NUSTAR Early Science - Commissioning & Plan for First Experiment

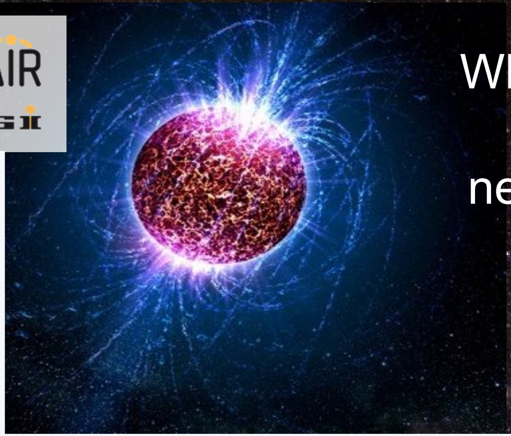
FAIR Commissioning Workshop
7th November 2024

H.M. Albers

Where are heavy elements created?

NUSTAR

What is in the interior of a neutron star?



CBM

PANDA

Glueballs:
What are protons and
neutrons made of?
What is the structure of hadrons?

APPA

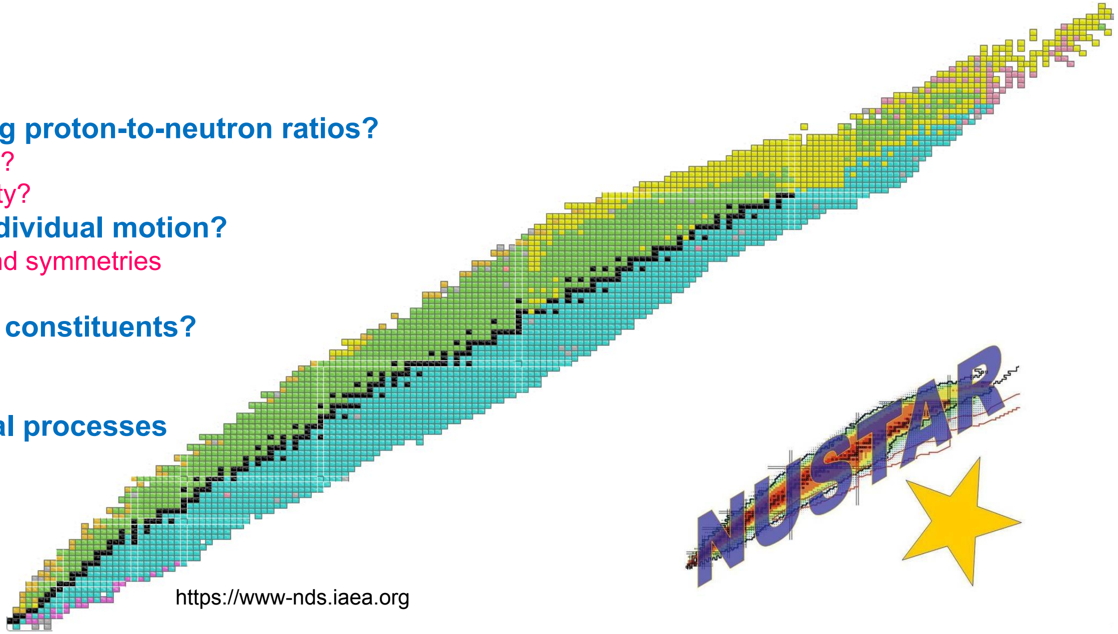
How do materials behave under high pressure?

Fotos: Uranus, Jupiter, Erde Quelle: http://de.wikipedia.org

NUSTAR Collaboration

- **NUSTAR - NUclear STructure, Astrophysics and Reactions**
- NUSTAR physics covers the entire nuclear chart!
- Complementary approaches to answer fundamental physics questions:

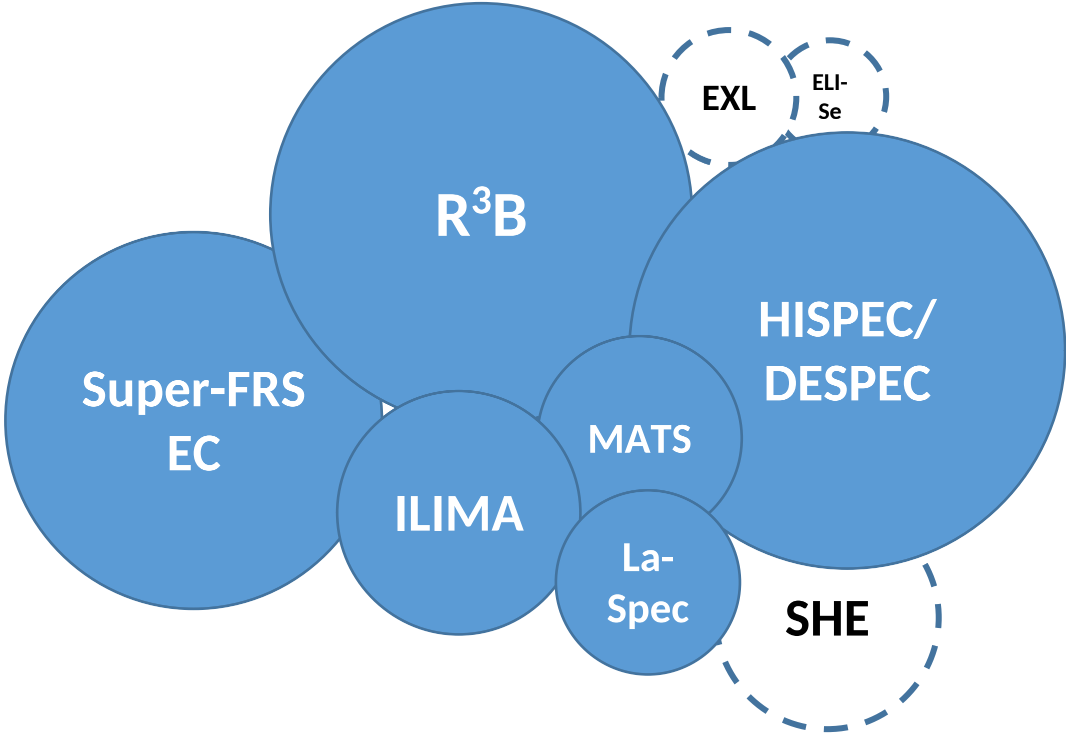
What are the limits for existence of nuclei?
Where are the proton and neutron drip lines situated?
Where does the nuclear chart end?
How does the nuclear force depend on varying proton-to-neutron ratios?
What is the isospin dependence of the spin-orbit force?
How does shell structure change far away from stability?
How to explain collective phenomena from individual motion?
What are the phases, relevant degrees of freedom, and symmetries
of the nuclear many-body system?
How are complex nuclei built from their basic constituents?
What is the effective nucleon-nucleon interaction?
How does QCD constrain its parameters?
Which are the nuclei relevant for astrophysical processes
and what are their properties?
What is the origin of the heavy elements?



https://www-nds.iaea.org

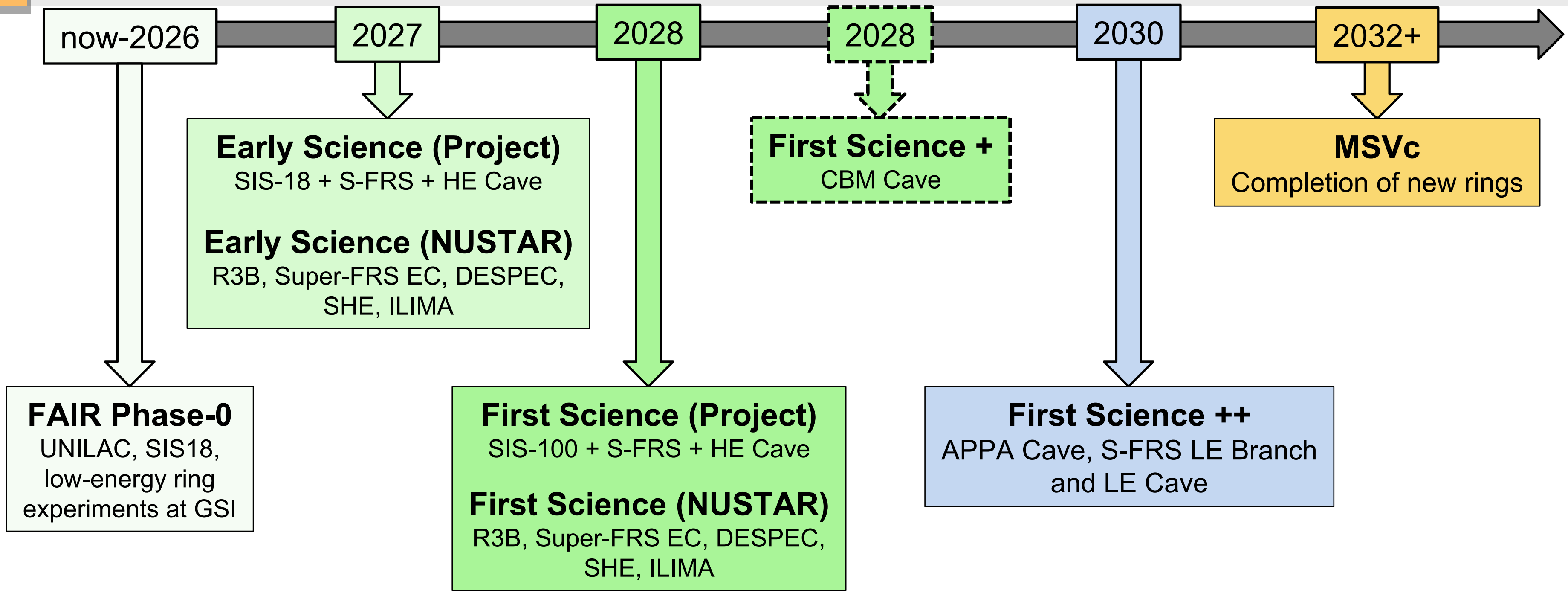
NUSTAR Collaboration

HISPEC/ DESPEC	In-beam γ-ray spectroscopy at low and intermediate energy, n-decay, high-resolution γ, α, β, p, spectroscopy
MATS	In-trap mass measurements and decay studies
LaSpec	Laser spectroscopy
R^3B	Kinematically-complete reactions with relativistic radioactive beams
ILIMA(*)	Large-scale scans of mass and lifetimes of nuclei in ground and isomeric states
Super-FRS EC	High-resolution spectrometer experiments
SHE(**)	Synthesis and study of super-heavy elements
ELISe(#)	Elastic, inelastic, and quasi-free e^--A scattering
EXL(#)	Light-ion scattering reactions in inverse kinematics



(*) NUSTAR experiment using existing FAIR/GSI rings until FAIR rings become available
(**) NUSTAR experiments using FAIR/GSI linear accelerators
(#) Experiments requiring NESR – alternative solutions within FAIR MSV under consideration

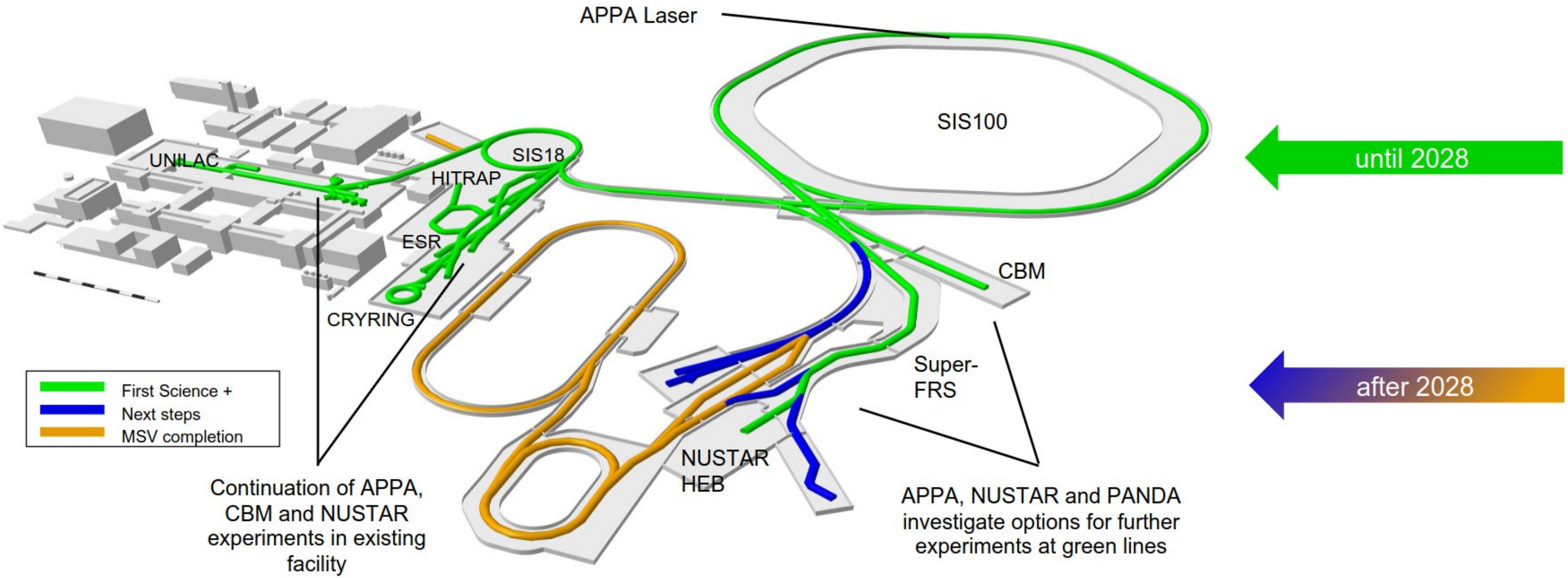
NUSTAR timeline



Green: Budget available
Green: Budget decision expected soon
Blue: Civil construction complete
Orange: Significant additional investment required

– Timeline dependent on Council decisions and timely delivery of SIS100 quadrupoles
– Additional funding needed in 2026 for continuation of skilled workforce

FAIR in 2028



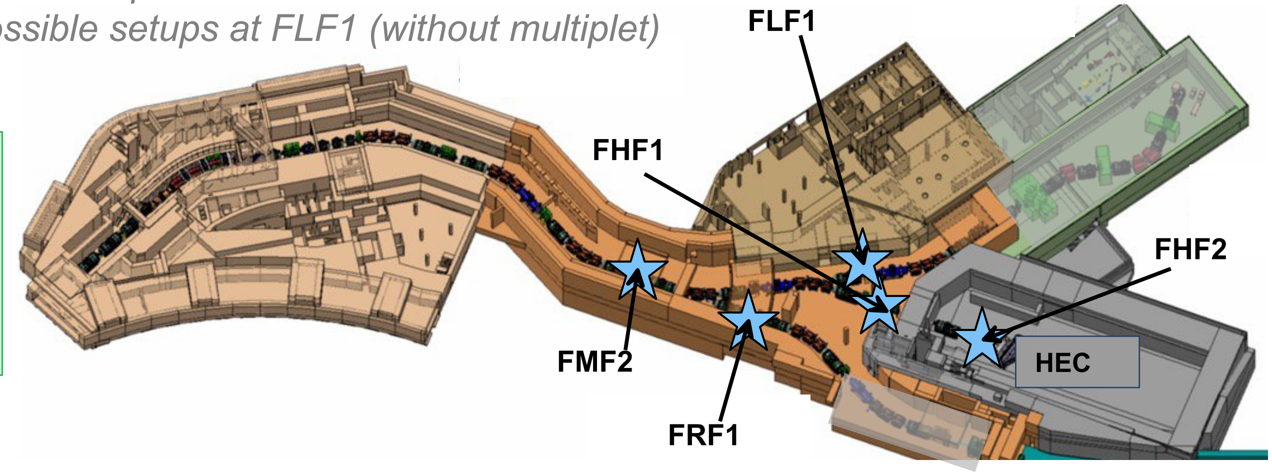
NUSTAR at the Super-FRS (**R³B**, **Super-FRS EC** and **DESPEC**) with SIS100 beams, plus **SHE** experiments at UNILAC and **ILIMA** at the low-energy rings

Early Science Locations

Key focal planes of the S-FRS:

- **FMF2** mid-point of main separator
- **FHF1** (tunnel)
- and **FHF2** (HEC) along high-energy branch
- *Some basic infrastructure planned for LEC to supply HEC, but no full TBI/beamline*
- *No ring branch; possible BIOMAT setup at the beginning of the ring branch (NUSTAR-BIOMAT MoU ready to sign)*
- *EXPERT neutron detectors NEURAD possible at FRF1*
- *Ongoing discussions about possible setups at FLF1 (without multiplet)*

NUSTAR Early/First science technical plans (FMF2, FHF1 and FHF2) **fully endorsed** by ECE/ECSG in the November 2023 meeting



Early Science Setups: R^3B in the HEC

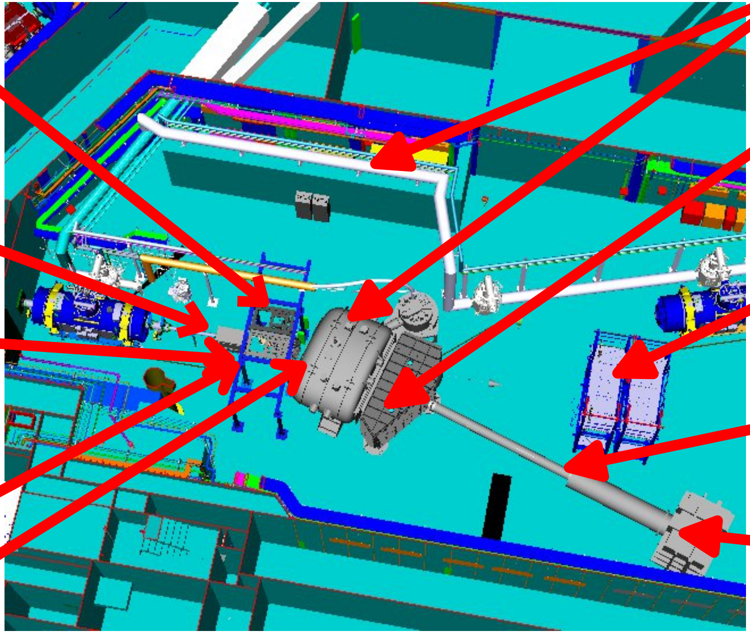
CALIFA with 832 new crystals in the Backward Barrel

New beam diagnostic

LH_2-target with different piping and safety system

TRT with new barrel geometry and 4 x more acceptance

FOOT in-beam tracker with new electronics



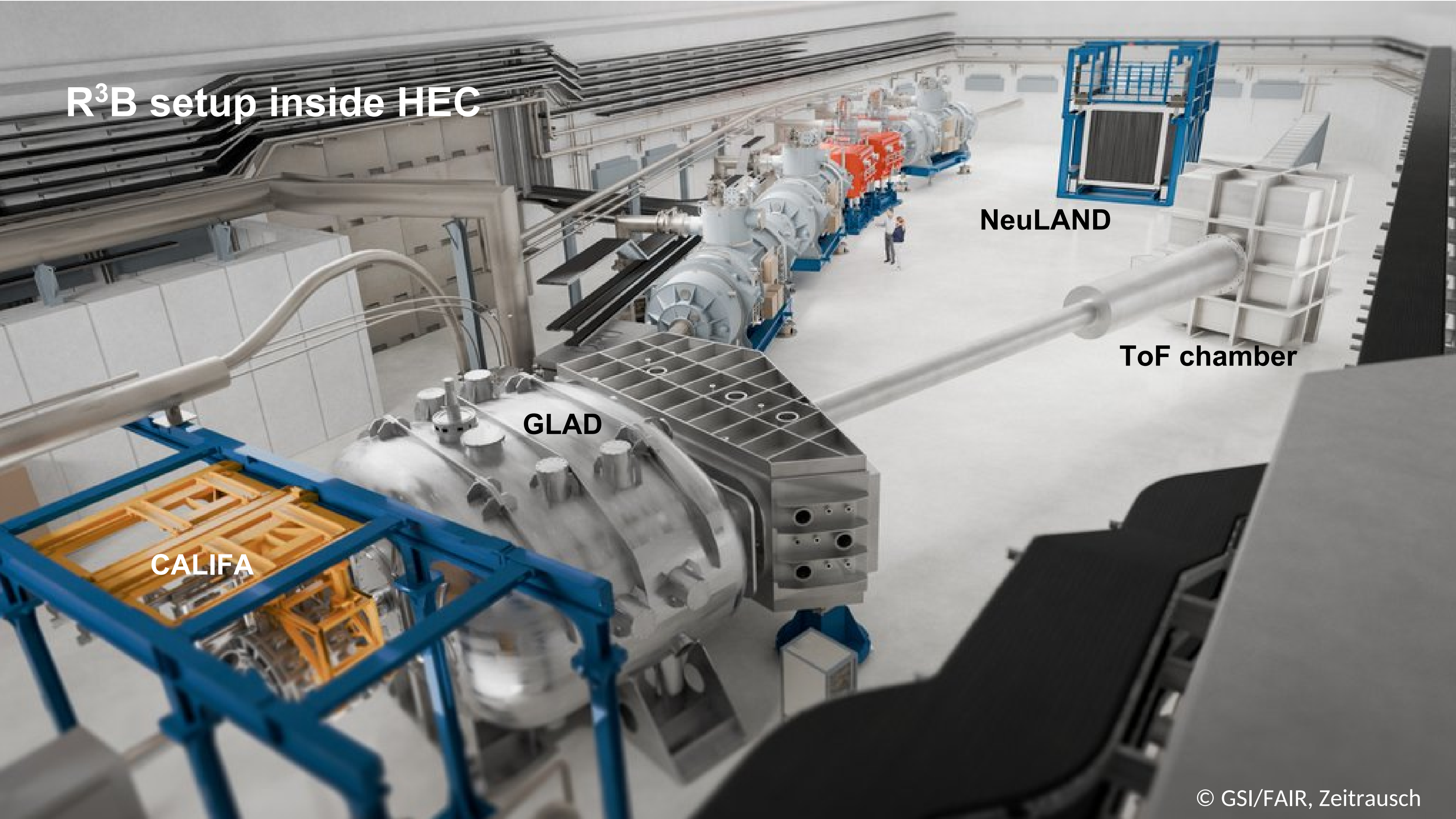
GLAD with new control system

PAS with full angular coverage and operation in vacuum

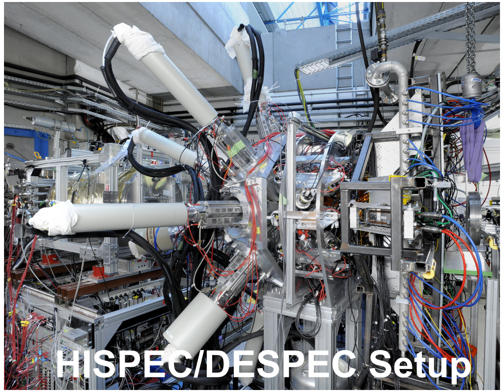
NeuLAND significantly more double-planes

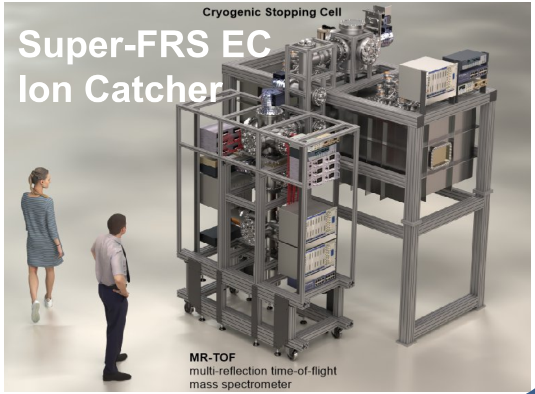
New HI Fiber tracker

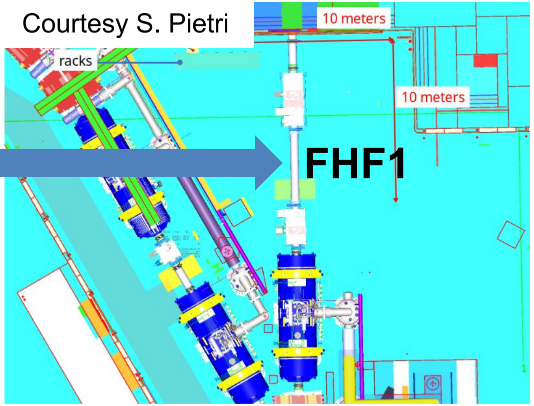
TOF-D with a new in vacuum operation

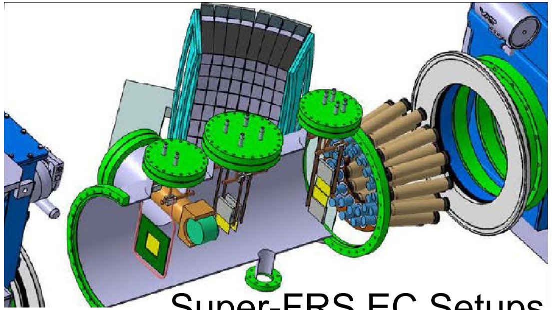

R3B setup inside HEC
NeuLAND
ToF chamber
GLAD
CALIFA
© GSI/FAIR, Zeitrausch

Early Science Setups: Compact setups FHF1/FMF2

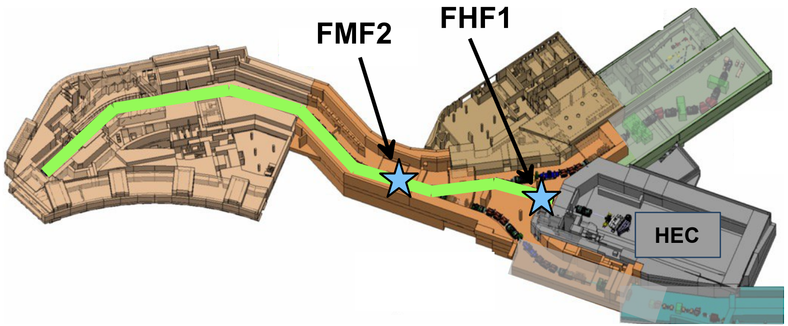








FMF2



NUSTAR Strategy towards Early Science

Handover "cave ready for installation"

↓

As soon as building is ready for installation, some infrastructure items can be installed (limited due to work on Super-FRS)

NUSTAR Strategy towards Early Science

Handover "cave ready for installation" → **06/26** HE Cave Handover from Super-FRS

As soon as HEB cave is "empty", handover MS from Super-FRS, installation of R3B can start

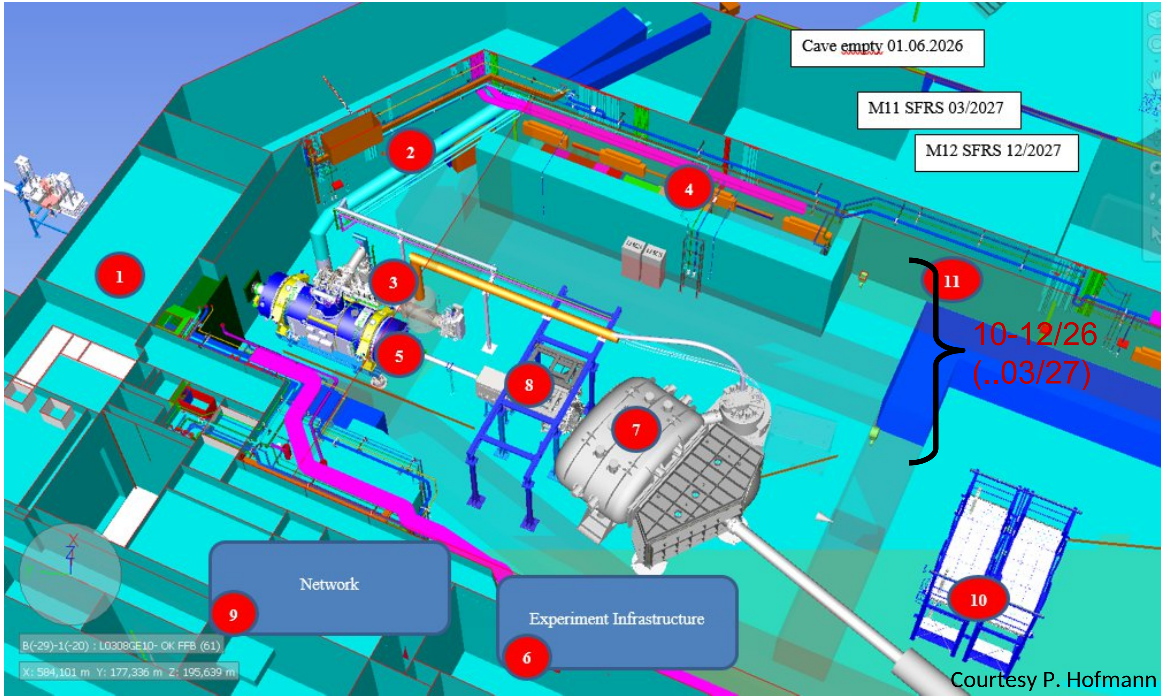
1) Mobile wall
2) Cryo Distribution Line
3) Local Cryo
4) Racks and cables (machine)
5) Multiplet (inc. connections to media)

Q3 2026*

6) Experiment Infrastructure
7) GLAD
8) CALIFA
9) Network
10) NEULAND

Q3-Q4 2026*

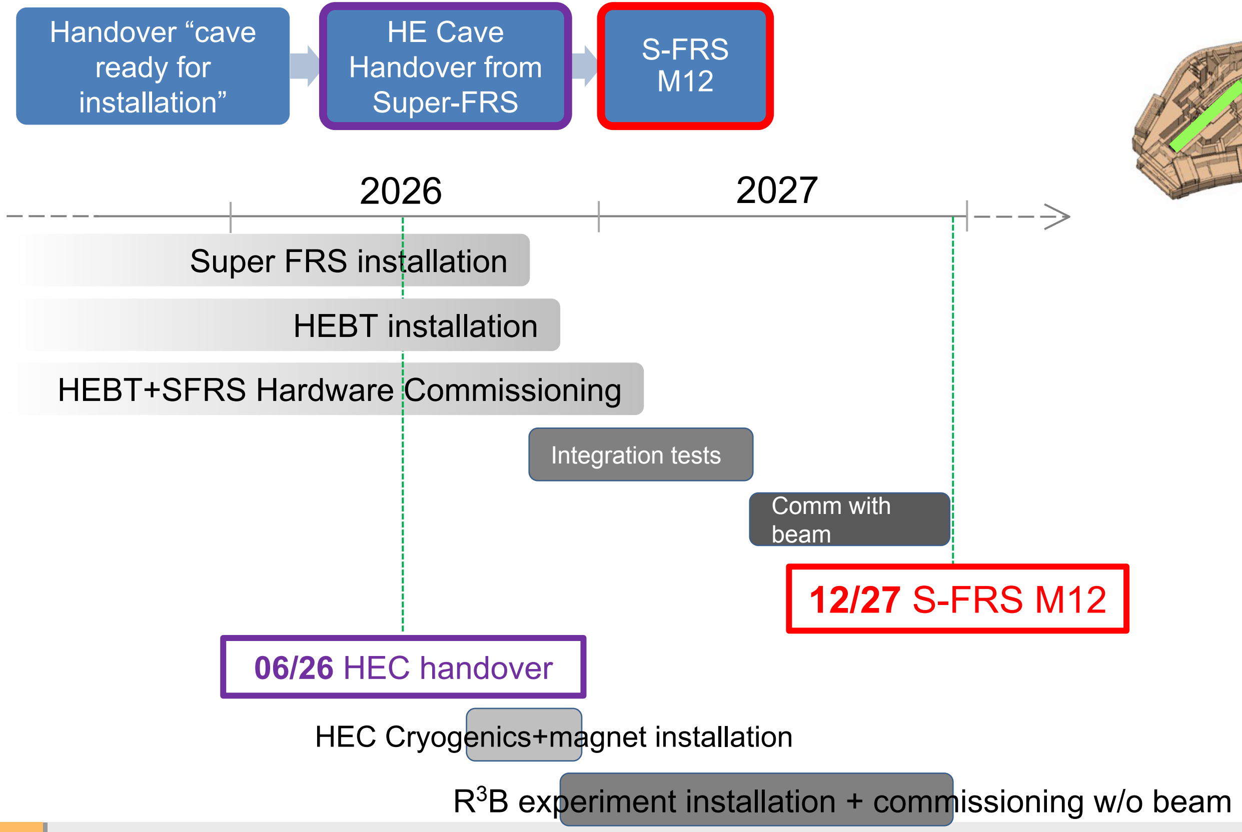
11) Closing of outside wall 03/27

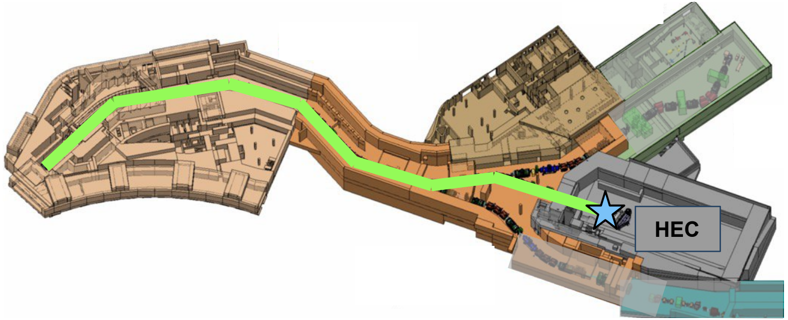


Courtesy P. Hofmann

Estimated dates - details being worked out in LCM Workshops

NUSTAR Strategy towards Early Science





- Super-FRS will be commissioned through to the final focal plane of the **high-energy branch FHF2**
- Super-FRS commissioning in **parallel to R^3B installation** and commissioning without beam
- Possible **synergies** between Super-FRS and R^3B commissioning
- **No access to HEC** once beam is beyond last branching dipoles before HEC

NUSTAR Strategy towards Early Science

Handover "cave ready for installation" → HE Cave Handover from Super-FRS → S-FRS M12 → NUSTAR Commissioning

Separate commissioning phases:

1. End of the Super-FRS commissioning - verification of particle identification (PID) with simple (compact) setup at FHF2
   - **Lead by Super-FRS**
     NUSTAR support (e.g. detector setup, maintenance, operation,...)
   - Commission Super-FRS/NUSTAR DAQ coupling

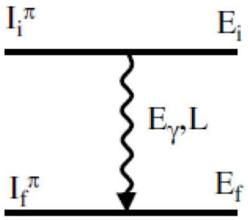
2. Physics run at FHF2, expansion of existing setup at FHF2
   - **Lead by NUSTAR**
     Super-FRS support (machine settings, implantation profile, ...)
   - Production of more exotic nuclei
   - Provide physics results for fast publication

3. Full in-beam commissioning of R^3B for 'First' experiment
   - **Lead by NUSTAR**
     Super-FRS support (machine settings, implantation profile, ...)
   - Removal of compact setup
   - In-beam commissioning of full R^3B instrumentation inside HEC

***Problem** - no interface between ACC (magnets, drives) and NUSTAR (Super-FRS detector + NUSTAR detector readout) planned*

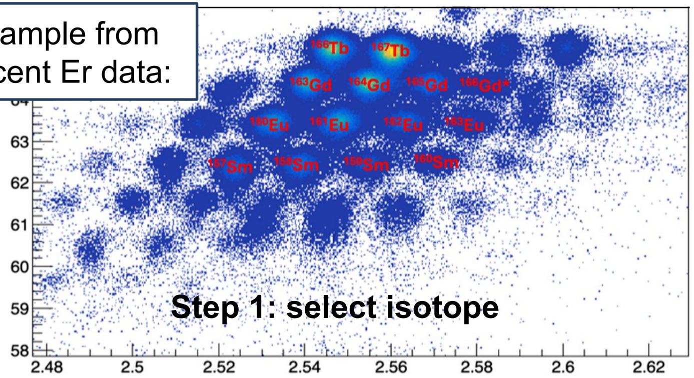
HPGe detectors for fast PID verification

- Gamma decay is a ***(simple!) electromagnetic process*** wherein a nucleus decays from an excited state to a state with lower energy via the emission of a photon, i.e the number of protons and neutrons remains the same
  - ✓ **(quite) easily observed**
  - ✓ **difficult to block**
  - ✓ **EM interaction well-understood**

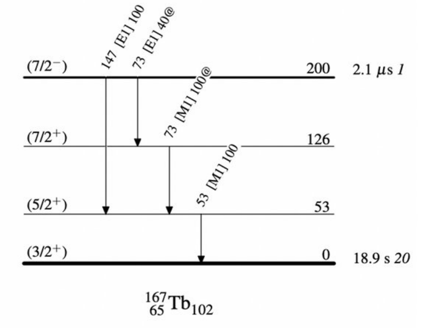


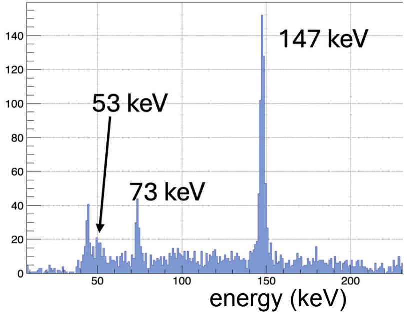
- HPGe detectors have **excellent energy resolution** and allow **fast observation** of peaks
- Typical nuclear states only live for a very short time (~femtoseconds)
- **Isomeric states** are those states where the decay is hindered for some reason
- Isotopes can stay in those states until the **end of the Super-FRS** where they can be stopped
- There is a wealth of data on known isomeric states spanning the nuclear chart

Example from recent Er data:

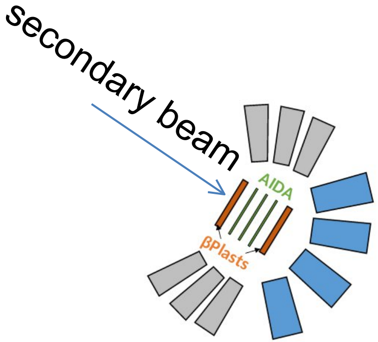


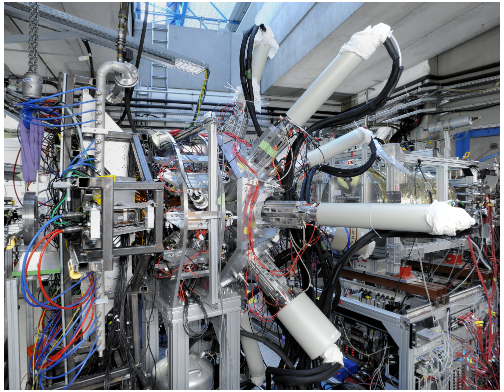
Step 2: stop isotope close to HPGe detectors
Step 3: observe gamma-rays emitted from isomeric states



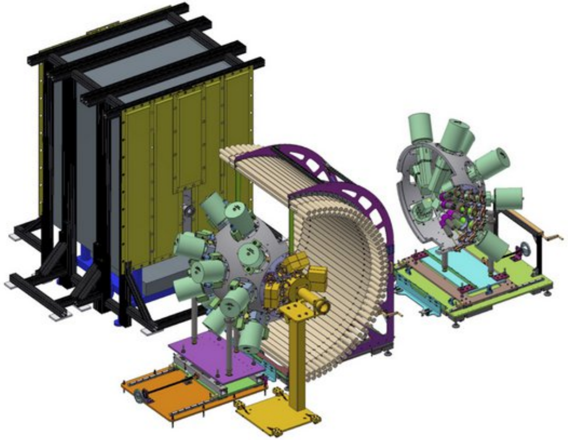


Example implantation-decay setups





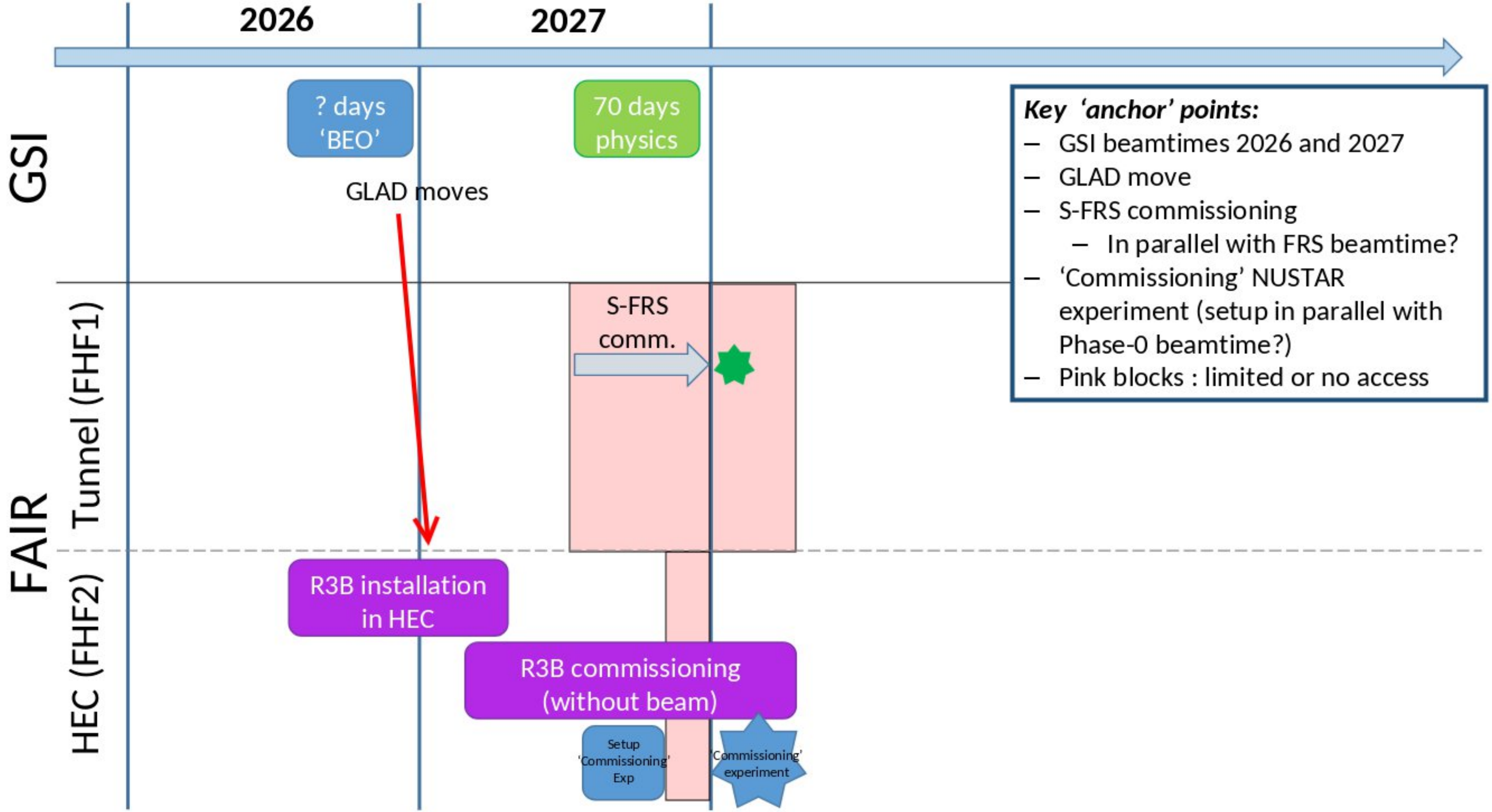
DESPEC setup at the FRS



FRIB Decay Station Initiator (FDSi, https://fds.ornl.gov/initiator/)

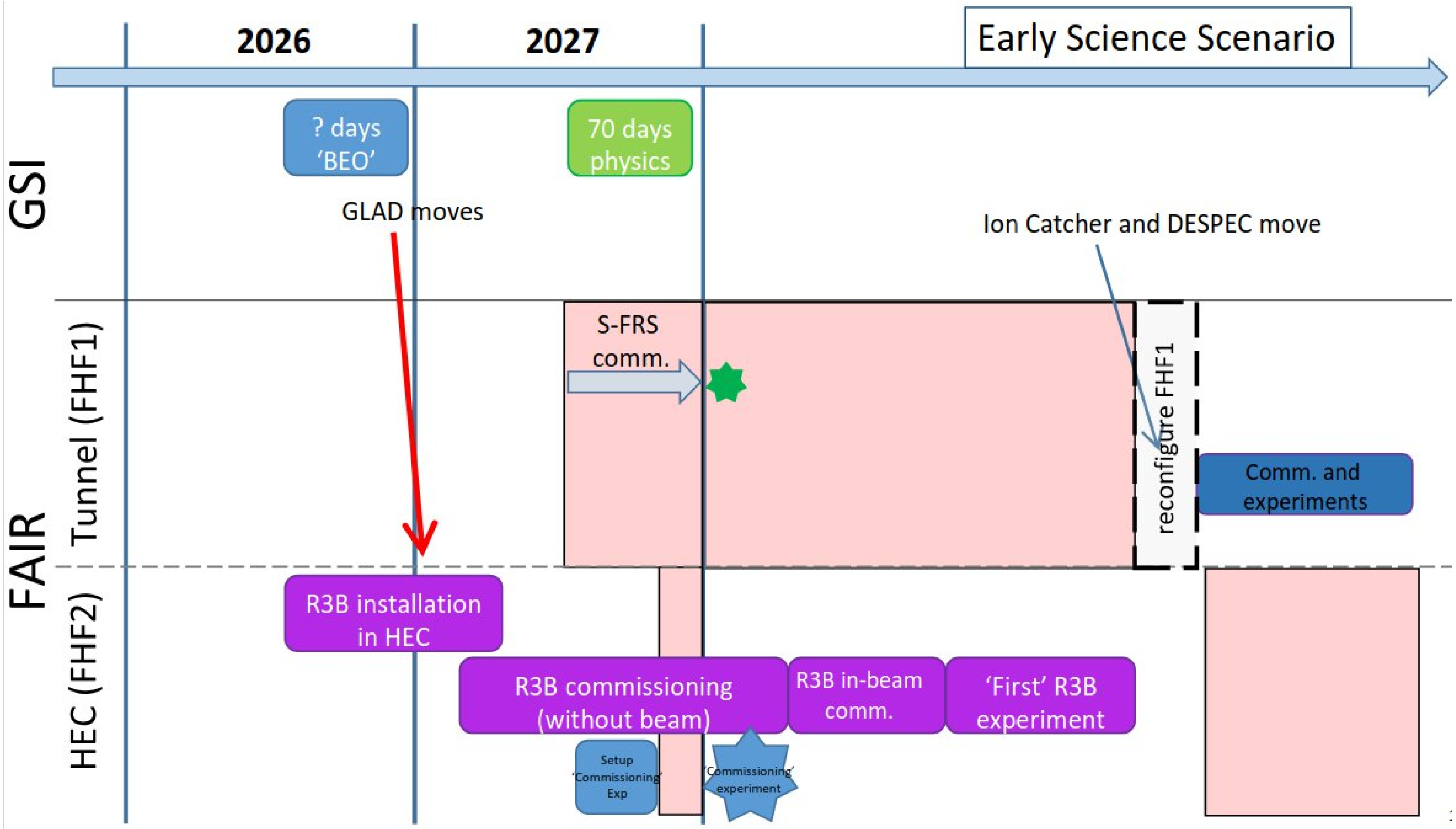
Timeline from FRIB:

- May 2022 first experiment
- PRL on new lifetimes N>28 (published Nov. 2022)
- PRL on unexpected isomer ^{32}Na (June 2023)
- PRL on new isotopes ^{198}Pt beam (Feb. 2024; exp Feb. 2023)



Key 'anchor' points:

- GSI beamtimes 2026 and 2027
- GLAD move
- S-FRS commissioning
  - In parallel with FRS beamtime?
- 'Commissioning' NUSTAR experiment (setup in parallel with Phase-0 beamtime?)
- Pink blocks : limited or no access



Early Science Scenario
2026
2027
GSI
FAIR
Tunnel (FHF1)
HEC (FHF2)
? days
'BEO'
70 days
physics
GLAD moves
Ion Catcher and DESPEC move
S-FRS
comm.
reconfigure FHF1
Comm. and
experiments
R3B installation
in HEC
R3B commissioning
(without beam)
R3B in-beam
comm.
'First' R3B
experiment
Setup
'Commissioning'
Exp
'Commissioning'
experiment

‘First’ experiment

- Question asked by Joint Scientific Council - what will be the **‘First’ experiment** to yield extremely high-impact scientific results?
- Full R^3B setup inside HEC focussing on **neutron skin measurements or fission**

Why?

- Improved **transmission** with Super-FRS
- Maximum **gain** for medium-heavy (Ca-Sn) nuclei
- **Cleaner** beams
- **Longer Time-Of-Flight** within HEC compared to Cave C at GSI (i.e. improved identification and angular resolution of R3B setup
- Successful preparatory experiments already carried in Phase-0

Unique → no other place with high-energy fragmentation beam

Beam requirements for both choices are in line with expected parameters:
$^{73+}$U via process chain
Source - UNILAC - TK - SIS18 - S-FRS - Exp

NUSTAR Early Science Beams

- NUSTAR requirements are outlined in the FAIR Operating Modes document
- Detailed input also given to the Performance Committee

Top priority for NUSTAR Early Science: **high-intensity U beams**

Requirements for the ‘First’ experiment are in line with projected availability
Scientific potential of ‘decay station’ experiments scale with intensity

BUT the NUSTAR science program needs a variety of beams (and even sometimes new ones!)

- Any stable (including enriched) isotope from H to U might be required
- Preference for heavy ions, Z>50
- Others: U, Bi, Pb, Au, Er, Xe, Kr, Ar, protons

R^3B Commissioning Plans

Detector	Version	Cave-C 2026	Cave-C 2027	HEC-offline	HEC -beam
CALIFA	forward		$^{1}H(p,p)$		
	Full		$^{1}H(p,p)$	2028	2028, $^{1}H(p,p)$, $^{12}C(p,2p)$
TRT	Stage1	^{238}U	$^{1}H(p,p)$		
	Stage2			2028	2028, $^{1}H(p,p)$, $^{50}X(p,2p)$
GLAD	full			2027	2028, $^{1}H(p,p)$, $^{50}X(p,2p)$
TOF-D	Full/50%	Frag	$^{1}H(p,p)$	2027	2028, $^{50}X(p,2p)$
PAS	prototype		$^{1}H(p,p)$	2028	2028, $^{1}H(p,p)$
	full			2028	2028, $^{1}H(p,p)$
DAQ	full	^{197}Au	$^{1}H(p,p)$	2027	2028, $^{1}H(p,p)$, $^{50}X(p2p)$
NeuLAND	14 – 20 DP			2027	2028, $^{2}H(p,2p)$
ACTAF1	new		$^{1}H(p,p)$		2029, $^{1}H(p,p)$, $^{50}X(p,2p)$
LH_2 Target	10 cm		$^{1}H(p,p)$	2028	2028, $^{1}H(p,p)$
HI Fibers	0.5/0.2 mm			2027	2028, $^{1}H(p,p)$, $^{50}X(p,2p)$
Sofia				2027	2028, ^{238}U

■ Partly commissioned, requires modification or extension

■ New devices that need full commissioning

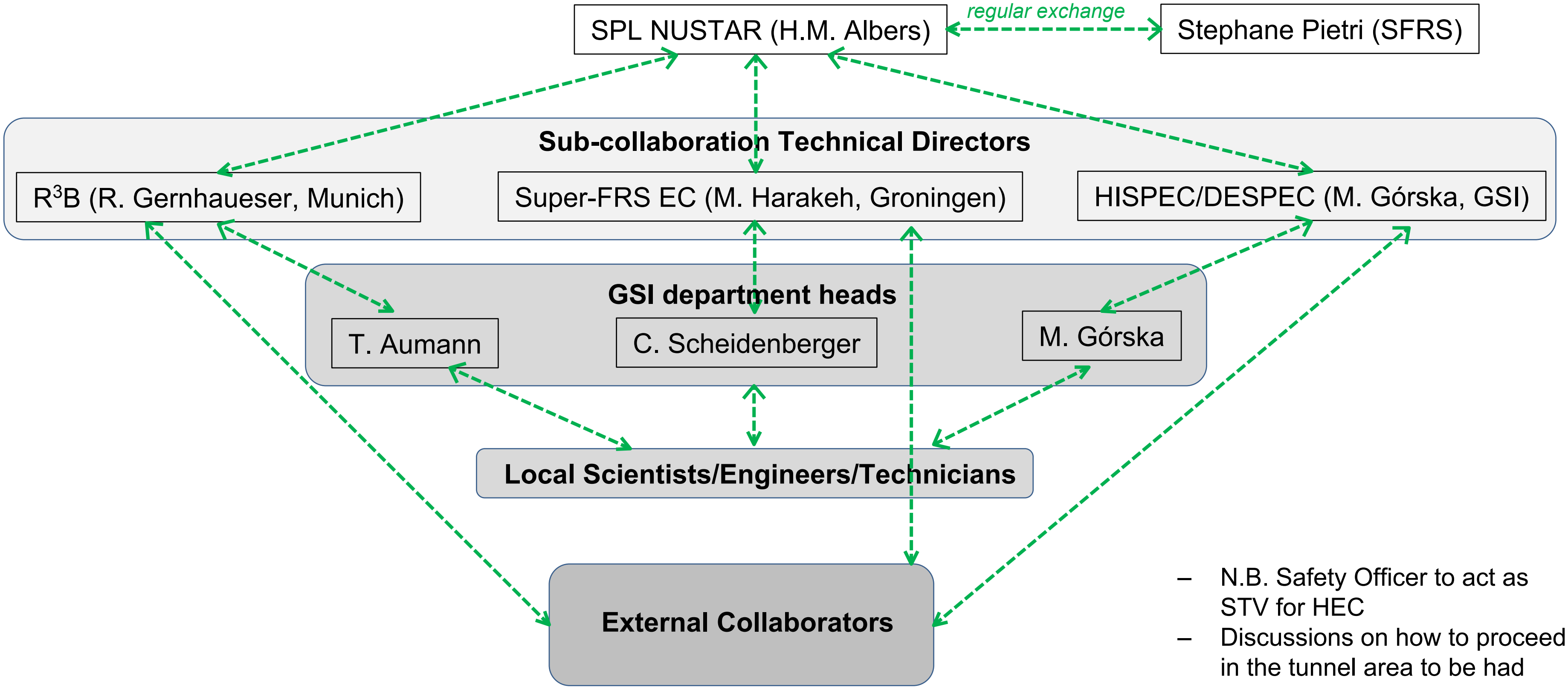
Commissioning resource planning

DRAFT

ROLE	DESCRIPTION	2025	2026	Type
NUSTAR Safety Officer	- Verification of procedures related to safety in NUSTAR areas (e.g. GBUs) - Ensure that NUSTAR components are compliant to proper safety standards, and that appropriate safety documentation is available - Ensure safety protocols are in place for in-beam commissioning of NUSTAR components - Take the role of STVp (eventually STV) for the High-Energy Cave			NEW, permanent
NUSTAR DAQ Specialist/ Coordinator	- Ensure that all NUSTAR DAQ infrastructure is properly installed ready for in-beam commissioning - Conduct final tests to ensure proper integration of NUSTAR DAQ with other FAIR DAQ systems - Coordination between NUSTAR sub-collaborations and S-FRS DAQ team - Maintenance and development (if required) of NUSTAR DAQ systems during all commissioning phases			NEW, permanent
Detector Specialist (1)	- System integration, verification and commissioning of NUSTAR ES detectors (HISPEC/DESPEC DEGAS)			NEW, temp (tbc)
Detector Specialist (2)	- System integration, verification and commissioning of NUSTAR ES detectors (Super-FRS Experiment Collaboration)			NEW, permanent
Engineer (1)	- Integration, verification and commissioning of R3B setups in the High-Energy Cave			NEW, permanent
Detector Specialist (3)	- System integration, verification and commissioning of NUSTAR ES detectors (R3B)			NEW, permanent
Engineer (2)	- Support with NUSTAR integration/commissioning			EXISTING, permanent
Engineer (3)	- Support with NUSTAR integration/commissioning			EXISTING, permanent

- First plan for manpower 2025 developed
- Top priorities covered (Safety Office, DAQ specialist, R^3B engineer,...)

Comissioning roles and responsibilities *(draft)*



- N.B. Safety Officer to act as STV for HEC
- Discussions on how to proceed in the tunnel area to be had

Summary

- The NUSTAR sub-collaborations have a **large variety** of experimental setups (and therefore commissioning requirements
- Is it important to distinguish between the **‘First’ experiment** (full R^3B) and experiments that will be carried out **earlier in time** (e.g. simple implantation setup)
- Part of the R^3B setup has been/will be commissioned in Cave C, but many devices will need **extended** or even **new** commissioning in the High-Energy Cave
- Further details of the ‘First’ and earliest experiments are being currently developed
- Regular exchange on all commissioning (and many other) topics (esp. NUSTAR – S-FRS) will continue

Thank you

NUSTAR Requirements I

- **Intense primary beam**
  - **Already needed now for Phase-0. The first experiments at FAIR (Early Science) will need large gains in intensities for new physics!**

- Beam spot size matching the emittance requirements of the separators (FRS and Super-FRS) (especially for high-intensity beams where emittance may grow)

- Any stable (including enriched) isotope from H to U might be required
  - preference for heavy ions, Z>50
  - often-used projectiles U, Bi, Pb, Au, Xe, Kr, Ar and protons

- Uniform spill structure: non-stochastic beam intensity spikes overload the experiments leading to severe data losses

- Fast and reliable switching from high intensity to a few kHz and vice versa

NUSTAR Requirements II

- Parallel operation, fast switching between experiments: parasitic startup commissioning, typical running times in order of ~1wk, optimised scientific output
- Shorter off-spill periods for slow extraction: increased integrated number of ions on target – allows for more exotic nuclei or shorter experiments
- Very short spills: 5-15 ms spill lengths important for Cryogenic Stopping Cell experiments (achieved in 2014 and 2016)
- Optimised transmission between FRS and ESR