Nuclear Fragmentation at the Future Electron-Ion Collider

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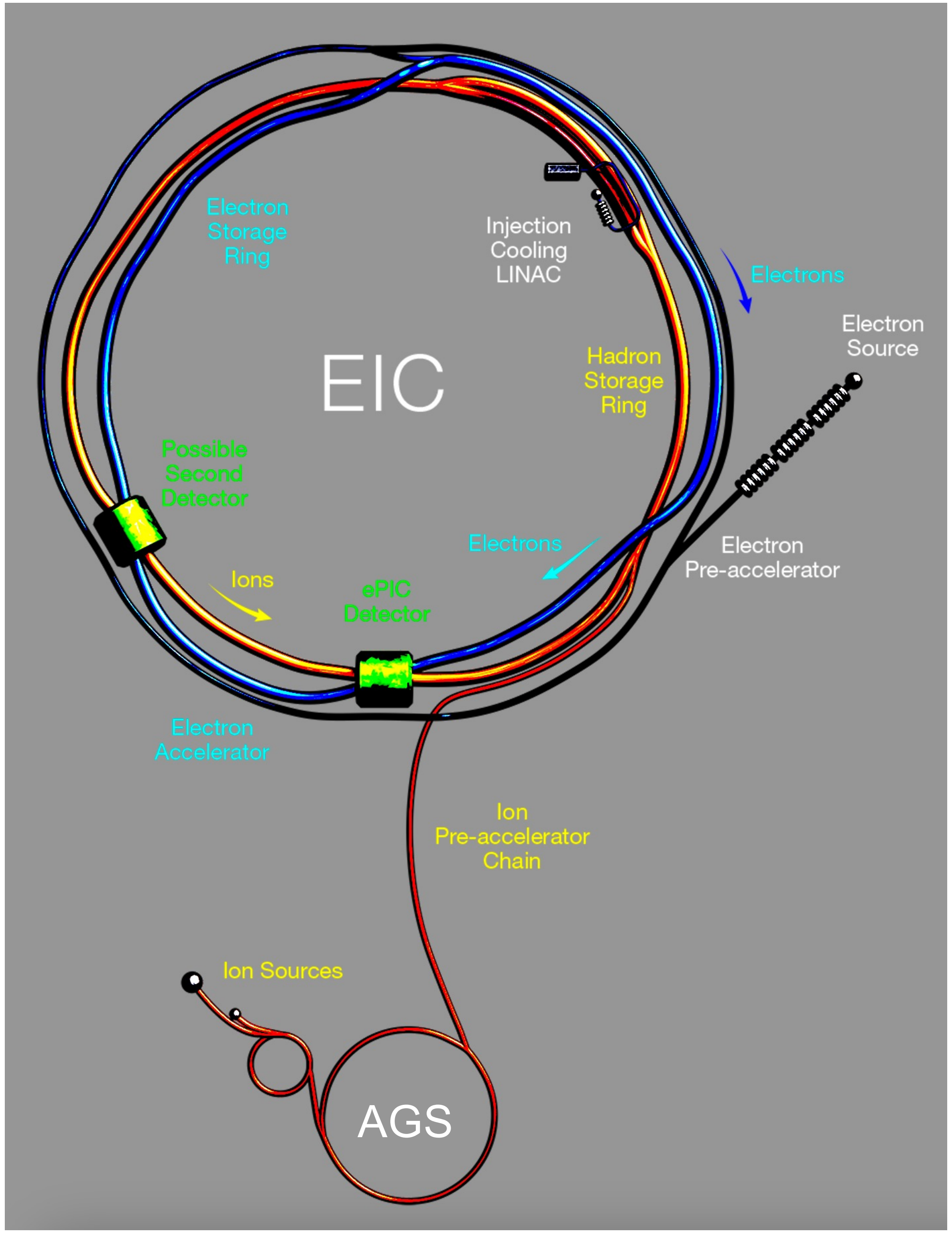
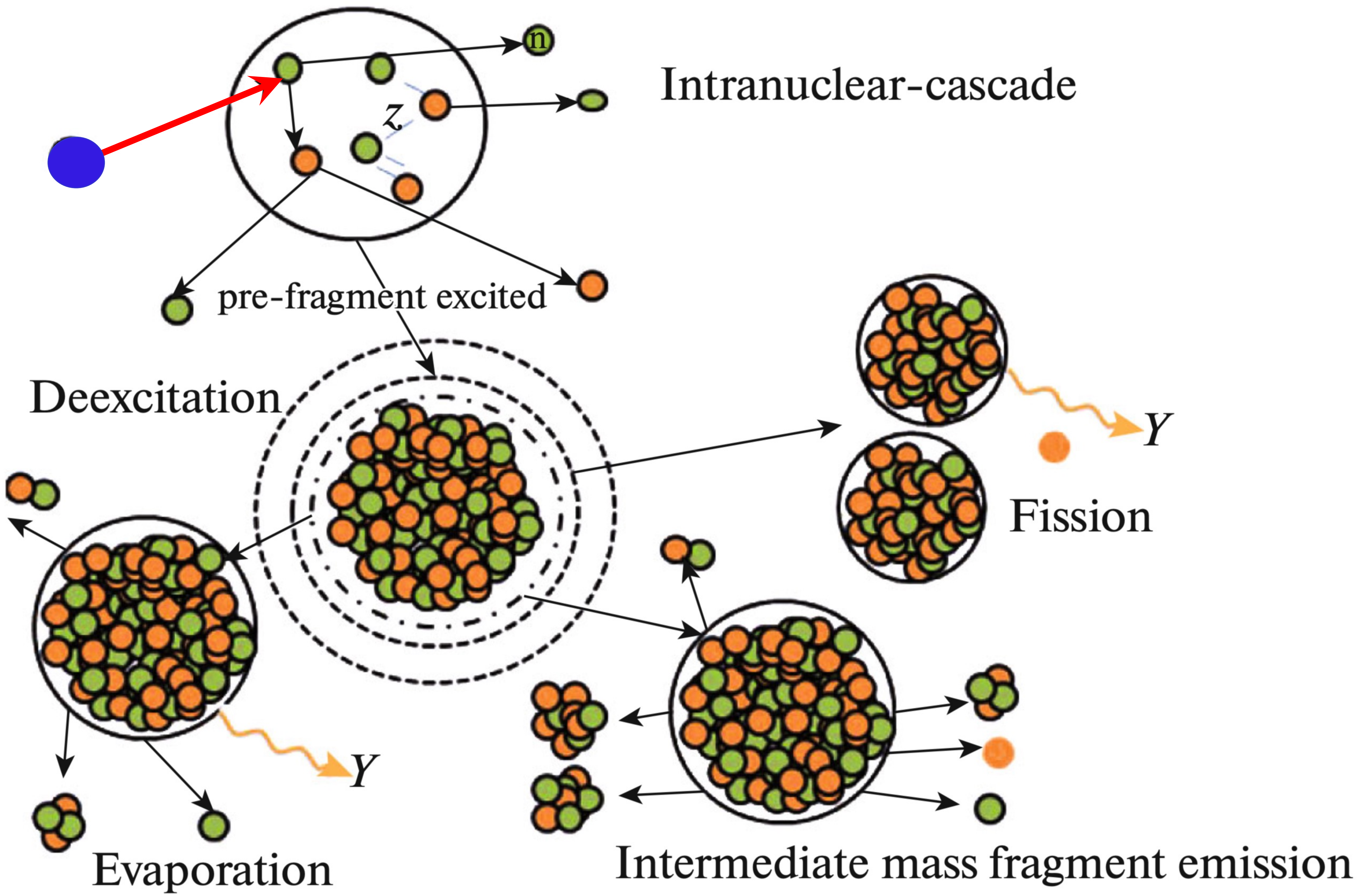
Electron Ion Collider (EIC)



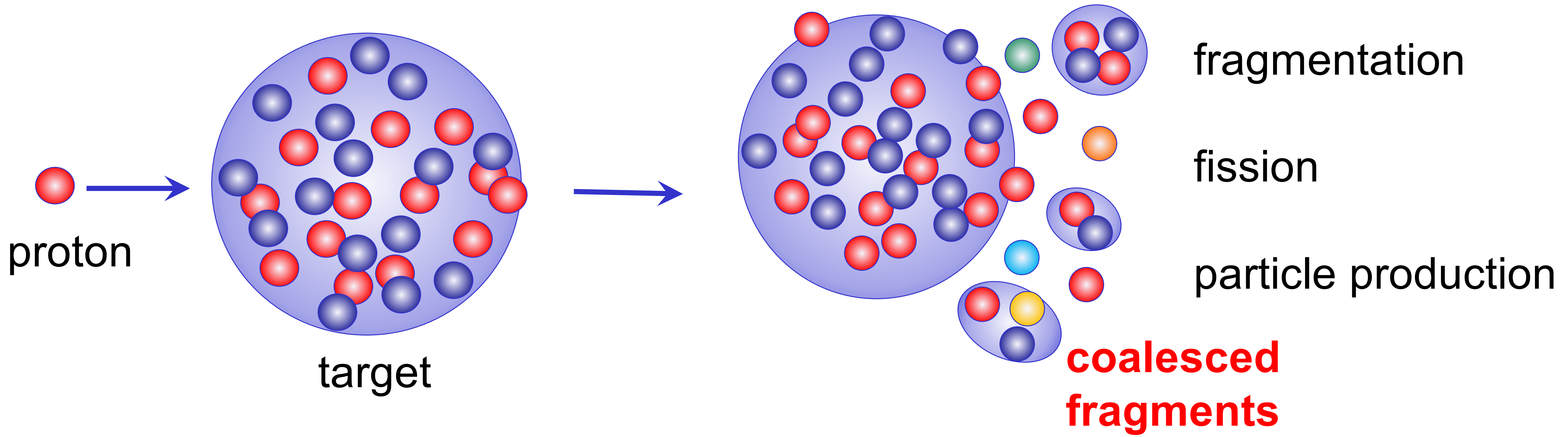
- High Luminosity: L= 10^{33} – 10^{34}cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Polarized beams: e, p, d, ^{3}He
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium

- **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.

Fragment production: Cascade & coalescence & evaporation



Transport equations + coalescence

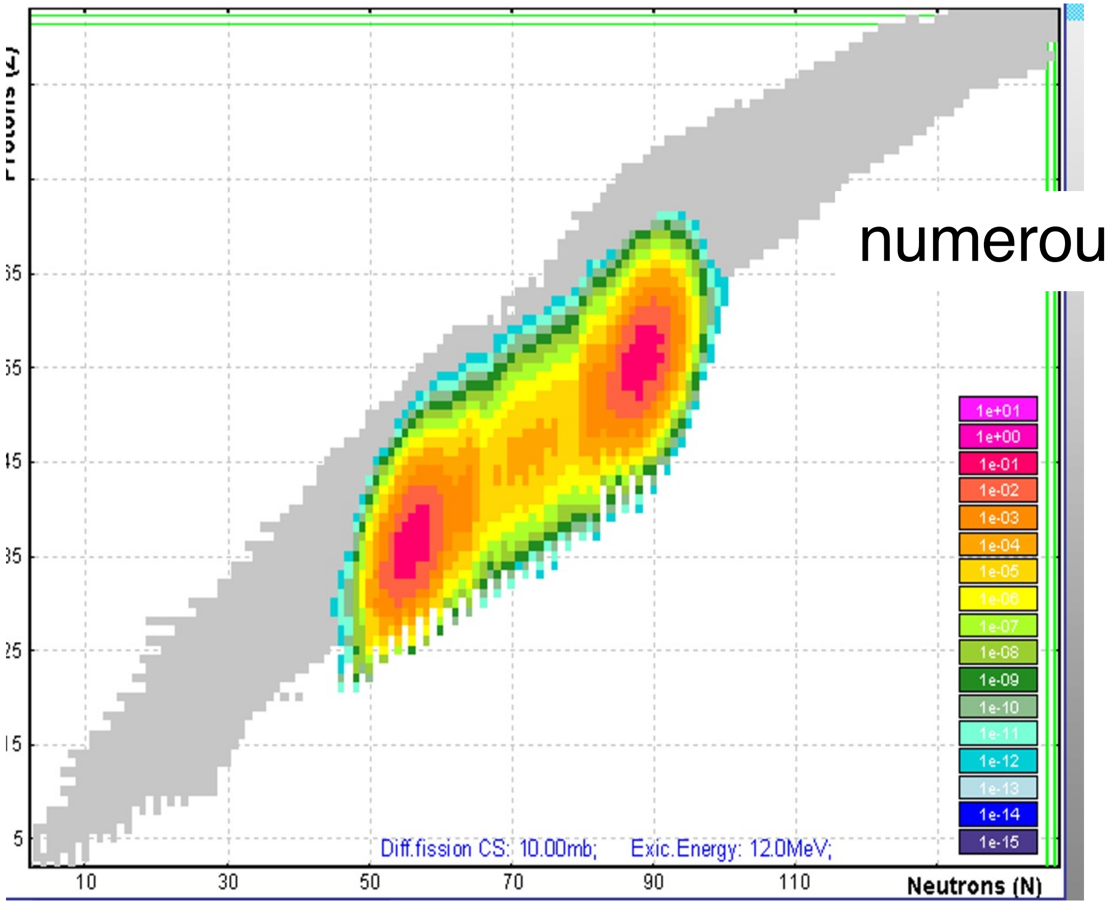


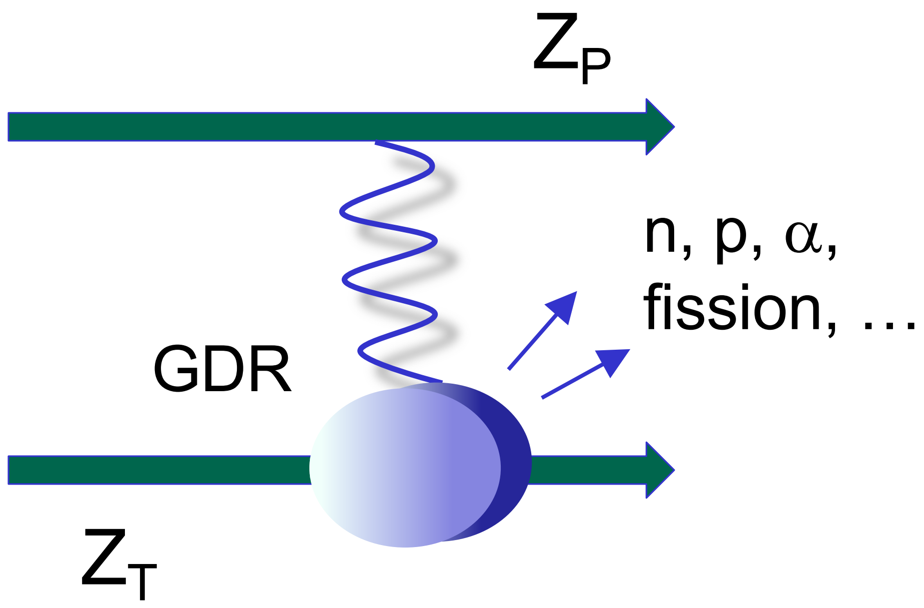
$$C_A = \frac{2J_A + 1}{2^A} \frac{1}{\sqrt{A} m_T^{A-1}} \left(\frac{2\pi}{R^2 + \left(\frac{r_A}{2}\right)^2} \right)^{\frac{3}{2}(A-1)}$$

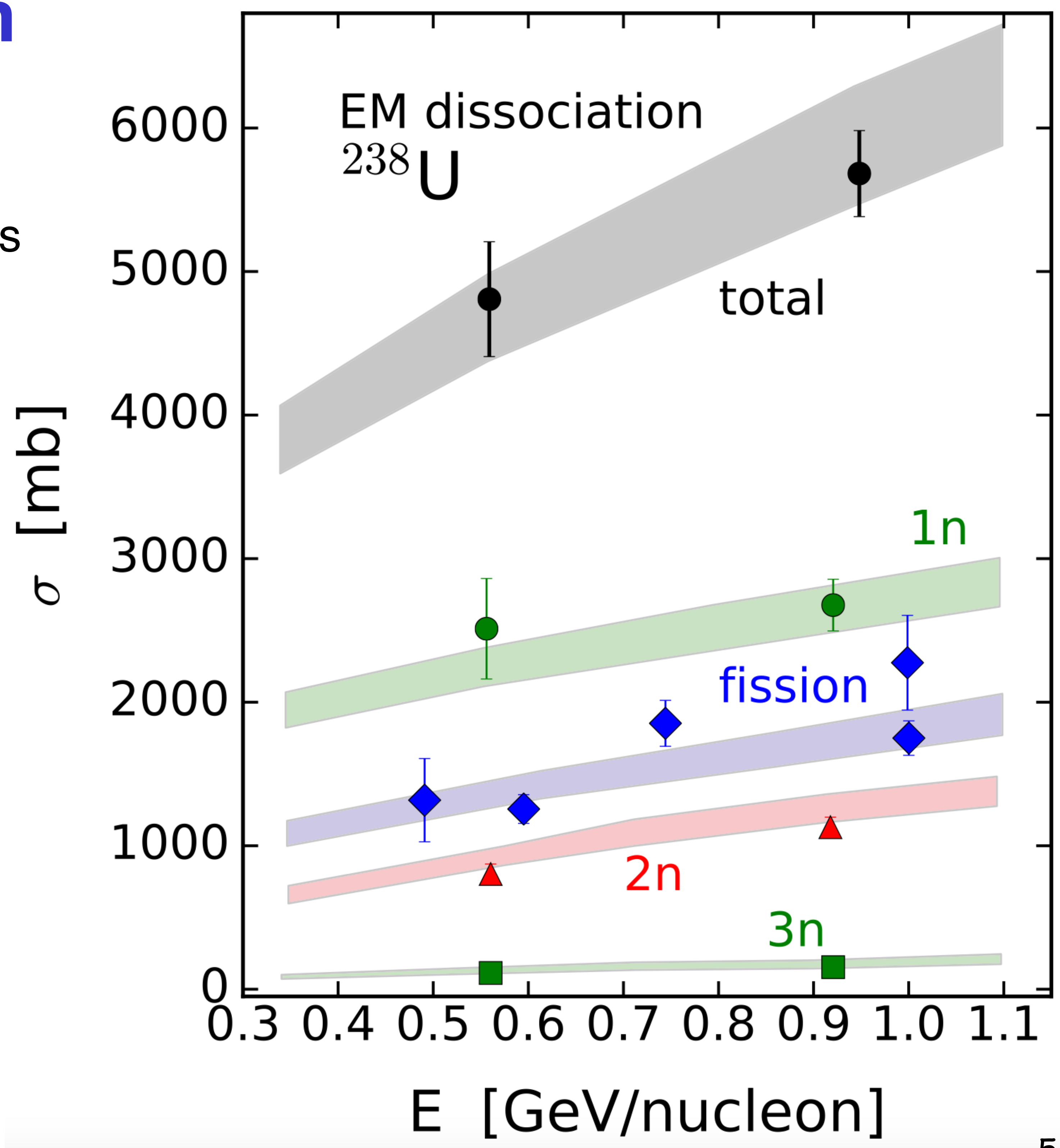
Particles produced coalesce into nuclei if they are close in space and momentum.

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

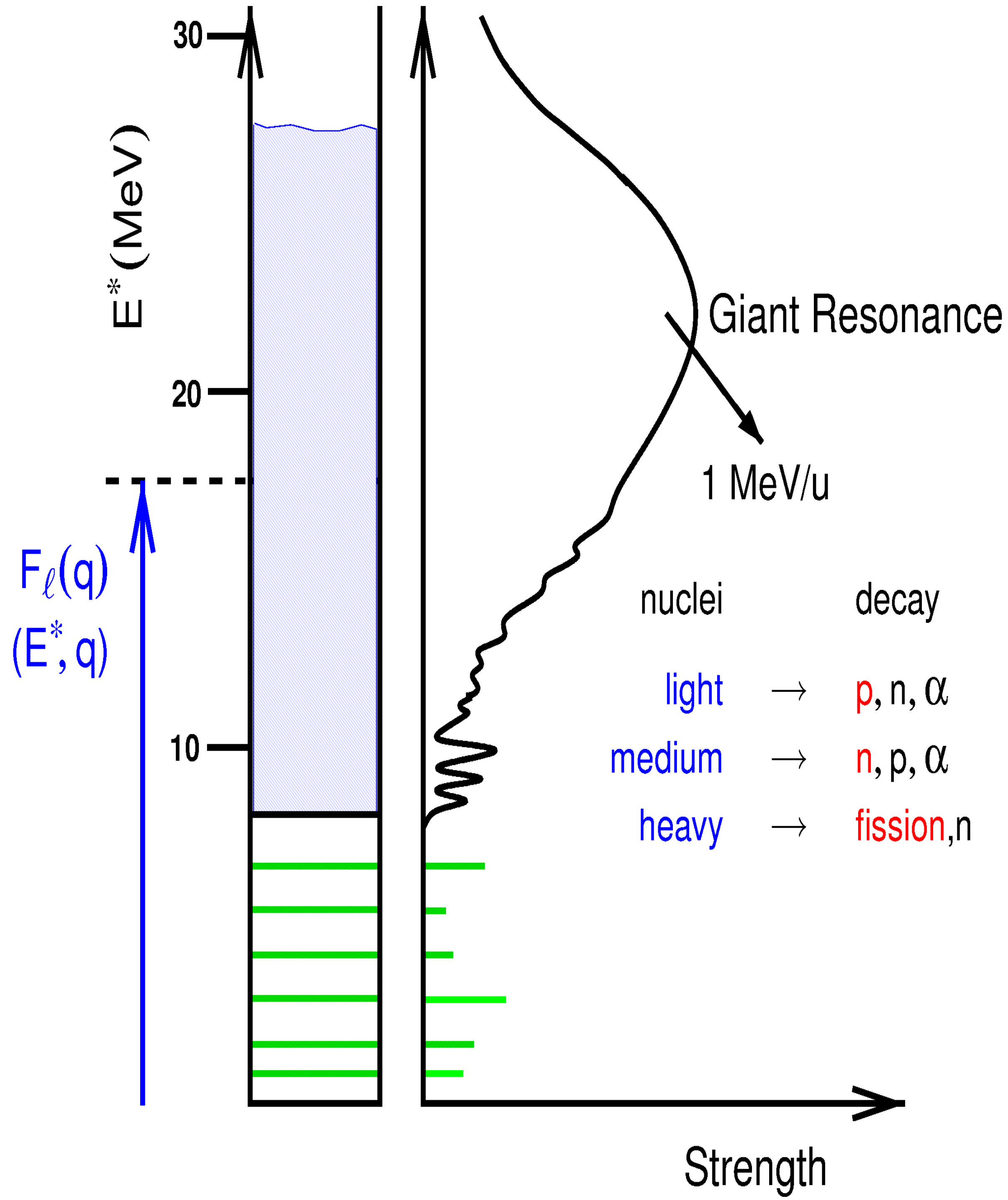
Electromagnetic fragmentation

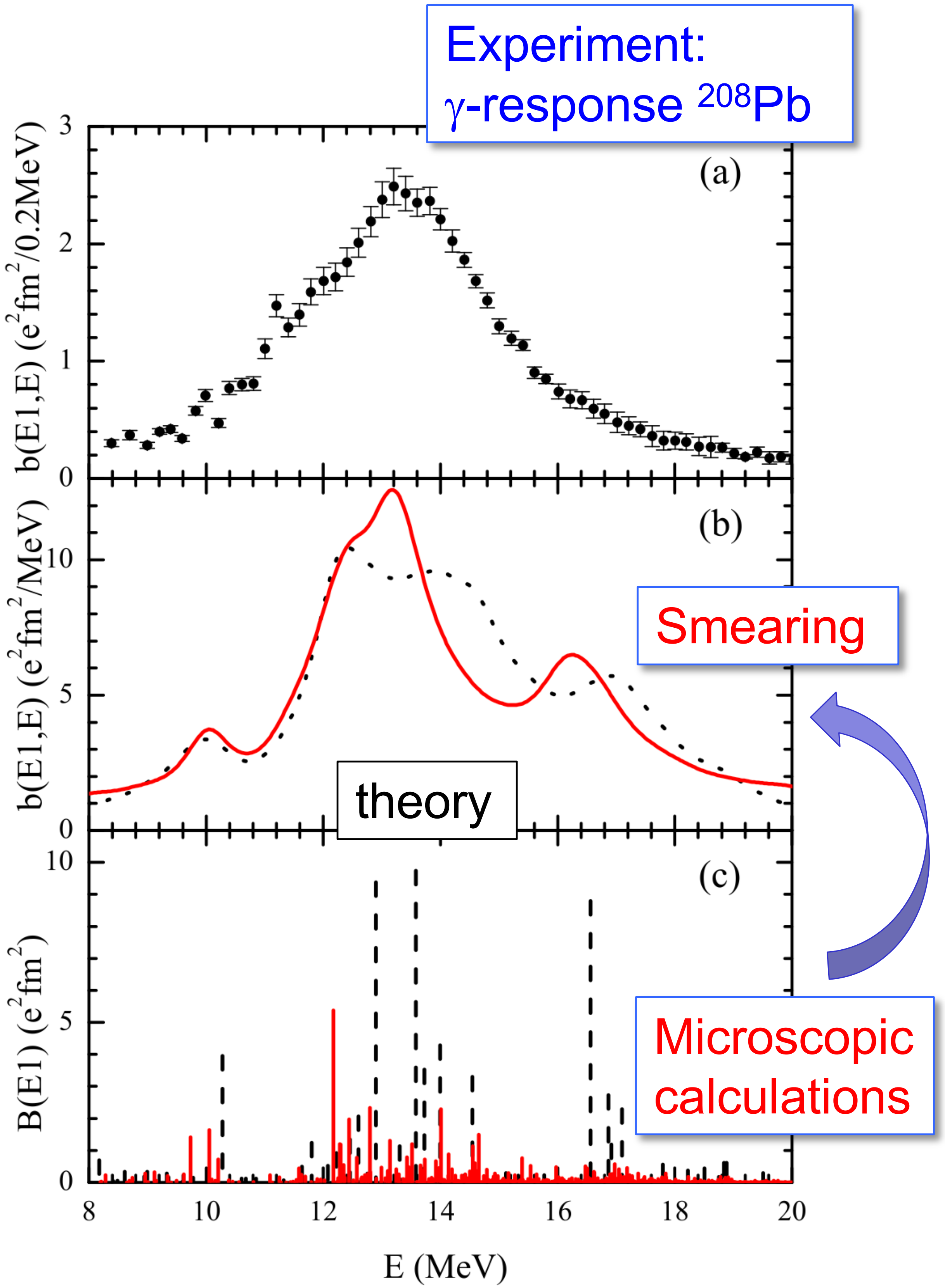




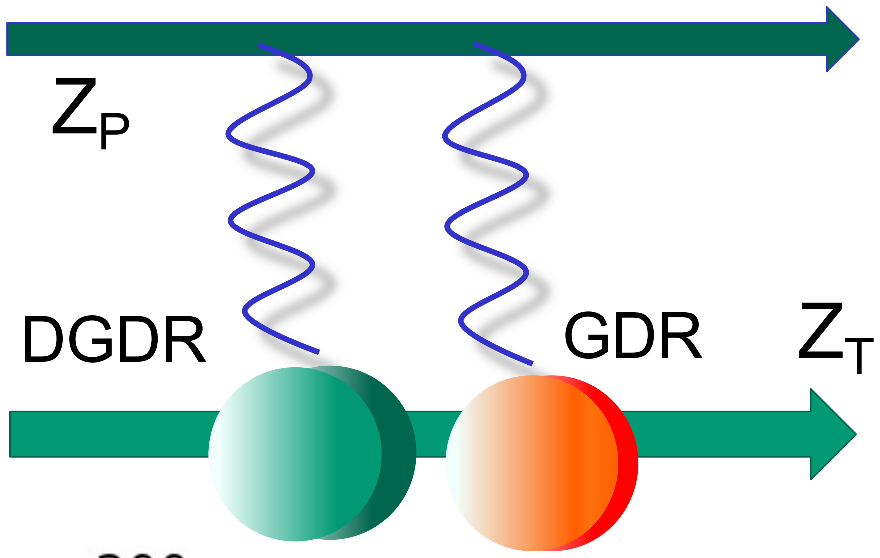


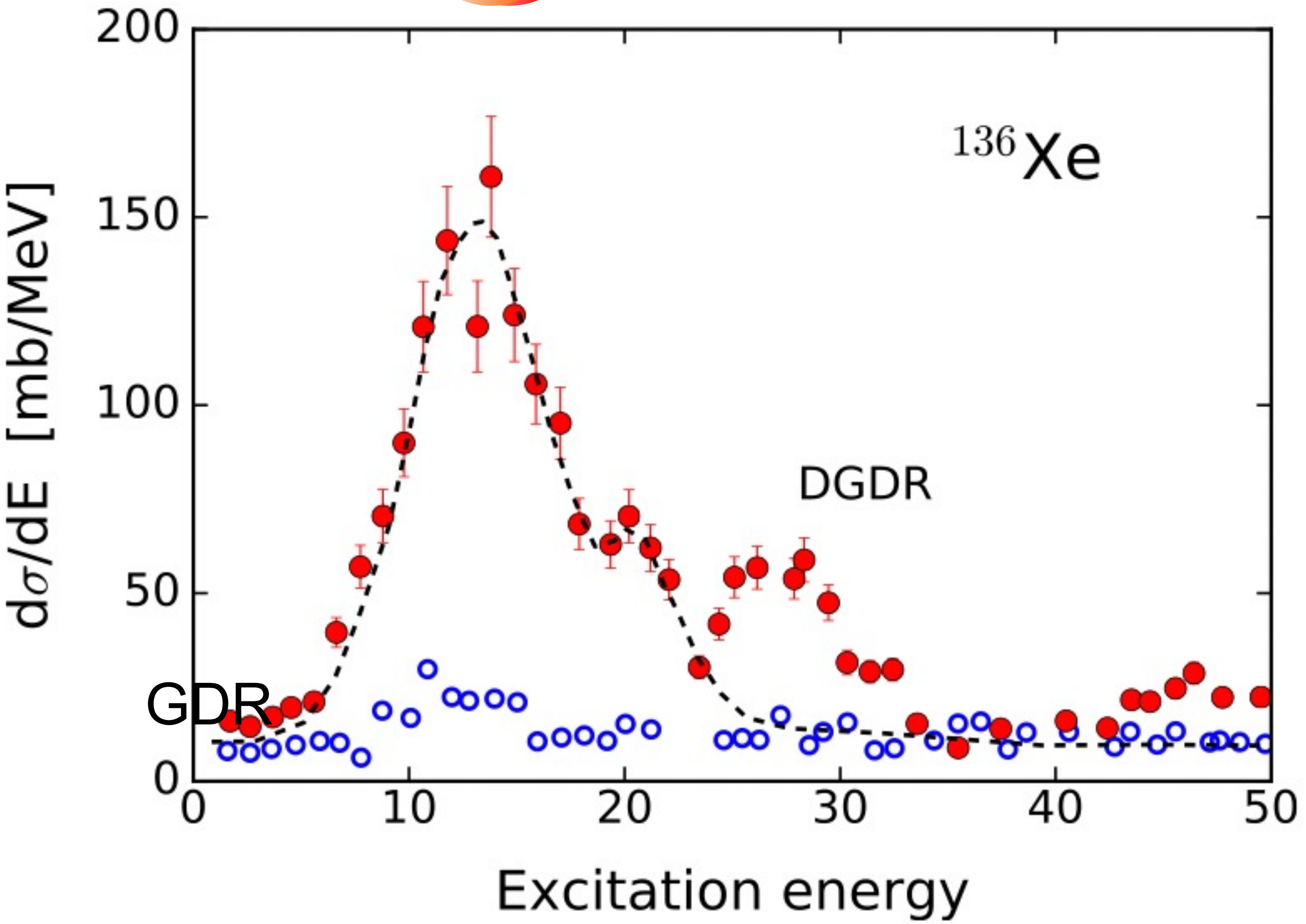
Giant resonances in nuclei

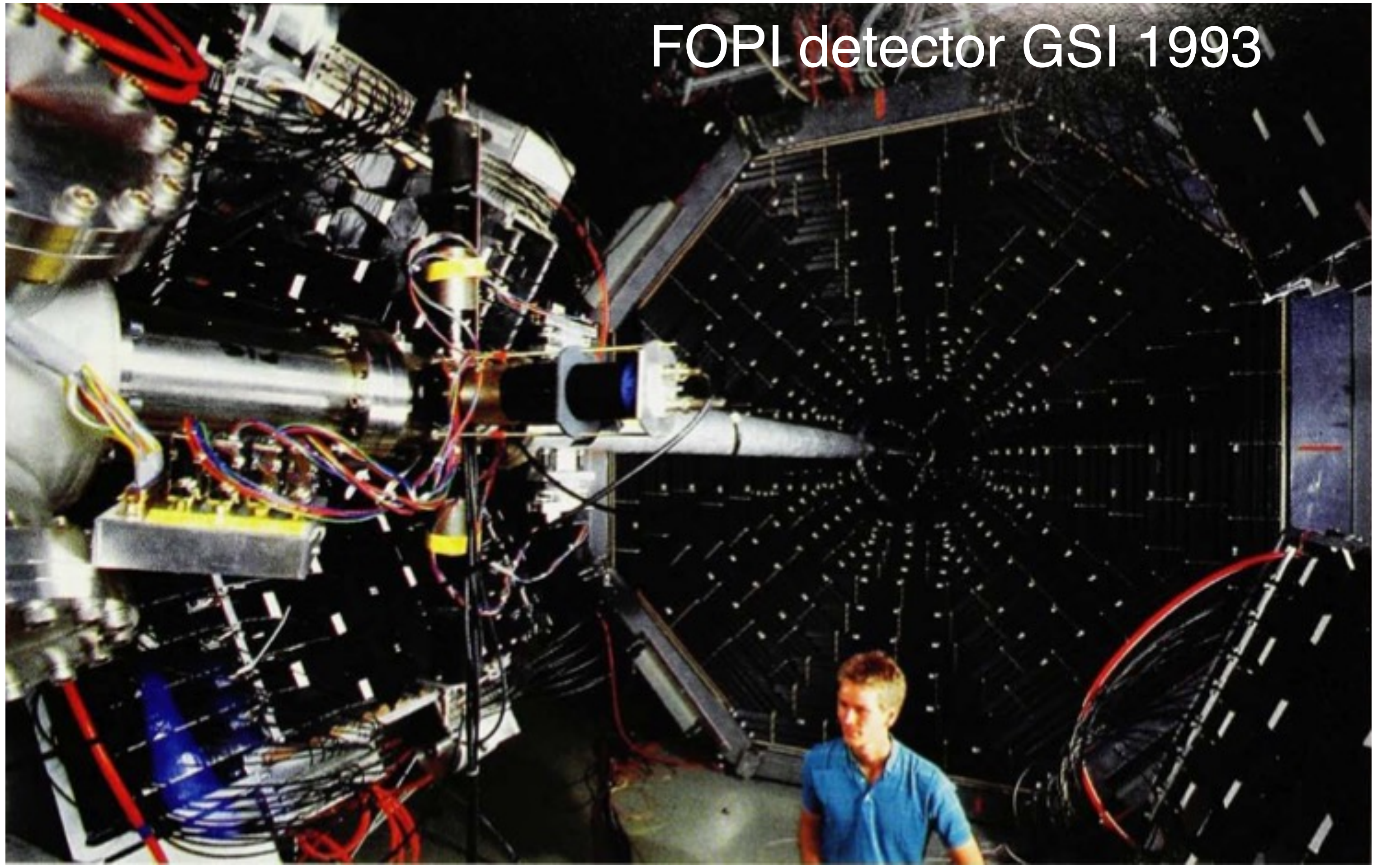


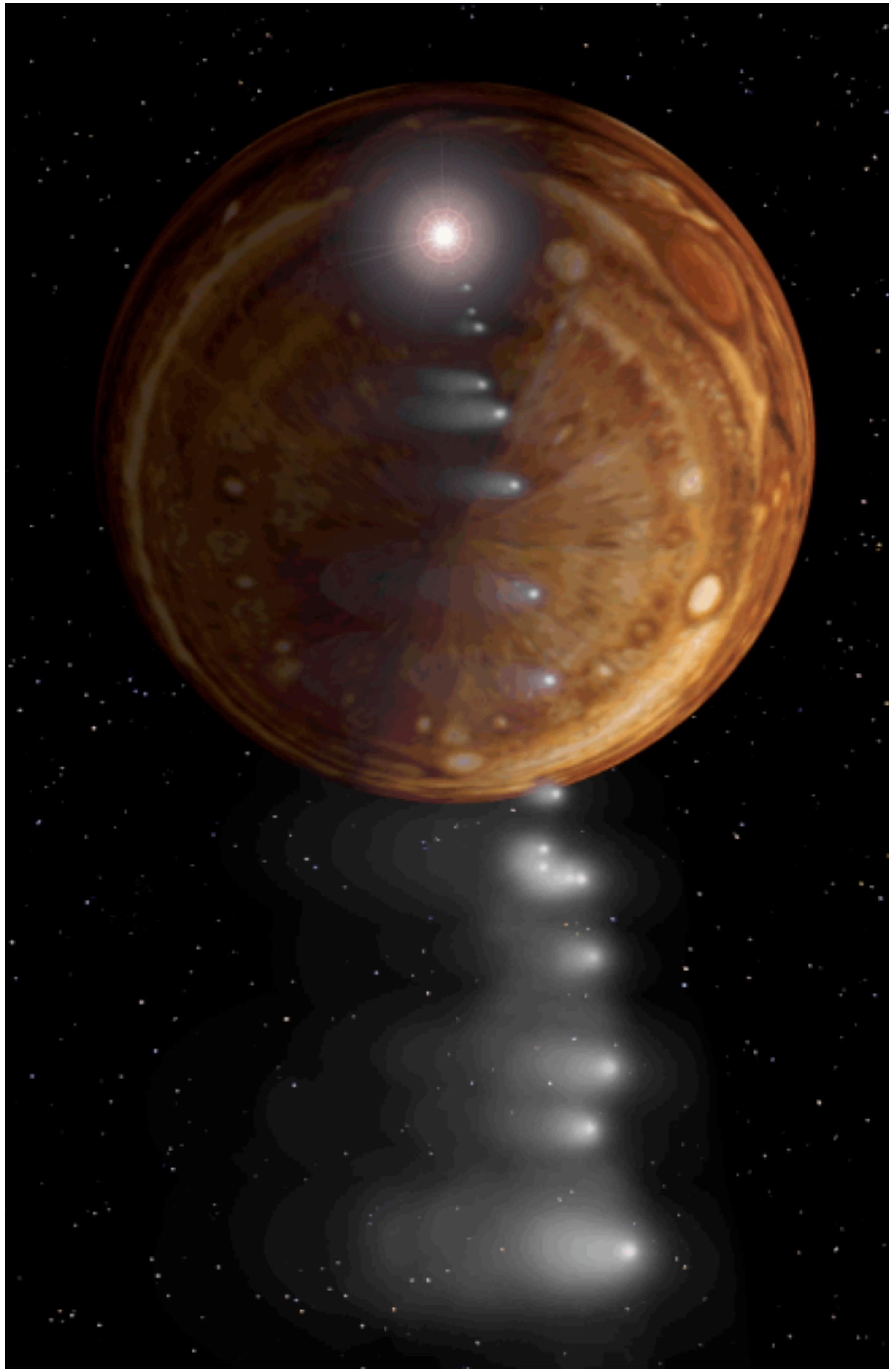


Double giant dipole resonance



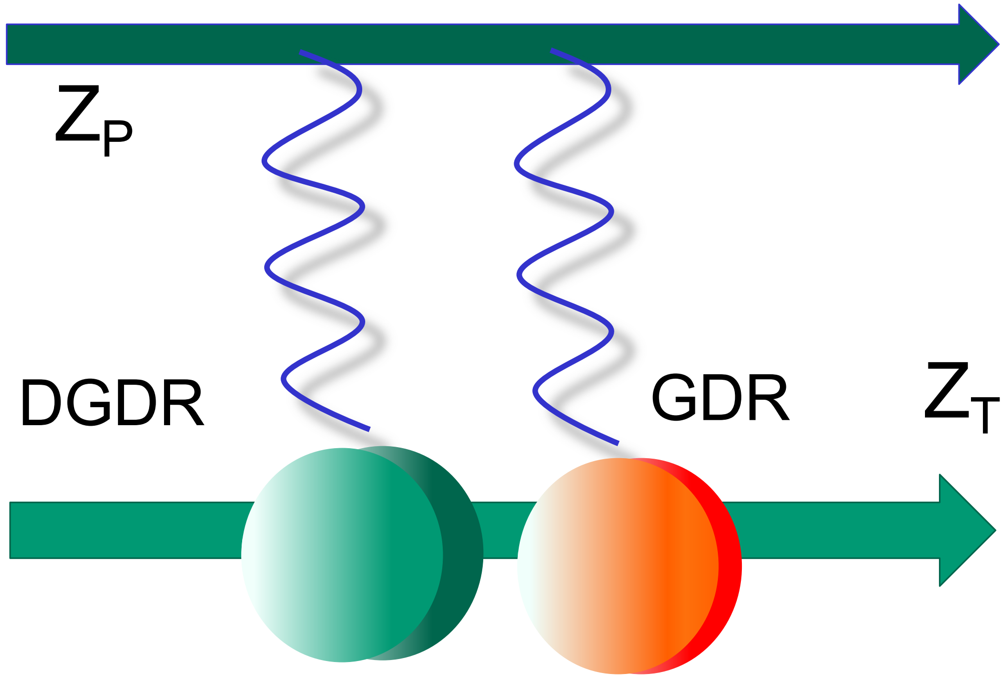






Shoemaker-Levi comet (July 1992)

Fragmentation: Classical and complicated



Fragmentation: Quantum and simpler

Hauser-Feshbach theory

Include angular momentum conservation in the Ewing-Weisskopf theory

CN ang. mom.

transmission probability

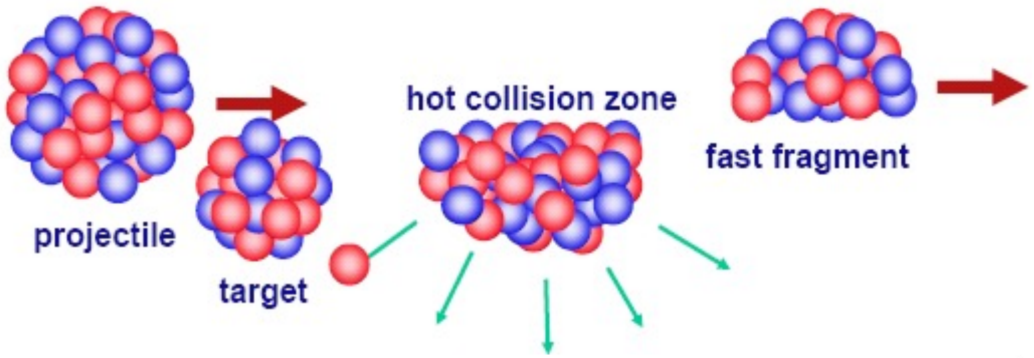
$$\sigma_{CN}(\alpha) = \frac{\pi}{k^2} \sum_J \frac{2J+1}{(2j_a+1)(2j_b+1)} \frac{T_{l,s}(\alpha)}{\prod_{l,s,\alpha'} T_{l,s}(\alpha')}$$

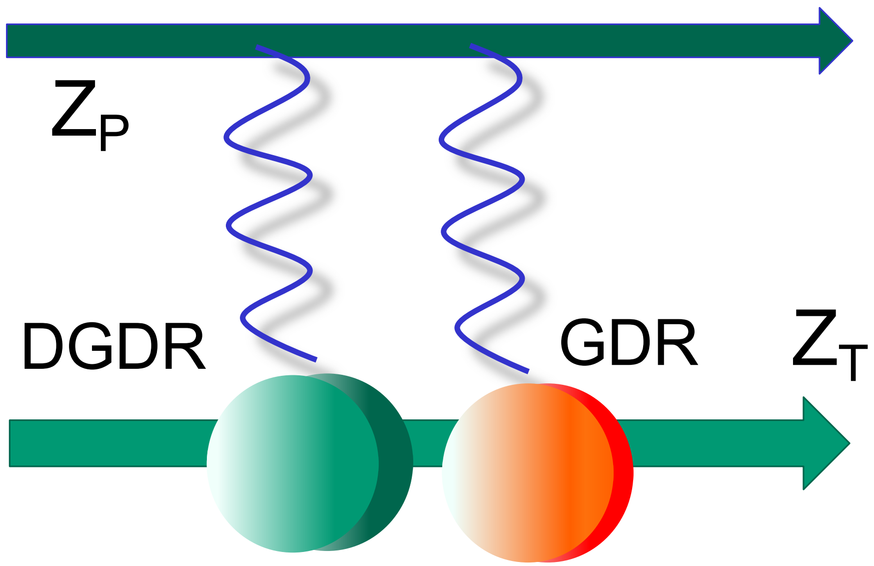
projectile spin

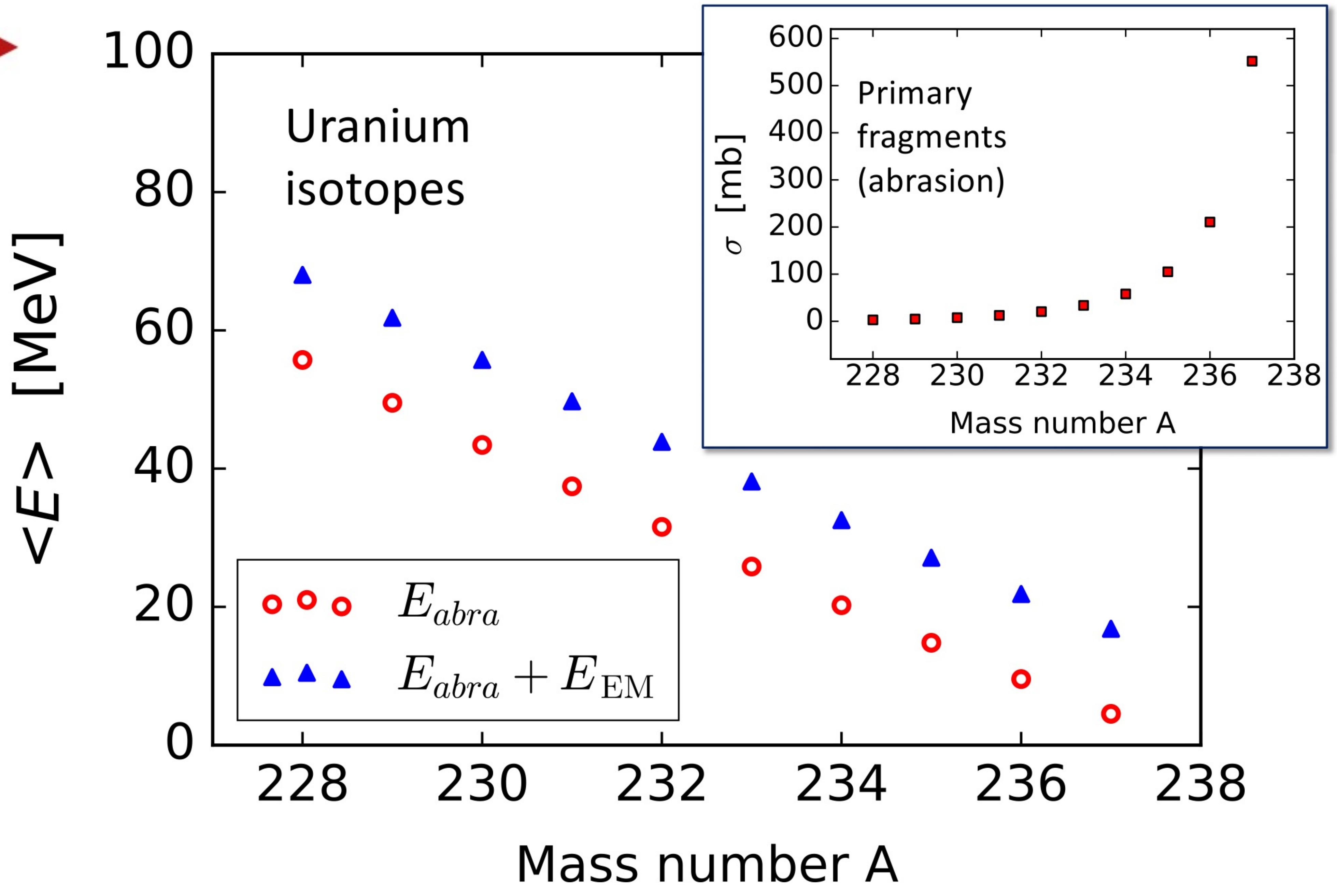
target spin

Optical potentials

Fragmentation in heavy ion collisions

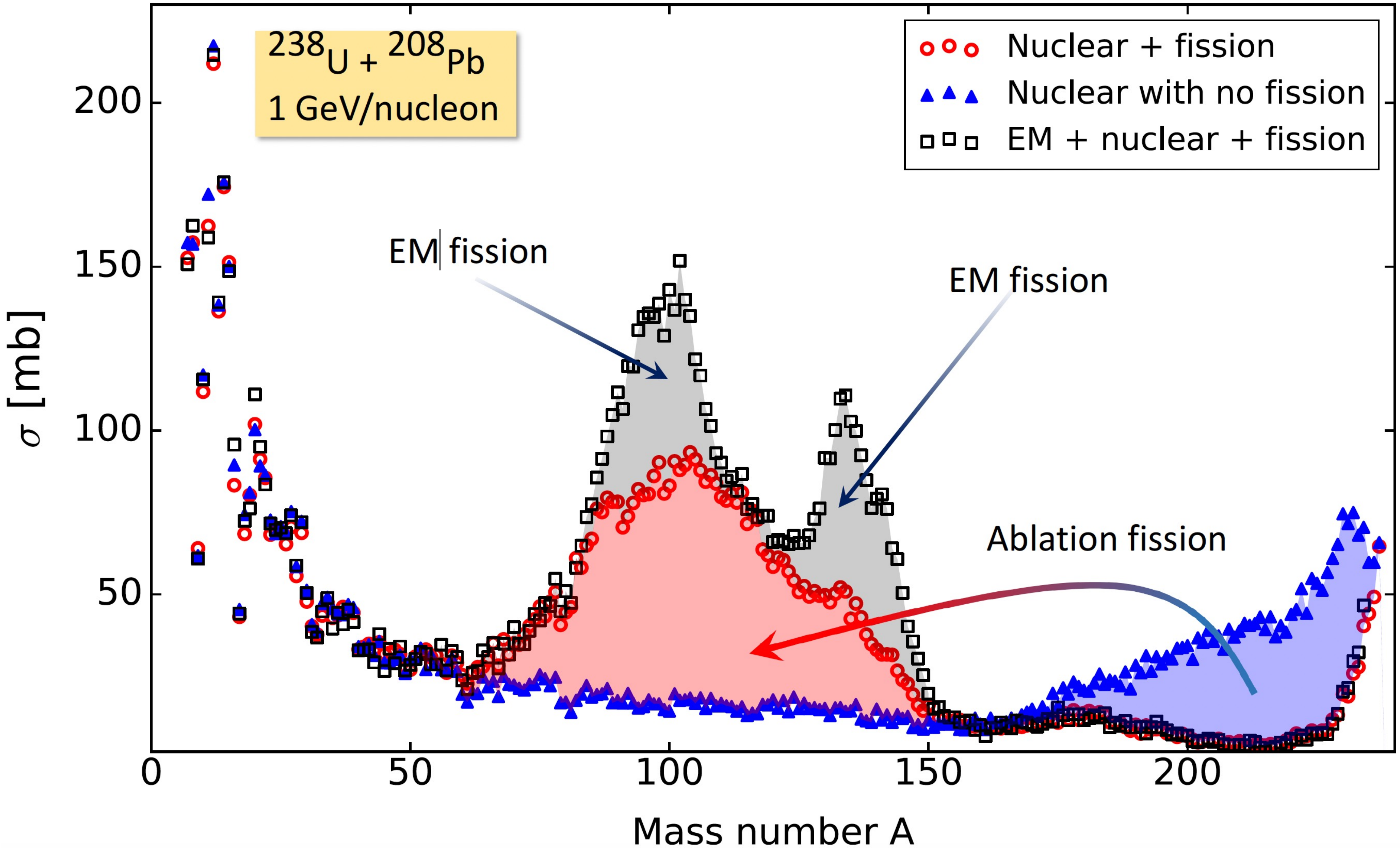


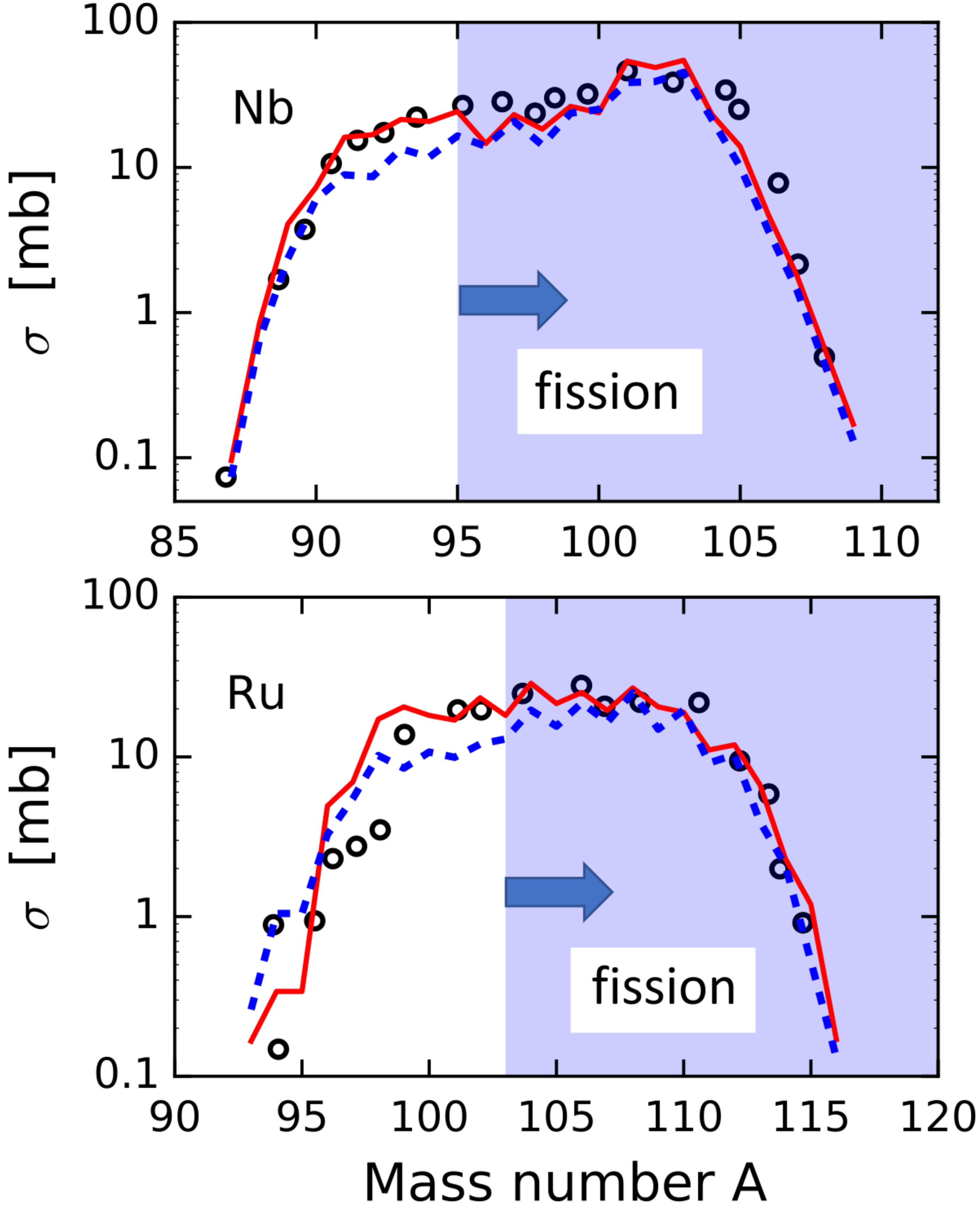


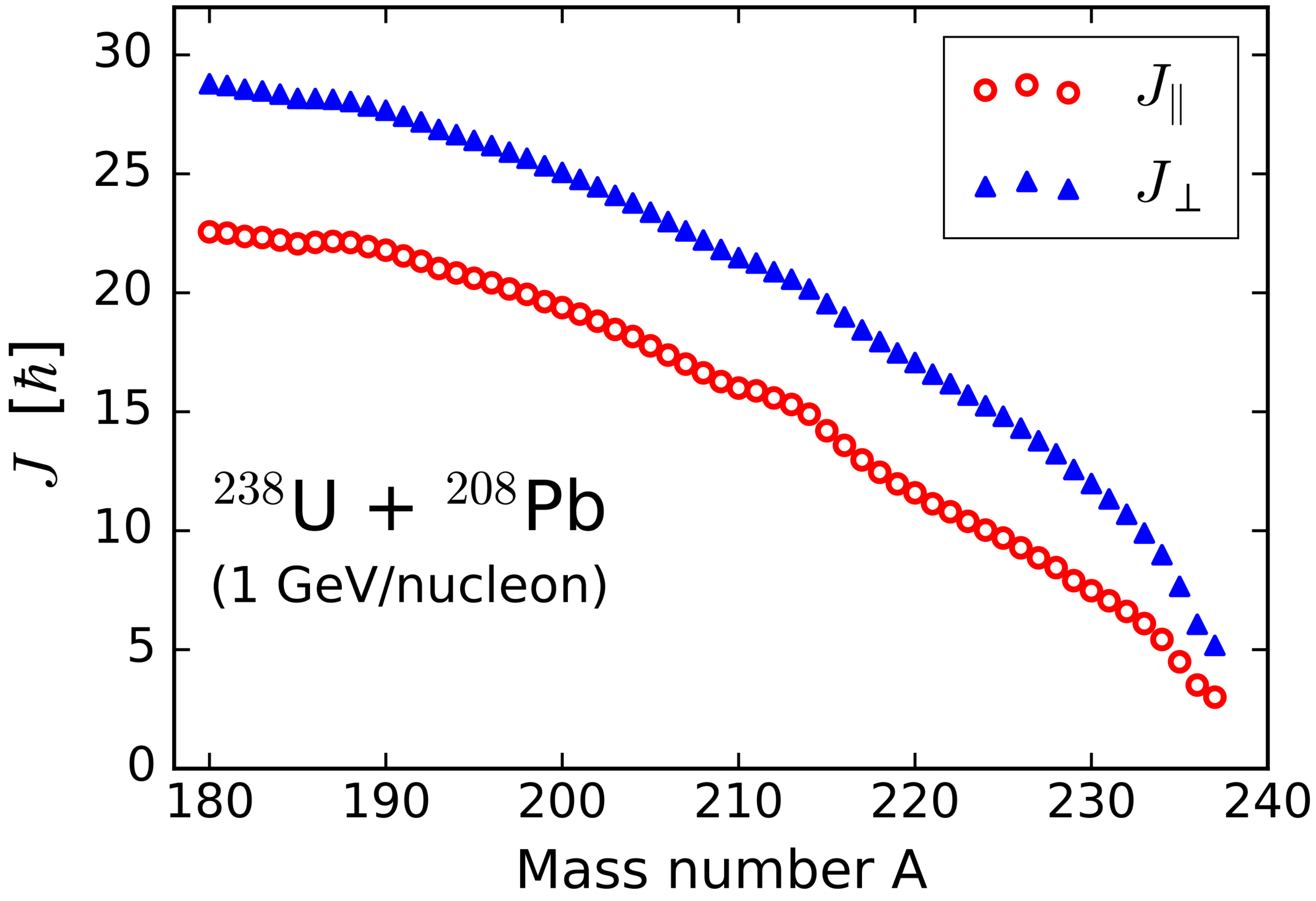


Fragmentation in heavy ion collisions

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

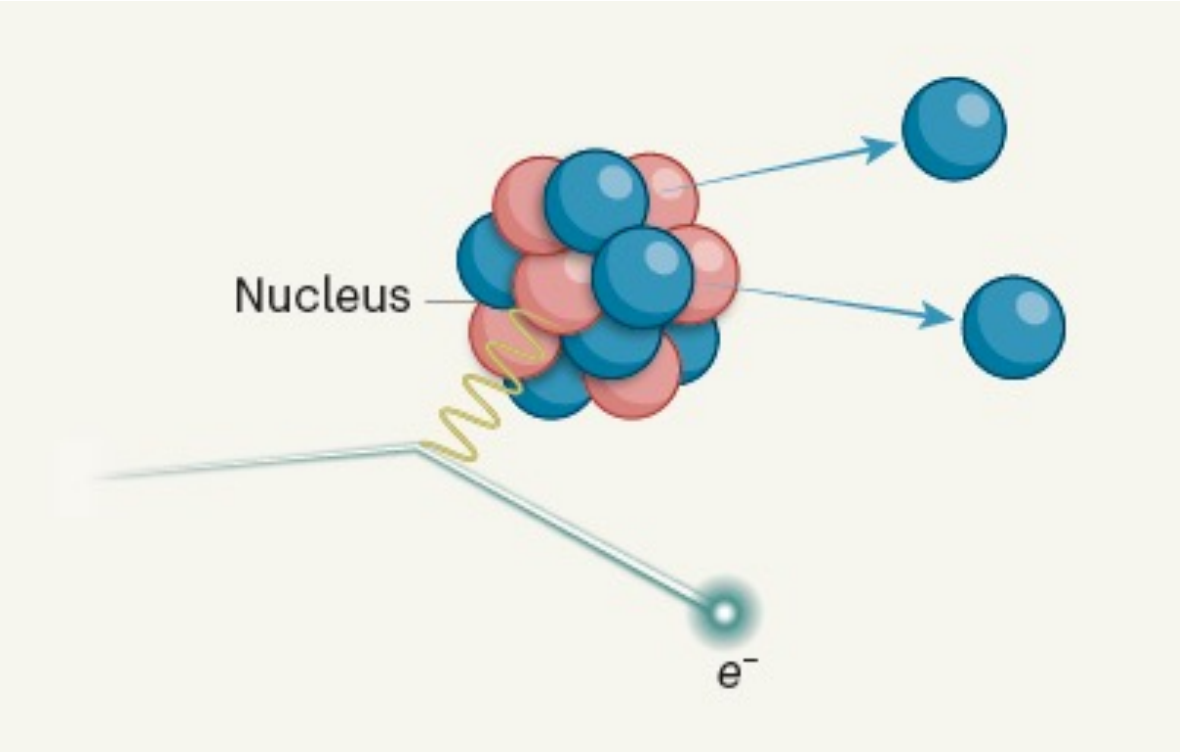






Five previously unknown isotopes
(182;183Tm, 186;187Yb, 190Lu)
PRL 132, 072501 (2024)

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

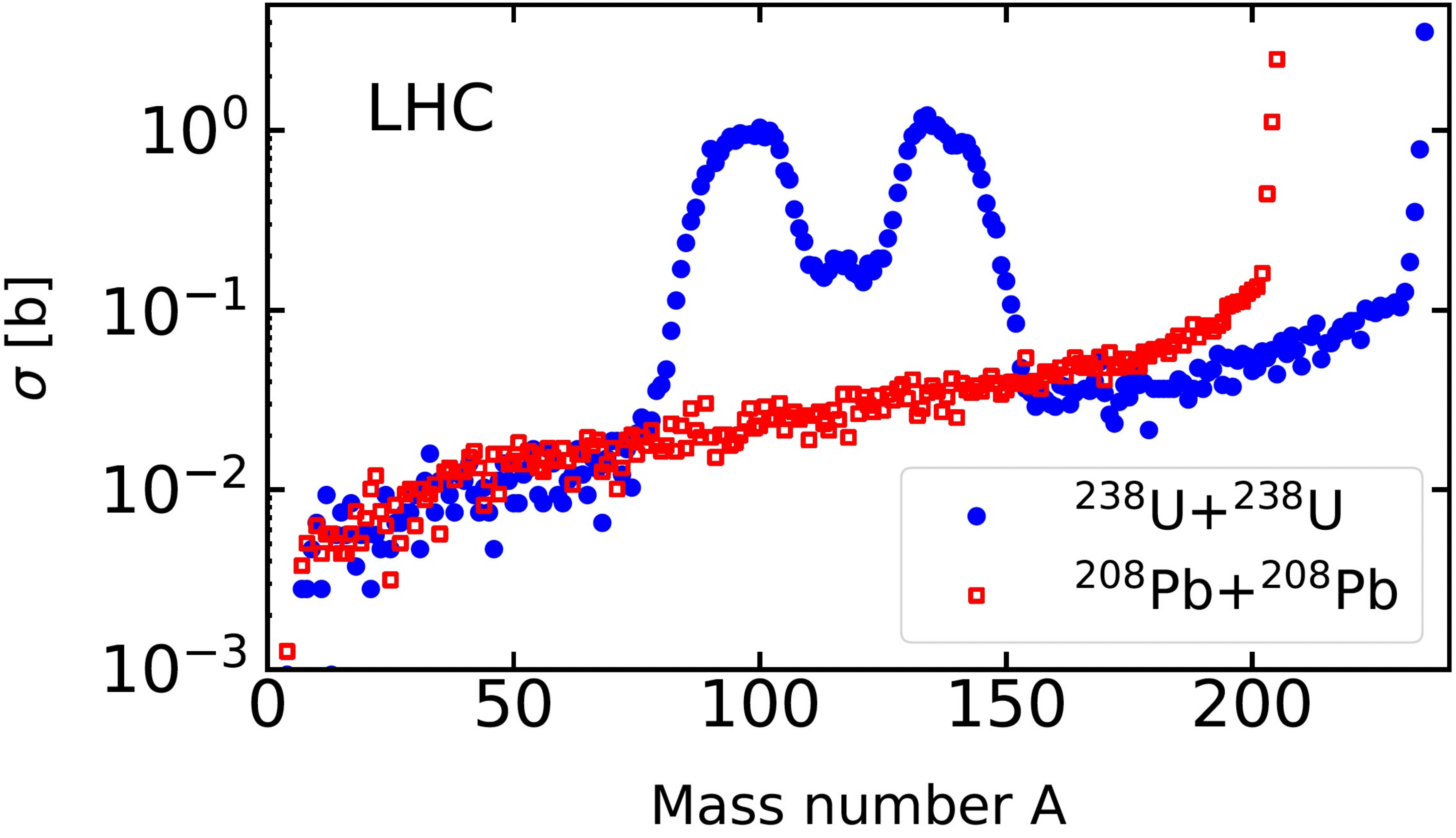
➡ Possible study of low energy physics of the isotopes.

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

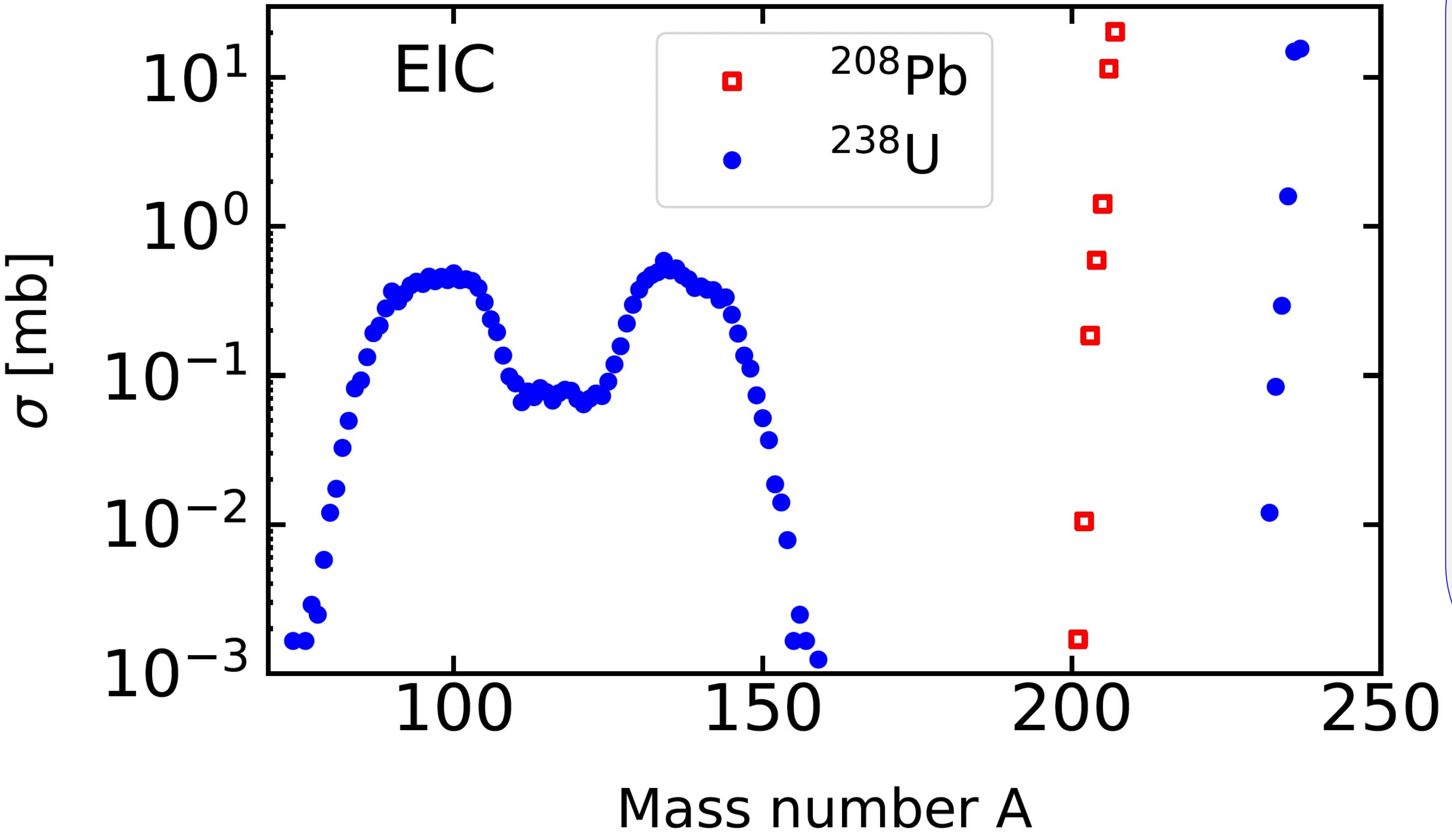
Nuclear fragmentation at the LHC

Excitation of GRs
+
evaporation

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



Nuclear fragmentation at the EIC



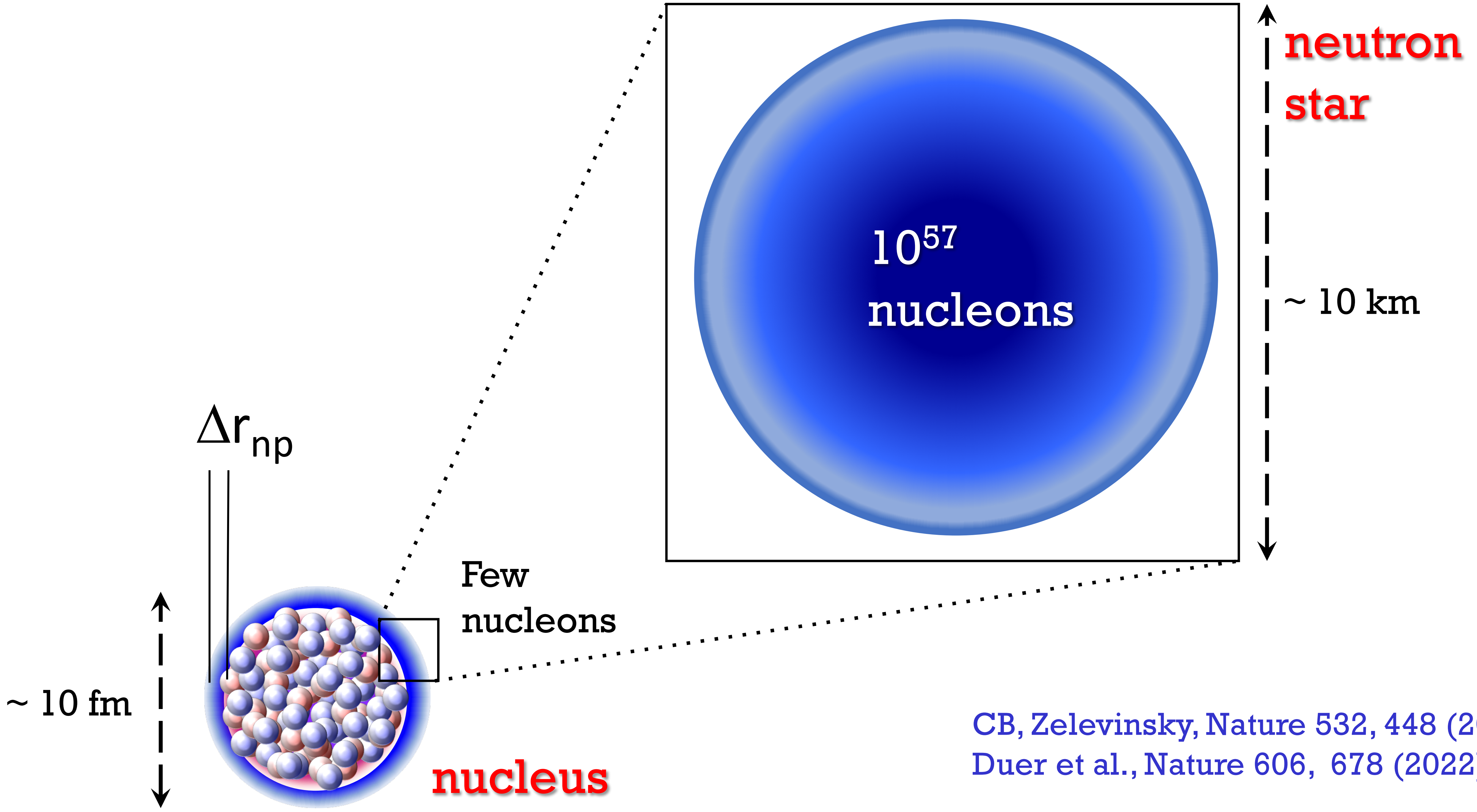
$$\frac{d\sigma}{d\omega dQ^2} = \sum_{\lambda} \frac{dN_\lambda}{d\omega dQ^2} \sigma_\gamma^\lambda(\omega)$$

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

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

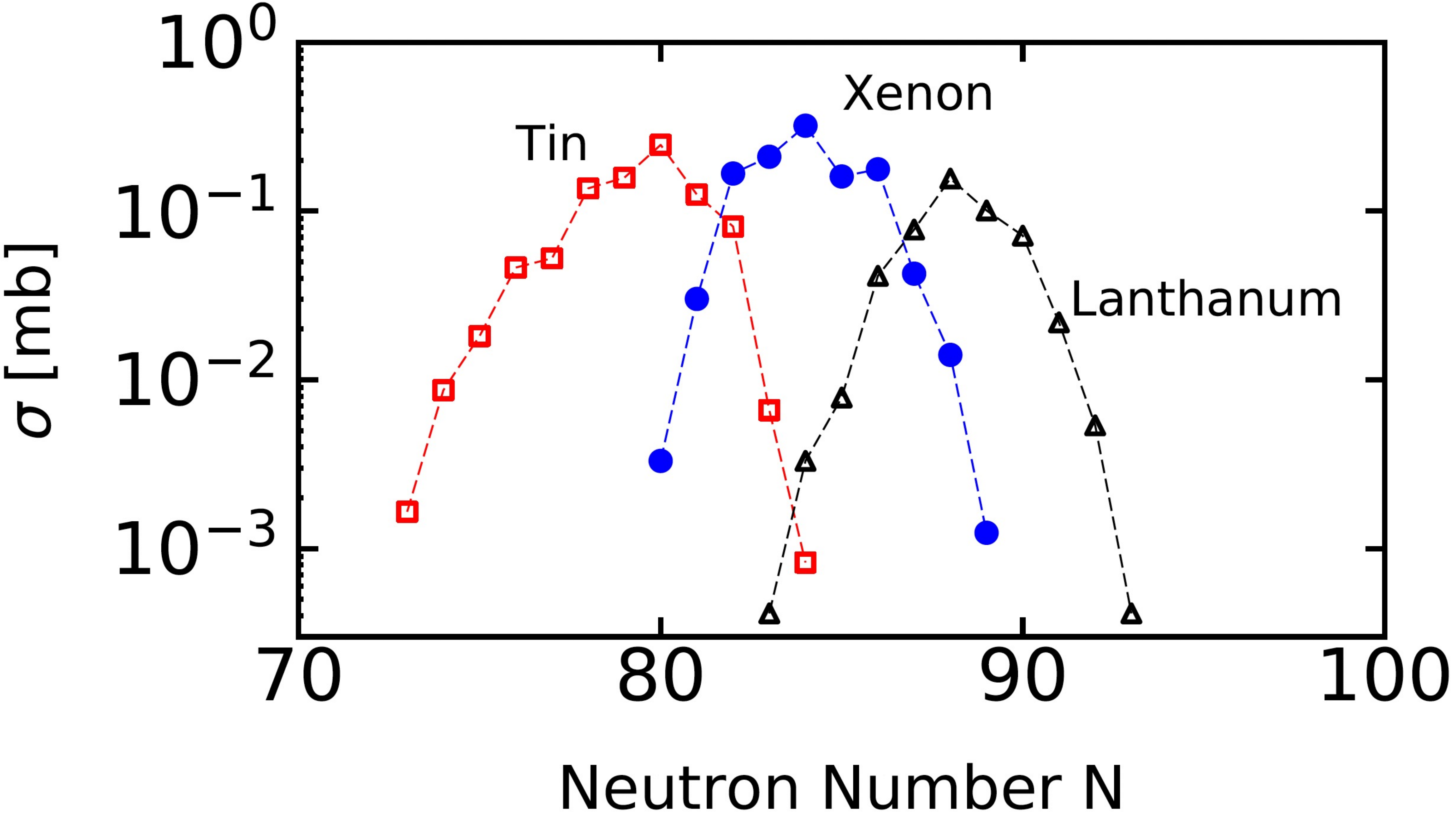
x = fragment

EM nuclear response and neutron stars



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

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%

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

Evaporation

Compound nucleus theory

Heisenberg relation: → for a state with width Γ

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

→ decay time:

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

If many decay channels → decay probability =

$$\frac{\Gamma_\alpha}{\sum_\alpha \Gamma_\alpha} = \frac{\Gamma_\alpha}{\Gamma}$$

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:

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

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

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

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 formula & resonances

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

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.

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