Exotic nuclei studied with NUSTAR at FAIR/GSI

NSP2021 by video

J. Gerl
for the local GSI DESPEC team

June 3, 2021

GSI/FAIR, Germany

GSI – The Laboratory

- German National Lab
- 1600 employees
- 1000 guest scientists

<u>Heavy ion accelerators:</u>

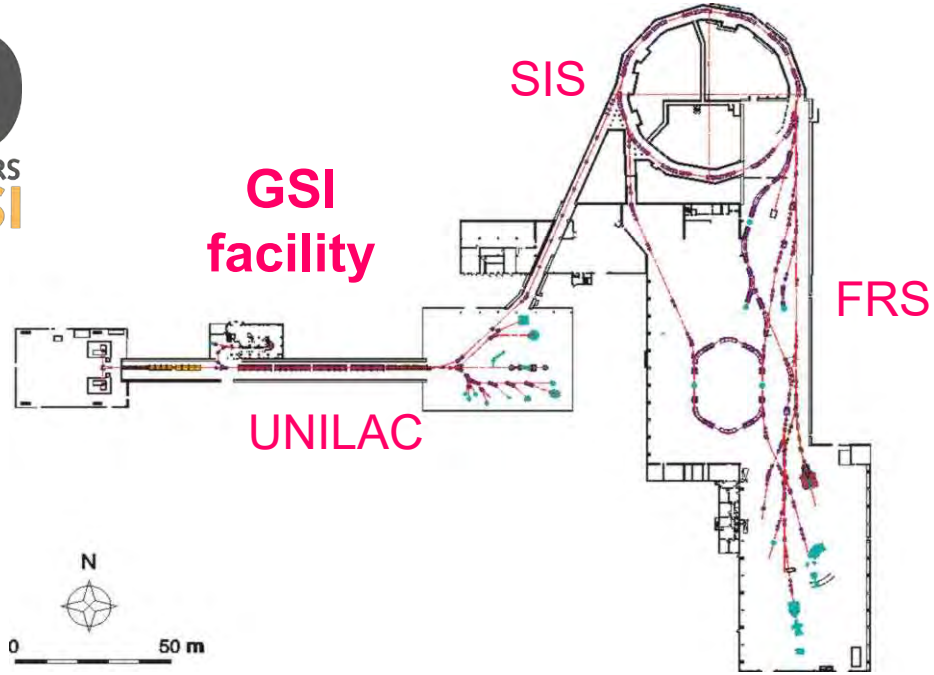
- p …U;
- 14 A·MeV … 2·AGeV

<u>Research areas:</u>

- Nuclear physics
- Atomic physics
- Biophysics/Medicine
- Materials research
- Instrumentation and applications

<u>Future megascience project:</u>

- FAIR, 2 Billion €
- Multi-national Lab



FAIR – The Future of GSI

FAIR will be the largest heavy-ion accelerator complex in the world with stable and radioactive ions of all elements and anti-protons, ion storage rings, and unique experimental set-ups

FAIR Accelerator Complex

FAIR

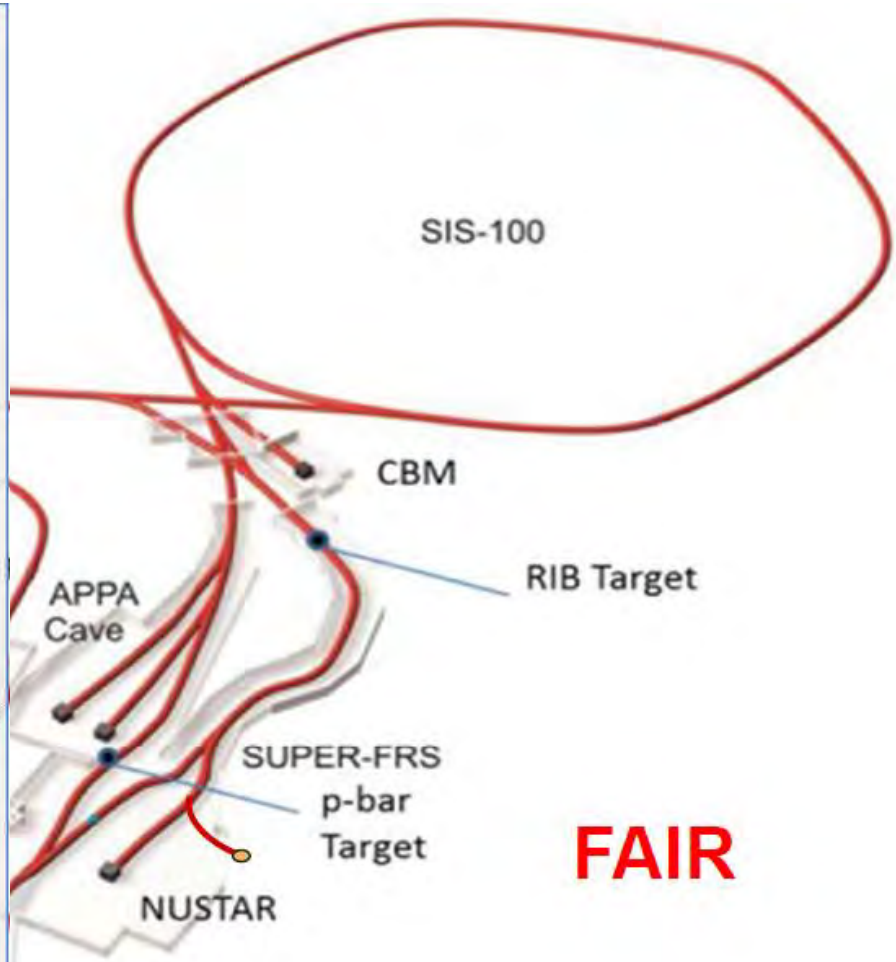
... accelerates particle beams from (anti)protons up to uranium ions with

- very high intensities
  - up to a factor of ~100 increase for primary Uranium beams (~ 5 x 10^{11} U^{28+} ions /s),
  - up to a factor of ~10.000 increase for secondary rare isotope beams
- high pulse power (up to ~ 50 kJ / 50 ns)
- suite of storage cooler rings equipped with stochastic and electron cooling for brilliant beam quality

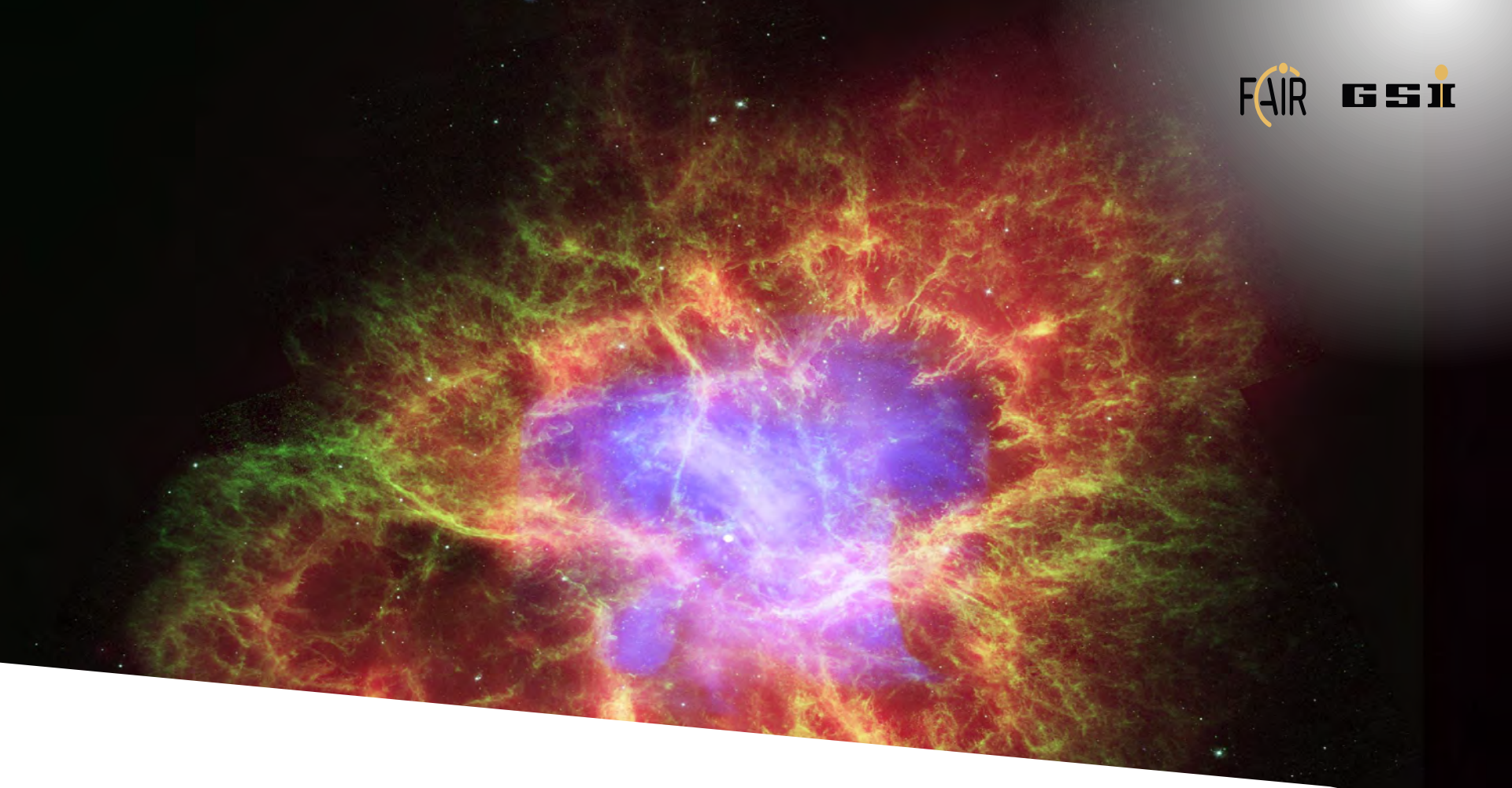
... develops and exploits innovative particle separation and detection methods, as well as novel computing techniques

... to perform forefront experiments towards the production and investigation of

New Extreme States of Matter.

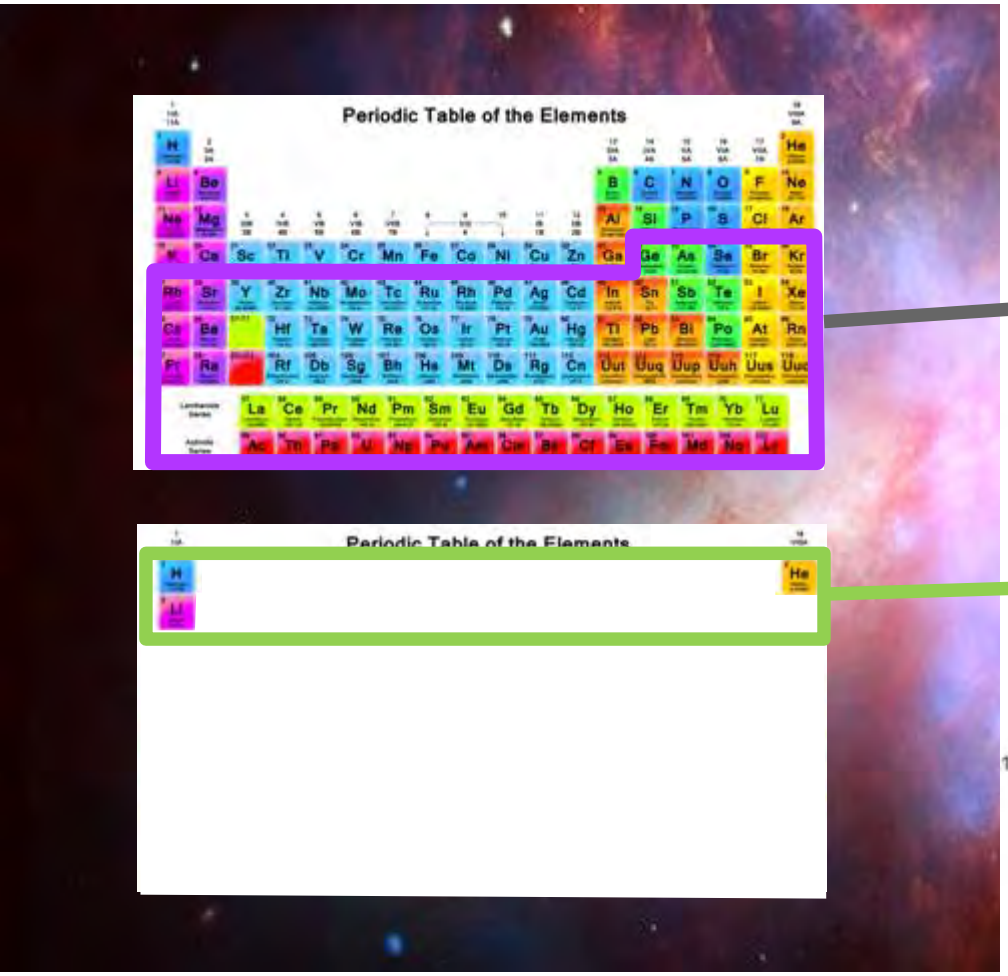


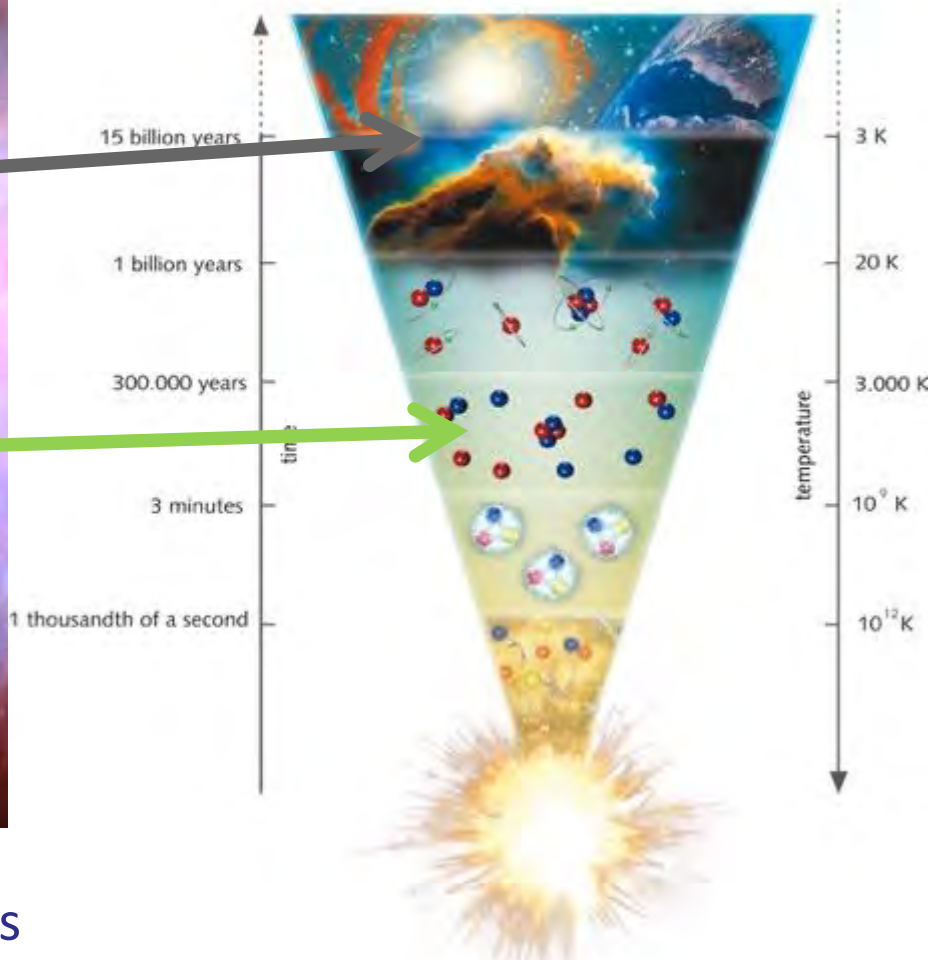
FAIR Construction



FAIR enables extraordinary new scientific results for a better understanding of the matter in the universe.

The Universe in the Lab
Example: Synthesis of the chemical elements

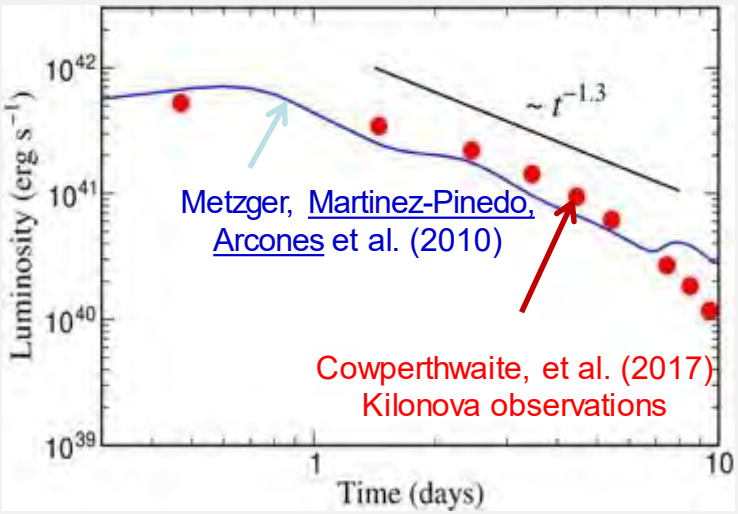




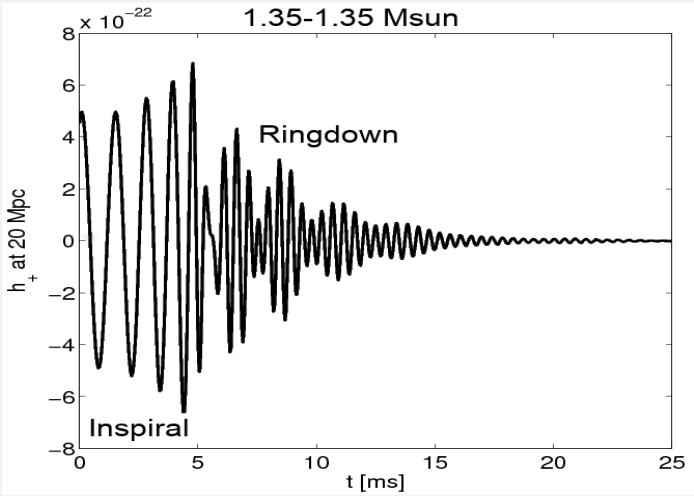
Where and how were the heavy elements made in the universe? ← *belongs to the top unanswered questions in physics*

Further push of FAIR science motivation

… by multimessenger study of a neutron-star merger in summer 2017



Electromagnetic "Kilonova" Signal



Gravitational Wave Signal

Theoretical prediction by GSI researchers (2010):

Neutron star mergers are the astrophysical site of the r-process producing the very heavy elements like Pt, Au and beyond,
thereby exhibiting a characteristic electromagnetic "Kilonova" signal.

Confirmation by Ligo, Virgo and other astronomer groups (2017)
via detection of both
gravitational and electromagnetic waves emerging from such an event.

FAIR was designed to study the properties of neutron star matter and to trace back the production paths of the heavy elements!

Interdisciplinary Research Approach:
Neutron Star Mergers and FAIR science …

Neutron Star Mergers

FAIR Research Pillars

- Equation of State (**Hades, CBM**)
  - Gravitational wave signal
  - Amount of ejecta
- Baryon-Baryon interaction (**PANDA**)
- Exotic neutron-rich nuclei (**NUSTAR**)
  - r-process nucleosynthesis and abundancies of the heaviest elements gold, platinum and beyond
- Plasma and atomic opacities (**APPA**)
  - Kilonova electromagnetic transient

FAIR offers unique opportunities for studying these fundamental questions!

NUSTAR - The Project

DESPEC	γ-, β-, α-, p-, n-decay spectroscopy
ELISE	elastic, inelastic, and quasi-free e^--A scattering
EXL	light-ion scattering reactions in invere kinematics
HISPEC	in-beam γ spectroscopy at low and intermediate energy
ILIMA	masses and lifetimes of nuclei in ground and isomeric states
LASPEC	Laser spectroscopy
MATS	in-trap mass measurements and decay studies
R3B	kinematically complete reactions at high beam energy
Super FRS	RIB production, identification and spectroscopy
SHE	Nuclear physics and chemistry of super-heavy elements

The Approach

Complementary measurements leading to consistent answers

The Collaboration

> 850 scientists

184 institutes

39 countries

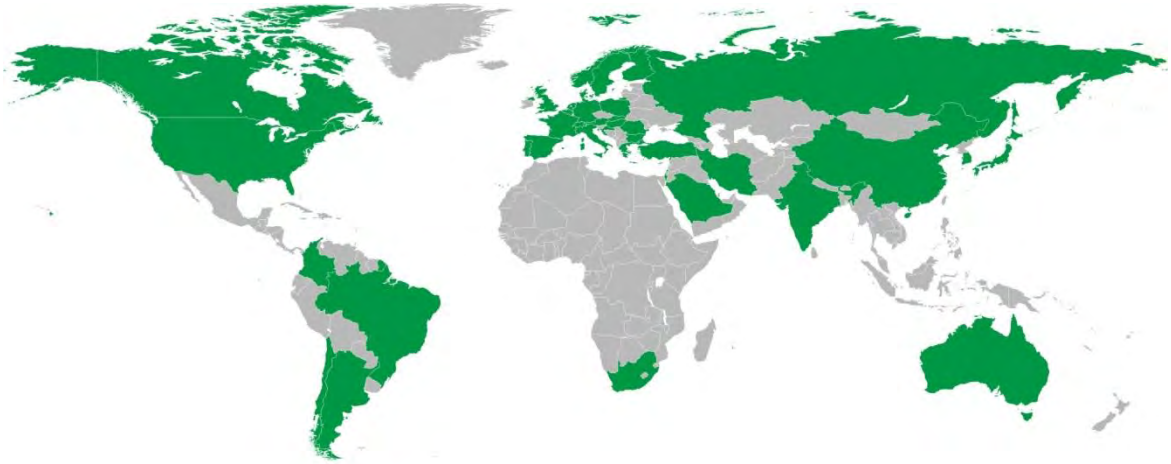
NUSTAR - The Project

Evolutionary approach:

Advancing instrumentation by continuous development and gaining experience by physics exploitation

The Approach

Complementary measurements leading to consistent answers



The Collaboration

> 850 scientists

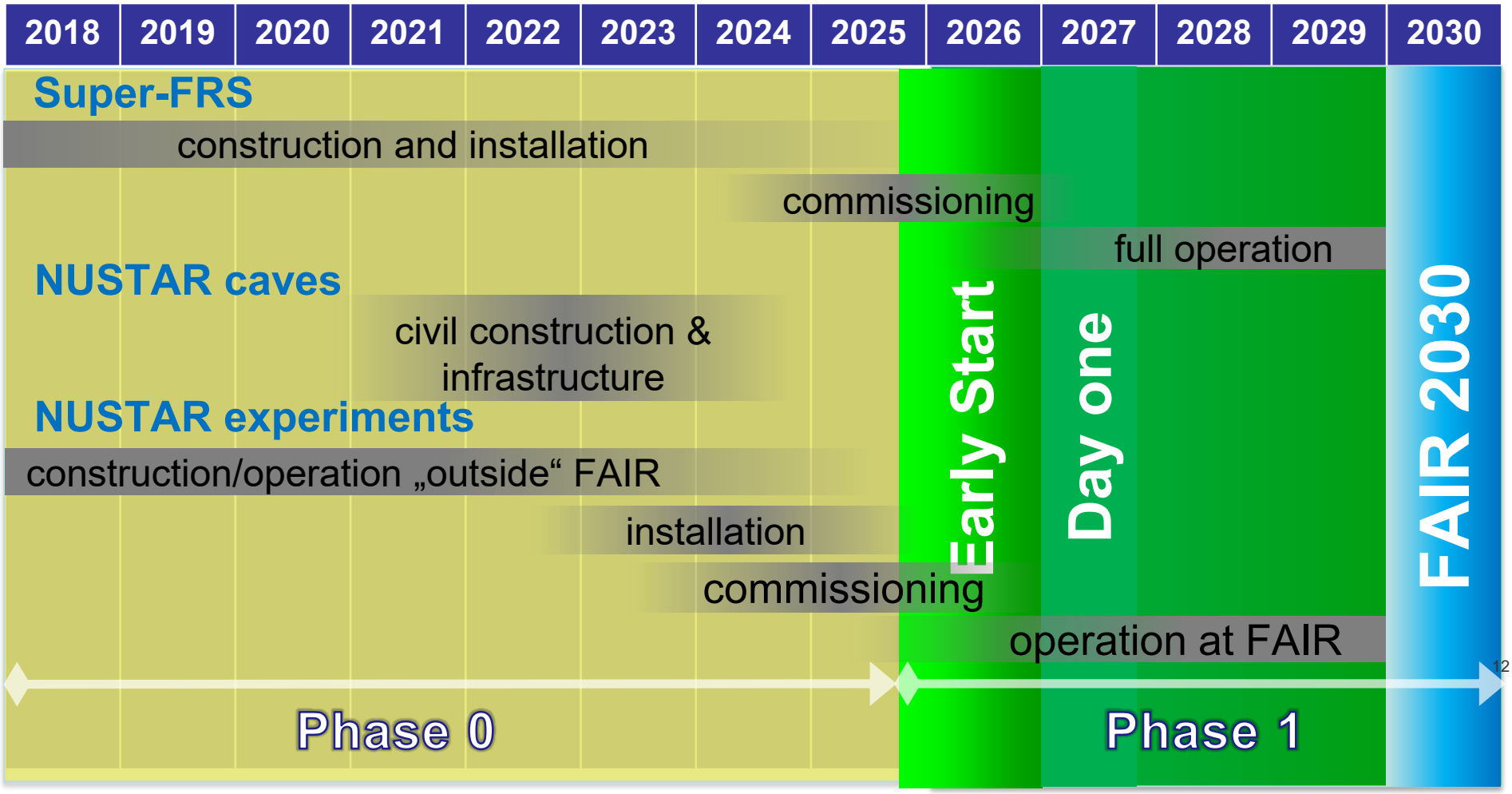
184 institutes

39 countries

>50 instrumentation sub-projects (MSV)

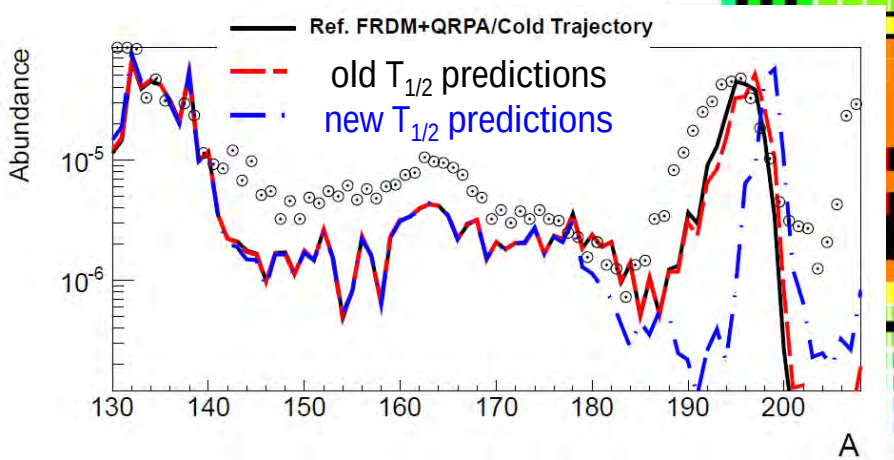
several 1000 major components

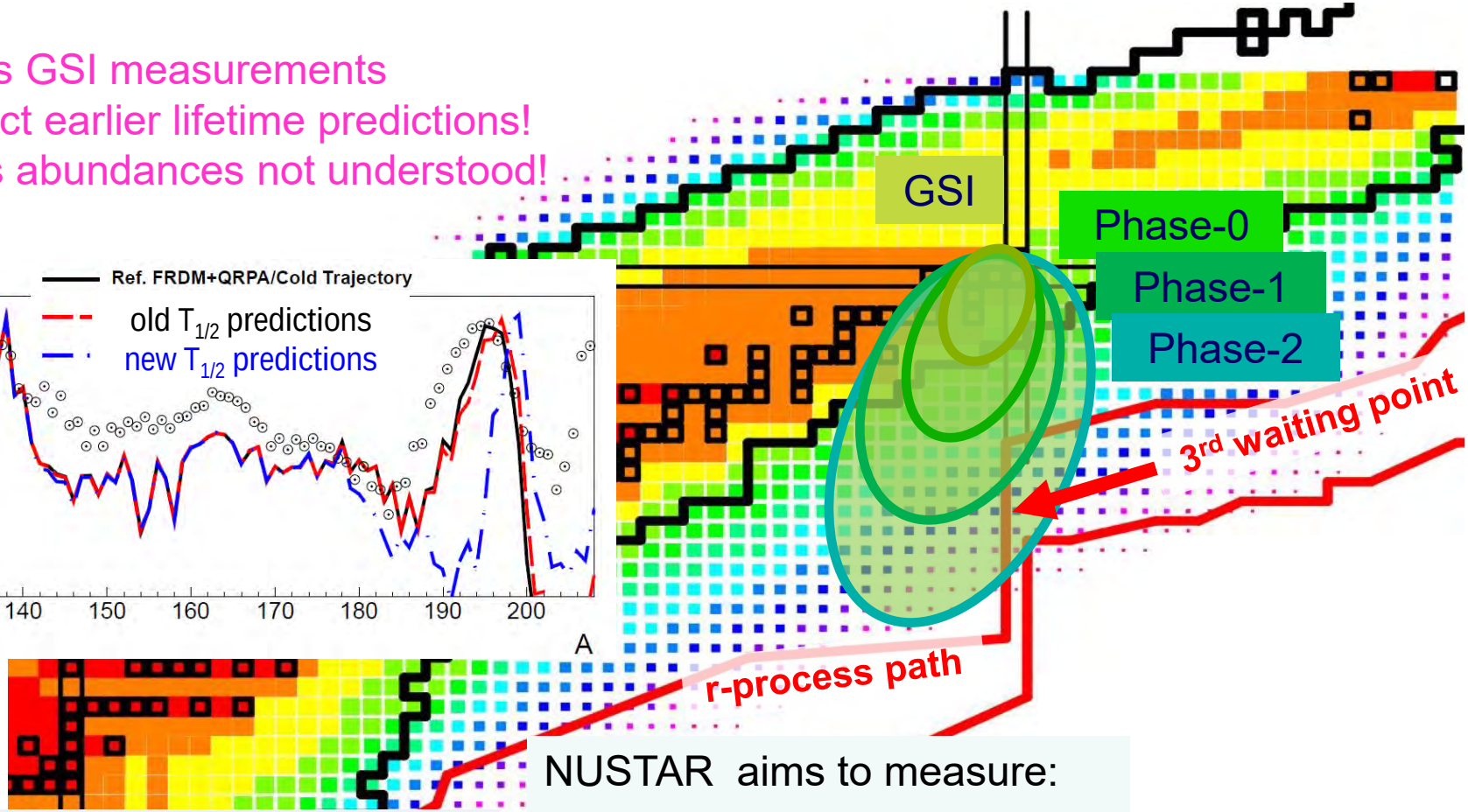
NUSTAR Overall Schedule



NUSTAR goes for the N=126 Physics Case

Previous GSI measurements contradict earlier lifetime predictions!
→ Mass abundances not understood!



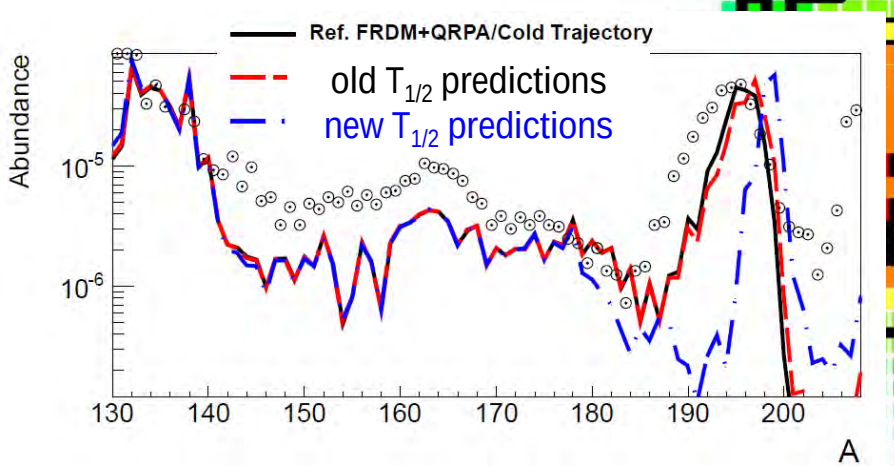


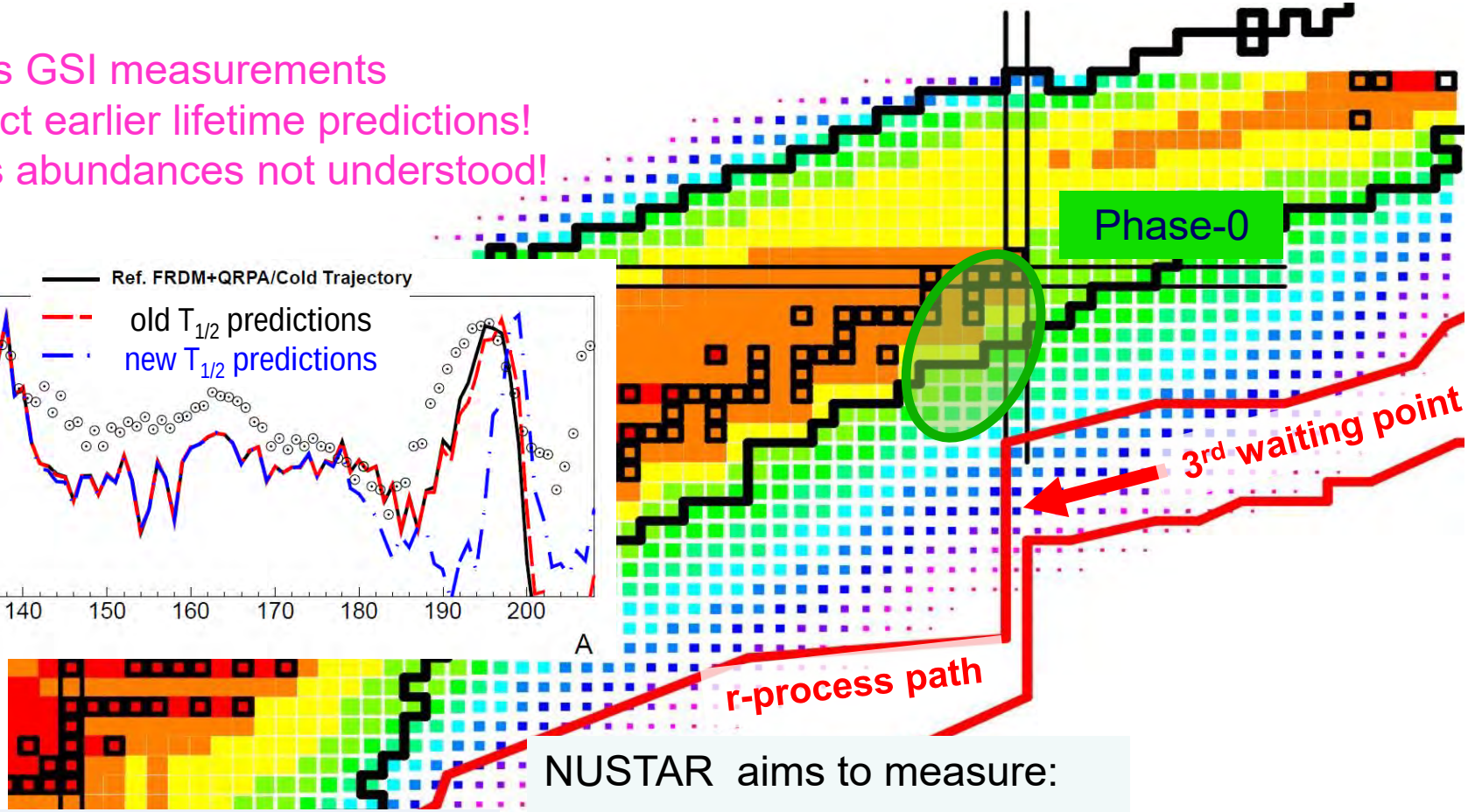
Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

NUSTAR aims to measure:
- masses
- β-lifetimes
- neutron-branchings
- strength distributions
- level structure

Phase-0 of the N=126 Physics Case

Previous GSI measurements contradict earlier lifetime predictions!
→ Mass abundances not understood!





Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

NUSTAR aims to measure:
- masses
- β-lifetimes
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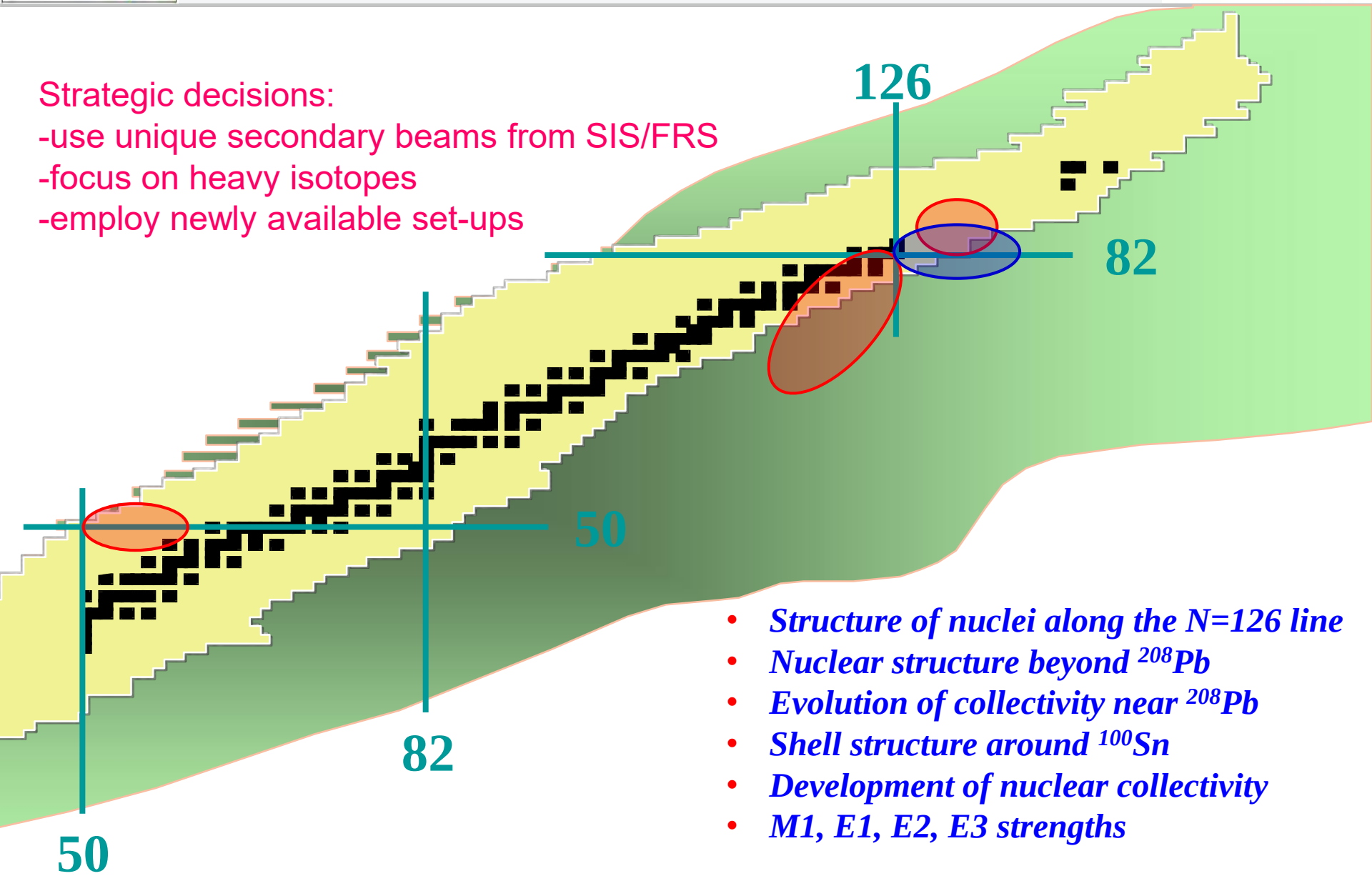
DESPEC Physics Programme

Strategic decisions:
-use unique secondary beams from SIS/FRS
-focus on heavy isotopes
-employ newly available set-ups



- *Structure of nuclei along the N=126 line*
- *Nuclear structure beyond ^{208}Pb*
- *Evolution of collectivity near ^{208}Pb*
- *Shell structure around ^{100}Sn*
- *Development of nuclear collectivity*
- *M1, E1, E2, E3 strengths*

DESPEC: Decay Spectroscopy

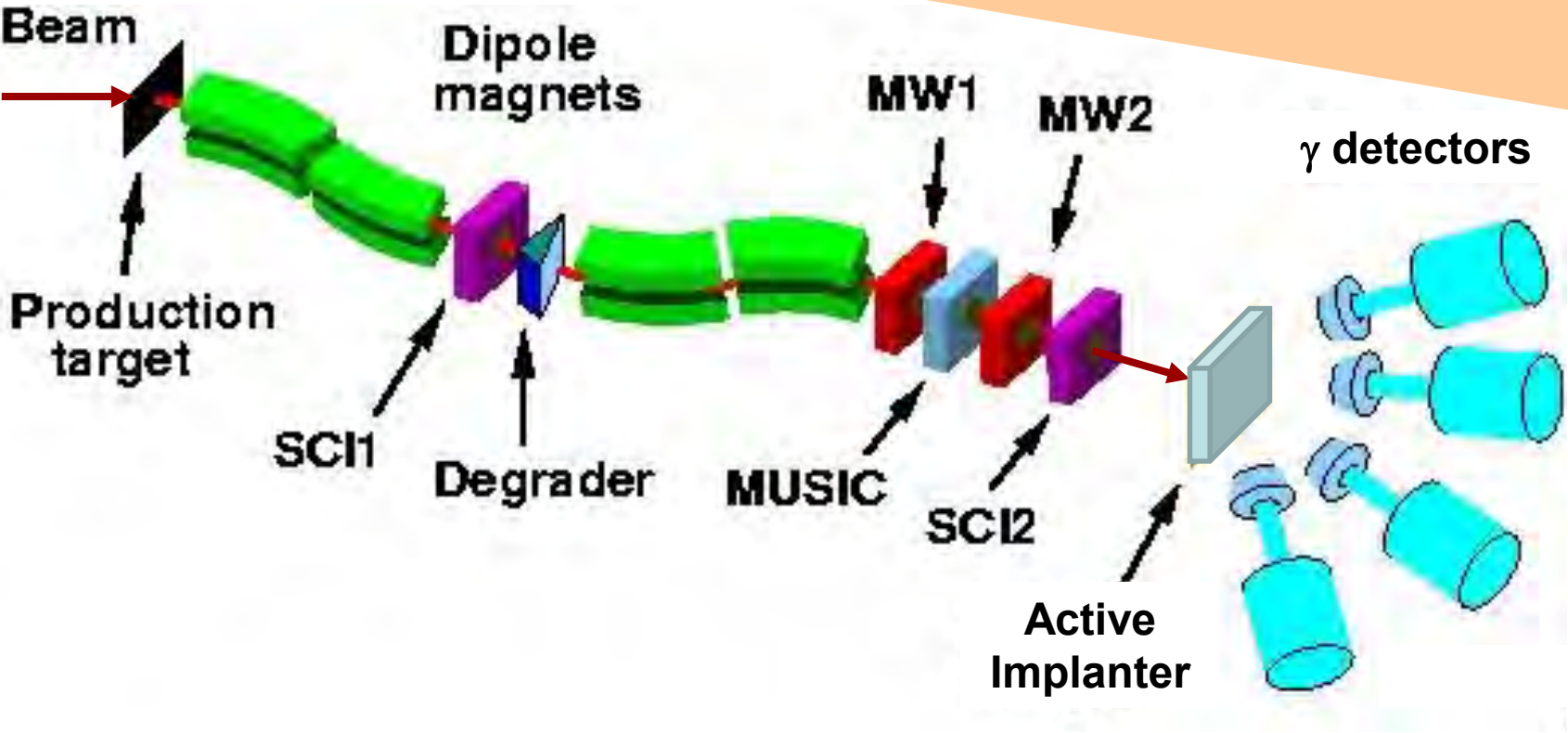
production

selection

identification

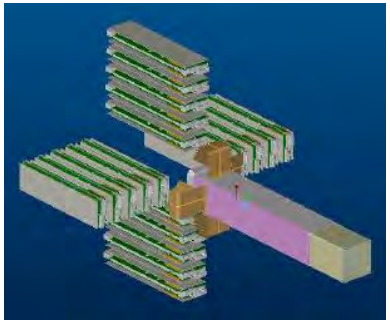
implantation

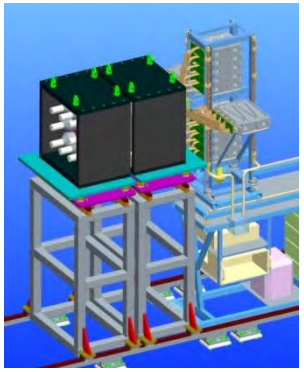
spectroscopy



To gain a deeper understanding…

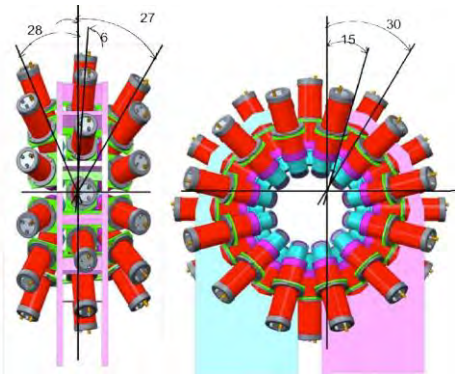
take AIDA as common active implanter

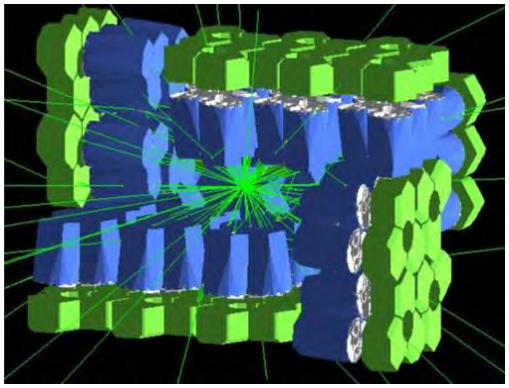




use DTAS to measure β-strength distributions

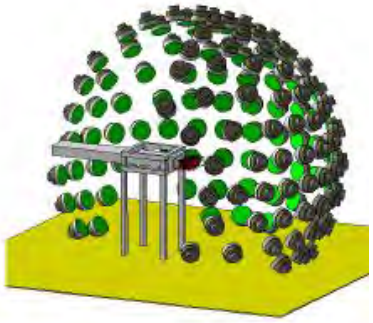
use FATIMA to measure lifetimes





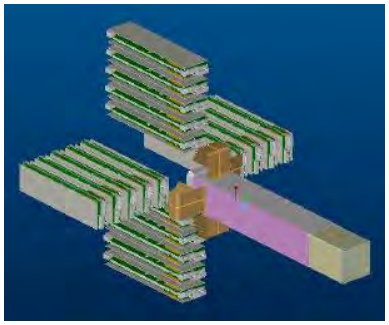
use DEGAS for high-resolution spectroscopy

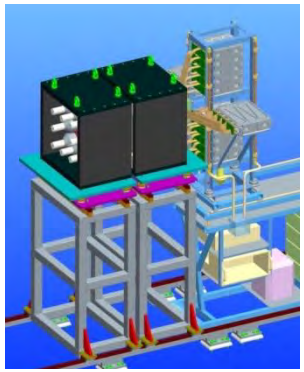
use MONSTER to perform neutron spectroscopy



Exploitation plan

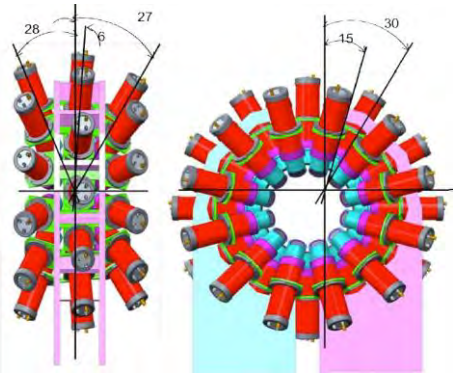
AIDA (narrow config.) used at RIKEN, served as initial implanter in 2020. AIDA (wide config.) to be built and commissioned for 2021 and later.

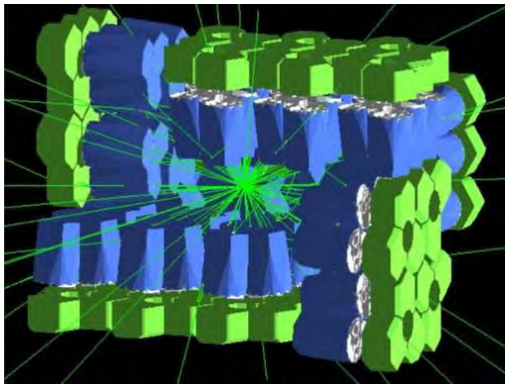




DTAS used at JYFL and RIKEN, is planned for the 2. set-up in 2022.

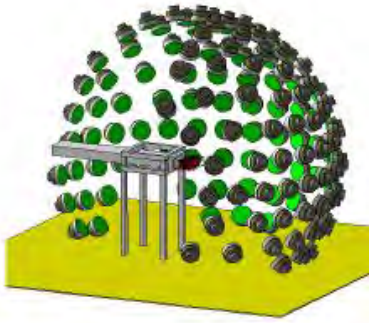
FATIMA used at IFIN-HH, RIKEN and GANIL, is planned for the 1. set-up in 2020/21





DEGAS is under construction and is planned to be used for the 3. setup in 2022.

MONSTER is under construction and shall be tested in 2020 parasitically, prior to proposing experiments



2019 Engineering runs for FRS and NUSTAR

Goals

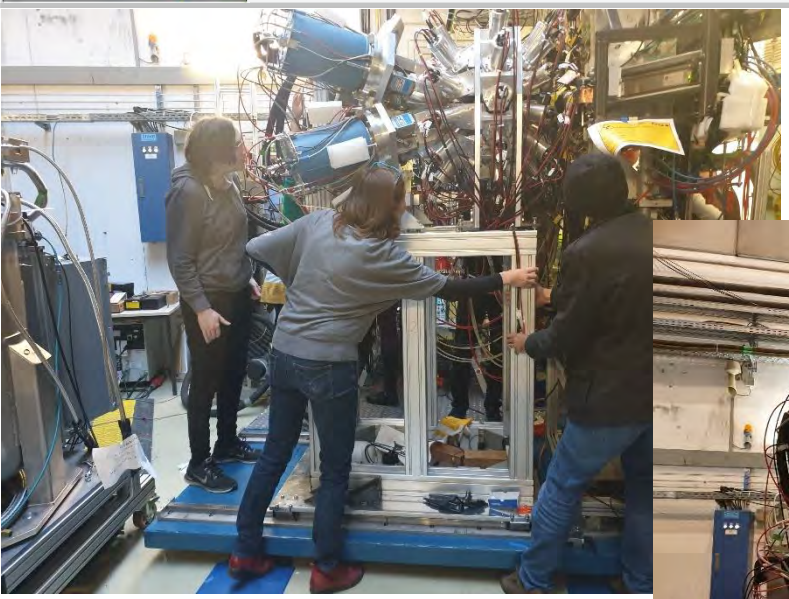
- Commissioning of the FRS - all 3 branches
  - Check signals from all detectors along the beamlines
  - Optics tests, Bρ calibration, new control system
- Training
  - Get used to new programs
  - How to run the FRS, its detectors, DAQ, online analysis, etc.
- Preparation for experiments in 2020
  - Beam tests of several detectors and detector systems
  - Proof of principle stopping measurements

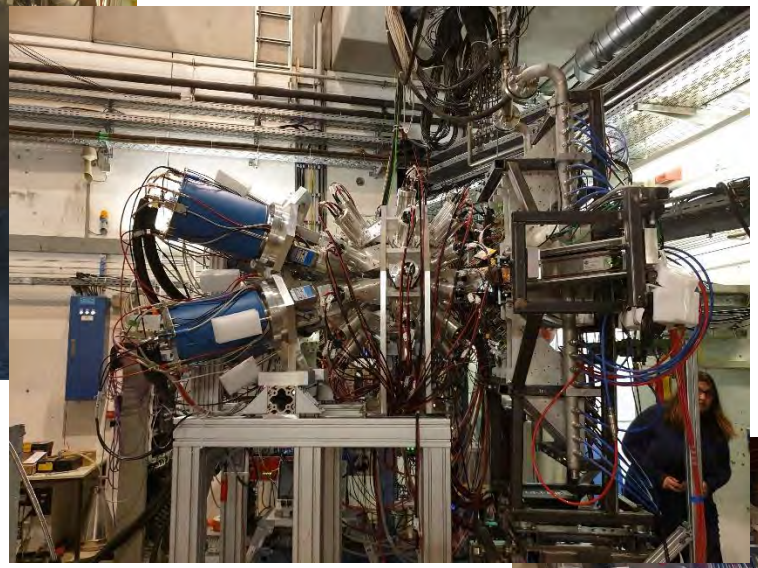
Preparation of Phase-0 experiments

- DESPEC
  - Ar beam and Ar fragments
  - U beam and U fragments
- R3B in Cave C
  - Ar beam and Ar fragments
- Ion Catcher
  - U beam and U fragments
- Isotope search
  - Test of experiment-specific beta-decay detector
- Energy loss measurements
  - Proof of principle measurement
  - Measurement at low magnetic rigidity (~ 2Tm)
- ESR via FRS
  - U beam was injected and stored in the ESR

DESPEC Commissioning beam time

Accelerator Engineering Runs
11.-12-2019





Initial DESPEC Set-up
AIDA + FATIMA +
GALILEO/DEGAS
incl. bPlast and Finger

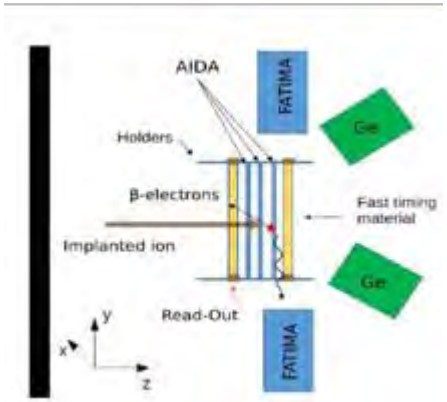
DESPEC Engineering Run

Implant↔decay ↔ γ-ray
Correlations tested and working

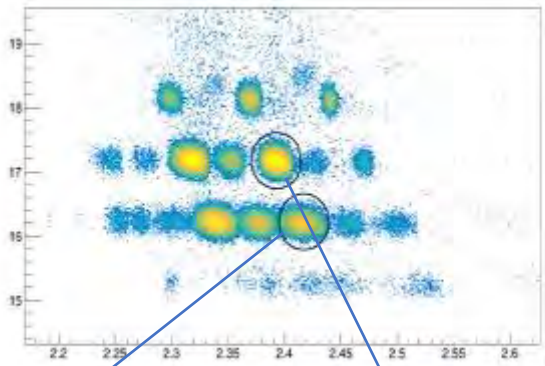
AIDA
implantation and decay detector

FATIMA
Fast Timing $LaBr_3$ Array

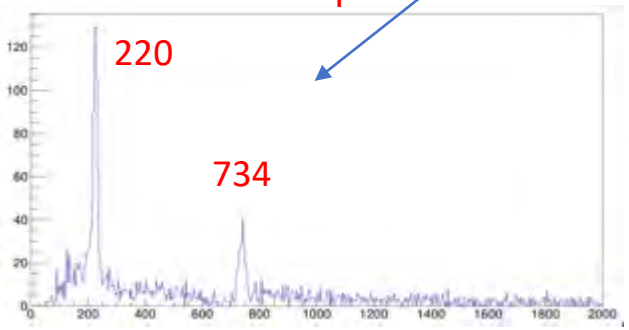
DEGAS/GTC
HPGe Array



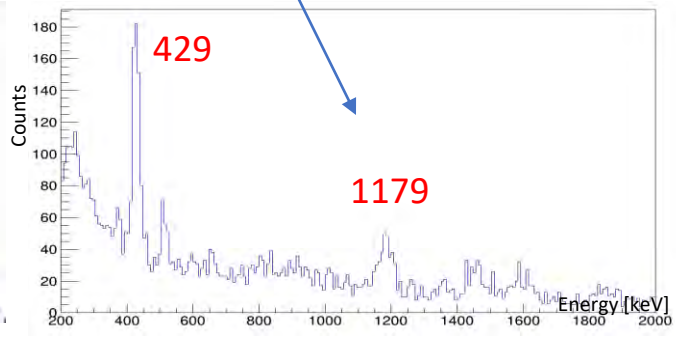
ID spectra



FATIMA isomer spectrum in ^{32}Al



Fatima spectrum of ^{34}Al beta decay



- Detectors fully performing
- Tested electronics from each branch
- Fully integrated DAQ
- On-line and off-line sorting programs

First “real” DeSpec experiment

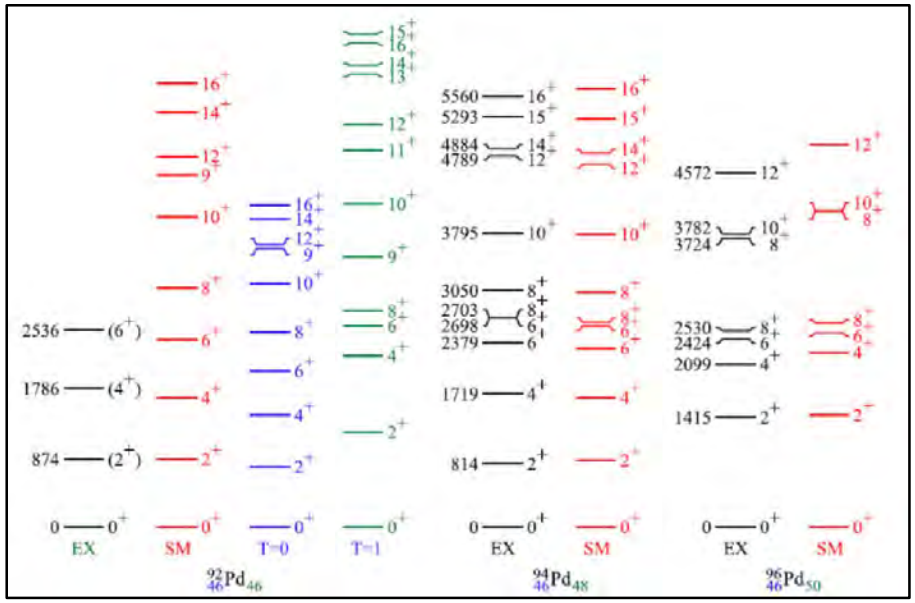
S480 ^{124}Xe beam 9 – 15 March 2020:

Structure of the heaviest N=Z nuclei: Seniority Transitions in ^{94}Pd

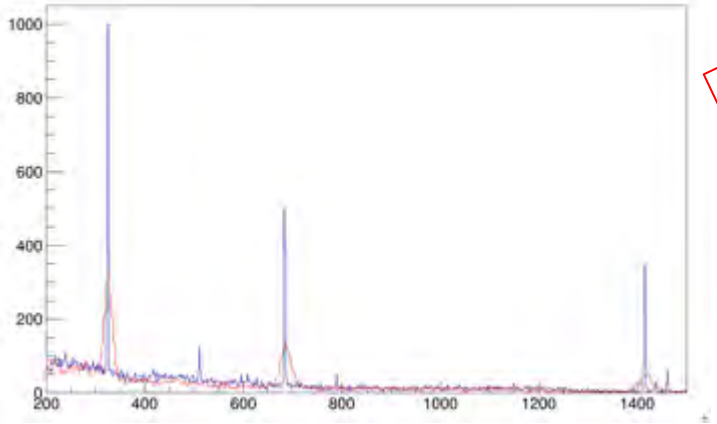
Spokespersons: P. Regan, M. Gorska, B. Cederwall

→ New lifetimes in the ps-to-ns regime

Level schemes of ^{92,94,96}Pd



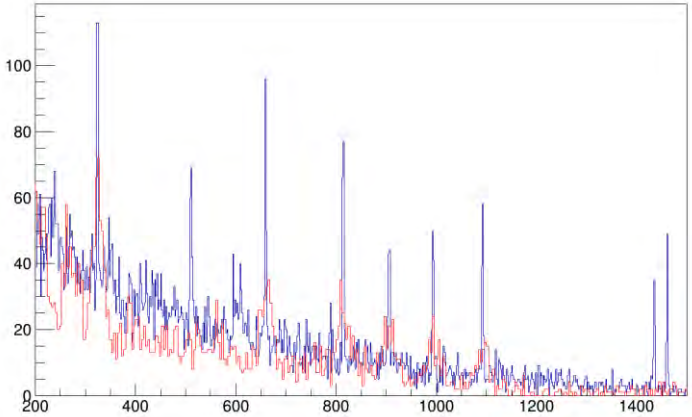
Reference nucleus ^{96}Pd



PRELIMINARY! from 16h of data

Galileo and FATIMA isomer spectra

^{94}Pd



2020 NUSTAR Phase-0 experiments

Beamtime in 2020 severely hampered by Covid-19 epidemy

- Safe working conditions possible (limited number of persons onsite etc.) ?
- Experimental set-up complete and team sufficient (locally and remote) ?
- Beamtime schedule relaxed (increased set-up time, extensions possible)

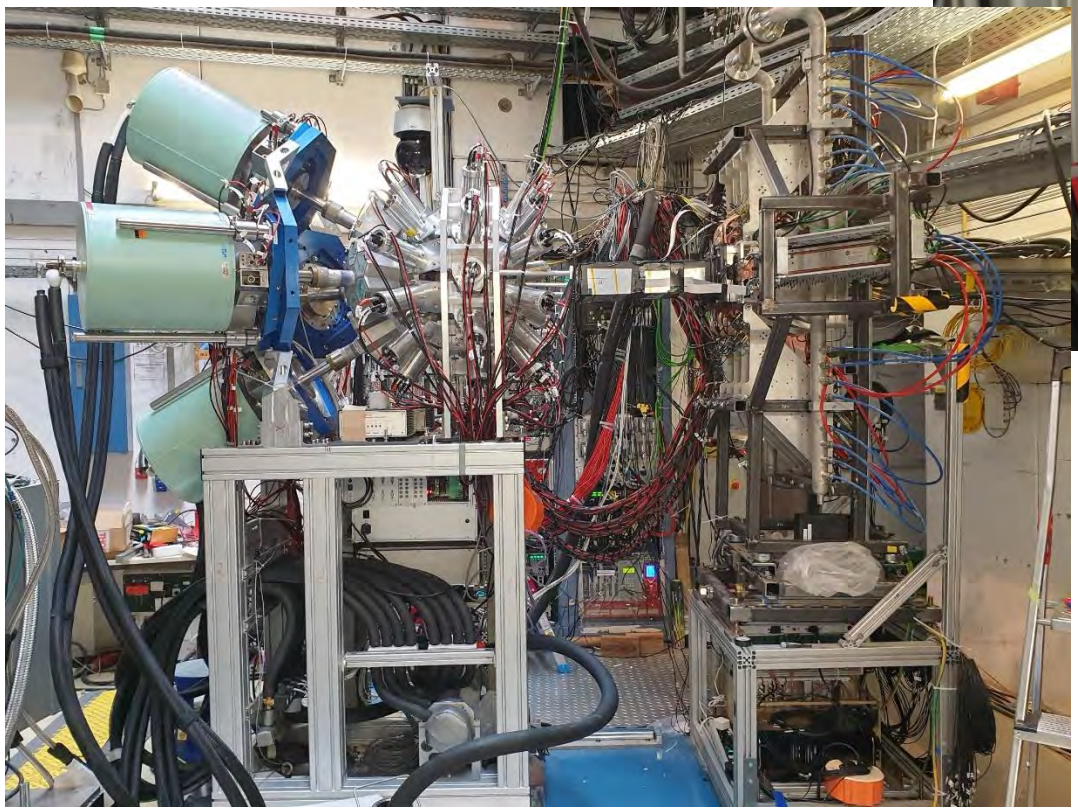
  → Spokespersons and local teams had to decide whether an experiment could be performed

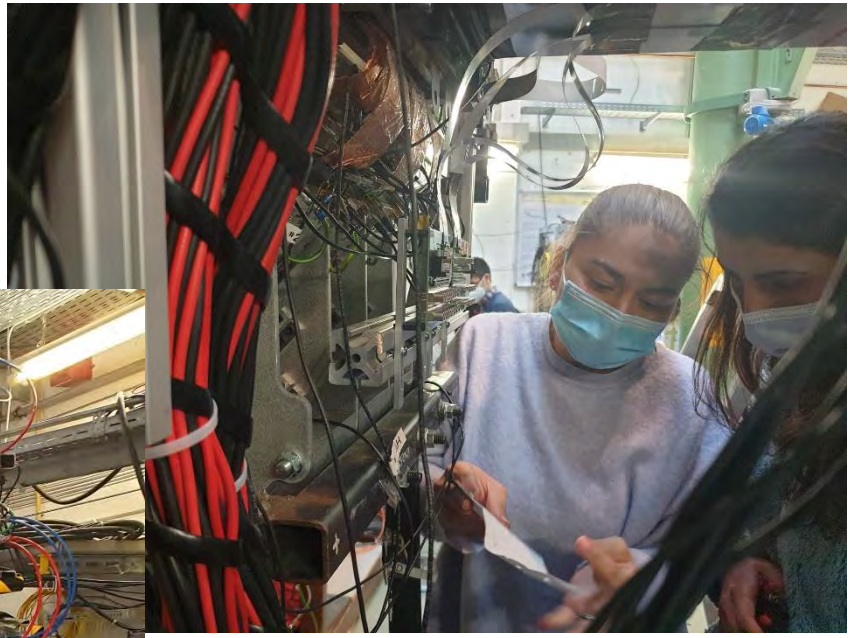
- ~50/70% of the NUSTAR-SIS18/UNILAC experiments could be performed
- Extended commissioning of **all NUSTAR equipment** incl. **FRS/ESR**

→ **Most DESPEC experiments shifted to 2021**

Preparation of DESPEC 2021

28 HpGe detectors FATIMA Wide AIDA





T. Arici and G. Aggez from Istanbul University

FAIR NUSTAR JG

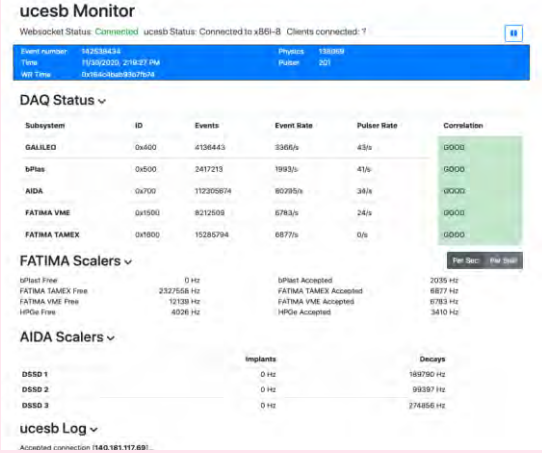
Remote Operation and Cooperative Working

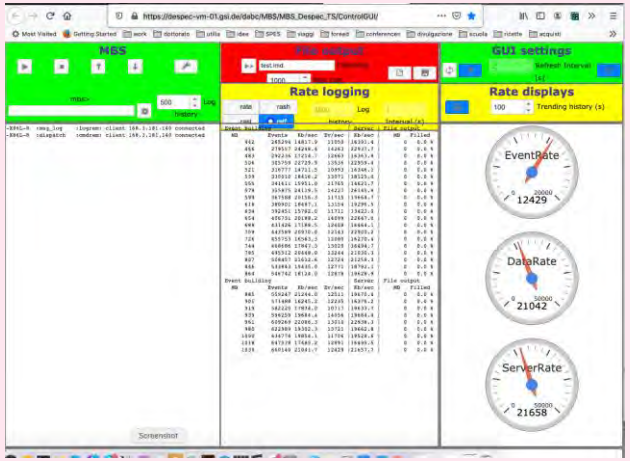
The Virtual Messhütte has been established

- Remote monitoring and control of detectors/DAQs
- 24/h Zoom sessions with breakout rooms
- E-LOG
- Instant messaging platforms

Experiment control

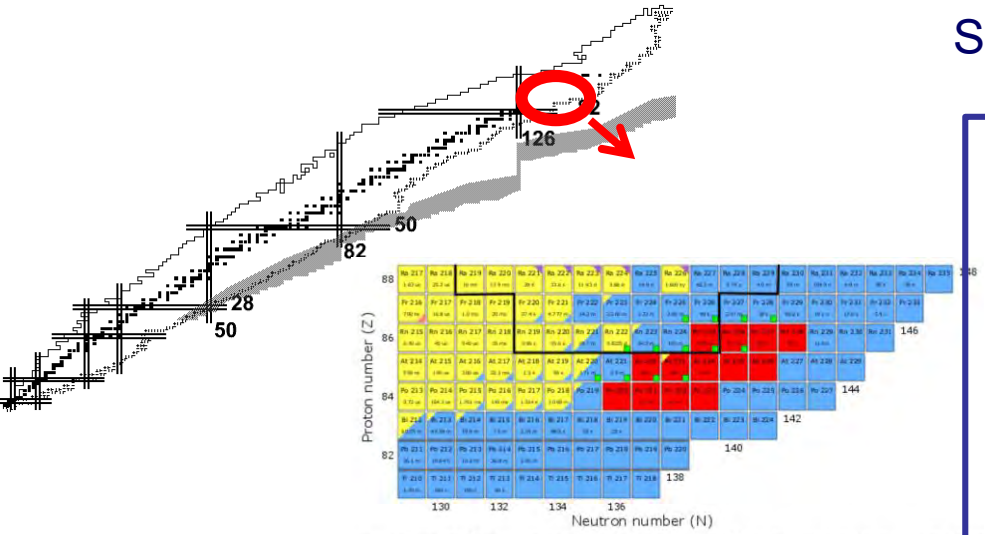
DAQ rates monitoring
Time sorter control
Time machine correlations
UCESB
FRS scalers
Go4 Online monitoring
Nearline histogramming
Remote oscilloscope
Grafana
Autofill
…

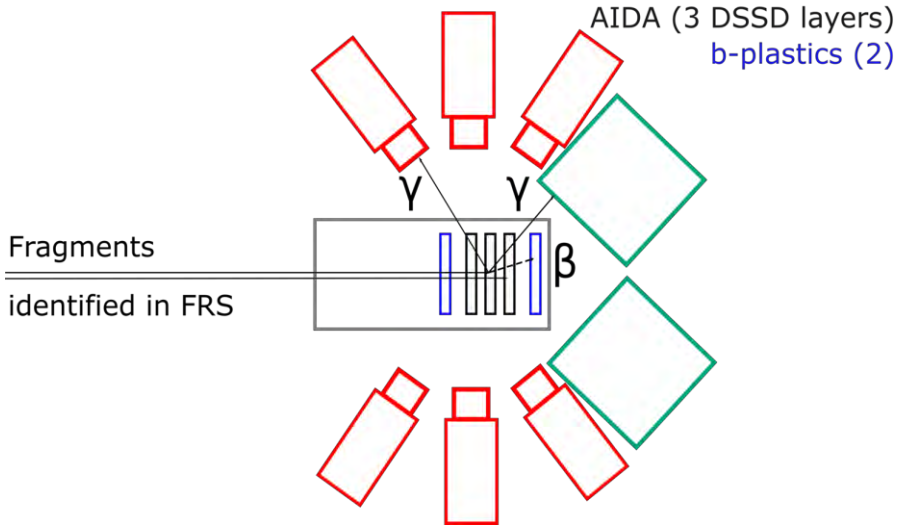




S460 Investigation of the A~225 island of octupole deformation

Spokesperson: *G. Benzoni*





1. Octupole deformation around A~225: Study the octupole degree of freedom and quadrupole-octupole correlations at the far end of the IOD

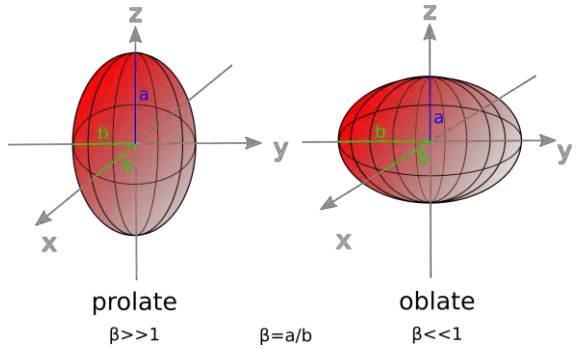
2. Test of nuclear models for r-process: Obtain new beta-decay information beyond N=126

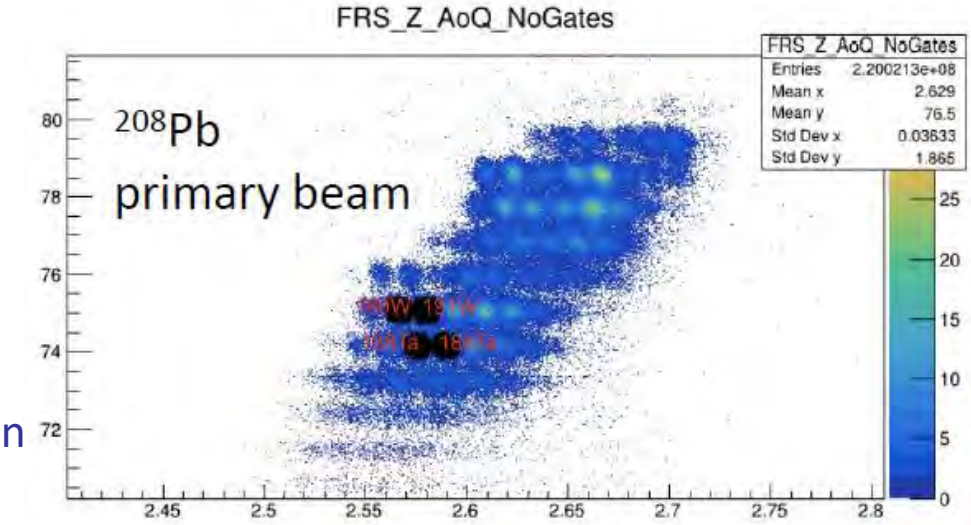
3. Shape isomers in ^{220,222}Po: Prove the existence of super-deformed bands at low excitation energies

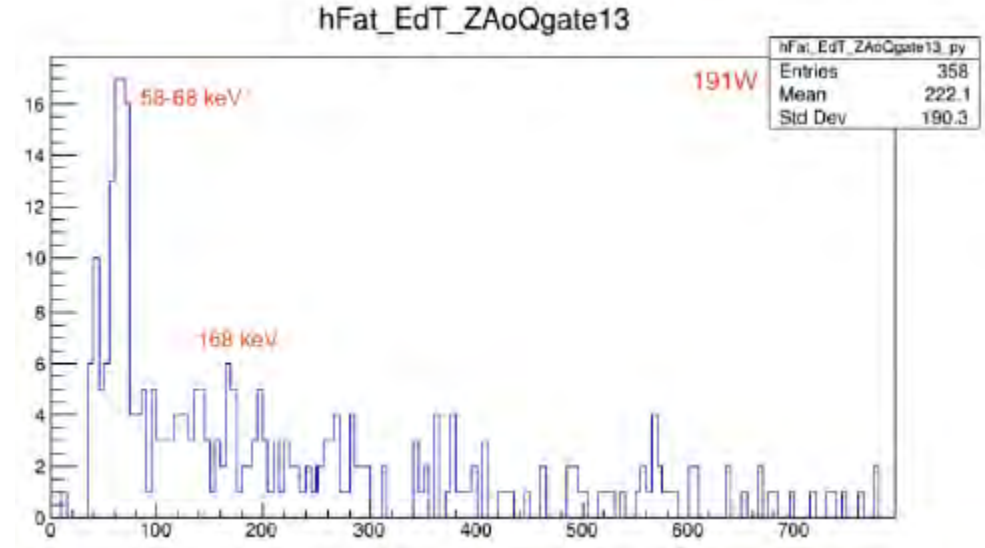
The fragments are implanted in AIDA, the β particles emitted by the β-decays are detected by both AIDA and the two b-plastic scintillators. The γ rays are detected by the FATIMA array and two EUROBALL clusters.

S452 Shape evolution in the Hf-W-Os region

Spokespersons: *V. Werner, P. Regan*



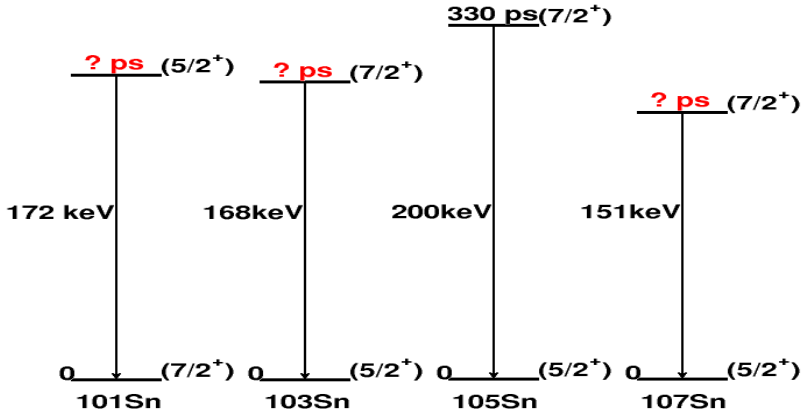


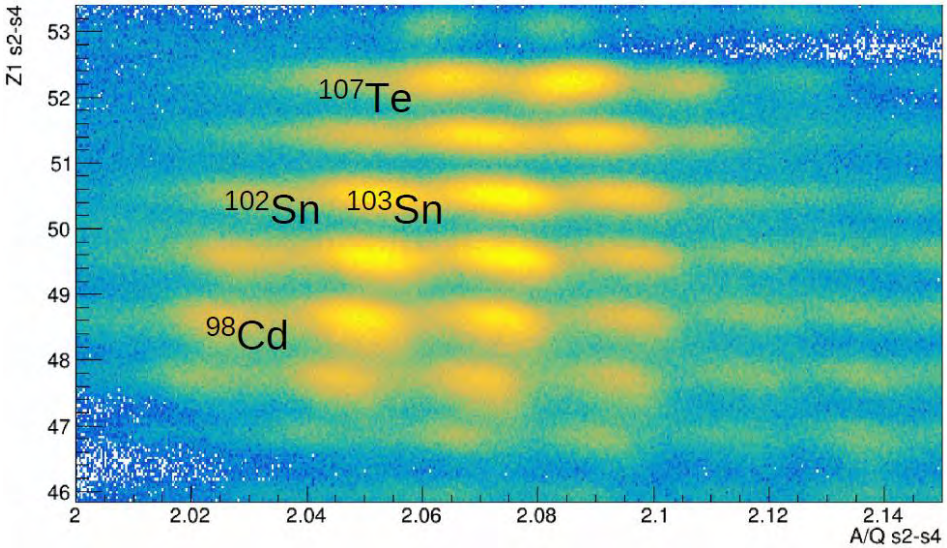


- Shape evolution in the Hf-W-Os region toward magic number N=128
- Transition from prolate to oblate nuclear shapes
- Isomerism and underlying structure relevant for nuclear synthesis and astrophysics
- Beta- and isomer-delayed fast-timing measurements, gamma-ray spectroscopy

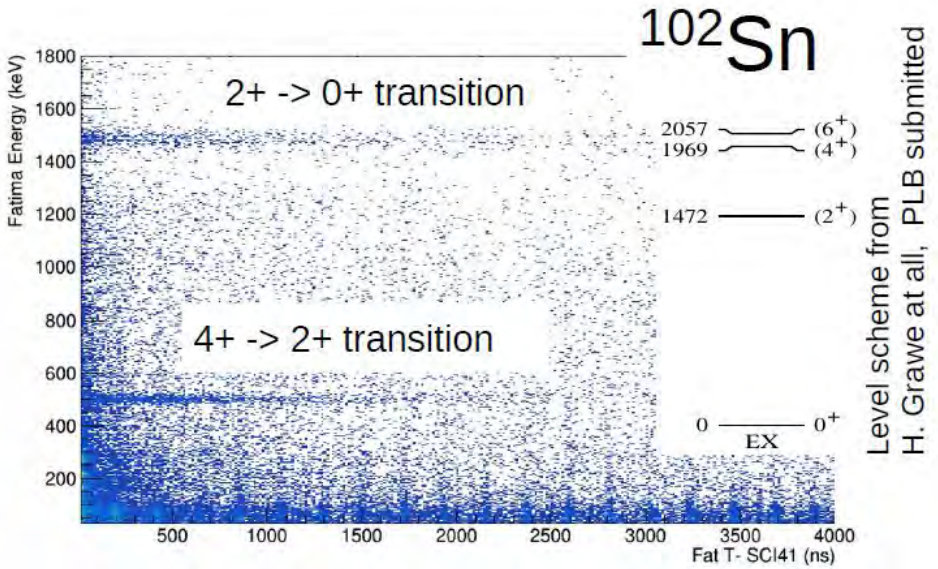
S496 Core-breaking in the most neutron-deficient Tin isotopes

Spokespersons: *G. Zhang, D. Mengoni*



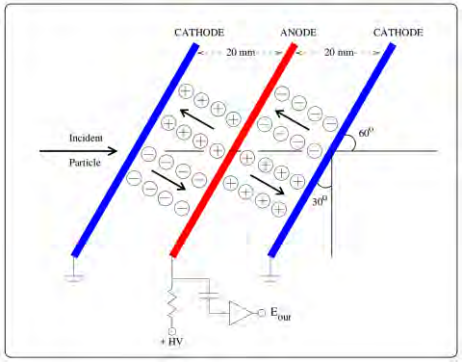


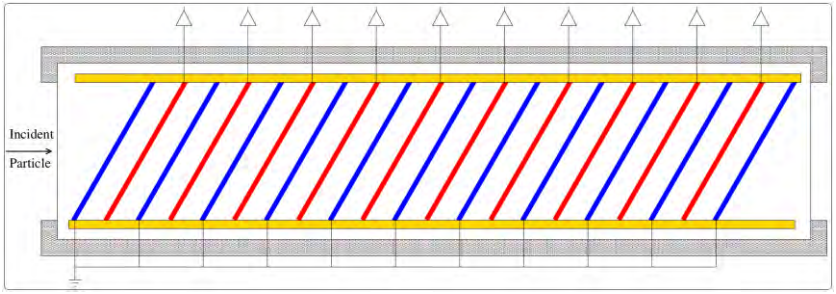
- No lifetime measurements in Sn isotopes lighter than ^{105}Sn have been performed so far (only rel. Coulex for ^{104}Sn).
- 103Sn: the measurement of B(M1 : 7/2+ → 5/2+) will be essential to shed light on the core-breaking contribution of the (7/2+) and (5/2+) states towards 101Sn.
- *B(E2 : 4+ → 2+) value in ^{102}Sn can probe the nature of first 4+ and 2+ states through the interplay of pairing and quadrupole interactions.*



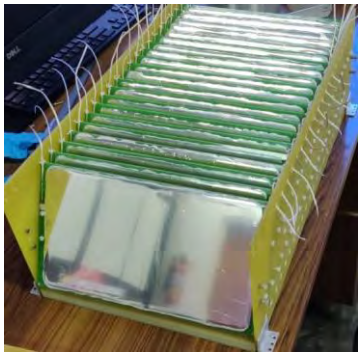
S470 Testing of the TEGIC Detector for LEB Experiments

Spokesperson: *A. Jhingan*





Tilted Electrode Gas Ionizaton Chamber



Aluminized
Mylar Electrodes

Operation principle 30° tilt for different trajectory of charge carriers and incident particles

- Particle detector for nuclear charge (Z) identification of secondary beam species
- Multiple differential energy loss measurements: DE – DE technique
- Tilted Electrode Geometry for fast counting and high count rate handling capability
- Ten differential energy loss signals

Conclusions

- NUSTAR at GSI/FAIR enables unique and important contributions to our understanding of the atomic nucleus
- Planned and available instrumentation is state-of-the-art
- Execution of NUSTAR Phase-0 experiments at GSI has started recently (hindered but not stopped by the corona pandemic)
- A strong experiment programme with more and more novel detectors is planned for the coming years at GSI until the early implementation of FAIR will start in 2025
- New collaborators are highly welcome
- Various fields of engagement: physics (experiment and theory), instrumentation development, and infrastructure