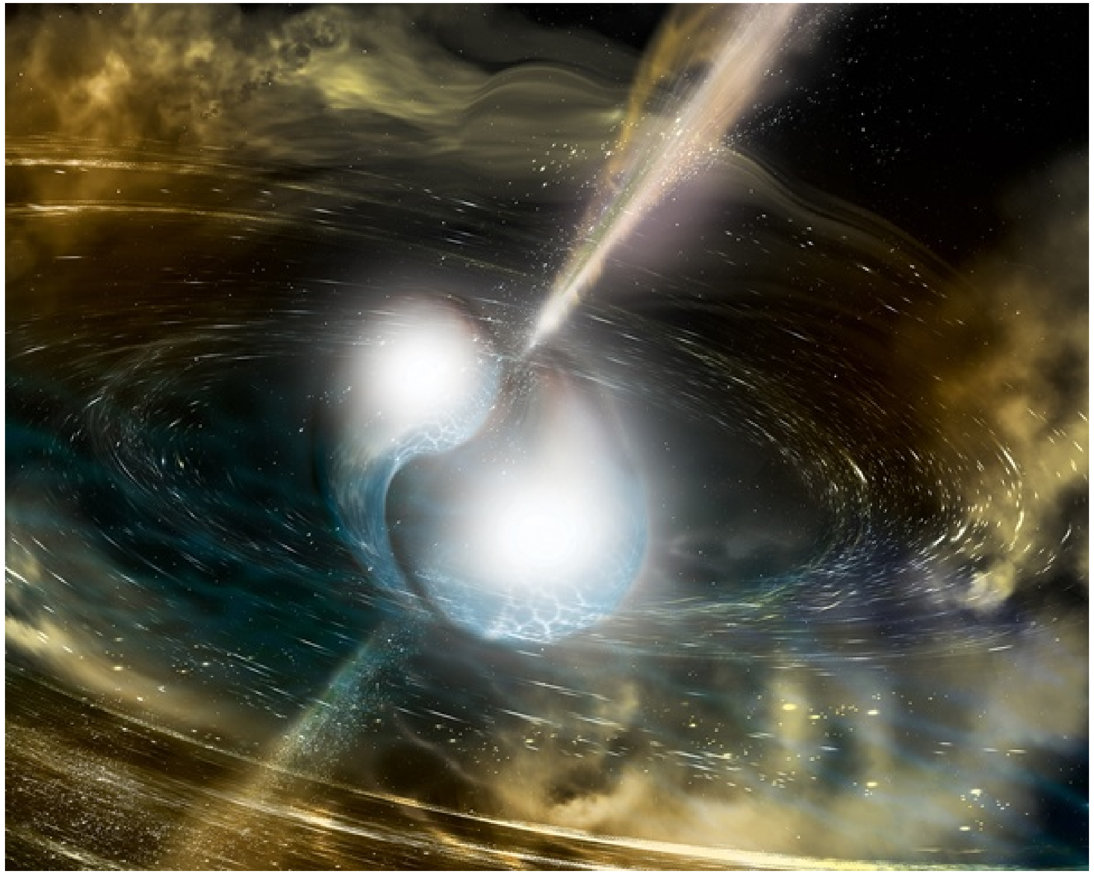
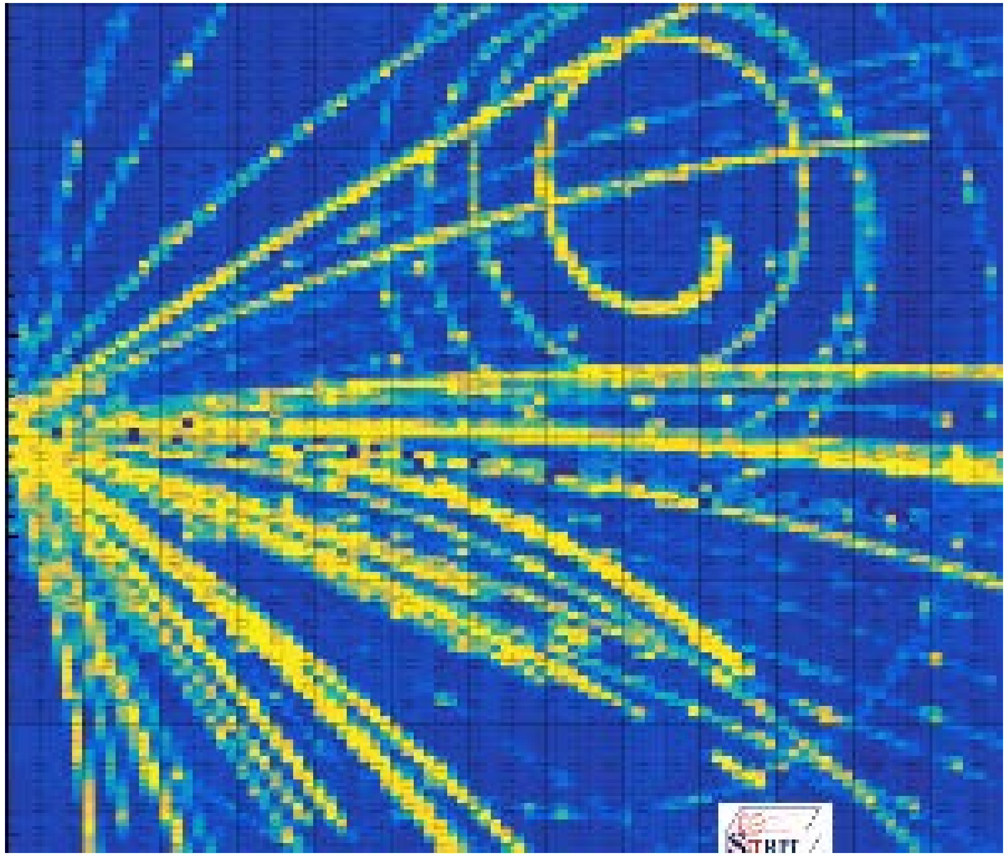
# Comparison of symmetry energy constraints from neutron star merger and heavy ion collisions

**LIGO Detects a Neutron Star Merger**



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

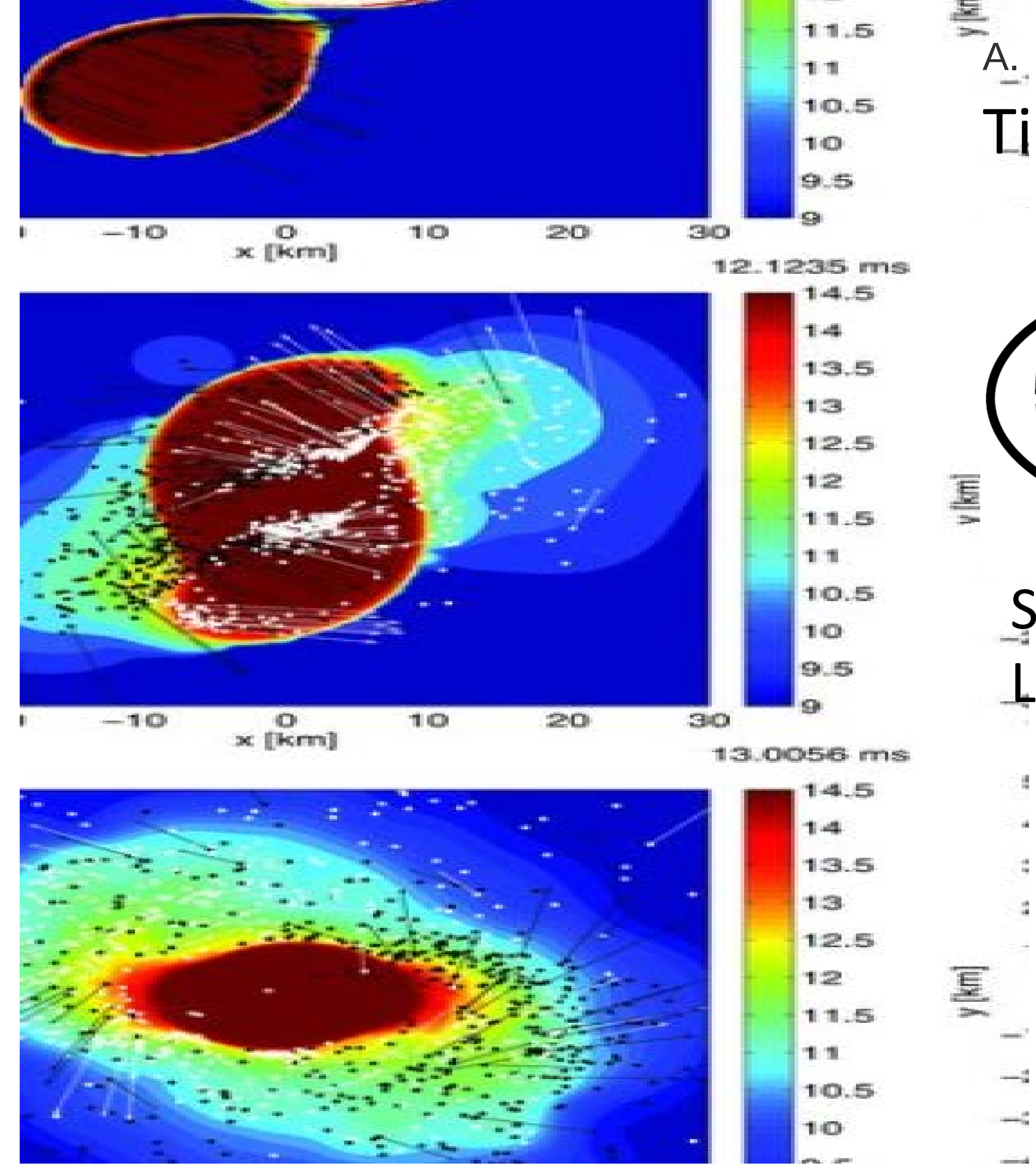



Betty Tsang, NSCL

Michigan State University

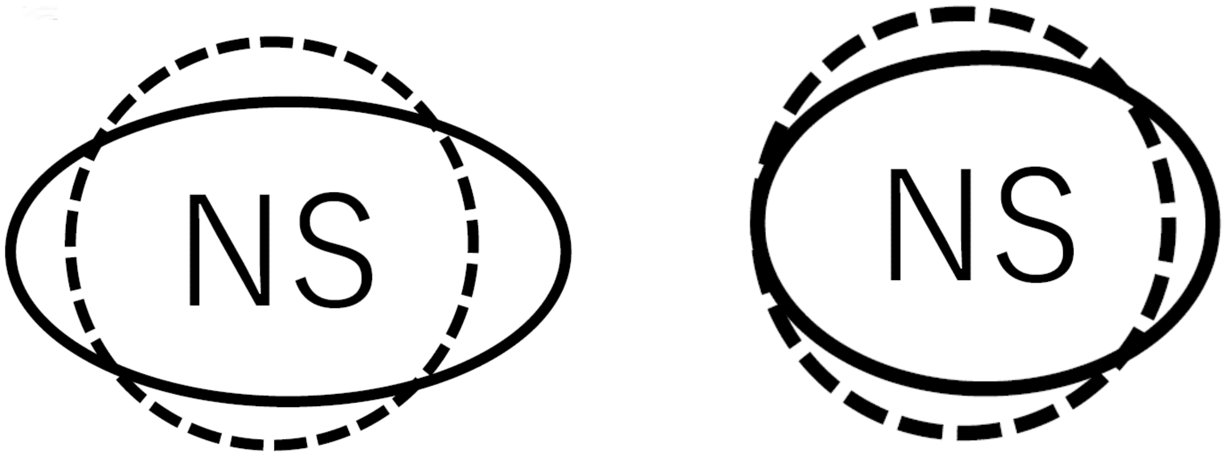

NuSYM 2018: 10/11-14

Busan, S. Korea




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

# Tidal deformation of the Neutron Star




Soft EoS
Large deformation

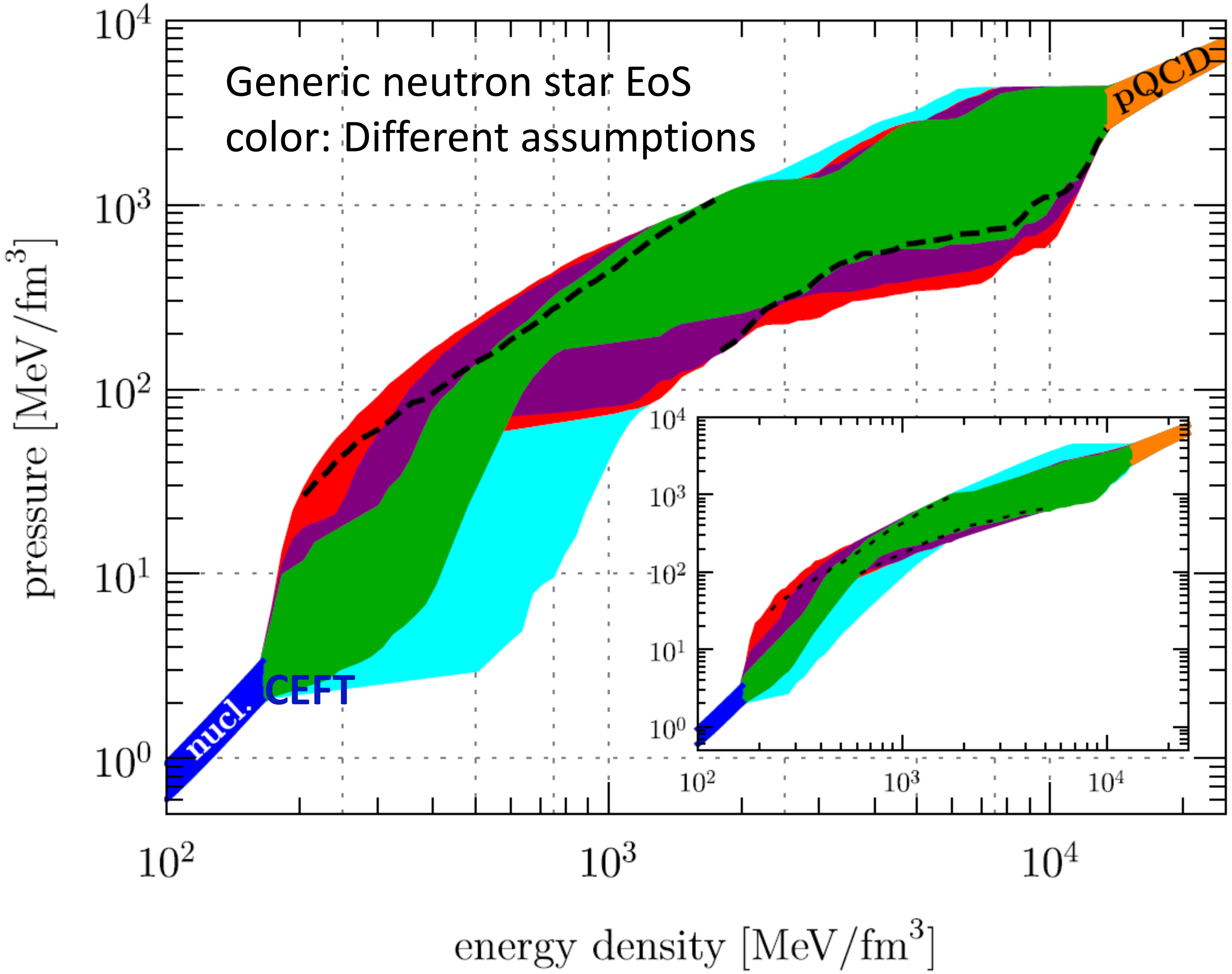
Stiff EoS
small deformation

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

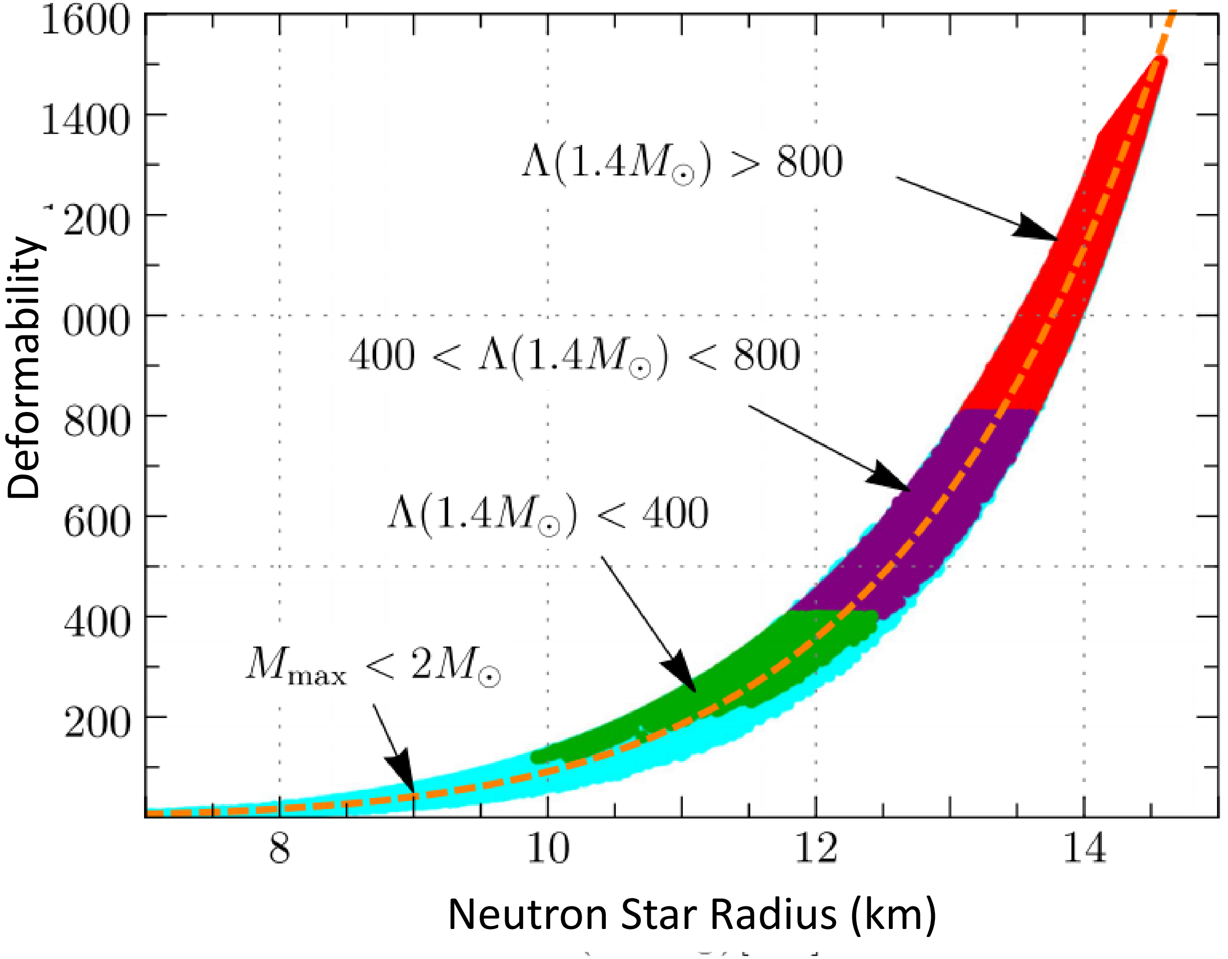
$\Lambda$<800 (90% confidence)

GW170817 PRL 119 161101

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




Love number k2 also depends on NS radius

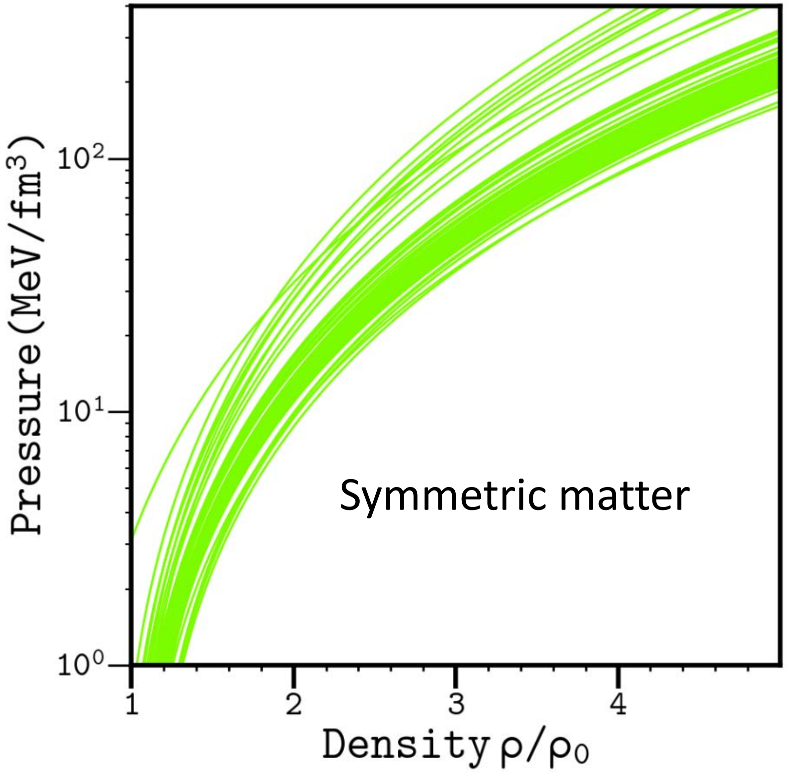


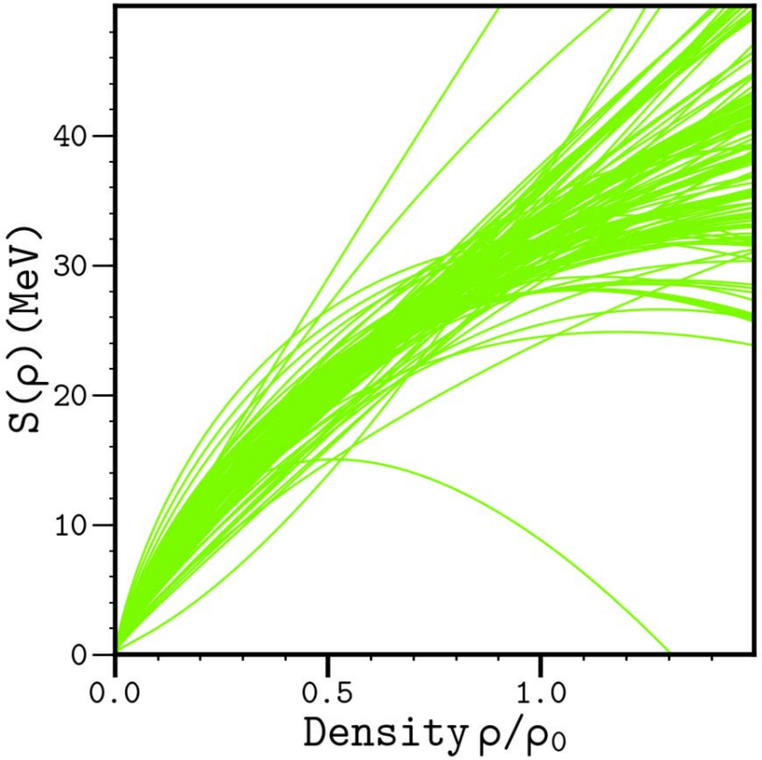

Annala et al., PRL 120, 172703

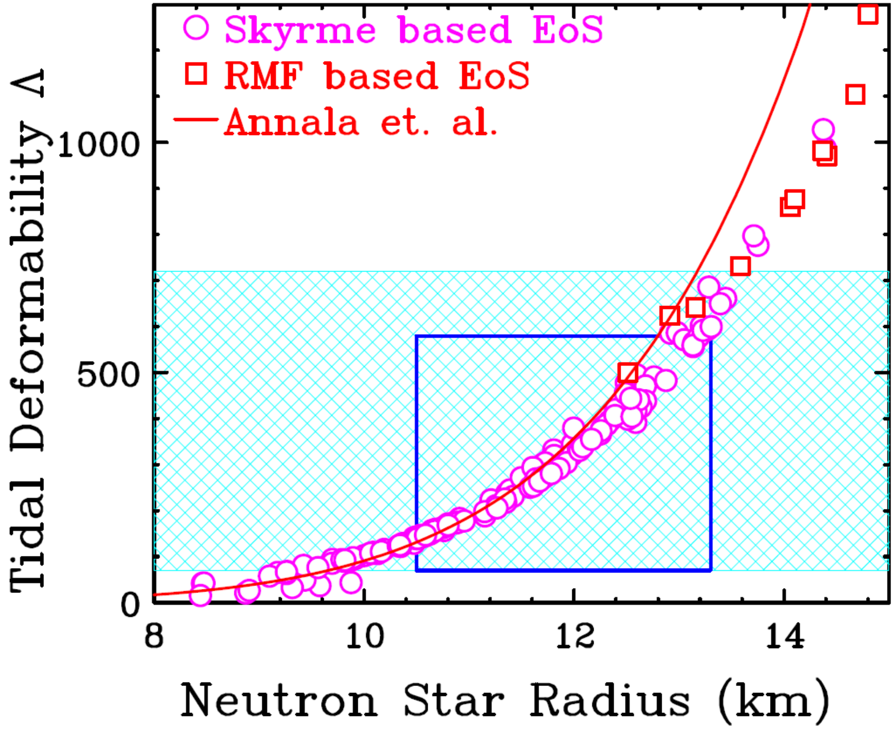
# Nuclear Physics ↔ Neutron Star Physics

## Using Skyrmes to conduct an overview study of Neutron star properties

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



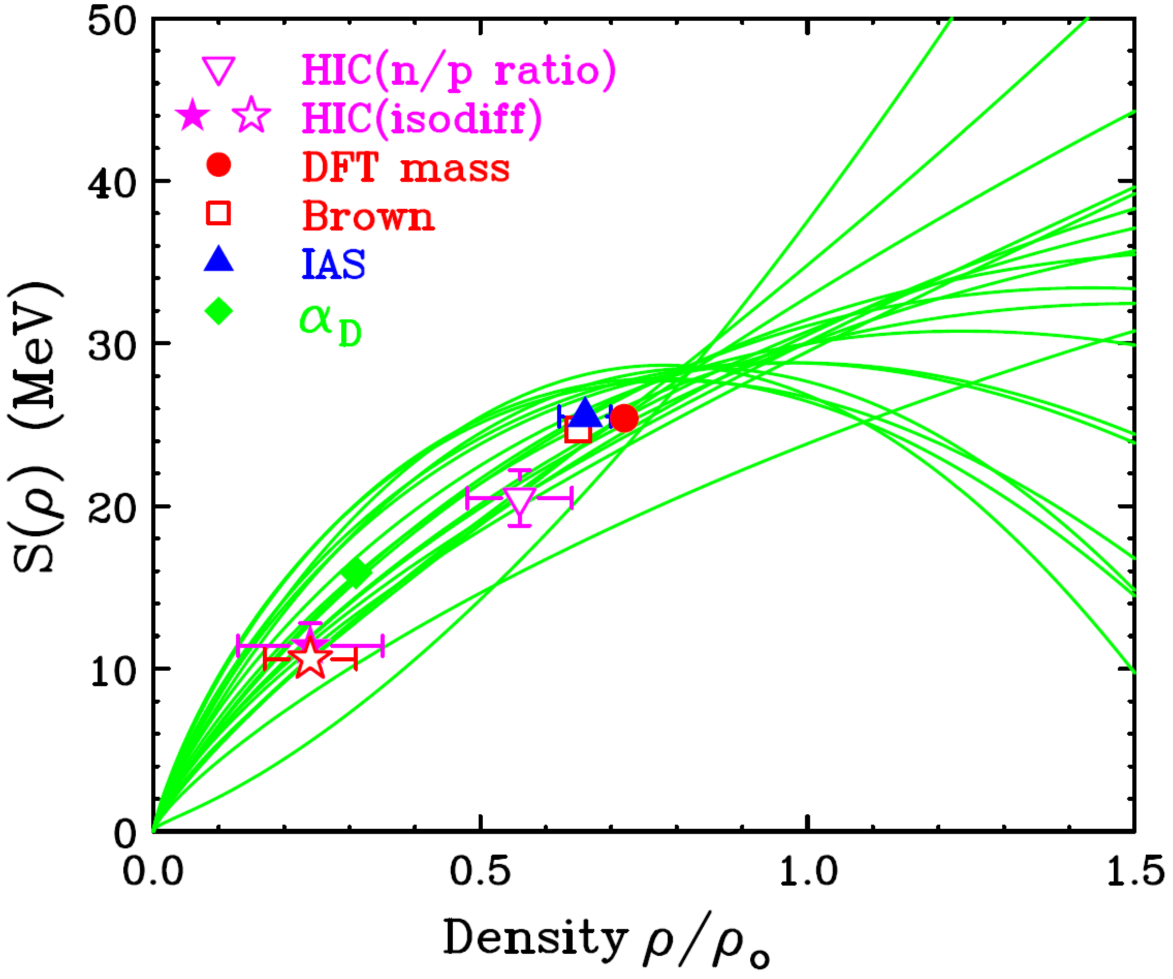



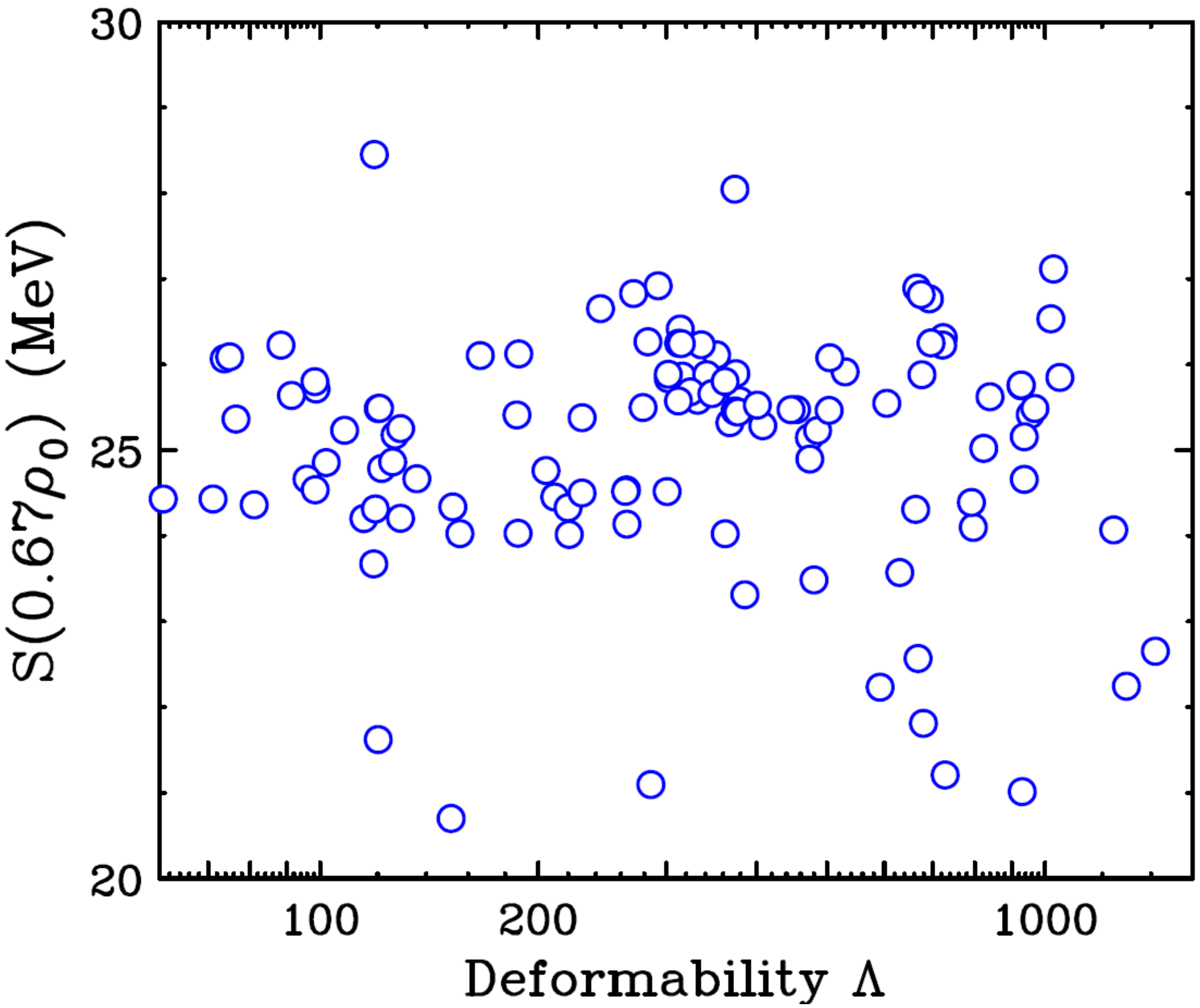

Tommy CY Tsang et al., ArXiv: 1807:06571

GW170817 arXiv:1805.11581 (2018)

Compare to experimental data

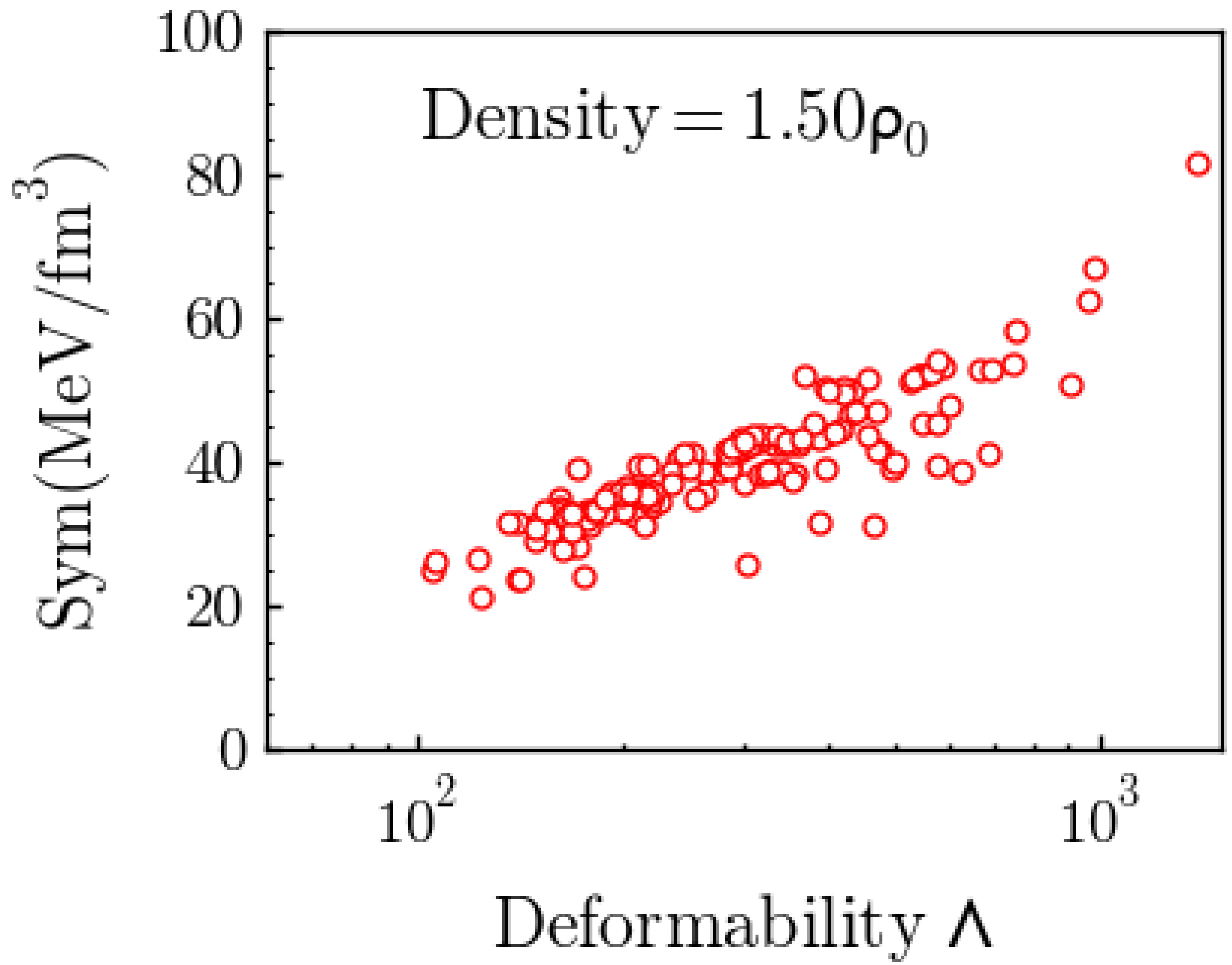
# Very little selectivity on tidal deformability at low density

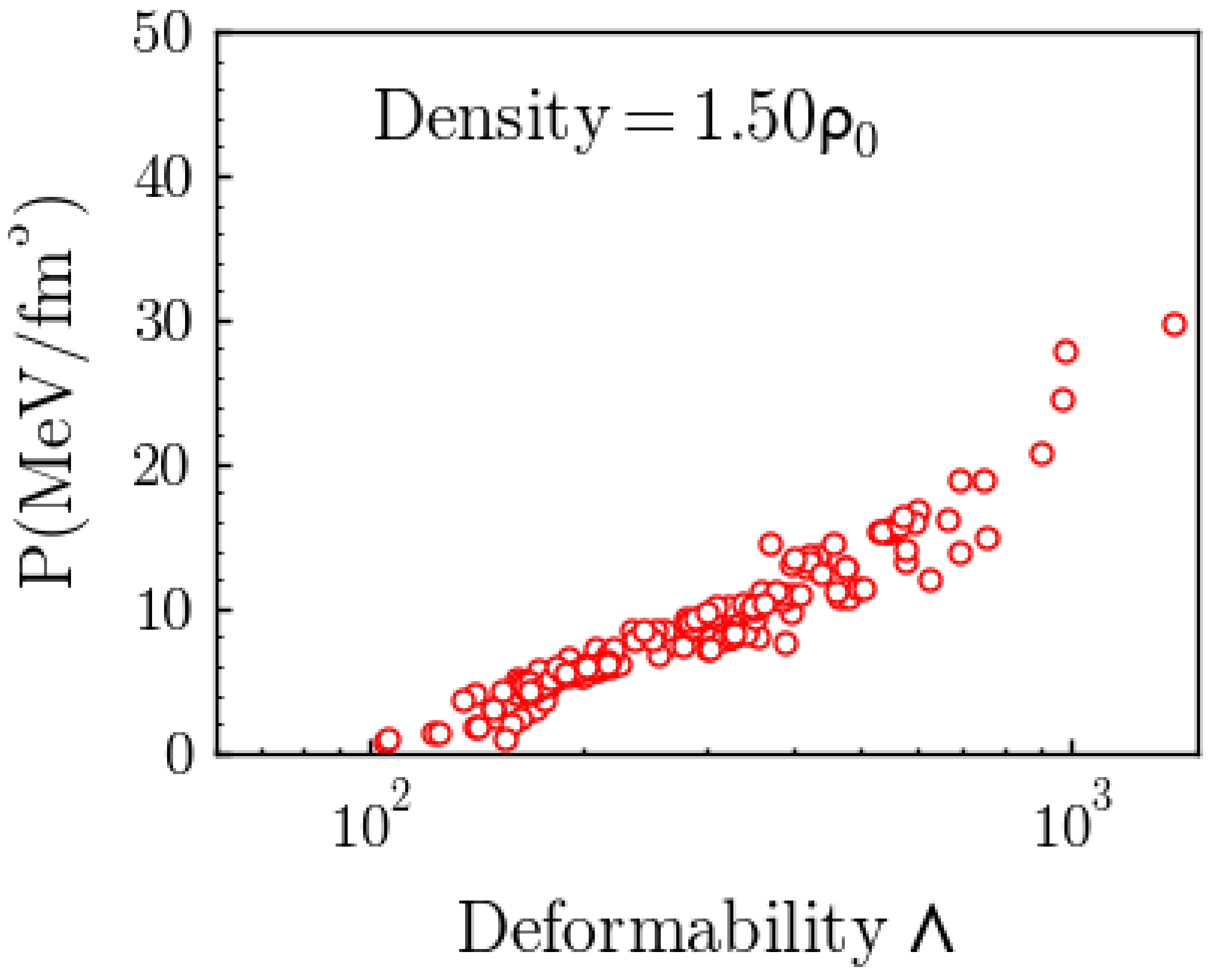



Sub-saturation constraints do not constrain the tidal deformability or neutron star radii.
However, these constraints are important to understand the neutron crust-core-transition.

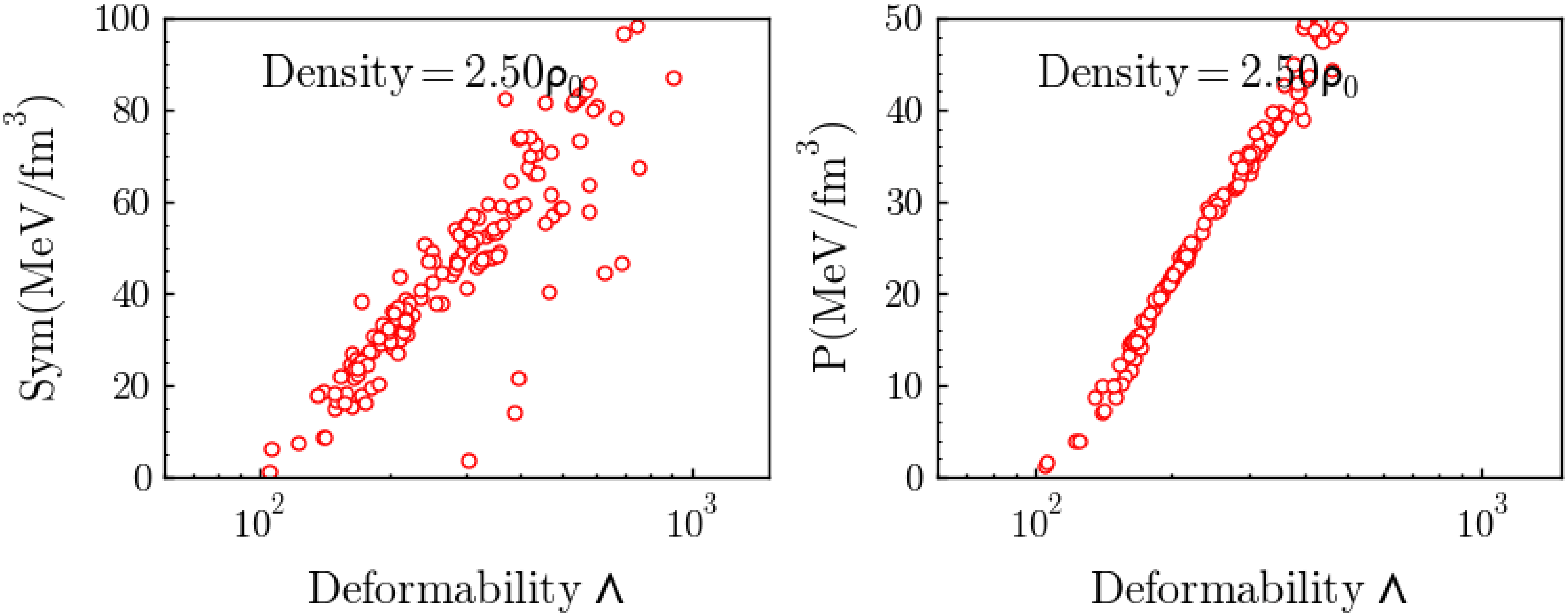
# Which Density to explore ?



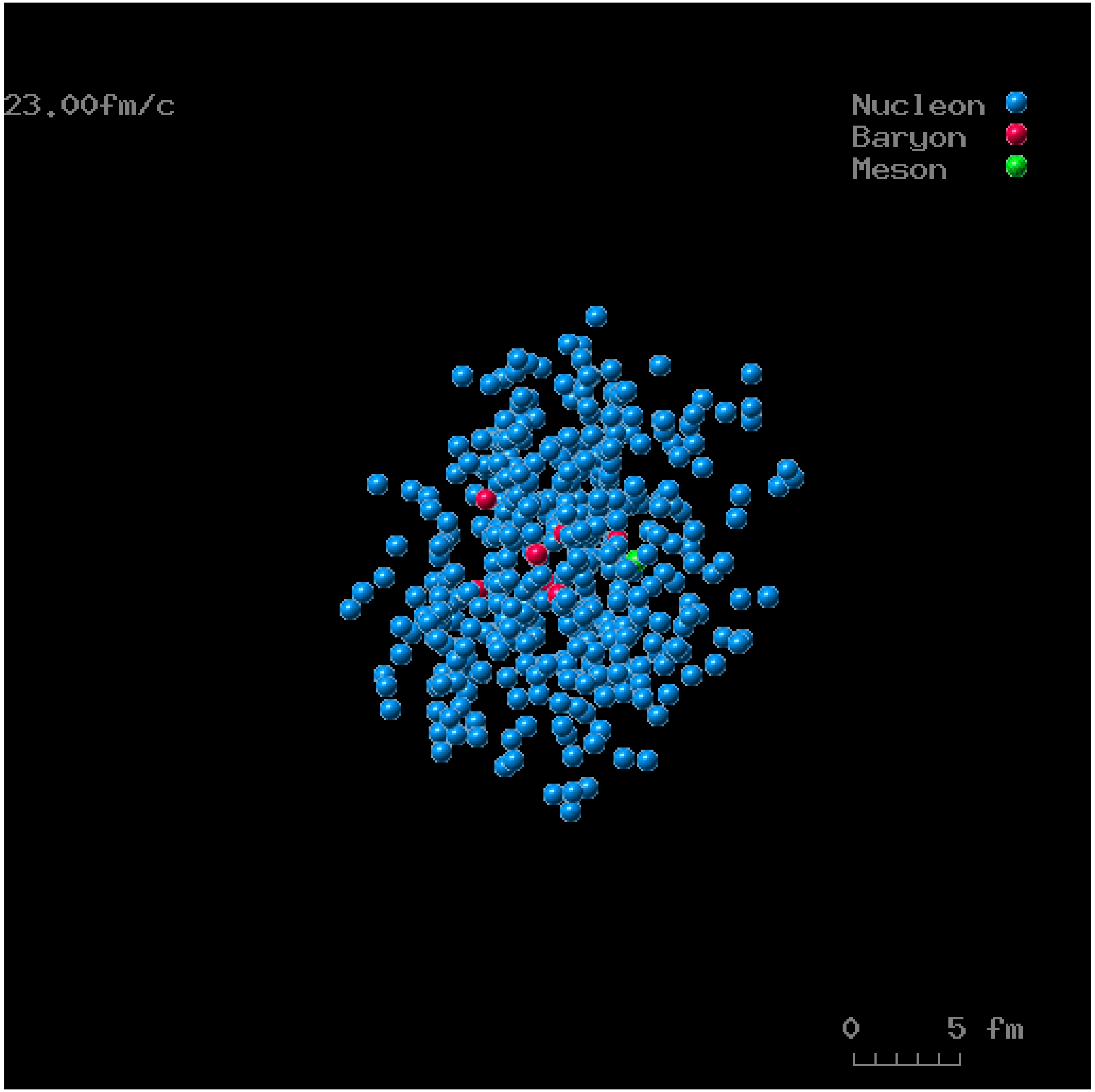

Tommy C.Y. Tsang et al., under

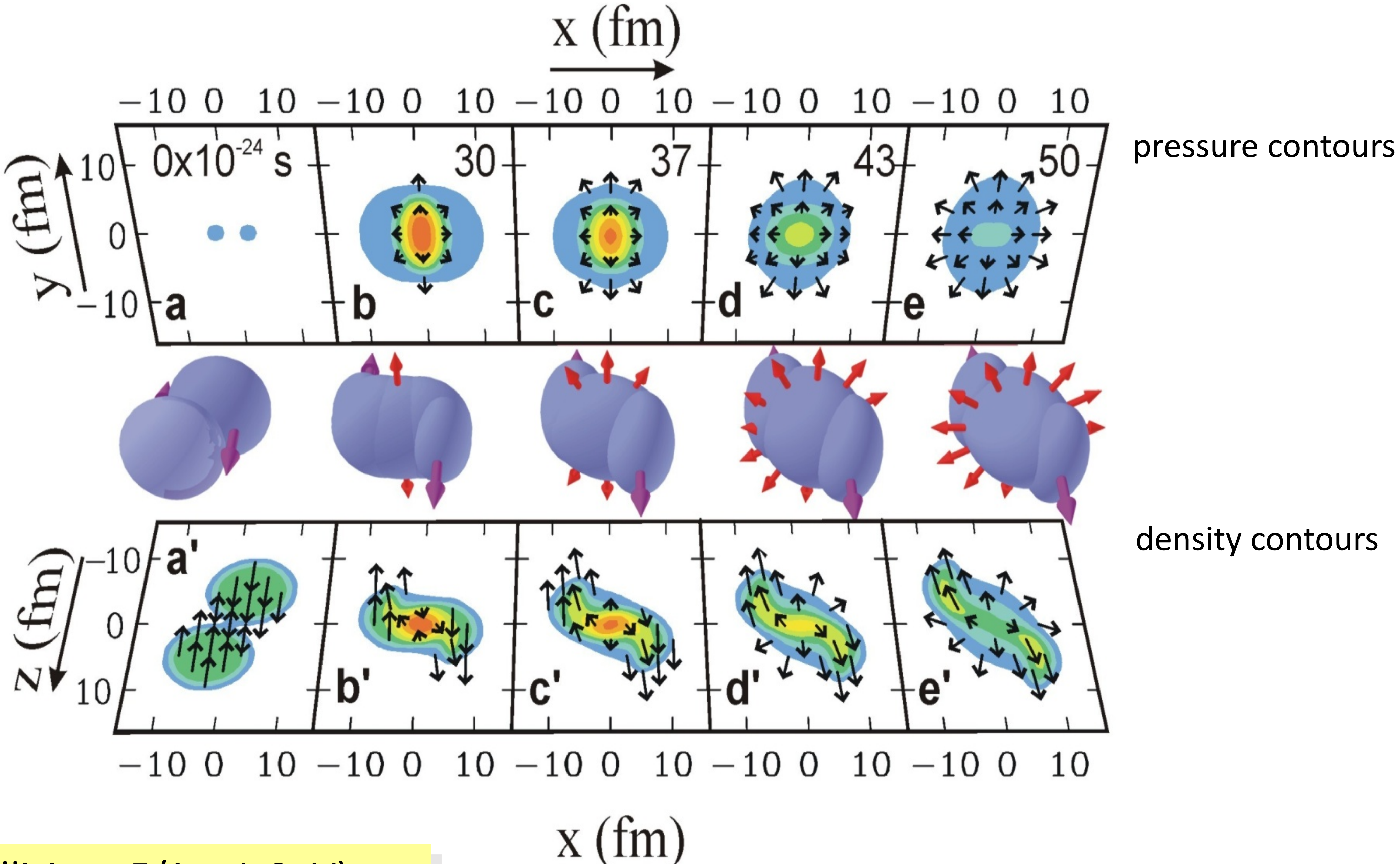
# What observable?




Tommy C.Y. Tsang et al., under preparation

# How to squeeze nuclear matter – Heavy Ion collisions






Au+Au collisions E/A = 1 GeV)

Danielewizc, Lacey, Lynch, **Science** 298 (2002) 1592

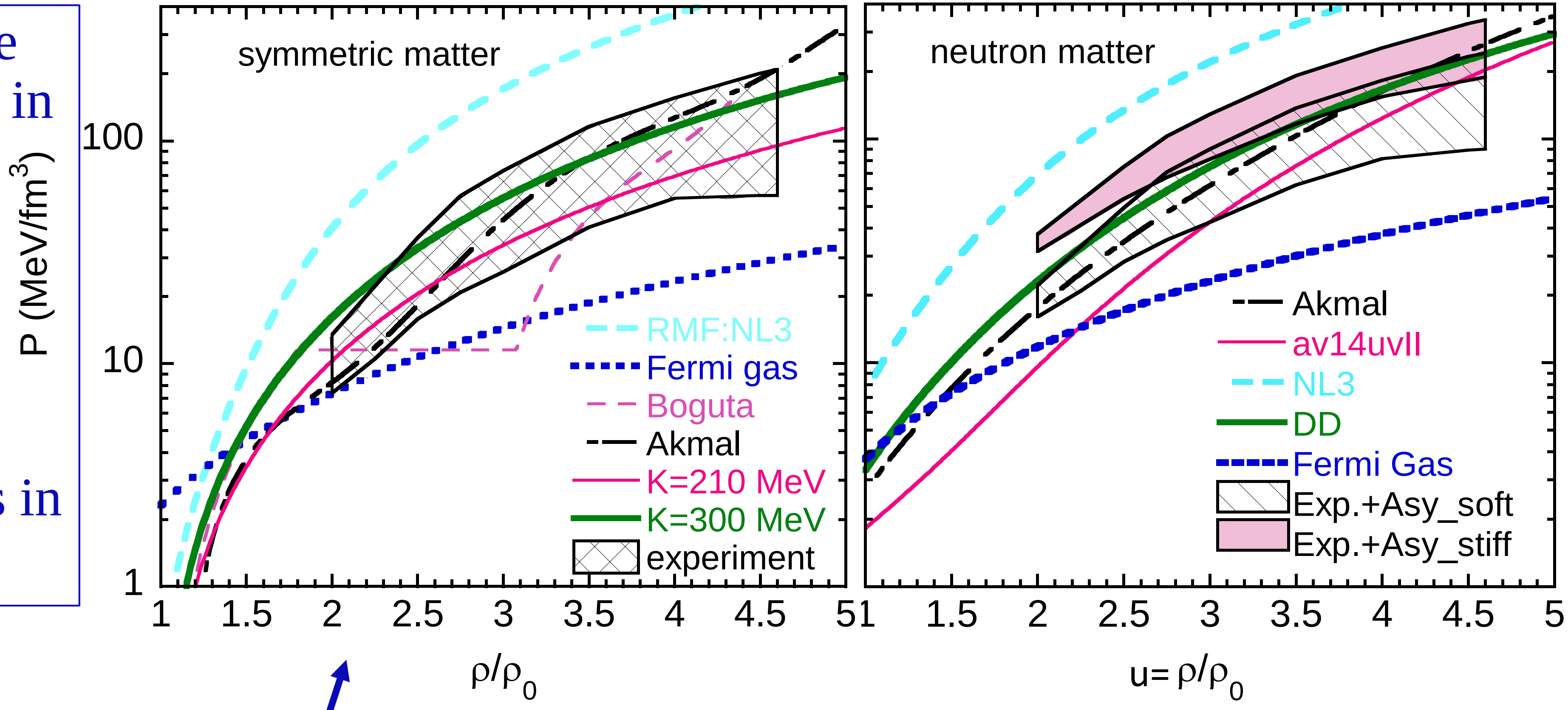
# Determination of symmetric matter EOS from heavy-ion collisions

Danielewicz et al., Science 298,1592 (2002).

Two observable from the high pressures formed in the overlap region:

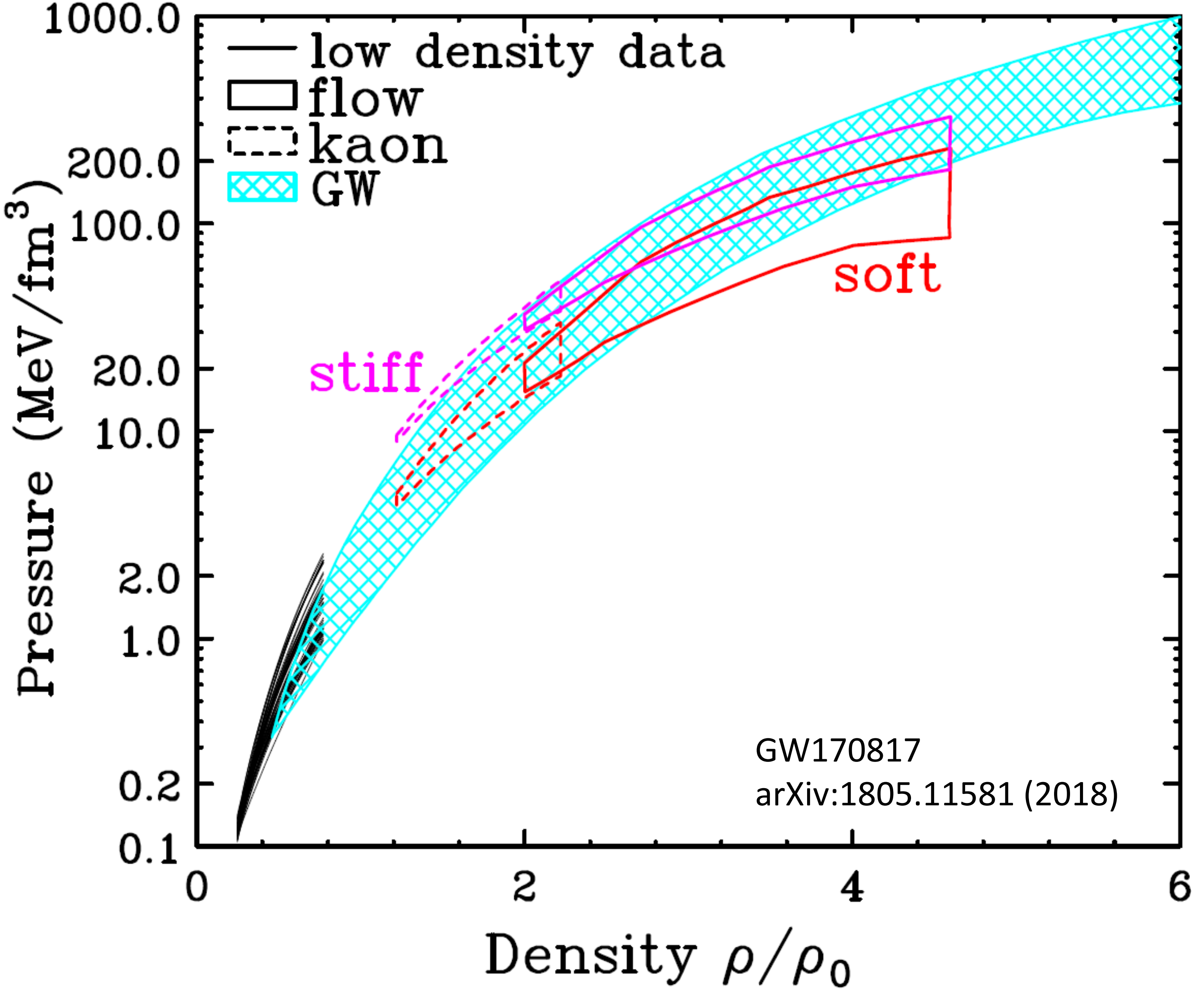
Nucleons are "squeezed out" above and below the reaction plane.

Nucleons from residues are deflected sideways in the reaction plane



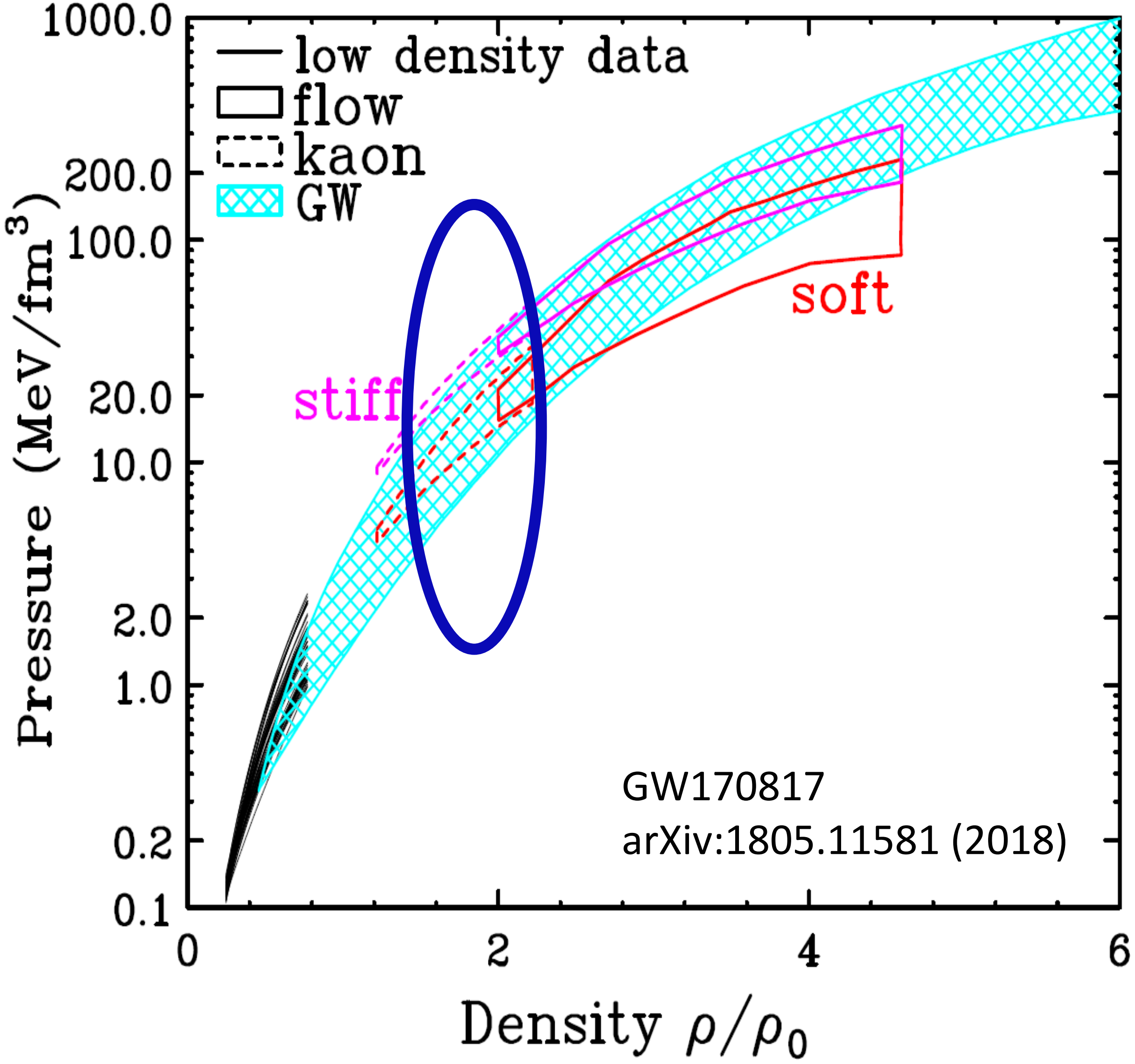

Asy_Stiff: $S_{int} \propto 2u^2/(1+u)$ Asy_Soft: $S_{int} \propto \sqrt{u}$

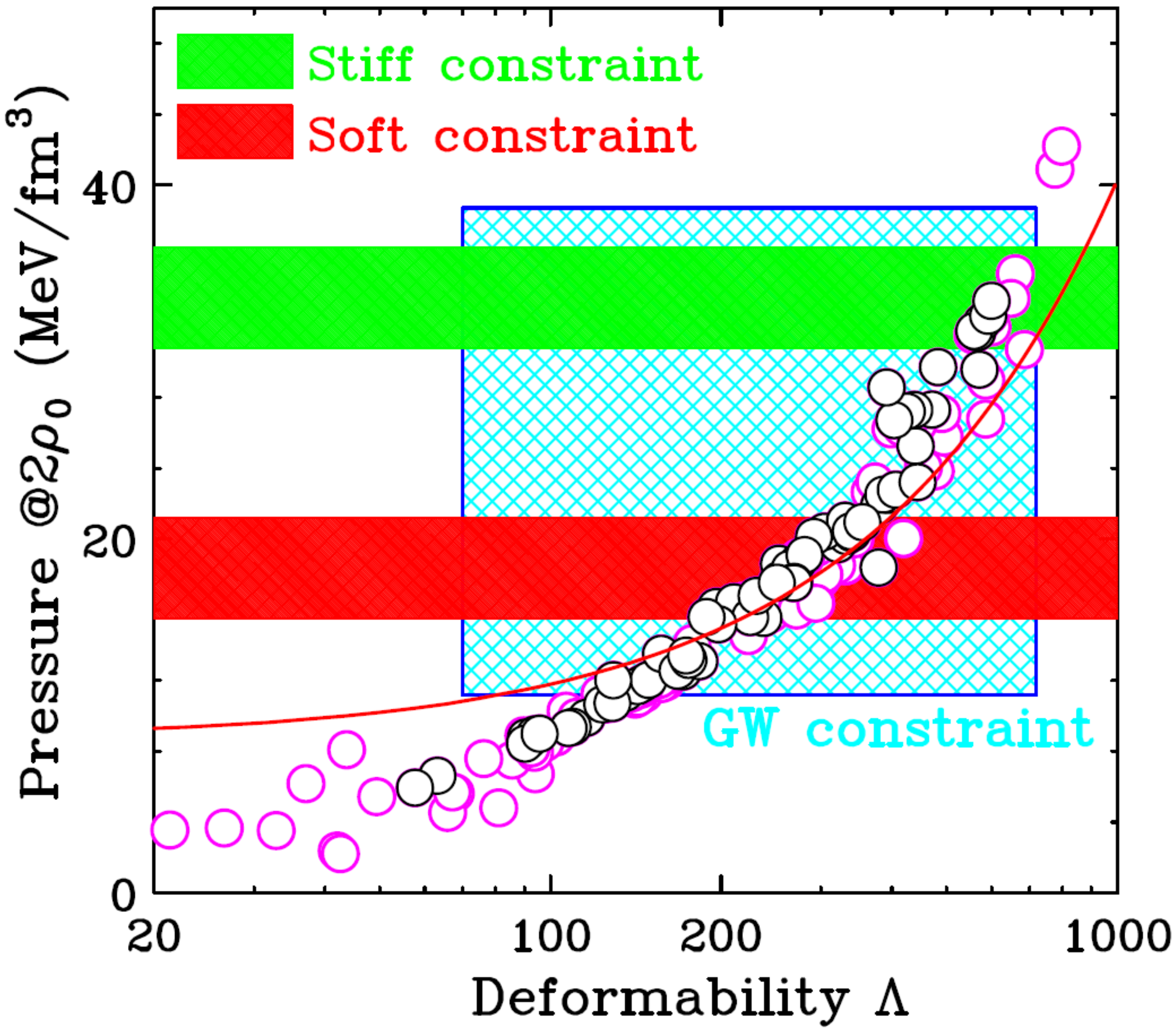
$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho); \qquad \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

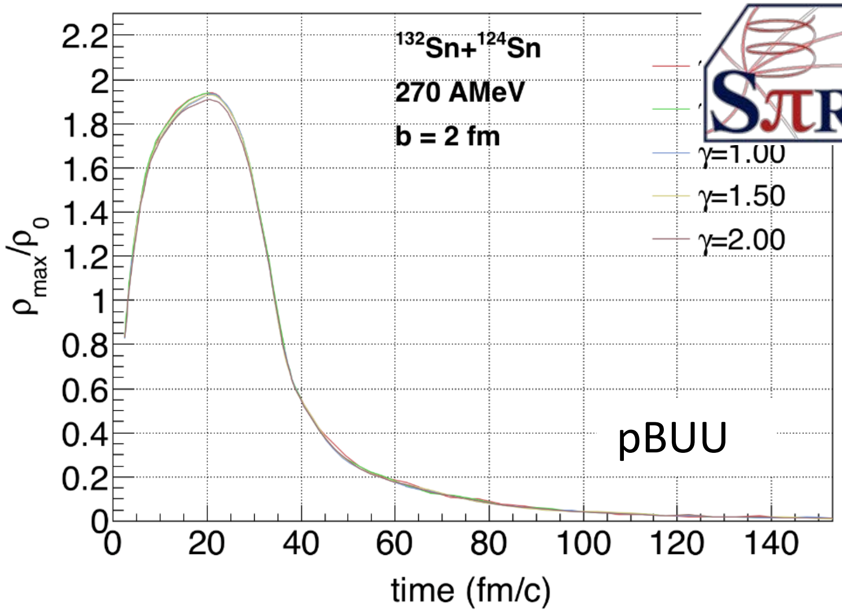



GW170817
arXiv:1805.11581 (2018)

# High density constraints from heavy-ion collisions

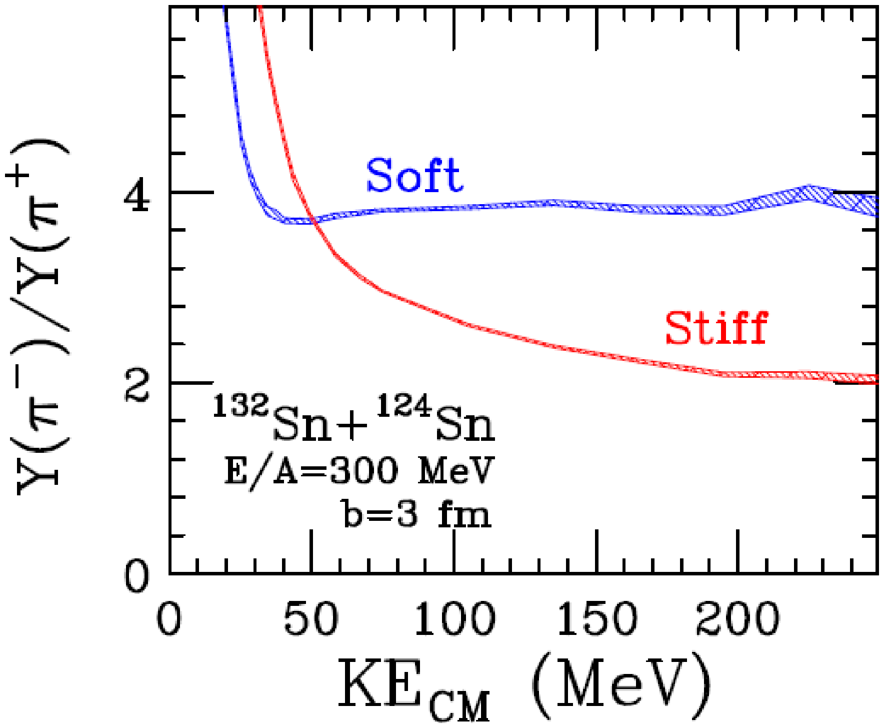


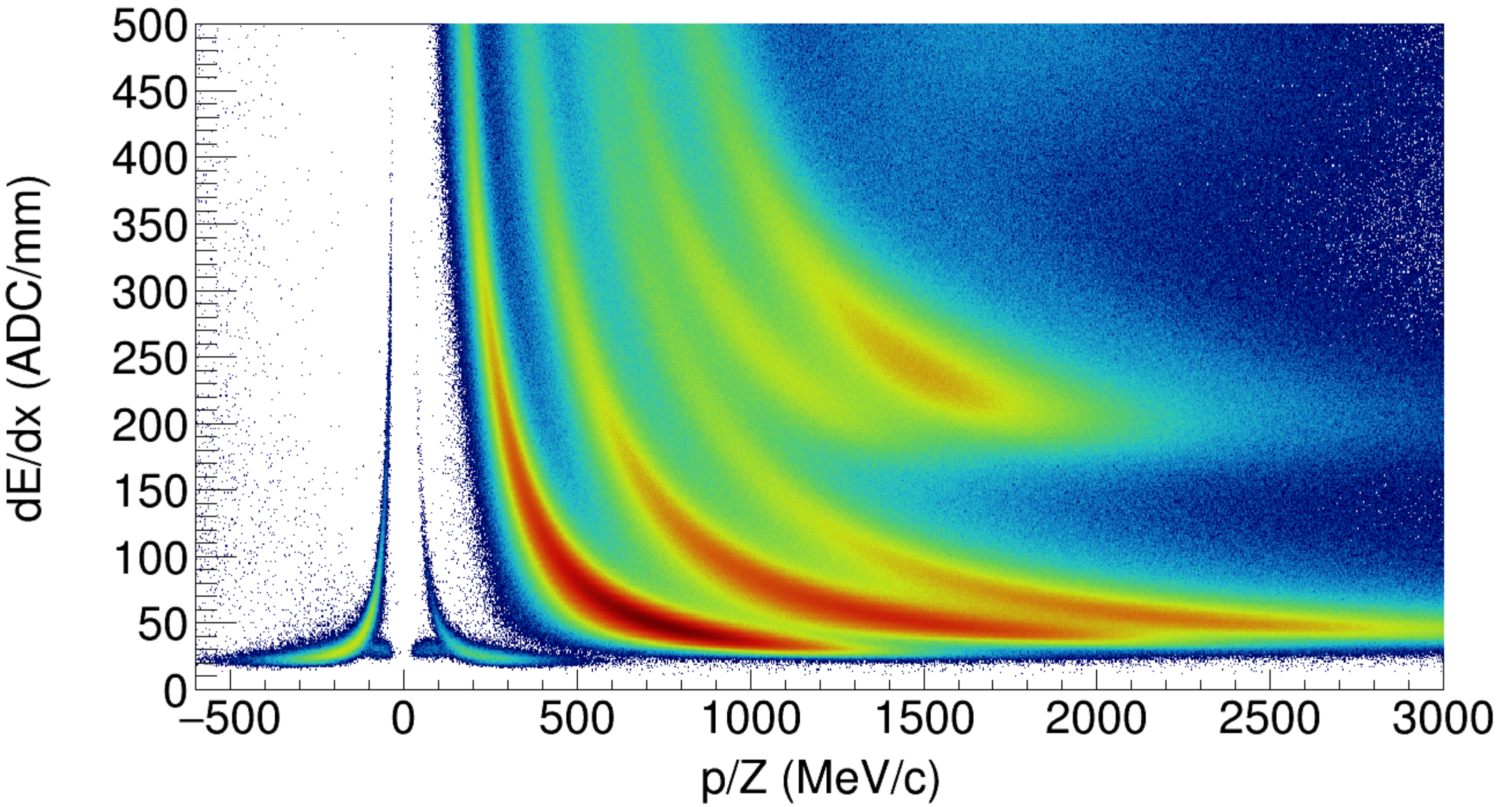






| Primary | Beam | Target | $E_{beam}/A$ | $\delta_{sys}$ | evt(M) | 2016 |
|---|---|---|---|---|---|---|
| $^{124}$Xe | $^{108}$Sn | $^{112}$Sn | 269 | 0.09 | 8 | 4/30-5/4 |
| | $^{112}$Sn | $^{124}$Sn | 270 | 0.15 | 5 | 5/4-5/6 |
| $^{238}$U | $^{132}$Sn | $^{124}$Sn | 269 | 0.22 | 9 | 5/25-5/29 |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

Talks by JW Lee, RS Wang, M. Nishimura, M. Kaneko, G. Jhang,



# Double Ratios vs. Single Ratios

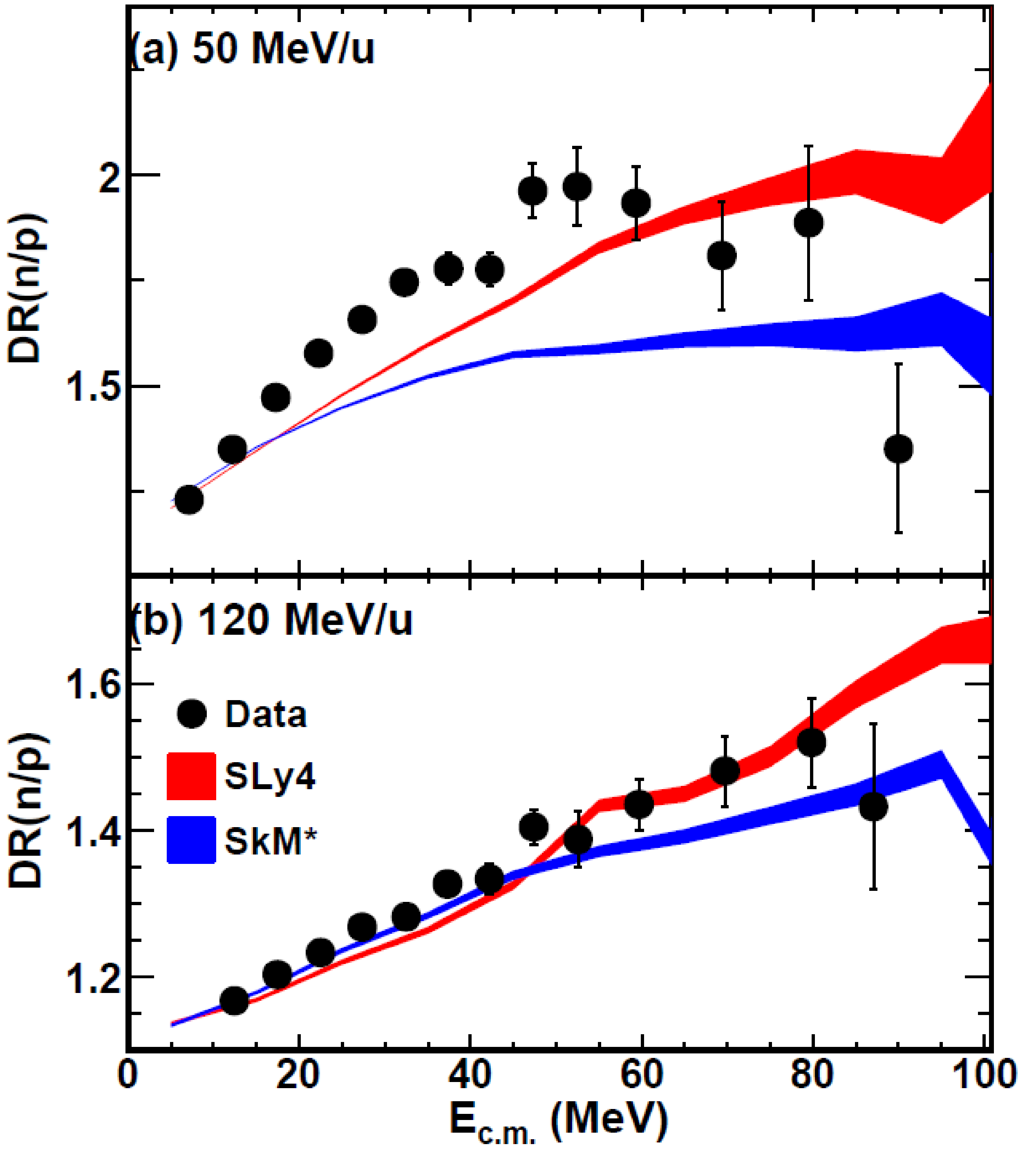
$R_{n/p}=Y(n)/Y(p)$

Experimental efficiencies not easily determined

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

Pros:
Minimize sensitivity to neutron and proton detector efficiencies.

Cons:
May lose sensitivities to symmetry energy or effective mass due to cancelation of effects.



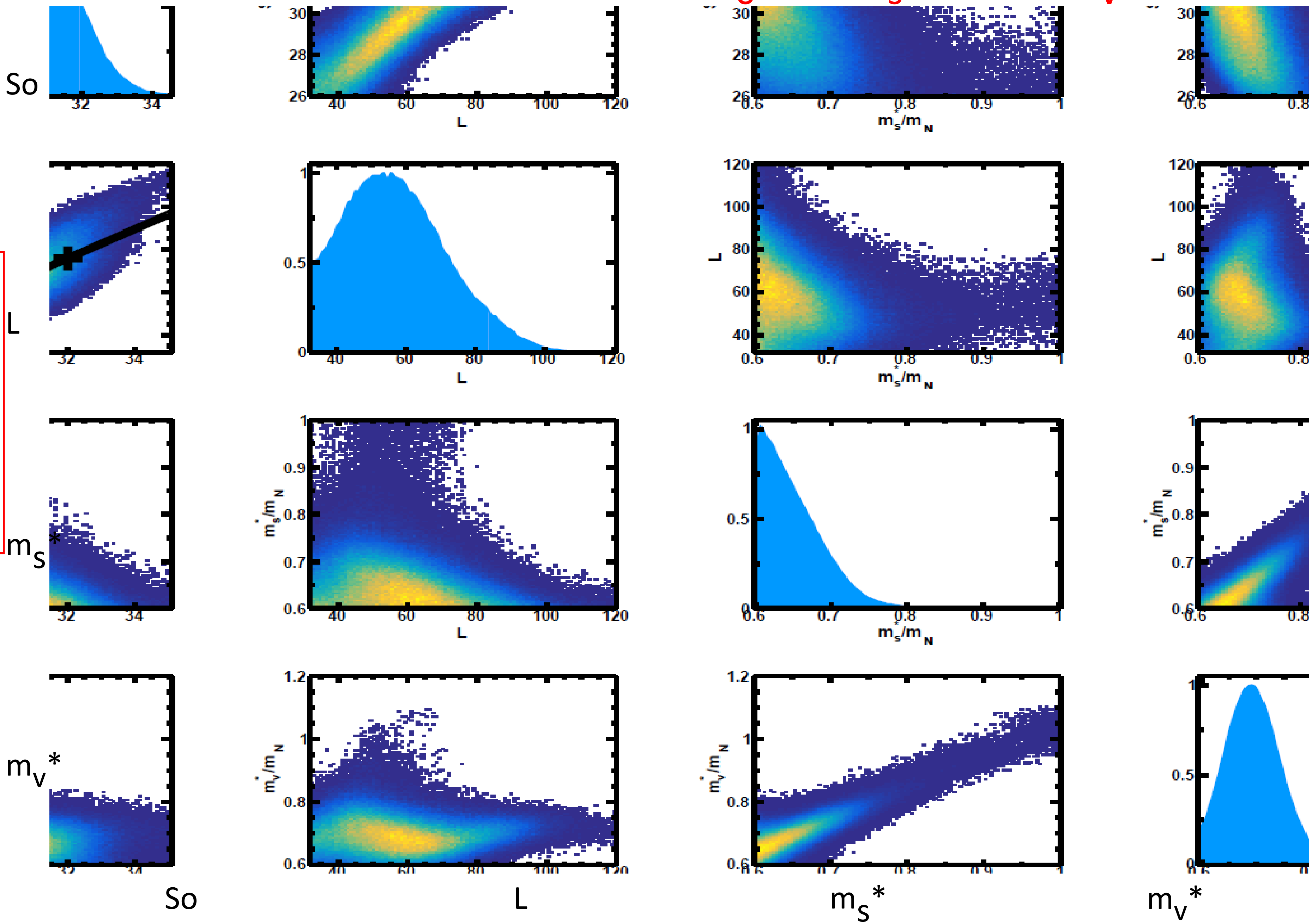
# Bayesian analysis of n/p ratios to constraint $S_0$, L, $m_s^*$ and $m_v^*$

Density Dependence
→So vs L
Momemtum Dependence
→ $m_s^*$ and $m_v^*$

**Experimental Data**

$$R_{n/p}=Y(n)/Y(p)$$

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



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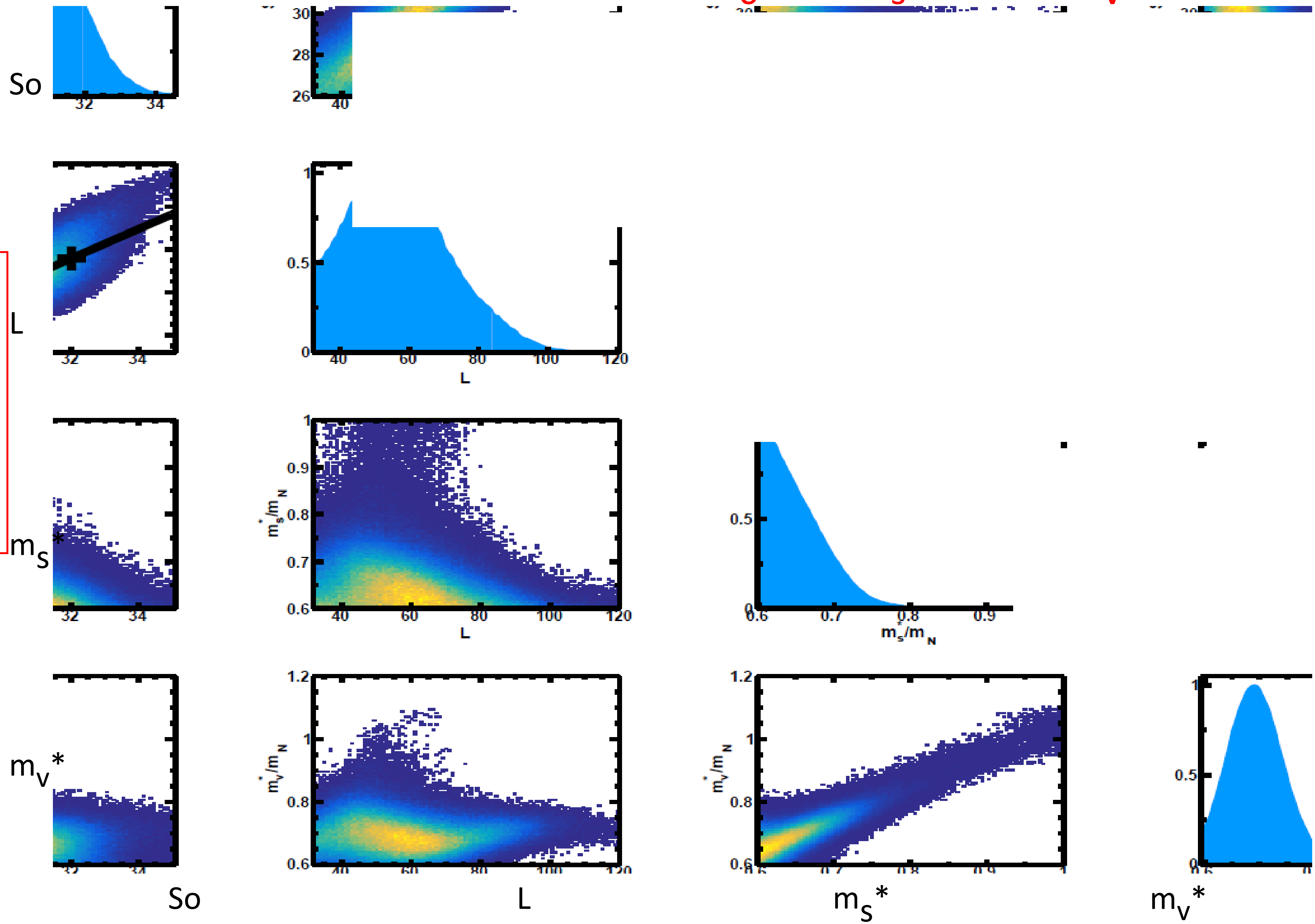
Strong correlation between L & S0 and mv* and ms*



# Bayesian analysis of n/p ratios to constraint $S_0$, L, $m_s$* and $m_v$*

Density Dependence
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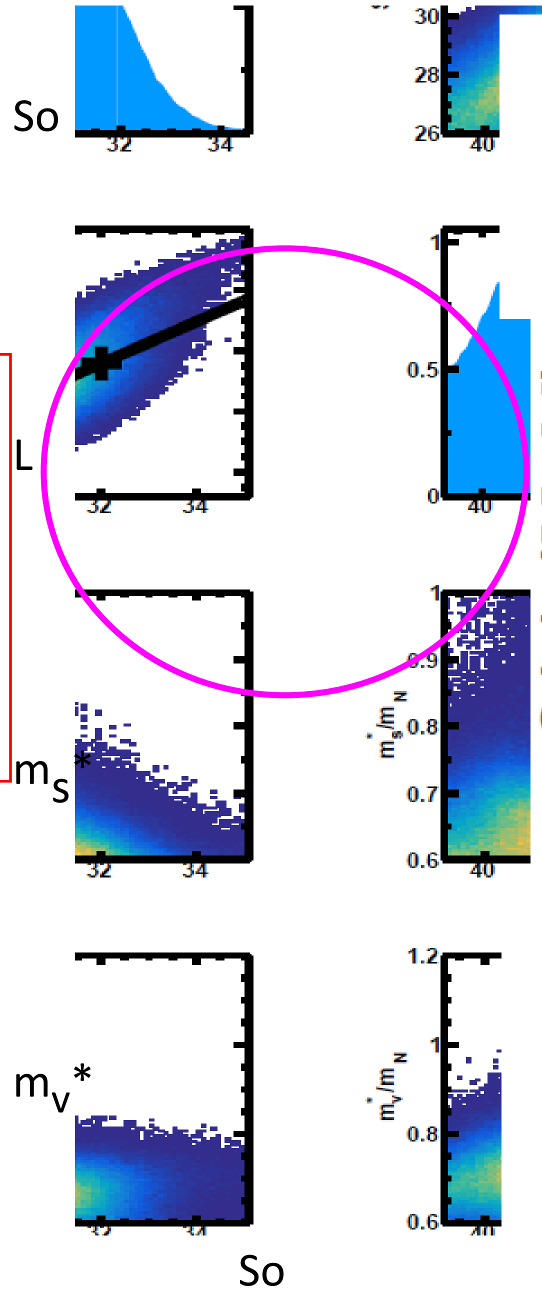
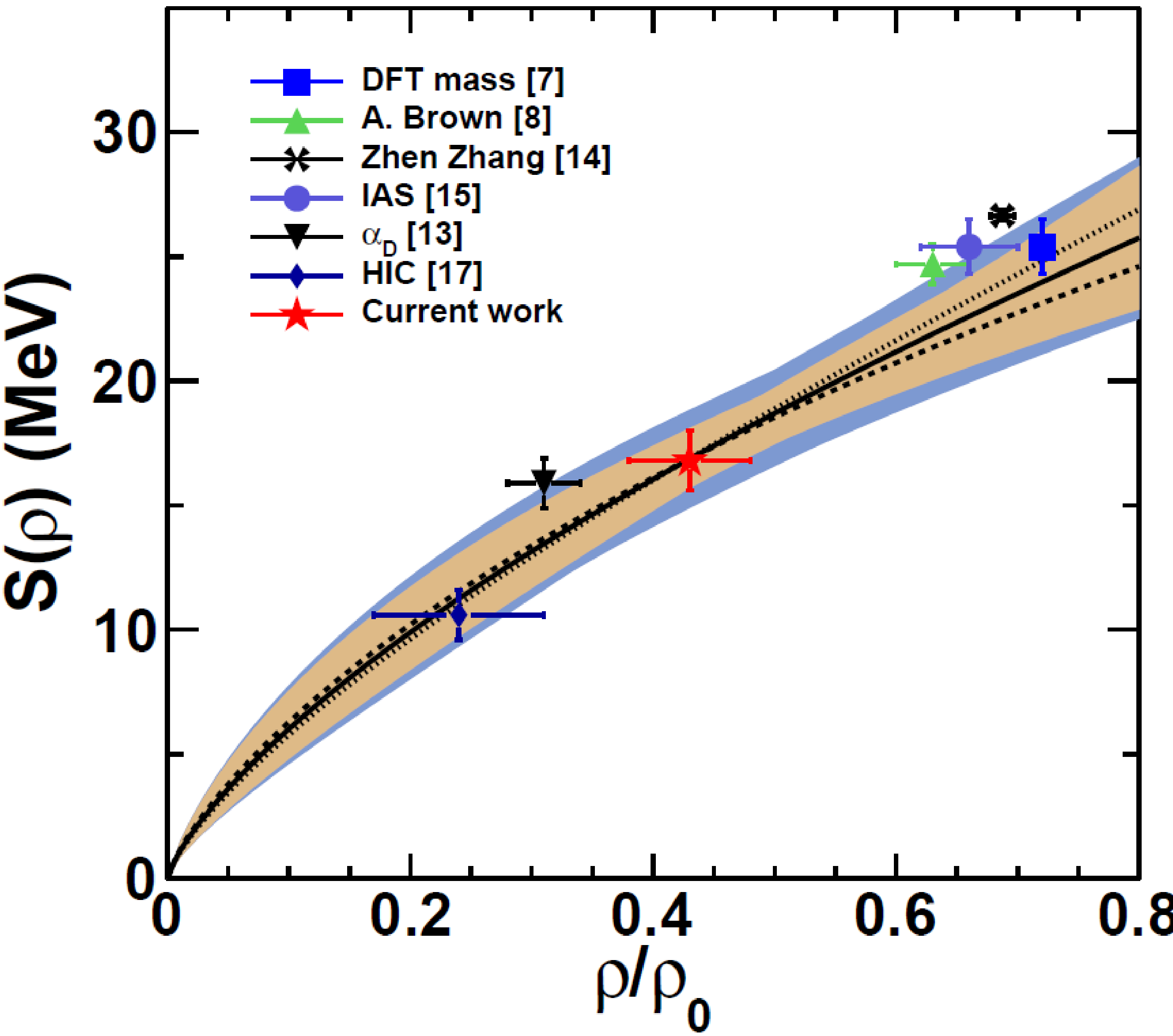


# Bayesian analysis of n/p ratios to constraint $S_0$, L, $m_s^*$ and $m_v^*$

Density Dependence

→So vs L

Momemtum Dependence

→ $m_s^*$ and $m_v^*$

## Experimental Data

$$R_{n/p} = Y(n)/Y(p)$$

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

Strong correlation between L & $S_0$ and $m_v^*$ and $m_s^*$

$\Delta m^*_{np}$=0.41+-0.15 or 0.27+-0.25

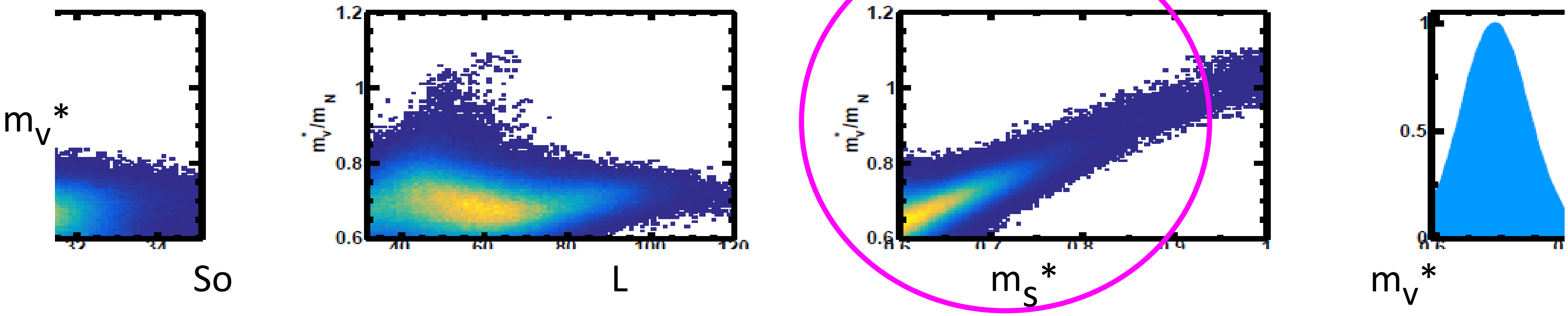
## Strong linear correlation between $m_v^*$ and $m_s^*$

$$f_I = \left(\frac{m_N}{m_s^*} - \frac{m_N}{m_v^*}\right) = \frac{1}{2\delta}\left(\frac{m_N}{m_n^*} - \frac{m_N}{m_p^*}\right)$$

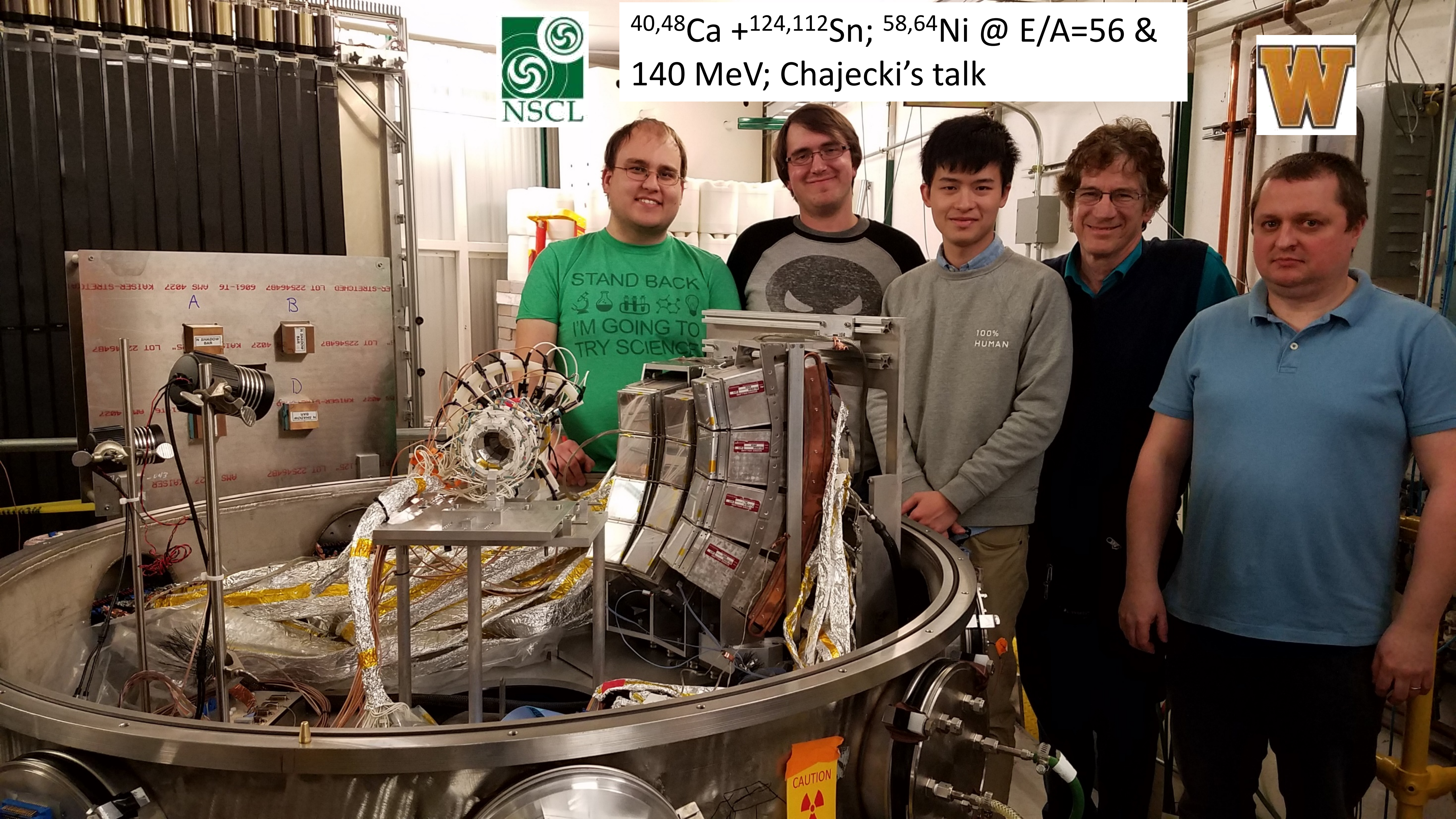
$$f_I \approx -\frac{1}{2\delta}\Delta m^*_{np}\left(\frac{m_N}{m_s^*}\right)^2,$$

$$\Delta m^*_{np} = (-0.08 \pm 0.07)\delta.$$

## Effective mass splitting



$^{40,48}Ca + ^{124,112}Sn$; $^{58,64}Ni$ @ E/A=56 & 140 MeV; Chajecki's talk



Physics insights including the EoS from heavy ion collisions depends heavily on transport model simulations

“All models are wrong; some models are useful”

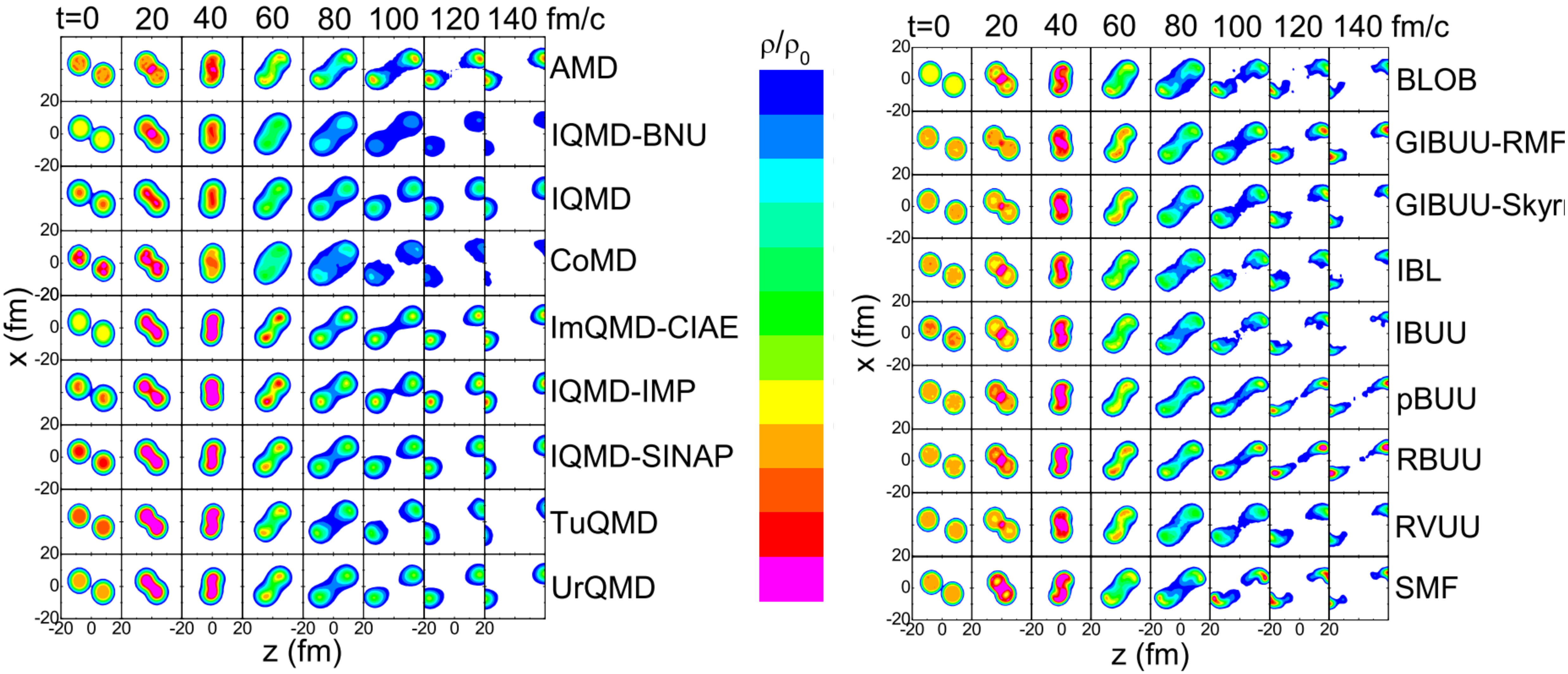
George Box, 1919-2013

# Transport Code Evaluation Project

Transport model workshop Sept 14-15, 2018

**Writing group**

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



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**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)**

Transport Workshop after NuSYM2018

# 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 SπRIT collaboration and others
- Improving the reliability of transport theory predictions.
  - Code evaluation project is making significant progress in this direction.
- Future direction discussions on Thursday 17:35 – 18:15
  - Connect our EoS results from HIC to the neutron star merger results
  - Send me topics and slides