Dense matter EOS and neutron star properties constrained by nuclear experiments and astrophysical observations

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Tommy Tsang
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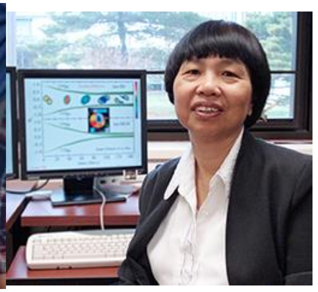
Betty Tsang
Chuck Horowitz



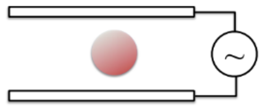

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Constraints from nuclear experiments and astrophysics observations

Nuclear experiments

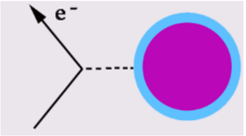
Nuclear Structure/Nuclear masses/GMR /HICs

Dipole polarizability



Tamii 2016

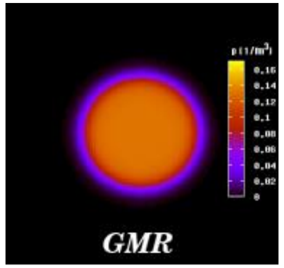
^{208}Pb neutron skin (PREX-II)



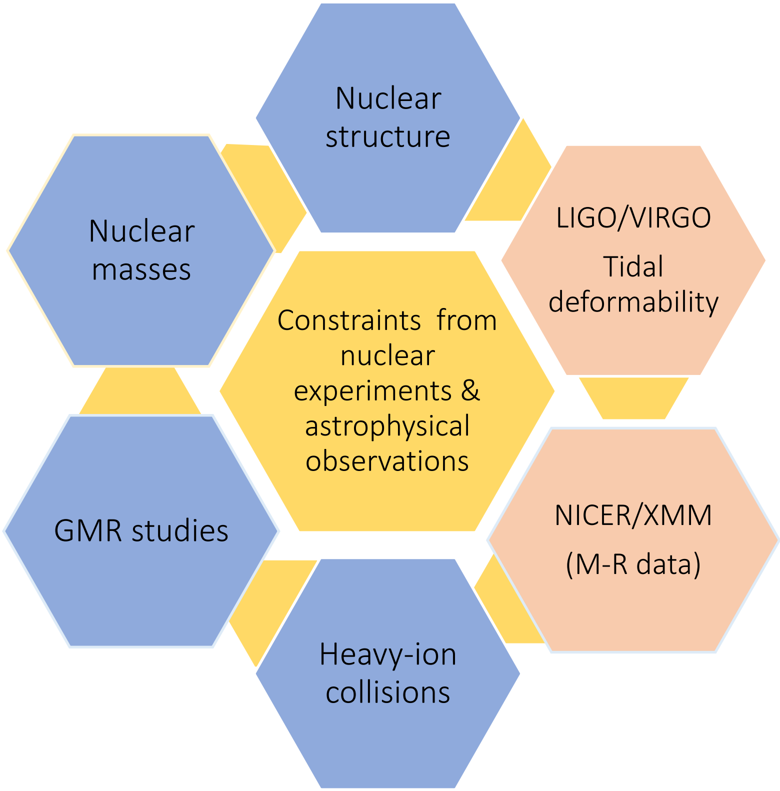
PRL 108, 112592 (2012)

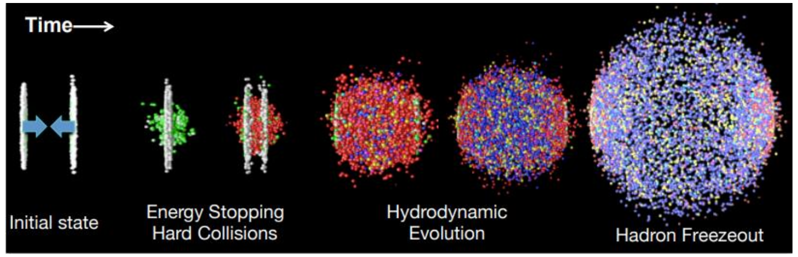
Isobaric Analog States

Giant Monopole Resonance Studies



Elliptical and collective Flow
Isospin diffusion
n/p spectra ratios
pion spectral ratios





Astrophysical constraints

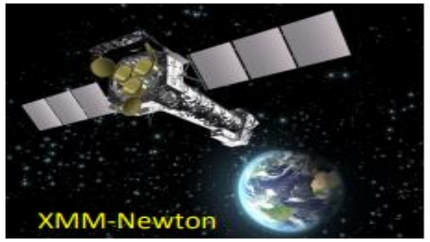
Tidal deformability of neutron star (GW170817)

LIGO
/VIRGO

Mass and Radius measurements of the neutron stars

NICER /XMM-Newton

PSR J0030+0451
PSR J0740+6620

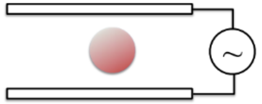


Constraints from nuclear experiments

Nuclear experiments

Nuclear Structure/Nuclear masses/GMR /HICs

Dipole polarizability



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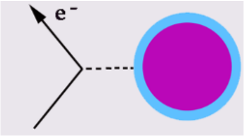
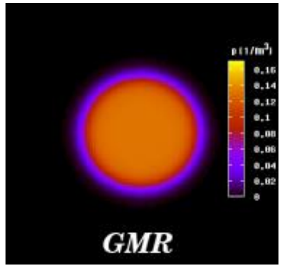


PRL 108, 112592 (2012)

Isobaric Analog States

Giant Monopole Resonance Studies



Elliptical and collective Flow
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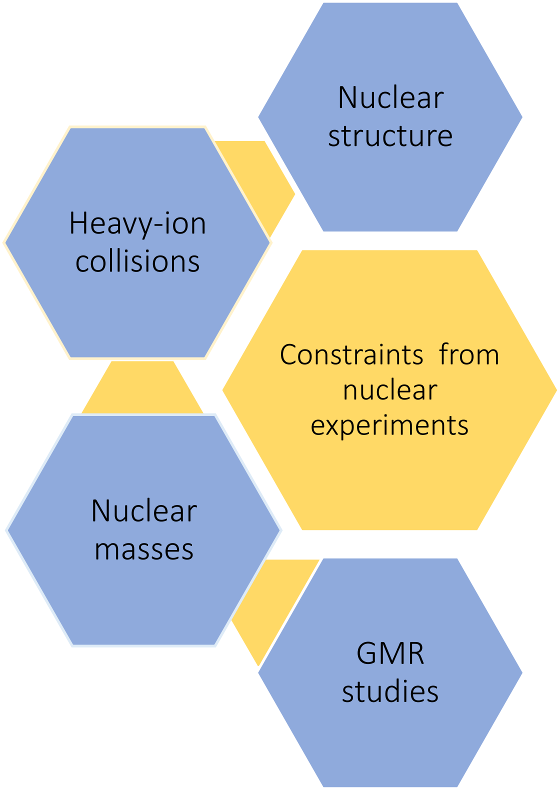
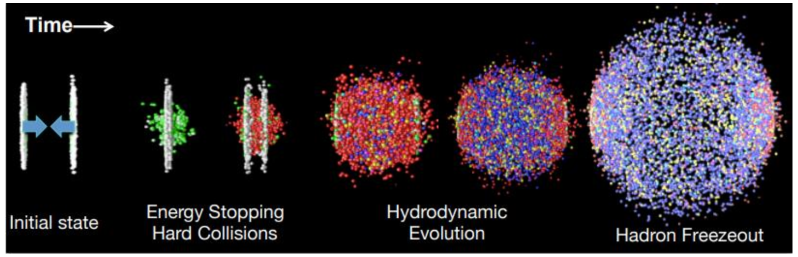




- Find observables sensitive to EoS
- What is each observable constraints (P_{SNM}, P_{sym}, S , L etc.)
- Sensitive density that is probed by that observable

Constraints: Symmetric nuclear matter

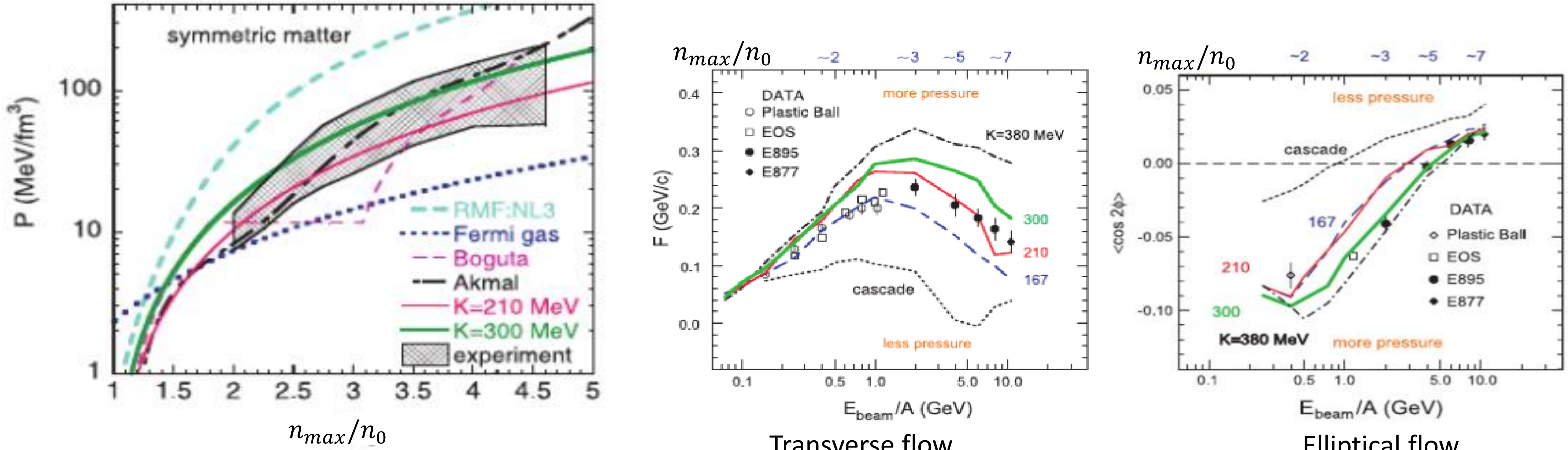
HIC

Determination of the Equation of State of the Dense matter

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

- Au + Au collision data in the energy range of 0.15 to 10 GeV/nucleon
- Transverse and elliptical flow are studied
- Flow data exclude very repulsive and very soft equations of state

$$2 < n/n_0 < 4.6$$



Transverse flow

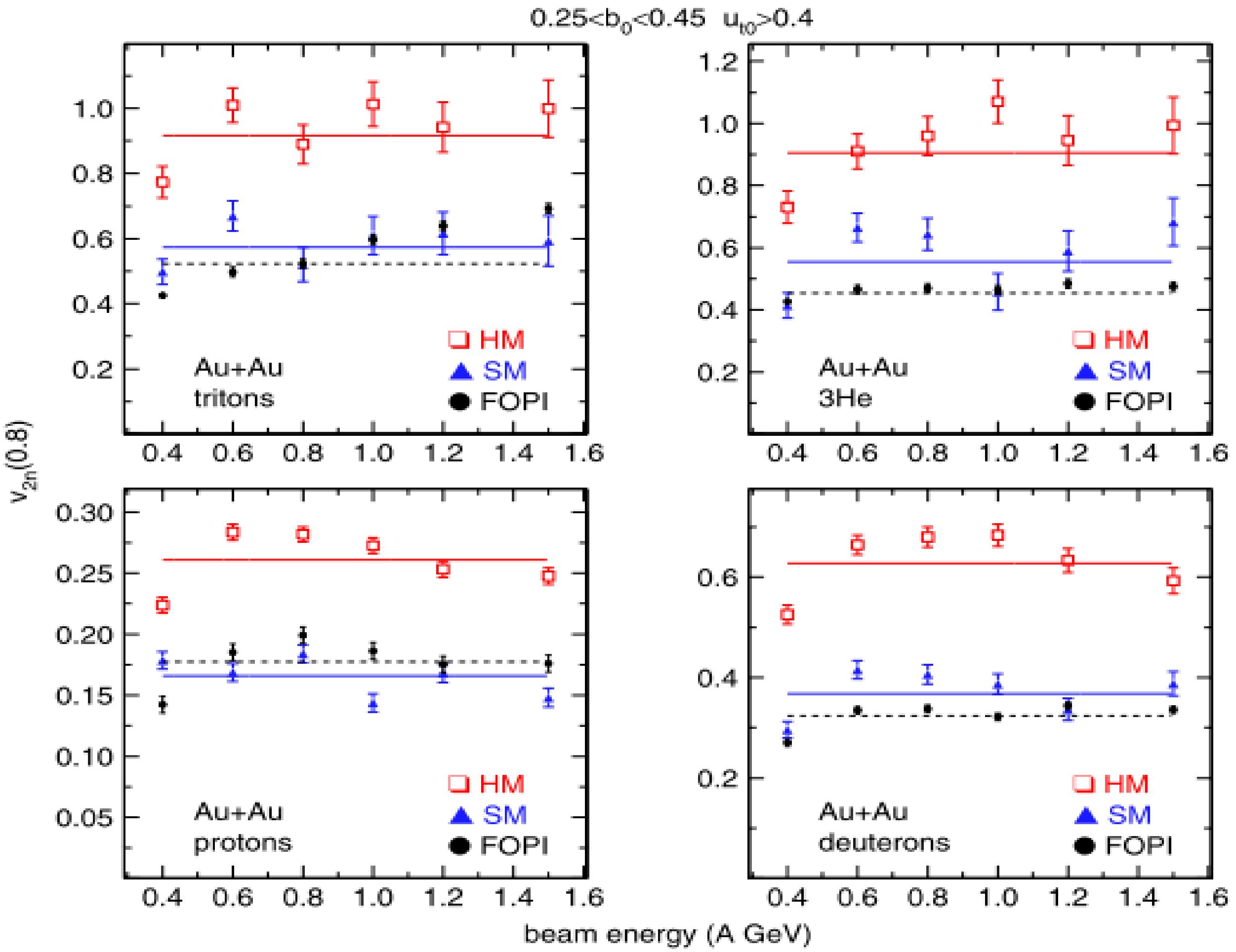
Elliptical flow

Constraints: Symmetric nuclear matter

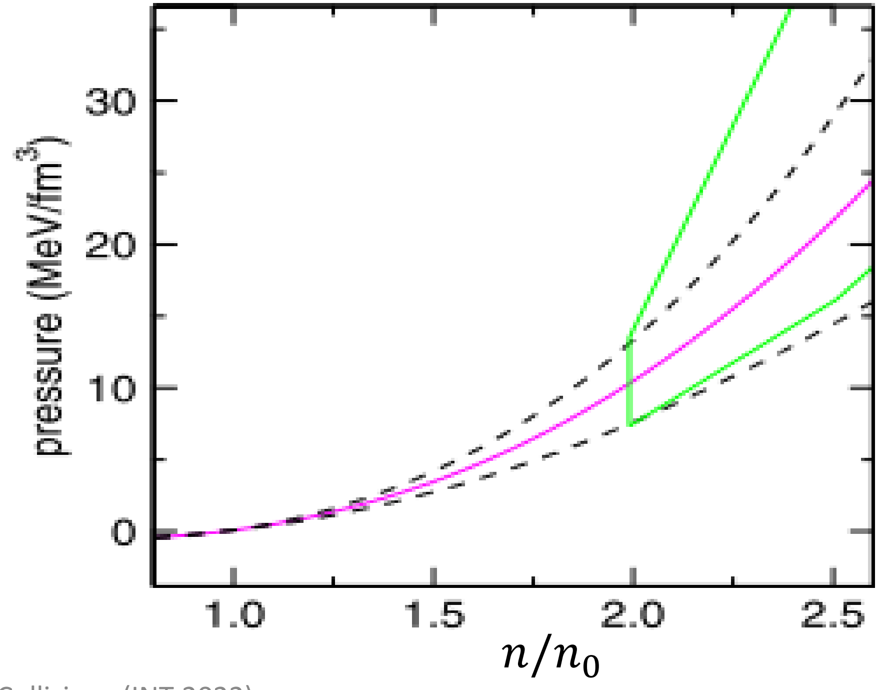
HIC

Constraining the nuclear matter equation of state around twice saturation density

Le Fevre, Leifels, Reisdorf, Aichelin, Hartnack, Nuclear Physics A 945, 112 (2016)



- FOPI experiments of Au+Au collisions at 0.4 to 1.5 GeV/nucleon
- Elliptic flow of protons and heavier isotopes



Constraints: Symmetric nuclear matter

GMR

Incompressibility of Nuclear Matter from the Giant Monopole Resonance

Youngblood et al., Phys. Rev. Lett. 82, 691 (1999)

GMR strength distributions in ^{40}Ca, ^{90}Zr, ^{116}Sn, ^{144}Sm and ^{208}Pb

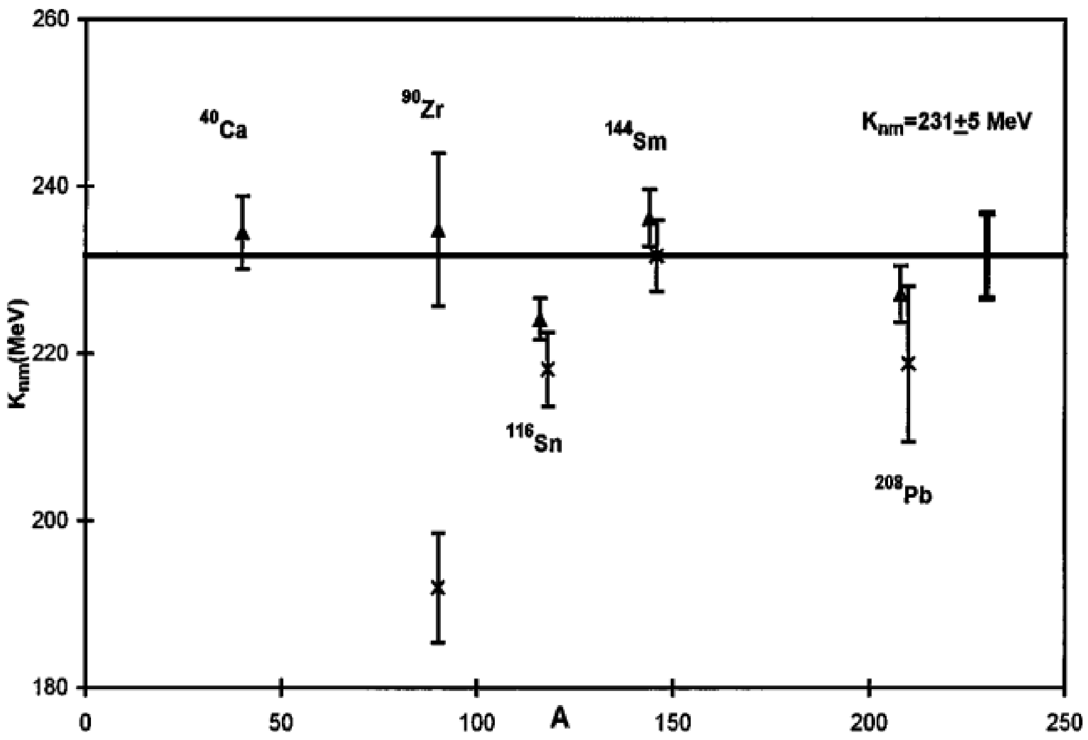
K_{sat} = 231 ± 5 MeV

Skyrme interaction and nuclear matter constraints

Dutra et al Phys. Rev. C 85, 035201 (2012)

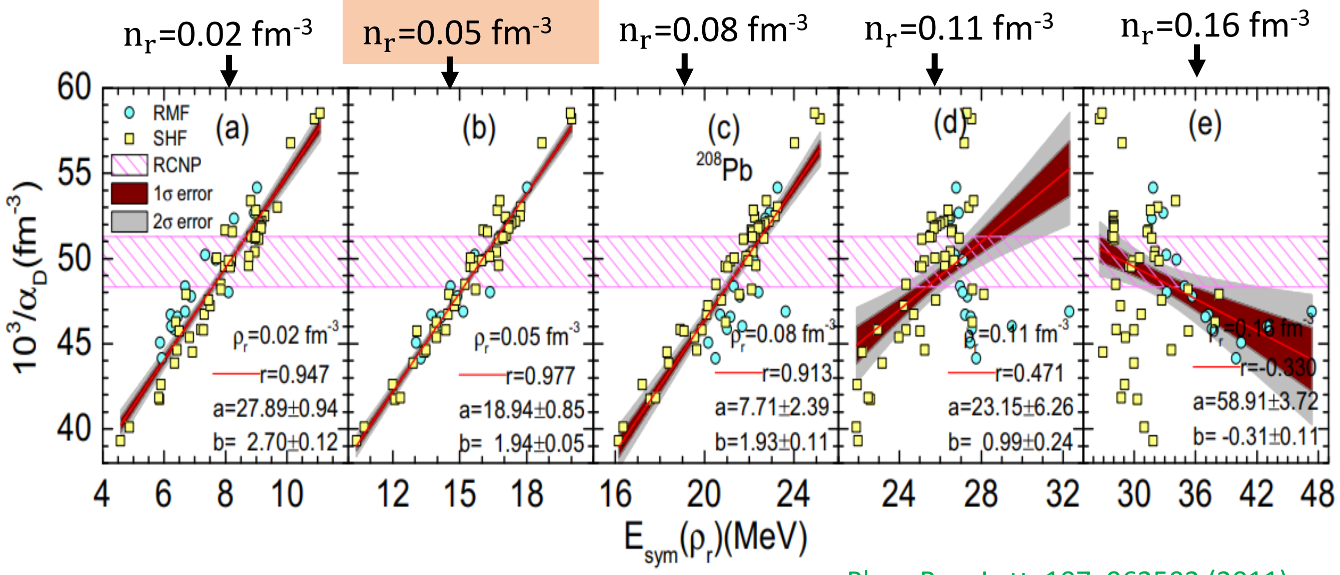
$^{112,\,116,124}Sn$!

K_{sat} = 230 ± 30 MeV



Constraints: Symmetry energy (low density)

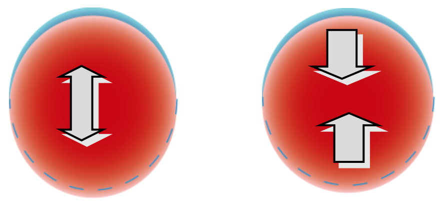
Electric dipole polarizability of ^{208}Pb:



Phys. Rev. Lett. 107, 062502 (2011)

Combined analysis:

- 47 Skyrme interactions
- 15 relativistic interactions
- Experimental data of RCNP, Japan



E-field restoring force

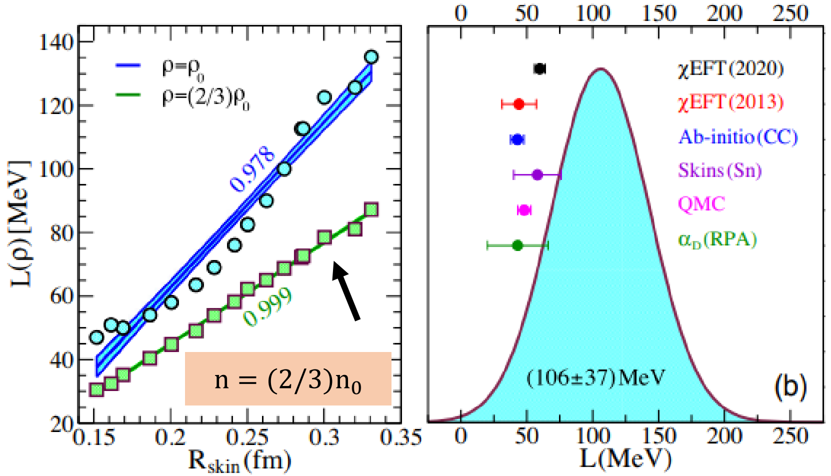
symmetry energy

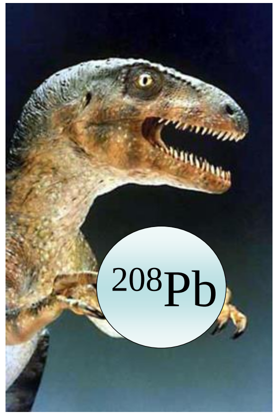
$$S(n = 0.31n_0) = 15.91 \pm 0.99\ MeV$$

Phys. Rev. C 92, 031301(R) (2015)

Pearson correlation analysis

Lead Radius EXperiment (PREX-II):





Jefferson Lab

- Pressure of the neutron matter pushed neutron out against the surface tension Radius difference between neutrons and protons is correlated with L
- neutron skin thickness of ^{208}Pb from the PREX-II measurements of parity violating electron scattering

$$R_{\text{skin}} = R_n - R_p = (0.283 \pm 0.071)\ \text{fm}$$

$$n = (2/3)n_0 \approx 0.1\ \text{fm}^{-3} \qquad L_{01} = 71.5\ \pm 22.6\ \text{MeV}$$

$$P_{sym}(n = (2/3)n_0) = 2.38 \pm 0.75\ \text{MeV fm}^{-3}$$

Phys. Rev. Lett. 126, 172502 (2021)
Phys. Rev. Lett. 126, 172503 (2021)

Constraints: Symmetry energy (low density)

Mass (Skyrme):

- 18 Skyrme energy density functionals
- Data used: binding energies, rms charge radii, and single-particle energies of doubly magic nuclei
- ^{16}O, ^{24}O, ^{34}Si ^{40}Ca, ^{48}Ca, ^{48}Ni, ^{68}Ni, ^{88}Sr, ^{100}Sn, ^{132}Sn, and ^{208}Pb

Results:

$$n = (0.63 \pm 0.03)n_0$$

$$S(n) = 24.7 \pm 0.8\ MeV$$

Phys. Rev. Lett. 111, 232502 (2013)
Phys. Rev. C 89, 011307(R) (2014)

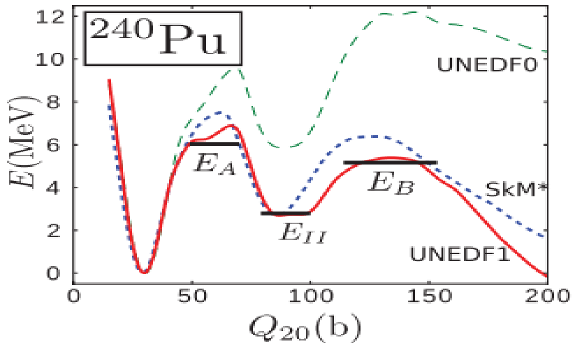
Mass (DFT):

Using DFT, masses of nuclei with $40 \le A \le 264$ are fitted with a greater emphasis on heavier nuclei

Data of 72 nuclei, only 11 are with mass <66

Excitation energies in MeV of fission isomers

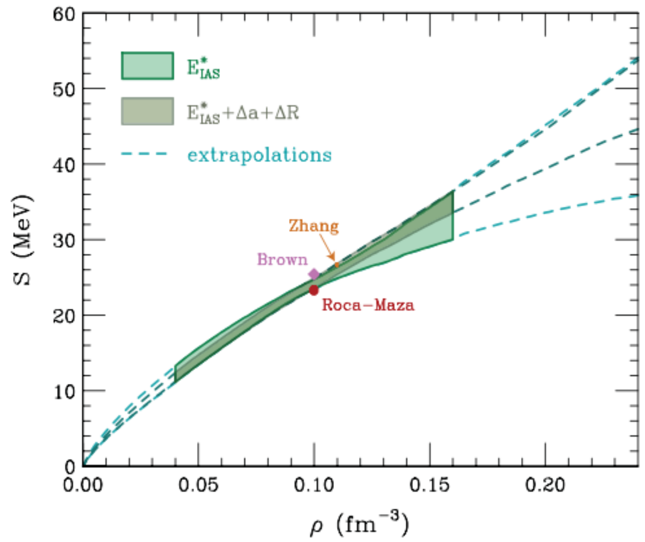
Nucleus	UNEDF0	UNEDF1	Expt.
^{236}U	5.28	2.42	2.75
^{238}U	5.73	2.71	2.557
^{240}Pu	5.74	2.51	2.8
^{242}Cm	5.27	1.85	1.9
^{192}Hg	6.33	2.62	5.3
^{194}Hg	7.27	3.79	6.017
^{192}Pb	5.20	1.25	4.011
^{194}Pb	5.99	1.99	4.643
^{196}Pb	7.26	3.52	5.63



Phys. Rev. C 82, 024313 (2010), 85, 024304 (2012)

Isobaric Analog States (IAS):

Simultaneous analysis of differential cross sections for elastic (p,p) and (n,n) reactions, and quasielastic (p,n) reactions to IAS, on four targets, ^{48}Ca, ^{90}Zr, ^{120}Sn and ^{208}Pb within the energy range of (10–50) MeV.



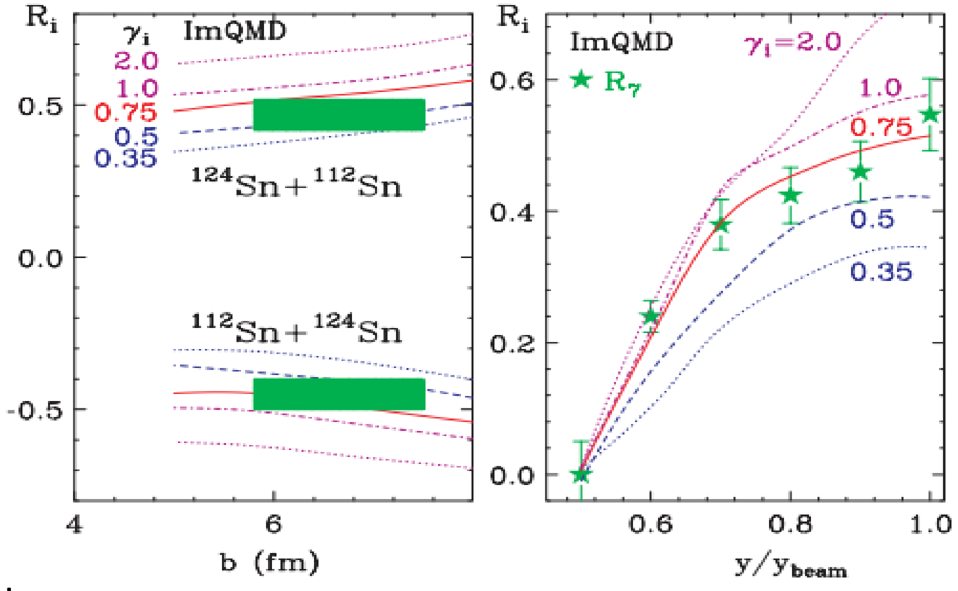
Nucl. Phys. A 958, 147 (2017)

Constraints: Symmetry energy (low density)

Isospin diffusion:

HIC

- $^{124,112}Sn + ^{124,112}Sn$ at an incident energy of 50 MeV/nucleon
- Isospin diffusion data: Study of transport of neutrons and protons during the expansion



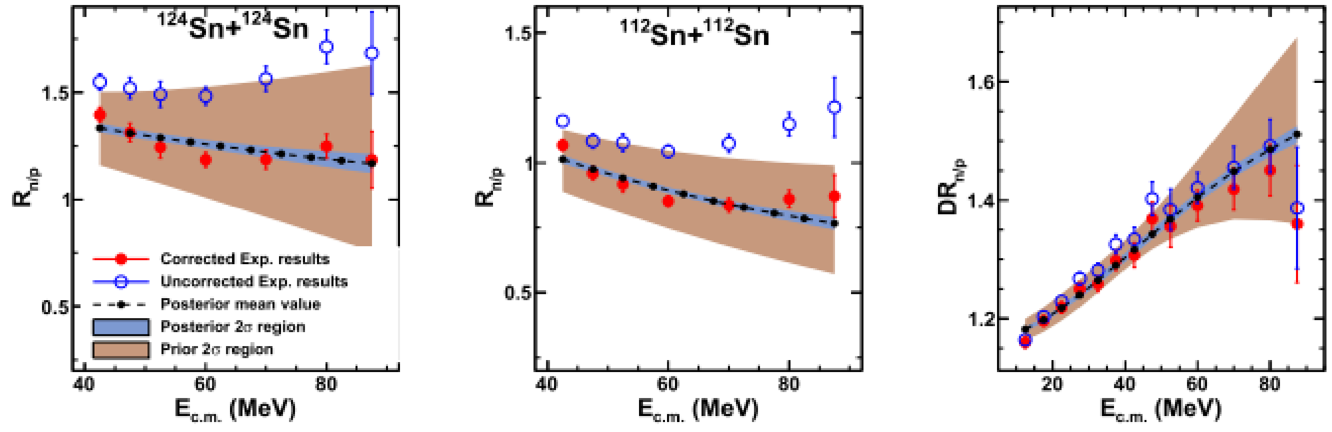
Results:

$$n = (0.22 \pm 0.07)n_0 \qquad S(n) = 10.3 \pm 1.0\ MeV$$

Phys. Rev. C 102, 122701 (2009)
Phys. Lett. B 830,137098 (2022)

Neutron-proton single and double ratios:

HIC



- $^{112}Sn+^{112}Sn$ and $^{124}Sn + ^{124}Sn$ collisions at an incident energy of 120 MeV/nucleon
- Combined analysis of single ratios of neutron and proton spectra & double ratios

Results:

$$n = (0.43 \pm 0.05)n_0 \qquad S(n) = 16.8 \pm 1.2\ MeV$$

Experimental data: NSCL, MSU

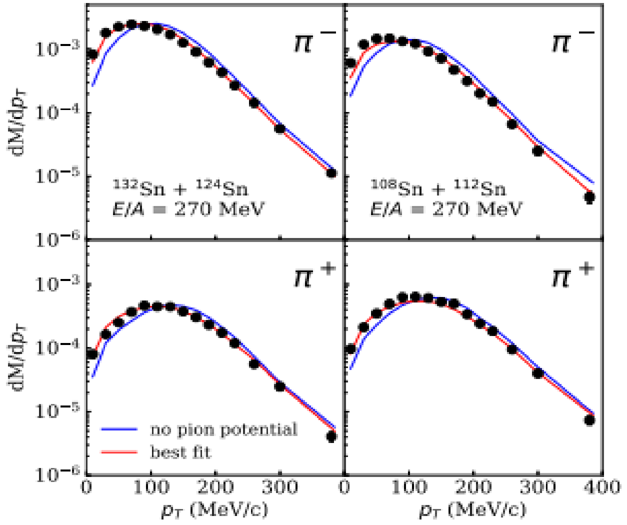
Phys. Lett. B 799, 135045 (2019)

Constraints: Symmetry energy (high densities)

Pion spectral ratios:

HIC

- $^{132}Sn + ^{124}Sn$ and $^{108}Sn + ^{112}Sn$ incident energy of 270 MeV/nucleon
- Observables: Charged pion transverse momentum spectra



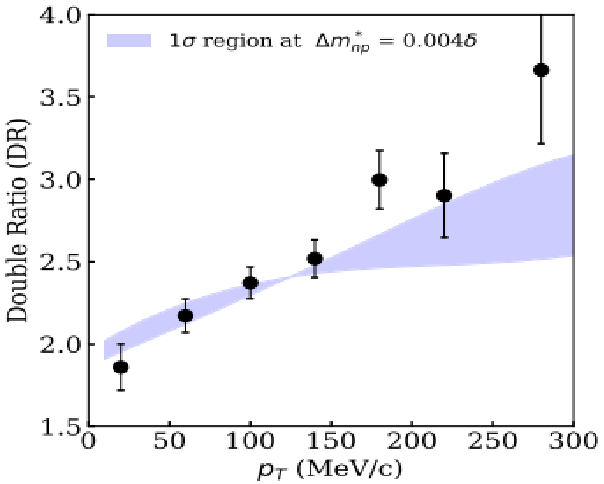
Results:

$n = 1.45 n_0$

$S(n) = 52 \pm 13$ MeV

$P_{sym}(n) = 10.9 \pm 8.7$ MeV fm^{-3}

PRL **126**, 162701 (2021)



SPiRIT TPC Experiments at RIKEN

Neutron to Charged particle flow ratios:

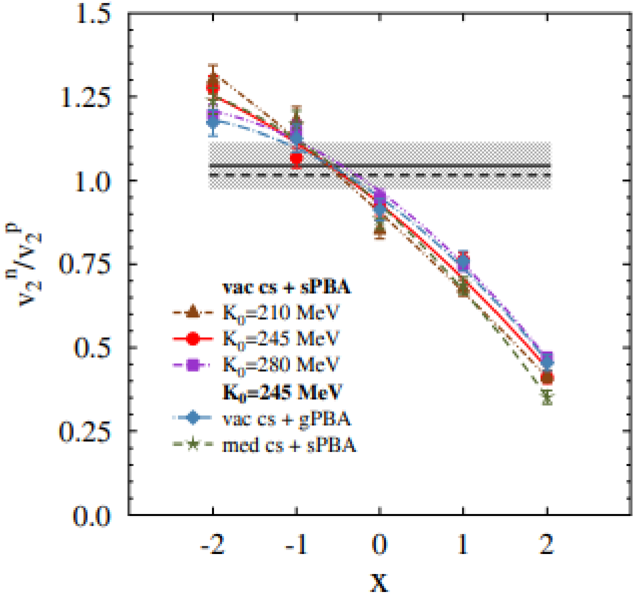
HIC

- Au+Au collisions at an incident energy of 400 MeV/nucleon
- FOPI-LAND neutron-to-proton and ASYEOS neutron–to–charged-particles elliptical flow ratios data

Results:

$n = 1.5 n_0$

$P_{sym}(n) = 12.1 \pm 8.4$ MeV fm^{-3}



Phys. Lett. B 697, 471 (2011)
Phys. Rev. C 94, 034608 (2016)
Eur. Phys. J. A 54, 40 (2018)

Decoding the symmetry energy sensitive densities

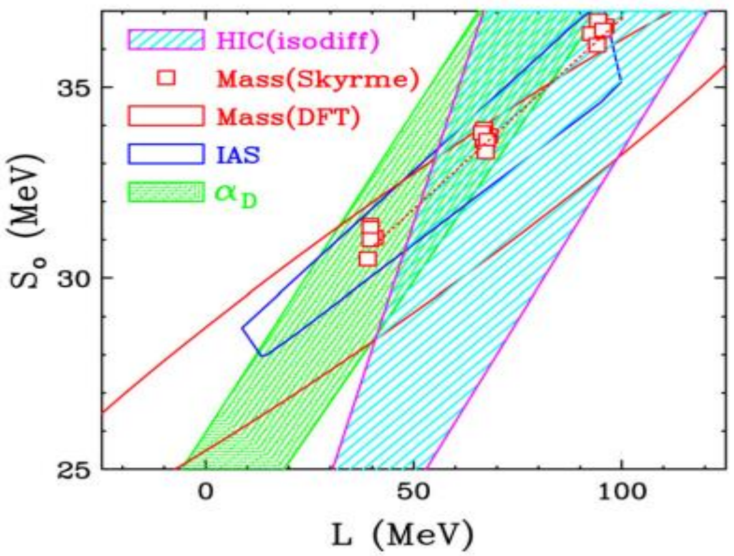
Symmetry energy:

$S(n) = S_{kin}(n) + S_{int}(n)$ $\quad\quad$ $S_{kin}(n) = A\,(n/n_0)^{2/3}$

WG Lynch, MB Tsang Physics Letters B 830, 137098 (2022)

Potential energy term:

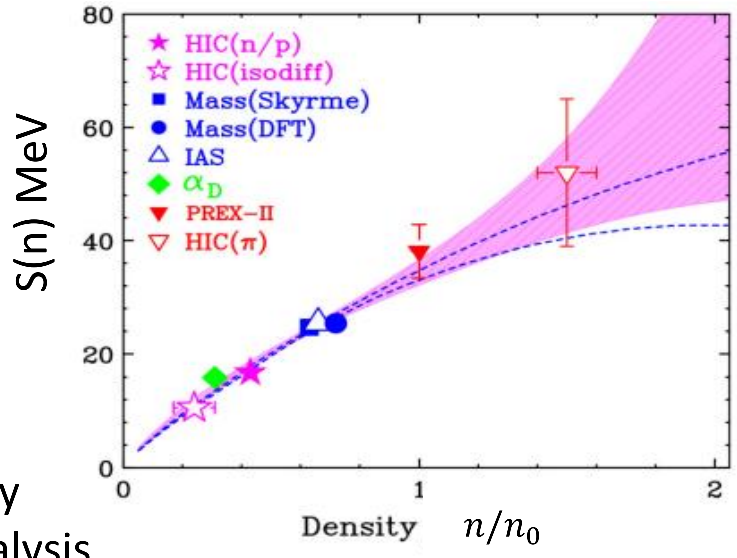
$$S_{int}(n) = S_{int}(n_{01}) + S'_{int}\,(n - n_{01}) + \frac{1}{2}S''_{int}\,(n - n_{01})^2 + \frac{1}{6}S'''_{int}\,(n - n_{01})^3 \qquad n_{01} = 0.1\ \mathrm{fm}^{-3}$$



Inclination analysis:

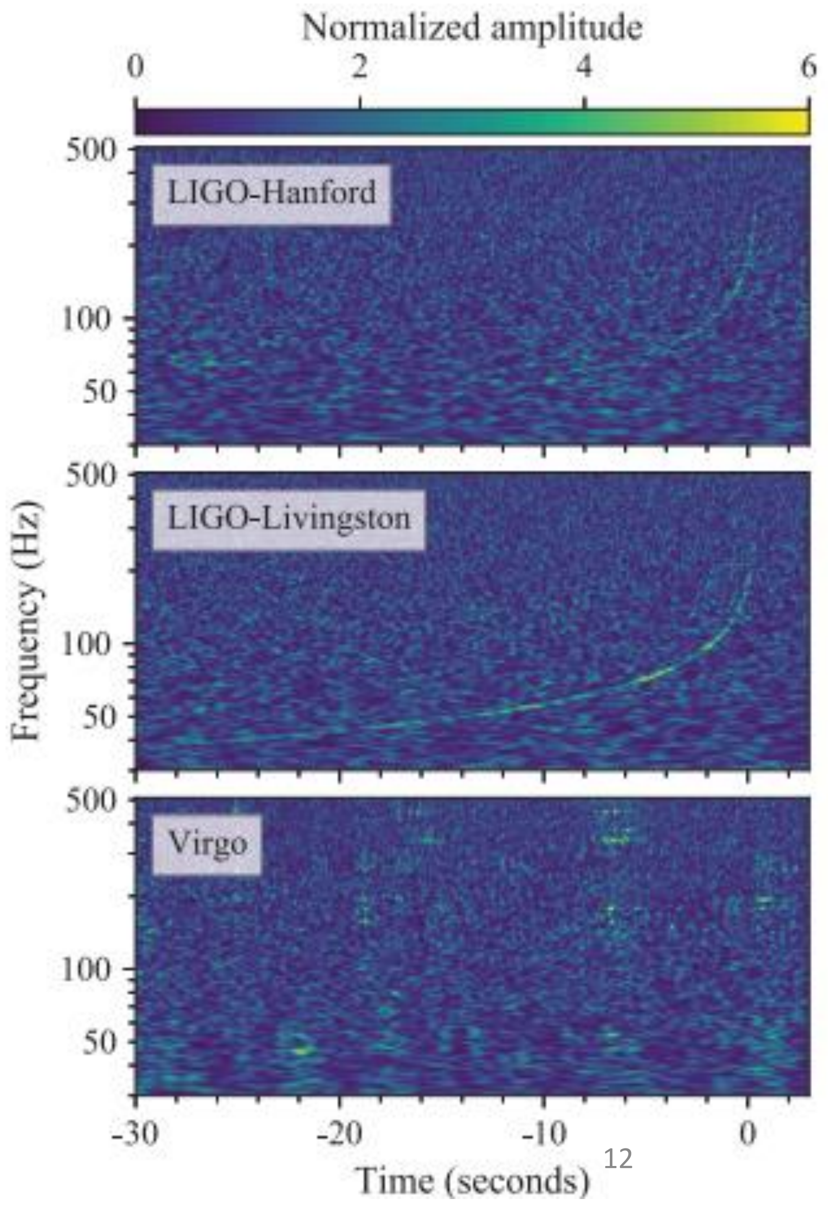
$$\tau = \frac{\Delta S_0}{\Delta L_0} = -\frac{\frac{\partial S(n)}{\partial L}}{\frac{\partial S(n)}{\partial S_0}}$$

τ depends monotonically on sensitive density
Sensitive densities consistent with cross-over analysis.



Multi-messenger Astronomy

- Neutron Stars emit Gravitational waves, neutrinos and photons (thermal X-rays, radio waves etc.).
- This leads to various observables: Mass, Radius, Tidal Deformability, Angular Momentum, Glitches, Temperature Colling curves etc.
- We are living in a new era of NS observations



GW170817:

On August 17, 2017, the LIGO-VIRGO detector network observed a gravitational-wave signal from the inspiral of two low-mass compact objects consistent with a binary neutron star (BNS) merger.

Gravitational tidal field distorts shapes of neutron stars just before they merge

Tidal deformability:

$$\Lambda\left(M = 1.4\ M_{\odot}\right) = 190^{+390}_{-120}$$

PRL 119, 161101 (2017); PRL 121, 161101 (2018)

Targeting pulsars with NICER

Pulse profile modeling of hot spots on the rapidly rotating neutron stars

PSR J0030+0451

- Isolated (no independent mass estimate)

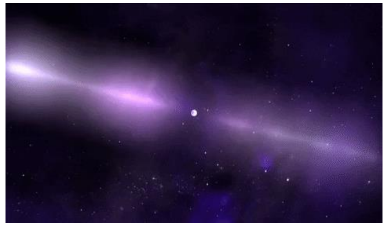
$$M = 1.34^{+0.15}_{-0.16} M_{\odot} \quad R = 12.71^{+1.14}_{-1.19}\ \mathrm{km}$$

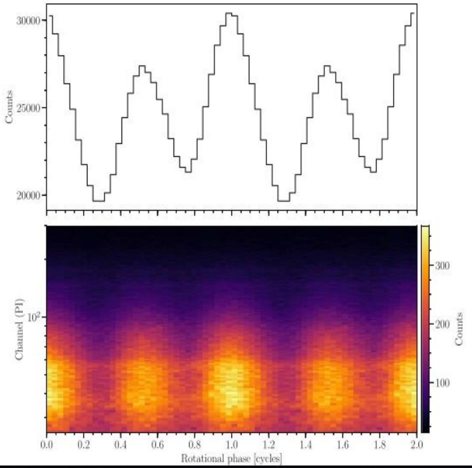
Riley et al., AJL 887, L21 (2019)

$$M = 1.44^{+0.15}_{-0.14} M_{\odot} \quad R = 13.02^{+1.24}_{-1.06}\ \mathrm{km}$$

Miller et al., AJL 887, L24 (2019)

Two independent analysis (with different emission geometry assumptions)





PSR J0740+6620

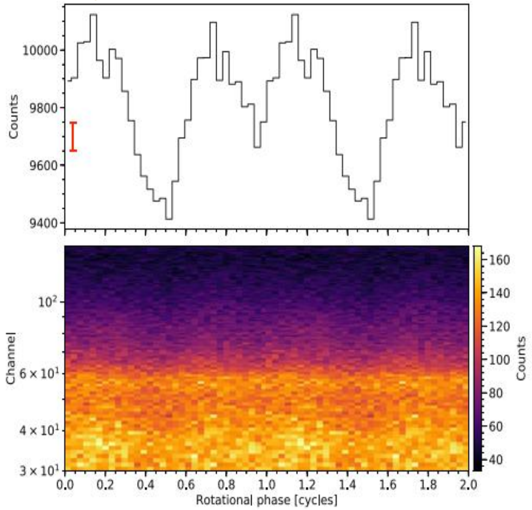
- Independent mass estimation orbital dynamics (Shapiro Time delay of radio pulsar signal). This helps The determination of the radius R.

$$M = 2.072^{+0.07}_{-0.07} M_{\odot} \quad R = 12.39^{+1.30}_{-0.98}\ \mathrm{km}$$

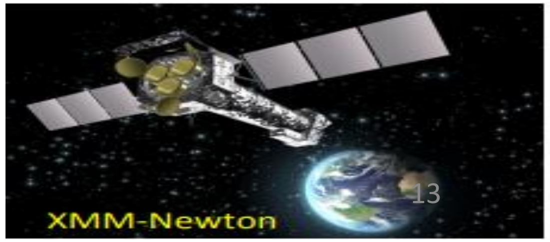
Riley et al., AJL 918, L27 (2021)

$$M = 2.08^{+0.07}_{-0.07} M_{\odot} \quad R = 13.7^{+2.6}_{-1.5}\ \mathrm{km}$$

Miller et al., AJL 918, L28 (2021)



- Combined NICER and XMM-Newton data
- J0740 is very faint in X-rays



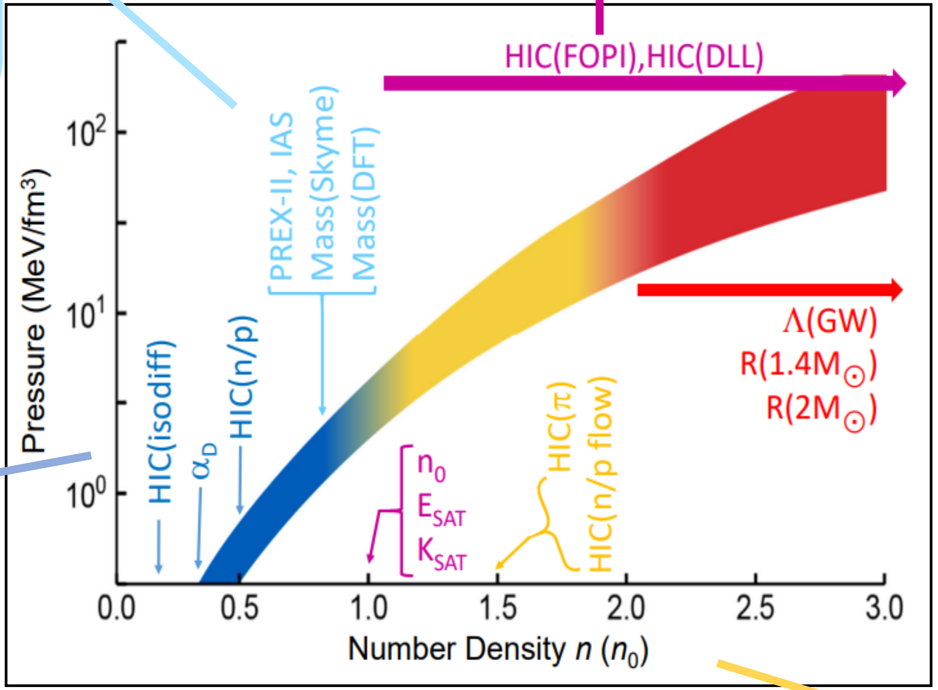
Constraints from nuclear experiments and astrophysics observations

- ^{208}Pb neutron skin (PREX-II):
  $n=0.67n_0$, $P_{sym}=2.38\pm0.75$ MeVfm^{-3}
  PRL 126, 172502 (2021);PRL 126, 172503 (2021)
- Isobaric Analog States (IAS):
  $n=0.66n_0$; $S(n)=25.5\pm1.1$ MeV
  NPA 958, 147 (2017)
- Mass (Skyrme):
  $n=0.63n_0$; $S(n)=24.7\pm0.8$ MeV
  PRL 111, 232502 (2013); PRC 89, 011307(R) (2014)
- Mass (DFT):
  $n=0.72n_0$; $S(n)=25.4\pm1.1$ MeV
  PRC 82, 024313 (2010); PRC 85, 024304 (2012)

Lynch and Tsang, Phys. Lett. B 830,137098 (2022)

- HIC Isospin diffusion:
  $n=0.22n_0$; $S(n)=10.3\pm1.0$ MeV
  PRL 102, 122701 (2009)
- Dipole polarizability:
  $n=0.31n_0$, $S(n)=15.9\pm1.0$ MeV
  PRC 92, 031301(R) (2015)
- HIC n/p spectral ratio:
  $n=0.43n_0$; $S(n)=16.8\pm1.2$ MeV
  PLB 799, 135045 (2019)

- HIC (DLL):
  $n=2n_0$; $P_{SNM}=10.1\pm3.0$ MeVfm^{-3}
  Science 298, 1592 (2002)
- HIC (FOPI):
  $n=2n_0$; $P_{SNM}=10.3\pm2.8$ MeVfm^{-3}
  NPA 945, 112 (2016)



- GMR: $n=n_0$; $K_{sat}=230\pm30$ MeV
  PRL 82, 691 (1999); PRC 85, 035201 (2012)

- **Tidal deformability:**
  $$\Lambda\left(\mathrm{M}=1.4\ \mathrm{M}_\odot\right)=190^{+390}_{-120}$$
  PRL 119, 161101 (2017); PRL 121, 161101 (2018)
- **PSR J0030+0451:**
  $$M=1.34^{+0.15}_{-0.16}M_\odot; R=12.71^{+1.14}_{-1.19}\ km$$
  Riley et al APL 887, L21 (2019)
  $$M=1.44^{+0.15}_{-0.14}M_\odot; R=13.02^{+1.24}_{-1.06}\ km$$
  Miller et al APL 887, L24 (2019)
- **PSR J0740+6620:**
  $$M=2.07^{+0.07}_{-0.07}M_\odot; R=12.39^{+1.30}_{-0.98}\ km$$
  Riley et al APL 918, L27 (2021)
  $$M=2.08^{+0.07}_{-0.07}M_\odot;\ R=13.7^{+2.6}_{-1.5}\ km$$
  Miller et al APL 918, L28 (2021)

- HIC pion spectral ratios:
  $n=1.45n_0$; $S(n)=52\pm13$ MeV,
  $P_{sym}=10.9\pm8.7$ MeVfm^{-3}
  PRL **126**, 162701 (2021)
- HIC n/p flow:
  $n=1.50n_0$; $P_{sym}=12.1\pm8.4$ MeVfm^{-3}
  PRC 94, 034608 (2016); EPJ A 54, 40 (2018)

Priors

Uniform prior distribution P(M) in the ranges of

Parameters	Priors
K_{sat} (MeV)	[0, 648]
Q_{sat} (MeV)	[-1100, 2100]
S_{01} (MeV)	[0, 50]
L_{01} (MeV)	[0, 120]
K_{01} (MeV)	[-300, 300]
Z_{sat} (MeV)	
Q_{01} (MeV)	

Prior ranges of SNM EOS and symmetry energy parameters based on nuclear experiments and astrophysical observations

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

Meta-modeling of nuclear EOS

PRC 97, 025805 (2018)

Form from Lynch and Tsang PLB 2022 based on constraints on symmetry energy term from various experiments.

- Phenomenological models of the nuclear equation of state can build in (often hidden) correlations due to the functional form of the EoS

Priors

Uniform prior distribution P(M) in the ranges of

Parameters	Priors
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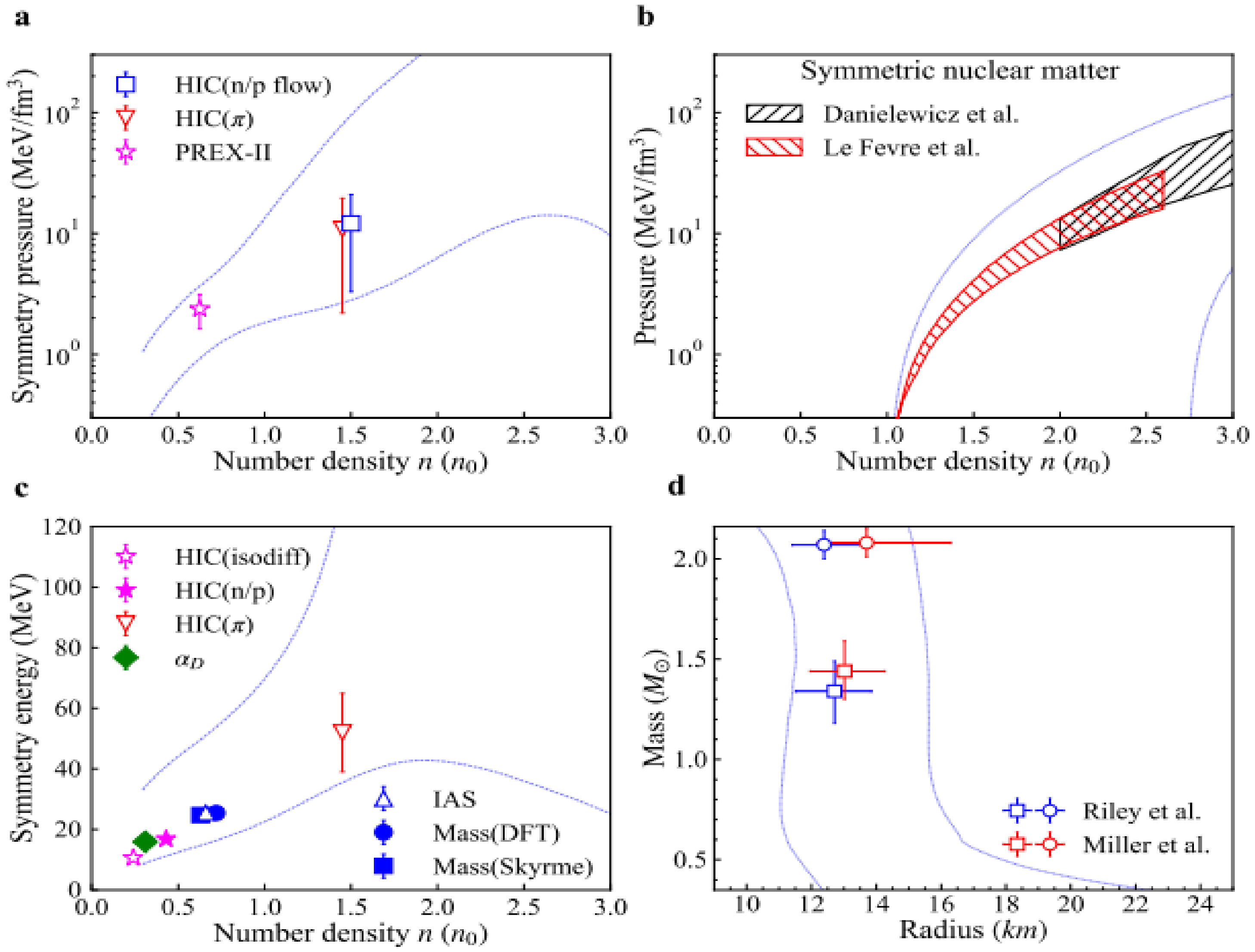
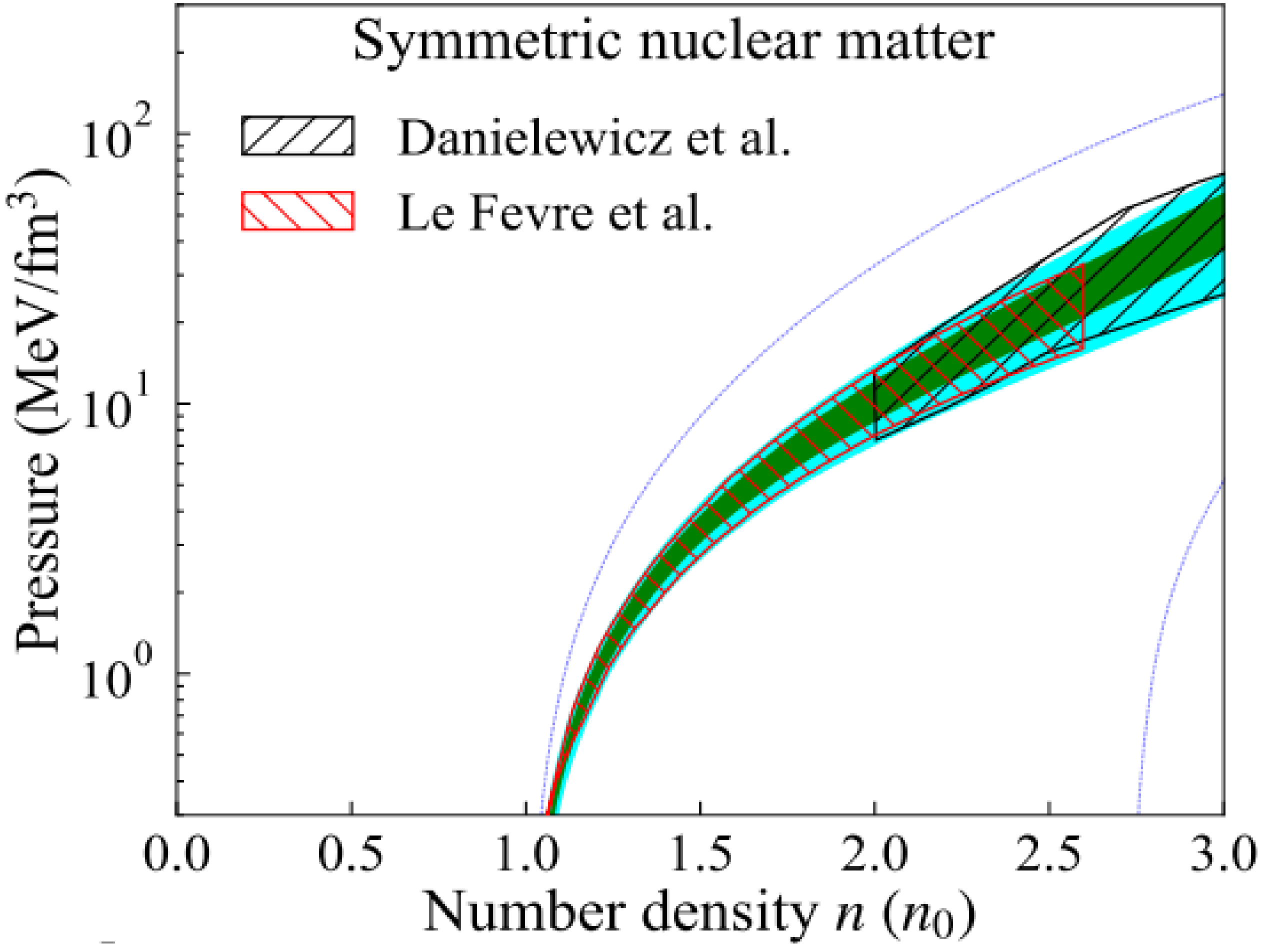
K_{01} (MeV)	[-300, 300]
Z_{sat} (MeV)	
Q_{01} (MeV)	

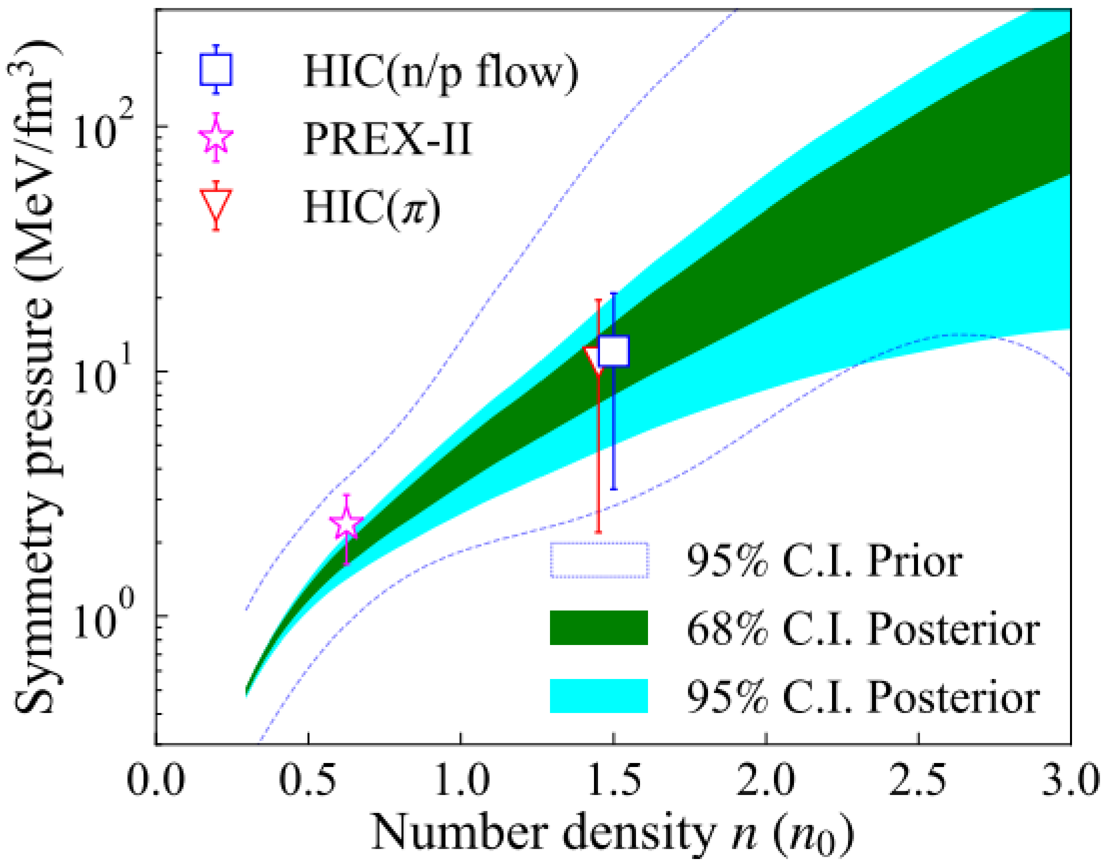
All equations of states have to support stable neutron star of mass 2.17 solar mass

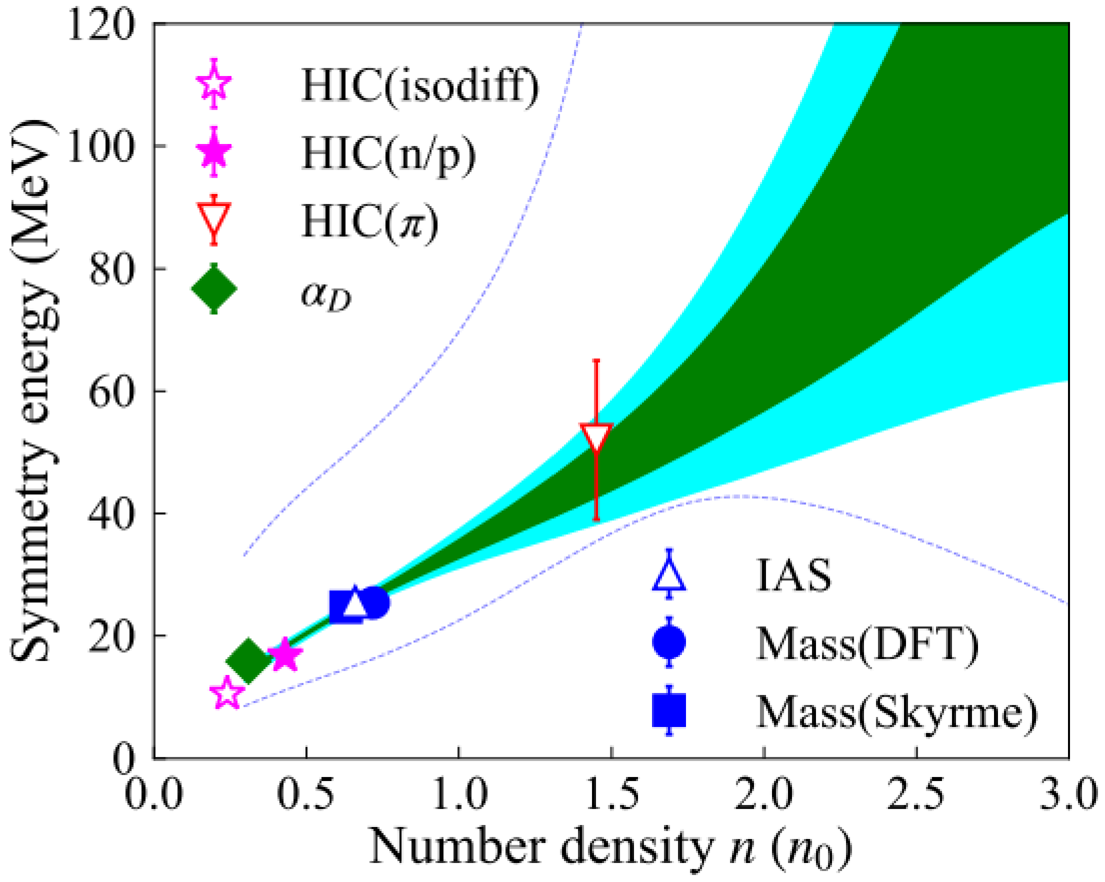


Symmetric nuclear matter

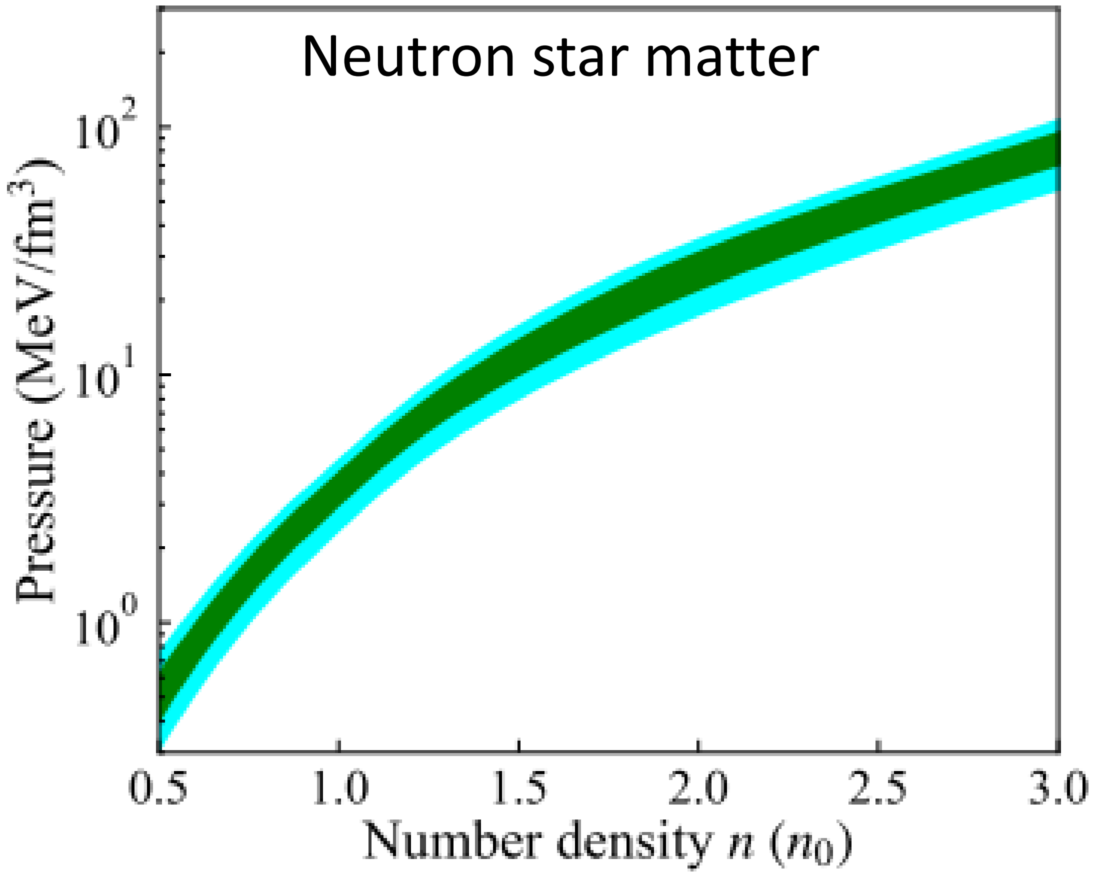


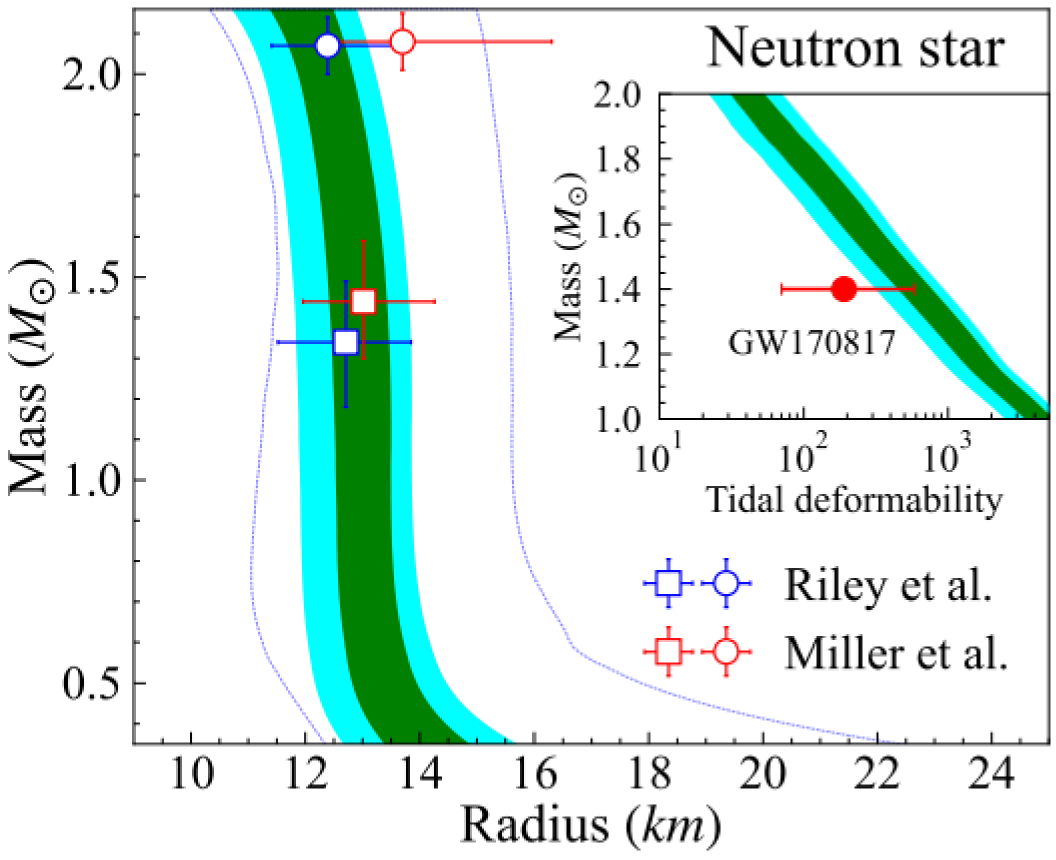
Symmetry pressure and symmetry energy





Neutron star equation of state

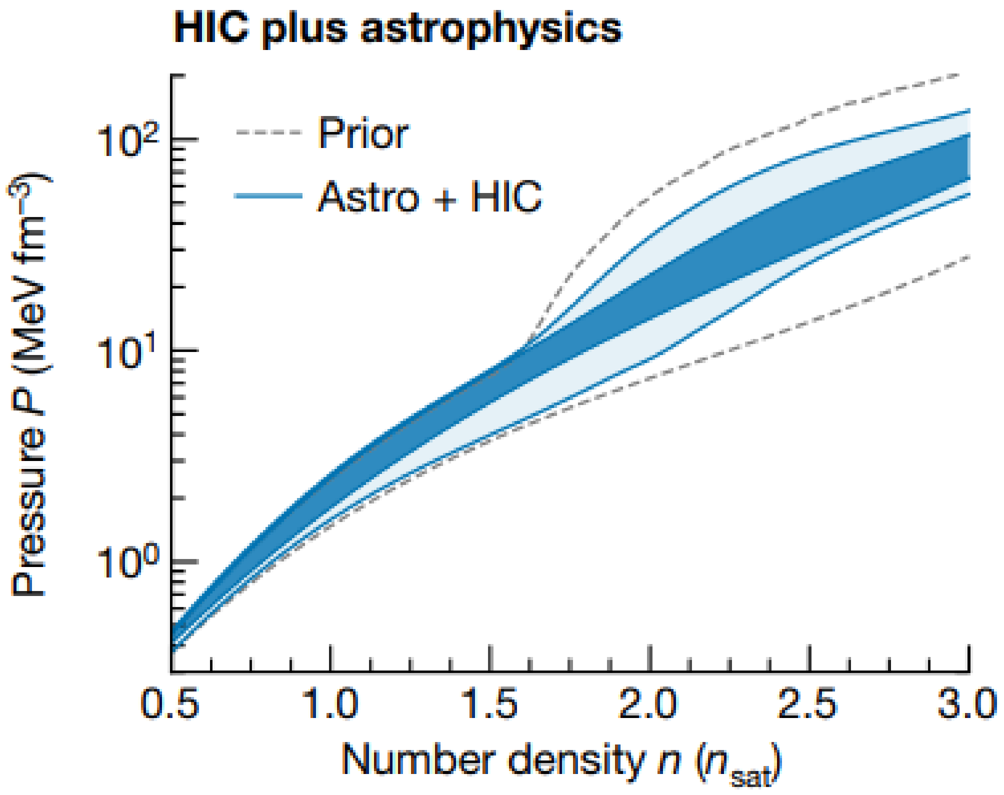




Neutron star equation of state

<u>Constraining neutron-star matter with microscopic and macroscopic collisions</u>

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



Chiral Effective Field theory (upto $1.5n_0$)

+

Heavy ion collisions

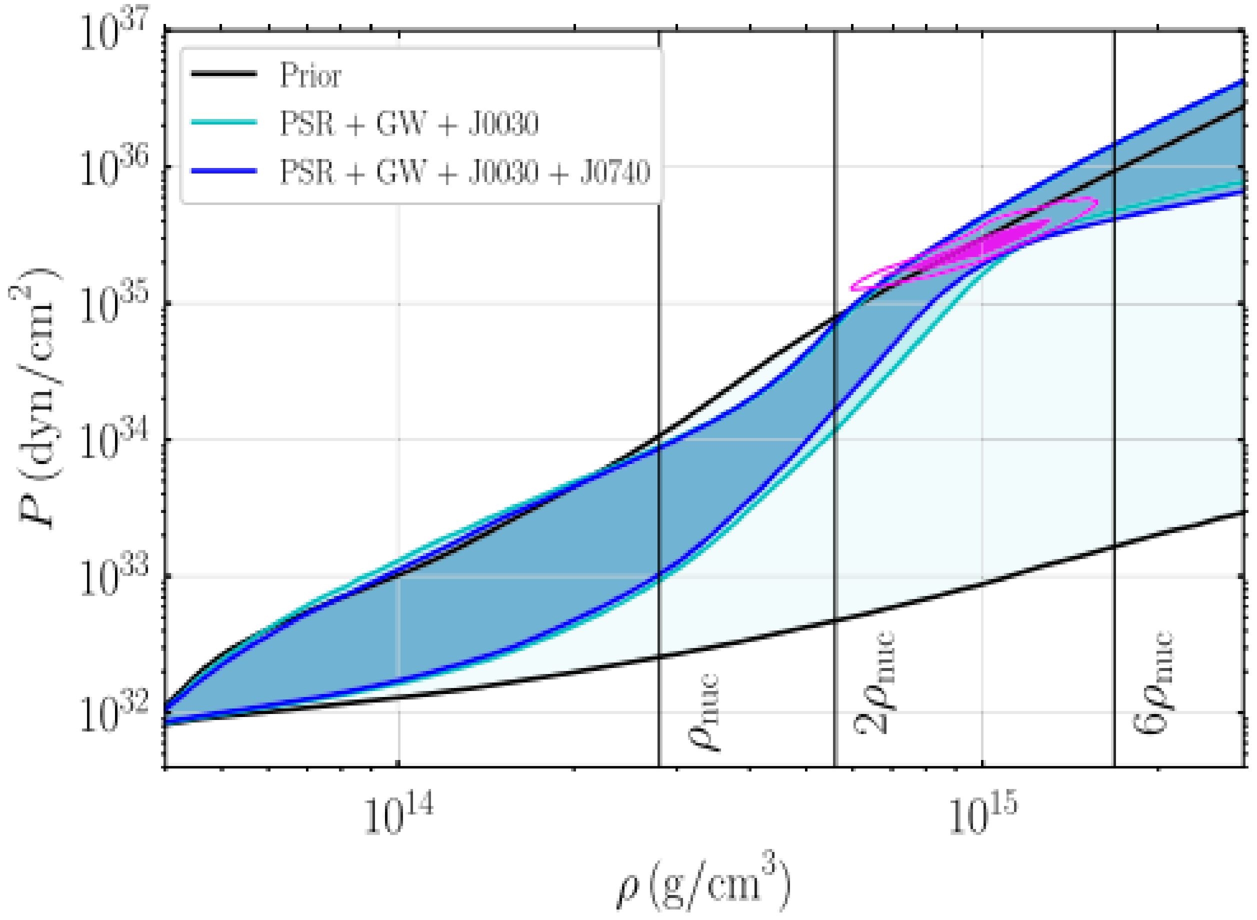
+

Constraints from Astrophysical measurements

Neutron star equation of state

<u>Impact of the PSR J0740 + 6620 radius constraint on the properties of high-density matter</u>

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

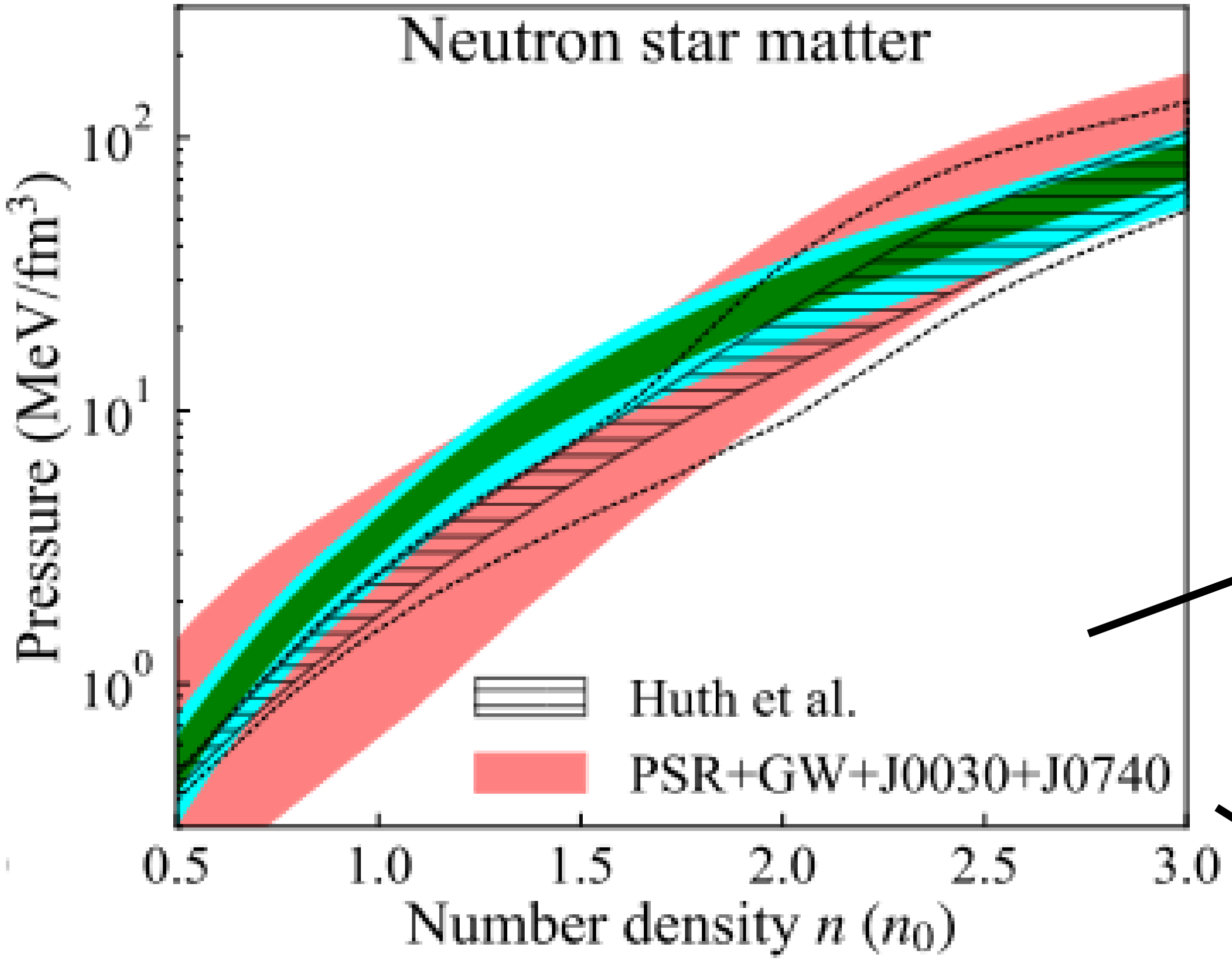


Non-parametric model

+

Constraints from Astrophysical measurements

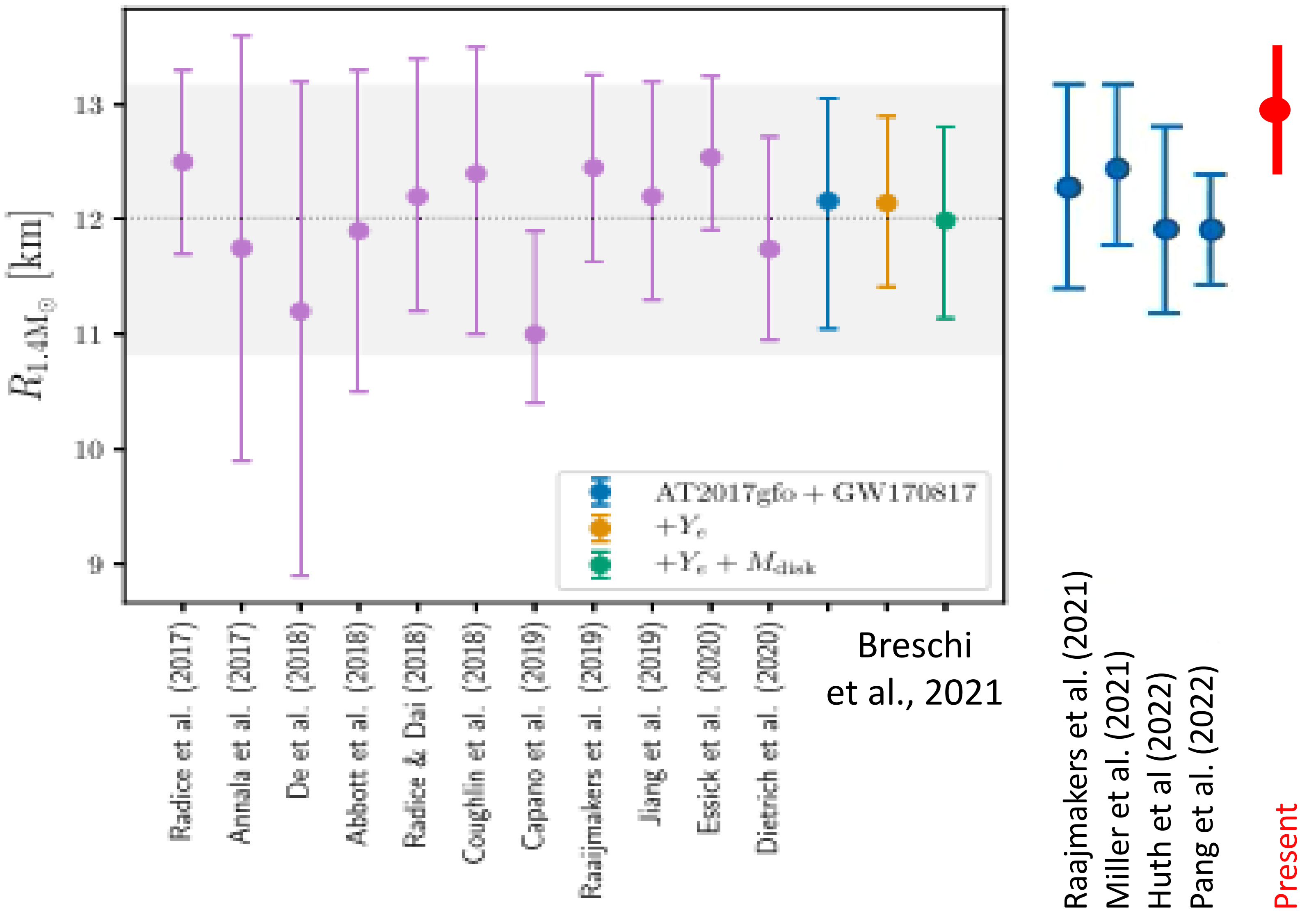
Neutron star equation of state



Huth, Pang et al., Nature 606, 279 (2022)
Chiral EFT +HIC+Astro

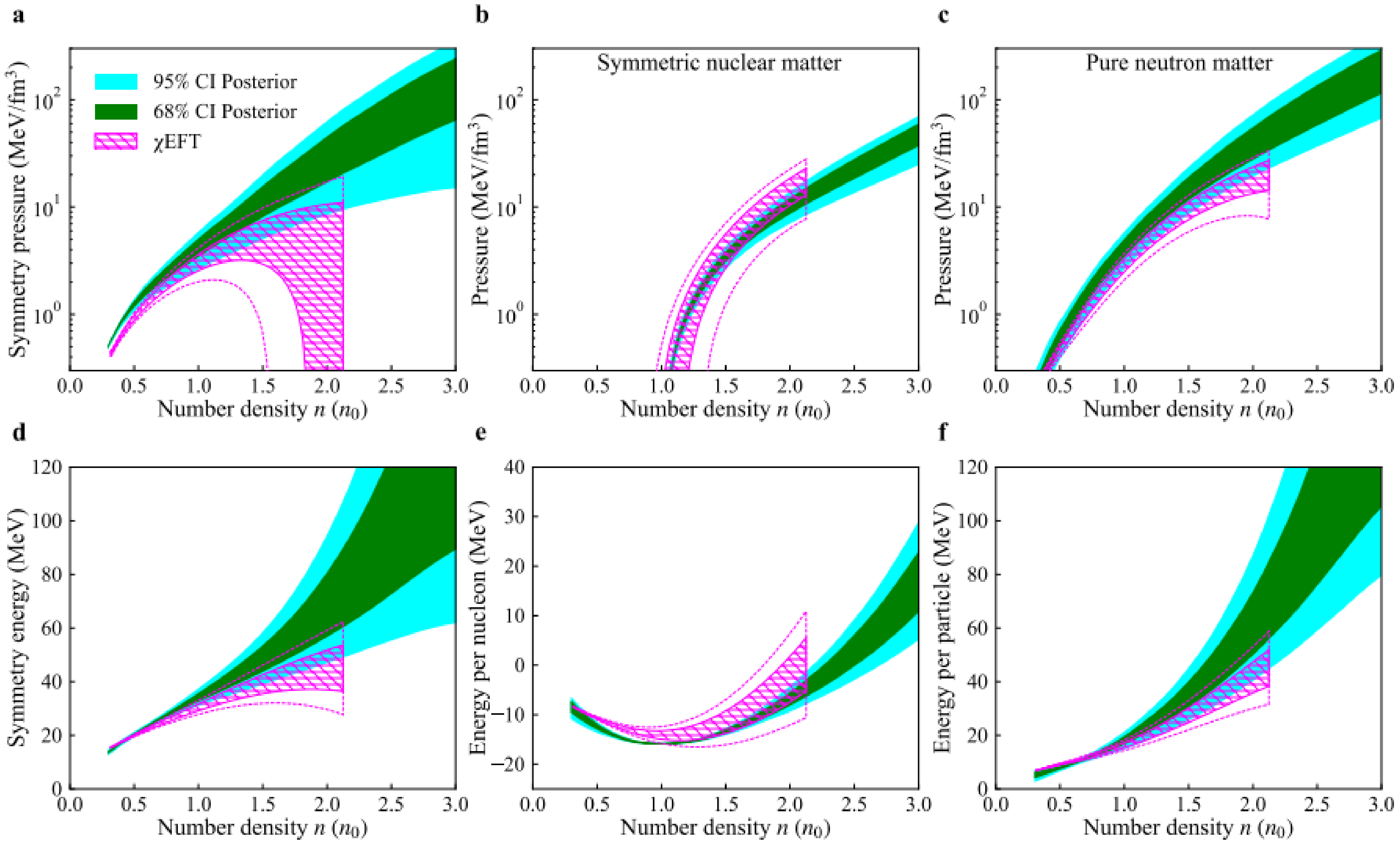
Legred et al., Phys. Rev. D 104, 063003 (2021)
Non paramateric model+ Astro only

Some comparisons



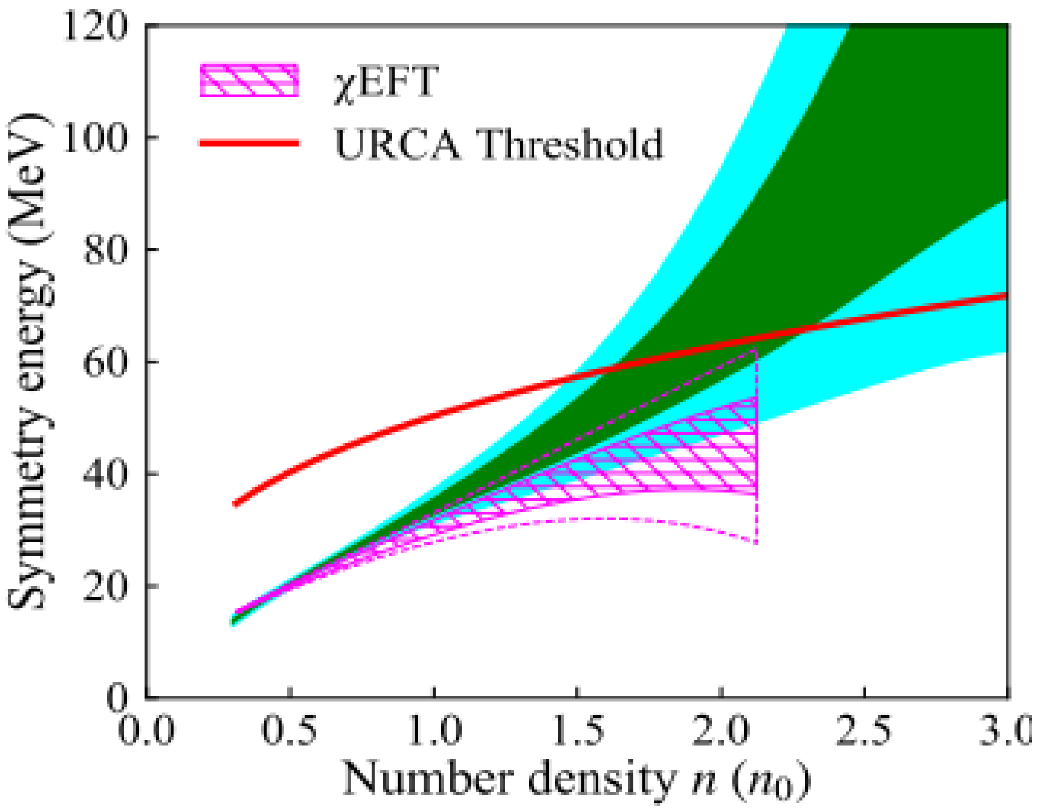
Radius of 1.4 solar mass neutron star

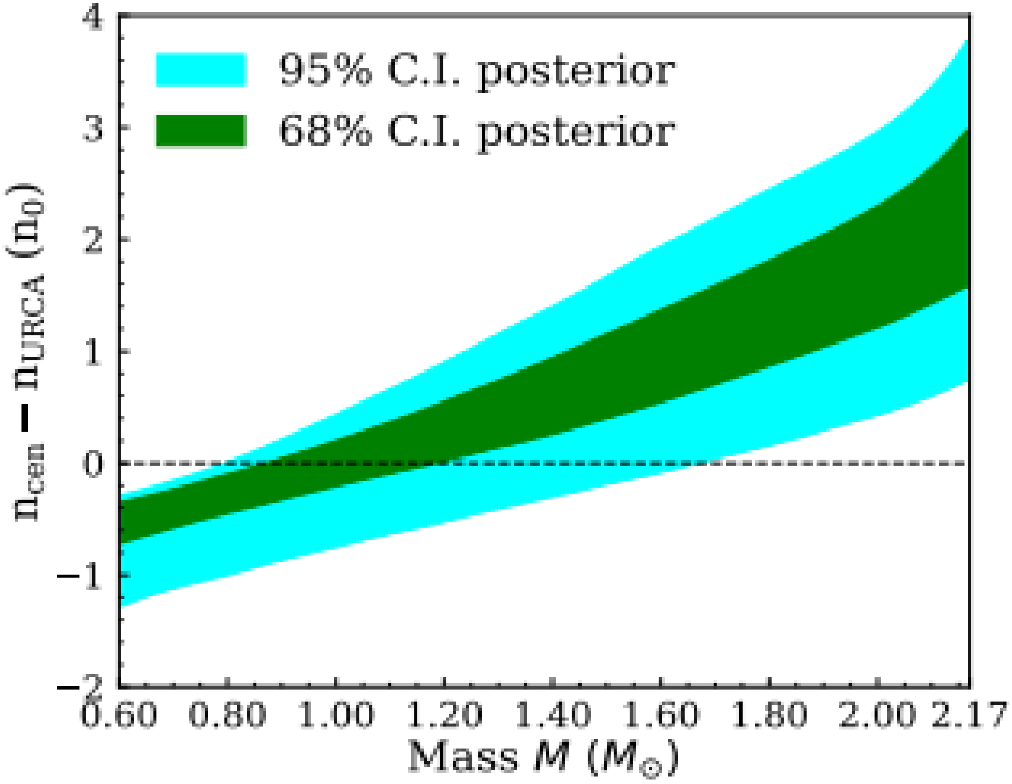
Comparisons with the Chiral Effective Field theory results



Drischler et al., PRL 125, 202702 (2020); PRC 102, 054315 (2020); PRL 122, 042501 (2019)

Neutron Star cooling by direct URCA process





Summary

- We have constrained the equation of state using the existing constraints from nuclear structure, masses, monopole resonance studies, heavy-ion collision studies and astrophysics observations.
- Theories can use these results as benchmarking equation of state for future developments
- We need better constraints at supra-saturation densities
- We need to improve on transport models to reduce the uncertainties in predictions

Thanks for your attention !!!