Albert Einstein Institute, June 2020

Impact of recent neutron star observations on the dense matter equation of state

Jérôme Margueron
iP2i Lyon

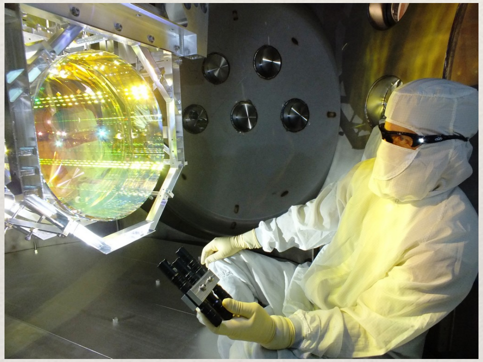
How we combine together nuclear physics knowledge and astrophysics observation to better understand dense matter properties?

Institut de Physique des 2 infinis (iP2i)

Micro-scale:
- Nuclear physics
- Particle physics @ CERN
- Neutrino physics

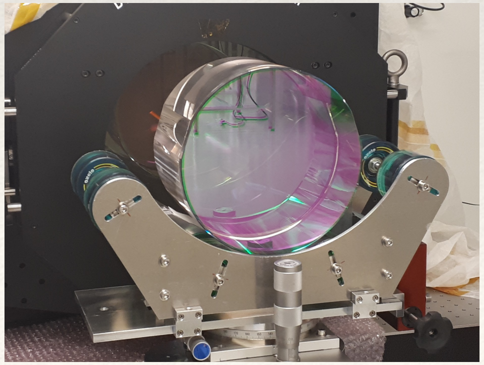
Macro-scale:
- Cosmology
- Astro-particle
- Astro-nuclear
- GW: LMA + Virgo

LMA manufactures mirrors for LIGO, Virgo,

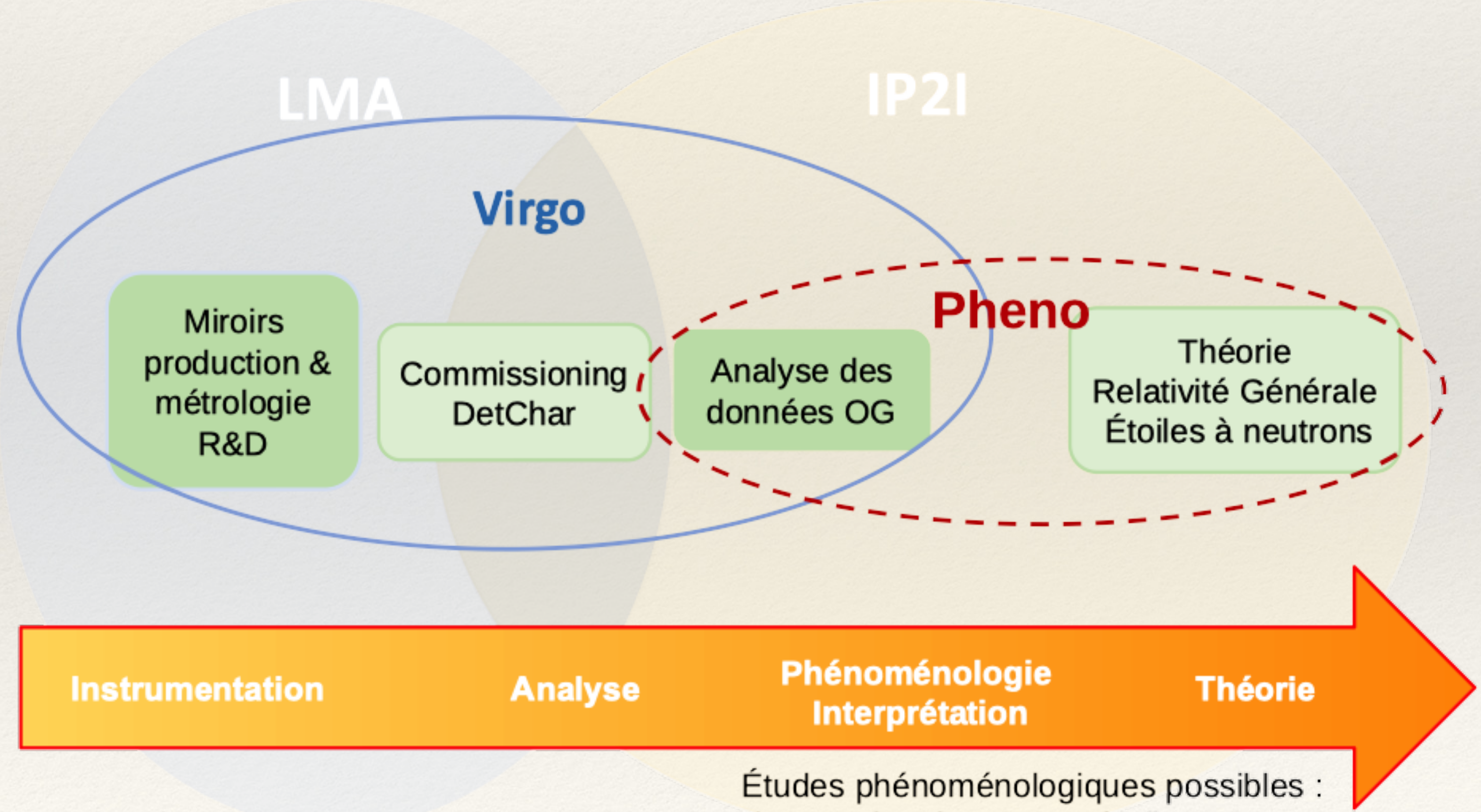


Credit Advanced LIGO

and KAGRA.



Credit LMA



LMA

IP2I

Virgo

Pheno

Miroirs production & métrologie R&D

Commissioning DetChar

Analyse des données OG

Théorie Relativité Générale Étoiles à neutrons

Instrumentation

Analyse

Phénoménologie Interprétation

Théorie

Études phénoménologiques possibles : formes d'ondes, en particulier pour NS.

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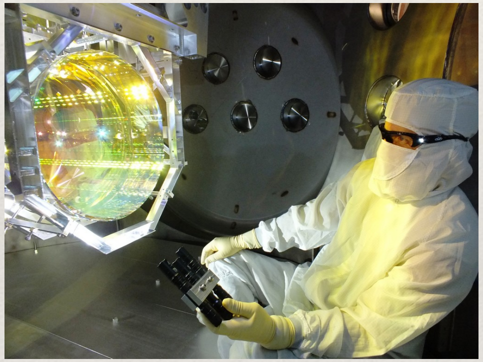

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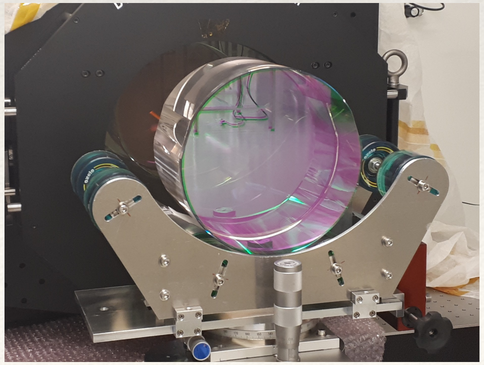

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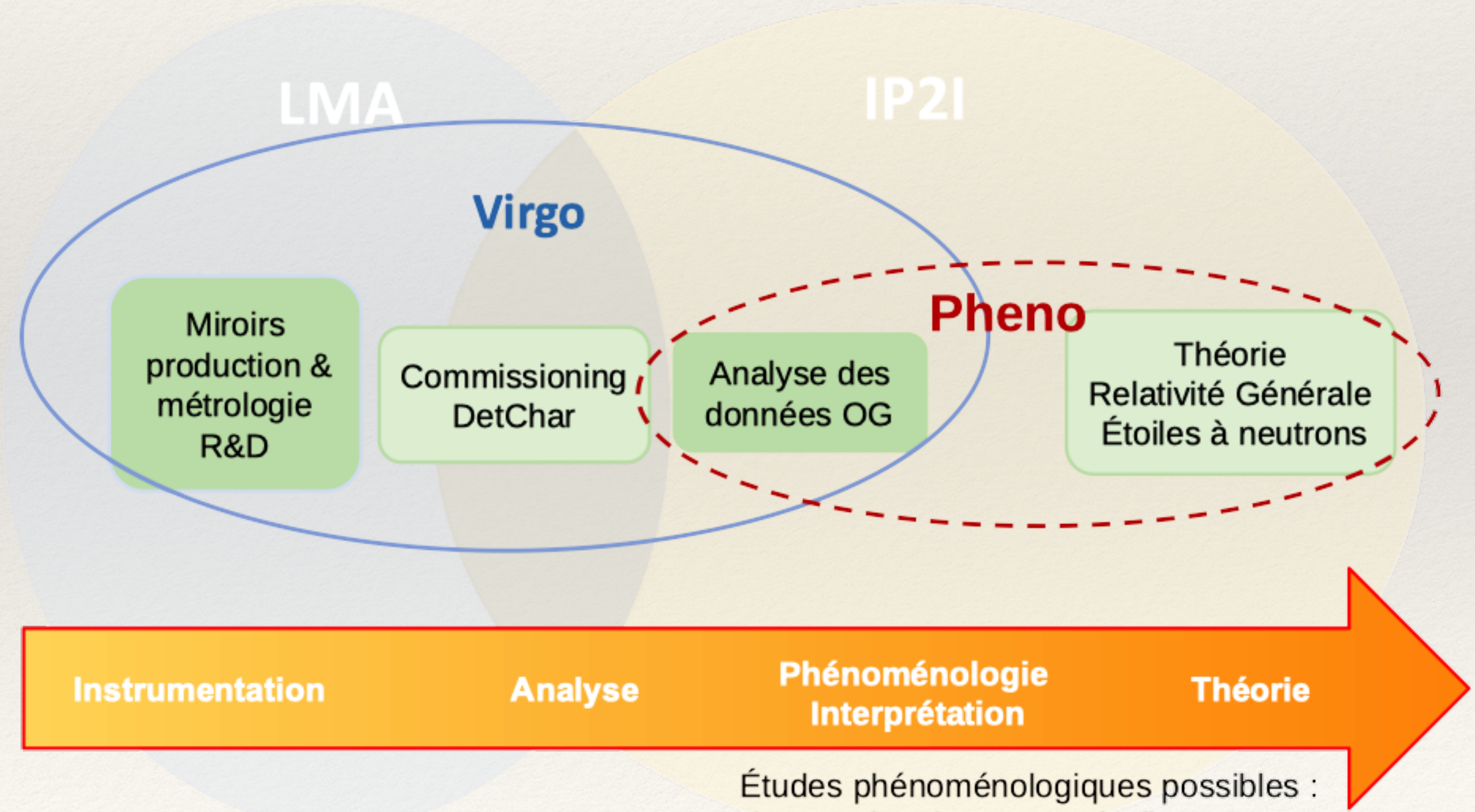

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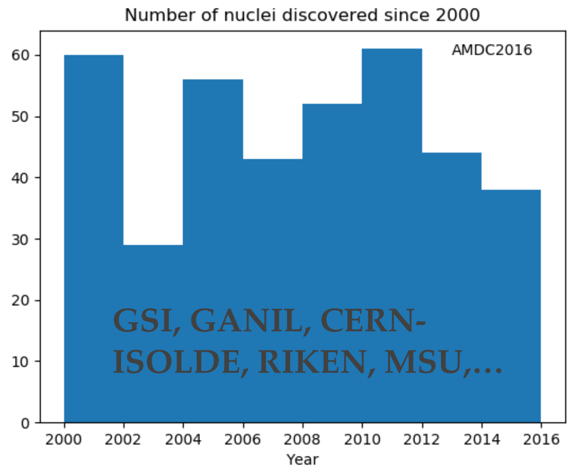
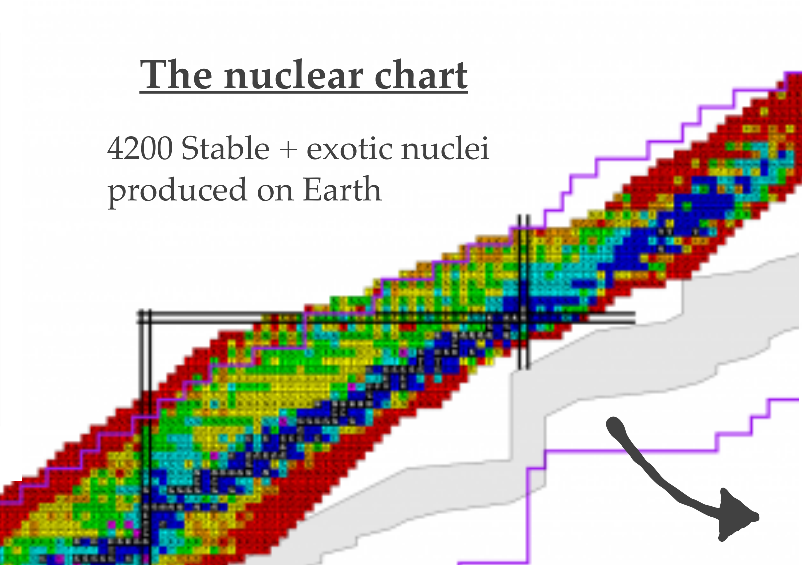
Nuclear physics: nuclei and matter

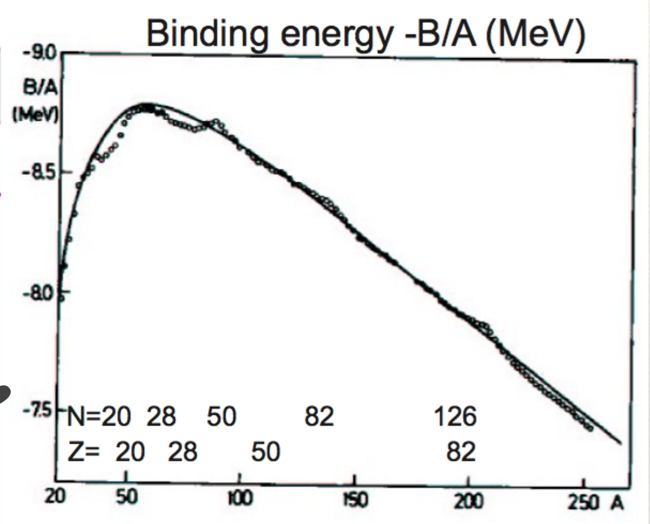


GSI, GANIL, CERN-ISOLDE, RIKEN, MSU,…



The nuclear chart

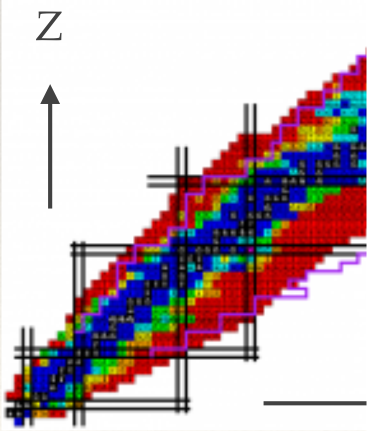
4200 Stable + exotic nuclei produced on Earth

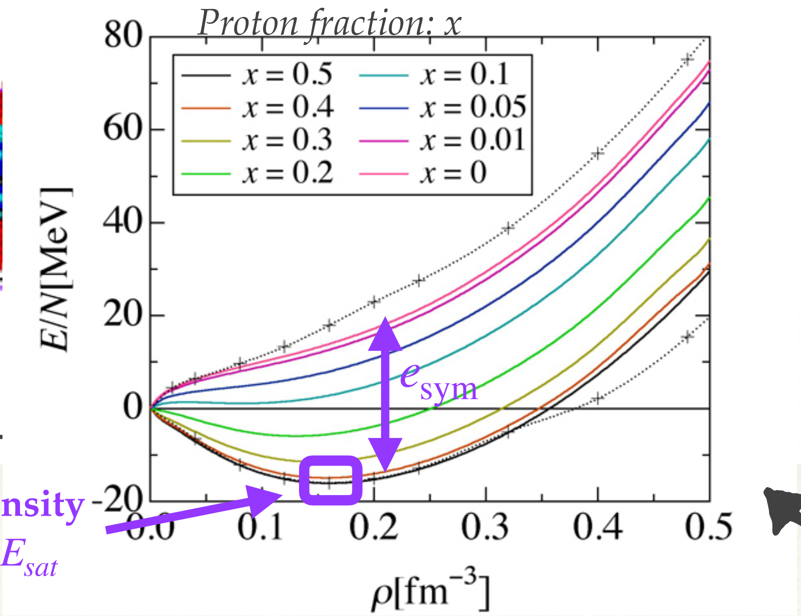


Empirical Bethe-Weizsäcker mass formula

$$E_{tot} = E_{bulk} + E_{sym} I^2 + E_{surf} + E_{Coul.} Z^2$$

Equation of state of uniform matter



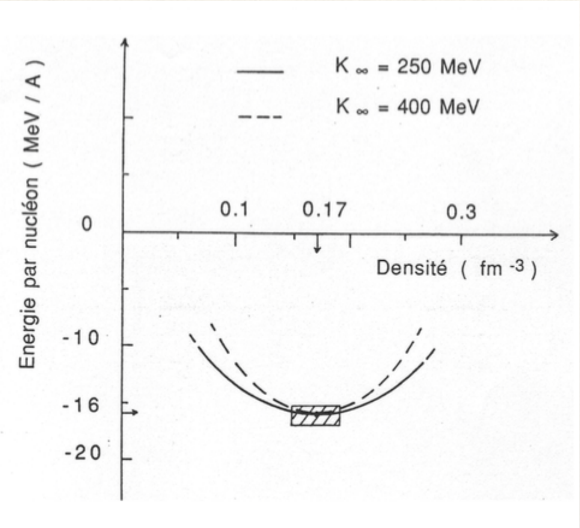


Saturation density n_{sat} & energy E_{sat}

Now: EDF, EFT, etc…

Nuclear physics: nuclei and matter

Density dependence of the energy around n_{sat}

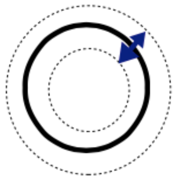


Compressible liquid-drop: $B(\rho) \approx B(\rho_0) + \frac{1}{2}K_\infty \left(\frac{\rho-\rho_0}{3\rho_0}\right)^2$

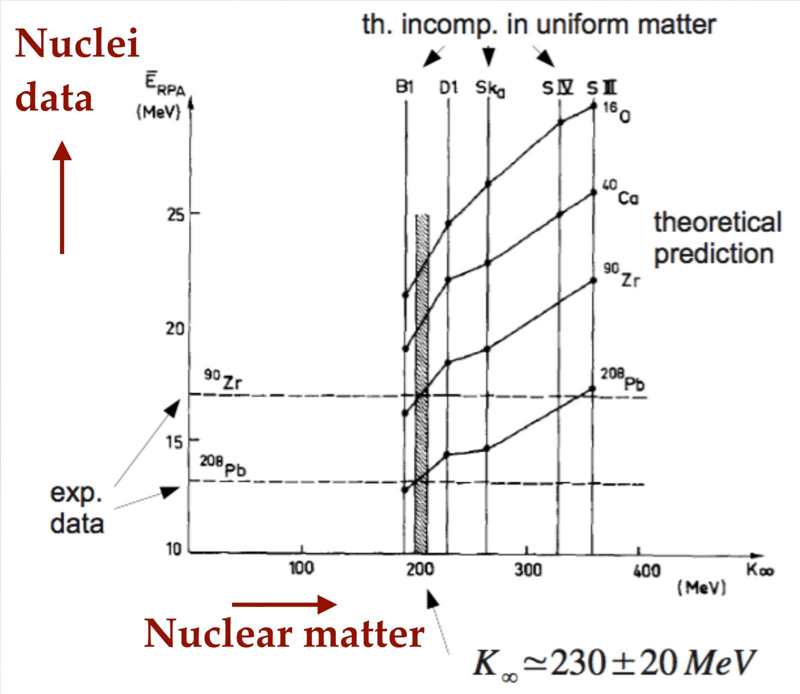
Incompressibility

How incompressibility is measured?

α scattering on nuclei
→ monopolar compression



Correlation analysis



Nuclei data

Nuclear matter

$K_\infty \simeq 230 \pm 20\, MeV$

J.P. Blaizot, Phys. Rep. 64 (1980) 171

Measured in different nuclei

Extracted

vibration frequency: $\hbar\omega = \hbar\sqrt{\frac{K_A}{mr_0^2}}A^{-1/3}$

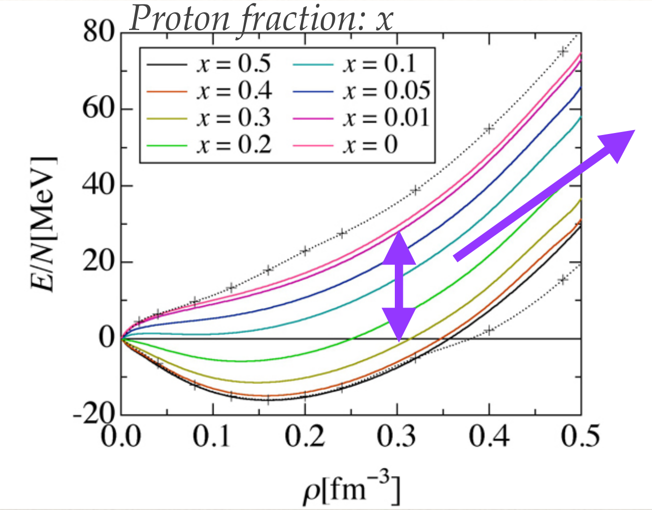
$$K_A = K_\infty + K_s A^{-1/3} + K_{sym}\left(\frac{N-Z}{N+Z}\right)^2 + K_{coul}\frac{Z^2}{A^{4/3}}$$

Uniform matter

Model dependence?

[Khan, JM, Vidaña PRL 2012]

Nuclear physics: towards neutron stars



Symmetry energy

e_{sym}

$$E_{sym} = \frac{\partial^2 E/A}{\partial I^2} \approx \frac{E}{A}(I=1) - \frac{E}{A}(I=0)$$

Difference between PNM and SNM

Major impact on the **beta equilibrium** in neutron stars

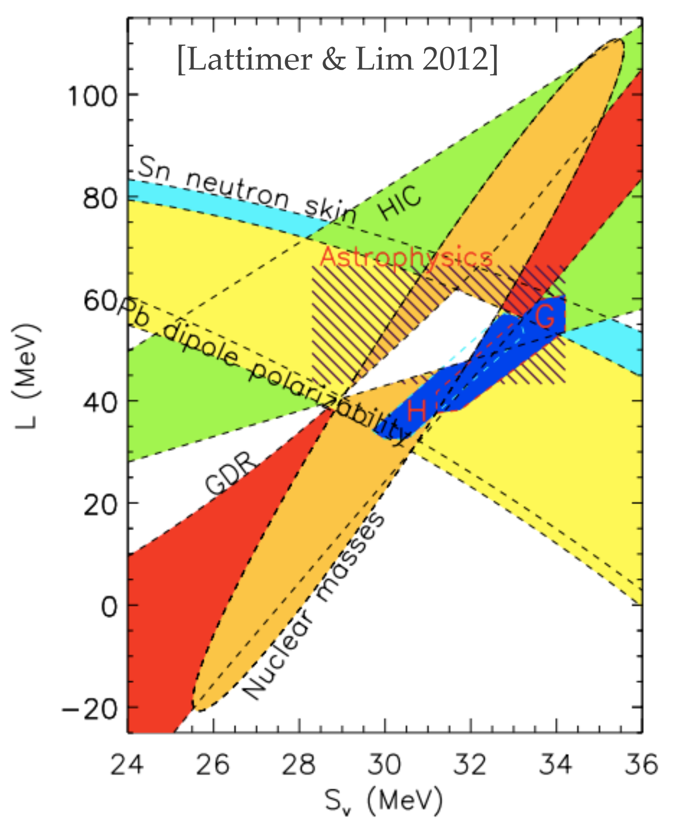
$$\mu_e = \mu_n - \mu_p = 4(1-2x)e_{sym}(n)$$

Empirical Bethe-Weizsäcker mass formula:

$$B(N,Z) = B_v A - B_s A^{2/3} - \frac{1}{2}\boxed{B_{sym}}\left(\frac{N-Z}{N+Z}\right)^2 - \frac{3}{5}B_{Coul}\frac{e^2}{r_0}\frac{Z}{A^{1/3}} + 12\,\delta(A,Z)\,A^{-1/3}$$

Slope of the symmetry energy (density dependence):

$$L_{sym} = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho}$$



Nuclear Empirical Parameters (NEP)

Energy in asymmetric matter: $$\frac{E}{A}(n,\delta) \approx e_{\mathrm{sat}}(n) + e_{\mathrm{sym},2}(n)\delta^2 + e_{\mathrm{sym},4}(n)\delta^4 + \ldots$$

with $\delta = (n_n - n_p)/(n_n + n_p)$

where the isoscalar and isovector terms are expressed as a Taylor expansion in x:

with $x = (n - n_{sat})/(3n_{sat})$

$$e_{sat} = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \ldots$$

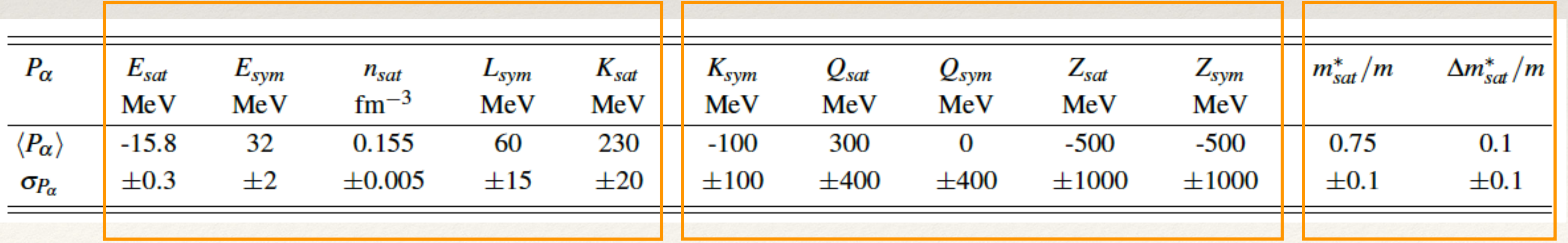
$$e_{sym} = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \ldots$$

The **nuclear empirical parameters** (NEP) capture the (topological) properties of the EoS around n_{sat}.

Small uncertainties

Large uncertainties

Large uncertainties



P_α	E_{sat} MeV	E_{sym} MeV	n_{sat} fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV	m^*_{sat}/m	$\Delta m^*_{sat}/m$
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500	0.75	0.1
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000	±0.1	±0.1

[JM, Casali, Gulminelli, PRC 2018]

Small impact at T=0

⚠ There are correlations among these parameters

Impact of high order NEP on correlations

[JM, Gulminelli PRC 2019]

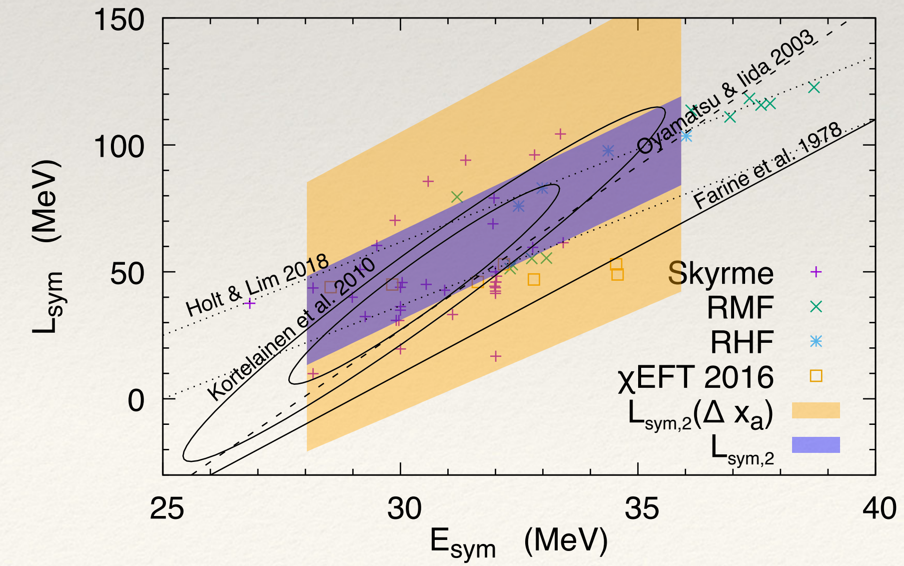
Nuclear exp.

$$E^a_{sym} = E_{sym}(n_a \approx 0.1 fm^{-3}) = 24.1 \pm 0.8 \text{ MeV}$$

[Colò, Garg, Sagawa, EPJA 2014
Trippa, Colò, Vigezzi, PRC 2008]

$$\boxed{L_{sym,i} = \beta_{EL} E_{sym} + \alpha_{EL,i}}$$

where $\alpha_{EL,4} = -x_a^{-1} E_{sym} + \frac{x_a}{2} K_{sym} + \frac{x_a^2}{6} Q_{sym} - \frac{x_a^3}{24} Z_{sym} + \ldots$

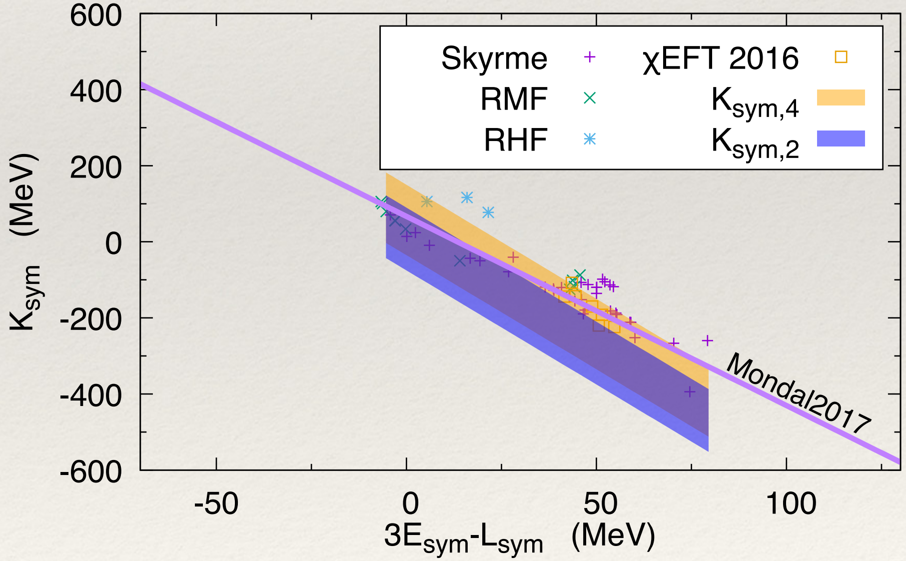


$$e_{NM}(n=0) = 0 \text{ MeV}$$

~~Undetermined reason~~

$$\boxed{K_{sym} = \beta(3E_{sym} - L_{sym}) + \alpha}$$

[Mondal+ PRC 2017]



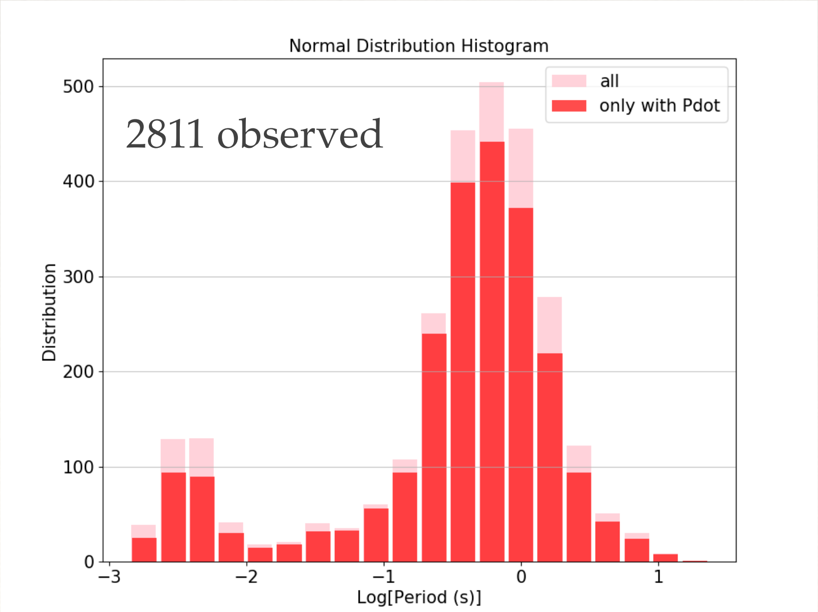
What is a neutron star?

Main properties:

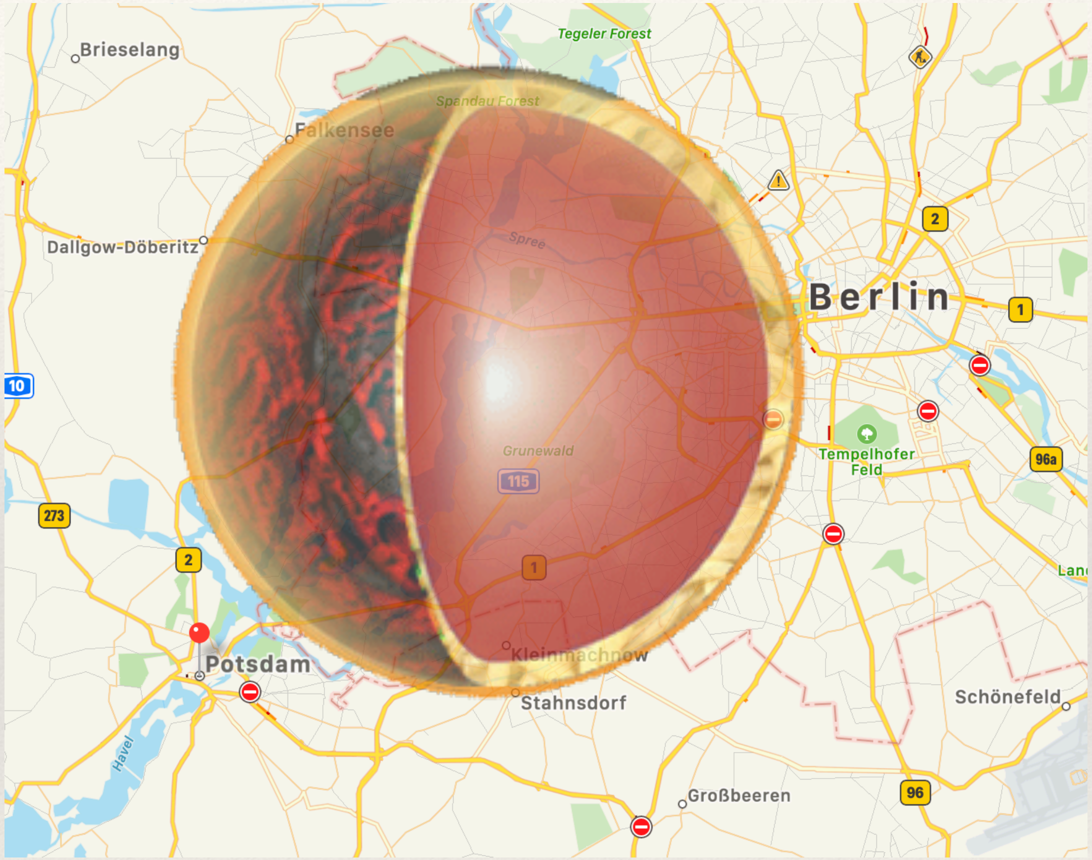
M # 1 - 2 M_o Average density # 10^{15} g cm^{-3}

R # 10 - 14 km B # 10^{12} - 10^{16} G

- Aftermath of a core-collapse supernovae,
- Isolated or in binary,
- Could be a pulsar: from radio to/or γ-rays,
- X-ray emission from accretion disk,
- Fast spinning.



2811 observed



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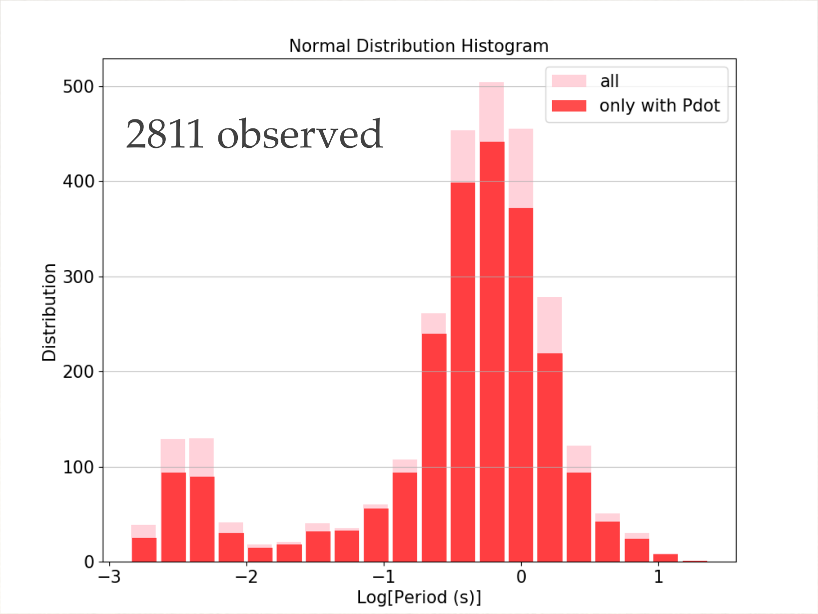
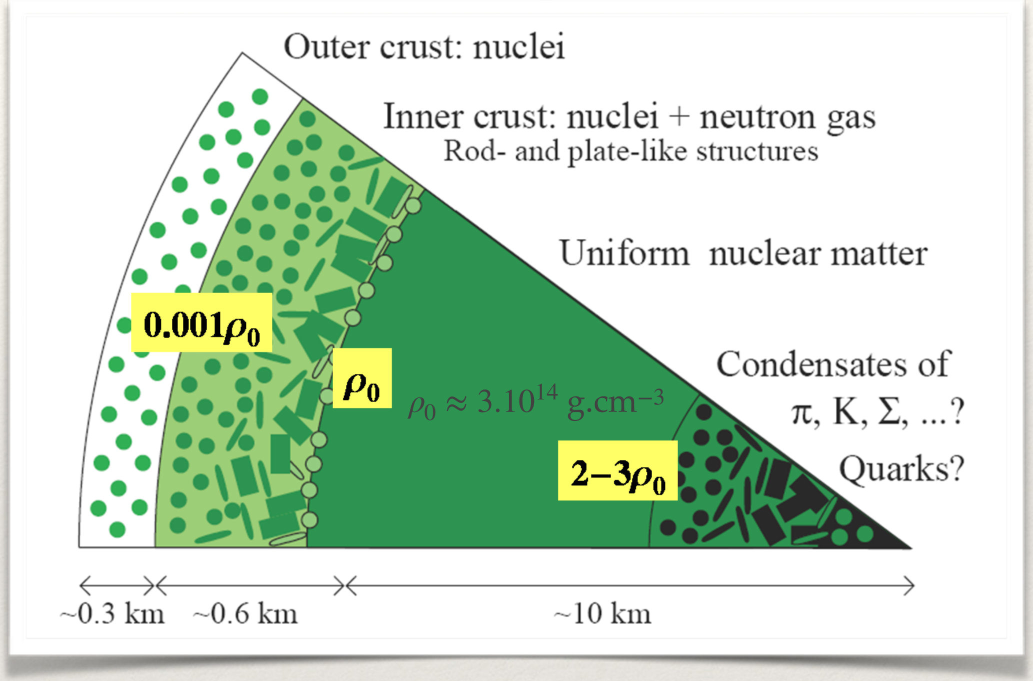


Neutron star composition:

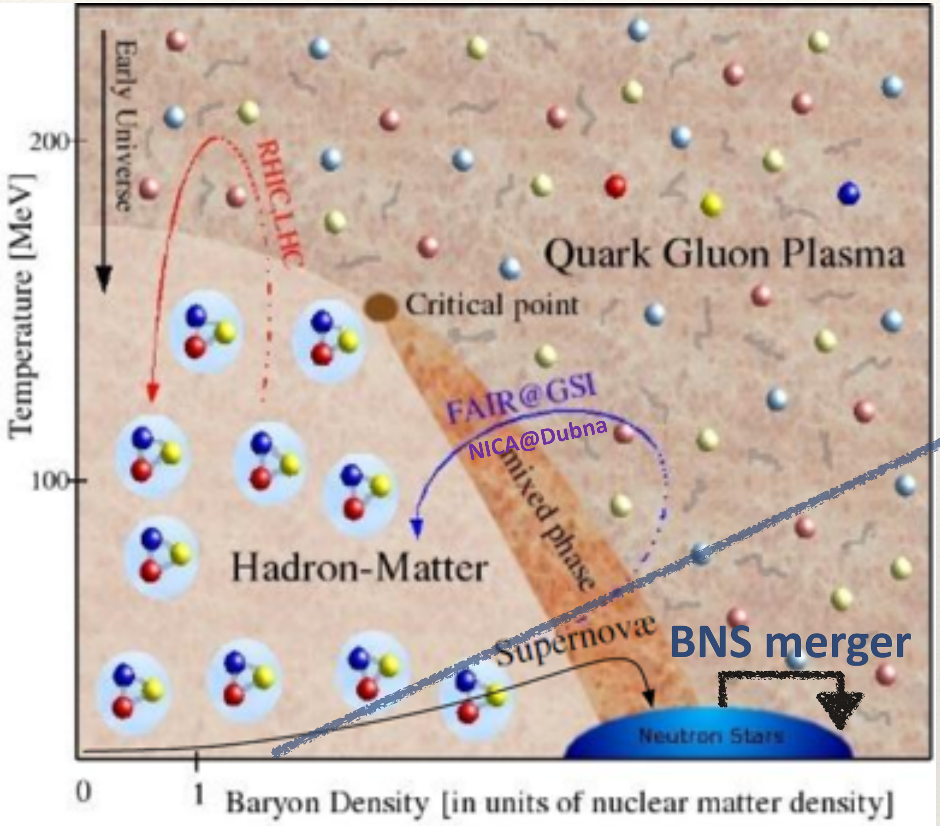


Requires the knowledge of dense matter equation of state.

-> Two main questions for nuclear physicists:

- How accurate is the nuclear physics knowledge?
- Is there a phase transition to hyperon matter or quark matter at high density?

Probing extreme matter physics with GW

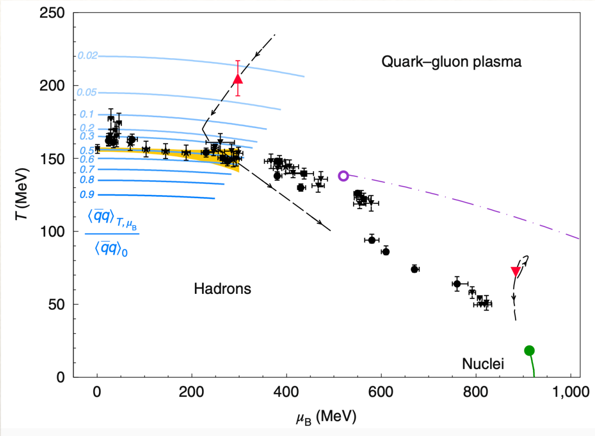


Particle and nuclear accelerators

Astrophysical observations

Neutron stars, supernovae, kilonovae…

Heavy Ion collision



[Hades, Nature phys. 2019]

Probe limits of extreme matter

Questions to be answered:

What is the **nuclear interaction** in dense, isospin asymmetric matter, hot?

Which **new particles** appear at supra-saturation densities?

At which density occurs the **deconfinement** from hadrons to Quarks-Gluons Plasma (QGP)?

How **neutrinos** propagate and what are the **transport properties** of extreme matter?

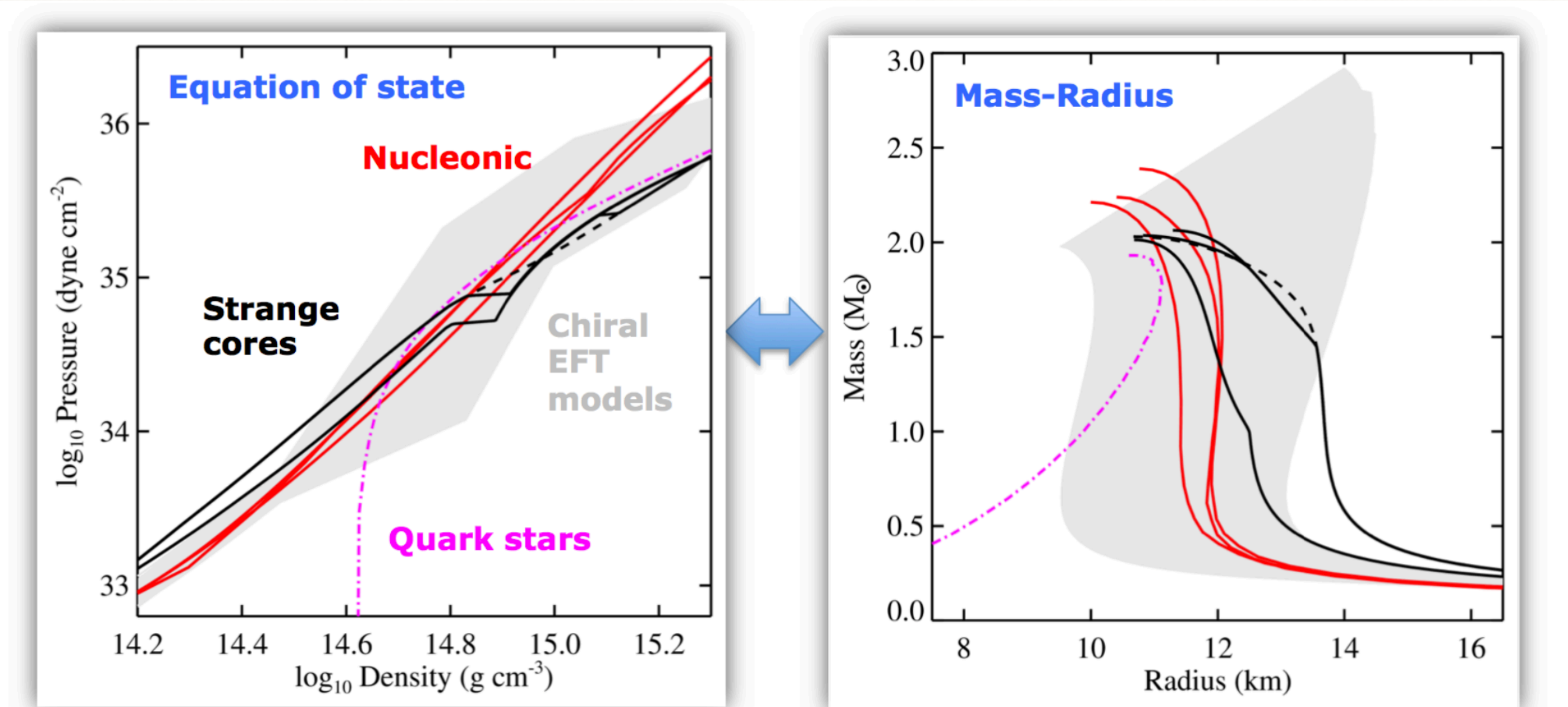
Are BNS the main astrophysical site for the **r-process**?

EoS [nuclear] <=> (M,R) [astro]

Tolmann-Oppenheimer-Volkov (TOV) GR equations

$P(n)$

$(M,R)(n_c)$



[A. Watts et al., PoD (AASKA 14) 043]

Reverse engineering,
Bayesian statistics

A semi-agnostic approach for the nuclear EoS

The **nuclear empirical parameters** (NEP) capture the properties of the EoS around n_{sat}:

$$e_{sat} = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \dots$$

$$e_{sym} = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \dots$$

with $\delta = (n_n - n_p)/(n_n + n_p)$ and $x = (n - n_{sat})/(3n_{sat})$

Semi-agnostic approach (Meta-model):

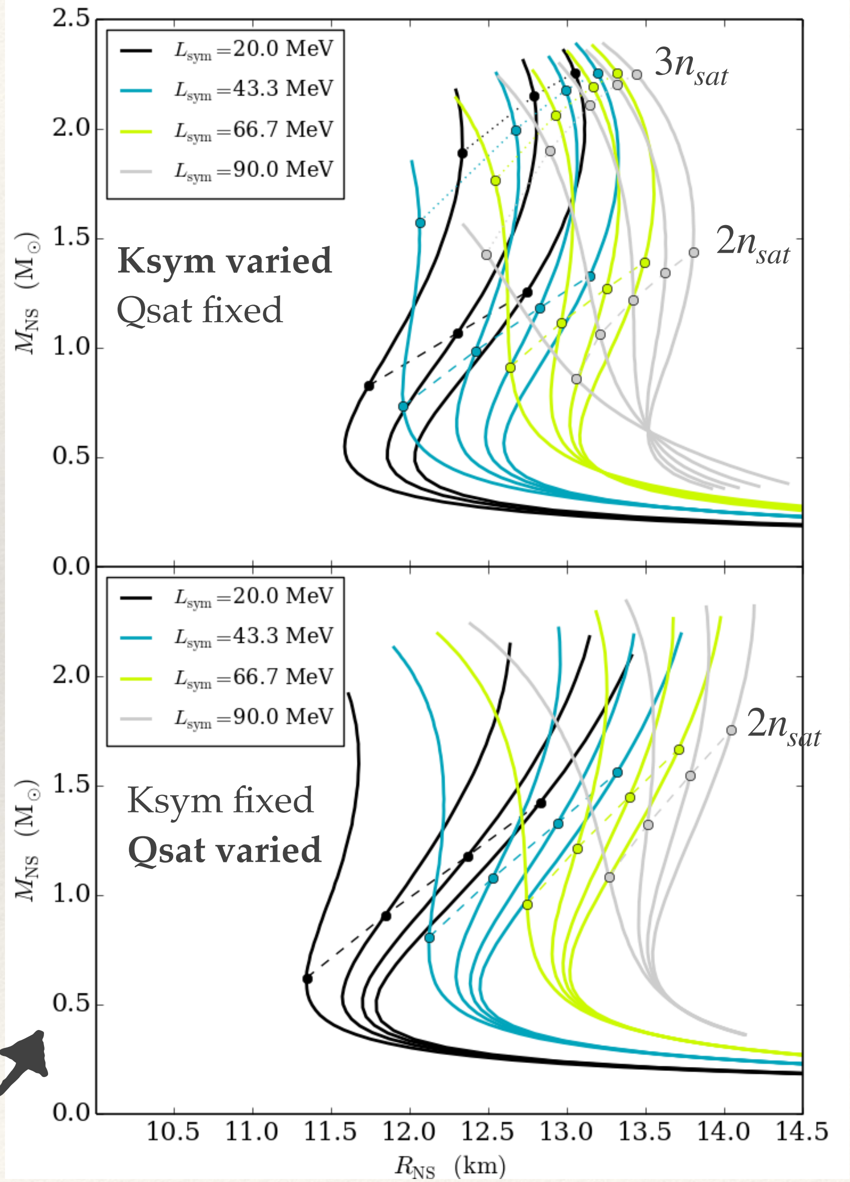
$$e(n,\delta) = t(n,\delta) + v(n,\delta)$$

Potential energy

Kinetic energy (Fermi gas)

$$v(n,\delta) = \sum_{\alpha=0}^{N}\left(v_\alpha^{\rm is} + \delta^2 v_\alpha^{\rm iv}\right)\frac{x^\alpha}{\alpha!}u(x),$$

Directly related to NEP



Neutron stars masses

NS masses estimation: $M \in [1.17 : 2] M_\odot$

Minimum masses:
$1.174(4) M_\odot$ [Ozel & Freire 2016]

Maximum masses:

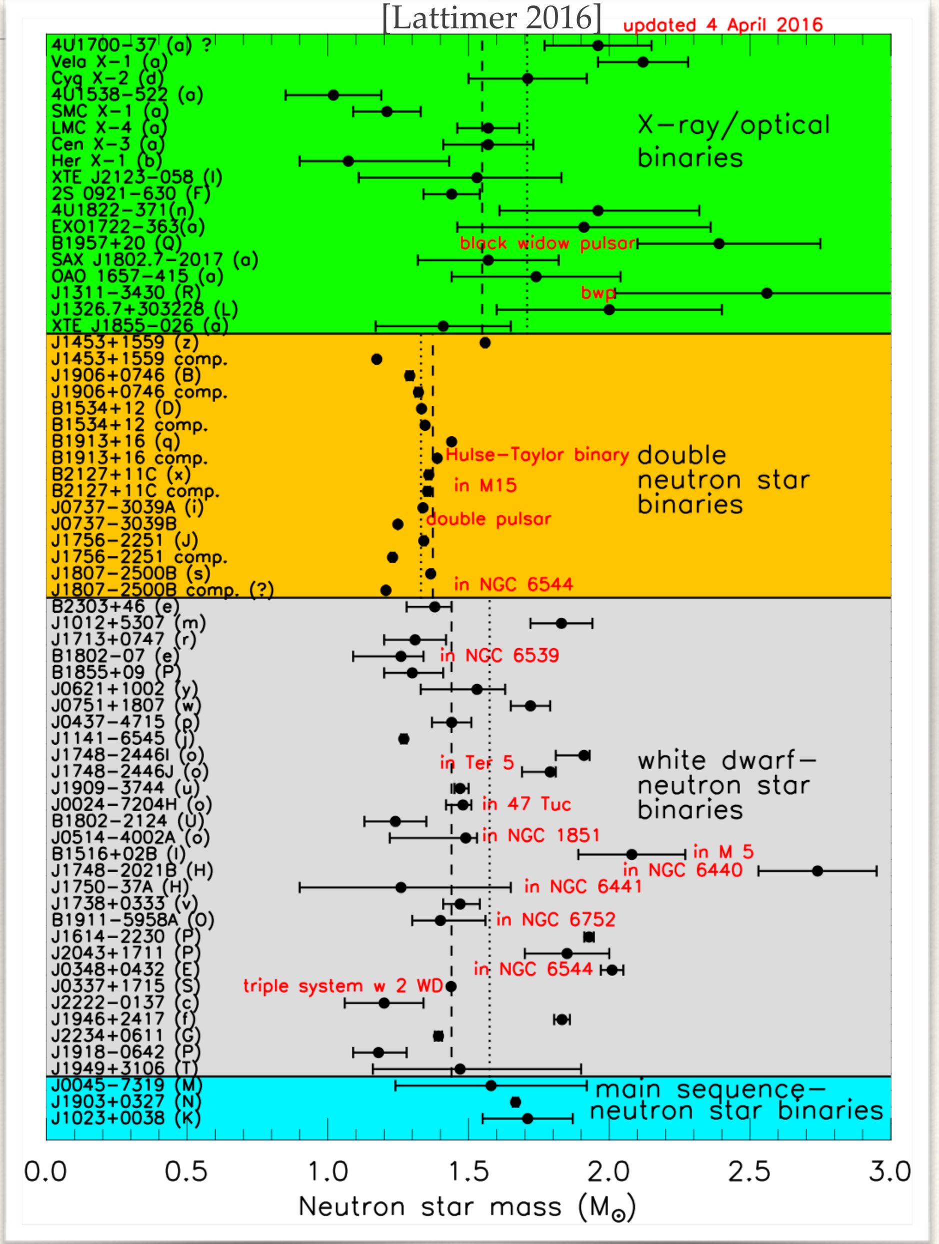
- PSR J1614-2230: $M = 1.908(16) M_\odot$

  [Arzoumanian et al. 2018, first Demorest et al.]

- PSR J0348+0432: $M = 2.01(4) M_\odot$

  [Antoniadis et al., 2013]

- Few observed high mass NS with large error-bars:
  - MSP J0740+6620: $M = 2.14(10) M_\odot$ (Shapiro delay) [Cromartie et al., 2019]
  - PSR J2215+5135: $M = 2.27(15) M_\odot$ (« redback », magnesium lines) [Linares et al. 2018]


[Lattimer 2016]

Neutron star radii

Radius estimation: $R_{1.4} \in [10:14]$ km for a 1.4 $M_\odot$ NS

(my own) **classification:**
low radii (10-11 km),
average radii (12-13 km),
large radii (>14 km).

How to extract a radius?

- **Thermal emission** from qLMXB (quiescient Low-Mass X-ray binaries)

  [Guillot 2013, Ozel 2016, Bogdanov 2016, Steiner 2018]
- **X-ray bursts**

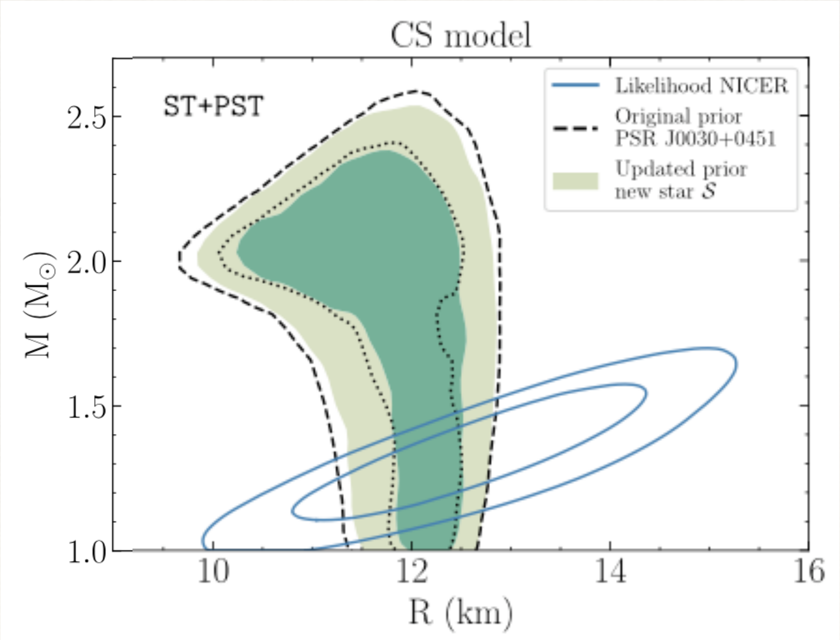
  [Poutanen 2013, Ozel 2016, Nattila 2017]
- **Gravitational waves** from binary NS mergers

  [LVC PRL 2017, Tews PRC 2018, …]
- **NICER** mission

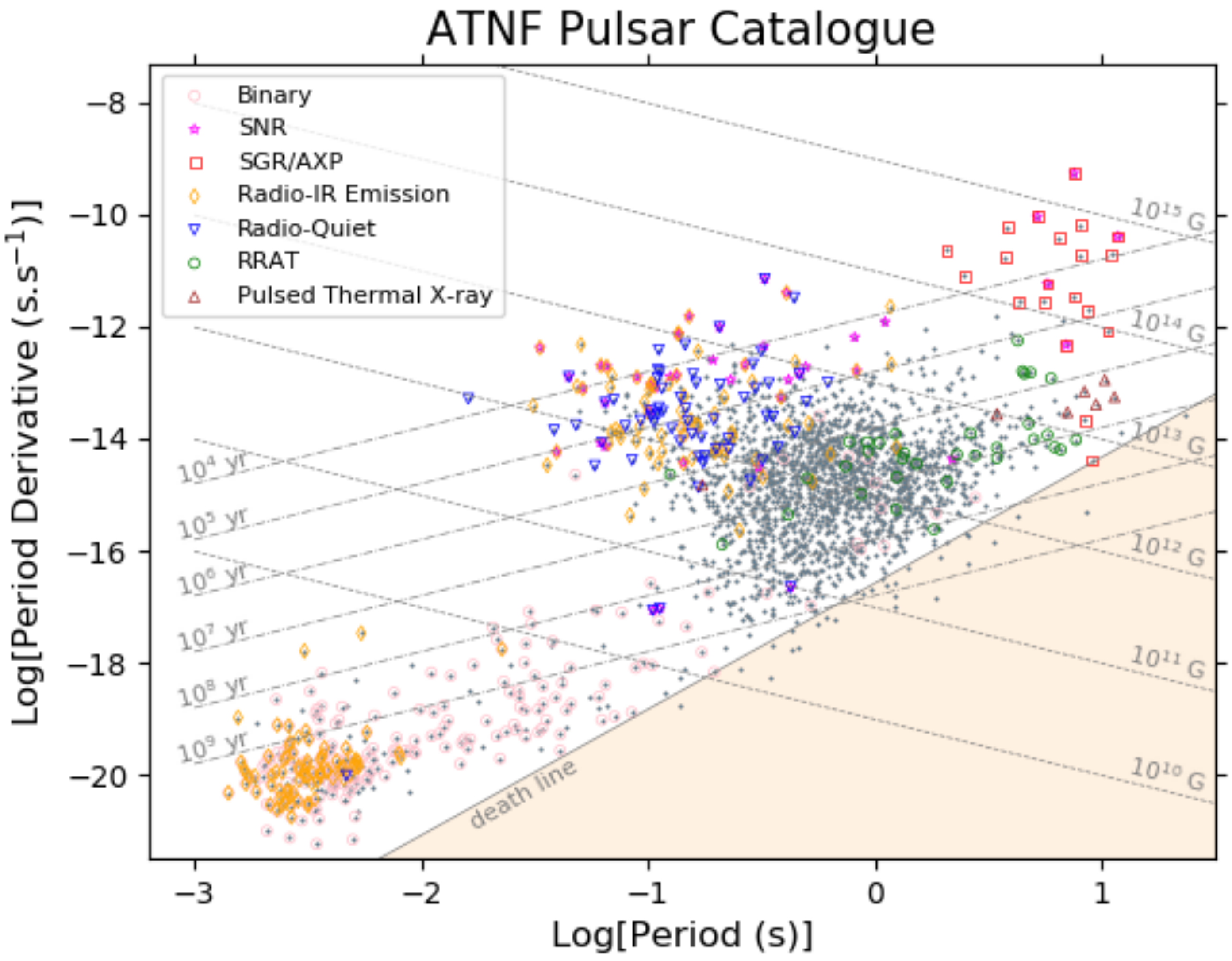
  [Watts 2019 *preliminary results*]
- Future: **ATHENA** mission

  [Barcons 2017]

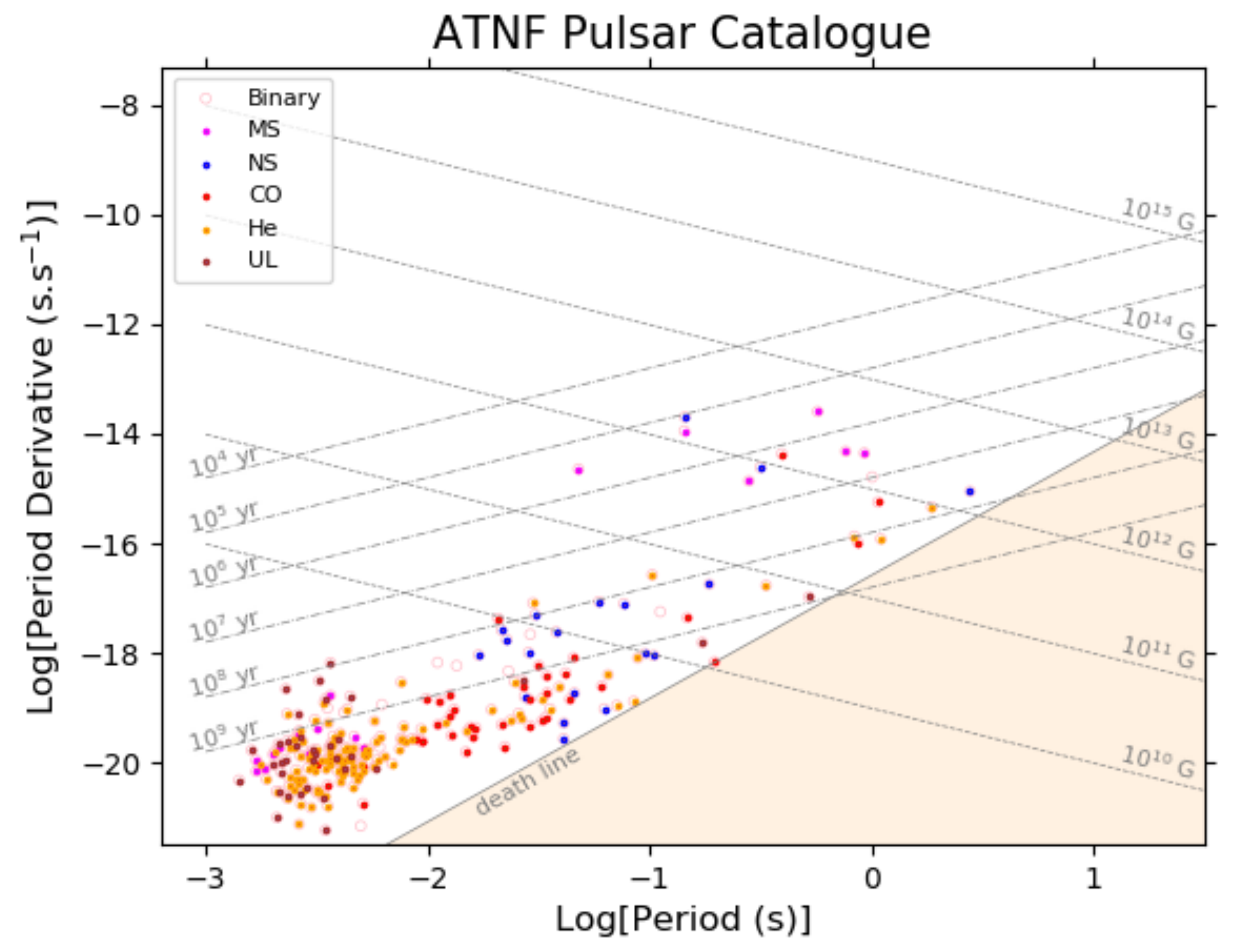
[Raaijmakers 2019 - NICER]



Neutron star diversity



BNS diversity



Thermal emission from qLMXB

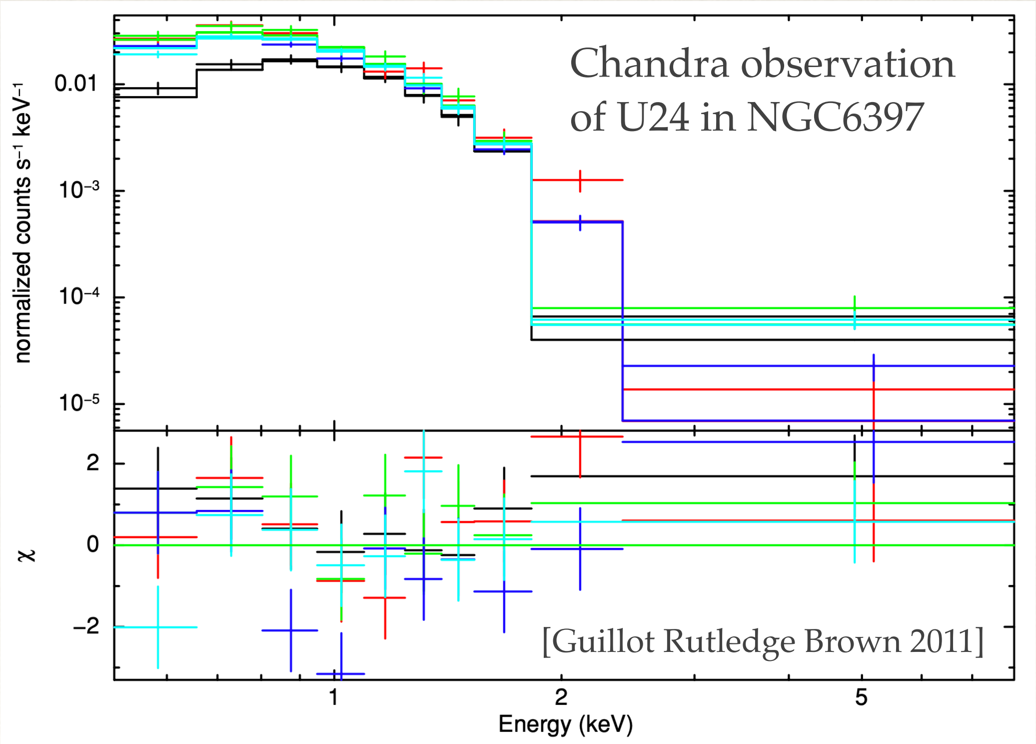
quiescent Low Mass X-ray binaries

7 sources (**quiescent Low Mass X-ray binaries**) in globular clusters:

- constant flux, purely H atmosphere,
- Low magnetic fields —> almost pure thermal components,
- In globular clusters —> accurate distances.

Black body like emission: $F \# T^4(R_{inf}/D)^2$

[Rutledge et al. 1999]



Chandra observation of U24 in NGC6397

[Guillot Rutledge Brown 2011]

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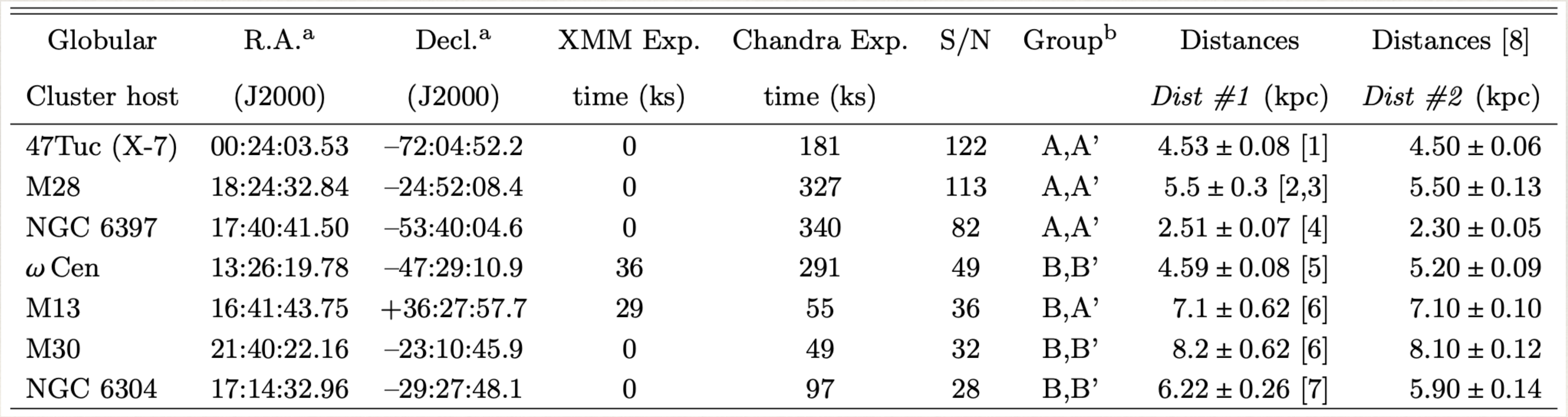
[Baillot d'Étivaux+, ApJ 2019]



Globular Cluster host	R.A.[a] (J2000)	Decl.[a] (J2000)	XMM Exp. time (ks)	Chandra Exp. time (ks)	S/N	Group[b]	Distances *Dist #1* (kpc)	Distances [8] *Dist #2* (kpc)
47Tuc (X-7)	00:24:03.53	−72:04:52.2	0	181	122	A,A'	4.53 ± 0.08 [1]	4.50 ± 0.06
M28	18:24:32.84	−24:52:08.4	0	327	113	A,A'	5.5 ± 0.3 [2,3]	5.50 ± 0.13
NGC 6397	17:40:41.50	−53:40:04.6	0	340	82	A,A'	2.51 ± 0.07 [4]	2.30 ± 0.05
ω Cen	13:26:19.78	−47:29:10.9	36	291	49	B,B'	4.59 ± 0.08 [5]	5.20 ± 0.09
M13	16:41:43.75	+36:27:57.7	29	55	36	B,A'	7.1 ± 0.62 [6]	7.10 ± 0.10
M30	21:40:22.16	−23:10:45.9	0	49	32	B,B'	8.2 ± 0.62 [6]	8.10 ± 0.12
NGC 6304	17:14:32.96	−29:27:48.1	0	97	28	B,B'	6.22 ± 0.26 [7]	5.90 ± 0.14

Recent publications

GAIA DRII 2018

Thermal emission from qLMXB

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7 sources (**quiescent Low Mass X-ray binaries**) in globular clusters:

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Modeling of the **X-ray spectra** with Xspec:

- **spectrum model** includes: « pile-up » [Davis 2001, Bogdanov 2016], « TBgas » absorption and « nsatmos » for the atmosphere [Heinke 2006] + « power-law ».
- **parameters**: pile-up parameter α, hydrogen column density on the line site $n_{H,22}$ (10^{22} cm^{-2}), power-law normalisation, distance to the star D (kpc), surface effective temperature T_{eff} (K), mass of the stars M ($M_{\odot}$).

Thermal emission from qLMXB

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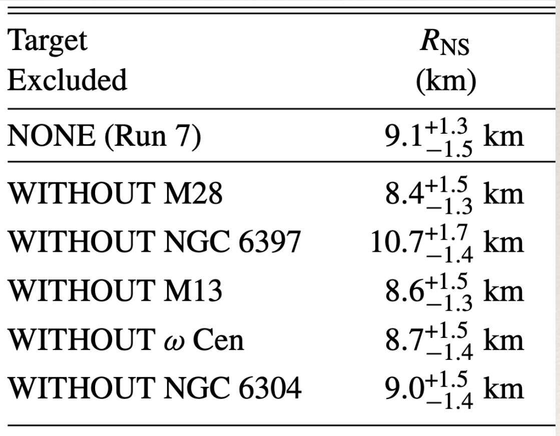
Exemple: constant radius model [Guillot 2013]

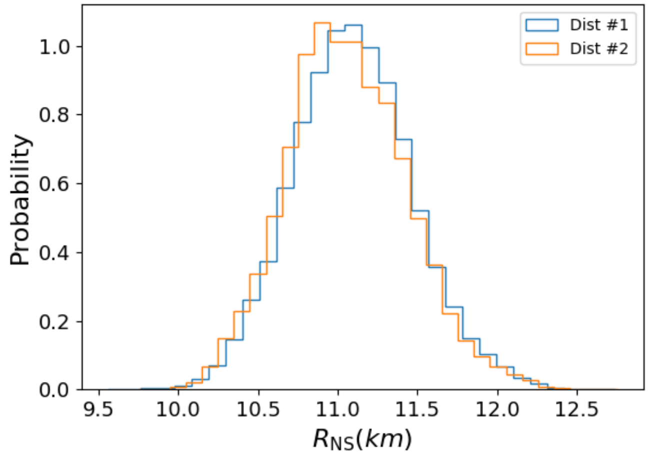


Target Excluded	R_{NS} (km)
NONE (Run 7)	$9.1^{+1.3}_{-1.5}$ km
WITHOUT M28	$8.4^{+1.5}_{-1.3}$ km
WITHOUT NGC 6397	$10.7^{+1.7}_{-1.4}$ km
WITHOUT M13	$8.6^{+1.5}_{-1.3}$ km
WITHOUT ω Cen	$8.7^{+1.5}_{-1.4}$ km
WITHOUT NGC 6304	$9.0^{+1.5}_{-1.4}$ km

—> very **low radii** (8-11 km)

With latest X-ray spectra model and new data :

[Baillot d'Étivaux+, ApJ 2019]



$$R_{NS} \approx 11.0(5)\ \mathrm{km}$$

—> *Is it compatible with nuclear physics?*

So…

Is there a **contradiction** between nuclear physics expectations and observations?

If confirmed, this contradiction may be solved by advocating **phase transition(s)**

—> producing **smaller radii**

But first, we should **cross-check** the observational analysis.

—> employing the meta-model directly **inside** the observational analysis.

Confronting the thermal emission from qLMXB with nuclear EoS

7 sources (**quiescent Low Mass X-ray binaries**) in globular clusters:

- constant flux, purely H atmosphere,
- Low magnetic fields —> almost pure thermal components,
- In globular clusters —> accurate distances.

Simultaneous analysis assuming a **single EoS** for all qLMXB (here the **nuclear meta-model**)

EoS **directly** implemented in the data analysis (***first time!***):

- **Observational** (emission model) parameters: M, D, T, n_H, …
- **Nuclear** EoS parameters: Lsym, Ksym, Qsat, etc…
- Functional relation between M and R through the EoS: $M \rightarrow_{(EoS)} R$.

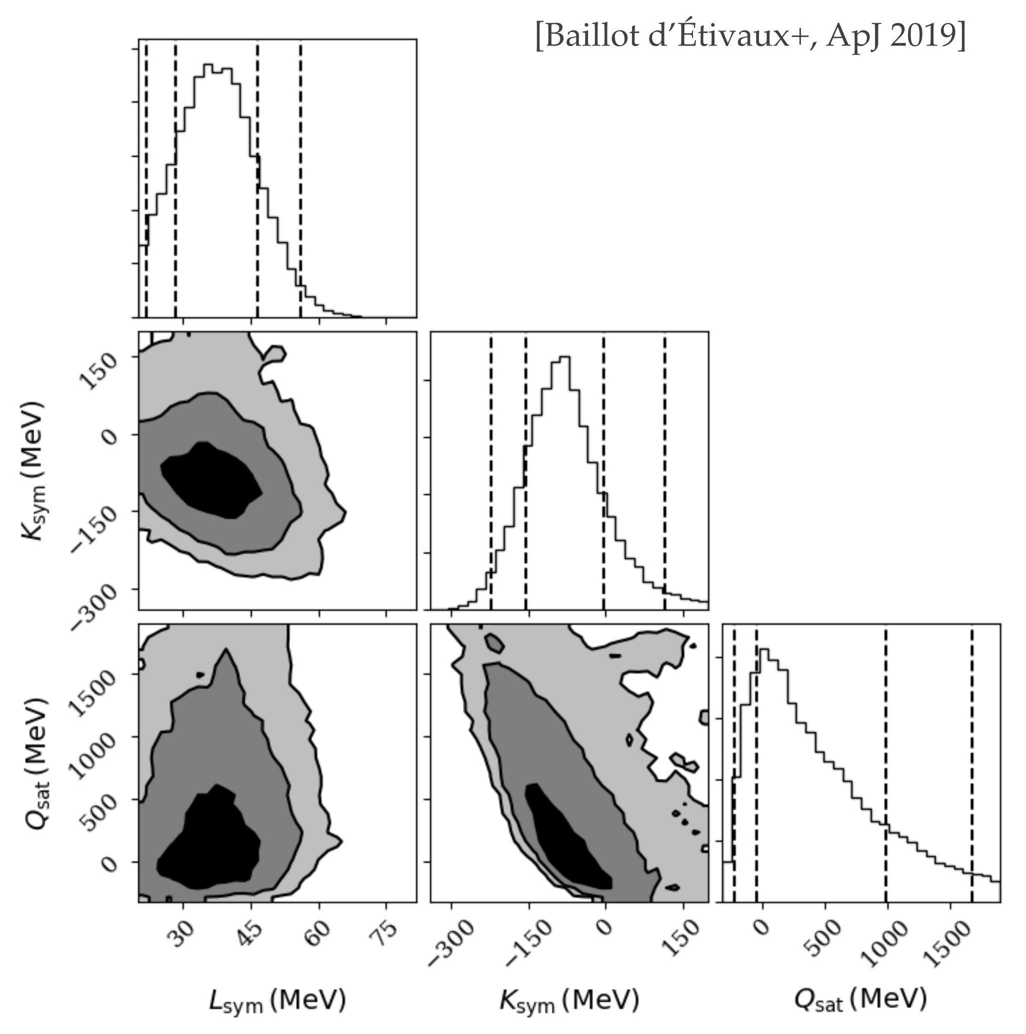
—> Fitting X-ray spectra provides the whole set of **observational + EOS parameters**.

~50 free parameters, ~1000 data

—> use of Bayesian method + MCMC (Markov-Chain Monte Carlo)

- Gaussian prior on the distances (recent publications, Gaia DRII-2018)
- Gaussian prior on the nuclear parameter Lsym (50 ± 10 MeV).

Confronting the thermal emission from qLMXB with nuclear EoS



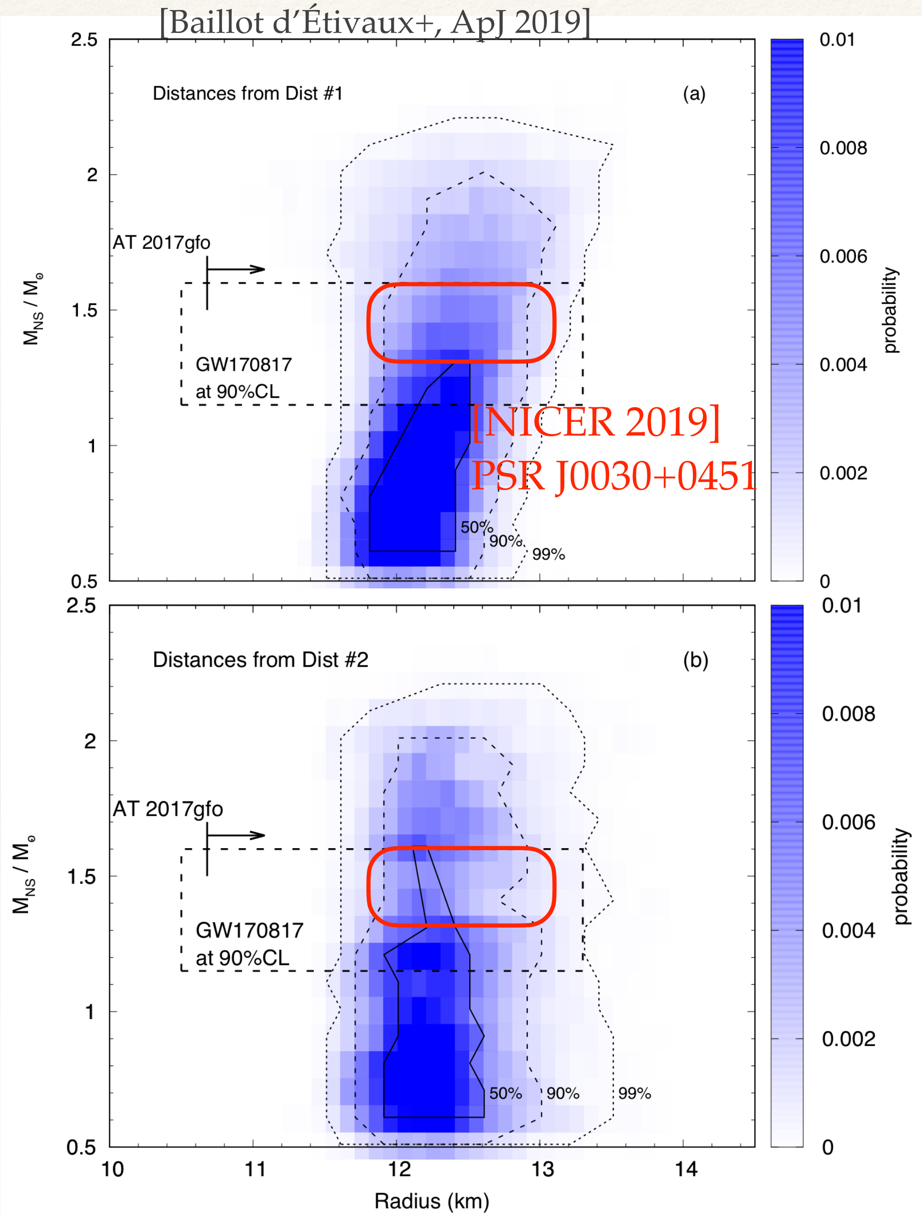
Bayesian analysis with prior:
Lsym = 50 ± 10 MeV
Ksym [-400:200] MeV
Qsat [-1300:1900] MeV

Posteriors:
Lsym = 38 ± 10 MeV
Ksym = −91 ± 80 MeV
Qsat = 350 ± 500 MeV

First extraction of Ksym and Qsat from data.

A recent analysis of pygmy GDR concludes:
Ksym = −120 ± 80 MeV [Sagawa 2019]

Confronting the thermal emission from qLMXB with nuclear EoS



[Baillot d'Étivaux+, ApJ 2019]

[NICER 2019]
PSR J0030+0451

—> The new analysis is compatible with nuclear physics.
(with same chi2 as previous analyses).
Average radii preferred.

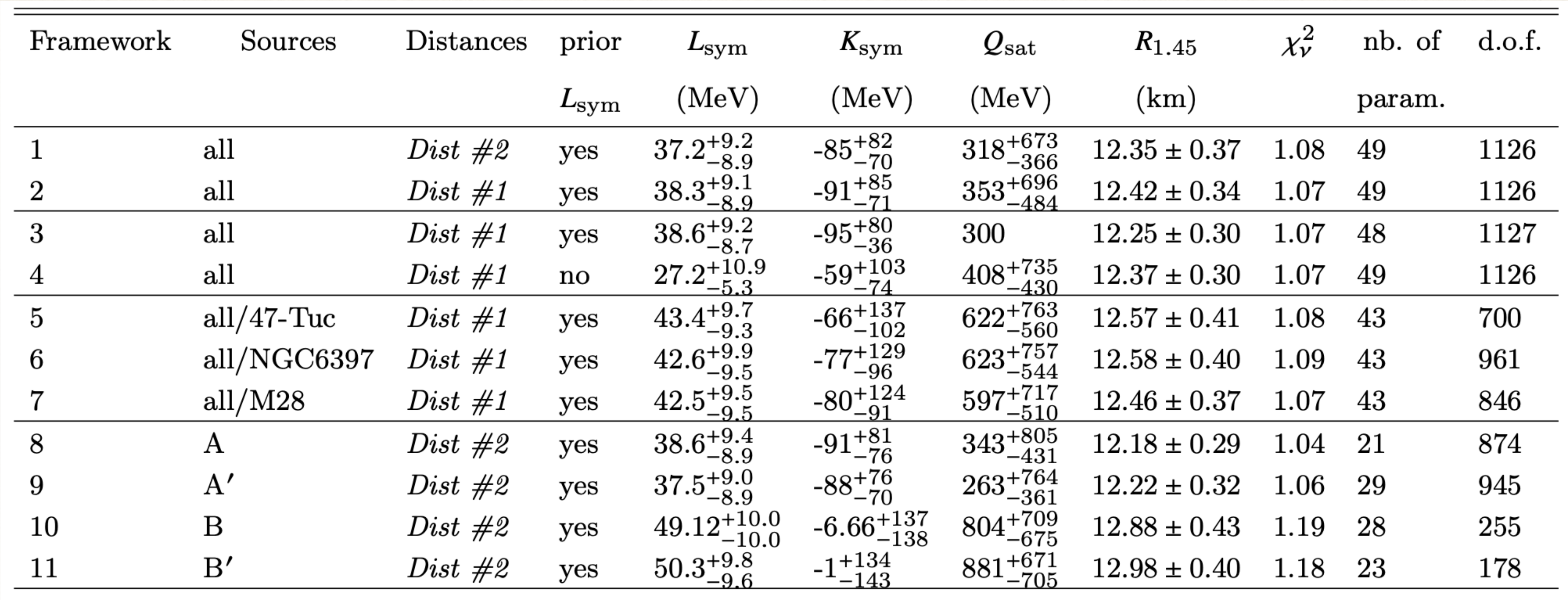
—> The comparison with other approaches (GW170817, AT2017gfo) provides a consistent understanding of the data.

—> But more recent GW170817 analyses prefer **lower radii**:

- $R_{1.4} = 11^{+0.9}_{-0.6}$ km [Capano, Tews+ nature 2020]
- $R_{1.4} \approx 11$ km [Güven+ arXiv:2001.10259]

Confronting the thermal emission from qLMXB with nuclear EoS

Sensitivity analysis

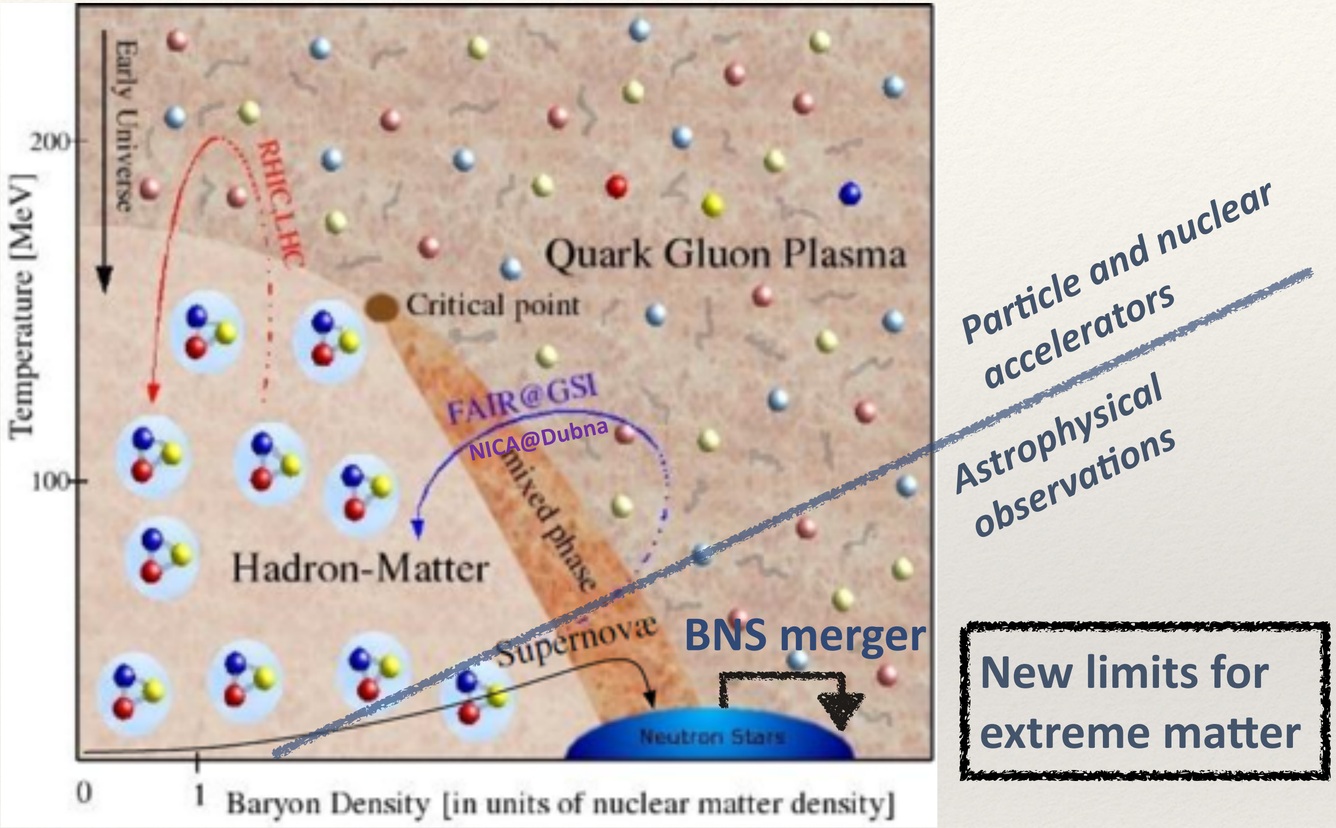


Framework	Sources	Distances	prior L_{sym}	L_{sym} (MeV)	K_{sym} (MeV)	Q_{sat} (MeV)	$R_{1.45}$ (km)	χ^2_ν	nb. of param.	d.o.f.
1	all	*Dist #2*	yes	$37.2^{+9.2}_{-8.9}$	-85^{+82}_{-70}	318^{+673}_{-366}	12.35 ± 0.37	1.08	49	1126
2	all	*Dist #1*	yes	$38.3^{+9.1}_{-8.9}$	-91^{+85}_{-71}	353^{+696}_{-484}	12.42 ± 0.34	1.07	49	1126
3	all	*Dist #1*	yes	$38.6^{+9.2}_{-8.7}$	-95^{+80}_{-36}	300	12.25 ± 0.30	1.07	48	1127
4	all	*Dist #1*	no	$27.2^{+10.9}_{-5.3}$	-59^{+103}_{-74}	408^{+735}_{-430}	12.37 ± 0.30	1.07	49	1126
5	all/47-Tuc	*Dist #1*	yes	$43.4^{+9.7}_{-9.3}$	-66^{+137}_{-102}	622^{+763}_{-560}	12.57 ± 0.41	1.08	43	700
6	all/NGC6397	*Dist #1*	yes	$42.6^{+9.9}_{-9.5}$	-77^{+129}_{-96}	623^{+757}_{-544}	12.58 ± 0.40	1.09	43	961
7	all/M28	*Dist #1*	yes	$42.5^{+9.5}_{-9.5}$	-80^{+124}_{-91}	597^{+717}_{-510}	12.46 ± 0.37	1.07	43	846
8	A	*Dist #2*	yes	$38.6^{+9.4}_{-8.9}$	-91^{+81}_{-76}	343^{+805}_{-431}	12.18 ± 0.29	1.04	21	874
9	A′	*Dist #2*	yes	$37.5^{+9.0}_{-8.9}$	-88^{+76}_{-70}	263^{+764}_{-361}	12.22 ± 0.32	1.06	29	945
10	B	*Dist #2*	yes	$49.12^{+10.0}_{-10.0}$	-6.66^{+137}_{-138}	804^{+709}_{-675}	12.88 ± 0.43	1.19	28	255
11	B′	*Dist #2*	yes	$50.3^{+9.8}_{-9.6}$	-1^{+134}_{-143}	881^{+671}_{-705}	12.98 ± 0.40	1.18	23	178

[Baillot d'Étivaux+, ApJ 2019]

Outlook:
Include phase transition
Confront with other observations

Probing extreme matter physics with GW



Particle and nuclear accelerators

Astrophysical observations

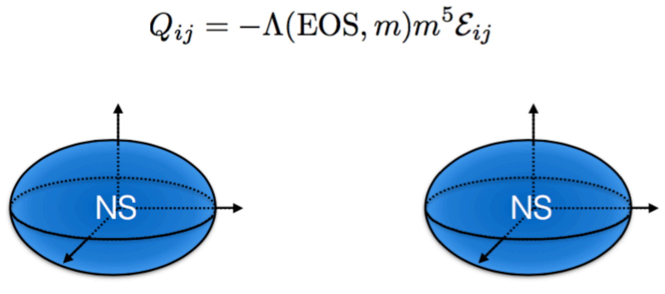
New limits for extreme matter

Neutron stars, supernovae, kilonovae…

What is the **nuclear interaction** in dense, isospin asymmetric matter, hot?
Which **new particles** appear at supra-saturation densities?
At which density occurs the **deconfinement** from hadrons to Quarks-Gluons Plasma (QGP)?
How **neutrinos** propagate and what are the **transport properties** of extreme matter?
Are BNS the main astrophysical site for the **r-process**?

Tidal deformability

- Tidal field E_{ij} from companion star induces a quadrupole moment Q_{ij} in the NS
- Amount of deformation depends on the stiffness of EOS via the tidal deformability Λ.

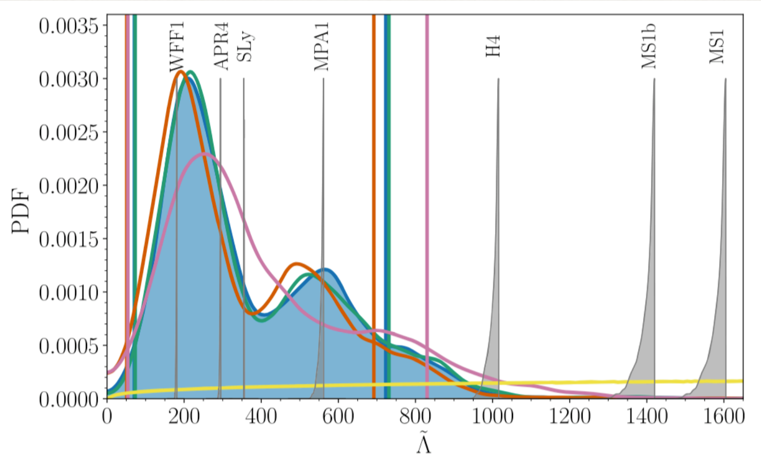


$$Q_{ij} = -\Lambda(\mathrm{EOS}, m) m^5 \mathcal{E}_{ij}$$

Post-Newtonian expansion of the waveform: Tidal effect enters at 5th order.

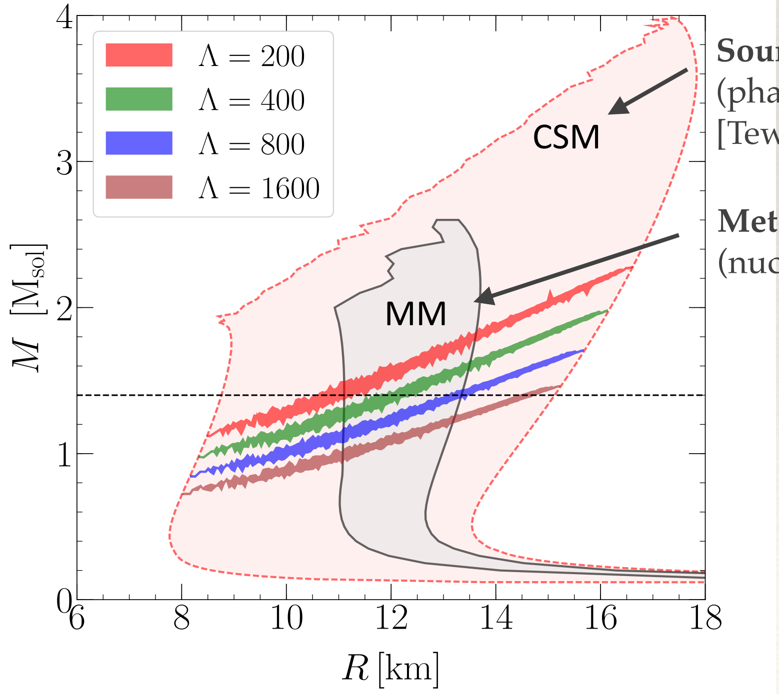
Hinderer+ 2008, Blanchet, Damour

LVC, Phys. Rev. X 9, 011001 (2019)



GW170817
→ 70 ≤ Λ ≤ 720 (90% CL)
→ +E-M 300 ≤ Λ ≤ 800

[Tews, JM, Reddy, EPJA special issue on GW (2019)]

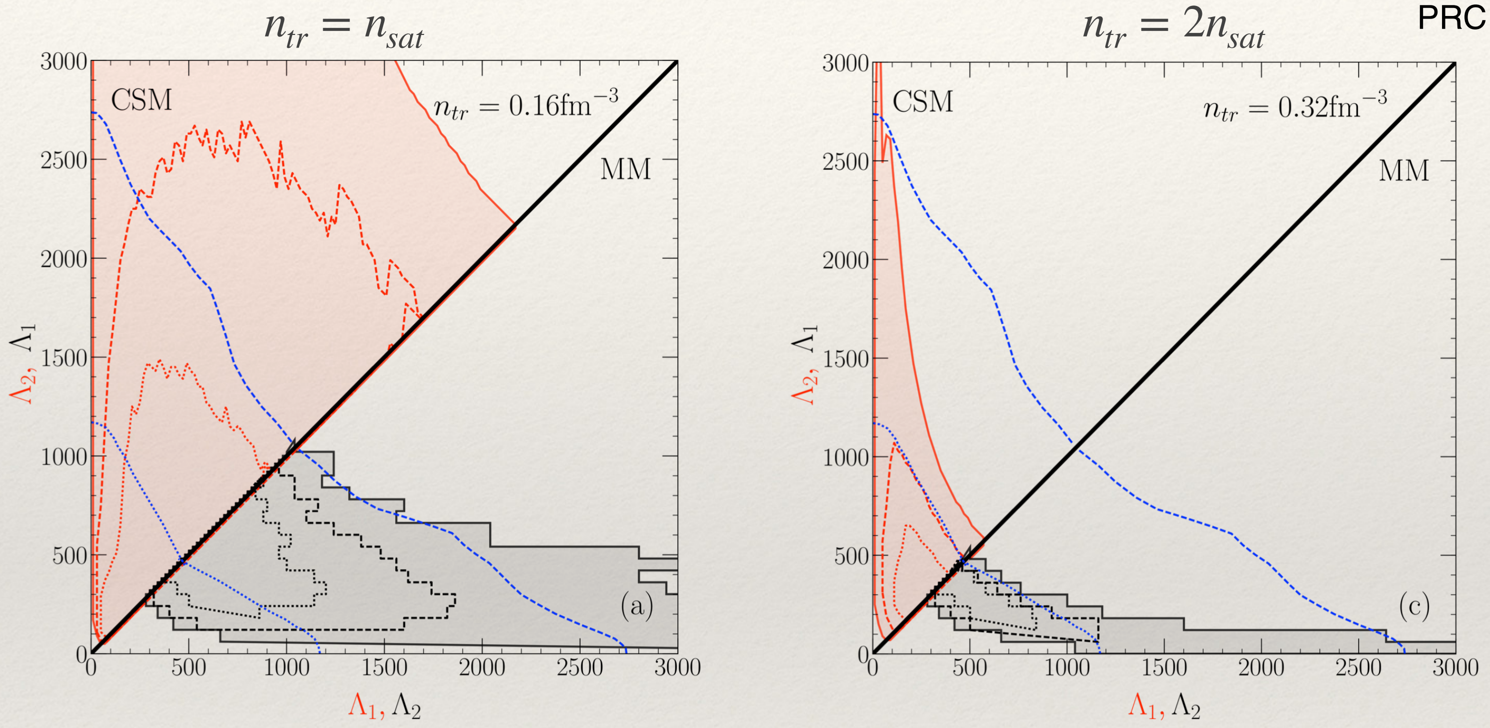


Sound-speed Model (phases transitions) [Tews+ 2018]

Meta-Model (nucleonic)

Confront EoS / GW

[Tews, JM, Reddy,
PRC 2018, EPJA 2019]



Required GW accuracy to improve our knowledge:

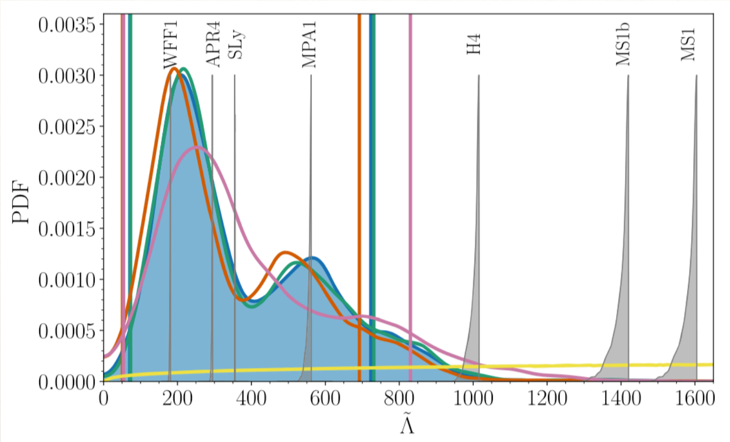
$\Delta\Lambda \approx$ 200-300 → Probe EOS from 1 to 2n_{sat}

Confirm or rule out nuclear physics

$\Delta\tilde{\Lambda} \approx$ 50-100 → Probe matter composition above 2n_{sat}

Using the full structure of the Λ-pdf

LVC, PRX 9 (2019)



Impact of 2 analyses from raw data:

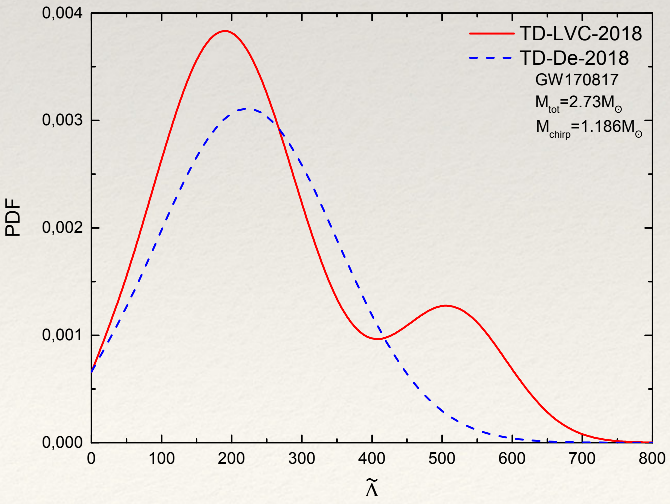
- LVC, PRX 9 (2019)
- De et al., PRL 121 (2019)

—> Bayesian analysis

Impact of 2 prior sets:

#1: small ranges defined from global nuclear physics analysis (JM 2018)

#2: large ranges (included non-zero probabilities)



GW170817

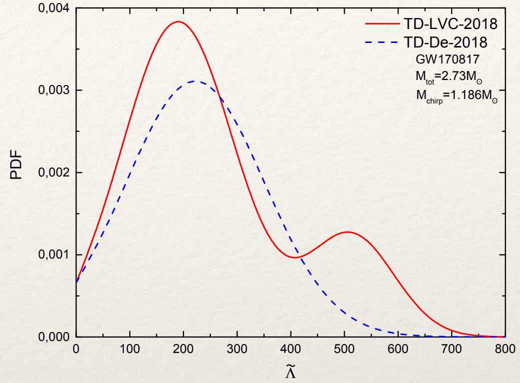
→ 70 ≤ L ≤ 720 (90% CL)

→ 70 ≤ L ≤ 500 (90% CL)

Using the full structure of the Λ-pdf

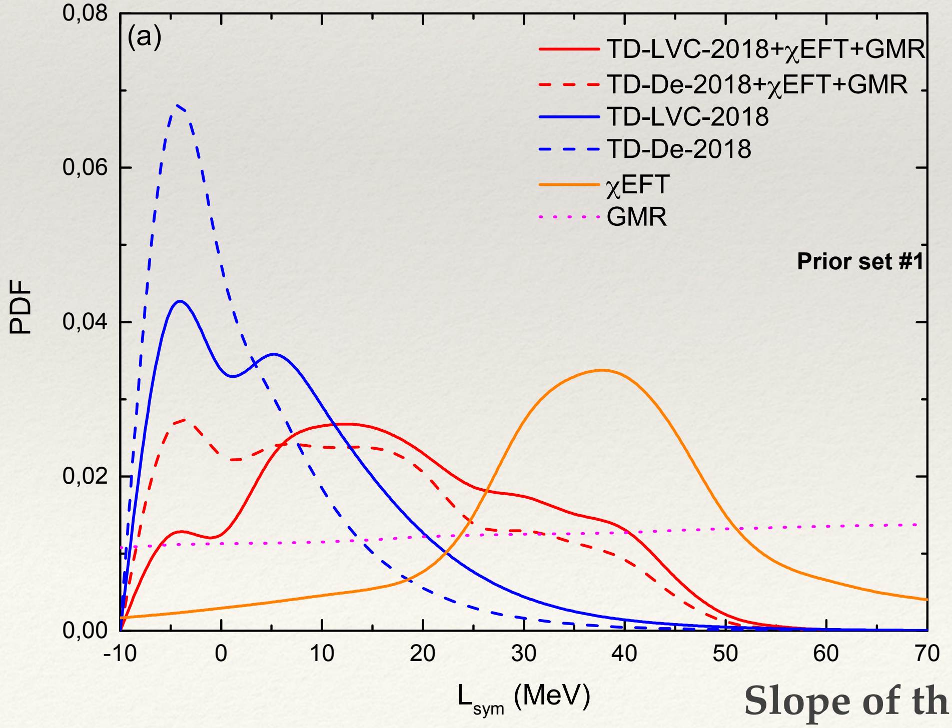
Impact of 2 analyses from raw data:
LVC, PRX 9 (2019)
De et al., PRL 121 (2019)

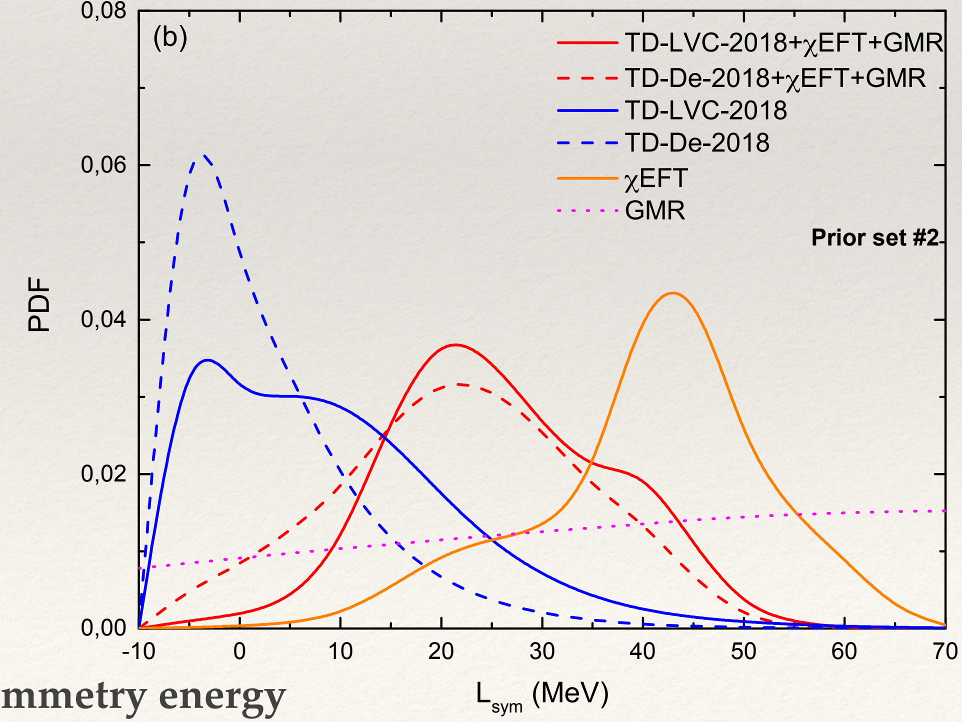
Impact of 2 prior sets:
#1: small ranges defined from global nuclear physics analysis (JM 2018)
#2: large ranges (included non-zero probabilities)



Marginalization over Lsym

H. Güven et al., to be submitted



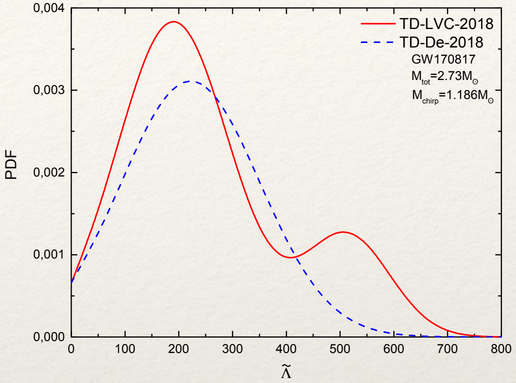


Slope of the symmetry energy

Using the full structure of the Λ-pdf

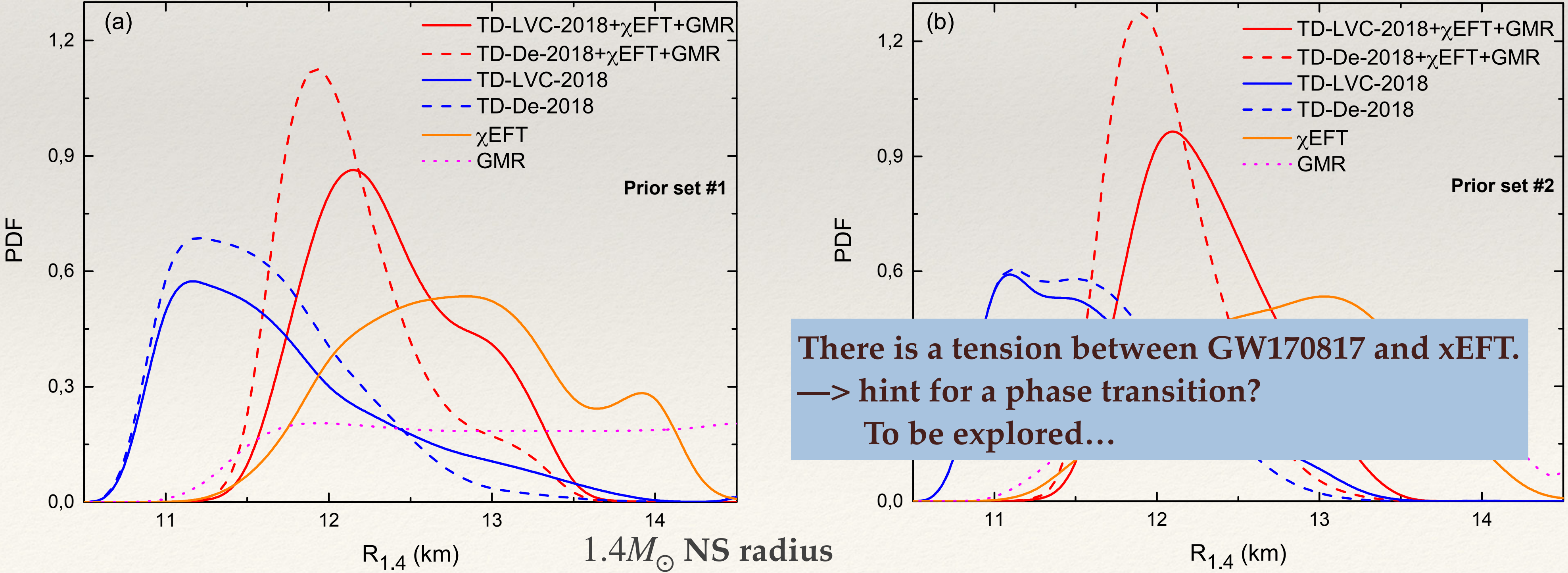
Impact of 2 analyses from raw data:
LVC, PRX 9 (2019)
De et al., PRL 121 (2019)

Impact of 2 prior sets:
#1: small ranges defined from global nuclear physics analysis (JM 2018)
#2: large ranges (included non-zero probabilities)



Marginalization over $R_{1.4}$

H. Güven et al., to be submitted



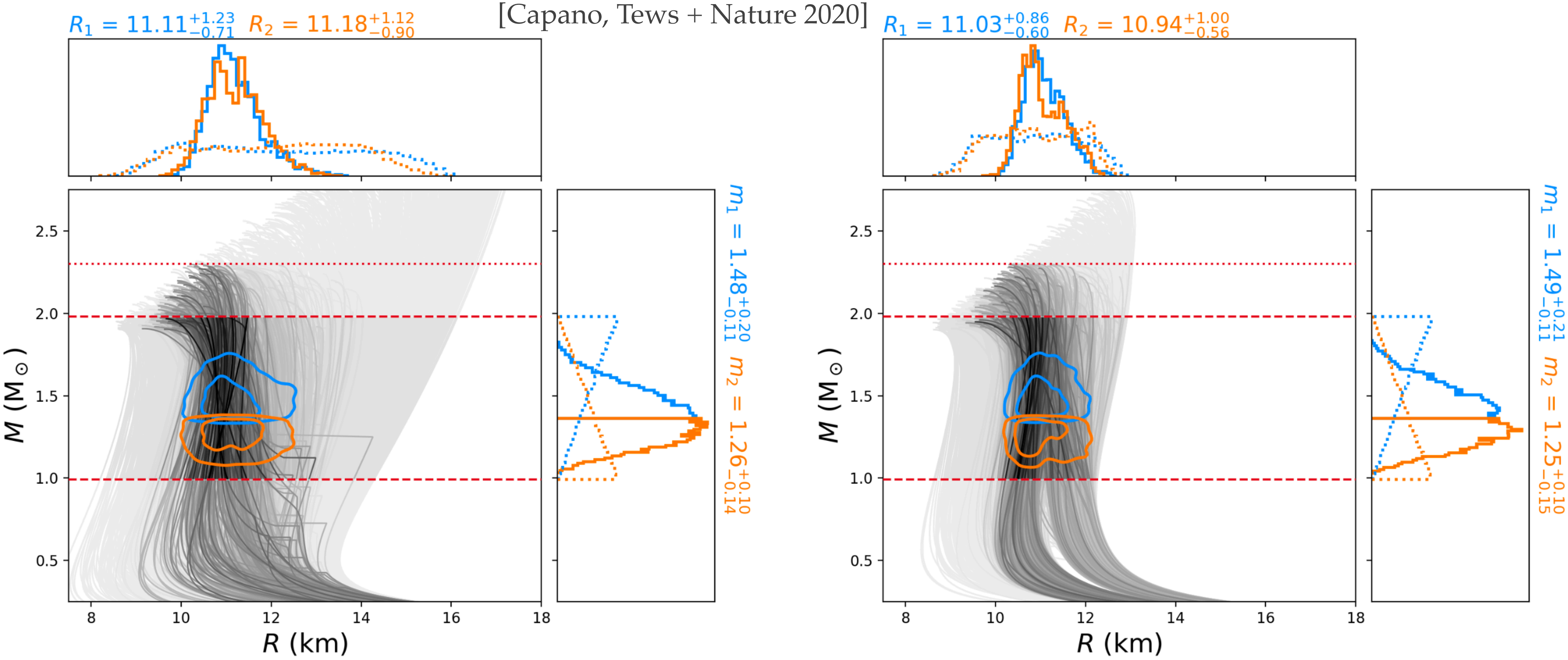
$1.4M_\odot$ **NS radius**

There is a tension between GW170817 and xEFT.
—> hint for a phase transition?
To be explored…

Stringent constraints on NS radii

Direct comparison of the GW waveforms to the raw data, with EoS modeling + $M_{\text{total}} \leq M_{\text{thresh}}(\approx 2.3 M_\odot)$.

$n_{tr} = n_{sat}$ $n_{tr} = 2n_{sat}$

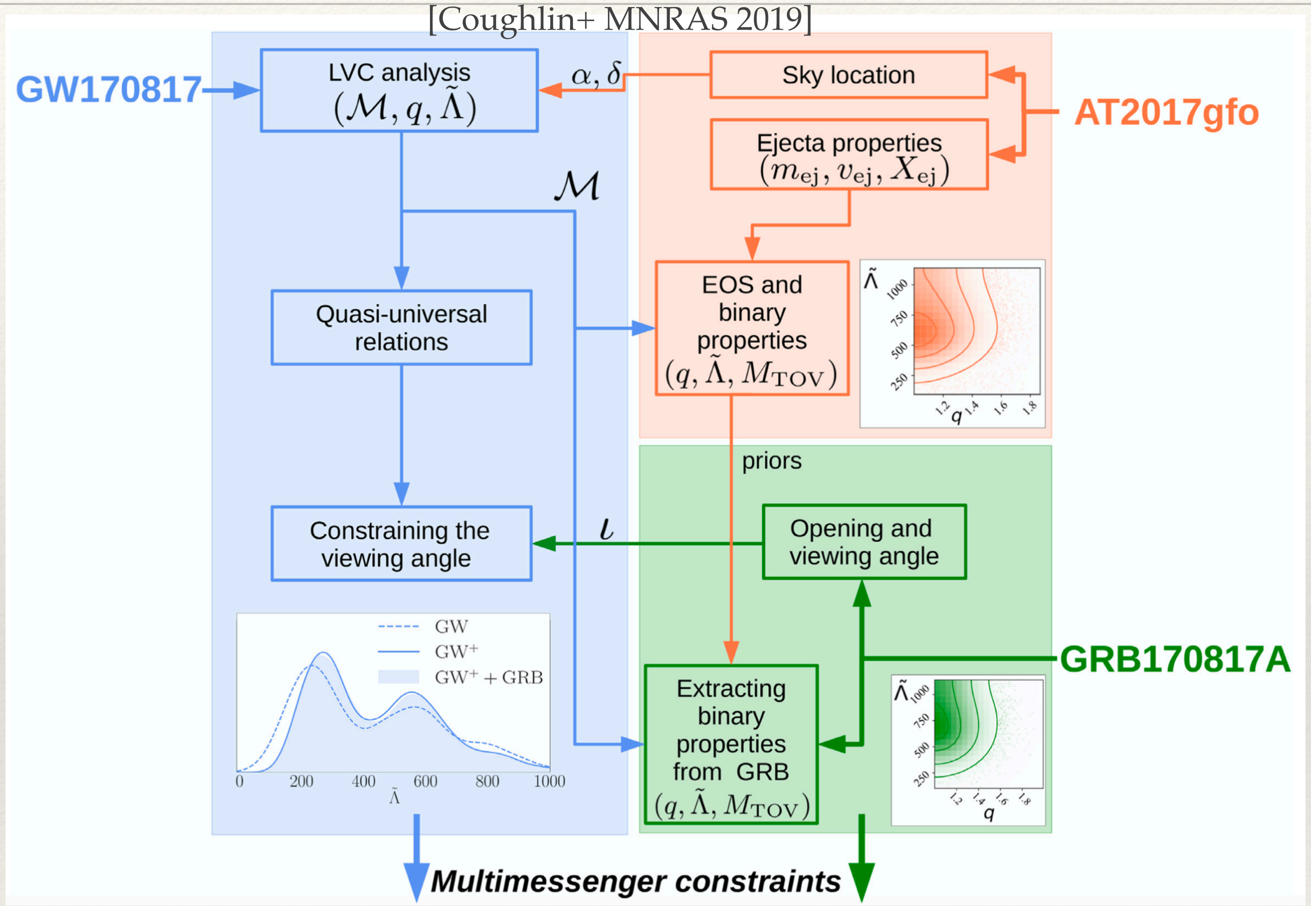


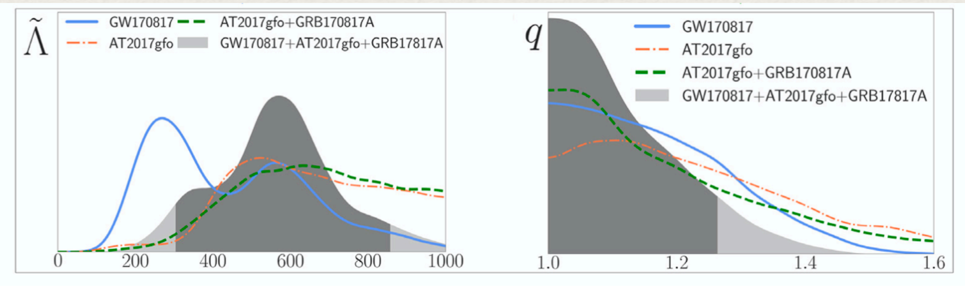
[Capano, Tews + Nature 2020]

—> **Low NS radii** also seems to be preferred.

Richness & complexity of multi-messenger analysis

[Coughlin+ MNRAS 2019]





GW170817
→ $70 \le \Lambda \le 720$ (90% CL)
→ +E-M $300 \le \Lambda \le 800$

If confirmed:
—> large radii are preferred.
But yet complex and highly model dependent.

In summary

Thermal emission from qLMXB:

Could predict **low radii**.
Could also be compatible with nuclear physics (**average radii**).

GW170817 + multi-messenger:

Requires improved precision for $\tilde{\Lambda}$.
More detailed analyses: tend to prefer **low radii** (~11 km).
Extended GW+EM analysis: prefer **average radii** (12-13 km).

NICER:

Data from
PSR J0030+0451: **average radii** seems to be preferred…

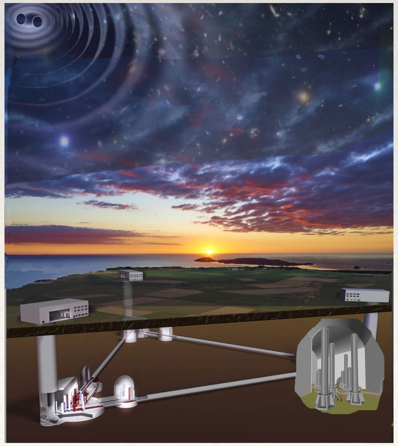
Tension seems to **emerge** between various observational signals.
—> to which extend it signs the existence of a **phase transition**?

Conclusion and outlook

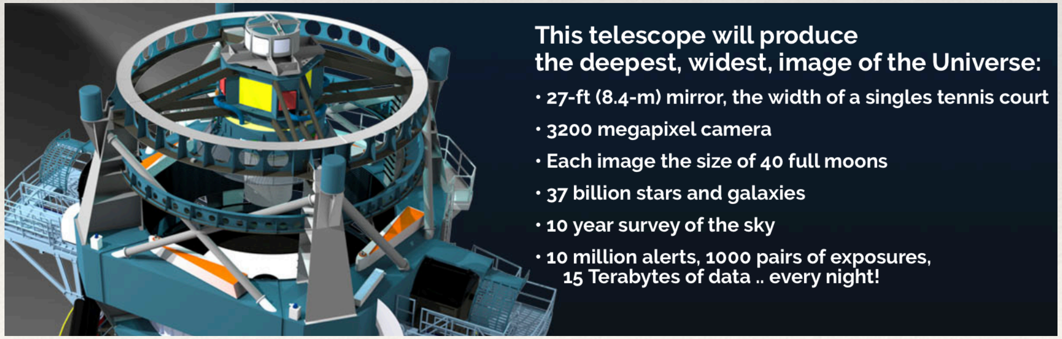
Multi-messenger observation: The BNS GW + kilonovae EM signal + GRB (+ neutrinos?).
Variety of GW sources: BNS, BH-NS, CCSN, continuous emission, etc…
(Futur) post-merger GW signal: investigation of phase transitions.

Future upgrades and new telescopes (a lot of new data):
GW interferometers: upgrades of LIGO-Virgo (KAGRA, LIGO India).
E-M follow-up: GRANDMA, ZTF → (future) LSST.
3rd generation (~2030-2040): Cosmic Explorer, Einstein Telescope.
Space interferometer (LISA ~2035): low frequencies (trigger future mergers).

ET



LSST



This telescope will produce
the deepest, widest, image of the Universe:

- 27-ft (8.4-m) mirror, the width of a singles tennis court
- 3200 megapixel camera
- Each image the size of 40 full moons
- 37 billion stars and galaxies
- 10 year survey of the sky
- 10 million alerts, 1000 pairs of exposures,
  15 Terabytes of data .. every night!

Blooming future —> answering questions about dense matter