Compact stars made of holographic QCD matter

Christian Ecker

GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN

22 October 2020

Based on
2009.10731 with Tuna Demircik and Matti Järvinen
&
1908.03213 with Matti Järvinen, Govert Nijs and Wilke van der Schee

Outline

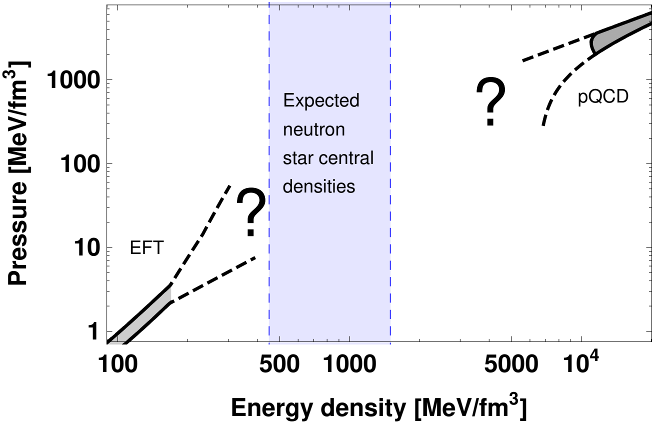
1. Introduction
2. Holographic QCD Model
3. Rapidly Rotating Neutron Stars
4. Neutron Star Mergers
5. Summary

1. Introduction

Neutron Stars

- Born in supernova explosions of massive $(8-25)M_{\odot}$ main sequence stars.
- Densest astrophysical objects which are not black holes
  $$M \approx (1-2)M_{\odot}, \quad R \approx (10-15)\mathrm{km}, \quad \rho_c \approx (2-5)\rho_0$$
  (nuclear saturation mass-energy density $\rho_0 = 2.5 \cdot 10^{14}\mathrm{g\,cm}^{-3}$)
- Can have huge magnetic fields (magnetars) $B \approx 10^{15}\mathrm{G}$
  $\big($cf. earth: $B_{\oplus} \approx 0.6\mathrm{G}$, RHIC: $B_{HIC} \approx 10^{18}\mathrm{G}\big)$
- Some rotate extremely fast (pulsars)
  first detection in 1967 as pulsar = rapidly rotating and highly magnetized NS
  record holder: PSR J1748-2446ad ($f = 716\mathrm{Hz}$, $v_R \approx 0.24c$)
- Hulse-Taylor binary pulsar (PSR B1913+16), first indirect proof for gravitational waves in 1974.
- GW170817: first direct detection of gravitational waves and electromagnetic counterpart of a binary neutron star merger.

Equation of State



Constraints from Astrophysical Observations

- NS-white dwarf binary PSR J0348+0432 (MSP J0740+6620)

$$M_{\rm max} > 2.01^{+0.04}_{-0.04}\,(2.14^{+0.1}_{-0.09})M_{\odot}.$$

[Antoniadis et al. arXiv:1304.6875, (Cromartie et al. arXiv:1904.06759)]

- LIGO/Virgo: constrains on tidal deformability from GW170817

$$\Lambda_{1.4} = 190^{+390}_{-120}\,, \quad \text{where} \quad \Lambda_M = \tfrac{2}{3}k_2\left(c^2 R/(G\,M)\right)^5$$

[LIGO/Virgo: arXiv:1710.05832, arXiv:1805.11579, arXiv:1805.11581]

- NICER: constrain on radius of PSR J0030+0451 ($f \approx 205$Hz)

$$M = 1.34^{+0.15}_{-0.16}\,(1.44^{+0.15}_{-0.14})M_{\odot}\,, \quad R = 12.71^{+1.14}_{-1.19}\,(13.02^{+1.24}_{-1.06})\text{km}$$

[Riley et al. arXiv:1912.05702, (Miller et al. arXiv:1912.05705)]

- From X-ray bursts of accreting neutron star 4U1702-429

$$M = 1.9^{+0.3}_{-0.3}\,M_{\odot}\,, \quad R = 12.4^{+0.4}_{-0.4}\text{km}$$

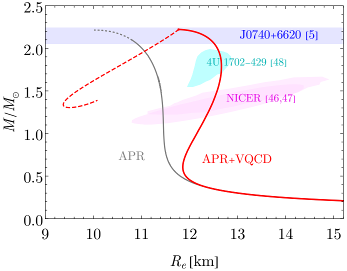
[Nättilä et al. arXiv:1709.09120]

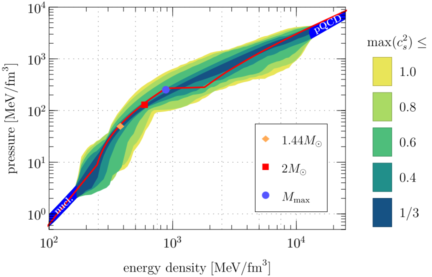
Hybrid Equation of State

Strategy: Combine nuclear matter EoS at low density with holographic model for QCD matter at intermediate and high densities.

The holographic model has to:

- Capture known features of QCD:
  Confinement, chiral symmetry breaking, consistency with lattice and perturbative QCD results in their respective regimes of validity.
- Satisfy theoretical and astrophysical constraints.





[Right plot by T. Gorda]

2. Holographic QCD

AdS/CFT Correspondence

Type IIB string theory on $\mathrm{AdS}_5 \times \mathrm{S}_5$

$=$

SU(N) $\mathcal{N} = 4$ Super Yang-Mills (SYM) theory on $\mathcal{M}_4$

[Maldacena arXiv:9711200]

- AdS/CFT is a strong-weak duality: if field theory is strongly coupled the gravity theory is weakly coupled and vice versa.
- Supergravity limit: Assuming point like strings ($\ell_s \to 0$) and small coupling ($g_s \ll 1$) reduces the string theory side to classical supergravity.
- Corresponds to the $N \to \infty$ and $\lambda \to \infty$ limit on the field theory side
- AdS/CFT as a Tool: Observables in strongly coupled field theory (very hard) can be obtained from classical gravity calculations (much easier).
- The holographic dual of QCD is not known. We follow a bottom-up approach and construct a gravity model that resembles QCD.

Holographic Veneziano QCD (I)

Two building blocks:

1. Improved holographic QCD (dilaton gravity) for gluon sector

$$S_{\rm g} = N_c^2 M^3 \int d^5x \sqrt{-g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$

   where $\lambda \equiv e^{\phi} \leftrightarrow \mathrm{Tr}F^2$ sources the 't Hooft coupling in YM theory

   [Gürsoy, Kiritsis arXiv:0707.1324; Gürsoy, Kiritsis, Nitti arXiv:0707.1349]

2. Tachyonic Dirac-Born-Infeld (DBI) action for flavor sector

$$S_{\rm f} = -N_f N_c M^3 \int d^5x V_{f0}(\lambda) e^{-\tau^2} \sqrt{-\det \left[g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab} \right]}$$

$$F_{rt} = \Phi'(r)\,, \quad \Phi(0) = \mu\,,$$

   where the tachyon $\tau \leftrightarrow \bar{q}q$ controls chiral symmetry breaking.

   [Bigazzi et al. arXiv:0505140; Casero et al. arXiv:0702155]

Holographic Veneziano QCD (II)

Several potentials: $\{V_g(\lambda), V_{f0}(\lambda), w(\lambda), \kappa(\lambda)\}$, chosen to match pQCD in UV ($\lambda \to 0$), qualitative agreement with QCD in IR ($\lambda \to \infty$) and tuned to lattice QCD in the middle ($\lambda \sim \mathcal{O}(1)$).

[For details see Appendix B of Ishii, Järvinen, Nijs arXiv:1903.06169]

Consider 1. + 2. in the Veneziano limit with full backreaction:

$$S_{\mathrm{V-QCD}} = S_{\mathrm{g}} + S_{\mathrm{f}}\,, \quad N_c \to \infty \text{ and } N_f \to \infty \text{ with } x \equiv N_f/N_c \text{ fixed}$$

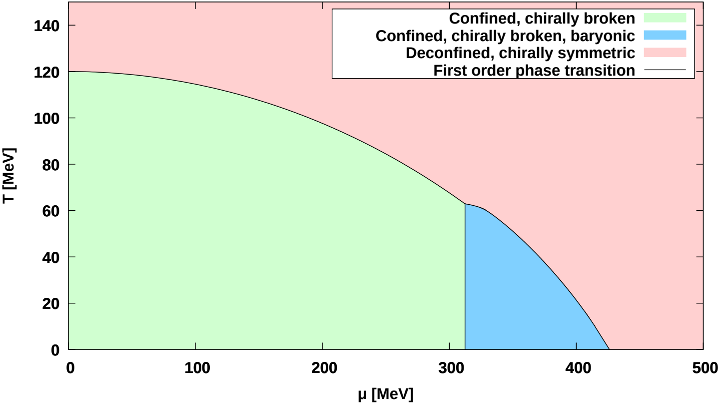
[Järvinen, Kiritsis arXiv:1112.1261]

Add probe baryons: simple approximation with homogeneous bulk soliton.

[Ishii, Järvinen, Nijs arXiv:1903.06169]

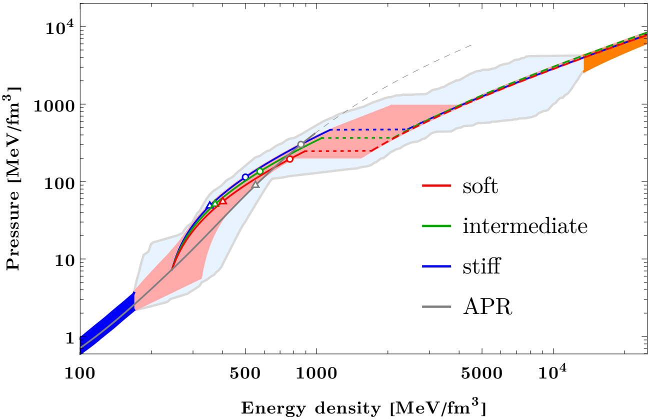
More details in Matti Järvinens High Energy Physics Seminar on 13/11/2020 - 12:00

Phase Diagram



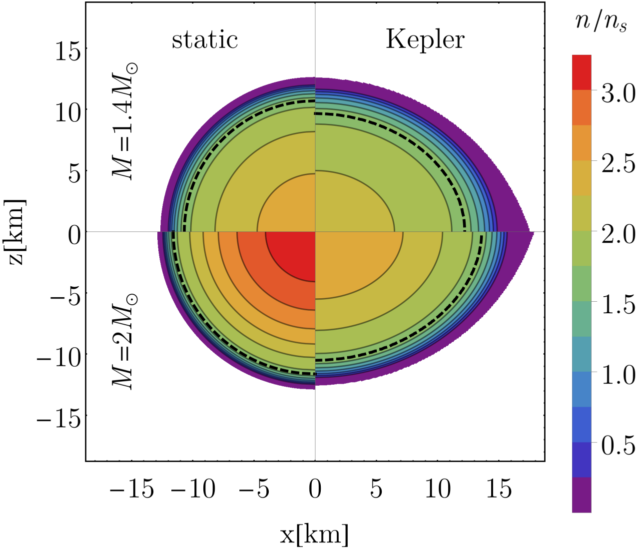
[Ishii, Järvinen, Nijs arXiv:1903.06169]

Hybrid Equations of State



Model	$\frac{n_{\mathrm{QM}}}{n_s}$	$\frac{M_{\mathrm{TOV}}}{M_\odot}$	$\frac{M_{\mathrm{max}}}{M_{\mathrm{TOV}}}$	$\frac{M_{\mathrm{b,max}}}{M_{\mathrm{max}}}$	$\frac{R_{\mathrm{e},1.4}}{\mathrm{km}}$	$\Lambda_{1.4}$	$\frac{f_{\mathrm{max}}}{\mathrm{kHz}}$	c_s^{max}
soft	4.89	2.04	1.238	1.172	[12.38, 17.33]	493	1.45	0.65
interm.	5.43	2.22	1.228	1.186	[12.51, 17.44]	536	1.54	0.72
stiff	5.61	2.35	1.231	1.194	[12.60, 17.52]	567	1.60	0.76
APR	–	2.21	1.192	1.202	[11.40, 16.14]	260	2.01	> 1

Density Profile



$M = 1.4\, M_\odot$: $R_{\rm match}/R_e = 0.85\,,\quad M = 2\, M_\odot$: $R_{\rm match}/R_e = 0.90$

3. Rapidly Rotating Neutron Stars

Rotating Neutron Stars

- After formation neutron stars rotate extremely fast.
  Record holder: PSR J1748-2446ad ($f = 716\mathrm{Hz}\,, v_R \approx 0.24c$)
- Initially expected to be differentially rotating, i.e., different layers rotate at different angular velocity.
- Convective and viscous effects enforce uniform rotation.
- In the following we will assume uniform rotation.
- Because centrifugal forces counteract gravitational pull, rotating neutron stars can support more mass than non-rotating stars.
- The maximum mass strongly depends on the high density part of the EoS where strong coupling and non-perturbative effects such as the deconfinement phase transition are important.

Maximum mass of rotating stars

- Turning-point criterion locates onset of instability to BH collapse

$$\left.\frac{\partial M(n_c, J)}{\partial n_c}\right|_{J=\mathrm{const.}} = 0\,.$$

[Friedman, Ipser, Sorkin 1988]

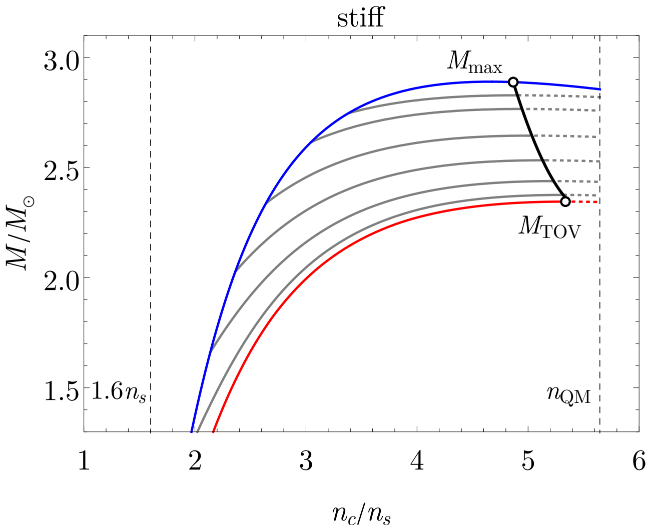
- For $J = 0$ the criterion is necessary and sufficient.
- For $J \neq 0$ only sufficient, not necessary, i.e., dynamically unstable stars exist at densities slightly smaller than the turning-point density.

[Takami, Rezzolla, Yoshida arXiv:1105.3069]

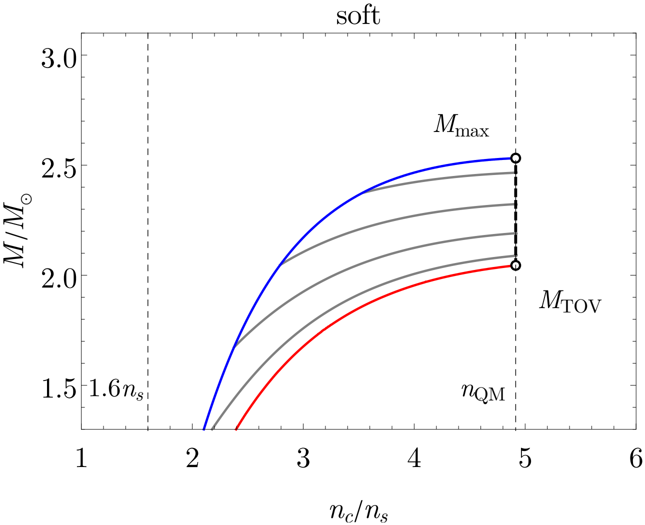
- To construct sequences of constant angular momentum J we use the publicly available RNS code.

[Stergioulas, Friedman arXiv:9411032; Cook, Shapiro, Teukolsky 1994,
http://www.gravity.phys.uwm.edu/rns/]

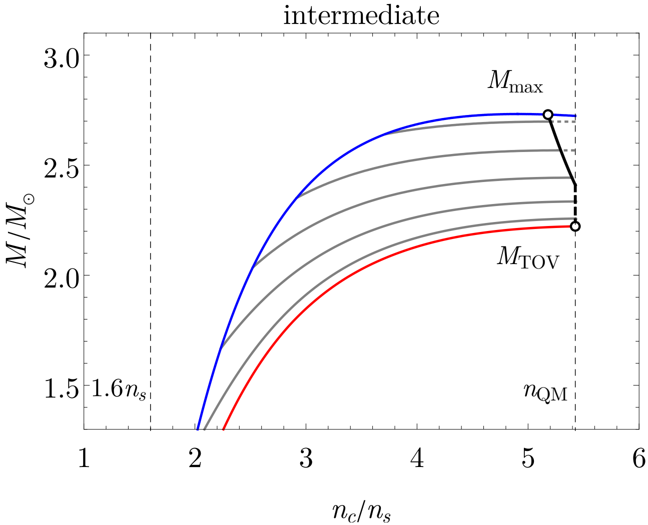
Maximum Mass



Maximum Mass

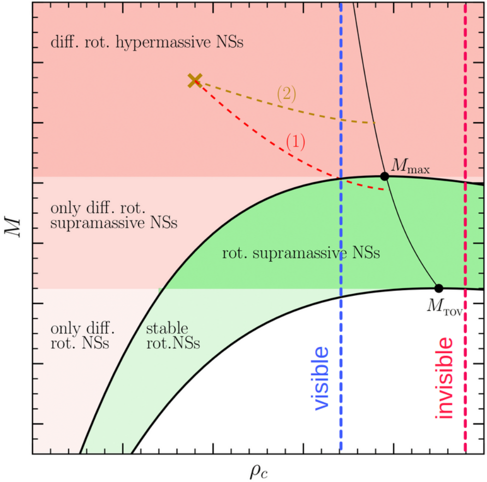


Maximum Mass



Consequences for Merger Remnants

- By monotonicity of the turning point line, it is sufficient to know the location of M_{TOV}, i.e., the static solution, to see if the phase transition can affect the lifetime of hypermassive merger remnants.



[Modified version of a plot in Rezzolla, Most, Weih arXiv:1711.00314]

Breu-Rezzolla Bound

- Universal ratio found for nuclear matter models without phase transition

$$\frac{M_{\mathrm{max}}}{M_{\mathrm{TOV}}} = 1.203^{+0.022}_{-0.022}$$

[Breu, Rezzolla arXiv:1601.06083]

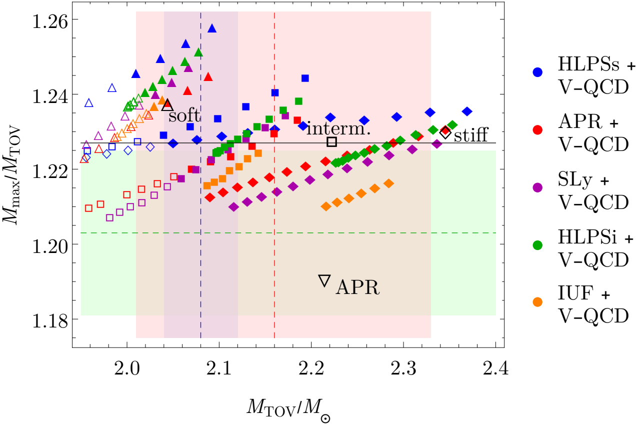
- Found by fitting a large number of nuclear matter EOSs

$$\frac{M_{\mathrm{crit}}}{M_{\mathrm{TOV}}} = 1 + a_2 \left(\frac{j}{j_{\mathrm{Kep}}}\right)^2 + a_4 \left(\frac{j}{j_{\mathrm{Kep}}}\right)^4$$

Maximum Mass

Using a large number of viable V-QCD hybrids with phase transition gives

$$\frac{M_{\max}}{M_{\mathrm{TOV}}} = 1.227^{+0.031}_{-0.016}\,, \quad \mathrm{Max}(M_{\mathrm{TOV}}) \approx 2.4 M_\odot\,, \quad \mathrm{Max}(M_{\max}) \approx 2.9 M_\odot$$



(red band) Upper bound from GRB 170817A: $M_{\mathrm{TOV}}/M_\odot \lesssim 2.16^{+0.17}_{-0.15}$.

[Rezzolla, Most, Weih arXiv:1711.00314]

(blue band) Lower bound assuming NS in GW190814: $M_{\mathrm{TOV}}/M_\odot > 2.08^{+0.04}_{-0.04}$.

[Most, Papenfort, Weih, Rezzolla arXiv:2006.14601]

GW190814

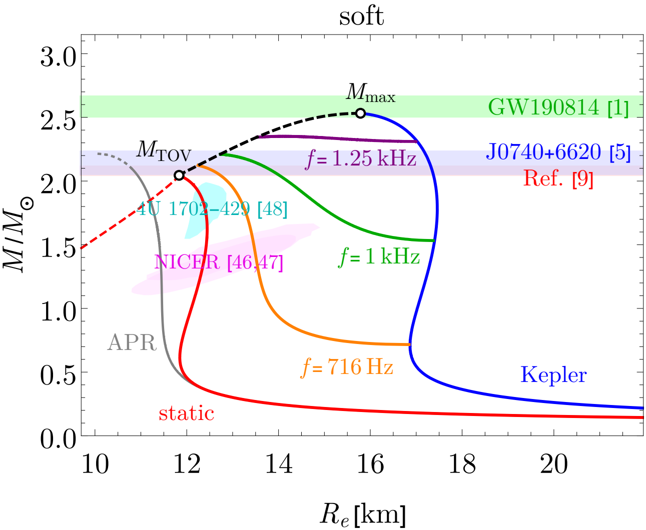
- Binary merger of a black hole and compact secondary object:

$$m_1 = 23.2^{+1.1}_{-1.0}\,\mathrm{M}_\odot\,, \quad m_2 = 2.59^{+0.08}_{-0.09}\,\mathrm{M}_\odot\,.$$

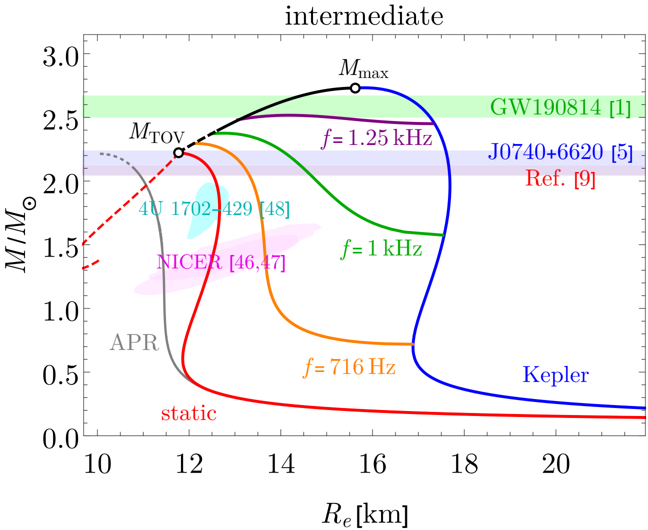
[The LIGO Scientific Collaboration, the Virgo Collaboration arXiv:2006.12611]

- Secondary component falls into so-called mass-gap region:
  either the heaviest NS or the lightest BH ever observed.
- m_2 is likely too large to be non-rotating, cf. V-QCD: $M_{\mathrm{TOV}}^{\mathrm{max}} \approx 2.4 M_\odot$.
- Does the V-QCD model allow it to be a spinning NS?
- If this is the case, how fast does it need to rotate?

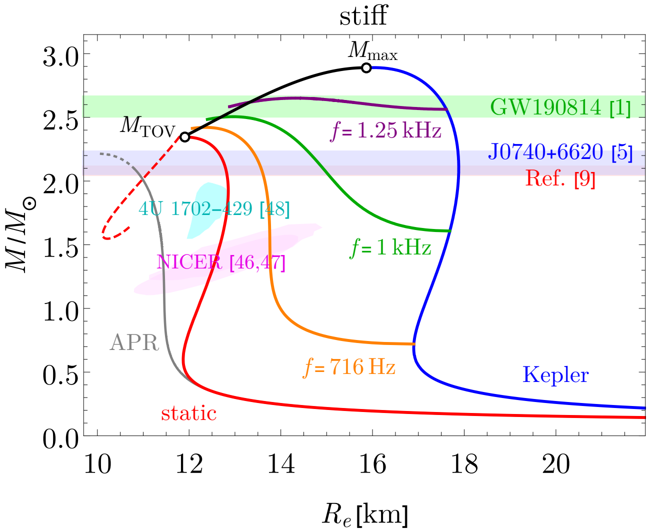
Mass Radius Relation



Mass Radius Relation



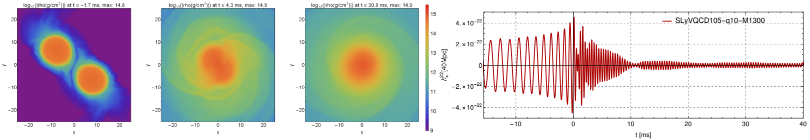
Mass Radius Relation



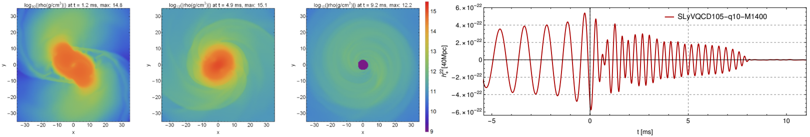
4. Binary Neutron Star Mergers

Merger Dynamics and Waveforms

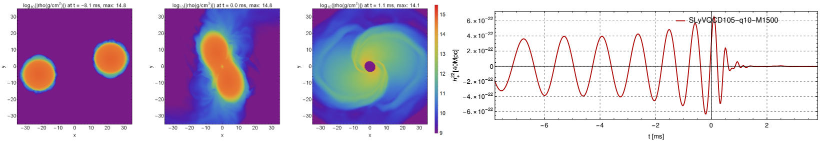
- $M = 1.3 + 1.3 M_\odot$: Formation of a long lived ($> 40 ms$) SMNS.



- $M = 1.4 + 1.4 M_\odot$: Formation of a short lived ($\approx 7.8 ms$) HMNS.

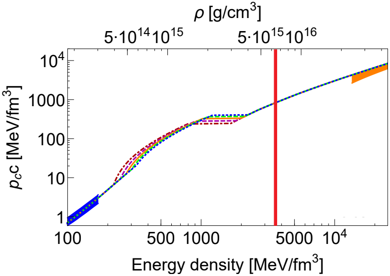


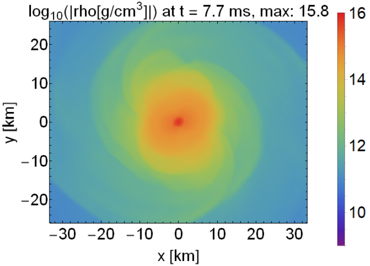
- $M = 1.5 + 1.5 M_\odot$: Prompt collapse to BH with dilute matter torus.

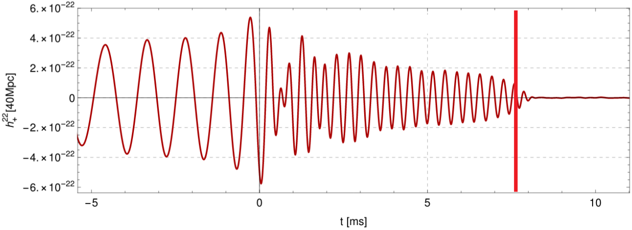


Intermediate Mass Binary

- Softening of EoS in the quark matter phase leads to phase transition induced collapse.





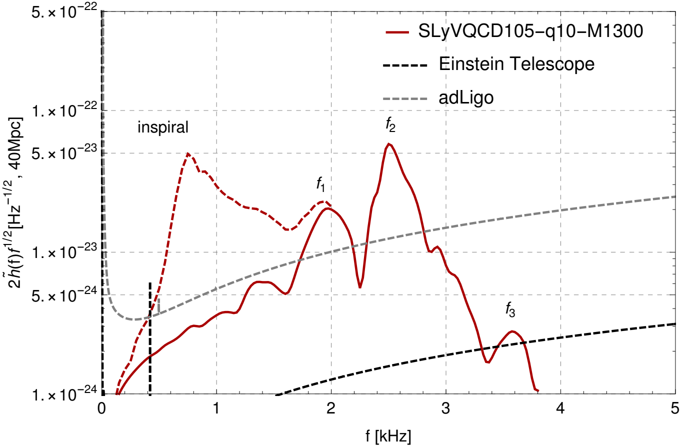


Power Spectral Density

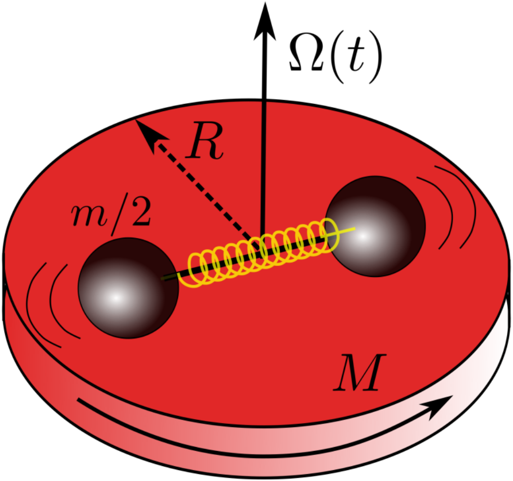
Post-merger power spectral density (PSD) has typical three peak structure

$$\tilde{h}(f) \equiv \sqrt{\frac{|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2}{2}}\,, \quad \tilde{h}_{+,\times}(f) \equiv \int h_{+,\times}(t) e^{-i2\pi f t} dt\,.$$

Characteristic frequencies f_1, f_2, f_3 encode information about EoS.

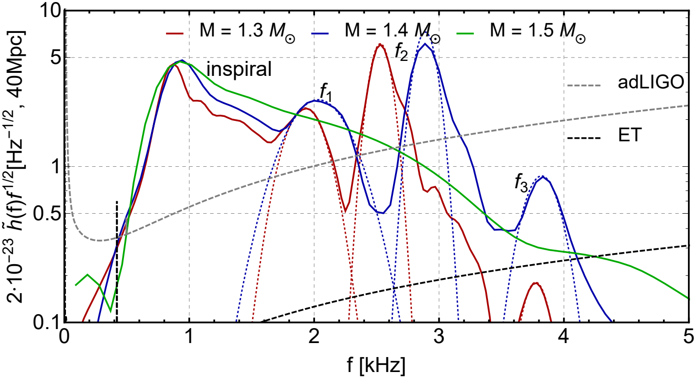


Mechanical Toy Model



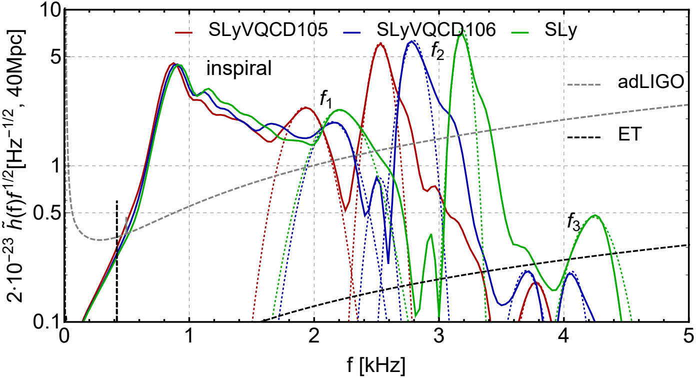
[Takami, Rezzolla, Baiotti arXiv:1412.3240]

Mass dependence of the Power Spectral Density



$M[M_\odot]$	EoS	b	f_1[kHz]	f_2[kHz]	f_3[kHz]
1.30	SLyVQCD105	10.5	1.93	2.53	3.77
1.35	SLyVQCD105	10.5	1.95	2.60	3.53 (3.90)
1.40	SLyVQCD105	10.5	2.03	2.89	3.82
1.50	SLyVQCD105	10.5	–	–	–

EoS dependence of the Power Spectral Density



$M[M_\odot]$	EoS	b	f_1[kHz]	f_2[kHz]	f_3[kHz]
1.30	SLyVQCD105	10.5	1.93	2.53	3.77
1.30	SLyVQCD106	10.6	2.15	2.80	3.70 (4.06)
1.30	SLy	-	2.21	3.19	4.24

4. Summary

Summary

- Holographic V-QCD gives nuclear and quark matter with first order phase transition in the same model.
- Allows to construct hybrid equations of state that satisfy known theoretical and observational constraints.
- Strong first order PT: V-QCD disfavours stable quark matter cores.
- M_{max} of rotating stars determined by secular instability (stiff) or phase transition (soft). Both cases possible in single (intermediate) model.
- Strong coupling approach predicts slightly higher $\frac{M_{\mathrm{max}}}{M_{\mathrm{TOV}}}$ than traditional nuclear matter models without phase transition:

$$\left.\frac{M_{\mathrm{max}}}{M_{\mathrm{TOV}}}\right|_{\mathrm{V-QCD}} = 1.227^{+0.031}_{-0.016} \quad \mathrm{vs.} \quad \left.\frac{M_{\mathrm{max}}}{M_{\mathrm{TOV}}}\right|_{\mathrm{nucl.}} = 1.203^{+0.022}_{-0.022}$$

- $M_{\mathrm{max}} \approx 2.9\, M_\odot$ possible. Compatible with secondary component ($2.9\, M_\odot$) of GW190814, but has to spin extremely fast: $f \gtrapprox 1$kHz.
- Phase transition induced collapse in neutron star mergers.
- Post merger GW spectrum allows to distinguish V-QCD hybrid from pure nuclear matter EOS.