EOS as deduced from HICs and astrophysics: status and perspectives

W. Trautmann, GSI Helmholtzzentrum
64291 Darmstadt, Germany

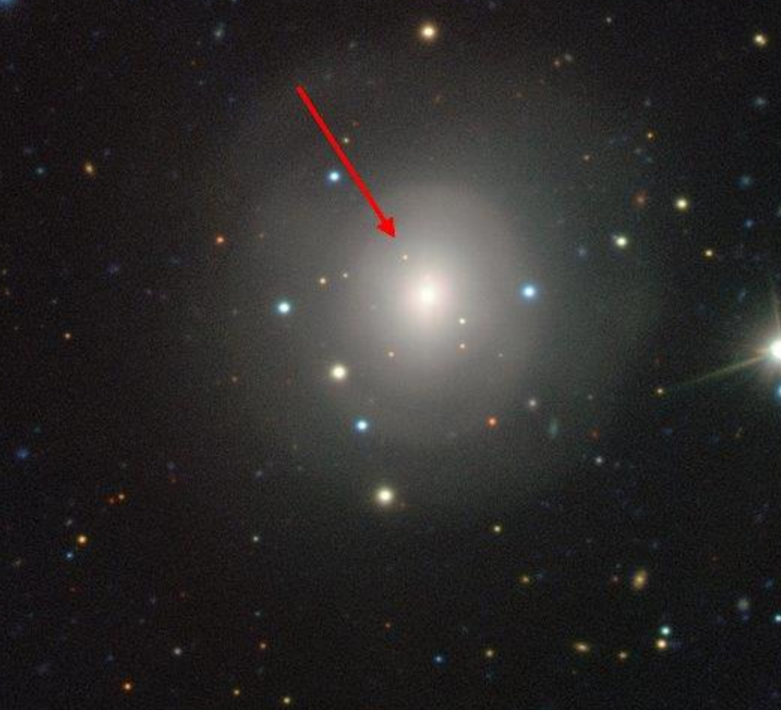
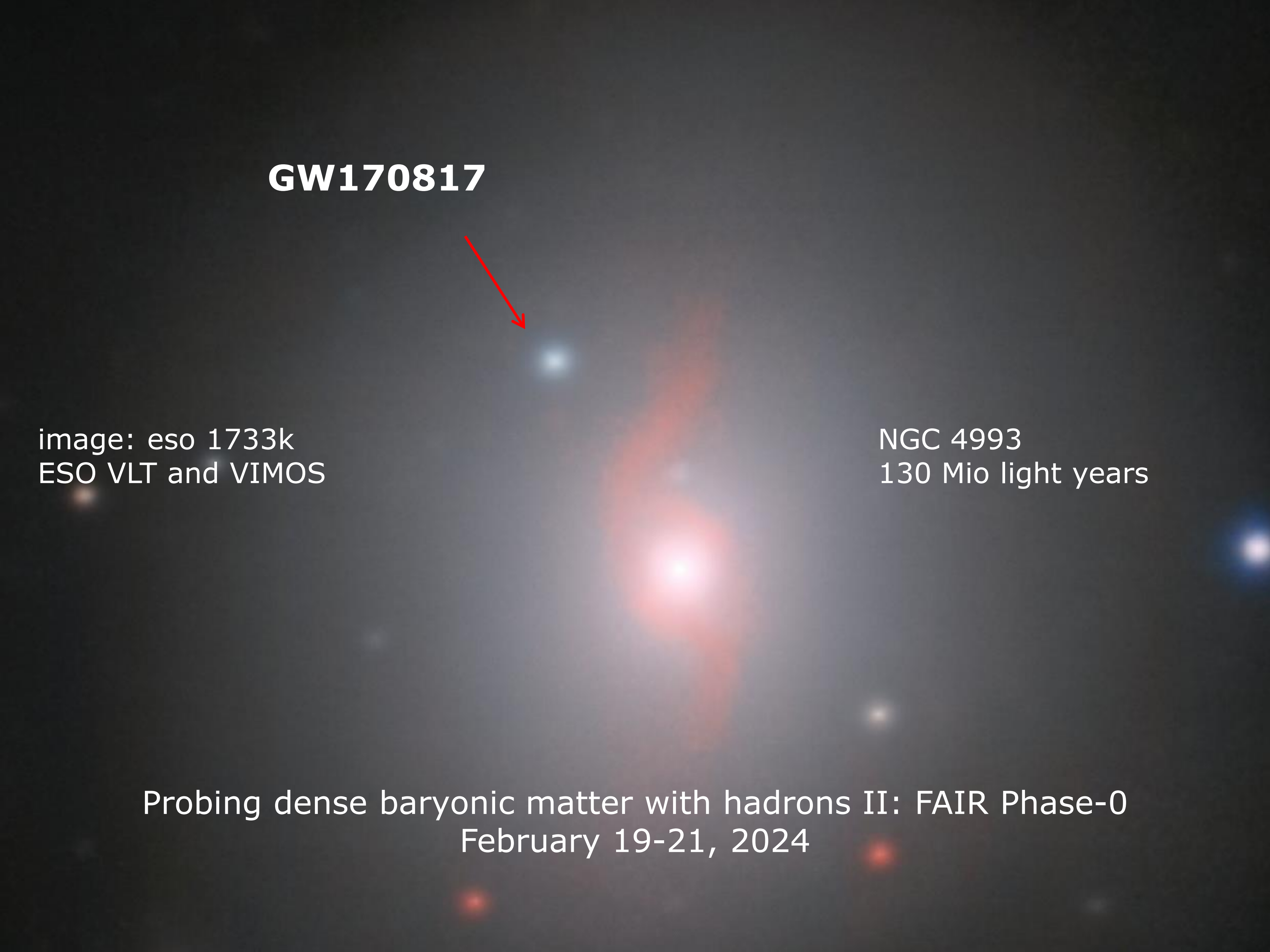


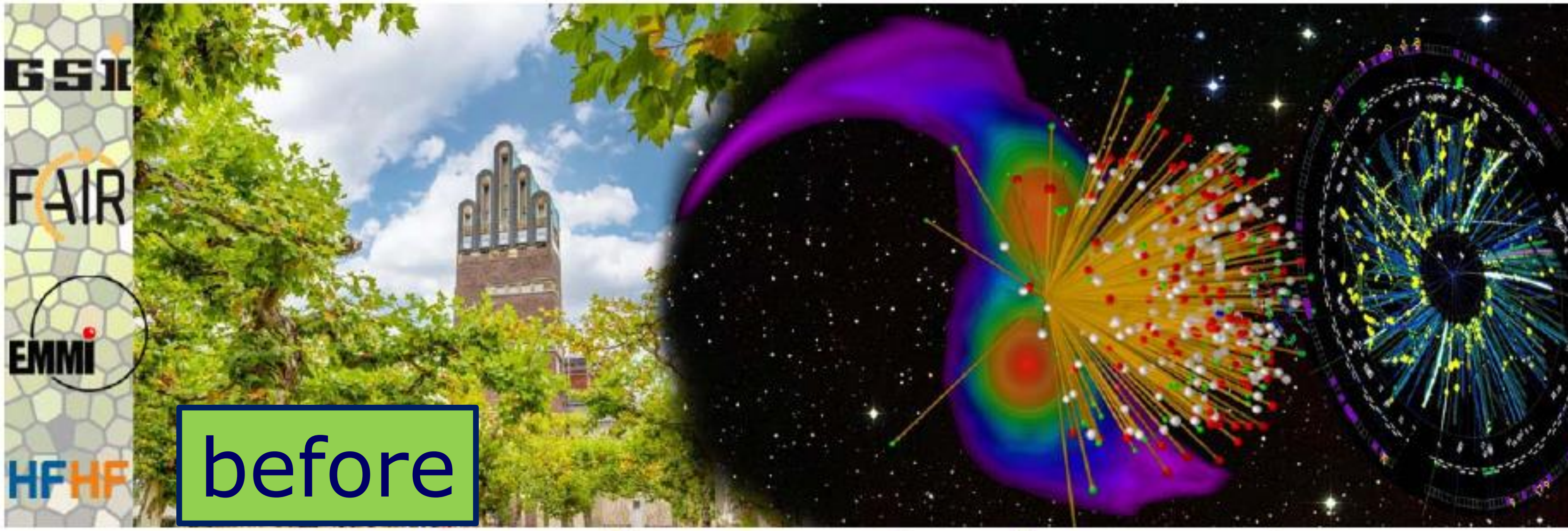
image: eso 1733k
ESO VLT and VIMOS

NGC 4993
130 Mio light years

Probing dense baryonic matter with hadrons II: FAIR Phase-0
February 19-21, 2024


GW170817
image: eso 1733k
ESO VLT and VIMOS
NGC 4993
130 Mio light years
Probing dense baryonic matter with hadrons II: FAIR Phase-0
February 19-21, 2024

NuSym23: find talks at https://indico.gsi.de/event/17017/overview



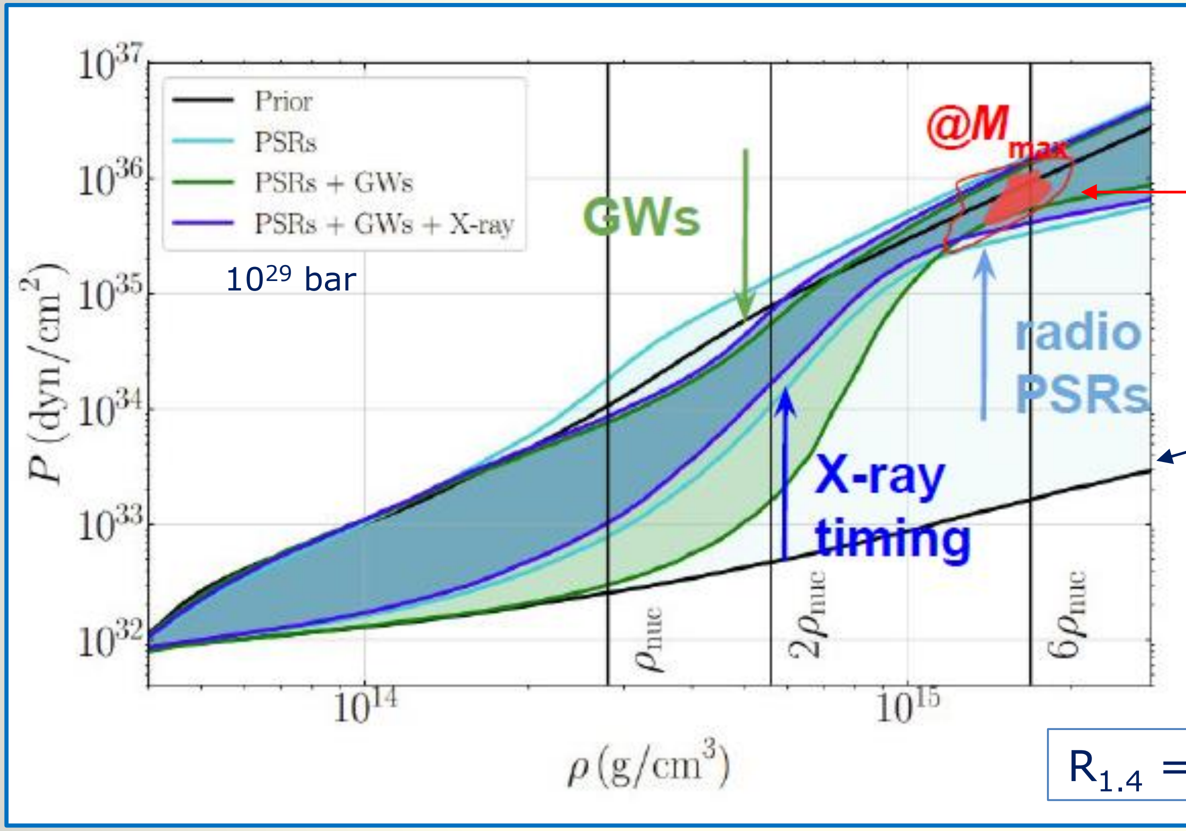
NuSym23, 11th International Symposium

on Nuclear Symmetry Energy

Darmstadt (Germany), September 18-22, 2023

The nuclear equation-of-state and the symmetry energy in laboratory experiments, astrophysical observations, and microscopic theories

Reed Essick at NuSym22 in Catania



Legred+, PRD 104, 063003 (2021)

50%/90% contours

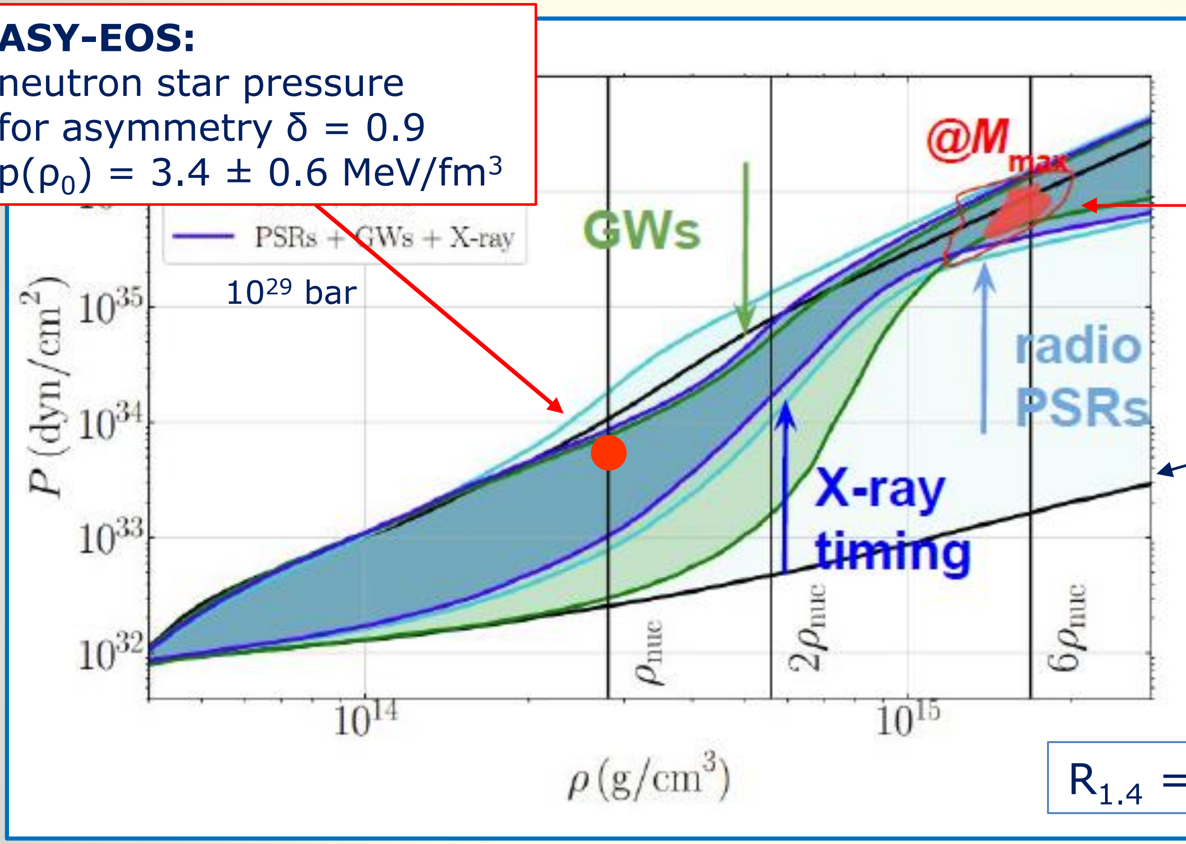
model-agnostic prior

with
PSR J0740+6620
$M=2.08 \pm 0.07\ M_{sun}$

$R_{1.4}$ = 12.6 ± 1.1 km (68%)

Reed Essick at NuSym22 in Catania

ASY-EOS:
neutron star pressure
for asymmetry $\delta = 0.9$
$p(\rho_0) = 3.4 \pm 0.6$ MeV/fm^3



Legred+, PRD 104, 063003 (2021)

50%/90% contours

model-agnostic prior

$R_{1.4} = 12.6 \pm 1.1$ km (68%)

$\mathbf{R_{1.4} p_{sat}^{-1/4} = 9.5 \pm 0.5}$ => $R_{1.4} = 12.9 \pm 0.6$ km $\pm$ 0.7 km (68%)
(stat.) (correl.)

for ASY-EOS: Russotto+, PRC 94, 034608 (2016)
for correlation: Lattimer, arXiv:2308.08001

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

Sabrina Huth[1,2,13] ✉, Peter T. H. Pang[3,4,13] ✉, Ingo Tews[5], Tim Dietrich[6,7], Arnaud Le Fèvre[8], Achim Schwenk[1,2,9], Wolfgang Trautmann[8], Kshitij Agarwal[10], Mattia Bulla[11], Michael W. Coughlin[12] & Chris Van Den Broeck[3,4]

Interpreting high-energy, astrophysical phenomena, such as supernova explosions or neutron-star collisions, requires a robust understanding of matter at supranuclear

11 authors from nuclear theory, heavy ion reactions, and astrophysics

Bayesian inference as in Dietrich+, Science 370, 1450 (2020)

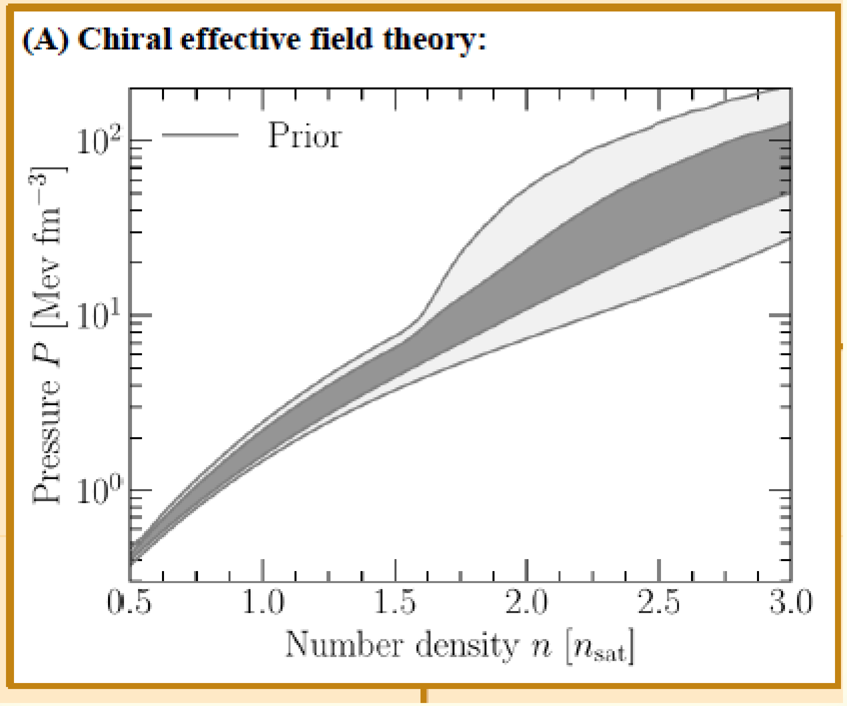
Huth et al., Nature 606, 276 (2022)

the prior: $R_{1.4}$ = 11.96 ± 1.18 km (final: 12.01 ± 0.78 km)

15000 EoS constructed with

EFT up to 1.5 ρ_0

speed-of-sound extension



stability $c_s > 0$

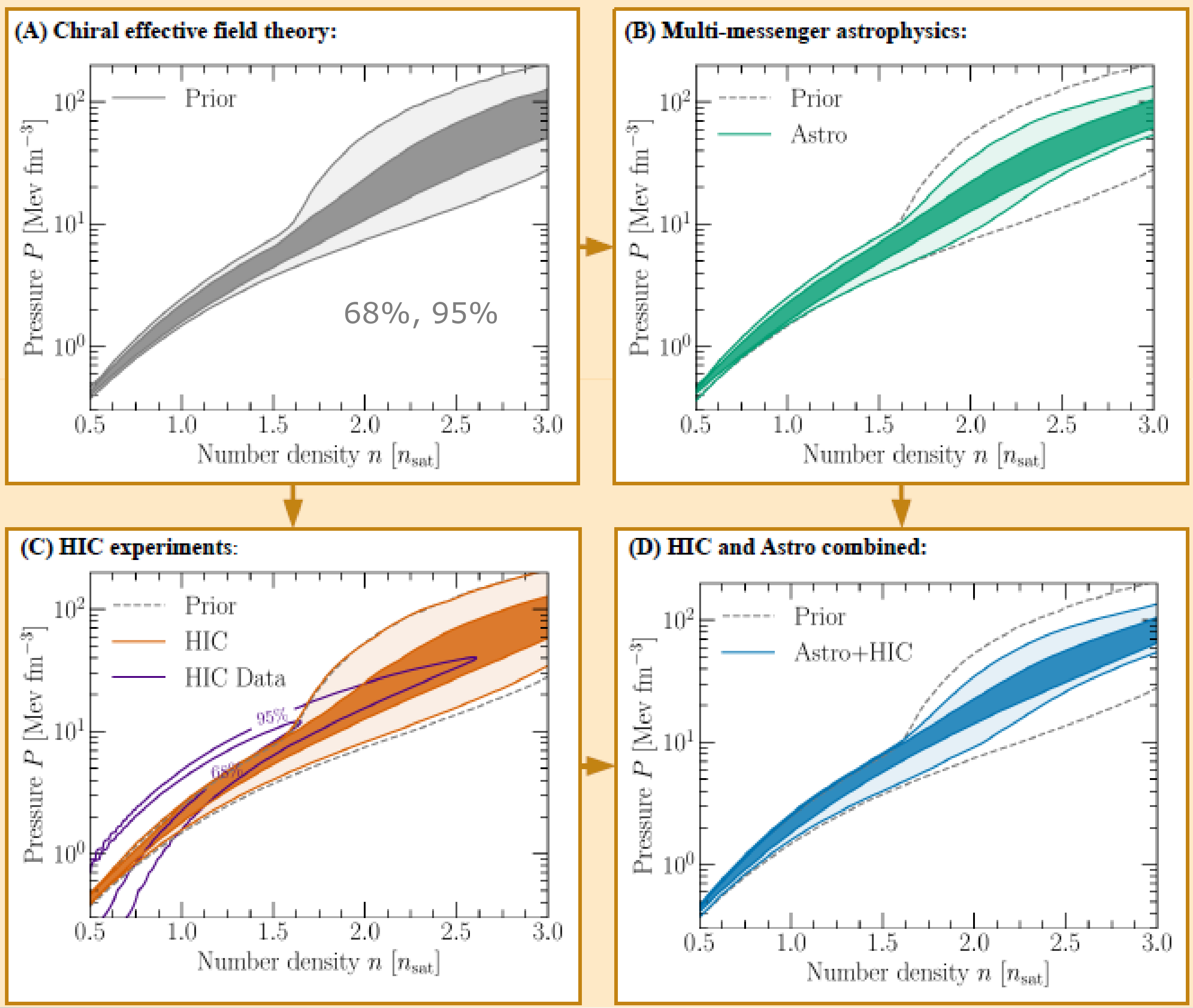
causality $c_s < c$

$\mathbf{M_{max} \geq 1.9\ M_{sun}}$

$$c_S^2 = \frac{\partial p(\epsilon)}{\partial \epsilon},$$

sections with $c_s = 0$ to allow for phase transition

χEFT prior + HIC + astro



Huth+ Nature 606

Fig. 1
neutron star matter

contours at 68% and 95% credibility

prior:
χEFT up to 1.5 ρ_0
c_s extension
$M_{max} \geq 1.9\ M_{sun}$

astro:
GW170817
+kilonova
GW190425
NICER 2 stars
XMM-Newton
$M_{max} \leq 2.17\ M_{sun}$

HIC:
PNM: ASY-EOS
SNM: FOPI, AGS

stability (from Extended Data and Supplementary Tables)

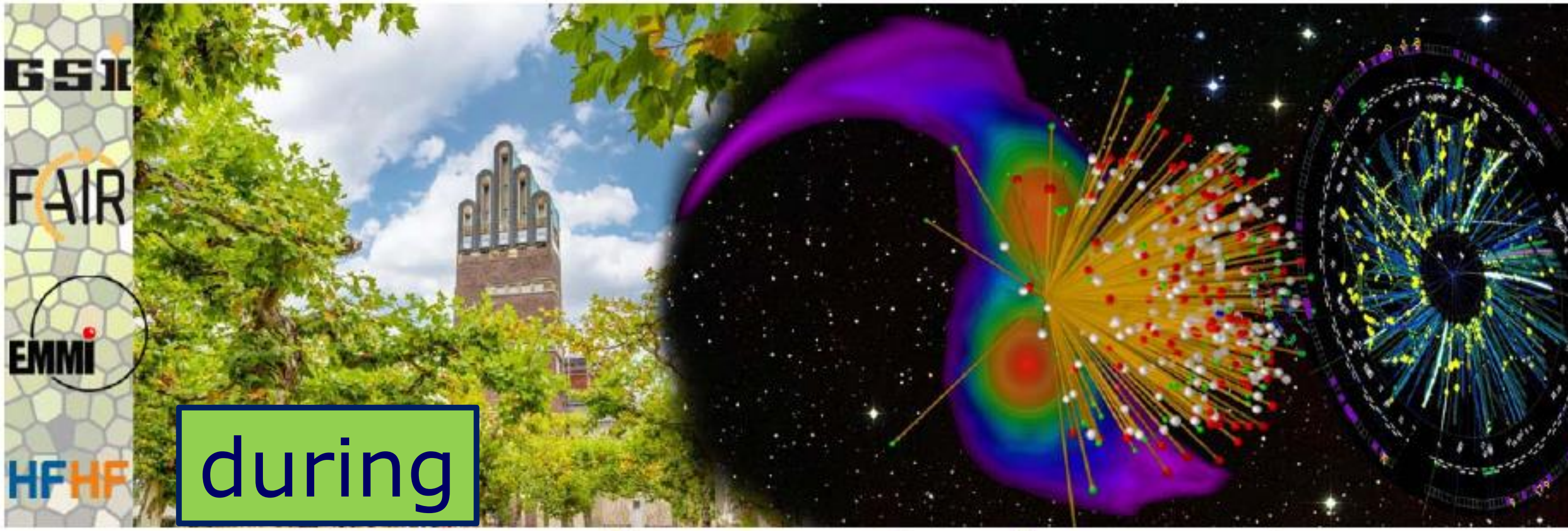
Huth+ Nature 606

adopted: χEFT up to 1.5 n_{sat}, natural prior, c_s extension, n/ch sensitivity, proton fraction 0.05 at n_{sat}

$R_{1.4}$ = 12.01 +0.78 -0.77 km (95%)
12.06 +1.13 -1.18 km (HIC only)
11.94 +0.79 -0.78 km (astro only)
11.96 +1.18 -1.15 km (prior: χEFT & M_{max} >1.9 M_{sun})

→ **12.56 +1.07 –1.01**	**χEFT up to 1.0 n_{sat}** ←
12.08 +1.18 –0.94	uniform prior
12.05 +0.83 –0.79	polytrope extension
12.00 +0.75 –0.80	inflated HIC errors
12.02 +0.78 –0.76	n/p sensitivity
12.21 +0.73 –0.76	1 GeV sensitivity
12.04 +0.72 –0.71	1 GeV & half HIC error
12.00 +0.77 –0.77	proton fraction 0–0.1
11.97 +0.77 –0.74	Taylor expansion for SNM
11.94 +0.87 –0.83	radius of 6620 (NICER) not used

NuSym23: find talks at https://indico.gsi.de/event/17017/overview



during

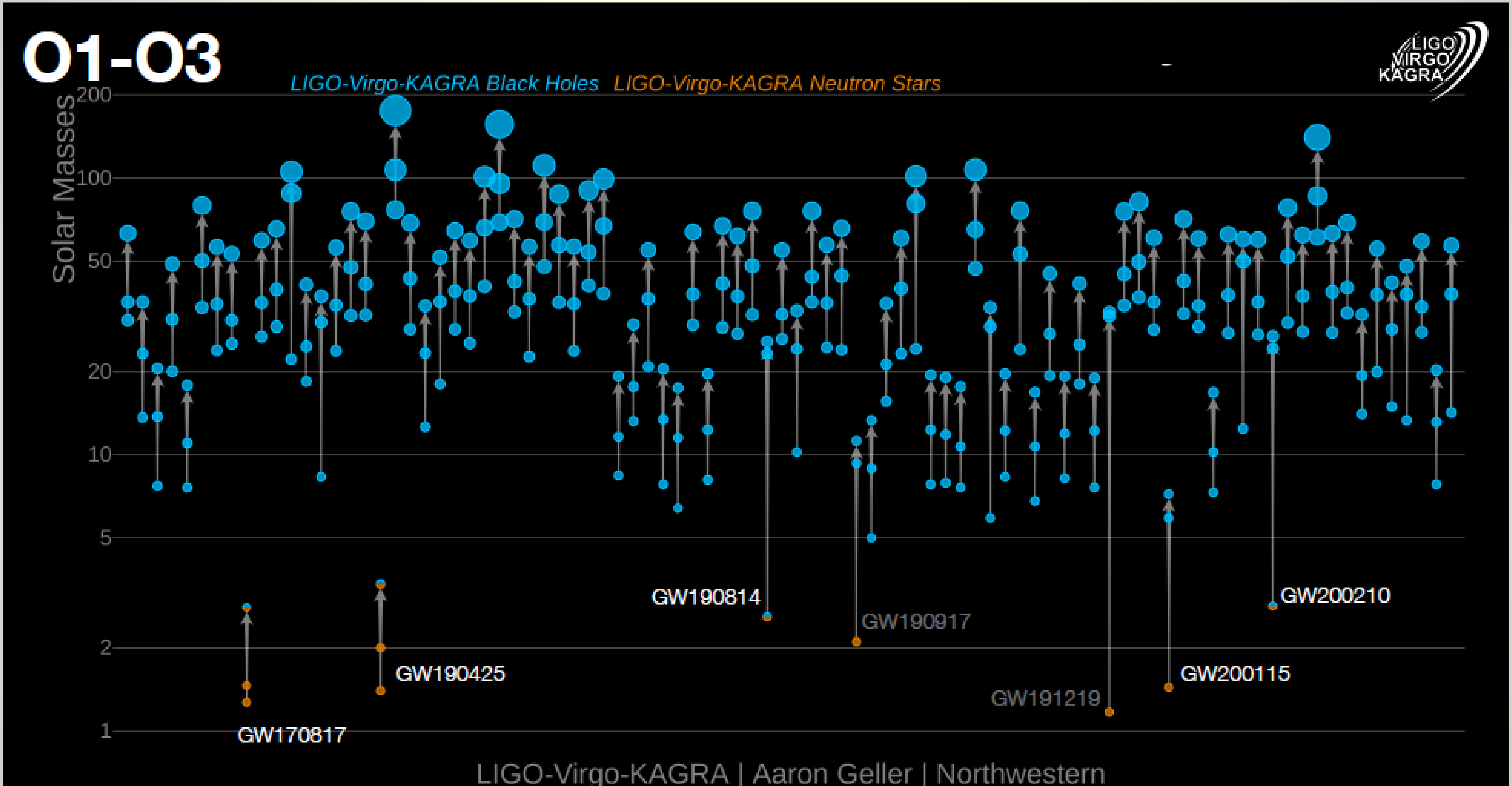
NuSym23, 11th International Symposium on Nuclear Symmetry Energy

>80 talks

Darmstadt (Germany), September 18-22, 2023

The nuclear equation-of-state and the symmetry energy in laboratory experiments, astrophysical observations, and microscopic theories

Jocelyn Read at NuSym23

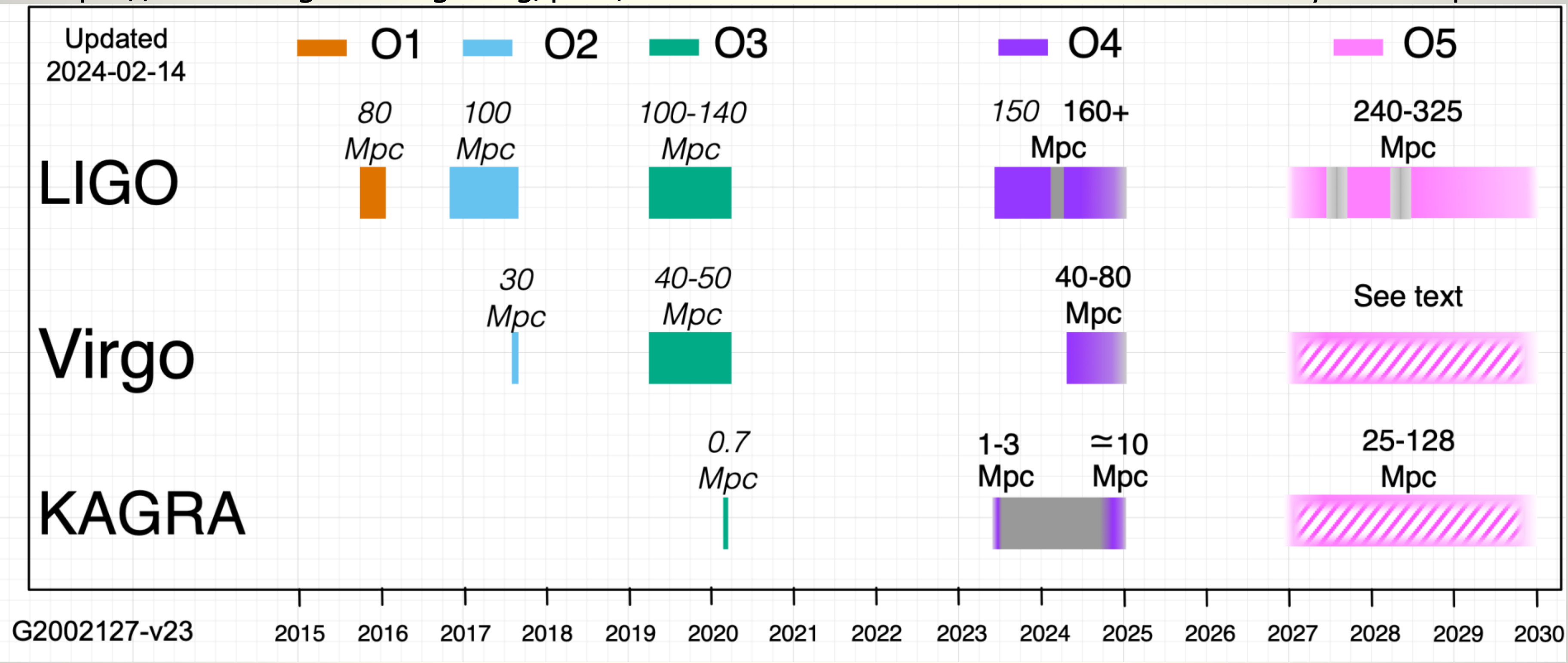


LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606 [6]

LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

LIGO, Virgo and KAGRA Observing run plans

https://observing.docs.ligo.org/plan/# 15 February 2024 update

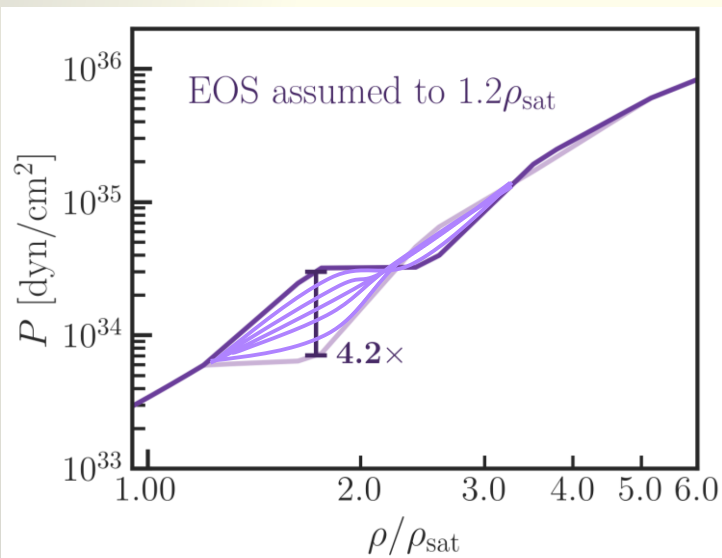


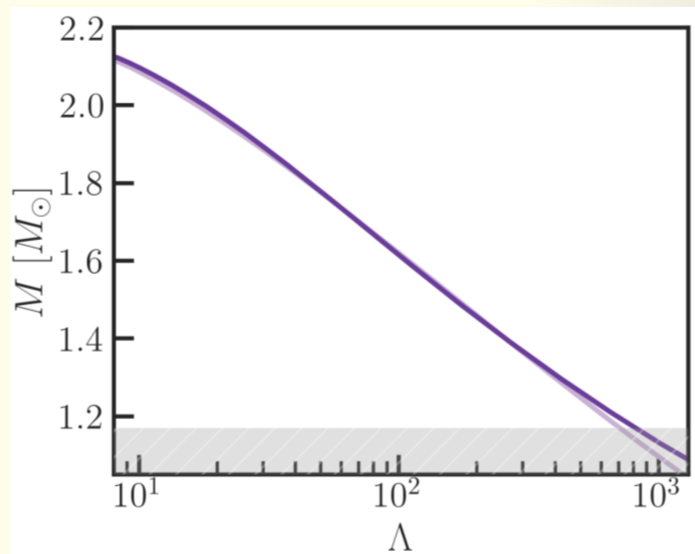
LIGO: O4 Observing run started on 24 May 2023
O4a ended 16 January 2024
LIGO+Virgo commence observing run O4b on 3 April 2024
KAGRA expected to join O4b before the end of O4

Tidal deformability "doppelgängers"

Non-Neutron Star Doppelgängers: Barack Obama (left) and Ilham Anas (right), a photographer from Java [Reuters]

- Very different EOSs (large differences in pressure above ρ_{sat})
- But nearly *identical* tidal deformability curves, across the full range of observed masses

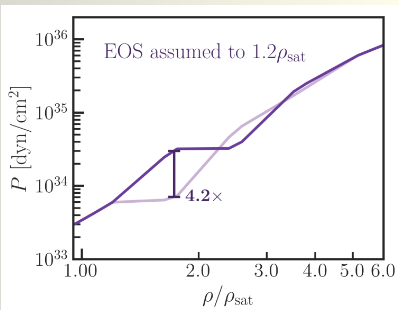


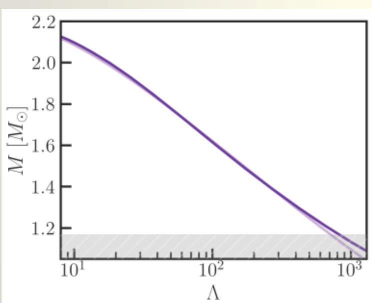


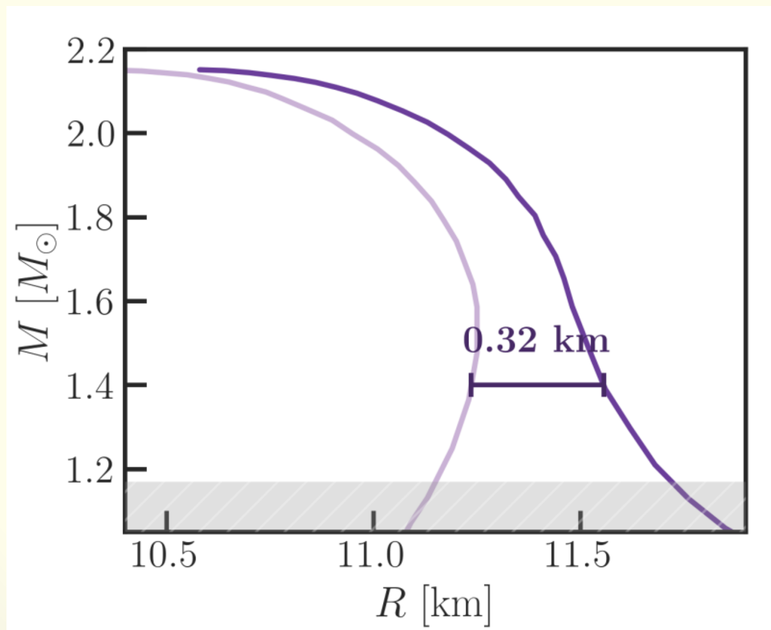
Raithel & Most 2023 (PRL, PRD)

How to break the degeneracy?

Solution #1: Incorporate X-ray radius measurements







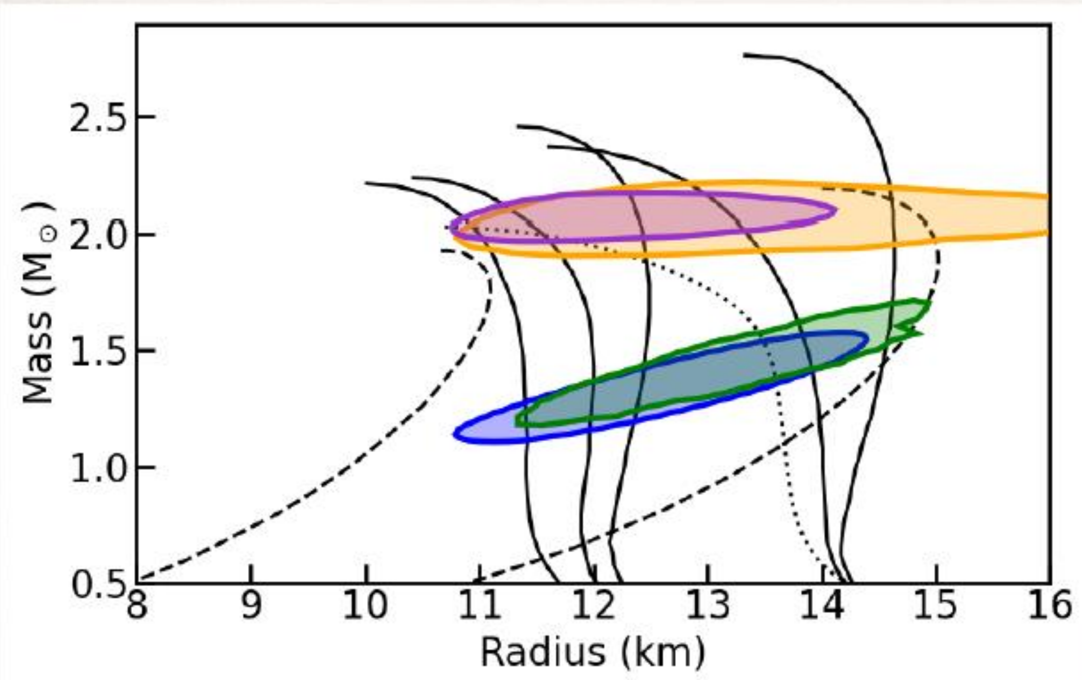
Even for very strict doppelgängers, the M-R relations can still differ by up to ~a few 100 m

Raithel & Most 2023 (PRL, PRD)

Solution #2: Incorporate further nuclear input at low-to-intermediate densities

Sebastien Guillot at NuSym23

The NICER Science Team published the results for two pulsars.



The two independent analyses for each target are consistent

- PSR J0030+0451
  - Riley et al. 2019
  - Miller et al. 2019

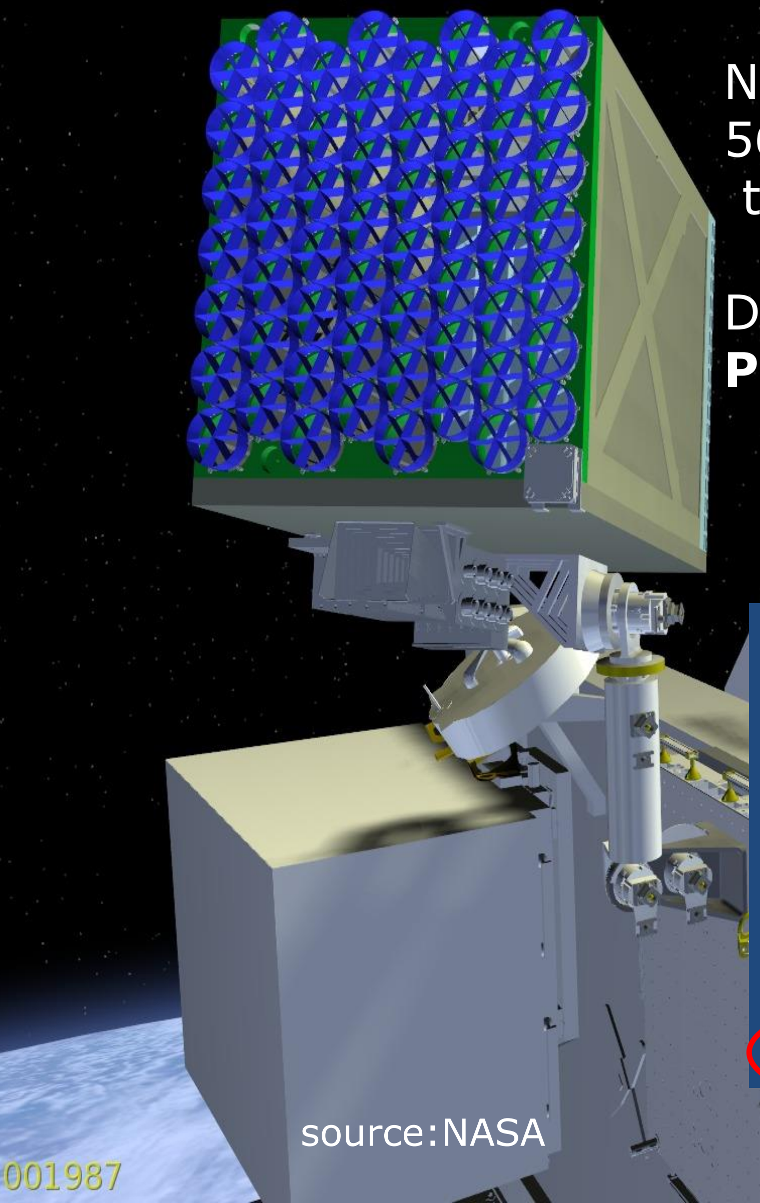
Vinciguerra, ApJ (2024)

- PSR J0740+6620
  - Riley et al. 2021
  - Miller et al. 2021

Sebastien Guillot at Bormio 2024:

- Salmi et al. 2024 & Dittmann et al. 2024 (both to be submitted) looked at PSR J0740+6620 with a lot more NICER data

NICER on the ISS



Neutron-star Interior Composition Explorer
56 X-ray concentrators (0.2-12 keV, **100 ns**)
time resolved X-ray emissions of neutron stars

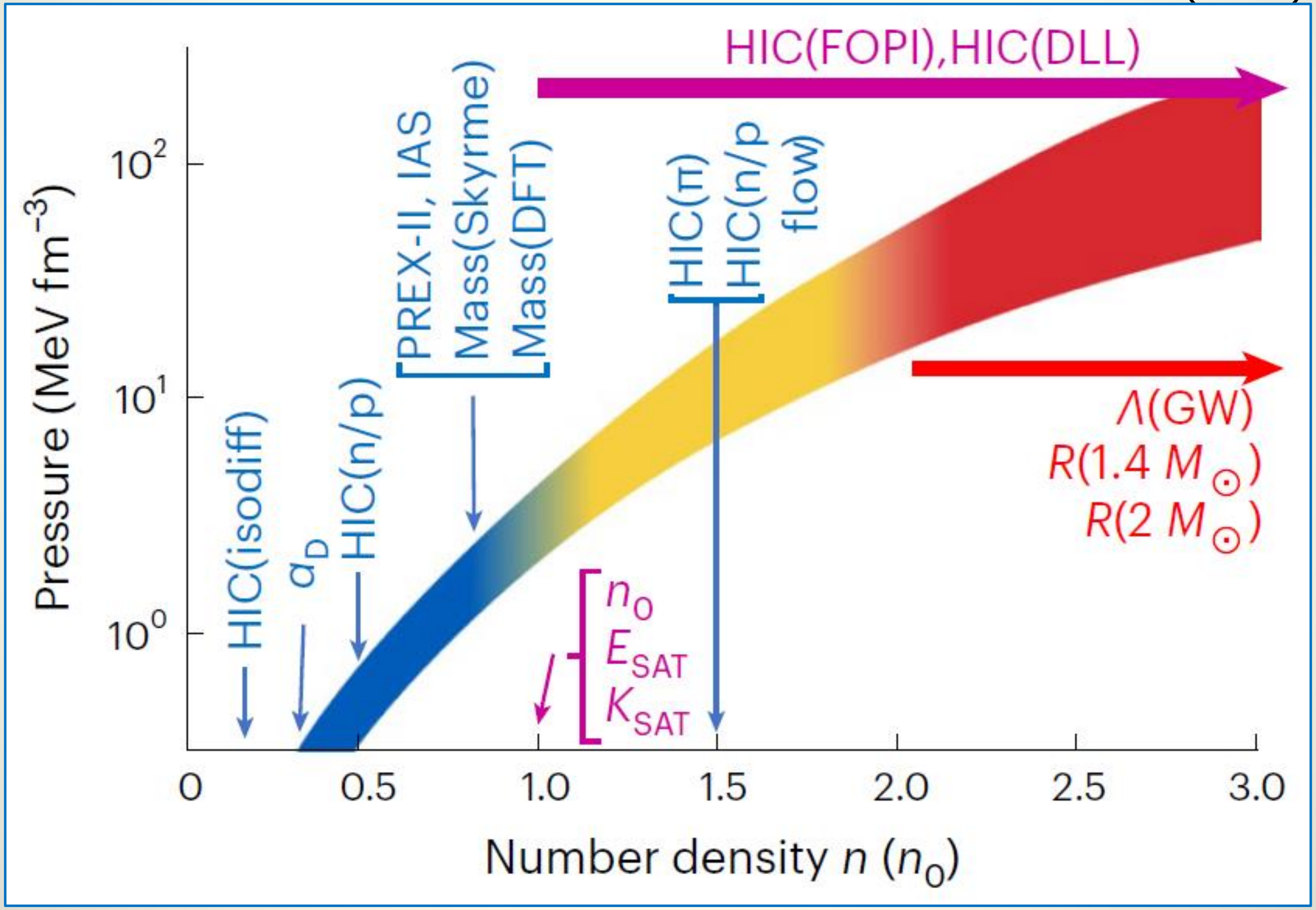
December 10, 2019, ApJL:
PSR J0030+0451: 4.9 ms 1.4 M_{sun}, 1060 l.y.
12.7 ± 1.1 km (Riley et al., 68%)
13.0 ± 1.2 km (Miller et al., 68%)

September 10, 2021
PSR J0740+6620: 2.08 M_{sun}, 3700 l.y.
12.39 +1.30 -0.98 km (68%)
Riley+, ApJL 918, L27
13.7 + 2.6 - 1.5 km (68%)
Miller+ ApJL 918, L28
with XMM-Newton, GW170817
$R_{1.4}$ = 12.45 ± 0.65 km (5% at 1 σ)

The Nuclear EoS from experiments and Astronomical Observations

presented by Betty Tsang for Tommy Tsang

figure from Tsang+, Nat Astron (2024)

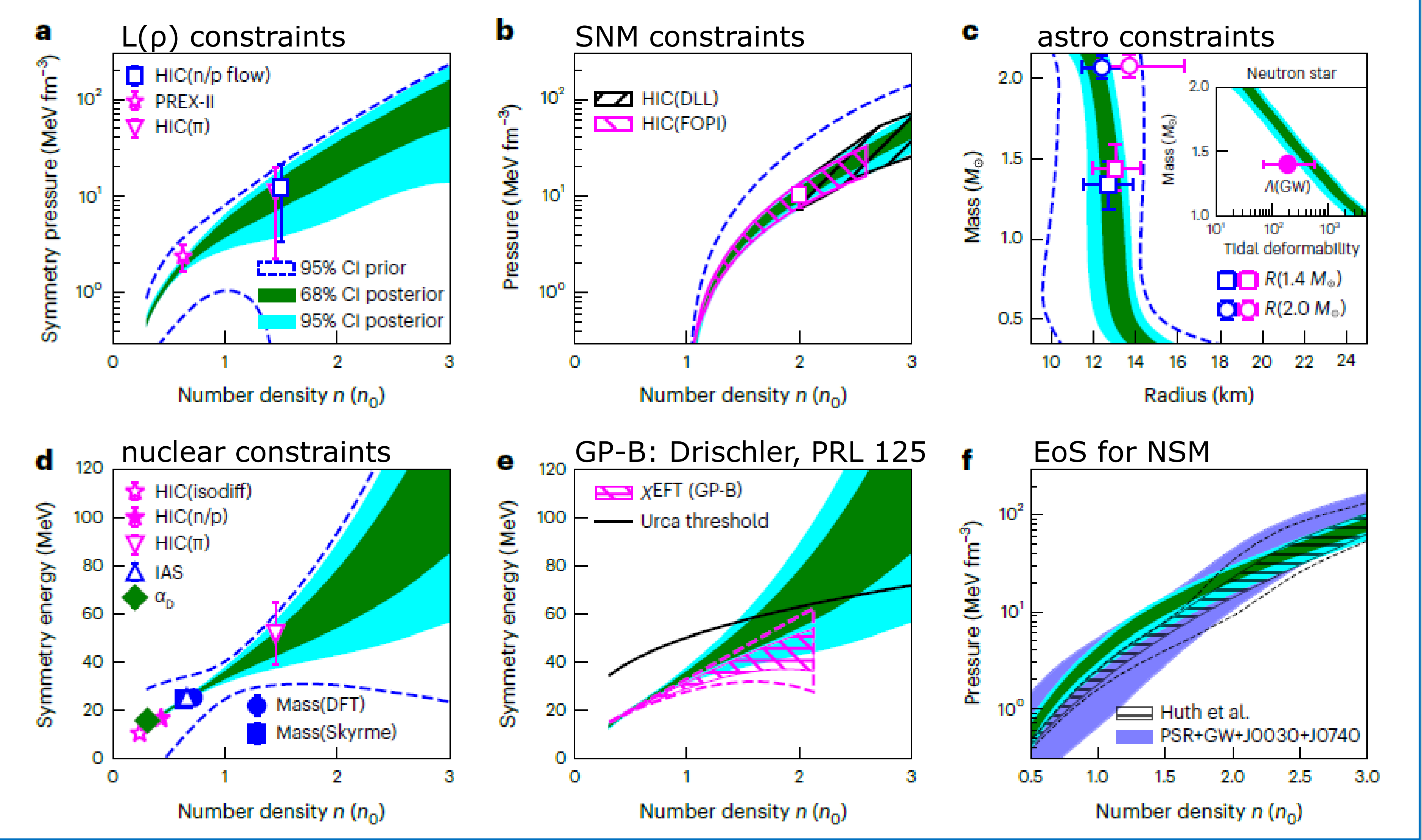


DLL: Danielewicz, Lacey, Lynch, Science
DFT: Density Functional Theory

The Nuclear EoS from experiments and Astronomical Observations

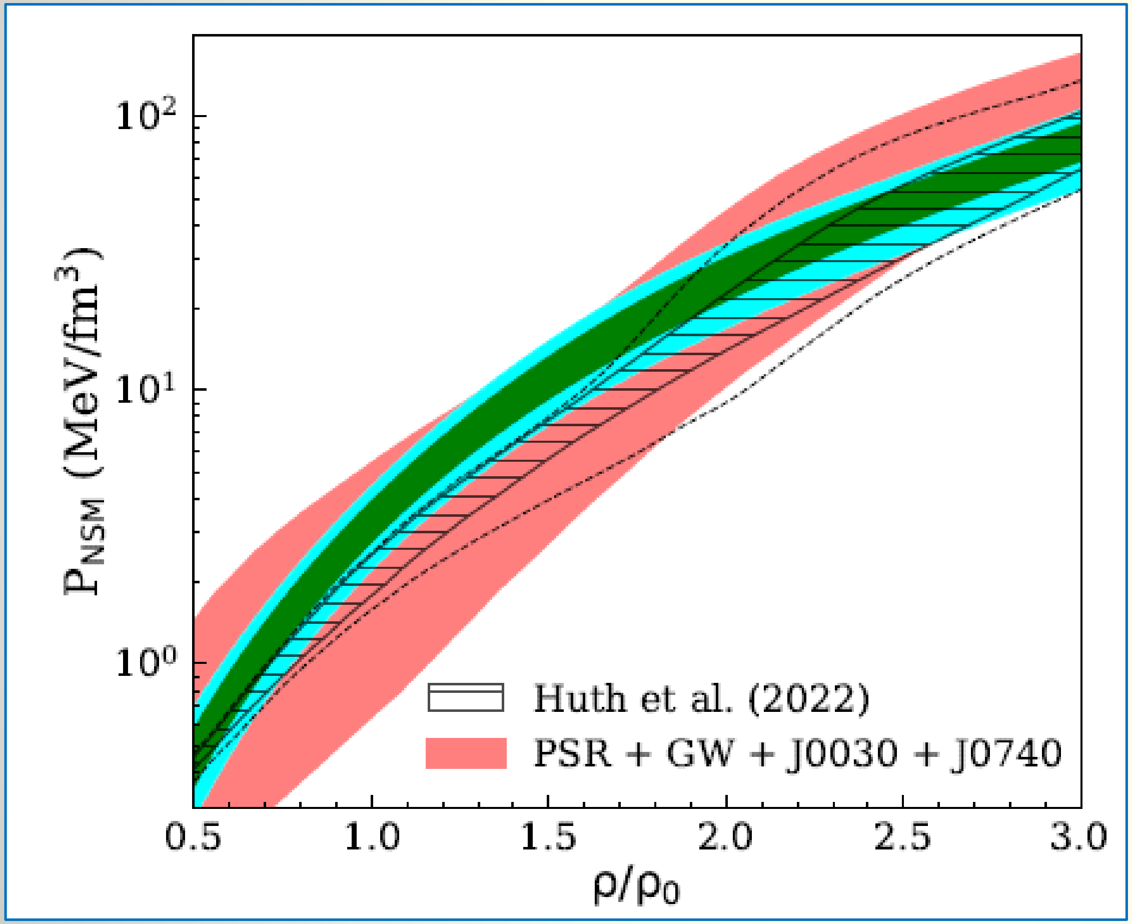
presented by Betty Tsang for Tommy Tsang

Fig. 2 in Tsang+, Nat Astron (2024)



The Nuclear EoS from experiments and Astronomical Observations

presented by Betty Tsang for Tommy Tsang (figure taken from talk)



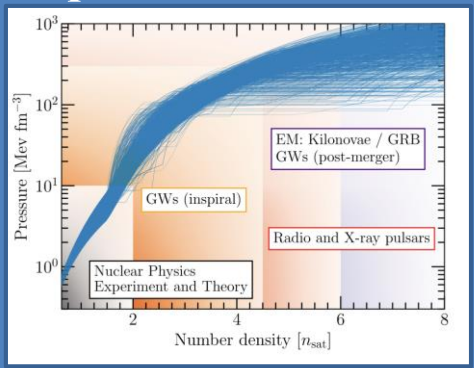
Tsang, Tsang, Lynch et al., Nat Astron (2024)
posterior (68%, 95%) from (mainly) HIC and astro
$R_{1.4}$ = **12.9** ± 0.5 km (68%)

Huth, Pang et al., Nature 606
prior from χEFT up to 1.5 ρ_0
posterior (68%, 95%) from HIC and astro
$R_{1.4}$ = **12.0** ± 0.4 km (68%)

Legred+, PRD 104 (2021)
agnostic prior with astro
$R_{1.4}$ = **12.6** ± 1.1 km (68%)

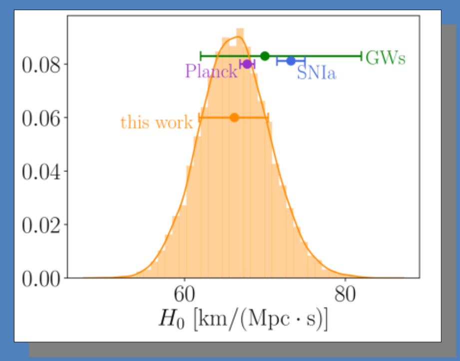
Science Cases of Neutron Star Research

Equation of State



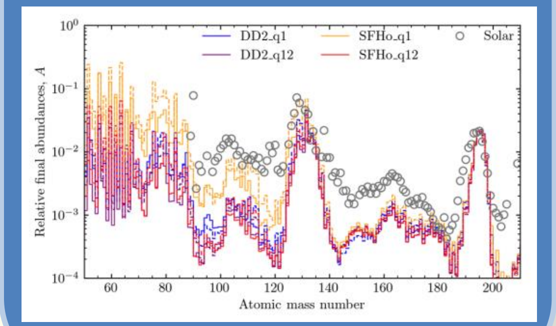
Pang et al., Nature Communication (accepted)

Hubble Constant



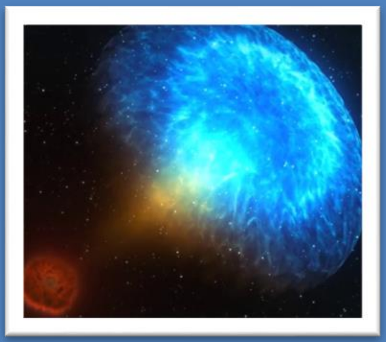
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Heavy element formation



Schianchi et al., 2307.94572

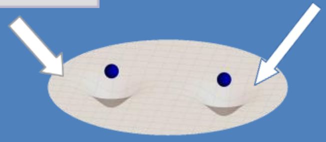
High-Energy astrophysics



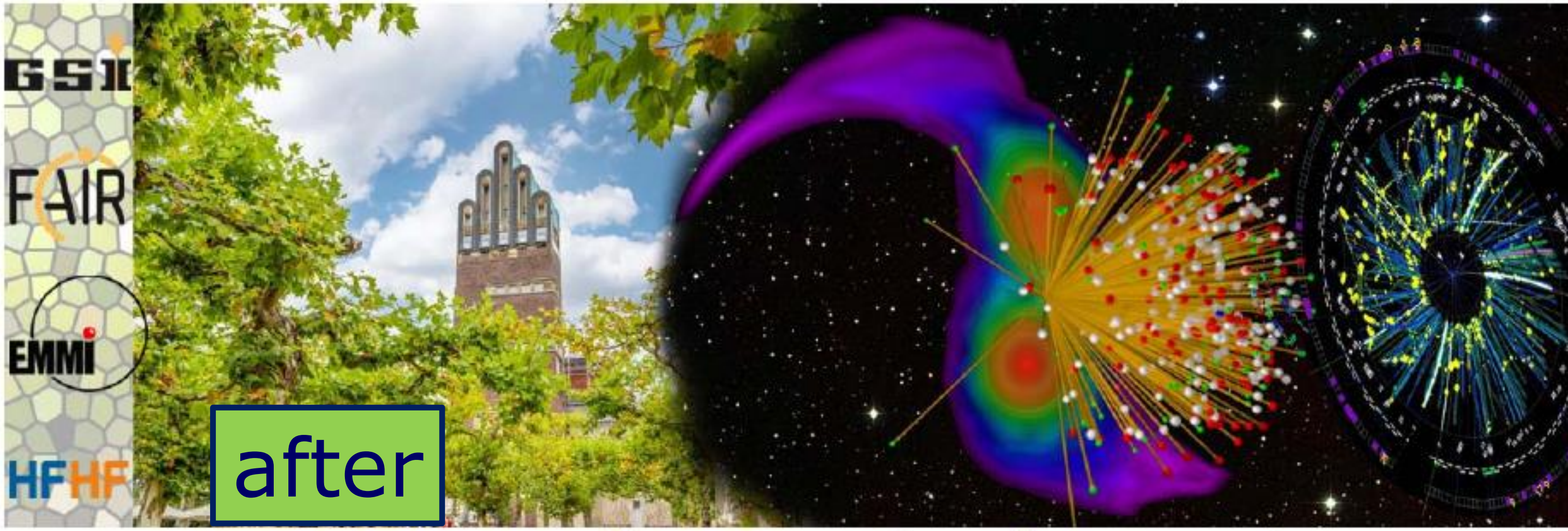
NASA

Tests of General Relativity

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



NuSym23: find talks at https://indico.gsi.de/event/17017/overview



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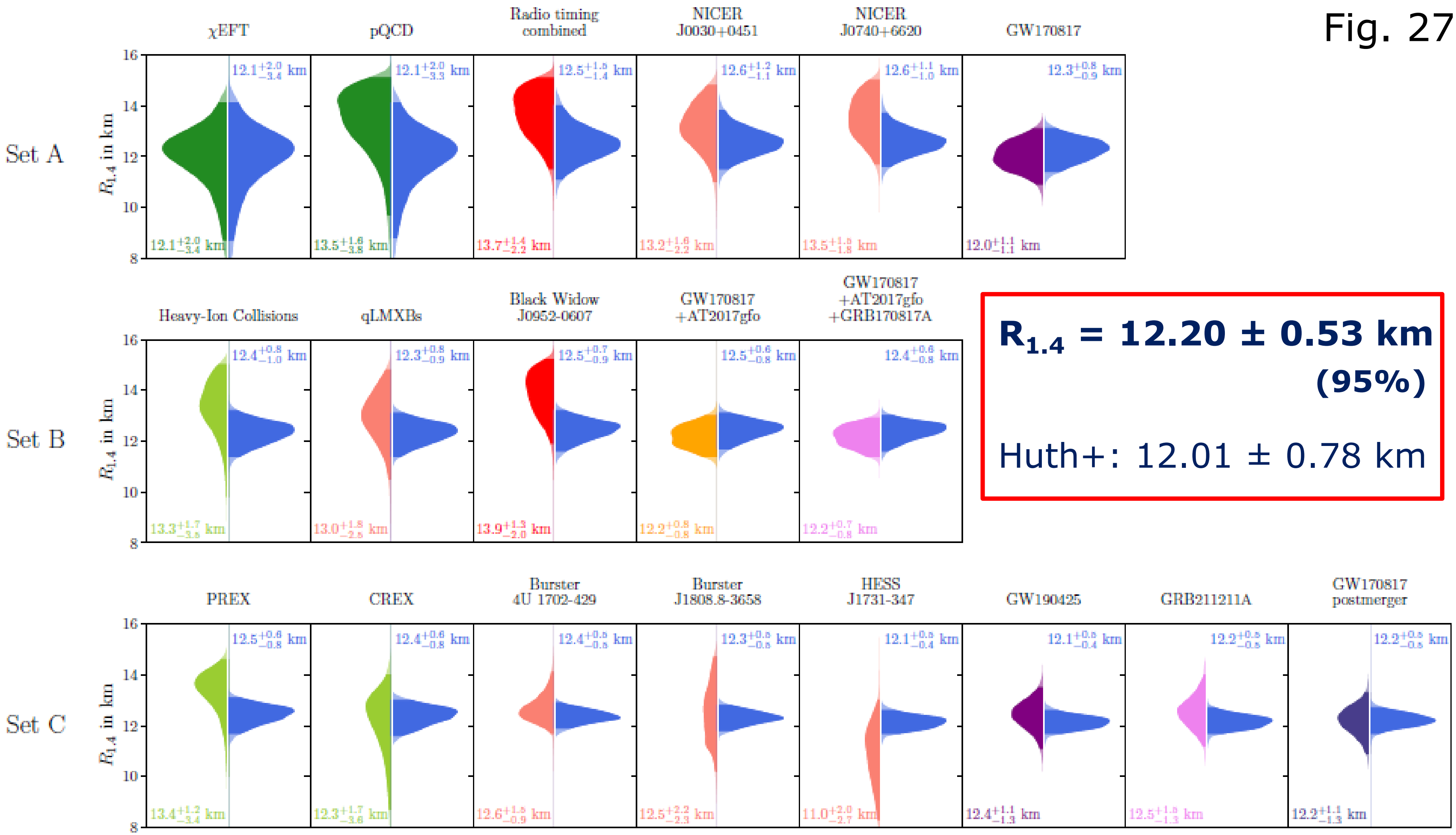
NuSym24: first announcement

NUSYM24 – XIIth International Symposium on Nuclear Symmetry Energy
September 09-13, Caen – France

status: Koehn+, arXiv:2402.04172 (6 Feb 2024)

Fig. 27



$R_{1.4}$ = 12.20 ± 0.53 km
(95%)

Huth+: 12.01 ± 0.78 km

prior: 100 000 from metamodeling and speed of sound extension to 25 n_{sat}

status: Koehn+, arXiv:2402.04172 (6 Feb 2024)

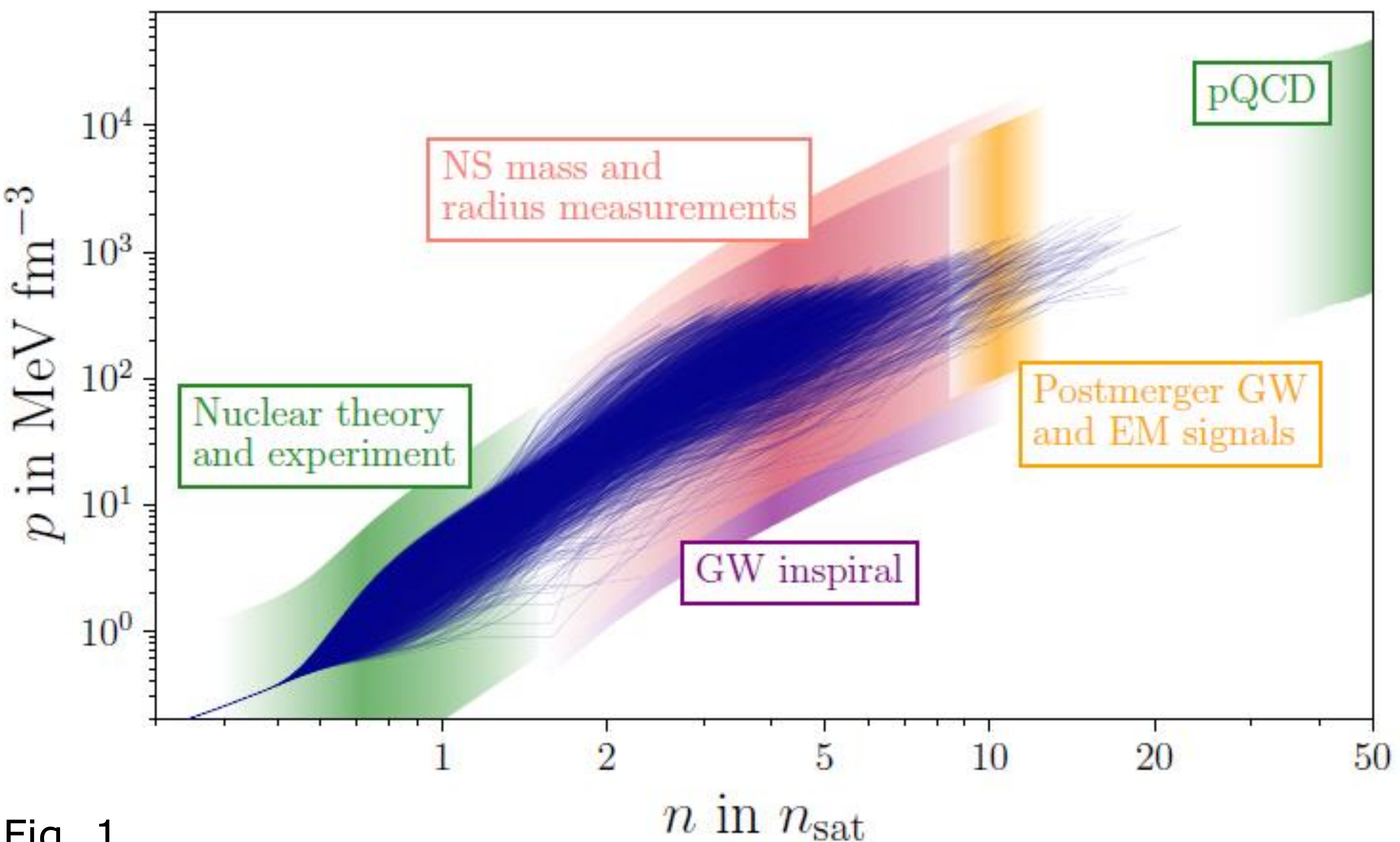


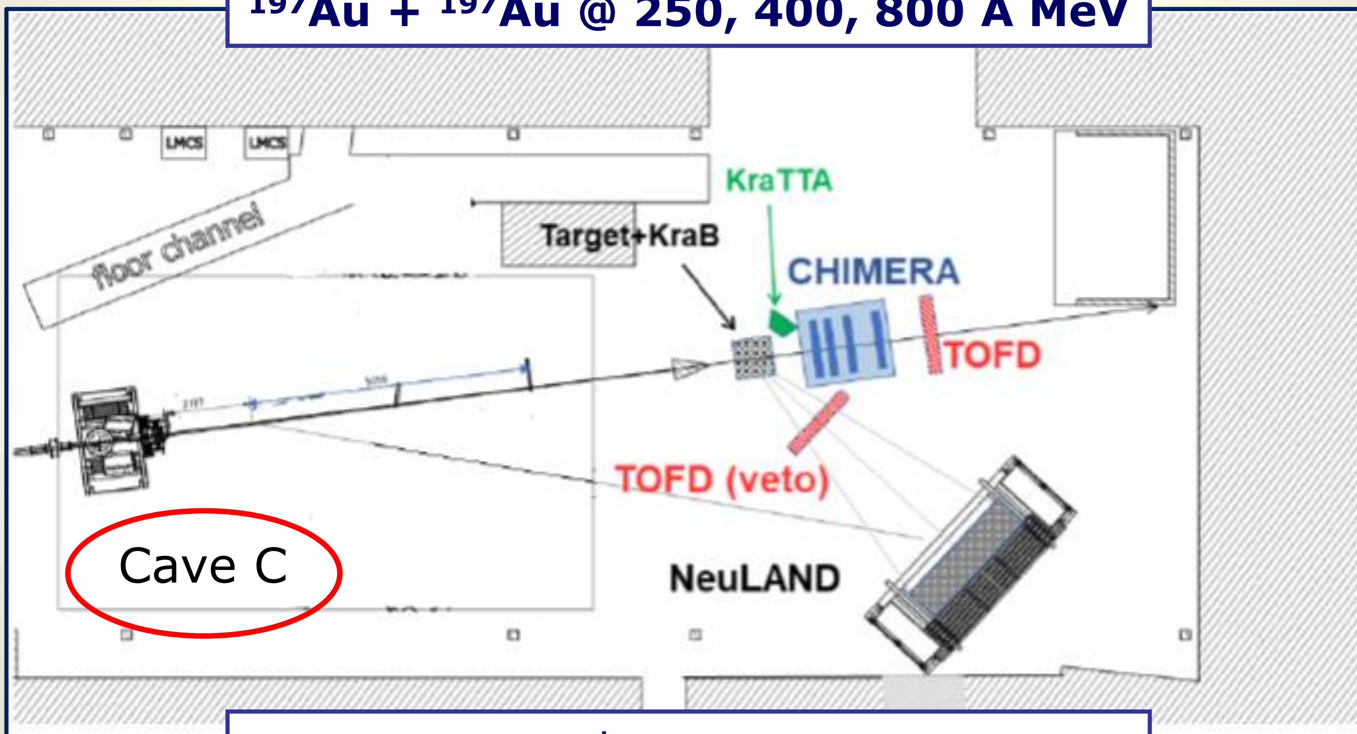
Fig. 1

perspectives: Paolo Russotto at NuSym23

ASY-EOS II – observables and expectations

studied reactions

^{197}Au + ^{197}Au @ 250, 400, 800 A MeV

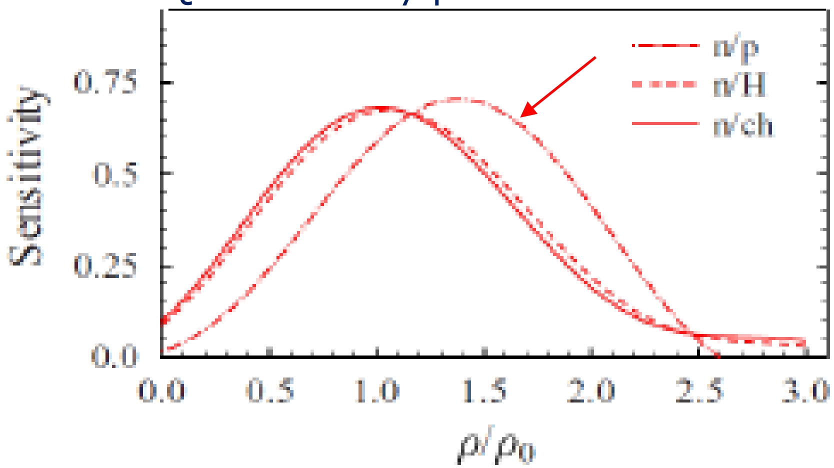


spokes persons

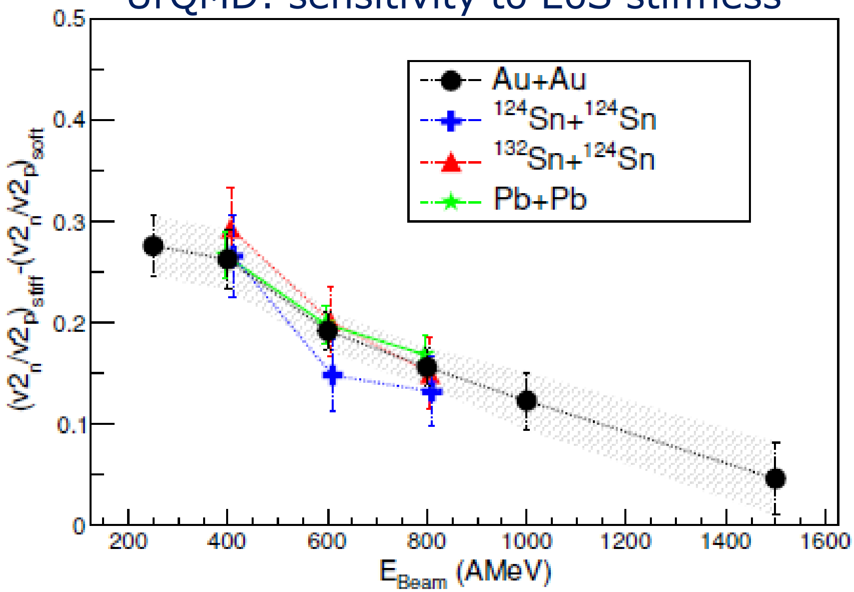
P. Russotto, J. Łukasik, A. Le Fèvre

ASY-EOS II proposal at FAIR (arXiv:2105.09233)

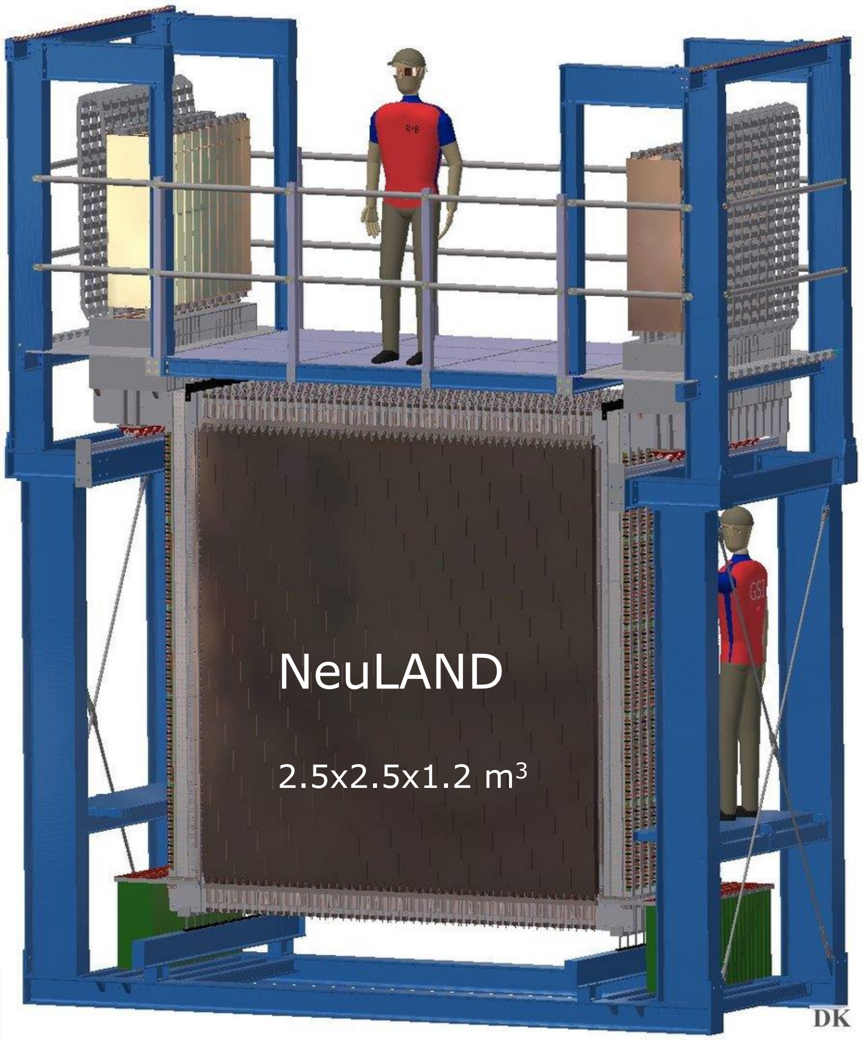
TüQMD: density probed at 400 AMeV



UrQMD: sensitivity to EoS stiffness



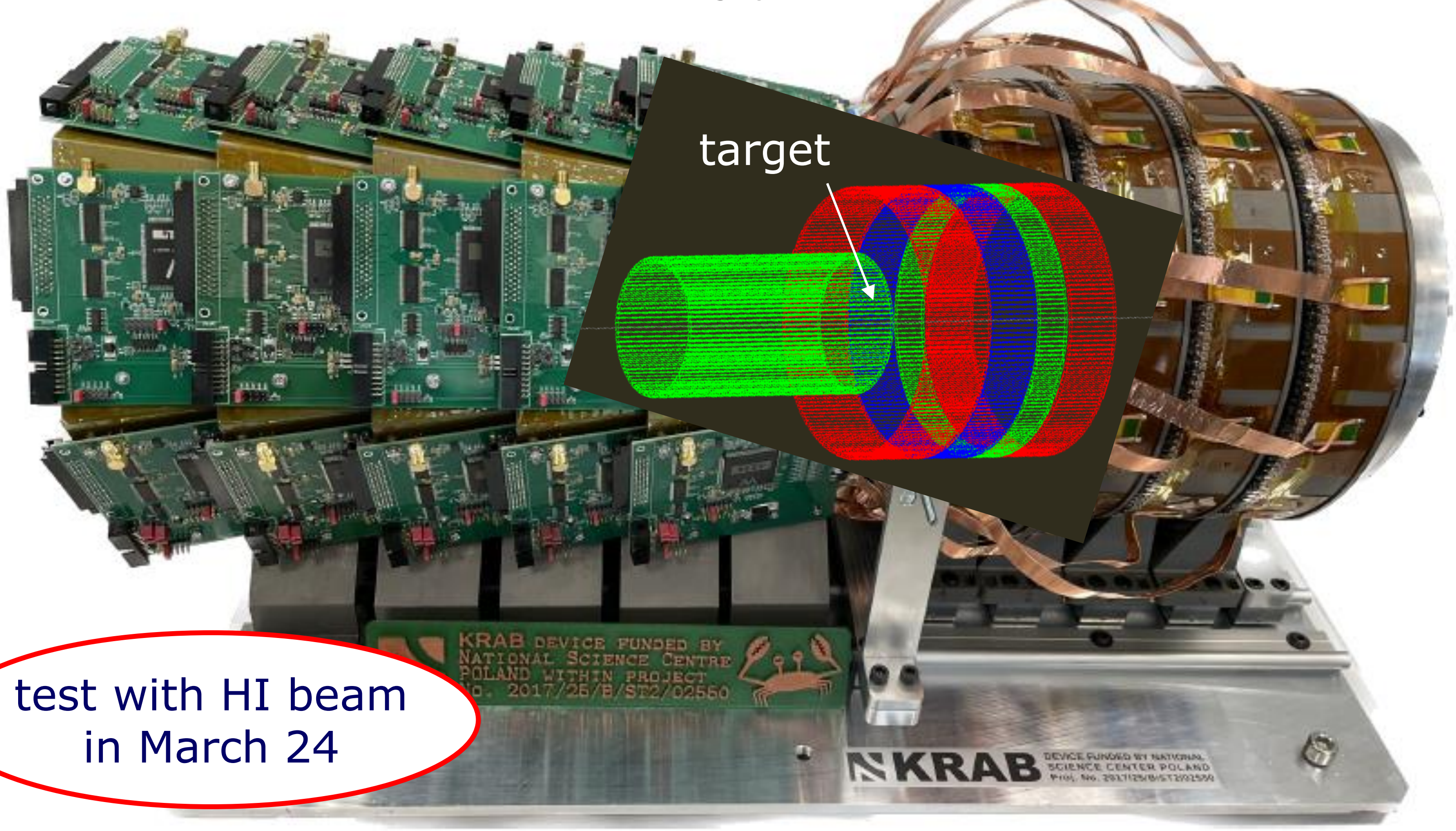
sensitivity to **higher density** with n/p flow at higher incident energy and new instrumentation



KRAB
Kraków Barrel

Main characteristics: 736 scintillation fibers 4x4 mm^2
arranged in 5 rings

43 cm



test with HI beam in March 24

NuSym23: find talks at https://indico.gsi.de/event/17017/overview

discussion of

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Betty Tsang at NuSym23

Conclusion: Comprehensive cold EOS is in sight

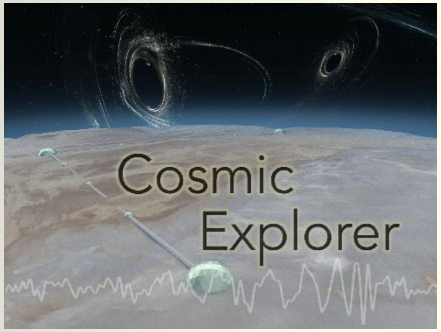
In past decade

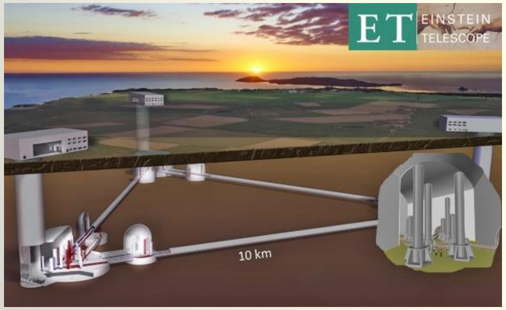
- Great new instruments: LIGO/VIRGO & NICER ⇒great measurements.
- Advances which connect experimental constraints for symmetric matter and asymmetric matter to neutron star.

Near Future

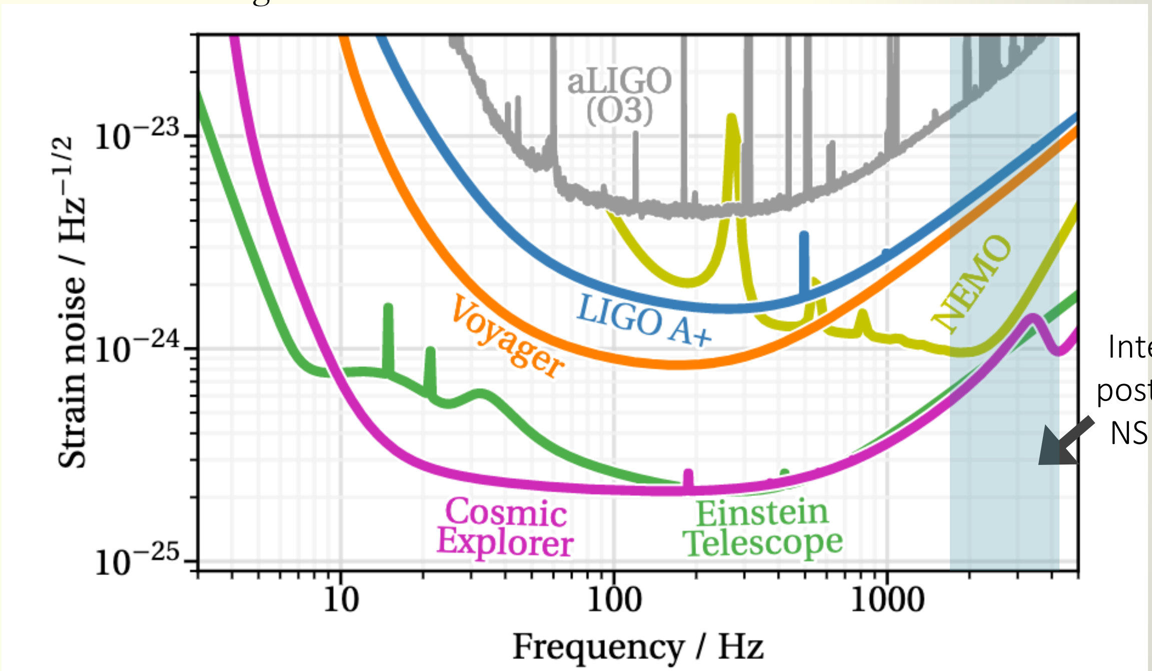
- Improvements/breakthroughs in transport model simulations.
- New neutron star measurements (O4) & update of symmetric matter constraints from Hades, BES …
- Improvement of symmetry energy constraints around 1.5 to 3 rho_0 (FRIB, FRIB400, RIKEN, SIS).
- NEW facility (FRIB400?, FAIR), NEW experiments and NEW theories to explore the golden era of neutron star physics with HIC .

Detectability of the post-merger gravitational waves





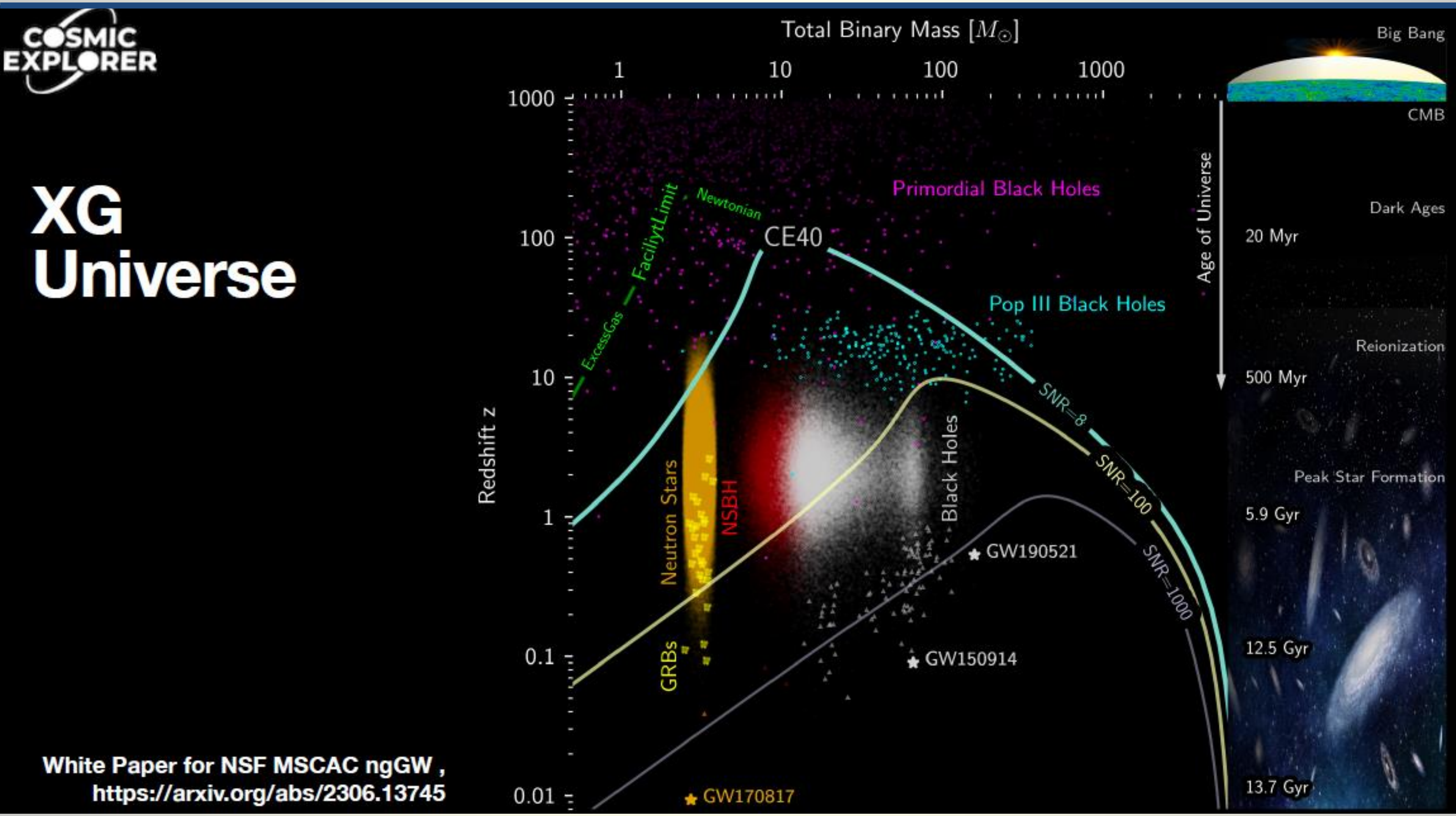
Next-generation of GW detectors will be ~10x more sensitive



Interesting post-merger NS physics

Evans et al. (2109.09882)

perspectives: Jocelyn Read at NuSym23



The reach of the Cosmic Explorer 40 km observatory for compact binary mergers as a function of total binary mass and redshift at various signal/noise (SNR) thresholds