



Equation of State program

INDRA-FAZIA collaboration

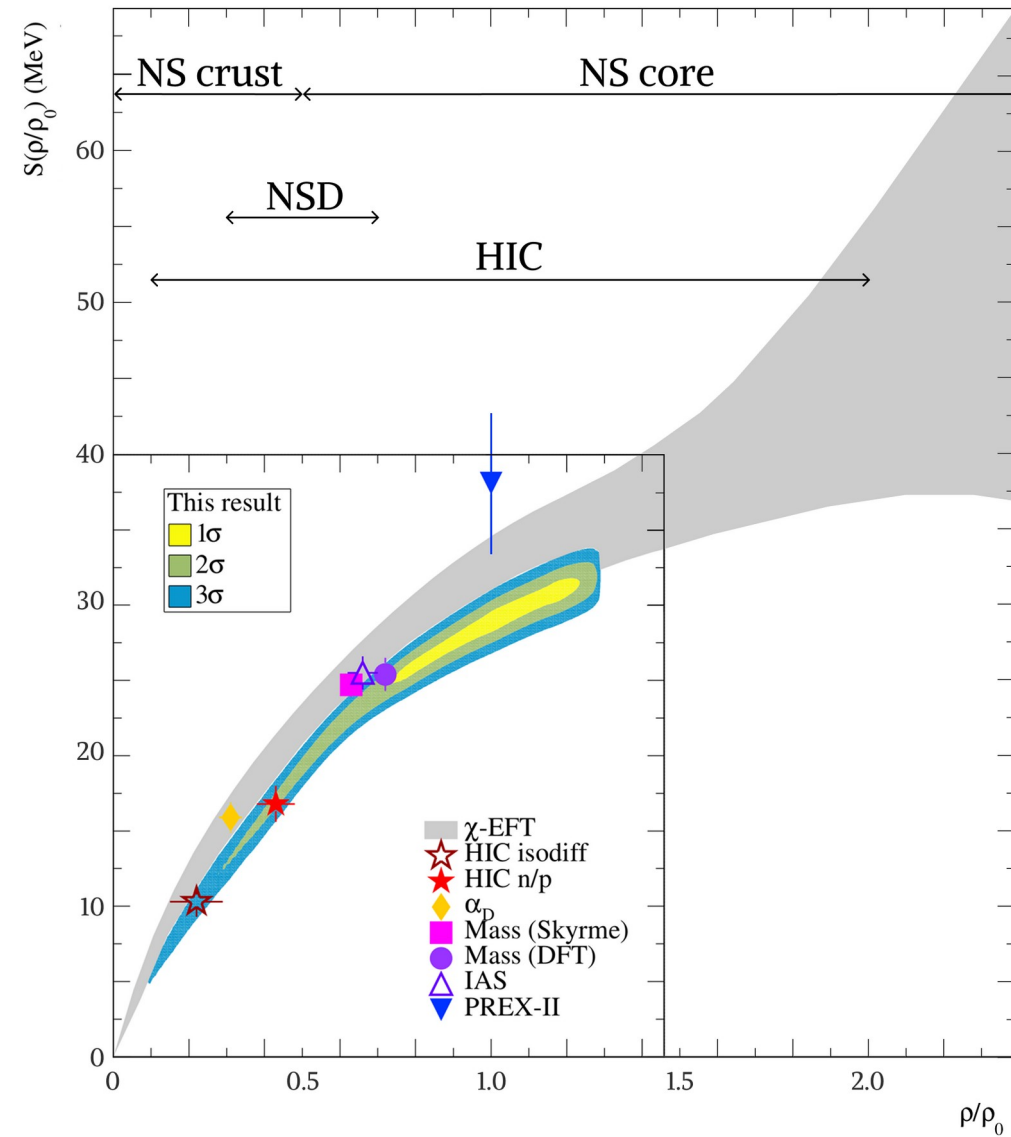
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Nicolas Le Neindre, LPC

John D. Frankland, GANIL

Challenge

What is the nature of neutron stars and dense nucleonic matter ? **What is the nuclear pressure at twice saturation density ?**



Challenge

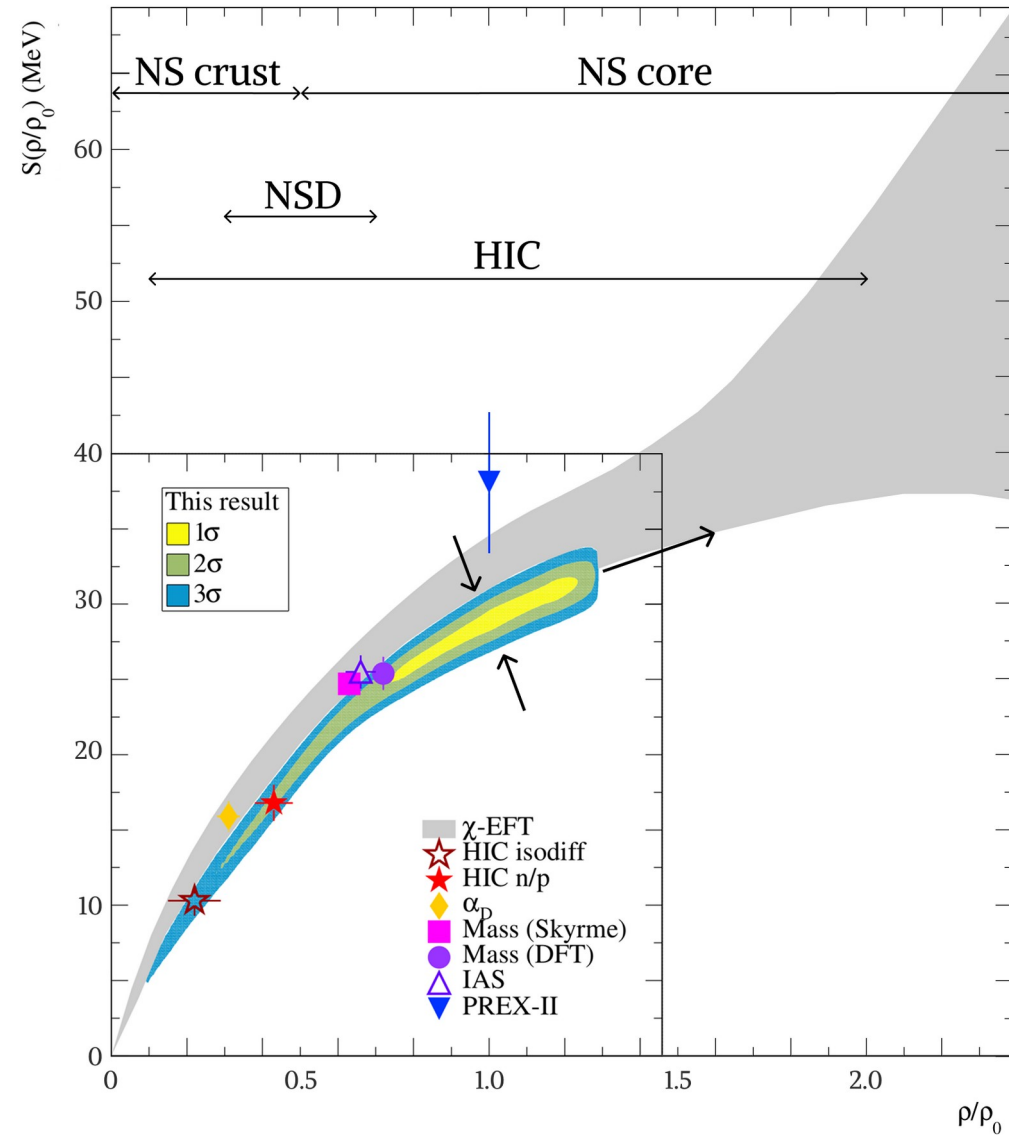
What is the nature of neutron stars and dense nucleonic matter ? **What is the nuclear pressure at twice saturation density ?**

Precision frontier

Improving the posterior on low-order Nuclear Matter Parameters with experimental constraints around saturation density will allow for safer extrapolation
→ **Better sensitivity using Radioactive Ion Beams**
→ **Potential FRIB-GANIL joint program (~5 years)**

Density frontier

Experimental constraints at densities around $2\rho_0$ would be game changer for neutron star predictions
→ **Higher energy RIBs to explore higher densities**
→ **Opportunities at FRIB400 and RAON (>5 years)**





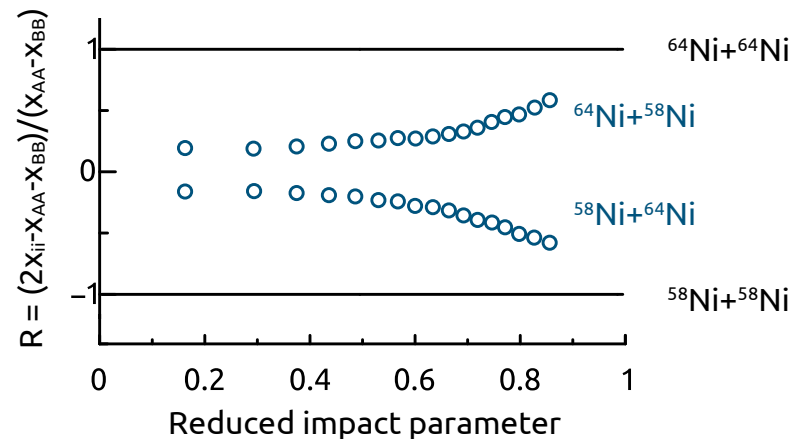
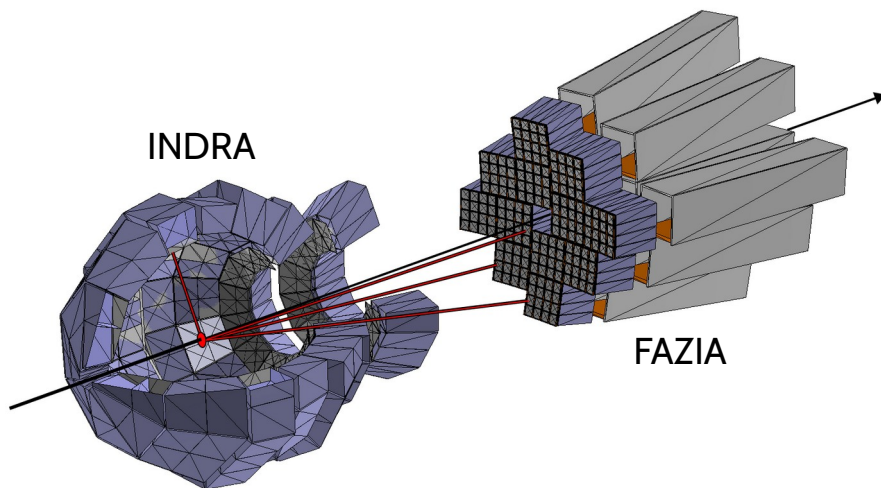
Precision frontier

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INDRA-FAZIA experiment @ GANIL

Isospin transport ratio computed from quasi-projectile N/Z using 4 reactions ($^{58,64}\text{Ni} + ^{58,64}\text{Ni}$ @ 32 MeV/nuc.)

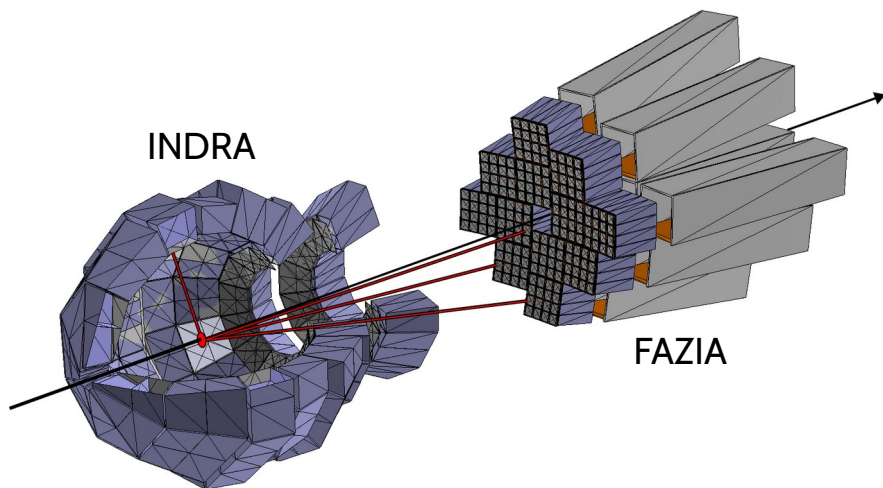
- Excellent isotopic resolution at forward angles (FAZIA)
- Impact parameter inferred from $P(b|M)$ deduced from $P(M)$
- All 4 reactions measured in the same conditions



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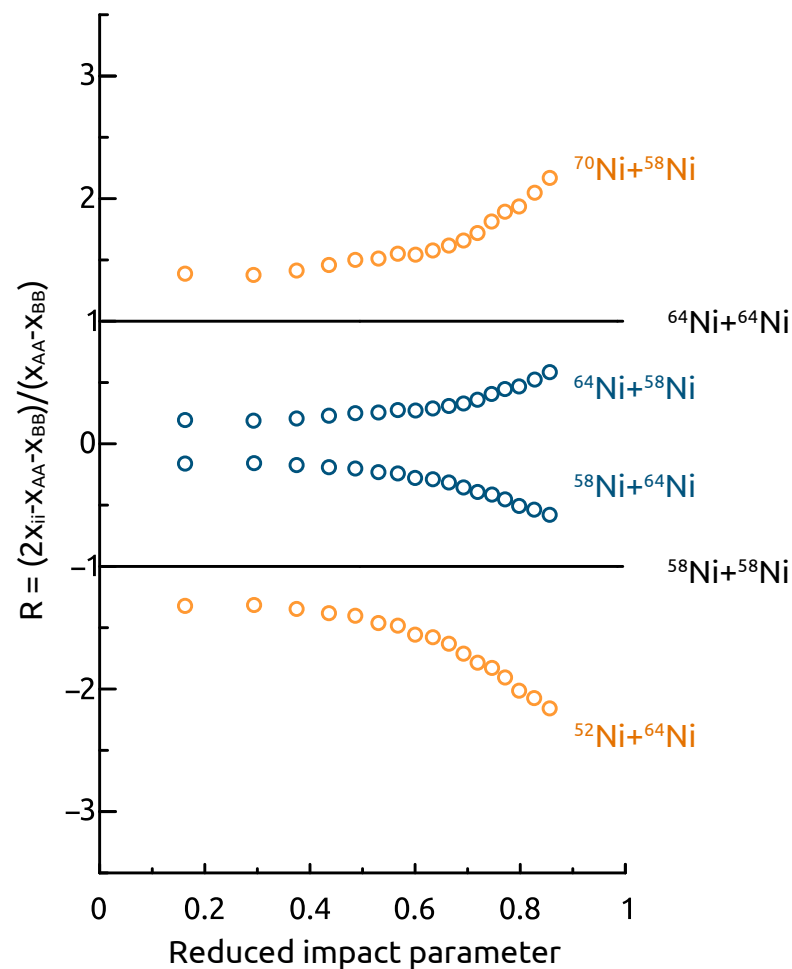
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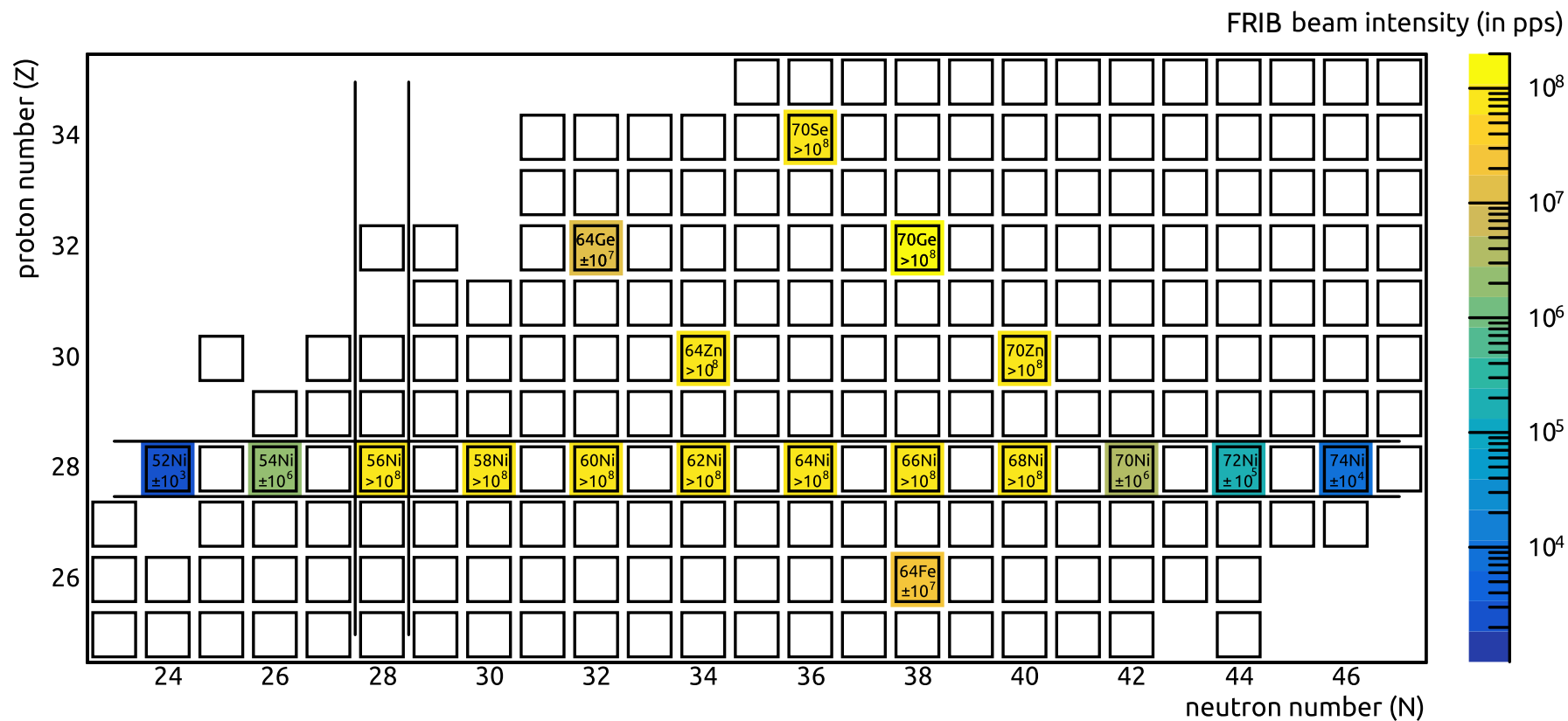


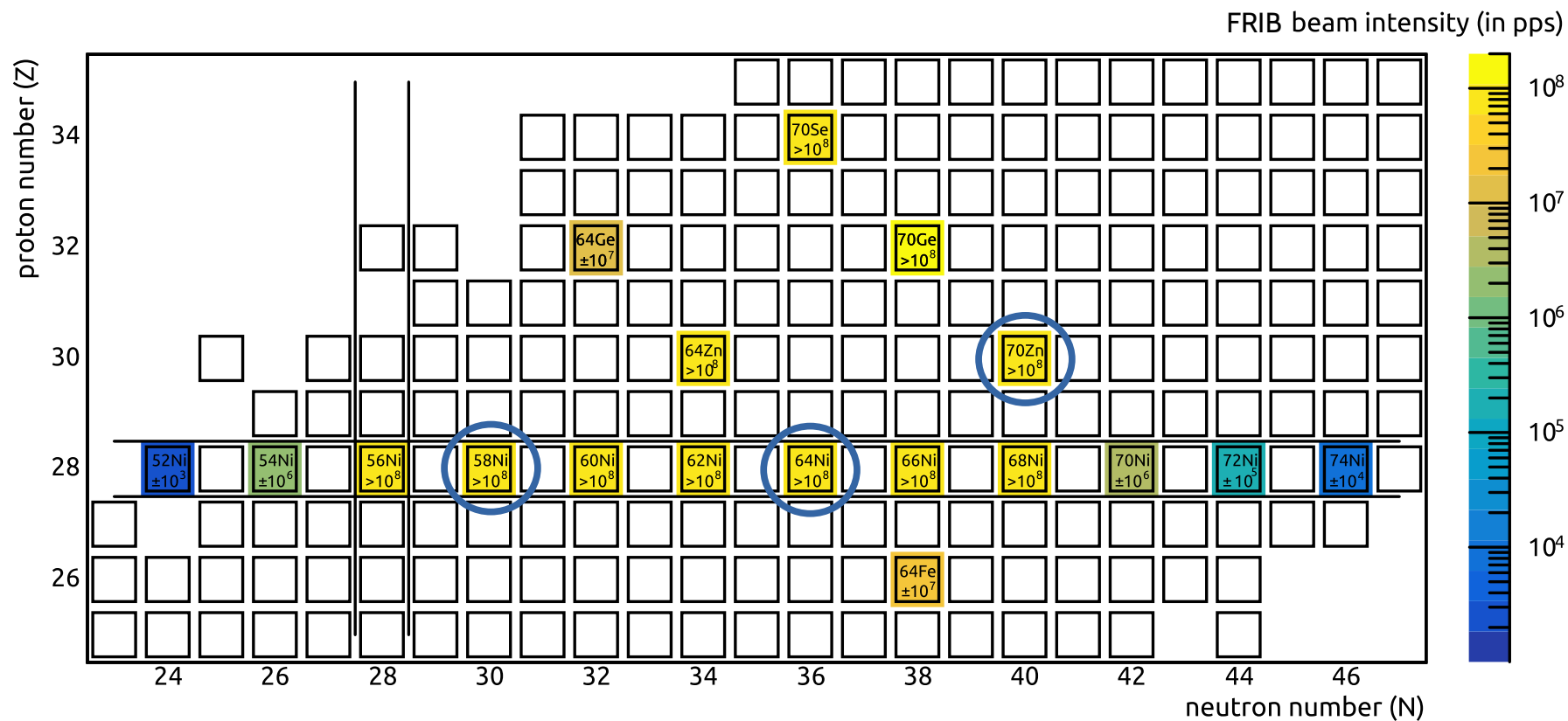
Using RIBs

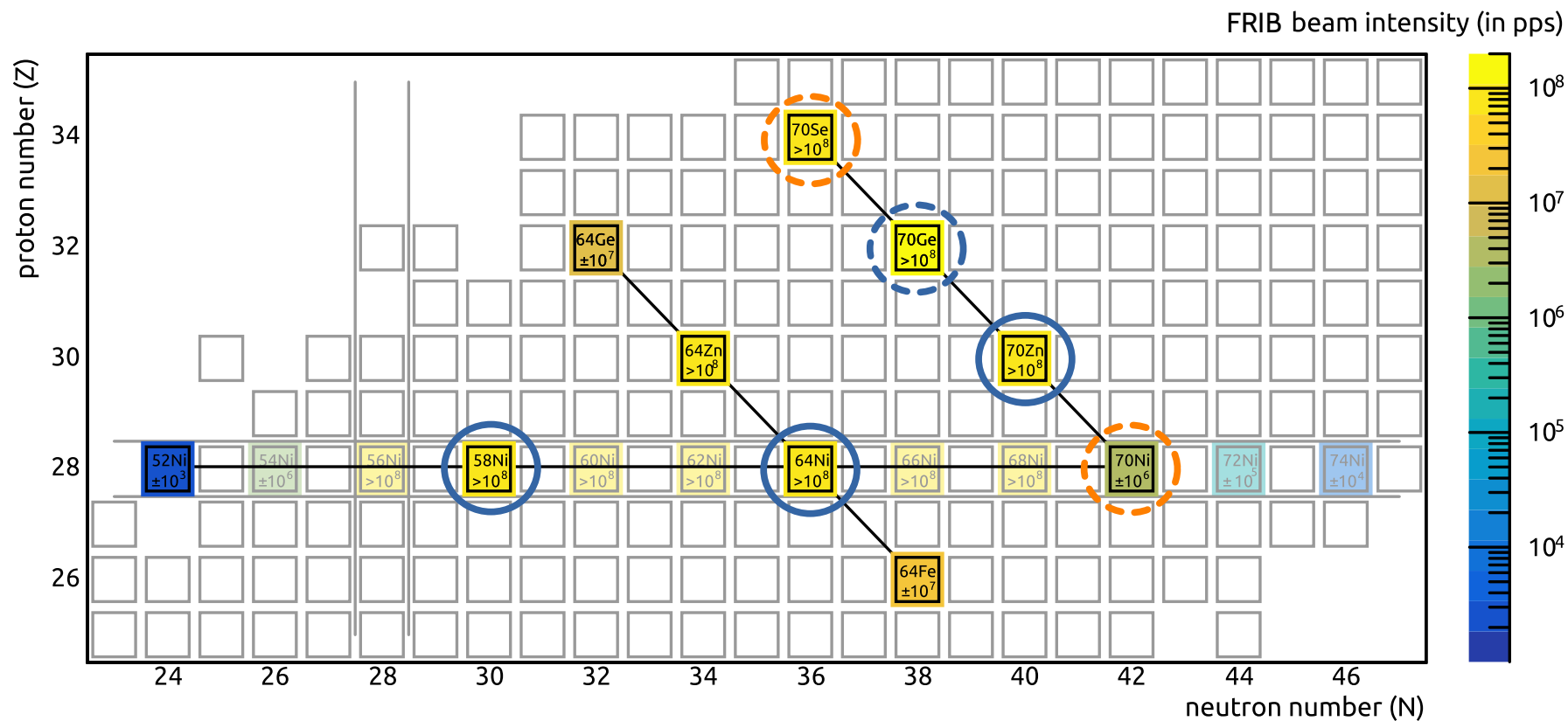
Improve the sensitivity by increasing the isospin difference between projectile and target : radioactive beams

- Measuring $^{70}\text{Ni} + ^{58}\text{Ni}$ (or $^{52}\text{Ni} + ^{64}\text{Ni}$) doubles the sensitivity !









INDRA-FAZIA@GANIL
FAZIA-FROG@FRIB

GANIL-FRIB joint program

Clear opportunity to improve the posterior on low-order Nuclear Matter Parameters with experimental constraints around saturation density taking advantage of the complementarity of GANIL and FRIB !

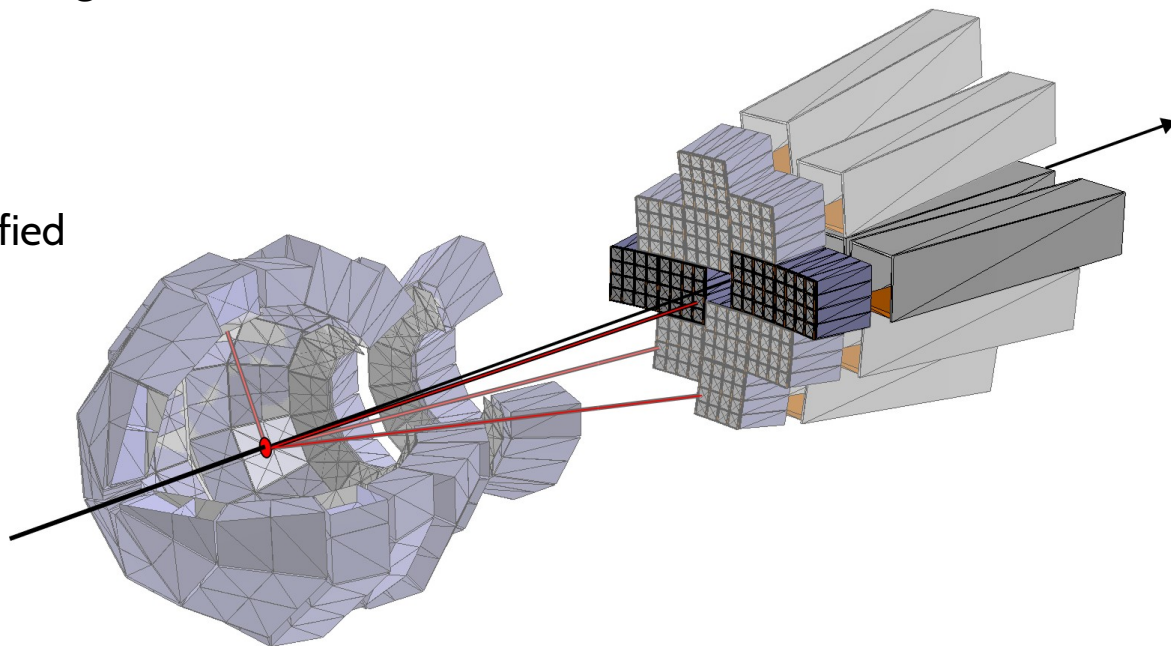
GANIL

Exclusive measurements of reference systems using the INDRA-FAZIA detector

FRIB

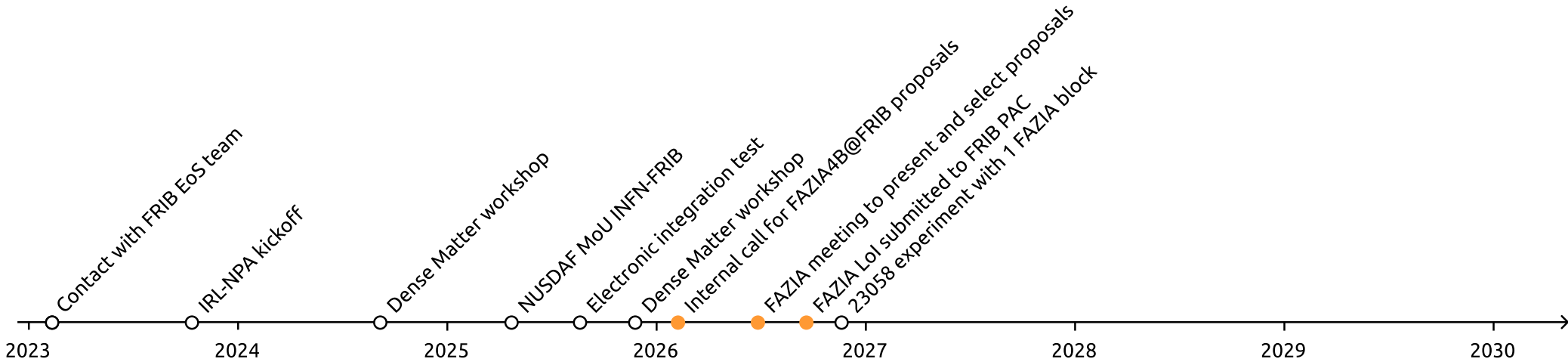
Quantification of the equilibration ratio with radioactive beam on stable target with a simplified setup : 4 FAZIA blocks + FROG

Chain	System	FRIB	GANIL
$Z = 28$	$^{52}\text{Ni} + ^{64}\text{Ni}$		
	$^{58}\text{Ni} + ^{58}\text{Ni}$	✓	✓
	$^{64}\text{Ni} + ^{64}\text{Ni}$	✓	✓
	$^{70}\text{Ni} + ^{58}\text{Ni}$	✓	
$A = 70$	$^{70}\text{Se} + ^{70}\text{Zn}$	✓	
	$^{70}\text{Ge} + ^{70}\text{Ge}$	✓	✓
	$^{70}\text{Zn} + ^{70}\text{Zn}$	✓	✓
	$^{70}\text{Ni} + ^{70}\text{Ge}$	✓	



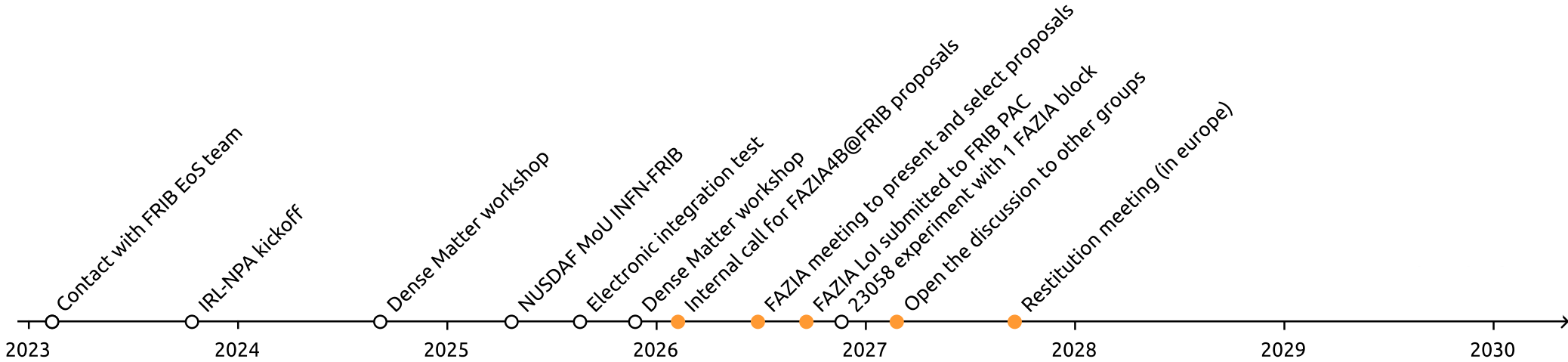
FAZIA LoI

- **Isospin transport with RIBs (FRIB-GANIL)**
- **Matter radius of exotic and mirror nuclei (FRIB)**
- **Dynamic Dipole Resonances (PARIS-VAMOS@GANIL ?)**
- **Multi-particle invariant mass spectroscopy (GANIL-FRIB)**



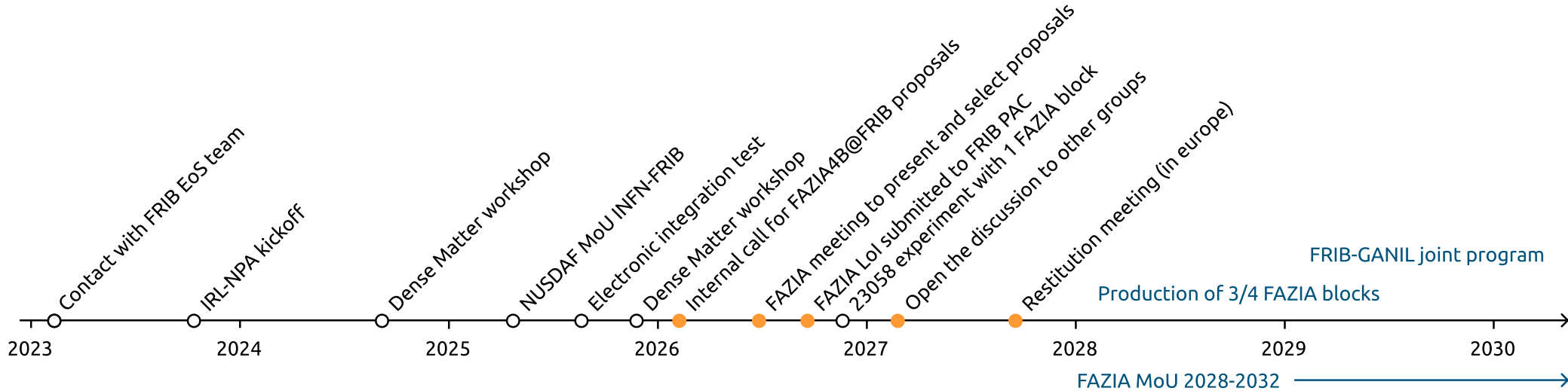
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Density frontier

→ Opportunities at FRIB, FRIB400 and RAON (>5 years)

Future opportunities

Constraints at densities around $2\rho_0$ would be game changer for neutron star predictions
Requires high energy RIBs (200-400 MeV/nuc.),
new observables and new detection systems

Observables

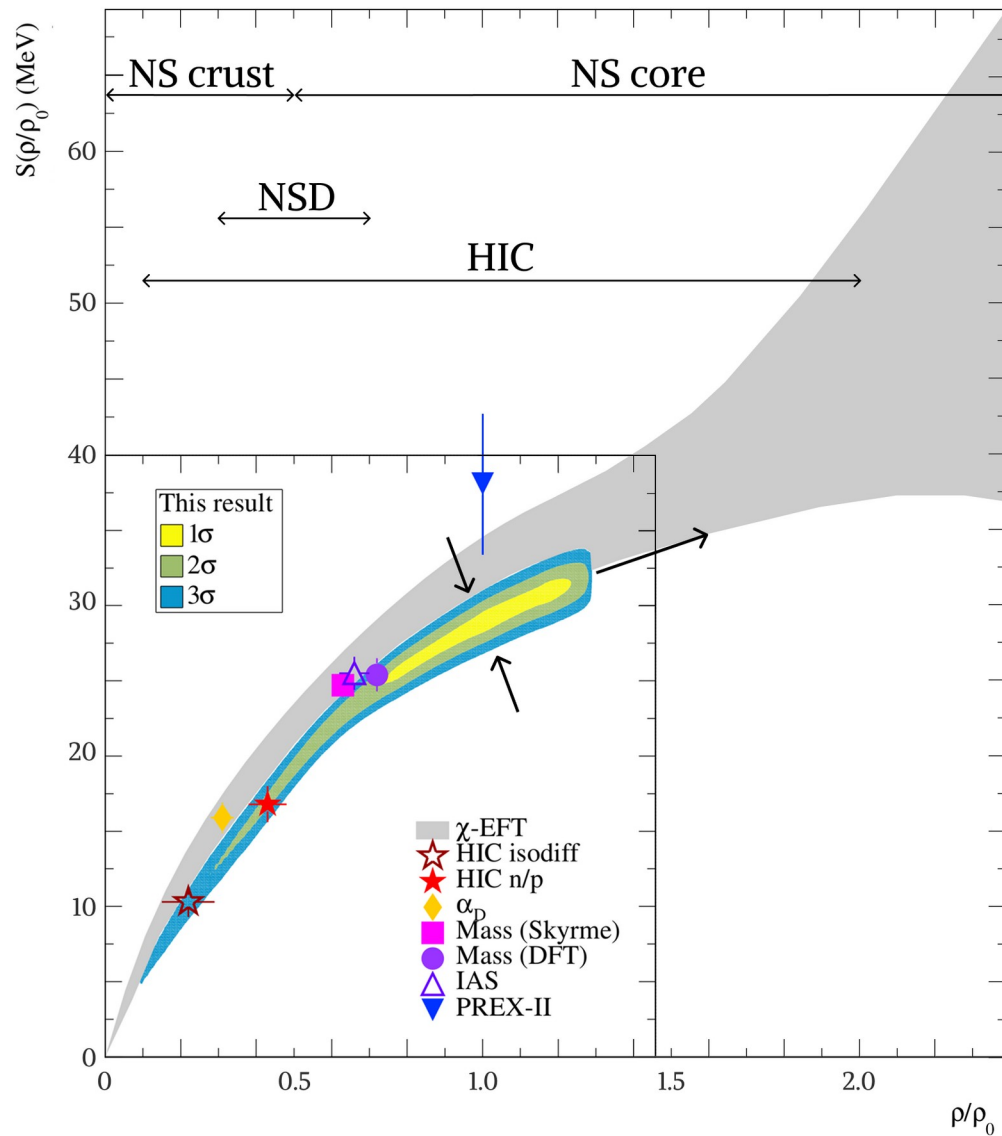
n/p spectrum ratios and flows (e23058)
Charged pions spectrum ratios and flows
Clusters...

Detection in FRIB and FRIB400

Solenoidal TPC (SOLARIS-like) ?
SPiRiT-like TPC in HRS magnet ?
→ Clear opportunity to contribute !

Detection in RAON

LAMPS TPC already built but no beam soon
→ Discussions to send LAMPS to FRIB



Executive summary

The energy upgrade of the FRIB linear accelerator to 400 MeV/u for uranium (FRIB400) will expand the already broad scientific reach of FRIB to encompass the full range of science envisioned by the scientific community and articulated in NSAC Long Range Plans and studies by the National Academies of Sciences. The scientific gains from FRIB400 above those to be realized initially at FRIB are significant and diverse: (i) Dense nuclear matter can be created and studied up to twice saturation density, critical for multi-messenger astrophysics; (ii) significant gains in isotope yields will be realized, nearly doubling the reach of FRIB along the neutron dripline and allowing study of extreme, neutron-rich nuclei; (iii) in experiments, thicker targets can be used, increasing the luminosity for measurements of nuclei in key regions of the nuclear chart; and (iv) nuclear reactions can be performed in an energy regime of optimum nuclear transparency, improving their interpretation by reaction theory.

The need for the FRIB400 upgrade has been made timely by the dawn of multi-messenger astronomy and the detection of gravitational waves and subsequent follow-up observations of electromagnetic radiation. The extremely neutron-rich environment of a neutron-star merger indicates that study of the most neutron-rich isotopes, many of which can only be made in sufficient quantities at 400 MeV/u, is necessary to understand r -process nucleosynthesis in a merger environment. Moreover, the gravitational-wave signature and amount of material ejected depend on the equation of state of very neutron-rich asymmetric nuclear matter at twice normal nuclear density, which can only be formed in the laboratory in nuclear collisions with rare isotopes at energies of 400 MeV/u or above.

1. Multi-messenger astronomy calls for higher FRIB beam energy

Science has entered a new era following the recent discovery of gravitational waves and high-energy cosmic neutrinos [Bar17]. It is the beginning of an age of multi-messenger astronomy where widely different observational data are recorded from astrophysical events. Interpretation of these disparate messages makes new demands on the underlying nuclear and particle science. It argues strongly that an upgrade of FRIB to 400 MeV/u beam energy is timely and necessary to address fundamental questions raised by the new data. The key is to have better access to the relevant rare isotopes that play a role in these extreme environments and to study nuclear matter under extreme conditions in nuclear reactions with sufficient energy to compress and probe nuclear matter at about twice nuclear saturation density, $2\rho_0$ [Rad18, Tsa19a]. In particular, because gravitational waves generated from neutron-star mergers are directly related to the equation of state (EOS) of nuclear matter [Abb17a, Abb18], the LIGO-Virgo collaboration's ground-breaking detection of the binary neutron-star merger event GW170817 has intensified efforts towards a comprehensive understanding of nuclear matter.

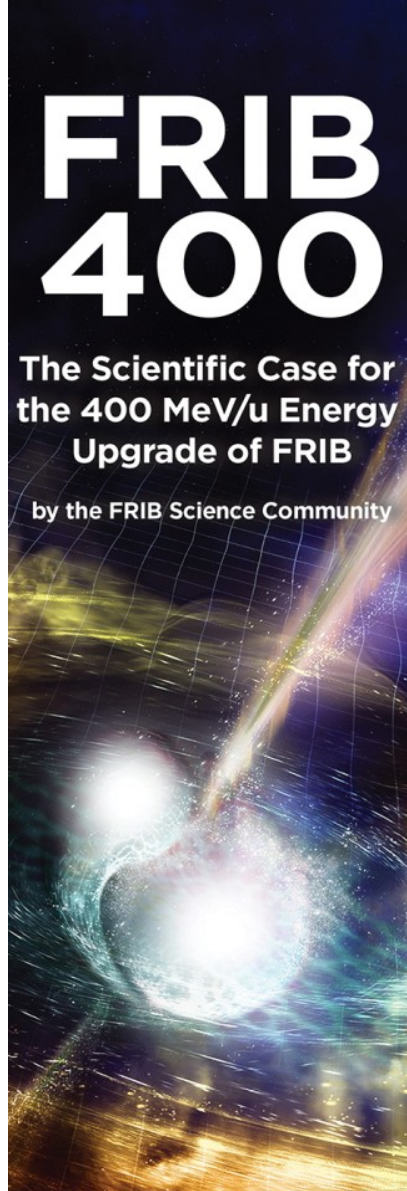
U.S. Department of Energy Office of Science Office of Nuclear Physics mission is accomplished by supporting scientists who answer overarching questions in major scientific thrusts of basic nuclear physics research			
Science Drivers from the National Research Council (NRC) Rare-Isotope Science Assessment Committee (RISAC)			
Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
Intellectual challenges from 2013 NRC Decadal Study and the 2015 NSAC Long Range Plan			
How does subatomic matter organize itself and what phenomena emerge?	How did visible matter come into being and how does it evolve?	Are fundamental interactions that are basic to the structure of matter fully understood?	How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?
Specific questions included in the challenges			
What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes? What is the origin of simple patterns in complex nuclei?	What is the nature of neutron stars and dense nuclear matter? What is the origin of the elements in the Cosmos? What are the nuclear reactions that drive stars and stellar explosions?	Why is there now more matter than antimatter in the Universe?	What are new applications of isotopes to meet the needs of society?
FRIB400 will help to answer the challenges formulated for the field			
17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research, 11 will benefit from FRIB400			
1. Shell structure 2. Superheavies 3. Skins 4. Pairing 5. Symmetries 13. Limits of stability 14. Weakly-bound nuclei 15. Mass surface	6. Equation of state (EOS) 7. r -process 8. $^{15}\text{O}(\alpha, \gamma)$ 9. ^{56}Fe supernovae 15. Mass surface 16. rp process 17. Weak interactions	12. Atomic electric dipole moment	10. Medical 11. Stewardship
FRIB400 will open new opportunities across all fields of rare-isotope science			

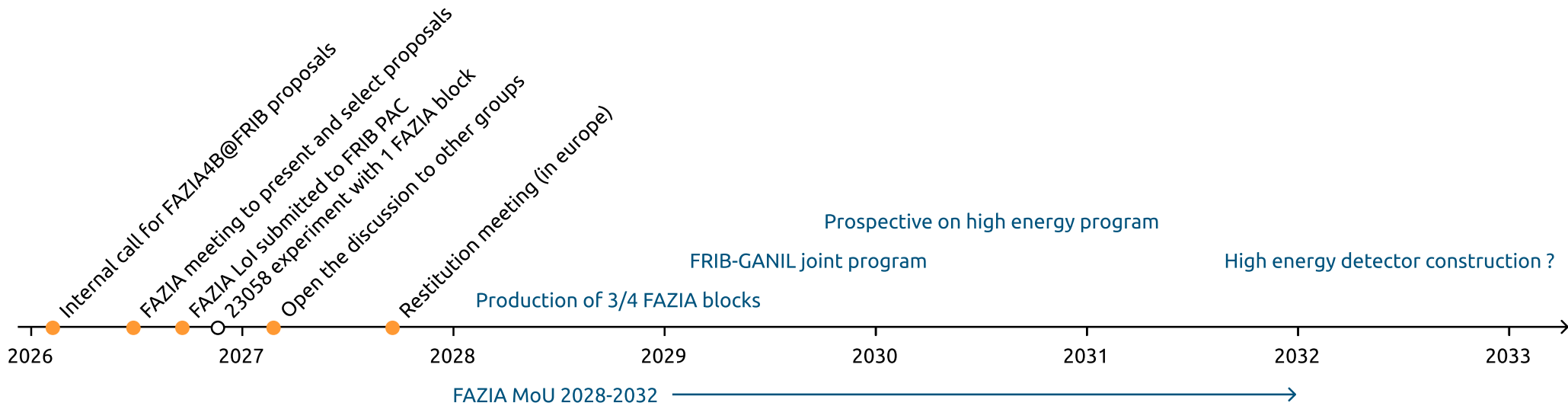
Figure: Science Drivers of rare-isotope science. The 400 MeV/u energy upgrade, FRIB400, will transform the study of 11 of the 17 Benchmarks (marked in bold) put forth by the Nuclear Science Advisory Committee (NSAC) Rare-Isotope Beam (RIB) Task Force (TF) to characterize the scientific potential of a rare-isotope facility [NSAC07].

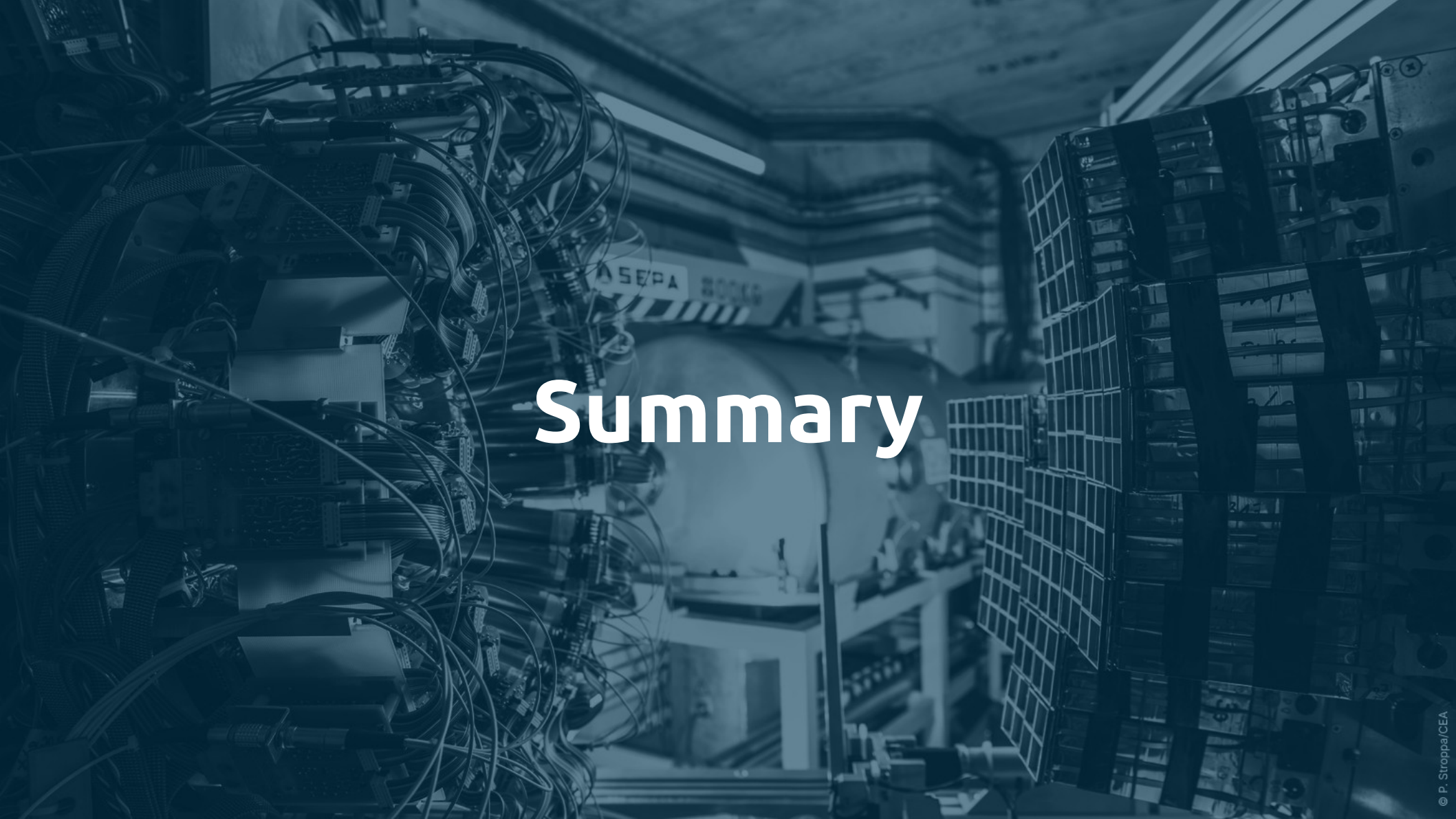
FRIB 400

The Scientific Case for
the 400 MeV/u Energy
Upgrade of FRIB

by the FRIB Science Community







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