Facility for Rare Isotope Beams
at Michigan State University

Betty Tsang (Tsang@FRIB.MSU.EDU)

Intersection of nuclear structure and high-energy nuclear collisions

INT-23-1A Program

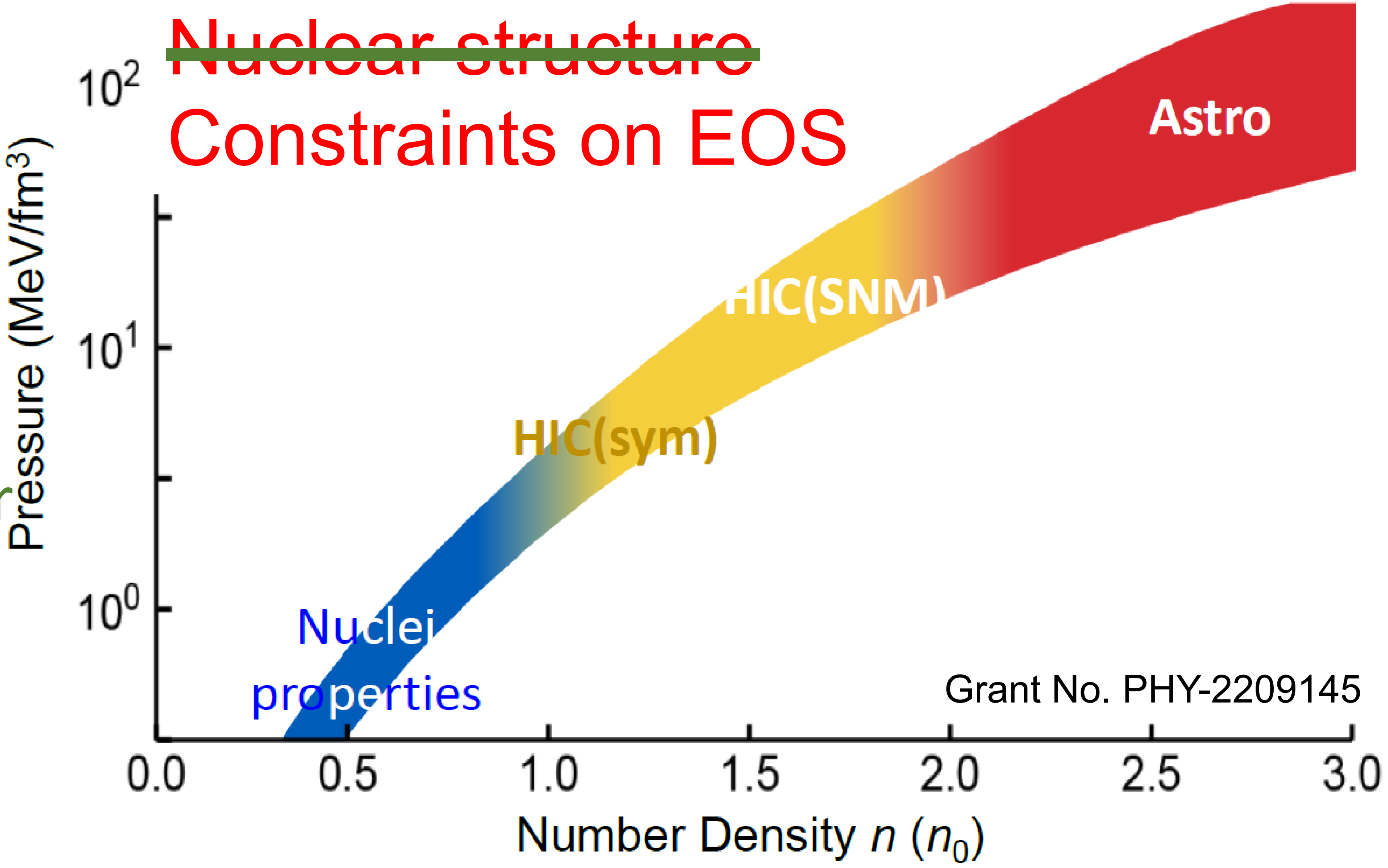
Institute for Nuclear Theory, UW, Seattle

1/23 – 2/24, 2023

Week 3 workshop

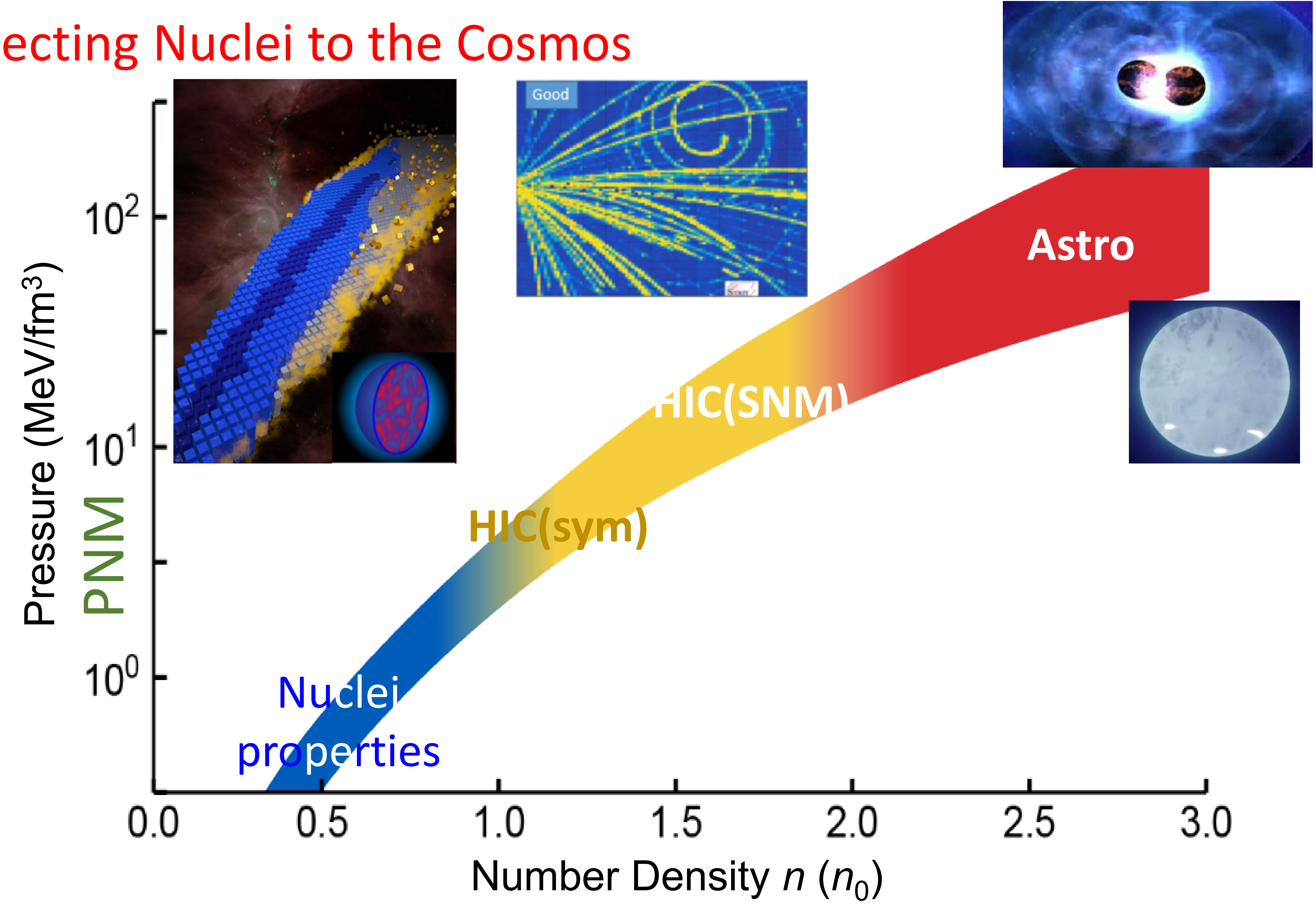
~~Nuclear structure~~

Constraints on EOS



Grant No. PHY-2209145

EOS : Connecting Nuclei to the Cosmos



Neutron Star Constraints

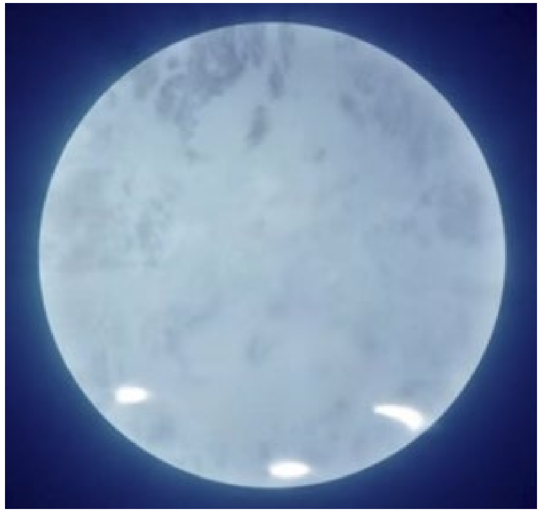
TOV Equations

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

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

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

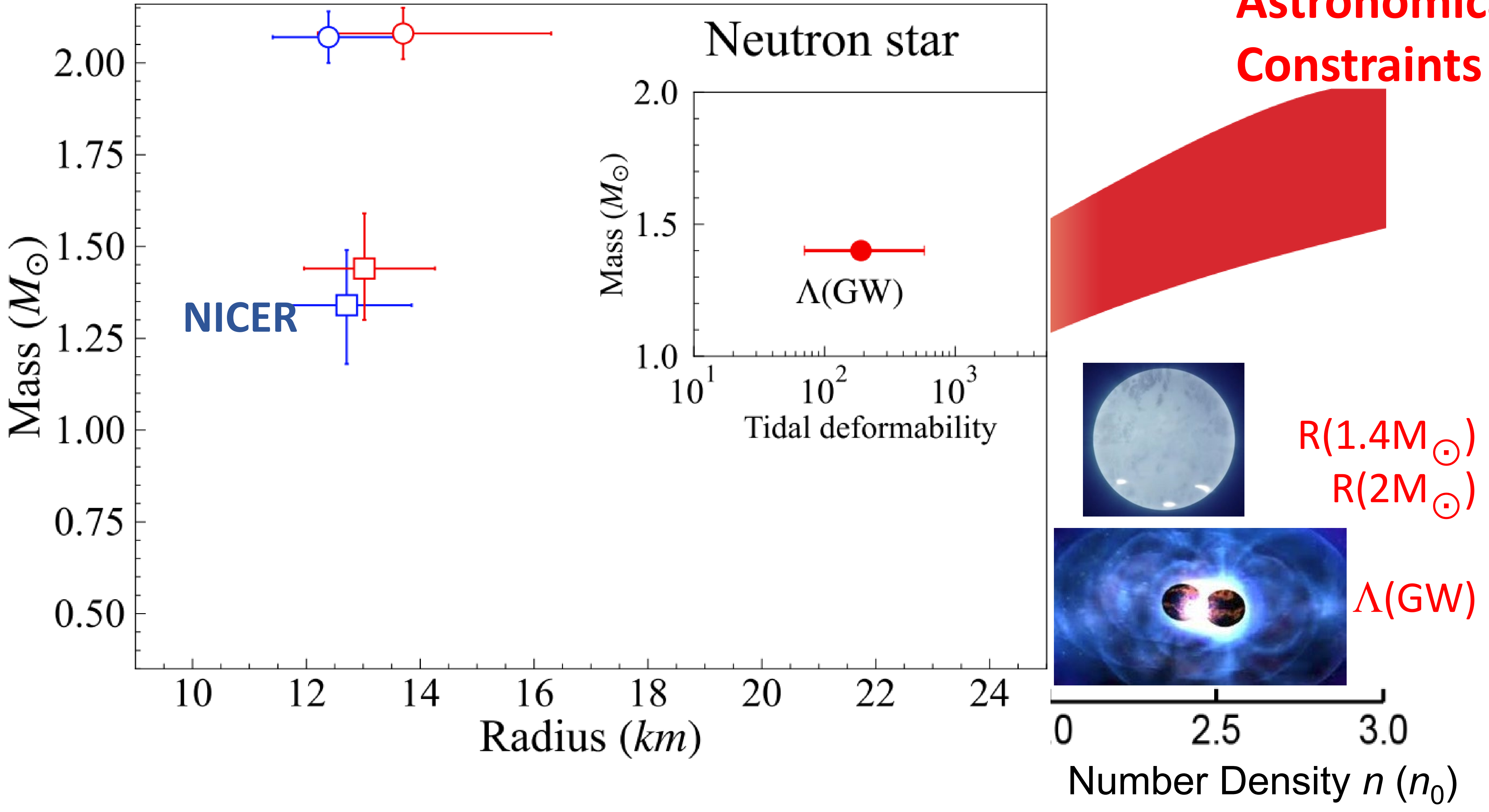
NICER



$R(1.4M_\odot)$

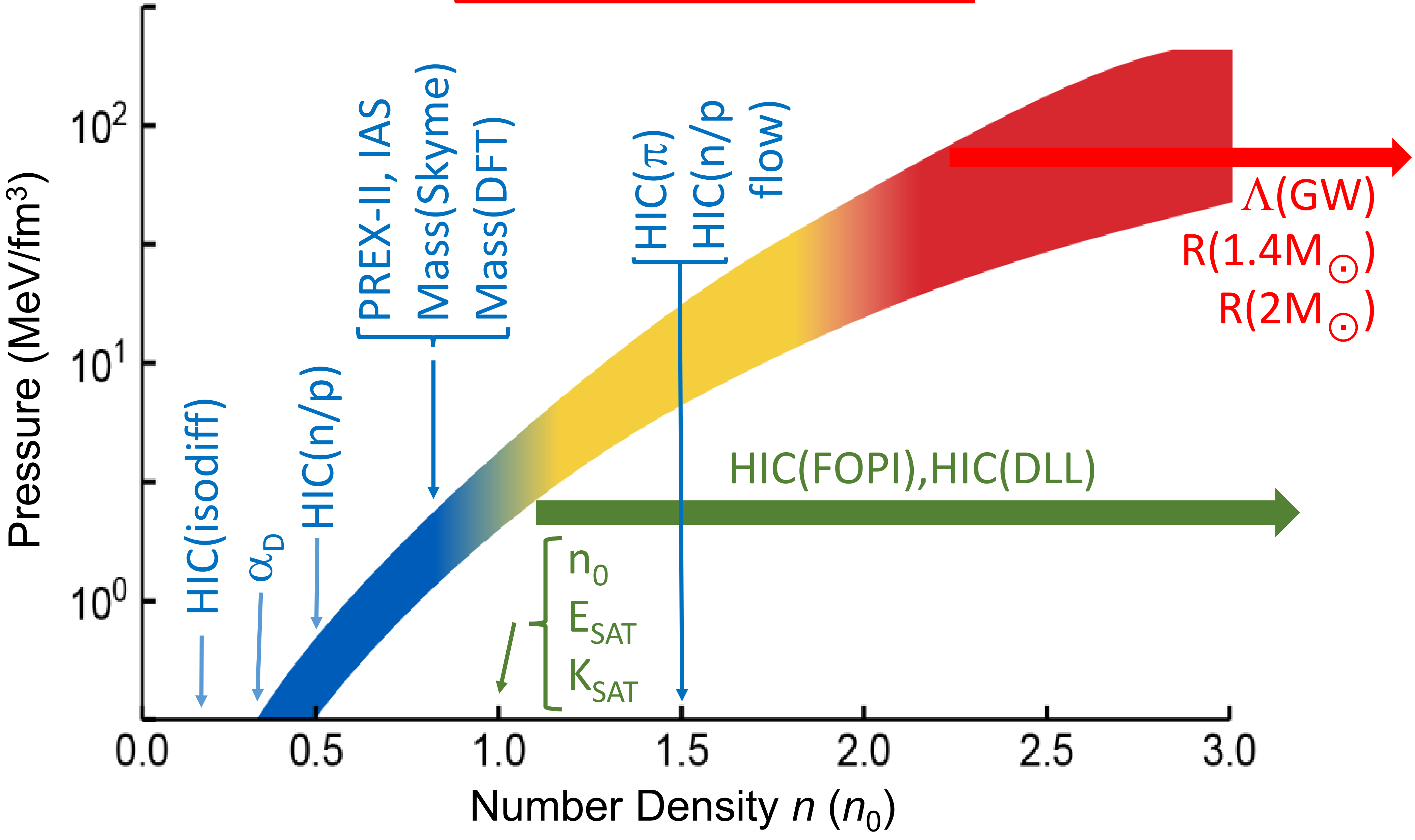
$R(2M_\odot)$

Astronomical Constraints



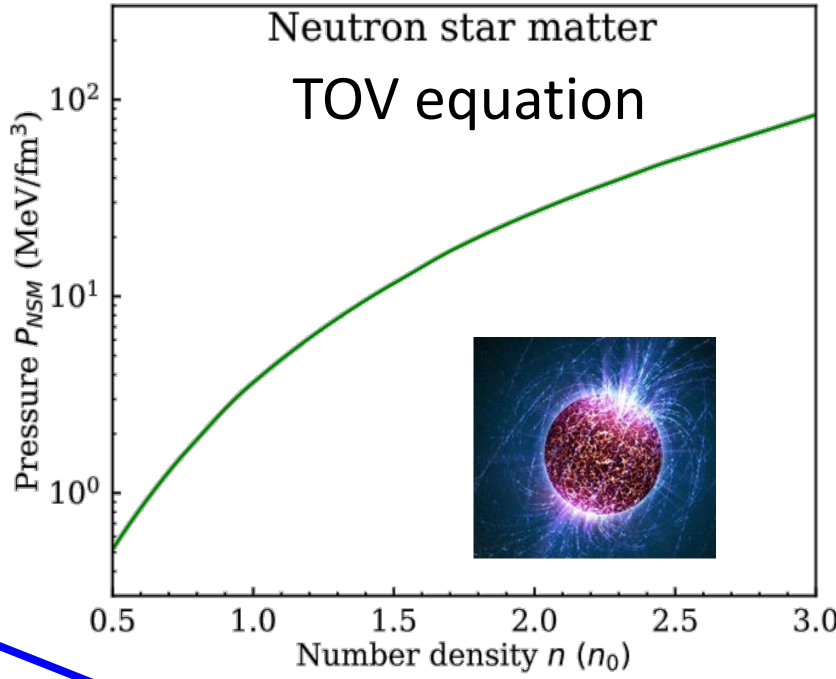
$\varepsilon(\rho,\delta=1)=\varepsilon(\rho,\delta=0)+S(\rho)$

Diverse Constraints



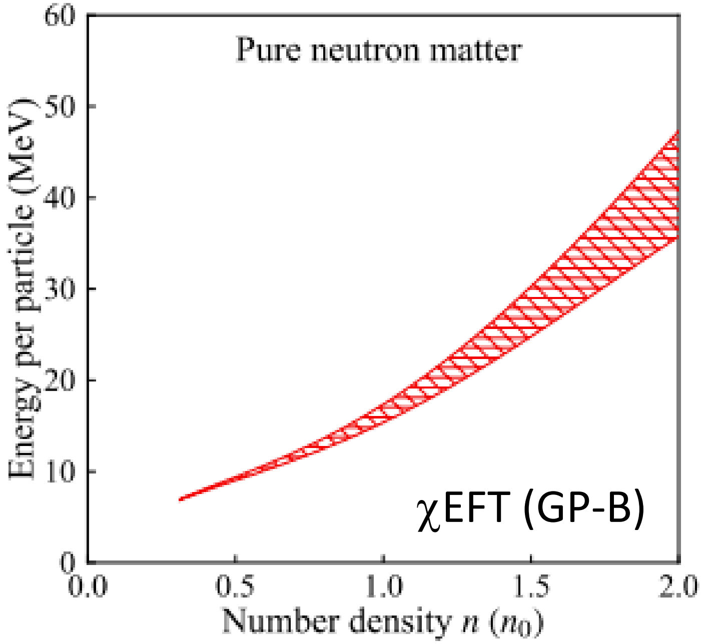
Equation of State of nuclear matter

$\varepsilon(\rho,\delta) = \varepsilon_{SNM}(\rho,0) + S(\rho)\delta^2; \quad \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$



PNM: δ=1

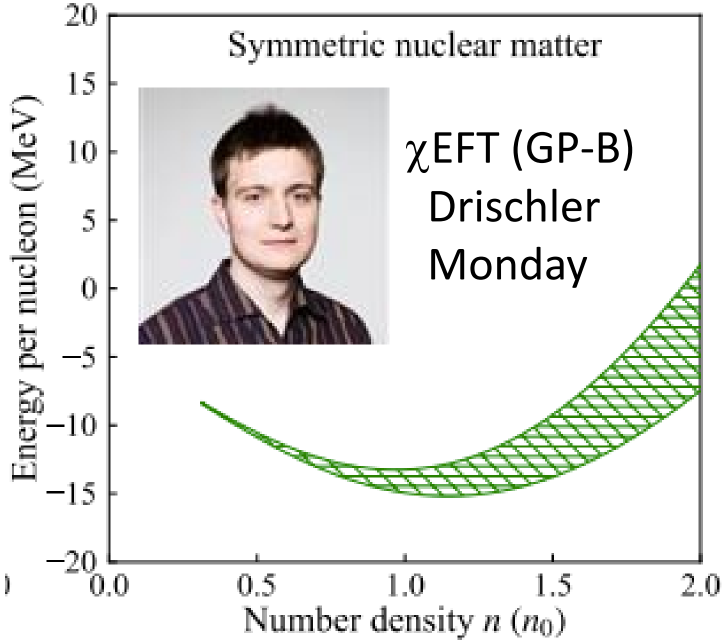
Pure Neutron Matter



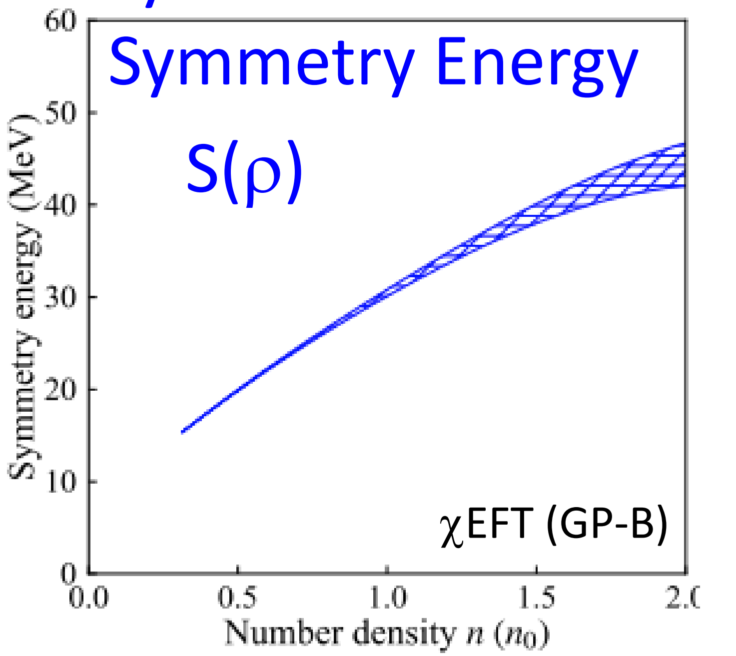
SNM: δ=0

Symmetric

Nuclear Matter



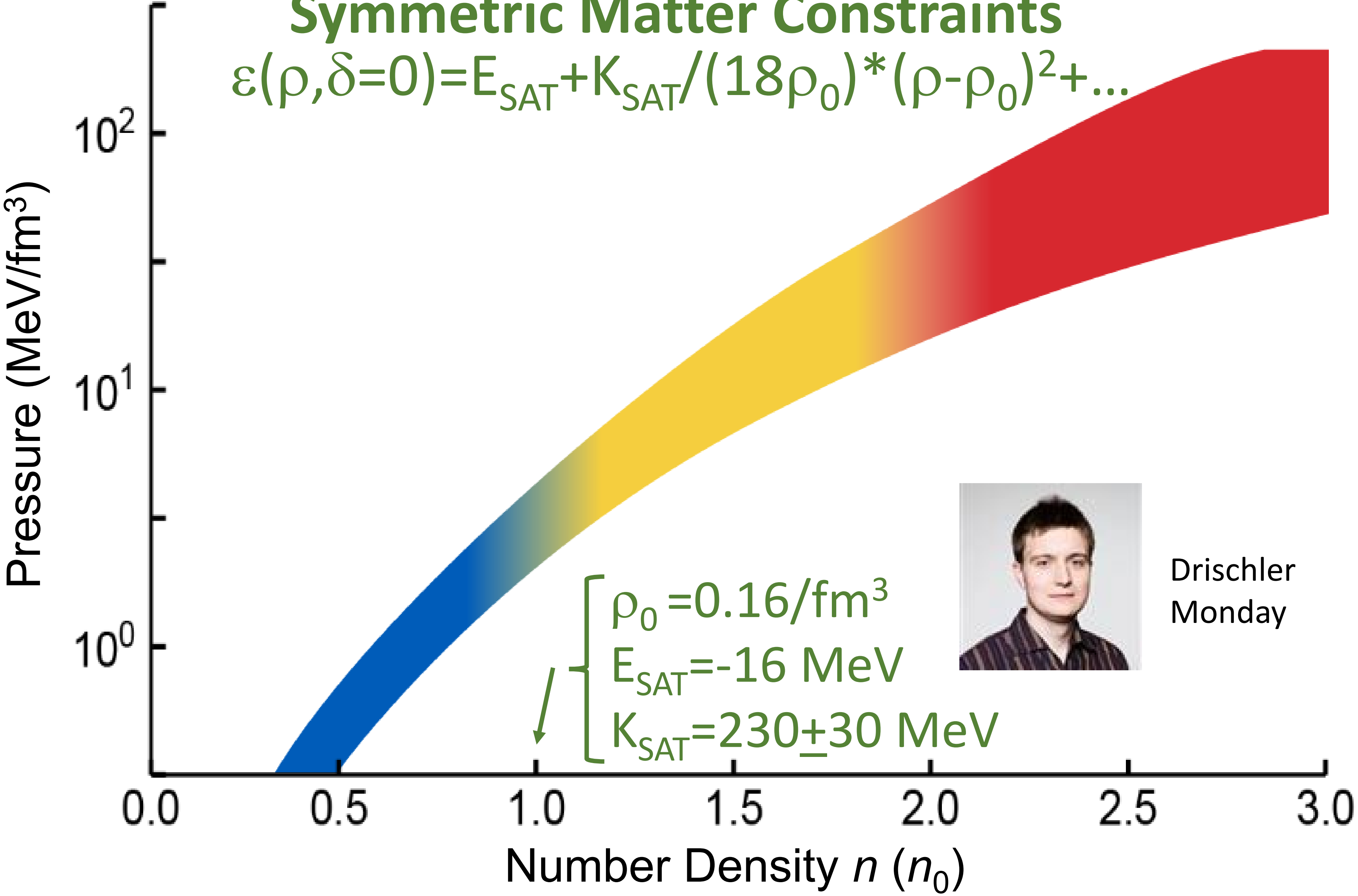
sym:



$$\varepsilon(\rho,\delta)=\varepsilon(\rho,0)+S(\rho)\delta^2$$

Symmetric Matter Constraints

$$\varepsilon(\rho,\delta=0)=E_{SAT}+K_{SAT}/(18\rho_0)*(\rho-\rho_0)^2+\ldots$$



$\rho_0=0.16/fm^3$

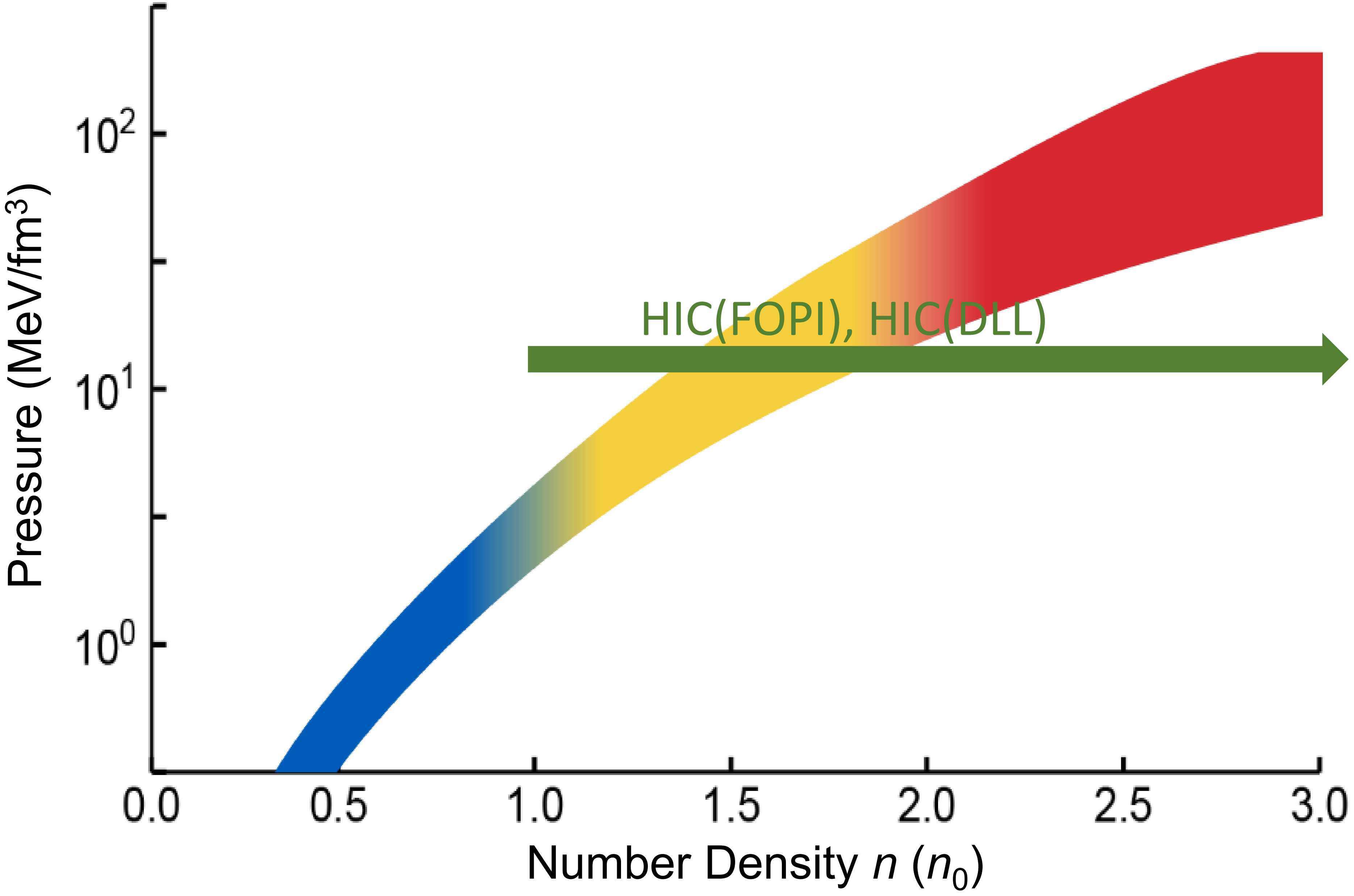
E_{SAT}=-16 MeV

K_{SAT}=230±30 MeV

Drischler
Monday

Symmetric Matter Constraints

HIC(FOPI),HIC(DLL)



Symmetric Matter Constraints

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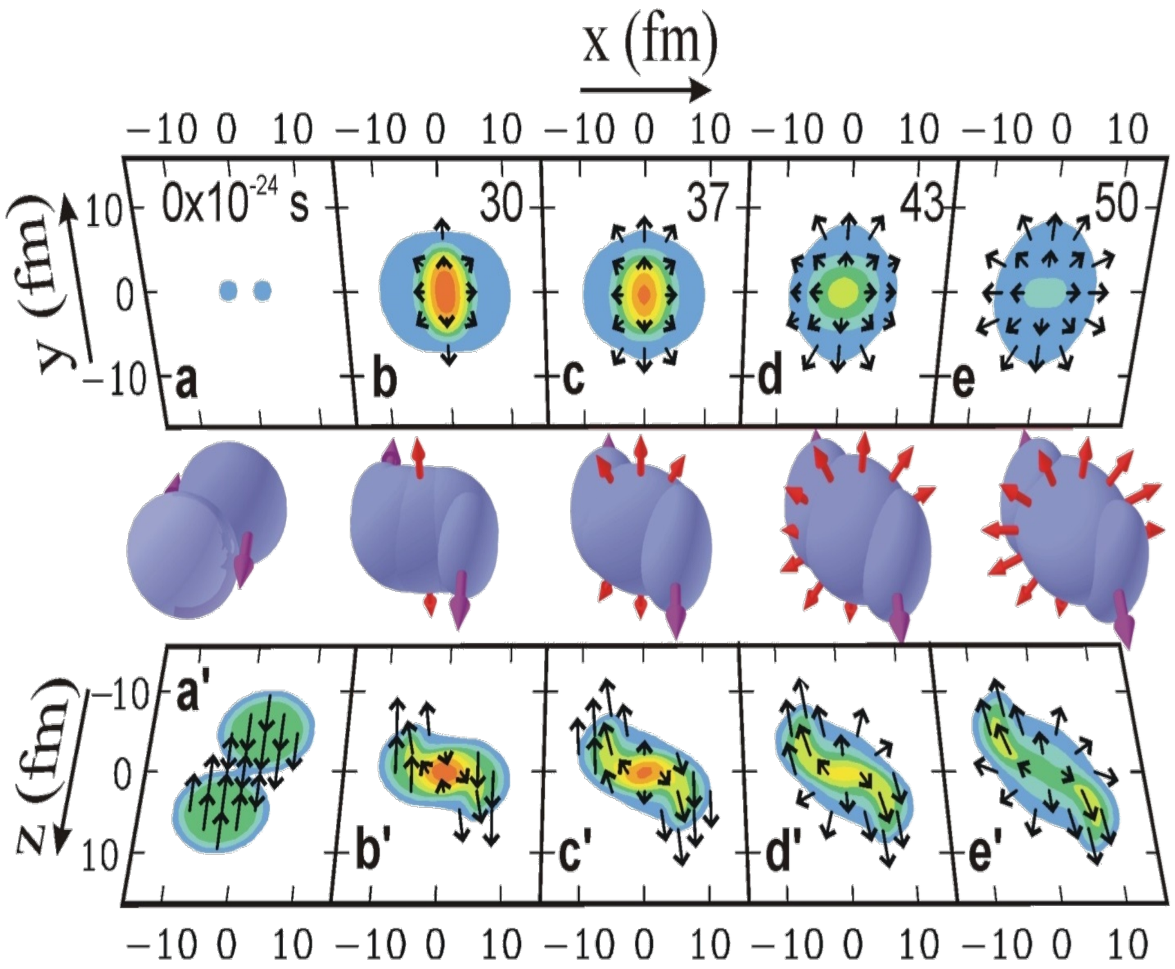
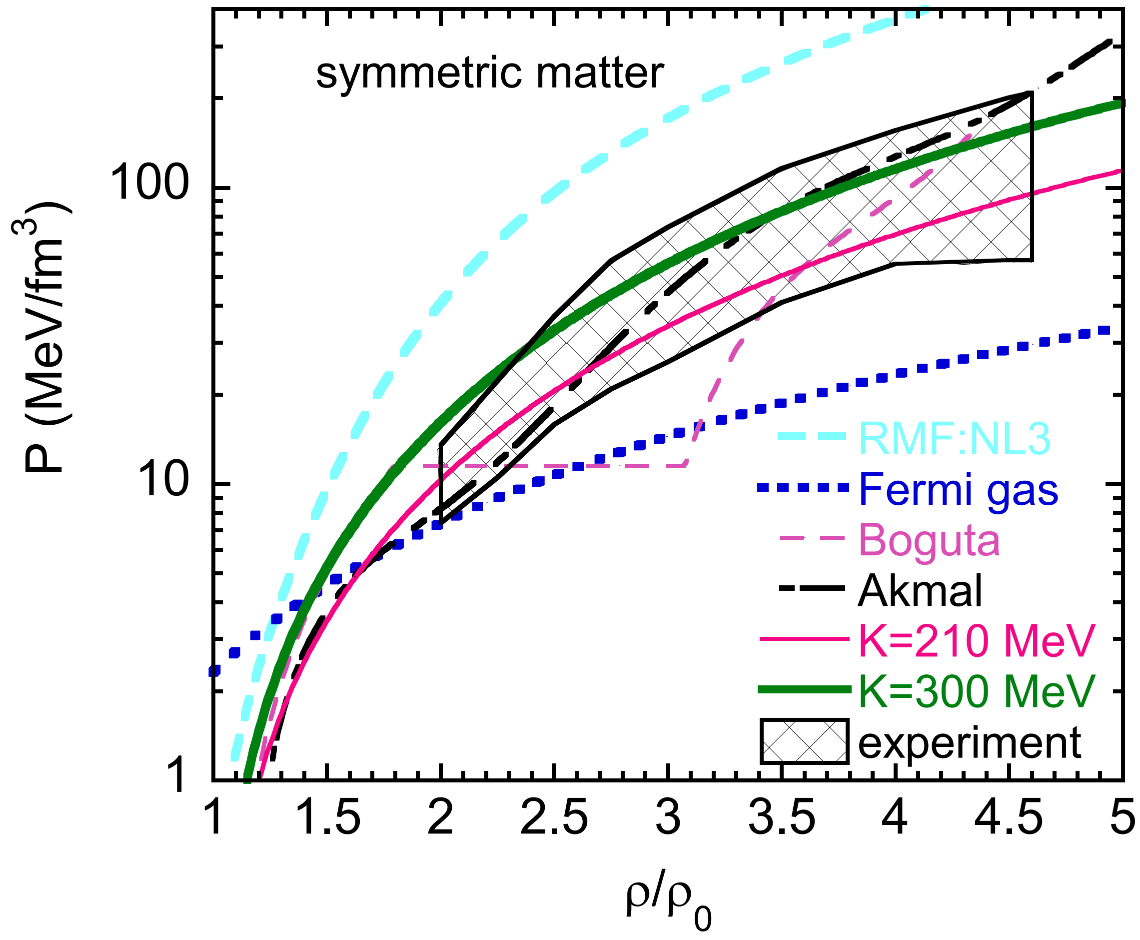


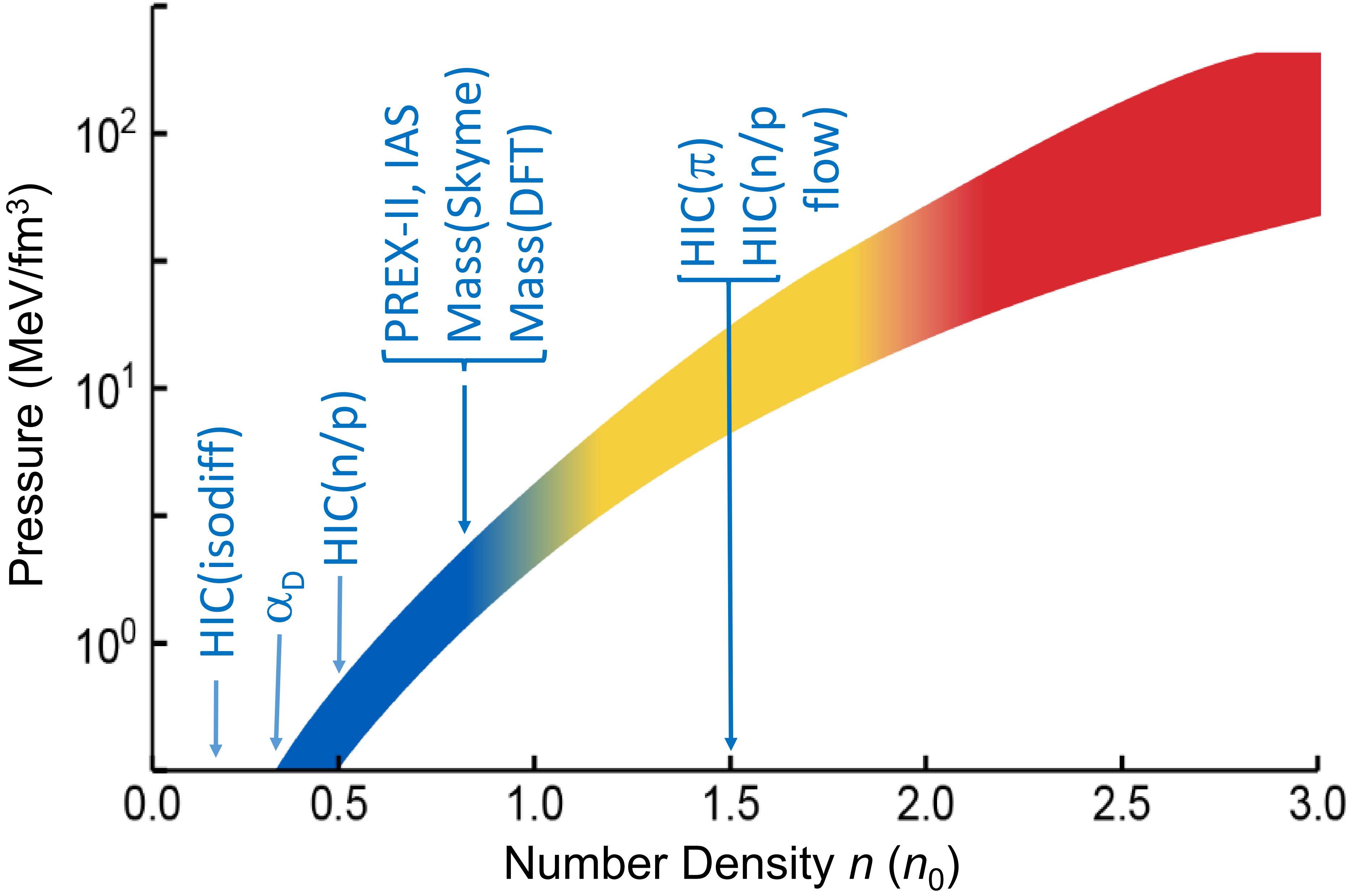
pBUU simulations

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



Symmetry Energy Constraints

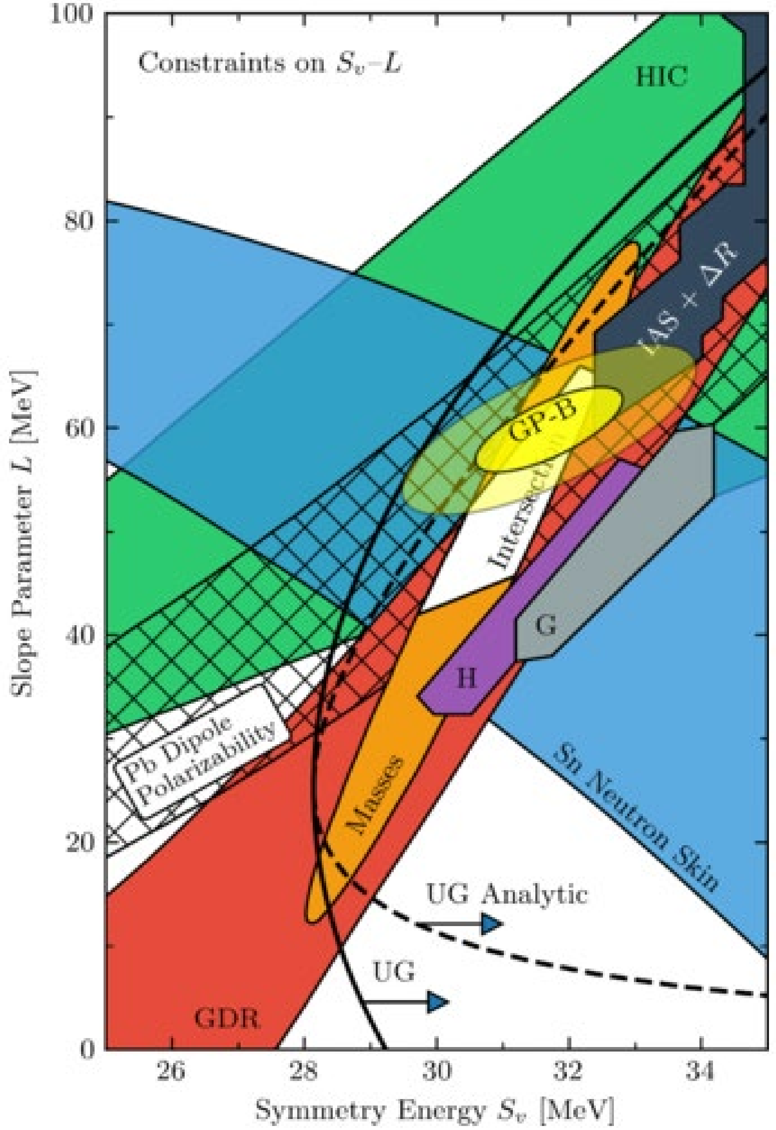
$\varepsilon(\rho,\delta=1)=\varepsilon(\rho,\delta=0)+S(\rho)$



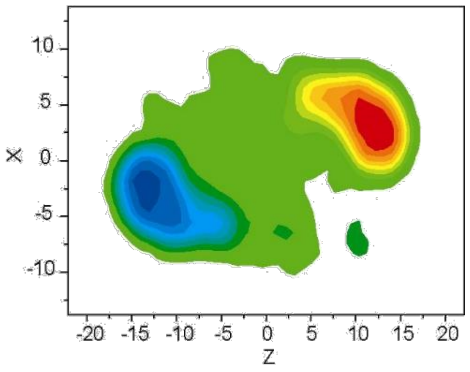
$$E(\rho,\delta) = E_{SNM}(\rho,0) + S(\rho)\delta^2$$

$$S(\rho) = S_0 + \frac{L}{3\rho_0}(\rho-\rho_0) + \frac{K_{\rm sym}}{18\rho_0^2}(\rho-\rho_0)^2 + \cdots$$

Symmetry Pressure : $P_0=(L\rho_0)/3$

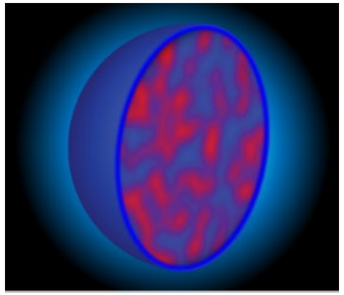


C. Drischler, et al. PRL **125**, 202702 (2020)

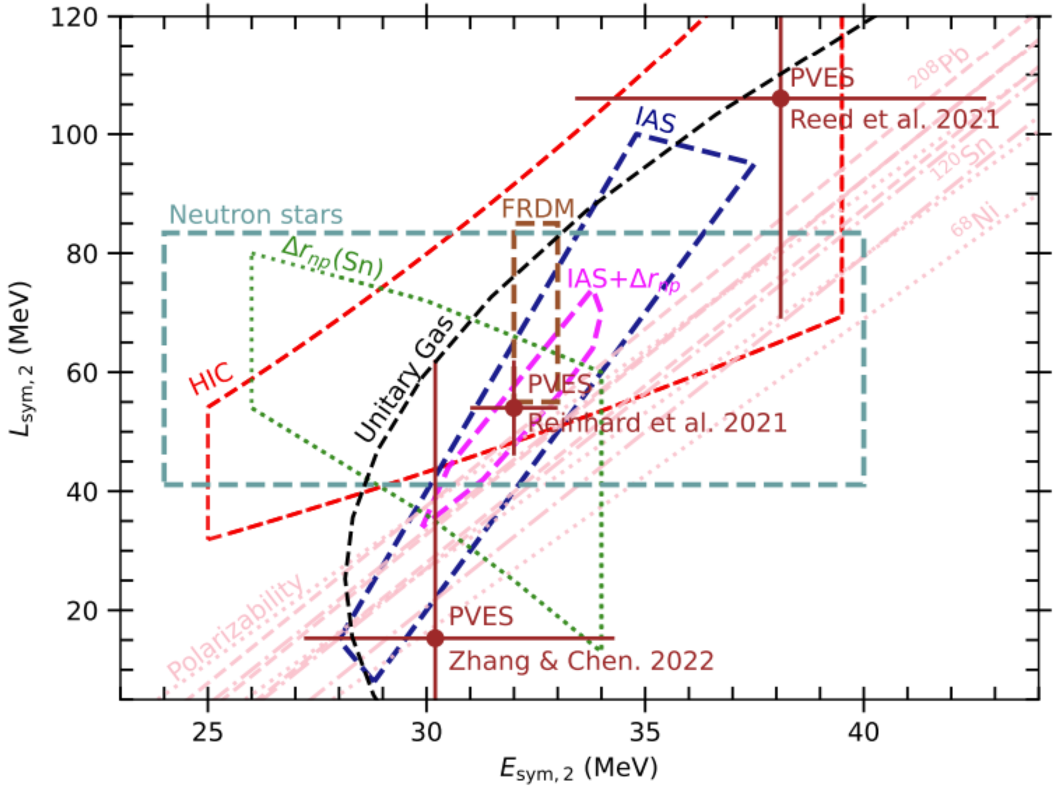


HIC; $\rho \sim 0.3\rho_0$

^{208}Pb

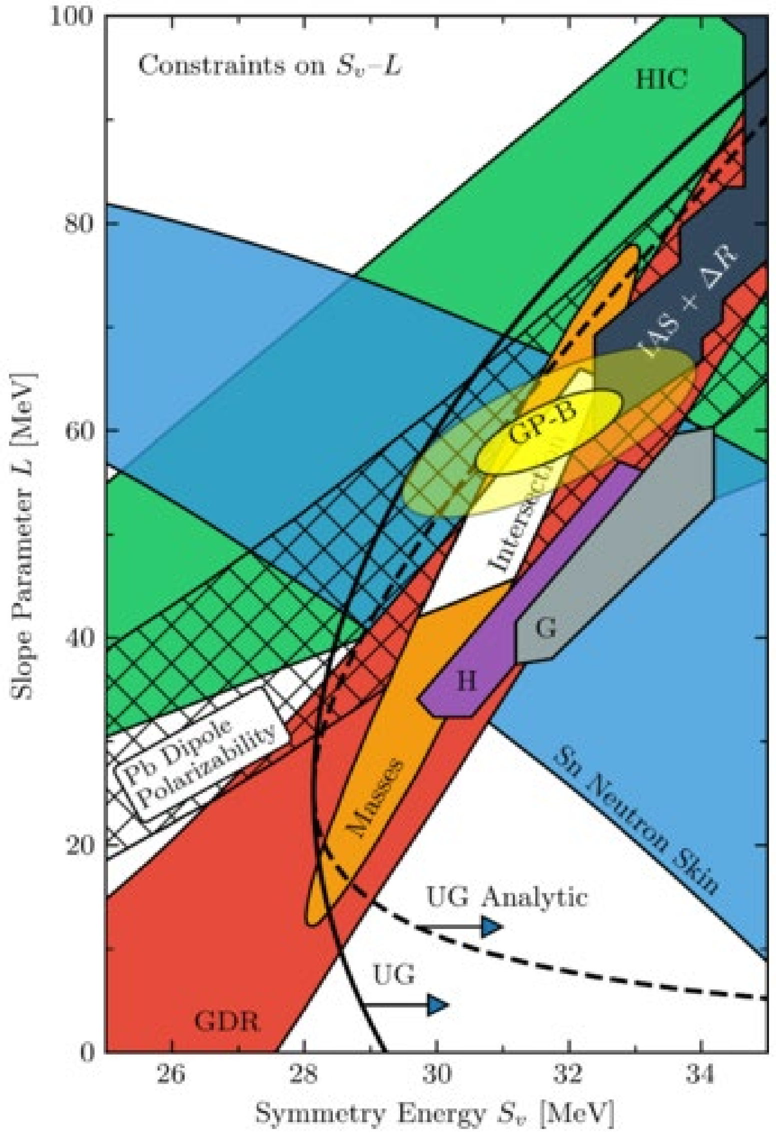


$\rho \sim 0.67\rho_0$



Carlson et al, arXiv:2209.03257v1

Density Dependence of the Symmetry Energy Constraints?

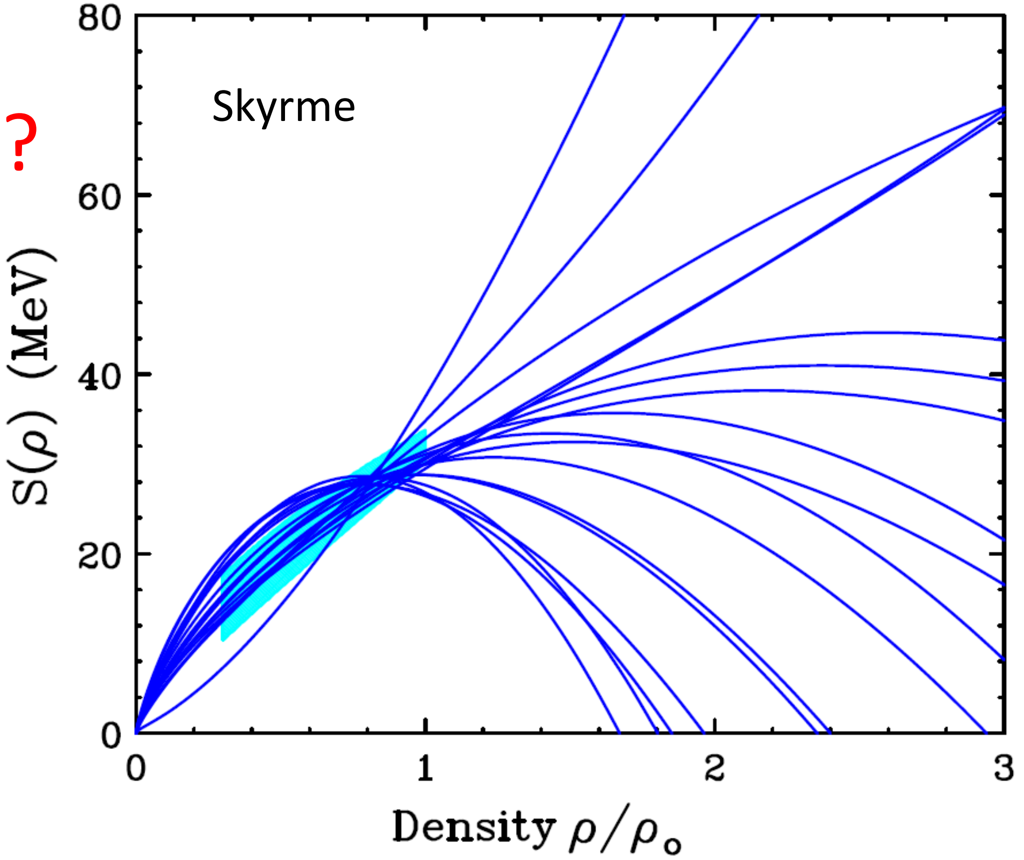


C. Drischler, et al. PRL **125**, 202702 (2020)

What happens?

?

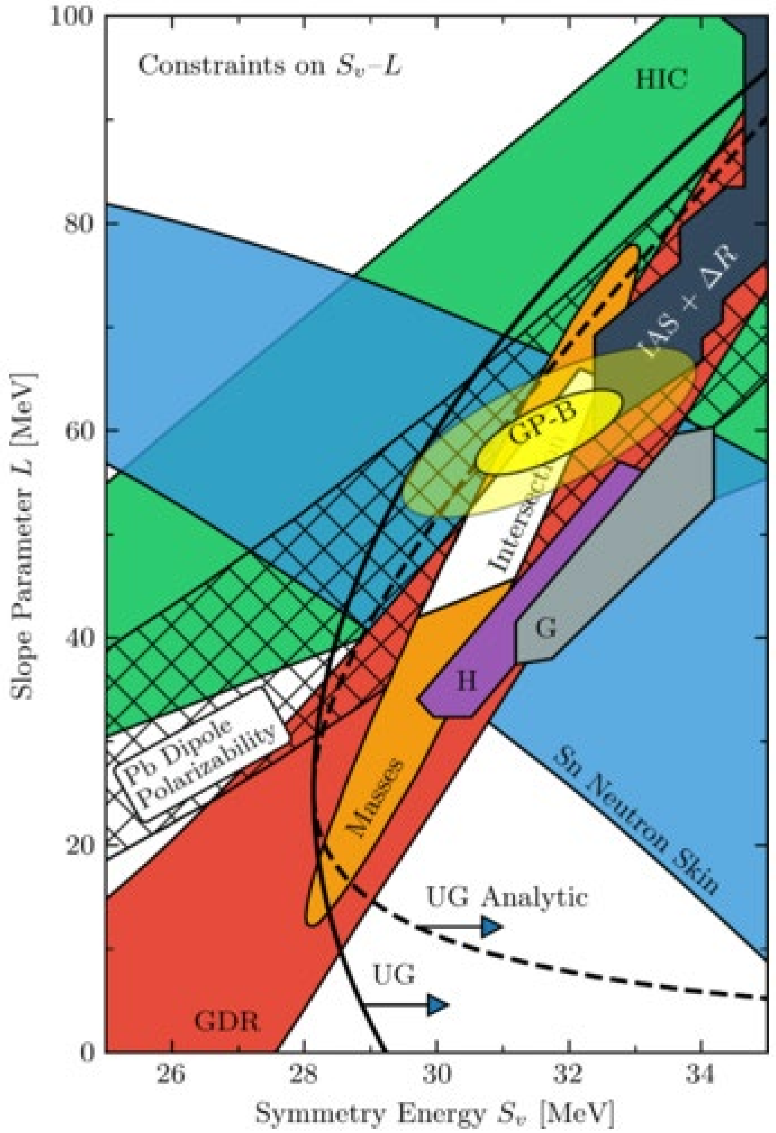
? ?



$$S(\rho) = S_0 + \frac{L}{3\rho_0}(\rho - \rho_0) + \frac{K_{sym}}{18\rho_0^2}(\rho - \rho_0)^2 + \cdots$$

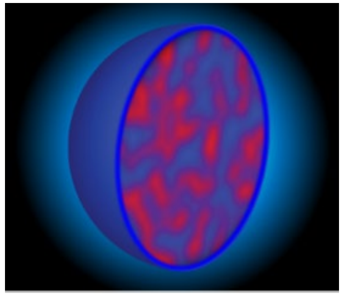
Symmetry Pressure : $P_0 = (L\rho_0)/3$

Density Dependence of the Symmetry Energy Constraints?

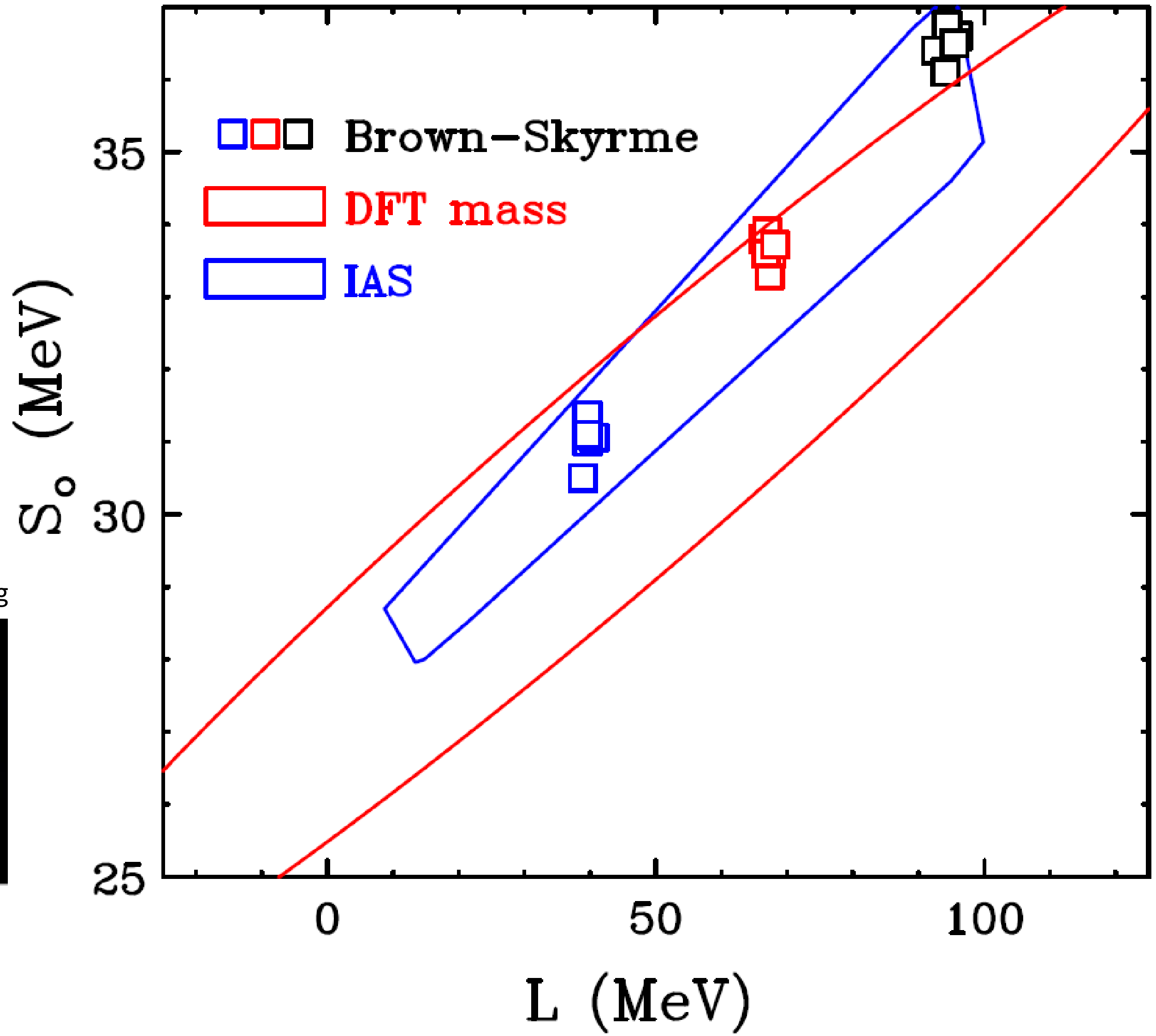


C. Drischler, et al. PRL **125**, 202702 (2020)

^{208}*Pb* AIP imag



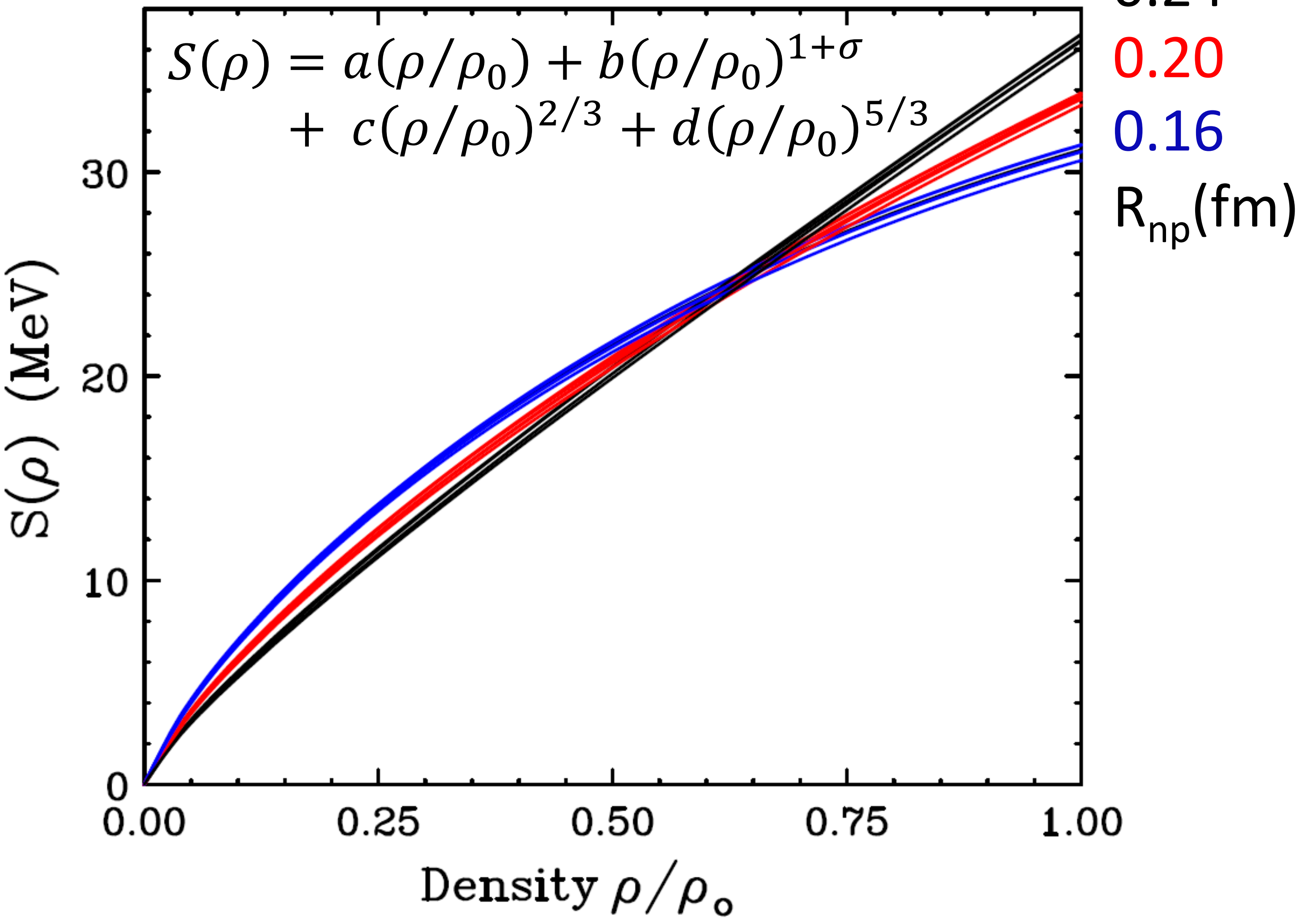
ρ~$0.67\rho_0$



Lynch & Tsang: PLB 830 (2022)137098

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

Cross-over method

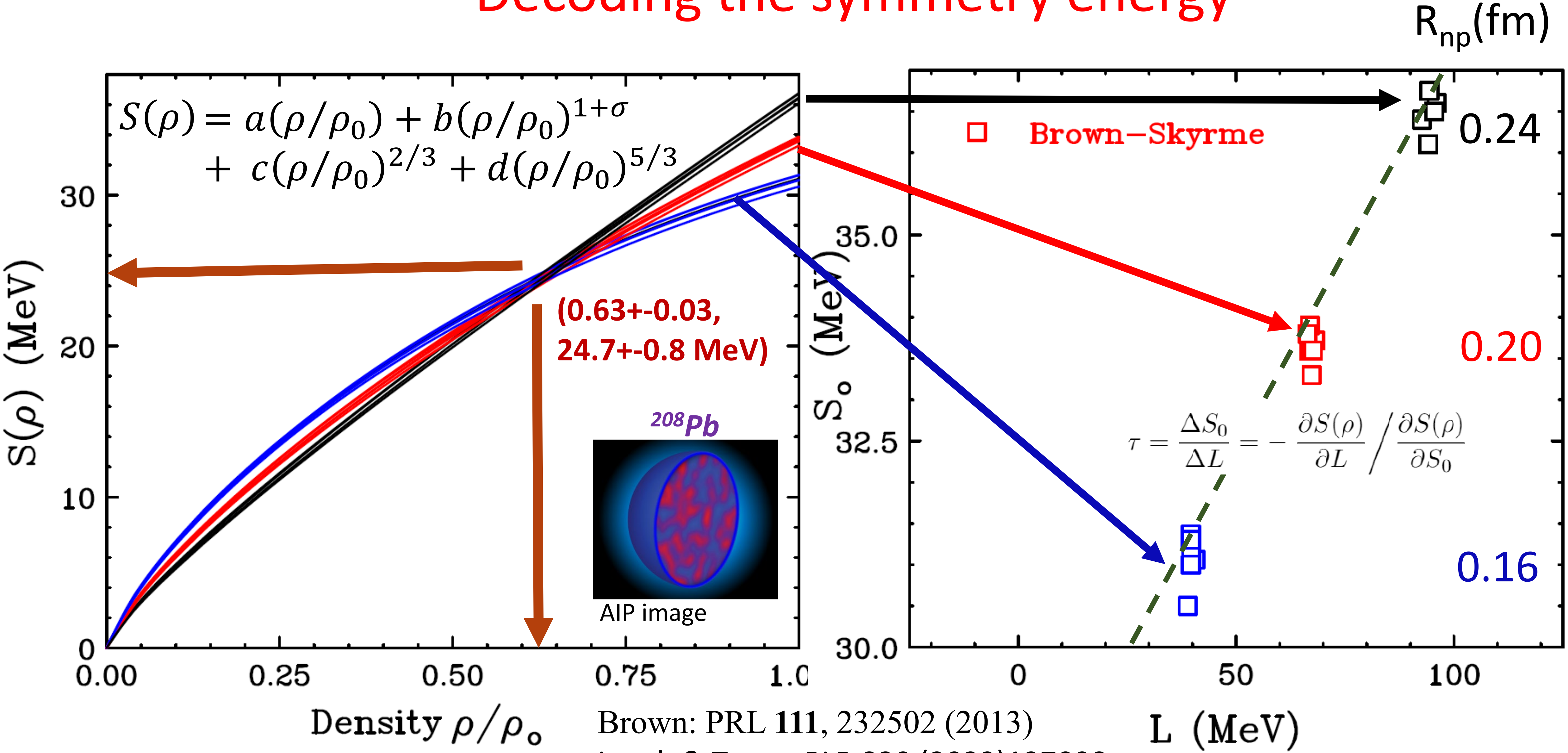


Alex Brown PRL **111**, 232502 (2013)

Use Skyrme interactions that fit Properties of "closed-shell" nuclei ^{16}O, ^{24}O, ^{34}Si, ^{40}Ca, ^{48}Ca, ^{48}Ni, ^{68}Ni, ^{88}Sr, ^{100}Sn, ^{132}Sn and ^{208}Pb"

3 skin values for ^{208}Pb

Decoding the symmetry energy

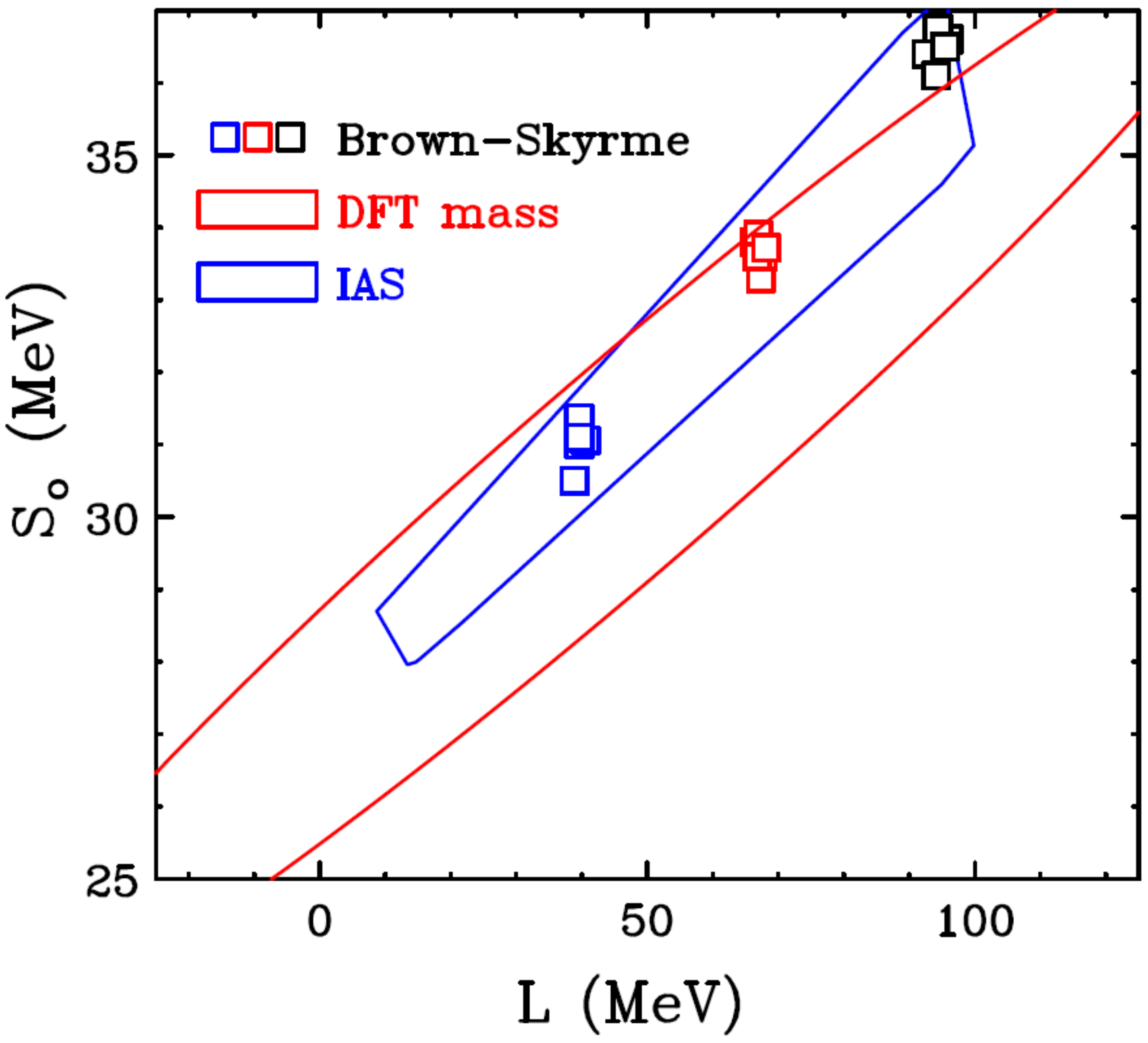


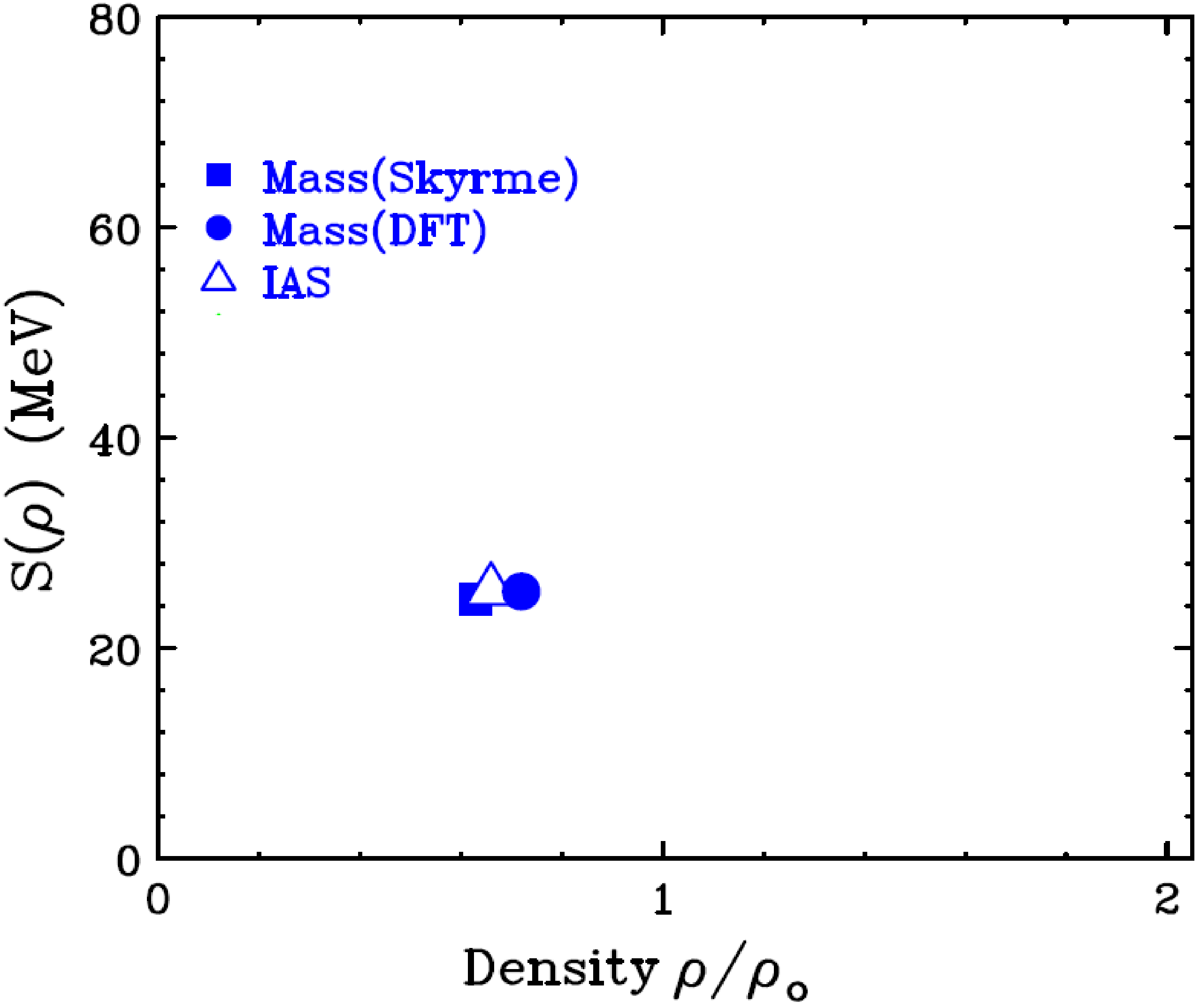
Brown: PRL **111**, 232502 (2013)

Lynch & Tsang: PLB 830 (2022)137098

Decoding the constraints on the Symmetry Energy

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





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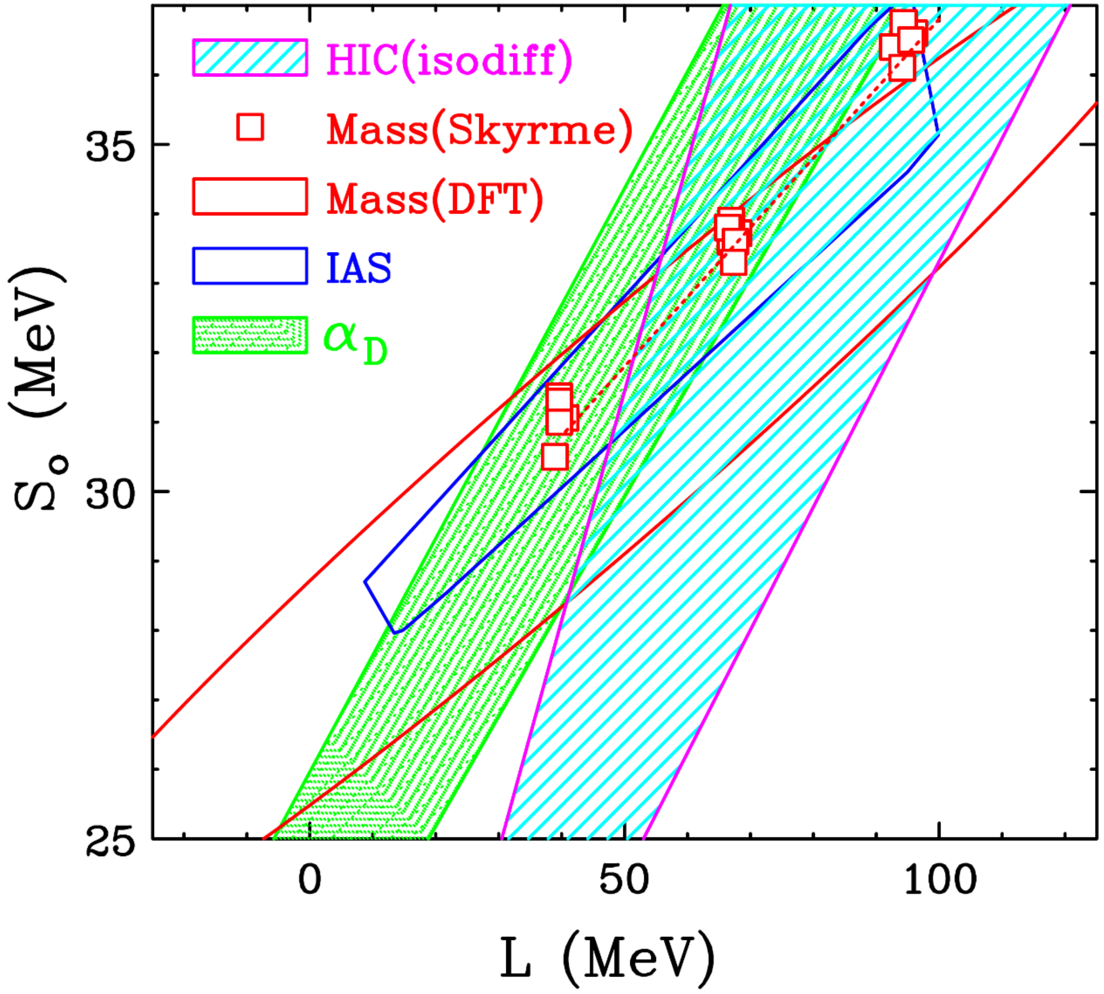
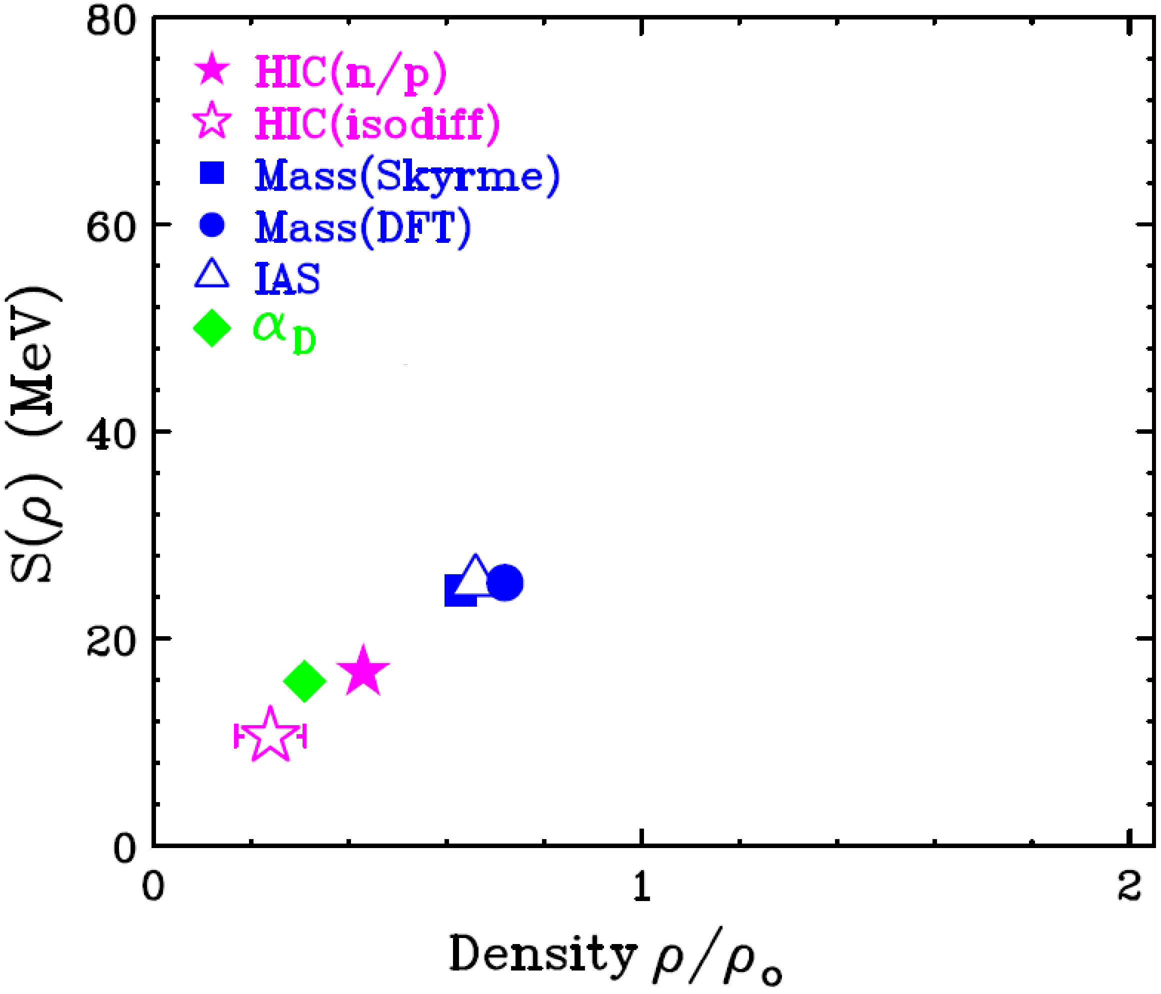
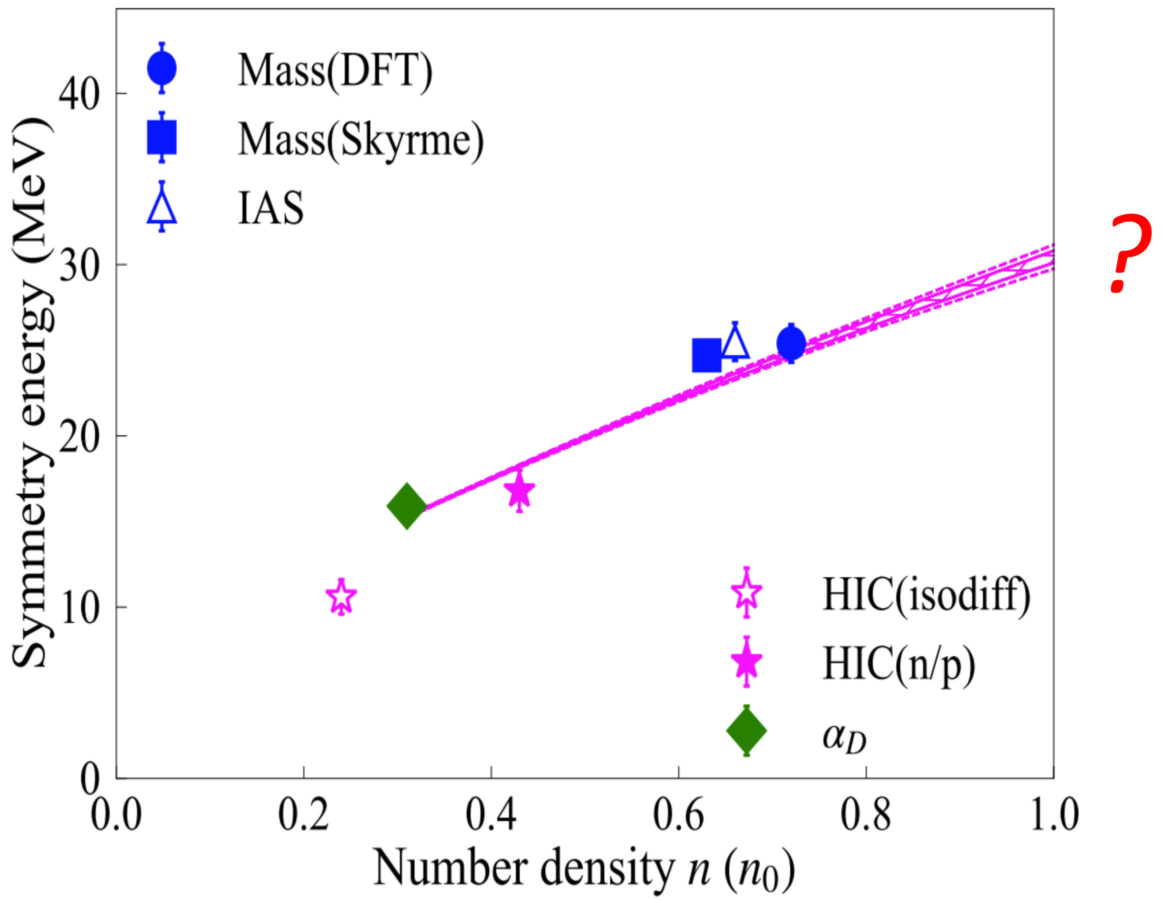




Lynch & Tsang: PLB 830 (2022)137098

SπRIT Collaboration

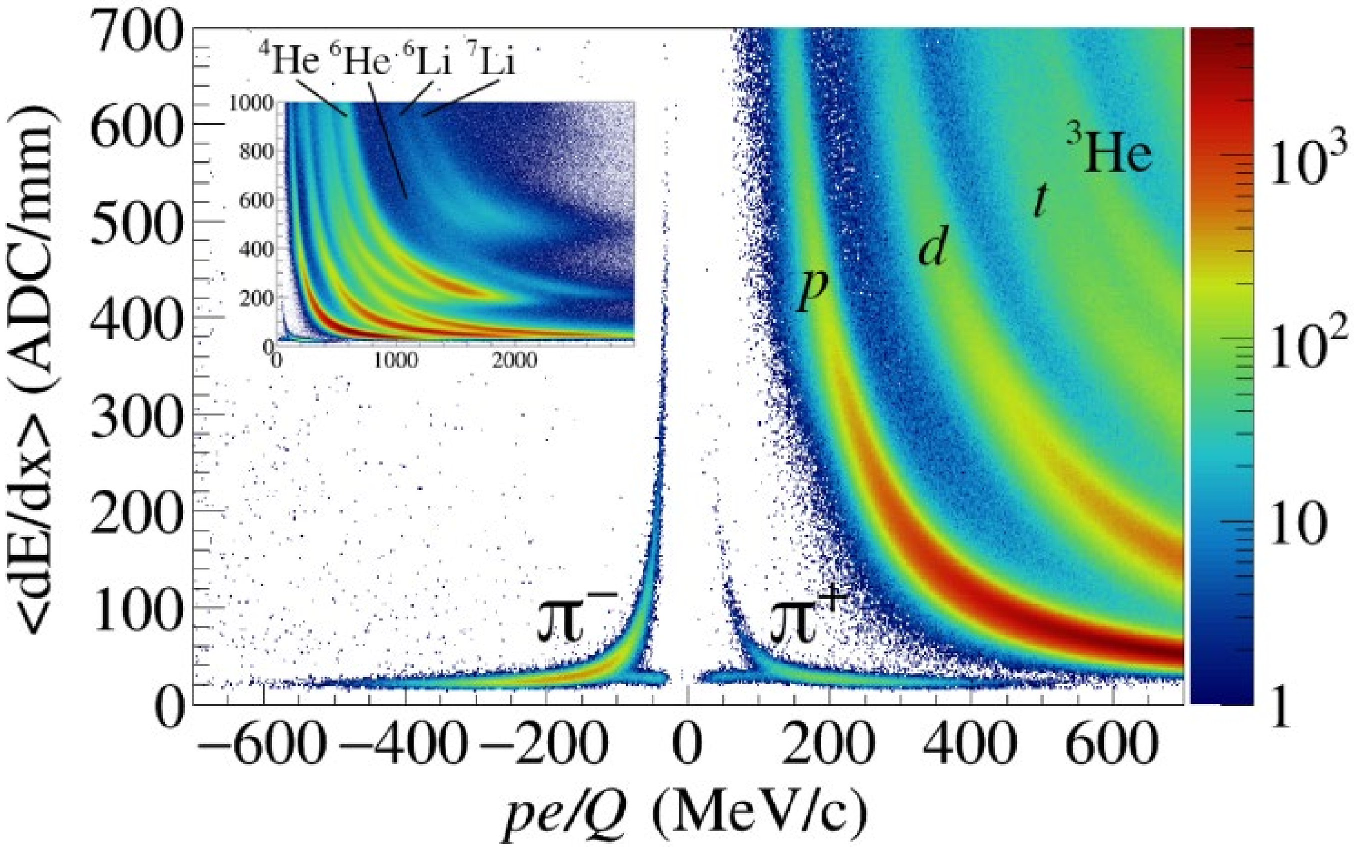


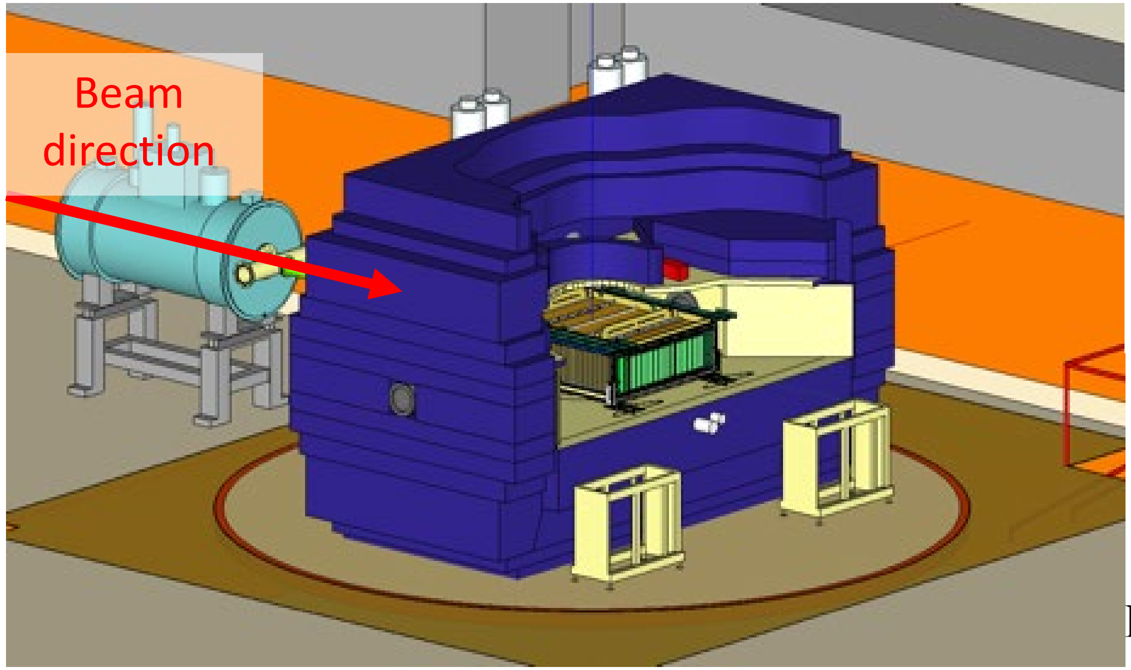
Drischler: PRL 125, 202702 (2020); PRC 102, 054315 (2020)
Lynch & Tsang: PLB 830 (2022)137098

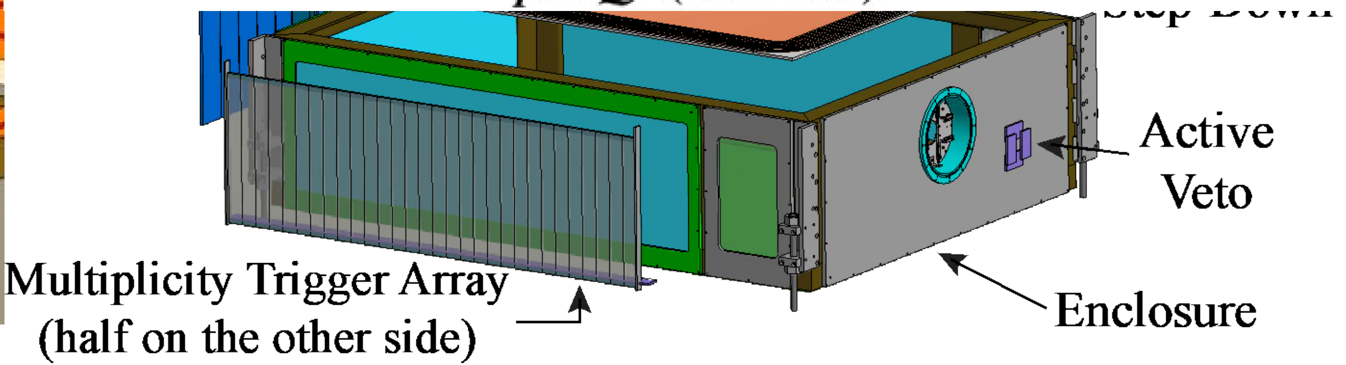
- Pions emitted in early stage of collisions reflect the high density environment.
- Total pion ratio $Y(\pi^-)/Y(\pi^+) \propto (n/p)^2$ → small effects ~10% effect & low energy pions depend on models
- Measure the pion spectral ratio for high energy pions
- Use radioactive beams in increase δ range.

SπRIT Collaboration

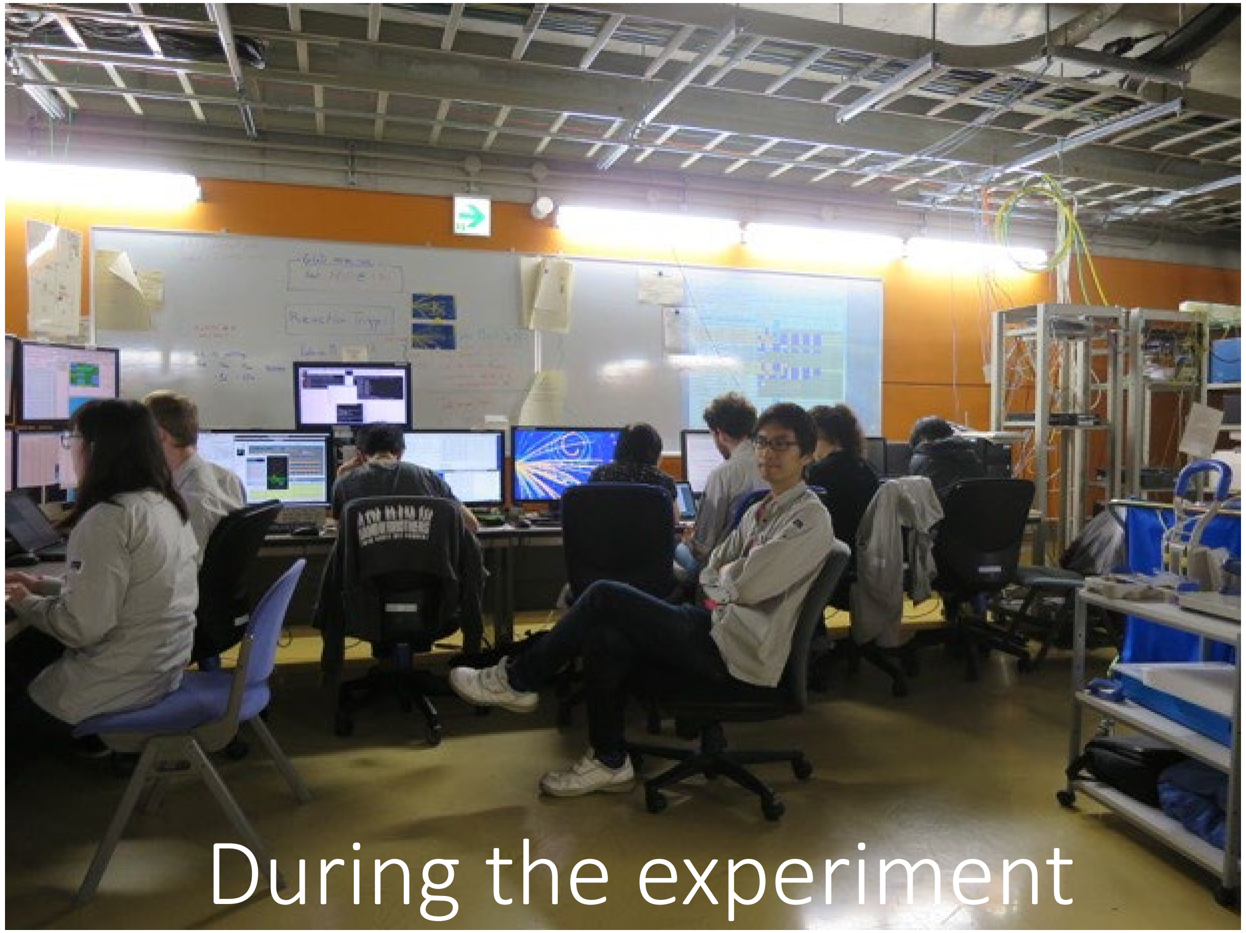
System	Energy (AMeV)	(N-Z)/A	#events (M)
$^{132}Sn+^{124}Sn$	270	0.22	3.8
$^{108}Sn+^{112}Sn$	270	0.09	2.4
$^{112}Sn+^{124}Sn$	270	0.15	1.8
$^{124}Sn+^{112}Sn$	270	0.15	.2

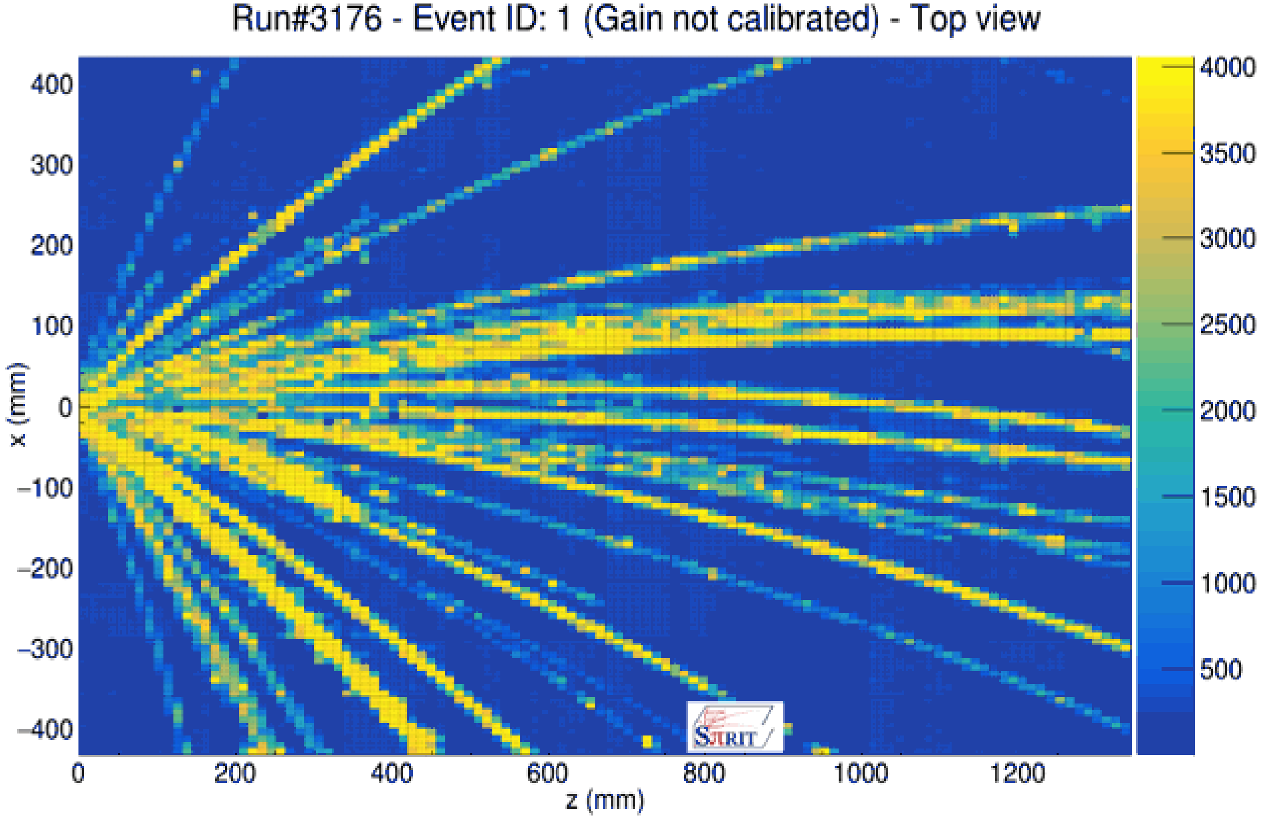






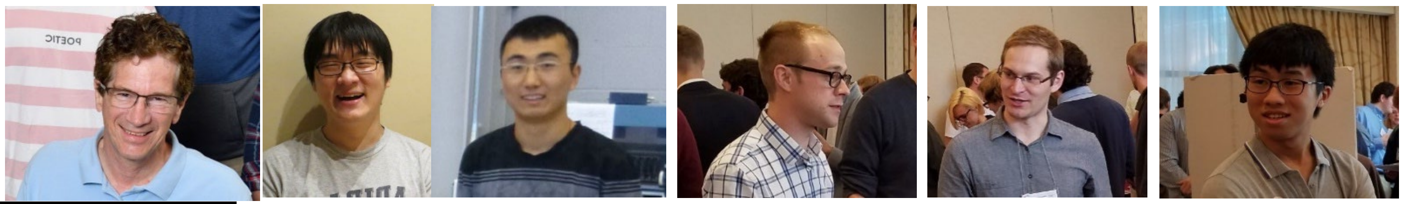
SπRIT Collaboration

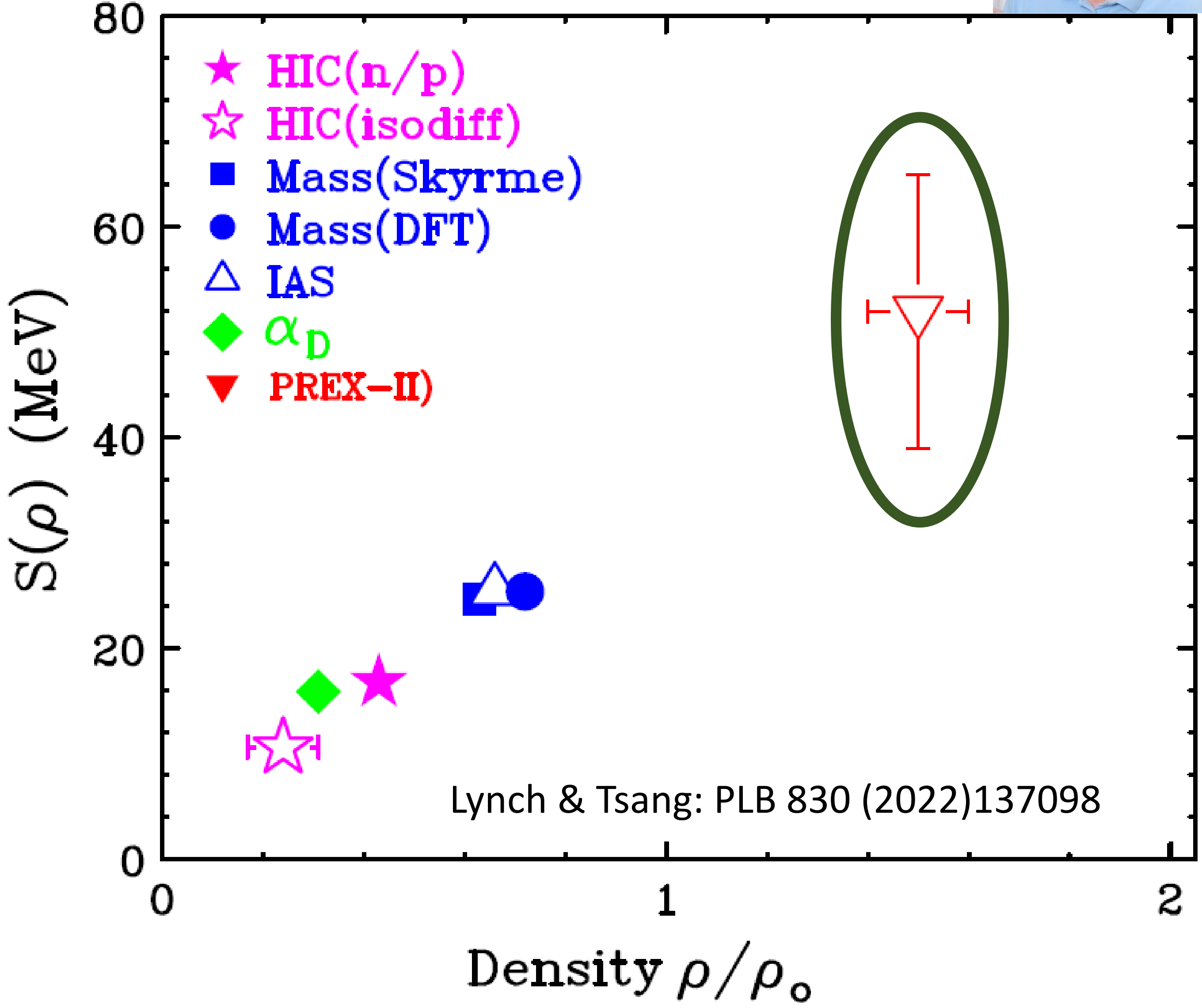


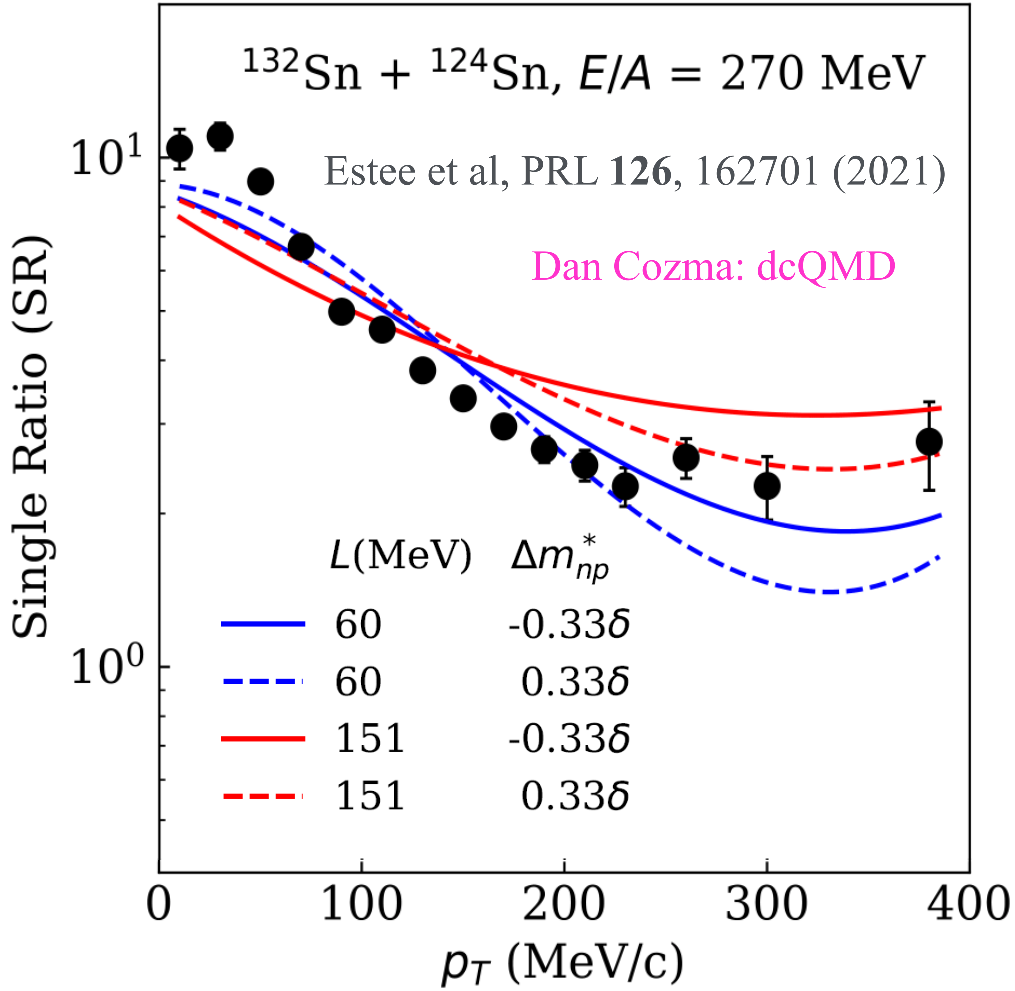


R. Shane et al., NIMA **784**, 513 (2015).
G. Jhang et al., JKPS 69, 144–151 (2016).
S. Tangwangchoren et al. NIMA 853, 44–52 (2017).
P. Lasko et al., NIMA 856, 92 (2017).
T. Isobe et al., NIMA 899, 43 (2018).
J. Estee et al., NIMA 944, 162509 (2019).
C.Y. Tsang et al. NIMA 959, 163477 (2020).
J.W. Lee et al., NIMA 965, 163840 (2020).
J. Barney et al., RSI (in press)
G. Jhang et al., PLB 813, 136016 (2021).
J. Estee et al., PRL 126, 162701 (2021).

SπRIT Collaboration

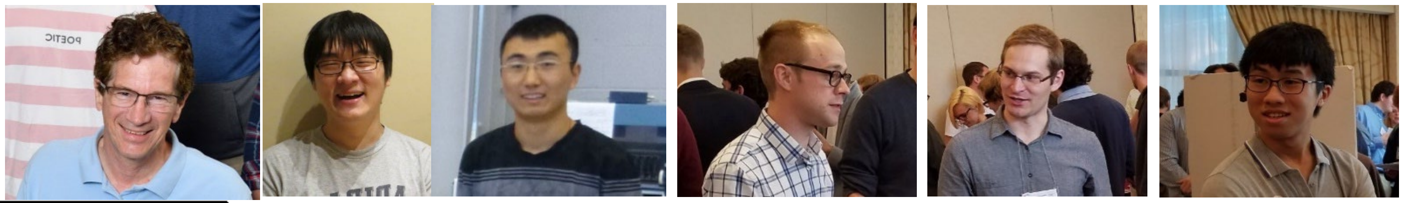


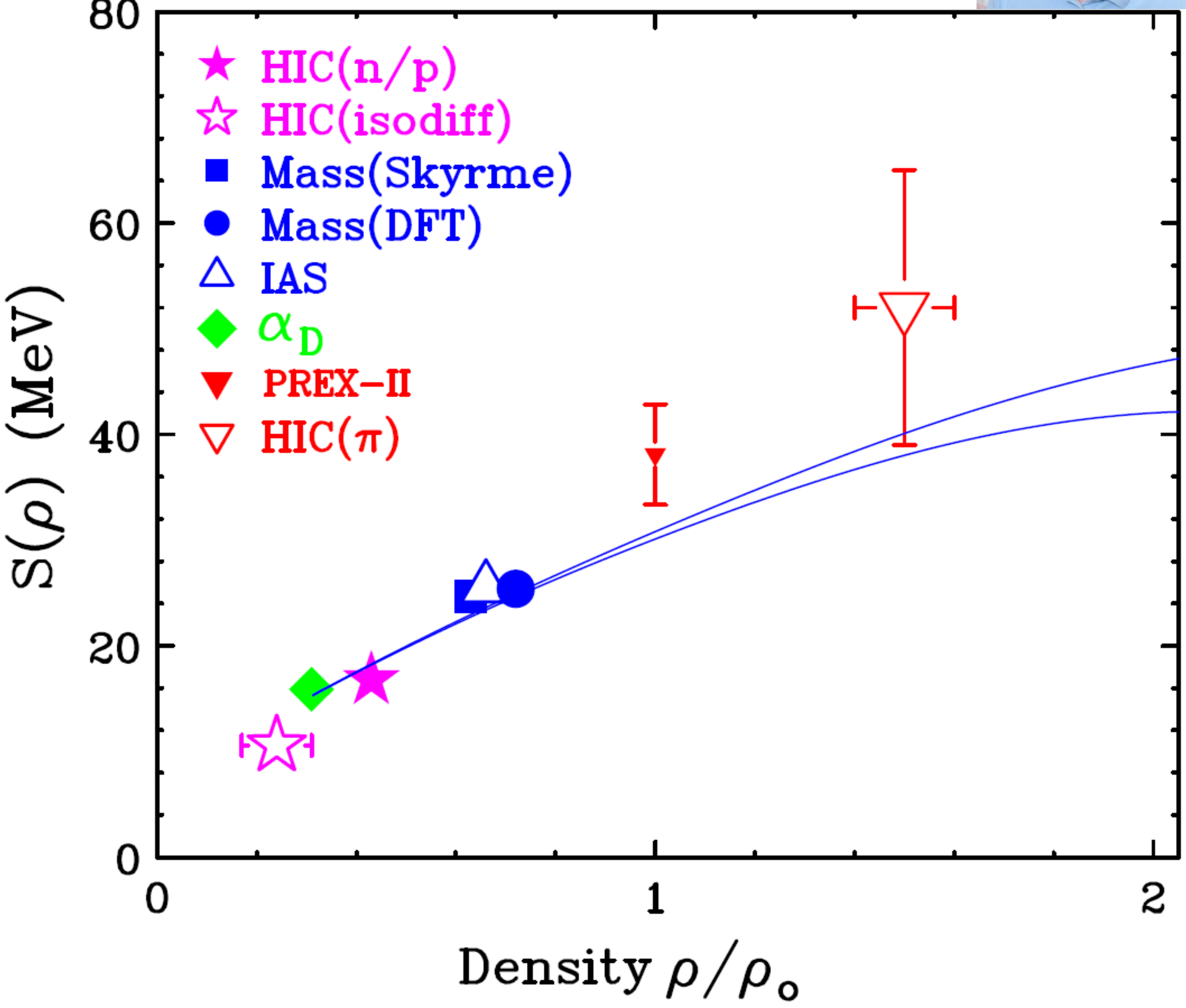


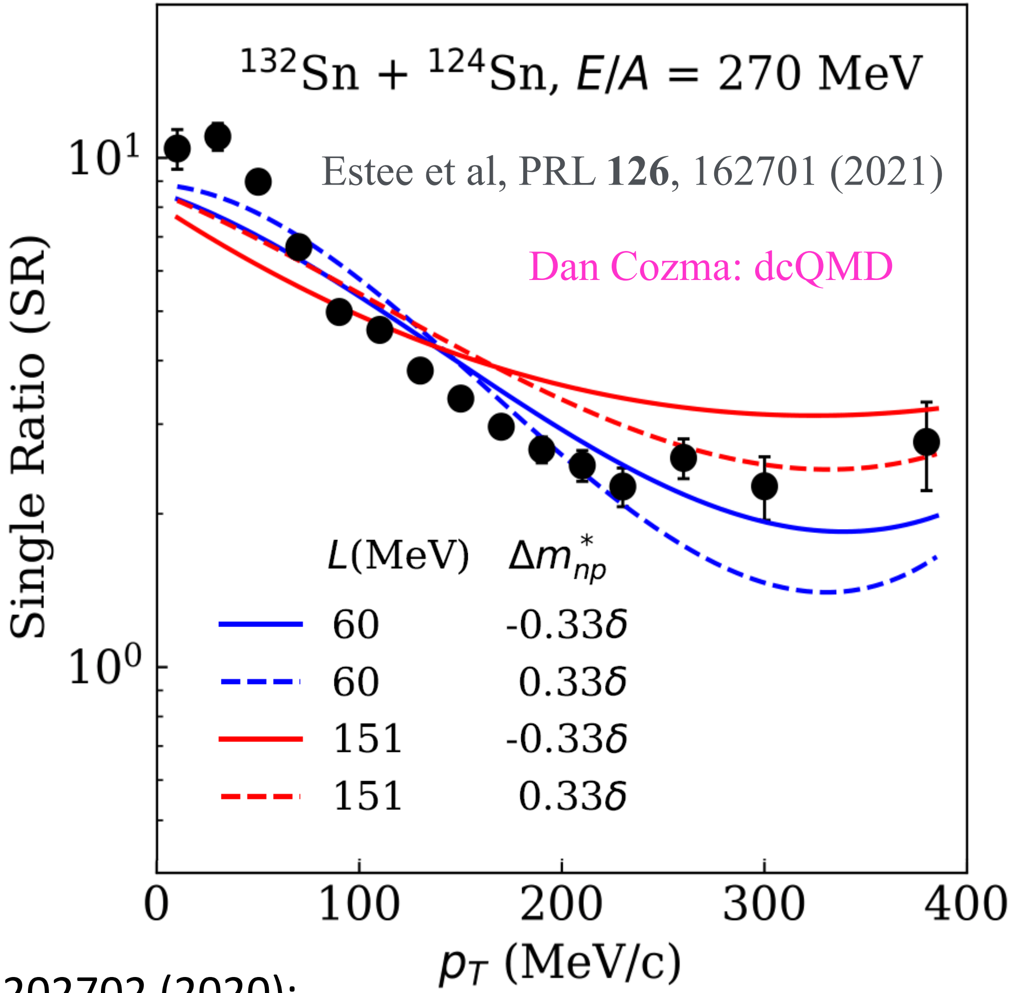


SπRIT Collaboration

Lynch Jhang Wang Barney Estee Tsang







L 125, 202702 (2020);

g: PLB 830 (2022)137098

Nuclear structure, reactions Astro (15) constraints

Symmetric matter Constraints	ρ (fm^{-3})	P_{SNM} (MeV/fm^3)	K_{sat} (MeV)	Ref.
HIC (Science)	0.32	10.1 ± 3.0		[1]
HIC (FOPI)	0.32	10.3 ± 2.8		[2]
GMR	0.16		230 ± 30	[3]

Asymmetric matter Constraints	ρ (fm^{-3})	S(ρ) (MeV)	P_{sym} (MeV/fm^3)	Ref.
Nuclear structure				
α_D	0.05	15.9 ± 1.0		[4]
PREX-II	0.1		2.38 ± 0.75	[5, 6]
Nuclear masses				
Mass (Skyrme)	0.101	24.7 ± 0.8		[7]
Mass (DFT)	0.115	25.4 ± 1.1		[8]
IAS	0.106	25.5 ± 1.1		[9]
Heavy-ion collisions				
HIC (Isodiff)	0.038	10.3 ± 1.0		[10]
HIC (n/p ratio)	0.069	16.8 ± 1.2		[11]
HIC(π)	0.232	52.0 ± 13	10.9 ± 8.7	[12]
HIC (n/p flow)	0.240		12.1 ± 8.4	[13–15]

Astronomical constraints	$M(\odot)$	R (km)	Λ	Ref.
LIGO	1.4		190^{+390}_{-120}	[16]
Riley PSR J0030+0451	$1.34^{+0.15}_{-0.16}$	$^{a}12.71^{+1.14}_{-1.19}$		[17]
Miller PSR J0030+0451	$1.44^{+0.15}_{-0.14}$	$^{a}13.02^{+1.24}_{-1.06}$		[18]
Riley PSR J0740+6620	$2.07^{+0.07}_{-0.07}$	$^{b}12.39^{+1.30}_{-0.98}$		[19]
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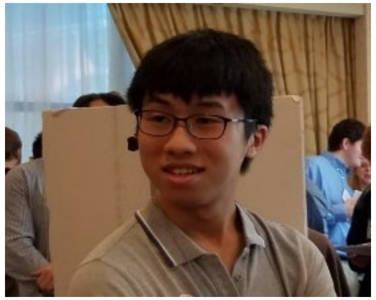
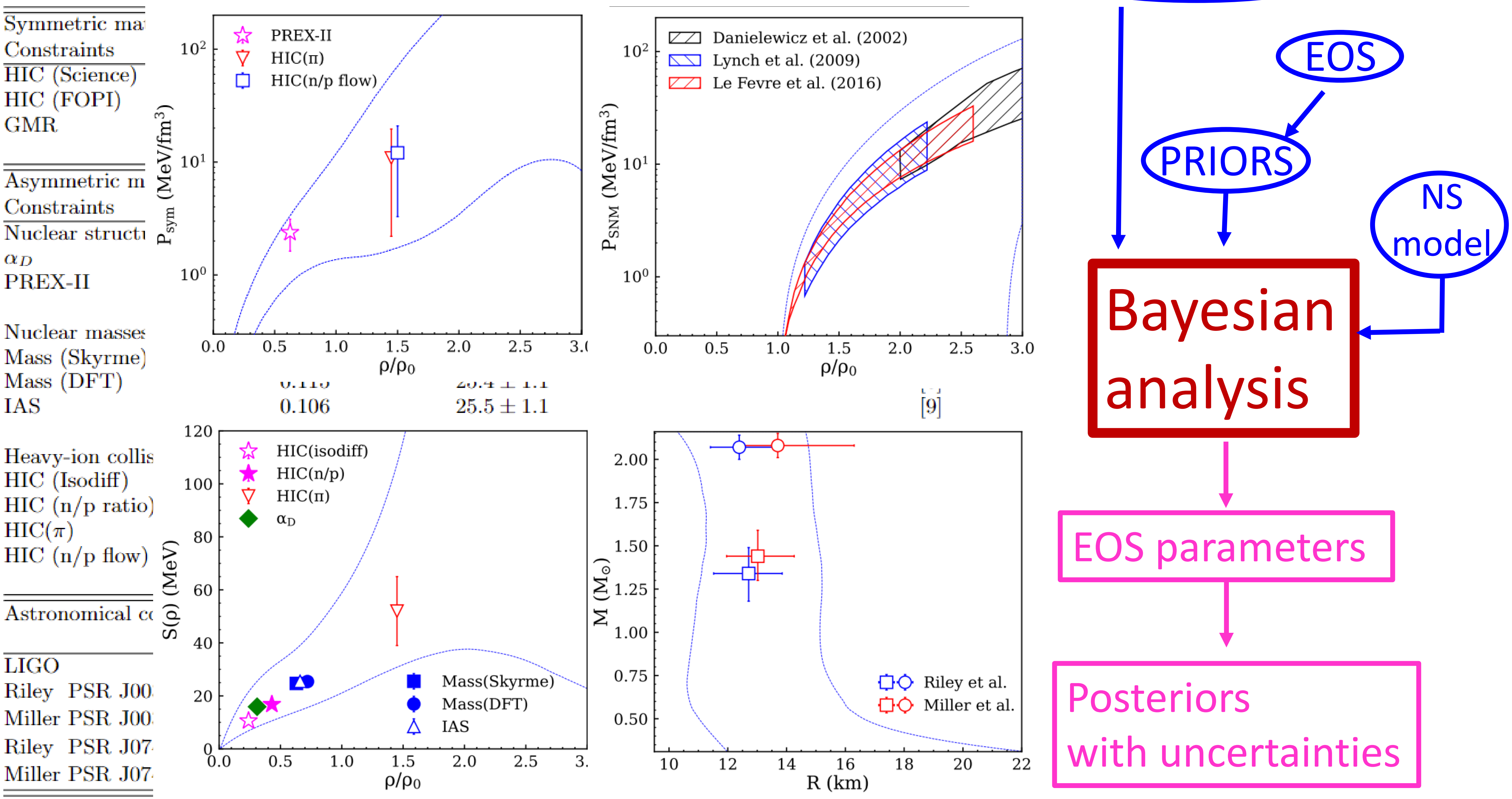

Tommy Tsang


Bill Lynch


Rohit Kumar

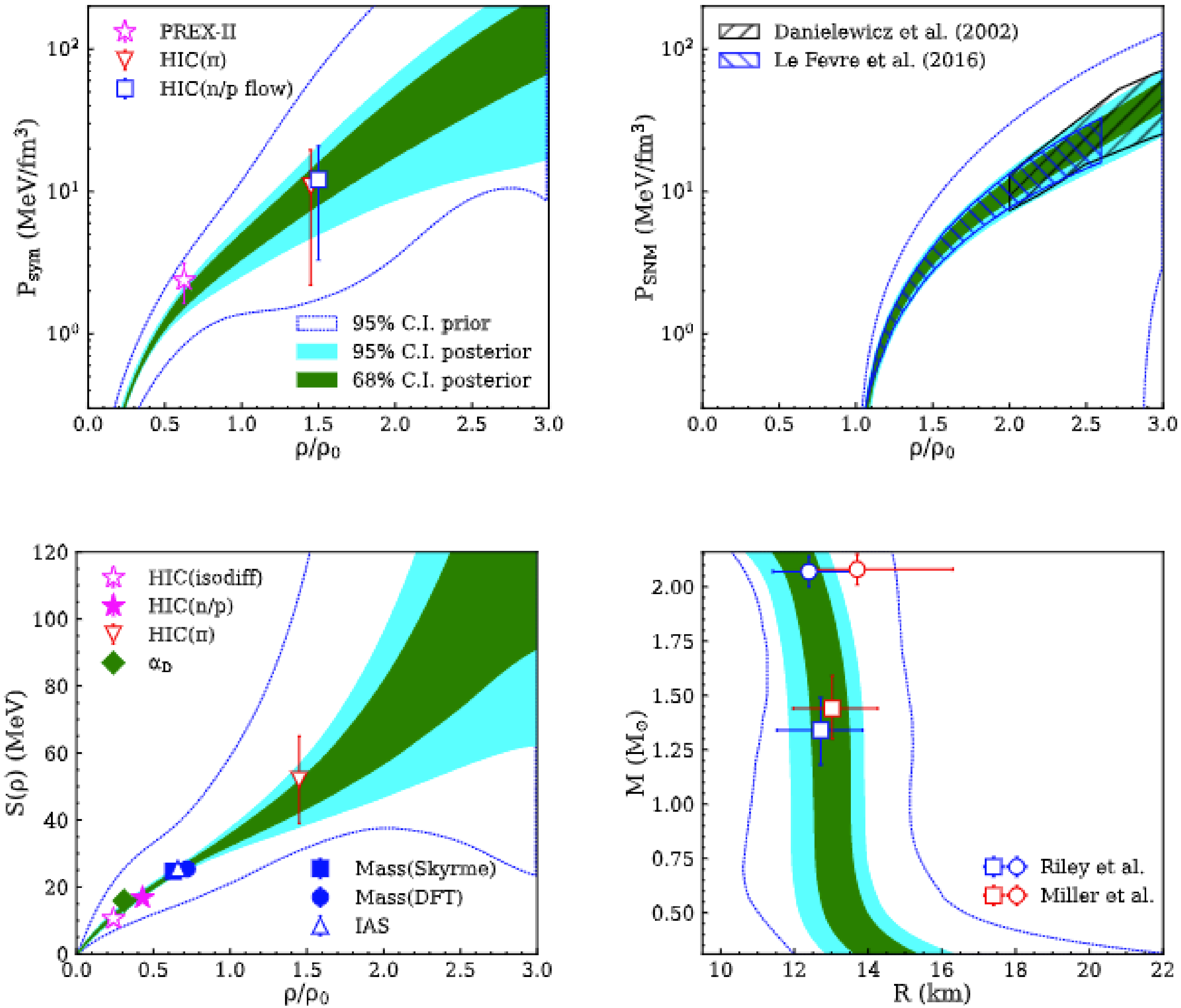
Nuclear structure, reactions Astro (15) constraints



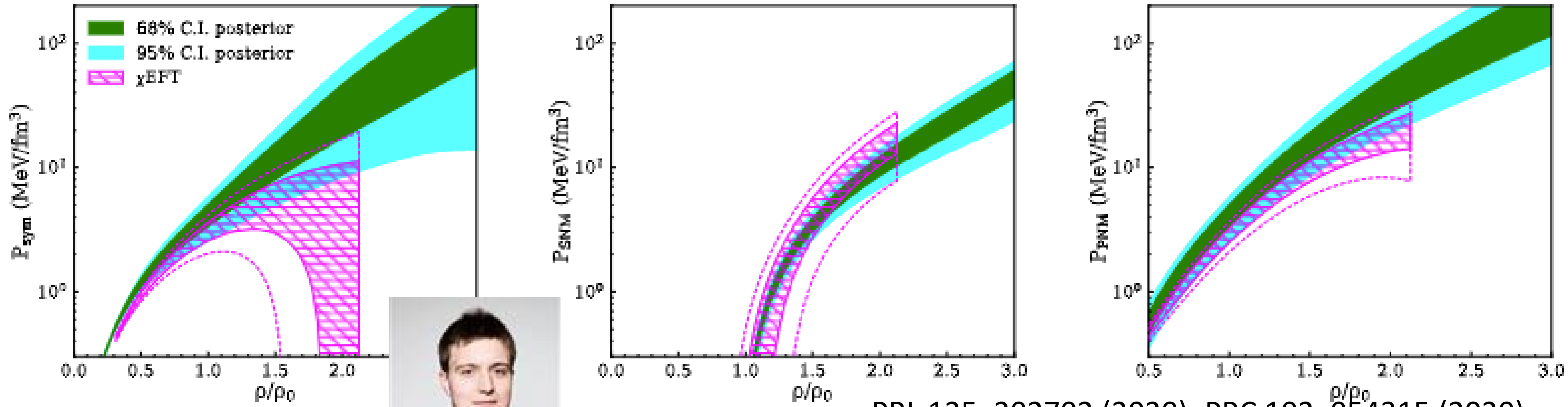
Posteriors of the parmeterized EOS using Bayesian analysis of the constraints + NS model.

68% & 95% distributions and agreements with data

P_sym > P_SNM
Symmetry term has large uncertainties at high densities

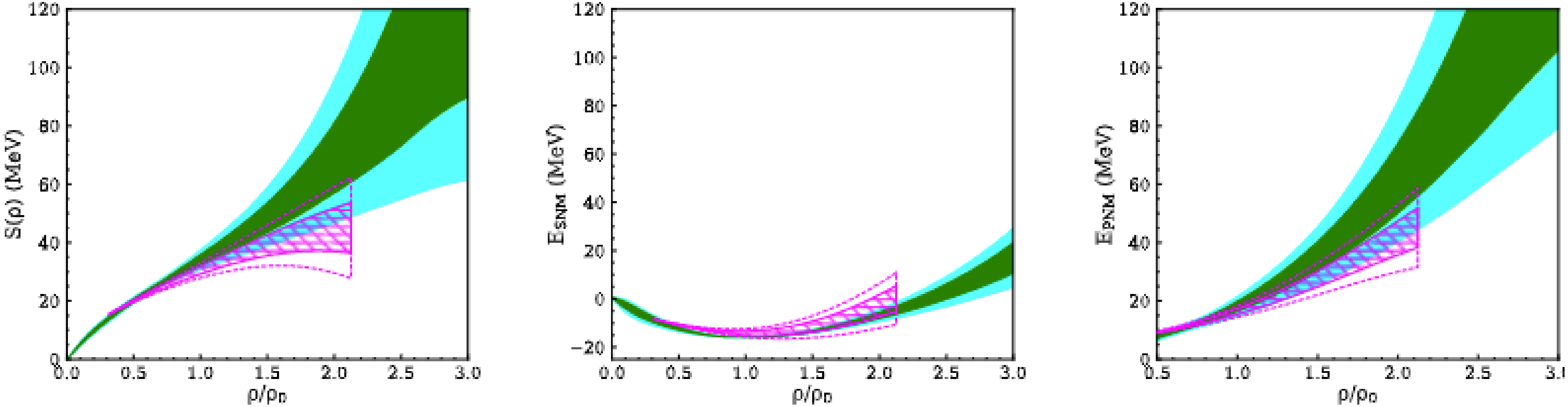


Challenges & Opportunities: Benchmarks for nuclear Theories

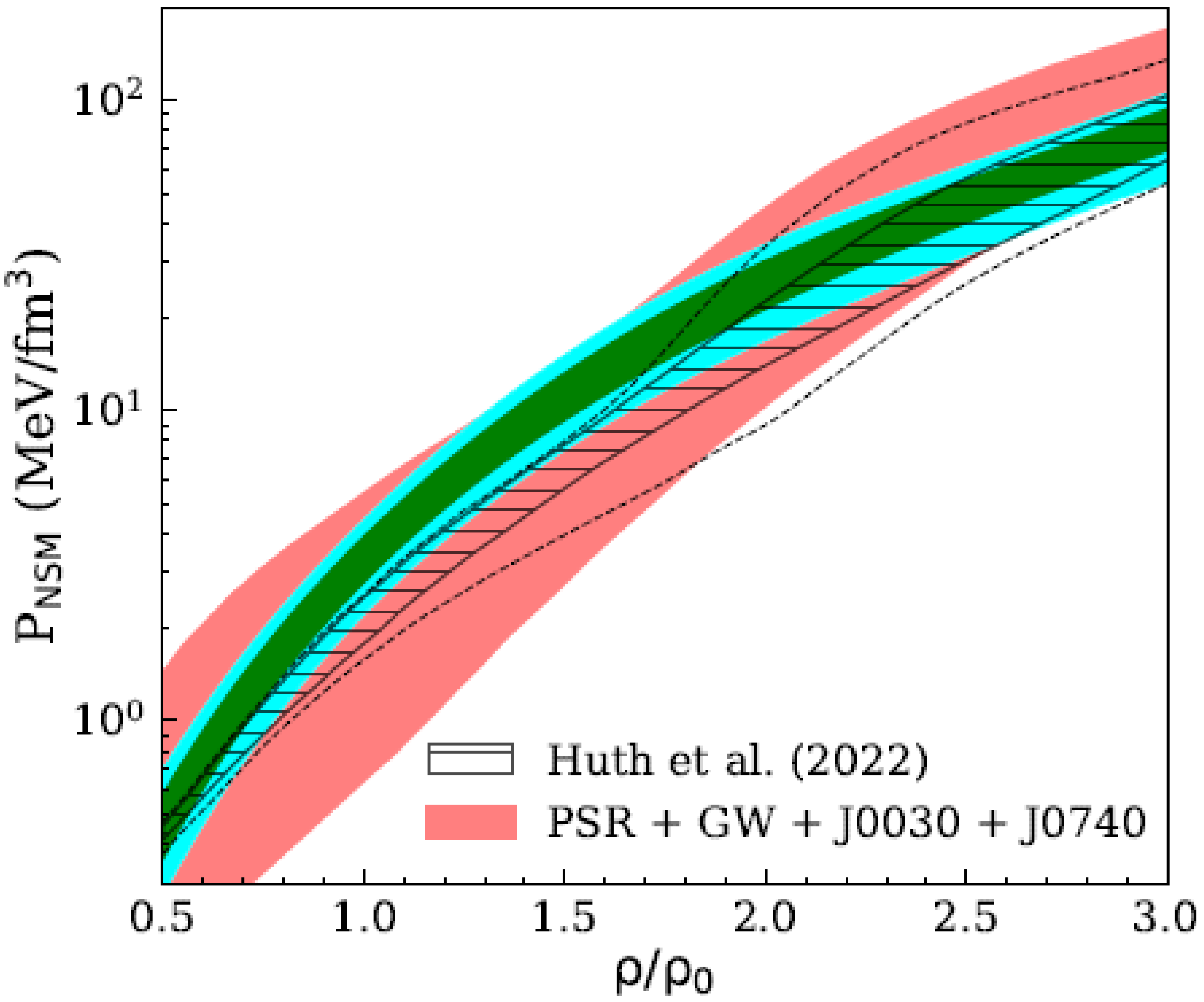


Christian Drischler

PRL 125, 202702 (2020); PRC 102, 054315 (2020); PRL 122, 042501 (2019)



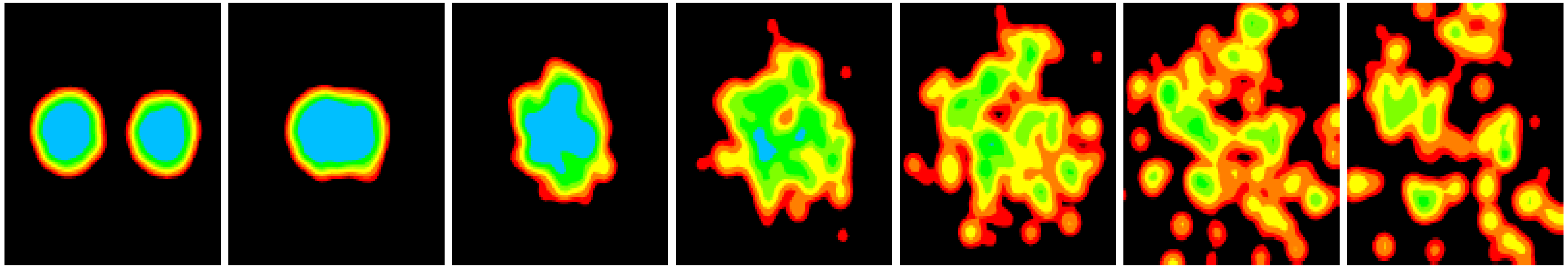
Comparisons with other neutron star EoS



Simulations with transport models to extract EoS parameters

Heavy Ion collisions

Experiment design



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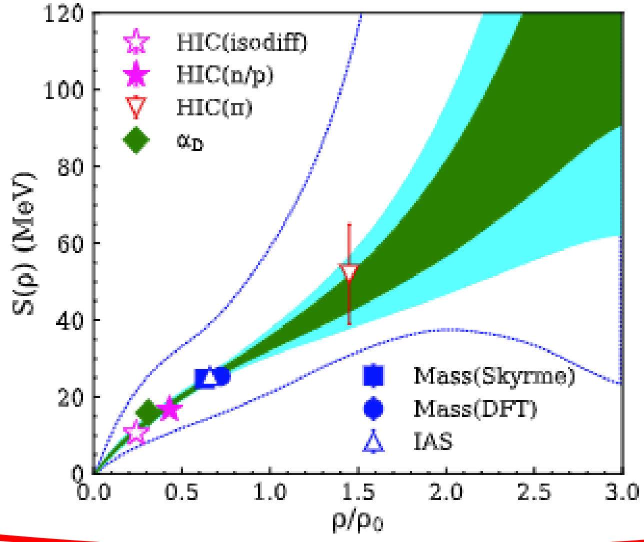
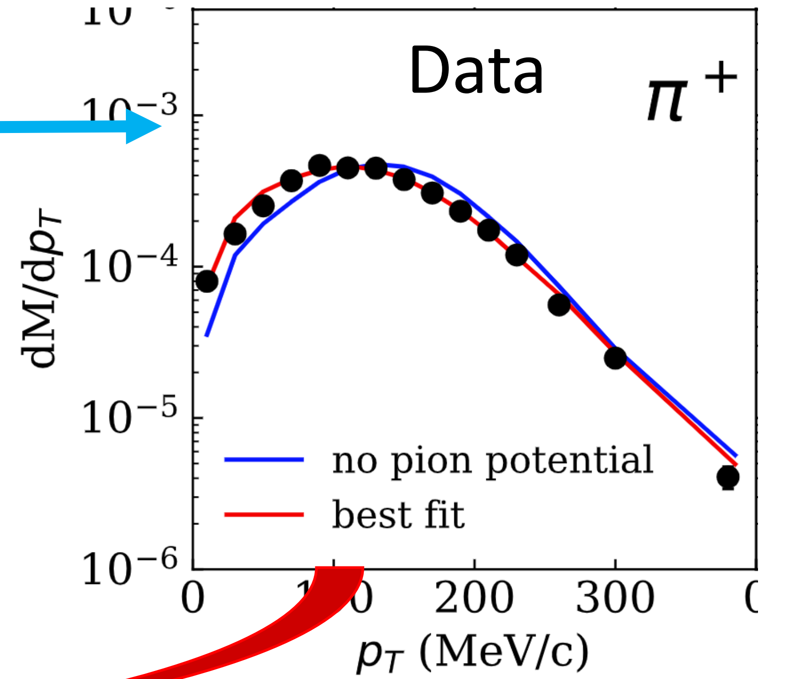
Input parameters

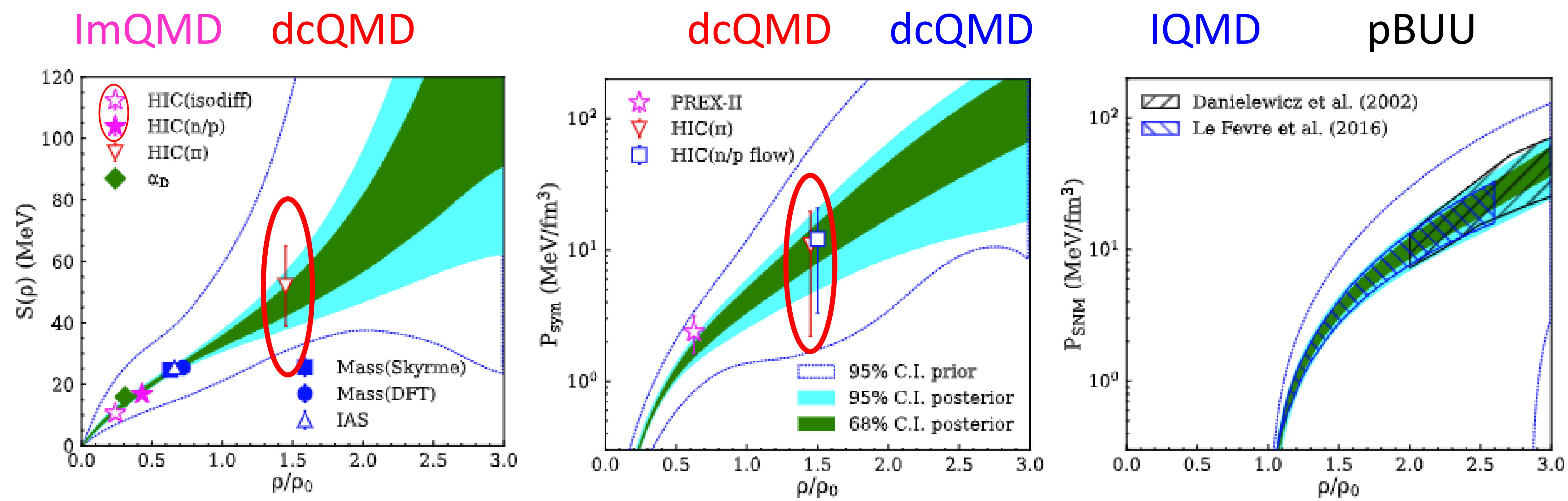
Transport Models (TMEP)

Wolter et al, PPNP 125(2022) 103962





EOS



Transport Models Evaluation Project (TMEP)

>20 codes; Different codes use different approaches/approximations

Agreement is very good for controlled box studies.

Comparison to data differ between codes → Need quantification of uncertainties

Wolter et al, PPNP 125(2022) 103962; Sorensen et al., arXiv:2301.13253

A White Paper for the 2023 US Nuclear Physics Long Range Plan

Dense Nuclear Matter Equation of State from Heavy-Ion Collisions;

Sorensen et al., arXiv:2301.13253

Contact Agnieszka.sorensen@gmail.com for comments & suggestions or to become an endorsing author

Conclusion: Comprehensive cold EOS is in sight

In past decade

- Great discoveries: GW170817 & NICER.
- Advance to connect experimental constraints for symmetric matter and asymmetric matter to neutron star.

Near Future

- New neutron star measurements & update of symmetric matter constraints from 2002 with new results from Hades, BES …
- Improvement of symmetry energy constraints around 1.5 to 3 rho_0 (FRIB, FRIB400, RIKEN).
- Improvements/breakthroughs in transport model simulations.
- There will be NEW facility (FRIB400?), NEW experiments and NEW theories to explore the golden era of neutron star physics with HIC

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https://groups.nscl.msu.edu/hira/cosmic/SpiritTPC.html

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