Constraining Neutron-Star Matter Combination of heavy-ion experiments and multi-messenger astronomy

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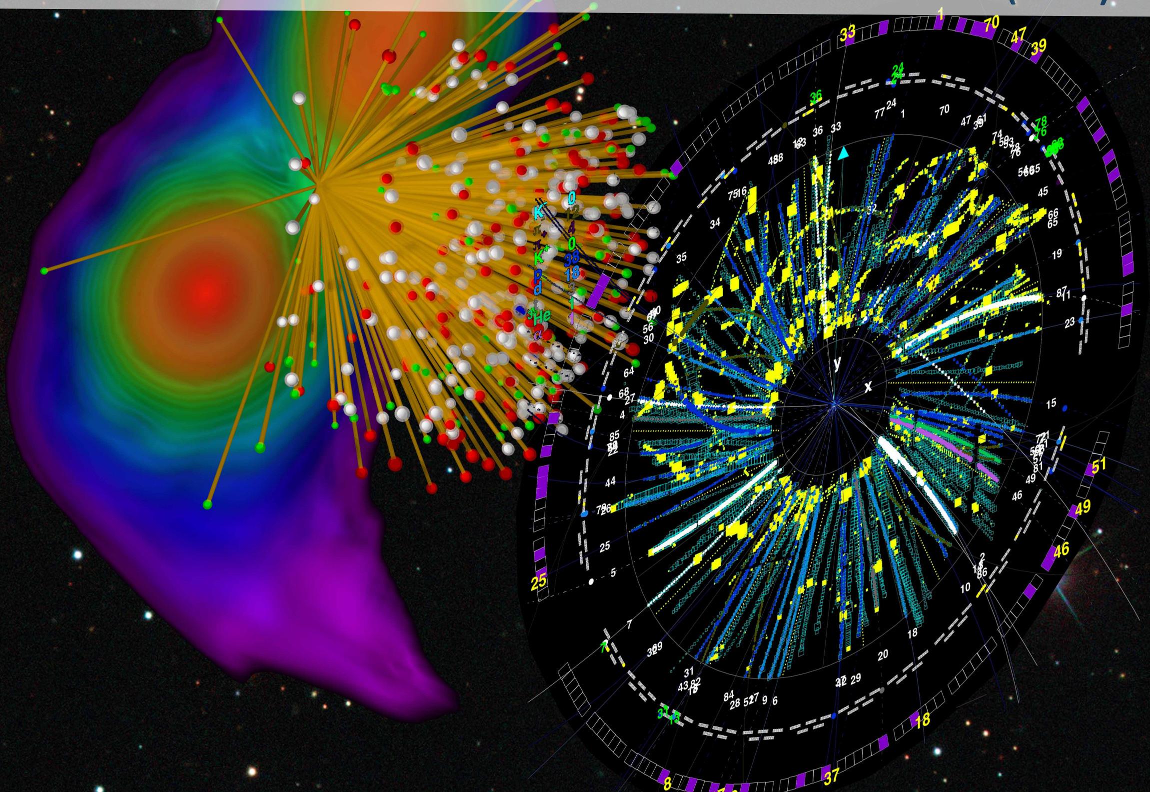

Picture: Tim Dietrich, Arnaud Le Fèvre, Kees Huyser; background: ESA/Hubble, Sloan Digital Sky Survey

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- Nuclear theory input (chiral effective field theory for nuclear forces)
- Multi-messenger astrophysics information
- Data from HIC experiments
- Final constraints on the pressure and the radius of neutron stars
- HIC input perspectives: Towards larger densities and improved

Picture: Tim Dietrich, Arnaud Le Fèvre, Kees Huyser; background: ESA/Hubble, Sloan Digital Sky Survey

GSI press release on June 8, 2022

New insights into neutron star matter — Combining heavy-ion experiments, astrophysical observations, and nuclear theory

Article

Nature 606, 276 (2022)

Constraining neutron-star matter with microscopic and macroscopic collisions

https://doi.org/10.1038/s41586-022-04750-w

Received: 13 July 2021

Accepted: 11 April 2022

Published online: 8 June 2022

Open access

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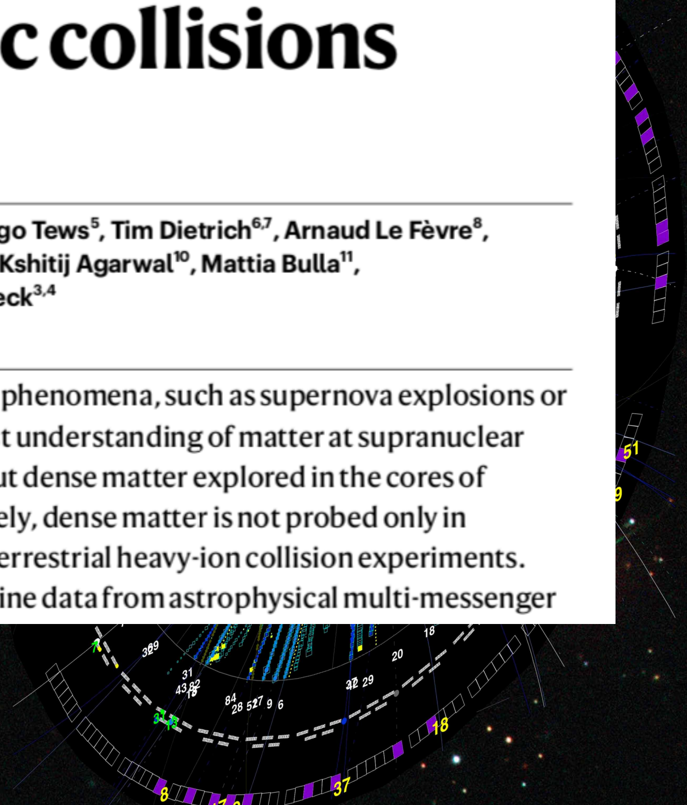
Interpreting high-energy, astrophysical phenomena, such as supernova explosions or neutron-star collisions, requires a robust understanding of matter at supranuclear densities. However, our knowledge about dense matter explored in the cores of neutron stars remains limited. Fortunately, dense matter is not probed only in astrophysical observations, but also in terrestrial heavy-ion collision experiments. Here we use Bayesian inference to combine data from astrophysical multi-messenger



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New insights into neutron star matter — Combining heavy-ion experiments, astrophysical observations, and nuclear theory

11 authors and their recent work

Sabrina Huth, Achim Schwenk:
New equations of state constrained by nuclear physics, observations, and QCD calculations of high-density nuclear matter,
PRC 103, 025803 (2021) (with C. Wellenhofer) ($R_{1.4\odot}$ = 12.35 km)

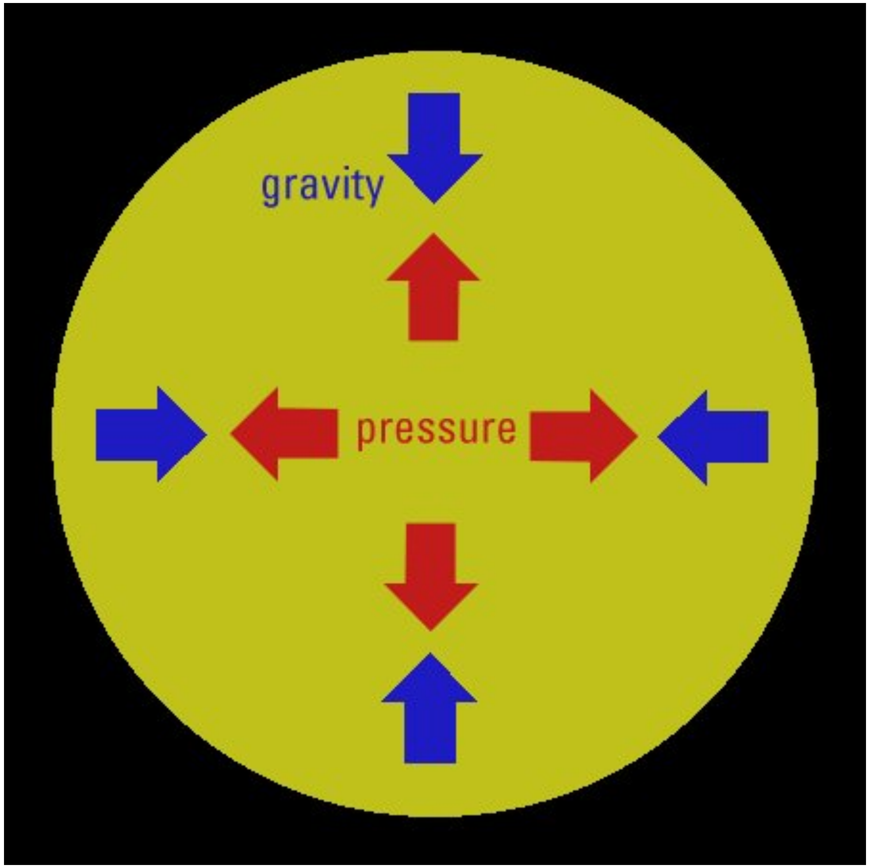
Peter T. H. Pang, Ingo Tews, Michael W. Coughlin, Mattia Bulla, Chris Van Den Broeck, Tim Dietrich:
Nuclear Physics Multimessenger Astrophysics Constraints on the Neutron Star Equation of State: Adding NICER's PSR J0740+6620 Measurement,
ApJ 922, 14 (2021) ($R_{1.4\odot}$ = 11.94 km)

Arnaud Le Fèvre (FOPI, IQMD), Wolfgang Trautmann (ASY-EOS), Kshitij Agarwal (CBM)

Picture: Tim Dietrich, Arnaud Le Fèvre, Kees Huyser; background: ESA/Hubble, Sloan Digital Sky Survey

Why are stars stable?

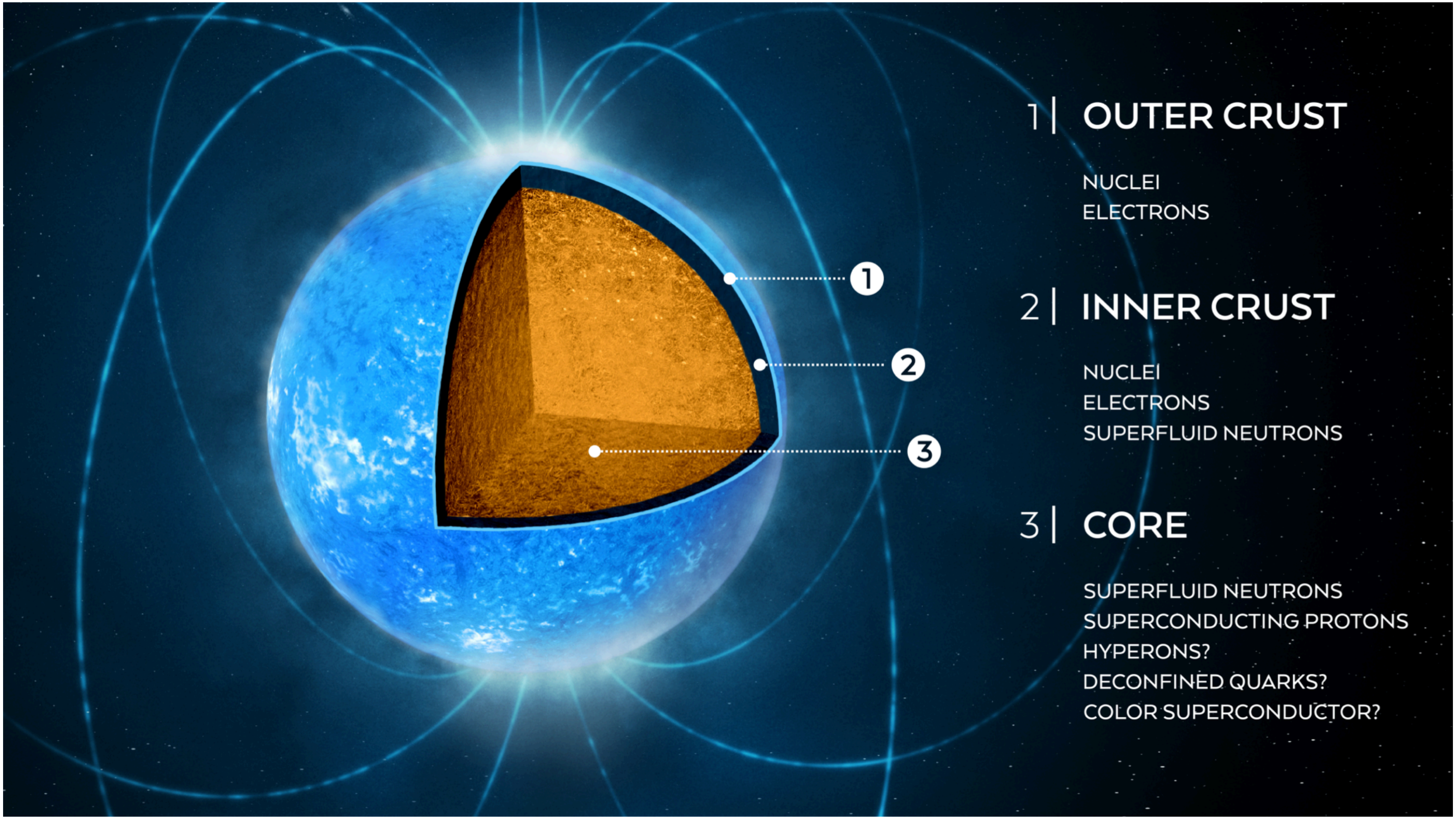
- Due to their mass, stars would undergo gravitational collapse
- Stabilised by the pressure of matter they consist of:
  equation of state → hydrostatic equilibrium



For neutrons:
pressure of Fermi gas
plus strong interactions

Extreme matter in neutron stars

Governed by the same strong interactions



Watts et al., RMP (2016)

Outline

What is new:
mass **and** radius of PSR J0740+6620 (Riley+, Miller+ 2021)

What existed:
framework for Bayesian inference with χEFT prior
informed by results of astrophysical observations (Dietrich+ 2020)

What was combined:
results from heavy-ion collisions (HIC) added into framework

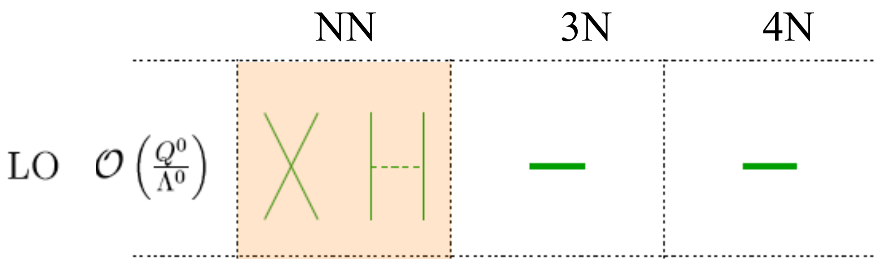
What was found: $R_{1.4\odot} = 12.01 \pm 0.78$ **km (95%)**
Measurements of HIC predict properties
of neutron stars that are **consistent** with those informed
by astrophysical observations

Merging HIC and astro results leads to **slight increase** (+0.26 km)
over the previously predicted value for the radius of a 1.4 solar mass
neutron star which is supported by the recent observations of **NICER**

New HIC results can be important!

Chiral effective field theory for nuclear forces

Systematic momentum expansion of nuclear forces (power counting) in low momenta $(Q/\Lambda)^n$



- Based on symmetries of strong interaction (QCD) between nucleons
- Long-range interactions governed by pion exchanges
- Expansion enables estimates of theoretical uncertainties
- Use of quantum Monte Carlo methods, which are among the most precise many-body methods to solve the nuclear many-body problem

Weinberg (1990,91)

Chiral effective field theory for nuclear forces

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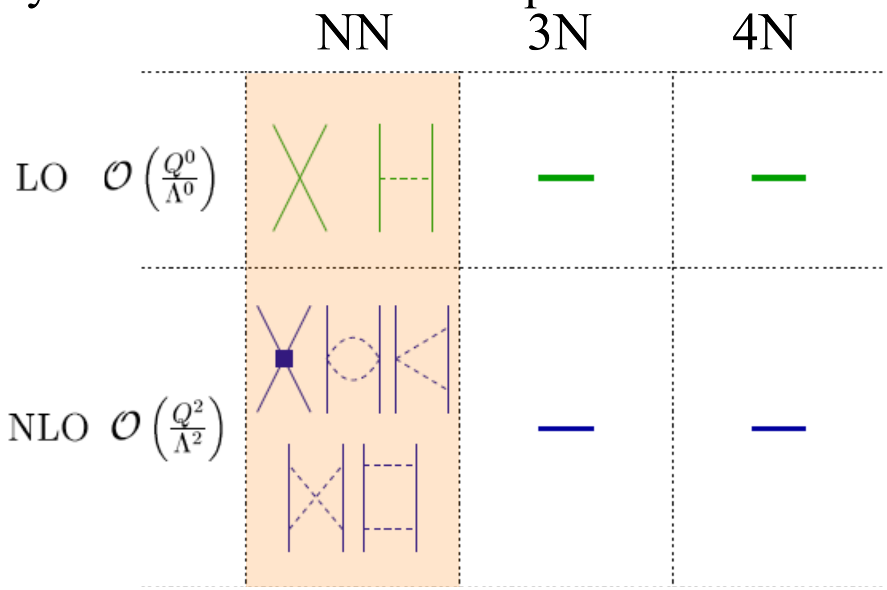

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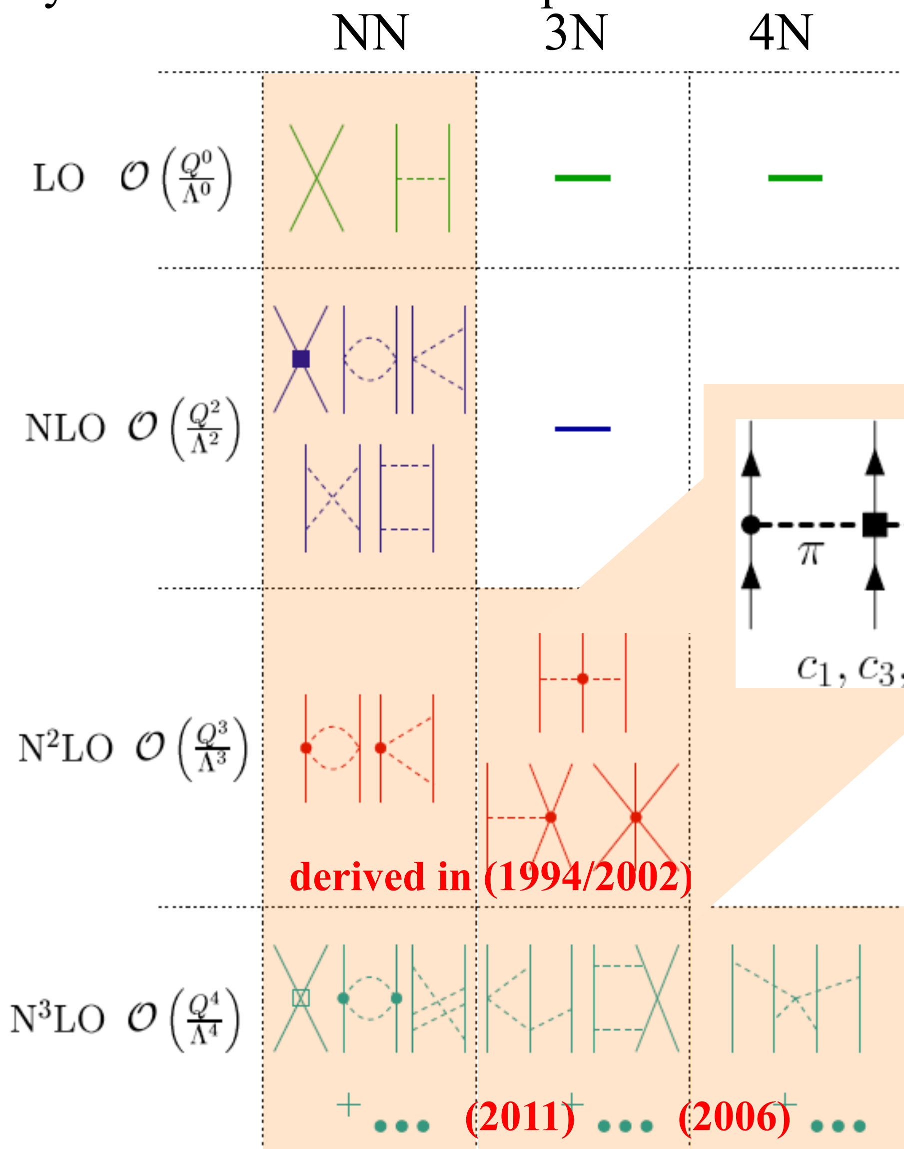
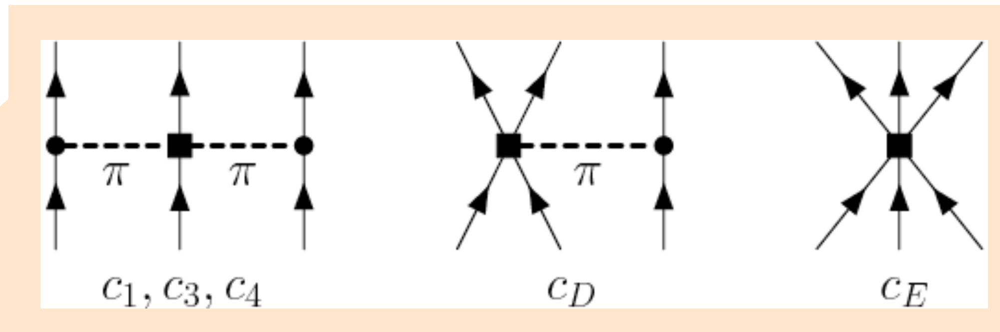


powerful approach for many-body interactions



only 2 new couplings at N^{2}LO

all 3- and 4-neutron forces predicted to N^{3}LO

Weinberg, **van Kolck (1992-1994),** Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Meissner,…

GSI FAIR HELMHOLTZ ASSOCIATION

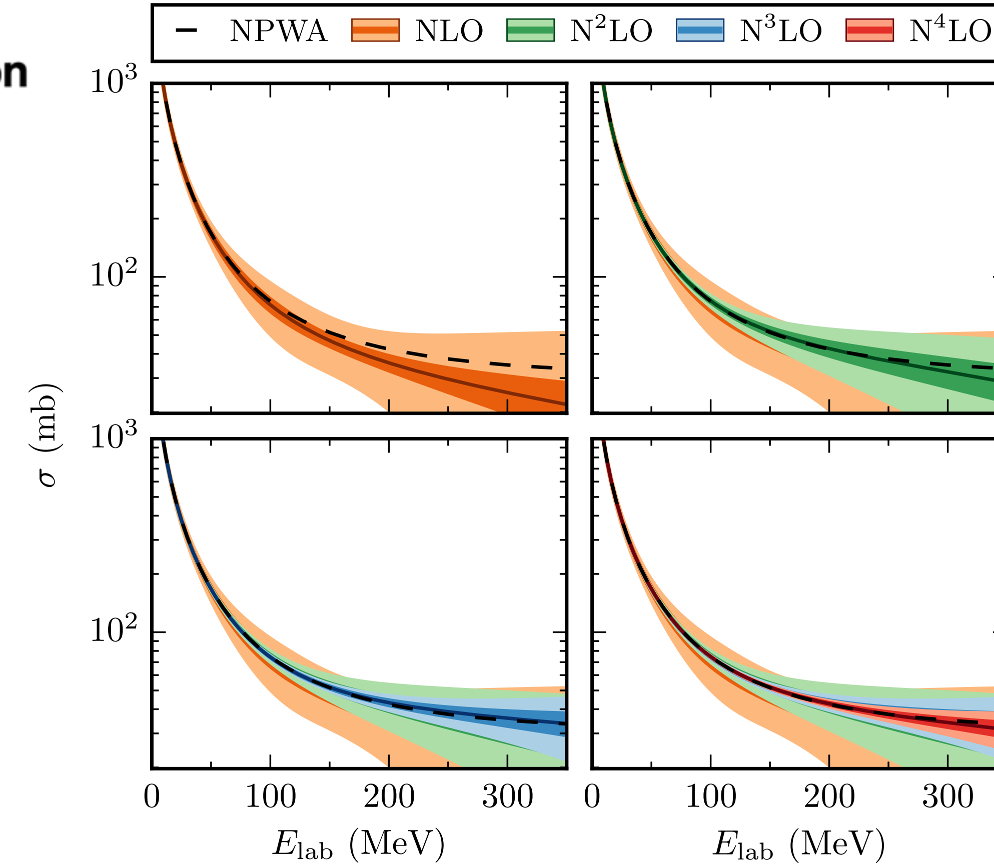
Chiral EFT calculations of neutron matter

IOP Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 42 (2015) 034028 (20pp) doi:10.1088/0954-3899/42/3/034028

A recipe for EFT uncertainty quantification in nuclear physics

R J Furnstahl[1], D R Phillips[2] and S Wesolowski[1]

Bayesian uncertainty estimates and model checking



Furnstahl, Phillips, Klos, Wesolowski, Melendez (2015-)

Chiral EFT calculations of neutron matter

How is built the prior of the Bayesian analysis (quasi-Monte-Carlo results):

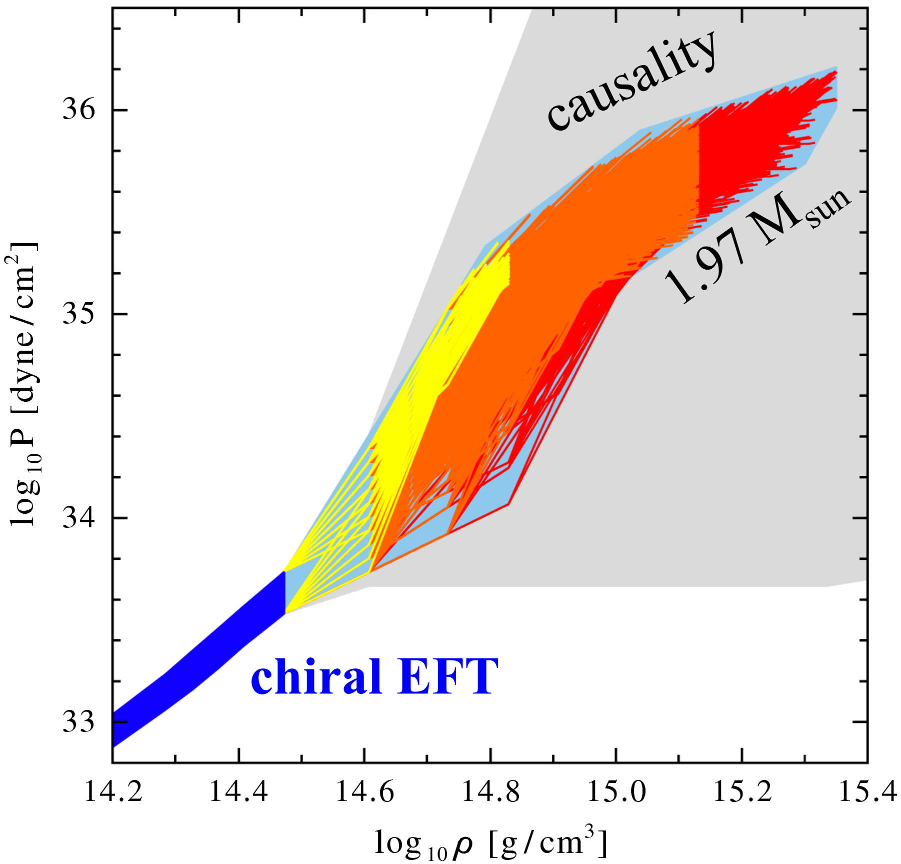
1. Generate a set of 15,000 EOSs that are constrained by nuclear theory calculations at low densities (local chiral EFT interactions) → span the theoretical uncertainty range of the chiral EFT calculation.
2. Based on local chiral 2- and 3-nucleon interactions.
3. Breakdown scale of the chiral EFT expansion ~500-600 MeV/c.

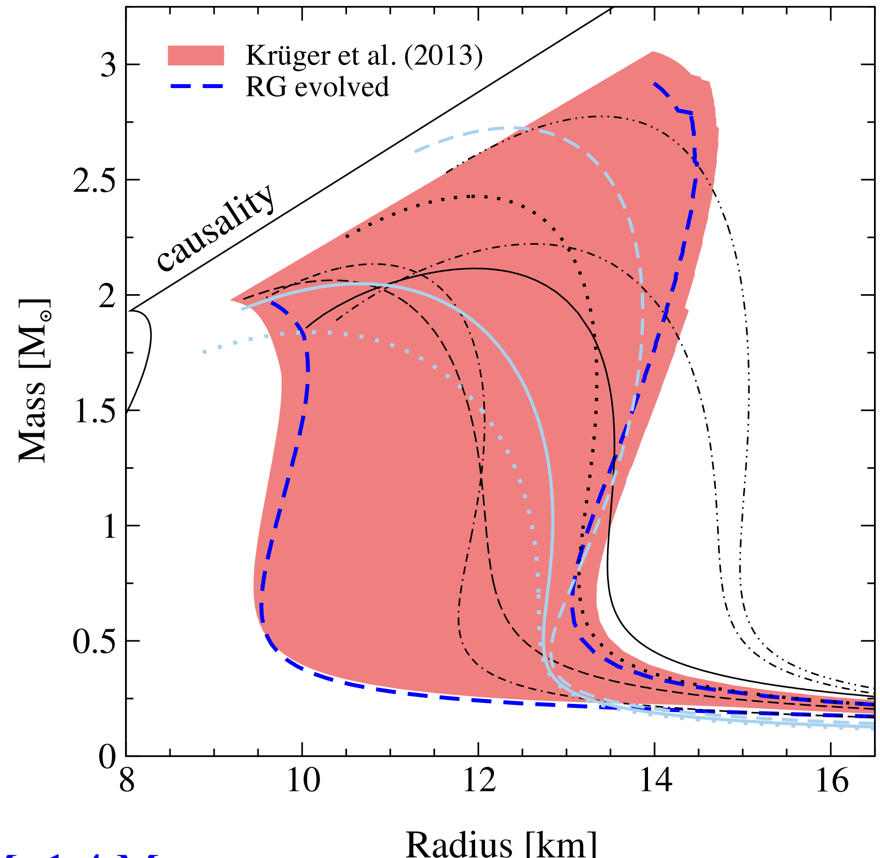
   ⇒ constrain our EOS set using chiral EFT input only up to $1.5\rho_0$ (corresponding to Fermi momenta of ~ 400 MeV/c)
4. But a variation within 1-2 ρ_0 shows no substantial impact on our final results for neutron-star radii.
5. Extend each EOS above $1.5\rho_0$ using an extrapolation in the speed of sound (c_s) in neutron-star matter, with constraints of causality ($c_s \leq c$) and stability of neutron-star matter ($c_s > 0$).
6. Allow EOSs implying $M_{NS} \geq 1.9\ M_\odot$, to remove EOSs to support combined observations of heavy pulsars.
7. The EOS prior is then used to analyse astrophysical observations and HIC experiments.

Impact on neutron stars

Hebeler et al., PRL (2010), ApJ (2013)

- Constrain high-density EOS by causality, require to support 2 $M_\odot$ star



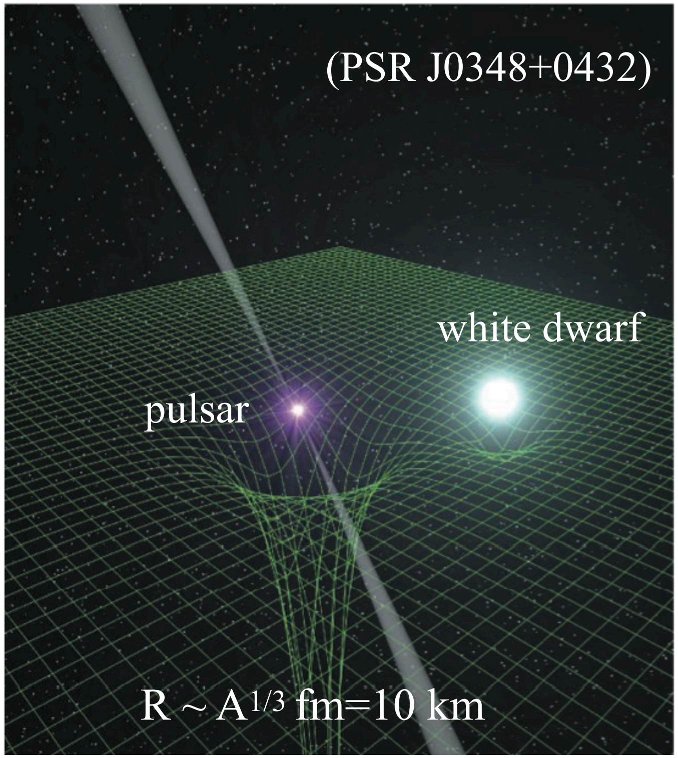


- Predicts neutron star radius: 9.7 - 13.9 km for M=1.4 $M_\odot$

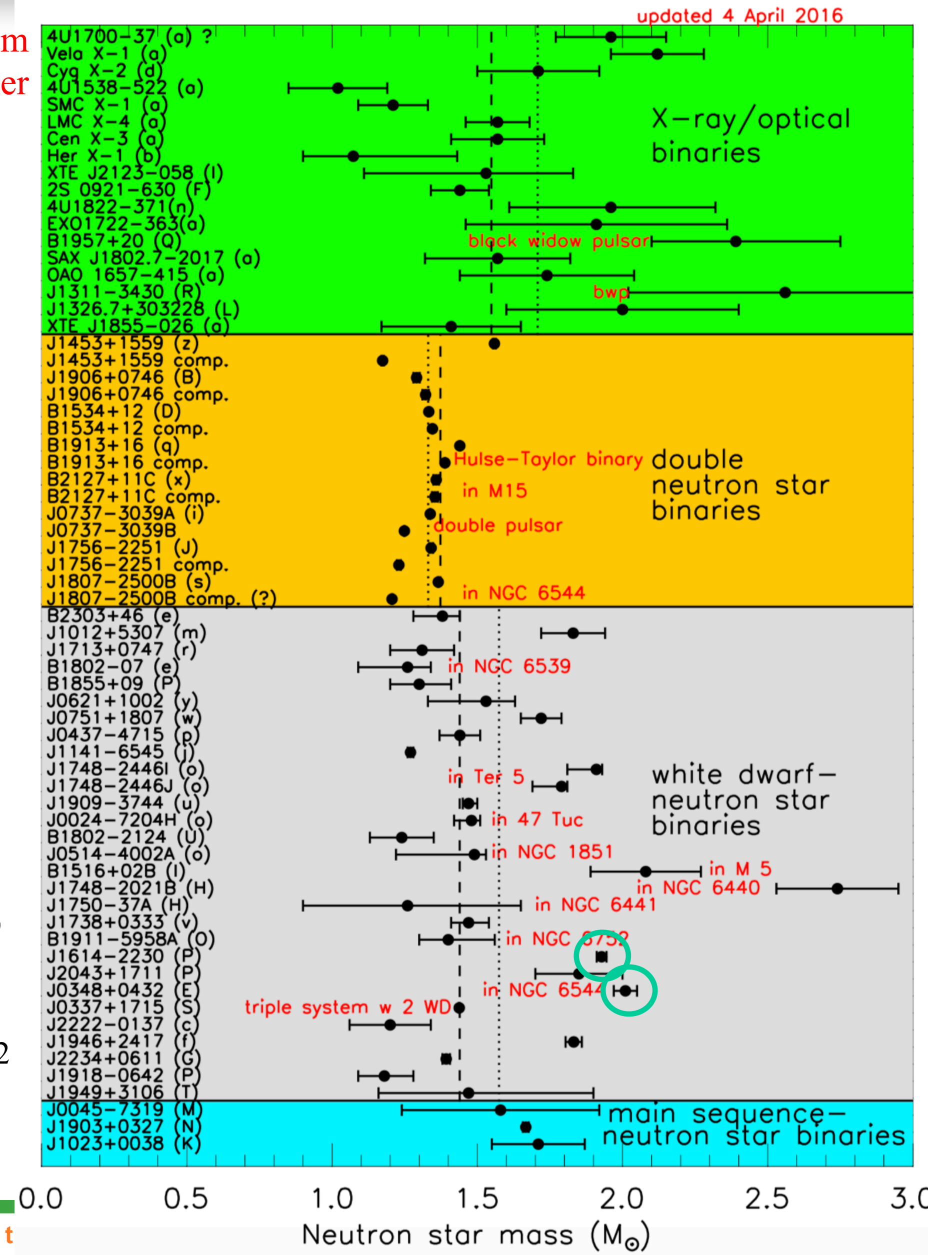
  1.8 - 4.4 ρ_0 modest central densities

- Speed of sound needs to exceed ~0.65c to get 2 $M_\odot$ stars Greif et al., ApJ (2020)

Multi-messenger astrophysics information: Neutron star masses



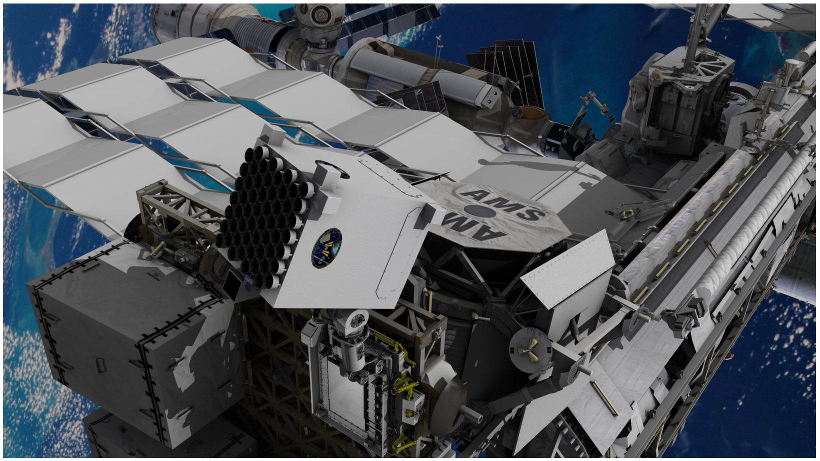
from
Jim Lattimer

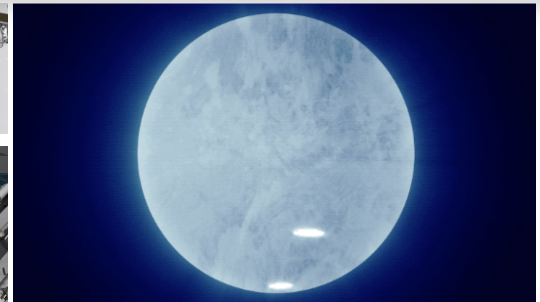


- three 2 $M_\odot$ neutron stars observed with high precision:

1. PSR J1614-223: 1.97 ± 0.04 $M_\odot$ (Demorest et al., *Nature* (2010))
2. PSR J0348+0432: 2.01 ± 0.04 $M_\odot$ (Antoniadis et al., *Science* (2013))
3. PSR J0740+6620 : 2.08 ± 0.07 $M_\odot$ (Fonseca et al., *ApJL* 915 L12 (2021))

NICER results





Neutron star radius from pulse profile modelling

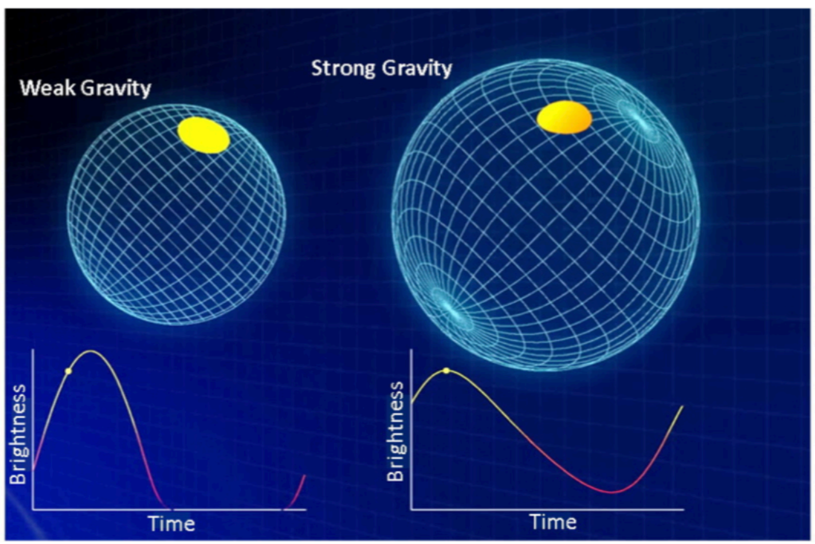
J0030 and J0740

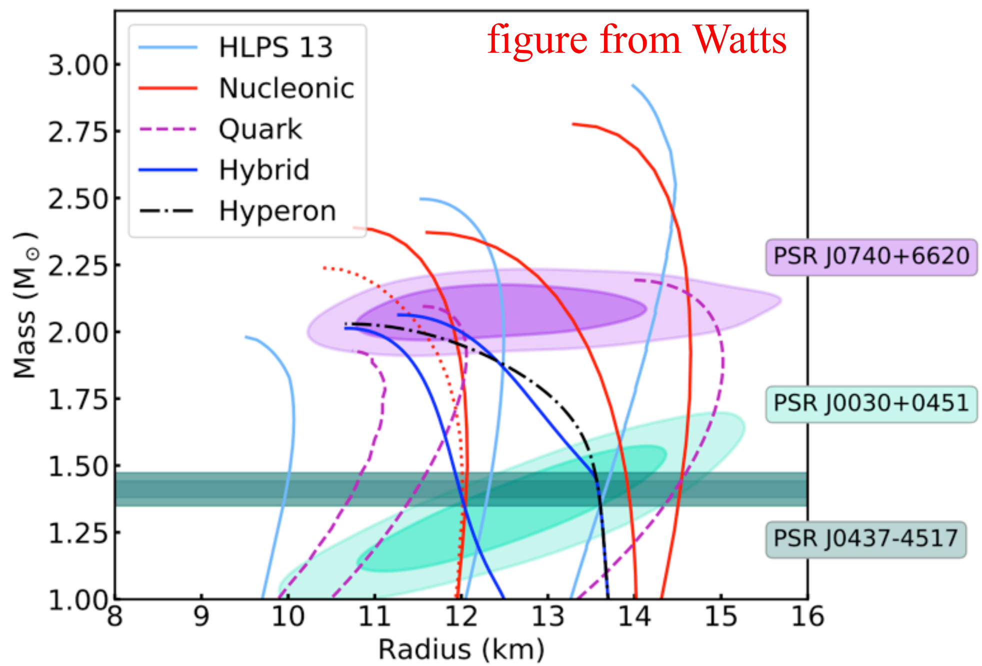
here: Amsterdam analysis

Riley et al., *ApJL* (2019), (2021)

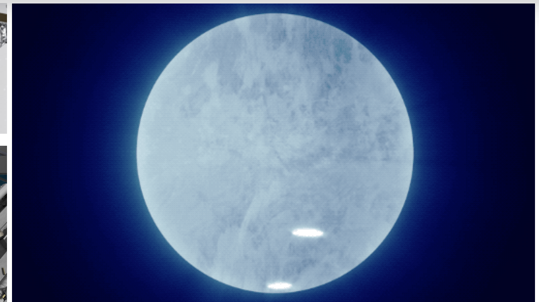
similar results from Illinois-Maryland analysis

Miller et al., *ApJL* (2019), (2021)





NICER results



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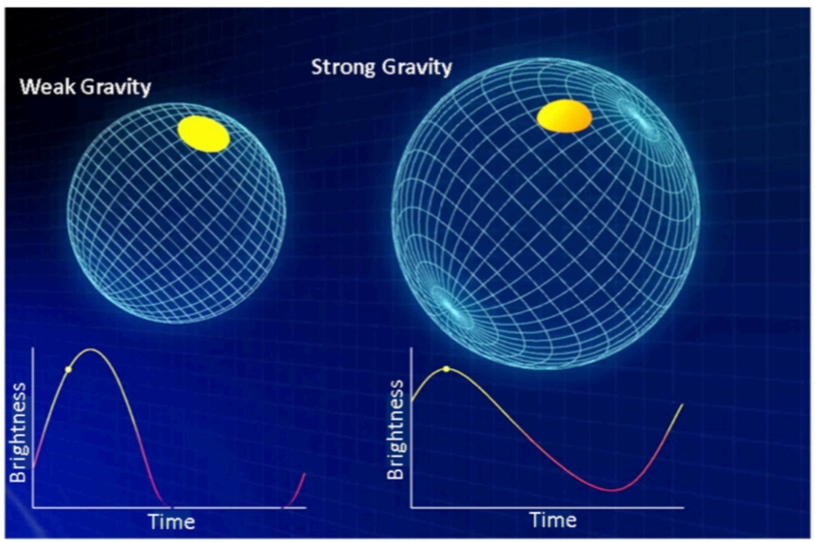

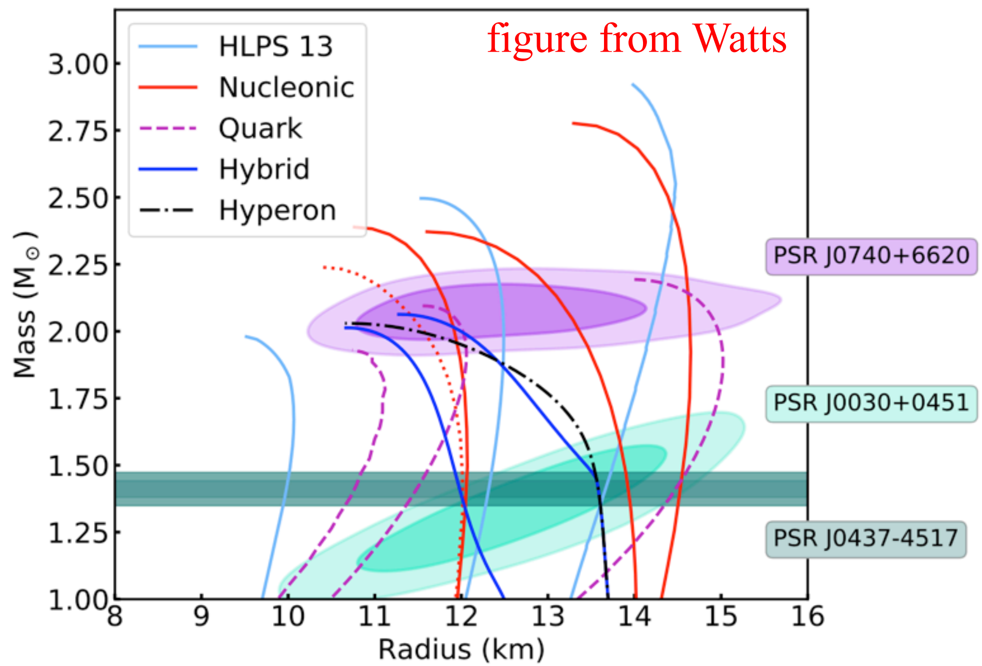

Multi-messenger astrophysics information

1. Mass measurements of the massive neutron stars PSR J0348+4042 and PSR J1614-2230
   → lower bound on the NS maximum mass
2. Binary neutron-star collision GW170817 in which a black hole was presumably formed after the coalescence maximum mass of neutron stars
   → upper bound on the maximum mass.
3. X-ray pulse-profile modelling of PSR J0030+0451 and PSR J0740+6620 using data from NICER and the X-ray Multi-Mirror Mission (XMM-Newton) are incorporated.
4. Bayesian inference techniques to analyse GW information from the 2 neutron-star mergers GW170817 and GW190425 by matching the observed GW data with theoretical GW models that depend on neutron-star properties.
5. Kilonova AT2017gfo associated with the GW signal. Kilonovae originate from the radioactive decay of heavy atomic nuclei created in nucleosynthesis processes during and after the merger of neutron stars, and are visible in the optical, infrared, and ultraviolet spectra. The EM observations are analysed with full radiative transfer simulations to extract information from the observed light curve and spectra.

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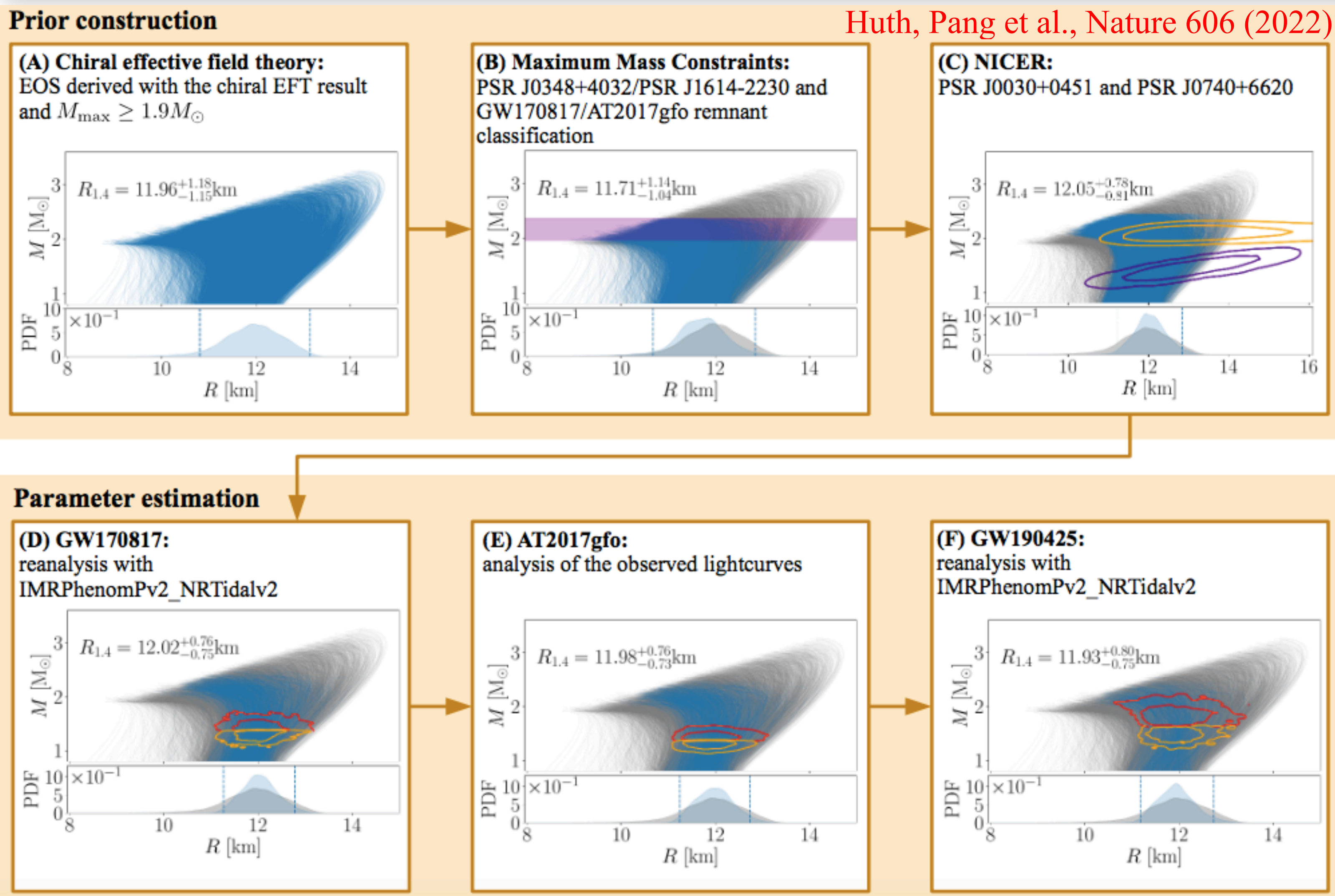
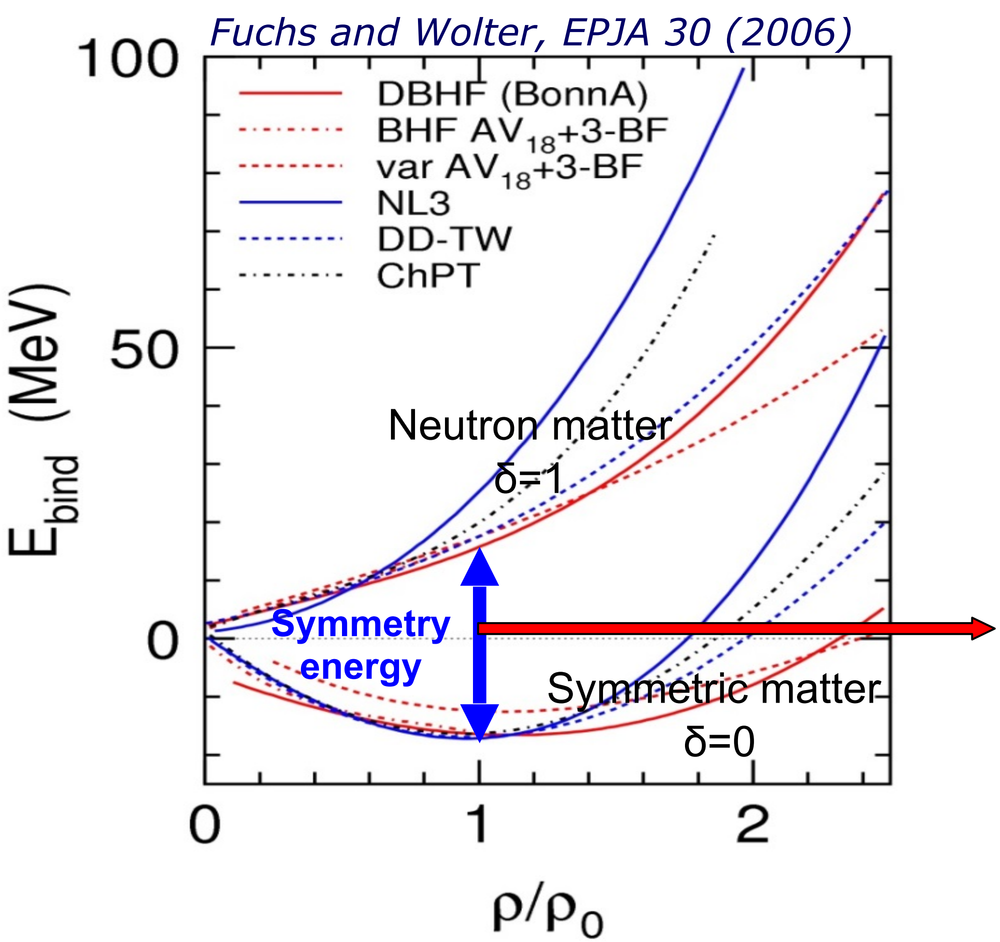
Multi-messenger astrophysics information



Constraints are strongest above 1.5ρ₀, where the extrapolation in the speed of sound is used for the EOSs. The **high-density astrophysical constraints affect mostly the high-mass region** in the mass-radius plane and **exclude the stiffest EOSs that lead to the largest radii**.

Constraints from heavy-ion collisions

The equation-of-state of nuclear matter



EOS in thermodynamics pressure P(ρ,T)

$$P = \rho^2 \frac{\partial E/A}{\partial \rho}\Big|_{T=const}$$

Nuclear physics EOS

$$\frac{E}{A} = E/A(\rho)\Big|_{T=0}$$

Nuclear incompressibility K

$$K = 9\rho^2 \frac{\partial^2 E/A}{\partial^2 \rho}\Big|_{\rho=\rho_0}$$

Asymmetry parameter $\delta = \dfrac{\rho_n - \rho_p}{\rho_n + \rho_p}$

Symmetry energy E_{sym}

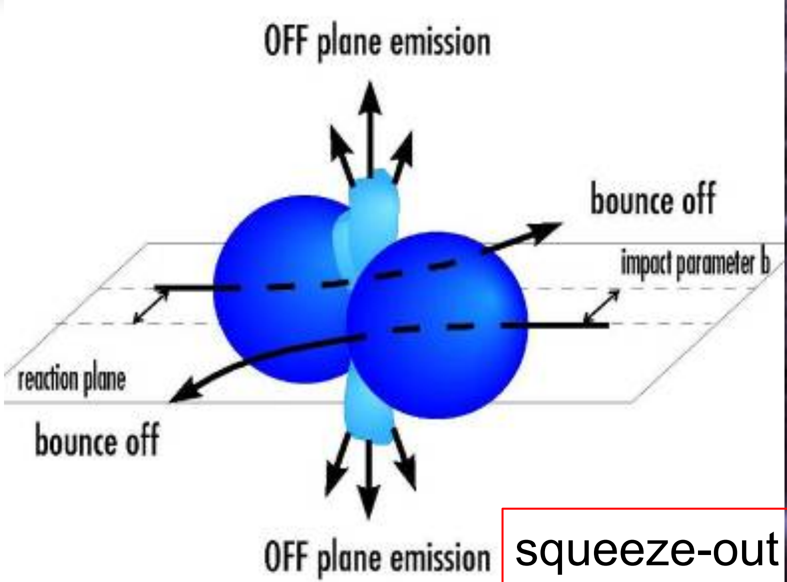
$$E(\rho,\ \delta) = E_{SNM}(\rho, \delta = 0) + \delta^2 E_{sym}(\rho) + O(\delta^4)$$

mit

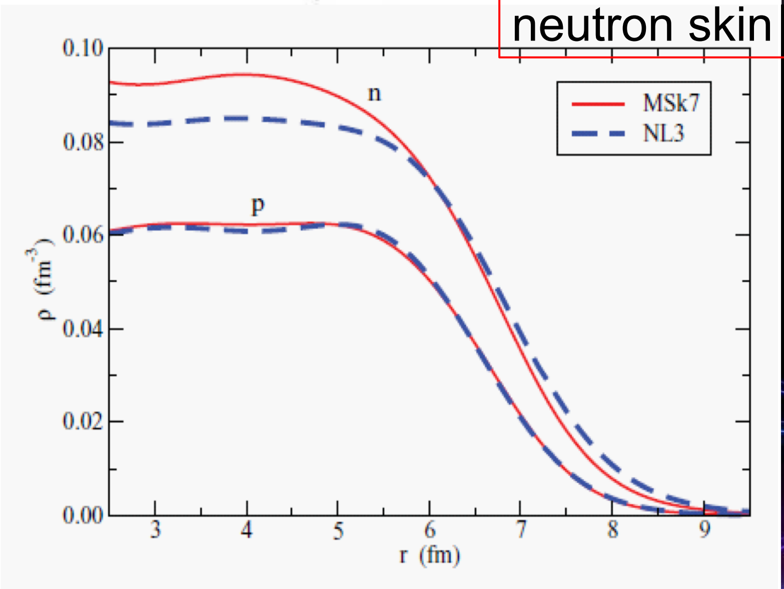
$$E_{sym} = E_{sym,0} + \frac{L}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \ldots$$

Slope $L = 3\rho_0 \dfrac{\partial E_{sym}}{\partial \rho}$

Constraints from heavy-ion collisions



squeeze-out tidal deformation
neutron skin neutron star radius



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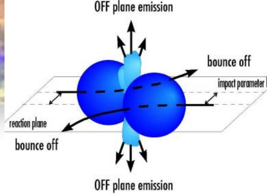
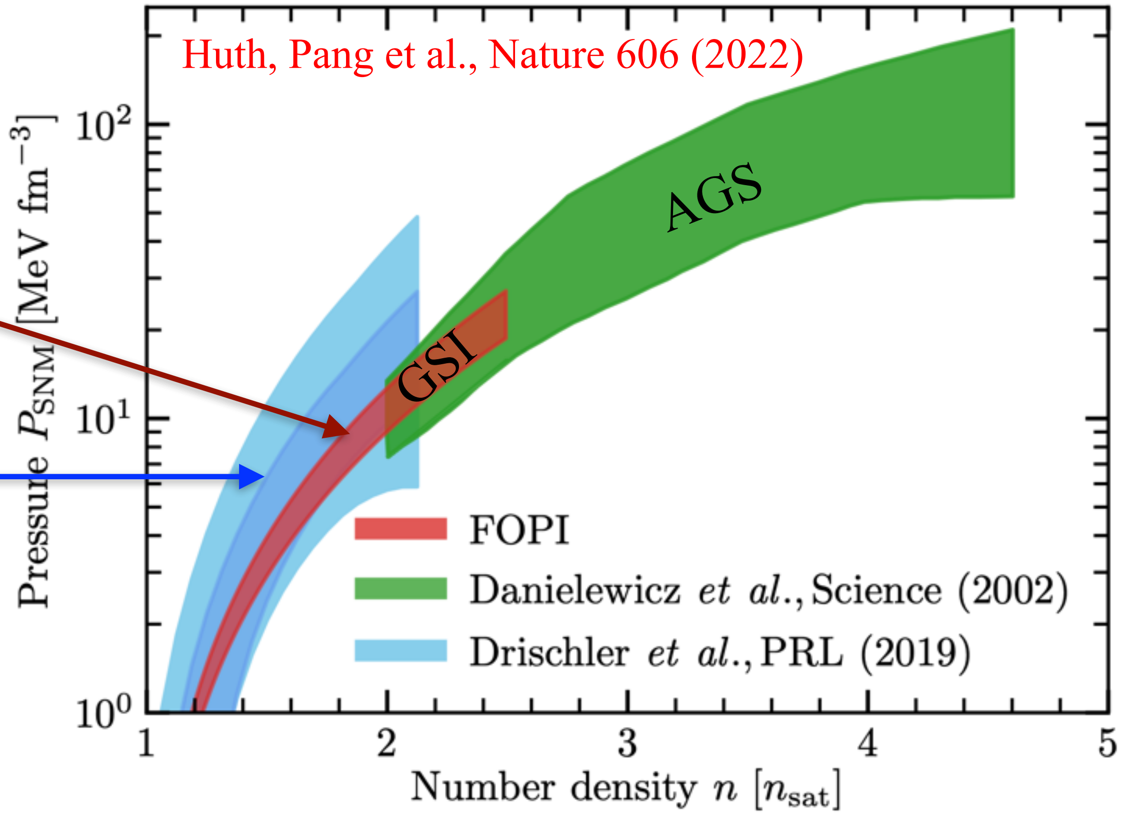


HIC contraints from **elliptic flow** of p, d, t, ^{3}He, ^{4}He
in Au+Au @ 250-1500A MeV

Symmetric matter contribution

FOPI result (1σ)
K_0=200±25 MeV

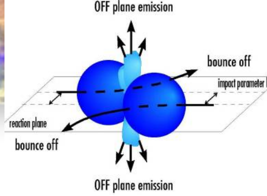
Drischler
N^{2}LO (light blue)
N^{3}LO (dark blue)



FOPI result obtained with

- **IQMD**: Skyrme +Yukawa +V_{mdi} +V_{sym} +V_{Coul} (4 options S, SM, H, HM)
  K_0 = 190±30 MeV   Le Fèvre et al., NPA 945, 112 (2016)
- **UrQMD**: 3 Skyrme forces Skxs15, MSK1, and SKX (similar S_0, L, different K_0)
  K_0 = 220±40 MeV   Yongjia Wang et al., PLB 778, 207 (2018)

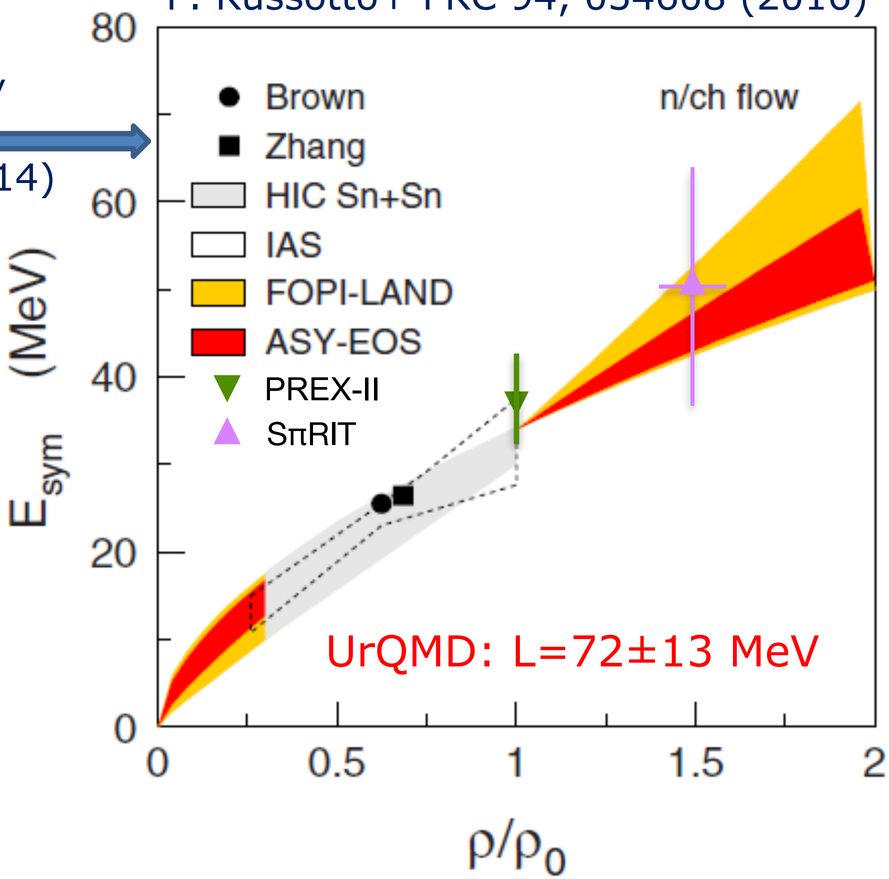
Constraints from heavy-ion collisions



HIC constraint from **elliptic flow** of **neutrons** and **light charged particles** in Au+Au @ 400A MeV

Asymmetric matter contribution

compiled by Horowitz+ JPhysG (2014)

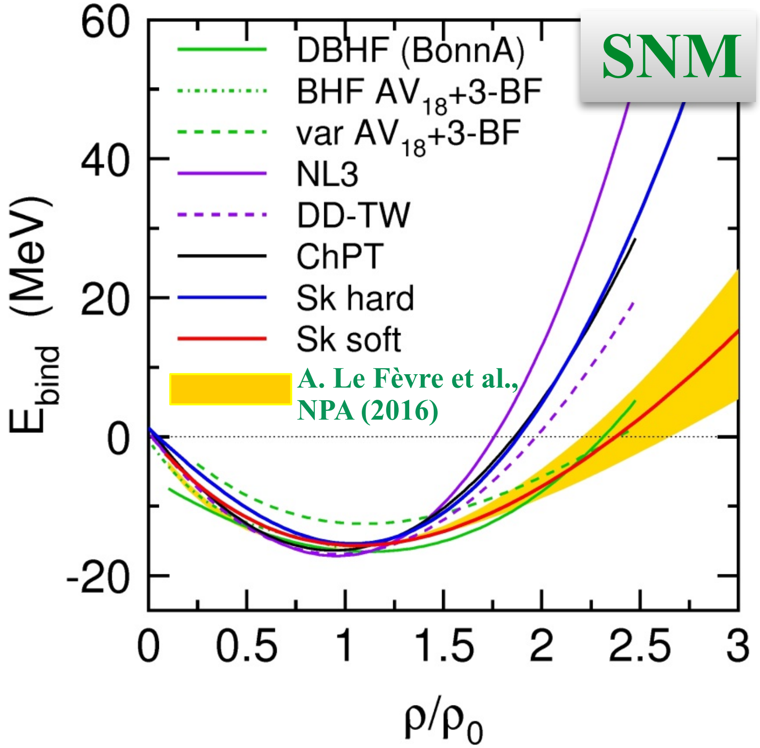


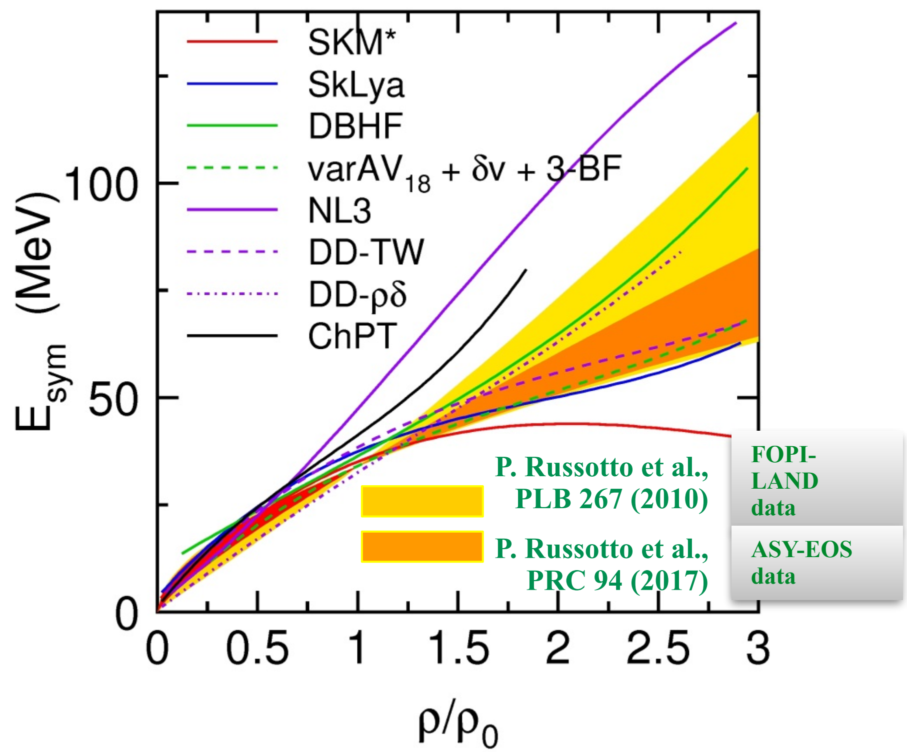
$E_{sym}(\rho_0)$ = 31 MeV => L= 63±11 MeV

S_0=34 MeV consistent with S(0.6 ρ_0)

Constraints from heavy-ion collisions

Synthesis at high densities of newest and most accurate HIC constraints





- equation of state of symmetric nuclear matter (SNM): FOPI (and KAOS)
- asymmetry energy: ASY-EOS
  - can be constrained by the systematic study of comparison of the flow of neutrons, protons and charged particles

Constraints from heavy-ion collisions

How can we combine FOPI, ASY-EOS and ALADiN results
to deduce the pressure in a neutron star?

- Have $(P_{NN}(K_0)+P_{asy}(L))\delta$
  δ = 0.9(5% protons + degenerate e^-)
- L as from ASY-EOS at 1-2ρ_0
- L as from ALADiN at 0.7ρ_0 (preliminary)
- K_0 as from FOPI flow data

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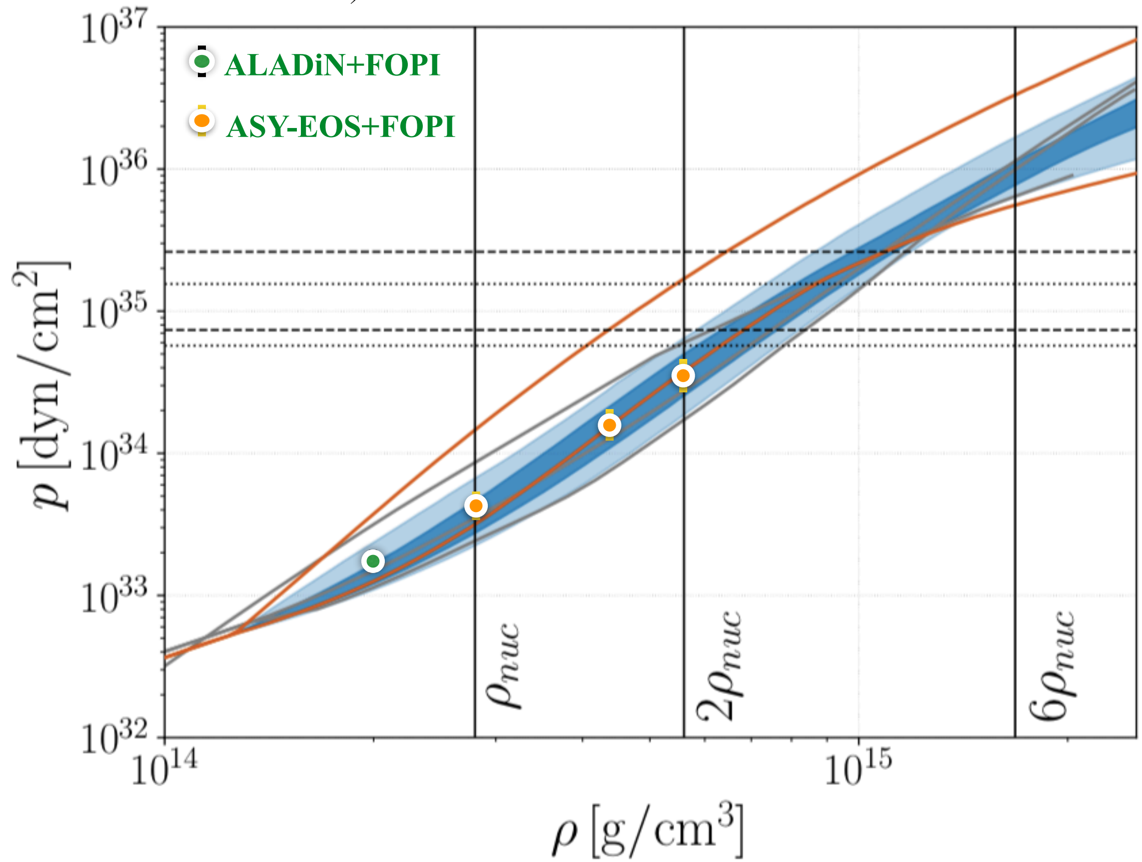
Gravitational Wave 170817
B. P. Abbott et al. (The LIGO Scientific Collaboration and the Virgo Collaboration)



Constraints from heavy-ion collisions

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

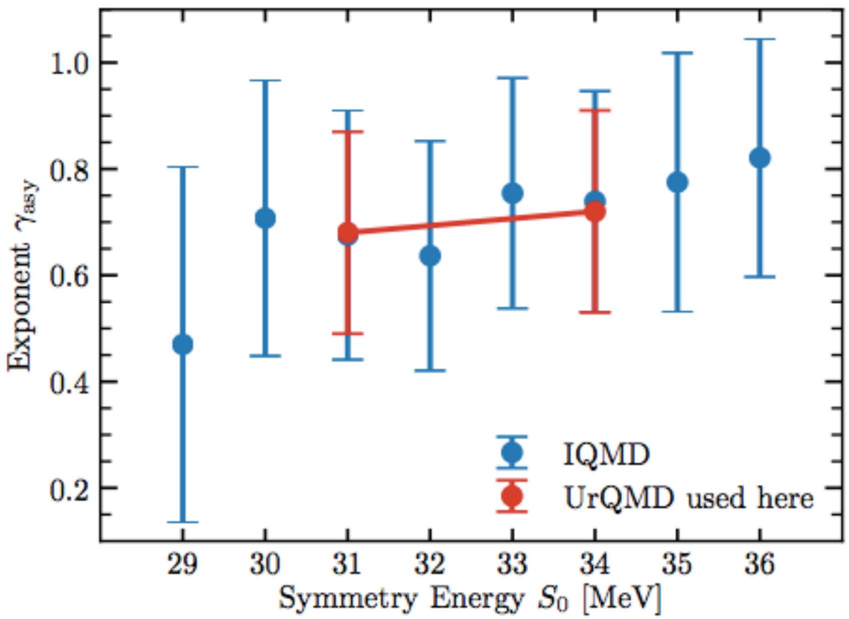
Introducing in the HIC prior a series of EoS samples according to intervals of variation of γ_{asy}, S_0, K_0

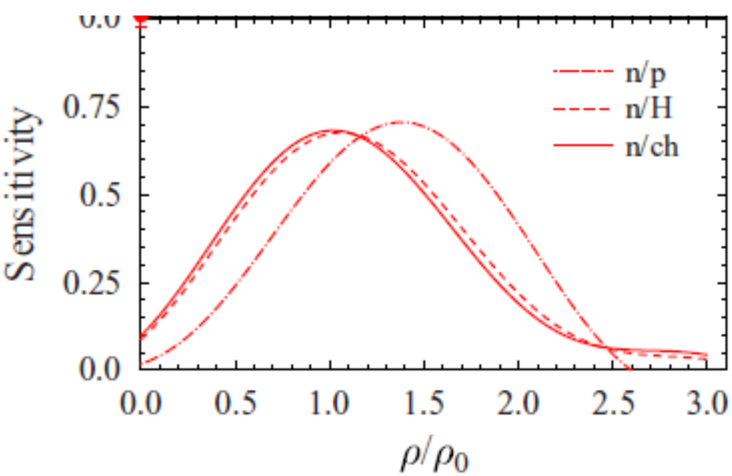
with a weight following the density sensitivity curve constrained by ASY-EOS (more limited than that of FOPI+AGS)

$$E_{asy} = E^{pot}_{asy} + E^{kin}_{asy} = E^{pot}_0 (\frac{\rho}{\rho_0})^{\gamma} + E^{kin}_0 (\frac{\rho}{\rho_0})^{2/3}$$

$$S_0 = E^{pot}_0 + E^{kin}_0$$

ASY-EOS data constraint (Au+Au @ 400A MeV)





density probed extends to 2.5 ρ_0

maximum near **saturation density**

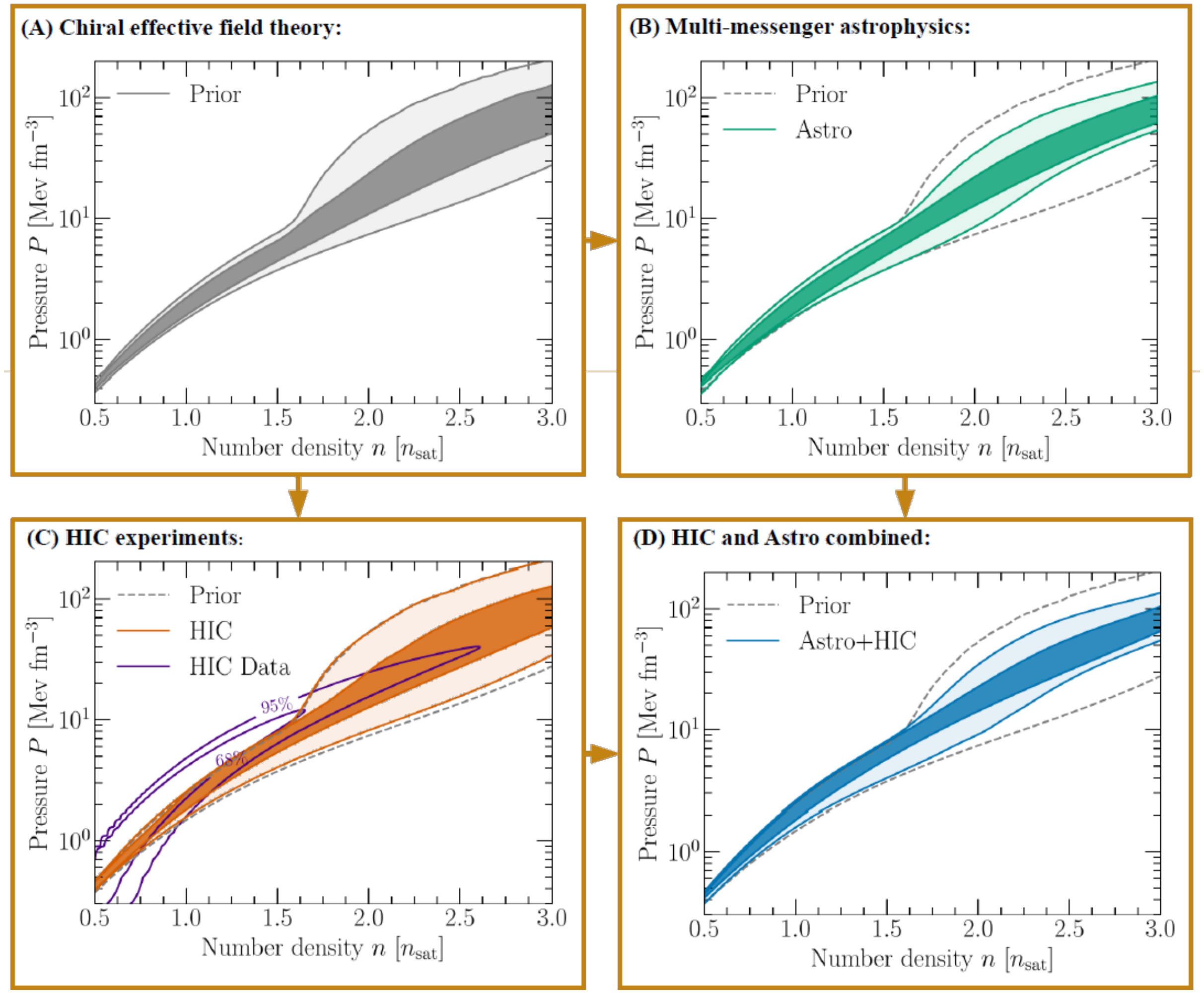
→ Linear relation between γ_{asy} and S_0

Constraints from heavy-ion collisions

Combining astronomical multimessengers and HIC's within the same bayesian analysis to constrain the neutron star matter EoS:

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

« HIC » = FOPI+ASY-EOS+AGS - « Astro » = GW, NICER (pulsar X-ray hot spots)



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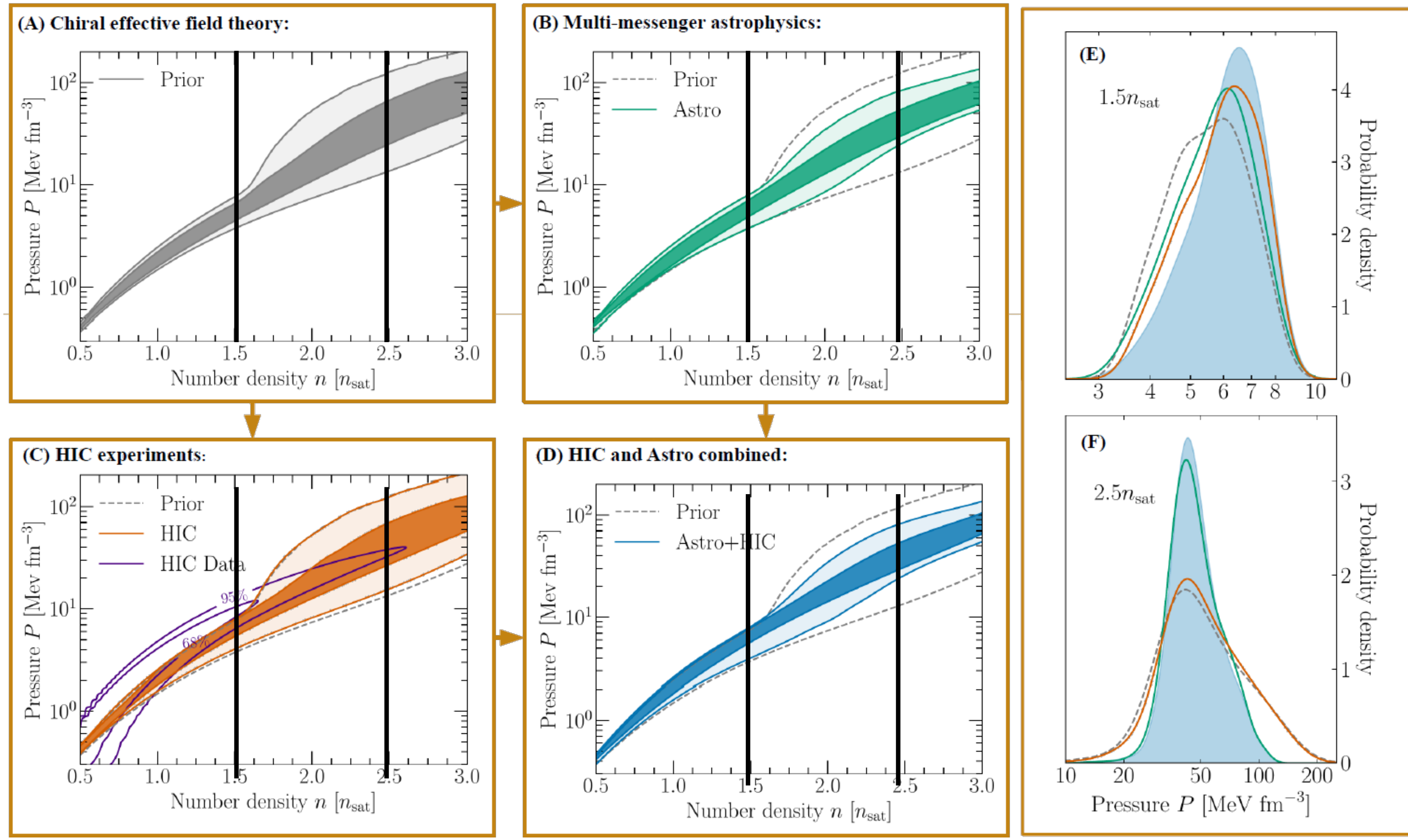

Constraints from heavy-ion collisions

Combining astronomical multimessengers and HIC's within the same bayesian analysis to constrain the neutron star matter EoS:

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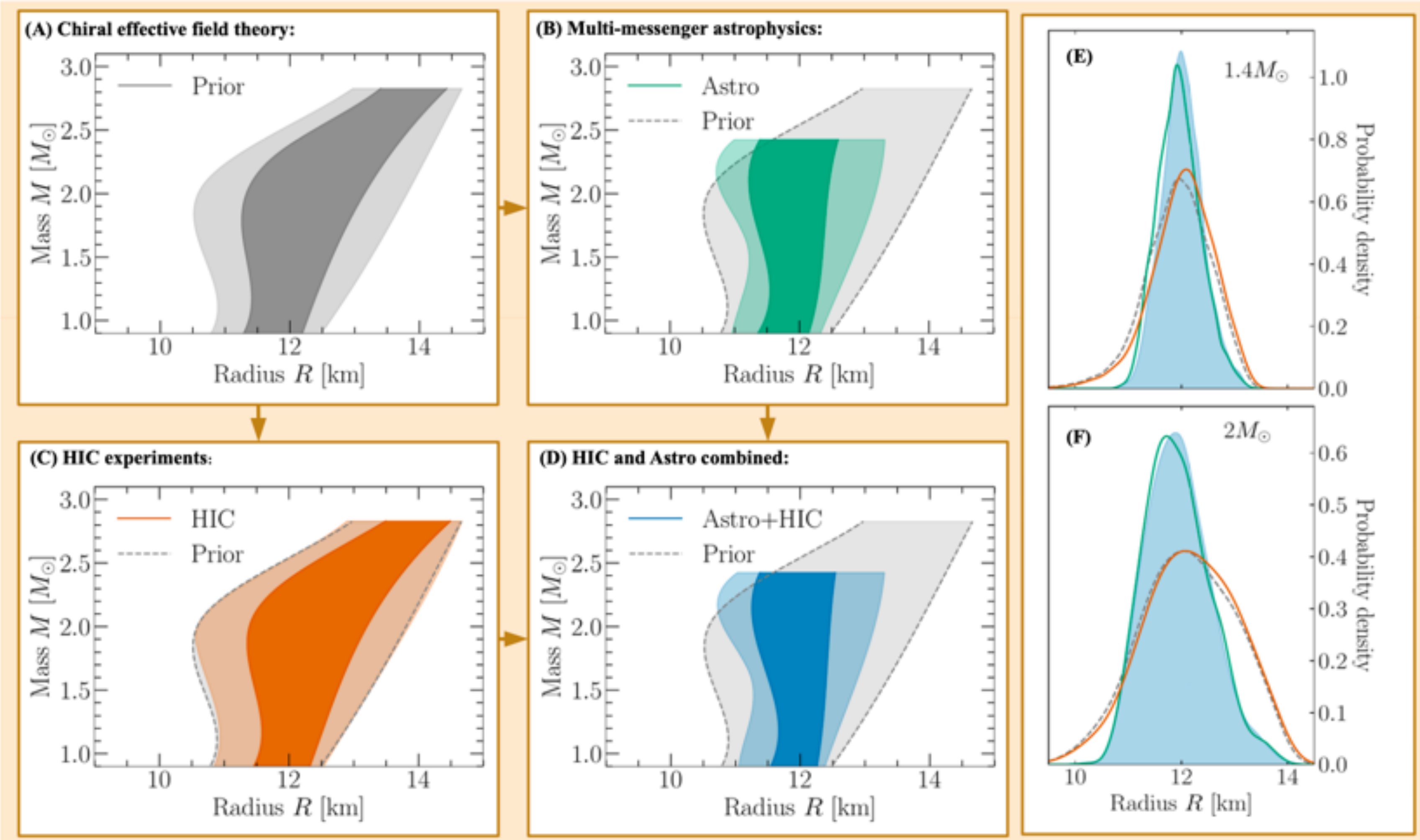

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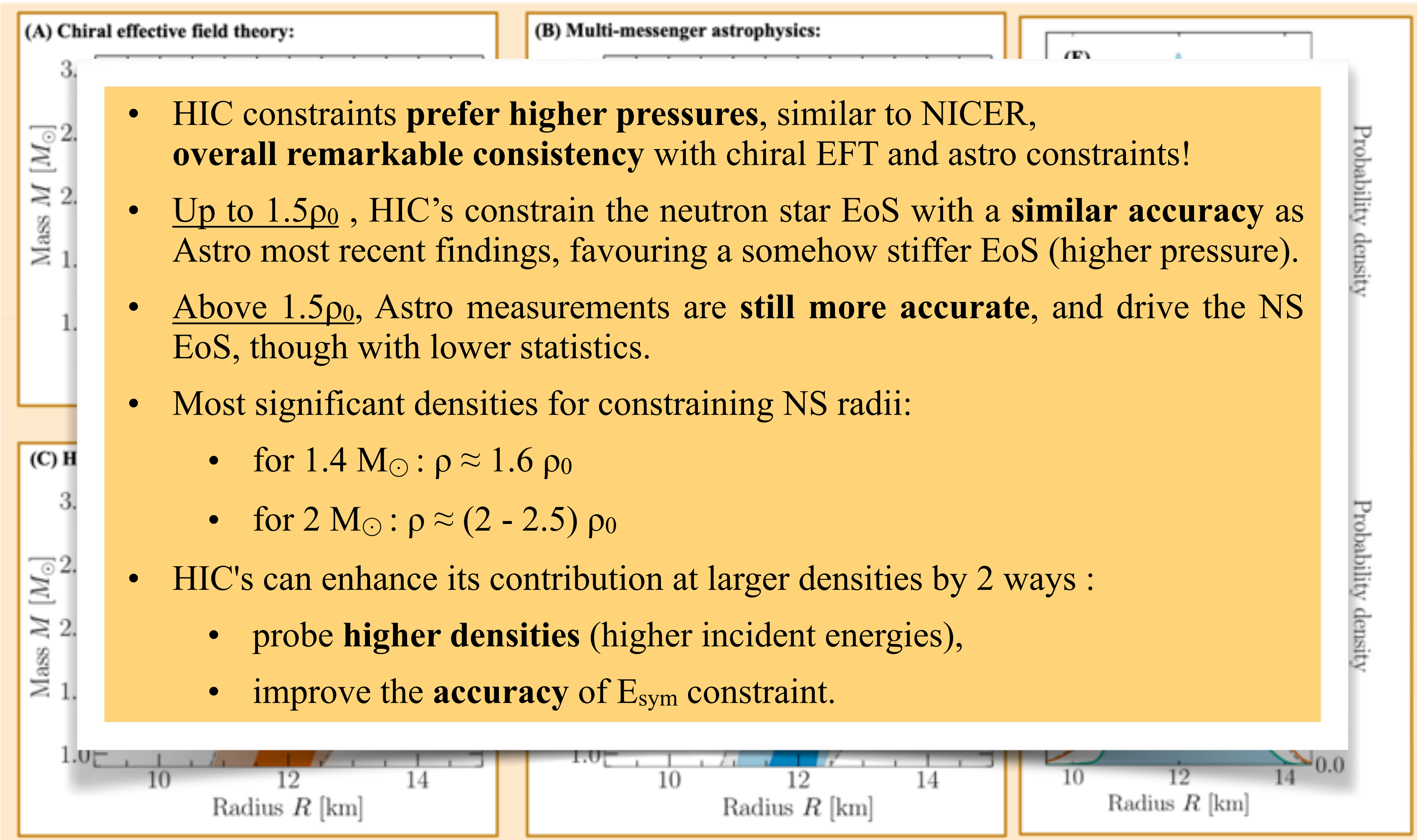

- HIC constraints **prefer higher pressures**, similar to NICER, **overall remarkable consistency** with chiral EFT and astro constraints!
- Up to $1.5\rho_0$, HIC's constrain the neutron star EoS with a **similar accuracy** as Astro most recent findings, favouring a somehow stiffer EoS (higher pressure).
- Above $1.5\rho_0$, Astro measurements are **still more accurate**, and drive the NS EoS, though with lower statistics.
- Most significant densities for constraining NS radii:
    - for 1.4 $M_\odot$: $\rho \approx 1.6\ \rho_0$
    - for 2 $M_\odot$: $\rho \approx (2 - 2.5)\ \rho_0$
- HIC's can enhance its contribution at larger densities by 2 ways :
    - probe **higher densities** (higher incident energies),
    - improve the **accuracy** of E_{sym} constraint.

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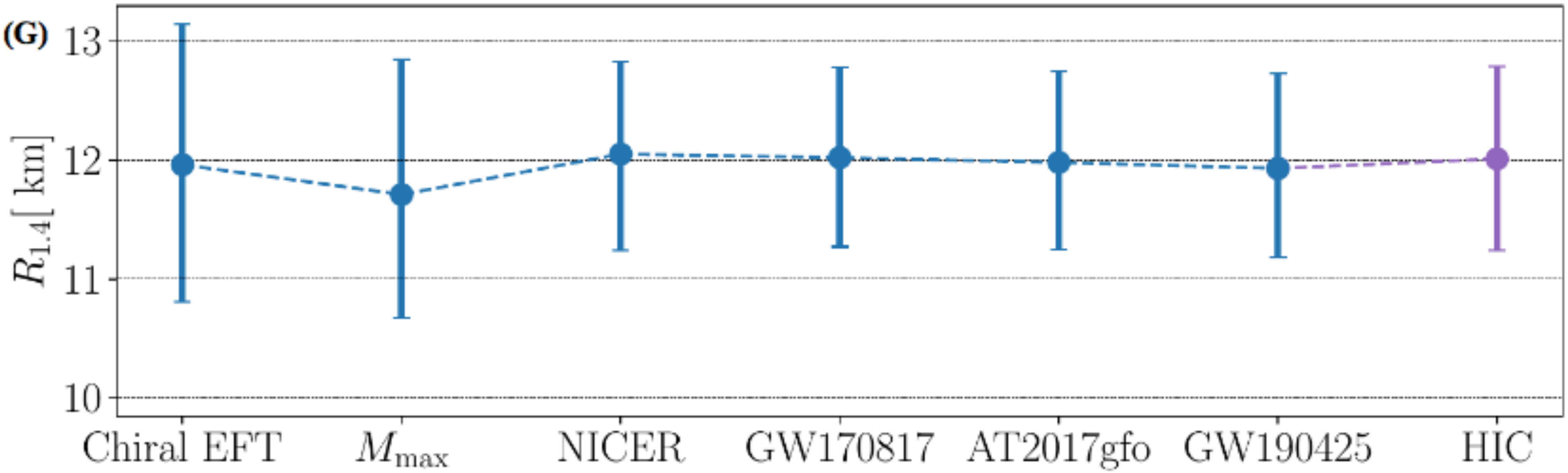


$\geq$ **1.9 M$_\odot$** constraint

(kilonova)

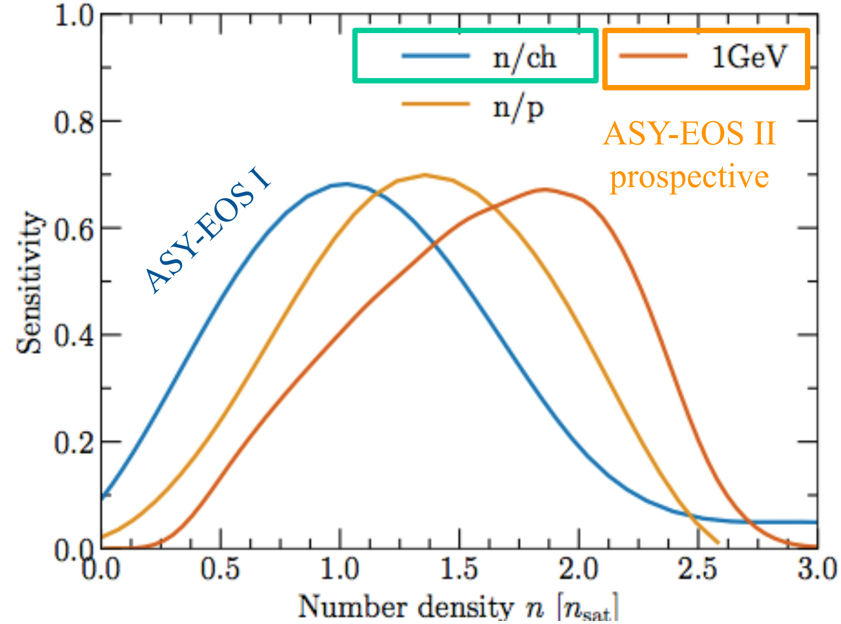
		Prior	Astro only	HIC only	Astro + HIC
pressure (MeV)	$P_{1.5n_{sat}}$	$5.59^{+2.04}_{-1.97}$	$5.84^{+1.95}_{-2.26}$	$6.06^{+1.85}_{-2.04}$	$6.25^{+1.90}_{-2.26}$
radius (km)	$R_{1.4}$	$11.96^{+1.18}_{-1.15}$	$11.93^{+0.80}_{-0.75}$	$12.06^{+1.13}_{-1.18}$	$12.01^{+0.78}_{-0.77}$

Perspectives

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

ASY-EOS II @ GSI

- larger densities probed:
  higher incident energies: Au+Au @ 250 - 1000 MeV/
- improved accuracy on E_{asy} constraint:
  with n, p, d, t identification in NeuLAND with large efficiency



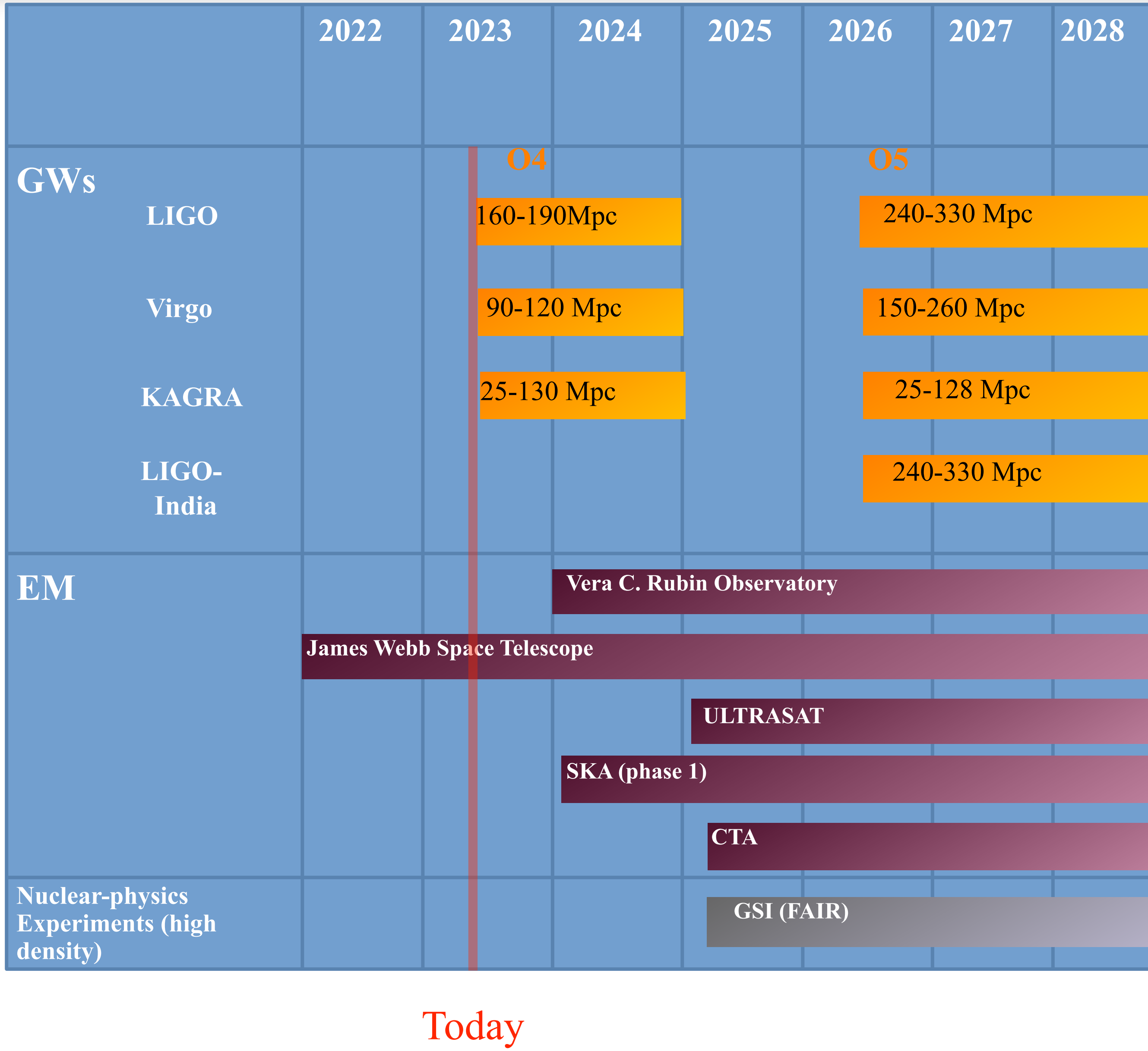
Predictions with present Easy HIC constraint:

ASY-EOS I @ 400A MeV

	P/R	n/ch sensitivity: HIC only	n/ch sensitivity: Astro+HIC	n/p sensitivity: HIC only	n/p sensitivity: Astro+HIC	Window 1-2n_{sat}: HIC only	Window 1-2n_{sat}: Astro+HIC
pressure (MeV)	$1.0n_{sat}$	$2.05^{+0.49}_{-0.45}$	$2.11^{+0.49}_{-0.52}$	$2.10^{+0.45}_{-0.49}$	$2.13^{+0.46}_{-0.54}$	$2.23^{+0.32}_{-0.50}$	$2.28^{+0.35}_{-0.55}$
	$1.5n_{sat}$	$6.06^{+1.85}_{-2.04}$	$6.25^{+1.90}_{-2.26}$	$6.23^{+1.68}_{-2.16}$	$6.34^{+1.83}_{-2.30}$	$6.76^{+1.15}_{-2.13}$	$6.93^{+1.39}_{-2.17}$
	$2.0n_{sat}$	$19.47^{+33.63}_{-11.67}$	$19.07^{+15.27}_{-10.53}$	$19.62^{+33.36}_{-10.81}$	$19.20^{+15.42}_{-9.21}$	$21.41^{+30.60}_{-9.02}$	$20.59^{+16.10}_{-8.36}$
	$2.5n_{sat}$	$47.78^{+75.96}_{-32.96}$	$45.43^{+40.41}_{-19.11}$	$47.61^{+79.33}_{-32.61}$	$45.62^{+40.81}_{-18.61}$	$54.71^{+66.27}_{-36.26}$	$48.60^{+39.47}_{-19.32}$
radius (km)	$1.0M_\odot$	$11.89^{+0.79}_{-0.98}$	$11.88^{+0.57}_{-0.76}$	$11.92^{+0.78}_{-0.95}$	$11.91^{+0.61}_{-0.73}$	$12.09^{+0.59}_{-0.63}$	$12.06^{+0.48}_{-0.56}$
	$1.4M_\odot$	$12.06^{+1.13}_{-1.18}$	$12.01^{+0.78}_{-0.77}$	$12.09^{+1.12}_{-1.14}$	$12.02^{+0.78}_{-0.76}$	$12.26^{+0.96}_{-0.84}$	$12.17^{+0.73}_{-0.60}$
	$1.6M_\odot$	$12.11^{+1.33}_{-1.33}$	$12.03^{+0.98}_{-0.75}$	$12.13^{+1.31}_{-1.30}$	$12.05^{+0.91}_{-0.79}$	$12.33^{+1.14}_{-1.05}$	$12.19^{+0.81}_{-0.76}$
	$2.0M_\odot$	$12.19^{+1.71}_{-1.59}$	$11.91^{+1.24}_{-1.11}$	$12.20^{+1.68}_{-1.60}$	$11.91^{+1.25}_{-1.11}$	$12.42^{+1.44}_{-1.48}$	$12.06^{+1.14}_{-1.20}$

Perspectives

Astro-multimessenger future program



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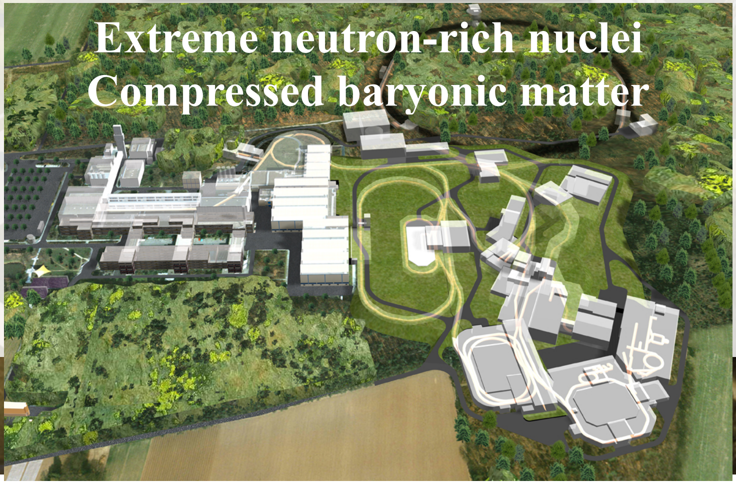
New experimental frontier



New observations in astrophysics