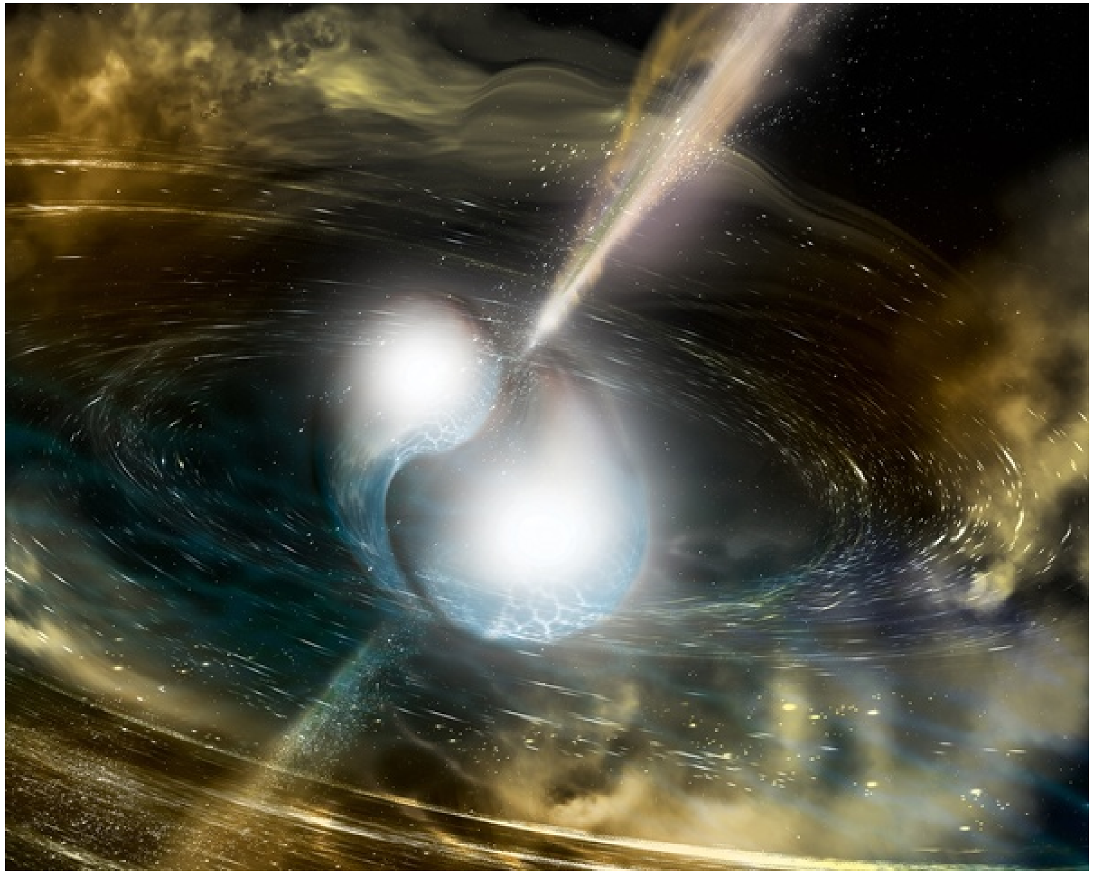
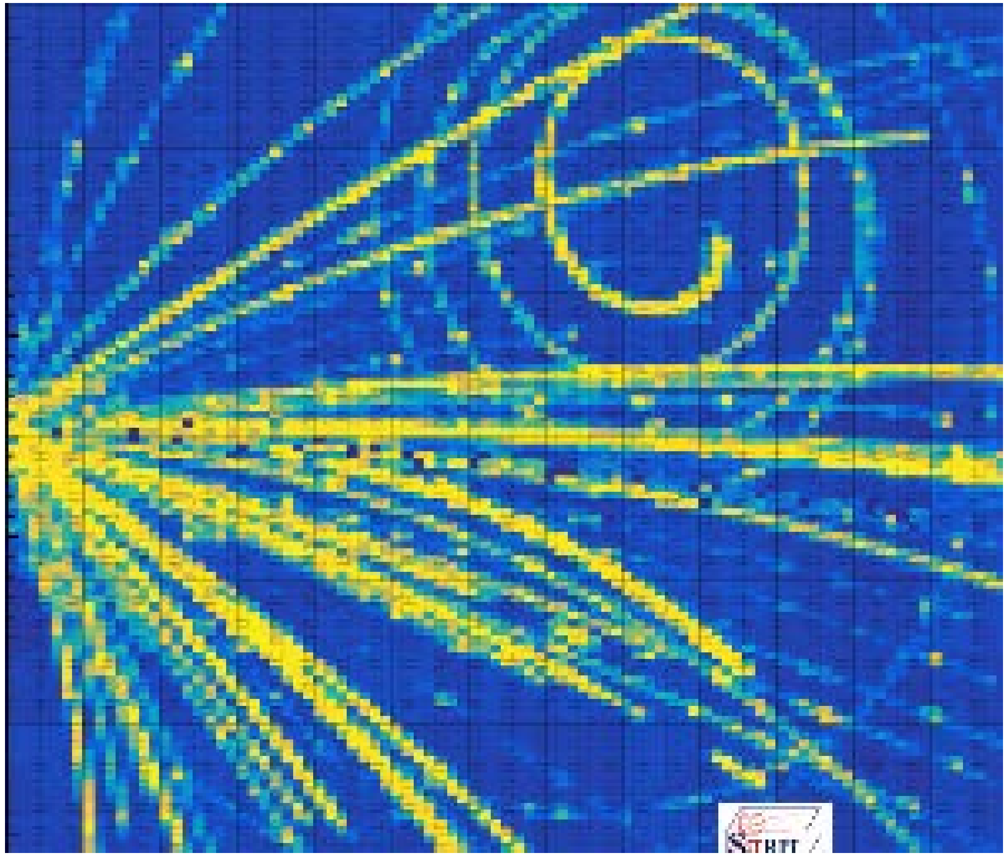
Experimental constraints on the Equation of State

LIGO Detects a Neutron Star Merger



$^{132}Sn+^{124}Sn$ @ E/A=270 MeV

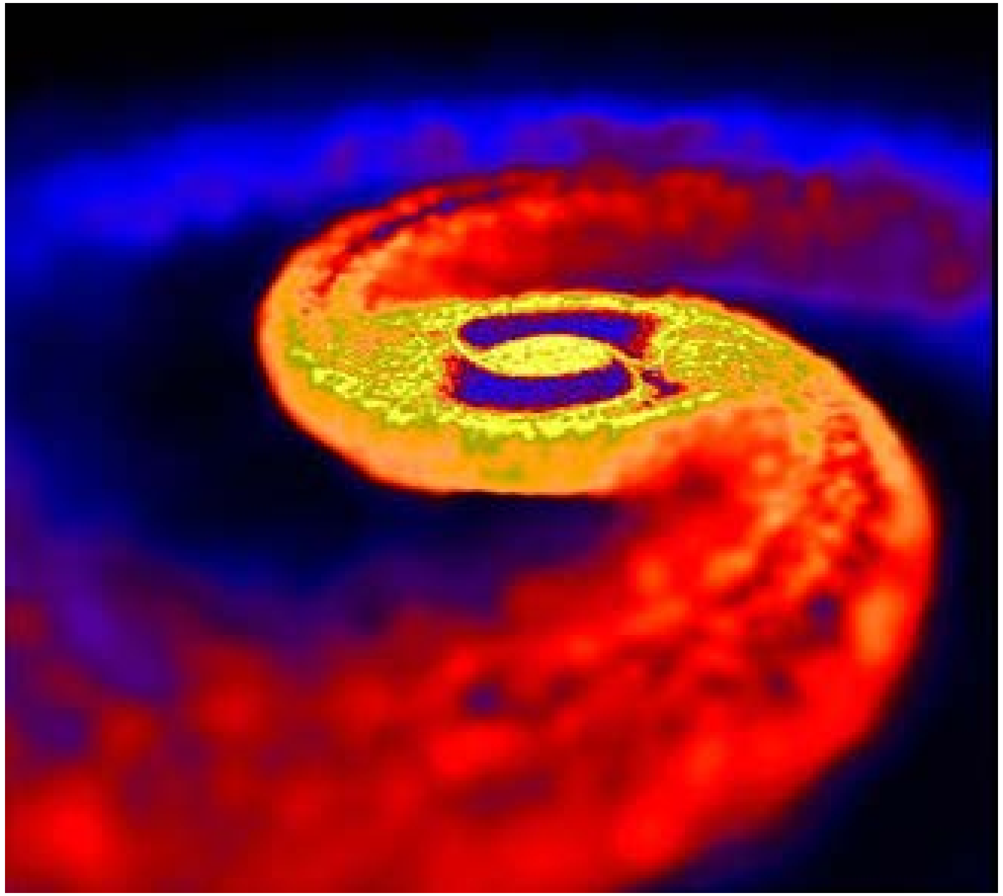


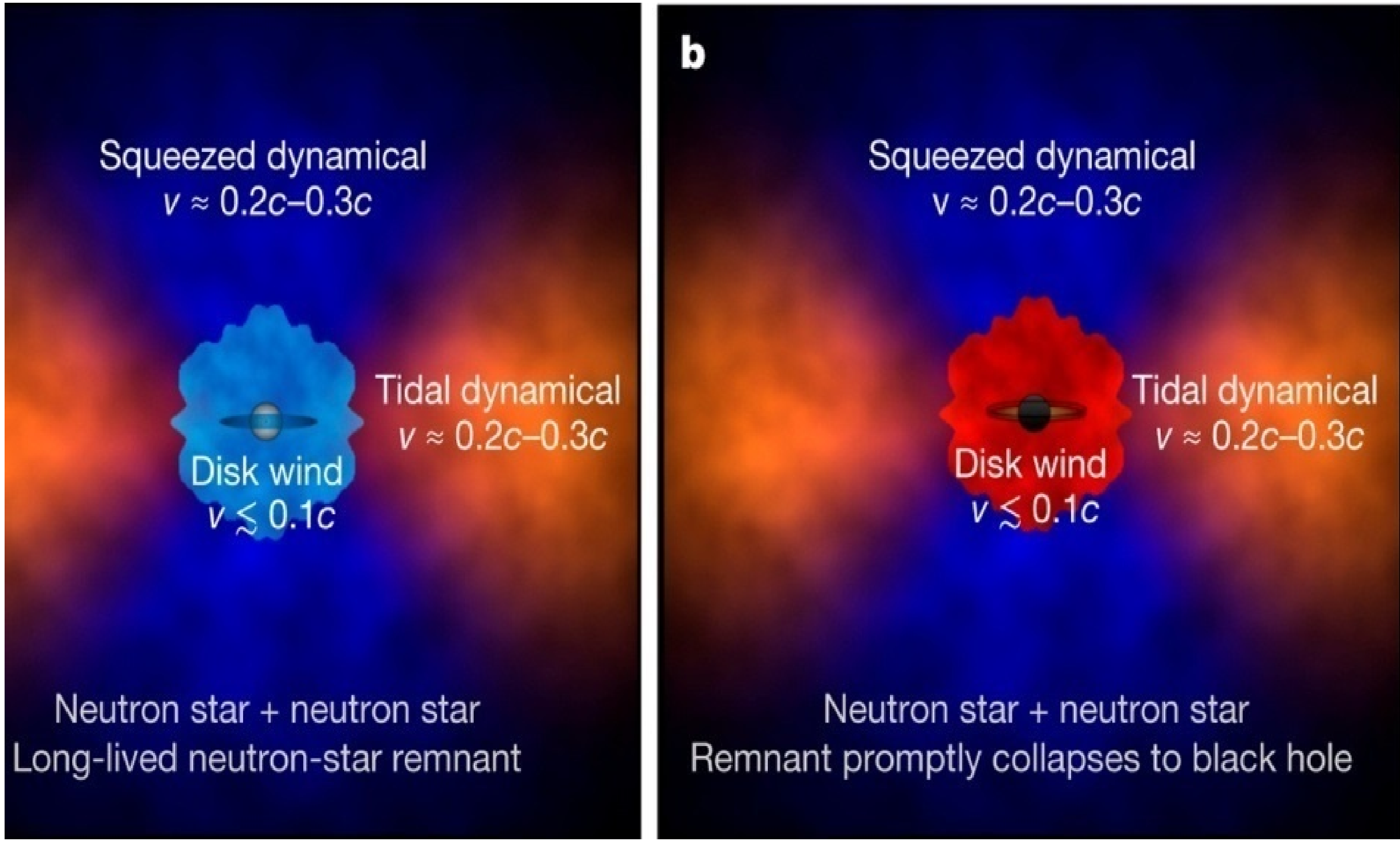
Betty Tsang, NSCL

Michigan State University

INT-JINA Workshop: 3/12-14/18

Equation of State and Dynamics of the Merger



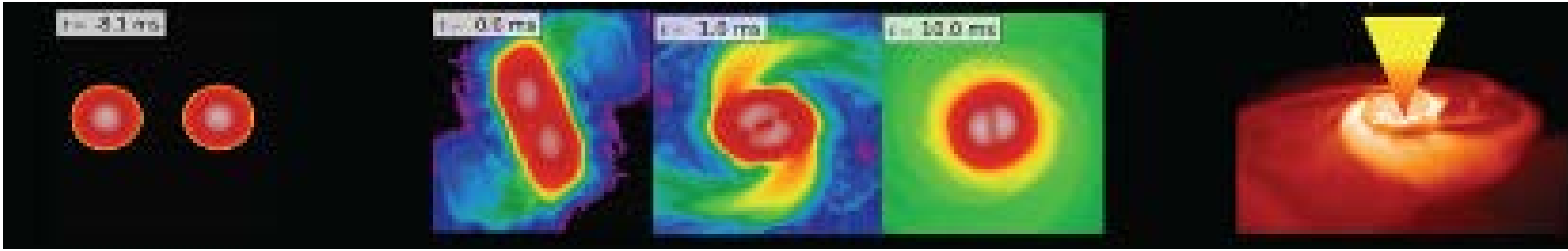


D Kasen *et al.* *Nature* **551,** 80–84 (2017) doi:10.1038/nature24453

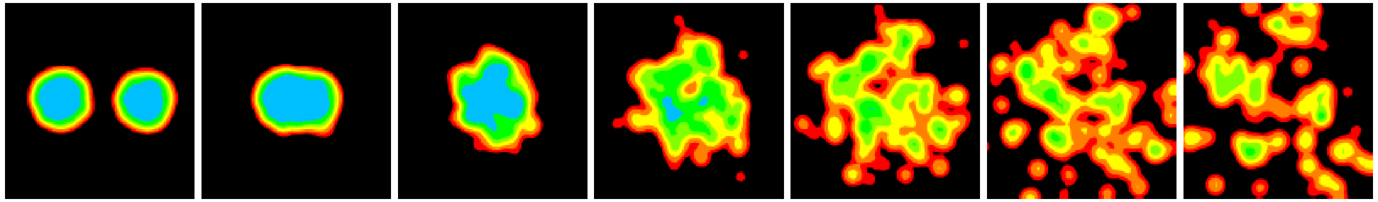
Fate of a Neutron Star Merger: n-star, black hole or transient?

EOS from dynamics of N-star merger and from nuclear collisions

N-Star merger: 10^8 year; Observation Estimates: <10/year



Nuclear-collisions: 10^{-21} sec; 10^6 collisions per experiment



Femto-nova explosion created by Heavy Ion collisions

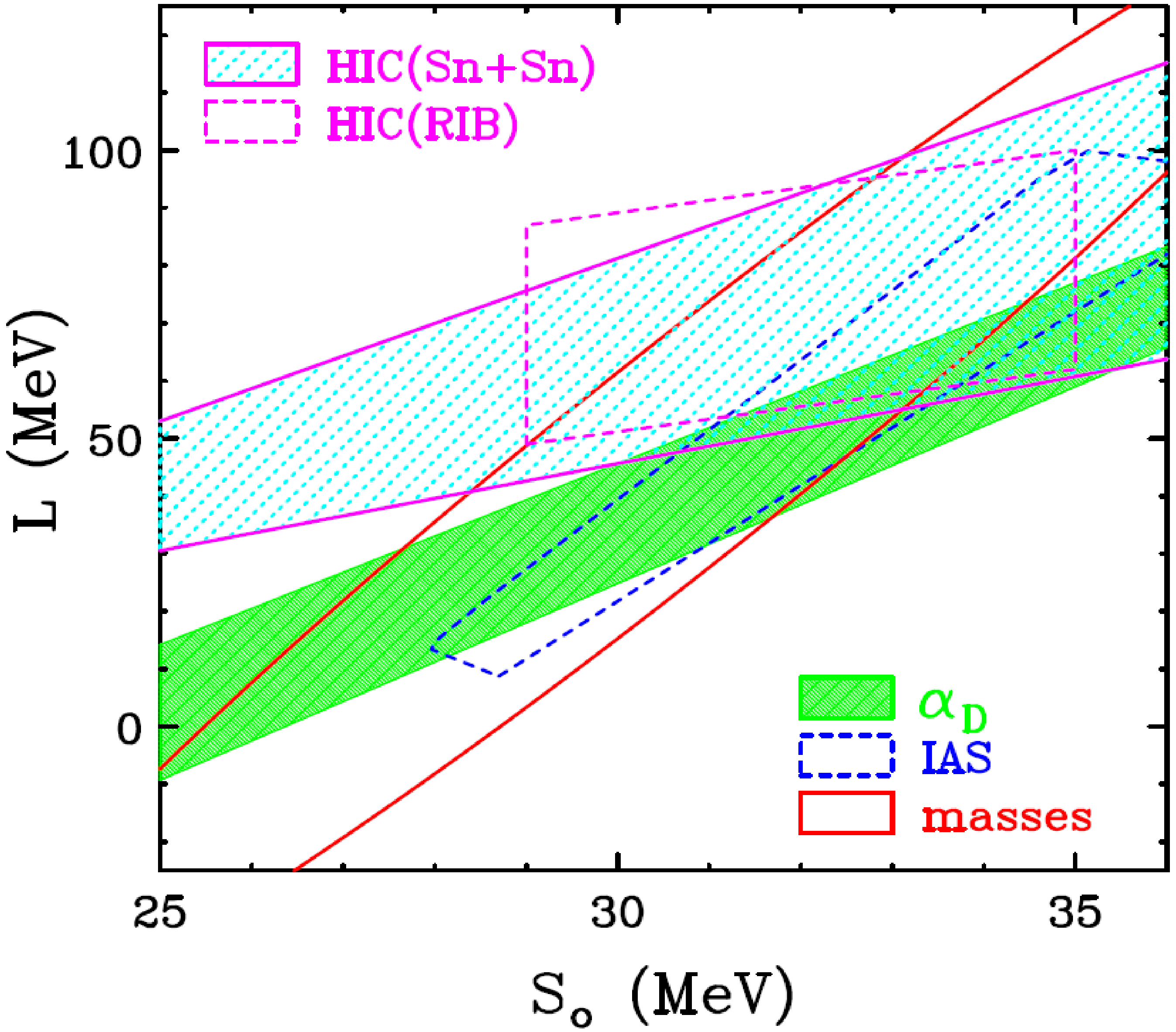
Equation of State of nuclear matter

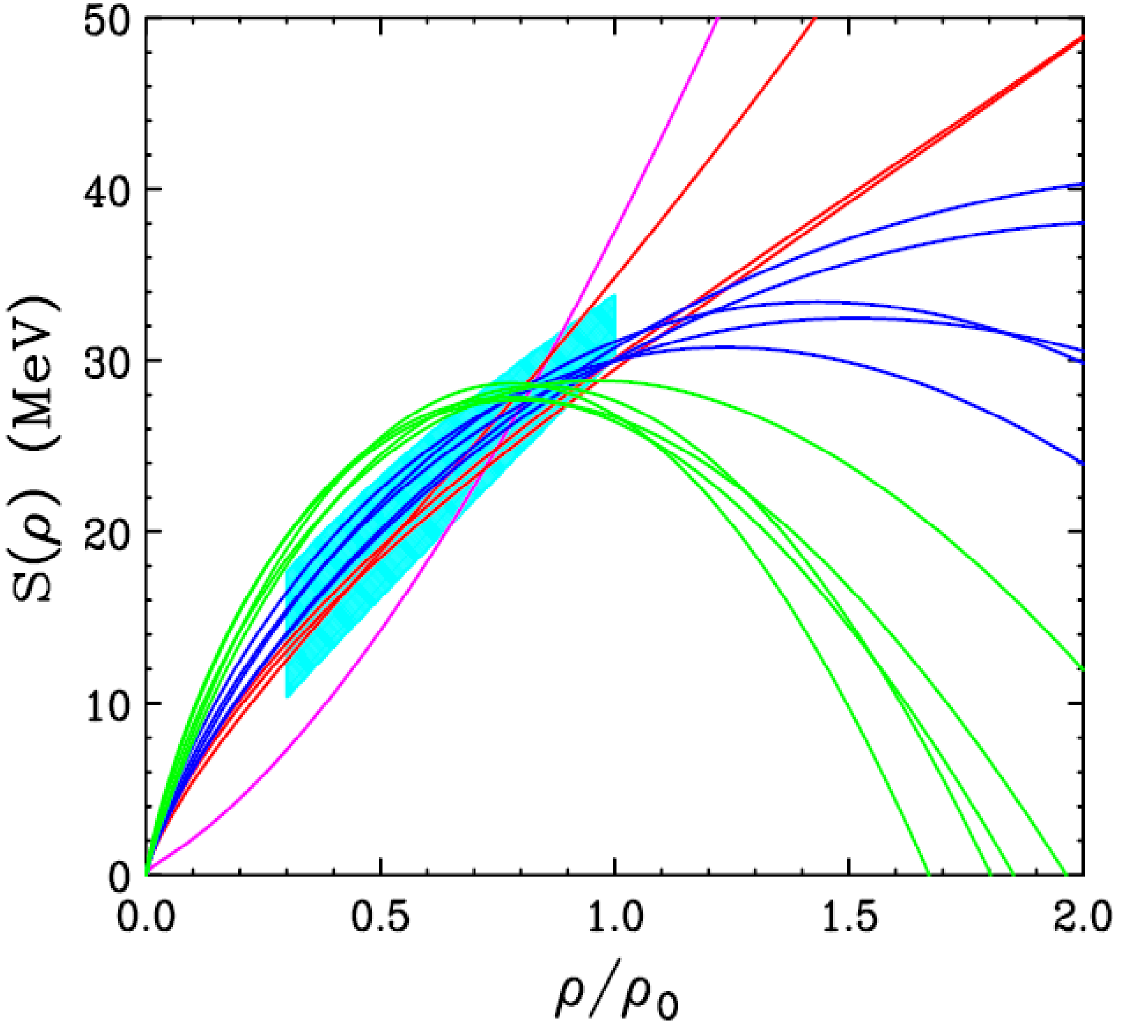
$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$

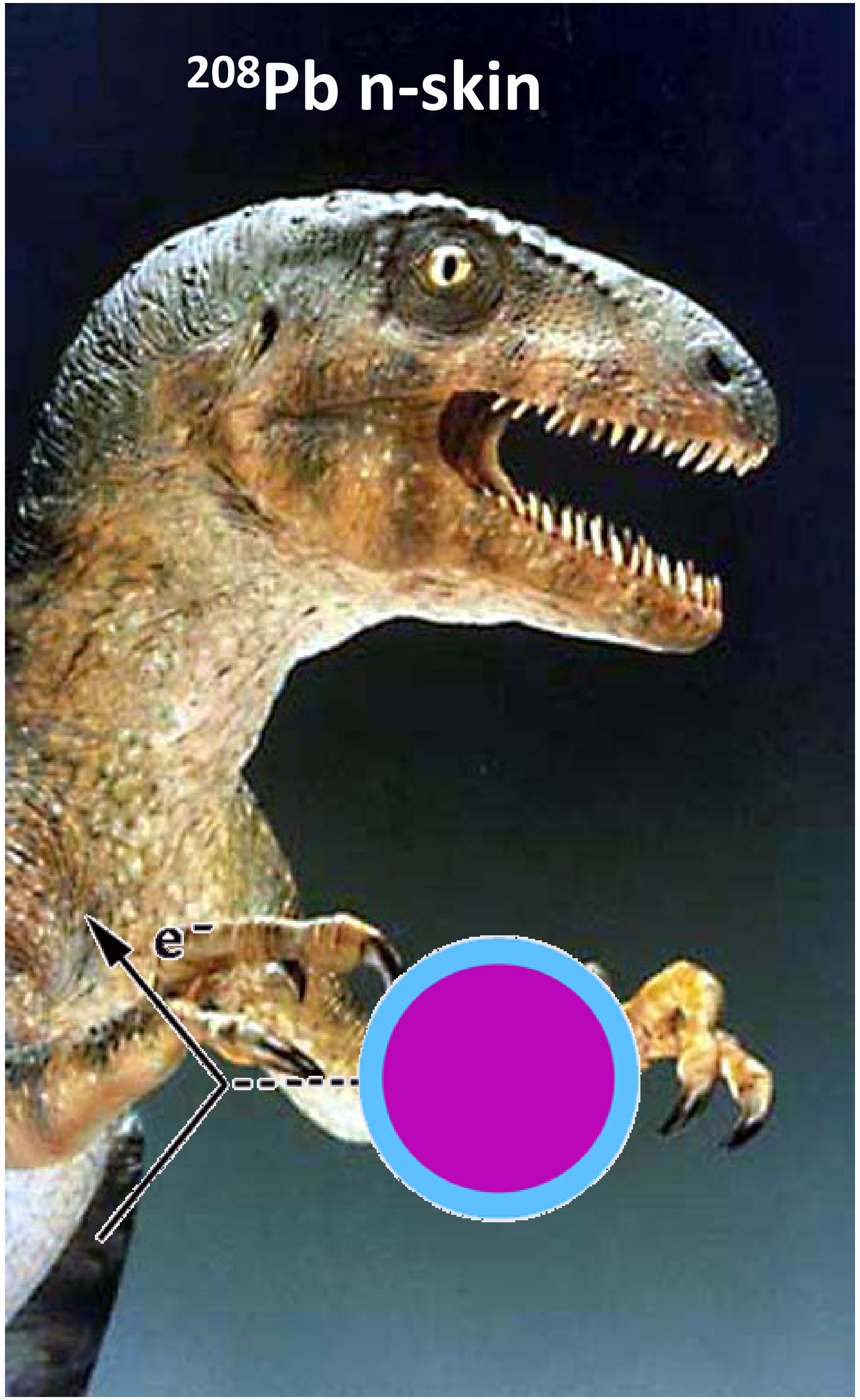
$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

A way Forward … (importance of theoretical errors)
J. Phys. G 41, 093001 (2014)

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





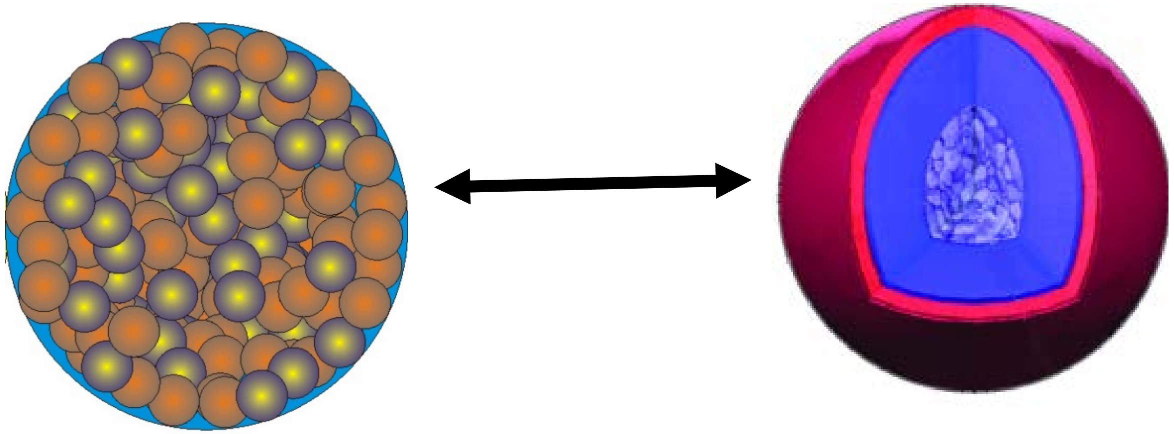


The physics, (symmetry energy), that governs the neutrons skin thickness of ^{208}Pb is the same as that governing the neutron star radius

C.J. Horowitz, J. Piekarewicz, PRL 86 (2001) 5647

~10^{-15} m

~10^{4} m



^{208}Pb

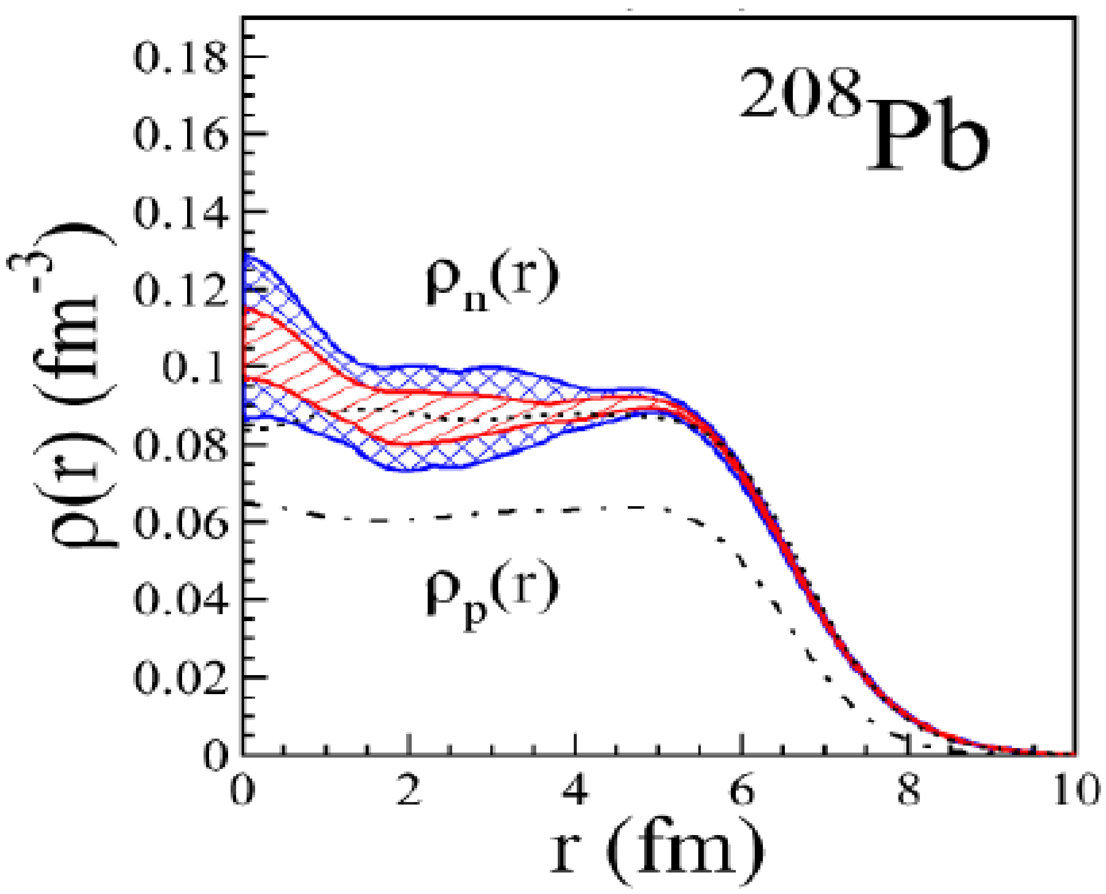
~208

Neutron Star

10^{57}

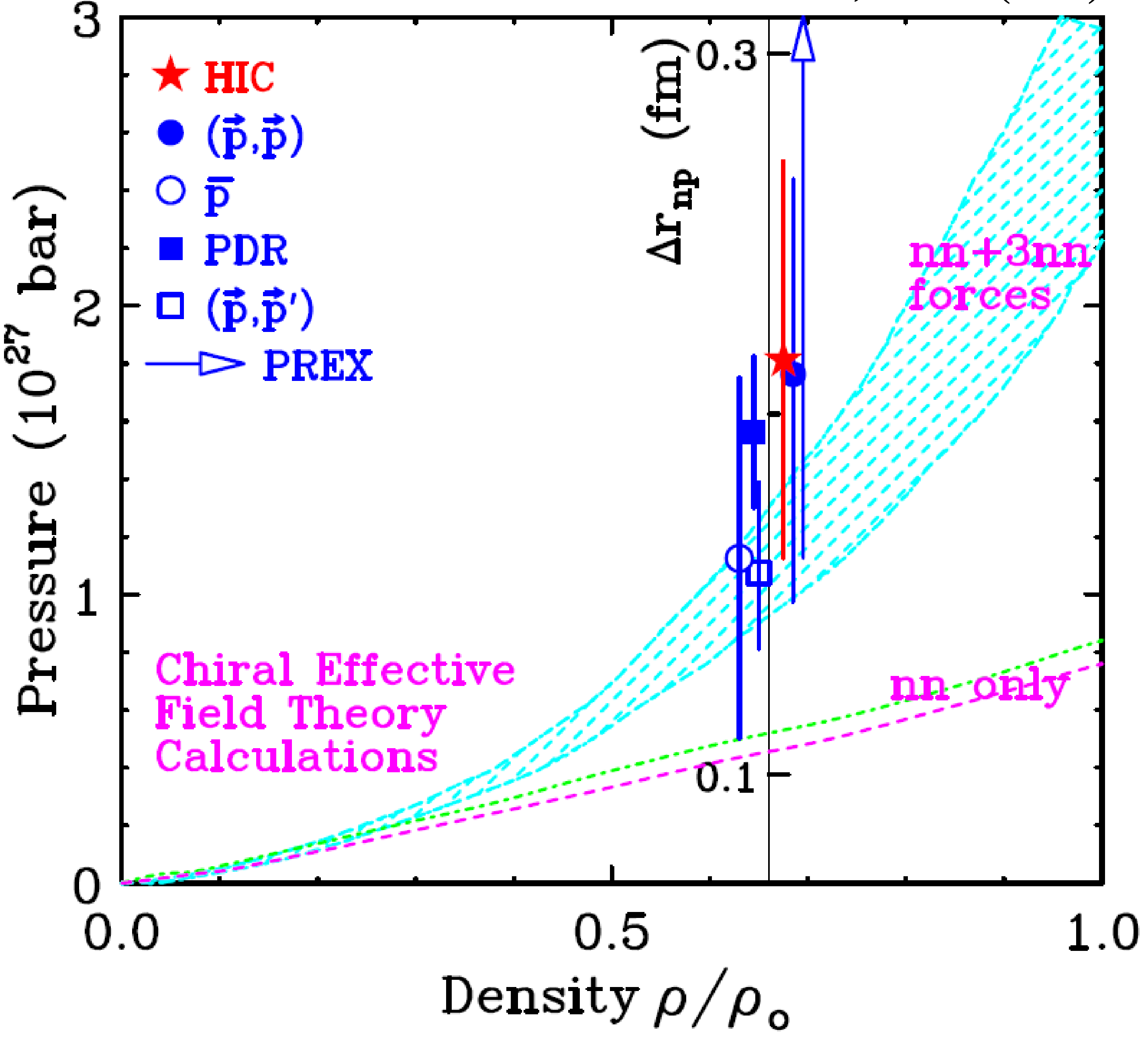
Parity Radius Experiment (P-ReX)

Neutron skin measurements

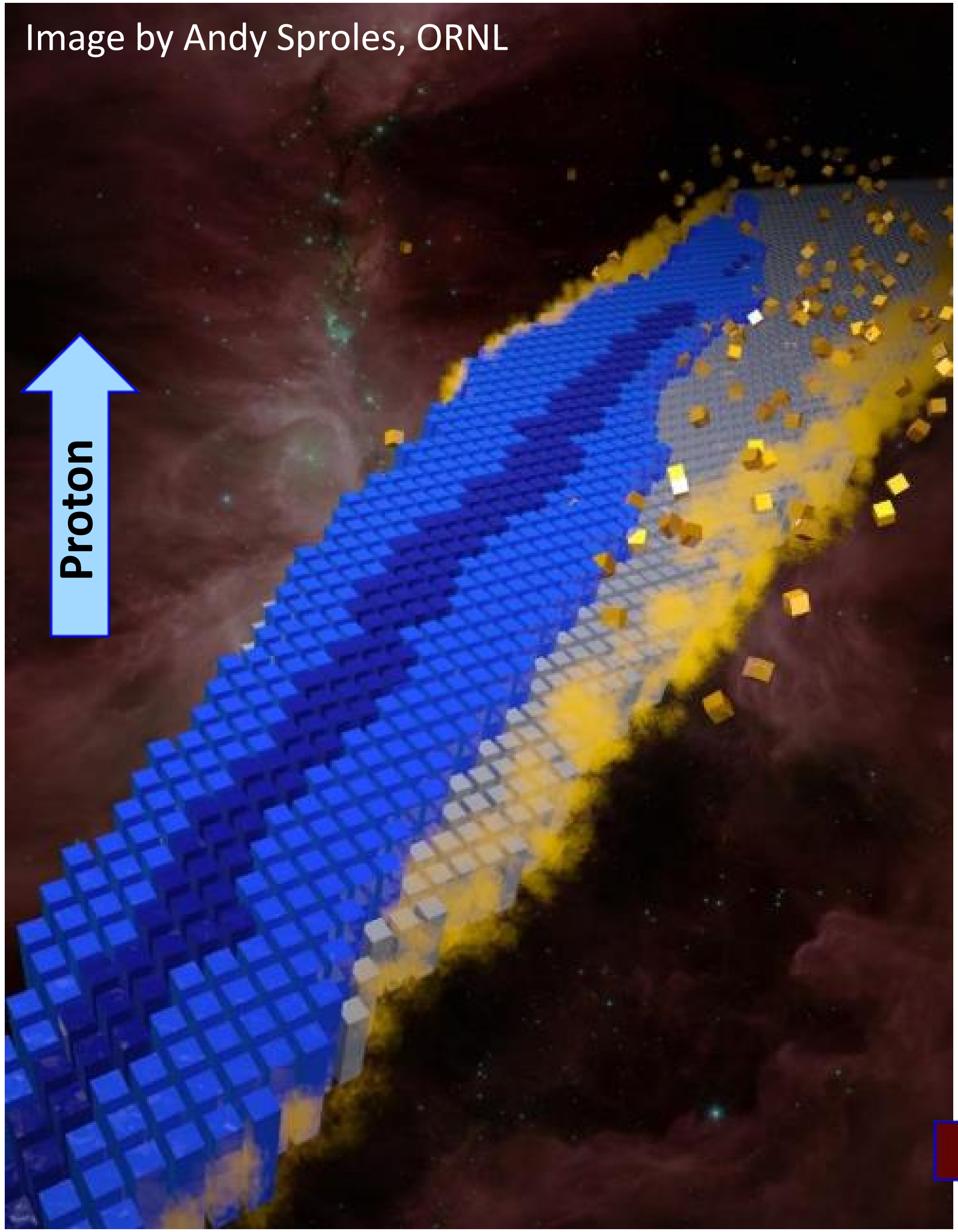


Zenihiro et al.: Phys. Rev. C**82**, 044611 (2010)

PRC. 86, 015803 (2012)



Symmetry Energy



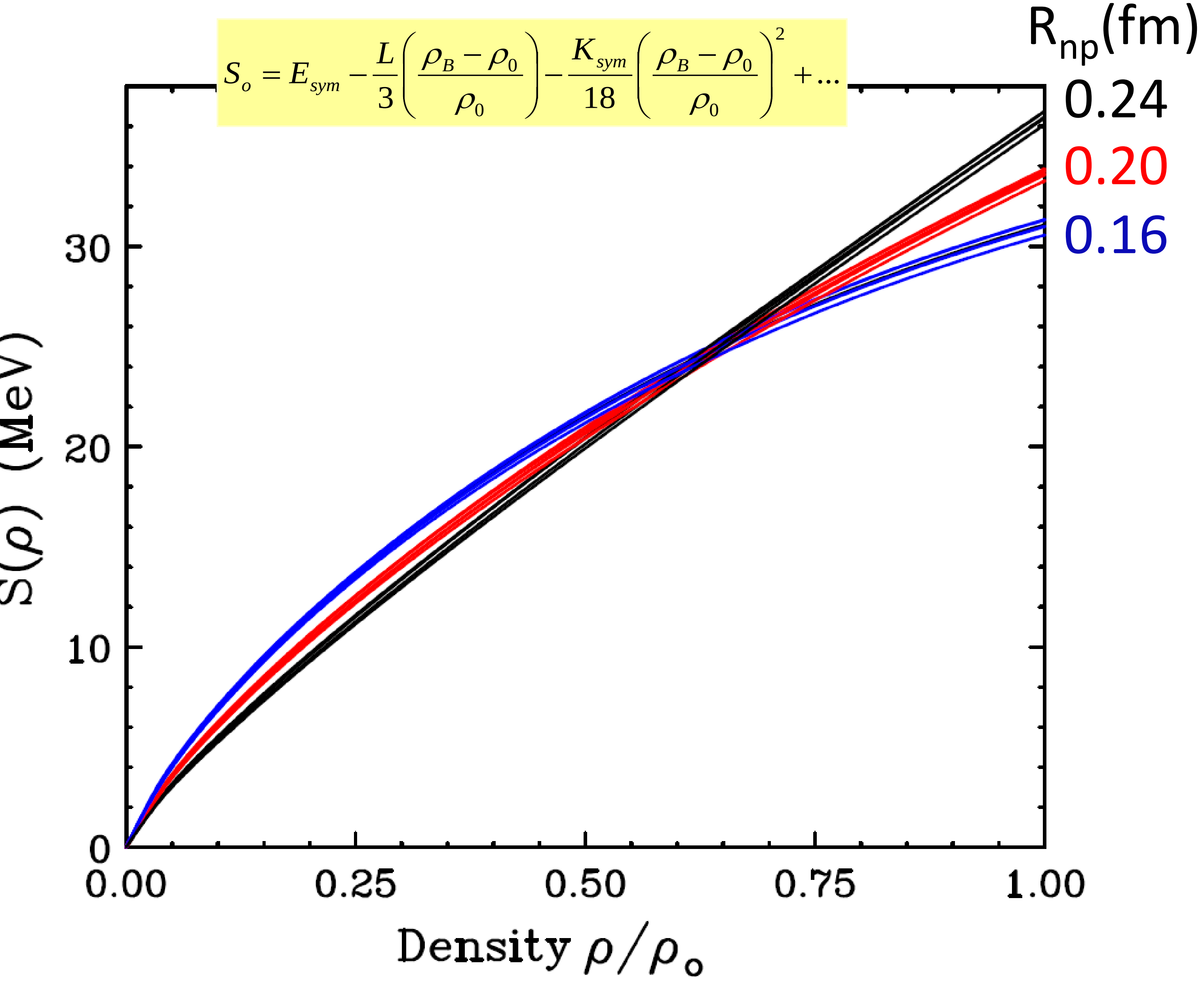
$$B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}}$$

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

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

Inclusion of surface terms in symmetry

Hubble ST



Alex Brown

PRL 111, 232502 (2013)

Use Skyrme interactions that fit the masses of double magic nuclei

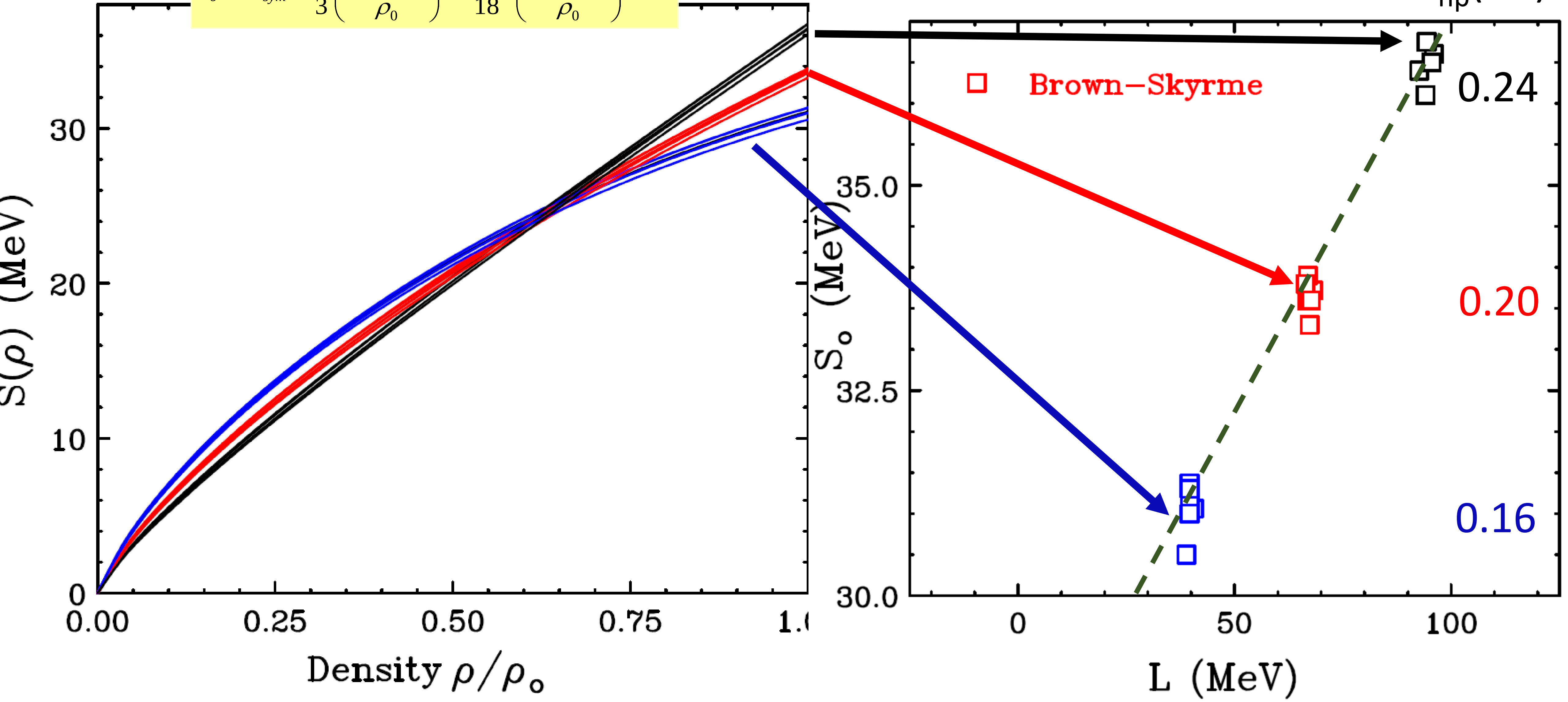
Masses and skin data are sensitive to $\rho \sim 0.65\rho_0$

$E_{sym}(\rho \sim 0.65\rho_0) \sim 25$ MeV

Masses and skin data are sensitive to ρ~0.65ρ$_0$

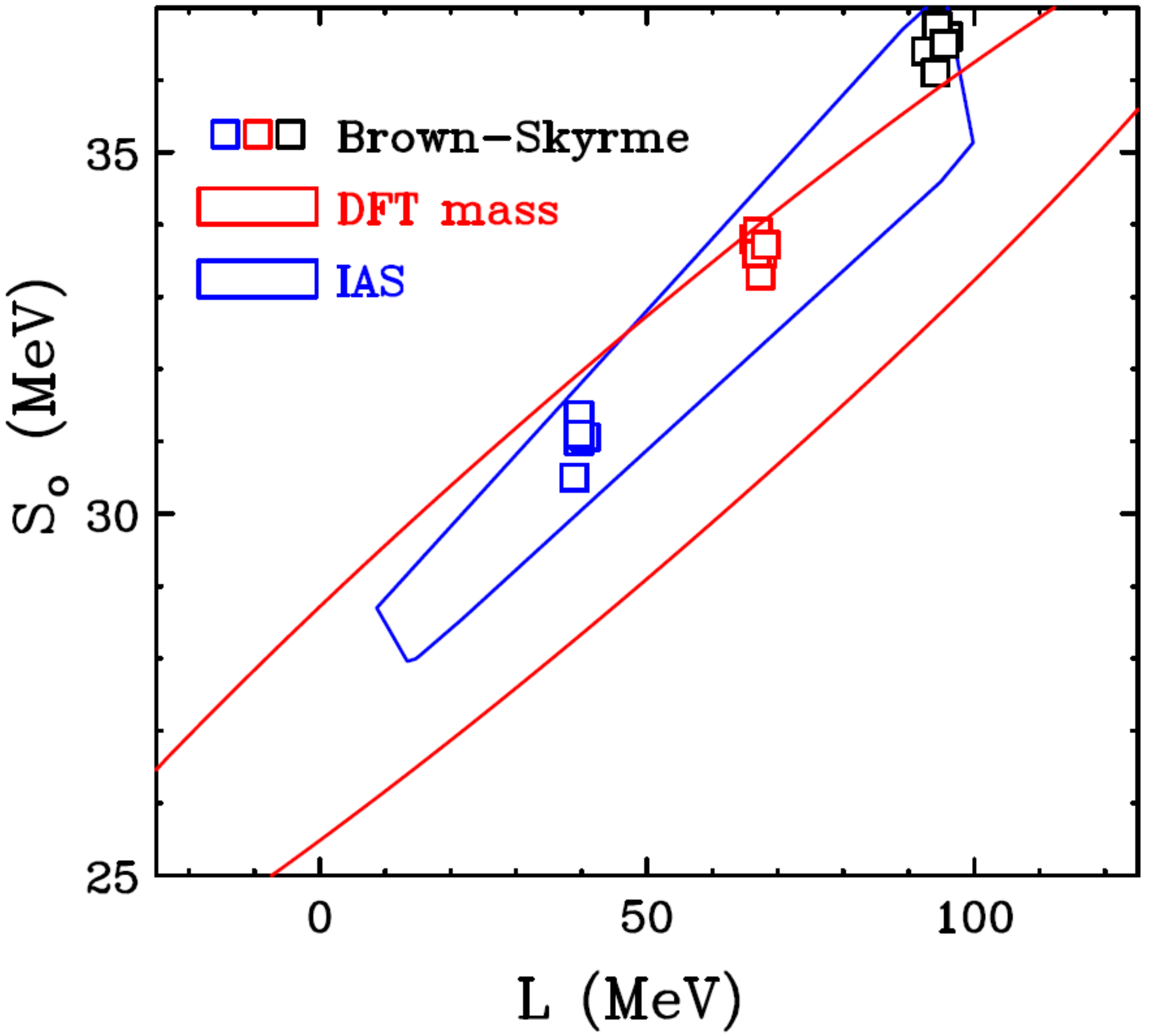
Same slope gives you sensitive density region of the observable

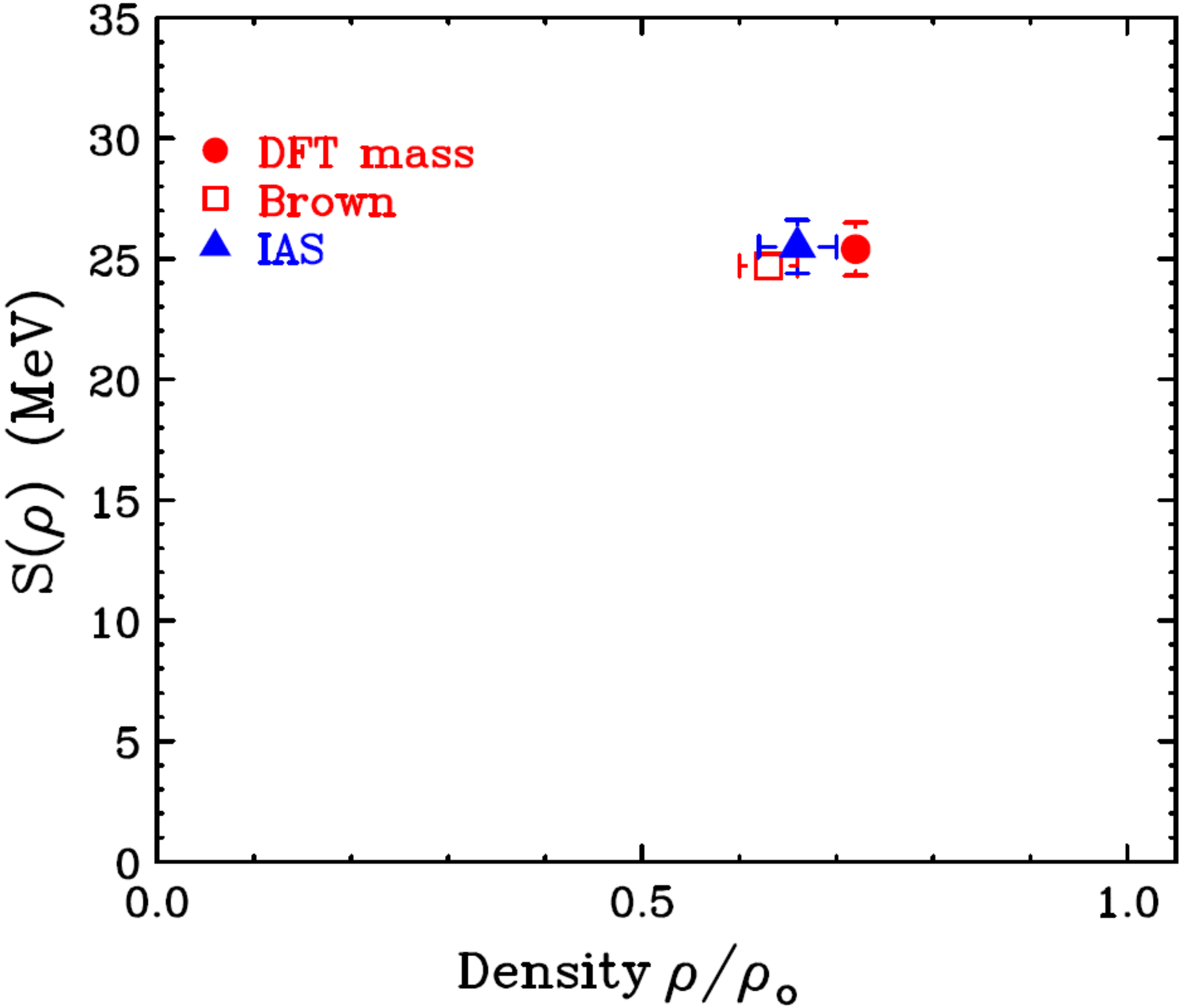
$$S_o = E_{sym} - \frac{L}{3}\left(\frac{\rho_B-\rho_0}{\rho_0}\right) - \frac{K_{sym}}{18}\left(\frac{\rho_B-\rho_0}{\rho_0}\right)^2 + \ldots$$



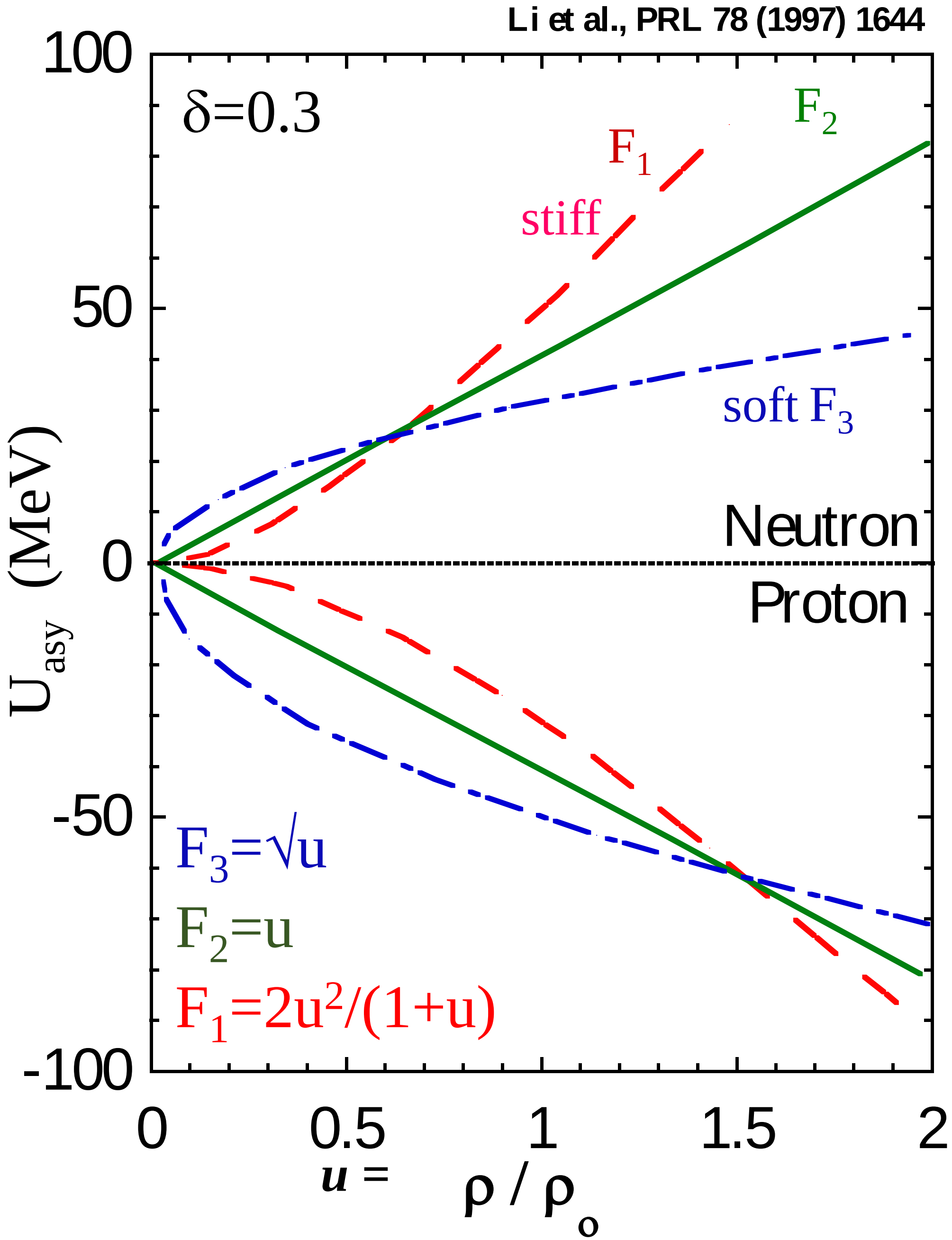
Symmetry Energy Constraints from masses

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



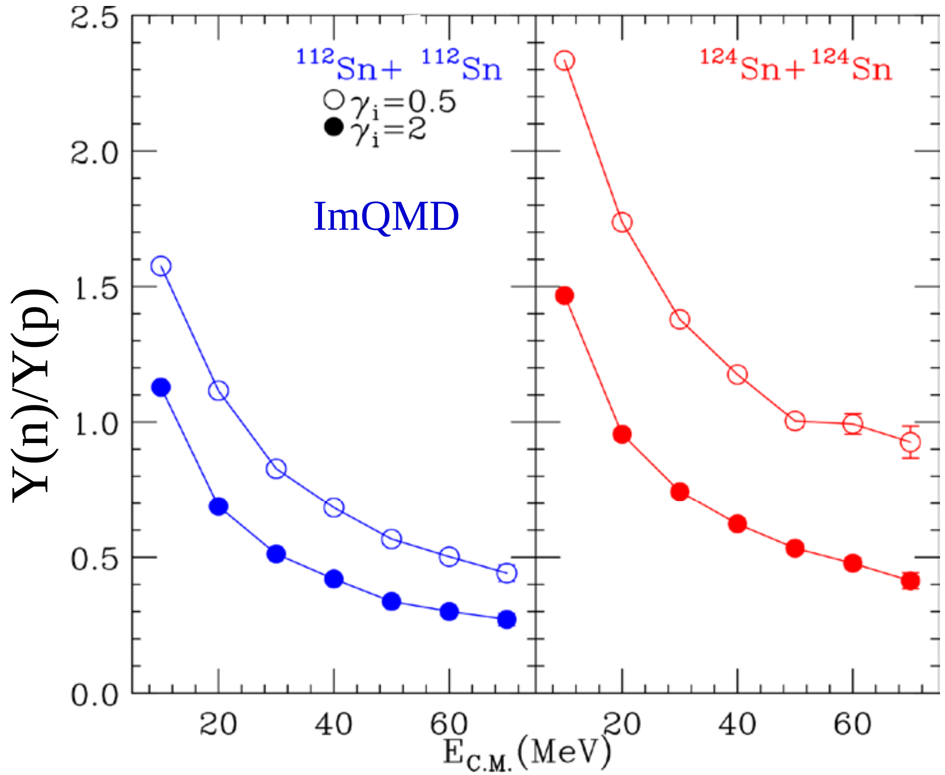


Experimental Observables: n/p yield ratios



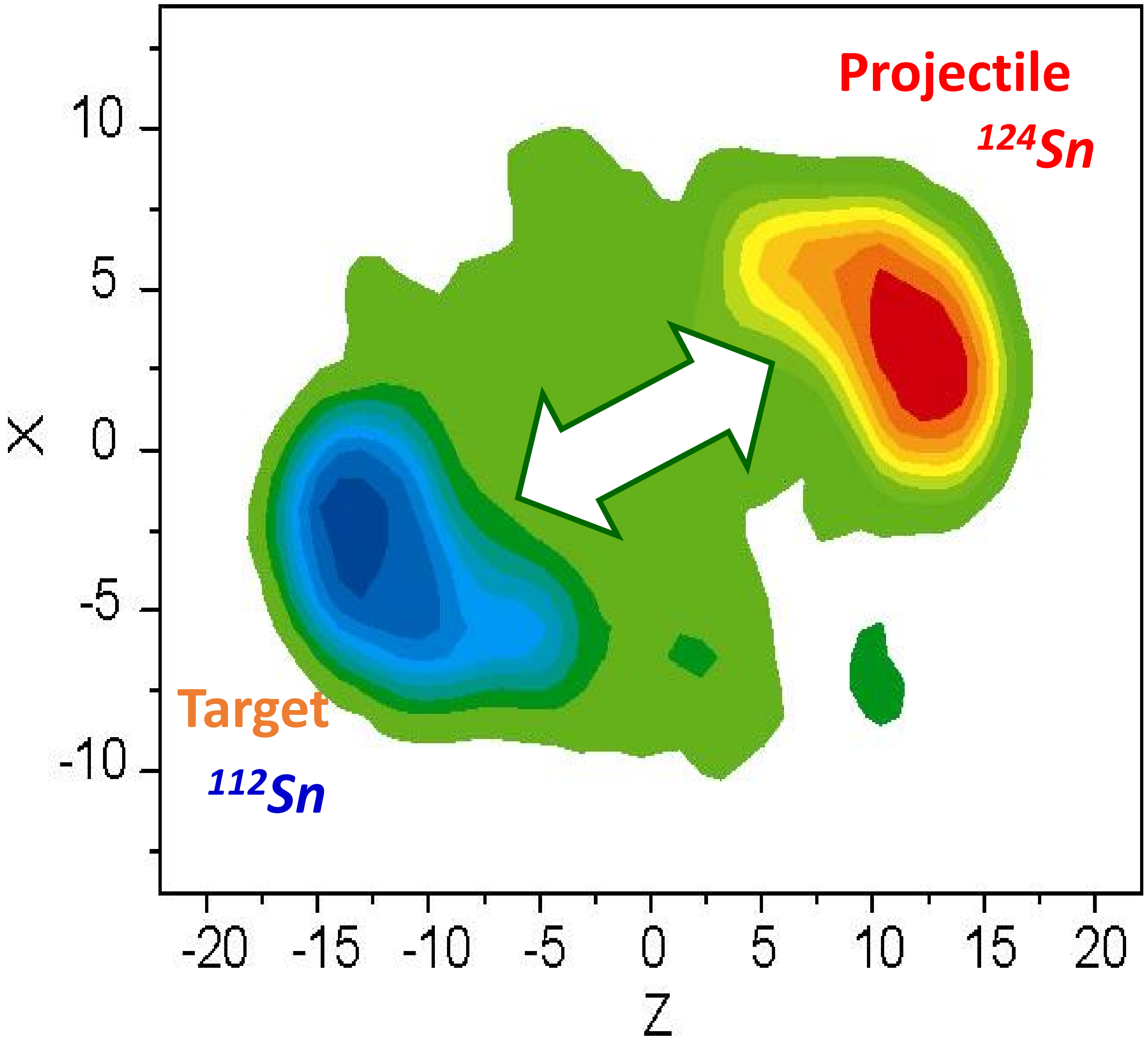
- *n and p potentials have opposite sign.*
- *n & p energy spectra depend on the symmetry energy → softer density dependence emits more neutrons at low density.*

$S(\rho)=12.5(\rho/\rho_o)^{2/3}+17.6(\rho/\rho_o)^{\gamma_i}$

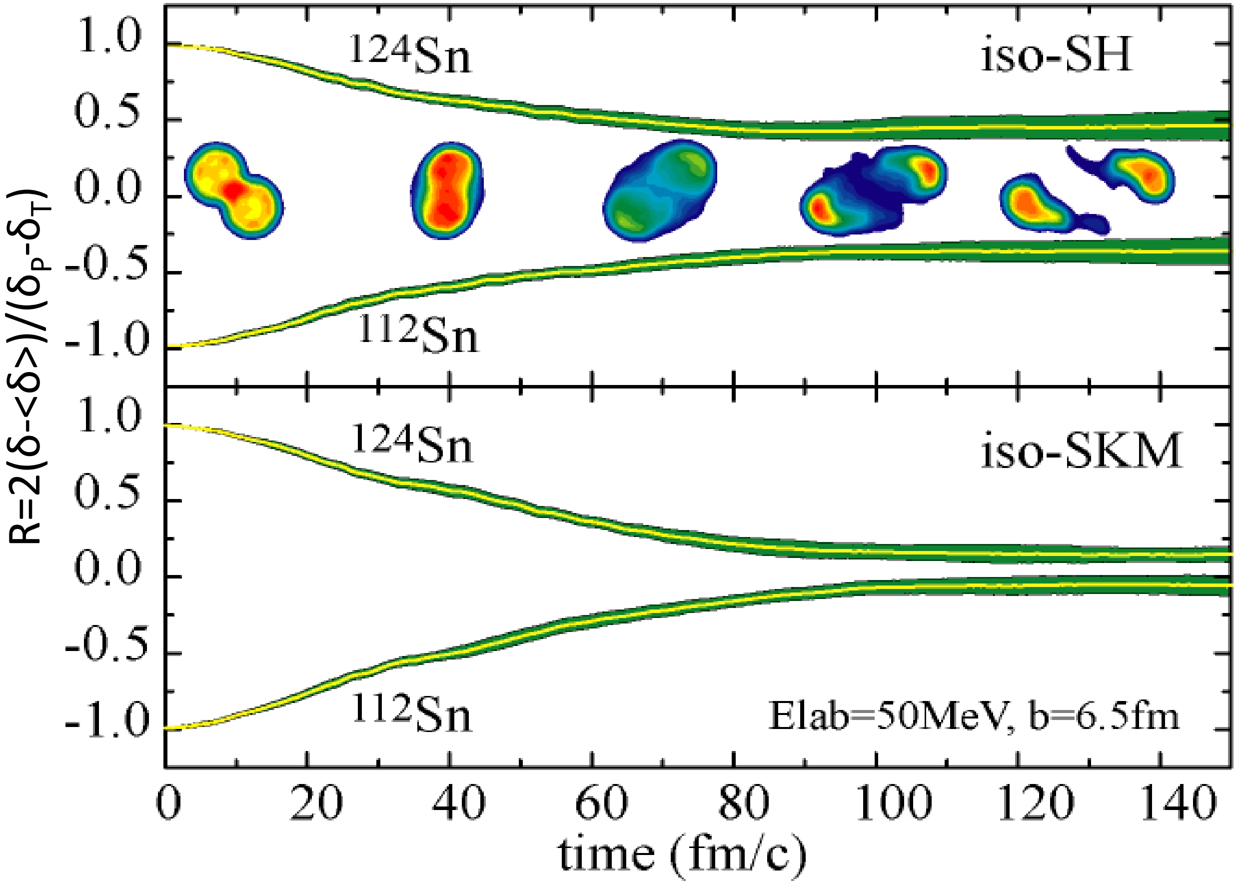


- *More n's are emitted from the n-rich system and softer iso-EOS.*

Isospin Diffusion to constrain low density EoS



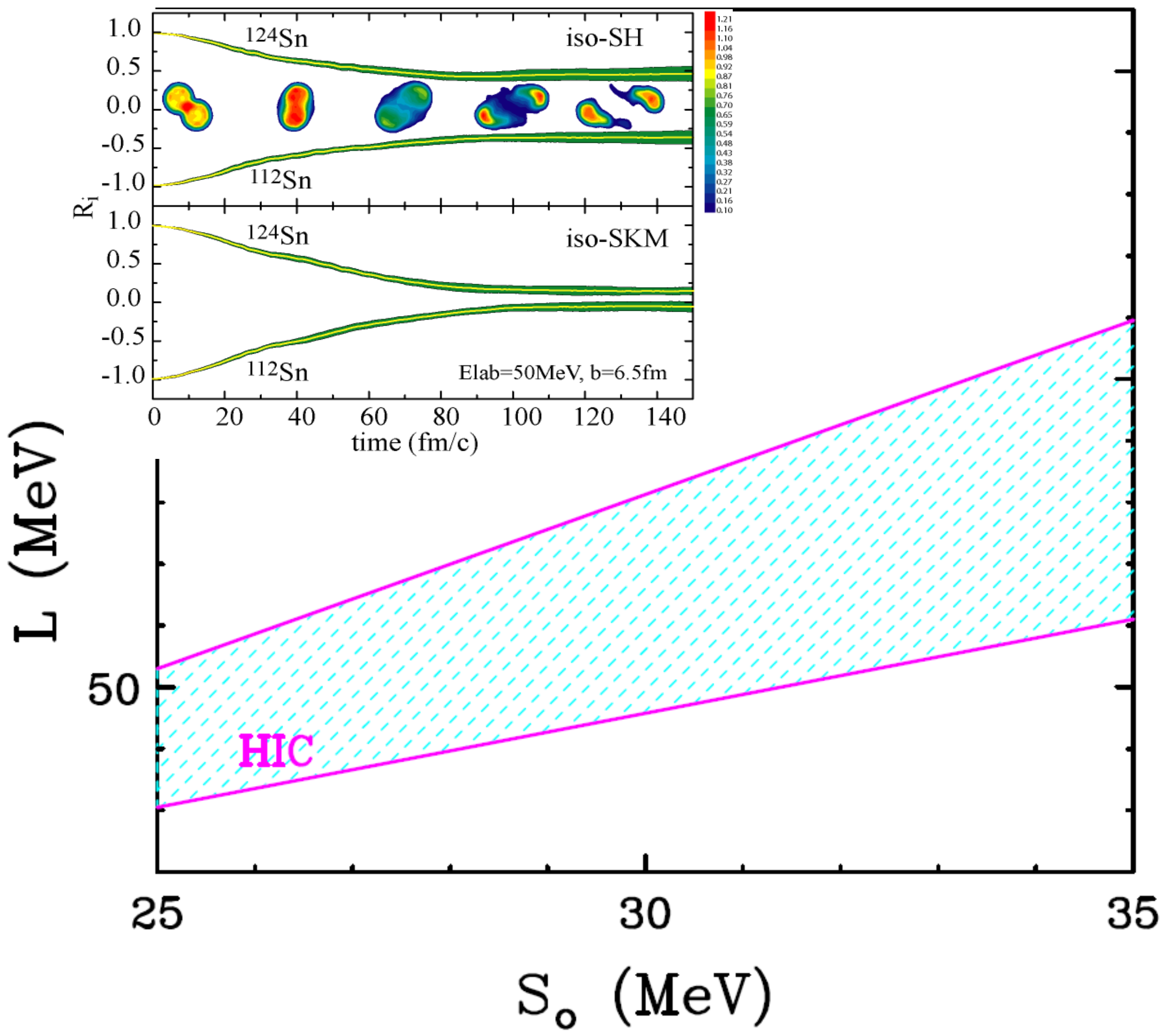
Isospin Diffusion; low ρ, E_{beam}



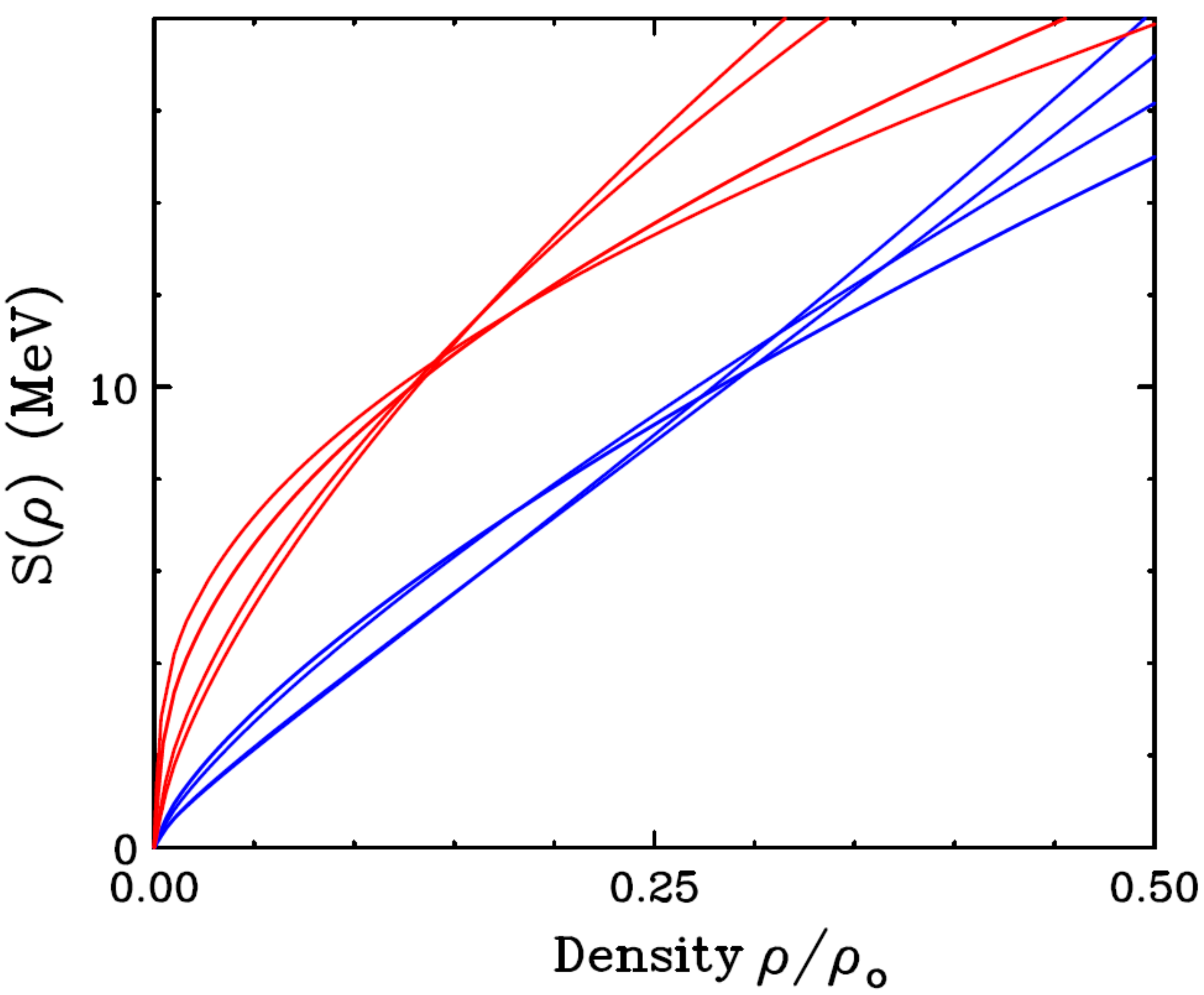
Tsang et al., PRL 92 (2004) 062701

Density dependence of Symmetry Energy at subsaturation density

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

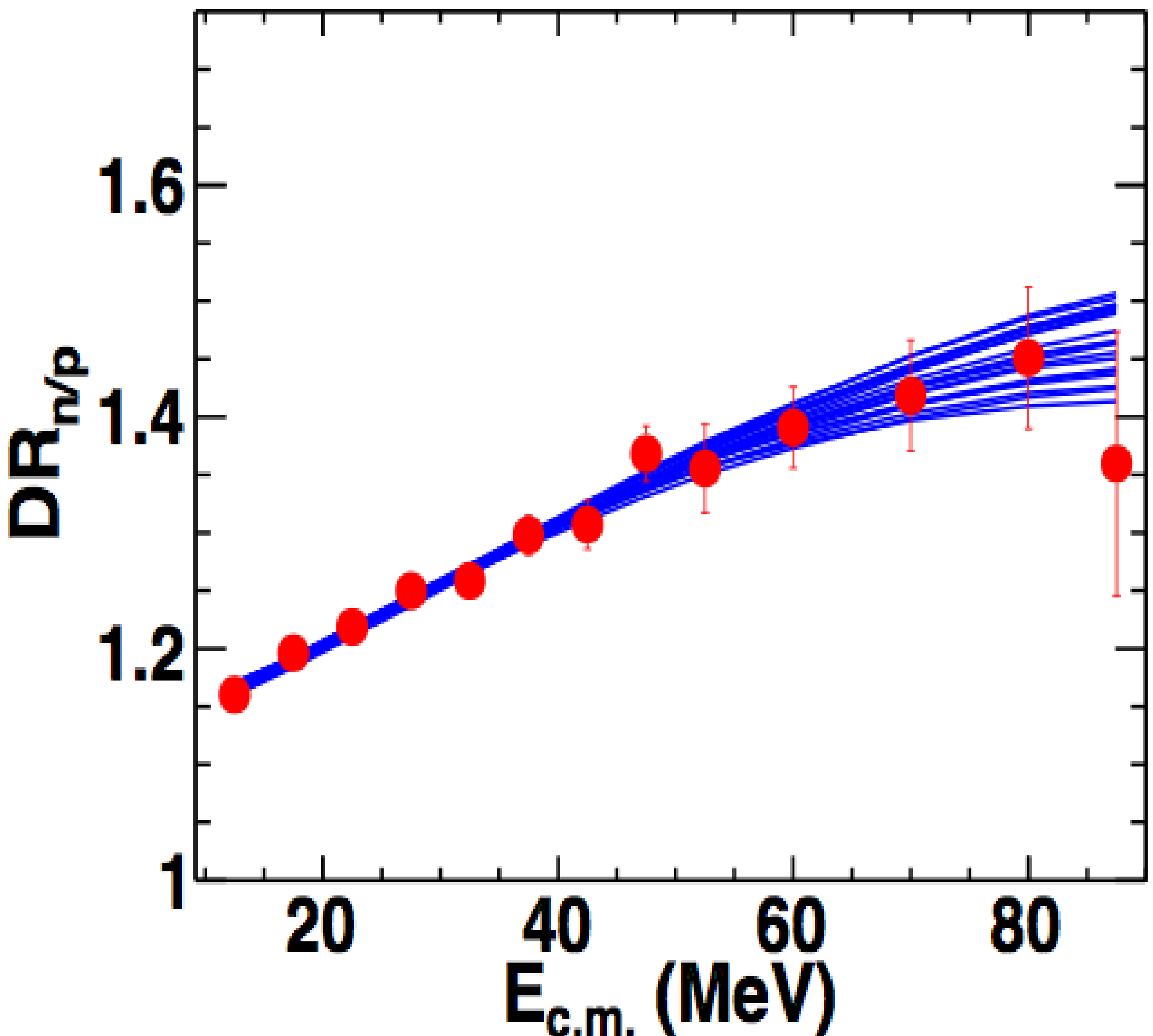


Isospin Diffusion

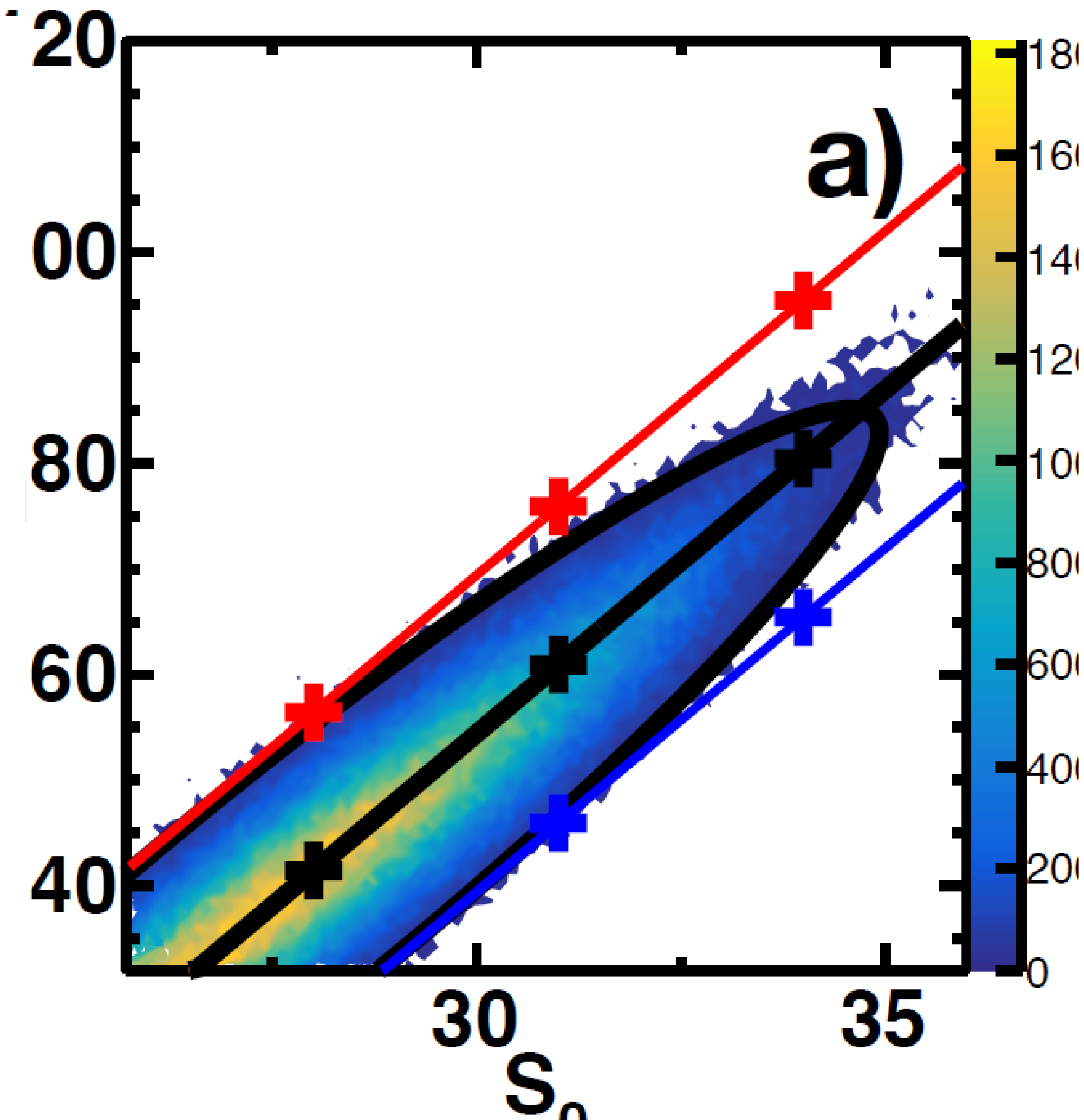


Density dependence of Symmetry Energy at subsaturation density

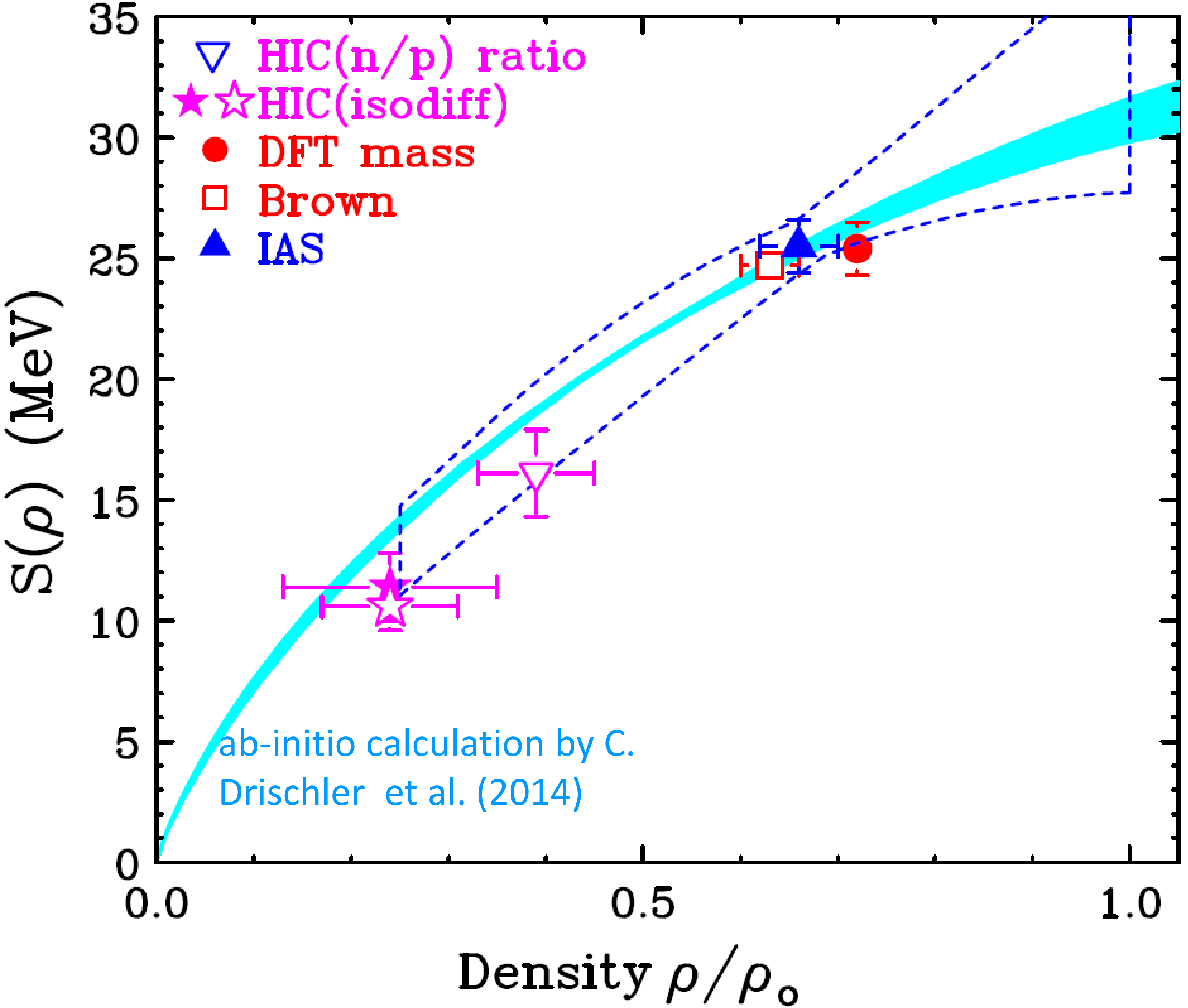
$$DR_{n/p} = \frac{R_{n/p}\left({}^{124}Sn + {}^{124}Sn\right)}{R_{n/p}\left({}^{112}Sn + {}^{112}Sn\right)}$$

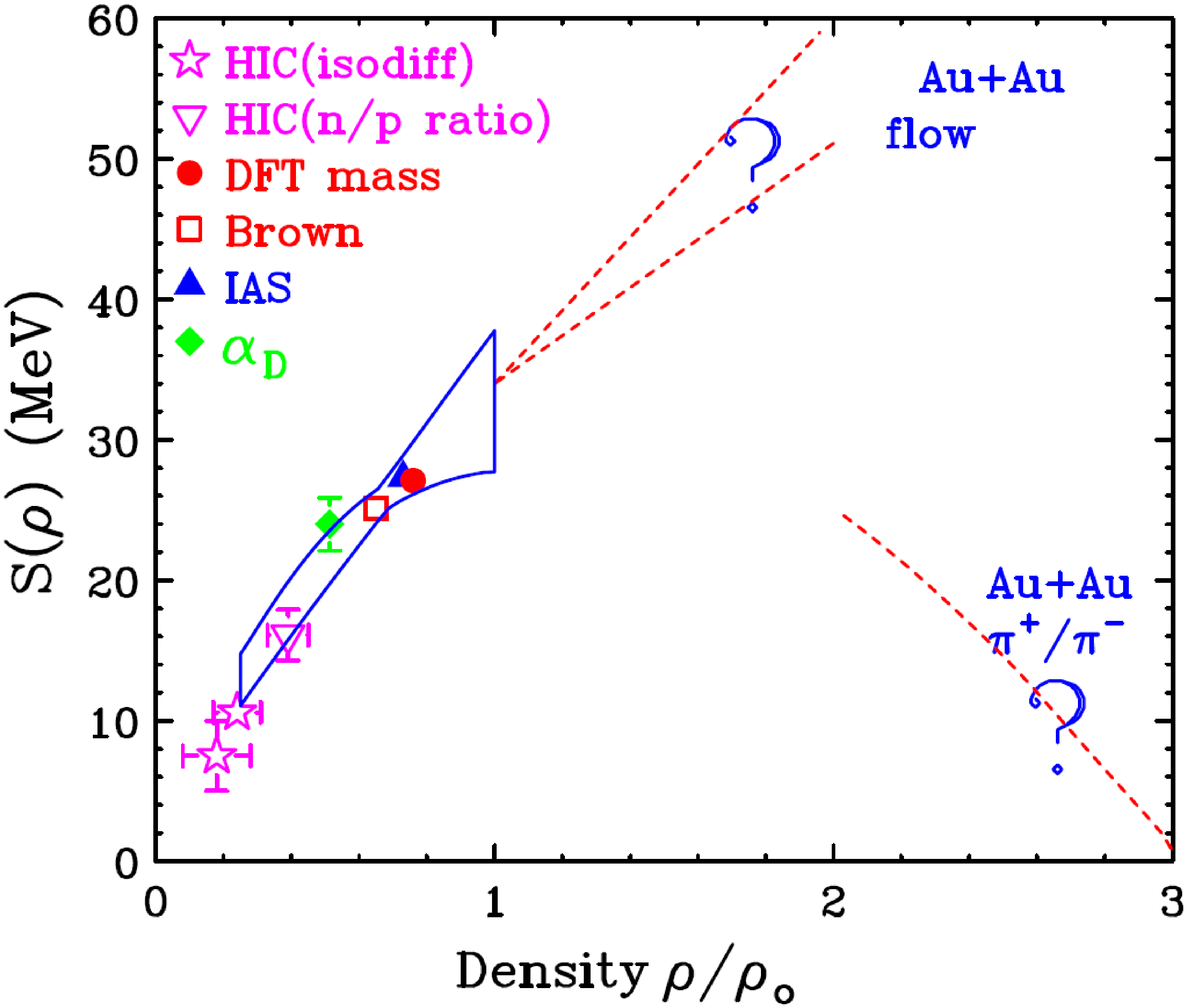


Bayesian analysis

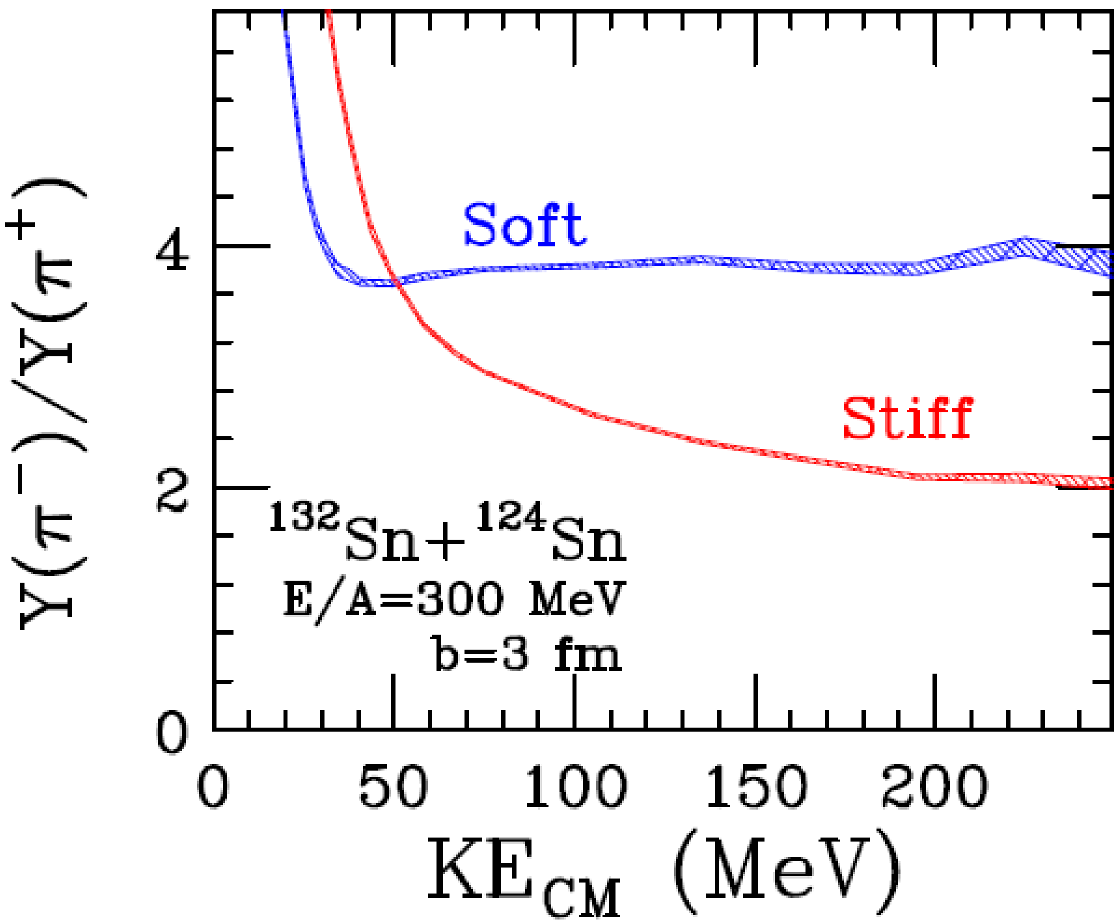


Current Status: Density dependence of Symmetry Energy @ $\rho < \rho_0$

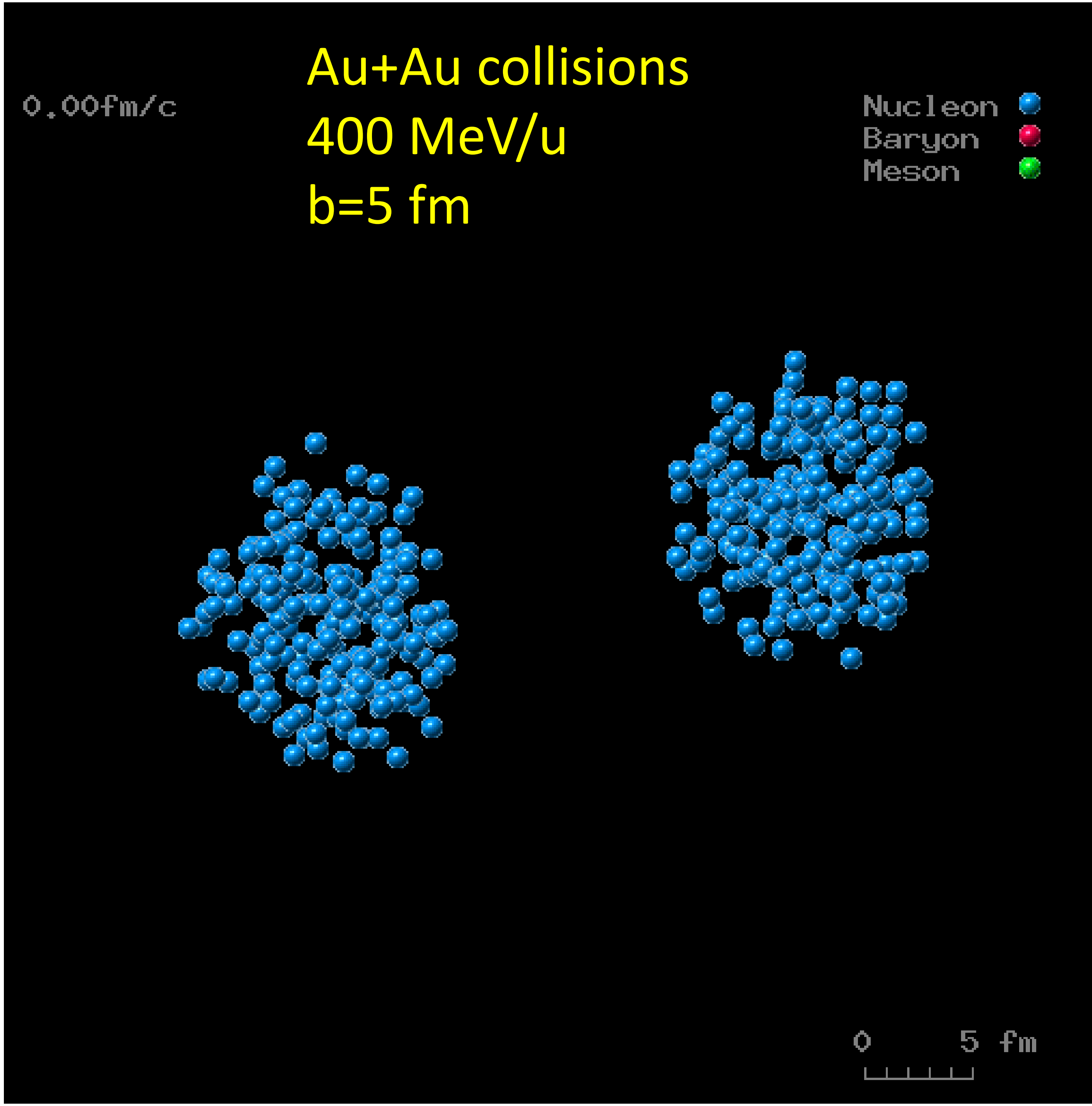




Large uncertainties above ρ_0. Need high energy heavy ion collisions to access this regions, especially $\rho \sim 2\rho_0$ where neutron star radius is sensitive to.



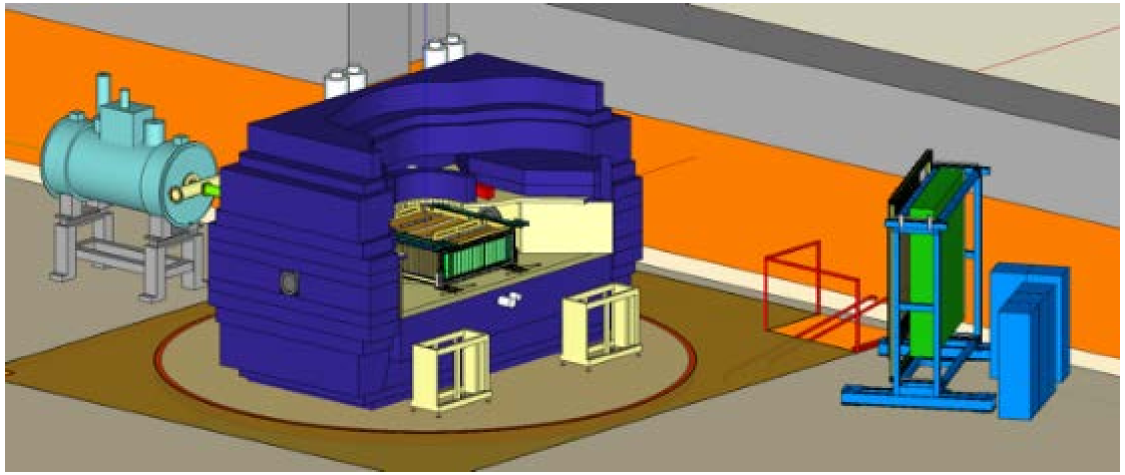
Y(π⁻)/Y(π⁺)
KE_CM (MeV)
Soft
Stiff
132Sn+124Sn
E/A=300 MeV
b=3 fm
0
2
4
0
50
100
150
200



Au+Au collisions
400 MeV/u
b=5 fm
0.00fm/c
Nucleon
Baryon
Meson
0
5 fm

Experimental Setup

Primary	Beam	Target	E_{beam}/A	δ_{sys}	evt(M)	2016
^{124}Xe	^{108}Sn	^{112}Sn	269	0.09	8	4/30-5/4
	^{112}Sn	^{124}Sn	270	0.15	5	5/4-5/6
^{238}U	^{132}Sn	^{124}Sn	269	0.22	9	5/25-5/29
	^{124}Sn	^{112}Sn	270	0.15	5	5/30-6/1
Z=1,2,3			100, 200		0.6	6/1



Other Participants: H. Baba, Chica, Ichihara, Kondo, T. Nakamura, H. Otsu, Saito, Togano

NeuLAND Collaboration: Leyla Atar, Tom Aumann, Igor Gasparic, A. Horvat, H. Scheit

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T. Isobe (RIKEN)*
G. Jhang (Korea U)
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P. Lasko (IFN, Krakow)
H. Lee (RISP)
J. Lee (Korea U)
J. Lukasik (IFN, Krakow)
W. Lynch (MSU)*
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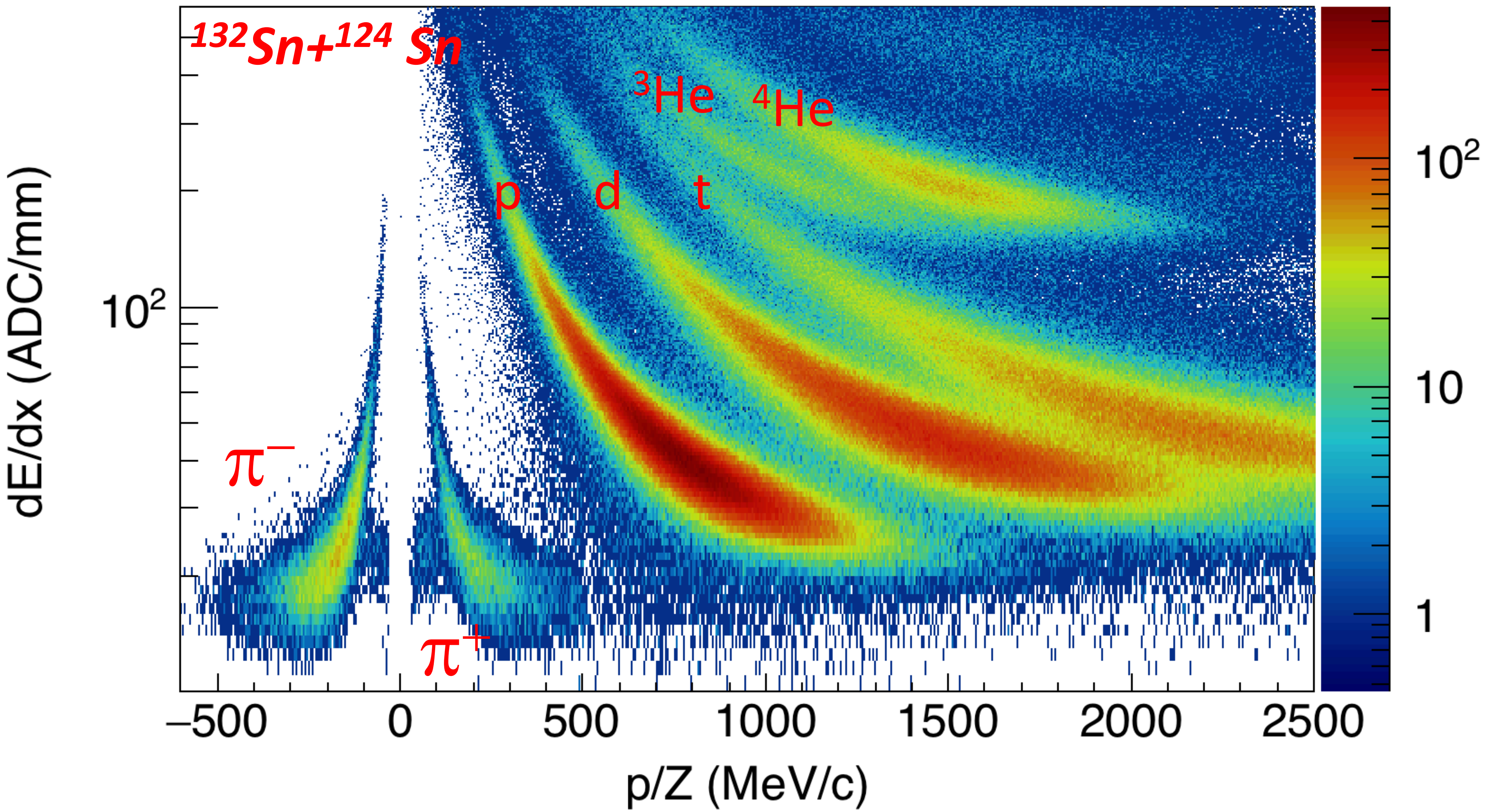
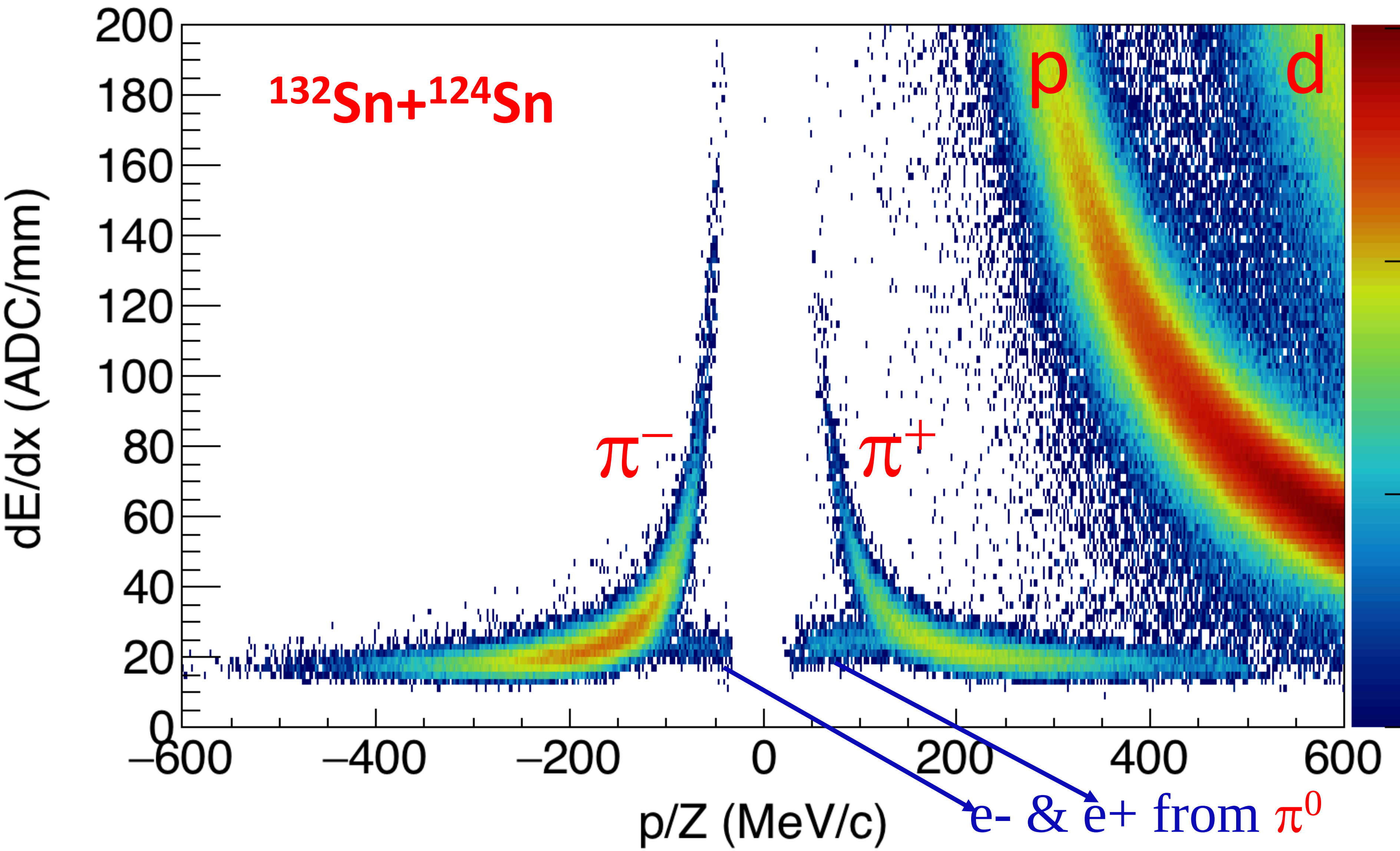
T. Murakami (Kyoto U)*
S. Nishimura (RIKEN)
P. Pawlowski (IFN, Krakow)
C. Santamaria (MSU)
R. Shane (MSU)
D. Suzuki (RIKEN)
B. Tsang (MSU)*
Y. Zhang (Tsinghua U)
*spokespersons

Particle ID spectra



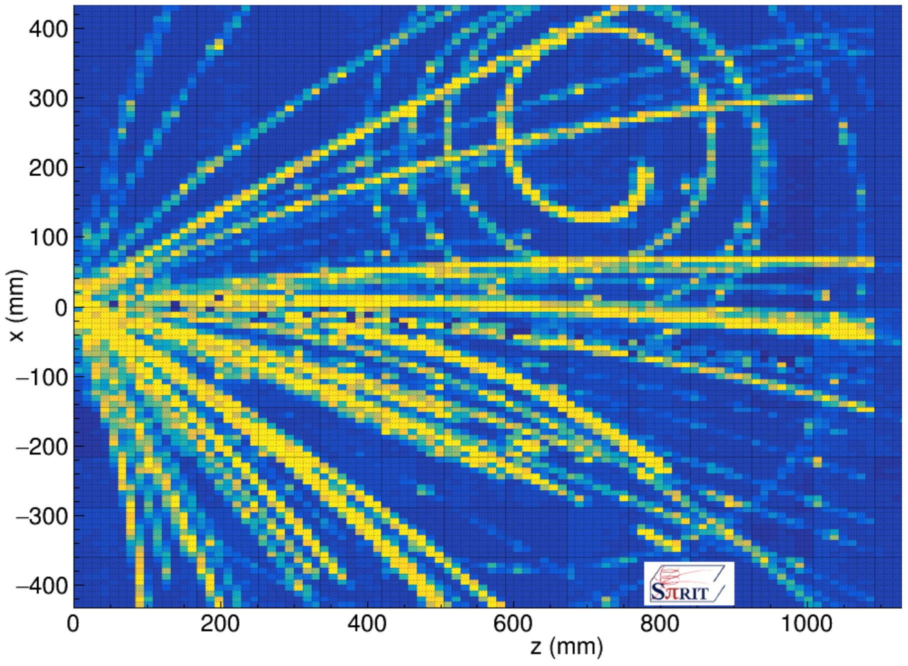
Need more analysis and understanding especially on detector and analysis efficiencies

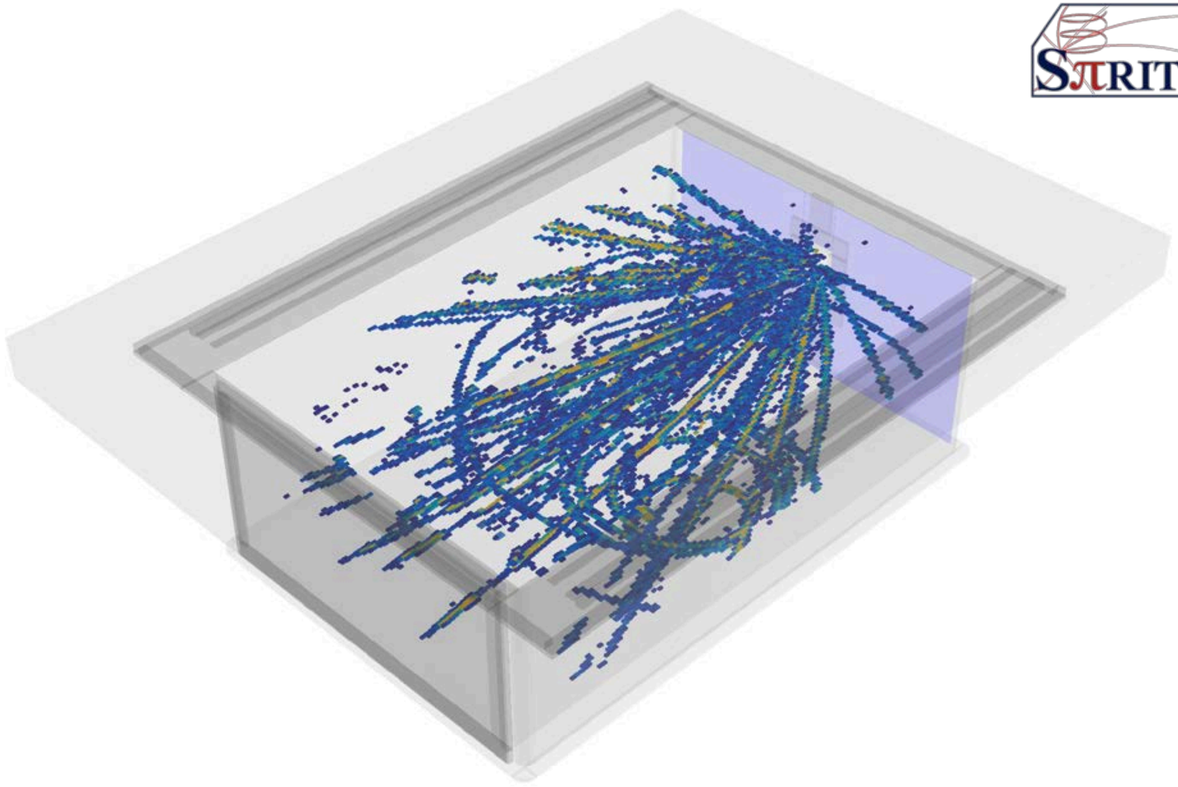
Symmetry energy is not an observable.
We have to use transport models to simulate the reactions and compare to data.
Mean field (symmetry energy) plus others parameters are input to the transport models.
Need to have different transport models under control?



Heavy Ion Collisions

TPC





1. Experimental Data -- > Detectors to measure species, momentum and angular distributions of emitted fragments
2. Simulate HIC with Transport models which allow the study of input parameters and ingradient of models: Nuclear Equation of state; In medium masses and cross sections; N/Z dependence of the asymmetry energy; Fragment and isotopic yields
3. Comparison of results to data

Transport Code Evaluation Project

Writing group

B. Tsang, H. Wolter, Y.X. Zhang[2], J. Xu[1], M. Colonna, P. Danielewicz, A Ono, Y.J. Wang

BUU Type	Code	flow pub	casc pub (Box)	Vlas (Box)	pion (Box)
BUU-VM[a]	S. Mallik		X	X	X
BLOB	P. Napolitani	X			
GIBUU-RMF	J. Weil	X	X		
GIBUU-Sky	J. Weil	X			
IBL	W.J. Xie	X			
IBUU	J. Xu	X	X	X	X
pBUU	Danielewicz	X	X	X	X
RBUU	K. Kim	X			
RVUU	C.M. Ko	X	X	X	X
SMASH	Oliinychenko		X		
SMF	M. Colonna	X	X	X	X

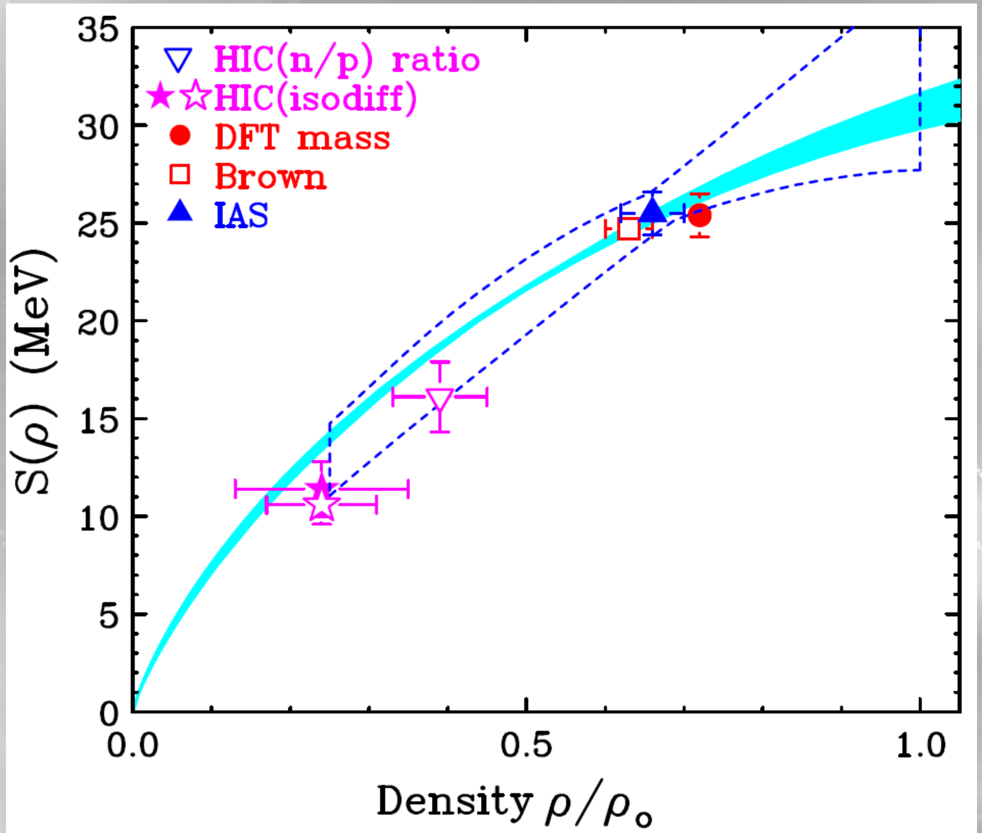
QMD Type	Code	flow pub	casc pub (Box)	Vlas (Box)	pion (Box)
ImQMD	Y.X. Zhang	X	X	X	
IQMD-BNU	J. Su	X	X	X	
IQMD	C. Hartnack	X			
IQMD-IMP	Z.Q. Feng	X	X	X	X
IQMD-SINAP	G.Q. Zhang	X			
JAM	A. Ono		X	X	X
JQMD	T. Ogawa		X	X	X
TuQMD	D. Cozma	X	X	X	X
UrQMD	Y.J. Wang	X	X	X	X

Pub: Xu et al., PRC.93.044609

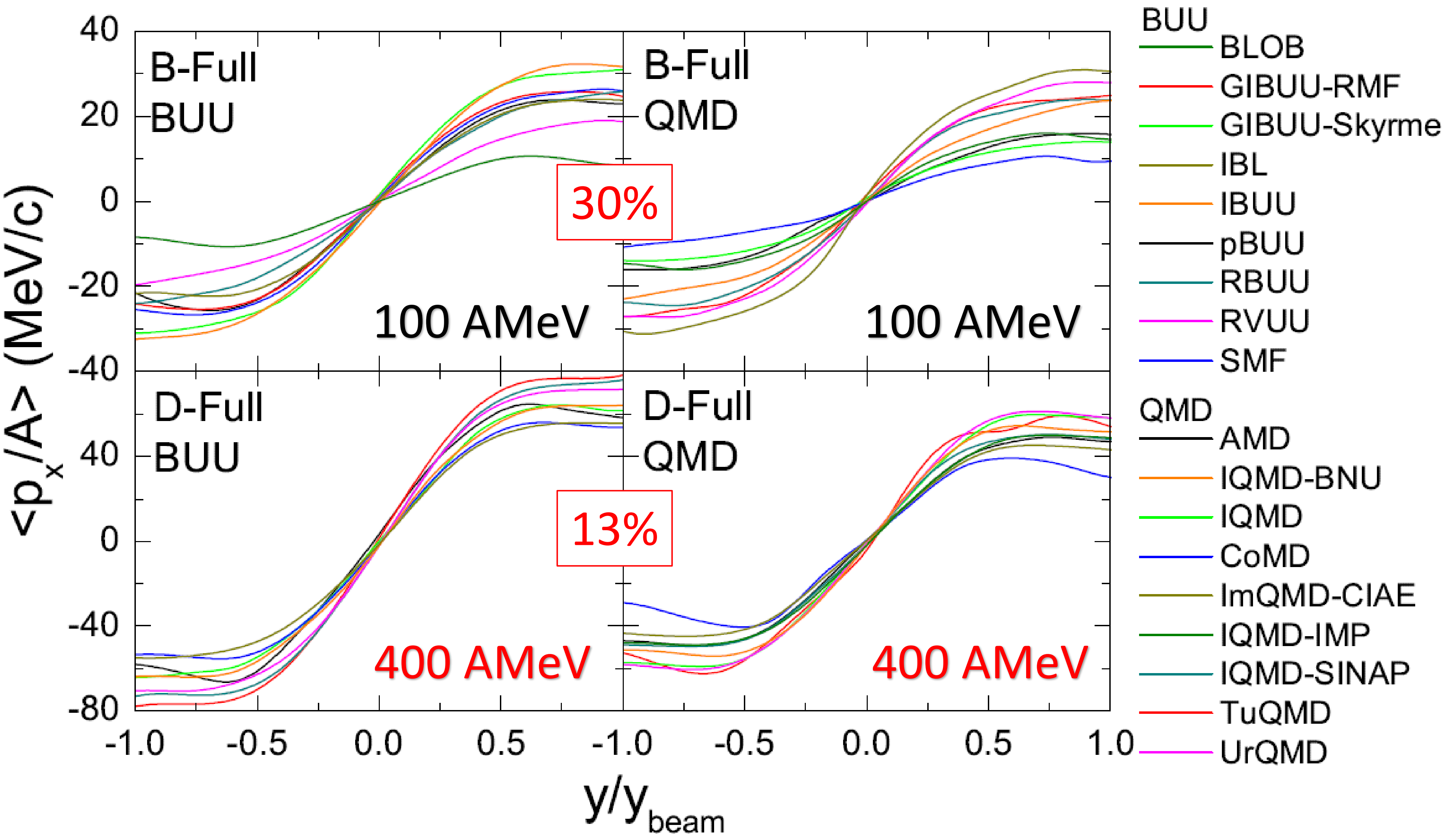
Pub : Zhang et al., arXiv:1711.05950

Summary and Outlook

- Laboratory measurements have provided constraints on the symmetry energy and the equation of state for neutron-rich matter.
  - Significant constraints at sub-saturation densities.
  - Constraints on effective mass splitting around and above saturation densities.
- The important density range of $\rho_0 \leq \rho \leq 2\rho_0$ is accessible via heavy ion reaction.
  - Experimental results from SpiRIT!
- Improving the reliability of transport theory predictions.
  - Code evaluation project is making significant progress in this direction.
- What do we learn about EoS from neutron star merger observations?

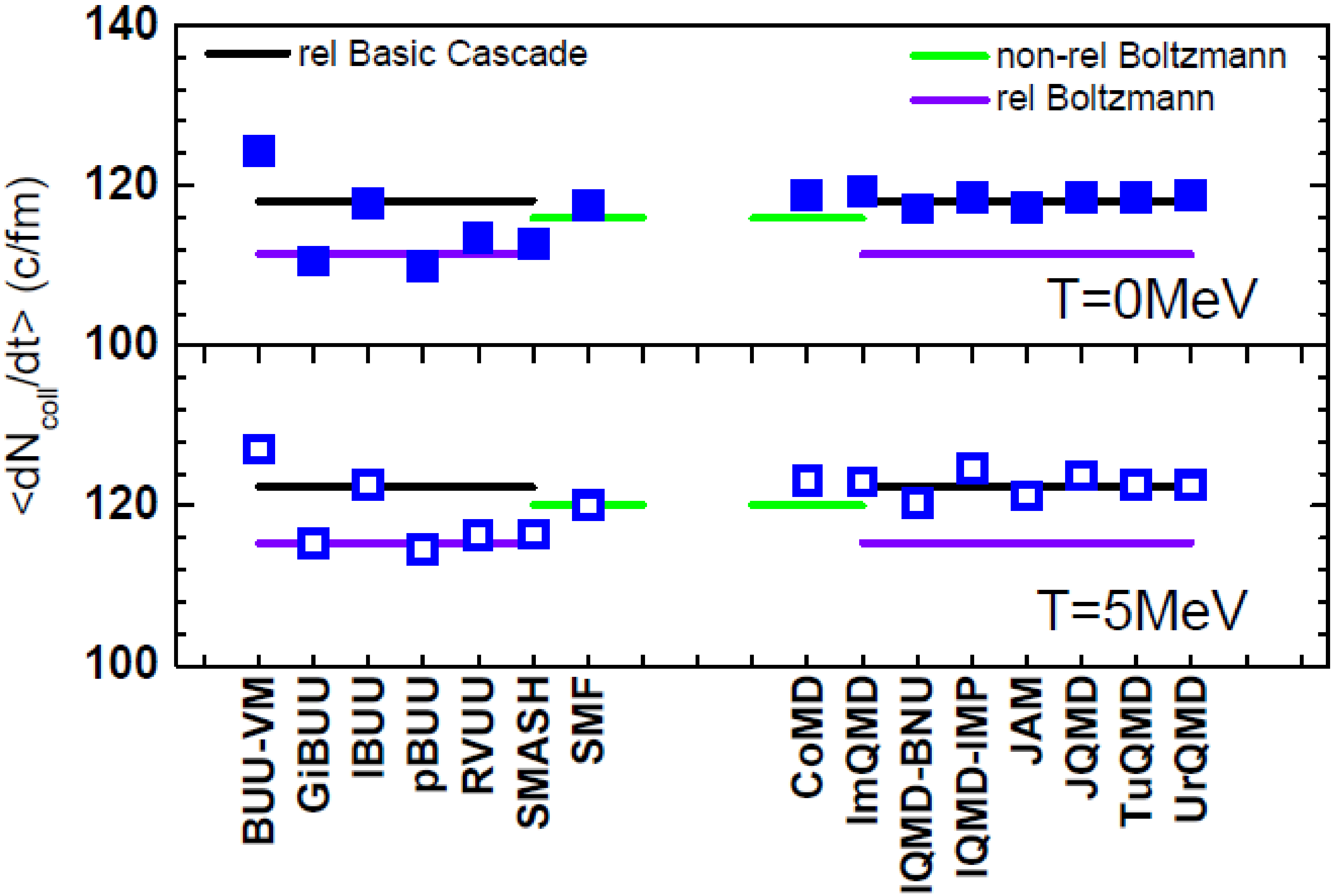


Code Evaluation Project I, PhysRevC.93.044609



Code Evaluation Project II -- Box Simulations on Collisions w/wo Pauli Blocking

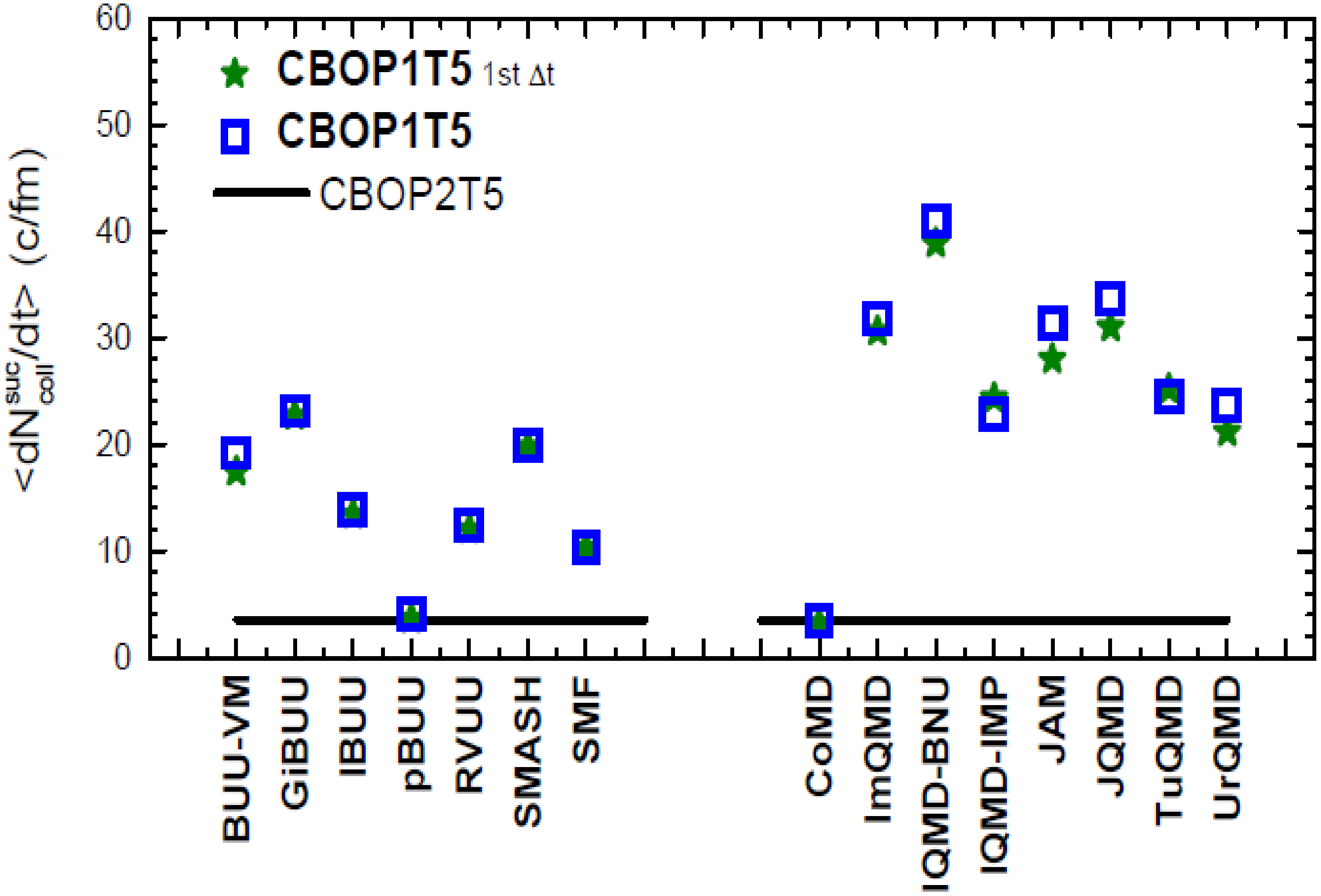
Comparison to Analytical limits : **Zhang et al., arXiv:1711.05950**



Without Pauli Blocking
Collisions well controlled.

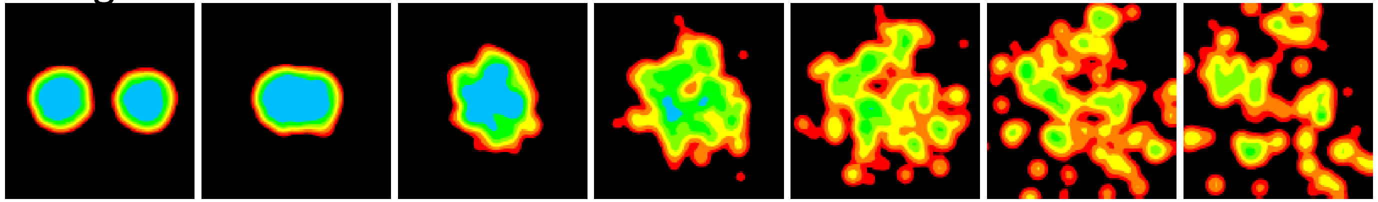
Code Evaluation Project II -- Box Simulations on Collisions w/wo Pauli Blocking

Comparison to Analytical limits : **Zhang et al., arXiv:1711.05950**



With Pauli Blocking: Results are different from analytical limits unless special procedures are employed.

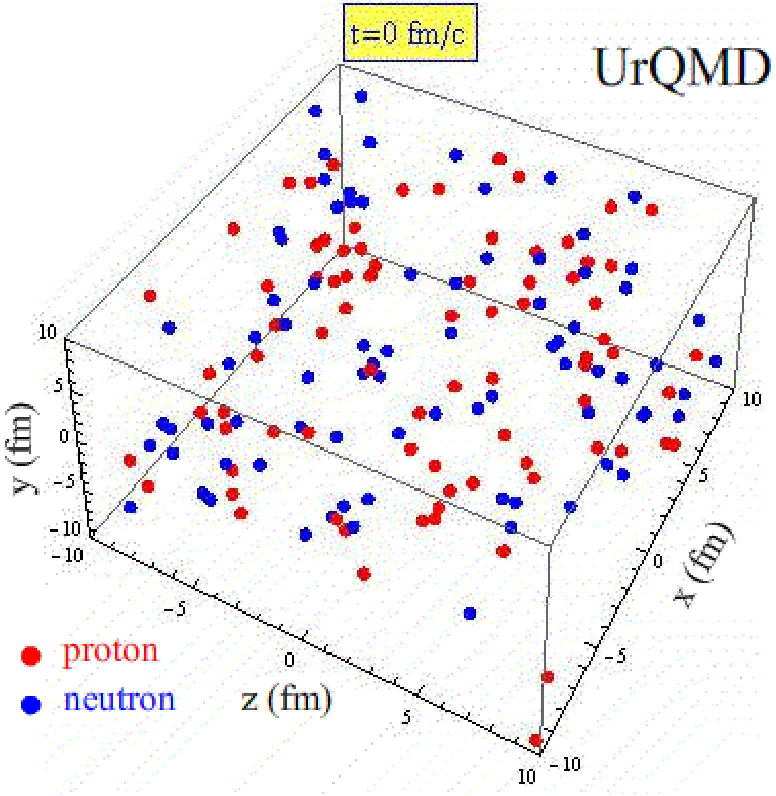
Images from A. Ono

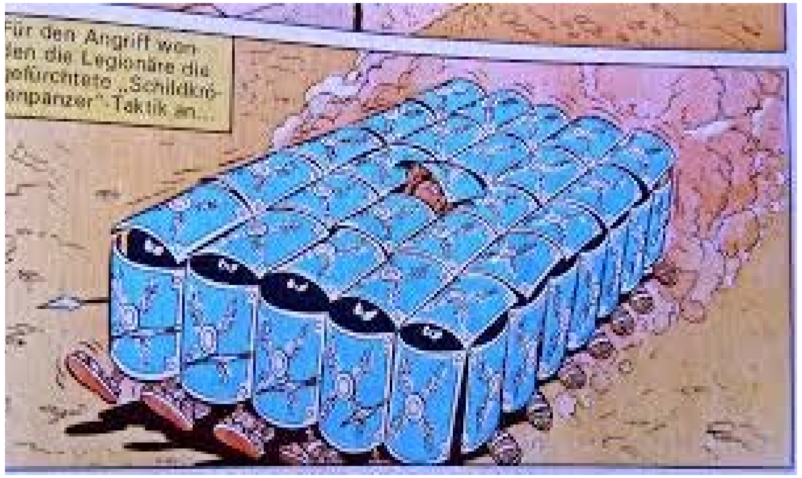


Femto-nova explosion created by Heavy Ion collisions

Reaction Dynamics

Images from H. Wolter





Mean Field :

low density: attractive

high density: repulsive

NN collisions: repulsive

Pauli Blocking

Initialization

Isolate effects from mean field and nucleon-nucleon collisions