Neutron detection in reactions with relativistic radioactive beams

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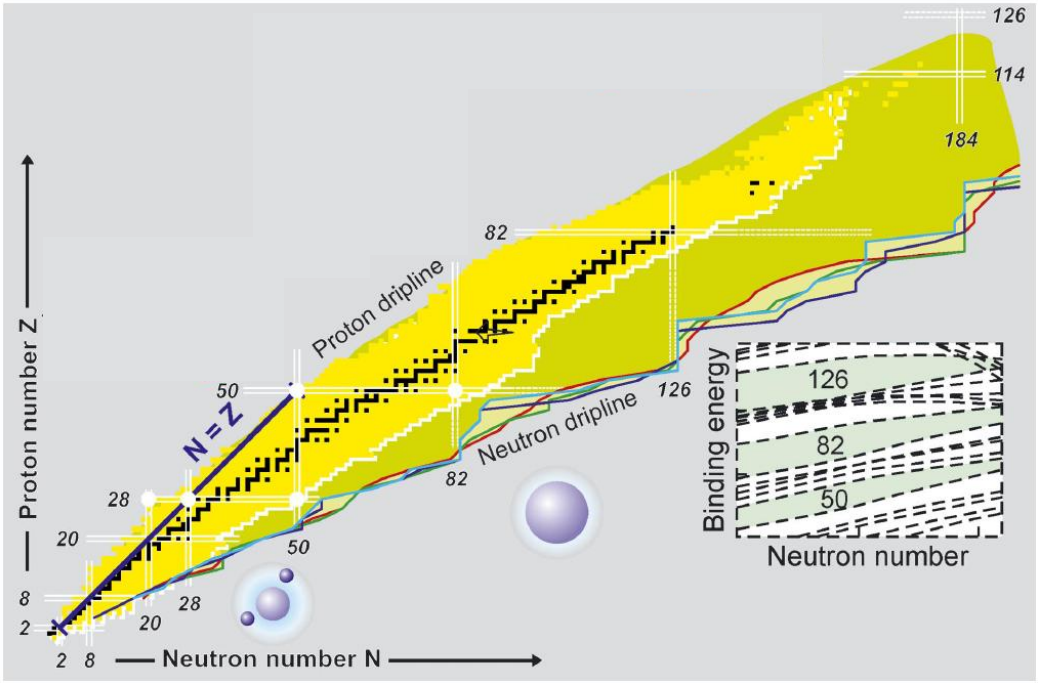
Overview

- Motivation
- R3B experimental setup at GSI-FAIR
- Neutron detector NeuLAND
- NeuLAND performance in FAIR Phase 0 experiments at GSI
- Summary and outlook

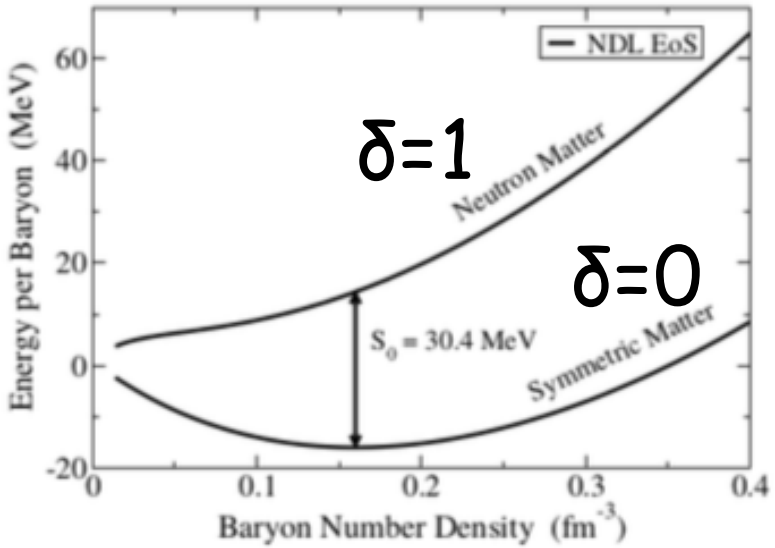
Nuclear physics program

- unexplored region of the chart of nuclides far from the valley of beta-stability
- nuclear structure
  - limits of existence
  - deviation from shell model
  - exotic structures
  - collective excitations
  - short-range correlations
- equation of state
  - isospin asymmetry
- nuclear astrophysics
  - neutron stars, neutron star mergers
  - nucleosynthesis



Nuclear equation of state (EOS)

- energy per nucleon as a function of density and proton/neutron asymmetry
- bulk properties of nuclear matter
- interior of medium heavy and heavy nuclei
- astrophysical processes and objects



$$e(\rho,\delta) = e(\rho,0) + \delta^2 S(\rho) + O(\delta^4) \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

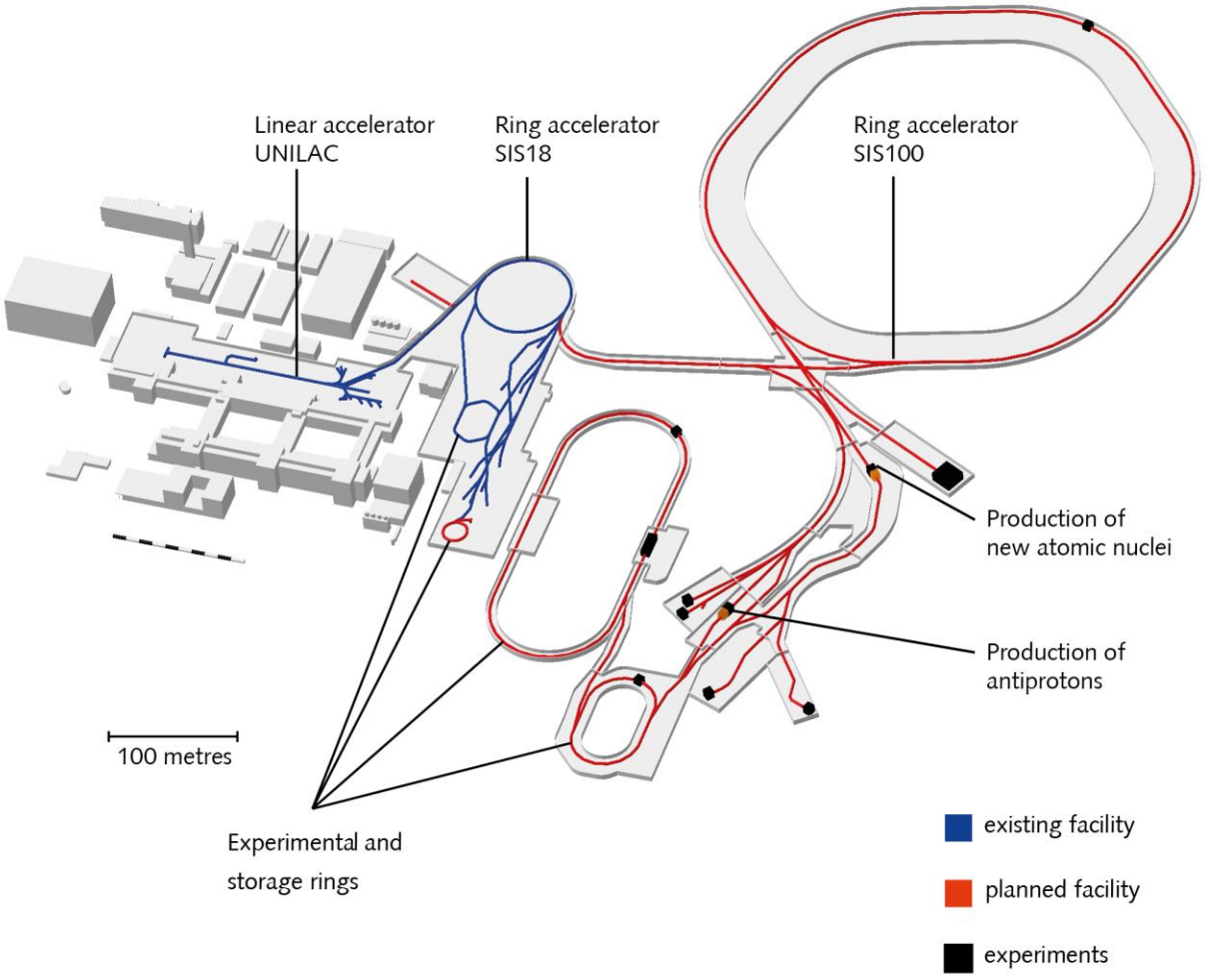
$$e(\rho,0) = e(\rho_0,0) + \frac{1}{2} K_0 \left(\frac{\rho - \rho_0}{3\rho_0} \right)^2 + \ldots$$

EOS for symmetric matter

$$S(\rho) = J + L \frac{\rho - \rho_0}{3\rho_0} + \frac{1}{2} K_{sym} \left(\frac{\rho - \rho_0}{3\rho_0} \right)^2 + \ldots$$

symmetry energy

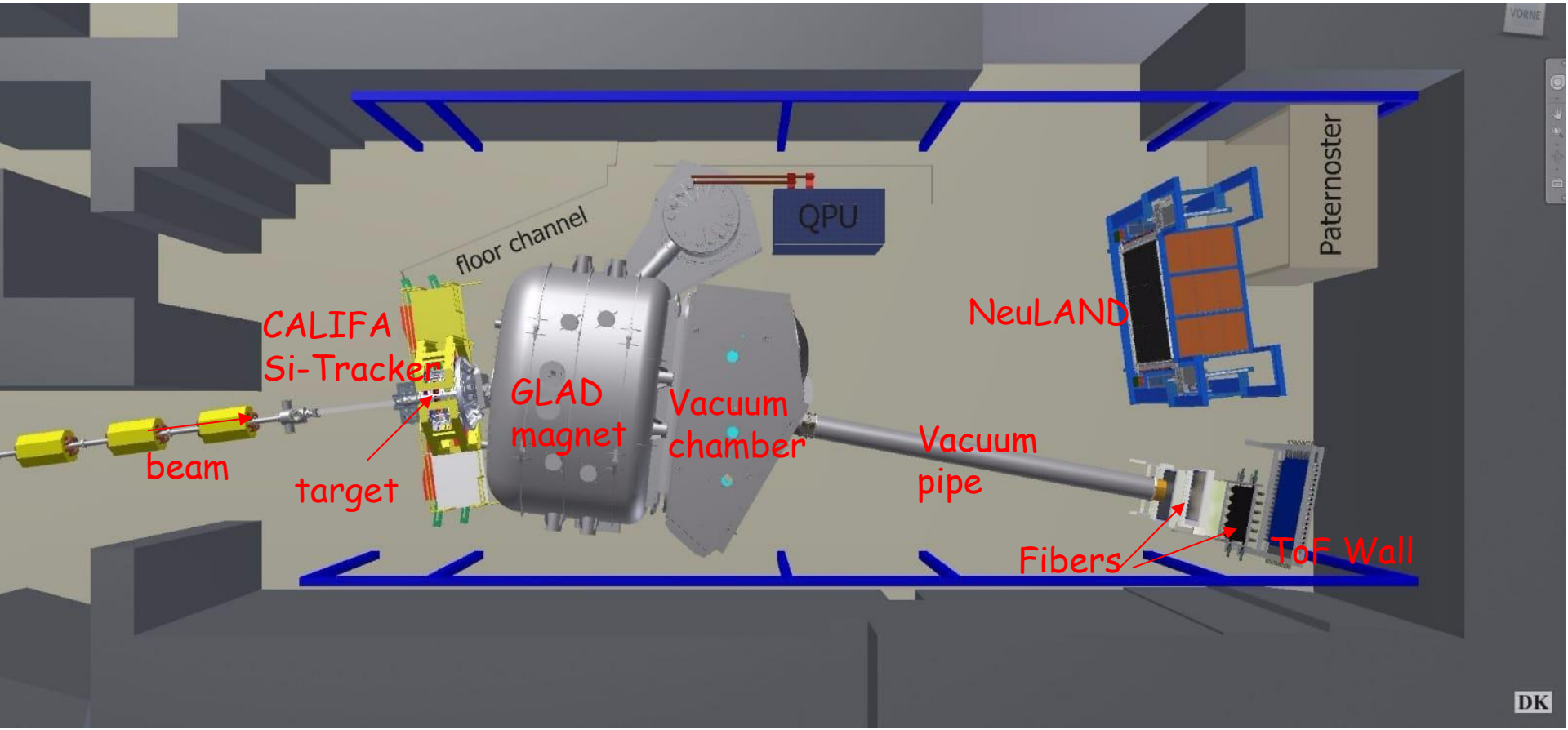
FAIR – Facility for Antiproton and Ion Research (https://fair-center.eu)



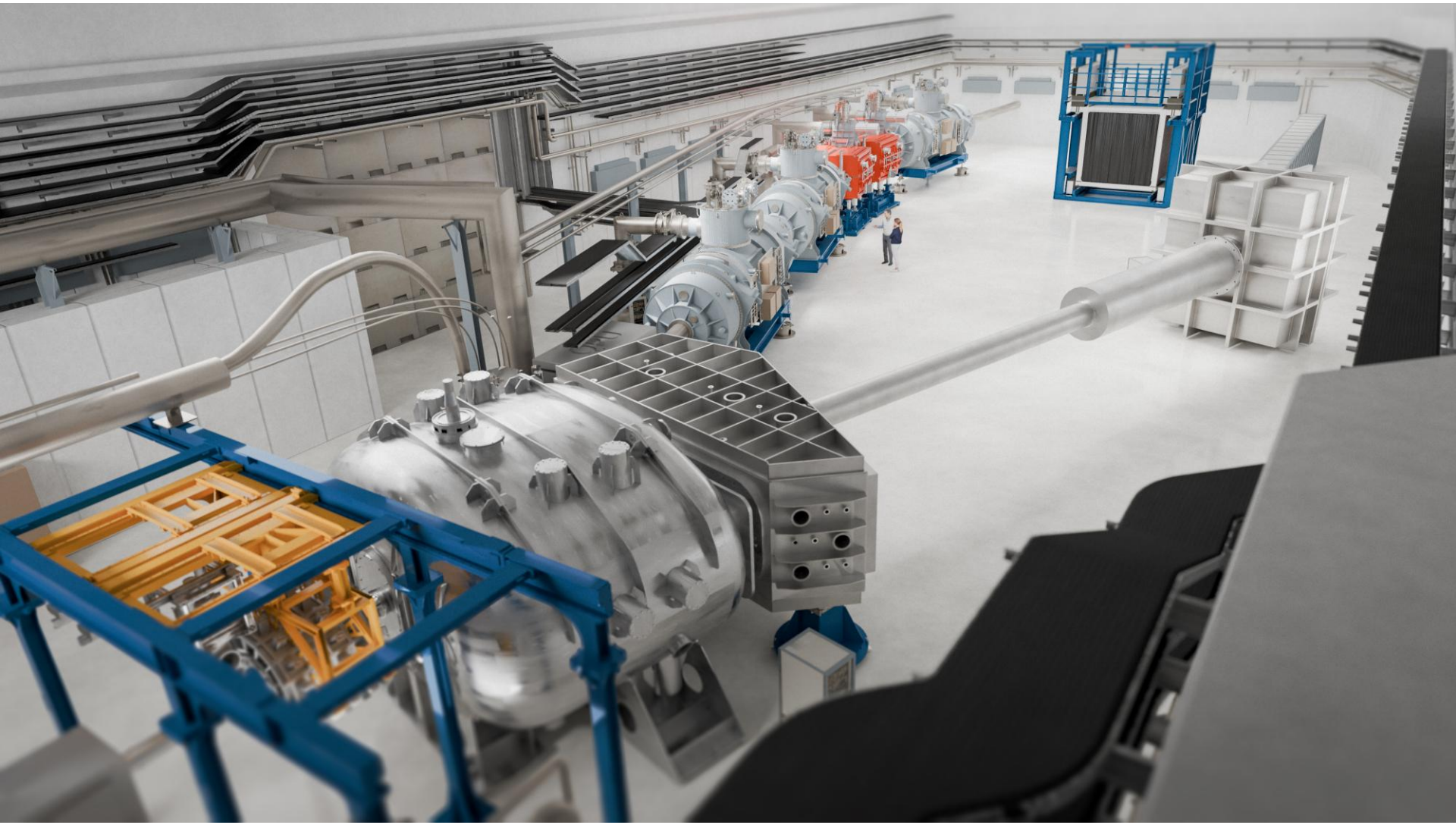
- international accelerator center (11 countries)
- 3.3 billion €
- all ions to 99% of speed of light
- beam energy x 5
- antiproton beam 30 GeV
- intensity of secondary beams (SuperFRS)
  - x 100 - 1000
- 4 scientific programs
  - NUSTAR
  - CBM
  - APPA
  - PANDA

R3B experimental setup

- Reactions with Relativistic Radioactive Beams
- versatile setup for full kinematical reconstruction of reactions with radioactive beams in inverse kinematics

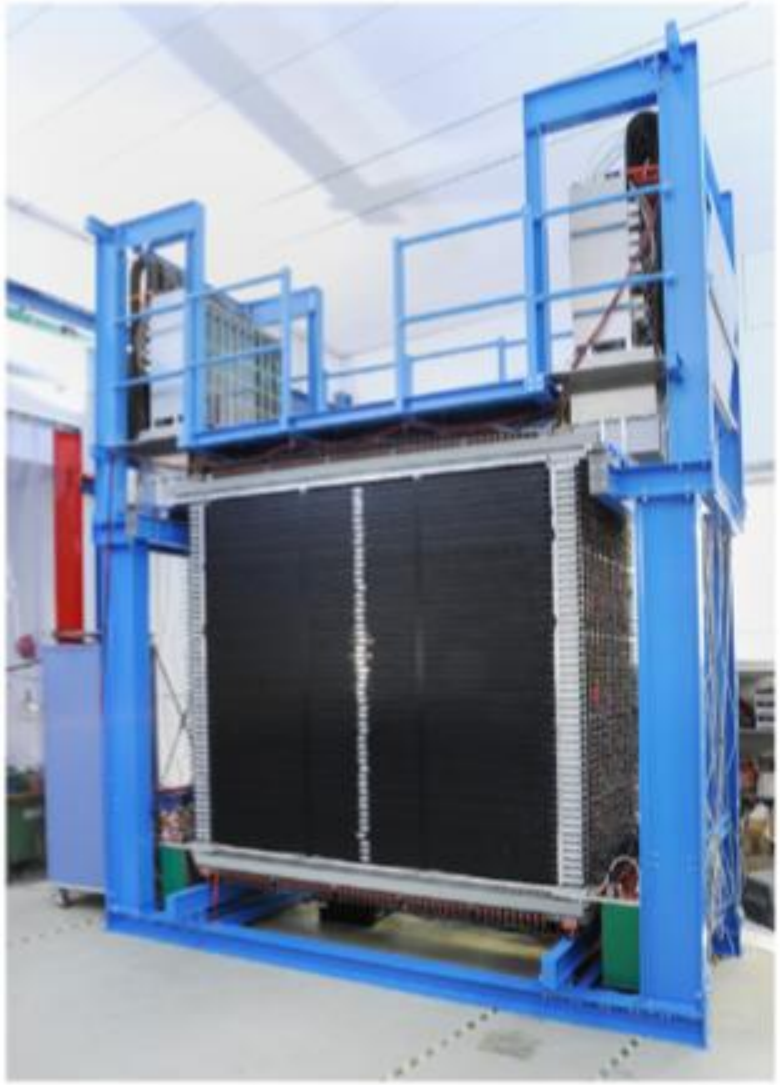


High Energy Cave at FAIR



NeuLAND (New Large-Area Neutron Detector)

- 3000 plastic scintillator (BC-408 equiv.) bars 250x5x5 cm^3
- 30 double planes with 100 bars, mutualy perpendicular bars in neighbouring planes
- total volume 2.5x2.5x3 m^3
- light readout by 6000 PMTs
- readout electronics TAMEX + FQT developed at GSI-u
- 15-35 m from target in HEC
- angular acceptance at 15 m $\pm$80 mrad (matches magnet exit window)
- $\sigma_t \leq 150$ ps, $\sigma_{x,y,z} \leq 1.5$ cm
- efficiency ~95% at energies 200-1000 MeV
- multi-neutron detection capability



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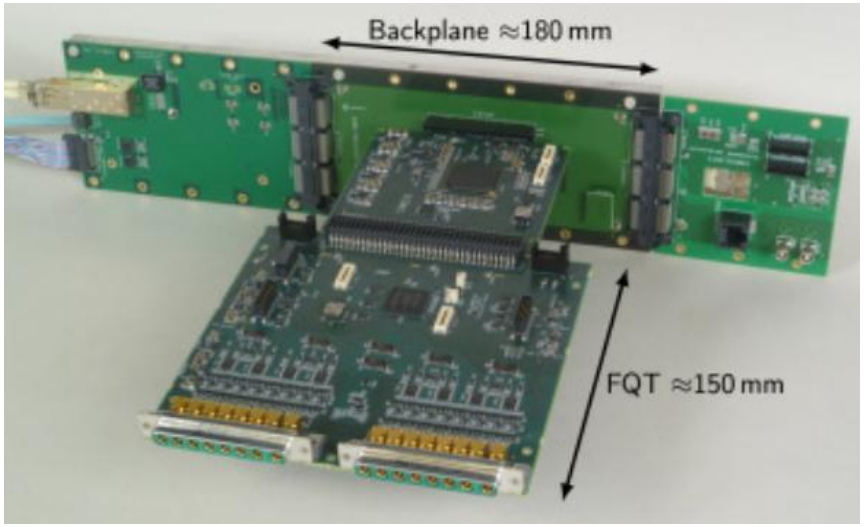
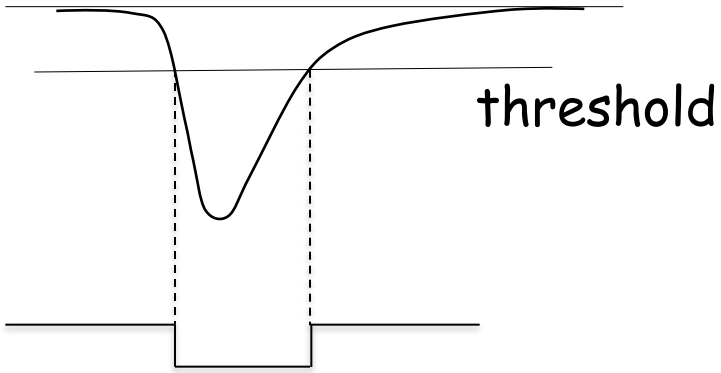
NeuLAND: The high-resolution neutron time-of-flight spectrometer for R^{3}B at FAIR

K. Boretzky [a,*], I. Gašparić [b,c,a], M. Heil [a], J. Mayer [d], A. Heinz [e], C. Caesar [a,c], D. Kresan [a,c], H. Simon [a], H.T. Törnqvist [c], D. Körper [a], G. Alkhazov [f], L. Atar [a], T. Aumann [c,a,g], D. Bemmerer [h], S.V. Bondarev [f], L.T. Bott [i], S. Chakraborty [j], M.I. Cherciu [k], L.V. Chulkov [l], M. Ciobanu [k], U. Datta [j], E. De Filippo [m], C.A. Douma [n], J. Dreyer [h], Z. Elekes [o], J. Enders [c,g], D. Galaviz [p,q], E. Geraci [r,m], B. Gnoffo [r,m], K. Göbel [i], V.L. Golovtsov [f], D. Gonzalez Diaz [c,s], N. Gruzinsky [f], T. Heftrich [i], H. Heggen [a], J. Hehner [a], T. Hensel [h,t], E. Hoemann [d], M. Holl [e], A. Horvat [c], Á. Horváth [u], G. Ickert [a], D. Jelavić Malenica [c,b], H.T. Johansson [e], B. Jonson [e], J. Kahlbow [c], N. Kalantar-Nayestanaki [n,1], A. Kelić-Heil [a], M. Kempe [h,2], K. Koch [a], N.G. Kozlenko [f], A.G. Krivshich [f], N. Kurz [a], V. Kuznetsov [f], C. Langer [v,a], Y. Leifels [a], I. Lihtar [b], B. Löher [a], J. Machado [w], N.S. Martorana [r,x], K. Miki [c], T. Nilsson [e], E.M. Orischin [f,2], E.V. Pagano [x], S. Pirrone [m], G. Politi [r,m], P.- M. Potlog [k], A. Rahaman [j], R. Reifarth [i,g], C. Rigollet [n], M. Röder [t], D.M. Rossi [c], P. Russotto [x], D. Savran [a], H. Scheit [c], F. Schindler [c], D. Stach [h], E. Stan [k], J. Stomvall Gill [e], P. Teubig [q], M. Trimarchi [m,y], L. Uvarov [f], M. Volknandt [i], S. Volkov [f], A. Wagner [h], V. Wagner [c], S. Wranne [e], D. Yakorev [h], L. Zanetti [c], A. Zilges [d], K. Zuber [t], for the R^{3}B collaboration

Readout electronics

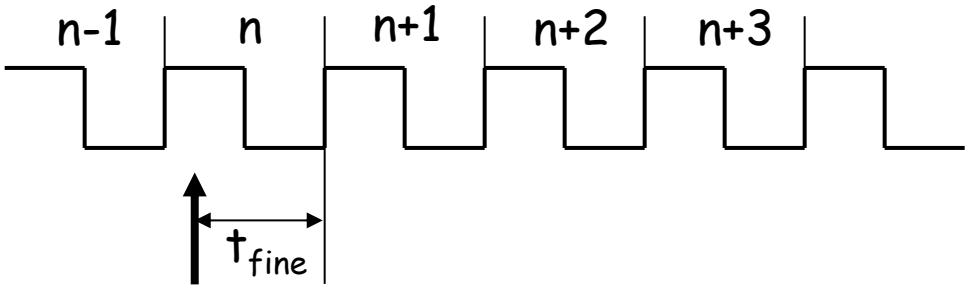
- FQT - front-end card
  - discrimination
  - shaping
  - EPICS slow control
- TAMEX – FPGA based TDC
  - 7 ps resolution
- 200 MHz clock
- ToT linear with signal charge





Time-over-Threshold = $t_{TE} - t_{LE}$

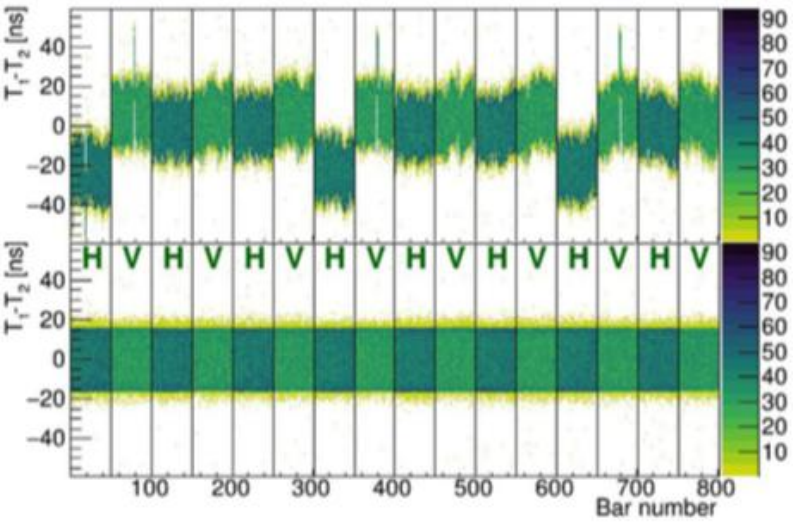
$t_{coarse} = n \cdot T$, n = 0 – 2047 , T = 5 ns

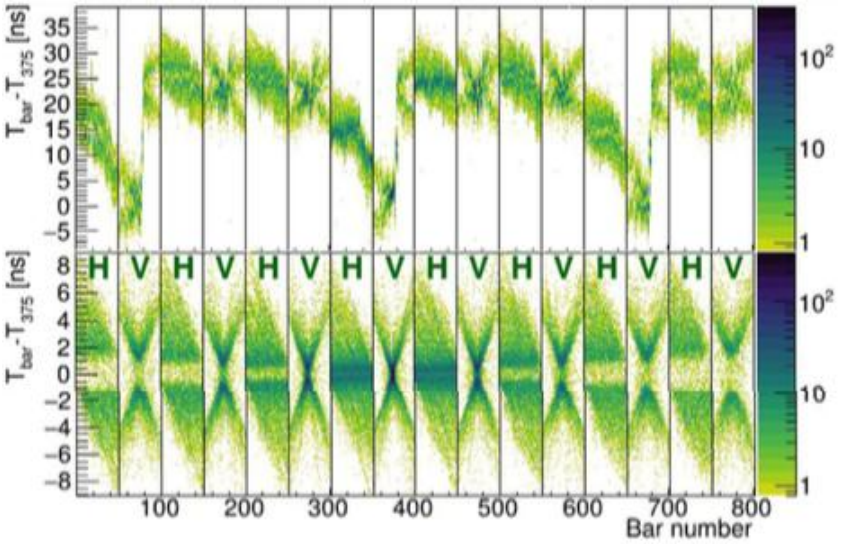


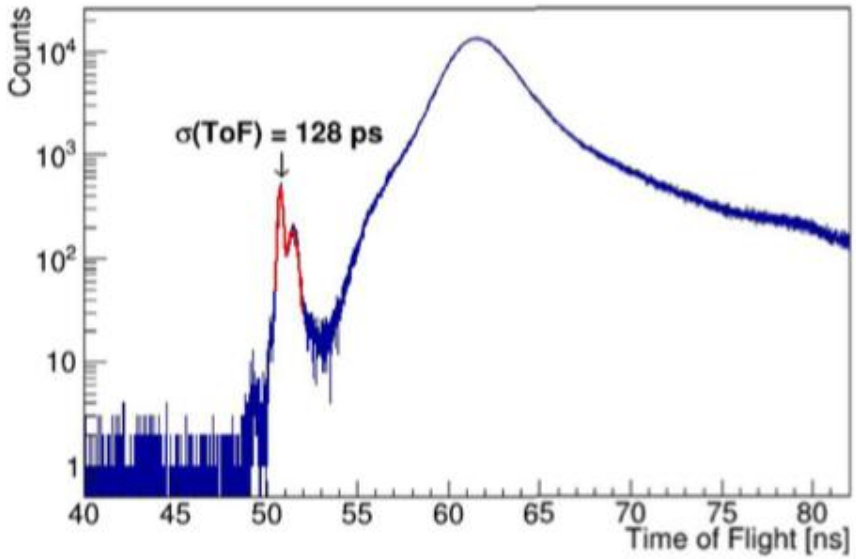
signal

Calibration

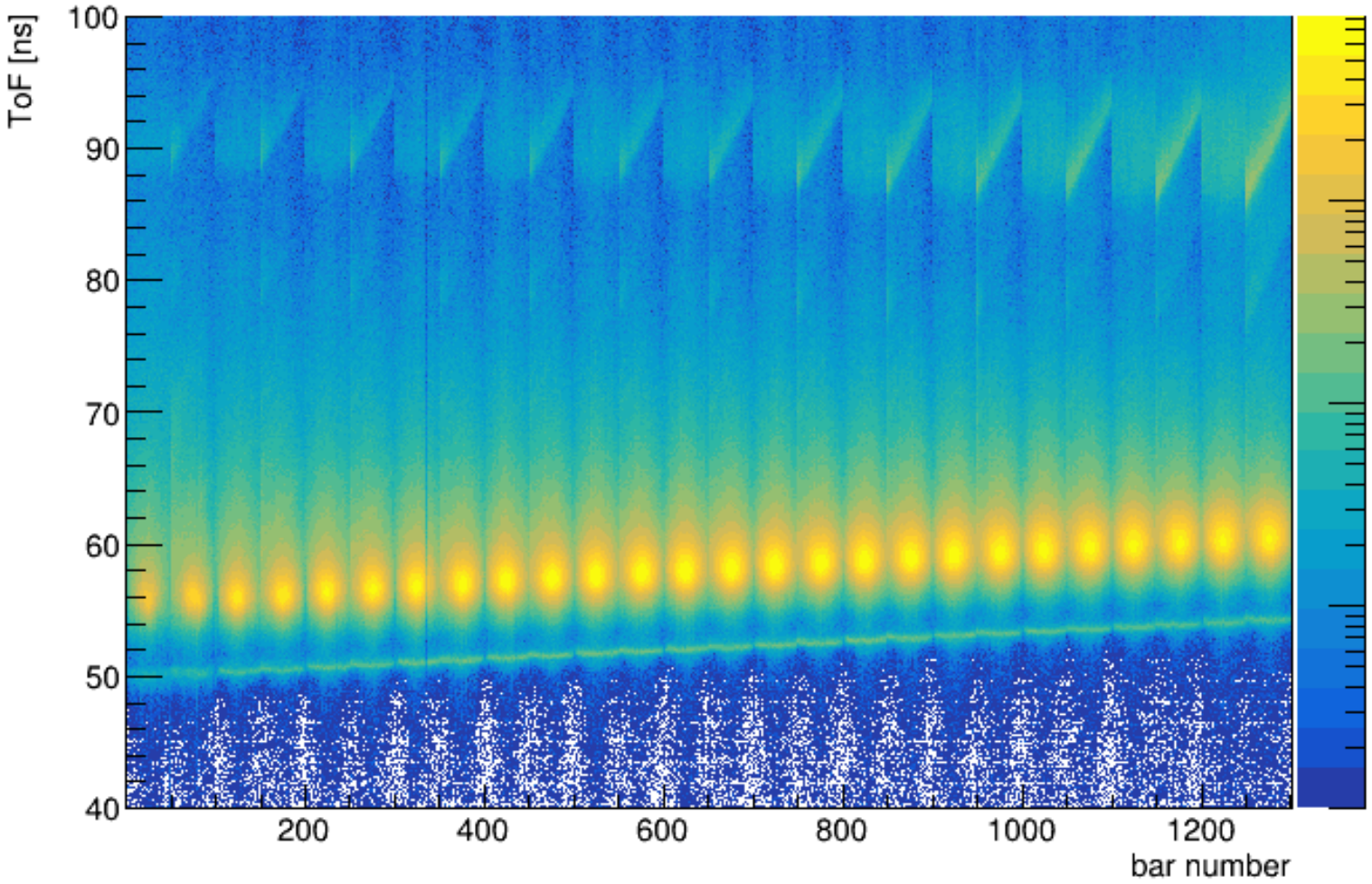
- cosmic muons
- straight tracks with speed of light
- minimum-ionizing particles
- signals like the ones from neutrons
- gamma peak in ToF spectrum for an absolute time calibration







Time-of-Flight spectrum in NeuLAND

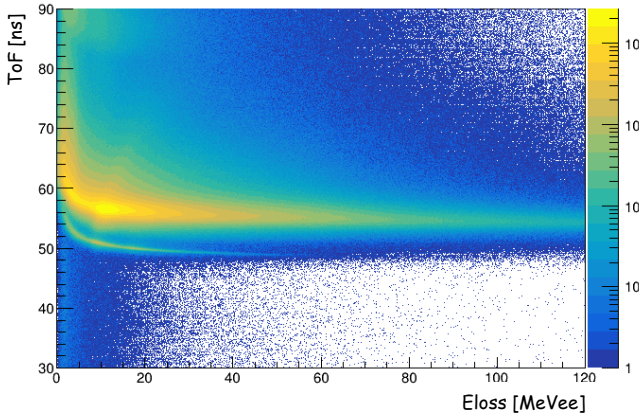


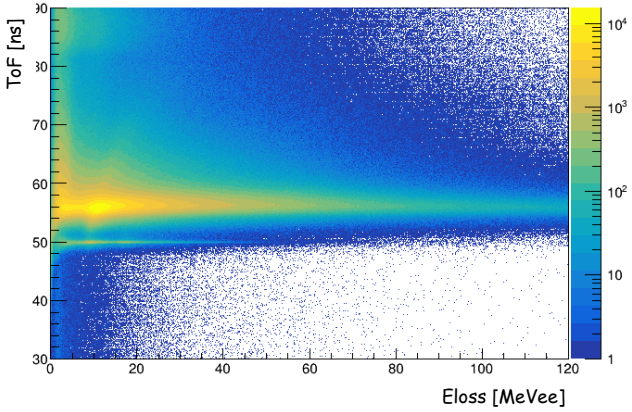
beam dump

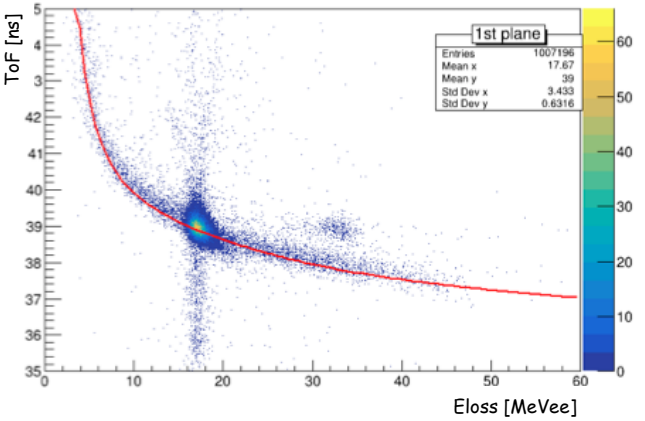
neutrons

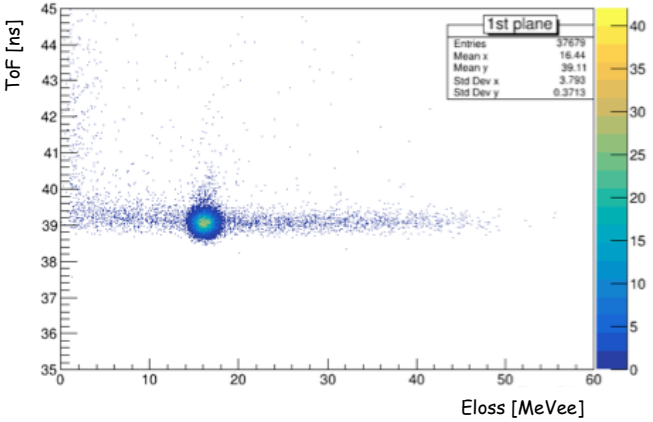
gammas

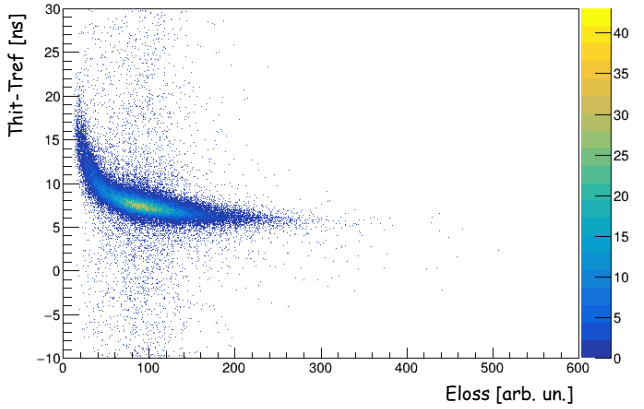
Walk correction

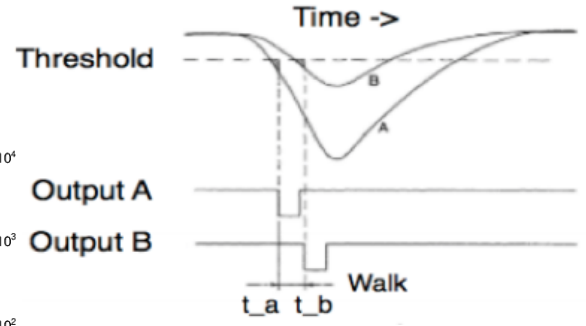










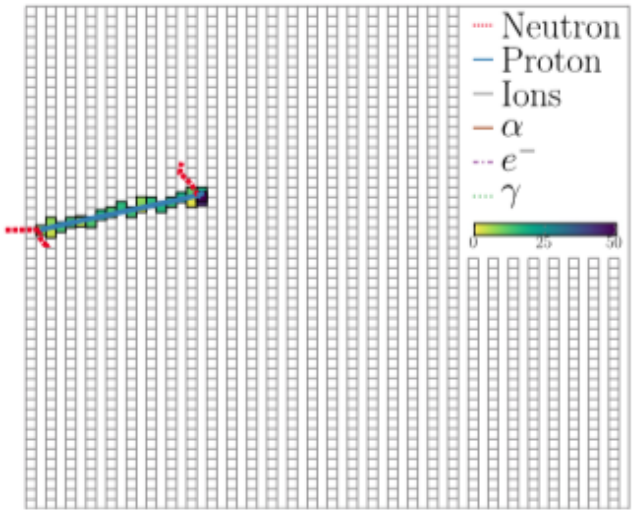


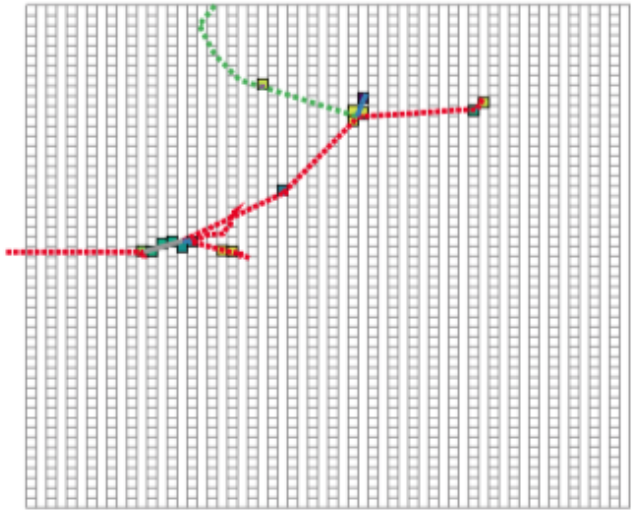
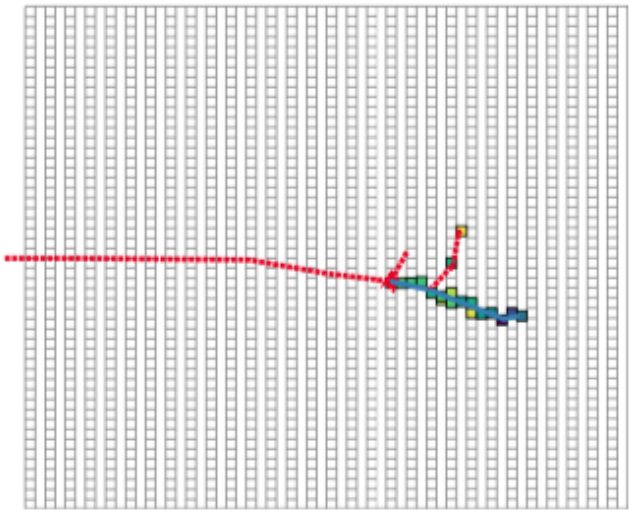
direct protons into NeuLAND

cosmics

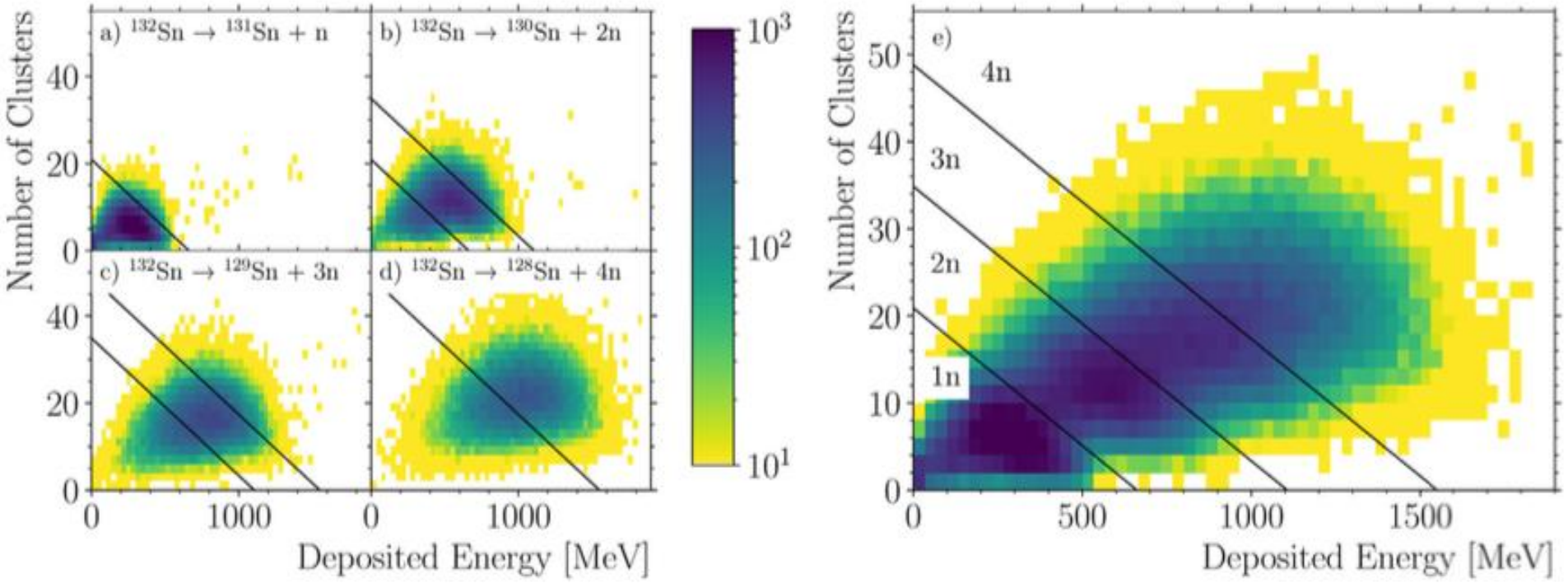
Reactions of 600 MeV neutrons in scintillator

QGSP_INCLXX_HP			QGSP_BERT_HP		
	Reaction products	[%]		Reaction products	[%]
1	$n+n+p+d+\alpha+\alpha$	7.7	1	$n+p+{}^{11}\mathrm{B}$	9.8
2	$n+n+n+p+p+\alpha+\alpha$	6.7	2	$n+n+n+p+p+\alpha+\alpha$	9.1
3	$n+p+{}^{11}\mathrm{B}$	4.9	3	$n+n+{}^{11}\mathrm{C}$	7.8
4	$n+n+{}^{11}\mathrm{C}$	4.4	4	$n+n+p+{}^{10}\mathrm{B}$	4.1
5	$n+n+n+p+p+d+d+\alpha$	2.7	5	$n+n+p+d+\alpha+\alpha$	4.0
6	$n+\alpha+\alpha+\alpha$	2.3	6	$n+\alpha+\alpha+\alpha$	3.3
7	$n+p+\alpha+{}^{7}\mathrm{Li}$	2.2	7	$n+p+{}^{11}\mathrm{C}+\pi^-$	2.6
8	$n+n+p+\alpha+{}^{6}Li$	2.0	8	$n+n+p+p+p+\alpha+\alpha+\pi^-$	2.1
9	$n+n+p+{}^{10}\mathrm{B}$	1.8	9	$n+{}^{12}\mathrm{C}$	1.7
10	$n+n+n+n+p+p+p+d+\alpha$	1.8	10	$n+n+n+n+p+p+p+d+\alpha$	1.4



Multi-neutron events



200 MeV		Generated 1	2	3	4
detected	0	7	0	0	0
	1	**90**	28	5	1
	2	3	**58**	24	5
	3	0	13	**48**	22
	4	0	0	23	**72**

600 MeV		Generated 1	2	3	4
detected	0	5	0	0	0
	1	**89**	20	2	0
	2	6	**66**	23	4
	3	0	14	**56**	26
	4	0	0	19	**69**

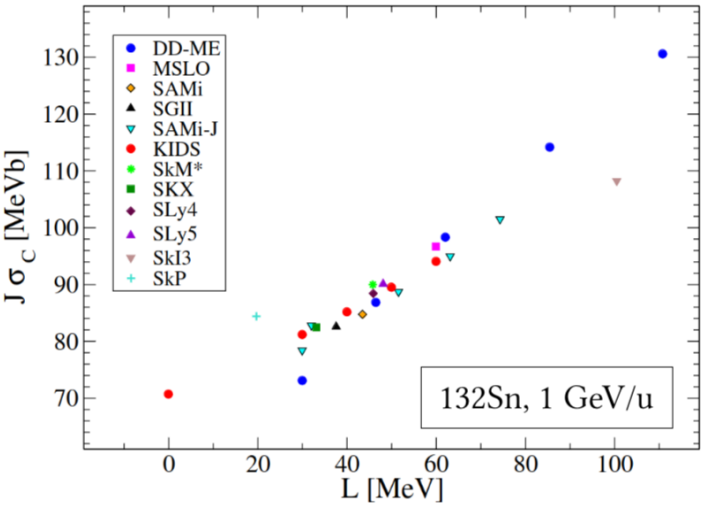
1000 MeV		Generated 1	2	3	4
detected	0	4	0	0	0
	1	**88**	18	2	0
	2	7	**70**	24	5
	3	0	11	**62**	30
	4	0	1	13	**66**

Experiments at RIKEN and GSI/FAIR

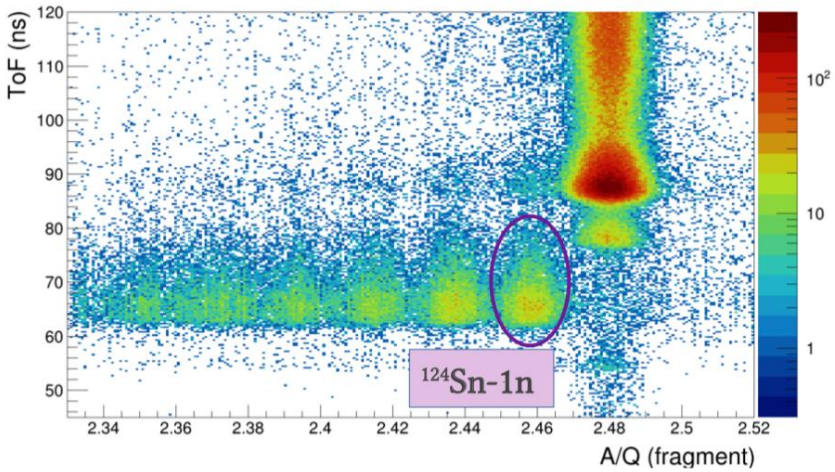
- 4 double planes – RIKEN 2015 – 2017
  - 12 experiments (^{28}O spectroscopy, ^{26}O lifetime, correlated 4n state in ^{8}He(p,pa)4n …)
- 8 double planes – GSI 2019-2020
  - ^{120}Sn – symmetry energy
  - ^{38}Ca - ^{50}Ca (p,2p) reactions, shell evolution
  - proton commissioning run, no magnet
- 12 double planes – GSI 2021
  - fission experiments (Coulomb induced, (p,2p))
  - ^{124}Sn – ^{132}Sn - symmetry energy
- 13 double planes – GSI 2022, 2024, 2025
  - short-range correlations (p, pp)
  - multi-neutron configurations
  - short-range correlations (p, pd)
  - commissioning experiment with deuteron/triton beam
  - ASYEOS II – symmetry energy
  - structure of ^{25}F in (p,pp) reaction

Tin experiment at GSI (S515)

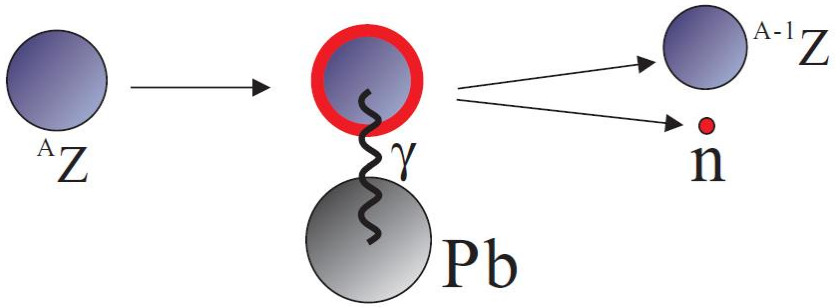
- Constraining energy-density functionals and the density-dependence of the symmetry energy by measurements of accurate cross sections with large acceptance at R3B
- secondary $^{124\text{-}132}$Sn beams from fragmentation of ^{136}Xe and fission of ^{238}U
- targets: Pb (980 mg/cm^2), C (1, 2 g/cm^2)
- energies: 400, 700, 900 MeV/u
- Couloumb excitation cross section (I. Lihtar, RBI)
- neutron-removal cross section (E. Kudaibergenova, TUDA)



[A. Horvat, private communication]

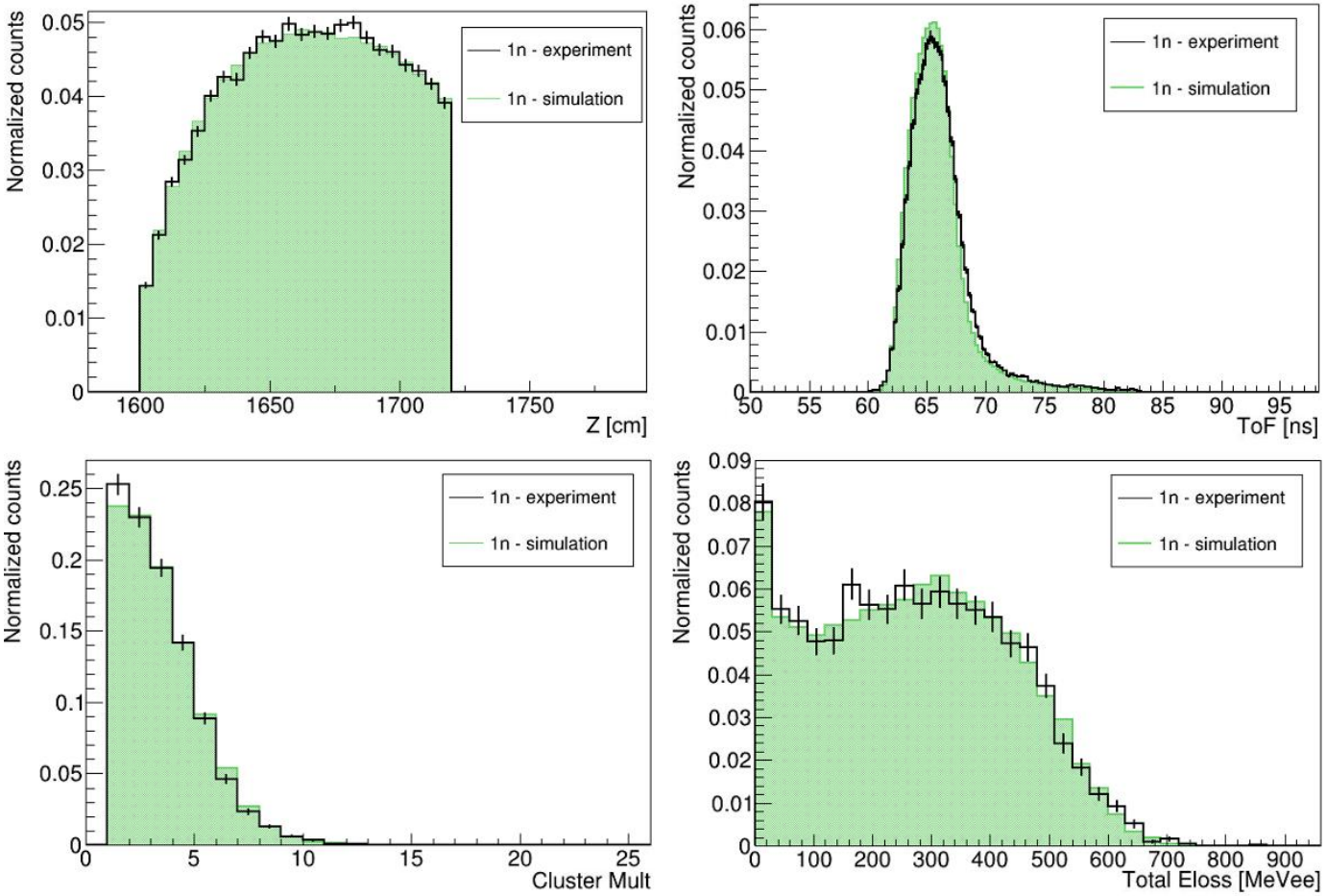


I. Lihtar, PhD thesis, University of Zagreb, 2025



1n detector response

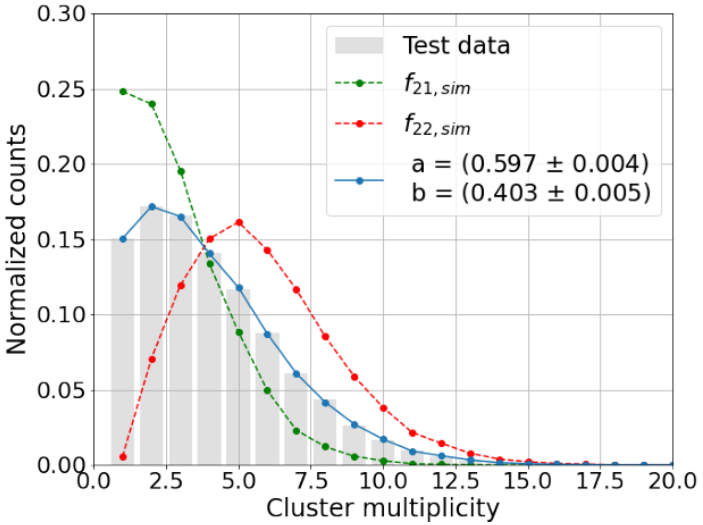
- INCLXX physics list in Geant (Intranucler cascade Liege model)
- data ^{124}Sn -> ^{123}Sn + n

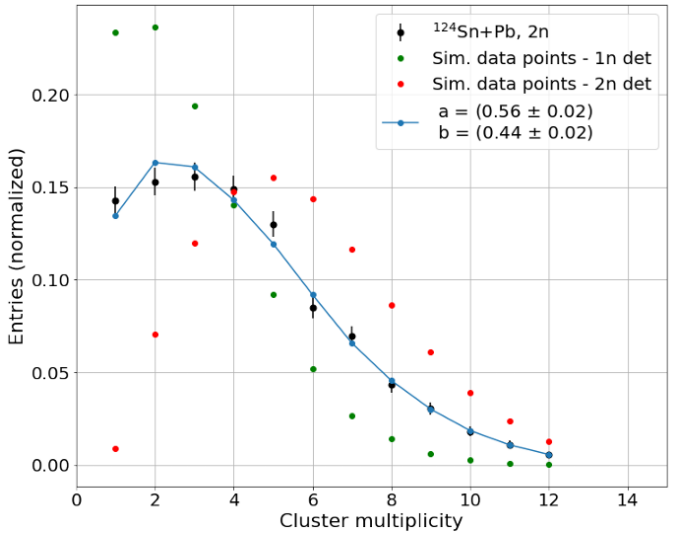


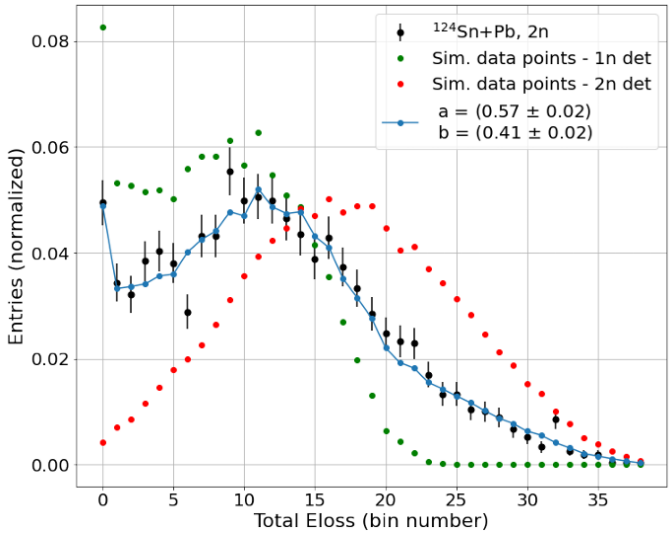
I. Lihtar, PhD thesis, University of Zagreb, 2025

1n and 2n events

- maximum number of detected neutrons determined by the detected fragment
- from the experimental distribution determine the contribution of events with 1n and 2n detected neutrons



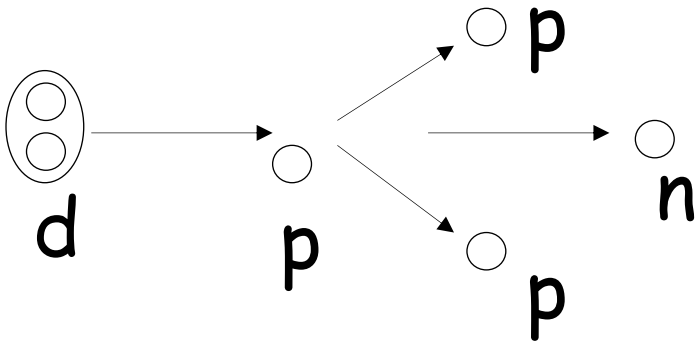


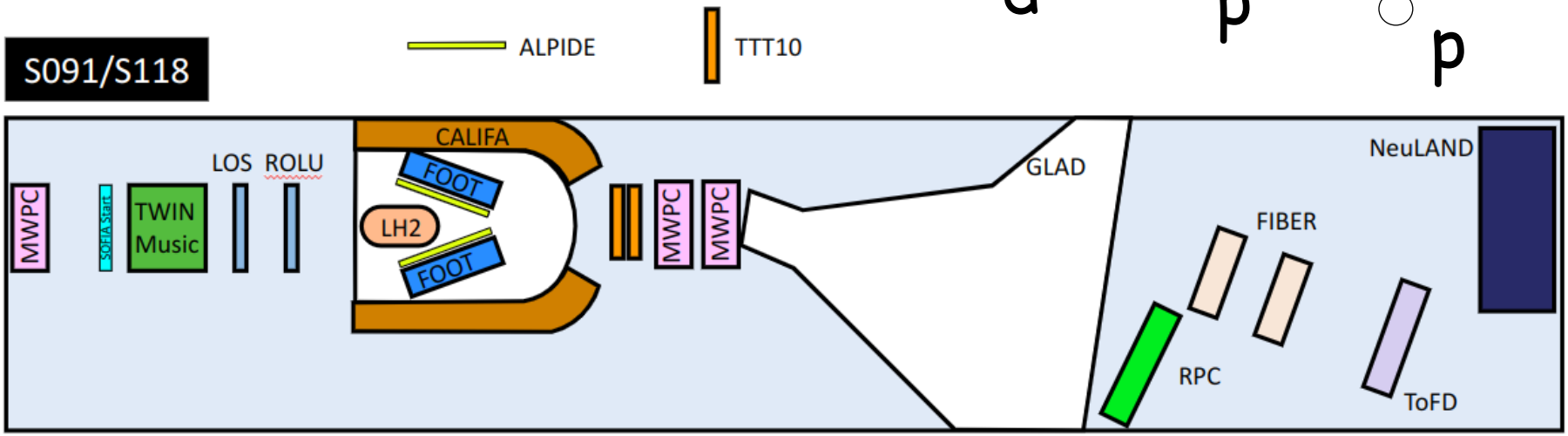


I. Lihtar, PhD thesis, University of Zagreb, 2025

Commissioning experiment with d and t beam

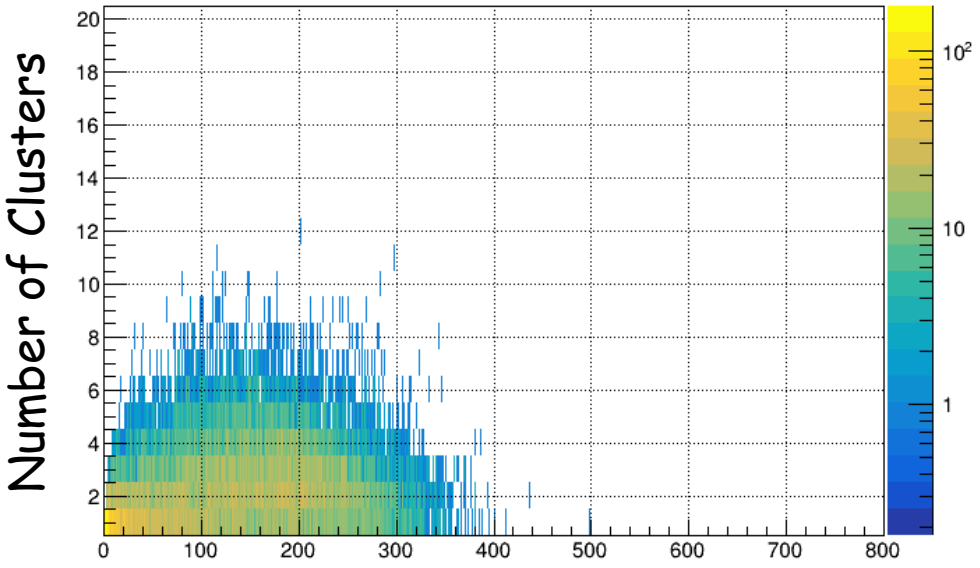
- (p,pp) reactions with deuteron and triton beams at 400 and 800 MeV/u on LH_2 target
- ^{12}C primary beam (on Pb target) 500 MeV/u
- direct triton beam in NeuLAND
- proton beam 400 MeV



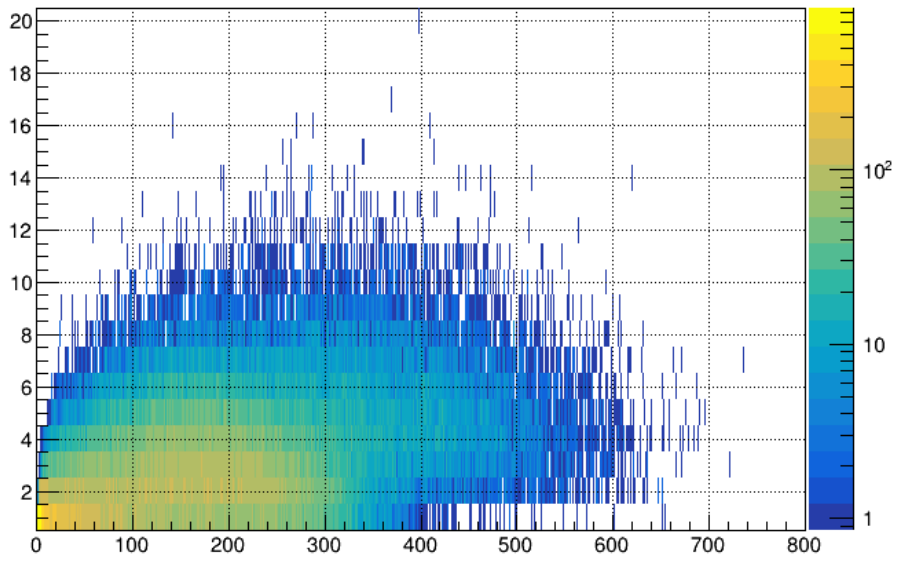


Multi-neutron recognition data

deuteron 400 MeV/u

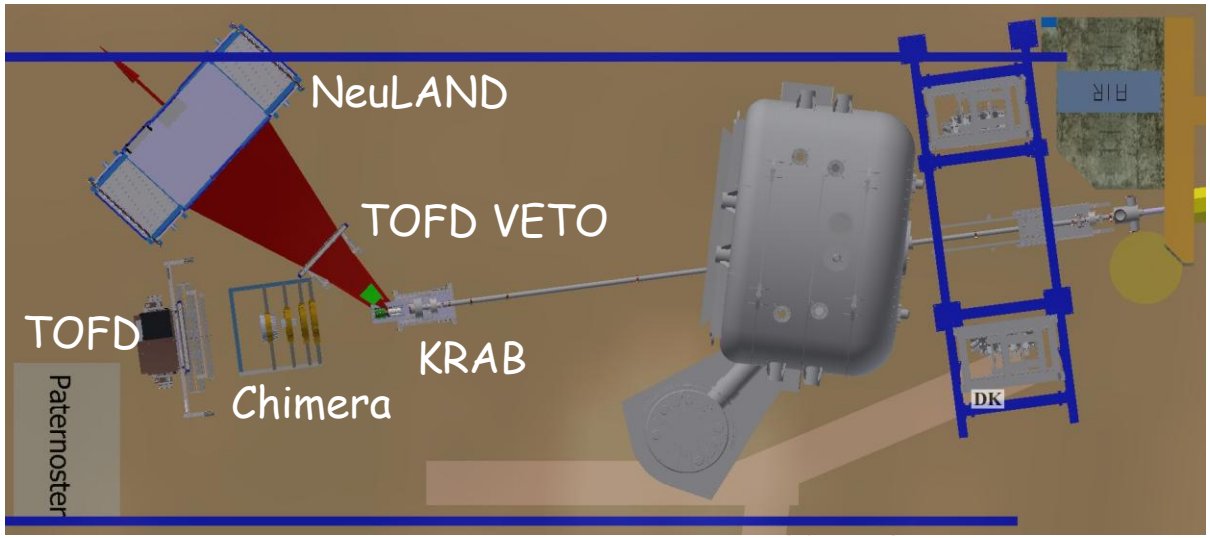


triton 400 MeV/u



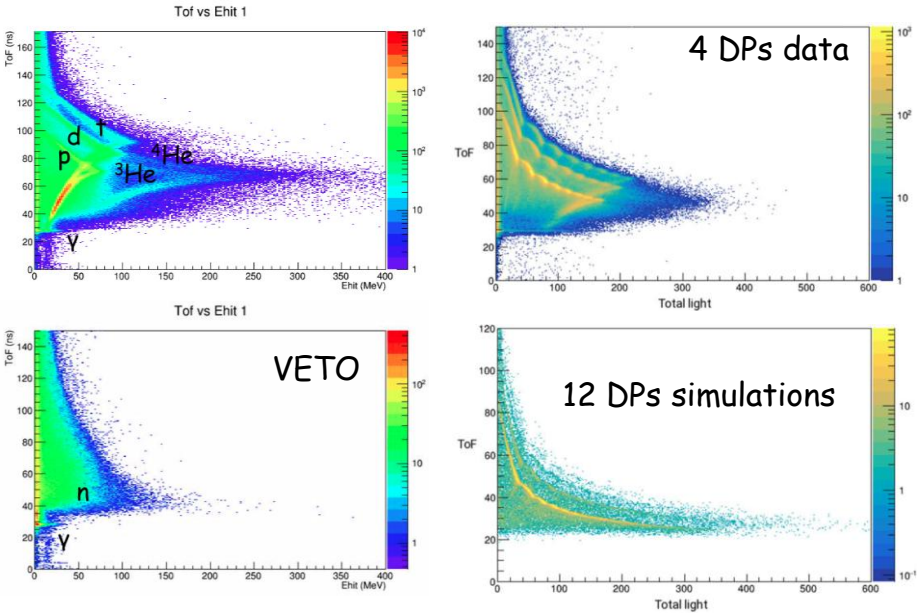
Asy-EOS II experiment

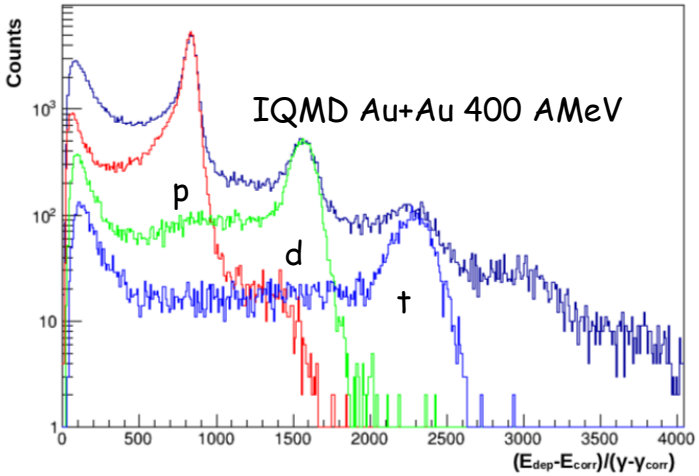
- symmetry energy at $2\rho_0$
- proton/neutron flow in heavy-ion collisions Au+Au at 280, 400, 600 and 1000 AMeV



Sπirit RIKEN Sn + Sn data

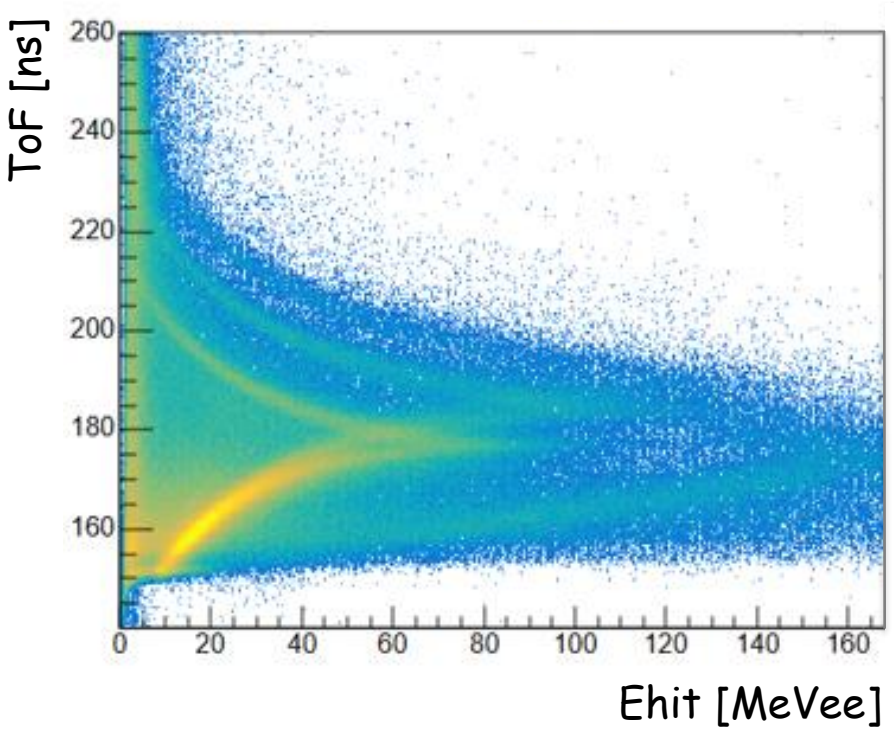
1st plane

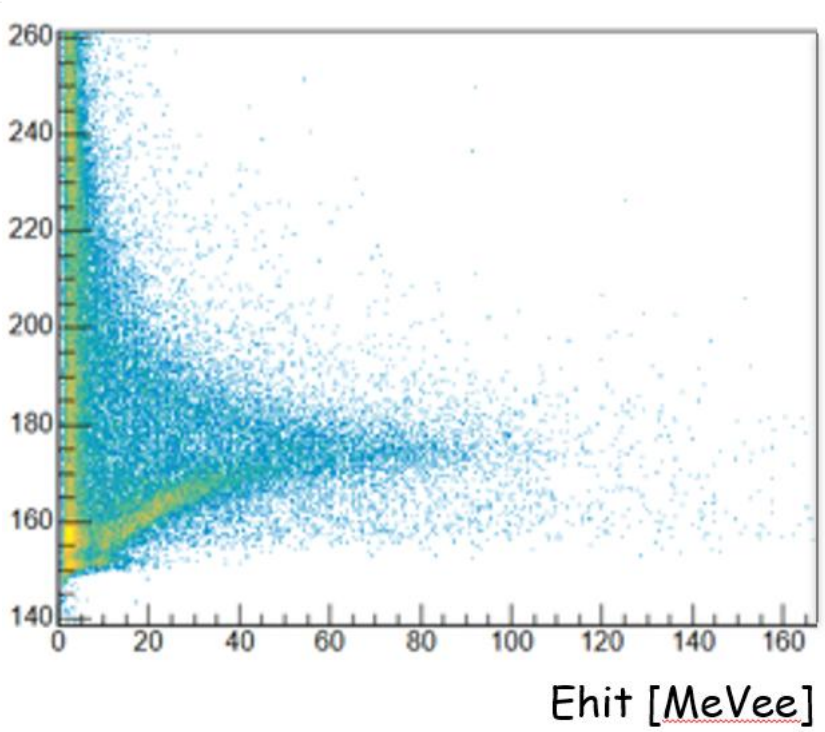




ASY-EOS II data

- How good is TOFD VETO?
- analysis is ongoing (Eulalia Gambera, Paolo Russotto, Fabio Risitano et al.)





Summary and outlook

- neutron detector NeuLAND is being built within R3B setup and being used in FAIR Phase-0 experiments
- NeuLAND demonstrator (4 double planes) used at RIKEN in 12 experiments
- 13 double planes out of 30
- Experiments studying symmetry energy of nuclear EOS performed
  - Coulomb excitation of tin isotopes – cross section
  - Heavy-ion collisions gold nuclei – proton/neutron elliptic flow
- main challenge multi-neutron recognition with (partially built) NeuLAND
- realistic simulation of detector response developed
- method for selection events with different neutron multiplicities
- analysis of the (p,2p) reactions with deuteron and triton beams points to a separation of 1n and 2n events
- continue with upgrade
- move to the new cave 2026/2027, first beam 2028

Thank you for your attention!

Special thanks to colleagues from WG NeuLAND and R^3B Collaboration