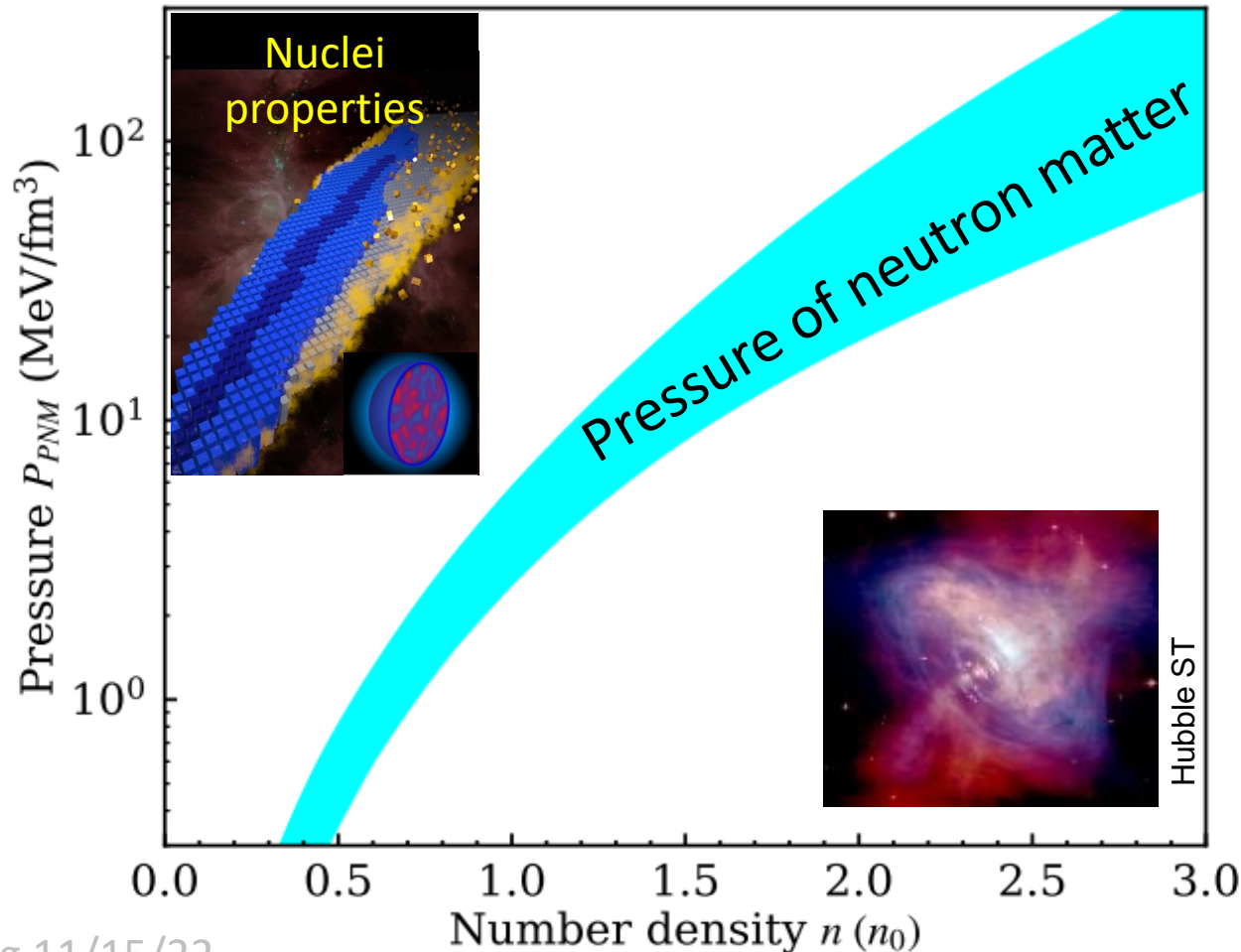




Facility for Rare Isotope Beams
at Michigan State University

Betty Tsang (Tsang@FRIB.MSU.EDU)

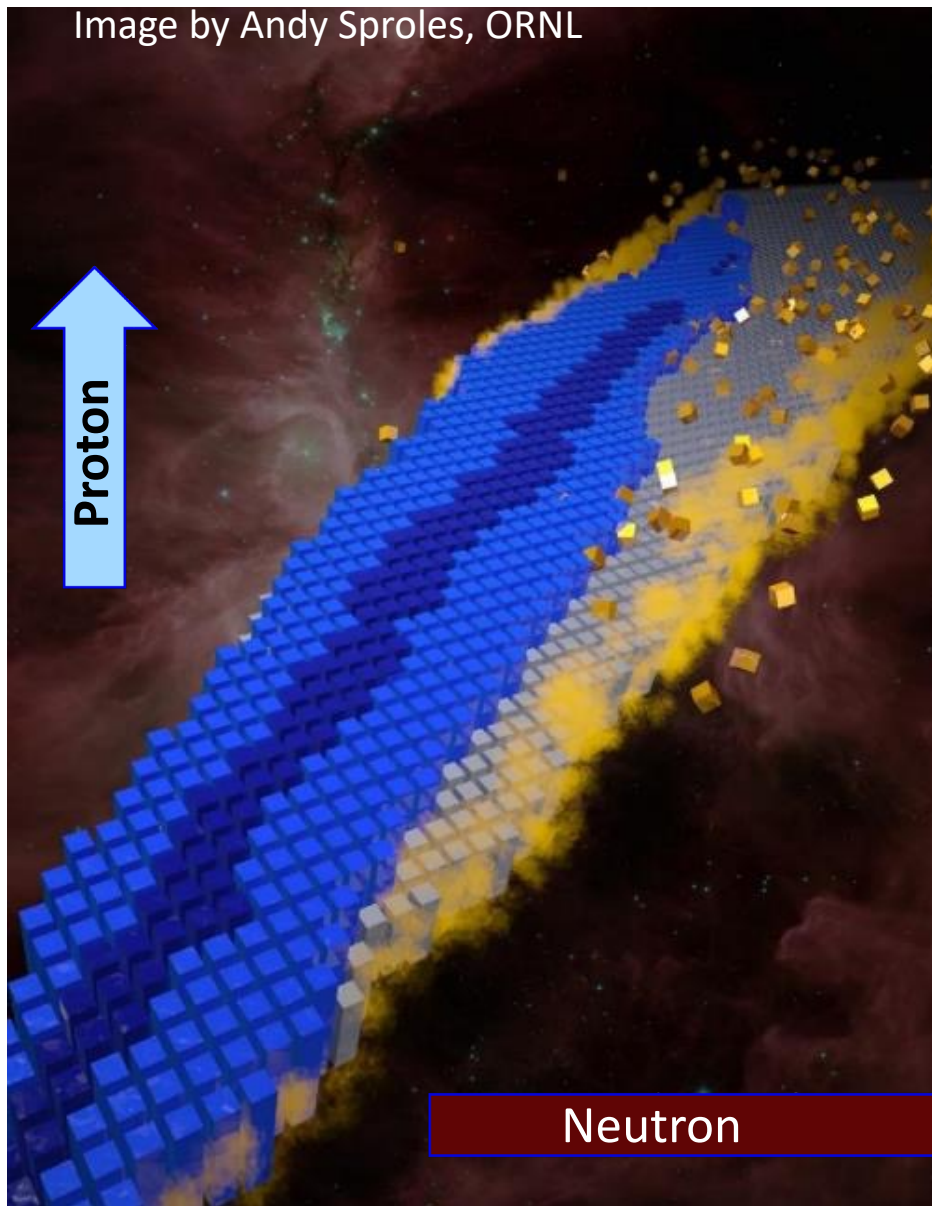
Neutron Stars and Dense Matter



Identify compelling scientific questions and opportunities for the next decade (within the U.S.) and their scientific impact.

Connecting Nuclei to NS via nuclear equation of state

LRP Town Hall Meeting
Argonne National Lab
Nov 15, 2022



Microscopic physics in the EOS

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

Neutron star
(giant nucleus)
($\sim 10^{57}n + \sim 10^{56}p$)



Hubble ST

$E_{sym} < 5\%$

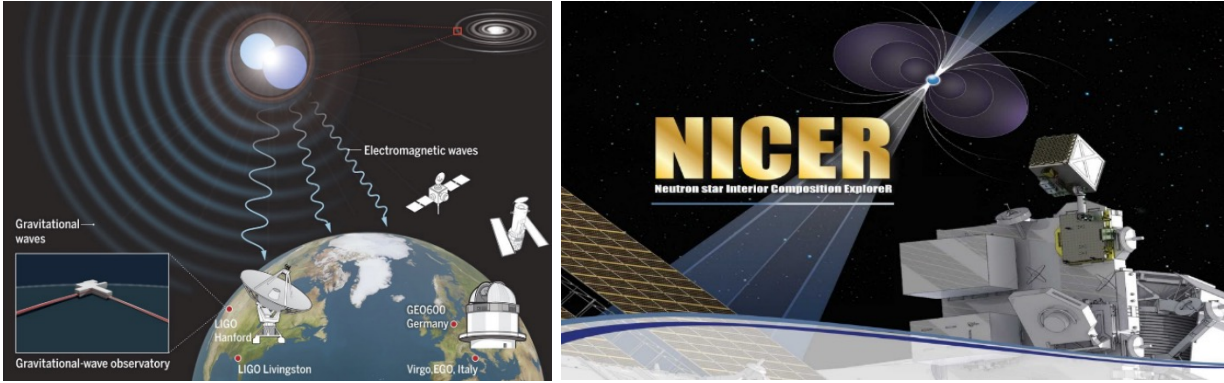
$\delta < 0.25$

$E_{sym} > 50\%$

$\delta > 0.8$

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

Big discoveries since LRP2015: Observation of BNS merger & Mass – Radius measurements with NICER

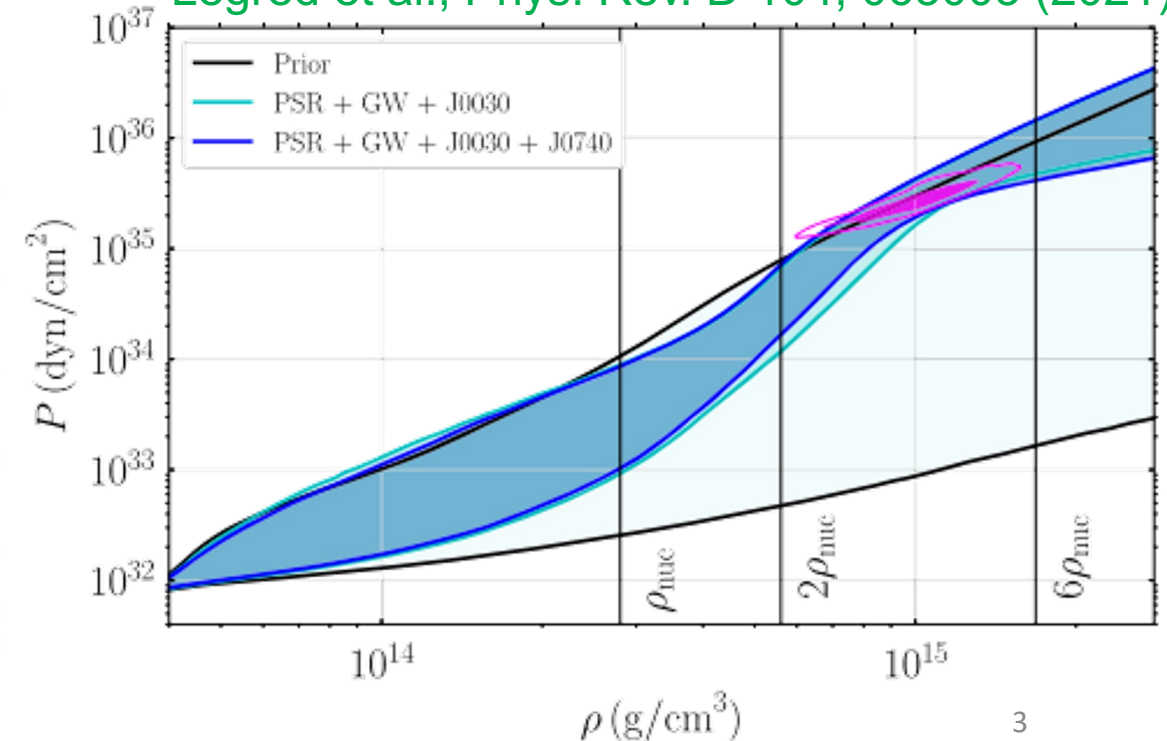
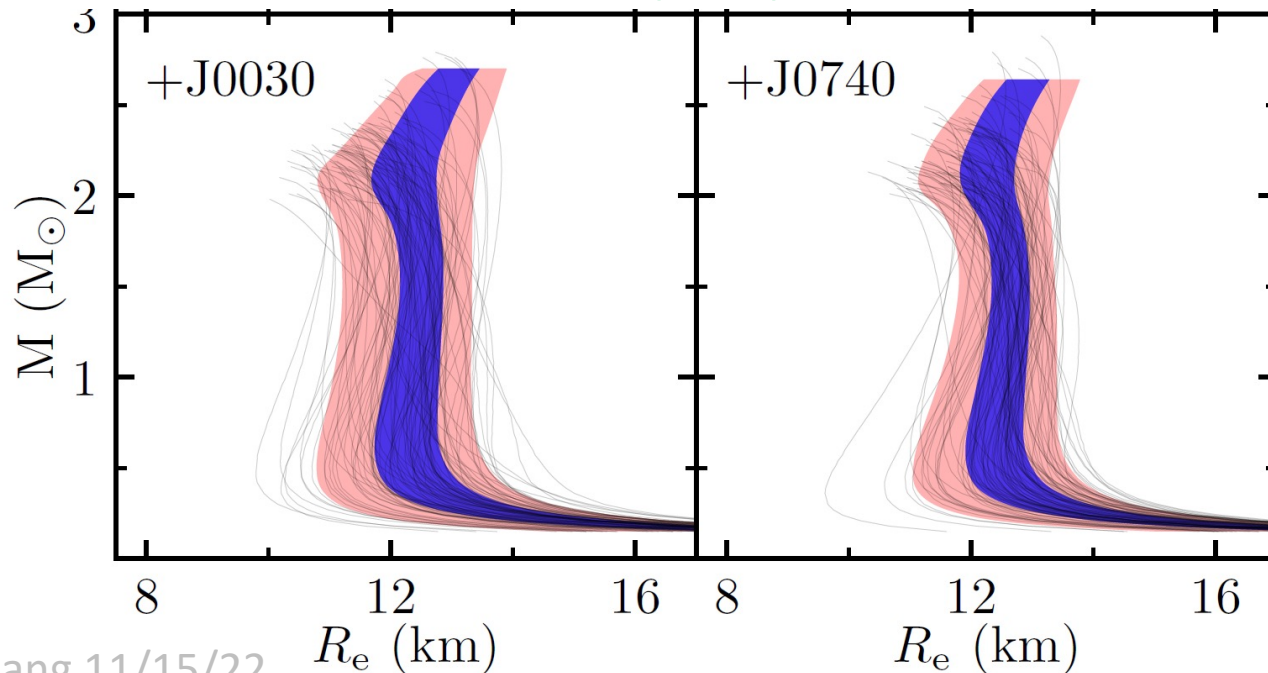


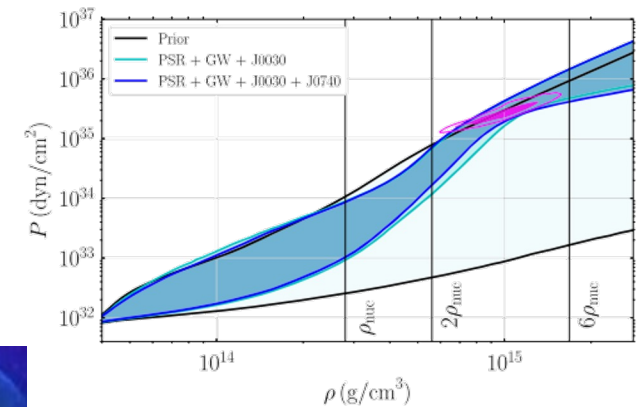
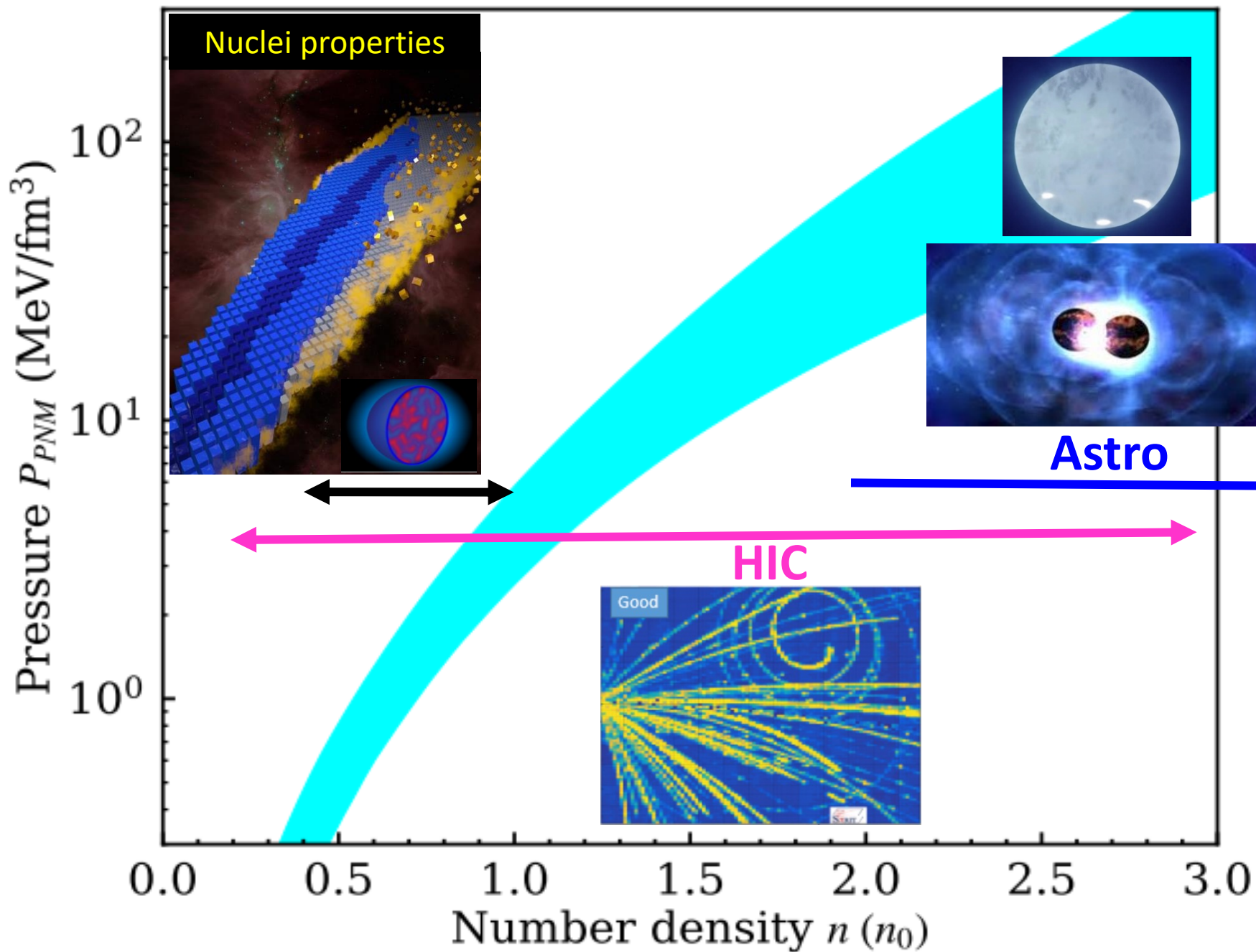
$$\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r)$$

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

Legred et al., Phys. Rev. D 104, 063003 (2021)

Miller et al., AJL918, L28 (2021)

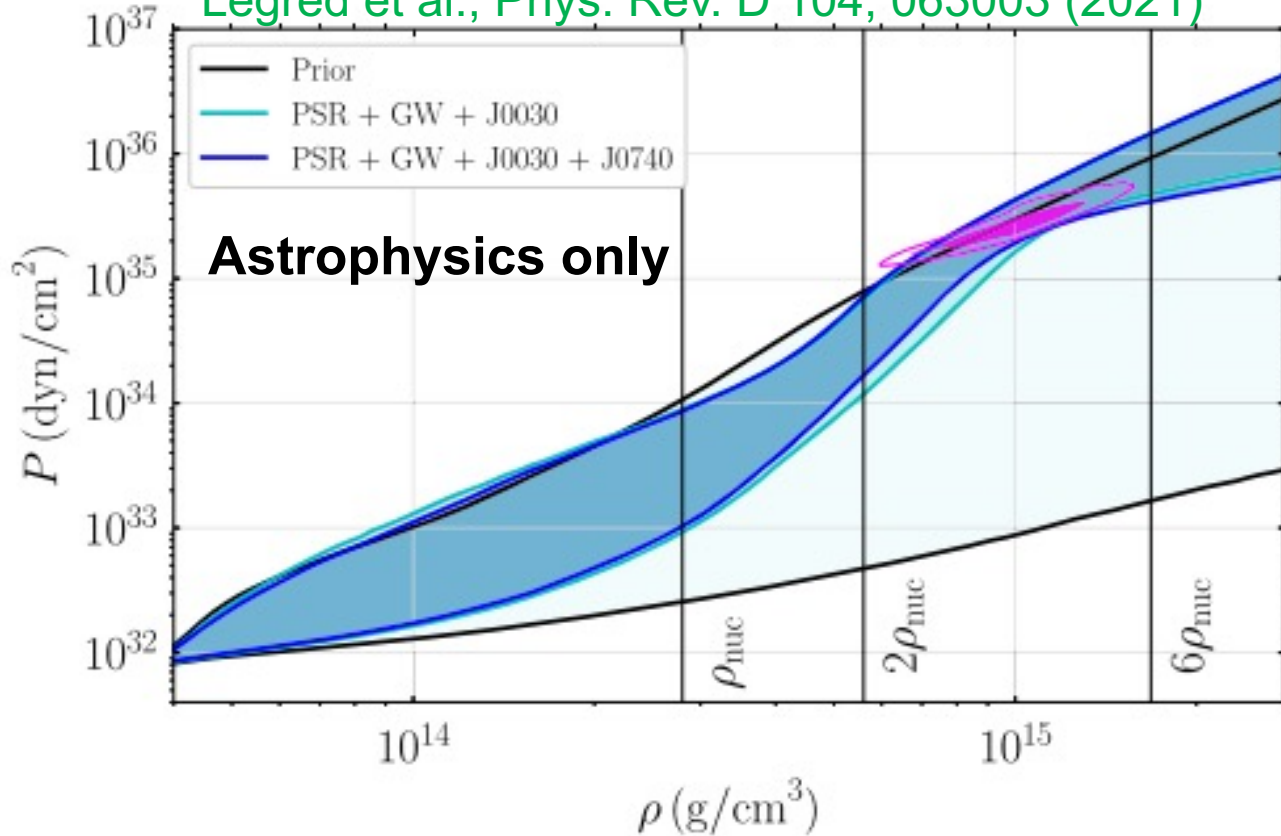




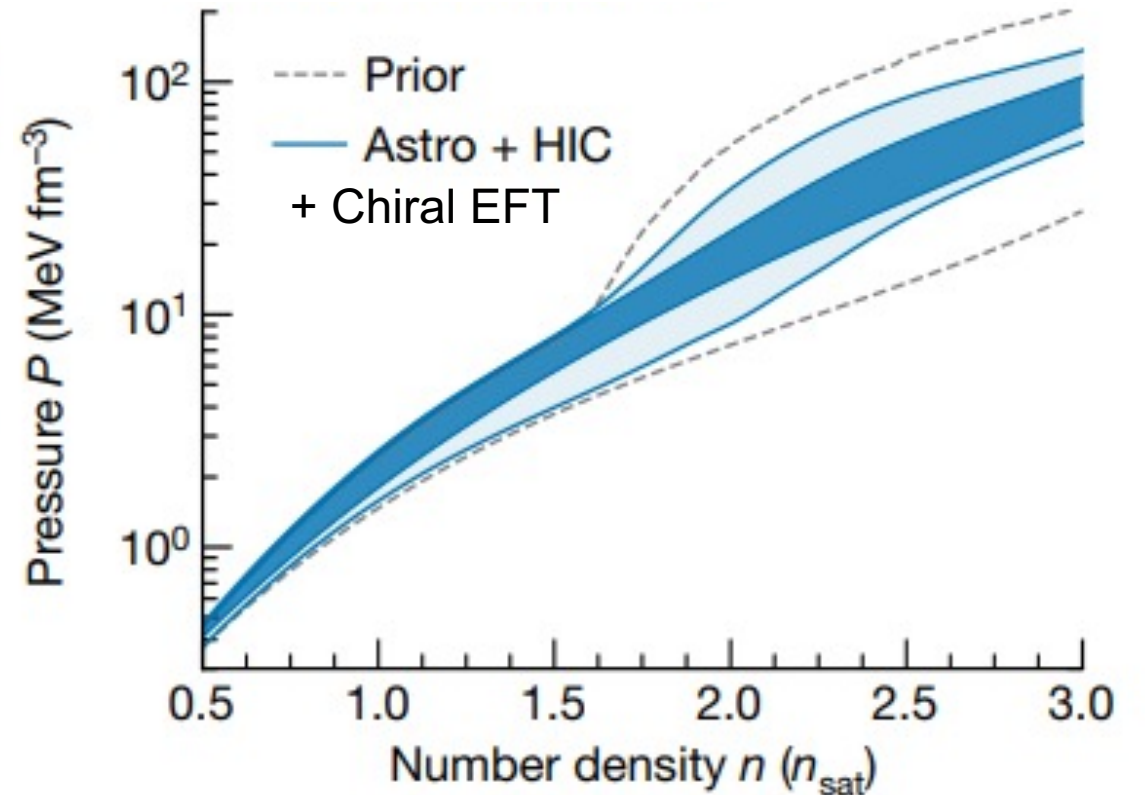
Different density regions require different observable, equipment and facilities.

Current Status: EOS for Neutron Star matter (achievement since 2015 LRP)

Legred et al., Phys. Rev. D 104, 063003 (2021)



Huth, Pang et al., Nature 606, 279 (2022)



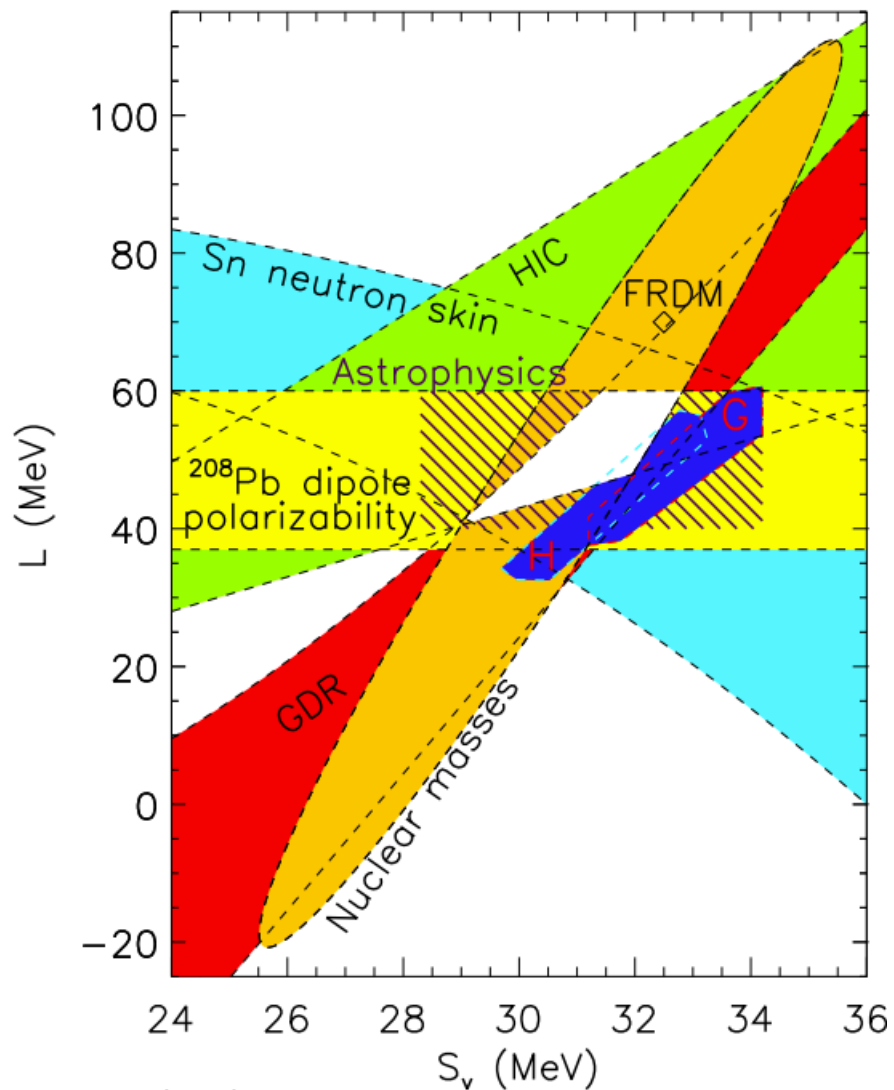
Goals from LRP 2023:

Constraints from Astro+HIC+structure?

2015 LRP

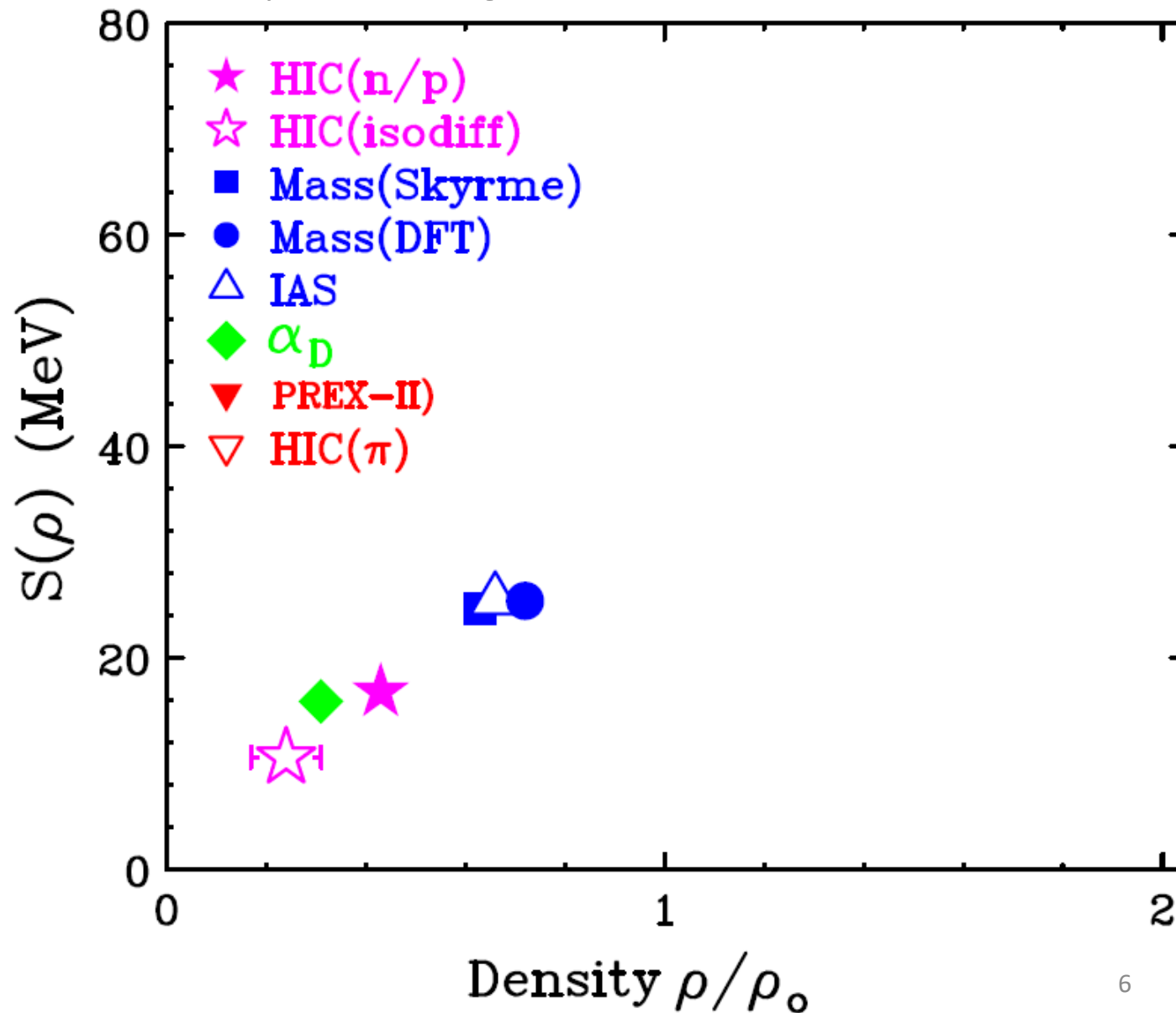
(Taylor expansion coefficients)

Lattimer & Lim: ApJ. 771, 51 (2013)



Density Dependence of the symmetry energy

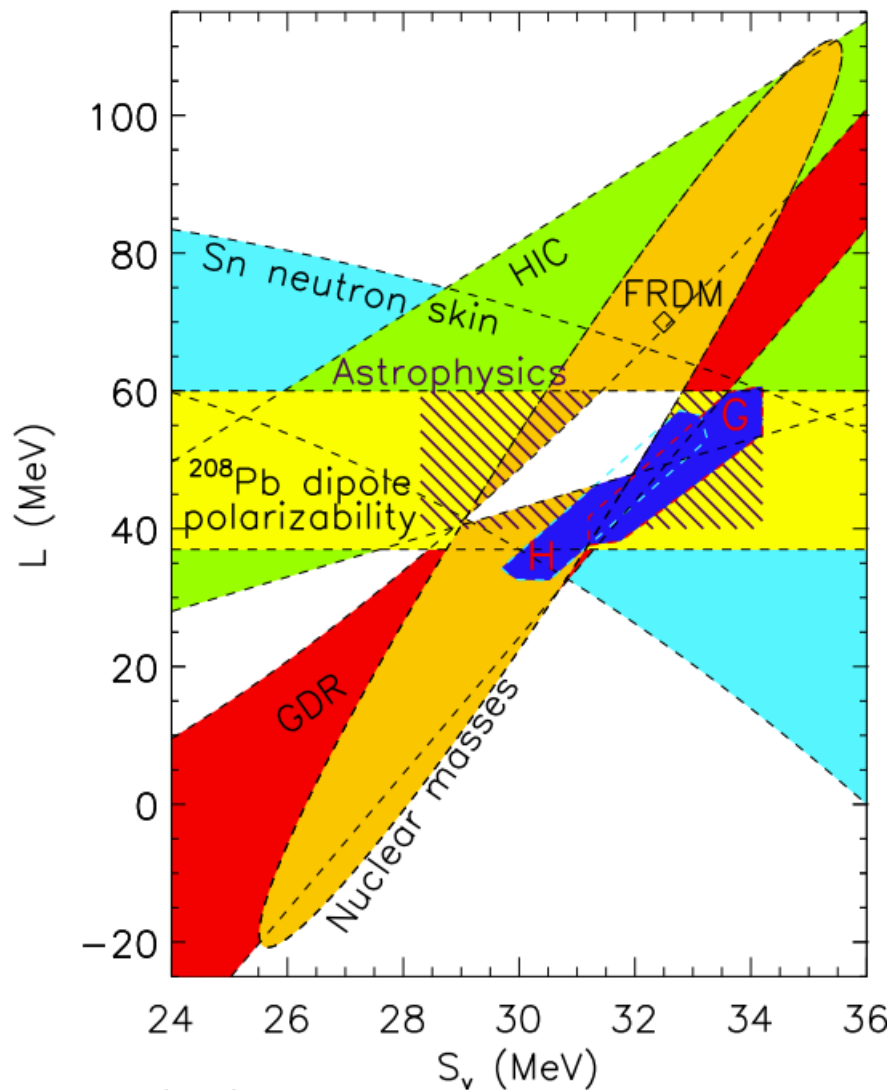
Lynch & Tsang: PLB 830 (2022)137098



2015 LRP

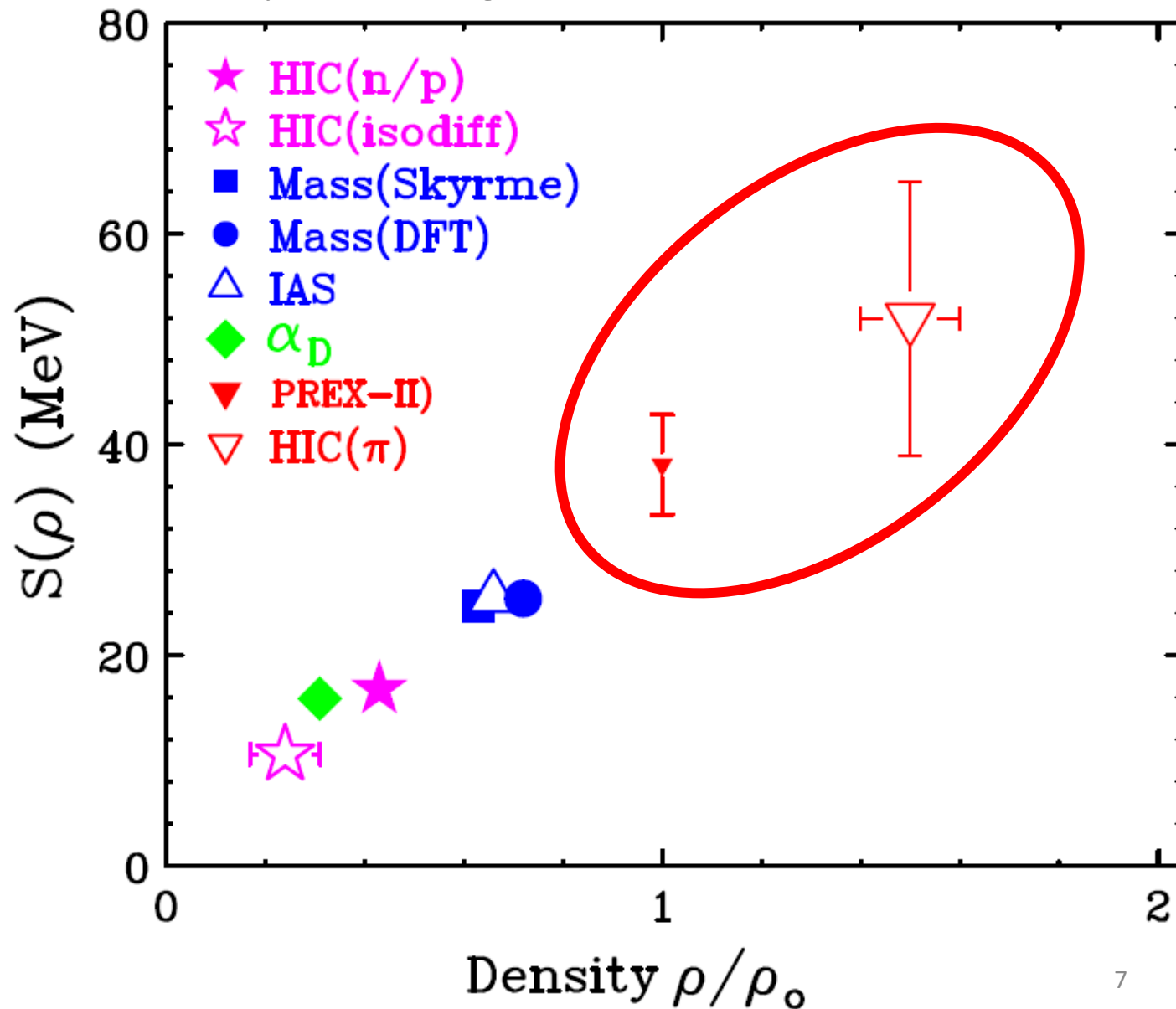
(Taylor expansion coefficients)

Lattimer & Lim: ApJ. 771, 51 (2013)



Density Dependence of the symmetry energy

Lynch & Tsang: 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 $^{-3}$)	$S(\rho)$ (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]
Miller PSR J0740+6620	$2.08^{+0.07}_{-0.07}$	$^{b}13.7^{+2.6}_{-1.5}$		[20]

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

Data centric approach
without reliance on
 χ EFT at low density

R. Kumar at Theory WGII

Nuclear structure, reactions Astro (15) constraints

Symmetric
Constraints
HIC (Scienc
HIC (FOPT)
GMR

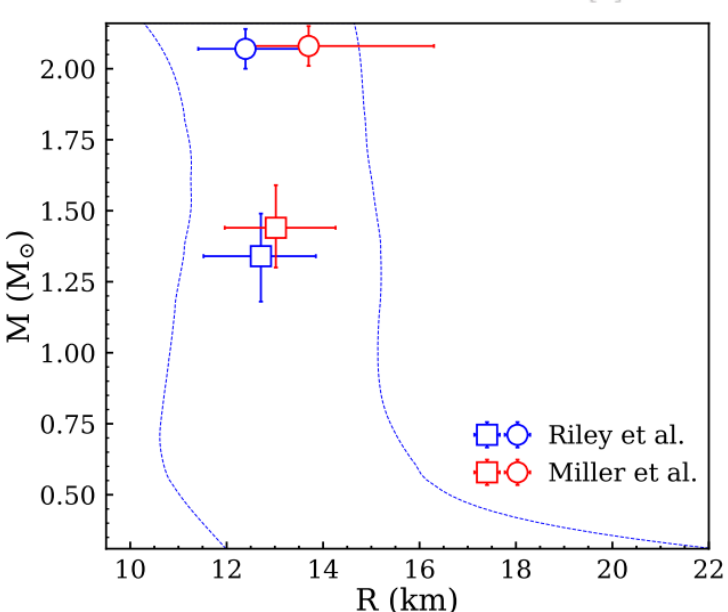
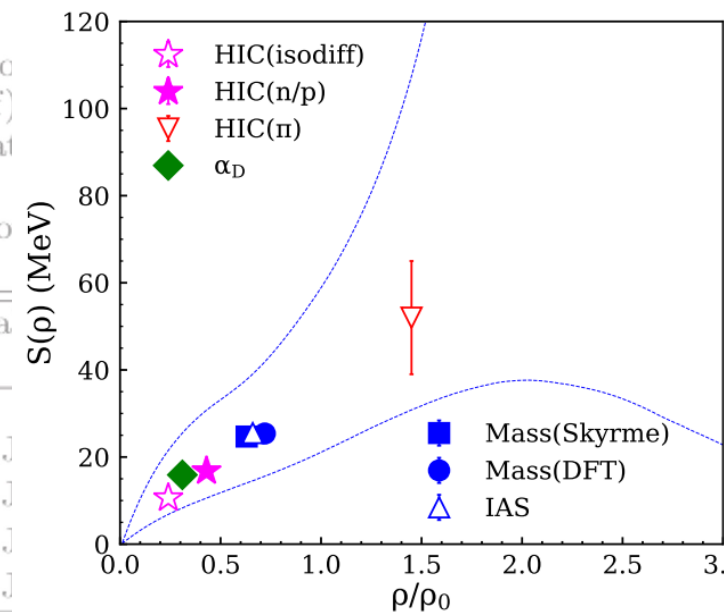
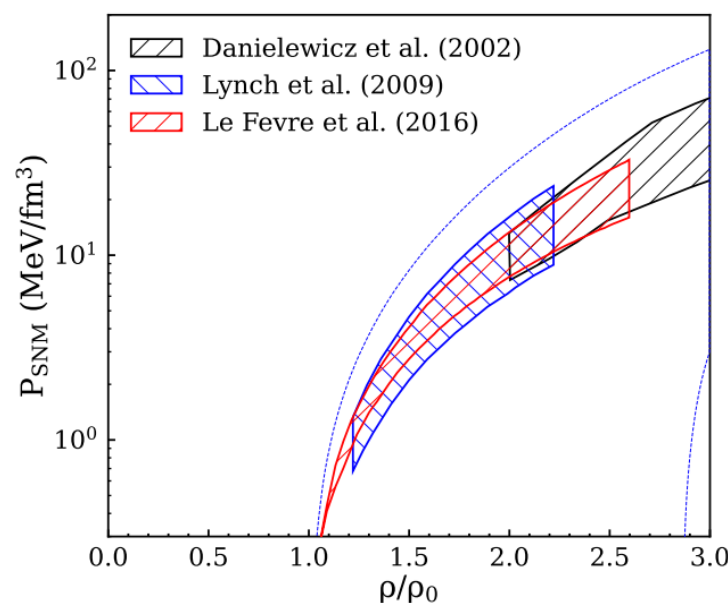
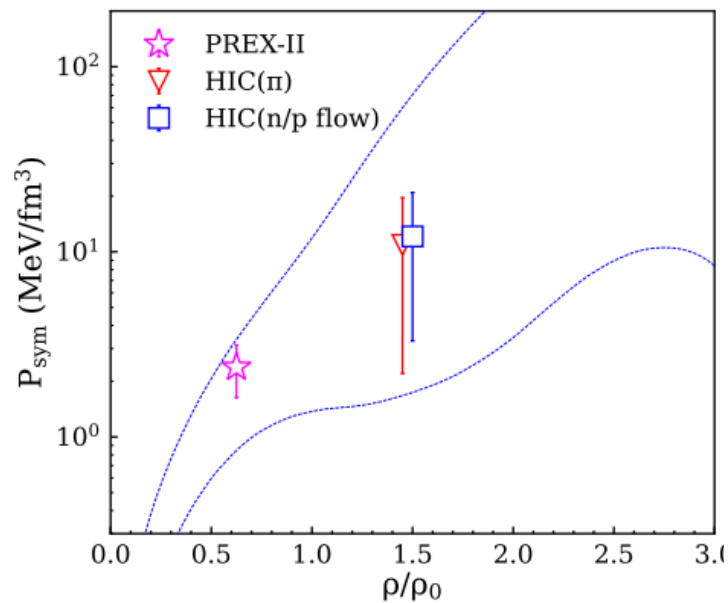
Asymmetric
Constraints
Nuclear stru
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Mass (Skyrr
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Astronomica

LIGO
Riley PSR J
Miller PSR J
Riley PSR J
Miller PSR J



Bayesian
analysis

EOS parameters

Posteriors
with uncertainties

EOS

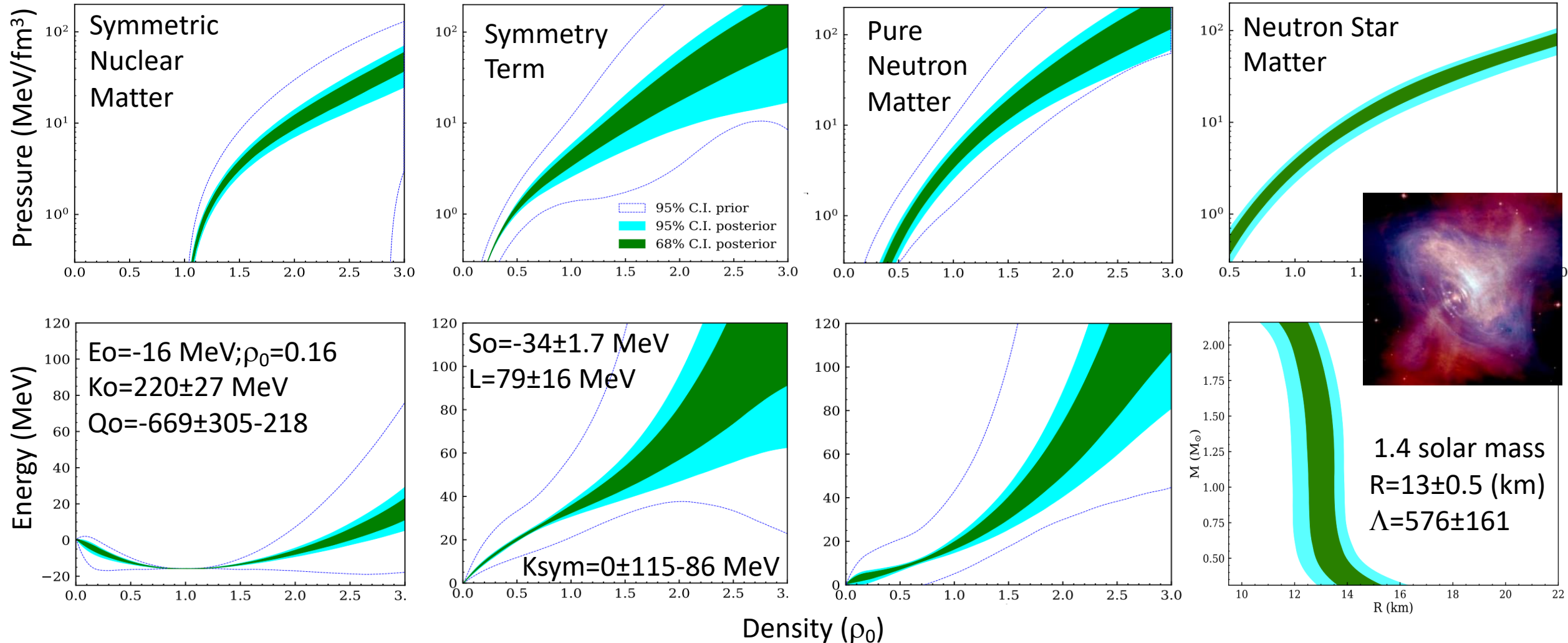
PRIORS

NS
model

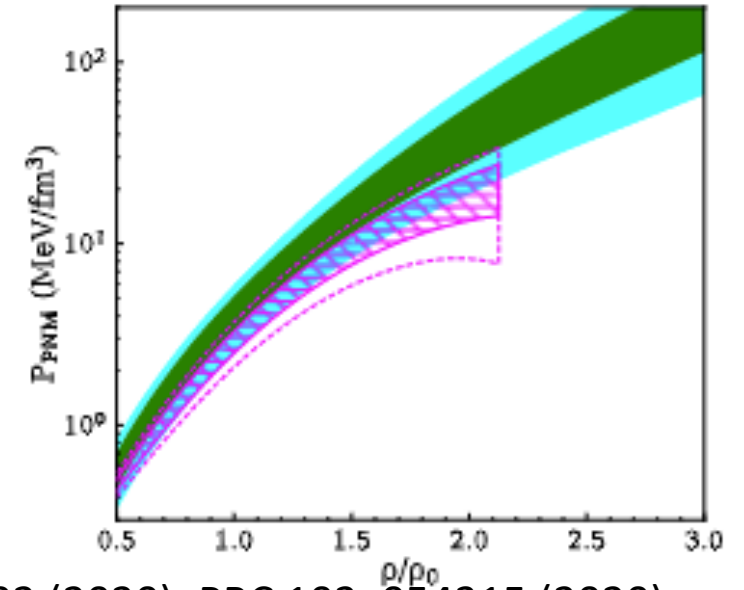
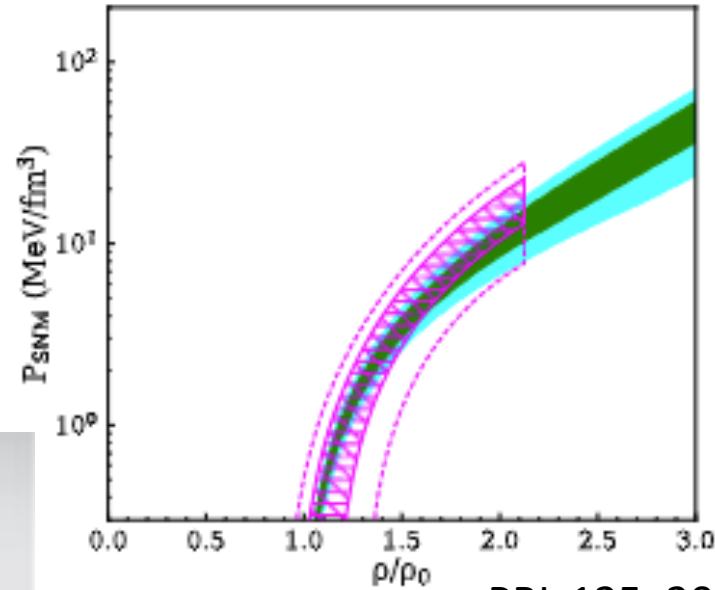
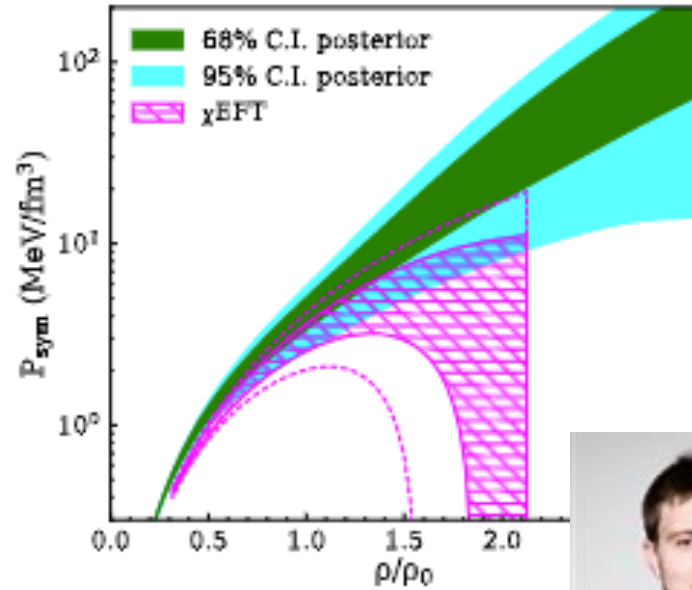
[9]

Equation of State of nuclear matter

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



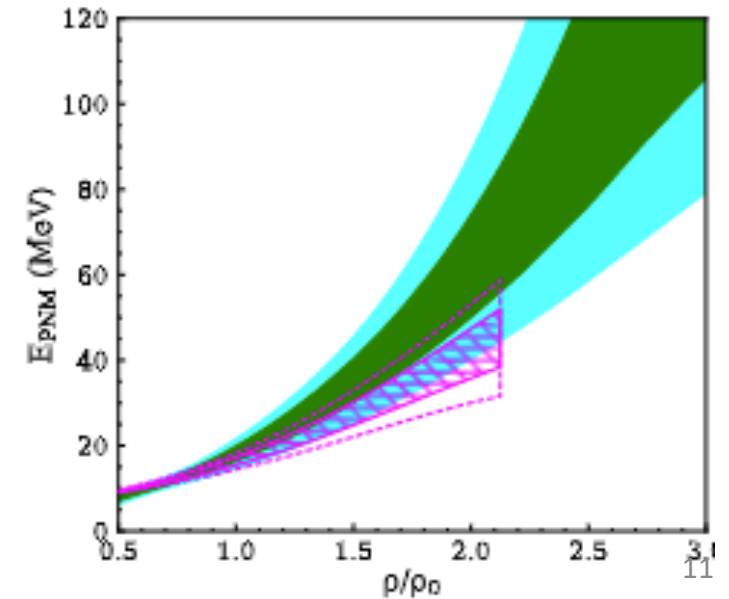
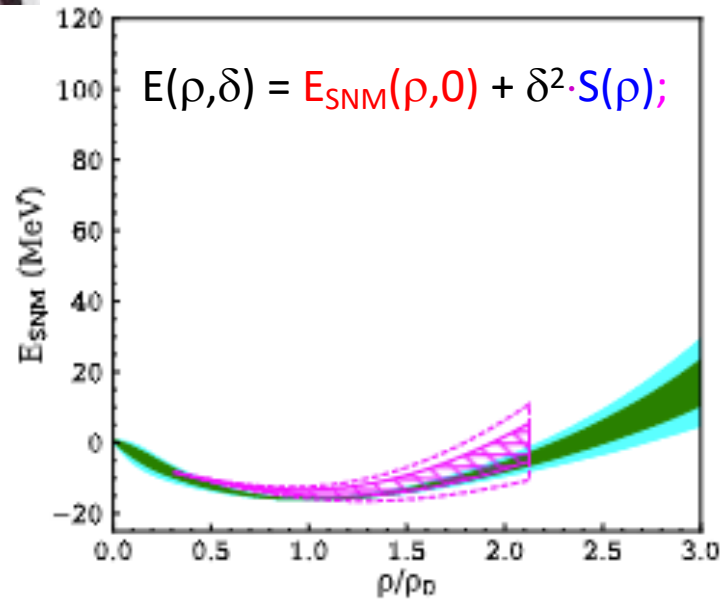
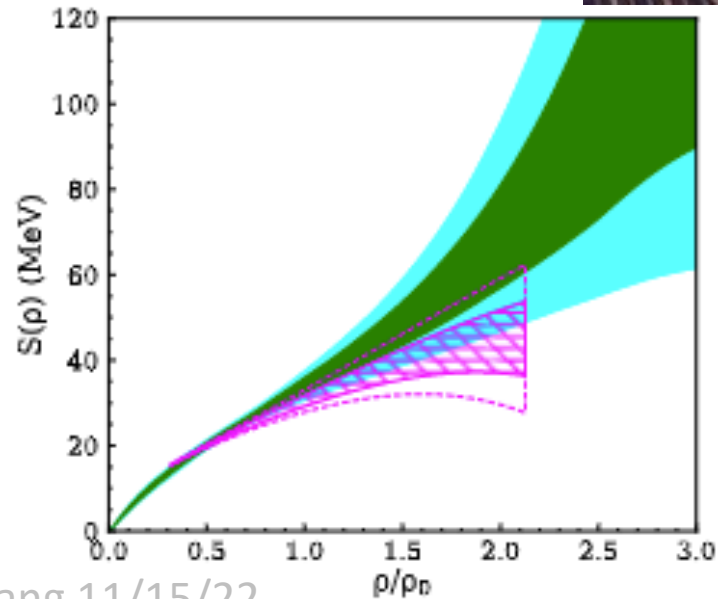
Challenges & Opportunities: Benchmarks for nuclear Theories



Christian Drischler

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

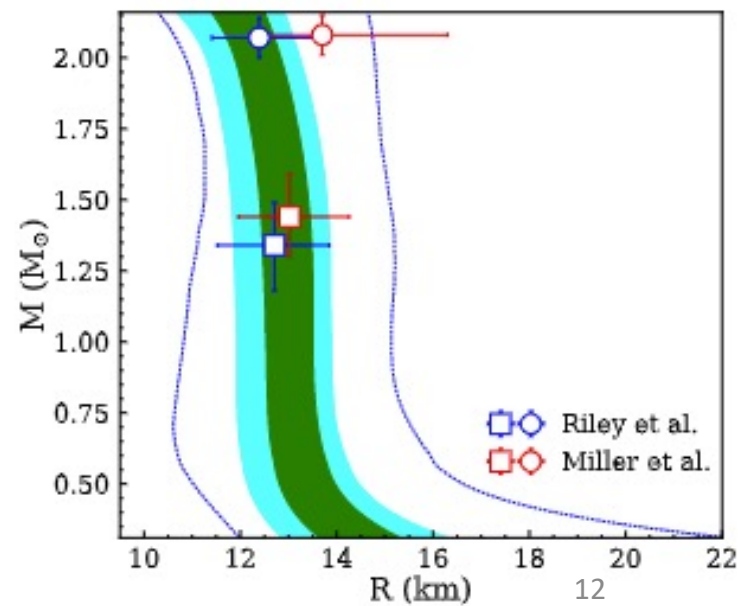
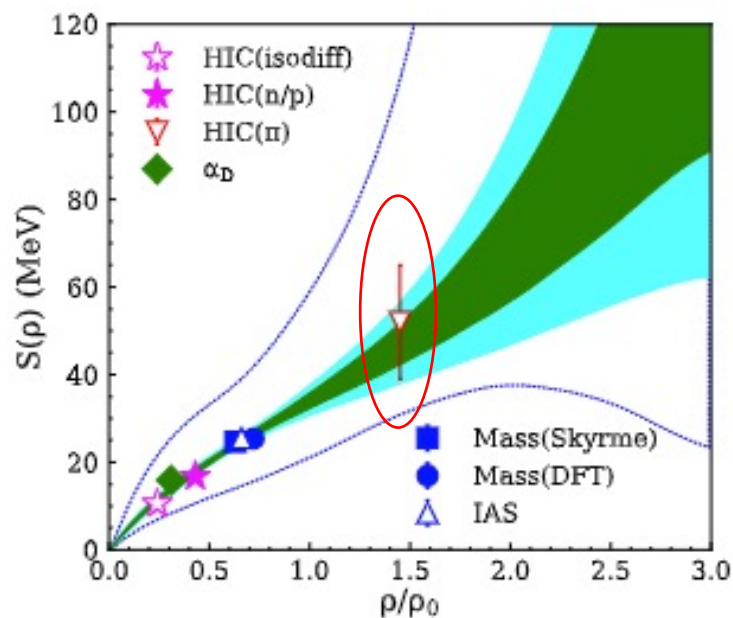
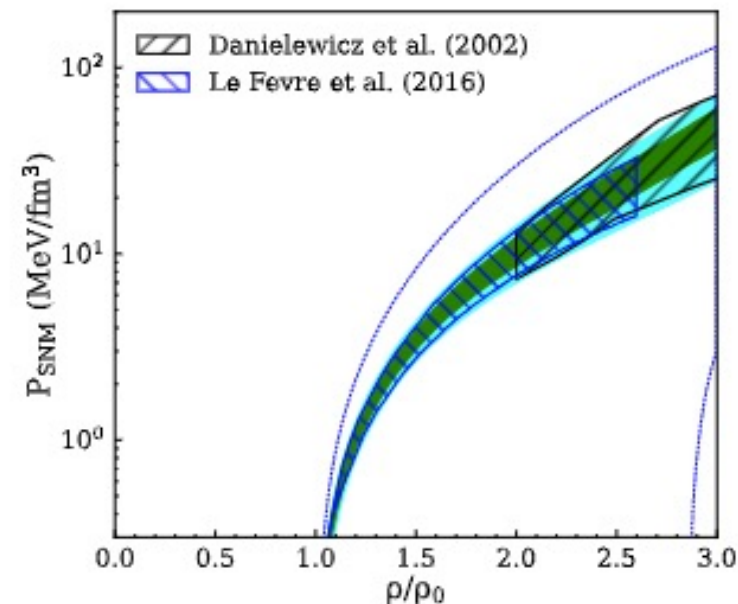
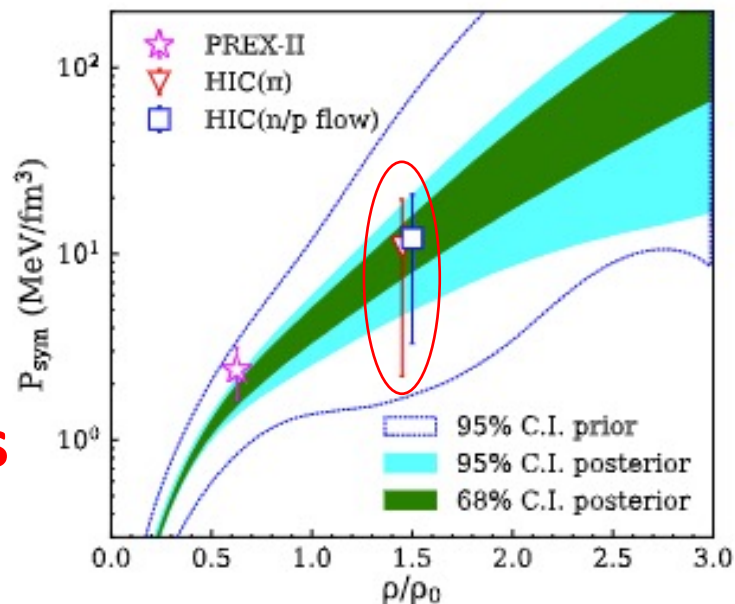
$$E(\rho, \delta) = E_{\text{SNM}}(\rho, 0) + \delta^2 \cdot S(\rho)$$



Opportunities and challenges

New experiments:
More precision symmetry
energy data at $1.5\text{--}2.5\ \rho_0$

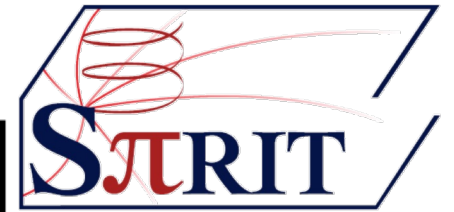
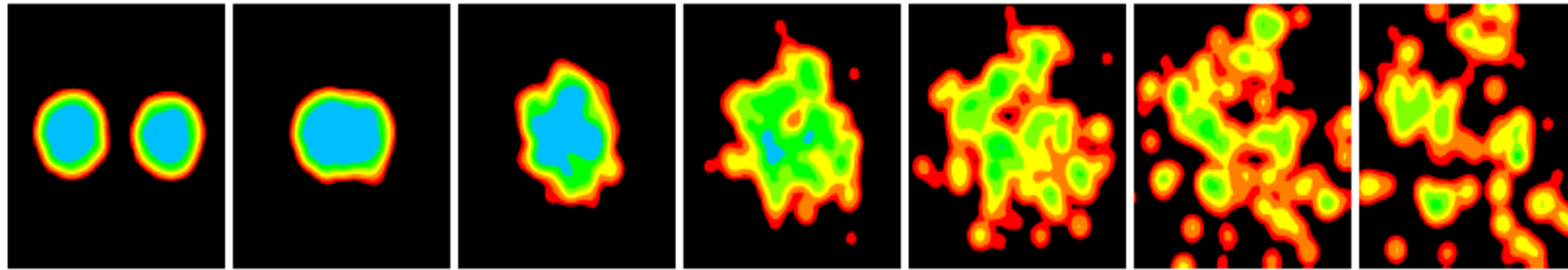
Chajecki, McIntosh →
flash presentations



Challenges & Needs: Simulations of Heavy Ion Collisions

Heavy Ion collisions

Experiment
design



Input
parameters

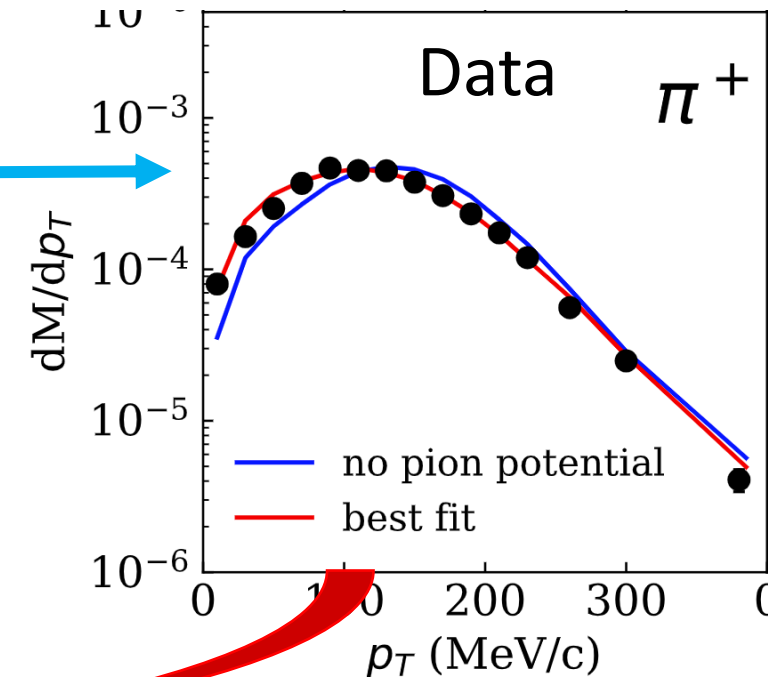
Transport Models

TM Evaluation Project (TMEP)

Wolter et al, PPNP 125(2022) 103962

(Danielewicz, Sorensen) at Theory WG2

EOS



Vision : Global EOS from low to high density, crust to core

Since LRP2015, major breakthroughs

- GW170817 & NICER
- New constraints on Symmetry energy from HIC and PREX
- Quantification of uncertainties in data & models → Bayesian Analysis
- Data-centric EOS

Synergy with other disciplines

- Astrophysics – more precise observations for M , R , Λ .
- Application of EOS to calculate NS properties, such as the proton fraction, composition of matter in the NS core, possible phase transitions and cooling process.
- Application of low density NP data to develop the crust EoS.

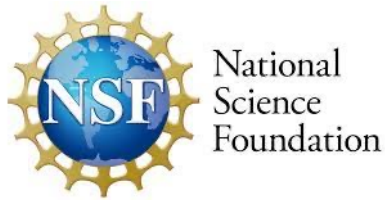
Vision : Global EOS from low to high density, crust to core

LRP2023 needs (Next 5-10 years)

1. More precise symmetric matter (RHIC BES measurements) and symmetry energy constraints.
2. More precise HIC measurements around 1.5 to 2.5 ρ_0 .
 - a. Facility upgrade (FRIB400)
 - b. Detector investments
 - c. Transport model improvements

Mini-White Paper on “Baryonic Equation of State from Astro observations and terrestrial experiments”

Anyone interested, please email tsang@FRIB.msu.edu

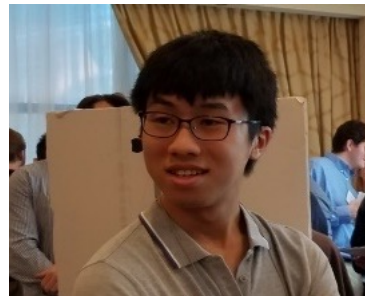


National
Science
Foundation



U.S. DEPARTMENT OF
ENERGY

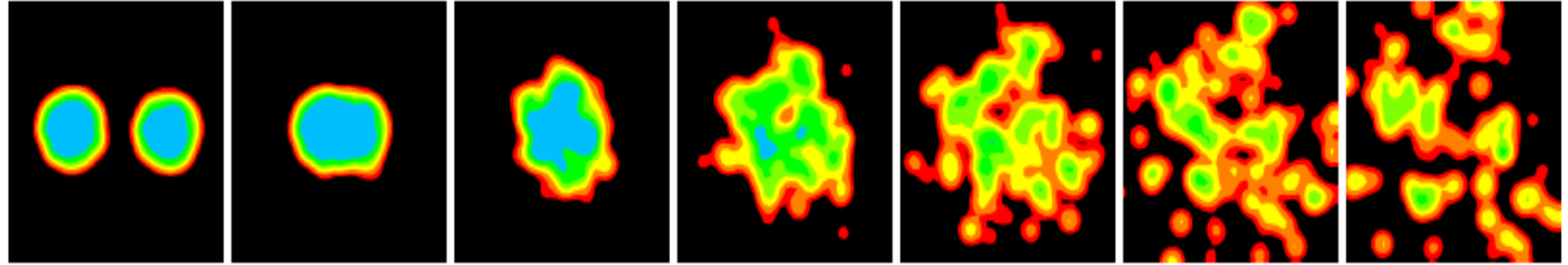
Office of
Science



Tommy Tsang
Bill Lynch
Rohit Kumar

Connecting Nuclei to the Cosmos

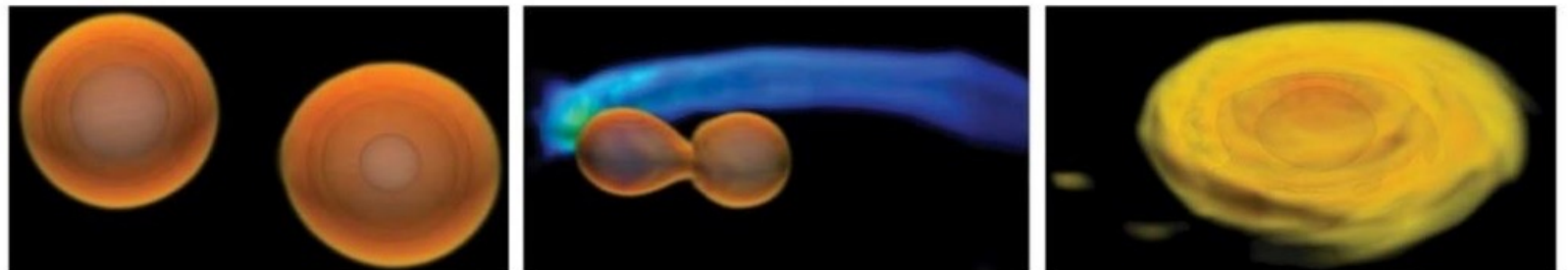
Heavy Ion collisions



HIC Dynamics requires simulations with transport models to extract EoS parameters

Dynamics of merger affects emission of NS material for nucleosynthesis and the fate of the post-merger object.

Neutron Star Merger



Late inspiral

Merger

Post merger