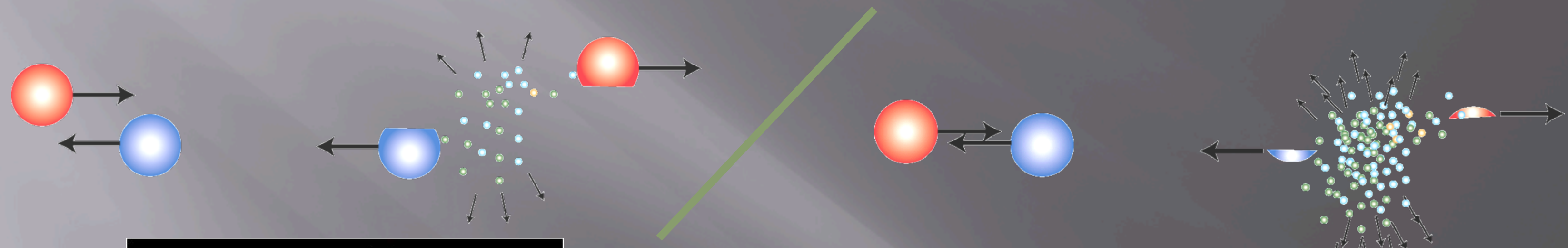
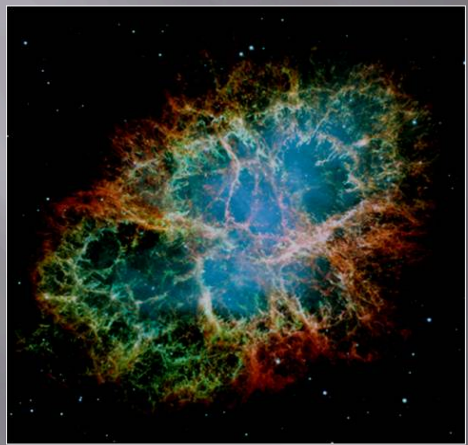
HOW TO PROBE EQUATION OF STATE OF NEUTRON-RICH NUCLEAR MATTER





Department of Physics
Kyoto University
Tetsuya MURAKAMI

Neutron Star Matter

Nuclear Equation of State

$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2 + o(\delta^4)$$

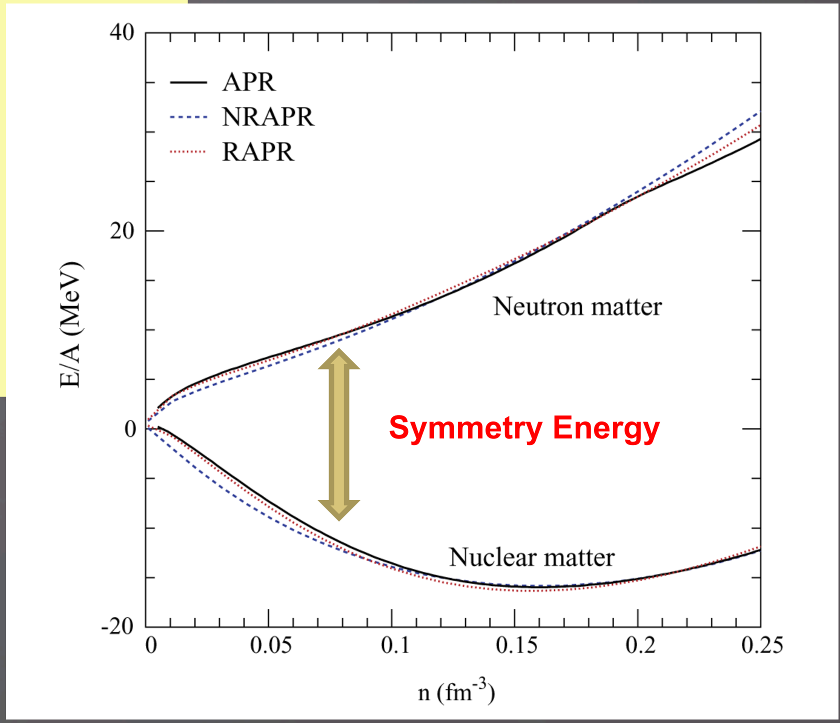
$$\delta = (\rho_n - \rho_p)/\rho$$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\varepsilon + \frac{K_{sym}}{2}\varepsilon^2 + o(\varepsilon^3)$$

$$\varepsilon = (\rho - \rho_0)/3\rho_0$$

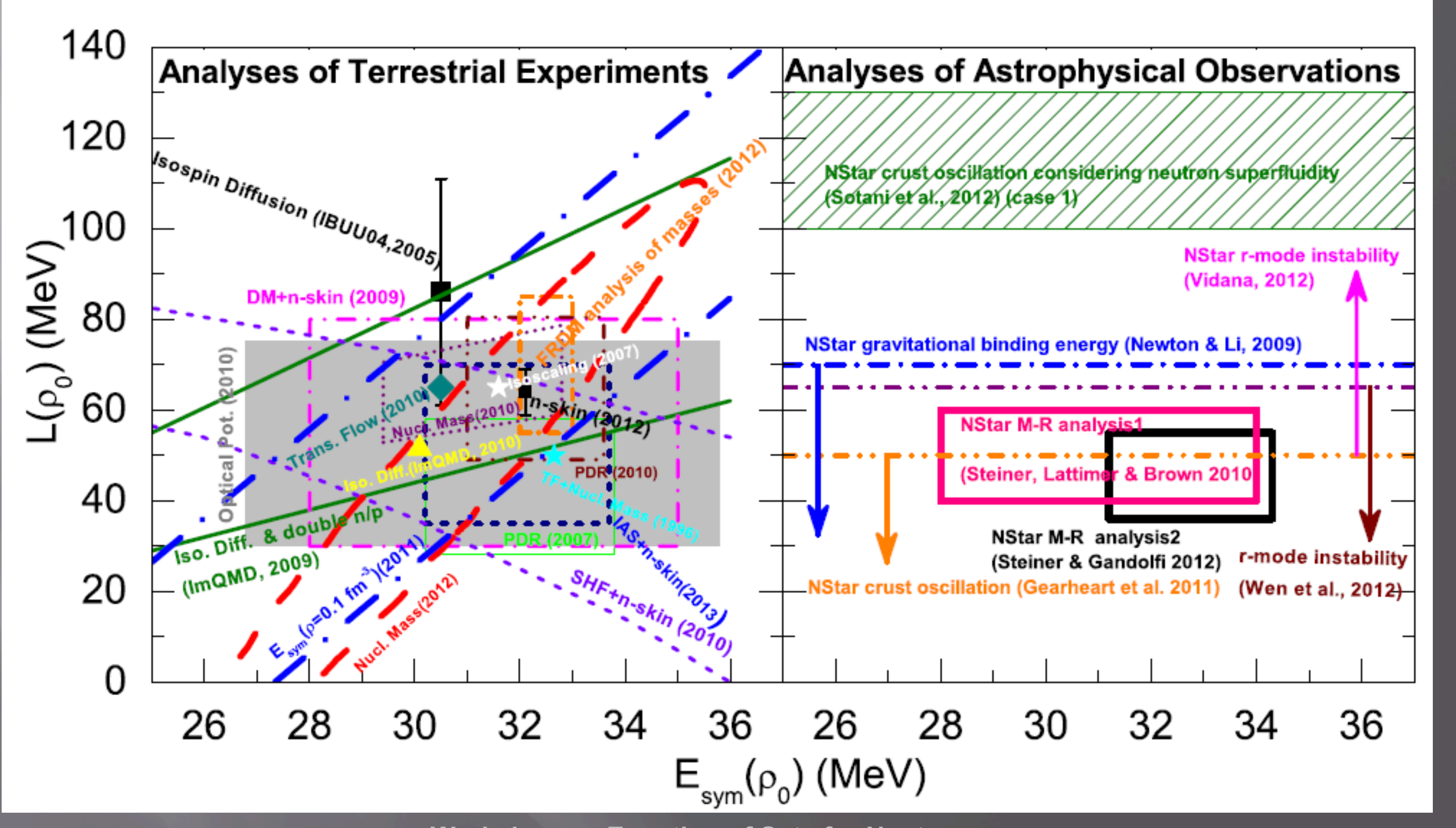
$$S_0 = E_{sym}(\rho_0) \Rightarrow J\,;sometimes$$

$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\bigg|_{\rho=\rho_0} = (3/\rho_0)P_0$$

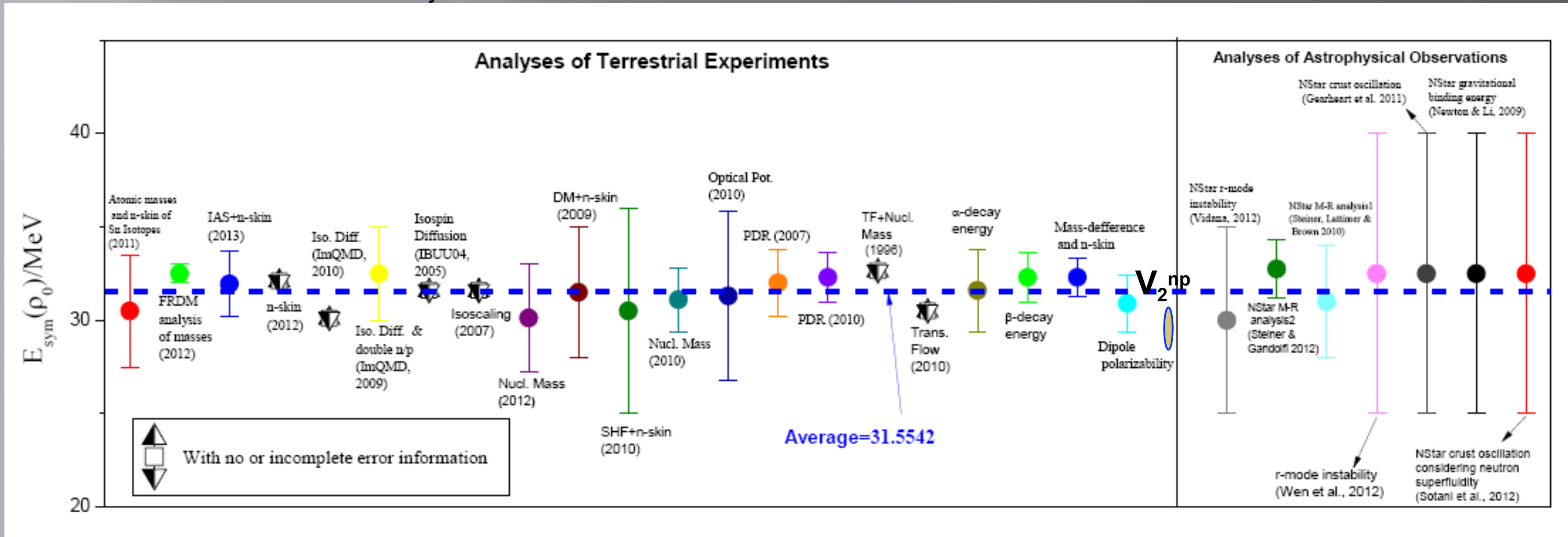


A.W. Steiner et al., Phys. Reports 411（2005）325

From summary talk at NuSYM13 by Bao-An Li (next two slides)

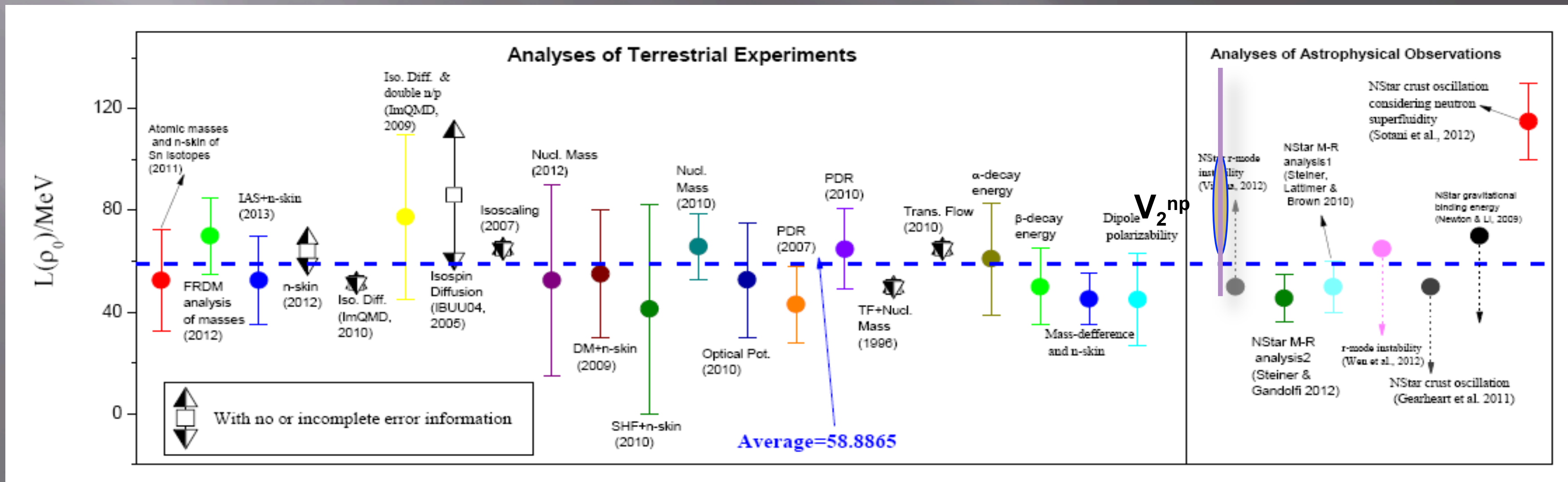


Nusym13 constraints on $E_{sym}(\rho_0)$ and L based on 29 analyses of some data



	E_{sym}	L
average of the means	31.55415	58.88646
standard deviation	0.915867	16.52645

Currently impossible to estimate a physically meaningful error bar



Quick Review of Each Approach Related "Our Innovative Area"

FRDM: mass formula

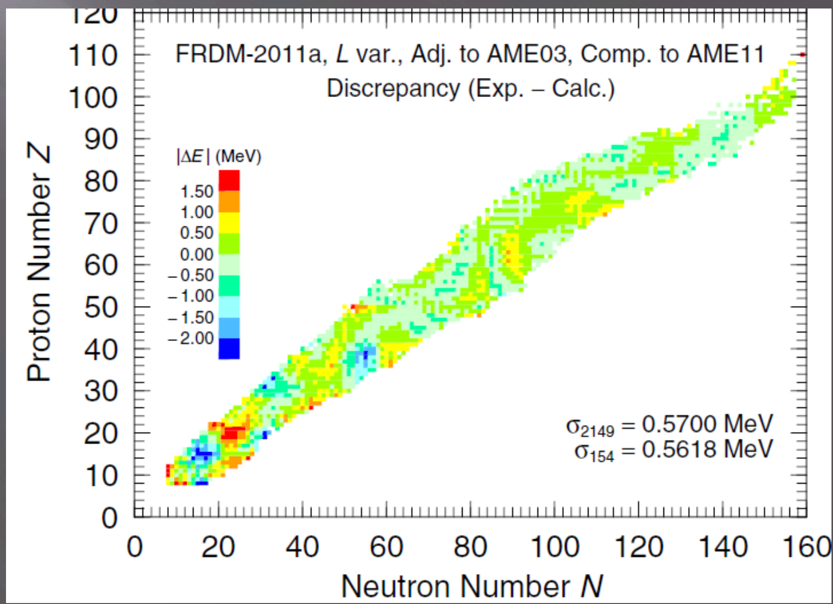
P. Moller et al. ; Phys. Rev. Lett 108 (2012) 052501

Conventional liquid drop model

$$BE = -a_1 A + a_2 A^{2/3} + a_3 (Z^2/A^{1/3}) + a_4 (N-Z)^2/A + \delta E$$

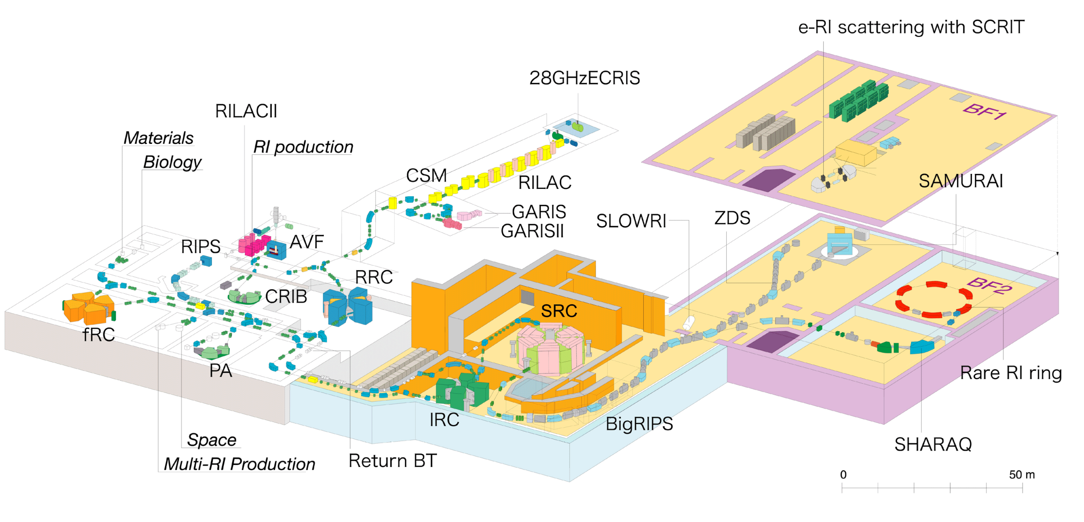
New approach using Finite Range Droplet Model incorporated with the density dependence of symmetry energy can provides accurate biding energies better than 0.2% for all mass available in AME10.

$S_0 = 32.5 \pm 0.5$ MeV and
$L = 70 \pm 15$ MeV

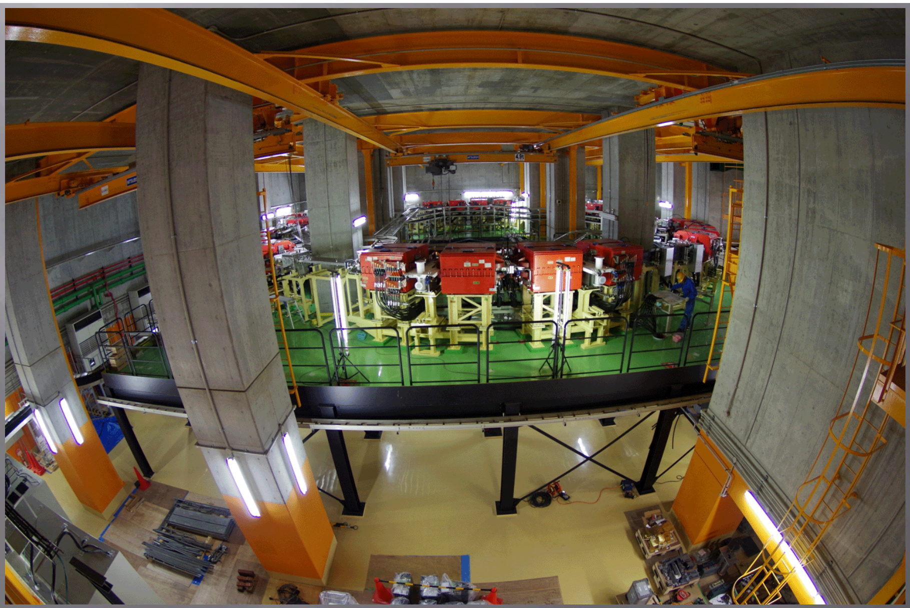


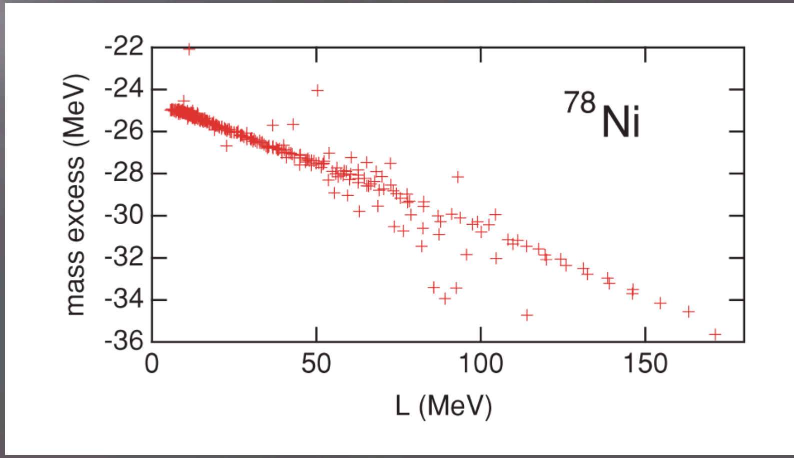
Future Direction of Mass Measurement:

A. Ozawa (Tsukuba Univ.) Group



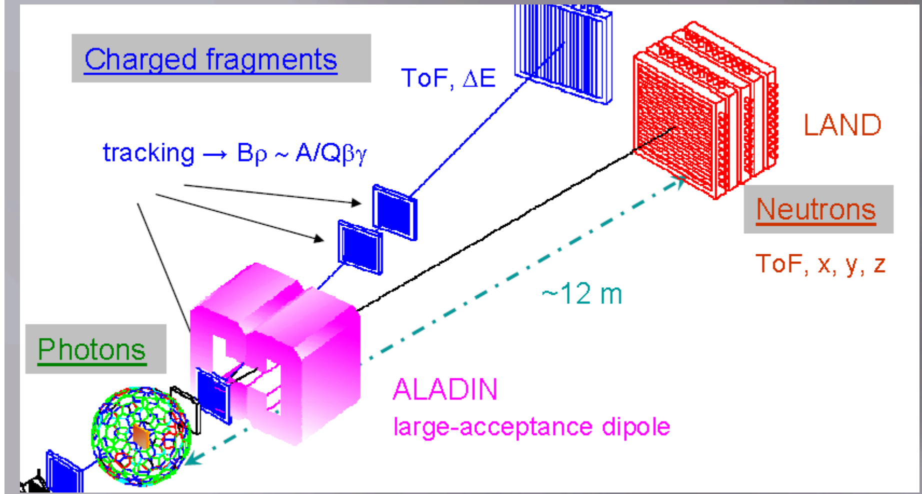
Measure mass of ^{78}Ni with an accuracy of 10^{-6} to determine L

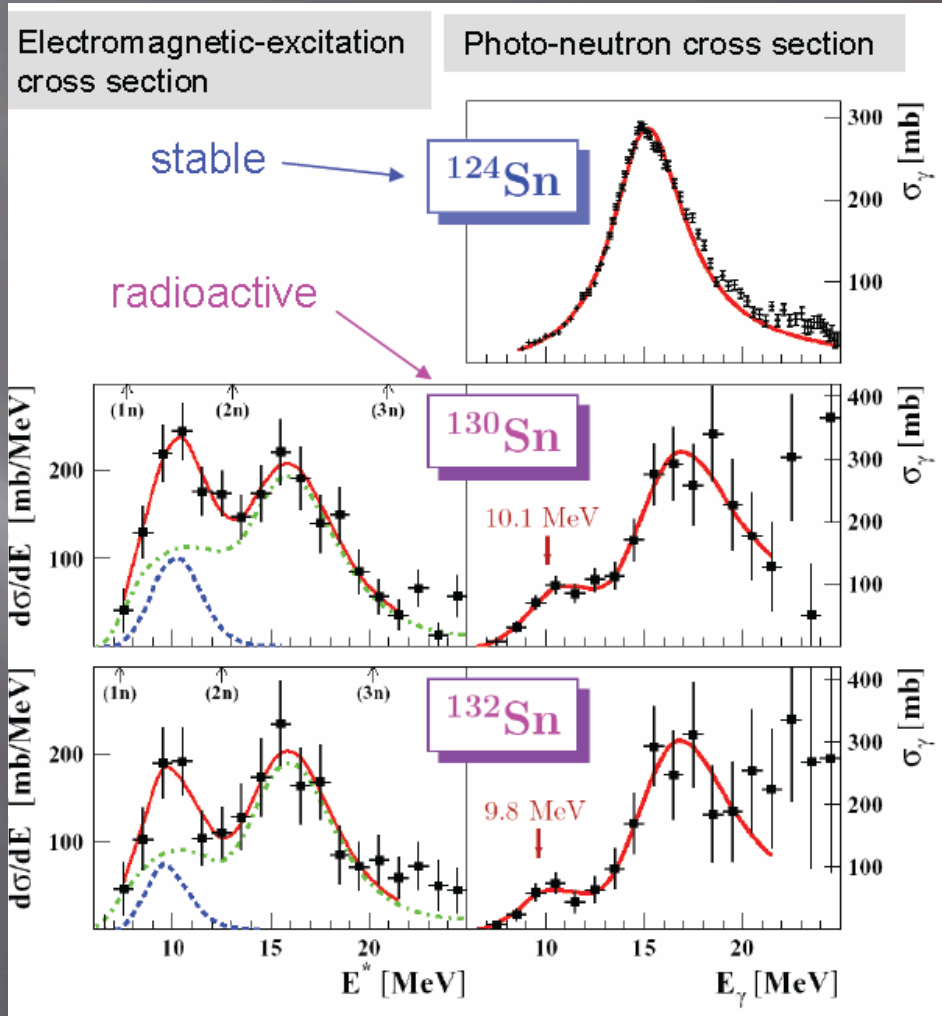




K. Oyamatsu and K. Iida, Phys. Rev. C 81 (2010) 054302

Pygmy Dipole Resonances



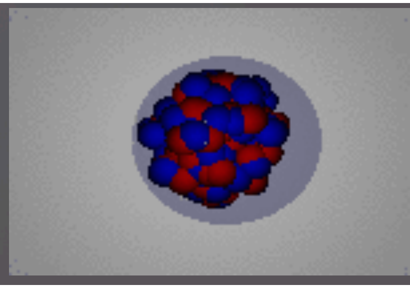


From ^{68}Ni and ^{132}Sn data

L **= 64.8 ± 15.7MeV and**

S_o=32.3±1.3 MeV

(Carbone et al. PRC 81, 041301 (2010))



SAMURAI Magnet

Superconducting Analuzer for Multi particles from Radio Isotope Beams

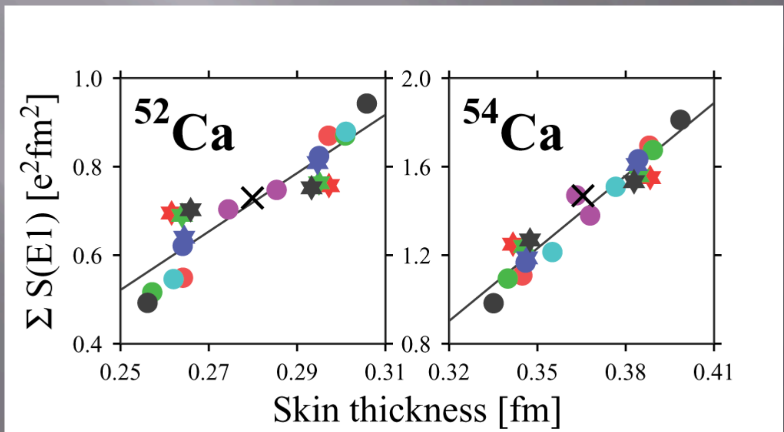
Future Direction:
CATANA for SAMURAI (T. Togano (TIT) et al.)

Isovector dipole response of $^{48\text{-}52}Ca$

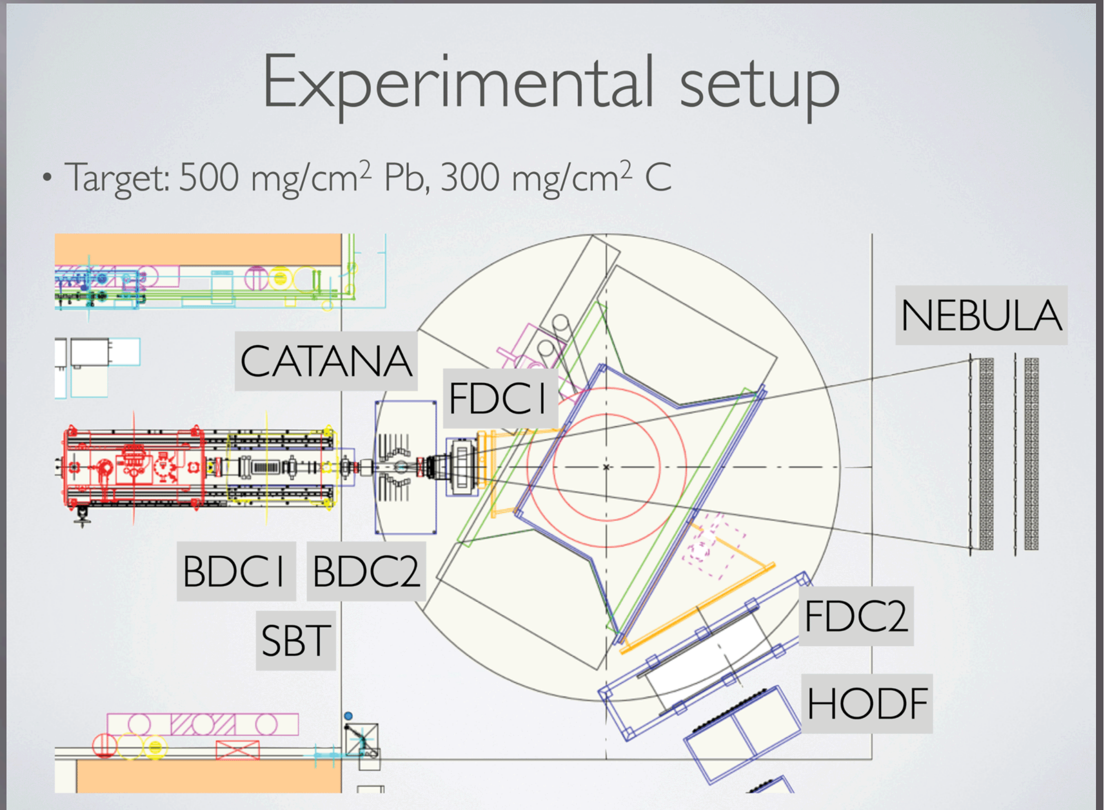
→ skin thickness, EOS

PDR strength and

dipole polarizability



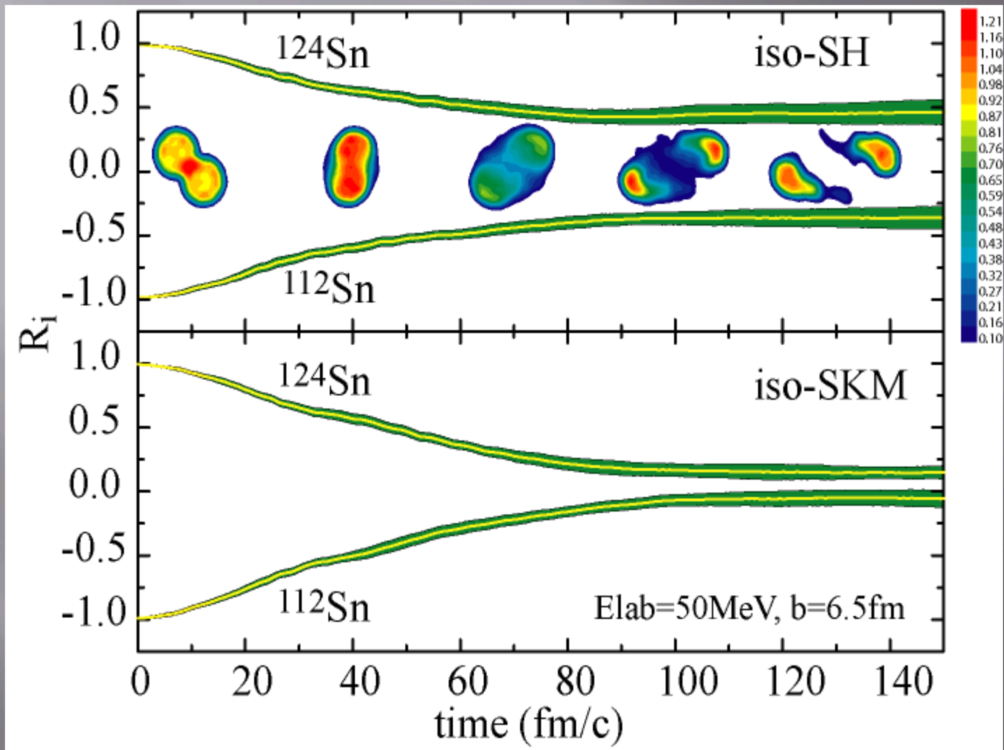
T. Inakura et al., arXiv:1306.3089

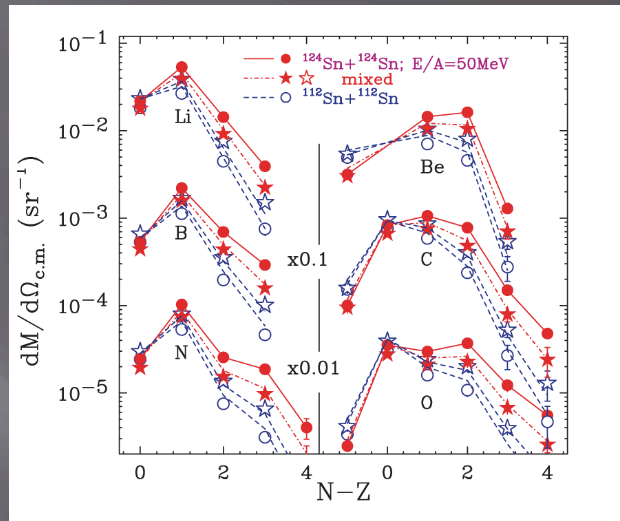


Heavy Ion Collisions
compared to transport theory calculation
NSCL/MSU group

- Isospin diffusion in peripheral collisions

Tsang et al., PRL 92 (2004) 062701





$$R_{21}(N,Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)} \approx C\exp(N\alpha + Z\beta)$$

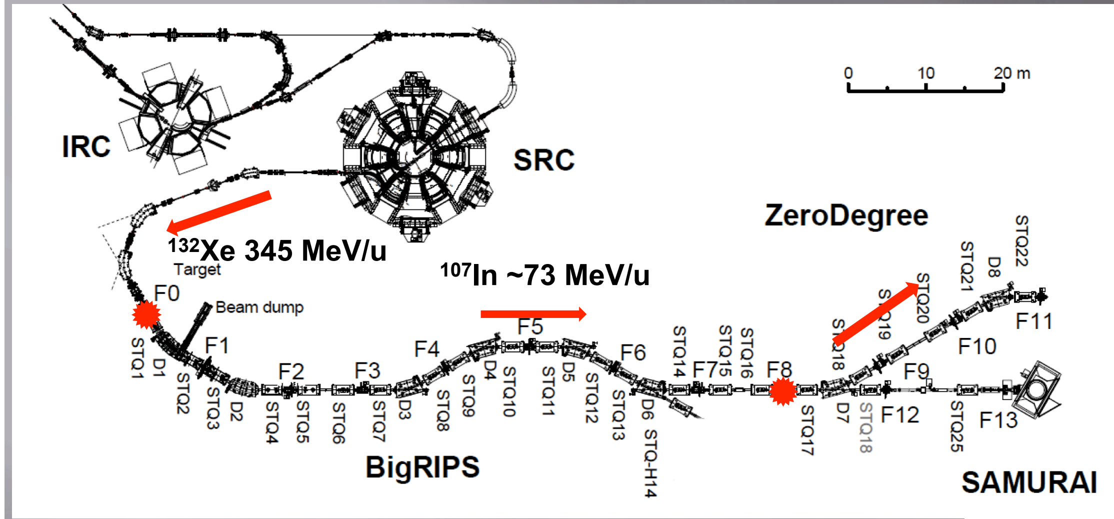
$$R_i(X) = 2\frac{X - (X_{A+A} + X_{B+B})/2}{X_{A+A} - X_{B+B}}$$

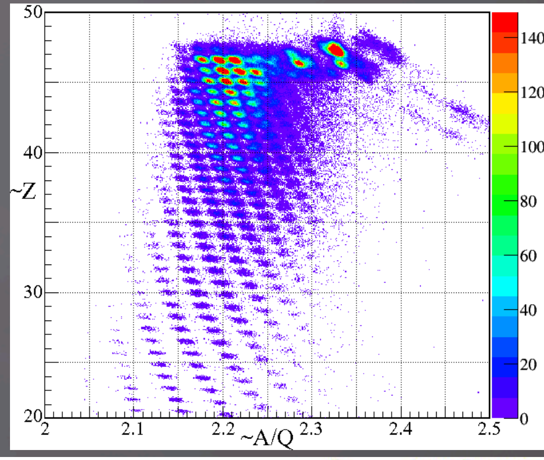
- Yield ratio of neutron and proton

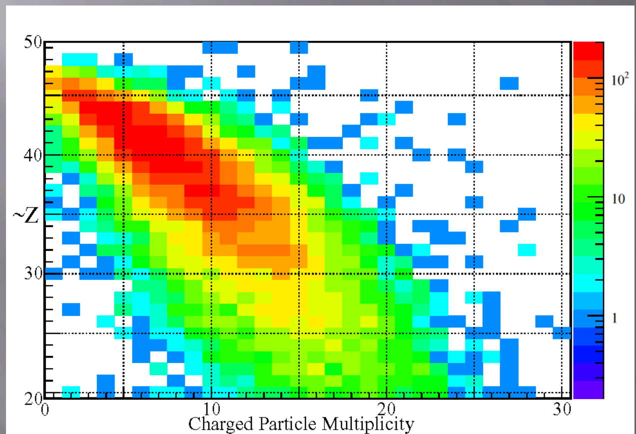
Zhang et.al.,Phys. Lett. B 664 (2008) 145

Extention at RIBF

MSU/TAMU/RIKEN/Kyoto Group in June 2013

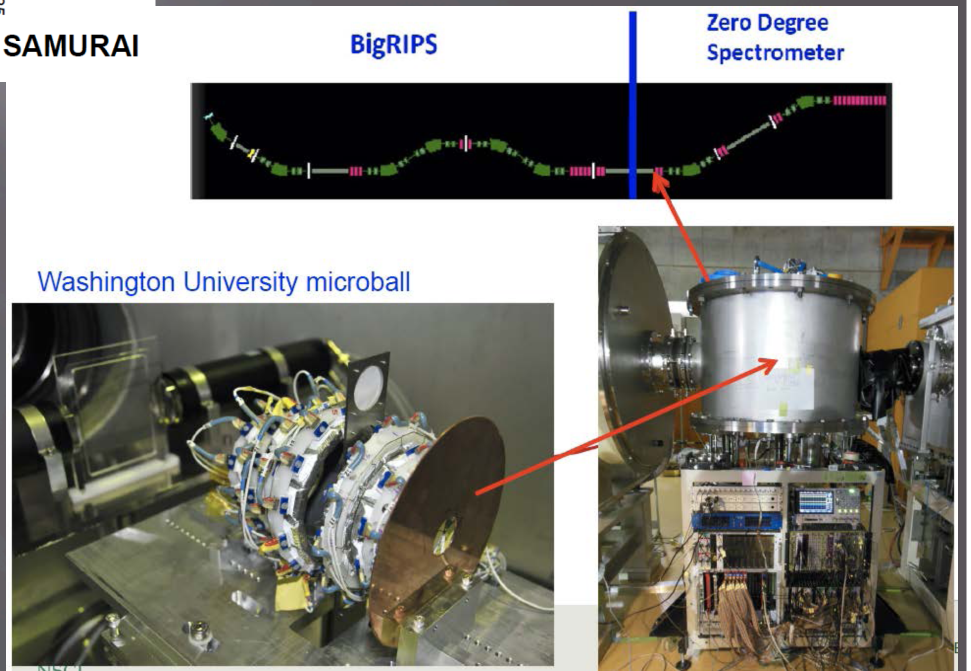






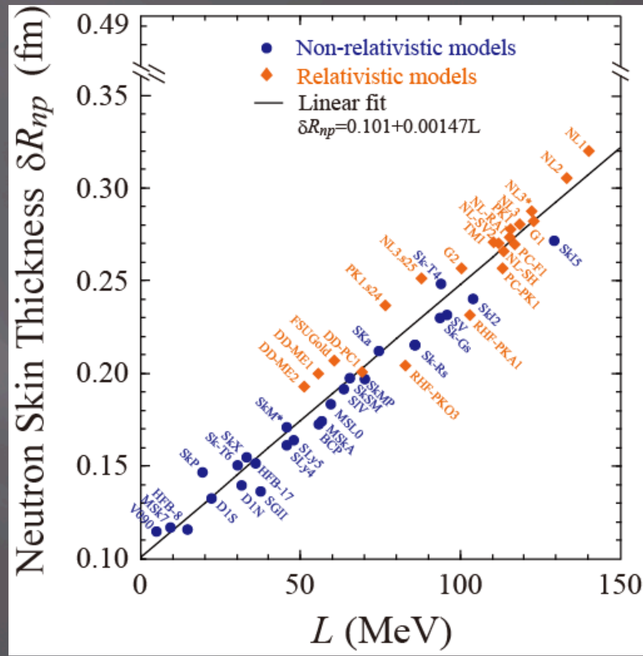
^{107}In(beam, ~73MeV/u) +^{124}Sn (Target)

^{112}Sn(beam, ~73MeV/u) +^{112}Sn (Target)



From neutron skin thickness for Pb

- Parity violation electron scattering
  Pb Radius Experiment (PREx) at Jefferson Lab.
  $\Delta R_{np}=0.33^{+0.16}_{-0.18}$ fm
  (S. Abrahamyan et al. PRL 108, 112502 (2012))
- Dipole Polarizability and PDR
  $\Delta R_{np}=0.156^{+0.025}_{-0.021}$ fm (Tamii et al. PRL 107, 062502 (2011))
  $=0.194\pm0.024$ fm (Carbone et al. PRC 81, 041301 (2010))
- Antiproton Atoms
  $\Delta R_{np}= 0.15\pm0.02$ fm (Trzcinska et al. PRL 87, 082501 (2001))
- Proton elastic scattering
  $\Delta R_{np}=0.211^{+0.054}_{-0.063}$ fm(Zenihiro et al. PRC82, 054607 (2010))

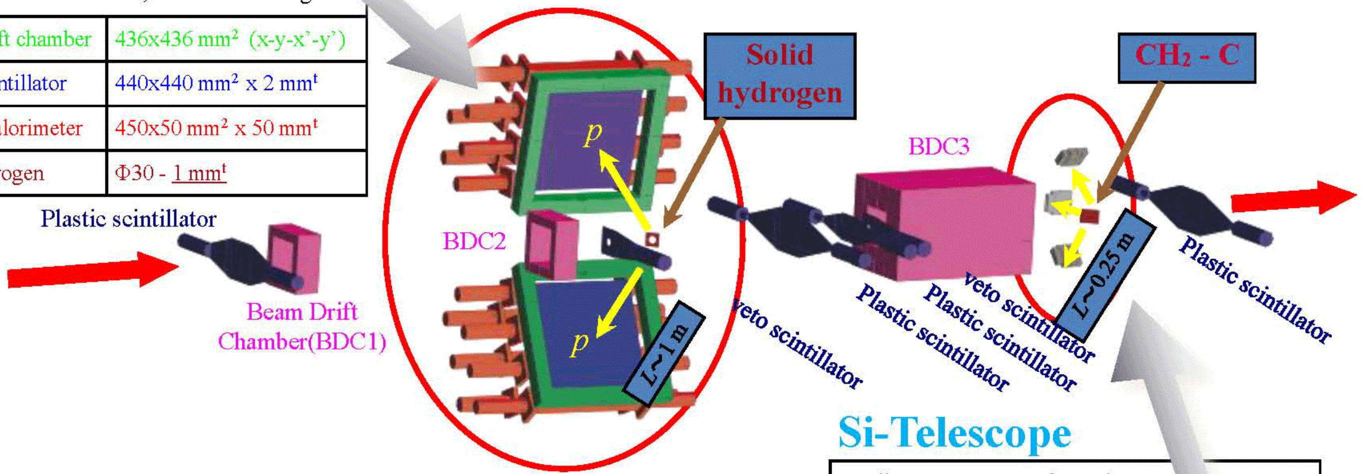


X. Roca-Maza *et al., PRL106, 252501 (2011)*

Future Direction:
ESPRI Group (J. Zenihiro et al.)

Recoil Proton Spectrometer (RPS)

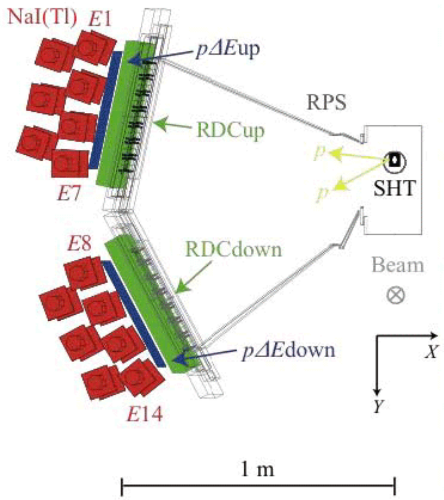
Large momentum transfer region θ_{lab} = 66 - 80°, Ep=20 – 120 MeV, ΔΩ∼10 msr/deg.		
RPS	Recoil drift chamber	436x436 mm² (x-y-x'-y')
	plastic scintillator	440x440 mm² x 2 mm^t
	NaI(Tl) calorimeter	450x50 mm² x 50 mm^t
Target	Solid hydrogen	Φ30 - 1 mm^t



Si-Telescope

Small momentum transfer region
θ_{lab} = 75 - 85°, Ep=5 – 50 MeV ΔΩ∼14 msr/deg.

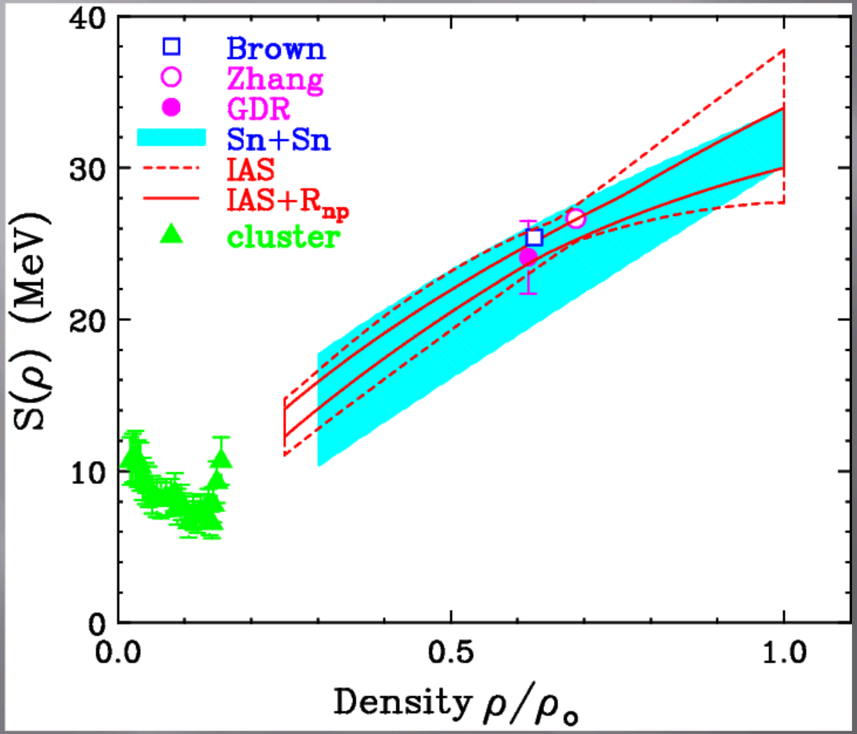
- Missing mass spectrometer : $P^{\mu}_{beam}+P^{\mu}_{p} \Rightarrow E_x$ (ΔEx~400 keV)
- Cover extensive momentum transfer region : up to ∼2.5 fm^{-1}

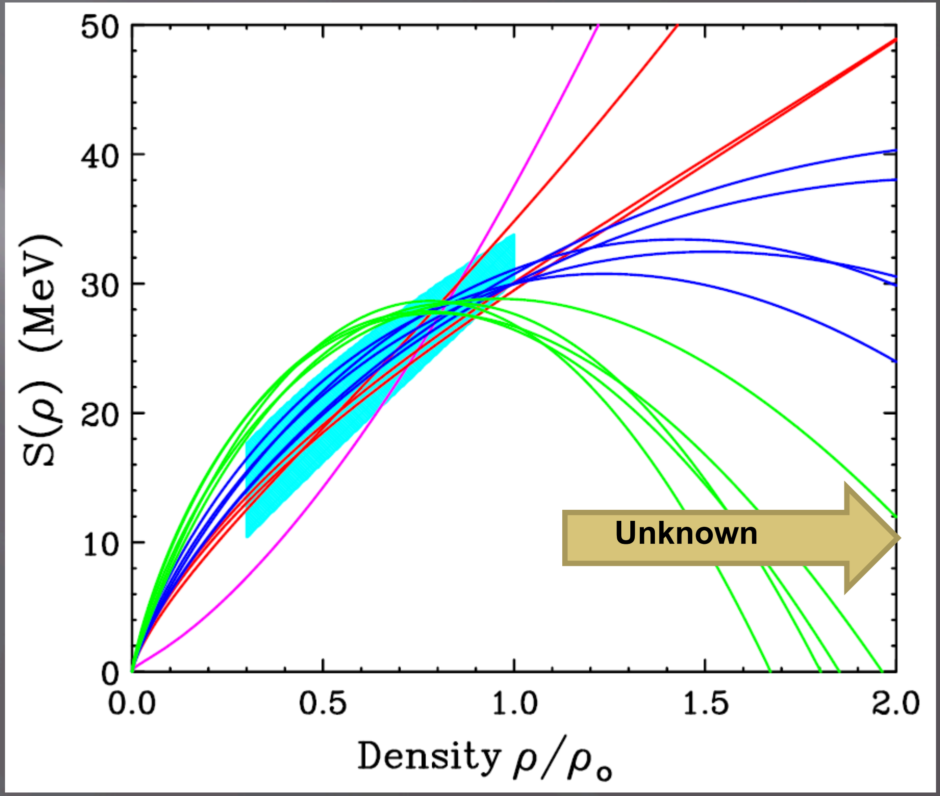


Elastic Scattering of Protons with RI beam

^{132}Sn : flag-ship nuclei as a next step from ^{208}Pb (NP1112-RIBF79)

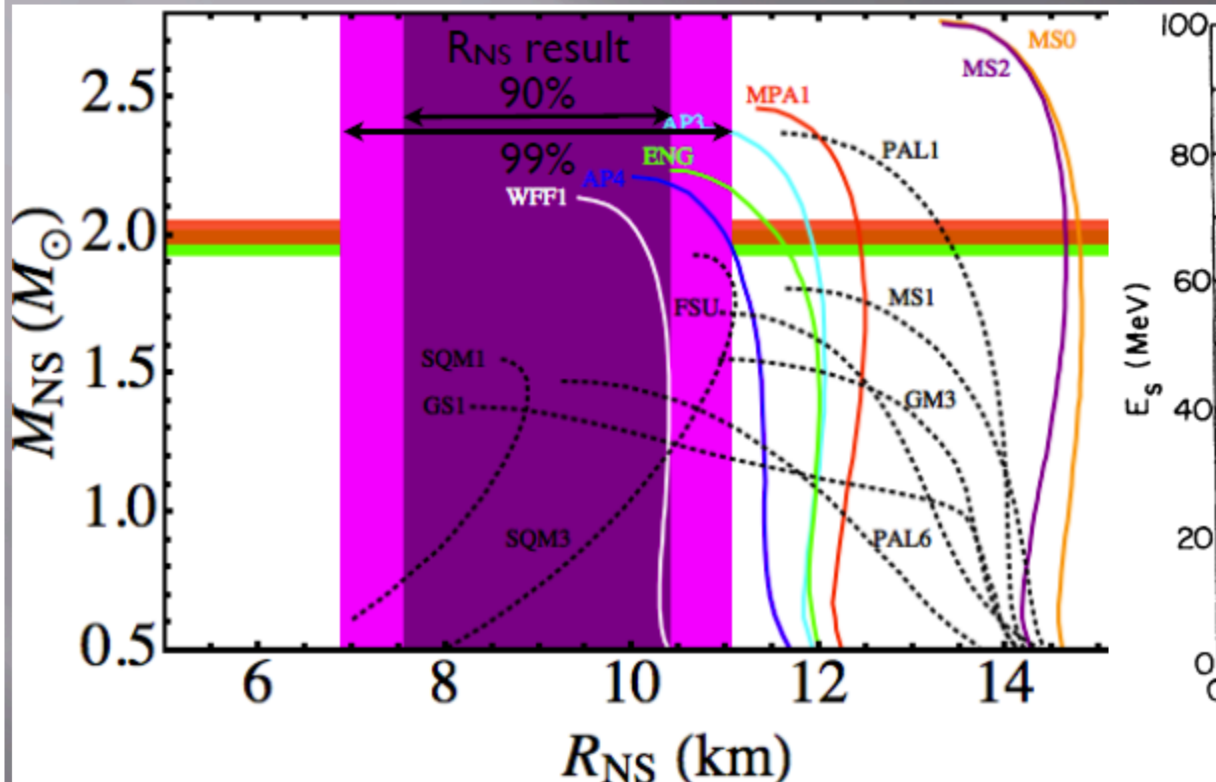
Updated Constraints from NuSYM13



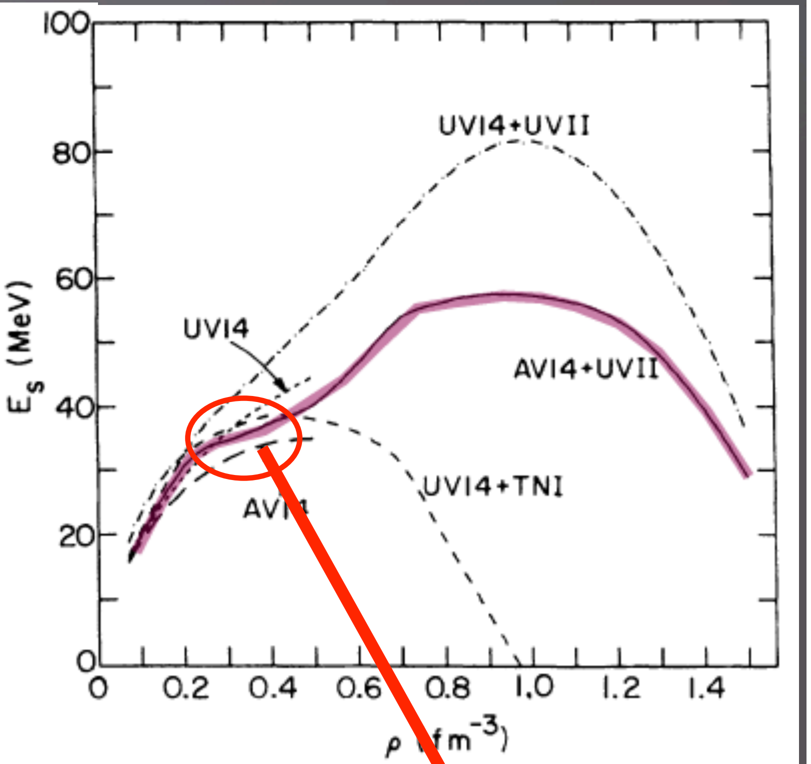


Surprising Astrophysical Observation!!

Neutron star (Rutledge, Gulliot et al.)
APJ 2013 to be published



AV14+UVII ;
Wiringa, Fiks, & Fabrocini ,
Phys. Rev. C 38, 1010 (1988)



Observation:

$M_{NS} \sim 2M_{sun}$

$R_{NS} \sim 9$ km

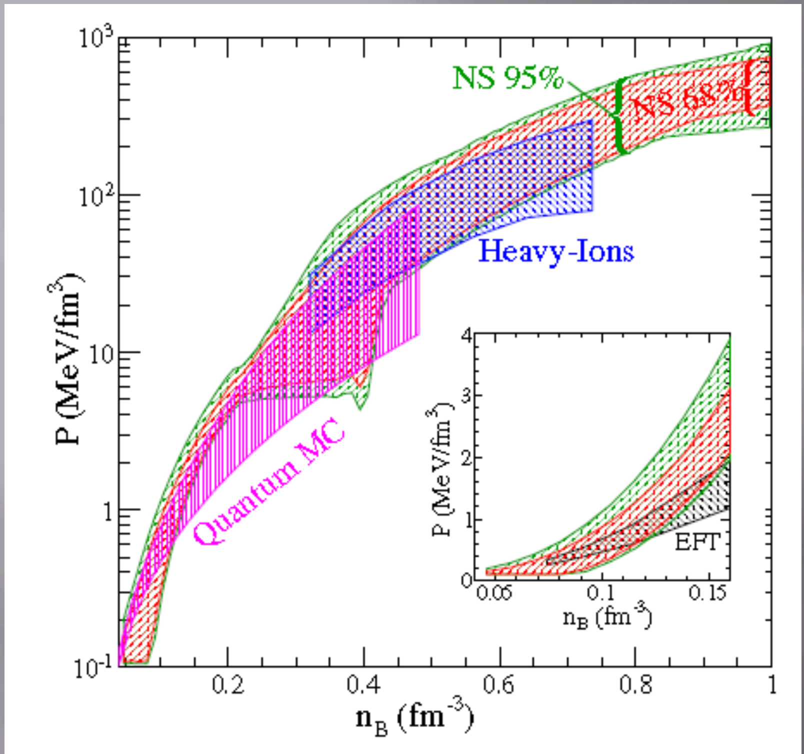
Equation of State

softening EoS at $\rho \sim 2\rho_0$

stiff EoS at high ρ

How to approach high density?

Motivation of SPiRIT



A.W.Steiner et al. APJ 765, L5 (2013)

- Constraints from nuclear structure, nuclear reactions and neutron stars .
- Neutron star constraints at high density obtained from X-ray burst light curves.
- QMC constraints extrapolate nuclear structure information to high density. Width is compatible with uncertainty expected for a successful PREX experiment.
- Heavy ion collision constraints combine those from collective flow with guesses about symmetry energy. >> Still uncertain!!

Goal is to decrease the factor of 2 uncertainty in symmetry pressure at $\rho \approx 2\rho_0$.

Prediction of Bao-An Li

NPA 708 (2002) 365

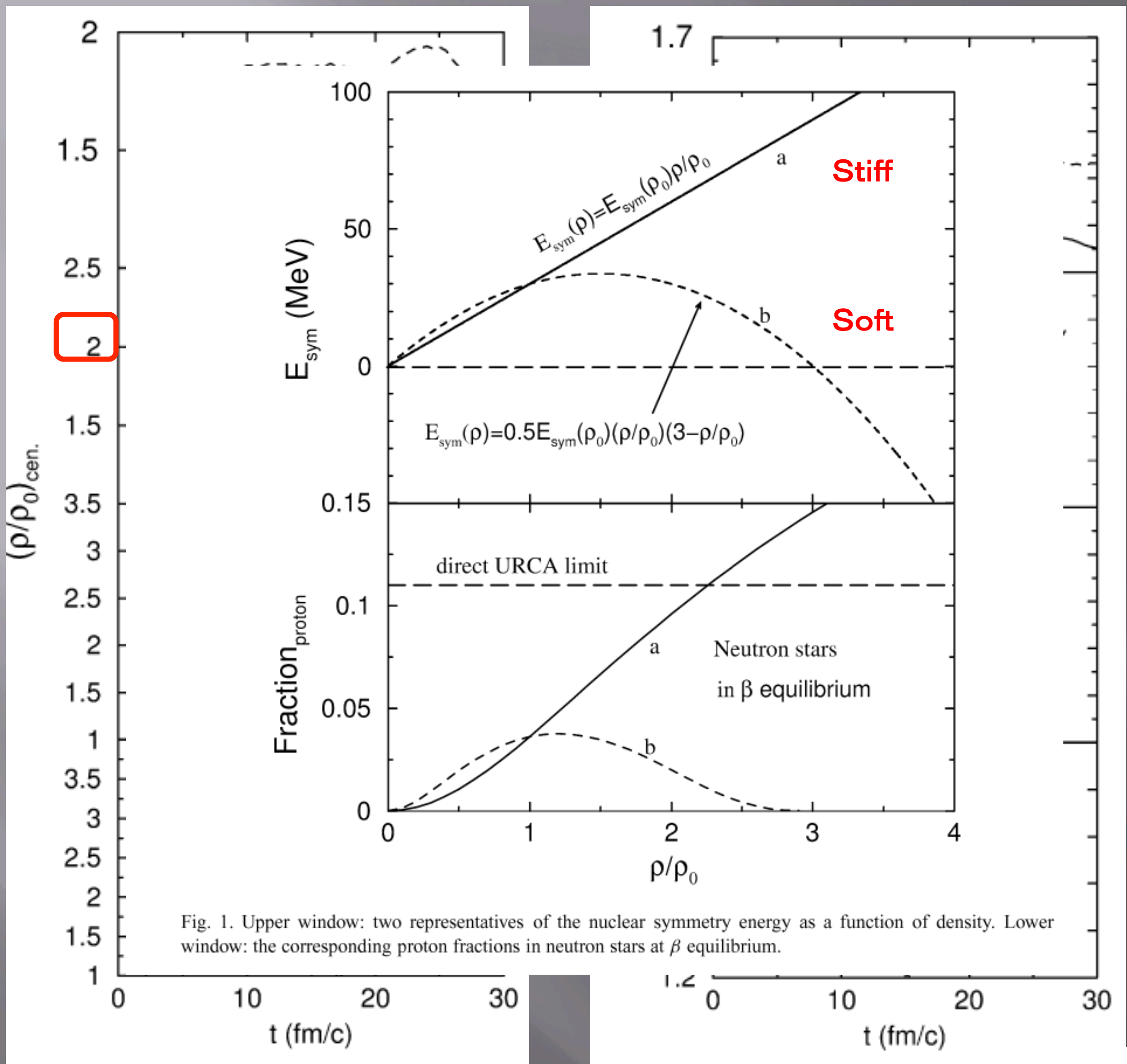
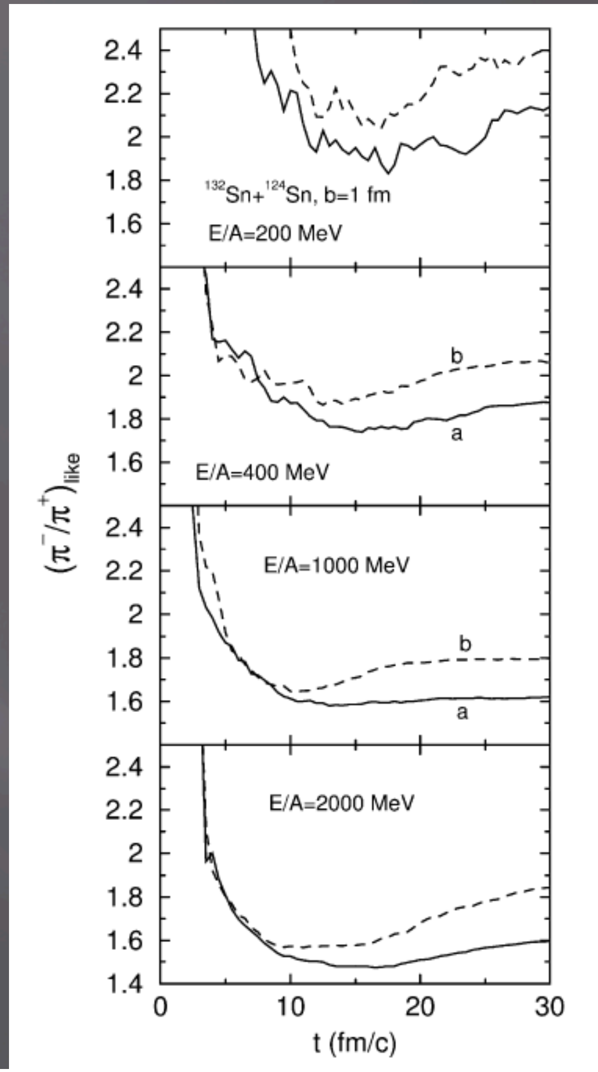


Fig. 1. Upper window: two representatives of the nuclear symmetry energy as a function of density. Lower window: the corresponding proton fractions in neutron stars at β equilibrium.



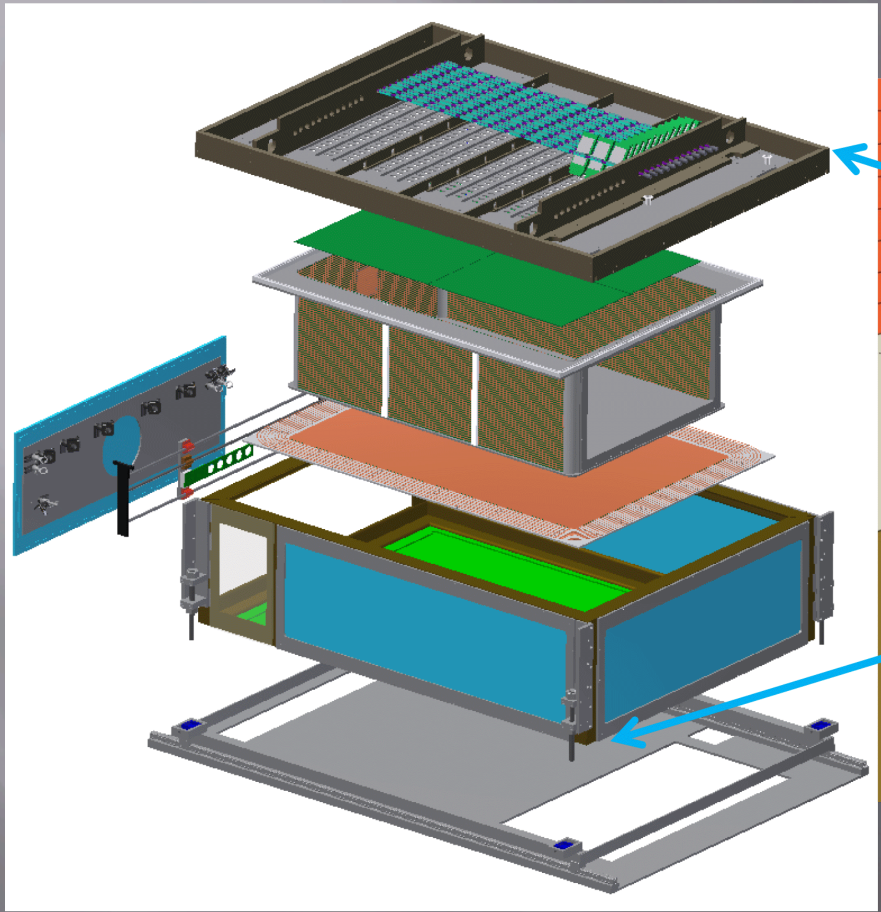
$$\pi^- / \pi^+ \equiv (5N^2 + NZ)/(5Z^2 + NZ)$$

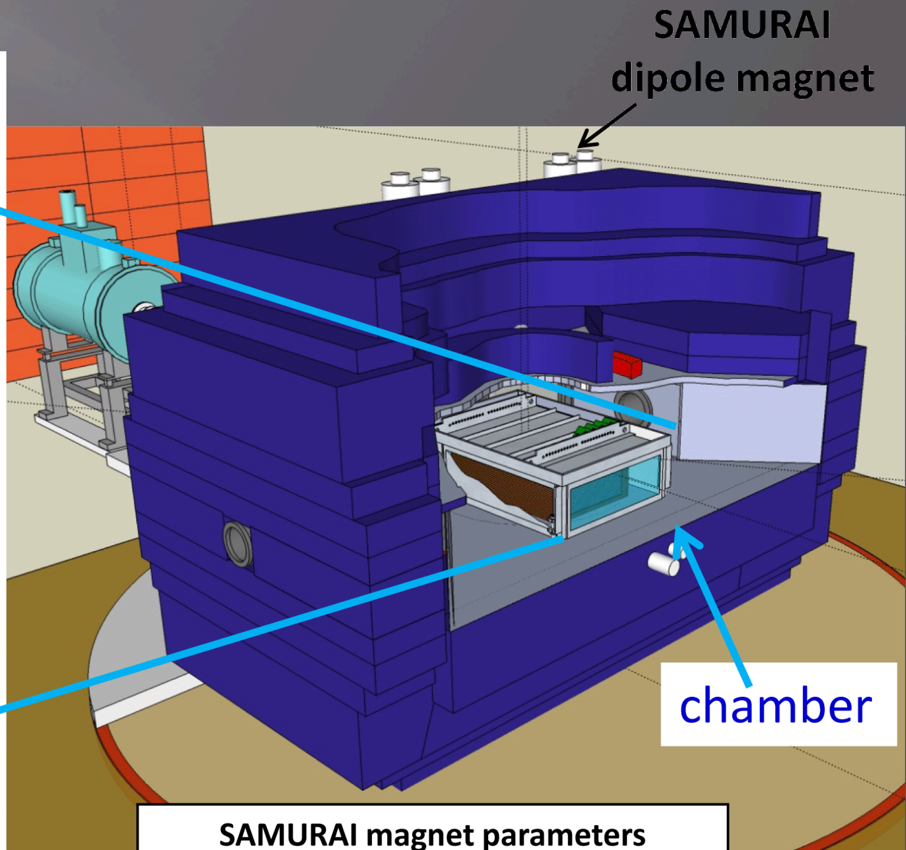
Influence of symmetry pressure; Possible Probe

The symmetry pressure expels neutrons from and attracts protons to high density region of neutron-rich system. This suppresses Y(n)/Y(p), Y(π^-)/Y(π+), etc.

- $\pi^+ - \pi^-$ ratio
- Proton-neutron ratio
- Light ion ratio (t-^{3}He)
- Particle flow of pions, protons, neutrons and light ions

Construction of SPiRIT

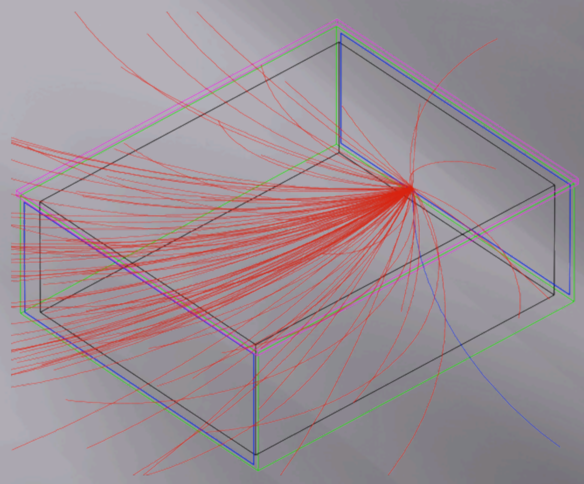




SAMURAI magnet parameters	
B_{typ}, B_{max}	0.5T, 3T
R, pole face	1 m
Gap	80 cm
Usable gap	75 cm

Supported by USA DoE funding ($1.2M), and Japanese Grant-in-Aid for Scientific Research on innovative areas ($1.3M).

Characteristics of SPiRIT(TPC?



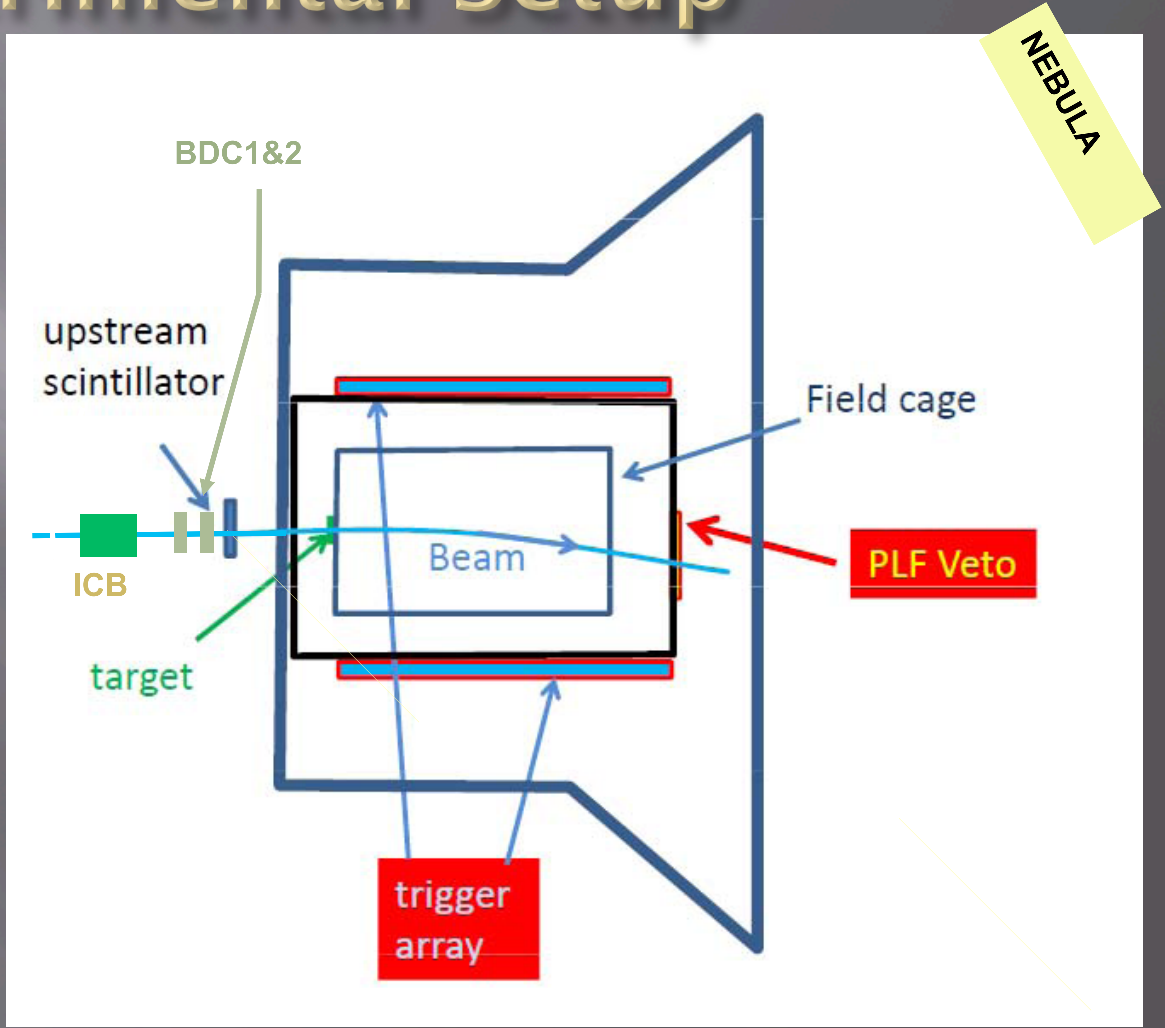
GEANT $^{132}Sn+^{124}Sn$ simulation collisions at E/A=300 MeV

- **Good efficiency for pion track reconstruction is essential.**
- Initial **design** is based upon EOS TPC, whose properties are well documented.

SAMURAI TPC parameters	
Pad plane area	1.34m x 086 m
Number of pads	12096 (108 x 112)
Pad size	12 mm x 8 mm
Drift distance	53 cm
Pressure	1 atmosphere
dE/dx range	Z=1-3 (STAR El.), 1-8 (GET El.)
Two track resolution	2.5 cm
Multiplicity limit	200 (may impact absolute pion eff. in large systems.)

Experimental Setup

- Equipment
  - TPC - measures:
    - π^+, π^-, p, d, t, ^{3}He, ^{4}He, IMF's
    - The SAMURAI chamber is at air
  - Trigger scint. array:
    - selects central collisions and suppresses peripheral collisions.
  - NEBULA:
    - provides neutron information



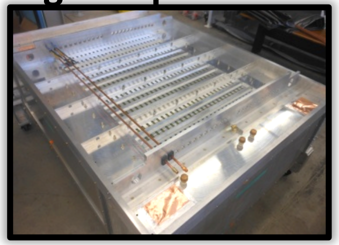
Magnet is at 0 degrees.

SPiRIT: Exploded View

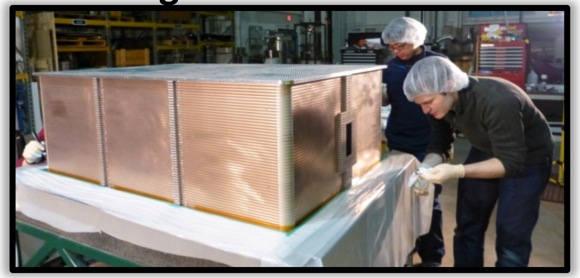
Samurai Pion- Reconstruction and Ion-tracker TPC

Front End Electronics

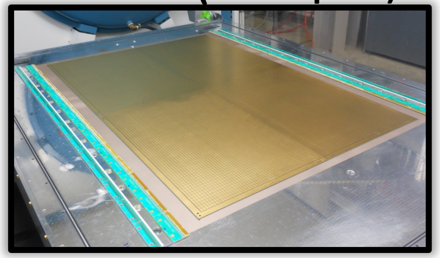
Rigid Top Plate

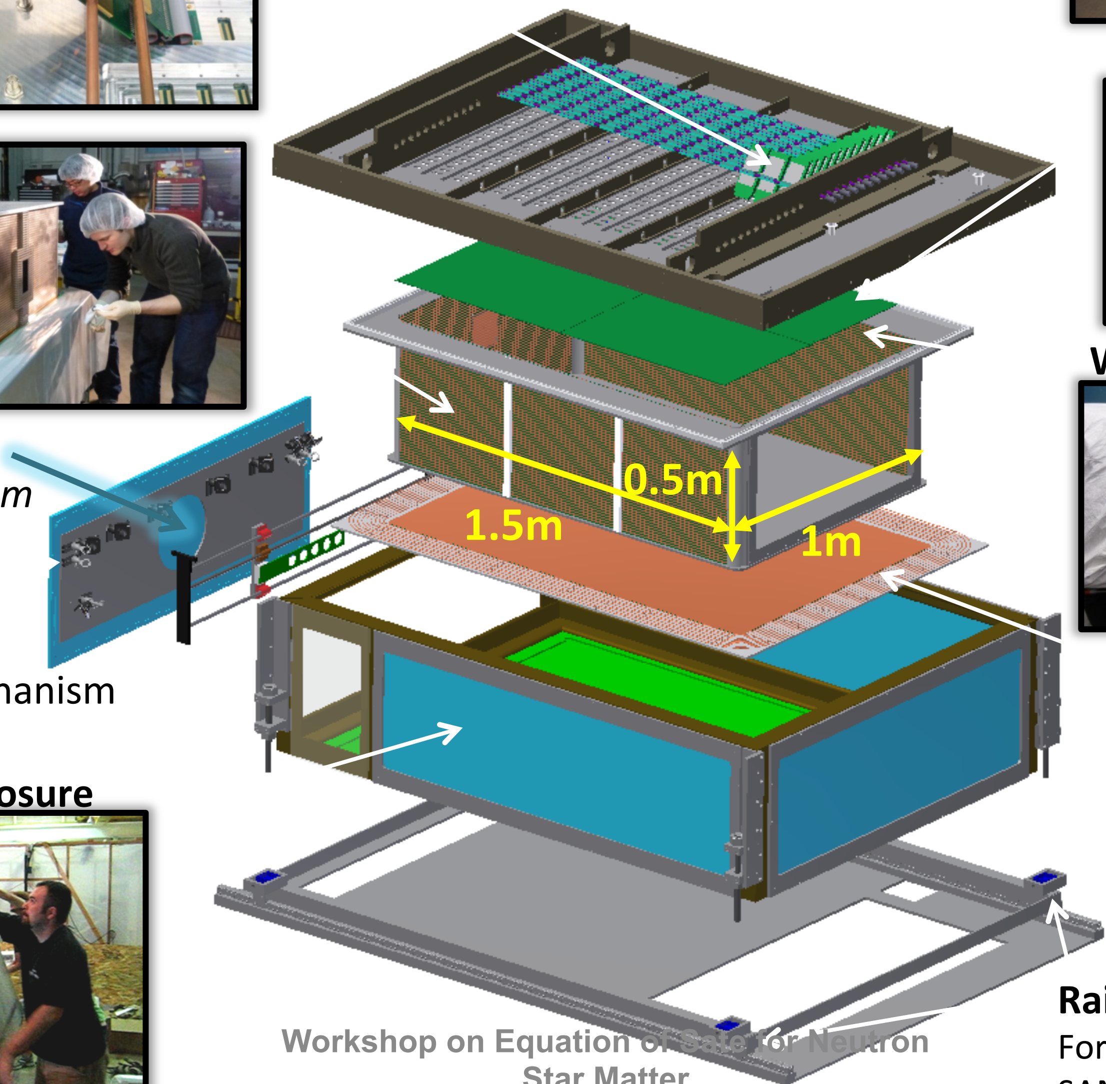


Field Cage



Pad Plane (12096 pads)

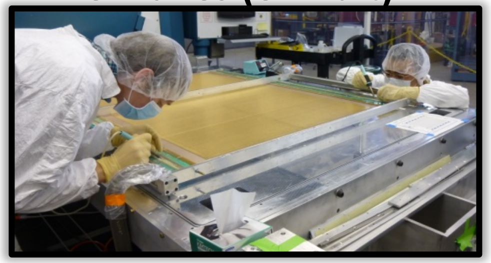




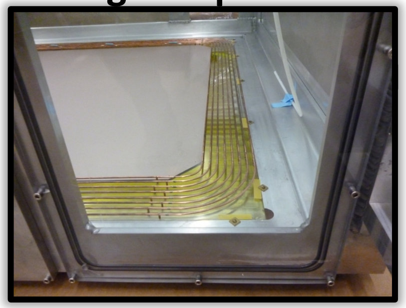
Calibration
Laser Optics

Target Mechanism

Wire Planes (e- mult)



Voltage Step-Down

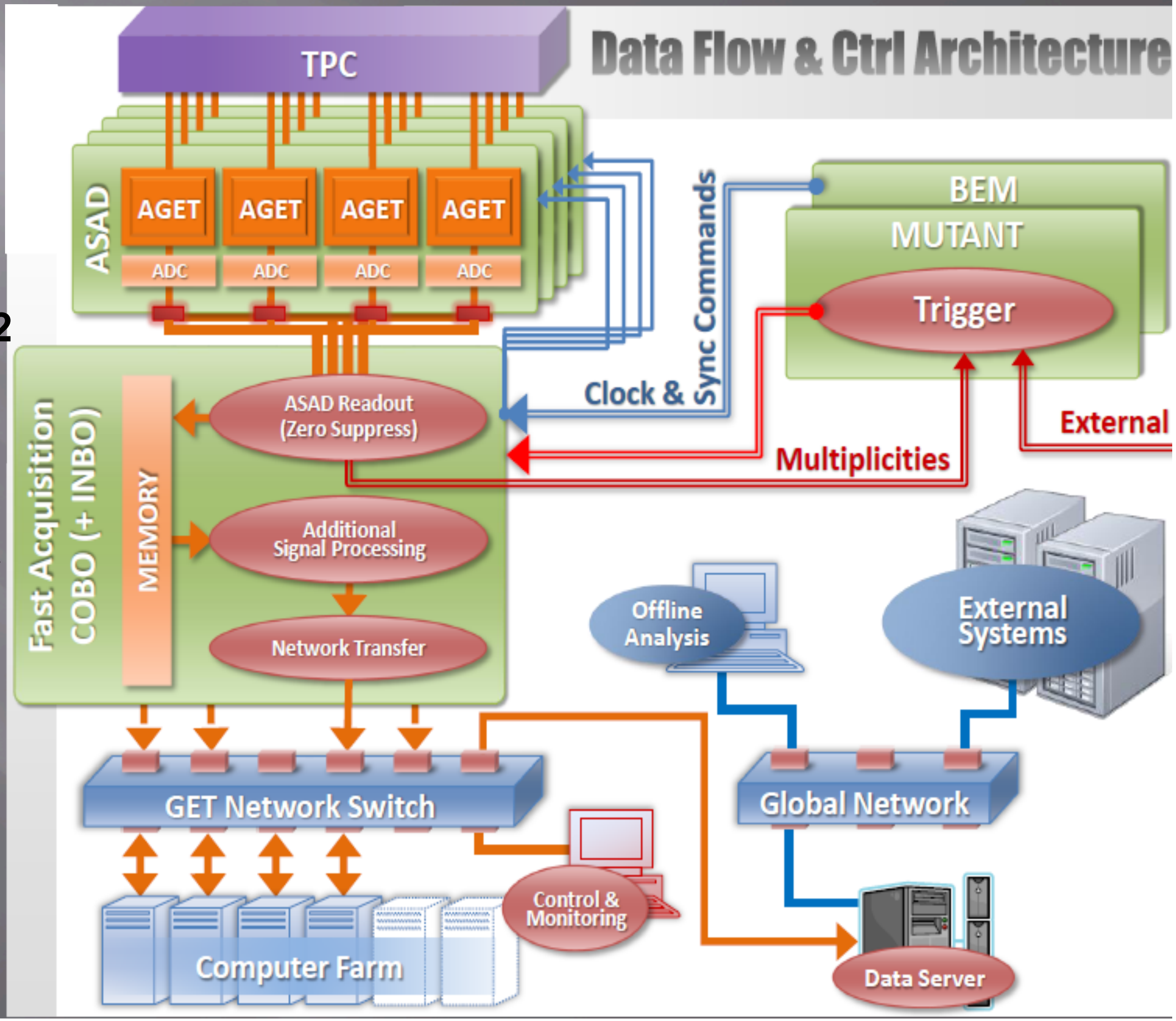


Thin-Walled Enclosure

Rails
For inserting TPC into
SAMURAI vacuum chamber

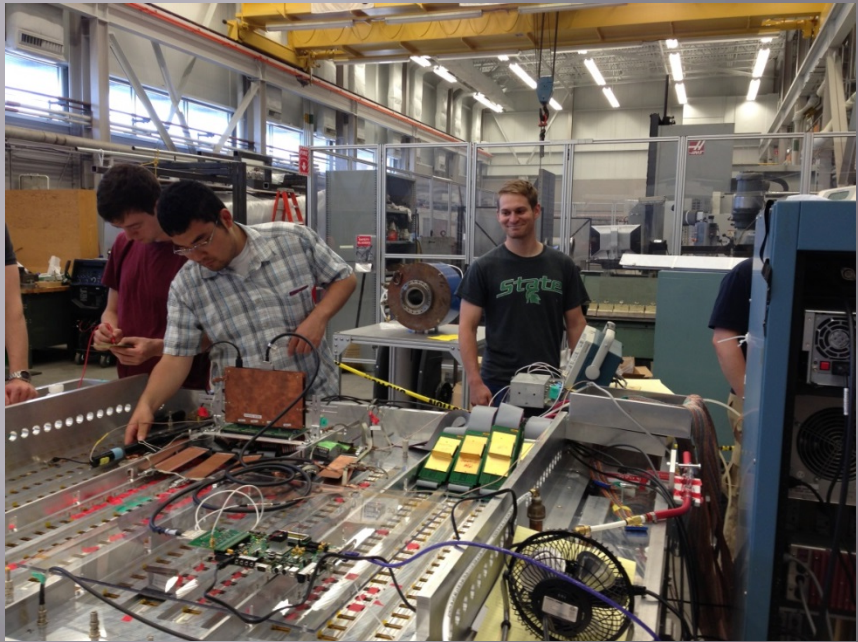
Read-out Electronics; GET

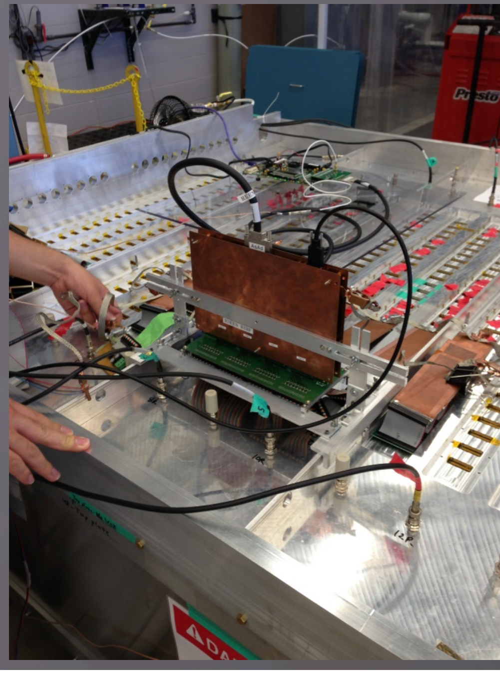
State of Arts
technology
Capable to handle
1KHz – 10Gb/s
Wide dynamic range
10.5 bits
Capacitive Array 1-512
Sampling 1-100MHz

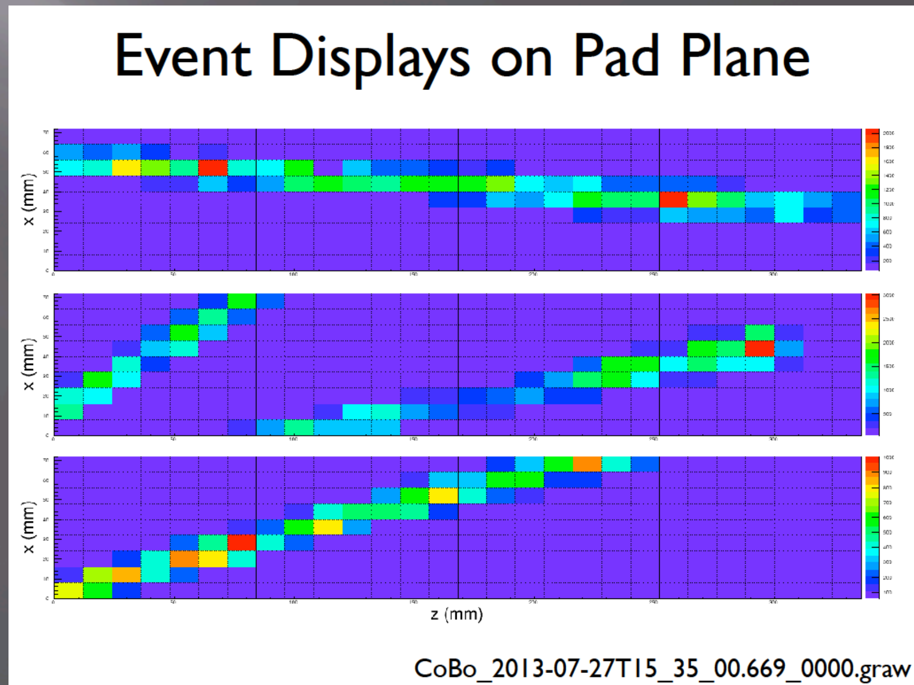


CEA/Bordeaux/GANIL/
MSU Collaboration

GET on SPiRIT



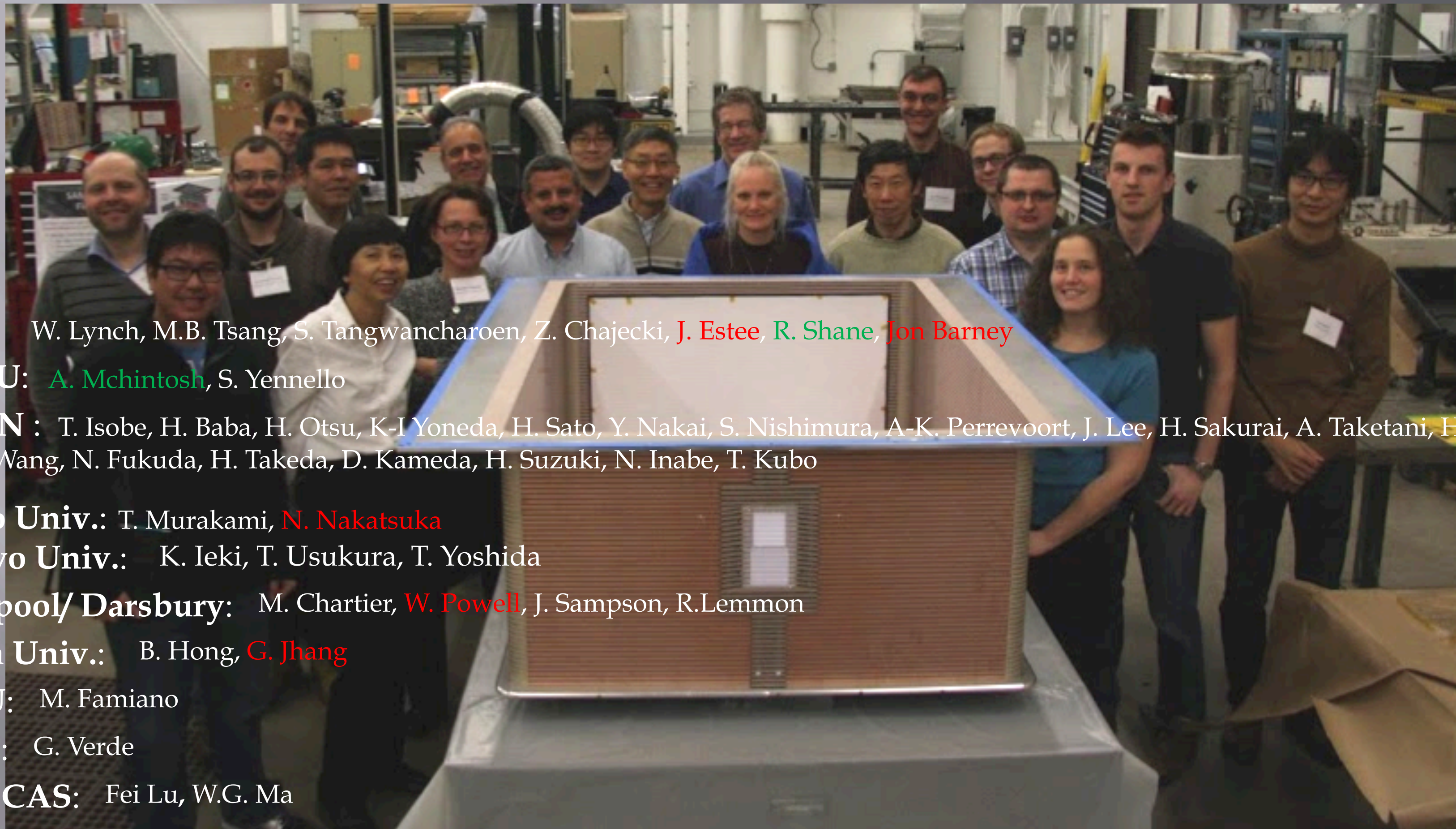




Summary

- Consistent constraints on the symmetry energy at sub-saturation densities with different experiments have been obtained.>> Heavy ion collisions should provide a good probe at high density..
- Astronomical observations suggest the importance of probing ~2ρ_0 region.
- We will be ready to measure pion and light fragment flow from $^{132}Sn+^{124}Sn$ and $^{124}Sn+^{112}Sn$ collisions at 300 MeV/u using the TPCs at RIKEN RIBF to constraint the symmetry energy above saturation densities by fall of 2014.

SPiRIT Collaboration



MSU: W. Lynch, M.B. Tsang, S. Tangwancharoen, Z. Chajecki, J. Estee, R. Shane, Jon Barney

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CEA: E. Pollacco

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ORNL: A. Galindo-Uribarri

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