The National Superconducting Cyclotron Laboratory

Michigan State University

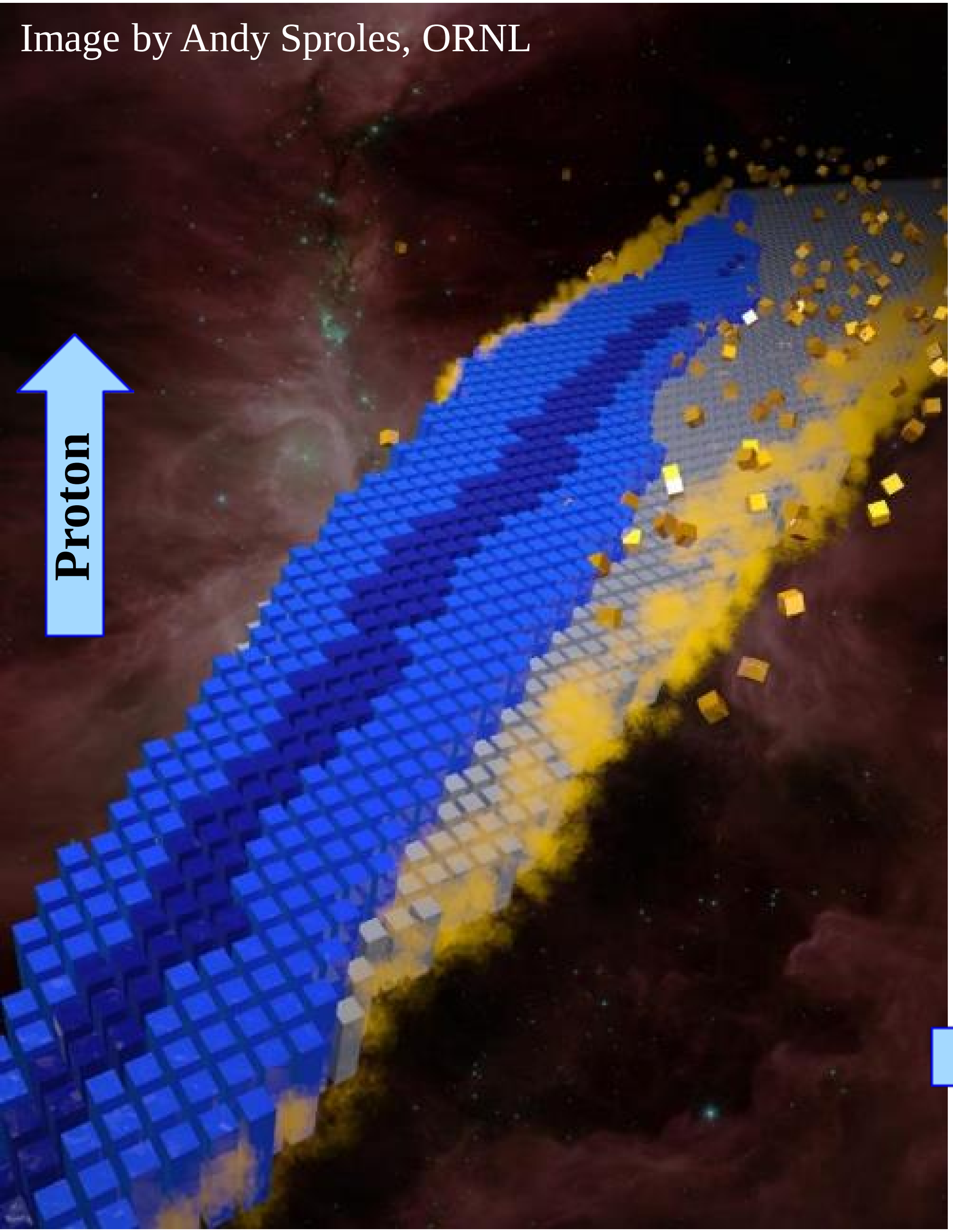
U.S. flagship user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications

Betty Tsang

Nusym15, Krakow
June 29-July 2

Nuclear Symmetry Energy: From Nucleus to Neutron Stars

Symmetry Energy



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

$$- a_{sym} \frac{(A-2Z)^2}{A}$$

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

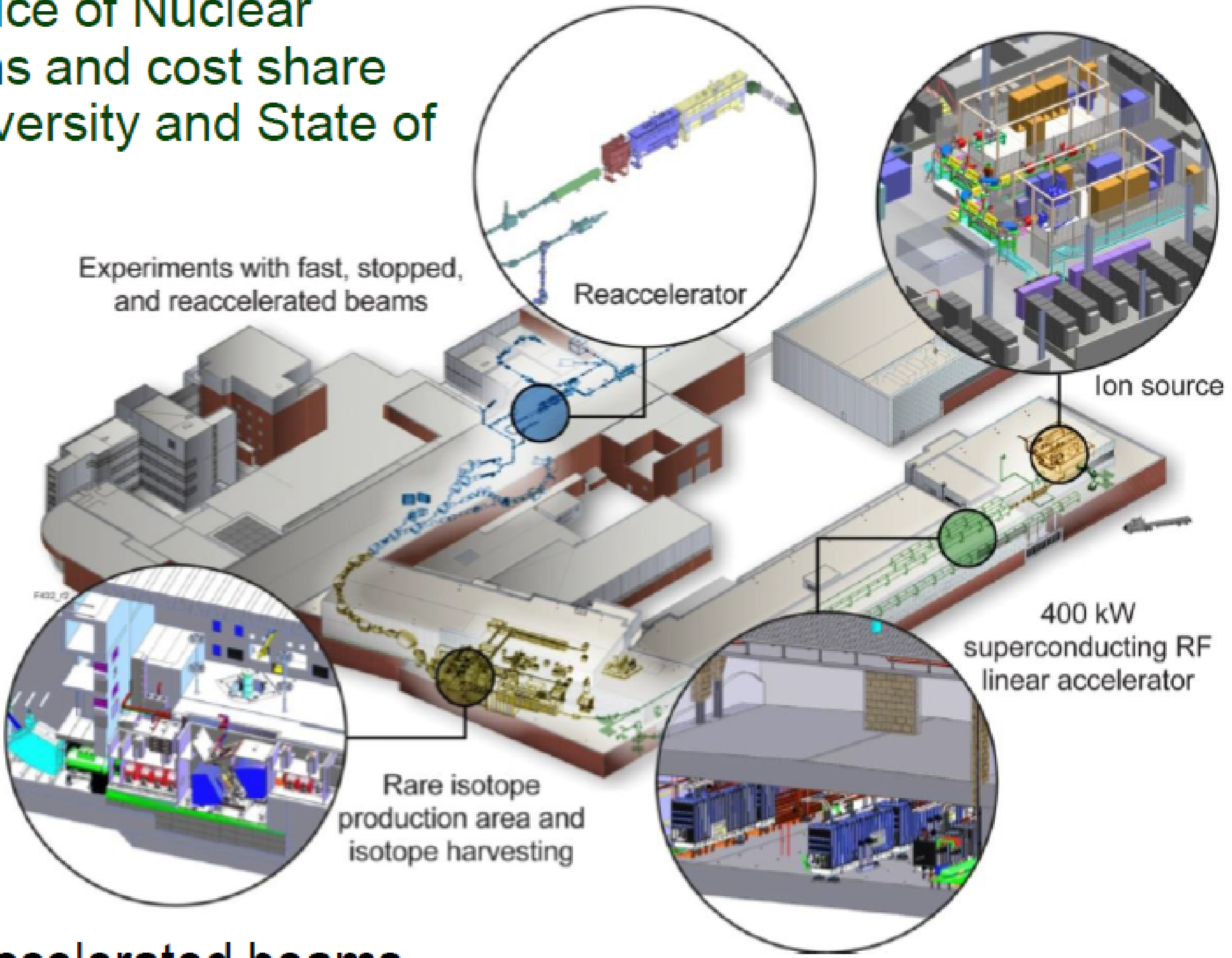
Inclusion of surface terms in symmetry

Neutron

Hubble ST

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 ($5x10^{13}$ $^{238}U/s$)
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped, and reaccelerated beams




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

FRIB

FRIB Construction Progress


March 17, 2014


above ground! April 1, 2015


Utility work on tunnel, April, 2015


Linac tunnel, May 2015

FIRB Construction Progress

6/25/2015

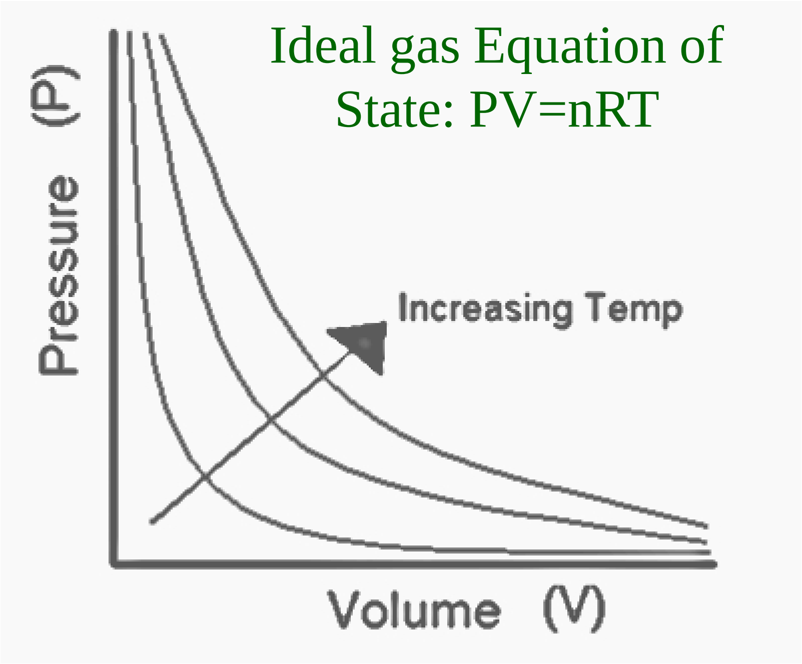
Nuclear Symmetry Energy: From Nucleus to Neutron Stars

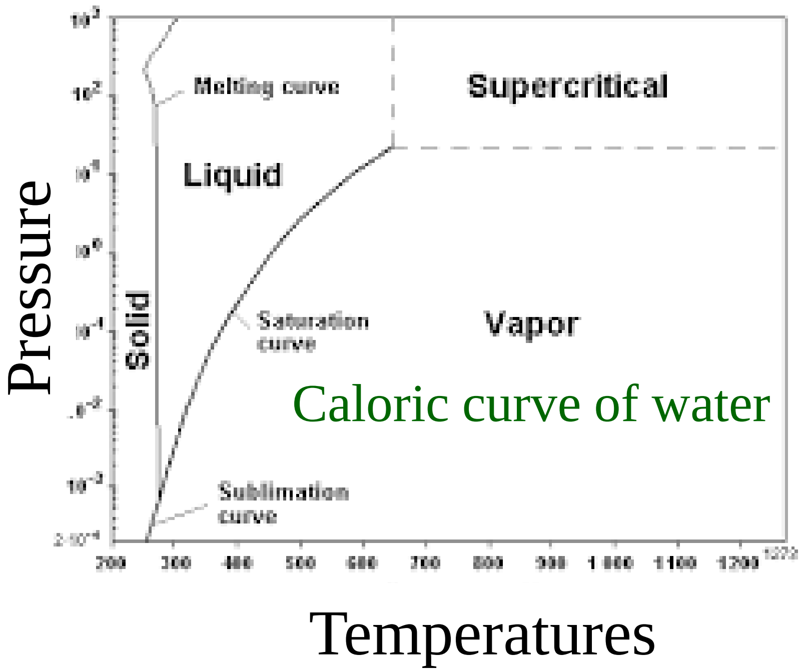
曾敏兒 -- Betty Tsang

Outline

1. Introduction : Different forms of EoS
2. How did we get here? Current constraints on density dependence of symmetry energy.
3. Where are we going? Future challenges and opportunities.
4. Summary

Equation of State: A mathematical relationship between thermodynamic variables and properties of matter

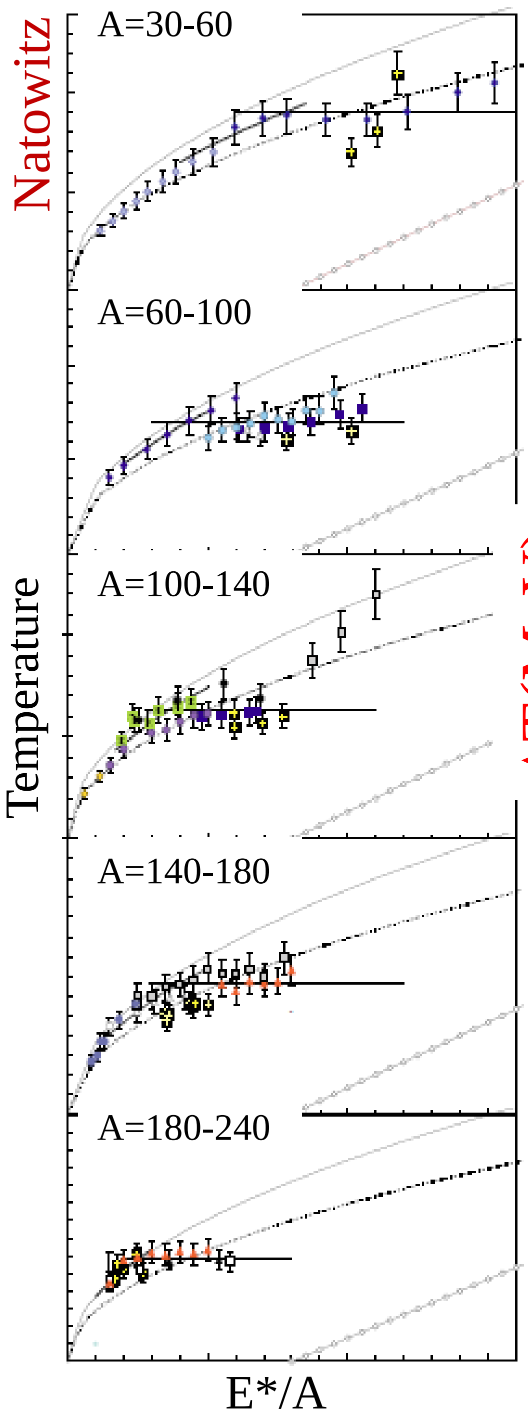


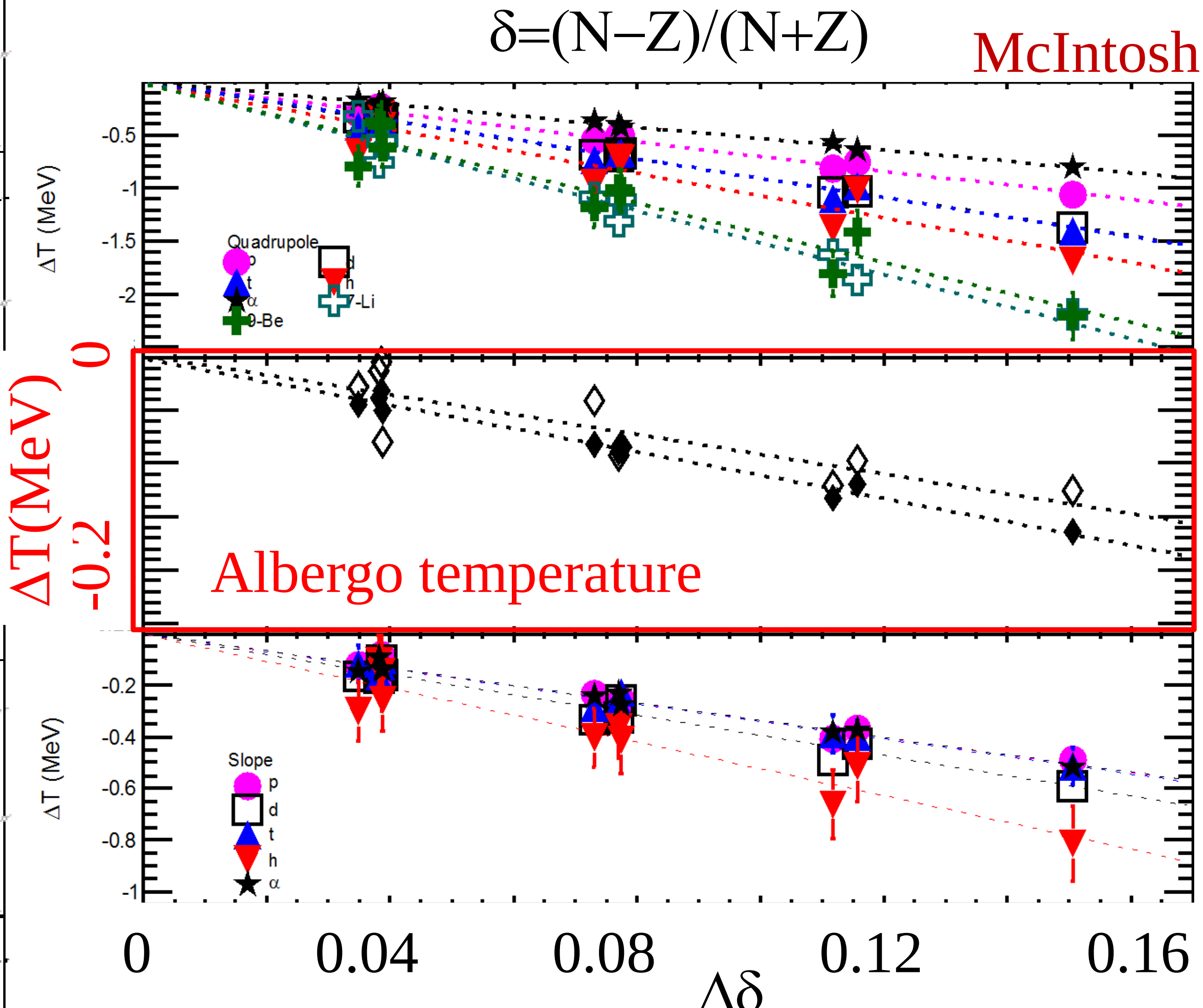


EOS of nuclear matter:

1. Thermal Dynamical properties
2. Mass-Radius relation of n-star
3. Density dependence of symmetry energy
4. S_0 vs. L at ρ_0

Asymmetry dependence of Caloric Curves

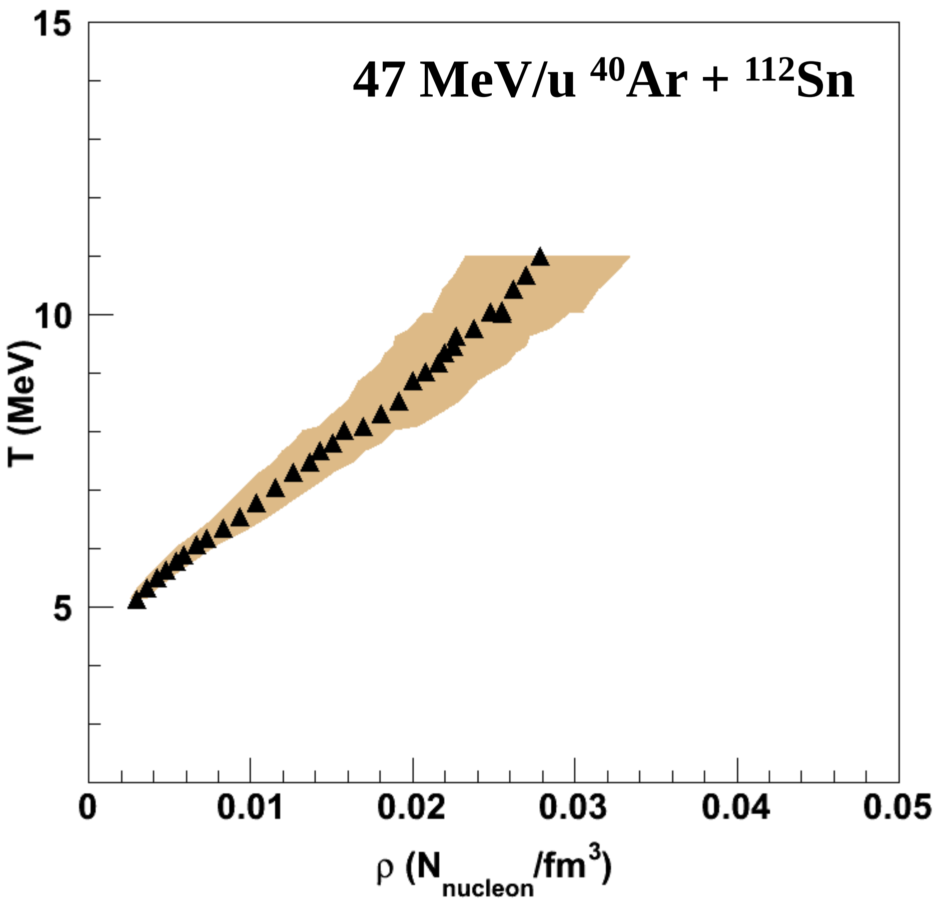


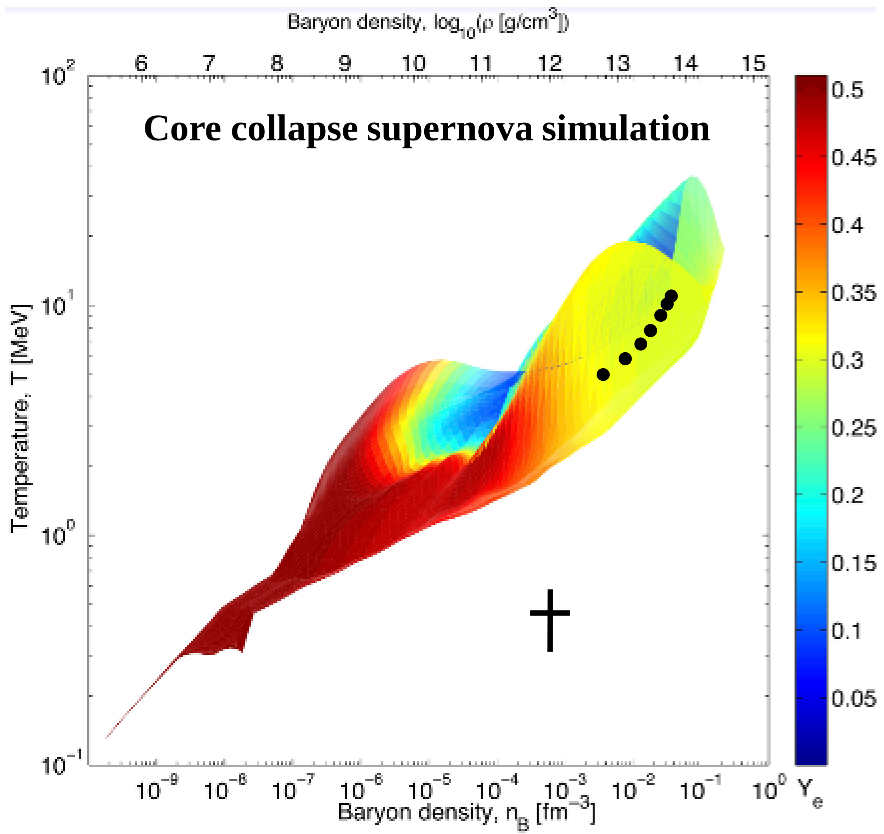


70Zn + 70Zn; 64Zn + 64Zn; 64Ni + 64Ni; E = 35A MeV

Temperatures and Densities

J. Natowitz
K. Hagel





Equation of State of Neutron Matter

Hubble ST

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

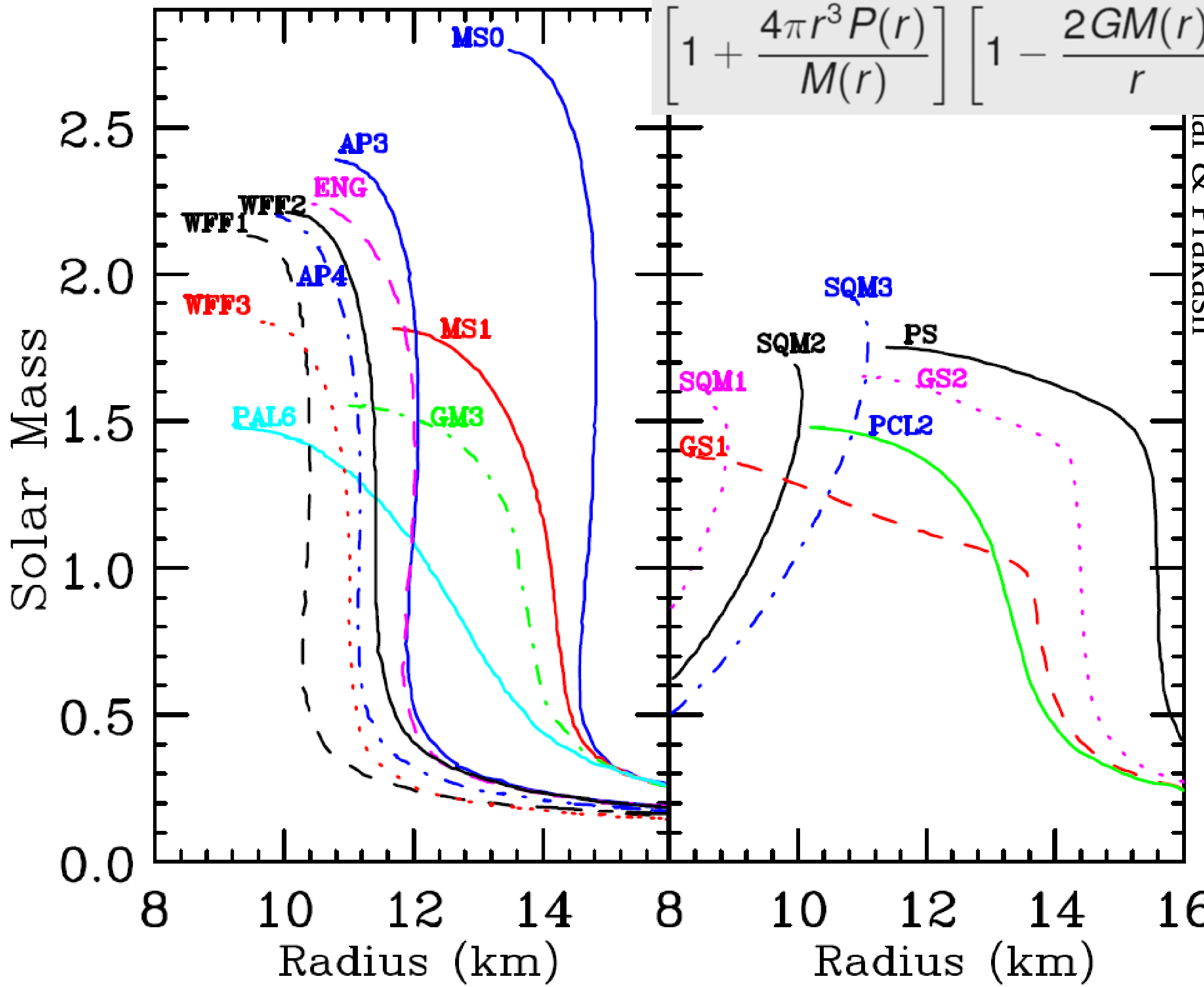
$$\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r)$$

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

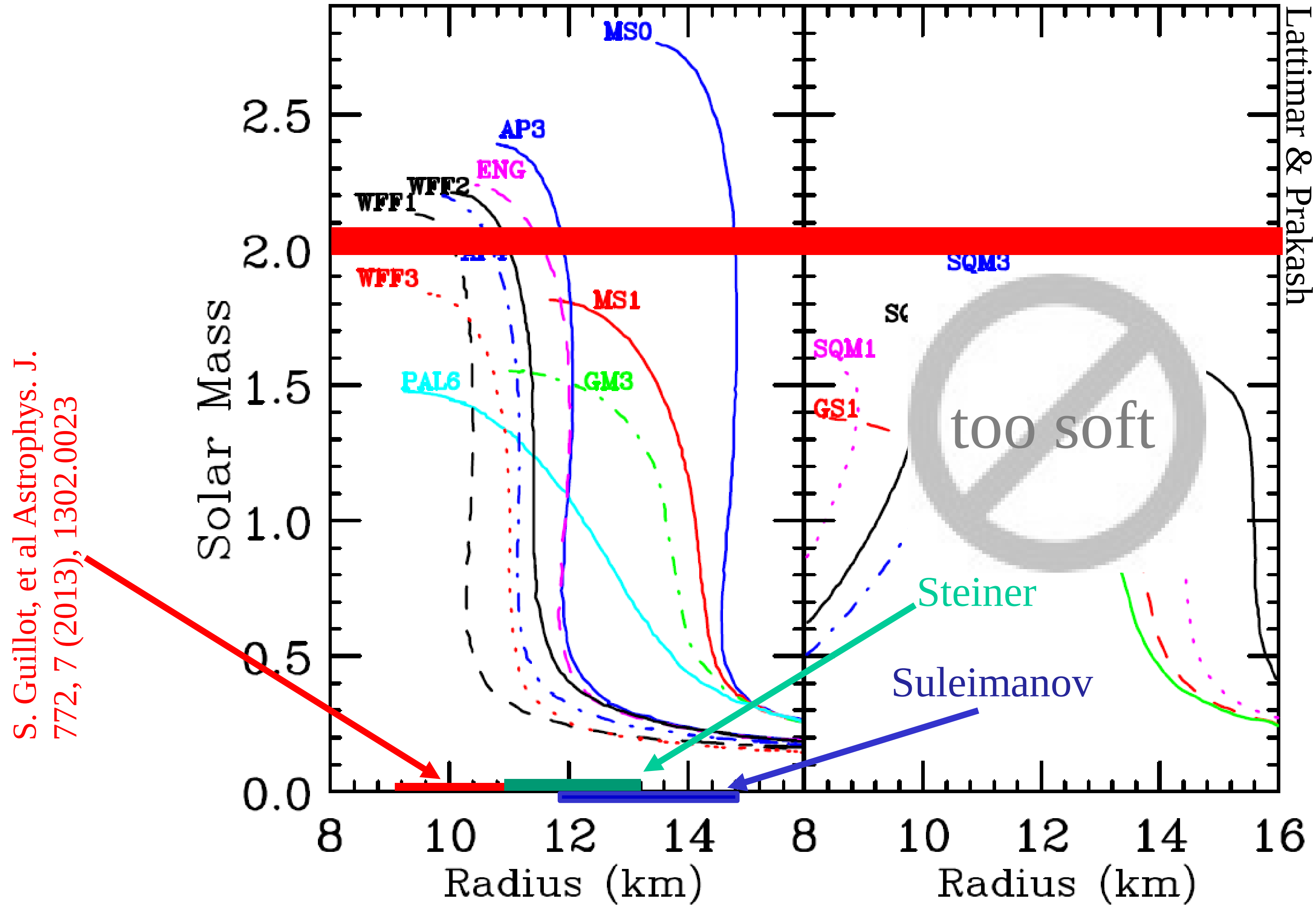
EoS of pure neutron matter: Symmetry Energy as function of pressure (density)

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

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

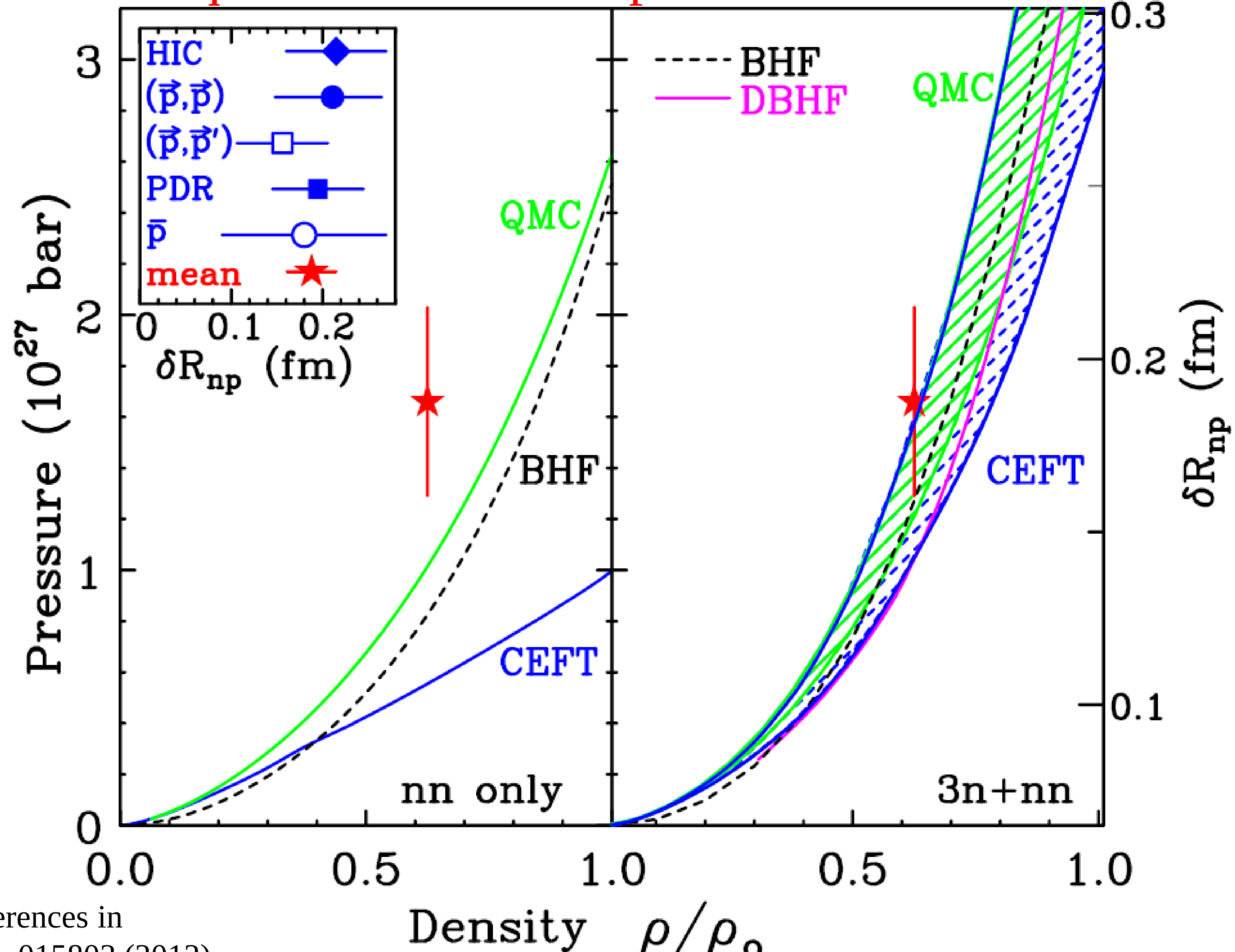


New observations of Neutron Stars (radius/Radii)



Very small Neutron Star radius rules out nearly all EOS

Importance of 3-body neutron-neutron force in the Equation of State of pure neutron matter



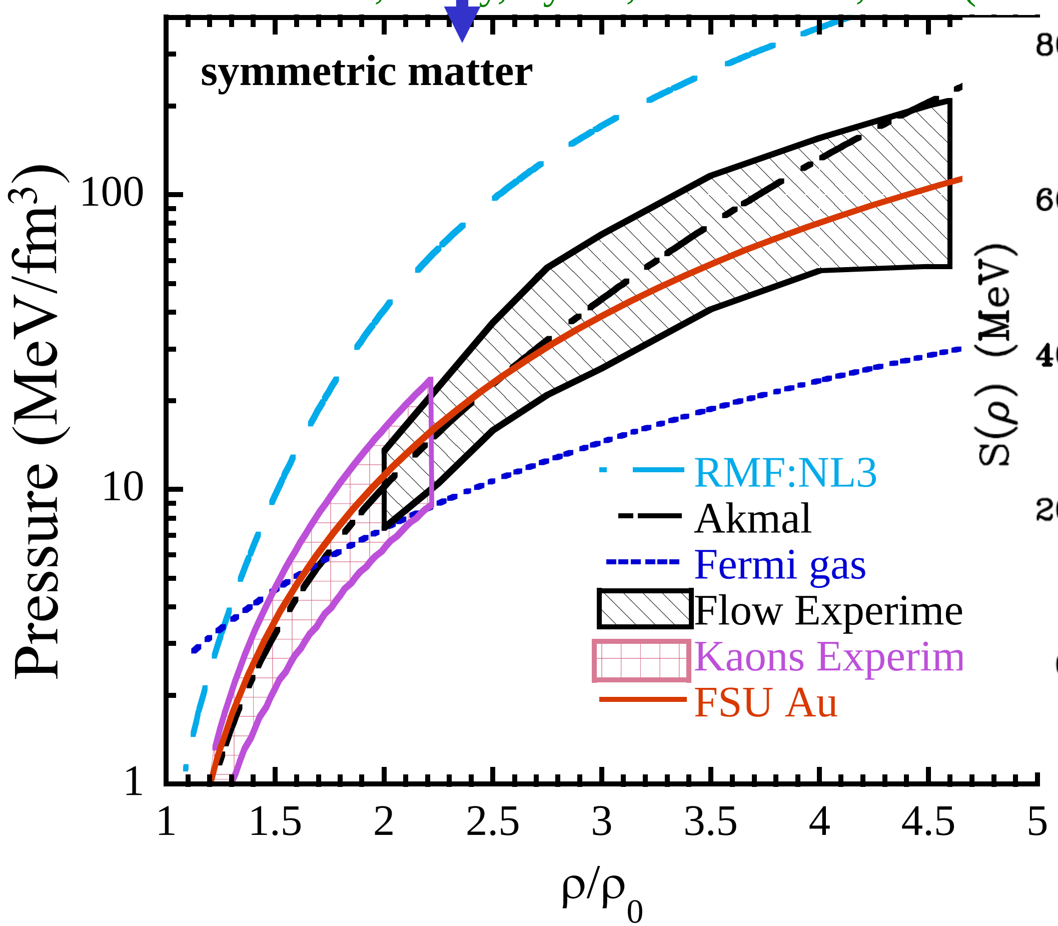
See references in
PRC 86, 015803 (2012)

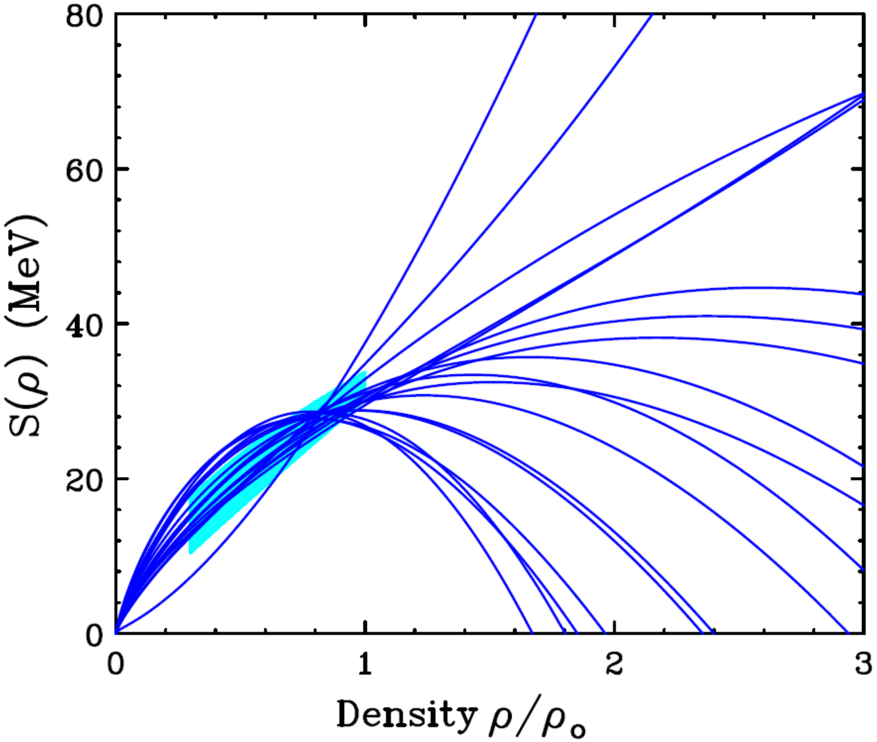
Nuclear Matter EoS

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

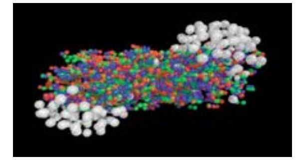
Symmetry energy

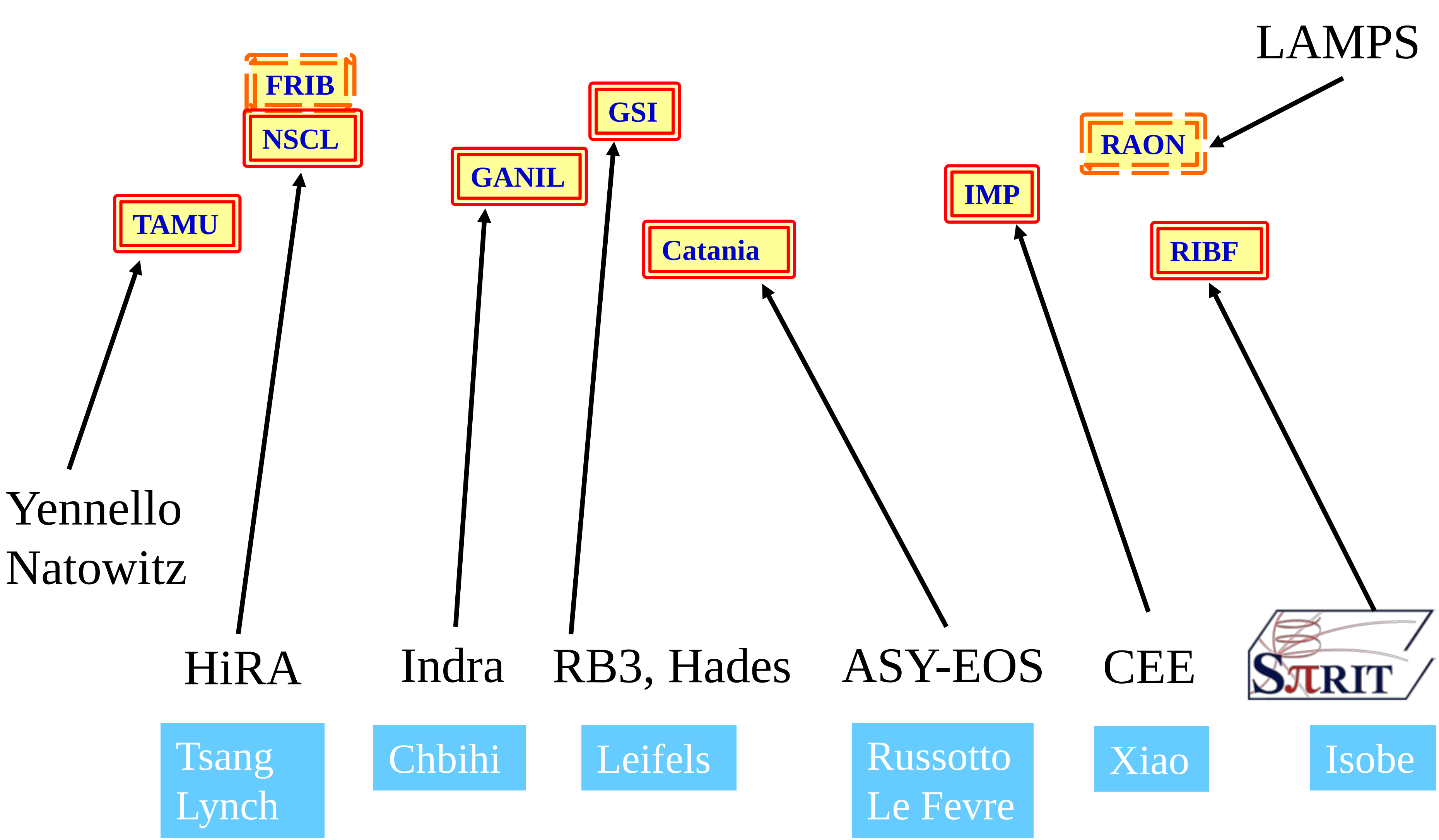
Danielewicz, Lacey, Lynch, Science 298,1592 (2002)



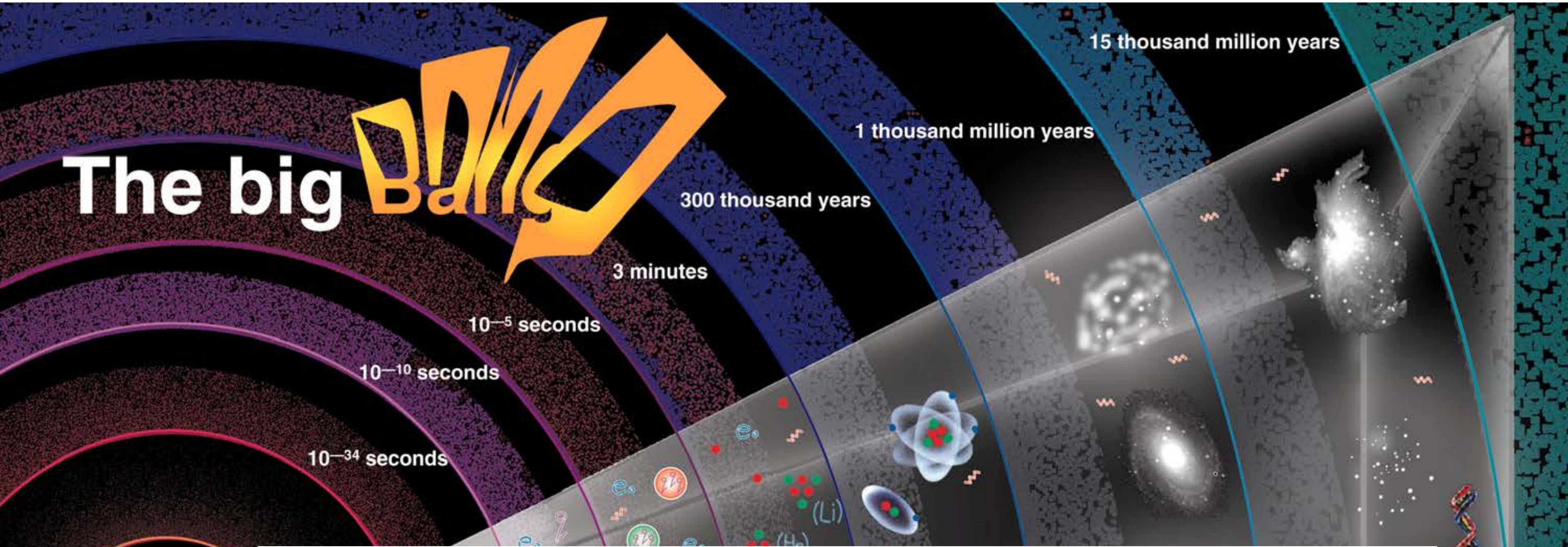


Symmetry Energy Project

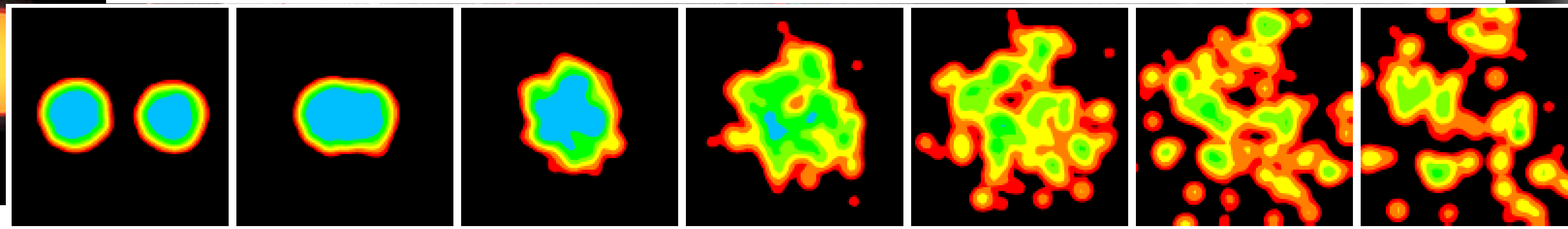




Productions of high intensity high energy Radioactive Isotope Beams for the EoS studies over a wide range of density



Femto-nova explosion created by Heavy Ion collisions

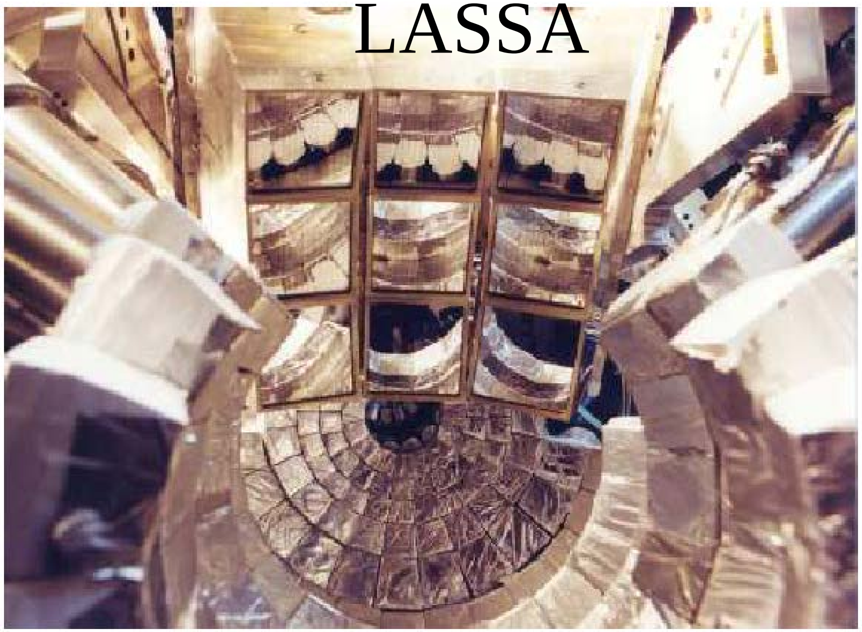


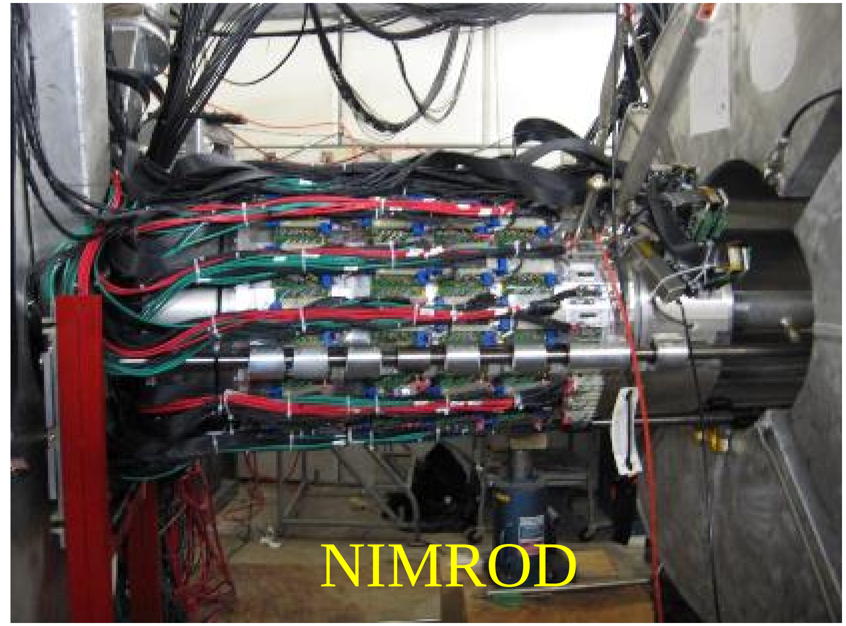
Chemical potentials in formation of light nuclei

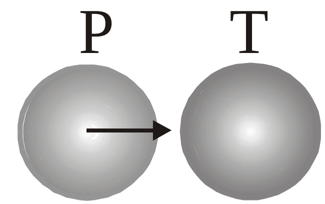
$$\mu(^{A}Z) = Z\mu_p + N\mu_n$$

Symmetry energy in asymmetric objects

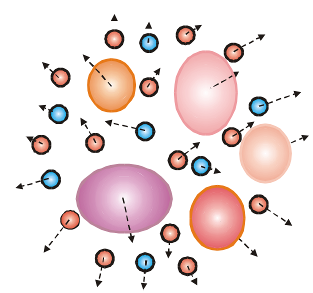
$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$







Multifragmentation



Chemical Potentials: E_{Coul} ,E_{sym} ,ρ_p ,ρ_n

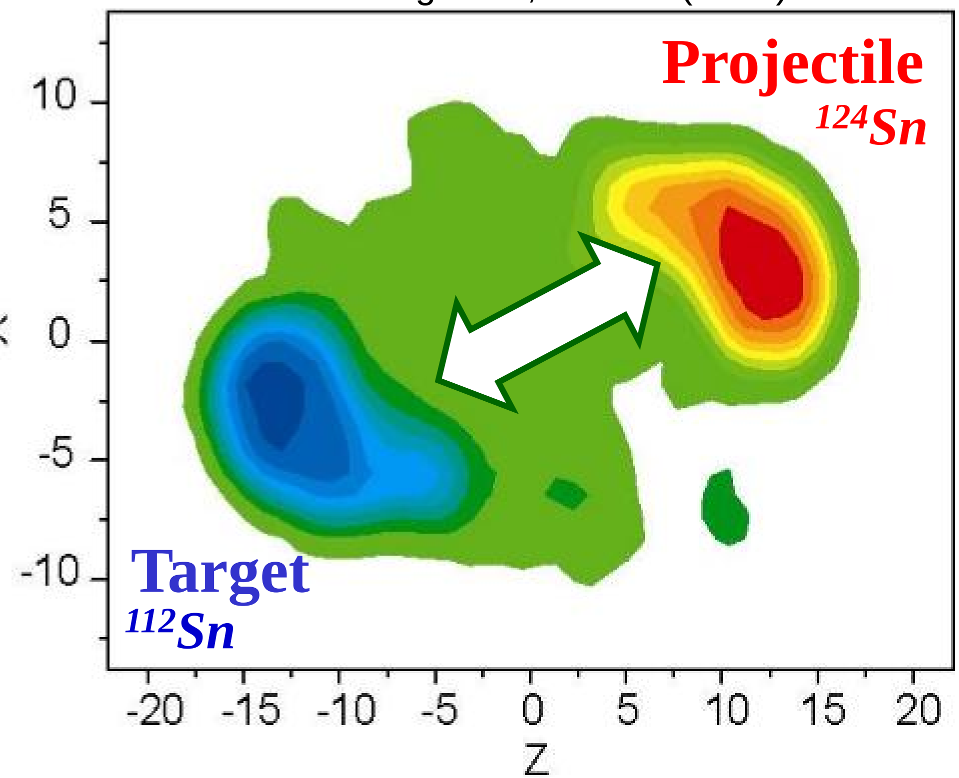
Isospin Diffusion observable to study E_{sym} with Heavy Ion Collisions

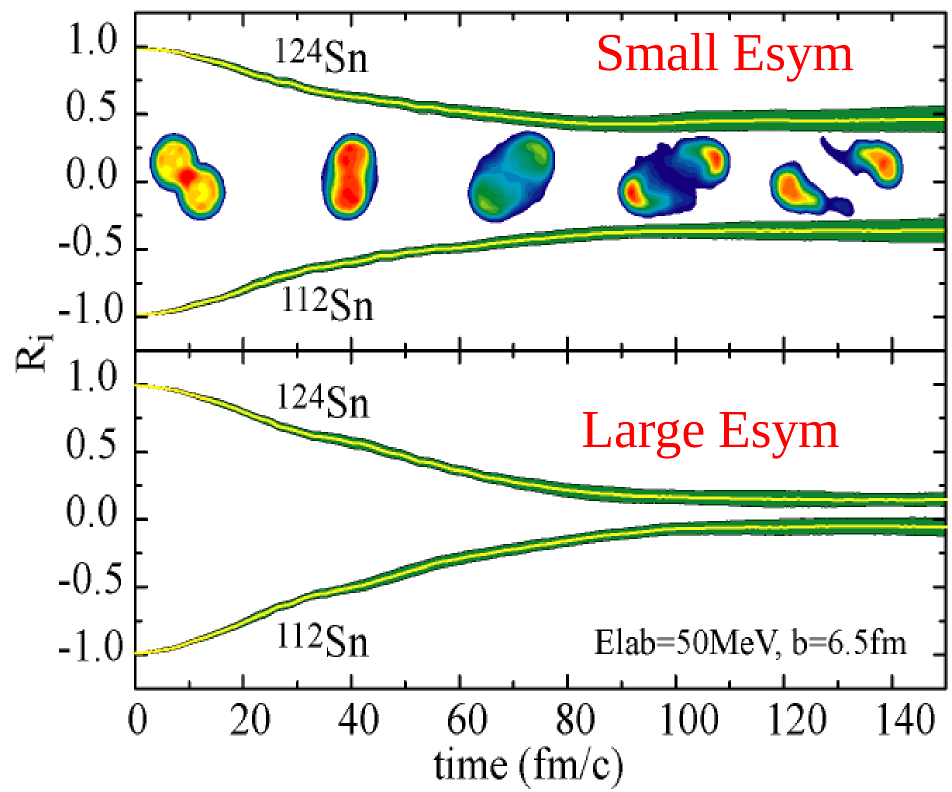
$\delta=(N-Z)/A$

Tsang et al., PRL 92 (2004) 062701

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

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





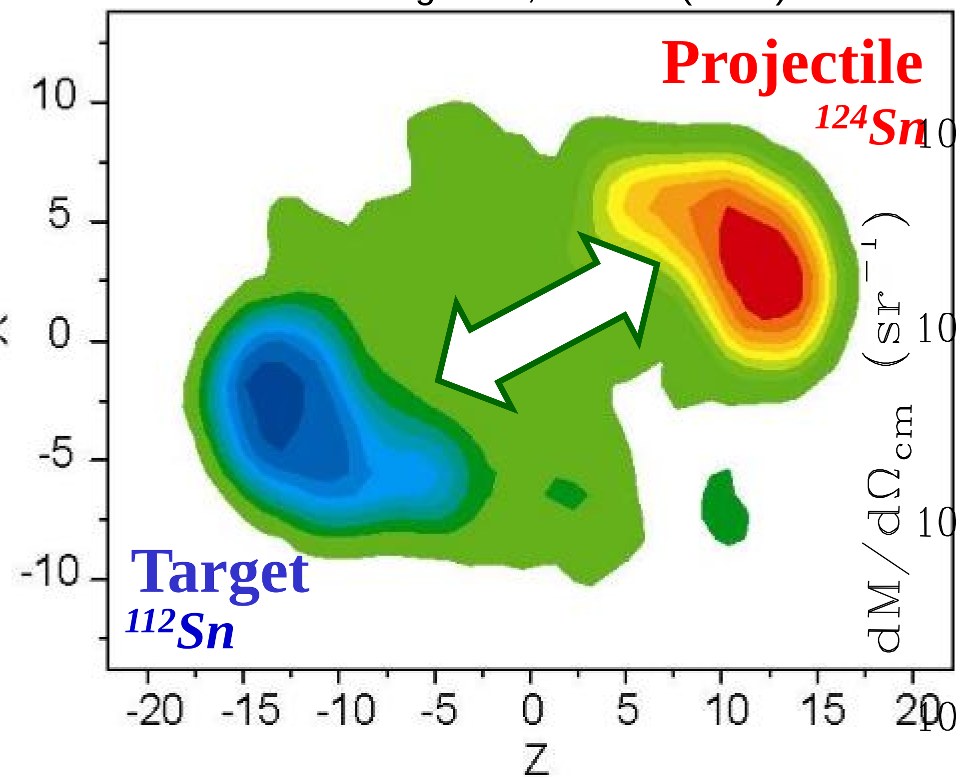
Isospin Diffusion; low ρ, E_{beam}

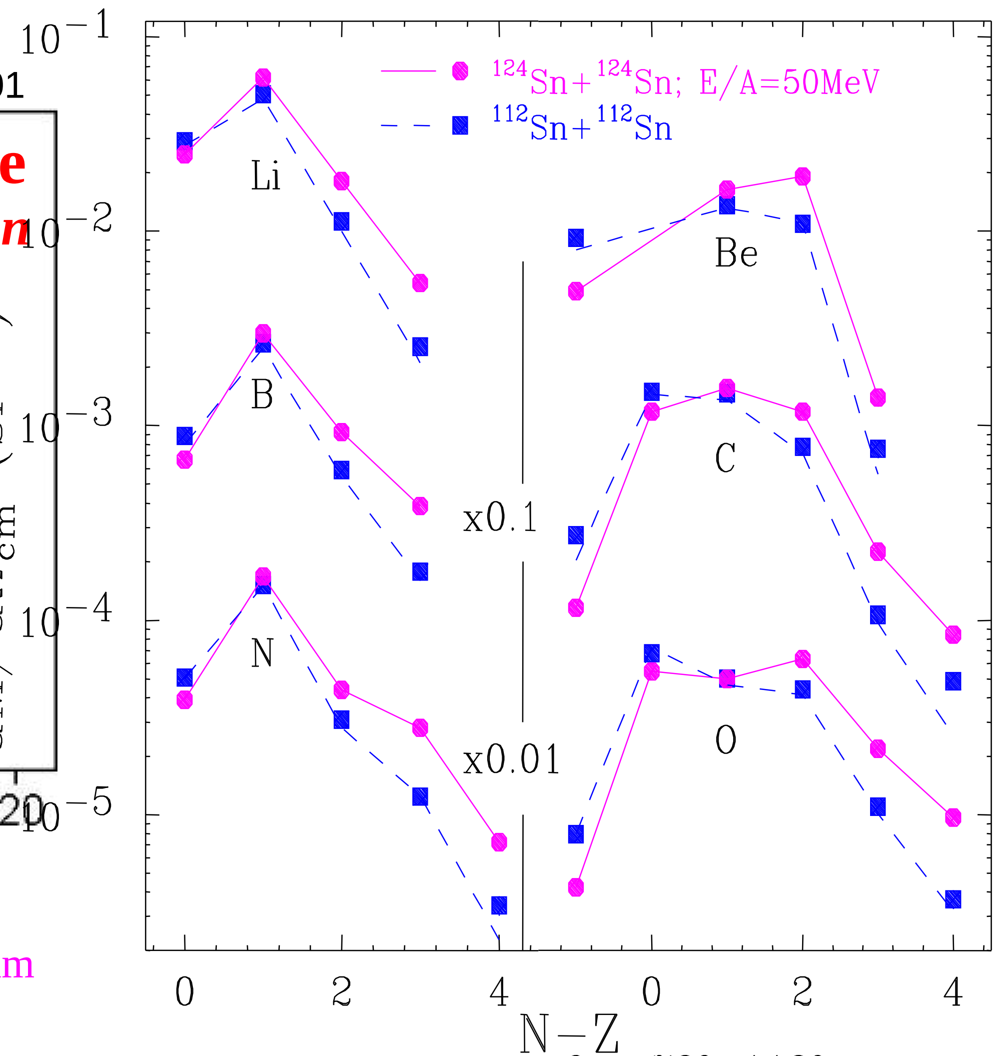
$$R_i = 2\frac{\delta_{AB}-(\delta_{AA}+\delta_{BB})/2}{\delta_{AA}-\delta_{BB}}$$

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

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

Tsang et al., PRL 92 (2004) 062701



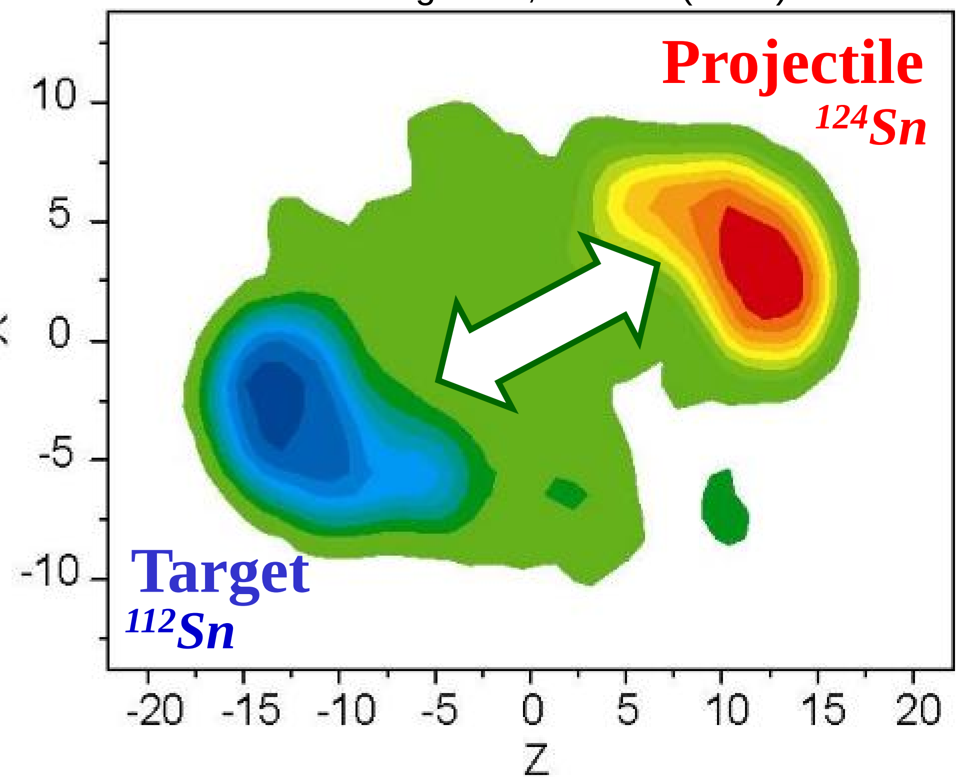


Isospin Diffusion; low ρ, E_{beam}

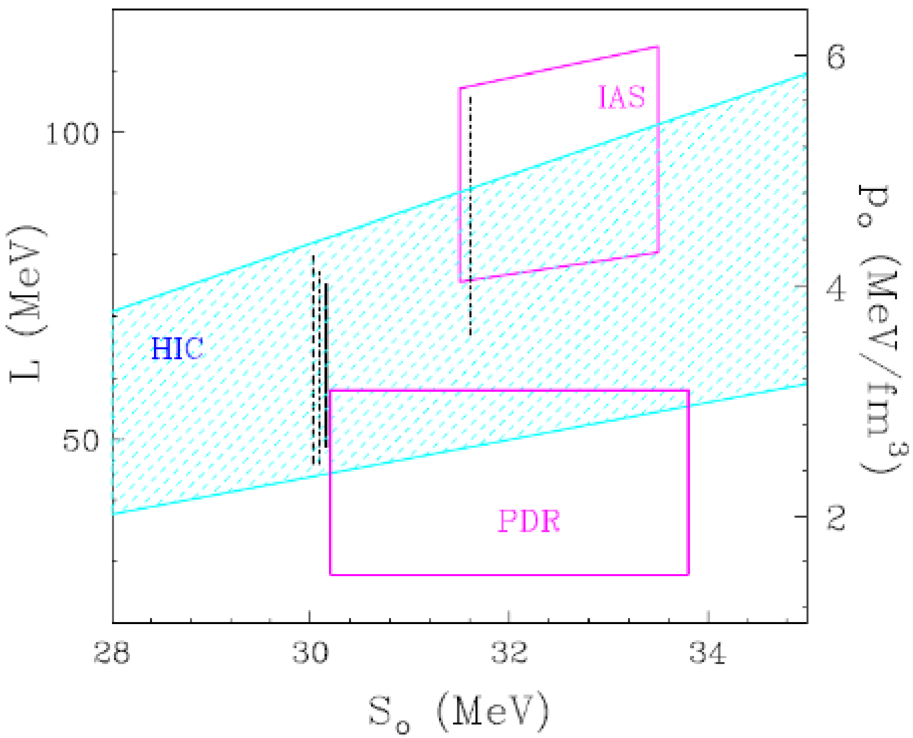
Isospin Diffusion observable to study E_{sym} with Heavy Ion Collisions

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

Tsang et al., PRL 92 (2004) 062701



Tsang, Zhang et al., PRL122, 122701(2009)

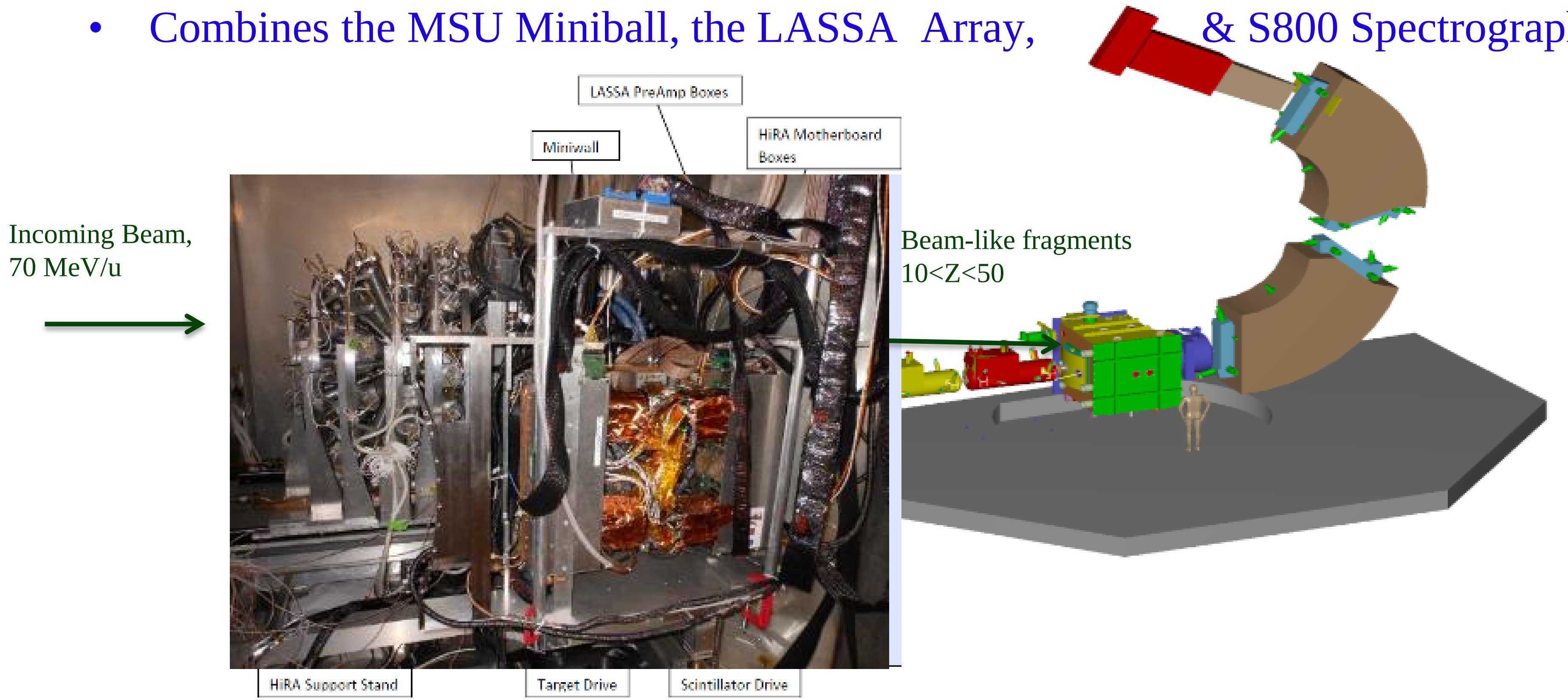


Isospin Diffusion; low ρ, E_{beam}

NuSYM10

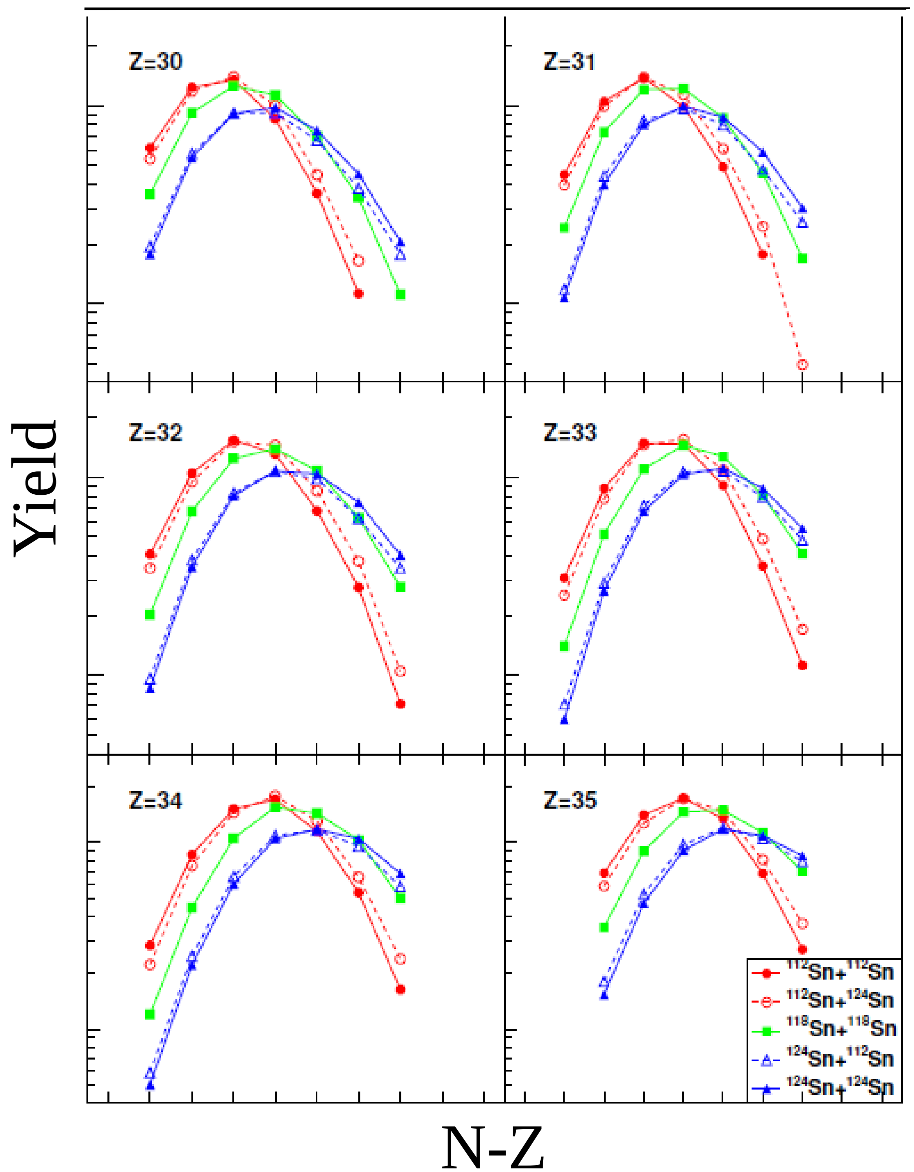
NSCL Experiment 07038: Precision Measurement of Isospin Diffusion

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

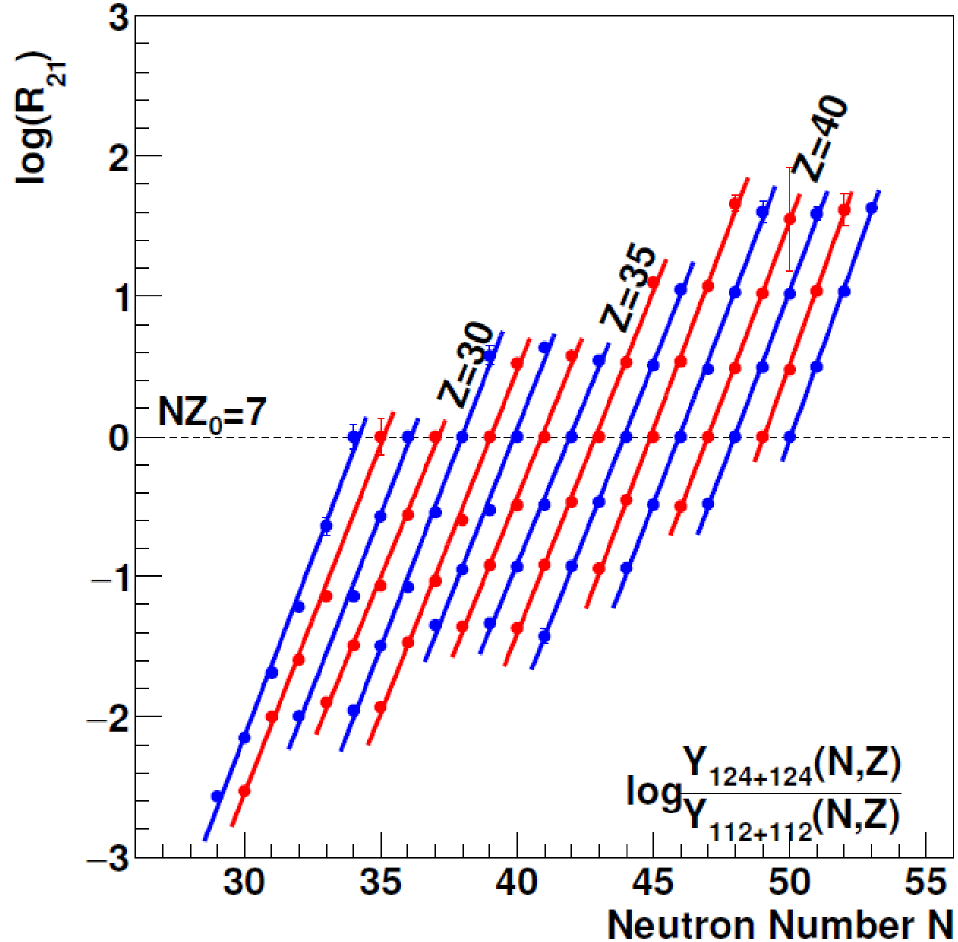


Jack Winkelbauer, PhD thesis

$^{112}Sn+^{112}Sn$; $^{112}Sn+^{124}Sn$; $^{118}Sn+^{118}Sn$; $^{124}Sn+^{112}Sn$; $^{124}Sn+^{124}Sn$



Isoscaling of PLF residue



Jack Winkelbauer, PhD thesis

Correlations between force parameters

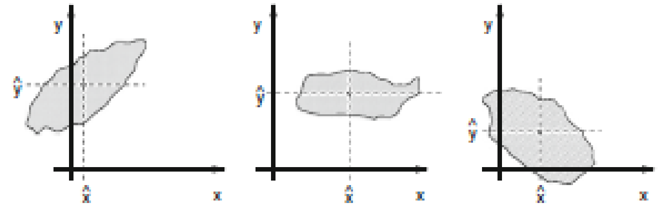
Y.X.Zhang

$$C_{AB} = \frac{cov(A,B)}{\sigma(A)\sigma(B)} \quad (1)$$

$$cov(A,B) = \frac{1}{N-1}\sum_i (A_i - <A>)(B_i - <B>) \quad (2)$$

$$\sigma(X) = \sqrt{\frac{1}{N-1}\sum_i (X_i - <X>)^2}, X = A, B \quad (3)$$

$$<X> = \frac{1}{N}\sum_i X_i, i = 1, N. \quad (4)$$



C_AB=1 0 -1

120 Skyrme sets

Skyrme Parameters

Skyrme Parameters

C_{AB}	K_0	S_0	L	ms*	mv*
K_0	1	0.003	0.161	0.131	0.295
S_0	0.003	1	**0.764**	0.397	0.228
L	0.161	**0.764**	1	**0.460**	0.212
ms*	0.131	0.397	**0.460**	1	**0.715**
mv*	0.295	0.228	0.212	**0.715**	1

Correlations between force parameters

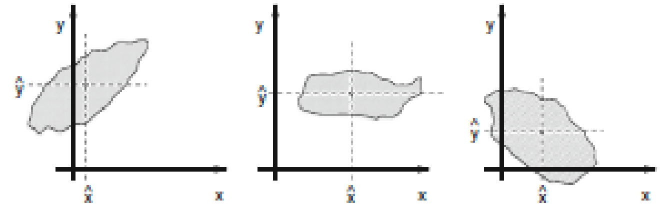
Y.X.Zhang

$$C_{AB} = \frac{cov(A,B)}{\sigma(A)\sigma(B)} \quad (1)$$

$$cov(A,B) = \frac{1}{N-1}\sum_i (A_i - \langle A \rangle)(B_i - \langle B \rangle) \quad (2)$$

$$\sigma(X) = \sqrt{\frac{1}{N-1}\sum_i (X_i - \langle X \rangle)^2}, X = A, B \quad (3)$$

$$\langle X \rangle = \frac{1}{N}\sum_i X_i, i = 1, N. \quad (4)$$



C_AB=1 0 -1

120 Skyrme sets

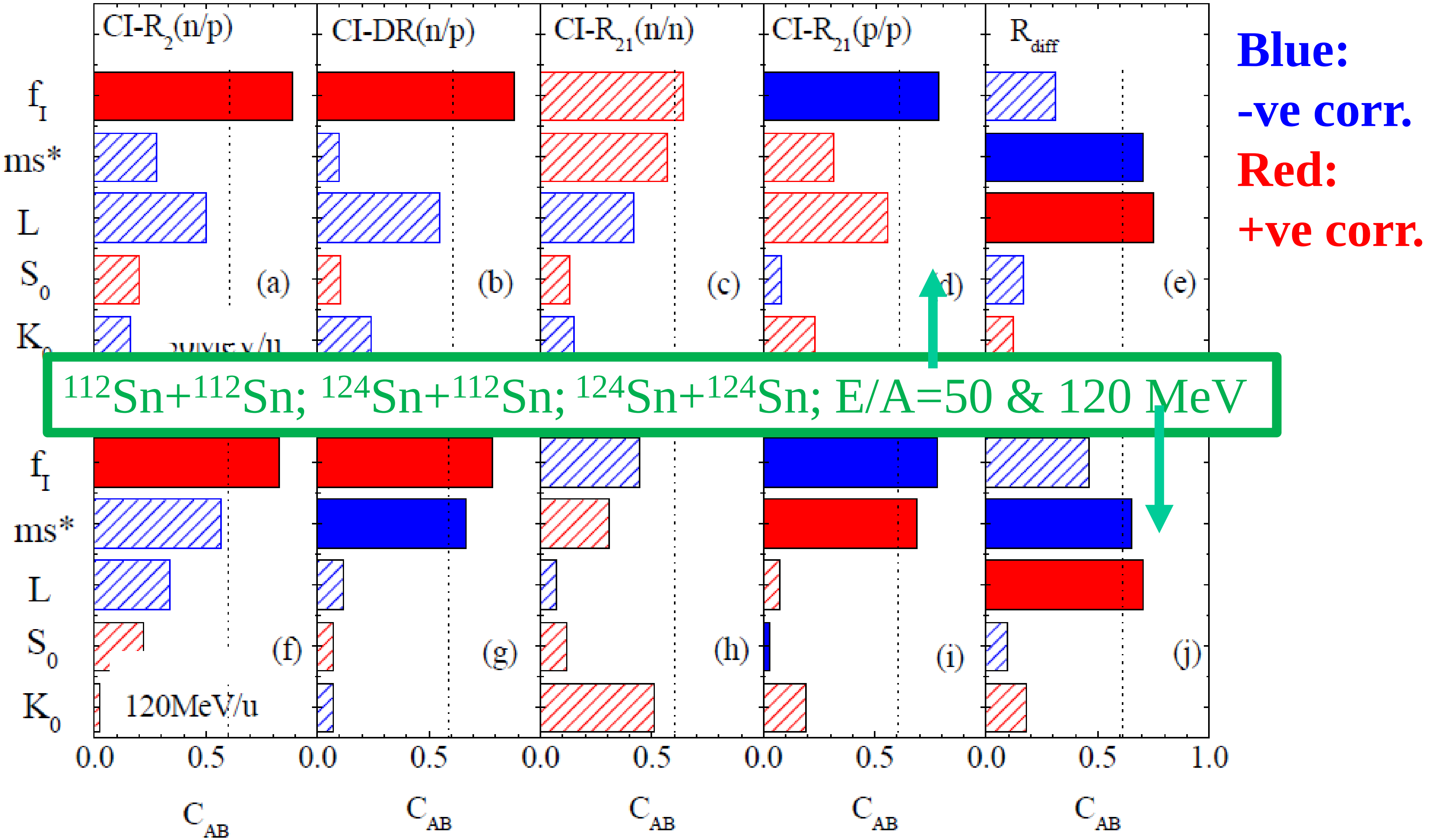
Experimental Observables

Skyrme Parameters

C_{AB}	R(n/p)	DR(n/p)	R(n/n)	R(p/p)	Rdiff
K_0	-0.16	-0.24	0.15	0.23	0.12
S_0	0.20	0.10	0.13	-0.07	-0.17
L	-0.50	-0.55	-0.42	0.55	0.75
ms*	-0.28	-0.09	0.57	0.31	-0.70
f_I(mass split)	0.89	0.88	0.64	-0.78	-0.31

Covariance analysis from 12 Parameter sets

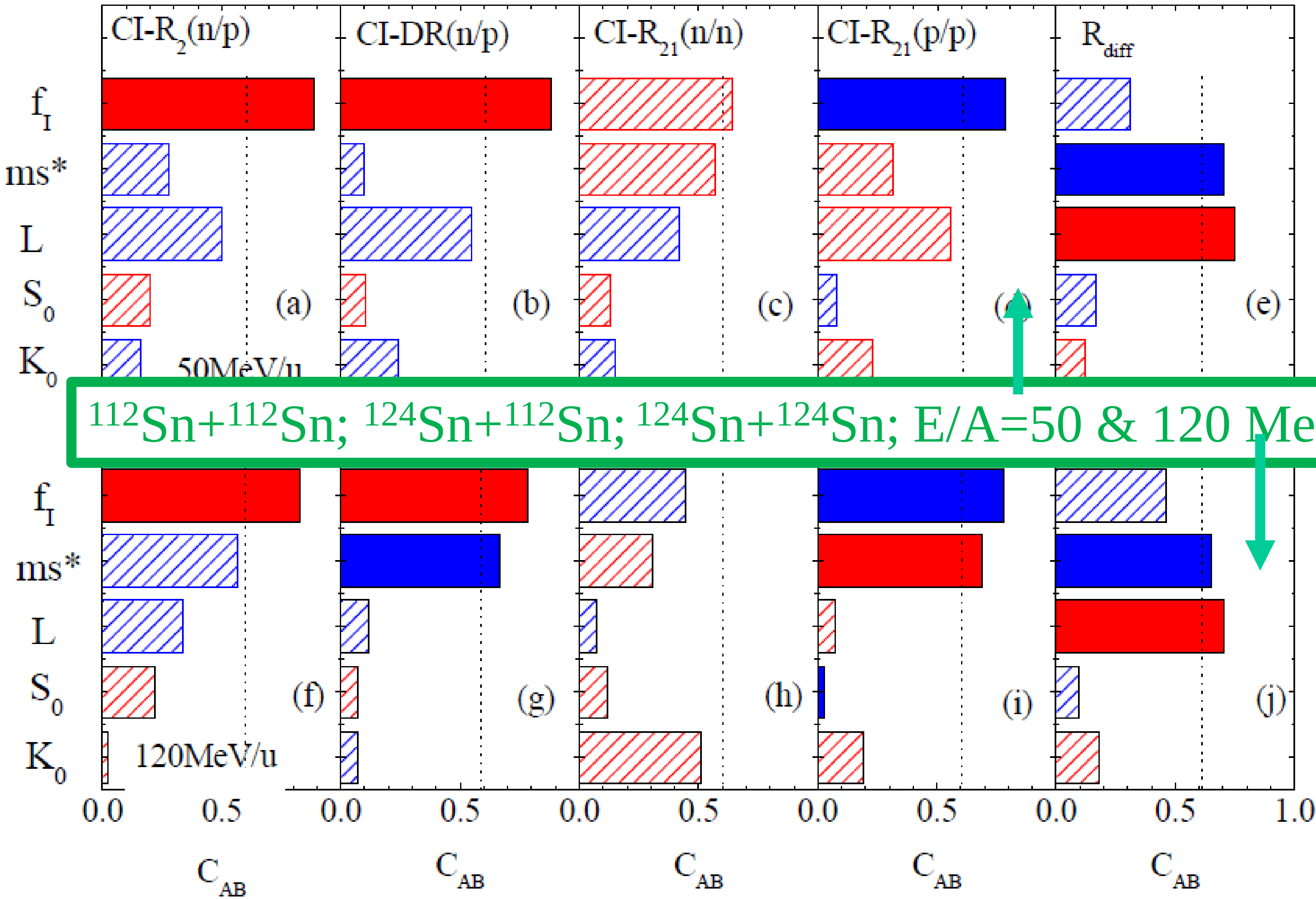
Y.X.Zhang, M.B.Tsang, Z.X.Li,



Coalescence Invariant with transverse angle cut and Ek>40MeV

Covariance analysis from 12 Parameter sets

Y.X.Zhang, M.B.Tsang, Z.X.Li,



Blue:
-ve corr.
Red:
+ve corr.

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

L is sensitive to Rdiff & p/p; mass splitting is sensitive to nucleon spectra at both energies; ms is correlated to Rdiff & p/p ratios

Covariance analysis from 12 Parameter sets

Y.X.Zhang et al

Table 1: List of twelve parameters used in the ImQMD calculations. $\rho_0 = 0.16 fm^{-3}$, $E_0 = -16 MeV$, and $g_{sur} = 24.5 MeV fm^2$, $g_{sur,iso} = -4.99 MeV fm^2$

Para.	K_0 (MeV)	S_0(MeV)	L (MeV)	m_s^*/m	f_I
1	**230**	**32**	**46**	**0.7**	**-0.238**
2	**280**	32	46	0.7	-0.238
3	**330**	32	46	0.7	-0.238
4	230	**30**	46	0.7	-0.238
5	230	**34**	46	0.7	-0.238
6	230	32	**60**	0.7	-0.238
7	230	32	**80**	0.7	-0.238
8	230	32	**100**	0.7	-0.238
9	230	32	46	**0.85**	-0.238
10	230	32	46	**1.00**	-0.238
11	230	32	46	0.7	**0.0**
12(SLy4)	230	32	46	0.7	**0.178**

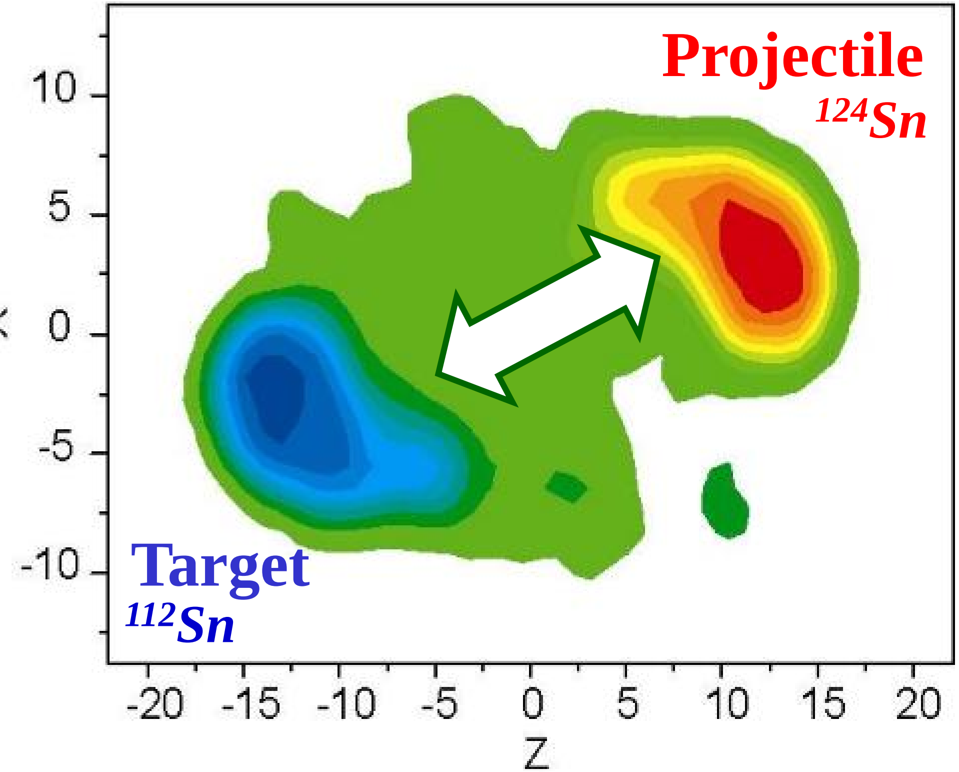
Parameter sets based on SLy4.

Need to check other parameter sets.

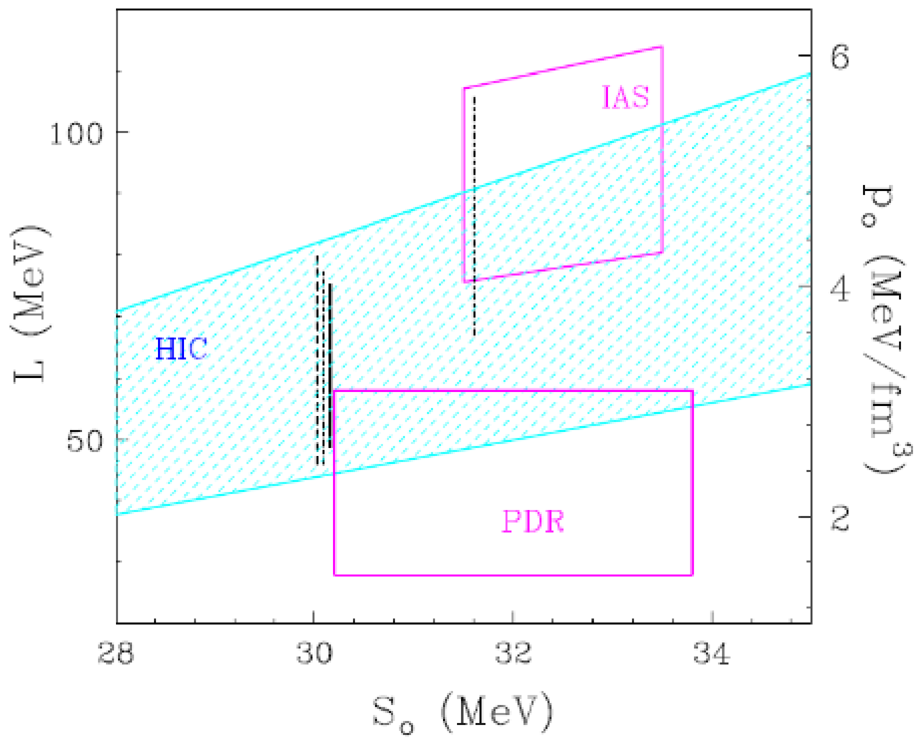
Progress that was made

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

Tsang et al., PRL 92 (2004) 062701



Tsang, Zhang et al., PRL122, 122701(2009)



Isospin Diffusion; low ρ, E_{beam}

NuSYM10

Consistent Constraints on Symmetry Energy from different experiments→ HIC is a viable probe

Isobaric Analogue States
NPA 818, 36 (2009)

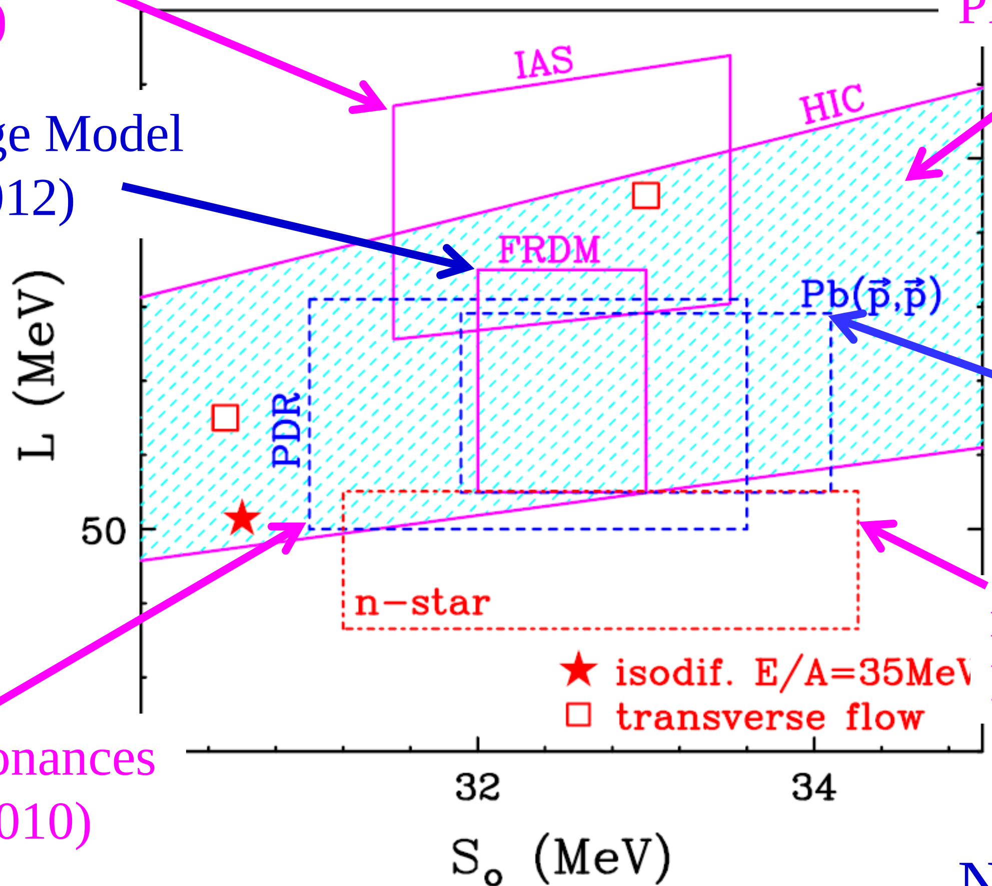
heavy ion collisions
PRL 102,122701(2009)

Finite Droplet Range Model
PRL108,052501(2012)

p elastic scattering
PRC82,044611(2010)

neutron-star radius
PRL108,01102(2012)

Pygmy Dipole Resonances
PRC 81, 041304 (2010)

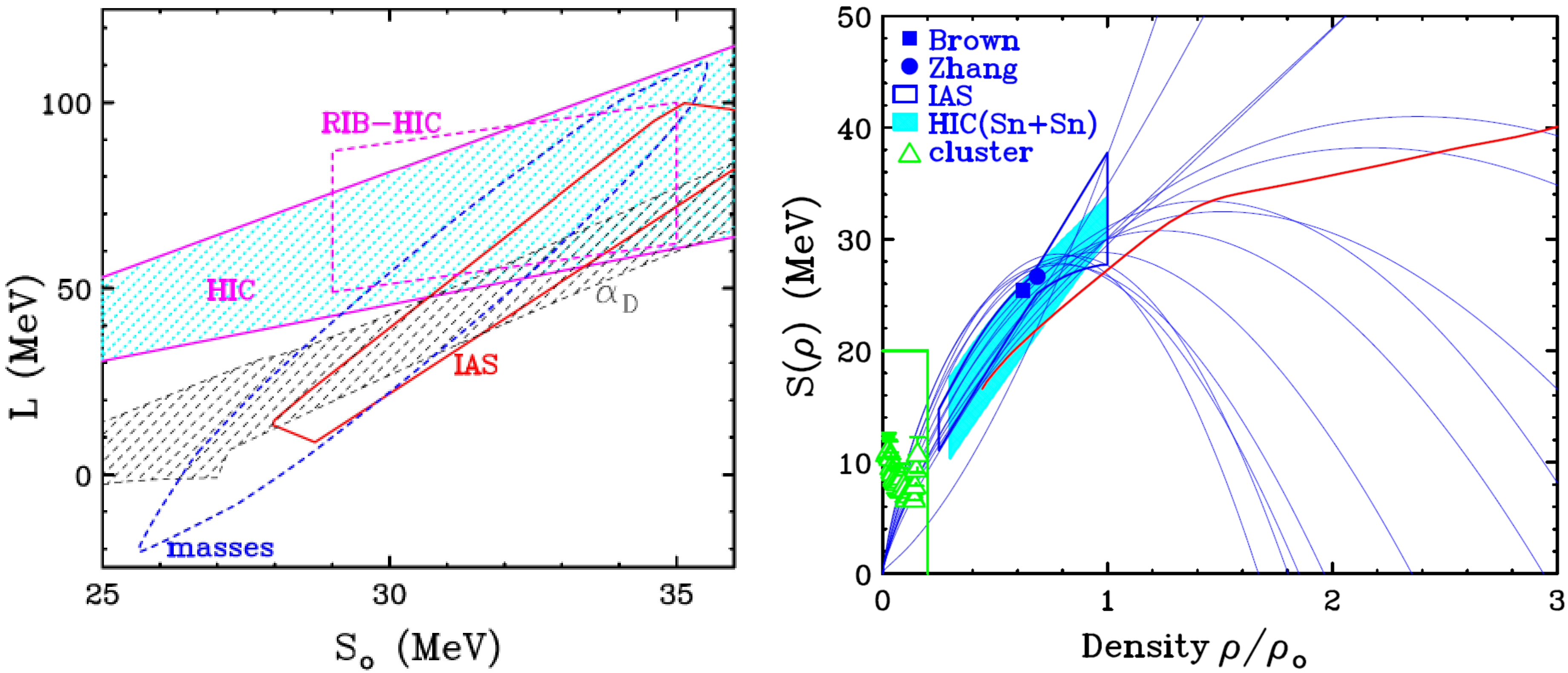


NuSYM11

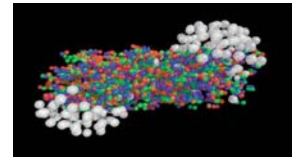
$$E_{sym} = S_o + \frac{L}{3}\left(\frac{\rho_B - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B - \rho_0}{\rho_0}\right)^2 + \ldots$$

Tsang et al. C 86, 015803 (2012)

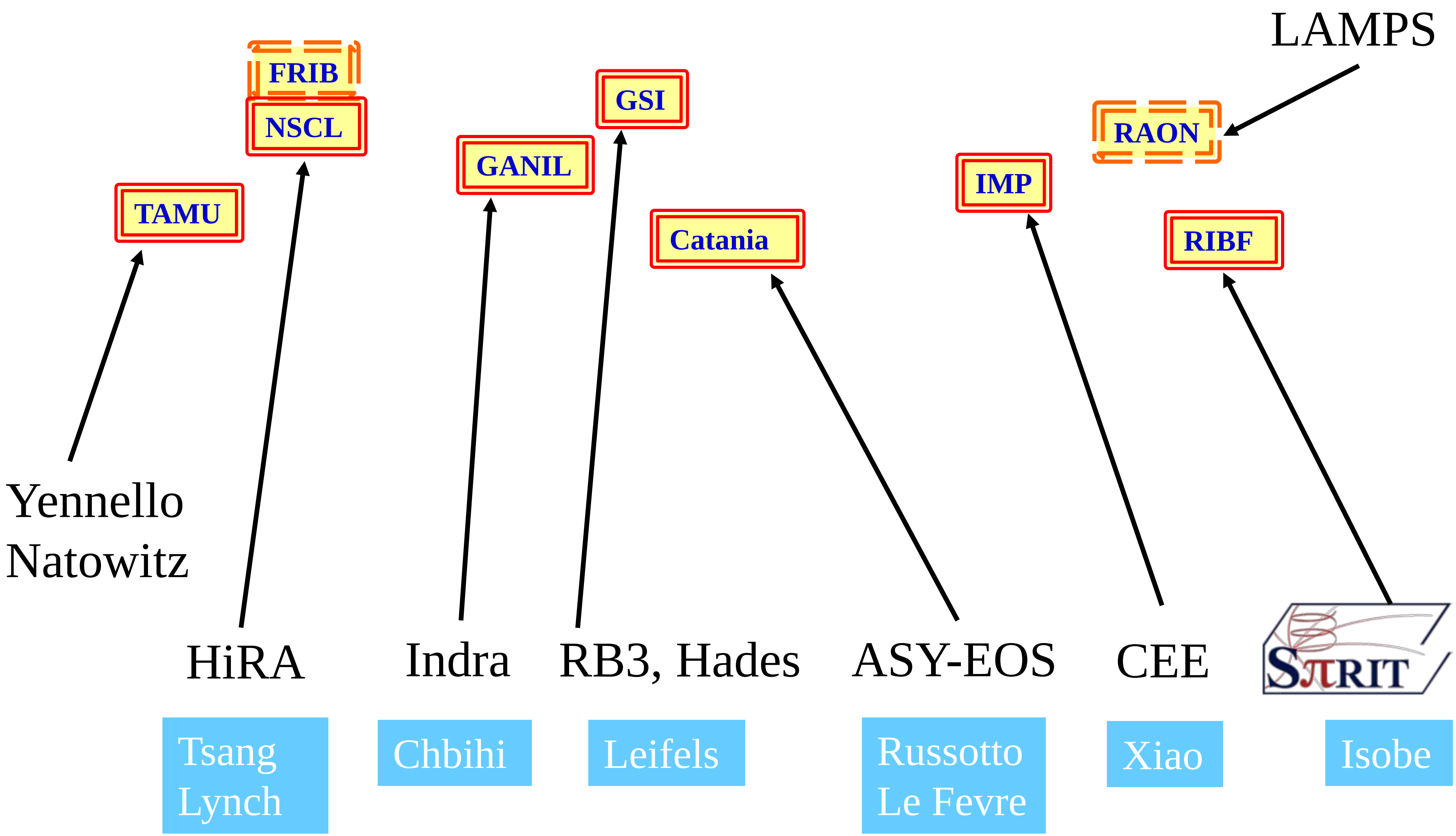
Updated Constraints with credible error bars from NuSYM13



Symmetry Energy Project

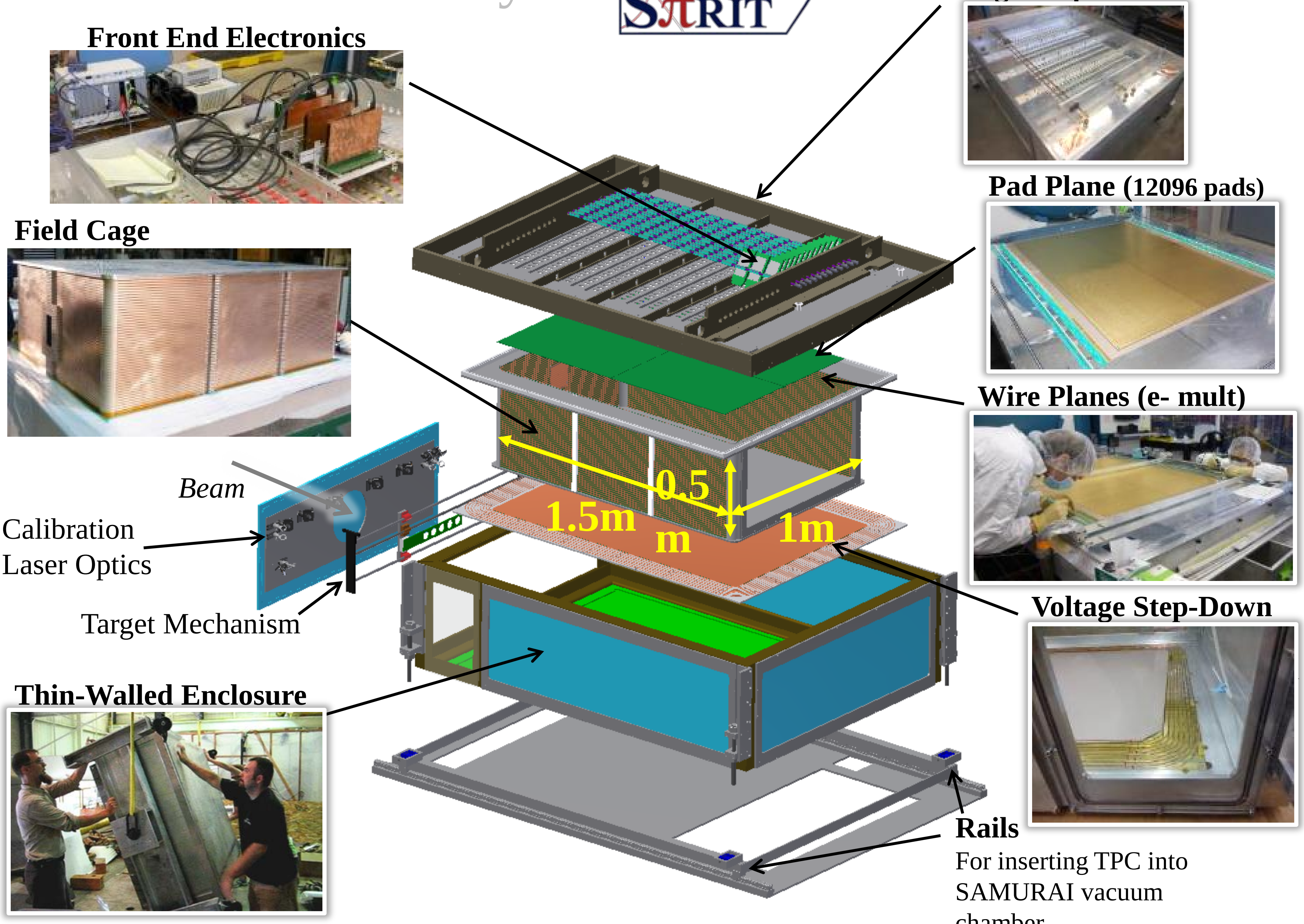


Kim



Productions of high intensity high energy Radioactive Isotope Beams for the EoS studies over a wide range of density

Anatomy of SπRIT



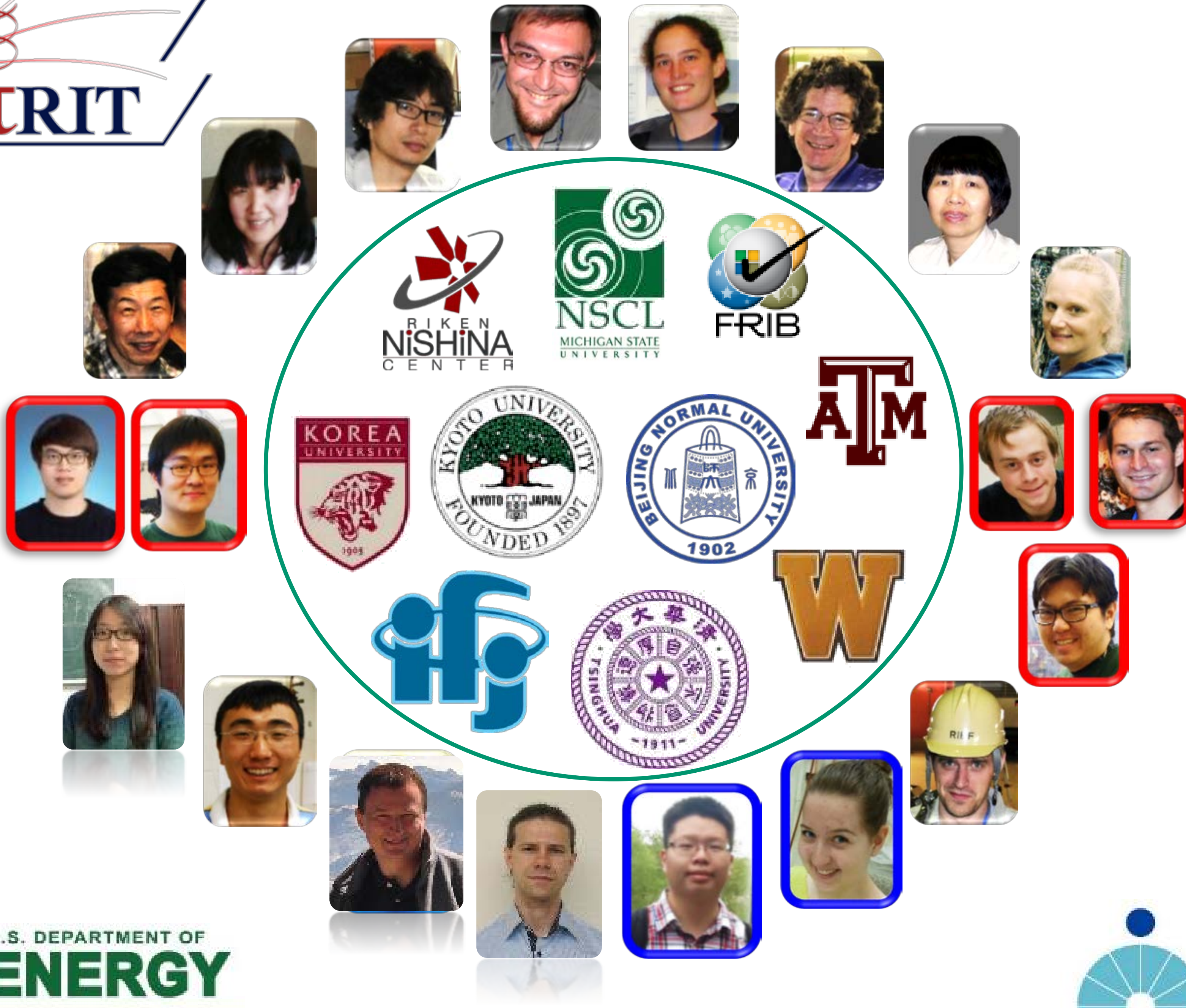
May, 2013

Feb, 2014

July, 2014

Feb, 2015

SπRIT



U.S. DEPARTMENT OF ENERGY
Office of Science

文部科学省
MEXT
MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

Workshop on Science with SπRIT

June 5-6, 2015, RIKEN

The availability of intense rare isotope beams offer opportunities for improved constraints on the EoS:

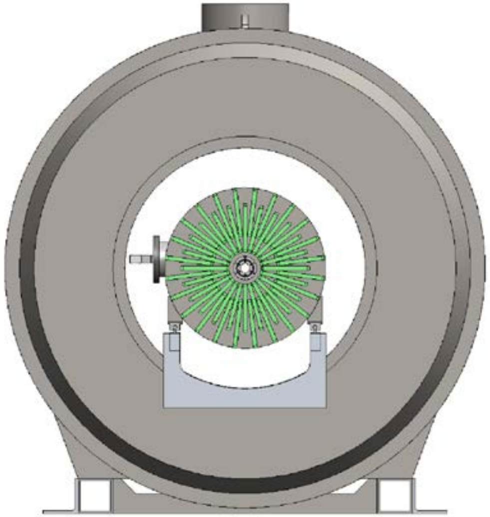
- At low densities relevant to crust core boundary of neutron stars.
- At supra-saturation densities relevant to the mass-radius relationship of neutron stars
- At finite temperatures:
    - For dilute matter: EoS of supernova neutrino-sphere
    - For dense matter: nucleon effective mass splitting
    - At temperature relevant to the “boiling point of finite nuclei”

Additional opportunities for probing low density EoS via studies of giant resonances

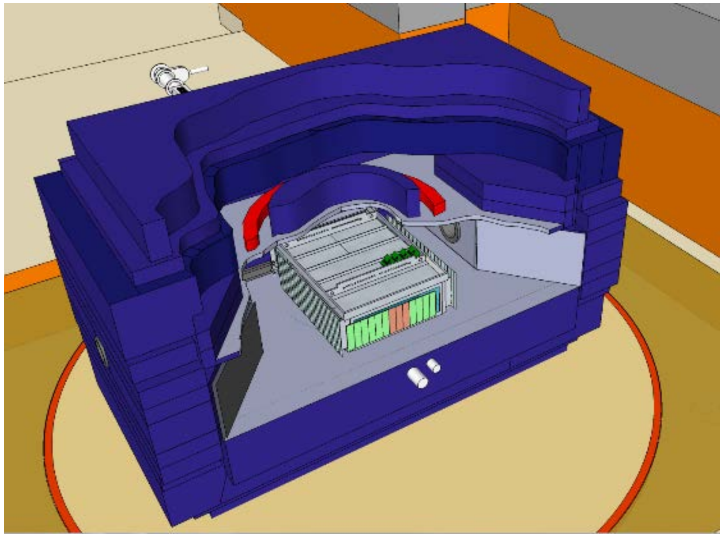
- GMR – K_sym for low density symmetry energy
- Gamov-Teller neutrino interaction rates in supernova

Fission decay of rare isotopes

- Extrapolation to fission processes occurring in r-process



Magnetic Field Considerations



Solenoid

- active shield magnets eliminate the Fe shielding
- Decrease the size and weight of solenoid→ “portable” solenoid.
- price of solenoid comes down by refurbishing MRI magnets
- Advance in large area micro-Megas and GEM to replace wire planes
- Availability of GET electronics

Dipole

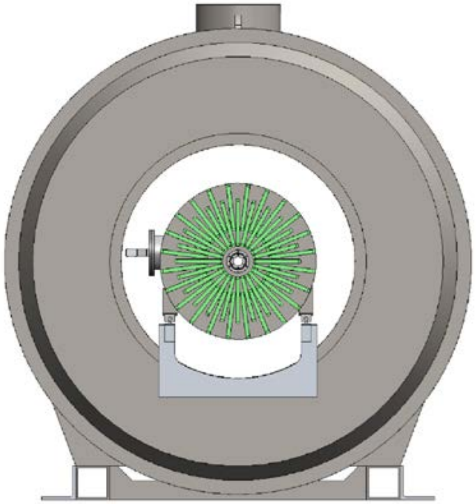
- dipole is expensive and heavy
- Not movable; Multi-users means difficulty with scheduling

HR-TPC: facilitating EoS and High resolution active target measurements with fast beams (Chajecki et al., WMU+MSU)

Adopts much of the design of the AT-TPC

- portable MRI magnet & MICROMEGAS gas amplification
- Beam enters through MICROMEGAS
- Cathode allows passage of charged particle ancillary detectors downstream.

Chajecki & Lynch



Summary and Outlook

- The availability of intense rare isotope (and also stable beams) provides opportunities to address the role of the EoS in astrophysical environments
  - Density dependence of the symmetry energy at sub-saturation densities. Here progress has already occurred.
  - EoS of dilute excited matter relevant to the neutrino-sphere. Promising beginning to address questions concerning core-collapse supernovae as the site of the r-process. Ties into general questions regarding dilute clustered nuclear matter.
  - Density and momentum dependence of the symmetry energy at supra-saturation densities. Here we expect a range of new results in the upcoming years.
- The ability to benchmark transport codes will allow us to have better confidence in interpreting our experimental results
- Using covariance analysis to examine correlations between parameters as well as to quantitatively understand the relationship between how experimental observables affect transport code parameters will hopefully lead to better theoretical uncertainties.