# Nuclear Fragmentation at the Future Electron-Ion Collider

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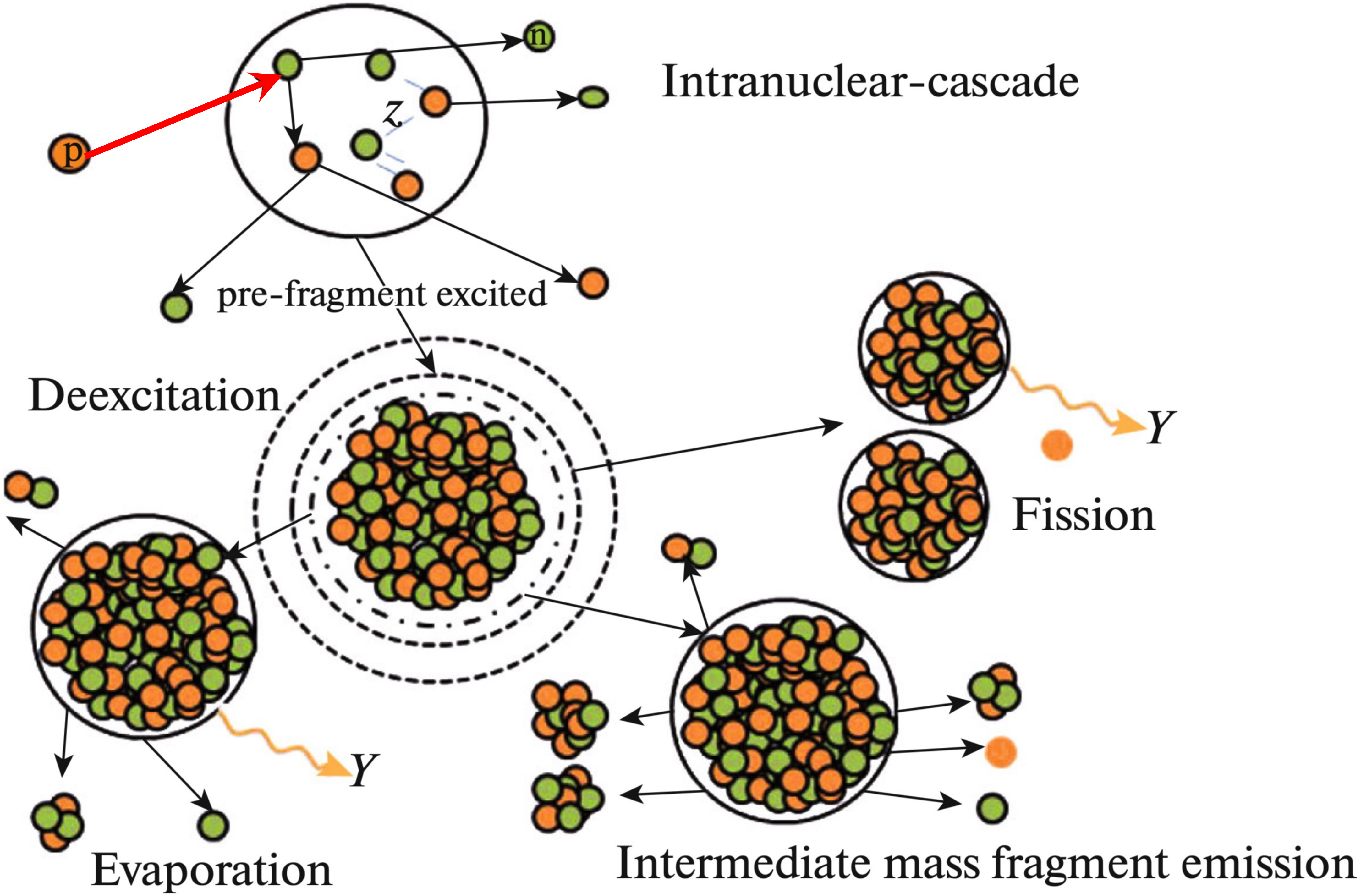
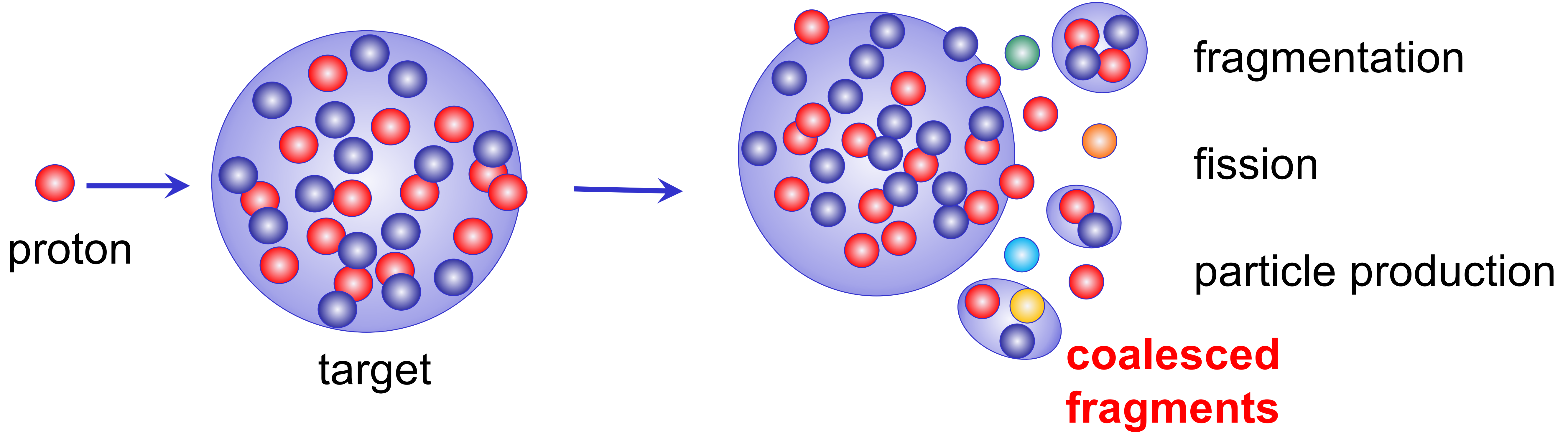
# Fragment production: Cascade & coalescence & evaporation



# Transport equations + coalescence

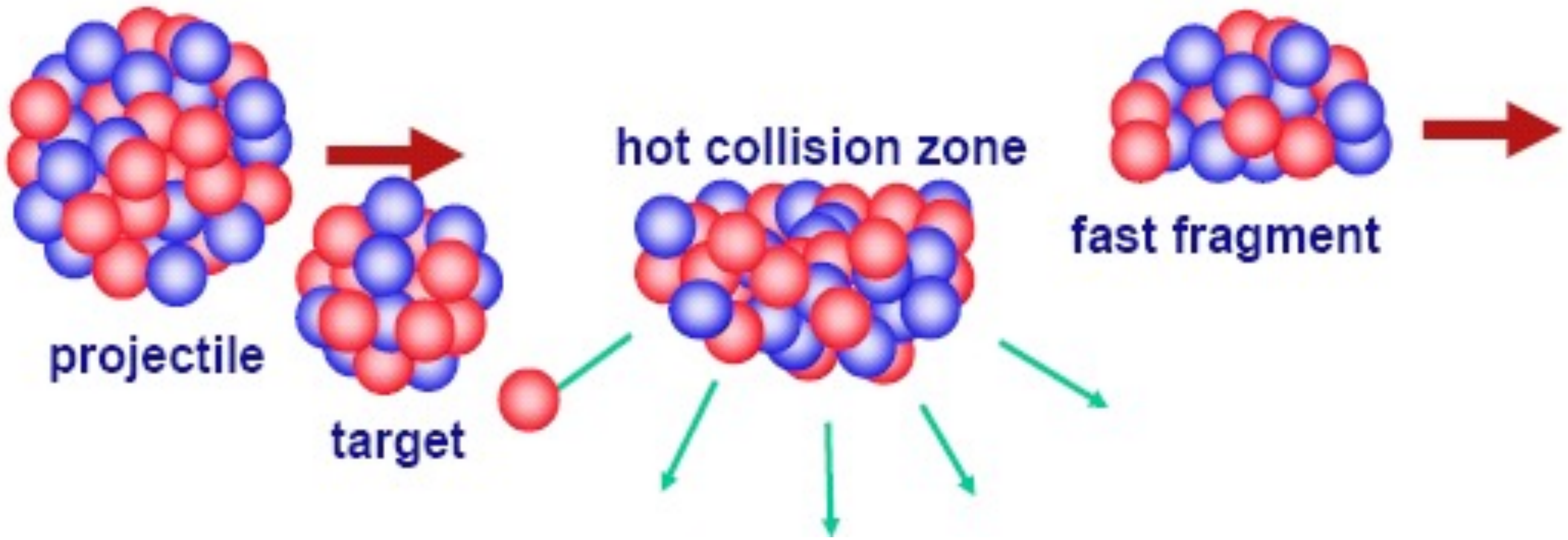



$$C_A = \frac{2J_A + 1}{2^A} \frac{1}{\sqrt{A} m_T^{A-1}} \left( \frac{2\pi}{R^2 + \left(\frac{r_A}{2}\right)^2} \right)^{\frac{3}{2}(A-1)}$$

Particles produced coalesce into nuclei if they are close in space and momentum.

$R$ = source size, $r_A$ = nuclear size
$m_T$ = transverse mass of coalesc. part.

# Glauber models + coalescence

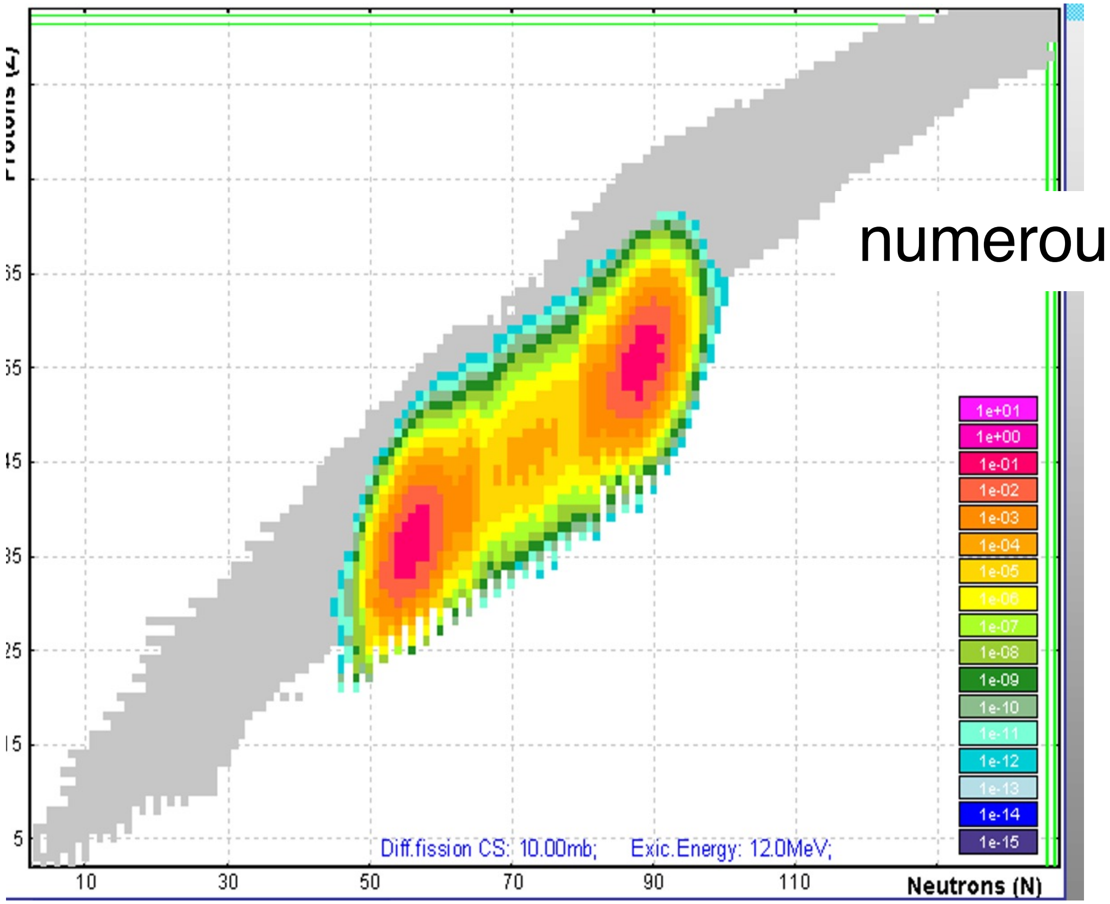


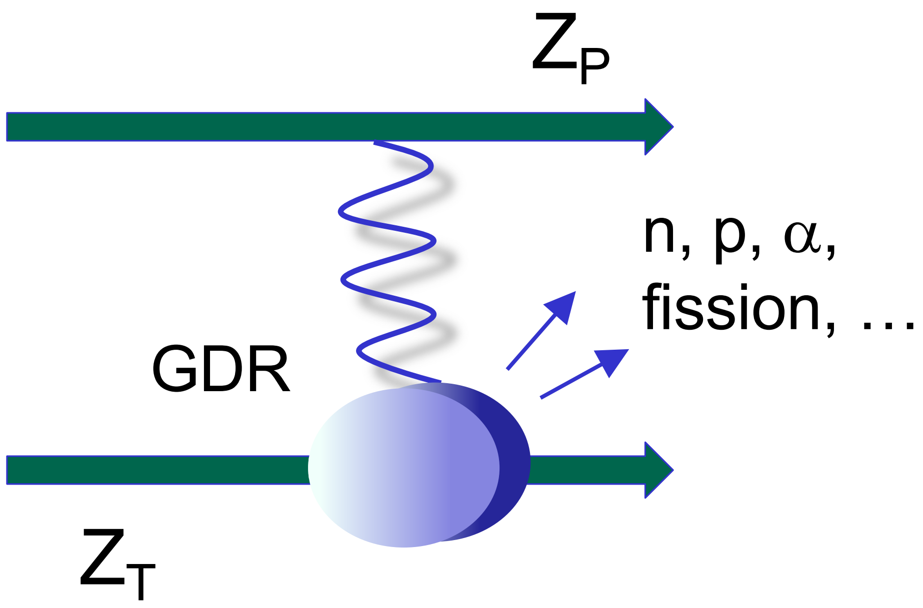

Glauber → fragment ($N_F$, $Z_F$) + evaporation

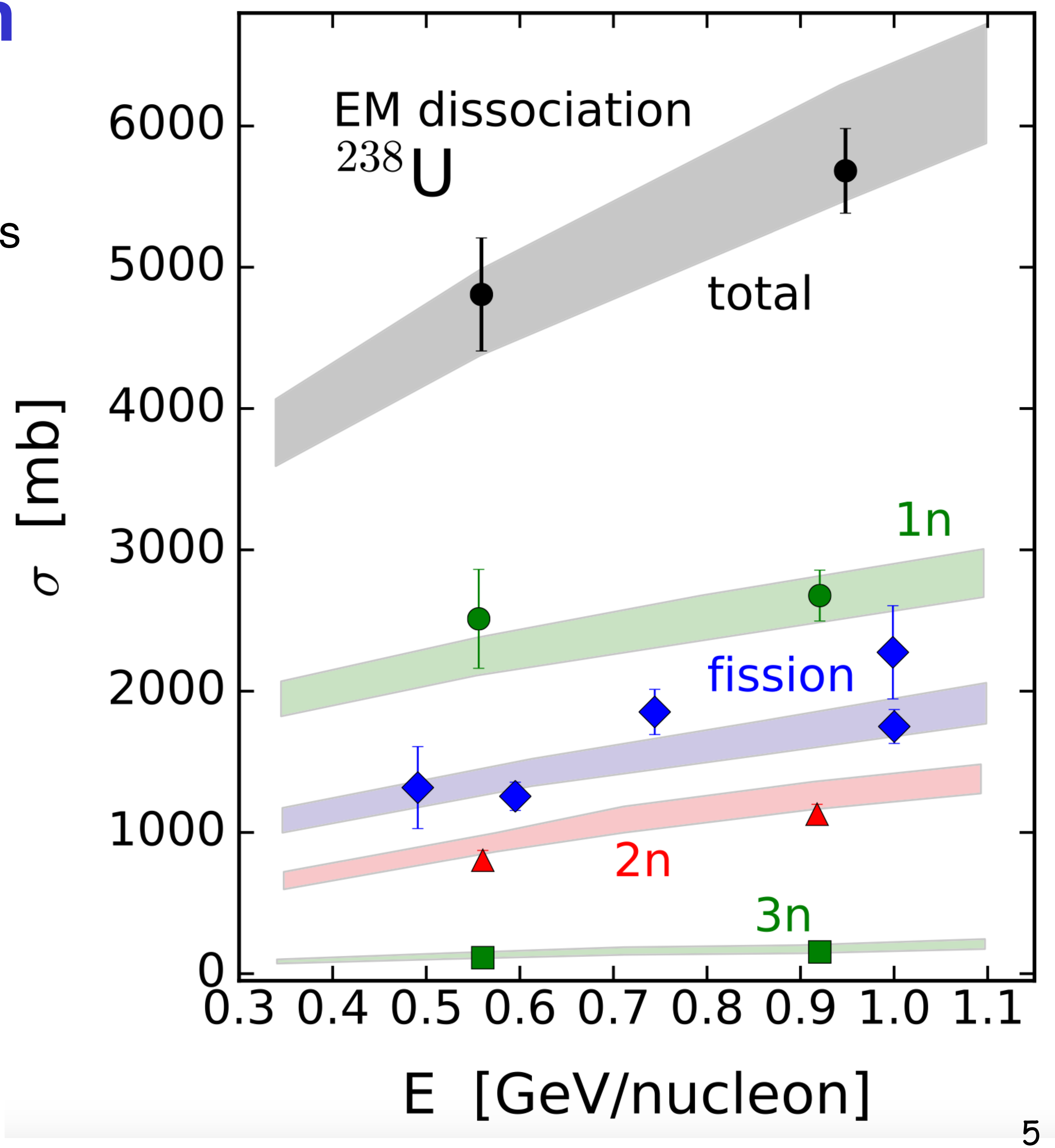
$$\sigma(N_F, Z_F) = \binom{N_P}{N_F}\binom{Z_P}{Z_F}\int d^2b\,[P_p(\mathbf{b})]^{Z_F}[P_n(\mathbf{b})]^{N_F} \times [1 - P_n(\mathbf{b})]^{N_P - N_F}\left[1 - P_p(\mathbf{b})\right]^{Z_P - Z_F}$$

$$P_p(b) = \int dz\, d^2s\, \rho_p^P(\mathbf{s}, z)\exp\left[-\sigma_{pp} Z_T \int d^2s\, \rho_p^T(\mathbf{b}-\mathbf{s}, z) - \sigma_{pn} N_T \int d^2s\, \rho_n^T(\mathbf{b}-\mathbf{s}, z)\right]$$

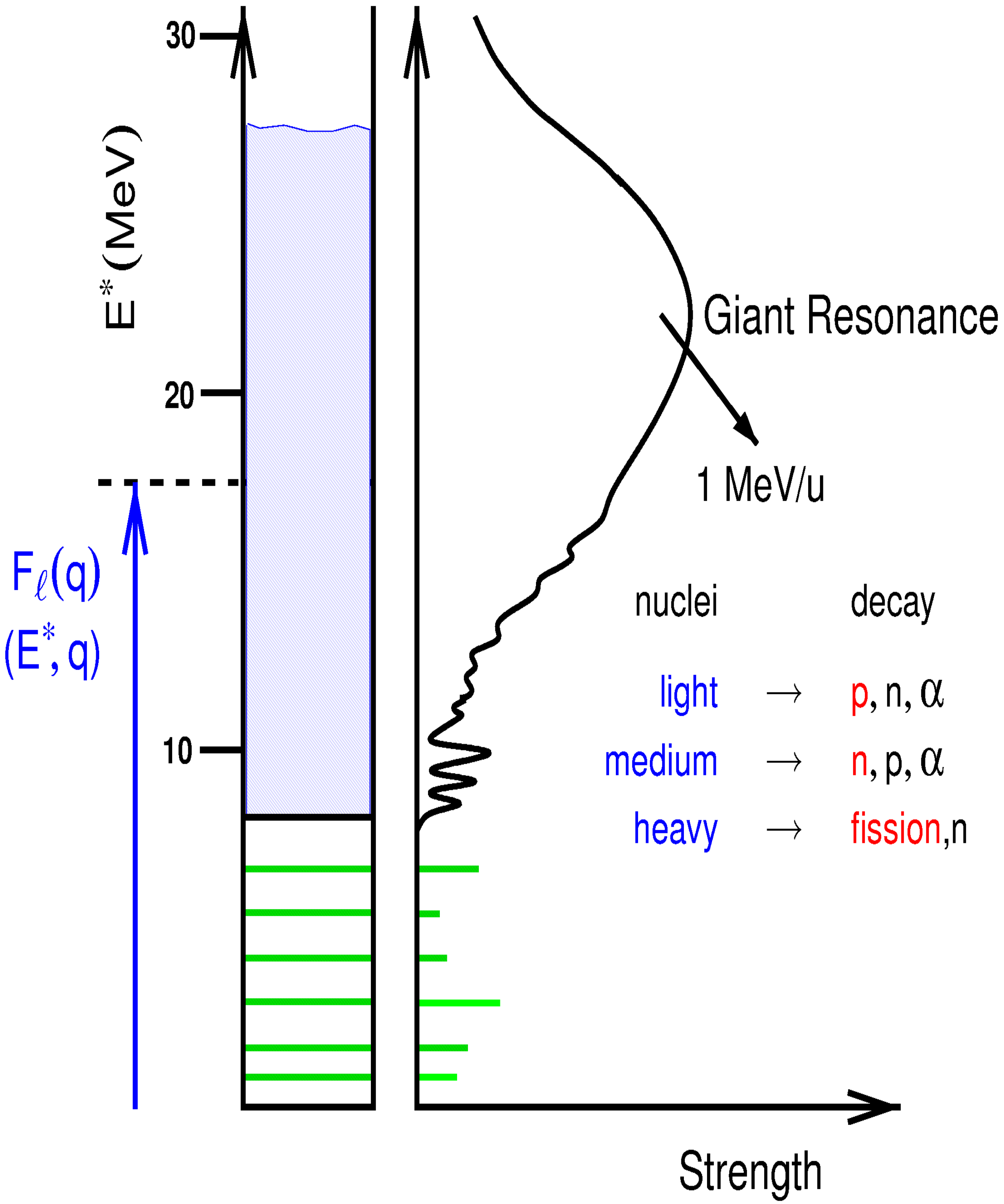
# Electromagnetic fragmentation

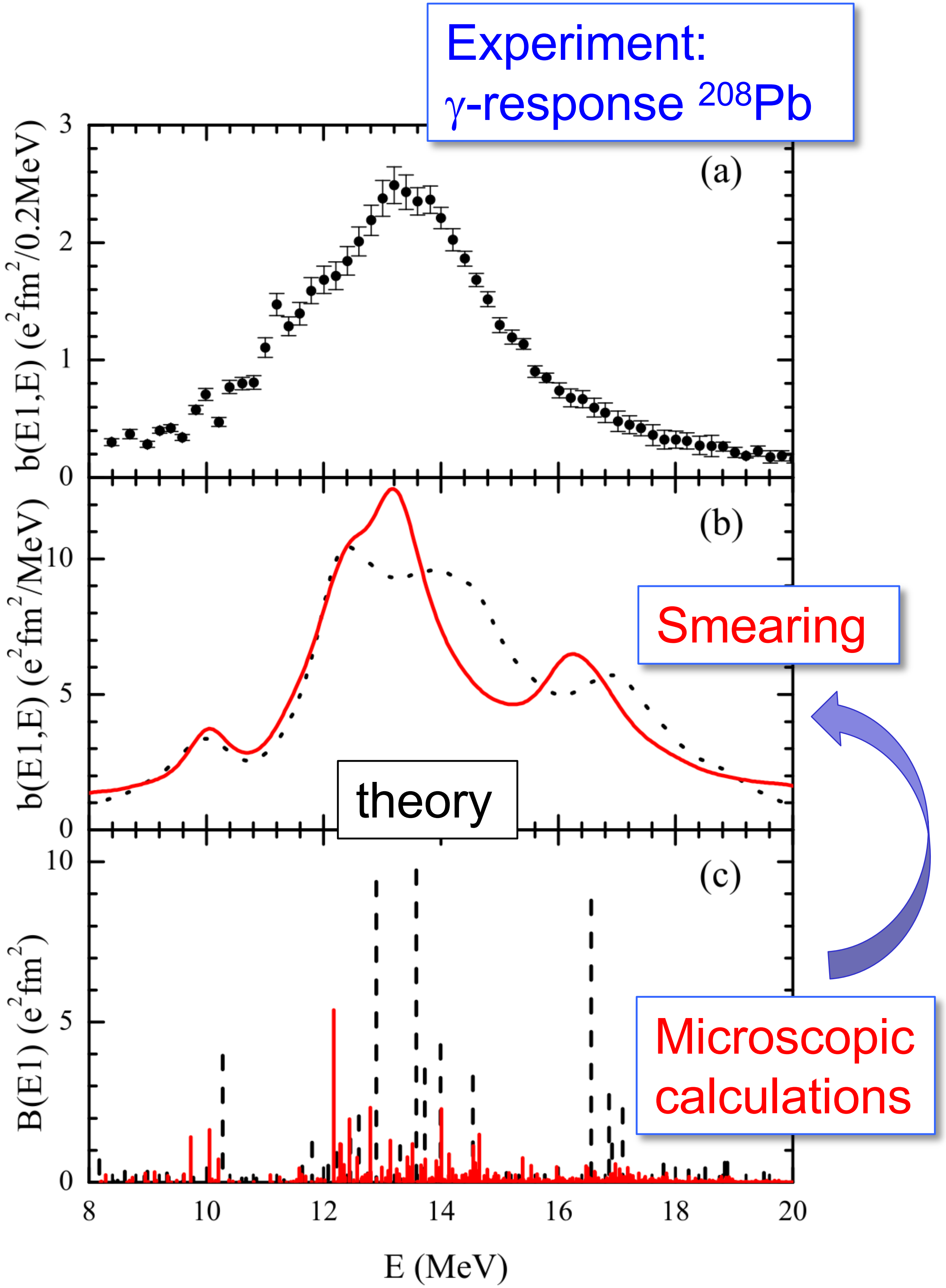


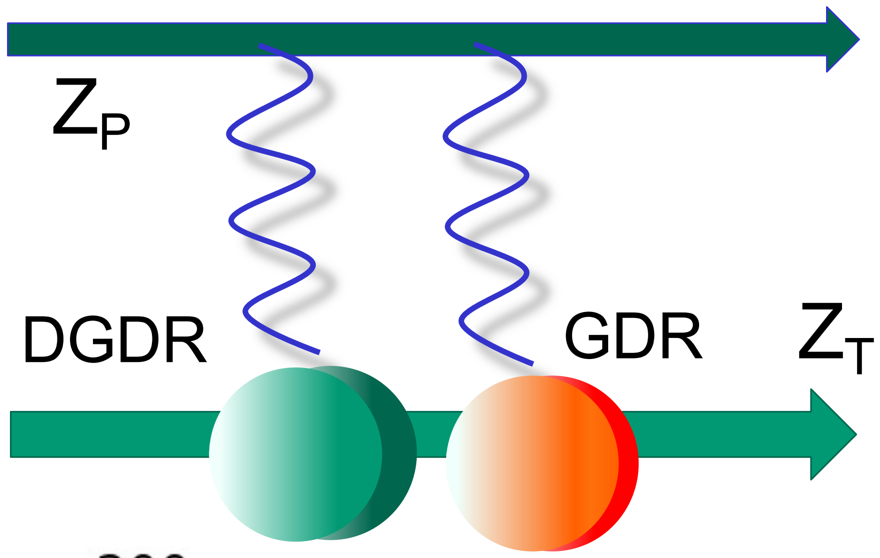



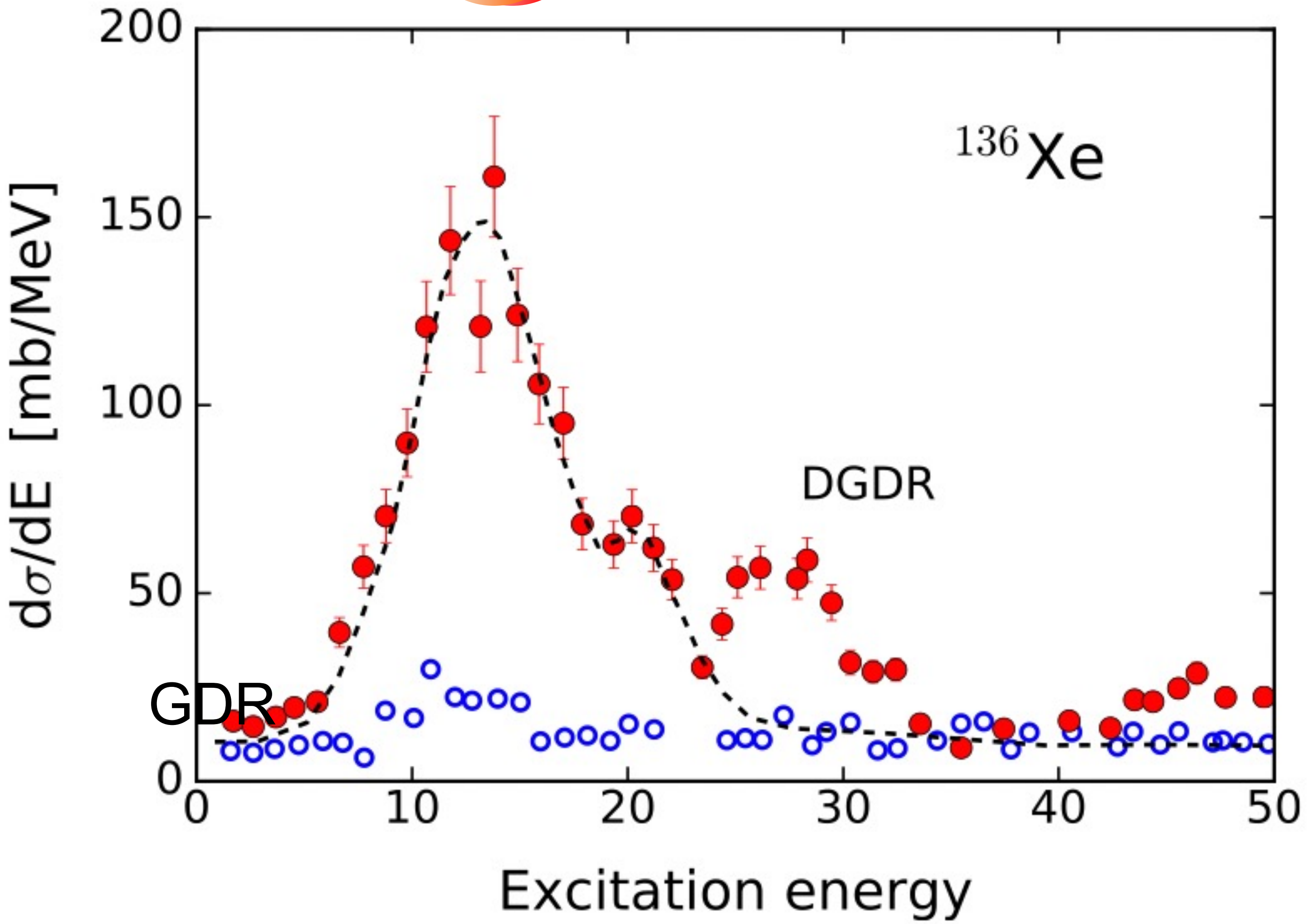
# Giant resonances in nuclei

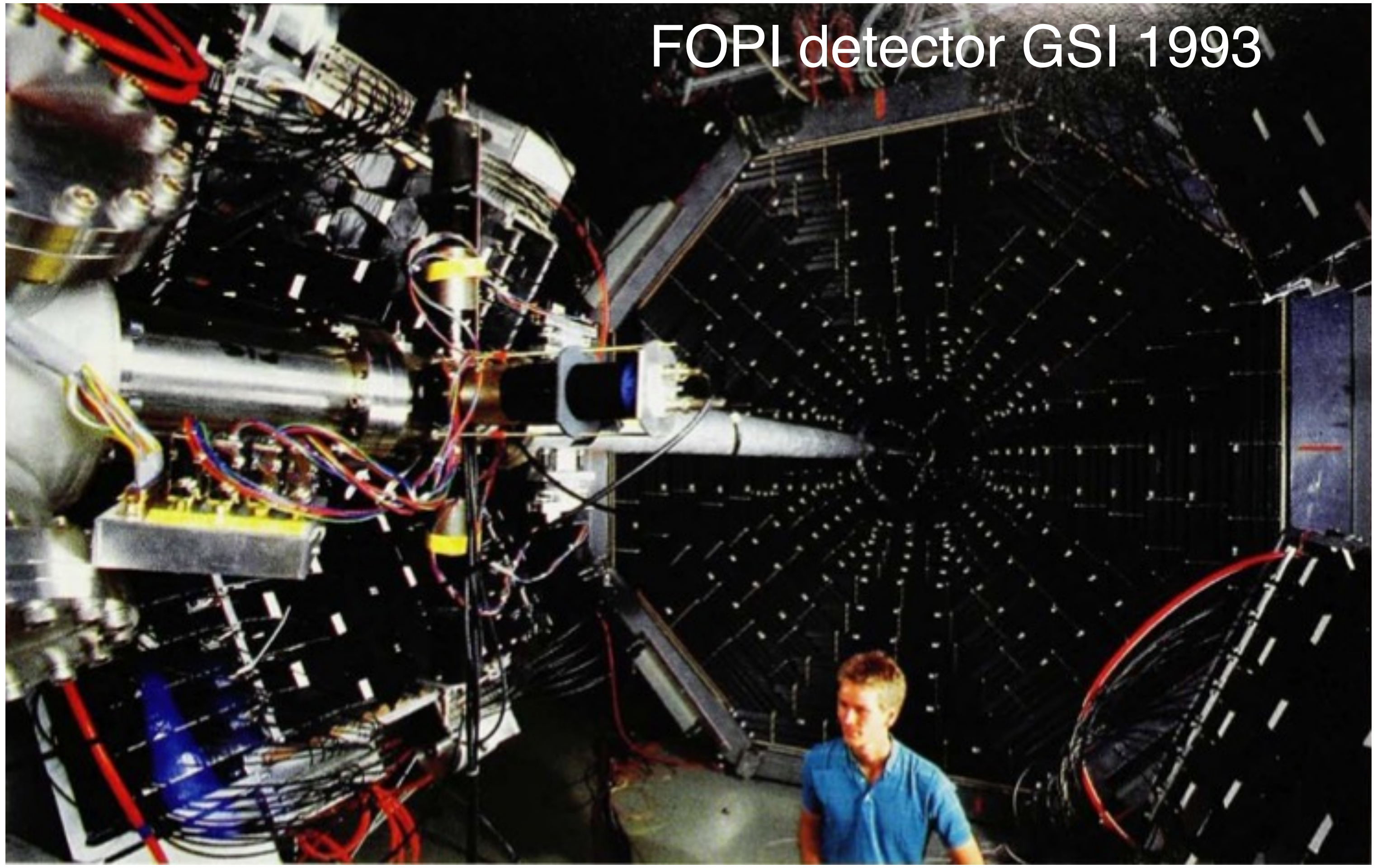


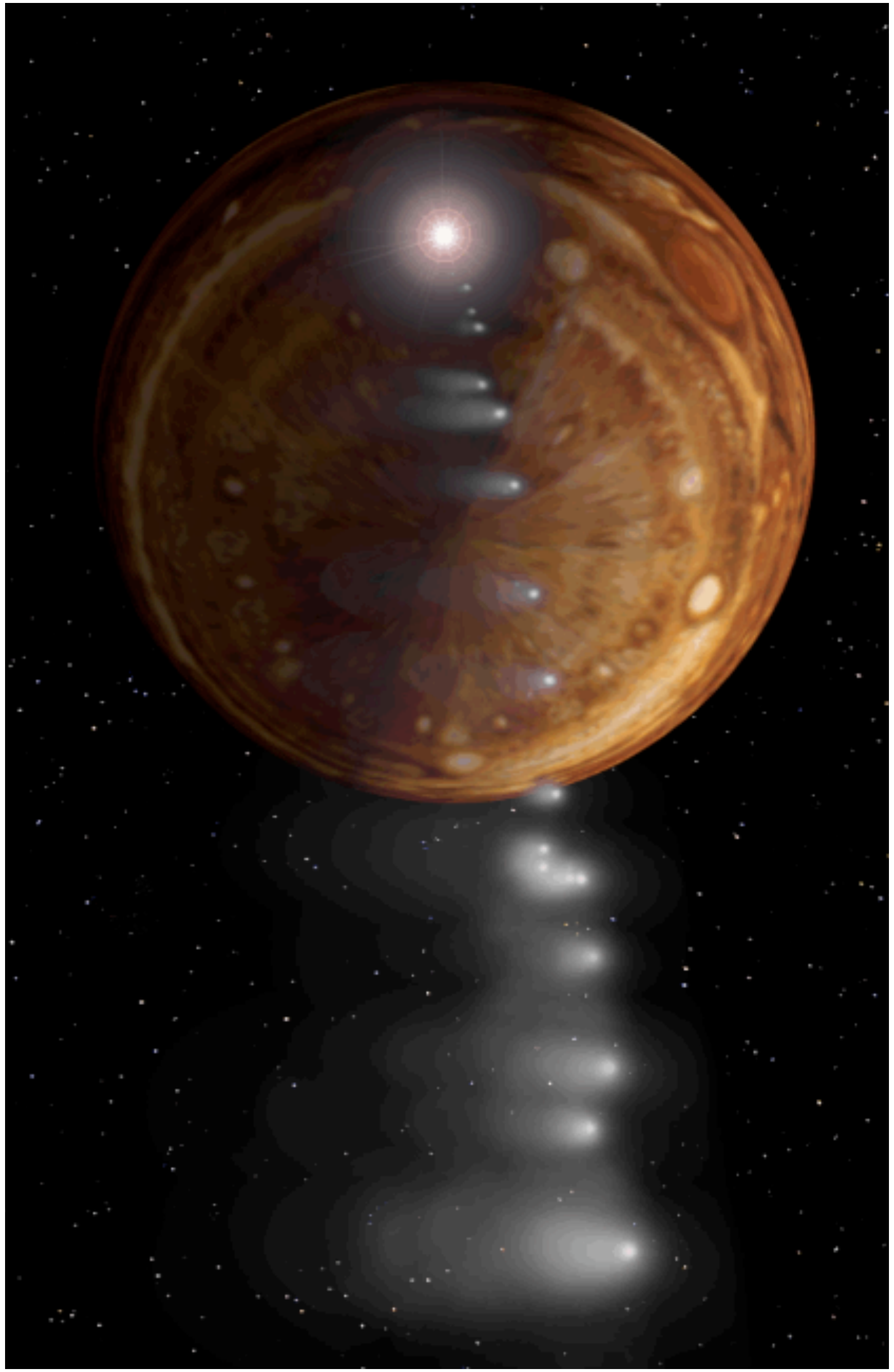



# Double giant dipole resonance



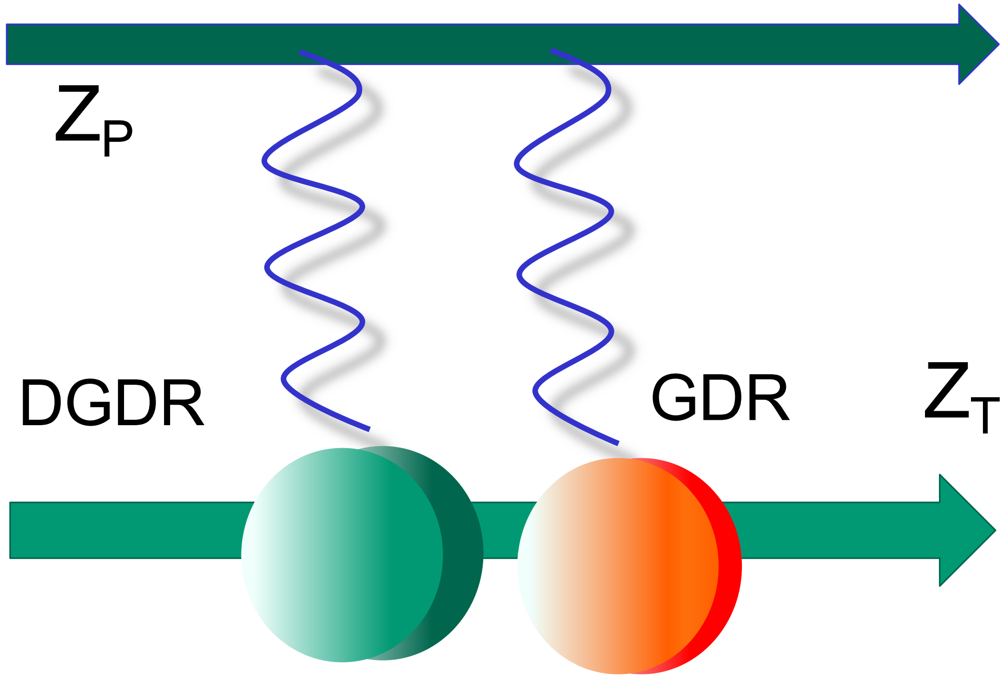





Shoemaker-Levi comet (July 1992)

**Fragmentation: Classical and complicated**




**Fragmentation: Quantum and simpler**

# Evaporation

## Compound nucleus theory

Heisenberg relation: → for a state with width $\Gamma$

$$\Delta E \Delta t \sim \hbar$$

→ decay time:

$$\Delta t \sim \frac{\hbar}{\Gamma_\alpha}$$

If many decay channels → decay probability = $\dfrac{\Gamma_\alpha}{\sum_\alpha \Gamma_\alpha} = \dfrac{\Gamma_\alpha}{\Gamma}$

Bohr hypothesis: formation independent of decay

$$\sigma_{\alpha\alpha'} = \sigma_{CN}(\alpha)\frac{\Gamma_{\alpha'}}{\Gamma}$$

a + b or c + d or ... $\xrightarrow[\text{formation}]{\alpha}$ X $\xrightarrow[\text{decay}]{\alpha'}$

# Ewing-Weisskopf theory

detailed balance:

$$g_\alpha k_\alpha^2 \sigma_{\alpha\alpha'} = g_{\alpha'} k_{\alpha'}^2 \sigma_{\alpha'\alpha}$$

spin counting

for CN:

$$g_\alpha k_\alpha^2 \sigma_{CN}(\alpha)\Gamma_{\alpha'} = g_{\alpha'} k_{\alpha'}^2 \sigma_{CN}(\alpha')\Gamma_\alpha$$

$$\frac{\Gamma_{\alpha'}}{g_{\alpha'} k_{\alpha'}^2 \sigma_{CN}(\alpha')} = \frac{\Gamma_\alpha}{g_\alpha k_\alpha^2 \sigma_{CN}(\alpha)} \quad \Rightarrow \quad \Gamma_\alpha = g_\alpha k_\alpha^2 \sigma_{CN}(\alpha)$$

introducing density of levels ρ of final states:

$$\sigma_{\alpha\alpha'} = \sigma_{CN}(\alpha) \frac{\mu_{\alpha'} E_{\alpha'} \sigma_{CN}(\alpha') \rho(E_{\alpha'})}{\sum_\alpha \int \mu_\alpha E_\alpha \sigma_{CN}(\alpha) \rho(E_\alpha) dE_\alpha}$$

# Hauser-Feshbach theory

Include angular momentum conservation in the Ewing-Weisskopf theory

CN ang. mom.

transmission probability

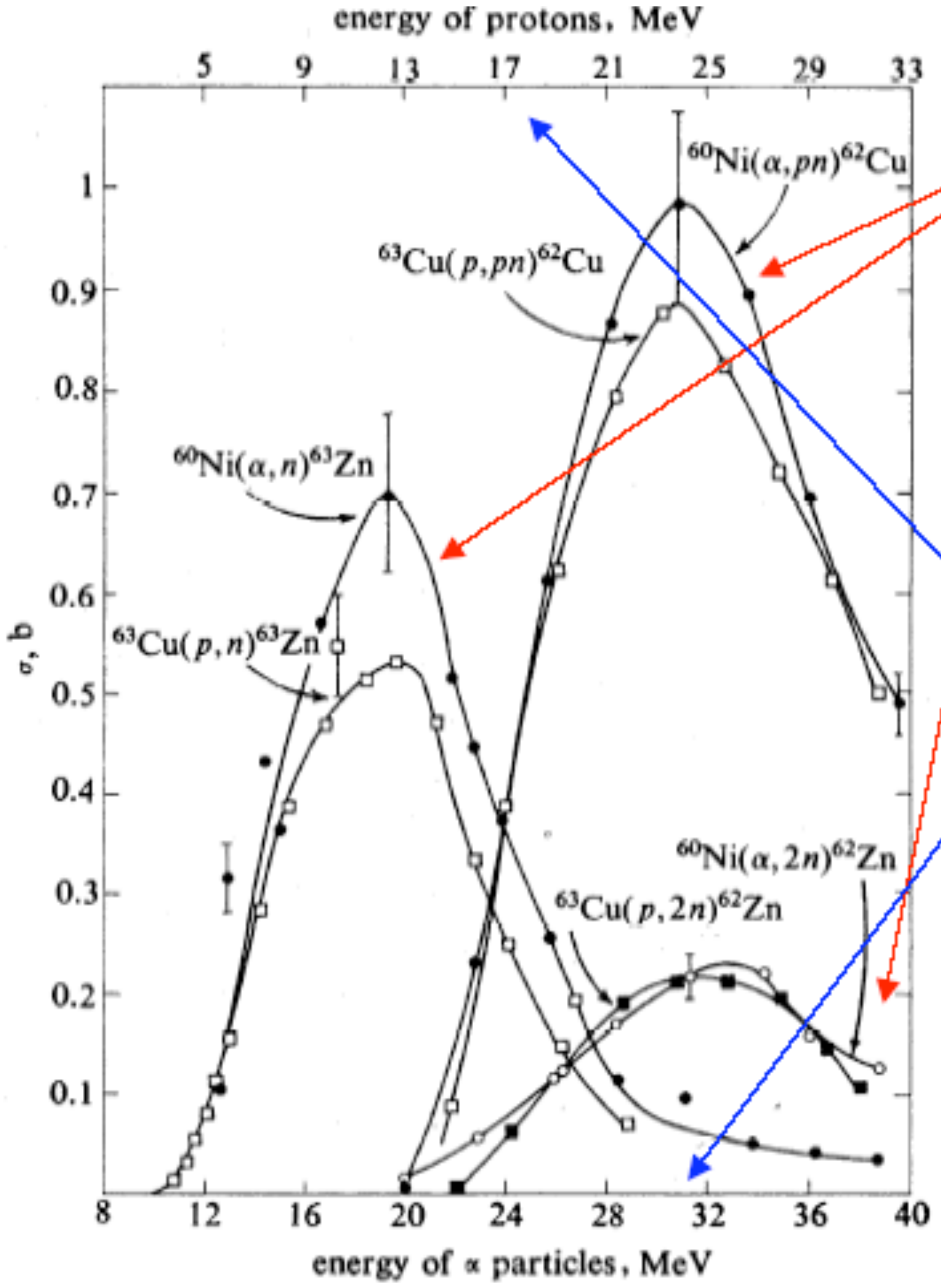
$$\sigma_{CN}(\alpha) = \frac{\pi}{k^2} \sum_J \frac{2J+1}{(2j_a+1)(2j_b+1)} \frac{T_{l,s}(\alpha)}{\prod_{l,s,\alpha'} T_{l,s}(\alpha')}$$

projectile spin

target spin

Optical potentials

# Compound nucleus formation & decay




*Same final state; different initial state*

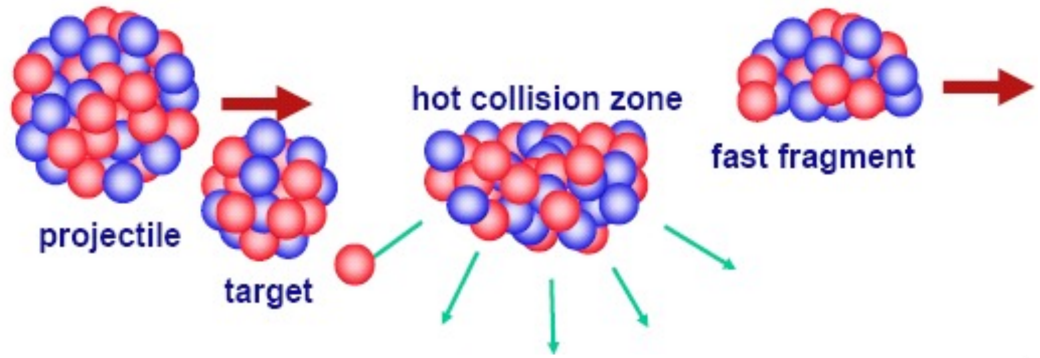
*Varying energies for p and α*

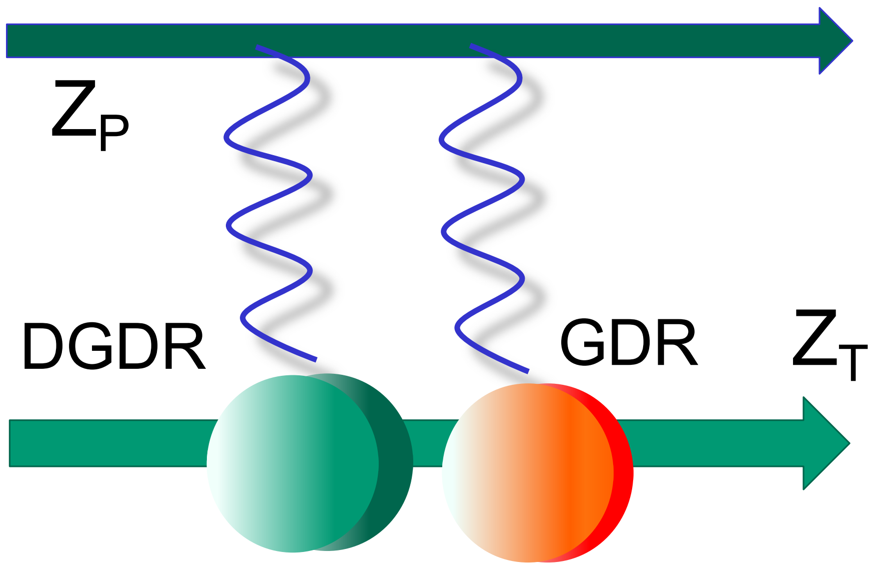
a + X → C* → Y1 + b1

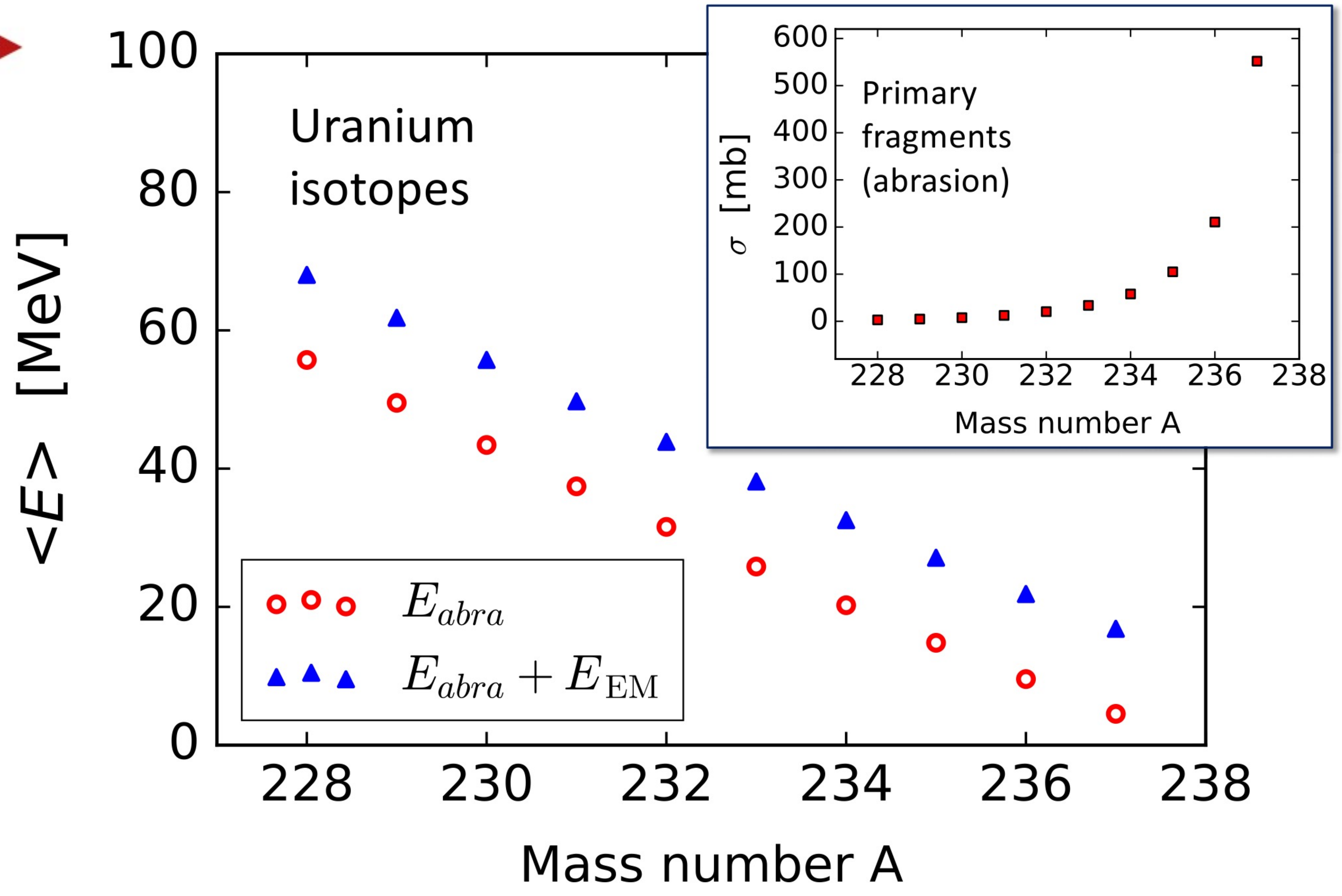
→ Y2 + b2
→ Y3 + b3
…..

Textbook example

# Fragmentation in heavy ion collisions

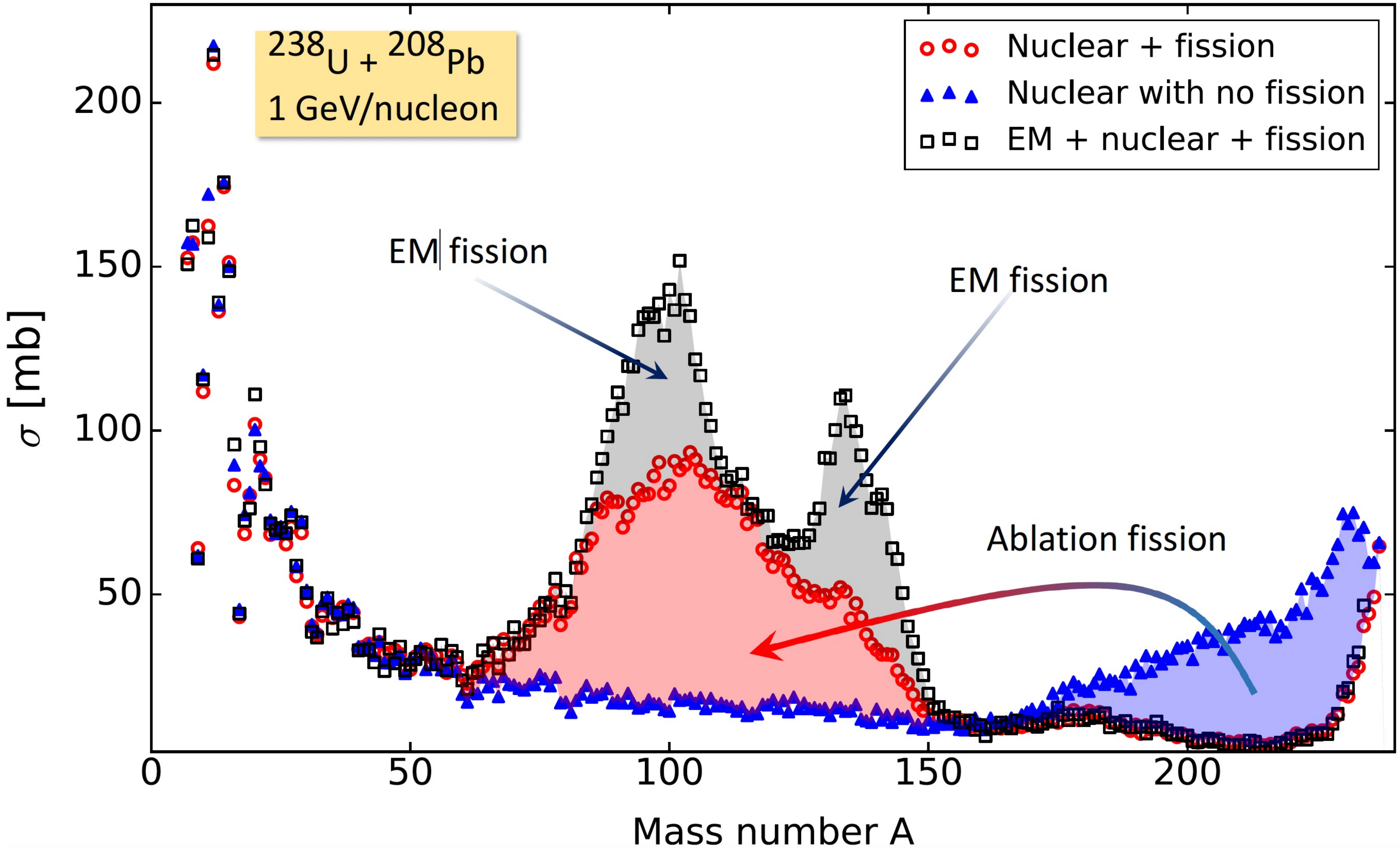


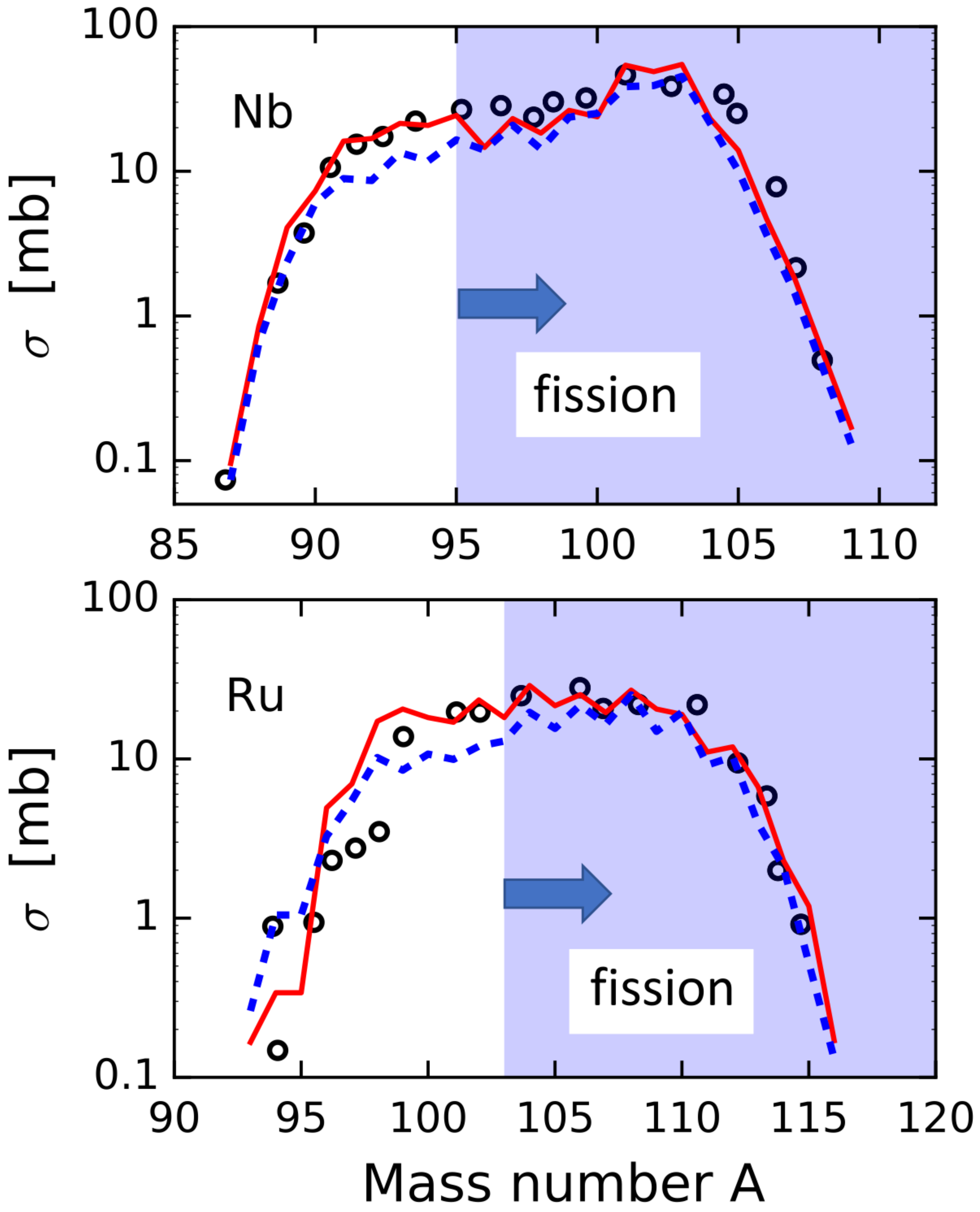



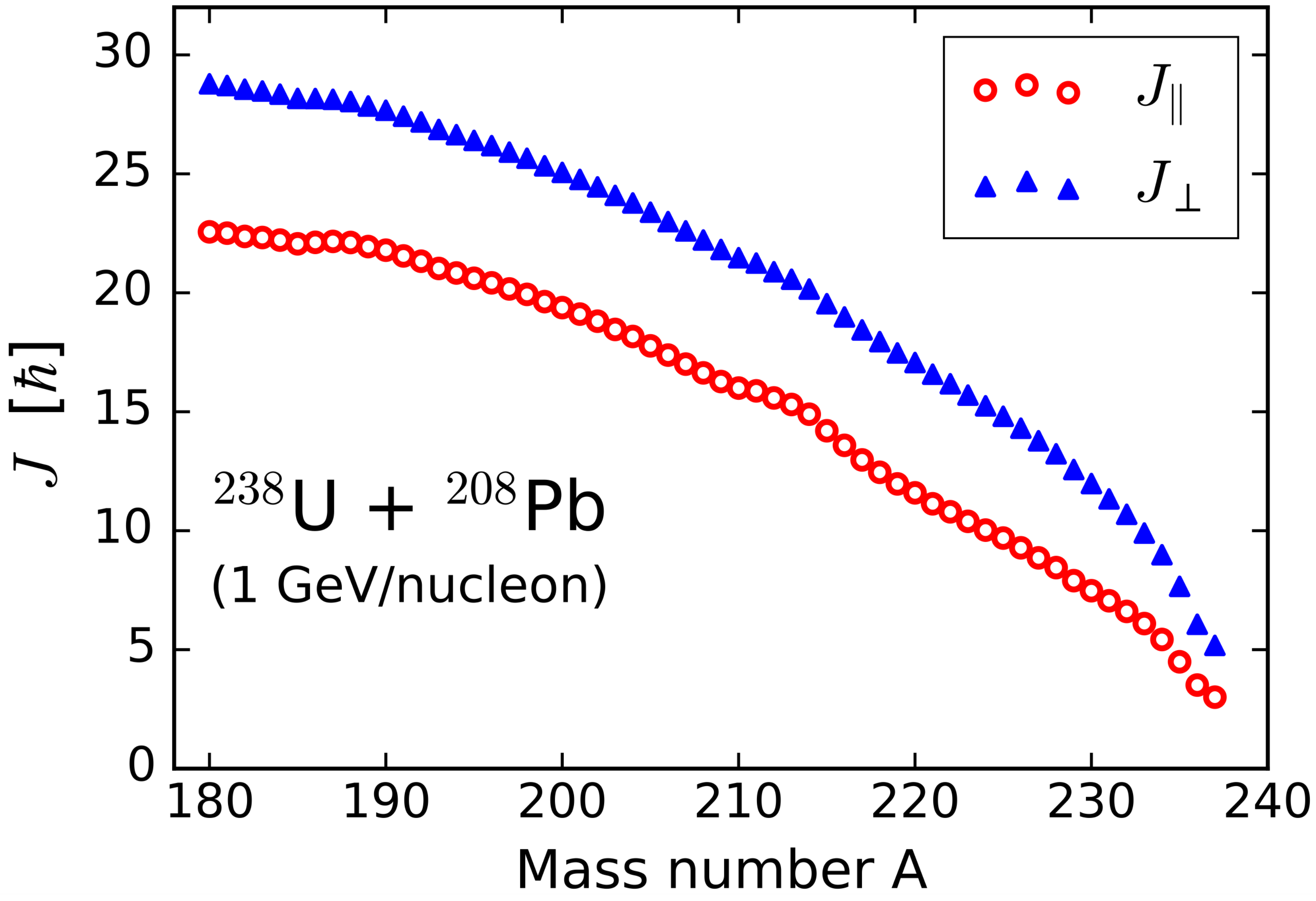



# Fragmentation in heavy ion collisions

CB, Kucuk, Lozeva, PRL 124, 132301 (2020)






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

# "Static" NS

**Tolman-Oppenheimer-Volkoff** +

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

NM incompressibility

$$S \equiv J = \frac{1}{2}\frac{d^2[E/A]}{d\delta^2}\bigg|_{\delta=0}$$

Symmetry energy

$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

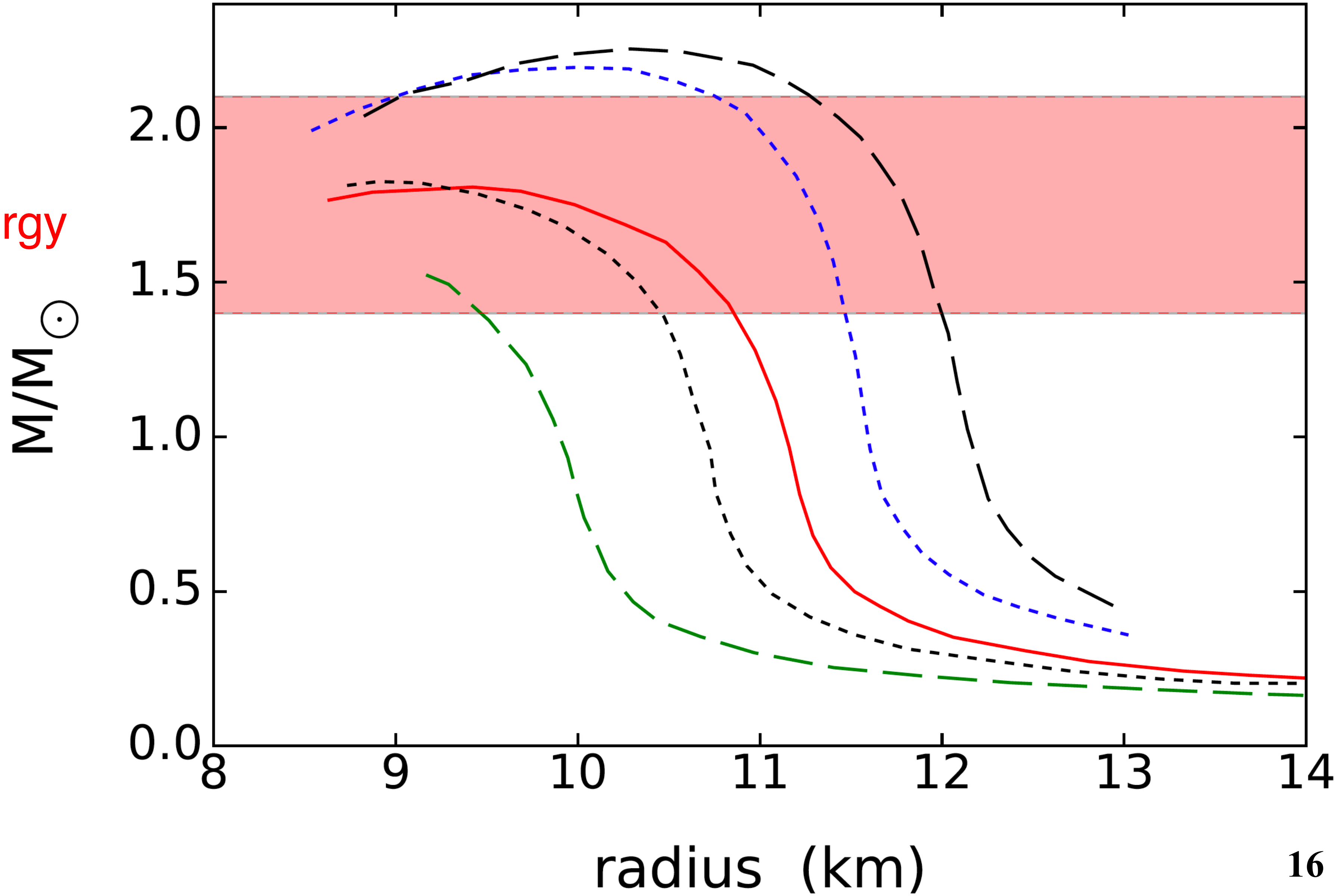
$$L = 3\rho_0 \frac{dS}{d\rho}\bigg|_{\delta=0}$$

Slope parameter

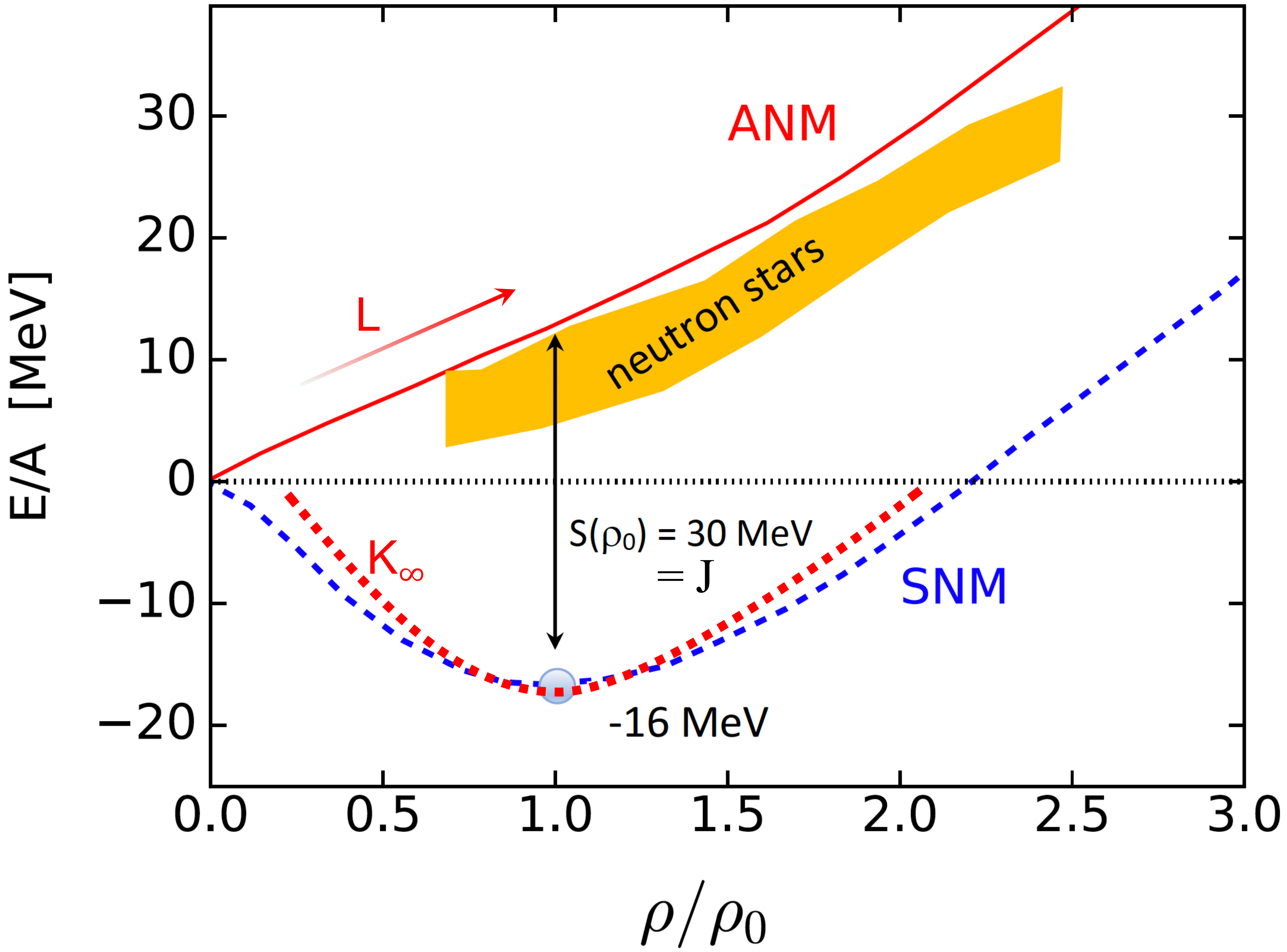
EOS

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

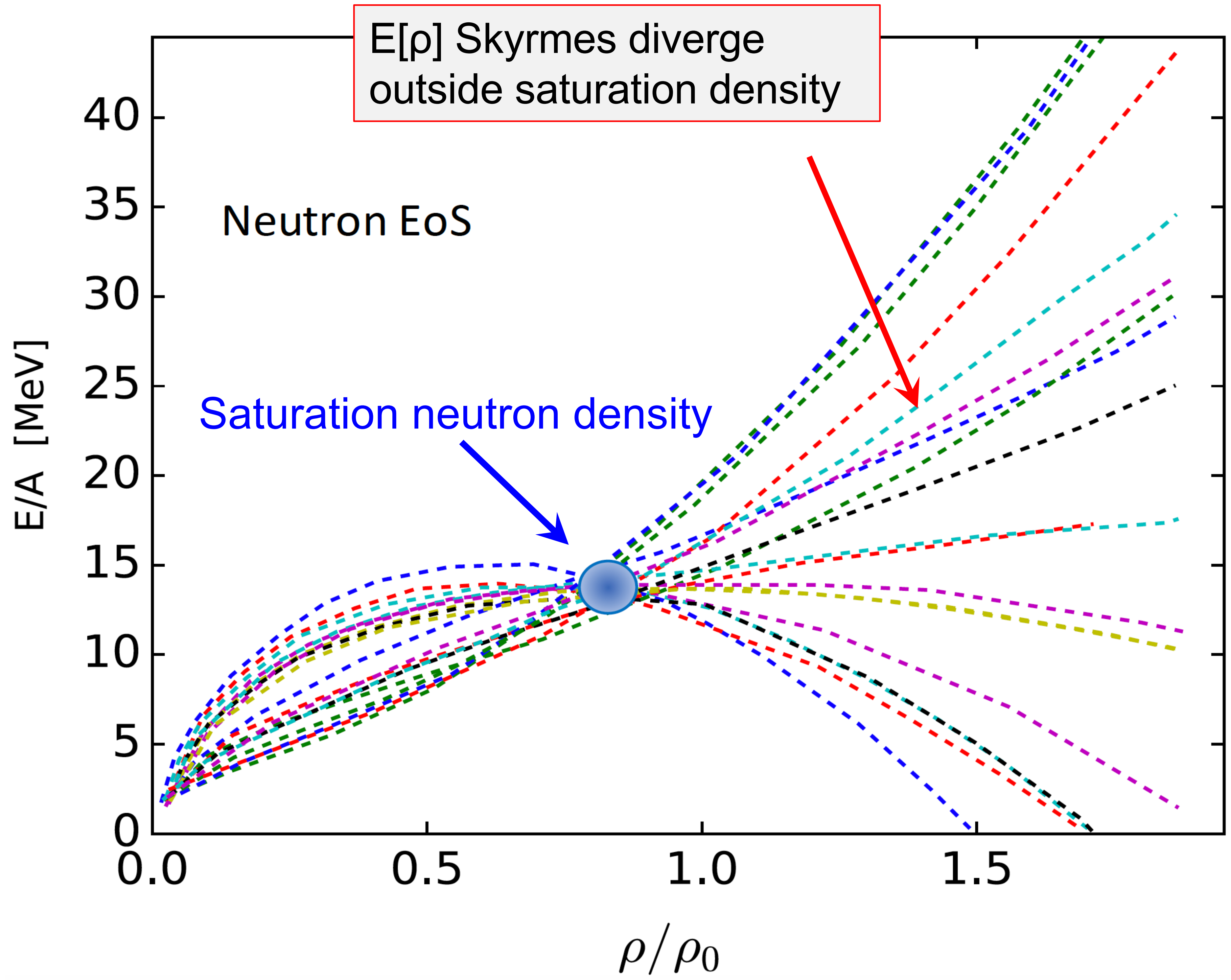
E(ρ)/A from microscopic calculations



# EOS of nuclear matter



# EOS & Neutron stars



# EOS + symmetry energy

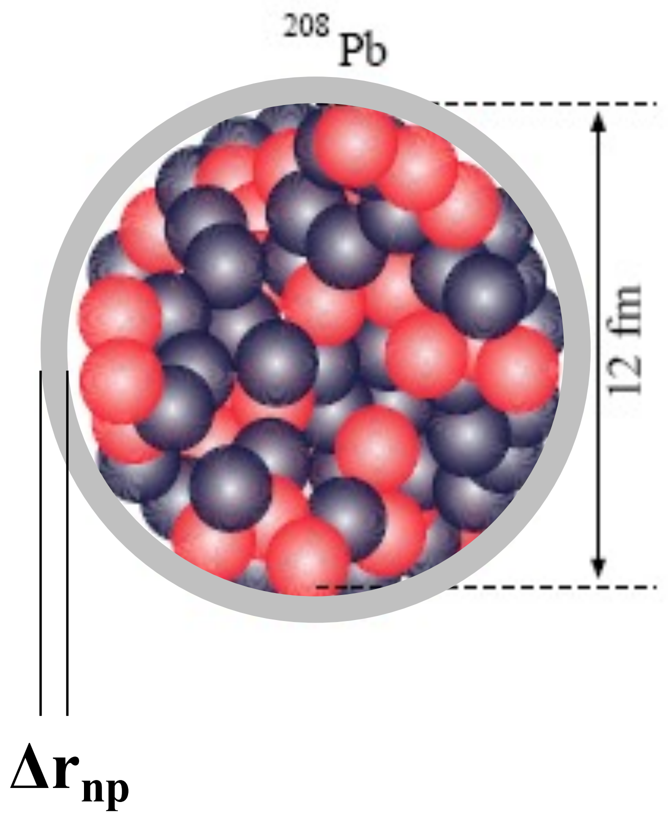
For $\rho \sim \rho_0$ and $\rho_p \sim 0$, $\Longrightarrow$ $p \sim \frac{\rho_0}{3} L$

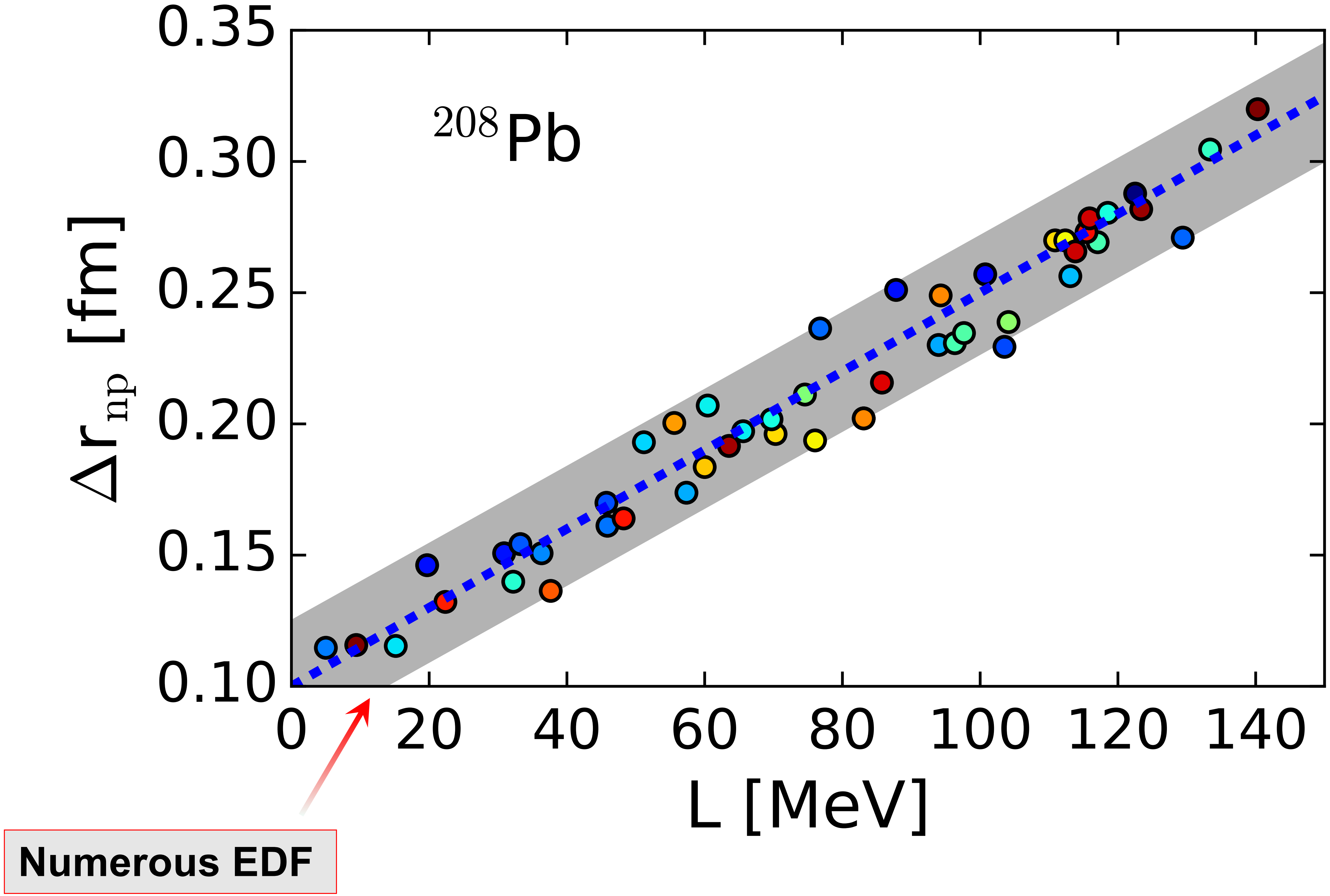
L crucial for neutron matter

| Skyrme | $\rho_0$ | $E_0$ | $K_\infty$ | 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 |

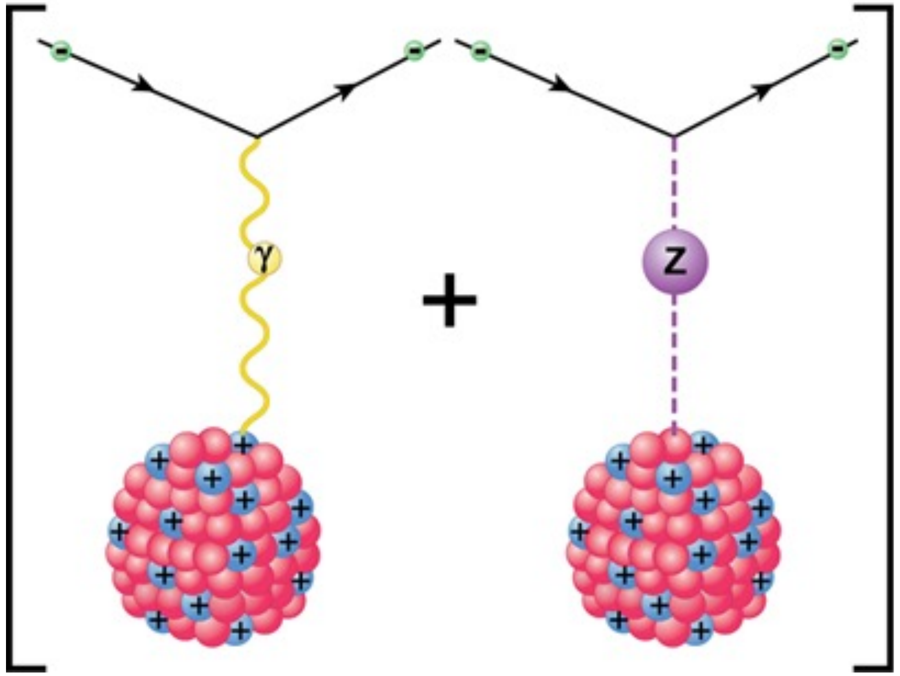
L not well known

# Neutron skins in nuclei



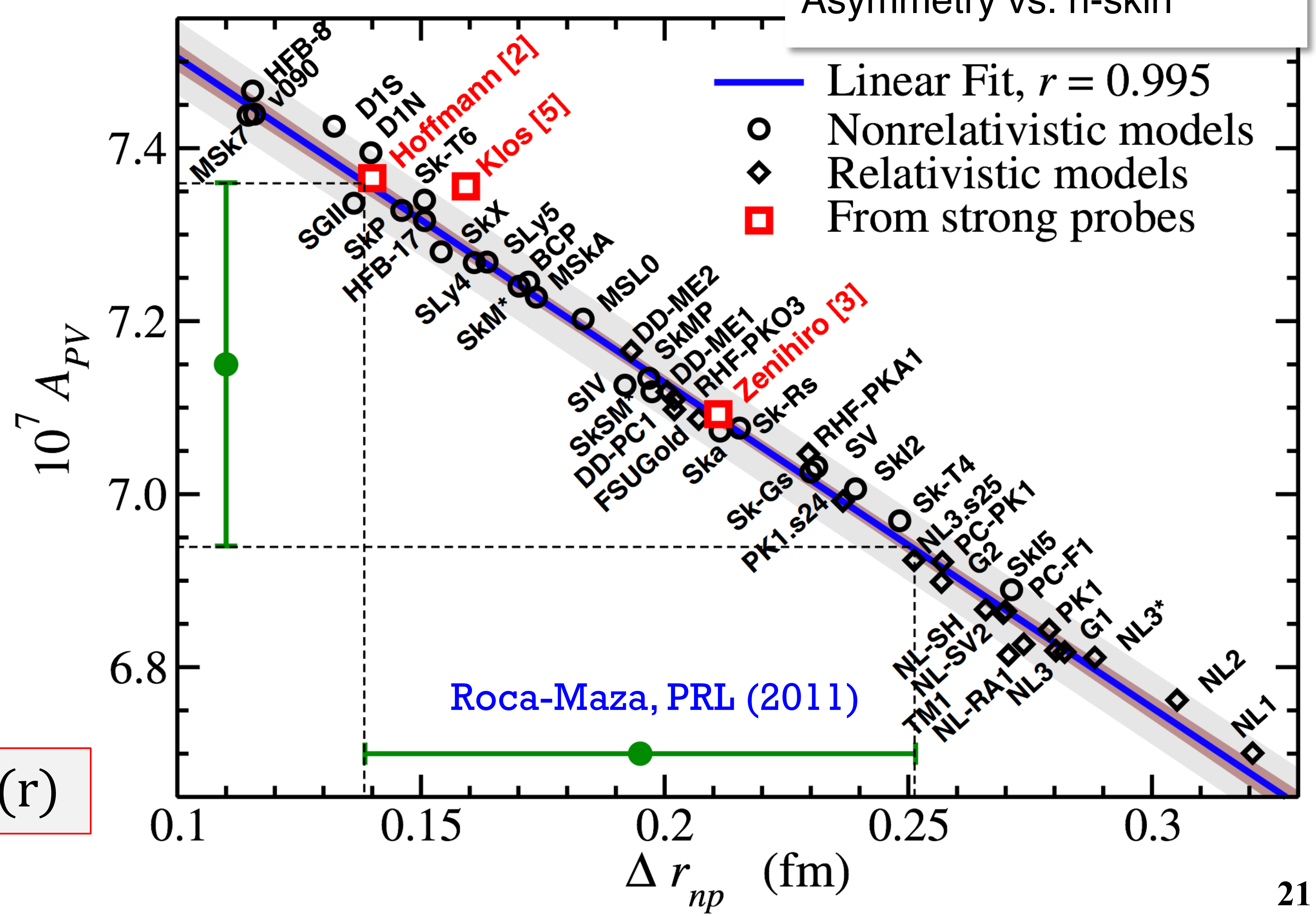
# n-skin from PV e⁻ scattering




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

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

Asymmetry vs. n-skin



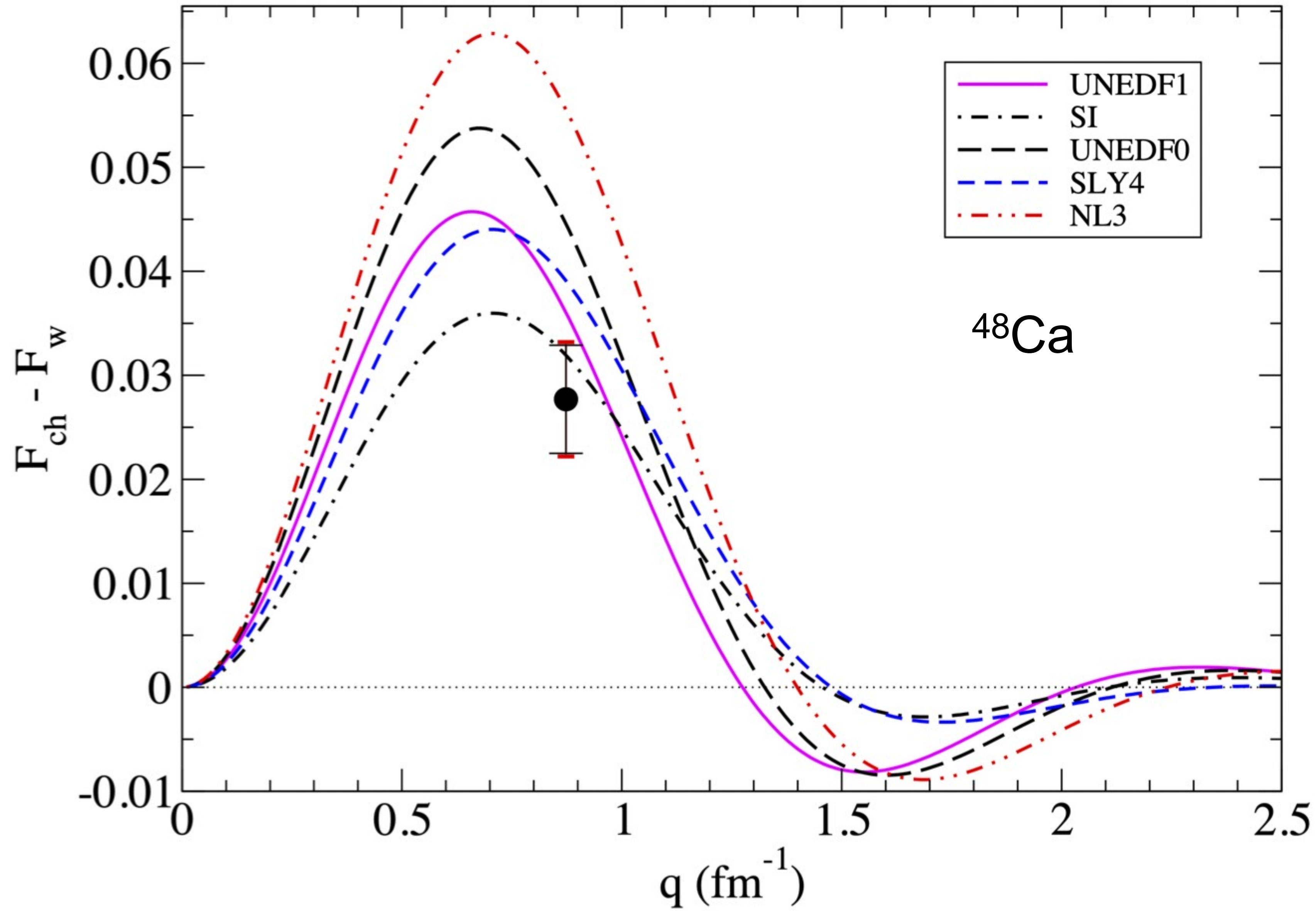

$$F_W \sim \int dr \frac{\sin(Qr)}{Qr} \rho_W(r)$$

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

# n-skin from e$^-$ PV scattering

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

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



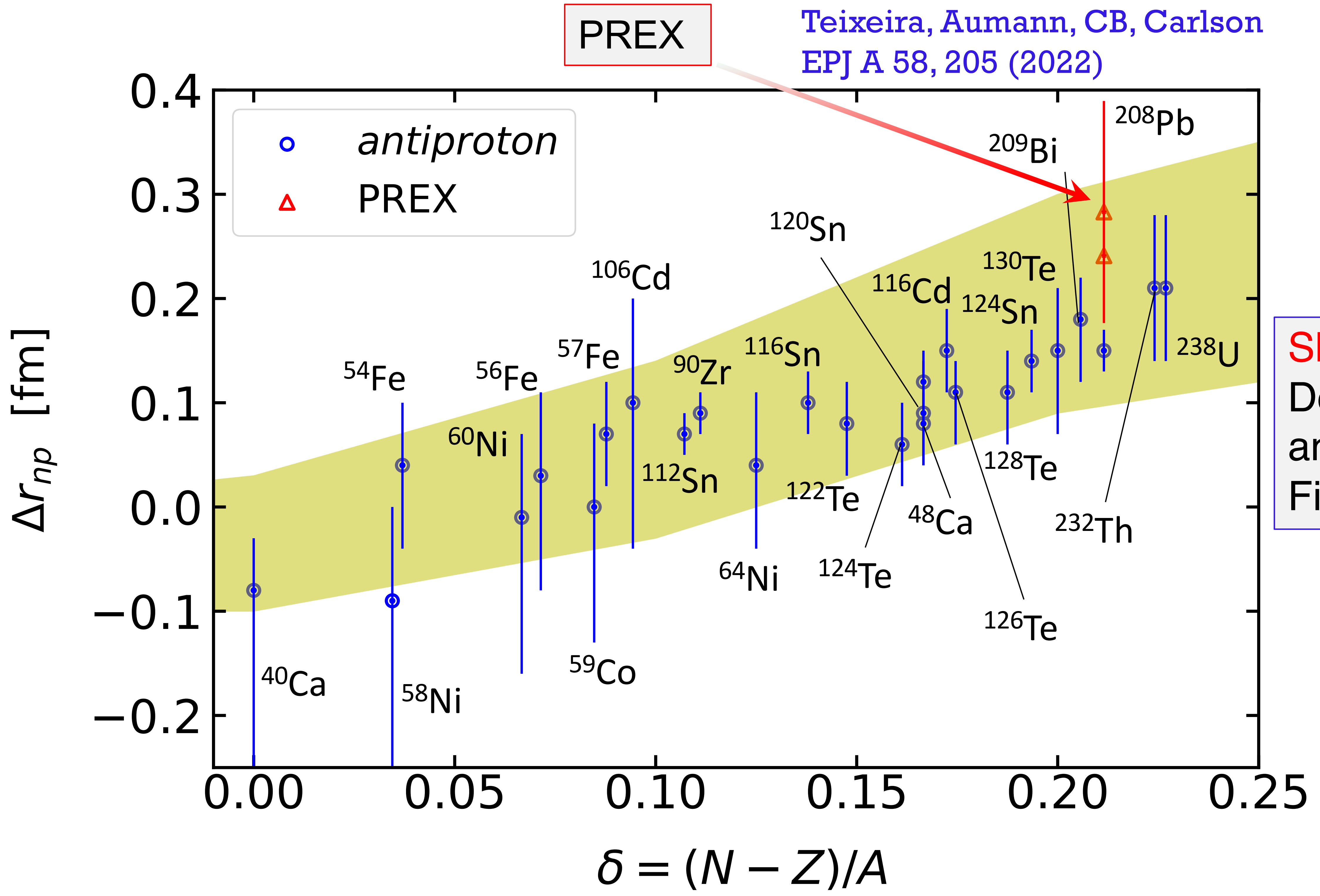

- PREX & CREX: measurement of parity violating asymmetry
- Determine n-skin and/or L by comparison to predictions from DFT

$(R_n – R_p)_{48Ca}$ = 0.121 ± 0.025 fm
$(R_n – R_p)_{208Pb}$ = 0.33 ± 0.17 fm

Adhikari et al, PRL 126, 172502 (2021)
PRL 129, 042501(2022)

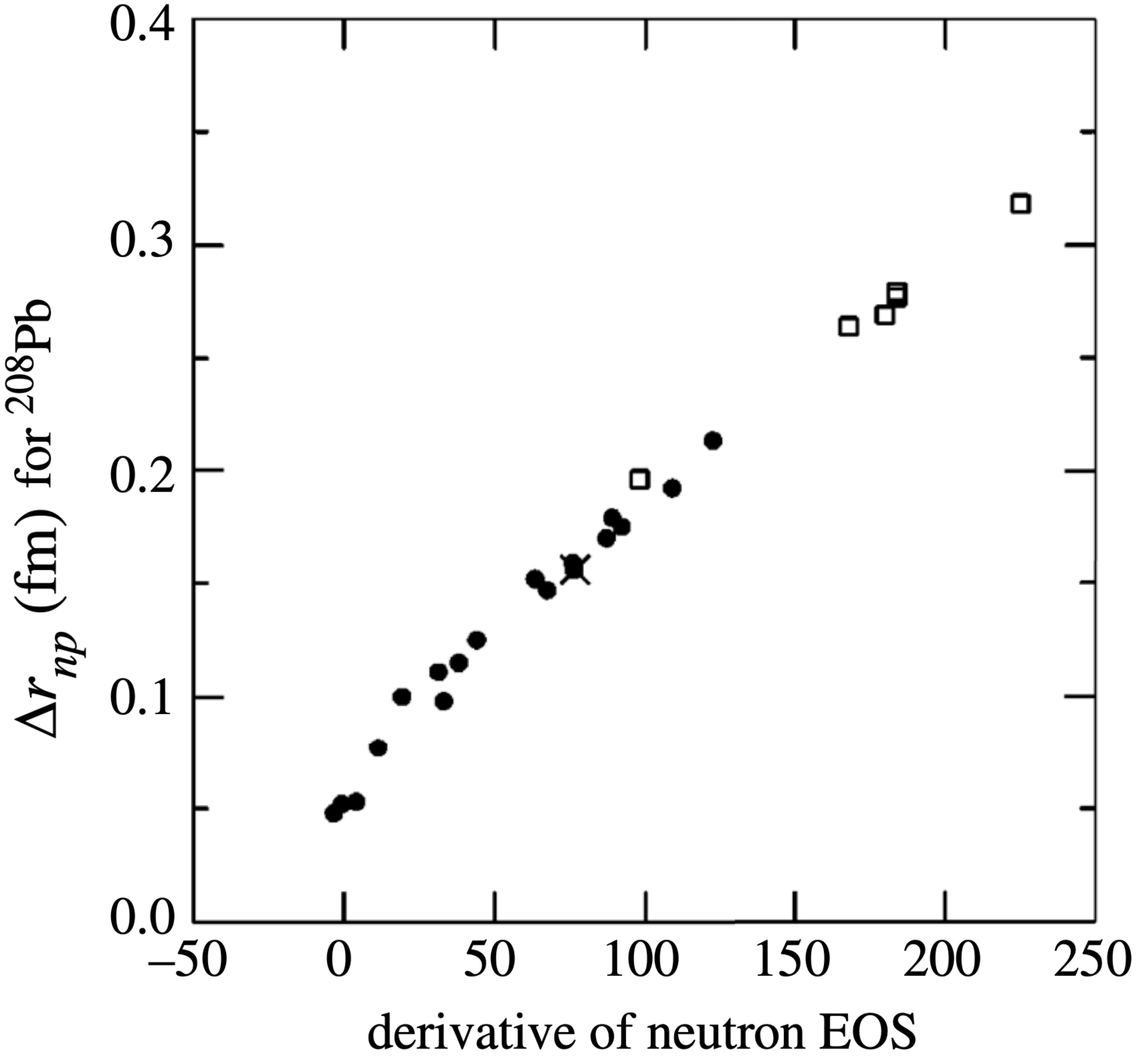
# Status of neutron skins

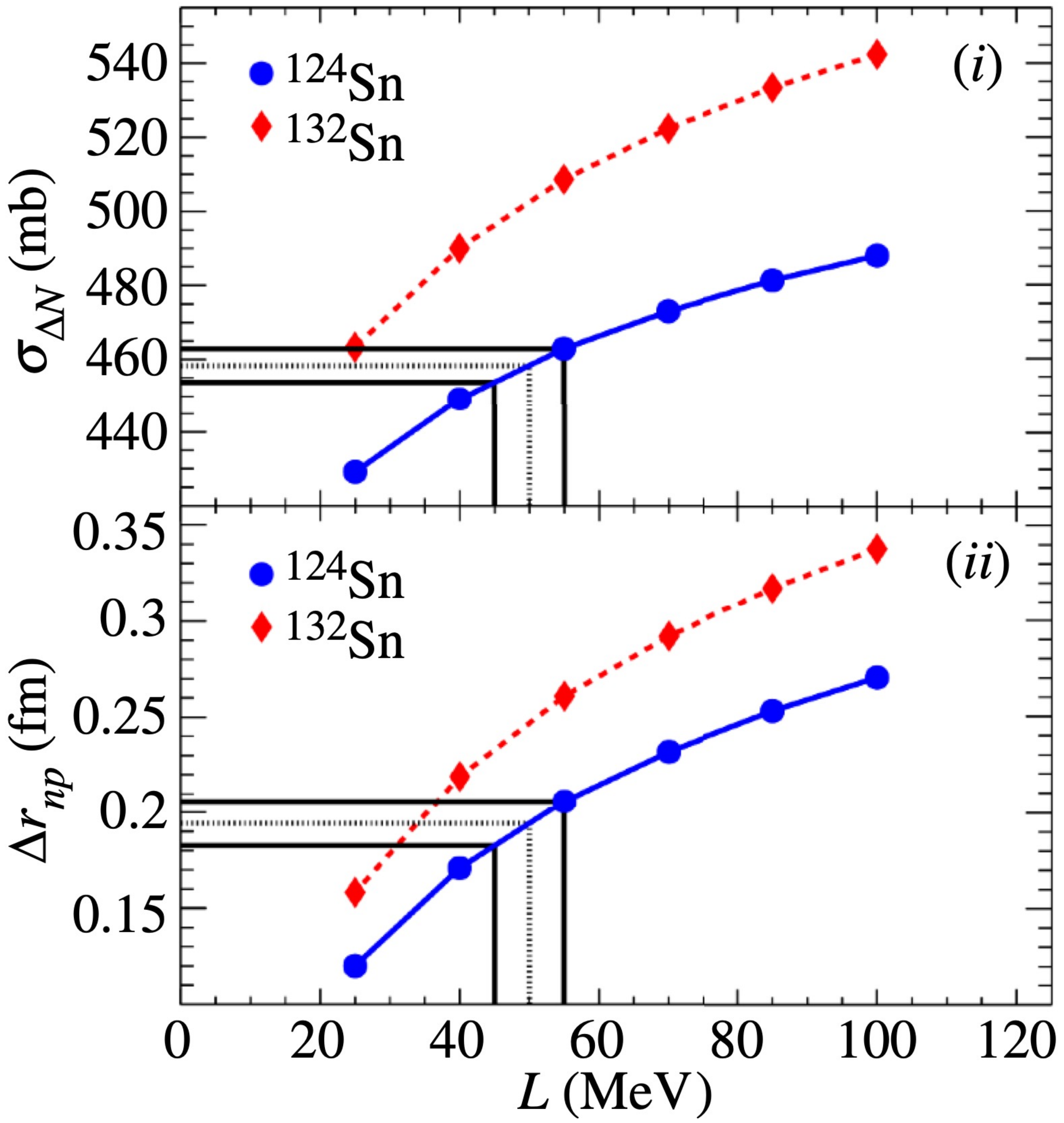
Teixeira, Aumann, CB, Carlson
EPJ A 58, 205 (2022)



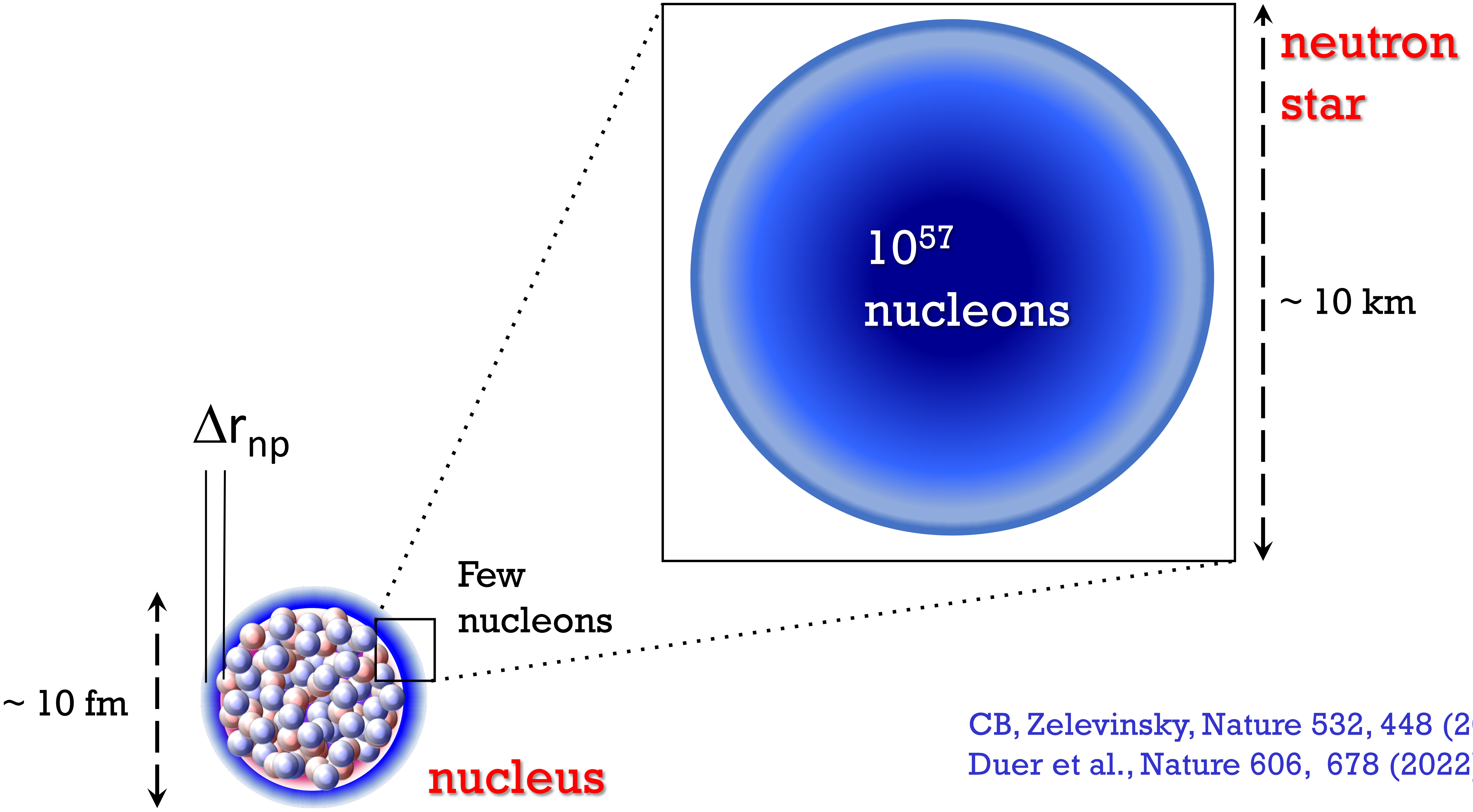

Shaded band:
Dozens of Skyrme HF and Relativistic Mean Field predicitons

# Fragmentation and symmetry energy



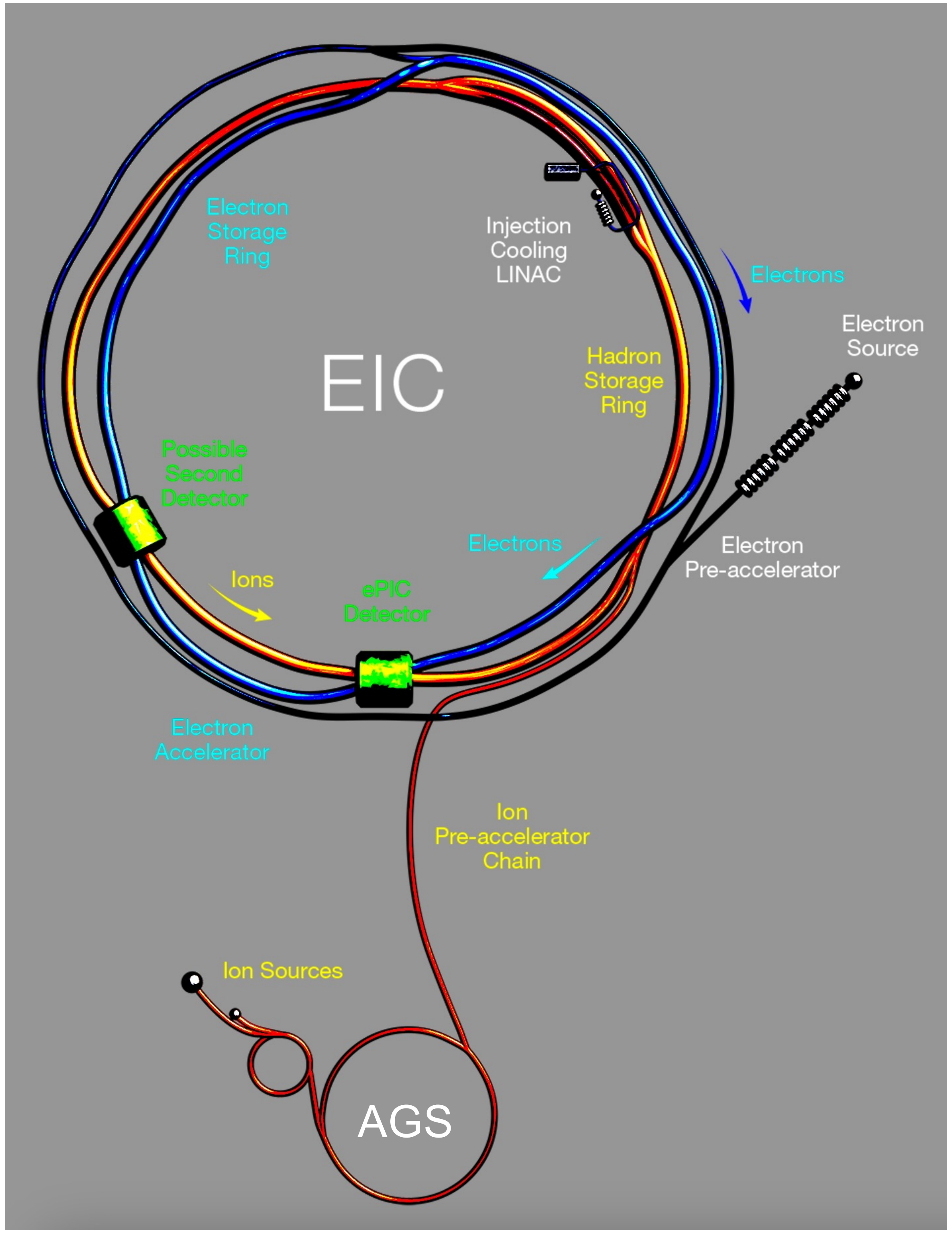



# EM nuclear response and neutron stars




CB, Zelevinsky, Nature 532, 448 (2016)
Duer et al., Nature 606, 678 (2022)

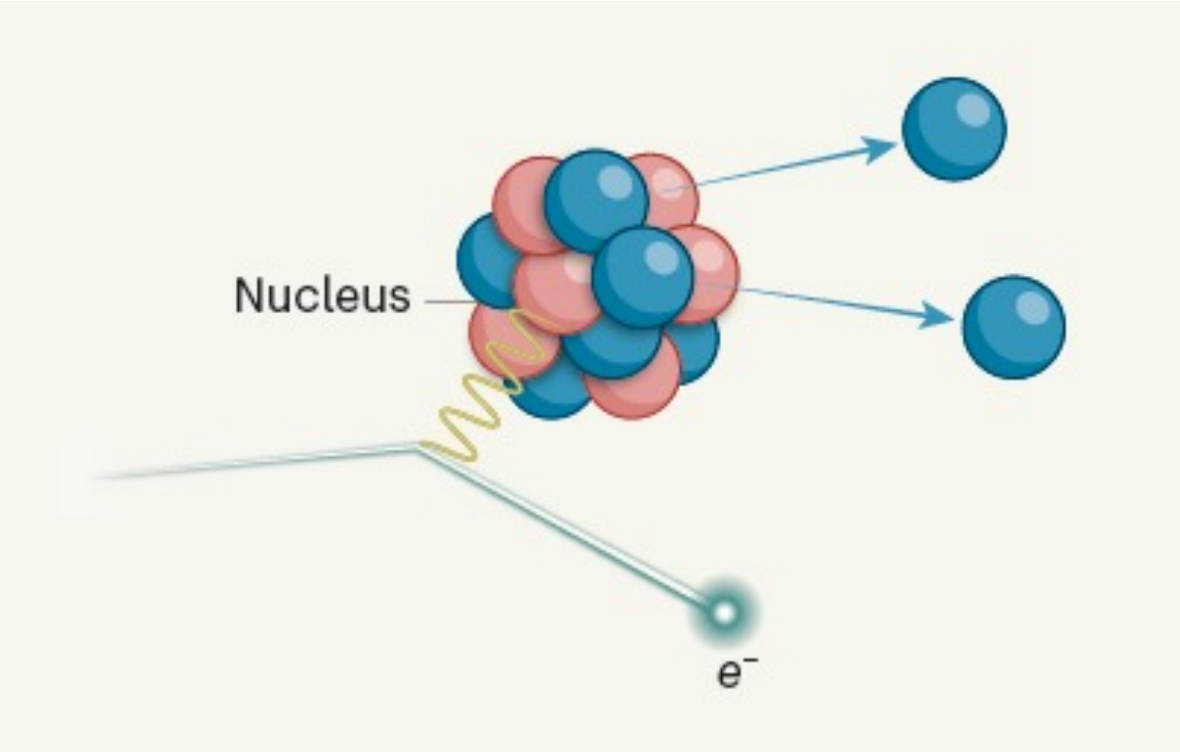
# Electron Ion Collider (EIC)




- 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

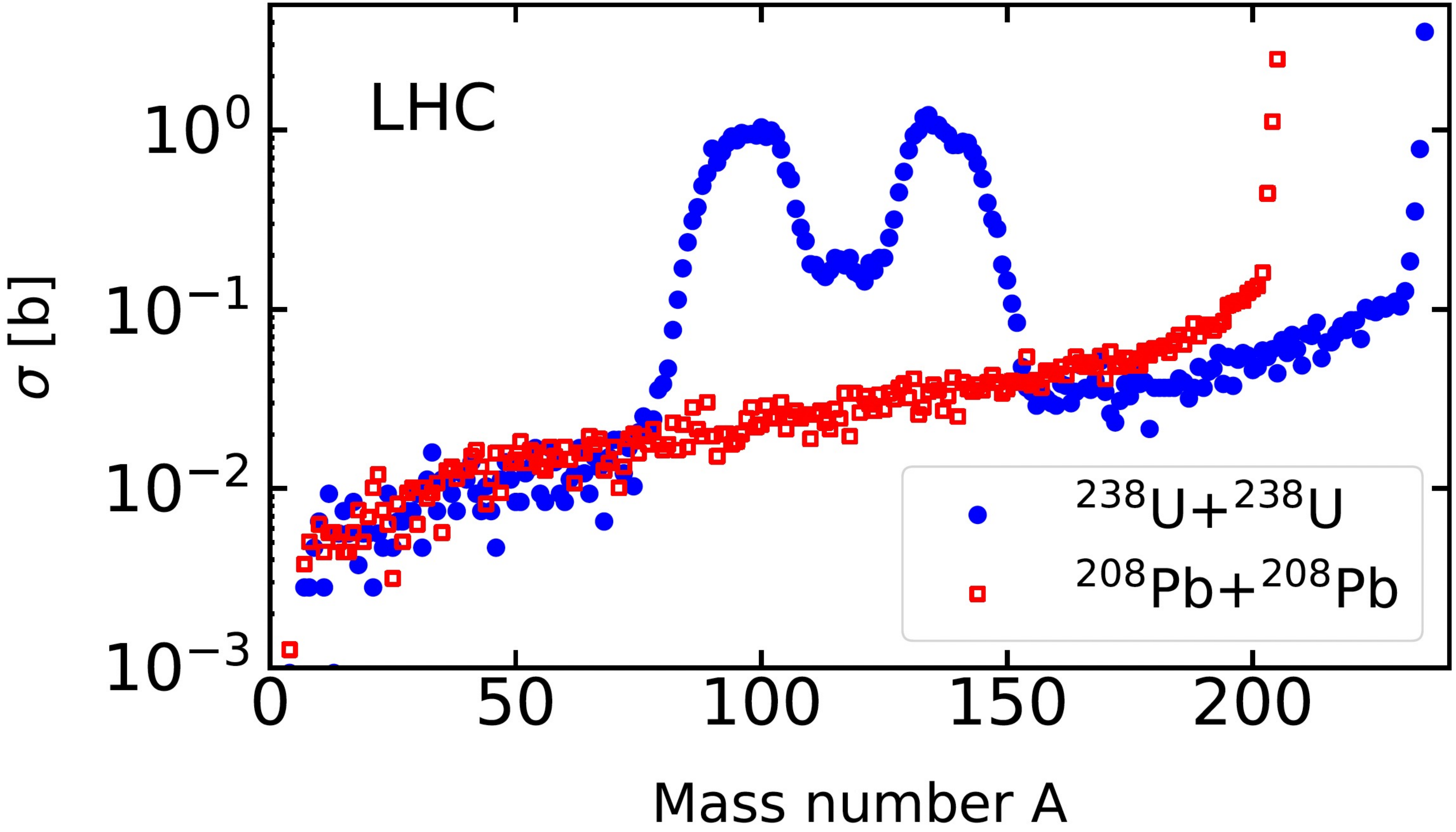
➡ Possible study of low energy physics of the isotopes.

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

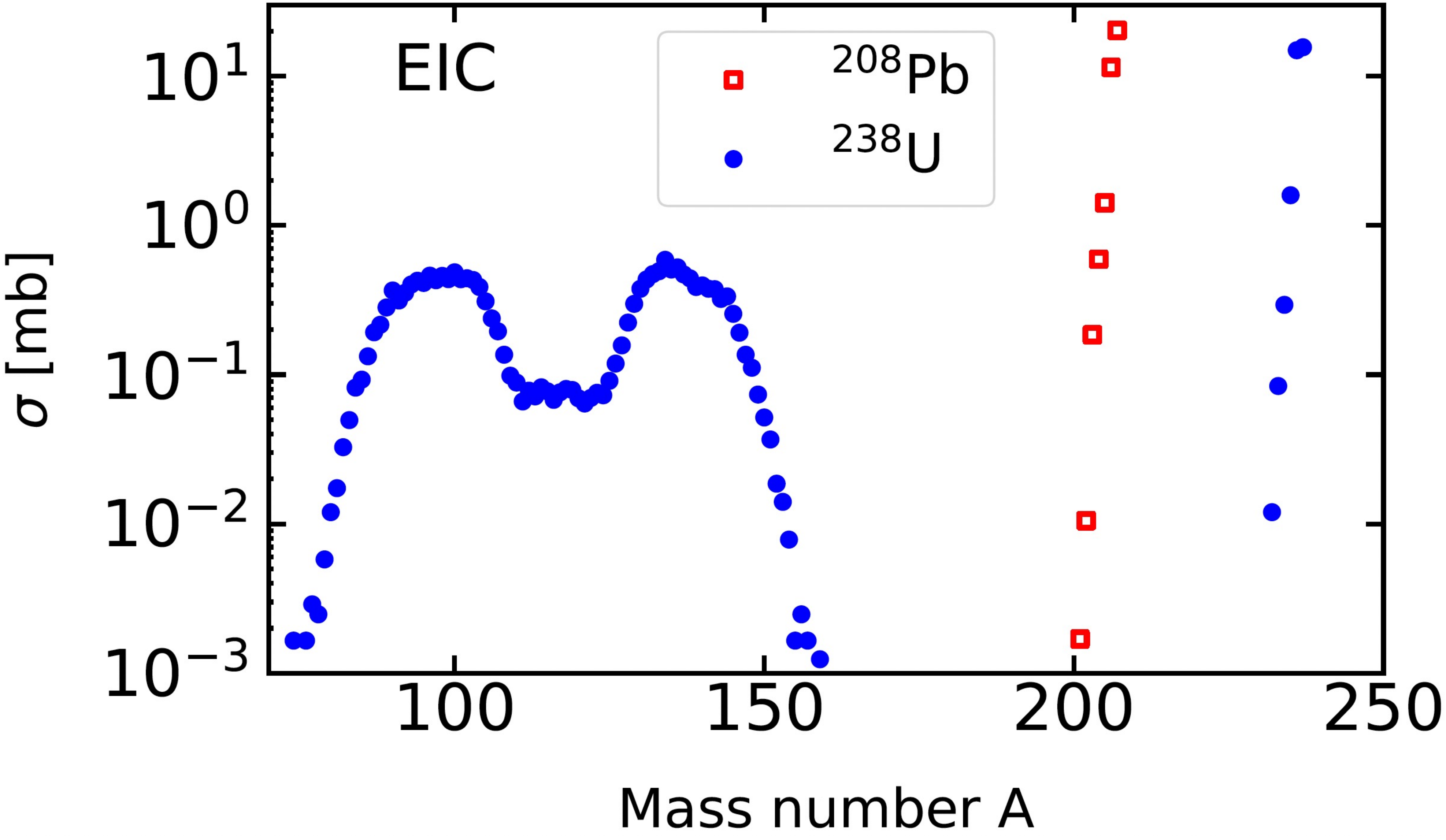
# Nuclear fragmentation at the LHC

Excitation of GRs
+
evaporation

CB, Kucuk, Navarra,
arXiv:2408.10157 (2024)



# Nuclear fragmentation at the EIC



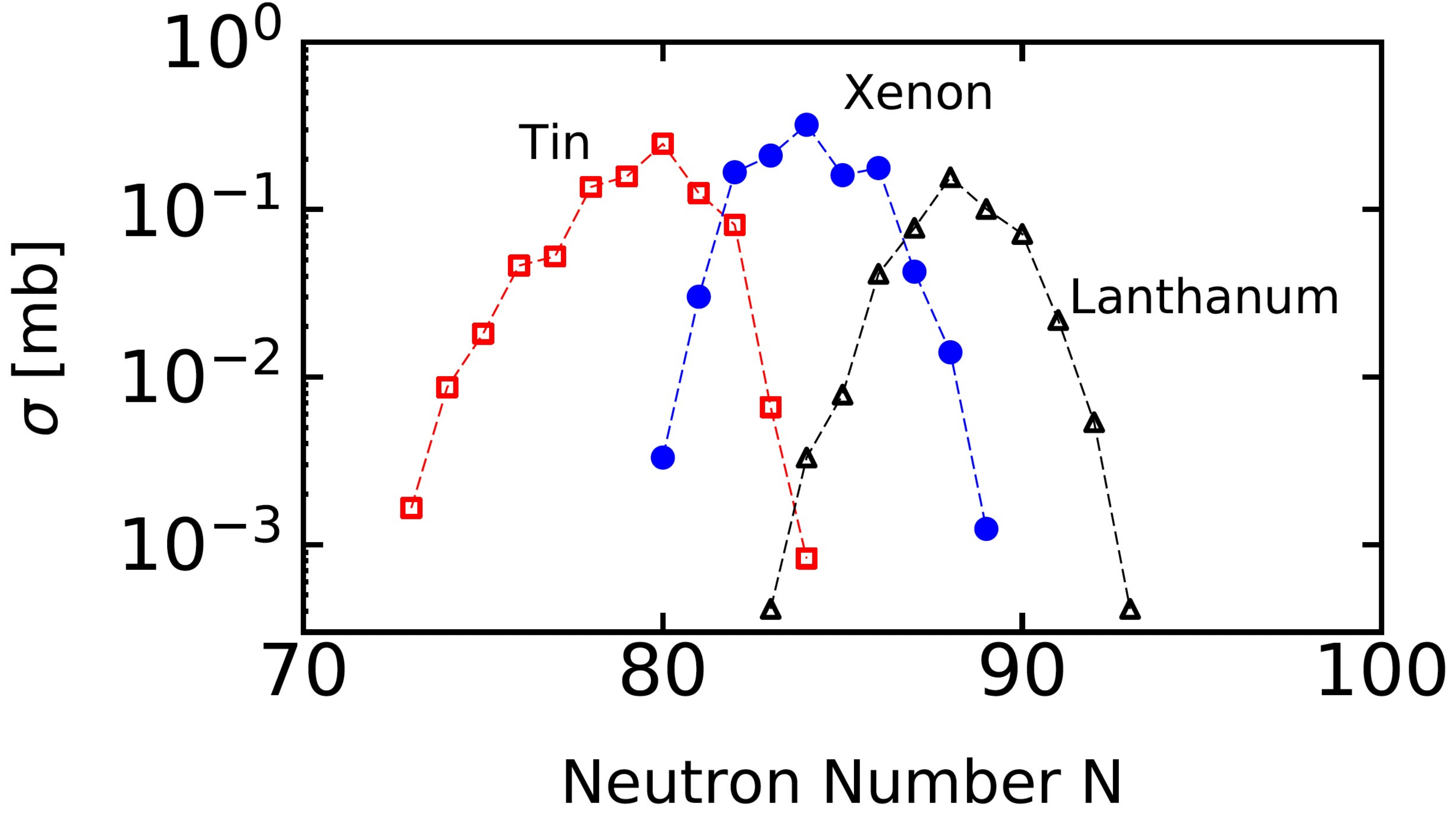

$$\frac{d\sigma}{d\omega dQ^2} = \sum_{\lambda} \frac{dN_\lambda}{d\omega dQ^2} \sigma_\gamma^\lambda(\omega)$$

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

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

$x$ = 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] |
| $\sigma_{-1n}$ | 33.93 | 33.20 | 20.24 | 15.58 |
| $\sigma_{-2n}$ | 18.89 | 30.59 | 11.45 | 14.88 |
| $\sigma_{-3n}$ | 2.546 | 3.537 | 1.416 | 1.591 |
| $\sigma_{-4n}$ | 1.091 | 0.784 | 0.5933 | 0.2934 |
| $\sigma_{fission}$ | 0 | 18.24 | 0 | 8.867 |
| $\sigma_{total}$ | 55.74 | 85.48 | 33.90 | 41.32 |
| Fission b.r. | 0% | 19.54% | 0% | 21.45% |

# Summary

## Physics at EIC

- Origin of nucleon mass and spin
- 3D structure of the nucleon and nucleus
- Gluon saturation
- Hadronization

## Physics at zero degree of EIC

- EIC is a cleaner probe
- EIC has the potential to produce new nuclear isotopes
- Fragments can be detected and identified using particle ID, ZDC, and other yet to be proposed detectors
- Level structure of produced isotopes would be assessed through the detection of the de-excitation photons

# Hauser-Feshbach formula & resonances

$$\langle\sigma\rangle = 2\pi^2\omega\frac{\Gamma_a\Gamma_b}{\Gamma D} = \pi D^2\omega\frac{T_a T_b}{T_{tot}}$$

where

$$T_a = 2\pi\left\langle\frac{\Gamma_a}{D}\right\rangle$$

- $T_a$ = dimensionless number between 0 and 1 = probability that a particle of type $a$ crosses the nuclear surface (with angular momentum $l$)

- $T_a$ is related to the "*strength function*", $<\Gamma/D>$, describing how width is distributed smoothly in the nucleus.

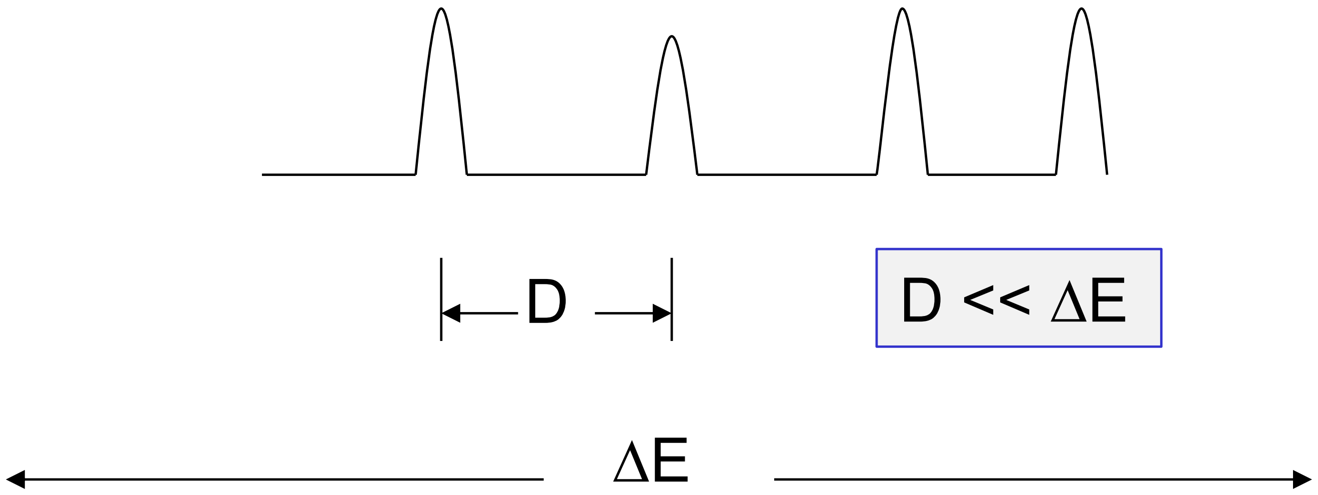
- These functions still contain the barrier penetration functions.

- This yields the Hauser-Feshbach formula for estimating cross sections where the density of resonances is high.

$$\bar{\sigma}_{ab} = \frac{\pi/k^2}{(2J_a+1)(2J_b+1)}\sum_{J^\pi}(2J^\pi+1)\frac{T_a^{l,s}(J^\pi,E)T_b^{l,s}(J^\pi,E)}{T_{tot}(J^\pi,E)}$$

# Hauser-Feshbach formula & resonances

Assume $N$ (>>1) equally spaced identical resonances in an energy interval $\Delta E$




Define average cross section:

$$\langle \sigma \rangle = \frac{\int_E^{E+\Delta E} \sigma(E)\,dE}{\Delta E}$$

$$\langle \sigma \rangle = \frac{1}{\Delta E} \int_E^{E+\Delta E} \frac{\Gamma_a \Gamma_b\, dE}{(E - E_r)^2 + \Gamma^2/4} = \frac{\Gamma_a \Gamma_b}{\Delta E} \int_0^{\infty} \frac{dE}{(E - E_r)^2 + \Gamma^2/4}$$

$$\int_0^{\infty} \frac{dE}{(E - E_r)^2 + \Gamma^2/4} = \frac{2\pi}{\Gamma}$$

$$\frac{N}{\Delta E} = \frac{1}{D}$$

and normalizing over the average distance $D$:

$$\frac{1}{\Delta E} = \frac{1}{D}$$