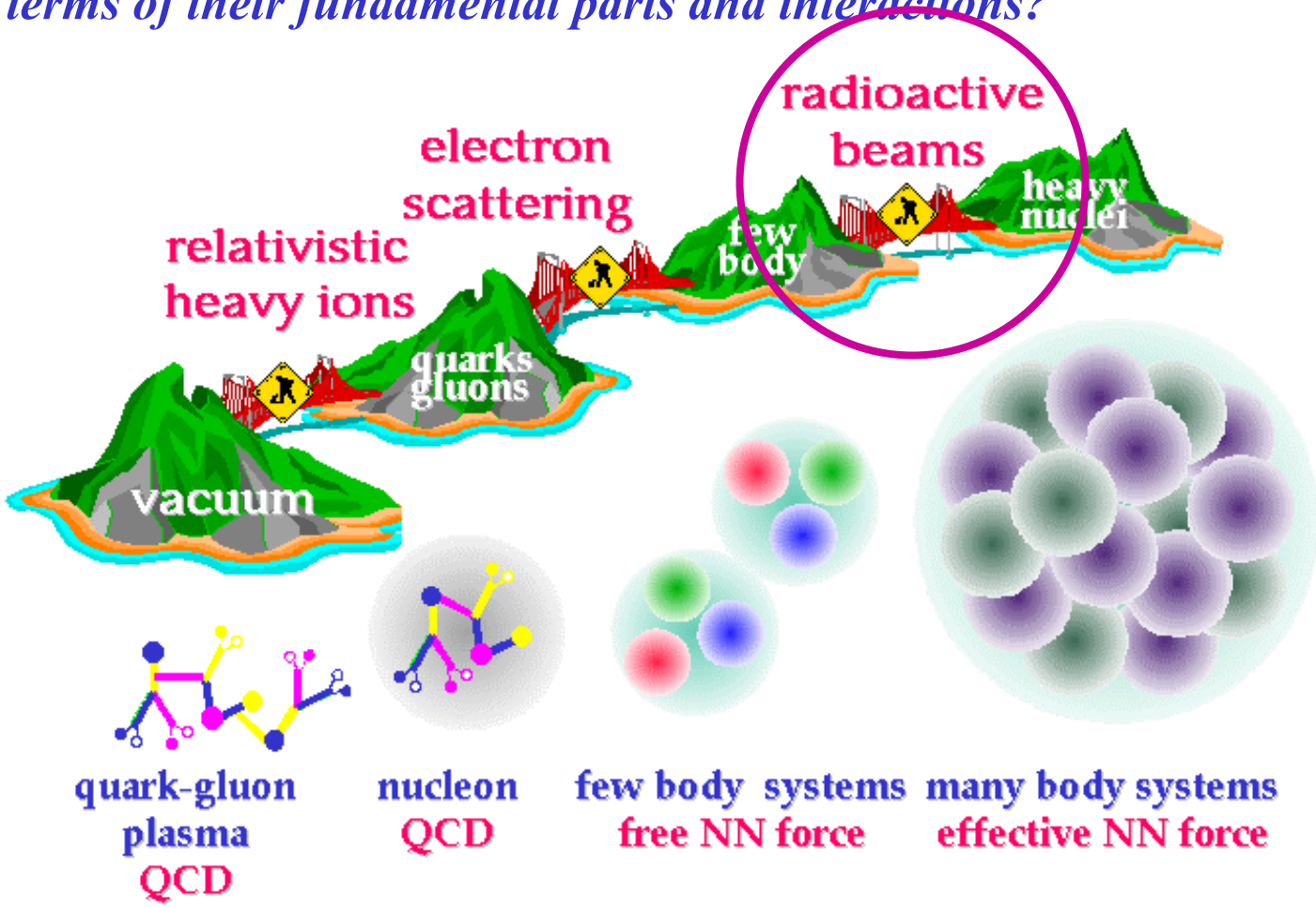
Overview of Nuclear Science

Nuclear science addresses the quantum quark/gluon and nuclear many body problems. How do we understand nuclei in terms of their fundamental parts and interactions?



W. Nazarewicz

Constraining symmetry energy with laboratory experiments

Outline:

RIA

NSCL/MSU

HI experiments to study the symmetry energy

Possible experiments at CSR

Lanzhou CSR workshop, July 1-5, 2005, Lanzhou, China

Betty Tsang

The National Superconducting Cyclotron Laboratory

Michigan State University

RIA (The Rare Isotope Accelerator)

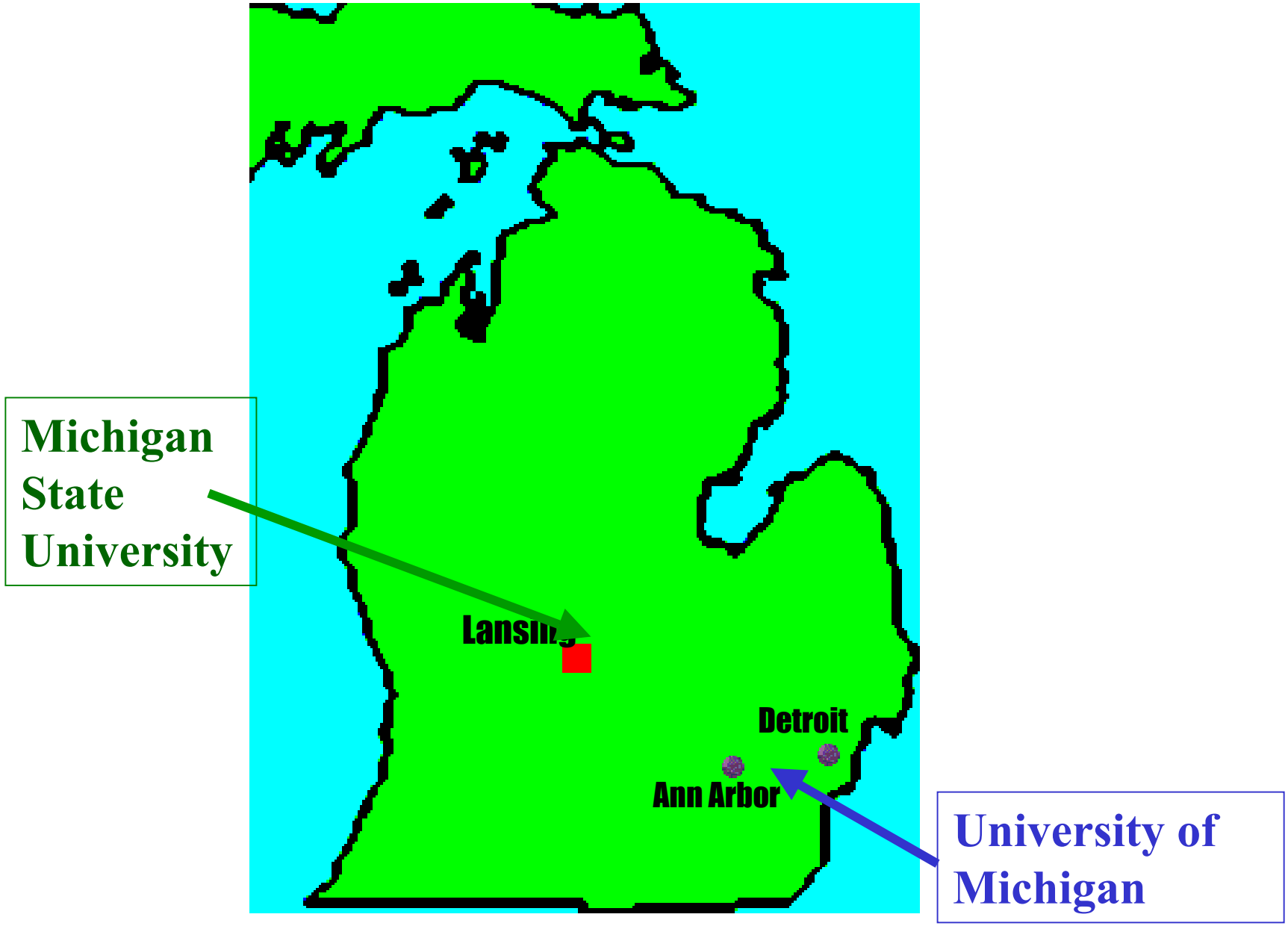
2001—The Nuclear Science Advisory Committee Long Range Plan endorses RIA as the highest priority for major new construction.
2004—RIA tied for 3rd place for future scientific facilities supported by the Department of Energy (DOE) to be built in 20 years.
2005—President Bush proposed 3.8% cuts in DOE science.
2005—Congress recommended DOE nuclear science increased by 3.9%

Construction (?) of RIA definitely will be postponed
RIA R&D continue;
Research with existing RI facilities such as NSCL
Cost of RIA ~ one week of war in Iraq

Window of opportunities for CSR

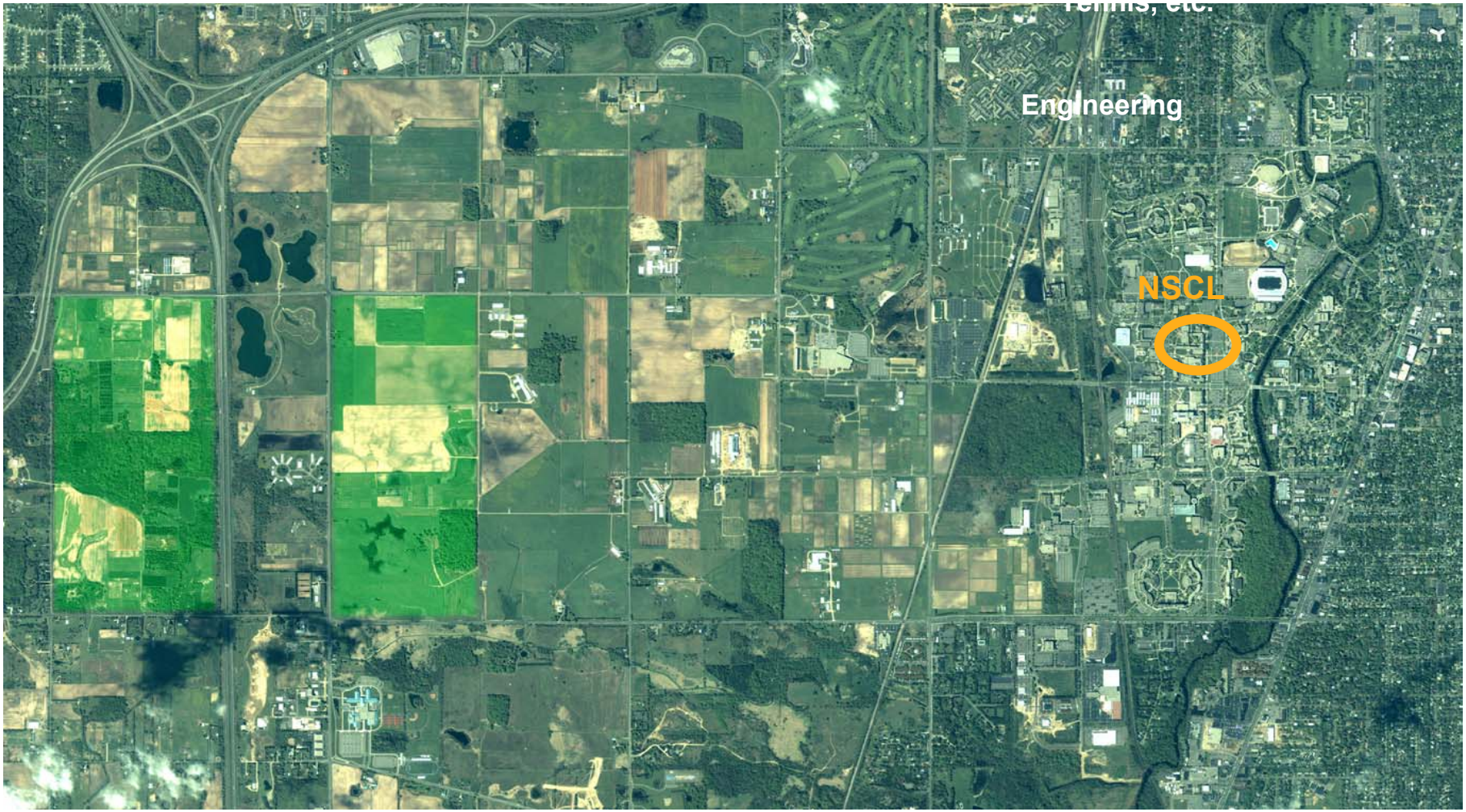
The National Superconducting Cyclotron Laboratory @ Michigan State University

Lansing is the capital of Michigan.
Michigan State University is located in East Lansing

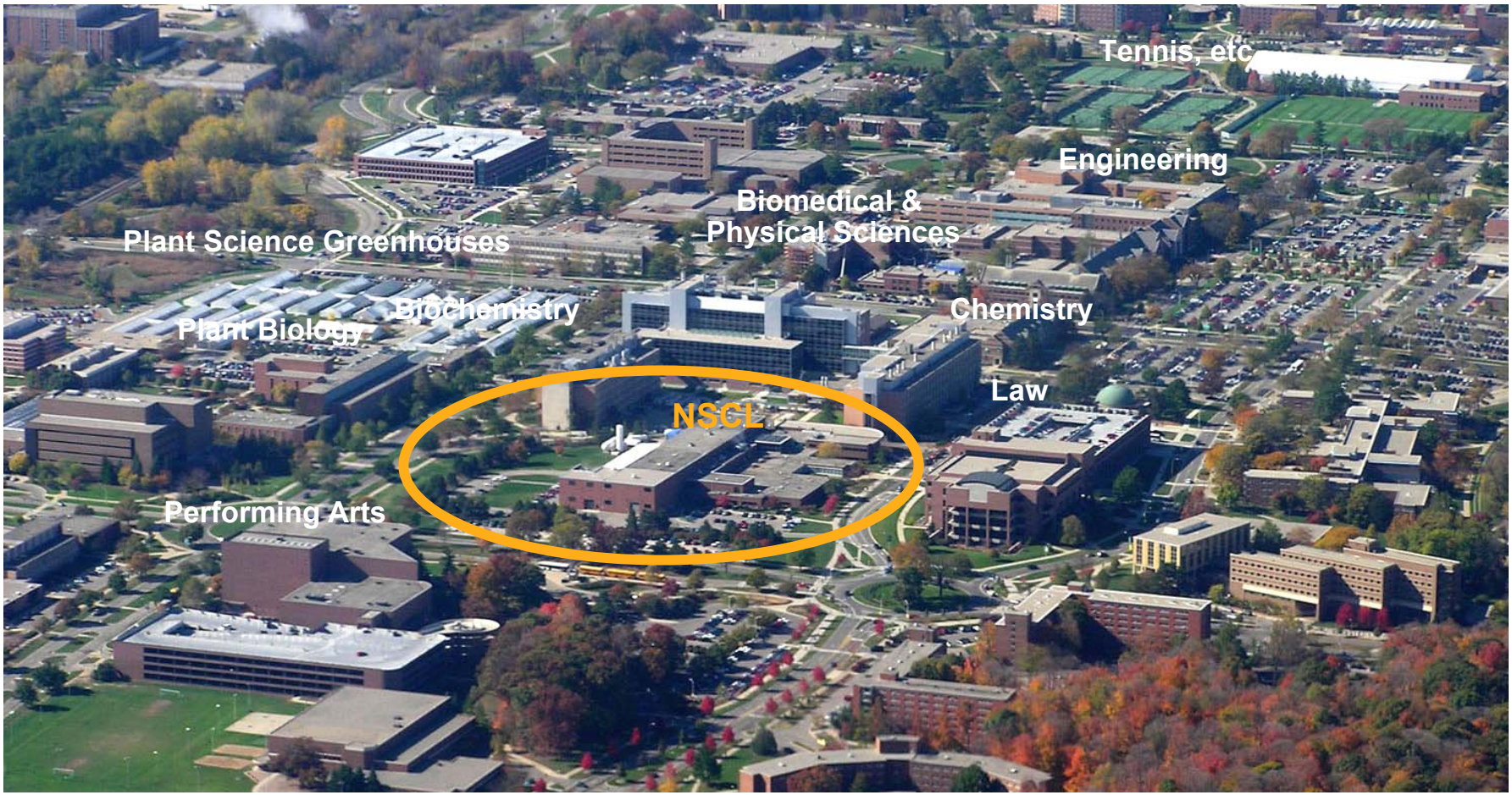


The National Superconducting Cyclotron Laboratory

Michigan State University



NSCL@MSU


Tennis, etc
Engineering
Biomedical &
Physical Sciences
Plant Science Greenhouses
Biochemistry
Plant Biology
Chemistry
Law
NSCL
Performing Arts

The National Superconducting Cyclotron Laboratory

Michigan State University

A national user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications

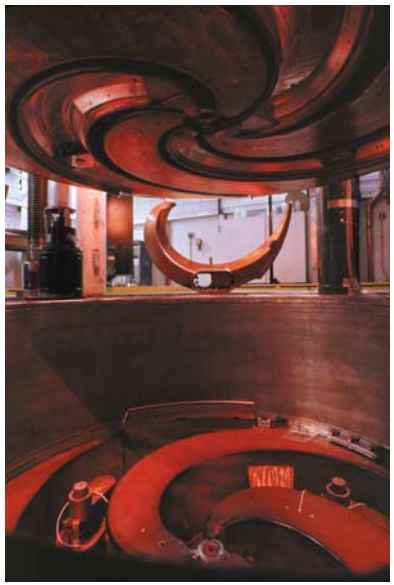
282 employees, incl. 51 undergraduate and 46 graduate students, 24 faculty

(as of March 05)

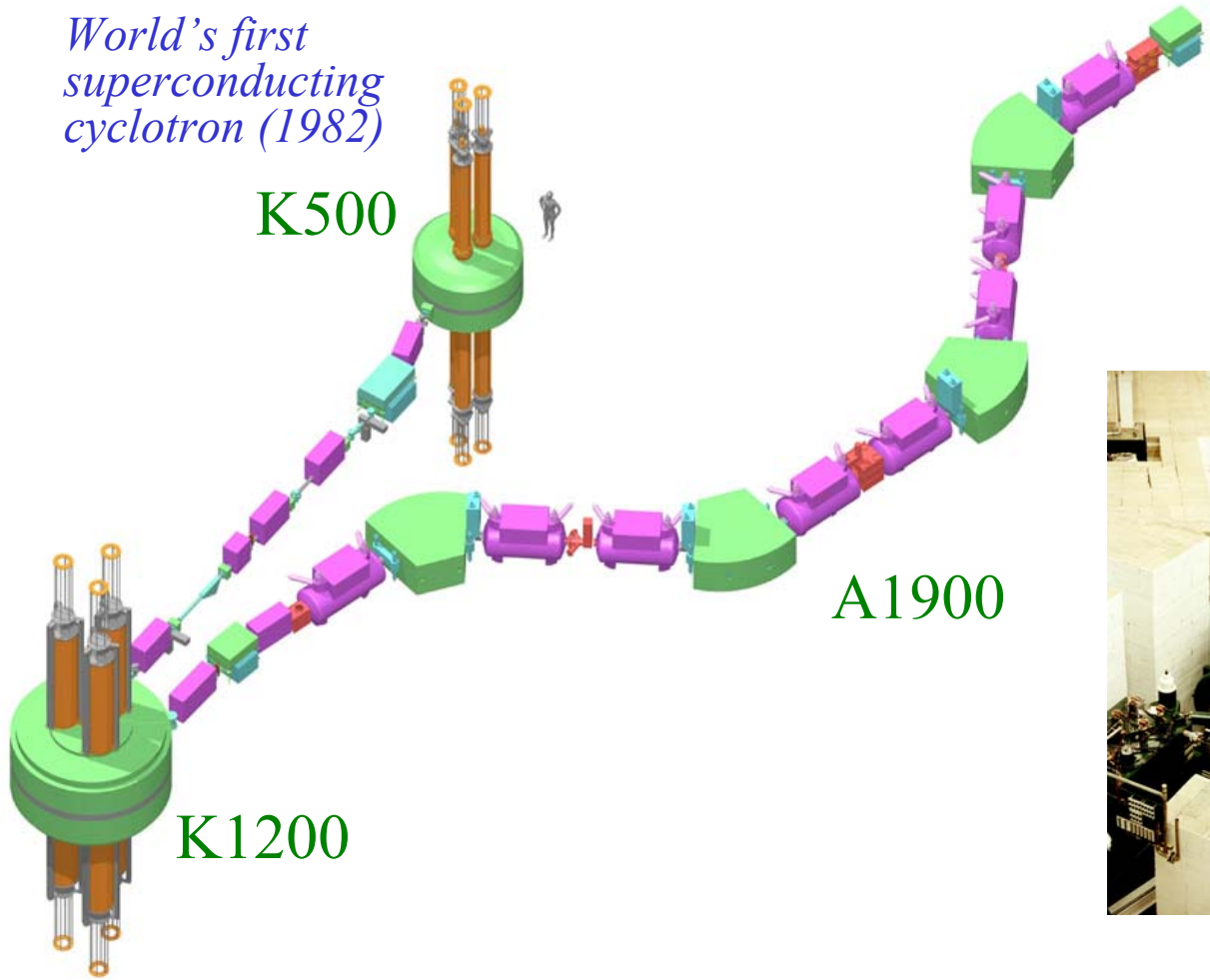
User group of over 600 CCF users

National Superconducting Cyclotron Laboratory

Coupled Cyclotron Facility (2001)

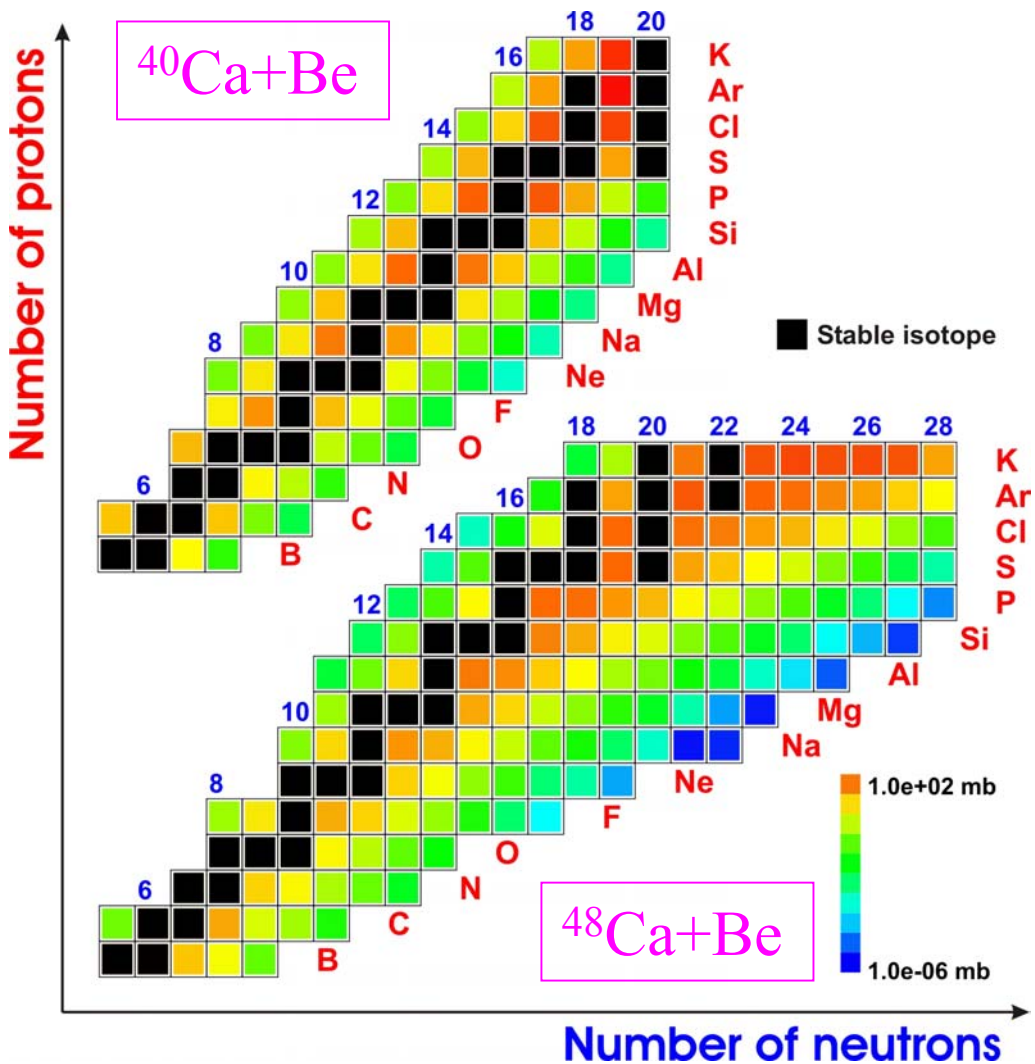


World's first superconducting cyclotron (1982)

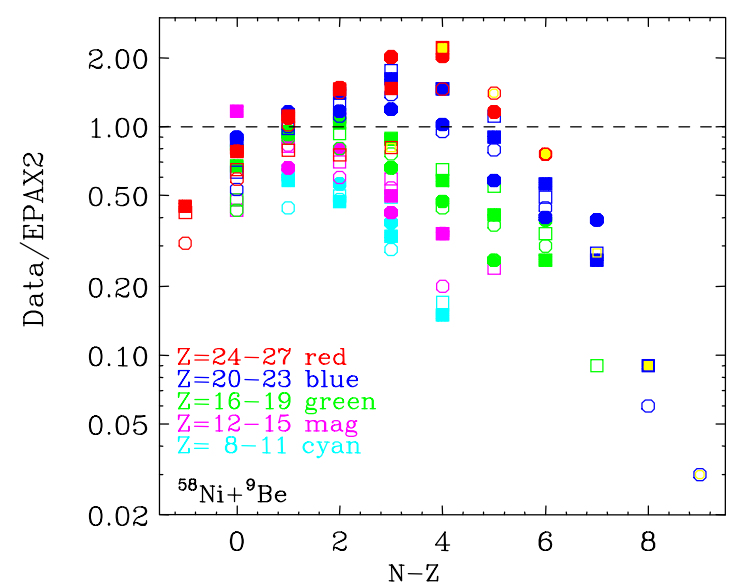


World's most powerful superconducting cyclotron (1988)

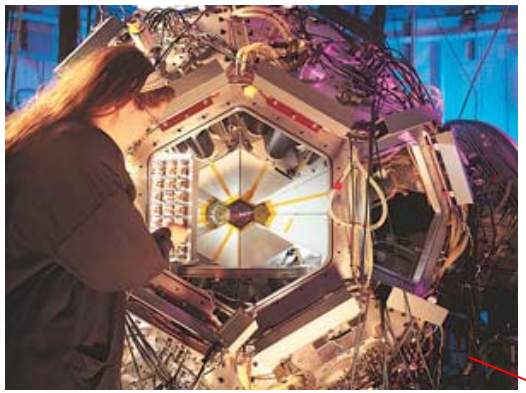
Rare Isotope Production:

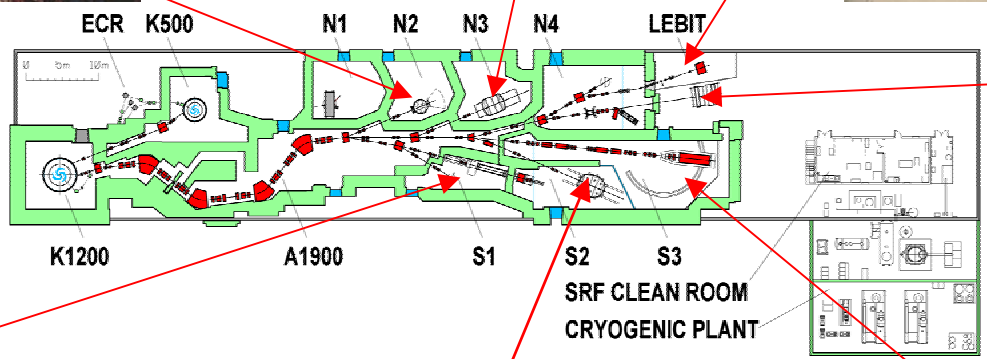


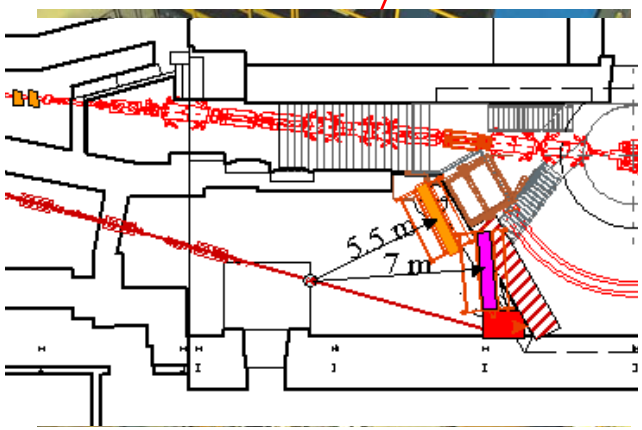
- ***Primary beams: ^{40,48}Ca, ^{58,64}Ni and unstable ^{68}Ni and ^{69}Cu beams.***
- ***Data reveal deficiencies of EPAX parameterization.***
- ***Improvement on theoretical understanding of the RI production mechanisms.***

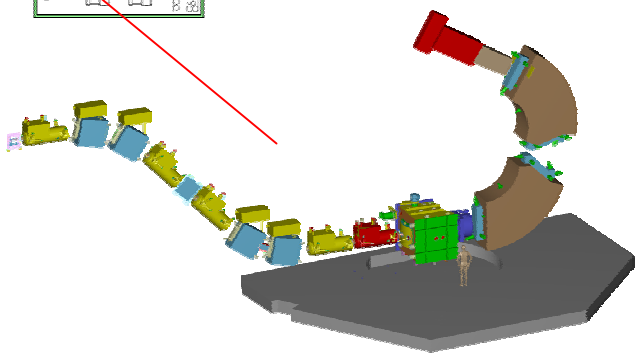


Experimental Areas at NSCL

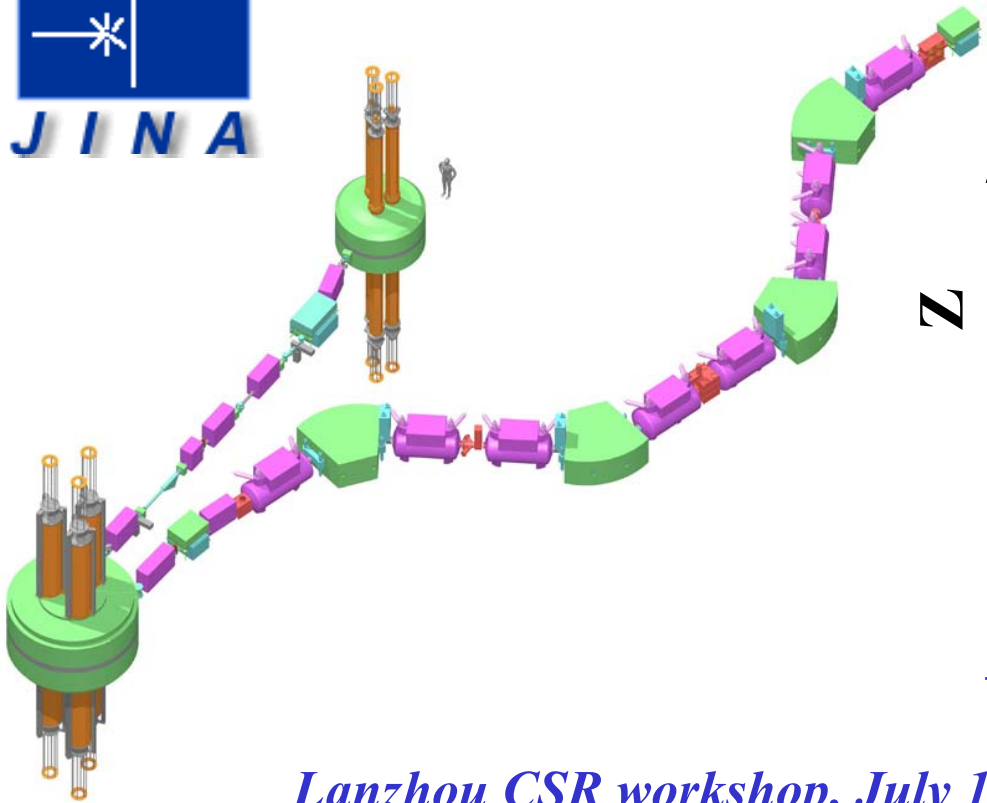


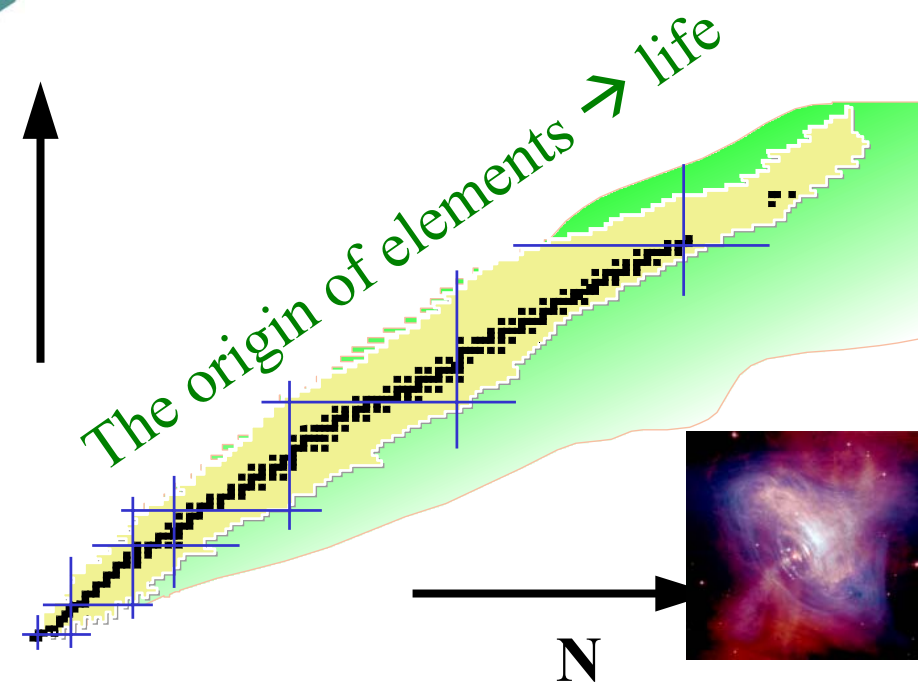






Constraining symmetry energy with laboratory experiments





Lanzhou CSR workshop, July 1-5, 2005, Lanzhou, China

Betty Tsang

The National Superconducting Cyclotron Laboratory

Michigan State University

Bao-An Li

The ultimate goal and major questions of studying heavy-ion reactions induced by neutron-rich (stable and/or radioactive) nuclei

To understand the isospin dependence of the nuclear Equation of State, extract the isospin dependence of thermal, mechanical and transport properties of asymmetric nuclear matter playing important roles in nuclei, neutron stars and supernove.

Among the currently most interesting topics in isospin physics

1. **EOS of neutron-rich matter, especially the density dependence of symmetry energy $E_{sym}(\rho)$ at high densities.**
   low
2. **Momentum-dependence of the symmetry potential and the neutron-proton effective mass splitting m_n^*-m_p^* in neutron-rich matter**
3. **Isospin-dependence of in-medium nucleon-nucleon cross sections and the nuclear stopping power in neutron-rich matter**
4. **Explore the phase diagram (T-ρ-δ) of neutron-rich matter along the isospin asymmetry δ axis (e.g, neutron distillation, n-Λ phase transition)**
5. **Isospin mixing of vector mesons (ρ^0-ω) and charge symmetry breaking in neutron-rich matter**

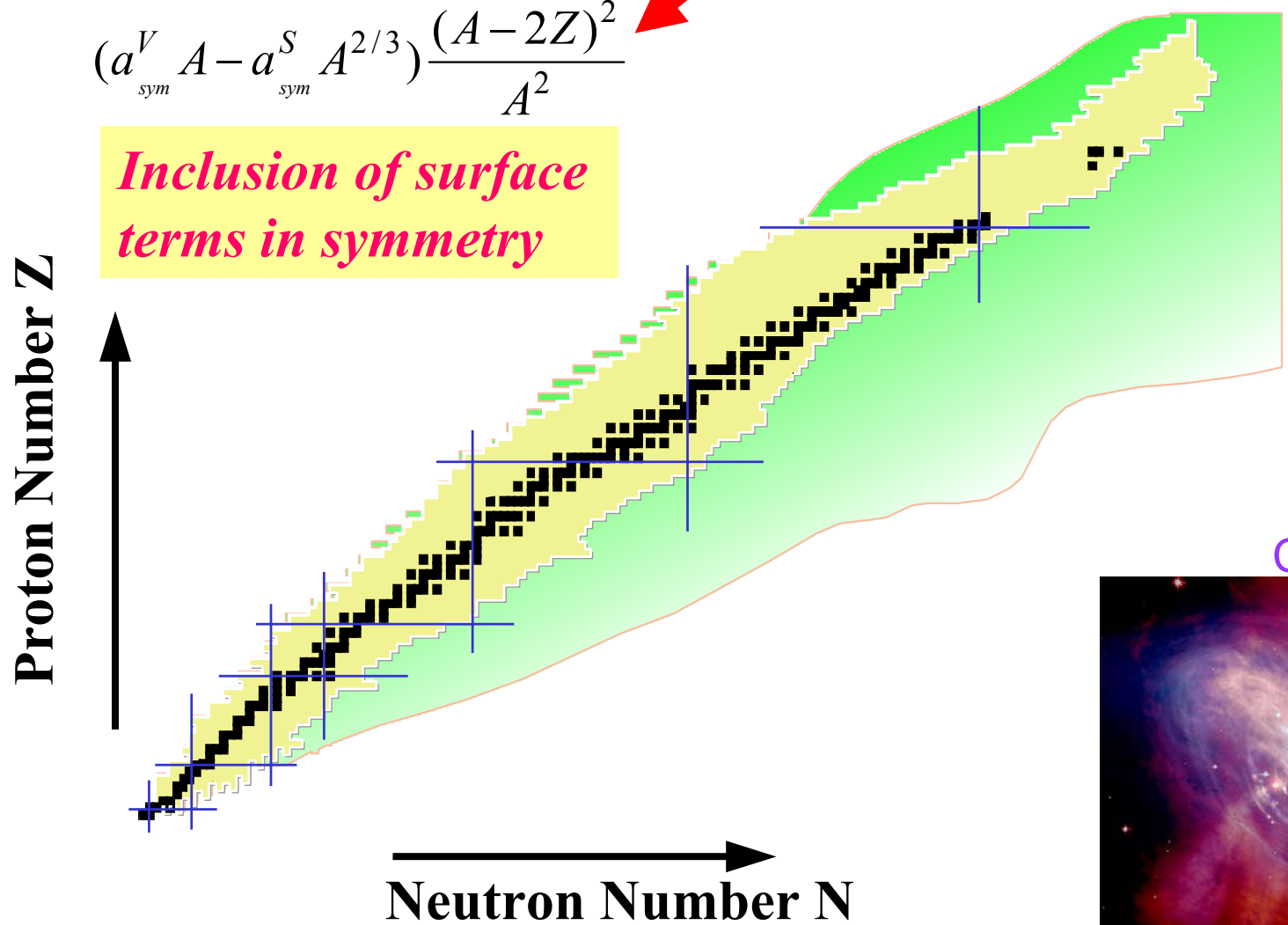
The most important question relevant to all of the above: What is the isospin dependence of the in-medium nuclear effective interactions

Symmetry Energy in Nuclei

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

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

Inclusion of surface terms in symmetry



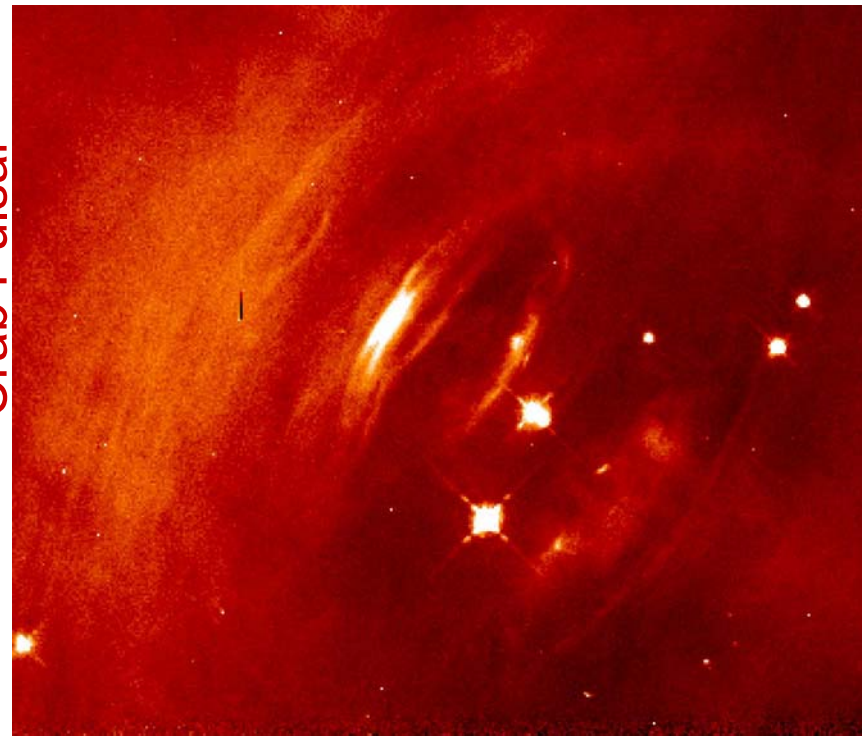
Crab Pulsar

Hubble ST

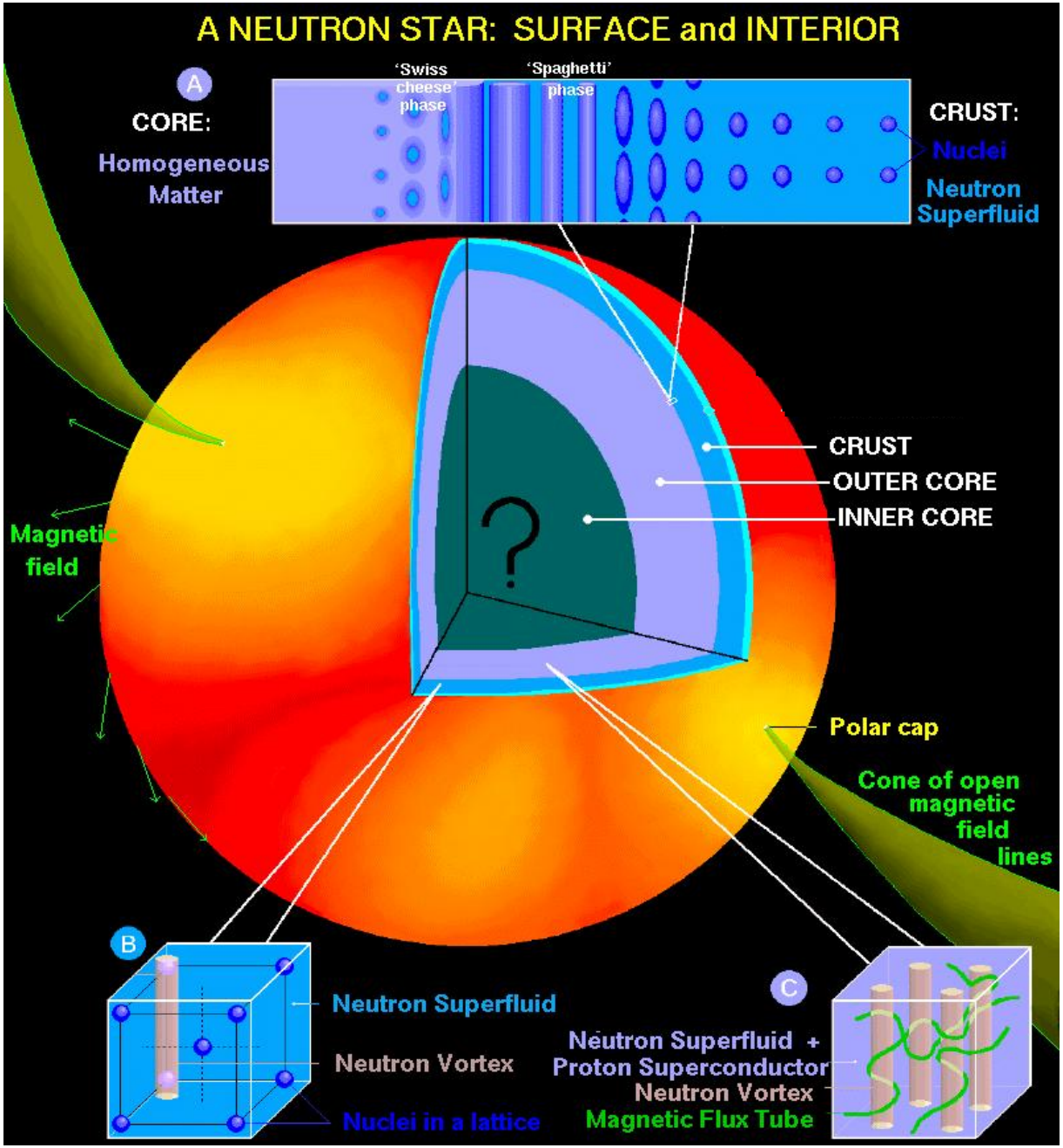
Birth of a Neutron Star

July 4, 1054, China

Crab Pulsar



Size & Structure of Neutron Star depends on EOS



EOS influence

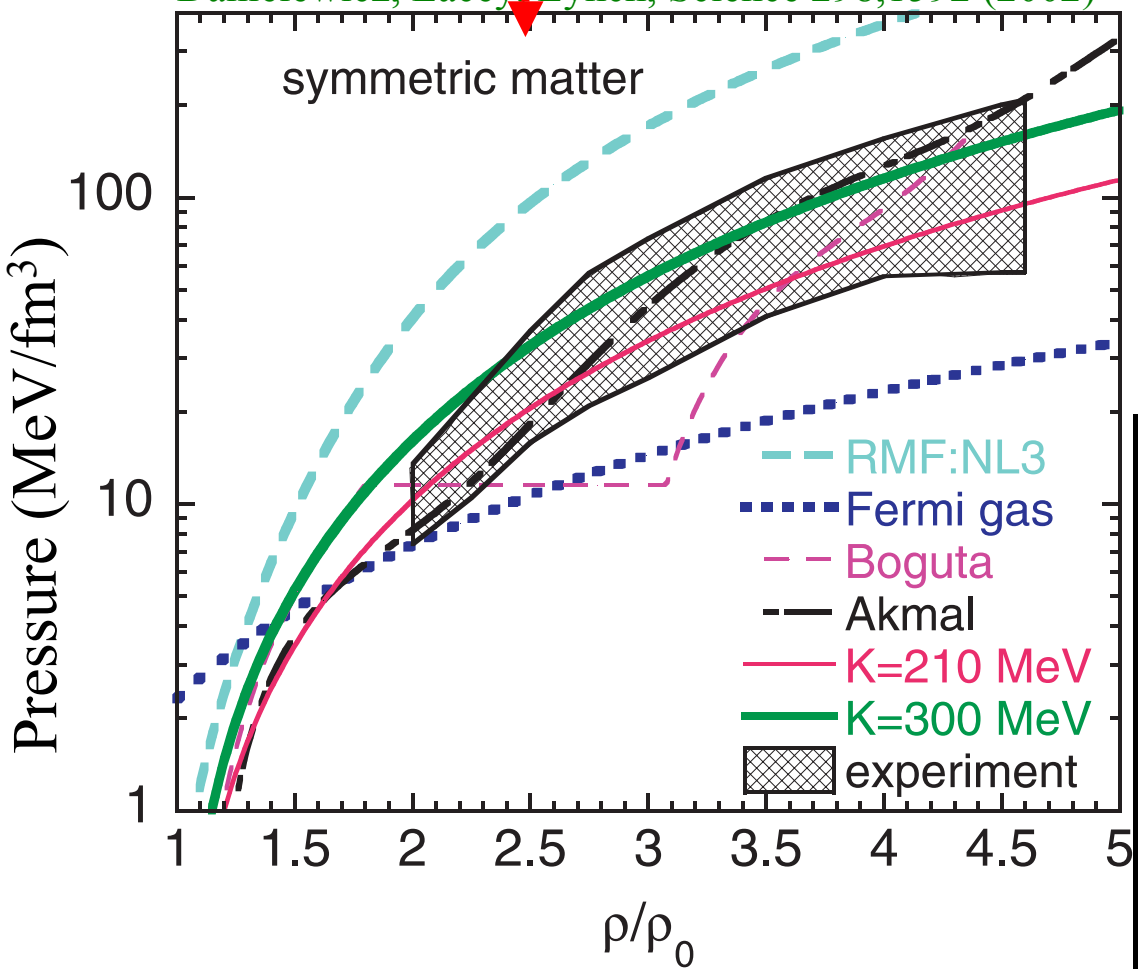
- ✓R,M relationship
- ✓maximum mass.
- ✓cooling rate.
- ✓core structure

D. Page

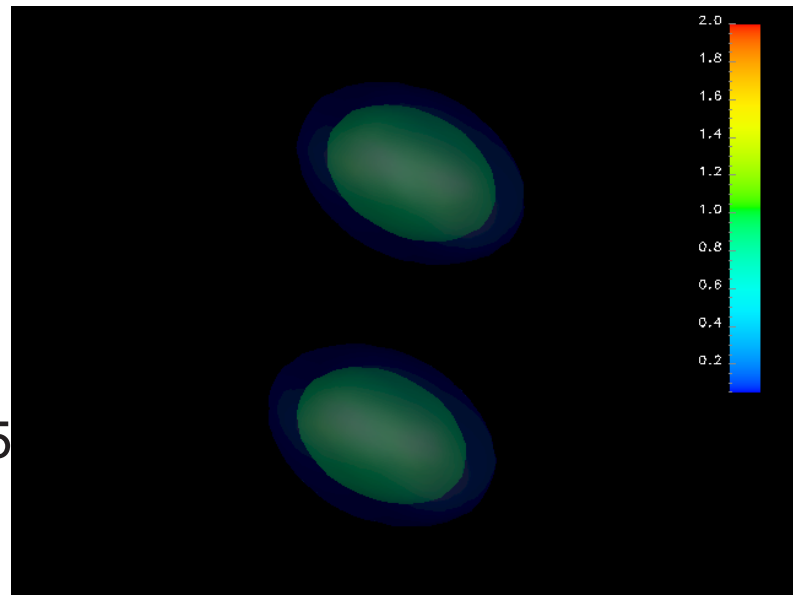
Heavy ion collisions :

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

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



Results from Au+Au flow (E/A~1-8 GeV) measurements include constraints in momentum dependence of the mean field and NN cross-sections



R. Lacey

Heavy ion collisions :

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

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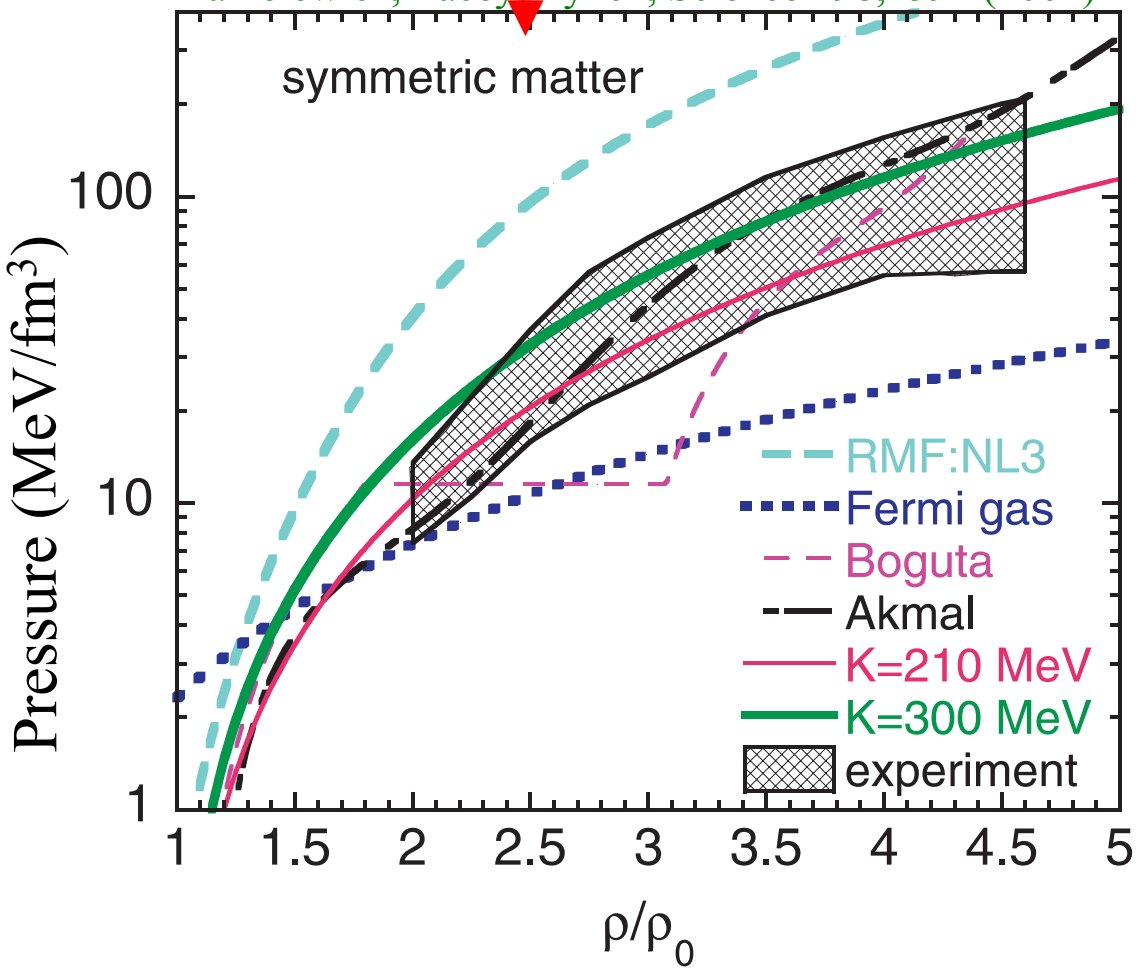


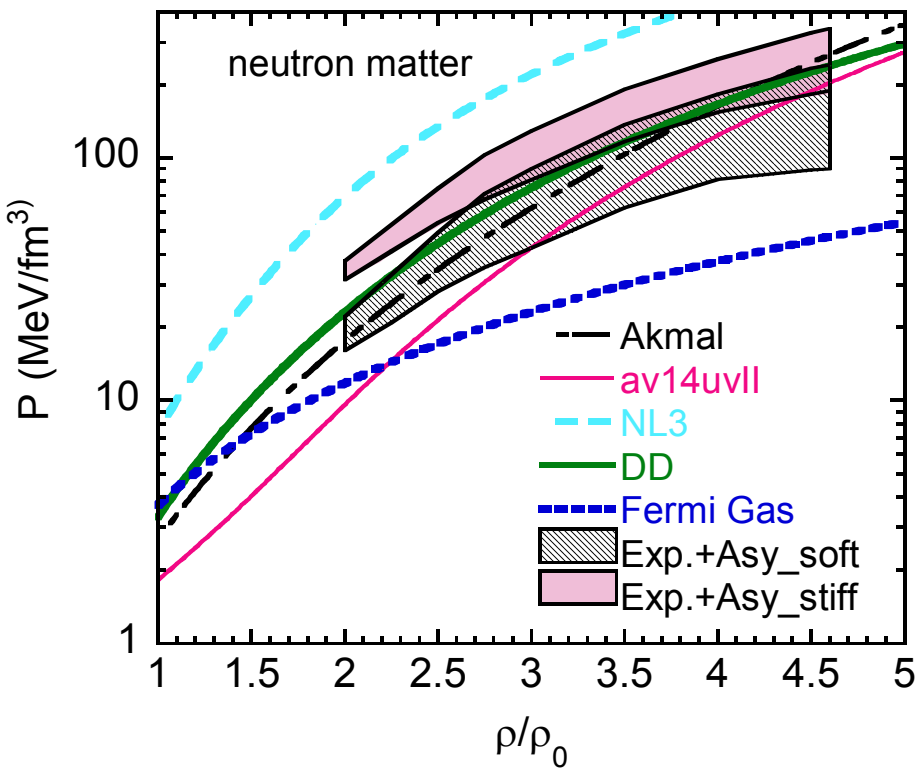
No experimental constraints on the symmetry terms

R. Lacey

Extrapolation to neutron stars

$E/A(\rho, \delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$ $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1$

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



- *The asymmetry term contributes greater uncertainty than does the symmetric matter EOS.*

Sensitive observables:

- ***At sub-saturation densities***
  - ***Isospin diffusion***
  - ***Asymmetry of bound residues.***
  - ***Pre-equilibrium n vs. p emission***
  - ***Transverse flow (n.vs.p).***
  - ***Difference between neutron and proton matter radii.***
- ***At supra-saturation densities (CSR)***
  - ***Isospin dependencies of pion production.***
  - ***n vs. p emission***
  - ***Transverse flow (n.vs.p).***
- ***Additional measurements are needed to constrain the n,p effective masses and the isospin dependences of the cross sections.***

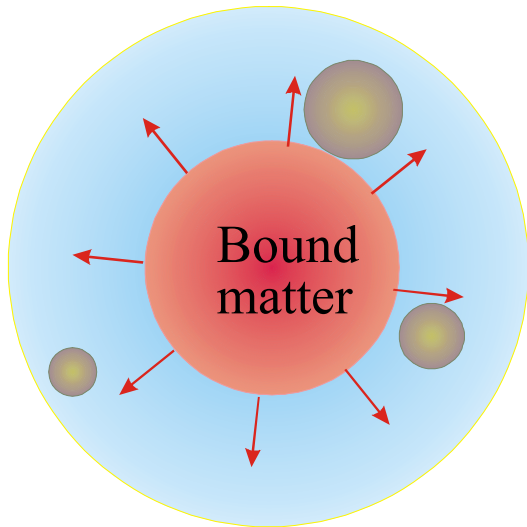
Observables in HI collisions

Assume $E_{sym}(\rho)=C_{cym}(\rho/\rho_0)^{\gamma}$

Heavy Ion Collisions:

Central collisions (isospin fractionation)

→ n/p ratios; $\langle E_n \rangle$, $\langle E_p \rangle$

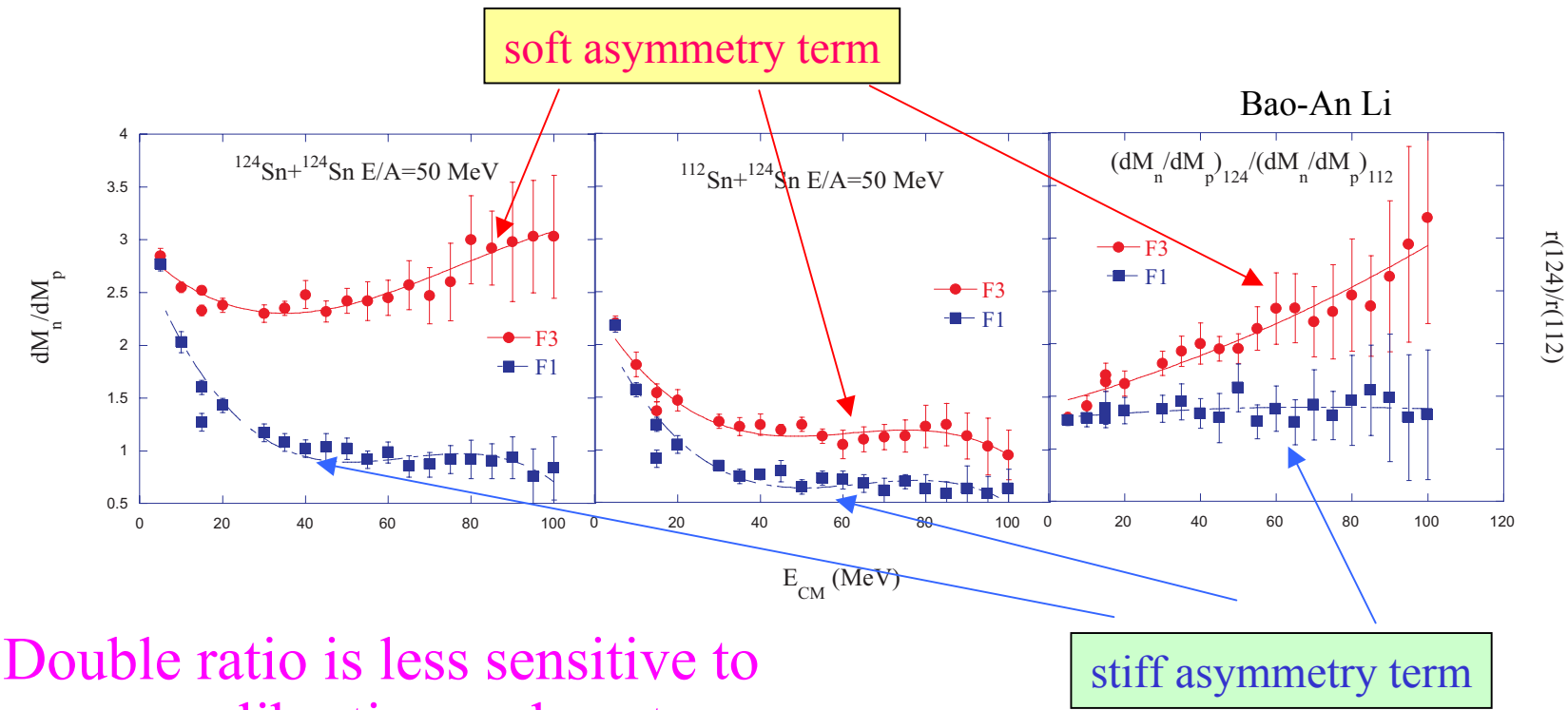


The symmetry term affects the emission of n and p.

n/p(stiff γ~1.1)<n/p(soft γ~0.6)

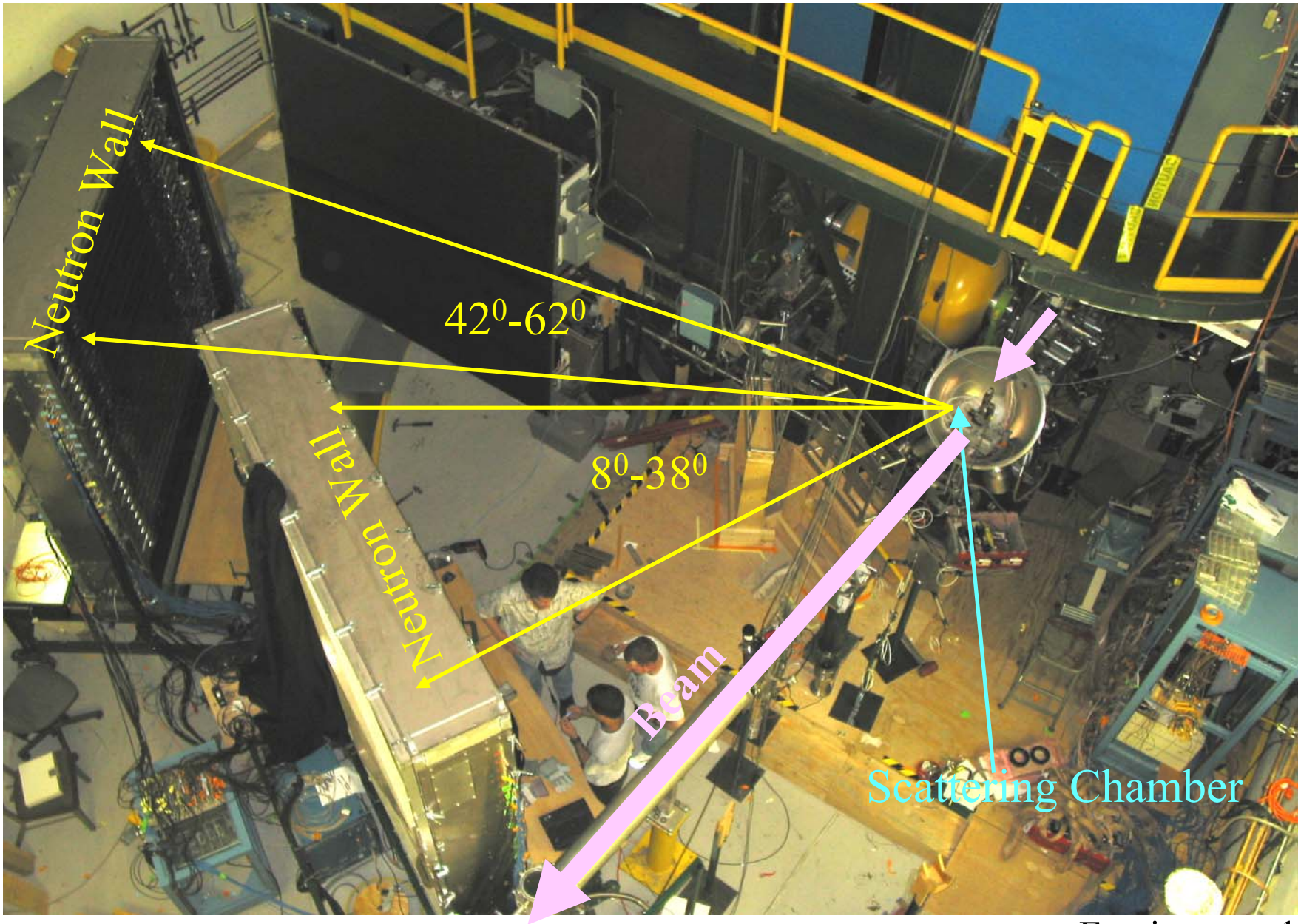
Studies of emitted n and p

- Direct measurements of n vs. proton emission rates and transverse flows - probes the pressure from asymmetry term at saturation density and below.
  - Predictions for emission rates:
  - Clusters can be addressed within coalescence invariant analyses



- Double ratio is less sensitive to energy calibration and neutron efficiency uncertainties.

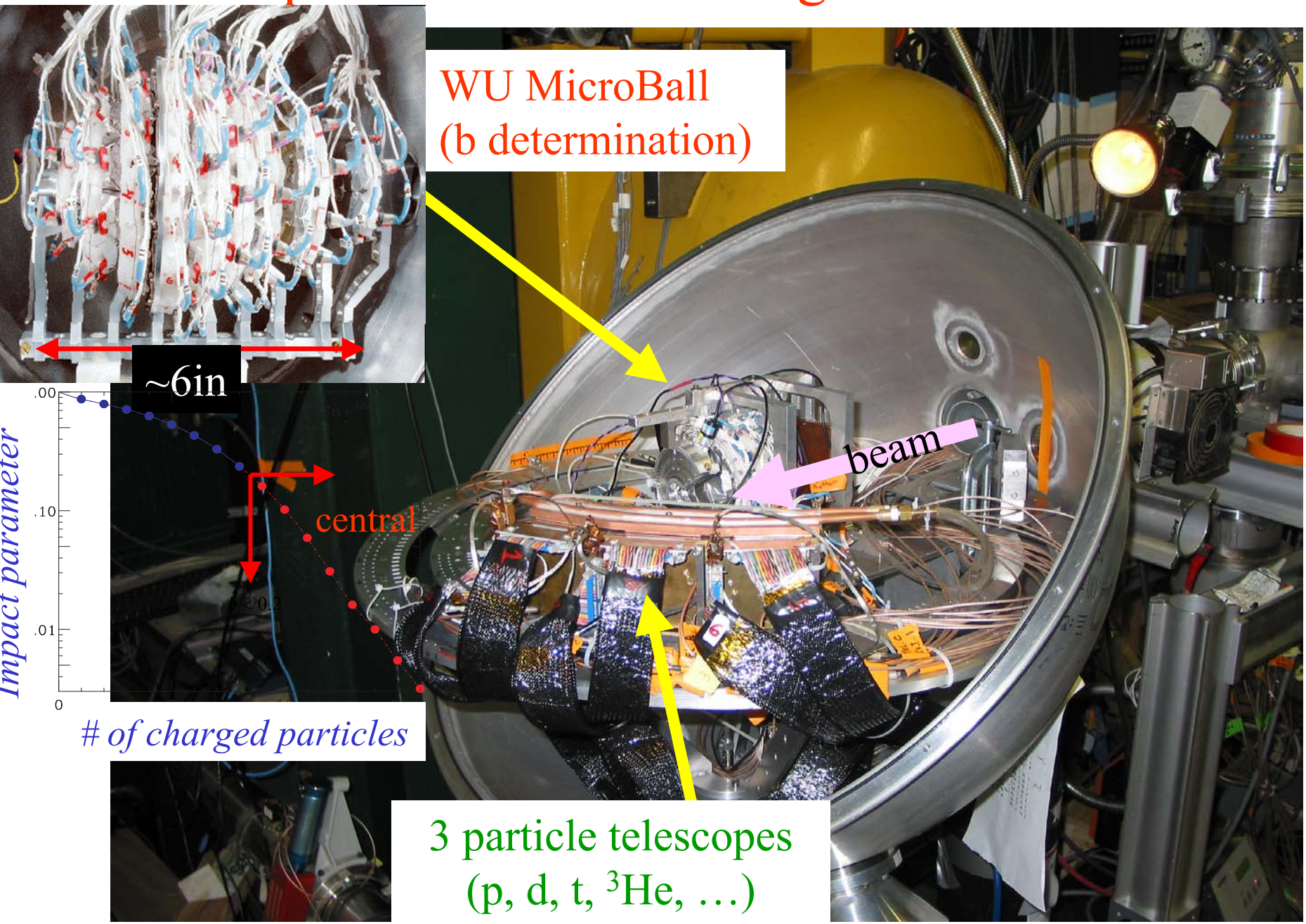
n/p Experiment $^{124}Sn+^{124}Sn$; $^{112}Sn+^{112}Sn$; E/A=50 MeV



Famiano et al

N-detection – neutron wall

p-detection: Scattering Chamber



n/p Double Ratios (central collisions)

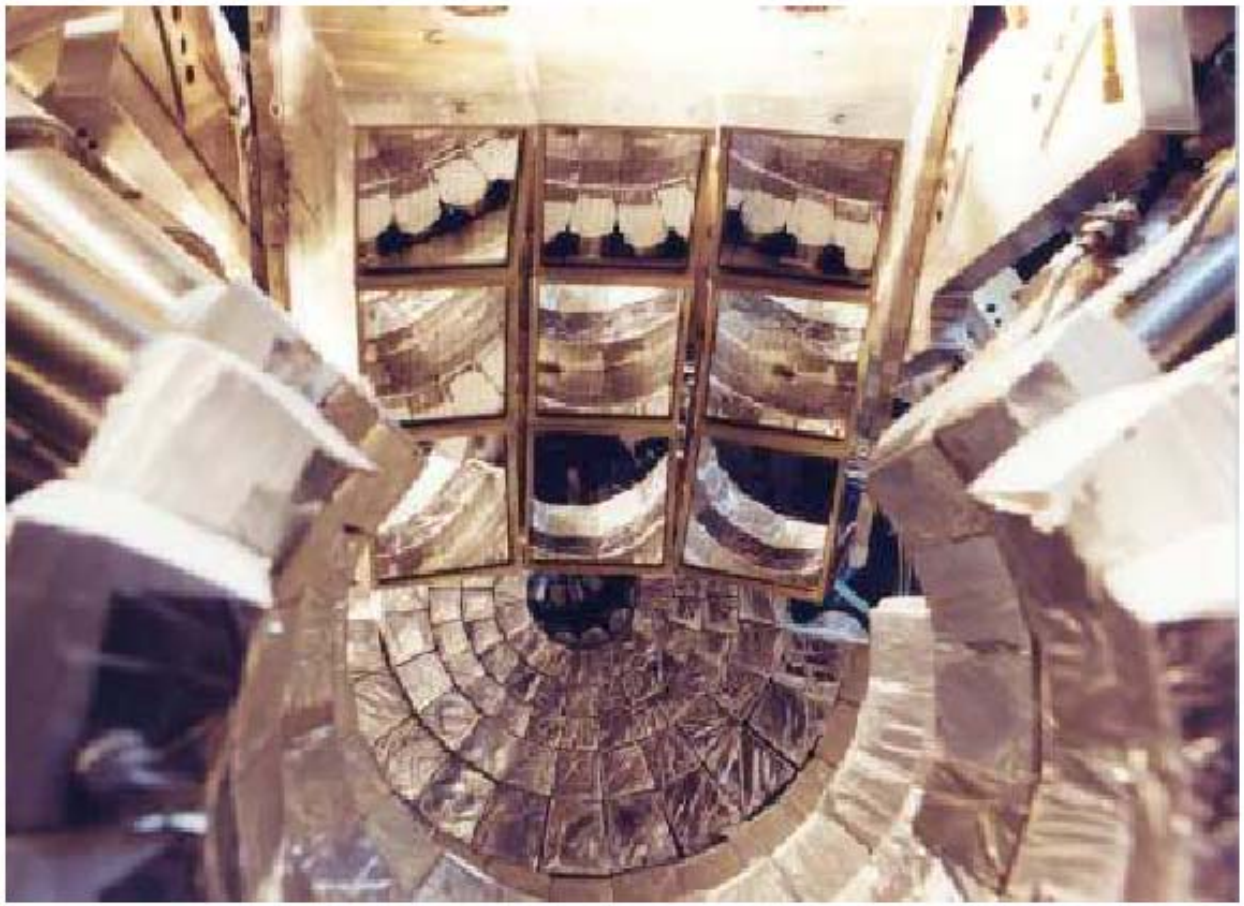
Double Ratio ➡ $\frac{^{124}Sn+^{124}Sn;Y(n)/Y(p)}{^{112}Sn+^{112}Sn;Y(n)/Y(p)}$ ➡ minimize systematic errors

There will be improvements in both data (analysis) and BUU (1997) calculations.

Isotope Distribution Experiment

MSU, IUCF, WU collaboration

Sn+Sn collisions involving ^{124}Sn, ^{112}Sn at E/A=50 MeV



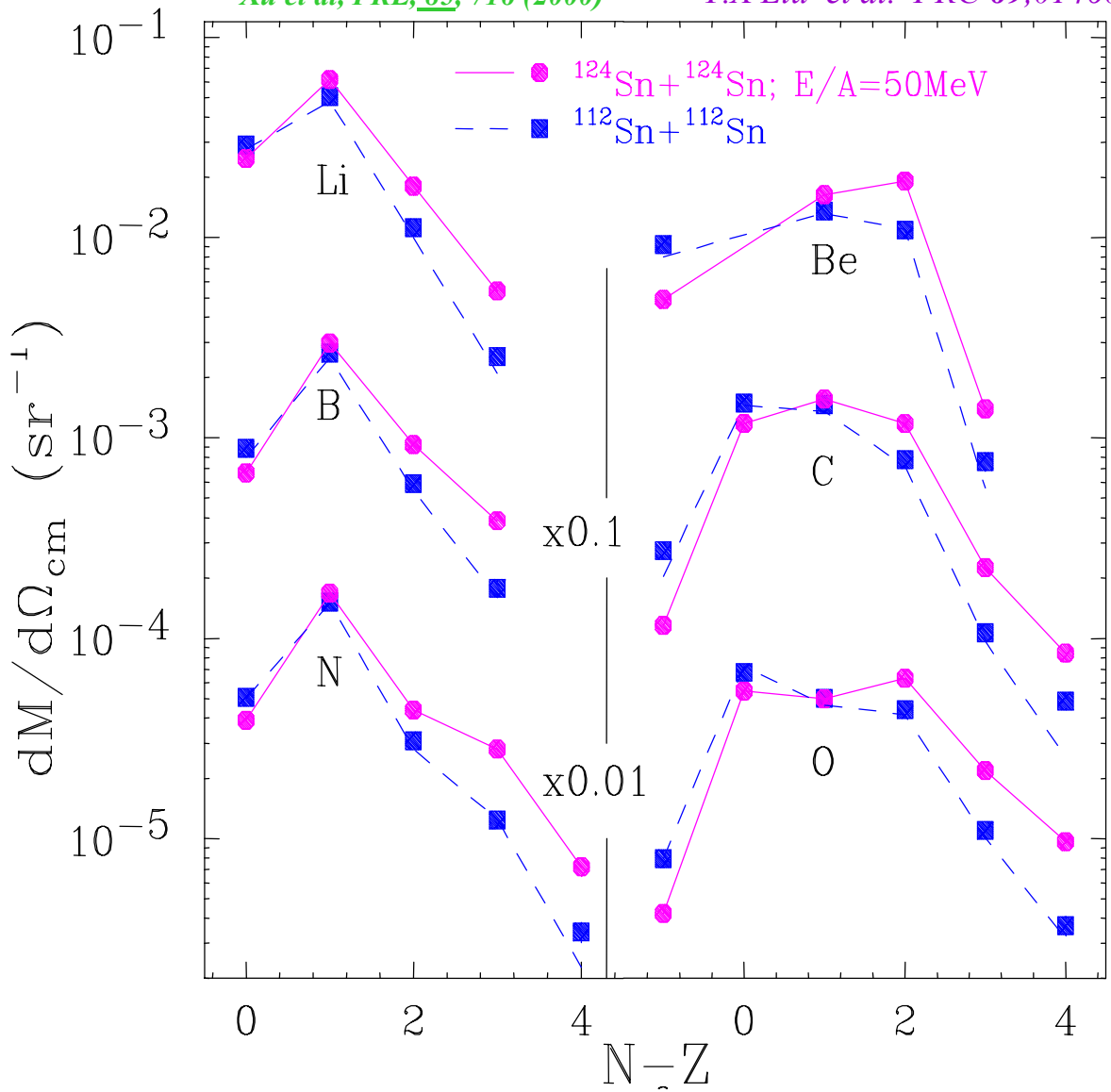
Miniball + Miniwall
4 π multiplicity array
Z identification, A<4

LASSA
Si strip +CsI array
Good E, position, isotope resolutions

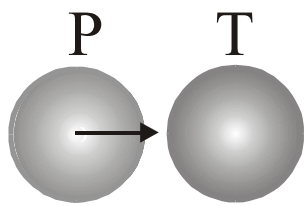
Xu et al, PRL, 85, 716 (2000)

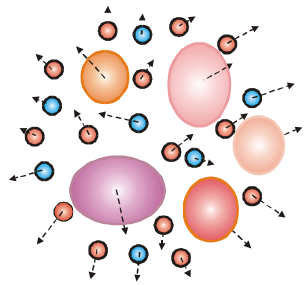
Measured Isotopic yields

Xu et al, PRL, 85, 716 (2000) *T.X Liu et al. PRC 69,014603*



Central collisions



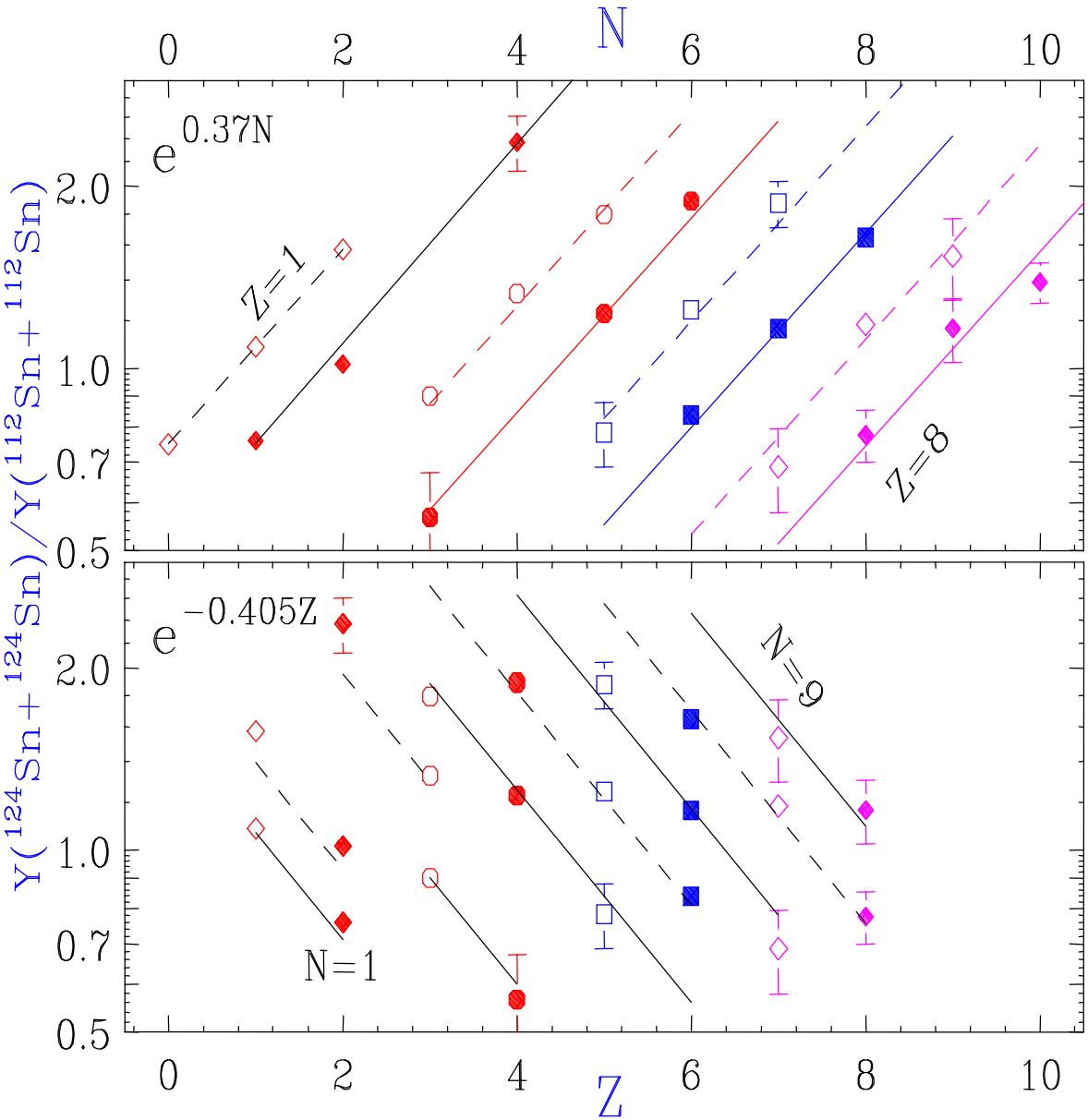


Multifragmentation

Similar distributions

$R_{21}(N,Z)=Y_2(N,Z)/\ Y_1(N,Z)$

Isoscaling from Relative Isotope Ratios



$R_{21}(N,Z)$
$=Y_2(N,Z)/\ Y_1(N,Z)$

$$\propto e^{\alpha N+\beta Z}$$

In statistical and dynamical models, α is related to the symmetry energy and asymmetry of the emitting source

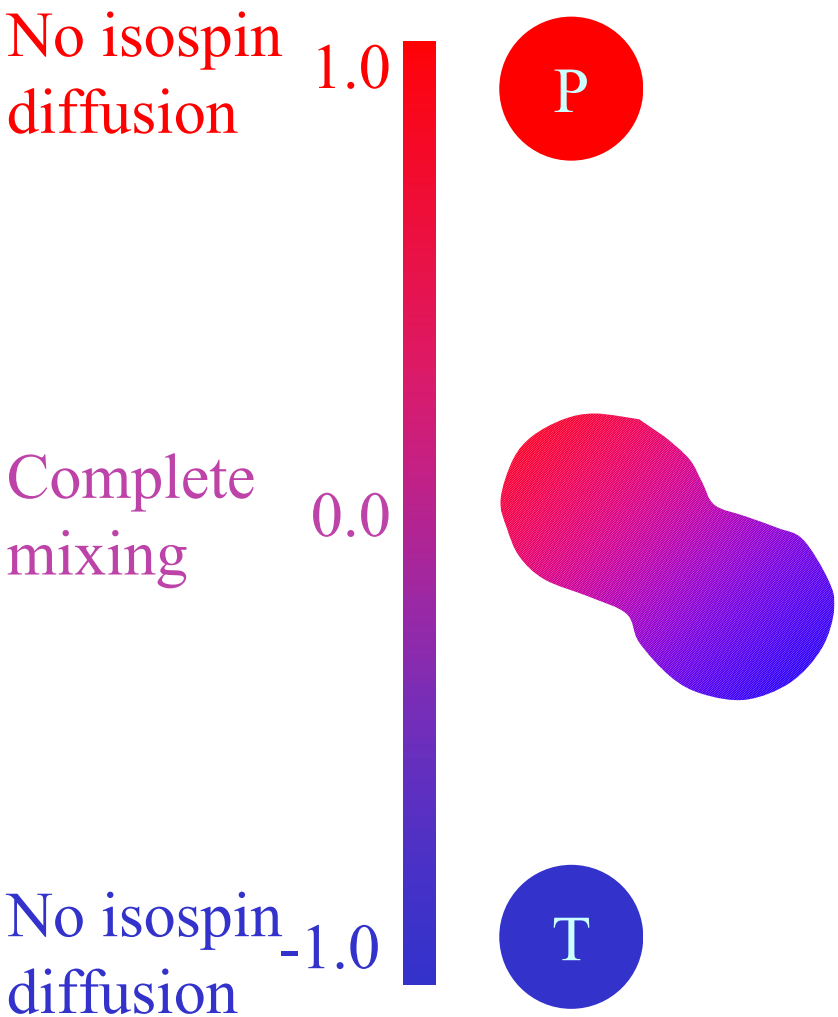
$\alpha=2C_{sym}[\Delta\delta(1-\delta)]/T$

Tsang et al, PRL, 86, 5023 (2001) *MB Tsang et al. PRC **64**,054615*

Isospin Diffusion

$$R_i = \frac{2\delta - \delta_{PP} - \delta_{TT}}{\delta_{PP} - \delta_{TT}}$$

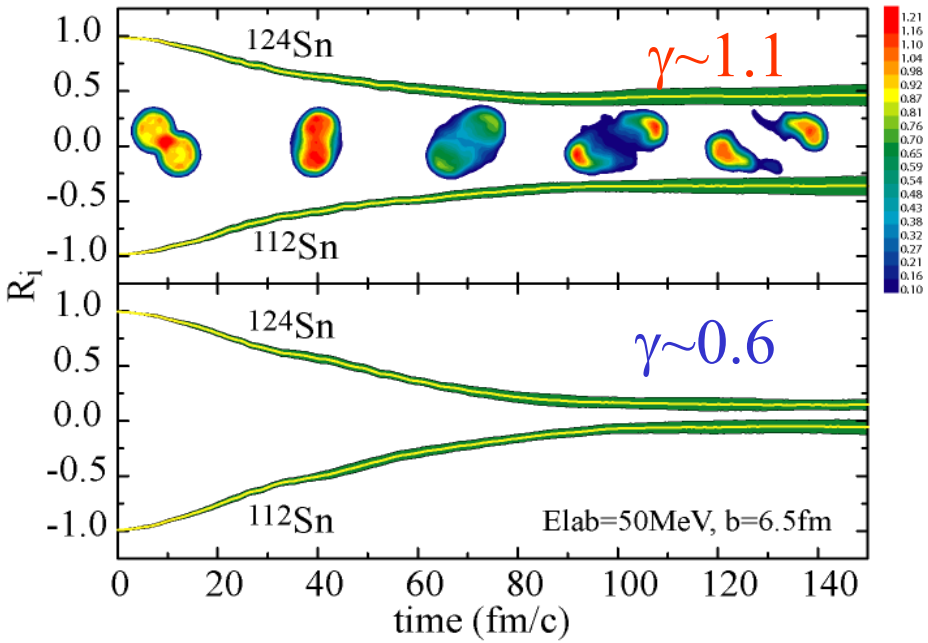
- *symmetry energy will act as a driving force to transport the n or p between projectile to target*

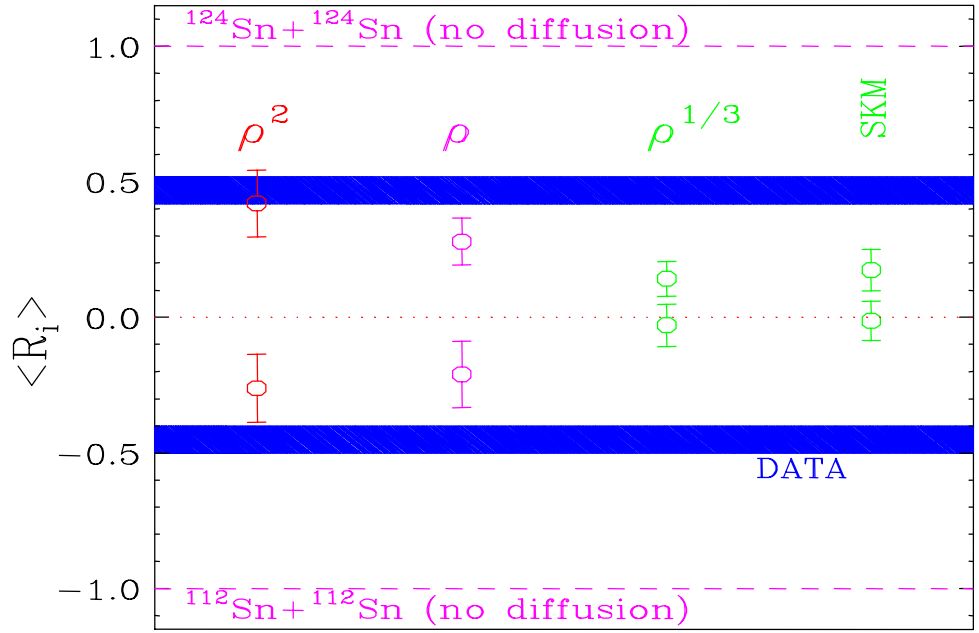


Difference between projectile and target spectator asymmetry, $\delta=(N-Z)/(N+Z)$, measures the isospin diffusion which can be used to extract information about symmetry energy.

Comparisons to data

Tsang et al. PRL 92, 062701(2004)





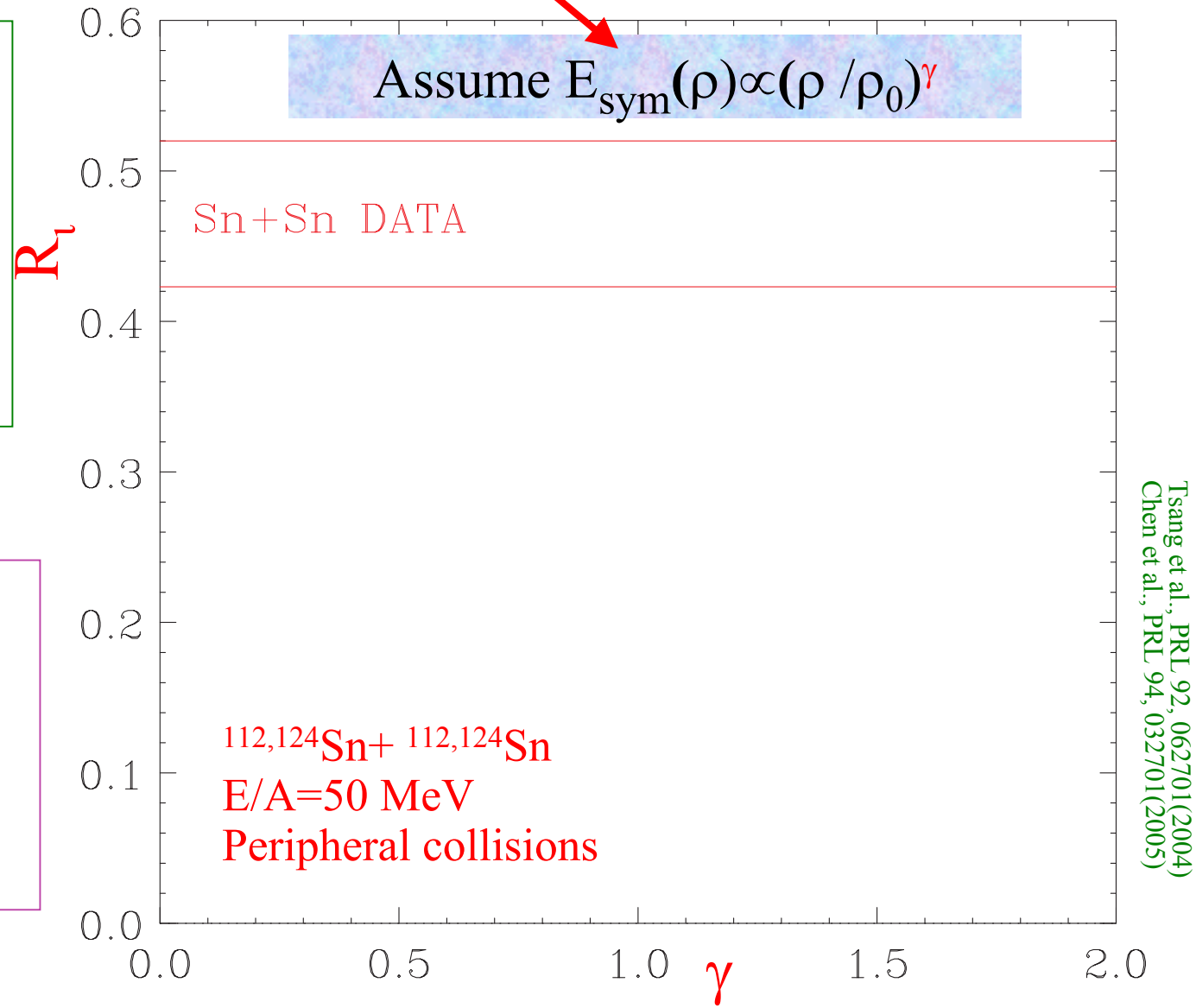
- *Diffusion occurs within ≈120 fm/c.*
- *More mixing with soft S(ρ)*
  - *consistent with large E_{sym} at $\rho<\rho_0$.*
- *Less mixing with stiff S(ρ).*

- *Explicit secondary decay correction gives same result.*
- *Stiff S(ρ) favored.*
- *Momentum-isospin dependence?*

Constraints on symmetry term in EOS from isospin diffusion

$$E(\rho, \delta) = E(\rho, 0) + E_{sym}(\rho)\delta^2; \quad \delta=(\rho_n-\rho_p)/(\rho_n+\rho_p)$$

BUU+m: Transport theory based on Boltzmann Equations & include* momentum dependence in mean field.

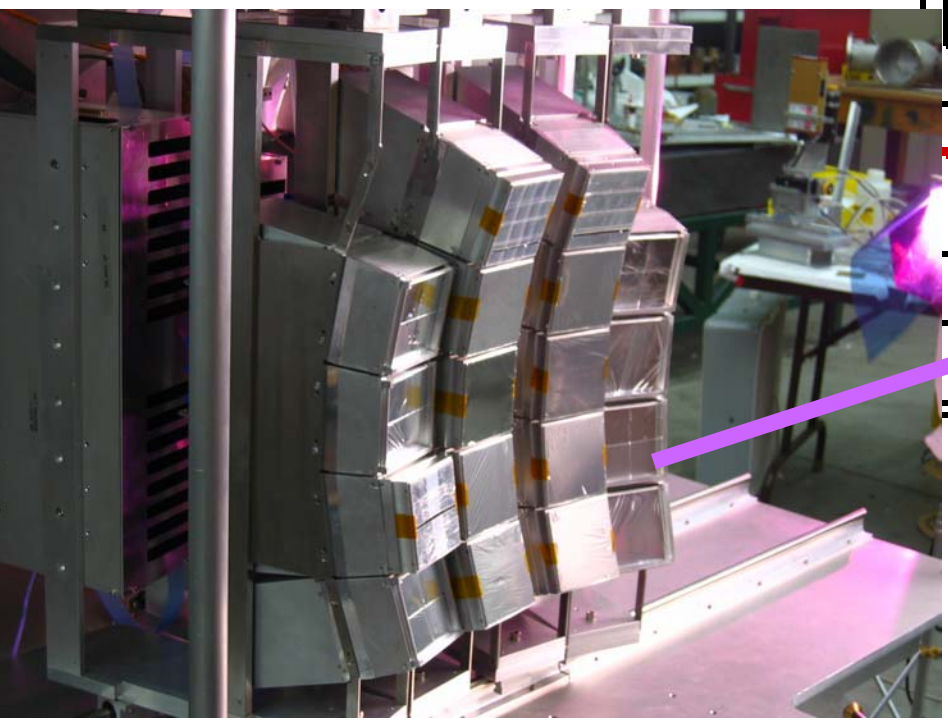


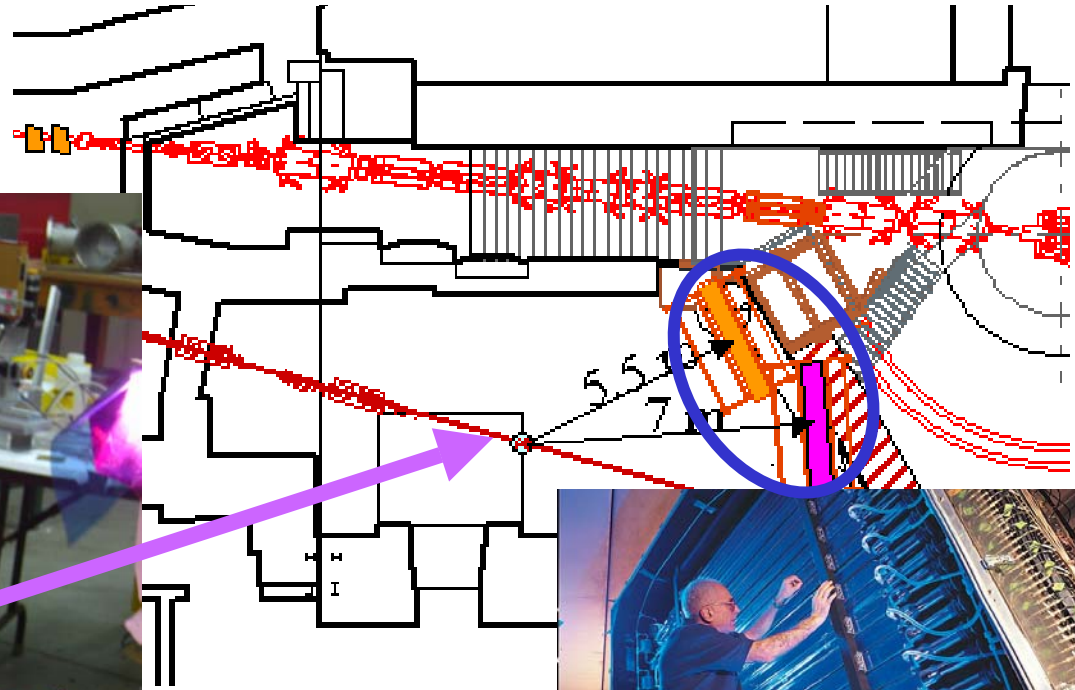
Need further constraints from n/p ratios and correlation experiments

Similar program can be implemented at CSR

- ***Objectives are to constrain $S(\rho)$, m^*_n, m^*_p, σ_{pp} and σ_{np}.***

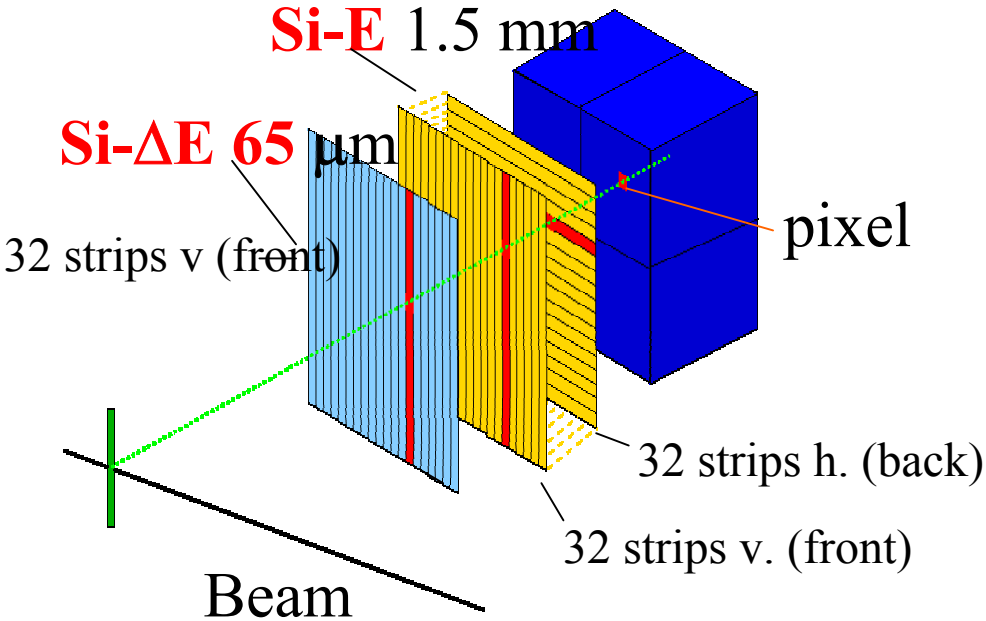
HiRA

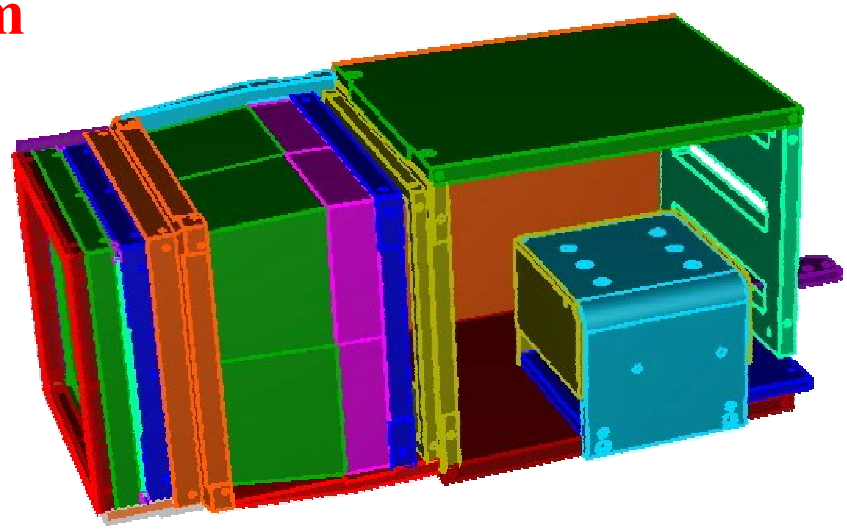


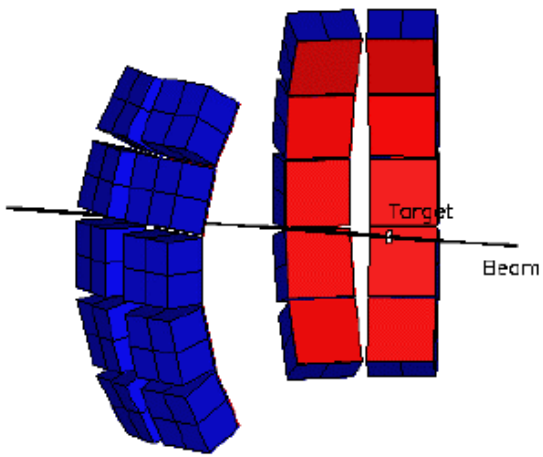


The High Resolution Array (HiRA)

4x CsI(Tl) 4cm



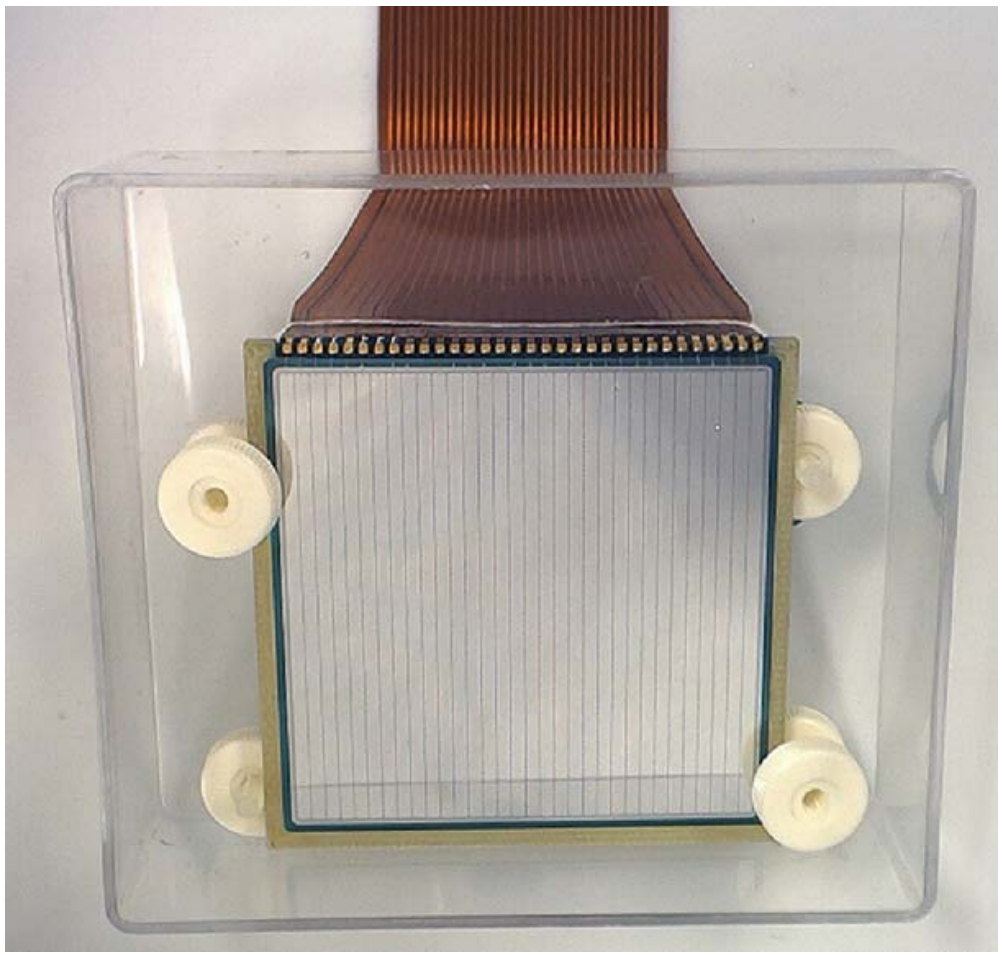




- *Flexible easily reconfigured array with 20 independent telescopes (can be expanded).*
- *High resolution:*
  - *–±0.1° at 50 cm.*
  - *–High resistivity silicon; ΔE≈35 KeV FWHM, per signal.*

Silicon Detectors

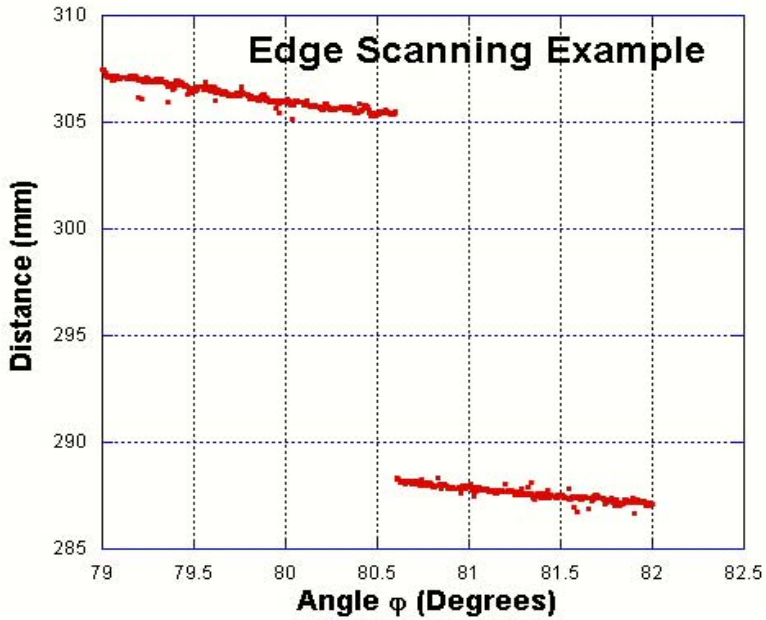
- **62.3 x 62.3 mm^2 Active Area**
- **Pitch 1.95 mm**
- **1024 Pixels per telescope**



- Bulk material is n type
- Interstrip on junction side is 25 μm
- Interstrip on ohmic side is 40 μm
  - P+ implant for better interstrip isolation
- Depletion voltage for 1.5 mm detector < 500 V
- 10 guard ring structure on periphery (2mm dead area region)

Laser Based Alignment System

- *Designed for precision measurement of detector positions relative to target.*
- *Adaptable to various configurations and other devices.*
- *Computer controlled.*



- Resolution:
  - ±0.005° for angular stages.
  - 100 microns for distance.

Electronic Readout

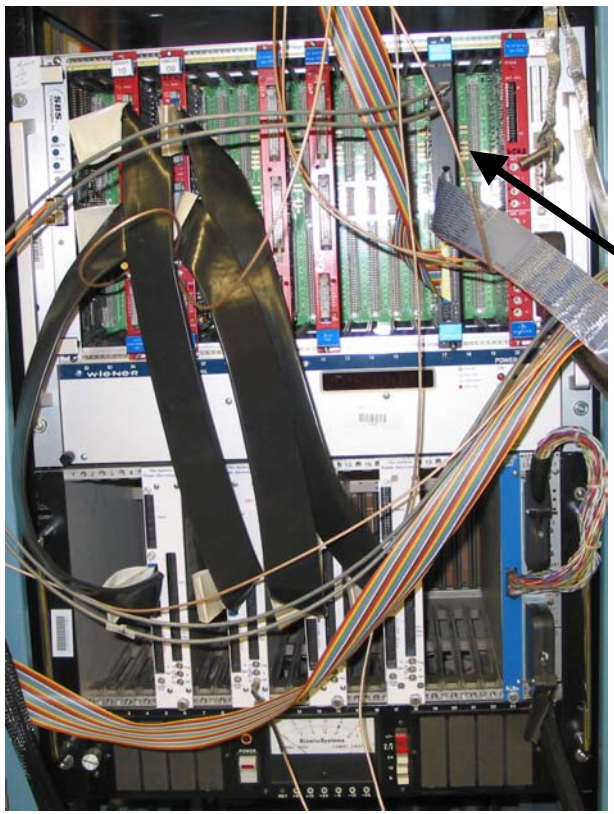
Developed at Washington University (St. Louis)

With 2000 channels to readout, cost of "traditional" readout is prohibitive.

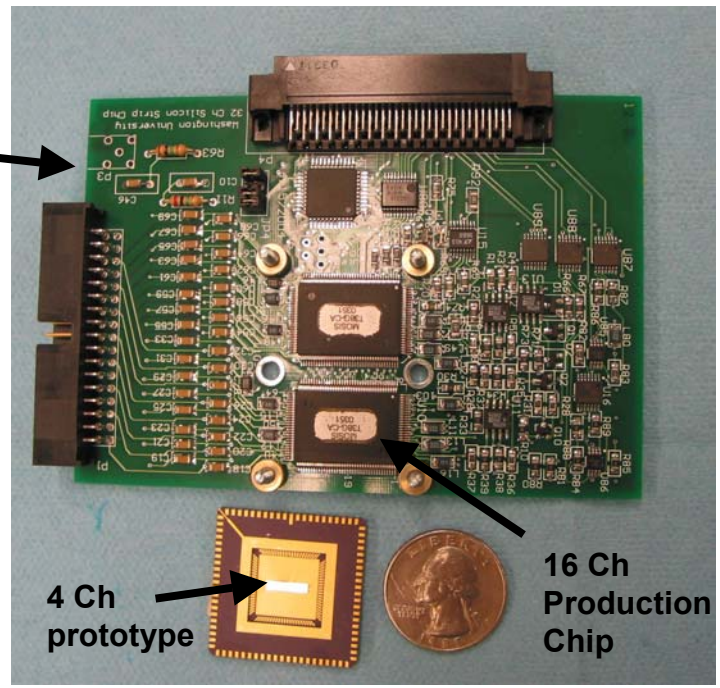
Application **S**pecific **I**ntegrated **C**ircuit

Design Includes:

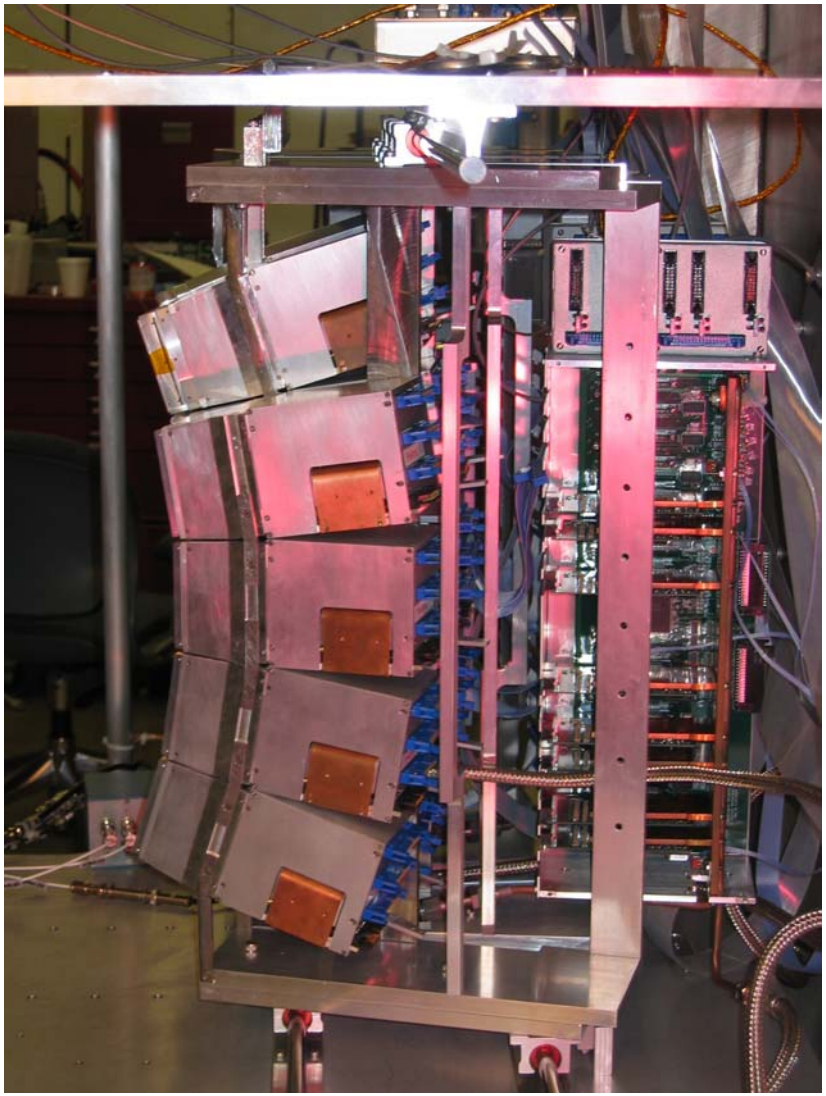
- **Multiple Preamps**
- **Shapers**
- **Discriminator**
- **Time to amplitude converters**

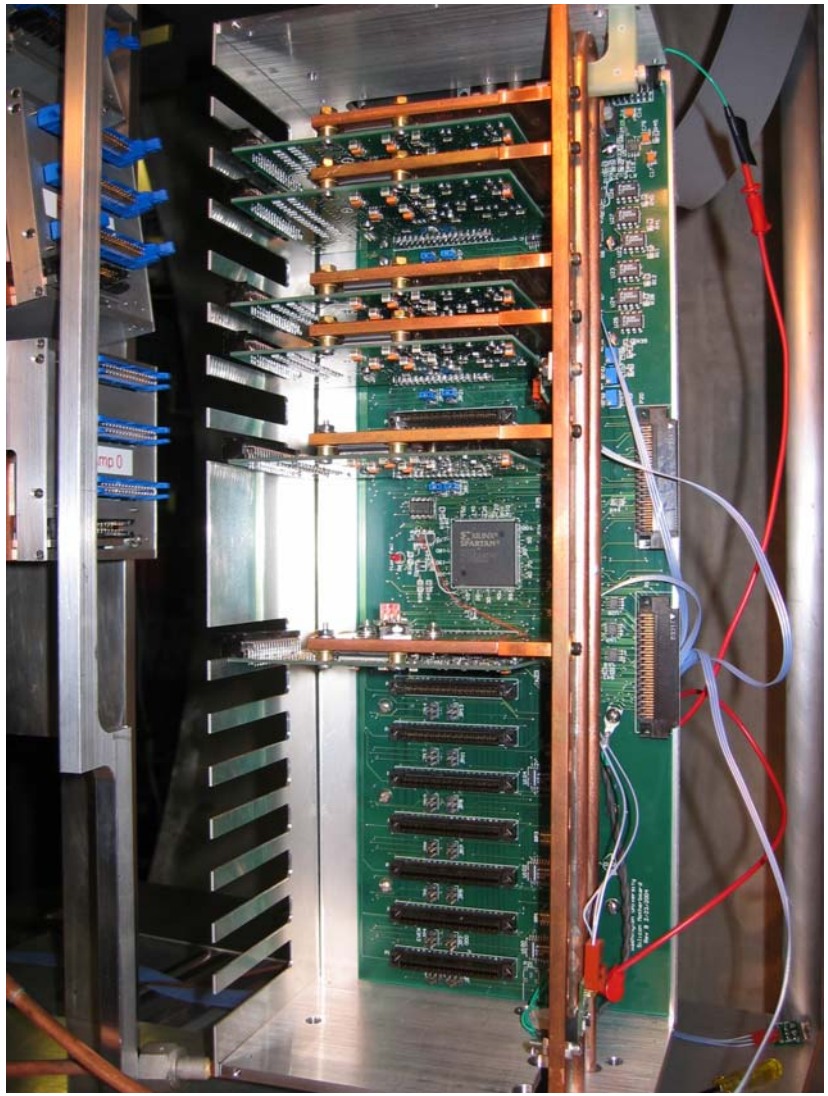


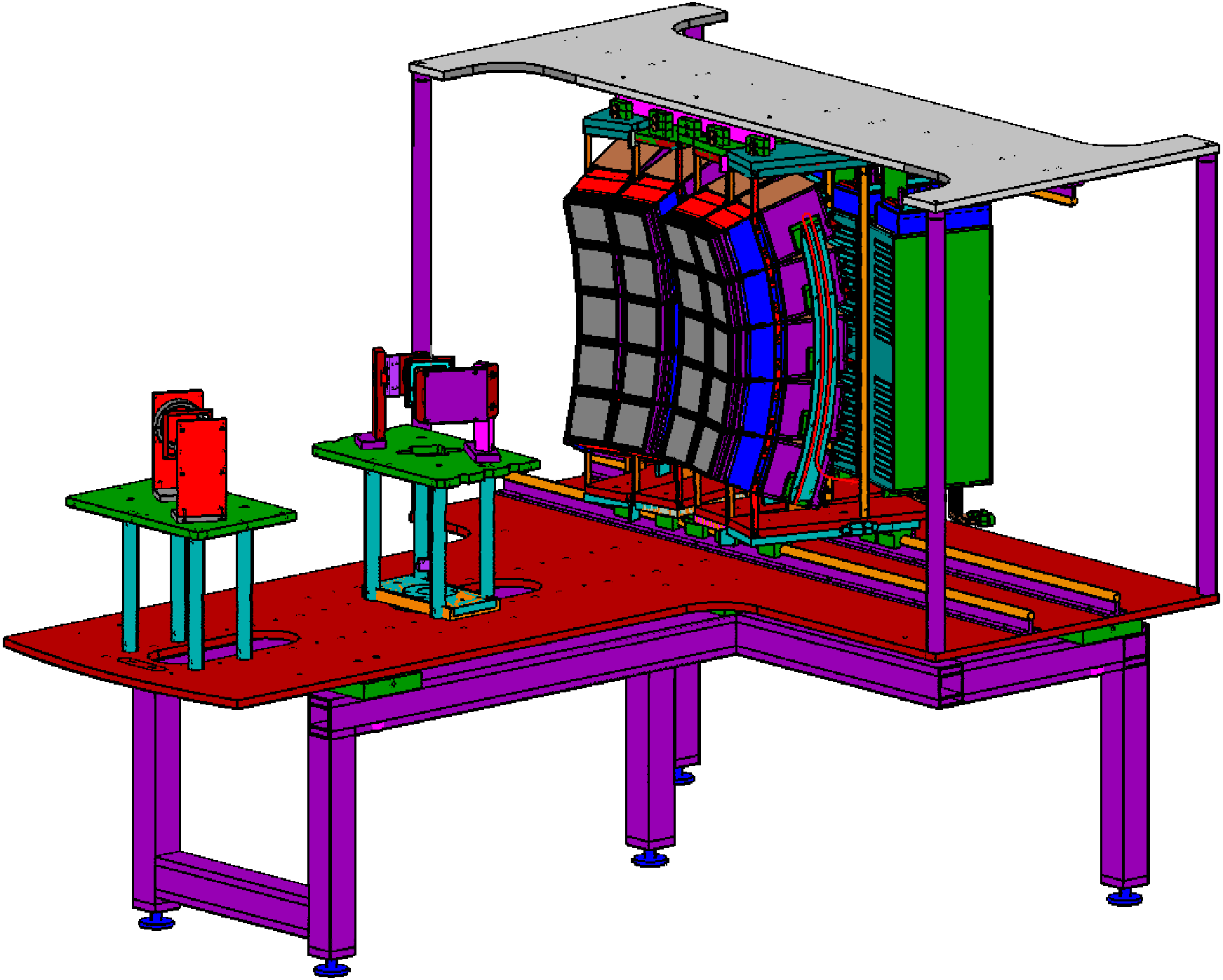
This chip board + one VME module replaces 32 pre-amp's, 32 Shapers, 32 TDCs and 32 ADCs



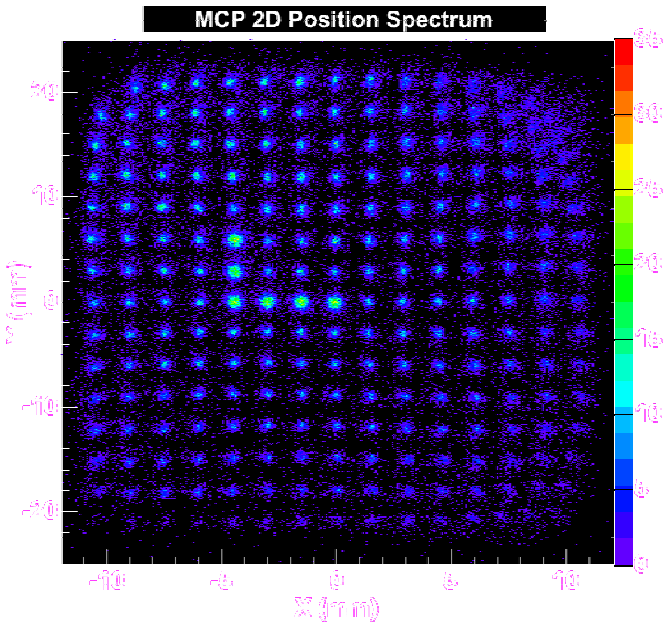
HiRA Electronics Setup Behind Detectors in Vacuum Chamber

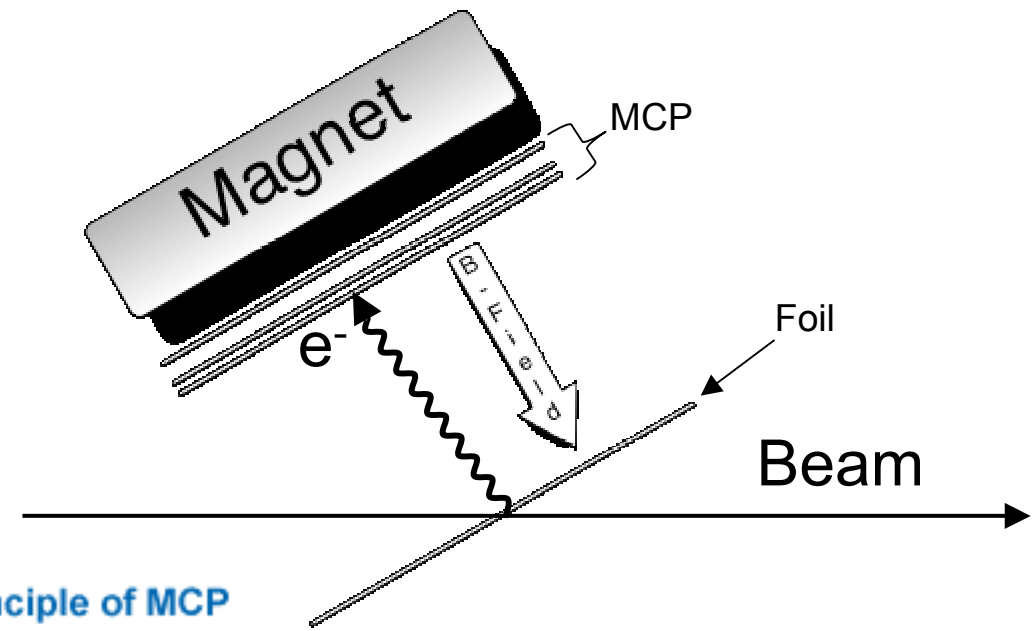


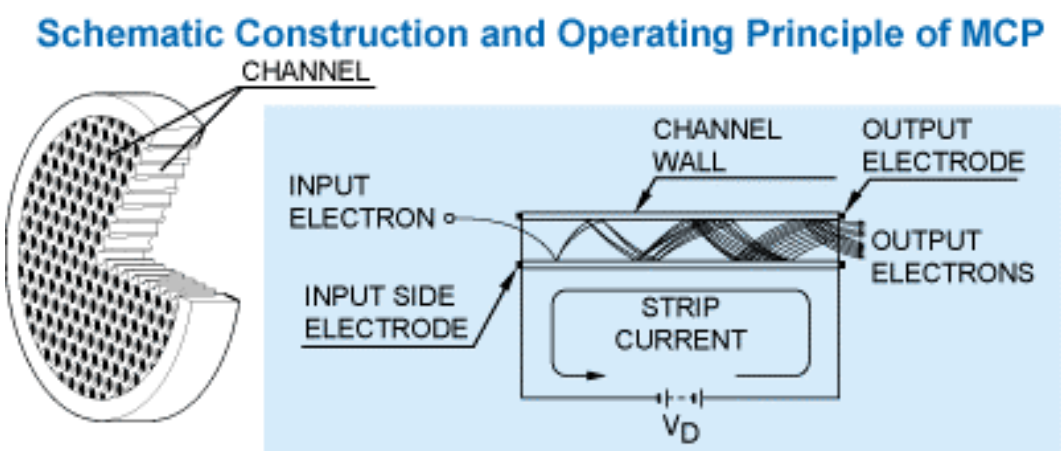


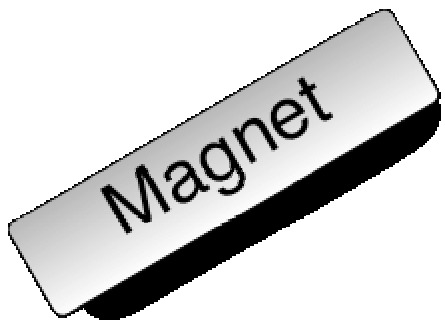


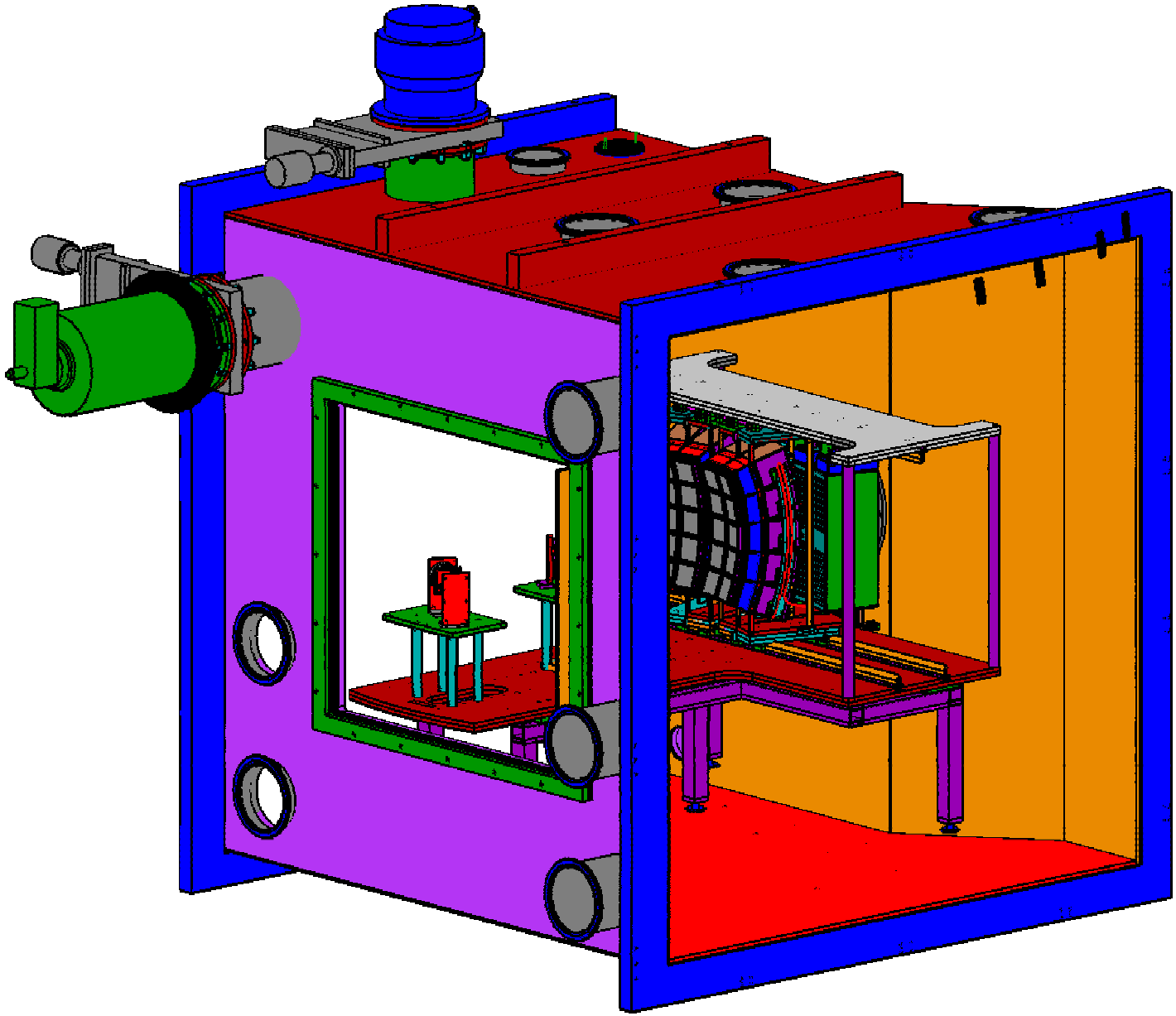
Beam Tracking Using Micro Channel Plate Detectors

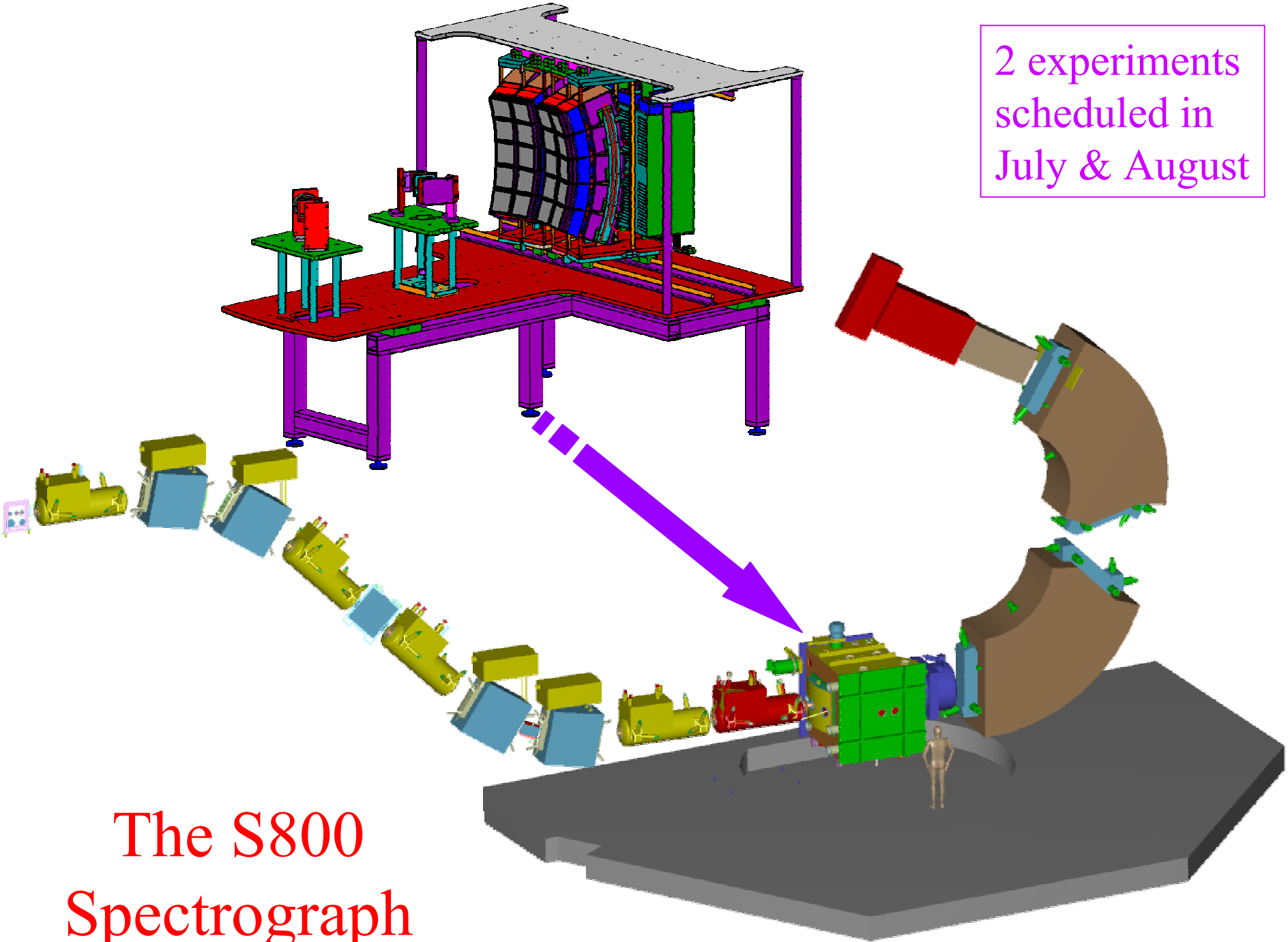











2 experiments scheduled in July & August
The S800 Spectrograph

List from Bao-An Li

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Among the currently most interesting topics in isospin physics

1. **EOS of neutron-rich matter, especially the density dependence of symmetry energy $E_{sym}(\rho)$ at high densities.**

2. **Momentum-dependence of the symmetry potential and the neutron-proton effective mass splitting m_n^*-m_p^* in neutron-rich matter**

3. **Isospin-dependence of in-medium nucleon-nucleon cross sections and the nuclear stopping power in neutron-rich matter**

4. **Explore the phase diagram (T-ρ-δ) of neutron-rich matter along the isospin asymmetry δ axis (e.g, neutron distillation, n-Λ phase transition)**

5. **Isospin mixing of vector mesons (ρ^0-ω) and charge symmetry breaking in neutron-rich matter**

The most important question relevant to all of the above: What is the isospin dependence of the in-medium nuclear effective interactions

TPC's maybe the best way to attack $E_{sym}(\rho,\delta)$

1) Have element and isotope resolution for light particles (FLOW + PE)
2) Can determine the reaction plane (FLOW)
3) Can measure π^+ and π^- spectra
4) Can handle interaction rates of up to ~ 100 events/second

   BUT

5) Require external:

   n-detectors (n-FLOW)

   MUSIC for heavier fragments at forward angles [Deflection (flow) of projectile spectators, projectile fragmentation and multifragmentation]

6) They require a good trigger!

Issues:

1) Magnet Design: Solenoid or Dipole? Size and shape of the magnet?
2) Geometry at forward angles:

   Access for neutron detection.

   DYNAMIC RANGE: Thresholds and resolution for fragment and projectile residue detection.

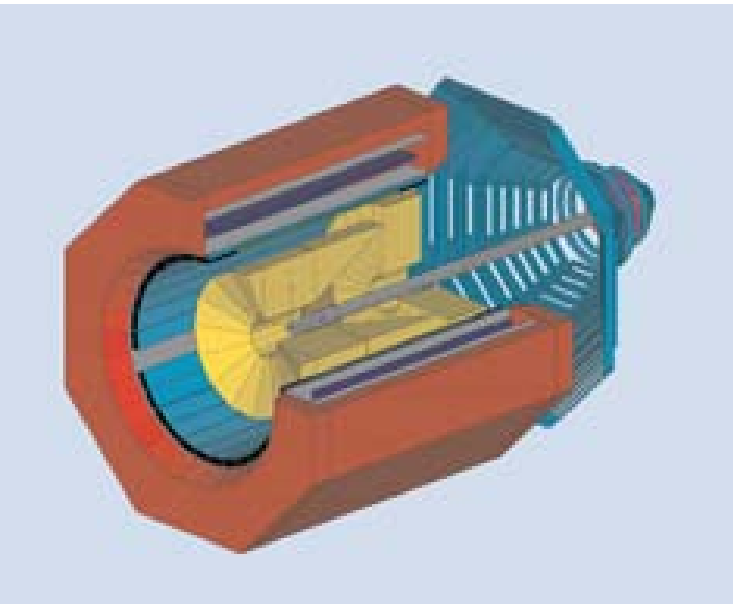
3) Complexity and cost of trigger.
4) Suppression of beam space-charge: issue for dipole design

Solenoidal design

Solenoidal drift chamber.
Open forward geometry covered by TOF wall.

Advantages:
Azimuthal symmetry favors elliptical flow analyses.

Disadvantages:
At forward angels: poor momentum res. & high detection thres.



FOPI at GSI

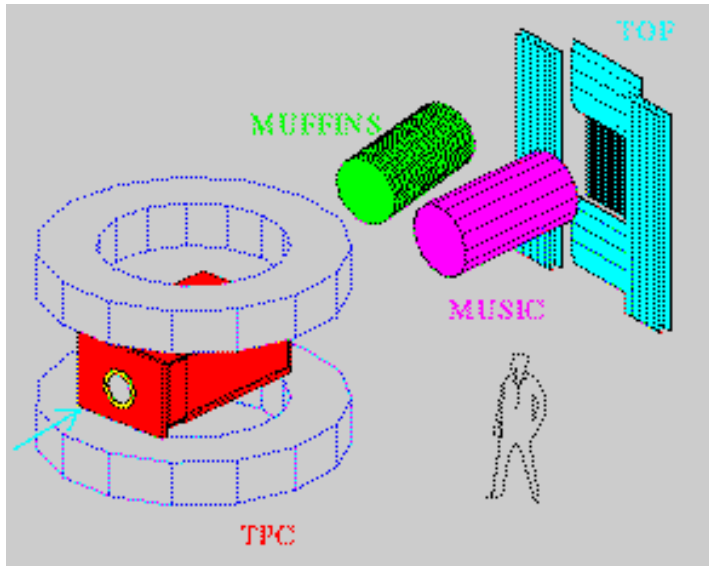
Dipole design

Rectangular TPC.
Open forward geometry providing access for TOF wall, neutron detector and MUSIC.

Advantages:
Good momentum res. at forward angles. Possibly lower detection thres. at forward angles.

Disadvantages:
Beam is perpendicular to magnetic field making beam line problematic.

EOS at LBL



Some observations

1. Radioactive Beams → have the highest discovery potentials.

   Large numbers of isotopes waiting to be discovered → impact on Astrophysics.

2. HI collisions

   Isospin Physics is the focus of the global HI communities.

   CSR has a window of opportunity in this area with the availability of >400 MeV/nucleon heavy beams while the rest of the world is still building.

   Requires "Simple" detectors, n, p (charged particle), π, simple impact parameter selection detectors.

3. State of art detectors include R&D in electronics and data analysis – Investments in these areas should not be neglected.