PAX

Extreme Matter Panel

S.Bernuzzi, S.Bhagwat, I.Bombaci, P.T.H.Pang

Almost two years after August 2017 event ...

- What did we learn from the GW170817 about nuclear matter ?
- What did we learn from the counterparts alone?
- What did we learn from combined data?

Looking forward:

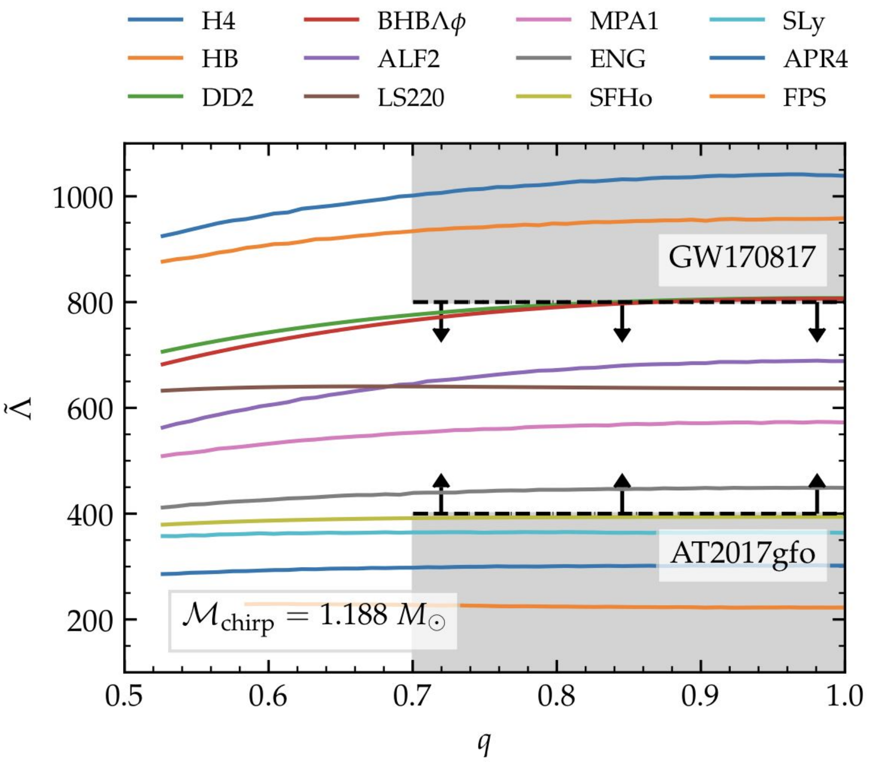
- How robust are the results?
- What are the limitations & caveats?
- What do we expect from future observations?
- What theory & analysis tools we need to go beyond?

Priority questions proposed by the panel

- Priors and degeneracies in GW analysis affecting tidal par measurement
- Systematics with multiple GW events combined
    - “Universal” relations, Waveform, Priors
- Nuclear physicists perspective
    - Nuclear interactions in high density regime (Symmetry energy et al)
    - Nonnucleonic d.o.f. (Hyperons)
    - Quark deconfinement phase transition

Swetha: Intro on PE for BNS, priors & degeneracies

Observational constraints with GW170817



Radice et al.

“Where” is the information on tides?

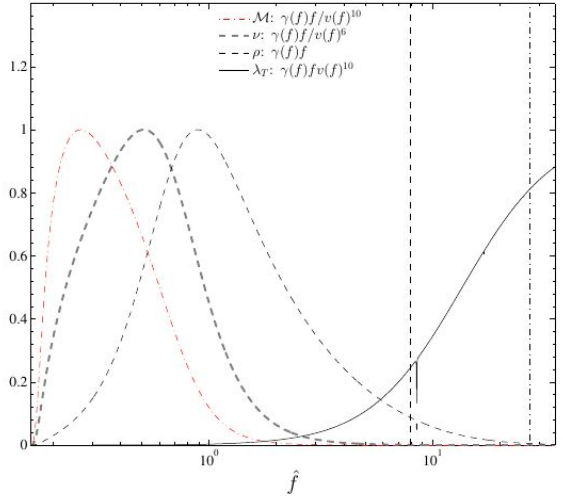


FIG. 3. Integrands, per frequency octave, of the integrals determining the measurability of $\mathcal{M}$, ν, ρ (SNR) and λ_T. While most of the SNR is gathered around frequencies $\hat{f} = f/(56.56\ \mathrm{Hz}) \sim 1$, the measurability of $\mathcal{M}$ and ν is concentrated towards lower frequencies ($\hat{f} = f/f_0 < 1$), and that of the tidal parameter λ_T gets its largest contribution from the late inspiral up to the merger. The rightmost vertical line indicates the merger frequency for $\mathcal{C} = 0.1645$, while the leftmost vertical line marks 450 Hz for a $1.4M_\odot + 1.4M_\odot$ BNS system.

Damour, Nagar, Villain (2011)

Harry, Hinderer (2015)

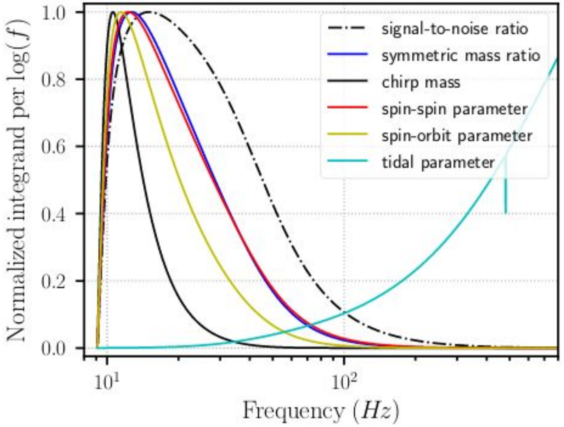
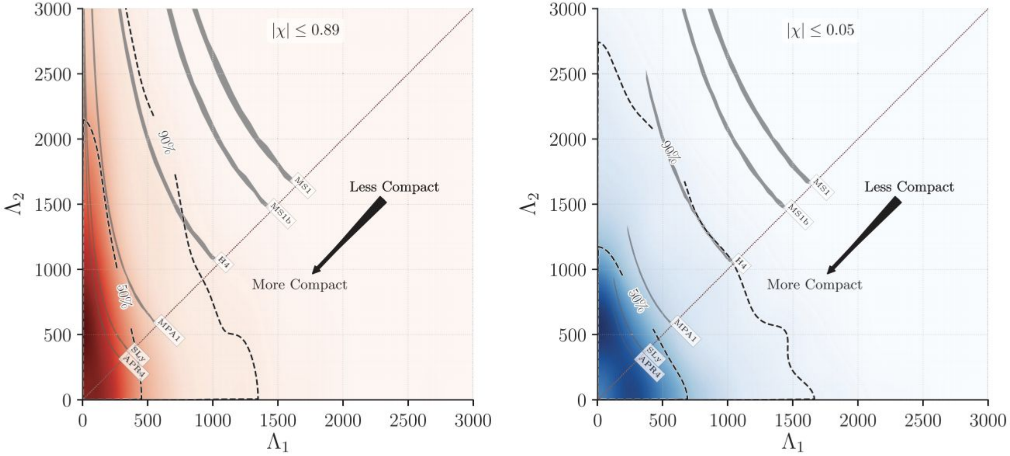


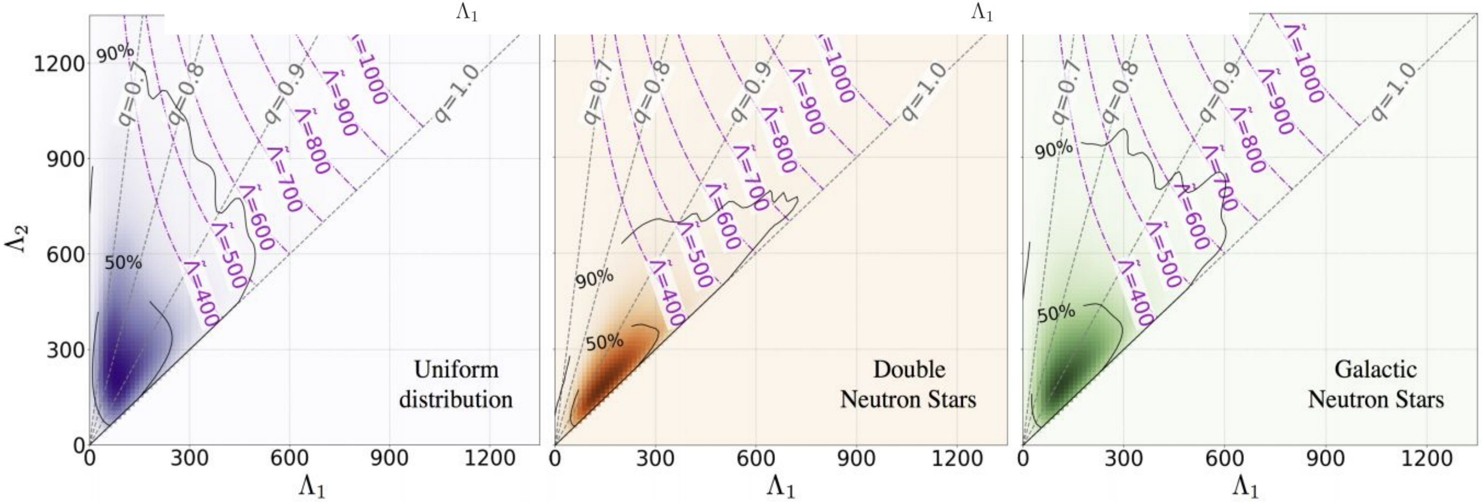
Figure 2. *Illustration of where in frequency the information about intrinsic binary parameters predominantly comes from.* The quantity shown on the $y-$axis is a normalized quantity characterizing the accumulation of information about the binary parameters ξ_i per logarithmic frequency interval. Specifically, the y-axis is $|(\partial\tilde{h}/\partial\xi_i)|^2/(f\ S_n)$ for S_n the zero-detuned high power configuration of Advanced LIGO and each curve normalized to its maximum value.

Dependency on priors!

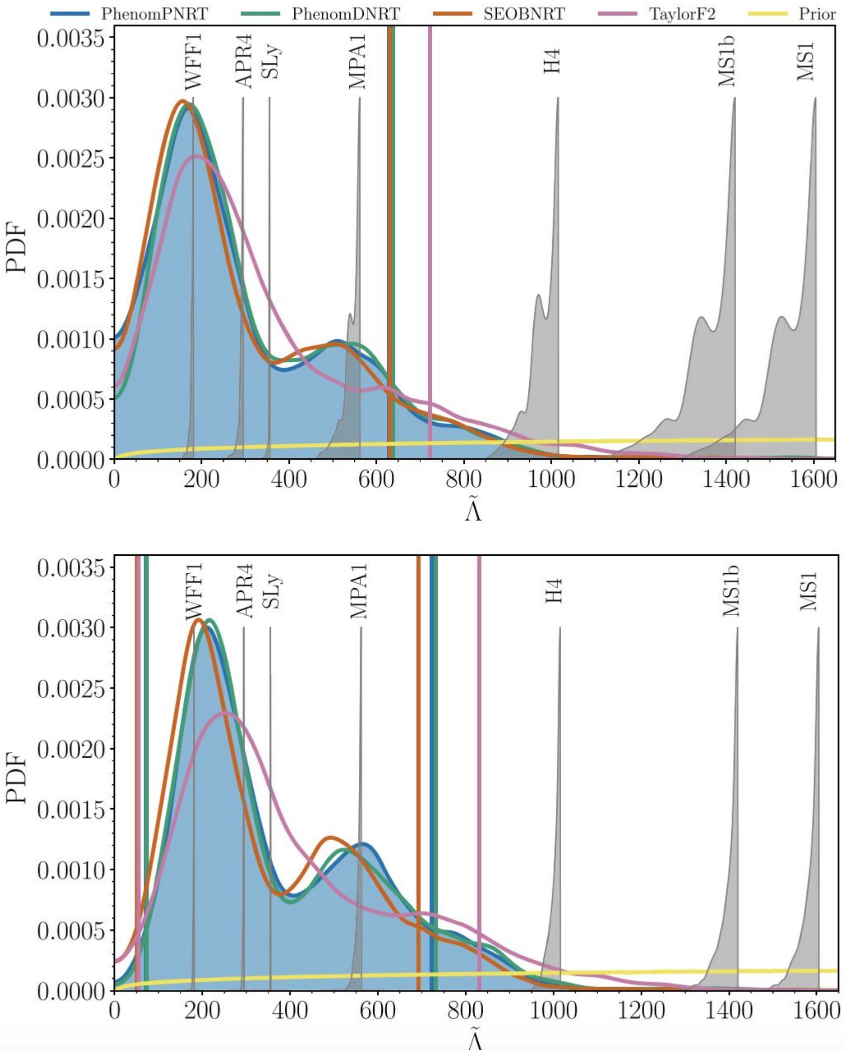


LIGO-Virgo result

The choice of mass prior:
PhysRevD.92.023012



De et al.



High Spin Prior v/s Low spin - LIGO-VIRGO result

Peter: GW BNS analysis, systematics

Difficulties of combining multiple events

Systematics can be significant

- Imperfect fitting in quasi-universal relations
- Waveform systematics
- Priors on parameters, e.g. mass

Employing universal* relation

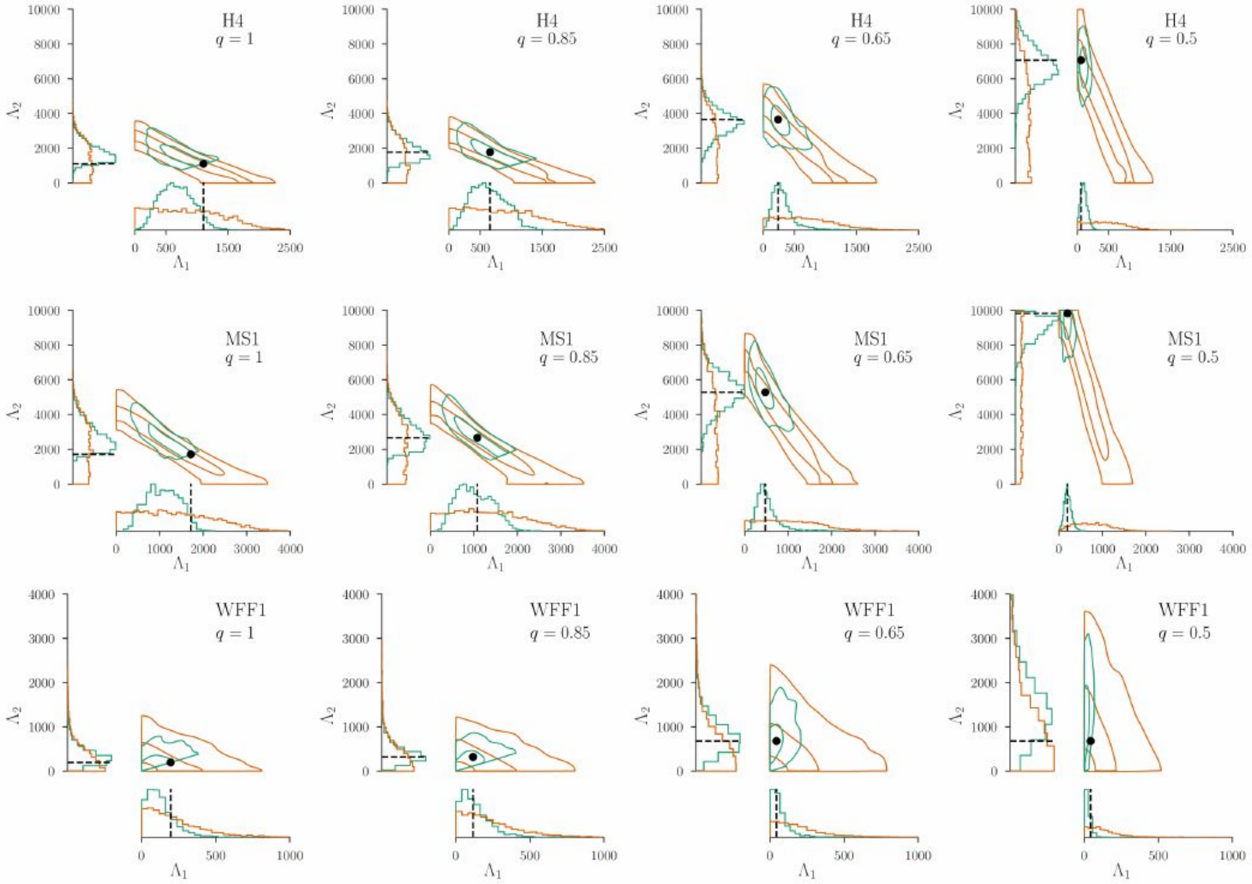
Advantages:

- Reduce statistical error
- Reduce the dimensionality of the parameter space to sample

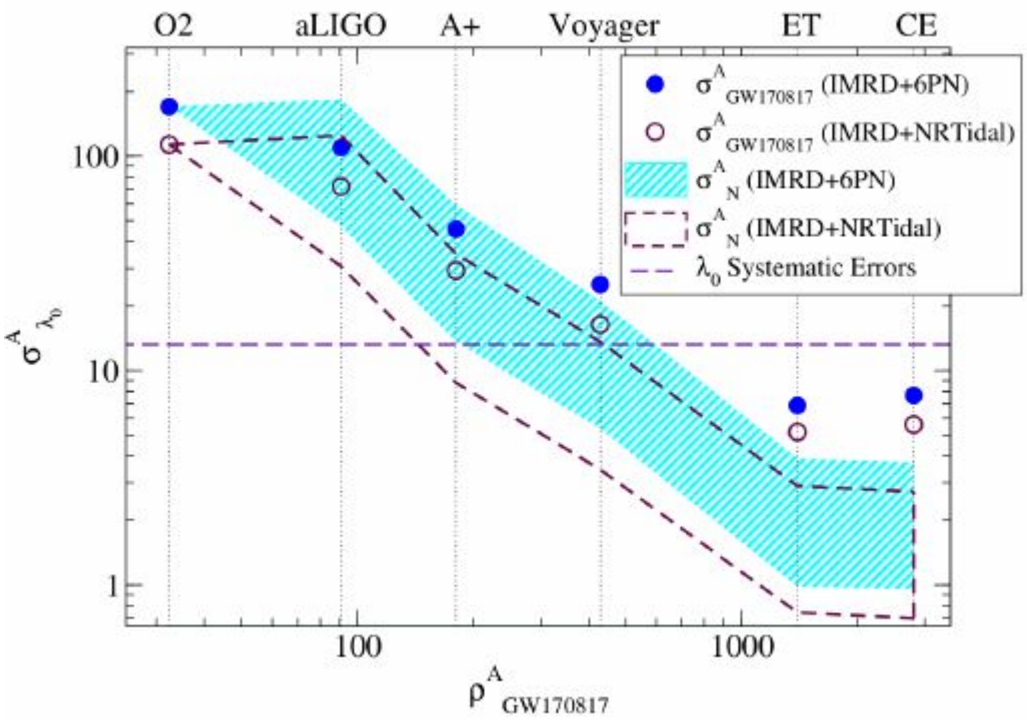
Disadvantages:

- Induced systematic error

*EoS-independent



Plot taken from Chatziioannou *et.al* (2018)



Plot taken from Carson *et.al* (2018)

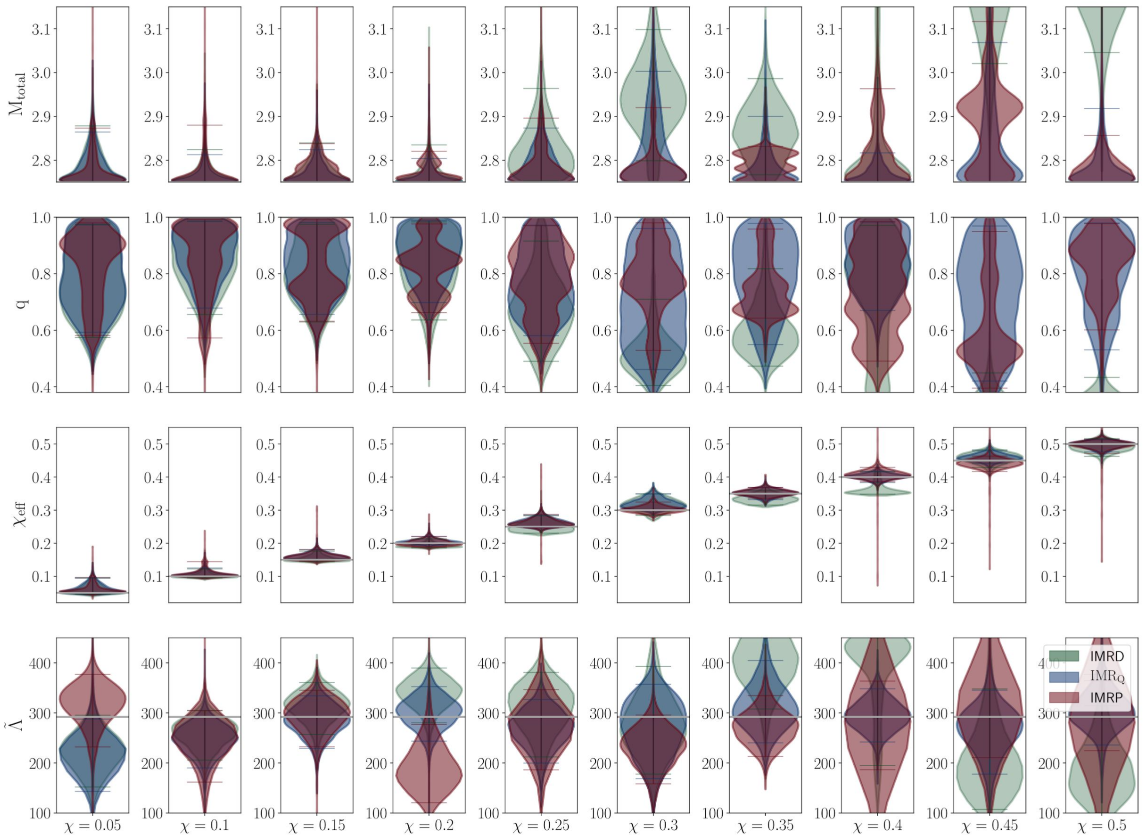
Waveform systematics

Systematics due to

- Quadrupole-monopole
- Spin Precession

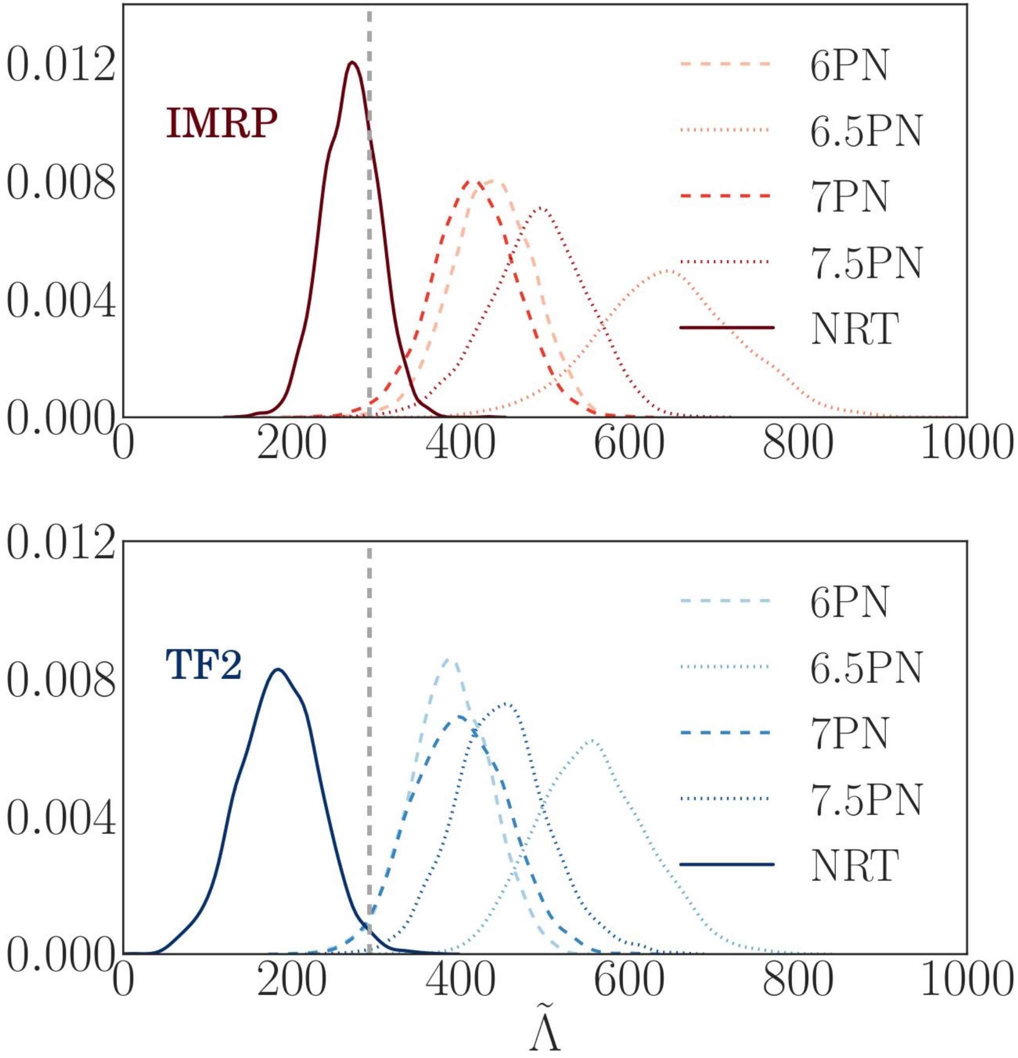
Samajdar *et.al* (2019)

- 1.375-1.375 solar mass
- aligned spin
- SNR of 80-90



Waveform systematics

Point-Particle Baseline modelling

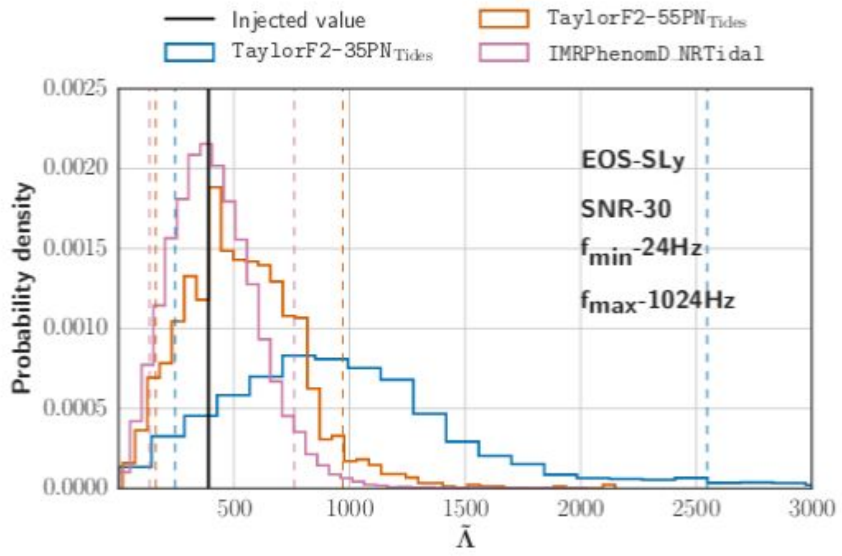


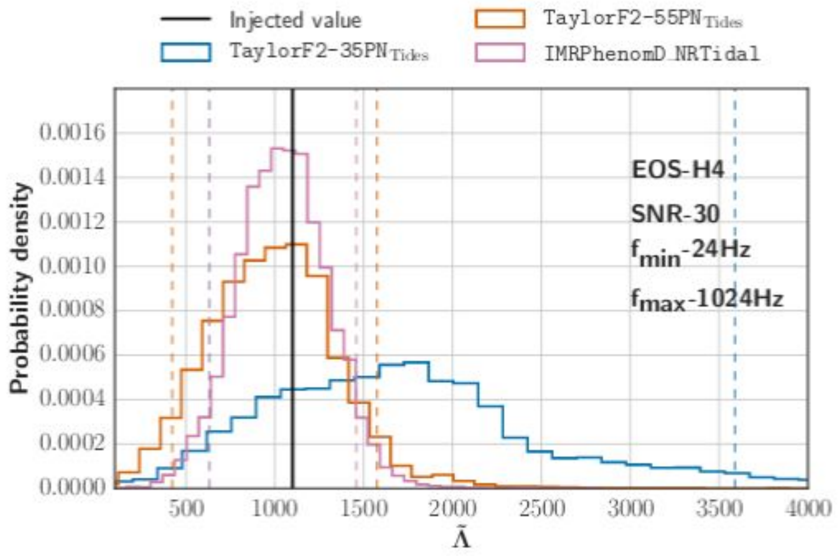
Plot taken from Samajdar *et.al* (2018)

Recovery of tidal parameter of

an unequal mass binary

Waveform systematics

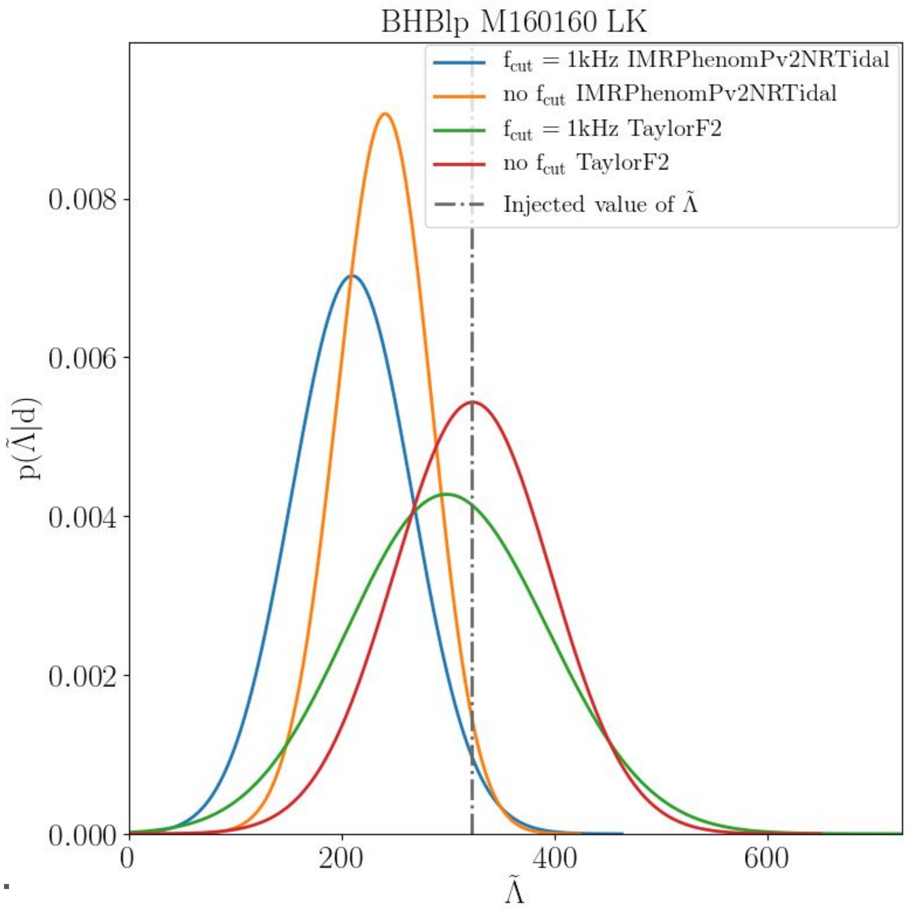




Messina, Dudi, Nagar, SB (2018)

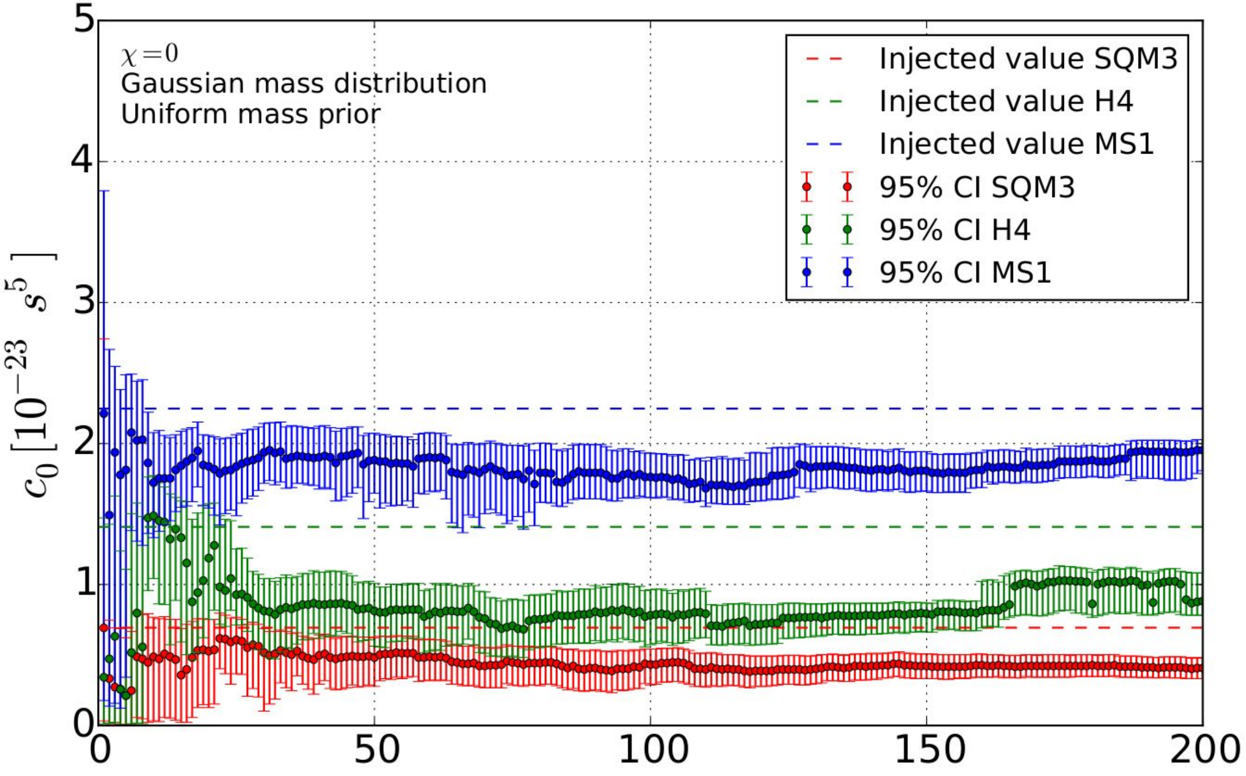
More waveform systematics

- TEOBResumS injection
- fmin 30 Hz
- fmax 1kHz or 2kHz
- Priors?



Agathos, Zappa, Breschi, SB (2019) Unpub.

Prior systematics



Plot taken from Agathos *et.al* (2015)

Ignazio: Nuclear physicists perspective

Probing extreme matter with GWs

One of the main scientific target of Gravitational Wave astronomy is to explore the properties of hot ($T \leq 100$ MeV) and dense ($\rho \leq 2.8 \times 10^{15}$ g/cm^3) matter

Astrophysical environments for extreme matter:

Core-Collapse SNe , proto-Neutron Stars, Neutron Stars , BNS mergers, and eventually ``exotic`` astrophysical processes as NS $\rightarrow$ SS conversion

Key questions

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   Density dependence of the nuclear symmetry energy ?

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   or the existence of Crystalline color superconducting quark matter ?

(cont.)

Key questions

4. Is there a single family of Neutron Stars" ?
or are there two-coexisting familes of ''Neutron Stars" ?
In the latter case what are the astrophysical implications,
and how GW observations could shed light on this issue?

Probing extreme matter with GWs

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4. Is there a single family of Neutron Stars" ?
   or are there two-coexisting familes of ''Neutron Stars" ?
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   and how GW observations could shed light on this issue?
5. How does dense matter transport properties (shear and
   bulk viscosity, thermal conductivity, etc.) affect the
   evolution and the fate of the post-merger remnant?
   (influence on $\tau_{\text{diff-rot}}$ differential-to-rigid-rotation
   damping time)

Probing extreme matter with GWs

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6. Neutrino-matter interactions rates Neutrino-driven explosion mechanism and neutrino signal in SNe. Proto-neutron star evolution. BNS merging (evolution of the post-merger remnant and its GW signal).

Key questions

7. **How do the properties of atomic nuclei far from the stability valley influence r-process nucleosynthesys and the EM counterpart of the merger?**

Modeling extreme matter and GWs with piecewise-polytropic EOS

$$P(\rho) = K_i \, \rho^{\Gamma_i} ; \quad \varrho_{i-1} \leq \rho \leq \varrho_i$$

Advantages:

very easy and efficient to use in GR numerical simulations;

Easy to include physical requirements as e.g. causality condition,

and $M_{max} \geq 2\, M_{\odot}$

Disadvantages:

No informations on the particle composition of matter.

No connection with the underlying microphysics of the strong interactions.

No fundamental physics of dense matter modeling BNS mergers with polytropic EOS

G. Raaijmakers, T.E. Riela, A.L. Watts,
A pitfall of piecewise-polytropic equation of state inference, MNRAS 478 (2018) 2177

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Nucleon Stars

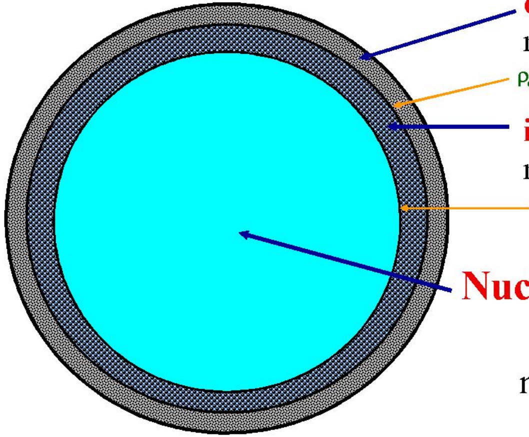
β-stable nuclear matter

$$p + e^- \leftrightarrow n + \nu_e$$

$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

$$\mu_e \geq m_\mu$$

$$e^- \rightarrow \mu^- + \nu_e + \bar{\nu}_\mu$$



- Equilibrium with respect to the weak interaction processes

$$\mu_n - \mu_p = \mu_e$$

$$\mu_\mu = \mu_e$$

- Charge neutrality

$$n_p = n_e + n_\mu$$

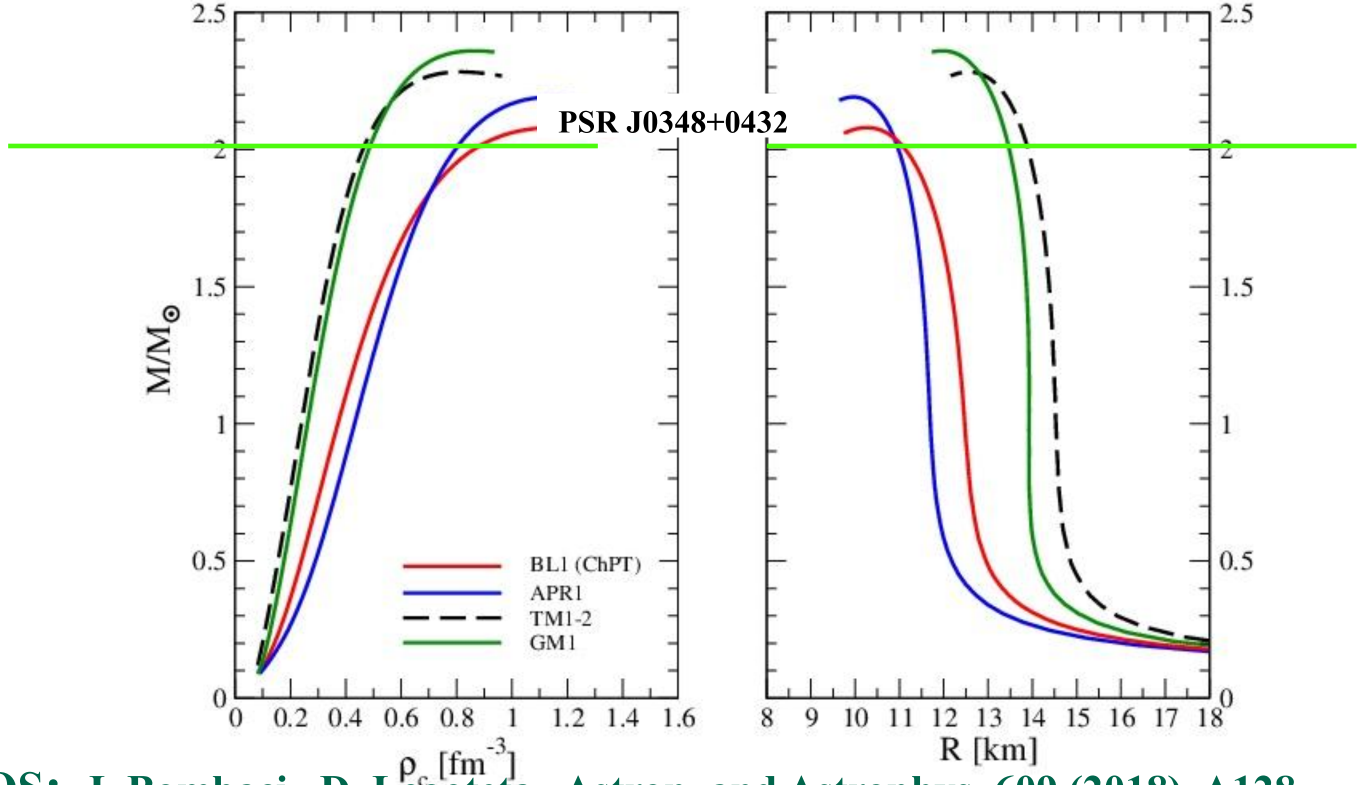
neutrino-free matter

$$\mu_\nu = \mu_{\bar{\nu}} = 0$$

To be solved for any given value of the total baryon number density n

Nucleon Stars (neutron stars with a nuclear matter core)

Comparison of different EOS models



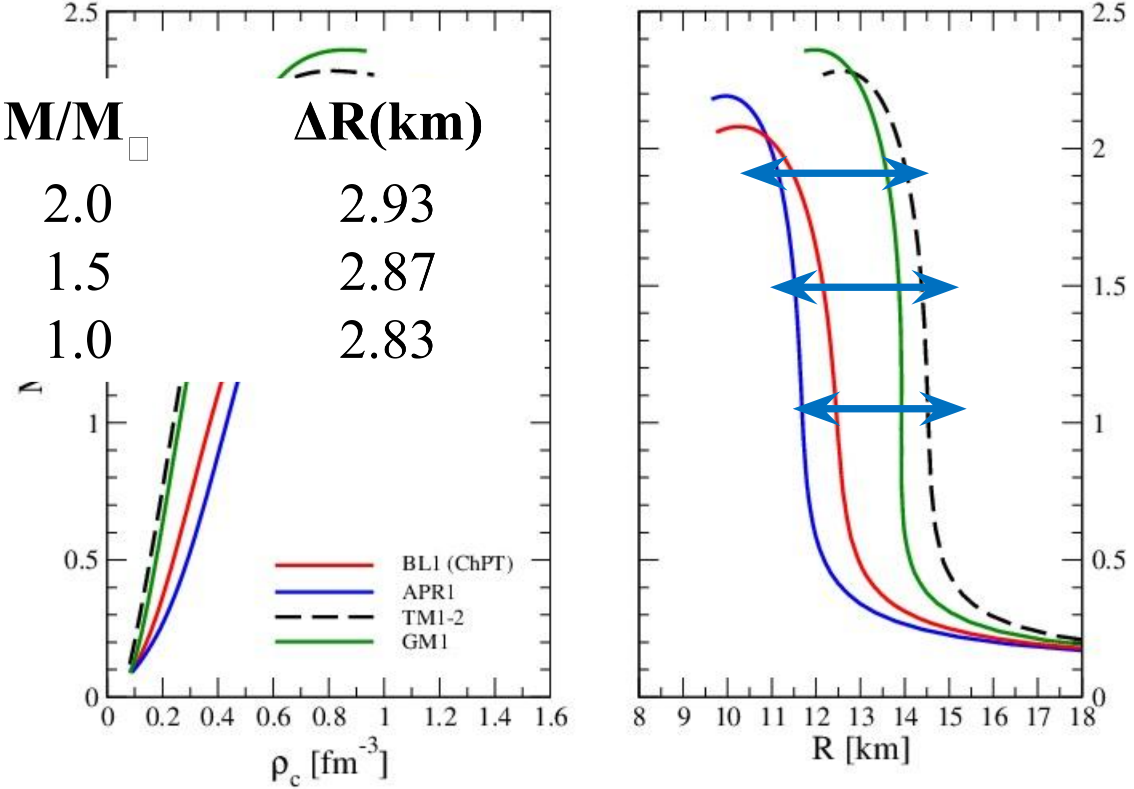
BL EOS: I. Bombaci, D. Logoteta, Astron. and Astrophys. 609 (2018) A128

I. Bombaci, D. Logoteta, (2017)

Nucleon Stars (neutron stars with a nuclear matter core)

NS radius vs nuclear matter EOS models

$M/M_\odot$	ΔR(km)
2.0	2.93
1.5	2.87
1.0	2.83



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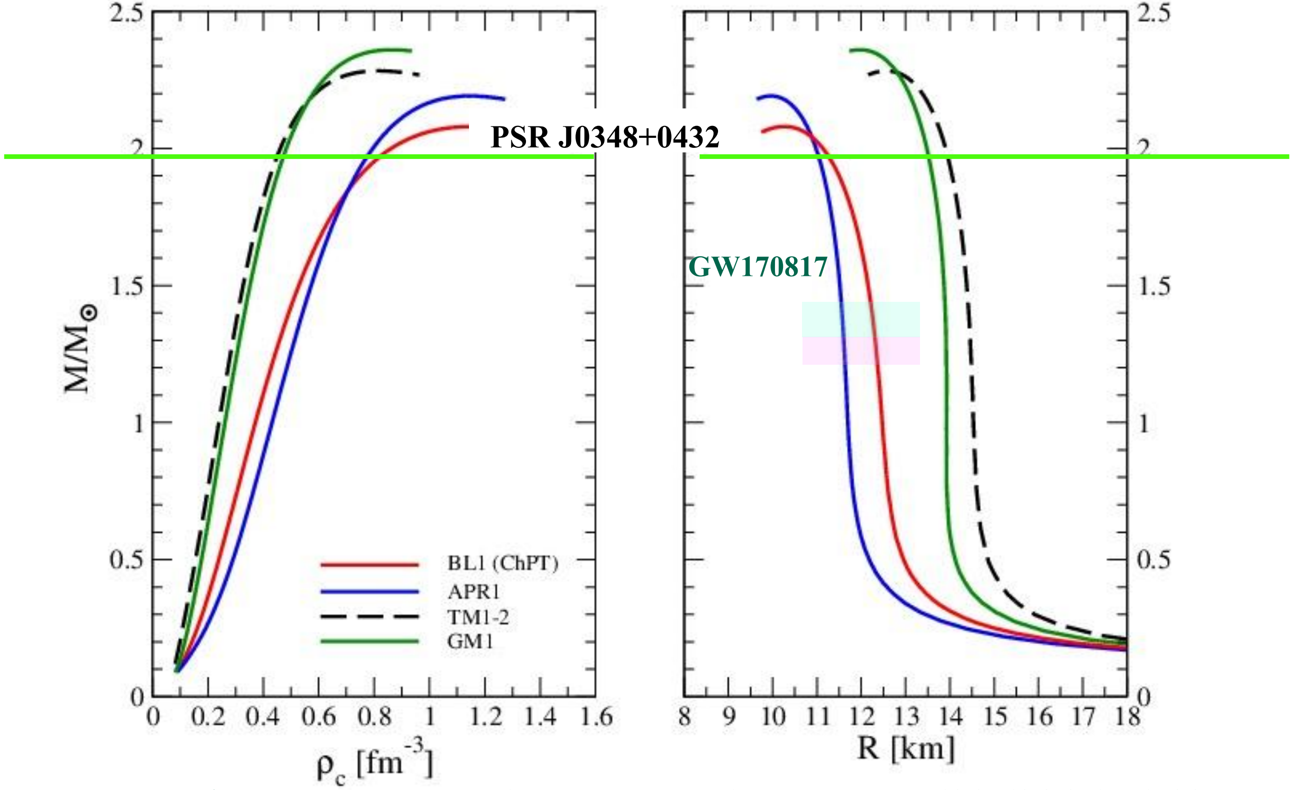

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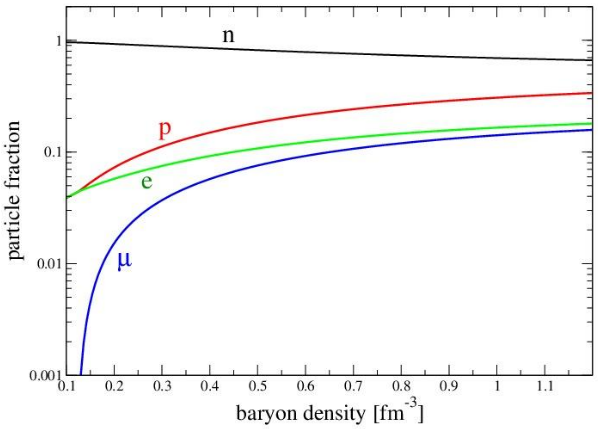
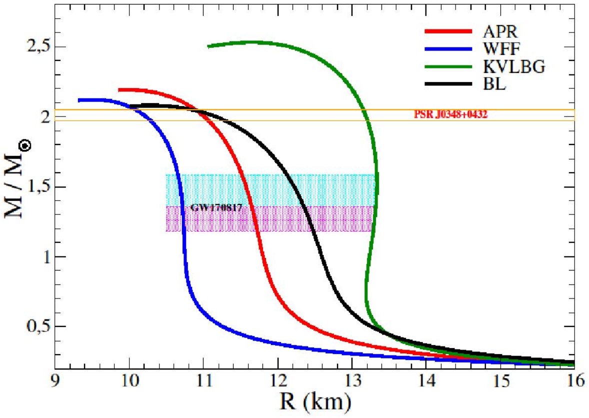
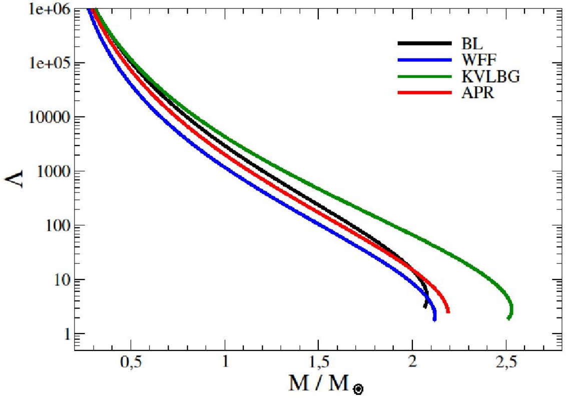
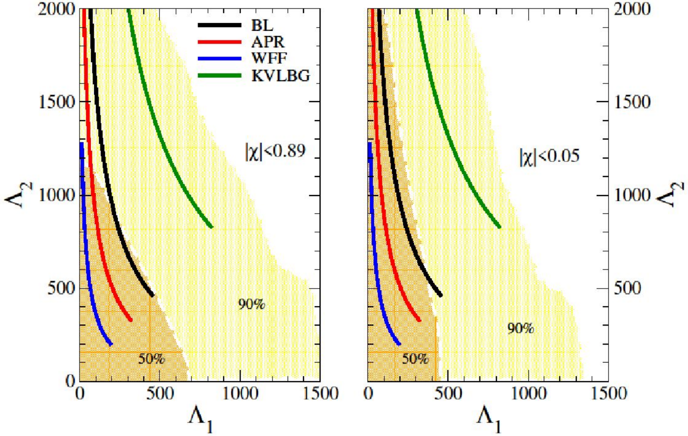




I. Bombaci, D. Logoteta, A & A 609 (2018) A128





I. Bombaci and D. Logoteta (2018)

GW170817 data from: **B. P. Abbot et al. (LIGO-Virgo collaboration), Phys. Rev. Lett. 119 (2017) 161101**

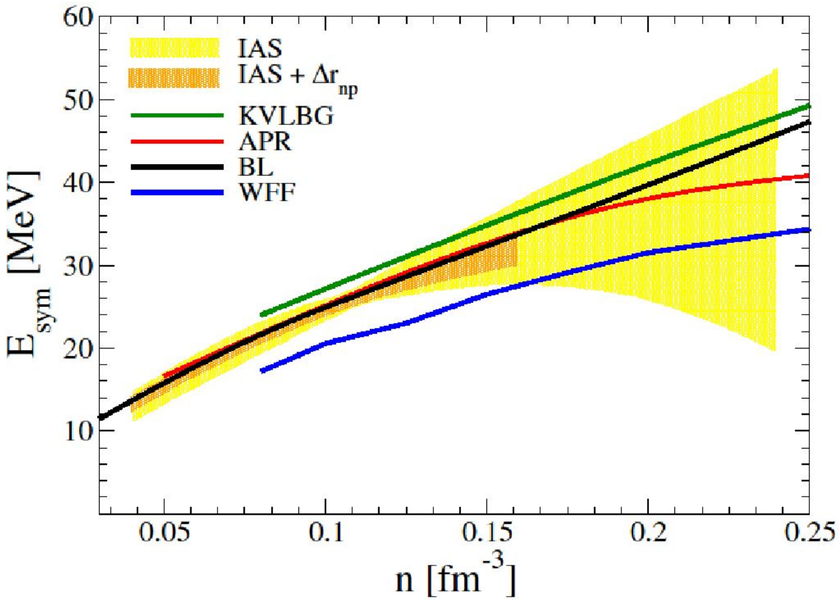
Selecting Nuclear Matter EOS:
basic requirements

A prerequisite of any EOS of dense matter to be used in numerical simulations of Binary Neutron Stars merging relates to its capability to reproduce the experimental data of atomic nuclei and the empirical properties of nuclear matter at and around the nuclear saturation density $n_0 = 0.16\ \mathrm{fm}^{-3}$

Nuclear matter properties at the saturation density

EOS	n_0 (fm^{-3})	E_0 (MeV)	E_{sym} (MeV)	L (MeV)	K_0 (MeV)
BL	0.17	-15.2	35.4	76.0	190
KVLBG	0.15	-16.1	35.2	70.2	251
WFF	0.19	-12.4	31.0	56.5	209
APR	0.16	-16.0	33.9	59.4	266
APR_{micro}	0.18	-12.4	32.8	69.4	----
empirical	0.16 ± 0.01	-16 ± 1	25 – 37	30 – 90	180 – 260

Density dependence of the symmetry energy

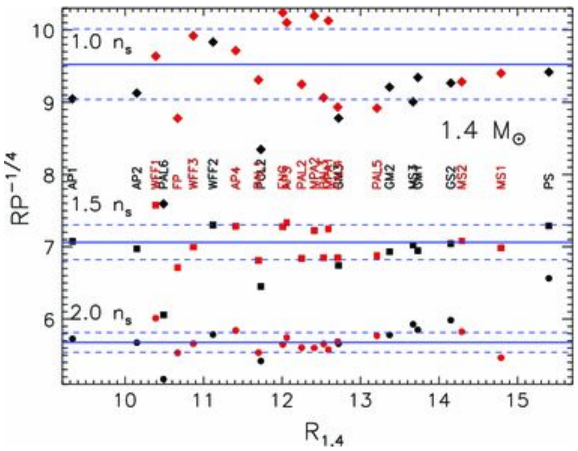


IAS = constraint from Isobaric Analog States in nuclei
(P. Danielewicz, J. Lee, Nucl. Phys. A922 (2014) 1)
Δr_{np} = neutron skin thickness of heavy nuclei
(X. Roca-Maza et al., Phys. Rev. C 87 (2013) 034301)

Symmetry energy and Neutron Star Radius

Pressure in β-stable nuclear matter at the saturation density n_0

$$P(n_0) \approx \frac{1}{3} n_0 L \left[1 - \left(\frac{4 E_{sym}(n_0)}{\hbar c} \right)^3 \frac{4 - \frac{3}{L} E_{sym}(n_0)}{3\pi^2 n_0} \right]$$



$$R_M = C(n, M) \left[P(n) \right]^{1/4}$$

J. M. Lattimer, M. Prakash, Astrophys. J. 550 (2001) 426

$M_{max} > 2.0\ M_\odot$

$$R_{1.4} = C(n_0, 1.4) \left[P(n_0) \right]^{1/4}$$

$$C(n_0, 1.4) = 9.52 \pm 0.49 \ \frac{\text{km}}{\left(\text{MeV/fm}^3\right)^{1/4}}$$

measured L, $E_{sym}(n_0)$

$$R_{1.4} = 11.9 \pm 1.2 \ \text{km}$$

J. M. Lattimer, Y. Lim, Astrophys. J. 771 (2013) 51

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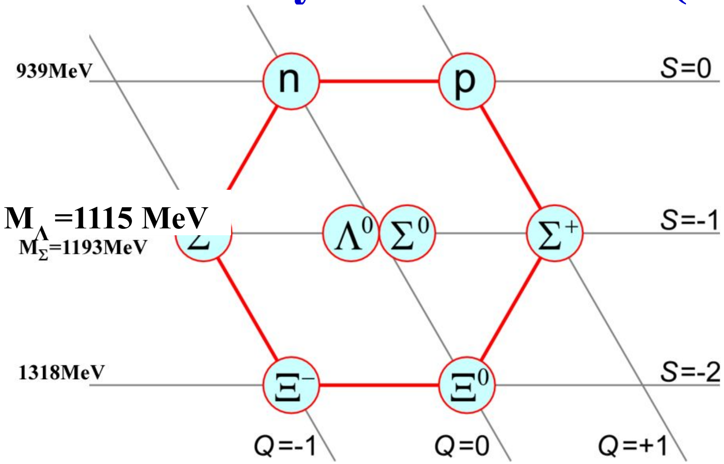
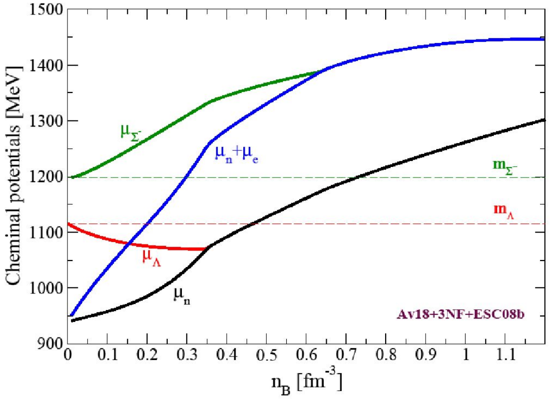
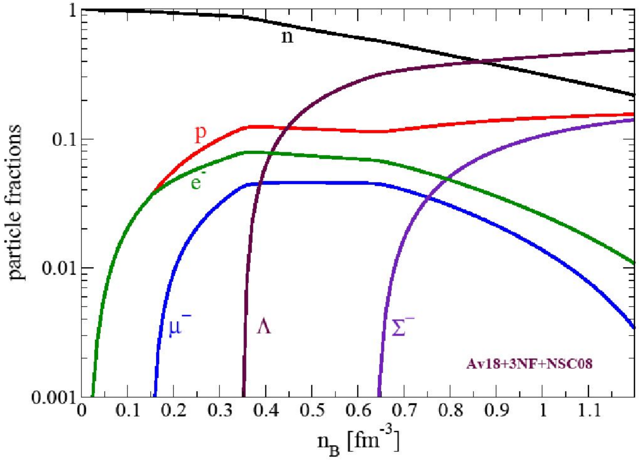
Hyperons in Neutron Stars: Hyperon Stars

baryon octet : $J^{\pi} = (1/2)^{+}$







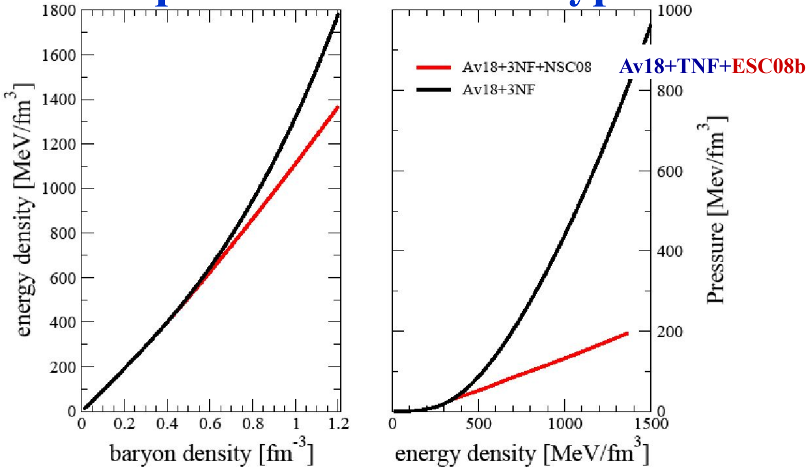
$$n + e^- \rightarrow \Sigma^- + \nu_e$$

$$p + e^- \rightarrow \Lambda + \nu_e$$

etc.

D. Logoteta, I. Bombaci (2014)

Equation of State of Hyperonic Matter



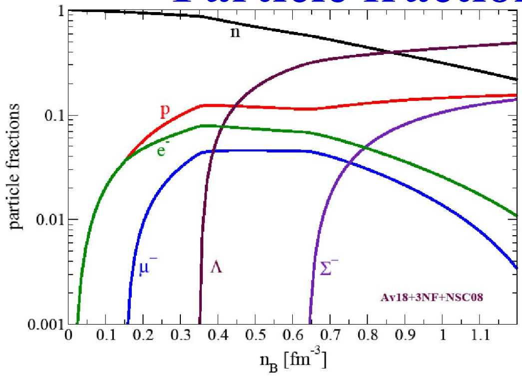
hyperons produce a strong softening of the EOS

NN(Av18) + NNN + NY(ESC08b)

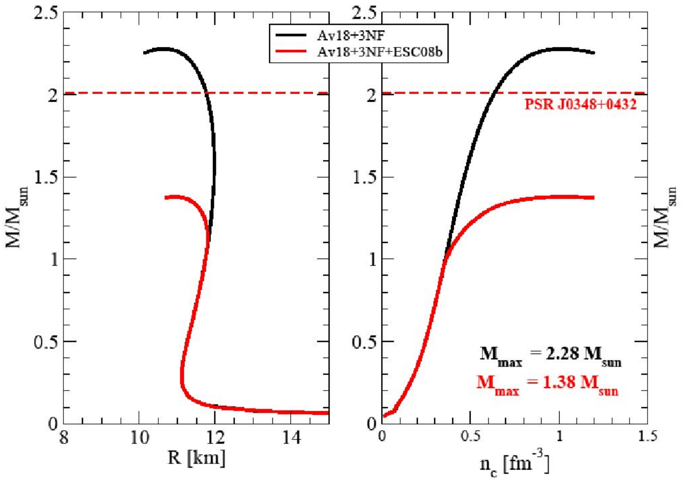
no hyperonic TBF

D. Logoteta, I. Bombaci (2014)

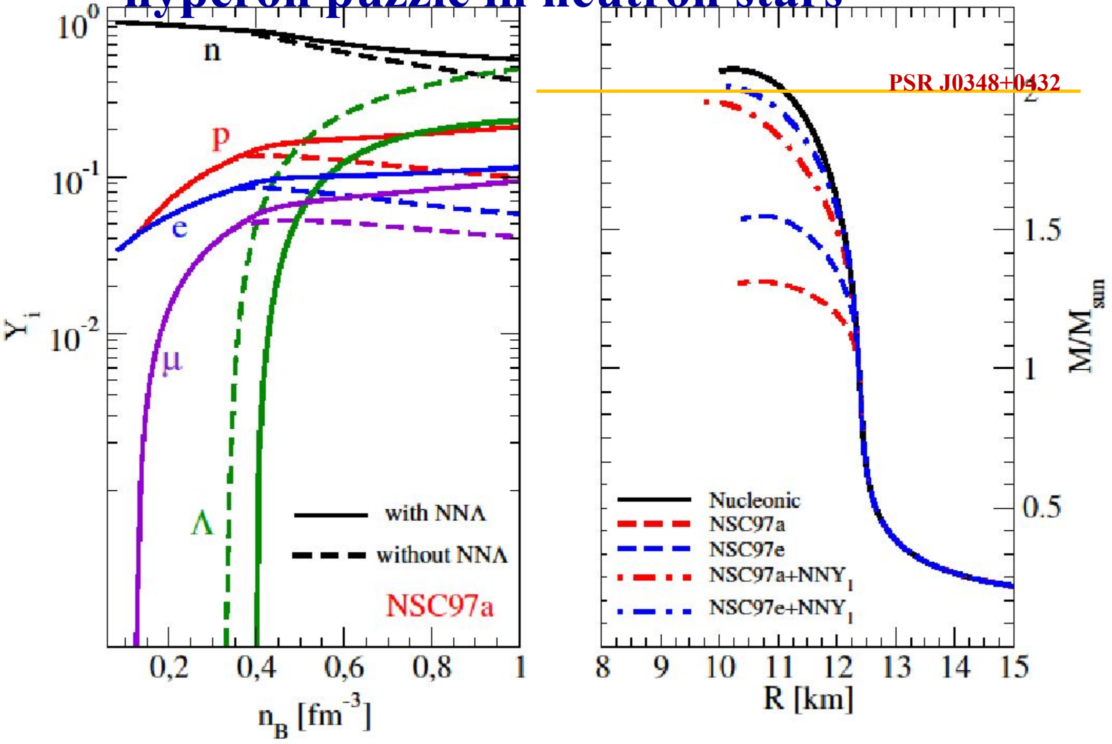
Particle fractions



Stellar mass



Hyperonic TBF as a possible solution of the hyperon puzzle in neutron stars



β–stable (n, p, Λ) matter **interactions: NN+NNN+NY+NNY**

D. Logoteta, I. Bombaci. I. Vidana (2019) preprint

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Neutron Stars in the QCD phase diagram

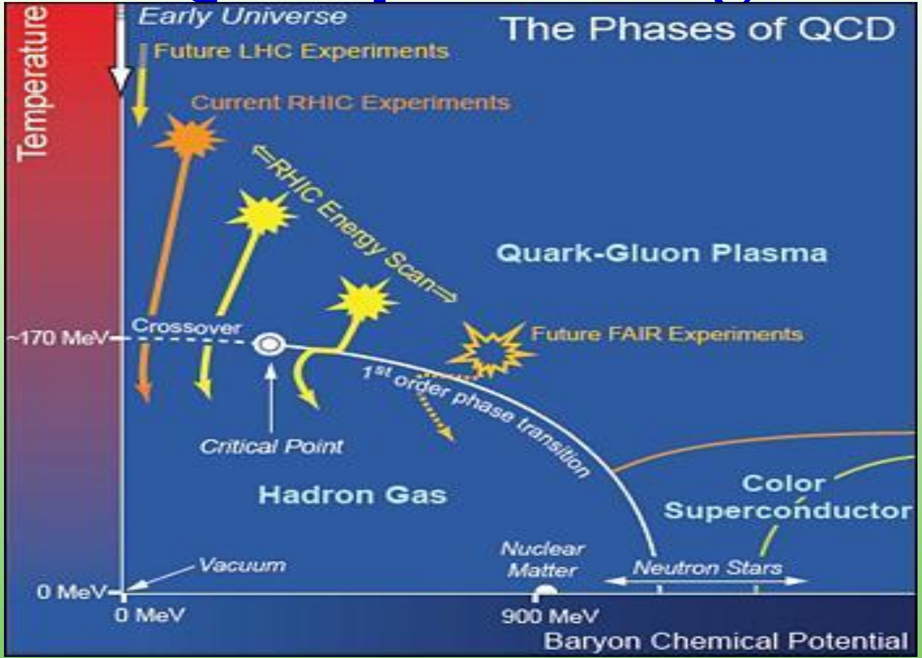
Lattice QCD
at μ_b=0 and finite T

► The transition to Quark Gluon Plasma is a crossover
Aoki et ,al., Nature, 443 (2006) 675

► Deconfinement transition temperature T_c

HotQCD Collaboration
T_c= 154 ± 9 MeV Bazarov et al., Phys.Rev. D85 (2012) 054503

Wuppertal-Budapest Collab.
T_c= 147 ± 5 MeV Borsanyi et al., J.H.E.P. 09 (2010) 073



Neutron Stars: high μ_b and low T

Lattice QCD calculations are presently not possible

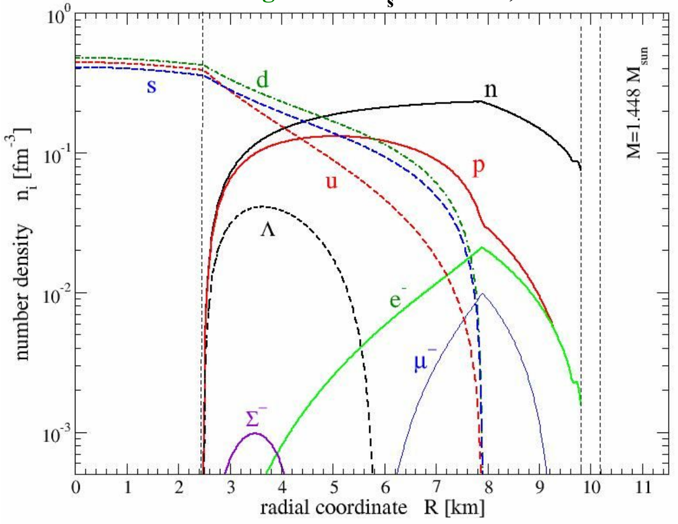
Quark deconfinement transition expected of the first order

Z. Fodor, S.D. Katz, Prog. Theor Suppl. 153 (2004) 86

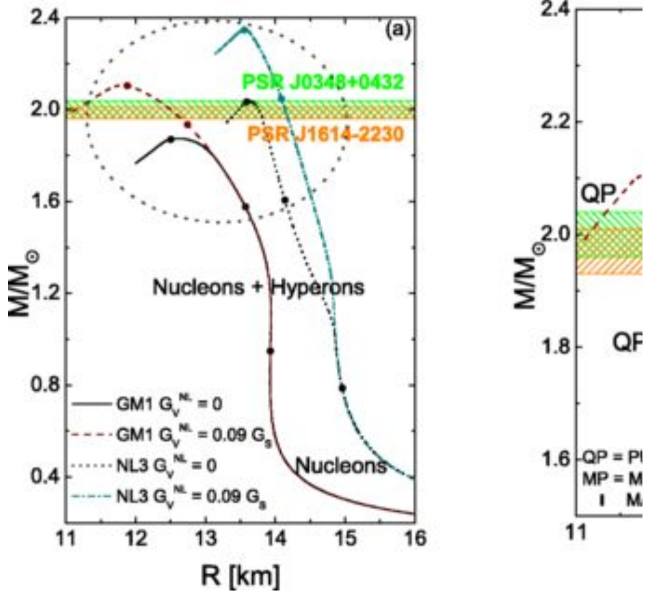
"A link between lattice QCD and measured neutron star masses"
I. Bombaci, D. Logoteta, Mont. Not. Royal Astron. Soc. 433 (2013) L79

Hybrid Stars (neutron stars with a quark matter core)

GM3+Bag model m_s=150 MeV, B=13.6.6Mev/fm^3



I. Bombaci, I. Parenti, I. Vidaña (2004)



M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, Phys. Rev. C 89 (2014) 015806

perturbative QCD calculations up to α_s^2

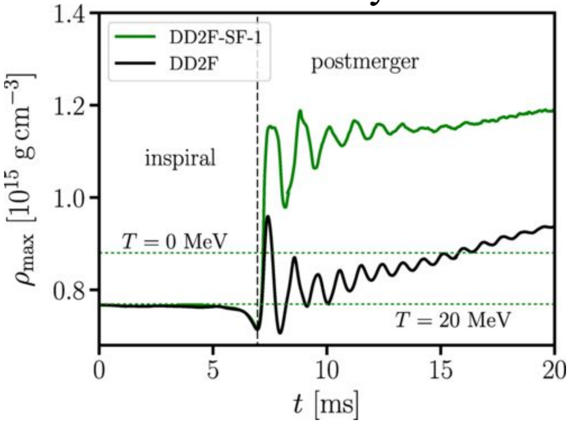
A. Kurkela et al., Phys. Rev. D 81, (2010) 105021

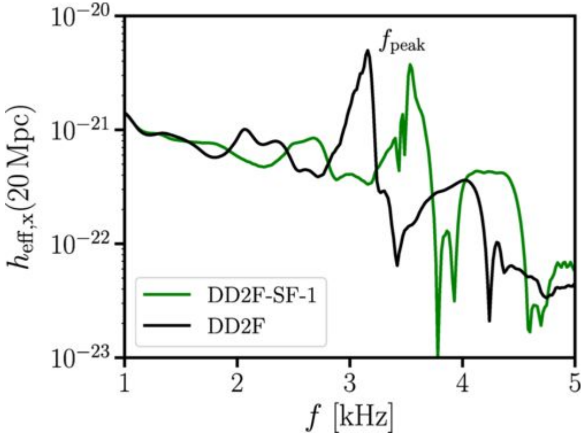
M_{max} up to ~ 2 $M_\odot$

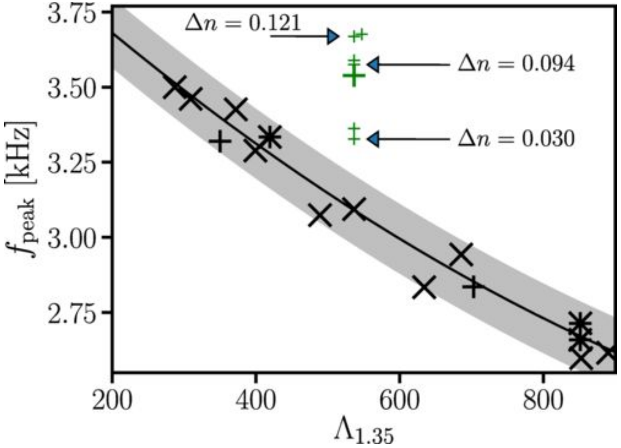
Present measured NS masses do not exclude the possibility of having QM in the stellar core

Identifying a first-order phase transition in NS mergers through GWs

A. Bauswein et al. Phys. Rev. Lett. 122 (2019) 061102

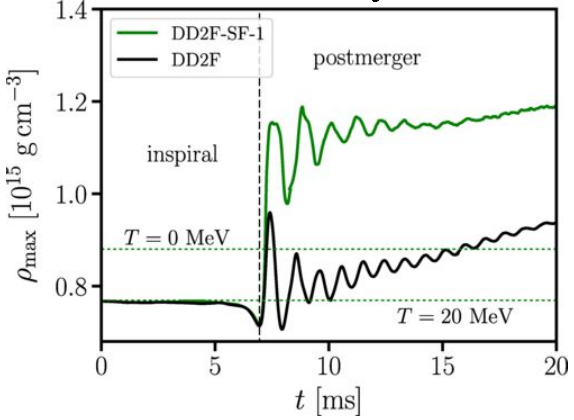


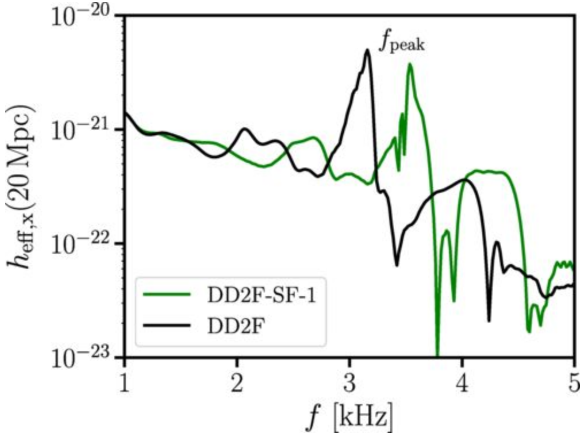


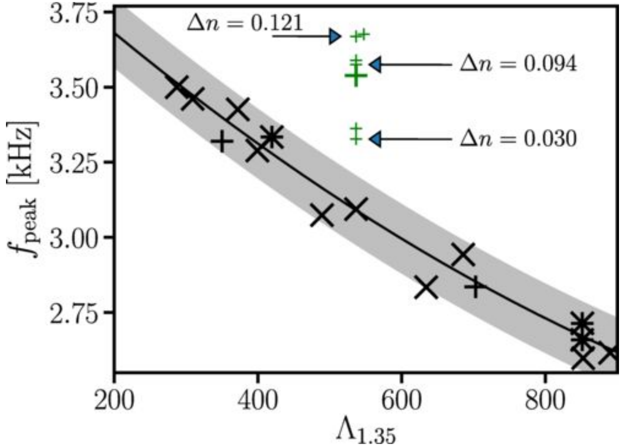


Identifying a first-order phase transition in NS mergers through GWs

A. Bauswein et al. Phys. Rev. Lett. 122 (2019) 061102







This results depends on the phase-transition construction. The authors used the Maxwell construction

First-order phase transitions: phase equilibrium

The Gibbs construction

Neutron star matter is a multi-component system with two conserved "charges" (electric charge and baryon number)

Global charge neutrality:
each of the two phases can have a net and opposite electric charge

→

The two phases can coexist (mixed phase) in a finite range of presure

The Maxwell construction

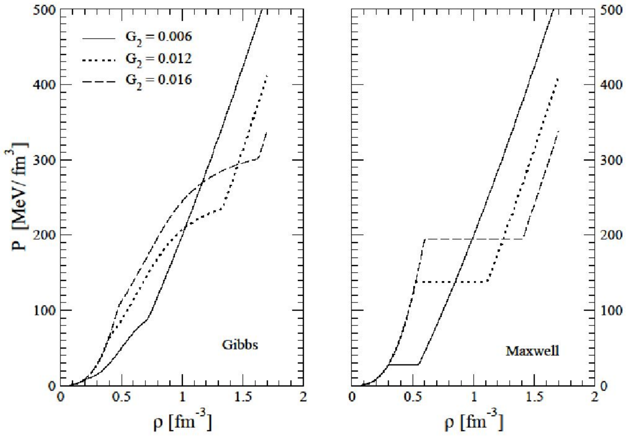
One-component system (e.g. water)

Local charge neutrality:
each phase in equilibrium is separately charge neutral.

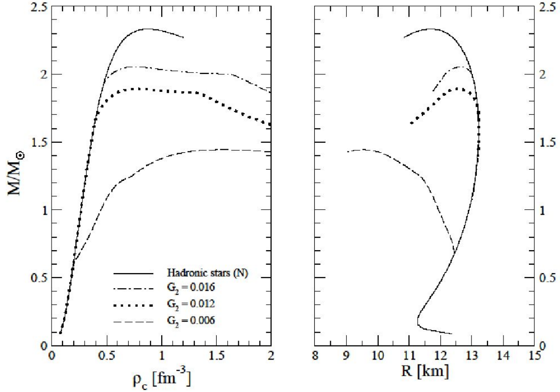
→

Constant pressure in the mixed phase. Since P(r) must be monotonic in NS, there is a sharp density discontinuity in the stellar core at the phase boundary.

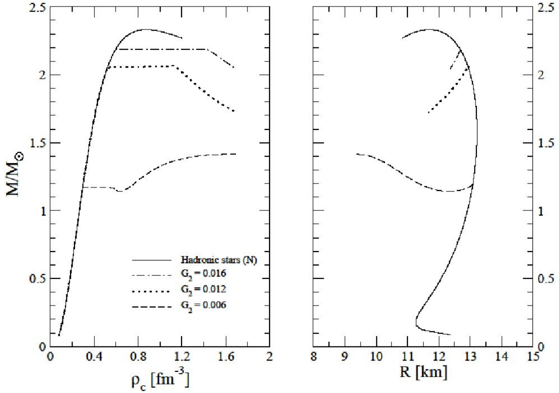
N. Glendenning, Phys. Rev. D 46 (1992) 1274
N. Glendenning, Compact Stars, Springer, 1997



Gibbs construction



Maxwell construction



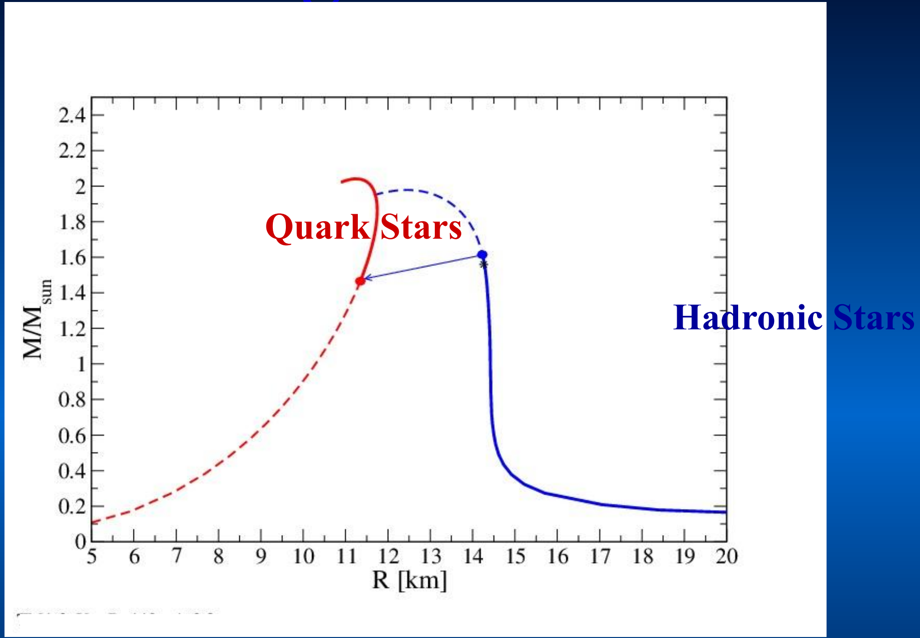
D. Logoteta, I. Bombaci, Phys. Rev. D 88 (2013) 063001

Probing extreme matter with GWs

Key questions

4. Is there a single family of Neutron Stars”
   or are there two-coexisting familes of ‘’Neutron Stars” ?
   In the latter case what are the astrophysical implications,
   and how GW observations could shed light on this issue?

Two coexisting-families of "Neutron Stars"



I. Bombaci, B. Datta, Astrophys. Jour. Lett. 530 (2000) L69
Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera, A. Lavagno, Astrophys. Jour. 586 (2003) 1250
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314
I. Bombaci, D. Logoteta, C. Providencia, I. Vidaña, Astr. and Astrophys. 528 (2011) A71
I. Bombaci, D. Logoteta, I. Vidaña, C. Providencia, EPJ A 52 (2016) 58
A. Drago et al, EPJ A 52 (2016) 40; EPJ A 52 (2016) 41

1^{st} **order phase transitions** are triggered by the **nucleation** of a **critical size drop** of the **new (stable) phase** in a **metastable mother phase**

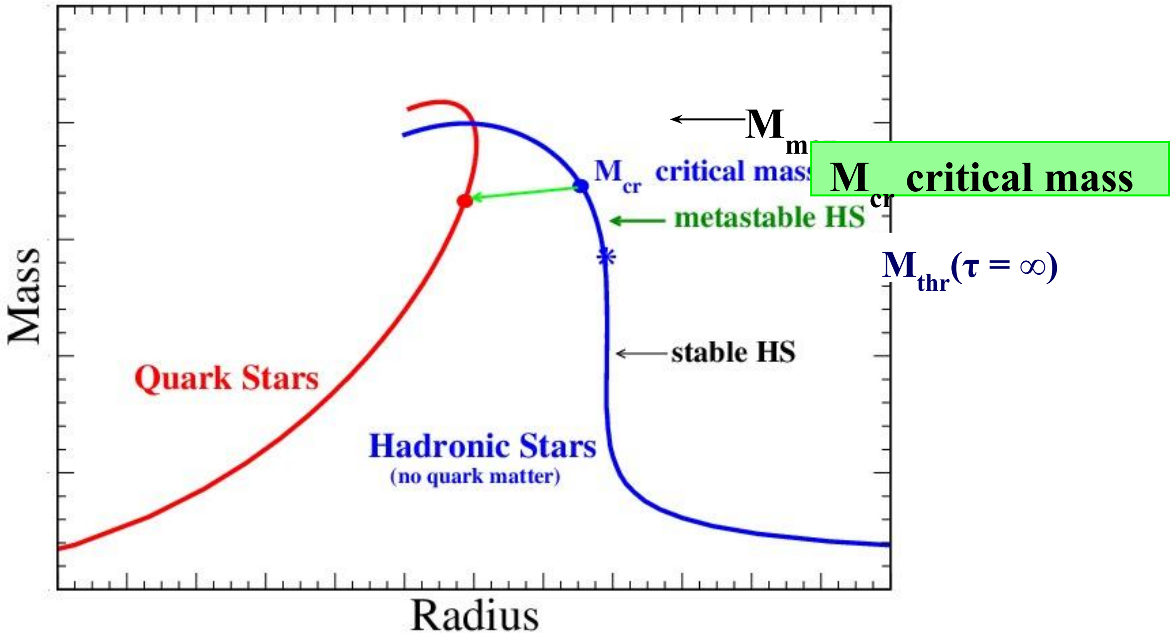
Virtual drops of the stable phase are created by small localized **fluctuations** in the state variables of the **metastable phase**

<u>A common event in nature</u>, e.g.:

- **fog or dew formation in supersaturated vapor**
- **ice formation in supercooled water**

Pure and distilled water at standard pressure (100 kPa) can be supercooled down to a temperature of -48.3 ºC. In the tempearture range (-48.3 — 0) ºC, water is in a metastable phase and ice cristals will form via a nucleation process.

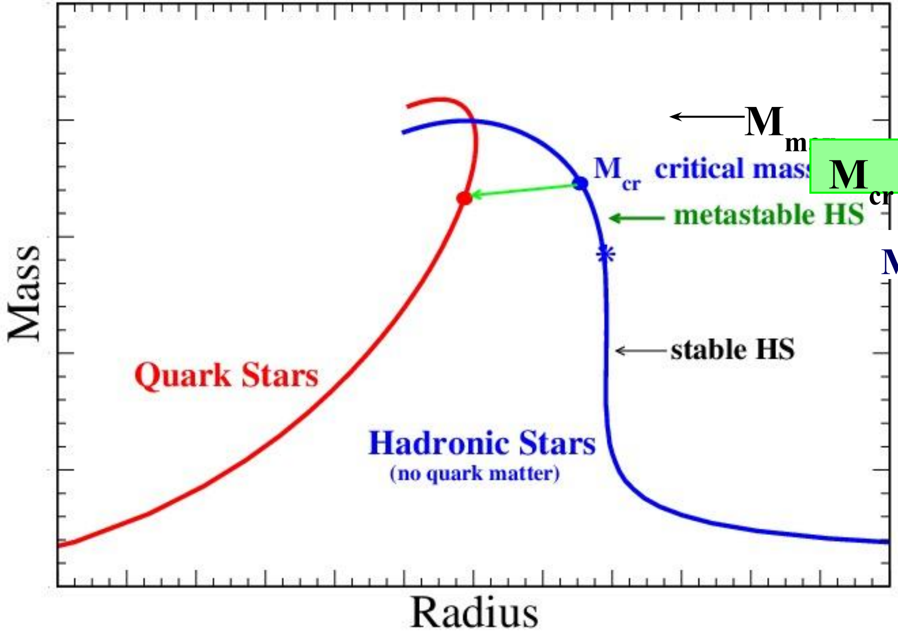
Metastability of Hadronic Stars



Hadronic Stars above a threshold value of their gravitational mass are metastable to the conversion to Quark Stars (QS) (hybrid stars or strange stars)

Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera, A. Lavagno, Astrophys. Jour. 586 (2003) 1250
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314
I. Bombaci, D. Logoteta, C. Providencia, I. Vidaña, Astr. and Astrophys. 528 (2011) A71
I. Bombaci, D. Logoteta, I. Vidaña, C. Providencia, EPJ A 52 (2016) 58
A. Drago, G. Pagliara, EPJA 52 (2016) 41

Metastability of Hadronic Stars



M_{cr} critical mass

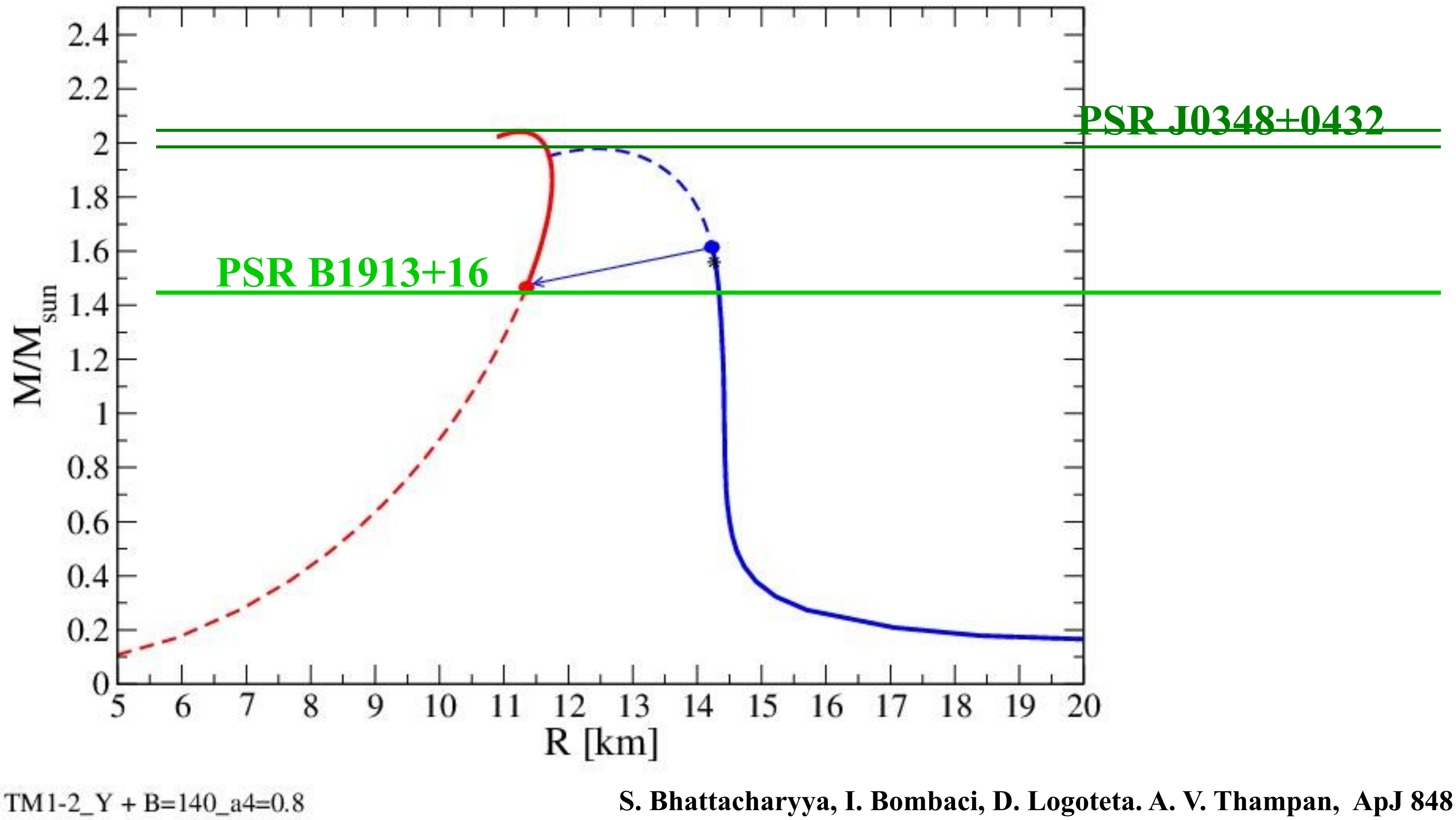
$M_{thr}(\tau = \infty)$

- M_{cr} , critical mass of hadronic stars.
- Two families of compact stars stellar conversion HS□QS
- $E_{conv} \sim 10^{53}$ erg (possible energy source for some GRBs)

extension of the concept of limiting mass of compact stars with respect to the *classical* one given by Oppenheimer and Volkoff

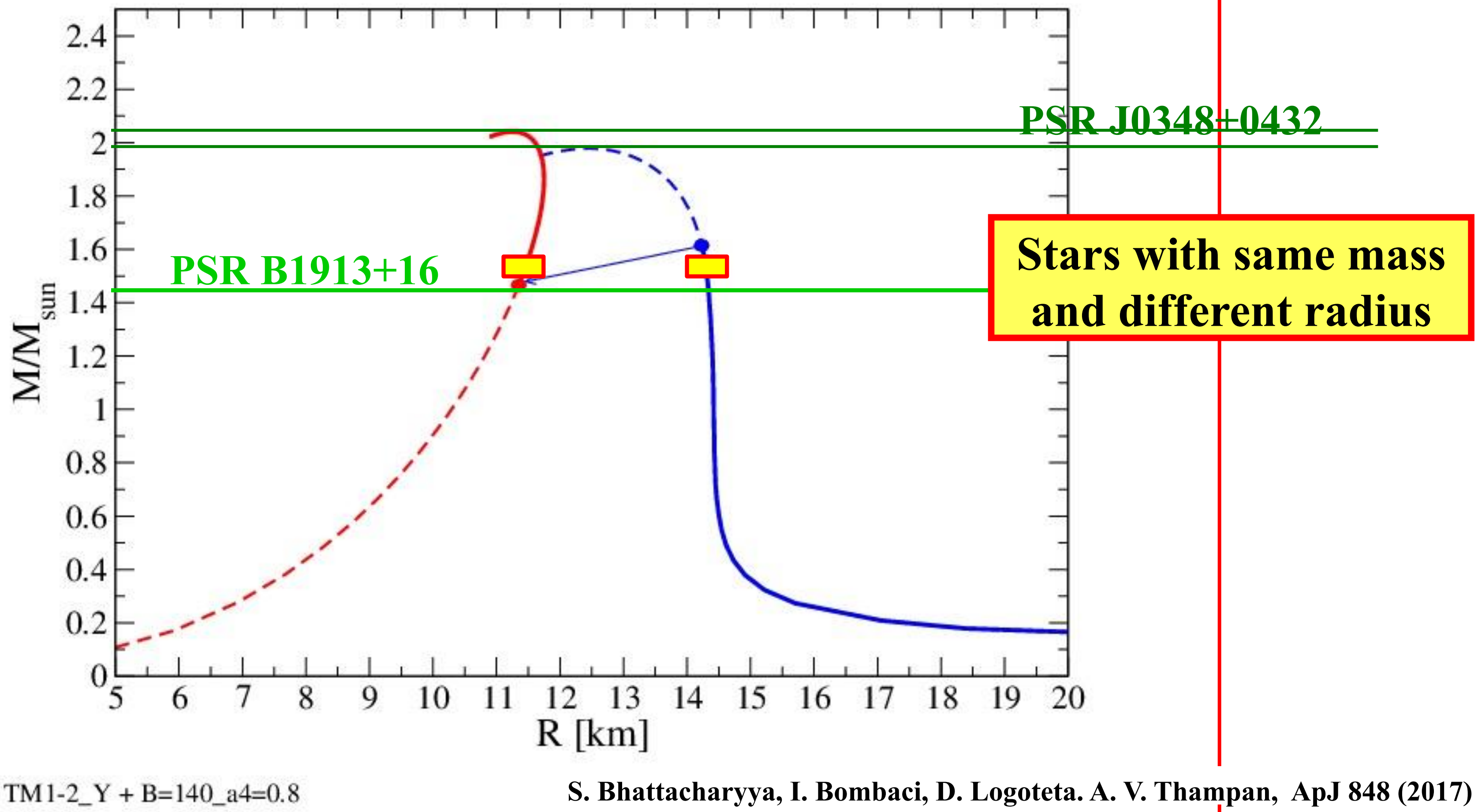
Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera, A. Lavagno, Astrophys
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314
I. Bombaci, D. Logoteta, C. Providencia, I. Vidaña, Astr. and Astrophys
I. Bombaci, D. Logoteta, I. Vidaña, C. Providencia, EPJ A 52 (2016) 58
A. Drago, G. Pagliara, EPJA 52 (2016) 41

Two families of compact stars



S. Bhattacharyya, I. Bombaci, D. Logoteta. A. V. Thampan, ApJ 848 (2017) 65

Two families of compact stars



S. Bhattacharyya, I. Bombaci, D. Logoteta. A. V. Thampan, ApJ 848 (2017) 65

Proto-Neutron Stars (new born NS)

Hot lepton-rich PNS $2\ \mathrm{s} < t < t_\nu \sim 20 - 30\ \mathrm{s}$

Trapped neutrinos

Hot matter $T_c = 10 - 30\ \mathrm{MeV}$

Hot neutrino-free PNS $t_\nu < t < t_{cool} \sim$ a few 10^2 s

Neutrinos free matter

Hot matter (isoentropic core) $S/N_b \sim const = 1 - 2\ k_B$

Cold deleptonized Neutron Stars

$t > t_{cool} \sim$ a few 10^2 s cooling time

Neutrinos free matter

Cold matter ($T \ll 1$ MeV)

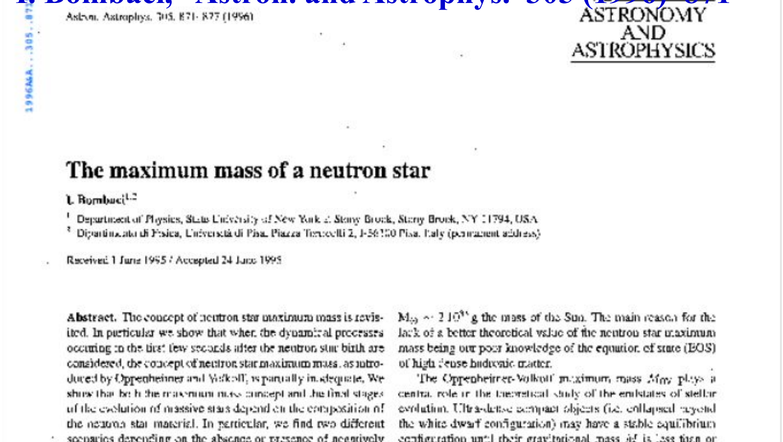
Burrows, Lattimer, ApJ 307 (1986) 178; Prakash et al, Phys. Rep.280 (1997) 1;
Pons et al. ApJ 513 (1999) 780

Thermal and neutrino-trapping effects on proto-neutron star evolution and M_{max} concept

When the dynamical processes occuring in the first few seconds after the neutron star birth are considered, it is necessary **to extend the concept of maximum mass** of a neutron star with respect to the *classical* one introduced by **Oppenheimer & Volkoff in 1939**

"The maximum mass of a neutron star"

I. Bombaci, Astron. and Astrophys. 305 (1996) 871



Astron. Astrophys. 305, 871-877 (1996)

ASTRONOMY AND ASTROPHYSICS

The maximum mass of a neutron star

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[2] Dipartimento di Fisica, Università di Pisa, Piazza Torricelli 2, I-56100 Pisa, Italy (permanent address)

Received 1 June 1995 / Accepted 24 June 1995

Abstract. The concept of neutron star maximum mass is revisited. In particular we show that when the dynamical processes occuring in the first few seconds after the neutron star birth are considered, the concept of neutron star maximum mass, as introduced by Oppenheimer and Volkoff, is partially inadequate. We show that both the maximum mass concept and the final stages of the evolution of massive stars depend on the composition of the neutron star material. In particular, we find two different scenarios depending on the absence or presence of negatively

$M_\odot \sim 2\,10^{33}$ g the mass of the Sun. The main reason for the lack of a better theoretical value of the neutron star maximum mass being our poor knowledge of the equation of state (EOS) of high dense hadronic matter.

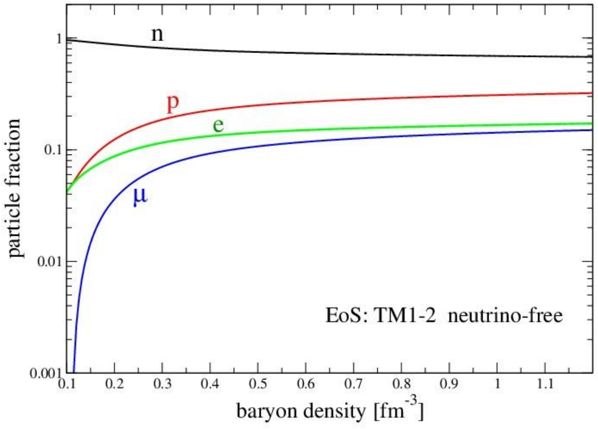
The Oppenheimer-Volkoff maximum mass M_{OV} plays a central role in the theoretical study of the endstates of stellar evolution. Ultra-dense compact objects (i.e. collapsed beyond the white dwarf configuration) may have a stable equilibrium configuration until their gravitational mass M is less than or

See also: **"Composition and structure of protoneutron stars"**

M. Prakash, I. Bombaci,
M. Prakash, P.J.Ellis, J.M. Lattimer, R. Knorren, Phys. Rep. 280 (1997) 1

Neutrino-trapping effects on proto-neutron star evolution and M_{max} concept

Neutrino-free matter

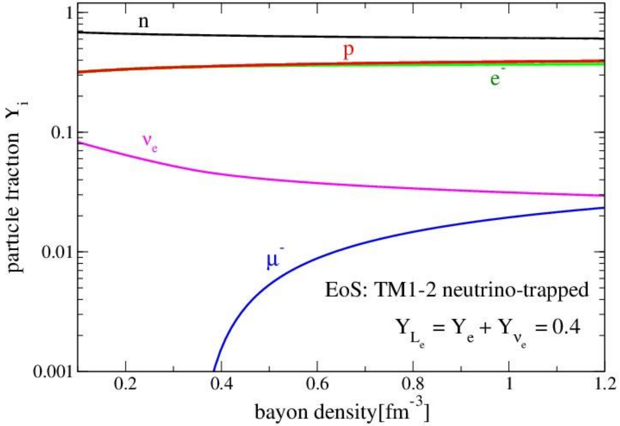


$$\mu_n - \mu_p = \mu_e$$

$$\mu_\mu = \mu_e$$

$$\mu_\nu = \mu_{\bar{\nu}} = 0$$

Neutrino-trapped matter



$$\mu_n - \mu_p = \mu_e - \mu_{\nu_e}$$

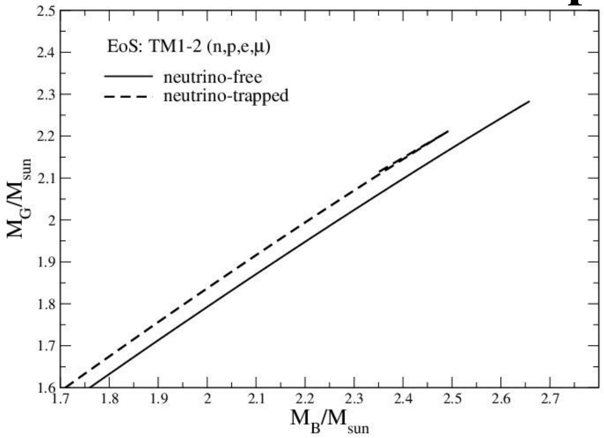
$$\mu_\mu = \mu_e - \mu_{\nu_e} + \mu_{\nu_\mu}$$

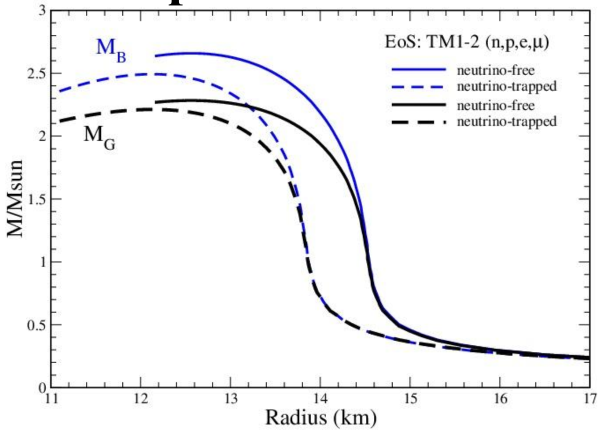
$$n_p = n_e + n_\mu$$

I. Bombaci, D. Logoteta (2016)

Neutrino-trapping effects on proto-neutron star evolution and M_{max} concept

Composition: nucleons + leptons





I. Bombaci, D. Logoteta (2016)

Neutrino-trapping effects on proto-neutron star evolution and M_{max} concept

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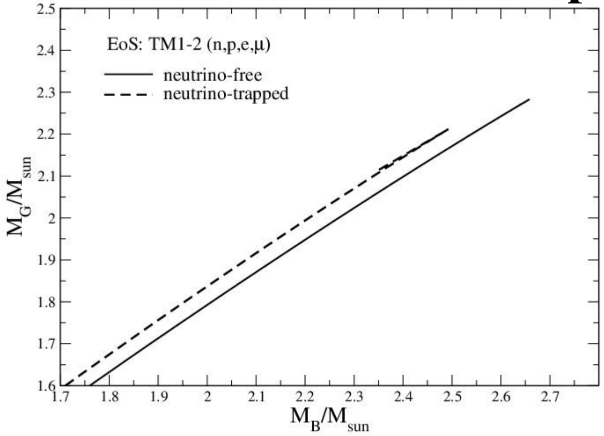
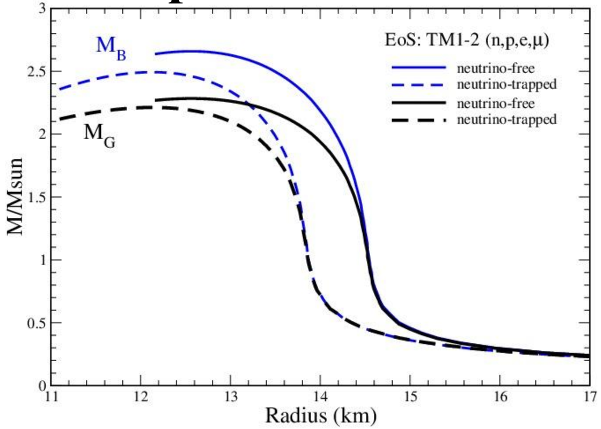


↓

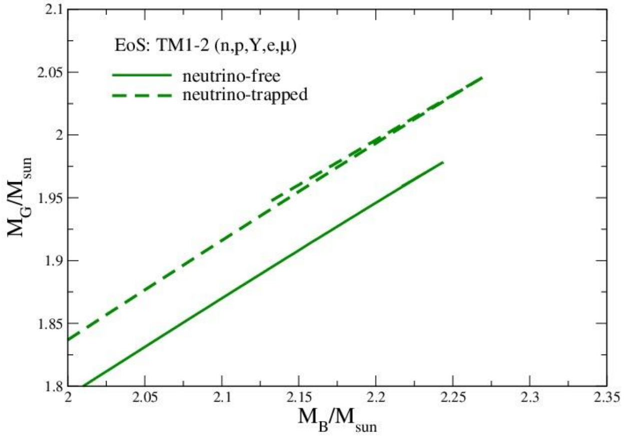
BH

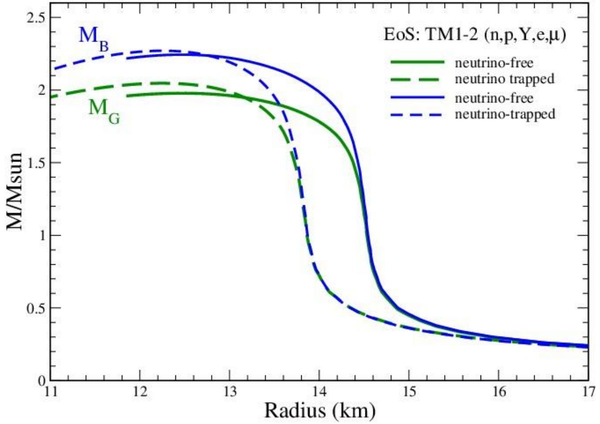


I. Bombaci, D. Logoteta (2016)

Neutrino-trapping effects on proto-neutron star evolution and M_{max} concept

Composition: nucleons + hyperons + leptons

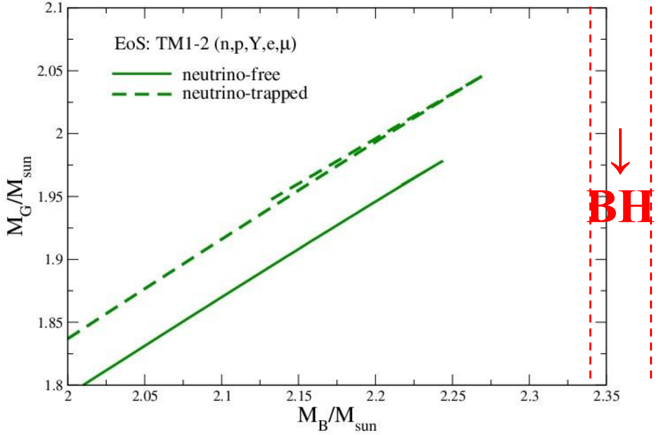


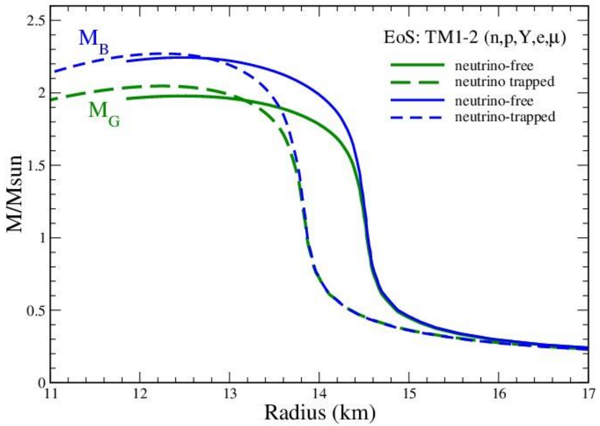


I. Bombaci, D. Logoteta (2016)

Neutrino-trapping effects on proto-neutron star evolution and M_{max} concept

Composition: nucleons + hyperons + leptons





I. Bombaci, D. Logoteta (2016)

NS-NS merging and dense matter EoS

1) Early-inspiral phase

$$d >> d_{merg} \equiv \min\left[(R_1 + R_2),\ \frac{6G}{c^2}(M_1 + M_2) \right]$$

point-like objects,

No EoS dependence (except M (EoS))

2) Late-inspiral phase

$$d \approx (1 \div 10)\ d_{merg}$$

tidal deformations of NSs

$$Q_{ij} = \lambda\ \varepsilon_{ij}$$

EoS : cold (T = 0) , neutrino-free matter

3) Post-merger compact object

rapidly-differentially-rotating proto-NS

EoS : hot (T = 10–100 MeV) , neutrino-trapped matter

$t_{weak} \sim 10^{-9}$ s , $t_{trapp} \sim (10 - 30)$ s

NS-NS merging and dense matter EoS

4) Post-merger evolution: final merger remnant

prompt Black Hole formation

hyper-massive proto-NS

differ .□ rigid rot.

delayed BH formation

ν-escape & cooling

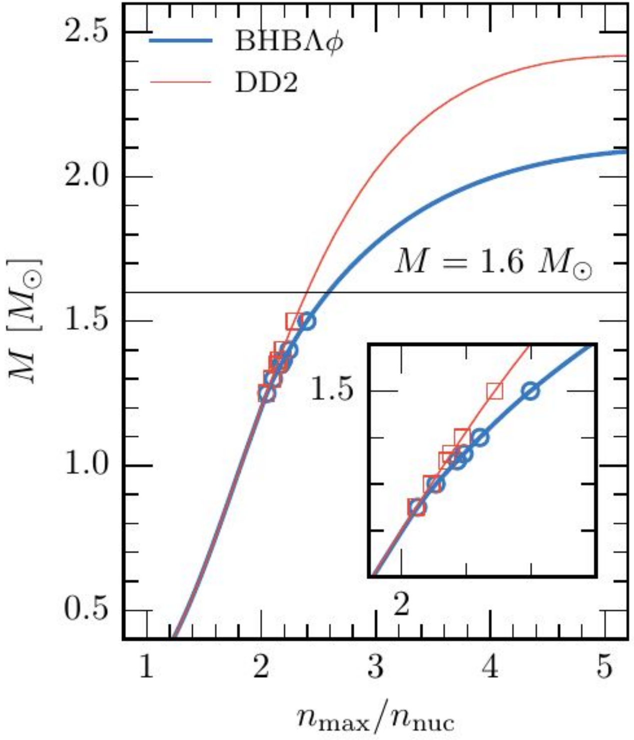
delayed BH formaion

metastable proto-NS

Extra slides

Merger remnant reaches extreme densities

Mass (or pressure)



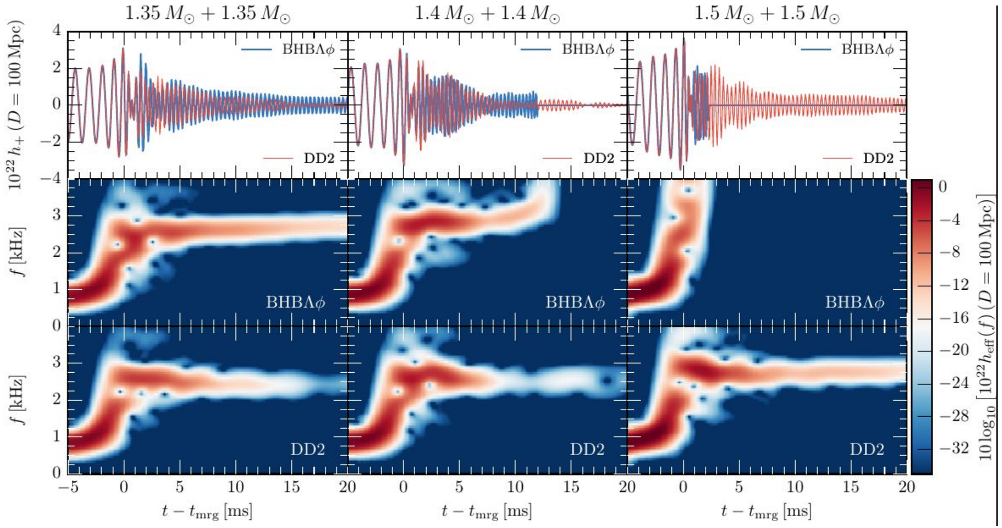
Baryon number density

- Baryon number density **$n \sim$ 3-5 n_{nuc}**
- Extra DOF/phase transitions?
- Specific model: Λ-hyperons [Banik+ 2014]
  Microphysical EOS compatible with astro and nuclear phys constraints
- In general:
  Can GW probe "softness" effects ?

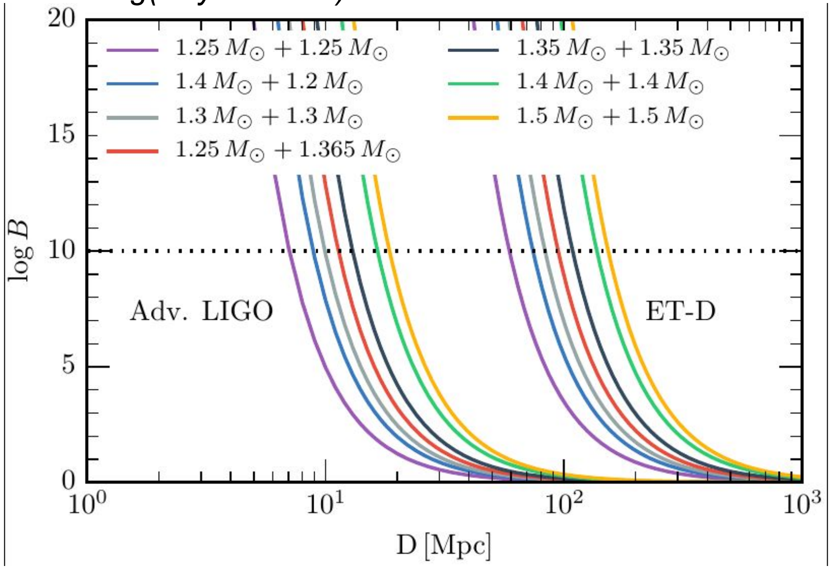
[Radice, SB, Del Pozzo, Roberts ApJL 2016]

See also [Sekiguchi+ 2011, Bauswein+ 2018, Most+ 2018]

Postmerger GWs and “softness effects”



log(Bayes factor) vs. Source distance



- Postmerger GW morfology contains unique info
- Detailed and generic models are necessary for DA studies
- High-freq. GW challenging to detect (→ Einstein telescope)

[Radice, SB, Del Pozzo, Roberts 2016]

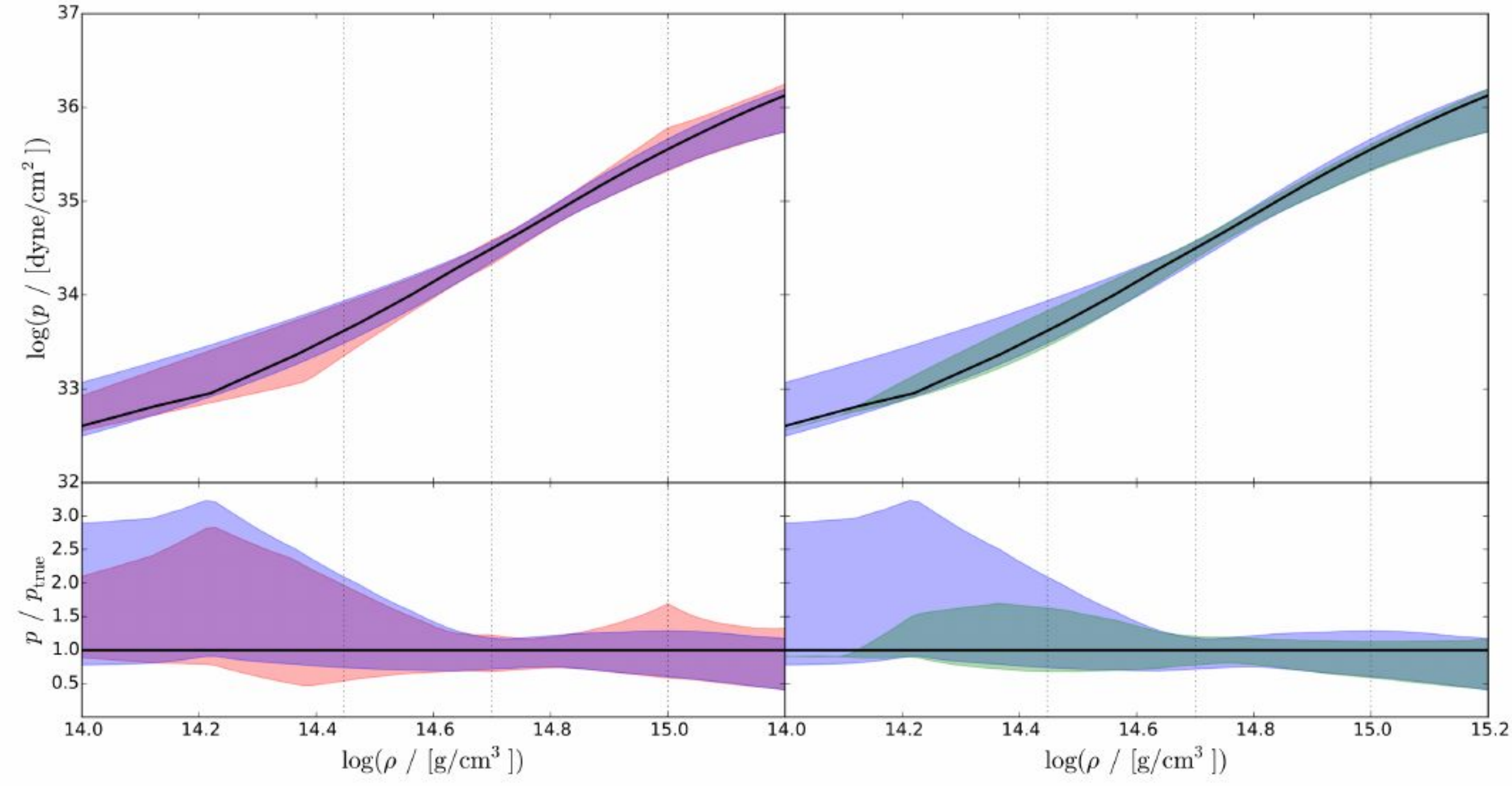
Sample over EoS

Advantages:

- Extract microphysics directly
- Include additional informations e.g. causality limit, minimum maximum-mass constraint
- Naturally combine multiple events

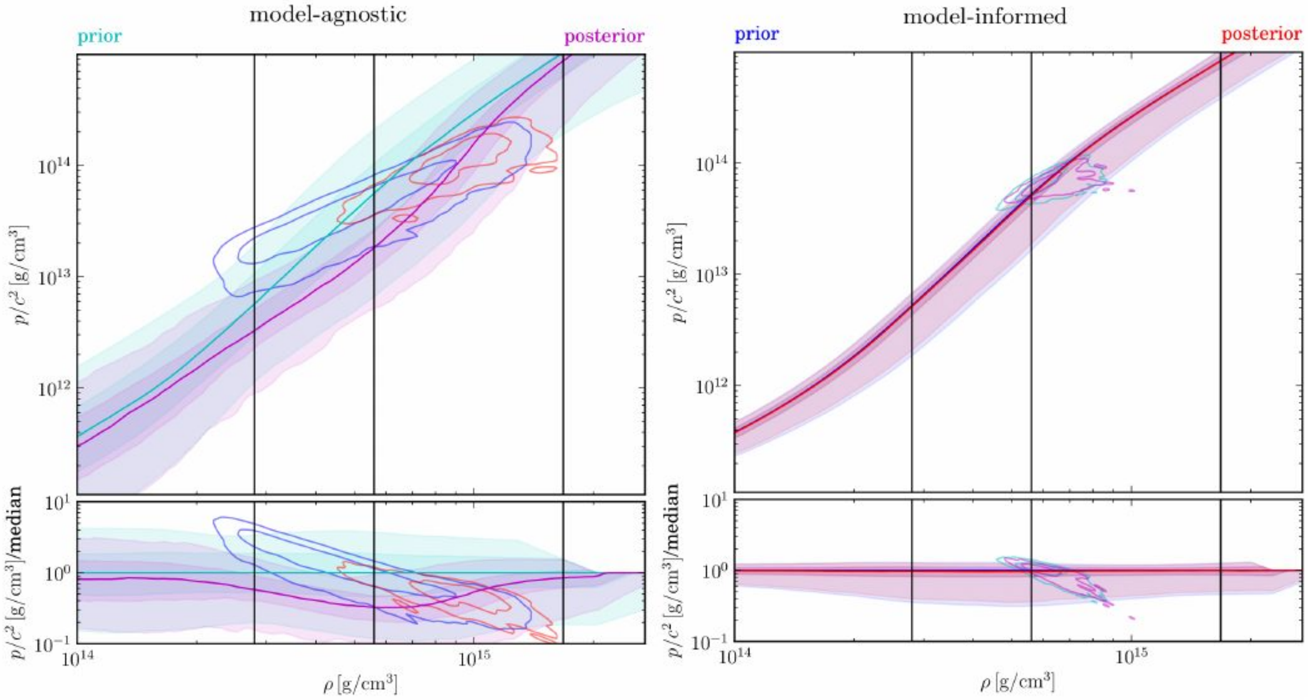
Disadvantages:

- Hard to sample
- Parameterization model dependent (Can be solved with Gaussian-Process)



Plot taken from Carney *et.al* (2018)

Can be overcome with Gaussian-Process with a cost



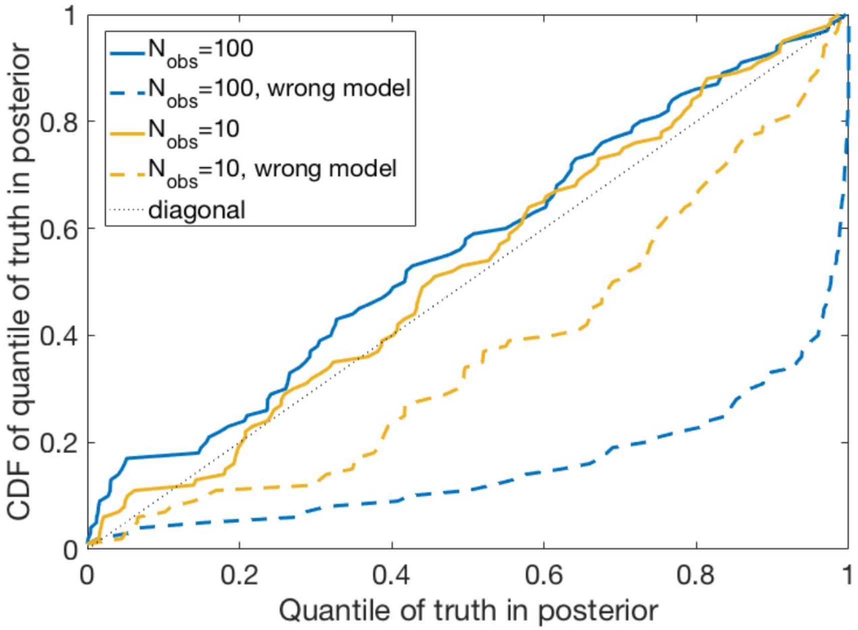
Plot taken from Landry *et.al* (2019)

Detectors (A)	GW170817		Multiple events					
			N_A			σ_N^A		
	$\rho^A_{\mathrm{GW170817}}$	$\sigma^A_{\mathrm{GW170817}}$	Low	Central	High	Low	Central	High
O2	3.2×10^1	1.7×10^2	–	–	–	–	–	–
aLIGO	9.1×10^1	1.1×10^2	2.0×10^1	9.8×10^1	3.0×10^2	1.8×10^2	8.3×10^1	4.7×10^1
A+	1.8×10^2	4.6×10^1	1.6×10^2	7.9×10^2	2.4×10^3	5.9×10^1	2.5×10^1	1.4×10^1
Voyager	4.3×10^2	2.5×10^1	2.2×10^3	1.1×10^4	3.2×10^4	2.1×10^1	9.6×10^0	5.3×10^0
ET-D	1.4×10^3	6.9×10^0	7.2×10^4	3.4×10^5	1.1×10^6	3.8×10^0	1.7×10^0	9.6×10^{-1}
CE	2.8×10^3	7.7×10^0	3.0×10^5	1.4×10^6	4.4×10^6	3.7×10^0	1.7×10^0	9.0×10^{-1}

- Systematic error of 13.19
- Statistical error become comparable with systematic error with detectors of Voyager-class or better

Table taken from Carson *et.al* (2018)

Selection bias



Plot taken from Mandel *et.al* (2019)

$$p(\{\vec{d}_i\}|\vec{\lambda}') = \prod_{i=1}^{N_{\rm obs}} \frac{\frac{1}{S_i}\sum_{j=1}^{S_i} p_{\rm pop}({}^j\vec{\theta}_i|\vec{\lambda}')\frac{p(\vec{d}_i)}{\pi(\vec{\theta})}}{\int d\vec{\theta} p_{\rm det}(\vec{\theta}) p_{\rm pop}(\vec{\theta}|\vec{\lambda}')}$$


MICRA 2019, 12-16 August, Jena
Microphysics In Computational Relativistic Astrophysics
ChETEC Action
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for Data-Driven and Simulation Science
FRIEDRICH-SCHILLER-UNIVERSITÄT JENA
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