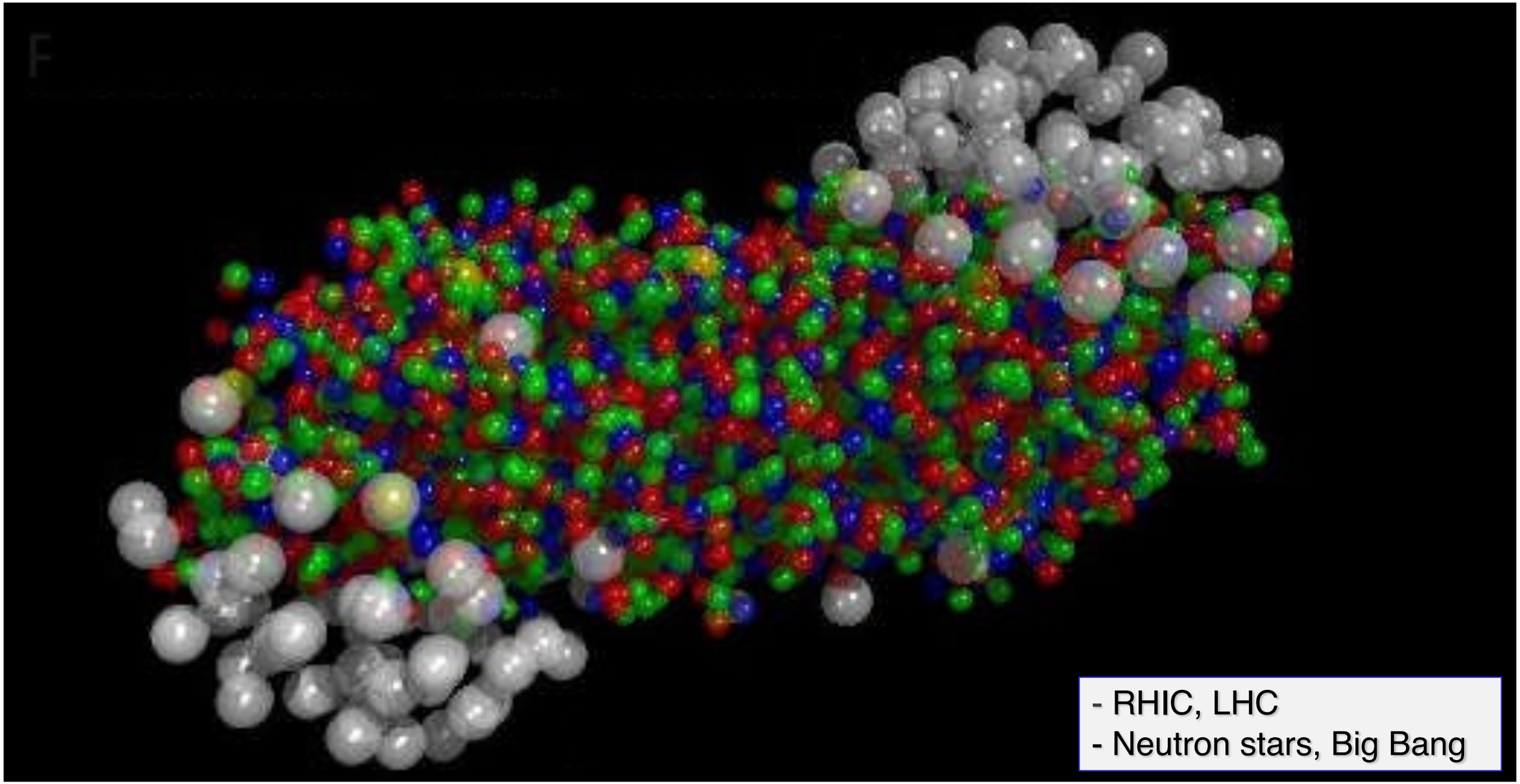
Gamma probes in relativistic heavy ion collisions

C.A. Bertulani

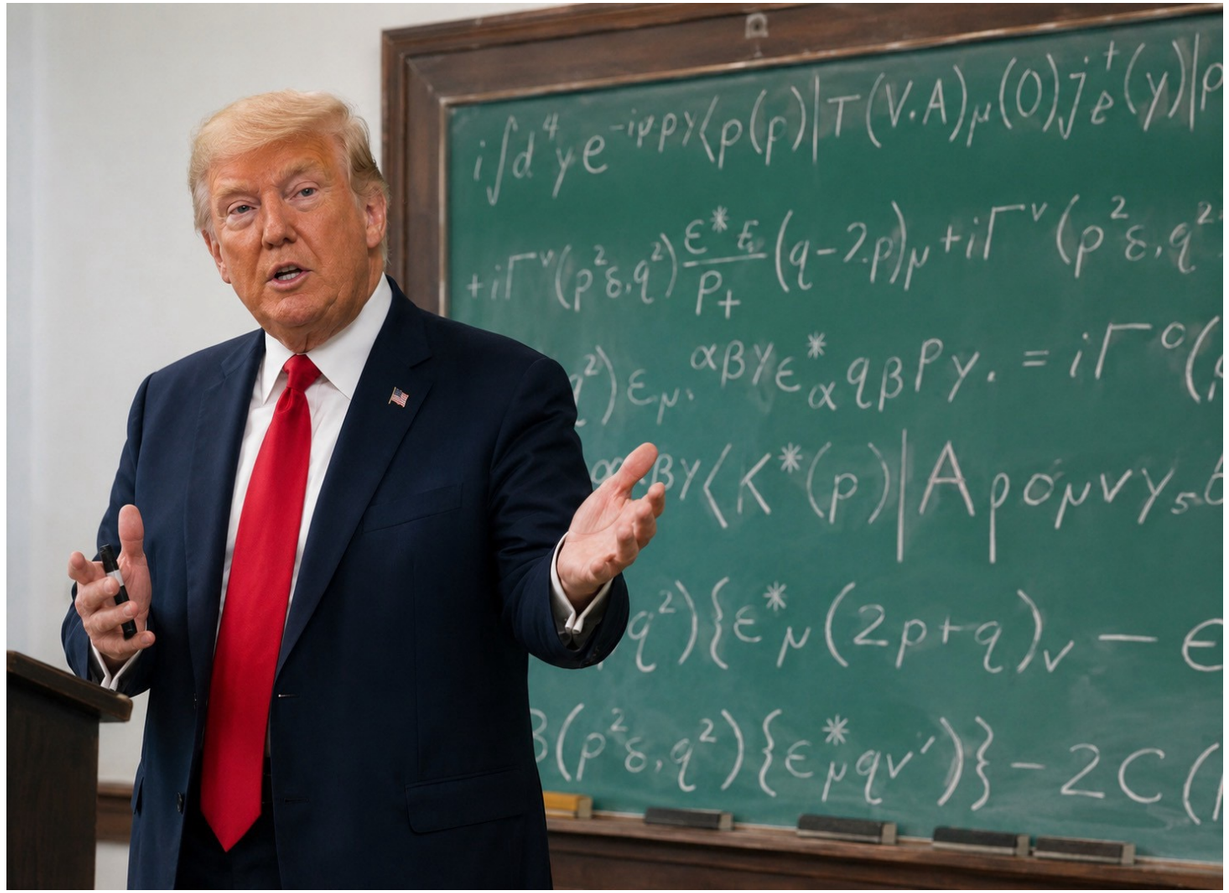
EAST TEXAS A&M UNIVERSITY

Relativistic Heavy Ion Collisions

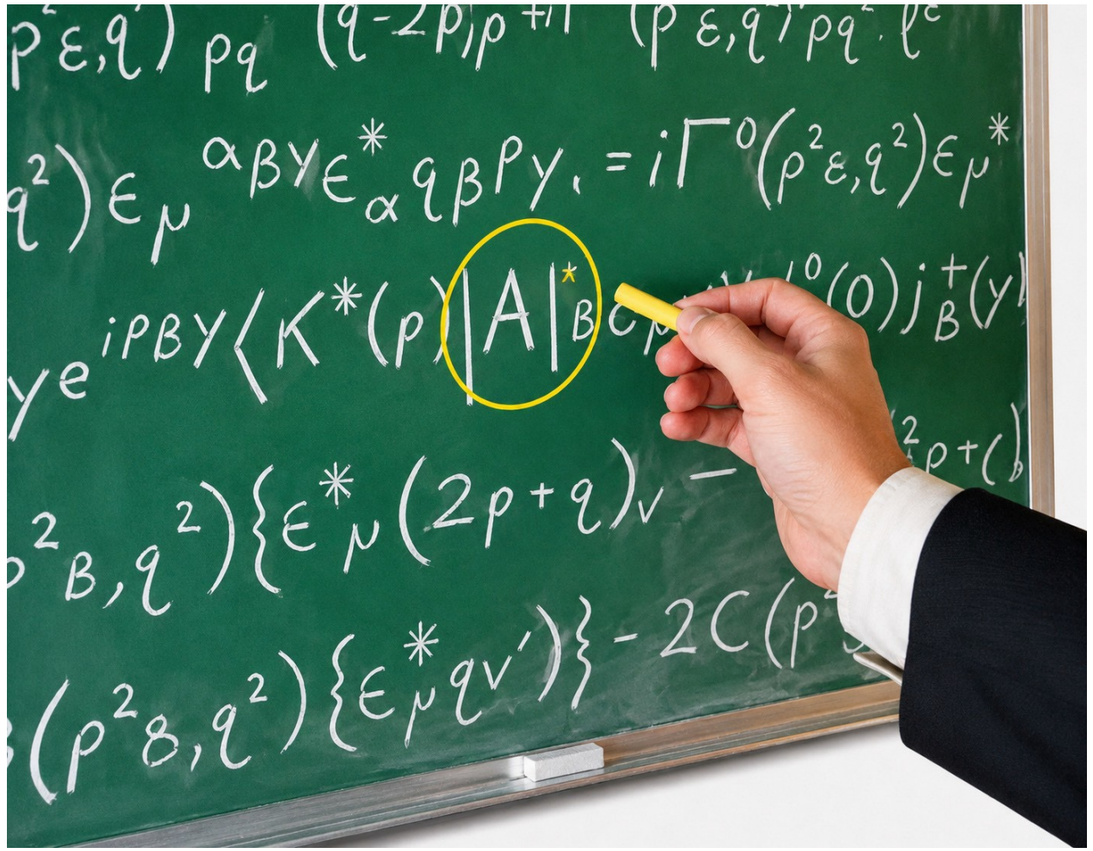


Trump finds error in CERN calculations

"Physics is a complex field, and ***even top scientists drop a decimal point or two every now and then***", Trump said.

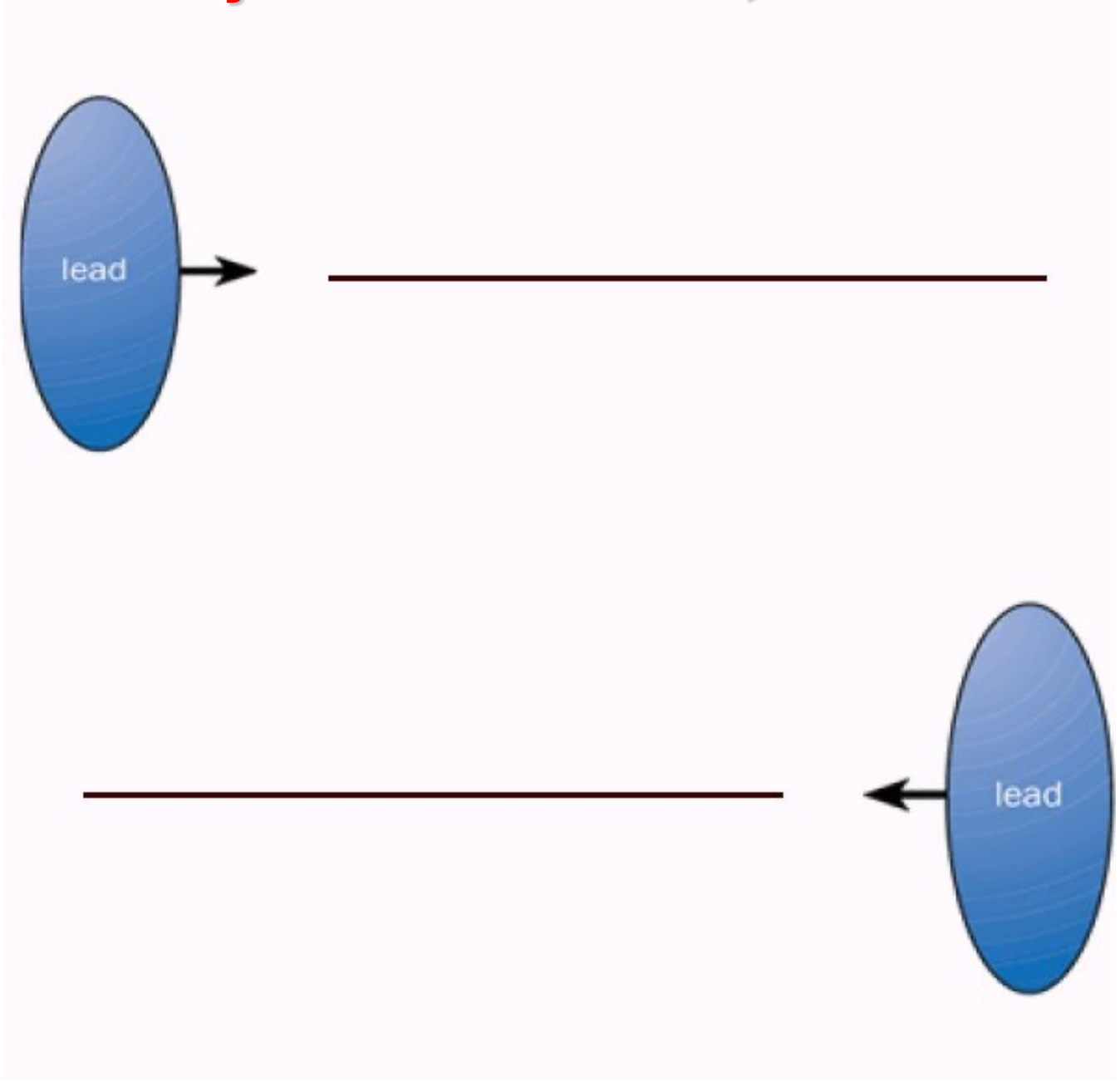


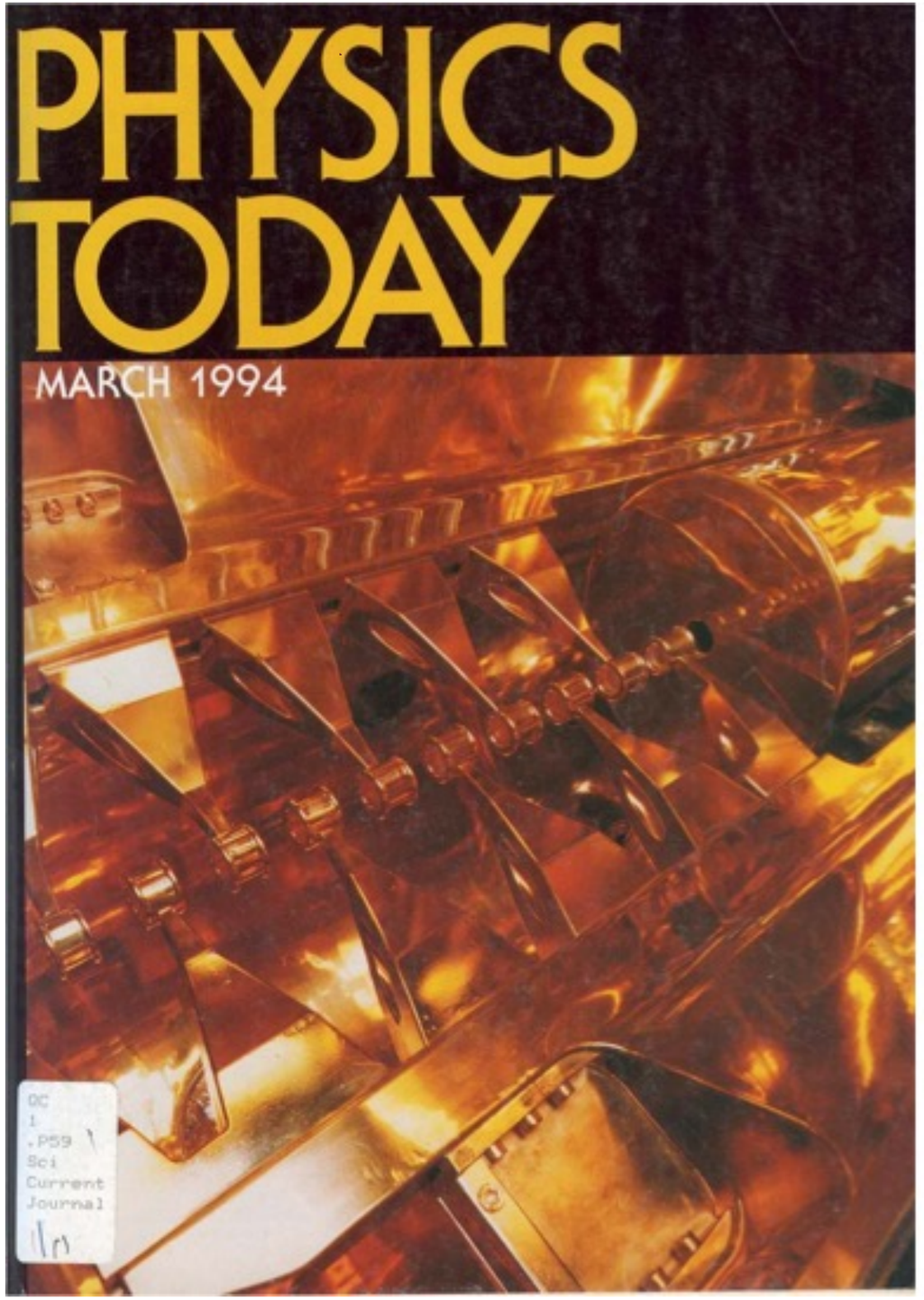
"CERN director said the ***US president is modest by an order of magnitude***"



Trump shows CERN physicists where they went wrong

Relativistic Heavy Ion Collisions, “without collisions”





RELATIVISTIC HEAVY-ION PHYSICS WITHOUT NUCLEAR CONTACT

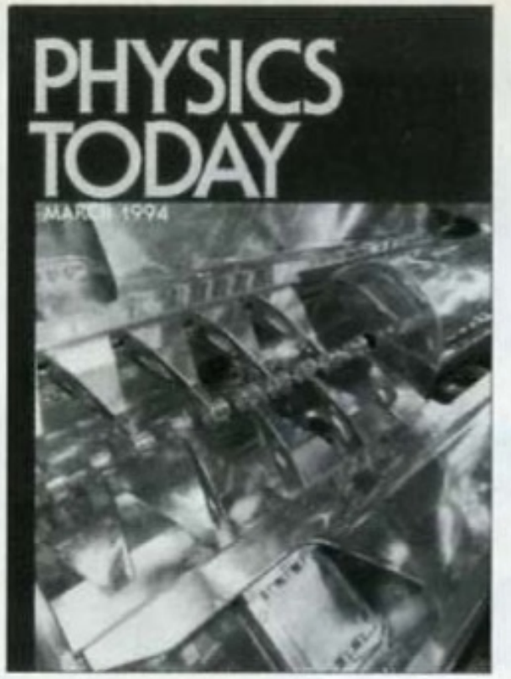
The large electromagnetic field generated by a fast heavy nucleus allows investigation of new electromagnetic processes not accessible with real photons.

Carlos Bertulani and Gerhard Baur

An increasing number of physicists are investigating nuclear collisions at relativistic energies. (See figure 1.) Accelerators completely devoted to the study of these collisions (such as the Relativistic Heavy Ion Collider at Brookhaven National Laboratory) are under construction. So are hadron colliders (such as the Large Hadron Colmately by $b/\gamma v$ and that the electric (or magnetic) field during this time interval is very intense: $E \simeq \gamma Ze/b^2$. The factor γ, which is $(1 - v^2/c^2)^{-1/2}$, is very large (on the order of 10^4–10^7) in relativistic heavy-ion colliders.

Theory

COVER: Inside of a compact high-frequency linear accelerator for heavy ions developed at the Technical University of Munich and at GSI in Darmstadt, Germany. The polished copper structure uses a quadrupole field to focus highly charged ions. Accelerators of this design at GSI and CERN bring ions up to high enough energies that the main accelerators can take them to relativistic energies. In their article on page 22, Carlos Bertulani and Gerhard Baur discuss the physics one can probe by colliding relativistic heavy ions without nuclear contact.



PHYSICS REPORTS

A Review Section of Physics Letters

ELECTROMAGNETIC PROCESSES IN RELATIVISTIC HEAVY ION COLLISIONS

Carlos A. BERTULANI and Gerhard BAUR

Volume 163 Numbers 5 & 6

June 1988

LAST ISSUE OF THIS VOLUME

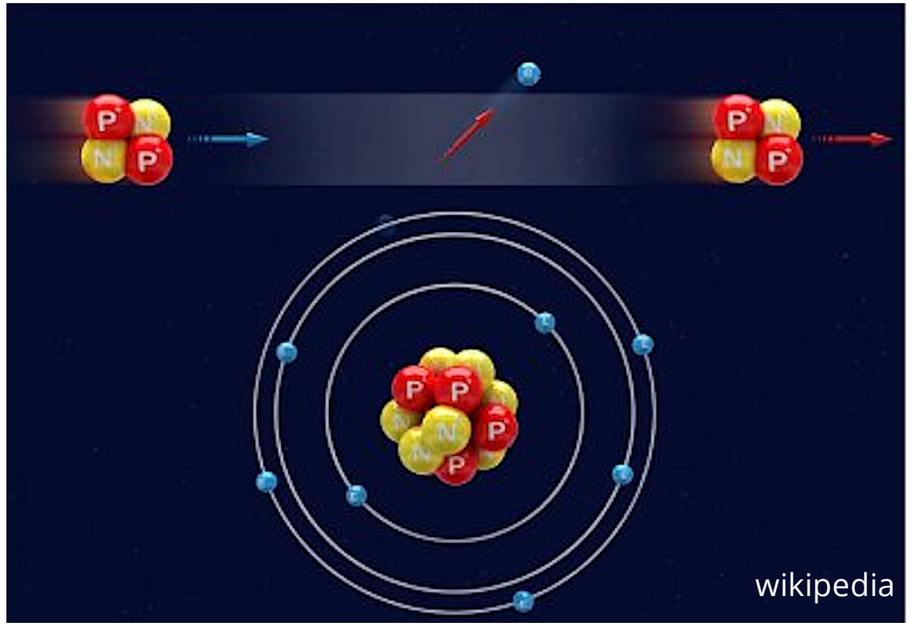
Atomic ionization by α-particles (1924)

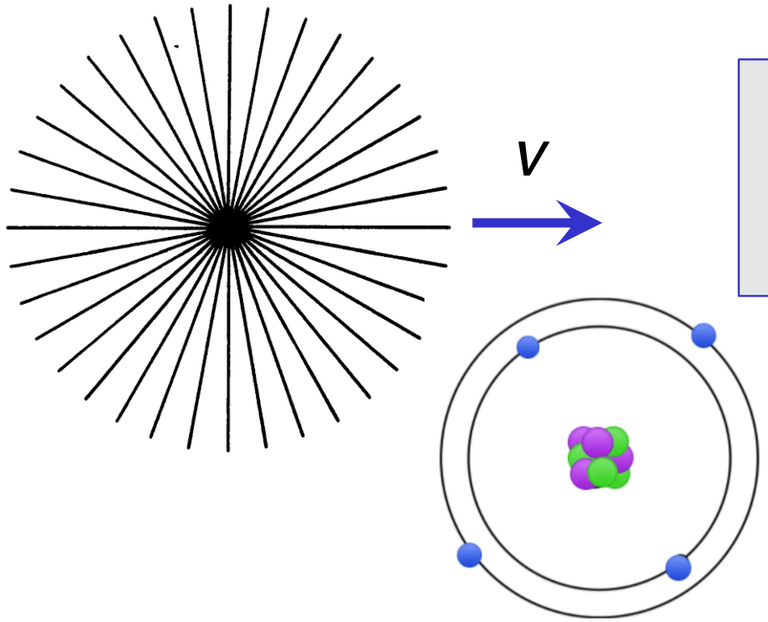
Fermi's method:

(a) calculate energy content of time-dependent EM field of α-particle

$$I(\omega) = \frac{c}{4\pi}|\boldsymbol{E}(\omega)\times\boldsymbol{B}(\omega)|$$

(b) Multiply $I(\omega)$ by photoionization cross section



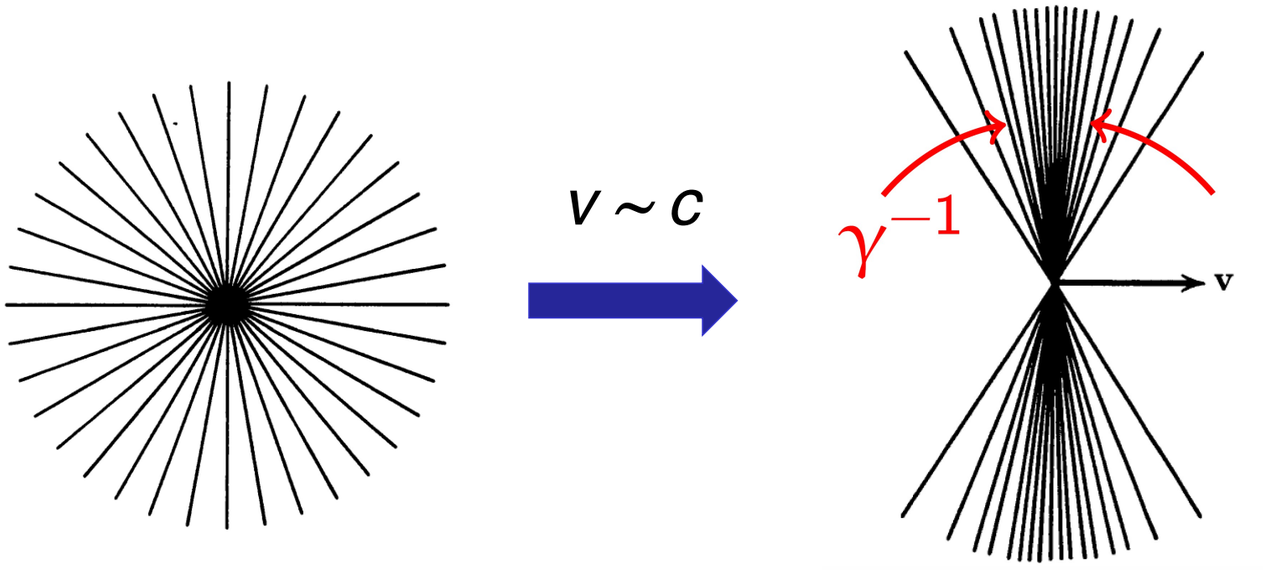


$$P(b) = \int I(\omega,b)\sigma_{ph}(\omega)d\omega = \int \frac{N(\omega,b)}{\omega}\sigma_{ph}(\omega)d\omega$$

Fermi, Z. Phys. 29, 315 (1924)
Fermi Nuovo Cimento 2, 143 (1925)

Weizsäcker, Z. Phys. 88, 612 (1934)
Williams, Phys. Rev. 45, 729 (1934)

Lorentz contraction

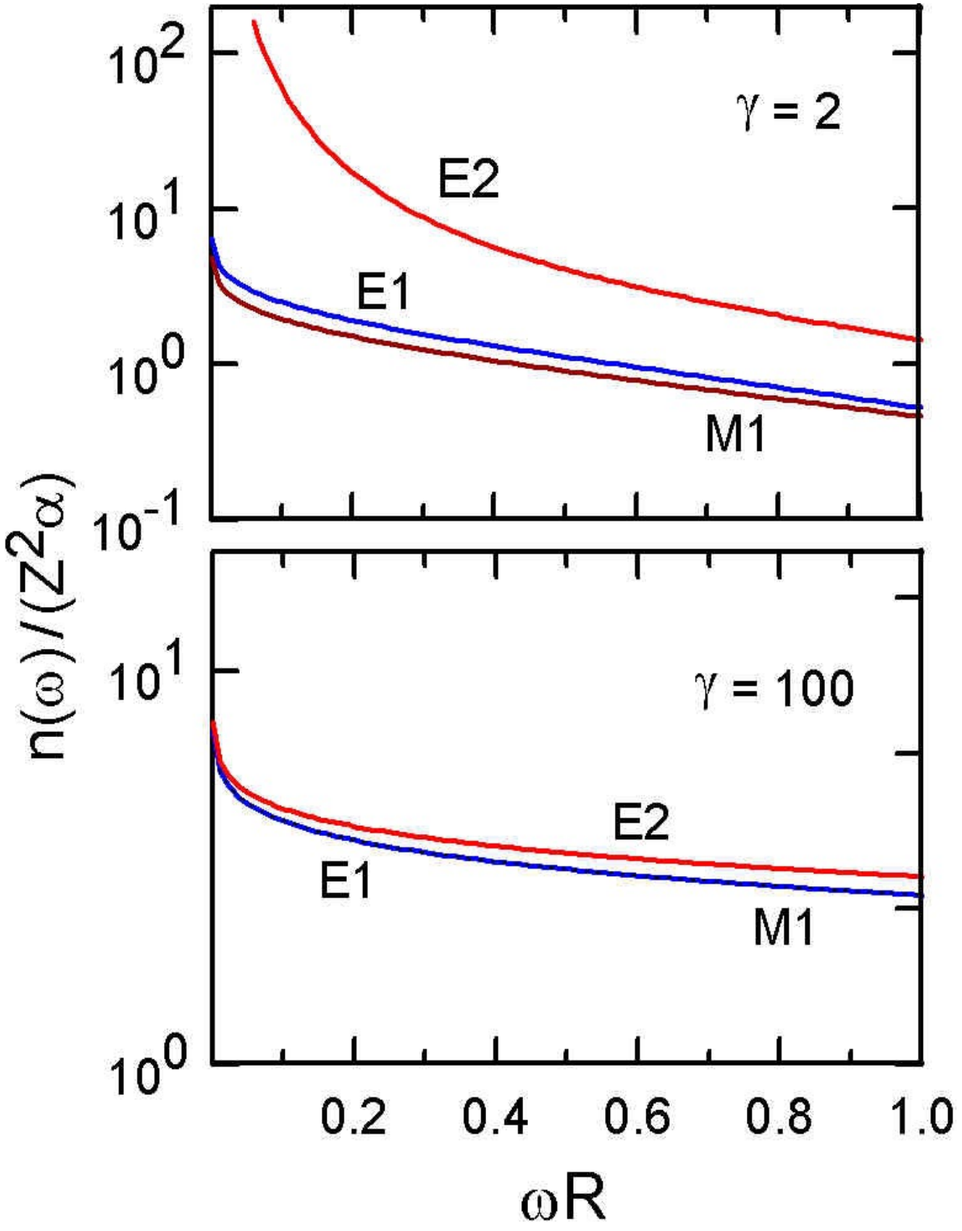


low-energy (tidal)

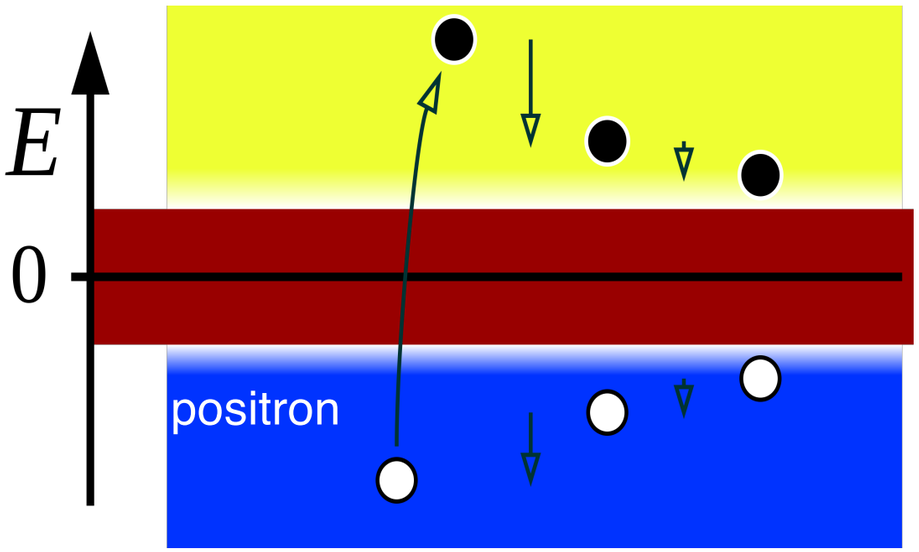
$$n_{E2} >> n_{E1} >> n_{M1} = \frac{v^2}{c^2} n_{E1}$$

high-energy (contraction)

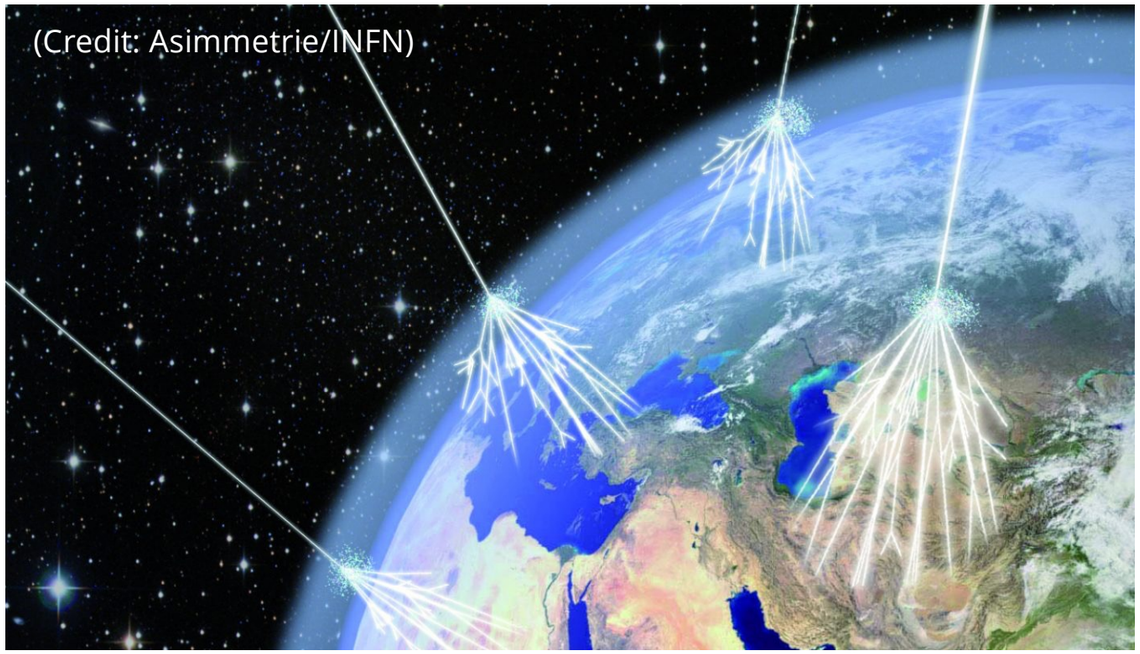
$$n_{E2} \sim n_{E1} \sim n_{M1}$$



Do antiparticles exist? (1930s)



Dirac (1930)



Search in cosmic rays → no QFT, no QED, no Feynman diagrams → brute force QM

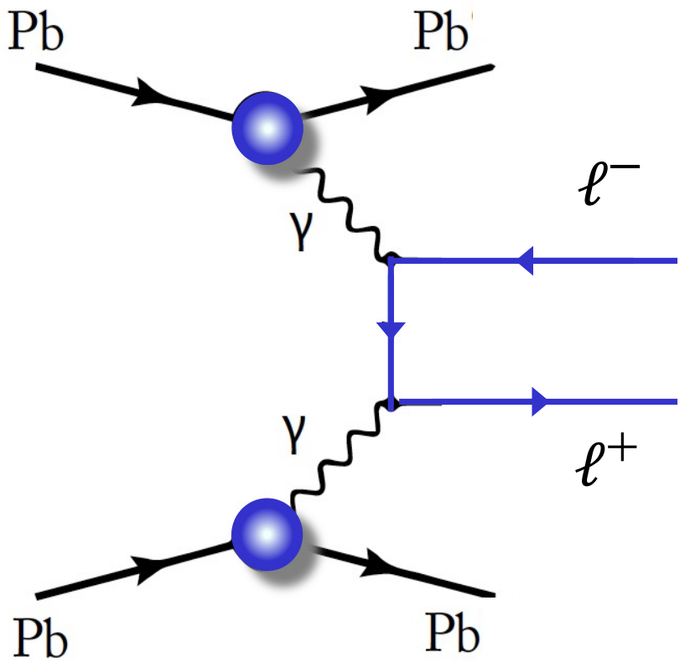
$$\psi = \psi_- + \psi_+ = \psi_0 + \psi_1 + \cdots$$

Perturbation theory

$$\left[-i\gamma^\mu \partial_\mu + m\right]\psi_n = -e\,\gamma^\mu A_\mu\,\psi_{n-1}$$

W.H. Furry and J.F. Carlson, Phys. Rev. 44, 238 (1933)
L.D. Landau and E.M. Lifshitz, Phys. Zs. Sowjet. 6, 244 (1934)
H.J. Bhabha, Proc. R. Soc. London Ser. A 152, 559 (1935)
Y. Nishina, S. Tomonaga and M. Kobayashi, Sci. Pap. Inst. Phys. Chem. Res. 27, 137 (1935)
G. Racah, Nuovo Cimento 14, 93 (1937)

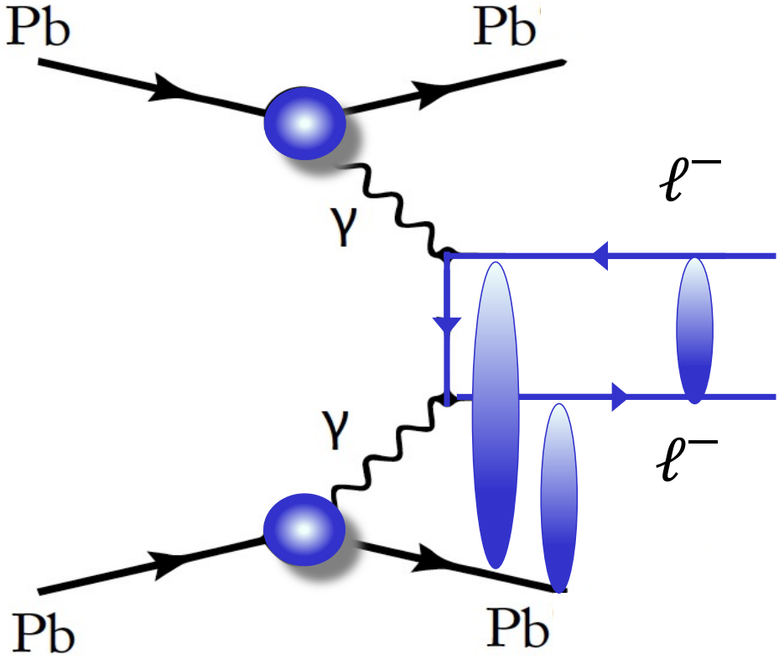
Free pair production



At the LHC (10^7 pairs/second)

$\sigma \sim 200\ kilobarns$

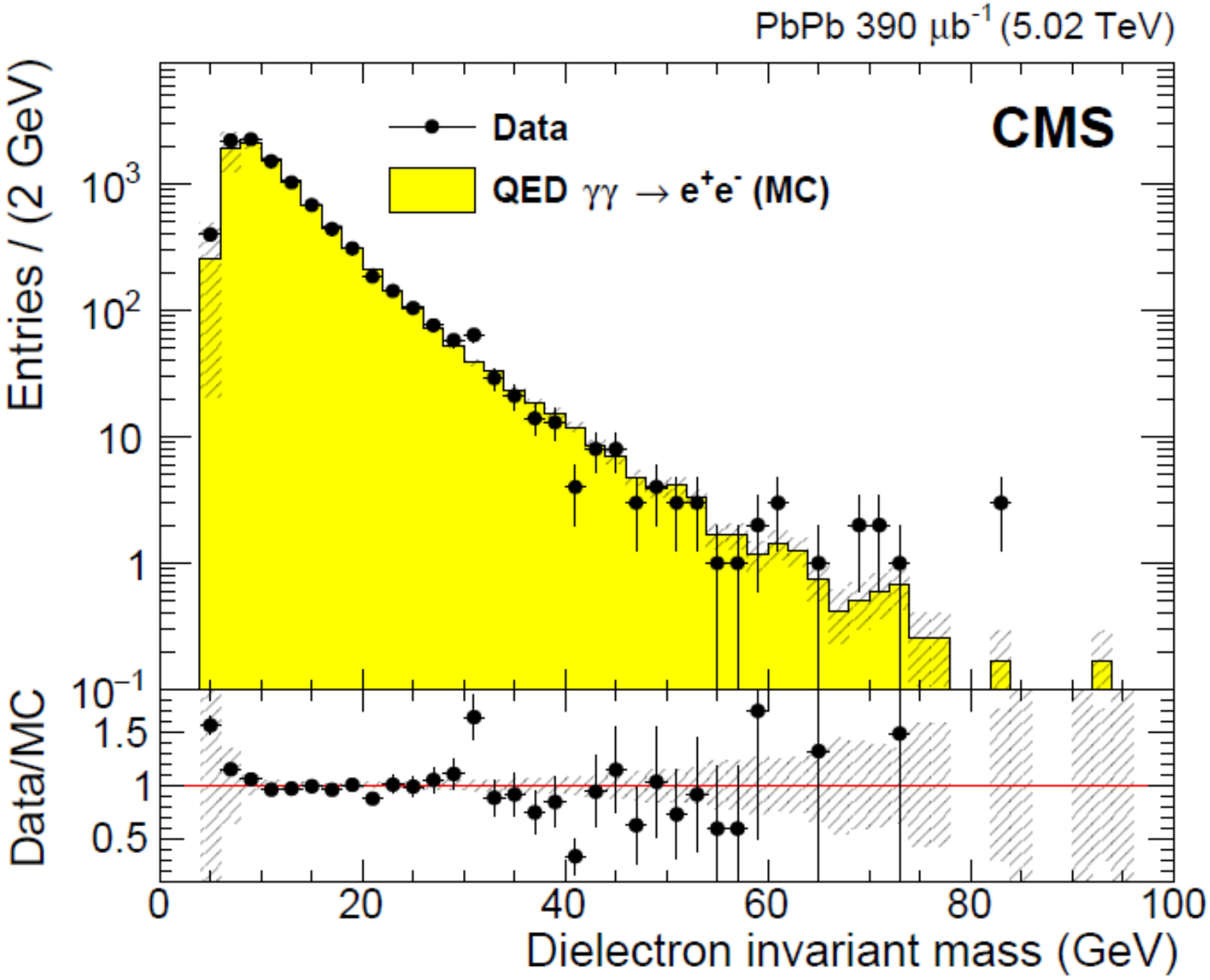
Coulomb distortions for large Z
Multiple pair production in UPC

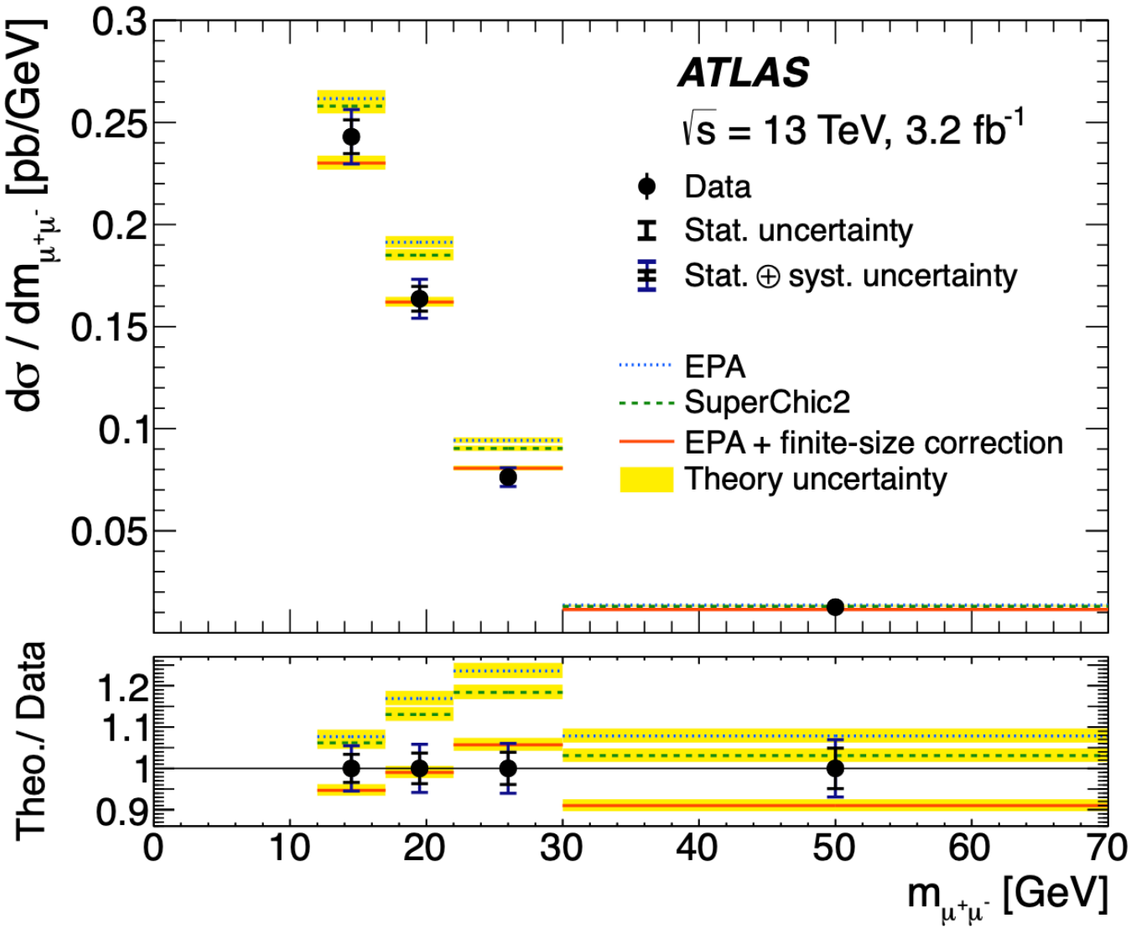


Cosmic rays experiments difficult

Laboratory experiments difficult and inconclusive for many decades

Free pair production

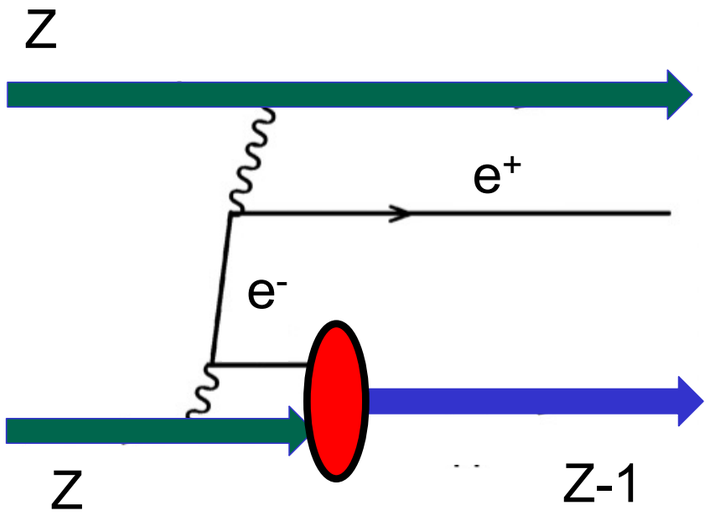




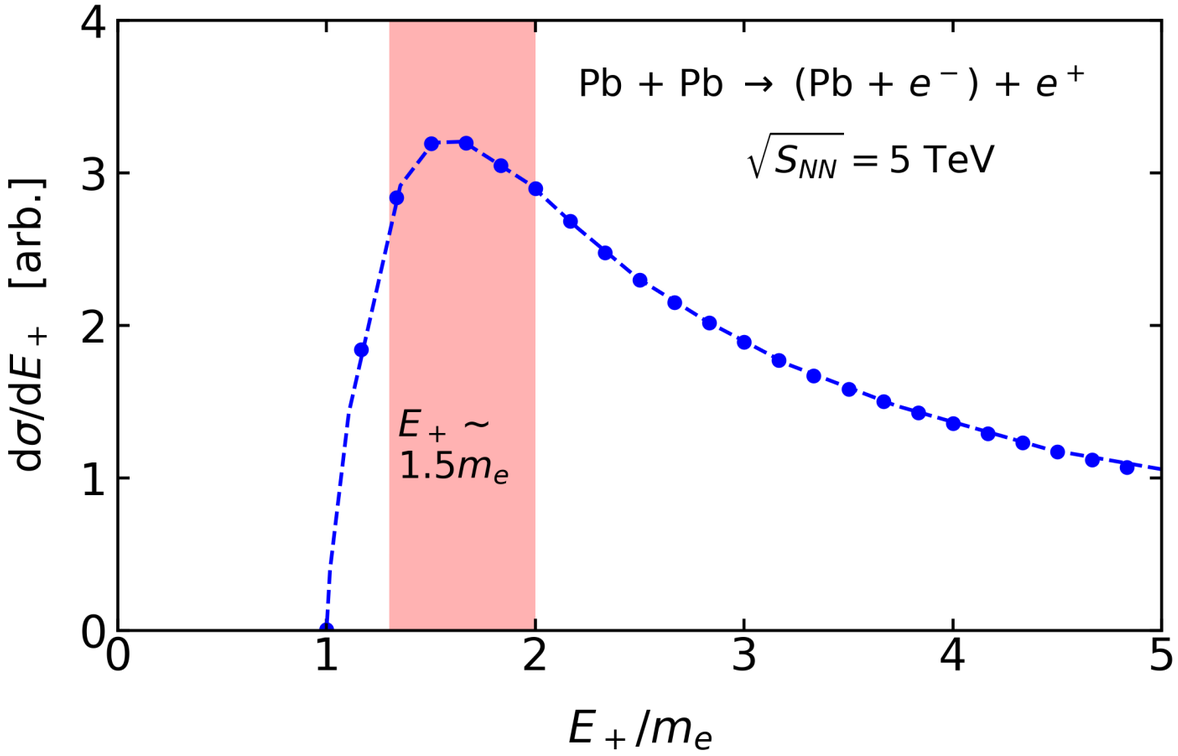
CMS collaboration, JHEP 1201, 052 (2012)

ATLAS collaboration, PLB 777, 303 (2018)

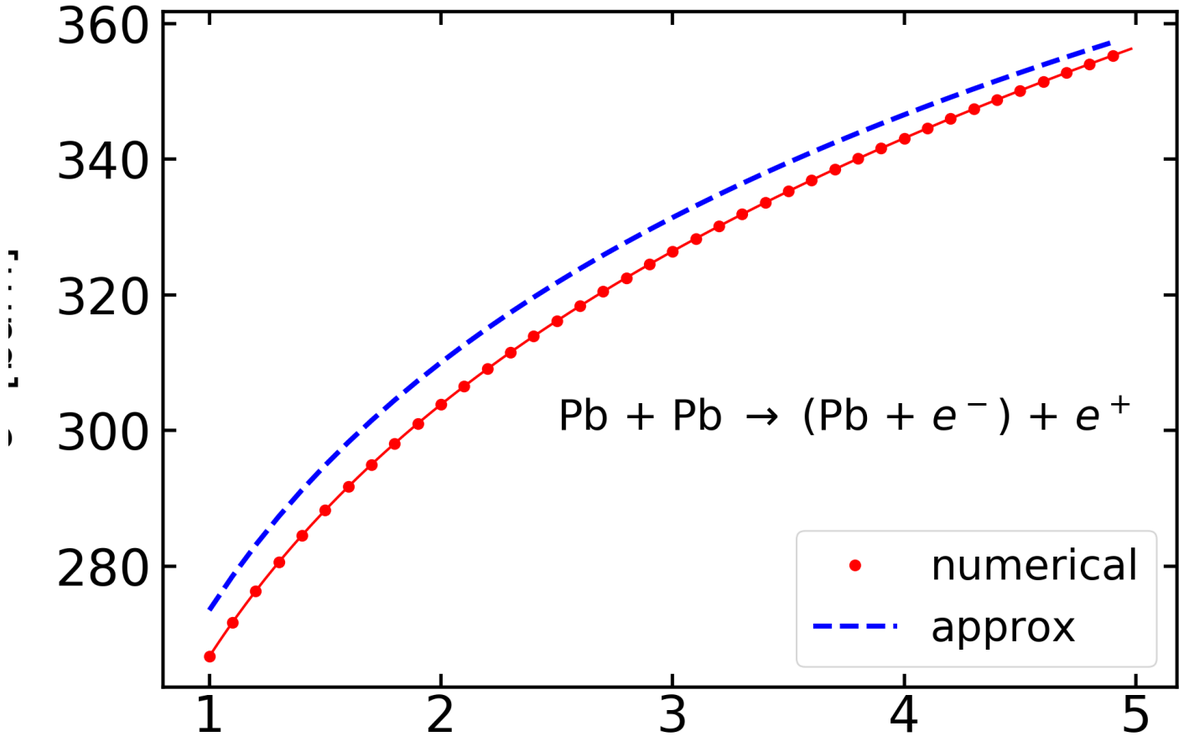
Pair production with capture



K-shell capture. Only 20% capture in higher orbitals.



Electron capture → beam loss at CERN



Experiment $\sqrt{S_{NN}}$ [TeV]

ALICE,
Phys. Rev. ST Accel. Beams 12, 071002 (2009)

First anti-atom (1996)

The New York Times

NY Times, January 5, 1996

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS

CERN (LEAR): 1996
9 events

PLB 368, 251 1996

Theory:

PRD 58, 034005 (1998)

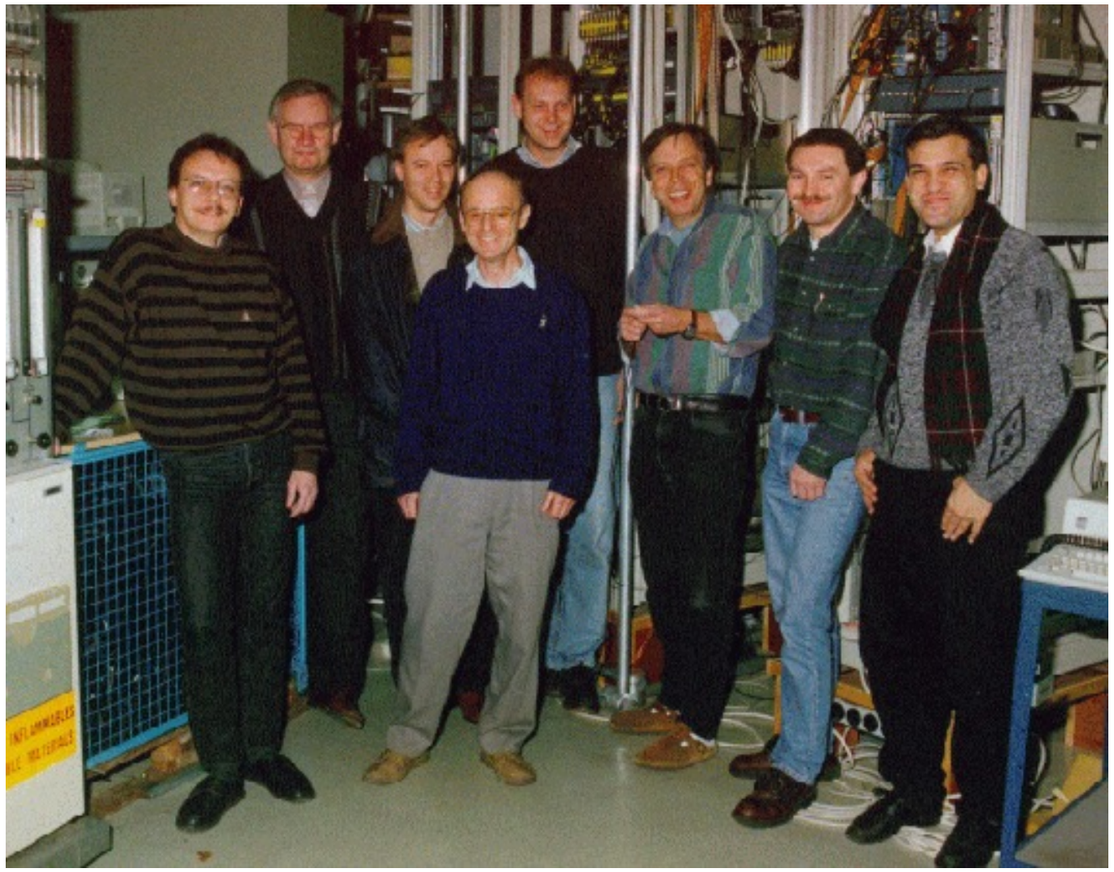
FERMILAB: 1998
57 events

Phys. Rev. Lett. 80, 3037 (1998)

Physicists Manage to Create The First Antimatter Atoms

By MALCOLM W. BROWNE
Published: January 5, 1996

But the neutrality of antihydrogen, like that of ordinary hydrogen, renders it impossible to contain or manipulate using magnetic fields. Moreover, an antiatom cannot be contained in an ordinary vessel, since the slightest contact with the container's wall causes it to annihilate. Consequently, other groups are developing enormously sophisticated methods, including interacting lasers, to manipulate and secure antiparticles inside vacuum chambers.



Why antihydrogen?

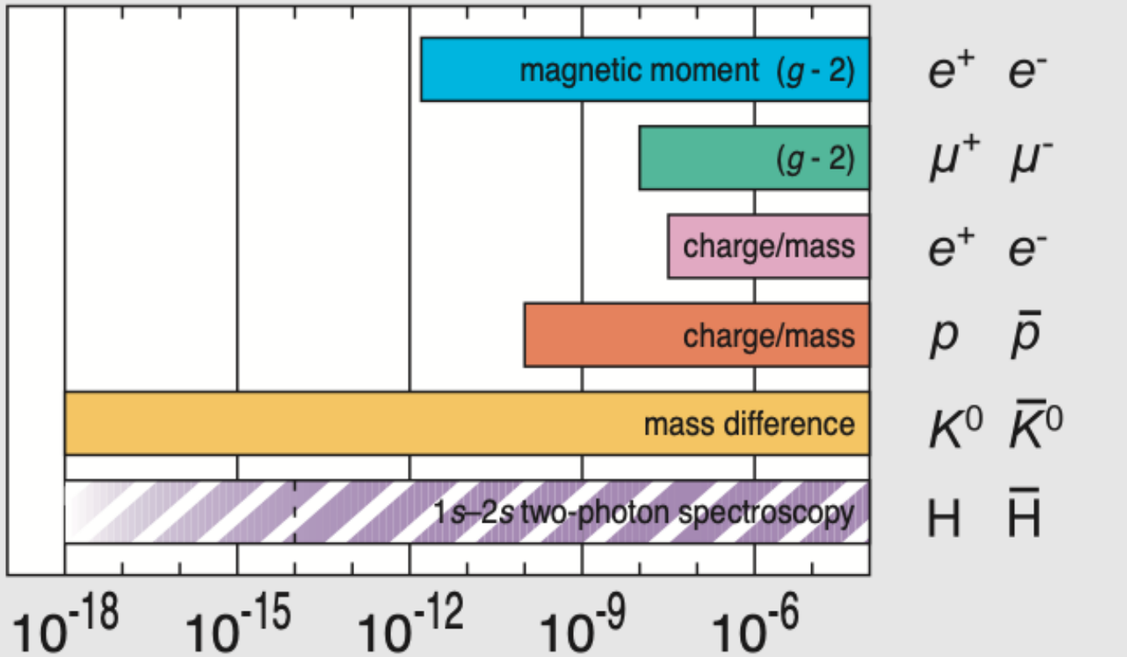
- QFT → CPT → Matter and antimatter are symmetric
  This assumes point like elementary particles (quarks and leptons). Experimentally < 10^{-16} cm.

- Finite size superstrings of 10^{-33} cm to achieve unification at 10^{19} GeV (Planck mass).
  CPT fails at 10^{19} GeV or perhaps at lower energies (as curled-up dimensions decrease the unification energy)

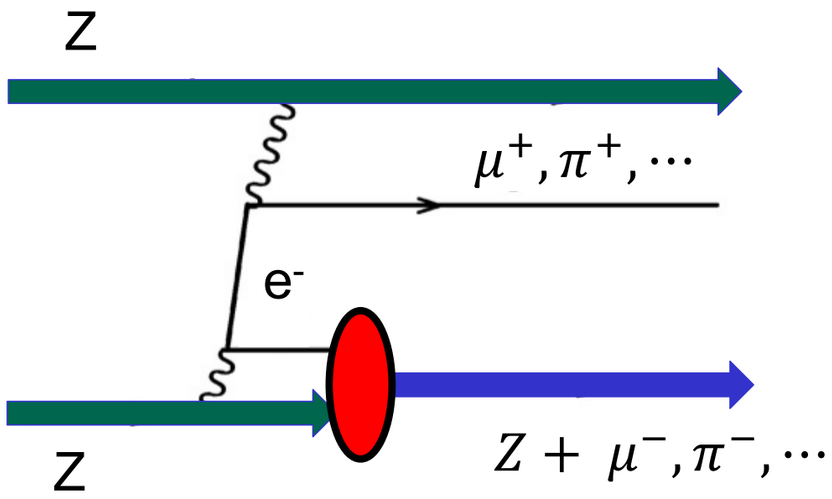
The CPT theorem rests on a foundation which is unsound at the Planck length.

The symmetry of matter and antimatter must rest on experimental evidence.

→ Antihydrogen experiments at CERN: ATHENA, ATRAP, ALPHA, GBAR, PUMA, etc.



Production of exotic Atoms



$$Z + Z \to (Z + \mu^-) + Z + \mu^+ \to (Z + \pi^-) + Z + \pi^+ \to \cdots$$

Ingredients:

1. Perturbation theory
2. LO + NLO

$$\Psi_+ = \left[\frac{2\pi a_+}{e^{2\pi a_+} - 1}\right]^{1/2} \left[e^{-i\boldsymbol{k}_+\cdot\boldsymbol{r}}\boldsymbol{v} + \Psi_{NLO}\right]$$

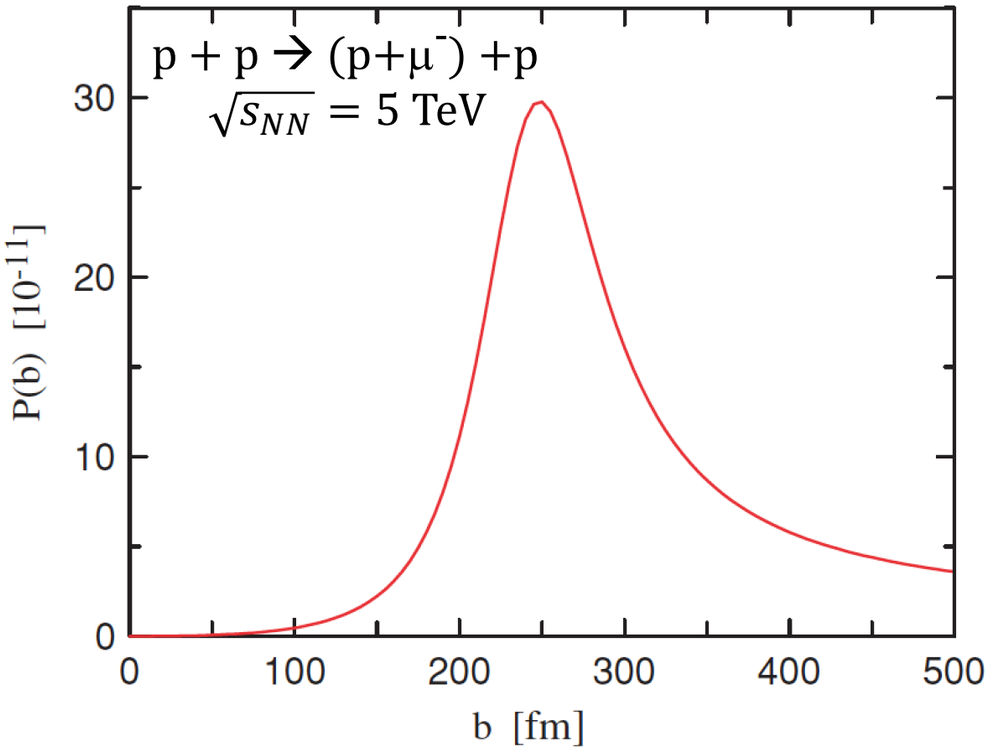
$$\Psi_{NLO} = \frac{Z\alpha}{2\pi^2}\int dq^3 e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\frac{2\gamma^0 E_+ + i\boldsymbol{\gamma}\cdot(\boldsymbol{q}-\boldsymbol{k}_+)}{(\boldsymbol{q}-\boldsymbol{k}_+)^2(q^2-k_+^2)}$$

3. Virtual photons expanded in multipoles (E1, E2, $\cdots$)
4. Bound state wavefunction for $\mu^-, \pi^-, \cdots$

$$\Psi_- = \left[\frac{(Zm\alpha)^3}{\pi}\right]^{1/2}\left[1 + \frac{i}{2}(Z\alpha)\boldsymbol{\alpha}\cdot\frac{\boldsymbol{r}}{r}\right]e^{-(Zm\alpha)r}\,u$$

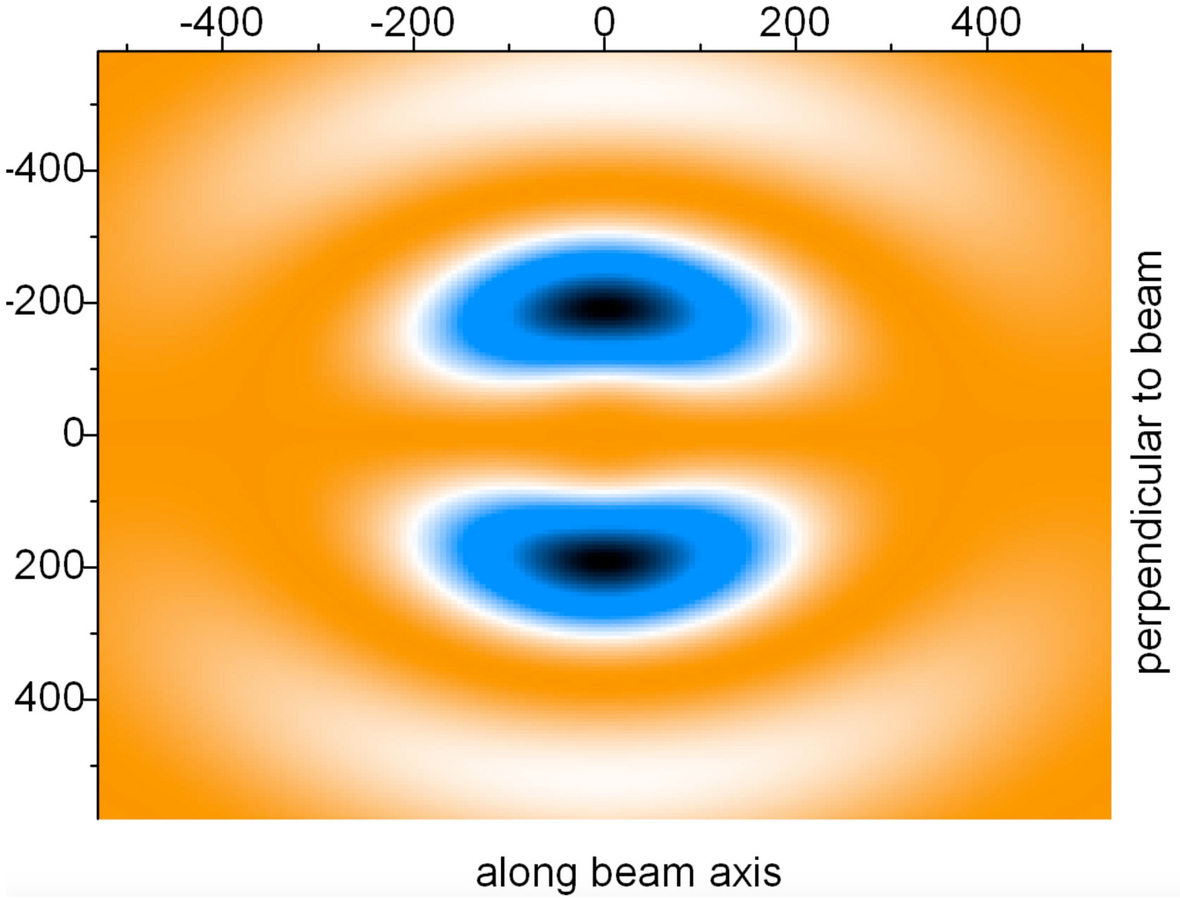
Production of exotic Atoms

PRC 81, 044910 (2010)

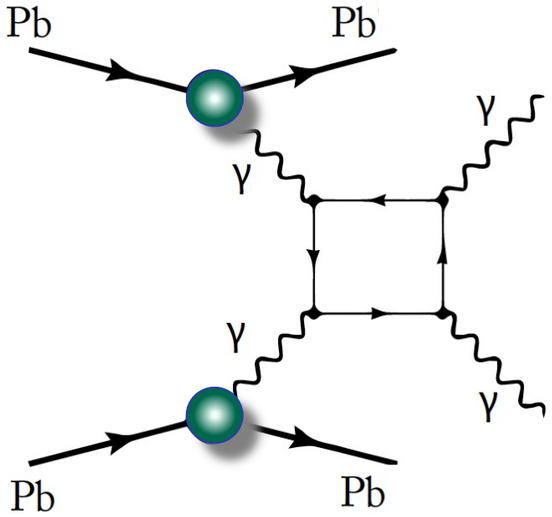


- Production probability maximum at impact parameters
  $b \sim a^{H}_{\mu,\pi,\ldots}$ (Bohr radius)
  e.g., $b \sim 255\ fm$ for muons

- Production dominated by electric dipole (~70%), but electric quadrupole has a substantial contribution (~30%)



Light-by-light scattering in UPCs

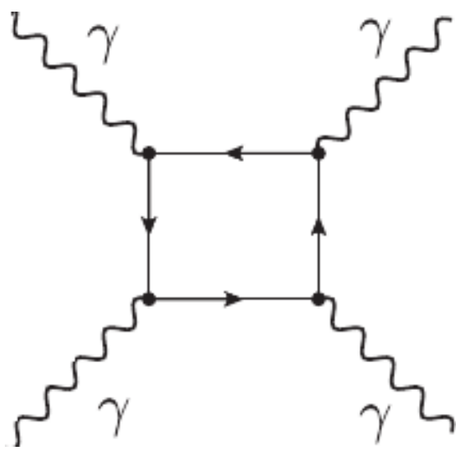


$$\sigma_{ZZ\to ZZ\gamma\gamma} = 2.54\frac{Z^4\alpha^6}{m_e^2}\left[ln^3x - \frac{3}{2}ln^2x + \frac{3}{2}lnx - \frac{3}{4}\right]$$

$$x = \frac{\gamma}{Rm_e}$$

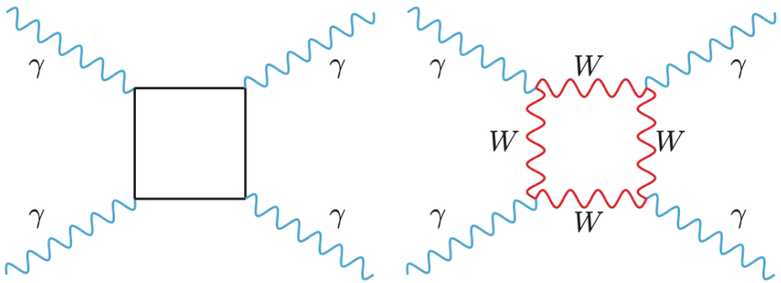
NPA 505, 835 (1989)

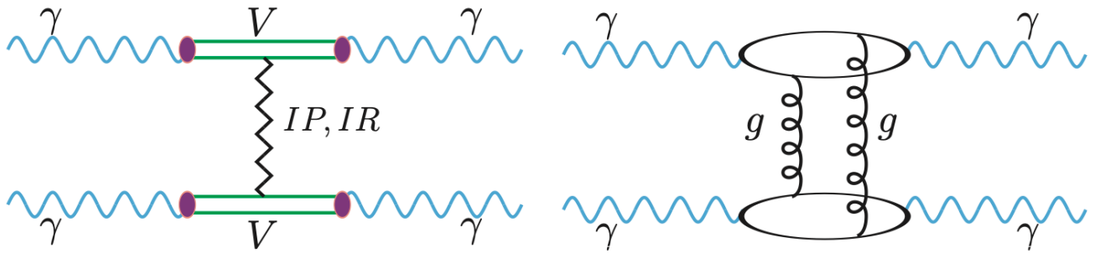
$\sigma \sim 10^8$ larger than in pp or e^+e^- collisions, although tiny (400 nb)



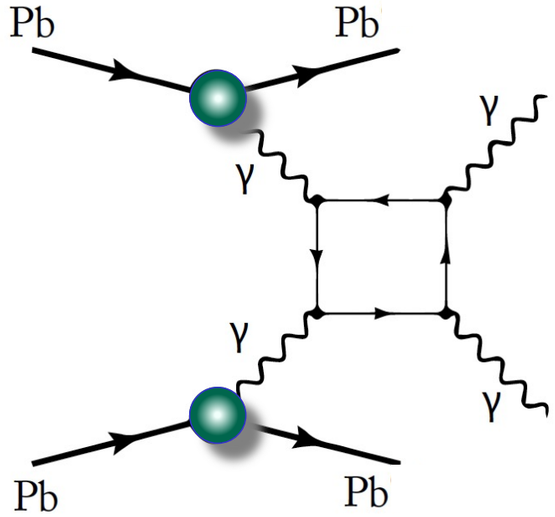
$\sim \mathcal{O}(\alpha^4)$

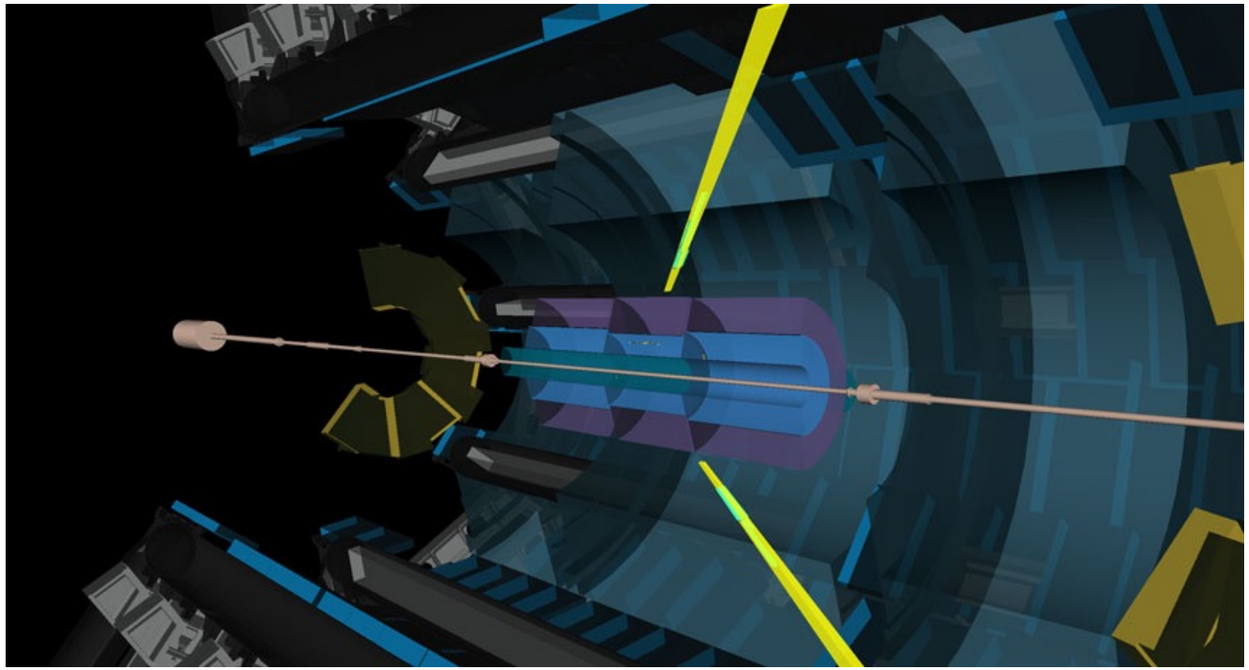
- Box might contain virtual charged particles (q,ℓ,W) from the SM.
- New charged particles (s-particles, monopoles, unparticles,...)

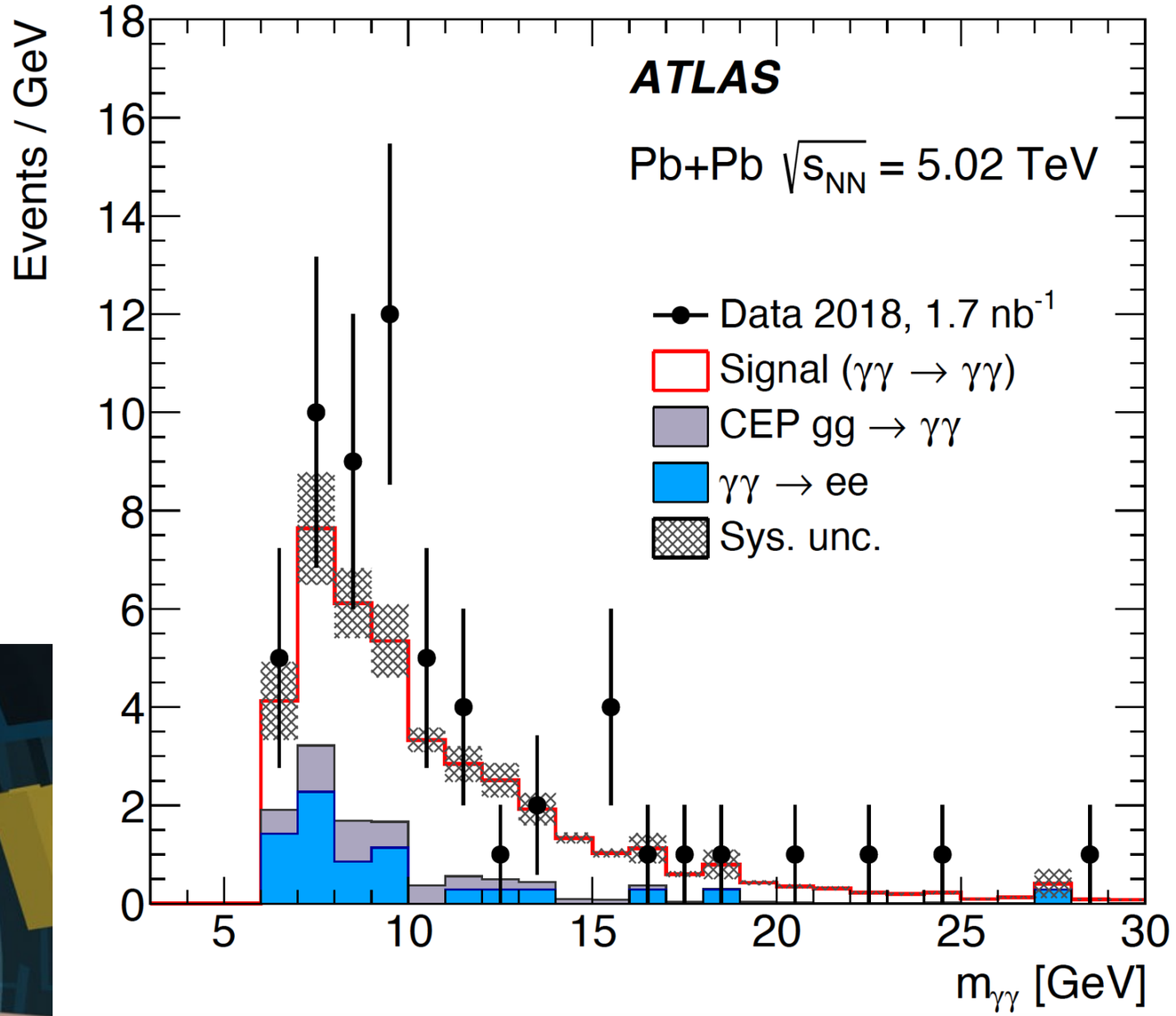




Light by light scattering





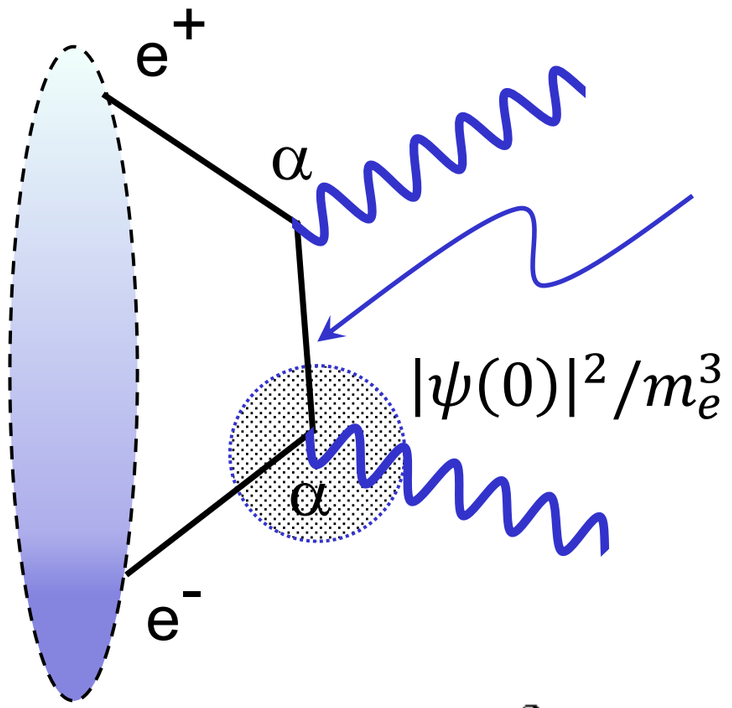


ATLAS collaboration,
Nature Physics 13, 852 (2017)

$\gamma\gamma \rightarrow$ bound states

$e^+e^- \rightarrow \gamma\gamma$ rate = $\alpha^{2\cdot}$. overlap probability / interaction time

$= \alpha^2 \,.(|\psi(0)|^2/m_e^3)\,.m_e$



$\Delta t = 1/m_e$ ➡ $\Gamma \sim \alpha^2|\psi(0)|^2/m_e^2$

RECIPE:

- replace electrons by quarks
- get rid of $|\psi(0)|^2$

Royen, Weisskopf, Nuovo Cimento A 50, 617 (1967)
Appelquist, Politzer, PRL 34, 365 (1975)

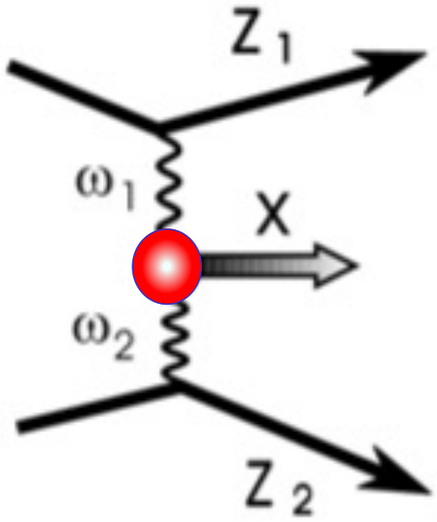
$$\Gamma_{\gamma\gamma}^{J=0} = \frac{48\pi\alpha^2}{M^2}|\Psi(0)|^2 \sum_i Q_i^4 \qquad \Gamma_{\gamma\gamma}^{(J=2)} = (2J+1)\Gamma_{\gamma\gamma}^{(J=0)} = 5\,\Gamma_{\gamma\gamma}^{(J=0)}$$

Example: parapositronium (S = 0) $\quad |\Psi(0)|^2 = (m_e\alpha)^3/8\pi n^3$

Exploring Widths of various Mesons at CERN: PRC 79, 047901 (2009)

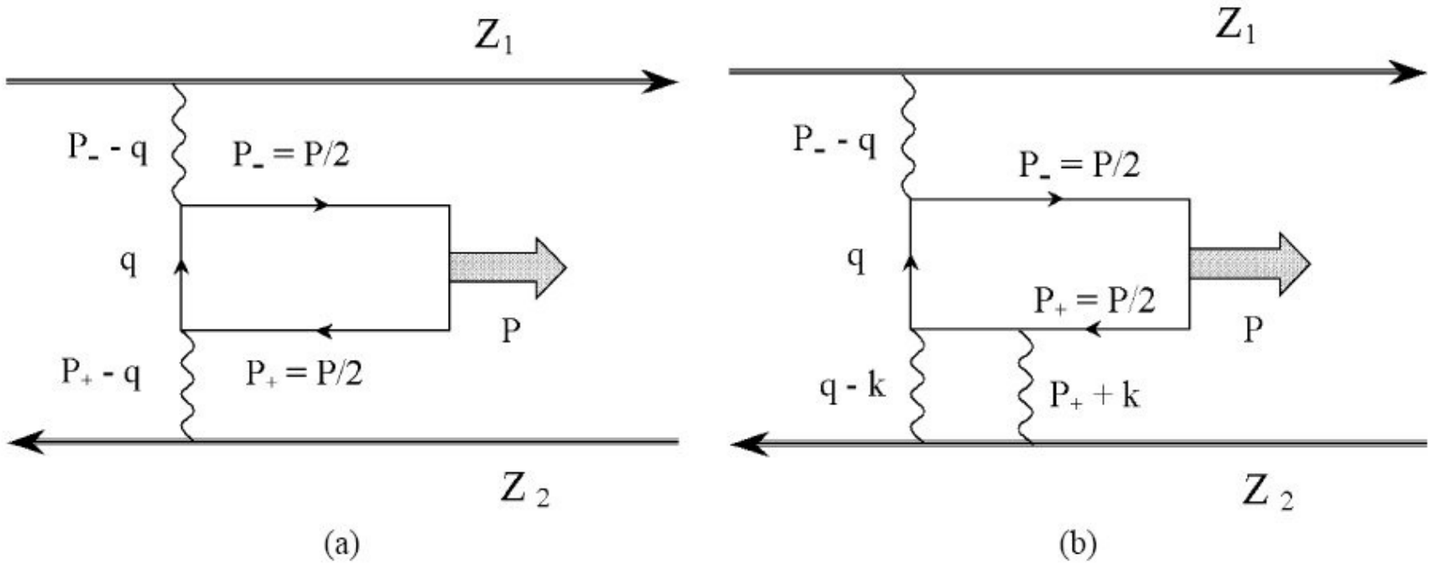
$\gamma\gamma \rightarrow$ bound states

Detailed balance + Fermi's golden rule Low, Phys. Rev. 120, 582 (1960)



$$\Rightarrow \quad \sigma^{X}_{\gamma\gamma}(\omega_1,\omega_2) = 8\pi^2(2J+1)\frac{\Gamma_{X\to\gamma\gamma}}{m_X}\delta(\omega_1\omega_2 \longrightarrow m_X^2)$$

Weisskopf-Royen projection

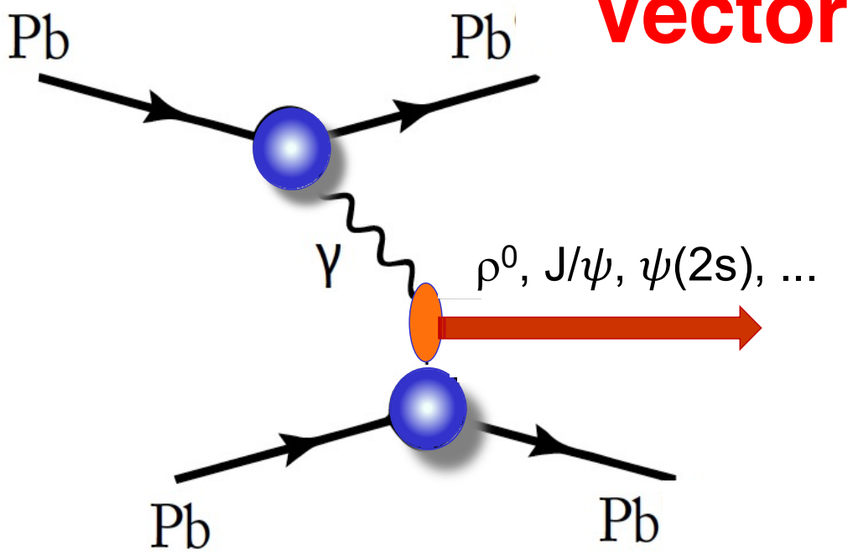


NPA 703 (2002) 861

J=0 $\quad \bar{u}Av \rightarrow \sqrt{2m_X}\, tr\left(\frac{A}{\sqrt{2}}\right)\psi(0)$

J=1 $\quad \bar{u}Av \rightarrow \sqrt{2m_X}\, tr\left(\frac{\hat{\boldsymbol{\epsilon}}.\boldsymbol{\sigma}}{\sqrt{2}}A\right)\psi(0)$

Vector meson production (direct, unresolved)

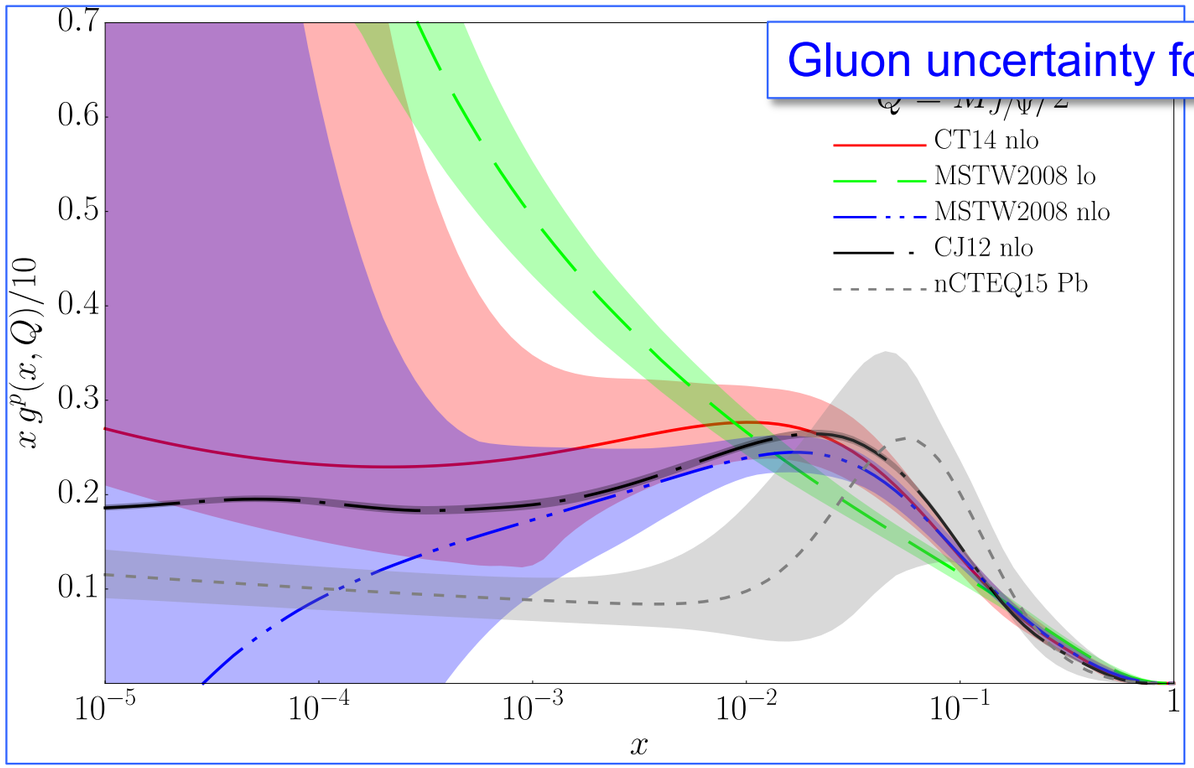


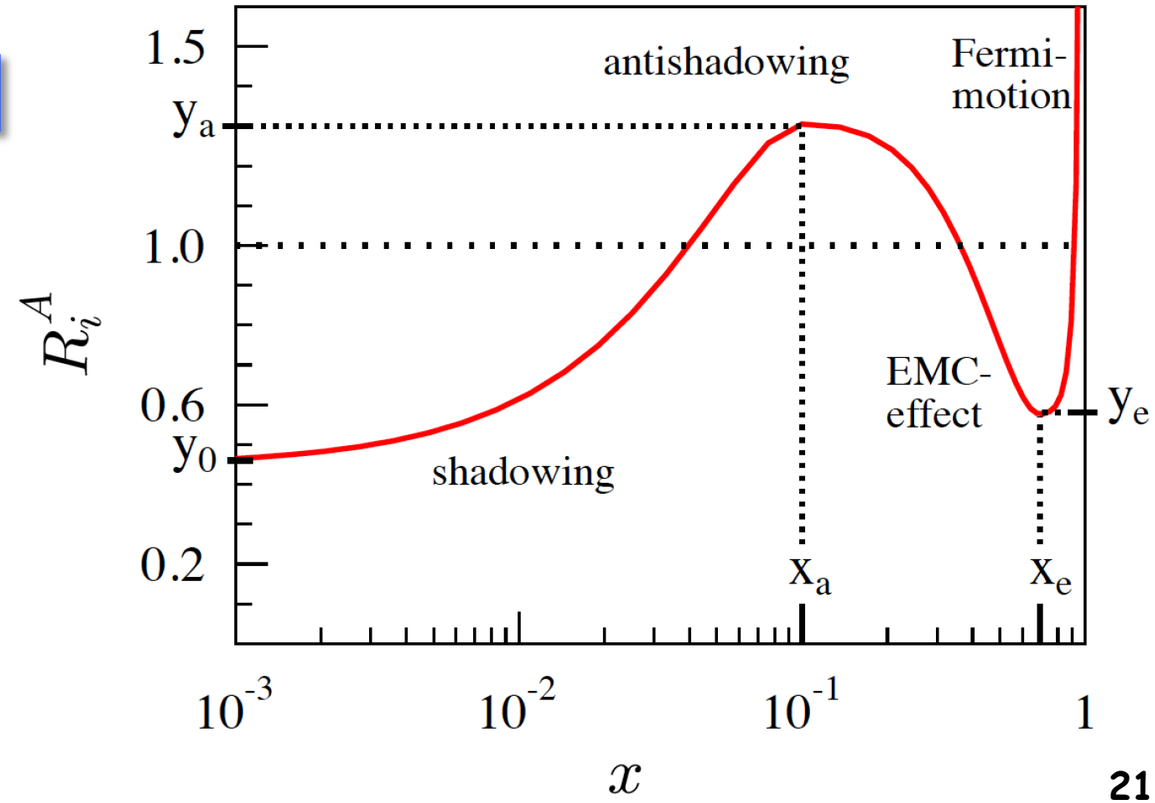
$$\left.\frac{d\sigma^{\gamma A\to VA}}{dt}\right|_{t=0} = \frac{16\pi^3\alpha_s\Gamma_{ee}}{3\alpha M_V^5}[xg_A(x,Q^2)]^2$$

gluons

PRC65, 054905 (2002); 85, 044904 (2012)

Direct dominant over resolved (photon $q\bar{q}$ content)

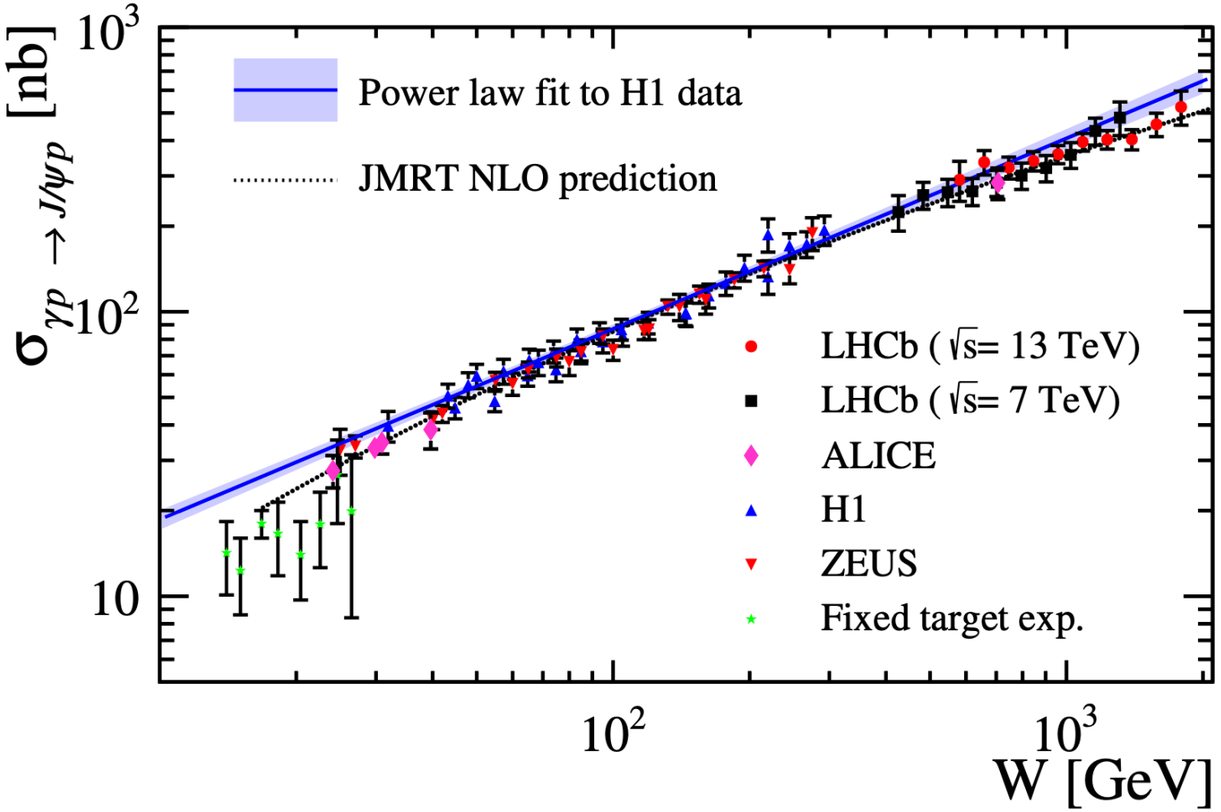


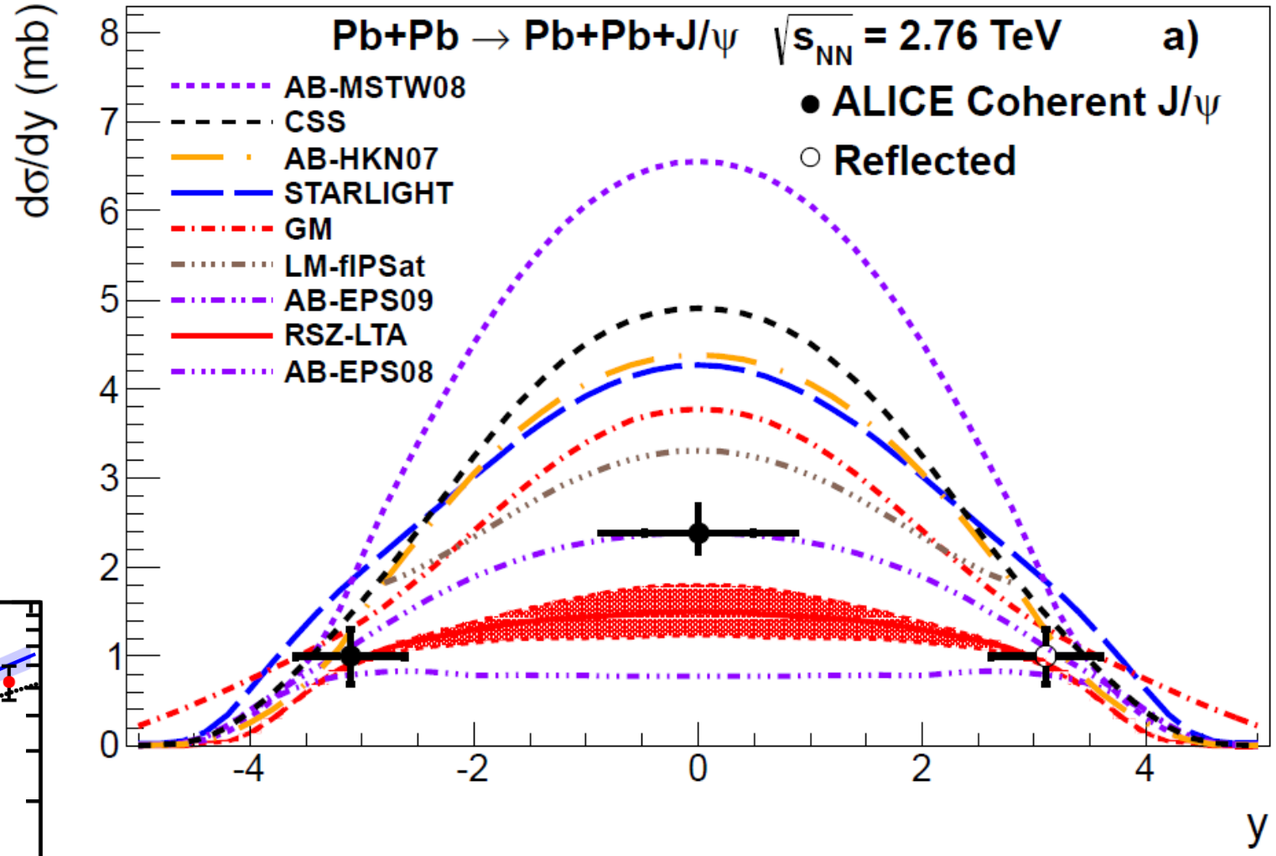


J/ψ production & PDFs

ALICE collaboration,
PLB 718, 1273 (2013)
EPJ C73, 2617 (2013)

CMS collaboration,
PLB 772 489 (2017)





LHCb collaboration,
JHEP 10, 167 (2018)

The future was bright

How to continue?

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERN COURIER
VOLUME 53 NUMBER 6 JULY/AUGUST 2013

LHC PHYSICS

CMS sees first direct evidence for γγ→WW

In a small fraction of proton collisions at the LHC, the two colliding protons interact only electromagnetically, radiating high-energy photons that subsequently interact or "fuse" to produce a pair of heavy charged particles. Fully exclusive production of such pairs takes place when quasi-real photons are emitted coherently by the protons rather than by their quarks, which survive the interaction. The ability to select such events opens up the exciting possibility of transforming the LHC into a high-energy photon–photon collider and of performing complementary or unique studies of the Standard Model and its possible extensions.

The CMS collaboration has made use of this opportunity by employing a novel method to select "exclusive" events based only on tracking information. The selection is made by requesting that two – and only two – tracks originate from a candidate vertex for the exclusive two-photon production. The power of this method, which was first developed for the pioneering measurement of exclusive production of muon and electron pairs, lies in its effectiveness even in difficult high-luminosity conditions with large event pile-up at the LHC.

The collaboration has recently used this approach to analyse the full data sample collected at $\sqrt{s}$=7 TeV and to obtain the first direct evidence of the γγ→WW process. Fully leptonic W-boson decays have been measured in final states characterized by opposite-sign and opposite-flavour lepton pairs where one W decays into an electron and a neutrino, the other into a muon and a neutrino (both neutrinos leave undetected). The leptons were required to have: transverse momenta p_T>20 GeV/c and pseudorapidity $|\eta|$<2.1; no extra track associated with their vertex; and for the pair, a total p_T>30 GeV/c. After applying all selection criteria, only two events remained – compared with an expectation of 3.2 events: 2.2 from γγ→WW and 1 from background (figure 2).

The lack of events observed at large values of transverse momentum for the pair, which would be expected within the Standard Model, allows stringent limits on anomalous quartic γγWW couplings to be derived. These surpass the previous best limits, set at the Large Electron–Positron collider and at the Tevatron, by up to two orders of magnitude (figure 3).

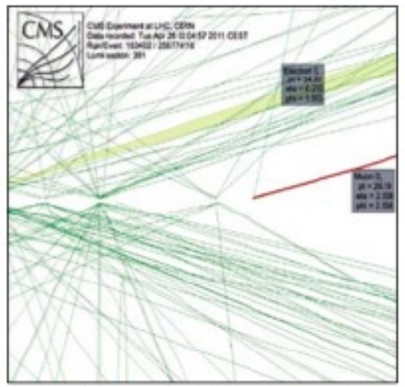


Fig. 1. Above: Proton–proton collisions recorded by CMS at $\sqrt{s}$=7 TeV, featuring candidates for the exclusive two-photon production of a W^+W^- pair, where one W boson has decayed into an electron and a neutrino, the other into a muon and a neutrino.

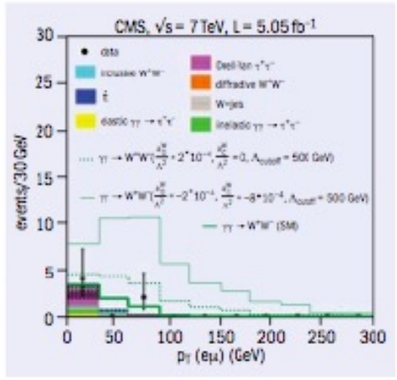


Fig. 2. Top right: The p_T distribution of eμ pairs in events with no extra tracks compared with the Standard Model expectation (thick green line) and predictions for anomalous quartic gauge couplings (dashed green histograms).

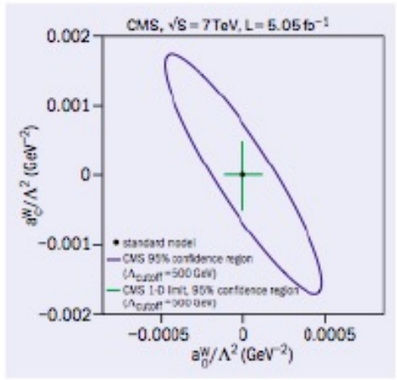


Fig. 3. Right: Limits on anomalous quartic γγWW couplings.

● **Further reading**

CMS collaboration 2013 arXiv:1305.5596 [hep-ex], submitted to *JHEP*.

Search for New Physics (SUSY particles)

MSSM

The Standard Model and supersymmetric particles.

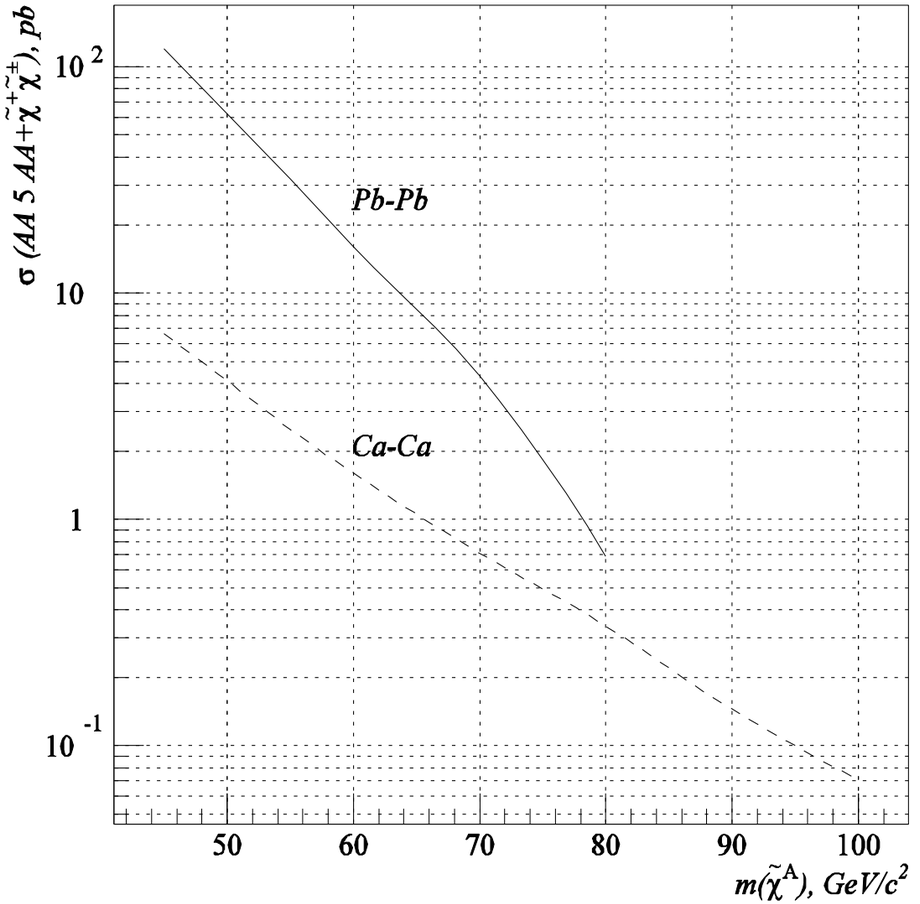
Standard Model	Supersymmetry
$\gamma,\ Z^0,\ h^0,\ H^0$	$\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0$
$W^+,\ H^+$	$\tilde{\chi}_1^+,\ \tilde{\chi}_2^+$
$e^-,\ \nu_e,\ \mu^-,\ \nu_\mu,\ \nu_\tau$	$\tilde{e}_R^-,\ \tilde{e}_L^-,\ \tilde{\nu}_e,\ \tilde{\mu}_R^-,\ \tilde{\mu}_L^-,\ \tilde{\nu}_\mu,\ \tilde{\nu}_\tau$
τ^-	$\tilde{\tau}_1,\ \tilde{\tau}_2$
$u,\ d,\ s,\ c$	$\tilde{u}_R,\ \tilde{u}_L,\ \tilde{d}_R,\ \tilde{d}_L,\ \tilde{s}_R,\ \tilde{s}_L,\ \tilde{c}_R,\ \tilde{c}_L$
b	$\tilde{b}_1,\ \tilde{b}_2$
t	$\tilde{t}_1,\ \tilde{t}_2$

$\gamma\gamma \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ (assuming $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0$)

But $M_{\tilde{\chi}_1^\pm} > 67.7$ GeV

$$\frac{dL}{dW_{\gamma\gamma}} \approx 0 \quad \text{for} \quad W_{\gamma\gamma} > 200 \text{ GeV}$$

(LHC)



(unlikely?)

Beyond the Standard Model

Higgs: $\gamma\gamma \to H$ $\sigma \approx 1\,\text{nb}$ at the LHC

Swamped by $\gamma\gamma \to b\bar{b}$ background

PRD 40, 92 (1989)

Extra dimensions (Kaluza-Klein):

$\gamma\gamma \to \text{graviton}$

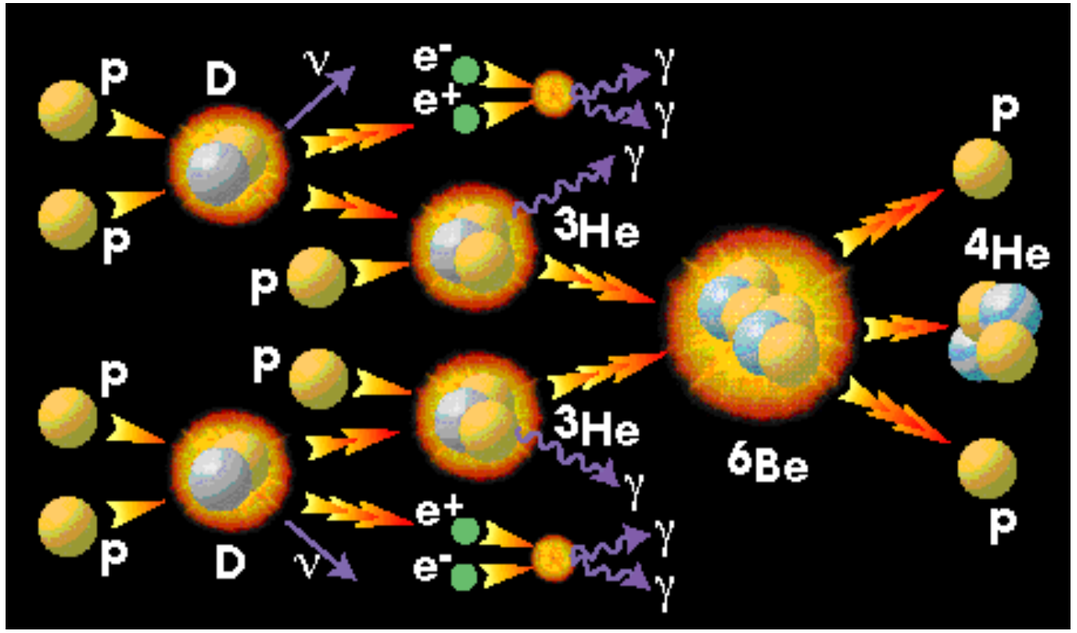
$$\sigma_{\gamma\gamma\to\text{graviton}}(\text{LHC}) >> \sigma_{e^+e^-\to\text{graviton}}(\text{LEPII})$$

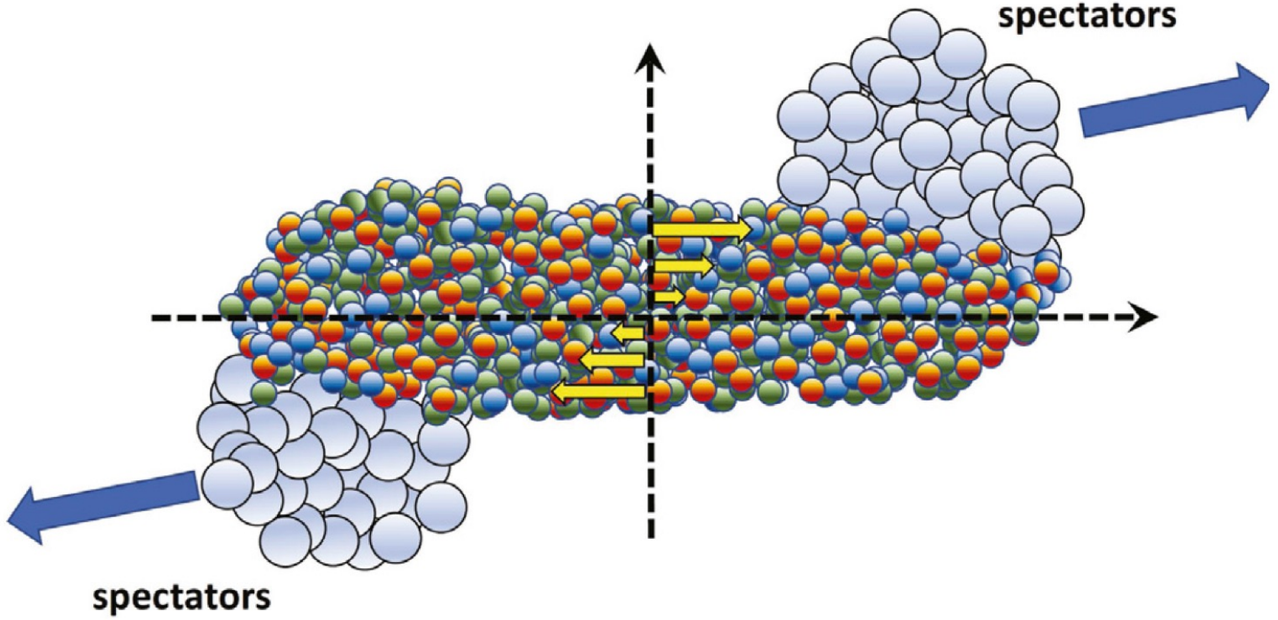
PRD 62, 116001 (2000)

Searching for axionlike particles with low masses

EPJ C 81, 522 (2021)

Nuclear reactions





keV

???

Stellar evolution

Elemental abundance

Nuclear many-body problem:

the hardest problem of all physics!

- Interactions are complicated
- Nucleons = composite particles

TeV

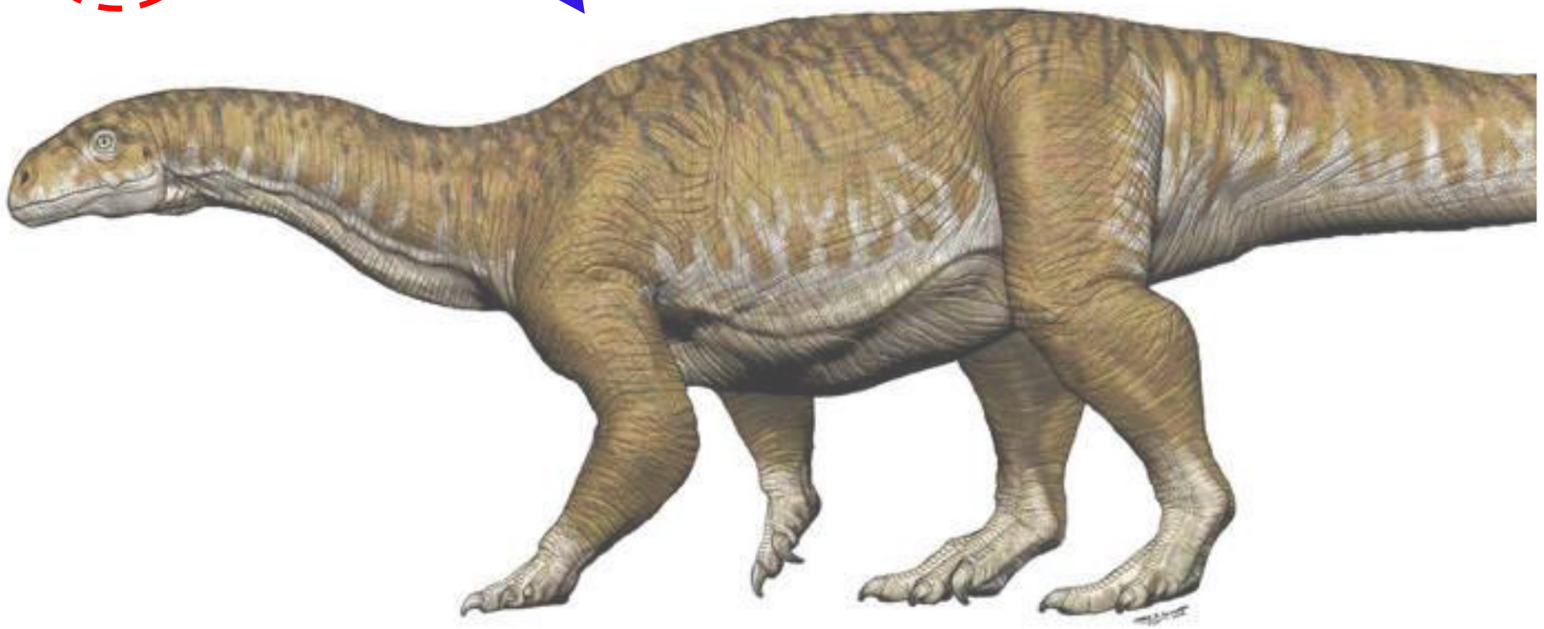
???

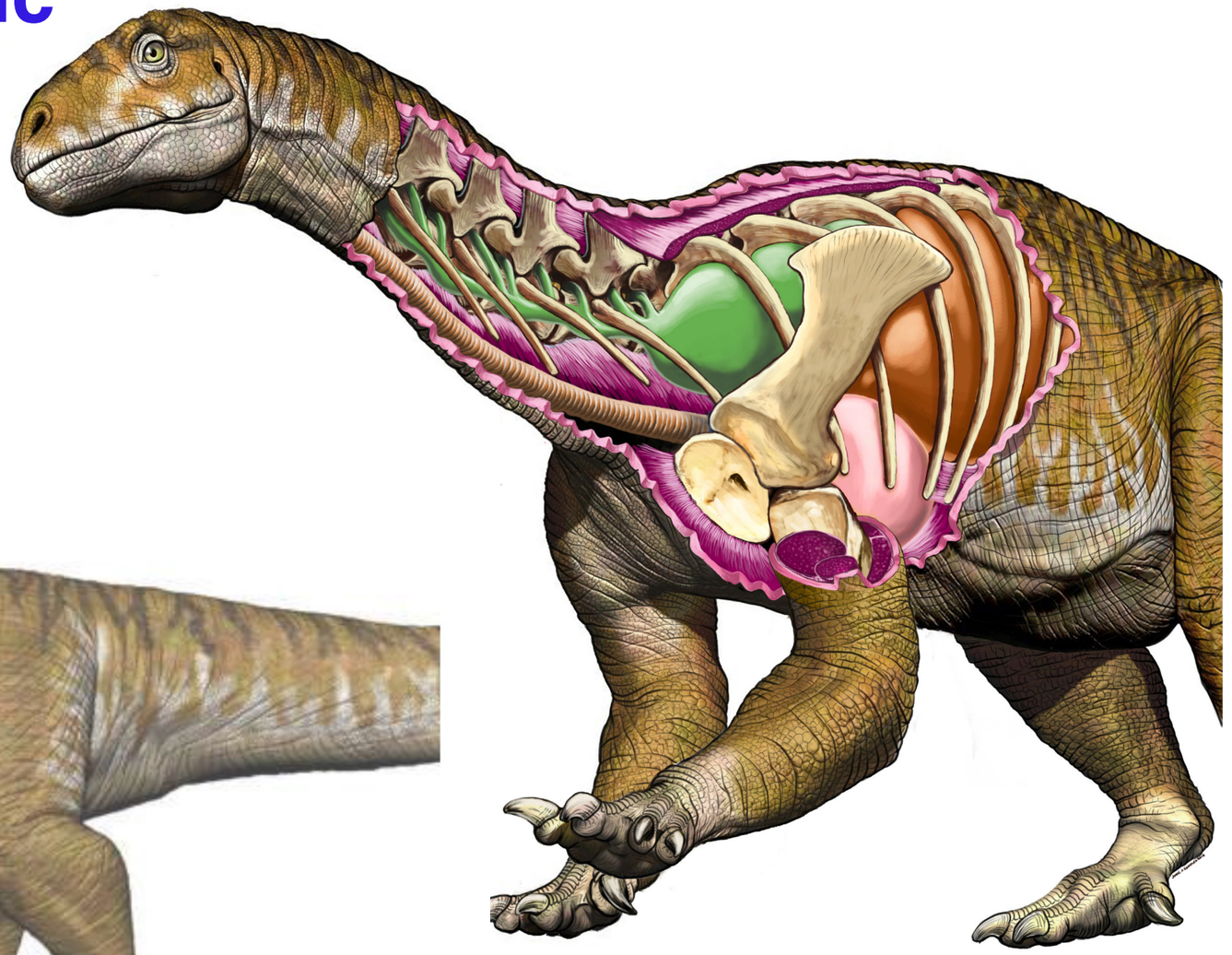
Big bang

neutron stars

“Microscopic” & Macroscopic







Nature Ecology & Evolution (2018)

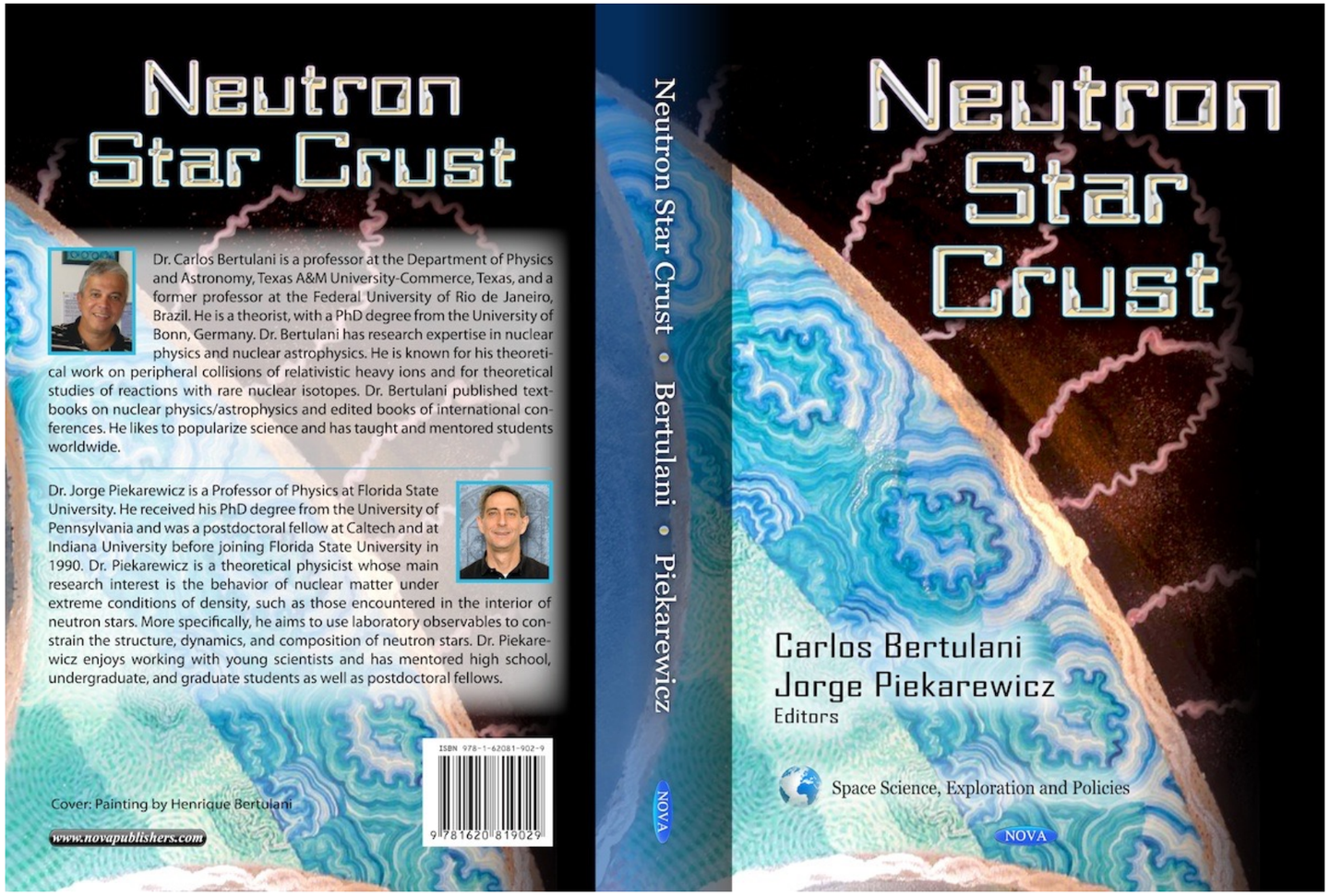
Reconstruction of Ingentia prima from the Late Triassic (205- 210Ma) of Argentina. Total length 8-10 me…

Neutron Stars



Jocelyn Bell at Texas A&M, 2010

Neutron Star Crust book (2013): (preface by Jocelyn Bell)



Jocelyn Bell Burnell *

University of Oxford, Denys Wilkinson Building
Keble Road, Oxford OX1 3RH, UK

I judge myself fortunate to be working in an exciting and fast moving area of science and at a time when the public has become fascinated by questions regarding the birth and evolution of stars, the nature of dark matter and dark energy, the formation of black holes and the origin and evolution of the universe.



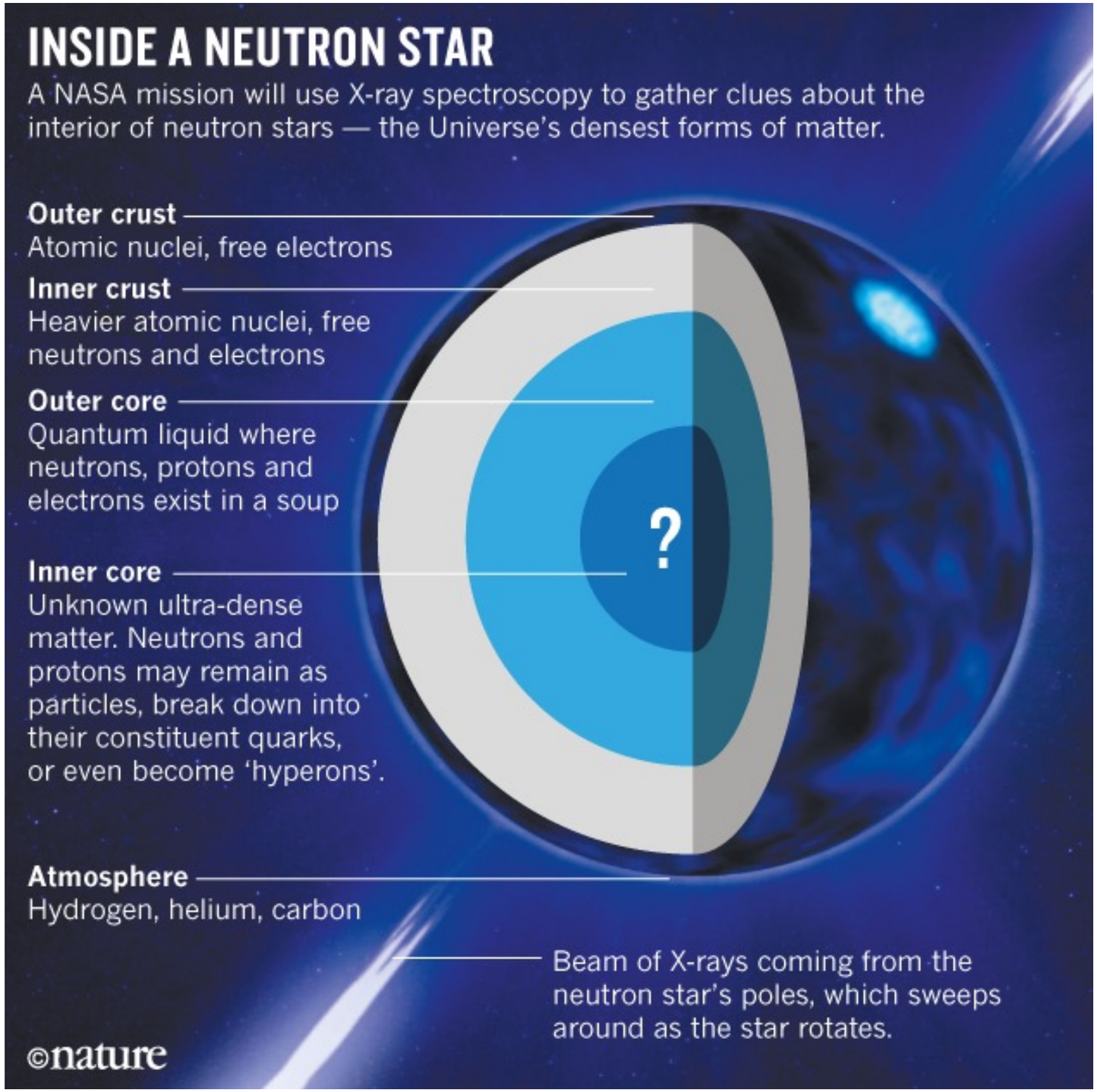
The physics of neutron stars is one of these fascinating subjects. Neutron stars are formed in supernova explosions of massive stars or by accretion-induced collapse of smaller white dwarf stars. Their existence was confirmed through the discovery of radio pulsars during my thesis work in 1967. Since then this field has evolved enormously. Today we know of accretion-powered pulsars which are predominantly bright X-ray sources, rotation-powered pulsars observed throughout the electromagnetic spectrum, radio-quiet neutron stars, and highly magnetized neutron stars or magnetars. No wonder there has been an explosion in the research activity related to neutron stars!

It is now hard to collect in a single book what we already know about neutron stars along with some of the exciting new developments. In this volume experts have been asked to articulate what they believe are the critical, open questions in the field. In order for the book to be useful to a more general audience, the presentations also aim to be as pedagogical as possible.

This book is a collection of articles on the neutron stars themselves, written by well-known physicists. It is written with young researchers as the target audience, to help this new generation move the field forward. The invited authors summarize the current status of

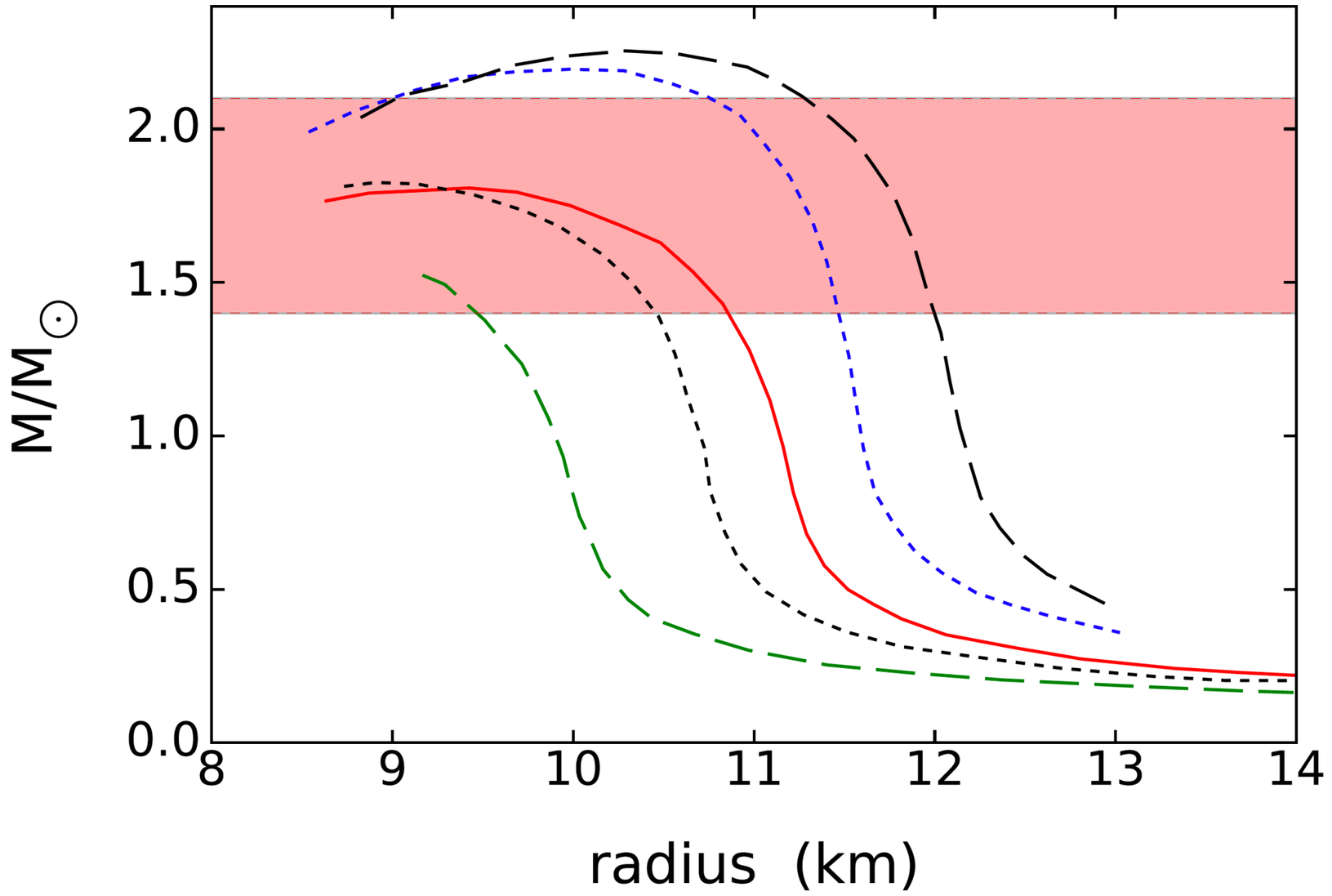
*j.bellburnell@physics.ox.ac.uk

Neutron stars

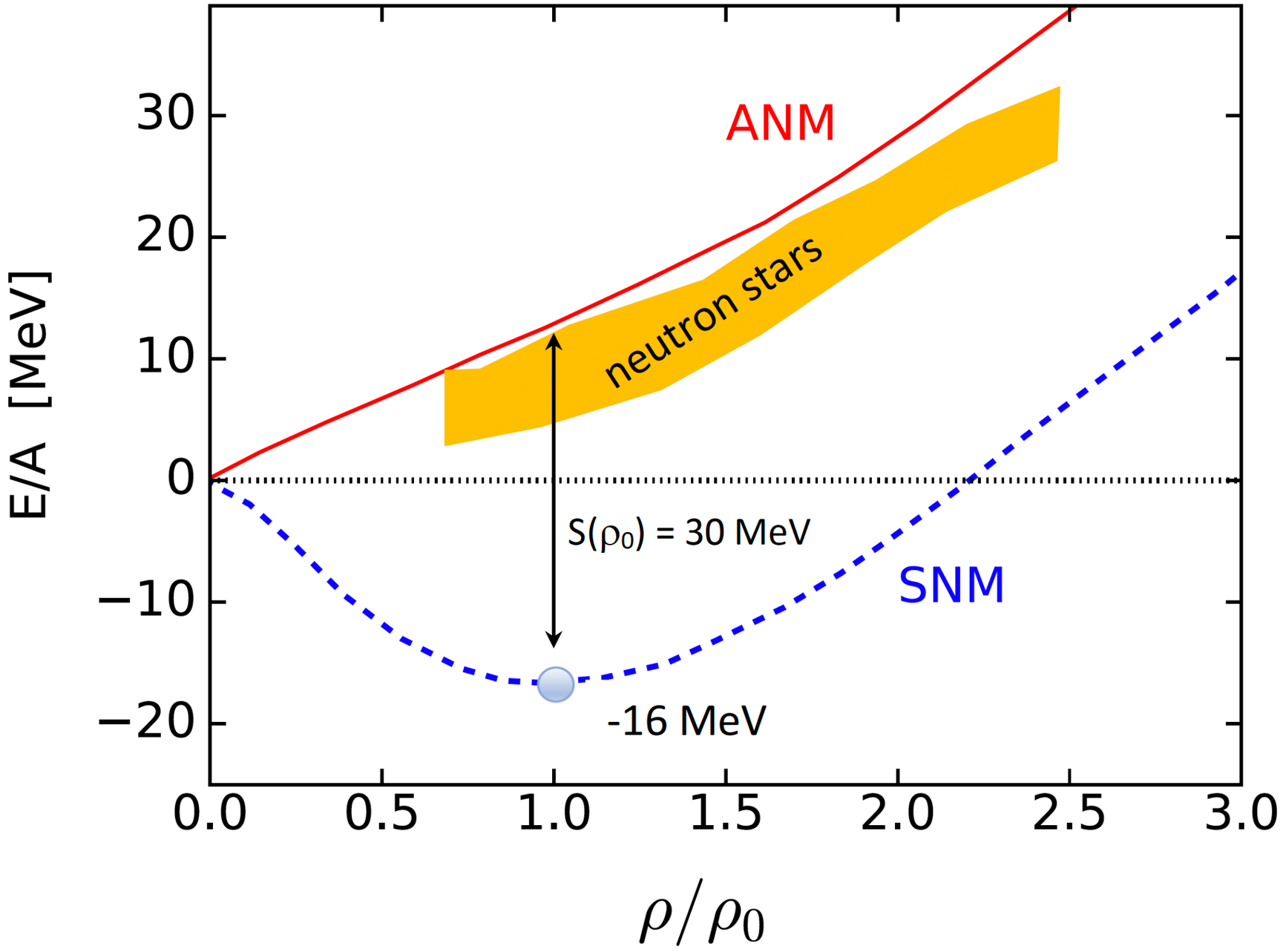


Neutron stars

EOS $$\frac{E}{A}[\rho] = \frac{E}{A}[\rho_0] + \frac{1}{18} K_\infty \left(\frac{\rho - \rho_0}{\rho_0} \right)^2 + S \left(\frac{\rho_n - \rho_p}{\rho} \right)^2 + \cdots$$



EOS of neutron stars



Density functionals

For the nucleon-nucleon interaction

$$V(\mathbf{r}_i,\mathbf{r}_j) = V_{ij}^{NN} + V_{ij}^{Coul}$$

$$V_{ij}^{Coul} = -\frac{e^2}{4}\sum_{i,j=1}^{A}\frac{\tau_{ij}^2+\tau_{ij}}{\left|\mathbf{r}_i-\mathbf{r}_j\right|},$$

$$\tau_{ij} = \tau_i + \tau_j$$

$$V_{ij}^{NN} = t_0(1+x_0P_{ij}^{\sigma})\delta(\mathbf{r}_i-\mathbf{r}_j)+\frac{1}{2}t_1(1+x_1P_{ij}^{\sigma})[\overleftarrow{\mathbf{k}}_{ij}^2\delta(\mathbf{r}_i-\mathbf{r}_j)+\delta(\mathbf{r}_i-\mathbf{r}_j)\vec{\mathbf{k}}_{ij}^2]+$$

$$t_2(1+x_2P_{ij}^{\sigma})\overleftarrow{\mathbf{k}}_{ij}\delta(\mathbf{r}_i-\mathbf{r}_{jj})\vec{\mathbf{k}}_{ij}+\frac{1}{6}t_3(1+x_3P_{ij}^{\sigma})\rho^{\alpha}\left(\frac{\mathbf{r}_i+\mathbf{r}_j}{2}\right)\delta(\mathbf{r}_i-\mathbf{r}_j)+$$

$$iW_0\overleftarrow{\mathbf{k}}_{ij}\delta(\mathbf{r}_i-\mathbf{r}_j)(\vec{\sigma}_i+\vec{\sigma}_j)\vec{\mathbf{k}}_{ij},$$

$t_i,\ x_i,\ \alpha,\ W_0$ **Skyrme** parameters

$$E[\rho] = \left\langle \Phi \middle| T + V_{ij}^{Coul} + V_{ij}^{NN} \middle| \Phi \right\rangle$$

+ pairing

HF + BCS

$$\Delta_i = \frac{1}{2}\sum_j \frac{G_{ij}\Delta_j}{\sqrt{\left(\varepsilon_j - \lambda\right)^2 + \Delta_j^2}}$$

HFB

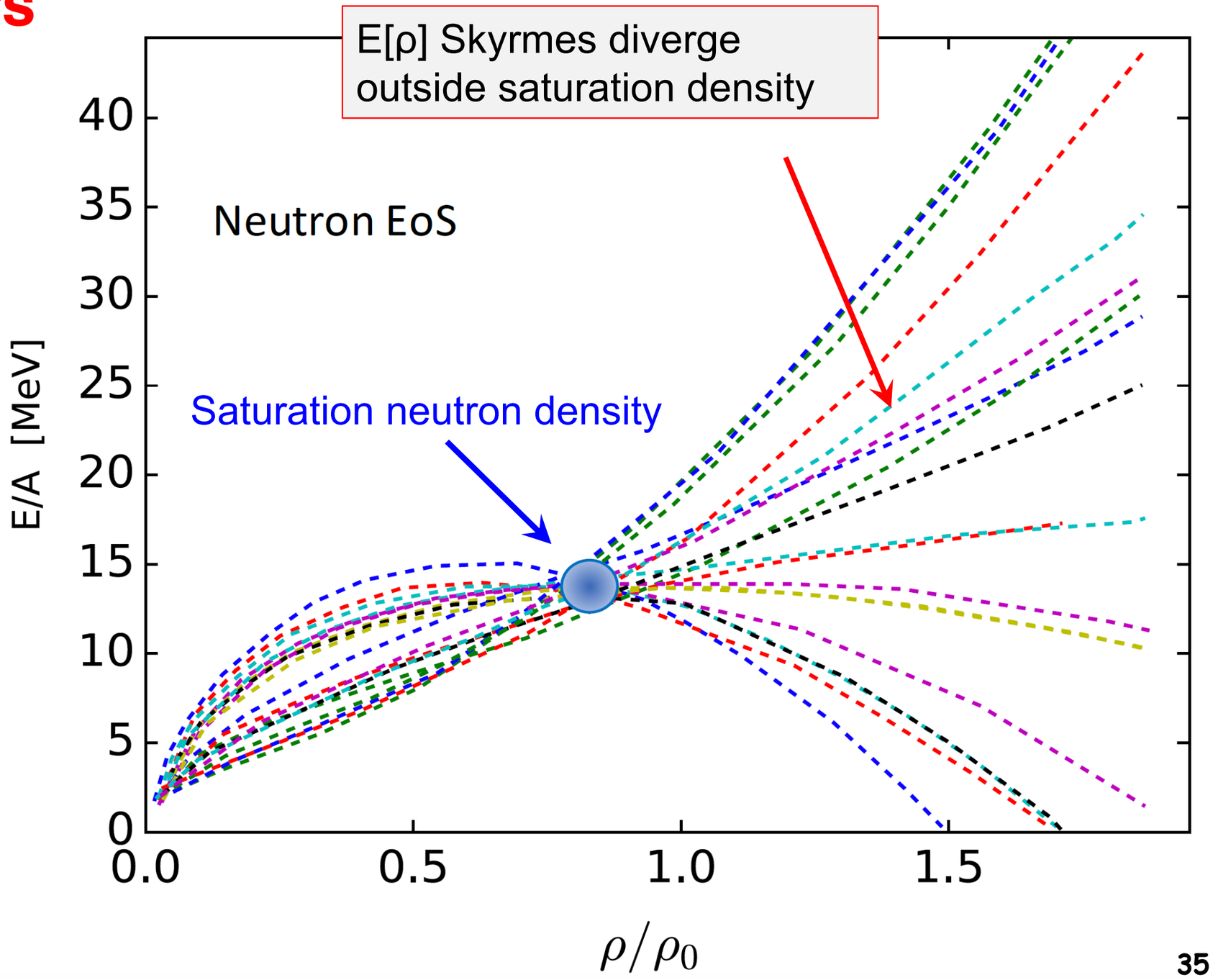
$$\begin{pmatrix} h_{HF} - \lambda & \Delta \\ -\Delta & -h_{HF} + \lambda \end{pmatrix}\begin{pmatrix} u_k \\ v_k \end{pmatrix} = E_k \begin{pmatrix} u_k \\ v_k \end{pmatrix}$$

$$V = V_0\left[1 - \eta\left(\frac{\rho(\mathbf{r})}{\rho_0}\right)^{\alpha}\right]\delta(\mathbf{r}_1 - \mathbf{r}_2), \qquad \rho_0 = 0.16\ \text{fm}, \quad \alpha = 1$$

$$\eta = \begin{cases} 0, & \text{"volume" pairing} \\ 1, & \text{"surface" pairing} \\ 1/2, & \text{"mixed" pairing} \end{cases}$$

EOS & Neutron stars

Pethick, Ravenhall,
ARNPS 45 (1995) 429



Symmetry energy

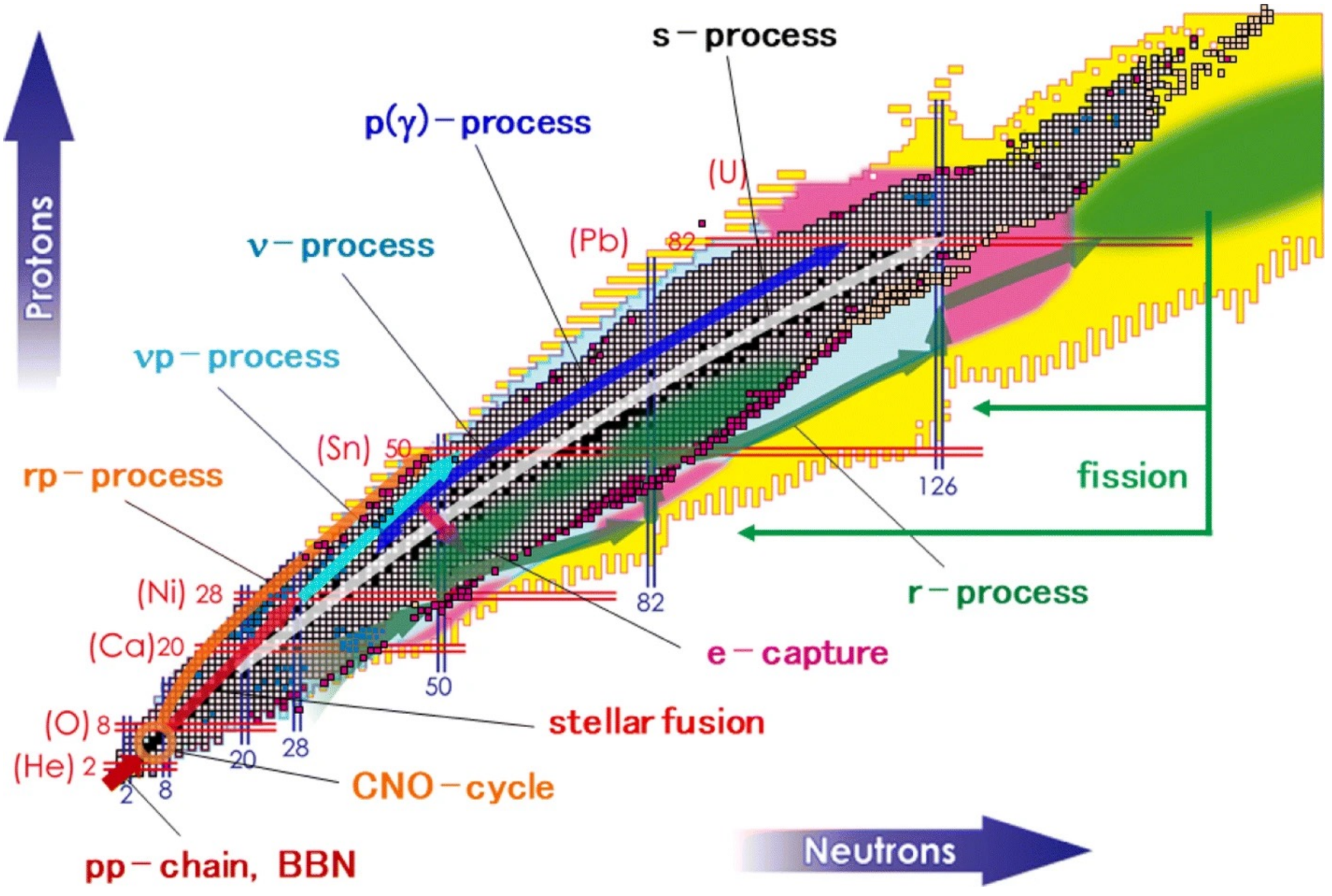
$$S = \frac{1}{2}\frac{\partial^2 (E/A)}{\partial \delta^2}\bigg|_{\delta=0} = J + Lx + \frac{1}{2}K_{sym}x^2 + O(x^3),$$

$$L = 3\rho_0 \frac{dS(\rho)}{d\rho}\bigg|_{\rho_0}, \quad \delta = \frac{\rho_n - \rho_p}{\rho}, \quad x = \frac{(\rho - \rho_0)}{3\rho_0}$$

Skyrme	ρ_0	E_0	K_∞	J	L
MSk6	0.157	-15.79	231.17	28.00	9.63
SKS4	0.163	-15.88	228.08	28.35	23.28
SLy5	0.161	-15.99	229.92	32.01	48.15
Skxs20	0.162	-15.81	201.95	35.50	67.06
SkI5	0.156	-15.82	255.57	36.63	129.27

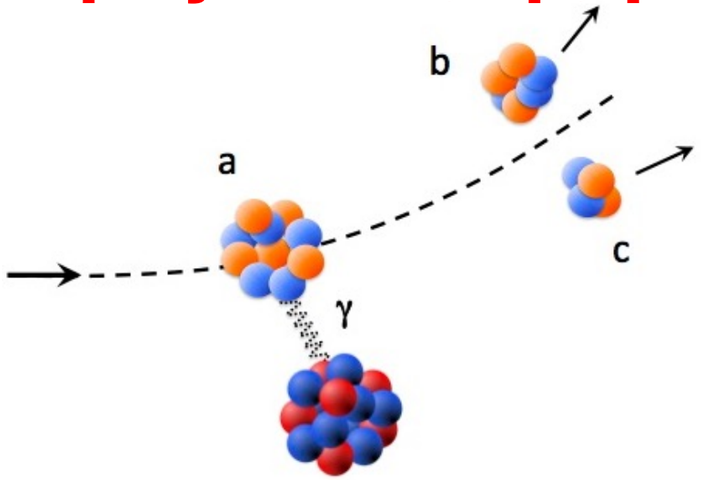
L crucial for neutron matter

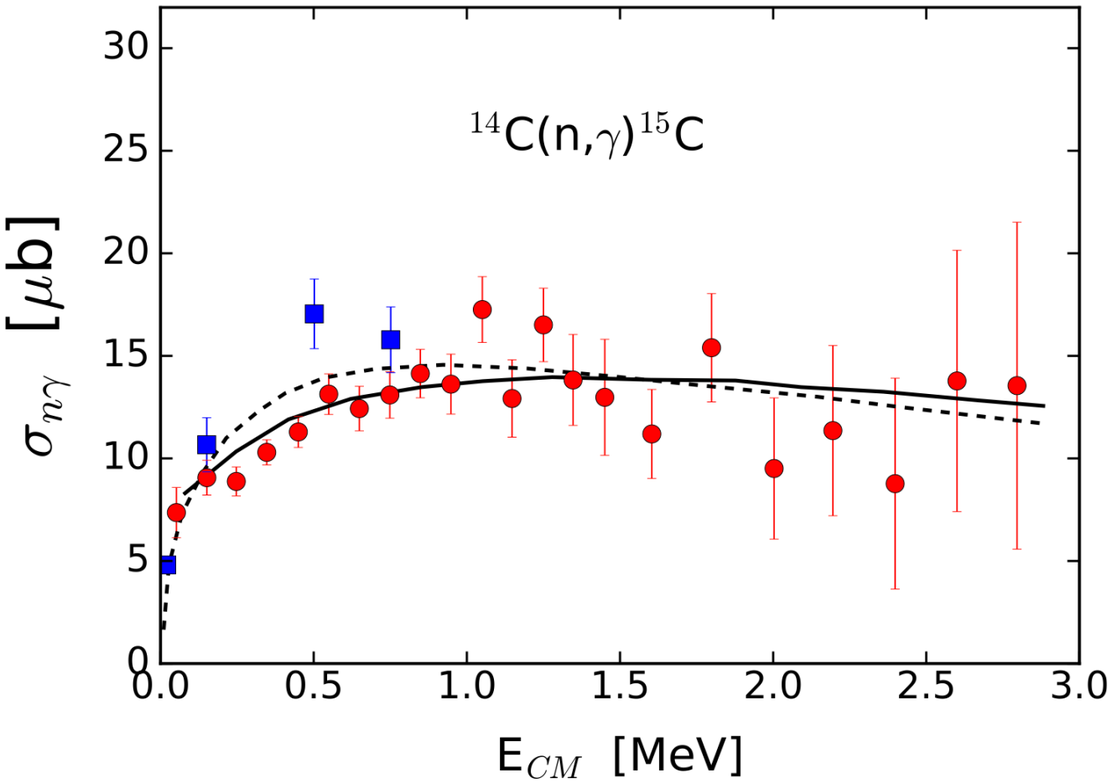
not well determined

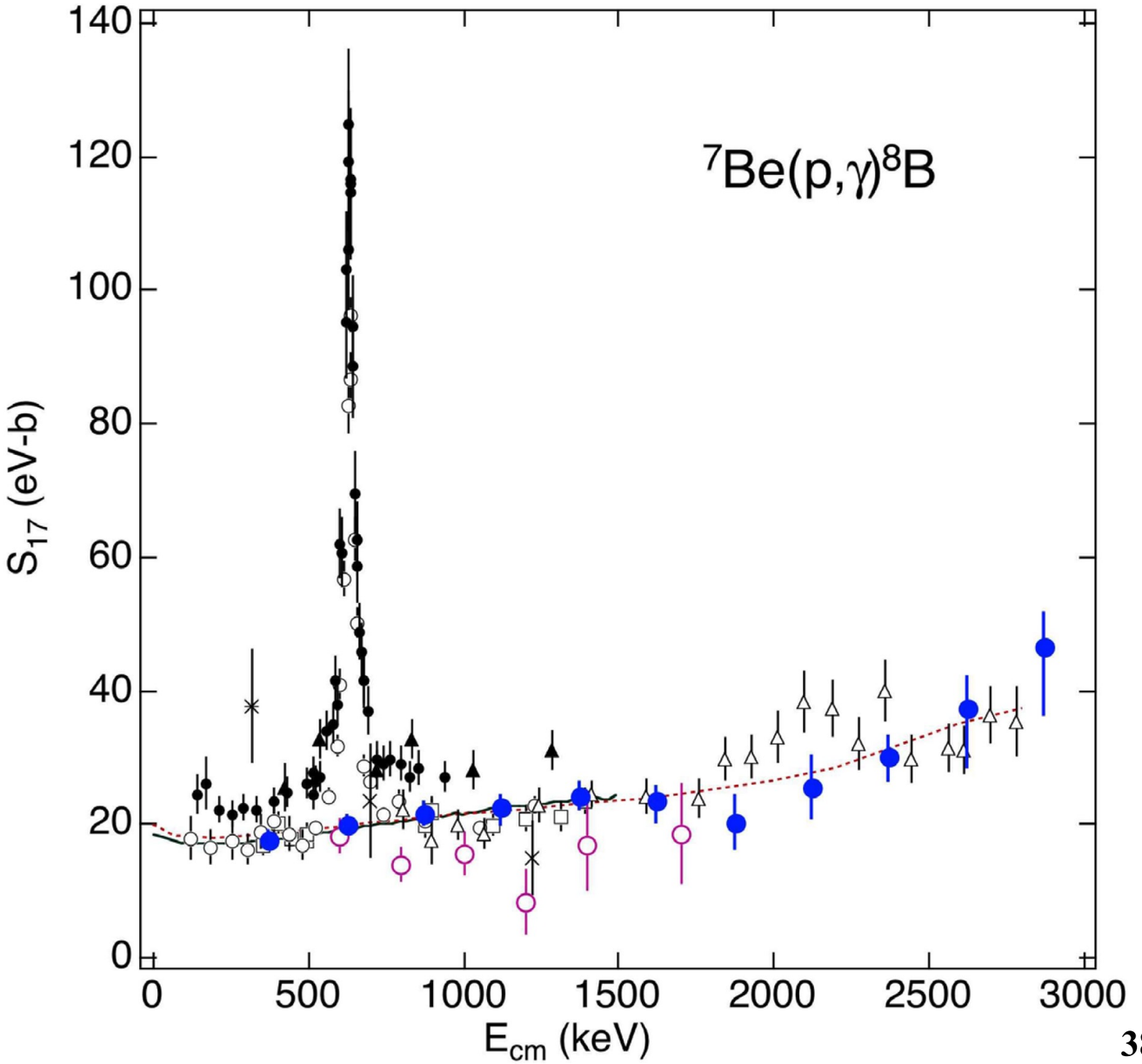

s − process
p(γ) − process
(U)
(Pb)
82
ν − process
νp − process
(Sn) 50
rp − process
126
fission
r − process
(Ni) 28
82
(Ca) 20
e − capture
50
(O) 8
stellar fusion
28
20
(He) 2
CNO − cycle
2
8
pp − chain, BBN
Protons
Neutrons

Astrophysics r, rp, process

NPA A458, 188 (1986)

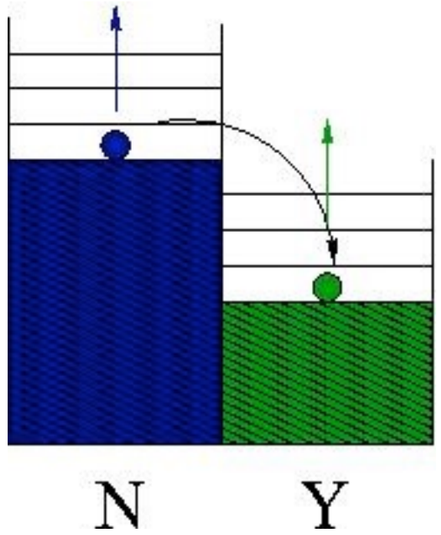


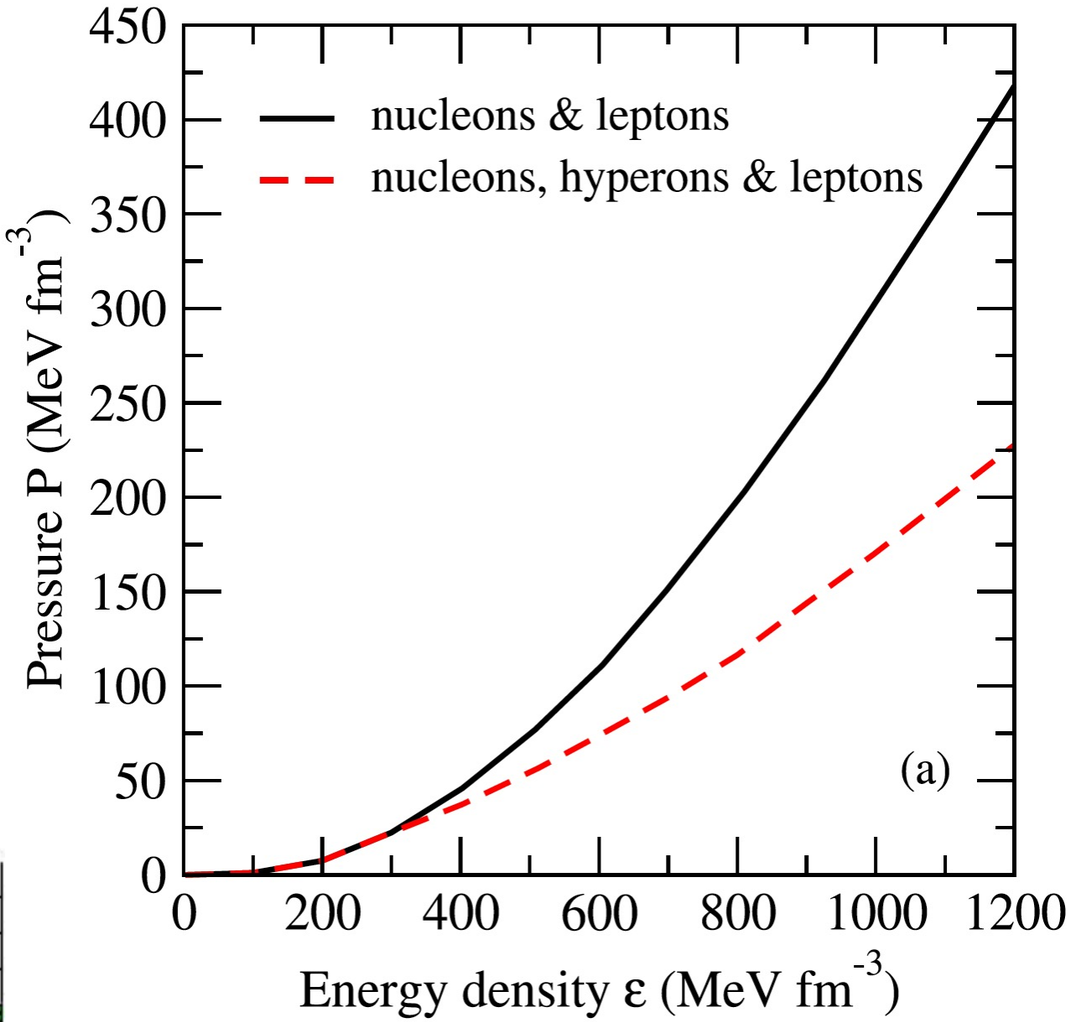


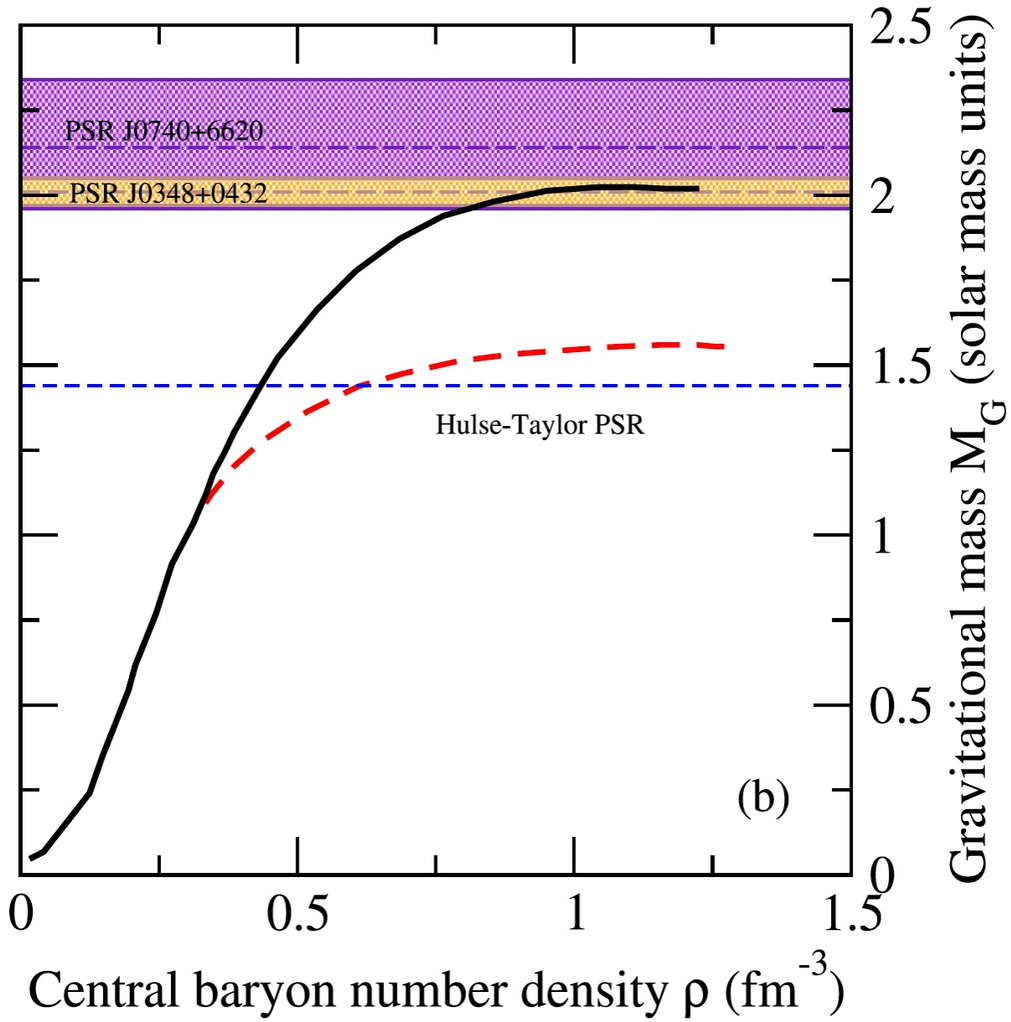


Hyperons and neutron stars

Hyperons make the EoS softer → reduction of the mass



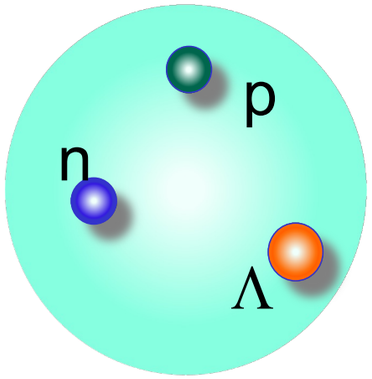




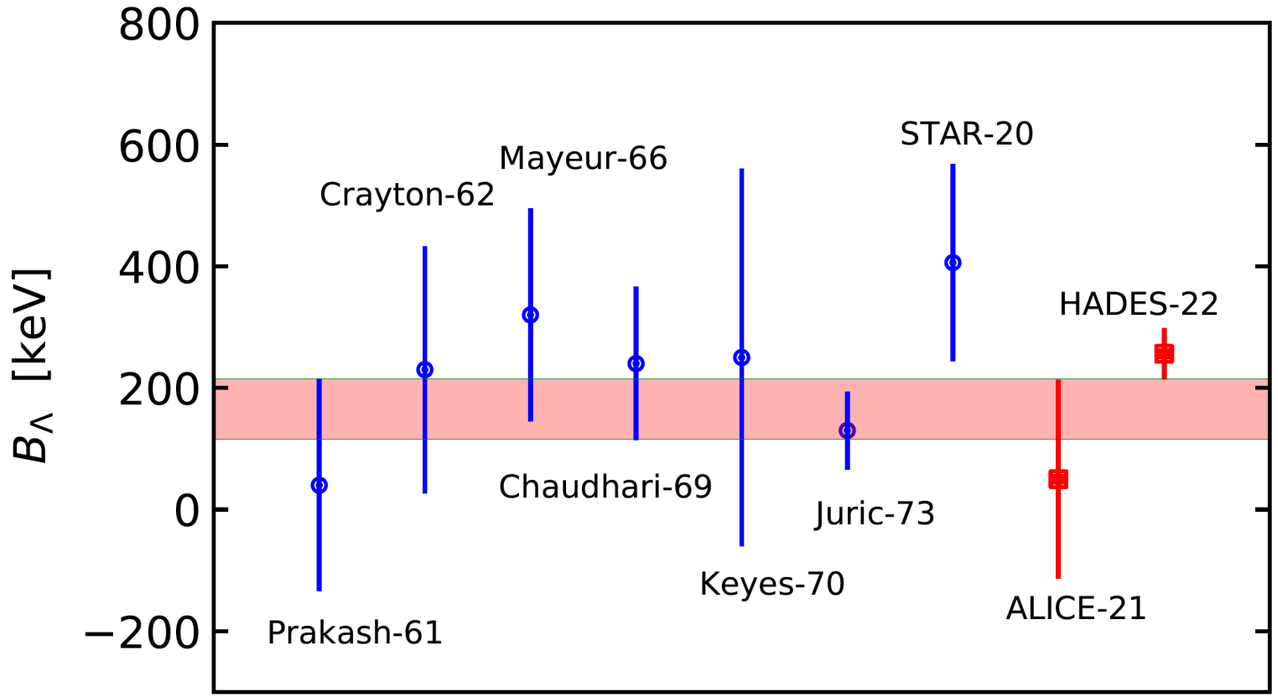
Hyperon "puzzle"

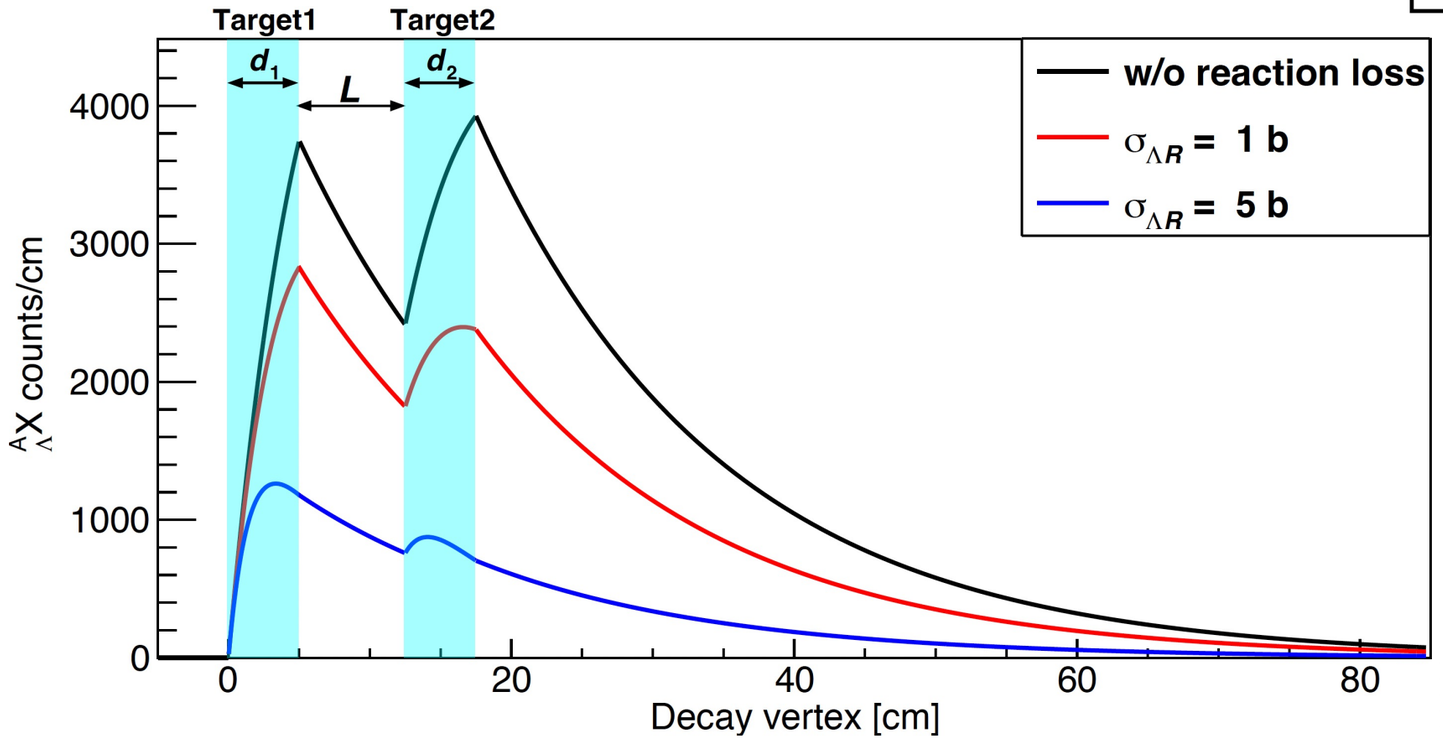
PPNP 112 103770 (2020)

Hypertriton, ΛN interaction



~ 10 fm

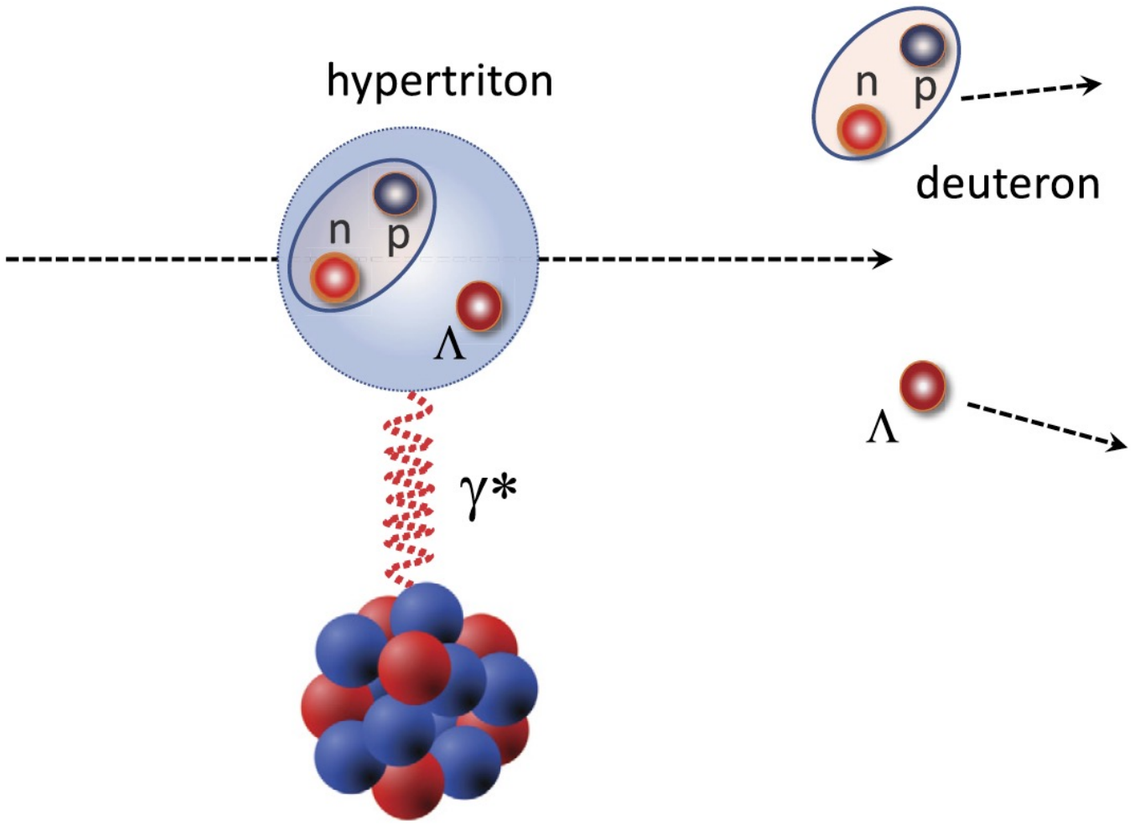


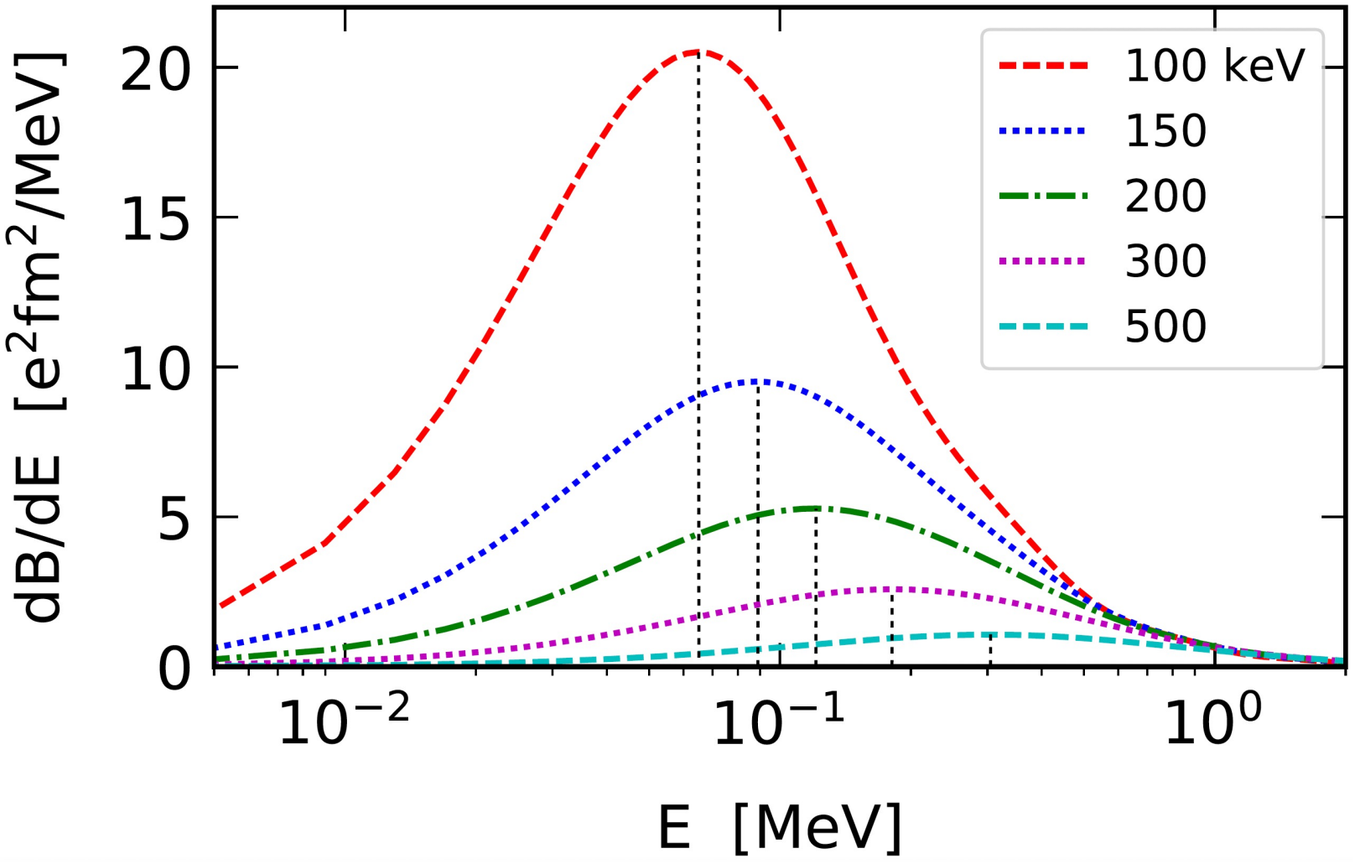


Production and breakup in an active target

PR C 98, 024903 (2018)

Electromagnetic response of the hypertriton

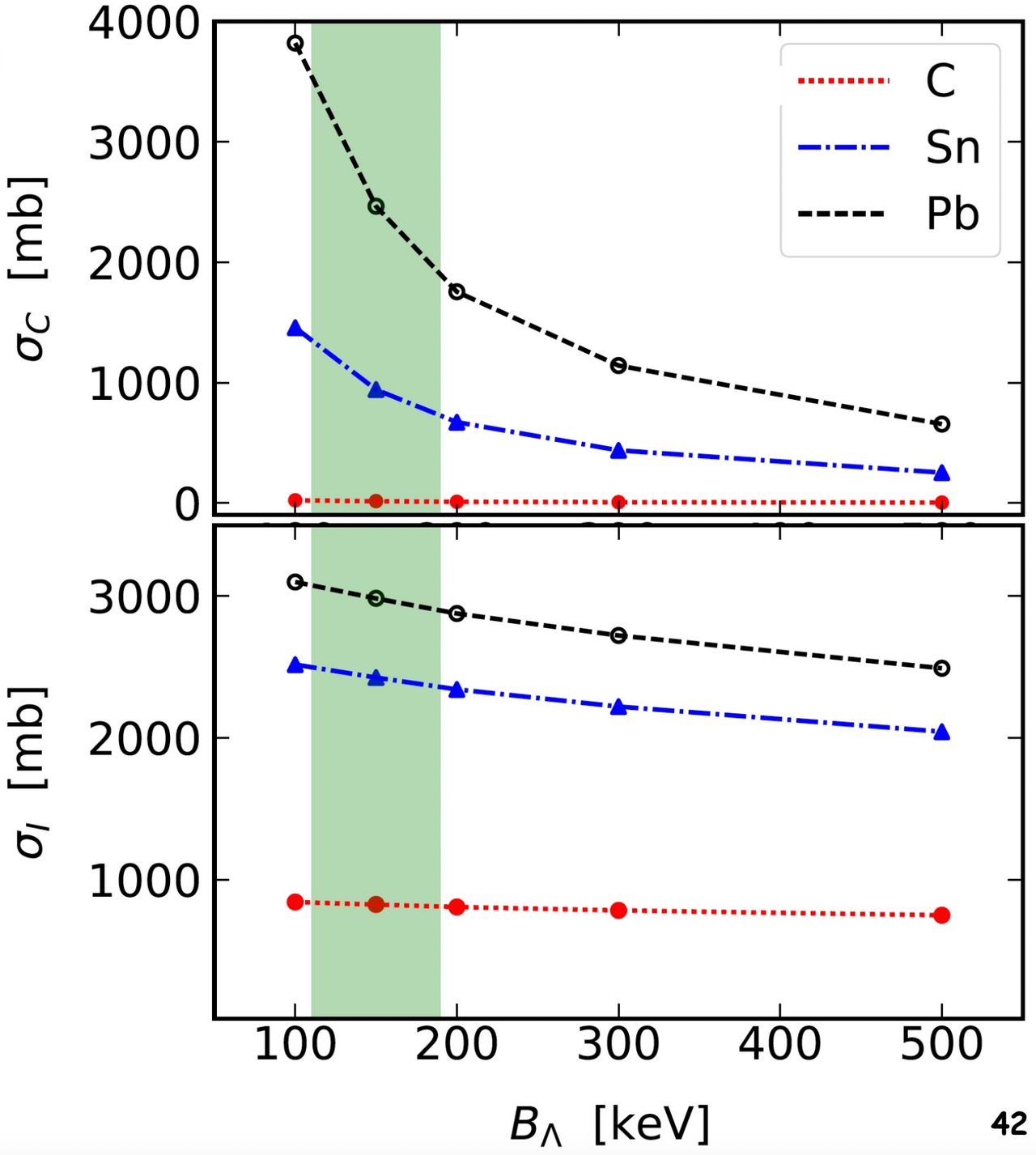




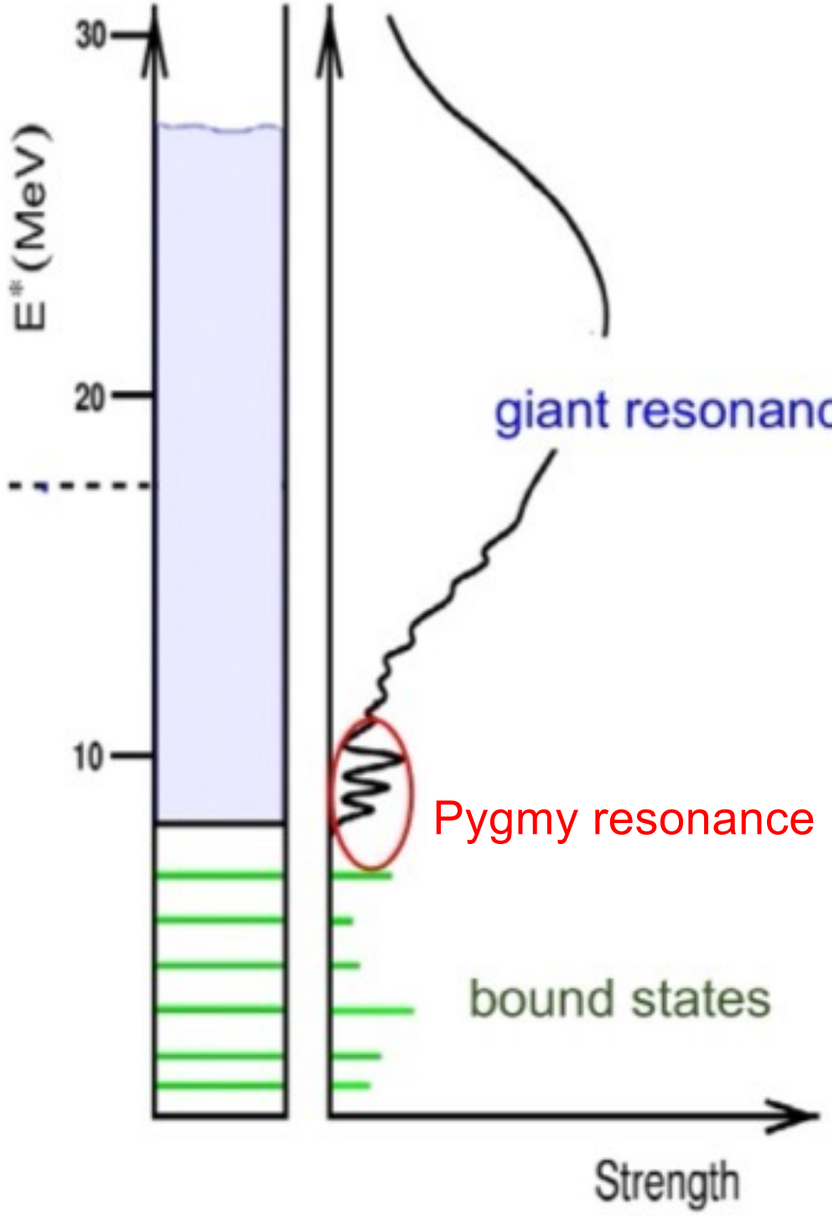
PLB 837, 137639 (2023)

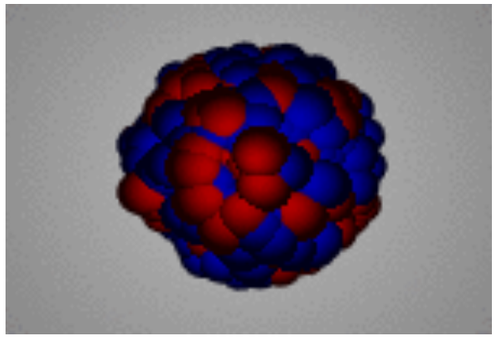
EM response of the hypertriton

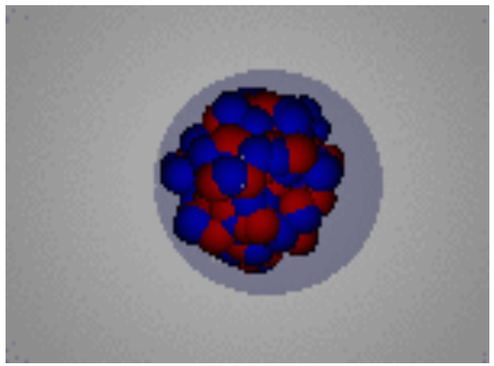
1.5 GeV/nuc. ${}^{3}_{\Lambda}\mathrm{H}$ incident on ${}^{12}\mathrm{C}$, ${}^{120}\mathrm{Sn}$, ${}^{208}\mathrm{Pb}$

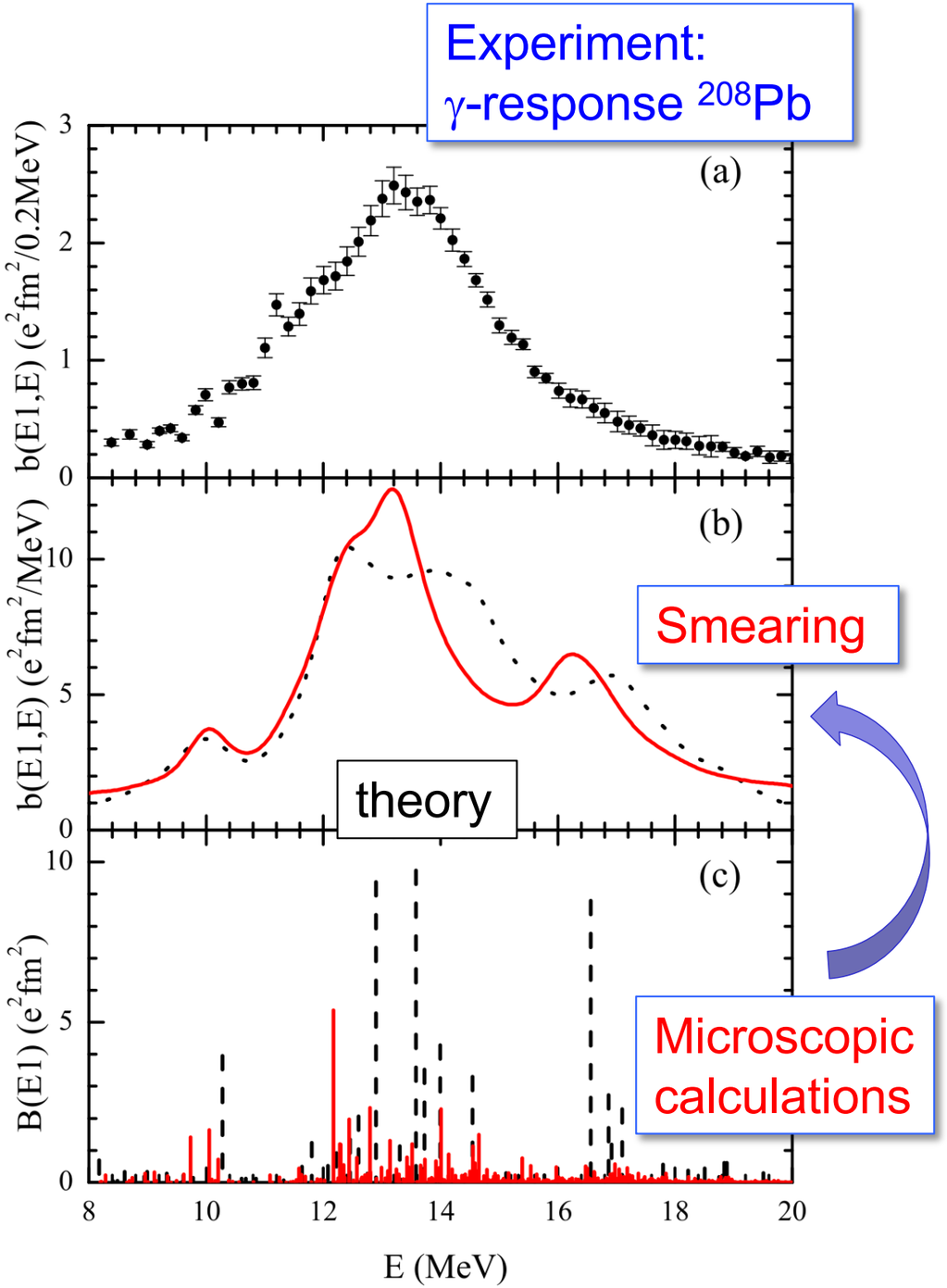


Giant and Pygmy resonances





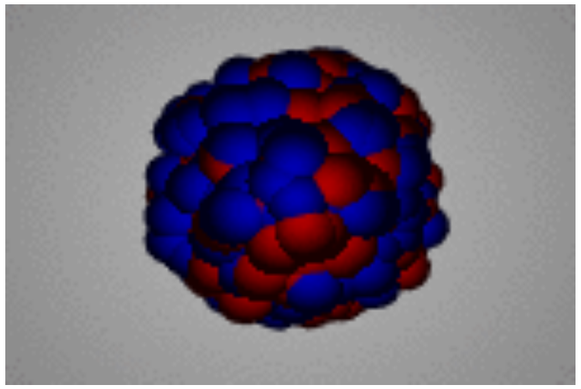


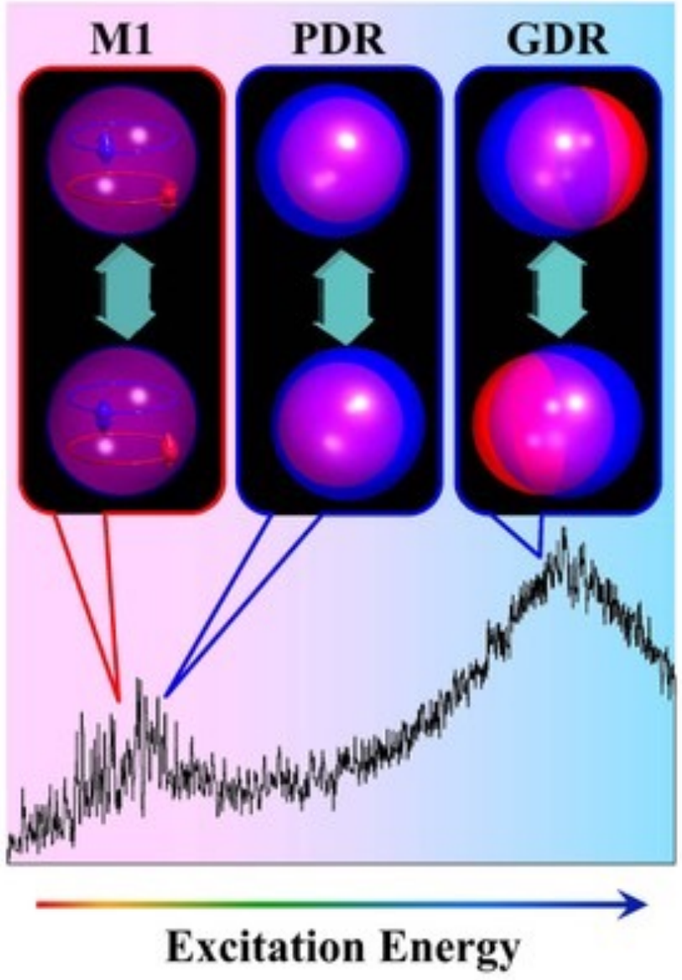


Peripheral HI probes

Excitation of GRs with, e.g., α-inelastic scattering

ISGMR is better reproduced Skyrme interactions with ($K_\infty \approx 200$ - 220 MeV)

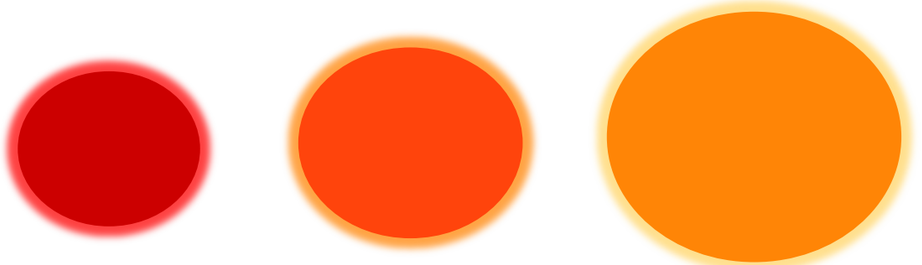




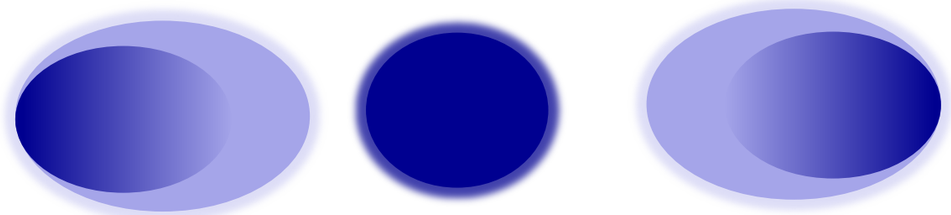
$$K_\infty = 9\rho^2 \left. \frac{d^2\left[E/A\right]}{d\rho^2} \right|_{\rho_0}$$

and Pygmy resonances

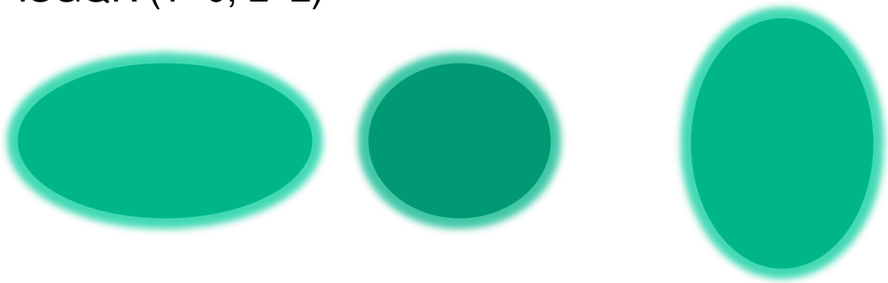
ISGMR (T=0, L=0)



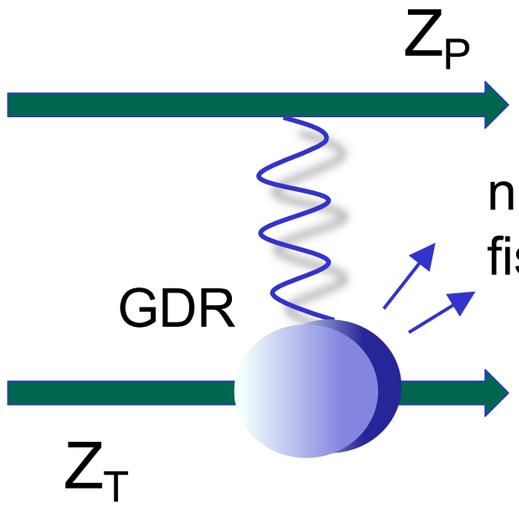
ISGDR (T=0, L=1)



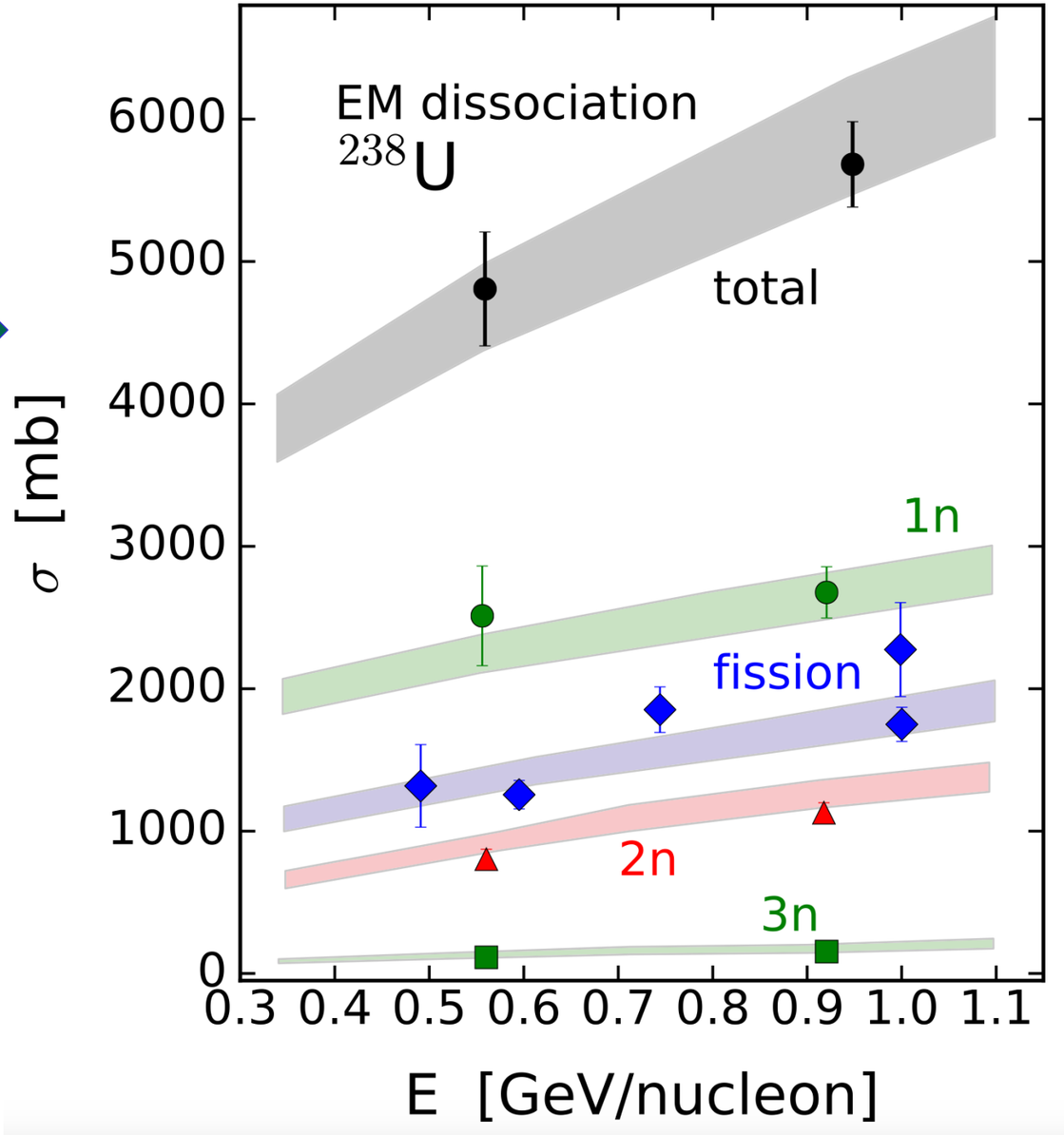
ISGQR (T=0, L=2)



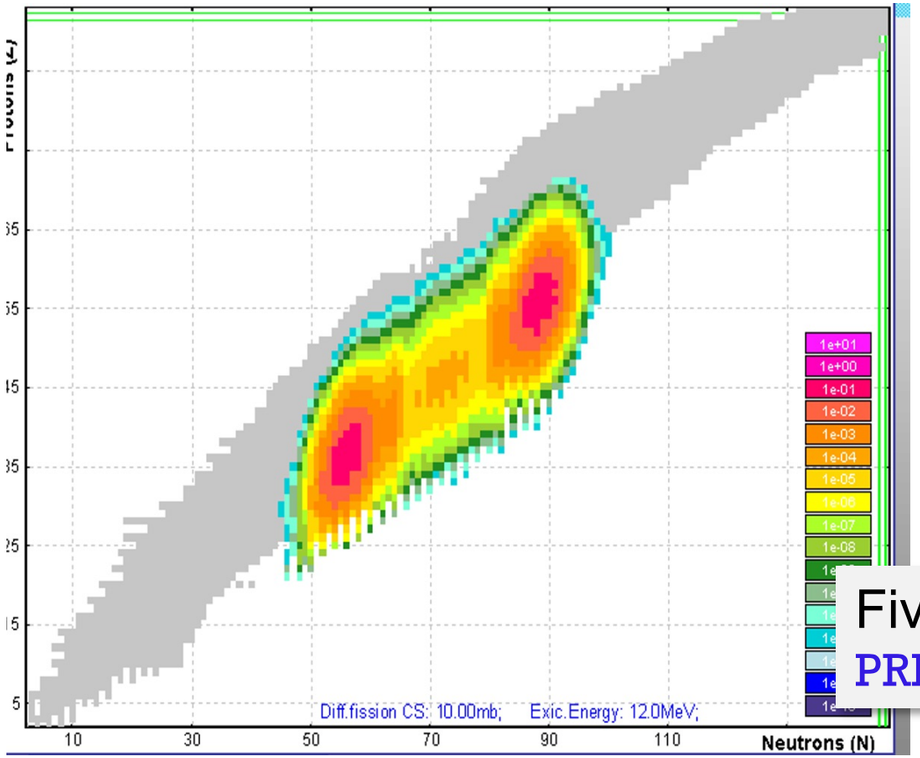
From GSI in 1990s to FRIB in 2020s



GSI 1990s



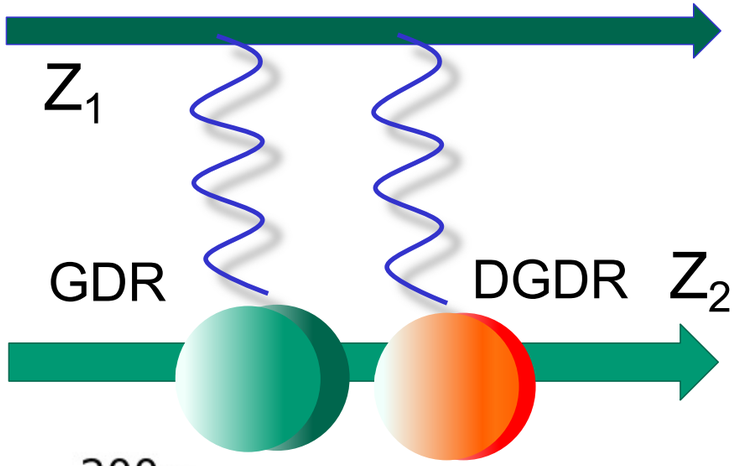
Numerous new isotopes

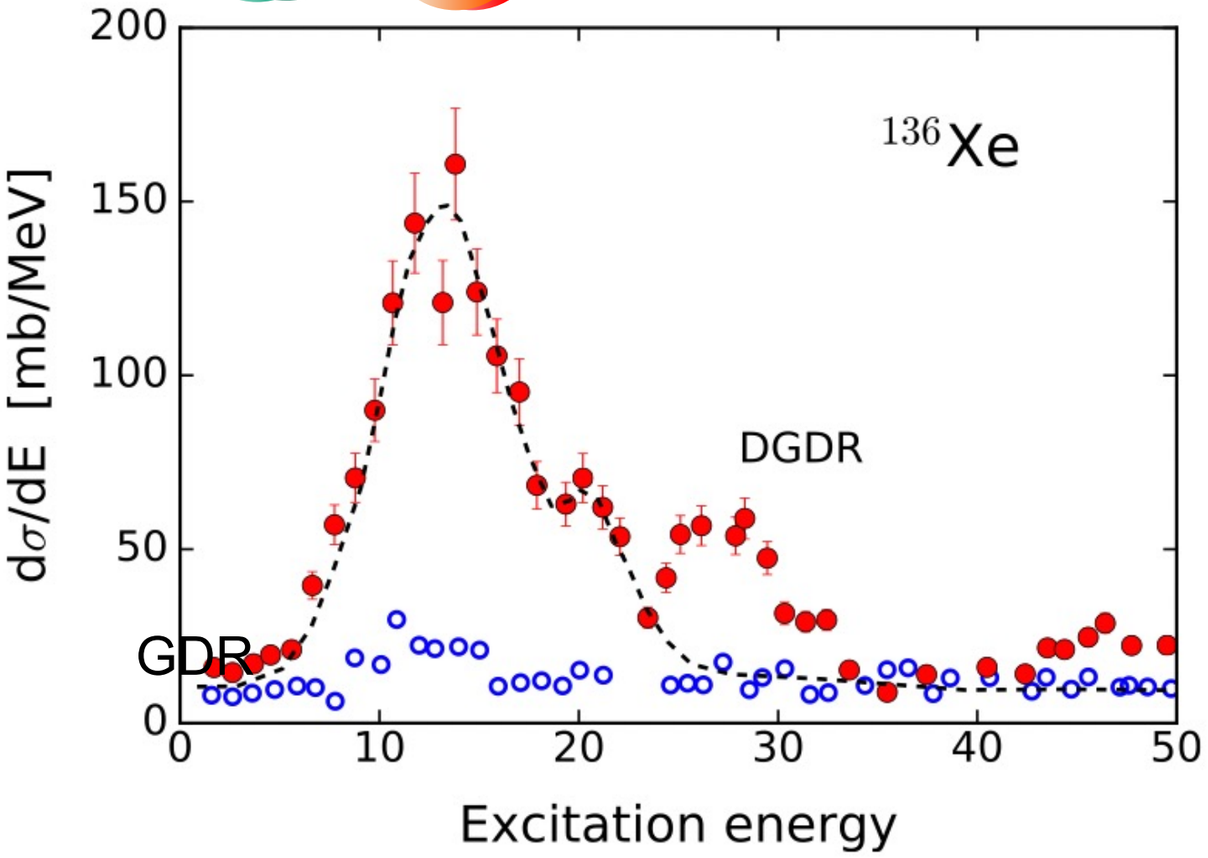


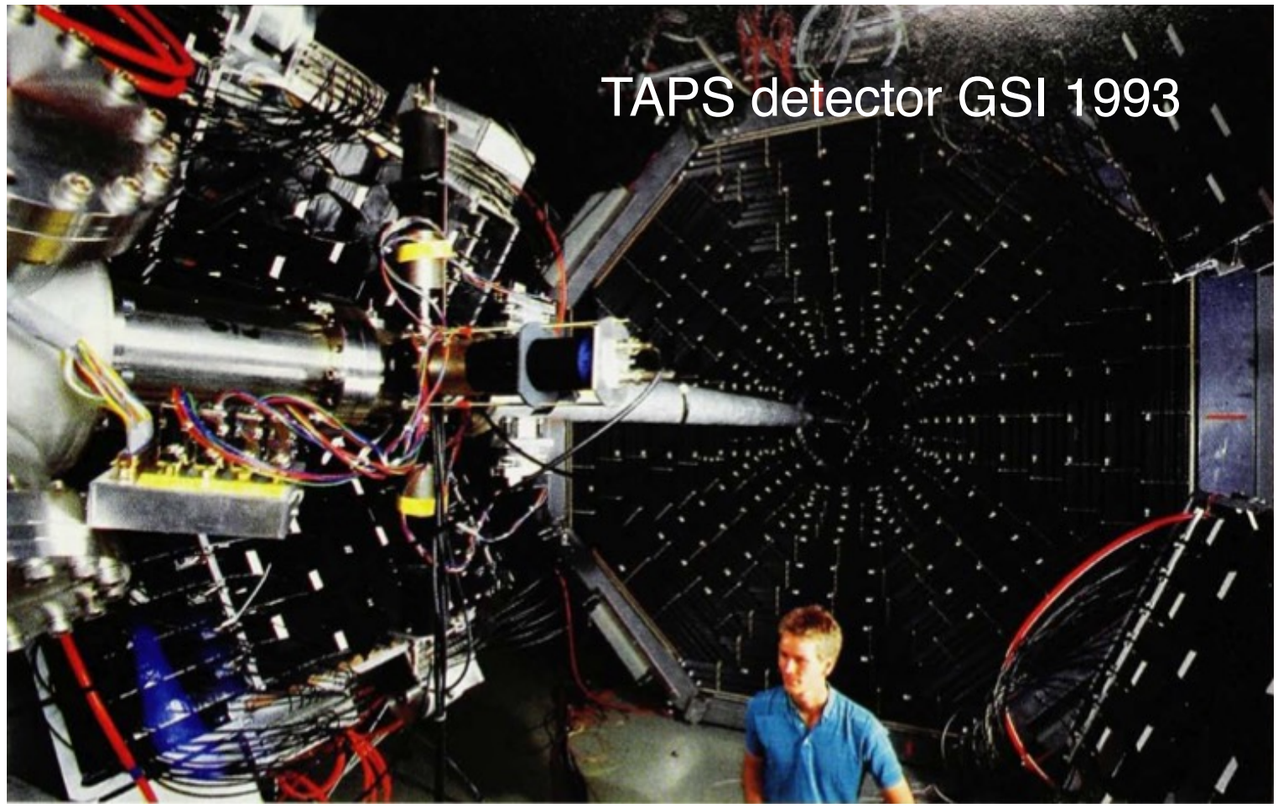
FRIB in 2024

Five previously unknown isotopes (182;183Tm, 186;187Yb, 190Lu)
PRL 132, 072501 (2024)

Double giant dipole resonance







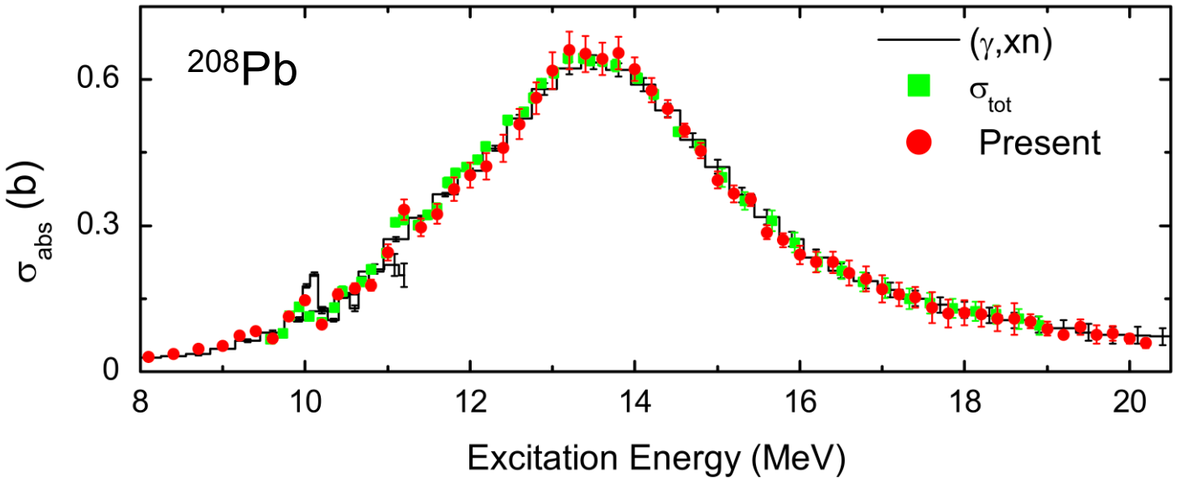
GSI experiments

PRL 70, 1767 (1993)
PRL 70, 533 (1993)

Tests of microscopic theories

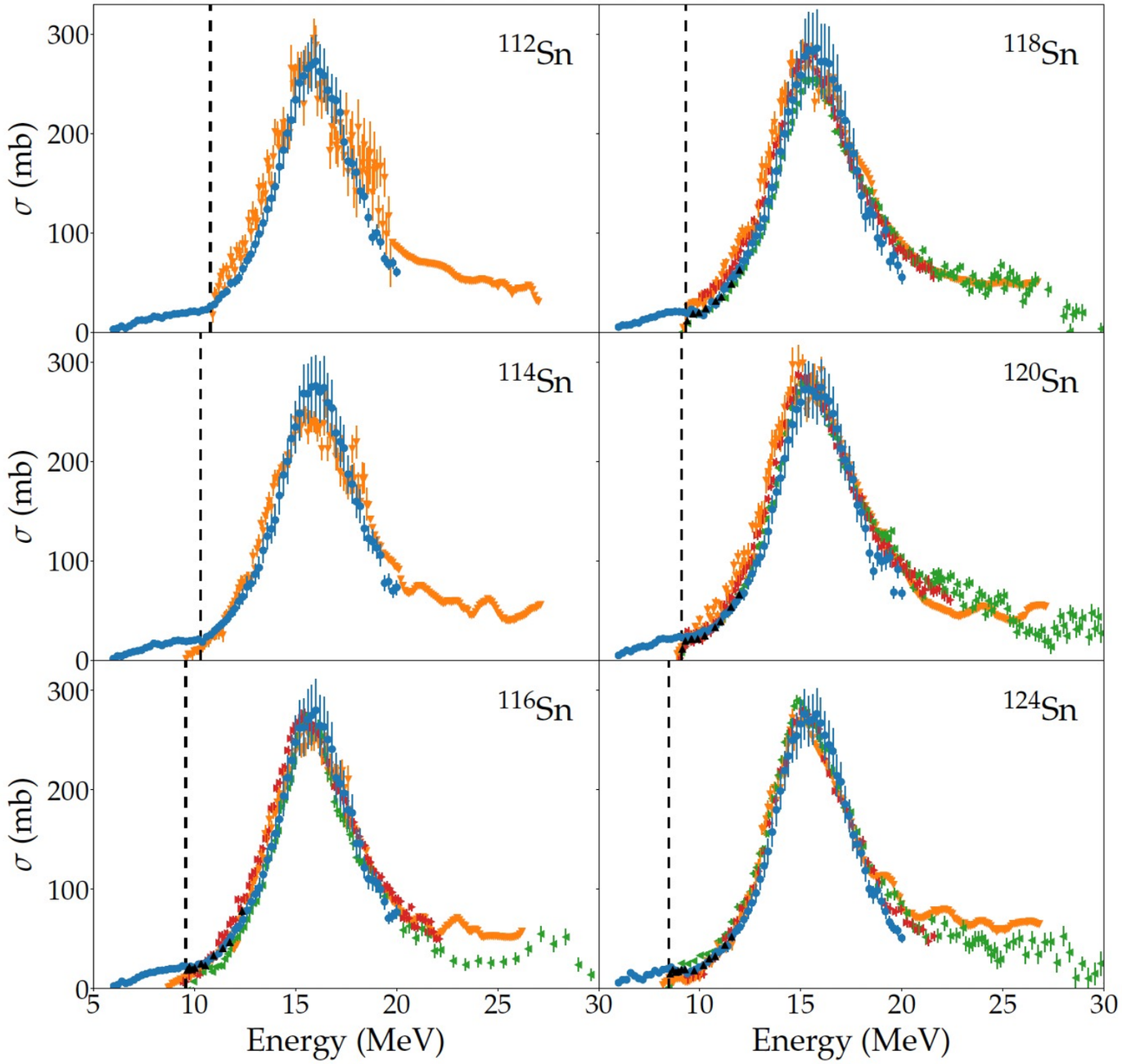
ARNPS 48, 351 (1998)
Phys. Rep. 321, 139 (1999)

Complete dipole polarizability



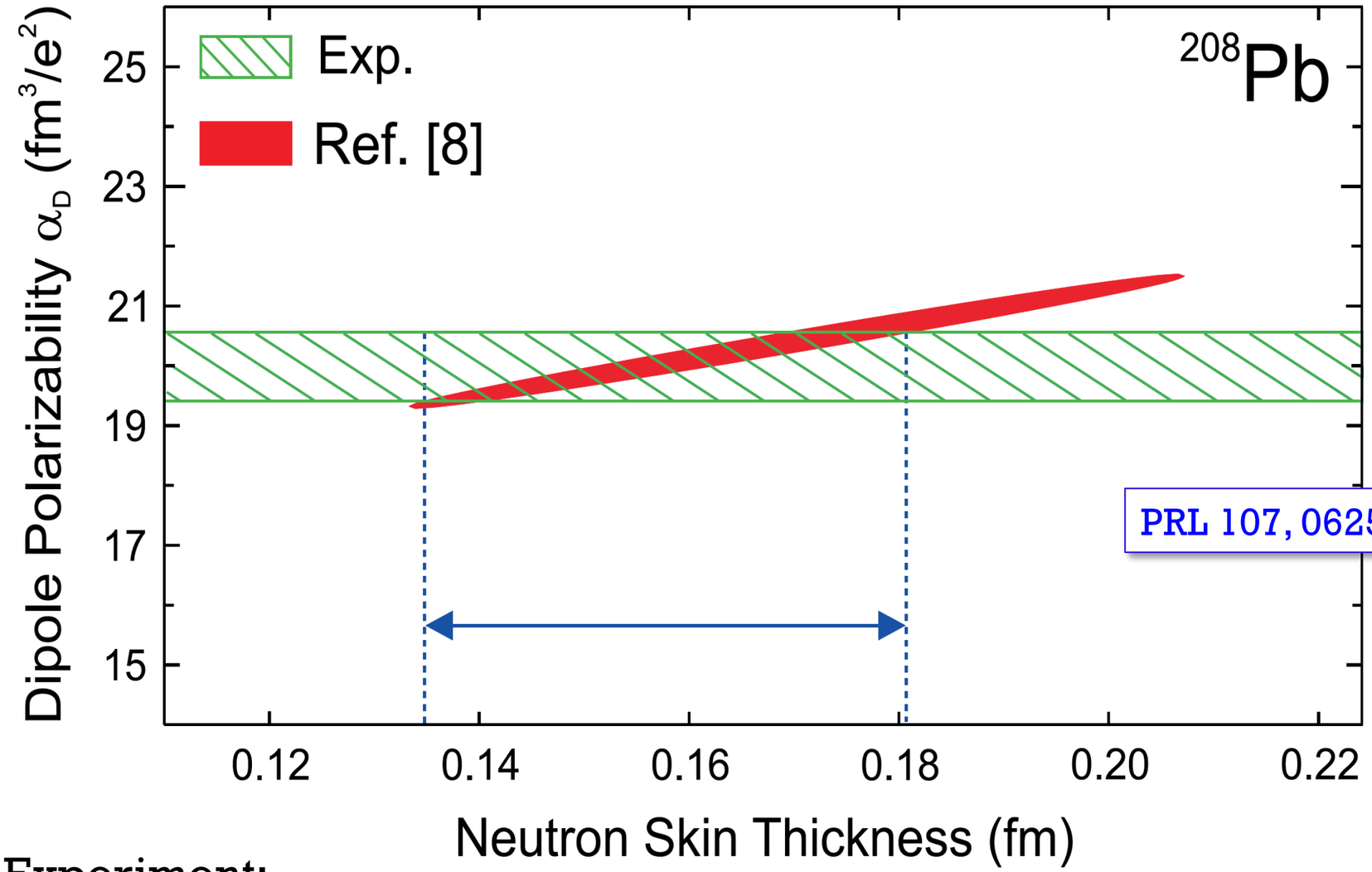
$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma_\gamma(E)}{E^2}dE$$

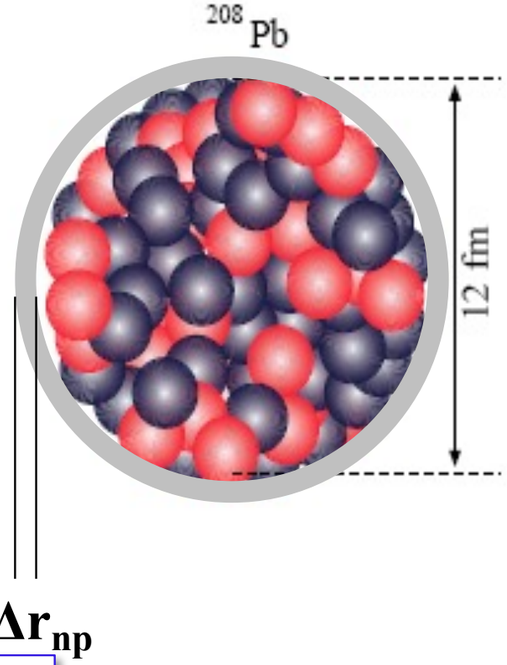
$$= \frac{8\pi}{9}\int \frac{B(E1,E_x)}{E_x}dE_x$$



PRL 107, 062502 (2011)
PRC 102, 034327 (2020)

Dipole polarizability vs neutron skin





PRL 107, 062502 (2011)

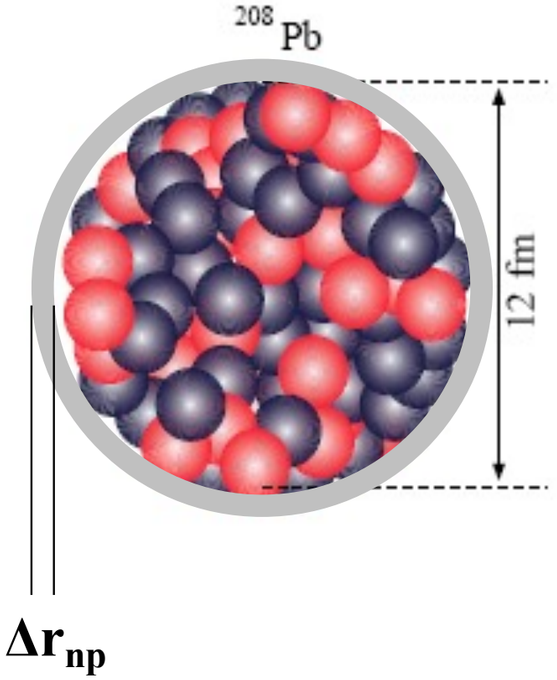
EFT:
PRL 105, 161102 (2010)

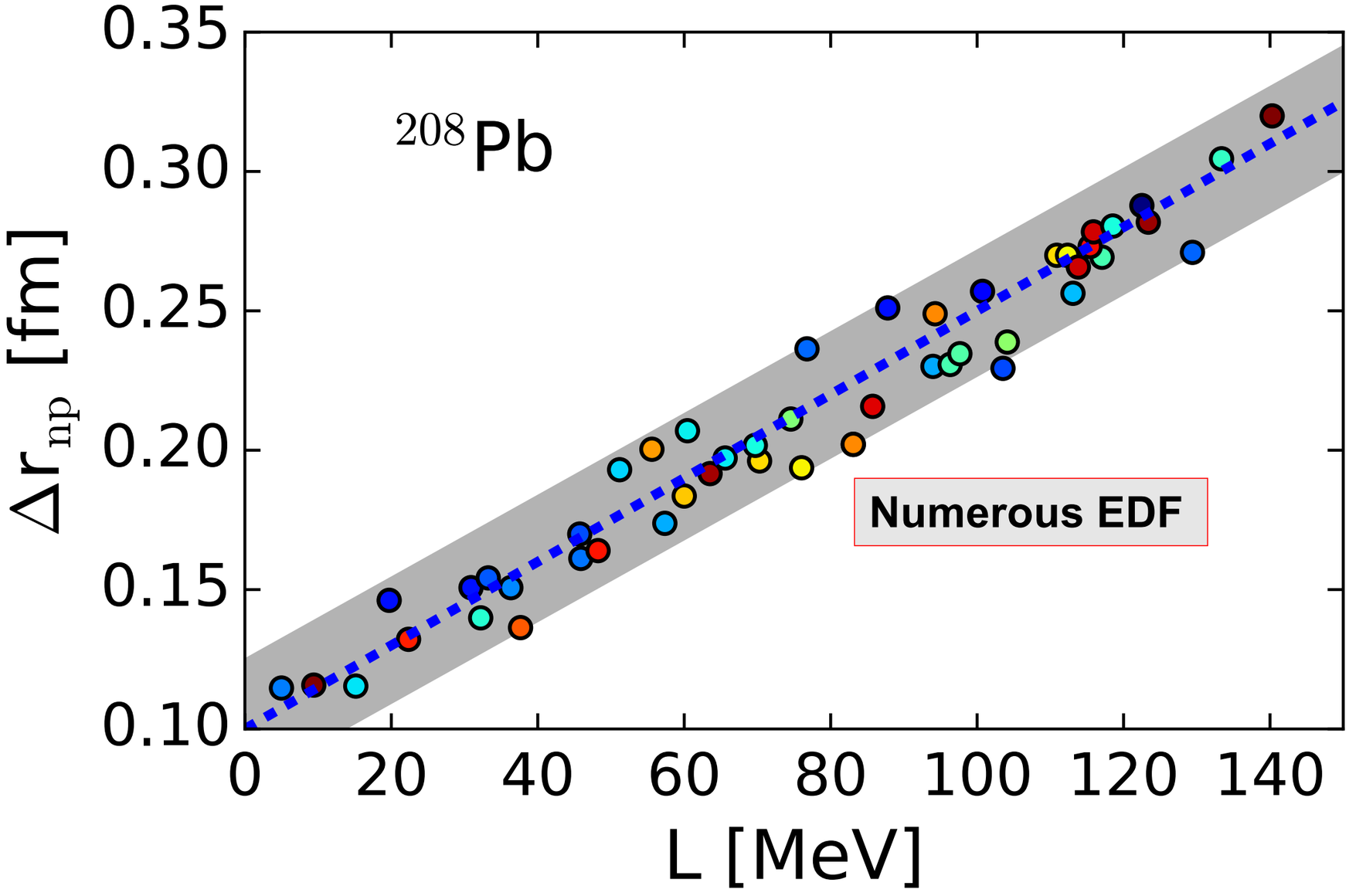
Experiment:

$\Delta r_{np} \sim 0.156$ fm

$\Delta r_{np} \sim 0.17$ fm

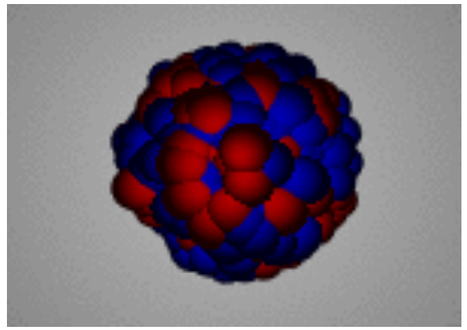
Symmetry energy, neutron skin



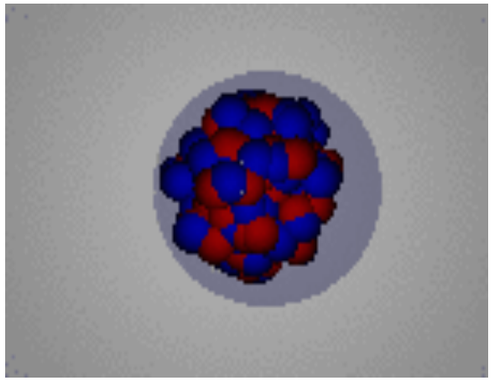


Pigmy resonances & E1 polarizability

$$P = \alpha_D E$$



Giant dipole

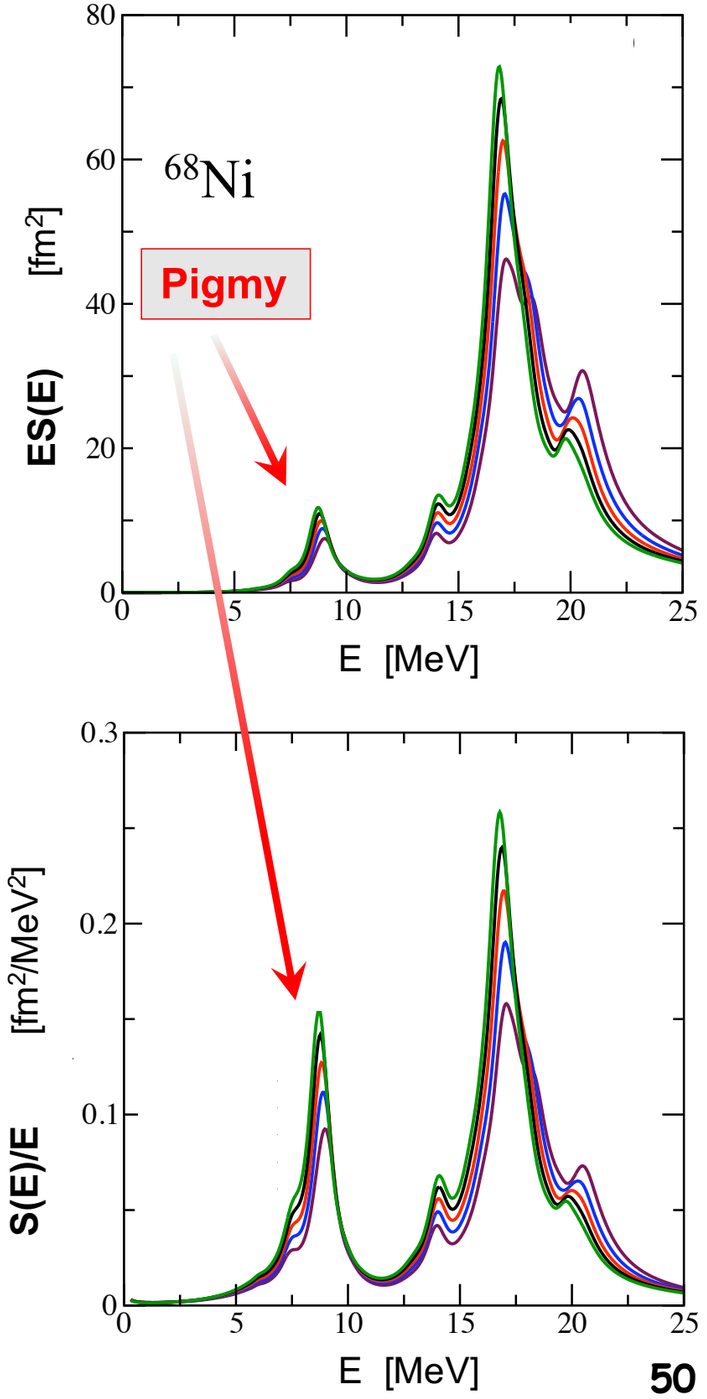


Pygmy dipole

$$\sigma_C \sim (\cdots) \int_0^\infty \frac{\sigma_\gamma(E)}{E^2} dE$$

$$\alpha_D = \frac{\hbar c}{2\pi^2} \int_0^\infty \frac{\sigma_\gamma(E)}{E^2} dE$$

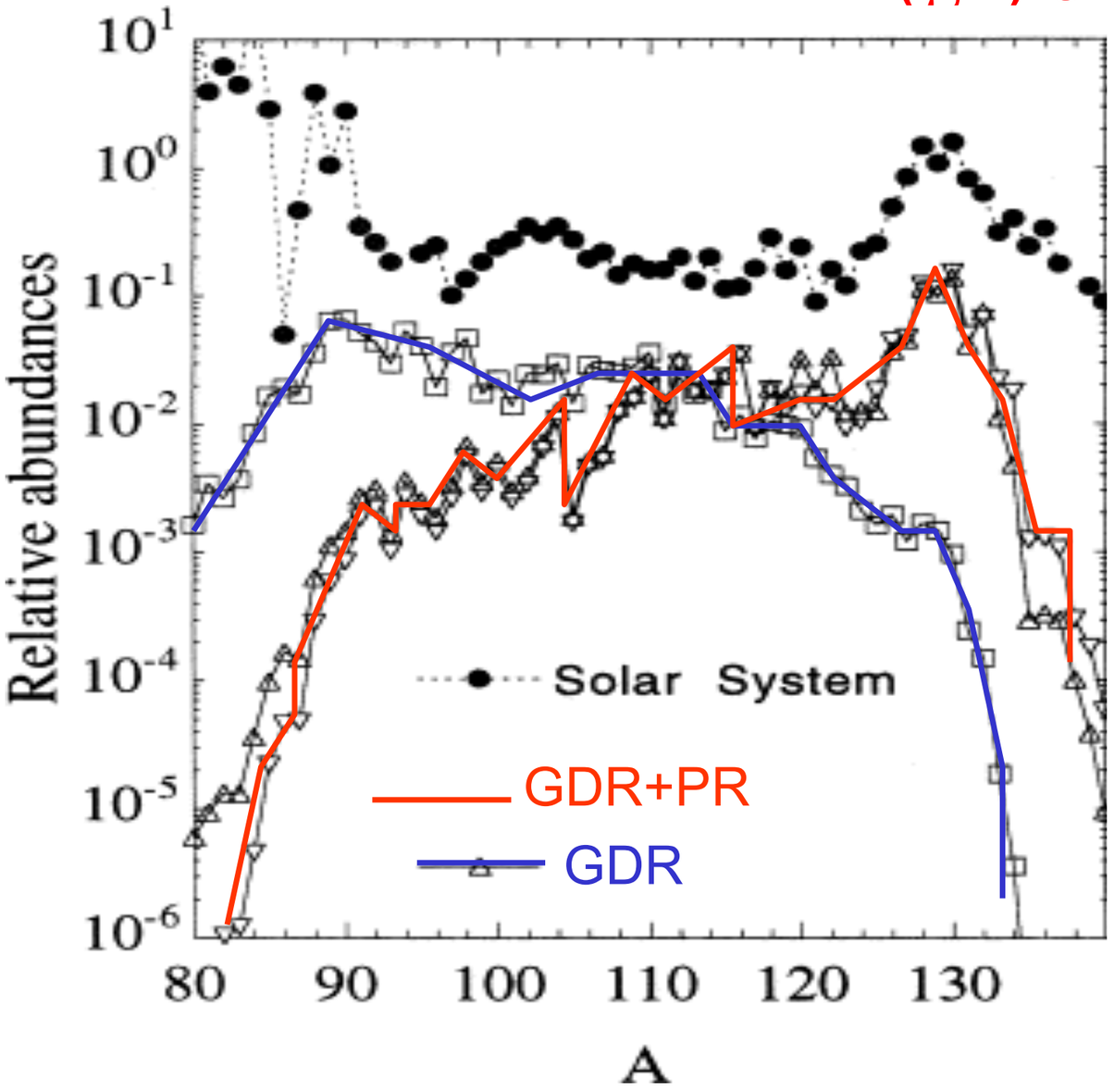
$$= \frac{8\pi}{9} \int \frac{B(E1, E_x)}{E_x} dE_x$$



Impact of pygmies on nucleosynthesis

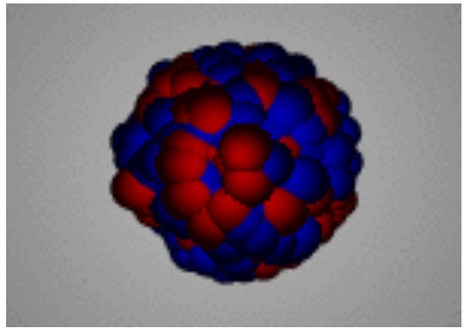
PLB 436, 10 (1998)

(γ,n) or (n,γ) cross sections in the r-process

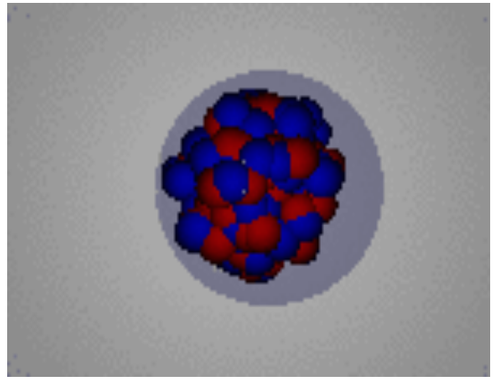


Impact: r-process abundances

- Calculation for
  $T = 10^9$ K, $N_n = 10^{20}$ cm^{-3}, τ = 2.3 s
- Under some conditions, PDR can enhance production in some regions

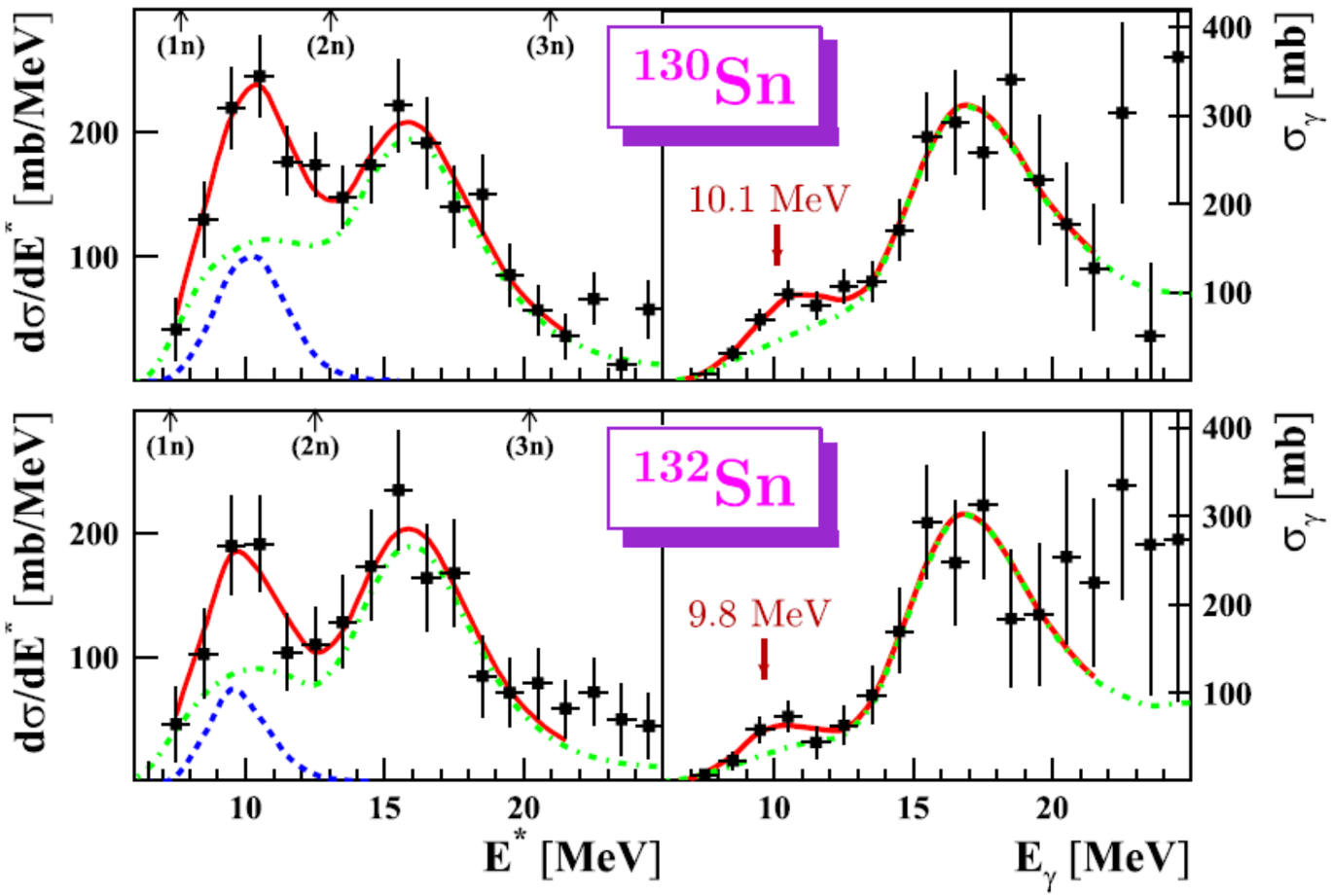


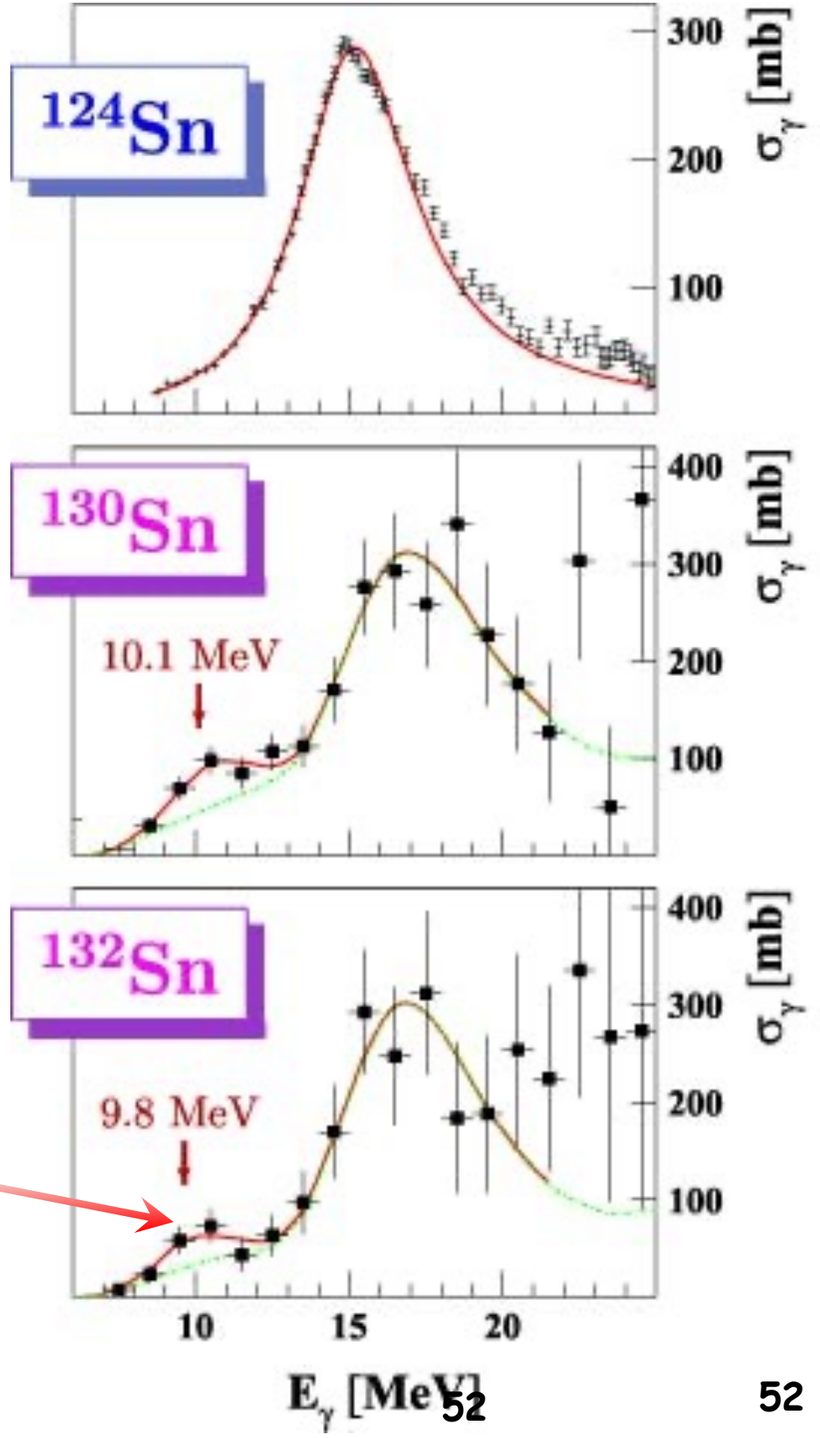
Giant dipole



Pygmy dipole

Dipole polarizability



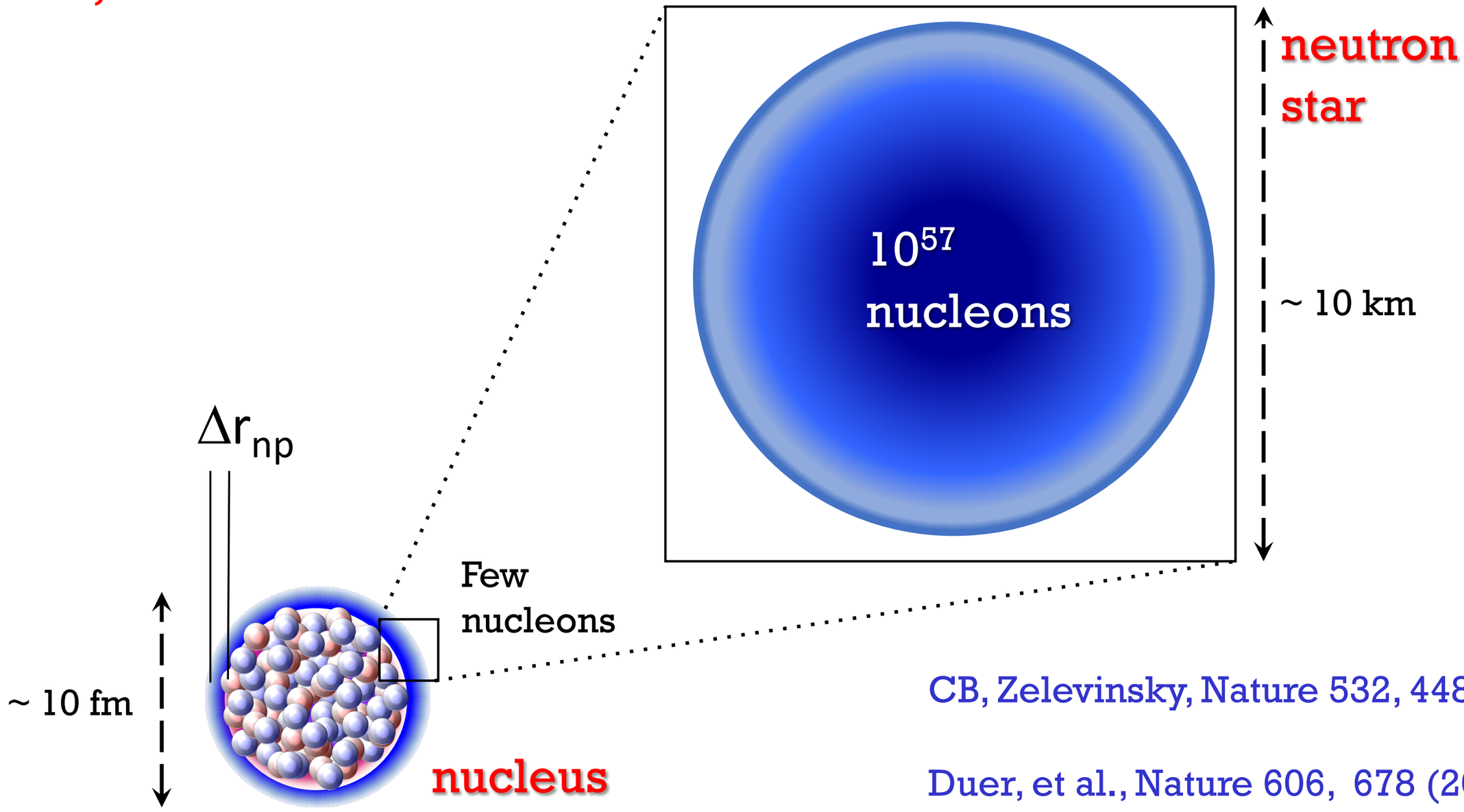


Rossi et al., PRL 111 (2013) 242503

Wieland et al., PRL 102, 092502 (2009)

52

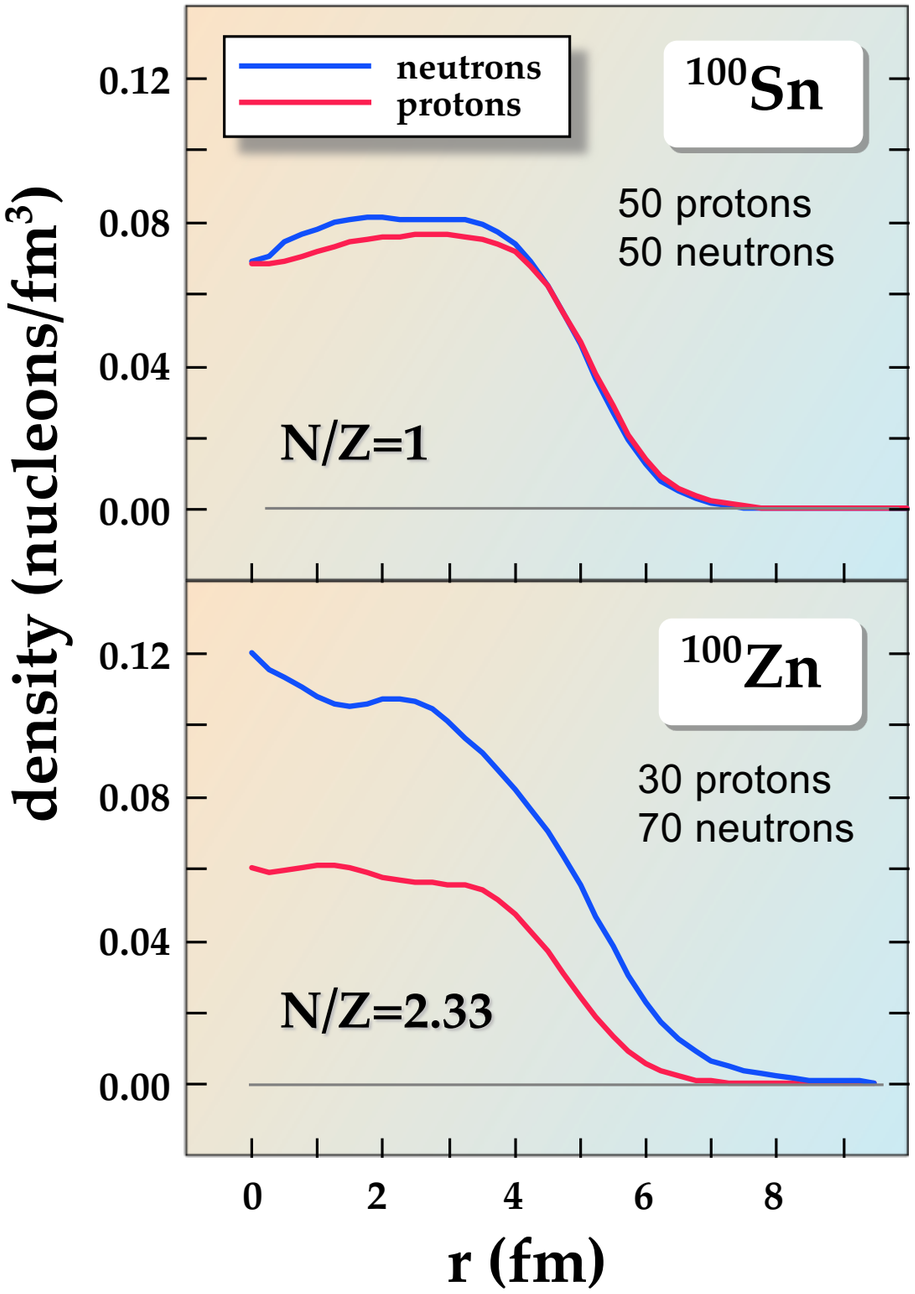
Skins, neutron stars

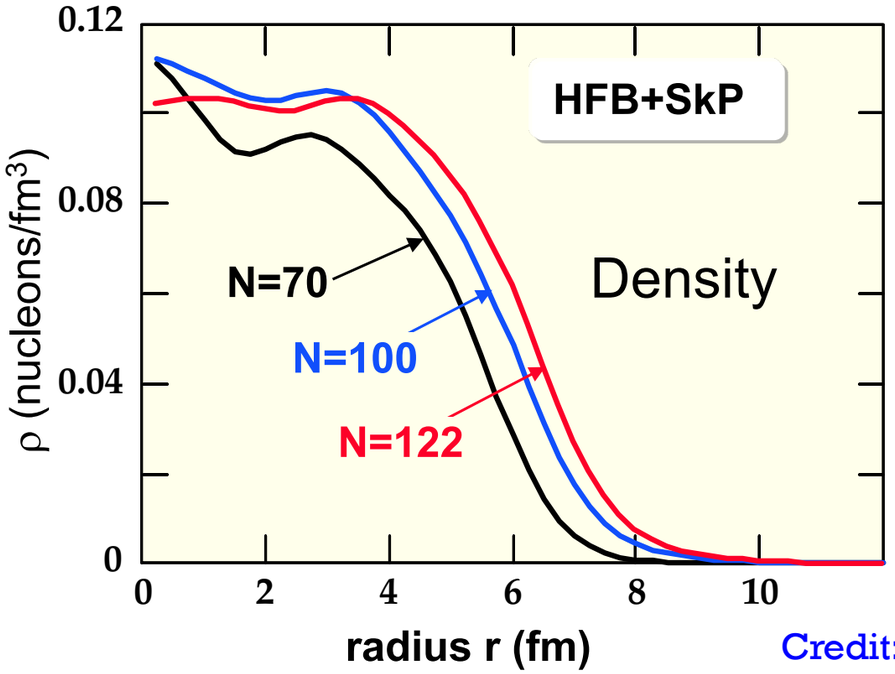


CB, Zelevinsky, Nature 532, 448 (2016)

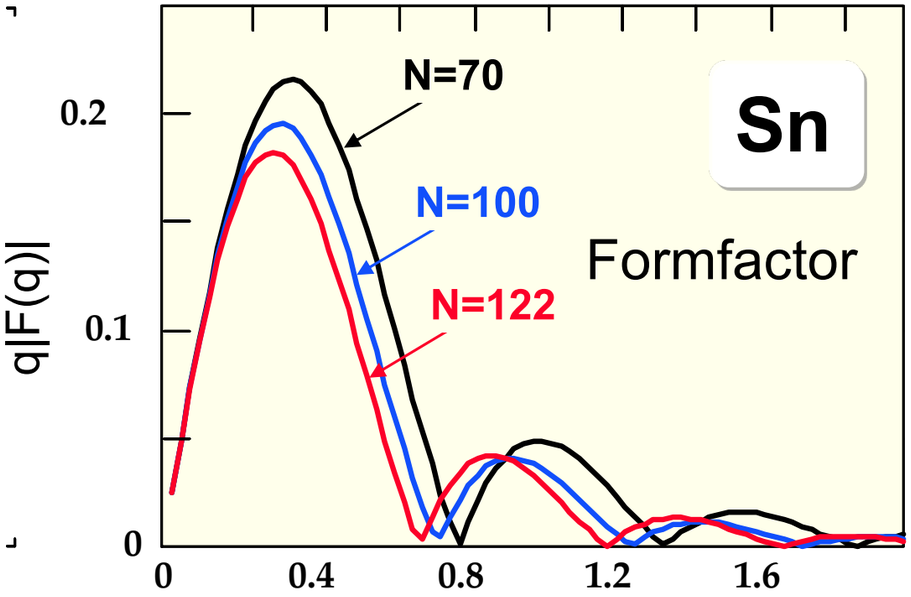
Duer, et al., Nature 606, 678 (2022)
(tetraneutron)

Neutron skins

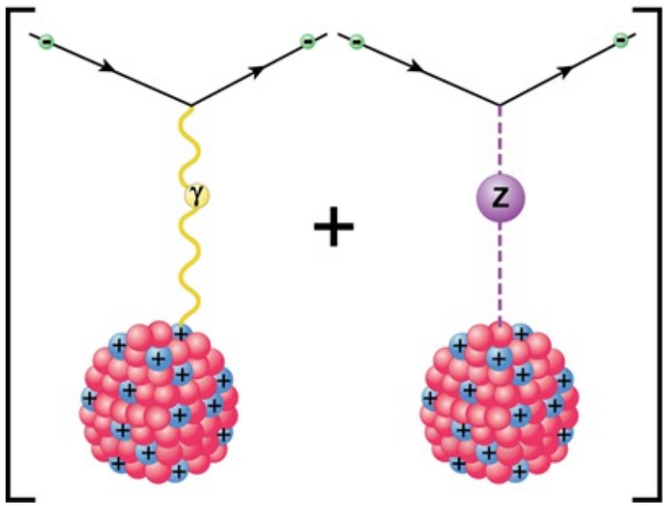




Credit: W. Nazarewicz



n-skin from PV e- scattering



PRL 108, 112502 (2012)

PRC 85, 032501(R) (2012)

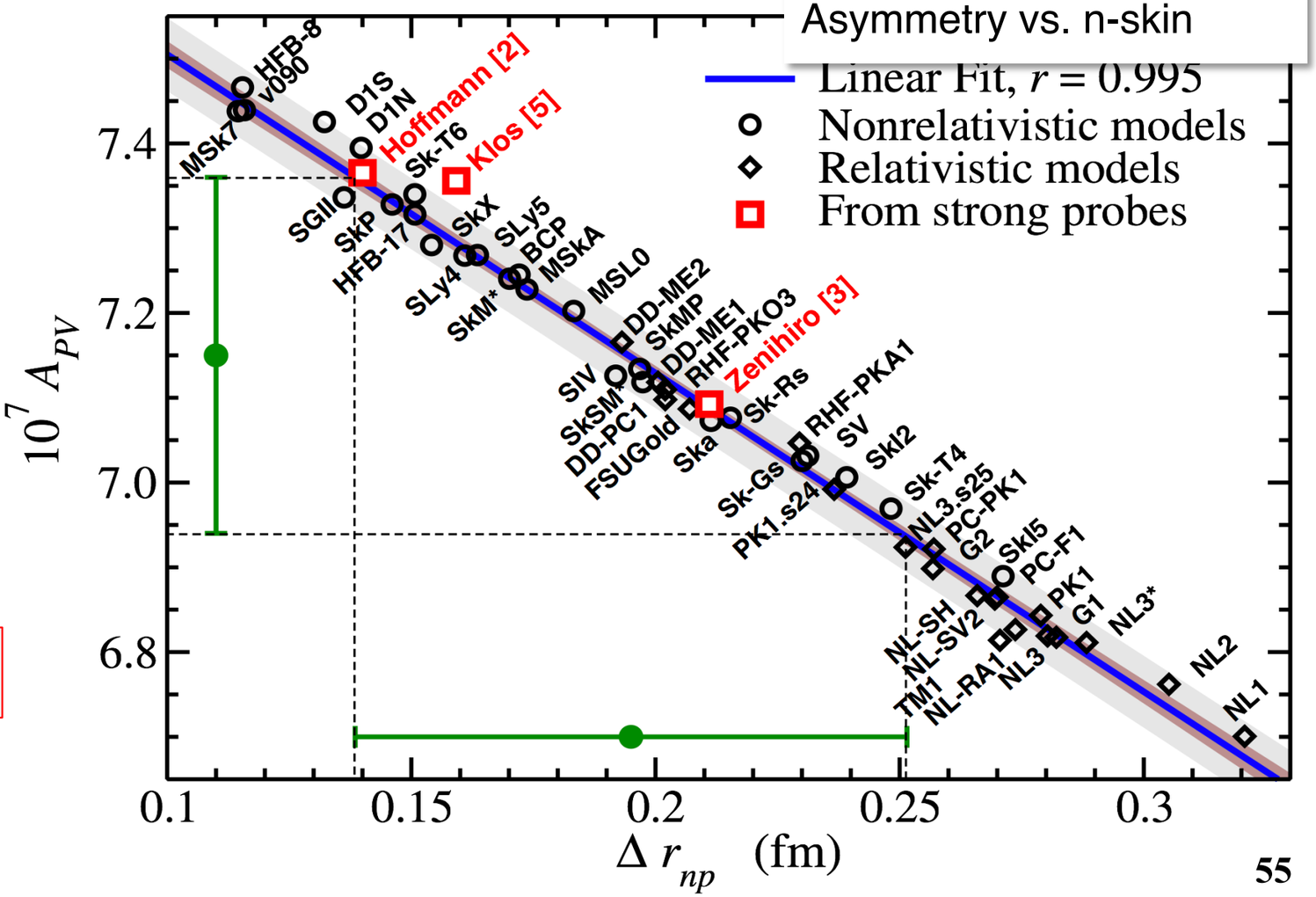
$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}$$

$$A_{PV}(Q^2) \sim \frac{F_w(Q)}{F_{ch}(Q)}$$

$$F_w \sim \int dr \frac{sin(Qr)}{Qr} \rho_w(r)$$

$$\rho_w(r) \sim \rho_{ch}(r) + c_n\rho_n(r) + c_p\rho_p(\mathrm{r})$$

Asymmetry vs. n-skin

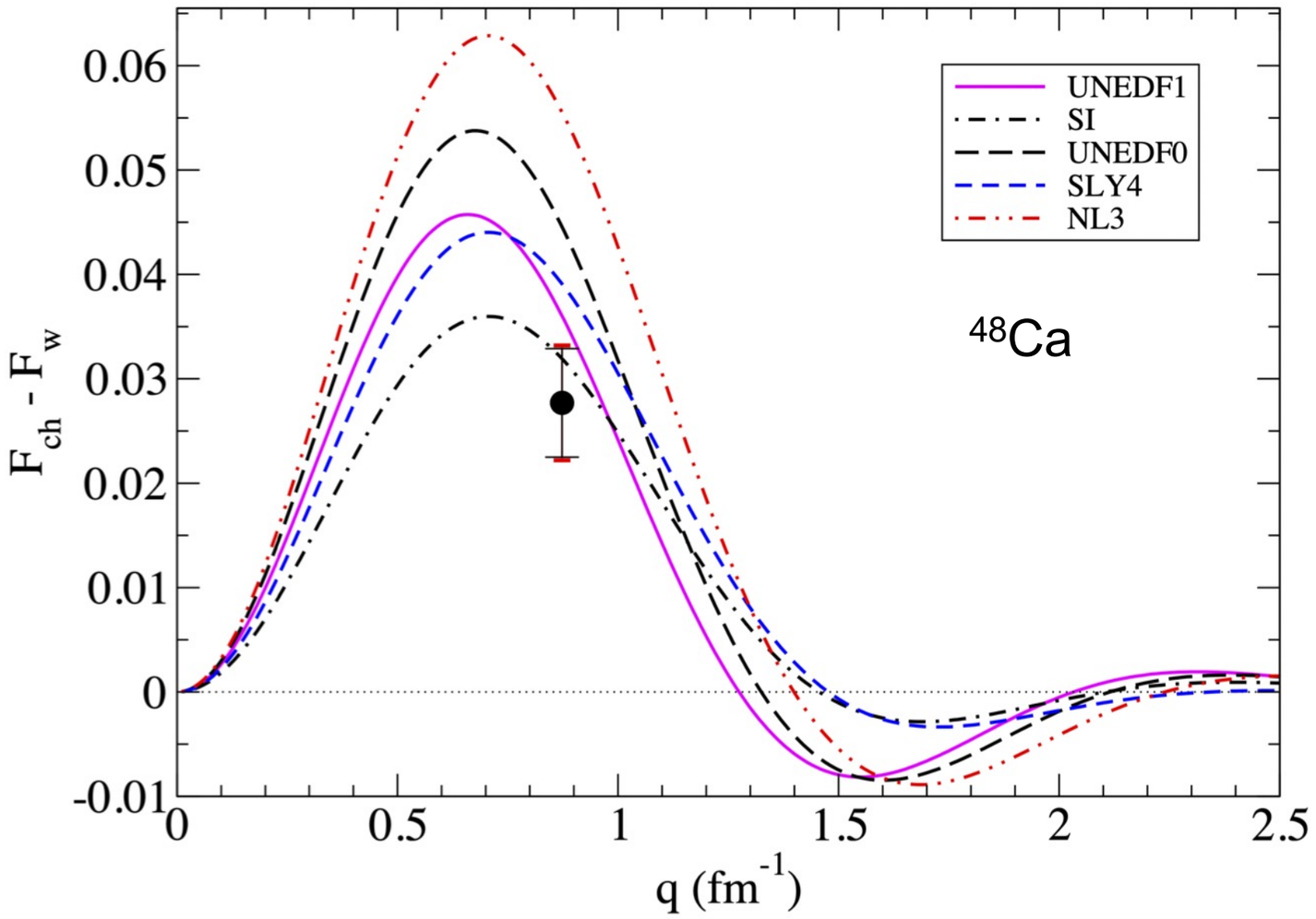


n-skin from e- PV scattering

$$F(Q^2) \sim 1 - \frac{1}{6} q^2 \langle r^2 \rangle$$

$$\langle r^2 \rangle \cong -6 \frac{dF(Q^2)}{dQ^2}$$

- PREX & CREX:
- n-skin, L and DFT



$(R_n - R_p)_{48Ca} = 0.121 \pm 0.025$ fm

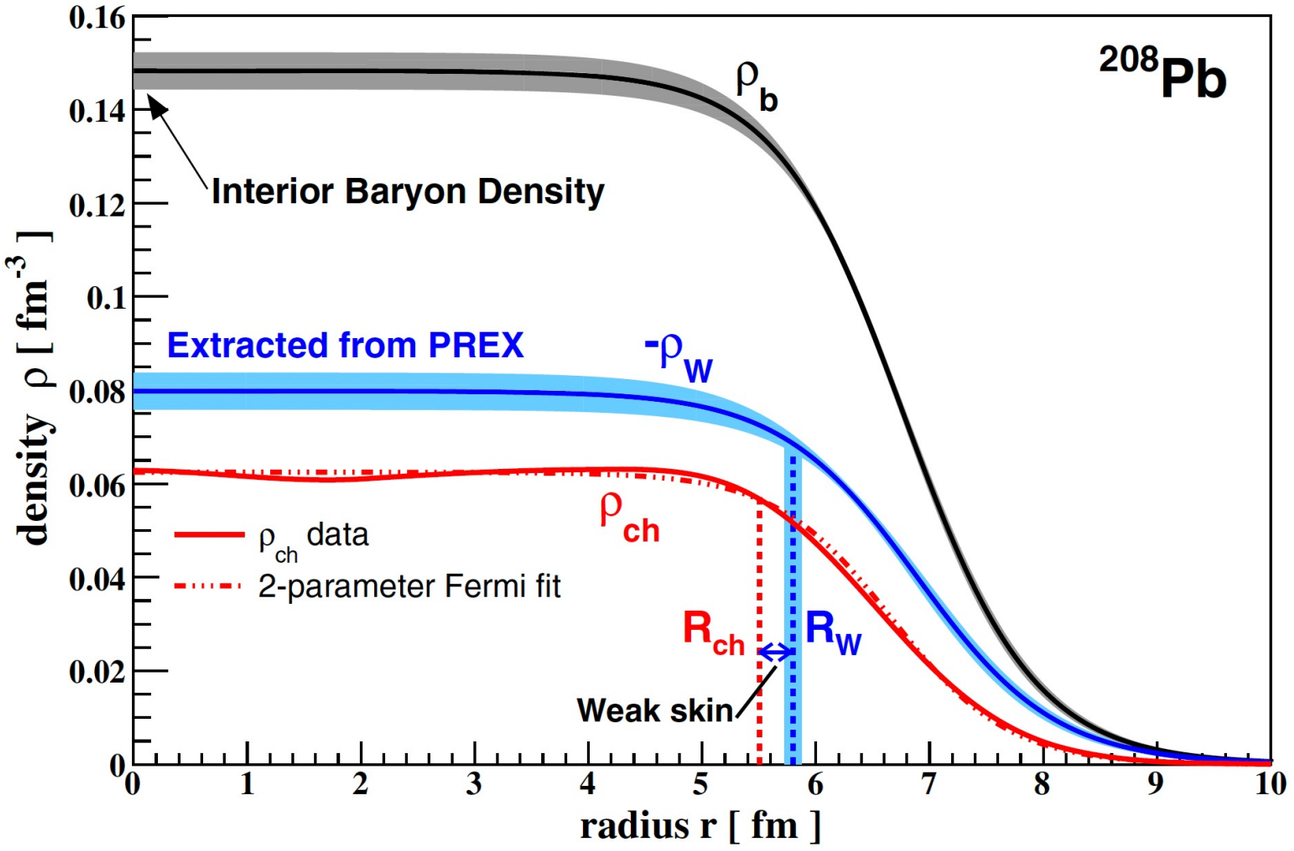
Adhikari et al, PRL 129, 042501(2022)

too large for Pb

$R_n - R_p = 0.33 \pm 0.17$ fm

Adhikari et al, PRL 126, 172502 (2021)

n-skin from e⁻ scattering ^{208}Pb



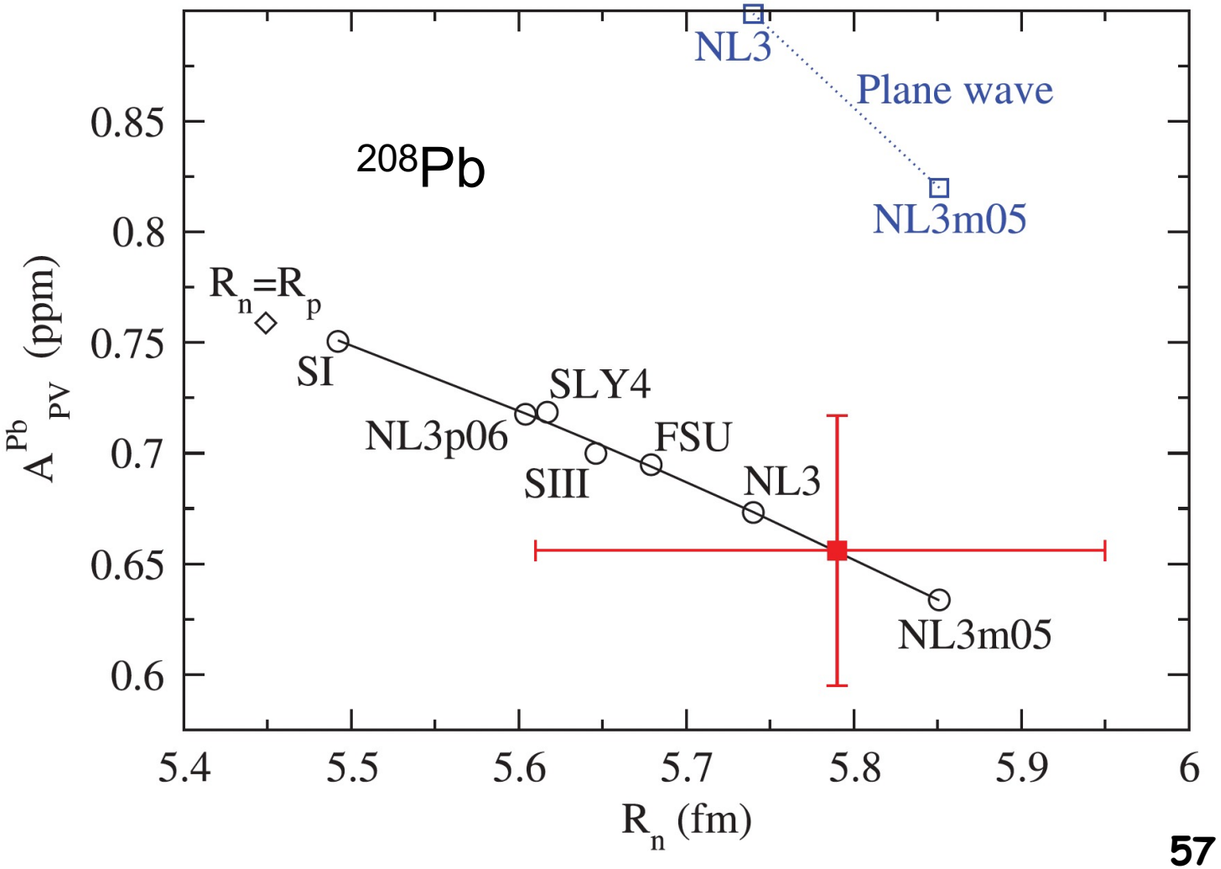
$\Delta r_{np} \sim 0.156$ fm

PRL 107, 062502 (2011)

very large value!

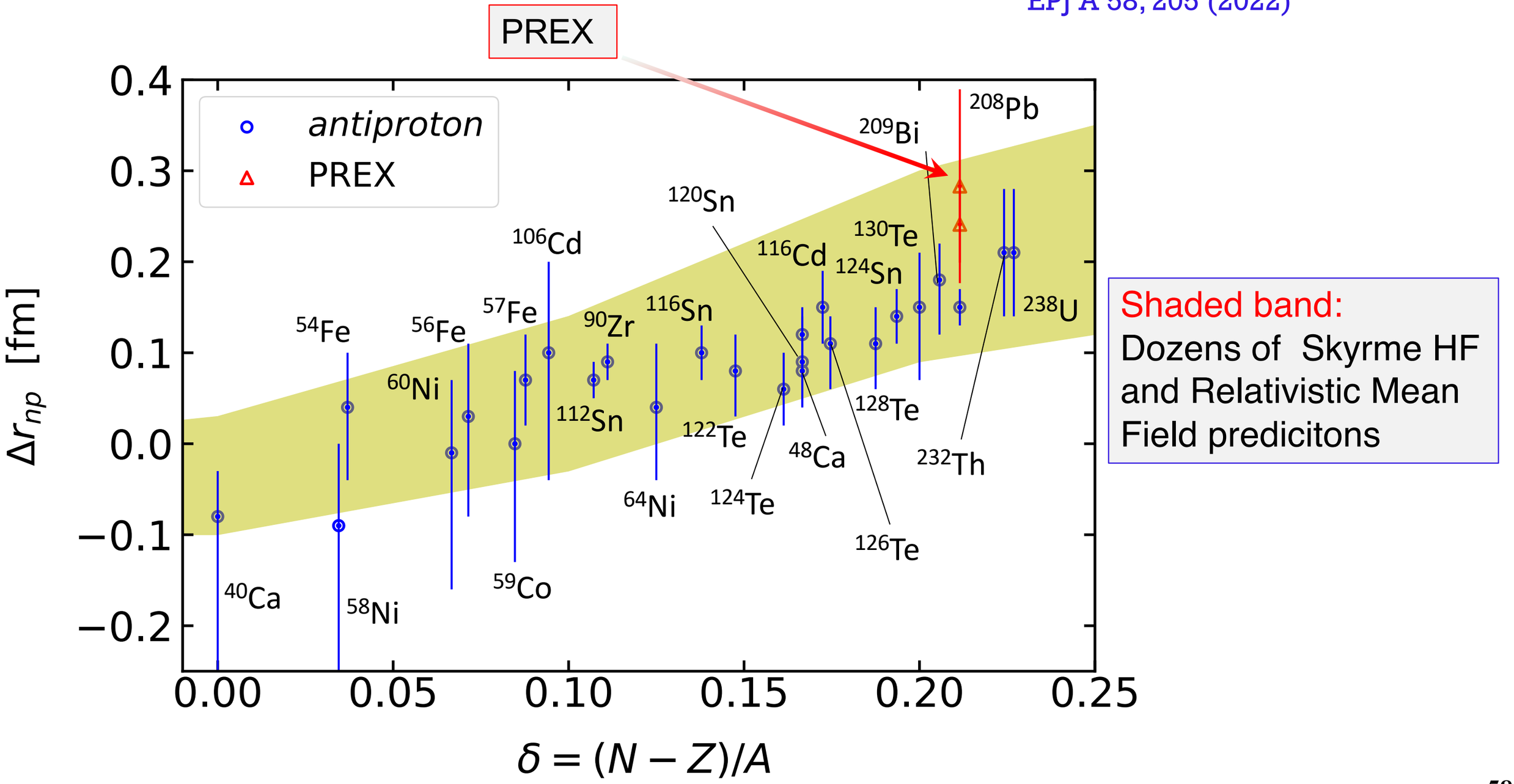
$R_n - R_p = 0.33 \pm 0.17$ fm

PRL 126, 172502 (2021)



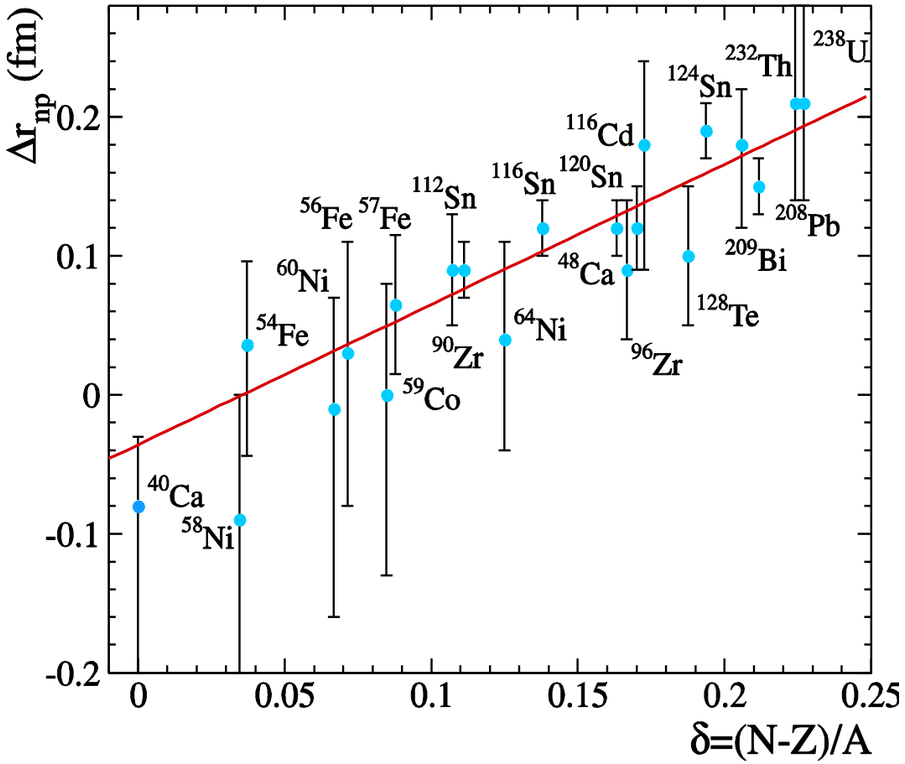
Status of neutron skins

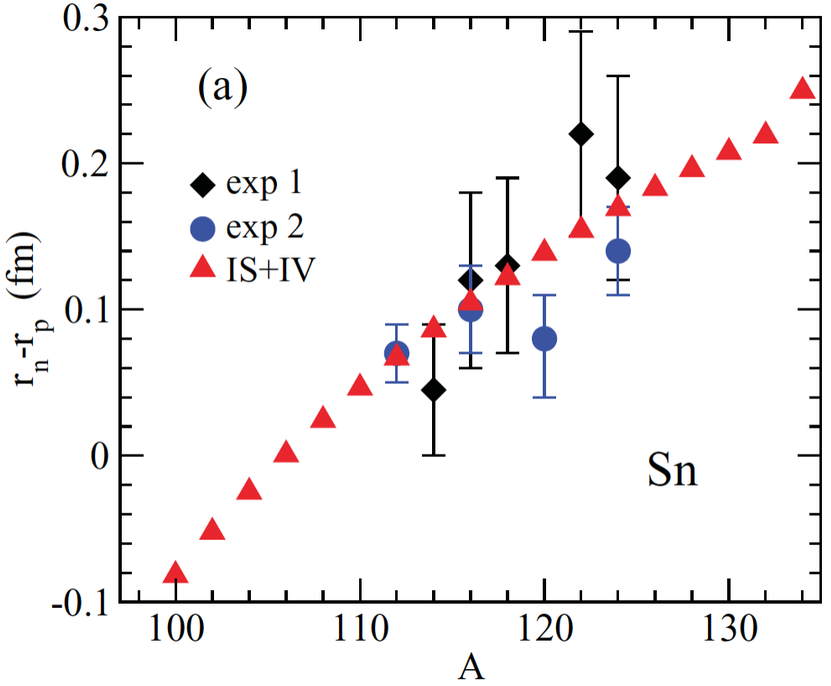
EPJ A 58, 205 (2022)



Shaded band:
Dozens of Skyrme HF and Relativistic Mean Field predicitons

Neutron skins measurements





Mean field calculations

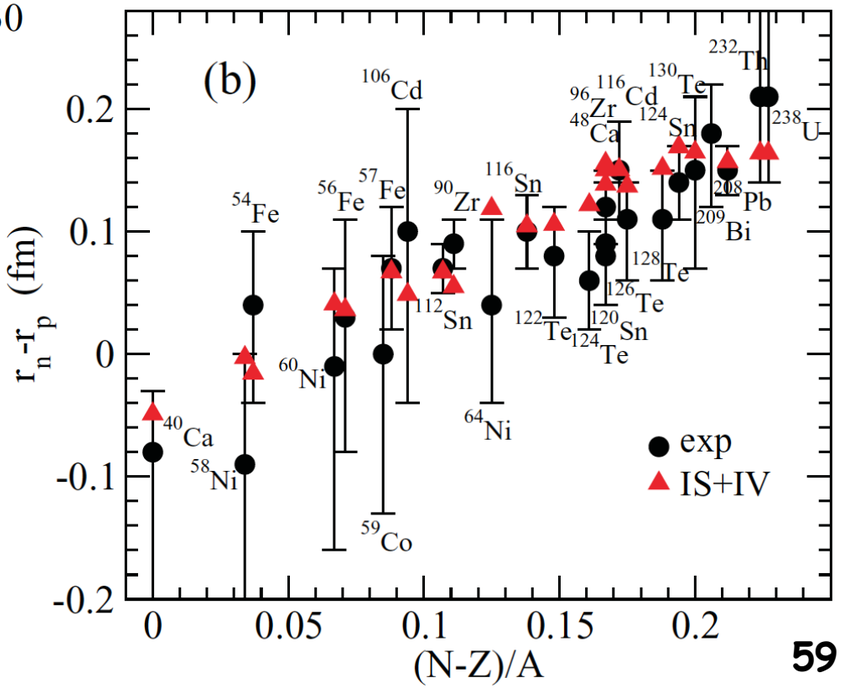
PRC 85, 014321 (2012)

Radii from spin-dipole resonances

PRL 82, 3216 (1999)

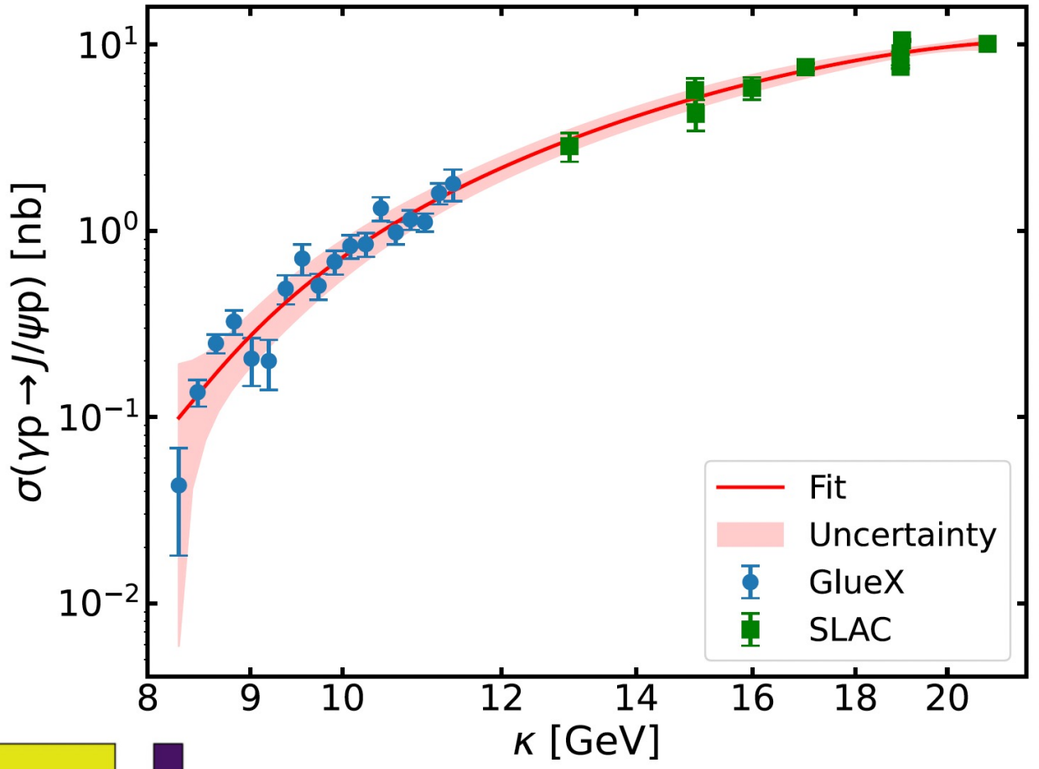
Antiprotonic atoms

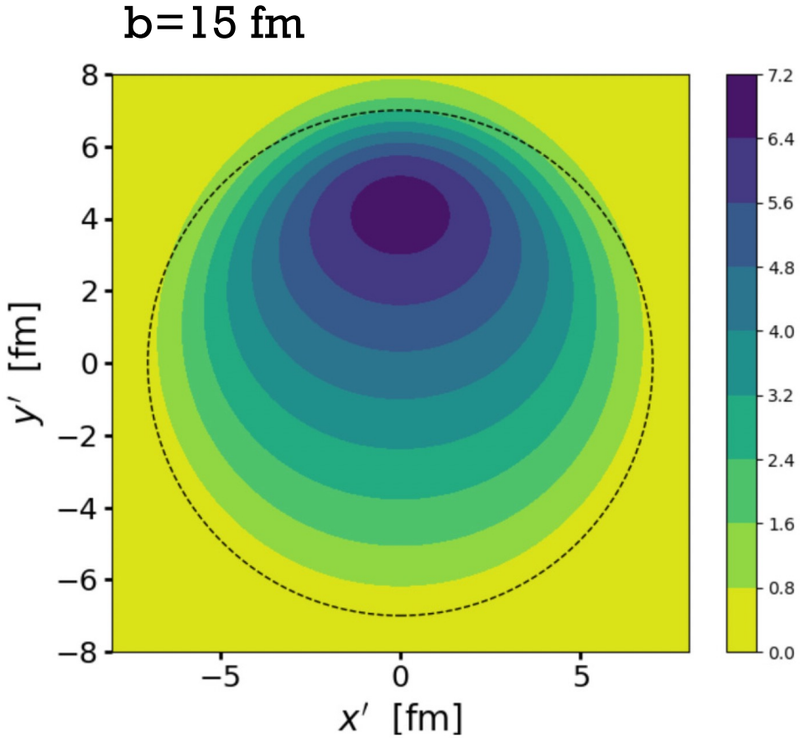
PRL 87, 082501 (2001)

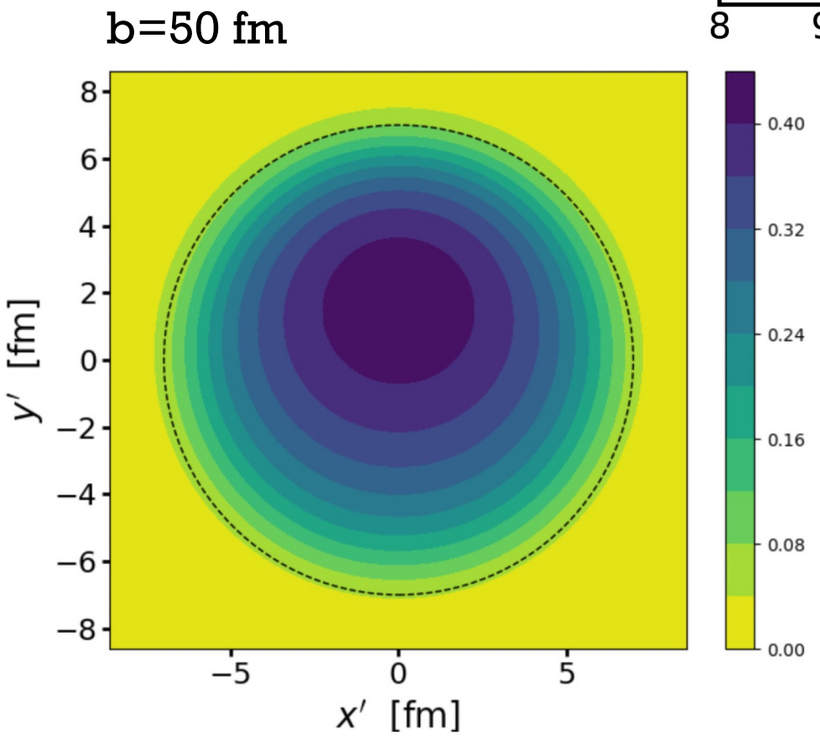


n-skin from UPC

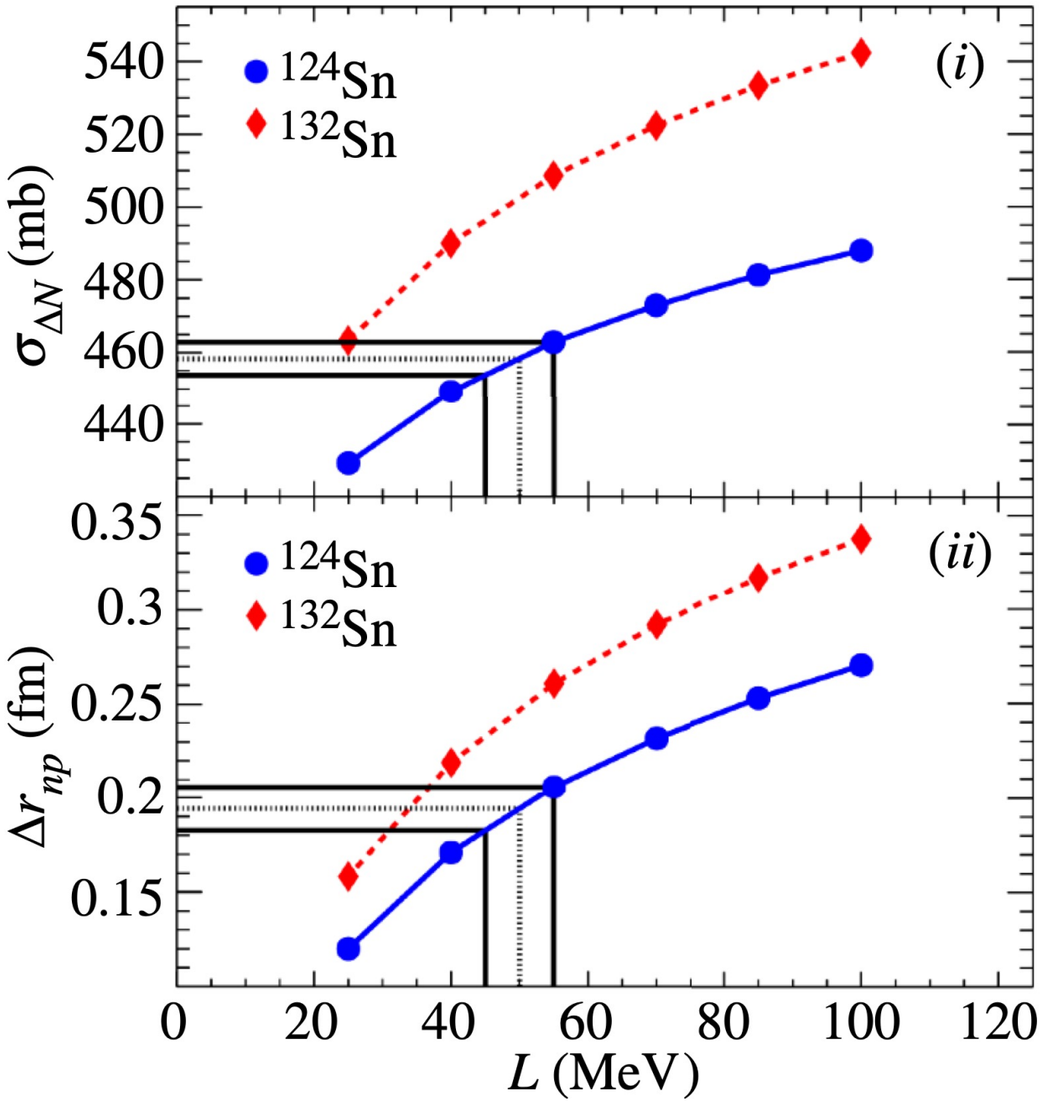
PRC 112, 034911 (2025)





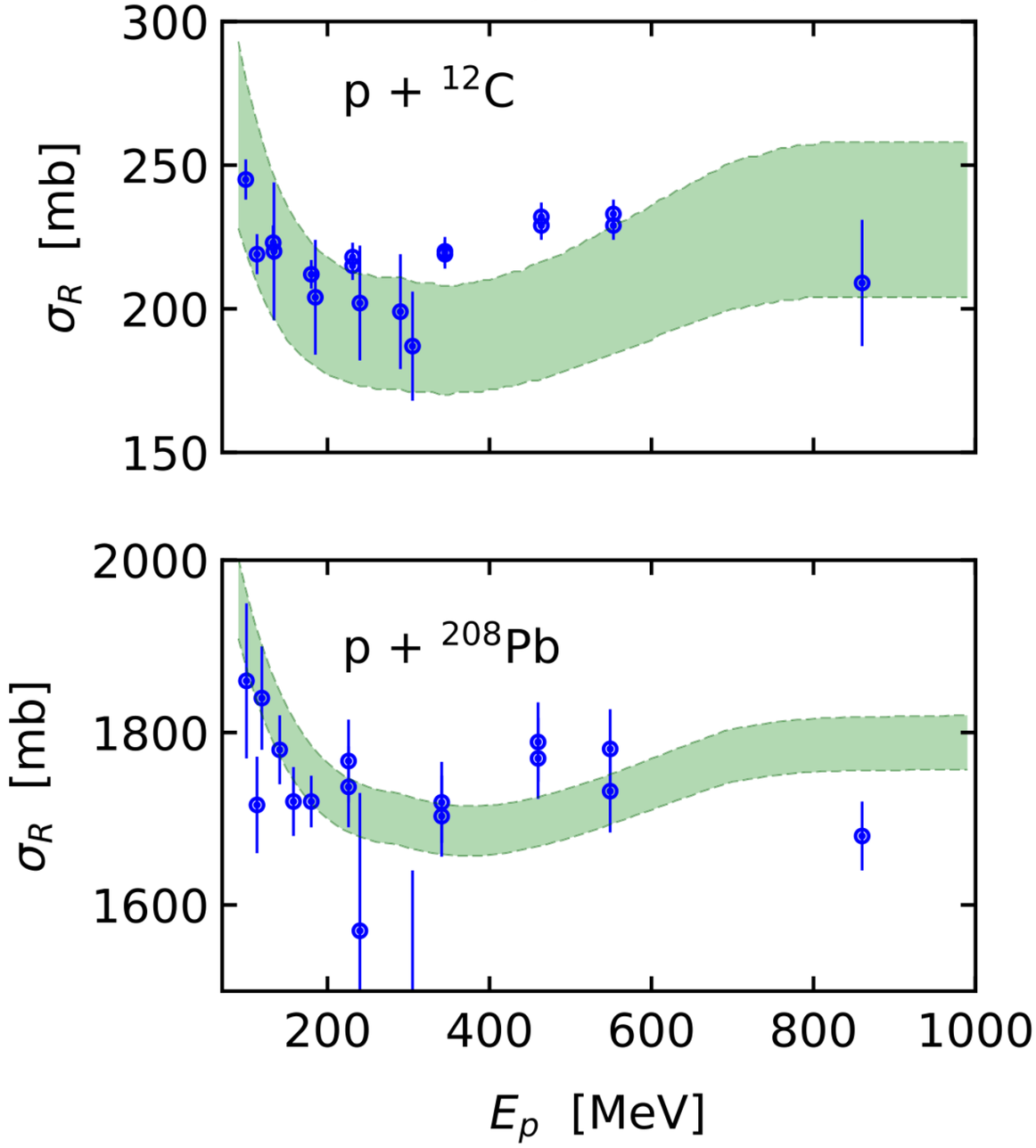


Fragmentation and symmetry energy

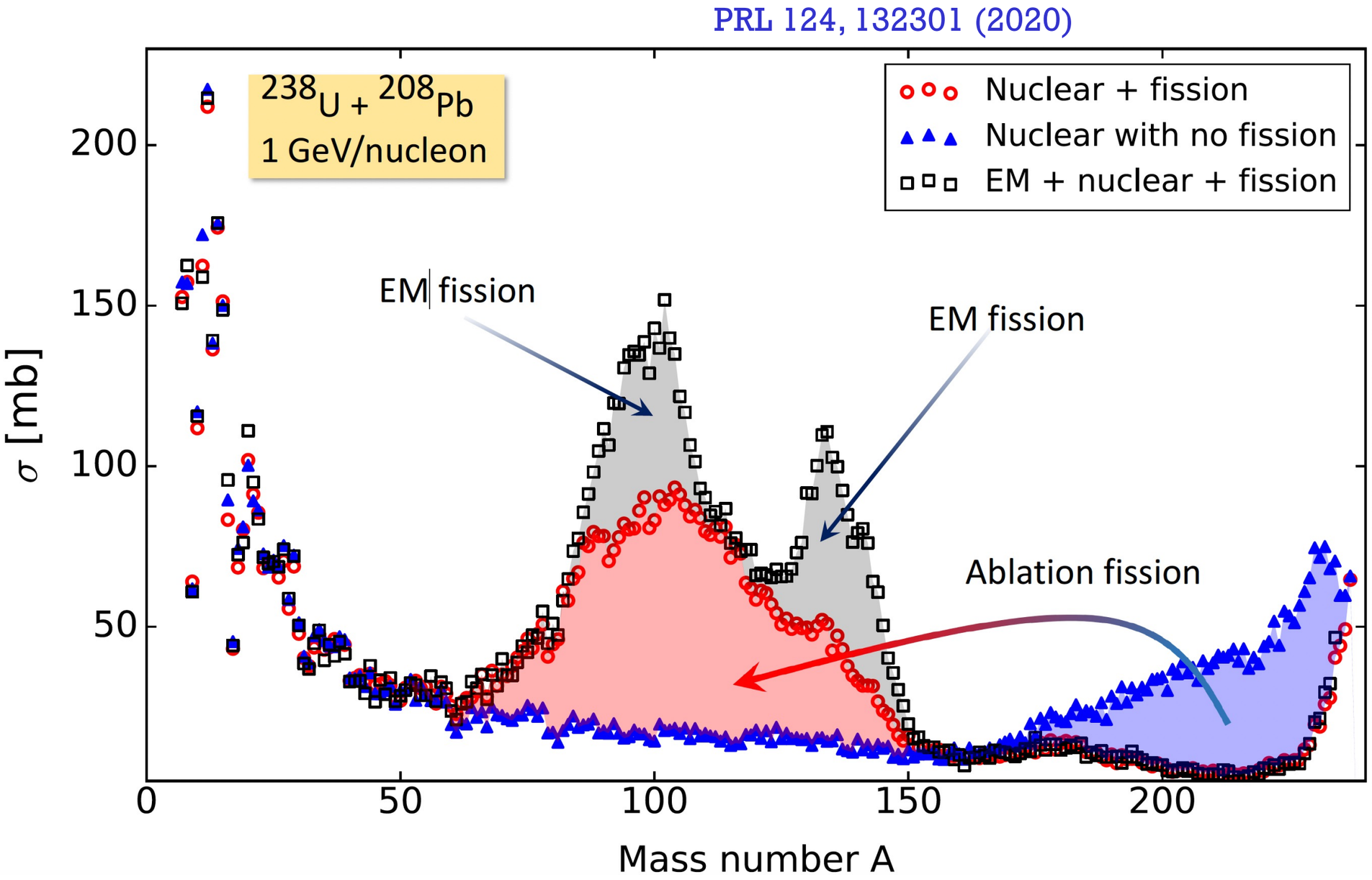


PRL 119, 262501 (2017)

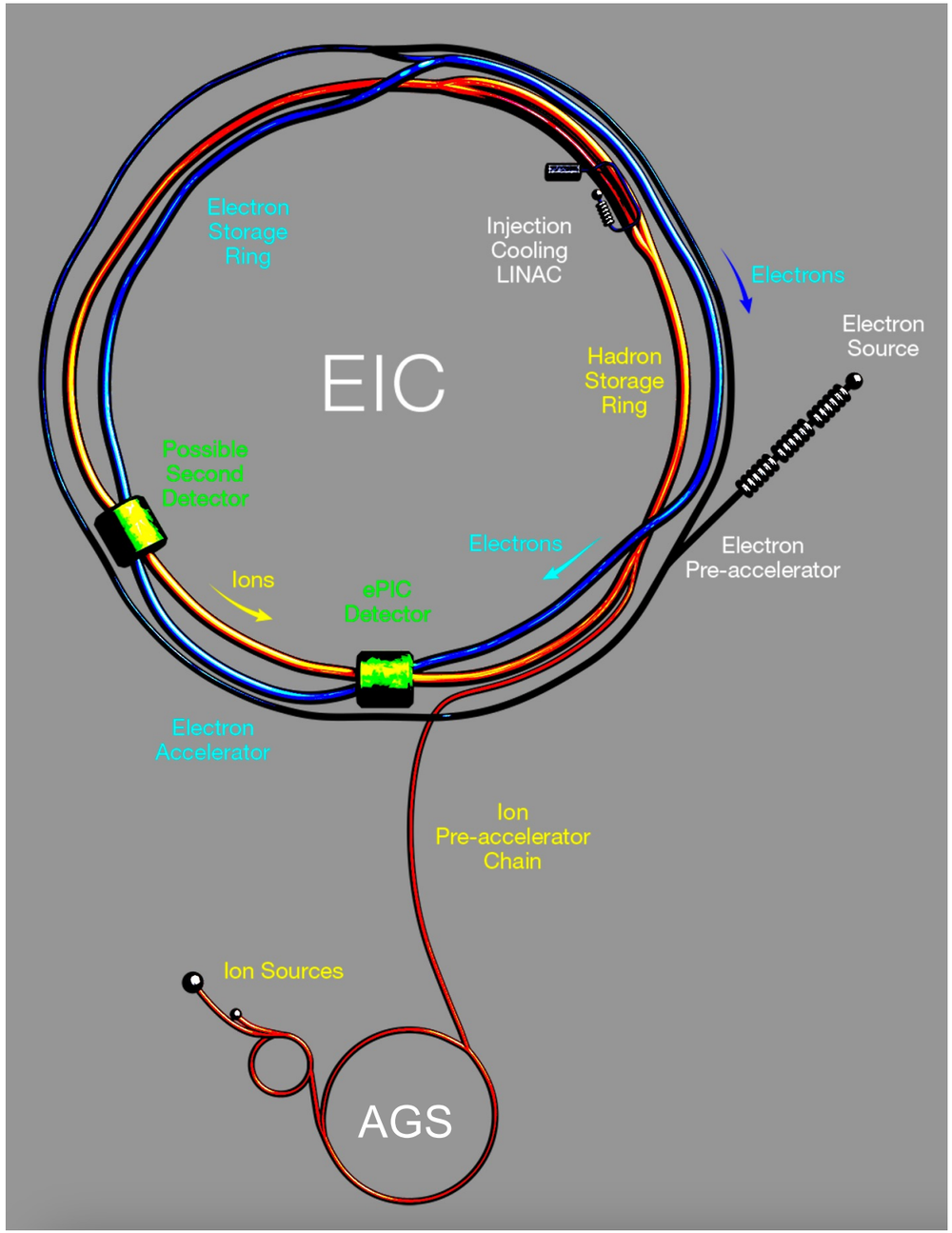
Teixeira, Aumann, CB, Carlson
EPJ A 58, 205 (2022)



Fragmentation in heavy ion collisions



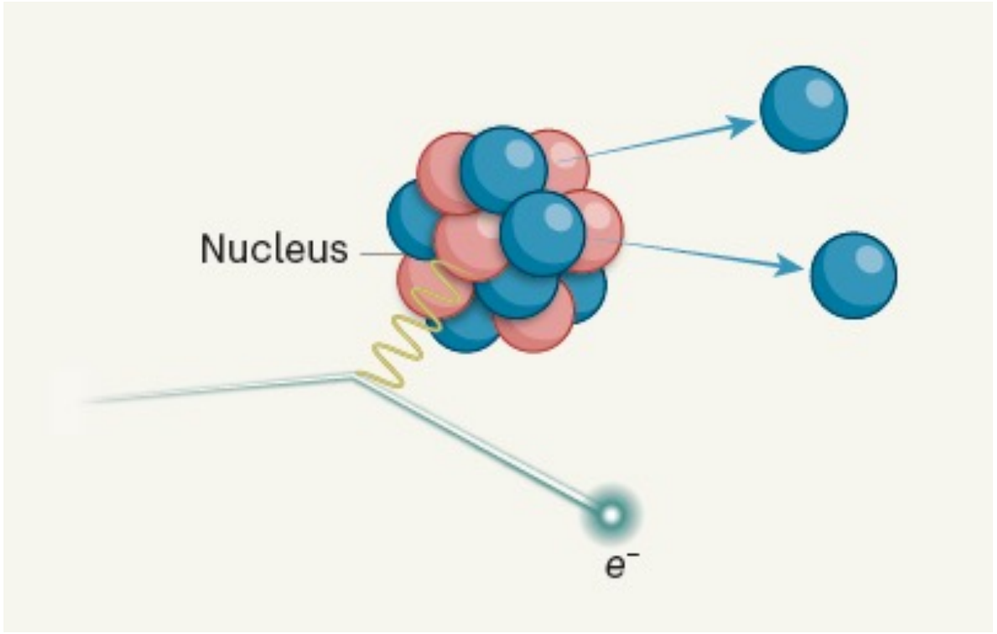
Electron Ion Collider (EIC)



- High Luminosity: L= 10^{33} – 10^{34}cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Polarized beams: e, p, d, ^{3}He
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium

- **How does the mass of the nucleon arise?**
  The Higgs mechanism accounts for only ~1% of the mass of the proton.
- **How does the spin of the nucleon arise?**
  The spin of the quarks accounts for only one-third of the spin of the proton.
- **What are the emergent properties of dense system of gluons?**
  The gluon saturation describes a new state of matter at extreme high density.

Zero degree physics at the EIC



- Fragments move at high energies (> 100 GeV/nucleon). Time dilation allows detection for lifetimes > 1 ns.
- De-excitation photons are boosted to energies much larger than background photons

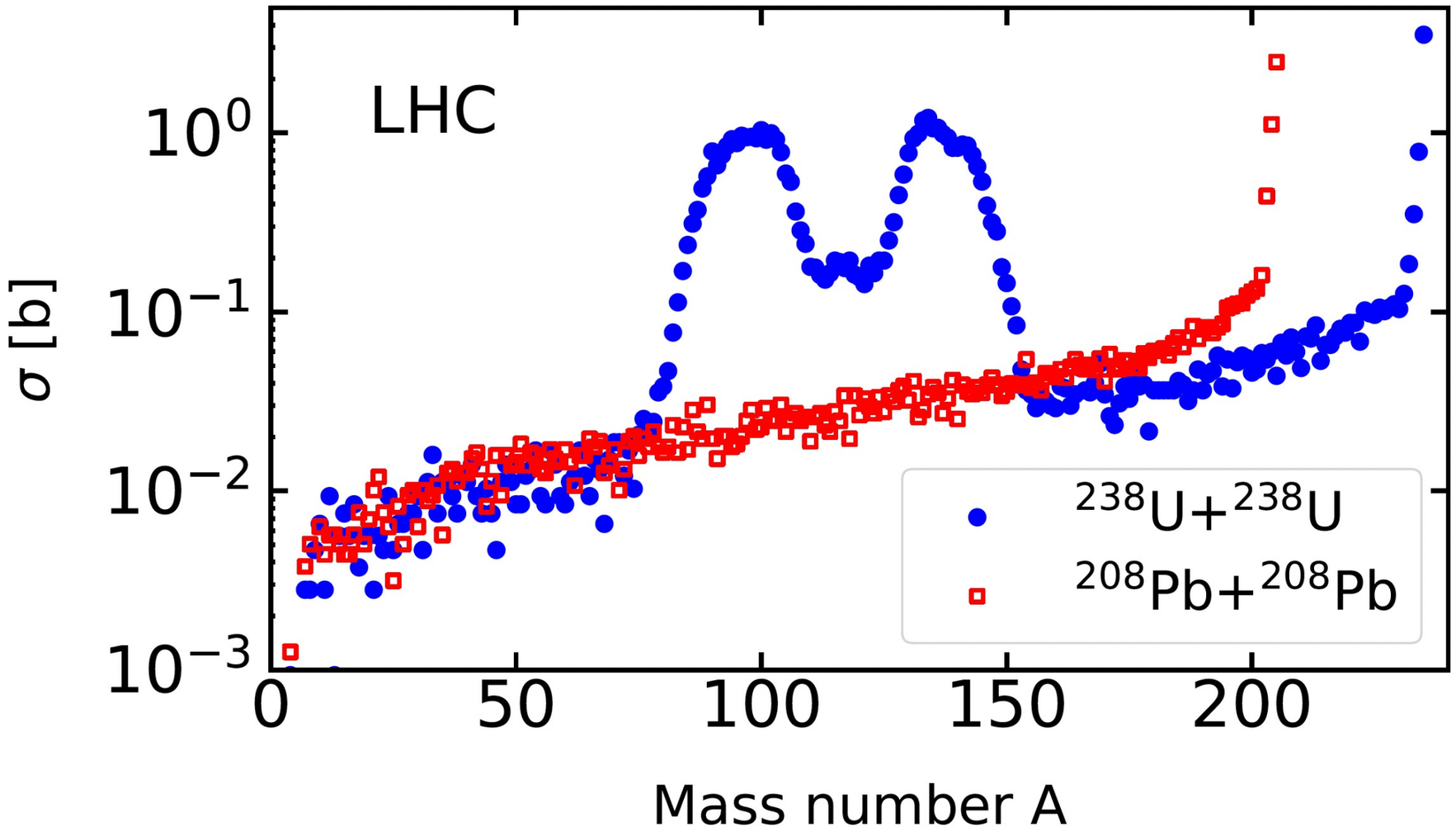
➡ Possible study of low energy physics of the isotopes.

No zero degree detector has been commissioned for the EIC, yet.

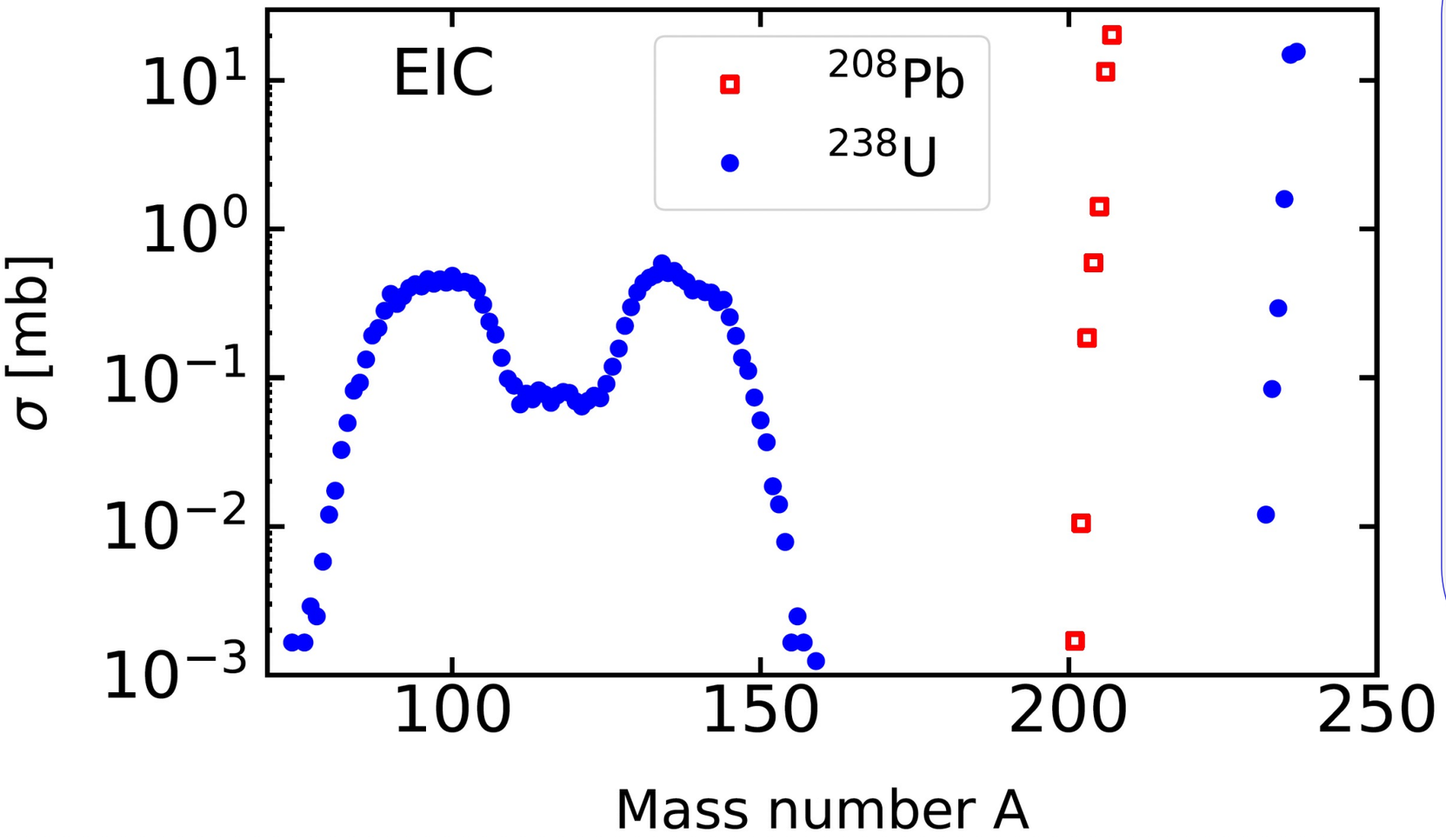
Nuclear fragmentation at the LHC

Excitation of GRs
+
evaporation

NPA 1059, 123093 (2025)



Nuclear fragmentation at the EIC



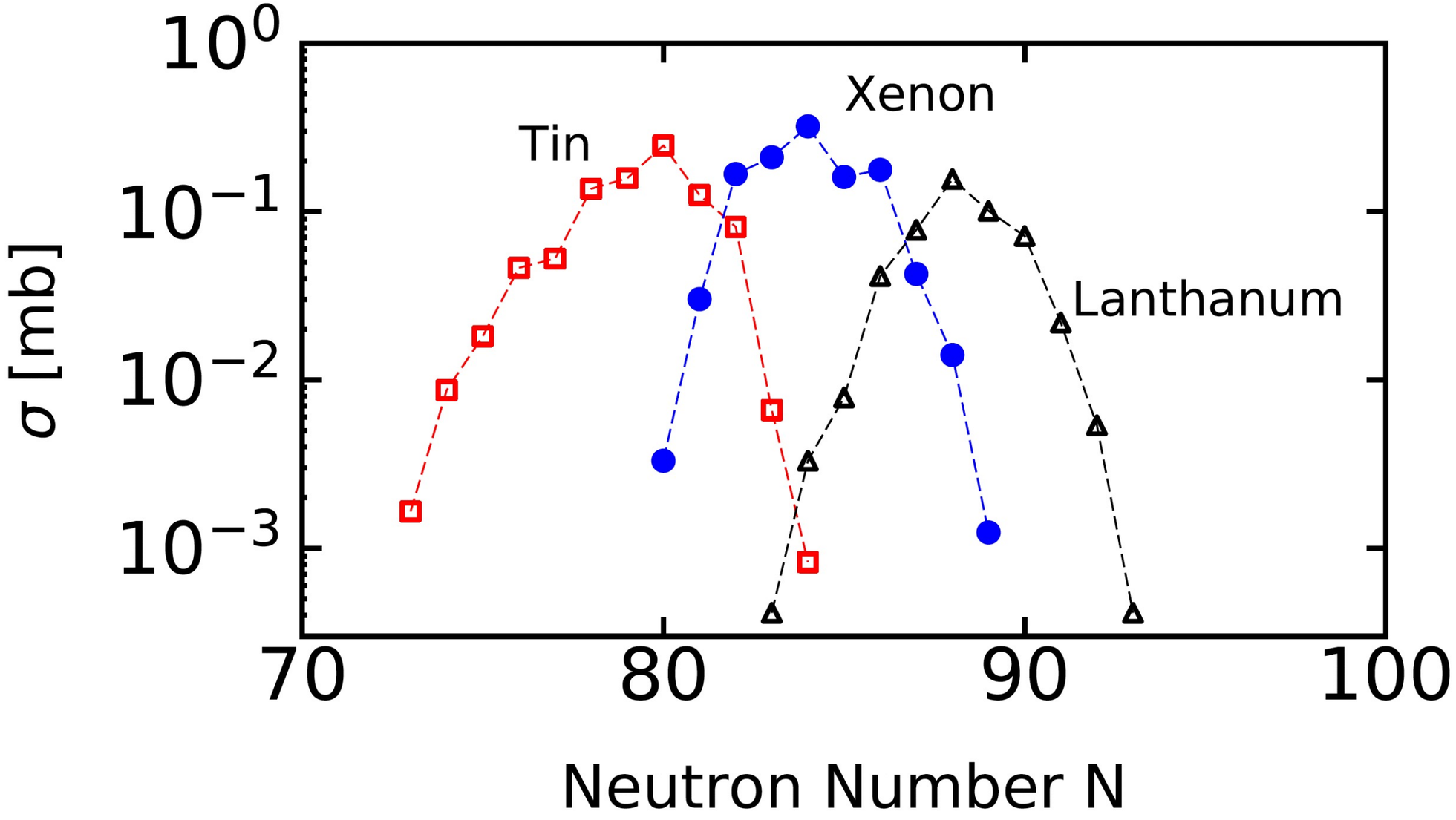
$$\frac{d\sigma}{d\omega dQ^2} = \sum_{\lambda} \frac{dN_{\lambda}}{d\omega dQ^2} \sigma_{\gamma}^{\lambda}(\omega)$$

$$\sigma_x^{GR}(\omega) = b_x(\omega) \sum_{GR} \sigma_{\gamma}^{GR}(\omega)$$

$$b_x(\omega) = \frac{\Gamma_x(\omega)}{\Gamma_{tot}(\omega)}$$

x = fragment

Nuclear fragmentation at the EIC



Nuclear fragmentation at the EIC

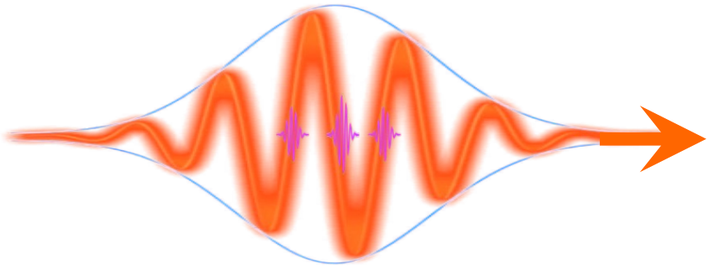
Cross sections	LHC	LHC	EIC	EIC
	Pb + Pb [b]	U + U [b]	e-Pb [mb]	e-U [mb]
σ_{-1n}	33.93	33.20	20.24	15.58
σ_{-2n}	18.89	30.59	11.45	14.88
σ_{-3n}	2.546	3.537	1.416	1.591
σ_{-4n}	1.091	0.784	0.5933	0.2934
$\sigma_{fission}$	0	18.24	0	8.867
σ_{total}	55.74	85.48	33.90	41.32
Fission b.r.	0%	19.54%	0%	21.45%

Conclusions

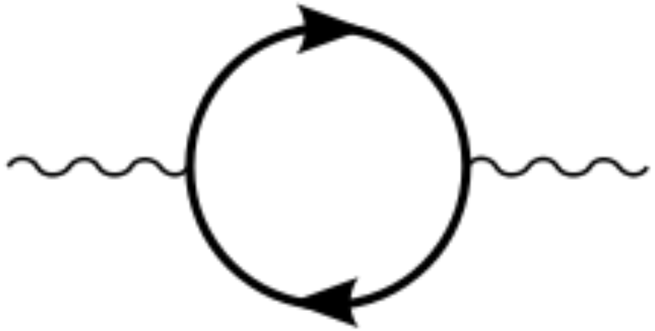
- Ultraperipheral Collisions (UPC) source of the strongest EM fields
- UPCs → antihydrogen, atomic and nuclear structure, giant resonances
- UPCs → (n,γ), (p,γ), (α,γ) for astrophysics
- UPCs → exotic meson production
- UPCs → parton distribution functions
- UPCs → Pygmy resonances, hypernuclei and neutron stars

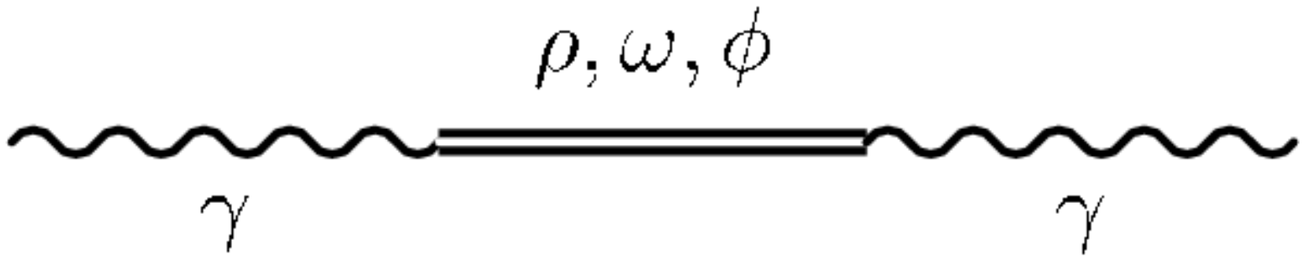
The clean photon and the dirty photon

* I won't talk about pomeron, dif. dis.



Can fluctuate into particle-antiparticle pairs, e.g., $e^+e^-,\ q\bar{q},\ etc$





$J^P = 1^-$ → fluctuates to ρ, ω, ϕ, J/Ψ
(Vector meson dominance model)

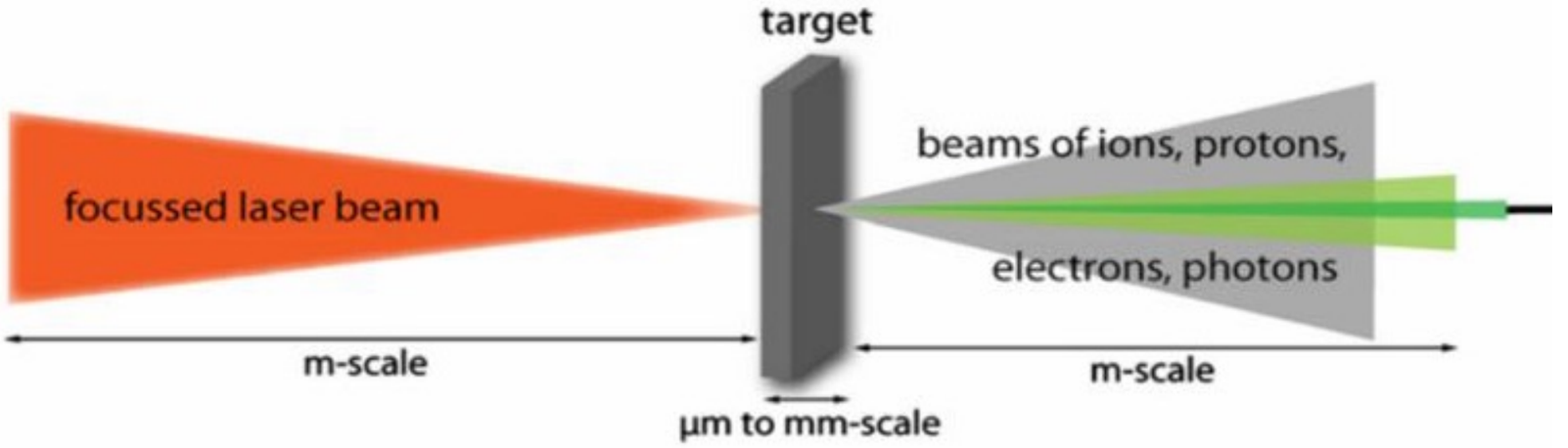
Photon wavefunction:

$$\left|\gamma\right\rangle = C_{\text{bare}}\left|\gamma_{\text{bare}}\right\rangle + C_{\rho}\left|\rho\right\rangle + C_{\omega}\left|\omega\right\rangle + C_{\phi}\left|\phi\right\rangle + \cdots + C_{q}\left|q\bar{q}\right\rangle$$

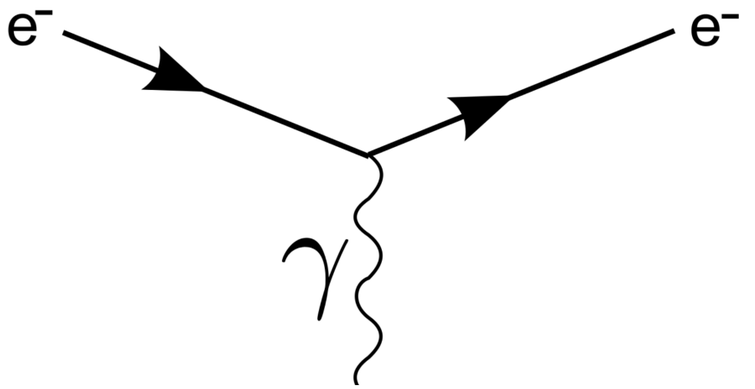
The photon as a probe

Real photons

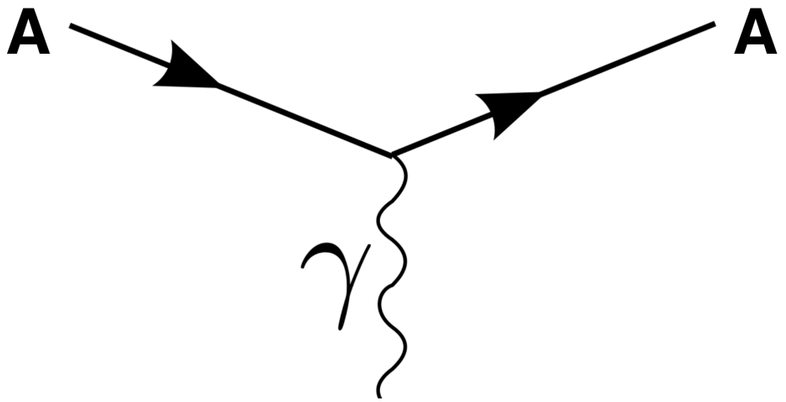
High output lasers



Virtual photons $\sigma(\Delta E, |\Delta \mathbf{p}| \neq \Delta E)$



JLAB, EIC



Quasi real photons $\sigma(\Delta E, |\Delta \mathbf{p}| \sim \Delta E)$

RHIC, CERN **(UPC)**

Electromagnetic response of the hypertriton

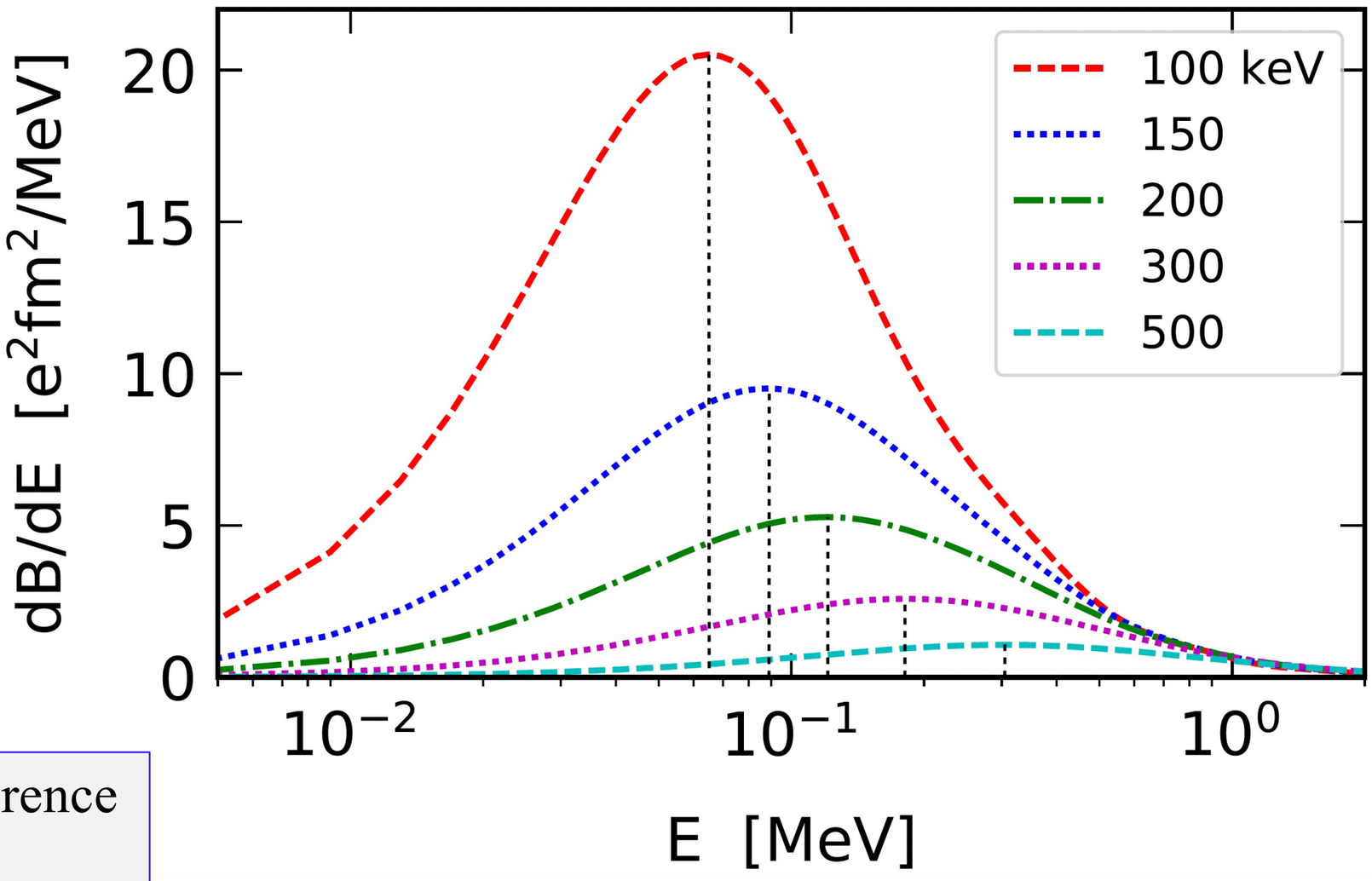
$$\frac{dB(E)}{dE} = \frac{1}{\hbar}\sqrt{\frac{\mu}{2E}}|\langle g.s.||\mathcal{O}_{E1}||E,l\rangle|^2$$

Analytical model:

CB, Sustich
Phys. Rev. C 46 (1992) 2340

$$\frac{dB(E)}{dE} = C\sqrt{B_\Lambda}\frac{E^{3/2}}{(E+B_\Lambda)^4}$$

$$E_{max} = \frac{3}{5}B_\Lambda$$



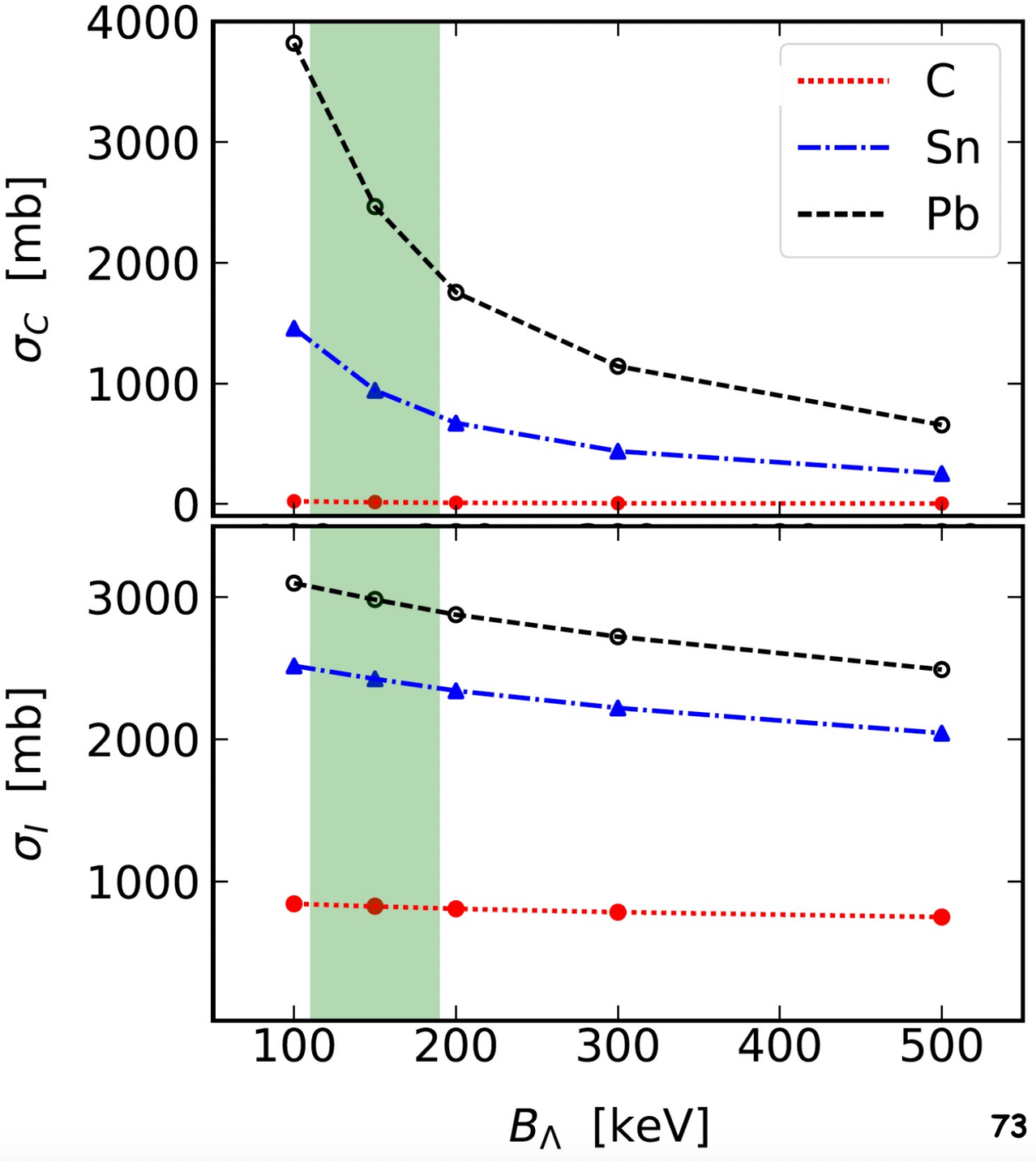
- Excellent agreement < 4% difference
- FSI small

EM response of the hypertriton

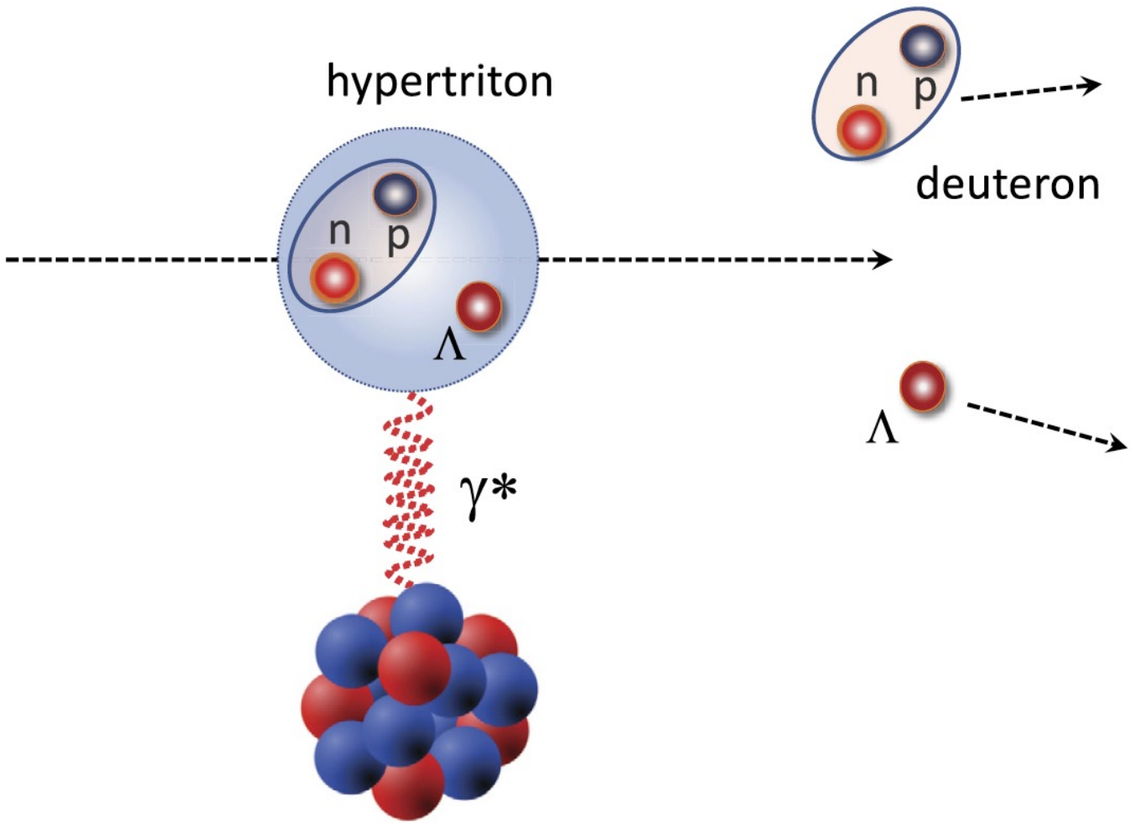
1.5 GeV/nuc. ${}^{3}_{\Lambda}$H incident on ^{12}C, ^{120}Sn, ^{208}Pb

B_Λ (keV)	σ_C (C)	σ_C (Sn)	σ_C (Pb)
100	22.9	1457.	3820.
150	14.9	942.	2464.
200	10.7	672.	1755.
300	7.1	438.	1142.
500	4.1	253.	656.

B_Λ (keV)	σ_I (C)	σ_I (Sn)	σ_I (Pb)
100	842.	2516.	3098.
150	824.	2424.	2982.
200	807.	2341.	2876.
300	783.	2220.	2721.
500	749.	2043.	2490.



Electromagnetic response of the hypertriton



$$\frac{d\sigma_C}{dE} = \frac{16\pi^3}{9\hbar c} n(E) \frac{dB(E)}{dE}$$

$$n(E) = \frac{2Z_T^2\alpha}{\pi}\left(\frac{Ec}{\gamma\hbar v^2}\right)^2 \int_0^\infty dbb\left[K_1^2 + \frac{1}{\gamma^2}K_0^2\right]T(b)$$

$$x = Eb/\gamma v$$

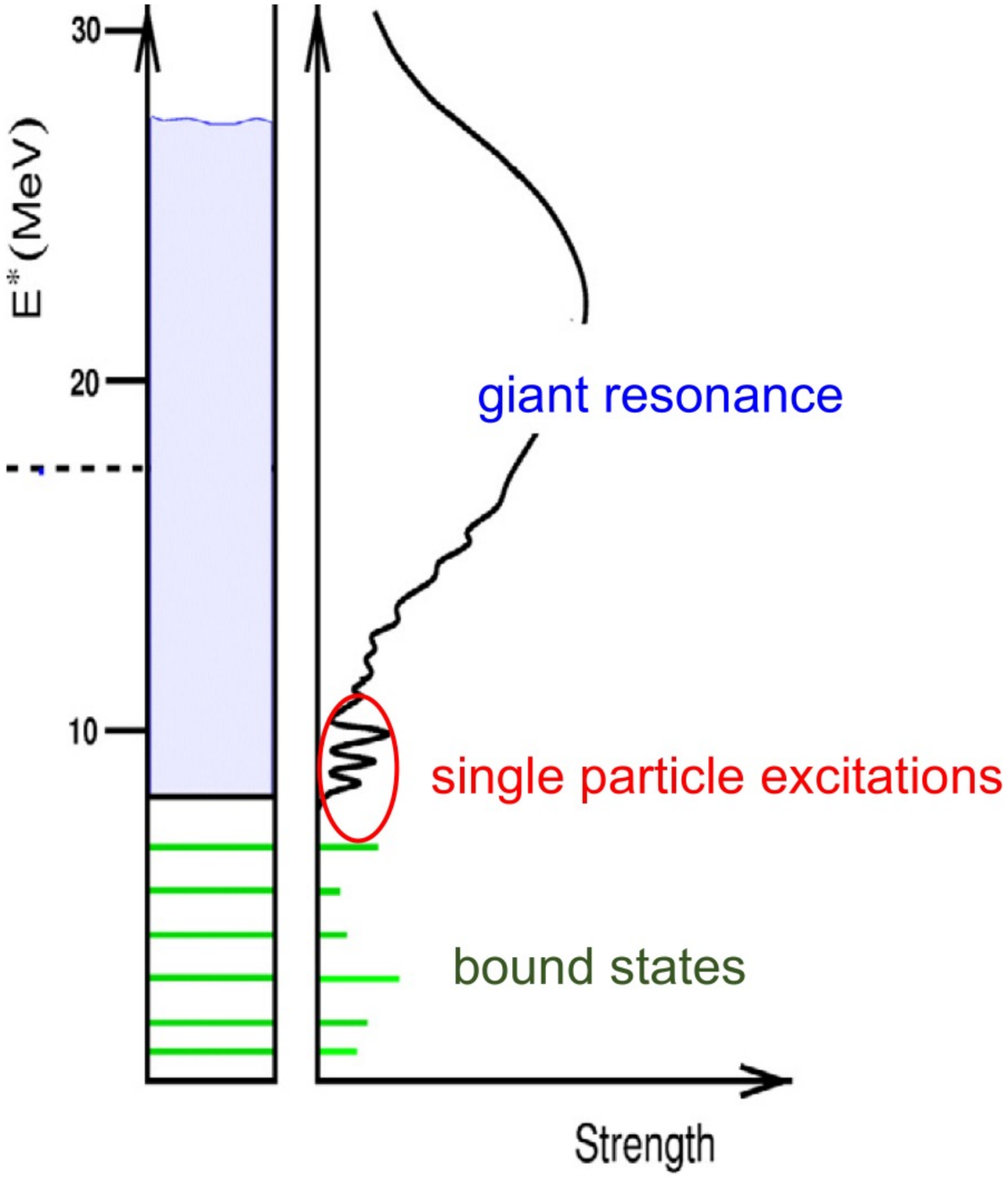
First-order perturbation theory

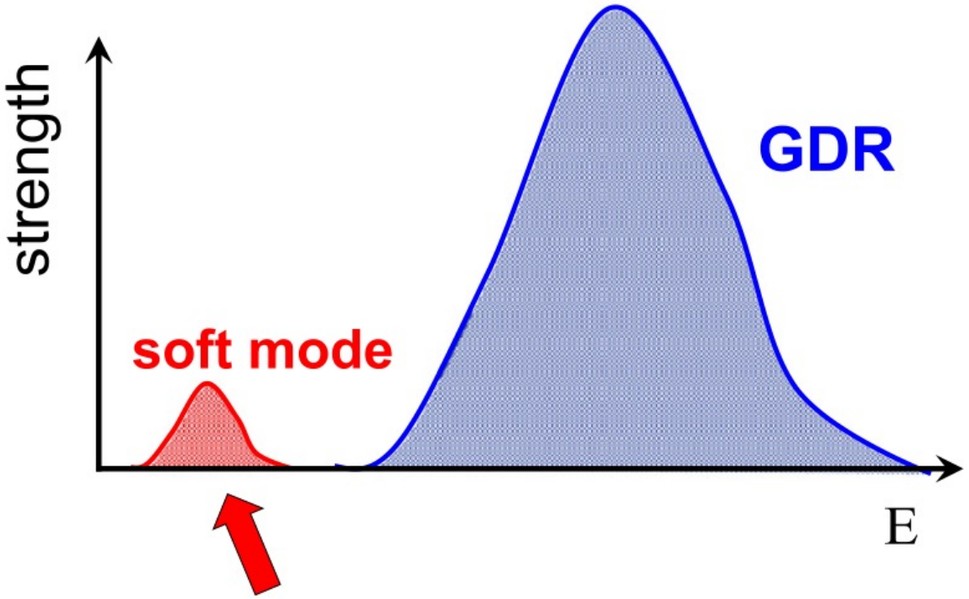
$$\frac{dB(E)}{dE} = \frac{1}{\hbar}\sqrt{\frac{\mu}{2E}}|\langle g.s.||\mathcal{O}_{E1}||E,l\rangle|^2$$

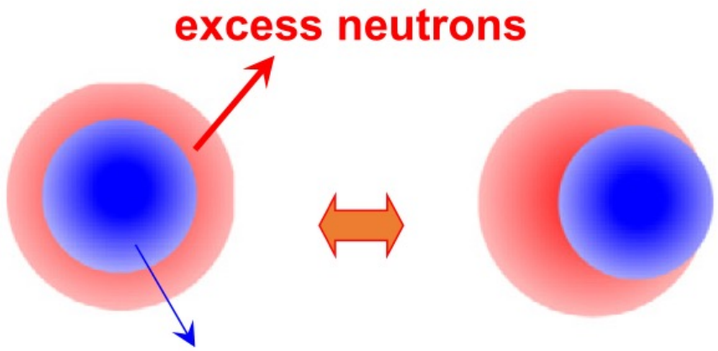
$$\langle g.s.||\mathcal{O}_{E1}||E,l\rangle = (-1)^l \frac{e_{eff}}{\sqrt{4\pi}}\int_0^\infty dr\, r u_{g.s.}(r) u_{E,l}(r)$$

$$u_{E,l}(r) \to \sqrt{2\mu_{\Lambda d}/\pi\hbar^2 k}\, e^{i\delta_l} sin(kr + \delta_l)$$

Pigmy resonances

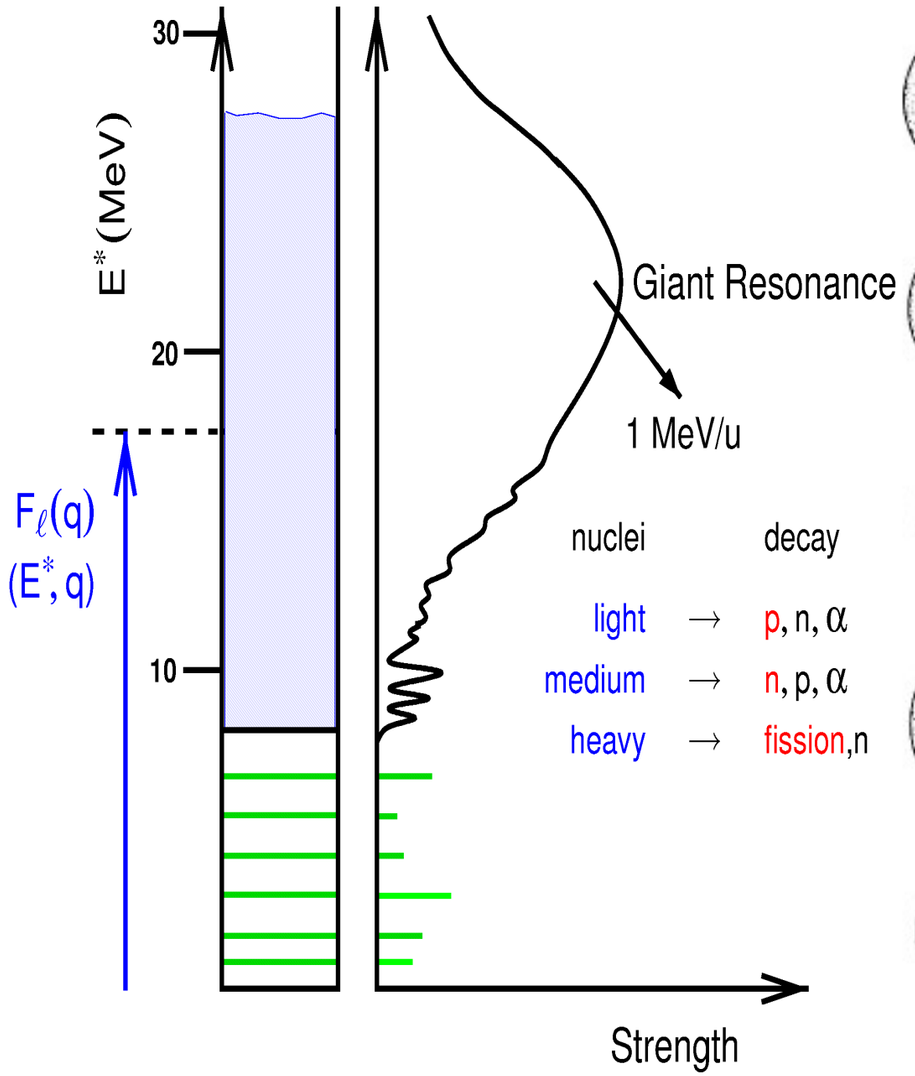


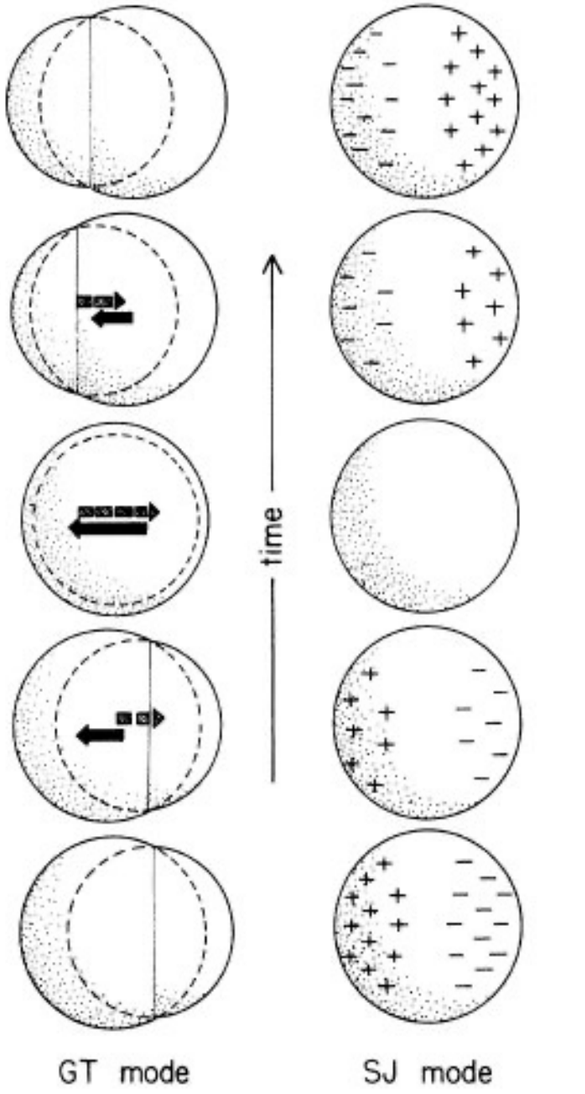




"core" with p and n

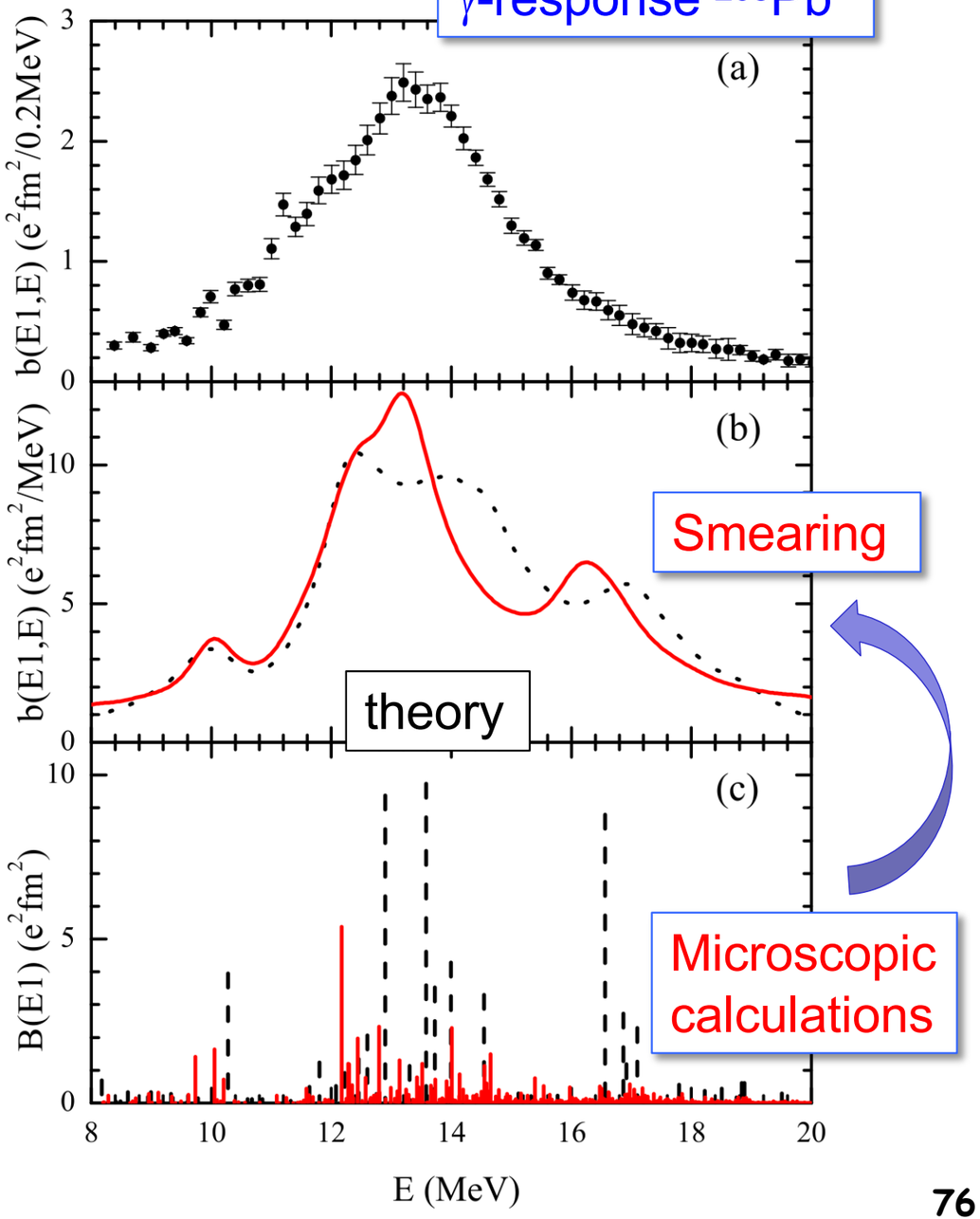
Giant resonances in nuclei (1960s-1970s)





hydrodynamical models

Experiment:
γ-response ^{208}Pb

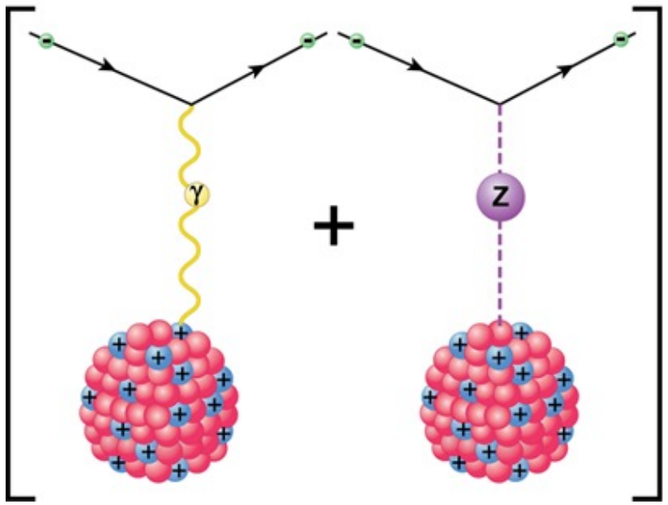


Smearing

Microscopic calculations

Bohr, Mottleson, Rainwater
Nobel prize 1975

n-skin from PV e- scattering

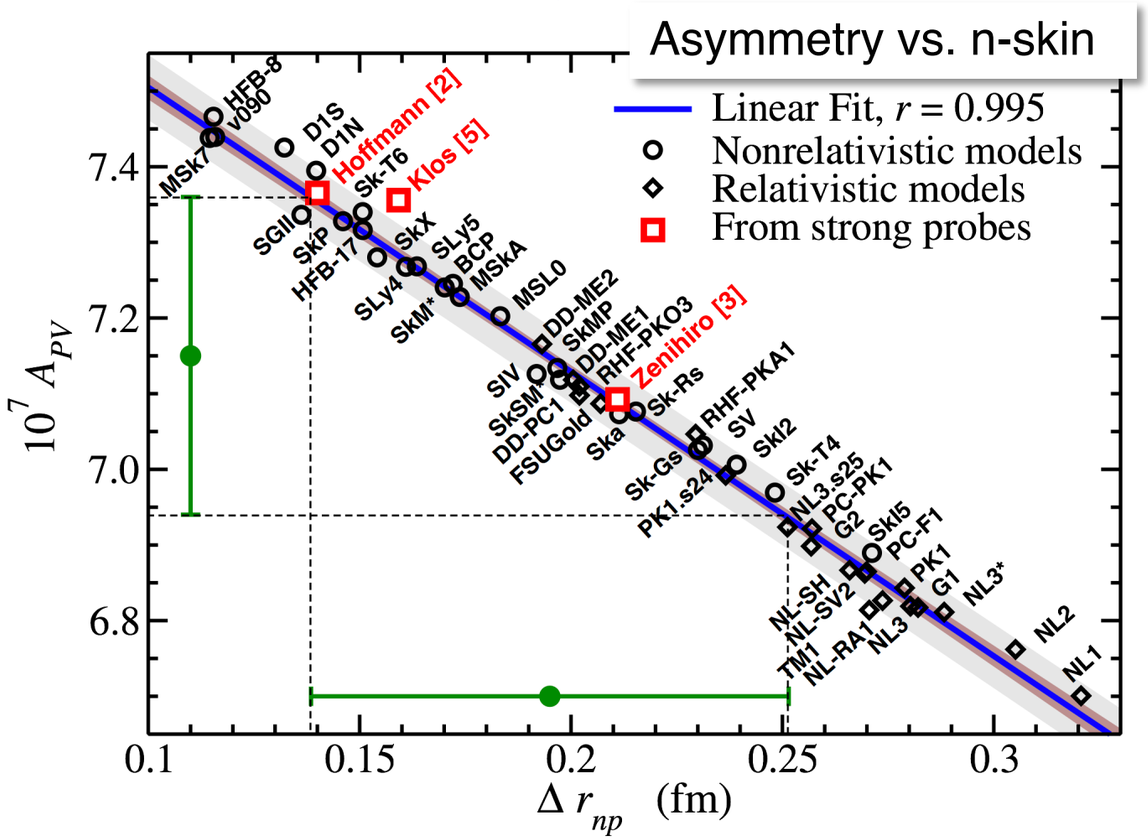


Abrahamyan et al,
PRL 108, 112502 (2012)

Howowitz et al,
PRC 85, 032501(R) (2012)

$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = F_w(Q)\,/F_{ch}(Q)$$

Roca-Maza, PRL (2011)



$$F_w = \frac{1}{Q_w}\int dr\,\frac{sin(Qr)}{Qr}\rho_w(r)$$

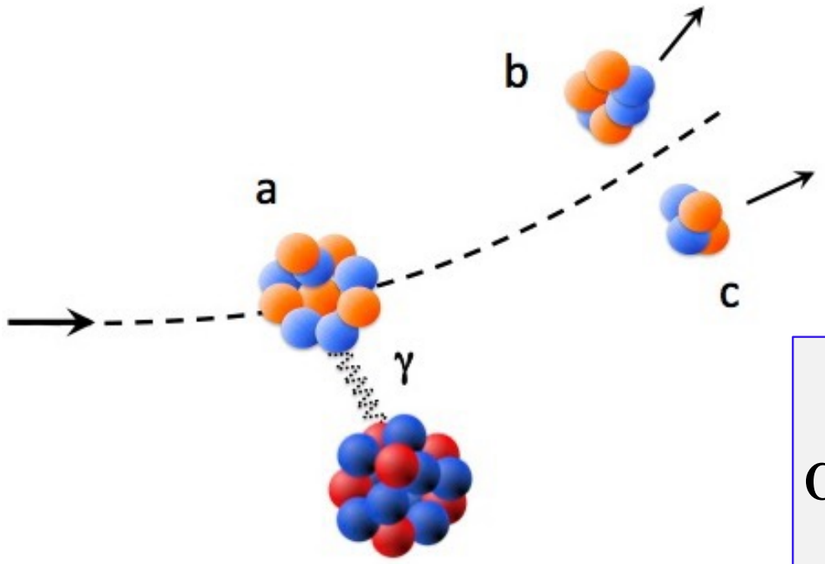
$$\rho_w(r) = q_p\,\rho_{ch}(r) + q_n\int d^3r'\left[G_E^p\rho_n + G_E^n\rho_p\right]$$

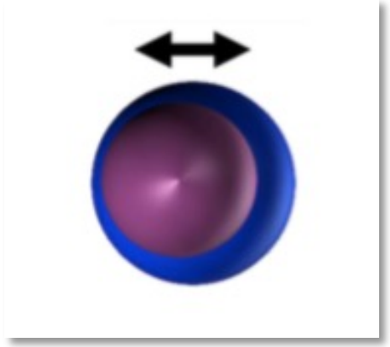
E1 polarizability

PRL 111 (2013) 242503

PRL 102, 092502 (2009)

$$\sigma_C \sim (\cdots)\int_0^\infty \frac{\sigma_\gamma(E)}{E^2}dE$$





$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma_\gamma(E)}{E^2}dE$$

$$= \frac{8\pi}{9}\int \frac{B(E1,E_x)}{E_x}dE_x$$

