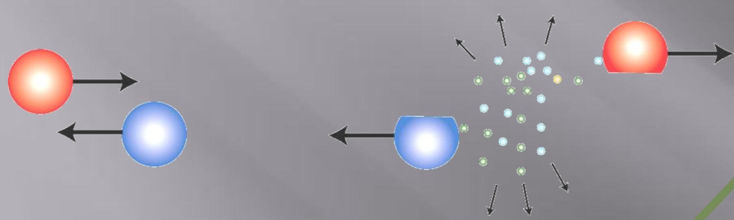
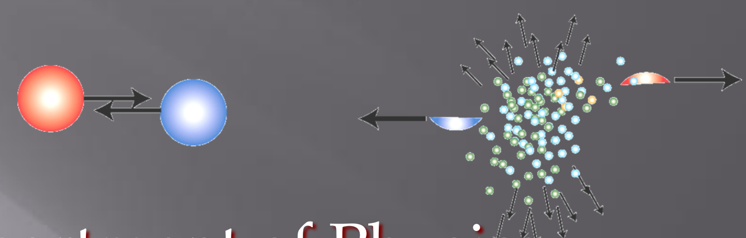
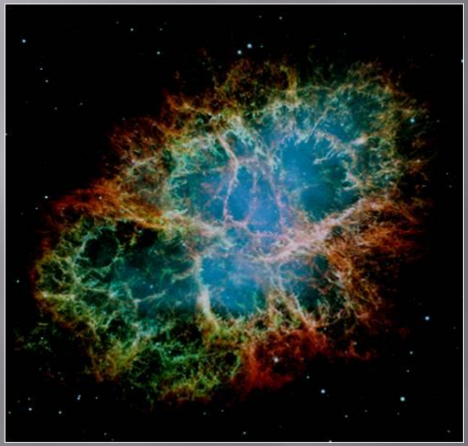
EQUATION OF STATES OF THE NEUTRON-RICH NUCLEAR MATTER AT SUPRA-DENSITY







Department of Physics
Kyoto University
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For the B01 collaboration, a part of project "Nuclear Matter in Neutron Stars investigated by Experiments and Astronomical Observations" (Grant-In-Aid for Scientific Research on Innovative Areas)

Equation of State

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

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

$$E(\rho,0) = E(\rho_0,0) + \frac{K_0}{2}\varepsilon^2 + o(\varepsilon^3)$$

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

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

$$K_0 = 9\rho_0^2 \frac{\partial^2 E(\rho,0)}{\partial \rho^2}\bigg|_{\rho=\rho_0}$$

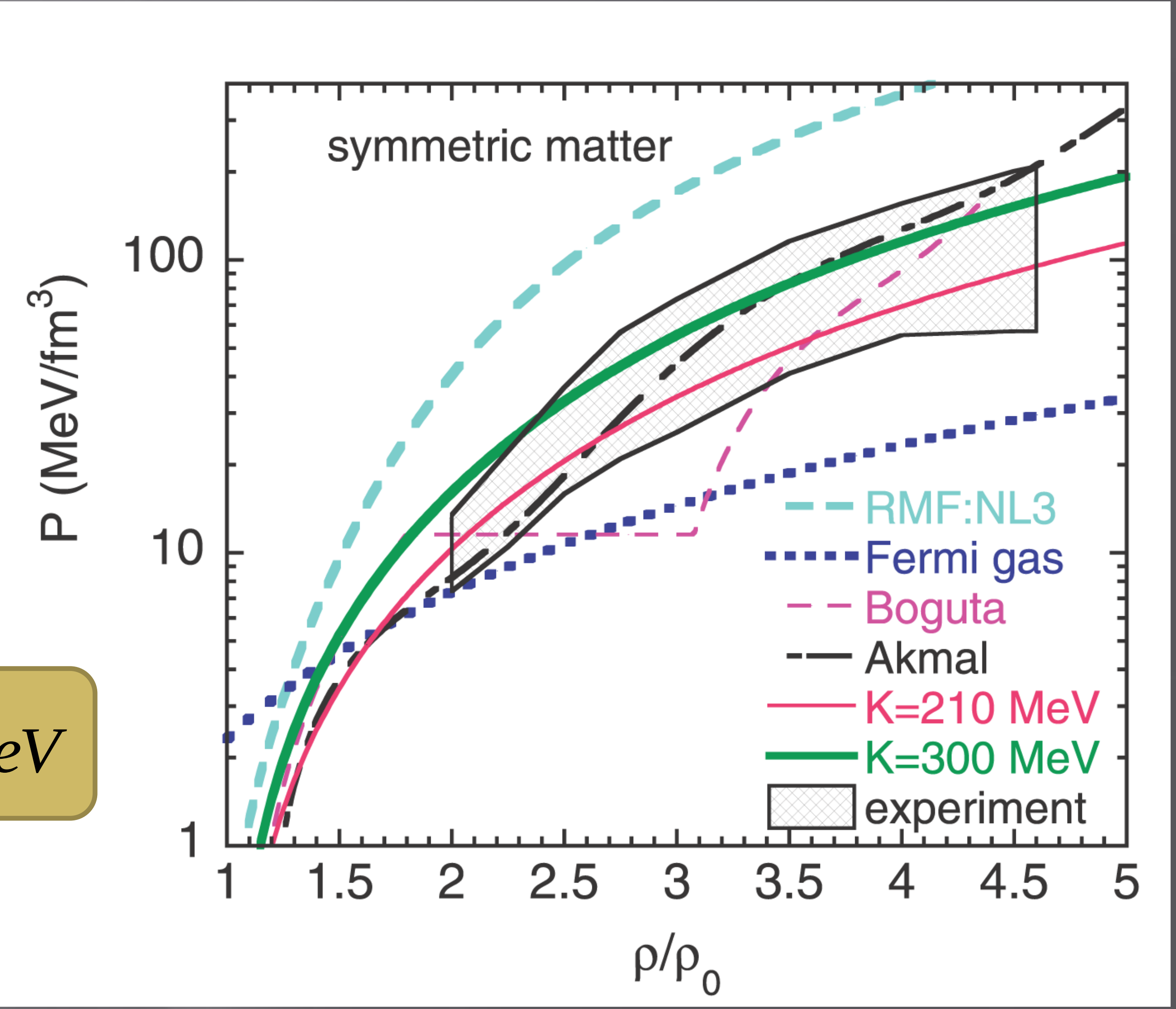
$$S_0 = E_{sym}(\rho_0)$$

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

$$K_{sym} = 9\rho_0^2 \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\bigg|_{\rho=\rho_0}$$

$$K_\tau \approx K_{sym} - 6L$$

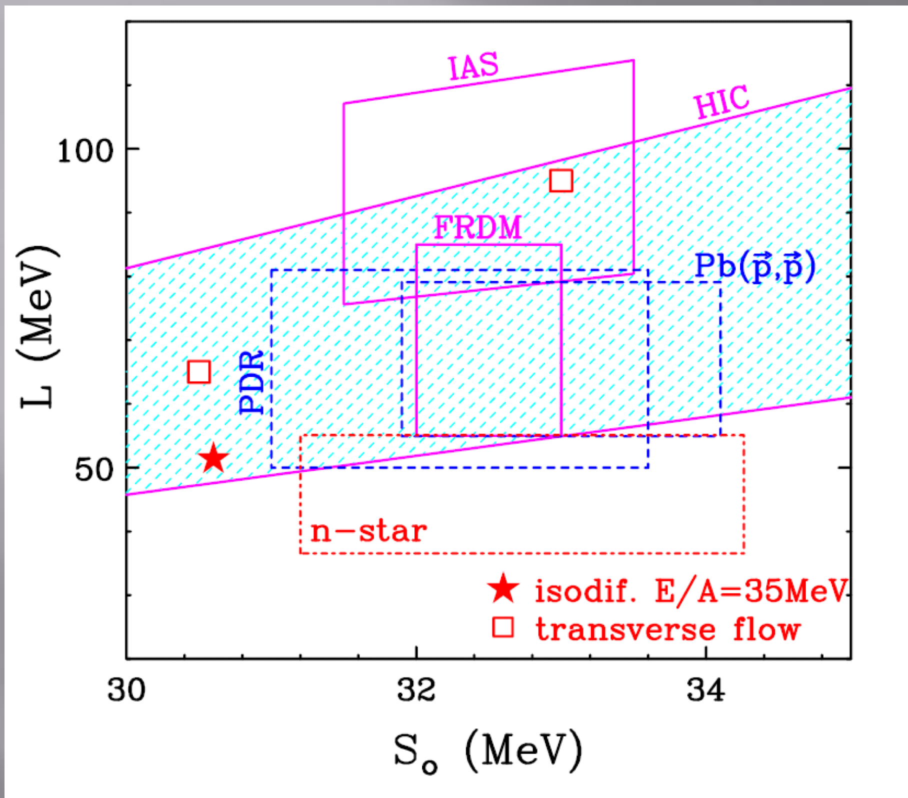
How much we know about symmetric matter

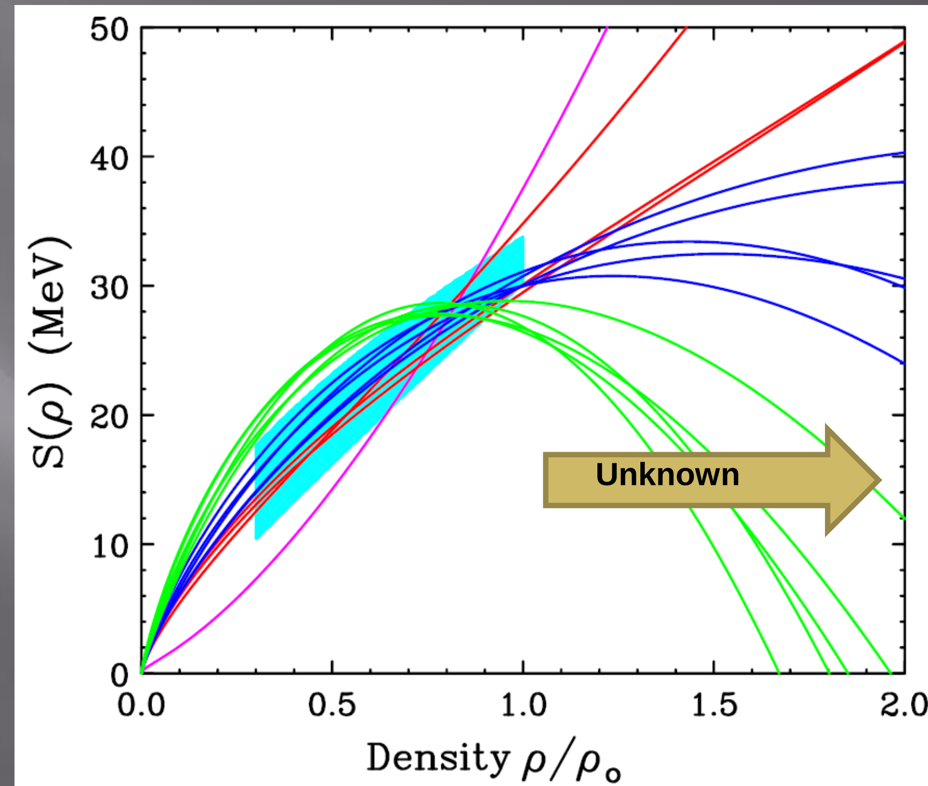


$$K_{nm} \approx 210 - 300 MeV$$

Danielewicz et al. Science 298 (2002) 1592.

How much we know about asymmetric matter (*L* and S_0)





PHYSICAL REVIEW C **86**, 015803 (2012)

Constraints on the symmetry energy and neutron skins from experiments and theory

M. B. Tsang,[1] J. R. Stone,[2] F. Camera,[3] P. Danielewicz,[1] S. Gandolfi,[4] K. Hebeler,[5] C. J. Horowitz,[6] Jenny Lee,[7] W. G. Lynch,[1] Z. Kohley,[1] R. Lemmon,[8] P. Möller,[4] T. Murakami,[9] S. Riordan,[10] X. Roca-Maza,[3] F. Sammarruca,[11] A. W. Steiner,[12] I. Vidaña,[13] and S. J. Yennello[14]

Prediction of Bao-An

NPA 708 (2002) 365

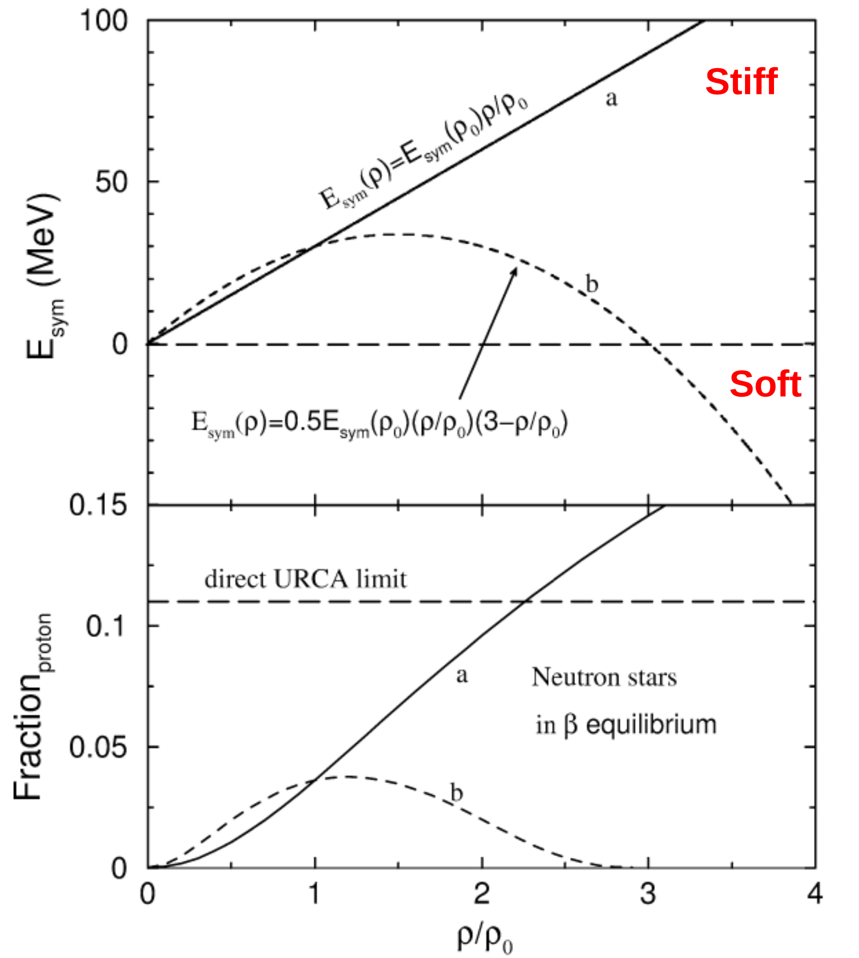
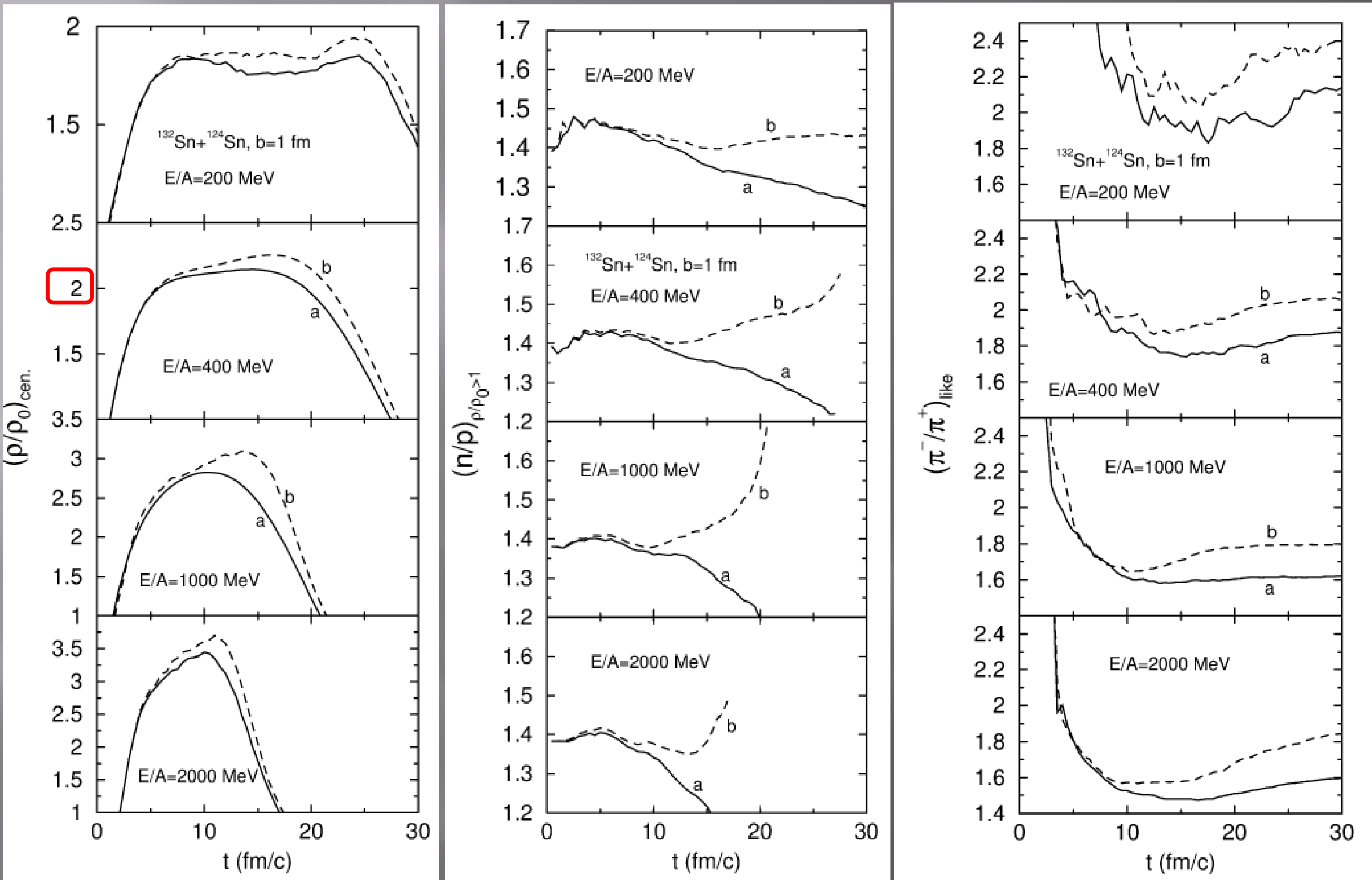


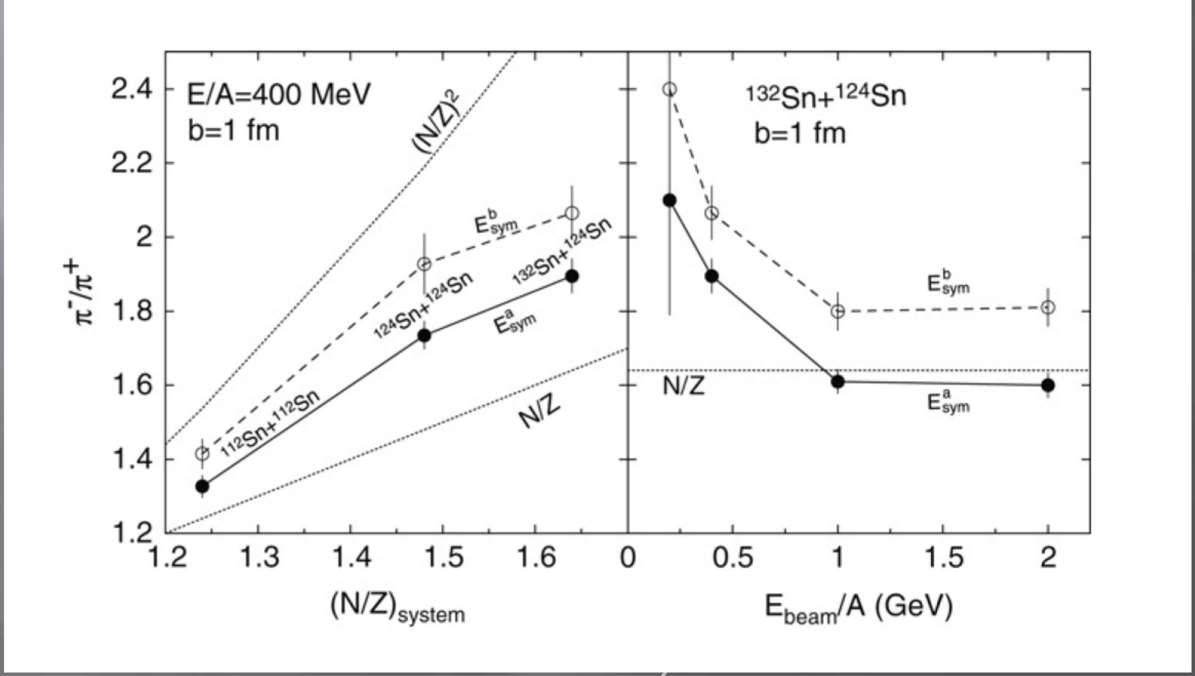
Fig. 1. Upper window: two representatives of the nuclear symmetry energy as a function of density. Lower window: the corresponding proton fractions in neutron stars at β equilibrium.



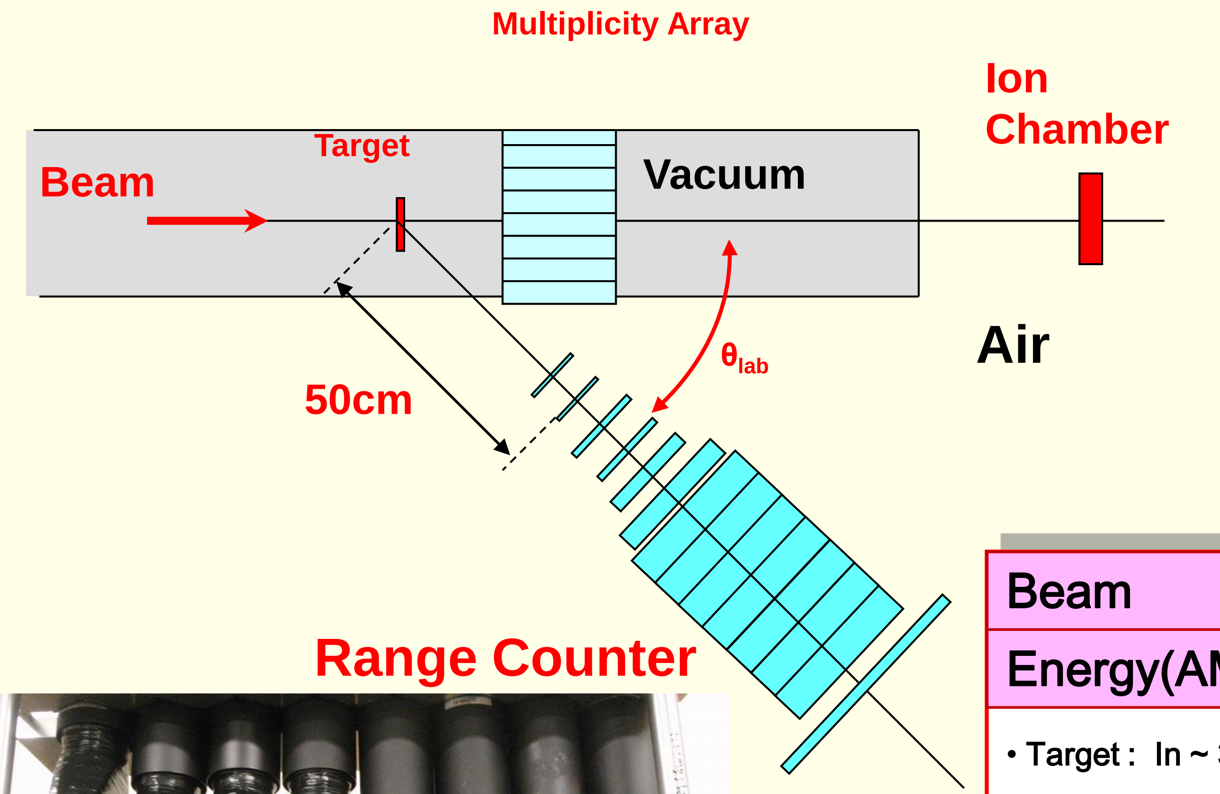
$$\pi^- / \pi^+ \equiv (5N^2 + NZ)/(5Z^2 + NZ)$$

Possible Probe

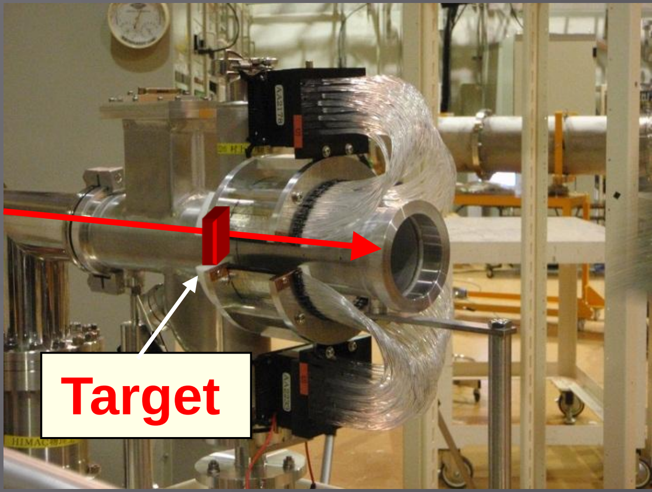
- $\pi^+-\pi^-$ ratio
- Proton-neutron ratio
- Light ion ratio (t-^{3}He)
- Particle flow of pions, protons, neutrons and light ions



Pilot Experiments at HIMAC (19P226)



Multiplicity Array

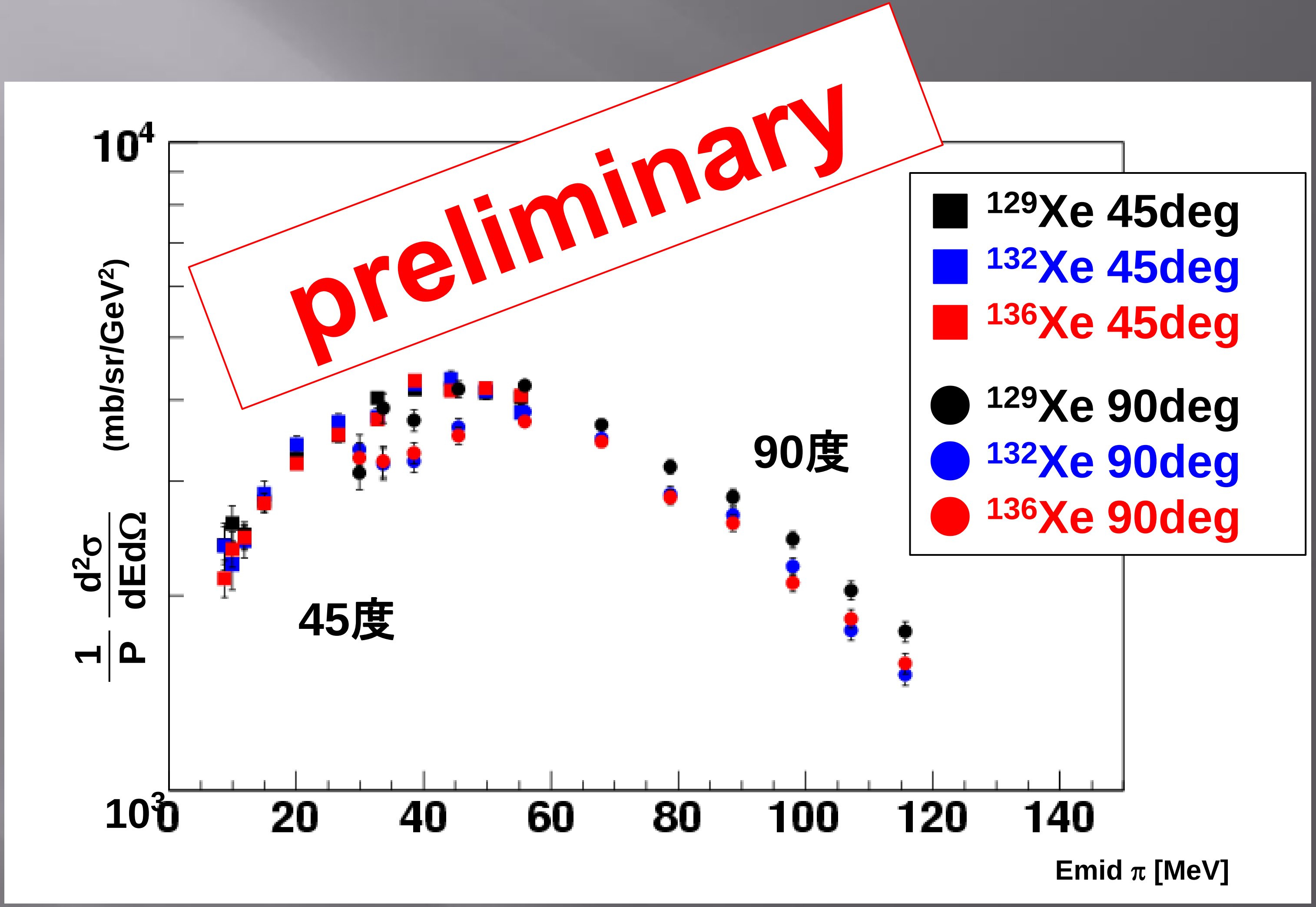


Range Counter

Beam	^{28}Si	^{132}Xe
Energy(AMeV)	400, 600, 800	400

- Target : In ~ 390 mg/cm^2
- Typical Intensity : ~ 10^7 ppp
- Range Counter : 14 layers (+2) of Sci.
- measured angle (θ_{lab})
  : 30, 45, 60, 75, 90, 120 degree
- solid angle : 10 msr

π^+ Cross Section for Xe+CsI Reactions



CsI ~^{130}Xe : <Z>=54 <N>=76 → N/Z= 1.41

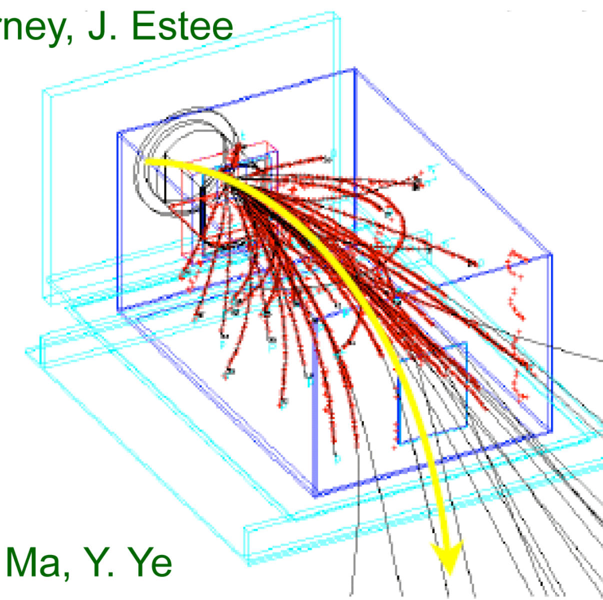
^{129,132,136}Xe N/Z=1.39-1.52

Nuclear Symmetry Energy (NuSym) collaboration

http://groups.nscl.msu.edu/hira/sep.htm

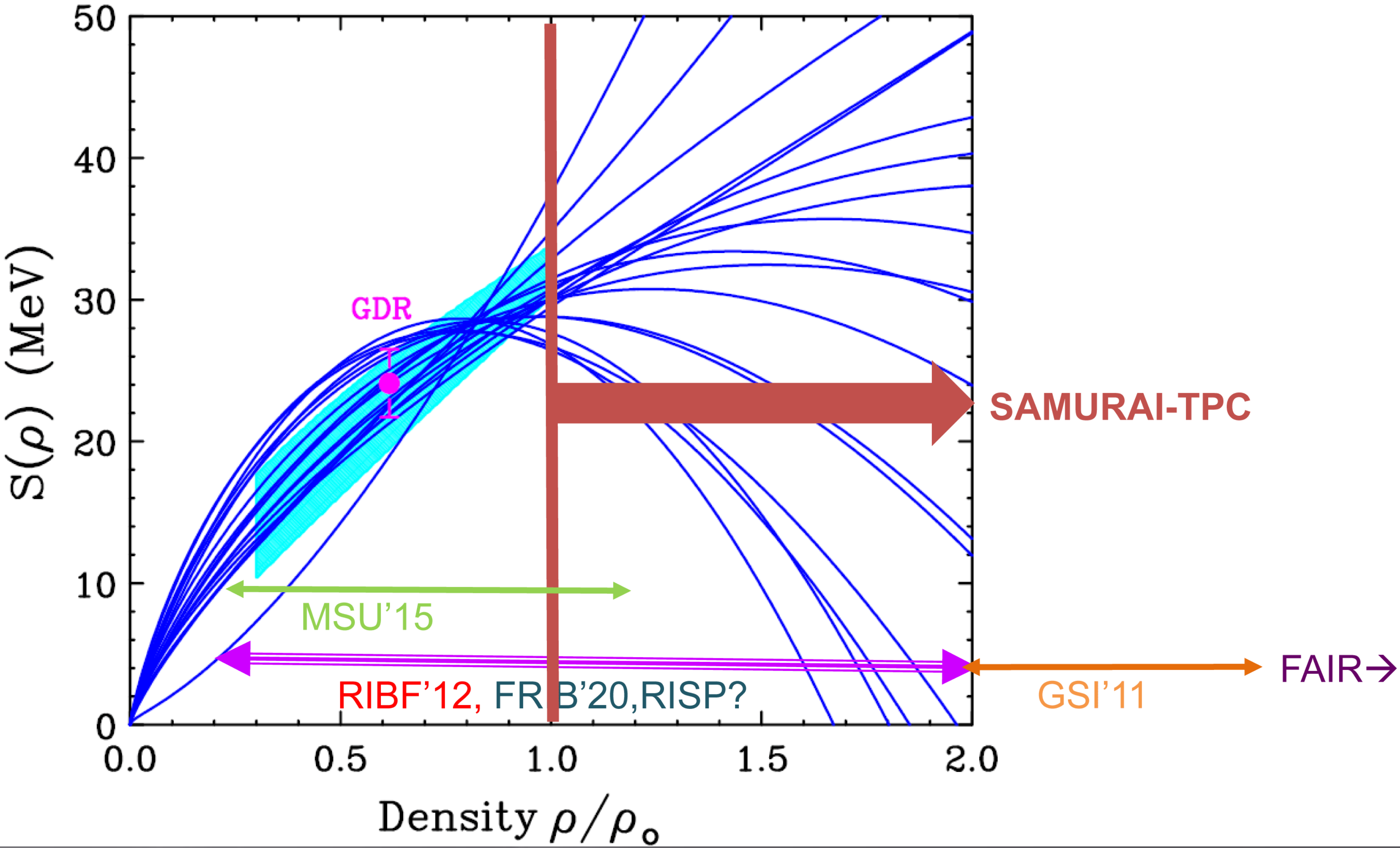
To map out the symmetry energy over a range of densities

MSU: B. Tsang & W. Lynch, P. Danielewicz, Z. Chajecki, R. Barney, J. Estee
Texas A&M University : S. Yennello, A. McIntosh
Western Michigan University : Michael Famiano
RIKEN, JP: TadaAki Isobe, Atsushi Taketani, Hiroshi Sakurai
Kyoto University: Tetsuya Murakami
Tohoku University: Akira Ono
GSI, Germany: Wolfgang Trautmann , Yvonne Leifels
Daresbury Laboratory, UK: Roy Lemmon,
University of Liverpool, UK: Marielle Chartier
INFN LNS, Italy: Giuseppe Verde, Paulo Russotto, Pagano
GANIL, France: Abdou Chbihi
CIAE, PU, CAS, China: Yingxun Zhang, Zhuxia Li, Fei Lu, Y.G. Ma, Y. Ye
Korea University, Korea: Byungsik Hong

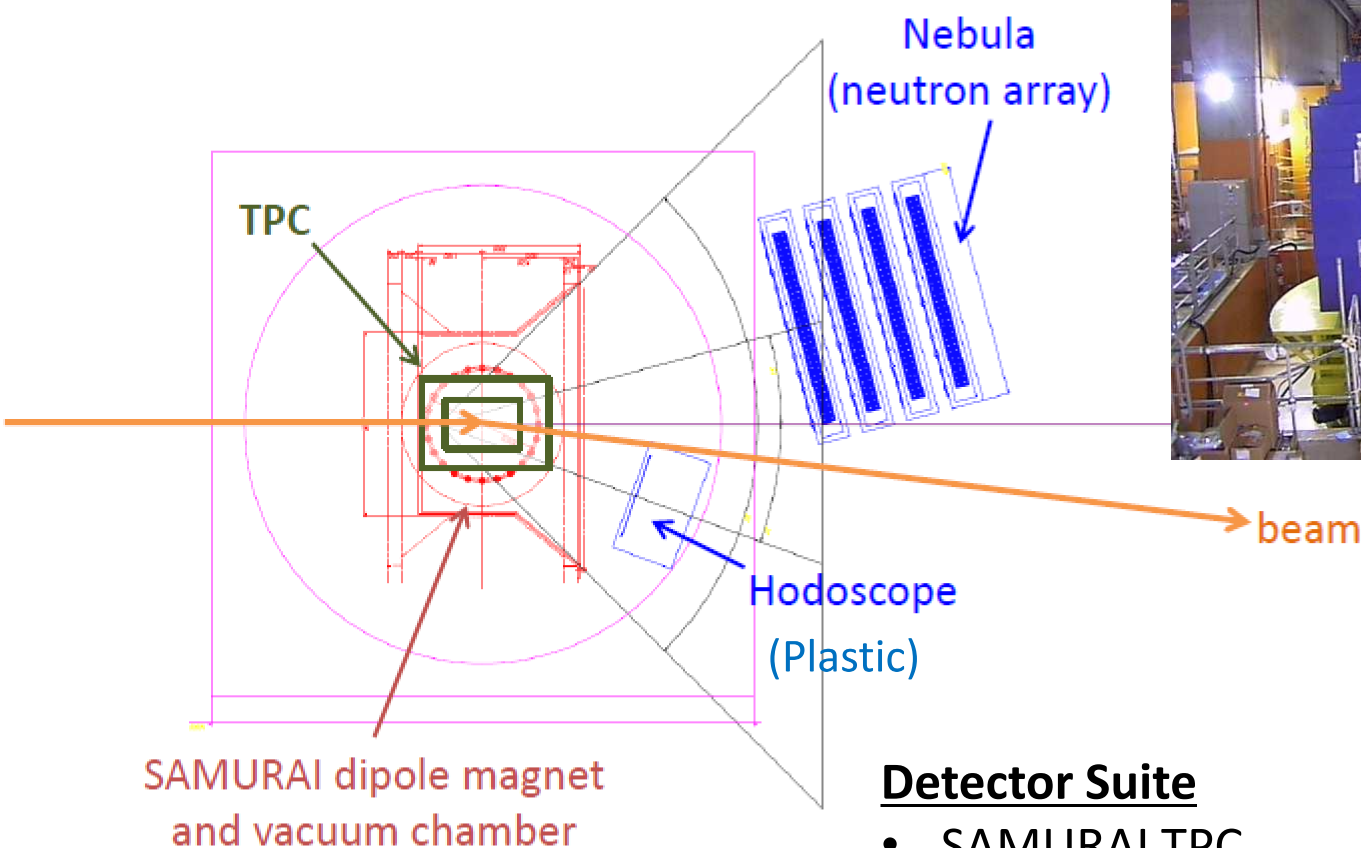


A Time Projection Chamber (TPC) is being built in the US to measure π^+/π^- & light charged particles in RIKEN

Symmetry Energy Project: International collaboration to determine the symmetry energy over a range of densities



EoS Experimental setup



Detector Suite

- SAMURAI TPC
- NEBULA neutron detector array
- Hodoscope for heavy residues
- Space is available for ancillary detectors
  - TPC is thin-walled

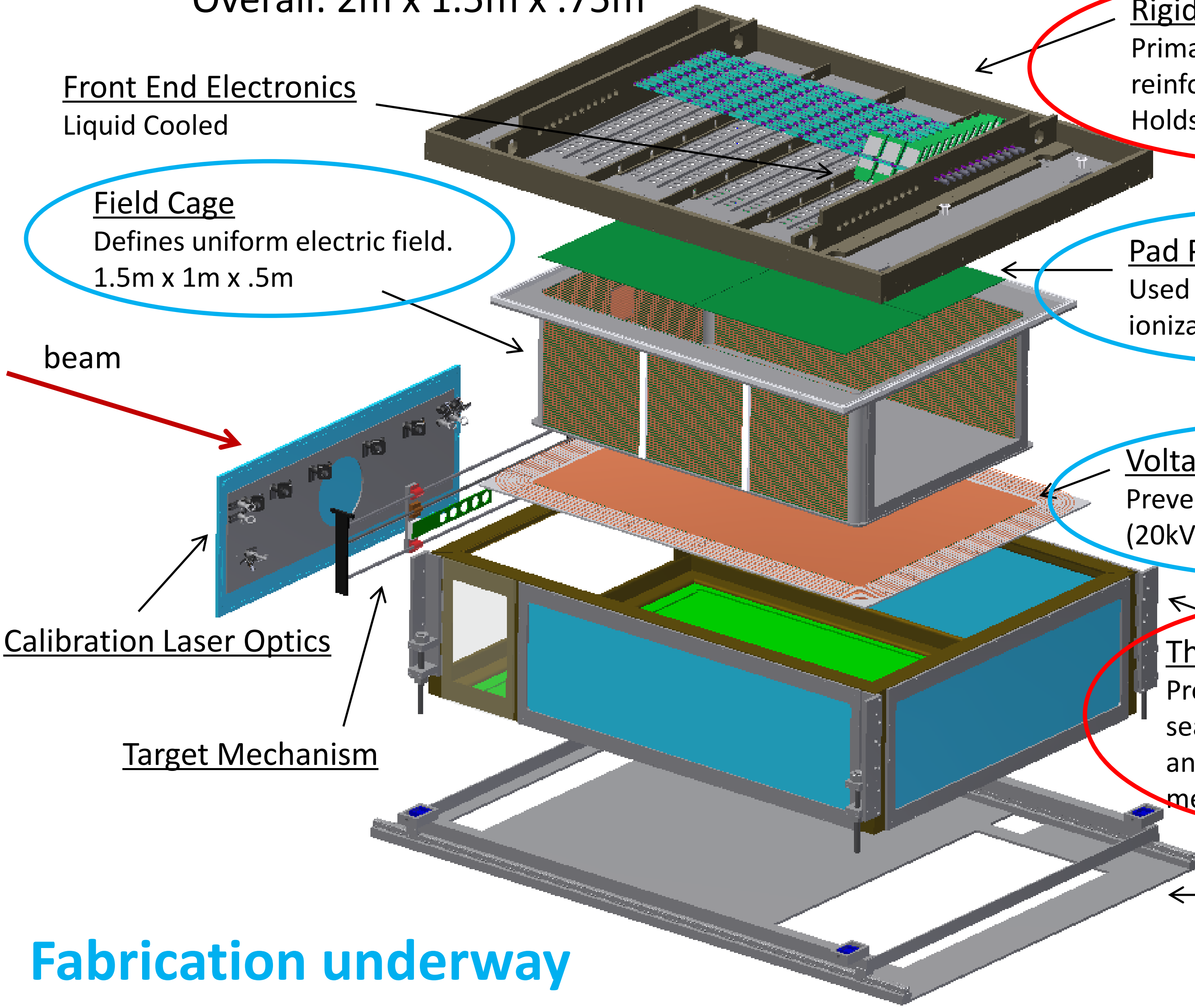
Agreement between US and Japan in 2008

- The U.S. collaborators will be responsible for the design and construction of the TPC and for initial testing of the TPC at MSU.
- RIKEN and the Japanese collaborators will be responsible for
  - Procurement of the SAMURAI dipole
  - Development of the TPC laser calibration system,
  - TPC gas handling system
  - TPC mounting and transportation hardware,
  - Target, the beam tracking
  - TPC electronics and data acquisition
  - Ancillary trigger scintillation array

Covered by B01 Budget

SAMURAI TPC Status

Overall: 2m x 1.5m x .75m



Fabrication underway

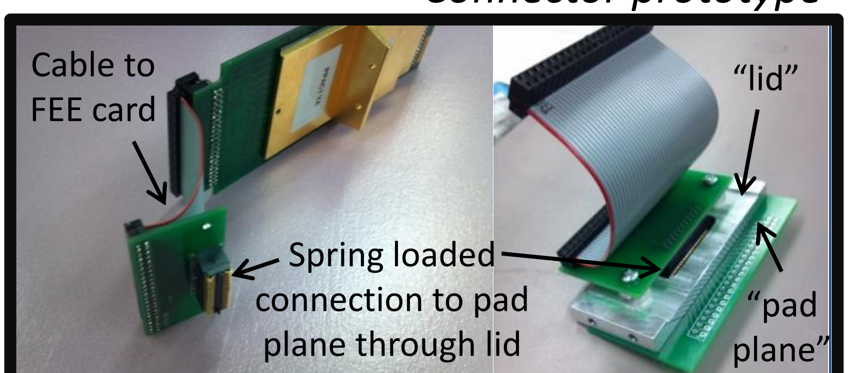
Top plate fabrication

- **Top plate**: pad plane and wire planes mounted on bottom
- **Ribs:** cross-braces to prevent bowing/flexing

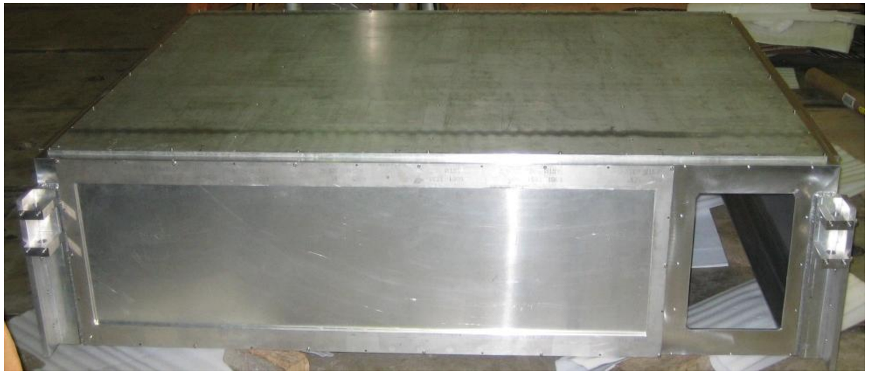
Holes for pad plane readout

Holes for electronic-card cooling lines

Connector prototype



Enclosure fabrication



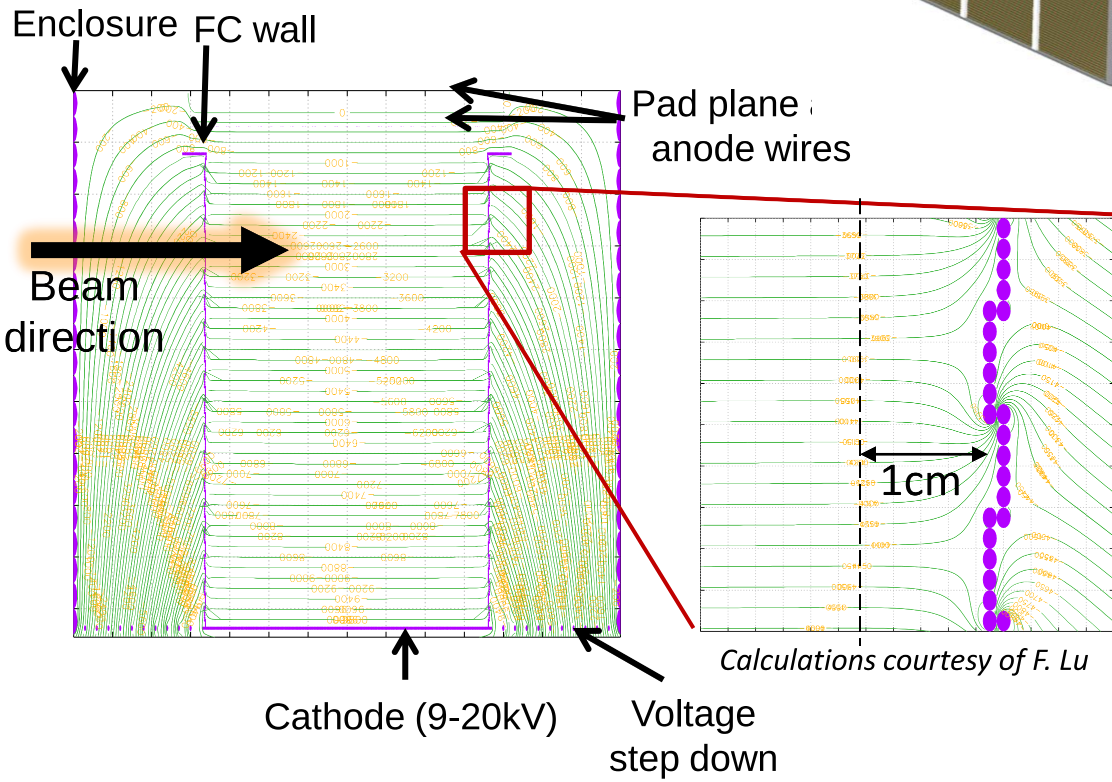
- Aluminum, plus Lexan windows
- **Skeleton**: Angle bar, welded and polished for sealing.
- **Sides & Downstream Walls**: framed aluminum sheet, to minimize neutron scattering
- **Bottom Plate**: Solid, to support voltage step-down
- **Upstream Plate**: Solid, ready for beamline coupling hole to be machined

SAMURAI TPC Manipulation

Motion Chassis and Hoist Beams work as designed.
The TPC Enclosure can be lifted and rotated with relative ease.

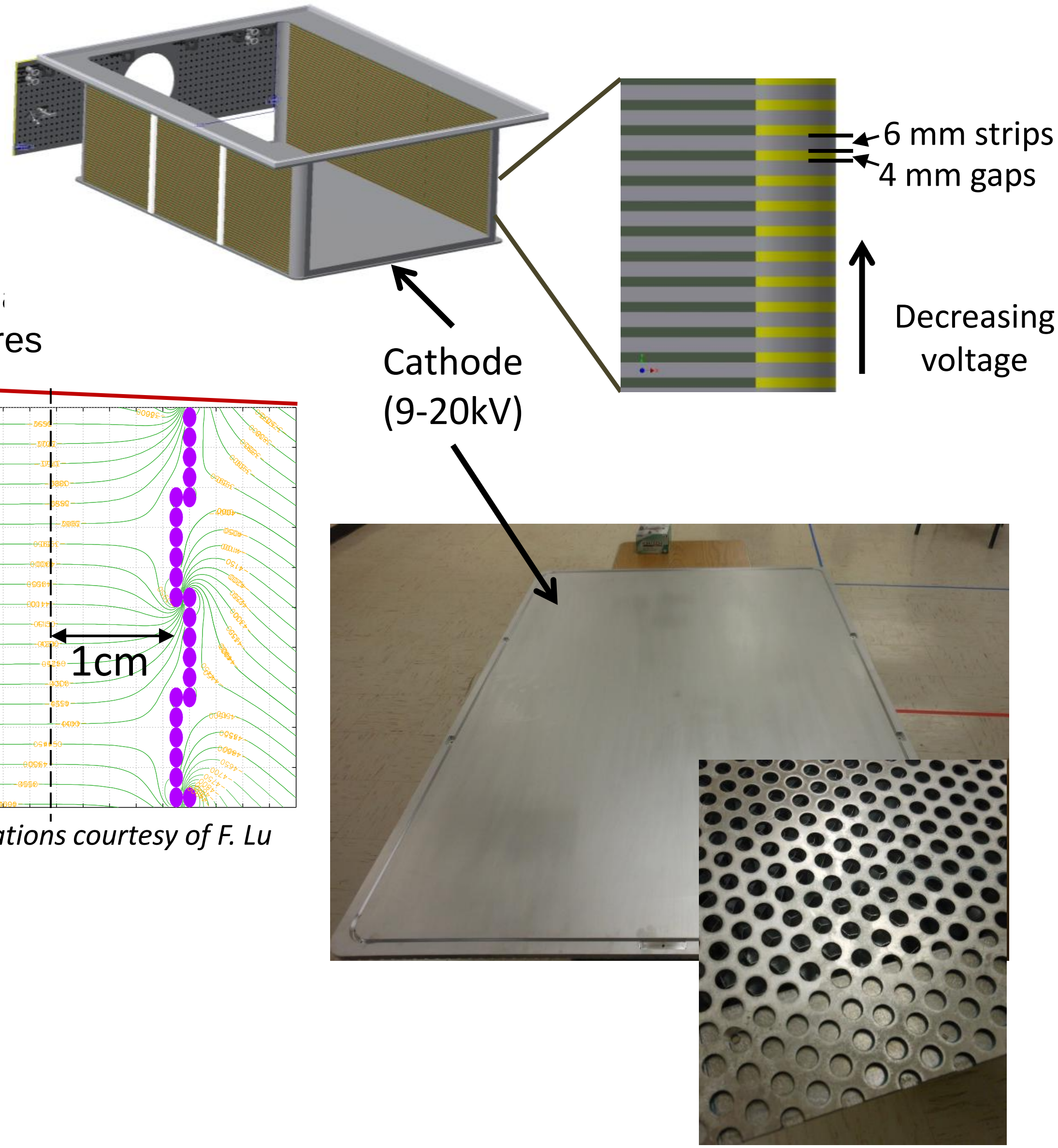
Field cage

- Made of printed circuit board
- Thin walls for particles to exit
- Gas tight (separate gas volumes)



Calculations courtesy of F. Lu

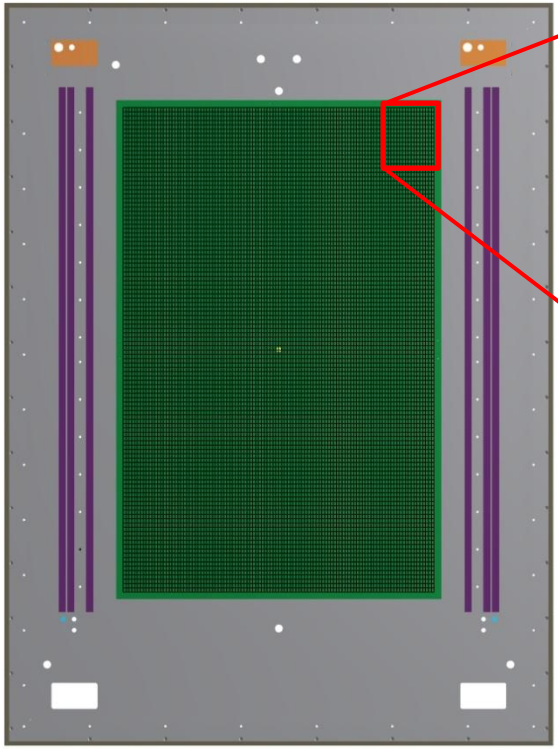
GARFIELD calculations
(on scaled field cage)
show uniform field lines
1cm from the walls

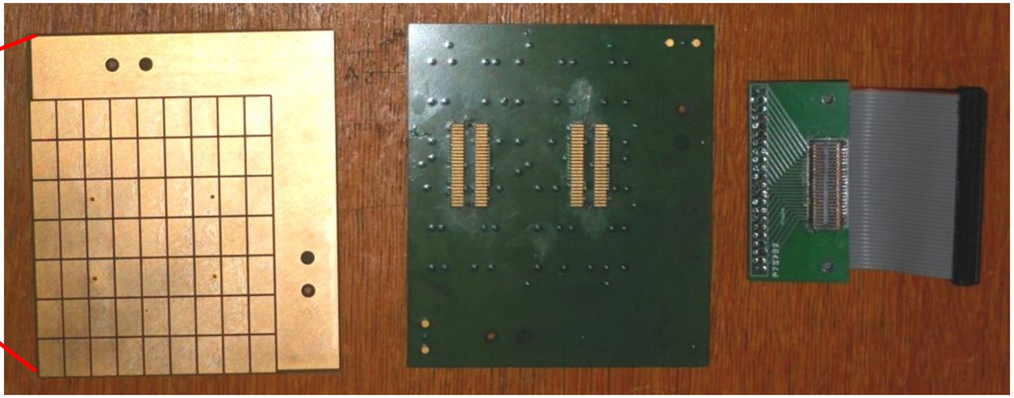


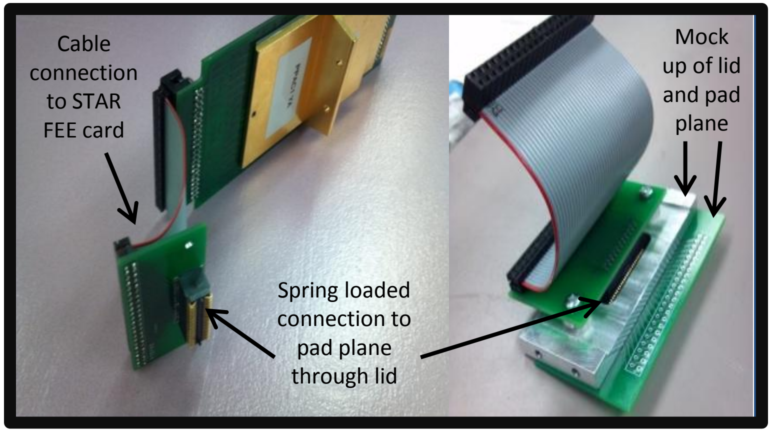
Pad plane

Full pad plane
- Mounted on bottom of lid
- 112 x 108 = 12096 pads
- Each pad: 12mm x 8mm
- *Fabrication underway*

Pad plane unit cell (192 in full plane)
- Capacitance: 10pf pad-gnd, 5pf adjacent pads
- Cross talk:
  - ~0.2% between adjacent pads
  - <0.1% between non-adjacent pads



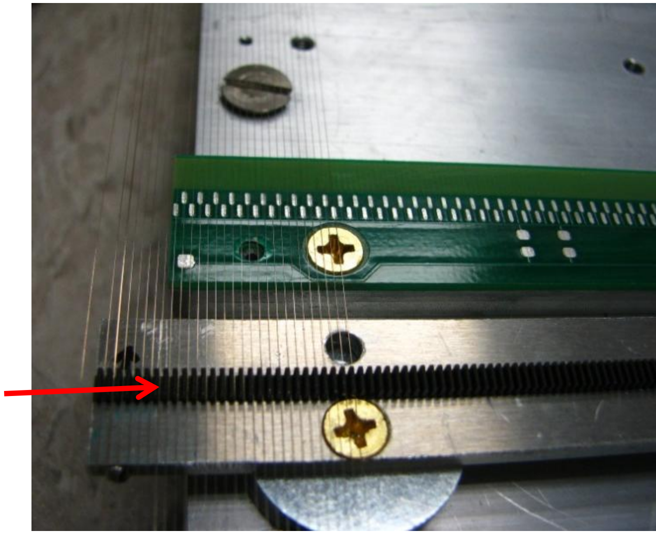




Wire planes – mounting (test setup)

- Wires are strung across frame
- Frame is positioned so that wires pass through teeth of comb and rest on circuit board (CB)
- Comb sets pitch, CB sets the height
- After gluing and soldering wires to CB, wires are cut and frame removed

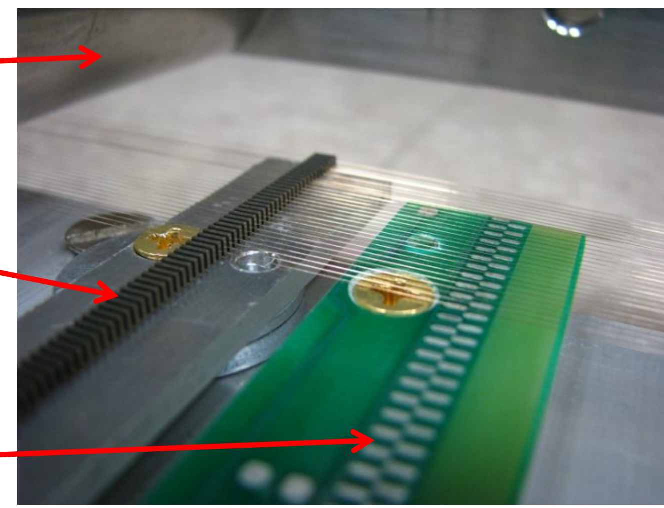
comb



frame

comb

circuit board with solder pads

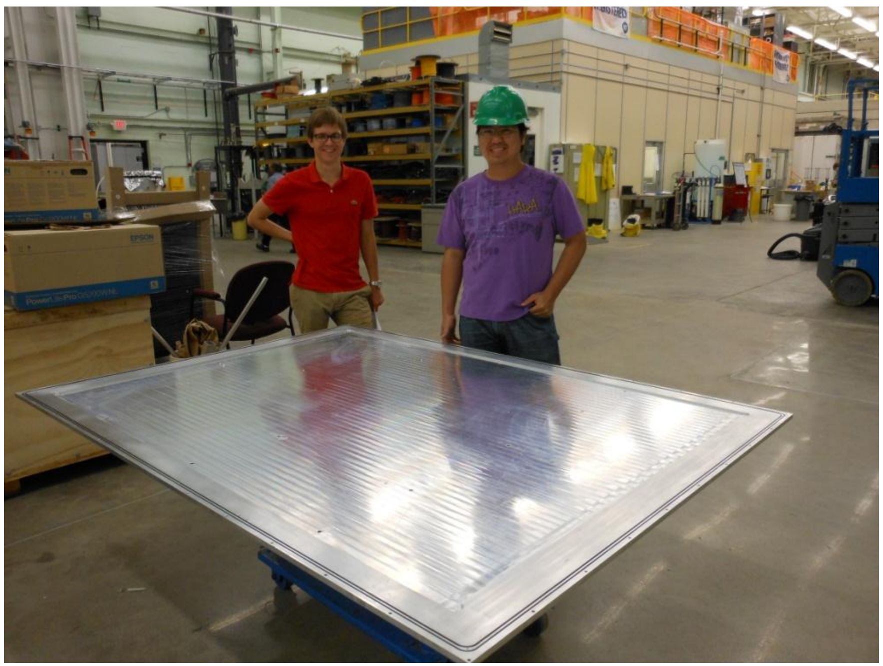


Voltage step down

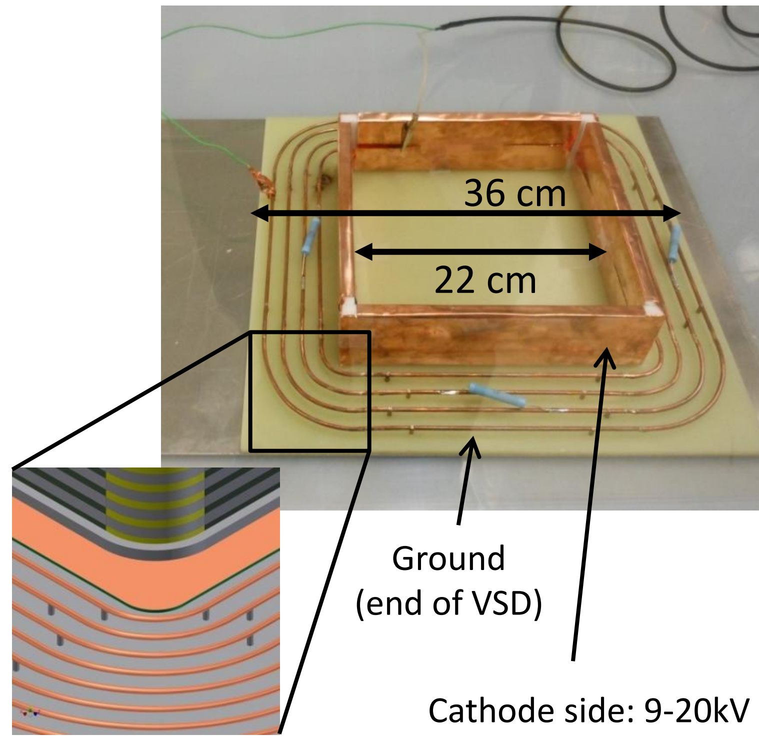
- Glued to recess in bottom plate
- Consists of 9 concentric copper rings with decreasing voltage from cathode to ground

VSD prototype: tested fabrication of rings, stability, and sparking

→ Full VSD fabrication underway



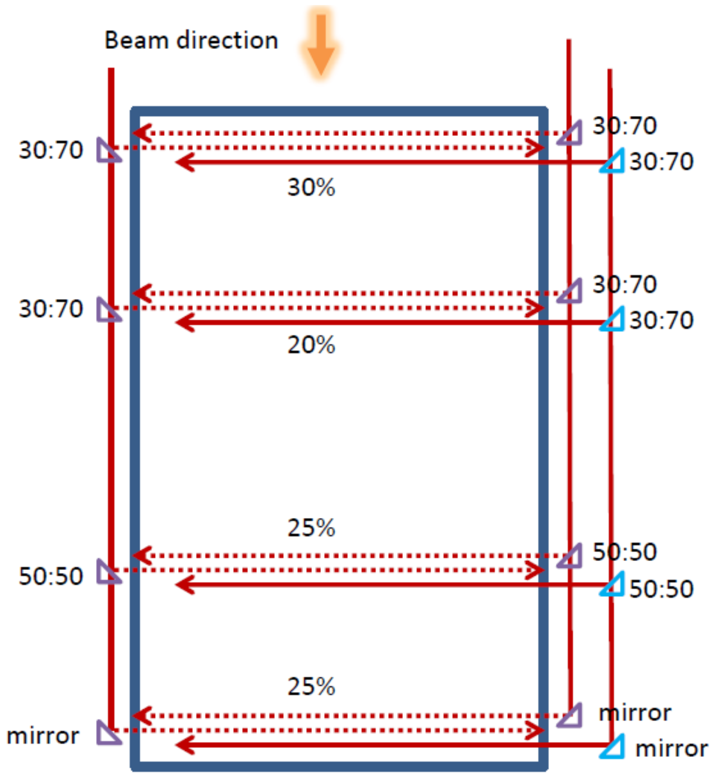
Bottom plate



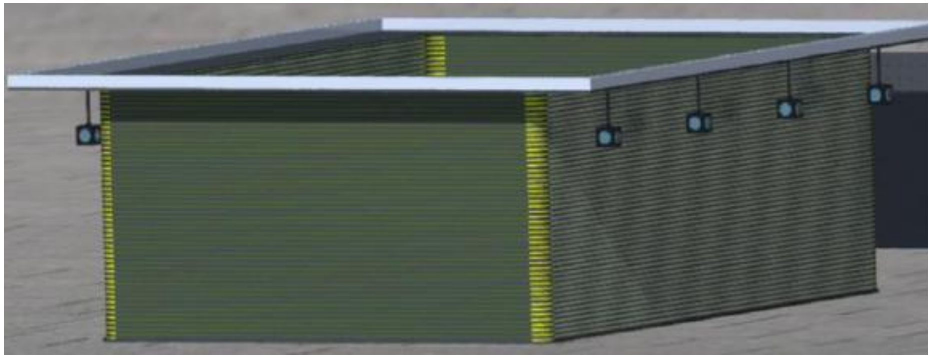
Ground (end of VSD)

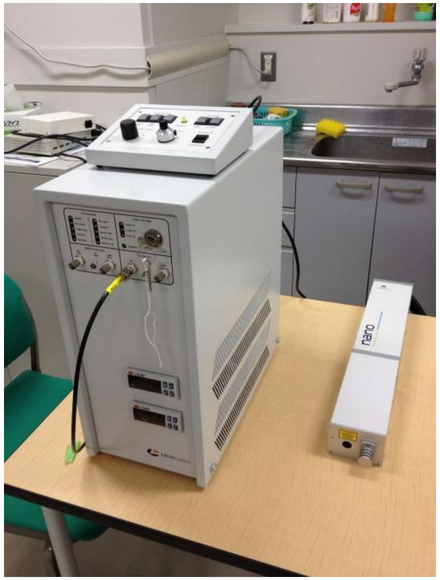
Cathode side: 9-20kV (used 10kV for test of 4 rings out of 9)

Laser Calibration System

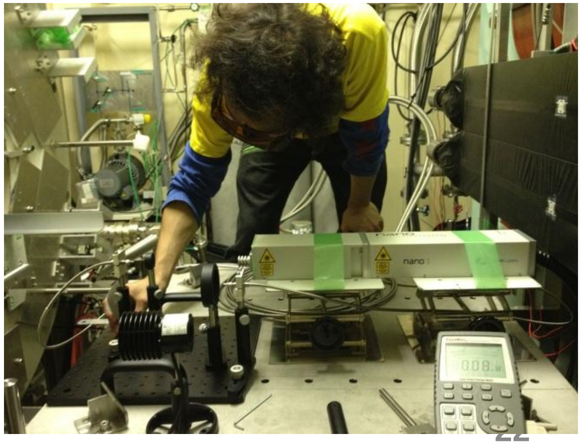


Top View

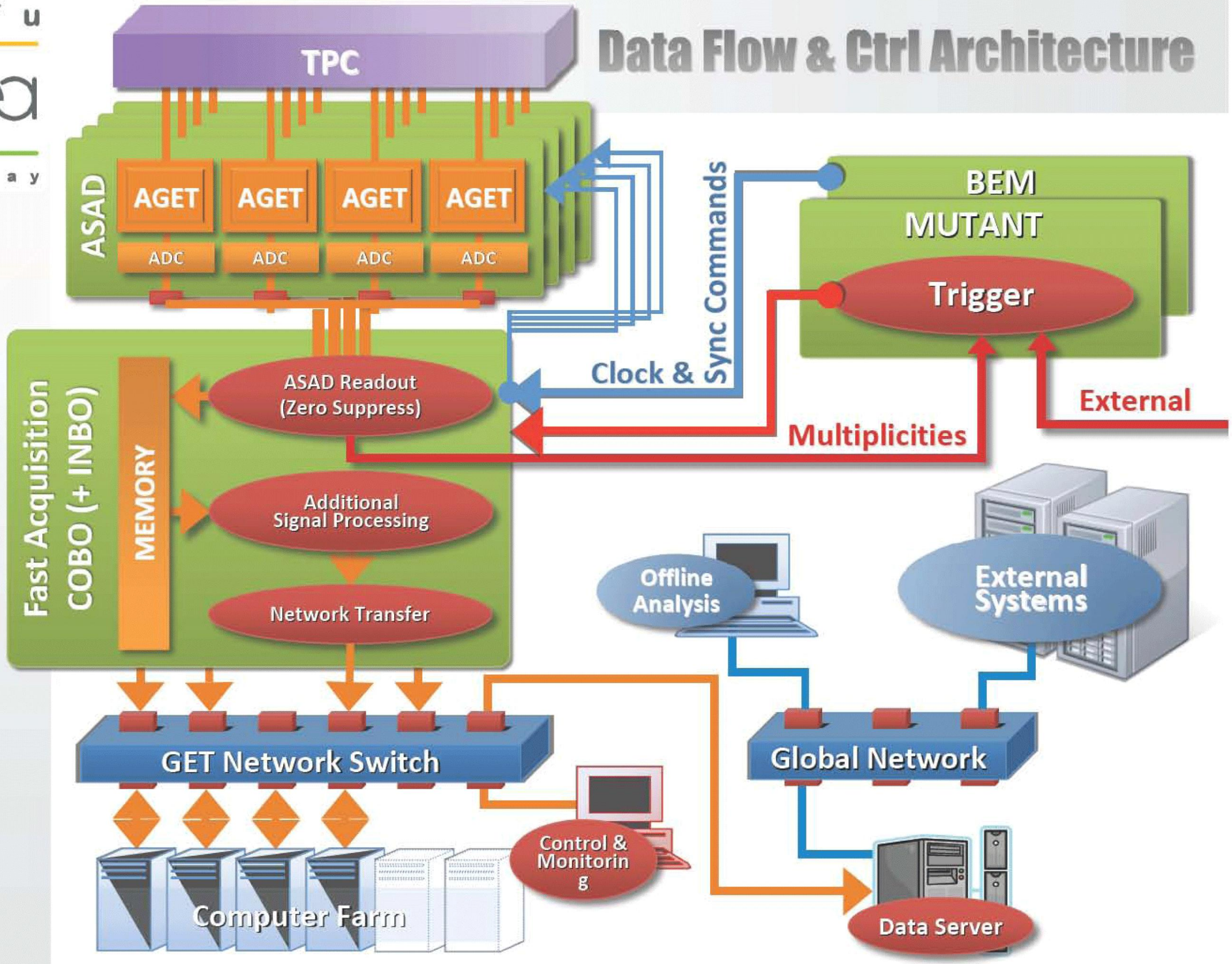




Litron Laser (Class 4)
266nm
15 mJ / pulse (10Hz)

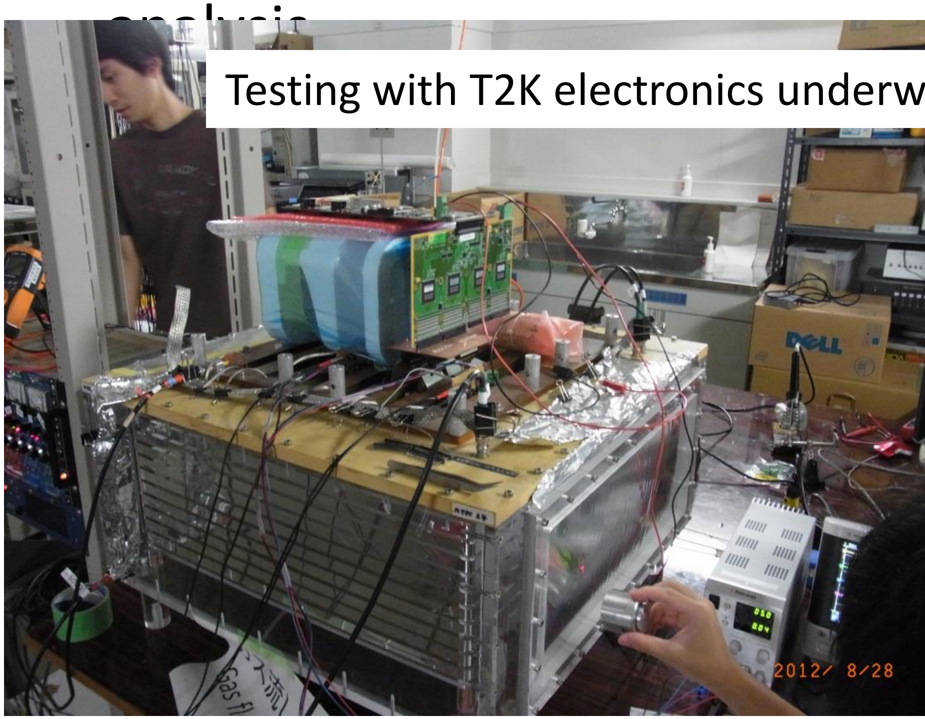


Data Flow & Ctrl Architecture

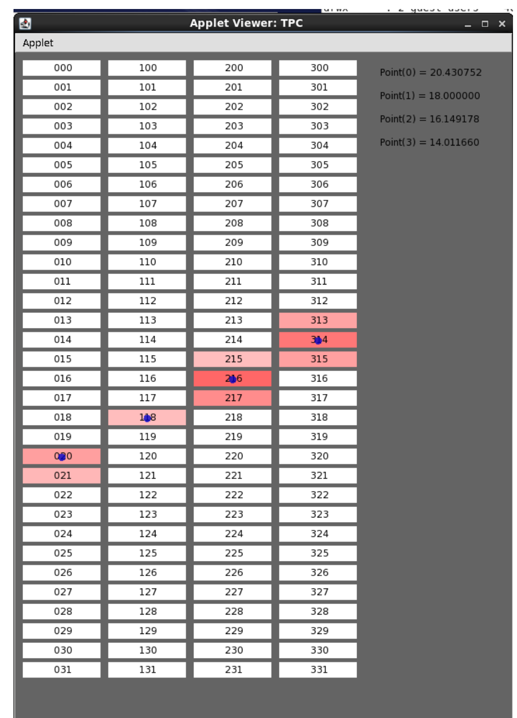


GET Electronics

- 12-bit ADC, 512 samples, 12k channels data taking under DAQ rate of about 1kHz.
- Expected data rate is quite high.
  - 100~300M Byte/sec, 60~180TByte/week.
  - Strong network infrastructure and offline computing facility is necessary for DAQ and online/offline data analysis.



Testing with T2K electronics underway



Planed Experiments

Commission experiments			350 MeV		
Beam	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
124Xe	124Sn	1.30	1.48	1.38	-0.18
124Xe	112Sn	1.30	1.24	1.27	0.06

Physics experiments:		200 MeV	& 300 MeV			
Beam	pro	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
132Sn	RI	124Sn	1.64	1.48	1.56	0.16
132Sn	RI	112Sn	1.64	1.24	1.44	0.40
108Sn	RI	124Sn	1.16	1.48	1.32	-0.32
108Sn	RI	112Sn	1.16	1.24	1.20	-0.08