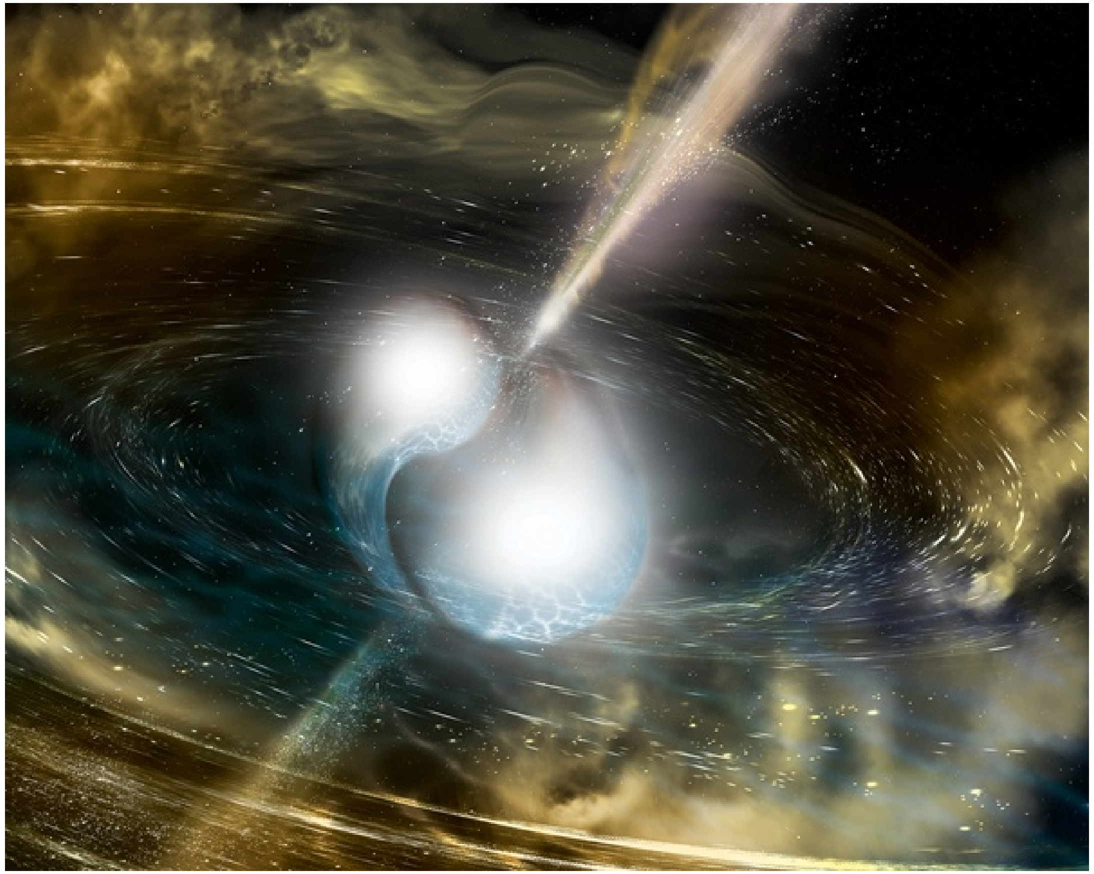
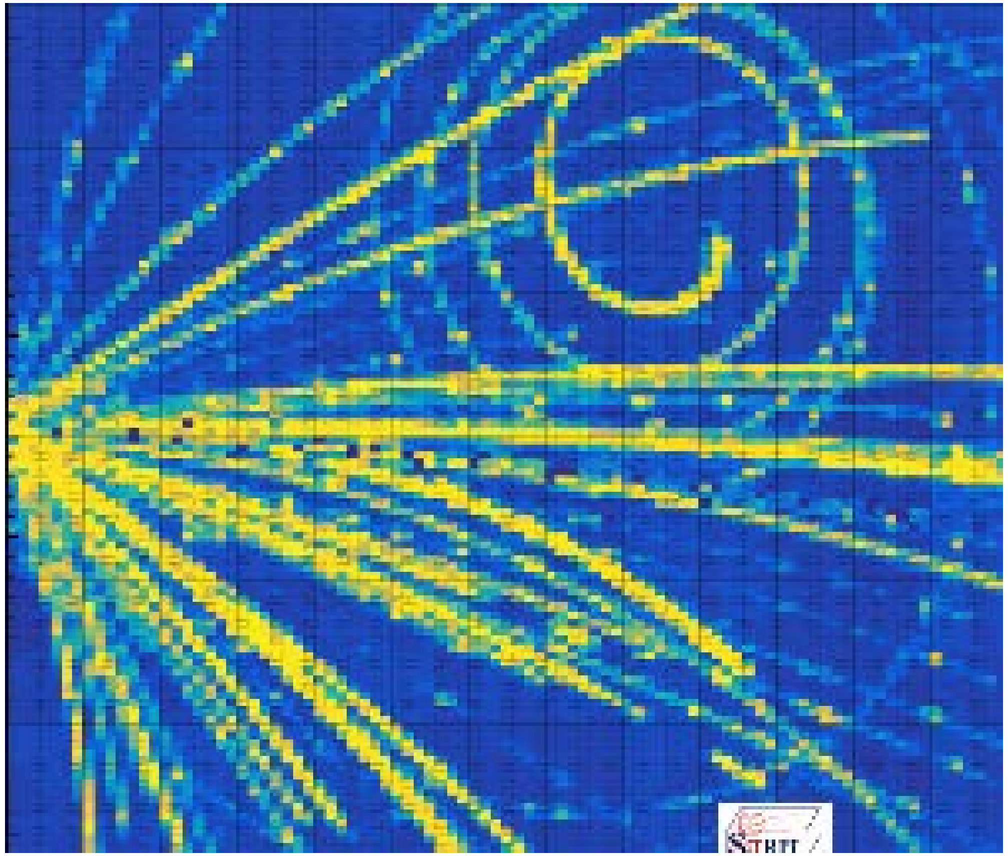
Laboratory Probes of the Neutron-Matter Equation of State

LIGO Detects a Neutron Star Merger



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

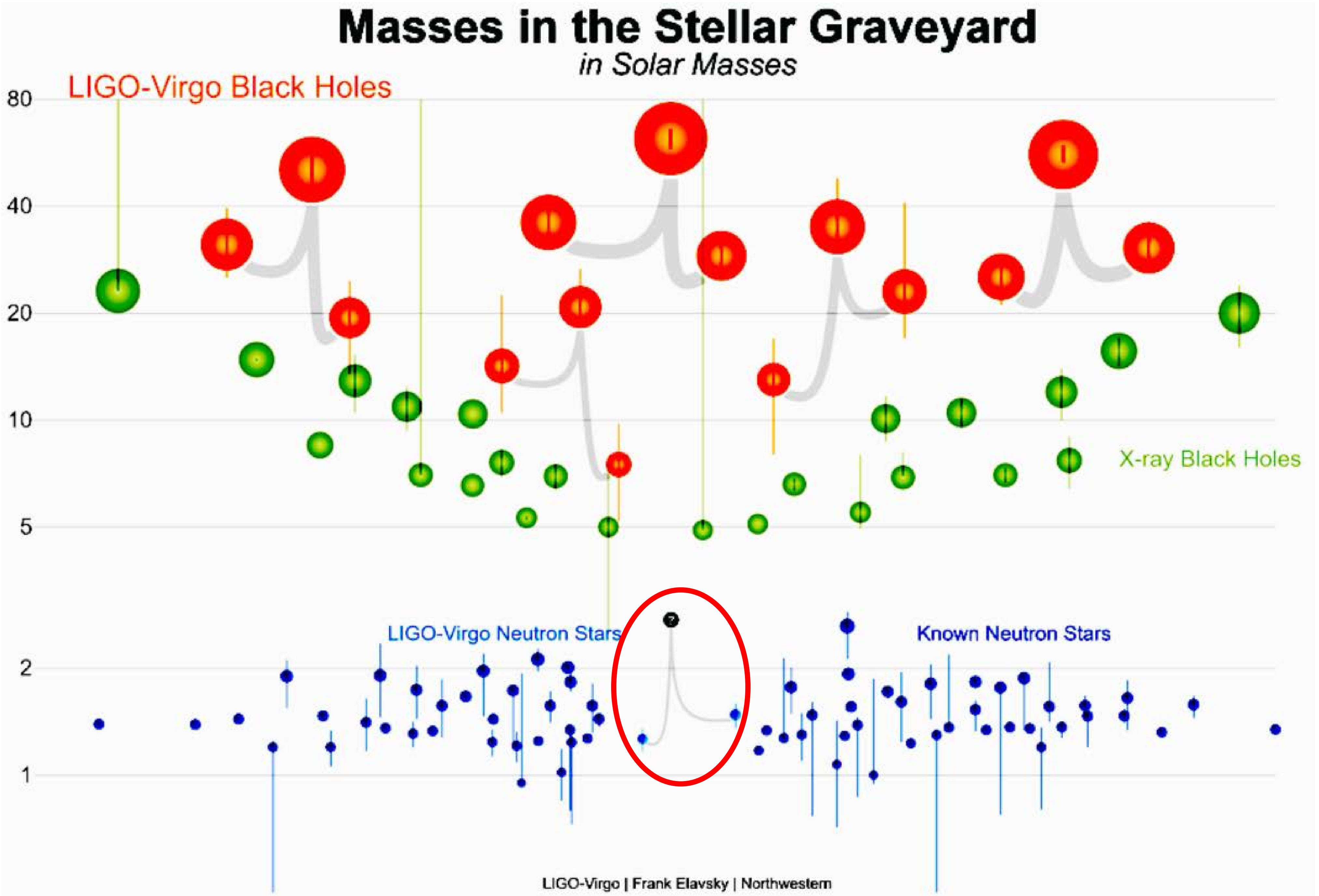


Betty Tsang, NSCL

Michigan State University

Tsinghua Symposium: 4/7-14/11

INT17



Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo | Frank Elavsky | Northwestern

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

Organizer:
Sanjay Reddy
Institute for Nuclear Theory
sareddy@uw.edu

Advisory Committee:
Charles Horowitz
Daniel Kasen
James Lattimer
Gabriel Martinez-Pinedo
Brian Metzger
David Radice
Jocelyn Read
Luke Roberts
Bangalore Sathyaprakash
Hendrik Schatz
Masaru Shibata
Rebecca Surman

Program Coordinator:
Kimberlee Choe
jy24@uw.edu
(206) 685-3509

Application form

Workshop Schedule

Talks Online

Exit Survey

INT-JINA Symposium INT-18-72R

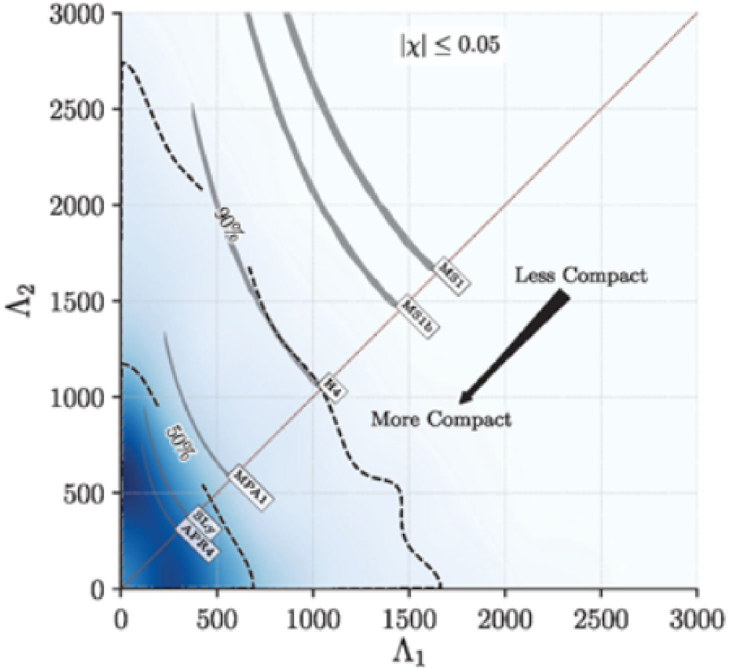
First multi-messenger observations of a neutron star merger and its implications for nuclear physics

March 12 - 14, 2018

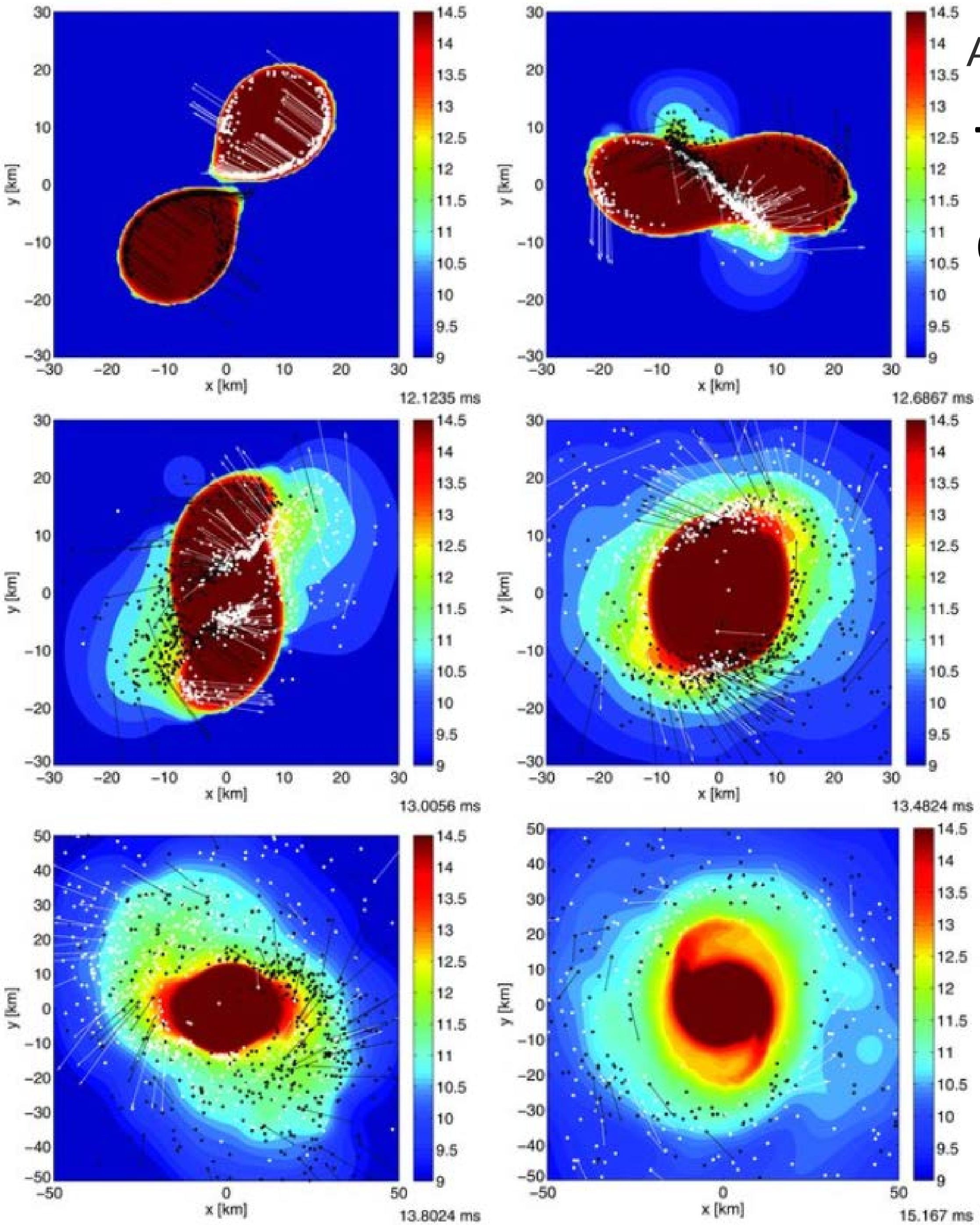
Selected for a Viewpoint in *Physics*
PRL 119, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

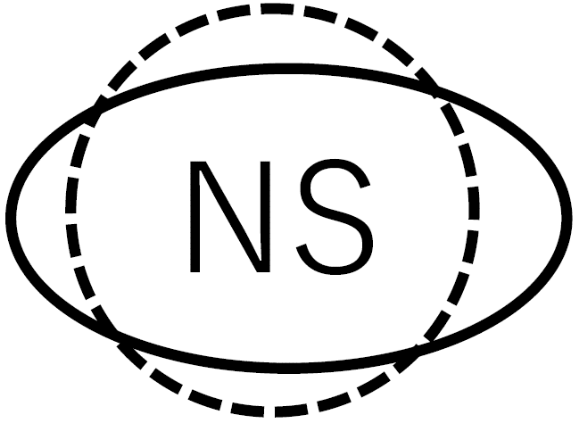


- Very stiff (unrealistic) EOS which predict R > 14 kms are disfavored.
- Data appears to favor a finite polarizability but cannot distinguish between radii in the range 9-13 kms.
- Systematic errors due to spin-orbit, spin-spin interactions are included in parameter estimation.

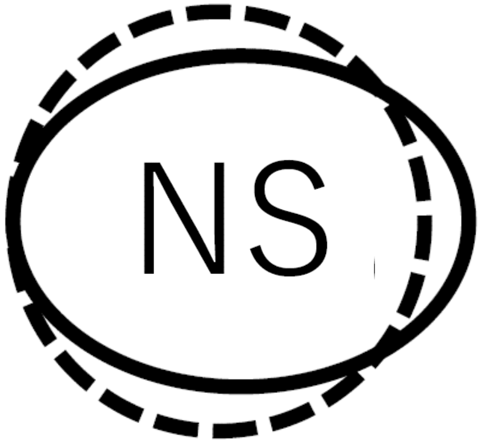


A. Bauswein, S. Goriely, and H.-T. Janka, APJ, 773, 21 (2013)

Tidal deformation of the Neutron Star depends on the compactness (M/R)



Soft EoS
Large deformation

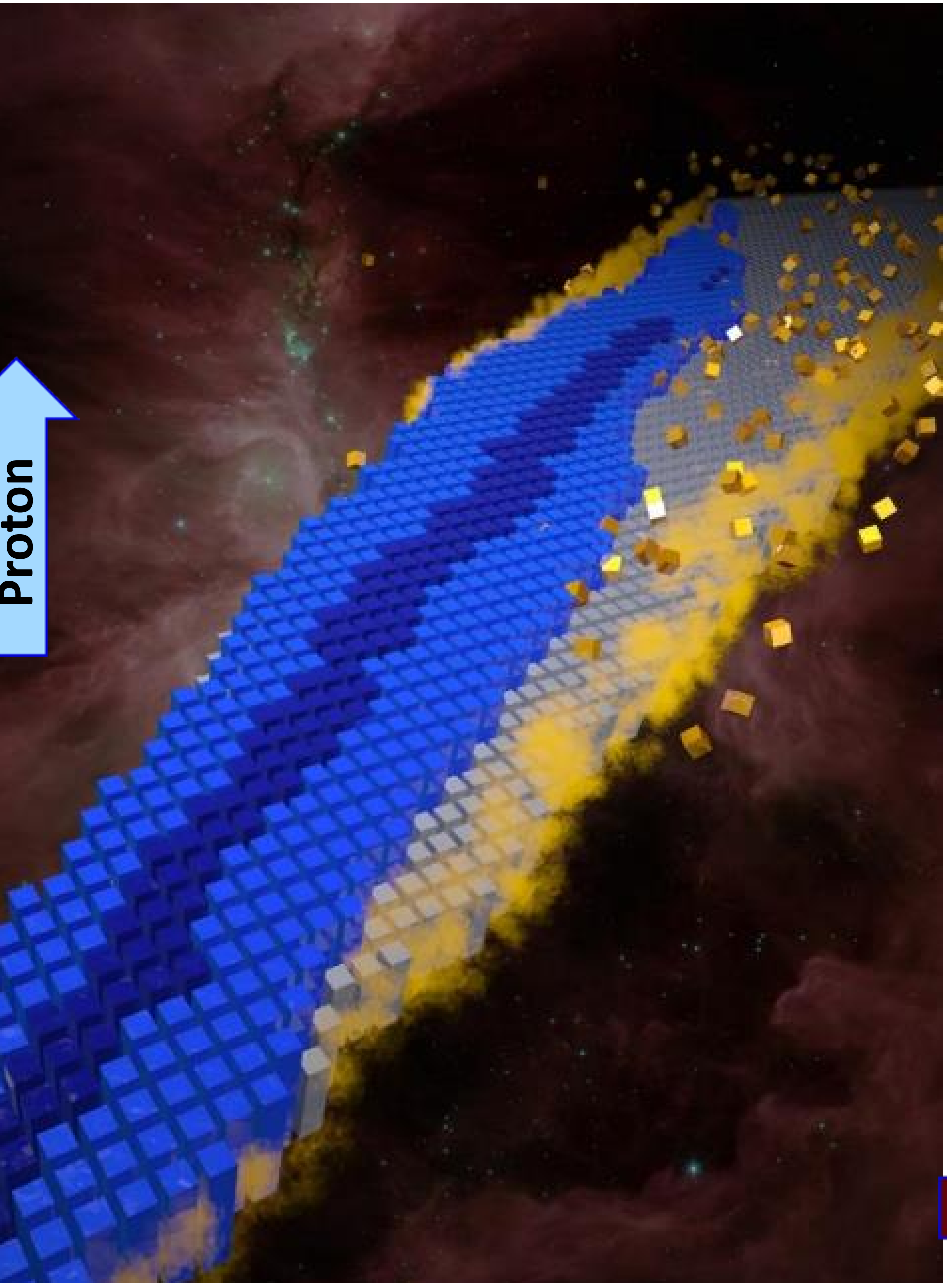


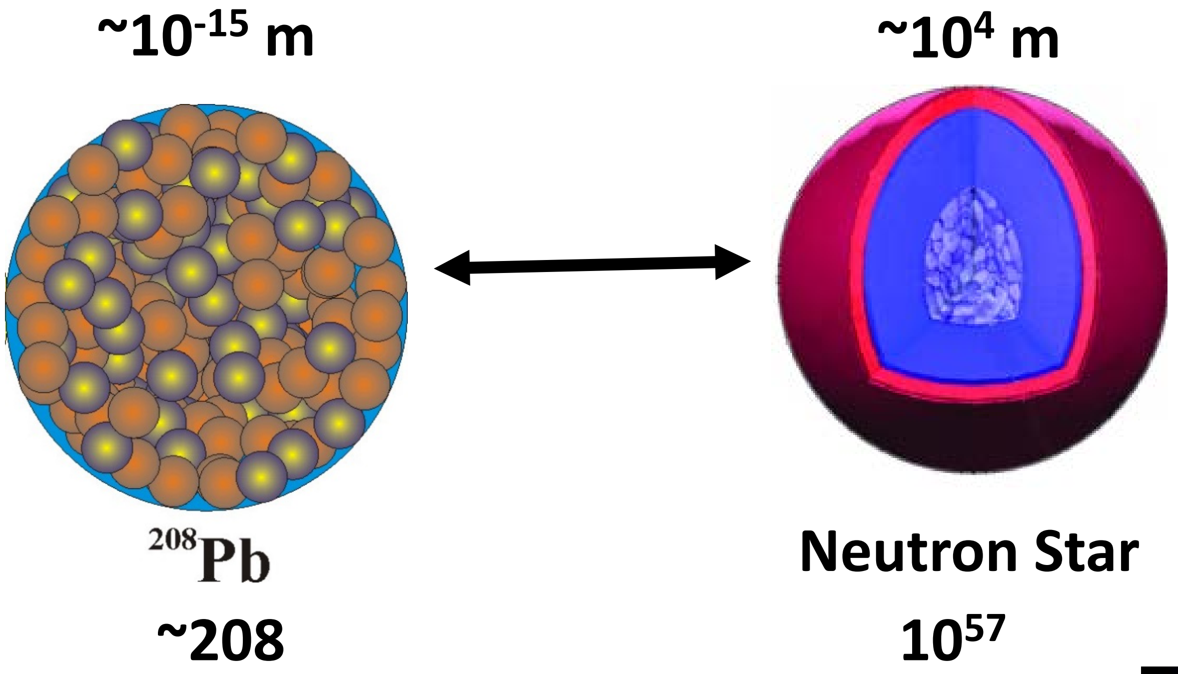
Stiff EoS
small deformation

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

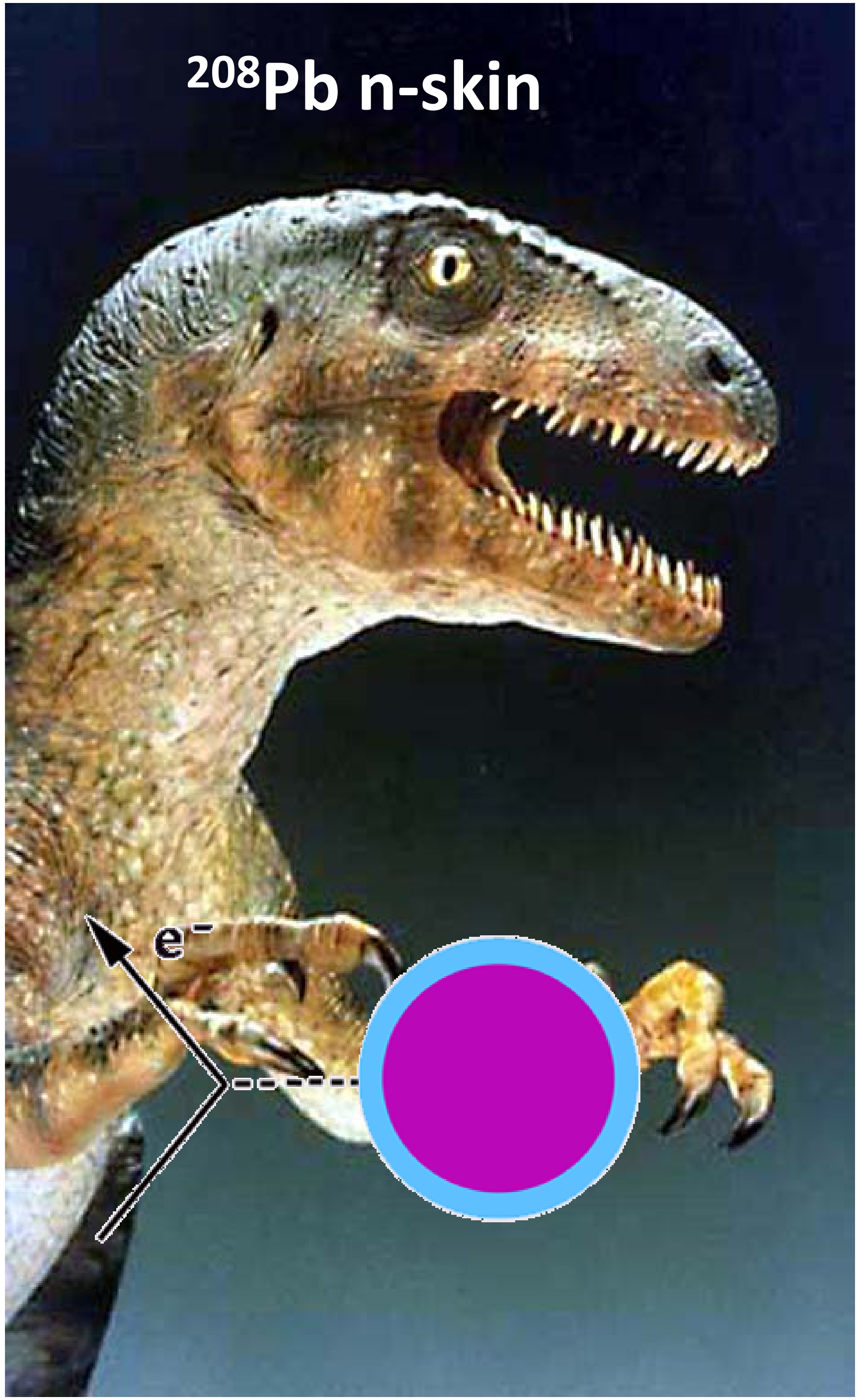
C.J. Horowitz, J. Piekarewicz, PRL 86 (2001) 5647

Parity Radius Experiment (P-ReX)





Hubble ST



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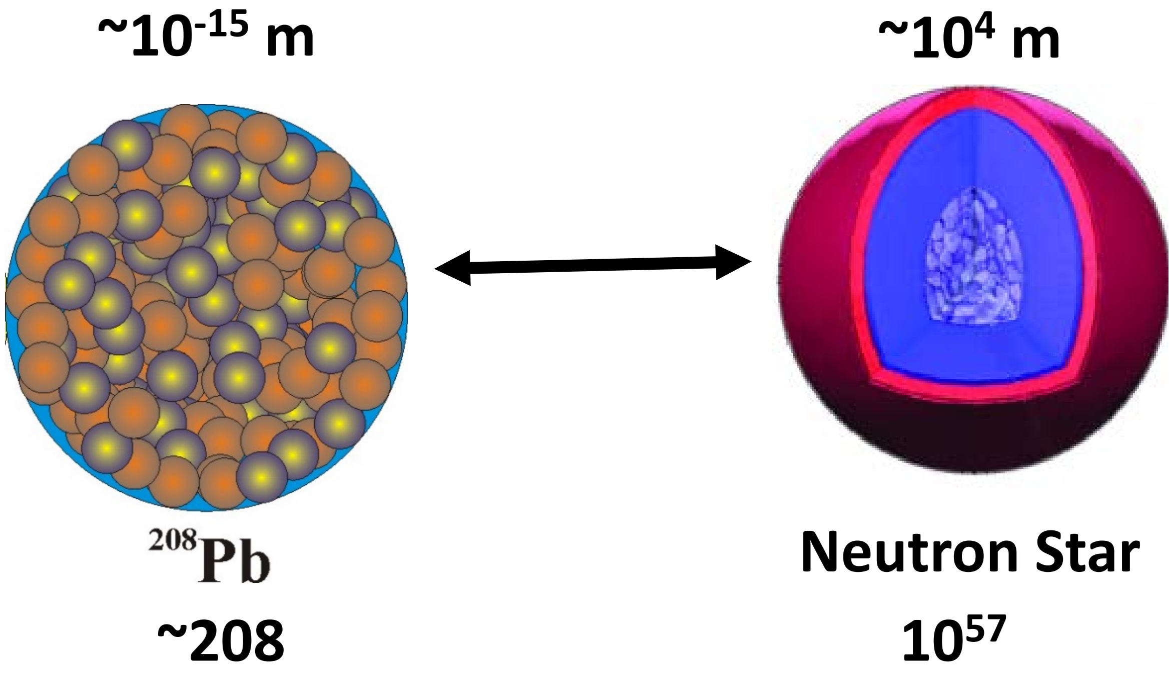


~10^{-15} m

^{208}Pb

~208

~10^{4} m

Neutron Star

10^{57}

$R_{np}(^{208}\text{Pb})<0.25$ fm

R(NS)<13.76 km

Fattoyev et al., arXiv:1711.06615

Symmetry Energy

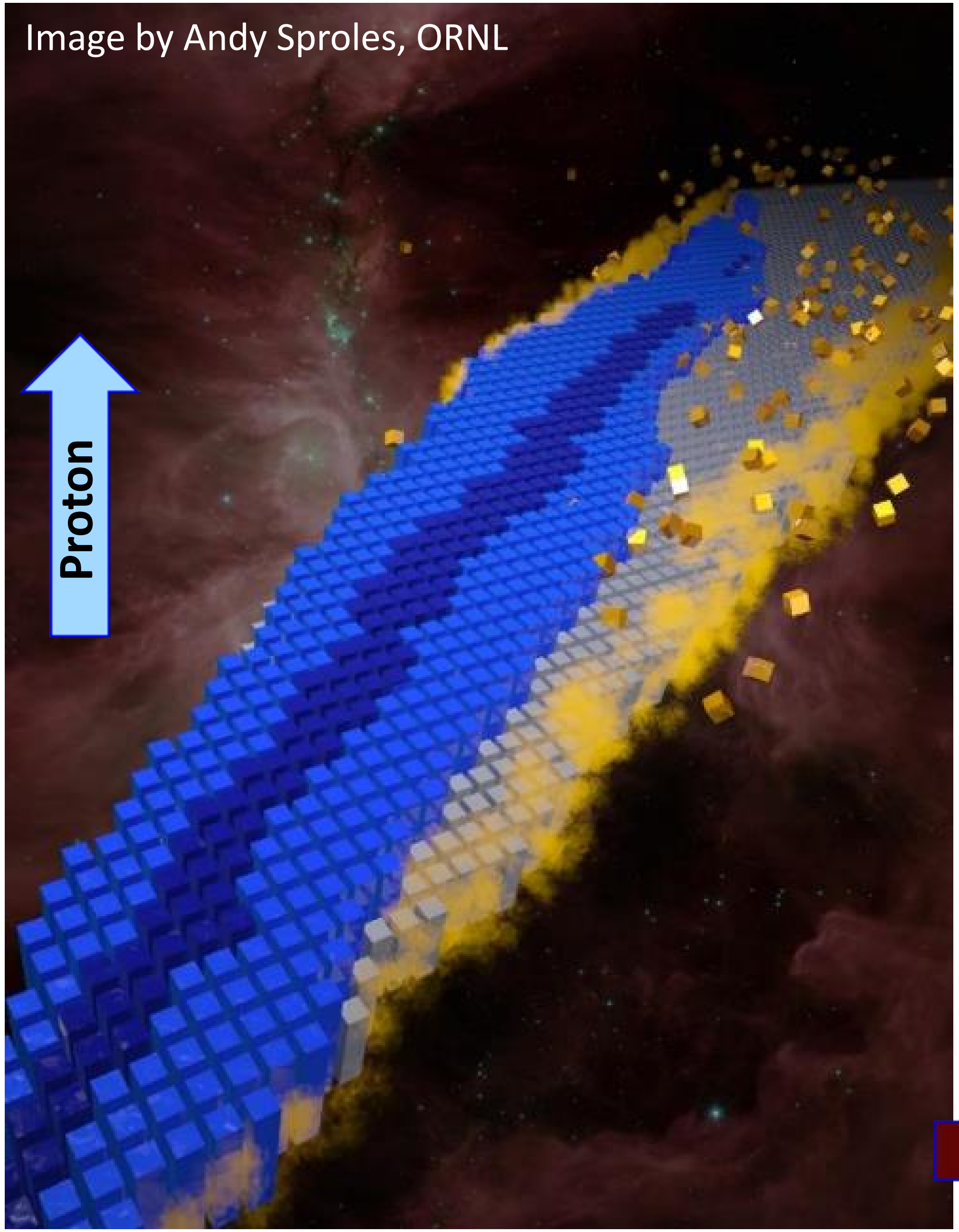


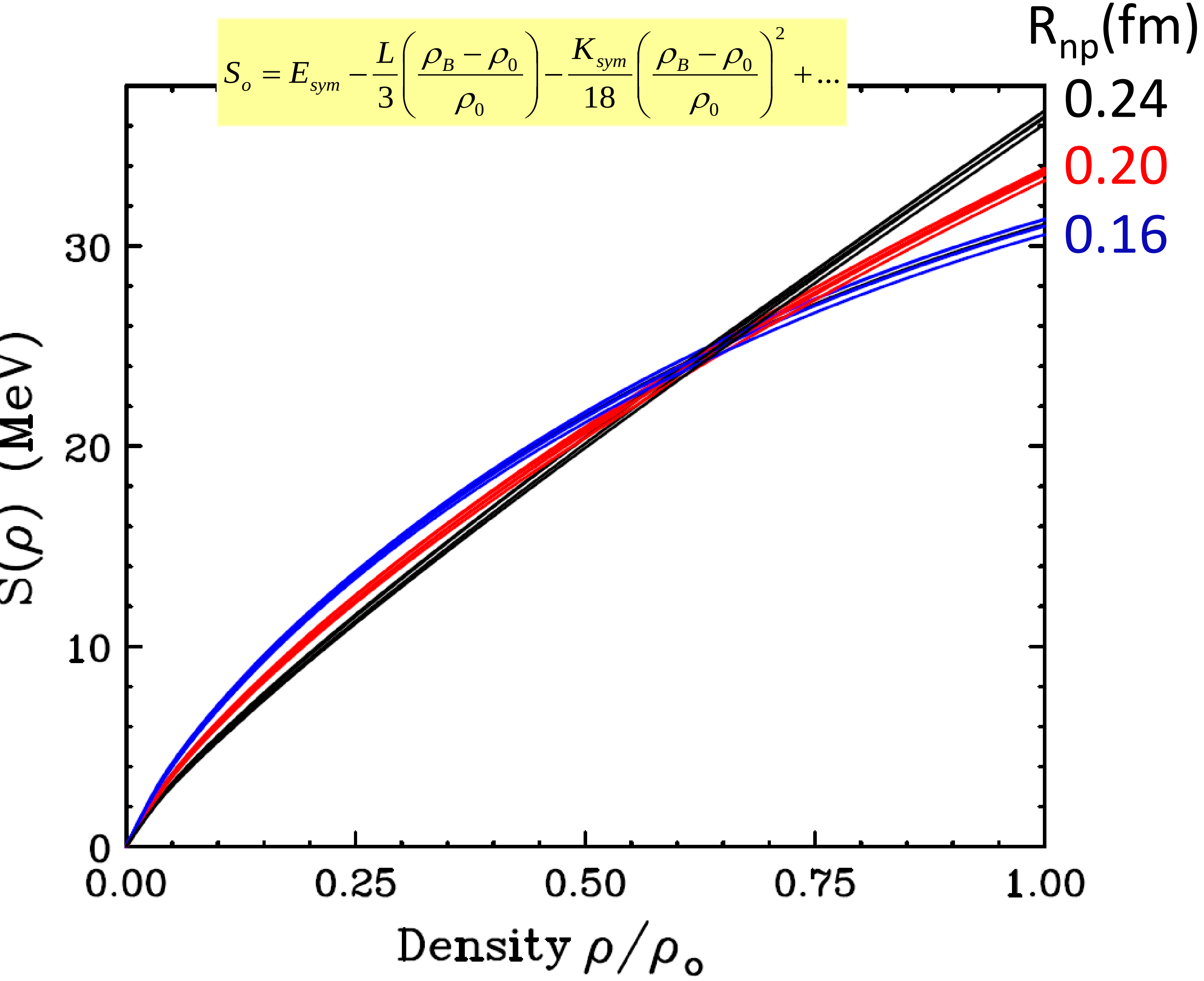
Image by Andy Sproles, ORNL

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

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

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

Inclusion of surface terms in symmetry



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

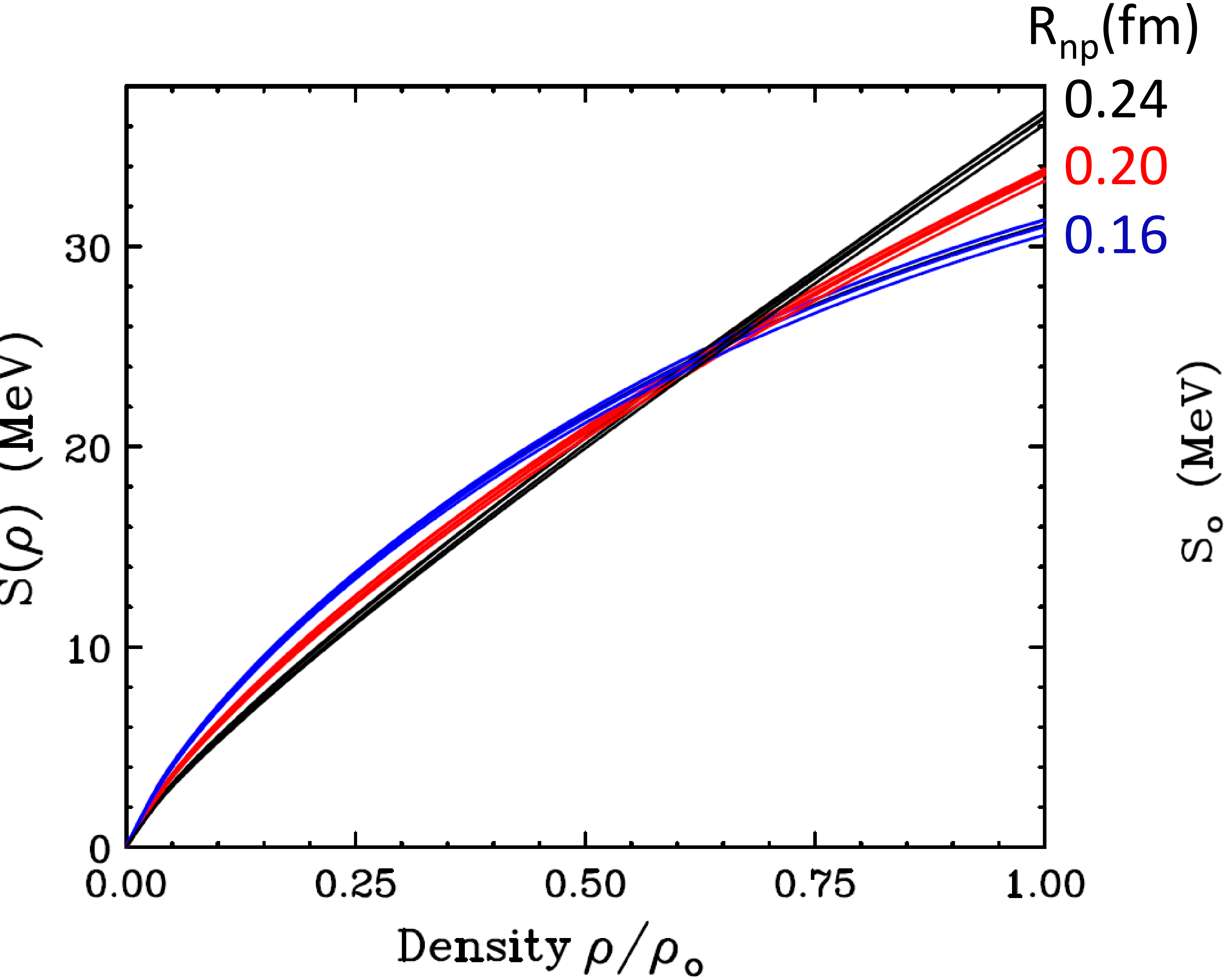
Alex Brown

PRL 111, 232502 (2013)

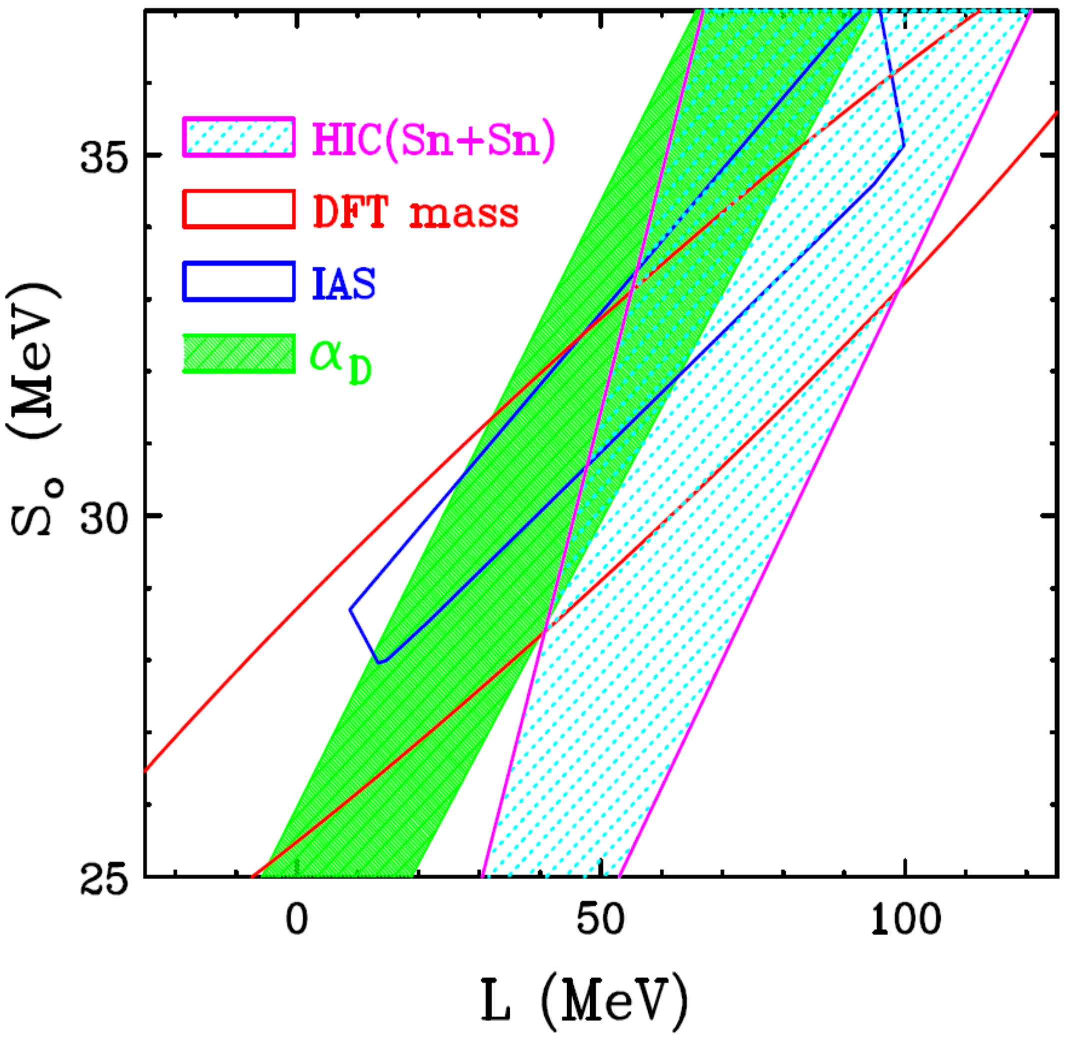
Use Skyrme interactions that fit the masses of double magic nuclei

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

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



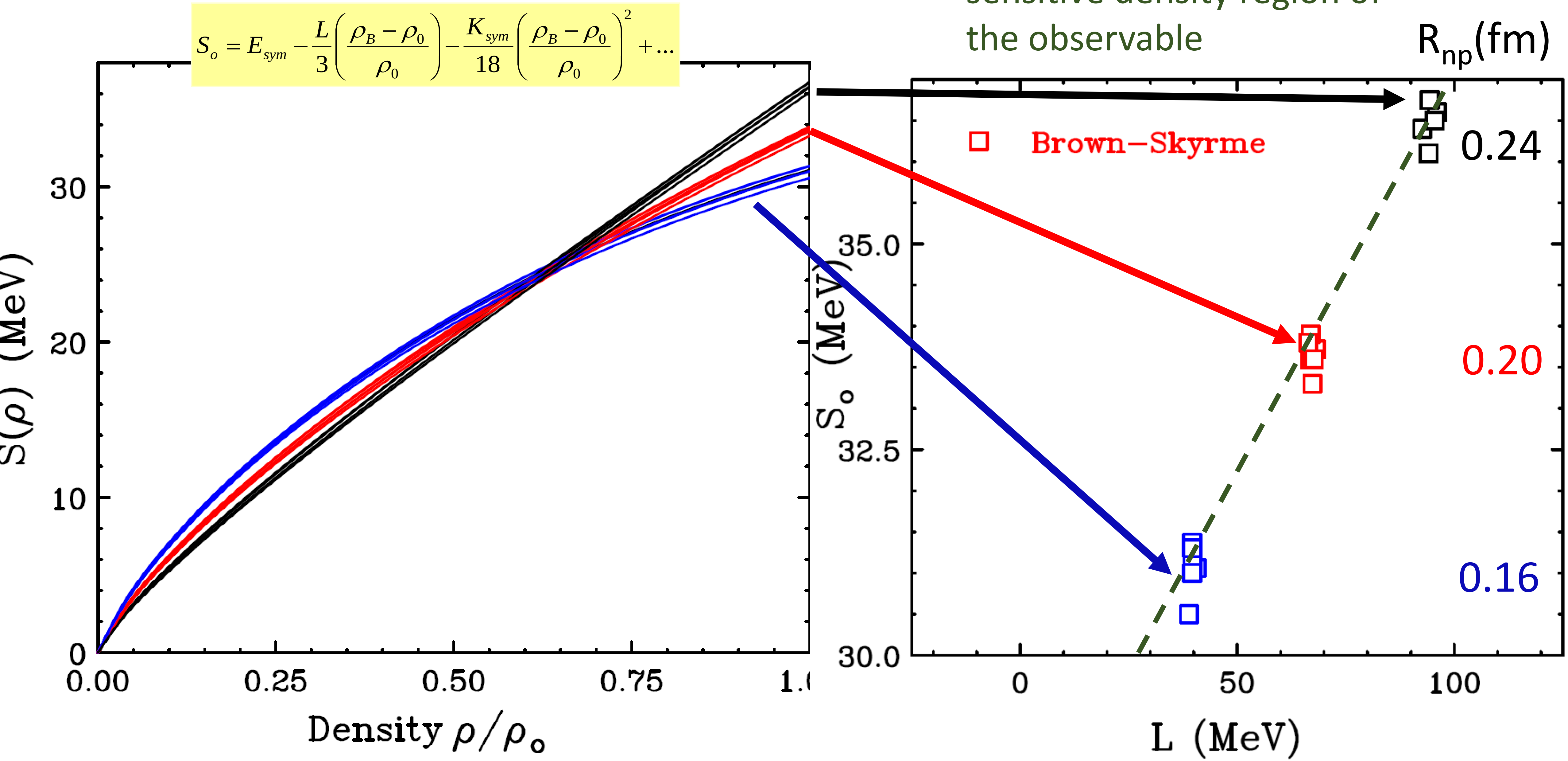
$$S_o = E_{sym} - \frac{L}{3}\left(\frac{\rho_B - \rho_0}{\rho_0}\right) - \frac{K_{sym}}{18}\left(\frac{\rho_B - \rho_0}{\rho_0}\right)^2$$



Horowitz et al., JPG 41, 093001 (2014)

Masses and skin data are sensitive to ρ~$0.65\rho_0$

Same slope gives you sensitive density region of the observable



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

Masses and skin data are sensitive to ρ~0.65ρ_0

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

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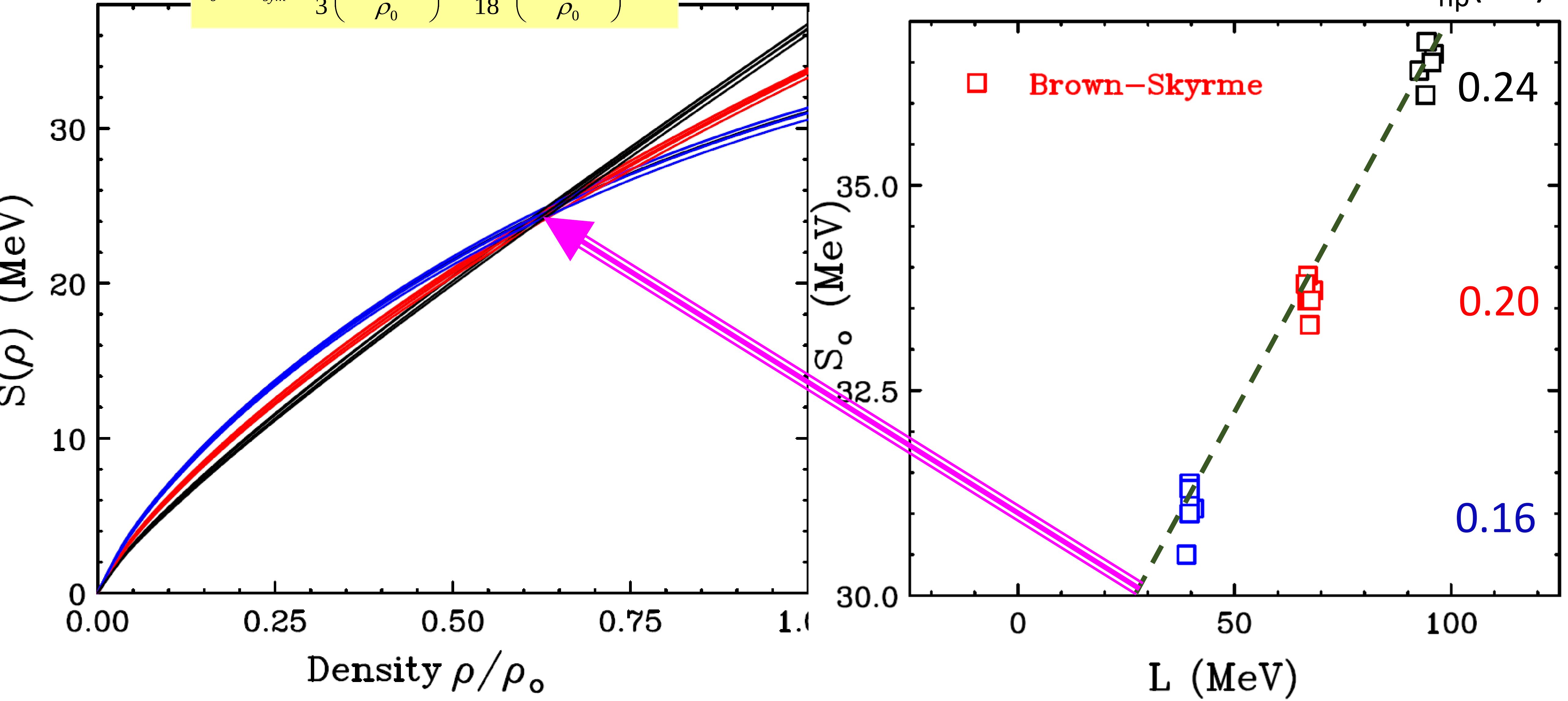
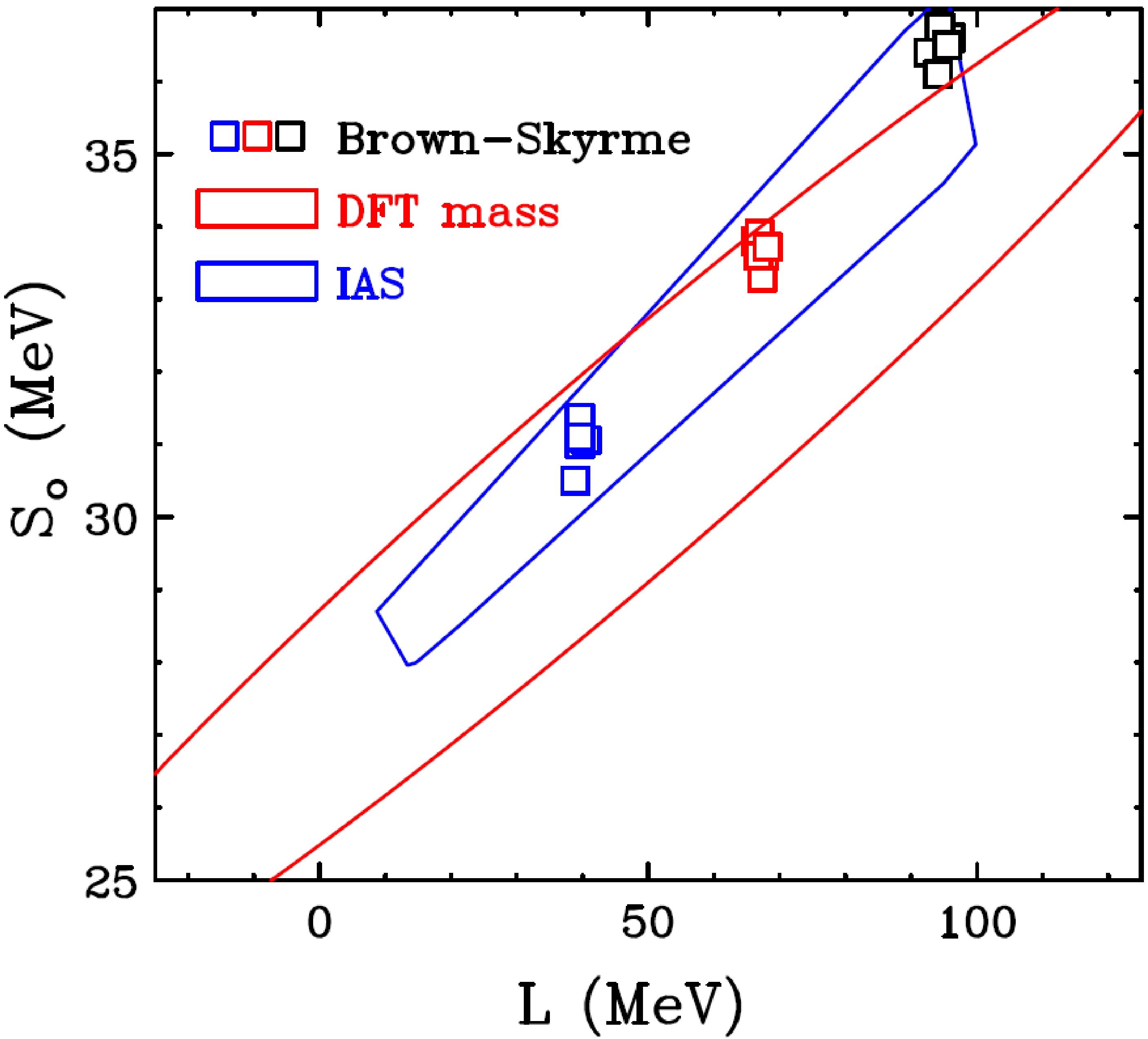


Symmetry Energy Constraints from masses



Skyrme Functionals

$$S(\rho) = a(\rho/\rho_0) + b(\rho/\rho_0)^{1+\sigma} + c(\rho/\rho_0)^{2/3} + d(\rho/\rho_0)^{5/3}$$

Brown: masses of doubly shell nuclei

ρ_s~$0.63\pm0.03\rho_0$ $E_{sym}(\rho_s)$ ~24.7 ± 0.8 MeV

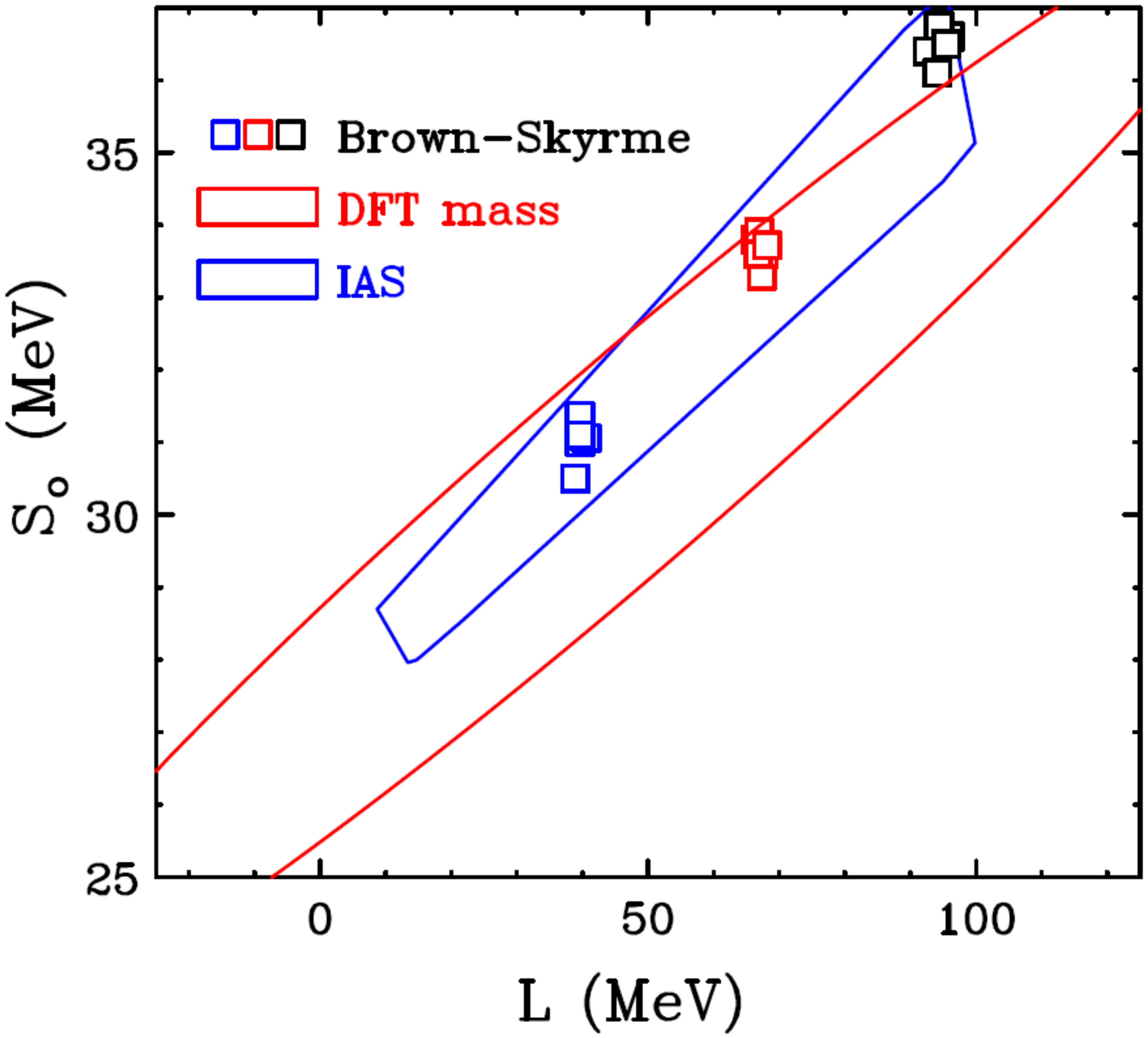
IAS: Isobaric Analog States

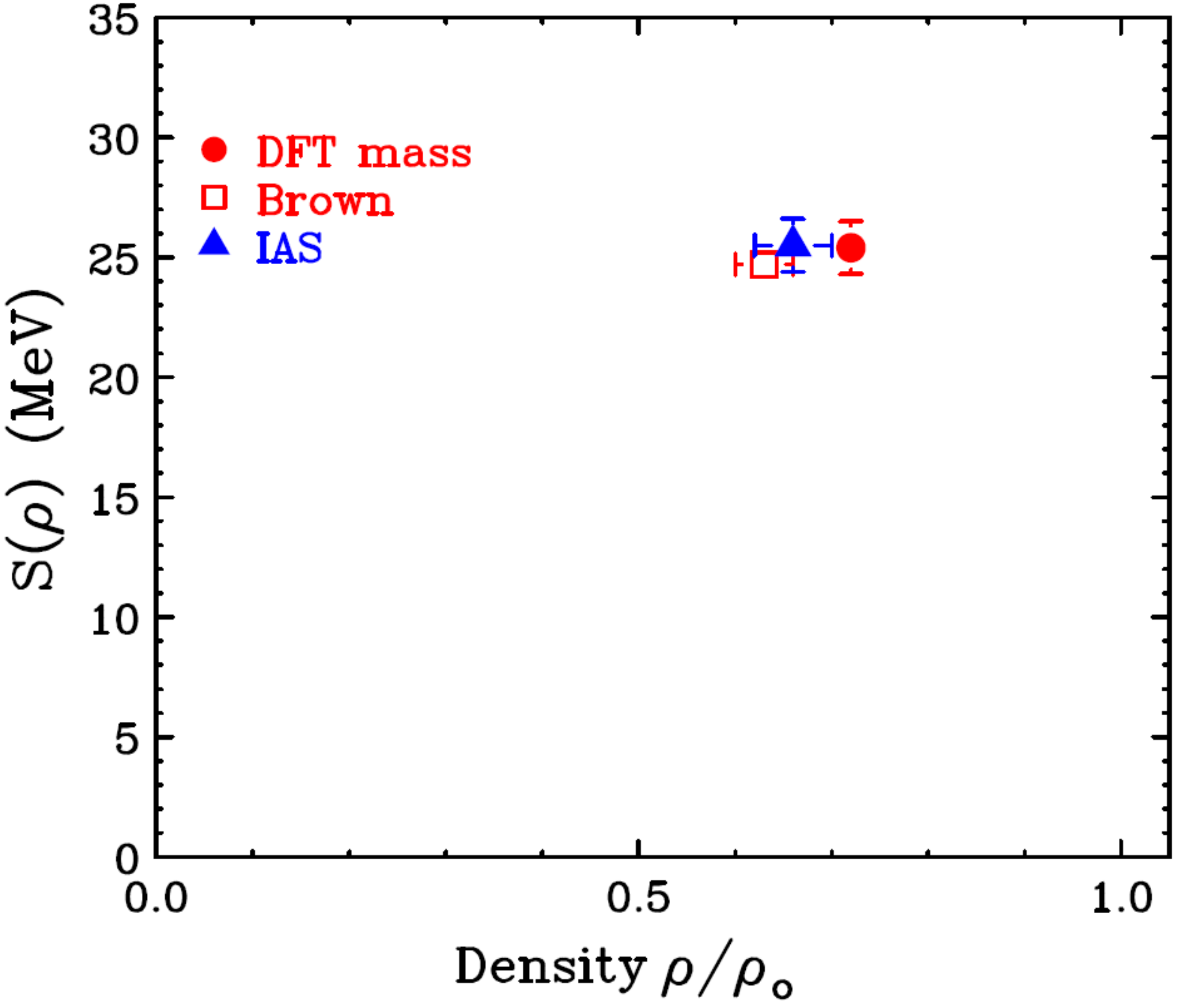
ρ_s~$0.67\pm0.03\rho_0$ $E_{sym}(\rho_s)$ ~25.1 ± 0.9 MeV

DFT: Density functional theory

ρ_s~$0.72 \pm 0.01\rho_0$ $E_{sym}(\rho_s)$ ~25.4 ± 1.1 MeV

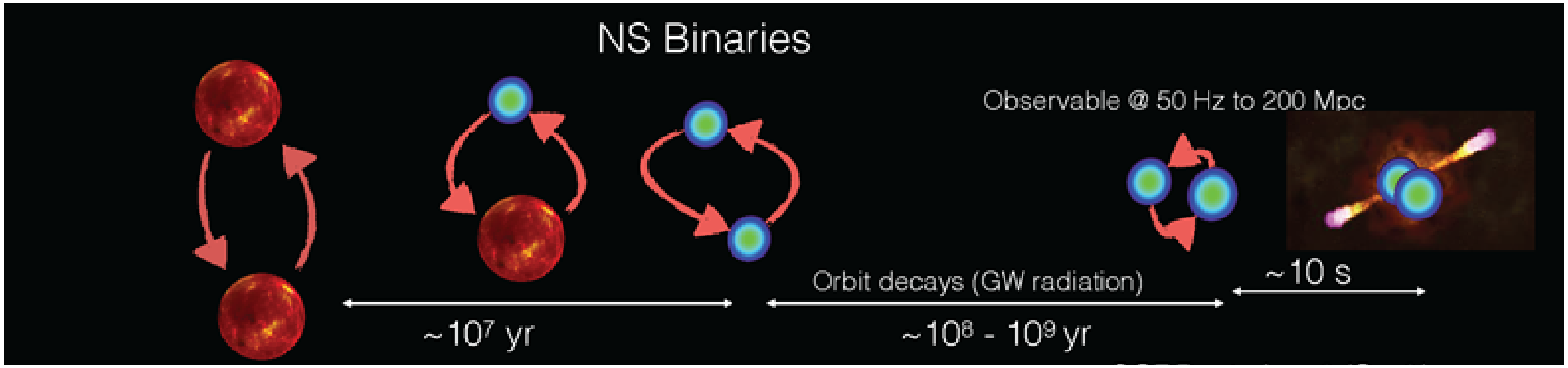
Symmetry Energy Constraints from masses



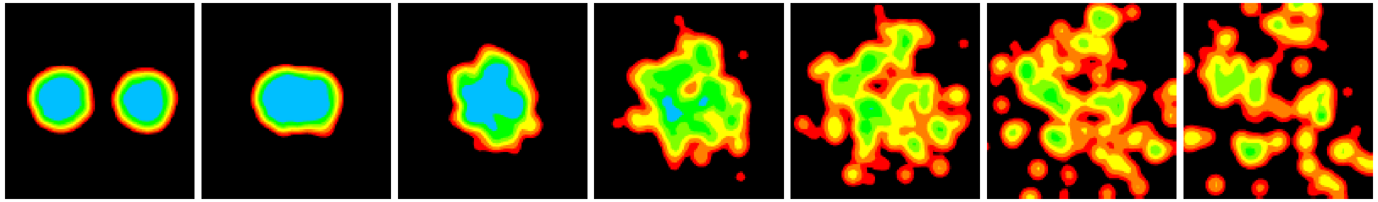


EOS from dynamics of N-star merger and from nuclear collisions

N-Star merger: 10^8 year; Observation Estimates: ~2/year



Nuclear-collisions: 10^{-21} sec; 10^7 collisions per experiment



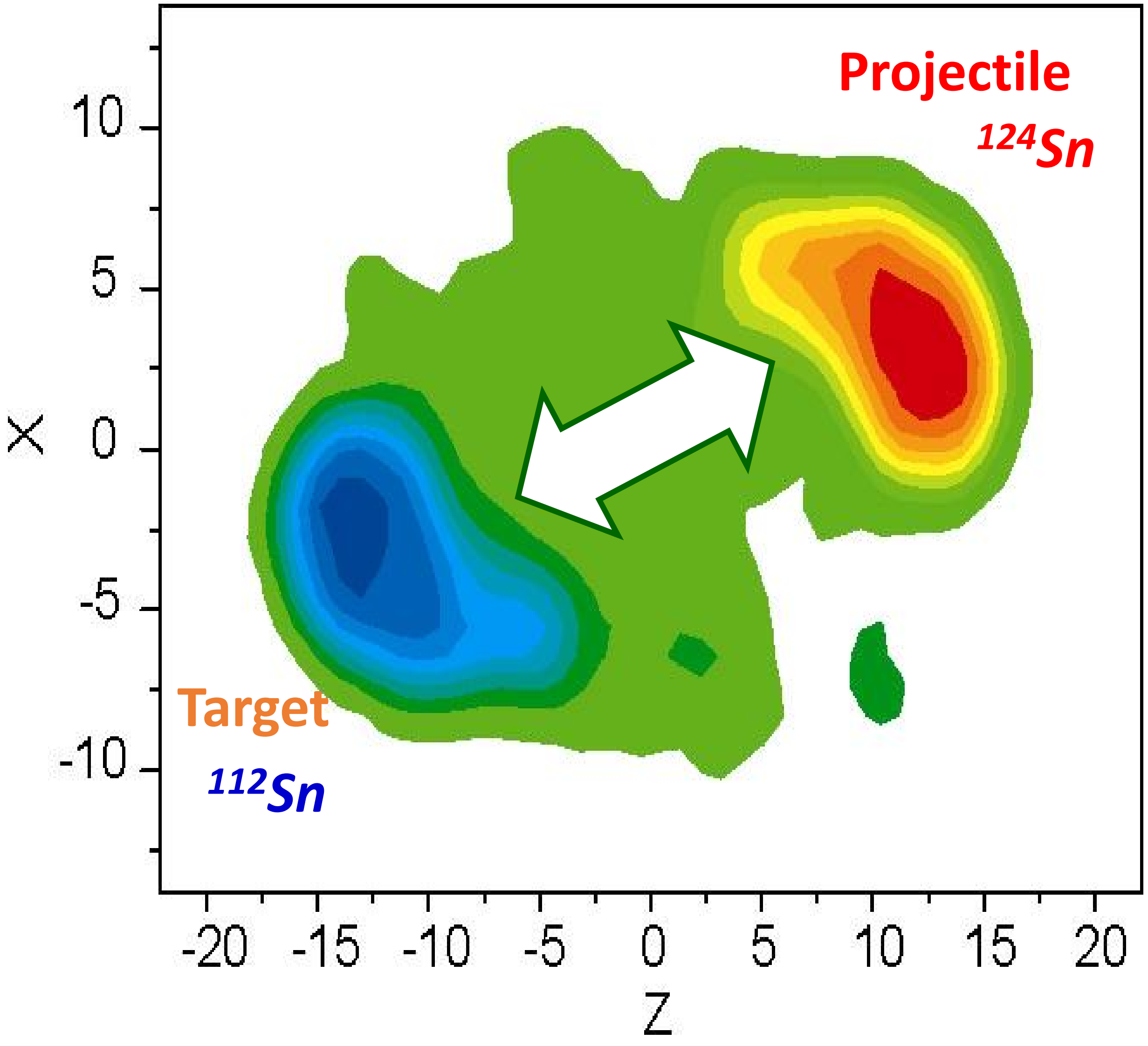
Femto-nova explosion created by Heavy Ion collisions

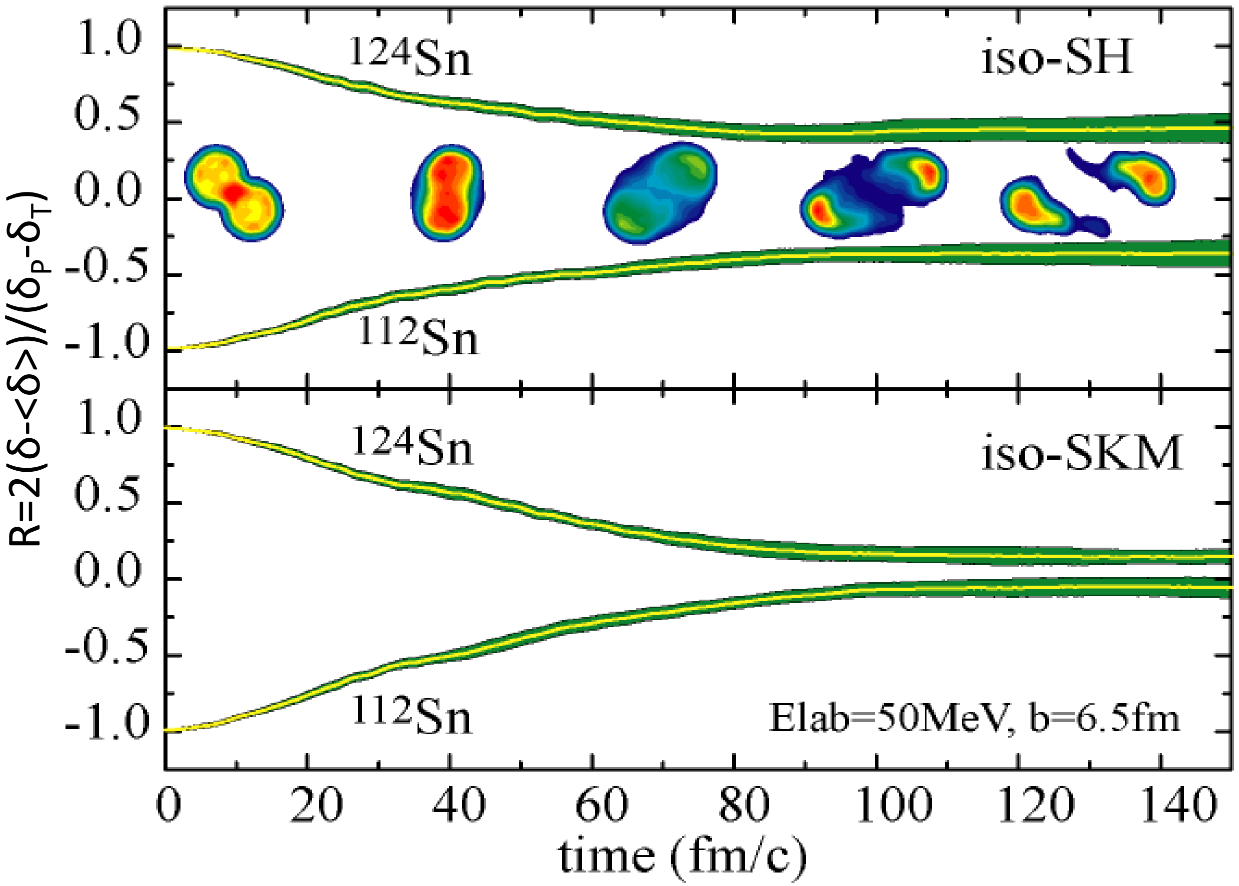
Equation of State of nuclear matter

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

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

Isospin Diffusion to constrain low density EoS



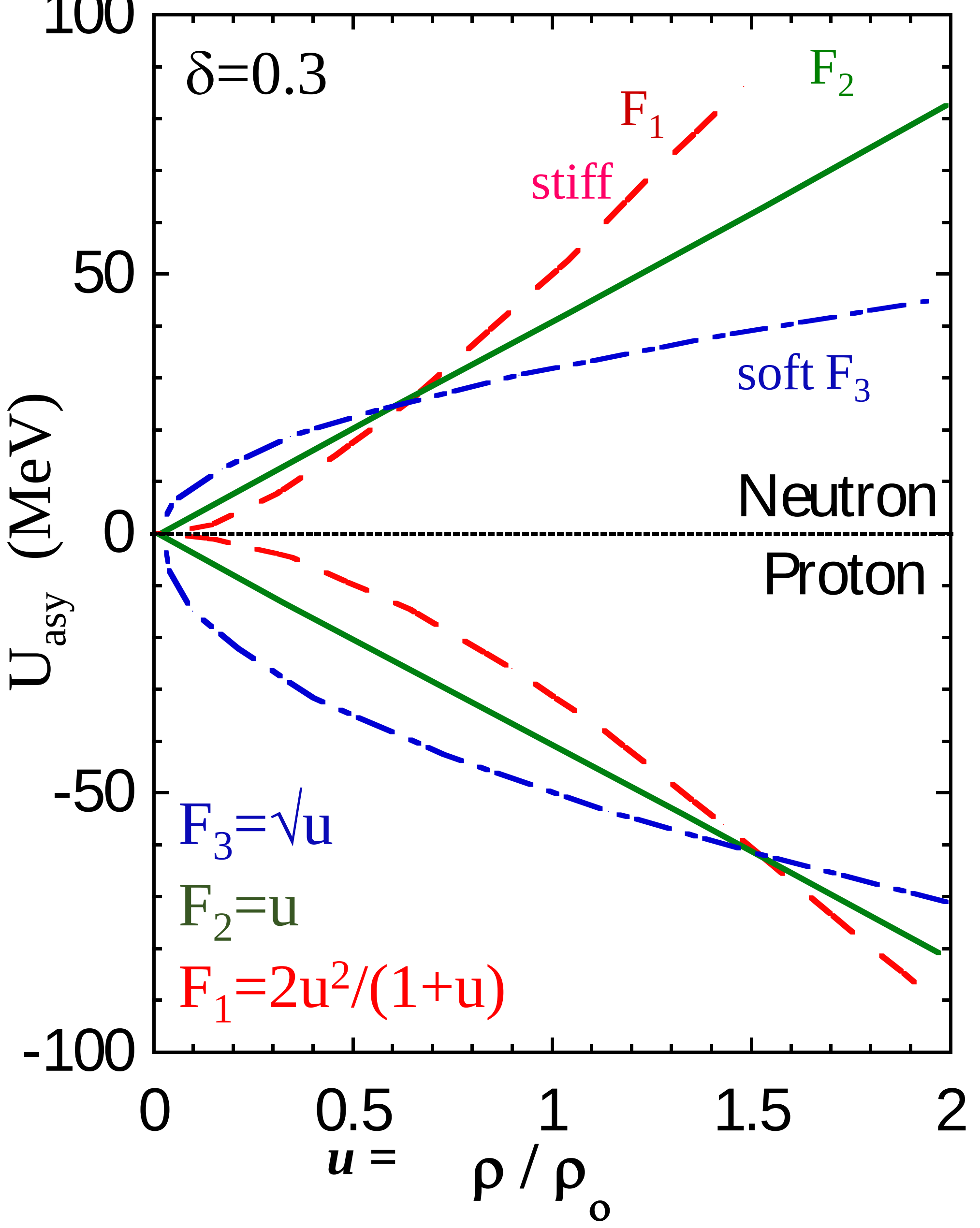


Isospin Diffusion; low ρ, E_{beam}

Tsang et al., PRL 92 (2004) 062701

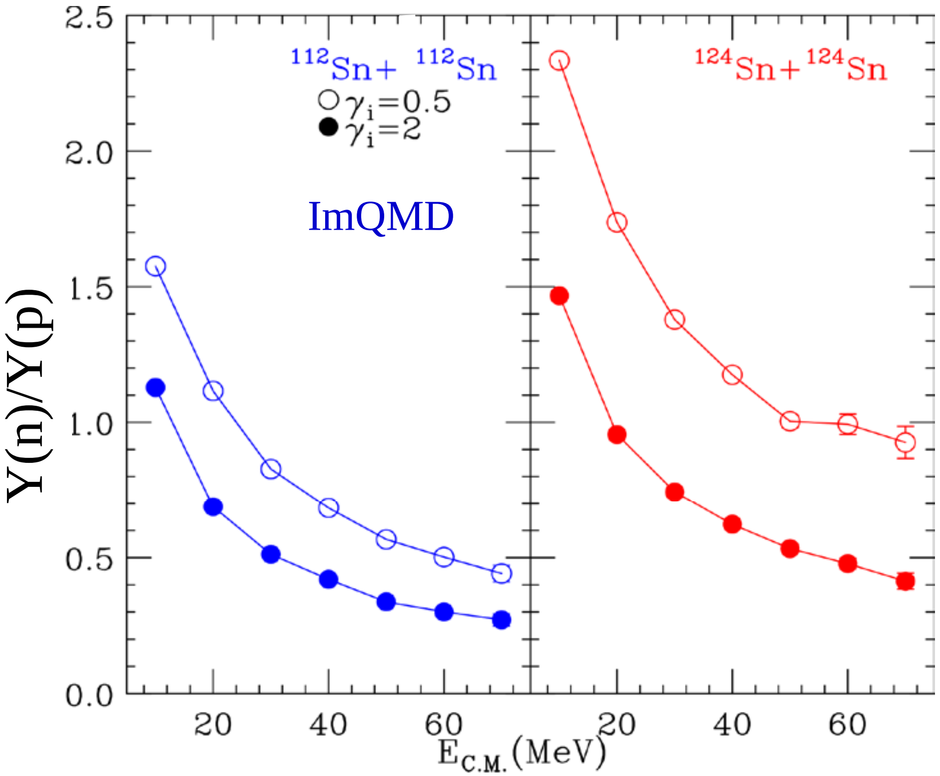
Experimental Observables: n/p yield ratios

Li et al., PRL 78 (1997) 1644



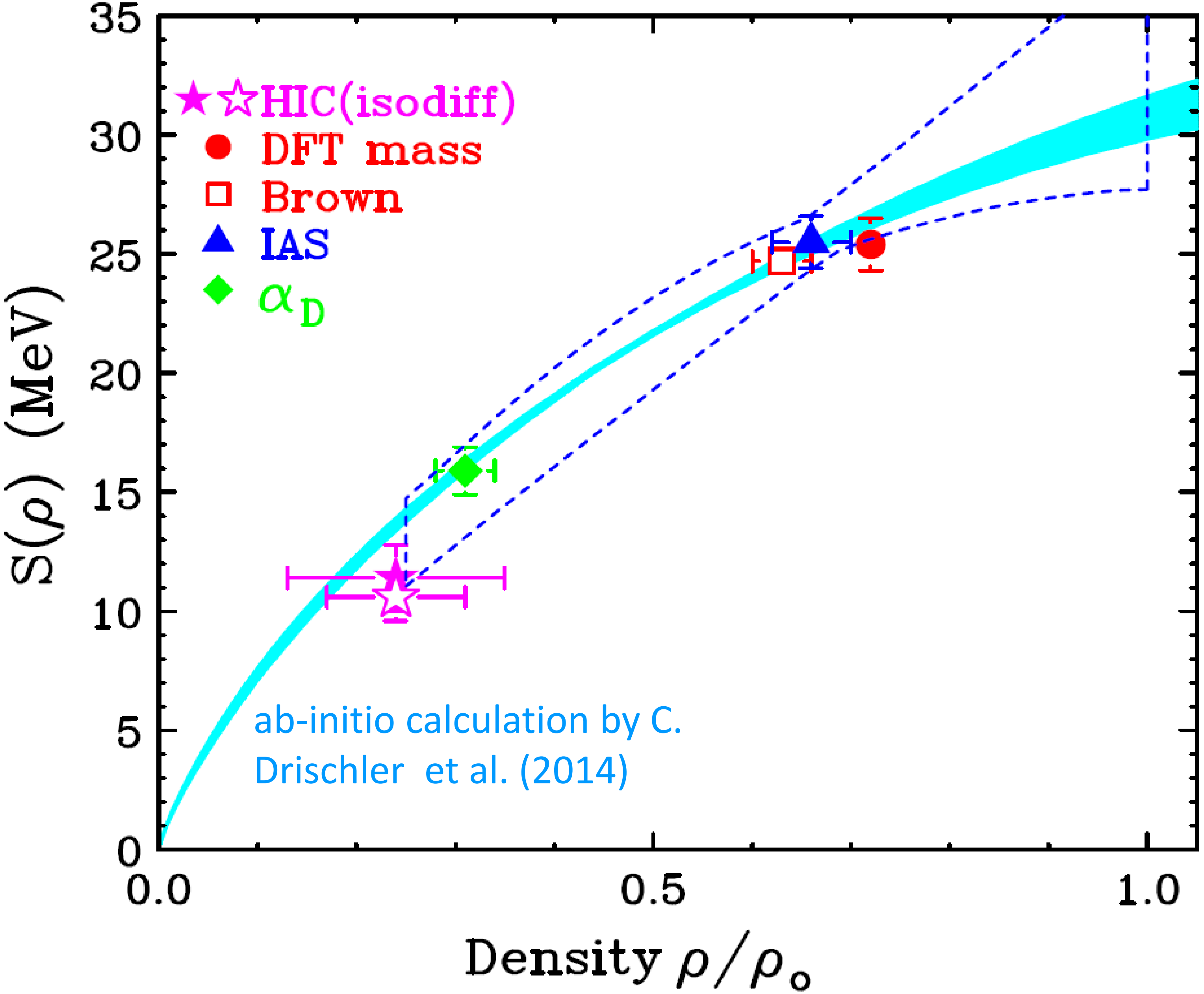
- *n and p potentials have opposite sign.*
- *n & p energy spectra depend on the symmetry energy → softer density dependence emits more neutrons at low density.*

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



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

Density dependence of Symmetry Energy at subsaturation density



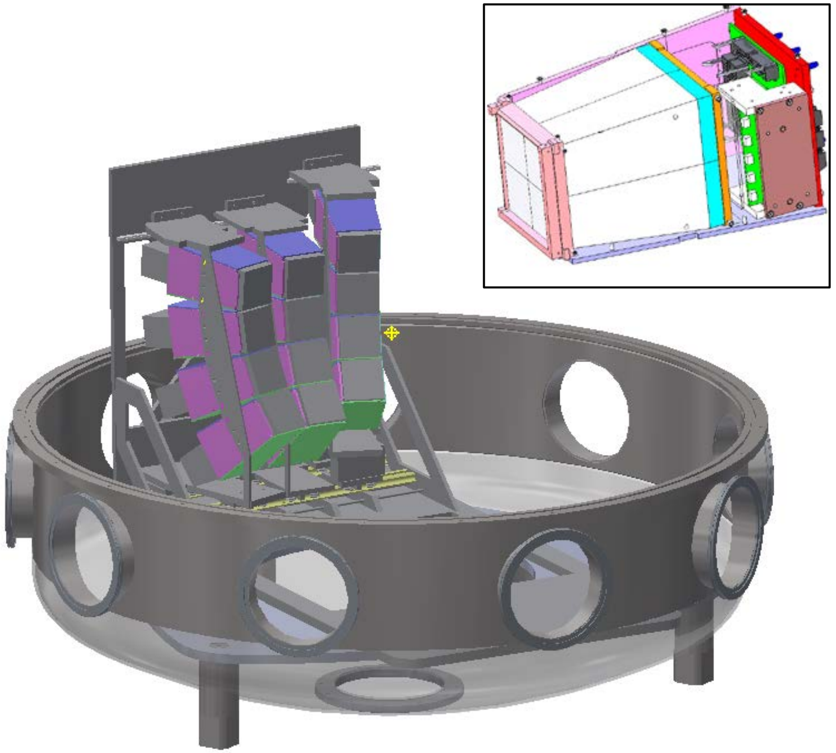
ab-initio calculation by C. Drischler et al. (2014)

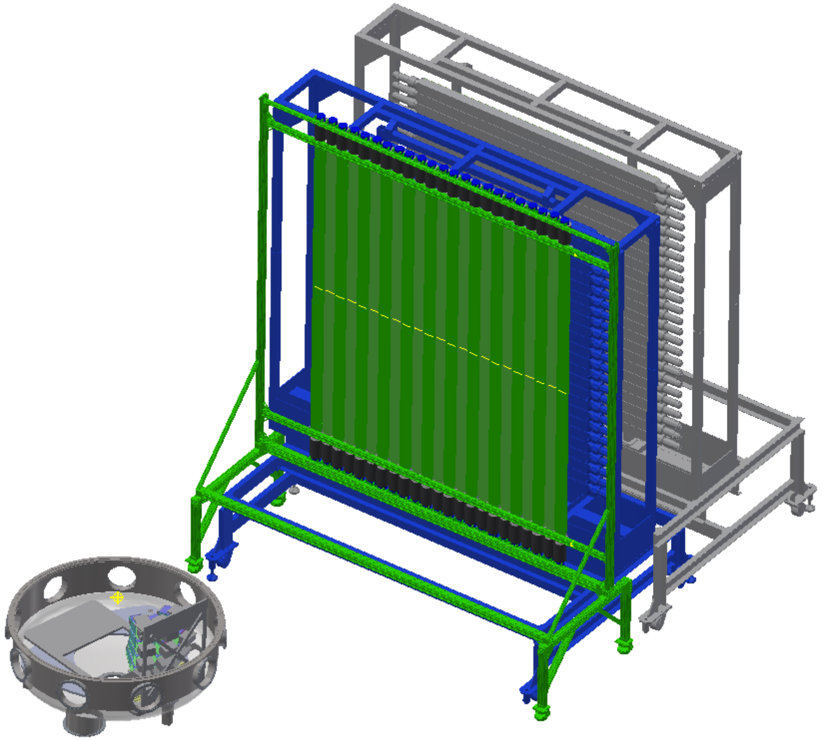
Lynch and Tsang (2007)

HiRA upgrade to improve constraints on symmetry energy and Δm*

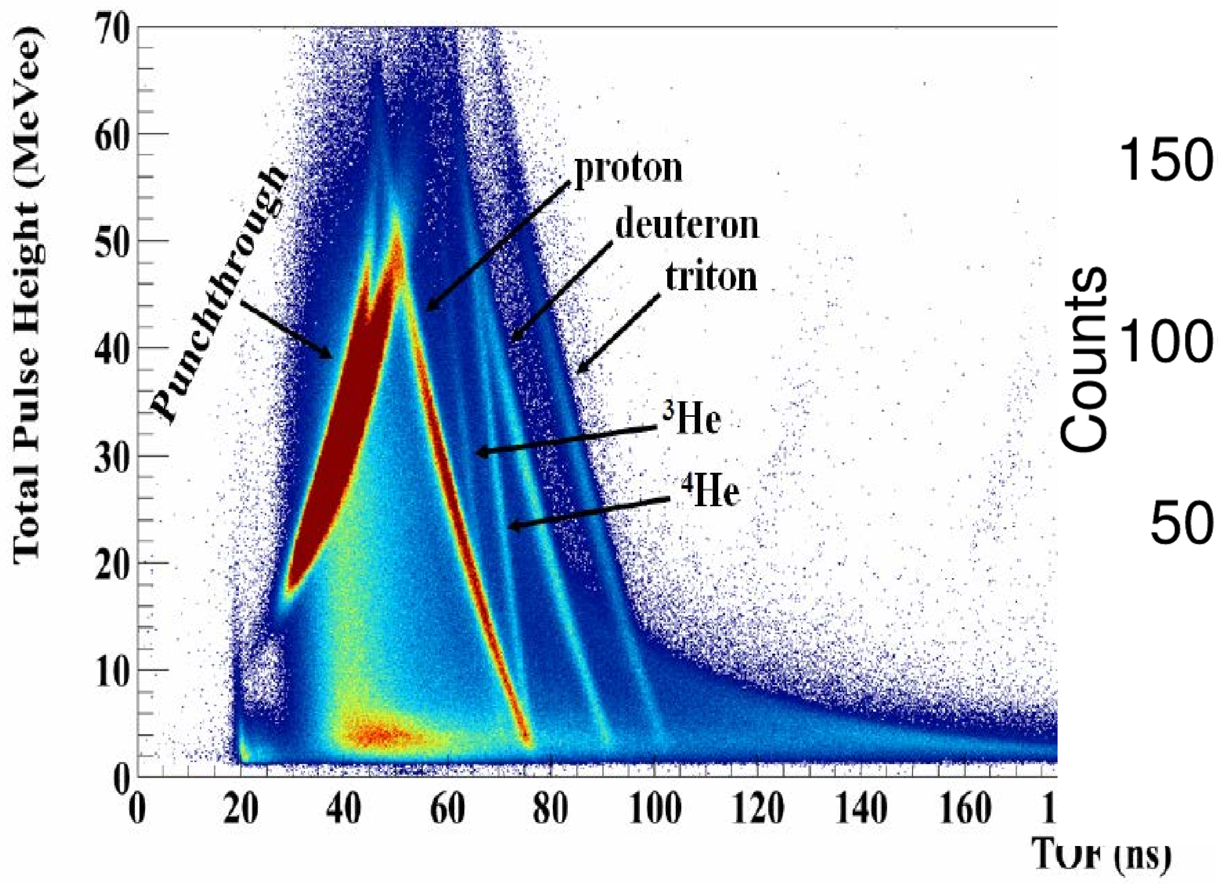
increase CsI from 4 cm to 10 cm;
the mass splitting effects increase
with particle energies.

Install a new charged
particle veto wall in front of
two neutrons walls

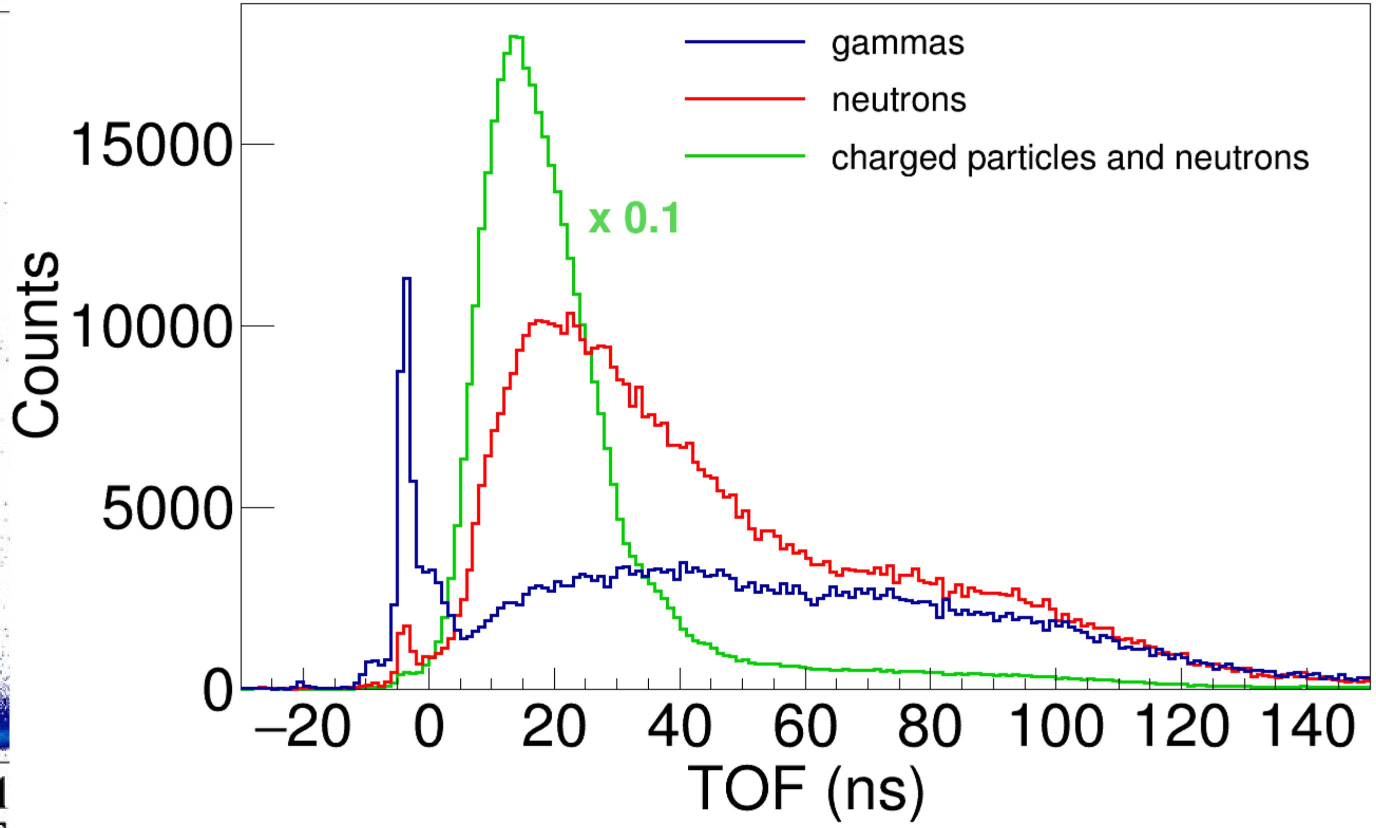




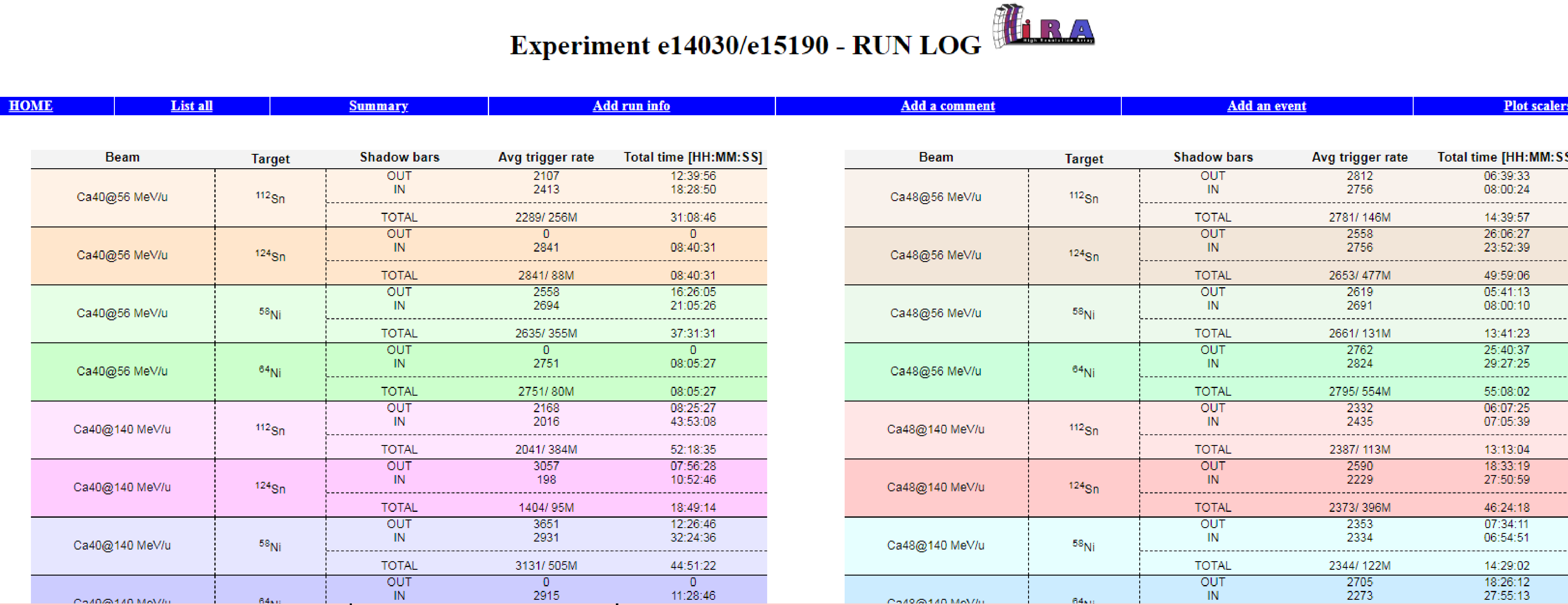
Experiments finished in Feb & March 2018 @ NSCL/MSU



^{124}Ca+^{124}Sn E/A=140 MeV
Coupland, 2009



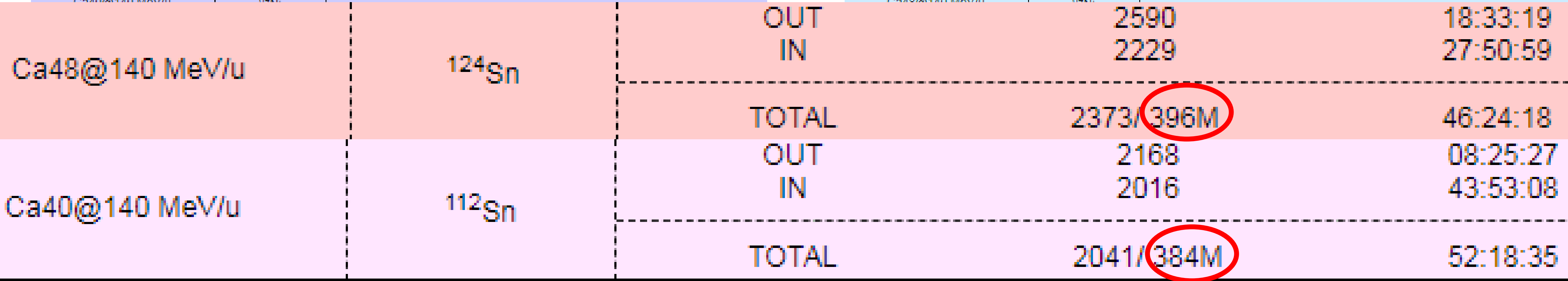
^{40}Ca+^{112}Sn E/A=140 MeV
HiRA, 2018



Experiment e14030/e15190 - RUN LOG

Beam	Target	Shadow bars	Avg trigger rate	Total time [HH:MM:SS]
Ca40@56 MeV/u	^{112}Sn	OUT	2107	12:39:56
		IN	2413	18:28:50
		TOTAL	2289/ 256M	31:08:46
Ca40@56 MeV/u	^{124}Sn	OUT	0	0
		IN	2841	08:40:31
		TOTAL	2841/ 88M	08:40:31
Ca40@56 MeV/u	^{58}Ni	OUT	2558	16:26:05
		IN	2694	21:05:26
		TOTAL	2635/ 355M	37:31:31
Ca40@56 MeV/u	^{64}Ni	OUT	0	0
		IN	2751	08:05:27
		TOTAL	2751/ 80M	08:05:27
Ca40@140 MeV/u	^{112}Sn	OUT	2168	08:25:27
		IN	2016	43:53:08
		TOTAL	2041/ 384M	52:18:35
Ca40@140 MeV/u	^{124}Sn	OUT	3057	07:56:28
		IN	198	10:52:46
		TOTAL	1404/ 95M	18:49:14
Ca40@140 MeV/u	^{58}Ni	OUT	3651	12:26:46
		IN	2931	32:24:36
		TOTAL	3131/ 505M	44:51:22
		OUT	0	0
		IN	2915	11:28:46

Beam	Target	Shadow bars	Avg trigger rate	Total time [HH:MM:S
Ca48@56 MeV/u	^{112}Sn	OUT	2812	06:39:33
		IN	2756	08:00:24
		TOTAL	2781/ 146M	14:39:57
Ca48@56 MeV/u	^{124}Sn	OUT	2558	26:06:27
		IN	2756	23:52:39
		TOTAL	2653/ 477M	49:59:06
Ca48@56 MeV/u	^{58}Ni	OUT	2619	05:41:13
		IN	2691	08:00:10
		TOTAL	2661/ 131M	13:41:23
Ca48@56 MeV/u	^{64}Ni	OUT	2762	25:40:37
		IN	2824	29:27:25
		TOTAL	2795/ 554M	55:08:02
Ca48@140 MeV/u	^{112}Sn	OUT	2332	06:07:25
		IN	2435	07:05:39
		TOTAL	2387/ 113M	13:13:04
Ca48@140 MeV/u	^{124}Sn	OUT	2590	18:33:19
		IN	2229	27:50:59
		TOTAL	2373/ 396M	46:24:18
Ca48@140 MeV/u	^{58}Ni	OUT	2353	07:34:11
		IN	2334	06:54:51
		TOTAL	2344/ 122M	14:29:02
		OUT	2705	18:26:12
		IN	2273	27:55:13



Ca48@140 MeV/u	^{124}Sn	OUT	2590	18:33:19
		IN	2229	27:50:59
		TOTAL	2373/ 396M	46:24:18
Ca40@140 MeV/u	^{112}Sn	OUT	2168	08:25:27
		IN	2016	43:53:08
		TOTAL	2041/ 384M	52:18:35

RL 119, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

$$\Lambda = \frac{2}{3}k_2\left(\frac{c^2R}{GM}\right)^5 = \frac{64}{3}k_2\left(\frac{R}{R_s}\right)^5$$

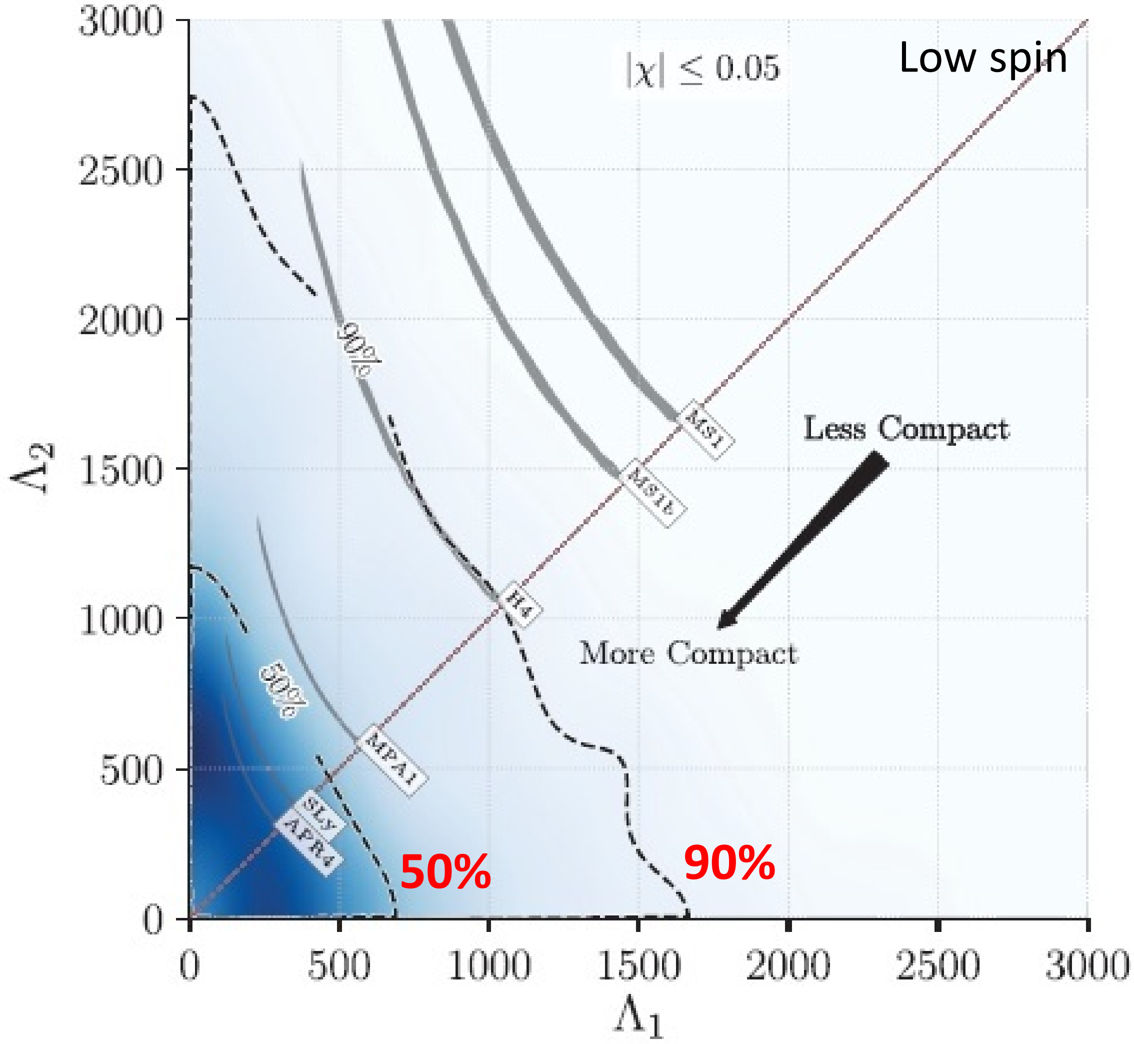
$$\tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_1+12M_2)M_1^4}{(M_1+M_2)^5}\Lambda_1 + \frac{(M_2+12M_1)M_2^4}{(M_1+M_2)^5}\Lambda_2\right]$$

<800 (90% confidence)

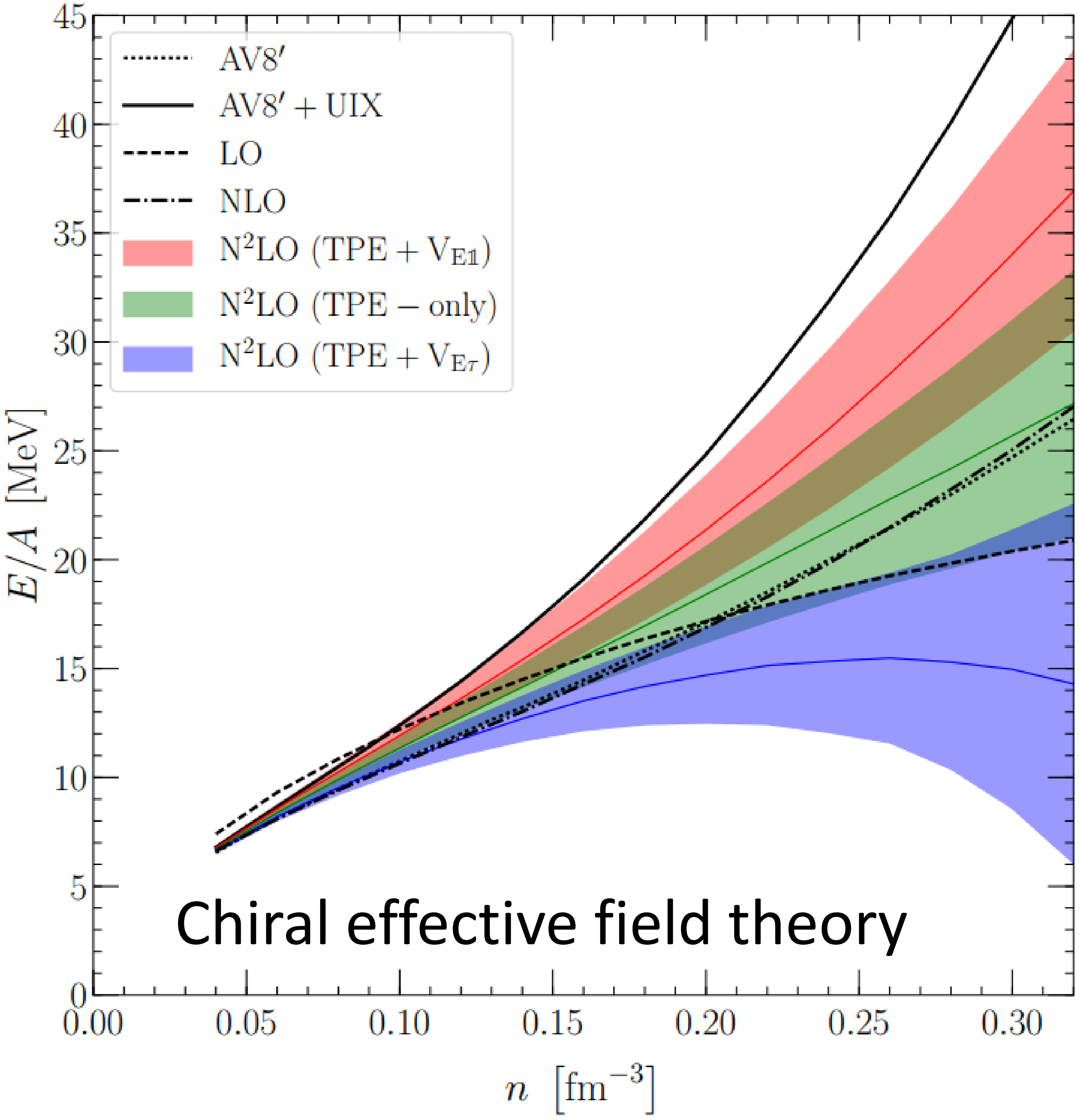
$\tilde{\Lambda}$: Preliminary analysis, waiting for updates from more sophisticated analysis (Ben Lackey)

With high uncertainties e.g. include correlation between M_2 and M_1

800→1100 (Lattimer)

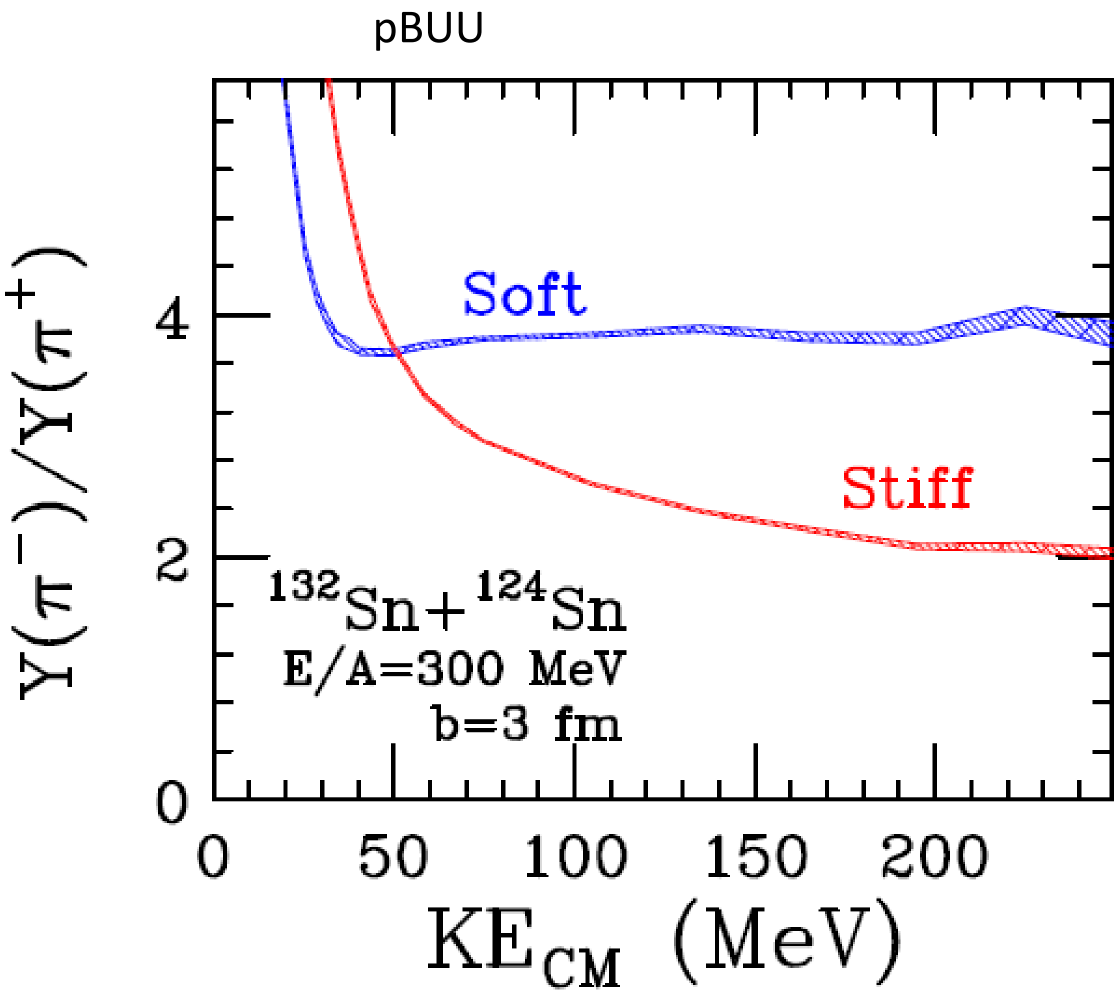


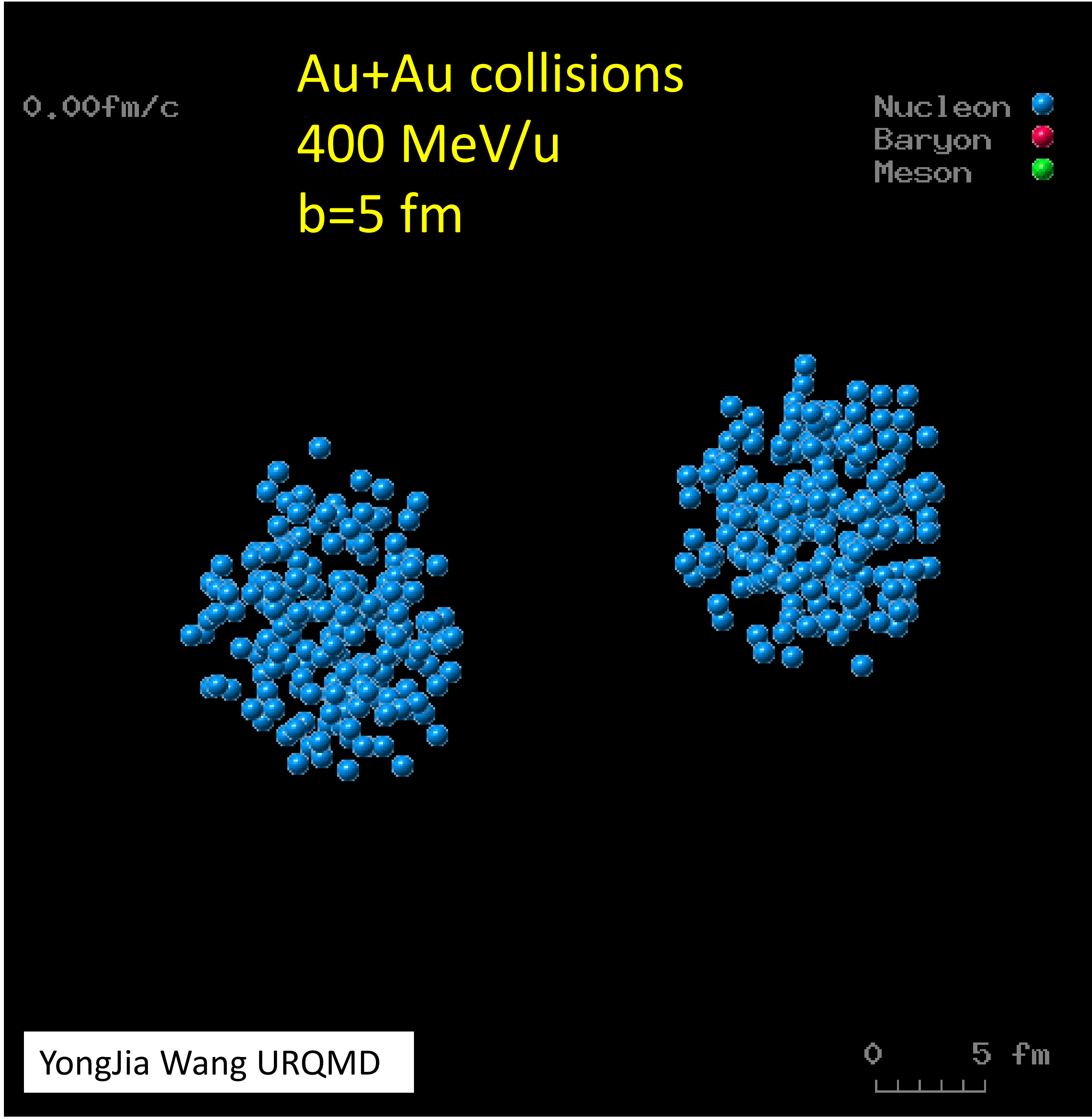
The binary tidal deformability R(NS)<13.76 km



Chiral effective field theory

Tews et al Arxiv:1801.01923

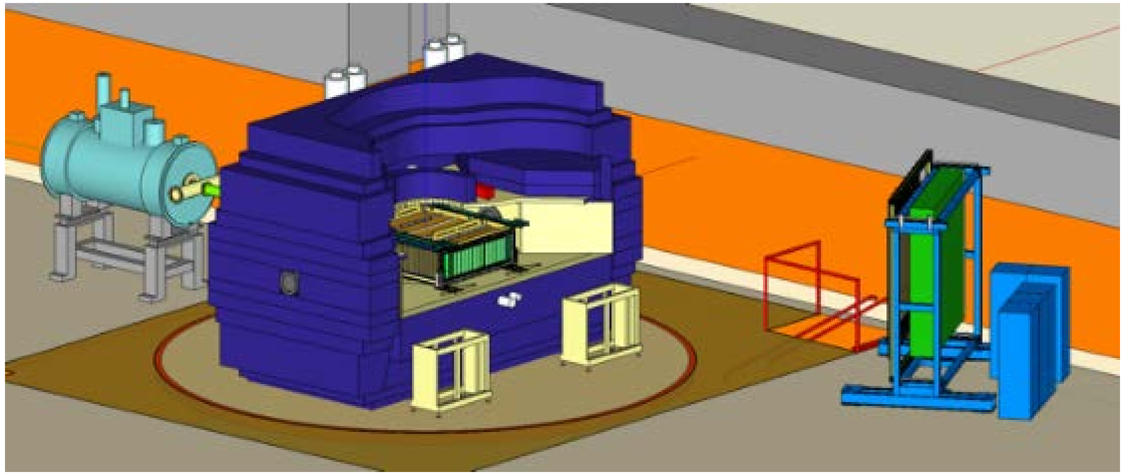




YongJia Wang URQMD

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



On Site Experimenters

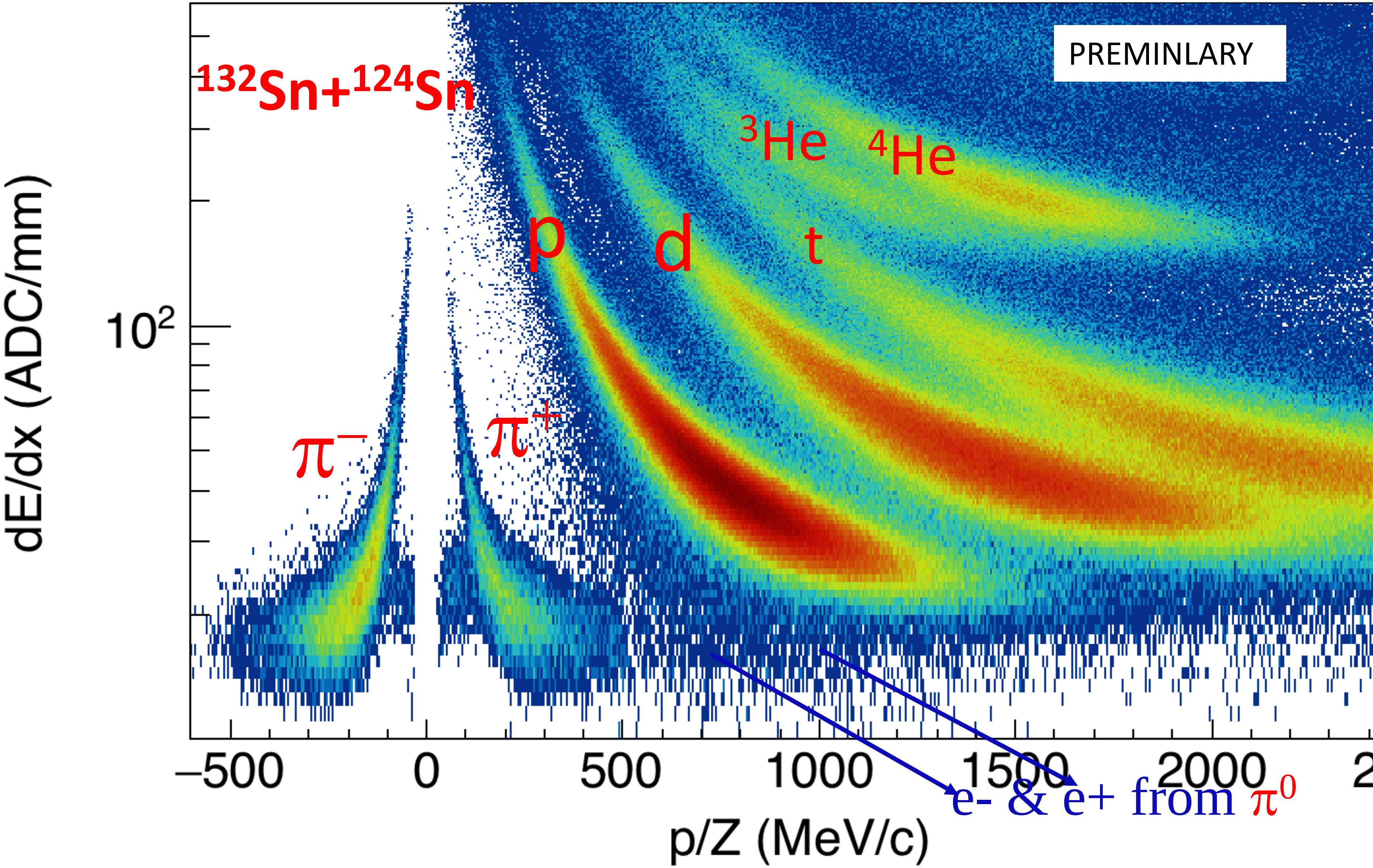
J. Barney (MSU)
G. Cerizza (MSU)
J. Estee (MSU)
B. Hong (Korea U)
T. Isobe (RIKEN)*
G. Jhang (Korea U)
M. Kaneko (Kyoto U)
M. Kurata-Nishimura (RIKEN)
P. Lasko (IFN, Krakow)
H. Lee (RISP)
J. Lee (Korea U)
J. Lukasik (IFN, Krakow)
W. Lynch (MSU)*
A. McIntosh (TAMU)
P. Morfouace (MSU)
T. Murakami (Kyoto 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

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

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?



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

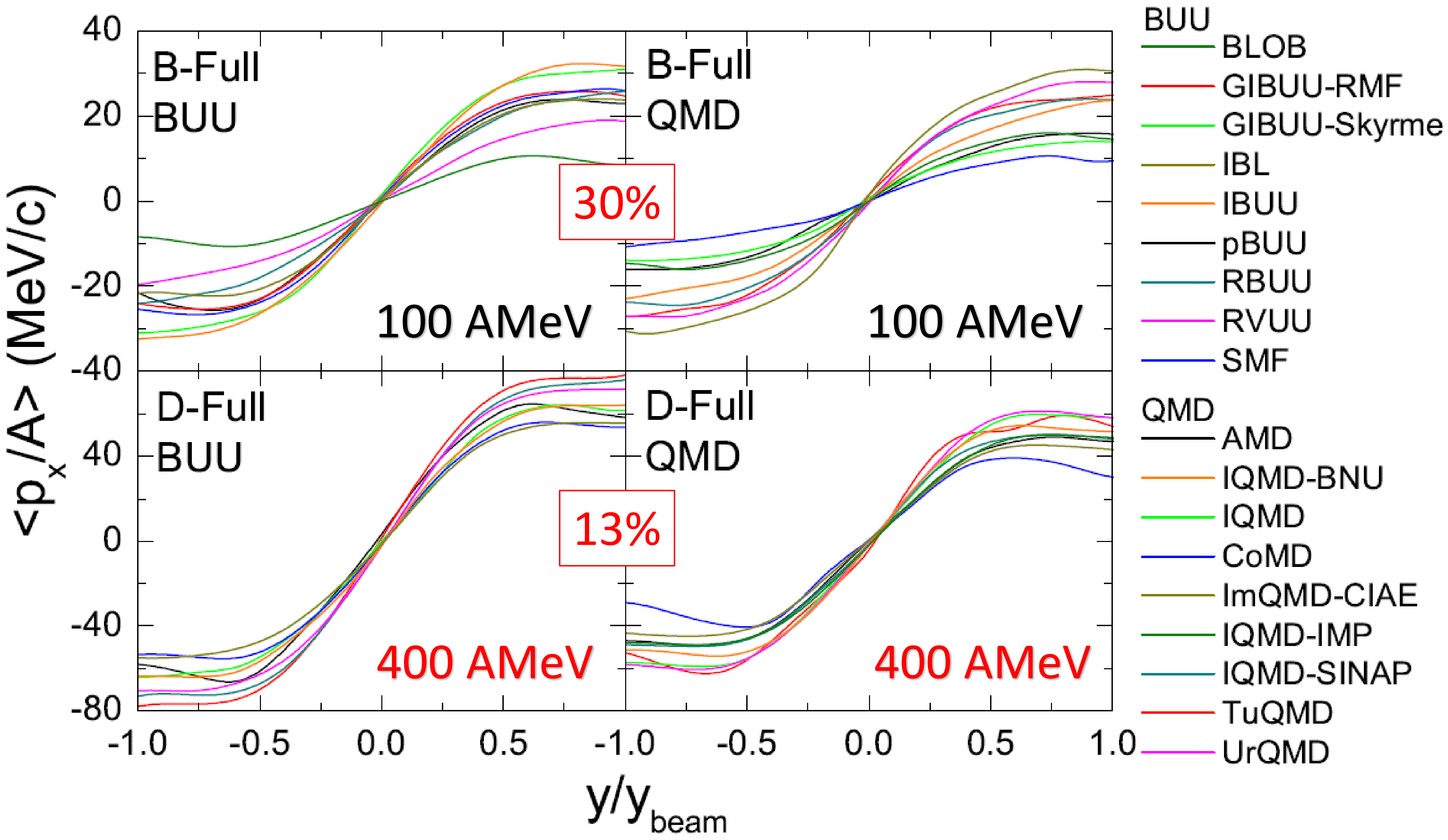
BUU Type	Code		Box		
		flow pub	casc pub	Vlas	pion
BUU-VM^a	S. Mallik		X	X	X
BLOB	P. Napolitani	X			
GIBUU-RMF	J. Weil	X	X		
GIBUU-Sky	J. Weil	X			
IBL	W.J. Xie	X			
IBUU	J. Xu	X	X	X	X
pBUU	Danielewicz	X	X	X	X
RBUU	K. Kim	X			
RVUU	C.M. Ko	X	X	X	X
SMASH	Oliinychenko		X		
SMF	M. Colonna	X	X	X	X

QMD Type	Code		Box		
		flow pub	casc pub	Vlas	pion
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 (2016)

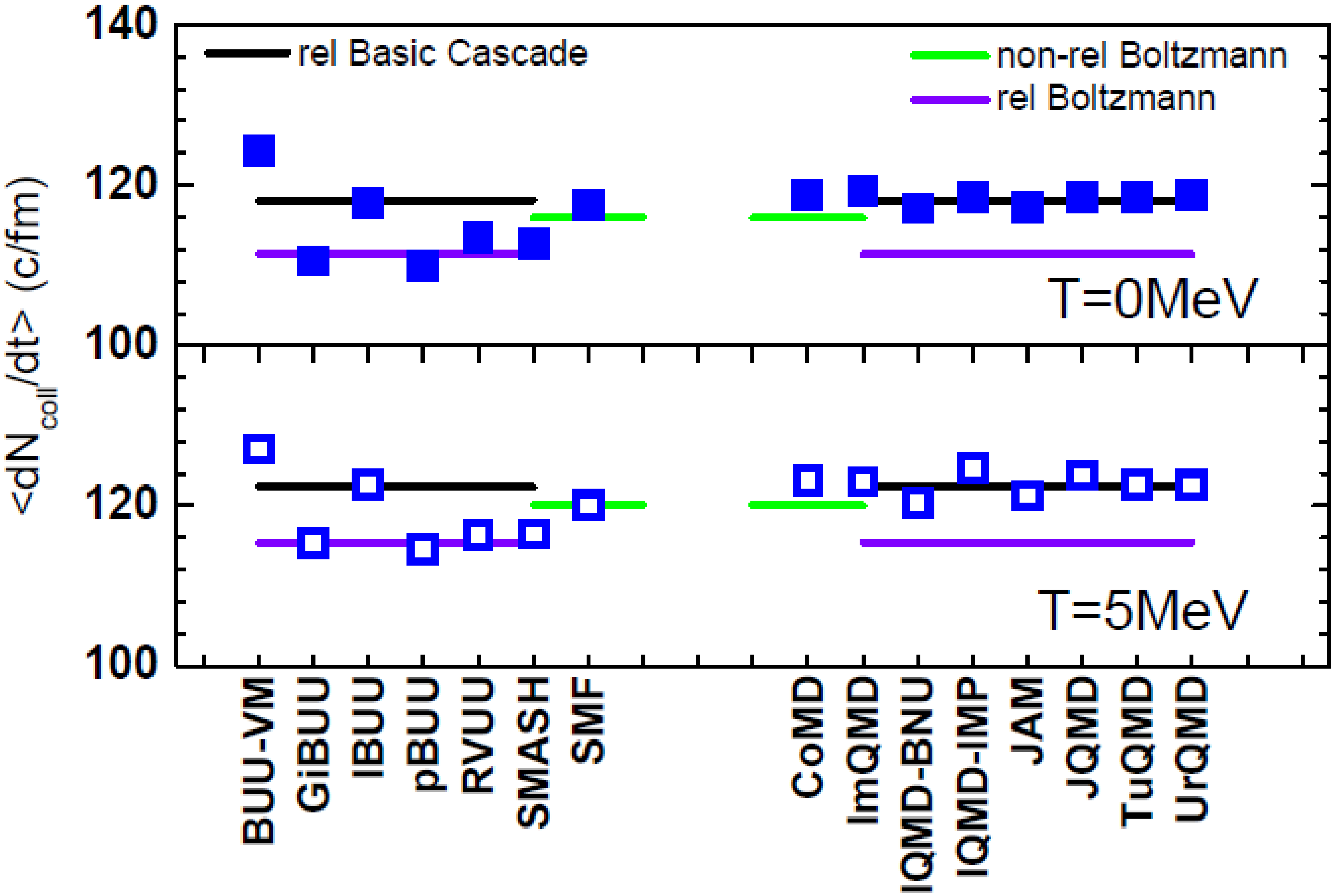
Pub : Zhang et al., PRC 97, 035505 (2017)

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.

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		Box		
		flow pub	casc pub	Vlas	pion
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		Box		
		flow pub	casc pub	Vlas	pion
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 (2016)

Pub : Zhang et al., PRC 97, 035505 (2017

SπRIT

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CULTURE, SPORTS,
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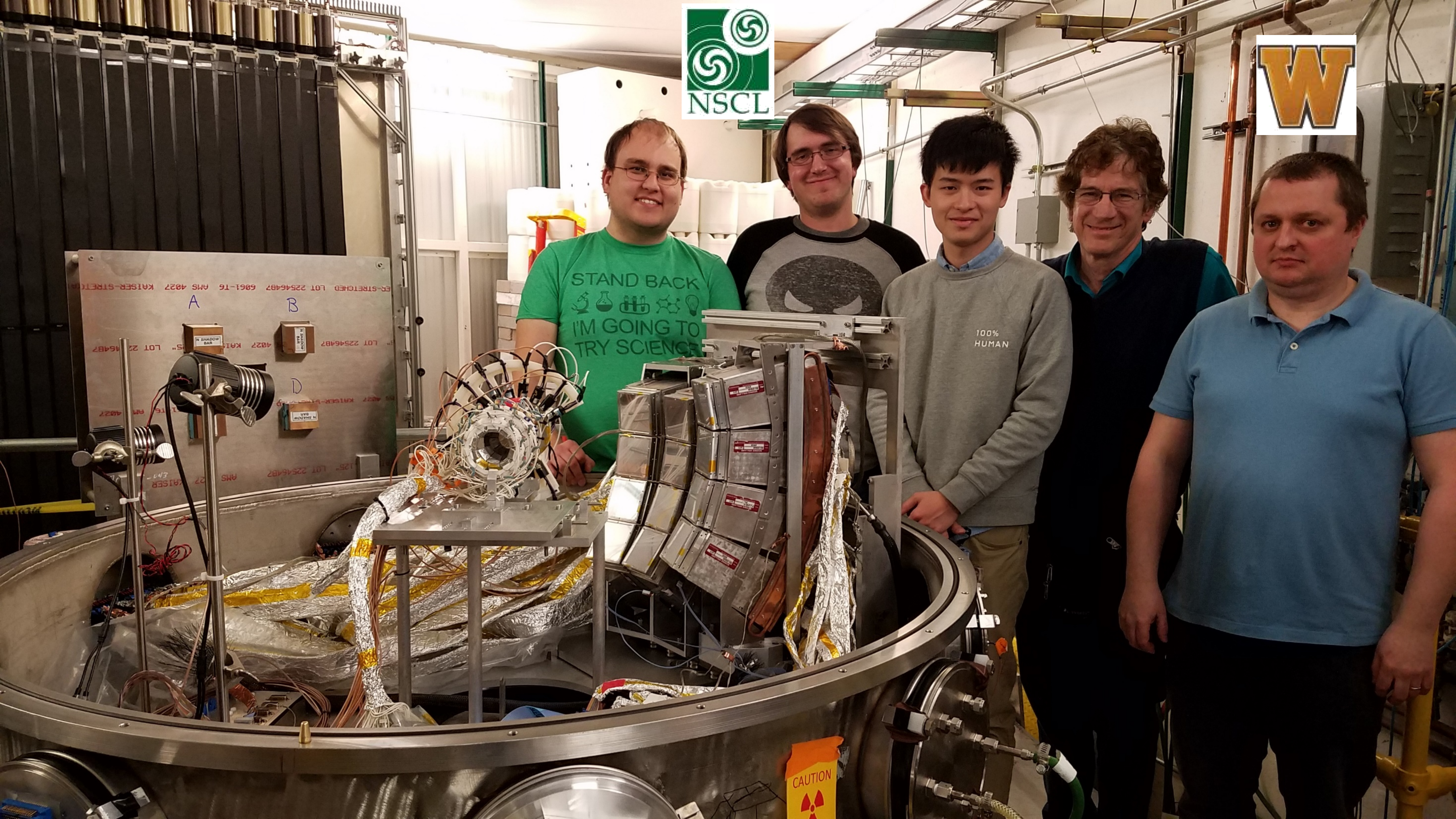
NSCL
STAND BACK
I'M GOING TO
TRY SCIENCE
100%
HUMAN
A
B
D
N SHADOW BAR
CAUTION

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.
- Need to connect our EoS results to the neutron star merger results