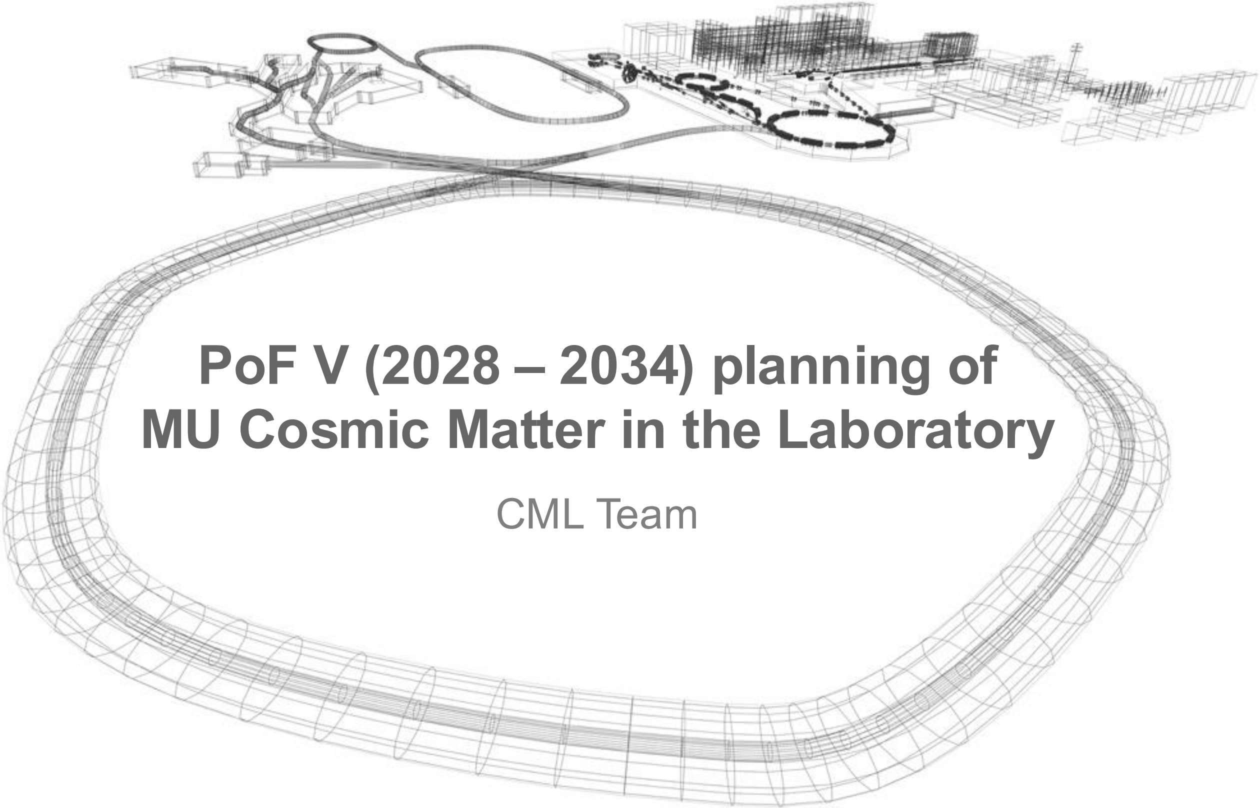


PoF V (2028 – 2034) planning of MU Cosmic Matter in the Laboratory

CML Team

Scientific Evaluation

of the GSI Helmholtzzentrum für Schwerionenforschung within Research Field Helmholtz Matter

FAIR GSI

HIM HELMHOLTZ Helmholtz Institute Mainz

HI JENA HELMHOLTZ Helmholtz-Institut Jena

GSI Helmholtzzentrum für Schwerionenforschung

Research Field Matter

Evaluation Report

Date: 30/04/2025

CML

Specific recommendations

- The PANDA groups at GSI and HIM should clearly define their plans concerning physics opportunities and detector construction.

Rating contribution to the topic Fundamental Particles and Forces (FPF)

Scientific achievements and impact				
X Outstanding	☐ Excellent	☐ Very good	☐ Good	☐ Fair
Originality and innovative potential				
☐ Outstanding	X Excellent	☐ Very good	☐ Good	☐ Fair
International standing and competiveness				
X Outstanding	☐ Excellent	☐ Very good	☐ Good	☐ Fair

Strategic Review PoF V

CML

MU Ion facilities

DMA

DTS

From Strategic Review 2020 POF IV (MU-CML)

Goals	Work Program	Competences and Resources	Impact and Risks
Outstanding	Excellent	Outstanding	Very Good

"The committee views the goals, work program, and team competencies positively. However, we are mindful that in 3 months of beam time per year there is little possibility of obtaining results comparable to those of the most highly rated topics. Hence the impact of FAIR Phase-0 will be low, despite its many benefits to the participants. While we are not able to rate the impact of FAIR phase higher than **"Very Good",** this is not a statement about the inherent value of the FAIR Phase-0 project."

Link to the document

Strategy of the Research Filed Matter for PoF V

Grand challenges Matter and the Universe for the next 10 years

- Understanding of the nature of dark matter, the origin of the matter-antimatter asymmetry in the universe, and the properties of neutrinos.
- Studying strong - interaction matter under extreme conditions in the laboratory, which is essential for unraveling the origin of heavy elements in the universe.
- Understanding the connection of particle physics and nuclear physics with the processes in the cosmos and how the most extreme events shape our universe.

MATTER AND THE UNIVERSE

→ Key contribution to the Helmholtz-Mission

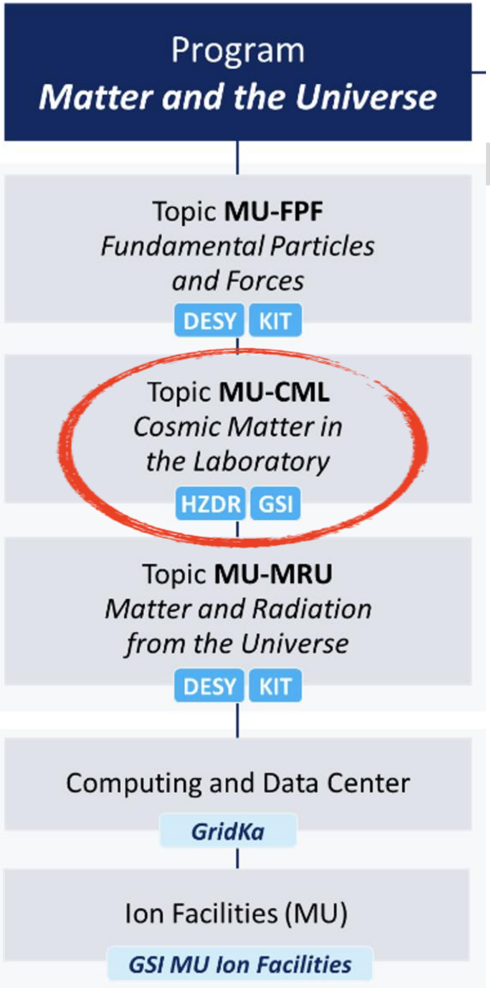
Link to the document

Strategy of the Research Filed Matter for PoF V

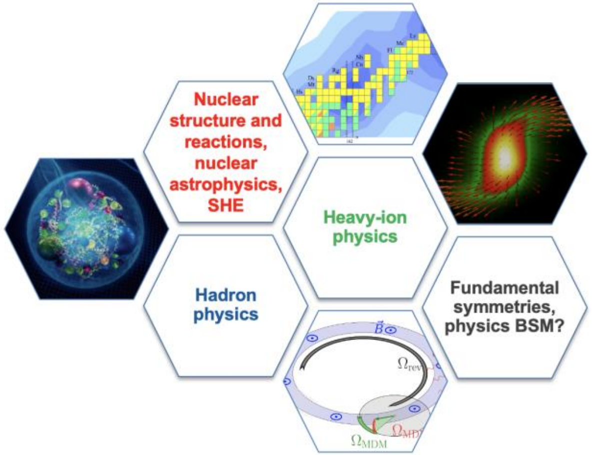
Scientific positioning (MU-CML)

Conducting experiments at primarily GSI/FAIR but also partly at CERN, we investigate hadronic processes in dense environments and the structure of exotic nuclei, thereby striving to understand how the properties and dynamics of matter and antimatter arise from fundamental symmetries and how they determine the evolution of stars and shape nucleosynthesis.

- We determine the phase structure and the equation of state of QCD matter at extreme values of density, temperature and isospin as exist in neutron star merger events employing state-of-the-art detector and computing technologies.
- We measure the nuclear properties and reactions that determine the production of elements in the universe, identify its astrophysical signatures, and predict how nuclei emerge from the underlying theory of QCD.
- We decipher the origin of matter-antimatter symmetry and test the fundamental symmetries.



PoF IV – research areas



PoF V – physics questions

QI
How the properties of matter originate from the strong interaction and what are the relevant degrees of freedom?

QII
What are the key nuclear properties that determine the production of heavy elements in the universe?

QIII
How can fundamental symmetries be tested? What is the origin of the matter–antimatter asymmetry?

MU
MATTER AND THE UNIVERSE

Q1

How the properties of matter originate from the strong interaction and what are the relevant degrees of freedom?

QI.1 What is the phase structure and microscopic properties of strong-interaction matter?

QI.2 How do the complex spectra of hadrons and nuclei arise from the strong force?

QI.3 How do hadrons form and how is their spectra determined by the strong force?

QI.4 How bound states of baryons appear and what are the limits of stability?

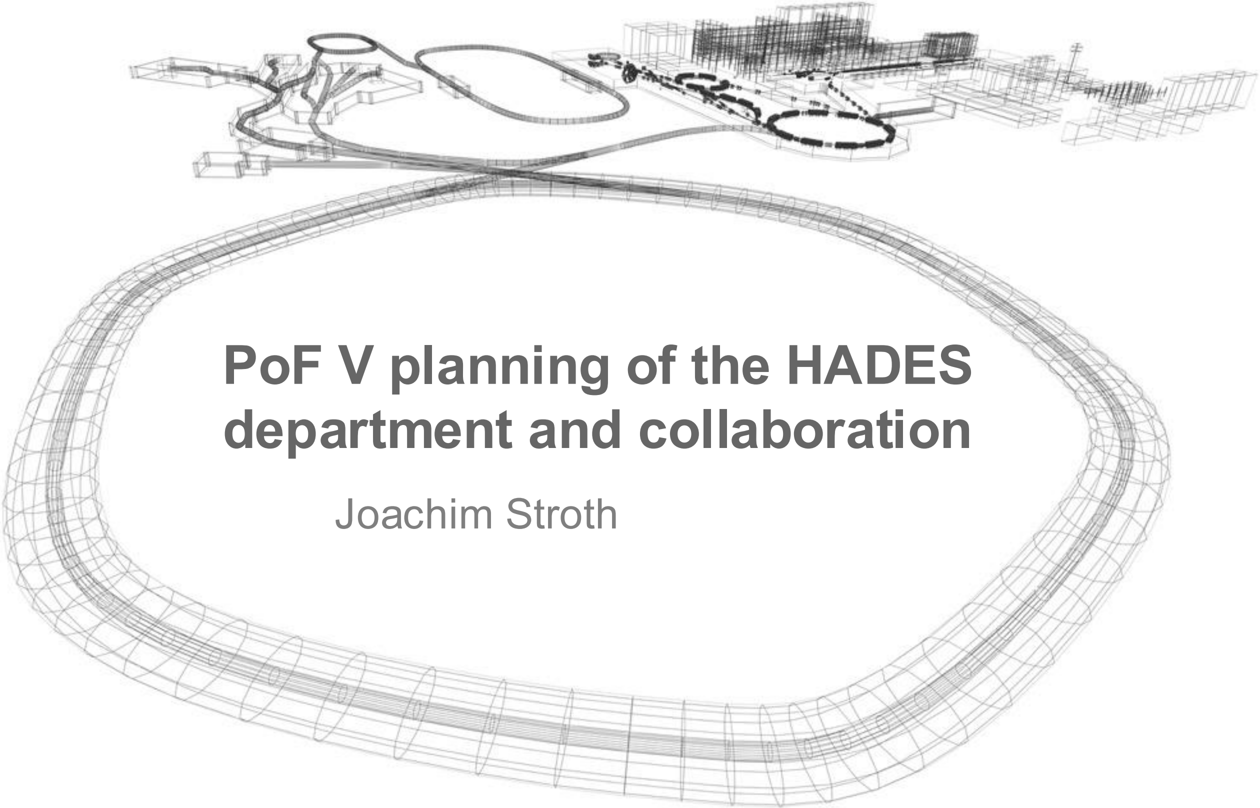
QI.5 How does the dynamics of matter determine the evolution of stars and nucleosynthesis?

QII

What are the key nuclear properties that determine the production of heavy elements in the universe?

QII.1 How does equation-of-state of high density and high n/p asymmetry matter govern the structure of neutron stars?

QII.2 What are the observational signatures of strong-interaction in astrophysical objects? (including neutrinos, GW, EM spectra, ...)



PoF V planning of the HADES department and collaboration

Joachim Stroth

HADES Physics Case

QI.1, QI.2, QI.3, QII.1

What: Exploration of the phase structure and microscopic properties of high-μ_B strong interaction matter

Why: Learn about the **limits of hadronic existence** and the **generation of mass**

Achievements:

- Dilepton excess radiation **demonstrating near complete melting of in-medium rho** and providing **direct temperature measurement** of the early stage of the collision
- **First measurement** of the **electromagnetic transition form factor** of baryon resonances in the time-like region demonstrating Vector Meson Dominance beyond naiive models
- Many hadronic observables with **unprecedented statistics and significance** (Strangeness production, collective behavior, event-by-event multiplicity fluctuations)

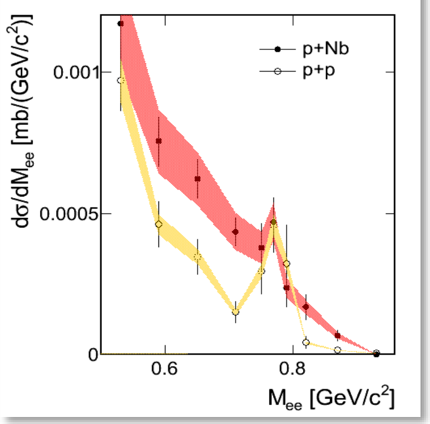
Tentalizing hints (limited statistics):

- **Omega melting in cold nuclear matter:** near recoil-less production. Shoud be repeated with pion beam(was th eeman reason to build a pion beam facility)

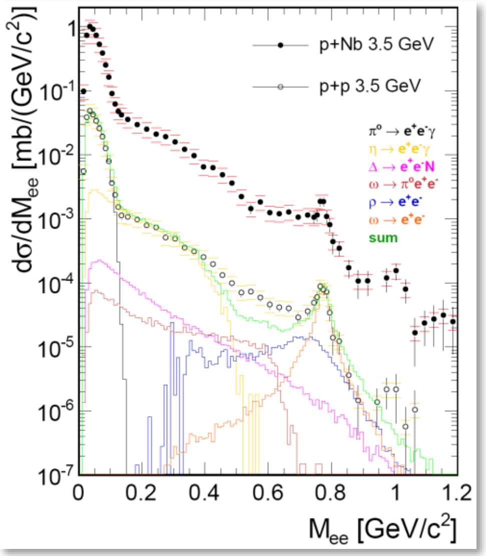
In-medium Vector Meson Masses

- Key observable to study the role of condensates in the generation of mass and in the splitting of the mass states
- Most sensitive approach is a line-shape measurement in cold matter. Needs very high statistics due to:
  - Suppression over hadronic decay $\sim\alpha^4$
  - Recoil-less production

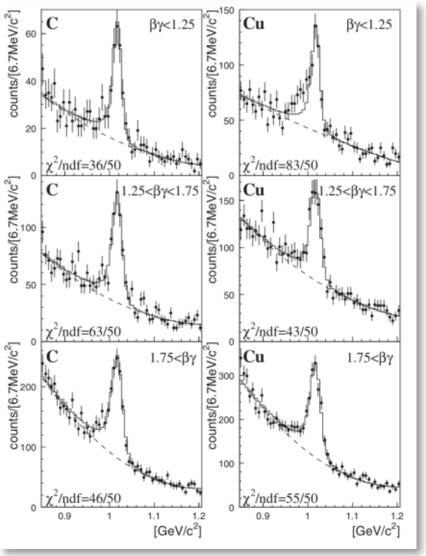
HADES



HADES



KEK-PS E325



HADES pion
JPARC E16

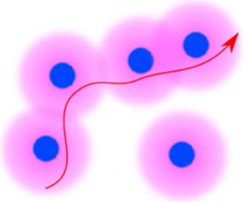
?

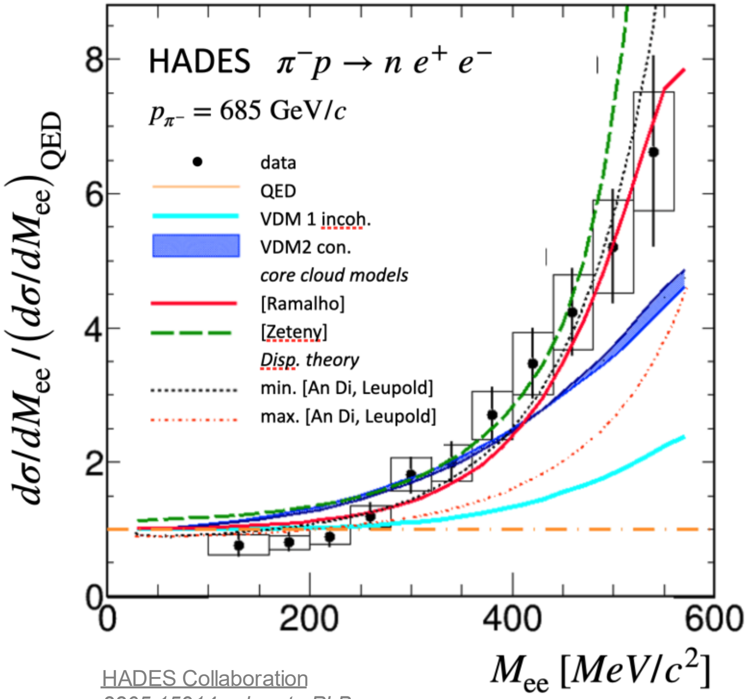
HADES, PLB 715 (2012)

KEK-PS E325, PRL 98, 042501 (2007)

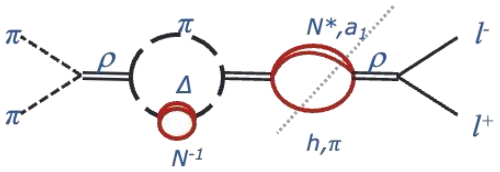
Vector Meson Dominance in the baryon sector

- First measurement of the time-like electromagnetic transition form factor of baryons in the time-like region
- Strong enhancement of the coupling to dileptons via intemediary rho mesons (VMD)
- Reason for the strong broadening of the in-medium ρ meson
- Excess radiation generated by vector excitations in the (entangled) meson cloud





$$\Pi^{\mu\nu}_{EM}(q) = \int d^4x e^{iqx}\, \Theta(x_0) \langle [j^{\mu}_{EM}(x), j^{\nu}_{EM}(0)] \rangle_T \; ; \quad \mathrm{Im}\Pi_{EM}(M) = \left(\frac{m_\rho^2}{g_\rho}\right)^2 \mathrm{Im}D_\rho(M)$$



L. McLerran, K. Toimela, Phys. Rev. D31 (1985)
Ralf Rapp arXiv-1110-4345
C. Gale, J. Kapusta: Nucl. Phys. B357 (1991) 65
R. Rapp, J. Wambach: Adv.Nucl.Phys. 25 (2000) 1
B. Friman, Nucl. Phys. A610 (1996) 358c;
B. Friman and H.J. Pirner, Nucl. Phys. A617 (1997) 496
M. Asakawa, C-M. Ko et al., PRC 46 (1992) R1159

HADES Collaboration
2205.15914 subm. to PLB
Phys.Rev.C 111 (2025) 2, 024908
Nature Phys. 15 (2019) 10, 1040-1045

ERuM pro FSP T06 HADES Groups

All universities groups also members of CBM

ERuM
FSP-T06
Compressed
Baryonic
Matter

RICH

U Wuppertal

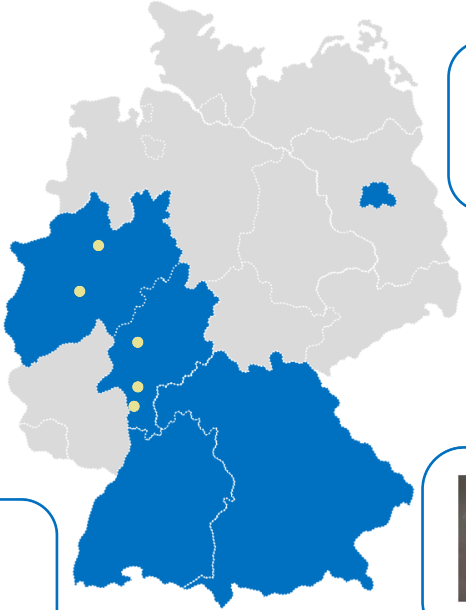


GSI

T0
MDC
ILSE

TU Darmstadt

T0



U Bochum

fSTS, iTOF

U Giessen

RICH

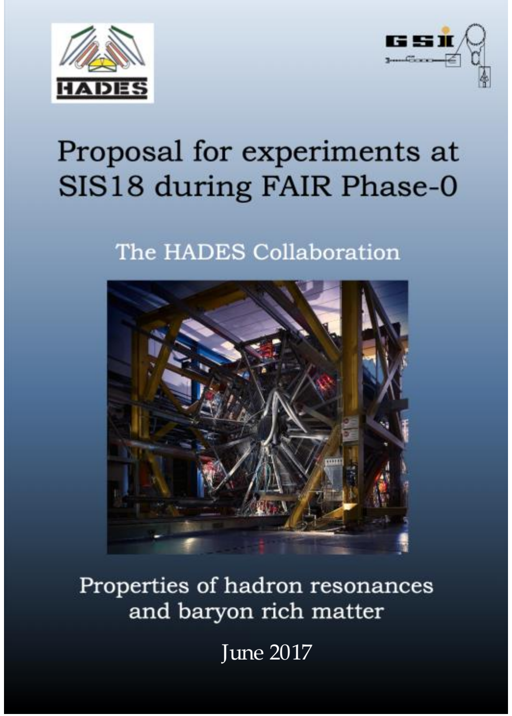

GU Frankfurt am Main

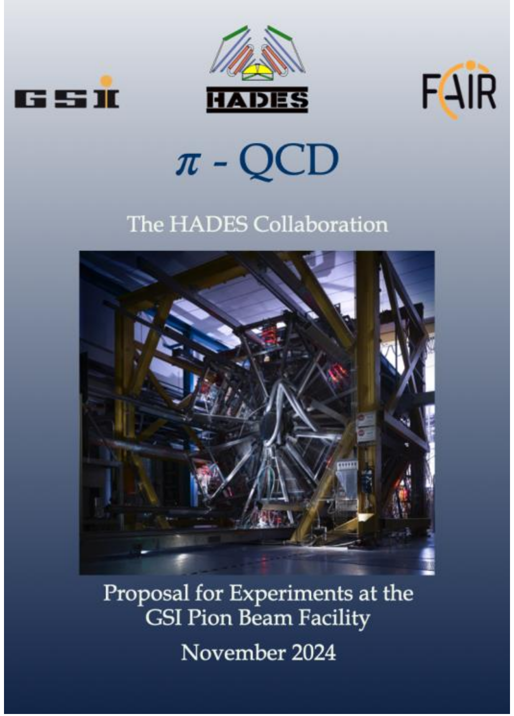
MDC
DAQ

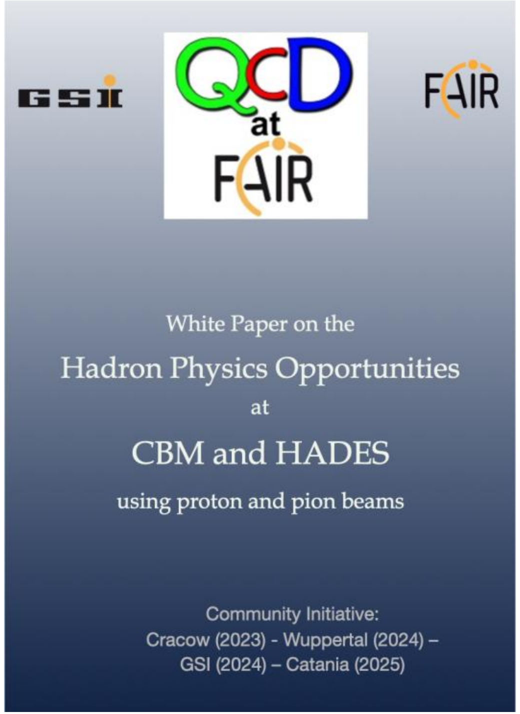
HIM HELMHOLTZ Helmholtz Institute Mainz
HI JENA HELMHOLTZ Helmholtz-Institut Jena

HADES Physics Program for SIS18

Rich, documented and with broad community interest





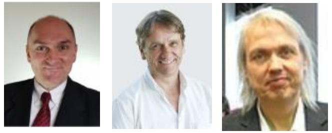


ERuM pro FSP T06 HADES Groups

Two joint positions to be filled soon (Wuppertal, Frankfurt)

RICH

U Wuppertal

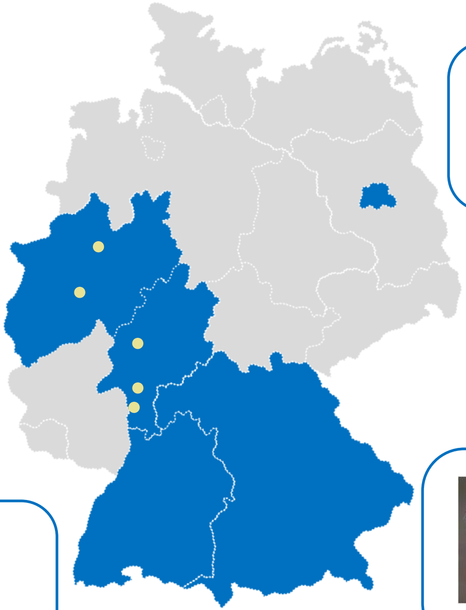


GSI

T0
MDC
ILSE

TU Darmstadt

T0



U Bochum

fSTS, iTOF

U Giessen

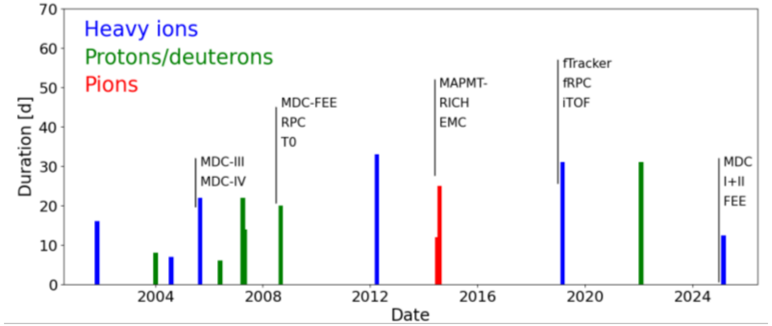
RICH

GU Frankfurt am Main

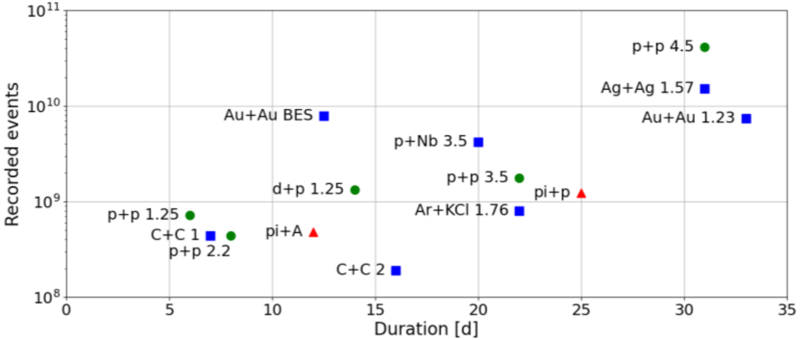
MDC
DAQ

HADES Physics Performance

- Only five runs in the last 15 years!!! Several substantial upgrades, though.



- Substantial increase of events/d (log scale!!!)

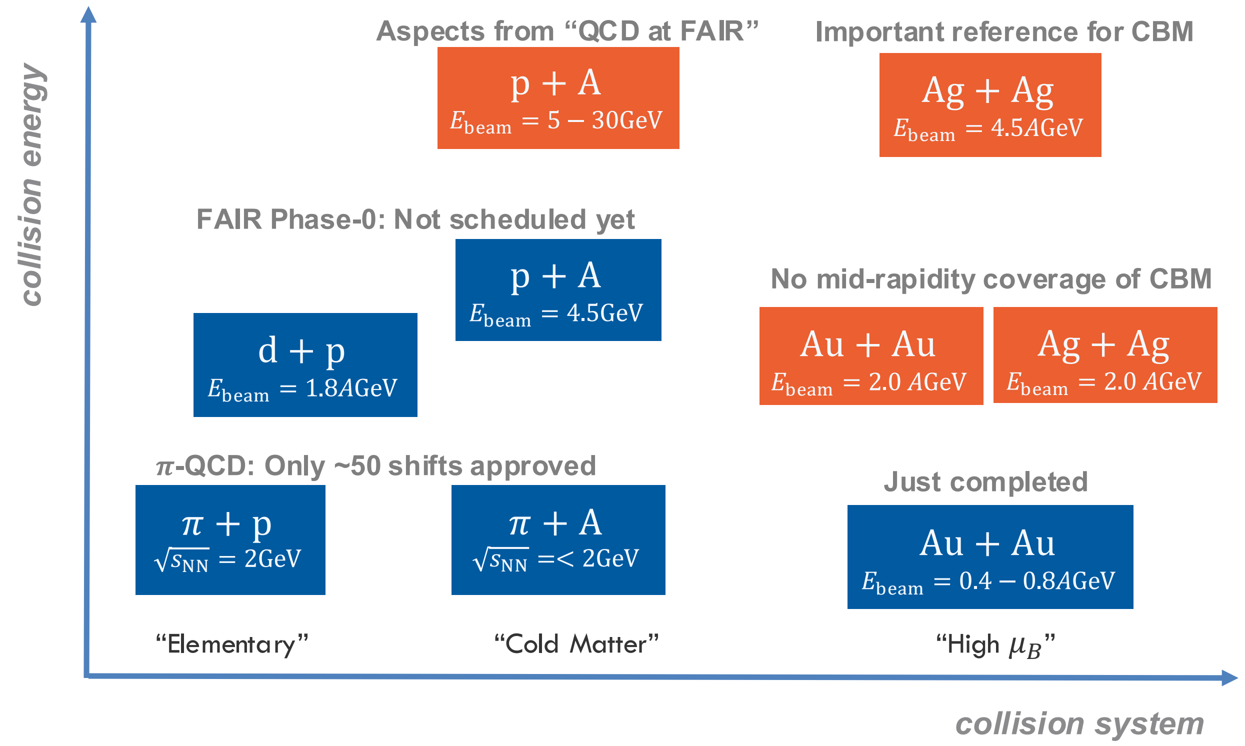


Experiment preparation, Calibration, Analysis, Paper writing effort independent of length of beam time!!!

Scientific merrit in some cases is!!!

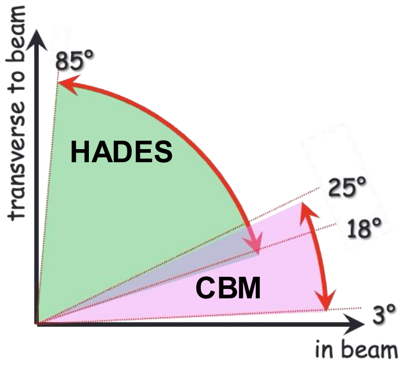
Run	*System*	*Publications*	*Citations*
NOV01	C+C 2.0	1.5	205
JAN04	p+p 2.2	1.5	83
AUG04	C+C 1.0	1	169
SEP05	Ar+KCl	7.5	585
APR06	p+p 1.25	2.5	209
MAY07	d+p 1.25	2	141
JAN04	p+p 2.2	1.5	83
APR07	p+p 3.5	8.5	498
SEP08	p+Nb 3.5	8.5	332
APR12	Au+Au 1.25	11.5	694
AUG14	pi+p	3	51
MAR19	Ag+Ag 1.65	0.5	51
FEB22	p+p 4.5	0	0
APR25	Au+Au BES	0	0
		48	2896

Future HADES Program as of 2023



SIS18

SIS100



Standardized Summary

- scientific goals:

  Complete (not really started yet) program with pion beam. Two more proposals at SIS18 using deuteron and proton beam. See pion beam proposal π-QCD.
- timelines:

  Depends very much on available beam time!!! Program good for more than 200 – 300 shifts.
- milestones:

  Q4 2027 – First run completed and running parallel to SIS100 commissioning/operation established

  Q4 2032 – SIS18 program completed
- technical requirements:

  Full support of HADES cave/infrastructure (e.g. cryogenics) and HEST until Q4 2032

  Full support of IT for high-performance computing
- beamtime requirements:

  Extended run times, possibly in parallel to commissioning periods (standby mode) of order 4 w/a beam on target
- required resources:

  Refurbishment of cryogenic system (and maintenance) with support of Cryo Department

  Department personnel and budget on the current level maintained

PoF V planning of ALICE

Silvia Masciocchi
Ralf Averbeck

Scientific goals

Heavy-ion, pp, pA collisions @ LHC: √sNN = 5 TeV

Until 2033

ALICE at the LHC Run (3+)4

~100 times statistics wrt 2010-2018

From 2036

ALICE 3: unprecedented physics reach

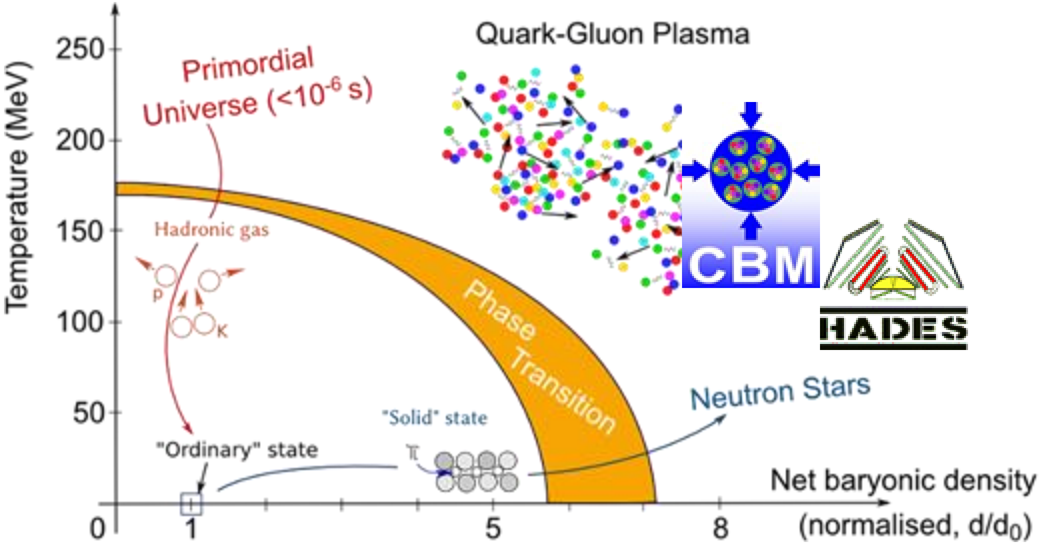
High-statistics, high-precision data

COMPLEMENTARITY

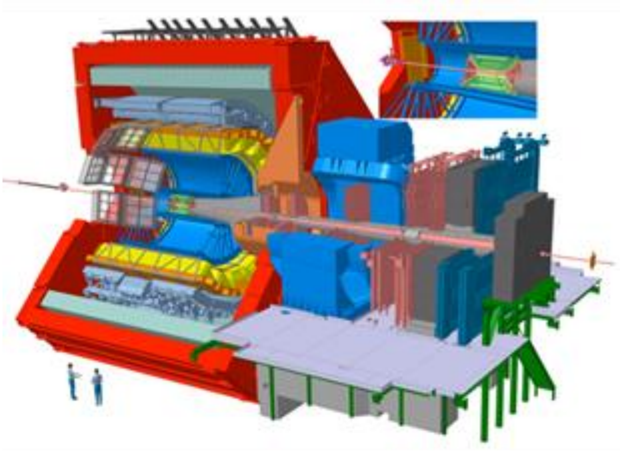
ALICE – hot QCD matter

HADES, CBM – dense QCD matter

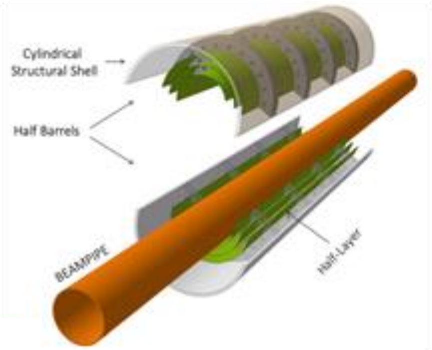
Phase diagram of strong-interaction matter



ALICE: experiment operation and upgrades

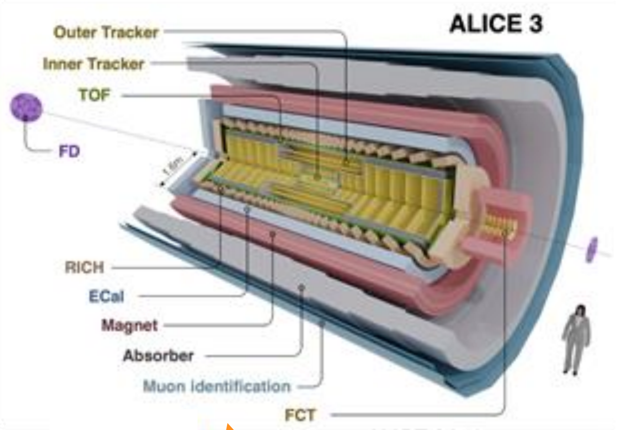


ITS 3



ITS3 TDR: [CERN-LHCC-2024-003]

ALICE 3



ALICE 3 LoI: CERN-LHCC-2022-009
SD: [CERN-LHCC-2025-002]

Schedule updated September 2024

POF V

QI.1, QI.2, QI.3, QII.1

HIM
HELMHOLTZ
Helmholtz Institute Mainz

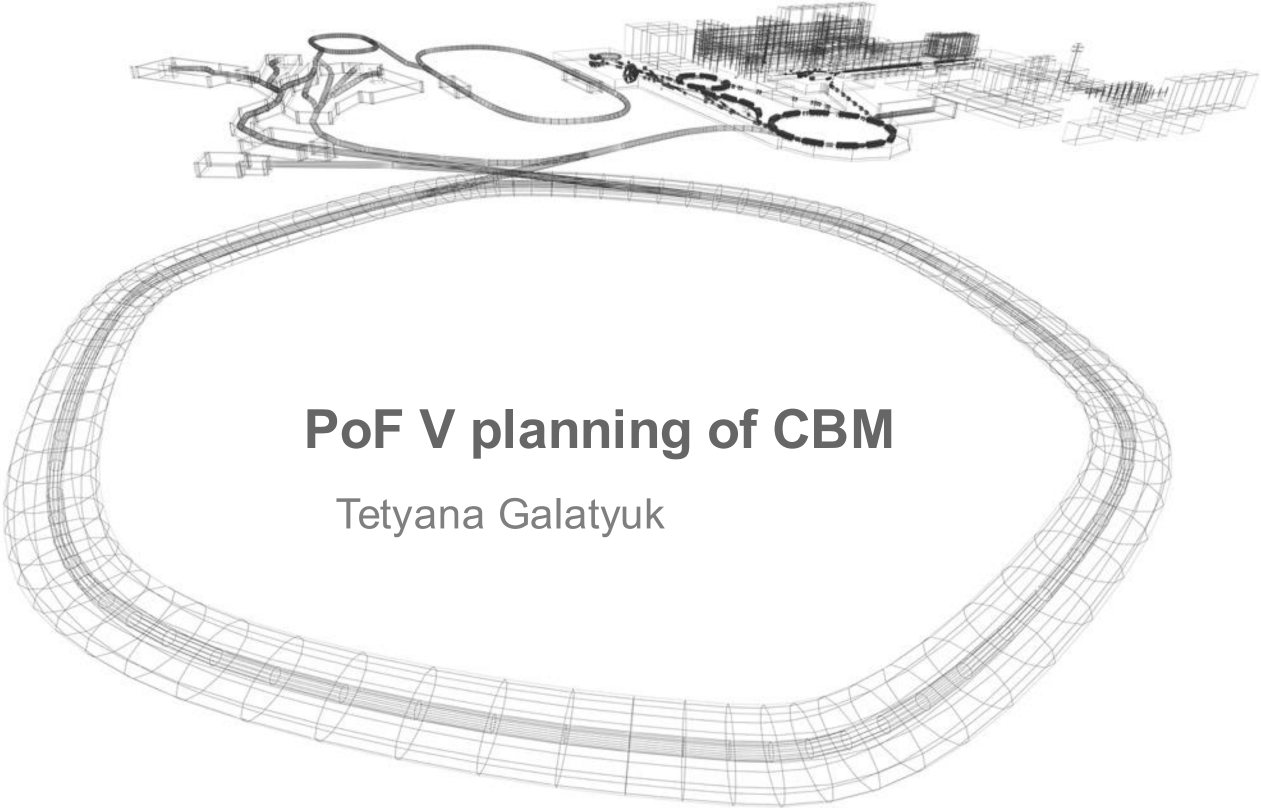
HI JENA
HELMHOLTZ
Helmholtz-Institut Jena

Scientific goals

- Open heavy-flavor hadrons
  in pp, p-Pb, Pb-Pb collisions, with the help of the KFParticle, strangeness tracking and machine learning methods. Production cross section, branching ratios, lifetime, hadronization mechanism, cold-nuclear matter effects, degree of thermalization in the QGP (for charm and for beauty, as a function of mass and temperature of the medium), femtoscopy studies (structure of exotic charm hadrons: synergy with PANDA, BES III, etc)
- Heavy quarkonia
  production cross section of prompt signals in all systems, extending from J/ψ to ψ(2S), χc, Y states. Femtoscopy studies (PANDA, QCD at FAIR with CBM). Non-prompt charmonia to study beauty hadrons.
- Hypernuclei and exotica
  precision measurements of hypernuclei: mass, lifetime and branching ratios. Powerful new techniques such as strangeness tracking with the help of the KFParticle code, will enhance the measurement precision. Search for exotic baryons. Synergy with CBM and hypernuclei at (S)FRS
- Collective effects and system size dependence
  Particle correlations, also wrt spectator plane. Understand the limit of applicability of the hydrodynamic description of the quark-gluon plasma
- Photons and neutral mesons electromagnetic radiation from the QGP
- Jets hard probes, tomography of the QGP

Standardized Summary

- scientific goals:
  Properties of hot QCD matter, studied via open and hidden heavy-flavor hadrons, hypernuclei, particle correlations, neutral mesons, photons and jets. Transport properties, phase transition, limit of applicability of the hydrodynamic description
- timelines:
  2022-2026 Run 3 → installation of ITS3 in 2029! (heavy-flavor and strangeness physics)
  2030-2033 Run 4 completion of program with current ALICE (including TPC)
  Construction of ALICE 3, installation in 2034-2035. Run 5 from 2036
- milestones:
  Hadronization, energy loss and possible thermalization of charm and beauty in the QGP
  Hypernuclei production and characteristics (CBM, SFRS); QGP temperature evolution
- technical requirements:
  ALICE operation until 2033, including TPC support, calibration, reconstruction. Commissioning of ITS3 in Run 4. Personnel on site for general and on-call shifts. Production of pixel staves for ALICE 3 Outer Tracker (incl. Det Lab)
- beamtime requirements:
  Possible detector tests during major shutdowns at DESY and CERN (e.g. Cave C)
- required resources:
  More or less "flat" budget for ALICE operation until 2033/35;
  Maintain current positions (staff replacements in 2029 x 1, 2035 and ff x 5);
  ALICE 3: technical support from Det Lab; (external) core budget for Outer Tracked construction (tbd)



PoF V planning of CBM

Tetyana Galatyuk

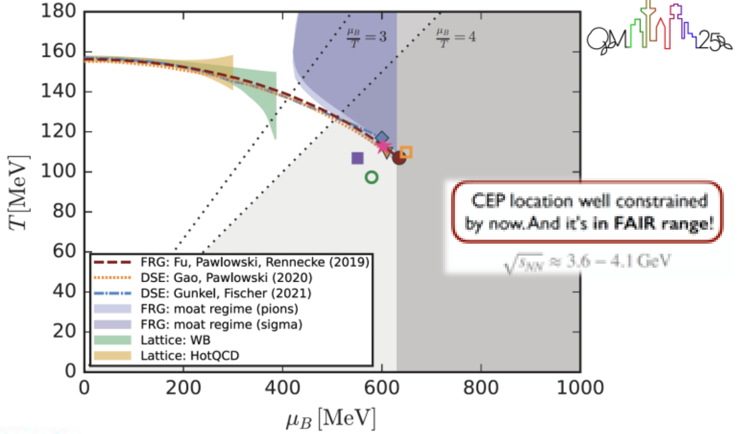
CBM Physics Case

Search for landmarks of the QCD matter phase diagram at high μ_B:

- isolate unambiguous signals of new phases of QCD matter, order of phase transitions, conjectured QCD critical point
- probe microscopic matter properties

→ **heavy-ion beams**

Fabian Rennecke, QM25

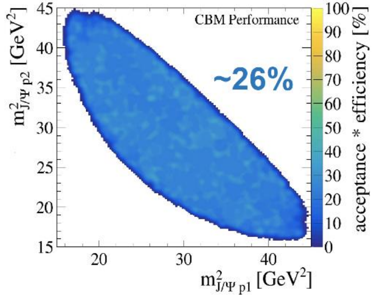


Study various aspects of meson/baryon physics:

- (*u, d, s, c*) hadron production mechanism, spectroscopy (|*s*|=2,3, |*c*|=1), interactions, hadron structure
- em transition form-factors

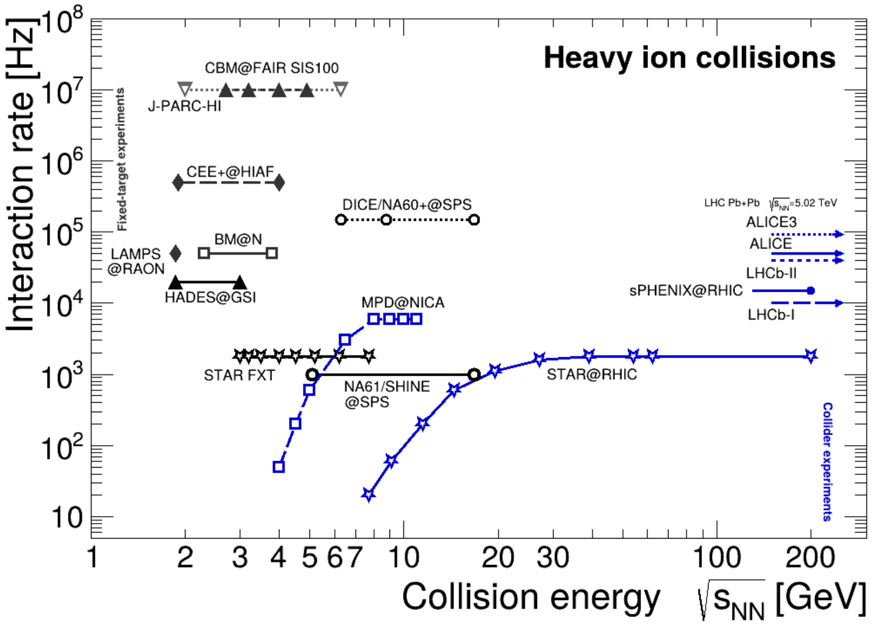
→ **p, d beams**

$pp \rightarrow pp\, J/\psi$



QCD at FAIR network

Some basic facts on extreme matter facilities



CBM will play a unique role in the exploration of the QCD phase diagram in the region of high μ_B with rare and electromagnetic probes: high rate capability

HADES: established thermal radiation at high μ_B, limited to 20 kHz

STAR FXT@RHIC: BES program completed; limited capabilities for rare probes

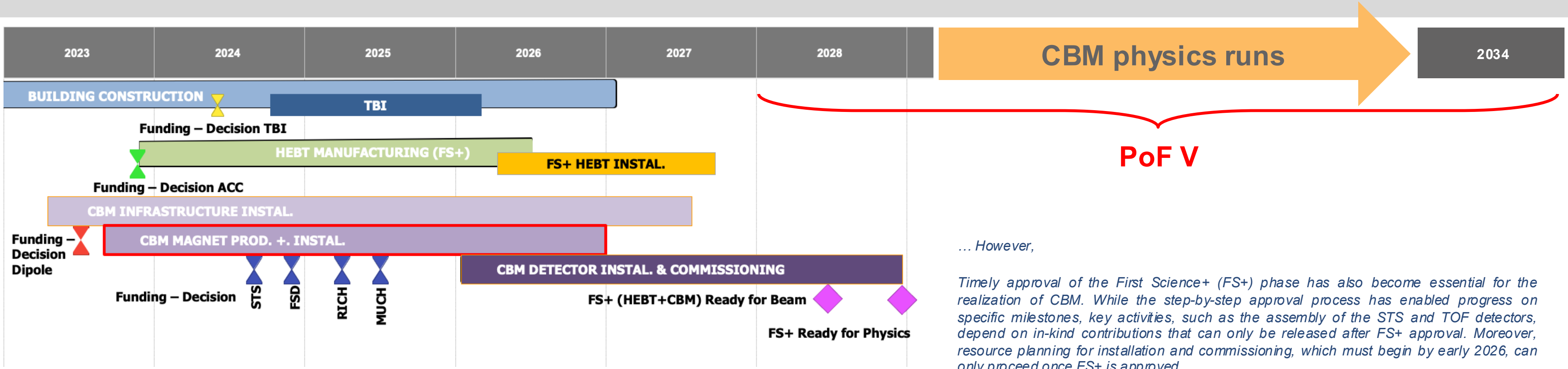
Construction: **CEE+@HIAF,**

Proposals: **DiCE/NA60+@SPS, J-PARC-HI**

ALICE/ALICE 3: exploit the forefront detector technologies and high luminosity potential of the LHC for ions

TG, NPA 982 (2019), update 2025 https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

Key milestones for timely CBM realization



… However,

Timely approval of the First Science+ (FS+) phase has also become essential for the realization of CBM. While the step-by-step approval process has enabled progress on specific milestones, key activities, such as the assembly of the STS and TOF detectors, depend on in-kind contributions that can only be released after FS+ approval. Moreover, resource planning for installation and commissioning, which must begin by early 2026, can only proceed once FS+ is approved.

From the CBM Referee Report
ECE21/ECSG12 8-9 May 2025

- **Magnet** re-procurement ***accomplished.***
- **High Energy Beam Transfer** to CBM cave. FAIR Council Jul. 2024: *Good news regarding time critical components for CBM beamline - magnets and vacuum components: the Council is supporting the procurement of these time critical items as long as the overall budget situation is positive.*
- **Technical Building Infrastructure** (**TBI**) of CBM building. ***FAIR Council 3-4 Dec 2024 approved the contracting of TBI engineering!***
- **Access to the building** is available since March '25, **crane installation** scheduled in CW20 (next week). Availability since CW27

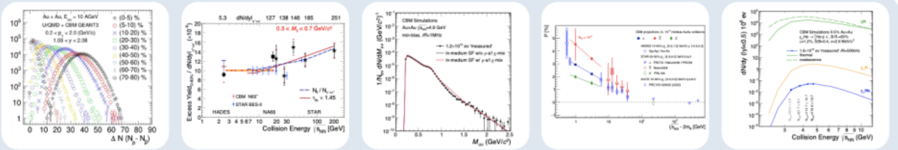
- **CBM components** (Russian IKCs)
- TBI realisation on the critical path! (Awaiting Council decision in July '25)

CBM runs first three years

Focus on beam energy scan (BES)

- Commisioning, with light ions (Ar), focus on highest (for Au+Au) energy to maximise particle production, <100 kHz
- Year 1: BES (Au+Au), 100 kHz, 60 days / year beam on target → factor 100 more statistics w.r.t. STAR FXT
- Year 2, 3 - subject to a reshaping depending on findings in year 1
  - if interesting energy range is identified, focus on this range in year 2
  - followed by proton program
  - followed by dimuon program

Publishable results within
- ⚫ 3 years
- 🟠 8 years …



	Fluctuations	LMR dileptons	IMR dileptons	Strangeness	Hypernuclei
How does the strong force produce confinement? (1st order p.t., bound states)	⚫🟠	⚫🟠	🟠	⚫🟠	⚫🟠
How are the fundamental QCD symmetries broken in nature?			🟠	🟠	
How do the complex spectra of hadrons and nuclei arise from the strong force?		⚫🟠		⚫🟠	🟠
How does nuclear matter behave under extreme conditions? (high μ_B EoS)	⚫🟠	⚫🟠	🟠	⚫🟠	⚫🟠

CBM beam

FAIR Operation Modes

Reference Modes for the Modularized Start Version (MSV)

This document summarizes the deliverables of the FAIR MSV.

Table 4-8: CBM Experiment requirements for the beam parameters from SIS100

CBM[VIII] Experiment requirements											
Beam Parameters	Ion type[IX]										
	p	^{40}Ar	^{58}Ni	^{107}Ag	^{197}Au	p	^{14}N	^{40}Ar	^{58}Ni	^{107}Ag	^{197}Au
	Commissioning					Operation in MSV					
Time structure	slow extraction										
Spill length [s]	5	10				5	10				
Number of ions per cycle	10^{10}	4×10^{8}		2×10^{8}	10^{8}	10^{12}	10^{11}	4×10^{10}		2×10^{10}	10^{10}
Energy range [GeV/u][X]	5-11, 14-29	3-11	2-11			5-11, 14-29	3-11		2-11		
Ref. energy [GeV/u]	29	11				29	11				
Transverse emittance (4σ) [mm mrad]	1 x 0.6										
Momentum spread (2σ)	5×10^{-4}										
Beam spot radius on target [mm]	1										

+ d beam

Different detector configurations

- Dielectron setup, 100 kHz, 1% target, Au 10^7 /s
- Dimuon setup, 10 MHz, 1% target, Au 10^9 /s

Setup	Included subsystems	Average day-1 interaction rate
ELEHAD	MVD,STS,RICH,TRD,TOF,FPW	0.1 MHz
MUON	STS,MUCH,TRD,TOF,FPW	1 MHz
HADR	STS,TRD,TOF,FPW	0.5 MHz

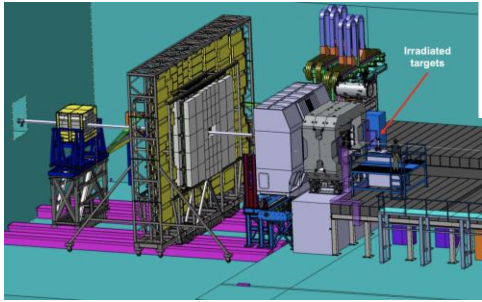
Timeline

LHCb OT at GSI/FAIR


Memorandum of Understanding
between
the PANDA and the CBM
collaborations

CBM MuST system

CBM ready for beam 2028



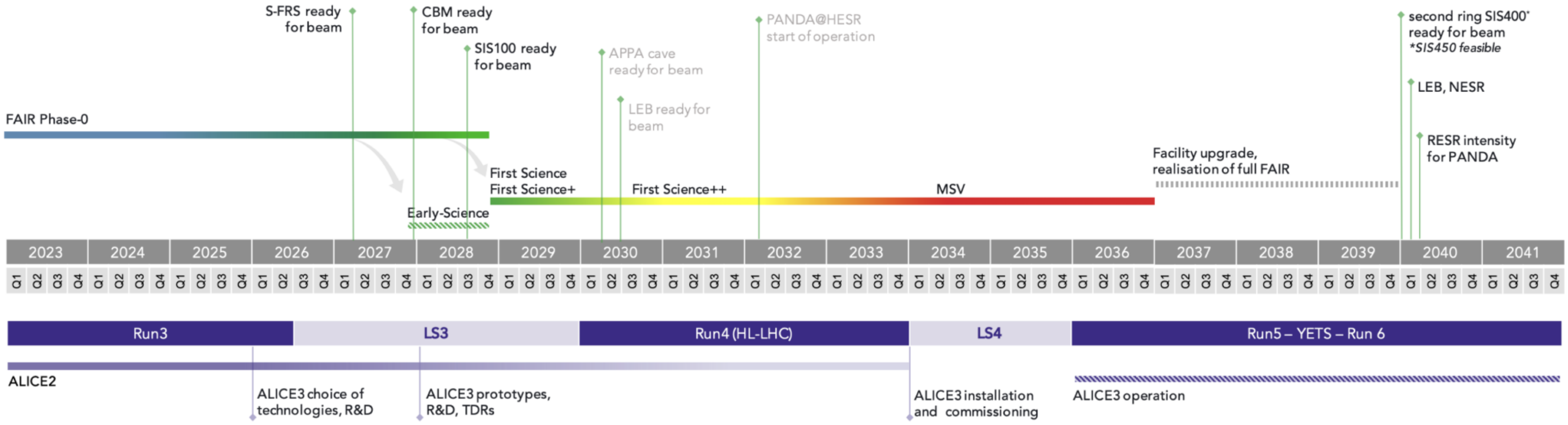

Memorandum of Understanding
between the
BIOMAT Collaboration
and the
CBM Collaboration

~2032, HADES at SIS100

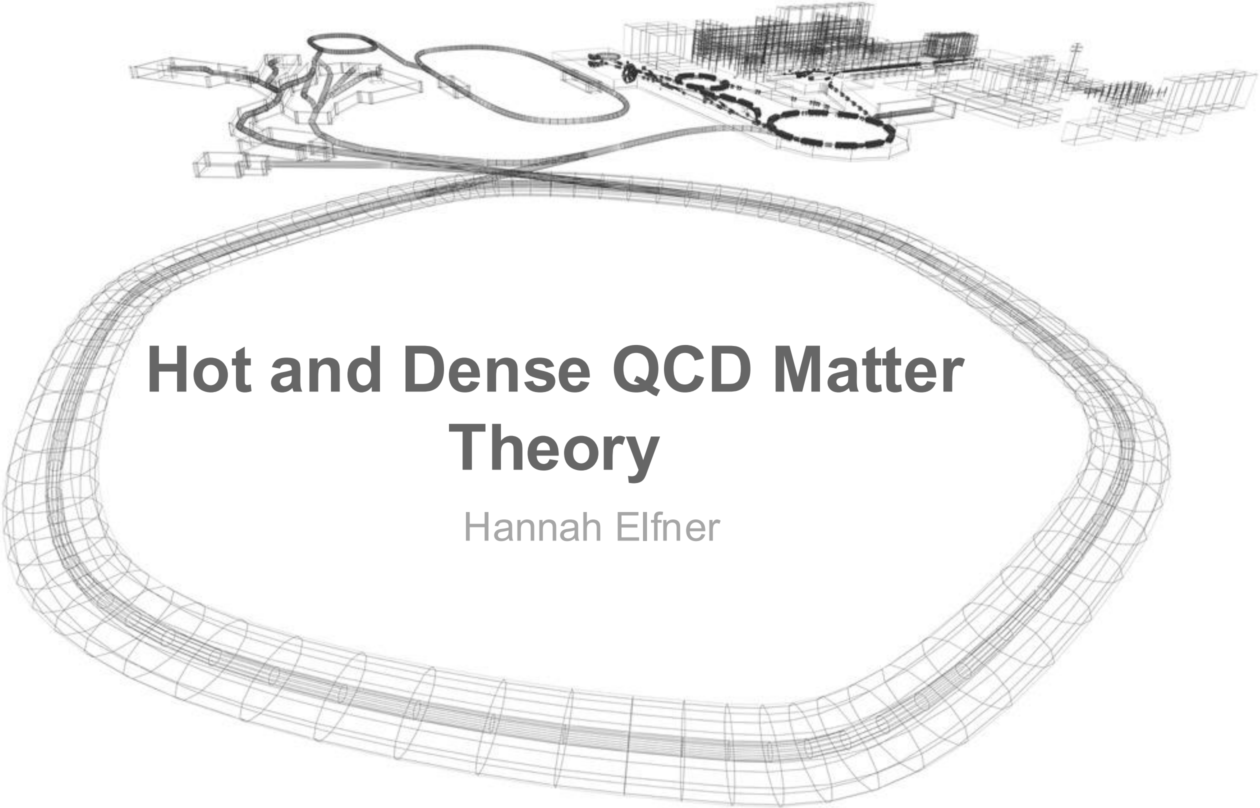
Standardized Summary

- scientific goals:
  - *Understand microscopic properties of QCD matter and search for landmarks of the QCD matter phase diagram at high μ_B*
  - *Study various aspects of meson/baryon physics*
- timelines:
  - *CBM ready for beam in 2028, production runs (Au, p) and physics harvest during PoF V*
- milestones:
  - *Q4 2028 – Detector commissioning with SIS100 beam*
  - *Q3 2029 – First results ready for publication (Flow of hyperons Λ, Ξ?)*
  - *Heuer review 2015: "Name 3 first PRLs"*
    - *The QCD matter equation of state at neutron star core densities studied in heavy-ion collisions*
    - *Restoration of chiral symmetry (chiral $\rho - \alpha 1$ mixing) observed in heavy-ion collisions*
    - *Evidence for a first order phase transition in QCD matter*
- technical requirements:
  - *Approval of FS+*
  - *Full support of IT for high-performance computing*
  - *Full support of CBM cave/infrastructure*
  - *Full support of DetLab (STS realization is a host lab responsibilities)*
- beamtime requirements:
  - *Extended run times ~60 days/year, beam for detector systems commissioning and tests (mCBM, cave C, …*
- required resources:
  - *Department personnel and budget on the current level maintained, + 2 FTE (PostDocs) for data analysis*

I had a dream…



Facilities already in operation are expected to continue to serve experiments during the phases of the FAIR project.
Steps beyond FS+ require additional funding, assumed to be in place by 2026, and alternative CR layout according to MAC recommendation



Hot and Dense QCD Matter Theory

Hannah Elfner

Science: Plans for 2028+

- Maintain a research program focused on the support of the experimental campaigns at GSI/FAIR, HADES, CBM, ALICE
- Tools: Open source transport codes and relativistic hydrodynamics
- Main themes:
  - Nuclear equation of state and connection to astrophysics
  - Medium modification of resonances
  - Properties of hot and dense QCD matter under extreme conditions
  - Electromagnetic probes
  - Light cluster production and properties
- Exploit connections to other areas within NUSTAR (e.g. nucleon correlations, hypernuclei production) and hadron physics (e.g. modeling of hadron properties)
- Extracting from the novel FAIR experimental data information on the EoS
- Investigating signatures of the 1st order phase transition
- Searching for signatures of in-medium and subthreshold effects on the strangeness and charm production at FAIR
- Investigation of possible indications of physics beyond the standard model (dark matter candidates) within heavy-ion data
- Focus on ultra rare observables, which becomes possible due to the outstanding luminosity of FAIR
- This opens the road for fluctuations and correlations, charm and dileptons
- Overcome the coarse graining method for dileptons

Standardized Summary

- scientific goals:
  To connect final results in the detector with QCD input, sophisticated dynamical evolution is necessary
  Relativistic hydrodynamics and transport theory are the main approaches pursued here

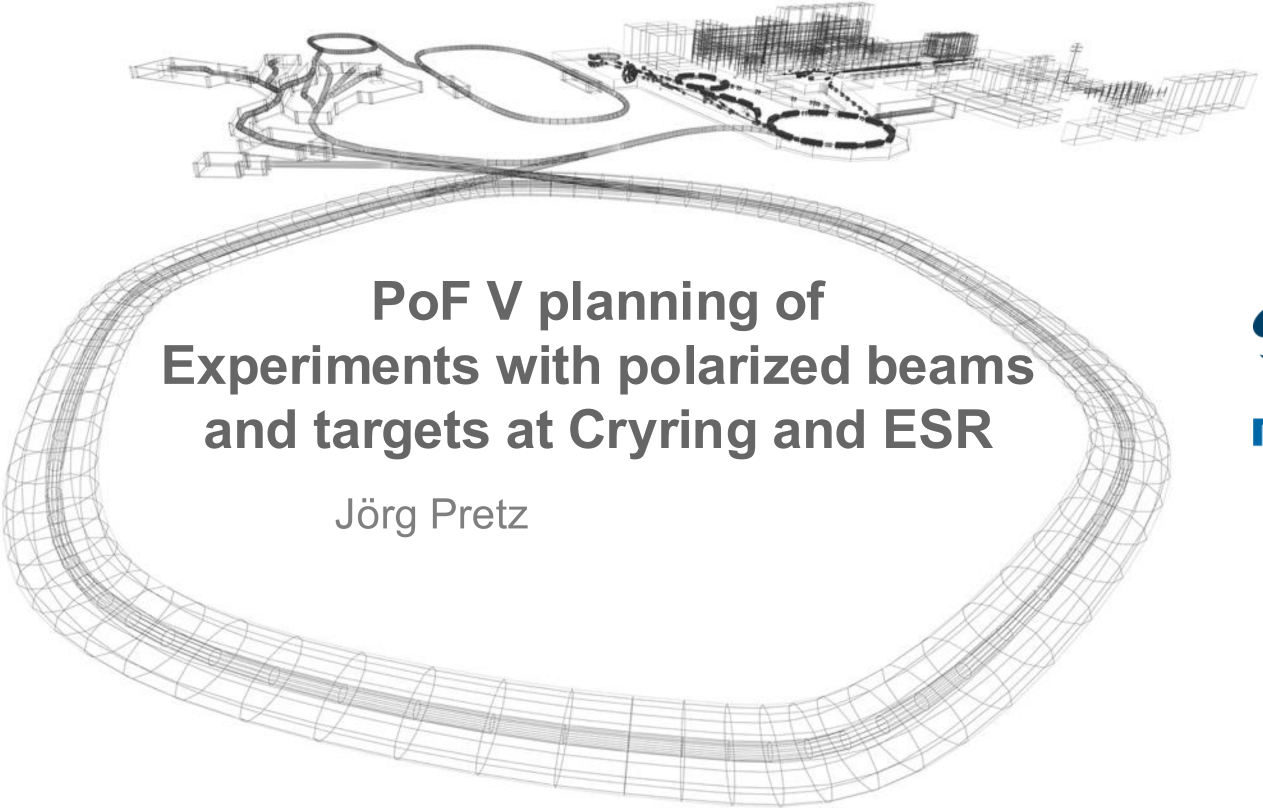
- timelines:
- milestones:
- technical requirements:

Department	CPU-Core hours /year	Storage (scratch)	Storage (home)	RAM per core
Hot and Dense QCD Matter (Status)	10 million (the+hyihp)	150 TB	120 GB	50 MB-13 GB
Hot and Dense QCD Matter (in 5 years)	30 million	300 TB	10 TB	Up to 20 GB

Permanent
Hannah Elfner
Elena Bratkovskaya
Marcus Bleicher
Horst Stöcker

- beamtime requirements:
  No

- required resources:
  Need for HPC
  Support for open source code development
  Good mixture of senior/junior personel through hirings over last ~10 years; in addition: 2 postdoc positions
  Relying heavily on third party funding, e.g. group by H.E.:
  1 postdoc by GSI and 1 PhD student F&E
  2 postdocs and 5 PhD students by CRC-TR, ELEMENTS, etc



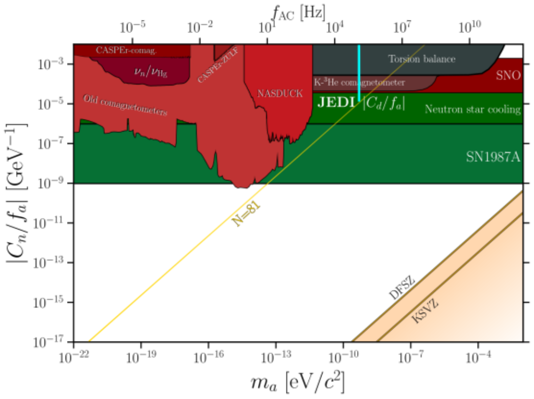
PoF V planning of Experiments with polarized beams and targets at Cryring and ESR

Jörg Pretz

Science

- Using polarized beams/targets offer many additional observables, some test C,P, and/or T symmetry.
- How to Explore a Wider Mass Range ma
  - Modify beam energy
  - Use different nuclei
  - Use additional electric field
- Studies started at COSY/FZJ ***could be continued at ESR***

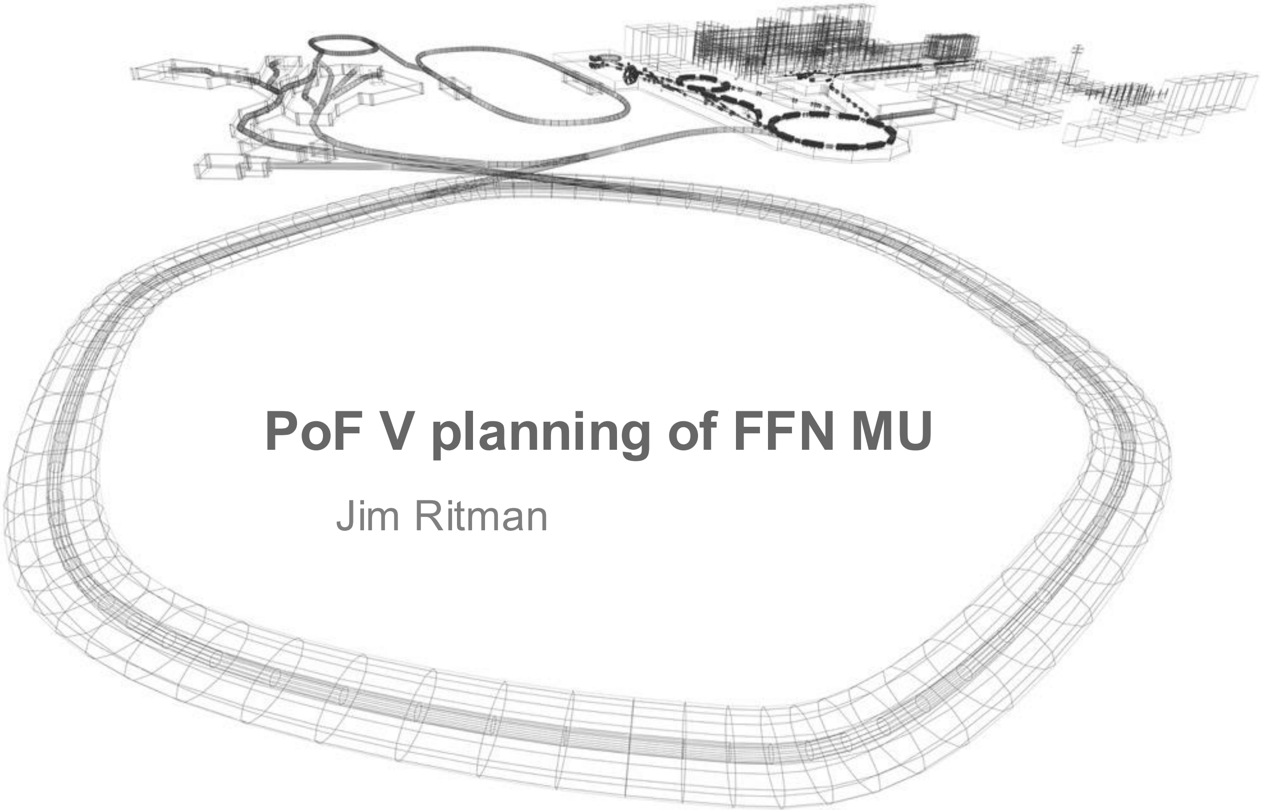
In an engineering run new limits on coupling constants were established



JEDI Collaboration, PRX 13 (2023) 031004

Research Topics to be addressed

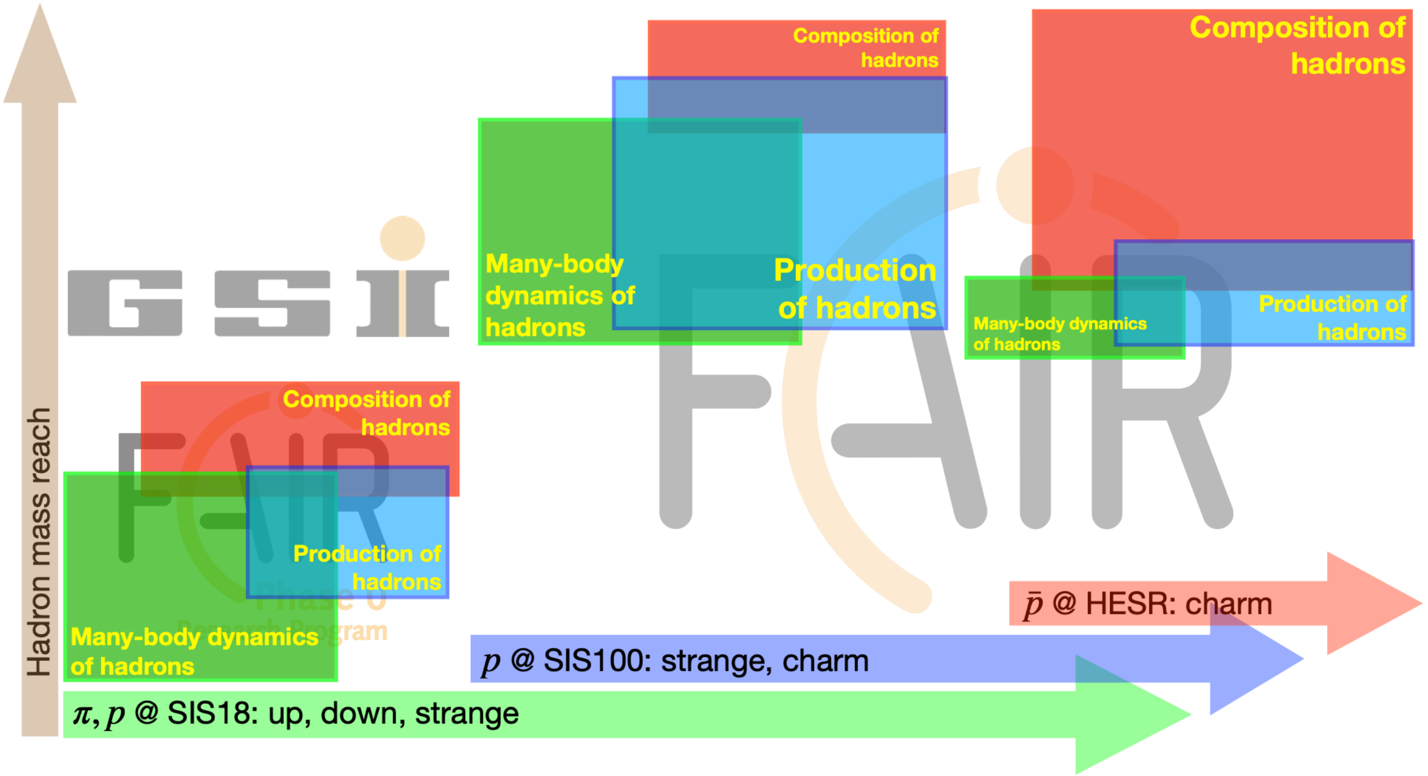
- Investigate possibilities for axion searches at ESR
  currently done by Daoning Gu (PhD student at RWTH)
- Installation of polarized source
  reuse sources available in Jülich?
- Spin Coherence Time studies
  mandatory to reach small statistical error
- Development of a polarimeter concept
  adapt concept developed for EDM storage ring (PhD thesis S. Siddique/RWTH)
- Injection Optimization using Reinforcement Learning
  continuation of work done for injection into COSY (PhD thesis A. Awal/RWTH)
- Investigate possibilties to disentangle different couplings
  (axion wind vs. oscillating EDM)



PoF V planning of FFN MU

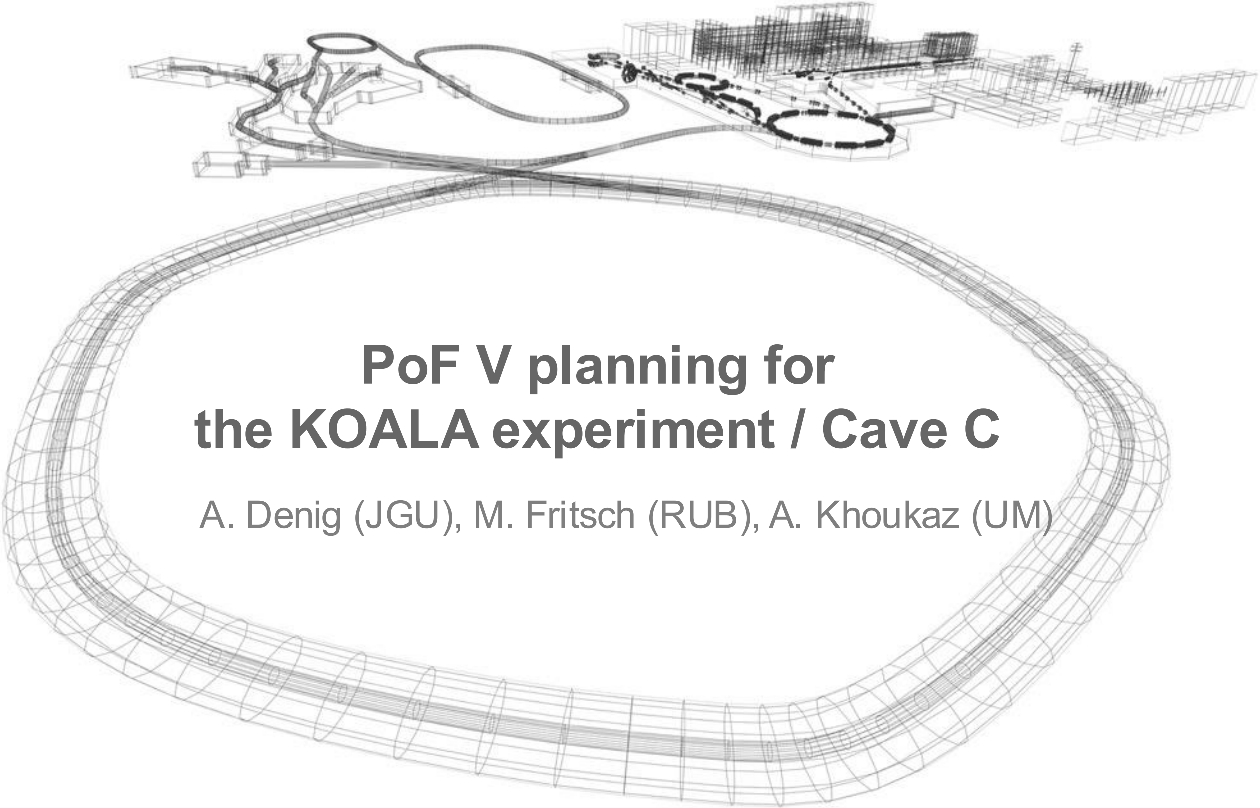
Jim Ritman

Hadron Physics at GSI and FAIR



Standardized Summary for FFN-HP

- scientific goals: Hadron physics using pion beams at HADES and proton beams at CBM
- timelines: Pion beam-HADES 2026-2028, Proton beam – CBM 2030→
- milestones: Pion beamtimes, Commissioning of CBM, Proton beamtimes at CBM
- technical requirements: completion of FS+,
- beamtime requirements: pion beam at SIS18, proton beam at SIS100
- required resources: personal, sach/investmittel, elec/mech-workshops

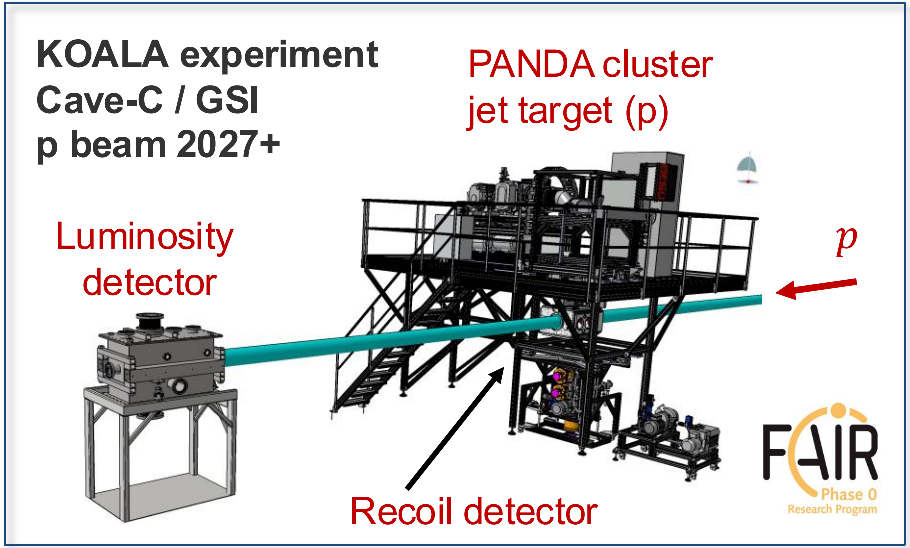


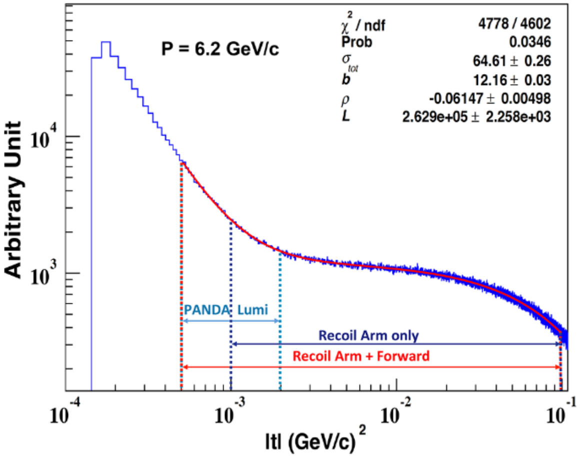
PoF V planning for the KOALA experiment / Cave C

A. Denig (JGU), M. Fritsch (RUB), A. Khoukaz (UM)

The KOALA Experiment at Cave-C

Goal: constrain hadronic part in elastic pp scattering by measuring interference btw. hadronic and Coulomb part
→ combining PANDA luminosity detector (HV-MAPS) + cluster jet target + recoil detector





→ improved understanding of hadron-hadron interaction

Continuation of program at COSY with improved instrumentation

Schedule : Proposal G-24-00235

- 2026: move of cluster target to GSI
- 2026: Tests w/o beam, commissioning
- 2027: First measurements of elastic pp
- 2028: Measurements with vertex reconstruction

Standardized Summary

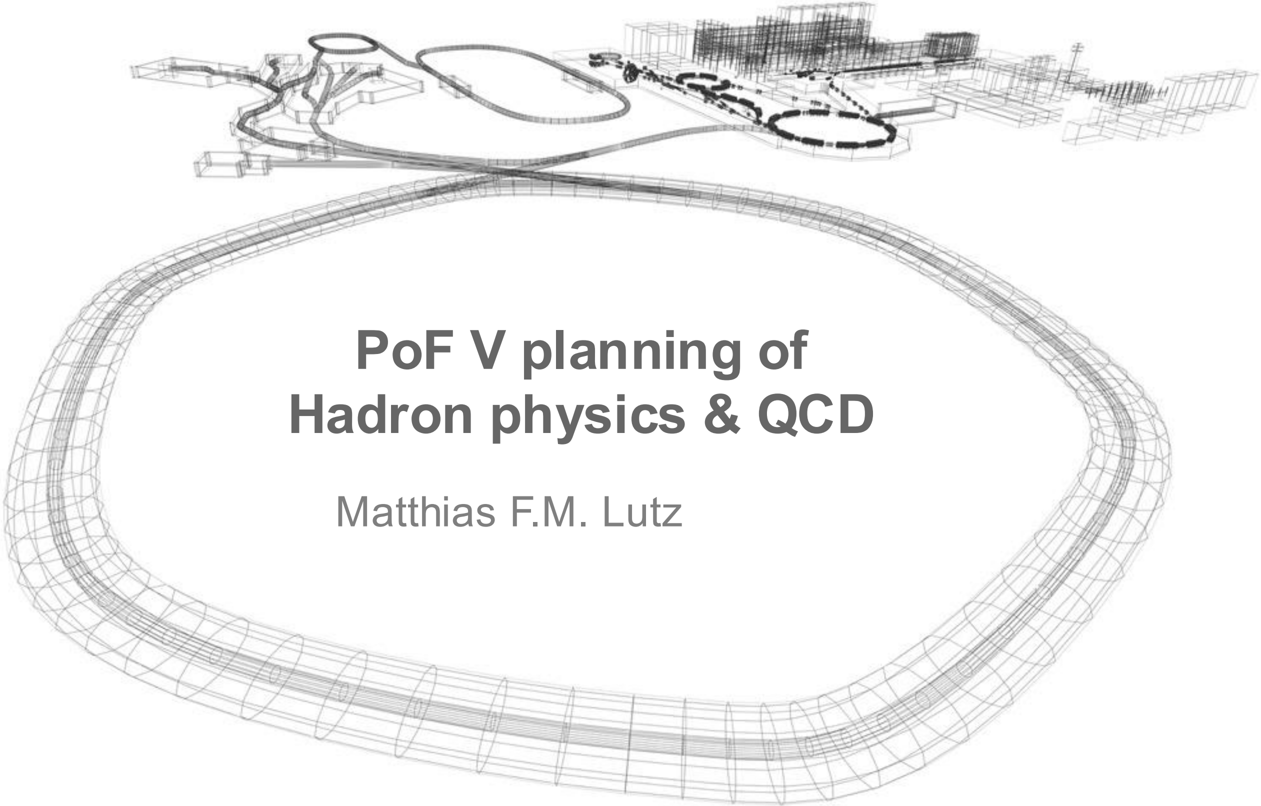
- Scientific goals:
  Precise measurement of the elastic pp scattering for very low momentum transfers to determine the hadronic part of the interaction
  Further topics under investigation

- Timelines and milestones:
  Move target to GSI in 2026, Commissioning run 2027, Vertex reconstruction 2028, further measurements

- Technical requirements:
  Nothing special, almost all (H2, detector gas, power, network, …) is already available in CaveC

- Beamtime requirements:
  2-3 weeks per year, protons and very light ions, maybe later other species

- Required resources:
  CaveC starting end of 2026 after GLAD moved out, some support by technical personnel (few weeks/y)



PoF V planning of Hadron physics & QCD

Matthias F.M. Lutz

Standardized Summary

- Scientific goals:
  - *Addresses key question: "How do hadrons and nuclei form and how are their spectra determined by the strong force" (to be updated with the final version)*
  - *Experimental connections to the pion beam programme (HADES), the proton beam programme (CBM), and to any future hadron physics programme.*
  - *Strategy: Computation of coupled-channel systems from Lattice QCD and Effective Field Theory.*
  - *Objectives:*
    - *Study meson-baryon interactions with u/d and s quarks (→pion and proton beam programme).*
    - *Quark-mass dependence of baryon structure and transitions.*

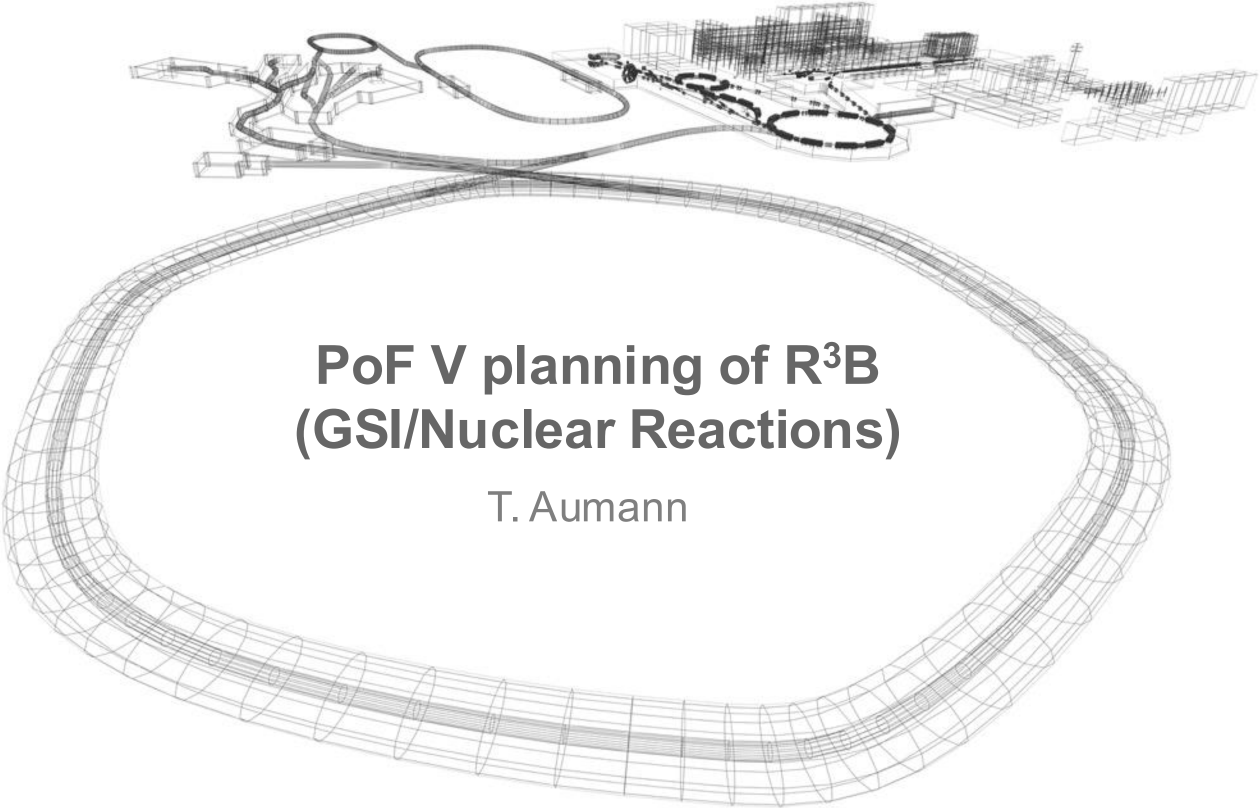
- Timeline: *Input for the GSI POF V strategy from 2028 onward.*

- Milestones:
  - *Quantitative study of systematic uncertainties in Lattice QCD studies of meson-baryon scattering.*
  - *Study of 1-loop contributions from the chiral Lagrangian to meson-baryon interactions.*
  - *Investigation of the role of 3-hadron thresholds in coupled-channel scattering.*

Standardized Summary (continued)

- Technical requirements:
  - *Developing suitable parameterizations for meson-baryon scattering amplitudes from the chiral Lagrangian.*
  - *Development of a (parallel) framework for amplitude-fits to finite-volume spectra from Lattice QCD.*

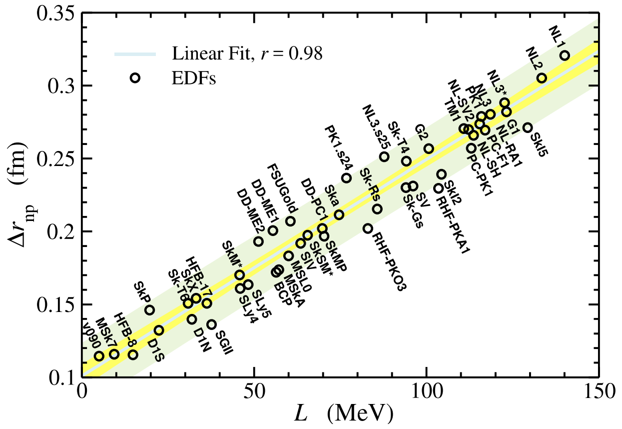
- Required resources:
  - *an HPC cluster setup that supports heterogeneous mpi jobs*
  - *Sustained personnel support of GSI Hadron physics & QCD (such as Postdoc/ student positions).*
  - *Significant local cluster resources (CPU and GPU) and IT support for HPC computations.*
  - *Significant cluster storage (scratch and for the whole POF V duration).*



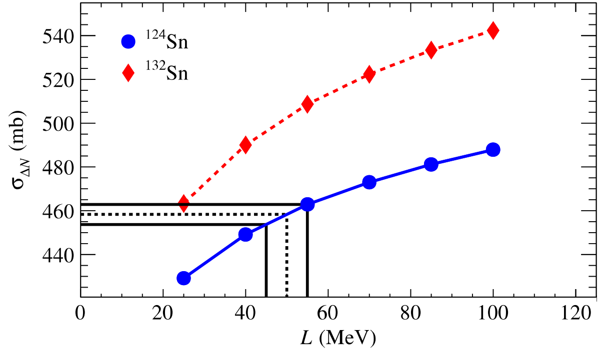
PoF V planning of R^3B (GSI/Nuclear Reactions)

T. Aumann

Constraining the EOS of neutron matter



Neutron-skin thickness and neutron pressure L



Observable: neutron-only removal cross sections

Goal: Derive tight constraints on L (+/-10 MeV) via different nuclear observables for neutron-rich nuclei

Key nuclei: ^{132}Sn, ^{208}Pb + development along isotopic chains

Comprehensive experimental program at R^{3}B:

- Neutron-only removal cross sections
- Proton elastic scattering (active target)
- Neutron radii for valence orbits from (p,pn) QFS reactions
- Dipole polarizability

- Additional EOS constraints:
  Giant monopole resonance (incompressibility)
  Short-range correlations (higher density)
  Properties of hypernuclei (higher density)

First experiment 2028 on neutron-only removal / neutron skin

Goal: Full program accomplished and published until 2035

Fission properties of neutron-rich nuclei towards the r-process

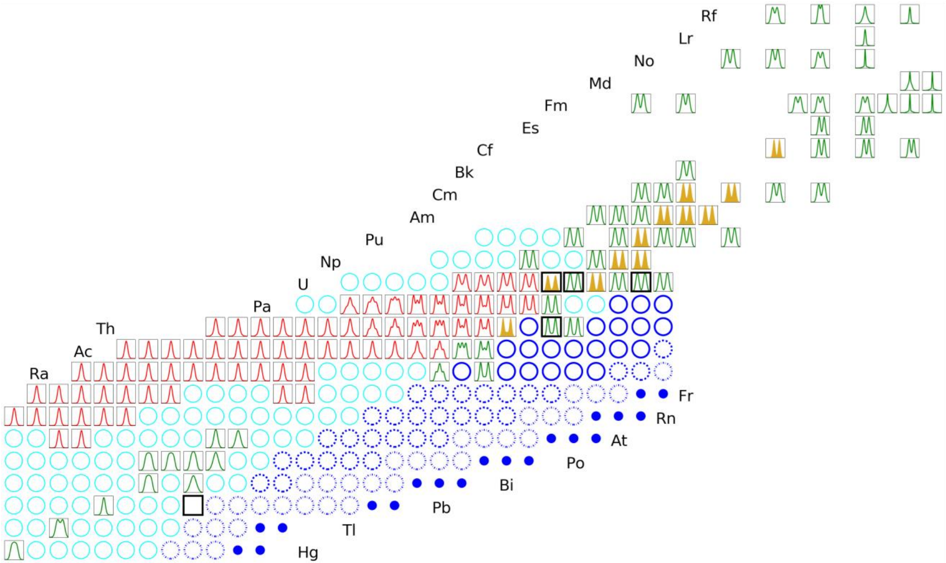


Table of nuclides showing the measured Z (red) and A (green) fission yields in actinides and pre-actinides together with the neutron-rich (dark blue circles and dots) and other nuclei (light blue circles) that can be investigated with R^3B at FAIR.

Goal: Measurement of fission properties as a function of neutron excess (towards the r-process)

Large area of neutron-rich and neutron-deficient heavy nuclei reachable at FAIR
-> systematic measurement of fission properties as a function of N/Z:

- Fragment charge and mass distributions
- Excitation-energy controlled by missing-mass measurement in (p,2p)fission quasi-free scattering
- Coincident neutron measurement
- Extraction of fission barriers

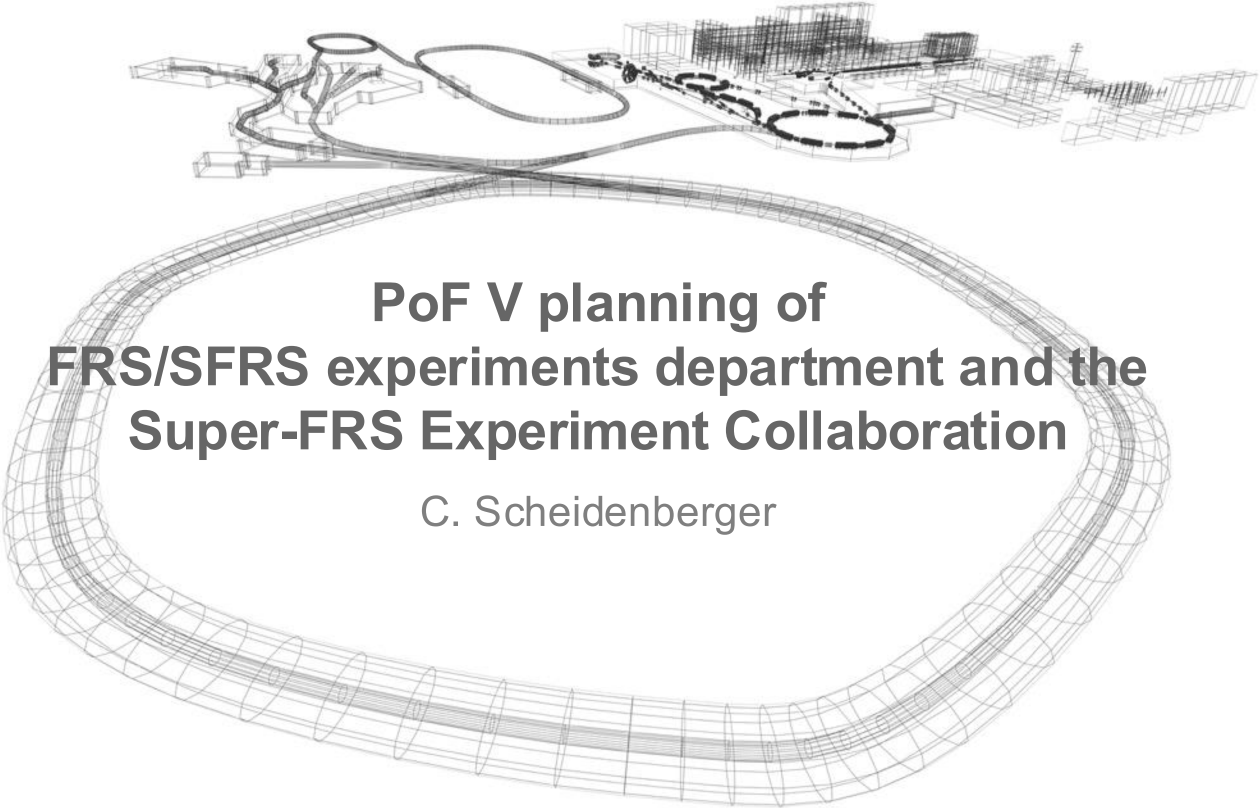
First experiment during 2028/29 Early Science program at R^3B

Goal: Systematics on fission barriers for neutron-rich nuclei until 2035 -> strong constraints for theoretical models needed for r-process predictions

Standardized Summary

- scientific goals: Constraining the pressure of neutron matter at saturation density by different observables
  Deriving fission barriers and fission properties for n-rich nuclei towards the r-process
  Establishing experirmntal programs Hypernuclei and Short-range correlations
  Completion of Proton-Arm Spectrometer and NeuLAND
  TDR and construction readiness report for High-Resolution Spectrometer
- timelines: 2028: Start of Early and First Science program at R^3B
  until 2035: Experimental program on EOS completed and final constraints on L derived
- milestones: Constraints on pressure of neutron matter obtained
  Systematics on fission properties for n-rich nuclei accomplished
- technical requirements: slow-extraction beams; cleanliness of secondary beams from Super-FRS;
  high-intensity primary beams
- beamtime requirements: commissioning and preparation beams; 2 months per year production beam time
- required resources: increase of personnel, budget for postdocs, technical support
  support EE, Detector Lab, Cryogenics, Target Lab, IT
  investment needs for NeuLAND completion, Support for R&D and maintenance

PoF V planning of FRS/SFRS experiments department and the Super-FRS Experiment Collaboration



C. Scheidenberger

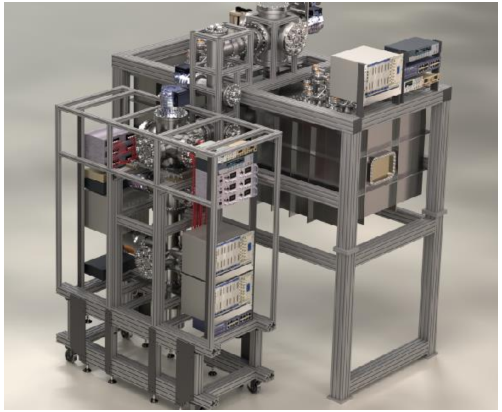
Science at the Super-FRS

Data for nuclear astrophysics

- PXN: multiple β-delayed neutron emmission
- Broad-band mass measurements
- MNT reactions with slowed-down n-rich secondary beams

Instruments:

Super-FRS Ion Catcher at final foci of Super-FRS



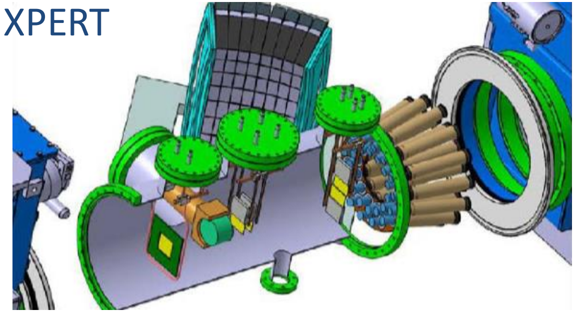
Study of nuclear structure at the extremes

- In-flight fragmentation cross-sections
- multiple proton-radioactivity using in-flight decay method
- Charge and matter radii and skins using transmission method

Instruments:

Tracking detectors and secondary targets at central focal plane of Super-FRS

- Travelling MUSICs
- EXPERT

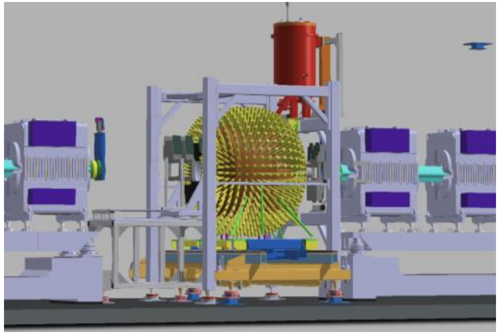


Science at the FRS

Strangeness in exotic nuclei
- Lifetimes
- Binding energies
- Kinematics

Meson-nucleus bound systems

Instruments:
WASA-2 (LHe free magnet,…)



MNT reactions slowed-down beams:
- Mass spectrometry for neutron rich heavy nuclides

Radioactive molecules:
- Formation and properties

Fission studies:
- Fission yields and fission isomers

Instruments: FRS-Ion Catcher

Science at and collaboration with other facilities

Complementary studies and opportunities

Mass measurements of ISOL beams for nuclear physics and astrophysics

→ TITAN @ TRIUMF, Canada

MNT and fission studies (i.e., fission isomers)

→ IGISOL @ JYFL, Finland

In-flight fragmentation cross-sections

→ FRIB, US

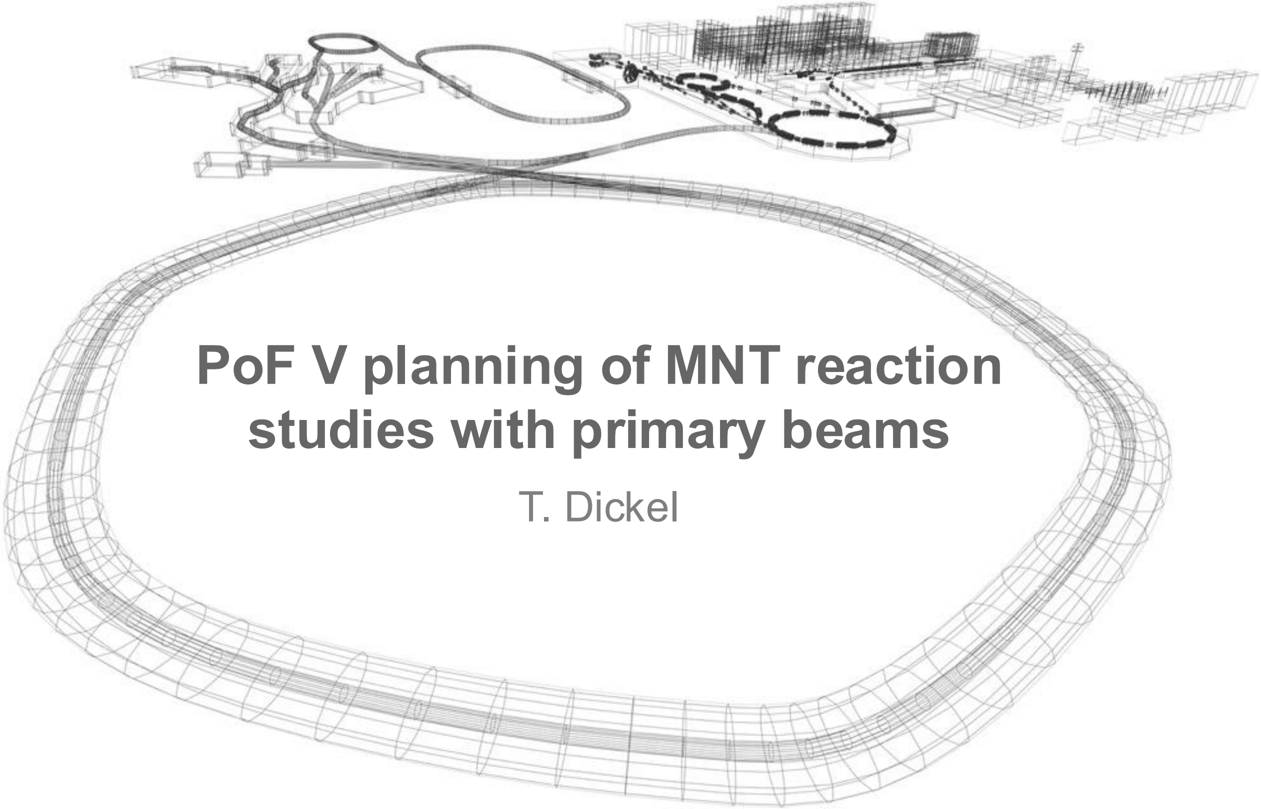
→ BigRIPS @ RIBF, Japan

Meson-nucleus bound systems

→ BigRIPS @ RIBF, Japan

Standardized Summary

• scientific goals:	• Data for nuclear physics and astrophysics, e.g., masses, radii and in-flight decays of nuclei far from stability • Studying exotic nuclear systems, e.g., hyperons in exotic nuclei, meson-nucleus bound systems • Formation and properties of radioactive molecules for fundamental studies, e.g., eEDM
• timelines:	• 2028: PXN measurements with the Super-FRS Ion Catcher at FHF1 • 2028-29: Radioactive molecule studies at the FRS • 2029: WASA-2 campaign at the FRS • 2030: MNT with slowed-down primary beams @ FRS Ion Catcher • 2031: Broadband mass measurements with the Super-FRS Ion Catcher • 2032: MNT with secondary beams @ Super-FRS Ion Catcher • 2033: In-flight decay of dripline nuclei and radii measurement at the Super-FRS • 2028-34: Selected complementary experiments at TRIUMF, FRIB, RIBF, JYFL
• milestones:	• 2028: First experiments with the Super-FRS Ion Catcher at the Super-FRS • 2029: Experiments with WASA-2 at the FRS • 2033: First experiments with detector (in air) and secondary targets at the mid focal plane of the Super-FRS (FMF2)
• technical requirements:	• C…U max. intensity at max. rigidity (slow extracted beam) with fast machine cycles, incl. ext. time down ~ 10 m • Proton beam at FRS with 2 GeV • Cryogenic lab at GSI and lab space for Super-FRS EC at FAIR
• beamtime requirements:	• On average 4 to 6 weeks of beamtime per year at the FRS and Super-FRS each (total 2-3 month) for commissioning of new equipment for FAIR experiments and physics beamtime
• required resources:	• Support by GSI scientific-technical infrastructure groups (detector lab, target lab, EE, IT, …) • Personal, invest and consumables for FAIR experiments • Operation budget for FRS experiments



PoF V planning of MNT reaction studies with primary beams

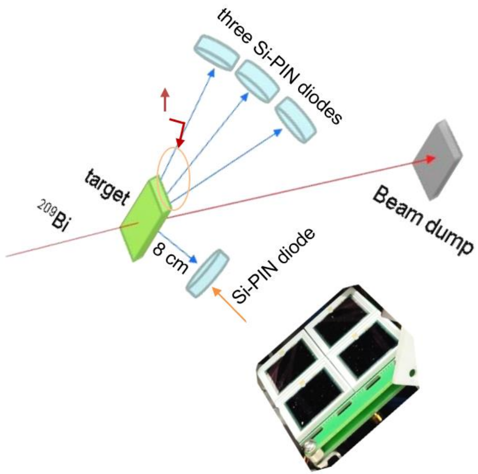
T. Dickel

Multinucleon Transfer reactions studies

Super-FRS EC

Two complementary approaches to measure isotopically resolved reaction cross-section

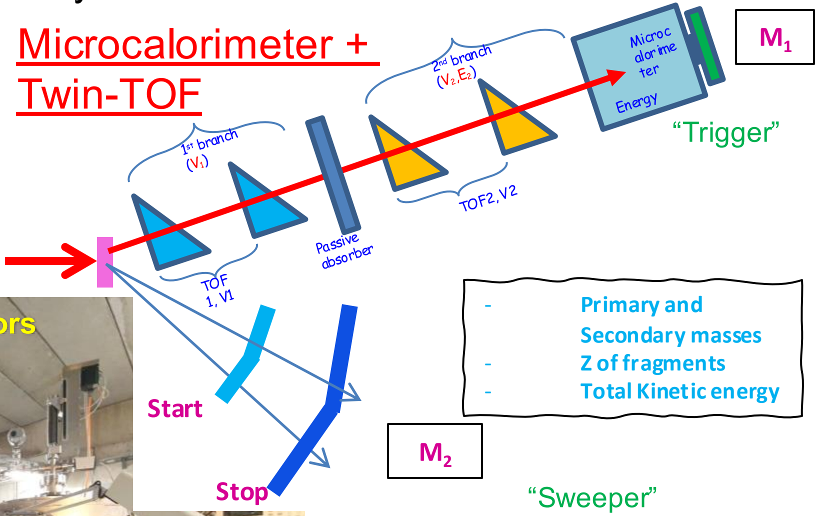
Alpha-Spectroscopy



Pulsed (~1% duty cycle)
^{208}Pb and ^{209}Bi beams
7 to 8 MeV/u
10^8 to 10^{10} ions per sec

Towards the understanding of MNT reactions with secondary beams to produce the most exotic species at the Super-FRS

Microcalorimeter + Twin-TOF



"DC" beams
^{136}Xe, ^{197}Ag and ^{238}U beams
6 to 8.5 MeV/u
10^8 to $5x10^{10}$ ions per sec

Standardized Summary

- scientific goals: Understanding of MNT reactions with secondary beams, so the most exotic species can be produced with secondary beams induced MNT reactions at the Super-FRS

- timelines: Installation in Cave and first test done in 2026. First full campaign in 2027/28, from 29 to mid of 2030 full exploitation of the available beams map a wide parameter space for identifying the best conditions for most exotic cases at the Super-FRS

- milestones: Full commissioning of Mirco calorimeter + TwinTOF and alpha spectroscopy setup in 2028

- technical requirements: Pulsed (~1% duty cycle) ^{208}Pb and ^{209}Bi beams, “DC” beams ^{136}Xe, ^{197}Ag and ^{238}U with 6 to 8.5 MeV/u and 10^8 to $5x10^{10}$ ions per sec

- beamtime requirements: 5 days in ’27, from ‘28 onwards 2 to 3 times five days per year

- required resources: Only Beam time, Detectors, electronics,… come form Napoli/Italy, THM Giessen, TIFR Mumbai, India and University of Edinburgh, UK. Cave is ready, Minimal amount of consumables to stay operational (<10k€/y)

PoF V planning of KSP

Magda Górska

HISPEC/DESPEC collaboration hosted by KSP

- **HISPEC: HI**gh-resolution in-flight **SPEC**troscopy (with **AGATA and LEB** or whenever one of those not available, for dedicated cases with HELIAC beams)
- **DESPEC: DE**cay **SPEC**troscopy with stopped ions

- Evolution of shell structure and nuclear shapes in **uncharted nuclear territory**
- Spectroscopic information for the **nucleosynthesis of heavy nuclei**
- GSI/FAIR provides **unique opportunities** for N~126 nuclei, rare earth and actinides
- AND e.g. Nuclear structure close to **doubly-magic Sn isotopes**

2019
Start of Phase-0 research program

FAIR Phase 0 Research Program

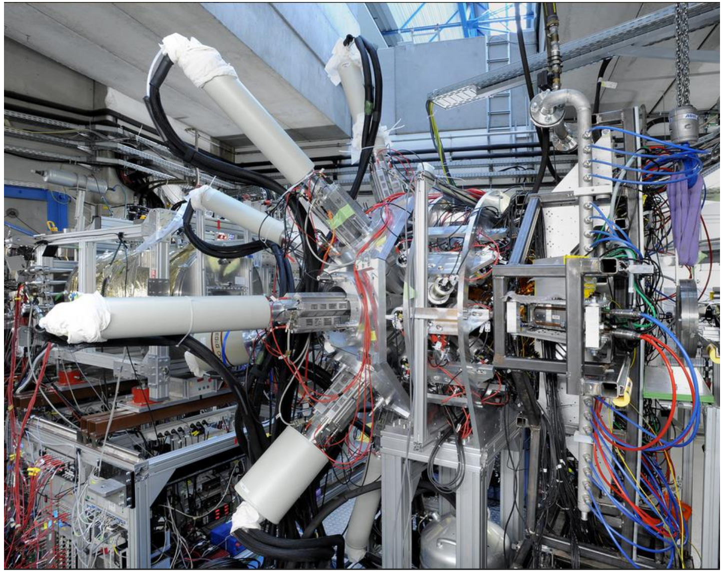
- Comprehensive decay information from key nuclei at secondary beam yields as low as
  - ✓ ***one ion per hour***
- Sensitive to nuclear lifetimes spanning
  - ✓ ***13 orders of magnitude*** (10ps-100s)
- Measurement of
  - ✓ ***any mode of nuclear decay***

Possible gamma-ray spectroscopy experiments with HELIAC

- Rare isotopes beam with 100% duty cycle at energy around the Coulomb barrier offer exceptional opportunities for uniquely-selected physics cases involving gamma-ray array as DEGAS or parts of AGATA in combination with ancillary detectors and possibly a compact spectrometer behind for recoil identification.

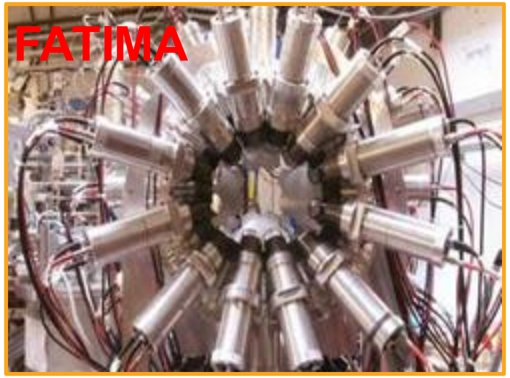
- Reaction mechanism being Coulex, fusion-evaporation or MNT reactions especially in inverse kinematics, and the decay spectroscopy for cases with high scientific impact.

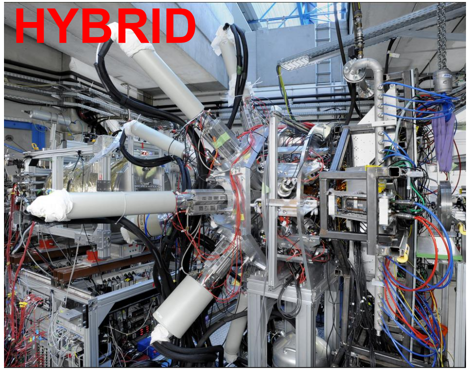
- Priority being FAIR high-energy beams and unique cases will be worth the effort of dedicated setup (among others, the known case made at MSEP in the year 2000: 94Ag21+ isomer, which until today was not confirmed at any facility in the world; and heavy actinide isotopes.)

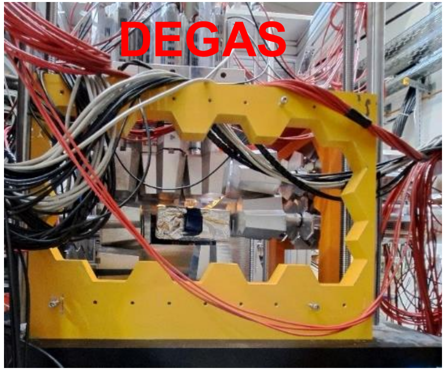


HELIAC as injector for SIS extracting beams to HISPEC/DESPEC

- HISPEC/DESPEC experiment require the full FAIR intensities to assure discovery potential for in-flight fragmentation/Coulex of radiactive beams or their decay.
- HELIAC beams may serve very well for the particular cases of fragmentation of less intense, rare and heavy beams and their decay, assuring that nuclei far from stability can be reached.
- Any HELIAC beams may serve for essential tests experiments.

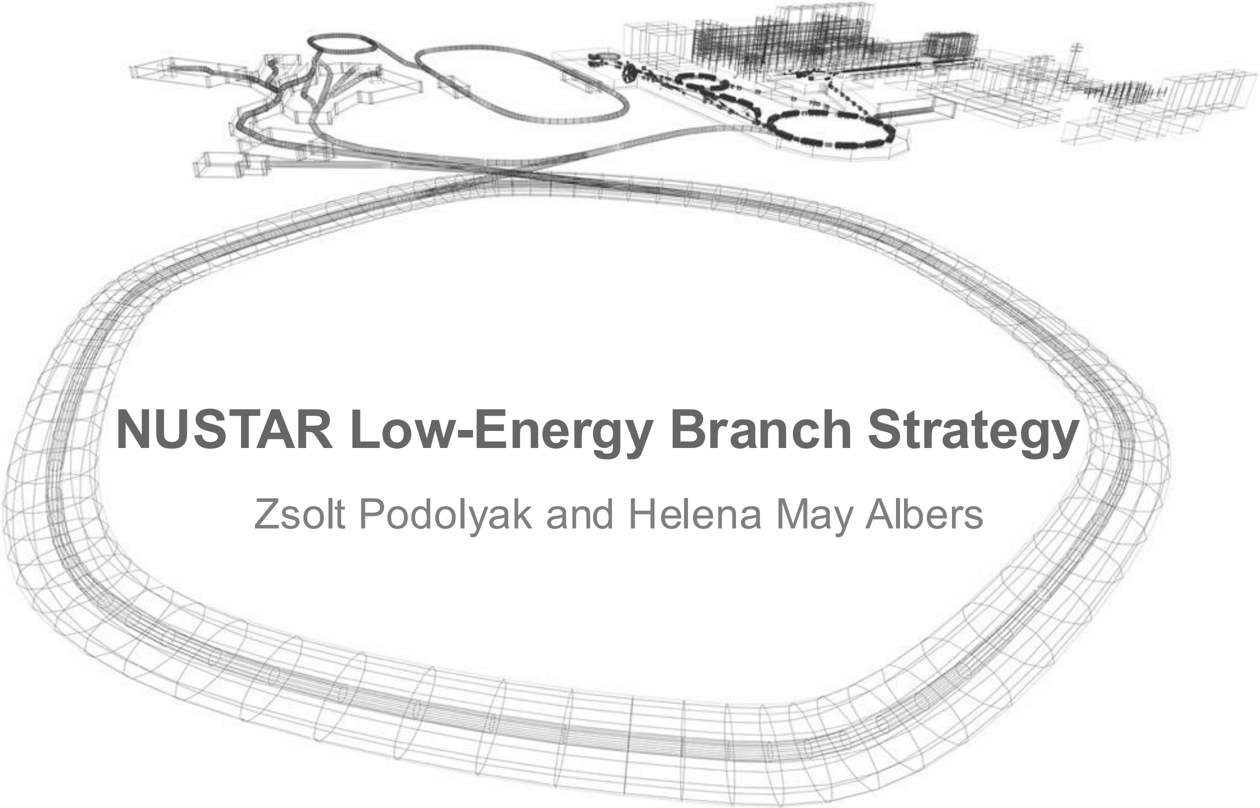






Standardized Summary

- scientific goals: structure of nuclei far of stability, transition energies and probabilities to obtain detailed and dynamic information of the nuclear wave functions and therefore shape and shell evolution
- timelines: DESPEC any time, HISPEC with Heliac beam (when available), with FAIR (when AGATA and LEB available, or in front of GLAD)
- milestones: HISPEC: AGATA completion, LEB; DESPEC: beam of high intensity, or less intense rare beams
- technical requirements: **the completion and commissioning of the LEB is essential to the H/D science program**; **beam intensity too**
- beamtime requirements: discovery potential will be there for at least 10e9 for physics experiments with rare beams, for standard beams 10e10; many less intense or fewer but high intensity beams.
- required resources: whatever needed for operational S-FRS, LEB, detector and computer infrastructure

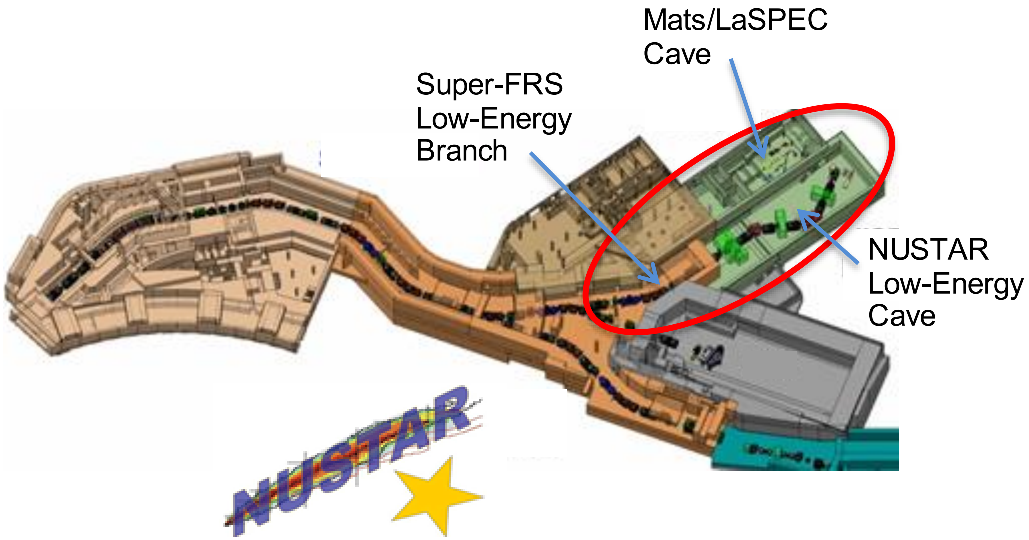


NUSTAR Low-Energy Branch Strategy

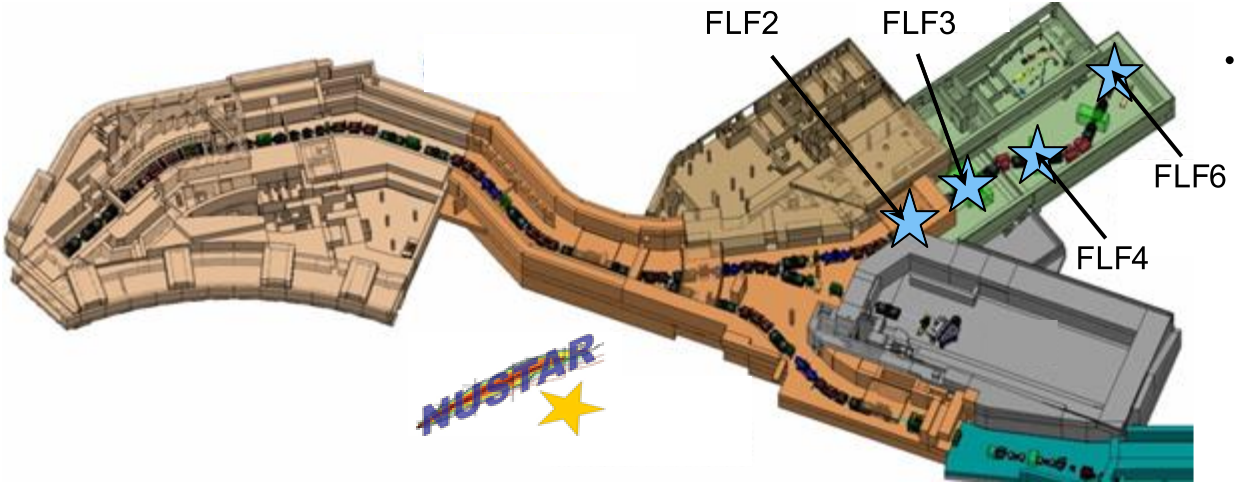
Zsolt Podolyak and Helena May Albers

NUSTAR Low-Energy Branch Overview

- The NUSTAR LEB comprises the Super-FRS Low-Energy Branch, the NUSTAR Low-Energy Cave (which houses the Energy Buncher) and the Mats/LaSPEC Cave
- The buildings for these areas exist but are not fully equipped with Technical Building Infrastructure
- The Low-Energy Cave is currently being used for pre-assembly of Super-FRS magnets

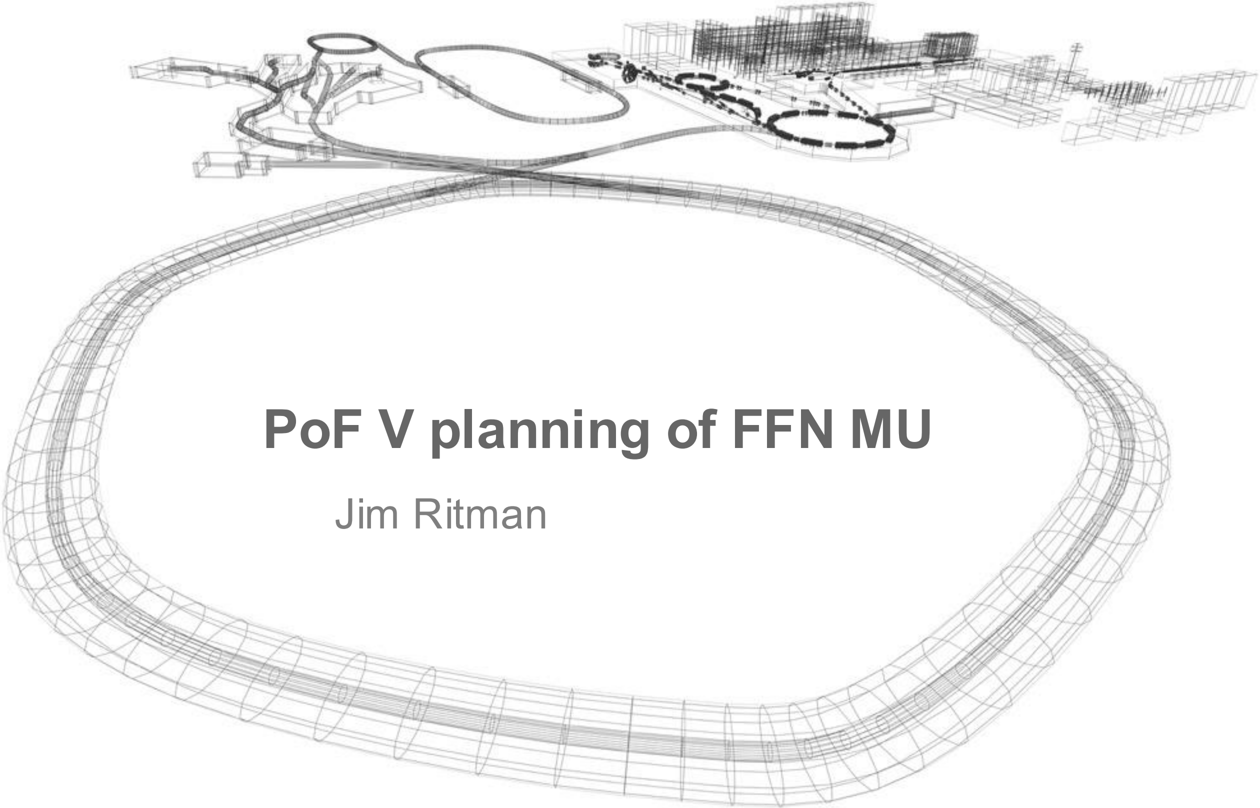


NUSTAR Low-Energy Branch steps to completion



- The completion of the low-energy branch to **FLF3** enables a sub-set of HISPEC/DESPEC (i.e. DESPEC including MONSTER) and Super-FRS EC experiments to take place (including the possibility of some LaSPEC experiments), with the advantage of a separate radiation area compared to the S-FRS tunnel and the High-Energy Cave, thus significantly reducing downtimes and increasing scientific output

- The completion of the Energy Buncher would enable AGATA experiments (with the AGATA spectrometer installed at **FLF3** and particle identification until **FLF4**) and full HISPEC/DESPEC and Super-FRS EC programs at **FLF6**
- The completion of the beamline from the Low-Energy Cave to the **Mats/LaSPEC cave** would enable a full Mats/LaSPEC program

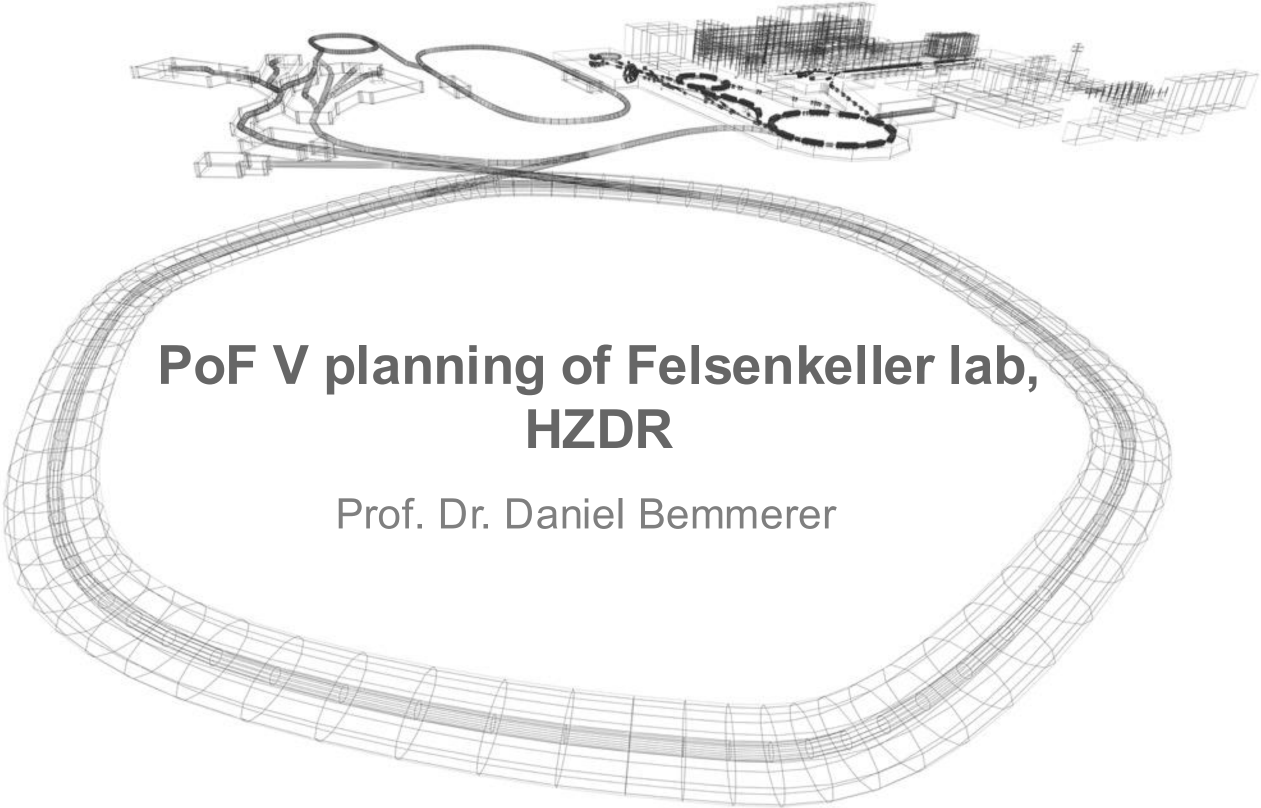


PoF V planning of FFN MU

Jim Ritman

Standardized Summary

- scientific goals: **Experimental neutrino physics and astrophysics**
- timelines: JUNO data taking begins in 2025. In first months/years, several important results can be obtained, while the main goal, neutrino mass ordering, will need about 6-7 years. In 2026 - 2027, eventually joining another neutrino project, KM3NET under consideration.
- milestones: JUNO – precision measurement of neutrino oscillation parameters with reactor neutrinos, measurement of geoneutrinos and solar neutrinos, first detection of atmospheric neutrinos with liquid scintillator detector, neutrino mass ordering determination and synergy with other neutrino experiments (combined fit)
- technical requirements: completion of the JUNO detector filling and comissioning
- beamtime requirements: none
- required resources: 600 kEuro/year from Helmholtz shared for group personnel and investment funds, additional funds for position of PI (L.L.)



PoF V planning of Felsenkeller lab, HZDR

Prof. Dr. Daniel Bemmerer

Science @ Felsenkeller lab in PoF V

Stellar hydrogen burning

- Precision measurements of solar fusion cross sections – Sun as calibrated source
- Higher hydrogen burning in asymptotic giant branch stars, e.g. $^{19}F(p,\gamma)^{20}Ne$

Helium burning

- Study of $^{15}N(\alpha,\gamma)^{19}F$, $^{18}O(\alpha,\gamma)^{22}Ne$, $^{22}Ne(\alpha,n)^{25}Mg$, $^{25}Mg(\alpha,n)^{28}Si$, et al.
- The Holy Grail of nuclear astrophysics, $^{12}C(\alpha,\gamma)^{16}O$, with an underground γ-spectroscopic measurement

Carbon burning

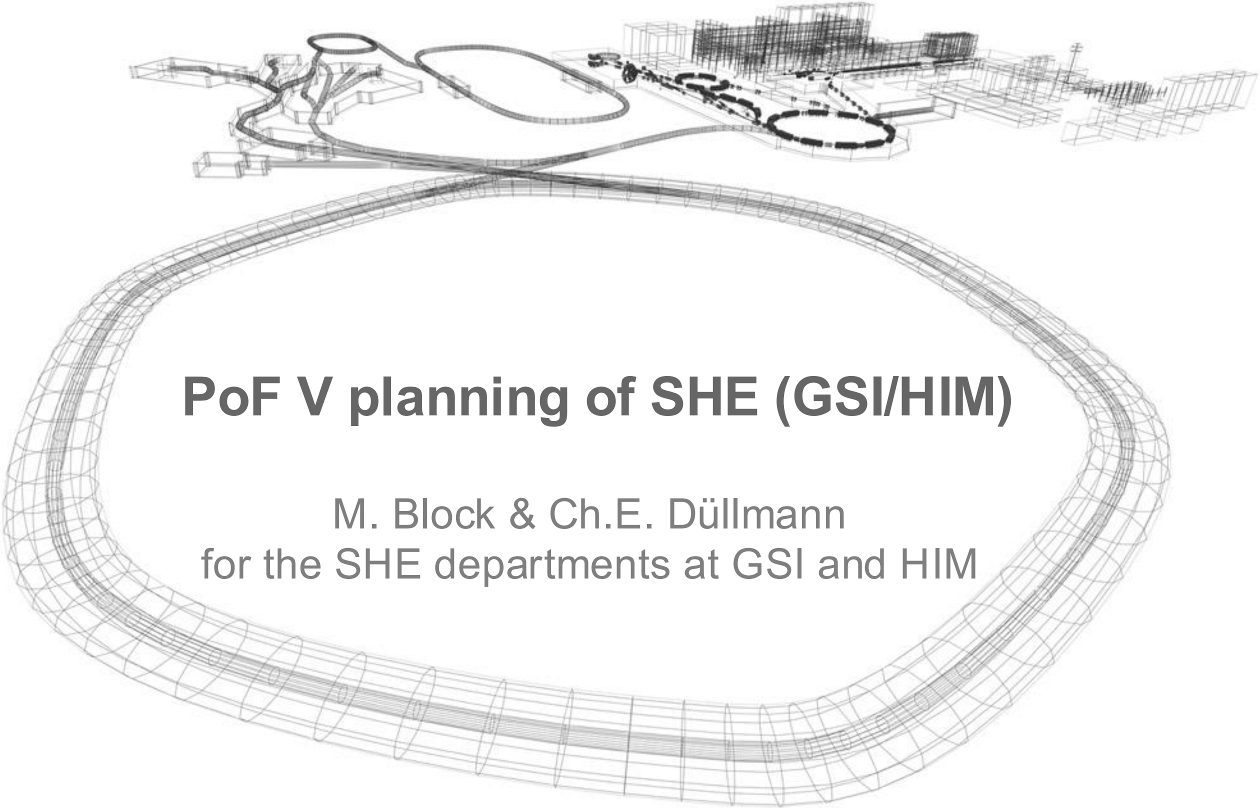
- $^{12}C+^{12}C$ reactions with particle spectroscopy and coincidences

Supernova nucleosynthesis

- Reactions of the α-rich freezeout, e.g. ^{44}Ti production and destruction

Standardized Summary

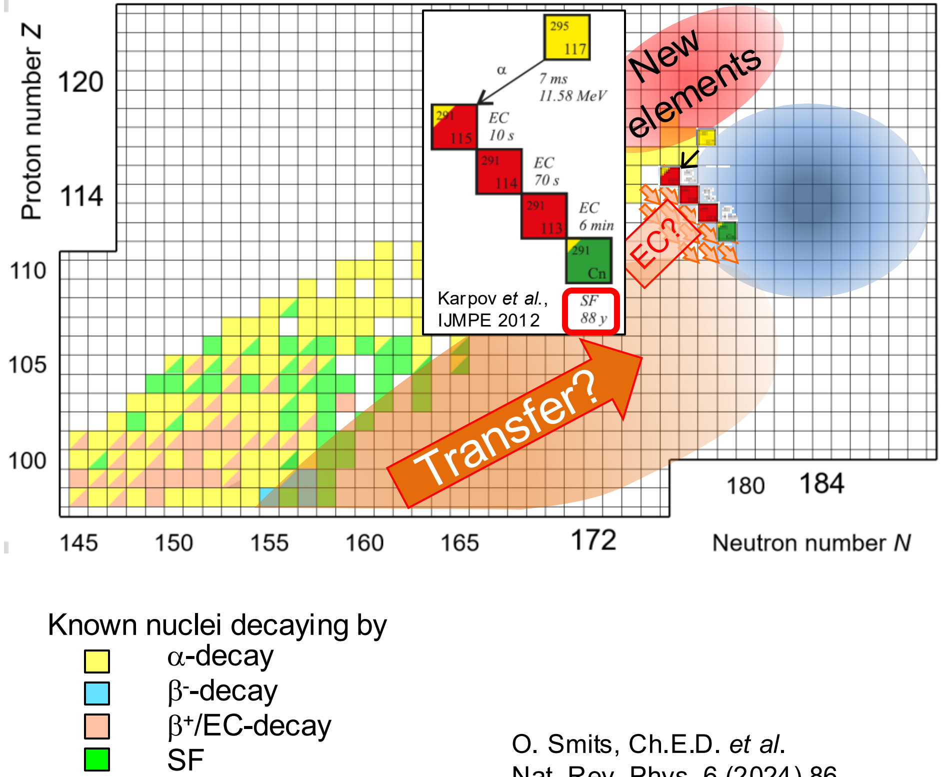
• scientific goals:	1) The Sun shall become a precisely calibrated particle source. 2) Fix the contribution of minor helium burning reactions to s-process nucleosynthesis (which produce ~50% of all chemical elements and also affect the r- and other processes) 3) Remove the nuclear physics uncertainty in the C/O ratio by measuring $^{12}C(\alpha,\gamma)^{16}O$	
• timelines:	2028	hydrogen burning
	2029	minor helium burning reactions, α-rich freezeout
	2030-31	$^{12}C(\alpha,\gamma)^{16}O$
	2032-33	$^{12}C+^{12}C$ with particle and coincidence setup
• milestones:	2030/1	Setup for g-spectroscopic study of $^{12}C(\alpha,\gamma)^{16}O$ commissioned
	2032	Nuclear Astro area in Deutsches Zentrum für Astrophysik underground lab set up
• technical requirements:	Felsenkeller 5MV underground ion accelerator wall jet gas target, with recirculation and purification to be added particle spectroscopy setup	
• beamtime requirements:	Usage of Felsenkeller ion accelerator, 3000 hours/year	
• required resources:	4 FTE (scientist), 1 FTE (engineer), 300 k€ / year invest	



PoF V planning of SHE (GSI/HIM)

M. Block & Ch.E. Düllmann
for the SHE departments at GSI and HIM

Exploration of the Island of Enhanced Stability



O. Smits, Ch.E.D. *et al.*
Nat. Rev. Phys. 6 (2024) 86

Goal 1: 2032+

Discover new elements, SHE identification via x-rays

Roadmap:

Ti+Bk -> E119 (best reaction, on Dubna roadmap for 2030+)

Ti+Cf -> E120 (best reaction, in prep. at LBNL)

Requirements:

High-intensity Ca-48 and Ti-50 stable beams

- Ti-50 + Bk-249: 1e20 dose in 6 mths (1 event @ 20 fb)
- Ti-50 + Cf-249: 2e20 dose (1 event, assuming σ=6 fb)
- Ca-48 + Am (Cm,Cf, etc): 2e20 dose (about 100 events)

Goal 2: 2032+

Identify a long-lived SHE by live observation in-trap

Roadmap:

Identify best pathway to n-rich SHE (^{22}Ne, ^{40}Ar, … ^{64}Ni)

-EC-decay? (needs spectroscopy setup advances)

-Transfer (needs non-0° separator)

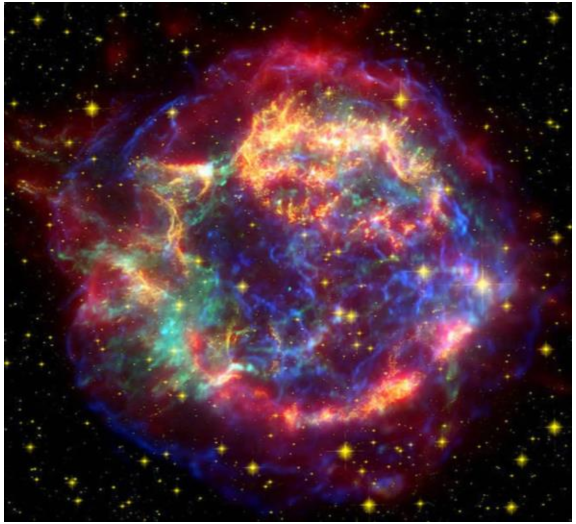
Gas-cell & single-ion trap MS (PI/FT-ICR, MR-TOF,…)

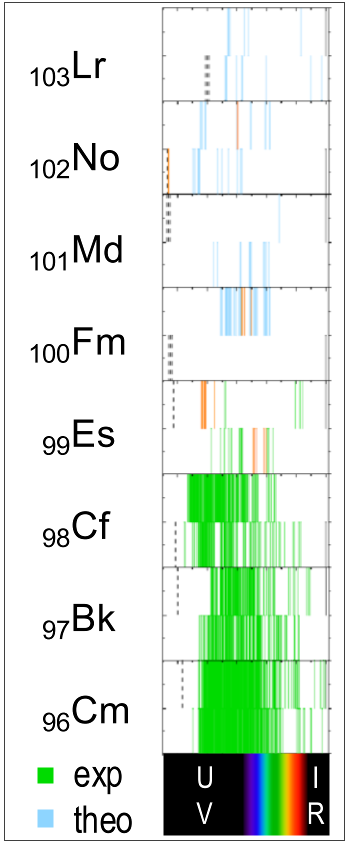
Requirements:

Beamtime!

Are superheavies made in the r-process?

- Information on elements produced by r-process from spectral lines
- No data for atomic lines of elements with Z > 102





Goal 3: 2032+

Identify spectral lines of SHE produced by r-process

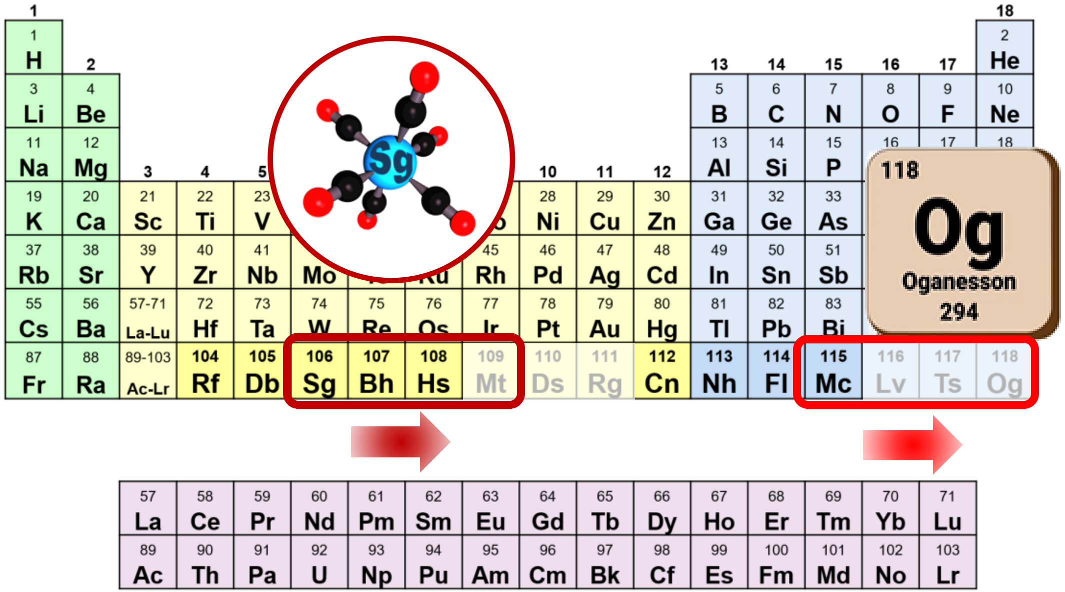
Roadmap:

- advance sensitivity of laser spectroscopy methods (RADRIS, JetRIS, LRC) to obtain spectral lines of heaviest elements
- benchmark and improve atomic theory predicitons
- develop novel methods for laser spectroscopy of SHE on single trapped ions
- Identify best pathway to n-rich SHE (^{22}Ne, ^{40}Ar, … ^{64}Ni)
  - extend indirect production schemes, e.g. EC-decay?
  - Transfer (needs non-0° separator, Gas-cell &,…)

Requirements:

Beamtime!

Structure of the periodic table



Opening the 8th period

(E119 may be more impactful for chemistry than for physics!)

Goal 4: 2028 - 2034

Characterization of chemically „unknonwn“ elements.

Roadmap:

Is Og a noble gas or not?

→ from Mc (2020/21) to Lv, Ts, and $_{118}$Og

Does Mt fit its position in the Periodic Table?

→ carbonyls: from Sg via Bh to $_{109}$Mt

Resources:

intense Ca-48 beams, Am and Cf targets
mixed Cf-target to make longer-lived Og-isotopes
UniCell for fast extraction
miniCOMPACT++

Beam doses:

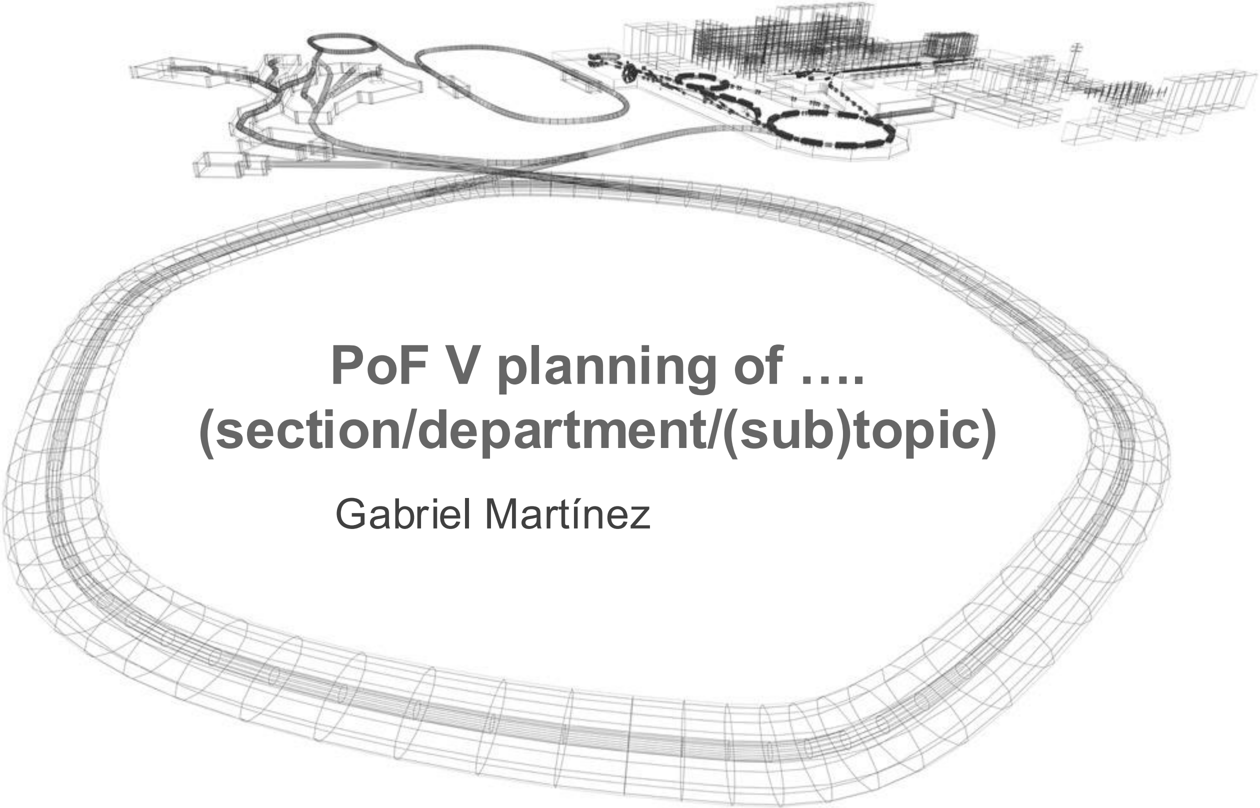
Og: 2032: 6e20 dose of ^{48}Ca to see 10 Og atoms

Bh: 2028: Part II of G22-00034 (6 weeks Mn-55)
Mt: 2032+: 1e20 Ca-48 for indirect Mt production (combined with “x-ray study“, goal 1)

Standardized Summary

- scientific goals: -Exploration of the island of enhanced stability (higher Z / higher N, single-ion live SHE detection)
  -Optical studies of heaviest elements, setting the ground for astrophysical identification (r-process)
  -Structure of the periodic table: atomic and molecular studies of new elements and compounds
- timelines: 2028+; HELIAC from 2032 on
- milestones: SHE experiments at UNILAC and HELIAC
- technical requirements: long-pulse heavy ion beams (Prio 1: ^{48}Ca, ^{50}Ti, ^{54}Cr; Prio 2: ^{22}Ne, ^{40}Ar, ^{36}S; ^{238}U?) to get doses of order 1e20 in realistic beamtimes (1-2 months).
  Cave to accept HELIAC beam intensities
- beamtime requirements: Phase-0: 3 months/year; 2029+: 6 mths per year
- required resources: Beamtime; personnel at current level (=refilling all positions that become vacant); radiochem. lab / SE renovation; beam and target isotopes, incl. actinides for collaboration activities

  Invest-intensive projects: R&D for new separator (w/ ACID?); ANSWERS+; Cryogenic SHIPTRAP, RADRIS, JetRIS++, LaserTRAP; support by tech. departments (target lab, EE, det. Lab, cryogenics)

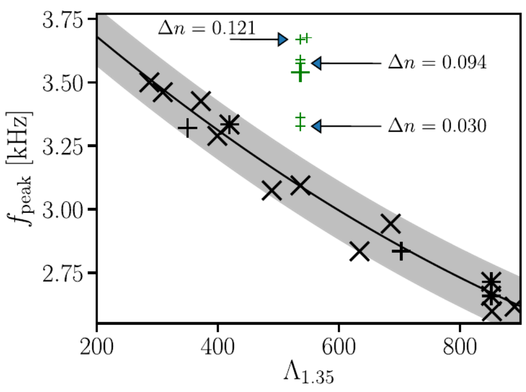


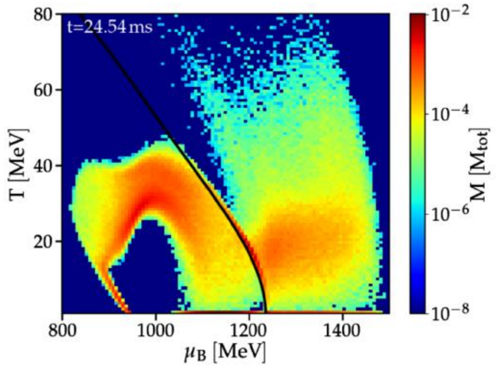
PoF V planning of ….
(section/department/(sub)topic)

Gabriel Martínez

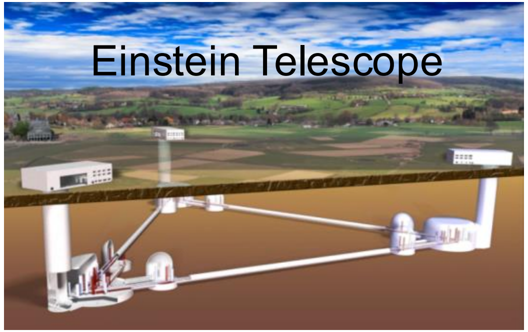
EoS: Connecting FAIR to GW observations

- Non-nucleonic degrees of freedom in high-density matter (HICs and NSs): hyperons, pions, muons, hadron-quark phase transition
- Identify signatures with Einstein Telescope*, ... complementing FAIR program (CBM) → disentangle observational ambiguities
- Multi-messenger observations (GW, Electromagnetic, Neutrinos, …) vs EoS constraints from laboratory experiments (NuSTAR)





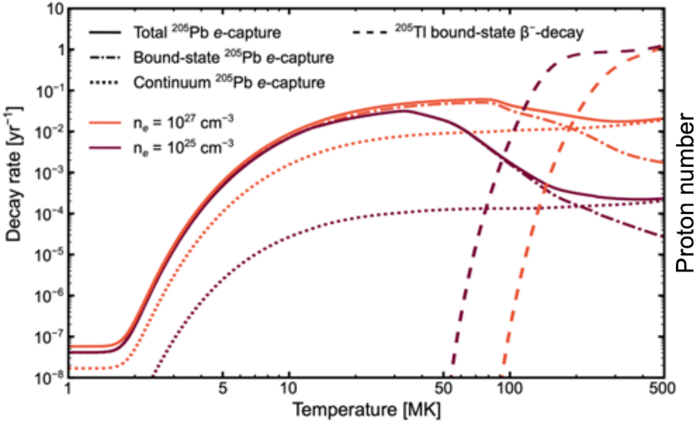
NS merger simulation

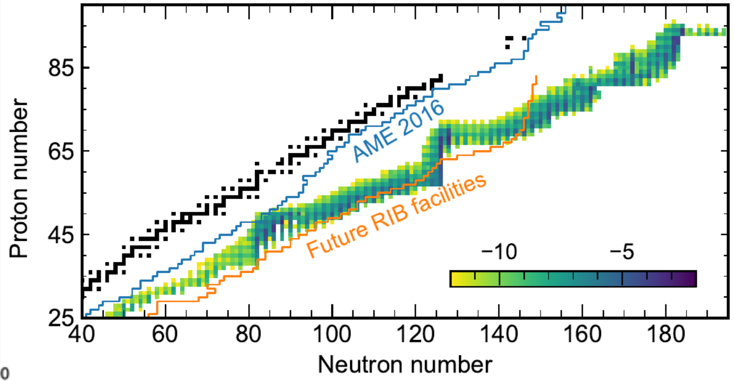


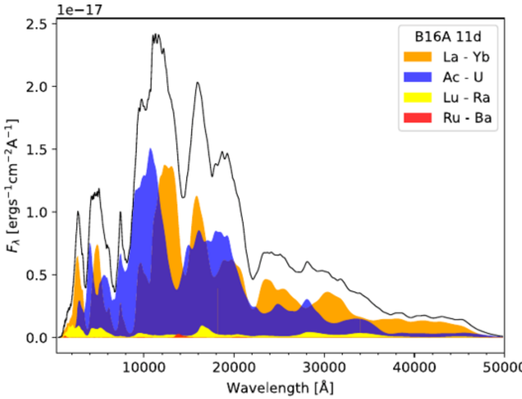
* Theory will join collaboration as Research Unit

Microscopic Input for Supernova and Mergers

- Description of weak processes for a broad range of astrophysical conditions (complementary to storage ring experiments)
- Masses, neutron-capture, beta-decay and fission rates for r-process nuclei (role of exotic and Superheavy nuclei in r-process)
- Atomic input for kilonova modelling: spectral signatures of element production



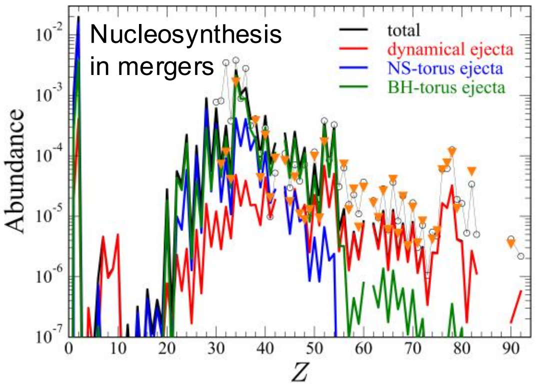




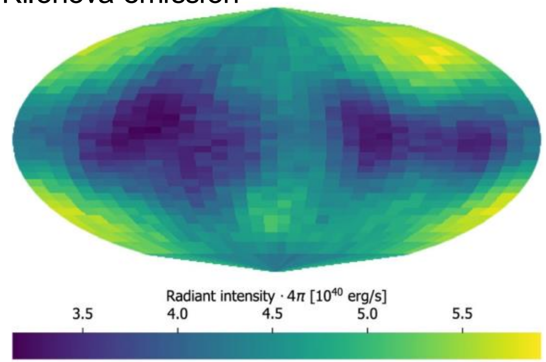
Actinides signatures

Mergers and supernova simulations

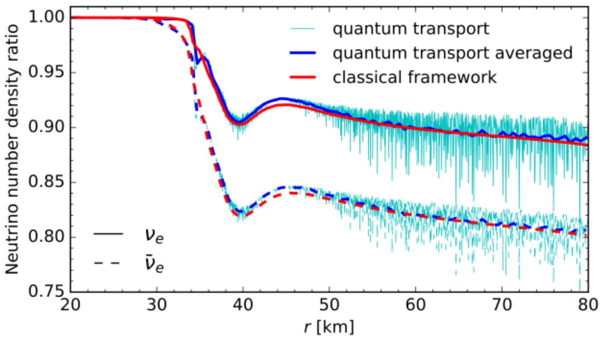
- Numerical simulations of stars and their final stages: supernovae, collapsars, neutron-star mergers, magnetar giant flares, accretion-induced collapse
- Link between theory, experiments and observations → constrain EoS, r-process nucleosynthesis, gamma-ray bursts, cosmology by observations
- Consistent description of EoS, nuclear reactions, neutrino rates and oscillations
- Spectra and light curves from Kilonova radiative-transfer modelling



Kilonova emission

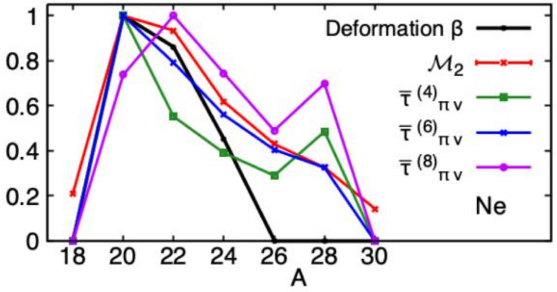


Neutrino flavor oscillations in supernovae

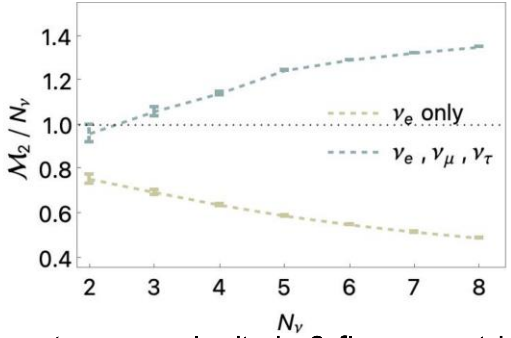


Quantum Information and Computation

- Investigate the role of quantum complexity in the structure and dynamics of many-body nuclear and neutrino systems (how is complexity generated by underlying forces, and how does it evolve as collectivity emerges?)
- Develop quantum-information guided efficient many-body methods leveraging hybrid classical-quantum computing environments
- Compute nuclear and neutrino processes relevant to astrophysics, work towards including decoherence



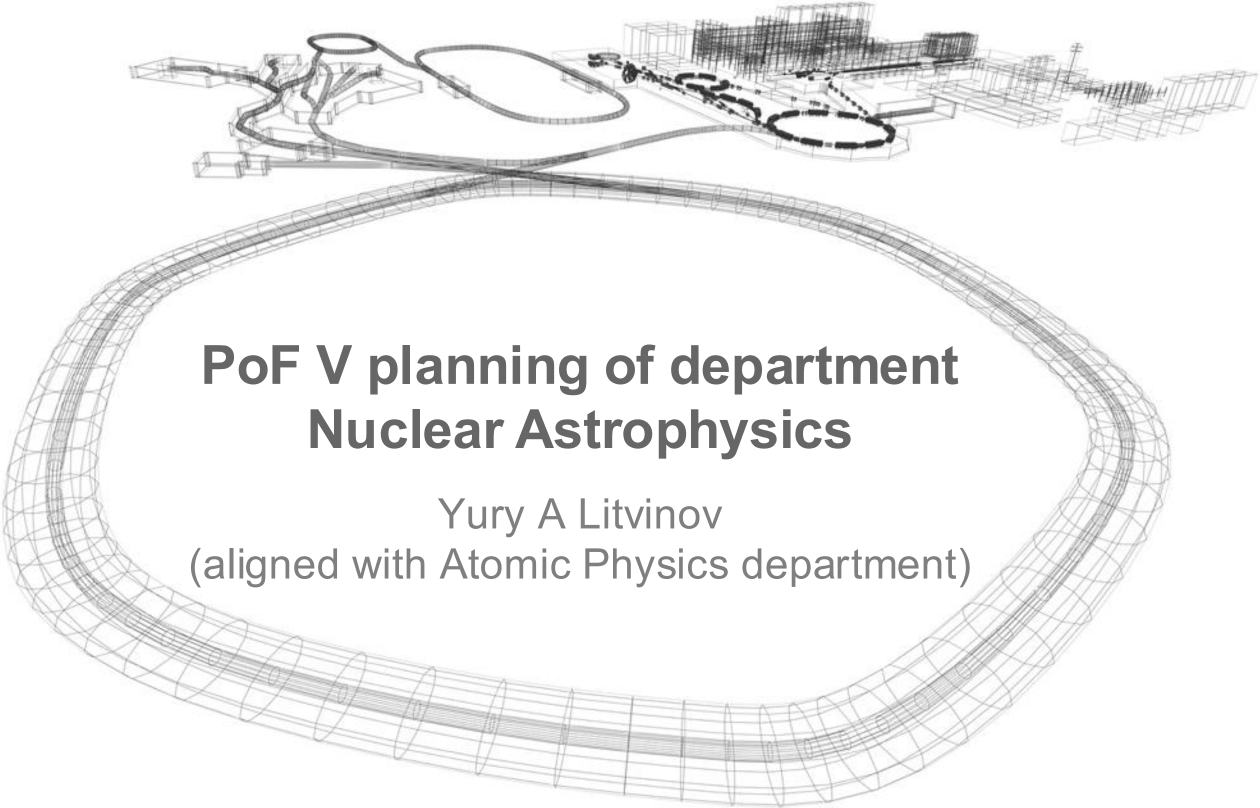
Deformation, entanglement and quantum magic in Ne nuclei
PRC 111, 034317 (2025)



Quantum complexity in 3-flavor neutrino evolution; *PRR 7, 023228 (2025)*

Standardized Summary

- scientific goals: Theoretical advances complementary and synergetic to FAIR program.
- timelines: adjusted to experimental program
- Milestones: coordinated with experimental program
- technical requirements: ~ 300 million CPU hours/year, 1500 TB storage
  machine learning techniques
  maintain CPU infrastructure (with respect to pure GPUs)
  code optimization support
- beamtime requirements:
- required resources: 4 Postdocs + third party funding



PoF V planning of department Nuclear Astrophysics

Yury A Litvinov
(aligned with Atomic Physics department)

Nuclear astrophysics with stored radioactive beams

Facilities: ESR and CRYRING

Nuclear reactions
Atomic masses
Isomeric states
Half-lives
Exotic decay modes

User support for ILIMA and SPARC collaborations

Nuclear astrophysics with stored radioactive beams

!! Every experiment in the past – without exceptions – led to at least a PRL publication !!

For example: 2024: Nature + 2 PRLs; 2025: 3 PRLs

Enormously large potential for frontier physics discoveries

For example:

Newly developed combined Schottky + Isochronous Mass Spectrometry is:

(1) simultaneous mass and lifetime measurement
(2) Broadband – covers more than 10% in m/q simultaneously
(3) Efficient – one ion is enough to get its mass (and lifetime)
(4) Precise – $\Delta m/m \sim 10^{-6}$ for a single ion
(5) Fast – measurement takes a few ms only

⇒Access to most rarely produced exotic nuclides

Nuclear astrophysics with stored radioactive beams

One of the major motivations for building CRYRING at GSI was to perform experiments with radioactive ion beams (see CRYRING@ESR Physics Book)

Recognized in 2024 NuPECC LRP as one of very few unique European strengths

For example: most of the astrophysical reactions declared as "the key" reactions in the NuPECC Long Range Plan 2024 can be readily studied at CARME@CRYRING, thereby addressing critical questions regarding BBN, Novae and X-ray bursts, SN, etc

CRYRING@ESR is a jewel with huge discovery potential

Nuclear astrophysics with stored radioactive beams

However, no radioactive beam stored in CRYRING till now

Why? Because one can schedule 3 experiments at FRS, ESR and CRYRING instead of one at FRS-ESR-CRYRING

!!! The rate of high-level paper output shows that nuclear physics with stored exotic ions should be a strategic focus of GSI/FAIR.

!!! This means the FRS-ESR-CRYRING complex should be treated with priority

!!! G-PAC should include a few experts from nuclear astrophysics field

Nuclear astrophysics with stored radioactive beams

ESR

Atomic masses - first broadband mass measurements using new combined S+IMS technique (impact: 3rd r-process peak, half-lives of isotones along N=126 and beyond)

Exotic decay modes - first direct observation of nuclear excitation by electron capture process (NEEC), bound-state electron-positron pair creation, bound state beta decay (impact: first observations, stellar enhancement factors, abundance puzzles)

Charge-particle induced reactions – simultaneous measurement of (p,g) and (p,n) reactions, extension towards (a,g), (a,p), (a,n) reactions (impact: e.g. Mo-Ru puzzle)

^{229}Th clock - a nuclear clock, the most precise time measurement (**ERC HITHOR Stöhlker**)

Surrogate reactions – simultaneous measurement of (d,p), (d,d'), (d,xn), (d,f) reactions (impact: fission recycling, social applications) [**ERC NECTAR Jurado**]

Nuclear astrophysics with stored radioactive beams

CRYRING

CARME- key astrophysical nuclear reactions with stored exotic beams in Gamow windows of various processes (Novae, x-ray burst, BB, SN, ...) (impact: ”the key reactions” as identified in the NuPECC LRP can be addressed) (**ERC ELDAR Bruno**)

Example: one of the main motivations to build ISAC 1 facility in TRIUMF was to measure $^{15}O(a,g)^{19}Ne$ reaction (break out of the hot-CNO and start of rp-process) – there it failed! It is feasible to measure it with CARME@CRYRING. (Theory – Langanke et al (1986))

NSTAR - world's first free neutron target for radioactive neutron capture reactions (impact: s- & i-process, applications to nuclear energy) (**ERC synergy grant under review**)

FISIC & CARME - nuclear reactions with crossed beams, ion-ion collisions impact: electron screening) (joint effort with ATP)

Nuclear astrophysics with stored radioactive beams

!!! Transmission efficiency FRS-ESR, TE-ESR, ESR-CRYRING
! Upgraded diagnostics in TE-line, injection into ESR, ESR-CRYRING line
!! Additional targets at the TE-stripper, stripping section before injection into the CRYRING
!!! Efficiency of slowing down in the ESR, extraction towards the CRYRING (HITRAP)
!! Extraction of neutron-capture products from the CRYRING
! Recycling systems for expensive gases at the ESR and CRYRING internal targets
! Installation of longitudinal Schottky-cavity-doublet and transversally-sensitive cavity in the ESR
! Installation of a slow-wave Schottky detector in the CRYRING
!! Rebuilding Y11 section of the CRYRING – installing particle detection inY11
!! New dedicated vacuum chamber for NECTAR experiments in the ESR
!! Rebuilding EEX line in the ESR: upgrade/remove-old/install-new detectors/scrapers
!!! Stochastic cooling / beam accumulation – must become standard ESR operations
!!! Primary Th beam – absolutely essential if GSI likes to win the ^{229}Th race
! Local source at CRYRING for long-lived radioactive ion beams (EBIS)
!!! Laboratory space for R&D, maintenance and pre-assembly of NA setups

Nuclear astrophysics with stored radioactive beams

What is the big physics goal of GSI? New SHE and carbon therapy are great masterpieces from last century! What will make GSI famous in this century?

^{229}Th clock or free-neutron target in a storage ring can be comparable achievements

Scandal: !!! Still NO astrophysics experiments with radioactive beams !!!

GSI must identify its most promising scientific priorities and accordingly streamline its resources

MU-CML PoF V

Start of FAIR2028 → Physics harvest during PoF V

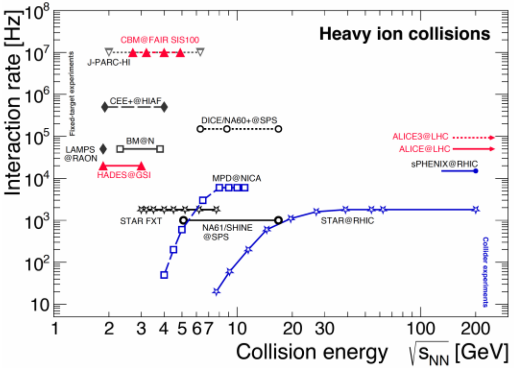
Super-FRS and SIS100 beams will enable key experiments on open questions in strong-interaction

Exploit the high luminosity potential of the LHC for ions: ALICE/ALICE 3

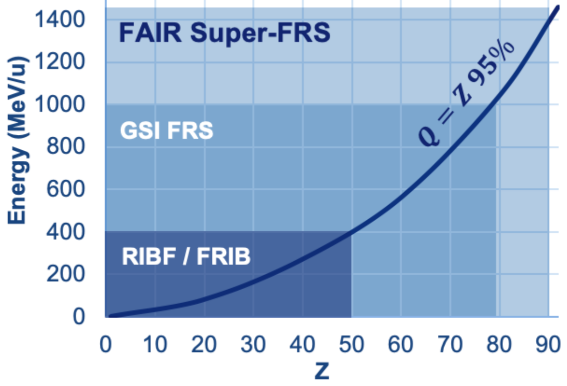
Strengthen the science outputs from gravitational wave and kilonova observations through theory and experiments at GSI/FAIR

Theory: interdisciplinary activities, predictions, tools, interpretation and guidance for experimental program

New in CML for PoF V: nuclear astrophysics at HZDR Felsenkeller underground ion beam (MML-RT1 in PoF IV)



Range of fully-stripped exotic nuclear beams



Discussion

- Various interesting projects, priorities to be defined (this retreat + follow up in the CML meeting on July 11th)
- Need to secure our uniqueness
  - Timely completion of FS+: unique physics program with CBM (discussions in U.S. to use AGS machine)
  - Relativistic Rare Radioactive beams in storage rings
- For most of projects “total cost of ownership” is missing, in particular human resources, which departments are behind? Project evaluation is needed (JSC)
- GSI = German Hub for nuclear and hadron physics! ALICE is a part of Hub. Relation GSI-FAIR - our vision is clear: GSI will stay in Helmholtz; LKI and part of the operation costs for GSI/FAIR will be covered by PoF, still BMFTR decision is needed and important
- How to involve the GSI/FAIR user community in the PoF V process?
- Timeline for anti-p and HESR availability is not clear. Not realistic to have PANDA realised by 2034. CML plan: follow up on positive statement of Center Evaluation Reviewers who appreciated a lot the move of the PANDA collaboration to participate in the "satellite" experiments and to enhance their physics outcome. The future strategy should be clearly discussed in the document. Just like in the MU-CML presentation we should emphasise that hadron physics at GSI/FAIR is represented by in-situ experiments at GSI and HIM already now and with CBM@FAIR in near future + strong theory support --> keep expertise in hadron physics on GSI and HIM campus. We should discuss uniqueness of PANDA physics, but we should avoid identifying milestones related to PANDA physics results in PoF V