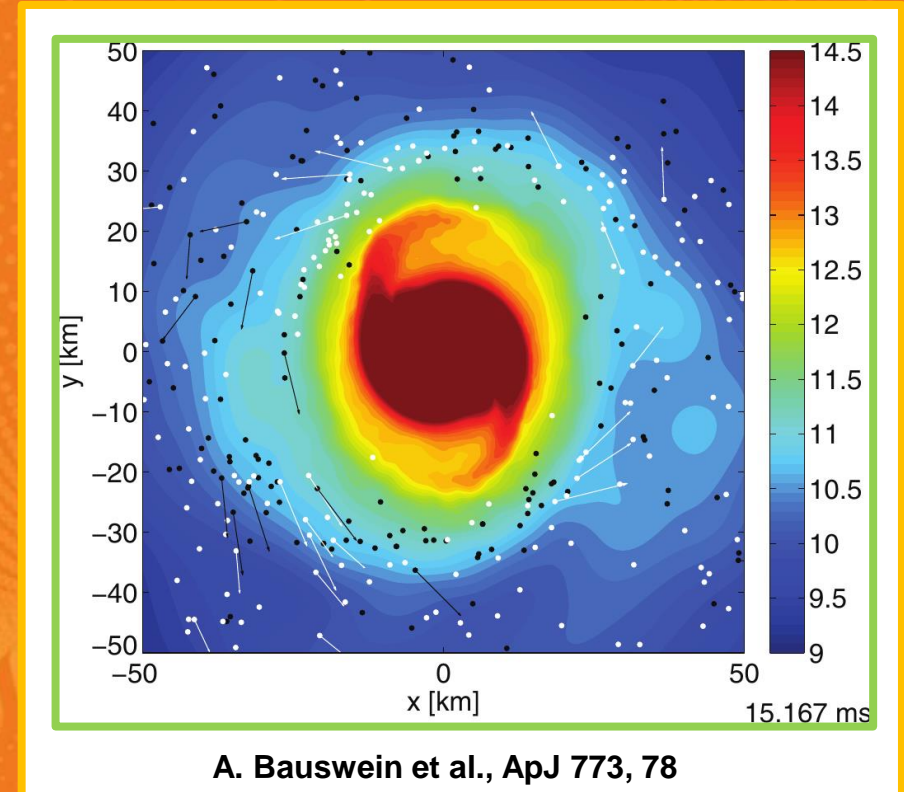


NUSTAR at SIS

Christoph Scheidenberger
(GSI, JLU, HFHF)



ENNA – „where“ and „what“ it is (in POF)

- Research **Field**: Matter
- Research **Program**: MU (Matter & Universe)
- Research **Topic** T2: CML (Cosmic Matter in the Laboratory) – F.Maas, T.Galatyuk
- Subtopics:
 - ST1: Hot and dense matter
 - **ST2: Exotic Nuclei and Nuclear Astrophysics**
 - Theory and Experiment
 - GSI (UNILAC+SIS18) and FAIR (Super-FRS, FS/ES, FS++ and beyond → LEB, CR...)
 - LK-1 and LK-2
 - ST3: Properties of hadrons and their excitations spectrum



Main pillars of sub-topic 2 (ST2 - ENNA) „Exotic Nuclei and Nuclear Astrophysics“:

- Superheavy element research (NUSTAR-SHE) → **C.E. Düllmann, M. Block**
- Experiments at SIS energies → **C. Scheidenberger**
- Theory for nuclear structure, astrophysics, reactions → **G. Martinez-Pinedo**
- Construction of Super-FRS → **H. Simon**

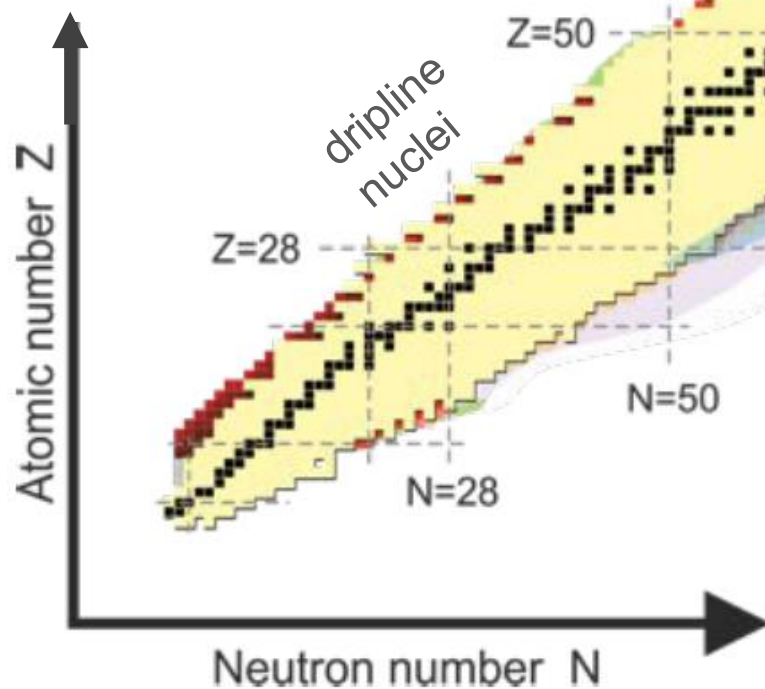
Contents of this contribution:

- Experiments with exotic nuclei at SIS (i.e.: SIS-18, SIS-100, ...) (including HISPEC/DESPEC, R3B, ILIMA, EXL, Super-FRS EC)
- Activities in POF-IV and plans for POF-V

Key questions and strategies

Key questions and applications:

- * Limits of stability, heaviest elements
- * Magic numbers, shell structure far-off stability, neutron skins, halo nuclei, neutron matter
- * Detailed understanding of the strong force, its isospin dependence, global nuclear models
- * New phenomena, new nuclear decay modes
- * Stellar nucleosynthesis, abundances, age and origin of chemical elements
- * Test of fundamental symmetries, search for possible extensions of the SM
- * Nuc.medicine & imaging, nuc.energy, transmutation, ...



Z=82

Z=50

Z=28

dripline nuclei

N=28

N=50

N=82

N=126

r-process

terra incognita

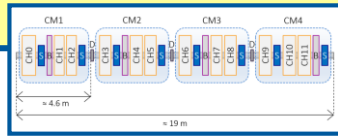
superheavy elements

Strategies:

- * **Observation of spontaneous nuclear decays, emission of particles resp. radiation**
 - Analysis of emitted particles and their properties, kinematics etc.
 - α -, β -, γ -decay spectroscopy, ...
- * **Response to external fields resp. energy (el.-mag., leptonic and hadronic probes)**
 - Atomic and nuclear reactions, analysis of particle dynamics
 - Laser spectroscopy, nuclear reactions, electron scattering, mass spectrometry, ...
- * **Understanding of properties and phenomena, test of models and predictions**
 - Test of hypotheses, nuclear and astrophysical modeling, phenomenological, analytical and numerical methods
 - Interactions, models (QCD, microscopic, SM, ...)

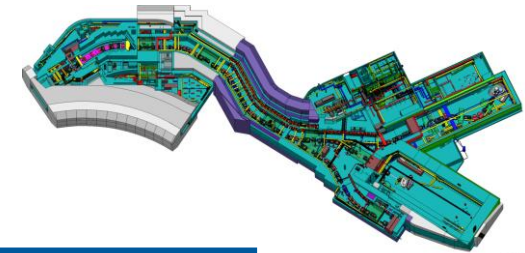
ENNA - unique instruments to approach the big quests

Superheavy elements
SHIP, SHIPTRAP,
TASCA, chemistry experiments
HELIAC



Radioactive beams & dripline nuclei
FRS-ESR/CRYRING, Cave-C, Cave-M
Phase-0: FAIR precursor experiments
(R3B, H/D, EXL, ILIMA, Super-FRS EC)

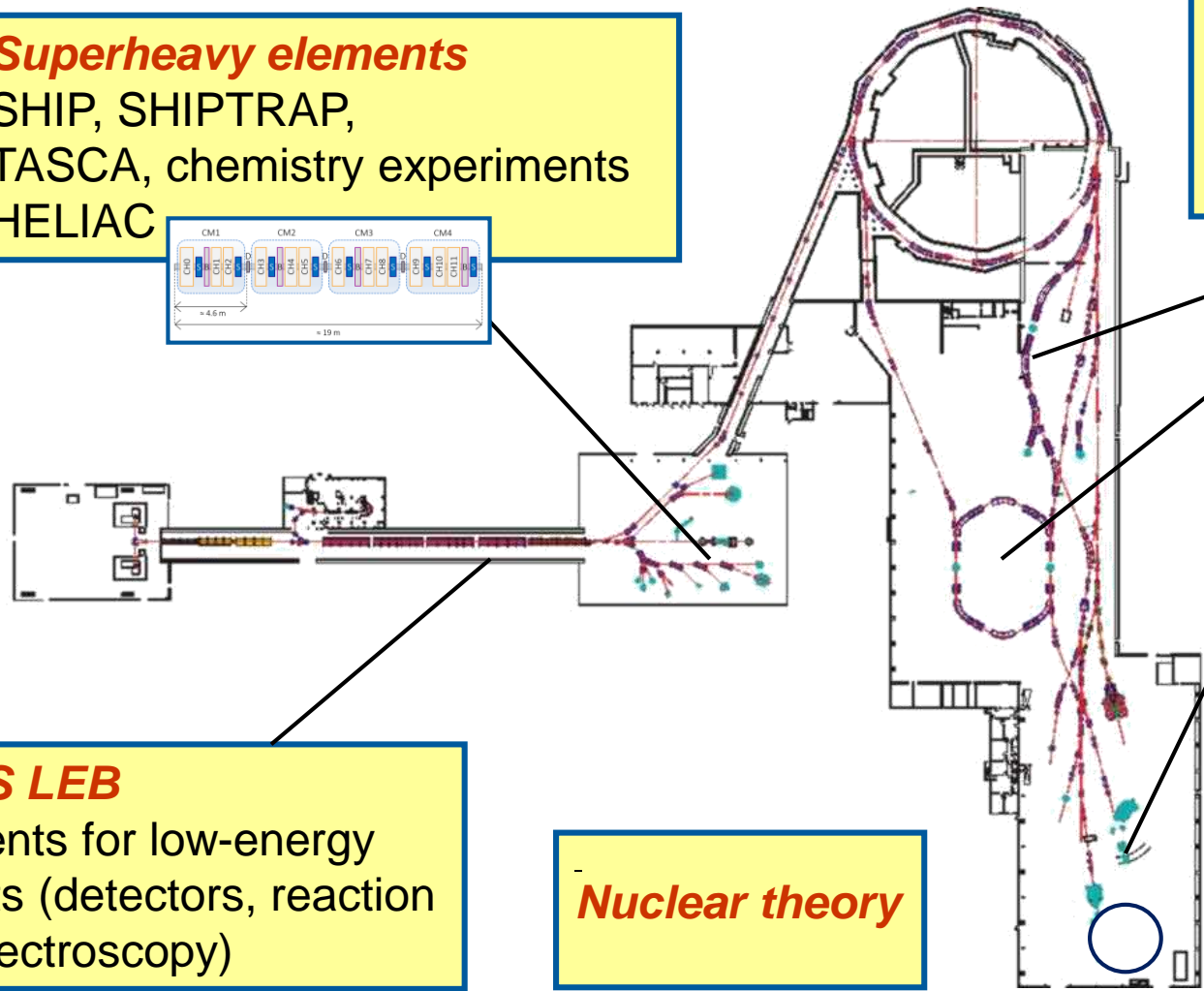
**NUSTAR facility with
Super-FRS at FAIR**
ES/FS, FS++, Phase-1



Nuclear astrophysics
(Astronomy, observations)
Astrophysical modeling
Nuclear physics data
Network calculations

Nuclear theory

Super-FRS LEB
Developments for low-energy
experiments (detectors, reaction
studies, spectroscopy)



ENNA contents of POF-IV (1)

In general:

- Combined effort of campus Darmstadt and HIM/Univ.MZ, i.e.: no separation of science questions according to different locations/institutes (GSI, HIM)
- Strong link and overlap of theory and experiment
- Overall goal: preparation and construction of NUSTAR experiments at Super-FRS@FAIR, including pilot experiments at GSI in FAIR Phase-0 and theory developments

Theory:

- Theory of superheavy elements, exotic nuclei, and application to nuclear astrophysics, support of the experimental groups working on different facets of nuclear physics
- Development of a full set of astrophysical reaction rates for r-process based on microscopic models including neutron captures, beta-decays and fission
- Determine signatures of the r-process in kilonova light curves and their sensitivity to nuclear physics
- Constrain the nuclear equation of state from collective behavior in heavy ion collisions in the context of astrophysical constraints from neutron stars/neutron star mergers

Experiment:

- Preparation of NUSTAR FAIR Phase-1 experiments in terms of simulations, development, construction, test and debugging of experiments and related setups, algorithms and analysis software, especially via the execution of commissioning and pilot experiments during FAIR Phase-0 using demonstrators and start versions of MATS/LASPEC, R3B, HISPEC/DESPEC, ILIMA and Super-FRS spectrometer experiments.

ENNA contents of POF-IV (2)

Physics and chemistry of superheavy elements, experiments at UNILAC energies:

- Reaction dynamics studies to extend the chart of nuclei towards higher Z (new elements, as soon as cw-linac is available) and higher N (closer approach towards center of island of stability) with GSI beams and potentially FAIR rare isotope beams.
- Detailed nuclear structure studies via decay spectroscopy, pushing into the region beyond Mc (element 115), which is the heaviest currently studied element; complemented by hyperfine structure studies beyond nobelium.
- Fingerprinting individual isotopes in the region beyond Z=113 for direct atomic number assignments
- High precision direct atomic mass measurements at SHIPTRAP (Z>100) and at TRIGA-TRAP (long-lived isotopes up to Cf)
- Atomic physics studies via laser spectroscopy pushing beyond Z=102
- Chemical studies of atomic systems (Z~112-116) and molecular systems (Z~106-109)
- Tailor-made samples for interdisciplinary research (e.g., Th-229 atomic clock and fundamental physics work)

Radioactive beams, experiments at SIS energies:

- Production of new isotopes and study of their ground-state properties
- Reaction studies at high beam and high excitation energies
- Studies of collectivity, shapes and shell structure far off stability
- Exploration of nuclear properties around the 3rd r-process abundance peak
- Study of light and medium-heavy hypernuclei
- Investigation of the nuclear EoS and of the role of tensor forces in nuclei

CML – ST2: milestones

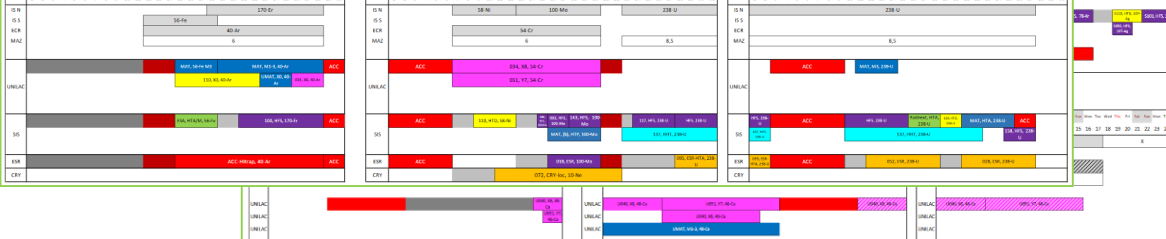
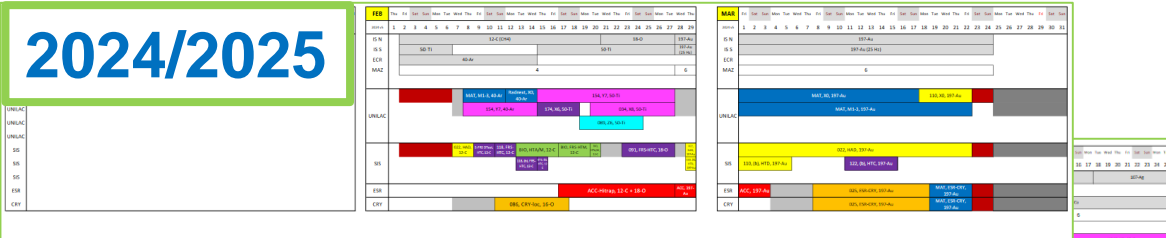
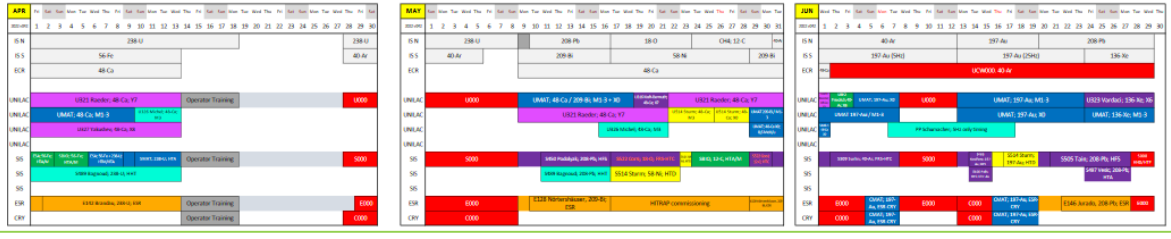
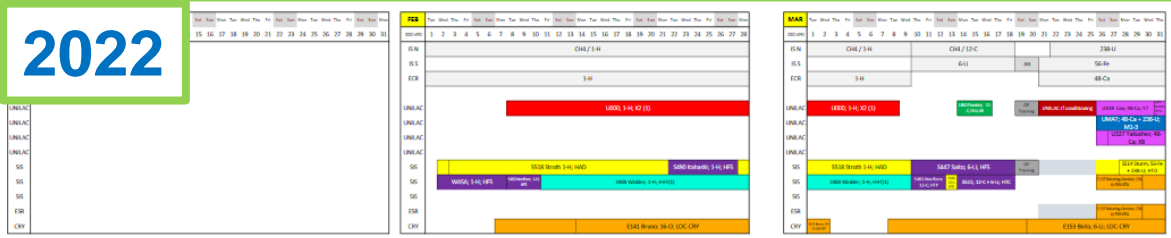
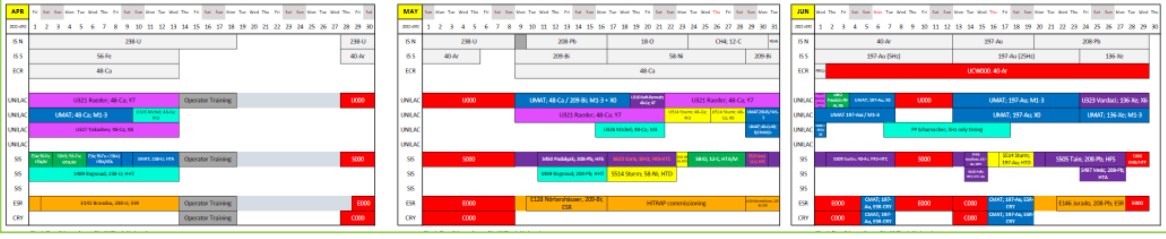
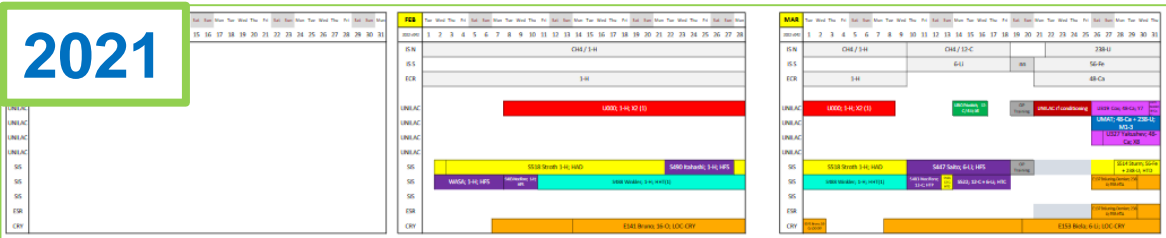
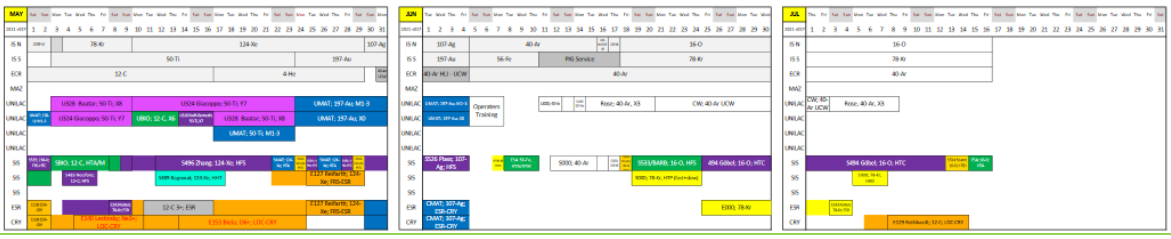
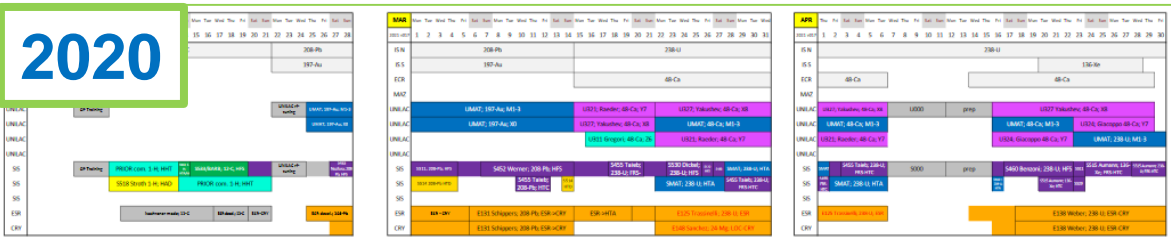
Table 2: Overview of milestones of the topic Cosmic Matter in the Laboratory.

Number	Year	Milestone
CML-14	2025	FAIR phase-0 NUSTAR experiments at FRS completed. Ready for experiments at Super-FRS @ FAIR
CML-15	2025	FAIR phase-0 NUSTAR experiments at SHIP(TRAP) and TASCA completed

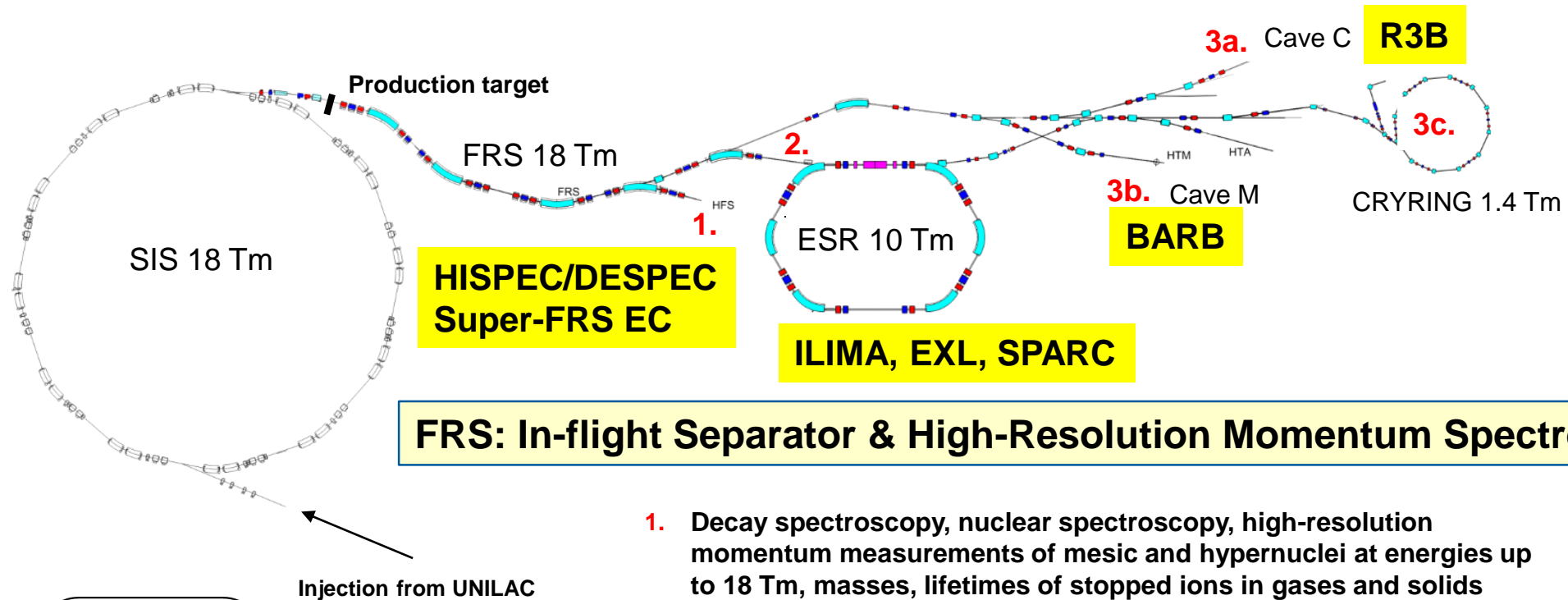
... In view of the complexity of the FAIR project, there exists a risk that the start of FAIR might be delayed, impacting both the science output and the attraction to the users. The FAIR phase-0 program allows mitigating this risk by early commissioning and usage of FAIR detector instrumentation, and by offering regular physics runs to the GSI/FAIR users - thereby bridging the transition time until the start of FAIR. ...

→ Milestones and mission accomplished

Experiments in FAIR Phase-0 performed successfully



Experiments with radioactive beams at SIS-18 in FAIR Phase-0



FRS: In-flight Separator & High-Resolution Momentum Spectrometer

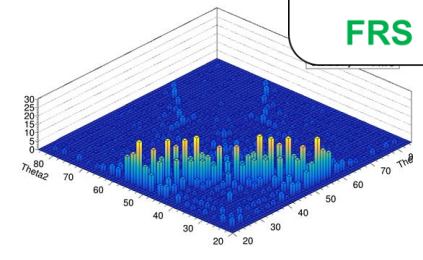
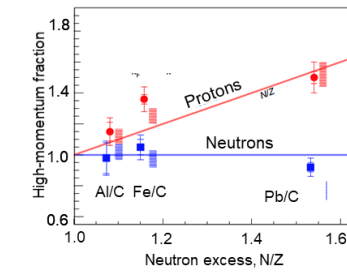
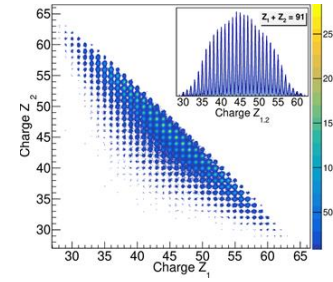


1. Decay spectroscopy, nuclear spectroscopy, high-resolution momentum measurements of mesic and hypernuclei at energies up to 18 Tm, masses, lifetimes of stopped ions in gases and solids
2. Lifetimes of highly-charged ions, isomeric beams, direct reactions, stored ions at 400 MeV/u – few MeV/u , bare and few-electron ions
- 3a. Reactions studies in complete kinematics
- 3b. Bio-medical experiments with positron emitters
- 3c. Astrophysical reaction studies in the Gamow window

Scientific highlights from FAIR Phase-0 experiments

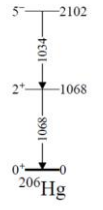
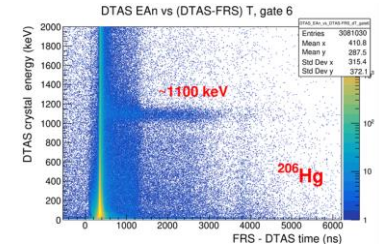
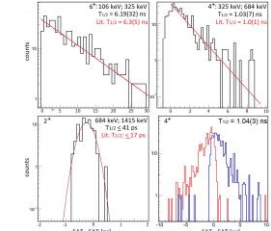
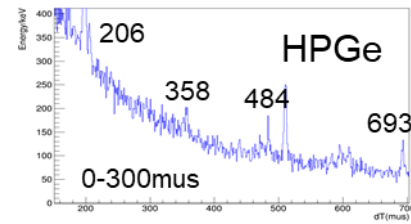
R3B:

- Fission studies with full kinematics detection (fiss. barriers in exotic nuclei, new fission modes)
- Study of short-range correlations in exotic nuclei
- Study of many-neutron configurations (e.g. in ^{16}C)



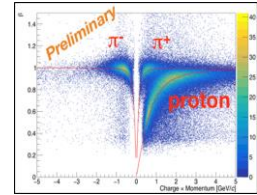
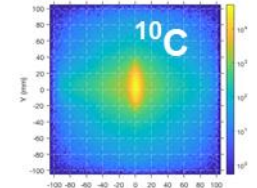
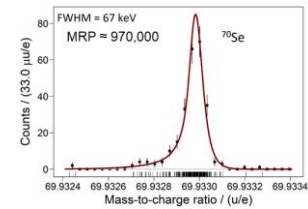
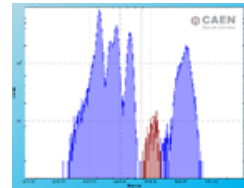
HISPEC/DESPEC:

- Core-breaking in very n-deficient Sn isotopes
- Lifetime measurements in $N \approx Z$ nuclei near ^{100}Sn
- Investigation of octupole deformation around $A=225$
- Study of nuclear shape evolution near $A=190$, beta strength near $N=126$



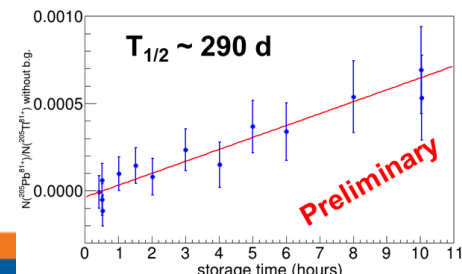
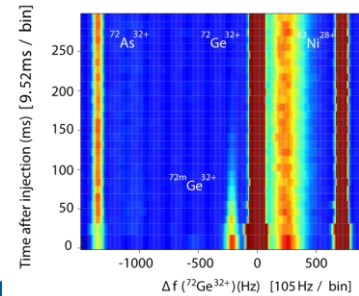
Super-FRS Experiment Collaboration:

- Search for fission isomers prod. via projectile fragmentation
- Direct mass measurements of heavy $N=Z$ and $N=Z-1$ nuclides
- PET imaging and nuclear interaction studies for ion-beam therapy with positron emitters
- Search for eta'-mesic nuclei and light hypernuclei studies



ILIMA:

- Bound-state beta decay of bare ^{205}Tl ions
- Nuclear two-photon decay in swift heavy ions





Report on NUSTAR from ECE/ECSSG (05/2022)

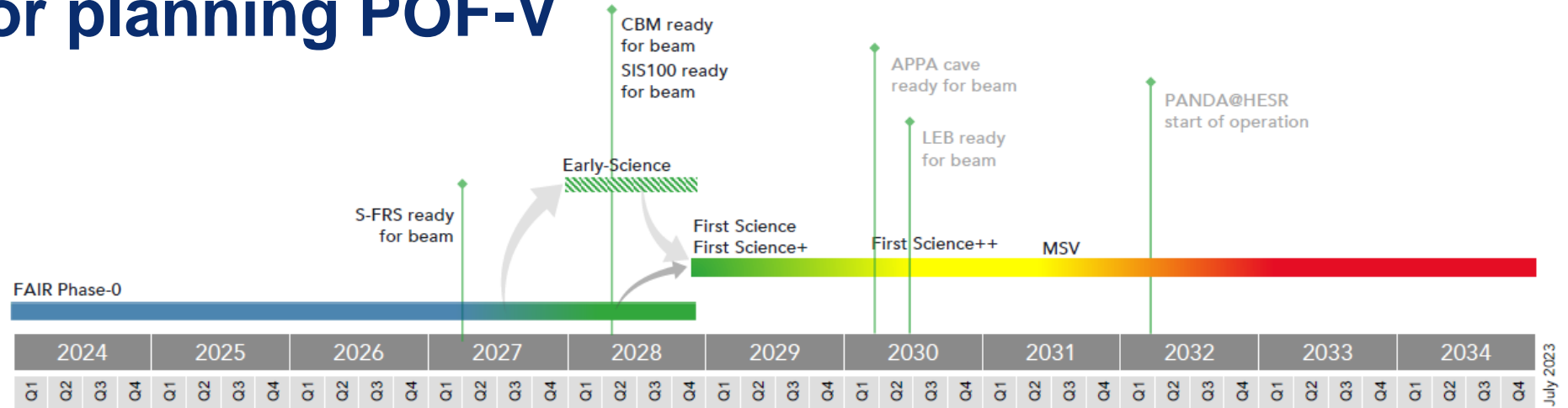


- The Science case remains strong and essentially not delayed - however the execution is affected due to Super-FRS schedule slip.
- Phase 0 is on-going and working very well with several tests, commissioning, and experimental campaign being successfully executed:

Examples:

- R³B executed a number of excellent campaigns including the test of the new tracker detector design (ALPIDE)
 - ALPIDE detectors tested at CERN and Juelich and results look very promising – TDR in preparation
 - DESPEC Astro-physics and nuclear structure, including N=126 measurements with ~100 people back on site for experiments.
 - WASA-FRS experiments as pilot test completed
 - ILIMA measurements on highly charged ions, life-time and decay measurements
- Phase 0 could benefit from extension, depending on Russia impact on overall schedule
- Phase 0 is very important and will be essential to help the entire community and collaboration.
- Day-1 preparation is progressing very well
 - All elements are on-track for completion as planned, impact of Russia conflict needs to be addressed
 - Early physics book is being revised in detail and considering practical aspects.
 - LCM workshops are good and useful, we encourage to continue.

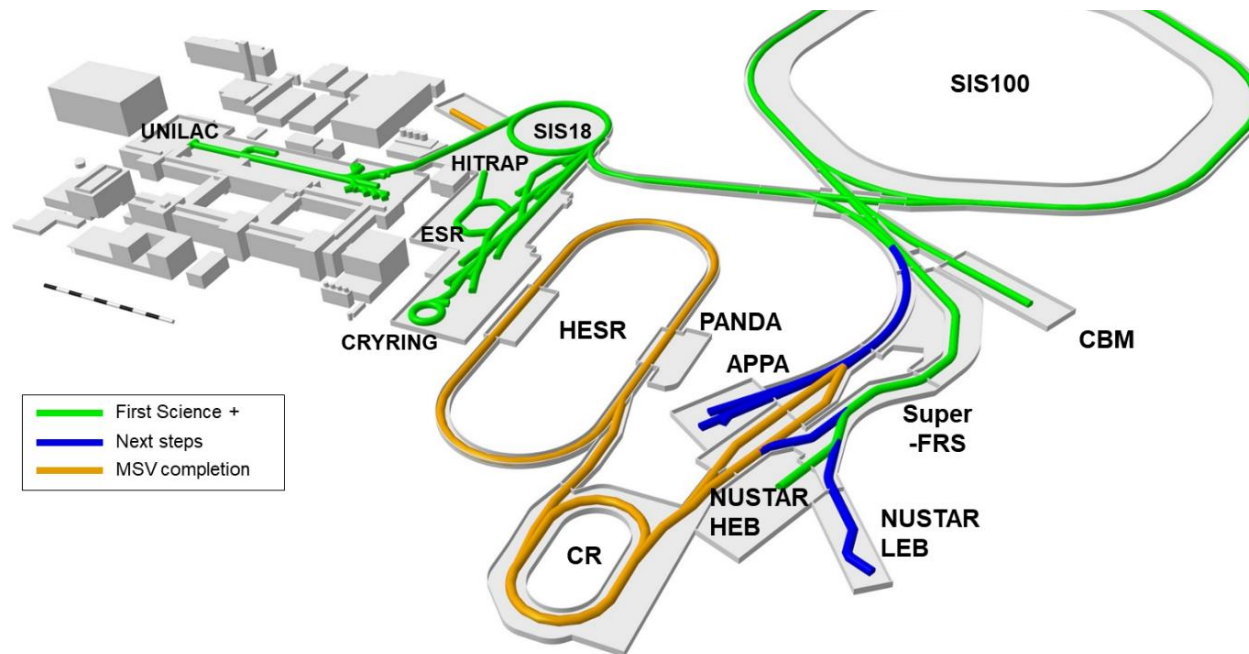
Basis for planning POF-V



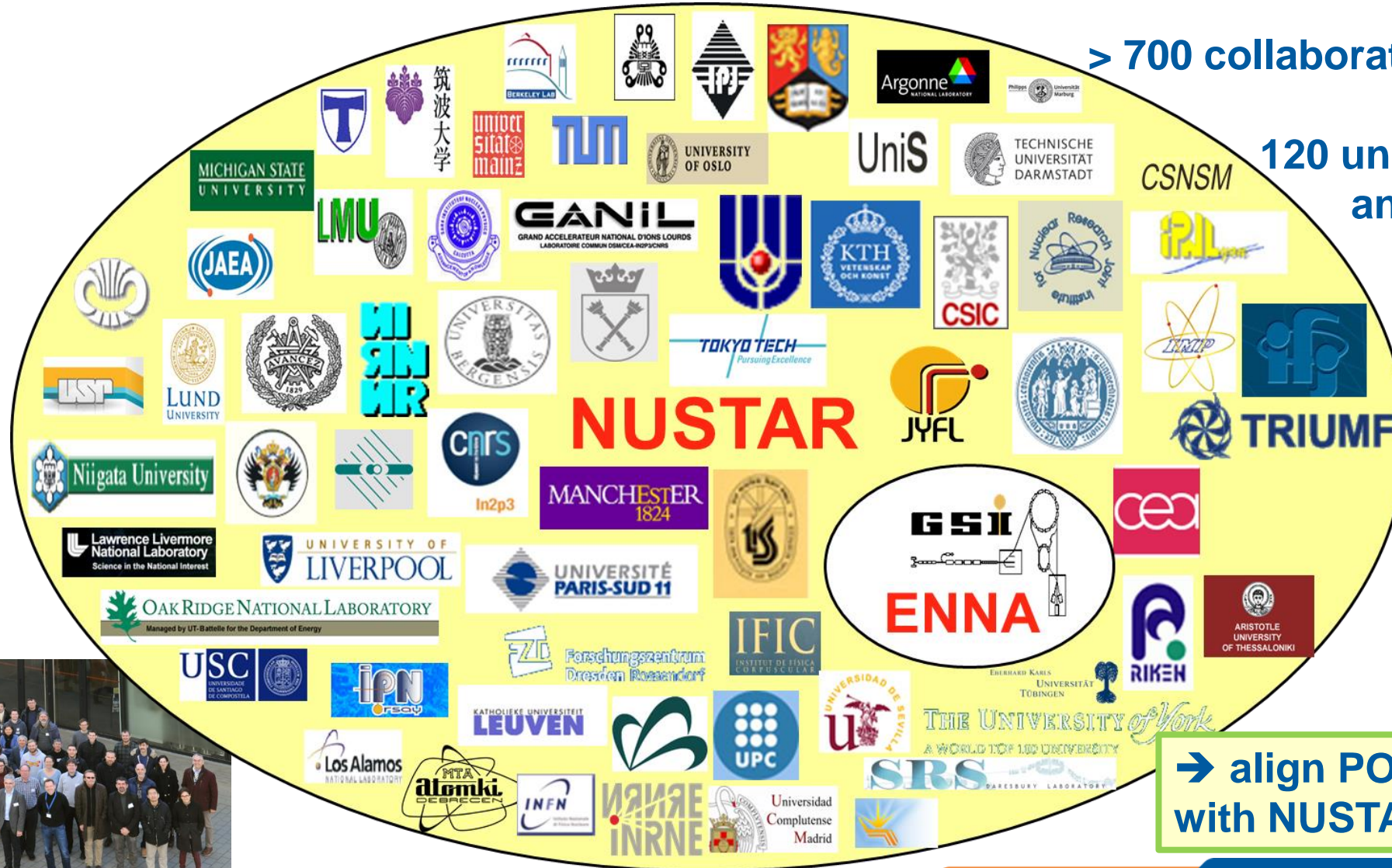
Working assumption pending on decisions by the shareholders of FAIR.

Facilities already in operation are expected to continue to serve experiments during all the phases of the FAIR project.

Steps beyond FS+ require additional funding, assumed to be in place by Q3 2025, and alternative CR layout according to MAC recommendation.



ENNA - the GSI contribution to the NUSTAR collaboration, with NUSTAR a driving force of FAIR science



> 700 collaborators

120 universities and institutes

36 countries

→ align POF-V contents with NUSTAR objectives!



Collaboration Meeting 2023



Research focus of ENNA (resp. NUSTAR) from Phase-0 via ES/FS to “Day 1” + 5(?)y

- **Understanding the 3rd r-process peak** by means of extensive measurements of lifetimes, masses, neutron branching ratios, dipole strength, and the level structure along the **N=126 isotones**
- **Equation of State (EoS) of asymmetric nuclear matter** by measuring the dipole polarizability and neutron-skin thicknesses of **heavy neutron-rich isotopes**
- **Exotics: Hypernuclei** with large N/Z asymmetry and **nucleon excitations** in nuclei

New opportunities at Super-FRS/FAIR allow a wider and wider science program

Construction of NUSTAR detectors for experiments at FAIR

ILIMA

PLEIADES for ILIMA



PLEIADES: TRIUMF in-kind co-ParticLE silicon-scintillator DET new multi purpose $\Delta E - E$ detector available for ESR experiments



Overview of ongoing technical developments



Micro calorimeters



DESPEC Setups for 2027-2030

A.K. Mistry et al., NIM A 1033 (2022) 166662



Cryogenic Stopping for Super-FRS



Christoph Scheidenberger

The core of

- Energy and lifetimes
- Beta-decay
- Lifetimes \rightarrow F
- Level scheme



HISPEC revolves around the core instrument AGATA

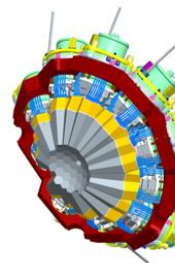
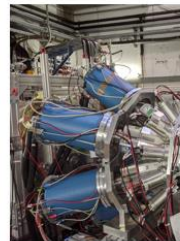
Physics opportunities with the Advanced Gamma Tracking Array: AGATA (W. Kortzen et al., Eur. Phys. J. A (2020) 56:137)

In-beam spectroscopy in exploring excited states and angular momentum

HISPEC experiments their predictive mission of exploring as well as the

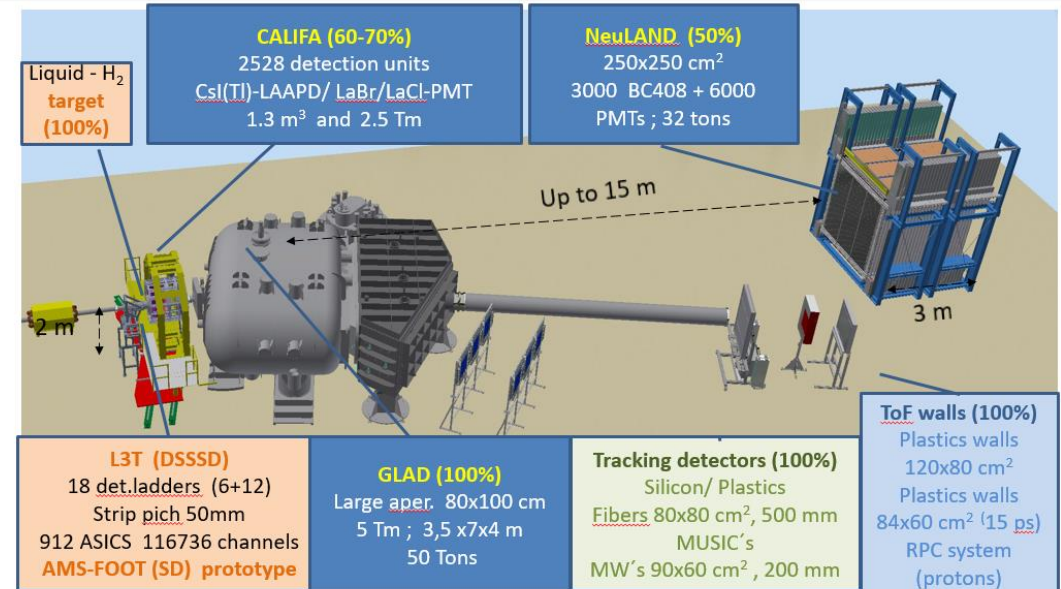
FAST TIMING

FATIMA eff. 2.9%
DEGAS eff. 5% at



R³B

R³B setup ready for move to FAIR site in 2025+



→ Many (sub)systems ready

Strategy towards first science / early science at Super-FRS

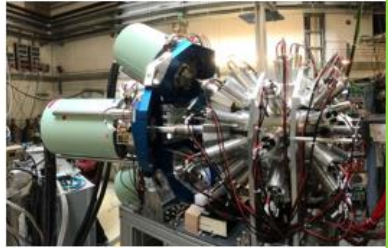


DESPEC Phase-0 campaigns in 2020/2022

a complete picture of the β -decay process requires both high-resolution and high efficiency studies



Large suite of detectors



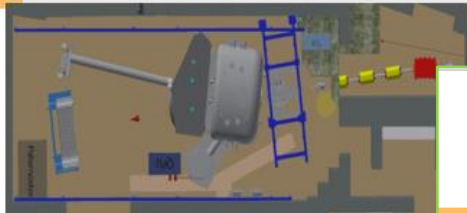
2020

FATIMA-bP
+AIDA single +DI

- ★ Since 2021: Full
- ★ 2022: Improved e
- ★ Successfully com

R³B

FAIR Phase-0 campaigns in 2021/2022



(Super-)FRS Experiment Collaboration: Pilot experiments in 2020-2022



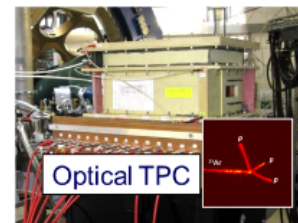
S455 Fission studies @
S515 Constraining ene
the density-dependen
S494 Coulomb dissoci
2021 S455

CALIFA + NeuLAND (12 DP)
+ LH2 + AMS



High-resolution spectrometer experiments with FRS and ancillary detectors
Broad science spectrum:

- **New isotopes**, new reaction studies (e.g. MNT)
- **Exotic nuclei** (proton radioactivity, fission isomers)
- **Atomic-collision** studies
- **Hyper nuclei**: $nn\Lambda$, ${}^3_{\Lambda}H$, ${}^4_{\Lambda}H$
- **Hadron physics**: search for eta-prime mesic nuclei
- **Applications**: nuclear astrophysics, biology, nuclear imaging



2020

- S468 New isotope search „south“ of Pb (N~126), masses and half-lives
- S469 Gas-solid difference in heavy ion stopping
- S474 Direct mass measurements around ${}^{100}Sn$
- S459+ In-flight decay spectroscopy of proton-unbound nuclei and mass meas.
- S482 Mean range bunching

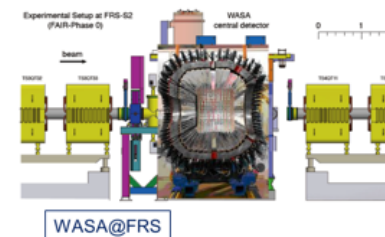
2021

- S526 Mass measurements of heavy N=Z nuclei
- S530 Fission isomer studies at FRS
- S533 Atomic and nuclear interaction studies for ion-beam therapy with β^+ -emitting nuclei

2022 (WASA)

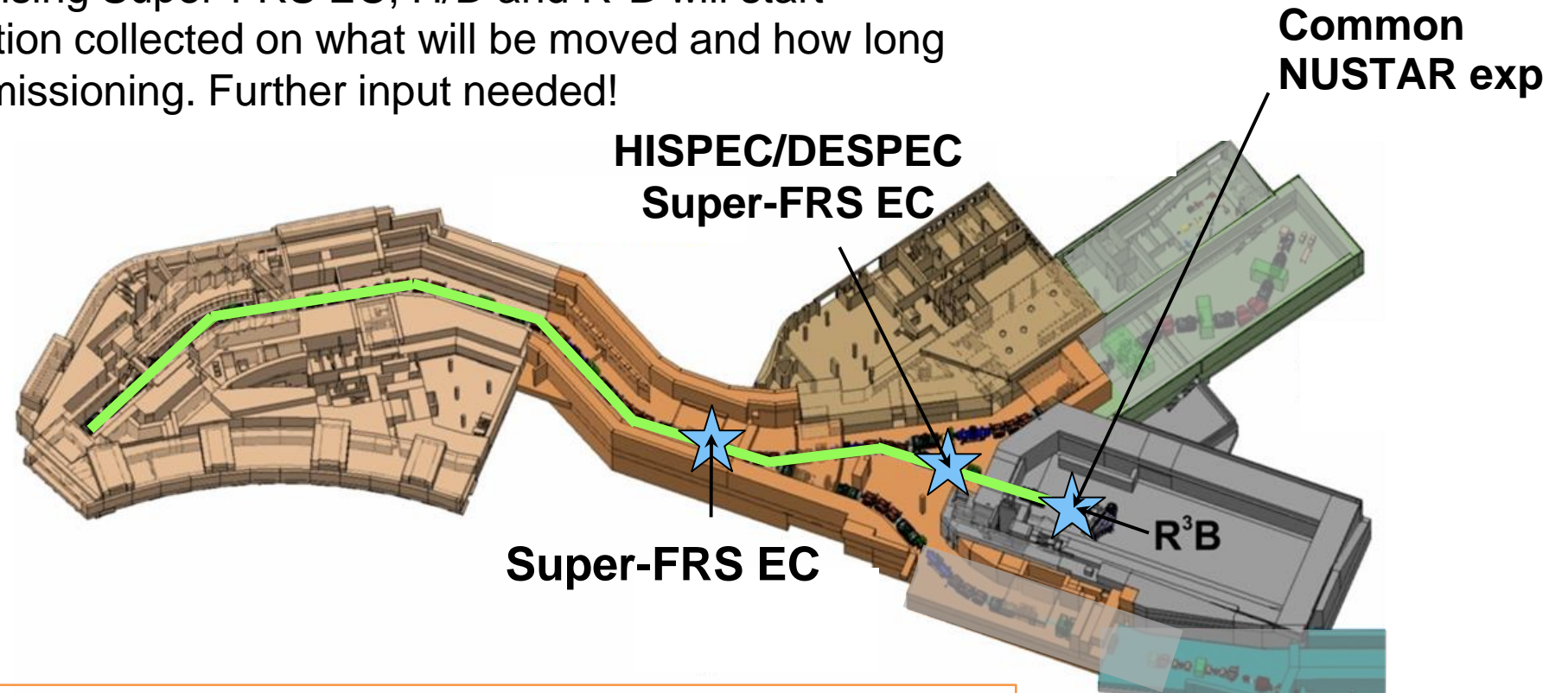
- S447 Studies of hypernuclei by new spectroscopy techniques with WASA@FRS
- S490 Search for eta'-mesic nuclei in ${}^{12}C(p,dp)$ reaction
- U323 Study of MNT processes in different reactions
- S523 In-cell MNT reactions at the FRS Ion Catcher

→ Development of detailed strategy started



NUSTAR ES/FS at the S-FRS

- Common NUSTAR Experiment to take place at FHF2 due to S-FRS commissioning at FHF1
- Then, ES/FS comprising Super-FRS EC, H/D and R³B will start
- Preliminary information collected on what will be moved and how long for installation/commissioning. Further input needed!



- Technical requirements* for Common experiment(s) and ES/FS at Super-FRS met in existing planning
- Small additional costs (€46k) included in Common Fund for platform modification and LN2 contribution

*Inc. electrical power, heat dissipation, cooling water, LN2 and other technical gases

NUSTAR Strategy towards FS

Handover “cave ready for installation”

HE Cave Handover from Super-FRS

S-FRS M12

Q4 2027

Common NUSTAR experiment @ FHF2

NUSTAR Early Science

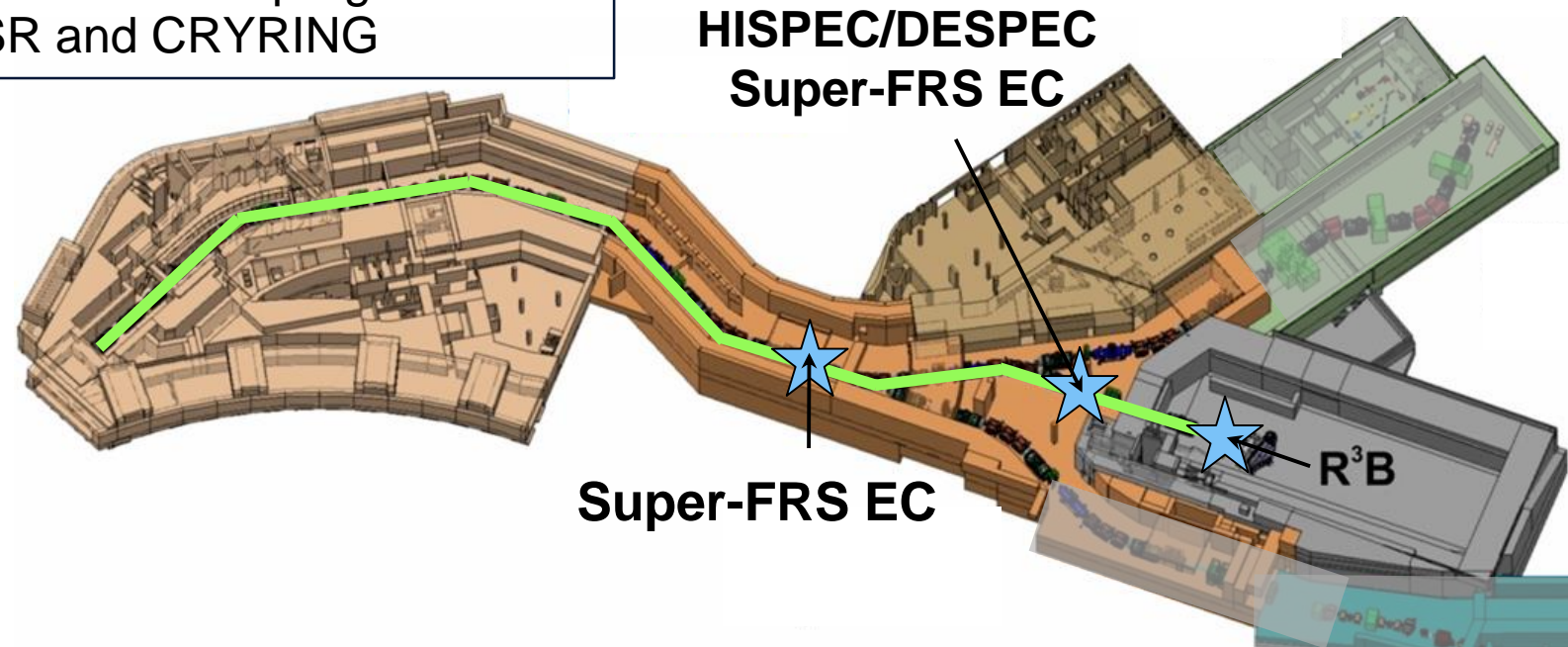
NUSTAR First Science

NUSTAR ES and FS:

individual sub-collaborations (**Super-FRS EC**, **partial HISPEC/DESPEC and R3B**) running PAC-approved experiments at S-FRS focal planes, continuation of the **SHE** program at UNILAC and **ILIMA** at the ESR and CRYRING

Detailed installation timelines to be developed and refined in LCM workshops

New “NUSTAR Technical Integration for ES” team planned



NUSTAR Strategy beyond FS (2028+)

Handover "cave ready for installation"

HE Cave Handover from Super-FRS

S-FRS M12

Q4 2027

Common NUSTAR experiment @ FHF2

NUSTAR Early Science

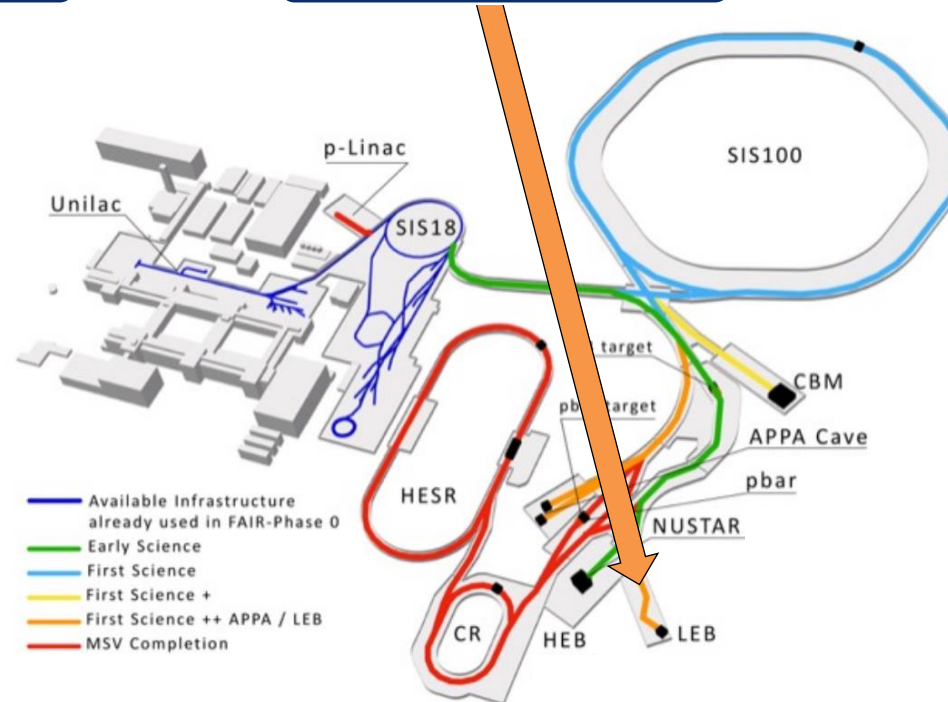
NUSTAR First Science

Funding decision on FS++ (Low Energy Branch) aimed for in **2025**

Low Energy Branch operation beginning **2030**

New experiment opportunities:

- AGATA
- MATS
- LaSpec



NUSTAR Strategy beyond FS (2028+)

Handover "cave ready for installation"

HE Cave Handover from Super-FRS

S-FRS M12

Q4 2027

Common NUSTAR experiment @ FHF2

NUSTAR Early Science

NUSTAR First Science

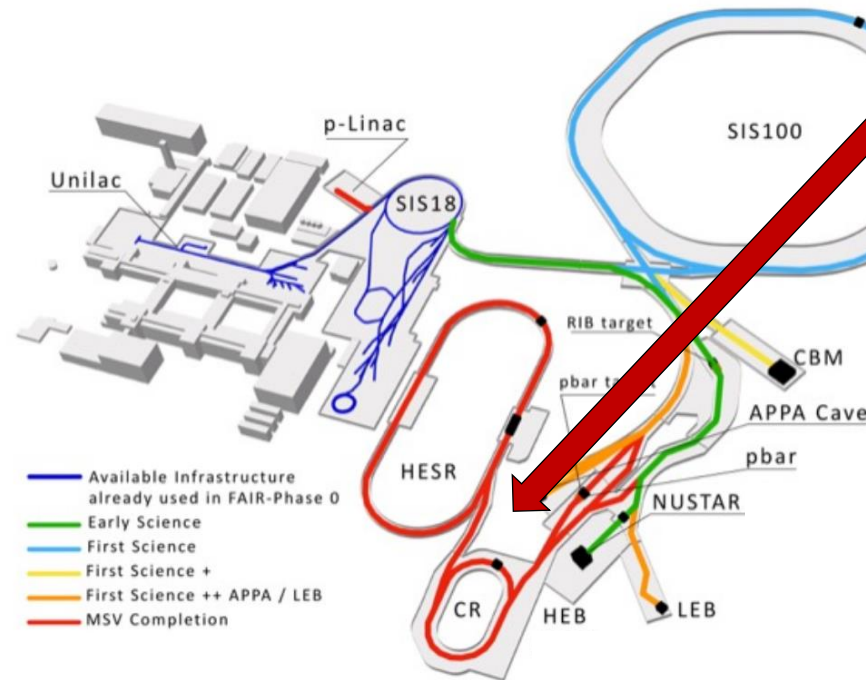
Funding decision on FS++ (Low Energy Branch) aimed for in **2025**

Low Energy Branch operation beginning **2030**

Full MSVc (including rings) **2032**

New experiment opportunities:

- ILIMA, EXL, ...





NUSTAR from Phase-0 to FAIR MSV

Facility	U beam intensity/spill at production target	Luminosity [fb ⁻¹]
Today at GSI with FRS (Phase-0)	$1 \dots 2 \cdot 10^9$	~0,1 (x20-50)
Early science with Super-FRS and UNILAC/SIS18	$2 \dots 5 \cdot 10^9$	2...5 (x4)
First Science with SIS100 (after commissioning)	$2 \cdot 10^{10}$	10...20 (x10)
First Science++ with SIS100 / MSV (full intensity)	$3 \dots 4 \cdot 10^{11}$	>100

Preparation
0.1 fb⁻¹
(near) stability



Discovery
2-5 fb⁻¹
exotic



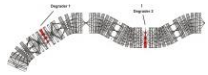
Detailed studies
100 fb⁻¹
very exotic nuclei



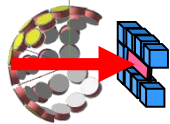
Long-term goal: all NUSTAR experiments at full FAIR facility



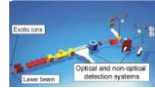
Super-FRS EC



HISPEC/DESPEC



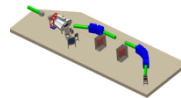
LASPEC



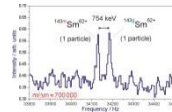
MATS



R3B



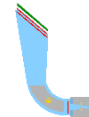
ILIMA



SHE



ELISE



EXL



	Super-FRS EC	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISE	EXL
Masses		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
Half-lives	ps...ns-range	ground state and isomers μ s...s			resonance width, decay up to 100ns	bare ions, ms...years			
Matter radii	interaction x-section				interaction cross sections				matter density distribution
Charge radii	charge-changing cross sections		mean square radii		charge...			charge density distribution	
Single-particle structure	high resolution, angular momentum	high-resolution particle and γ -ray spectroscopy	magnetic moments, nucl. spins	evolution...	three knockout, short-range & tensor correlations	evolution of shell closures, pairing corr.	shell structure of SHEs		low momentum transfers
Collective behavior		electromagnetic transition strength		halo structure	dipole response, fission	changes in deformation		electromagnetic transition strength	monopole resonance
EoS					polarizability, neutron skin			neutron skin	neutron skin, compressibility
Exotic Systems	bound mesons, hypernuclei and exotic e.m. nucleon resonances	and particle decays			n-rich hypernuclei	exotic decay modes			

The strength of NUSTAR is the variety and versatility of its experiments

Summary:

- Theory and experiment activities of POF-IV successfully underway
 - Phase-0 experiments extremely important (training, publications, debugging,...)
 - Construction/commissioning of NUSTAR@FAIR experiments ongoing → establish FAIR science in the int'l. landscape
- Experiments at Super-FRS (begin of POF-V): detailed preparations for ES/FS in progress

Outlook:

- Experiments beyond FS...
 - ...open-up new scientific opportunities in POF-V with AGATA, MATS, LaSpec, ILIMA, EXL
 - ...need to be prepared (specific region of interest and science case, setup, simulations,...)
 - ...rely on early (funding) decisions for LEB and RB
 - ...need beam-intensity upgrades and other accelerator developments