Position Sensitive Detectors in Nuclear Physics

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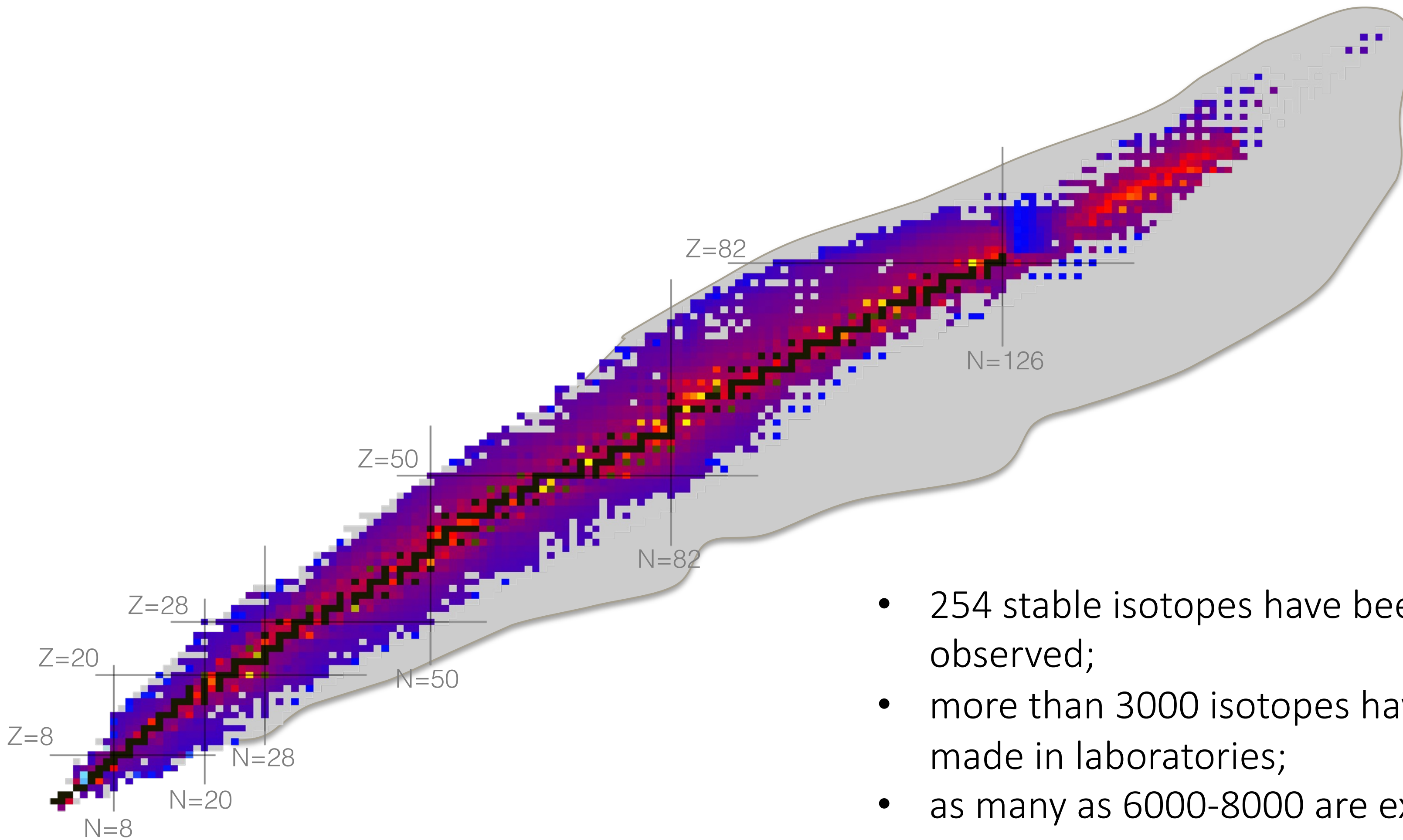
13th International Conference on Position Sensitive Detectors, Oxford, September 3rd-8th 2023

Frontier science: studies of exotic nuclei



- 254 stable isotopes have been observed;
- more than 3000 isotopes have been made in laboratories;
- as many as 6000-8000 are expected to possibly exist

Why do we study exotic nuclei?

Origin of the elements

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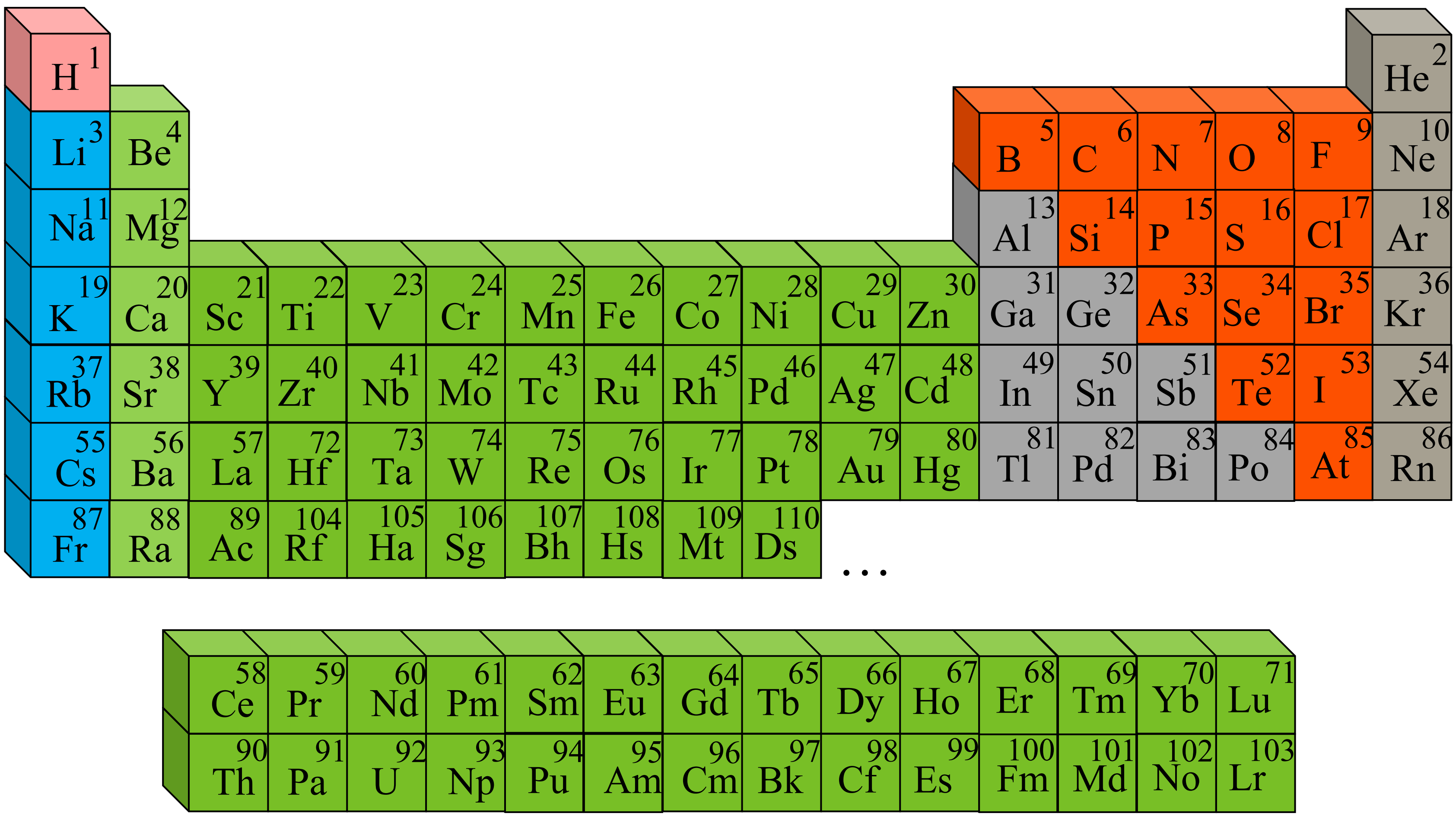
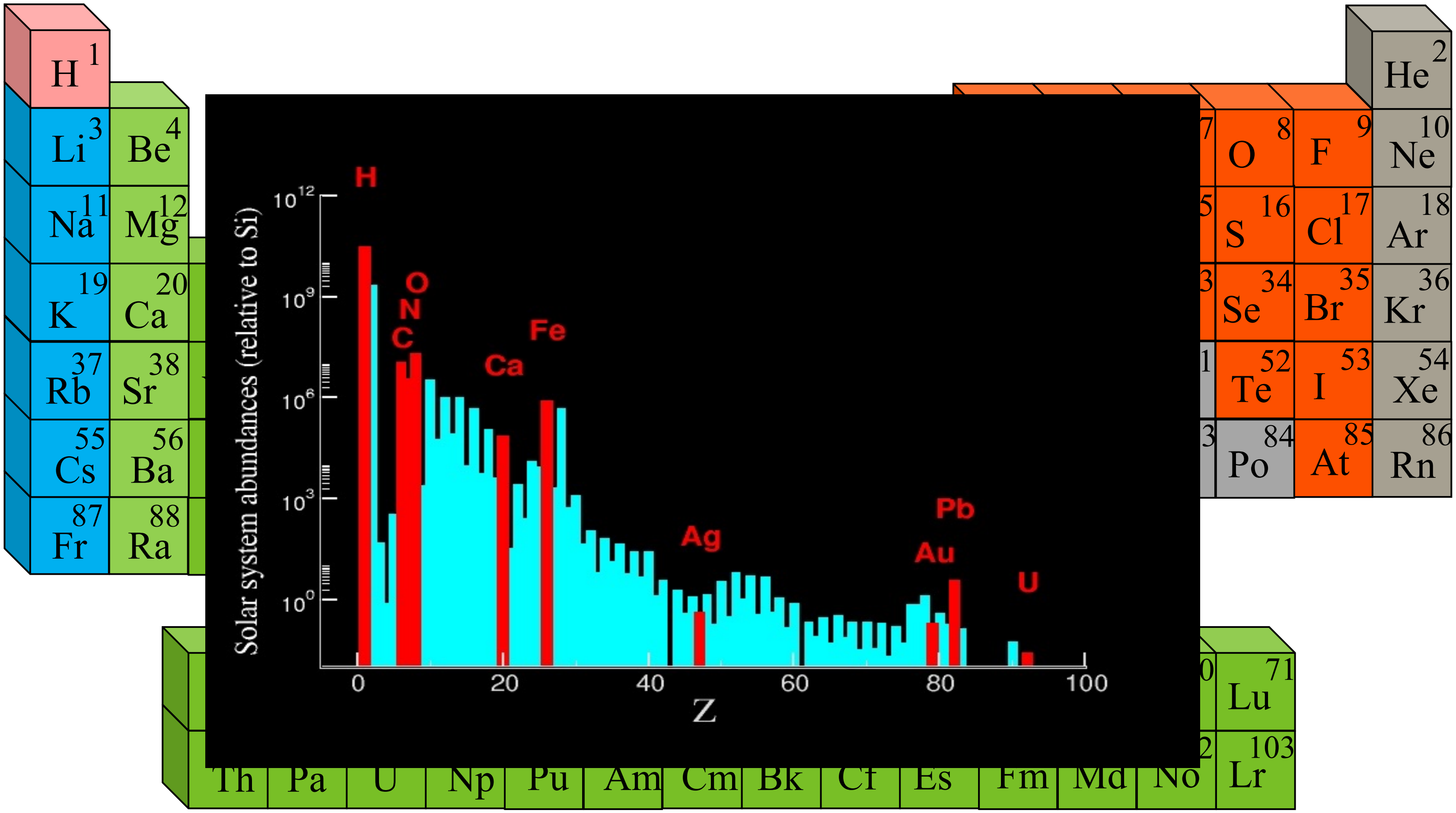


Nucleosynthesis: How are the elements made?

Origin of the elements



Nucleosynthesis: How are the elements made?

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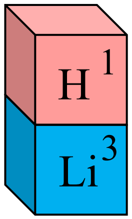

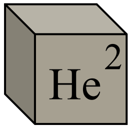

Origin of the elements

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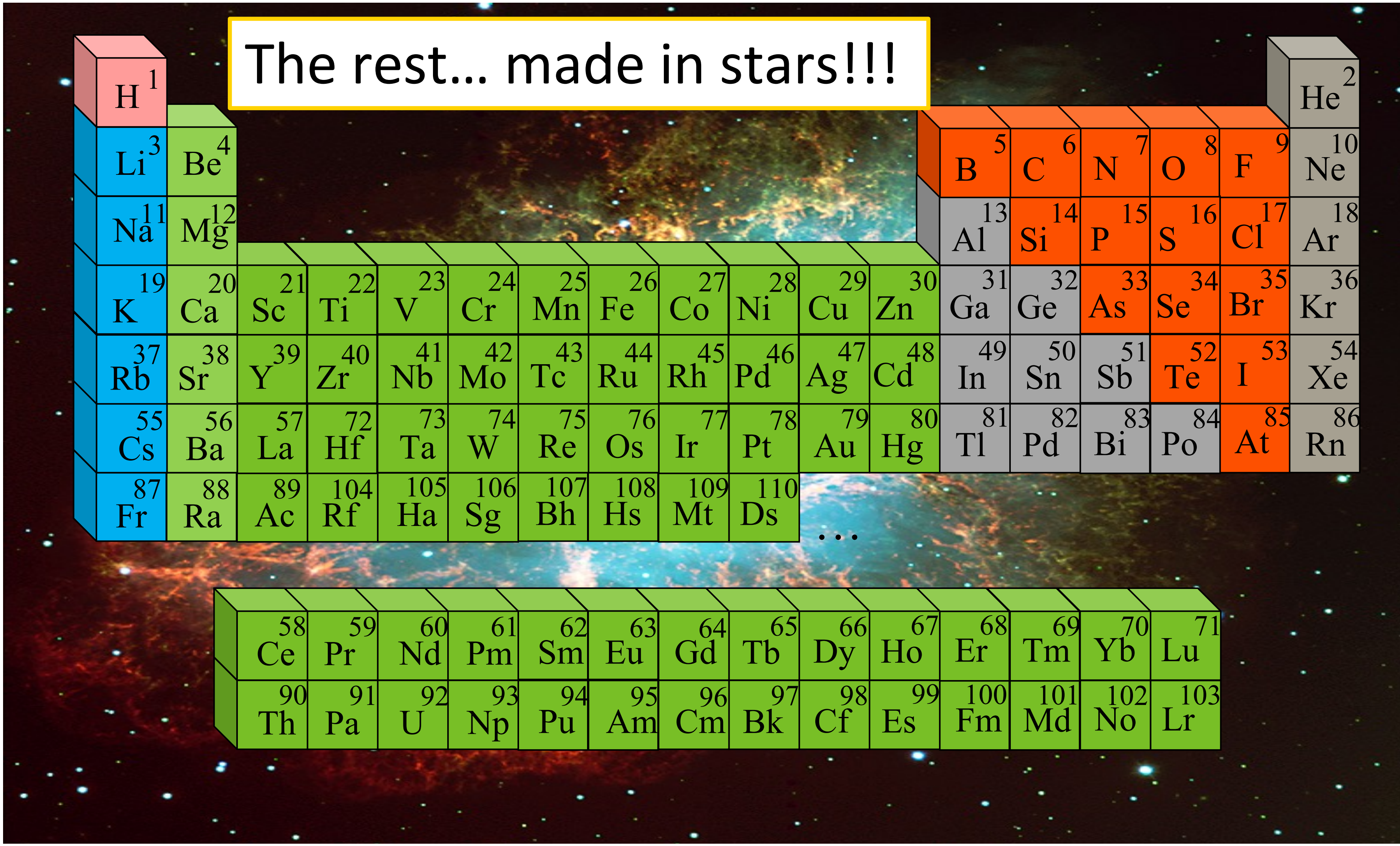
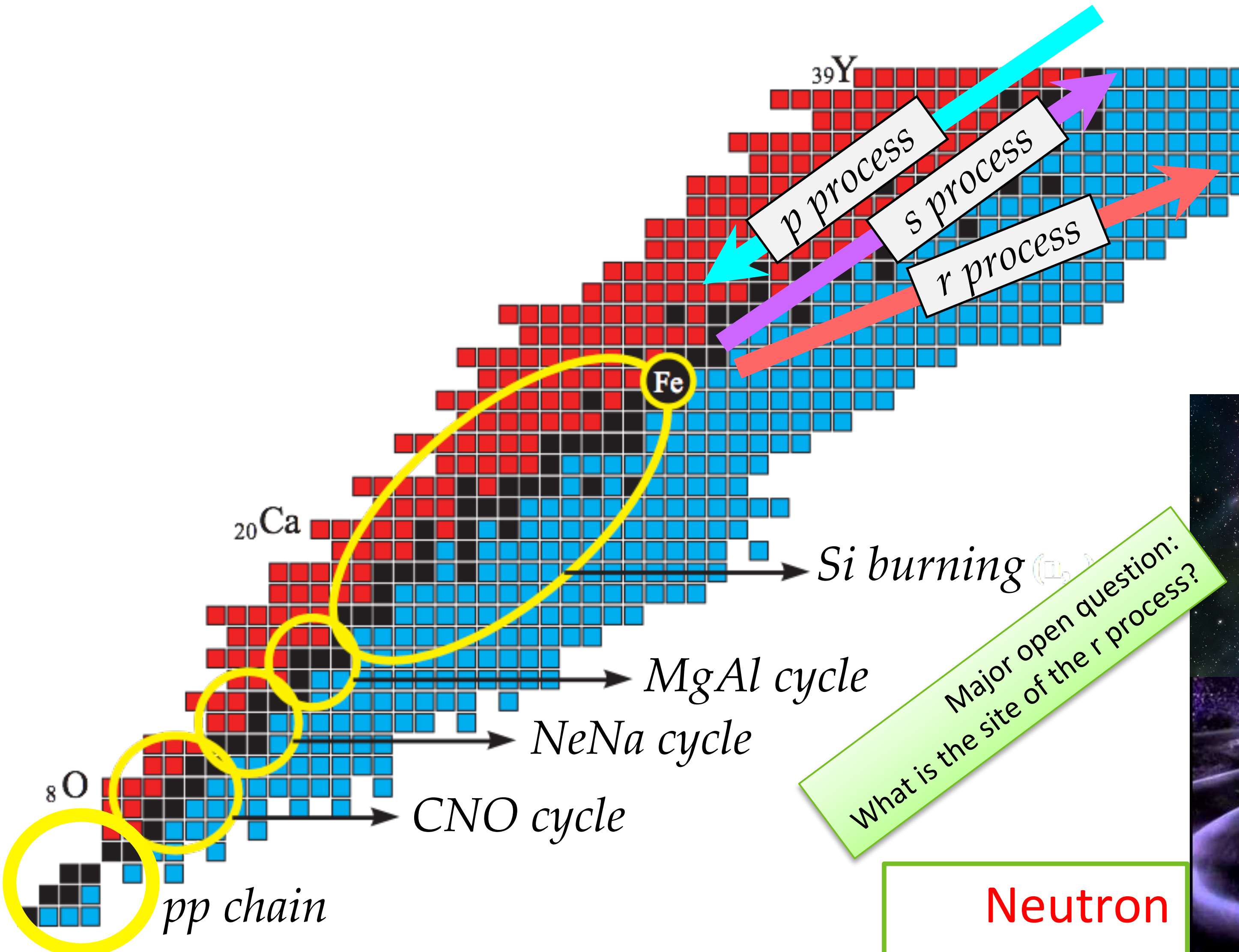


Origin of the elements



masses, neutron capture cross sections, beta decays and fission properties (e.g., barriers and yield distribution) for very n-rich nuclei

Supernova

Major open question:
What is the site of the r process?

Neutron star merger

Can we predict?

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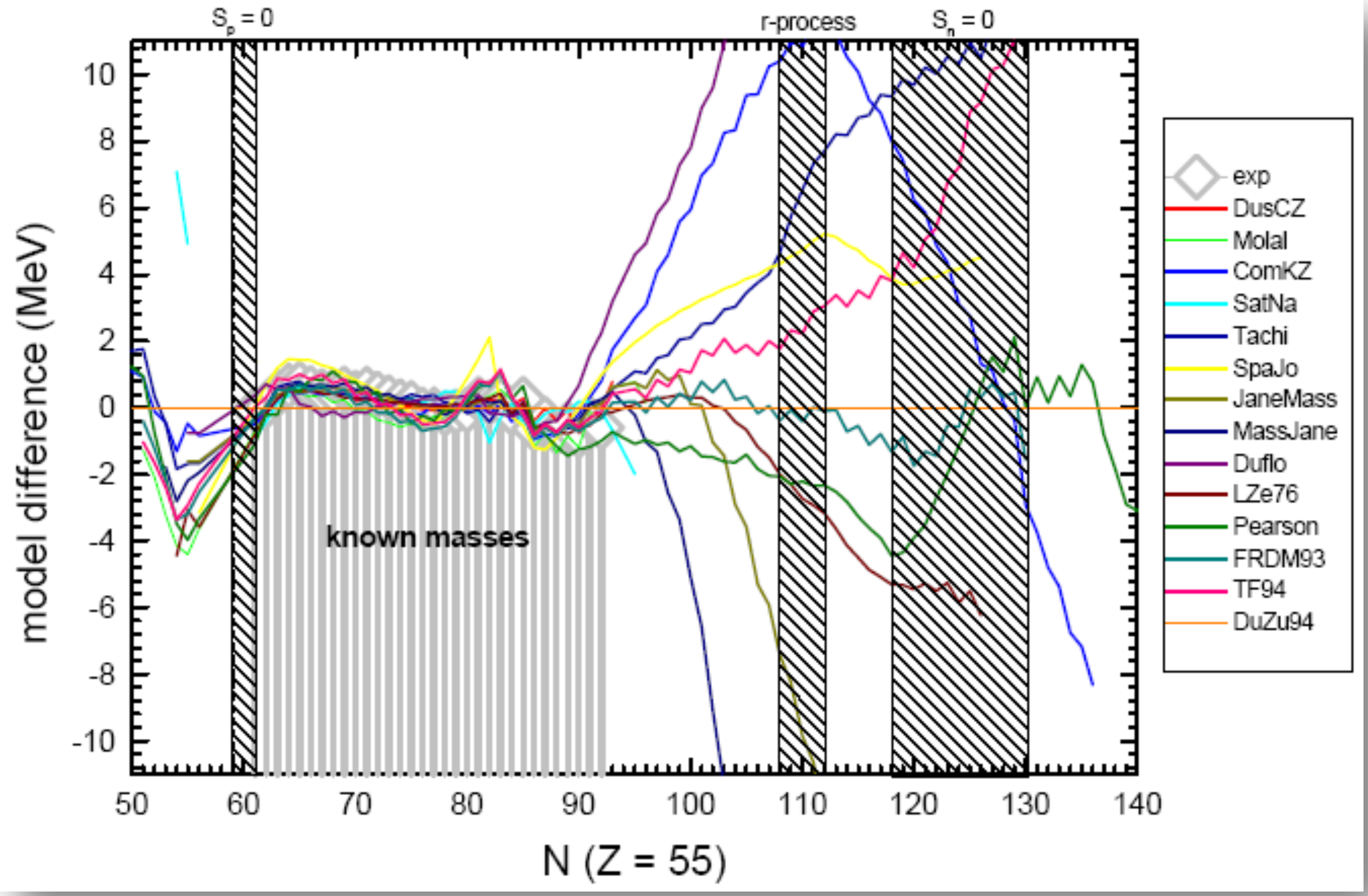
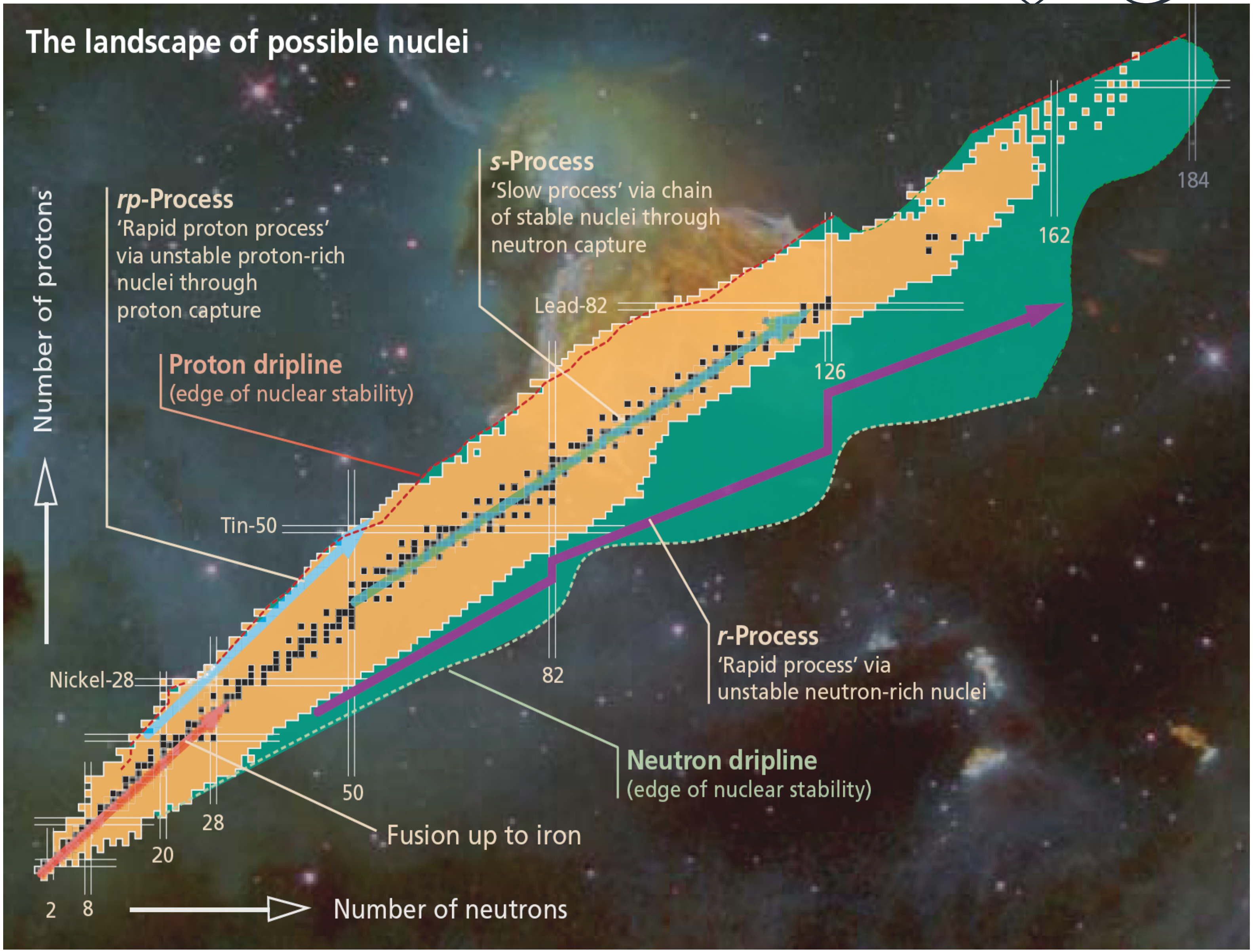
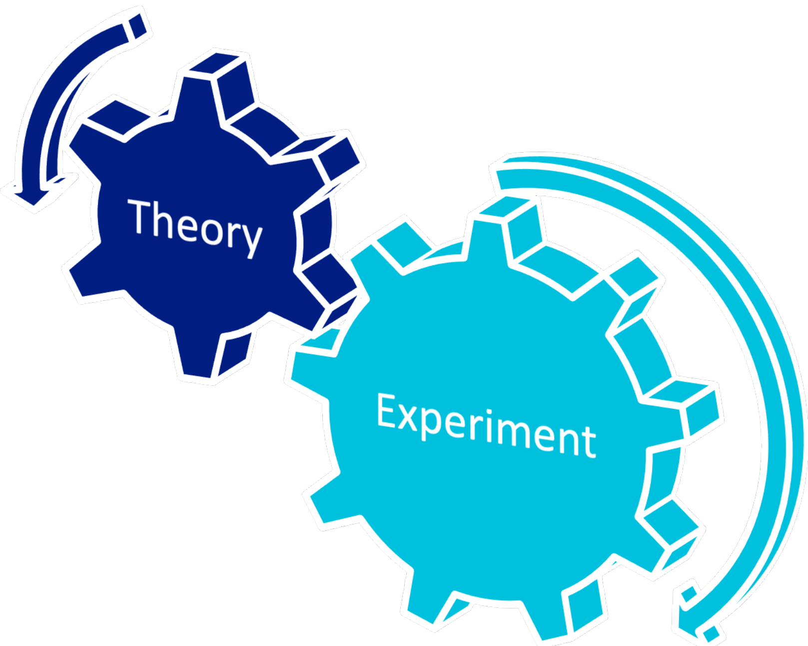


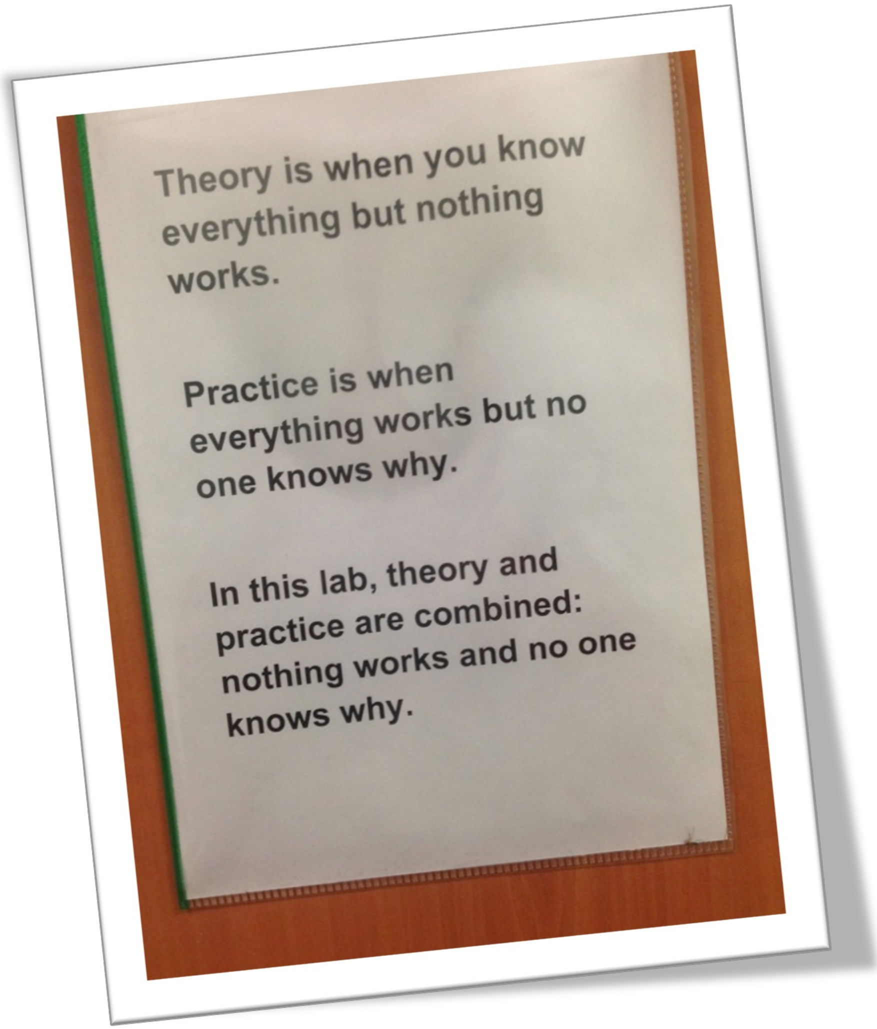
Away from available data, predictions still vary widely.

Can we measure?

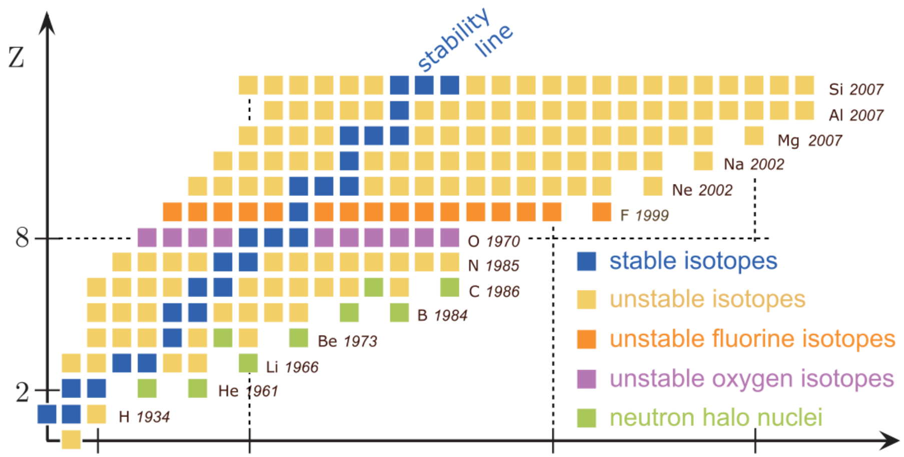


The synergy between theory and experiment





Advance our understanding of **nuclear structure:** oxygen "anomaly"



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First observation of ^{28}O

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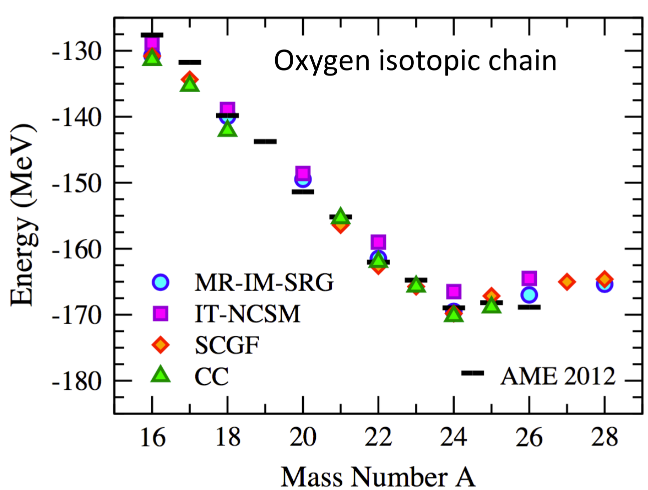
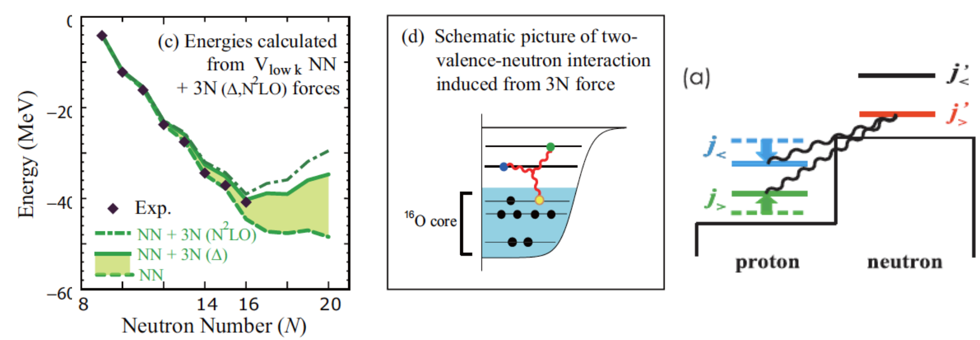
Y. Kondo[1,2], N. L. Achouri[3], H. Al Falou[4,5], L. Atar[6], T. Aumann[6,7,8], H. Baba[2], K. Boretzky[7], C. Caesar[6,7], D. Calvet[9], H. Chae[10], N. Chiga[2], A. Corsi[9], F. Delaunay[3], A. Delbart[9], Q. Deshayes[3], Zs. Dombrádi[11], C. A. Douma[12], A. Ekström[13], Z. Elekes[11], C. Forssén[13], I. Gašparić[2,6,14], J.-M. Gheller[9], J. Gibelin[3], A. Gillibert[9], G. Hagen[15,16], M. N. Harakeh[7,12], A. Hirayama[1], C. R. Hoffman[17], M. Holl[6,7], A. Horvat[7], Á. Horváth[18], J. W. Hwang[19,20], T. Isobe[2], W. G. Jiang[13], J. Kahlbow[2,6], N. Kalantar-Nayestanaki[12], S. Kawase[21], S. Kim[19,20], K. Kisamori[2], T. Kobayashi[22], D. Körper[7], S. Koyama[23], I. Kuti[11], V. Lapoux[9], S. Lindberg[13], F. M. Marqués[3], S. Masuoka[24], J. Mayer[25], K. Miki[22], T. Murakami[26], M. Najafi[12], T. Nakamura[1,2], K. Nakano[21], N. Nakatsuka[26], T. Nilsson[13], A. Obertelli[9], K. Ogata[27,28,29], F. de Oliveira Santos[30], N. A. Orr[3], H. Otsu[2], T. Otsuka[2,23], T. Ozaki[1], V. Panin[2], T. Papenbrock[15,16], S. Paschalis[6], A. Revel[3,30], D. Rossi[6], A. T. Saito[1], T. Y. Saito[23], M. Sasano[2], H. Sato[2], Y. Satou[20], H. Scheit[6], F. Schindler[6], P. Schrock[24], M. Shikata[1], N. Shimizu[31], Y. Shimizu[2], H. Simon[7], D. Sohler[11], O. Sorlin[30], L. Stuhl[2,19], Z. H. Sun[15,16], S. Takeuchi[1], M. Tanaka[32], M. Thoennessen[33], H. Törnqvist[6,7], Y. Togano[1,34], T. Tomai[1], J. Tscheuschner[6], J. Tsubota[1], N. Tsunoda[24], T. Uesaka[2], Y. Utsuno[35], I. Vernon[36], H. Wang[2], Z. Yang[2], M. Yasuda[1], K. Yoneda[2] & S. Yoshida[37]





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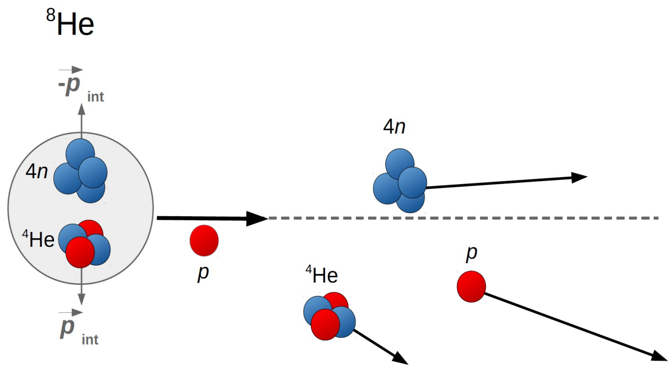
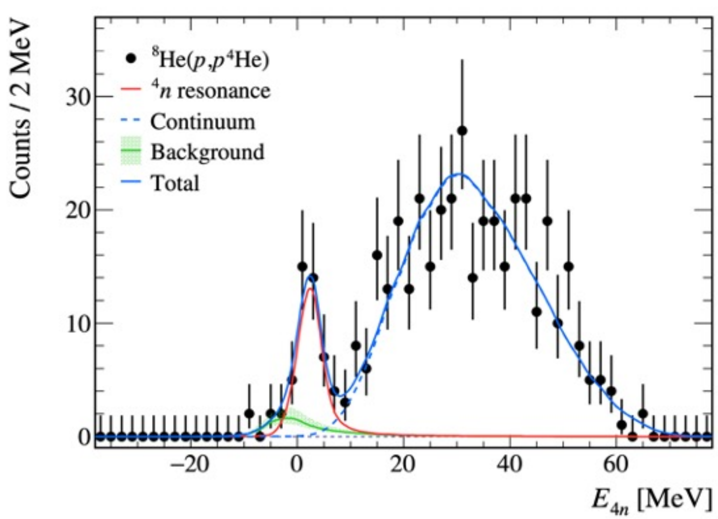
Advance our understanding of **nuclear structure:** correlated four-neutron system

A 60 year-long quest

$^{8}He(p,p\alpha)^{4}n$ Quasi-free reaction to probe the four-neutron system





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Article

Observation of a correlated free four-neutron system

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Check for updates

M. Duer[1✉], T. Aumann[1,2,3], R. Gernhäuser[4], V. Panin[2,5], S. Paschalis[1,6], D. M. Rossi[1], N. L. Achouri[7], D. Ahn[5,16], H. Baba[5], C. A. Bertulani[8], M. Böhmer[4], K. Boretzky[2], C. Caesar[1,2,5], N. Chiga[5], A. Corsi[9], D. Cortina-Gil[10], C. A. Douma[11], F. Dufter[4], Z. Elekes[12], J. Feng[13], B. Fernández-Domínguez[10], U. Forsberg[6], N. Fukuda[5], I. Gasparic[1,5,14], Z. Ge[5], J. M. Gheller[9], J. Gibelin[7], A. Gillibert[9], K. I. Hahn[15,16], Z. Halász[12], M. N. Harakeh[11], A. Hirayama[17], M. Holl[1], N. Inabe[5], T. Isobe[5], J. Kahlbow[1], N. Kalantar-Nayestanaki[11], D. Kim[16], S. Kim[1,16], T. Kobayashi[18], Y. Kondo[17], D. Körper[2], P. Koseoglou[1], Y. Kubota[5], I. Kuti[12], P. J. Li[19], C. Lehr[1], S. Lindberg[20], Y. Liu[13], F. M. Marqués[7], S. Masuoka[21], M. Matsumoto[17], J. Mayer[22], K. Miki[1,18], B. Monteagudo[7], T. Nakamura[17], T. Nilsson[20], A. Obertelli[1,9], N. A. Orr[7], H. Otsu[5], S. Y. Park[15,16], M. Parlog[7], P. M. Potlog[23], S. Reichert[4], A. Revel[7,9,24], A. T. Saito[17], M. Sasano[5], H. Scheit[1], F. Schindler[1], S. Shimoura[21], H. Simon[2], L. Stuhl[16,21], H. Suzuki[5], D. Symochko[1], H. Takeda[5], J. Tanaka[1,5], Y. Togano[17], T. Tomai[17], H. T. Törnqvist[1,2], J. Tscheuschner[1], T. Uesaka[5], V. Wagner[1], H. Yamada[17], B. Yang[13], L. Yang[21], Z. H. Yang[5], M. Yasuda[17], K. Yoneda[5], L. Zanetti[1], J. Zenihiro[5,25] & M. V. Zhukov[20]

A near-threshold resonance-like structure:

$E_r = 2.37 \pm 0.38(\text{stat.}) \pm 0.44(\text{sys.})$ MeV

$\Gamma = 1.75 \pm 0.22(\text{stat.}) \pm 0.30(\text{sys.})$ MeV

Challenges for experiments with exotic nuclei

- The observables we're interested in for stable nuclei are the same ones we're interested in for exotic systems (e.g. half-life, mass, decay modes, electric/magnetic moments, cross-sections, momentum distributions, transition probabilities, ….
- Most techniques translate as well… but radioactive nuclei add some experimental challenges.

<u>Biggest challenges:</u>

- Half-life → how do you study an isotope that lives for a fraction of a second (ms timescale for beta-unstable nuclei)
- Production → how do you study nuclei with low yields?

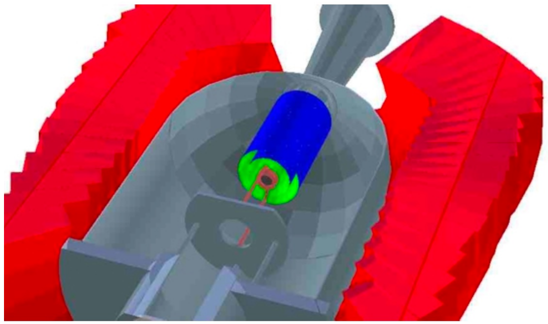
We need new tools and techniques

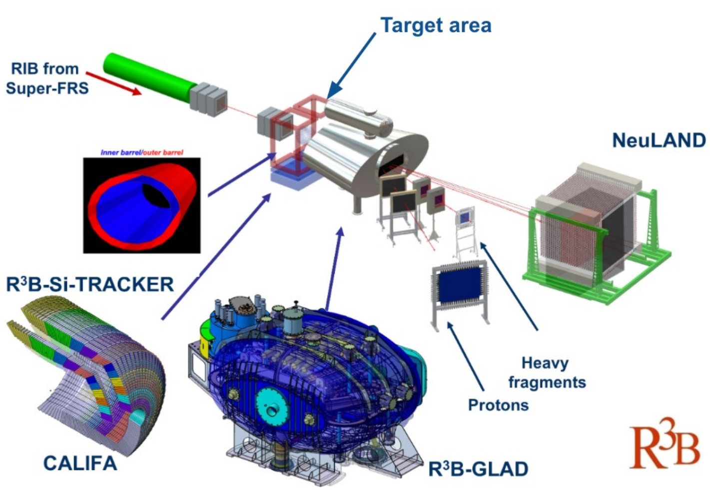
We need to upgrade our armoury

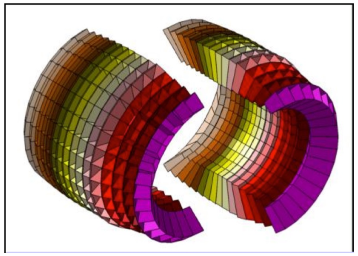
State-of-the-art tools and techniques

Light charge-particle detection

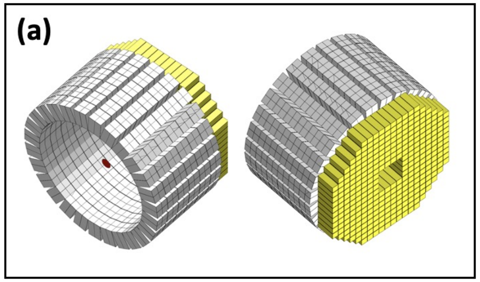
Gamma-ray detection



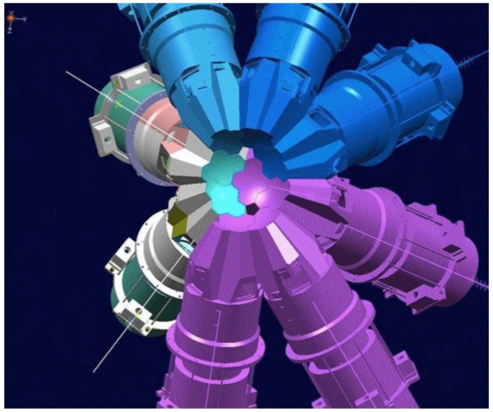




State of the art
Scintillator arrays



State of the art
semiconductor arrays



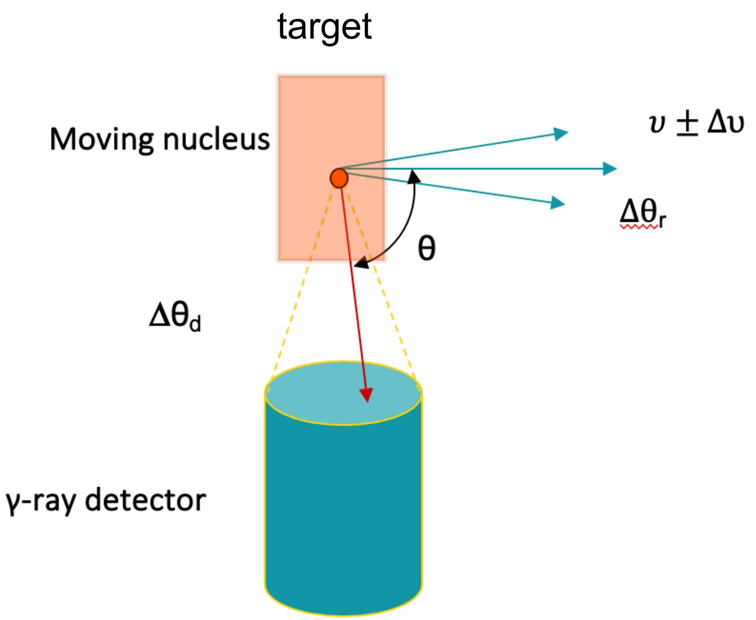
Gamma-ray spectroscopy

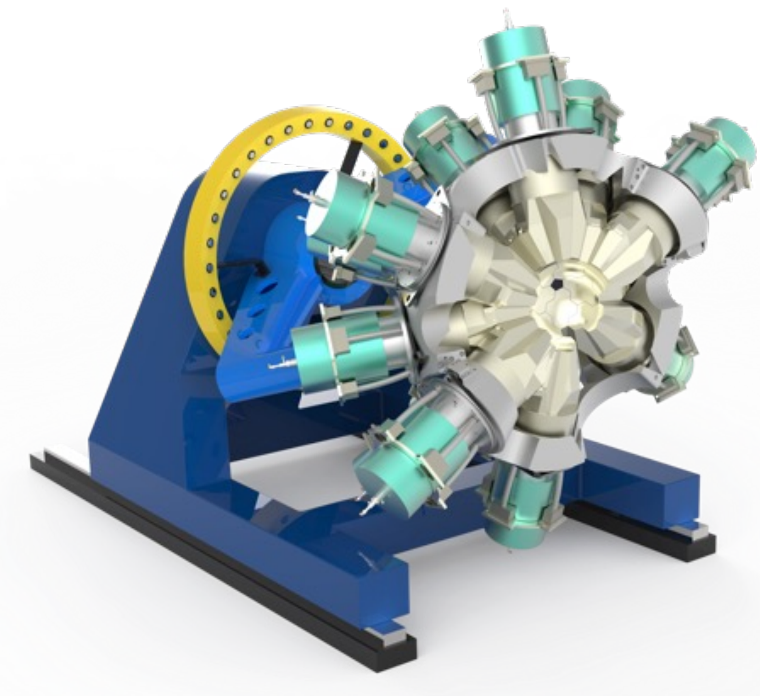
has been one of the most sensitive probes of nuclear structure over the past decades and continues to play a major role in our current understanding of the structure of atomic nuclei

In **fast-beam experiments** the measurement is hindered by the high beam energies and by the necessary use of thick targets to increase the yield

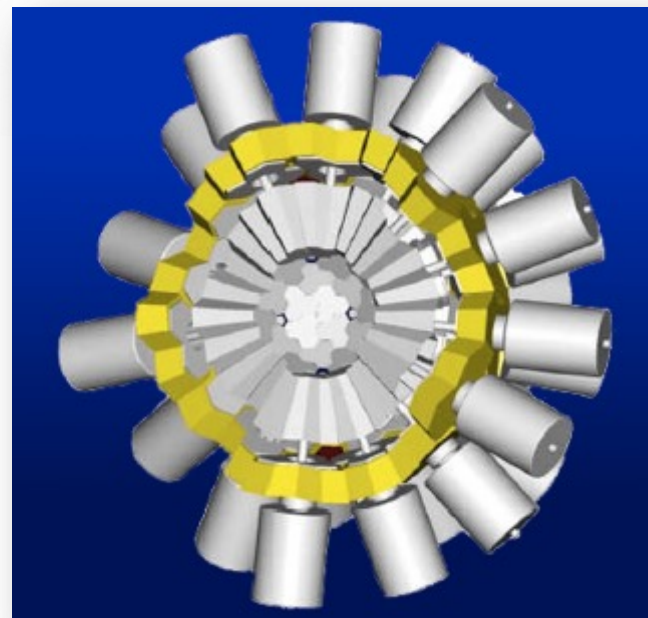
Broadening of detected gamma-ray energy:

- velocity change in target (unknown interaction depth), momentum spread
    - E.g. thin target or particle tracking for reaction vertex reconstruction
- $\Delta\theta$ due to opening angle detector and trajectory of nucleus
    - E.g. position resolution of gamma-ray detector and spectrometer/detector





GRETA



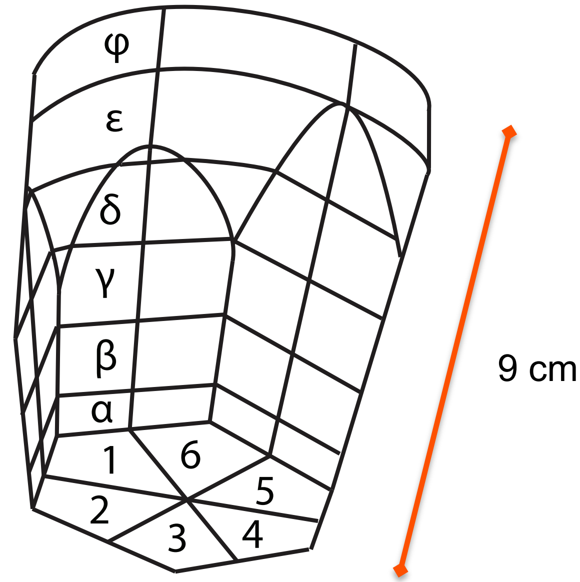
AGATA
ADVANCED GAMMA TRACKING ARRAY

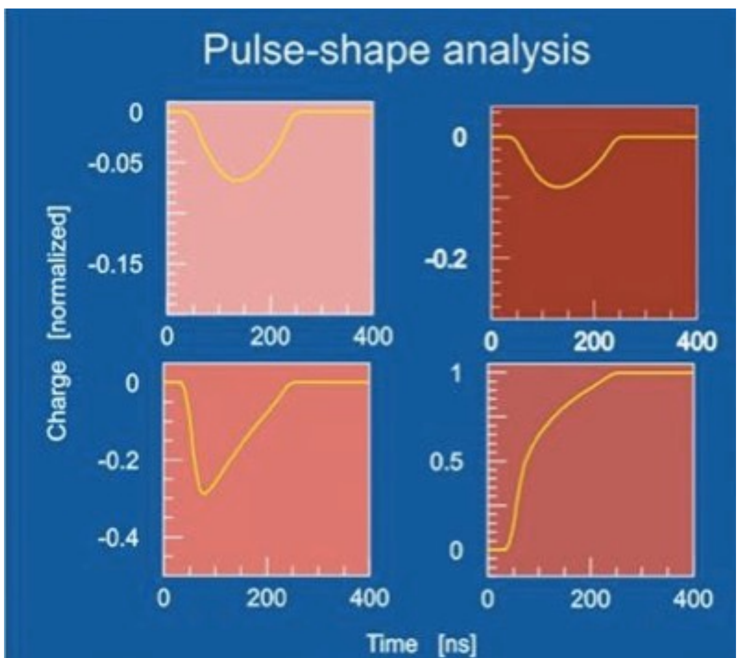
ADVANCED GAMMA TRACKING ARRAY

Gamma-ray tracking: Principle of operation

A 3D position sensitive HPGe detector
- Electrically segmented
- Pulse shape analysis

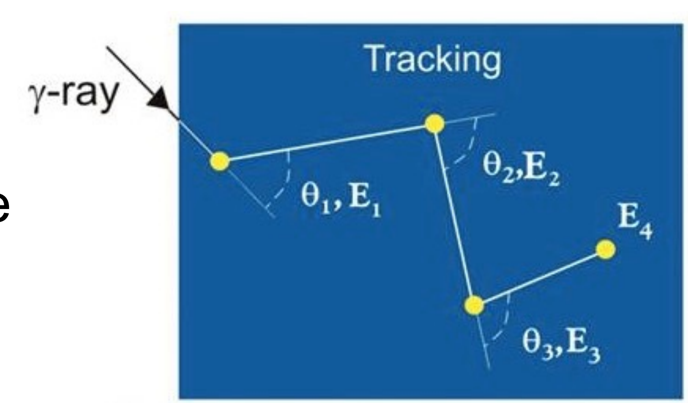
of position sensitive signals

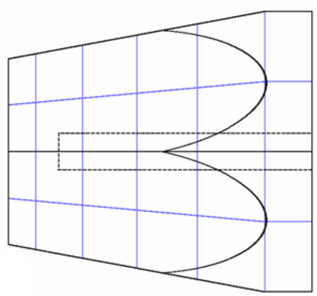


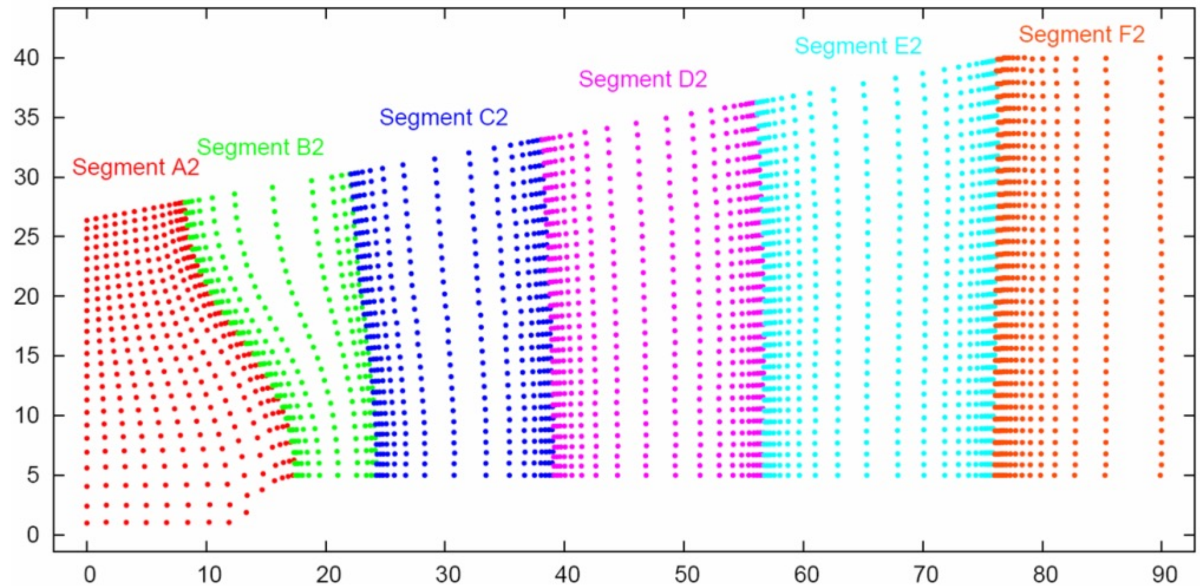


Determine interaction points

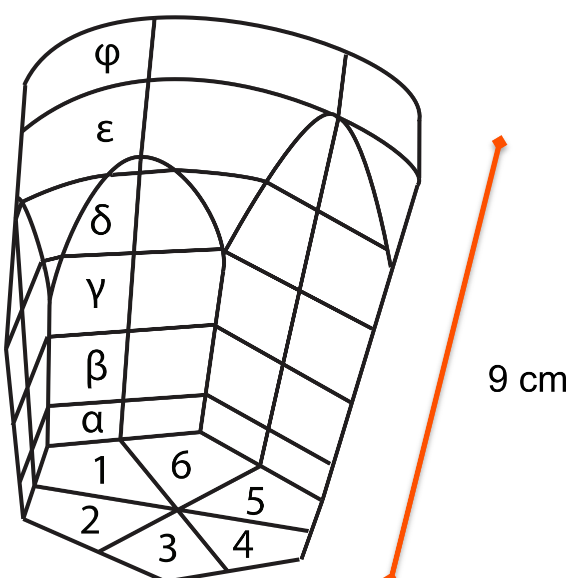
Determine scattering sequence



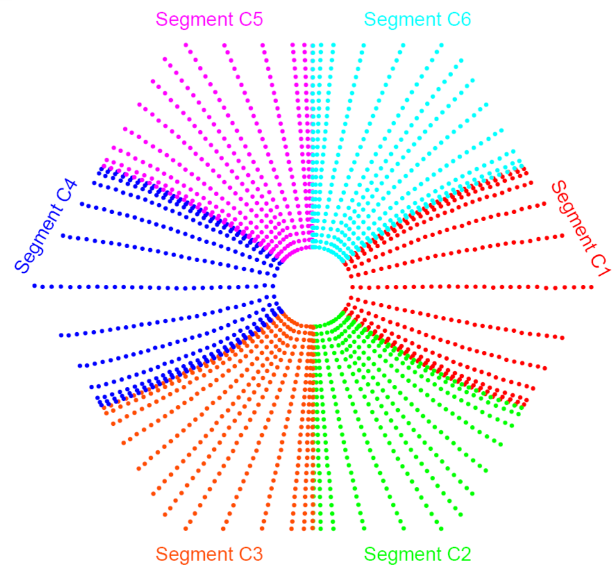




Segment A2
Segment B2
Segment C2
Segment D2
Segment E2
Segment F2
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60
70
80
90

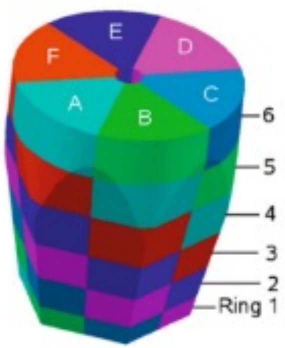


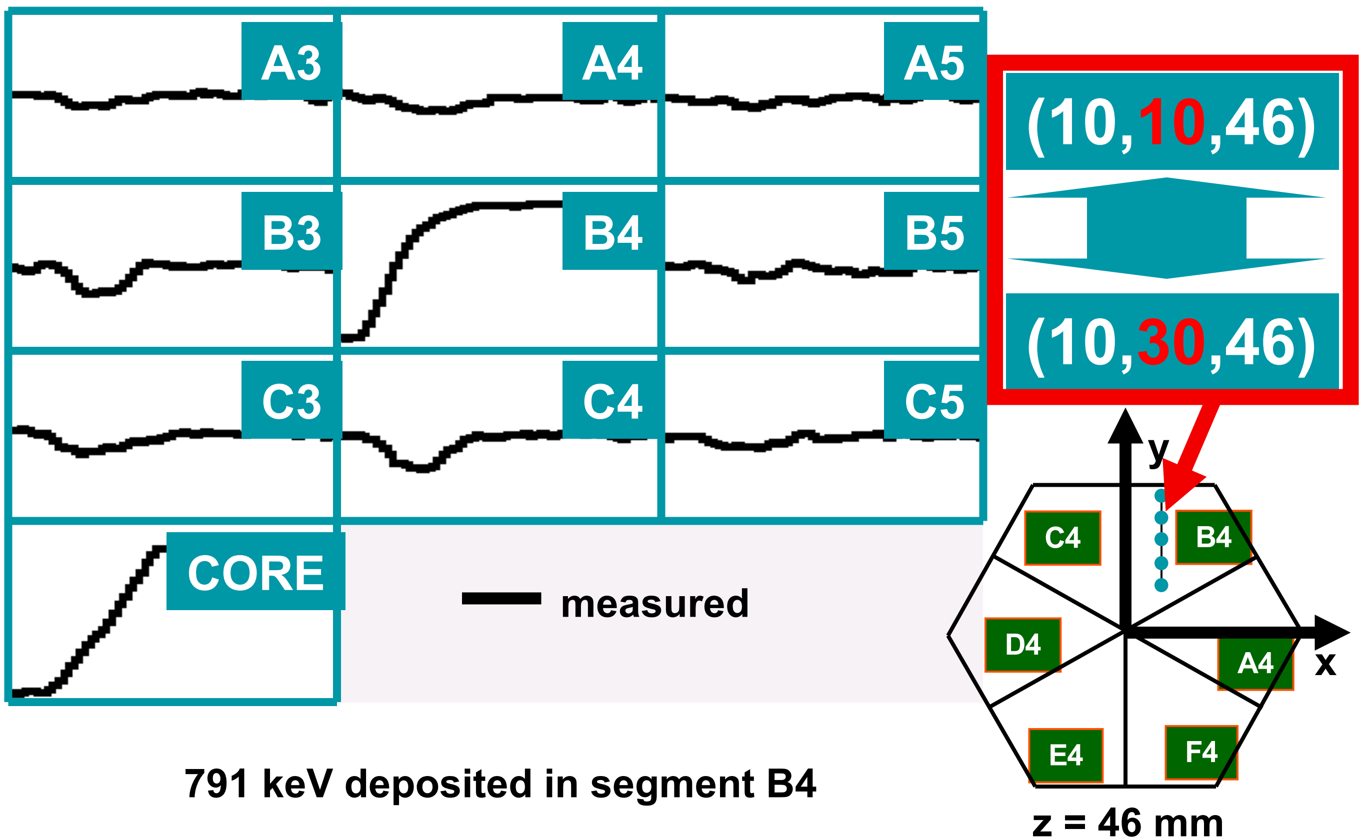
φ
ε
δ
γ
β
α
1
6
5
2
3
4
9 cm



Segment C5
Segment C6
Segment C4
Segment C1
Segment C3
Segment C2

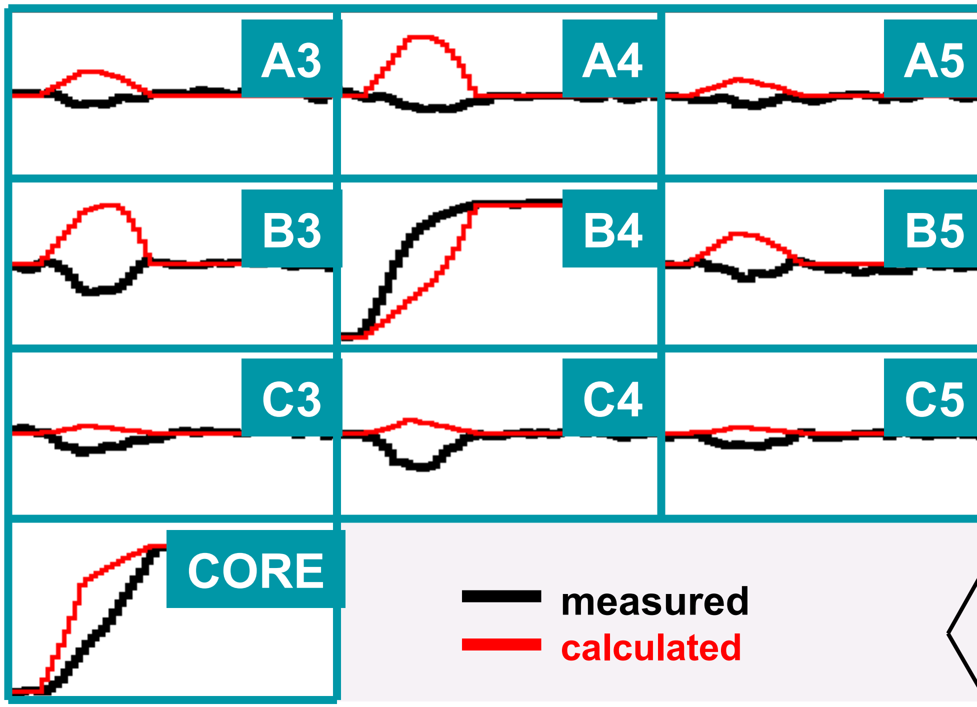
Pulse shape analysis concept





791 keV deposited in segment B4

Pulse shape analysis concept



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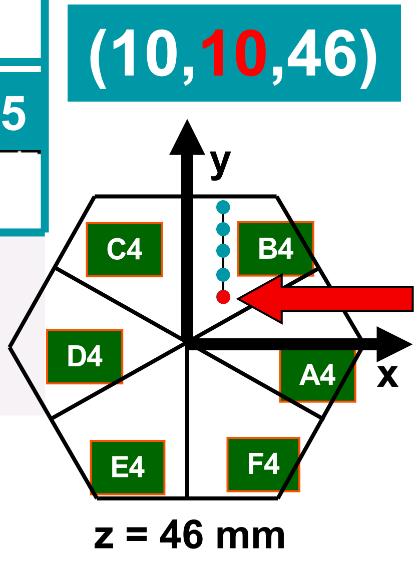

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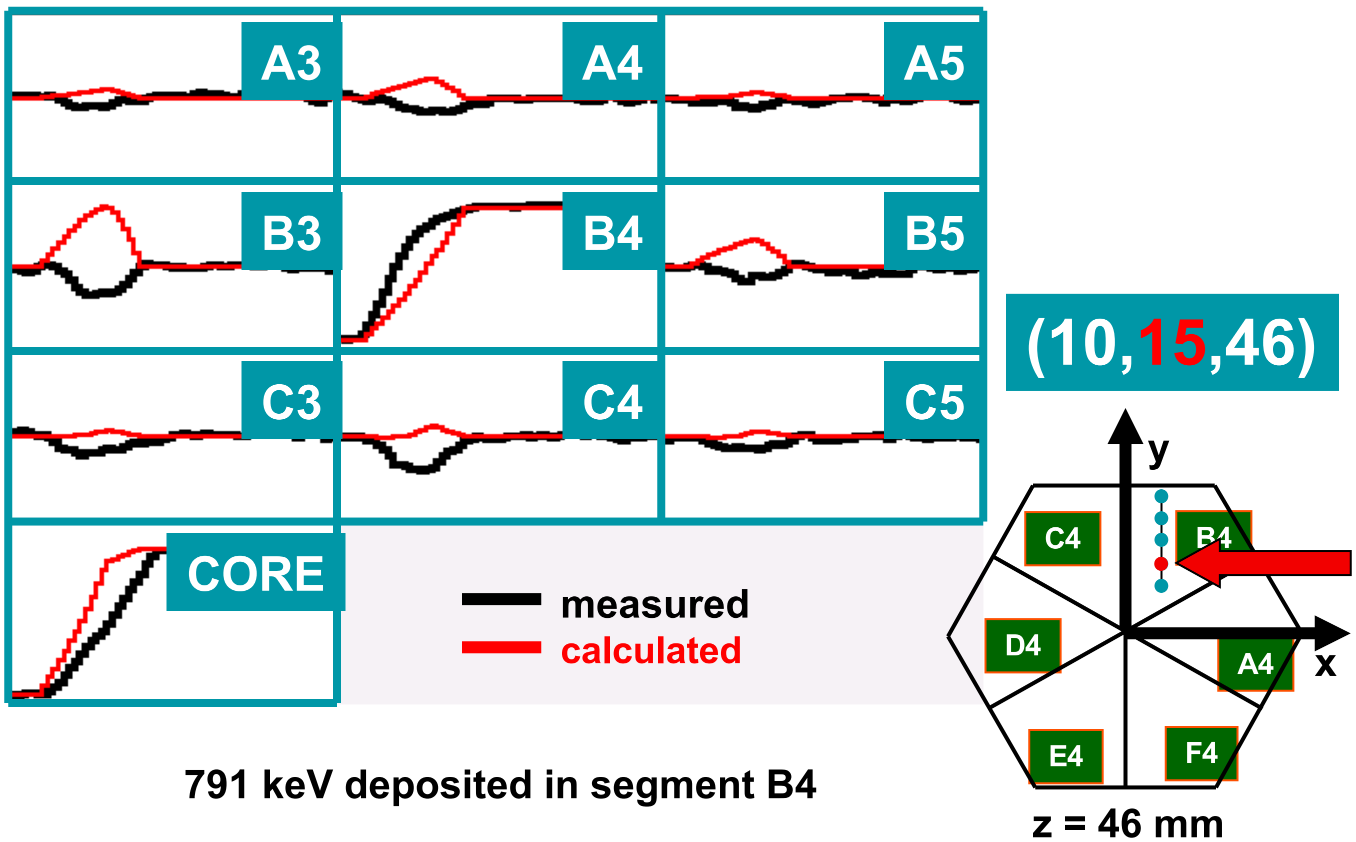

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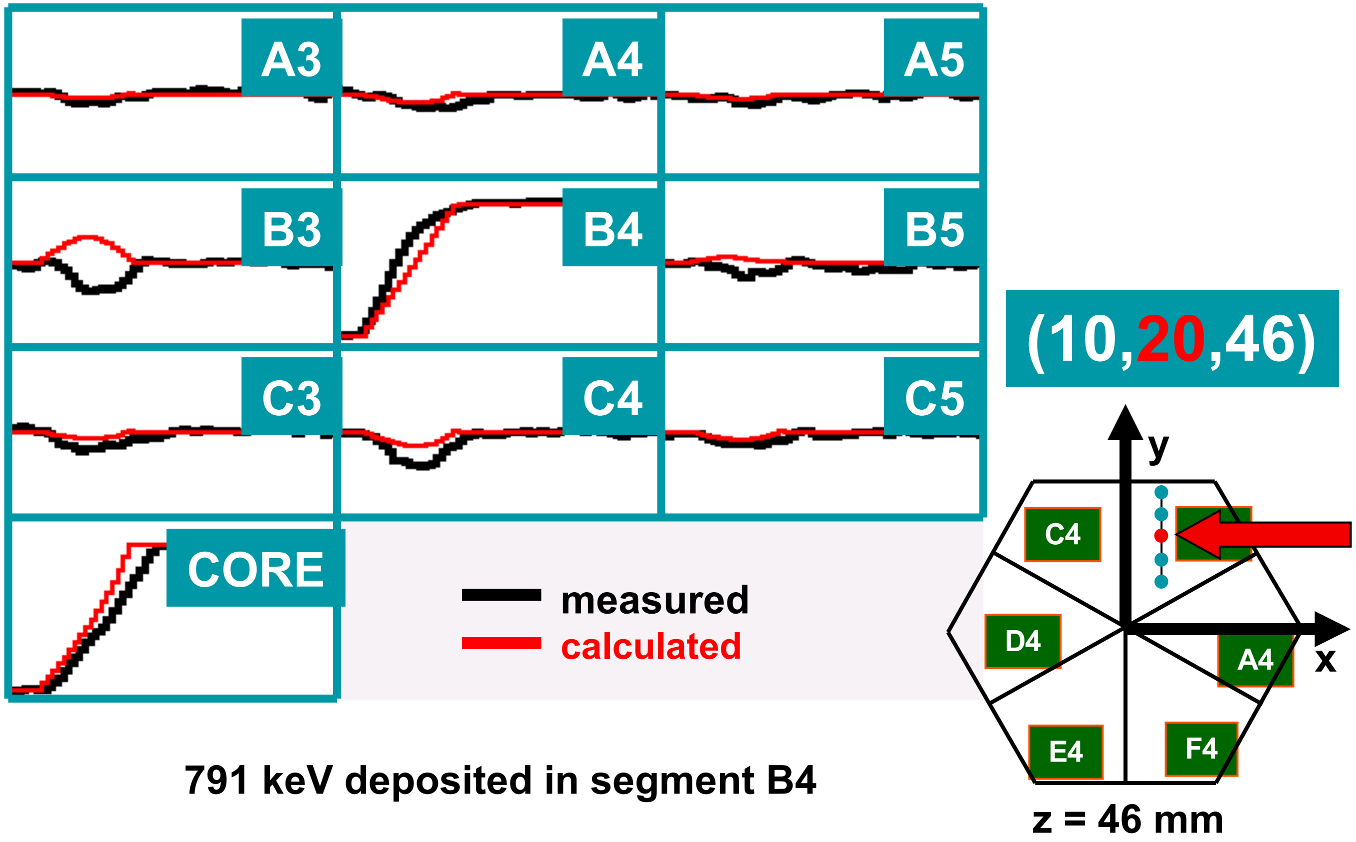

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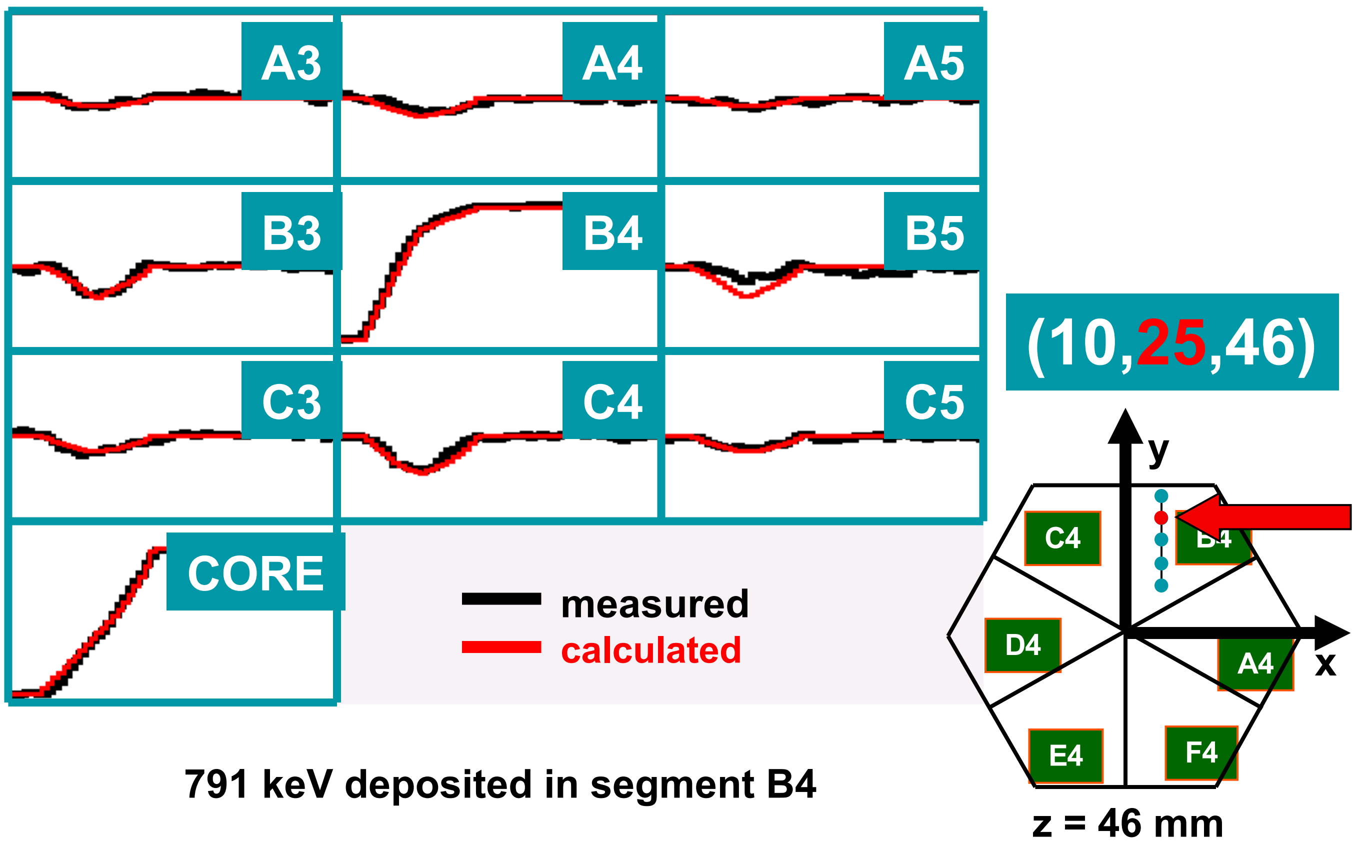

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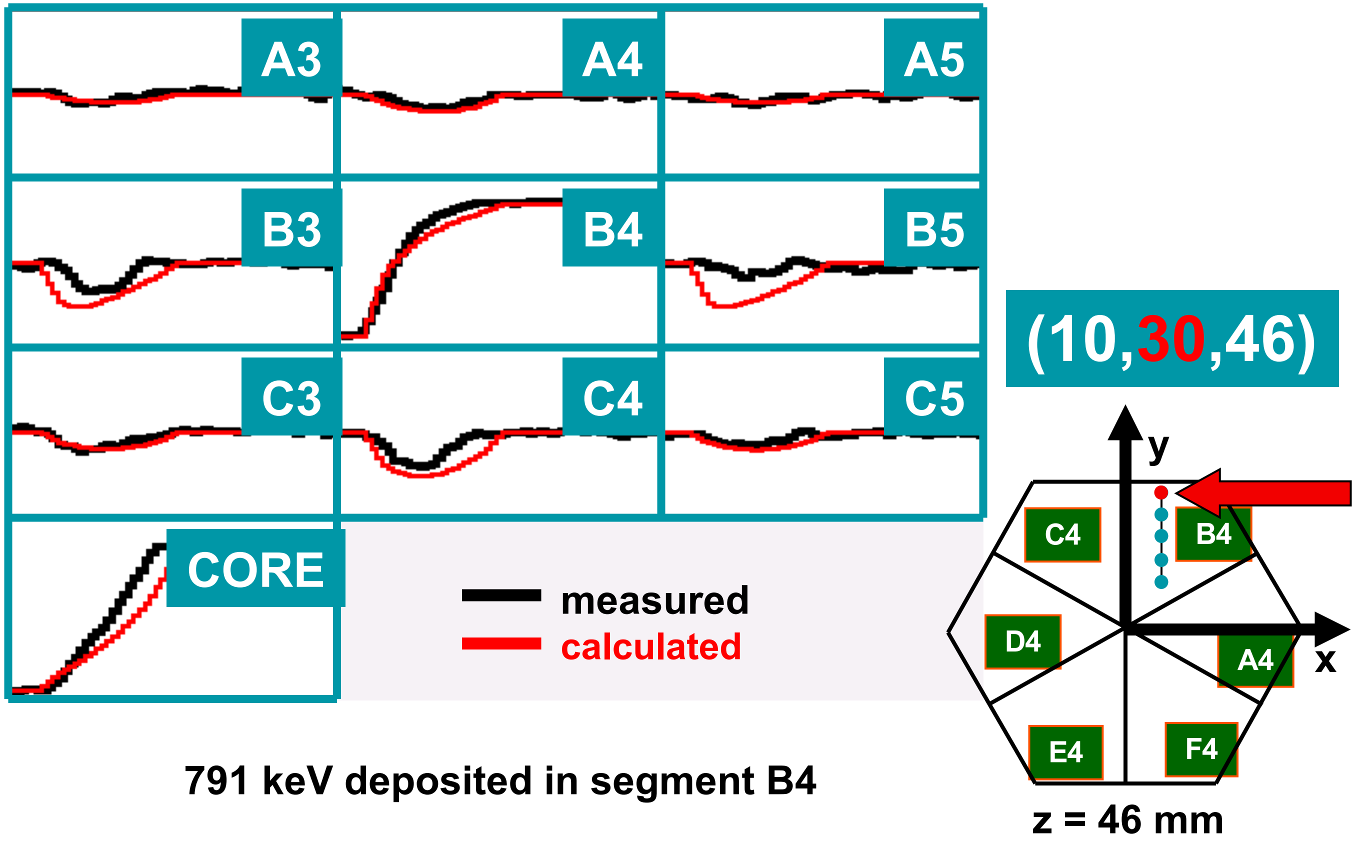

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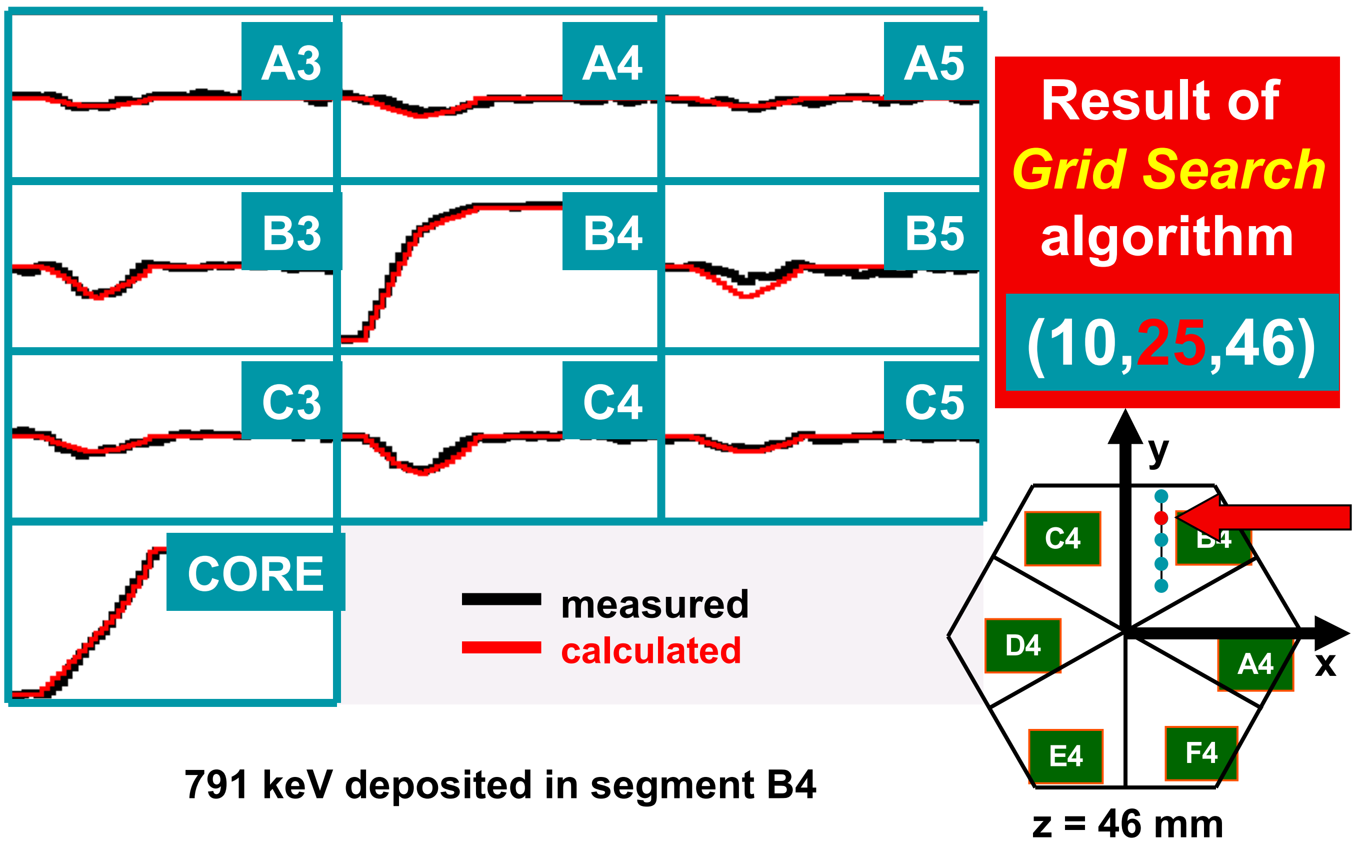
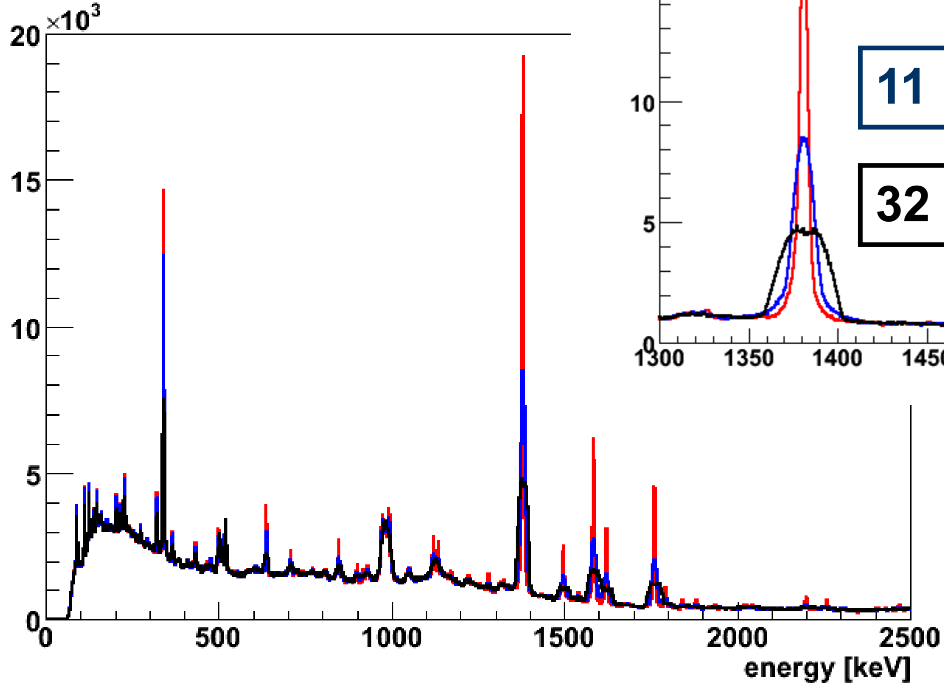
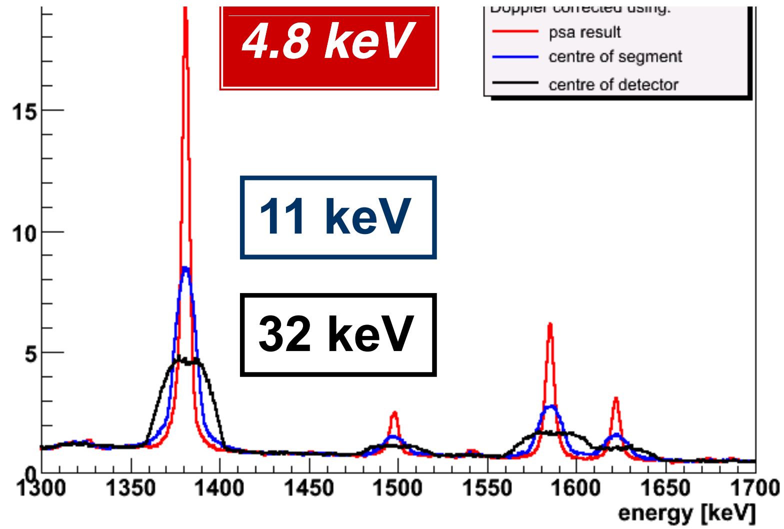


791 keV deposited in segment B4

Doppler correction using position information





Full statistics used

PSA algorithm:

Grid Search

From F. Recchia, PSD8 conference

Current challenges

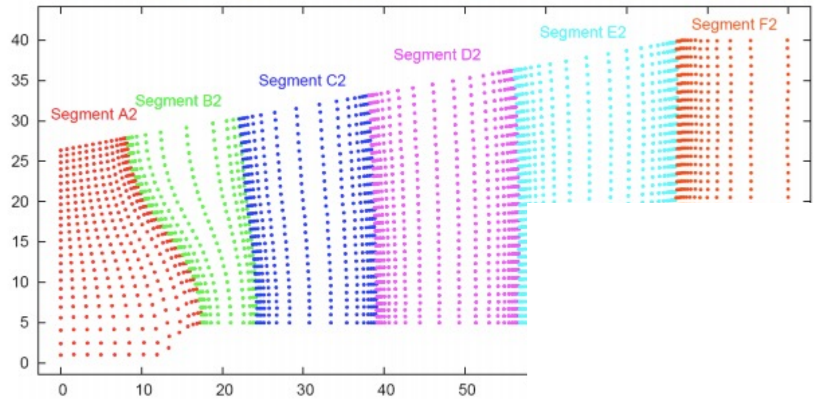
signal basis generation

Experimental (scanning)

- long acquisition times
- different conditions between scanning and experiment, e.g. noise, radiation damage
- mechanical alignment

Analytical (calculated)

- intrinsic space-charge density
- the electron/hole mobility
- crystal temperature and
- crystal orientation
- passivated and contact thickness
- shape of charge cloud



Self-calibration concept

- Generate signal basis in experimental way

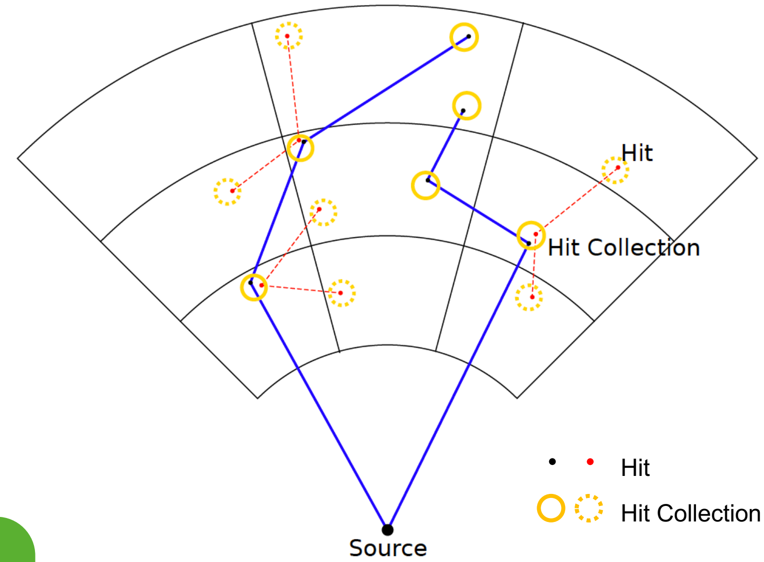
S. Heil, S. Paschalis, and M. Petri,
Eur. Phys. J. A (2018) **54**: 172

Group interaction points from different gamma-rays into hit collections

Use Compton formula to order interaction points

Define tracks between interaction points that also link the hit collections with each other

Optimise coordinates of hit collection using the tracks that link their constituent points and Compton formula



- Produce pulse shape basis for all detectors simultaneously
- Strong gamma source illuminate the whole array
- Compton formula optimize scattering events

Self-calibration concept

- Generate signal basis in experimental way

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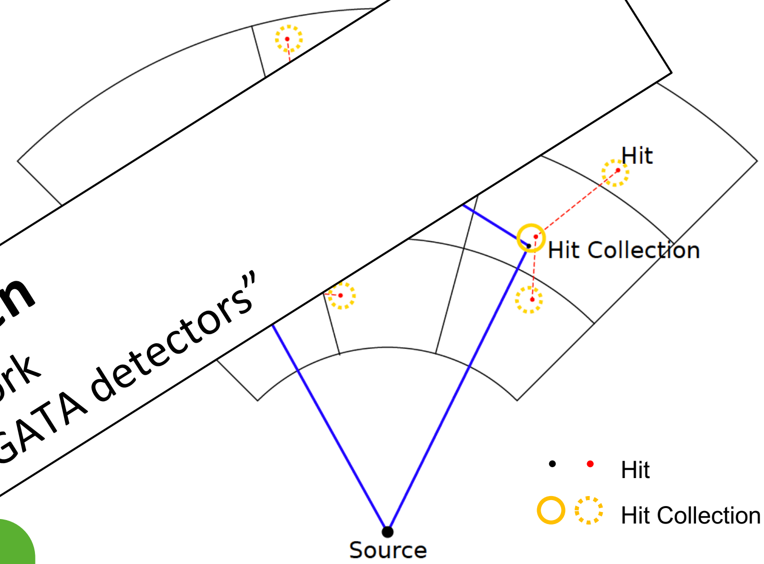
Sidong Chen
PDRA at York
“Self-calibration of AGATA detectors”



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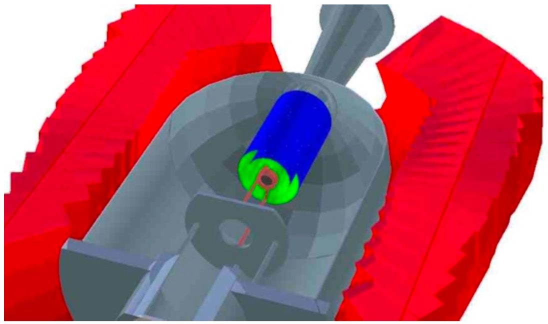
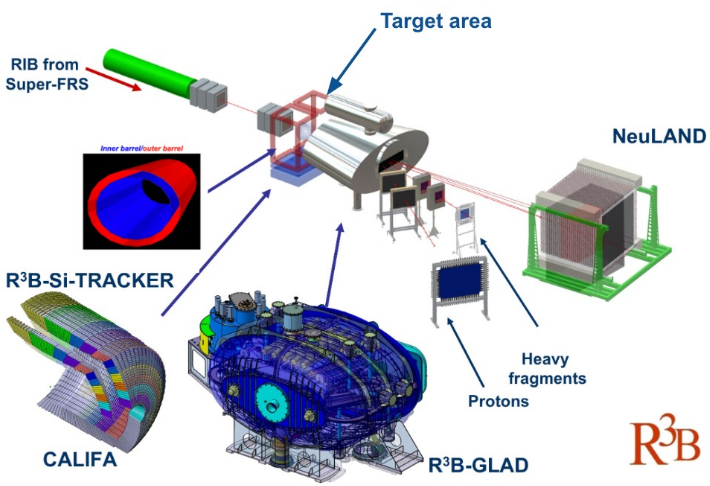
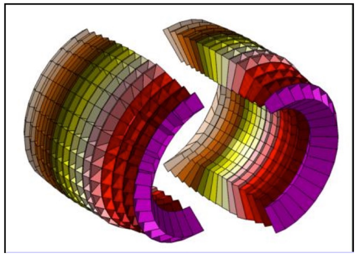
State-of-the-art tools and techniques

Light charge-particle detection

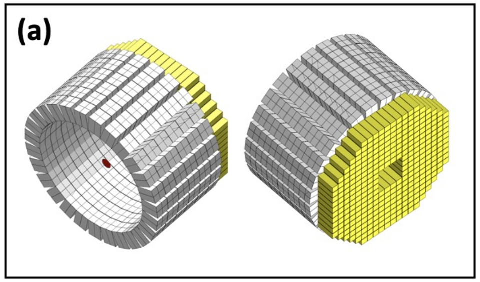




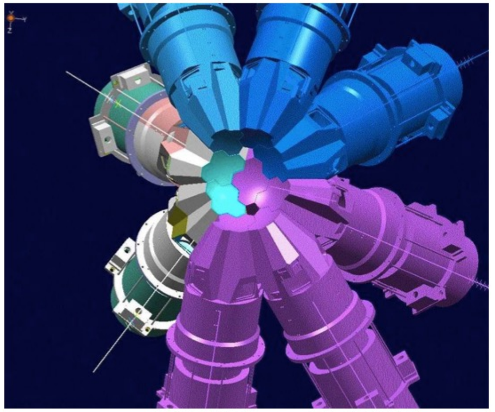
Gamma-ray detection



State of the art Scintillator arrays



State of the art semiconductor arrays



γRIBF-UK:
Scintillator-based high-resolution γ-ray spectrometer at RIBF

PI: Marina Petri

Partners: UYork, DL, UWS, NPL

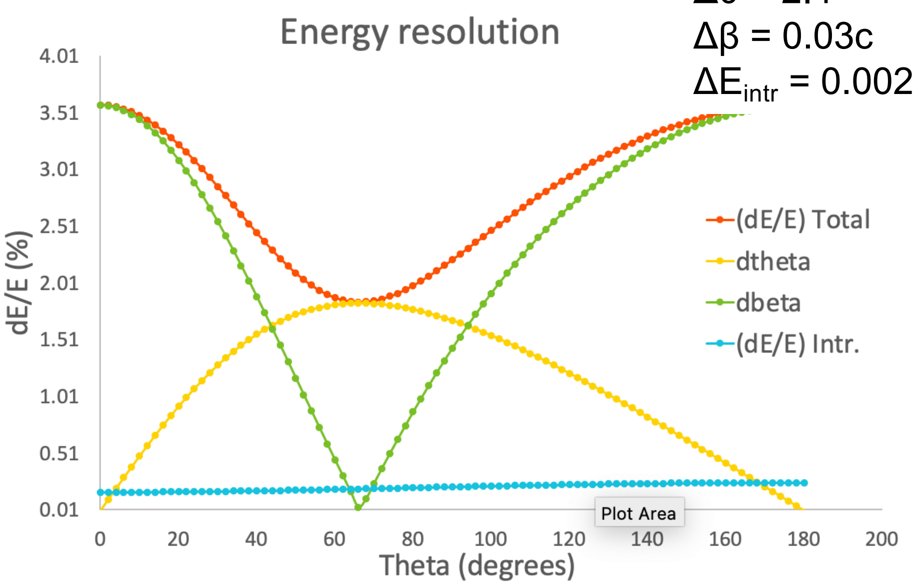
Science and Technology Facilities Council

Scintillators vs HPGe ?

UNIVERSITY of York

- Where the HPGe supreme energy resolution (ER ~ 0.2%) is compromised due to beam properties (ER > 1.0 %) and NaI/CsI arrays (ER ~ 8%) are inadequate
- Where high counting rate dictates detector response time
- Where fast timing <1ns is essential
- Where the price tag hinders progress

β = 0.4c
$\Delta\theta$ = 2.4°
$\Delta\beta$ = 0.03c
ΔE_{intr} = 0.002 MeV



β = 0.4c
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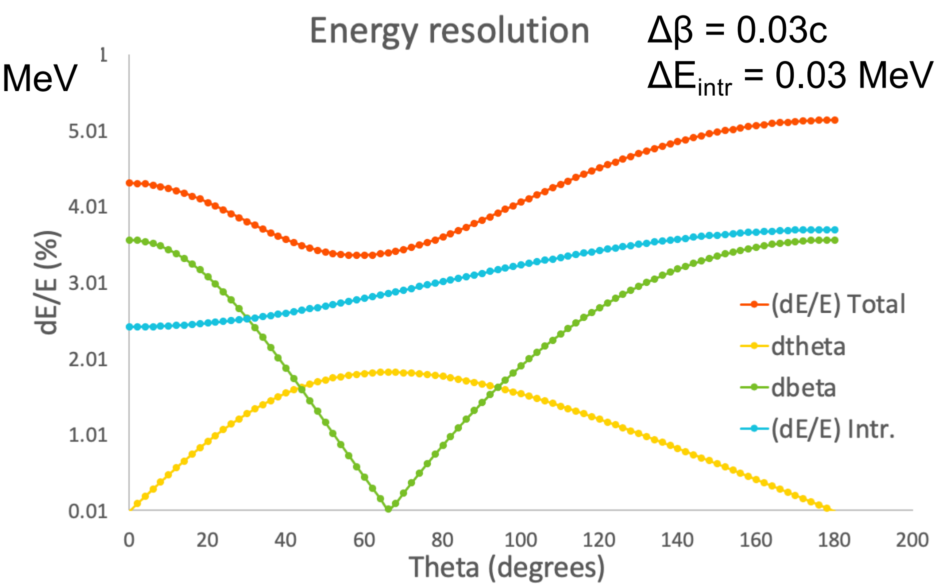
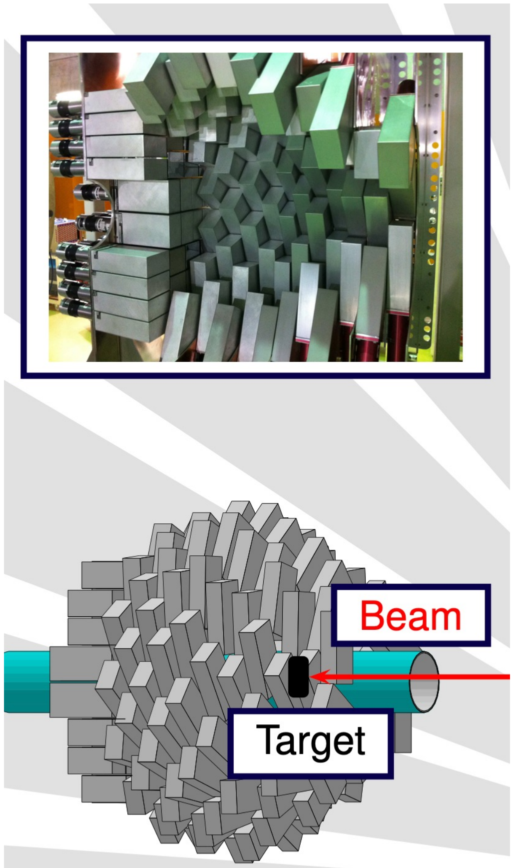
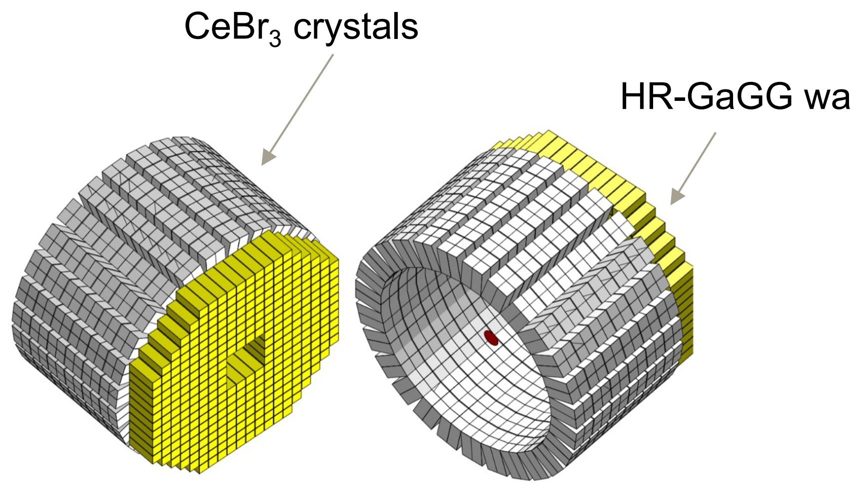


Scintillator array based on HR-GaGG and $CeBr_3$ to gradually upgrade DALI2 array



Geometry of the DALI2+ scintillator array at RIBF. The new array with compatible geometry



Hybrid array of 384 HR-GaGG(Ce) (yellow) and 624 CeBr3 (grey) crystals covering angles up to 120 degrees in the laboratory frame

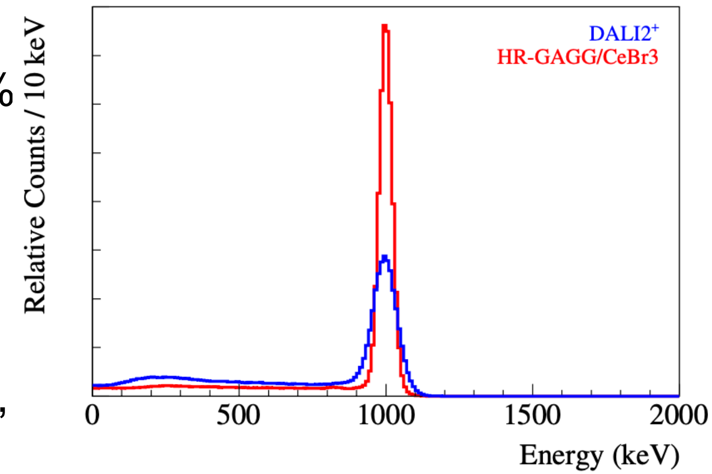
Comparison to DALI2+

1) **higher efficiency** with respect to DALI2+ (from 35% to 53%)

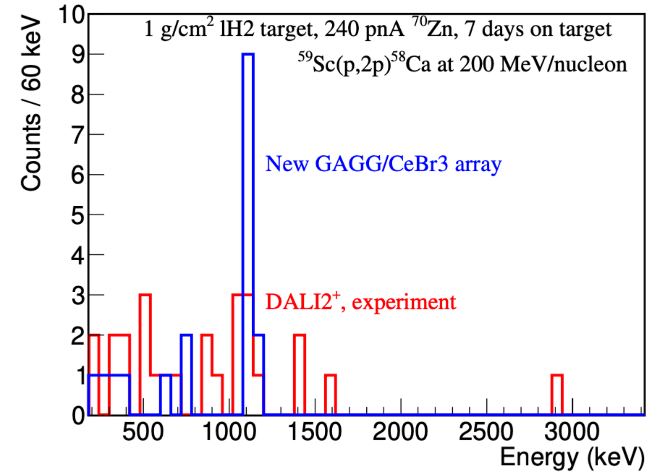
2) **better energy resolution** (from 10% to ≤5%)

3) **superior Peak-to-Total** (P/T) (from 0.5 to ≥0.7)

4) **superior time resolution** (from several ns to ≤1ns), important for **background suppression**, while opening up the way to perform **lifetime measurements**

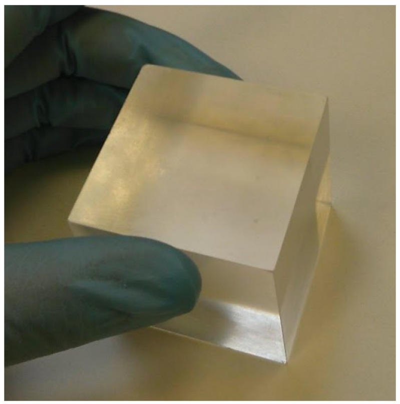


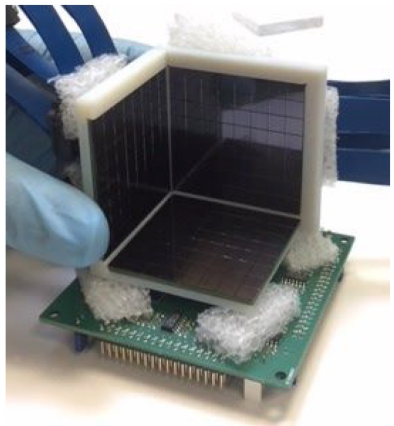
All these superior performance parameters result in an overall improvement in sensitivity of x5

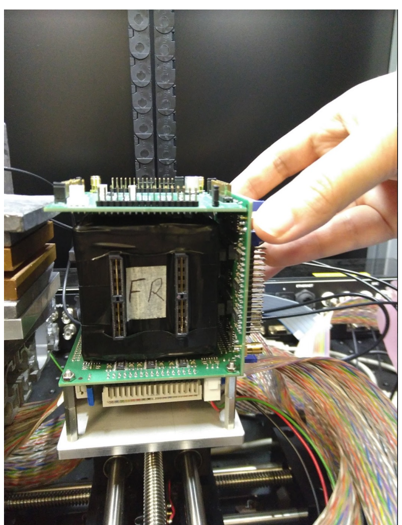


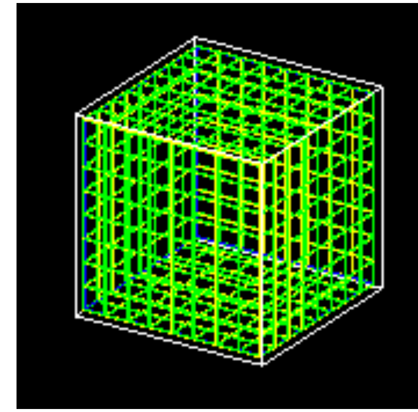
Position sensitive scintillator detectors

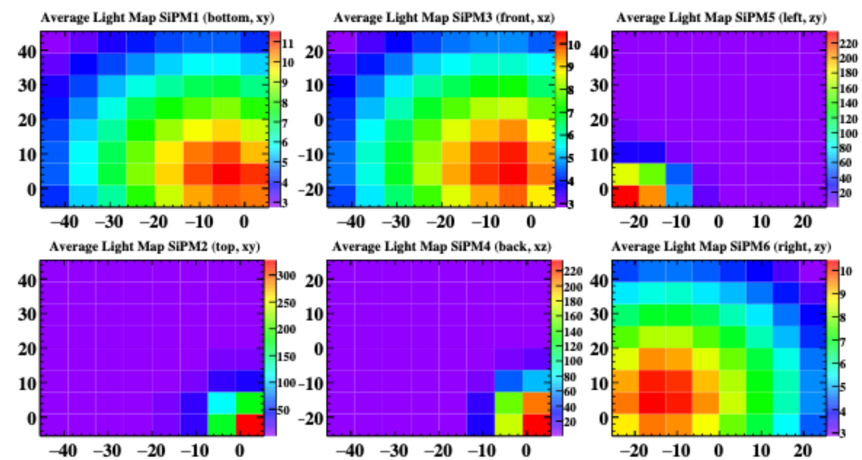
S. Paschalis, Developments through York STFC IPS and FoF projects (Kromek industrial partner)

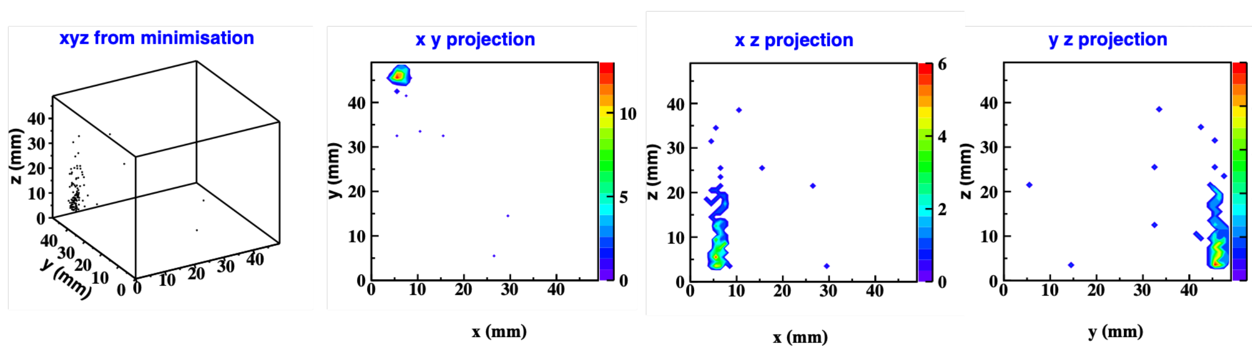






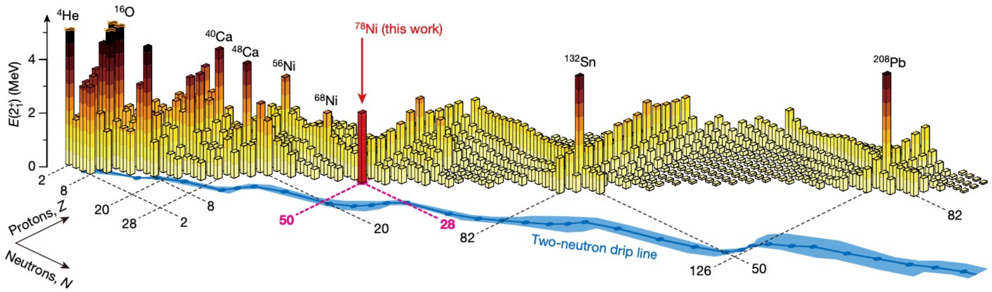






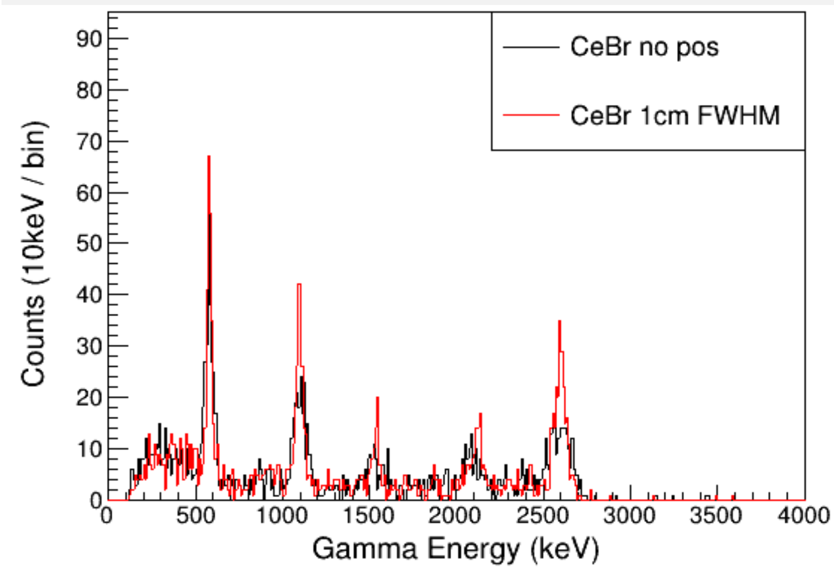
^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

RESEARCH ARTICLE



R. Taniuchi et al., Nature **569** (2019) 53

220 MeV/u ^{79}Cu(*p*,2*p*)^{78}Ni on LH2 target, 5mm vertex resolution, 60pnA 10days



Simulations: S. Chen

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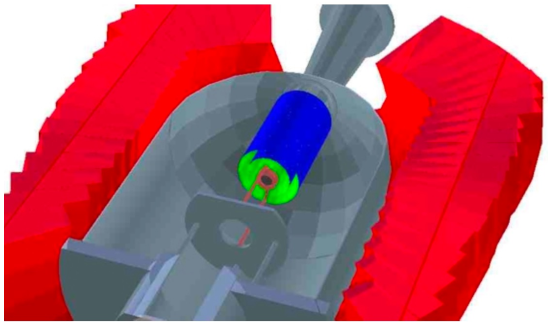
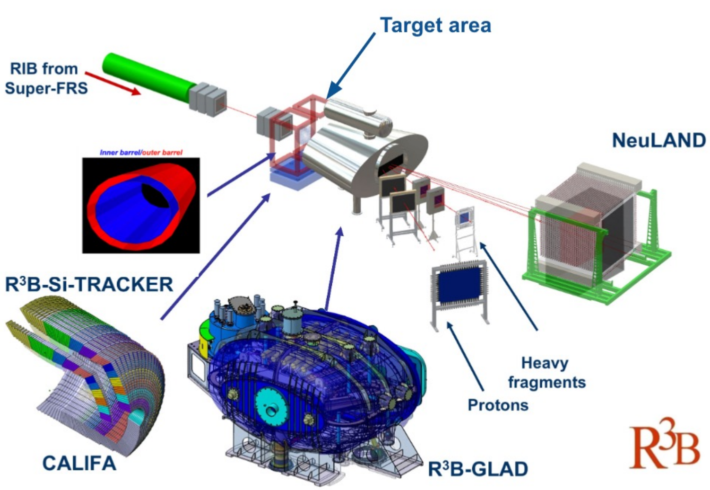
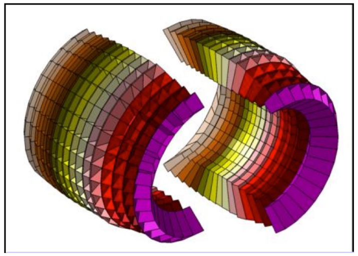
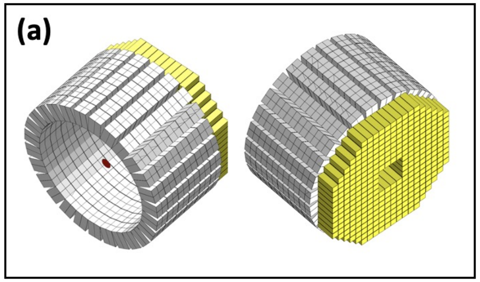
Gamma-ray detection



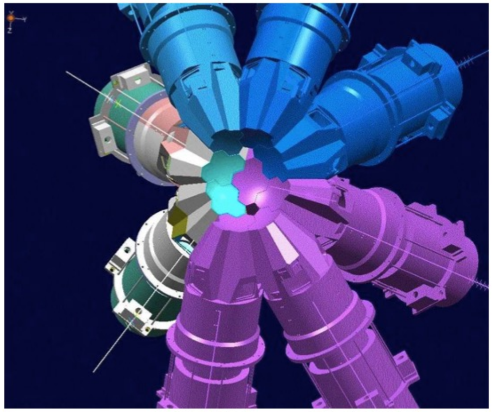




State of the art
Scintillator arrays



State of the art
semiconductor arrays



Compact TPC – vertex reconstruction

PI: A. Obertelli

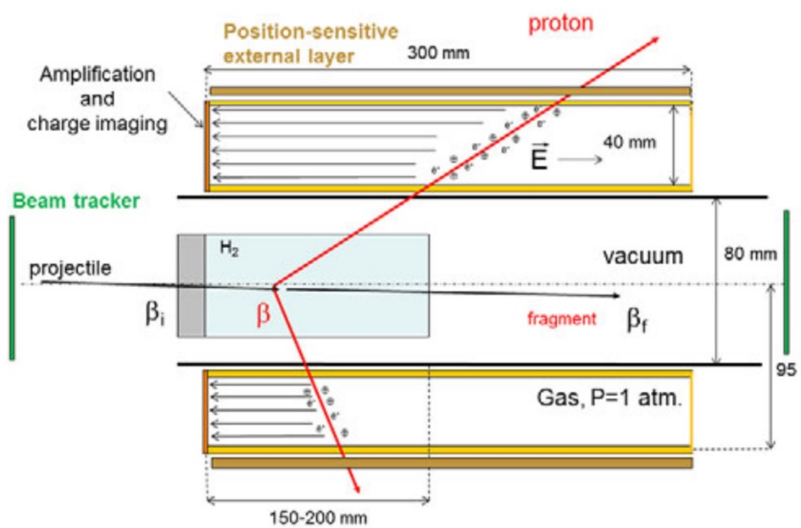
Eur. Phys. J. A (2014) 50: 8
DOI 10.1140/epja/i2014-14008-y

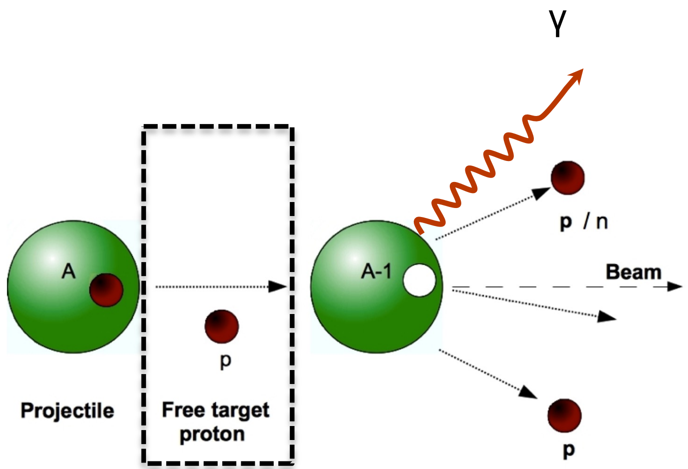
THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

MINOS: A vertex tracker coupled to a thick liquid-hydrogen target for in-beam spectroscopy of exotic nuclei

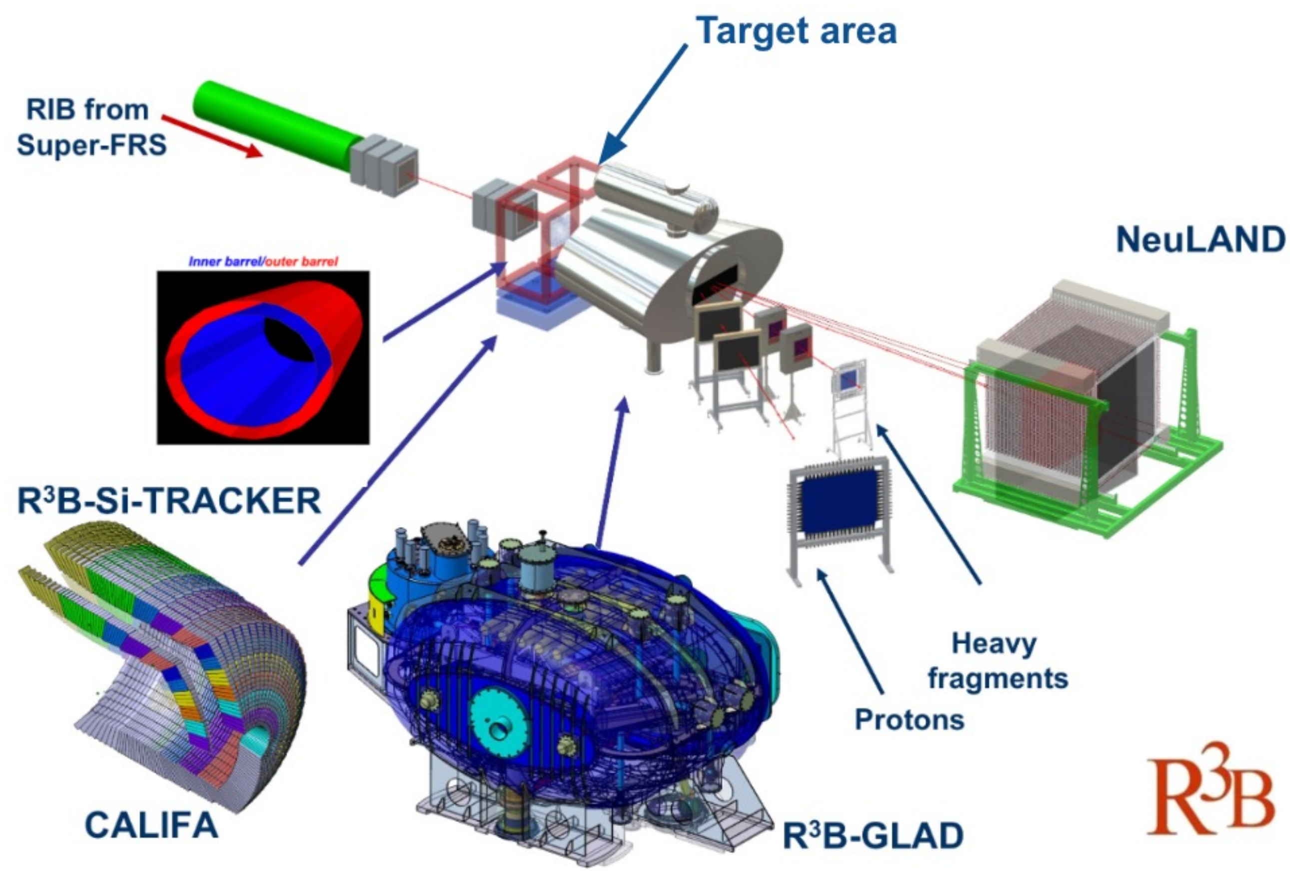
A. Obertelli[1,a], A. Delbart[1], S. Anvar[1], L. Audirac[1], G. Authelet[1], H. Baba[2], B. Bruyneel[1], D. Calvet[1], F. Château[1], A. Corsi[1], P. Doornenbal[2], J.-M. Gheller[1], A. Giganon[1], C. Lahonde-Hamdoun[1], D. Leboeuf[1], D. Loiseau[1], A. Mohamed[1], J.-Ph. Mols[1], H. Otsu[2], C. Péron[1], A. Peyaud[1], E.C. Pollacco[1], G. Prono[1], J.-Y. Rousse[1], C. Santamaria[1], and T. Uesaka[2]





R3B setup at FAIR (Germany)

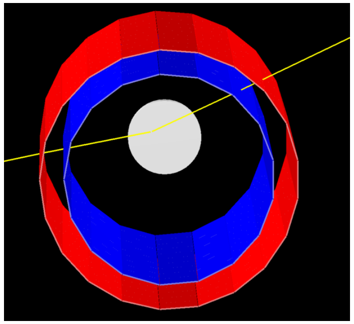
kinematically complete measurements



The R3B setup and the function of the Target Recoil Tracker (TRT) device

Construction of the TRT device has
been recently approved as UK-led for R3B

1. Reaction vertex reconstruction

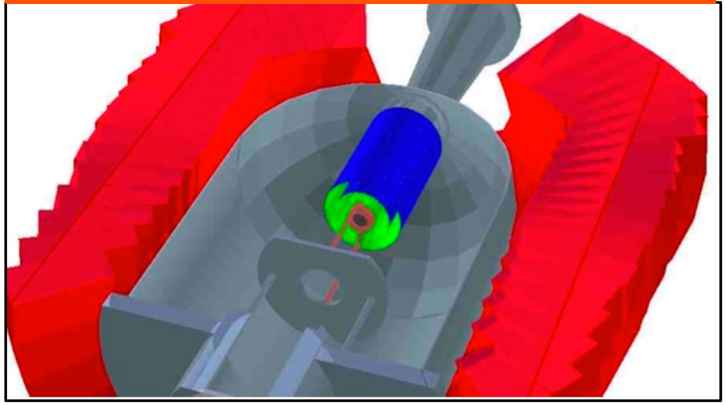


TRT detects light charged particles that scatter
at large angles from the target (e.g. QFS protons)

It measures primarily the angle and serves
two purposes:

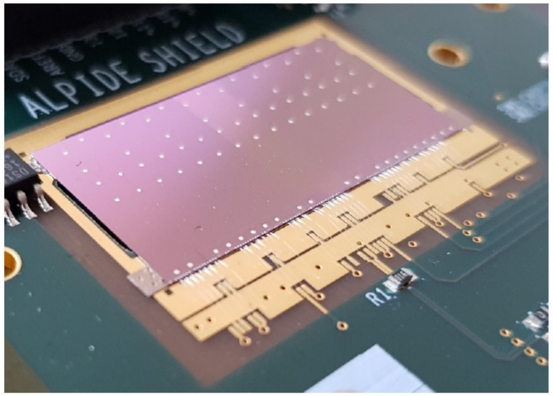
1. Reaction-vertex reconstruction
2. Missing-mass reconstruction

2. Missing-mass reconstruction
(when combined with CALIFA)



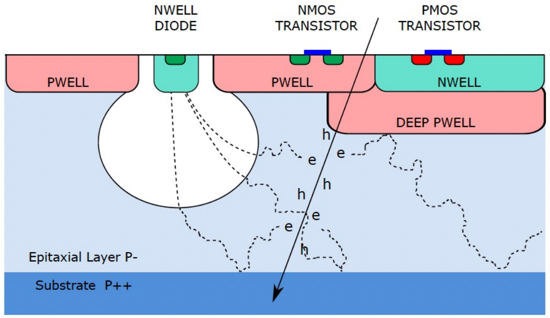
Its material budget should be as little as possible,
it directly affects and dominates the reconstructed
resolution!

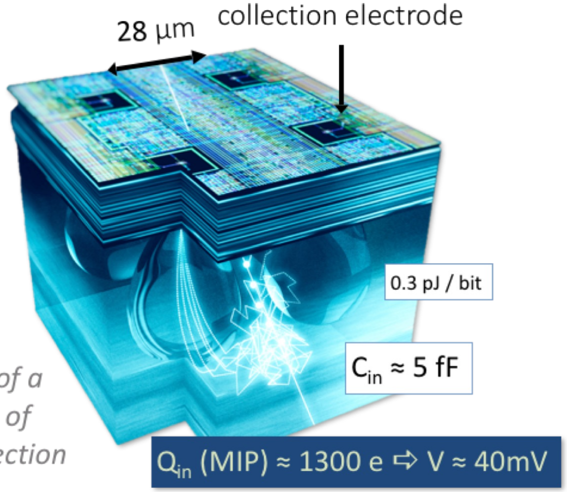
R3B TRT device will employ the ALPIDE sensor of the ALICE collaboration



Pixel Sensor CMOS 180 nm Imaging Process (TowerJazz)

In-pixel amplification
In-pixel discrimination
In-pixel (multi-) hit buffer



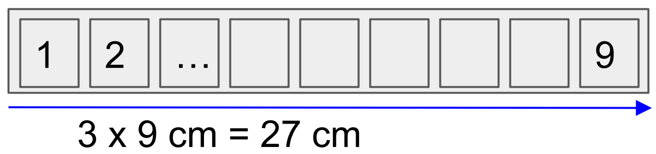


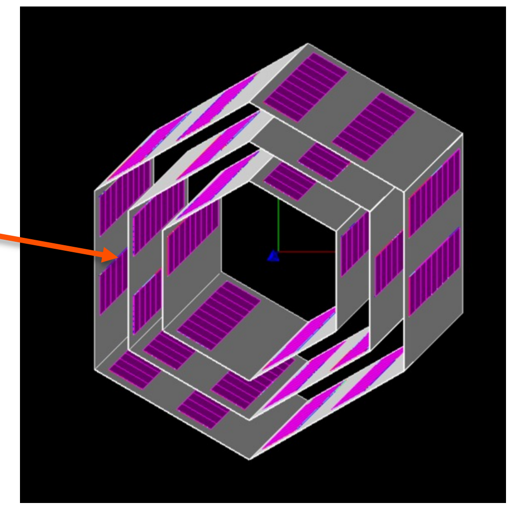
Artistic view of a SEM picture of ALPIDE cross section

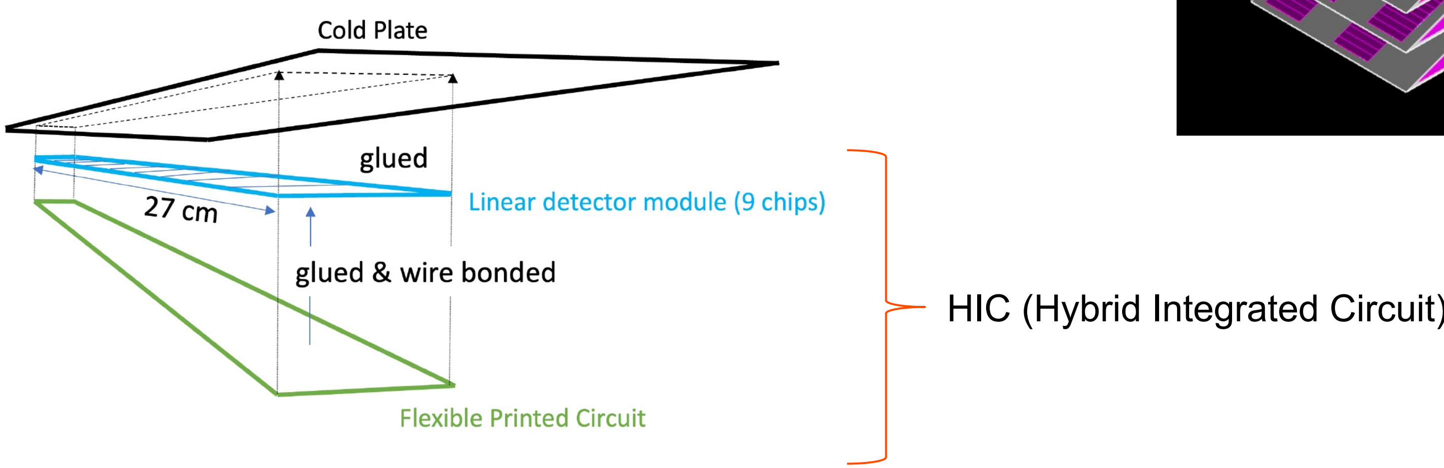
29 um x 27 um pixel pitch
Continuously active front-end
Global shutter
Zero-suppressed matrix readout Triggered or continuous readout modes

G. Aglieri Rinella, NIM A845 (2017) 583
A. Di Mauro, NIM A936 (2019) 625
F.Reidt, NIM A 1032 (2022) 166632

Stave module components for the R3B TRT

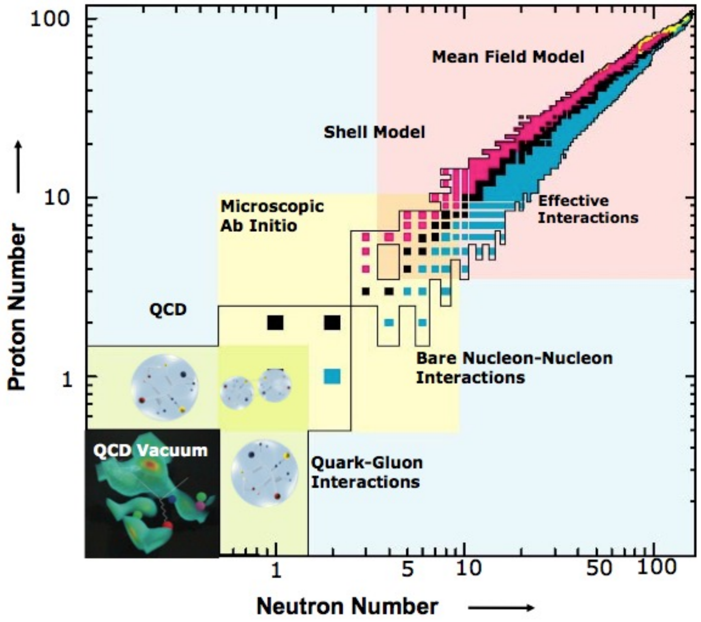






Conclusions

- Position sensitive detectors play an ever increasing role in Nuclear Physics
- Greater synergies between different scientific communities are emerging
- Combination of new instrumentation, upgraded facilities and advancement of nuclear theory brings us closer to understanding the atomic nucleus from first principles



Thank you !