Photon-induced interactions in relativistic heavy ion collisions

C.A. Bertulani

TEXAS A&M UNIVERSITY
COMMERCE

Gerhard Baur

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(20 January 1944 – 16 June 2023)

The physicist specialized in nuclear reaction theory and nuclear astrophysics.

Carlos Bertulani

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Gerhard Baur passed away on 16 June 2023 in Stuttgart, Germany, after a long and debilitating disease. He was a distinguished theorist working in nuclear reaction theory at the University of Basel in Switzerland.

Gerhard was born on 20 January 1944 in Stuttgart. In 1970 he earned his PhD from the University of Basel, with work on “Particle vibration coupling and the giant dipole resonance,” mentored by Kurt Alder. From 1971–74 he worked as a postdoc at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, and in 1974 he was hired as a guest scientist at the Weizmann Institute of Science in Rehovot, Israel. From 1975 to 2009 he had a very productive career as a senior scientist at the Jülich Research Center in Germany.

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ELECTROMAGNETIC PROCESSES IN RELATIVISTIC HEAVY ION COLLISIONS

Carlos A. BERTULANI and Gerhard BAUR

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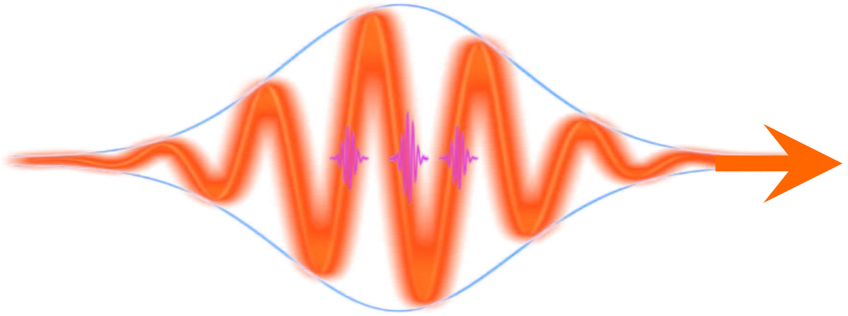
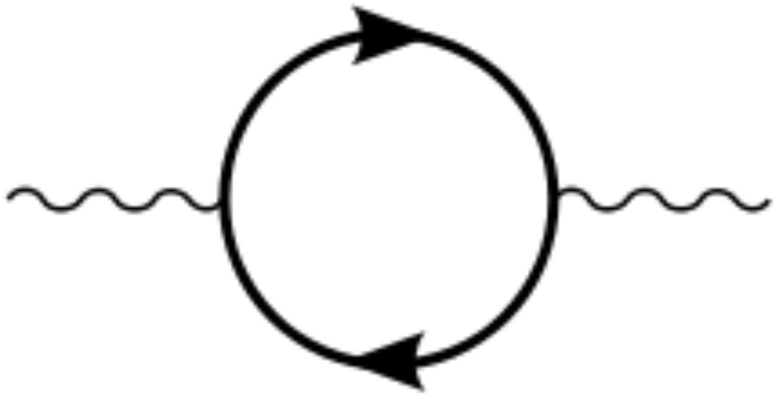
LAST ISSUE OF THIS VOLUME

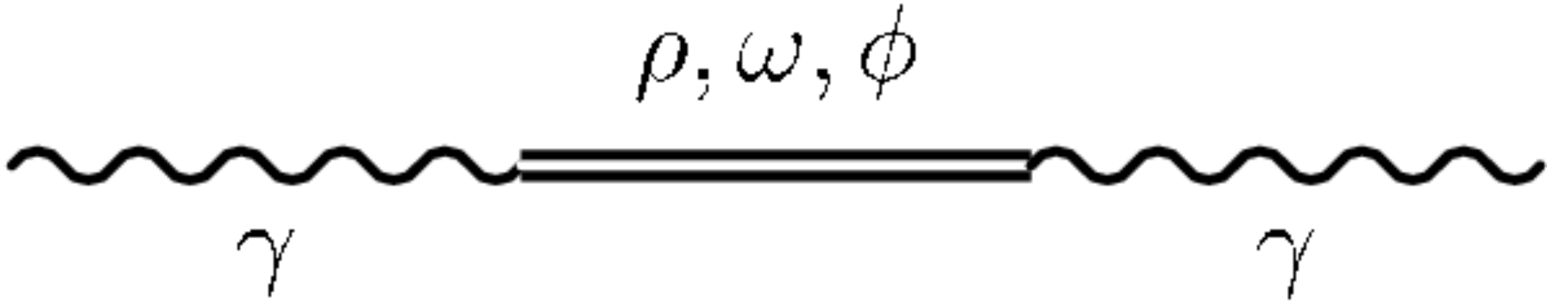
The clean photon and the dirty photon

*** 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)

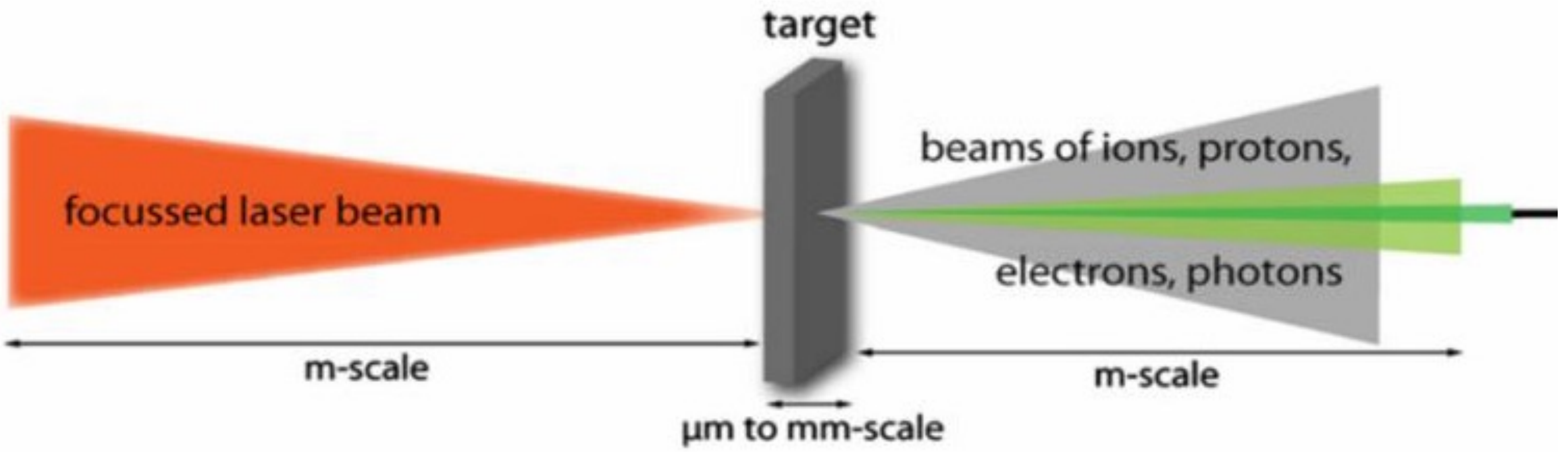
Photon wavefunction:

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

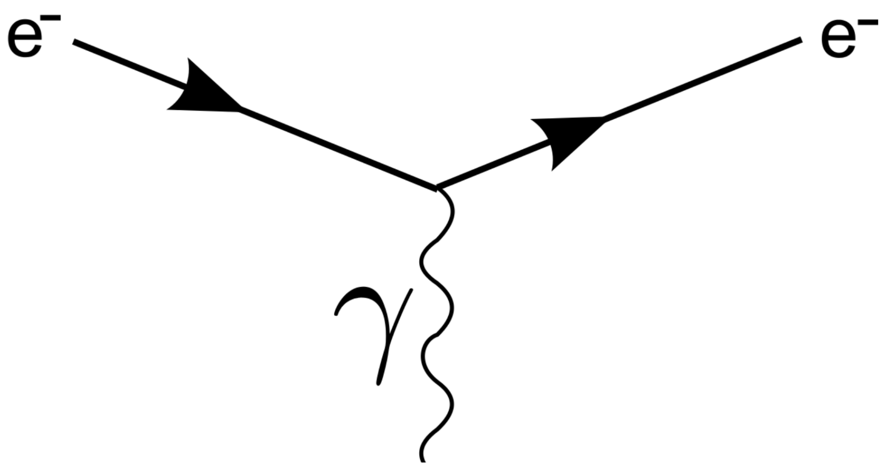
The photon as a probe

Real photons

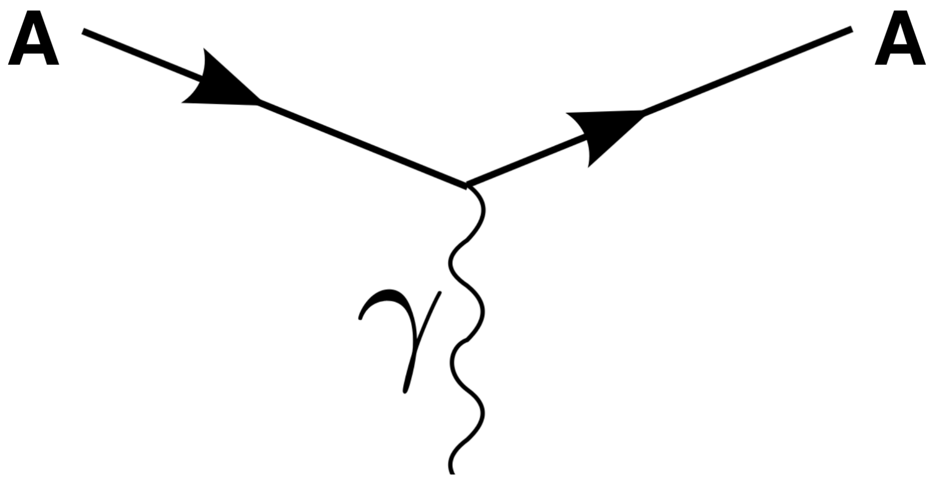
High output lasers



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)**

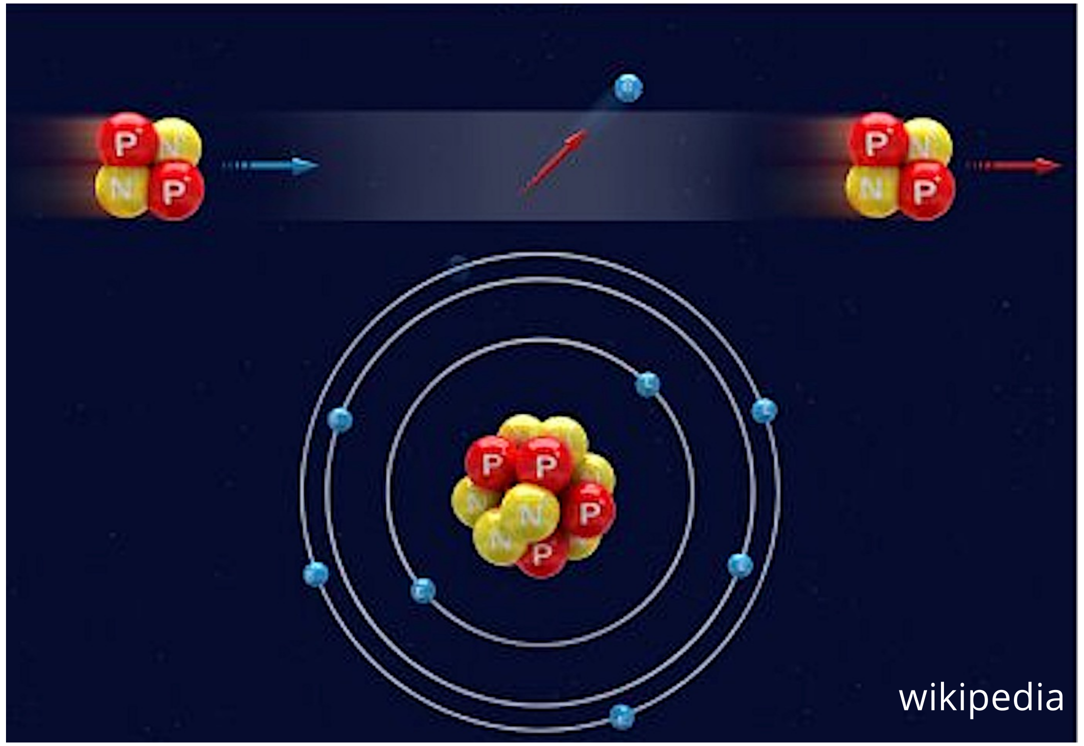
Atomic ionization by α-particles (1924)

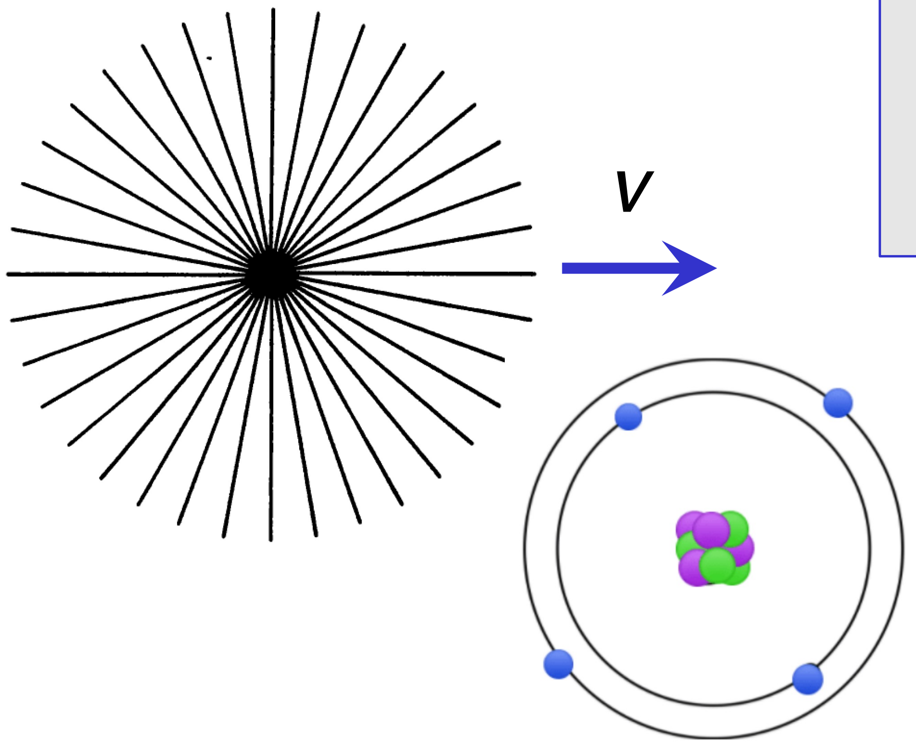
Fermi's method:

(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





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

α-particle in a straight-line motion →

$$N(\omega,b) = \left(\frac{Zec}{\pi v}x\right)^2 [K_1^2(x) + K_0^2(x)], \qquad x = \frac{\omega b}{v}$$

E. Fermi, Z. Phys. 29, 315 (1924)

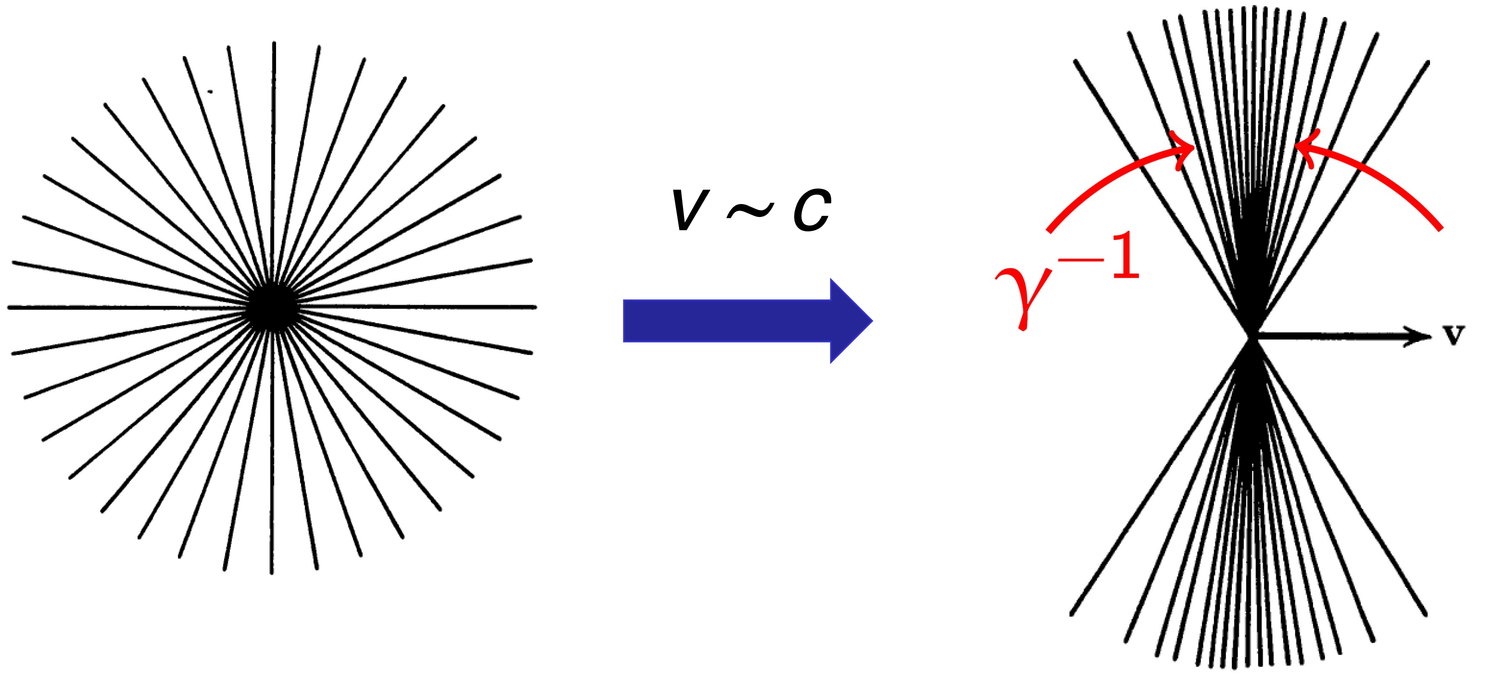
E. Fermi Nuovo Cimento 2, 143 (1925)

Lorentz contraction

Weizsäcker & Williams:

(a) Use Fermi's method

(b) Include Lorentz contraction



$$N(\omega, b) = \left(\frac{Zec}{\pi v} x\right)^2 \left[K_1^2(x) + K_0^2(x)\right]$$

Fermi → Weizsäcker & Williams

$$N(\omega, b) = \left(\frac{Zec}{\pi v} x\right)^2 \left[K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x)\right], \qquad x = \frac{\omega b}{\gamma v}$$

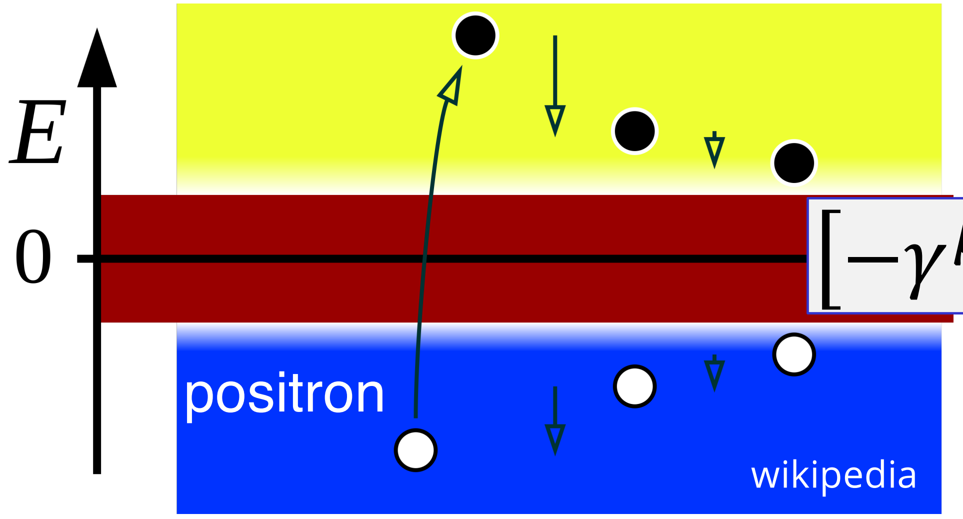
C.F. Weizsäcker, Z. Phys. 88, 612 (1934)

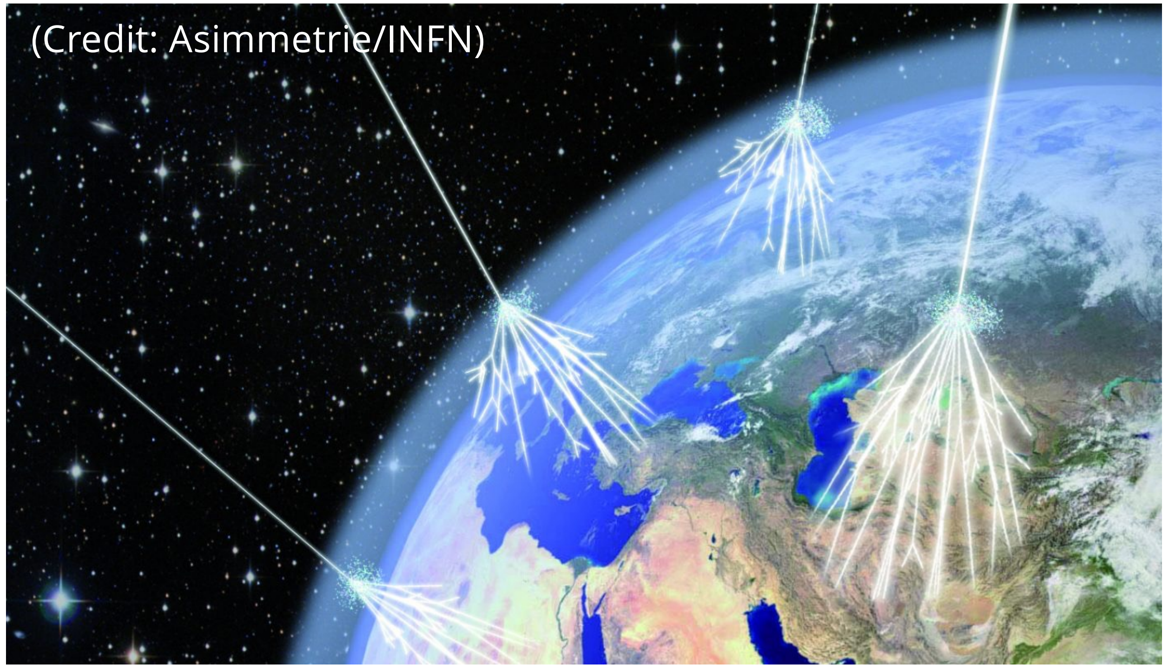
E.J. Williams, Phys. Rev. 45, 729 (1934)

Next 50 years → applications in atomic, nuclear, but mainly in particle physics

Known as the *equivalent photon method* and *N* the *equivalent photon numbers*

Do antiparticles exist? (1930s)





Dirac (1930)

$$\left[-\gamma^{\mu}\left(i\partial_{\mu} - eA_{\mu}\right) + m\right]\psi = 0$$

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

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

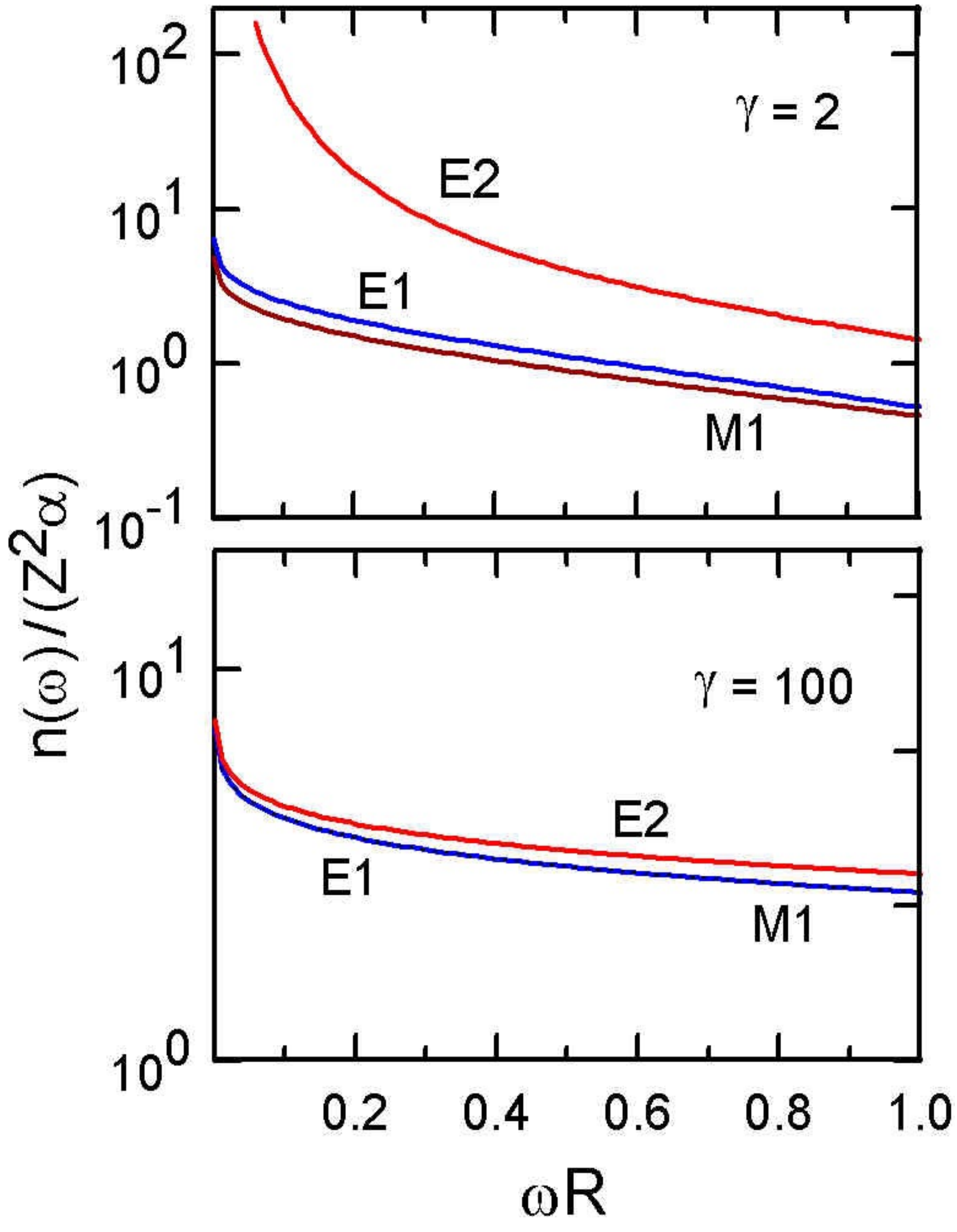
Perturbation theory

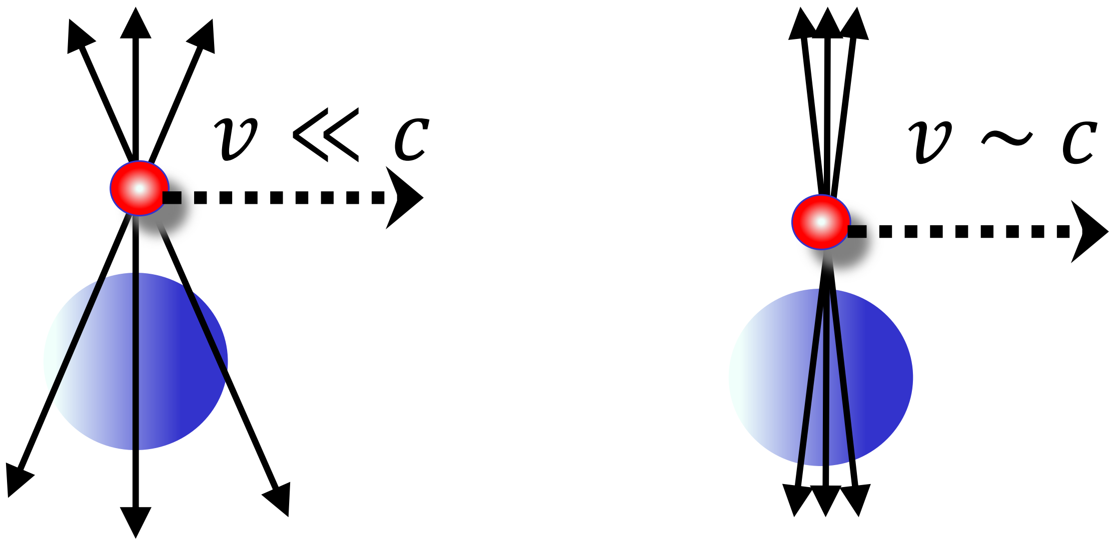
$$\left[-i\gamma^{\mu}\partial_{\mu} + m\right]\psi_n = -e\,\gamma^{\mu}A_{\mu}\,\psi_{n-1}$$

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)

$$\sigma_{e^+e^-} = \frac{28}{27\pi}\left(\frac{Z_1 Z_2 e^4}{m_e}\right)^2 \left[ln^3\left(\frac{0.681\gamma}{2}\right) + \mathcal{O}(ln^2)\right]$$

50 years forward (1985): GSI, RHIC, CERN → UPC





low-energy (tidal)

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

high-energy (contraction)

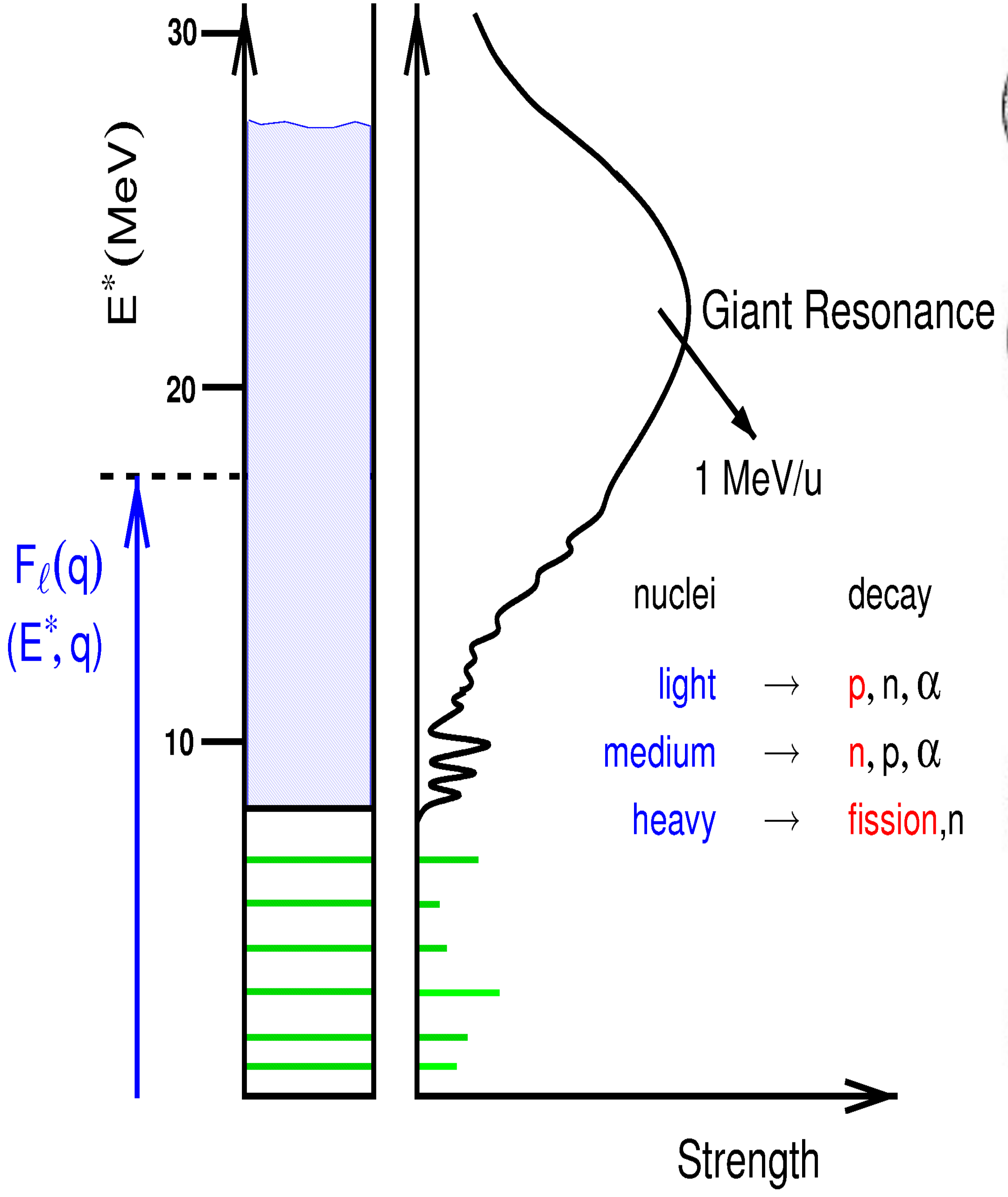
$$n_{E2} \sim n_{E1} \sim n_{M1}$$

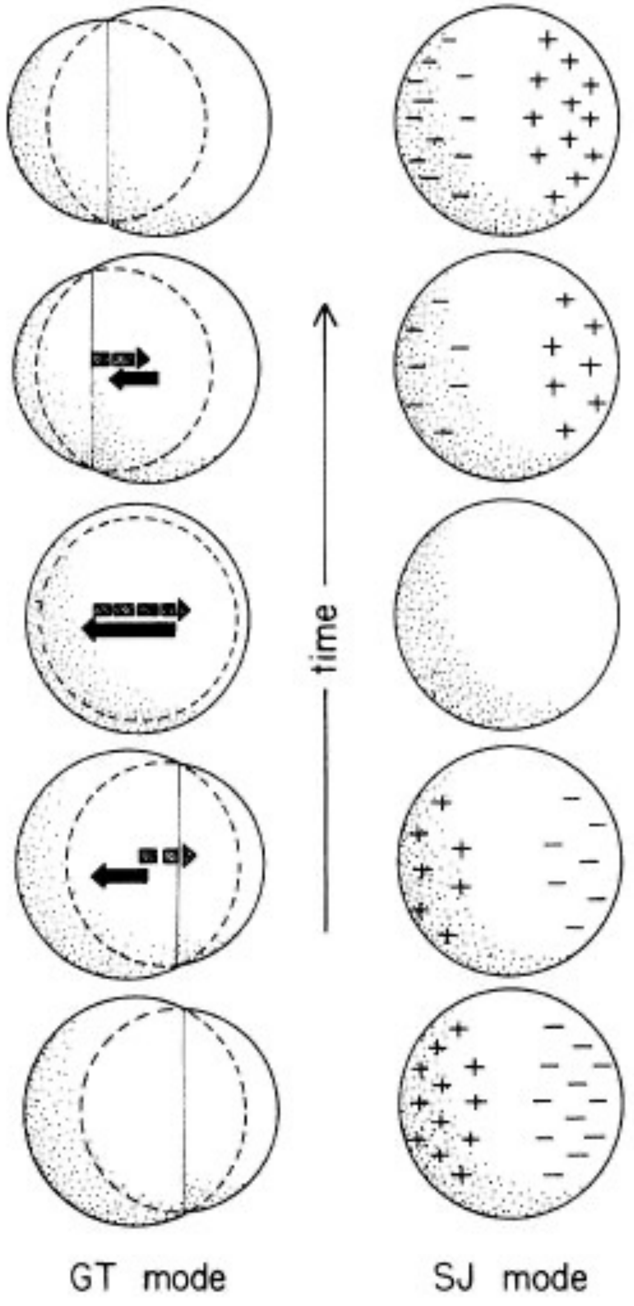
CB, Baur,
NPA 442, 739 (1985)
Phys. Rep. B 163, 299 (1988)

$$n(\omega, b) = \frac{2Z^2\alpha\omega^2}{\pi\gamma^2}\left[K_1^2\left(\frac{\omega b}{\gamma}\right) + \frac{1}{\gamma^2}K_0^2\left(\frac{\omega b}{\gamma}\right)\right]S_{absorption}(b)$$

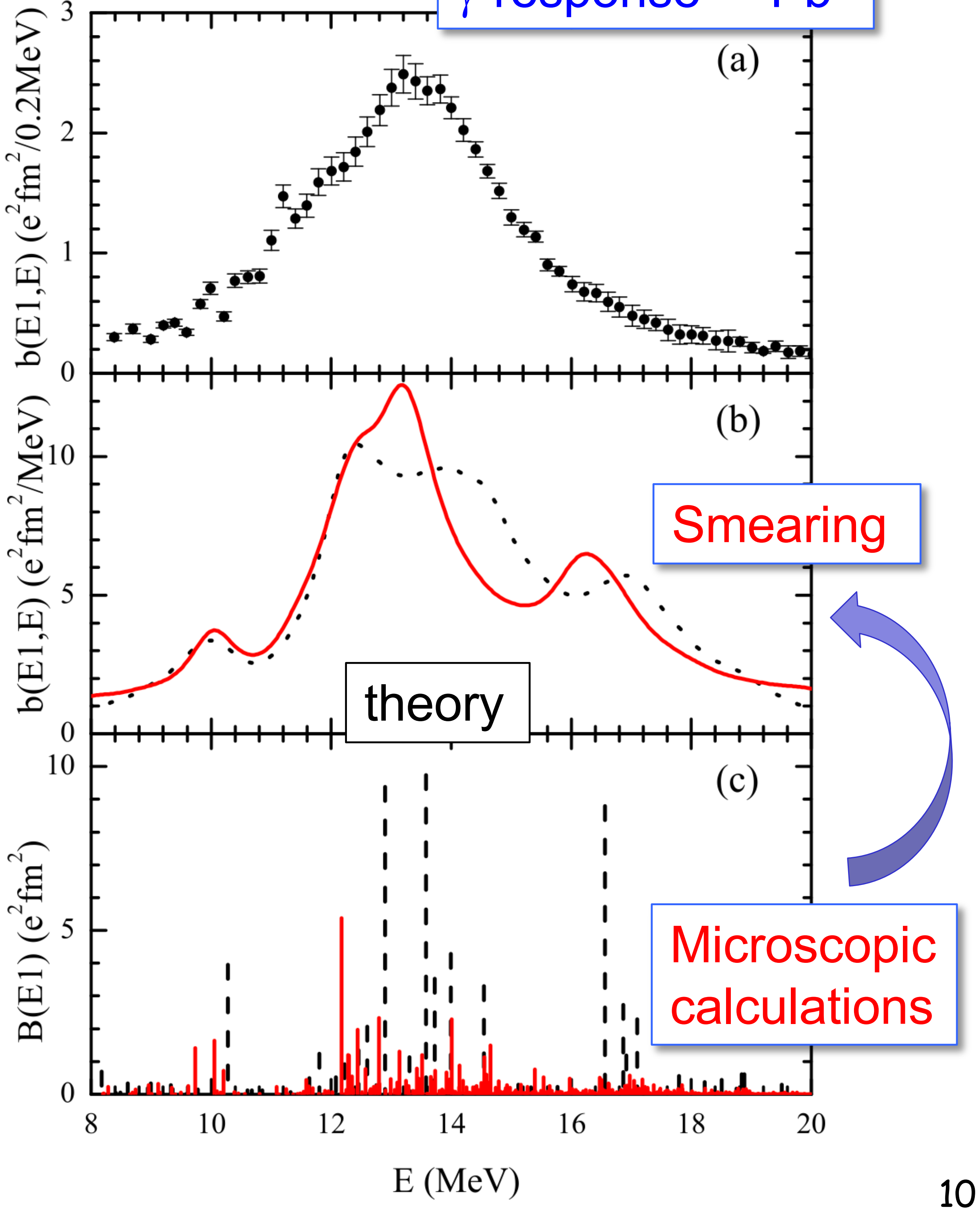
Giant resonances in nuclei (1960s-1970s)

Experiment:
γ-response ^{208}Pb





hydrodynamical models

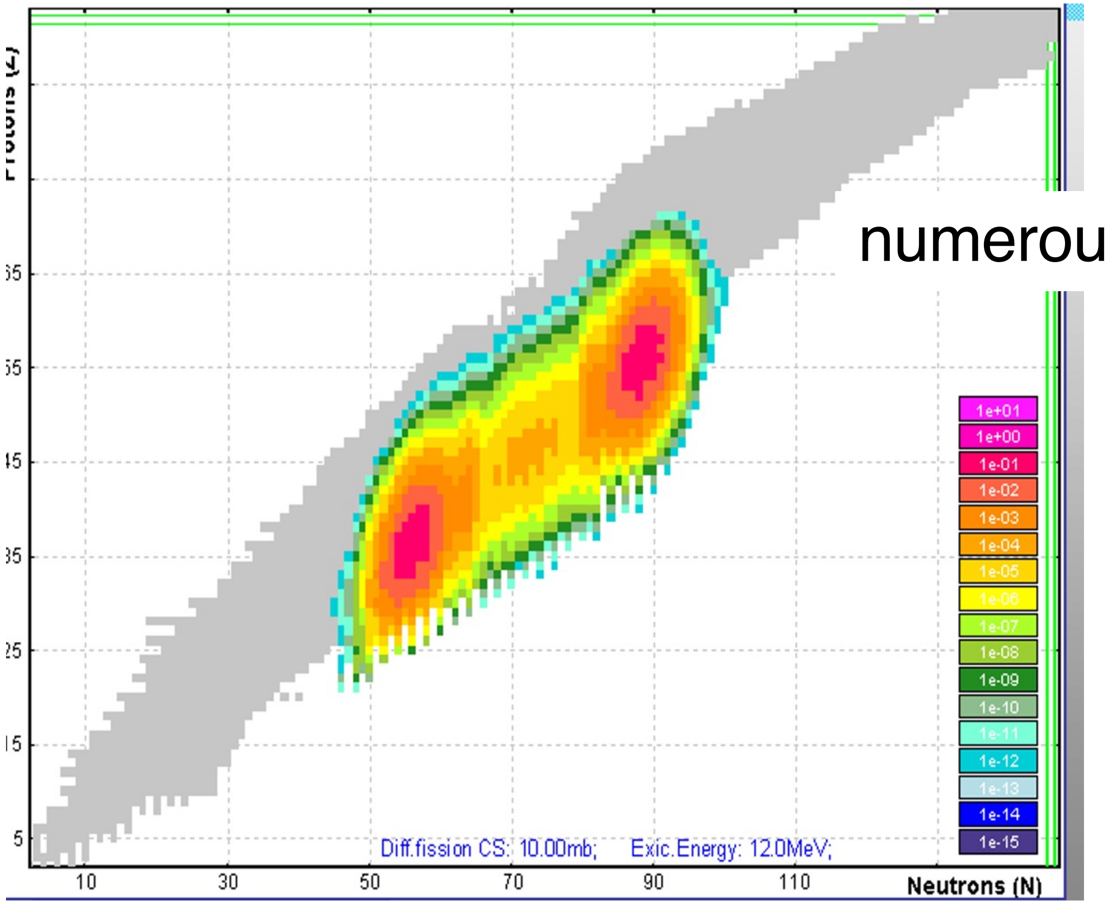


Smearing

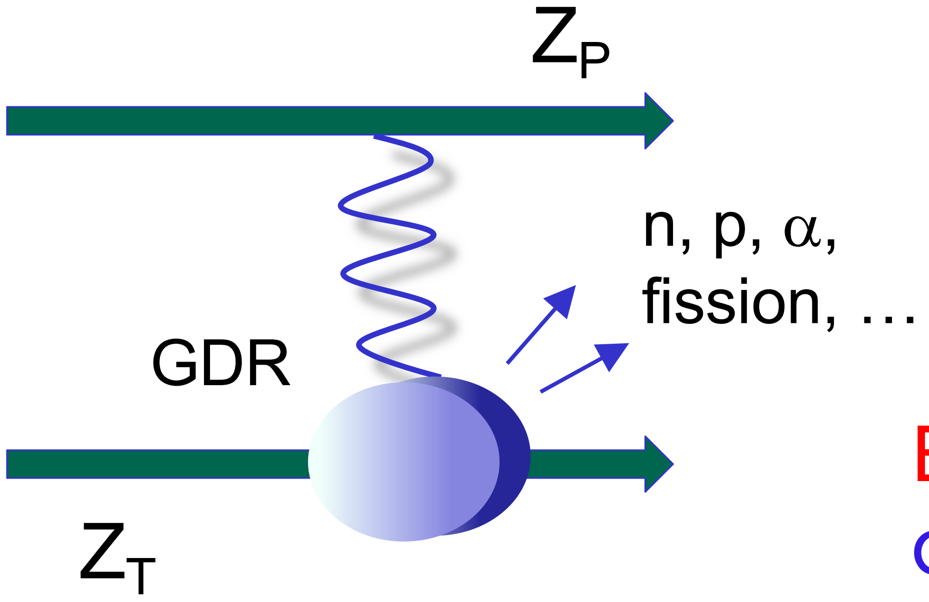
Microscopic calculations

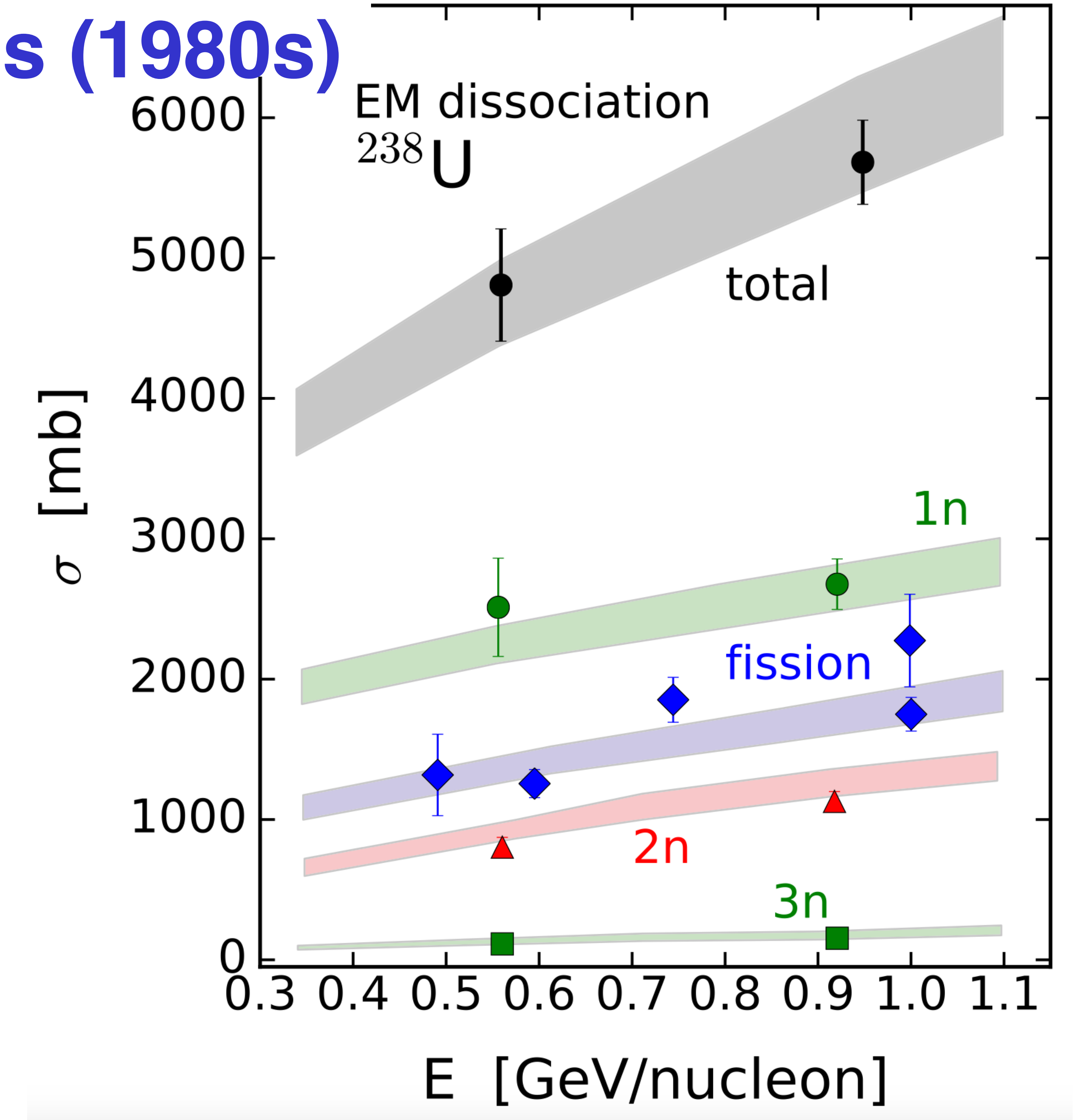
A. Bohr, B. Mottleson, J. Rainwater
Nobel prize 1975

UPC excitation of giant resonances (1980s)



numerous new isotopes

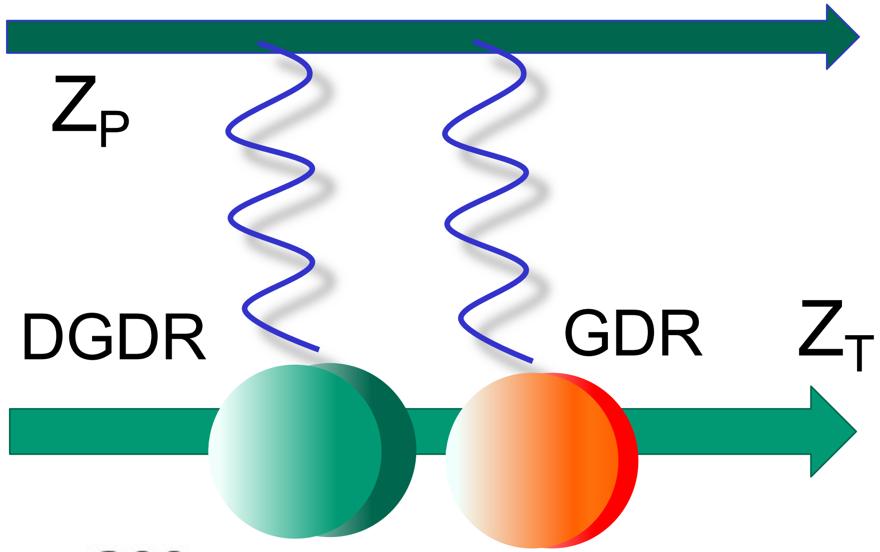


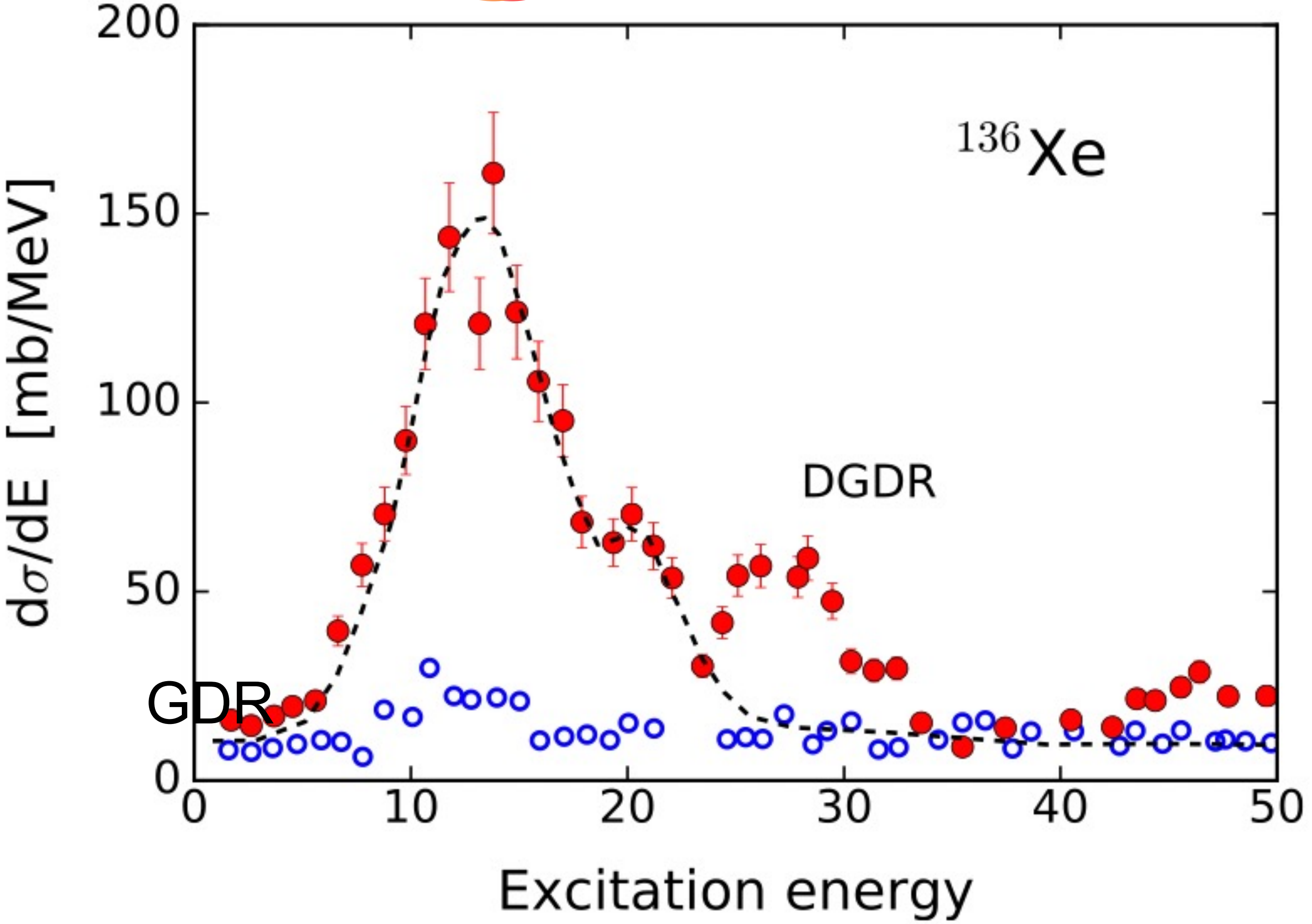


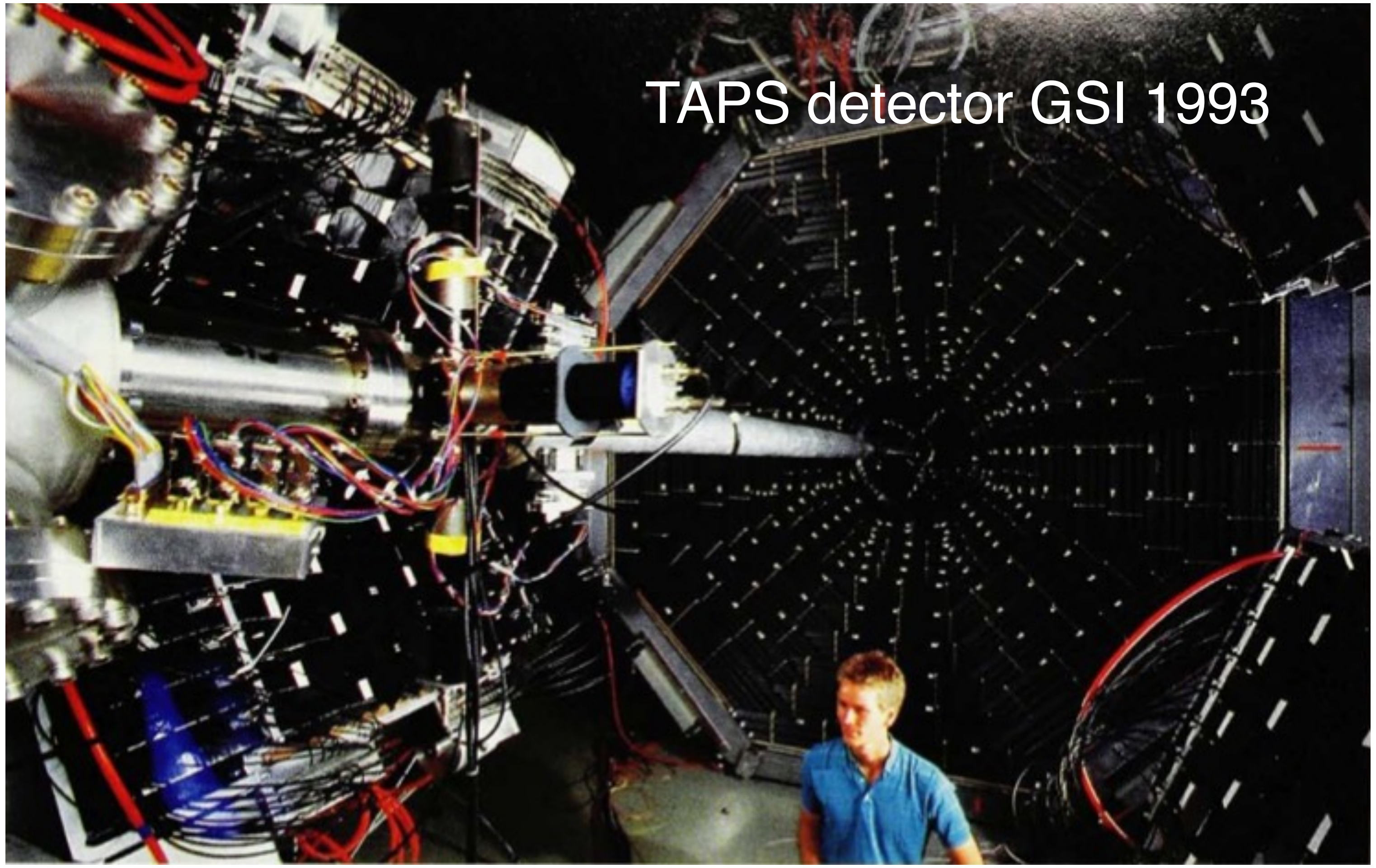
Excitation of multiple giant resonances (prediction)

G. Baur and CB, Nucl. Phys. A482, 313 (1988)

Double giant dipole resonance (1990s)







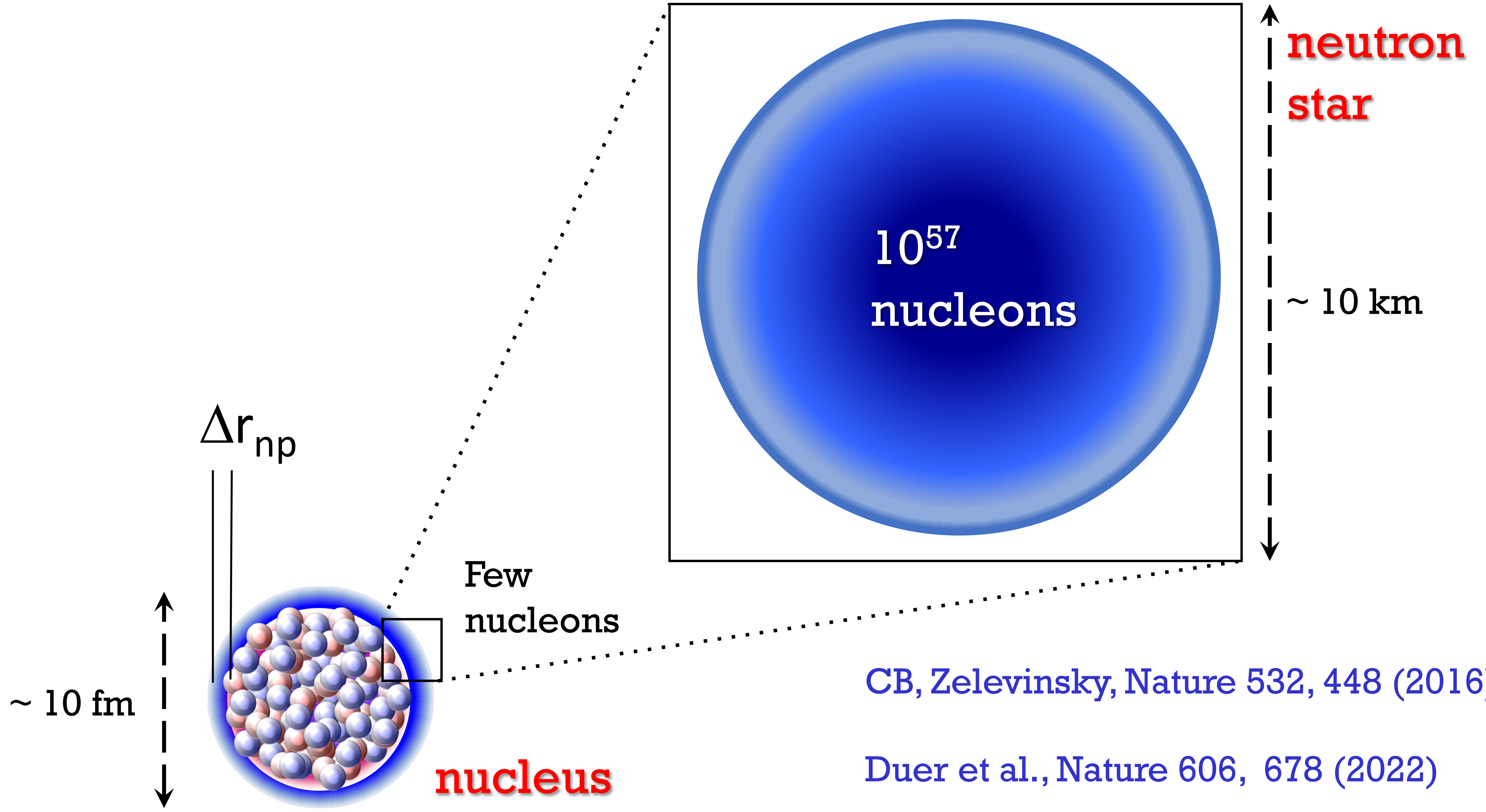
Experimentally found

R. Schmidt *et al.*, PRL 70, 1767 (1993)
J. Ritman *et al.*, PRL 70, 533 (1993)

Tests of nuclear microscopic theory

CB, V. Ponomarev, Phys. Reports 321, 139 (1999)

EM nuclear response and neutron stars



CB, Zelevinsky, Nature 532, 448 (2016)

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

Neutron stars

$$\frac{dP}{dr} = -\frac{G\rho(r)M(r)}{r^2}\left[1+\frac{P(r)}{\rho(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

$$\frac{dM}{dr} = 4\pi r^2 \rho(r)$$

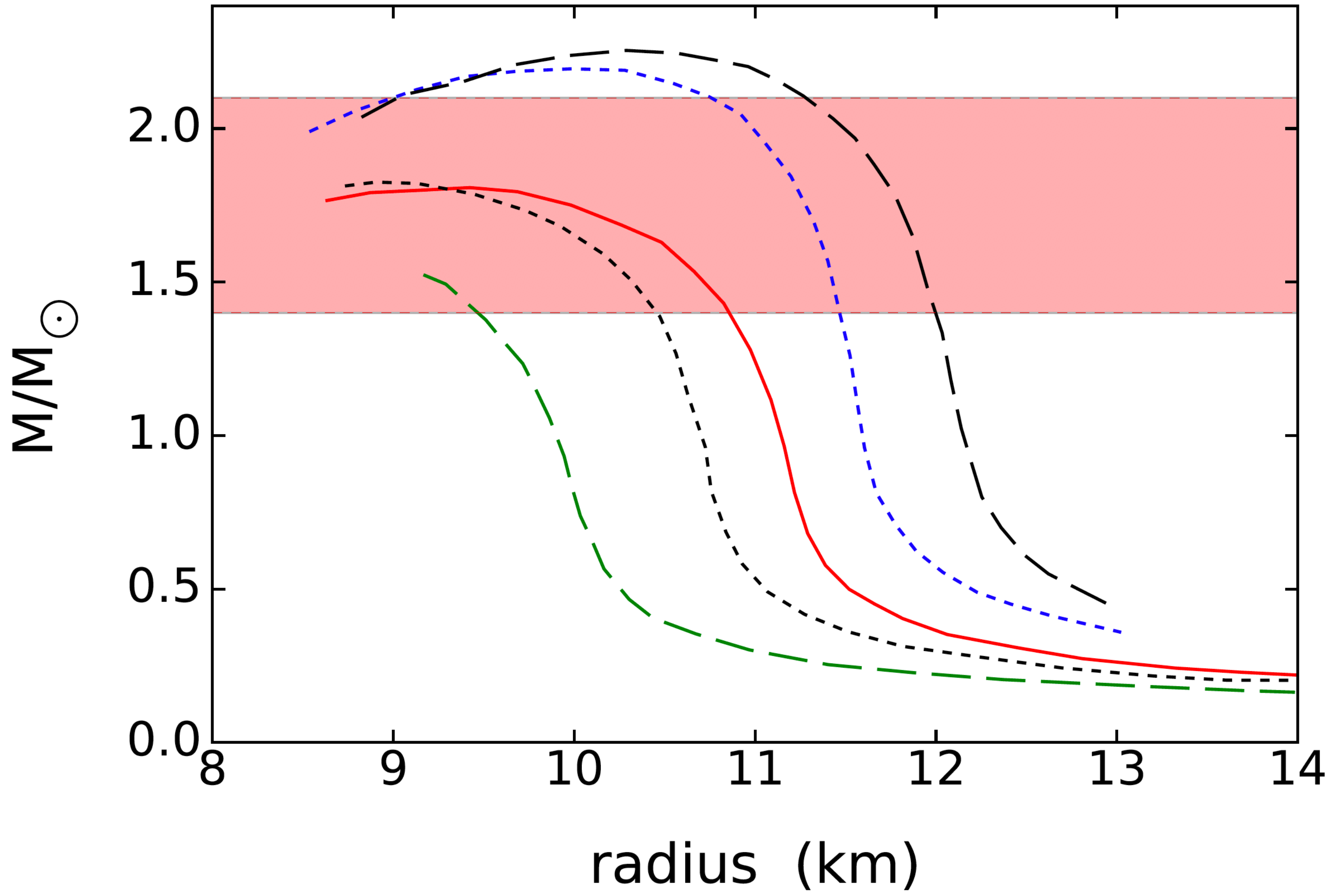
Tolman-Oppenheimer-Volkoff

EOS

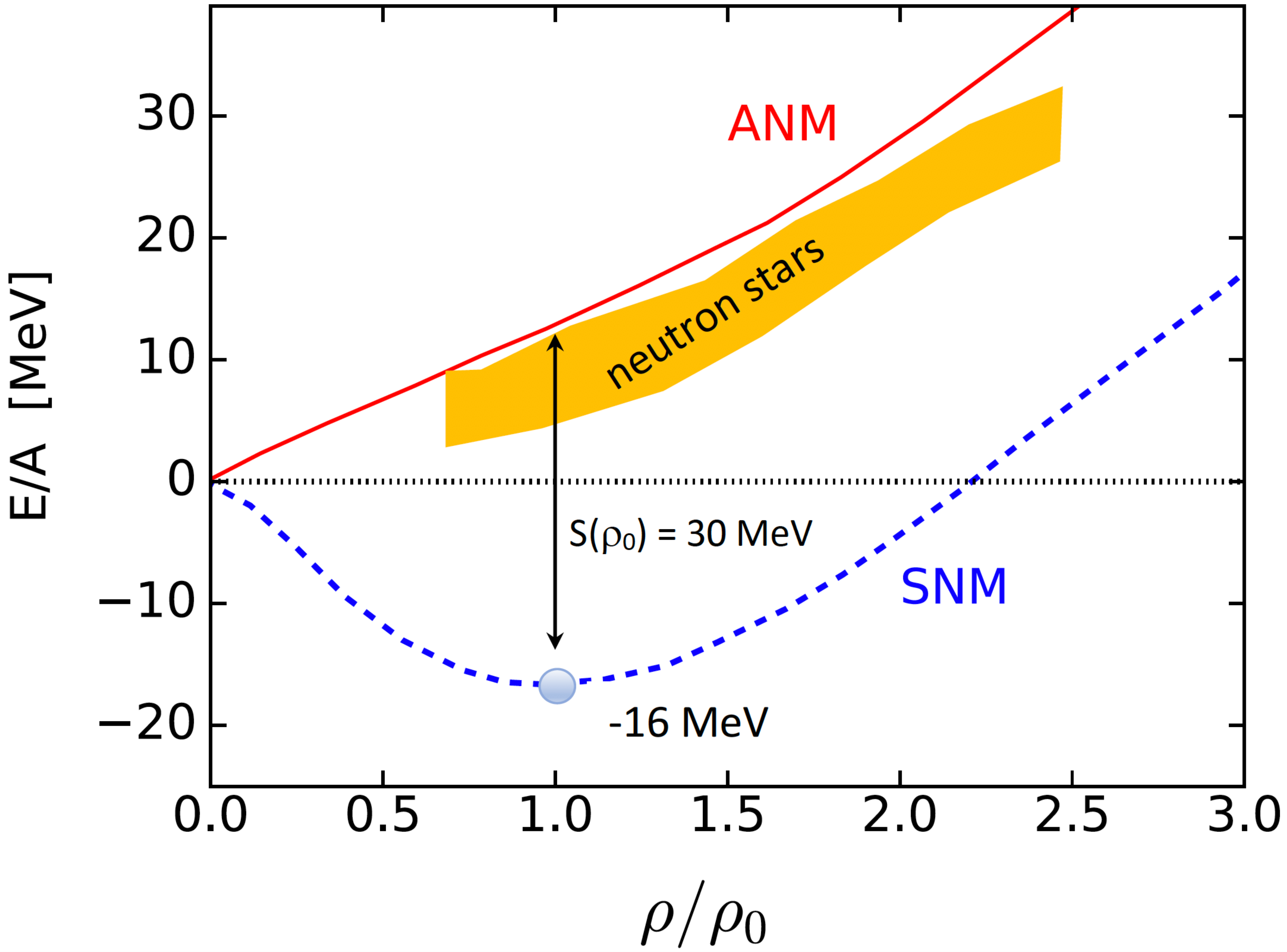
$$p[\rho] = \rho^2 \frac{d}{d\rho}\left(\frac{E}{A}[\rho]\right)$$

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

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

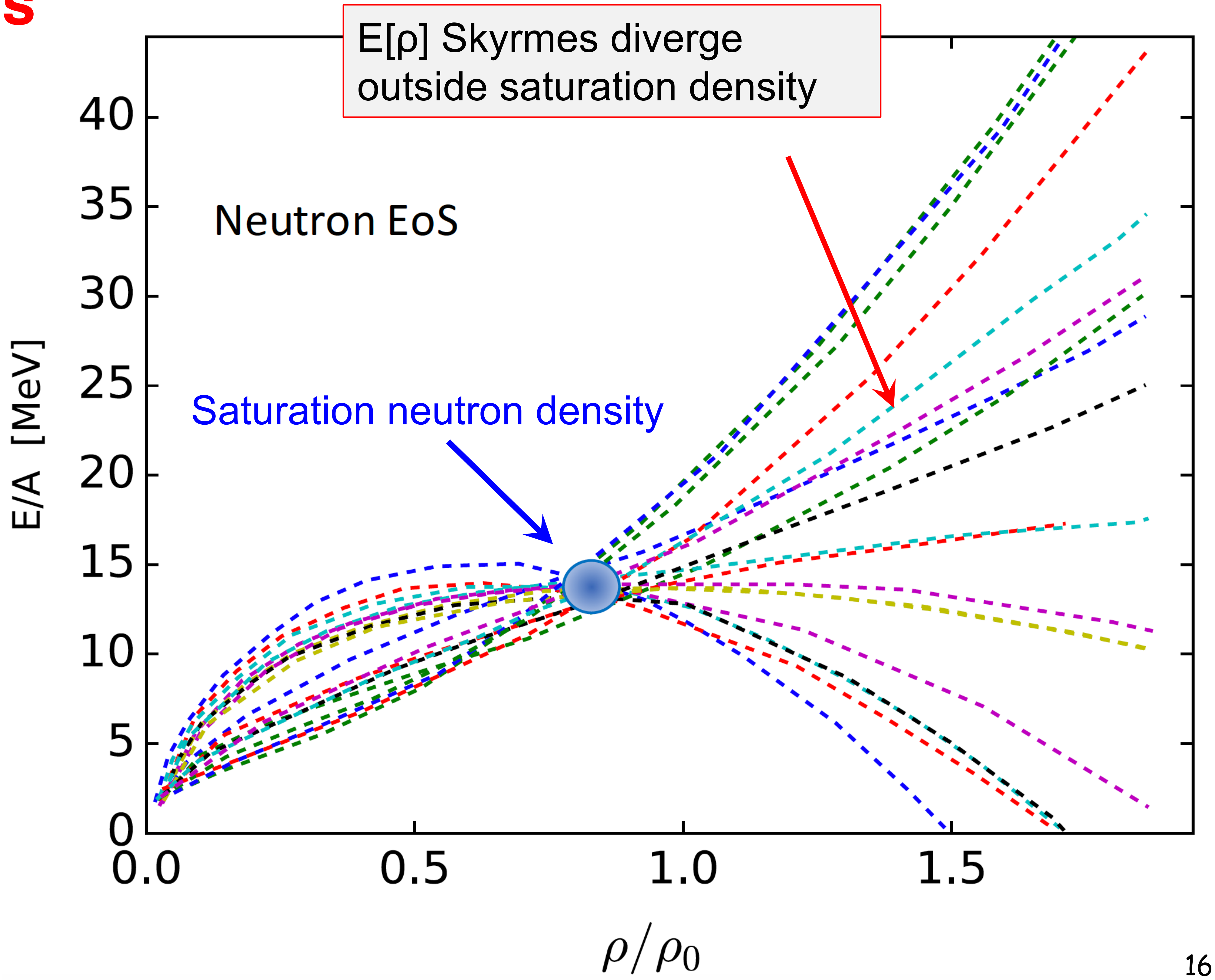


EOS of neutron stars



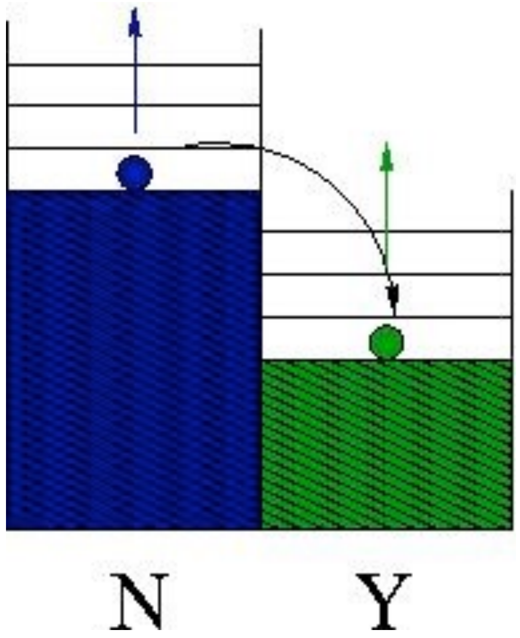
EOS & Neutron stars

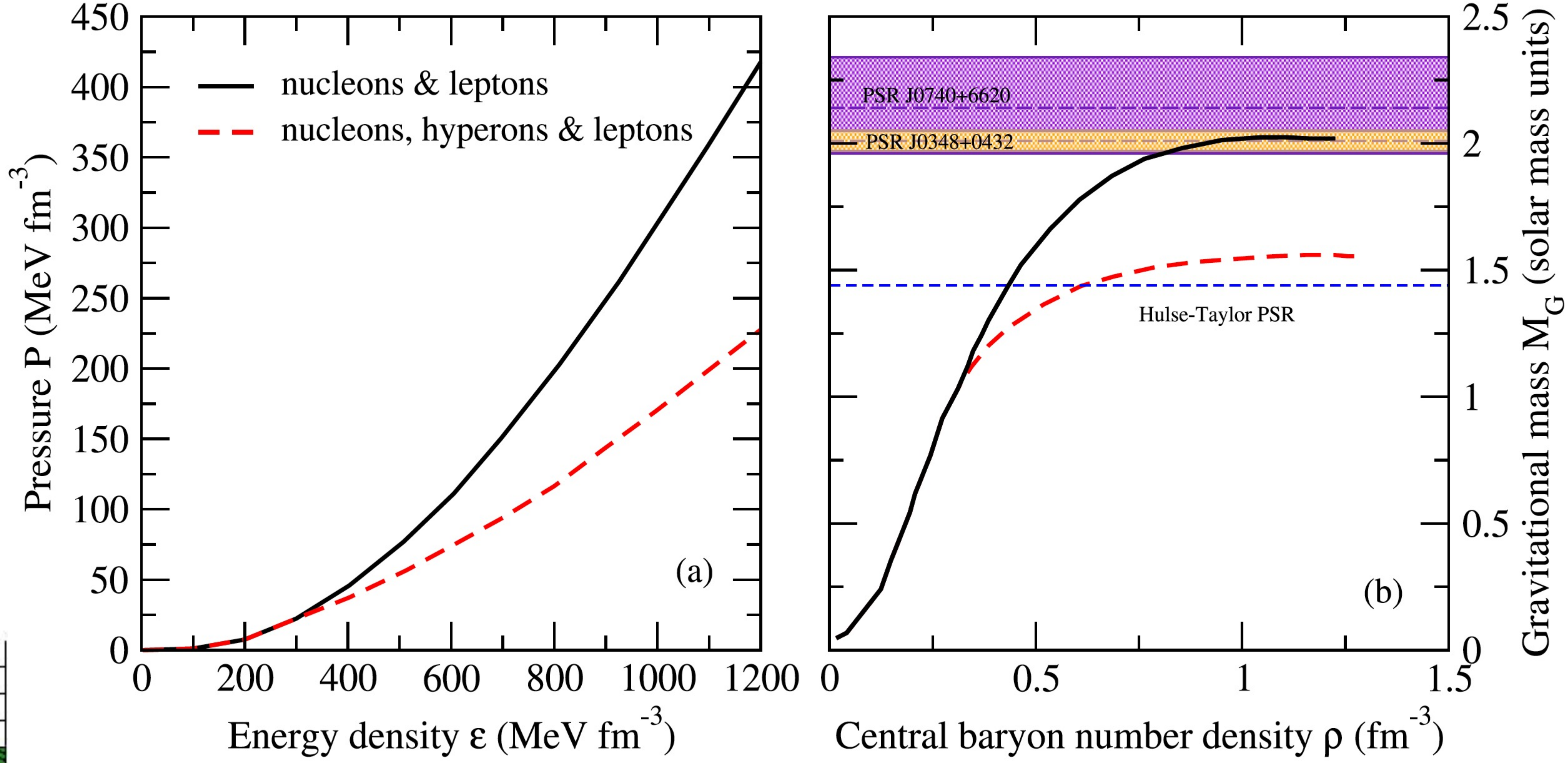
Pethick, Ravenhall, ARNPS 45 (1995) 429



Hyperons and neutron stars

Hyperons make the EoS softer → reduction of the mass





Hyperon "puzzle"

Tolos, Fabbietti, PPNP 112 103770 (2020)

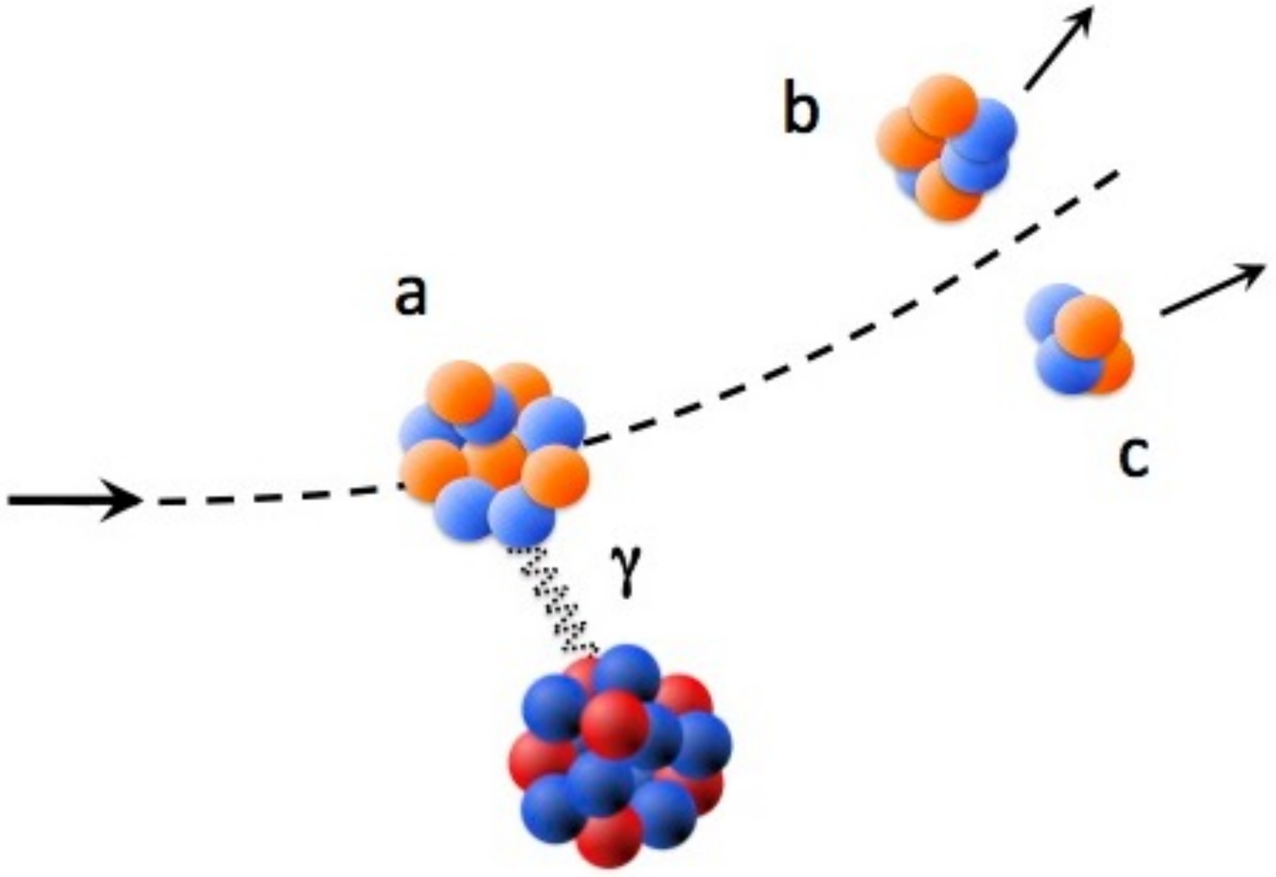
Nuclear astrophysics

Baur, CB, Rebel, NPA (1986)

$$\frac{d\sigma}{dE_\gamma d\Omega} = \frac{1}{E_\gamma}\sum_l \frac{dn_l(E_\gamma,\Omega)}{dE_\gamma d\Omega}\,\sigma_{\gamma + a \to b + c}(E_\gamma)$$

Theory

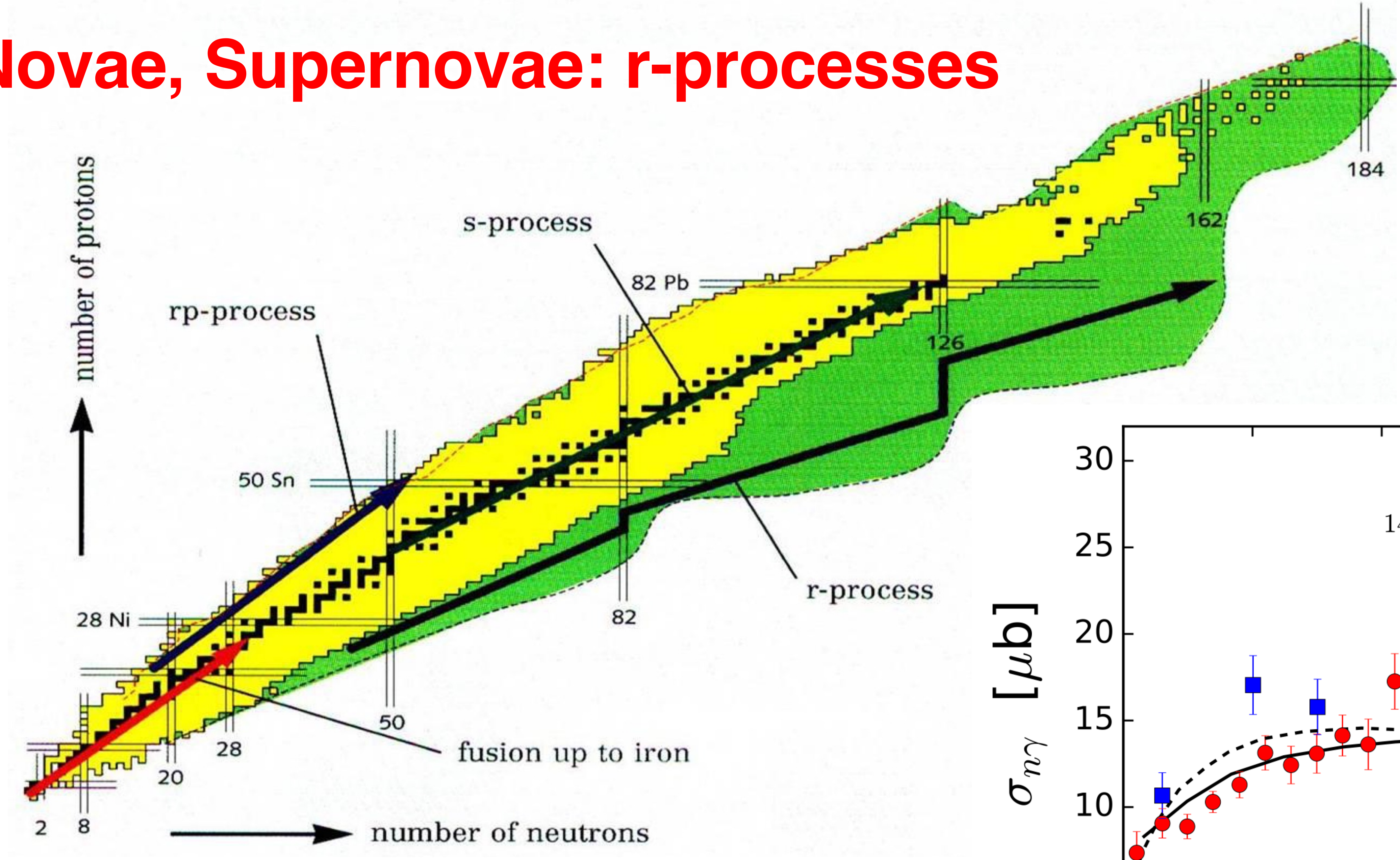
detailed balance

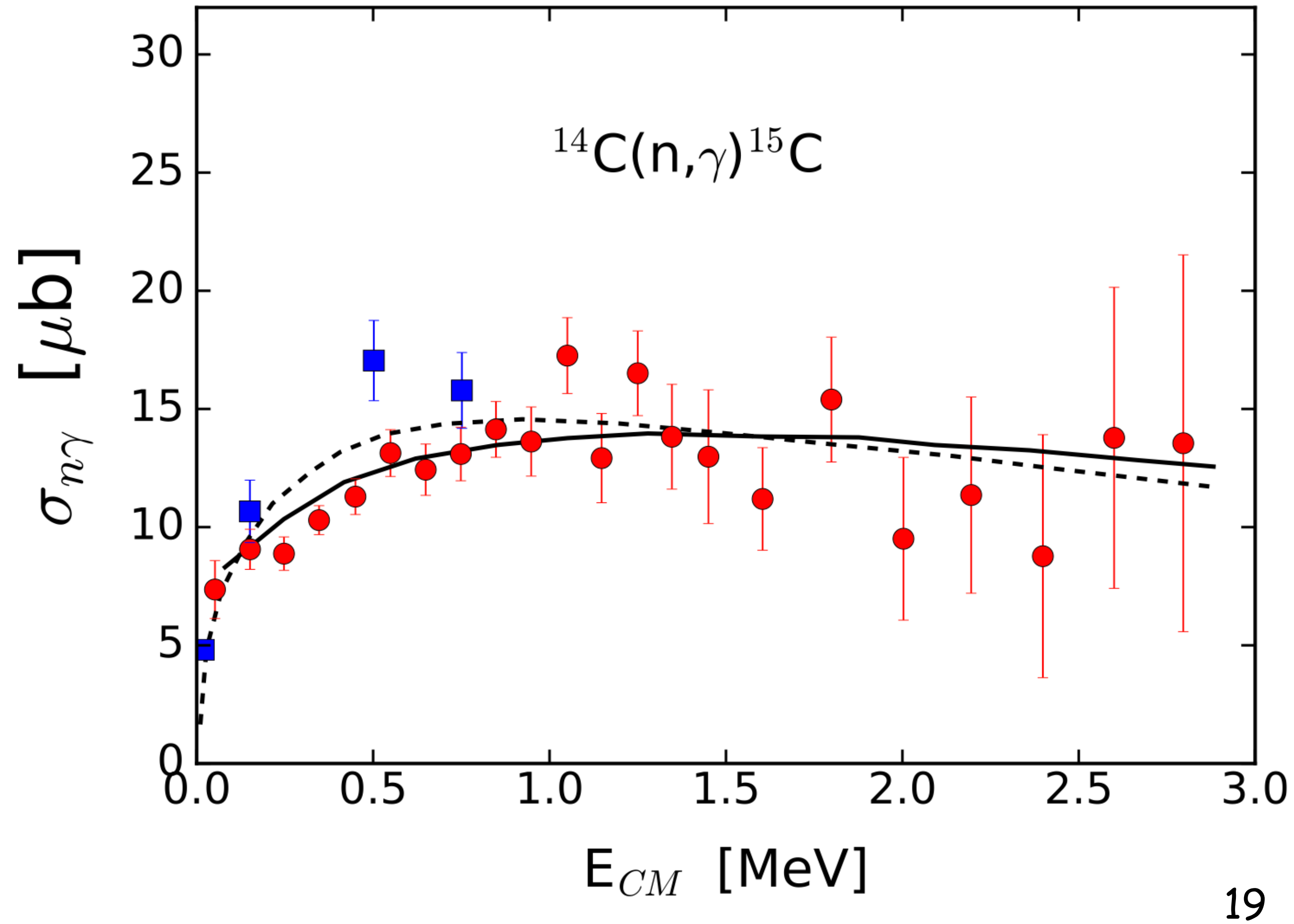


$$\sigma_{b+c\to a+\gamma} = \frac{2(2j_a+1)}{(2j_b+1)(2j_c+1)}\frac{k_{bc}^2}{k_\gamma^2}\sigma_{\gamma+a\to b+c}$$

Applications to radiative capture (n,γ) and (p,γ) reactions in nuclear astrophysics

Novae, Supernovae: r-processes





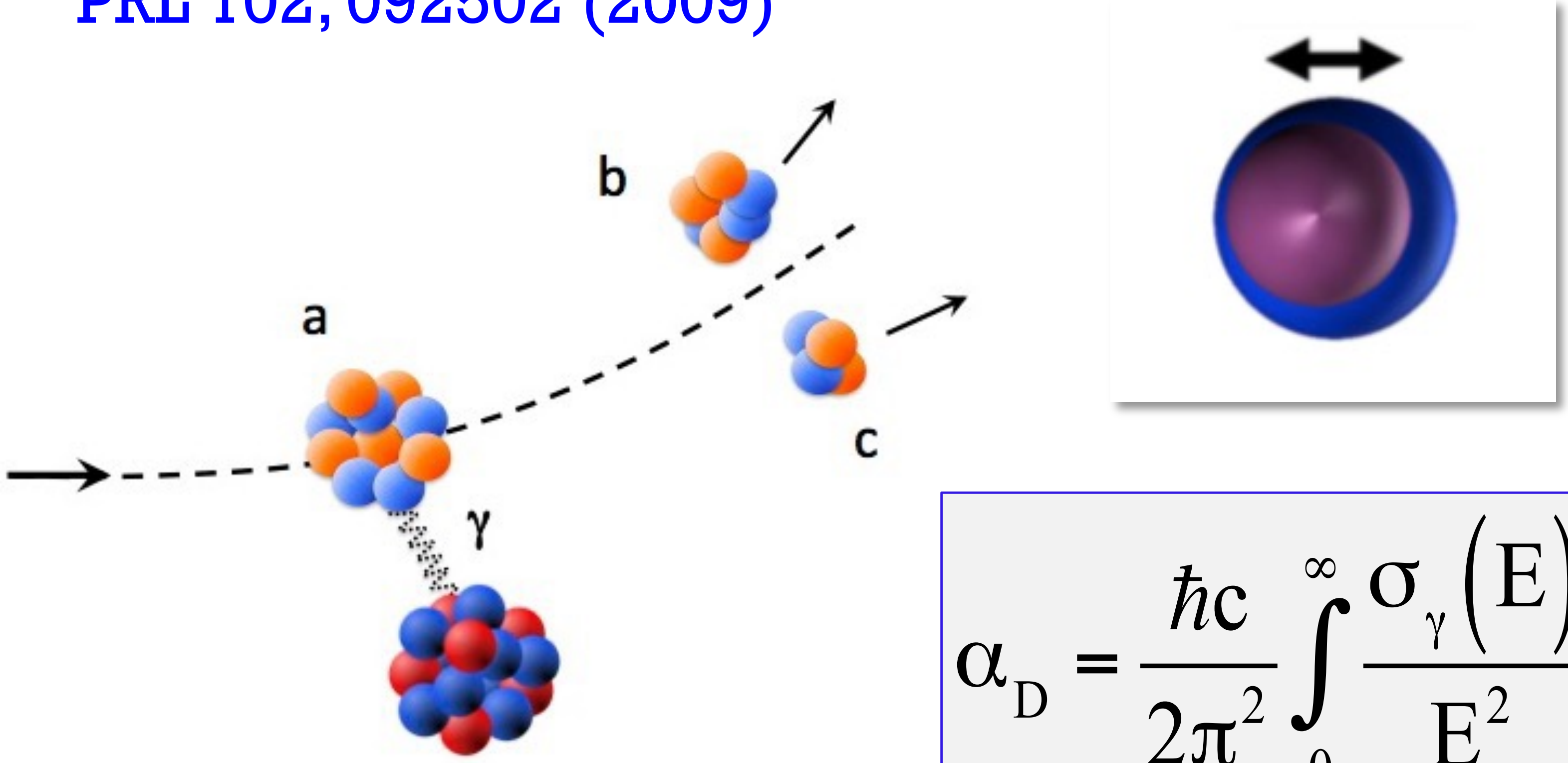
Aumann, Nakamura,
Phys. Scr. T152 (2013) 014012

Pigmy resonances & Dipole polarizability

Rossi et al.
PRL 111 (2013) 242503

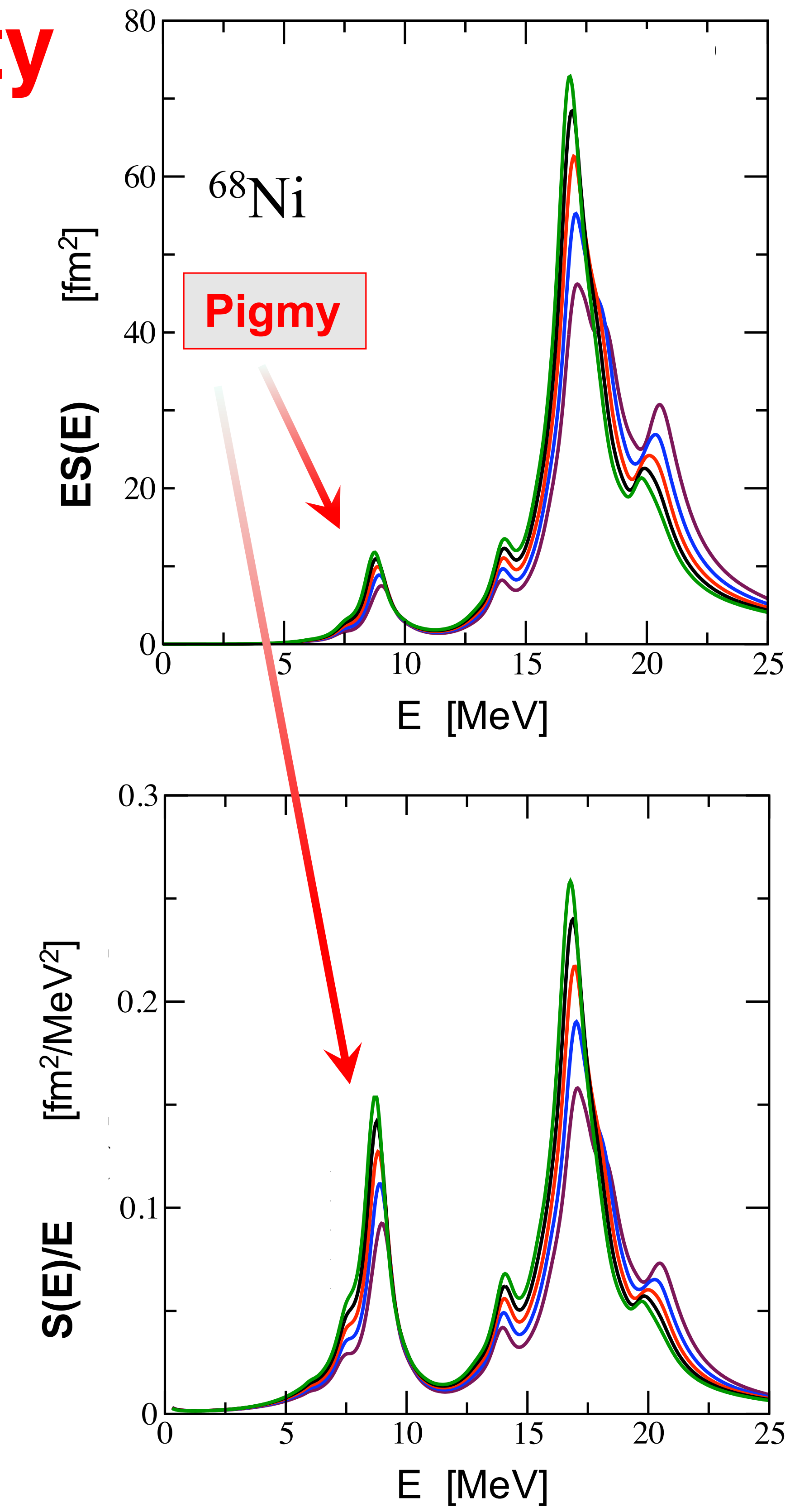
Wieland et al.
PRL 102, 092502 (2009)

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

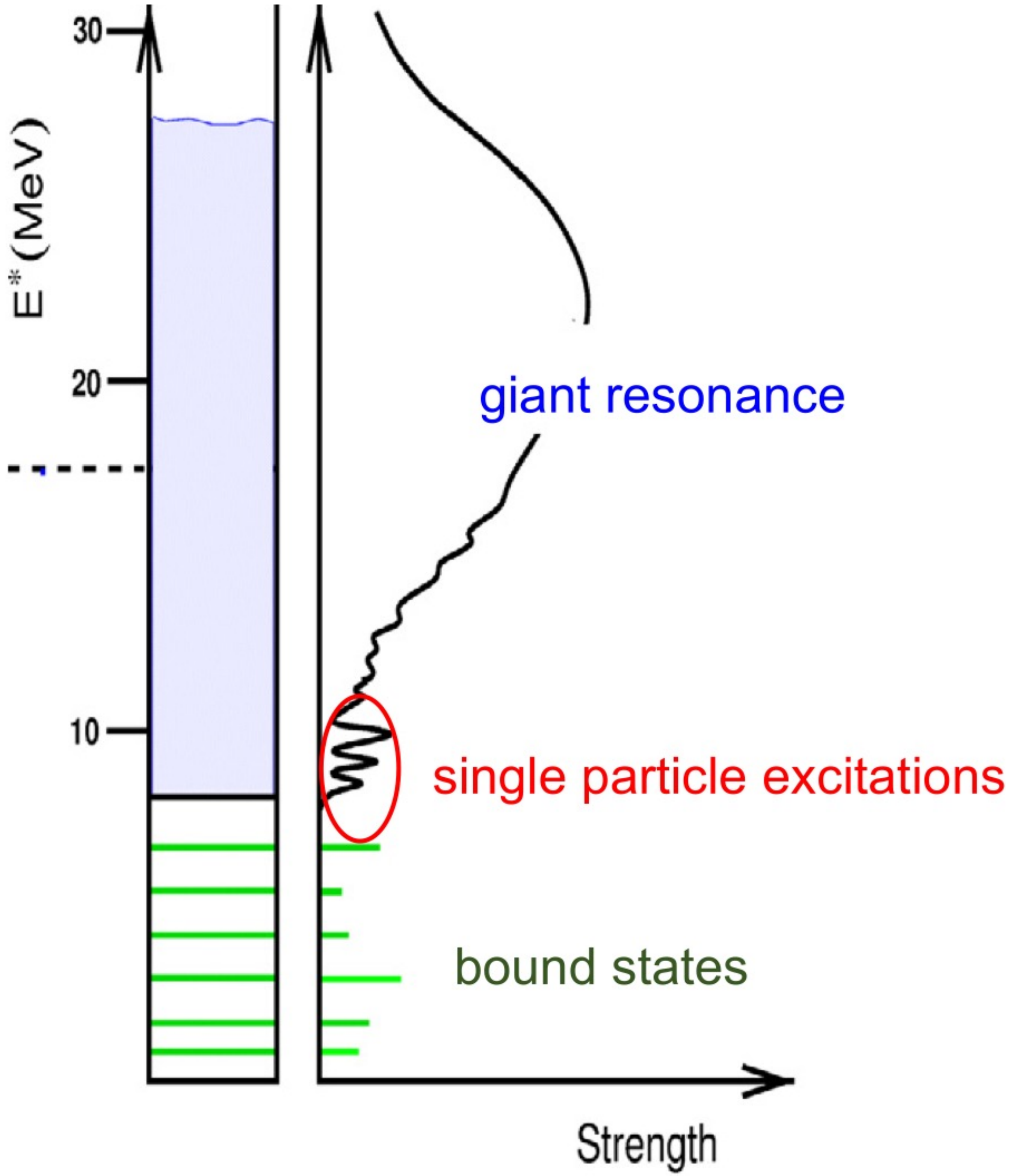


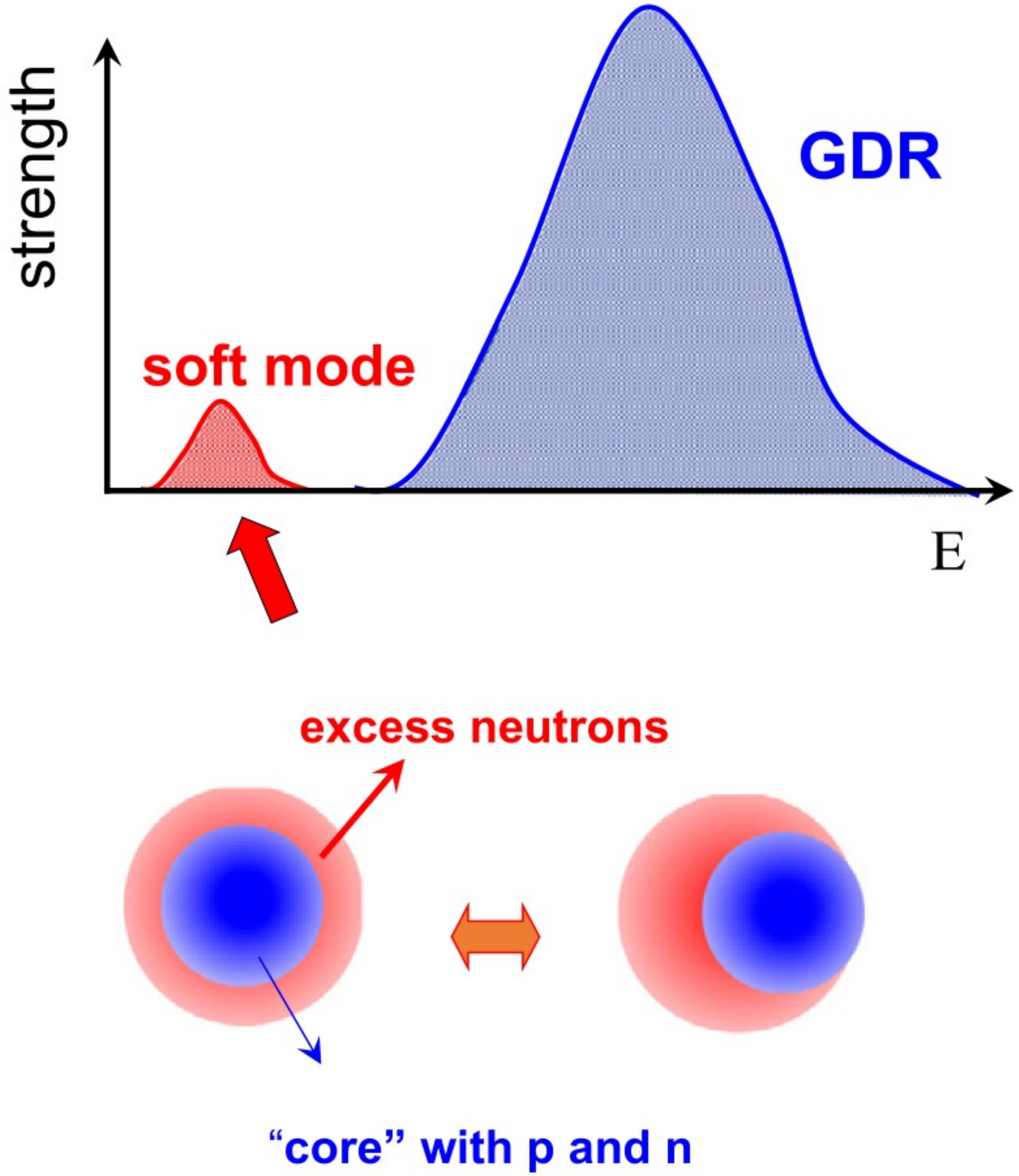
$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma_\gamma(E)}{E^2}dE$$

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



Pigmy resonances

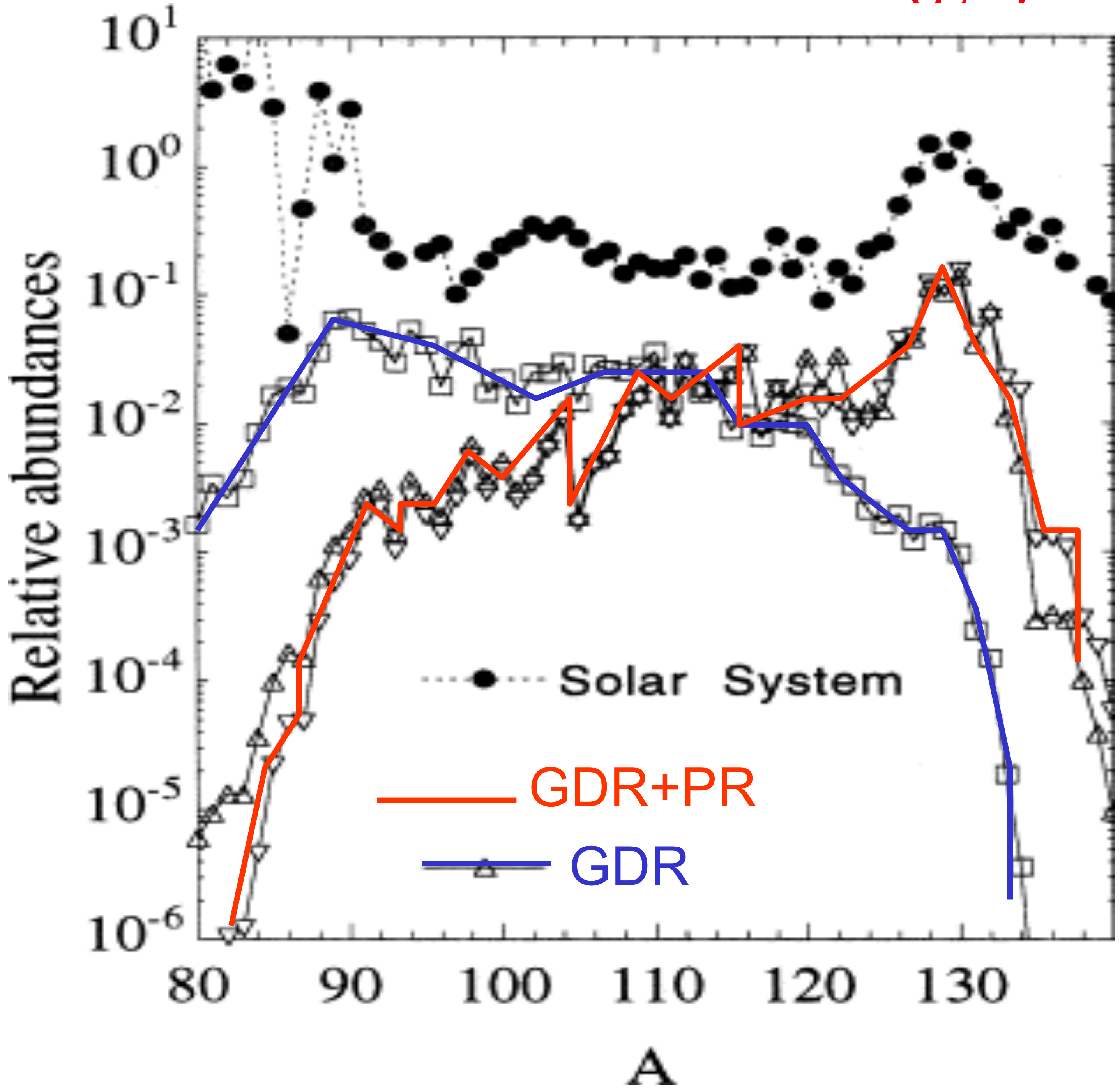




Impact of pygmies on nucleosynthesis (??!)

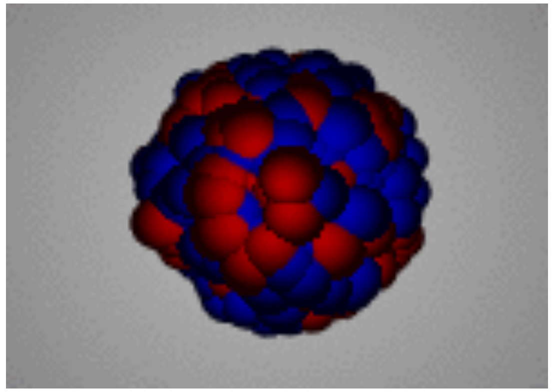
Goriely, PLB 436, 10 (1998)

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

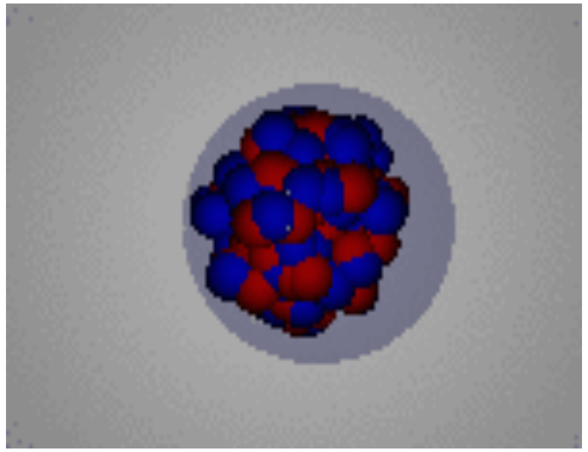


Impact: r-process abundances

- 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

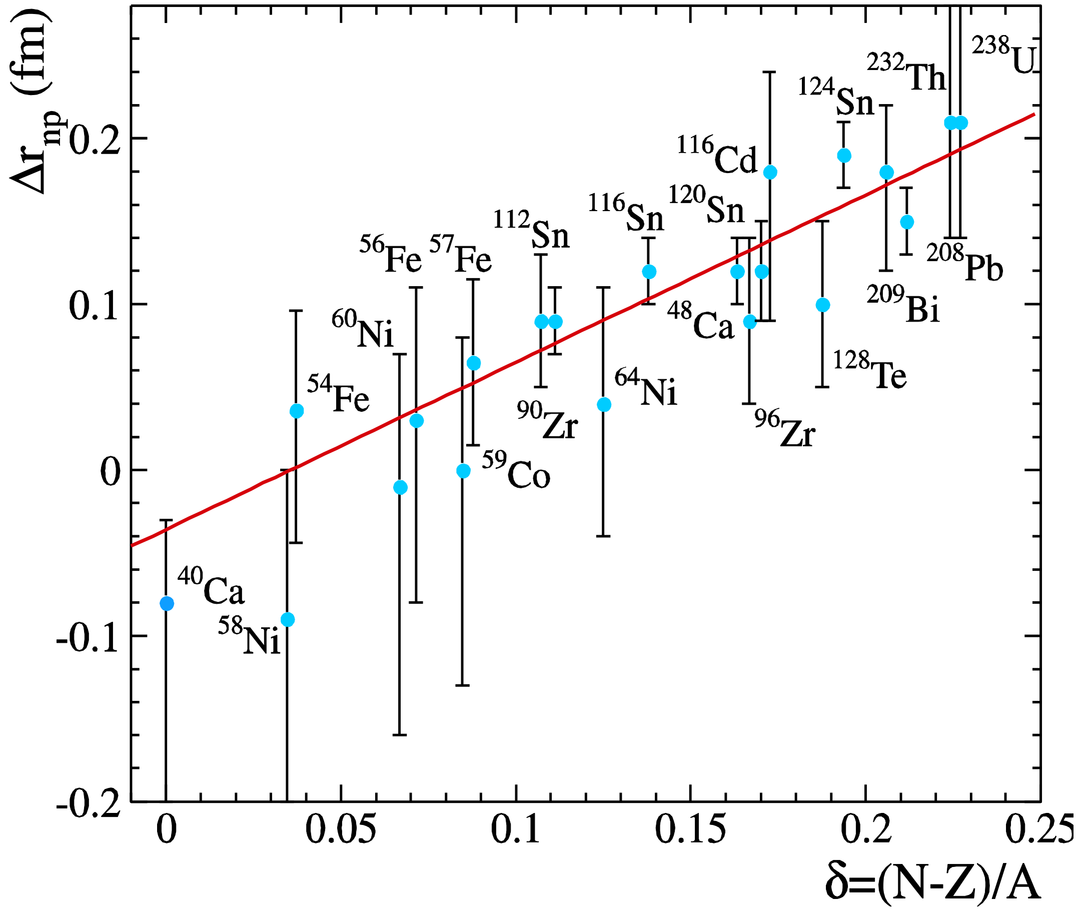


Giant dipole



Pygmy dipole

Neutron skins measurements

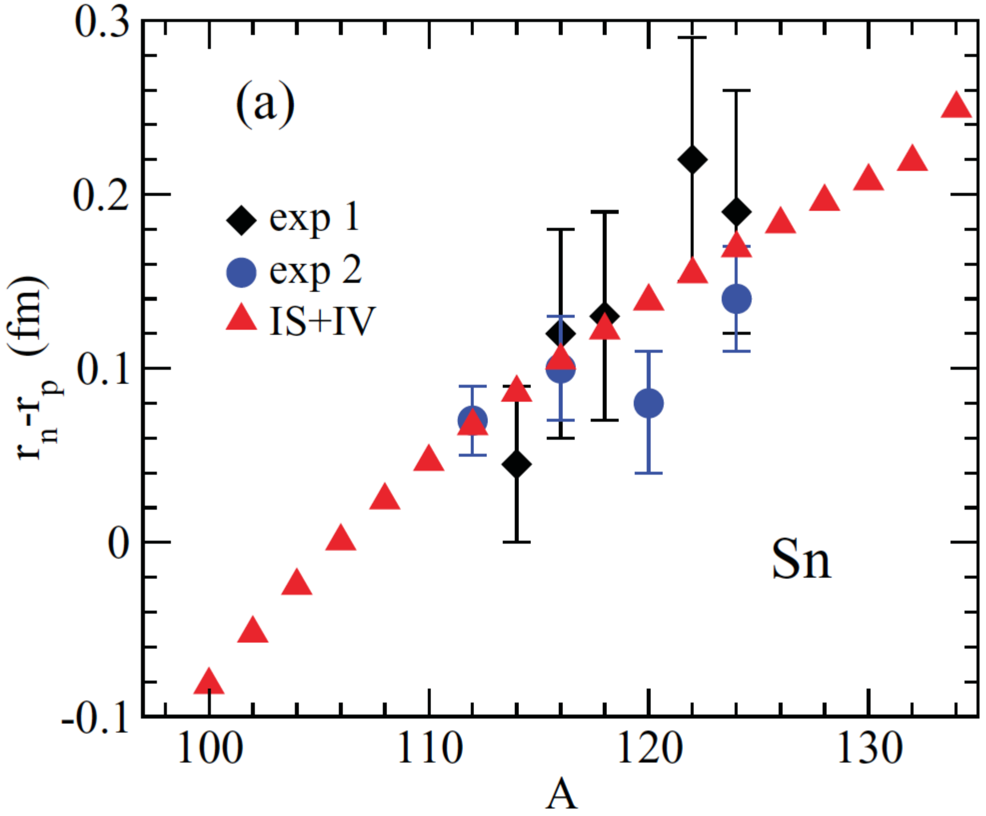


Radii from spin-dipole resonances

Krasznahorkay et al., PRL 82, 3216 (1999)

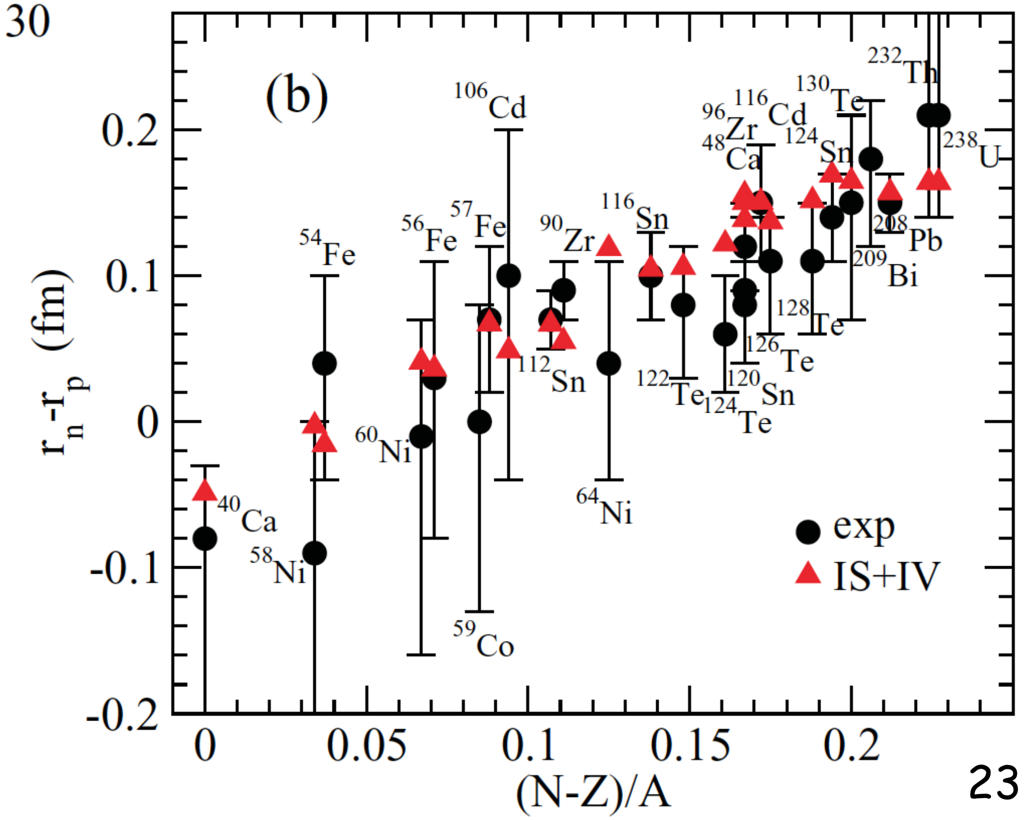
Antiprotonic atoms

Trzcinskaet al., PRL 87, 082501 (2001)



Mean field calculations

CB, Liu, Sagawa,
PRC 85, 014321 (2012)



EOS + symmetry energy

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

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

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

For $\rho \sim \rho_0$ and $\delta \sim 1 \Rightarrow p = \frac{L\rho_0}{3}$

Skyrme	ρ_0	E_0	K_∞	J	L	K_{sym}
SLy5	0.161	-15.99	229.92	32.01	48.15	-112.76
Skxs20	0.162	-15.81	201.95	35.50	67.06	-122.31
SkI5	0.156	-15.82	255.57	36.63	129.27	-155.94

L crucial for neutron matter

Density functional models

For the nucleon-nucleon interaction

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

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

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

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

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

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

$t_i,\ x_i,\ \alpha,\ W_0$ are 10 **Skyrme** parameters

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

+ pairing

HF + BCS

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

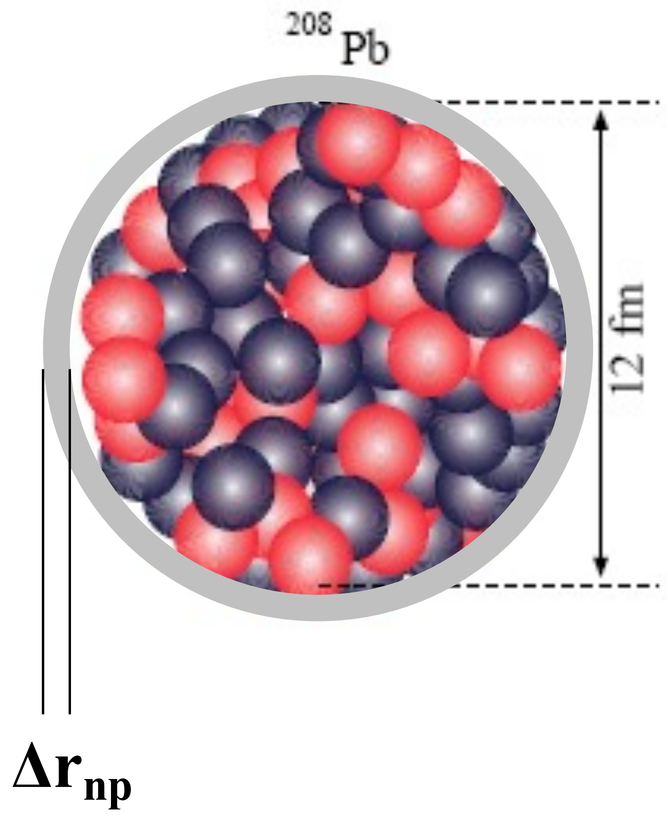
HFB

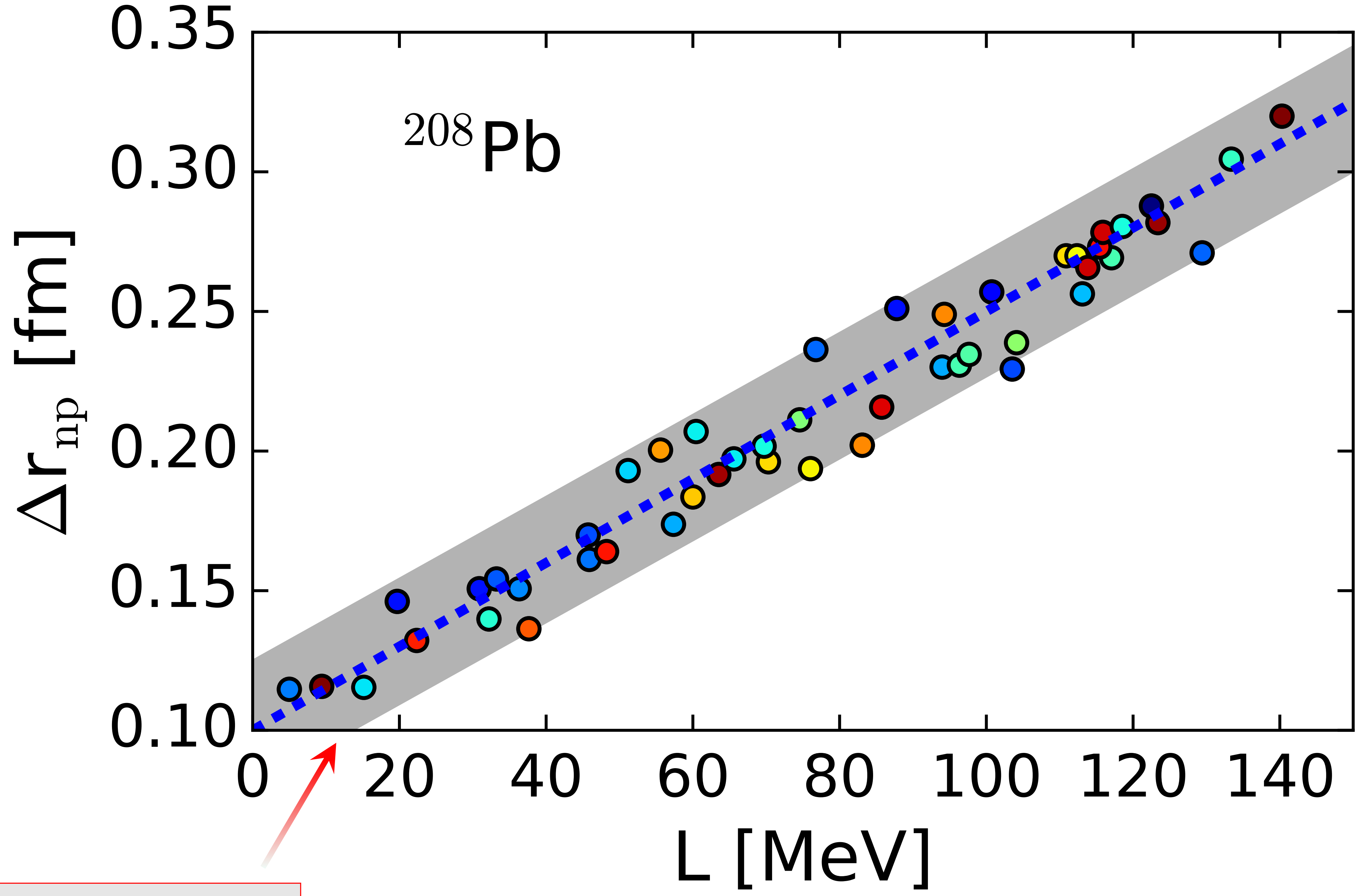
$$\begin{pmatrix} h_{HF} - \lambda & \Delta \\ -\Delta & -h_{HF} + \lambda \end{pmatrix}\begin{pmatrix} u_k \\ v_k \end{pmatrix} = E_k \begin{pmatrix} u_k \\ v_k \end{pmatrix}$$

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

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

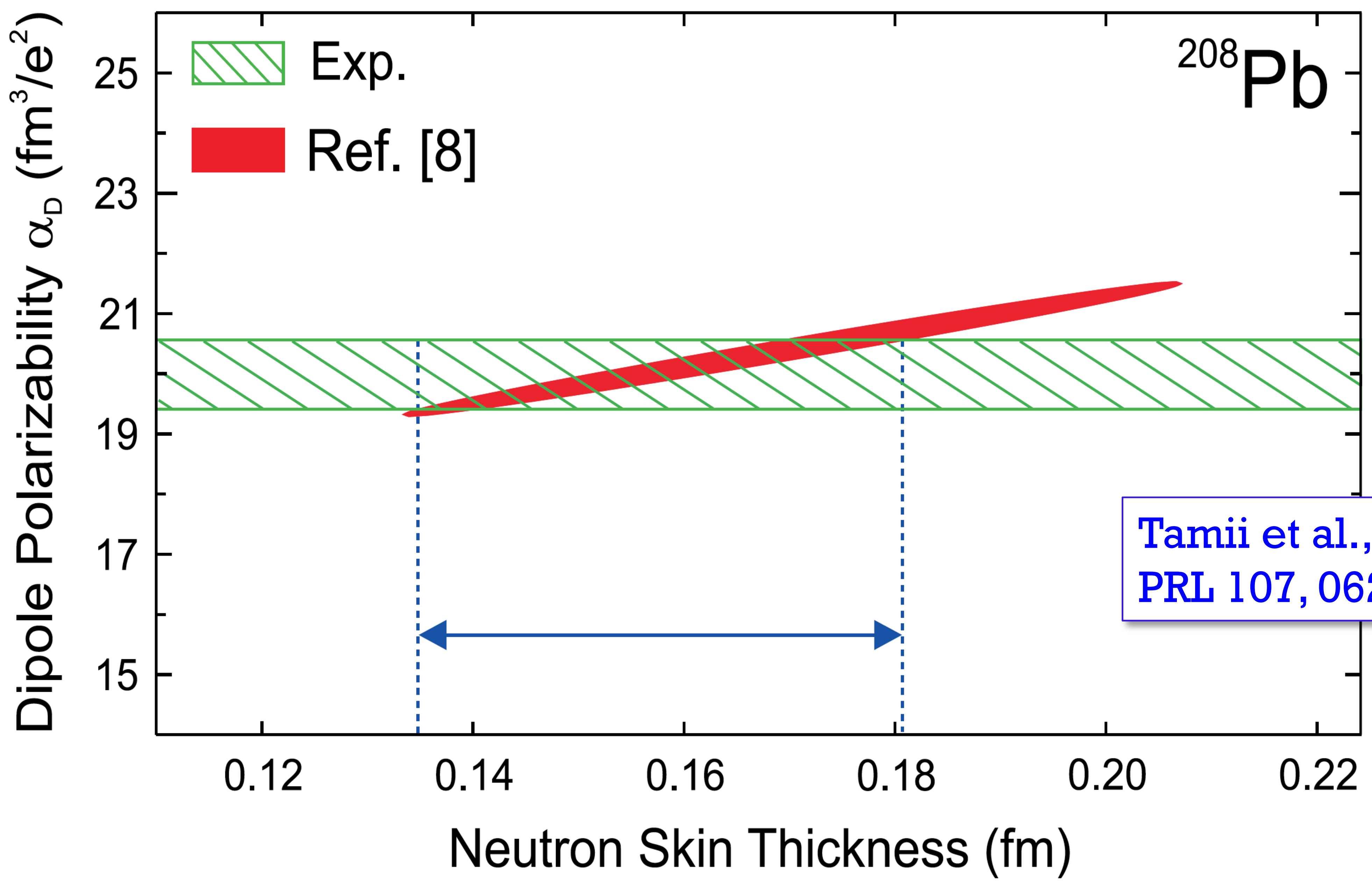
Correlation between symmetry energy & neutron skin





Numerous EDF

Dipole polarizability & neutron skin



Reinhard, Nazarewicz, PRC 81, 051303(R) (2010)

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

Experiment:

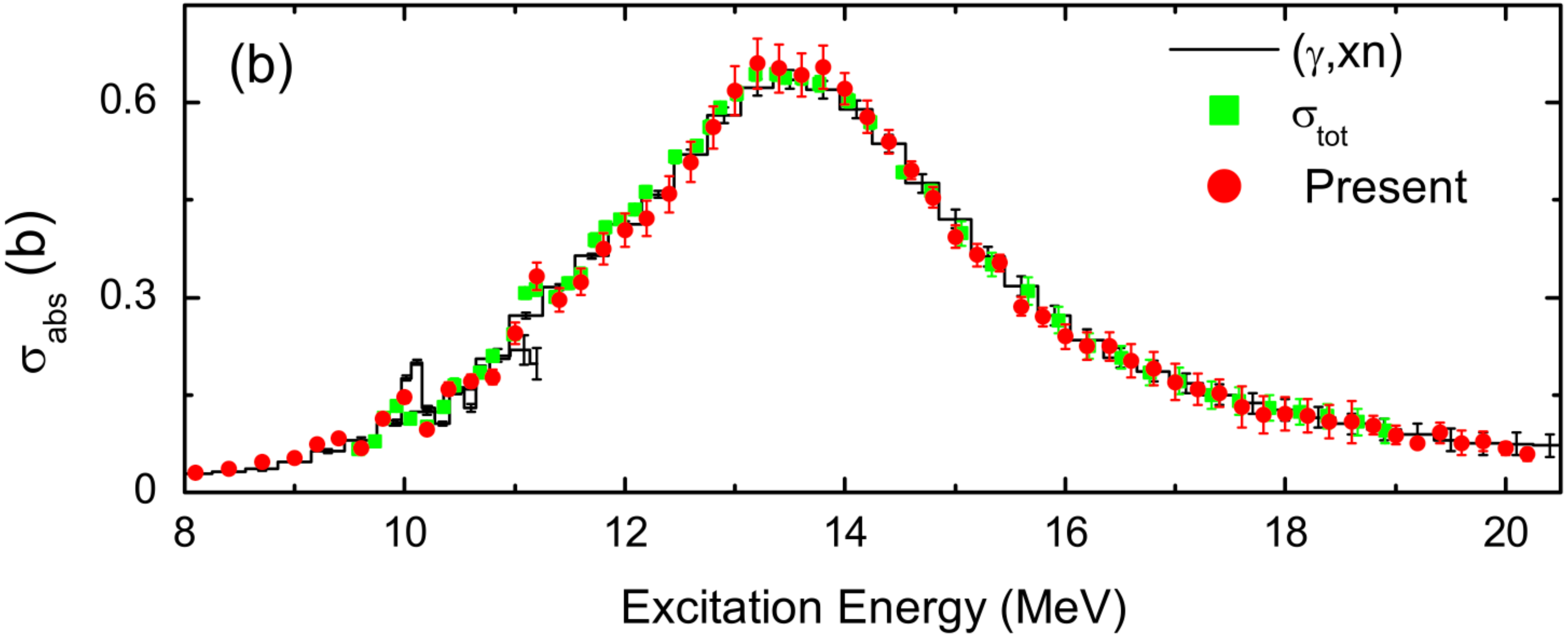
$\Delta r_{np} \sim 0.156$ fm

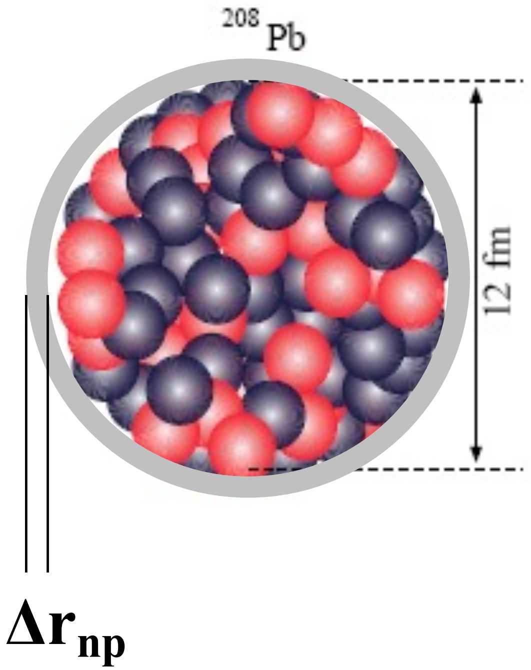
EFT:

Hebeler et al., PRL 105, 161102 (2010)

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

Dipole polarizability & neutron skin



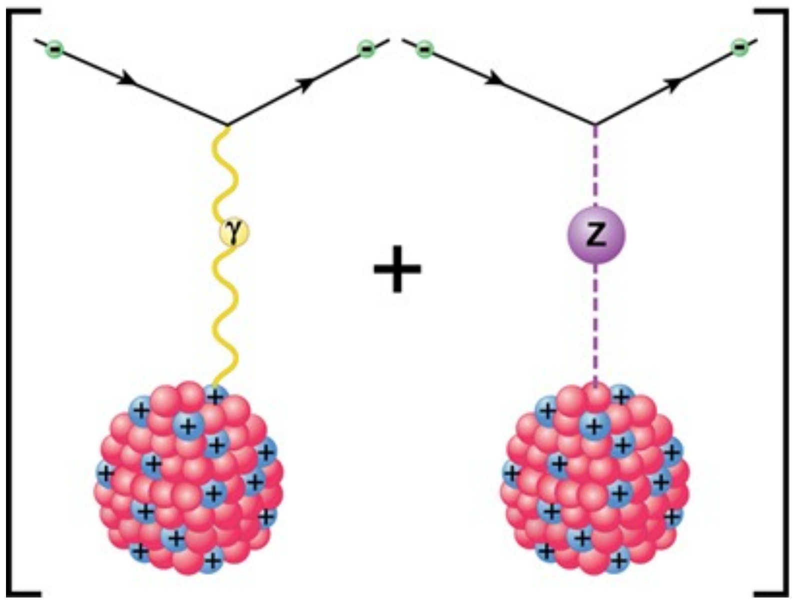


Tamii et al.,
PRL 107, 062502 (2011)

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

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

n-skin from PV e⁻ scattering

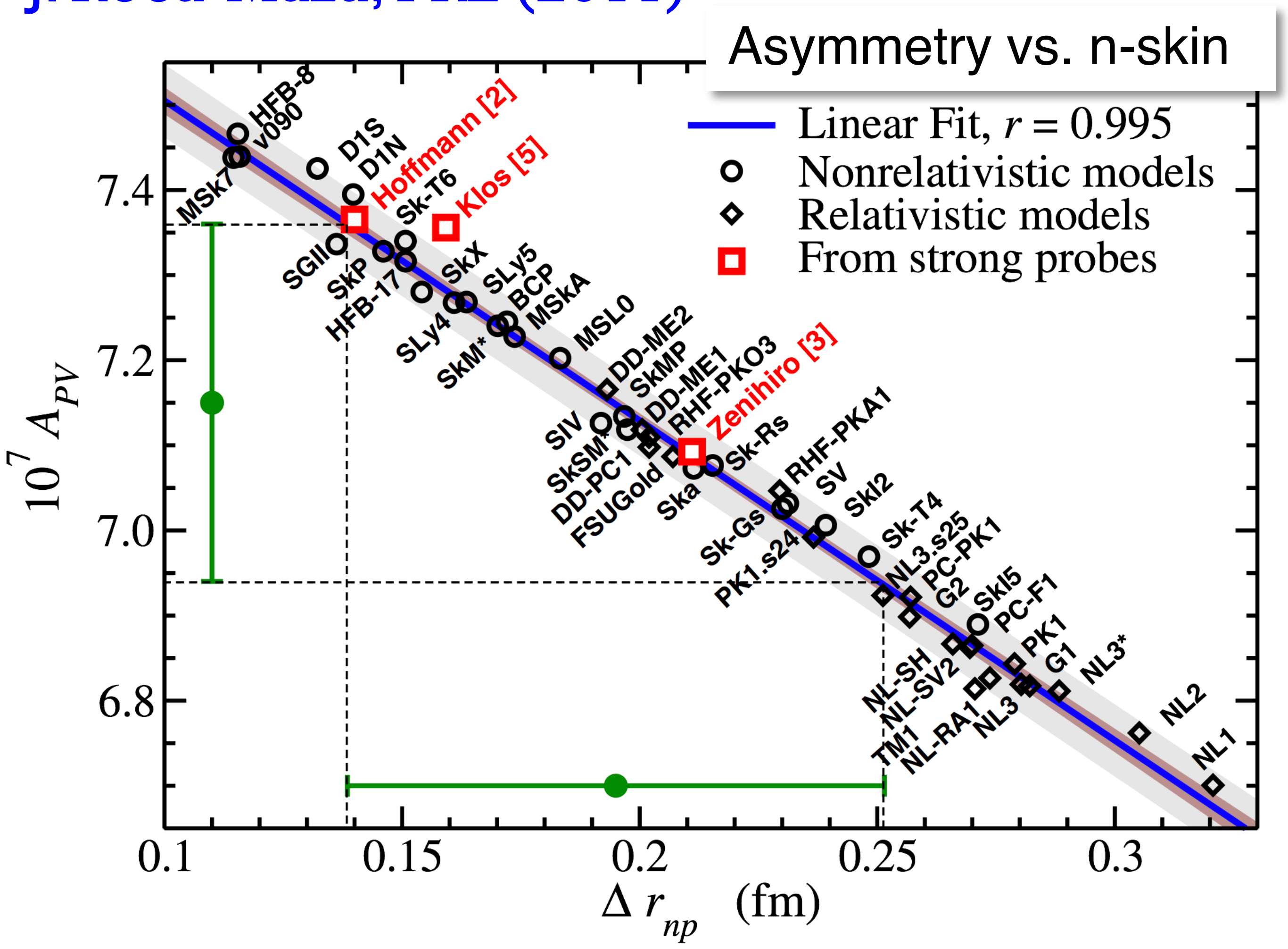


Abrahamyan et al,
PRL 108, 112502 (2012)

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

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

J. Roca-Maza, PRL (2011)



$$A_{PV}(Q^2) \sim \frac{G_F Q^2}{4\pi e^2\sqrt{2}} \frac{F_W(Q)}{F_{ch}(Q)}$$

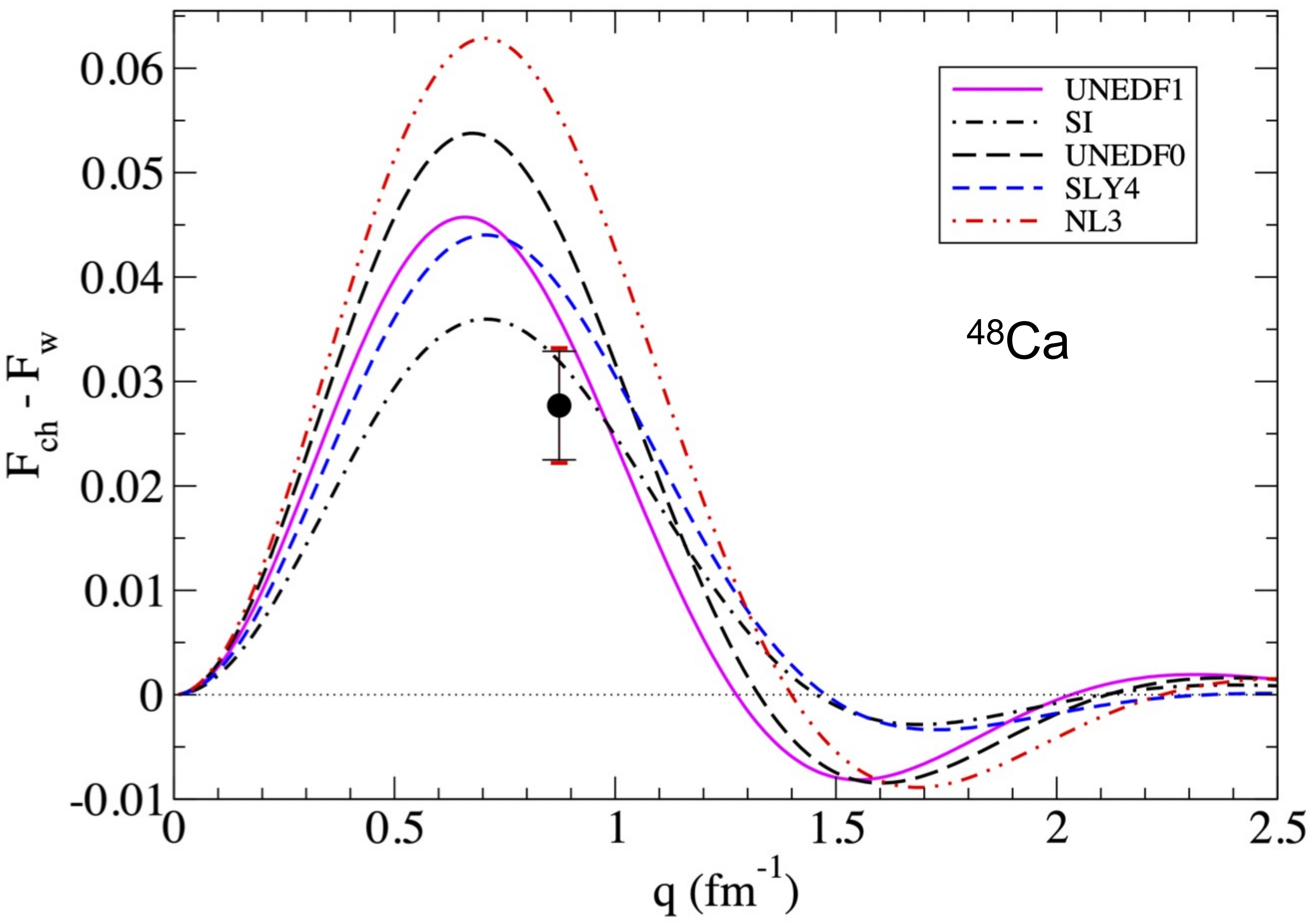
$$F_W = \frac{1}{Q_W} \int dr \frac{\sin(Qr)}{Qr} \rho_W(r)$$

$$\rho_W(r) = q_p\, \rho_{ch}(r) + q_n \int d^3r' \left[G_E^p \rho_n + G_E^n \rho_p\right]$$
$$q_p = 0.0721, \qquad q_n = 0.0721,$$

n-skin from e⁻ PV scattering ^{48}Ca

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

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



- PREX & CREX: measurement of parity violating asymmetry
- Determine n-skin and/or L by comparison to predictions from DFT

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

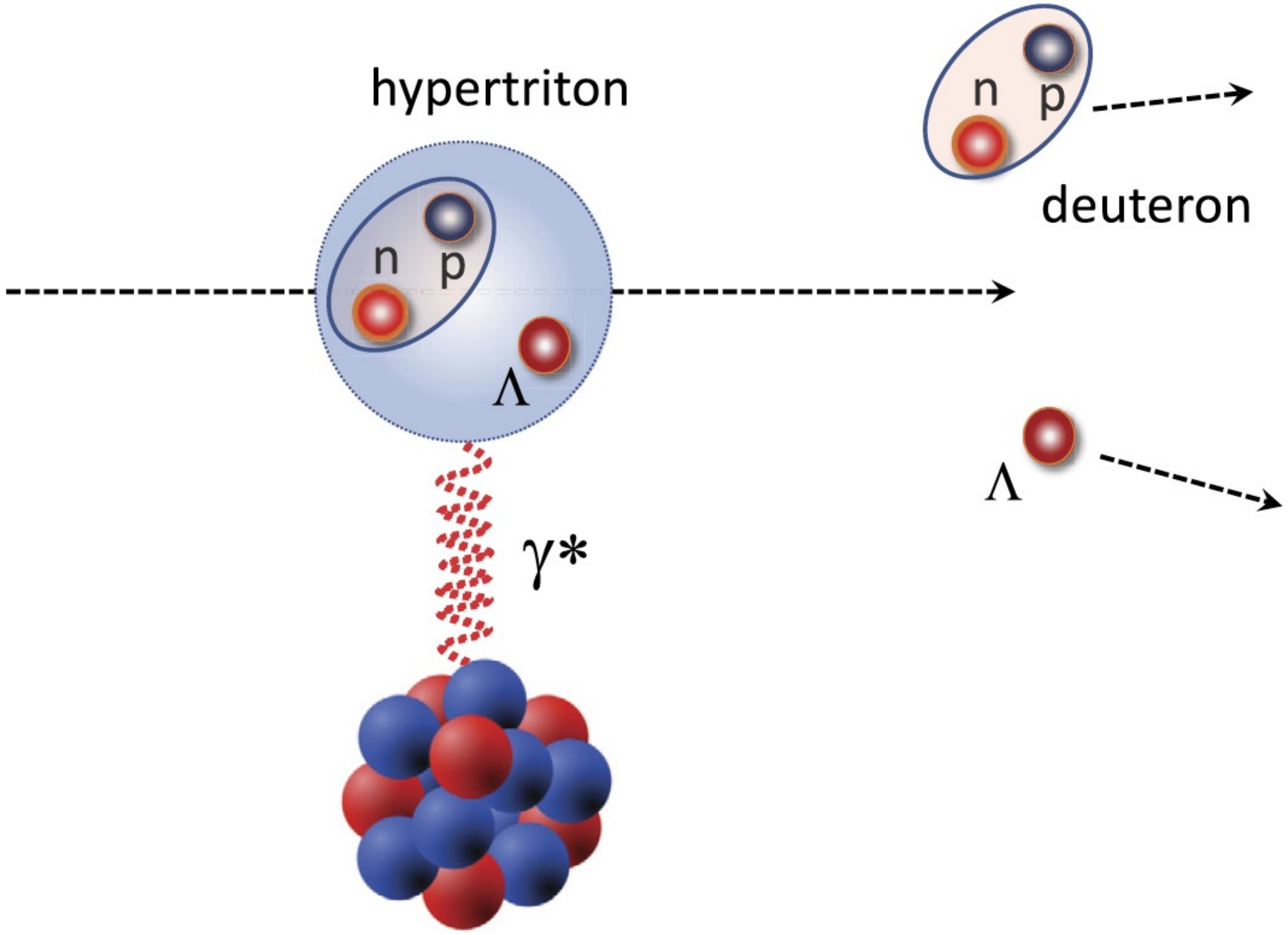
Adhikari et al, PRL 129, 042501(2022)

too large value for Pb

$R_n - R_p = 0.33 \pm 0.17$ fm

Adhikari et al, PRL 126, 172502 (2021)

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

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

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

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

Electromagnetic response of the hypertriton

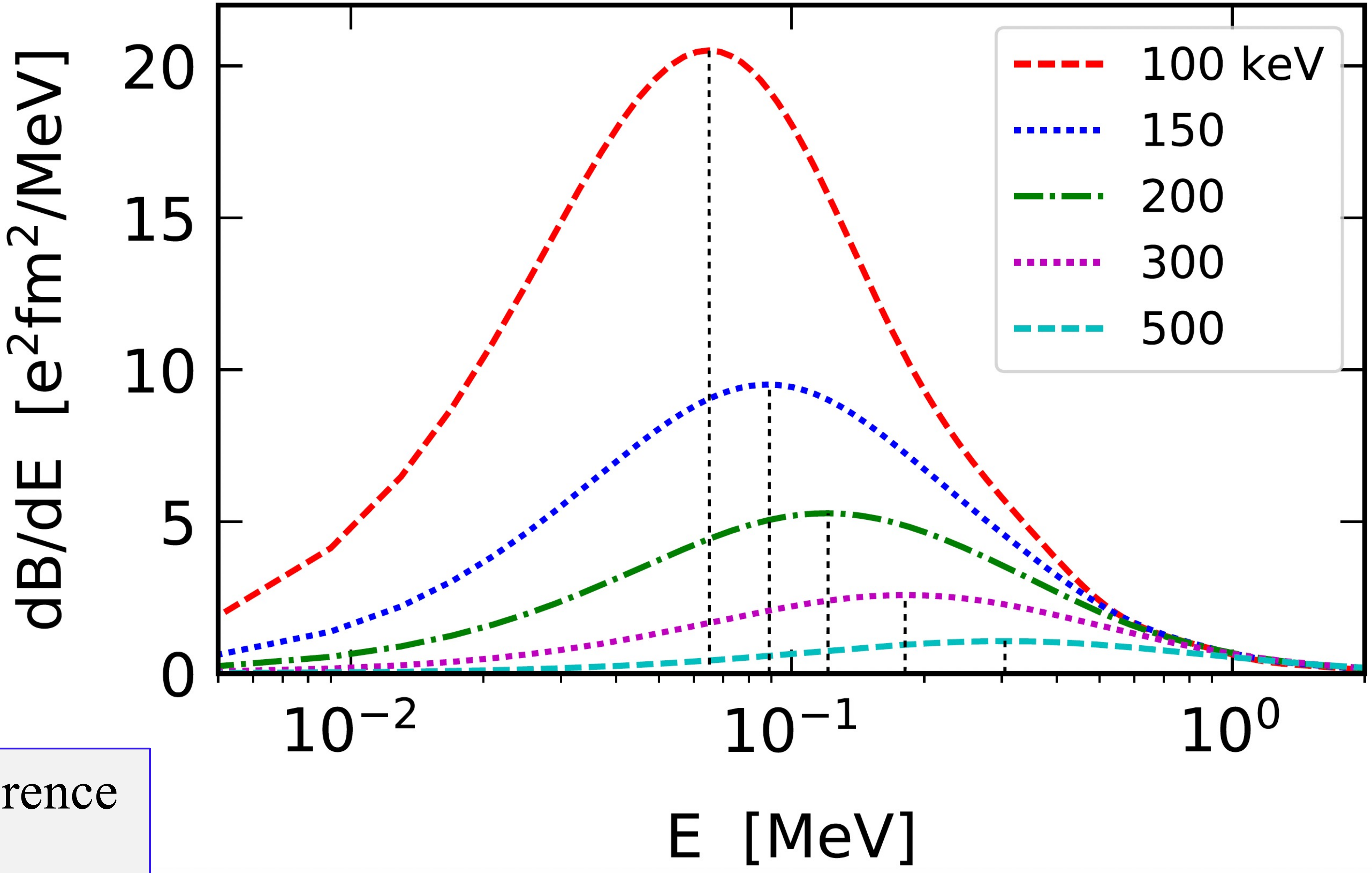
$$\frac{dB(E)}{dE} = \frac{1}{\hbar}\sqrt{\frac{\mu}{2E}}\,|\langle g.s.||\mathcal{O}_{E1}||E,l\rangle|^2$$

Analytical model:

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

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

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



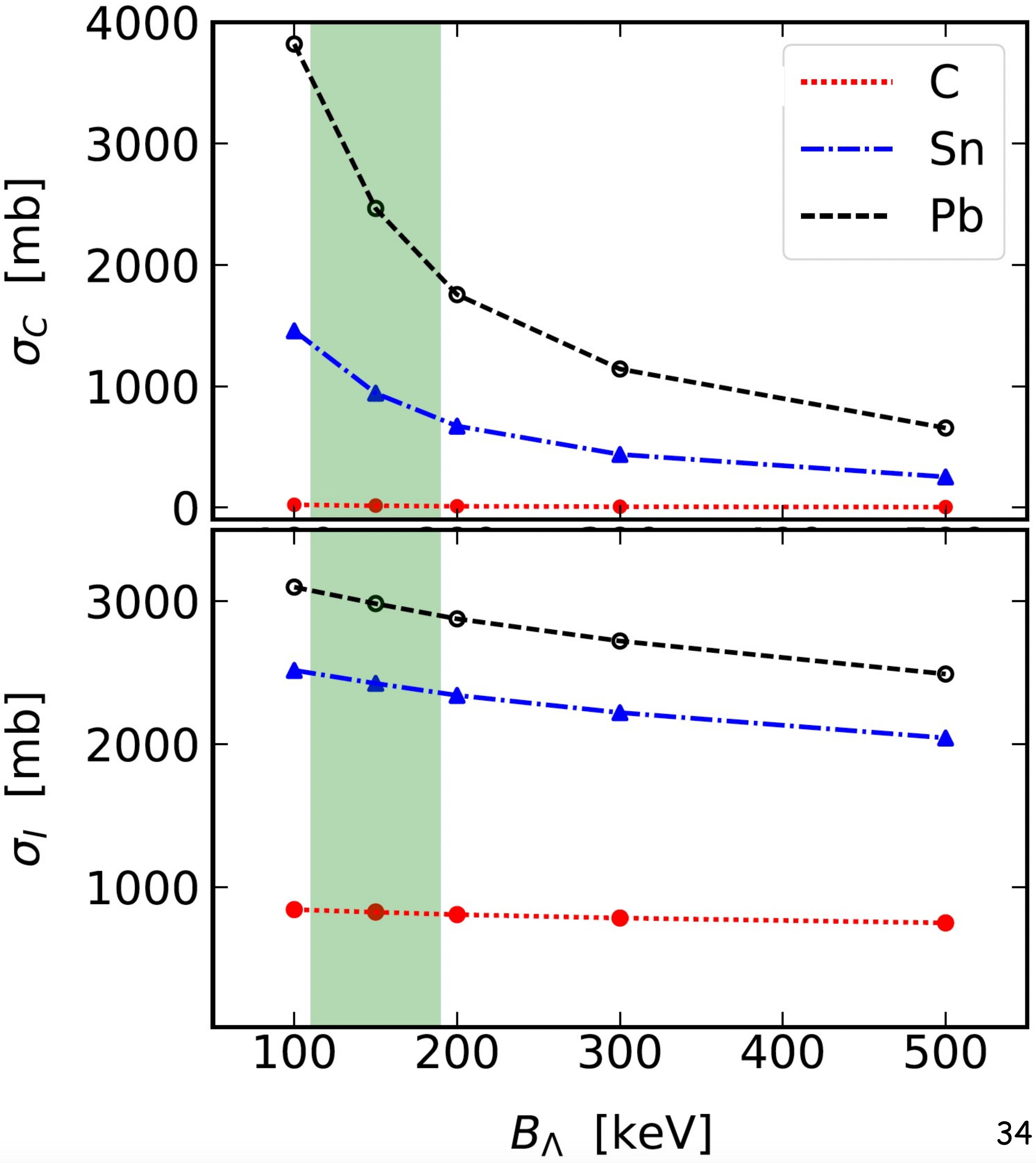
- Excellent agreement < 4% difference
- FSI small

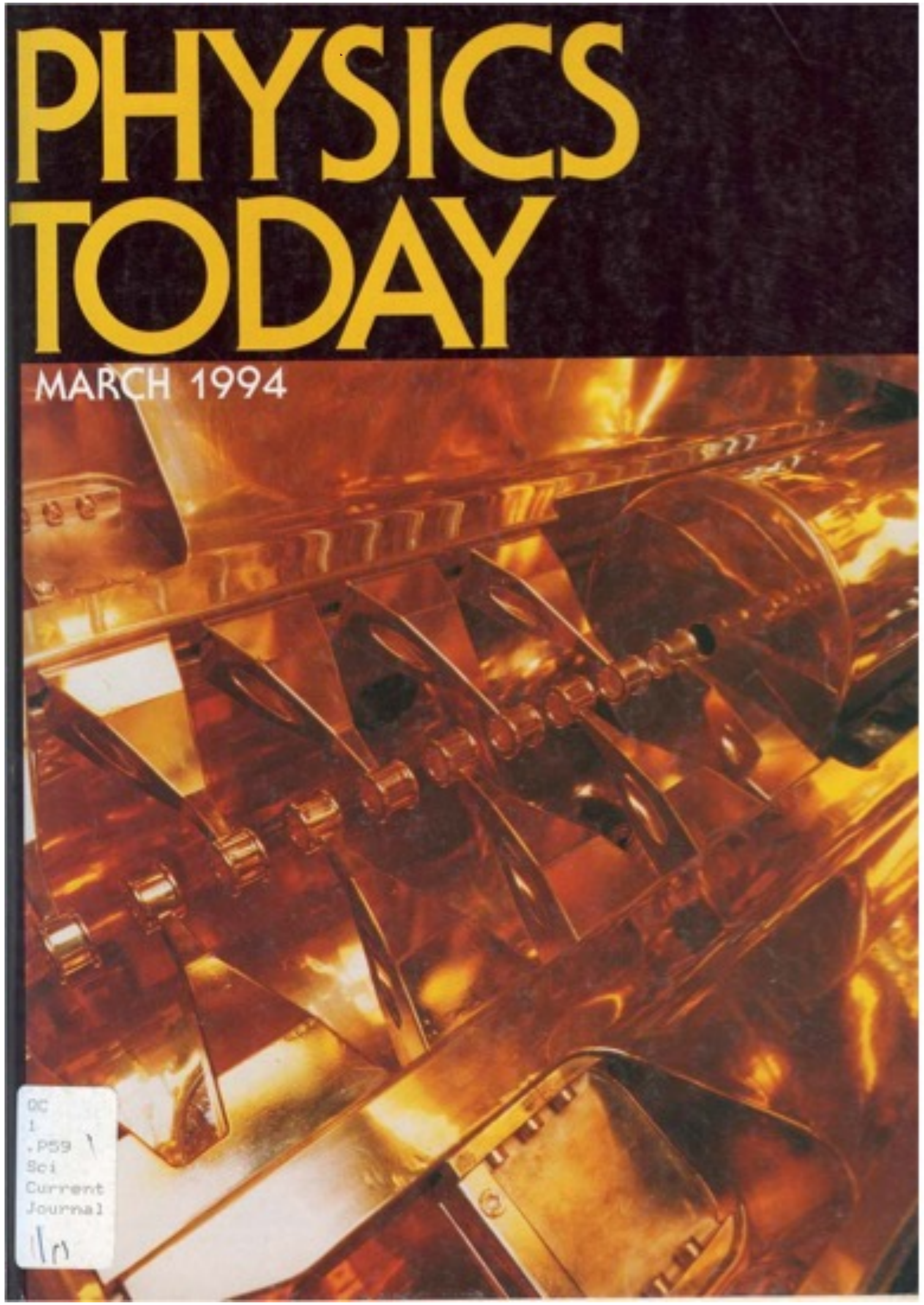
EM response of the hypertriton

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.





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

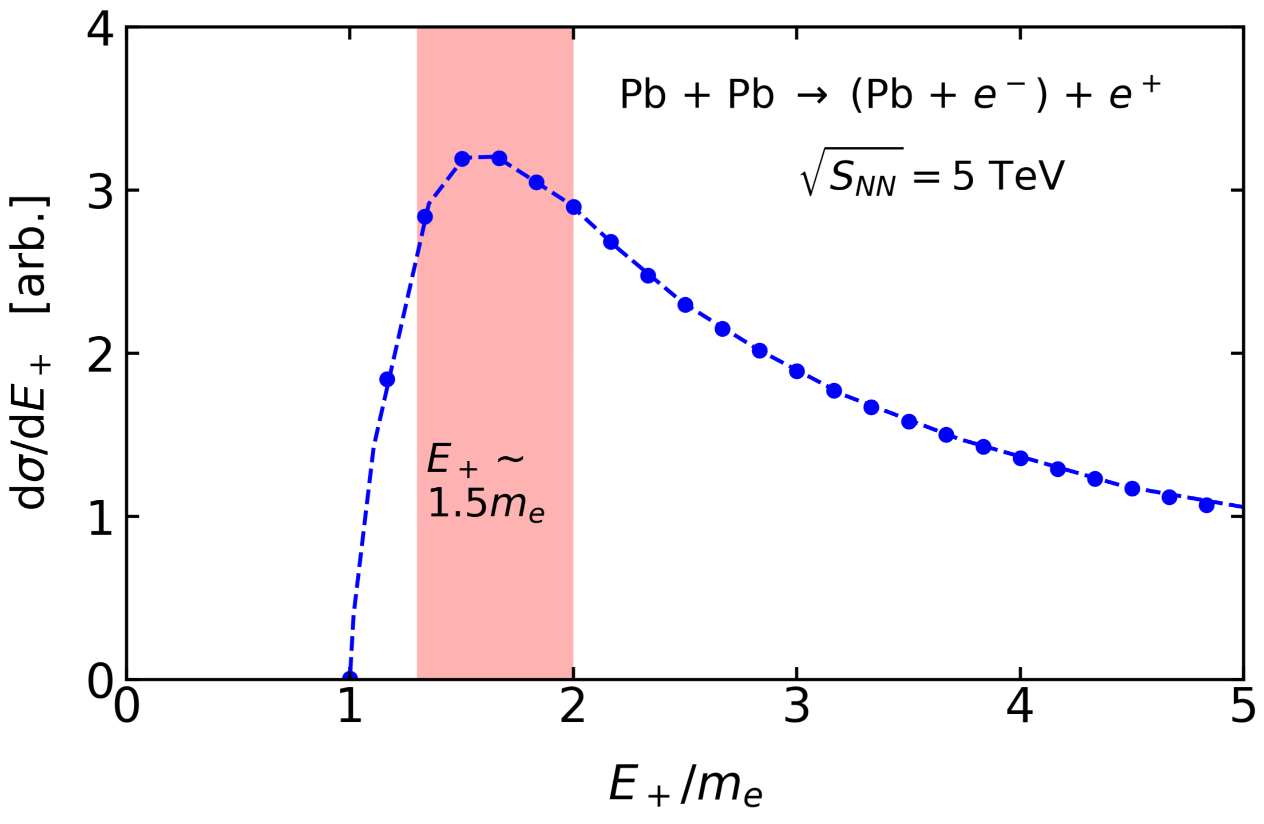
An increasing number of physicists are investigating nuclear collisions at relativistic energies. (See figure 1.) Accelerators completely devoted to the study of these collisions (such as the Relativistic Heavy Ion Collider at Brookhaven National Laboratory) are under construction. So are hadron colliders (such as the Large Hadron Col-

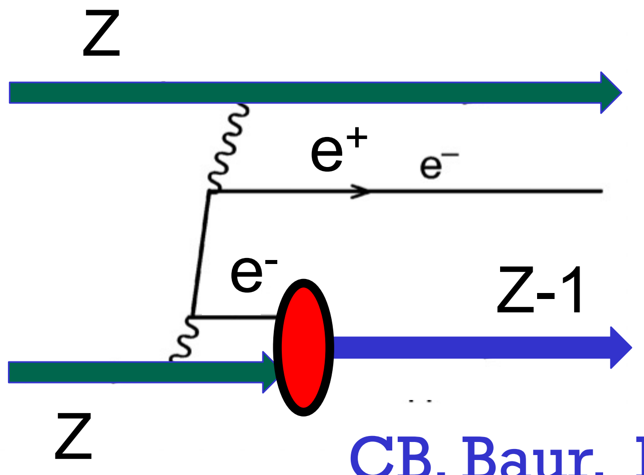
mately by $b/\gamma v$ and that the electric (or magnetic) field during this time interval is very intense: $E \simeq \gamma Ze/b^2$. The factor γ, which is $(1 - v^2/c^2)^{-1/2}$, is very large (on the order of 10^4–10^7) in relativistic heavy-ion colliders.

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.

Pair production with capture

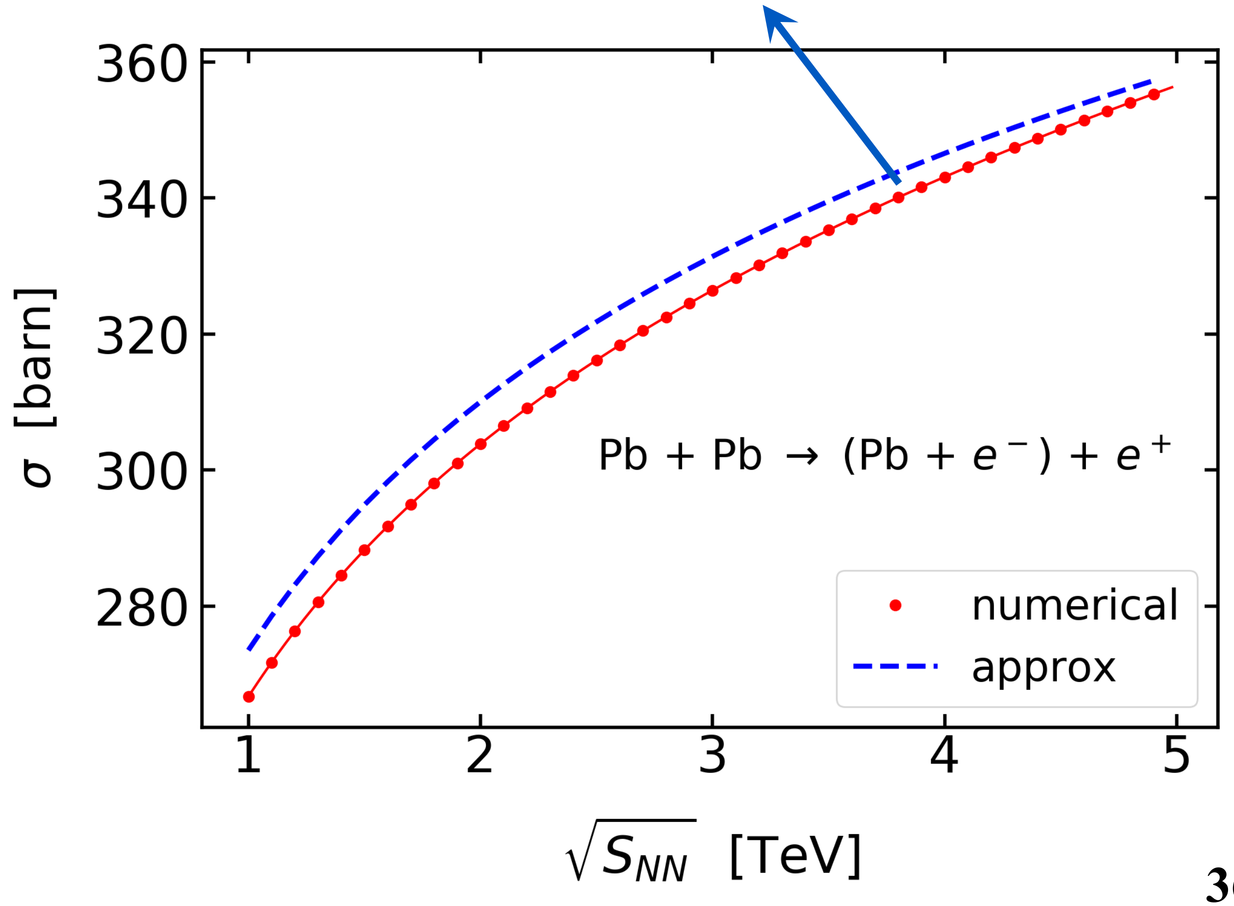




K-shell capture. Only 20% capture in higher orbitals.

CB, Baur, Phys. Rep. B 163, 299 (1988)

$$\sigma = \frac{33\pi}{10}\frac{(Z\alpha)^8}{m_e^2}\frac{1}{e^{2\pi Z\alpha}-1}[\ln\gamma - 2.051]$$



Electron capture → beam loss at CERN

Theory and calculation:

Electromagnetic physics at relativistic heavy ion colliders, for better and for worse

G. Baur and CB, Nucl. Phys. A505, 835 (1989)

Experiment

R. Bruce et al, 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

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.

Theory:

G. Baur, Phys. Lett. B 311, 343 (1993)

CERN (LEAR): 1996
9 events

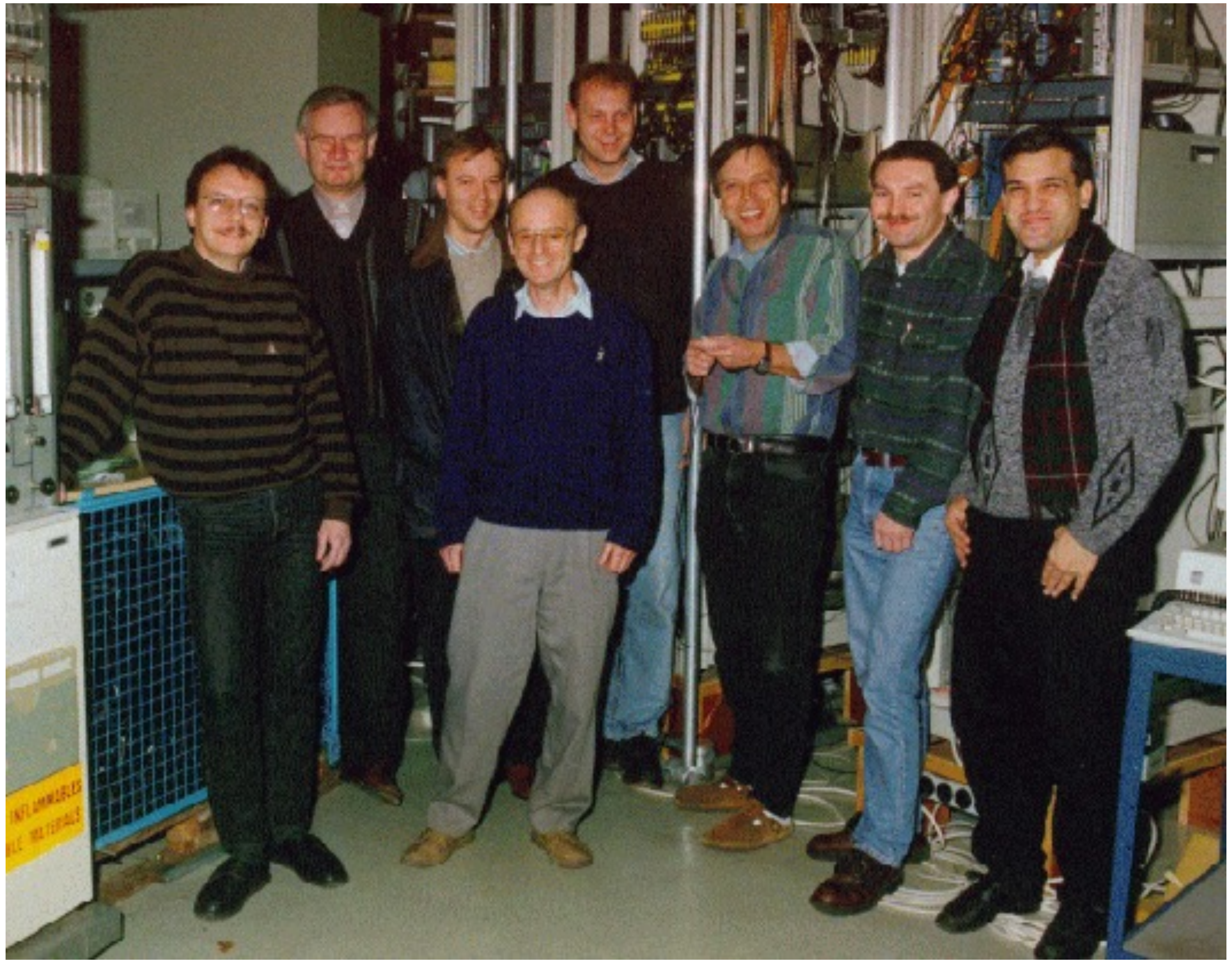
G. Baur *et al.*, Phys. Lett. B 368, 251 1996

Theory:

CB, G. Baur, Phys. Rev. D 58, 034005 (1998)

FERMILAB: 1998
57 events

G. Blanford et al., Phys. Rev. Lett. 80, 3037 (1998)



Why antihydrogen?

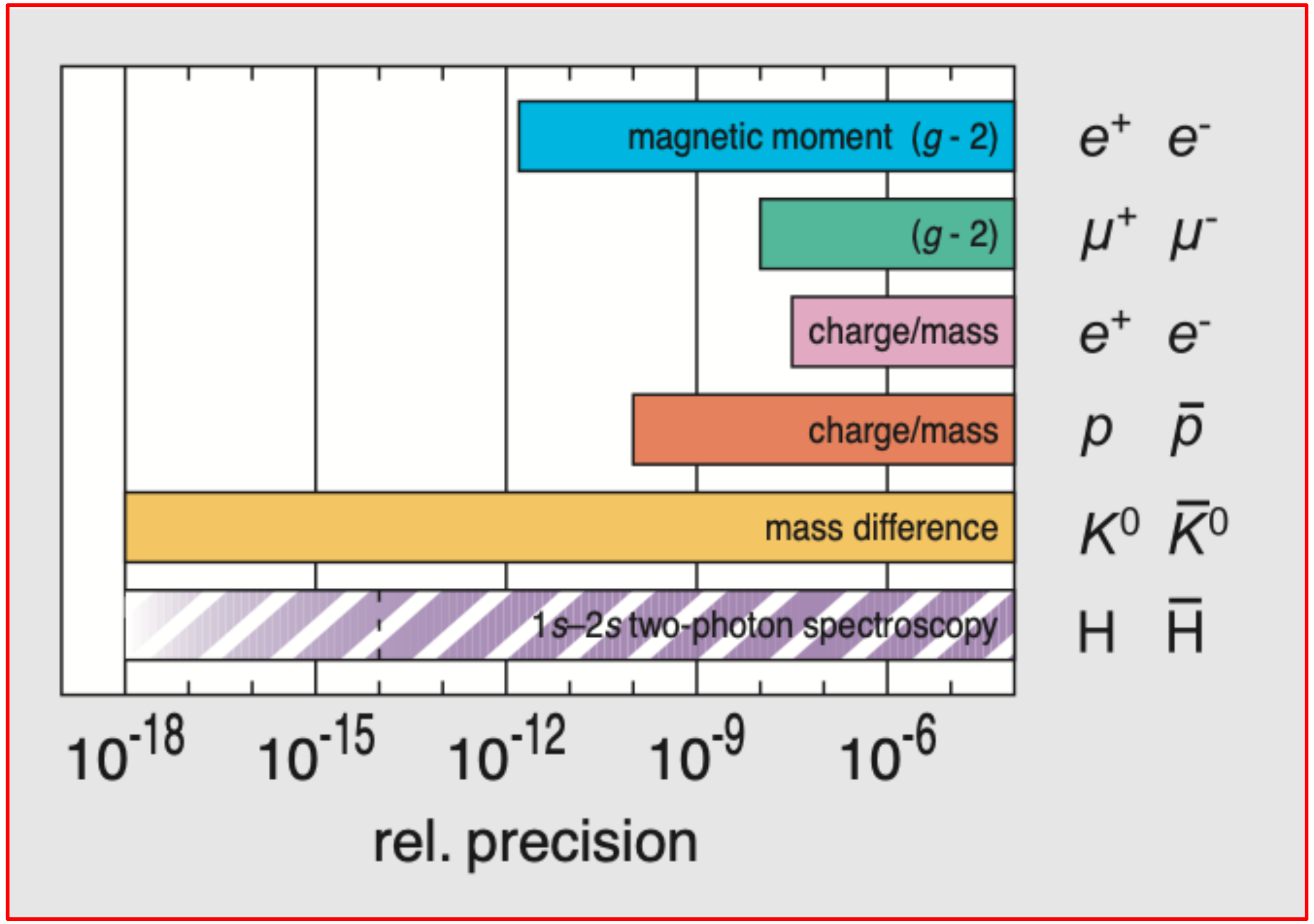
- QFT → CPT → Matter and antimatter are symmetric
  This assumes point like elementary particles (quarks and leptons). Experimentally < 10^{-16} cm.

- 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.

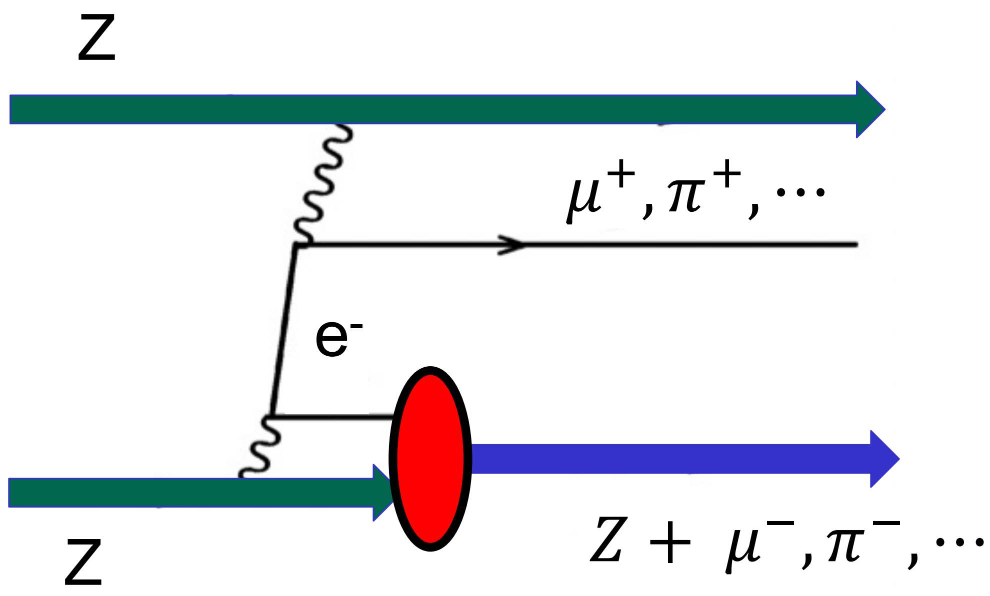
The symmetry of matter and antimatter must rest on experimental evidence.

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



Production of exotic Atoms

Bertulani, Ellerman, PRC 81, 044910 (2010)



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

Ingredients:

1. Perturbation theory
2. LO + NLO

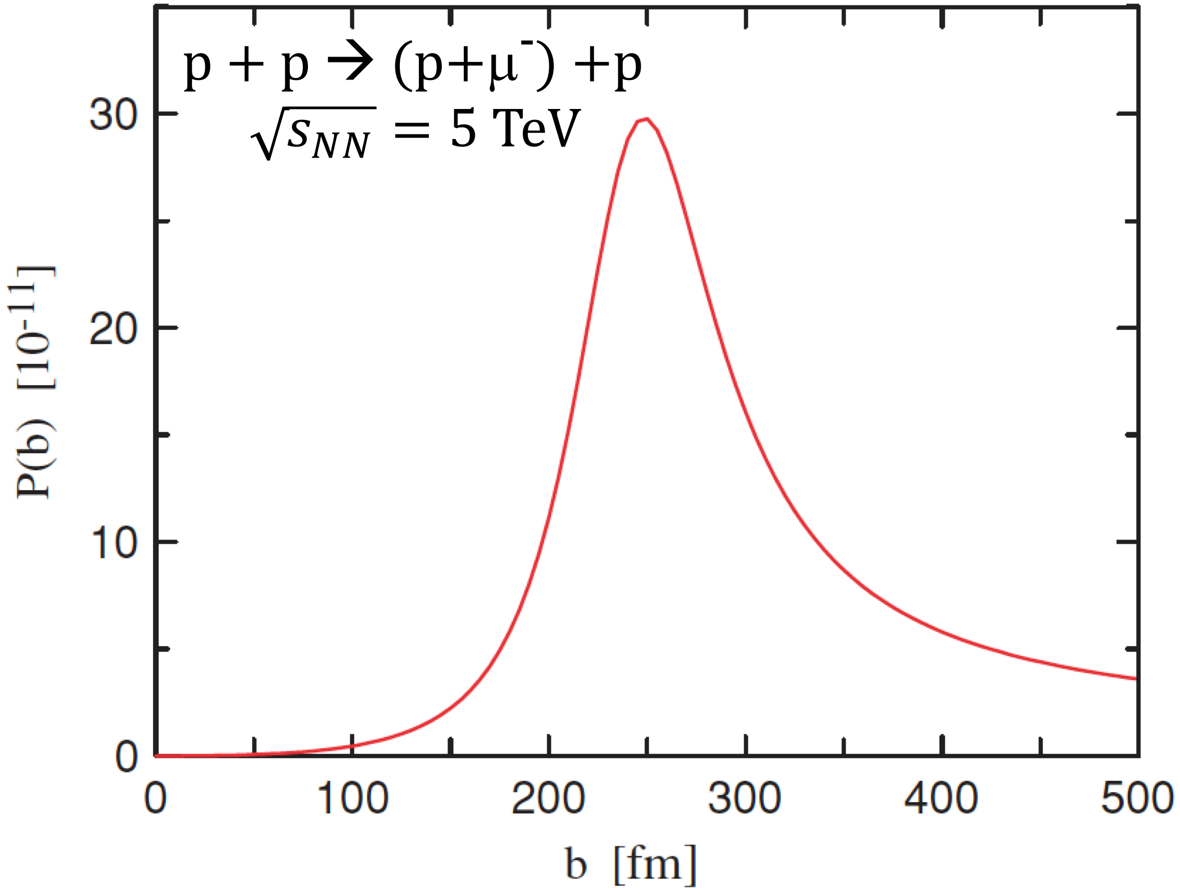
$$\Psi_+ = \left[\frac{2\pi a_+}{e^{2\pi a_+} - 1}\right]^{1/2} \left[e^{-i\mathbf{k}_+\cdot\mathbf{r}}\boldsymbol{v} + \Psi_{NLO}\right]$$

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

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

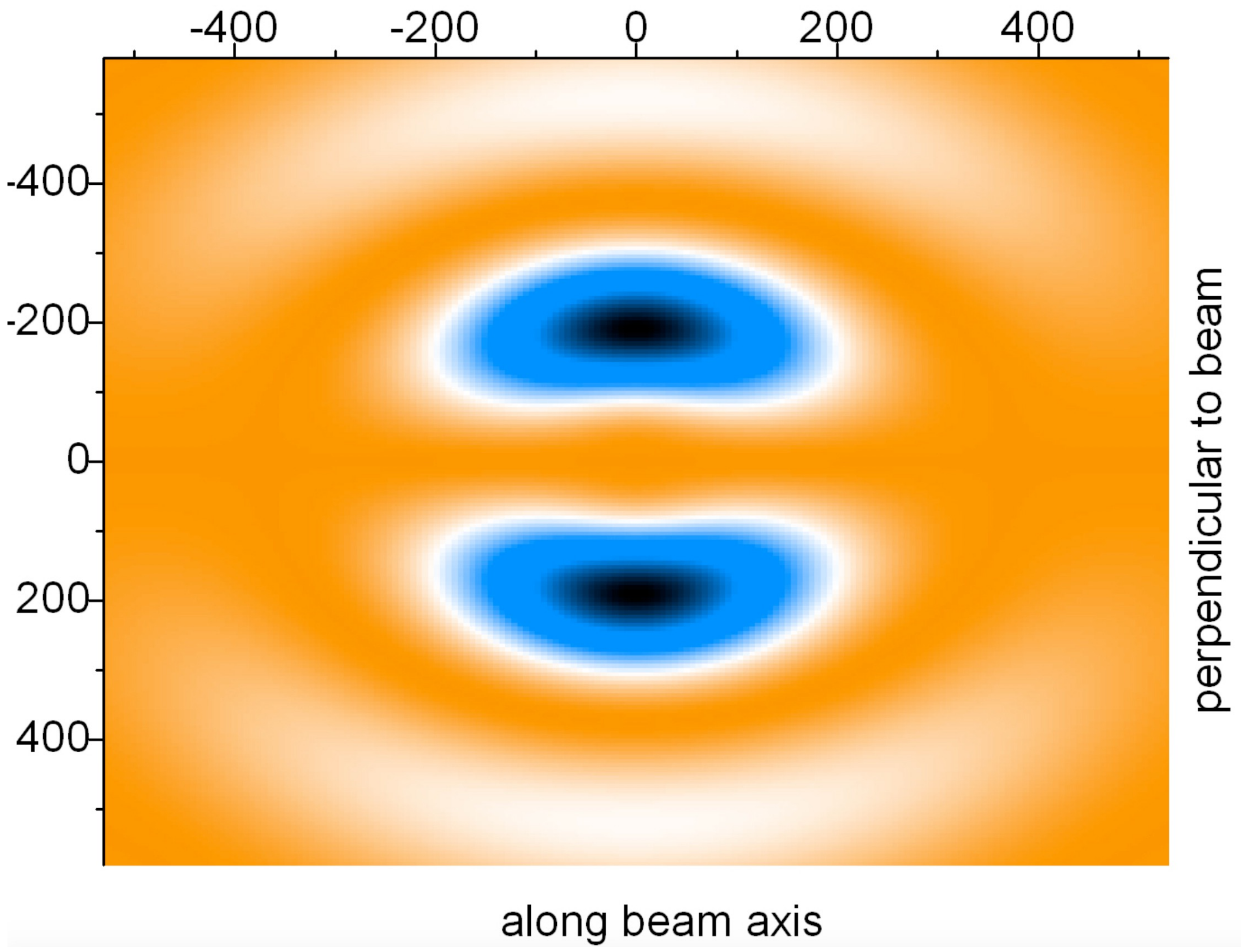
$$\Psi_- = \left[\frac{(Zm\alpha)^3}{\pi}\right]^{1/2}\left[1 + \frac{i}{2}(Z\alpha)\boldsymbol{\alpha}\cdot\frac{\mathbf{r}}{r}\right] e^{-(Zm\alpha)r}\, u$$

Production of exotic Atoms

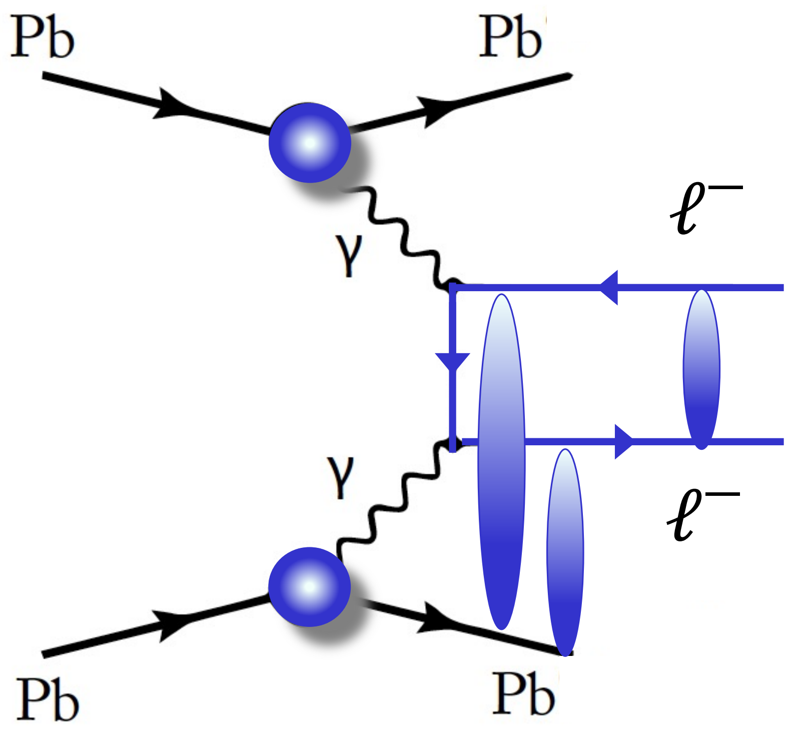


- Production probability maximum at impact parameters
  $b \sim a^{H}_{\mu,\pi,\ldots}$ (Bohr radius)
  e.g., $b \sim 255\ fm$ for muons

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



Free pair production

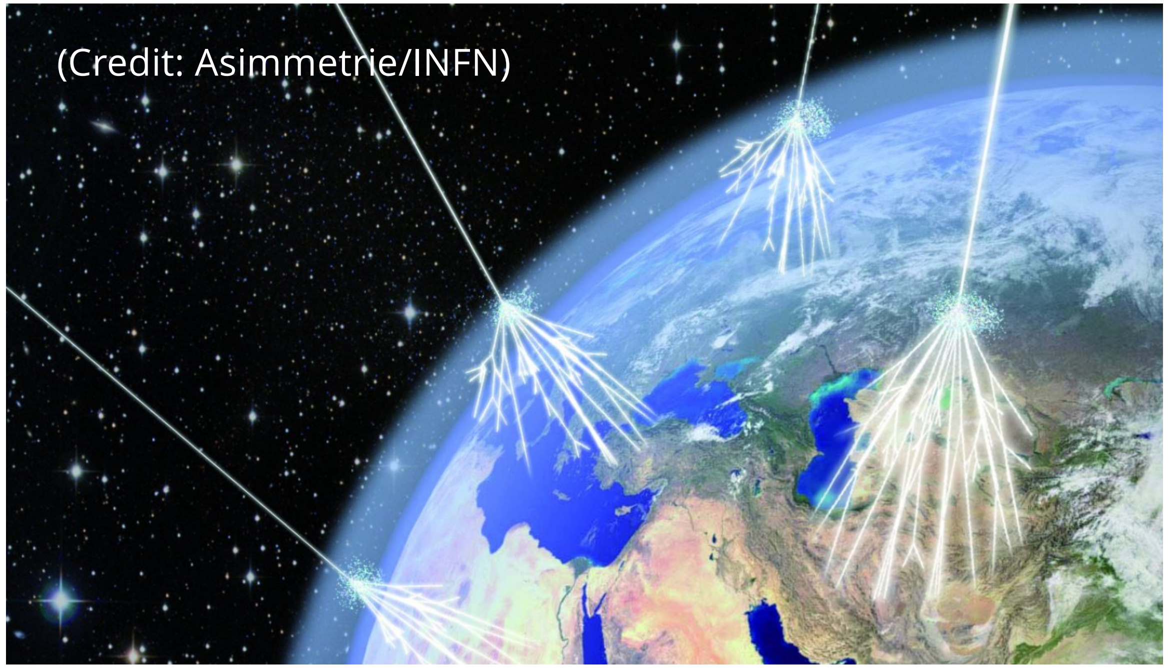


Because of Dirac (and cosmic rays):
Lifshitz (1934), Bhabha (1935), Racah (1937), Nishina, Tomonaga, Kobayashi (1935), Landau (1934)

$\sigma \sim 200\ kilobarns$

at the LHC (10^7 pairs/second)

Coulomb distortions important for large Z
CB, Baur, Phys. Rep. 163, 299 (1988)

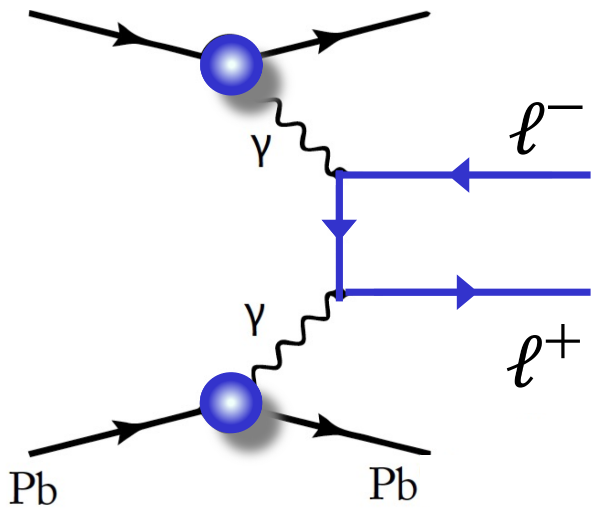


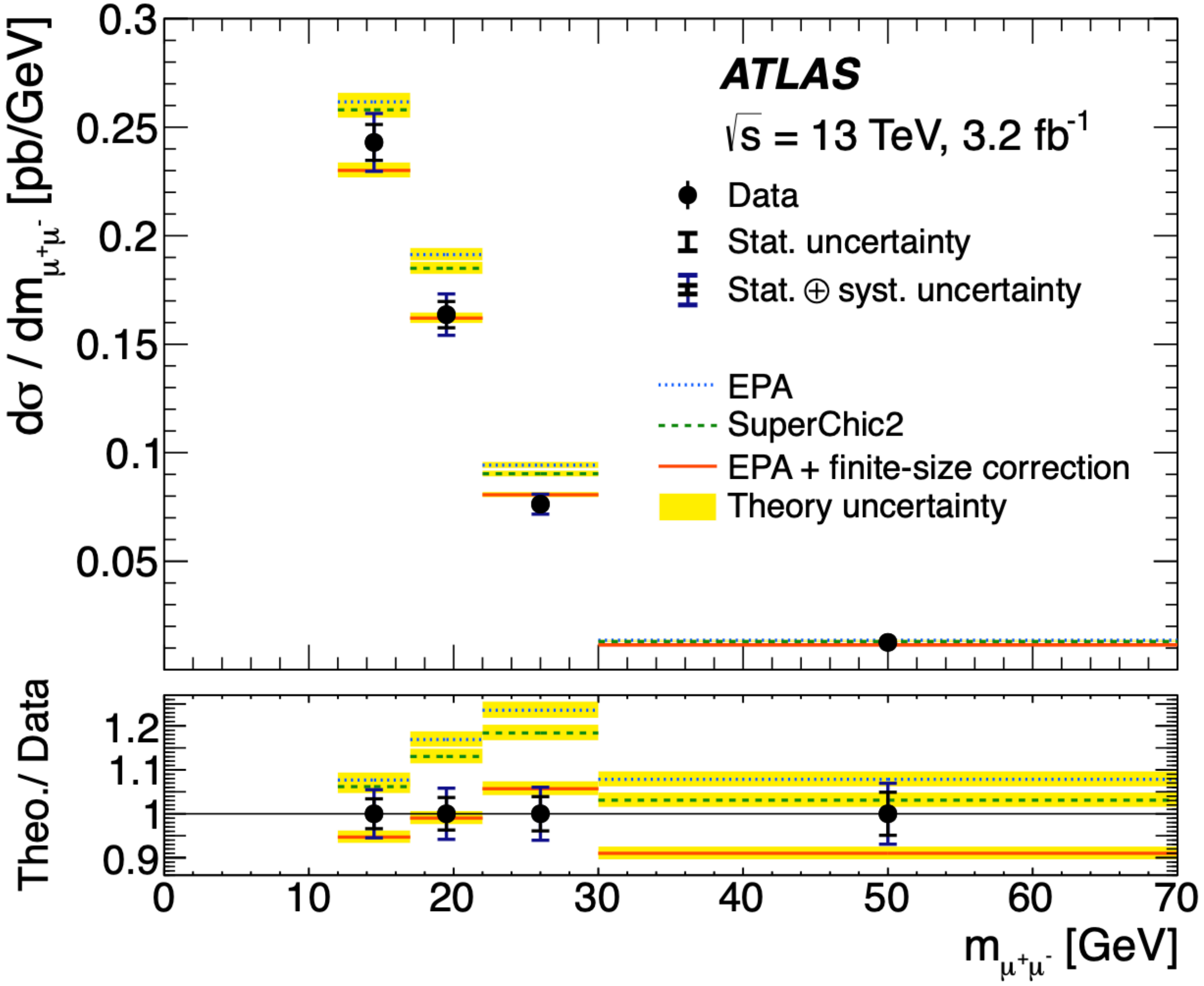
Higher order corrections and multiple pair production
Baur et al., Phys. Rep. 364, 359 (2002)

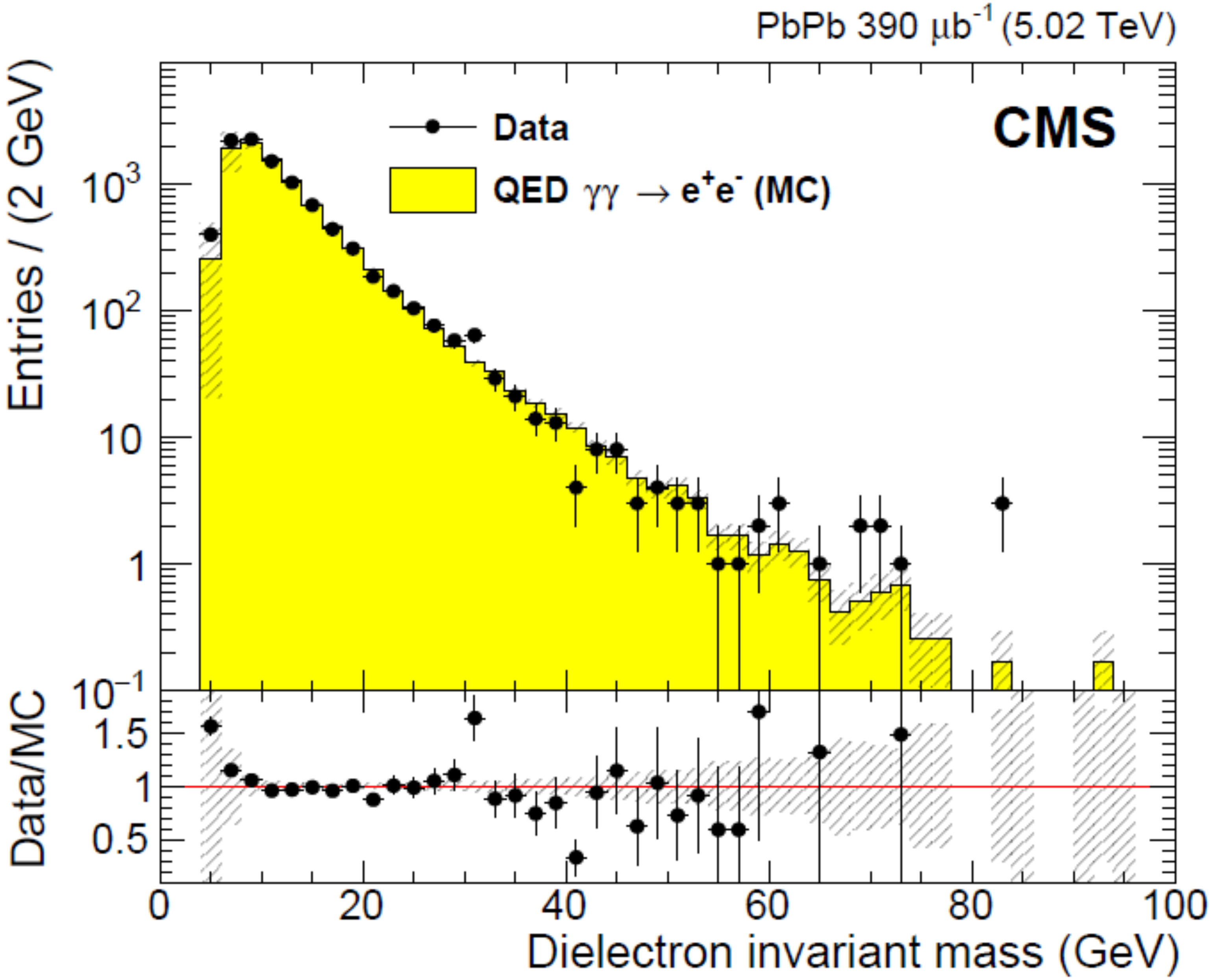
Cosmic rays experiments difficult

Laboratory experiments difficult and inconclusive for many decades

Free pair production



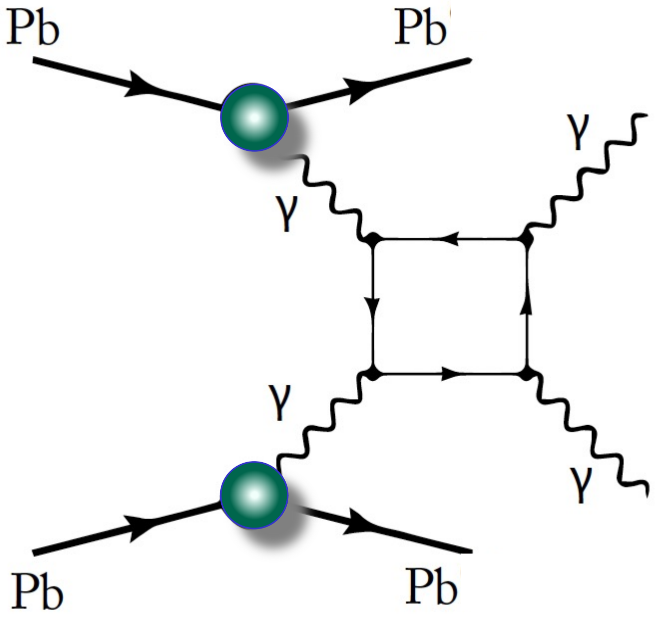




CMS collaboration, JHEP 1201, 052 (2012)

ATLAS collaboration, PLB 777, 303 (2018)

Light-by-light scattering in UPCs



First proposed in

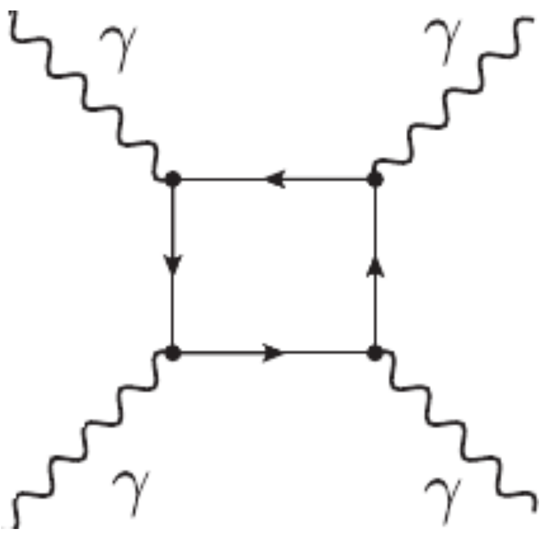
Electromagnetic physics at relativistic heavy ion colliders, for better and for worse

G. Baur and CB, Nucl. Phys. A505, 835 (1989)

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

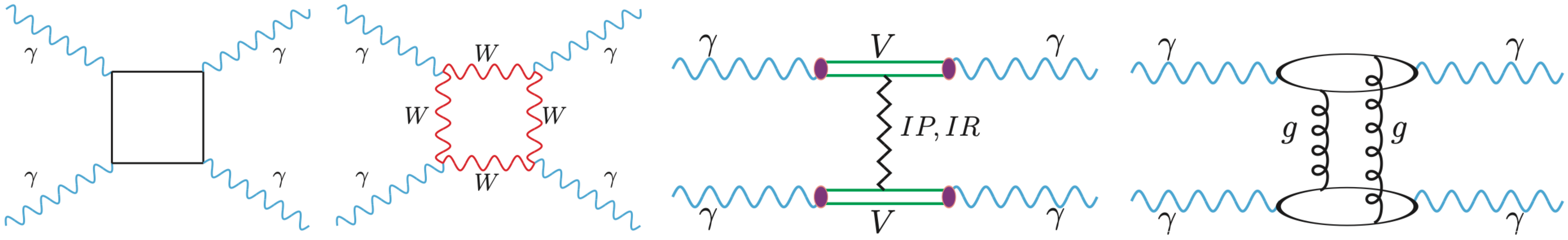
$$x = \frac{\gamma}{R m_e}$$

σ ~ 10^8 larger than in pp or e^+e^- collisions, although tiny (400 nb)



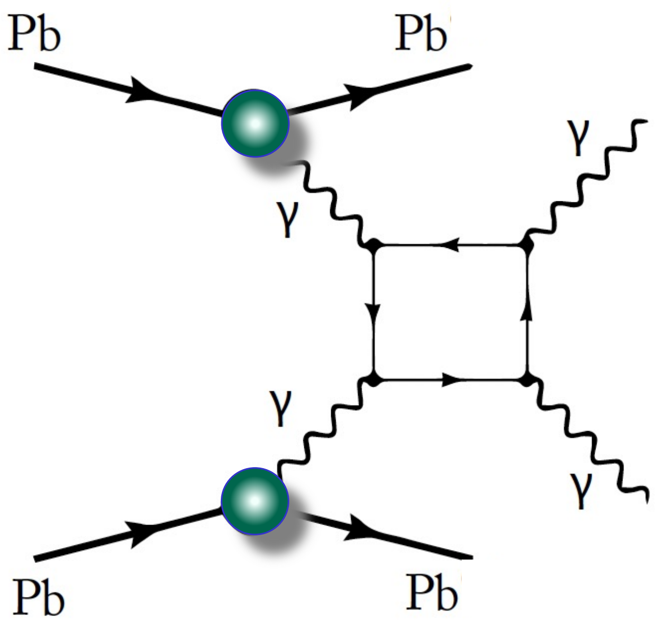
~ $\mathcal{O}(\alpha^4)$

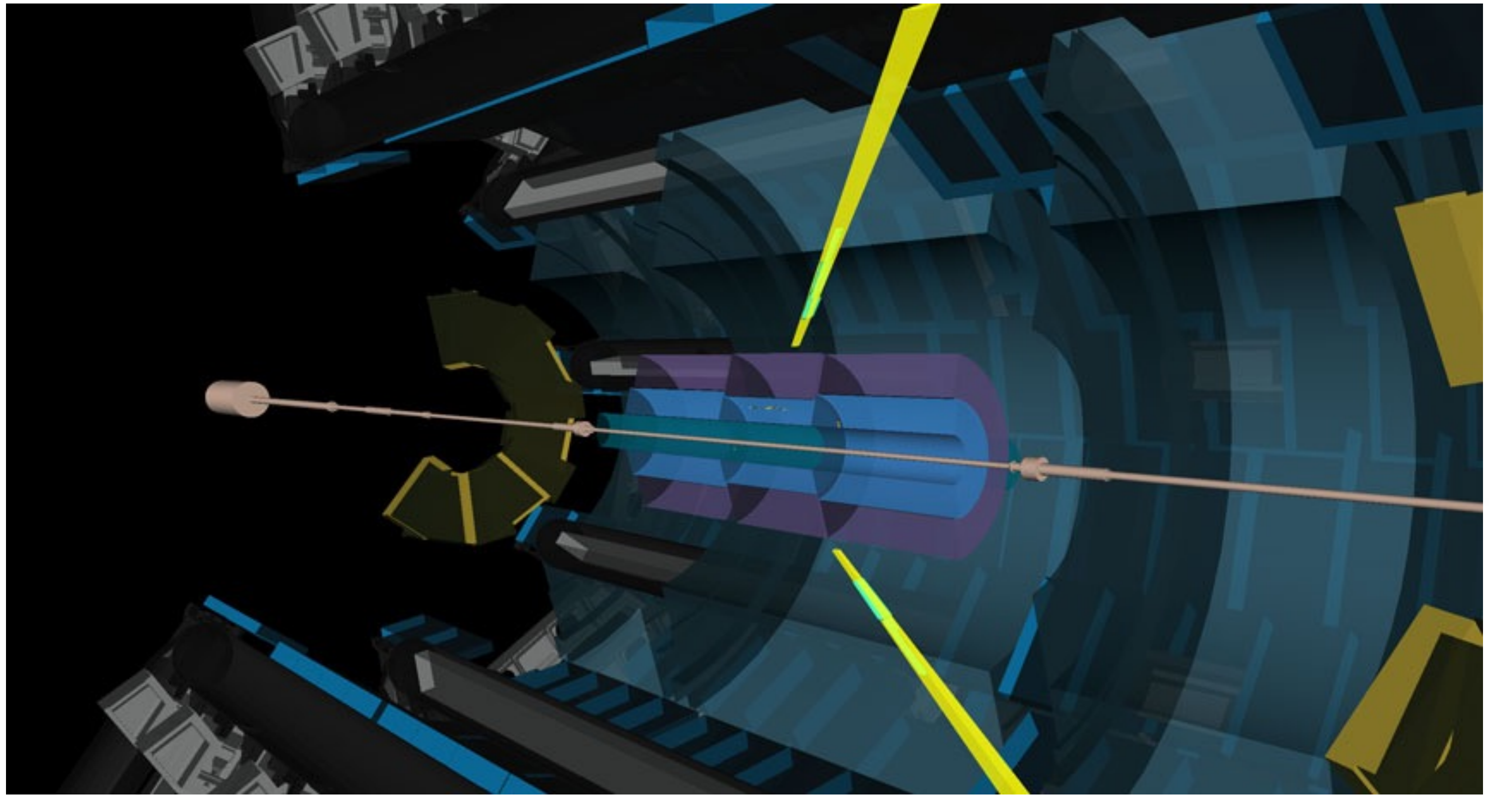
- Box might contain virtual charged particles (q,ℓ,W) from the SM.
- New charged particles (s-particles, monopoles, unparticles,...)

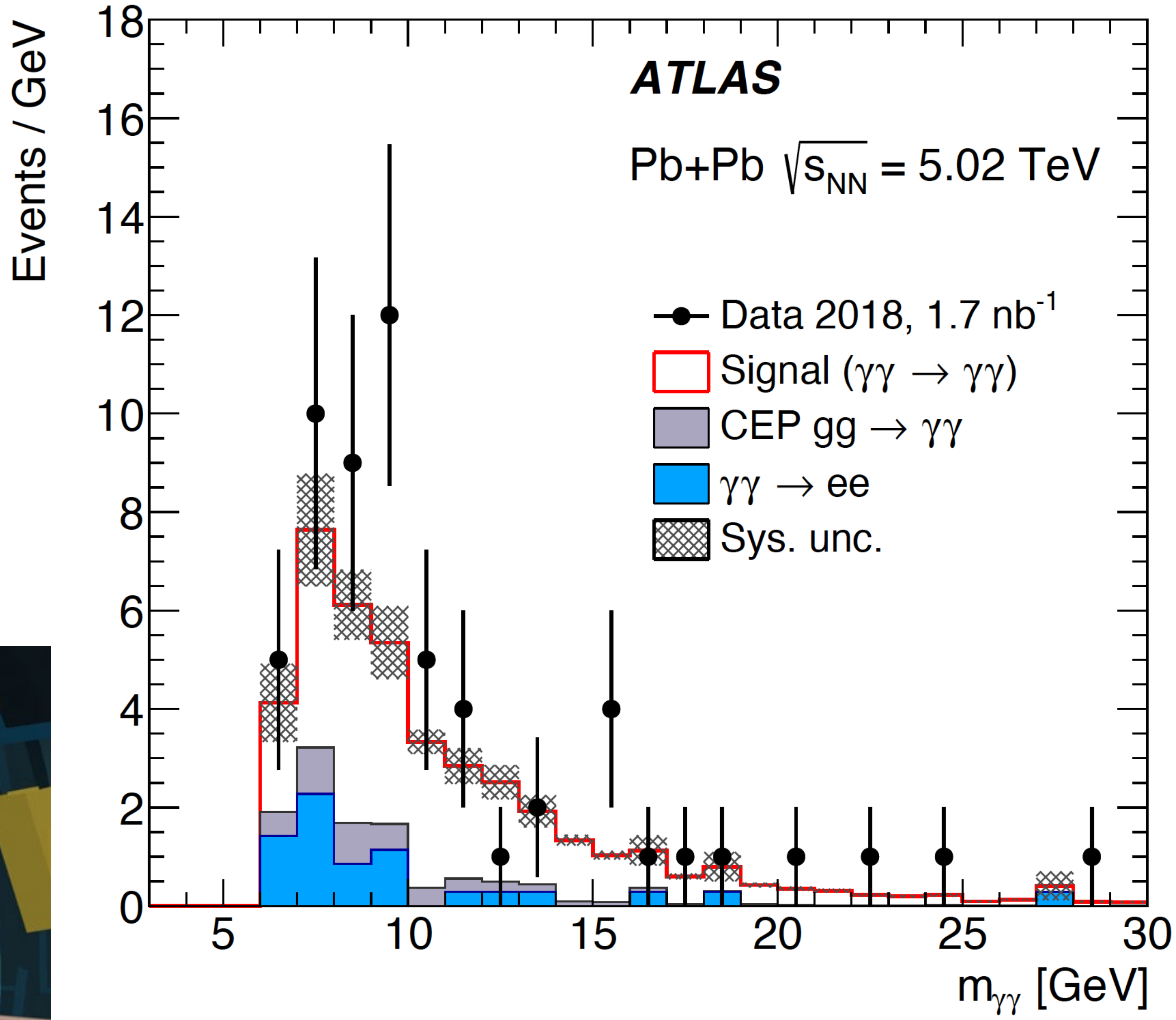


Kłusek-Gawenda, Lebiedowicz, Szczurek, PRC 93, 044907 (2016)

Light by light scattering

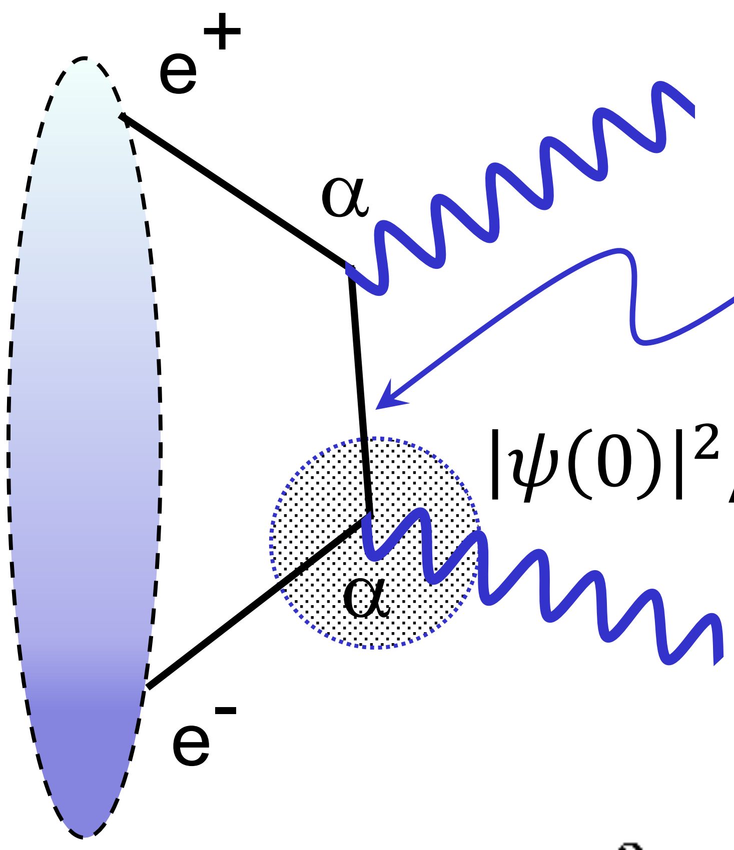






ATLAS collaboration,
Nature Physics 13, 852 (2017)

$\gamma\gamma \to$ bound states



$e^+e^- \to \gamma\gamma$ rate = α^2 . overlap probability / interaction time

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

$|\psi(0)|^2/m_e^3$

$\Delta t = 1/m_e$

$$\Gamma \sim \alpha^2 |\psi(0)|^2/m_e^2$$

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

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

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

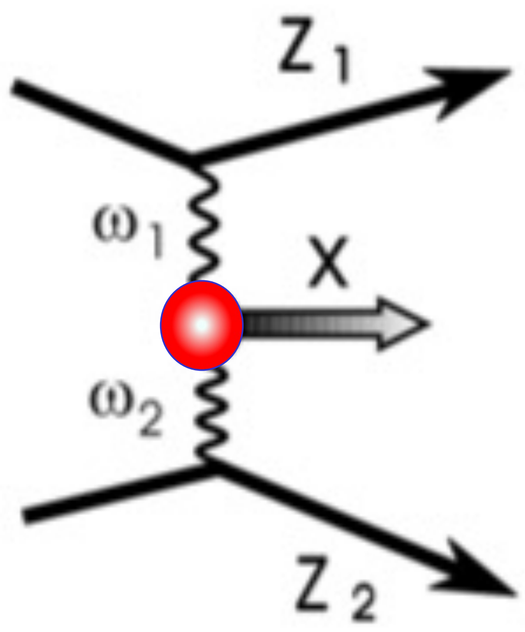
$$\Gamma_{\gamma\gamma}^{(J=2)} = (2J+1)\Gamma_{\gamma\gamma}^{(J=0)} = 5\,\Gamma_{\gamma\gamma}^{(J=0)}$$

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

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

$\gamma\gamma$ → bound states

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

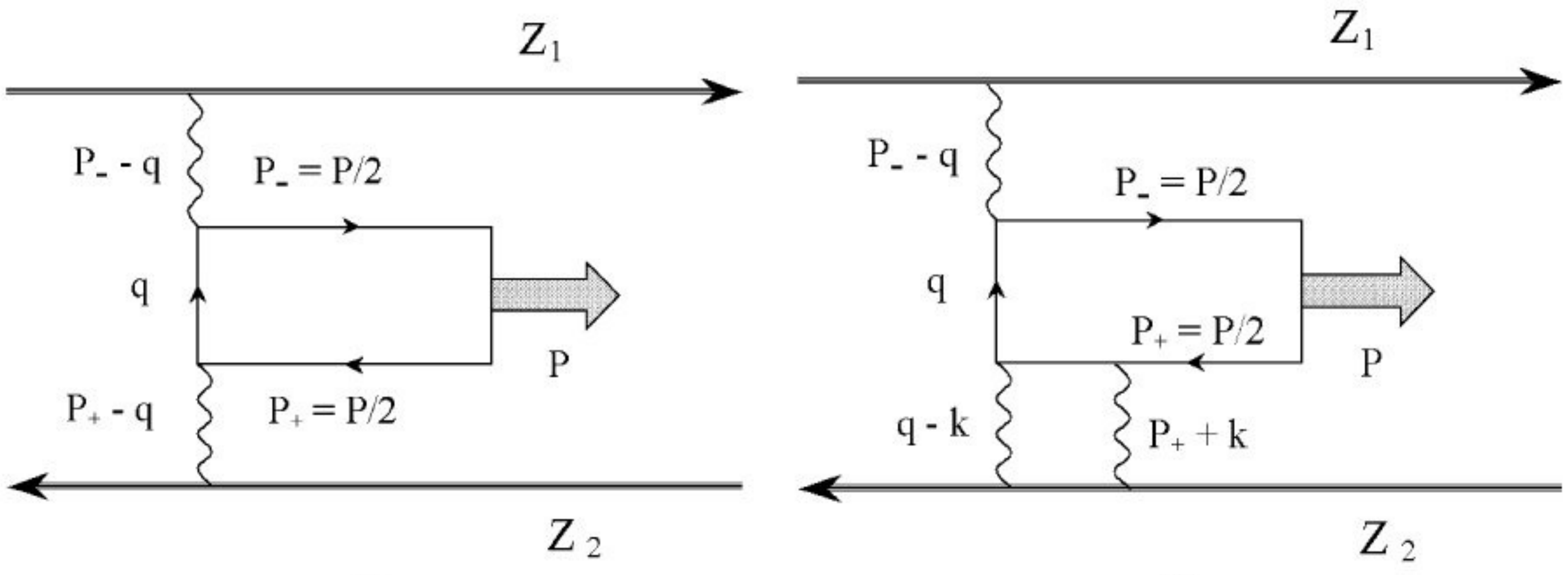


$$\sigma^X_{\gamma\gamma}(\omega_1,\omega_2) = 8\pi^2(2J+1)\frac{\Gamma_{X\rightarrow\gamma\gamma}}{m_X}\delta(\omega_1\omega_2 \longrightarrow m_X^2)$$

EPA method: G. Baur and CB, Nucl. Phys. A505, 835 (1989)

$$\sigma_{ZZ\rightarrow ZZ+X} = \int \frac{n_1(\omega_1)}{\omega_1}\frac{n_2(\omega_2)}{\omega_2}\sigma^X_{\gamma\gamma}(\omega_1,\omega_2)d\omega_1 d\omega_2$$

Or calculate corresponding Feynman diagrams and use Weisskopf-Royen projection



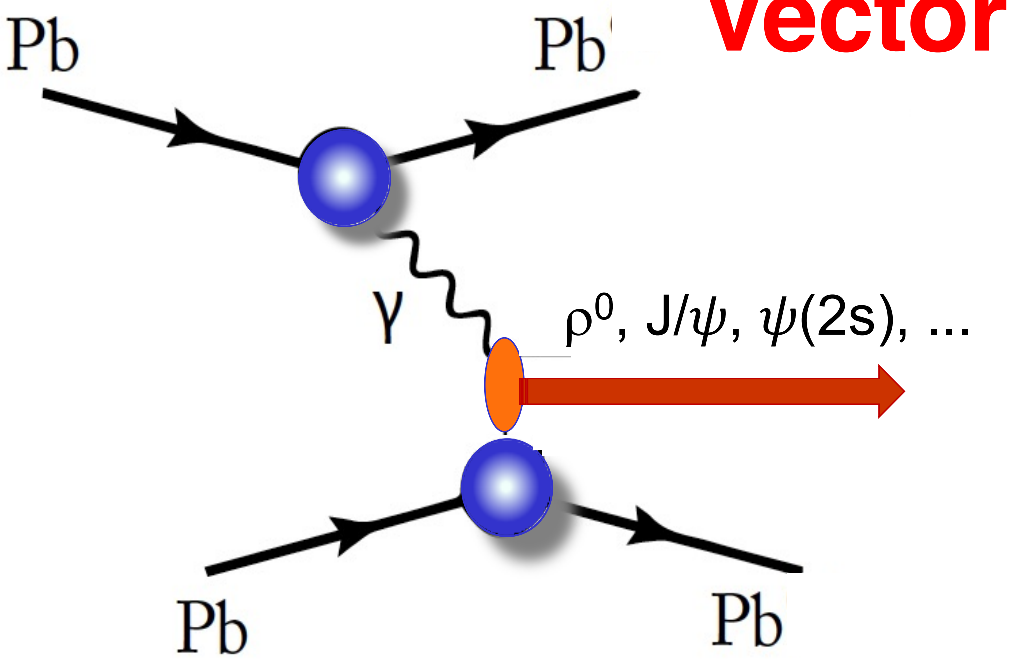
(a) (b)

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

Vector meson production (direct, unresolved)

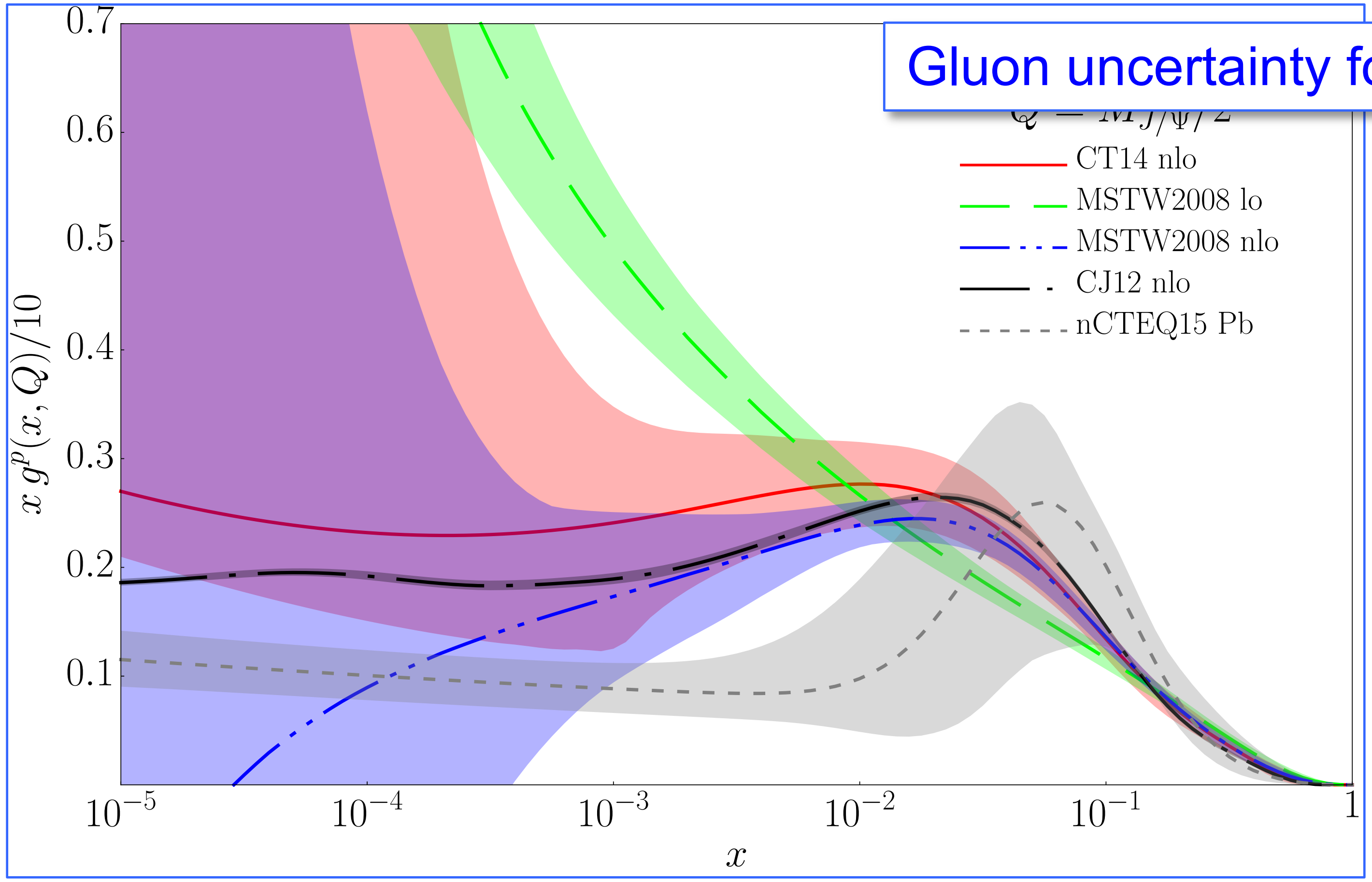


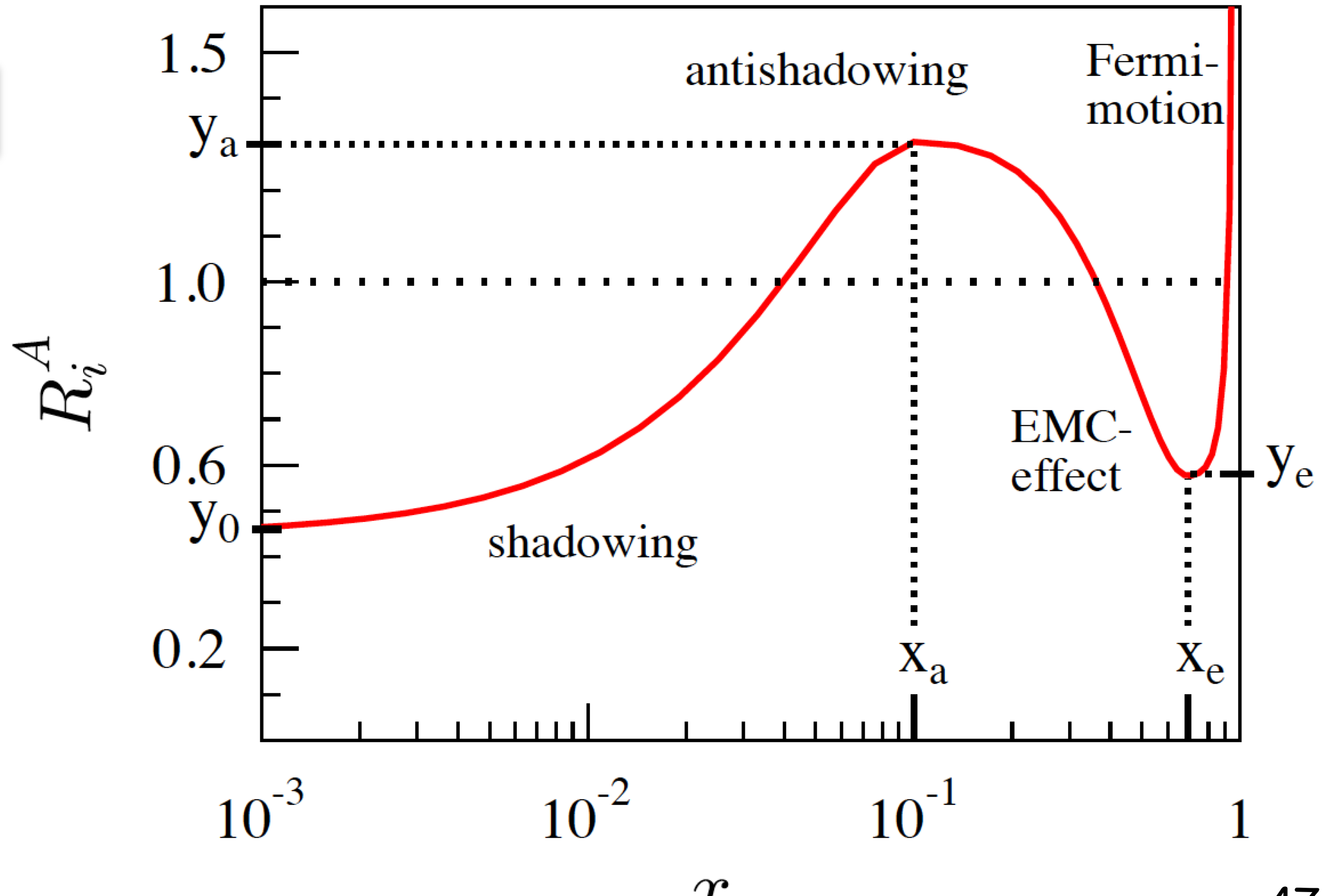
$$\left.\frac{d\sigma^{\gamma A\to VA}}{dt}\right|_{t=0} = \frac{16\pi^3\alpha_s\Gamma_{ee}}{3\alpha M_V^5}\left[xg_A(x,Q^2)\right]^2$$

gluons

Goncalves, CB, PRC65, 054905 (2002)
Adeluyi, CB, PRC 85, 044904 (2012); C 85, 044904 (2012)

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

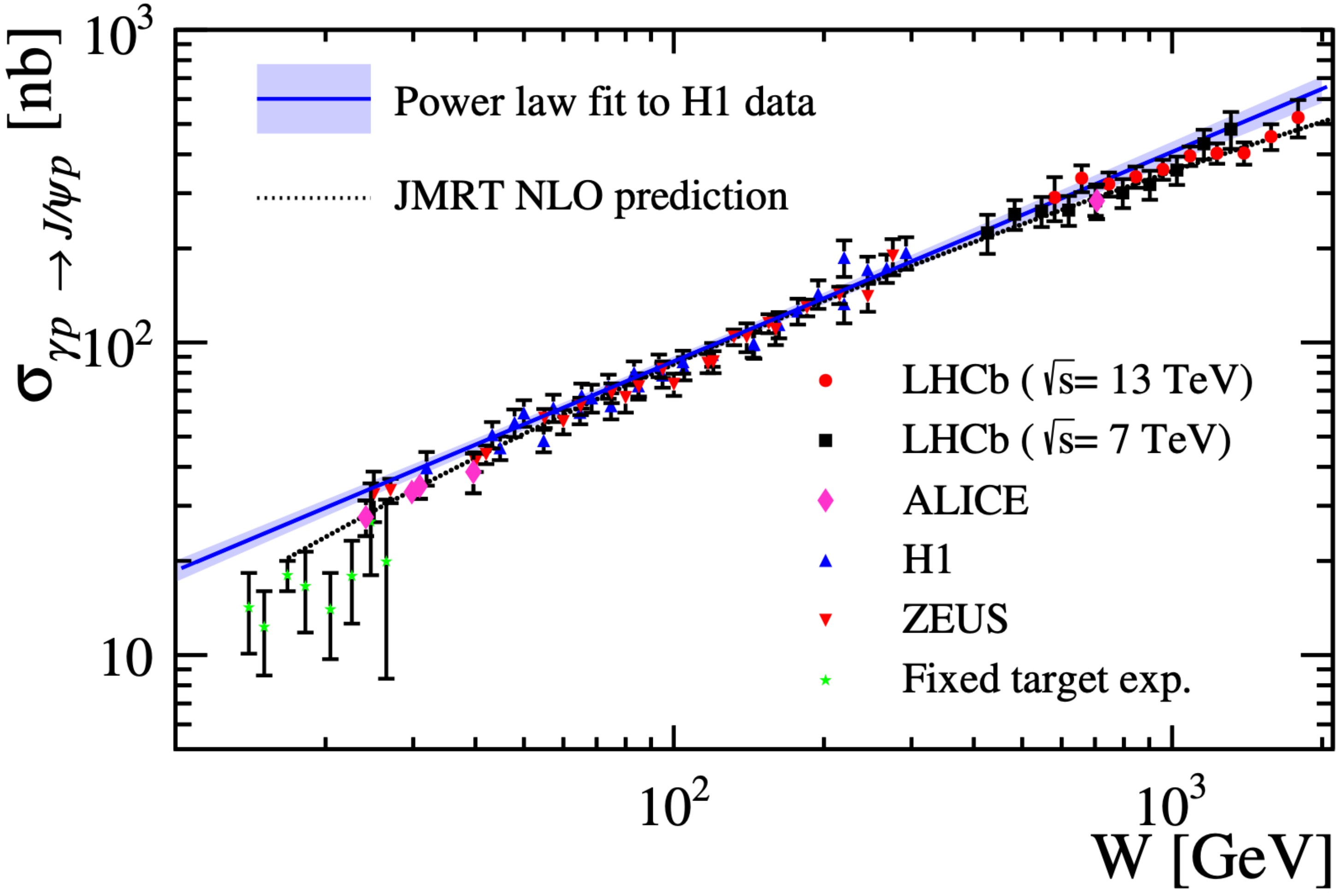


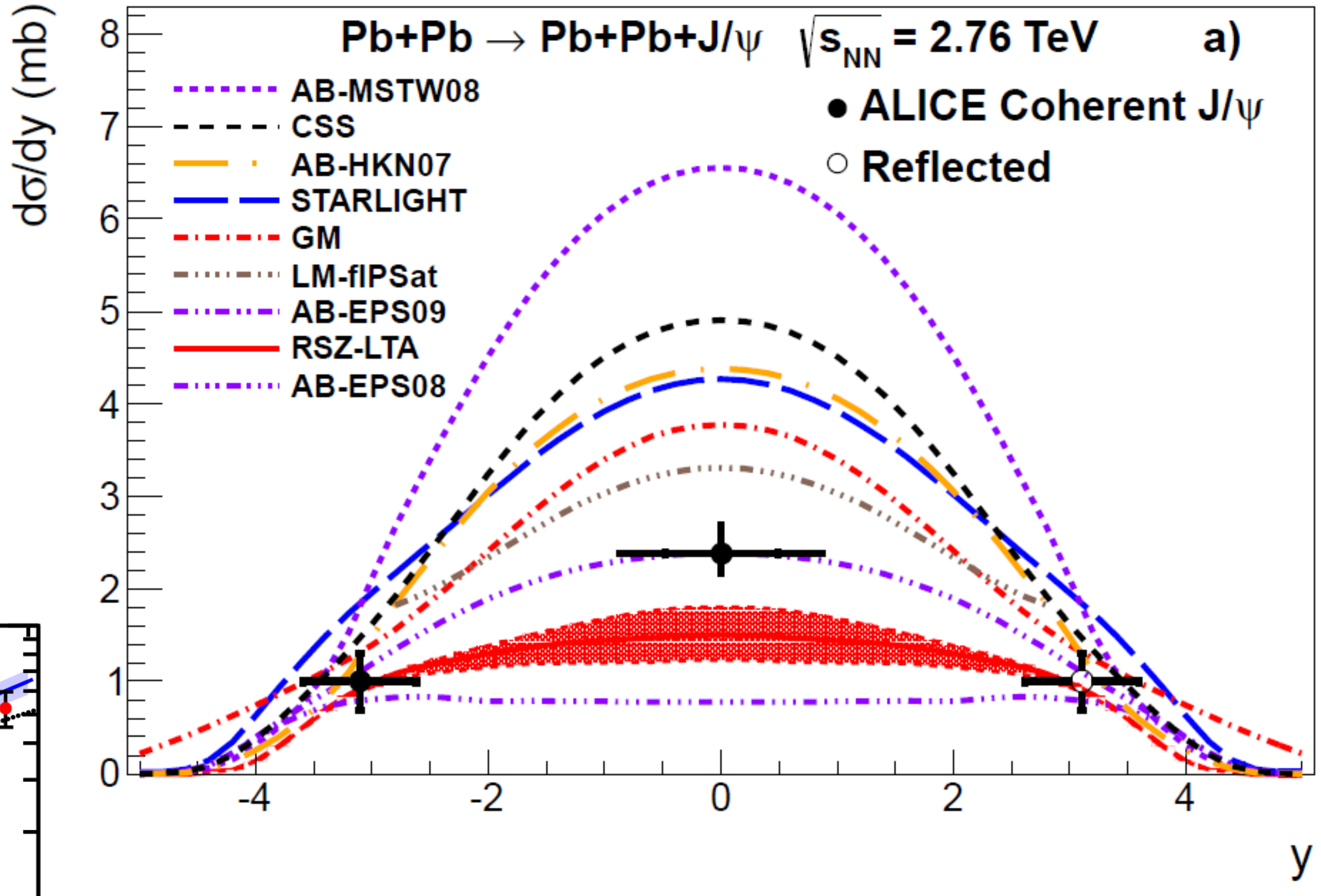


J/ψ production & PDFs

ALICE collaboration,
PLB 718, 1273 (2013)
Eur. Phys. J. C73, 2617 (2013)

CMS collaboration,
PLB 772 489 (2017)





LHCb collaboration,
JHEP 10, 167 (2018)

The future was bright

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How to continue?

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 |η|<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).

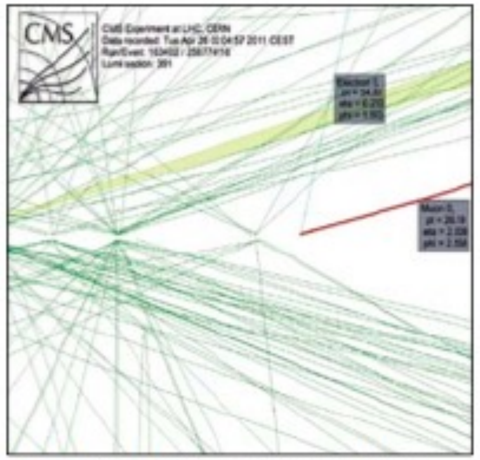


Fig. 1. Above: Proton–proton collisions recorded by CMS at $\sqrt{s}$=7 TeV, featuring candidates for the exclusive two-photon production of a W^+W^- pair, where one W boson has decayed into an electron and a neutrino, the other into a muon and a neutrino.

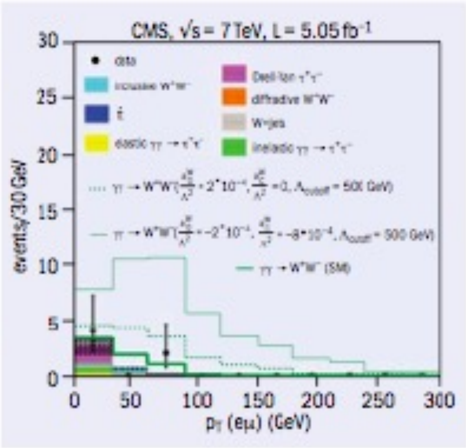


Fig. 2. Top right: The p_T distribution of eμ pairs in events with no extra tracks compared with the Standard Model expectation (thick green line) and predictions for anomalous quartic gauge couplings (dashed green histograms).

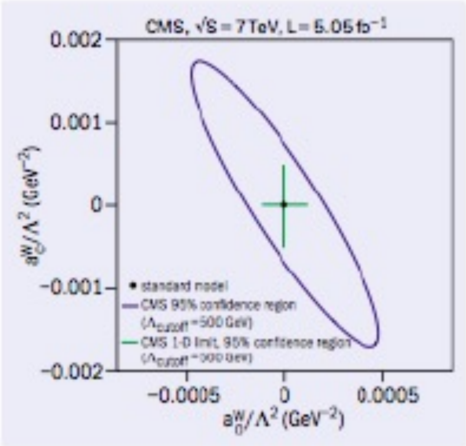


Fig. 3. Right: Limits on anomalous quartic γγWW couplings.

● **Further reading**

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

Search for New Physics (SUSY particles)

Baur et al., Phys. Rep. 364, 359 (2002)

MSSM The Standard Model and supersymmetric particles.

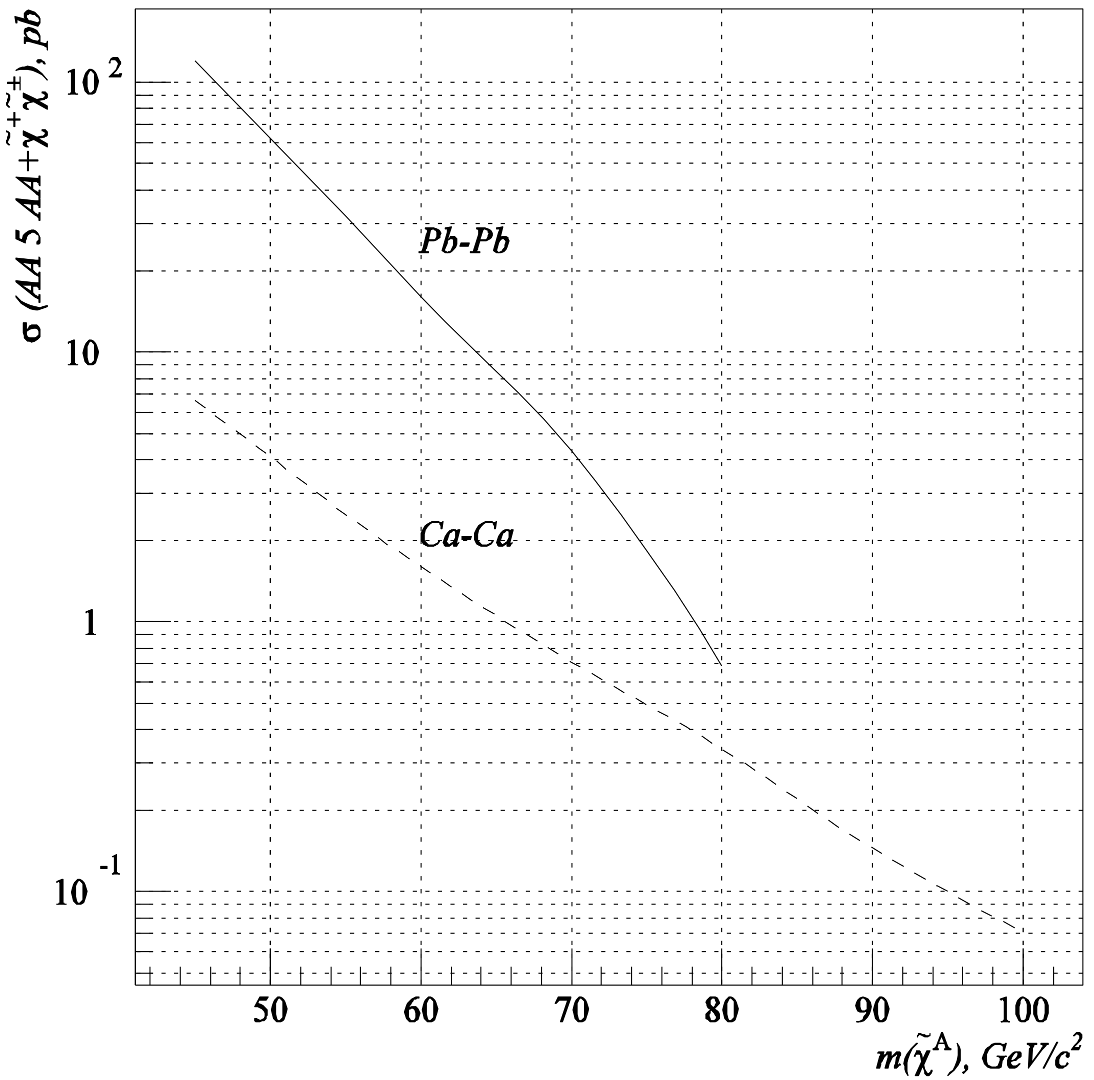
Standard Model	Supersymmetry
γ, Z^0, h^0, H^0	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
W^+, H^+	$\tilde{\chi}_1^+, \tilde{\chi}_2^+$
$e^-, \nu_e, \mu^-, \nu_\mu, \nu_\tau$	$\tilde{e}_R^-, \tilde{e}_L^-, \tilde{\nu}_e, \tilde{\mu}_R^-, \tilde{\mu}_L^-, \tilde{\nu}_\mu, \tilde{\nu}_\tau$
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

(LHC)

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



(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

Papageorgiu, PRD 40, 92 (1989)

Extra dimensions (Kaluza-Klein):

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

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

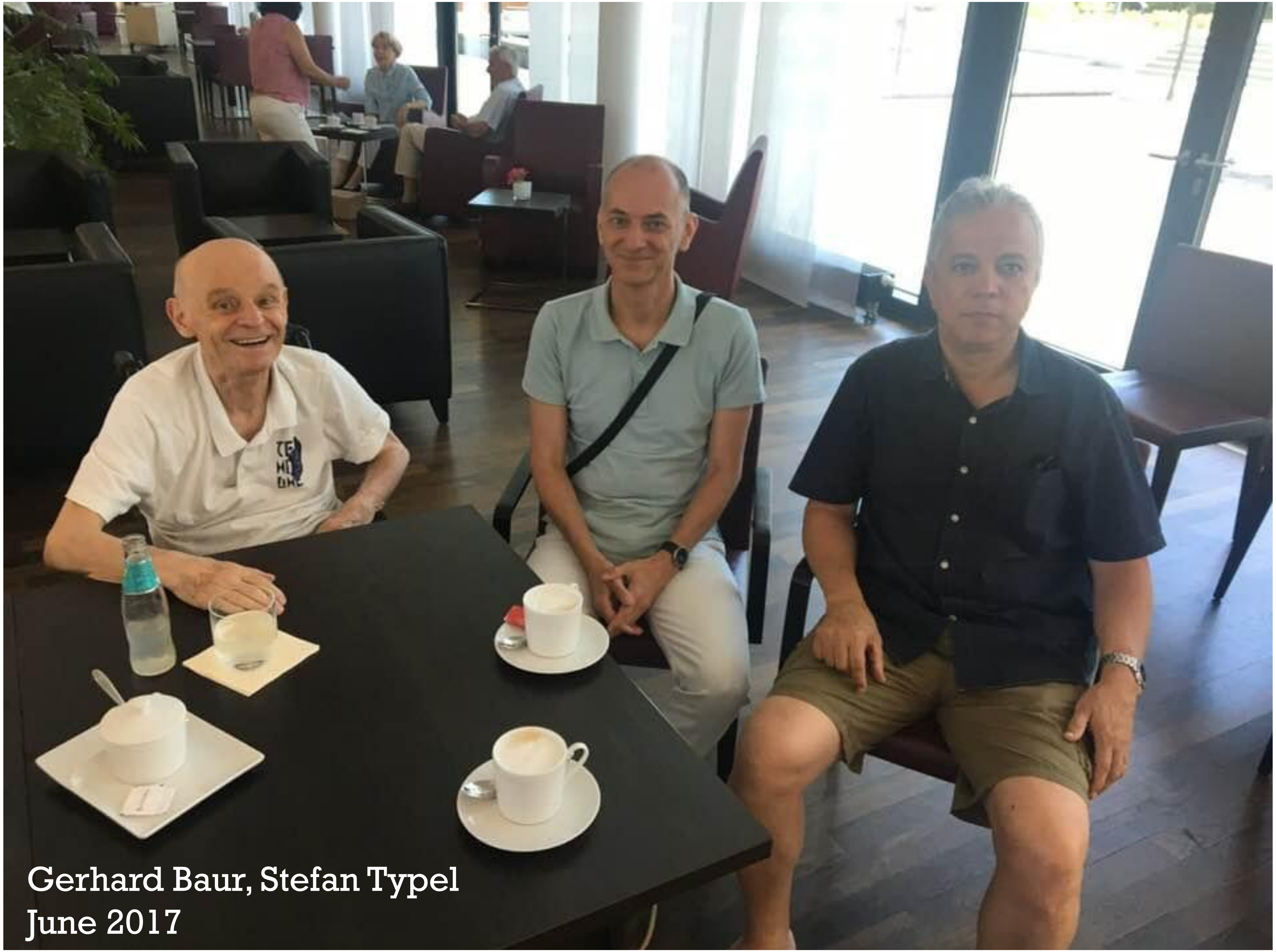
Ahern, Norbury, Poyser, PRD 62, 116001 (2000)

Searching for axionlike particles with low masses

Goncalves, Martins, Rangel, Eur. Phys. J C 81, 522 (2021)

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



Gerhard Baur, Stefan Typel
June 2017