Heavy-ion collision program at FRIB

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Special thanks to Kyle Brown, MSU/FRIB

WESTERN MICHIGAN UNIVERSITY

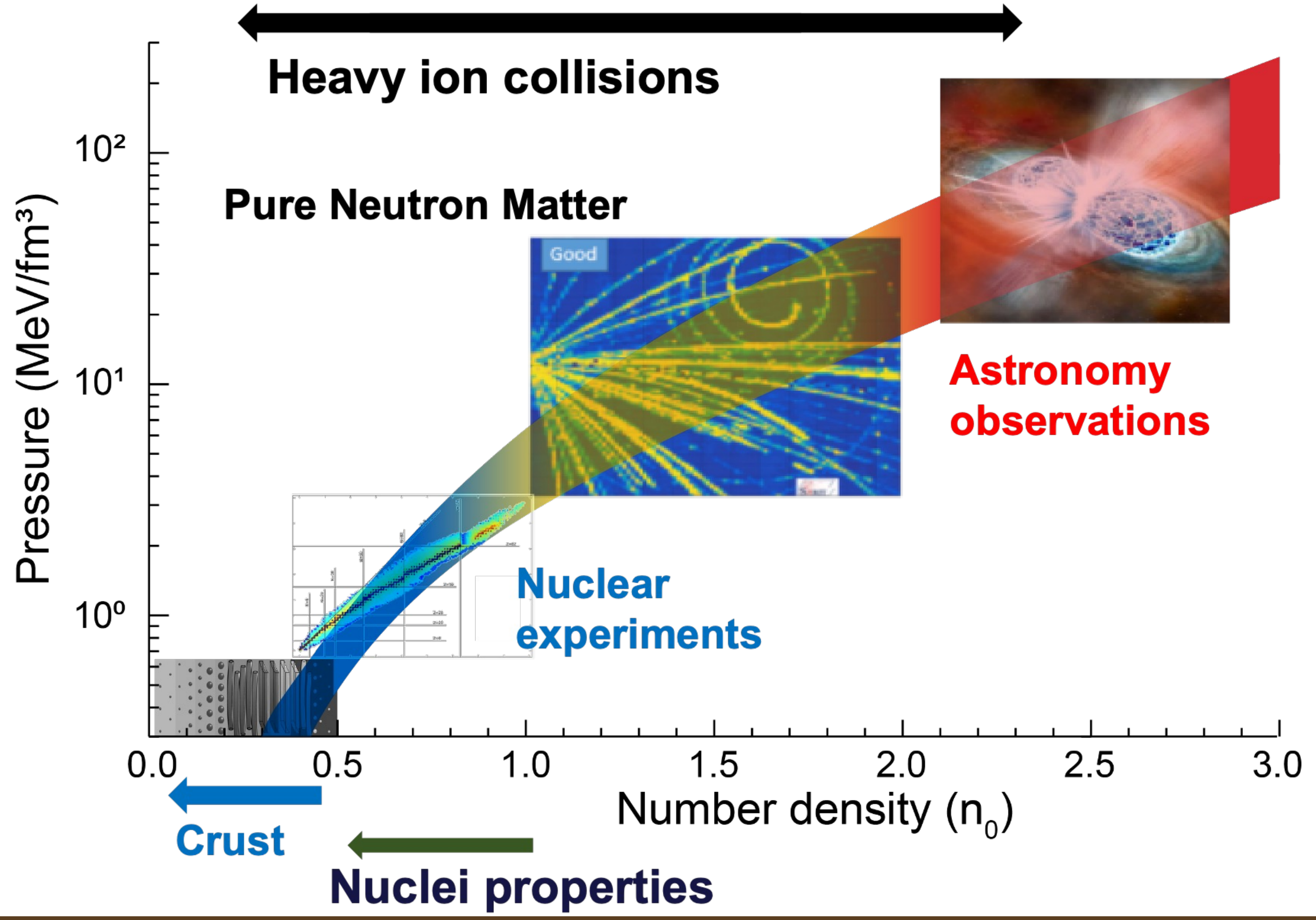
From Nuclei to Neutron Stars

Equation of State of nuclear matter

$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$

$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$

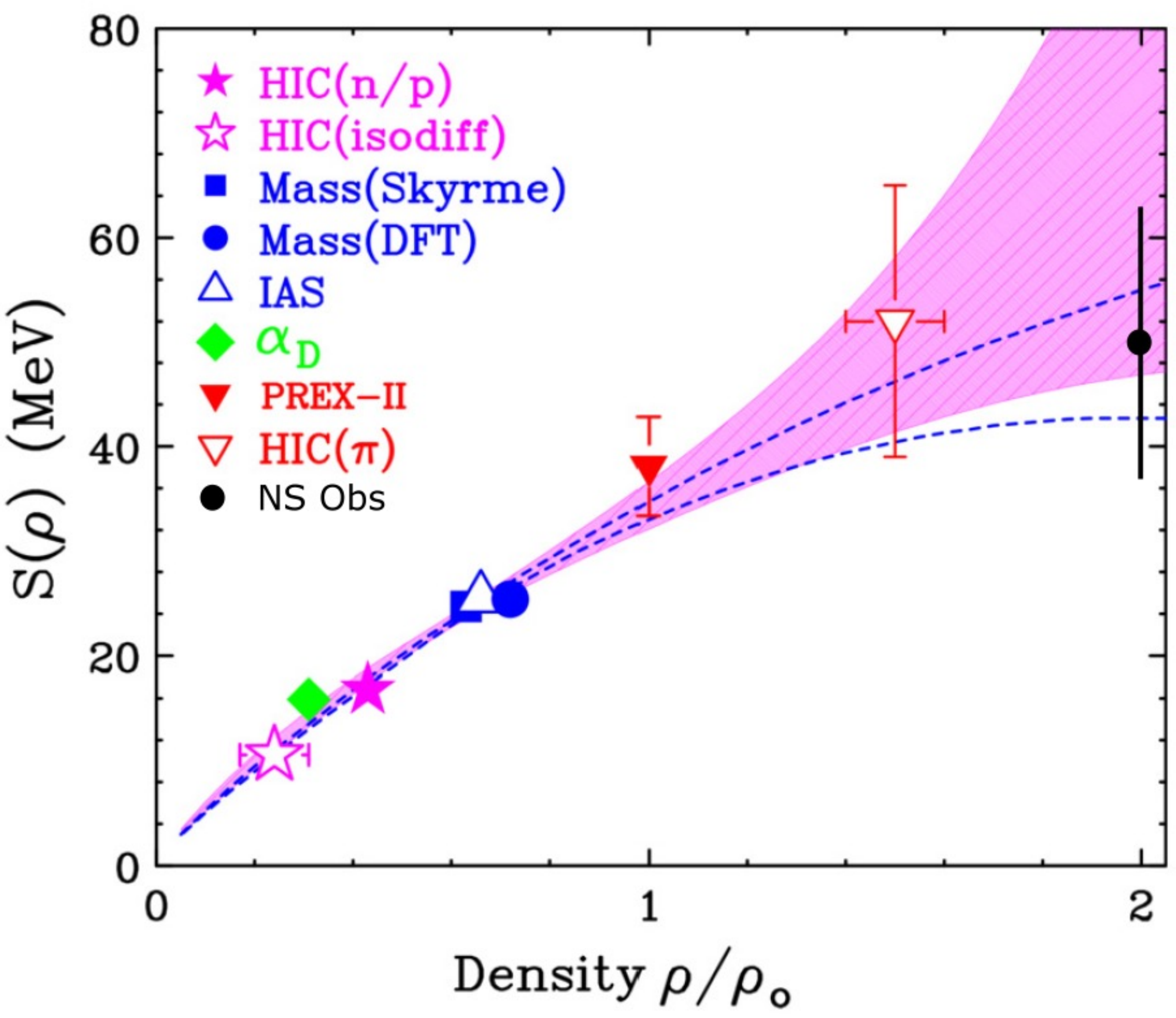
Symmetry Energy of asymmetric matter



The role of heavy-ion collisions

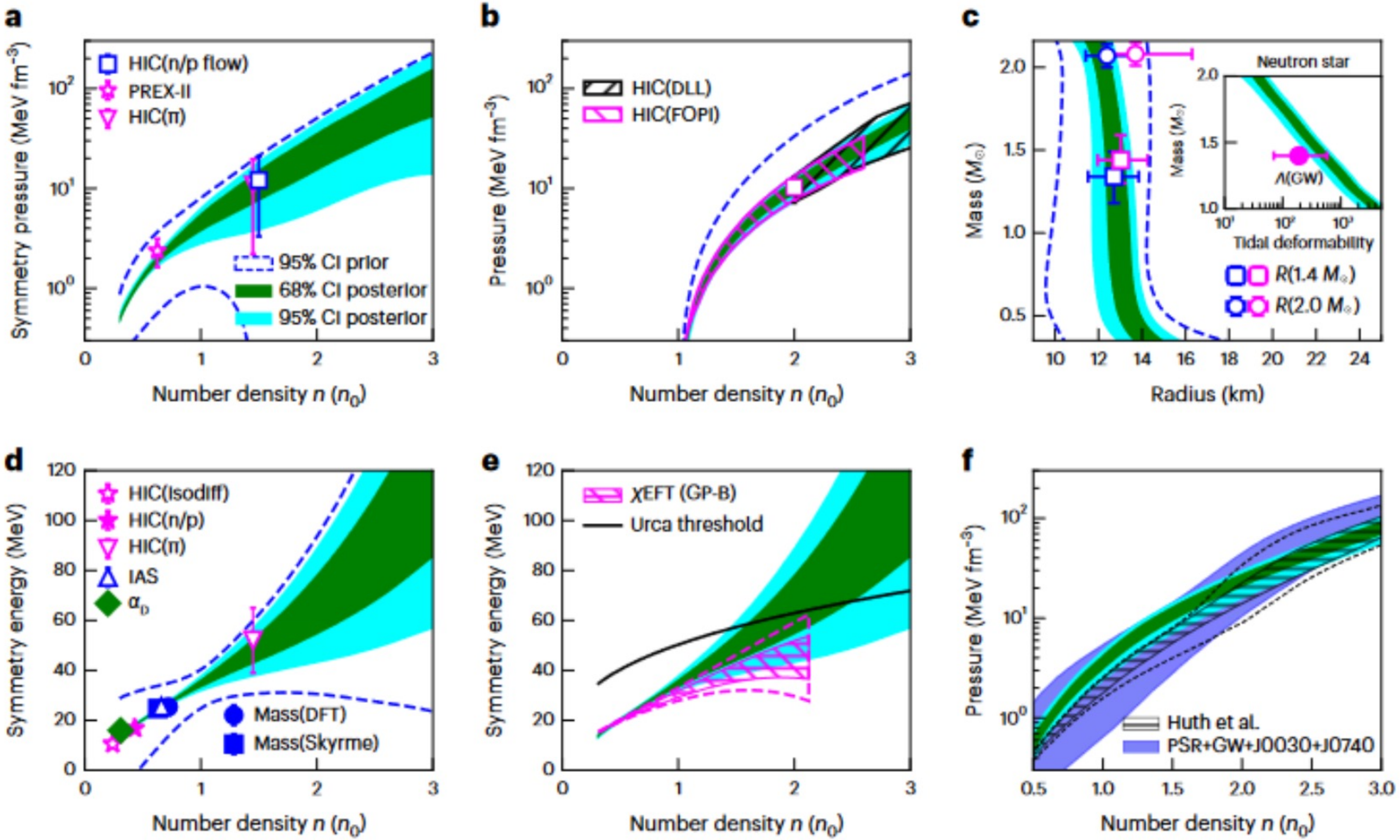
- Astronomers have constrained the EoS of Neutron Star (NS) matter by measurements of:
  - Gravitational waves from the merger of two neutron stars from which the NS deformabilties were obtained.
  - Radii of NS that are pulsers with known masses.
- Both observables mainly provide the total pressure. To understand the composition of NS matter and its pressure, we need to know how the EoS depends on its constituent particles.
  - For nucleonic matter, one needs to know how the energy/nucleon
- NS cooling rates may provide some information.
- **Nucleus-nucleus collision data provide that information.**

Experimental constraints



Lynch, Tsang, PLB 830, 137098 (2022)

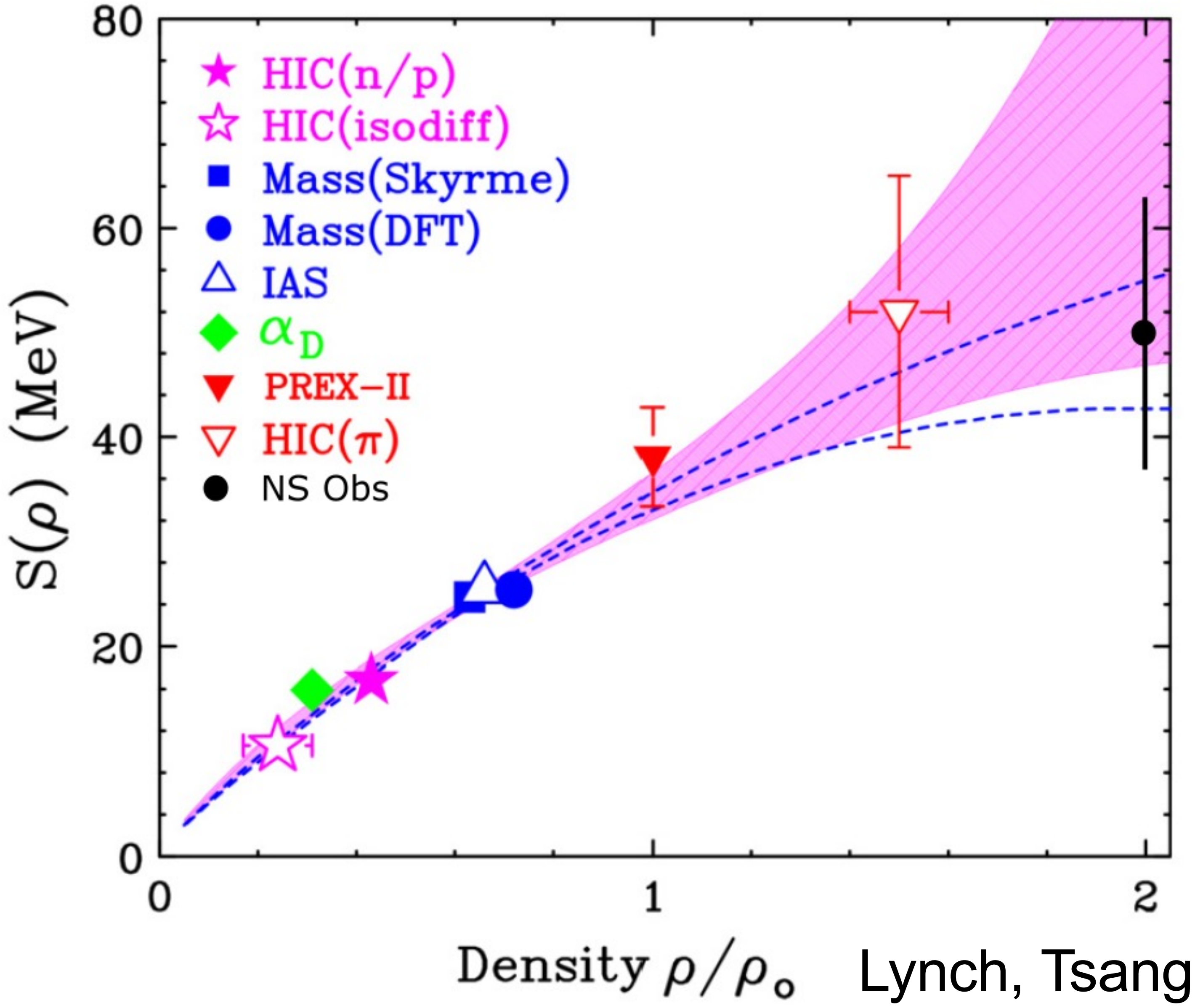
Current constraints on EOS



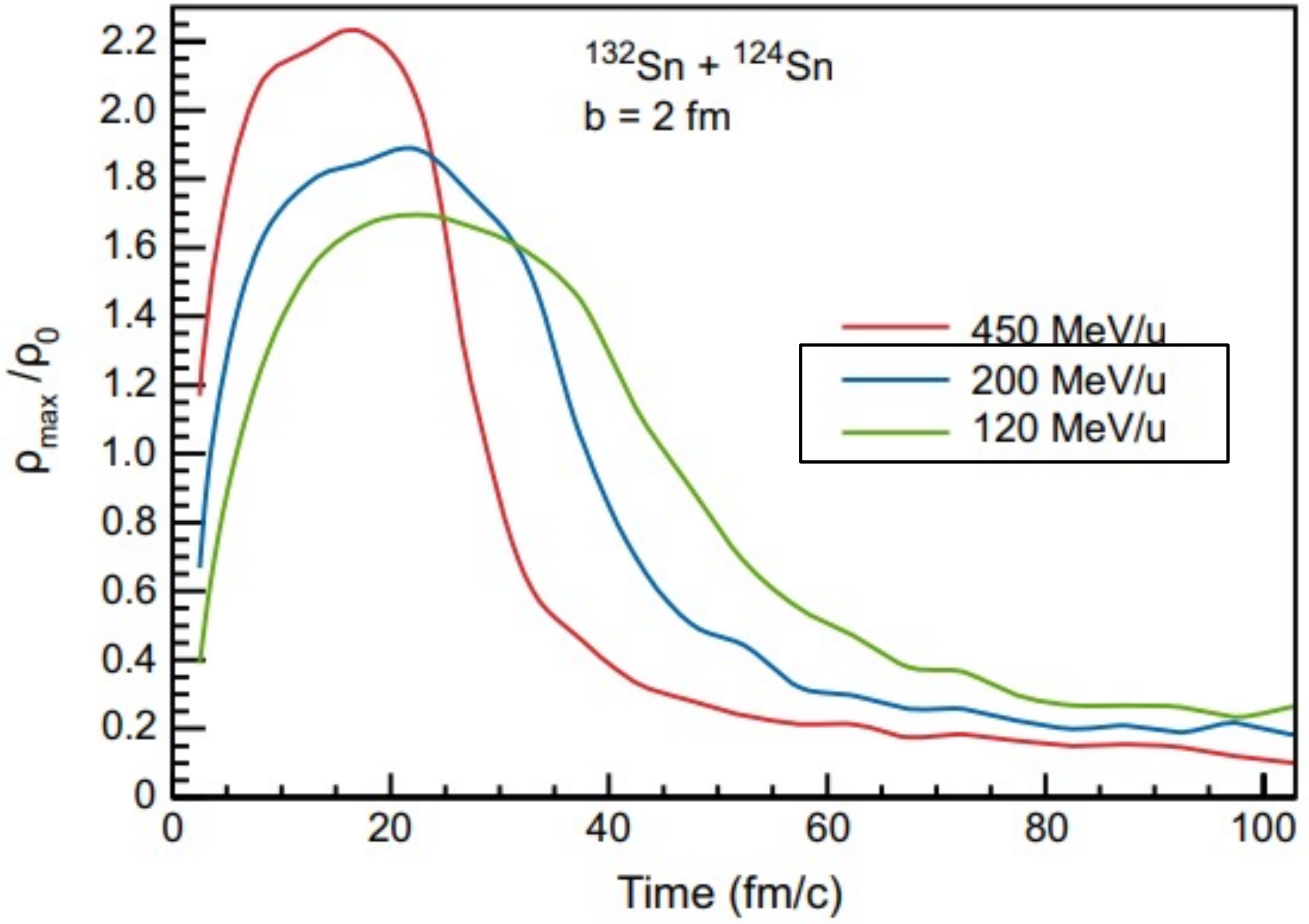
C. Y. Tsang Nature Astronomy 8, 328 (2024)

EoS Studies at FRIB

Goal: Comprehensive nuclear matter EOS: density and momentum (effective mass) dependence of nuclear potentials



FRIB Upgrade Whitepaper



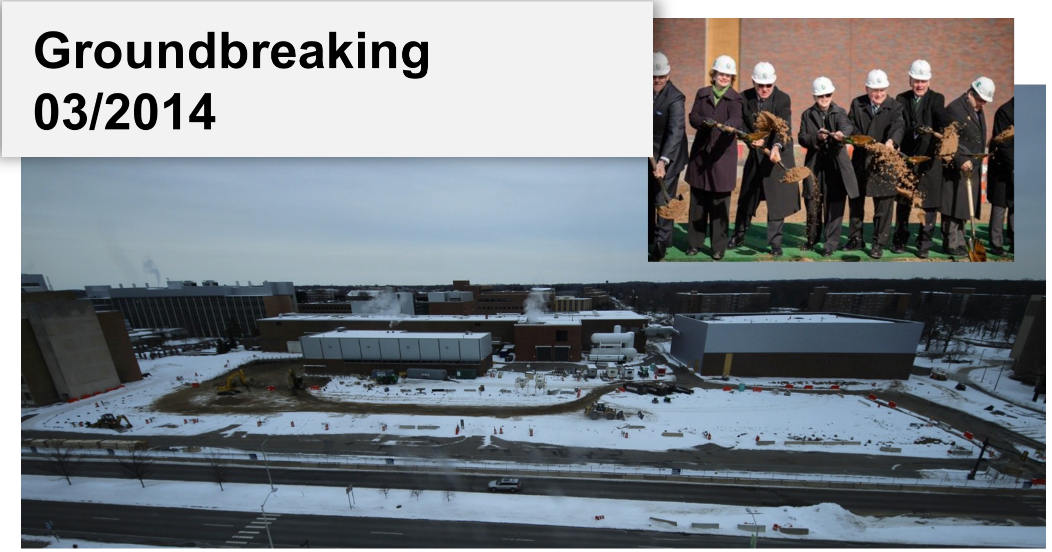
Lynch, Tsang, PLB 830, 137098 (2022)

FRIB Laboratory

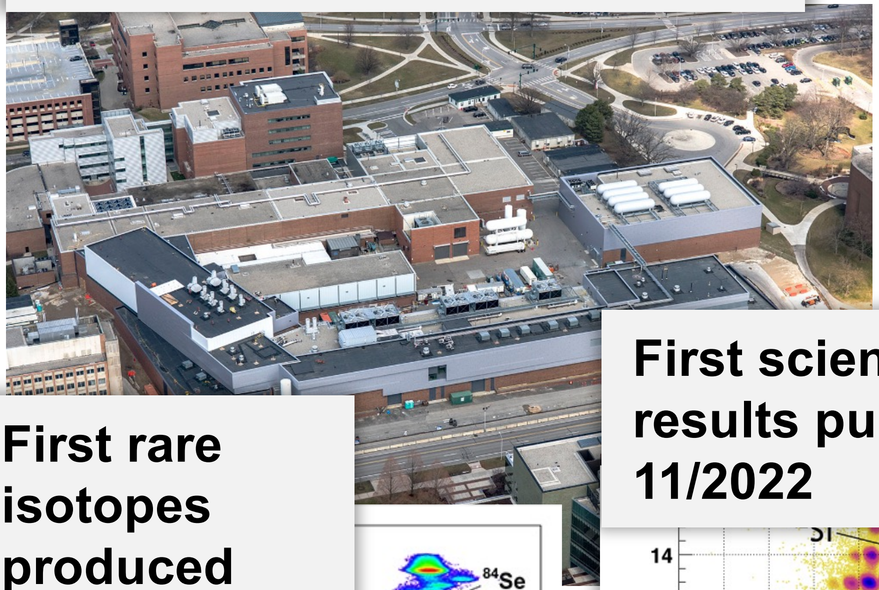
~650 employees, incl. >45 faculty, 123 graduate and ~112 undergraduate students as of March 2023

- For decades, NSCL was funded by the U.S. National Science Foundation to operate a user facility for rare isotope research and education in nuclear science, nuclear astrophysics, accelerator physics, and societal applications
- FRIB Project is completed - is a national user facility for the U.S. Department of Energy Office of Science with **first beam to an experiment in May 2022**

Groundbreaking 03/2014

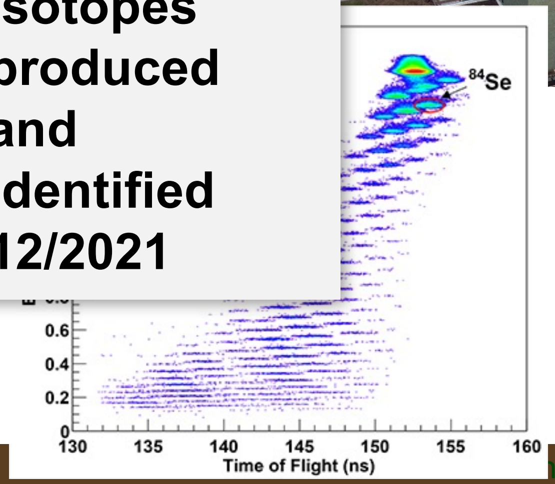


Beneficial occupancy 03/2017

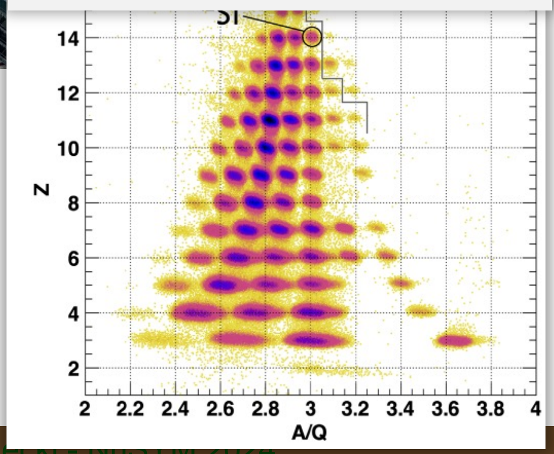


Designated as DOE-SC User Facility 09/2020

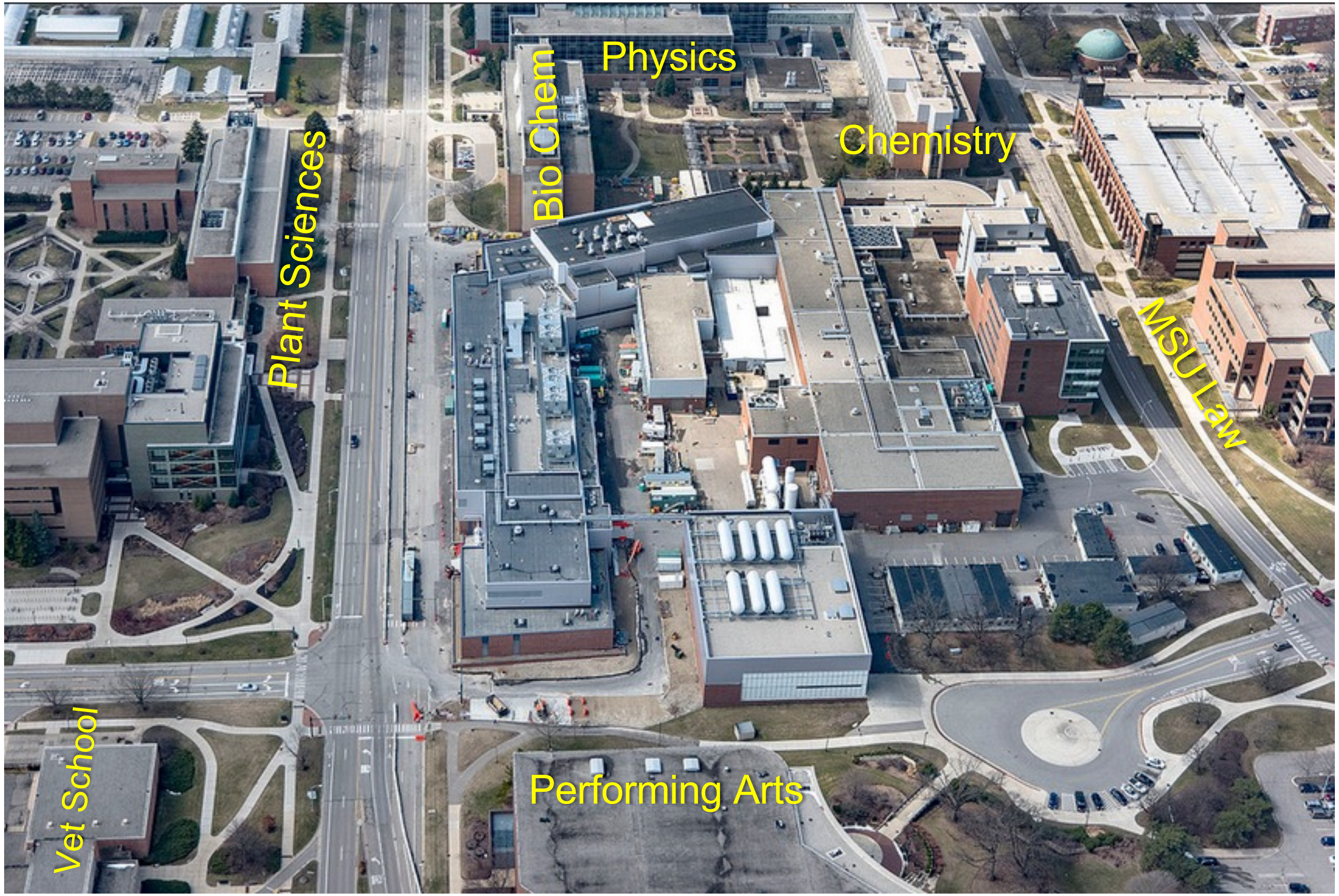
First rare isotopes produced and identified 12/2021



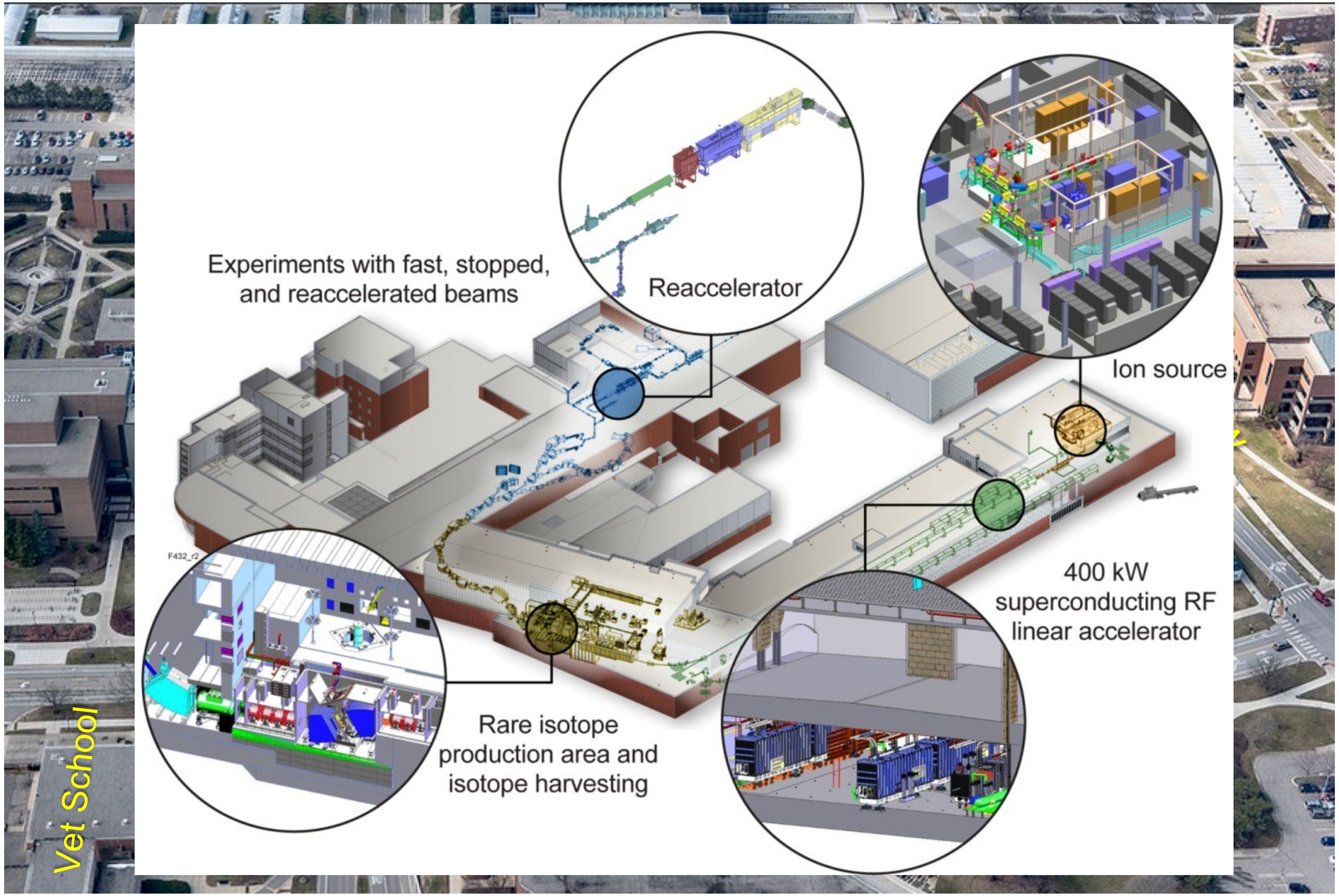
First science results published 11/2022



… located in the middle of the MSU Campus



… located in the middle of the MSU Campus



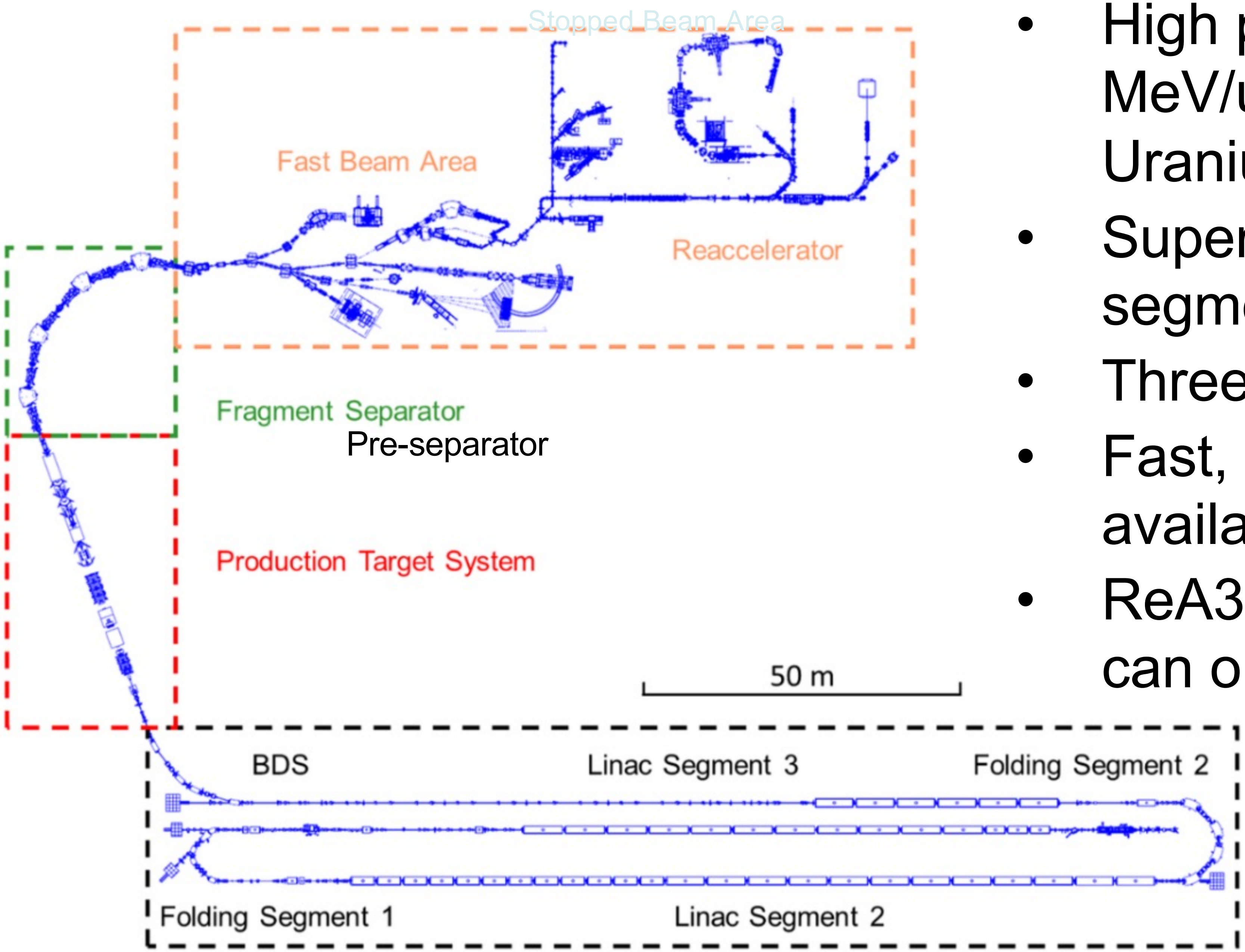
1,800 Users Engaged and Ready for Science - www.fribusers.org

- Users organized as part of independent FRIB Users Organization (FRIBUO)
  - Chartered organization with an elected executive committee
  - 1,800 members (125 U.S. colleges and universities, 13 national laboratories, 53 countries) as of 31 January 2024
  - 21 working groups on instruments

- Strong interest from user community wanting to use FRIB beams
  - Users establishing programs for FRIB science
  - Two PACs run to date, 3rd PAC in Fall 2024
  - >20,000 hrs of beam-on-target requested

- User needs and high user satisfaction are important to FRIB
  - ISO 9001 quality systems to assess user satisfaction
- Annual meetings
  - User meeting (three days with 200-300 participants)
  - » August 2022: Meeting hosted by ANL
  - » August 2023: Meeting hosted by FRIB
  - » August 2024: Meeting to be hosted by University of Tennessee Knoxville

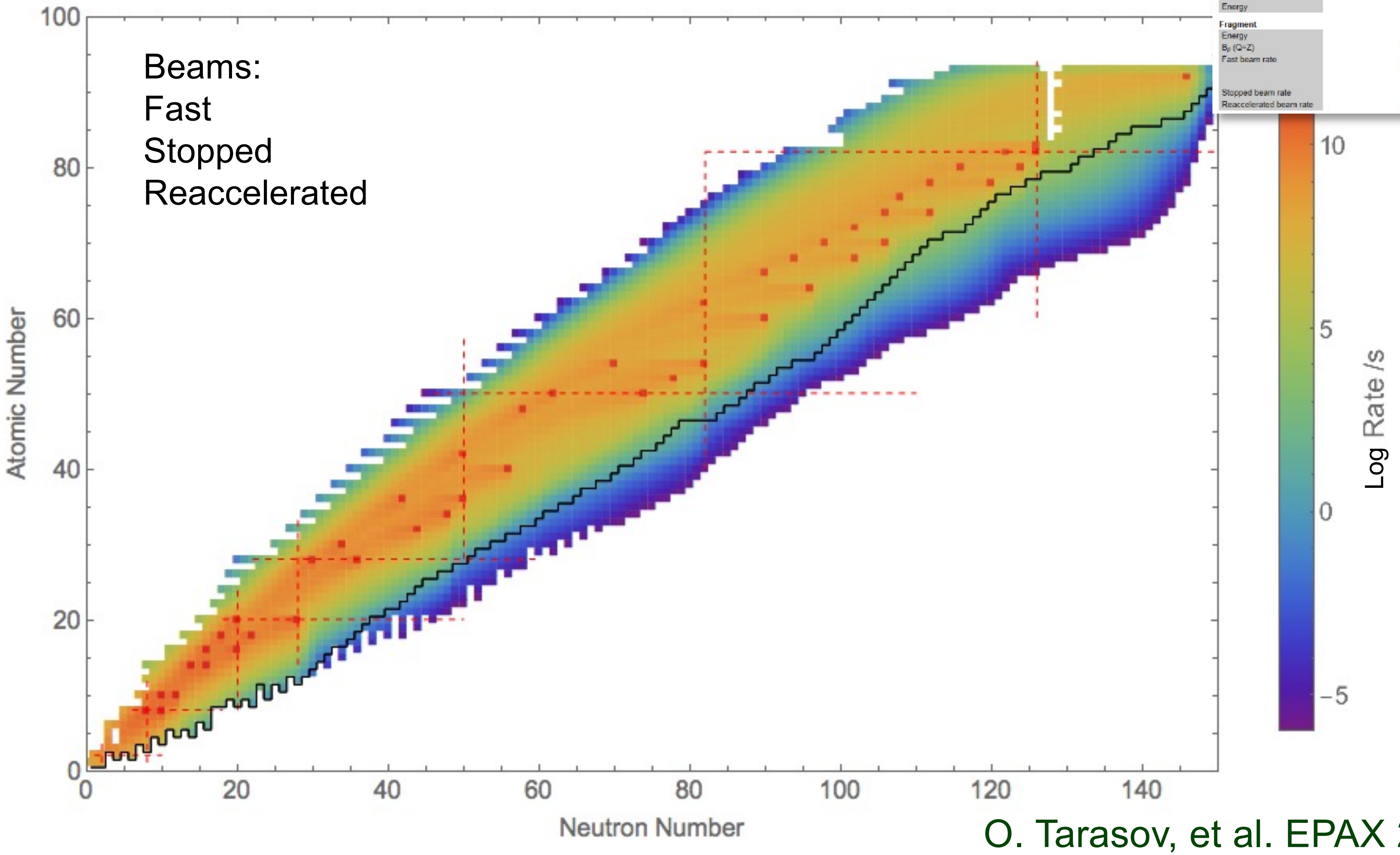
Schematic Overview of the FRIB Facility



- High power heavy ion accelerator (200 MeV/u, 400 kW for all beams Oxygen to Uranium)
- Superconducting linear accelerator with 3 segments – 46 total cryomodules
- Three-stage fragment separator
- Fast, Stopped and Reaccelerated beams available
- ReA3,6 (up to 10 MeV/u re-accelerator); can operate in stand-alone mode

FRIB Estimated Beam Rates

https://groups.nscl.msu.edu/frib/rates/fribrates.html



O. Tarasov, et al. EPAX 2.15

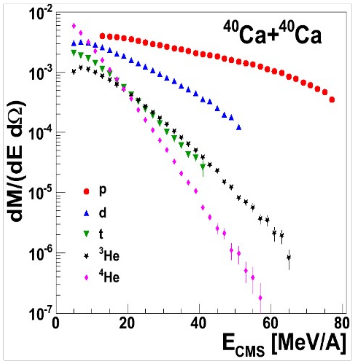
Production Rate of ^{100}Sn Illustrates the Future Gains (approximate)

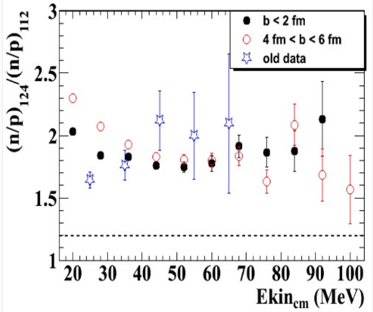
- Hypothetical increase over time; no promises, rates at the experiment will be lower
- FRIB start of operations: 1 kW
- December 2022: 3 kW (0.04/s measured)
- EPOCH 1: 2023-4: 10 kW (0.1/s)
- EPOCH 2 2025: 20 kW (0.25/s)
- EPOCH 3 2026: 50 kW (0.8/s)
- EPOCH 4 2027: 100 kW (2/s)
- EPOCH 5 : 2028: 200 kW (4/s)
- EPOCH 6 2029: 400 kW (8/s)
- TBD: FRIB400 (40/s)
- To be TBD: FRIB400 with a lithium target upgrade (250/s)

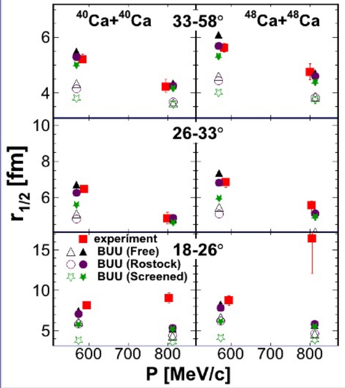
Importance of collaboration

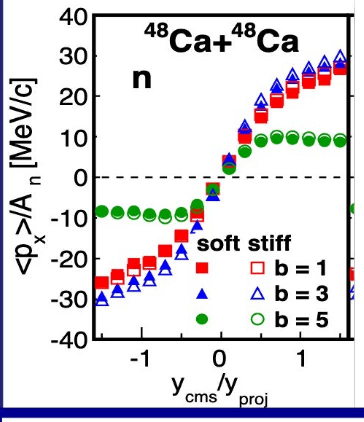
- Experiments & detector development require long-term planning
- No-small projects at FRIB
  - Preferable campaigns with the same setup (not only EOS experiments)
  - IN2P3-FRIB agreement
  - INFN-FRIB agreement (in progress)
  - EOS physics is a key component of FRIB400
- Support from the transport model theorists
  - Testing the transport models with many observables using the same setup is essential
  - A. Sorensen et al., Dense Nuclear Matter Equation of State from Heavy-Ion Collisions, arXiv: 2301.13253 (nucl-th)

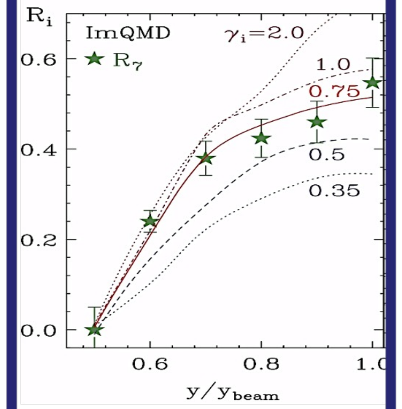
What we hope to learn from HIC collisions?











Transport model ingredients ↓

Observables	Spectra	(Double-) ratios	Femtoscopy	Flow	Isospin diffusion
Symmetry energy		✔		✔	✔
Effective mass		✔		?	?
Cross section	✔	✔	✔	✔	✔
Cluster production	✔	✔	✔	✔	✔

Our approach: Use different isotopes
(fix Z of your initial system and vary N)

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- No-small projects at FRIB
  - Preferable campaigns with the same setup (not only EOS experiments)
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  - A. Sorensen et al., Dense Nuclear Matter Equation of State from Heavy-Ion Collisions, arXiv: 2301.13253 (nucl-th)
- We have homework to do:

  what physics, what experiments (not just EOS), new hardware
- Future: Time Projection Chamber detectors for FRIB & FRIB400

FRIB: Short-term plan

First EOS approved experiment at FRIB

Measuring the isospin dependence of the nucleon effective mass at supersaturation density

$^{56,70}Ni + ^{58,64}Ni$ @ 175 MeV/u

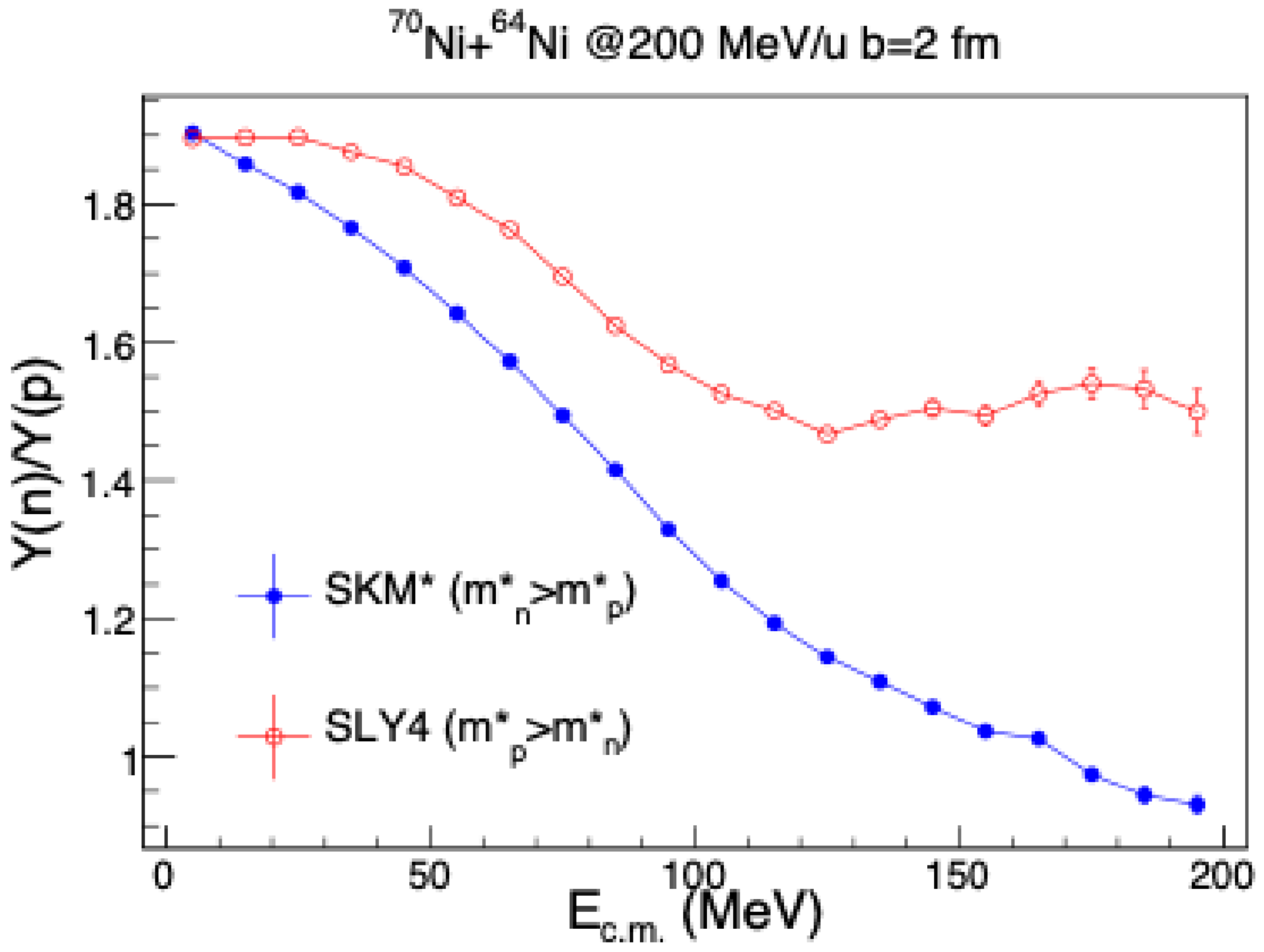
Main goals of the experiment are to measure

- Energy spectra for light-charged particles and neutrons
- Precise single and double n/p ratio (including coalescence invariant ratios)
- Transverse and elliptic flow

Collaboration between:

MSU: K. Brown, W. Lynch, B. Tsang
WMU: Z. Chajecki
INFN: G. Verde, D. Dellaquila, I. Lombardo
IN2P3: A. Chbihi, D. Gruyer, Q. Fable, C. Ciampi,
F. Quentin, J.-E. Ducret
Texas A&M: K. Hagel, A. Mcintosh

First EOS Experiment at FRIB (PAC2)



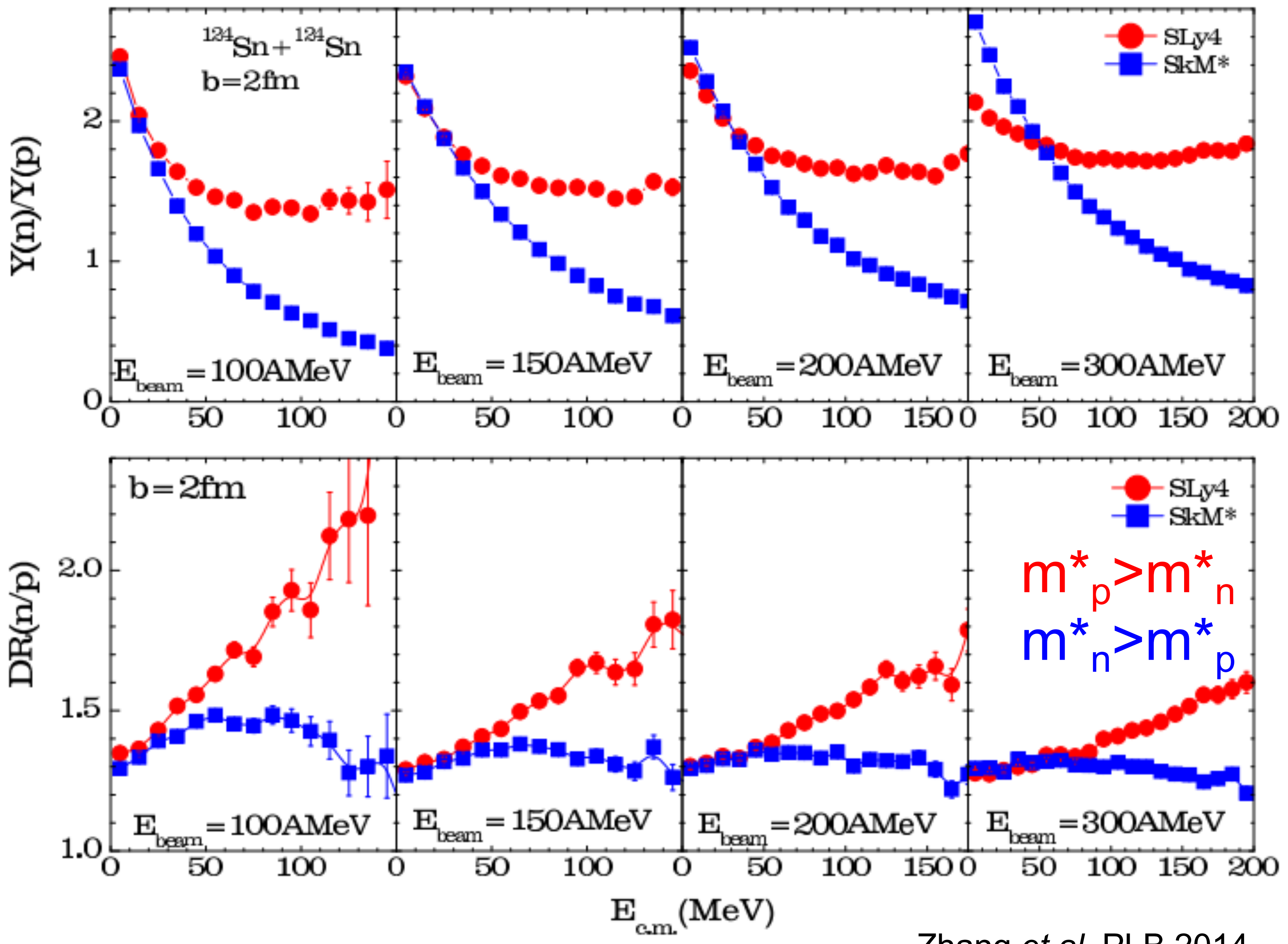
F = m*a
If m* ↓, then a↑ E_{kin} ↑

- First experiments at FRIB will focus on the momentum dependence with two observables
  - n/p spectral ratio
  - Directed and elliptical flow
- ^{70}Ni+^{64}Ni and ^{56}Ni+^{58}Ni at 175 MeV/u
- ImQMD calculations show n/p ratio still sensitive to effective mass difference

Momentum dependence (effective masses)

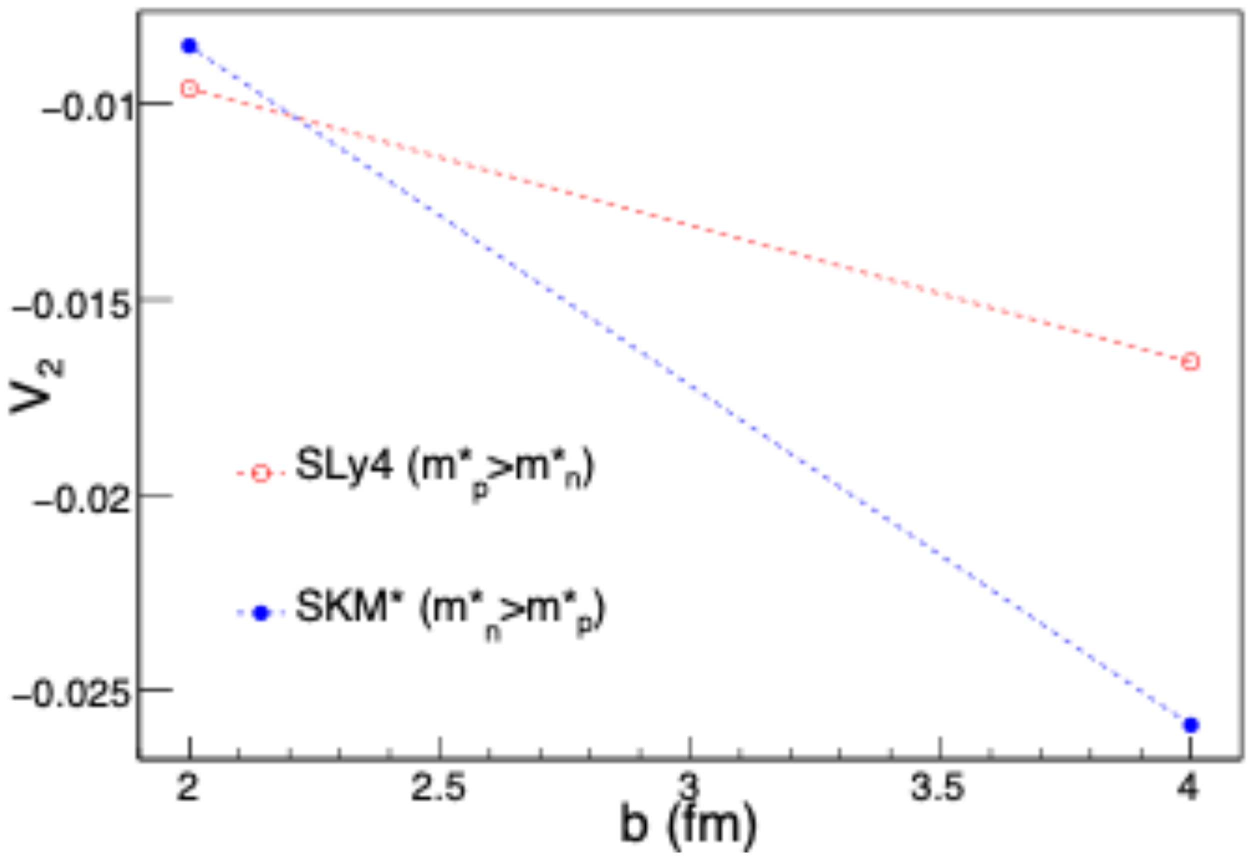
- The sensitivity of the n/p ratio on the effective mass (momentum dependence) drops off with beam energy
- If we want to measure this for higher density, we need another observable

F = m*a
If m* ↓, then a↑ E_{kin} ↑

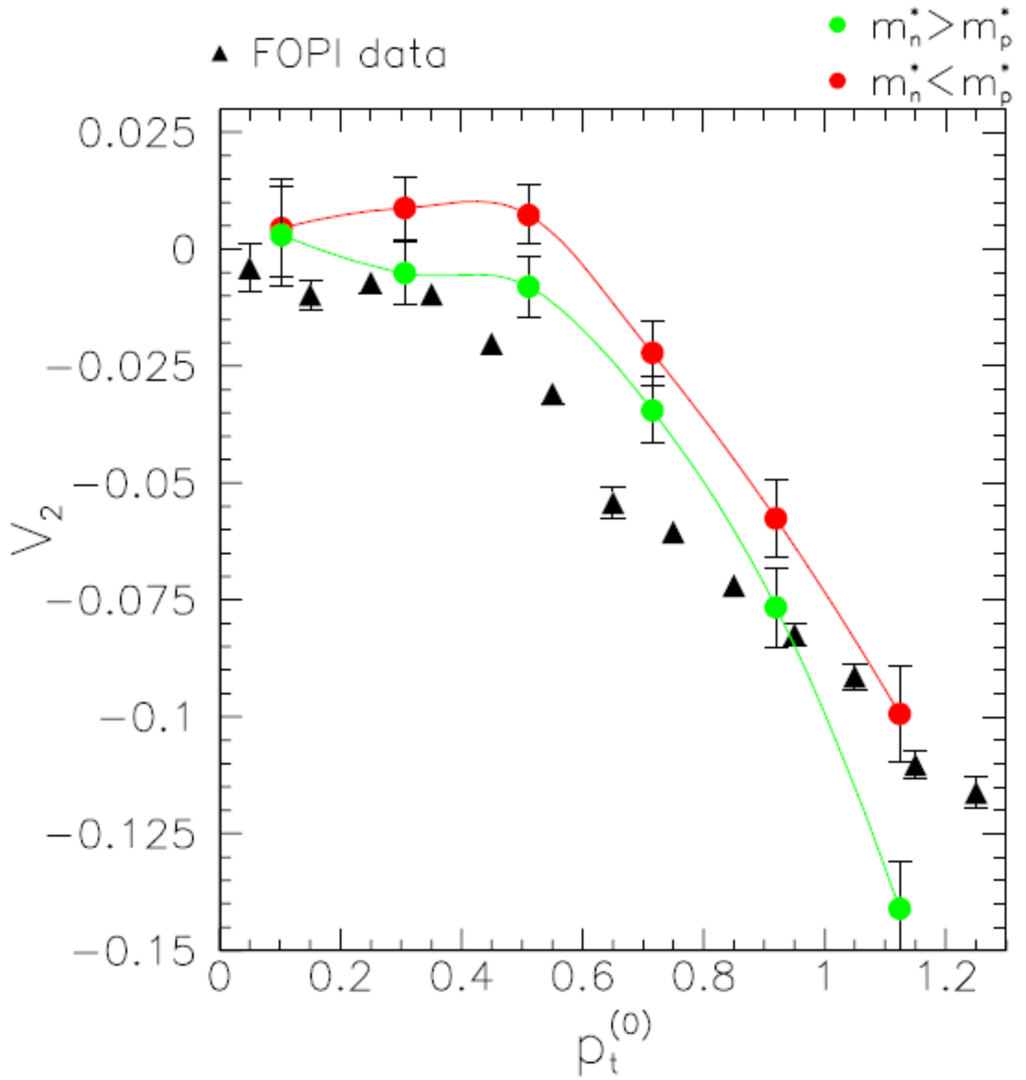


Zhang *et al*. PLB 2014

Elliptic flow



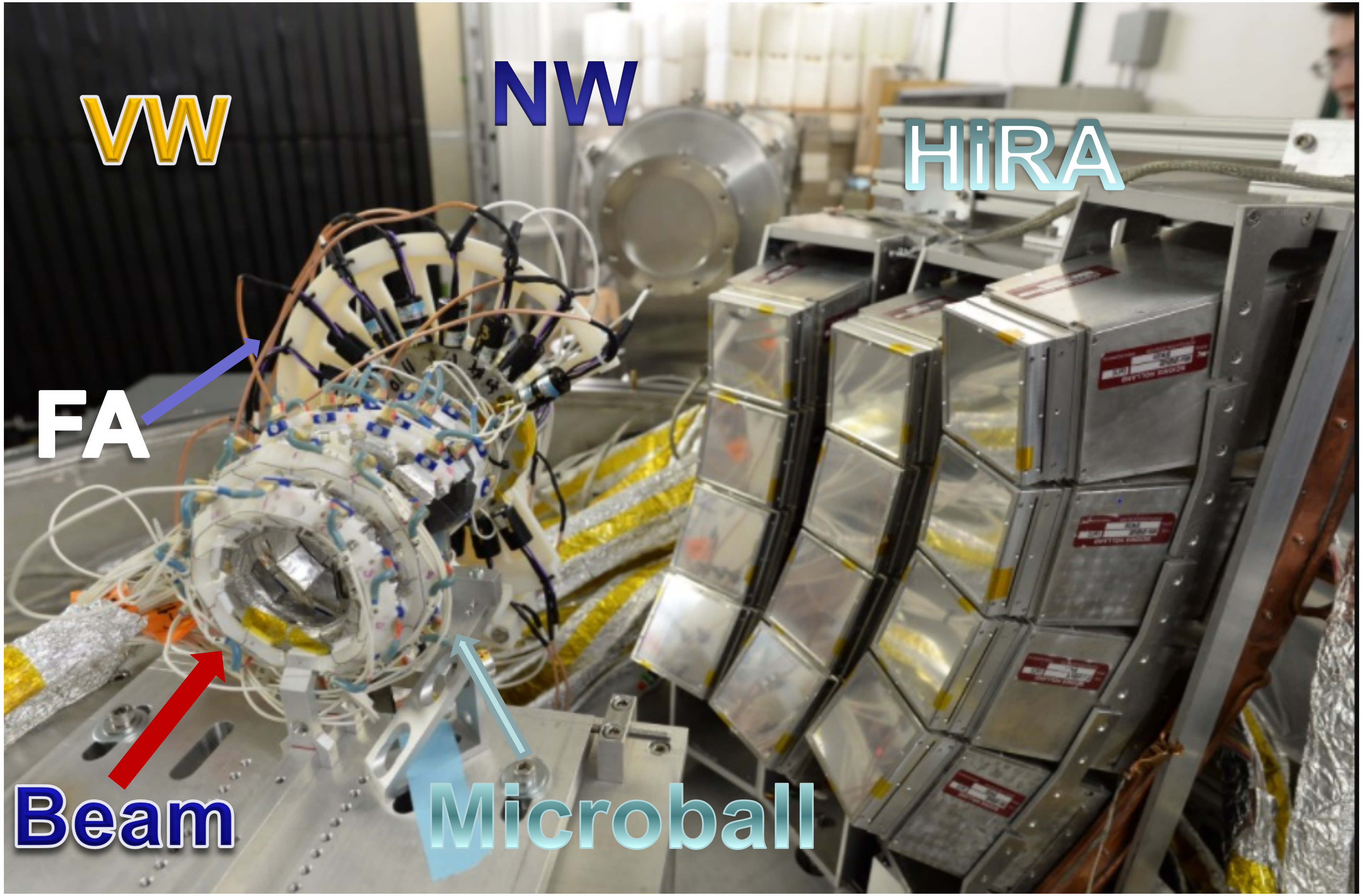
Elliptic flow in $^{197}Au + ^{197}Au$ collisions at 250 MeV/u as a function of p_t



M. Di Toro, S.J. Yennello, and Bao-An Li, EPJ A30, 153–163, 2006

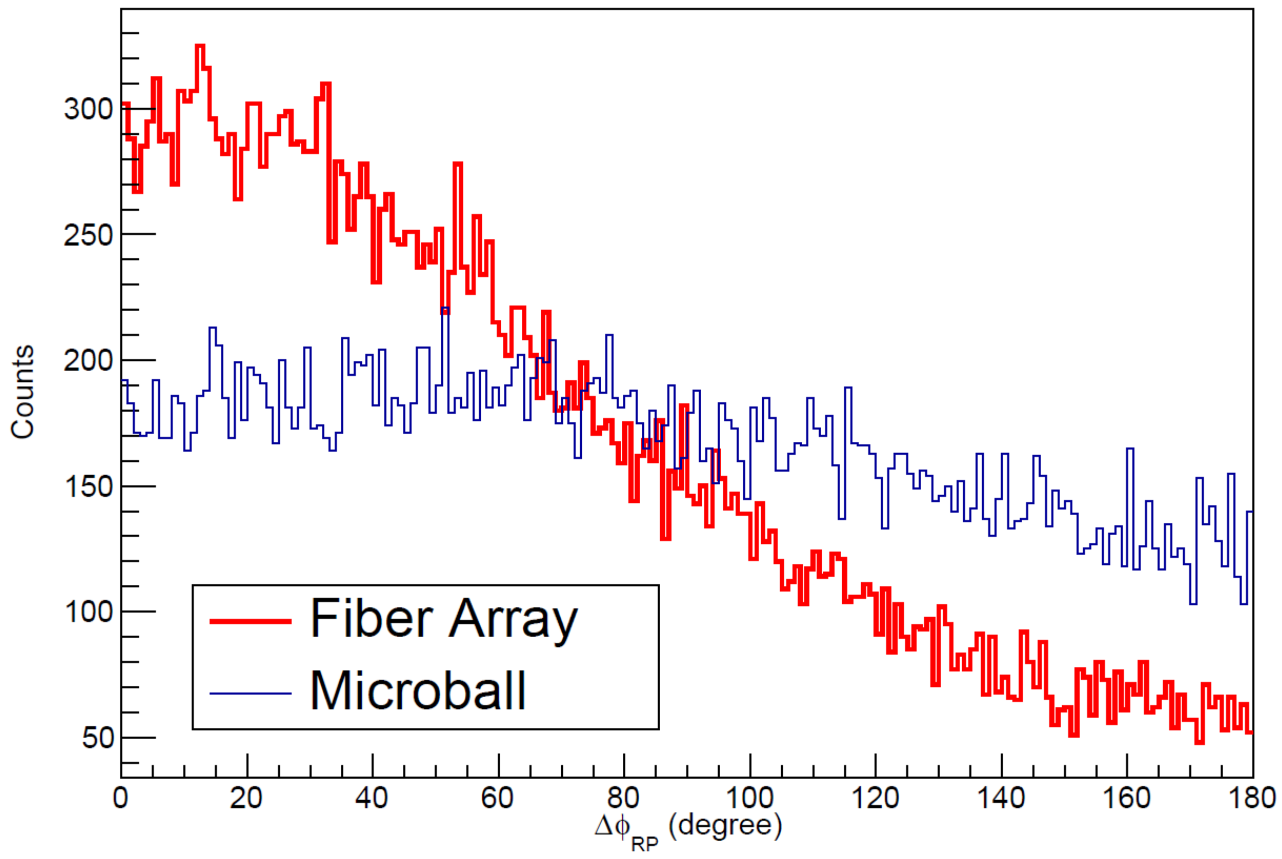
- The transverse and elliptic flow will be used to place constraints on the pressure due to the symmetry energy
- At larger b v_2 shows sensitivity to the effective mass
- GSI experiments showed sensitivity of the elliptic flow to the symmetry energy

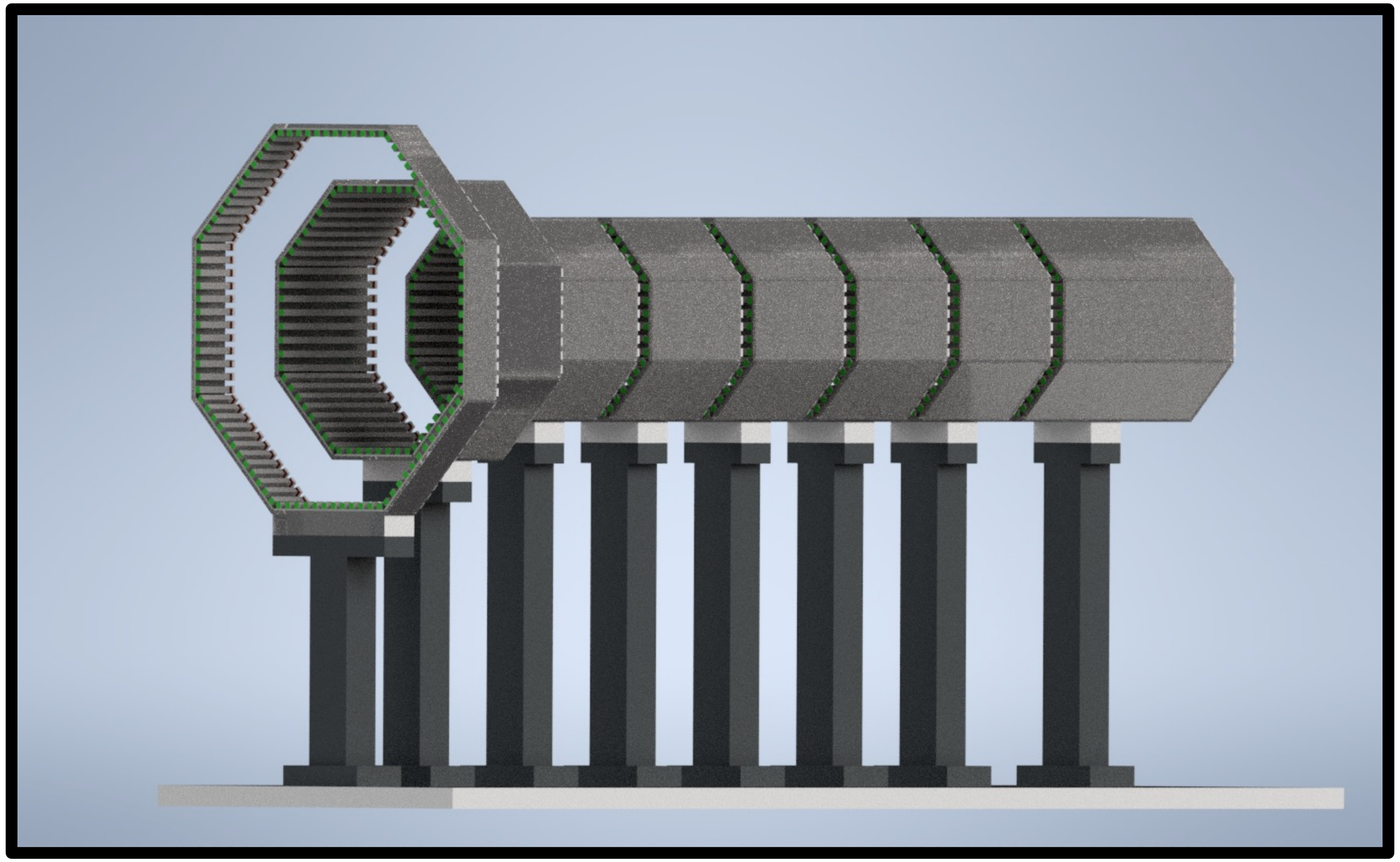
Our (previous) experimental setup



Reaction Planes with new Fiber Array

Creation of a new fiber array for reaction plane and multiplicity determination





K. Brown, MSU/FRIB

Neutron Detection

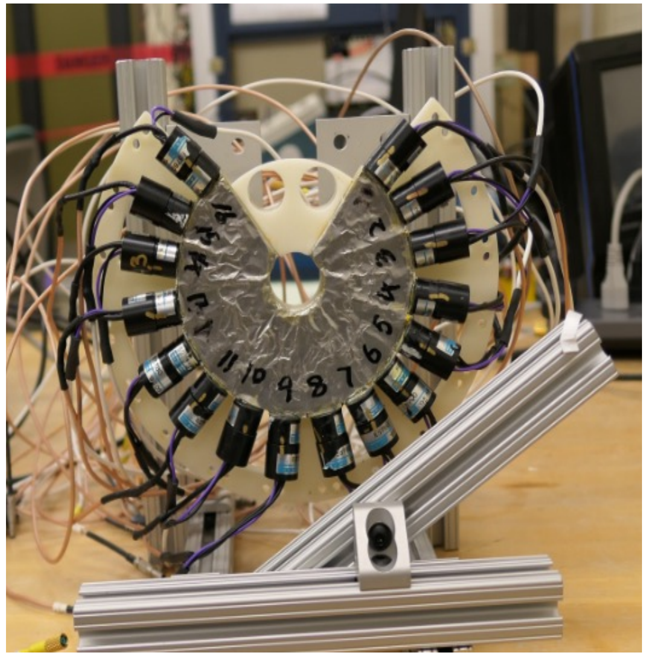
Neutron Walls

UPGRADE
Use liquid scintillator for Pulse Shape Discrimination

Proton Veto Wall

- 25 Plastic Scintillator bars
- Used to remove charged particles from the NW Spectra
- Made at WMU

Forward array



- 18 Plastic scintillator wedges
- Used as the start time for the neutron time of flight

Additional upgrades of the Experimental Setup

Collaboration with INFN/IN2P3

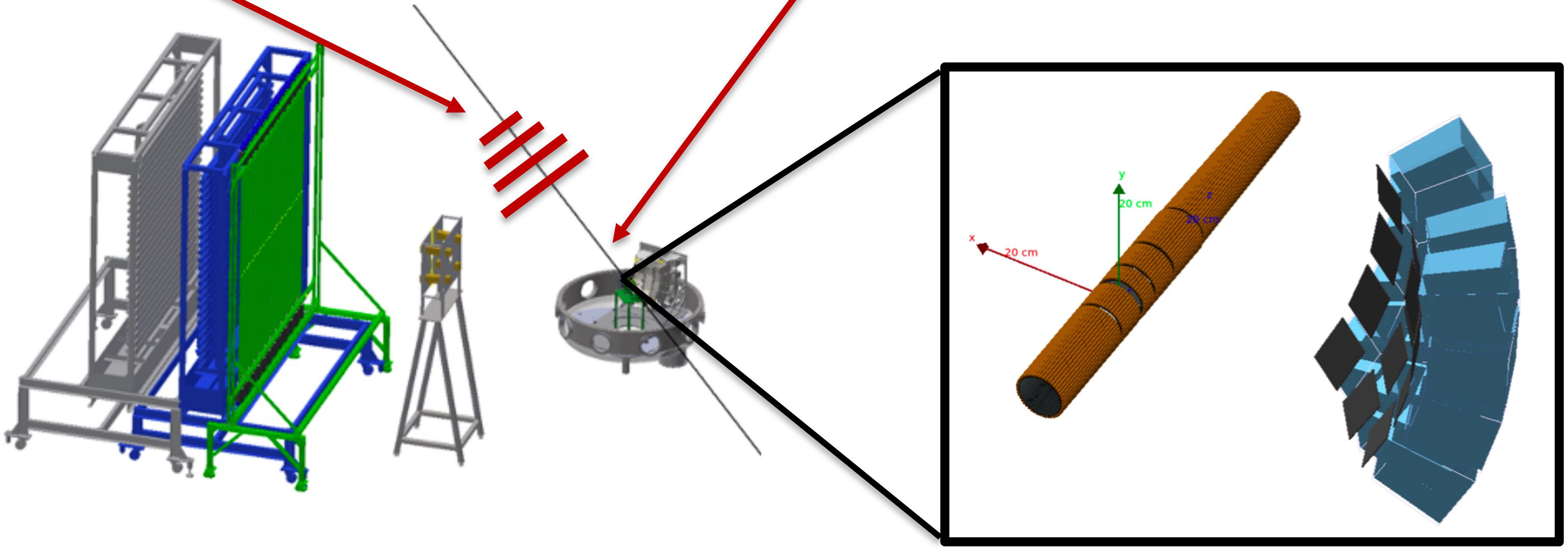
Improved reaction plane detector: Adding rings of CsI(Tl) (≈400 CsI(Tl) crystals) – Chimera/Indra-like

FAZIA blocks: Spectrometer like resolution of projectile spectators

Increase solid angle of correlator with FARCOS blocks (CHIRONE)

Same experimental setup for multiple physics outcomes:

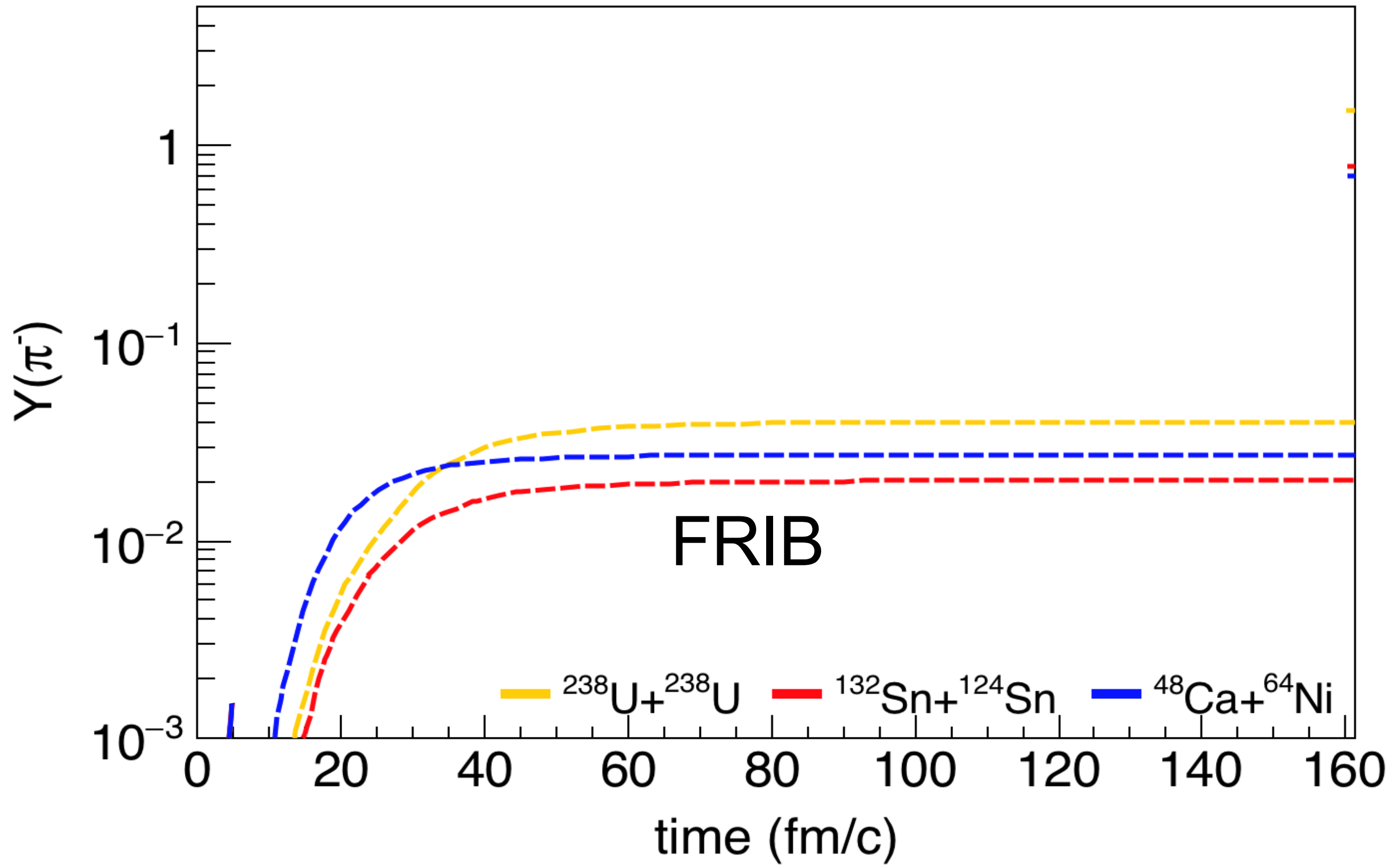
- EoS
- Particle Decays
- Double charge exchange:
  $t+{}^3He \rightarrow 3n+3p$
- Nuclear Astrophysics



FRIB: mid- and long-term plan

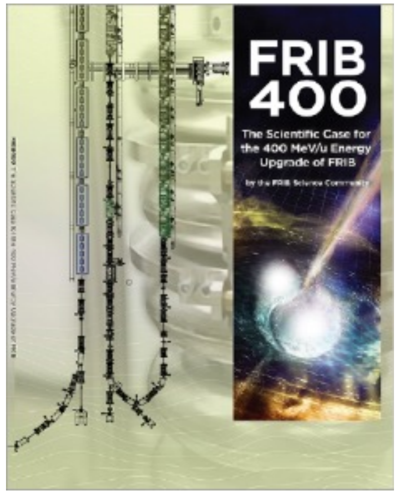
Pions @ FRIB

- The detection of all charged reaction products will uniquely allow both the low and high density channels to be measured simultaneously providing the requisite experimental consistency that is lacking in the current data.
- Due to the wide variety of exotic beams available at FRIB, collision systems with large isospin asymmetries can be studied.
- **This provides a unique opportunity to study the density dependence of the symmetry energy in the 1-2ρ_0 regime where data is currently lacking thus bridging the existing density and knowledge gap.**
- **Pions are essential to probe the EOS at higher densities**



FRIB Energy Upgrade to 400 MeV/nucleon

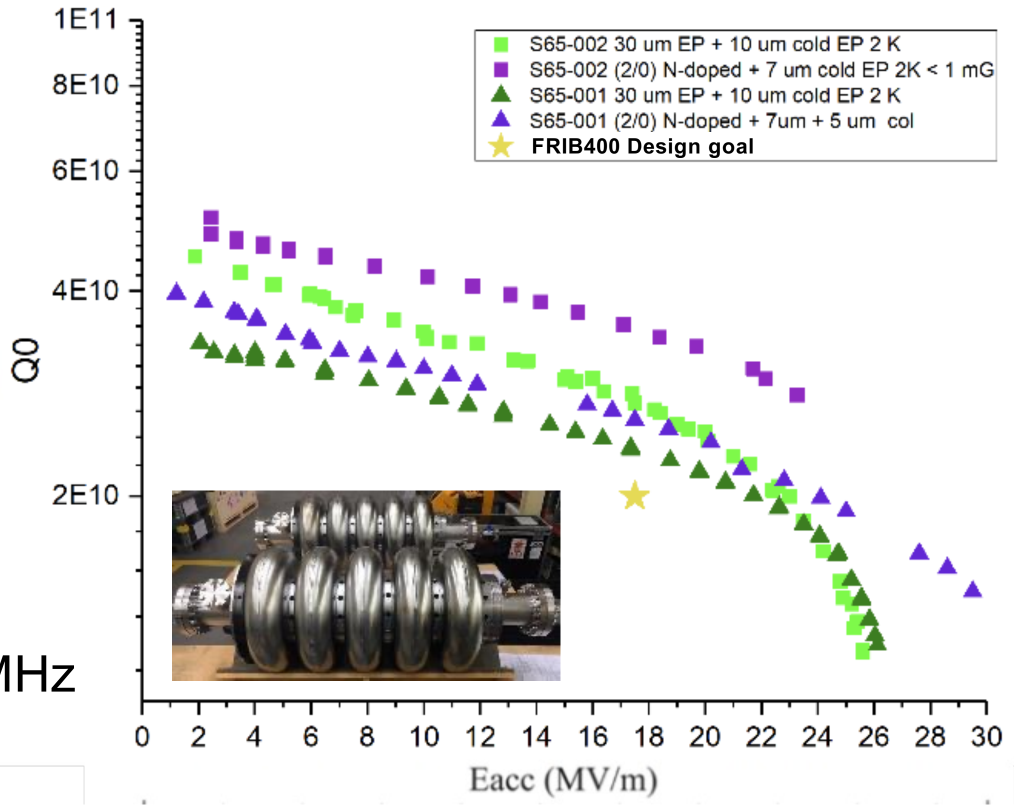
Science Case Made, Technology Being Demonstrated



FRIB400 White Paper

- Community made science case
  - **Access to key regions** needed to model nucleosynthesis in neutron-star mergers
  - **Luminosity gain over 50** for rarest isotopes
  - Energy better matched to exploring **nuclear equation of state for neutron-star merger**
  - Energy better matched for knockout and charge-exchange reactions

FRIB400 SRF Cavity R&D Progress

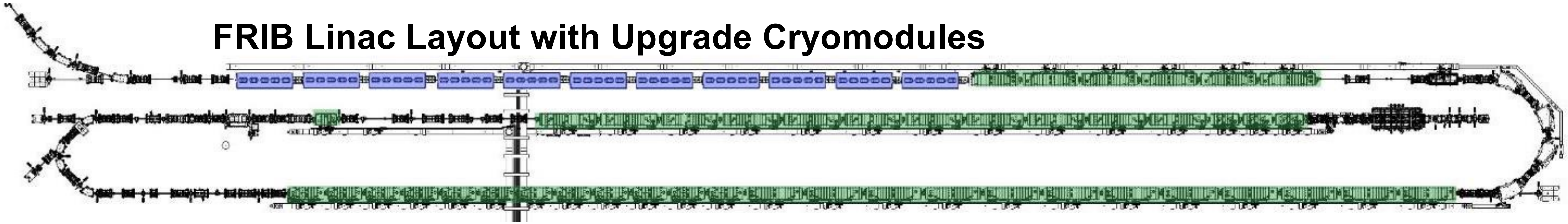


P Ostromouv et al.

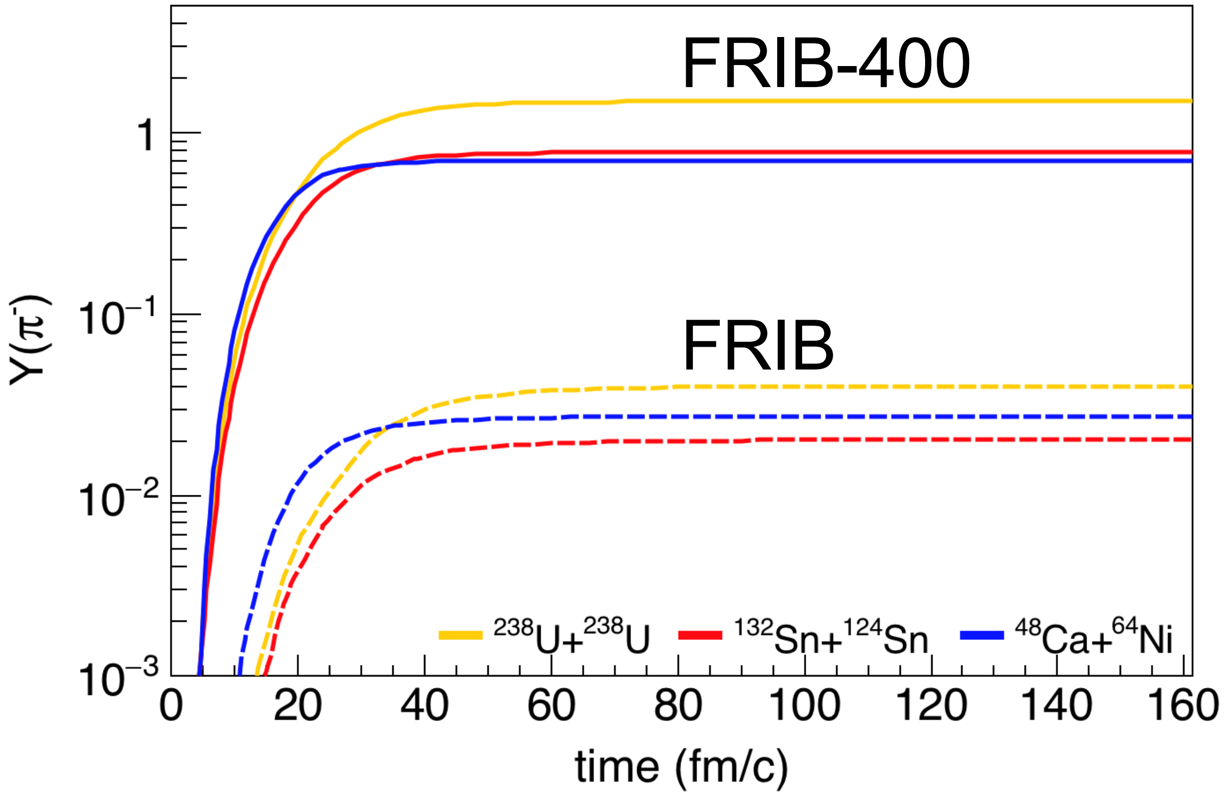
- LINAC Upgrade
  - Add 11 cryomodules, each with five β=0.65 elliptical cavities operating at 644 MHz

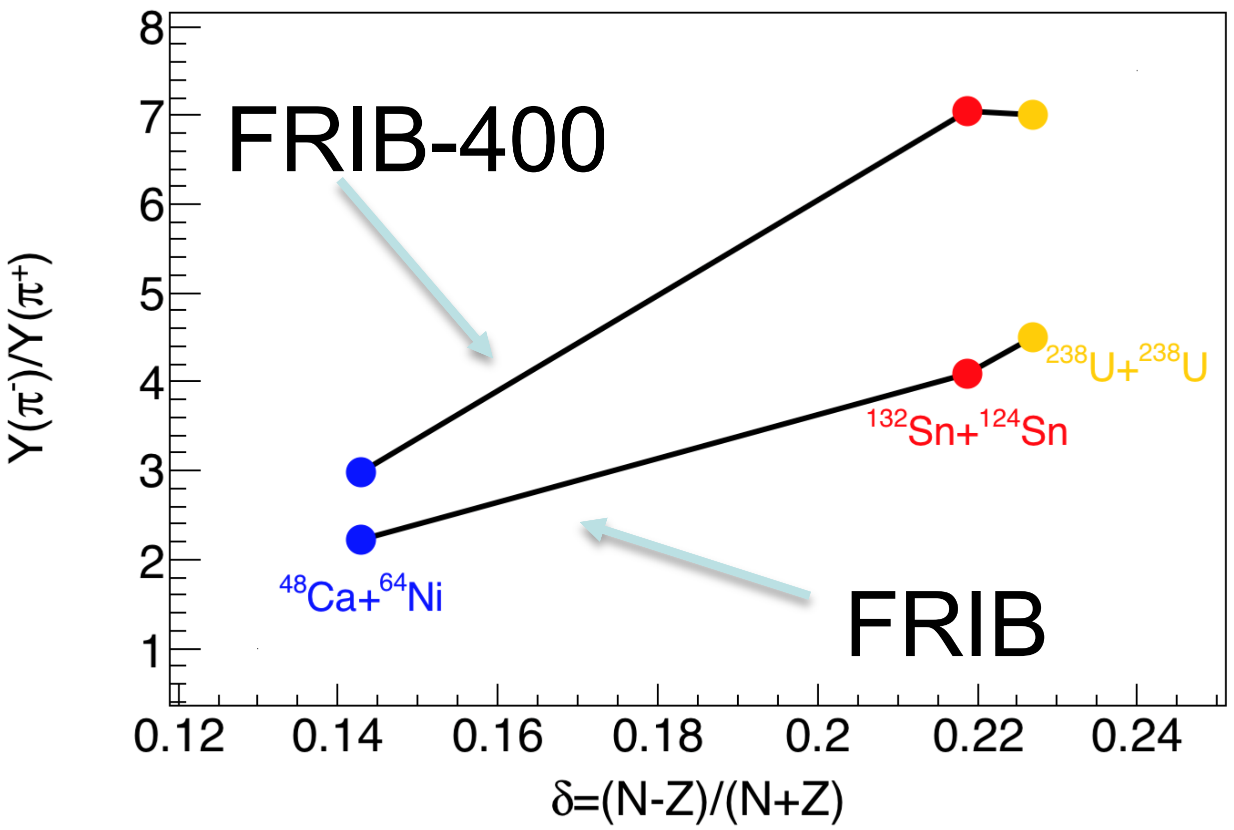
- Demonstrated that the design goal can be met with standard ILC EP. Pursuing R&D on advanced surface treatment such as nitrogen doping (see right)

FRIB Linac Layout with Upgrade Cryomodules



Pions @ FRIB





FRIBU boost intensities, asymmetry and pion cross-sections

Pion rates will go up by the order of magnitude!)

Intensity increase: Allow explorations of more asymmetric systems.

Energy increase: yields increase exponentially above pion thresholds

Regions at $\rho>1.8\rho_0$ become more extensive

Opportunities and challenges for EOS at FRIB

Goal:

Comprehensive nuclear matter EOS from crust to outer core is in sight

EOS at FRIB:

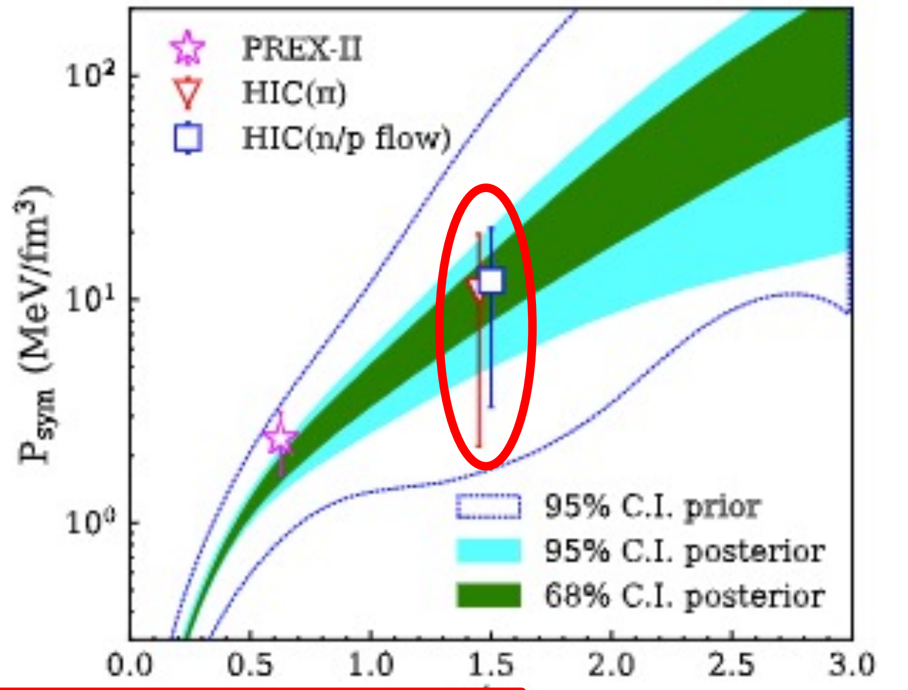
More precision symmetry energy data at 1.5-2.5 ρ_0

Primary observables:

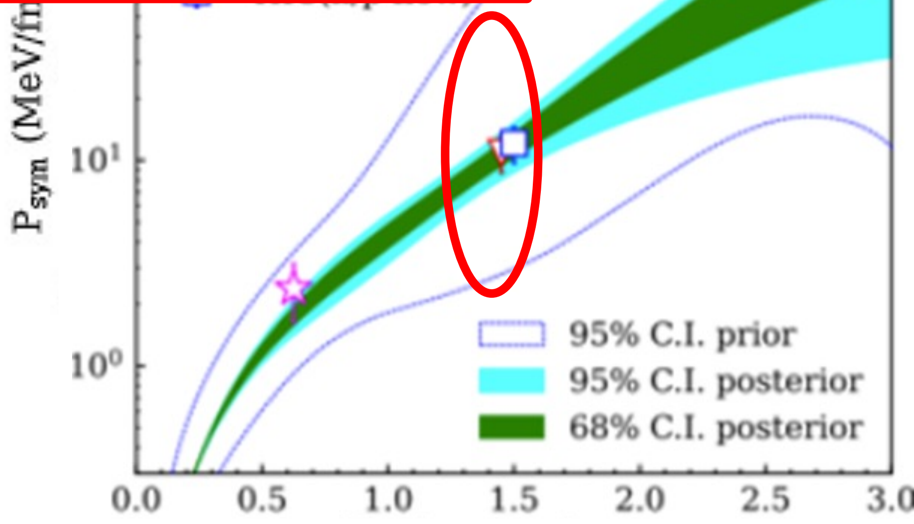
- pion and n/p differential flow→ Symmetry energy
- proton flow → symmetric matter constraints
- Fission → surface symmetry energy

What we need:

Investment in detector development to measure pions, charged particles and neutron with high granularity ➡ Time Projection Chamber for FRIB

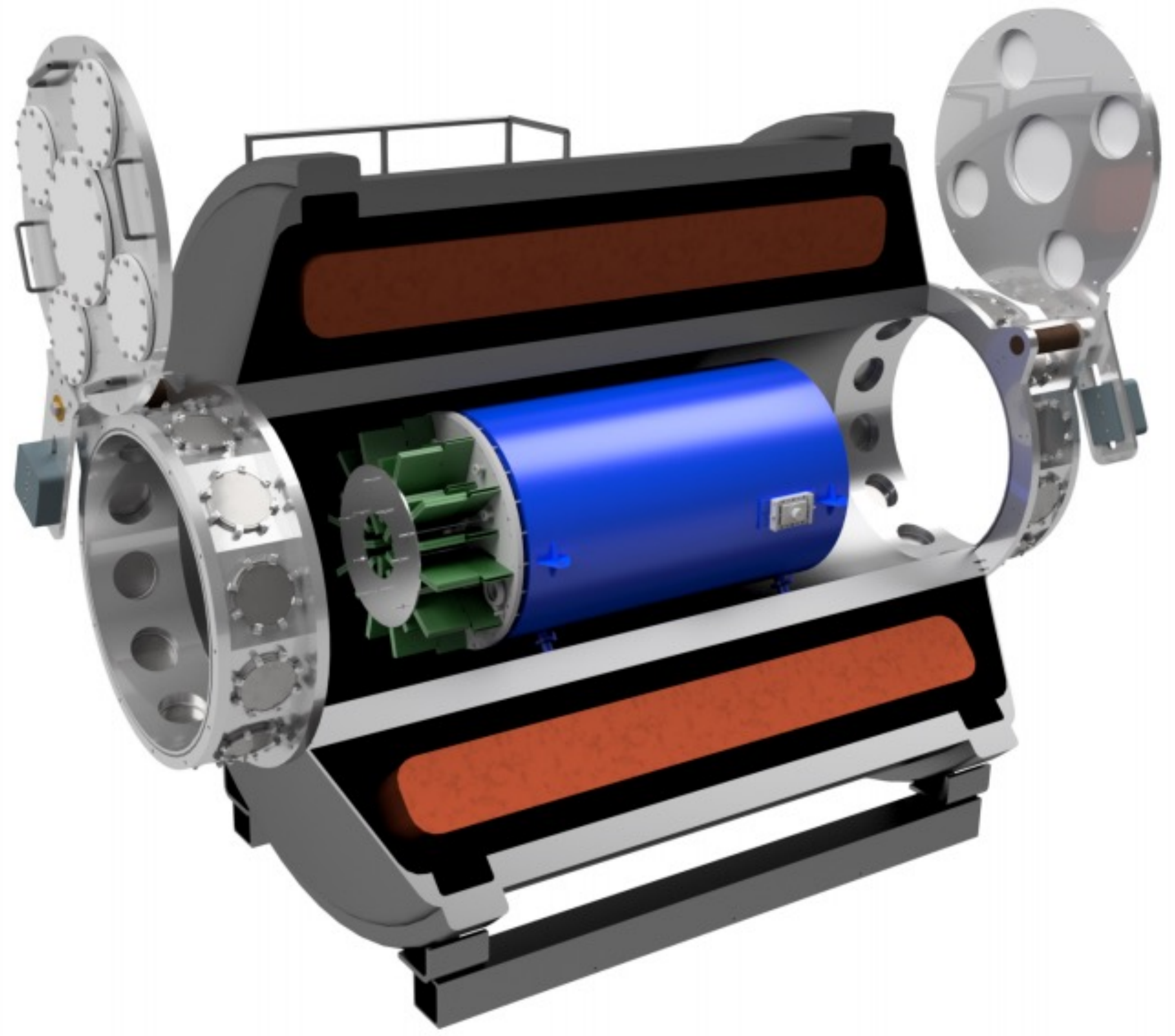


Effect of reducing error bars to 20%



Pions with TPC at FRIB

Option: TPC in SOLARIS (AT-TPC-like)

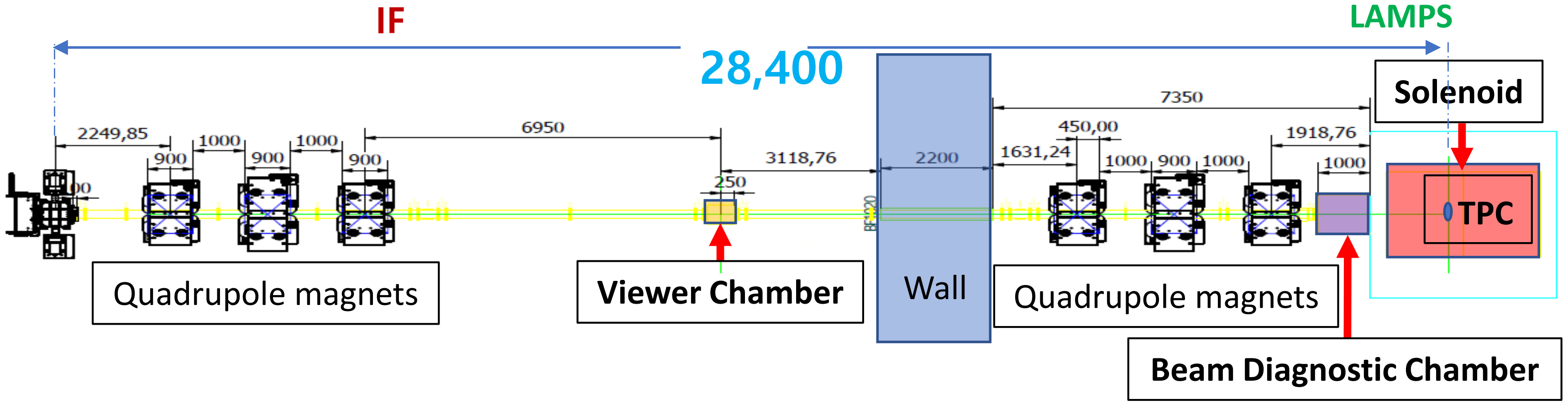


- Requires the fabrication of a new readout pad plane with a higher density of pads in the central region.
- Need to have inner field cage for high ionization in beam region

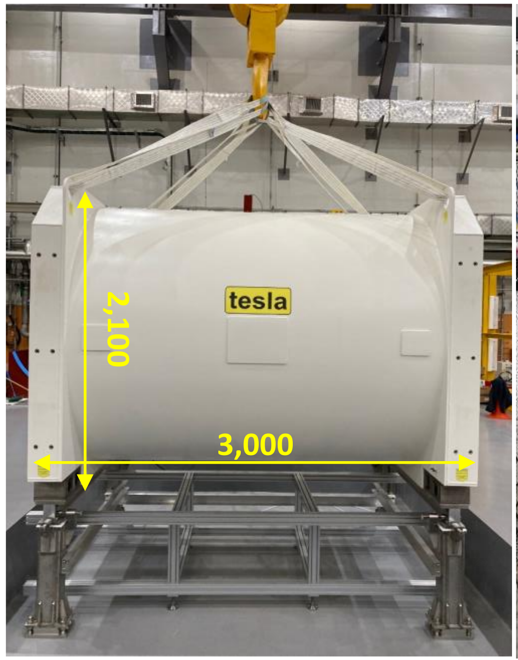
SOLARIS Whitepaper

RAON TPC – option to consider

RAON LAMPS

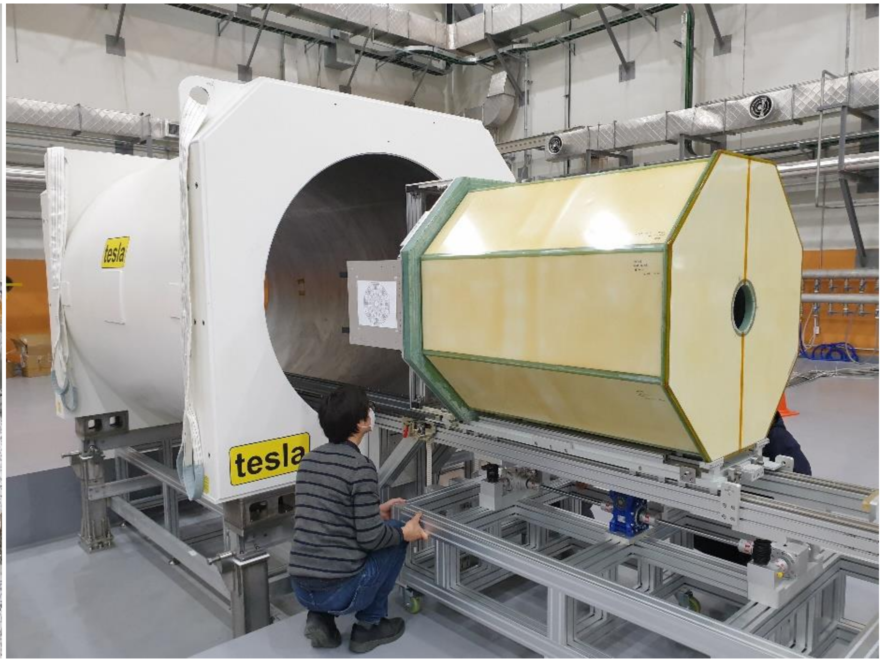


Beamline (Left: IF side, Right: LAMPS side)



SC solenoid magnet (B_{max} = 1 T)

TPC

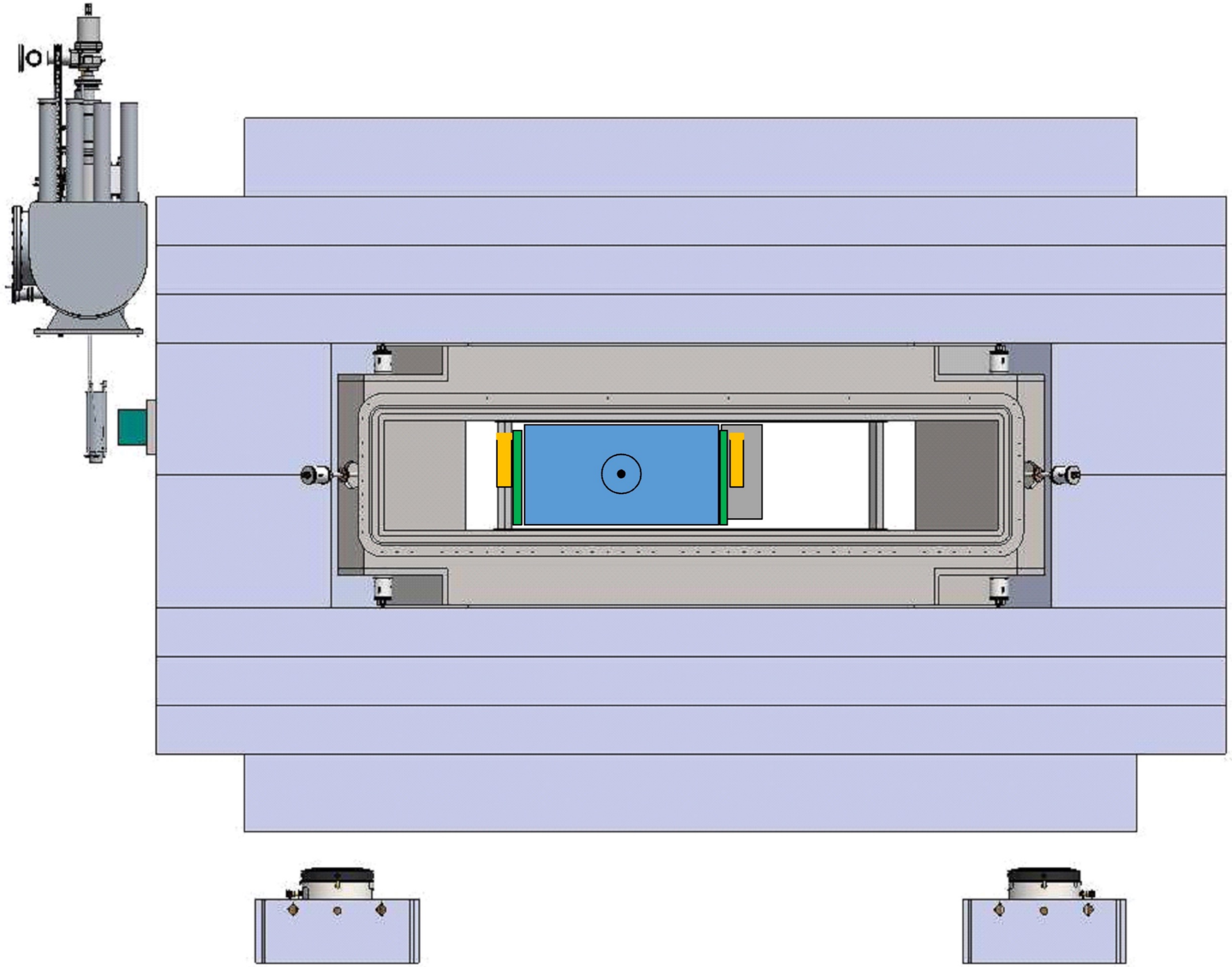


Installation of TPC inside the magnet

Neutron detector array

High Rigidity Spectrometer (HRS)

Future EOS studies with HRS



- The SπRIT TPC could be modified to fit into the High Rigidity Spectrometer or a similar detector could be built with modern improvements
- Needs to fit in 60 cm gap of D1
- This will enable measurements of pion production and elliptical flow
- Can be coupled with neutron walls

Moving forward: FRIB TPC Whitepaper

- **GOAL:** Write scientific cases and technical requirements into a short ~20-25 page whitepaper
  - ~2 pages per science case
  - ~1 page technical requirement per case
    - DAQ, detector geometry, ancillary detectors, targets

- **Timeline:**
  - Science community has been collected and section leaders identified
  - Writing to start soon, with hopes to have mostly final draft by Winter break
  - MRI proposal to FRIB-TPC next year, based on science and technical case

- Contact: S. Hudan & K. Brown (FRIB)

Summary / Take away

- FRIB and FRIB 400 will enable new experimental constraints on the nuclear EOS at high density
- We are taking a staged approach to the experimental efforts on the high-density EoS at FRIB
  - Short term: discrete arrays of detectors for detecting n and LCPs to study particle ratios and flow
  - Mid Term: “AT-TPC”-like device to study sub-threshold pion production near 200 MeV/u
  - Long Term: Either “AT-TPC”-like and/or “SπRIT”-like TPC with the HRS and HRS/FRIB400
- We need further input from transport theory to guide the most efficient use of beam time. **Are there other observables we should rather or also be focused on?**
- Opportunities for research and collaboration at FRIB