Status of symmetry-energy studies at R3B

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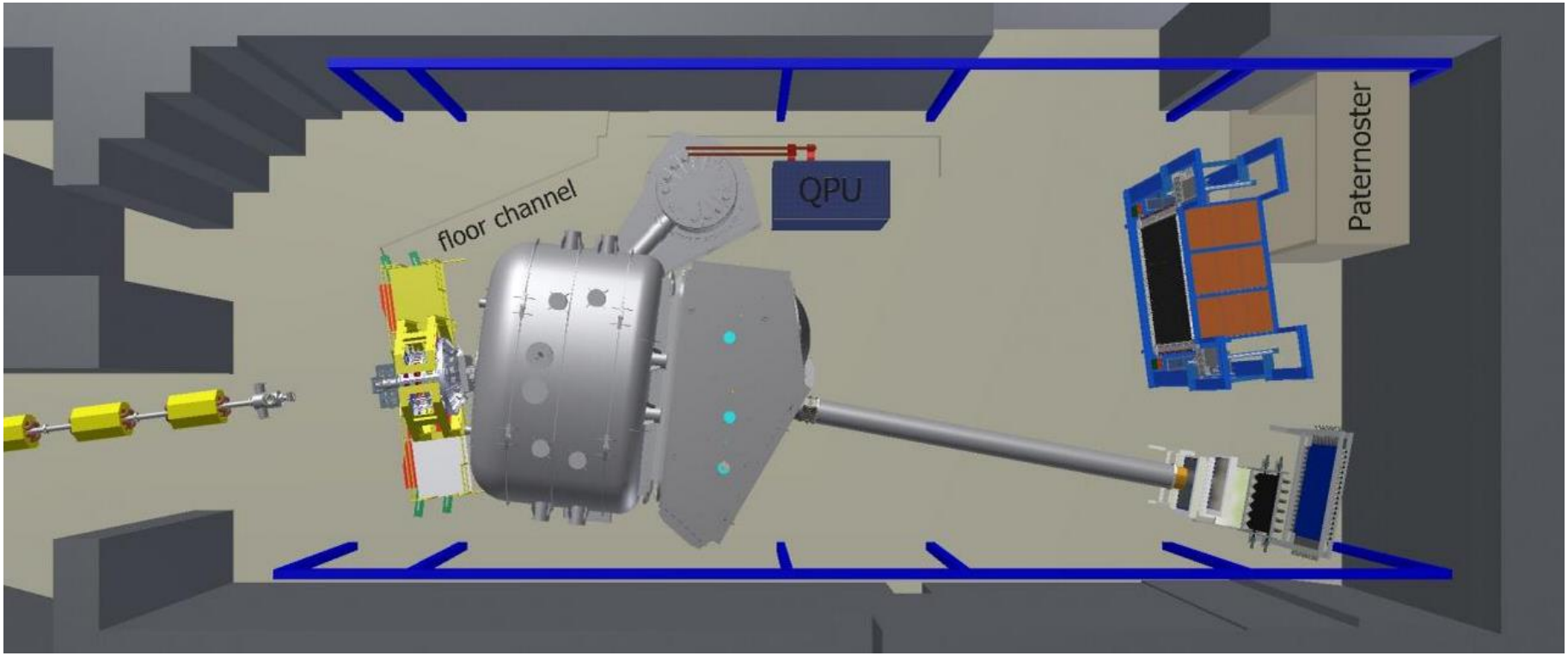
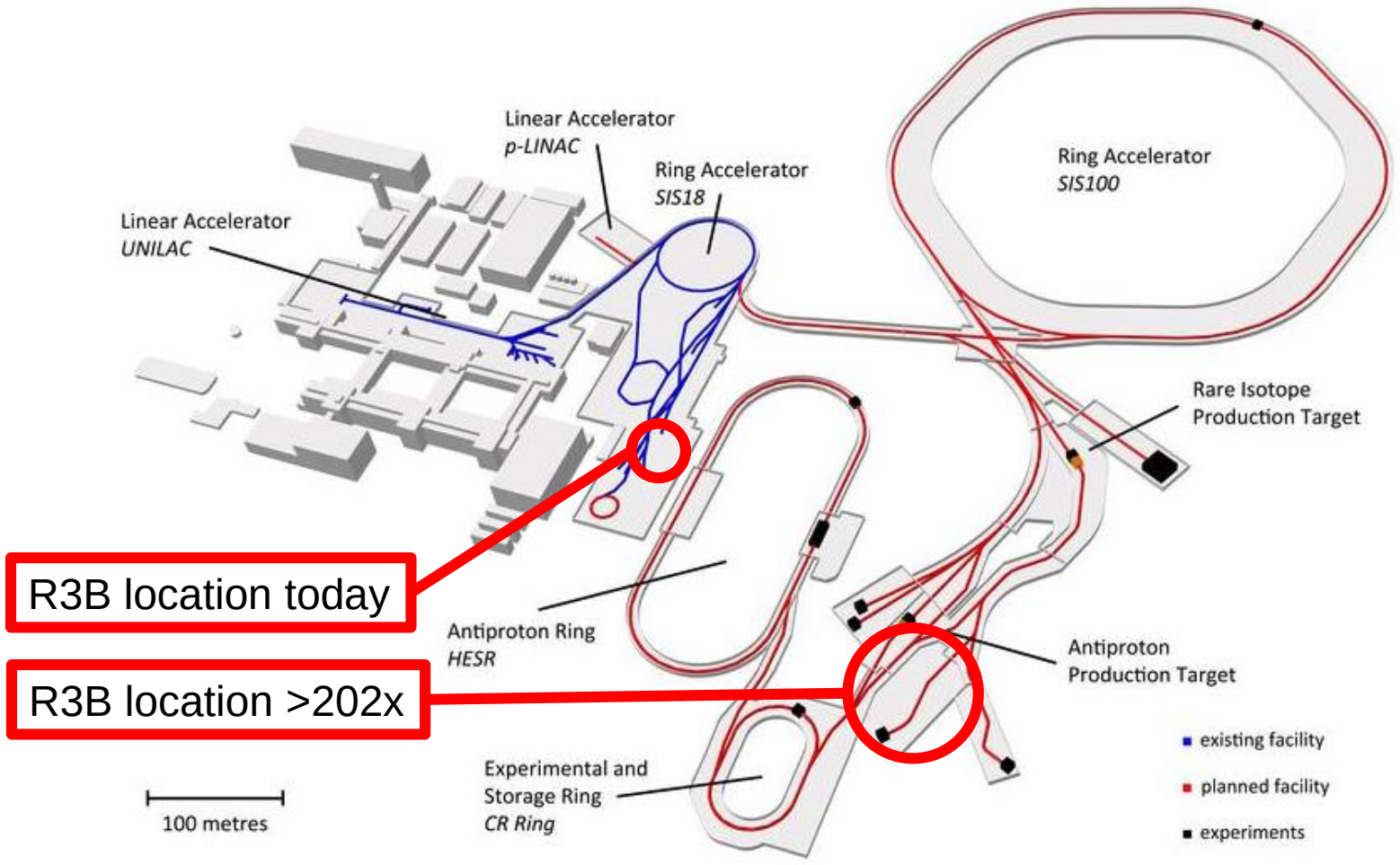
NuSYM 2018, Busan, South Korea

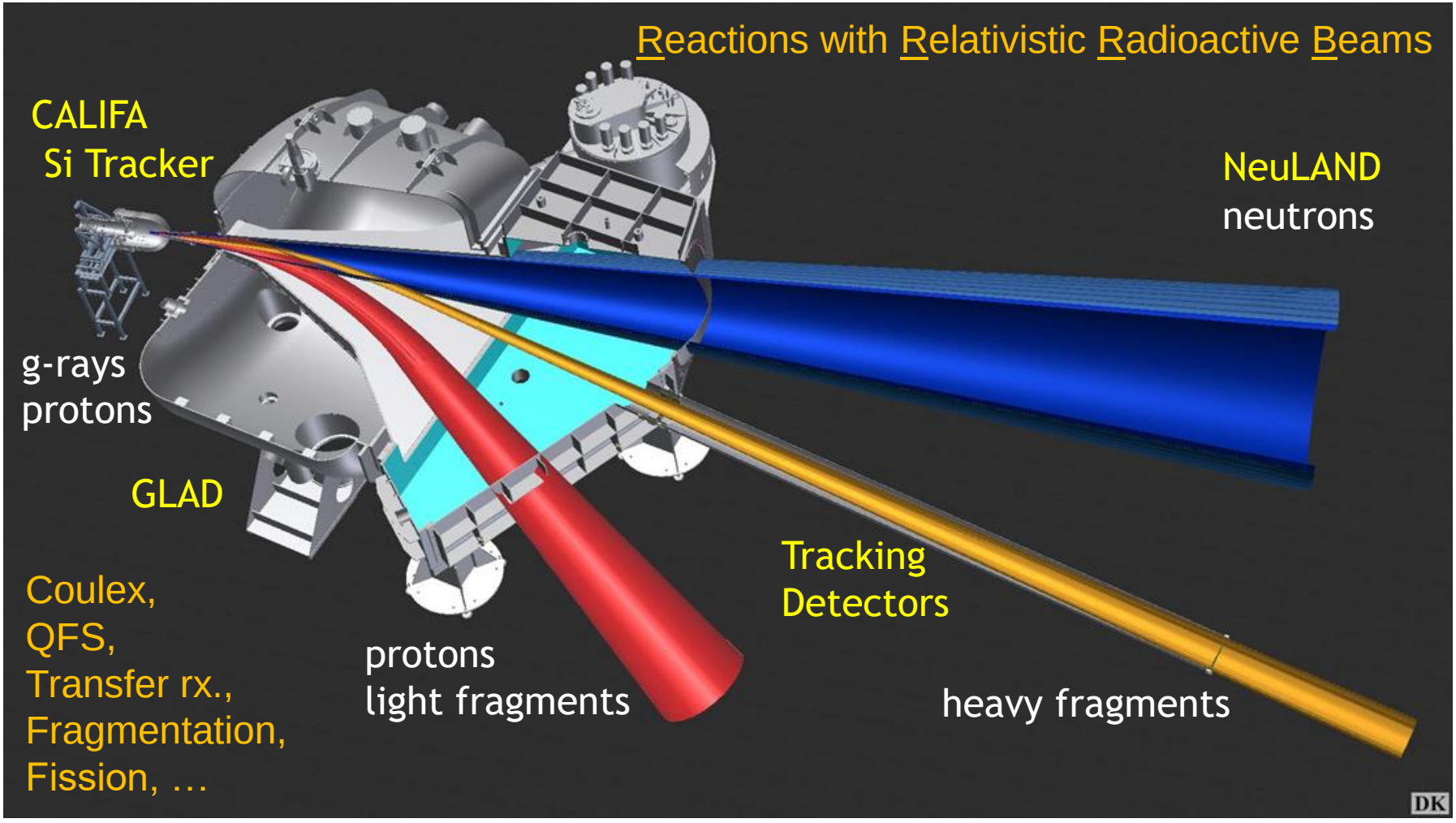
Dominic Rossi



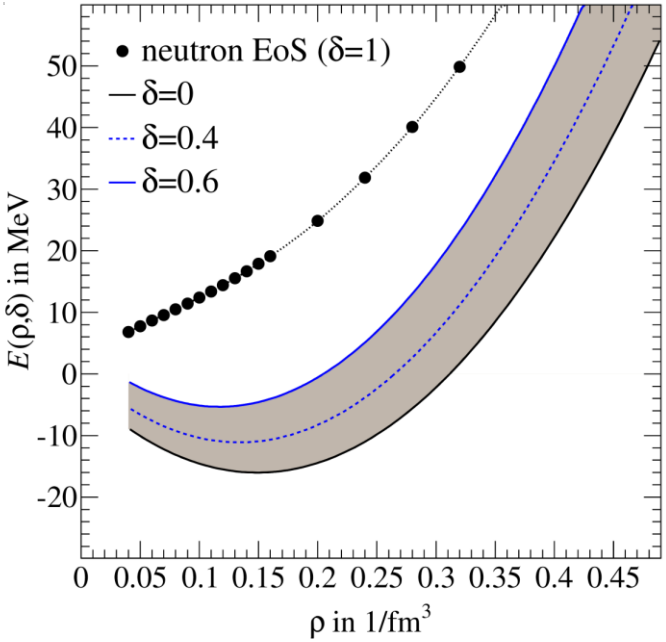
GSI and FAIR complex



R3B Overview

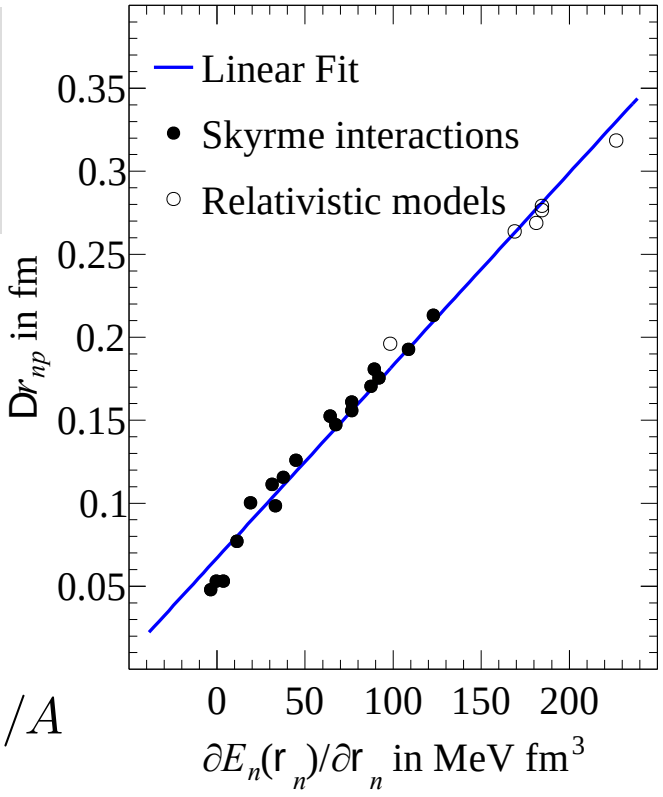


Nuclear EOS



• strong linear correlation between neutron-skin thickness and parameters (*J*, *L*)

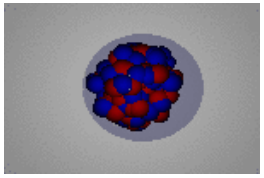
*S. Typel and B.A. Brown, Phys. Rev. C **64** (2001) 027302*



$$E(\rho,\delta) = E(\rho,0) + S(\rho)\delta^2 + \mathcal{O}(\delta^4) \qquad \delta = (N-Z)/A$$

$$S(\rho) \approx J + L\epsilon(\rho) + \frac{1}{2}K_{sym}\epsilon^2(\rho) \qquad \epsilon(\rho) = \frac{\rho - \rho_{sat}}{3\rho_{sat}}$$

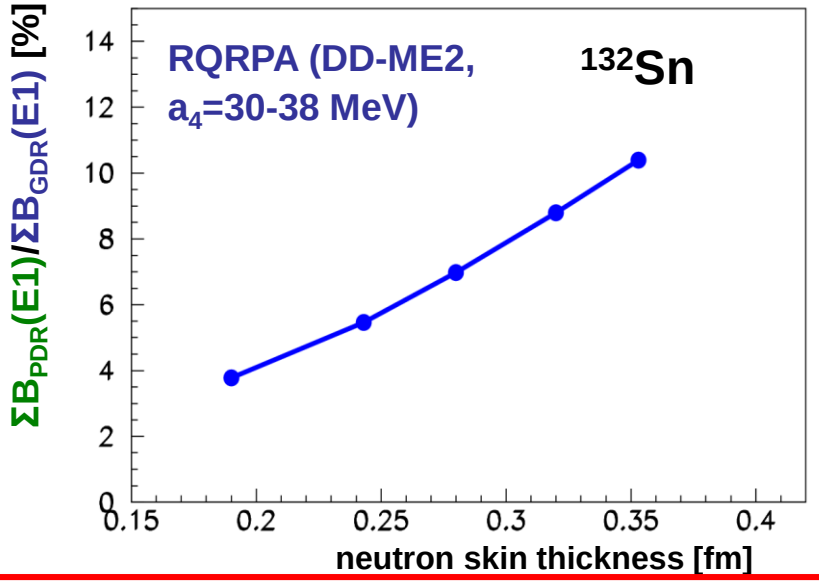
EOS from Pygmy Dipole Resonance



P. Adrich *et al.*, PRL **95**, 132501 (2005)

GDR ➔ Breit-Wigner
PDR ➔ Gaussian

- RQRPA calculations provide correlation between the measured PDR strength and the neutron skin thickness



- Requires assumption of a specific line-shape of PDR and GDR
- Photoabsorption c.s. not very sensitive to low-lying E1 strength

Selecting a better experimental observable

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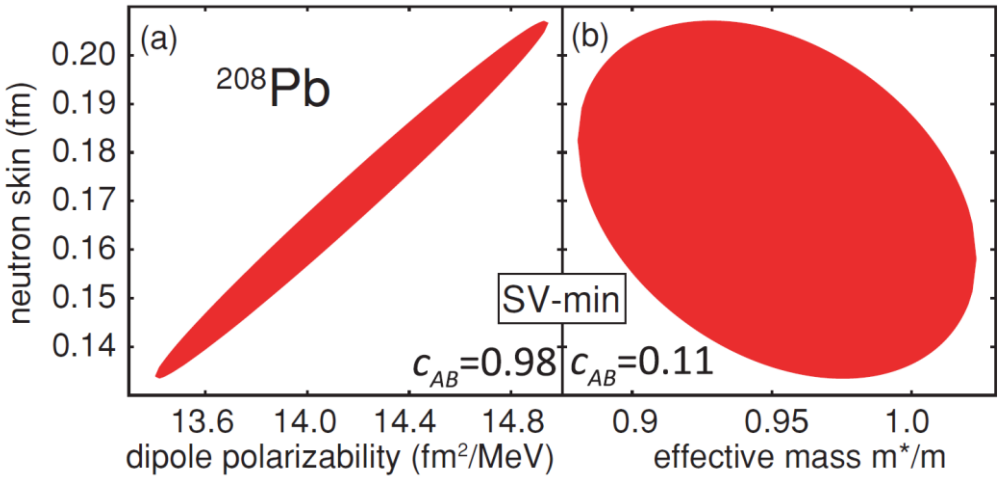
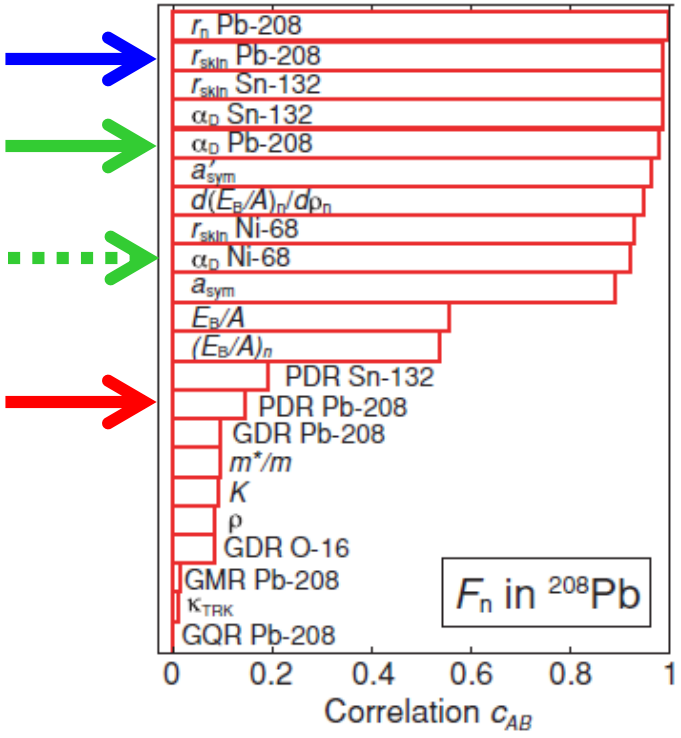
PHYSICAL REVIEW C **81**, 051303(R) (2010)

Information content of a new observable: The case of the nuclear neutron skin

P.-G. Reinhard[1] and W. Nazarewicz[2,3,4,5]





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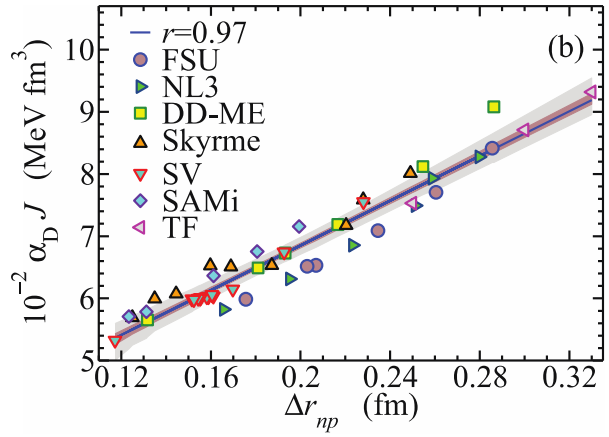
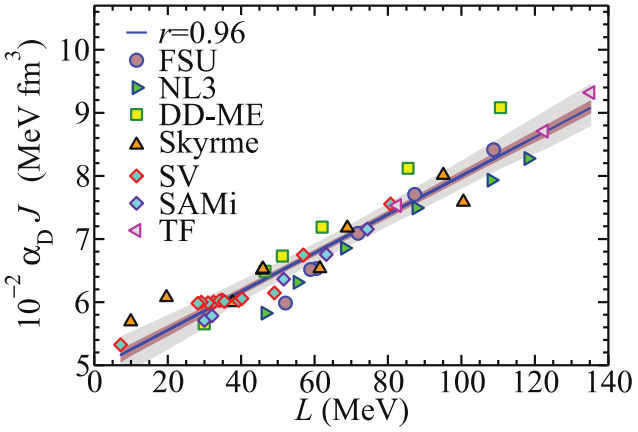
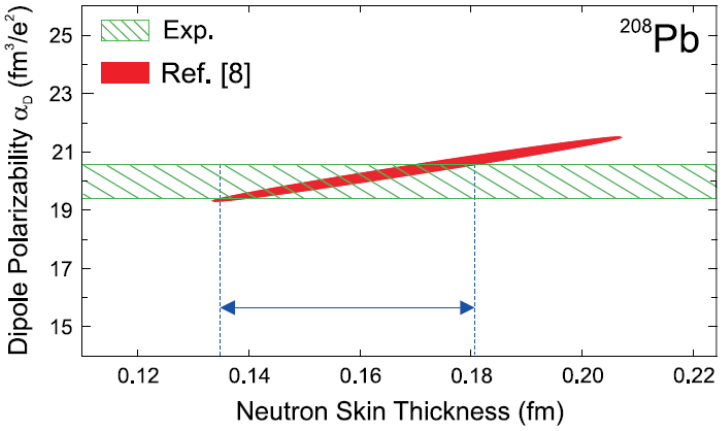
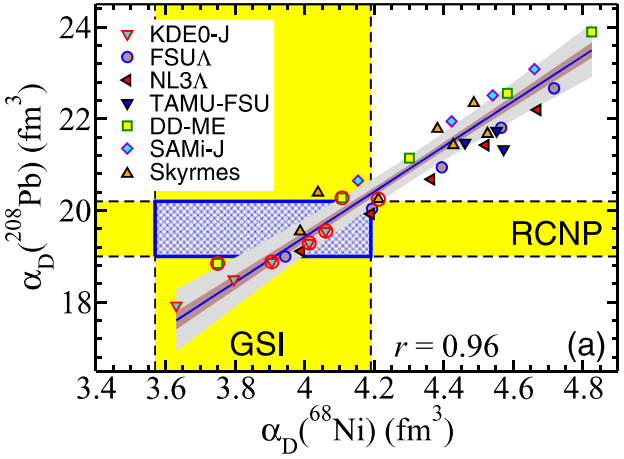
Dipole polarizability





X. Roca-Maza *et al.*, PRC 88 (2013) 024316





X. Roca-Maza *et al.*, PRC 92 (2015) 064304

Experiment:
S. Tamii *et al.*,
PRL 107 (2011)

Theory:
P.-G. Reinhard and
W. Nazarewicz,
PRC 81 (2010)

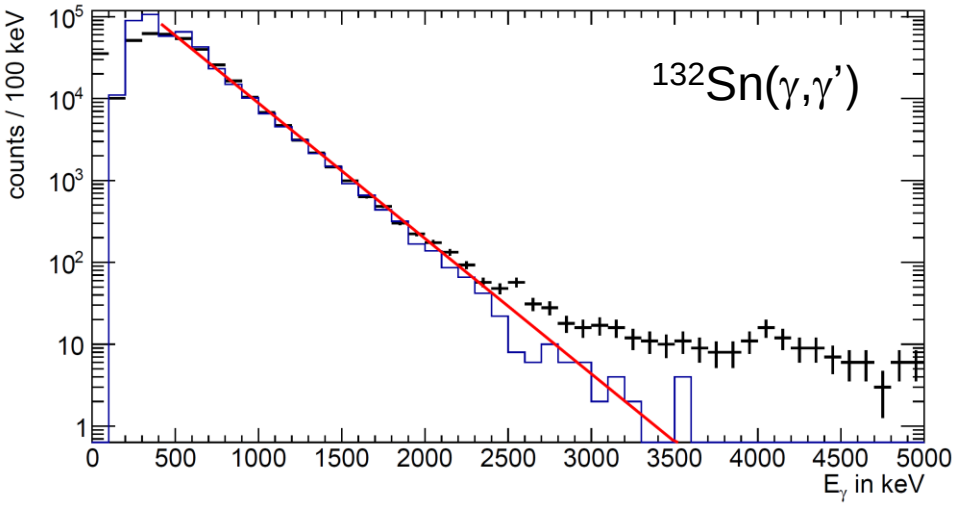
Experiment:
RCNP: A. Tamii *et al.*
GSI: D. Rossi *et al.*,
PRL 111 (2013)

$$30 \leqslant J \leqslant 35\,\mathrm{MeV}$$

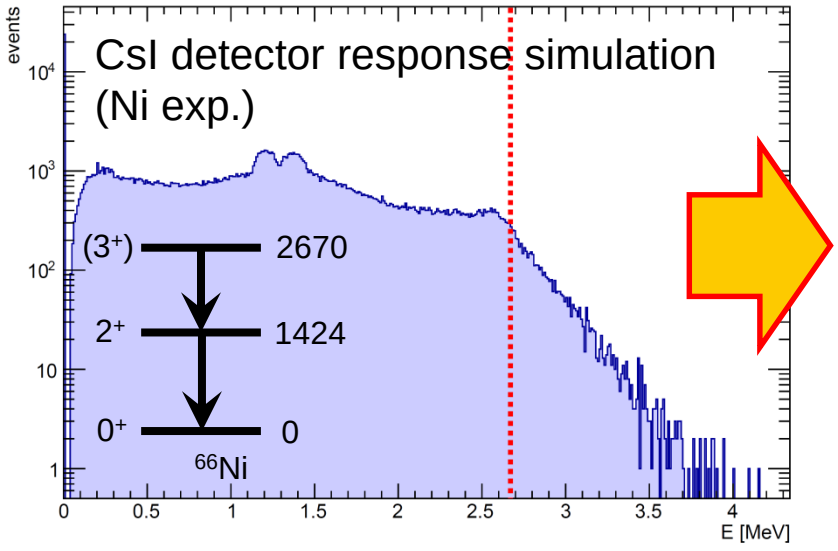
$$20 \leqslant L \leqslant 66\,\mathrm{MeV}$$

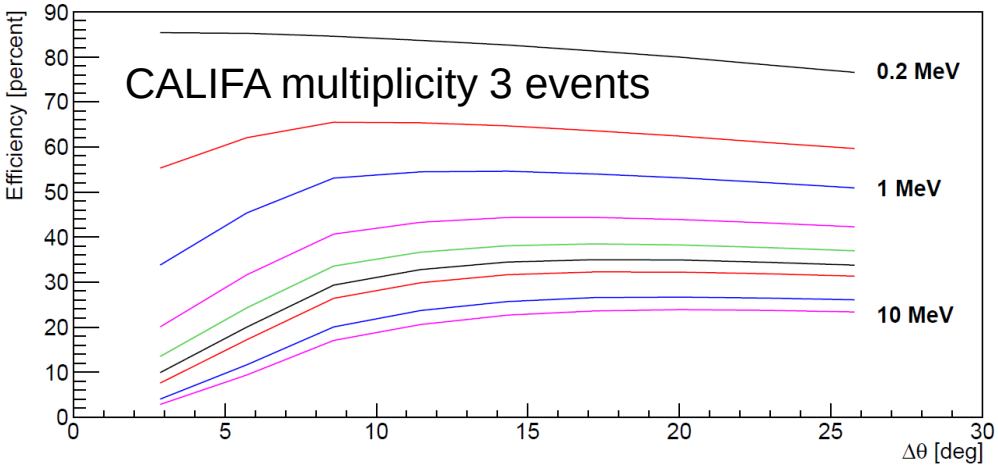
Dipole polarizability in n-rich Sn

- Experiment in 2012
- Production of $^{128\text{-}134}$Sn
- Measurement above and below neutron threshold
- Analysis still in progress



P. Schrock, PhD thesis





CALIFA TDR

GLAD: Installation in Cave C in 2016

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CALIFA: CALorimeter for In Flight detection of gamma rays and high-energy charged pArticles

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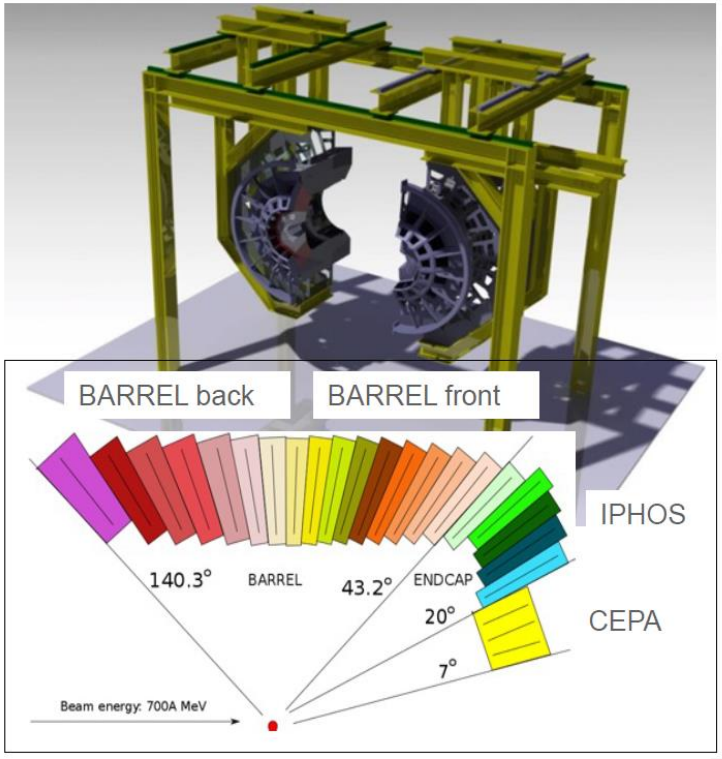

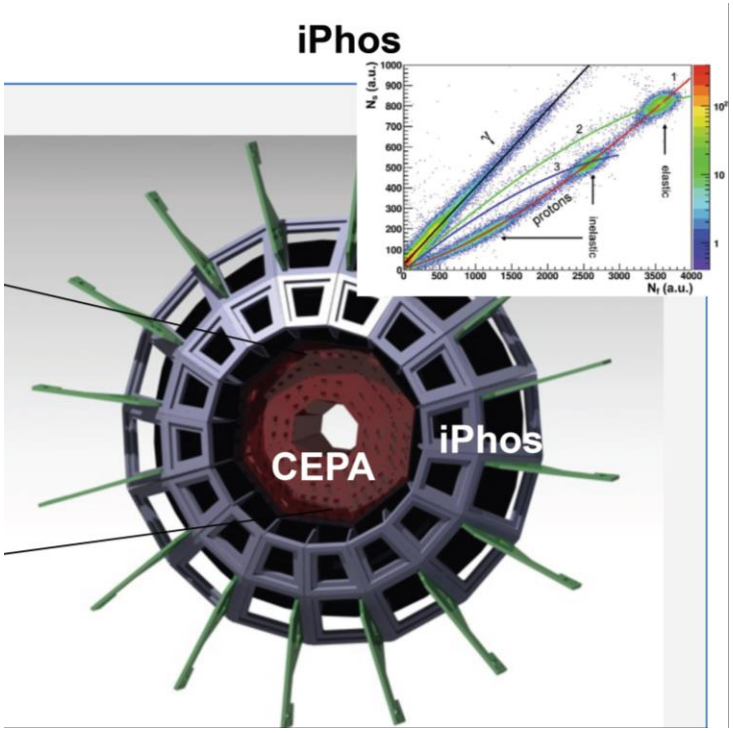

CALIFA barrel:

- Total of 1952 CsI(Tl) crystals (1152 in front half)
- 896 crystals expected to be ready end of 2018

- CEPA (CsI(Tl)): fully funded, first module built
- iPhos ($LaBr_3$/$LaCl_3$): 75% funded

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NeuLAND

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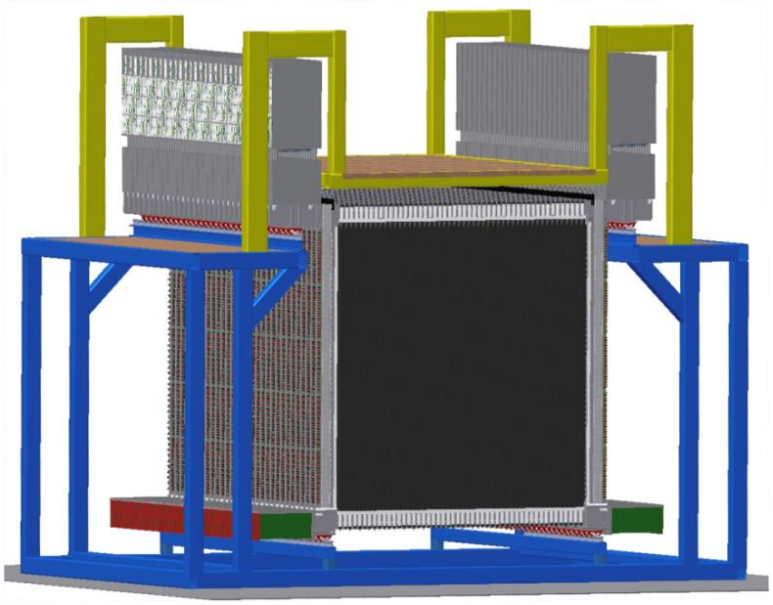

NeuLAND detector parameters:

- full active detector using RP/BC408
- face size 250x250 cm^2
- active depth 300 cm
- 3000 scintillator bars + 6000 PMTs
- 32 tons
- $\sigma_{x,y,z} \approx 1cm$ & $\sigma_t < 150$ ps

Design goals:

- **>**90% efficiency for 0.2-1.0 GeV neutrons
- multi-hit capability for up to 5 neutrons
- invariant mass resolution down to $\Delta E < 20$ keV at 100 keV above thr.

double plane 11 during bar mounting

Courtesy of K. Boretzky

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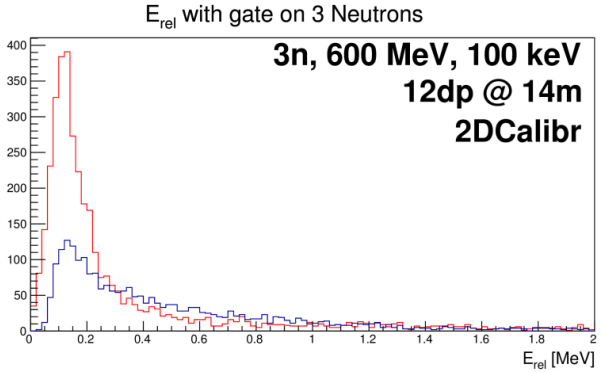
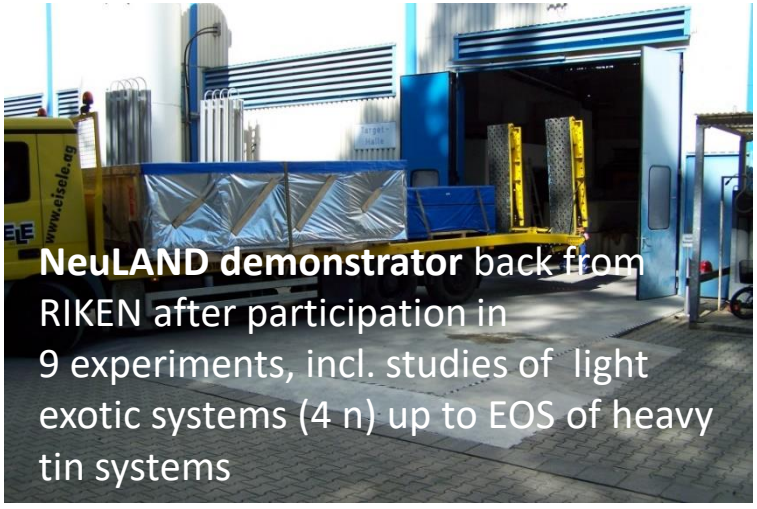
NeuLAND

NeuLAND Phase 0

- 130 cm active depth
- 2600 channels
- >40% detector



simulation prediction: **reconstruction efficiency** of the order of 20% for 3 n, 10 % for 4 n (600 MeV, preliminary)



NeuLAND demonstrator back from RIKEN after participation in 9 experiments, incl. studies of light exotic systems (4 n) up to EOS of heavy tin systems

SAT test of in-house developed **NeuLAND electronics** underway:

- multichannel front-end electronic card TAMEX for high-resolution time and charge measurements

Courtesy of K. Boretzky

Tracking Detectors: TOF Wall

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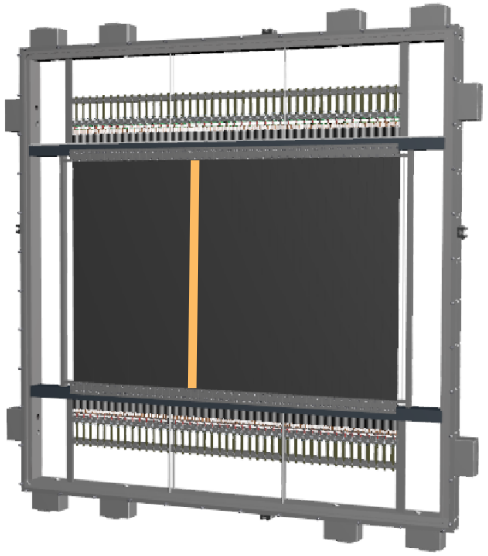
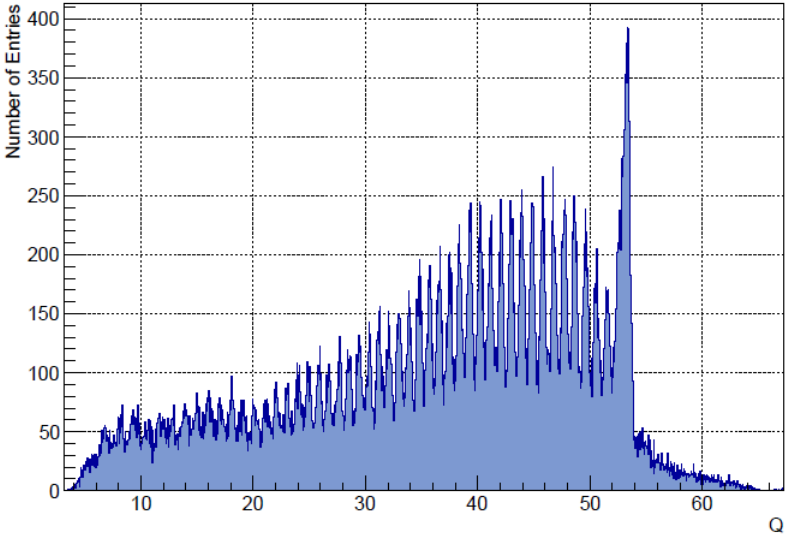
Z separation	σ_E < 1%
A separation	σ_t < 38 ps
Rate	1 MHz

- Size: 120 x 100 cm²
- Total of 176 paddles, arranged into 4 layers
- No light guide, PMT R8619 coupled directly to scintillator
- Movable holding structure to sweep TOF wall across beam





Courtesy of M. Heil

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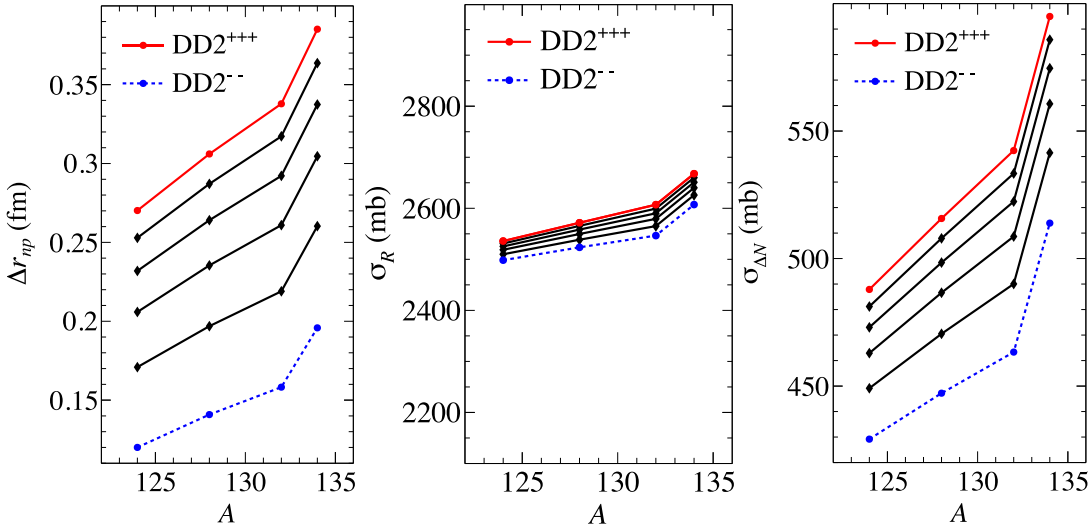
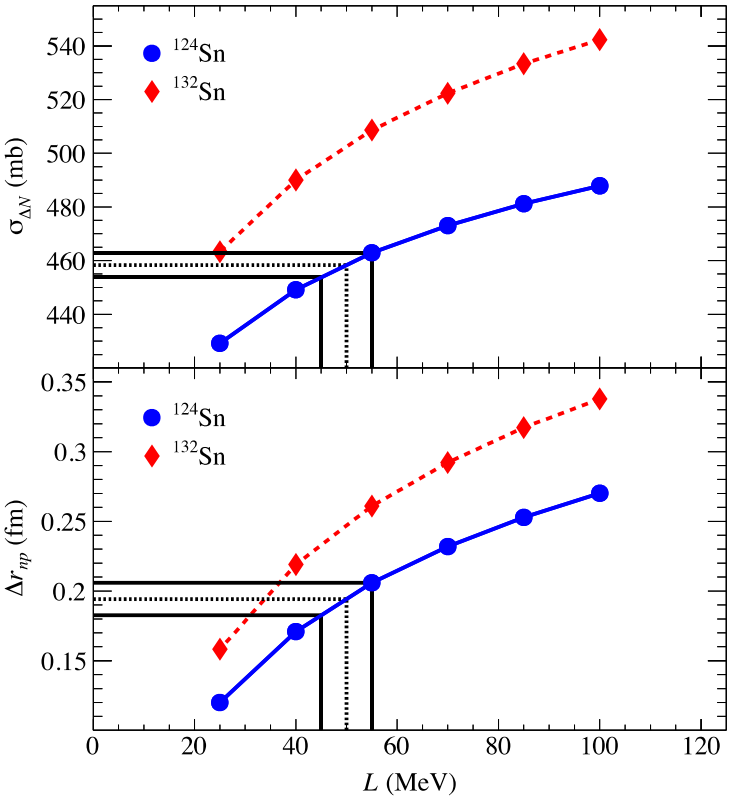
Total n-removal cross section measurement



- We use RMF DD interactions with systematic variation of L
- n-skin changes accordingly by about 0.19 fm for ^{132}Sn
- Total reaction cross section changes only by 2.5%
- Total neutron-removal cross section changes by about 20%

  Variation $\delta L = \pm 5$ MeV → $\delta\Delta r_{np} \approx \pm 0.01$ fm and $\delta\sigma_{\Delta N} \approx \pm 1\%$

  → $\sigma_{\Delta N}$ very sensitive, limit given by DFT predictions reached
- But: relation of $\sigma_{\Delta N}$ to L or Δr_{np} needs reaction theory !



Relativistic Mean Field Theory (DD2):
S. Typel, Phys. Rev. C **89**, 064321 (2014)

Reaction theory

$$\sigma_R = \begin{pmatrix} Z_P \\ Z \end{pmatrix} \begin{pmatrix} N_P \\ N \end{pmatrix} \int d^2b \left[1 - P_p(b)\right]^{Z_P - Z} P_p^Z(b) \times \left[1 - P_n(b)\right]^{N_P - N} P_n^N(b)$$

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

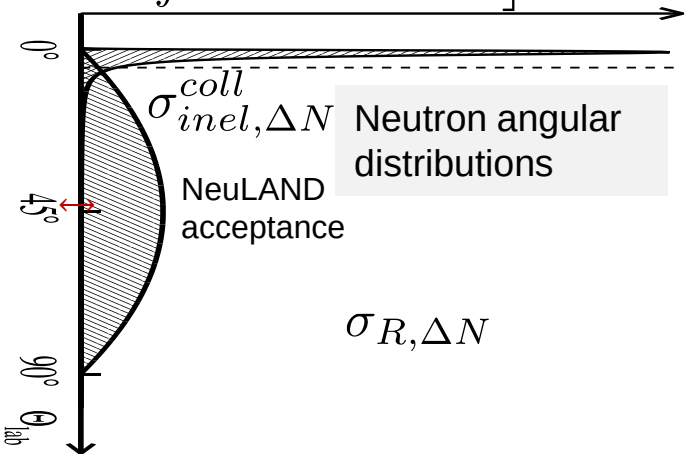
Input

Bertulani, Danielewicz, *Introduction to Nuclear Reactions* (CRC Press, London, 2004)

Experiment (4 independent measurements):

$$\sigma_I = \sigma_R + \sigma_{inel}^{coll\Delta N} = \sigma_{R,\Delta Z} + \sigma_{R,\Delta N} + \sigma_{inel,\Delta N}^{coll}$$

Glauber/Eikonal theory



Neutron angular distributions

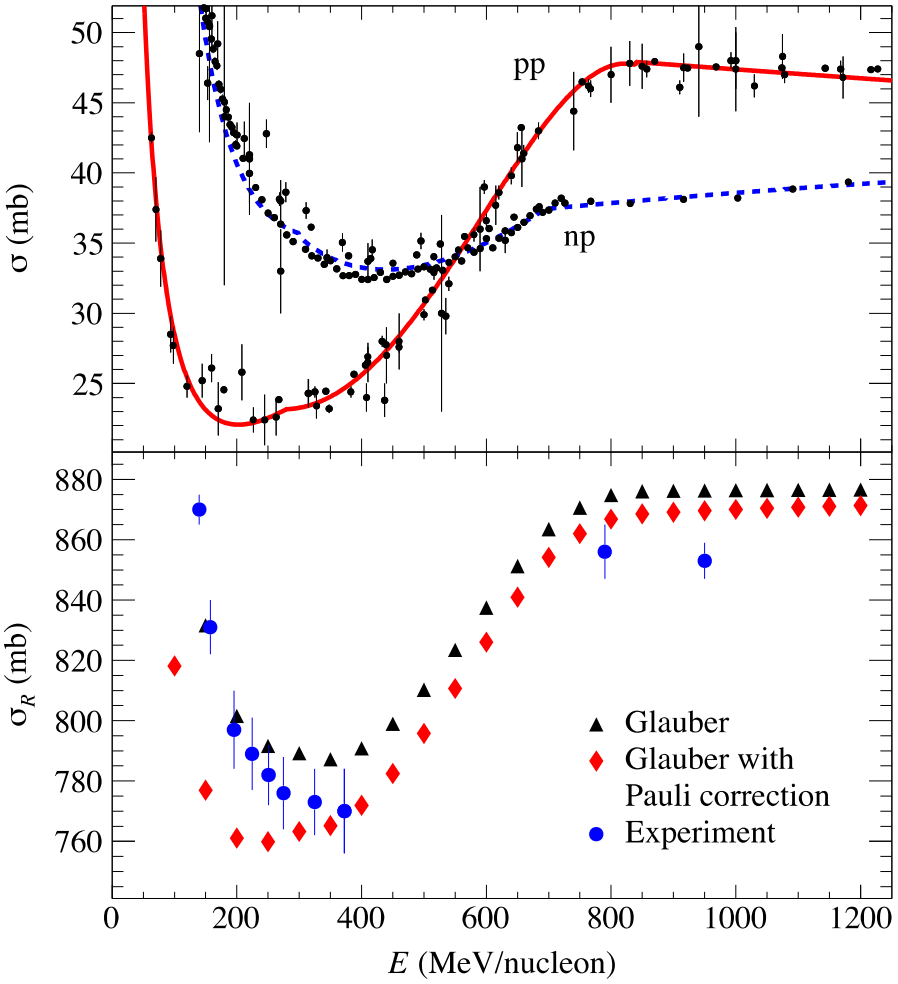
σ_{inel}^{coll} - Collective (Coulomb + nuclear) excitation (of giant resonances) + neutron evaporation:
for Sn ≈ 100 mb $(20\%$ of $\sigma_{\Delta N})$

⇒ has to be determined experimentally

⇒ Relation $\sigma_{\Delta N} \Leftrightarrow L$

⇒ Task: Testing and quantifying uncertainties of Eikonal reaction theory

Test of Eikonal reaction theory



T. Aumann *et al.*, PRL 119, 262501 (2017)

<u>Test with energy dependence of ^{12}C + ^{12}C total reaction cross section</u>

Parameter-free Eikonal prediction overestimates cross sections

Expected deviations due to:
1) In-medium effects: Pauli blocking
2) Fermi motion
3) Higher-order
4) Collective excitations

Taking into account Pauli blocking:
C.A. Bertulani, C. De Conti, PRC 81 (2010)
Higher-energy data point overestimated by ≈2%

Theoretical improvements needed

But:
only three data points in the range 0.4 to 1.2 GeV/u
→ Precise data needed incl. energy dependence

FAIR Phase-0 experiment

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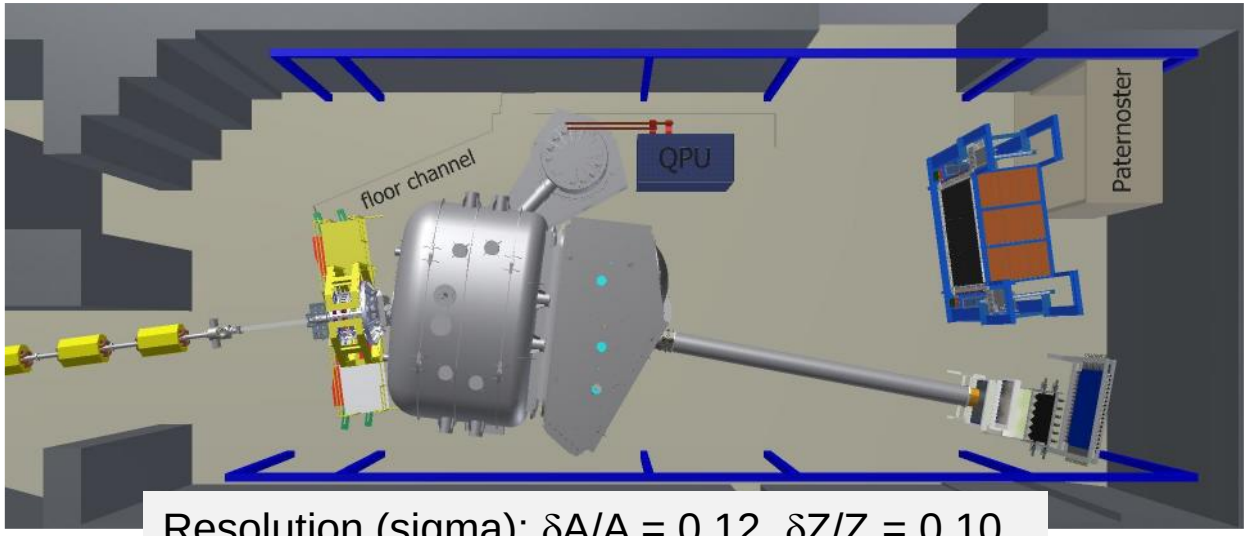
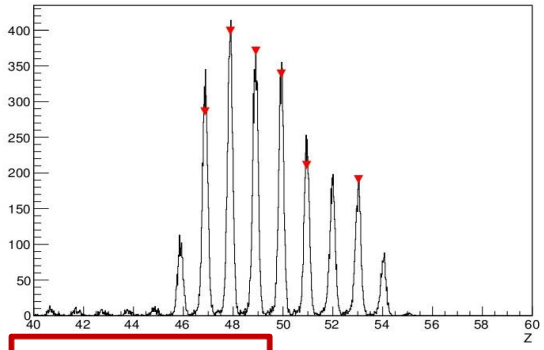


Resolution (sigma): $\delta A/A = 0.12$, $\delta Z/Z = 0.10$

Measured quantity	Method	Uncertainty
σ_I	Absorption	<1%
$\sigma_{\Delta Z}$	ΔE after target	<1%
$\sigma_{\Delta N}$	Mass spectrum	1%
$\sigma^{coll}_{inel,\Delta N}$	(A-x) fragment + x neutrons	<5%
$\sigma_{R,\Delta N} = \sigma_{\Delta N} - \sigma^{coll}_{inel,\Delta N}$		1-2%

NeuLAND:
Measure collective cross section up to three-neutron decay

Fragment spectrometer **GLAD:**
Acceptance 15%
(up to 13 neutron removal)



→ Theory
→ n-skin
→ L

T. Aumann, C.A. Bertulani, F. Schindler, S. Typel, PRL 119 (2017)

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Summary

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- Dipole polarizability data analysis still ongoing for n-rich Sn isotopes
- Key detectors for polarizability studies will be finalized and commissioned in the near future
- Cross section measurements for EOS studies already planned for FAIR Phase-0

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The R3B Collaboration

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Aksouh, Farouk; Al-Khalili, Jim; Algora, Alejandro; Alkhasov, Georgij; Altstadt, Sebastian; Alvarez, Hector; Atar, Leyla; Audouin, Laurent; Aumann, Thomas; Pellereau, Eric; Martin, Julie-Fiona; Gorbinet, Thomas; Seddon, Dave; Kogimtzis, Mos; Avdeichikov, Vladimir; Barton, Charles; Bayram, Murat; Belier, Gilbert; Bemmerer, Daniel; Michael Bendel; Benlliure, Jose; Bertulani, Carlos; Bhattacharya, Sudeb; Bhattacharya, Chandana; Le Bleis, Tudi; Boilley, David; Boretzky, Konstanze; Borge, Maria Jose; Botvina, Alexander; Boudard, Alain; Boutoux, Guillaume; Boehmer, Michael; Caesar, Christoph; Calvino, Francisco; Casarejos, Enrique; Catford, Wilton; Cederkall, Joakim; Cederwall, Bo; Chapman, Robert; Alexandre Charpy; Chartier, Marielle; Chatillon, Audrey; Chen, Ruofu; Christophe, Mayri; Chulkov, Leonid; Coleman-Smith, Patrick; Cortina, Dolores; Crespo, Raquel; Csatlos, Margit; Cullen, David; Czech, Bronislaw; Danilin, Boris; Davinson, Tom; Paloma Diaz; Dillmann, Iris; Fernandez Dominguez, Beatriz; Ducret, Jean-Eric; Duran, Ignacio; Egelhof, Peter; Elekes, Zoltan; Emling, Hans; Enders, Joachim; Eremin, Vladimir; Ershov, Sergey N.; Ershova, Olga; Eronen, Simo; Estrade, Alfredo; Faestermann, Thomas; Fedorov, Dmitri; Feldmeier, Hans; Le Fevre, Arnaud; Fomichev, Andrey; Forssen, Christian; Freeman, Sean; Freer, Martin; Friese, Juergen; Fynbo, Hans; Gacsi, Zoltan; Garrido, Eduardo; Gasparic, Igor; Gastineau, Bernard; Geissel, Hans; Gelletly, William; Genolini, B.; Gerl, Juergen; Gernhaeuser, Roman; Golovkov, Mikhail; Golubev, Pavel; Grant, Alan; Grigorenko, Leonid; Grosse, Eckart; Gulyas, Janos; Goebel, Kathrin; Gorska, Magdalena; Haas, Oliver Sebastian; Haiduc, Maria; Hasegan, Dumitru; Heftrich, Tanja; Heil, Michael; Heine, Marcel; Heinz, Andreas; Ana Henriques; Hoffmann, Jan; Holl, Matthias; Hunyadi, Matyas; Ignatov, Alexander; Ignatyuk, Anatoly V.; Ilie, Cherciu Madalin; Isaak, Johann; Isaksson, Lennart; Jakobsson, Bo; Jensen, Aksel; Johansen, Jacob; Johansson, Hakan; Johnson, Ron; 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Nacher, Enrique; Najafi, Ali; Nakamura, Takashi; Neff, Thomas; Nilsson, Thomas; Nociforo, Chiara; Nolan, Paul; Nolen, Jerry; Nyman, Goran; Obertelli, Alexandre; Obradors, Diego; Ogloblin, Aleksey; Oi, Makito; Palit, Rudrajyoti; Panin, Valerii; Paradela, Carlos; Paschalis, Stefanos; Pawlowski, Piotr; Petri, Marina; Pietralla, Norbert; Pietras, Ben; Pietri, Stephane; Plag, Ralf; Podolyak, Zsolt; Pollacco, Emanuel; Potlog, Mihai; Datta Pramanik, Ushasi; Prasad, Rajeshwari; Fraile Prieto, Luis Mario; Pucknell, Vic; Galaviz -Redondo, Daniel; Regan, Patrick; Reifarth, Rene; Reinhardt, Tobias; Reiter, Peter; Rejmund, Fanny; Ricciardi, Maria Valentina; Richter, Achim; Rigollet, Catherine; Riisager, Karsten; Rodin, Alexander; Rossi, Dominic; Roussel-Chomaz, Patricia; Gonzalez Rozas, Yago; Rubio, Berta; Roeder, Marko; Saito, Takehiko; Salsac, Marie-Delphine; Rodriguez Sanchez, Jose Luis; Santosh, Chakraborty; Savajols, Herve; Savran, Deniz; Scheit, Heiko; Schindler, Fabia; Schmidt, Karl-Heinz; Schmitt, Christelle; 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