Constraining neutron-star matter with microscopic and macroscopic collisions

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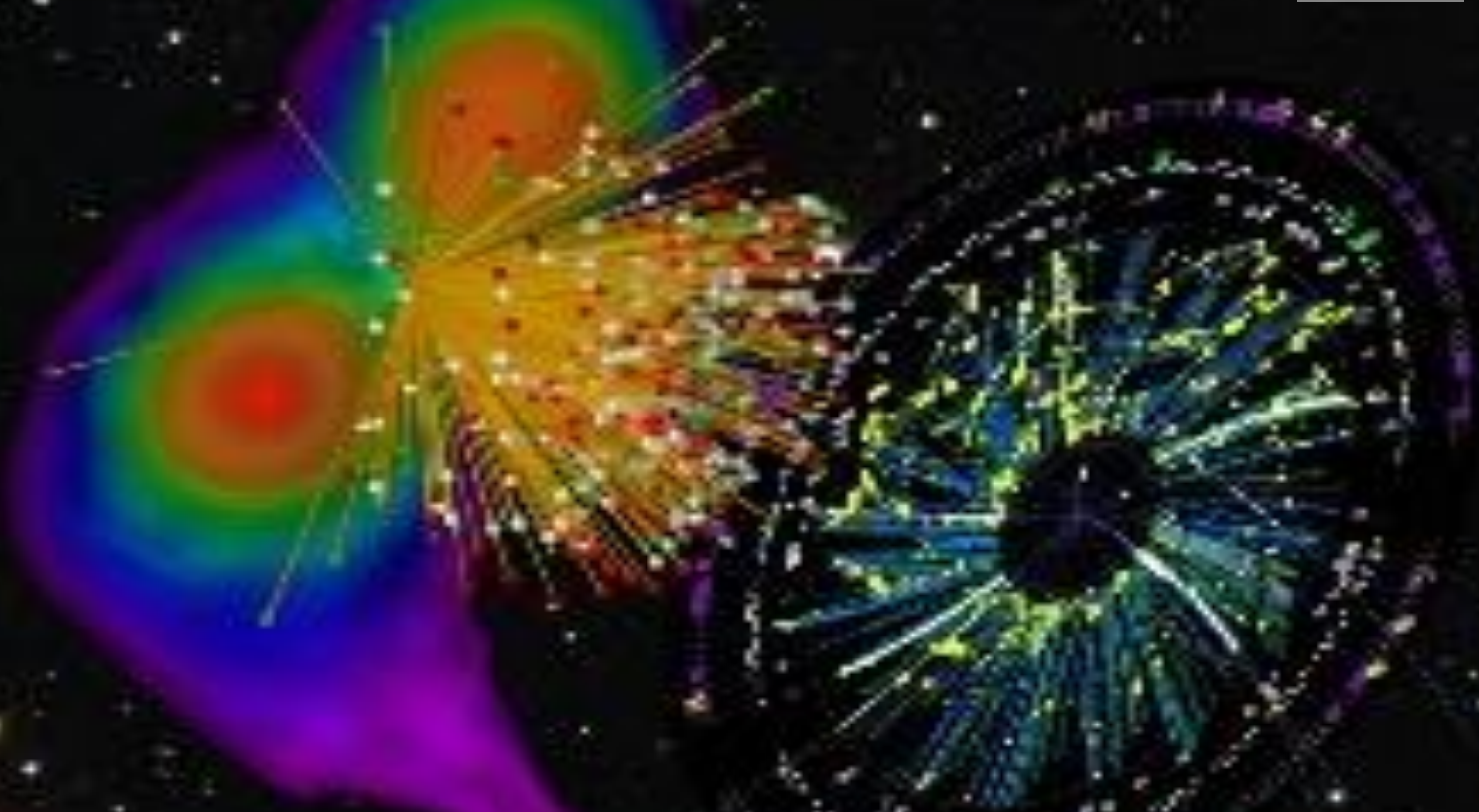
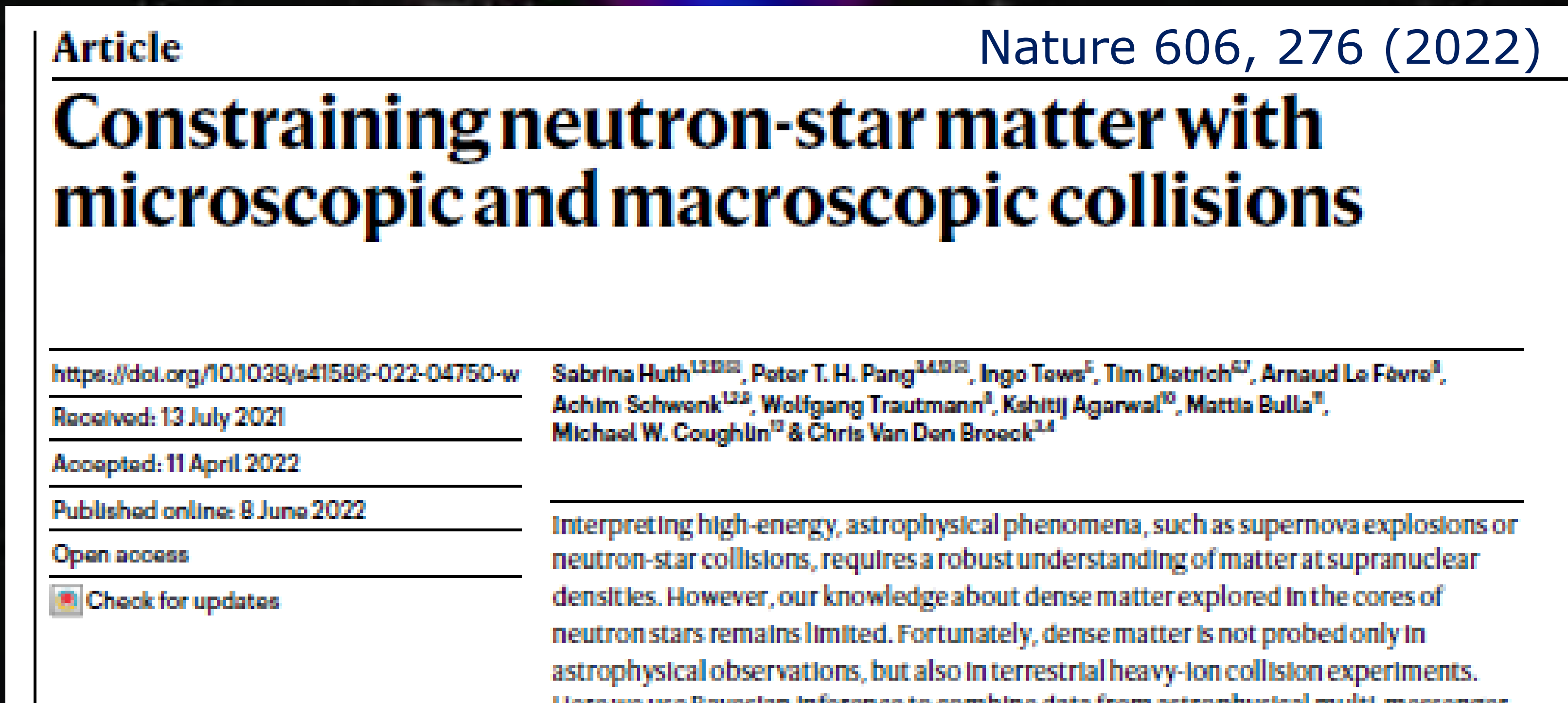


Bormio, January 24, 2023

GSI press release on June 8, 2022

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



Article

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Constraining neutron-star matter with microscopic and macroscopic collisions

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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

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

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

Bormio 2018-2020

Astro in 2018: 2-solar mass neutron stars observed (Shapiro delay)
and gravitational wave signals of GW170817 analyzed

2018 Anna Watts: pulse profiles of NICER but no final analysis

2019 Chuck Horowitz: PREX II but not yet CREX

2019 W.T.: neutron star pressure from elliptic-flow ratios in Au+Au

2019 Hans-Thomas Janka: NS mergers as source of r-process nuclei

2020 Jim Lattimer: results from GW170817 and first radius of NICER

2020 Wolfram Weise: hyperon puzzle probably not existing

2020 Jorge Piekarewicz: Neutron rich matter in the cosmos and on earth

2017: merger event GW170817 and launch of NICER

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+, Science 2020)

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

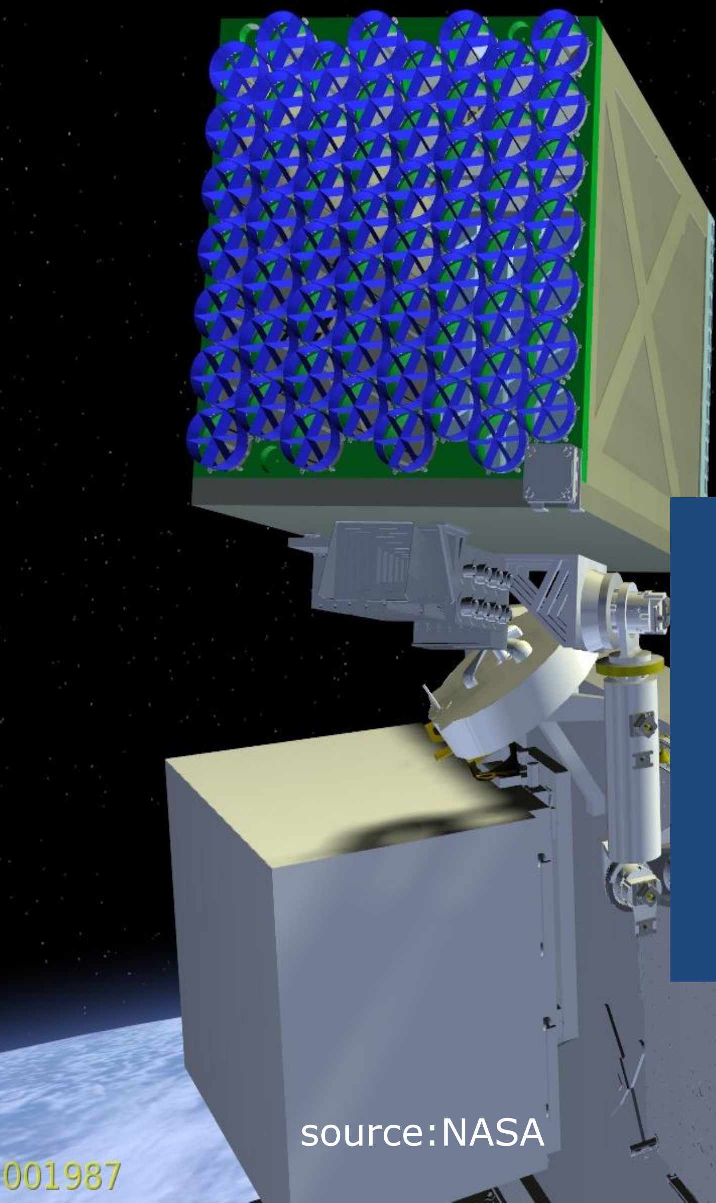
What was found: **$R_{1.4}$ = 12.01 ± 0.78 km (95%)**

Measurements of heavy-ion collisions 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!

NICER on the ISS



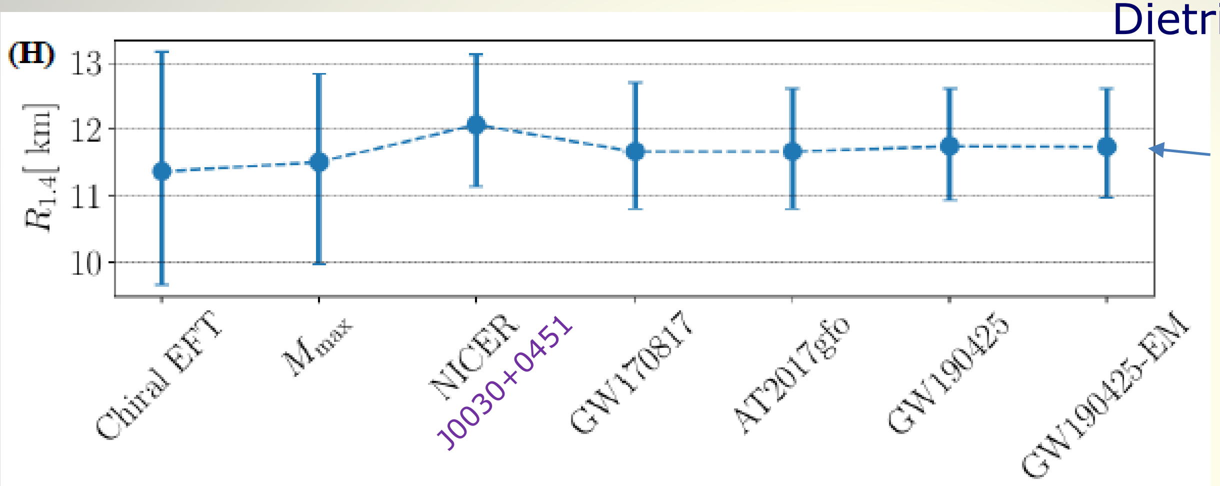
Neutron-star Interior Composition Explorer
56 X-ray concentrators (0.2-12 keV, 100 ns)
time resolved X-ray emissions of neutron stars

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: 2.9 ms, 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)

χEFT + astro: frame work based on Bayesian inference

Dietrich+, Science 370 (2020)



$R_{1.4} = 11.75$ km $^{+0.86}_{-0.81}$ (90%)

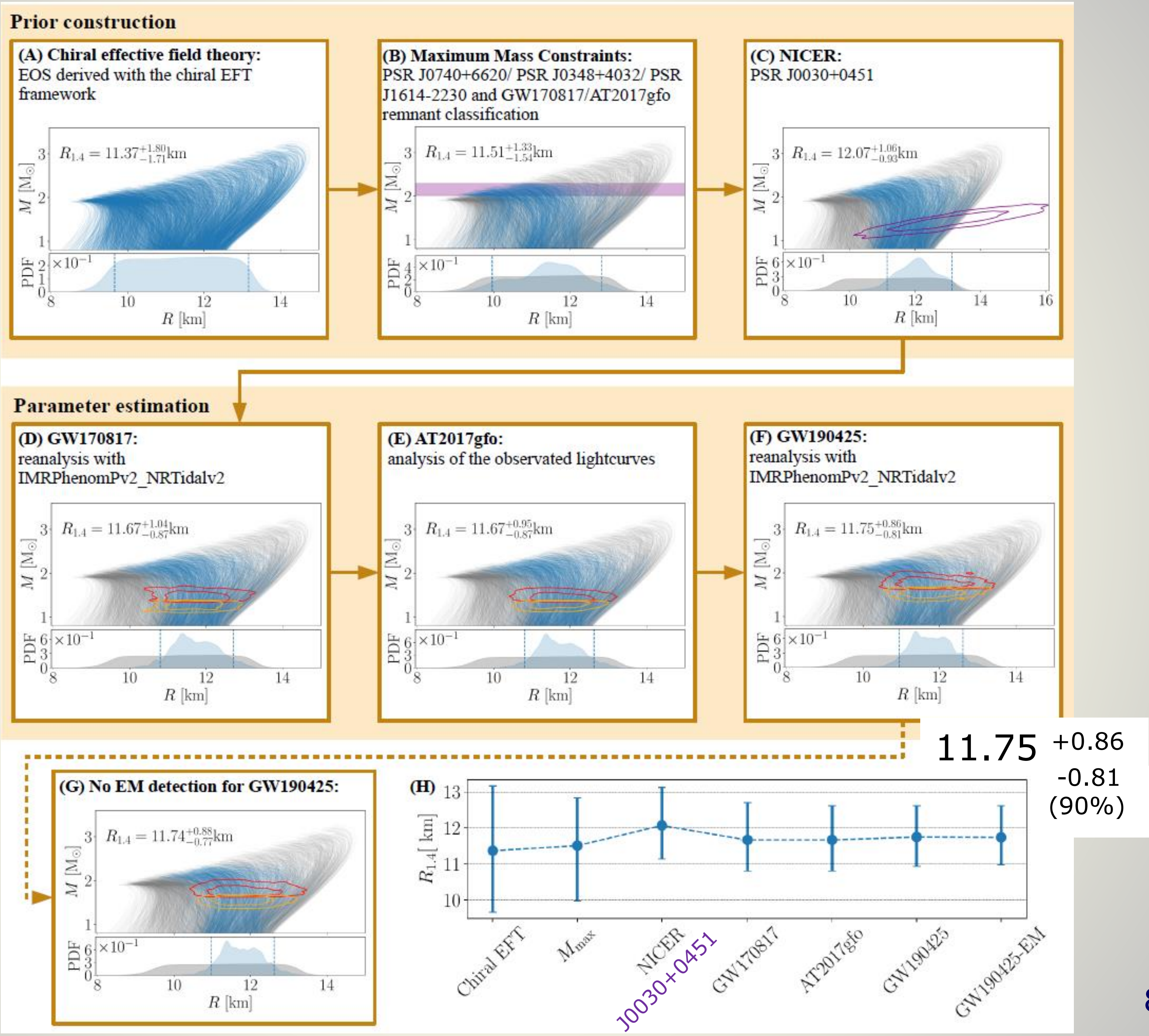
for refs. see paper Dietrich+

heavy PSRs	J0740+6620, J0348+0432, J1614-2230	
M_{max} (remnant)	$M_{max} < 2.16 \pm 0.16$ modeling of collapse considering rotation	Rezzolla+ (2018)
NICER	PSR J0030+0451 R=13.0 km mass = 1.44 ± 0.15 M_{sun}; error ~±1.2 km (68%)	Miller+ (2019)
GW170817	new analysis of inspiral signal f ϵ [23; 2048]Hz	
AT2017gfo	new kilonova modeling	
GW190425	combined mass 3.4 M_{sun}	Abbott+ (2020)
GW190425-EM	no EM counterpart	Coughlin+(2020)

2020
Dietrich+
Science

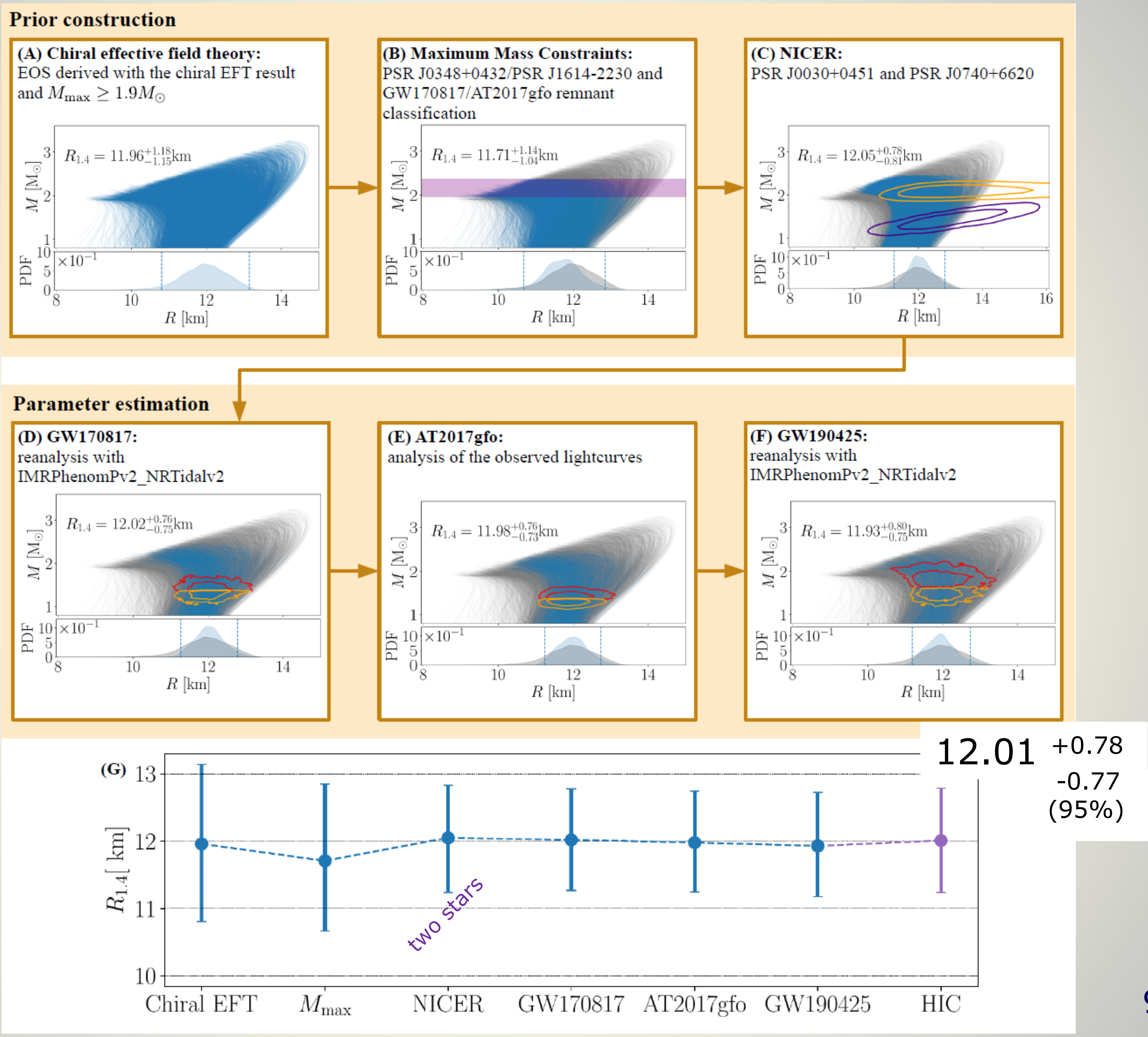
5000 EoS

Fig. 1



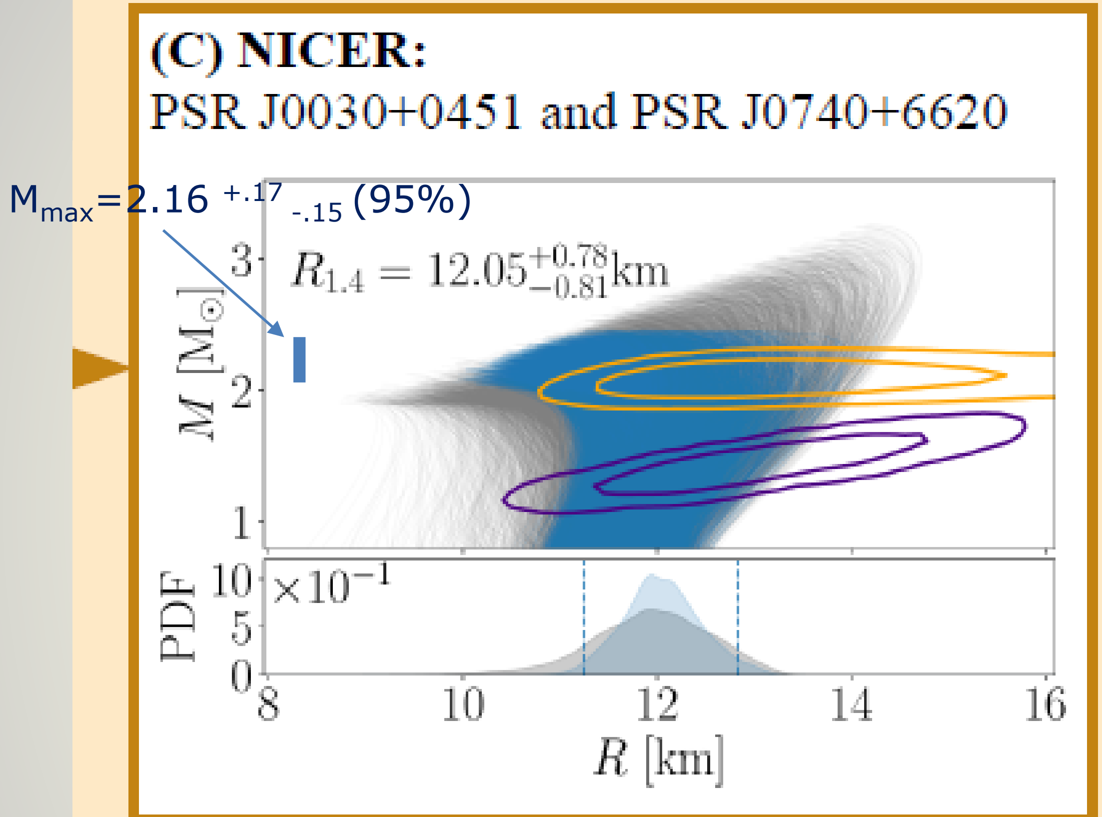
2022 Huth+ Nature

15000 EoS

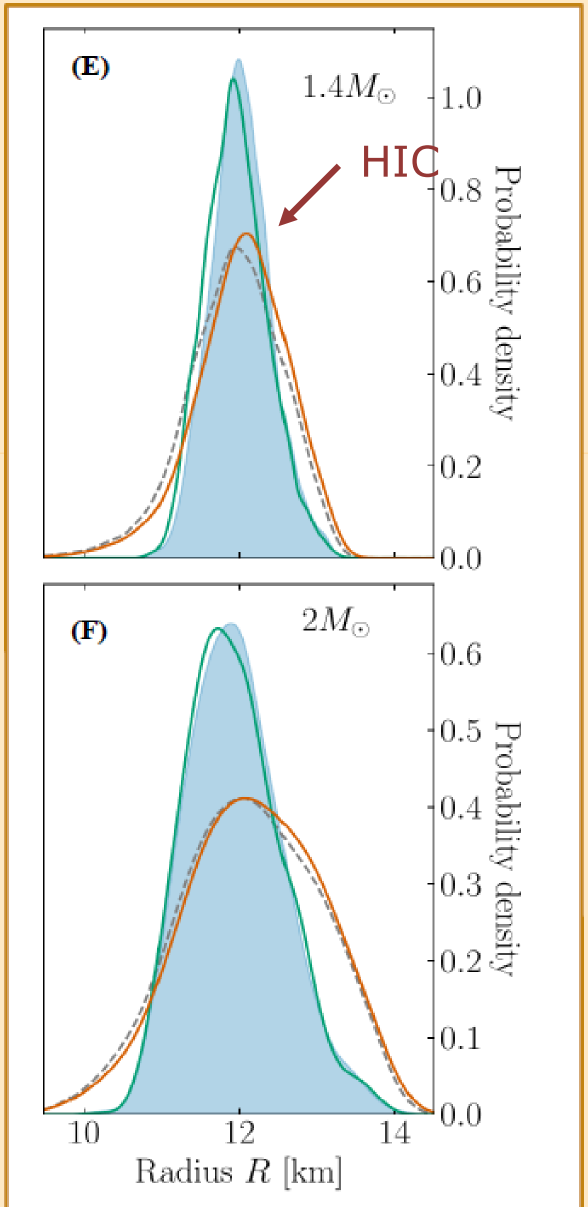


Extended Data Fig. 3

mass vs radius for neutron stars



from Extended Data Fig. 3

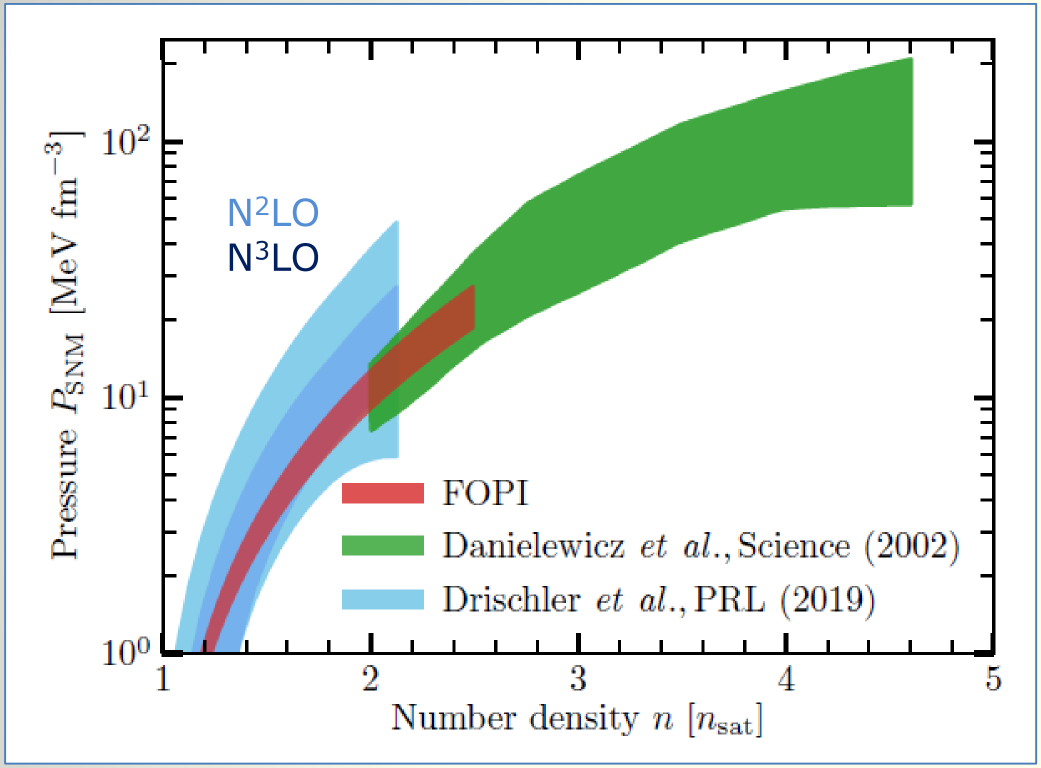


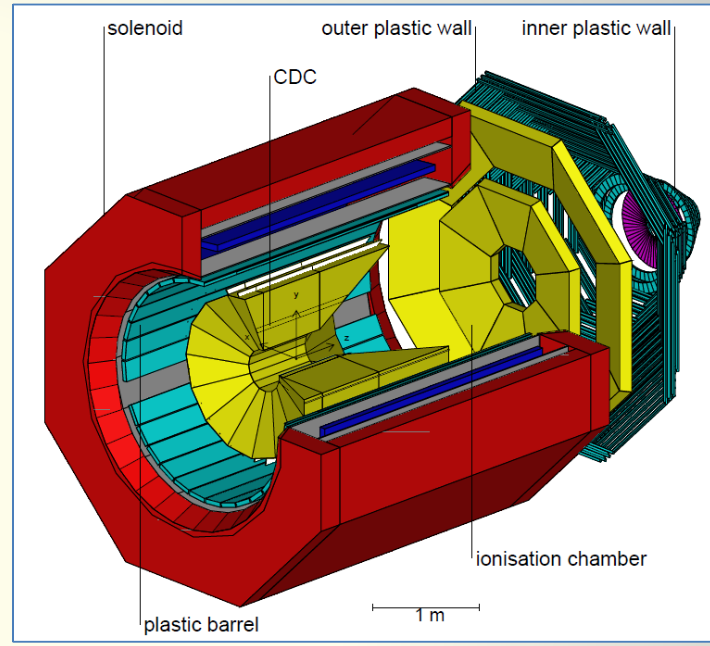
from Fig. 2
contours 68%
and 95%

Huth+, Nature (2022)

pressure vs density for symmetric nuclear matter

Extended Data Fig. 5 Huth et al., Nature 606

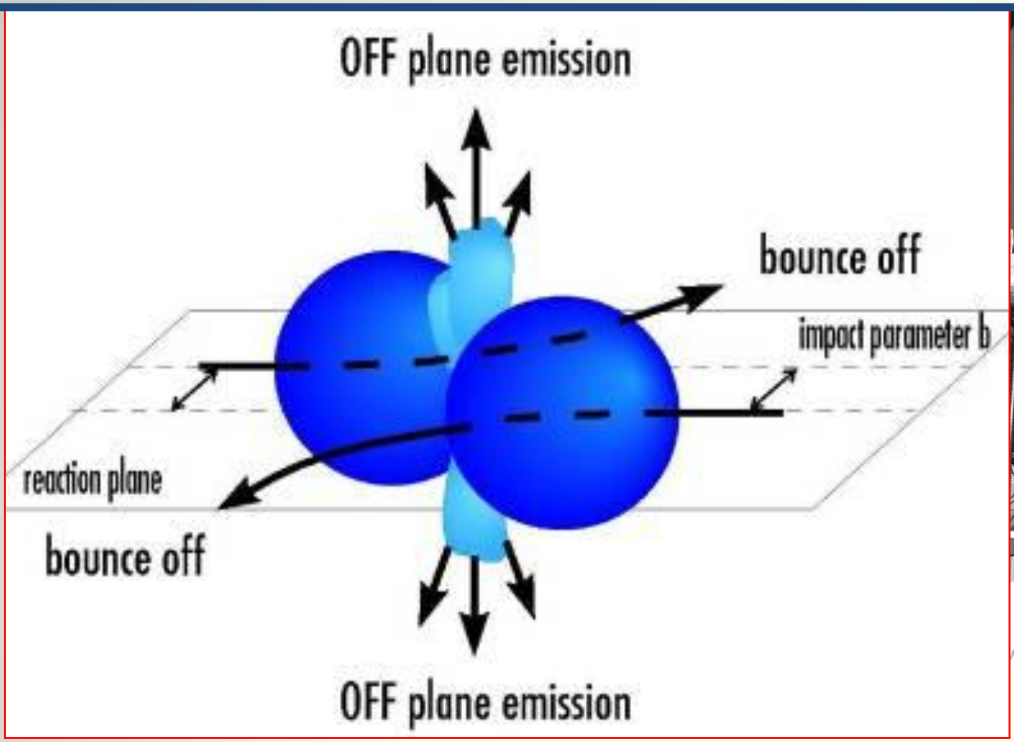


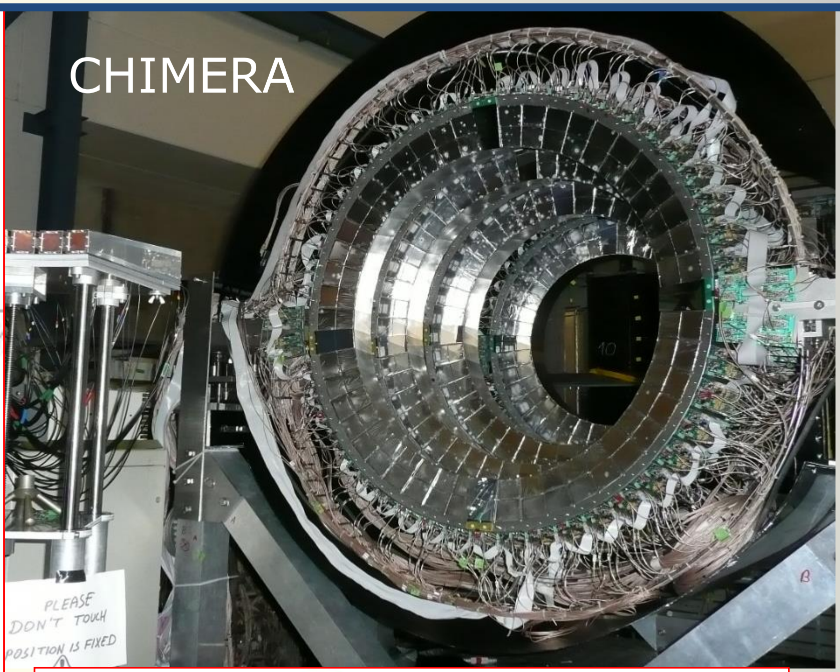


adopted
FOPI result (1σ)
K_0=200±25 MeV

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)

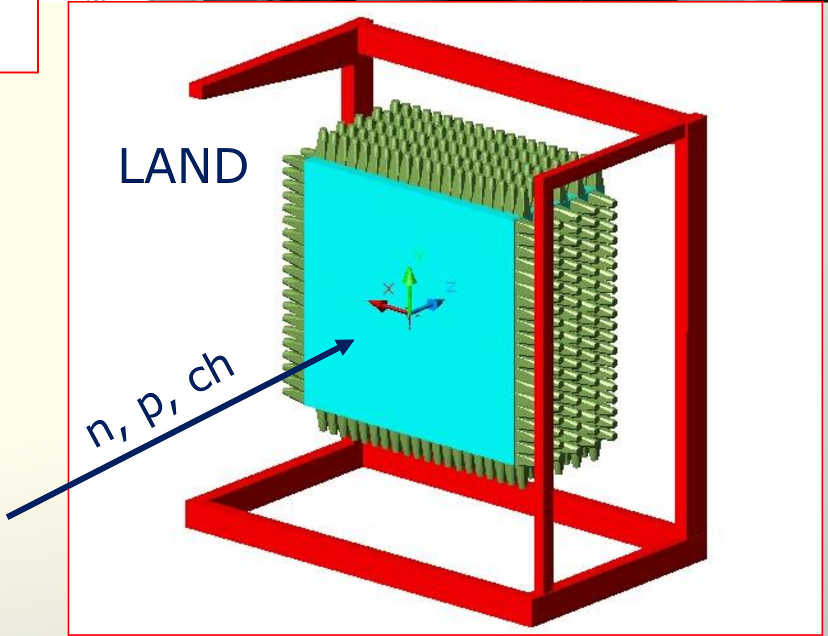
ASY-EOS: neutron vs charged-particle elliptic flow ratio





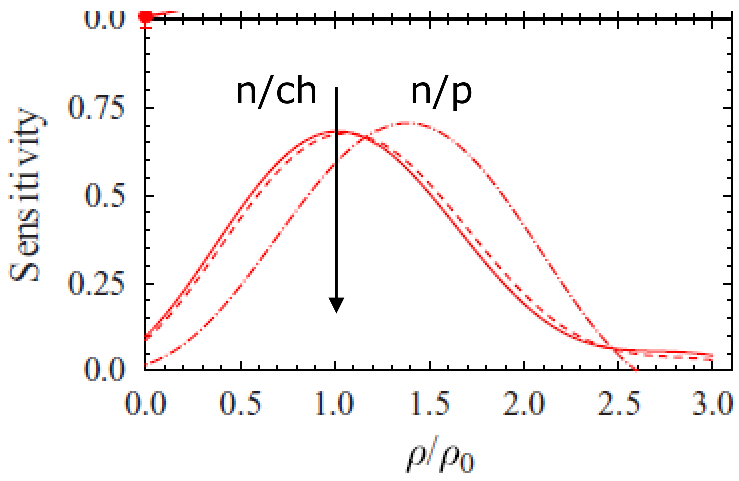
tested with existing **FOPI-LAND** data
^{197}Au + ^{197}Au @ 400 A MeV
Russotto+ PLB 697 (2011)

ASY-EOS experiment in 2011
^{197}Au + ^{197}Au @ 400 A MeV
Russotto+ PRC 94 (2016)



ASY-EOS: neutron vs charged-particle elliptic flow ratio

sensitivity to density

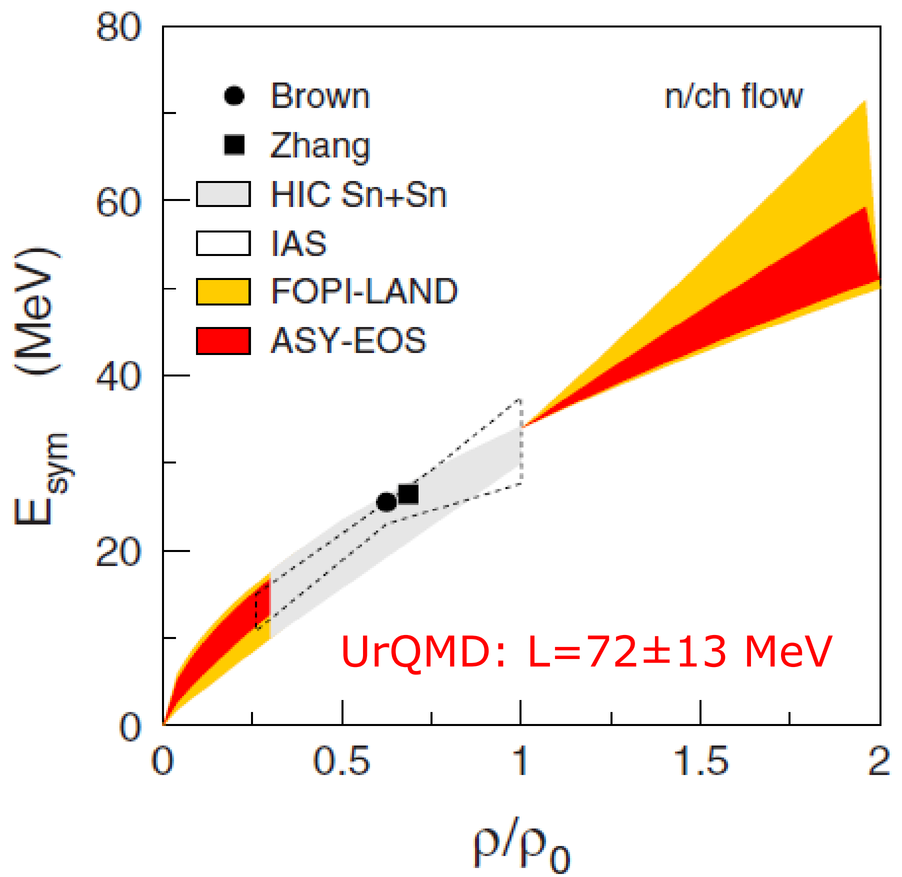


density probed extends to 2.5 ρ_0
maximum near **saturation density**

$$L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho}\Big|_{\rho=\rho_0}$$

pressure $p_0 = L \cdot \rho_0/3$

P. Russotto+ PRC 94, 034608 (2016)



χEFT prior + HIC + astro

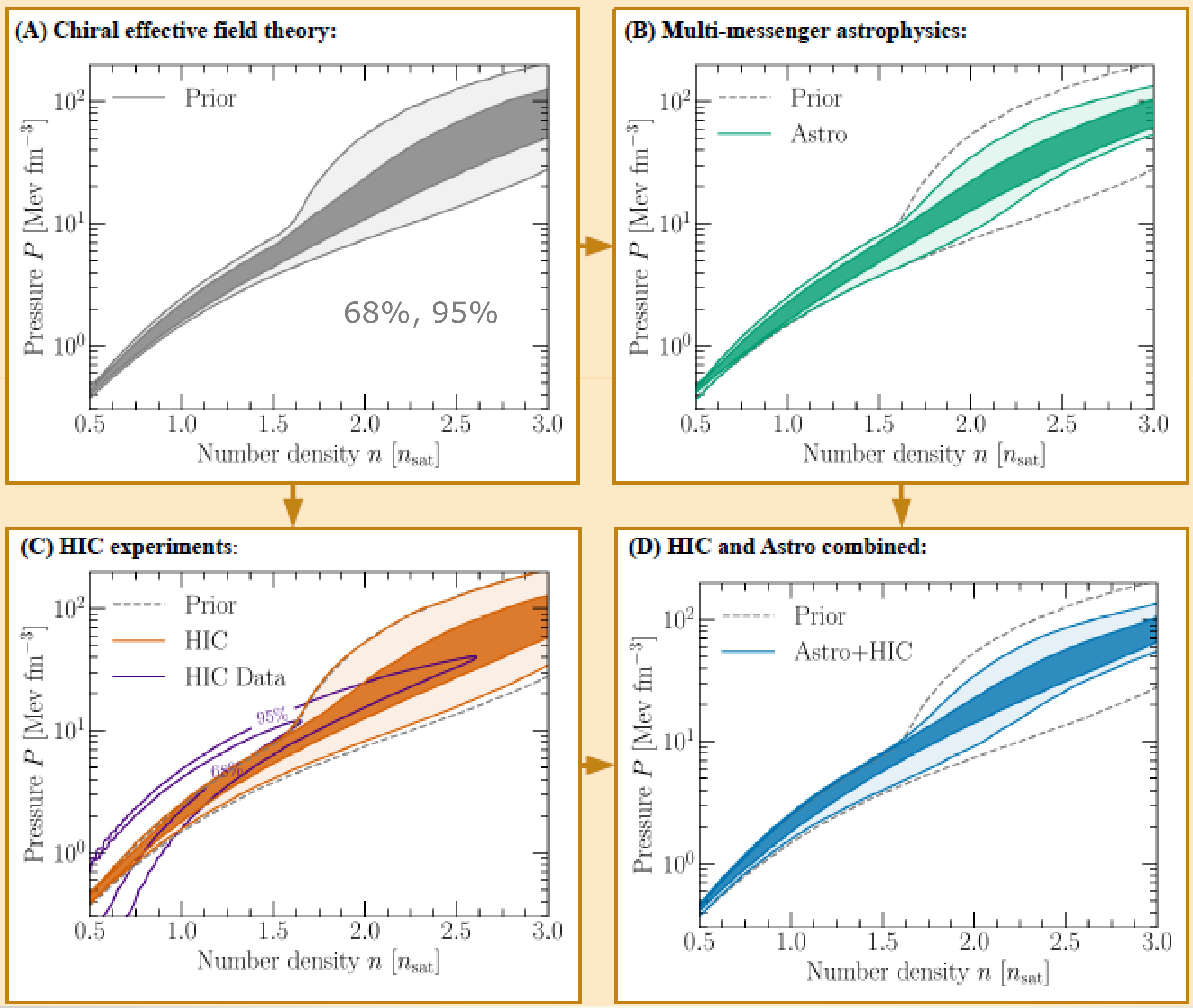


Fig. 1
neutron star matter

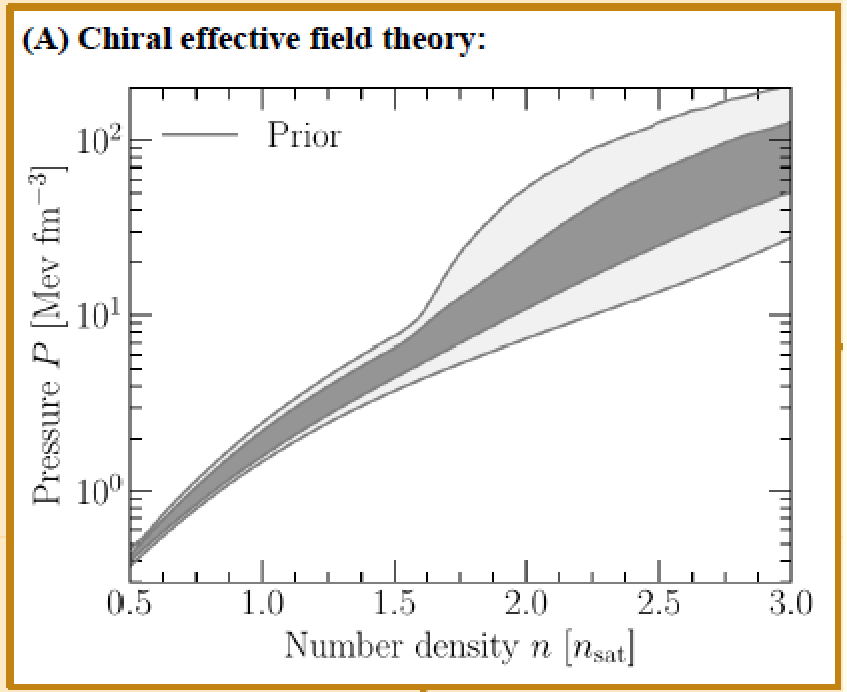
contours at 68% and 95% credibility

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

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

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

EFT ->1.5 ρ_0



stability $c_s > 0$

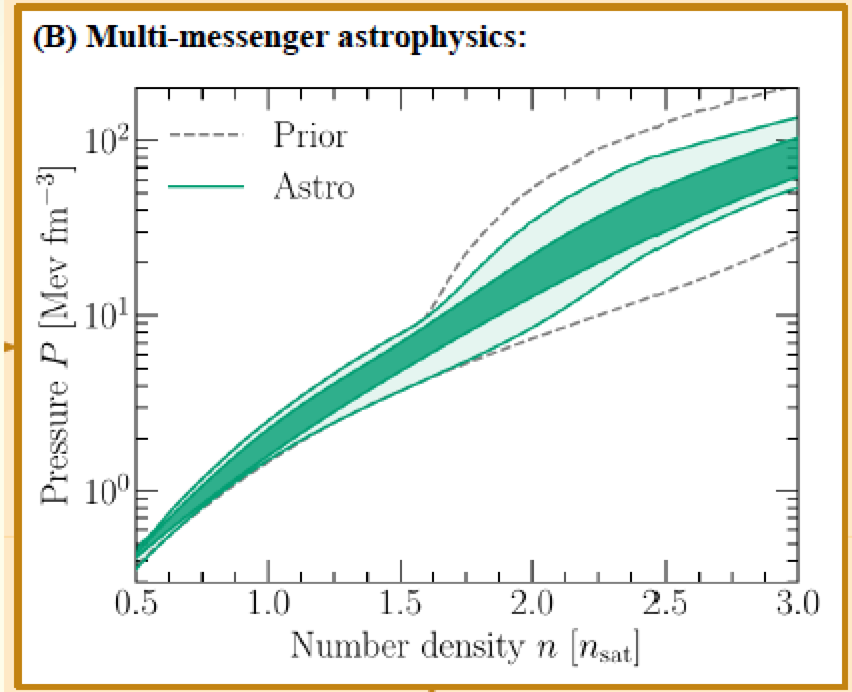
causality $c_s < c$

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

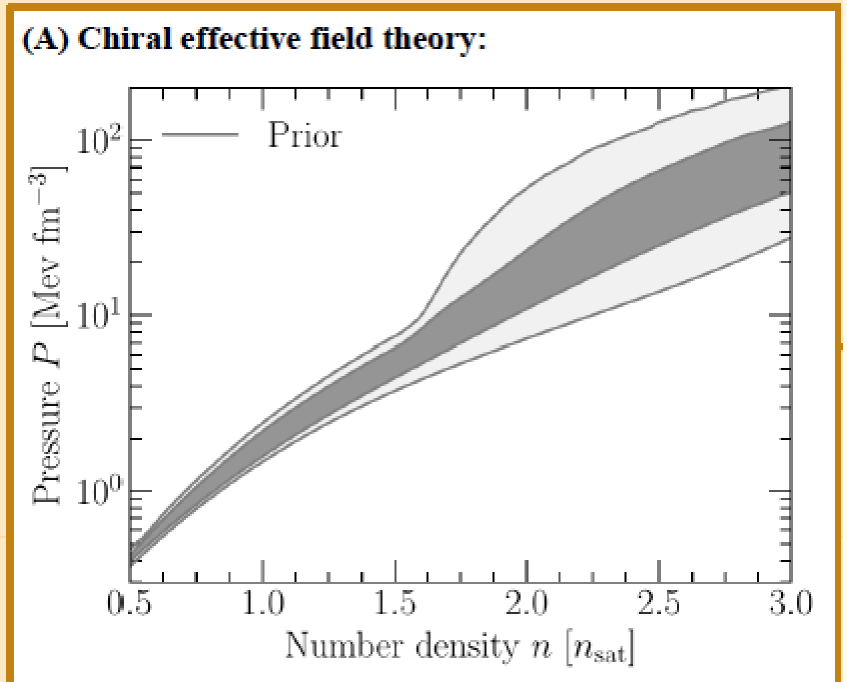
$$c_S^2 = \frac{\partial p(\epsilon)}{\partial \epsilon},$$

see Essick+ PRC 102 (2020) for χEFT breakdown scale:

„NICER observations suggest that the EoS stiffens relative to χEFT predictions at or slightly above nuclear saturation density.“ (using radius of PSR J0030 + 0451)



EFT ->1.5 ρ_0



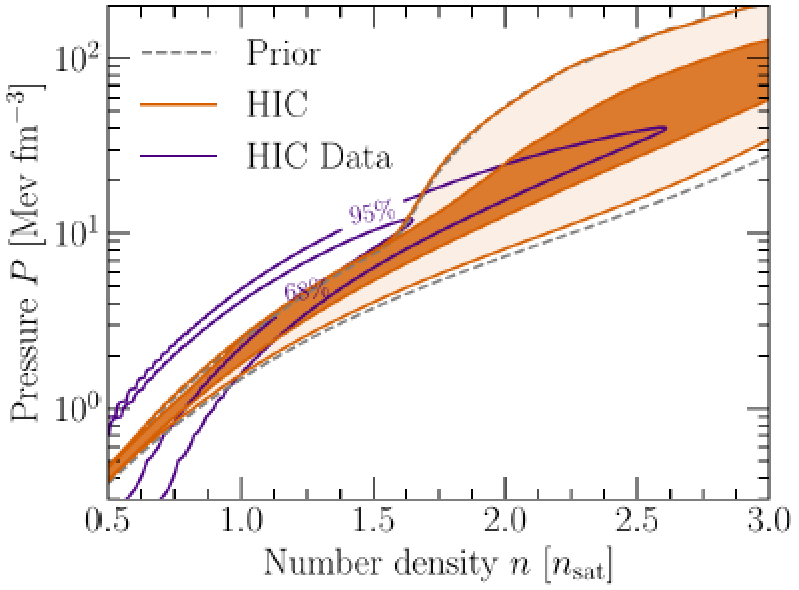
stability $c_s > 0$

causality $c_s < c$

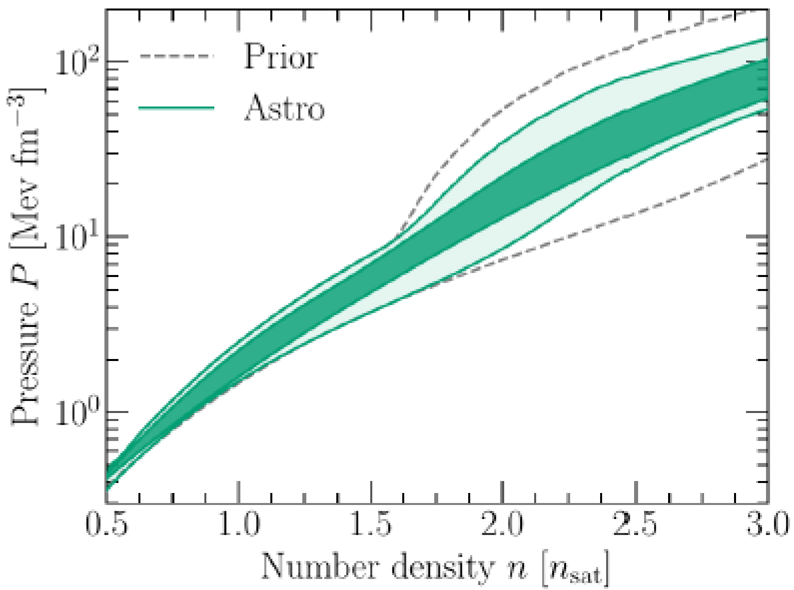
$M_{max} \geq 1.9\ M_{sun}$

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

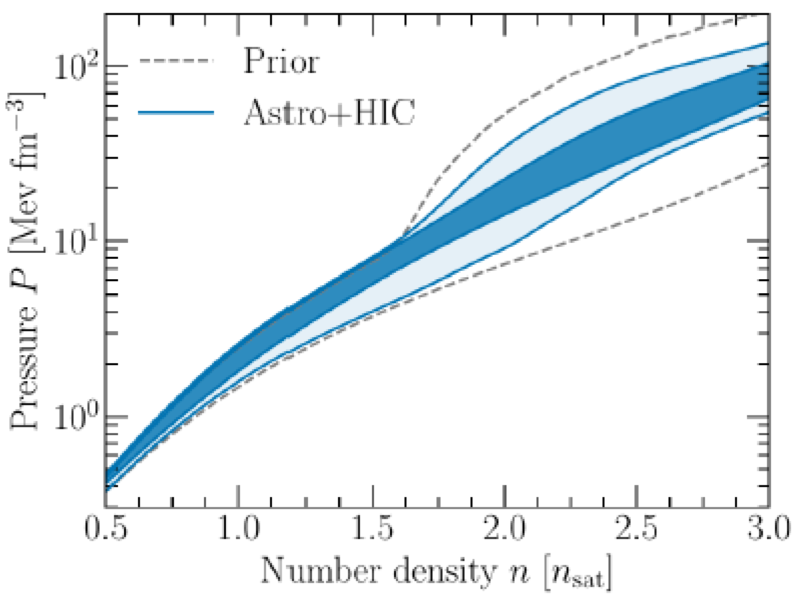
(C) HIC experiments:



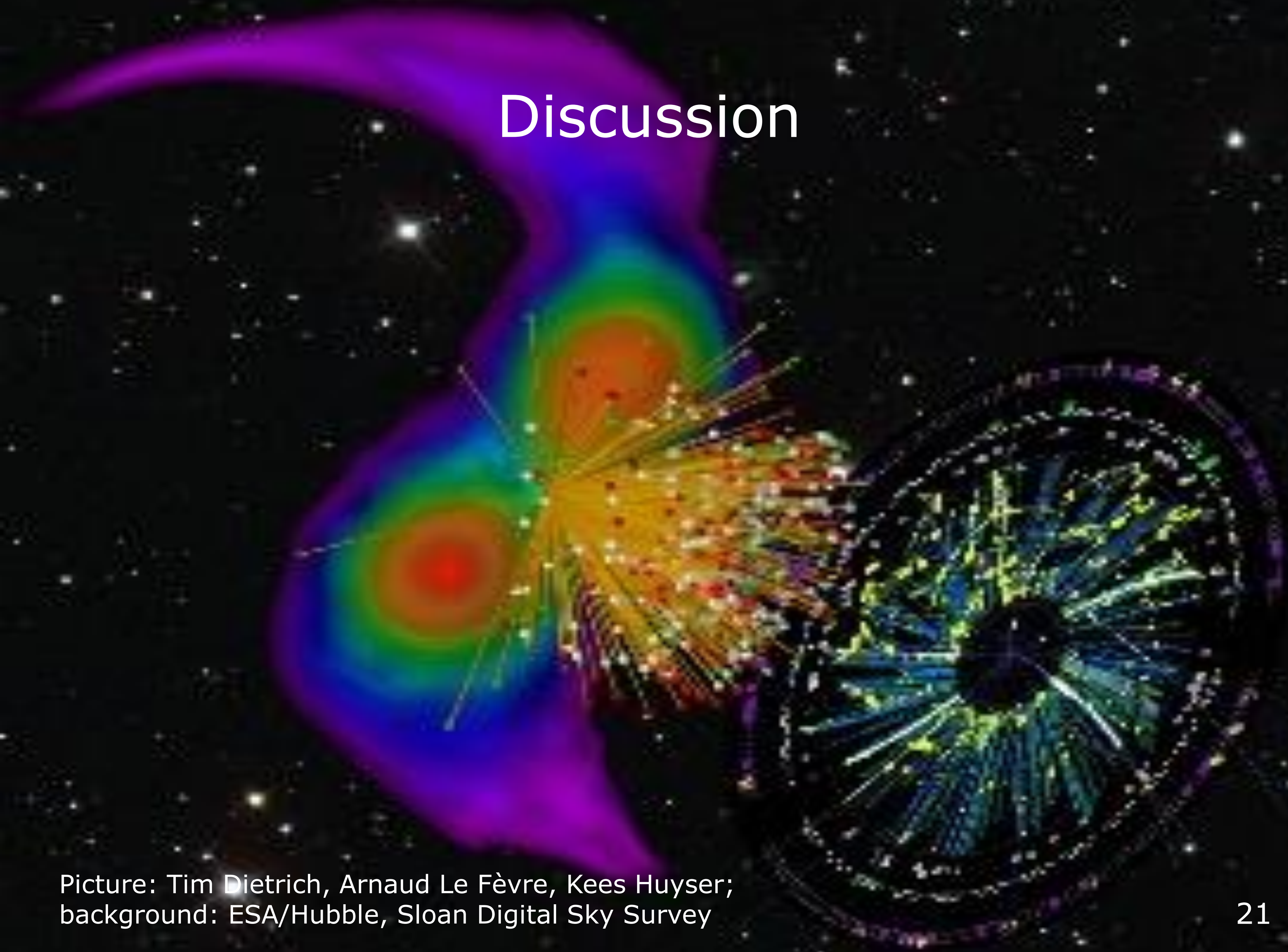
(B) Multi-messenger astrophysics:



(D) HIC and Astro combined:



Discussion



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

stability (from Extended Data and Supplementary Tables)

Huth et al., Nature 606, 276

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

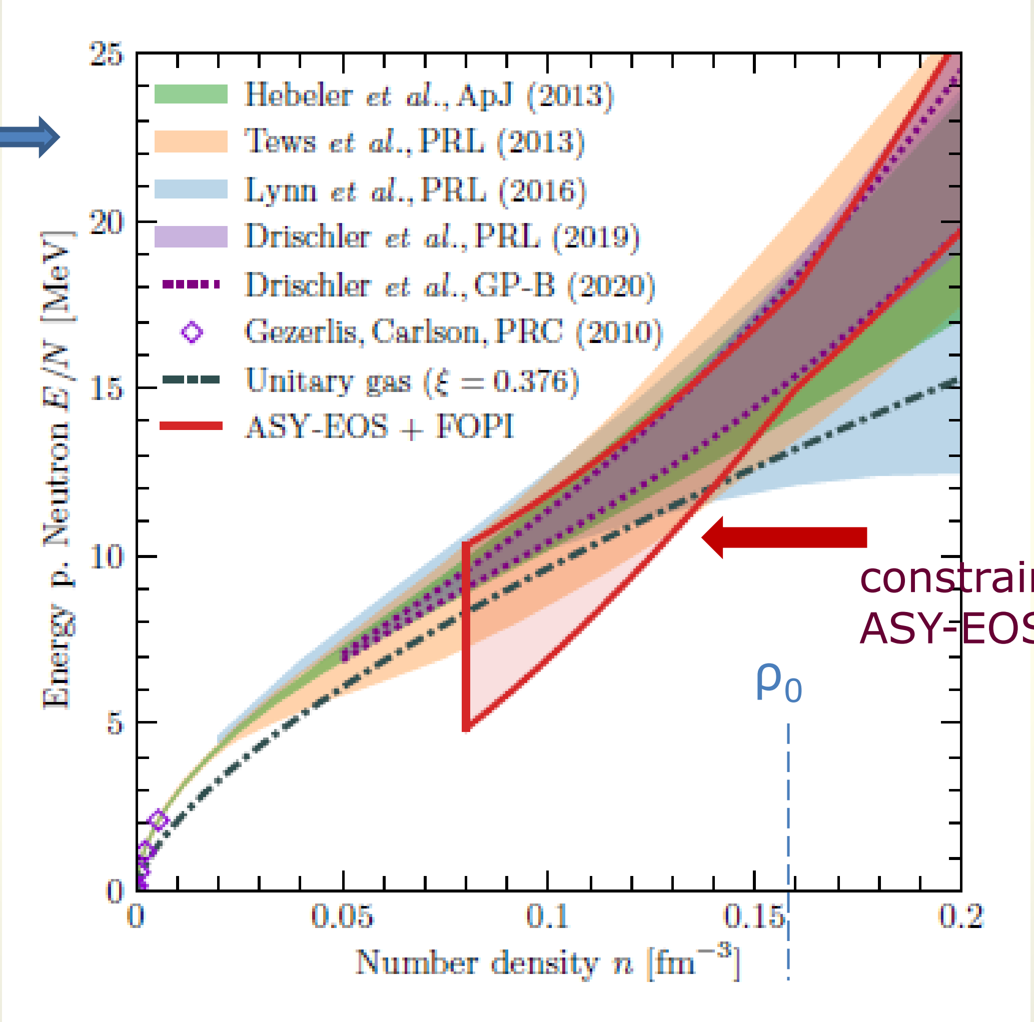
$R_{1.4}$ = 12.01 +0.78 -0.77 km (95%)
12.06 +1.13 -1.18 km (HIC only)
11.94 +0.79 -0.78 km (astro only)
11.96 +1.18 -1.15 km (prior: χEFT & M_{max} >1.9 M_{sun})

→ **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 (instead of n/ch)
12.21 +0.73 –0.76	1 GeV sensitivity
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

χEFT and HIC

EFT predictions

pure neutron matter



constraint deduced from ASY-EOS and FOPI data

Huth et al., Nature 606, 276

Extended Data Fig. 4

summary and outlook

progress by **combining terrestrial** and **astrophysical** information

strongest effect from using **χEFT up to 1.5 ρ_0**

further improvements possible with

laboratory data for 1-2 ρ_0 (**ASY-EOS II**, Sπrit II, HADES, CBM, …)

expect **new data from gravitational wave observatories**

LIGO O4 (March 2023), Virgo, KAGRA (March 2023)

expect **smaller errors for PSR J0740+6620 radius and mass**

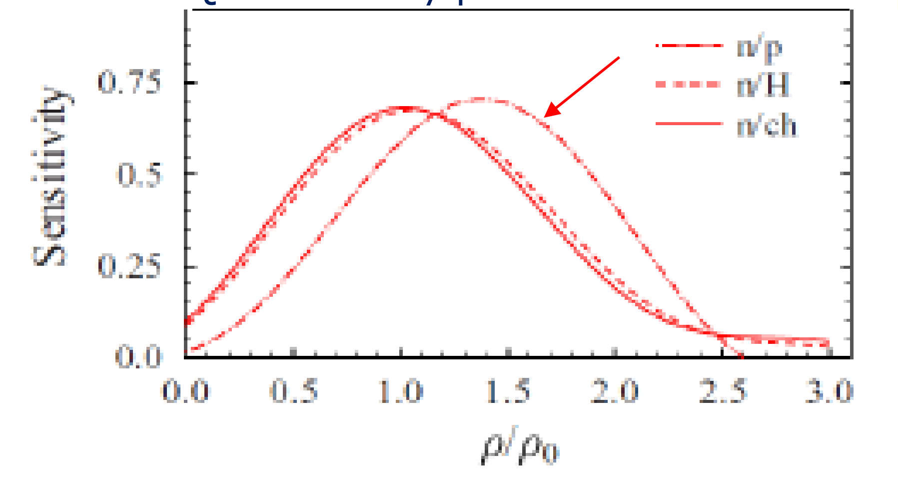
from improved NICER modeling (see Riley+ ApJL 918:L27) and

from continued timing observations (see Fonseca+ ApJL 915:L12)

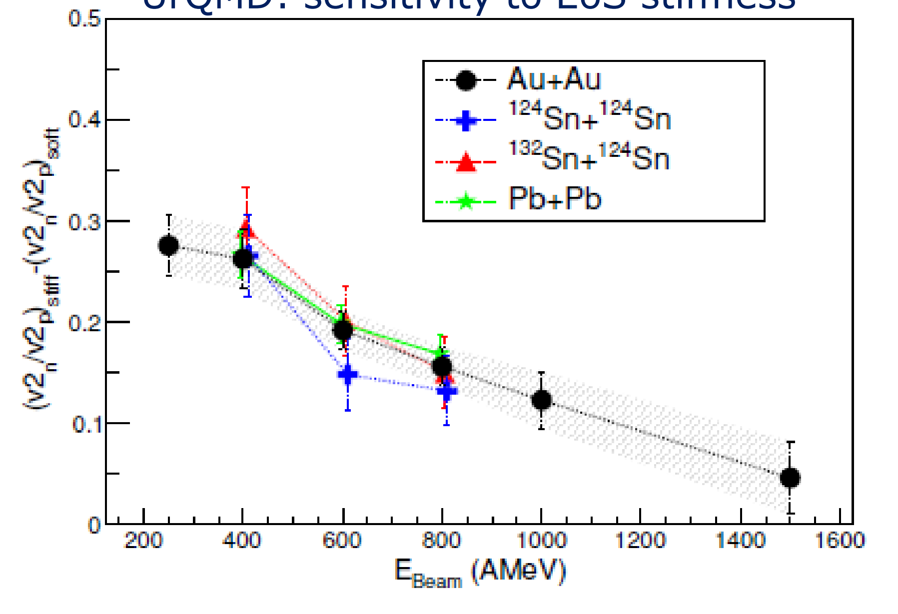
S. Huth, P. T. H. Pang, I. Tews,
T. Dietrich, A. Le Fèvre, A. Schwenk,
W. T., A. K. Agarwal, M. Bulla,
M. W. Coughlin & C. Van Den Broeck

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

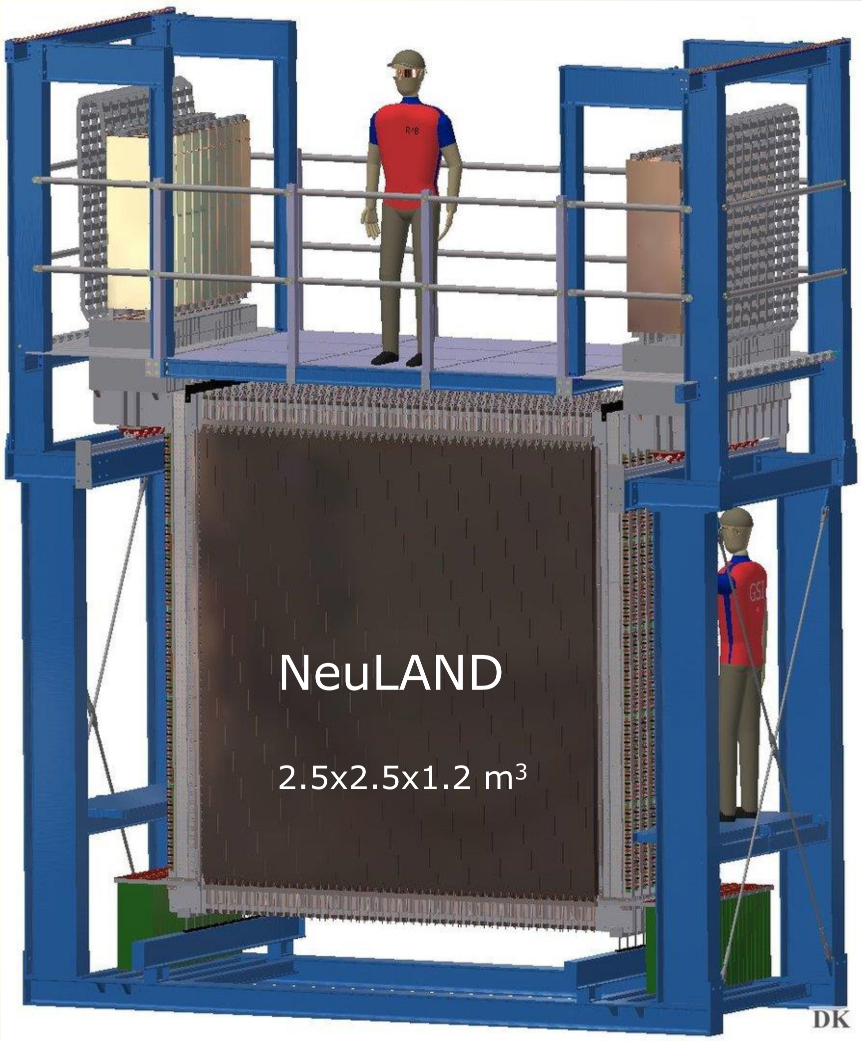
TüQMD: density probed at 400 AMeV



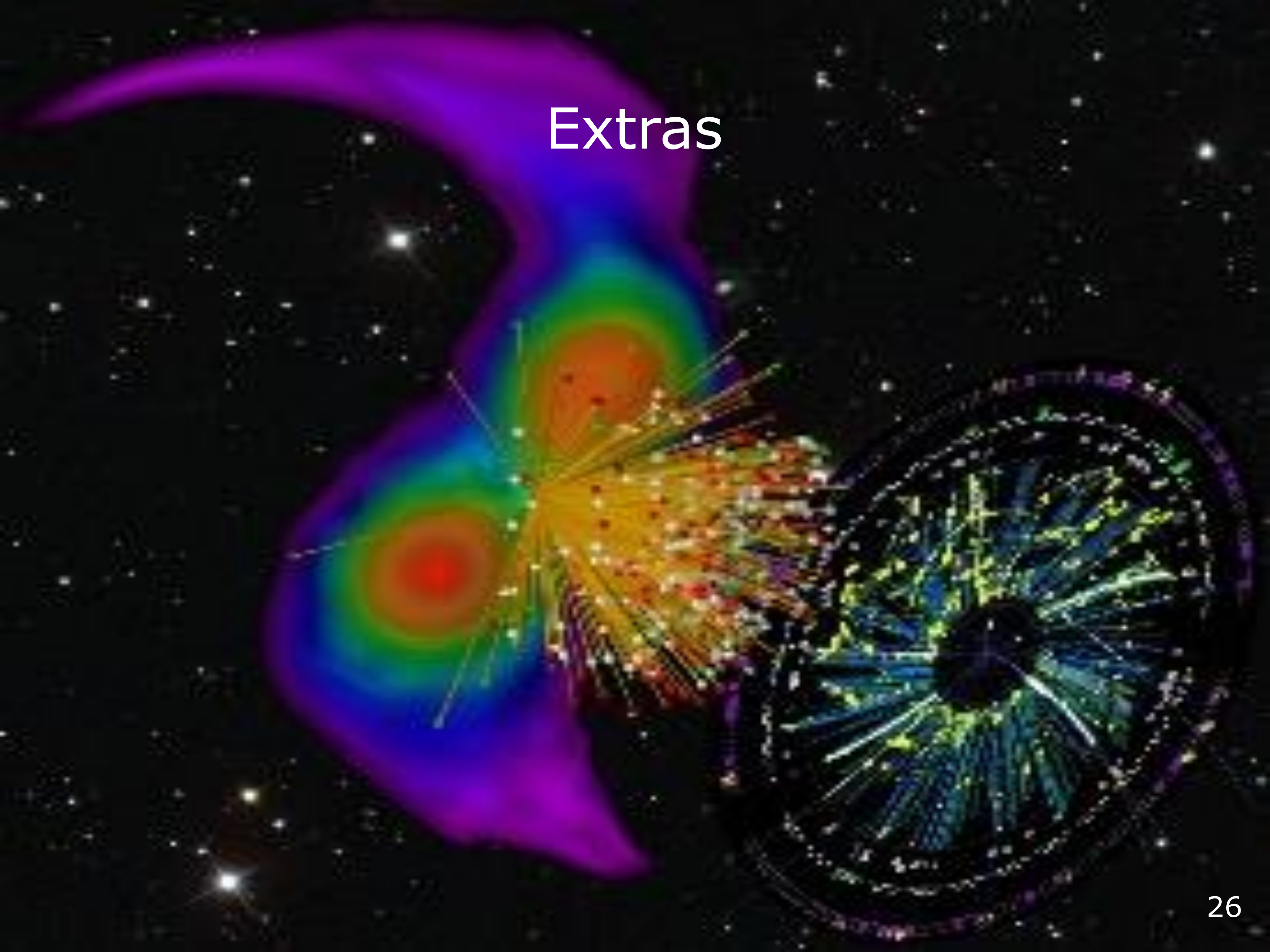
UrQMD: sensitivity to EoS stiffness

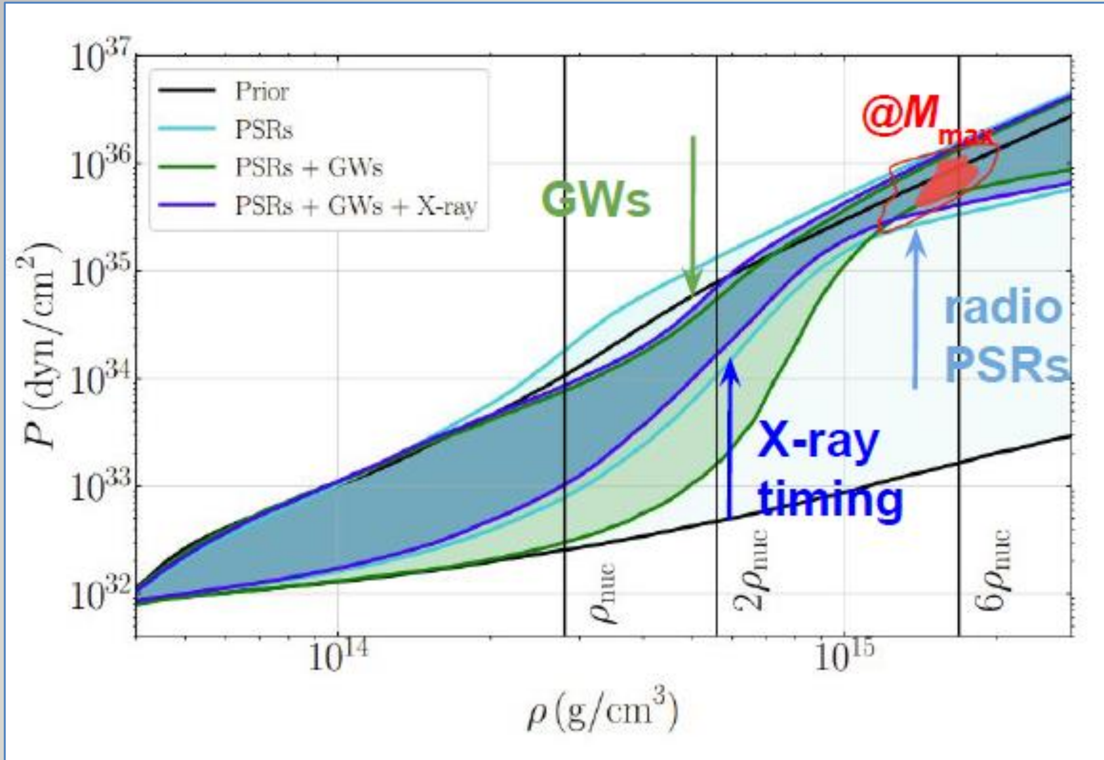


sensitivity to **higher density** with n/p flow at higher incident energy and new instrumentation



Extras





Reed Essick
talk at NuSym2022
Catania, Sept 2022

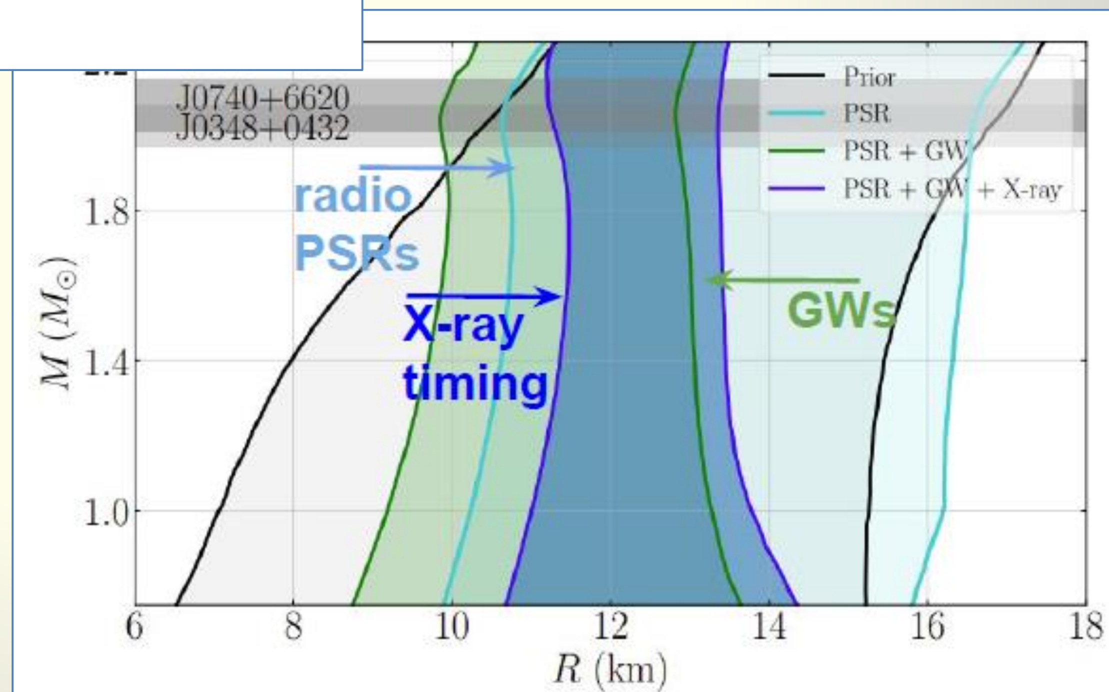
see **Legred+, Landry+**
PRD 104, 063003 (2021)
PRD 101, 123007 (2020)

model-agnostic prior

Result (90%)

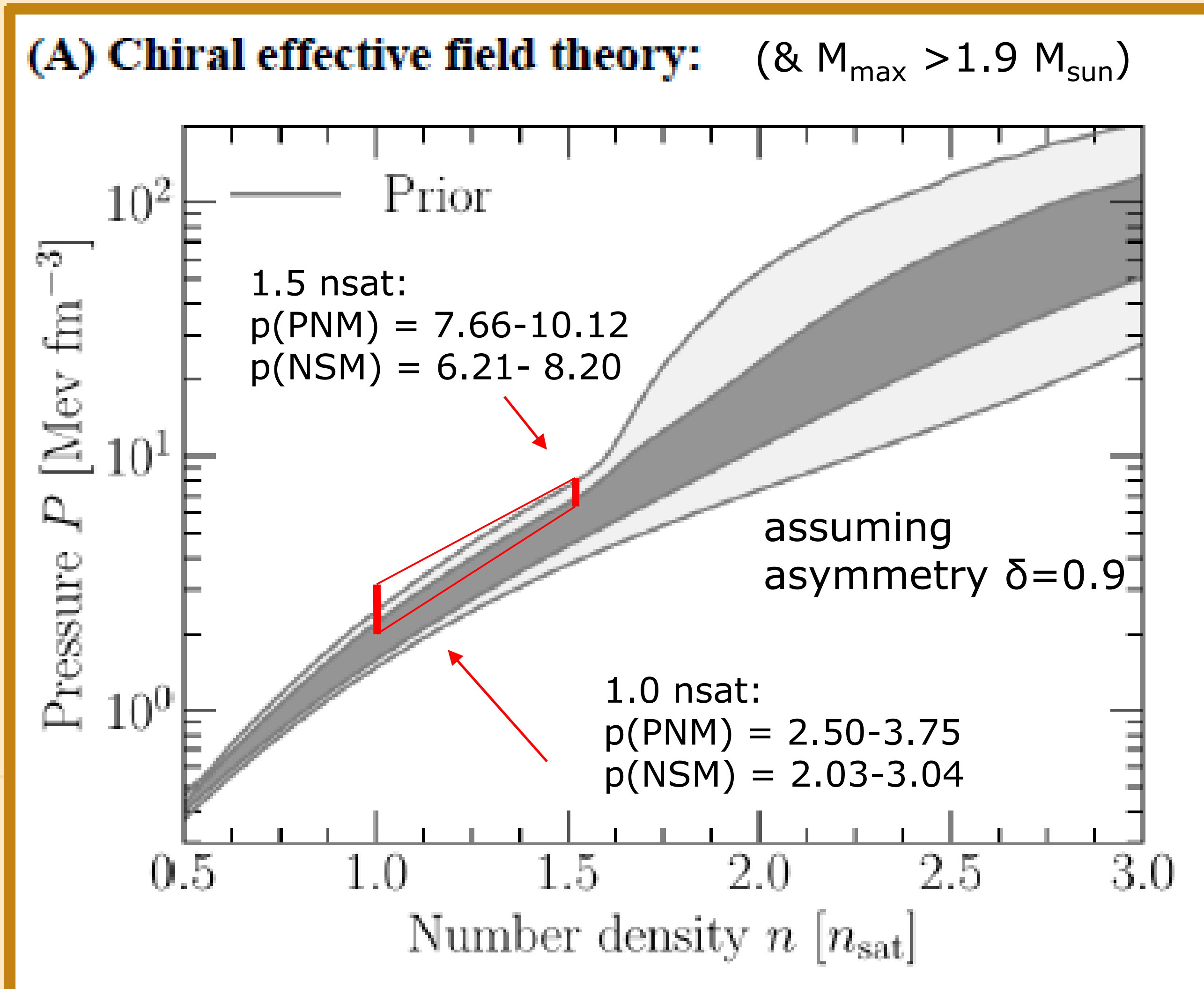
with Miller+ for J0740.6620
$\mathbf{R_{1.4} = 12.56}$ +1.00 -1.07 km

with Riley+ for J0740.6620
$\mathbf{R_{1.4} = 12.34}$ +1.01 -1.25 km



developments in EFT

example: Drischler+ PRL 125 (2020)

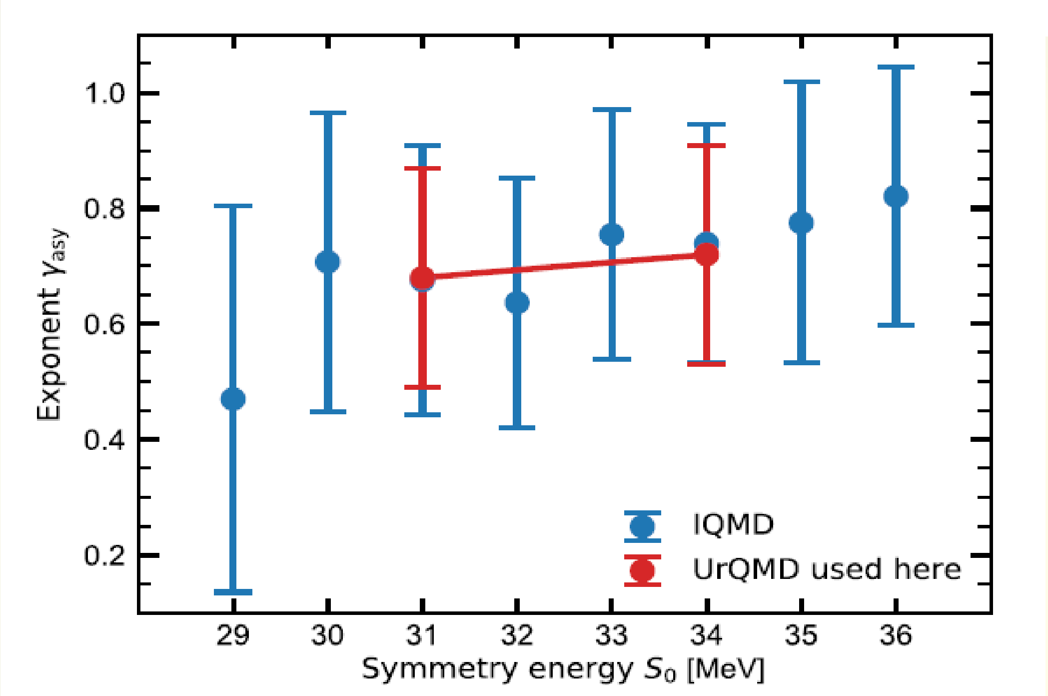


role of S_0

$$\mathbf{E_{sym}(\rho)} = (S_0\text{-}12\text{ MeV})\cdot(\rho/\rho_0)^{\gamma}+12\text{ MeV}\cdot(\rho/\rho_0)^{2/3}$$

Huth et al., Nature 606

Extended Data Fig. 2



IQMD/Le Fèvre

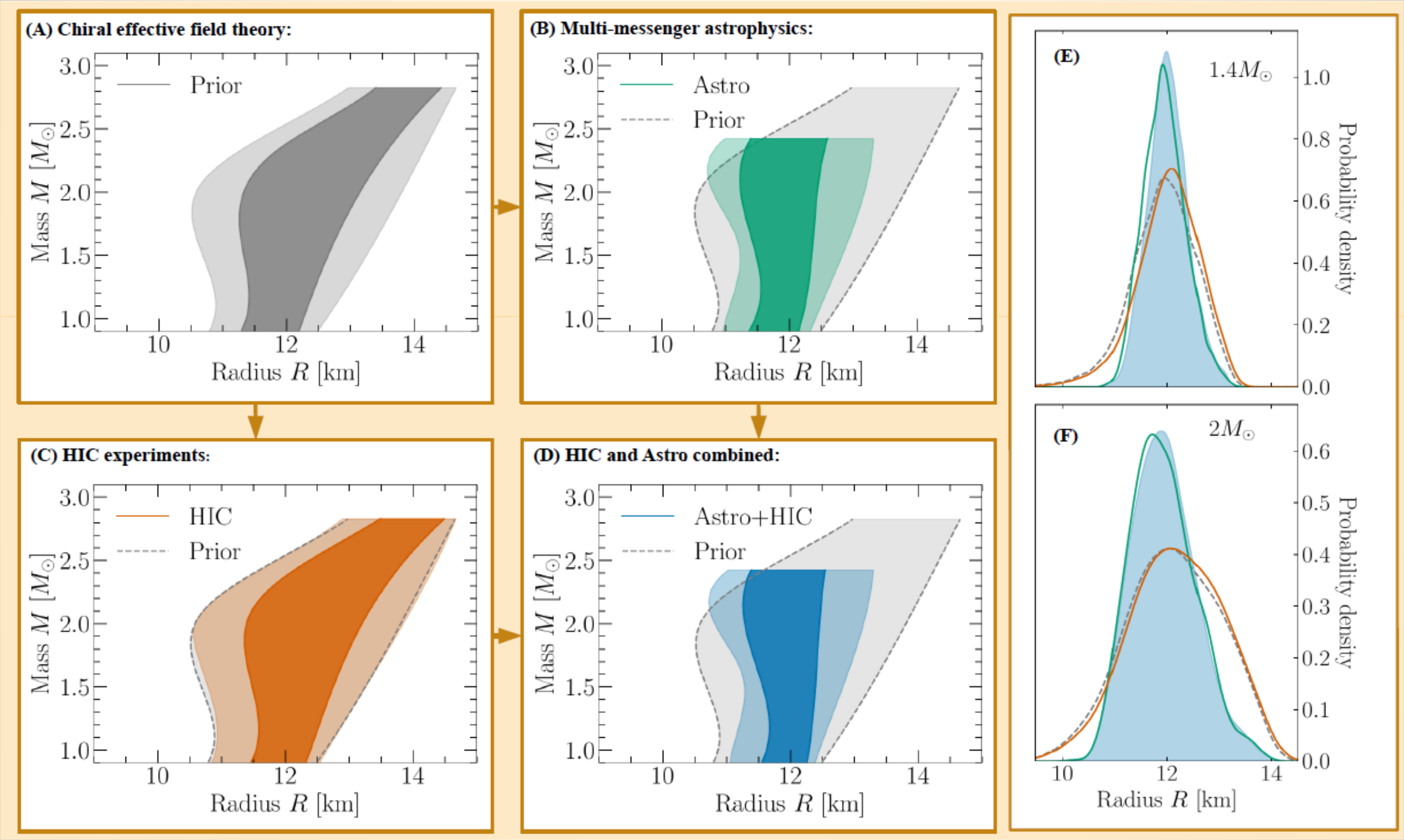
UrQMD/Li, Wang, Russotto

QMD results for exponent γ_{asy} as a function of the value assumed for S_0

mass vs radius relation

Fig. 2 (contours 68% and 95%)

Huth et al., Nature 606, 276



HIC affects radius for 1.4 M_{sun}