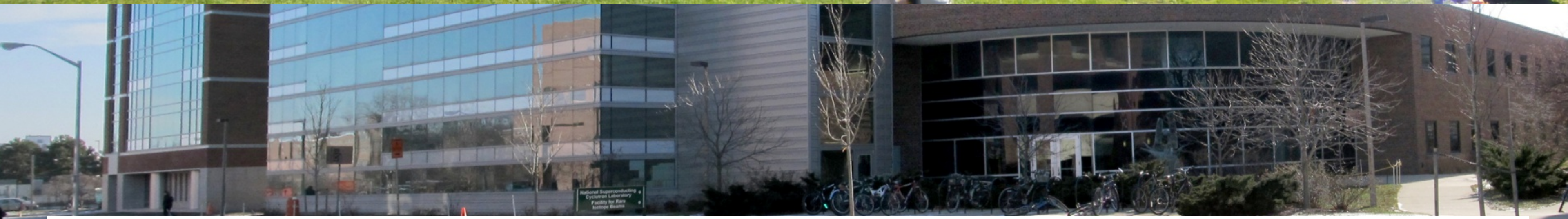
The National Superconducting Cyclotron Laboratory

Michigan State University



Symmetry Energy Project: To bring heavens down to earth


USA
State and Capital
N
CANADA
New York City
Chicago
San Francisco
Los Angeles
PACIFIC OCEAN
MEXICO
CANADA
Pacific Ocean
Pacific Ocean

NSCL

Michigan State University

Nuclear Physics: To bring heavens down to earth

Person

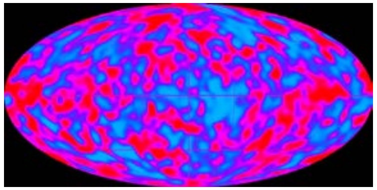
Earth

Solar system

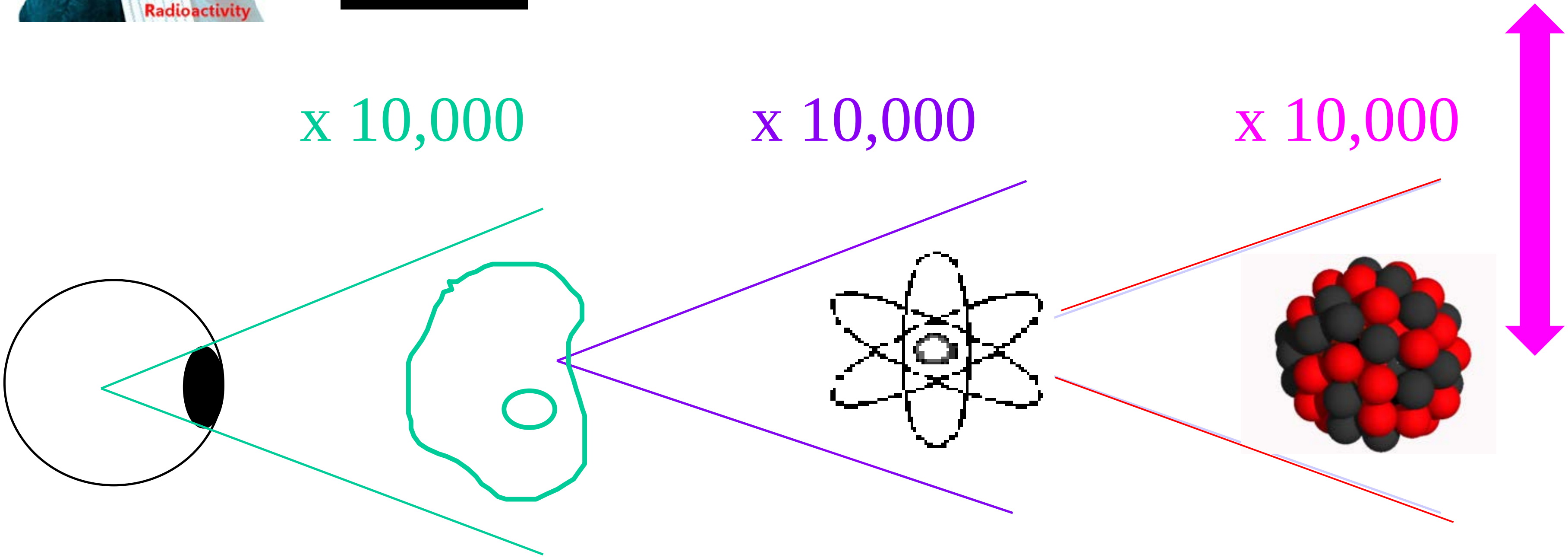
~ x 1,000,000

Milky way

Universe

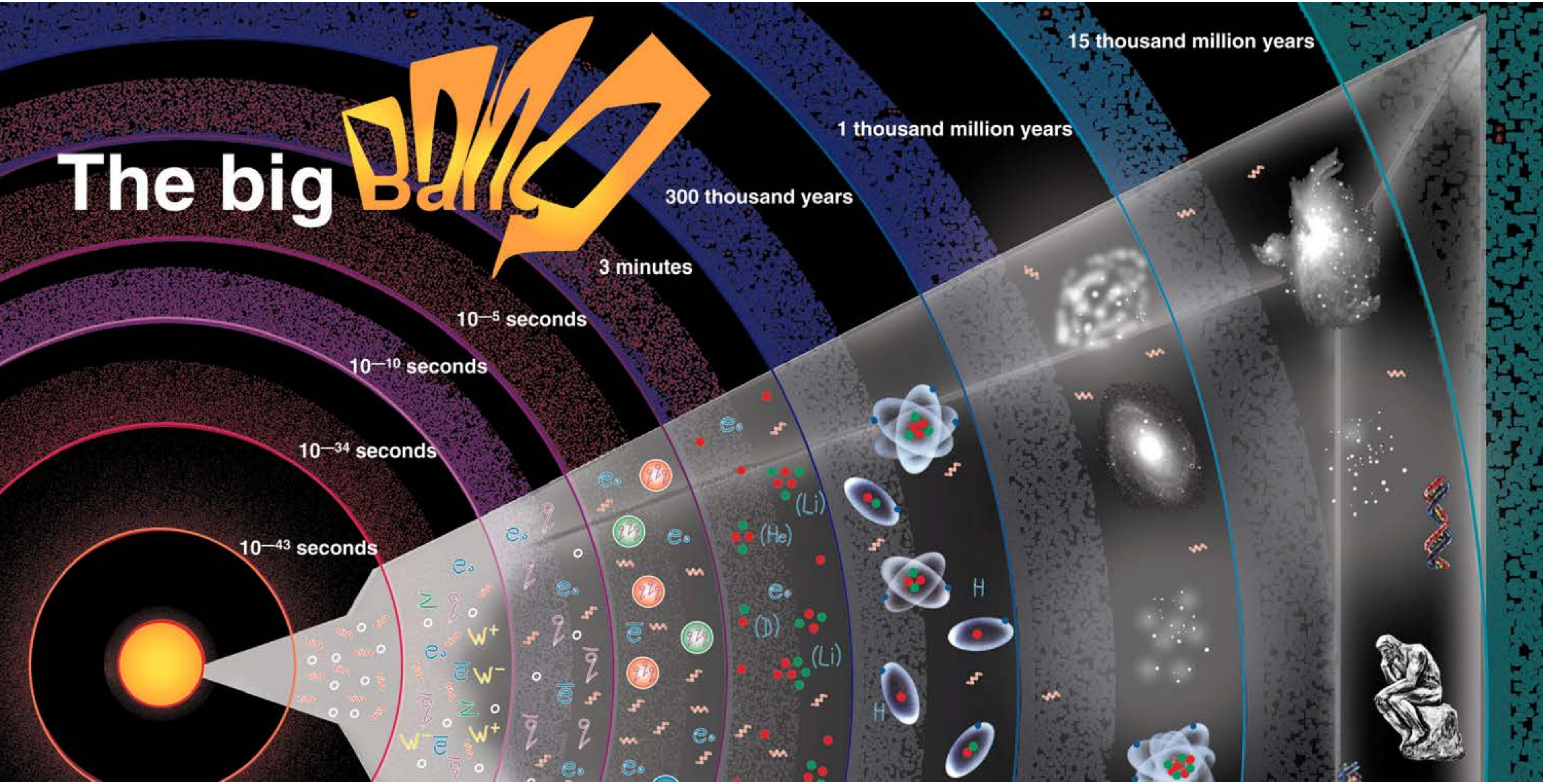


x 10,000 x 10,000 x 10,000



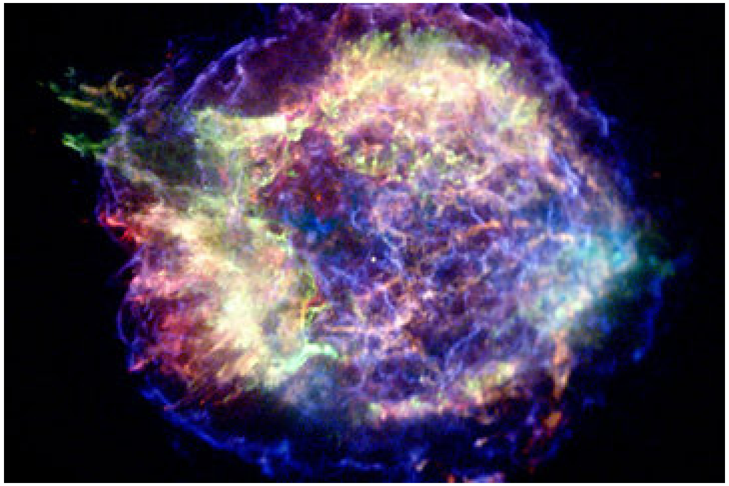
Eye **Cell** **Atom** **Nucleus**

Nuclear Physics: 3 minutes after the Big Bang



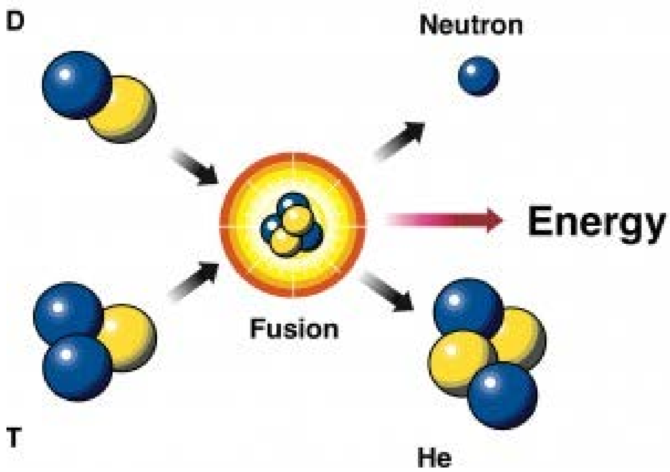
13.7 Billion years after the Big Bang

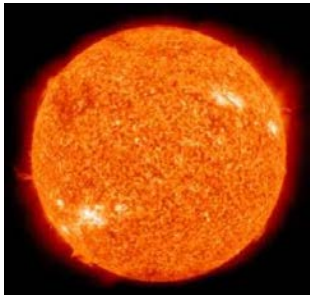
Star Physics



Nuclear medicine

Nuclear Power





Nuclear fusion

The National Superconducting Cyclotron Laboratory
Michigan State University

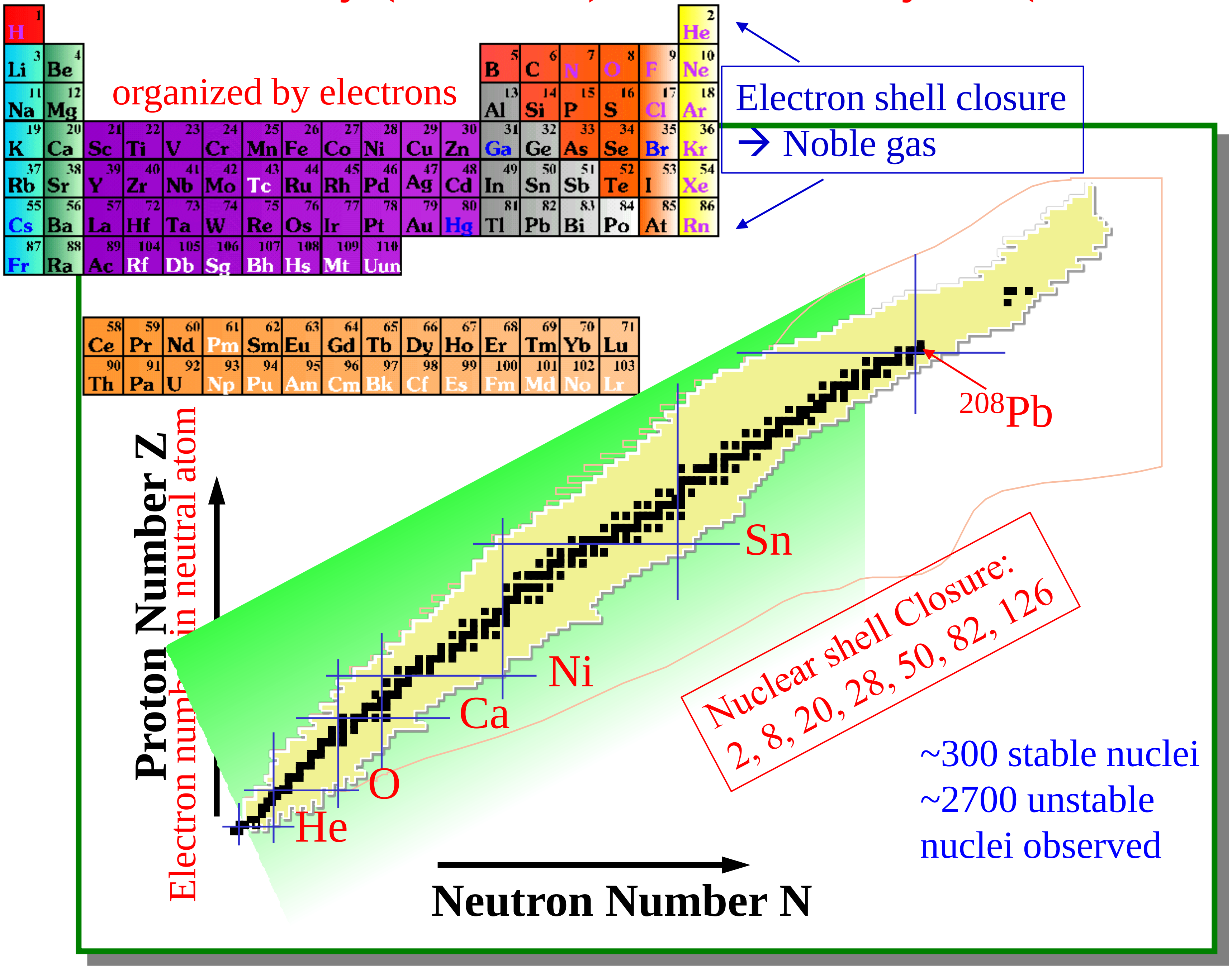
曾敏兒 -- Betty Tsang

Symmetry Energy Project: To bring heavens down to earth

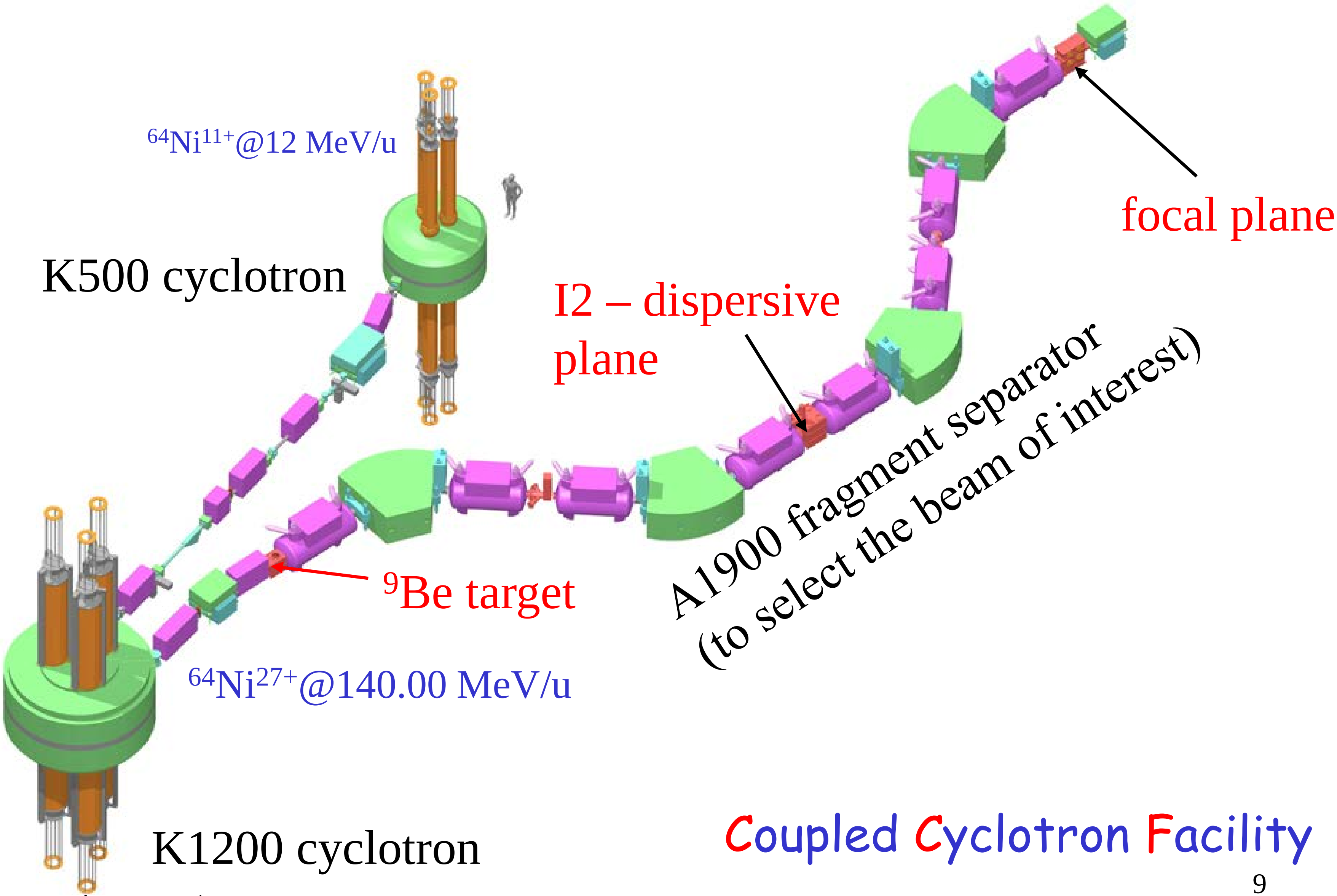
Outline

1. Introduction
2. From Chemistry (elements) to Nuclear physics (rare isotopes)
3. From NSCL to FRIB
4. From Nuclei to neutron star → Symmetry Energy
5. Density Dependence of Symmetry Energy
5. Results from Low density
6. Planned Experiments at high density
   HIC with radioactive beams
   Relevance to new observation of neutron star properties. .

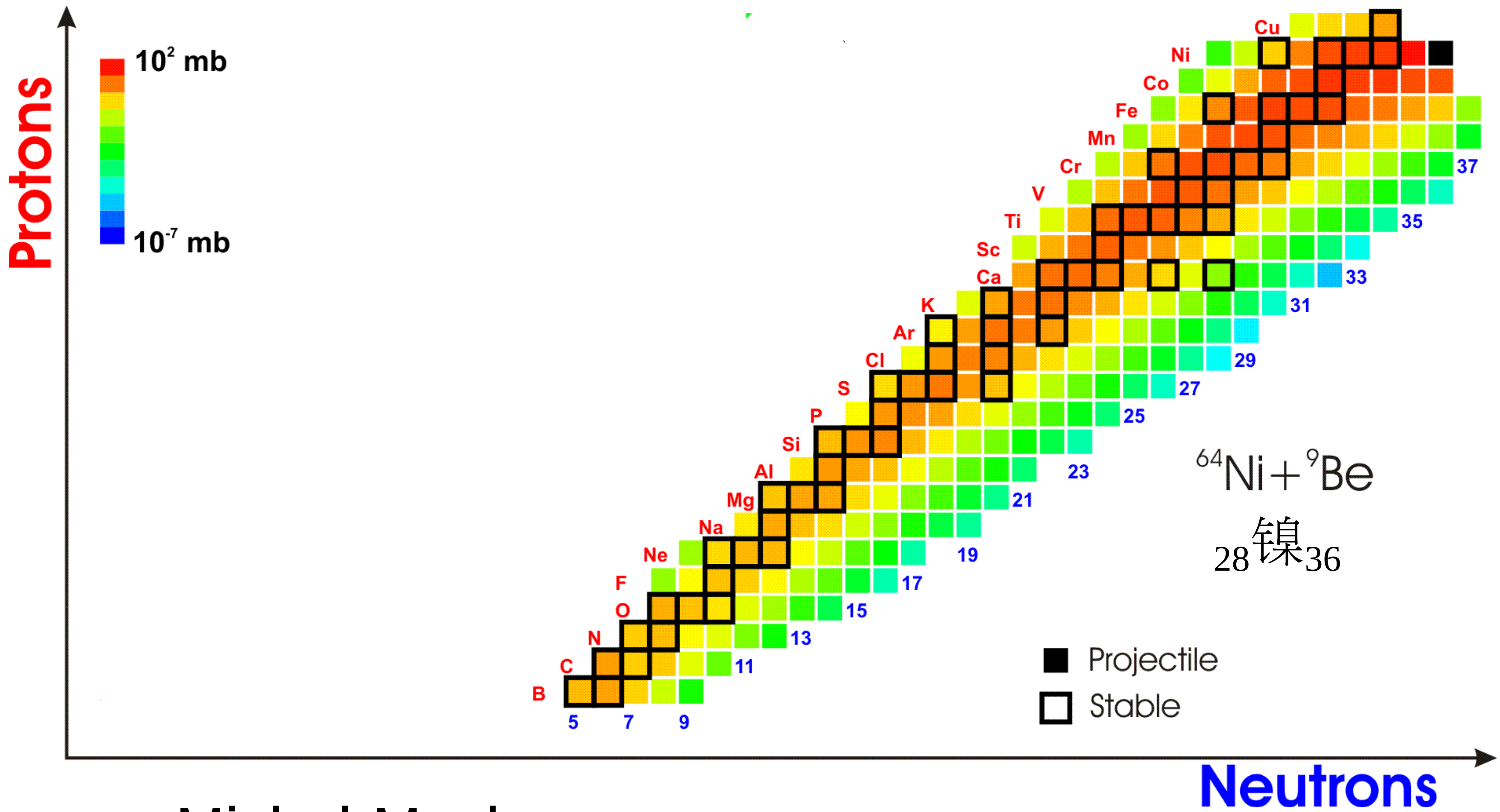
From Chemistry (Elements) to Nuclear Physics (Rare isotopes)



Rare Isotope Beam production at NSCL



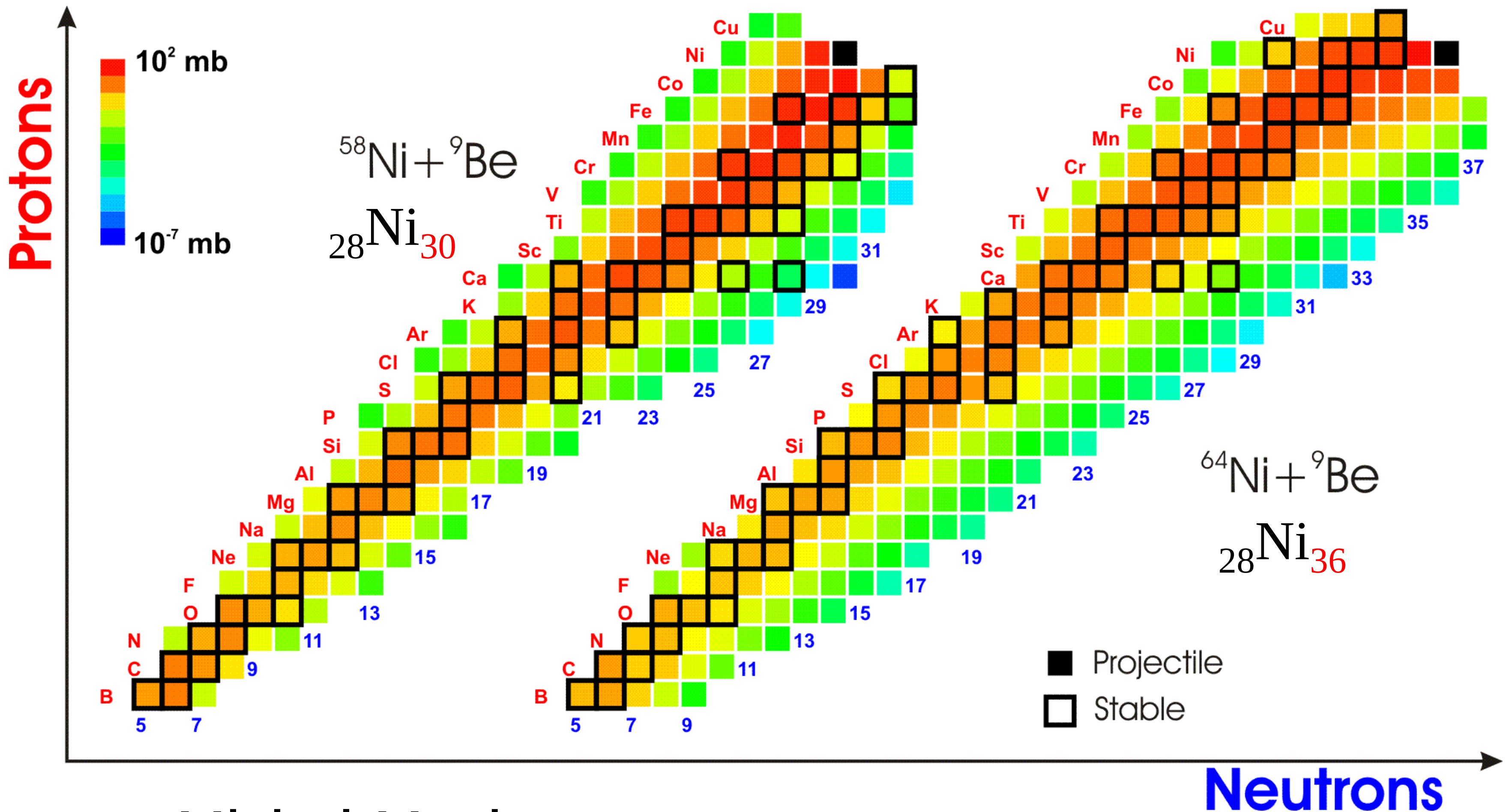
Radioactive Ion Beam production at NSCL



Michal Mocko

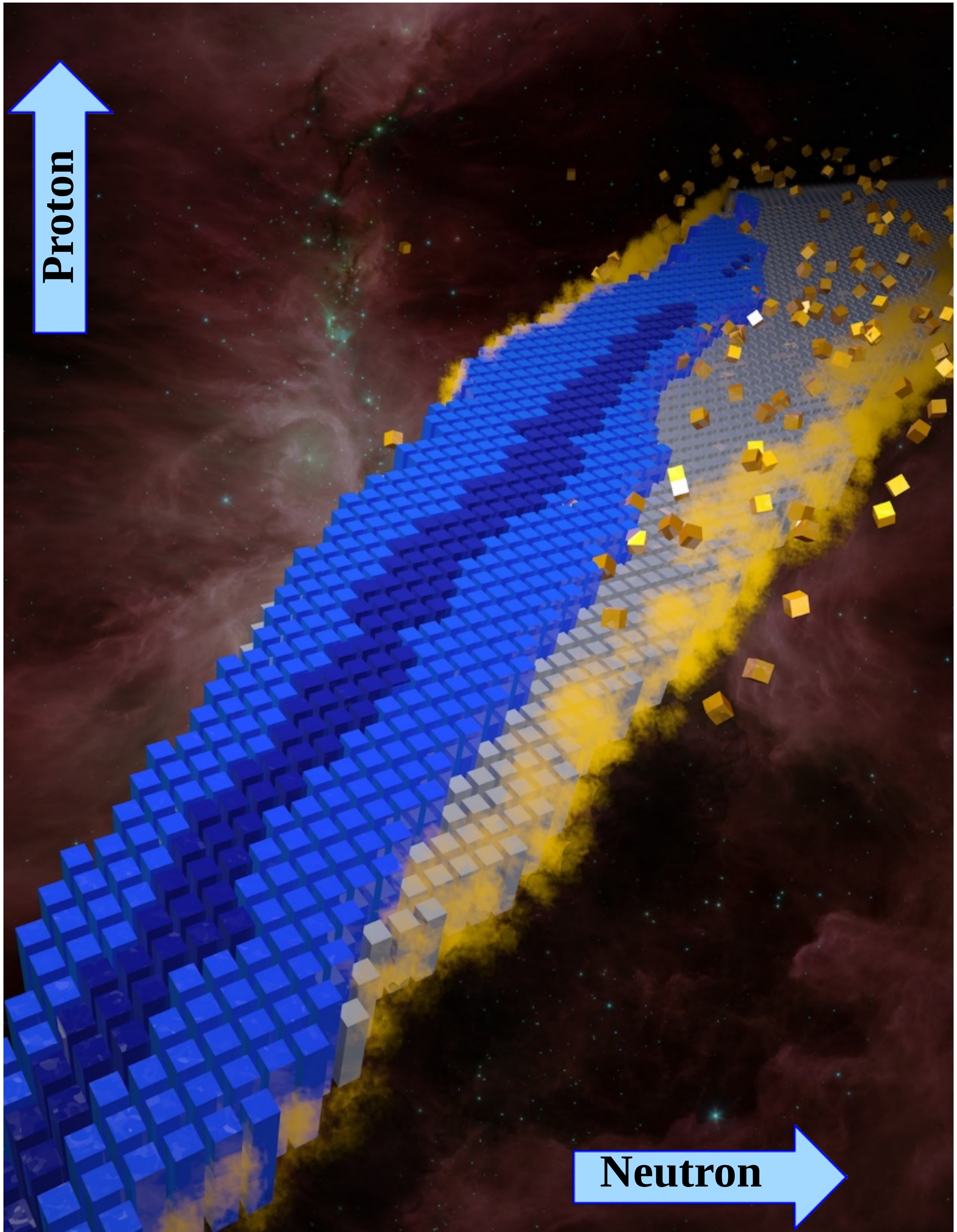
Thesis defense, MSU-NSCL

Radioactive Ion Beam production at NSCL



Michal Mocko

Thesis defense, MSU-NSCL



Nuclear Landscape

~300 stable nuclei
~2700 unstable nuclei observed
~6000 predicted

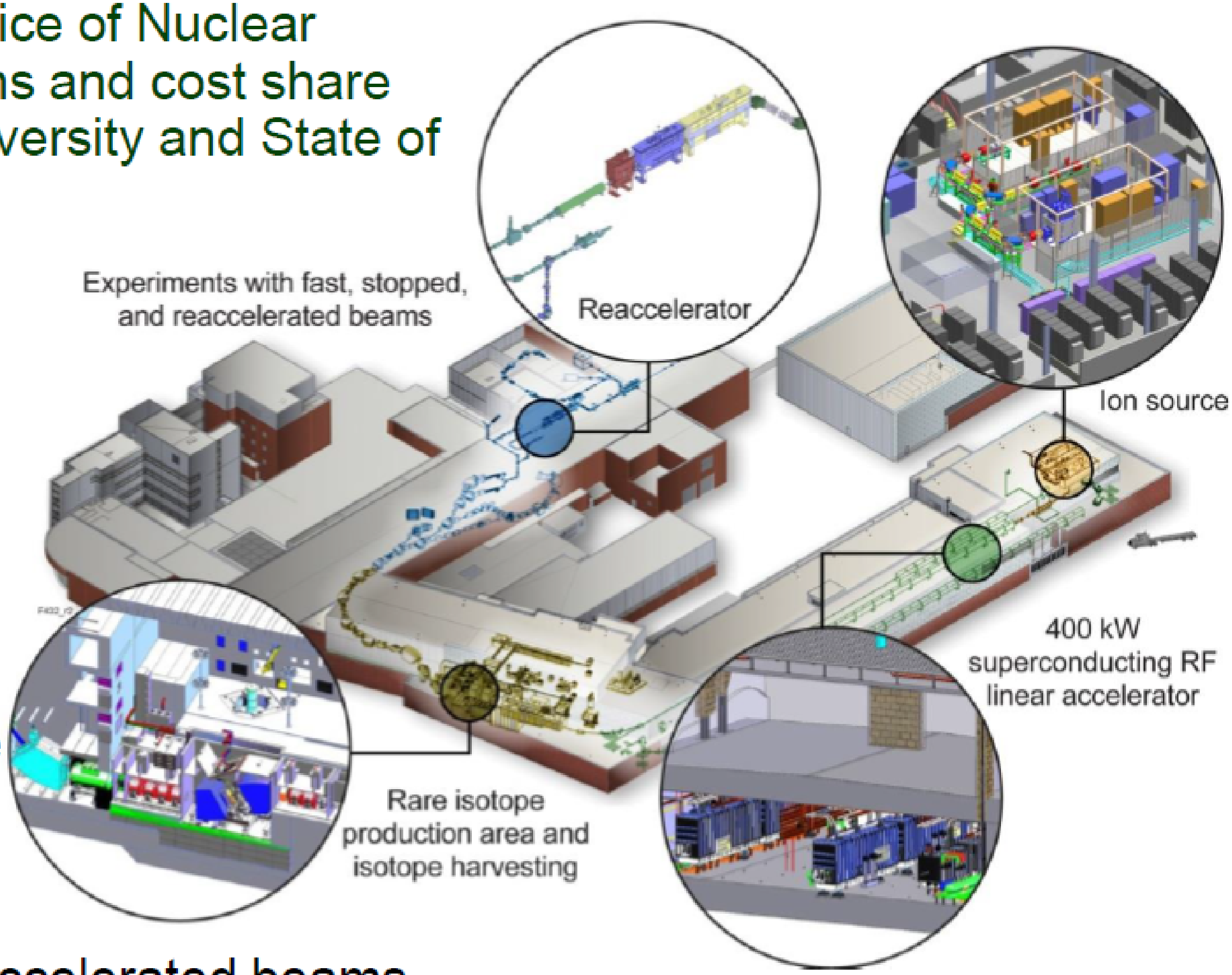
Discovery Potentials
New isotopes
Limit of nuclei existence
Property of n-rich matter

Next generation of RIB accelerators

Image by Andy Sproles,
Oak Ridge National Laboratory

From NSCL to Facility for Rare Isotope Beams (FRIB)

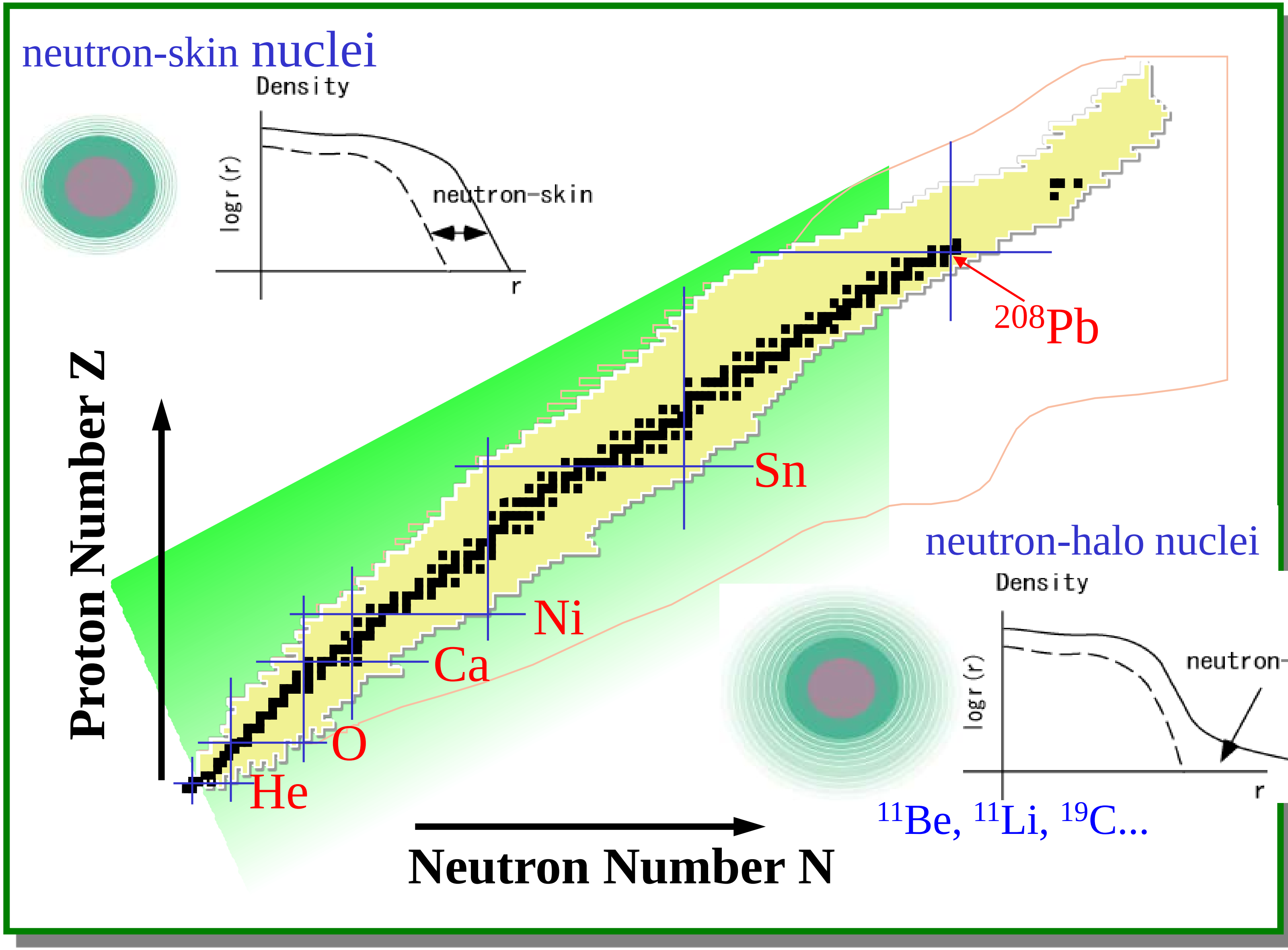
- Funded by DOE–SC Office of Nuclear Physics with contributions and cost share from Michigan State University and State of Michigan
- Managing to early completion in Dec 2020
- Key feature is 400 kW beam power for all ions (5×10^{13} ^{238}U/s)
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped, and reaccelerated beams



Status on the construction of Facility for Rare Isotope Beams (FRIB)

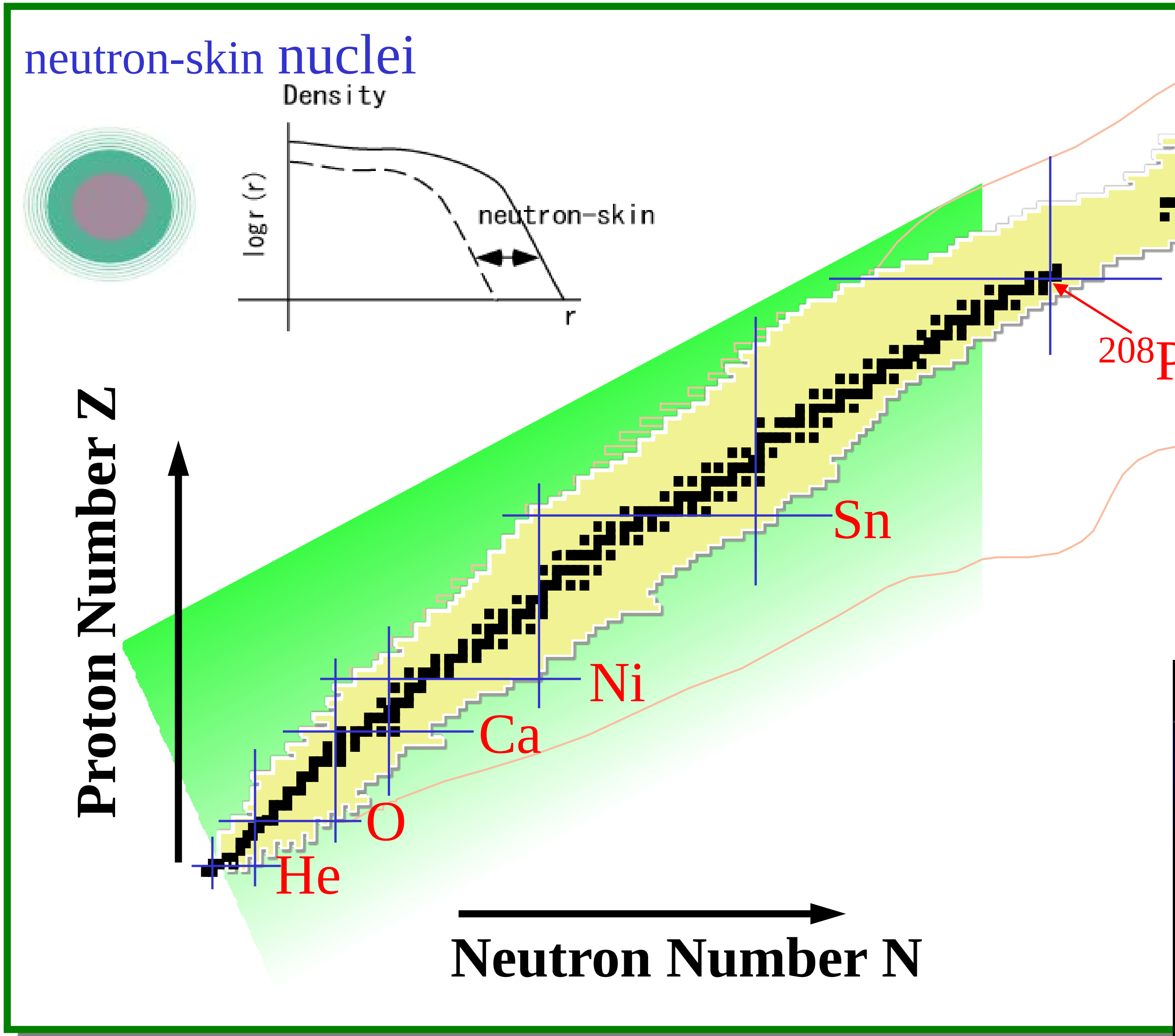
From Stable nuclei to Neutron-rich nuclei

$r = r_0 \times A^{1/3}$ (r_0=1.2 fm)?? isospin dependence of nuclear radii



From Nucleus to Neutron Star -- Nuclear Symmetry Energy

Same physics governs n-rich nuclei also governs n-star

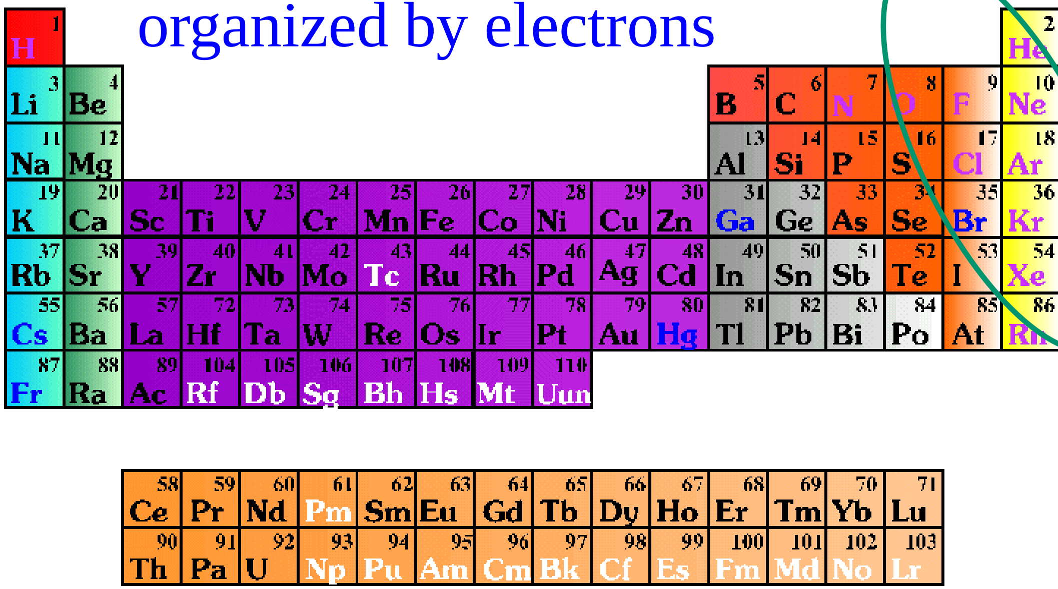


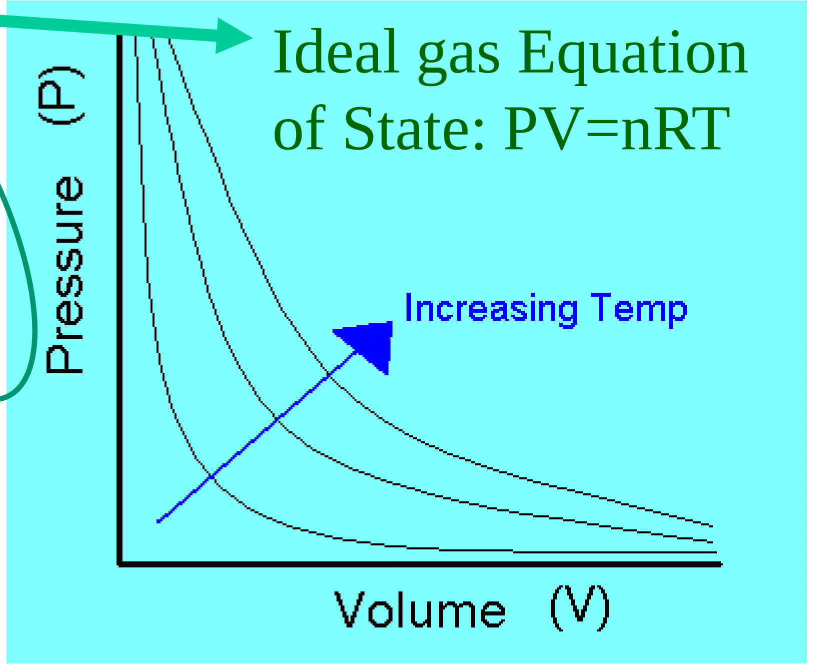
Crab Pulsar

Hubble ST

Equation of State of Gases

Periodic Table
organized by electrons





Equation of State of Neutron Matter

Hubble ST

Neutron Star: balance of Gravity (pulls in) and Symmetry energy pressure (pushes out): Masses vs. Radii

$$\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r)$$

$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1 + \frac{P(r)}{\mathcal{E}(r)}\right]\left[1 + \frac{4\pi r^3 P(r)}{M(r)}\right]\left[1 - \frac{2GM(r)}{r}\right]^{-1}$$

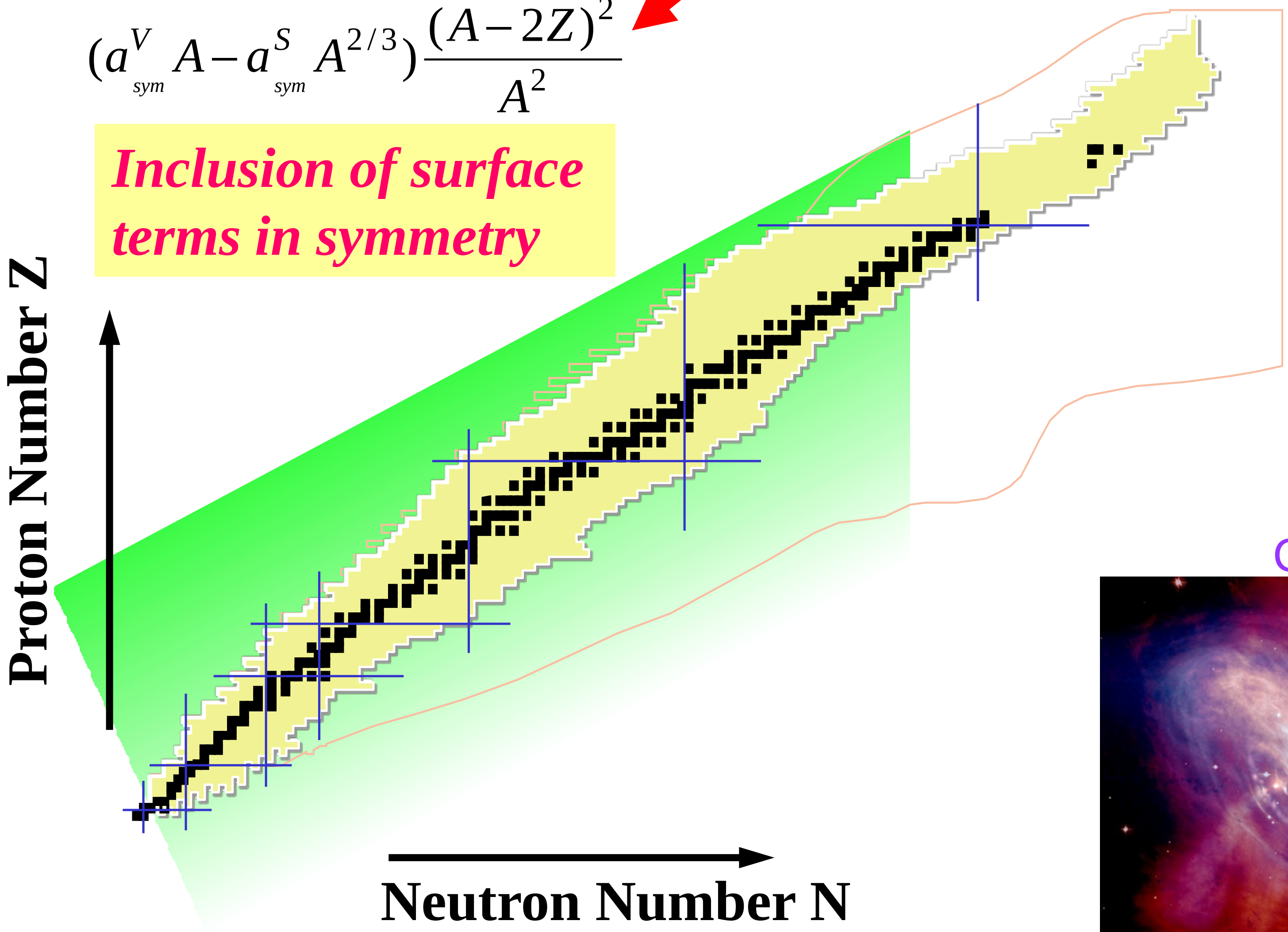
EoS of pure neutron matter: Symmetry Energy as function of pressure (density)

Symmetry Energy in Nuclei

$$B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \frac{(A-2Z)^2}{A}$$

$$(a^V_{sym} A - a^S_{sym} A^{2/3}) \frac{(A-2Z)^2}{A^2}$$

Inclusion of surface terms in symmetry

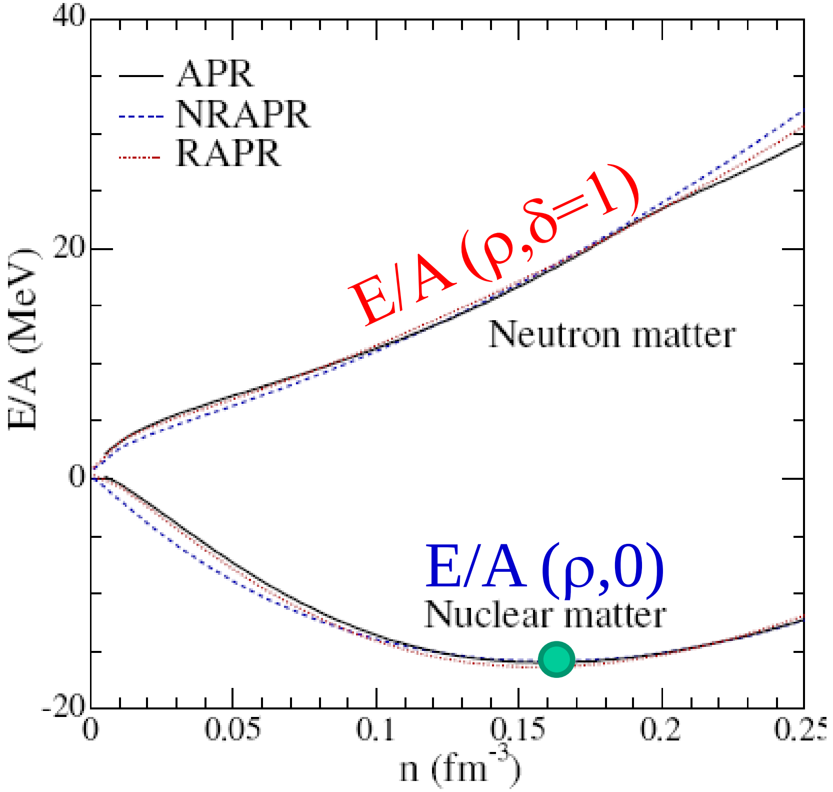


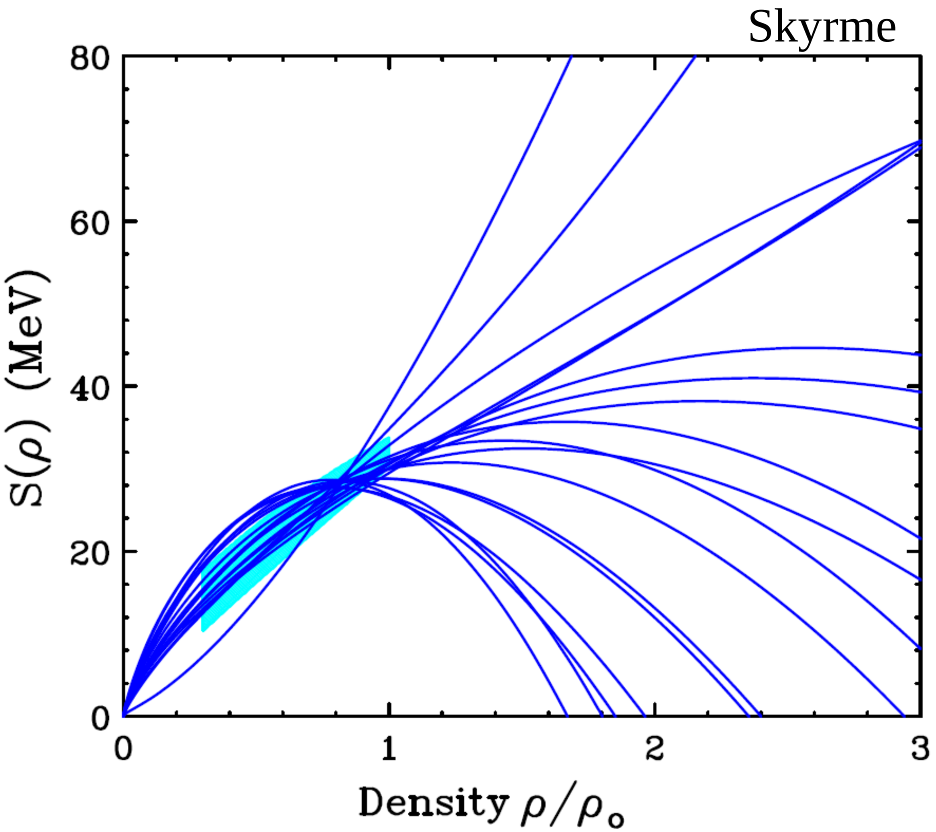
Crab Pulsar

Hubble ST

Nuclear Equation of State of asymmetric matter

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$
$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$





Density dependence of symmetry energy

How to obtain the information about EoS using heavy ion collisions?

Experiments :

Accelerator: Projectile, target, energy

Detectors: Information of emitted particles – identity, spatial info, energy, yields

→construct observables

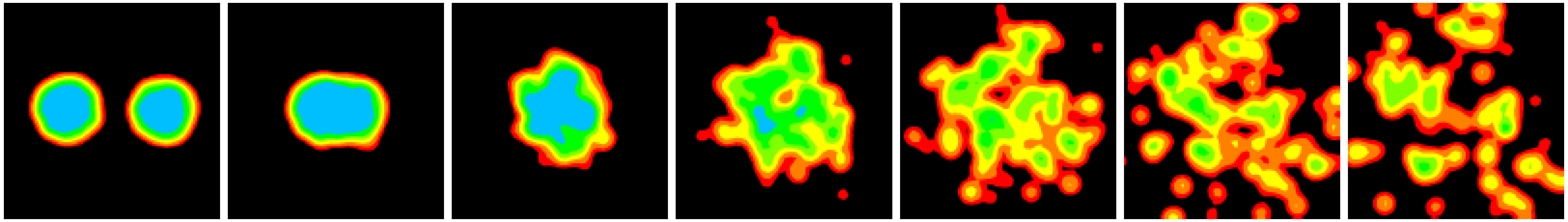
Models

Input: Projectile, target, energy.

Simulate the collisions with the appropriate physics

Success depends on the comparisons of observables.

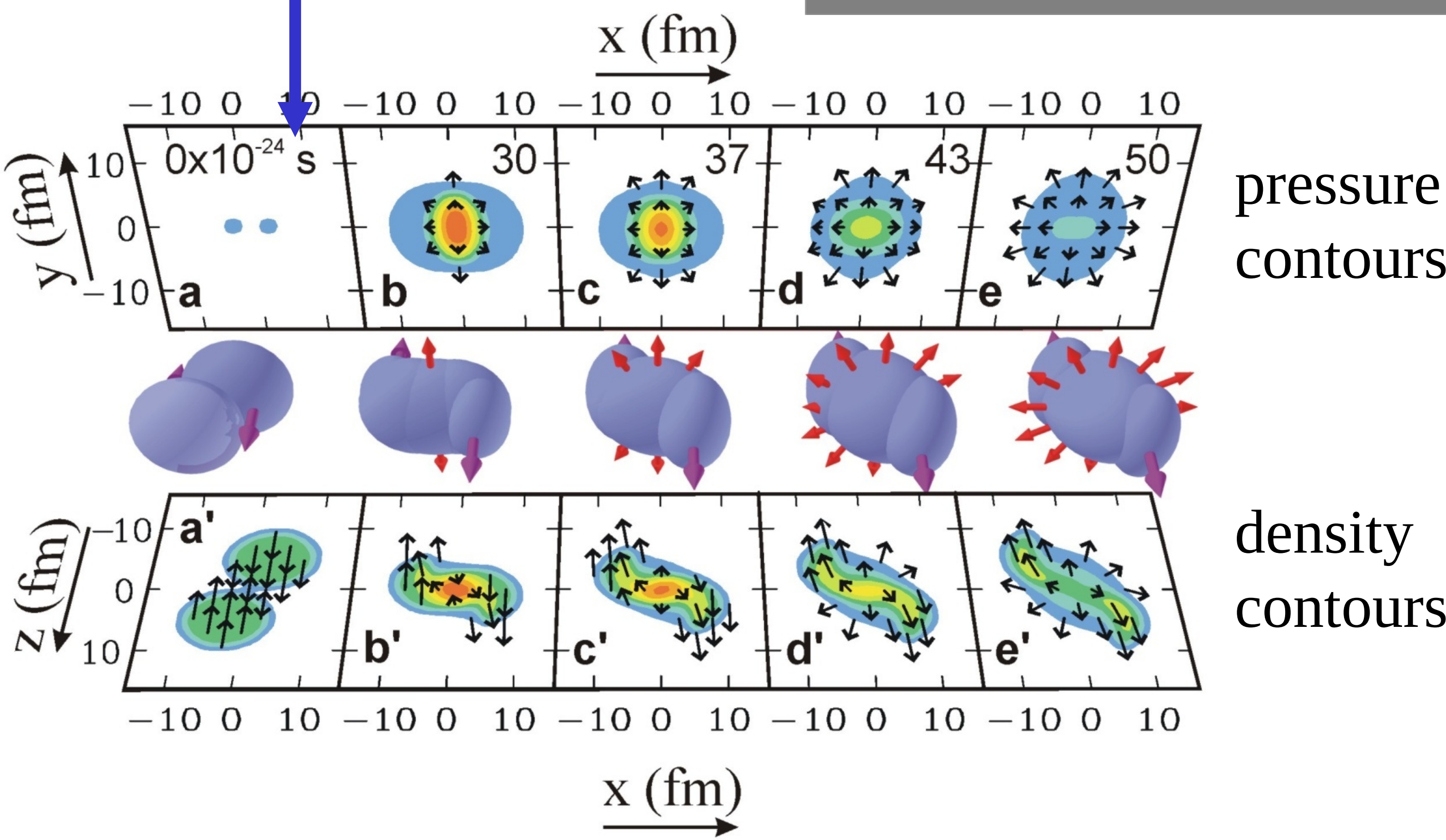
Theory must predict how reaction evolves from initial contact to final observables



Constraining the EoS using Heavy Ion collisions

$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho);$ $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$

Au+Au collisions E/A = 1 GeV)



Two observable due to the high pressures formed in the overlap region:

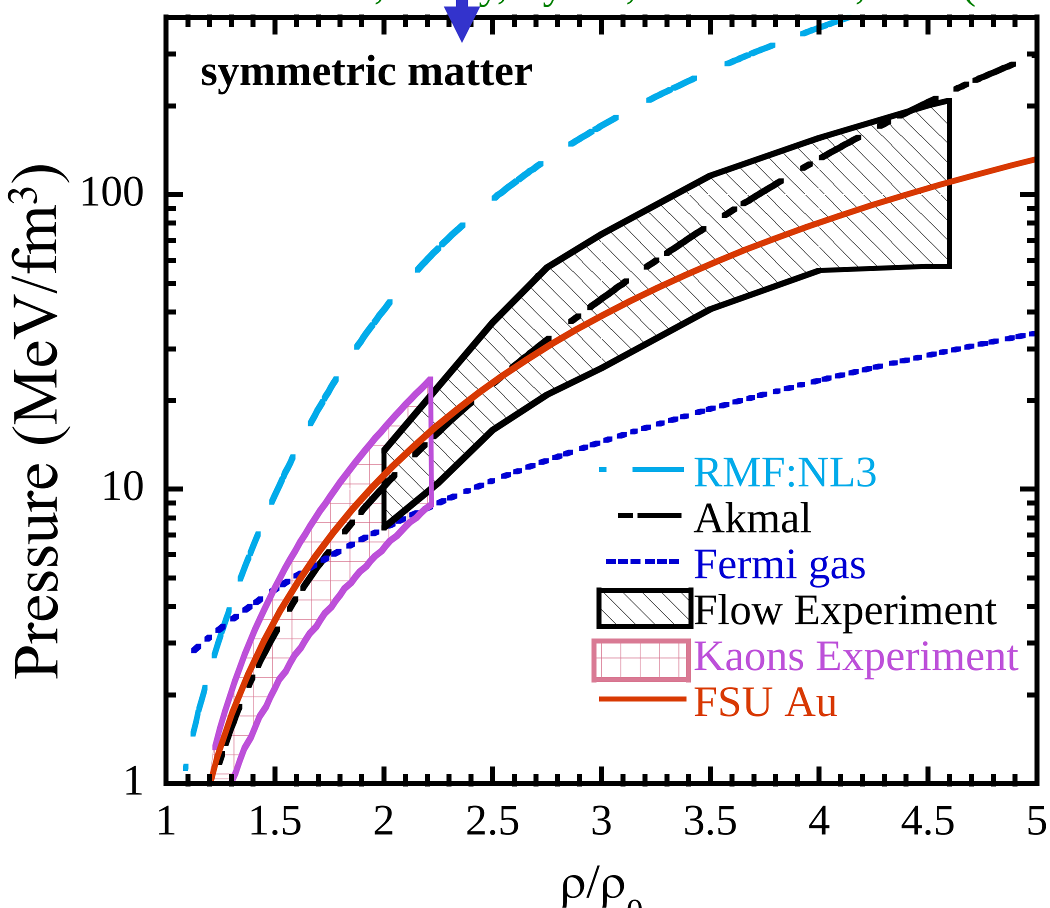
- Nucleons are "squeezed out" above and below the reaction plane.
- Nucleons deflected sideways in the reaction plane.

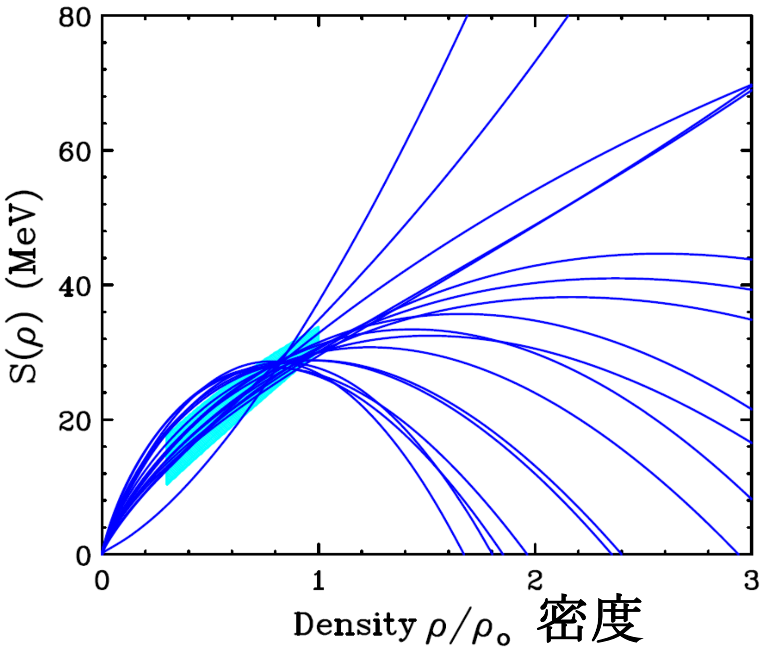
Density dependence of Symmetry Energy

$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$; $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$

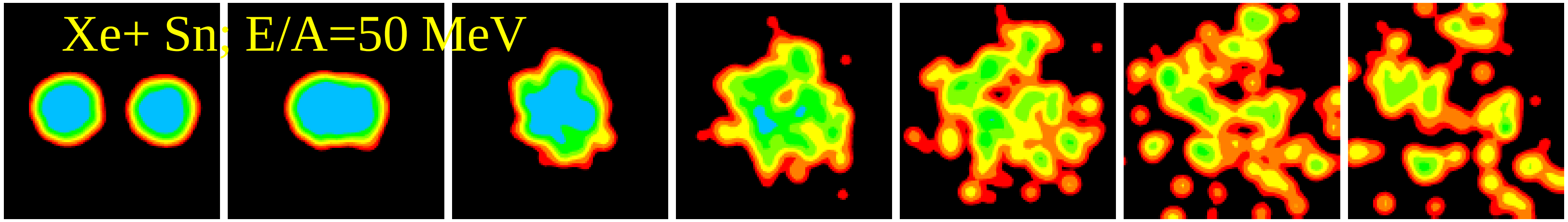
?? Symmetry energy

Danielewicz, Lacey, Lynch, Science 298,1592 (2002)





Creating low to high density nuclear matter



Akira Ono NuSYM13

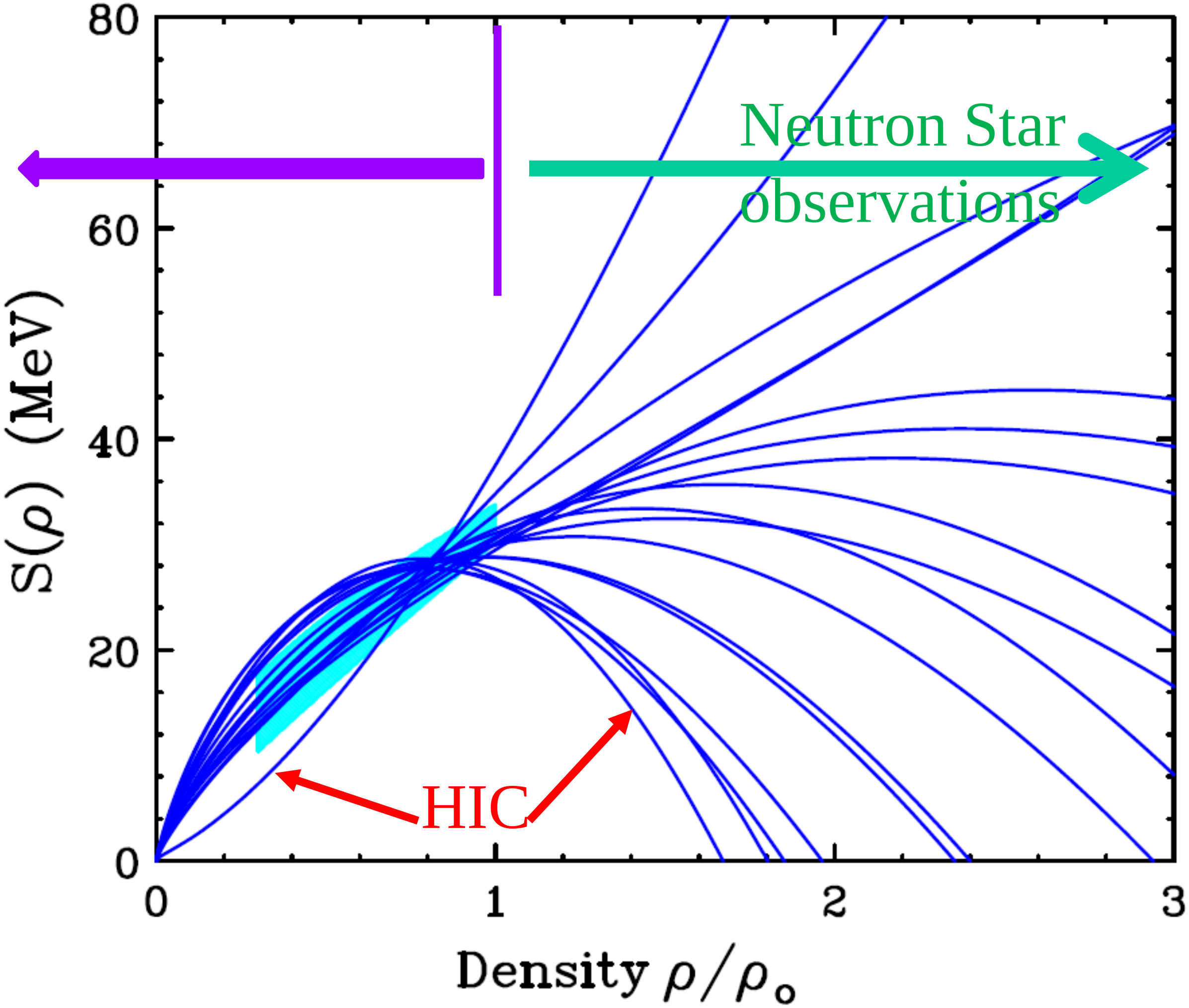
Observables

ρ=0.3-1 ρ_0

Nuclear masses (g.s. & IAS)
Neutron skins
Collective motion (movement of neutron against protons)
Dipole polarizability
Giant Monopole Resonance
Pygmy Dipole Resonance
HIC : Heavy Ion Collisions

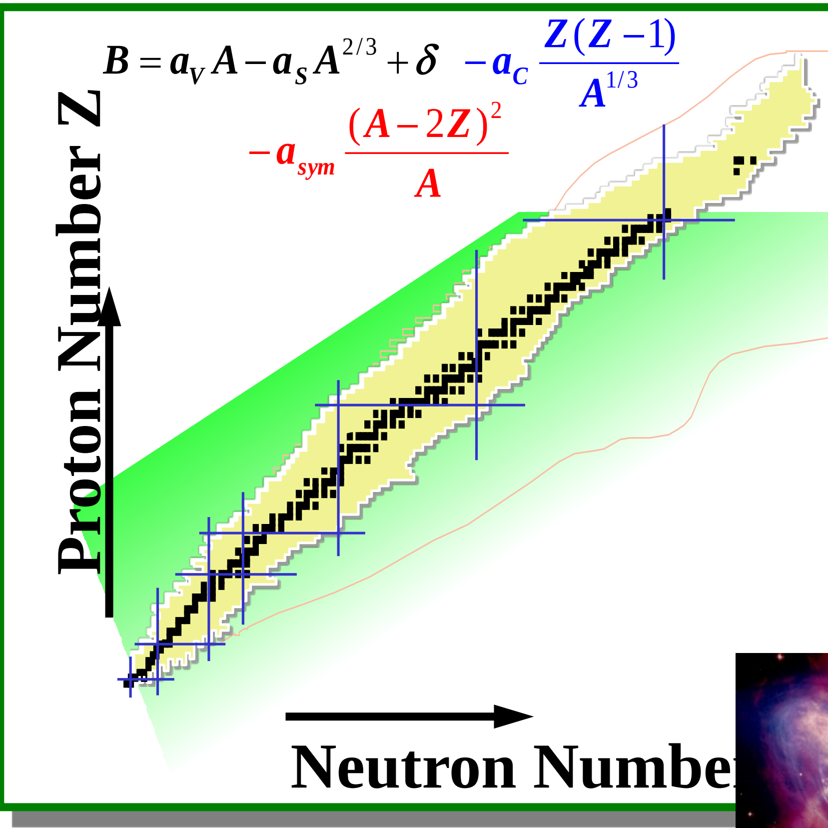
ρ>>ρ_0

Neutron Star observations
HIC : Heavy Ion Collisions

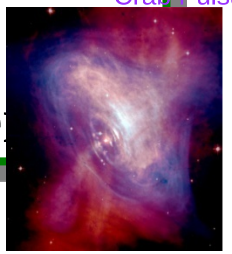


Strategies used to study the symmetry energy with Heavy Ion collisions below E/A=100 MeV

Isospin degree of freedom



Crab Pulsar

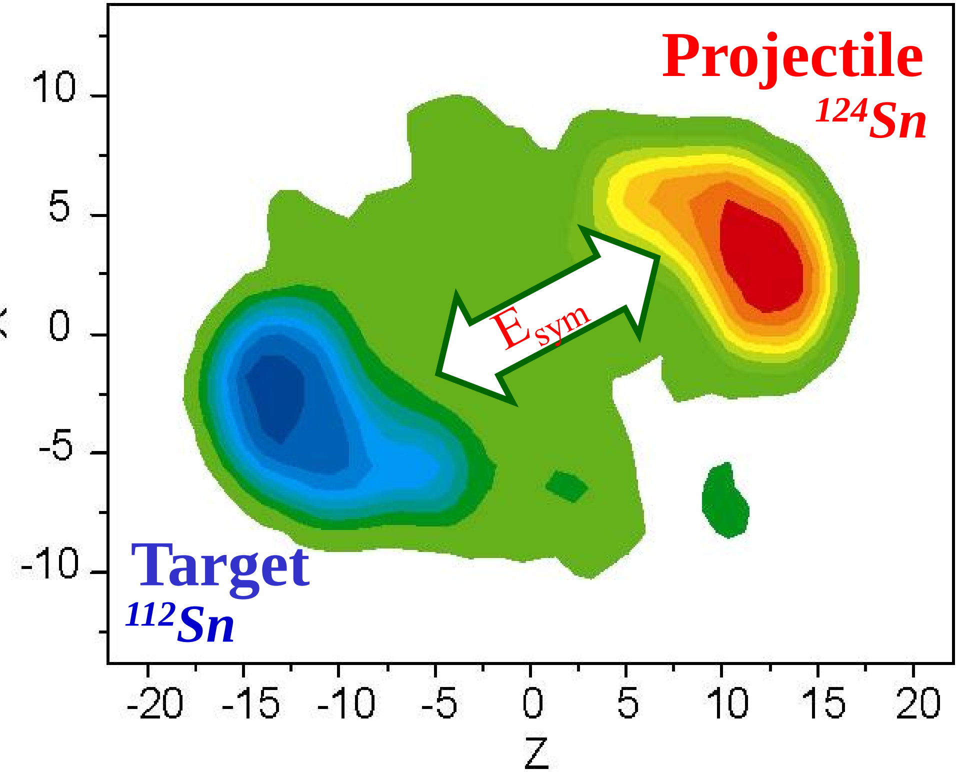


- Vary the N/Z compositions of projectile and targets
- Measure N/Z compositions of emitted particles
  - n & p yields
  - isotopes yields: isospin diffusion
- Simulate collisions with transport theory
  - *Find the symmetry energy density dependence that describes the data.*
  - *Constrain the relevant input transport variables.*

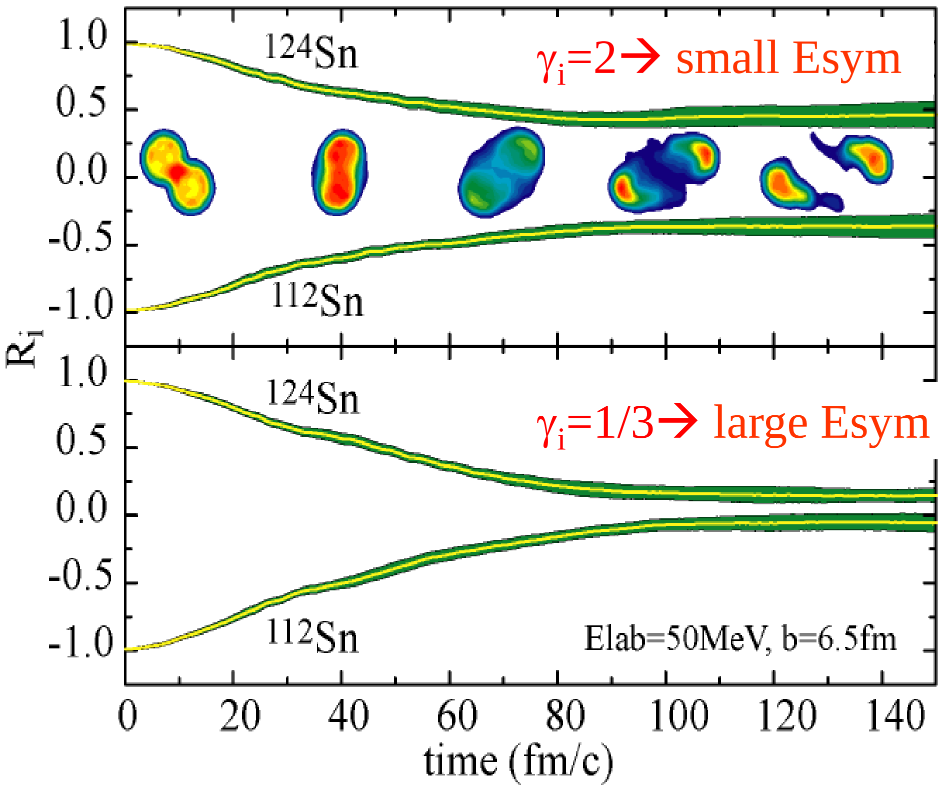
Isospin Diffusion observable to study E_{sym} with Heavy Ion Collisions

$$S(\rho)=12.5(\rho/\rho_o)^{2/3}+C(\rho/\rho_o)^{\gamma_i}$$

Tsang et al., PRL 92 (2004) 062701



Tsang, Shi et al., PRL92, 062701(2004)



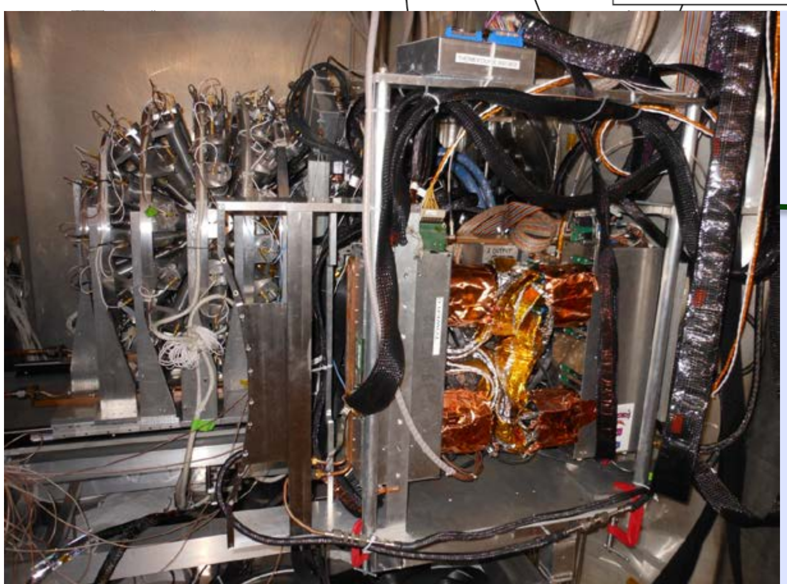
Isospin Diffusion; low ρ, E_{beam}

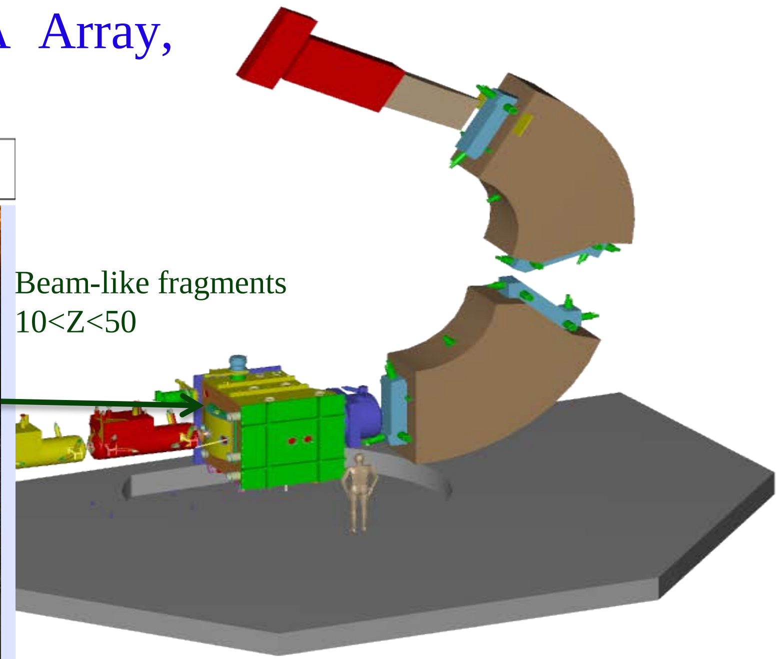
Bao-An Li et al., Phys. Rep. 464, 113 (2008)
Tsang, Zhang et al., PRL122, 122701(2009)

NSCL Experiment 07038: Precision Measurement of Isospin Diffusion

- Investigates the density-dependence of the nuclear symmetry energy using isospin diffusion from residues – new observable
- ^{112,118,124}Sn+ ^{112,118,124}Sn Collisions
- Combines the MSU Miniball, the LASSA Array, & S800 Spectrograph

Incoming Beam,
70 MeV/u





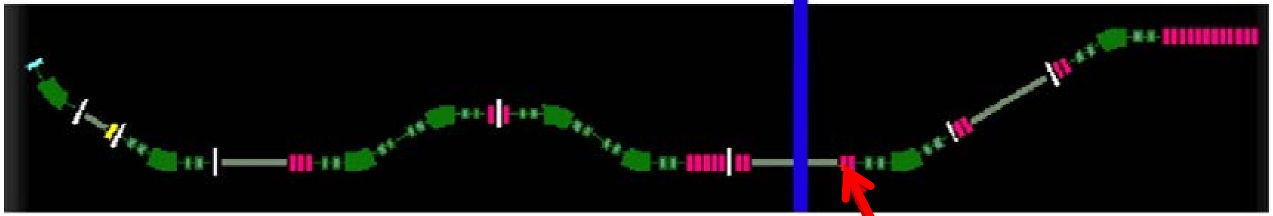
Jack Winkelbauer, PhD thesis

Experiment set up for NP0709

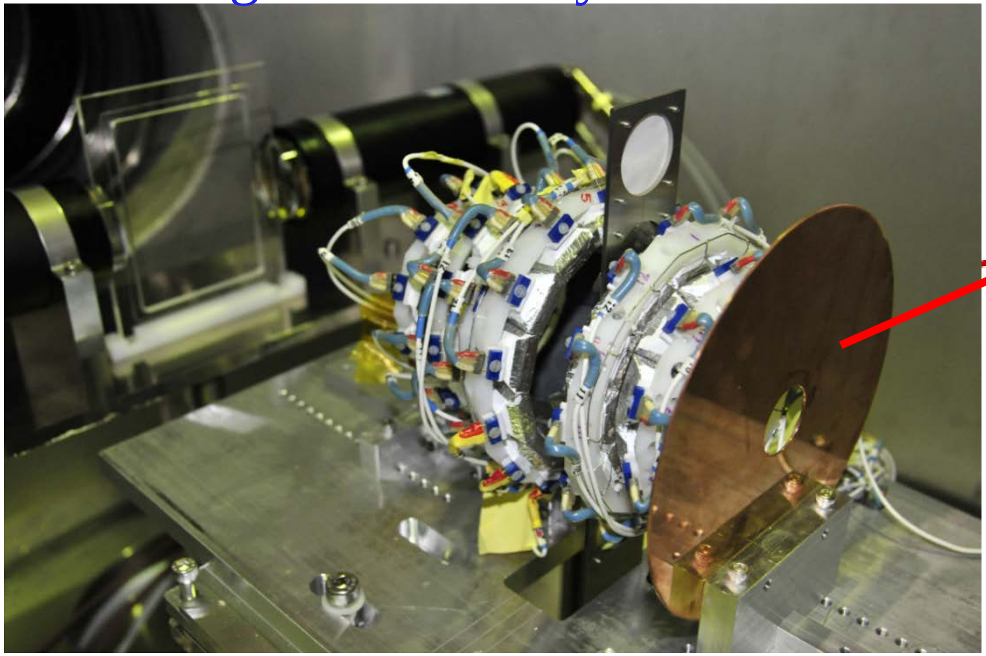
RIKEN, June 11-15, 2013 (USA/Japan/Korea/UK/

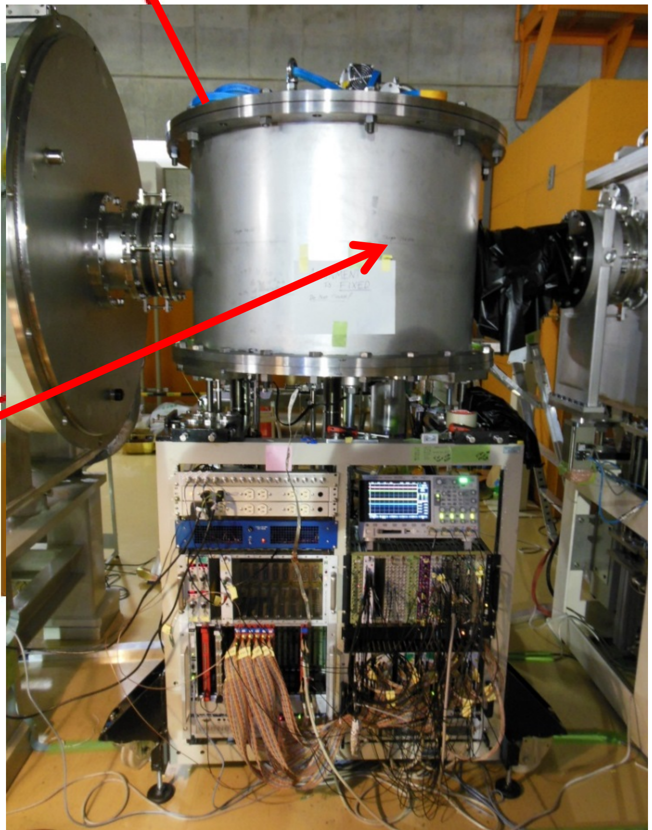
BigRIPS

Zero Degree Spectrometer 零度角探测器



Washington University microball





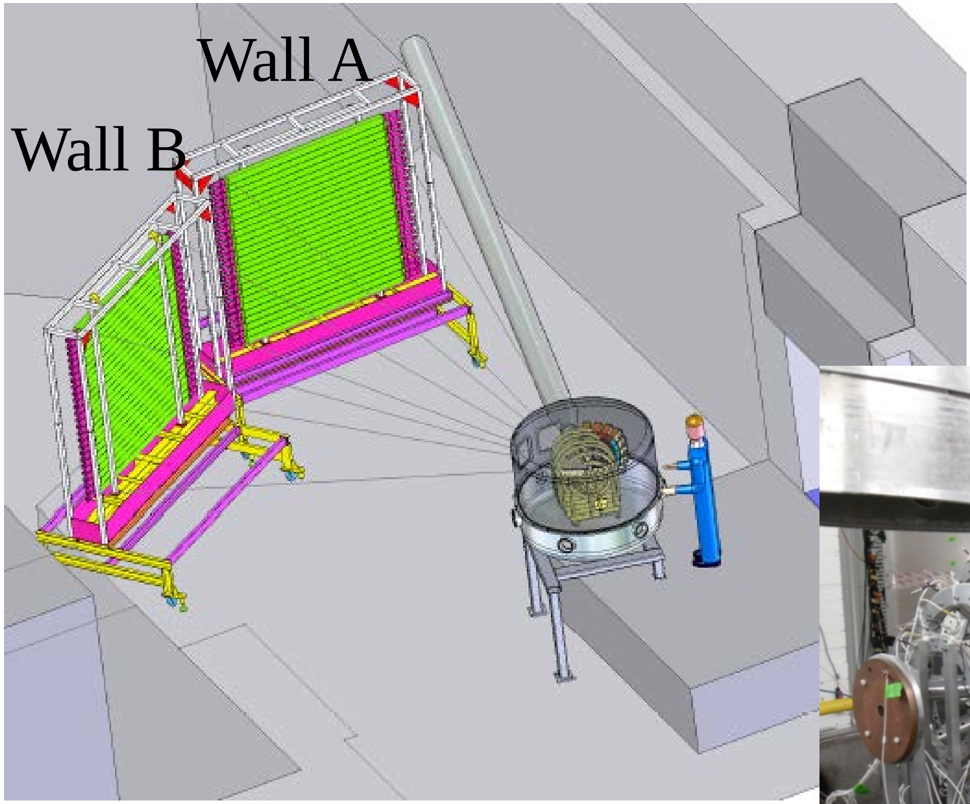
Experimental Layout

PhD thesis: Daniel Coupland, Michael Youngs, Rachel Hodges

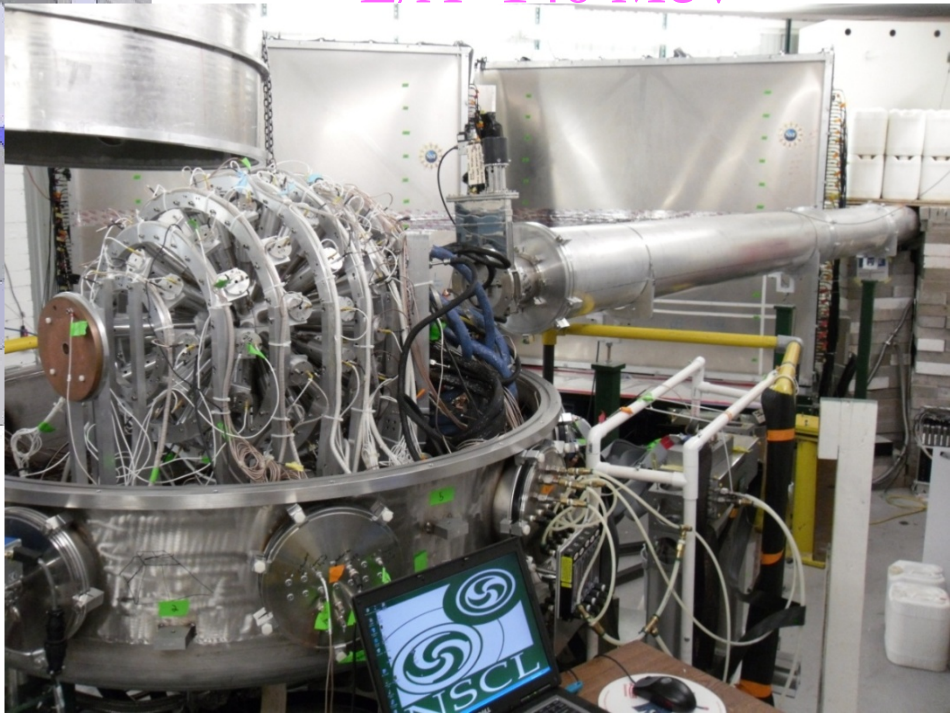
LASSA – charged particles
Miniball – impact parameter

$^{124}Sn+^{124}Sn$; $^{112}Sn+^{112}Sn$
E/A=50 & 120 MeV

$^{48}Ca+^{124}Sn$; $^{48}Ca+^{112}Sn$
E/A=140 MeV



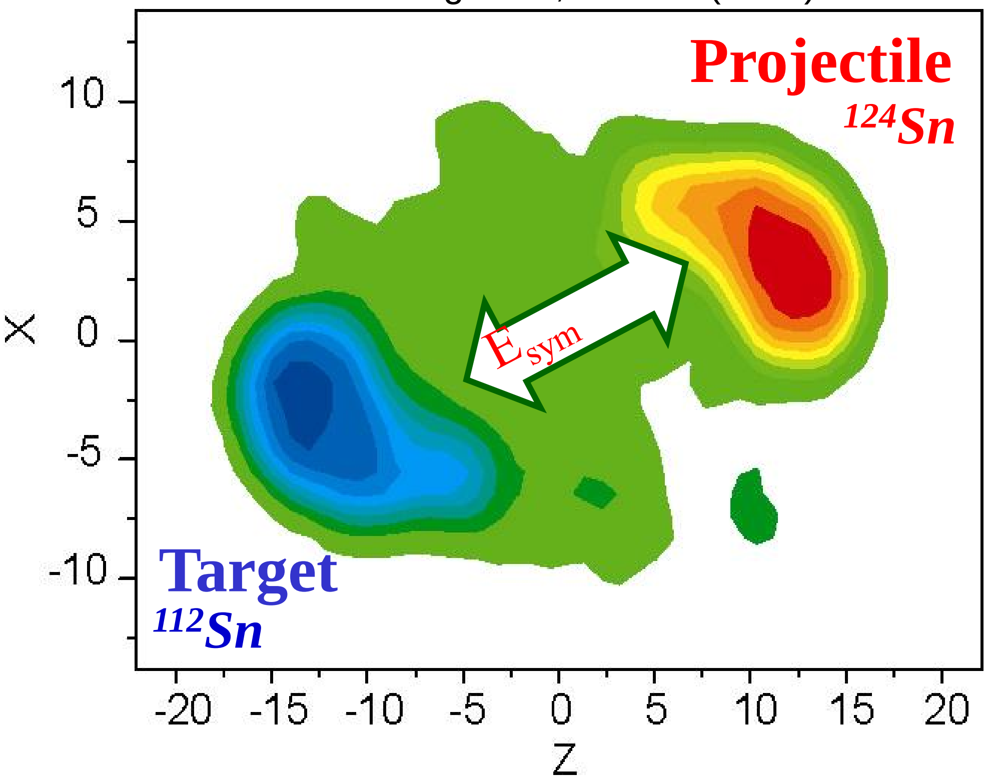
Courtesy Mike Famiano

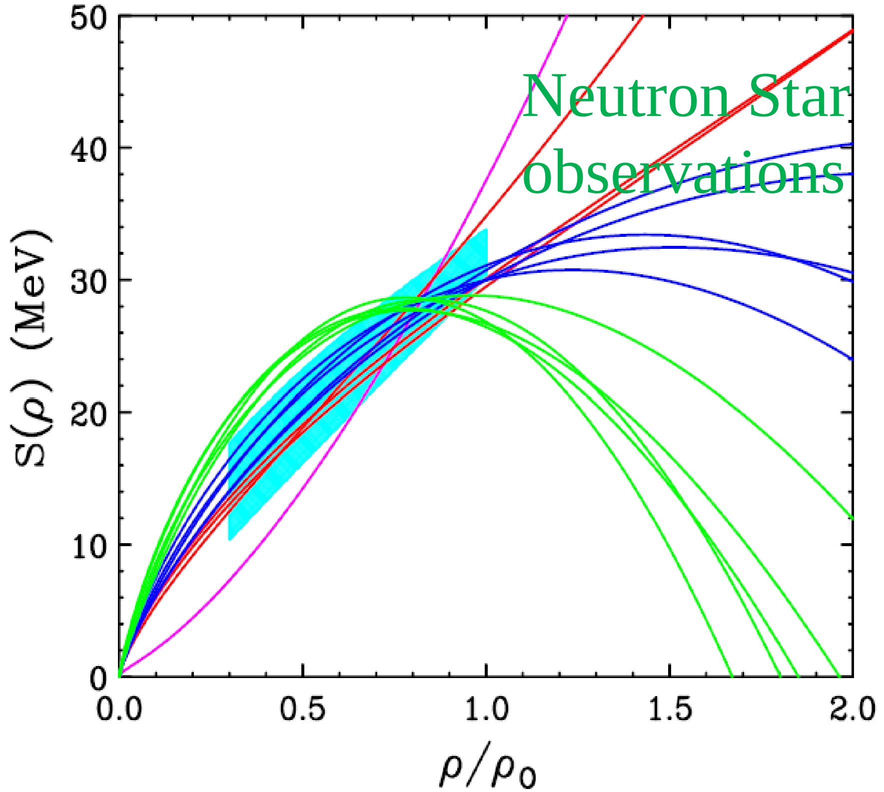


Neutron walls – neutrons
Forward Array – time start
Proton Veto scintillators

Isospin Diffusion(同位旋扩散) observable to study E_{sym} with Heavy Ion Collisions(重离子碰撞)

Tsang et al., PRL 92 (2004) 062701

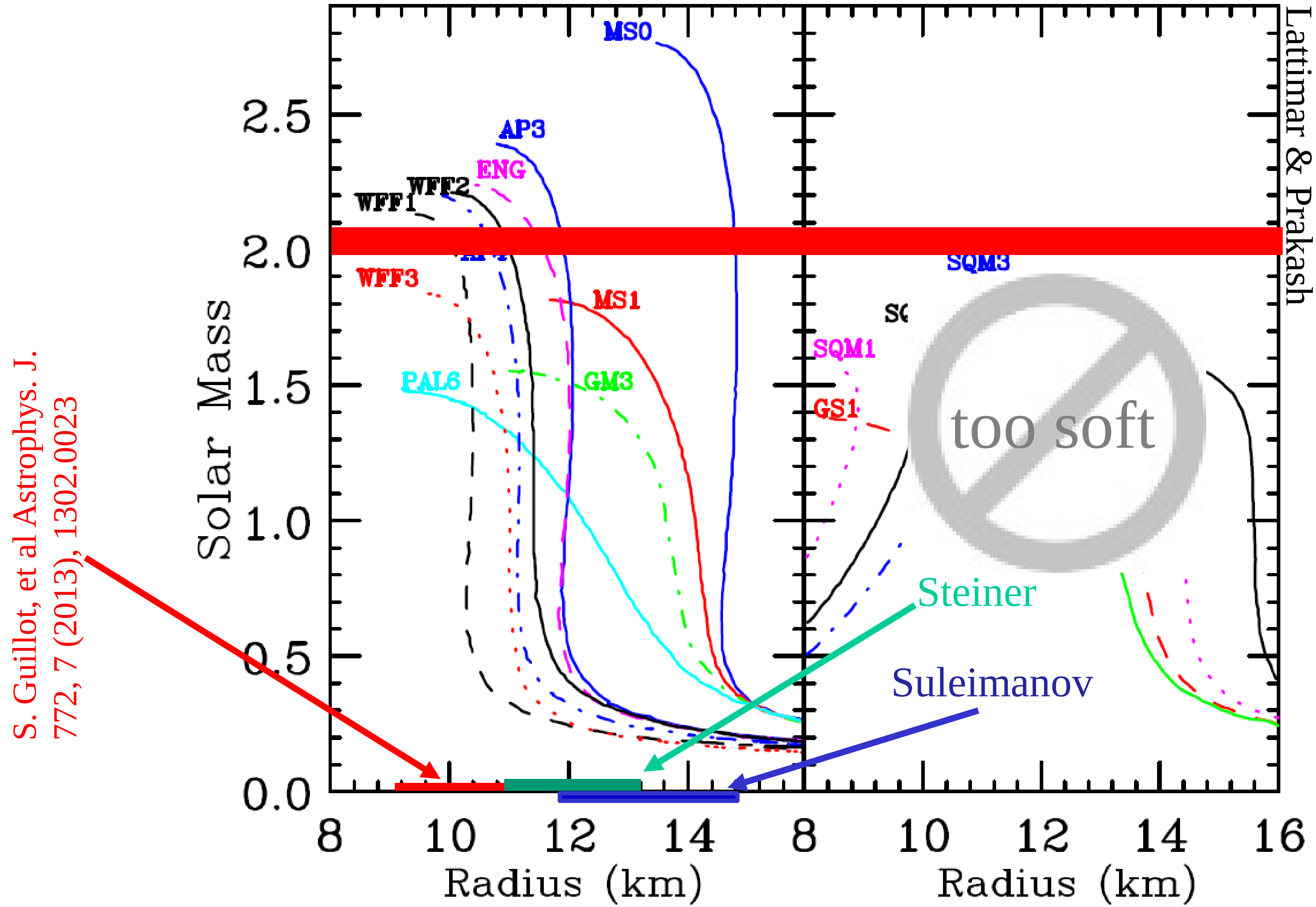




Isospin Diffusion; low ρ, E_{beam}

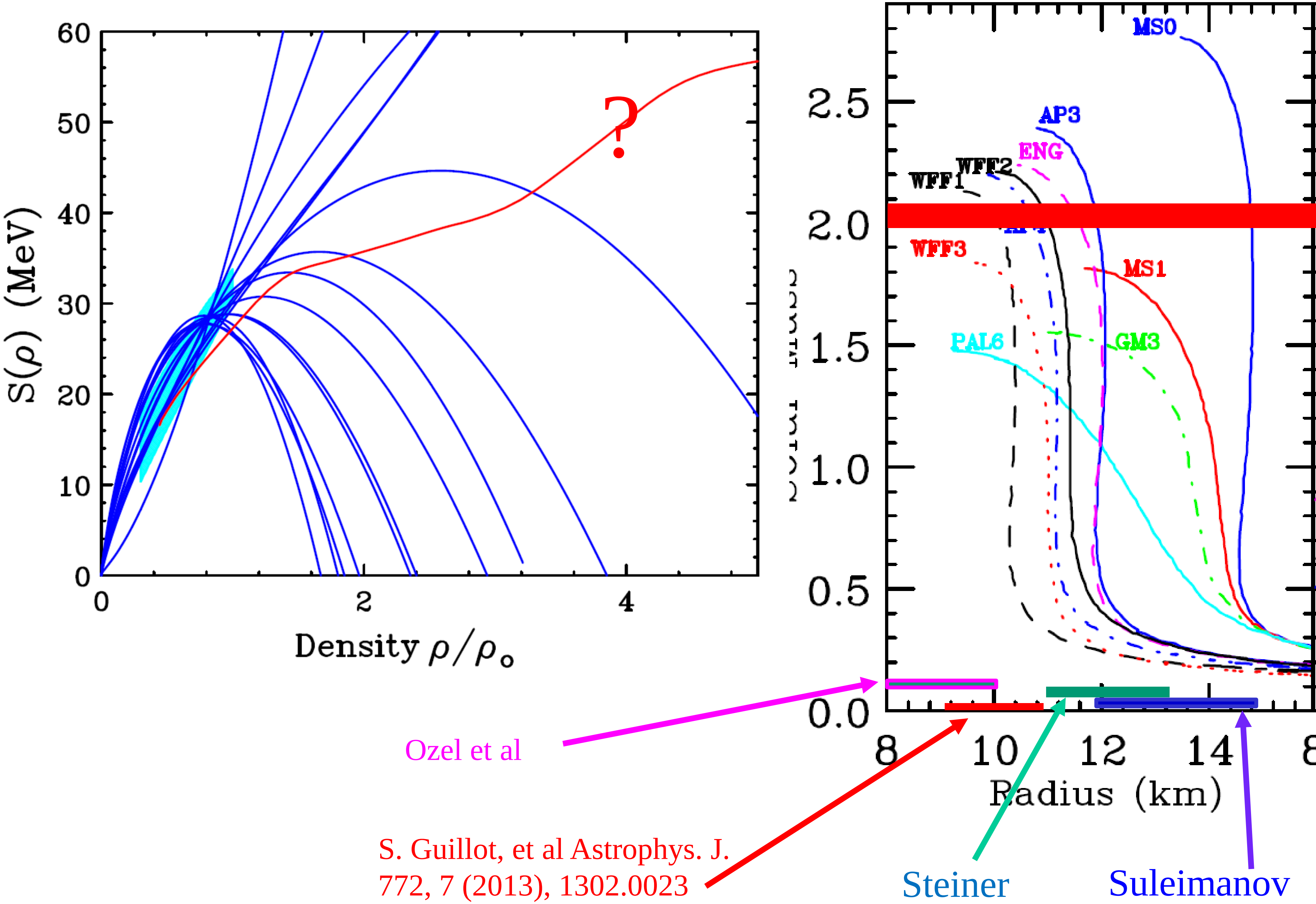
Bao-An Li et al., Phys. Rep. 464, 113 (2008)
Tsang, Zhang et al., PRL122, 122701(2009)

New observations of Neutron Stars (radius/Radii)

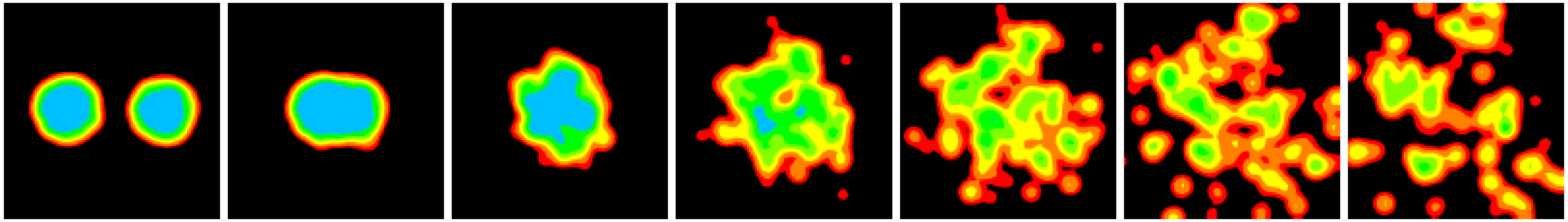


Very small Neutron Star radius rules out nearly all EOS

New observations of Neutron Stars (radius/Radii)



Symmetry Energy at twice saturation density



Experiments @ ~2ρ_0:

Accelerator: high energy (>300 MeV) radioactive ion beams → low intensity

Detectors: Information of emitted particles – identity, spatial info, energy, yields →Time projection chamber

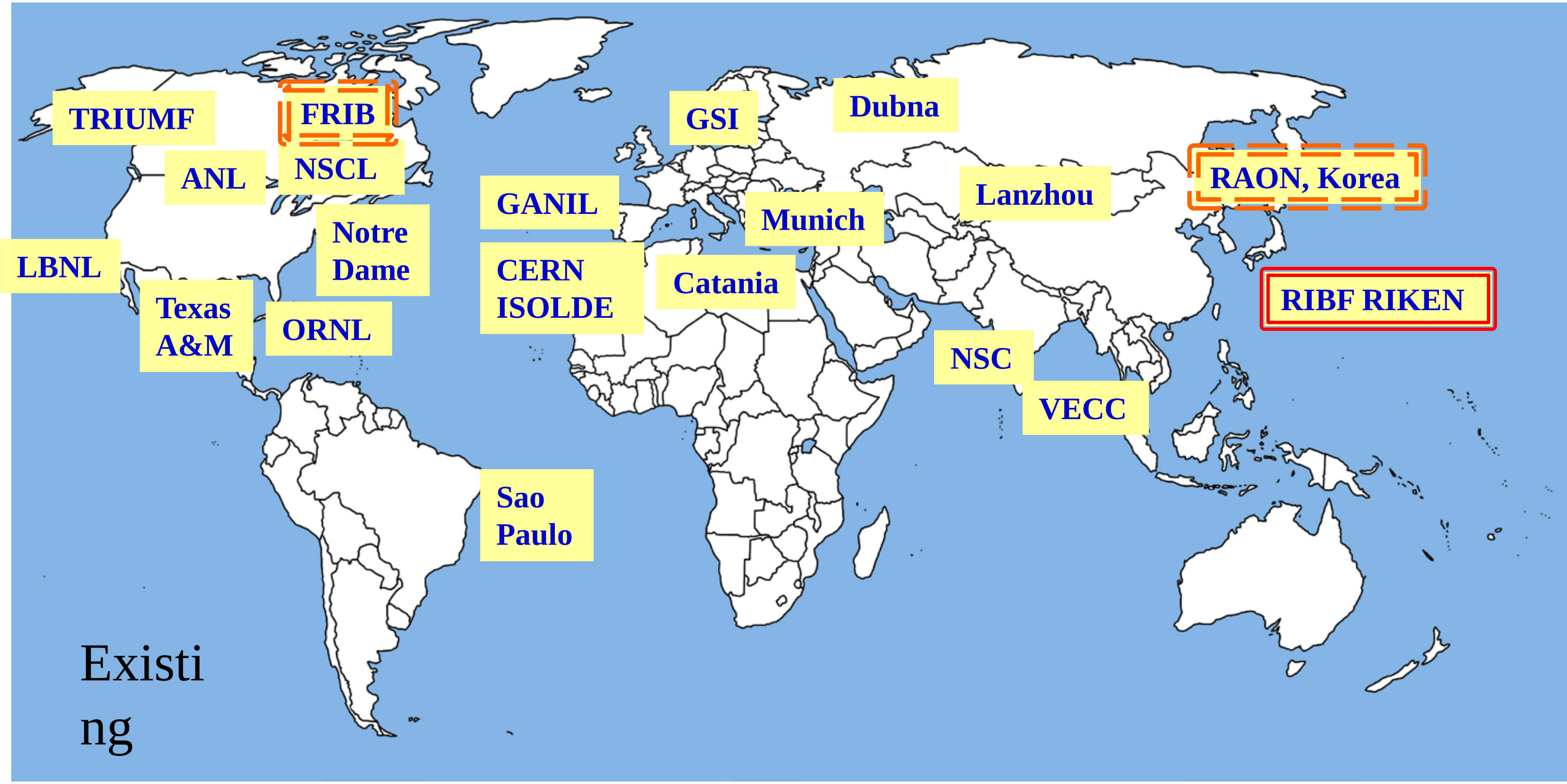
New Observables: multiplex ratios to enhance the symmetry energy signals

π^-/ π^+; n/p; t/^{3}He

Simulate the collisions with the appropriate physics

Success depends on the comparisons of observables.

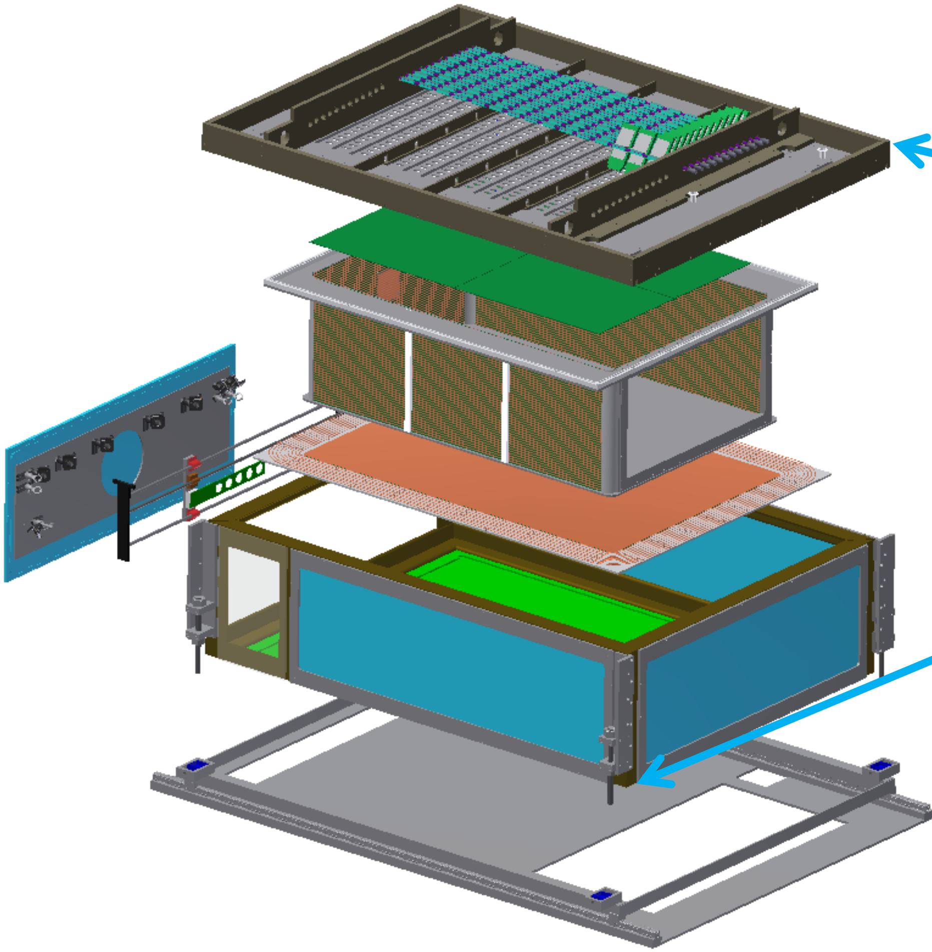
Where?

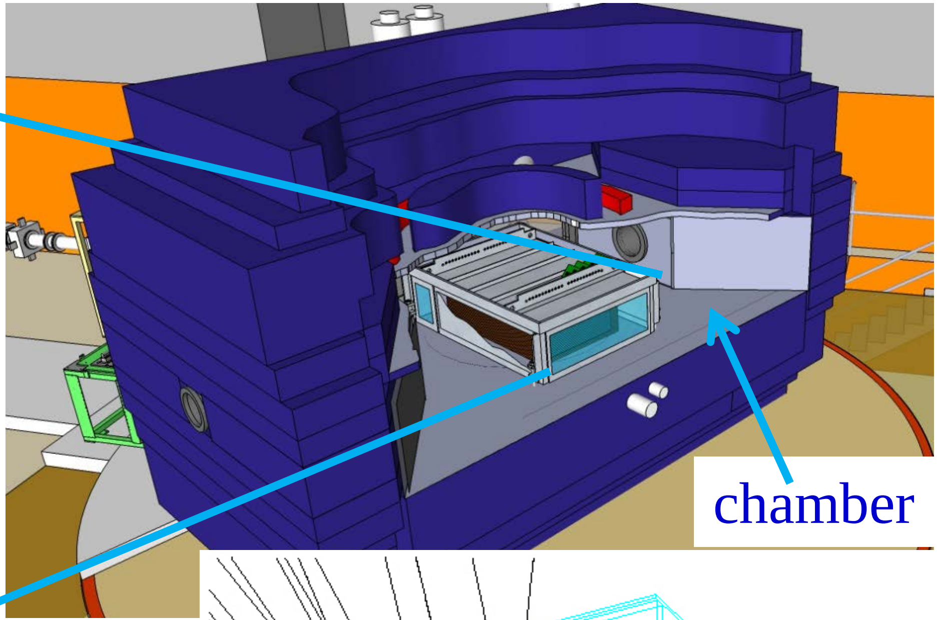


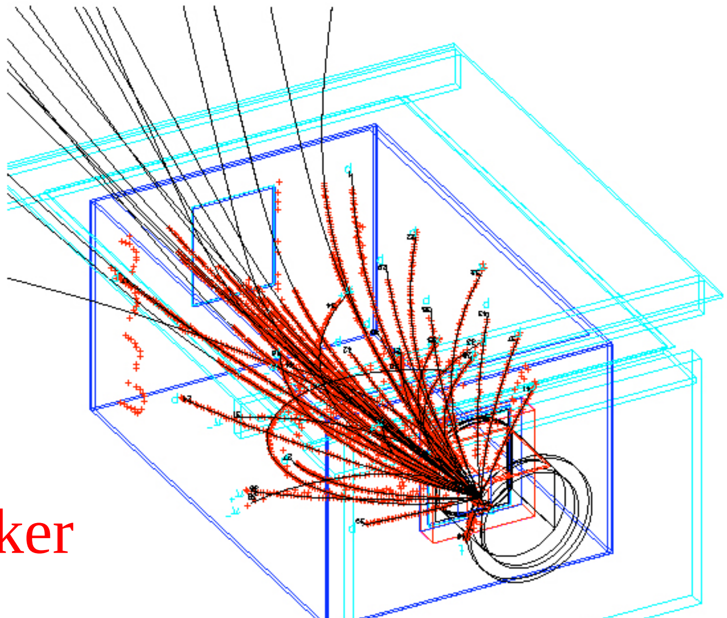
Productions of high intensity high energy Radioactive Isotope Beams

SπRIT Collaboration

Time Projection Chamber to detect pions, charged particles at $\rho \sim 2\rho_0$







SAMURAI pion
Reconstruction Ion Tracker

TPC

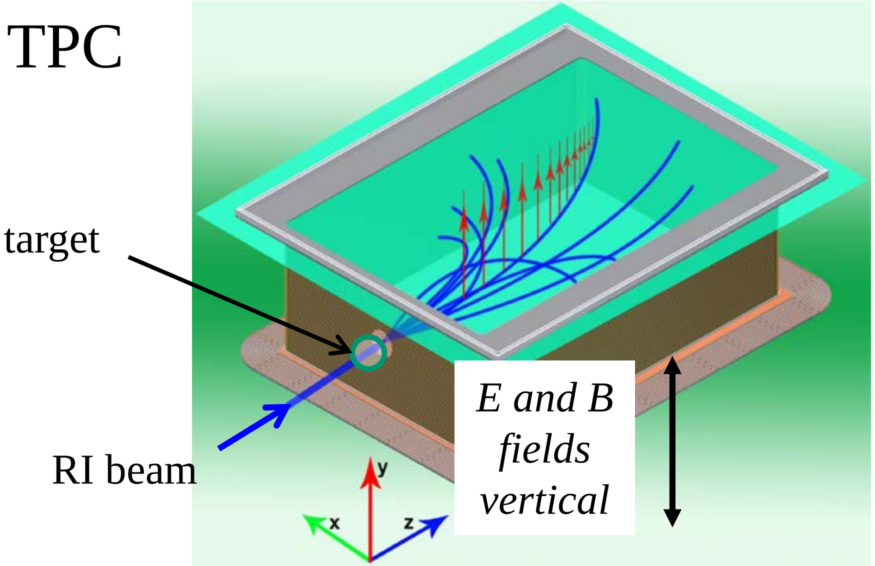


Figure courtesy of J. Estee

A Way Forward – Data

Data – Ratio observables from RIB :

- Choose observables that are less sensitive to the assumptions of the transport models
- New observables (π^+/π^- ratios) requires new detectors (TPC)

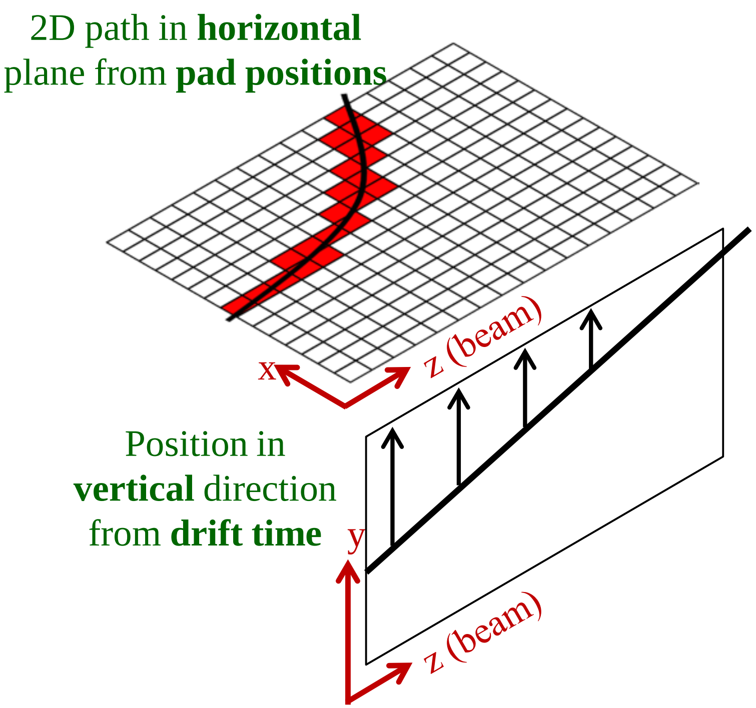
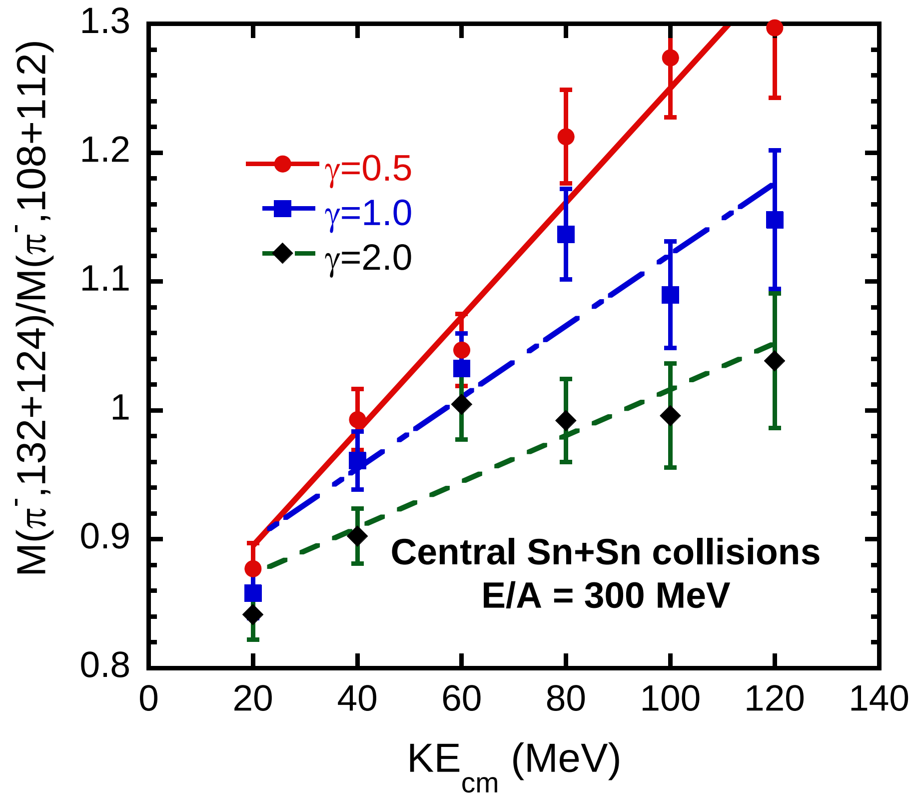
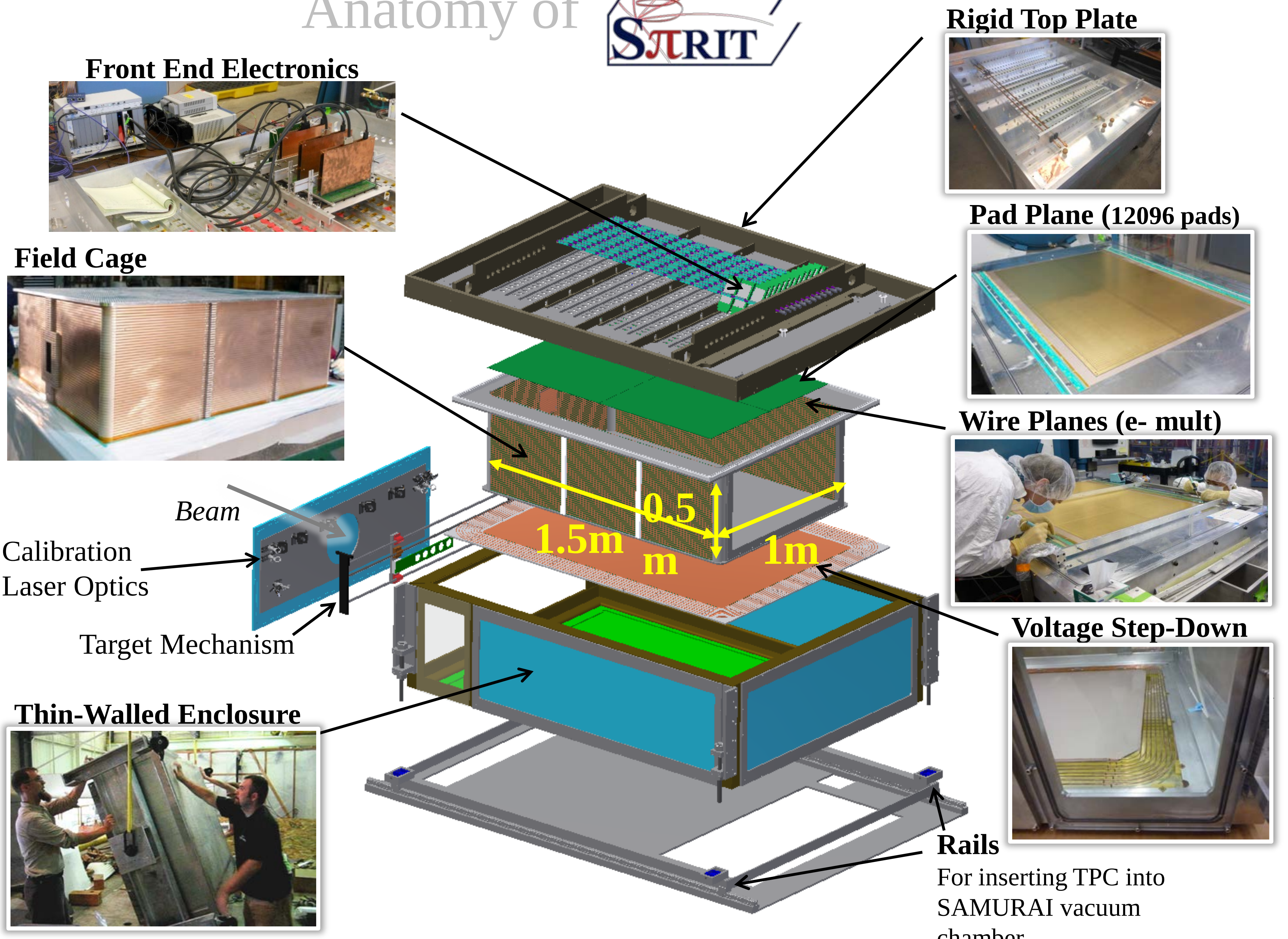


Figure courtesy of J. Barney

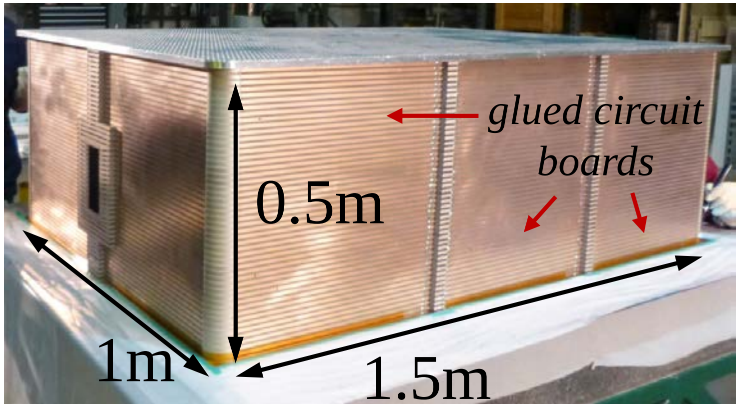


Anatomy of SπRIT

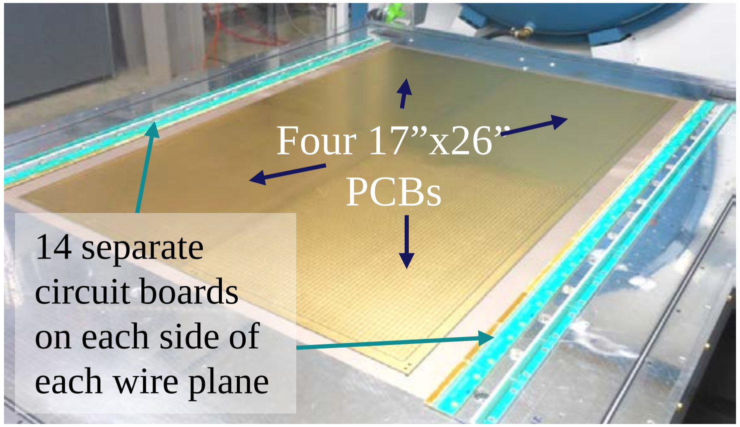


Mission Accomplished at MSU

Gluing field cage together, Feb 2013



Pad and wire planes, March 2013

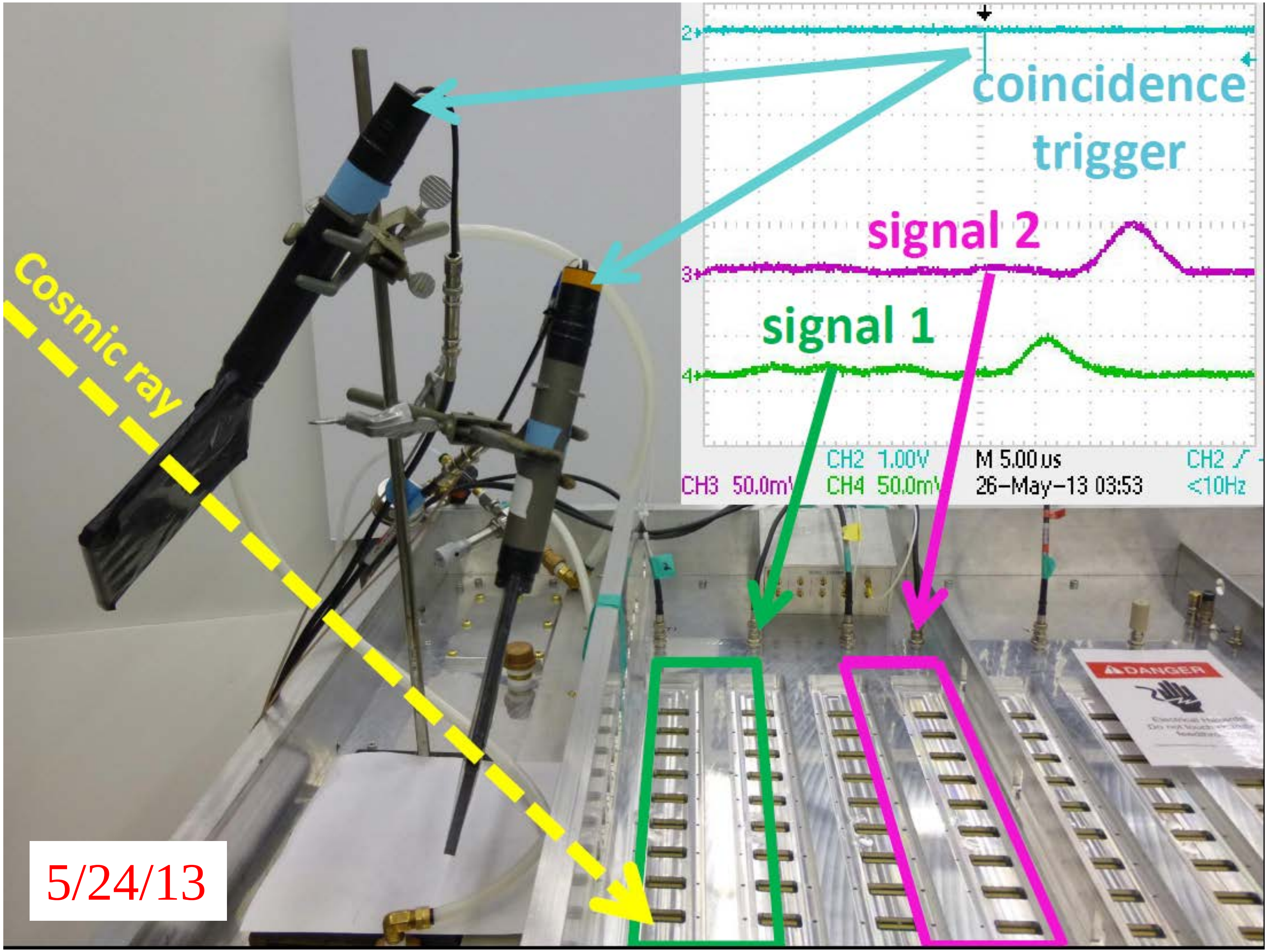


Assembled for initial testing, May 2013

- Pad plane flat to within 0.005" (125 um)
- Field cage and enclosure gas-tight
- Cathode of field cage tested to 5 kV
- Anode wires tested to 2 kV

Before shipping, low tech quality control

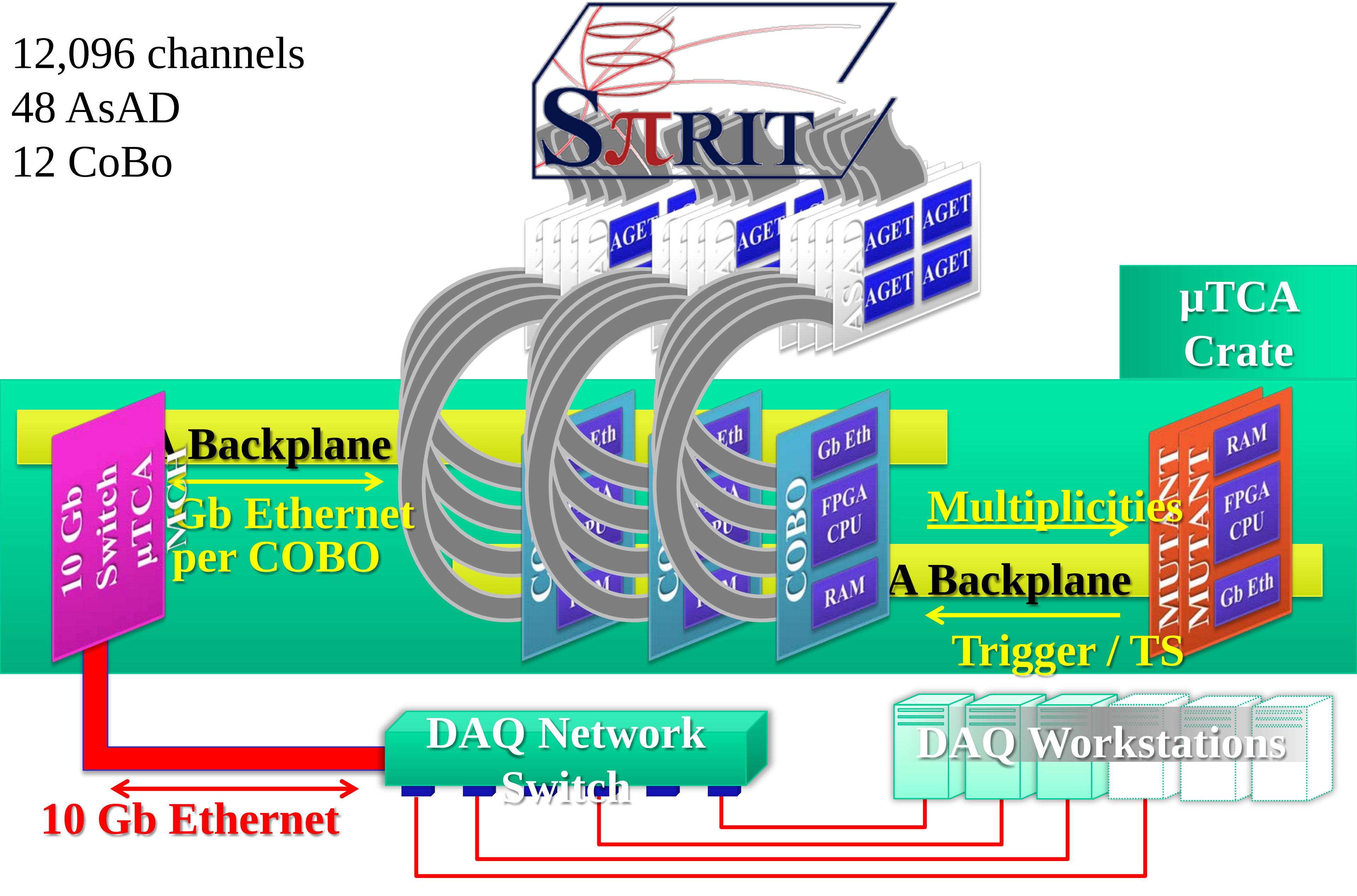
Detection of cosmic signals



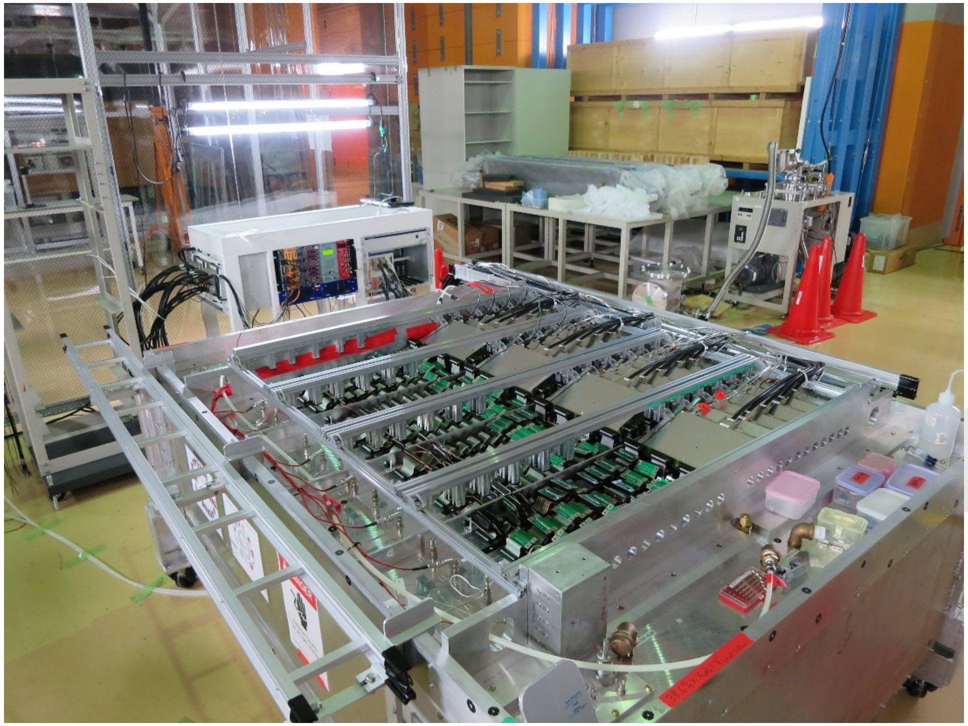
What did Genie do in summer of 2014

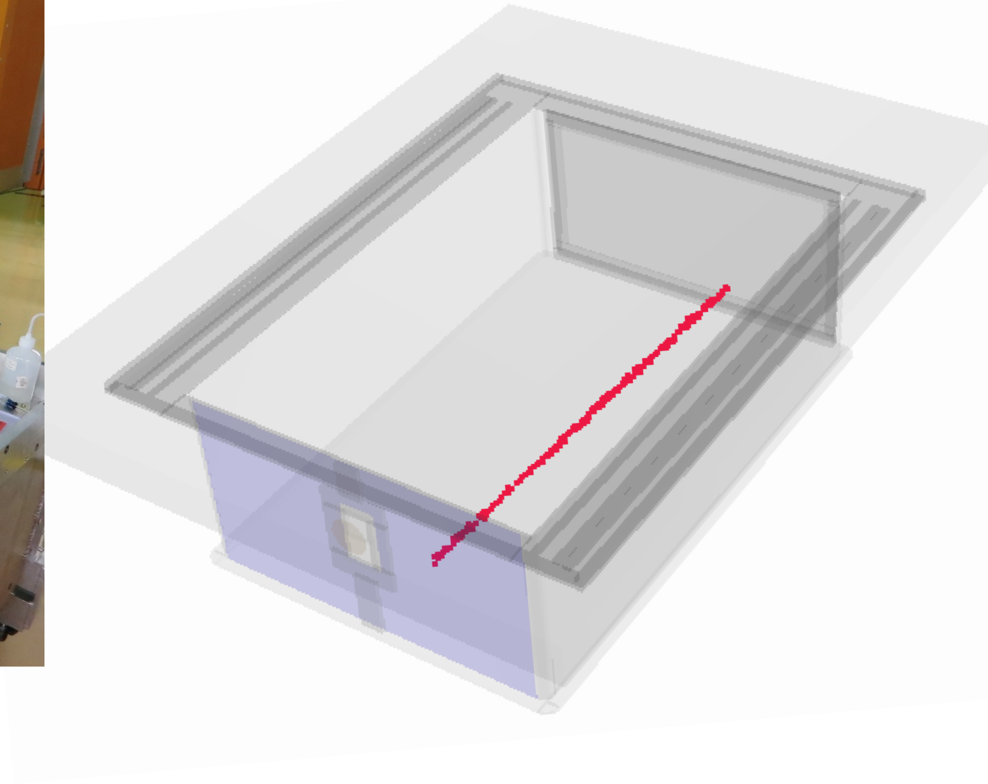
Hardware Architecture – GET

12,096 channels
48 AsAD
12 CoBo



Cosmic tracks with GET (6048 channels)





Heavy Ion Collisions at high density with RIB

Old data: Au+Au, E/A=150 to 1500 MeV

Proposed New Experiments at RIB facilities

pi-/pi+		300 MeV & 200 MeV			
Beam	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
132Sn	124Sn	1.64	1.48	1.56	0.16
132Sn	112Sn	1.64	1.24	1.44	0.40
108Sn	124Sn	1.16	1.48	1.32	-0.32
108Sn	112Sn	1.16	1.24	1.20	-0.08
124Sn	124Sn	1.48	1.48	1.48	0.00
112Sn	112Sn	1.24	1.24	1.24	0.00
112Ru	112Sn	1.55	1.24	1.38	0.31
126Sn	112Sn	1.52	1.24	1.38	0.28

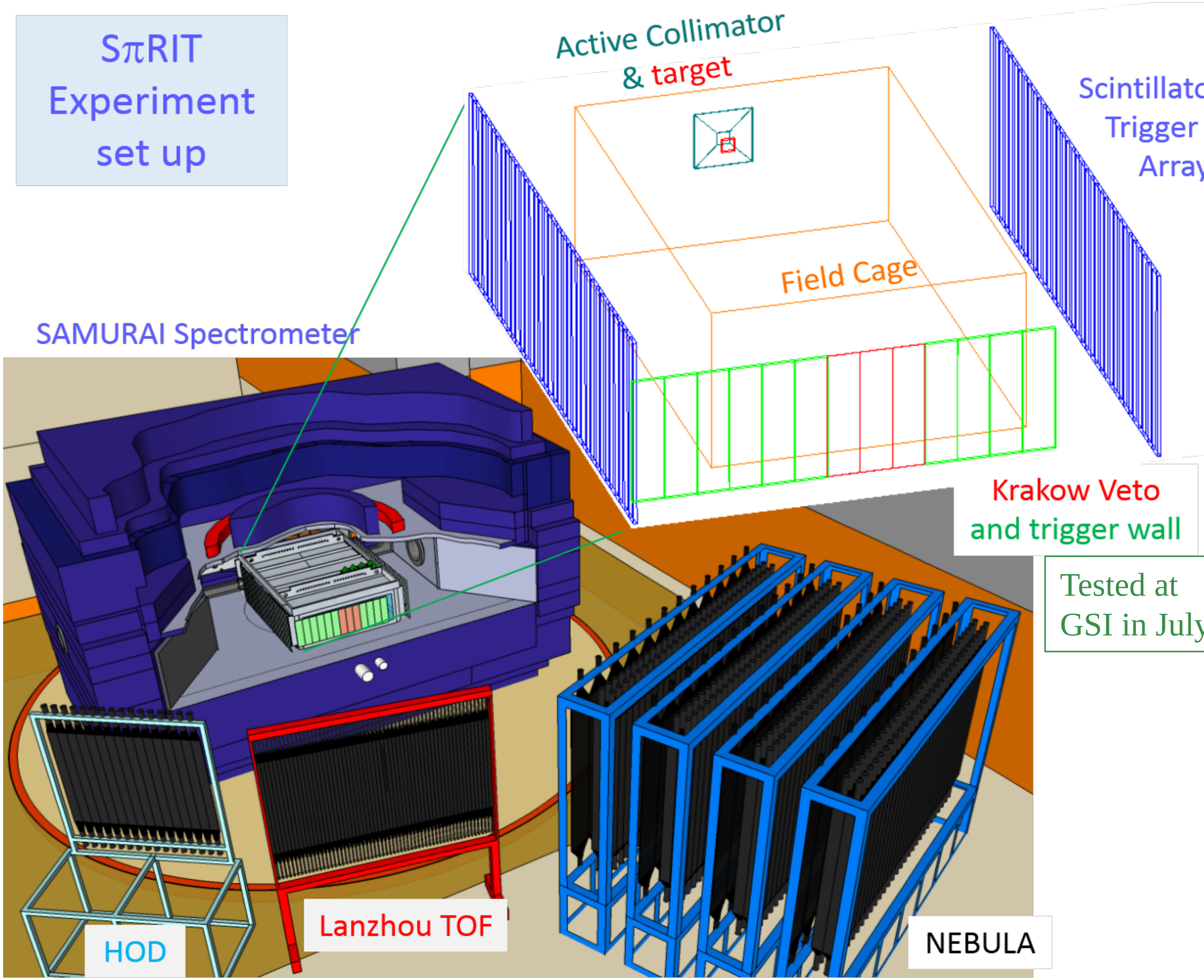
Beam	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
132Sn	64Ni	1.64	1.29	1.51	0.35
108Sn	58Ni	1.16	1.07	1.13	0.09

Beam	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
56Ni	58Ni	1.00	1.07	1.04	-0.07
68Ni	64Ni	1.43	1.29	1.36	0.14

13.5 days approved by June and Dec, 2013 RIKEN PAC

Day 1 experimental setup

To be Tested at
HIMAC in Nov.

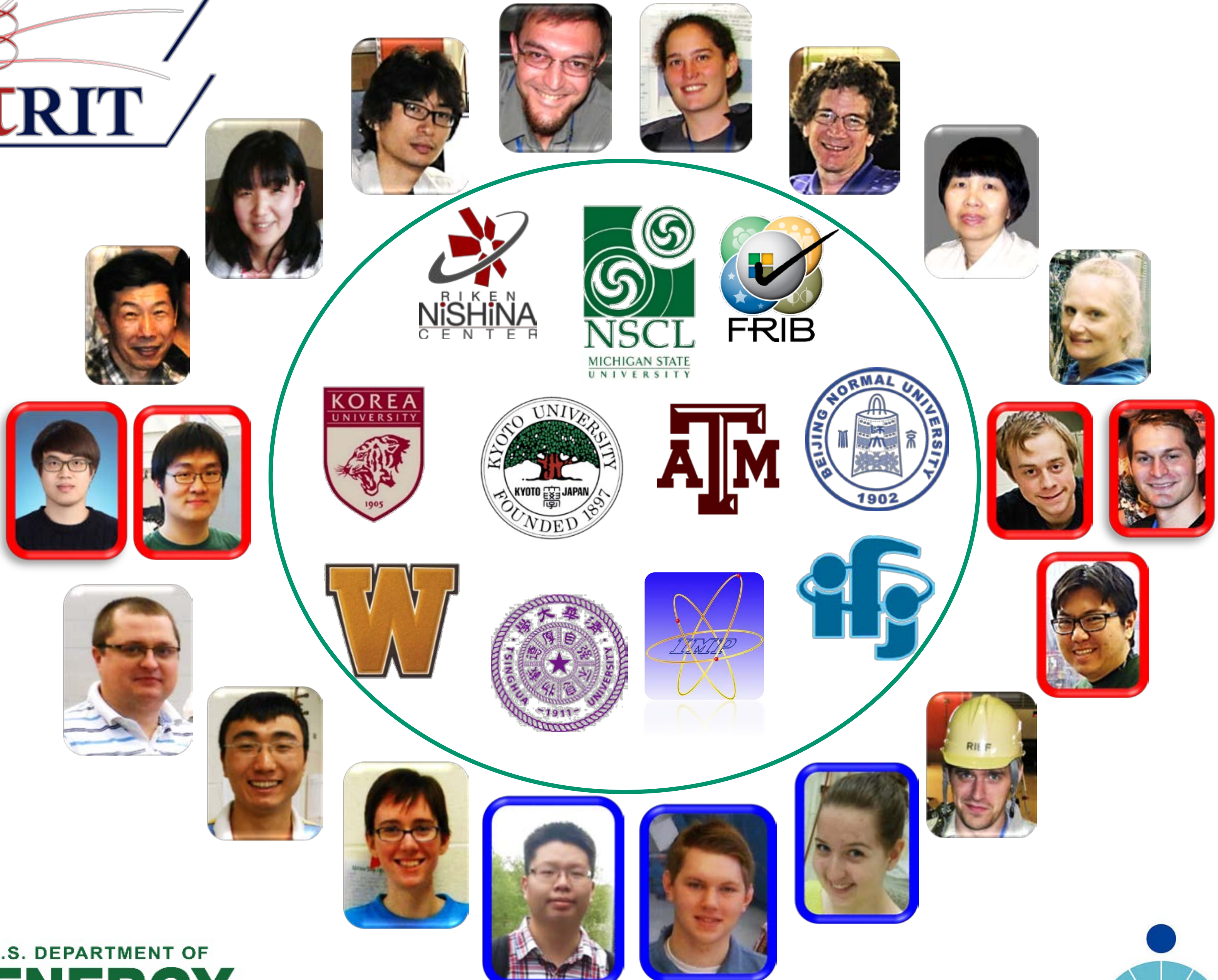


Tested at
GSI in July

Summary

- Nuclear Physics is important for our understanding of our world and compact objects in our universe.
- Consistent constraints on the symmetry energy at sub-saturation densities with different types of experiments suggest that heavy ion collisions provide a good probe at high density.
- Observation of small NS radius and high mass suggests a softening of SE at $\rho \sim 2\rho_0$ → Next frontier is the Heavy Ion collisions at RIB facilities ~200-300 MeV per nucleon.
- SπRIT collaboration is ready for action this Fall.
- Workshop on Science with SπRIT TPC, June 5-6, RIKEN, Japan

SπRIT



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