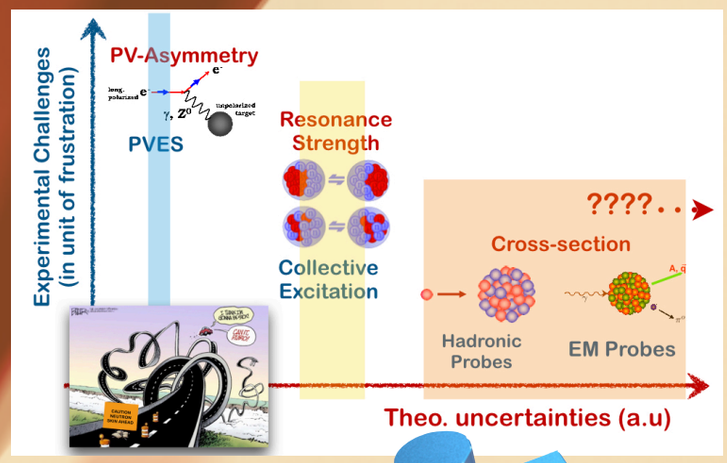
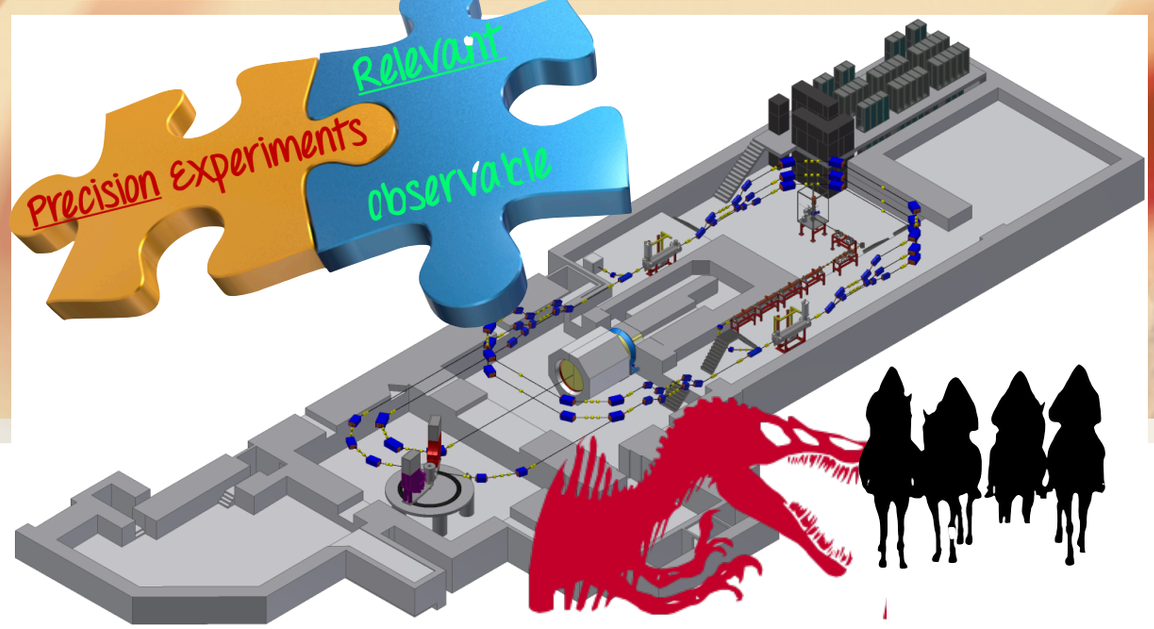
The Good...

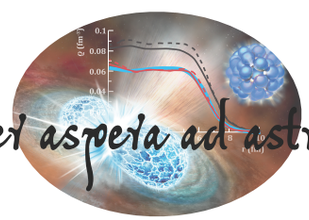


...the bad...



AND THE UGLY

...also new data for the *proton crisis*, search for exotic particles, reactions for astrophysics ...



... per aspera ad astra ...

"Wen Gott strafen will, dem erfüllt er seine Wünsche"

CONCETTINASFIENTI

JG|U