Constraining the nuclear equation of state

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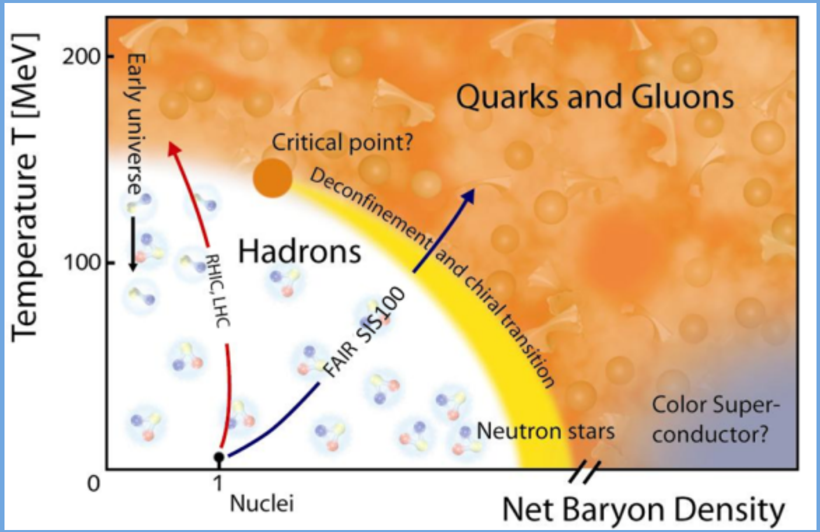
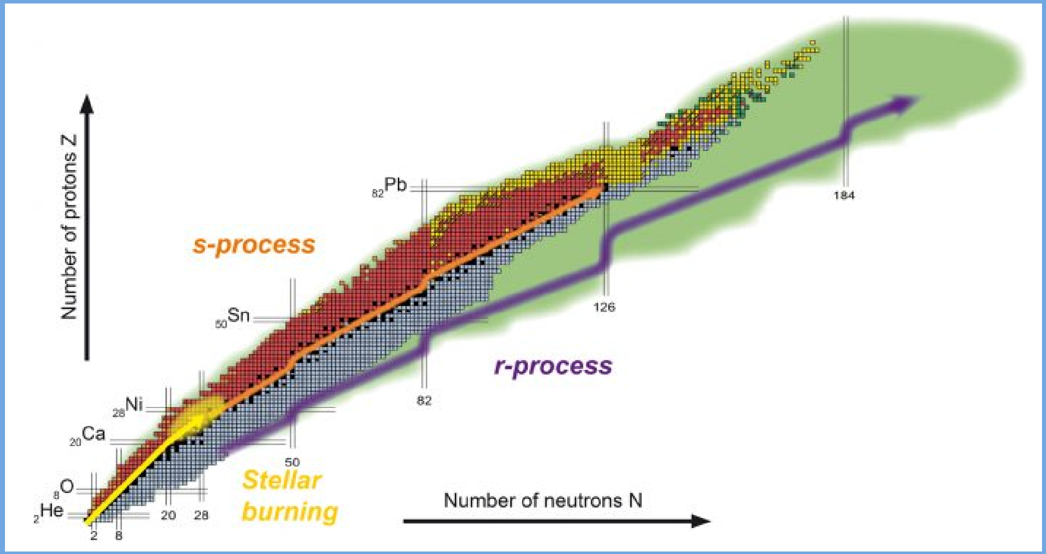
Why is EOS important?

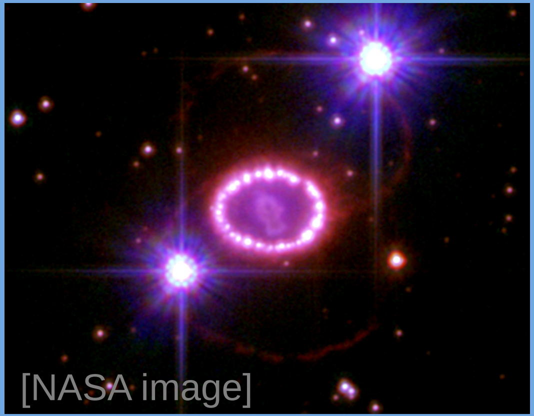


[Denisovskaya, 2009, arxiv]

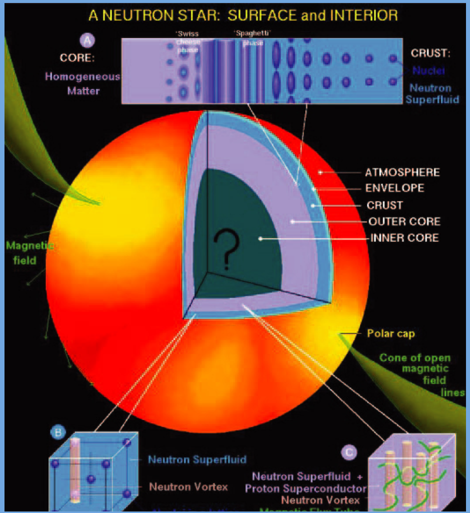


[EMMI, GSI/Different Arts]

[ESA artist impression]



[NASA image]



[Piekarewicz, Phys.Today, Vol. 72, 2019.]

EOS (for cold (T=0) nuclear matter)

$$E(\rho,\delta)=E(\rho,0)+S(\rho)\,\delta^2+O(\delta^4),\ \delta=\frac{\rho_N-\rho_Z}{\rho}$$

$$S(\rho)=S(\rho_{SAT})+L\,\frac{\rho-\rho_{SAT}}{3\rho_{SAT}}+\frac{K_{sym}}{2}\left(\frac{\rho-\rho_{SAT}}{3\rho_{SAT}}\right)^2+O((\rho-\rho_{SAT})^3)$$

→ energy per nucleon

δ = isospin asymmetry

$S(\rho)$ = symmetry energy

- $S(\rho_{SAT})$, L, K_{sym} → values that we want to constrain!

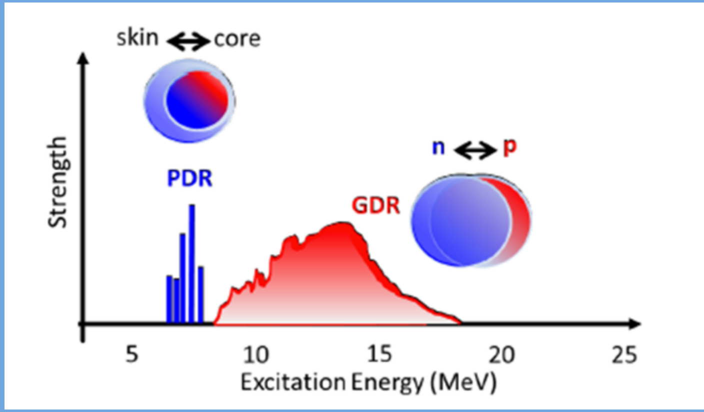
→ for ^{132}Sn → δ^2 = 0.059 – hard to access symmetry energy in experiments

→ relation with isovector channel of nucleon-nucleon interaction

→ search for isospin dependent observables!

Giant resonances and EOS

[Bracco et al., Prog.Part.Nucl.Phys., Vol. 106, 2019]



- Giant resonances – collective states at high excitation energies characterized by multipolarity L, isopin T and spin S quantum numbers
- Density oscillations caused by perturbation from ground state ⟶ probing EOS around saturation density

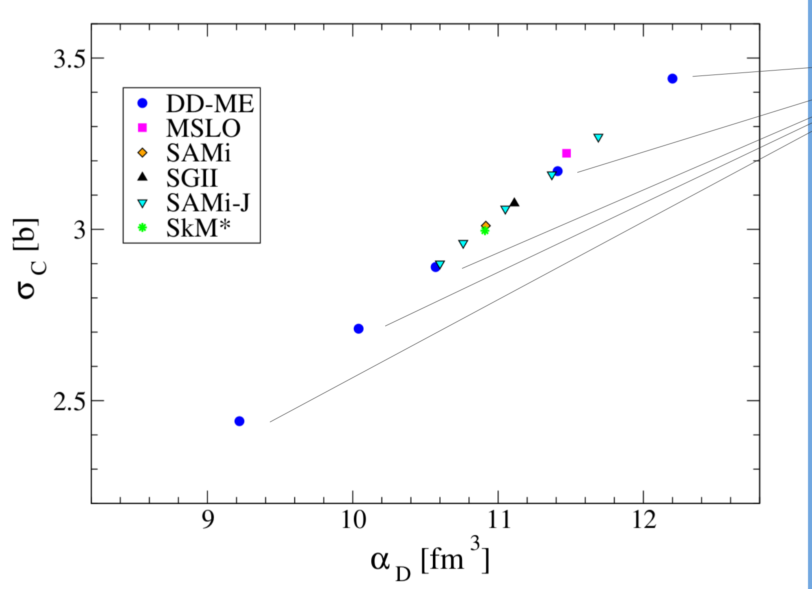
- IVGDR (**i**so**v**ector **g**iant **d**ipole **r**esonance) – out of phase collective oscillation of proton against neutron density ($\Delta L=1$, $\Delta T=1$, $\Delta S=0$)

- Link between theory and experiment – sum rules ⟶ for isovector electric dipole transitions ⟶ TRK sum rule (almost 100 % GR)

- TRK sum rule ⟶ dipole polarizability α_D (established sensitive observable in EOS research) ⟶ connection to Coulomb excitation cross section σ_C

What can we learn from σ_C?

- Comparison with results of density functional theory ⟶ constraint on different energy density functionals!



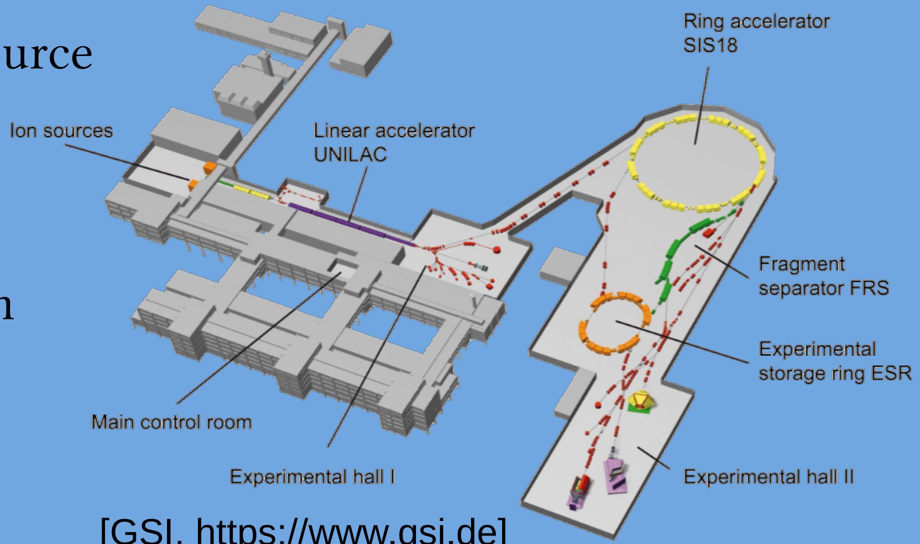
σ_C for 1AGeV ^{132}Sn

[A. Horvat, 2019, PhD thesis]

eg. experimental σ_C is expected to favour (within experimental error) one of these predictions of DD-ME functional

Relativistic heavy ion research

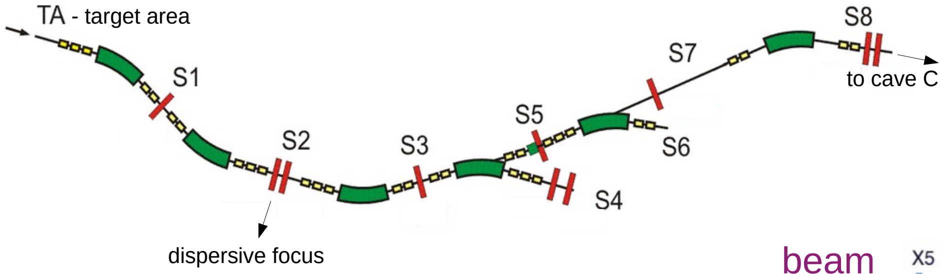
- GSI (@ future FAIR) – R3B (**R**eactions with **R**elativistic **R**adioactive **B**eams) collaboration
- S515 experiment ⟶ May 2021
- Access to radioactive nuclei (inverse kinematics)
- UNIversal Linear ACcelerator (UNILAC) – accepts and accelerates isotopes produced by the ion source
- SIS18 synchrotron
- Secondary beam production on target
- Fragment Separator (FRS) – in flight separation
- Cave C experimental hall



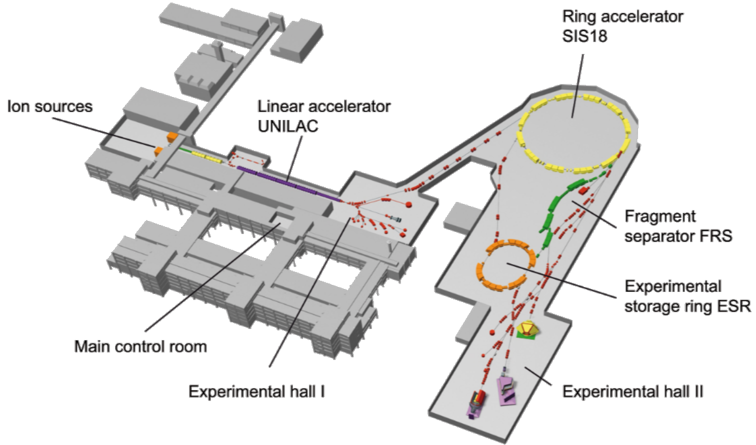
[GSI, https://www.gsi.de]

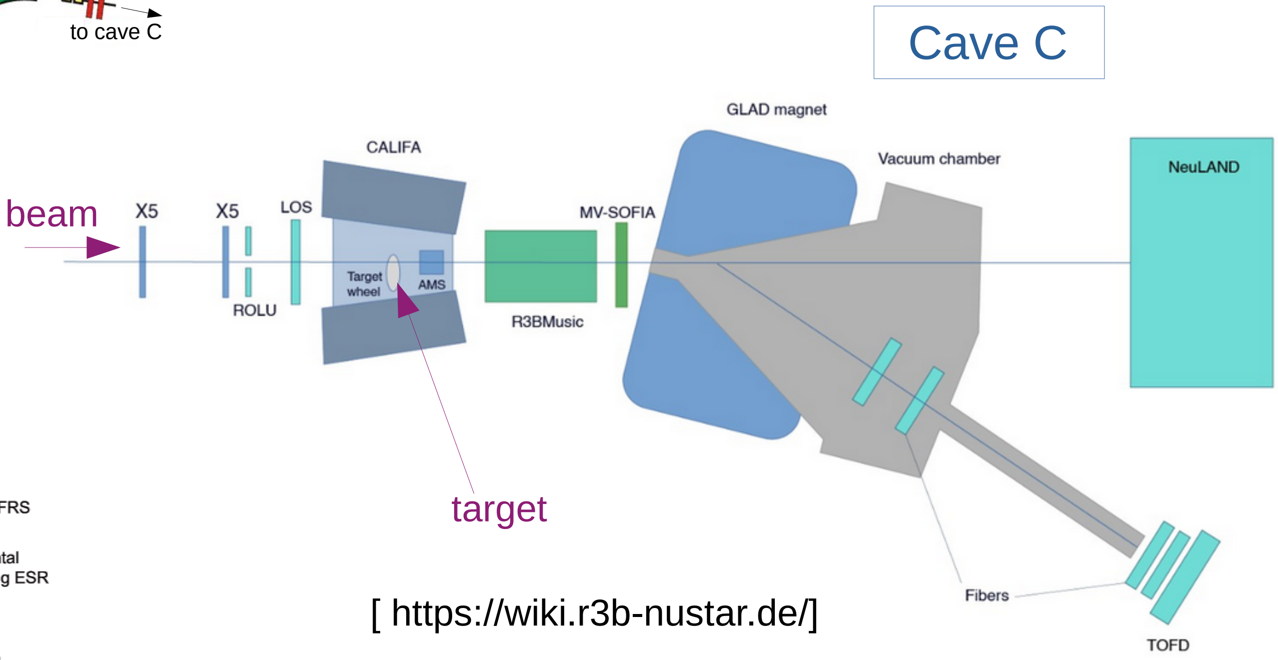
Experiment – setup and agenda

- $^{124-132}$Sn beams produced using projectile fragmentation (^{136}Xe on Be production target) and fission (^{238}U) and separated in magnetic elements of FRS facility ⟶ on C, CH2, Pb target
- Primary beam energies used: 600 AMeV, 800 AMeV, 1080 AMeV



[https://www-windows.gsi.de/frs]

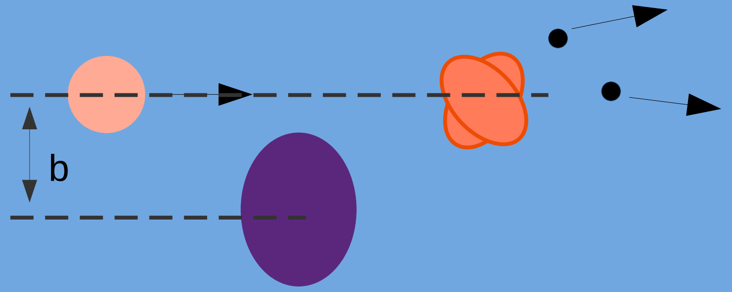




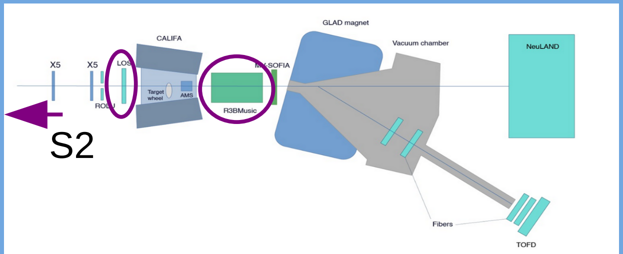
[https://wiki.r3b-nustar.de/]

Measuring Coulomb excitation cross section - σ_C

- Relativistic Coulomb excitation of projectile Sn nuclei in the field of Pb target
- Dominant decay mode for medium - heavy and heavy nuclei is via neutron evaporation (1-3 neutrons) + ɣ emission
- Evaporated neutrons emmited in forward direction
- Detection in neutron detector NeuLAND in coincidence with fragment (mass loss equals to the number of evaporated neutrons) detected in fragment detector TOFD
- Neutron removal cross section (nuclear reactions!) - different angular distribution of emmited neutrons!



Analysis in progress…



- beam identification ⟶ **Z vs. A/Q plot**

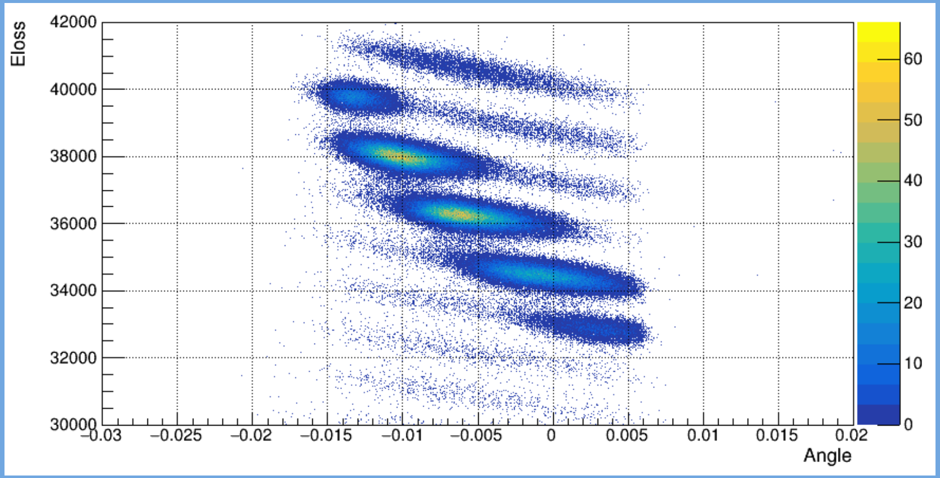
⟶ beam velocity – TOF measurement

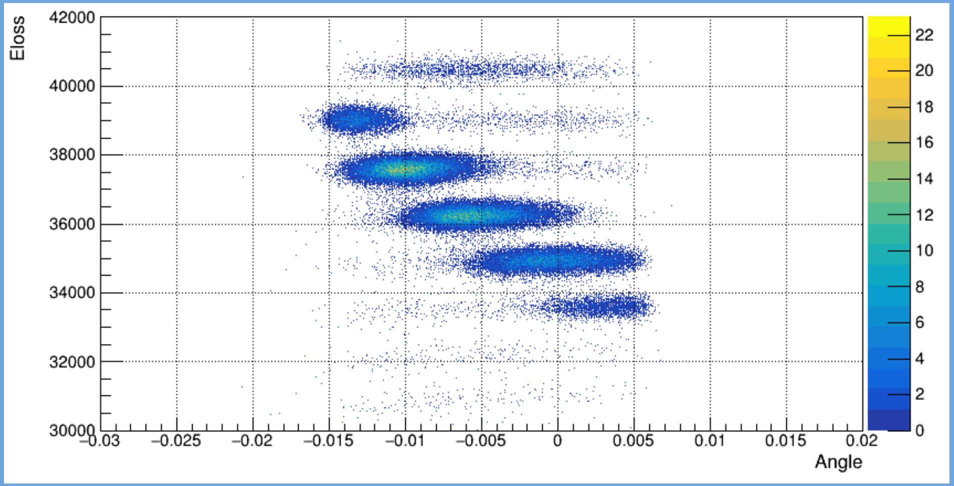
⟶ B ρ - position measurement

⟶ charge – E_{loss} measurement

$$B\rho = 3.107 \frac{A}{Z} \beta \gamma [Tm]$$

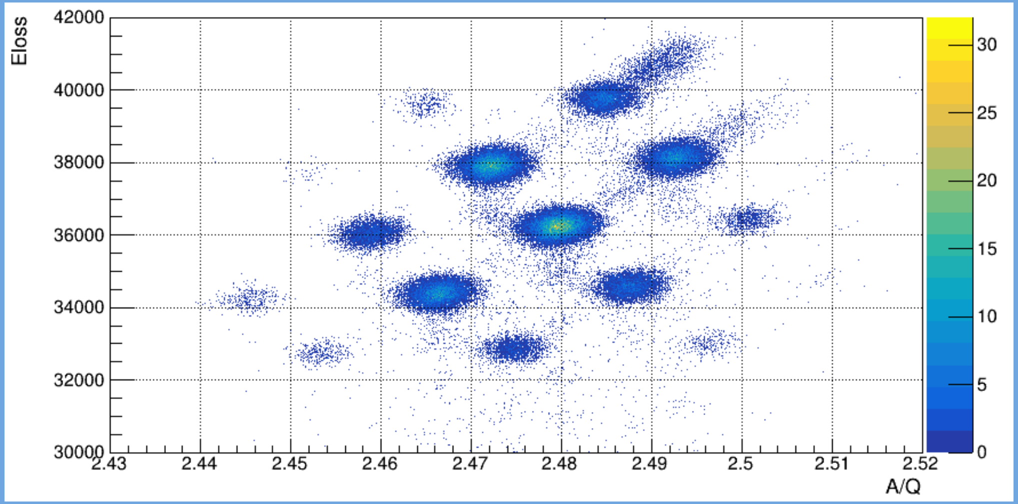
⟶ angle correction for energy loss in MUSIC detector applied

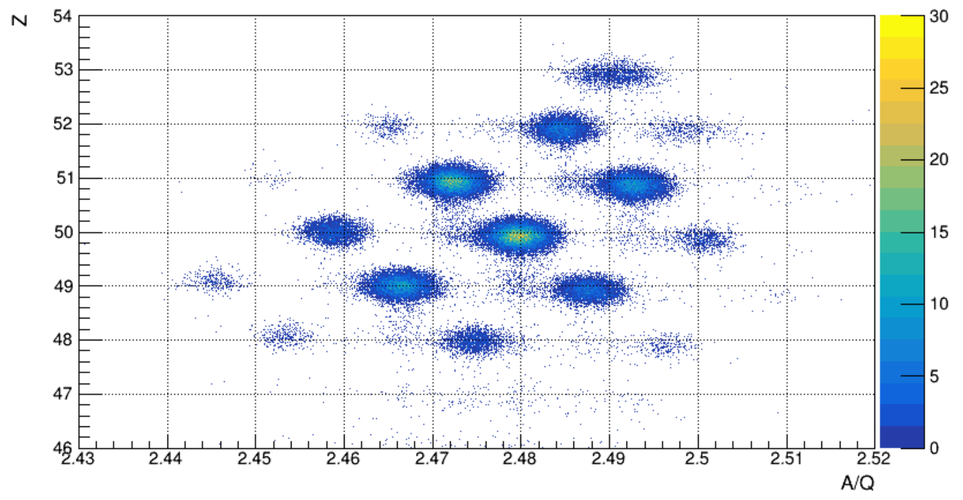




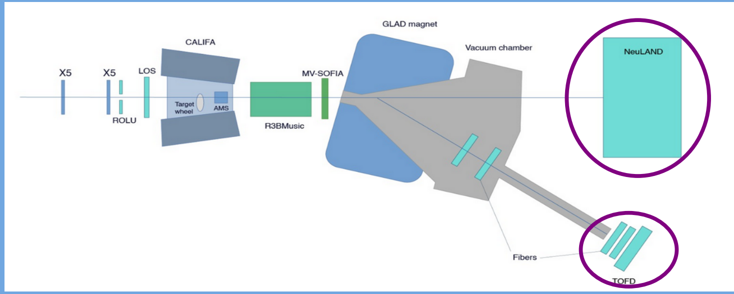
Identification plot

- ^{124}Sn setting (production from ^{136}Xe primary beam), B ρ = 13.0721 Tm (Z=50, A/Q=2.48)



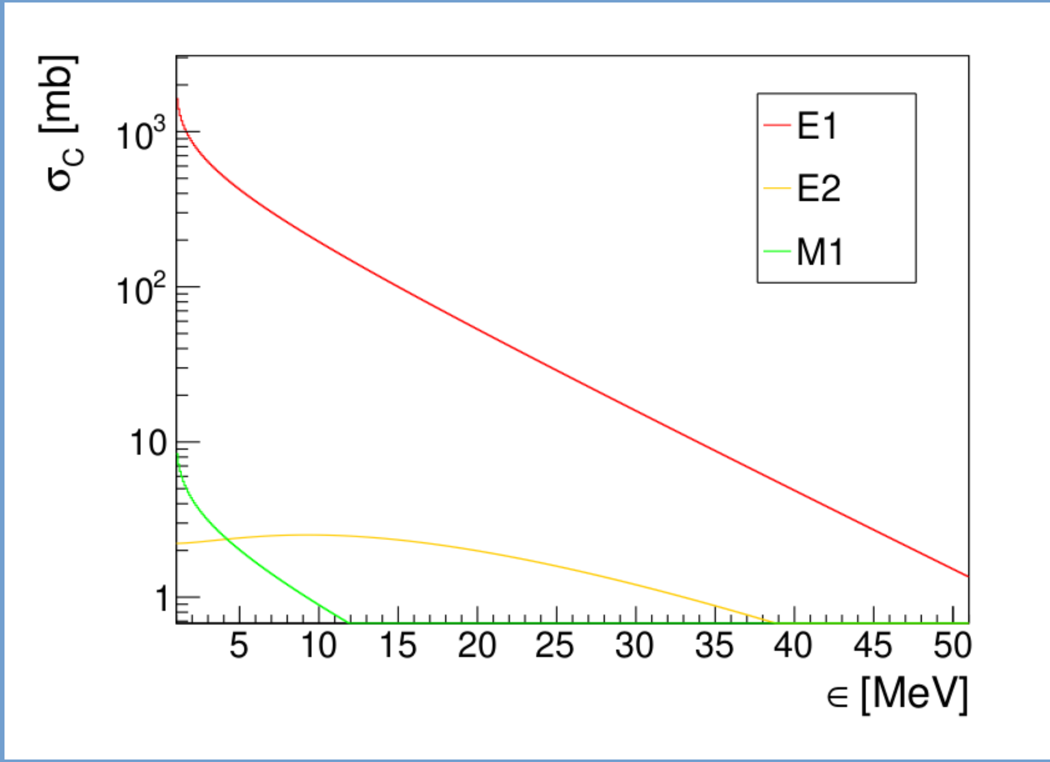


- Next : fragment and neutron detection



The end.
Questions?

Coulomb excitation cross section spectrum with one Weisskopf unit (W.u.) for the reduced transition probability for ^{124}Sn projectile on a ^{208}Pb target at 572 AMeV incident energy



[A. Horvat, private communication]