Overview of the EOS program at FRIB

Zbigniew Chajęcki

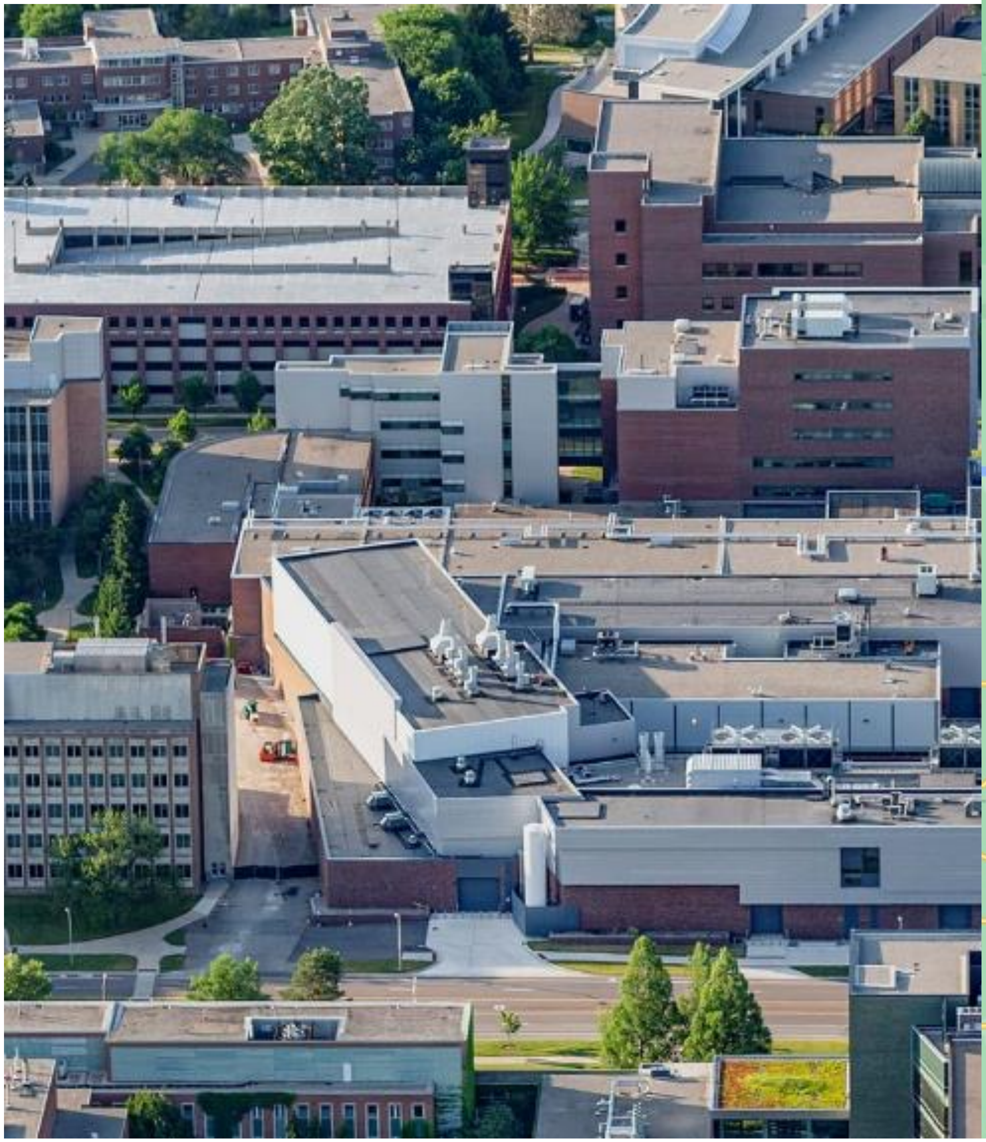
Western Michigan University

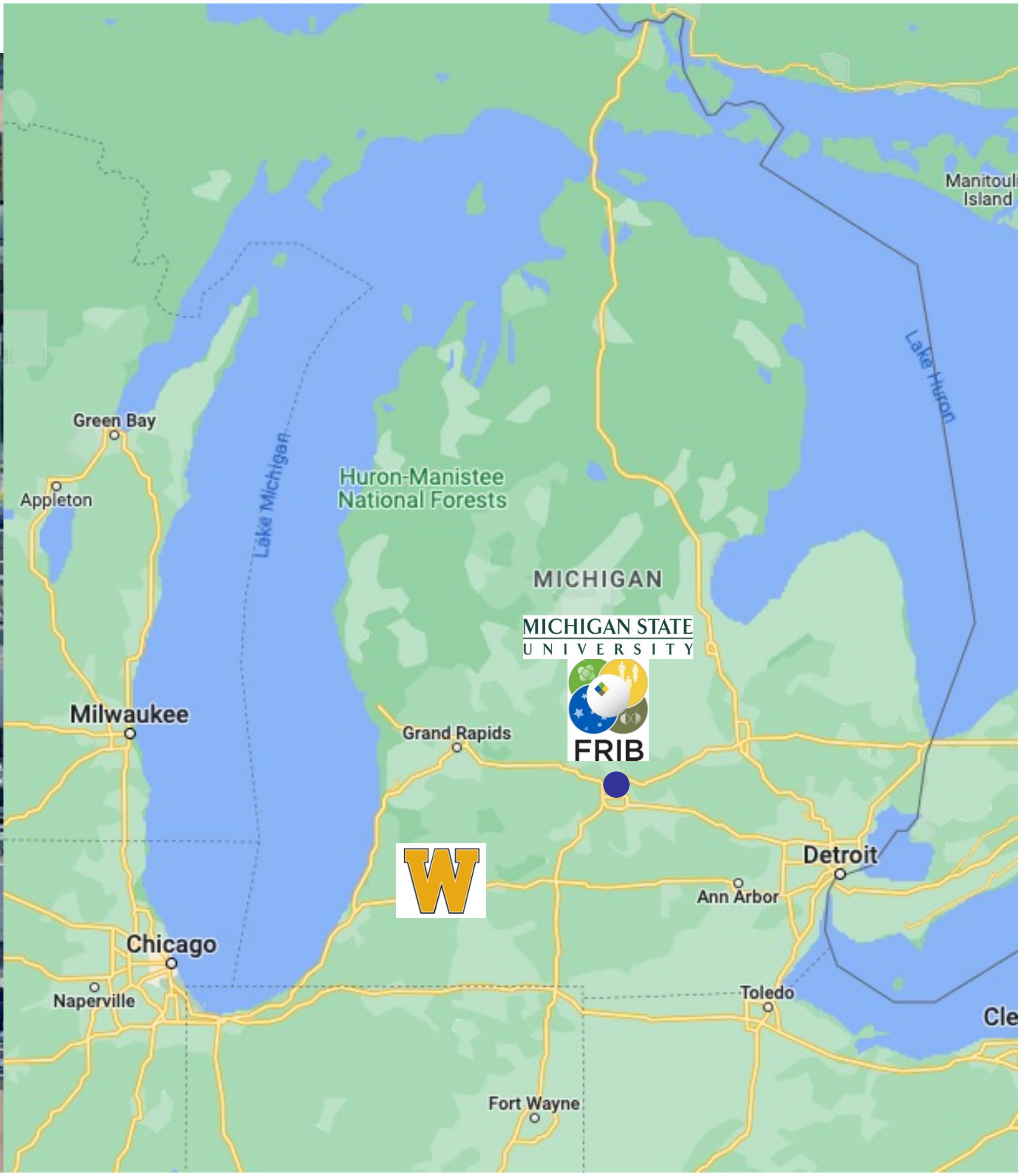
WESTERN MICHIGAN UNIVERSITY

Facility for Rare Isotope Beams

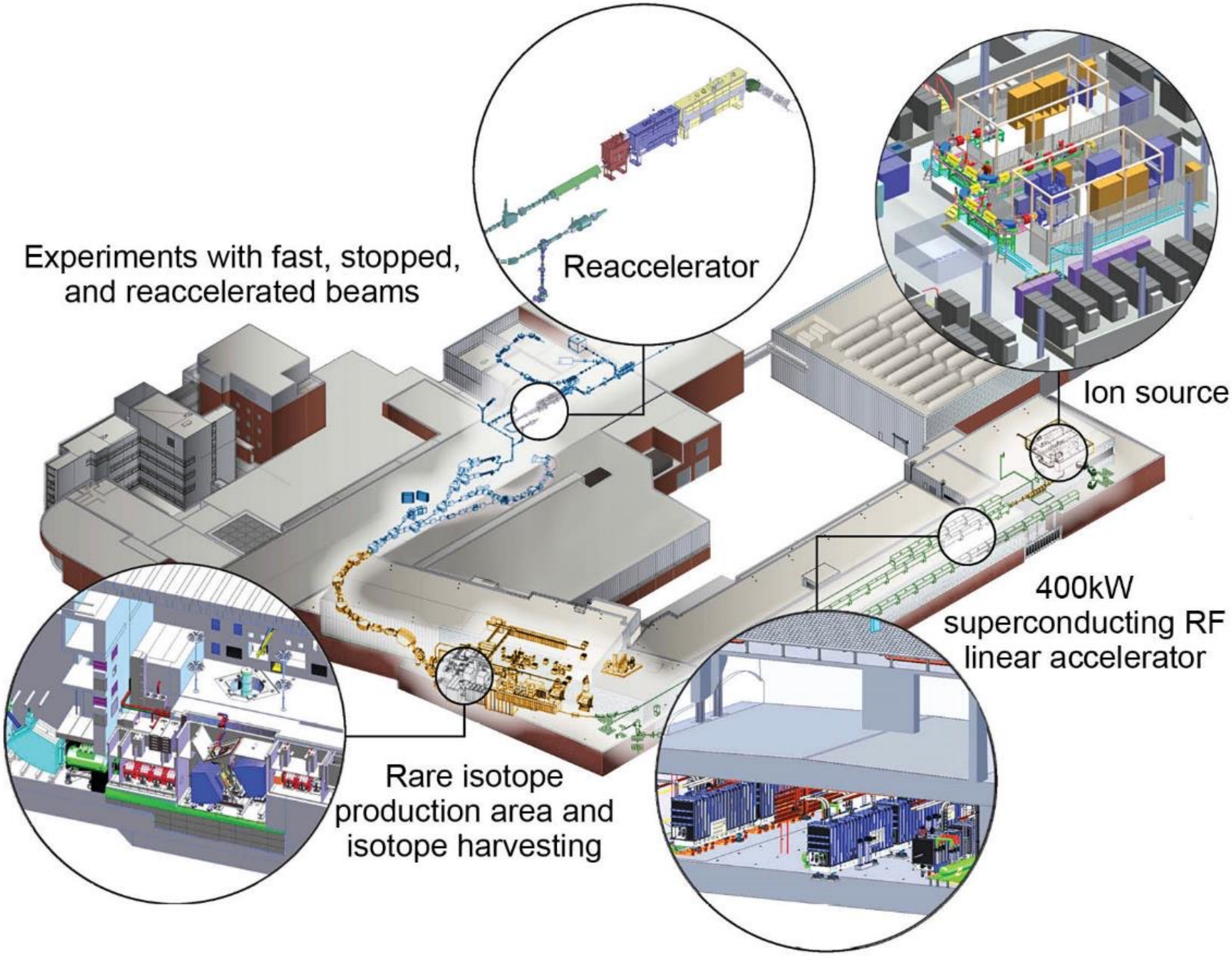
- FRIB is a $730 million scientific user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB Project started in 2008, concluded on budget and ahead of schedule in January 2022, ribbon cutting and first experiments started in May 2022
- FRIB is a DOE-SC user facility for world-unique rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC
- Rare isotopes are combinations of protons and neutrons that do not naturally exist on earth – they are made in stars and FRIB can make them until they decay
- FRIB enables scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society

FRIB Site

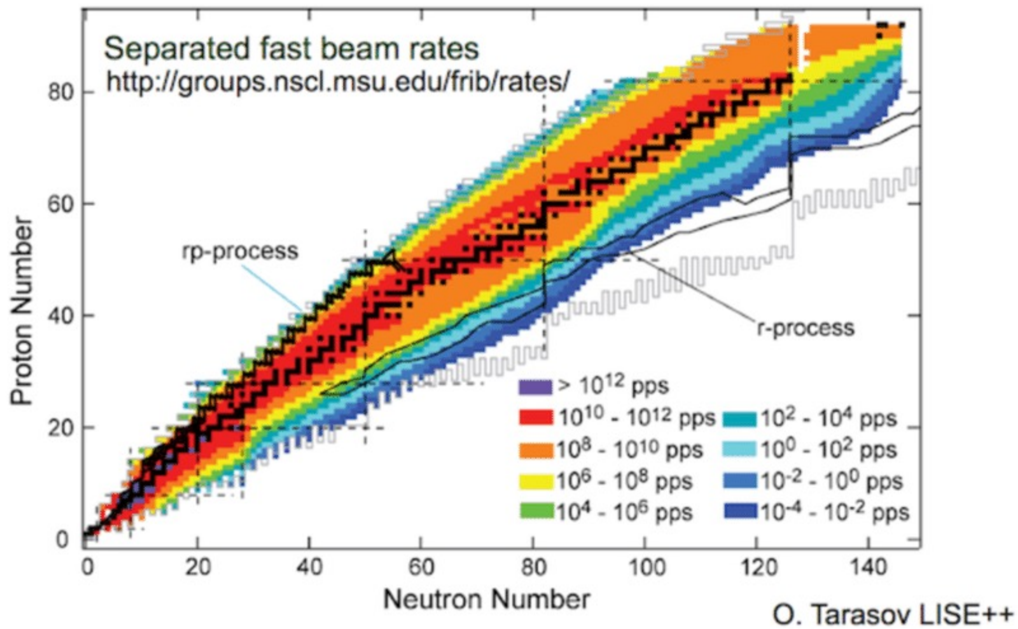



Green Bay
Appleton
Lake Michigan
Huron-Manistee
National Forests
MICHIGAN
MICHIGAN STATE
UNIVERSITY
FRIB
Milwaukee
Grand Rapids
Detroit
Ann Arbor
Chicago
Naperville
Toledo
Fort Wayne
Lake Huron
Manitoulin Island

Optimized for Science with Fast, Stopped and Reaccelerated Rare Isotope Beams



Available beams (for PAC2)



Projected secondary beam intensities at FRIB with full power estimated with the program LISE++.

https://frib.msu.edu/users/beams/index.html

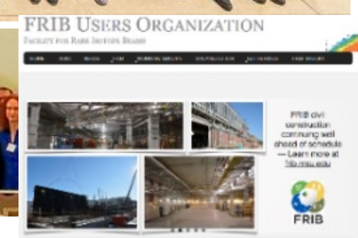
FRIB PRIMARY BEAMS

Element	Z	A	Maximum energy (MeV/u)	Maximum power (kW)
O	8	16	288	10
O	8	18	253	10
Ne	10	22	258	10
Ar	18	36	288	10
Ca	20	48	238	10
Ni*	28	58	263	10
Ni*	28	64	241	10
Zn*	30	70	238	10
Kr	36	78	256	10
Se	34	82	230	10
Kr	36	86	231	10
Mo	42	92	248	10
Xe	54	124	227	10
Pt*	78	198	186	5
Pb*	82	208	185	5
U	92	238	180	5

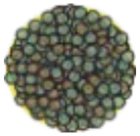
1,800 Users Engaged and Ready for Science

fribusers.org

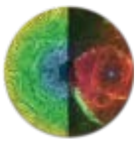
- Users organized as part of independent FRIB Users Organization (FRIBUO)
  - Chartered organization with an elected executive committee
  - 1,800 members (125 U.S. colleges and universities, 12 national laboratories, 51 countries) as of 31 January 2023
  - 22 working groups on instruments
- First experiments have begun
  - February 2021: 82 proposals received representing 597 scientists
  - August 2021: FRIB Program Advisory Committee (PAC1)
  - May 2022: First user experiments
  - January 2023: 84 proposals received representing 611 scientists
  - March 2023: FRIB Program Advisory Committee (PAC2)
- 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



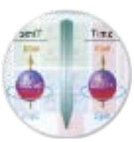
FRIB Enables Scientists to Make Discoveries Science Aligned with National Priorities



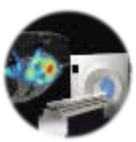
- Properties of atomic nuclei
  - Develop a predictive model of nuclei and their interactions
  - Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



- Astrophysics: What happens inside stars?
  - Origin of the elements in the cosmos
  - Explosive environments: novae, supernovae, X-ray bursts…
  - Properties of neutron stars



- Tests of laws of nature
  - Effects of symmetry violations are amplified in certain nuclei



- Societal applications and benefits
  - Medicine, energy, material sciences, national security

Science is aligned with national priorities articulated by

- Nuclear Science Advisory Committee to DOE and NSF *Long Range Plan for Nuclear Science* (2015)
- National Research Council *Decadal Survey of Nuclear Physics* (2012)
- National Research Council *Rare Isotope Science Assessment* report (2006)

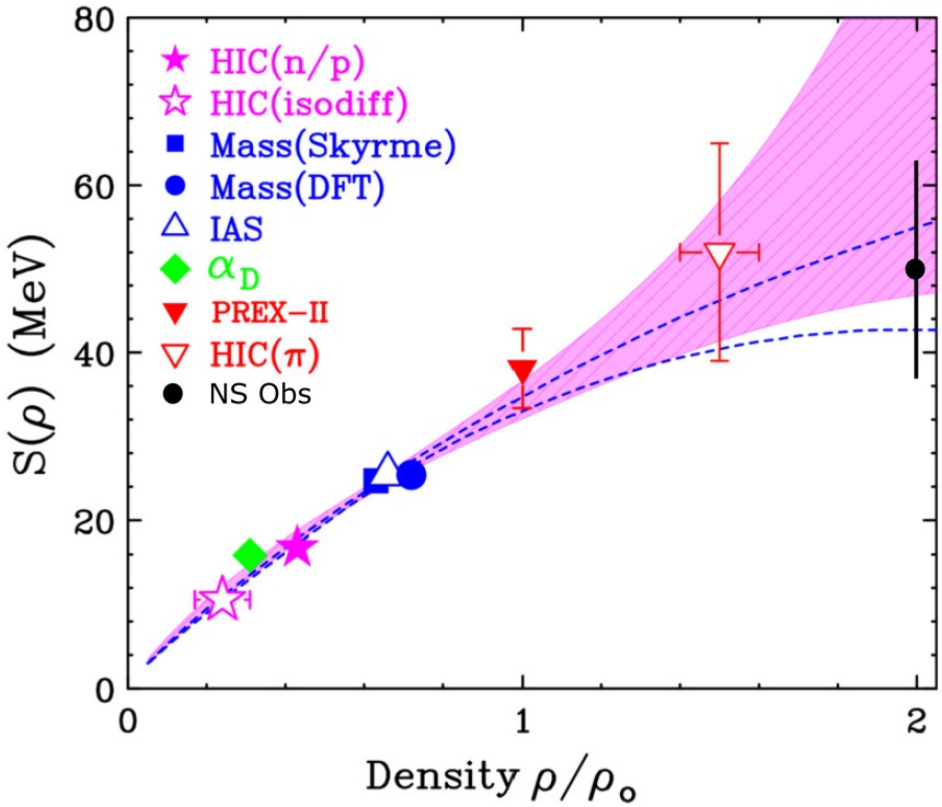
Opportunities articulated in

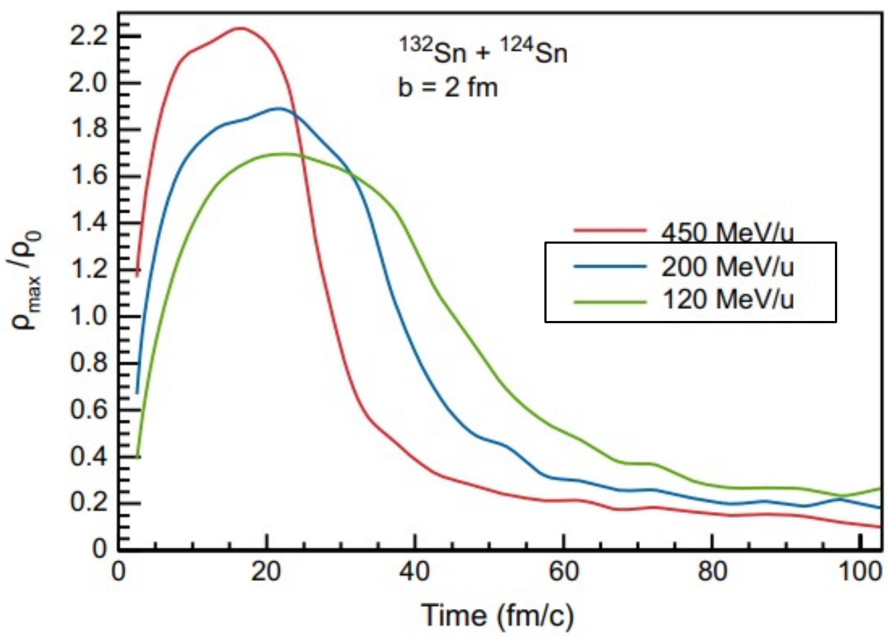
- Nuclear Science Advisory Committee SC *2015 Long Range Plan for the DOE-NP Isotope Program*

EoS Studies at FRIB

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

Lynch, Tsang, PLB 830, 137098 (2022)





FRIB Upgrade Whitepaper

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

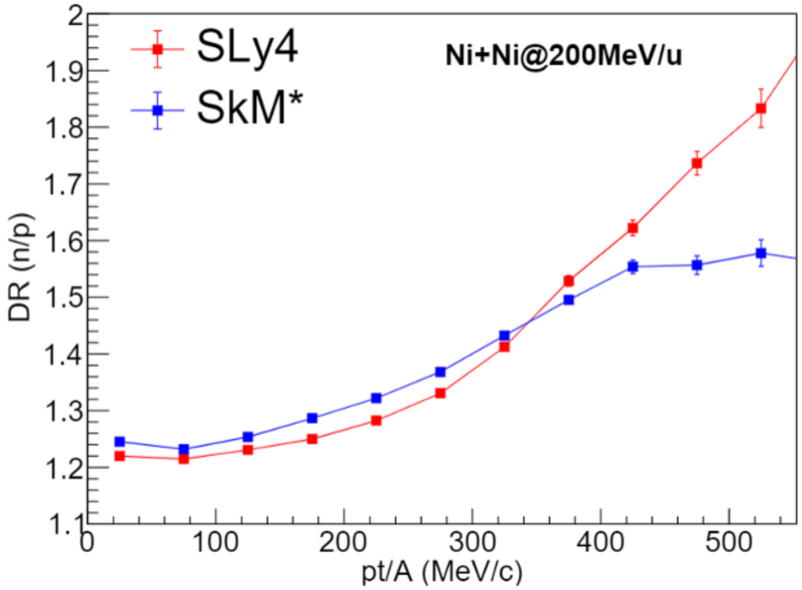
Main goals of the experiment are to measure

- 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:

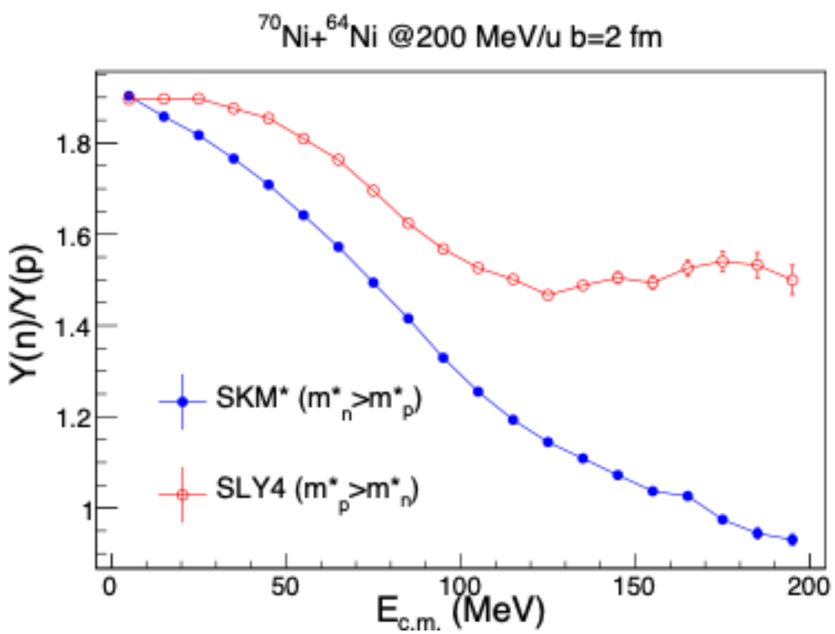
MSU: K. Brown, W. Lynch, B. Tsang
WMU: Z. Chajecki
INFN: G. Verde, D. Dellaquila, I. Lombardo
IN2P3: A. Chbihi, D. Gruyer, Q. Fable, C. Ciampi, F. Quentin, J.-E. Ducret
Texas A&M: K. Hagel, A. Mcintosh

n/p ratios

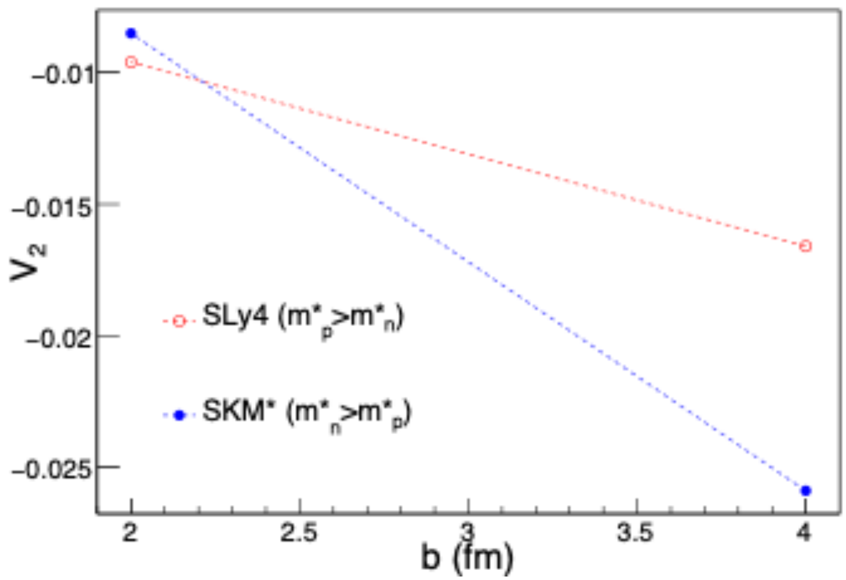


$^{56,70}Ni+^{58,64}Ni$ @ 175 MeV/u

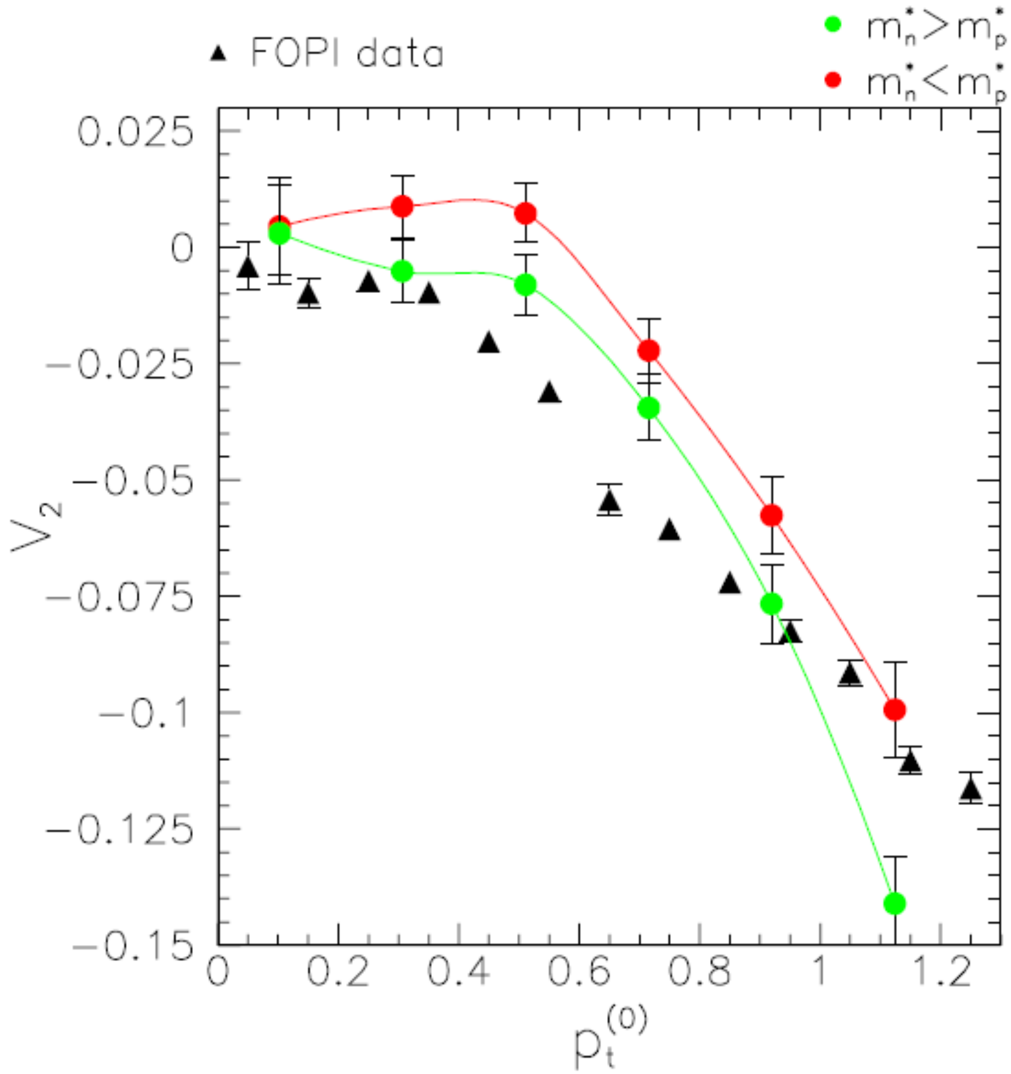
The spectral ratios will be used to obtain a constraint on isospin dependence of the nucleon effective masses.



Elliptic flow



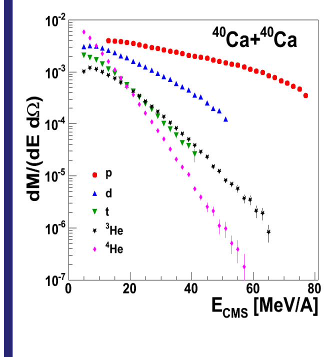
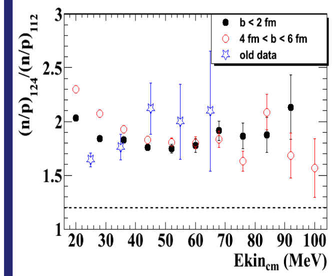
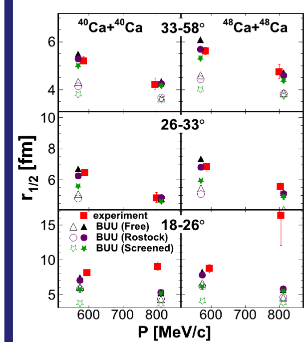
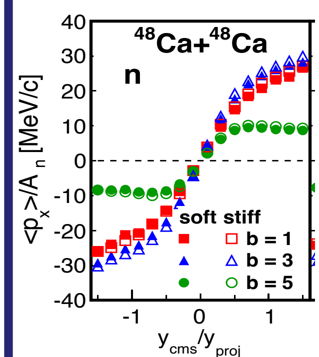
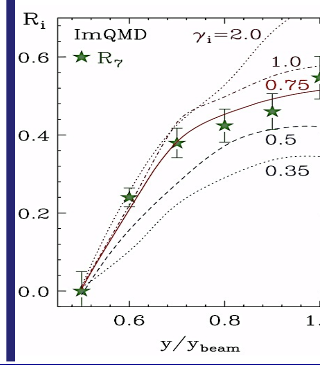
Elliptic flow in ^{197}Au +^{197}Au collisions at 250 MeV/u as a function of p_t



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

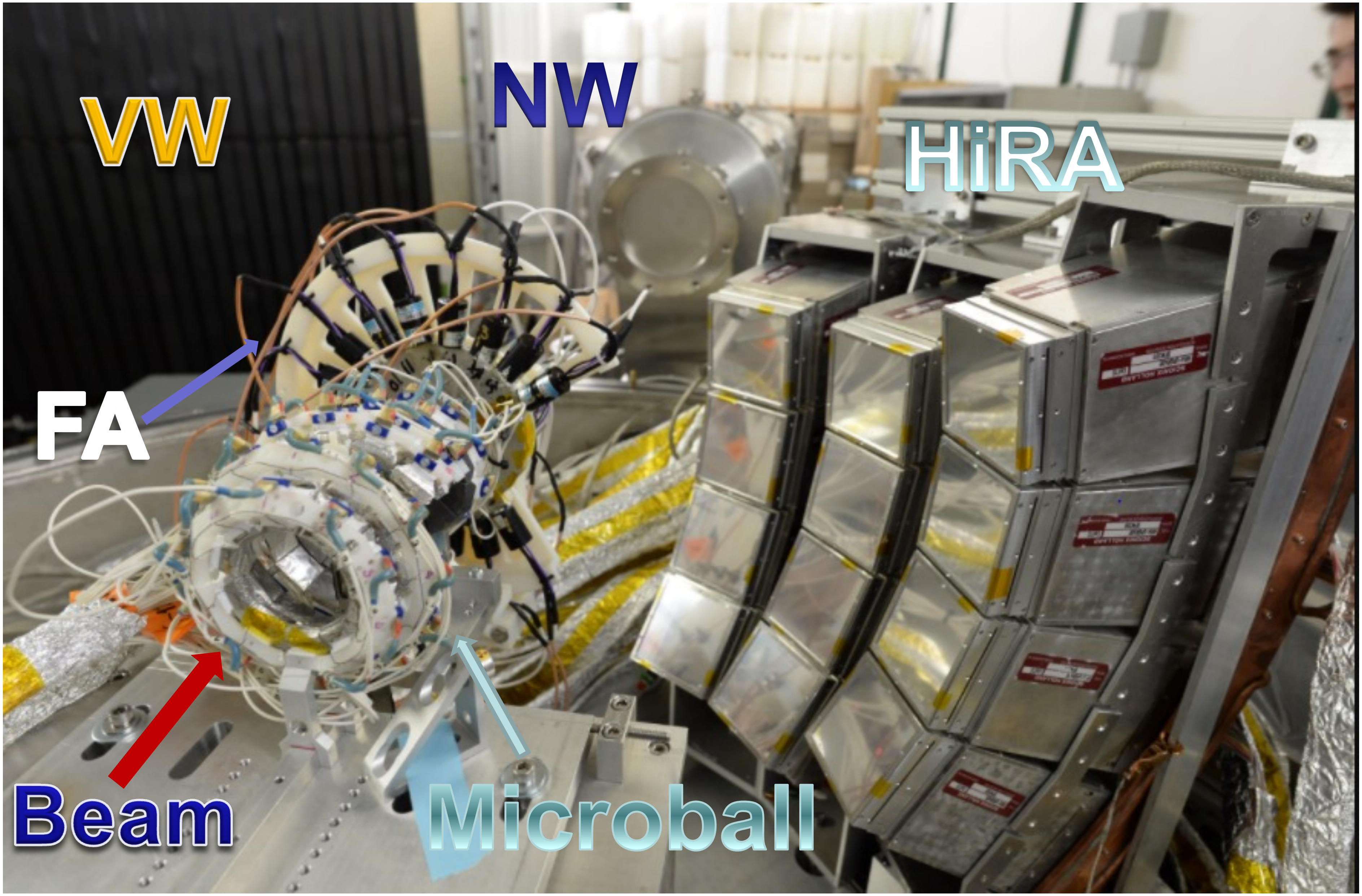
What we hope to learn from HIC collisions?

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

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

Our experiment

Our (previous) Experimental setup

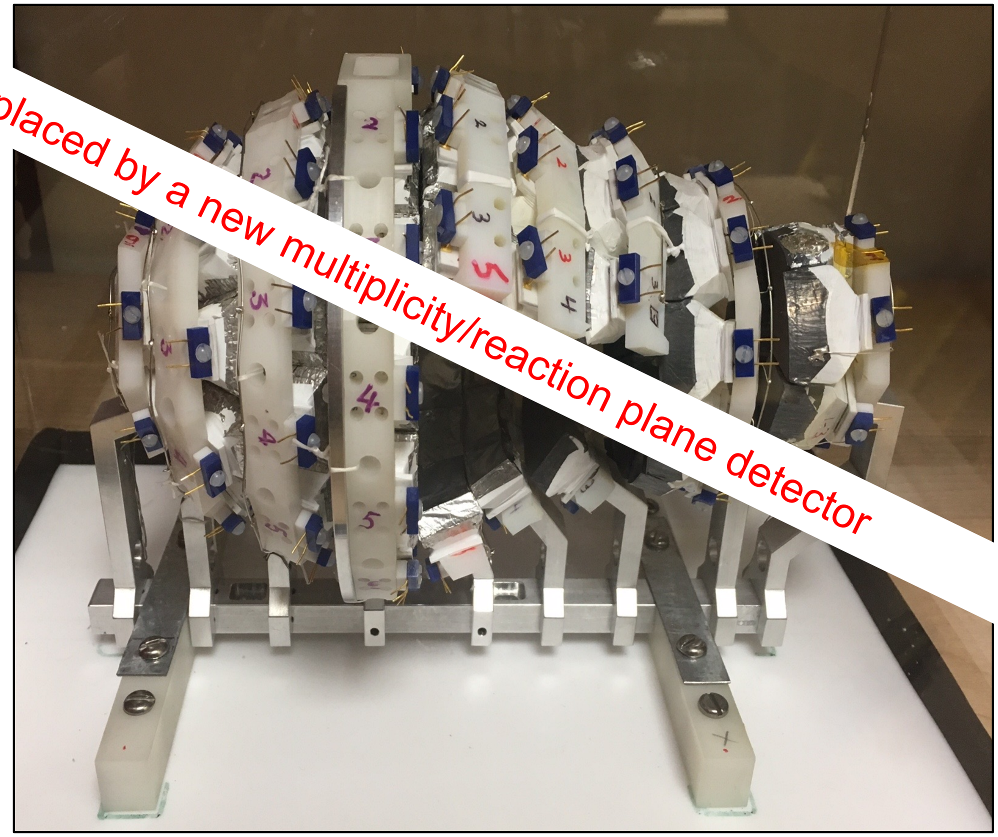


Experiment: Charged particle detection

Upgraded HiRA10

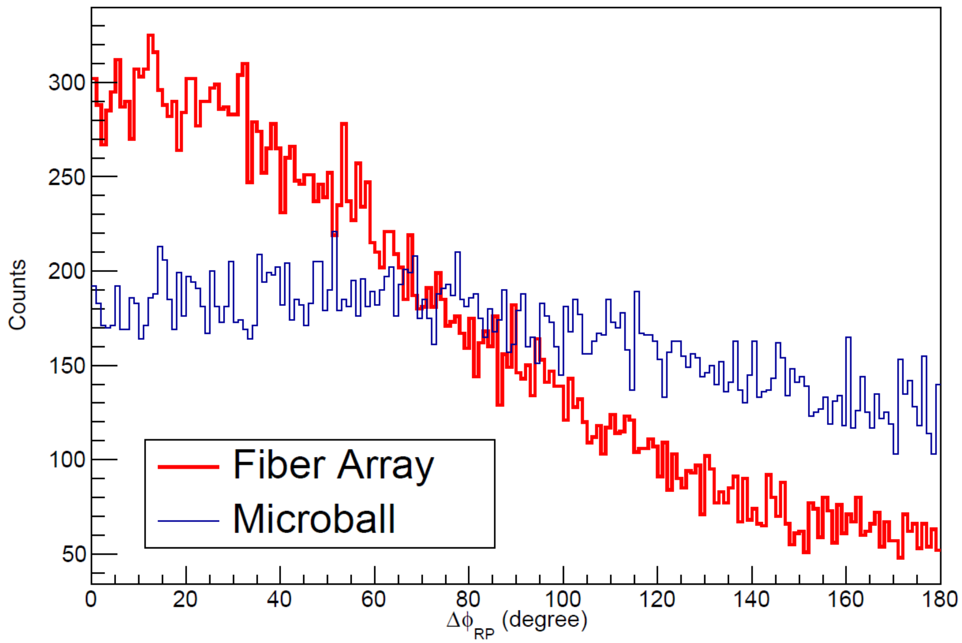
- 12 Silicon-CsI(Tl) telescopes
- Each telescope has 4, 10-cm CsI(Tl) crystals and a 1.5mm thick DSSD with 32 strips on each side
- At ~50 degrees off the beam axis, covers ~30 to ~70 degrees

Microball

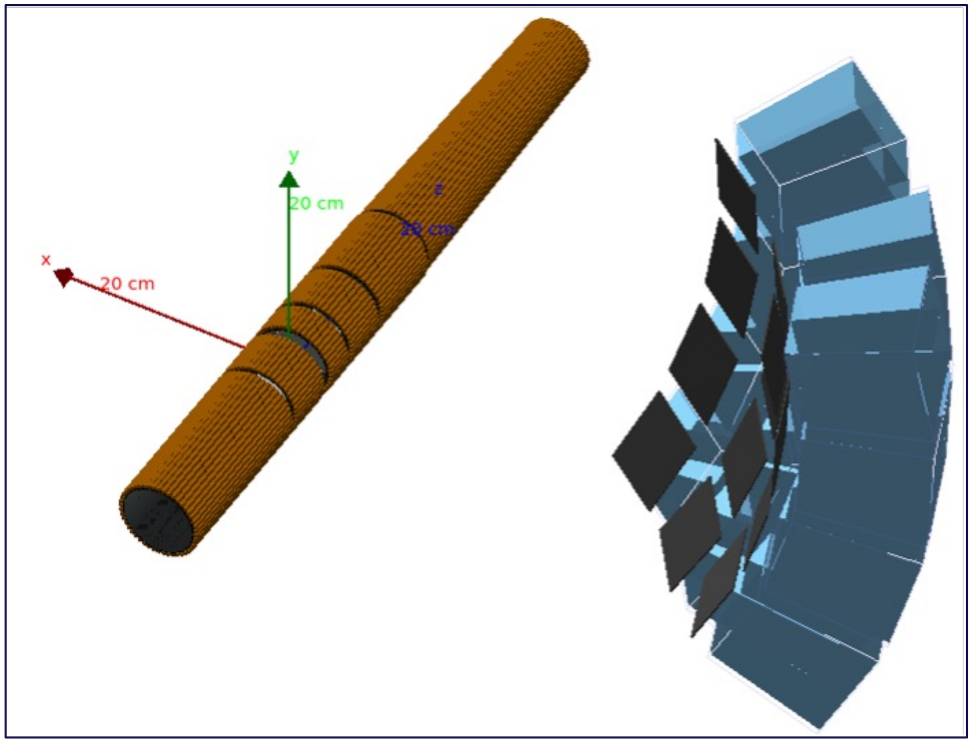


- Rings of CsI Crystals
- Used as a Multiplicity trigger
- Used for impact parameter determination
- The hole is for HiRA detector

Experiment: Charged particle detection



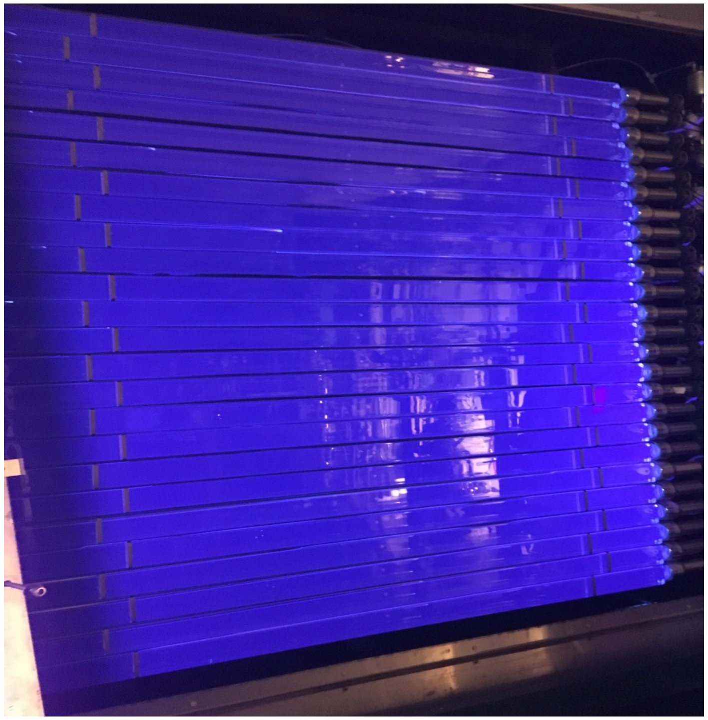
Fiber Array



- No need to remove a section of the detector that overlaps with the HiRA Si Array due to minimal energy loss in the FA material
- Complete azimuthal coverage will allow reaction plane determination

Neutron Detection

Neutron Walls

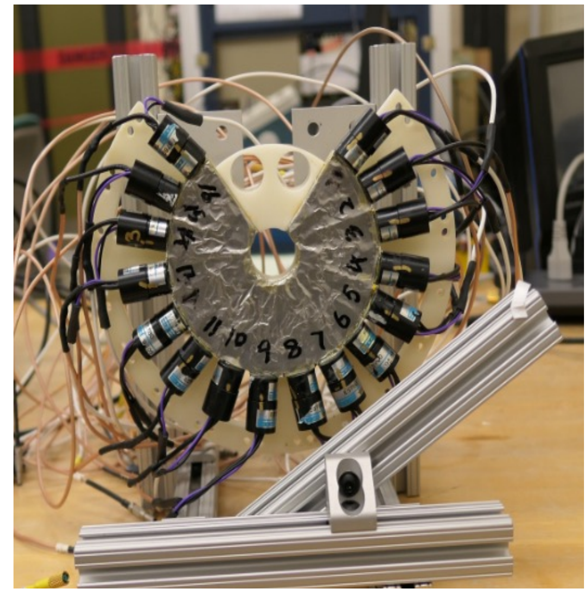


UPGRADED
Use EJ-309 liquid scintillator for Pulse Shape Discrimination

Proton Veto Wall

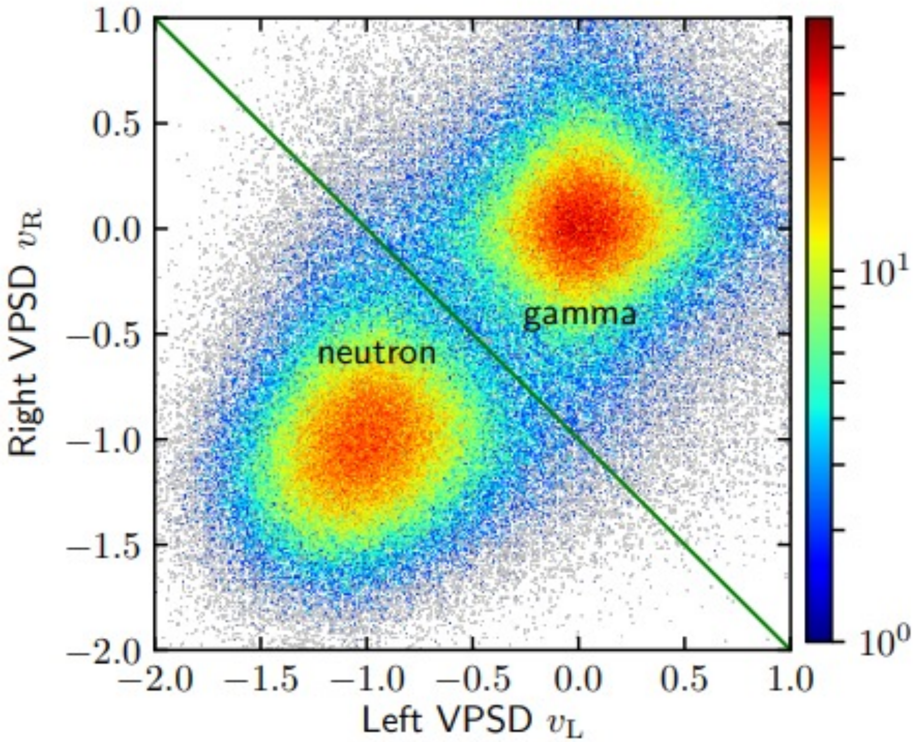
- Made at WMU
- 25 Plastic Scintillator bars
- Used to remove charged particles from the NW Spectra

Forward array



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

Large Area Neutron Array (LANA)



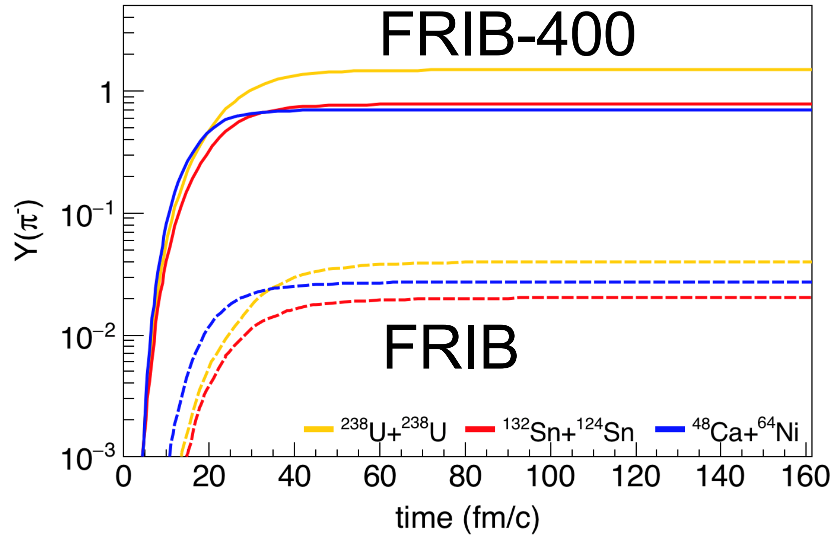
- LANA is comprised of:
  - Two Walls of 25 scintillator bars
    - 2 meters long, 7.7 cm square cross-section
    - NE-213 liquid scintillator → Being replaced with EJ-309 (No more xylene!)
- ~8 cm position resolution
- 500 ps time resolution
- ~10% detection efficiency
- Excellent Neutron/Gamma discrimination

F. C. E. Teh *et al.*, *IEEE Transactions on Nuclear Science* 68 vol 8, 2294 (2021)

EoS: pion production at high densities

Advantages:

- 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.**



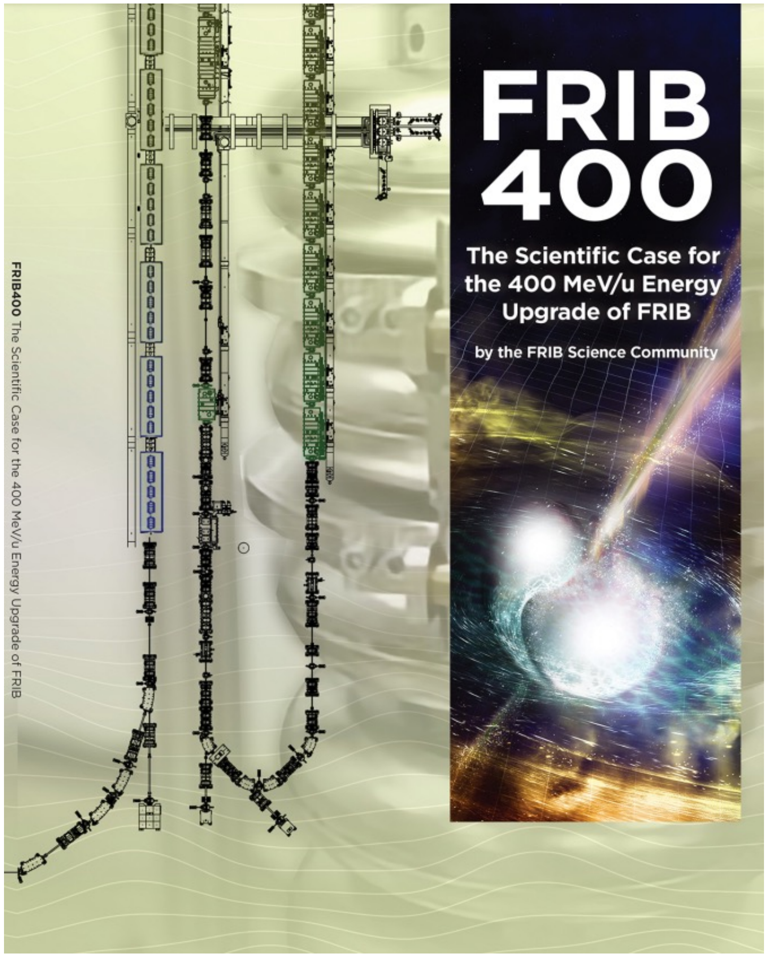
FRIB400 Upgrade

Three main motivations for FRIB 400 (from whitepaper)

- **Charge exchange**
- **Neutron stars- Equation of state (EOS) physics**
- Quasi-free scattering

EOS physics is essential for FRIB 400

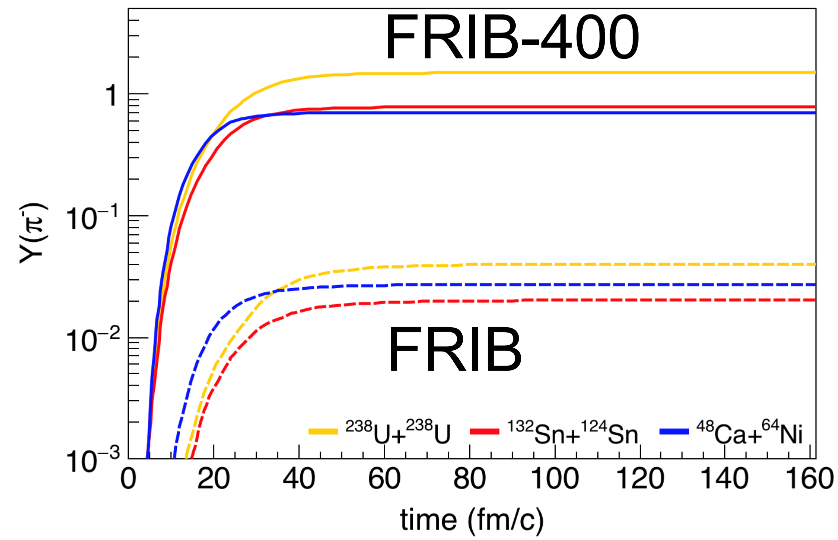
Pion rates will go up by the order of magnitude



EoS: pion production at high densities

Advantages:

- 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.**

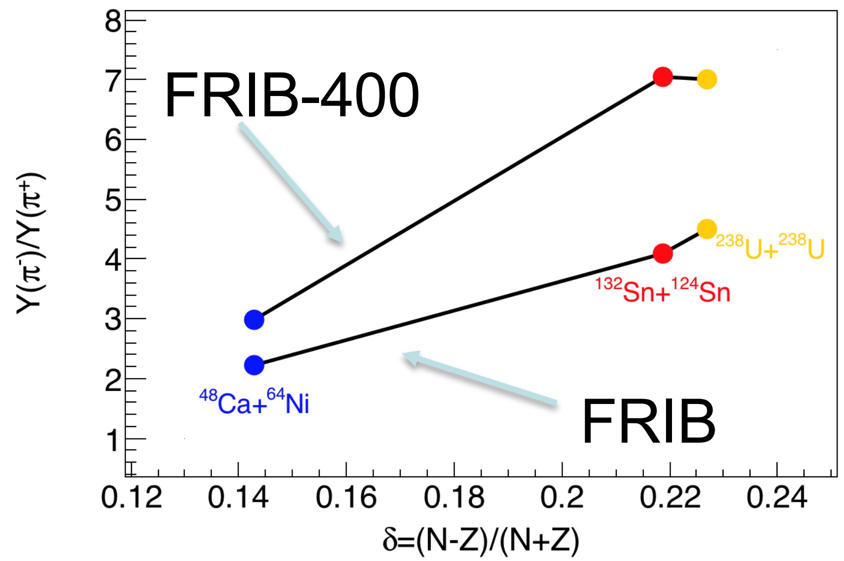


FRIB400 will boost intensities, asymmetry and pion cross-sections

Intensity increase: Allow explorations of more asymmetric systems.

Energy increase: yields increase exponentially above pion thresholds

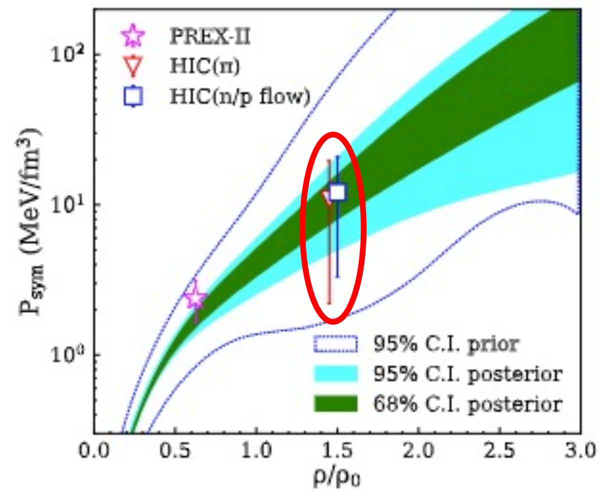
Regions at $\rho>1.8\rho_0$ become more extensive



Opportunities and challenges for EOS at FRIB

Goal:

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

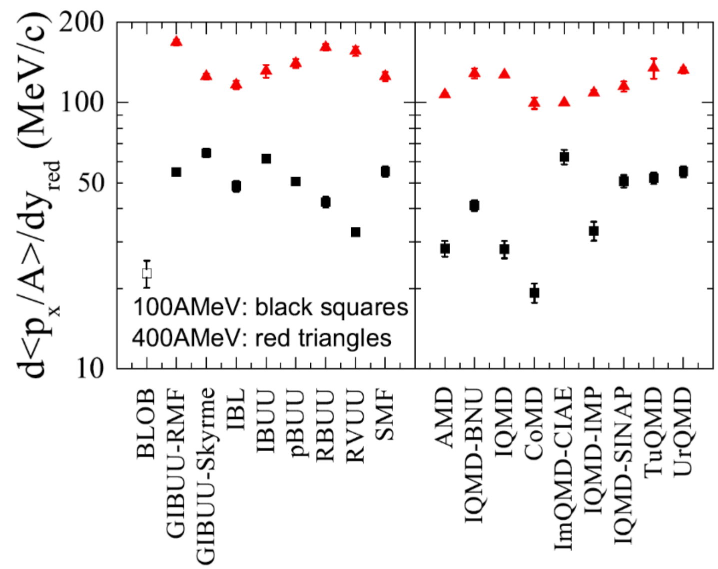


EOS at FRIB:

More precision symmetry energy data at 1.5-2.5 ρ_0

Primary observables:

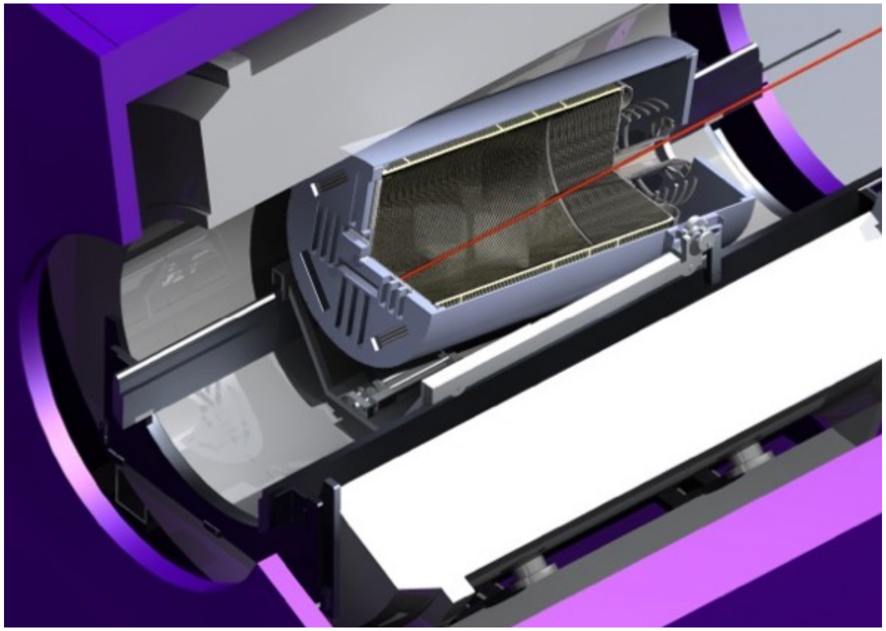
- pion and n/p differential flow→ Symmetry energy
- proton flow→ symmetric matter constraints



What we need:

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

Requirements for TPC at FRIB

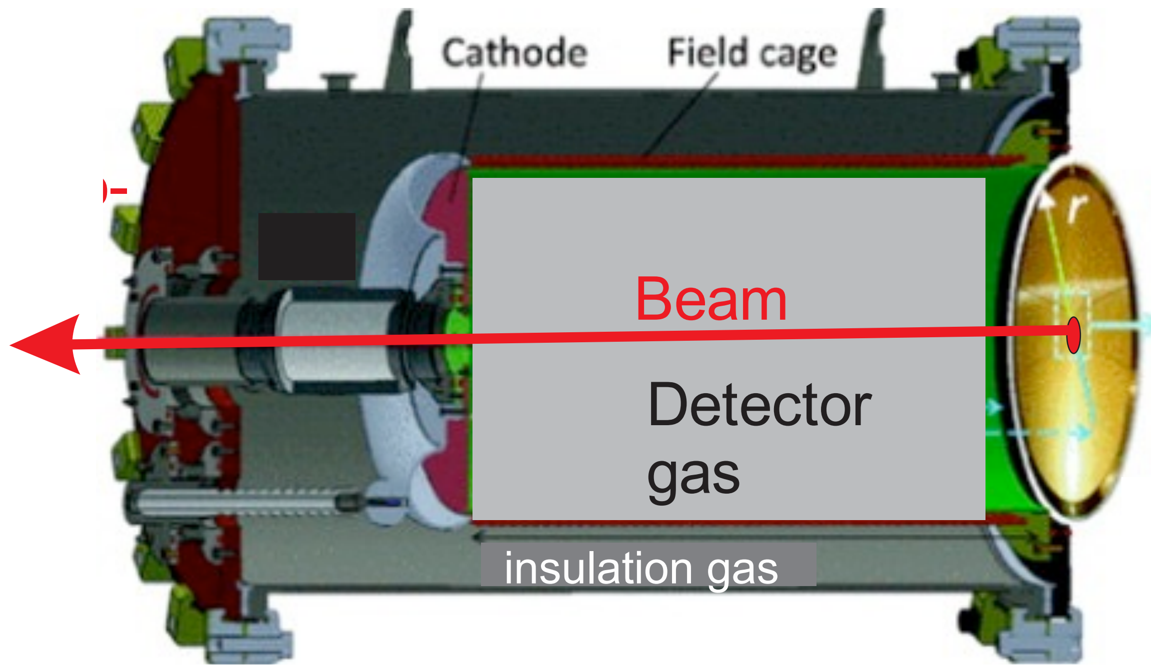


- Placed inside the solenoid magnet
  Improves tracking and PID
- good resolution at low-energy
- thick target
- 4π acceptance of reaction products
  (improves reaction plane determination)
- Minimize the particle energy loss
- Good vertex resolution
- Multitrack event reconstruction
  (including close track separation: track merging, track splitting)
- **Possibility of using auxiliary detectors (neutron wall, detectors for heavier fragments)**
- **"removal" of δ-electrons**
- Avoid saturation of the electronics when beam enters the active volume
- Run detector in both Active Target and solid target mode

*Primarily based on design of **AT-TPC detector at NSCL***

(Why) do we need AT-TPC?

- ❖ The early conceptual design of AT-TPC suggested it could function as an active target for both low energy reaccelerated beams and for fast fragmentation beams.
- ❖ The actual AT-TPC solenoid, however, requires it to be housed in a massive iron magnetic shield, which is not portable and too large to be installed e.g. in the S800 beam line or s2 vault.
- ❖ An Optimized AT-TPC for fast beam experiments leads to different design decisions than the current AT-TPC.



The detector would consist of a gas filled volume at pressures ranging from 0.2 to 1 atm contained within a stainless-steel cylinder with a length of 120 cm and radius of 35 cm.

AT-TPC with fast beams

Two modes of operation

the active target mode	Detector mode
- High efficiency - Low thresholds **Fission** **Charge exchange** **Giant resonances**	- Detection of products created in collisions between isospin asymmetric heavy ions - Detector can handle high intensity beams - **Equation of state of nuclear matter** (density dependence of the symmetry energy)

Scientific program

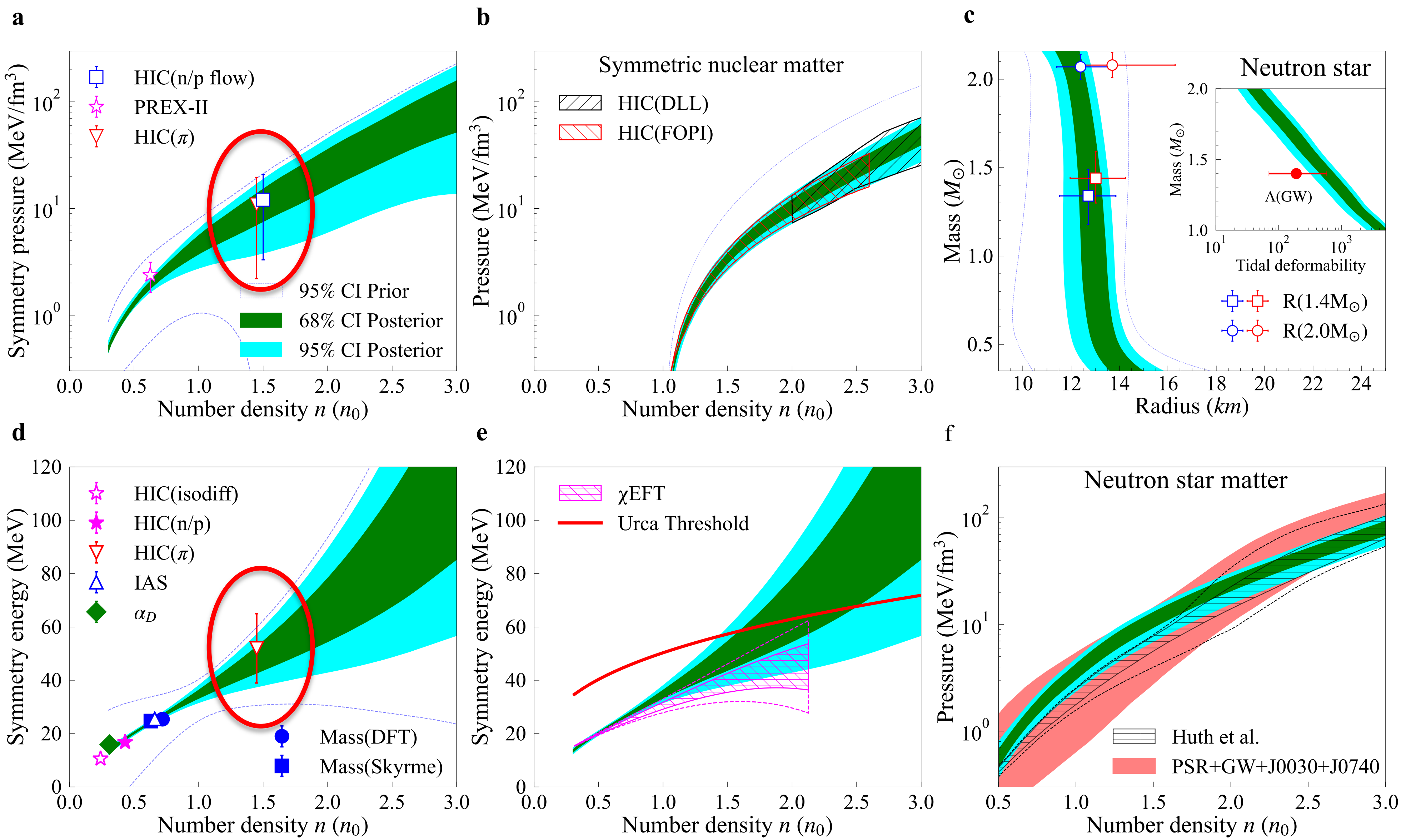
Measurement	Physics	Beam Examples
charge exchange reactions (d,2p)	Electron capture rates in Supernovae	^{52}Ca, ^{68}Ni, ^{74}Zn, ^{94}Sr, ^{120}Cd
Fission Barriers	Nuclear Structure	^{199}Tl, ^{192}Pt
Giant Resonances	Nuclear EOS, Nuclear Structure.	^{56}Ni-^{70}Ni, ^{108}Sn-^{132}Sn
Heavy Ion Reactions	EoS of neutron – rich matter	^{108}Sn-^{132}Sn

Summary

- ❖ FRIB and FRIB 400 will enable new experimental constraints on the nuclear EOS at high density
  - ❖ The first EOS experiment at FRIB is approved
- ❖ An optimized and portable Active Target detector is essential to accommodate a broad experimental program and the coupling to a wide range of equipment the science requires
  - ❖ Essential at FRIB 400 to measure pions
  - ❖ Another TPC for HRS is also being discussed
- ❖ Opportunities for research and collaboration at FRIB

….

Current constraints on EOS



W.G. Lynch and M.B. Tsang, PLB 830 137098, 2022