Constraints on the symmetry energy using Spectral Pion Ratios

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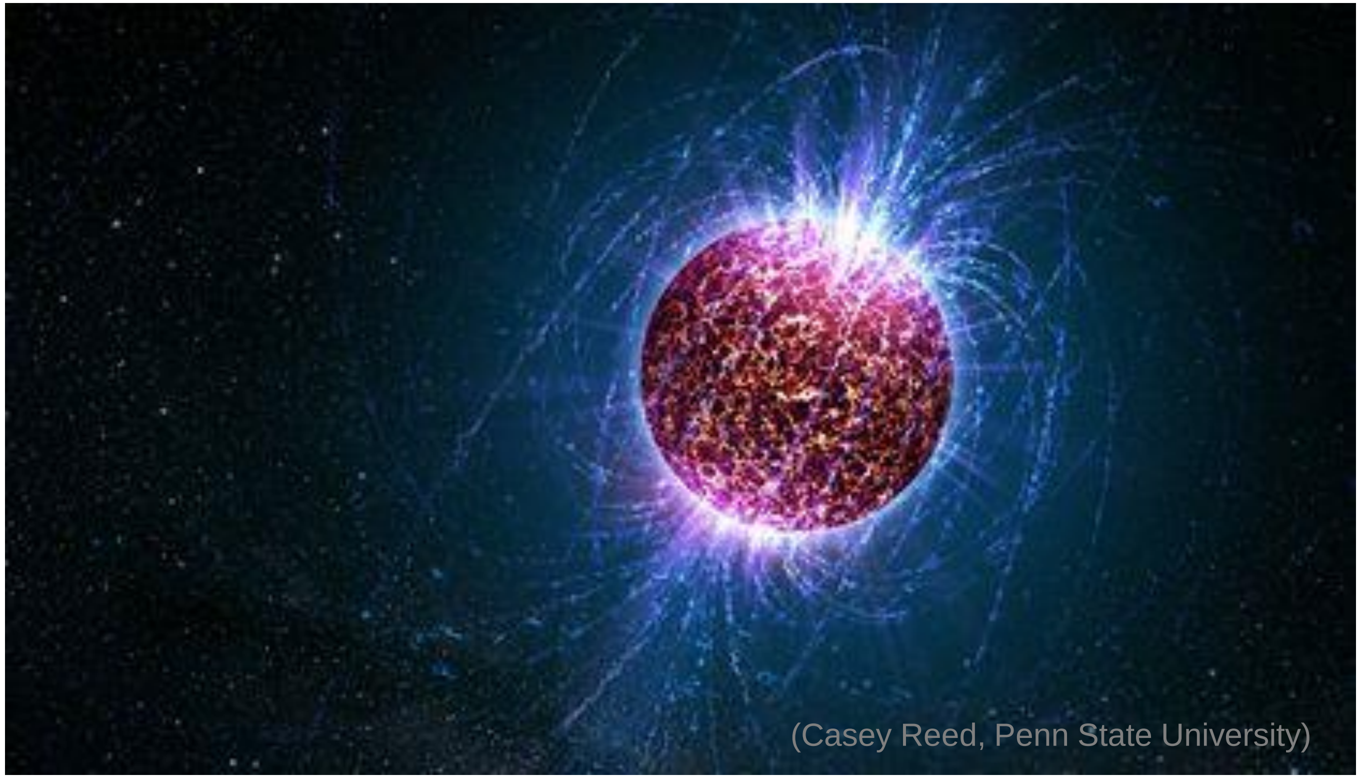
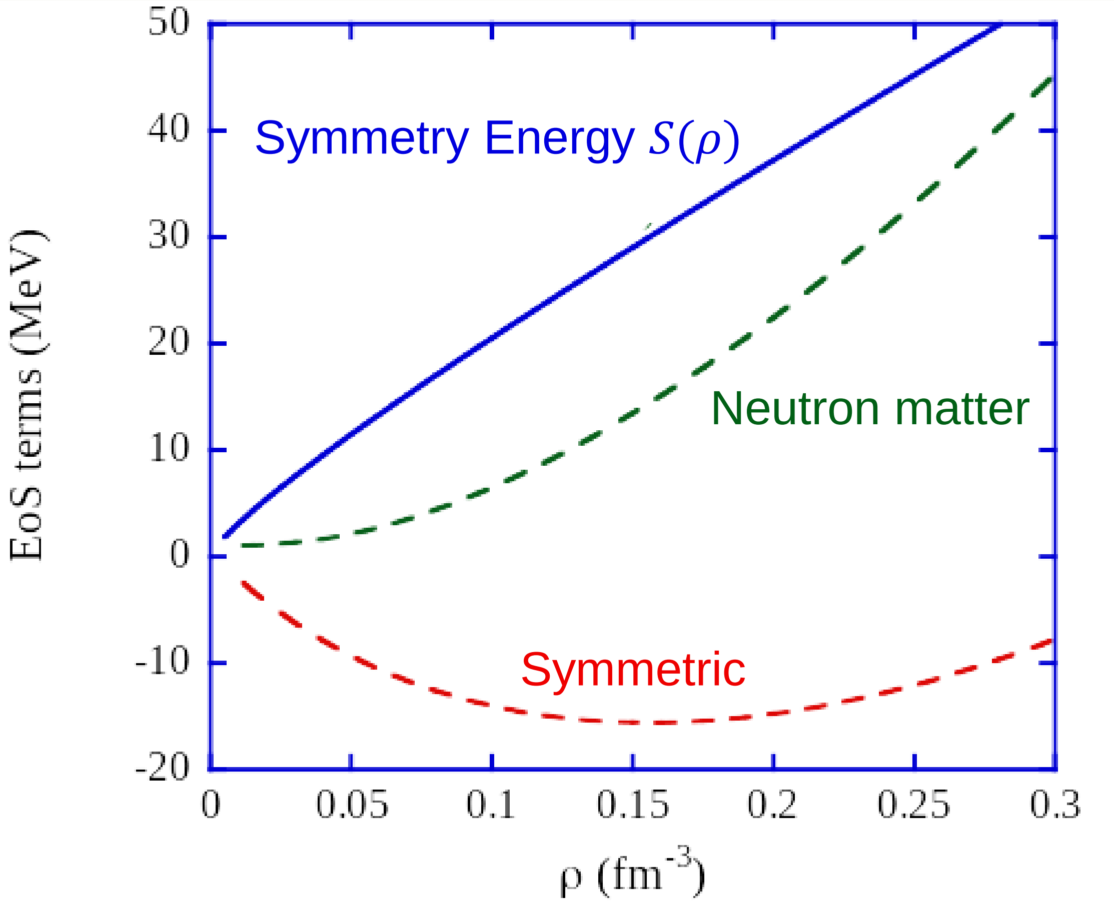
for the SπRIT Collaboration

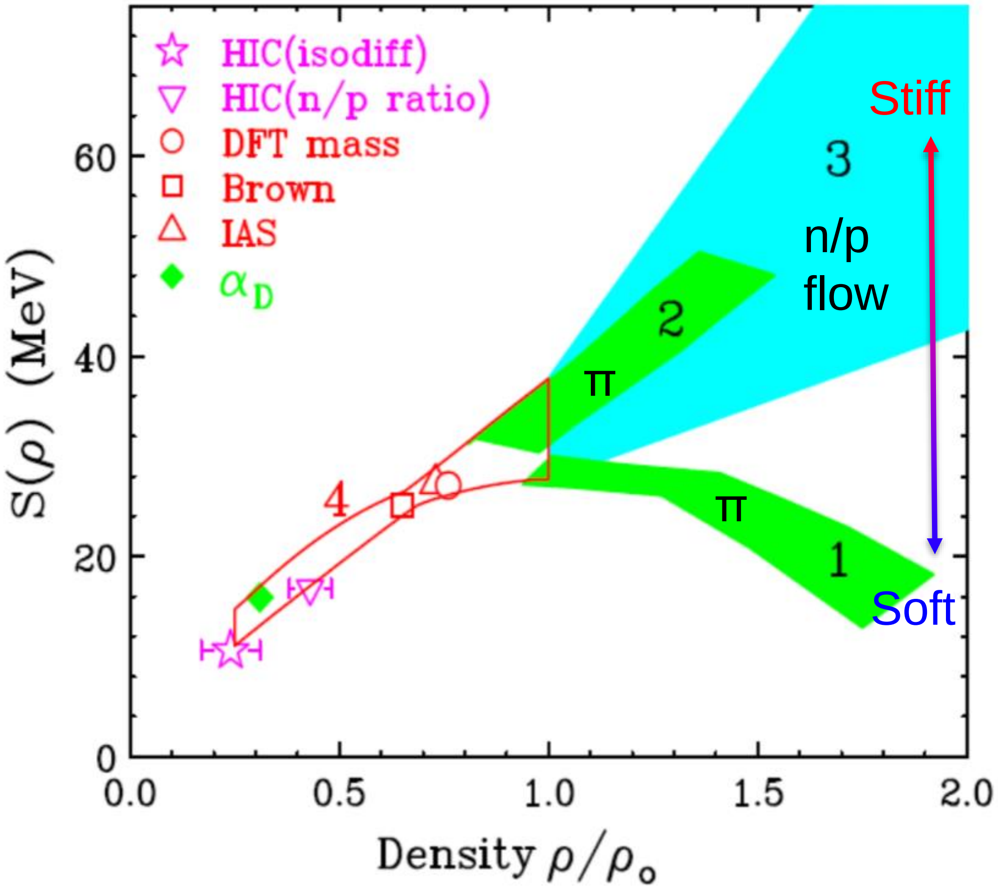
Dense Nuclear Matter in the Universe



- What nuclear interactions govern properties of the neutron star?
- Density inside neutron stars can reach $4\rho_o$ and in some models up to $9\ \rho_o$
- Observables in the lab to approximate this matter → neutron-rich heavy ion collisions

Equation of State for Nuclear Matter





$$\epsilon(\rho,\delta) = \epsilon(\rho,\delta=0) + S(\rho)\delta^2 \qquad \delta = \frac{\rho_n - \rho_p}{\rho}$$

$$S(\rho) = S_0 + Lx + \frac{1}{2}K_{sym}x^2 + \ \ldots \qquad x = \frac{\rho - \rho_0}{3\rho_0}$$

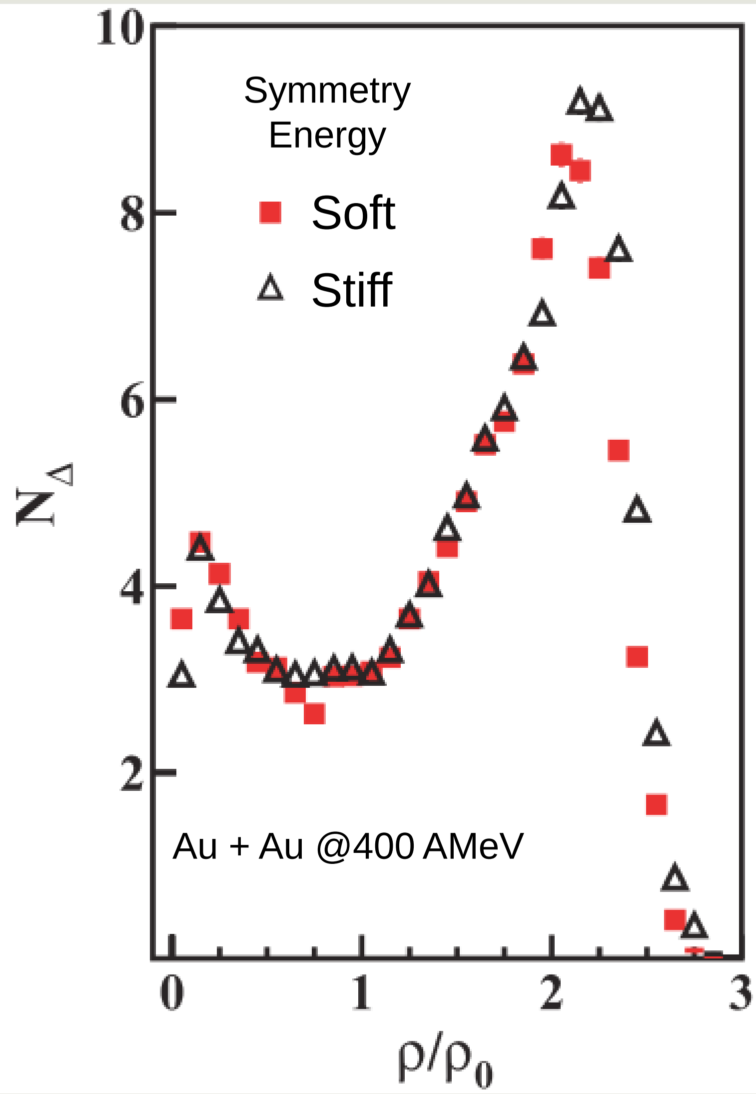
1.) Z. Xiao et al. Phys Rev. Lett. 2009
W. Xie et al. Physics Lett. B 2013
2.) Z. Feng et al. Phys. Lett. B 2010
3.) Russotto et al., Phys. Lett. B 2011

Pion Production

Δ Branching Ratio			
	π^-	π^0	π^+
nn	5	1	0
pp	0	1	5
np or pn	1	4	1

Delta resonance model

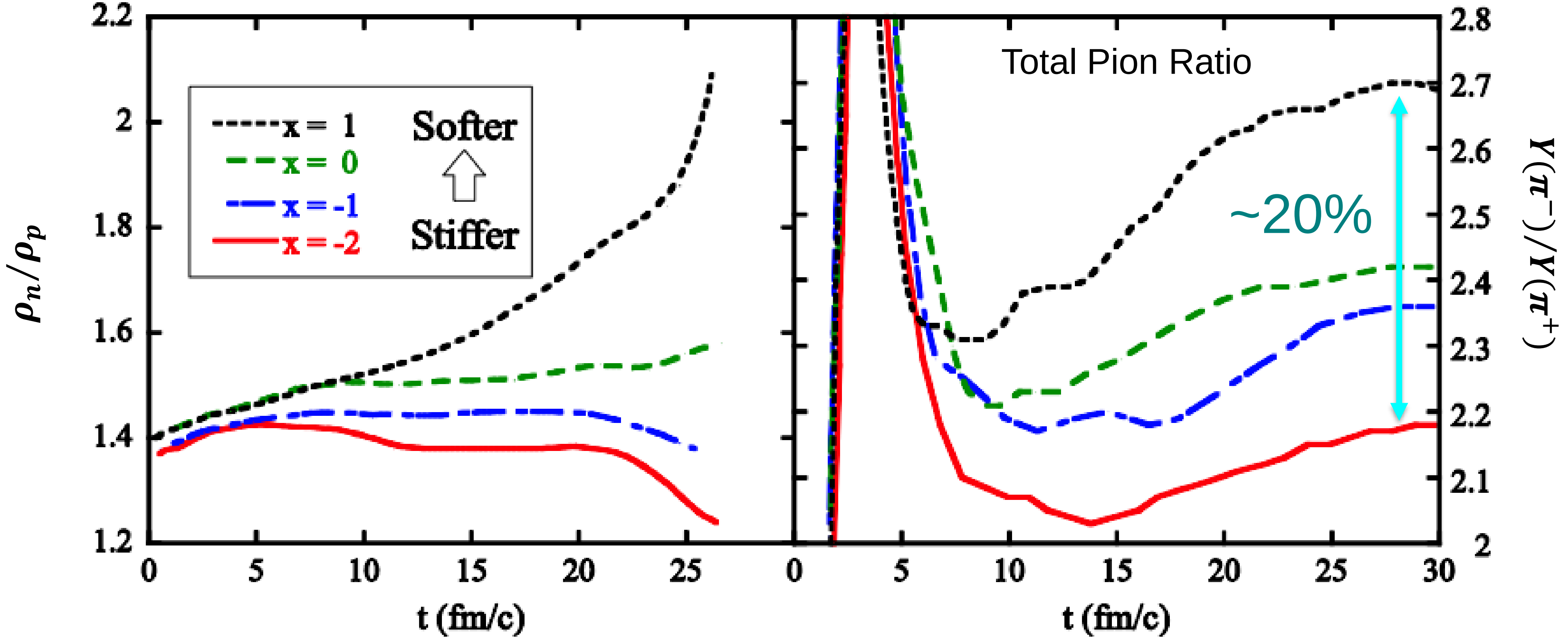
$$Y(\pi^-)/Y(\pi^+) \approx (\rho_n/\rho_p)^2$$



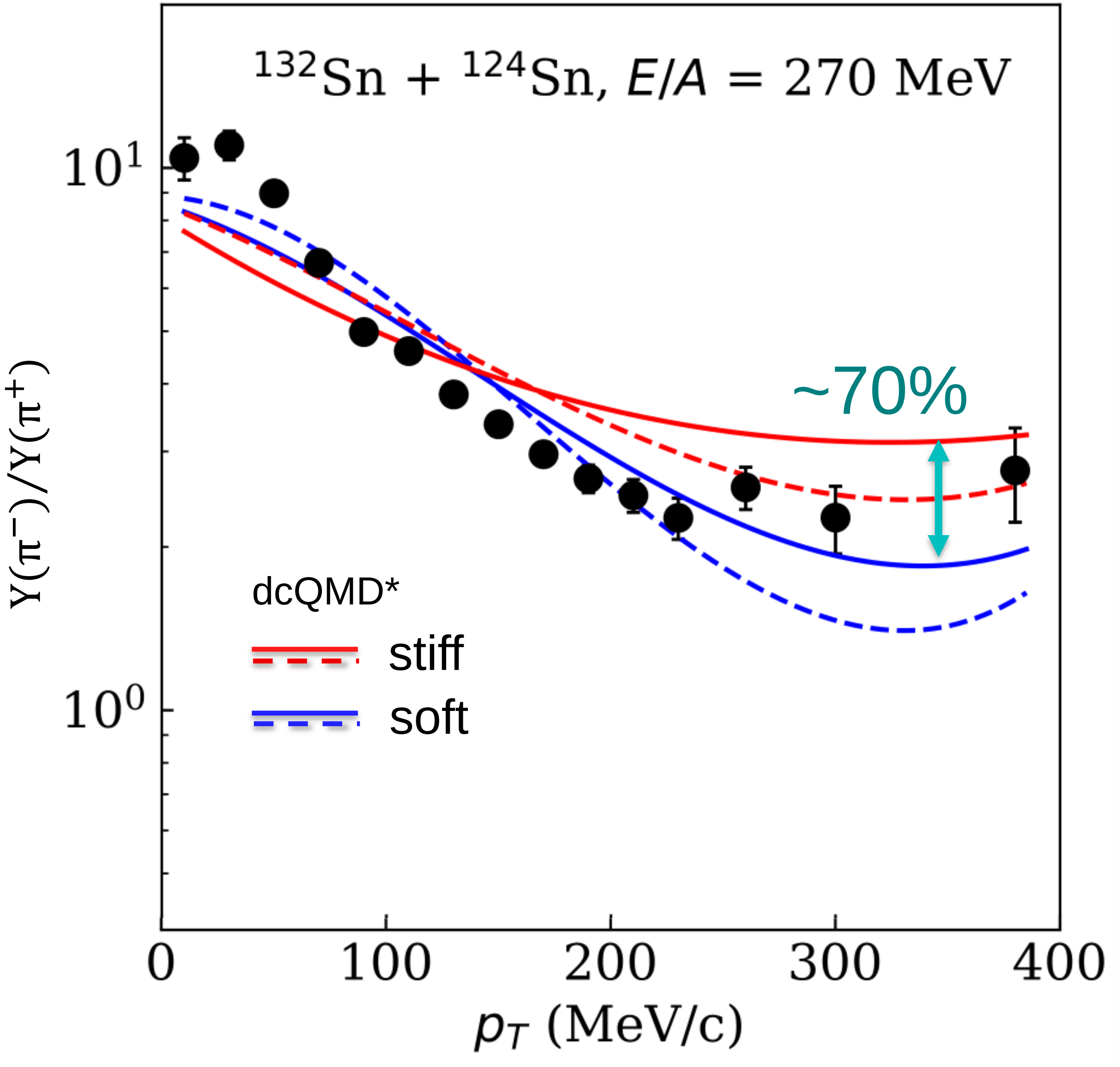
Adapted from Ming Zhang et. al. Phys. Rev. C 80 (2009)

Pion Observable

B.A Li, Phys. Rev. Lett. 88, 192701 (2002)



Pion Spectral Ratio

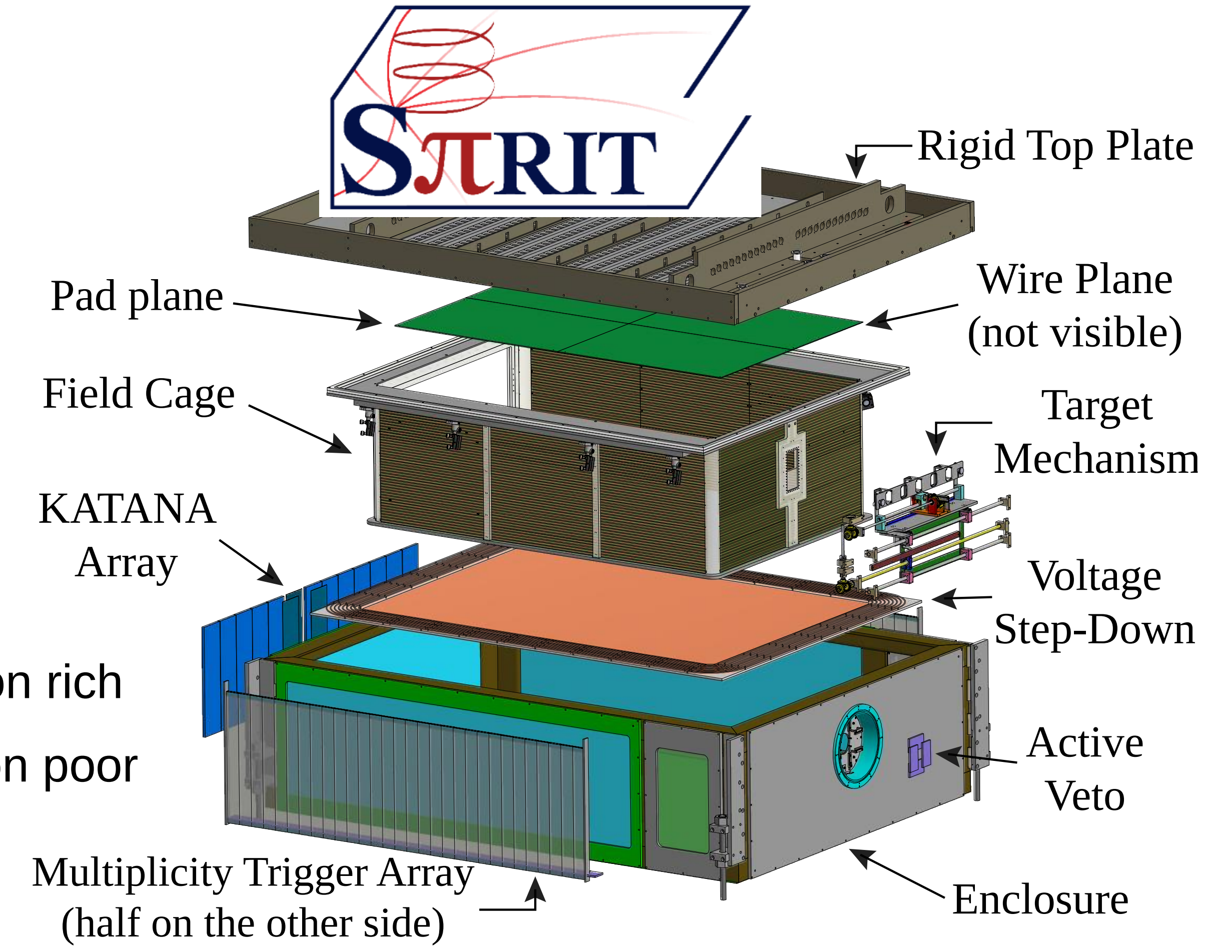


*dcQMD : Dan Cozma

SAMURAI pion Reconstruction Ion Tracking (SπRIT) TPC

- Experimental Campaign (RIKEN) (2015-2016)
- Measure pions to low energies
- high efficiencies
- good momentum reconstruction

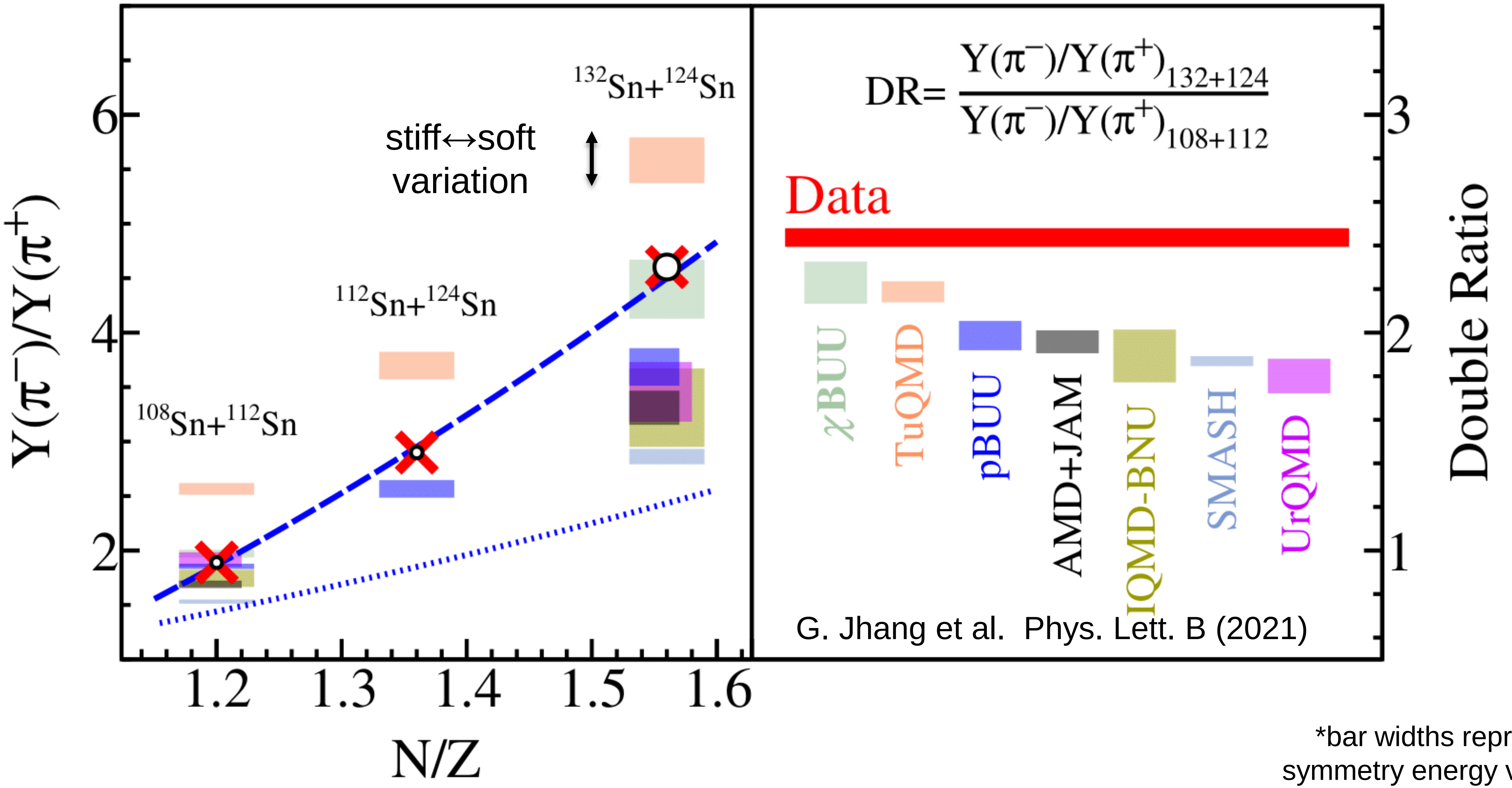
System	Energy (AMeV)	(N-Z)/A	#events (M)	
^{132}Sn+^{124}Sn	270	0.22	3.8	← Neutron rich
^{108}Sn+^{112}Sn	270	0.09	2.4	← Neutron poor
^{112}Sn+^{124}Sn	270	0.15	1.8	
^{124}Sn+^{112}Sn	270	0.15	0.2	



G. Jhang *et al.*, J. Korean Phys. Soc. **69** (2016) 144

R. Shane *et al.*, Nucl. Instr. and Meth. A **784** (2015) 513

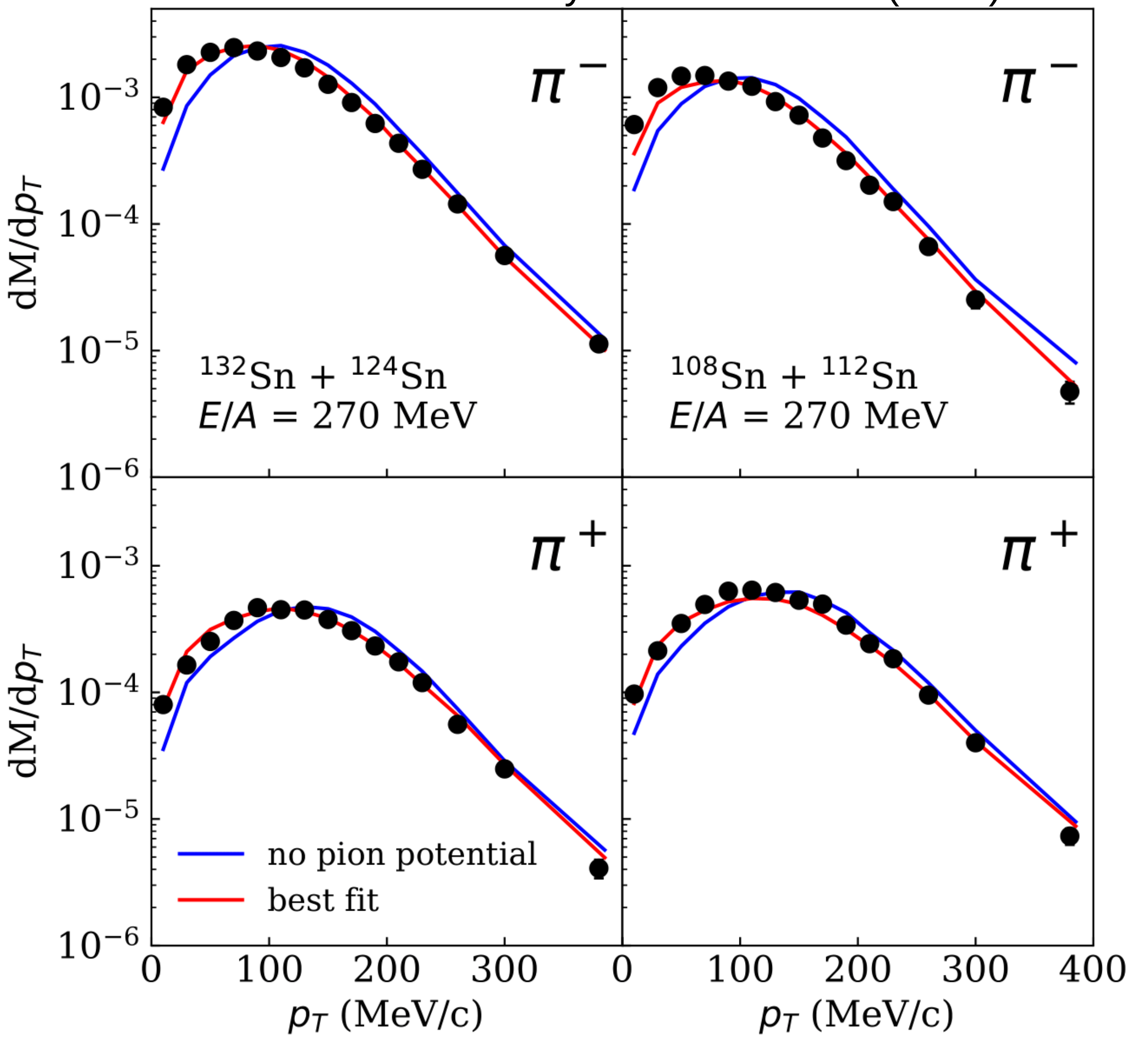
Total Pion Ratio Results



*bar widths represent stiff to soft symmetry energy variation in theories

Pion Potential Affects Low Energy Pions

J. Estee et al. Phys. Rev. Lett. 126 (2021)



All comparisons made with dcQMD code*

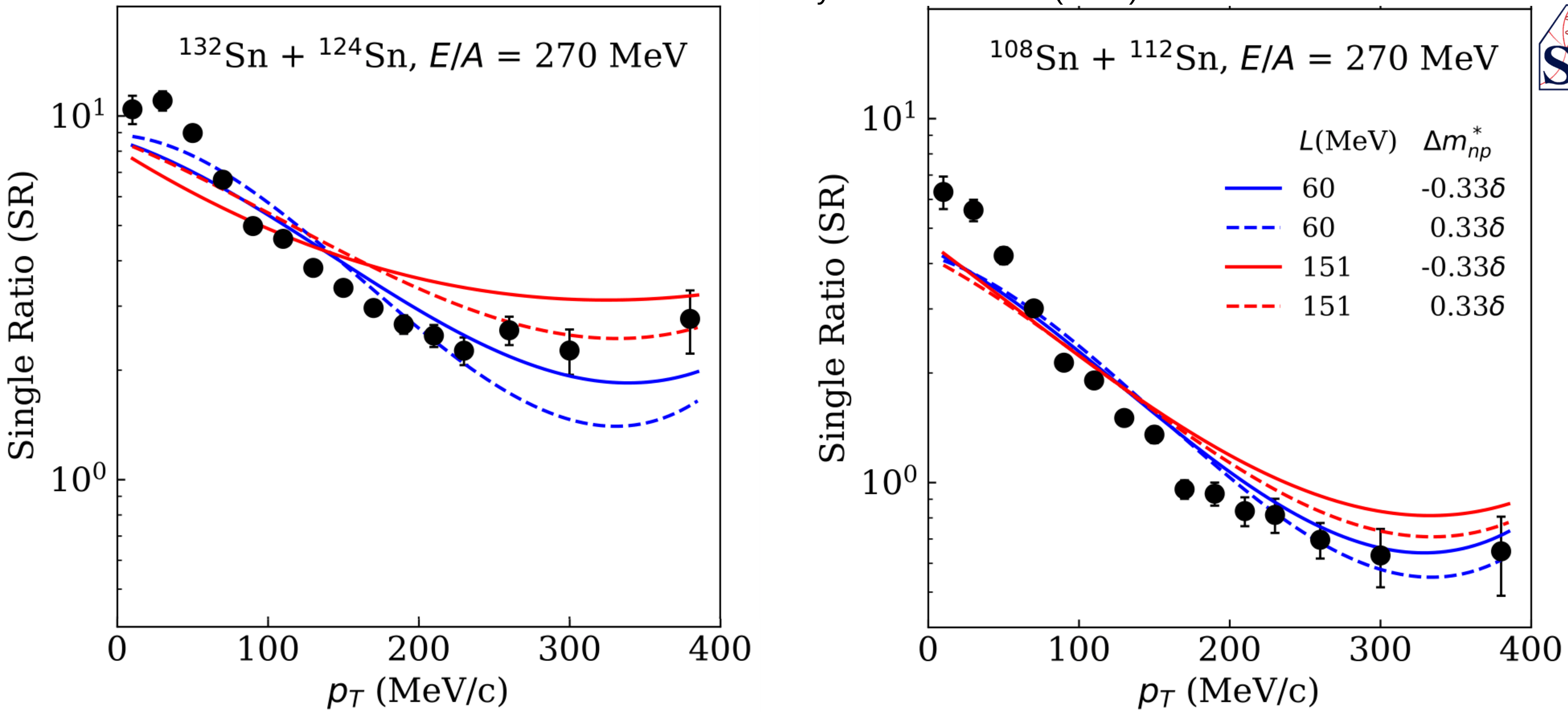
Delta potentials have been constrained

M.D. Cozma and M.B. Tsang
arXiv:2101.08679

*Dan Cozma: dcQMD

Pion Spectral Single Ratio $Y(\pi^-)/Y(\pi^+)$

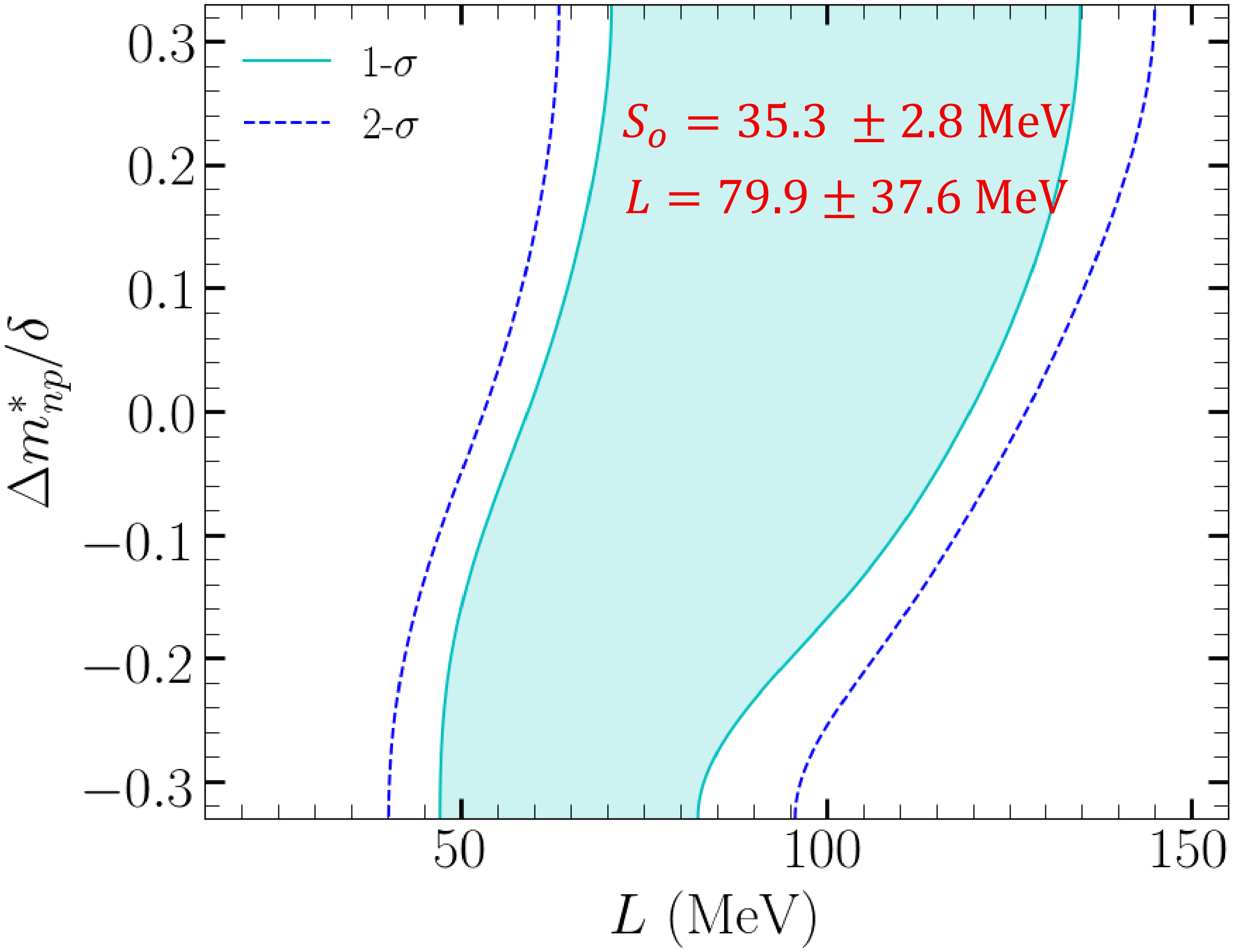
J. Estee et al. Phys. Rev. Lett. 126 (2021)



$\Delta m_{np}{}^* = m_n^* - m_p^*$

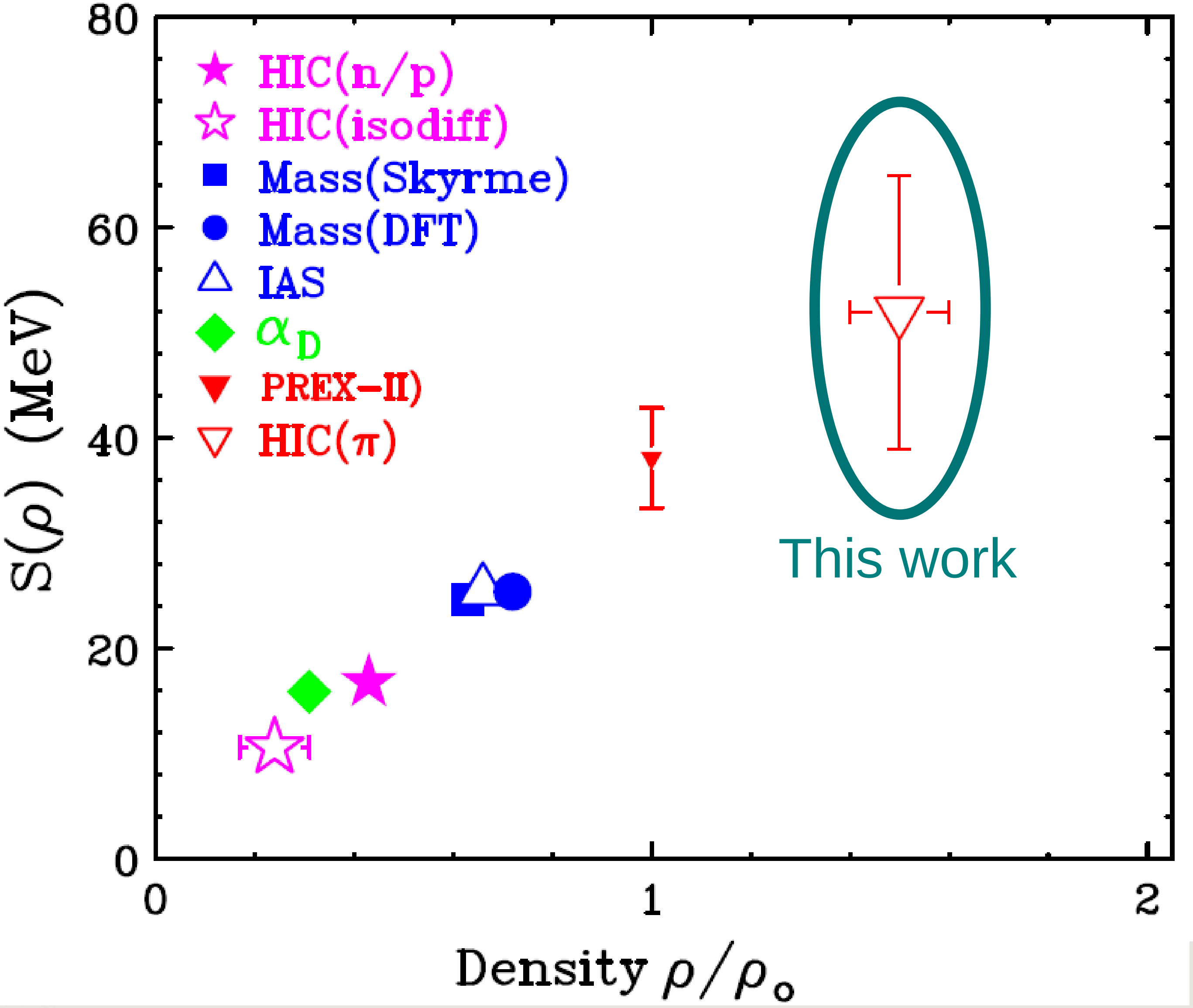
Constraints on L and Effective Mass Difference

J. Estee et al. Phys. Rev. Lett. 126 (2021)



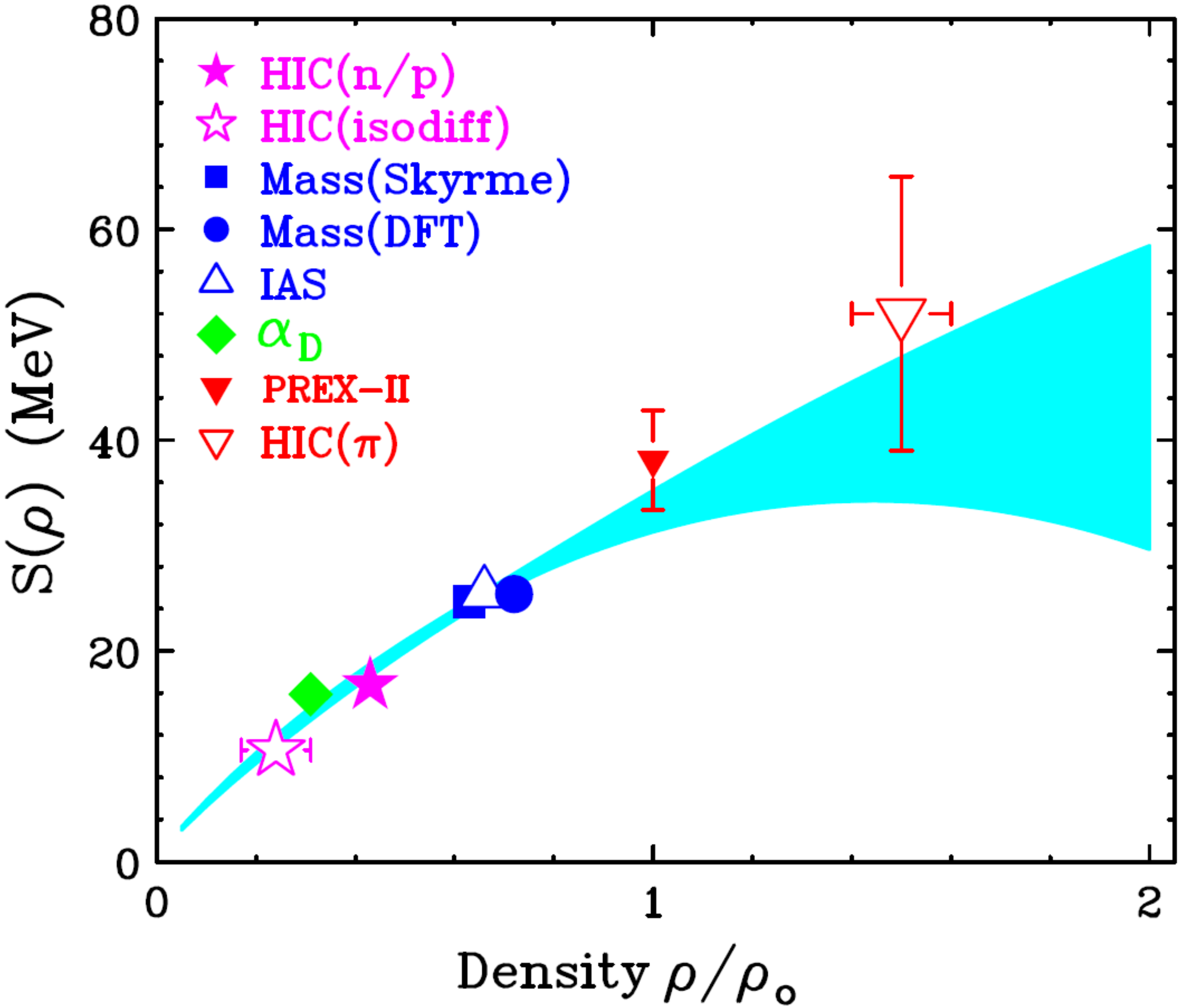
$\Delta m_{np}{}^* = m_n^* - m_p^*$

High Density Symmetry Energy Constraints



High Density Symmetry Energy Constraints

https://arxiv.org/abs/2106.10119



(units in MeV)

S_{01}= 24.2 ± 0.5

L_{01} = 53.1 ± 6.1

K_{01} = -79.2 ± 37.6

R_{np} = 0.23 ± 0.03 fm

ρ_{cc}~$0.5\rho_0$

(units in MeV)

S_0 = 33.3 ± 1.3

L = 59.6 ± 22.1

K_{sym}=-180 ± 96

Conclusion

- Stiff symmetry energy is observed, ruling out a super soft symmetry energy

  $L = 79.9 \pm 37.6\ MeV$ $S_o = 35.3\ \pm 2.8\ MeV$

- $S(1.45\rho_0) = 58 \pm 13$ MeV
- PREX-II is consistent with our measurement (within error)
- Ongoing efforts of the theoretical transport model community will allow for more robust exploration of the nuclear EoS
- Theoretical code must include pion and delta potentials, momentum dependence, energy conservation (threshold effects)
- Xe + Sn at 334 AMeV approved experiment RIKEN to follow up on pion production and better understanding delta/pion potentials

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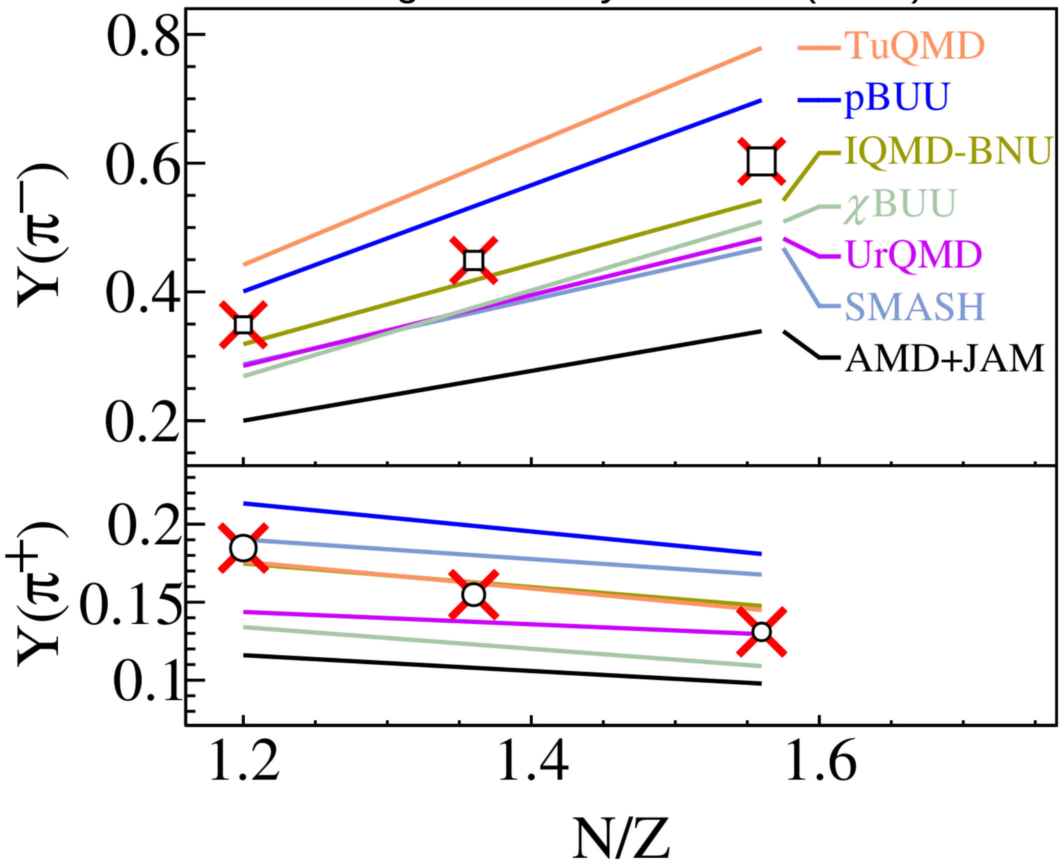
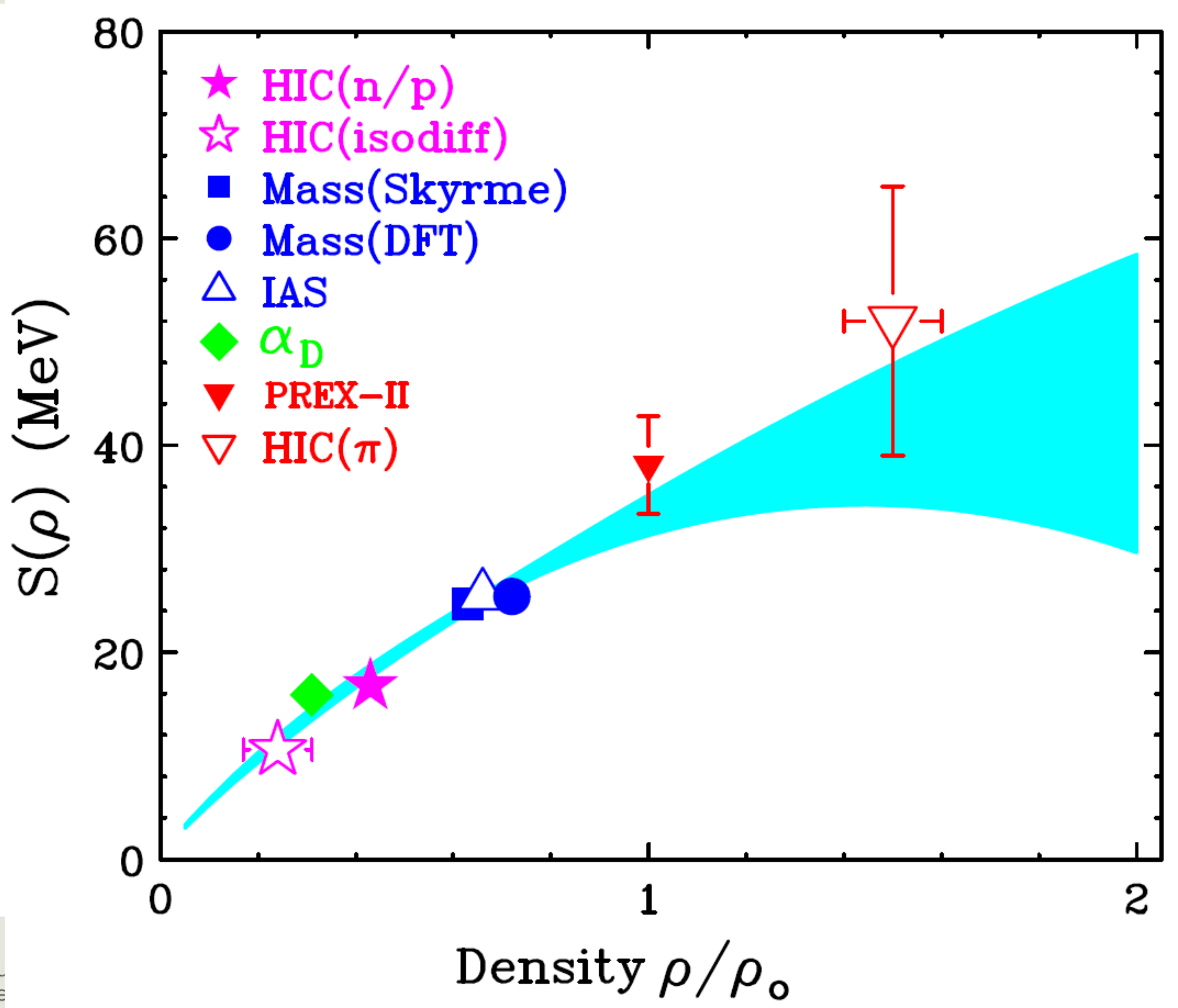
Total Pion Yields

G. Jhang et al. Phys. Lett. B (2021)



- Only one similar Symmetry Energy is plotted here. The variation between codes is very large
- No one code can predict both charged pions at the same time

High Density Symmetry Energy Constraints



S_{01}=24.2+-0.5 MeV
L_{01}=53.1+-6.1 MeV
K_{01}=-79.2+-37.6 MeV

R_{np}=0.23+-0.03 fm
ρ_{cc}~0.5ρ_0

S_0=33.3+-1.3 MeV
L=59.6+-22.1 MeV
K_{sym}=-180+-96 MeV

P_{sym}= 3.2+-1.2 MeV
Λ(1.4)= 500-720
R(1.4) = 13.1+-0.6 km

Constraints on L and Effective Mass Difference

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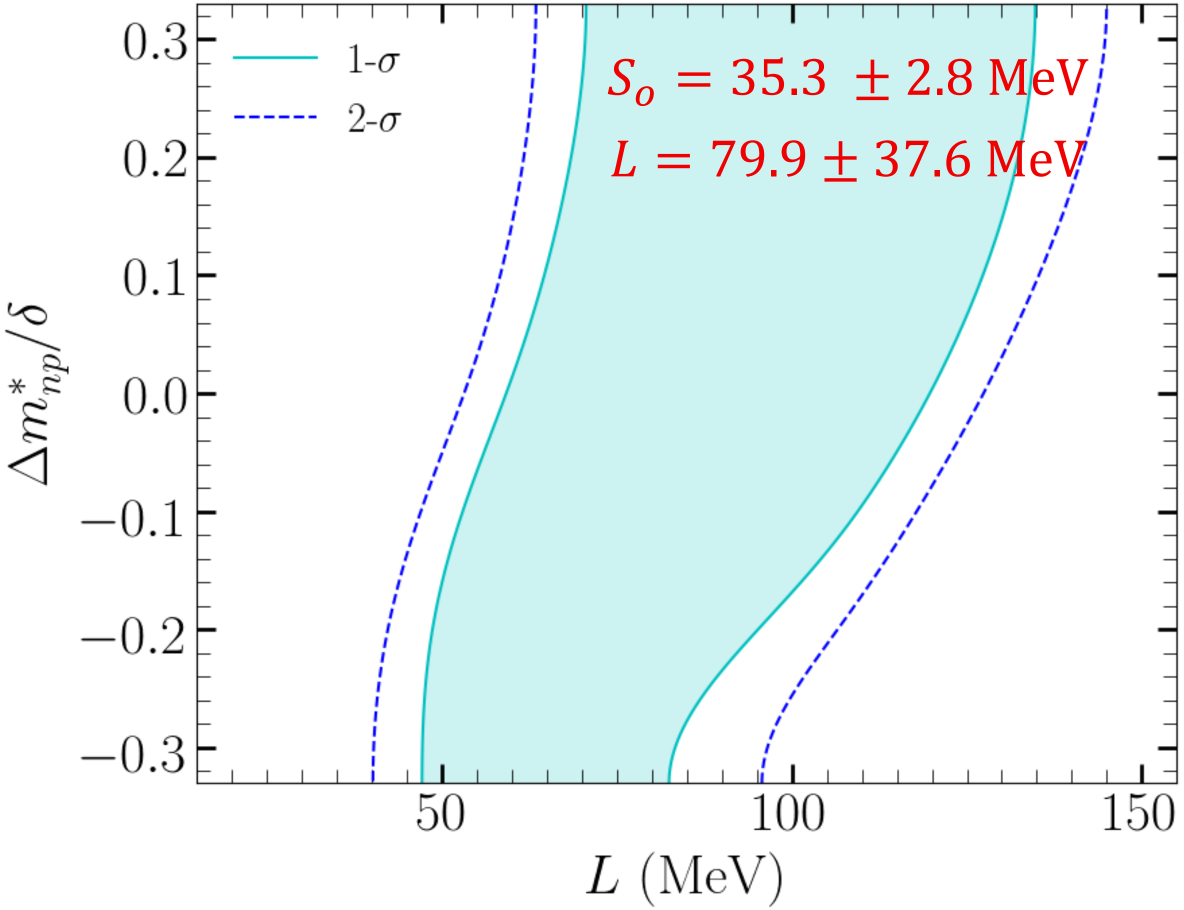
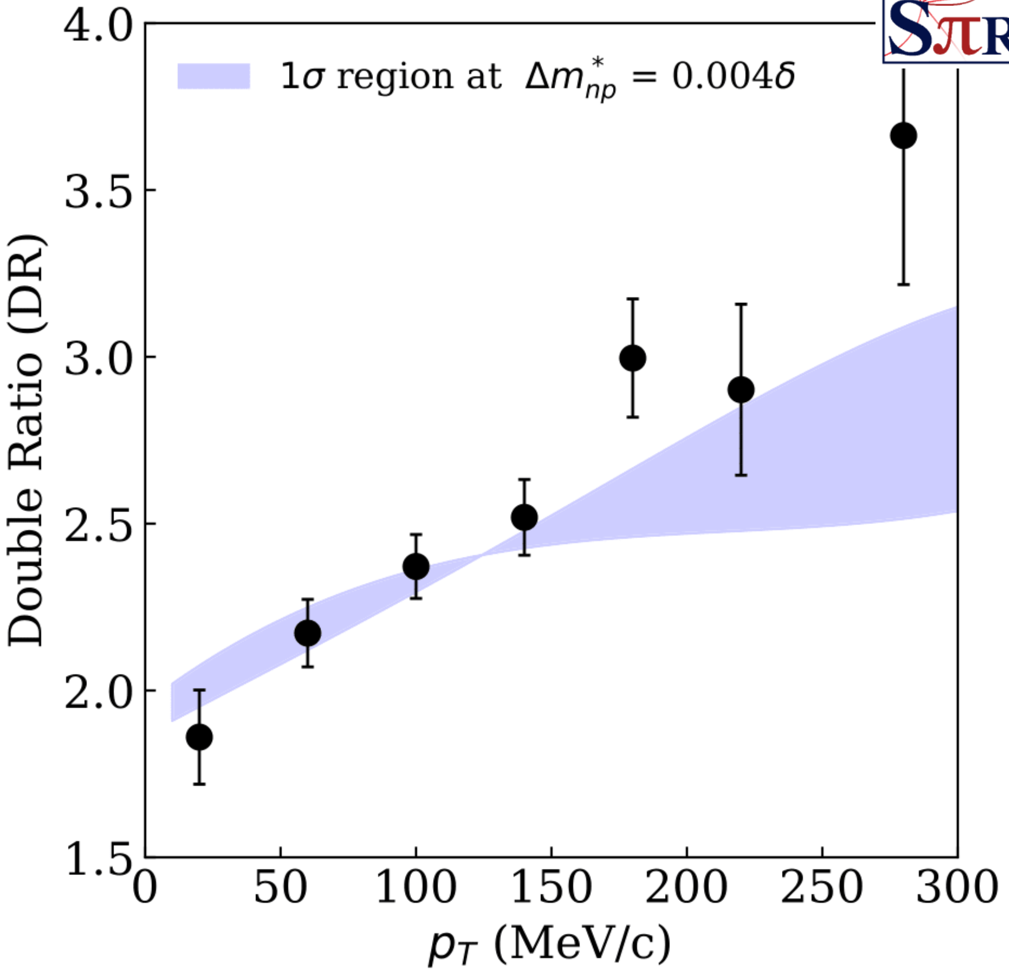
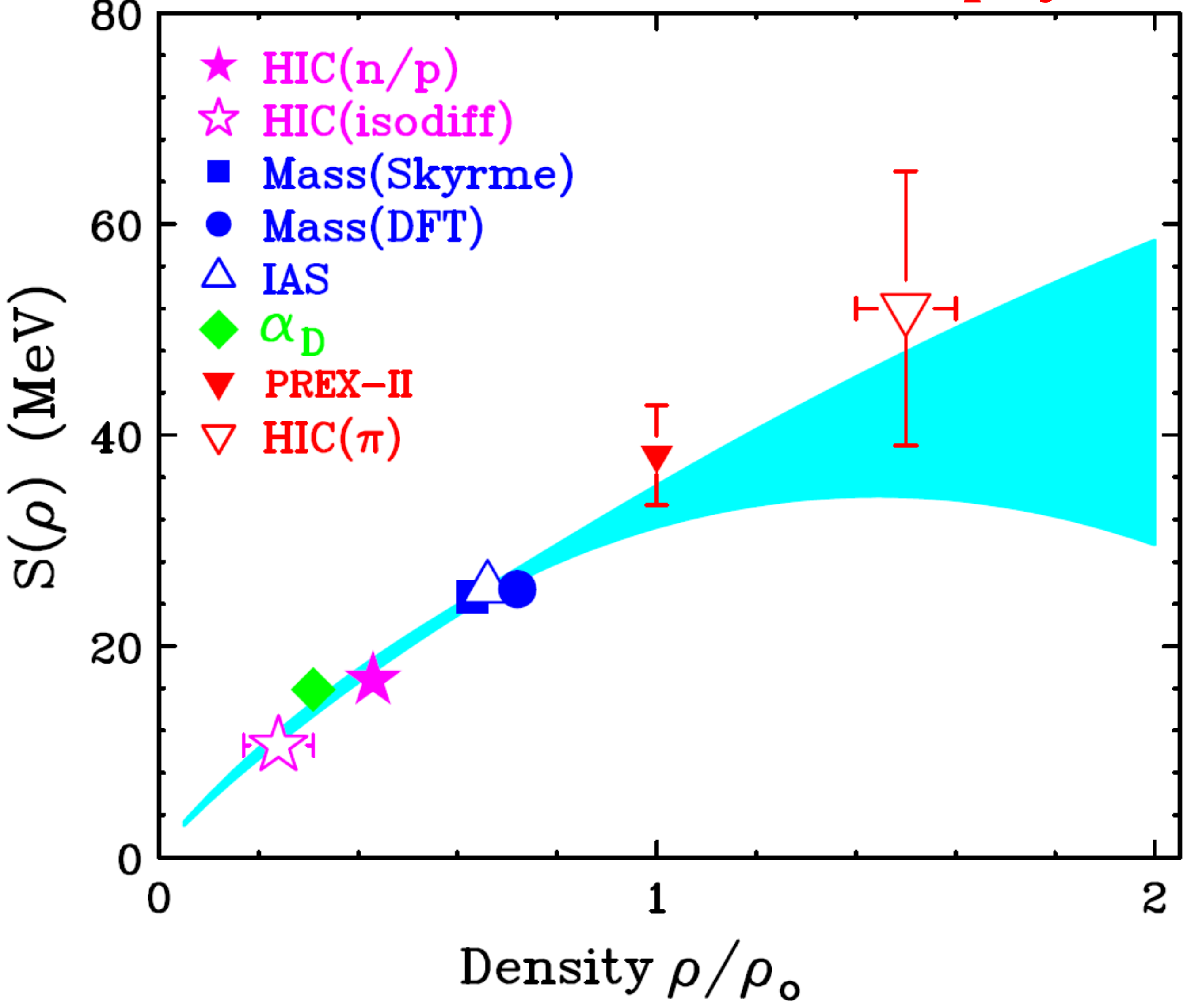




DR = SR(132)/SR(108) $\Delta m_{np}{}^* = m^*_n - m^*_p$

Conclusion – Some Astrophysics & Physics implications



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More to come when the new density functional is included in NS calculations.

Pion Potential Affects Low Energy Pions

- This analysis uses Dan Cozma's QMD (dcQMD)
  - Submitted Journal Phys. G arXiv:2101.08679 [nucl-th]
- Code which has the delta, pion optical potentials, momentum dependent interaction, and appropriate energy conservation
- Pion potential is needed to describe low momentum pions
- Conversely high momentum pions are less affected by pion potential

J. Estee et al. Phys. Rev. Lett. 126 (2021)