

Gravitational Waves from Holographic Neutron Star Mergers

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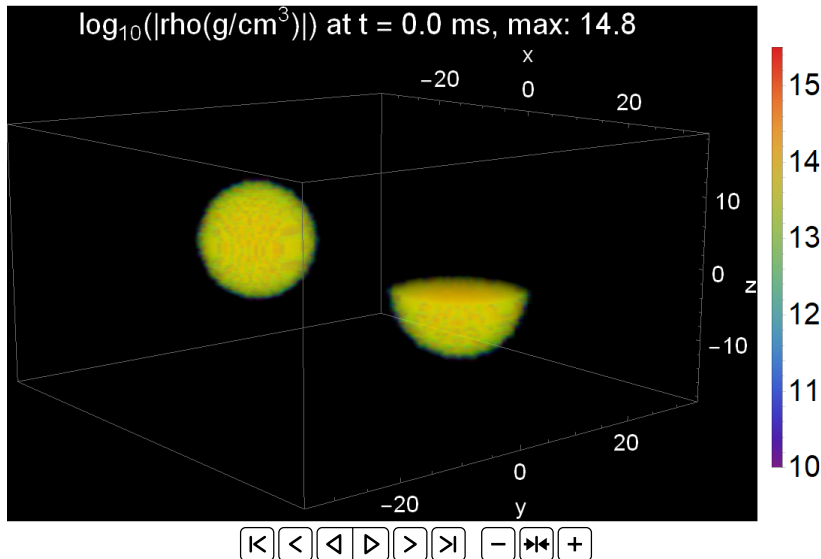
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Based on [arXiv:1908.03213](https://arxiv.org/abs/1908.03213)

with Matti Järvinen, Govert Nijs and Wilke van der Schee

Neutron star merger with holographic EoS



Outline

1. Introduction
2. Holographic model
3. Merger simulations
4. Results
5. Summary and Outlook

1. Introduction

Neutron stars

- ▶ Neutron stars (NSs) are born in supernova explosions of massive ($8 - 25M_{\odot}$) main sequence stars.

- ▶ Densest astrophysical objects which are not black holes (BHs)

$$M \approx 1.4M_{\odot}, \quad R \approx 10\text{km}, \quad \rho \approx 2 - 5\rho_0$$

(nuclear saturation mass-energy density $\rho_0 = 2.5 \cdot 10^{14} \text{ g cm}^{-3}$)

- ▶ Can have huge magnetic fields (magnetars) $B \approx 10^{15} \text{ G}$

(cf. earth: $B_{\oplus} \approx 0.6 \text{ G}$, RHIC: $B_{\text{HIC}} \approx 10^{18} \text{ G}$)

- ▶ Some rotate extremely fast (pulsars) $\nu_{\text{rot}} \lesssim 1 \text{ ms}^{-1}$

first detection in 1967 as pulsar = rapidly rotating and highly magnetized NS

record holder: PSR J1748-2446ad ($v_R \approx 0.24c$)

- ▶ Neutron stars are cool: T in keV range

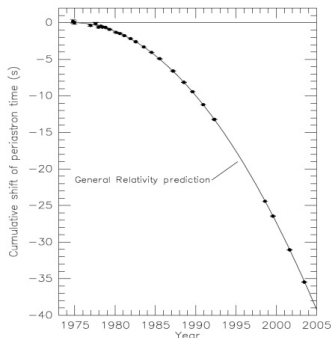
$T \ll \Lambda_{\text{QCD}} \implies T = 0$ good approx., located at bottom of QCD phase diagram.

neutrino cooling: from $10^{11} \text{ K} \approx 10 \text{ MeV}$ after supernova to keV within days.

shock heating: finite temperature contributions become important during merger.

Neutron star binaries

- ▶ Binary NS systems are most likely formed in main-sequence star binaries¹, less likely by dynamical capture.
- ▶ First discovery in 1974: Hulse-Taylor binary pulsar (PSR B1913+16), successful test of Einstein gravity and indirect proof for gravitational waves (GWs).
- ▶ Known binary NS systems typically have:
[J.M. Lattimer 2012, see also www.stellarcollapse.org]
 - ▶ Masses around $M_{1,2} \approx 1.4 M_{\odot}$
 - ▶ Mass ratio $q \equiv M_1/M_2 \approx 1$
 - ▶ Several million years of inspiral phase, i.e. enough time to cool down by neutrino cooling and circularize orbits by GW emission.

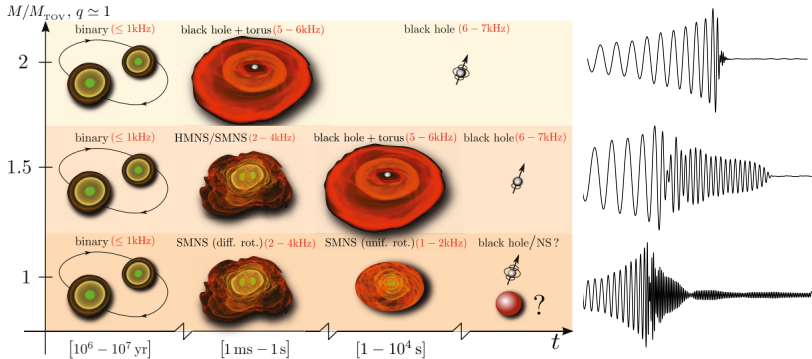


[picture: Weisberg, Taylor
[astro-ph/0407149](https://arxiv.org/abs/astro-ph/0407149)]

¹Most stars (up to $\approx 85\%$) are actually in binary systems. (see www.atnf.csiro.au)

Neutron star mergers

- ▶ Significant sources of gravitational radiation.
- ▶ Microscopic properties of dense matter encoded in GW and EM signal.
- ▶ Likely the origin of short gamma-ray bursts (SGRBs)
- ▶ and of heavy elements like gold, platinum, or uranium.

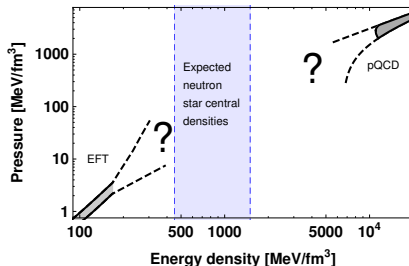
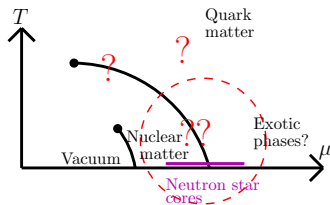


[picture: Baiotti, Rezzola arXiv:1607.03540]

(SMNS: $M_{\text{TOV}} < M < M_{\text{max}} \approx 1.2M_{\text{TOV}}$, HMNS: $M > M_{\text{max}}$)

Neutron star equation of state

- ▶ Equation of state (EoS) $p(\epsilon, T, \dots)$ required to close EOMs in fluid description of neutron stars.
- ▶ EoS of neutron stars is currently unknown because:
- ▶ Nuclear matter models typically only reliable for $\rho \lesssim \rho_0$.
- ▶ First principle QCD calculations at relevant densities not feasible:
 - ▶ pQCD only at asymptotically large densities and/or T .
 - ▶ Lattice QCD has sign problem at finite densities.



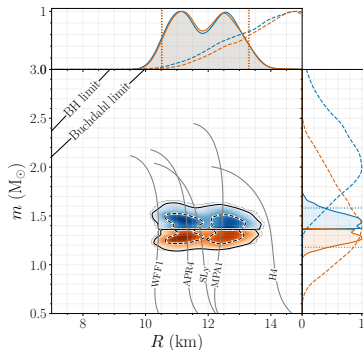
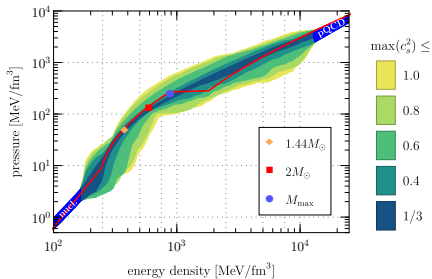
Constraints on the EoS

From theory:

- By causality the speed of sound has to satisfy: $c_s^2 = \left(\frac{\partial p}{\partial \epsilon}\right)_s < 1$.
- QCD is asymptotically free at large densities: $c_s^2 \rightarrow 1/3$.

From observation:

- NS-white dwarf binary PSR J0348+0432: $M_{\max} > 2.01 \pm 0.04 M_{\odot}$.
[Antoniadis et. al. arXiv:1304.6875]
- GW170817 constrains tidal deformability: $\Lambda = \frac{2}{3} k_2 (c^2 R / (Gm))^5 \lesssim 600$.
[LIGO/Virgo: arXiv:1710.05832, arXiv:1805.11579, arXiv:1805.11581]



[Annala, Gorda, Kurkela, Nättilä, Vuorinen arXiv:1903.09121, left plot by T. Gorda]

2. Holographic Model

Holographic model: V-QCD

Bottom-up construction with dynamical quark and gluon sectors and potentials tuned to mimic QCD.

Two building blocks of Veneziano QCD (V-QCD):

1. Improved holographic QCD (IHQCD) for gluon sector (dilaton gravity).
[Gürsoy, Kiritsis, Nitti; Gubser, Nellore]
2. Sen-like tachyonic Dirac-Born-Infeld (DBI) actions for flavor sector and chiral symmetry breaking via tachyon condensation.
[Bergman, Seki, Sonnenschein; Dhar, Nag; Bigazzi, Casero, Cotrone, Kiritsis, Paredes; Gürsoy, Kiritsis, Nitti; Iatrakis, Kiritsis, Paredes]

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

$$N_c \rightarrow \infty \text{ and } N_f \rightarrow \infty \text{ with } x \equiv N_f/N_c \text{ fixed}$$

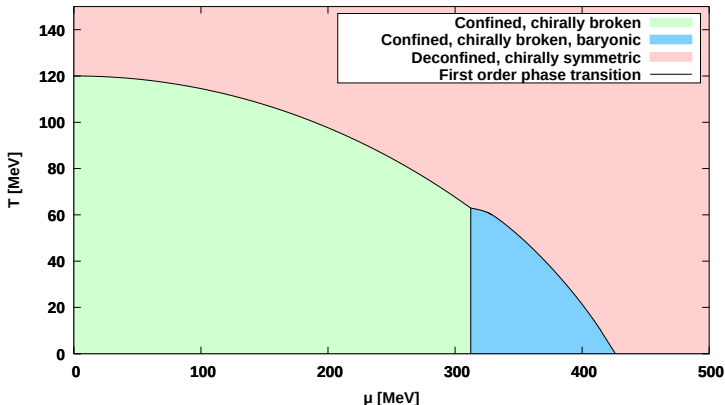
[Järvinen, Kiritsis arXiv:1112.1261]

Add probe baryons: simple approximation with homogeneous bulk soliton.
One free parameter: b = coupling between baryon and chiral condensate.

[Ishii, Järvinen, Nijs arXiv:1903.06169]

Phase diagram

- ▶ Baryons appear at medium μ in the confined phase
- ▶ Nontrivial nuclear and quark matter EoS from the same model
- ▶ Free parameter of the holographic model b chosen to set the correct μ_c at vacuum-baryon transition



[Ishii, Järvinen, Nijs arXiv:1903.06169]

Hybrid Equation of State (I)

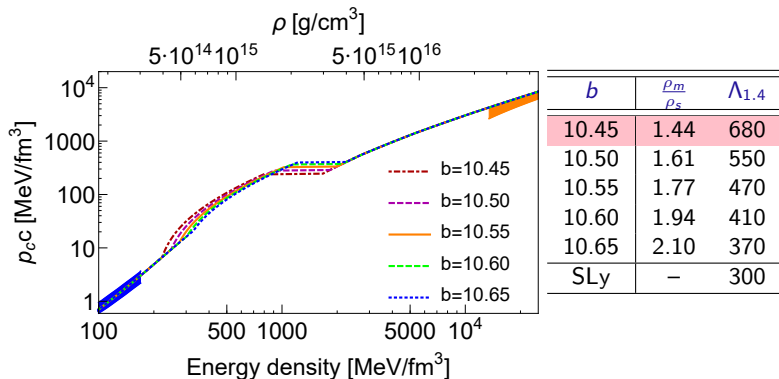
Construction of the hybrid EoS:

- ▶ In the crust and for low densities (up to $1.5 - 2\rho_0$) we use the SLy nuclear matter EoS. Here the nuclear matter EoS is expected to be more reliable than the holographic model.
[Haensel, Pichon nucl-th/9310003, Douchin, Haensel astro-ph/0111092]
- ▶ For dense nuclear matter the baryonic V-QCD is matched² to SLy.
- ▶ Baryon onset in SLy part $\implies$ freedom in holographic parameter b .
- ▶ Changing b shifts μ_{match} $\implies$ more/less SLy at low densities.
- ▶ At high densities the V-QCD EoS transitions to the quark phase $\implies$ same model for holographic baryon and quark phase.

²Matching point μ_{match} and normalization c_b of the action are chosen to give continuous $p(\mu)$ and $p'(\mu)$ at matching point.

Hybrid Equation of State (II)

- ▶ Second order phase transition at matching between SLy and VQCD.
- ▶ Strong³ first order nuclear to quark matter phase transition.
- ▶ LIGO observation GW170817 constrains $b \gtrsim 10.45 \rightarrow \Lambda_{1.4} \approx 680$.



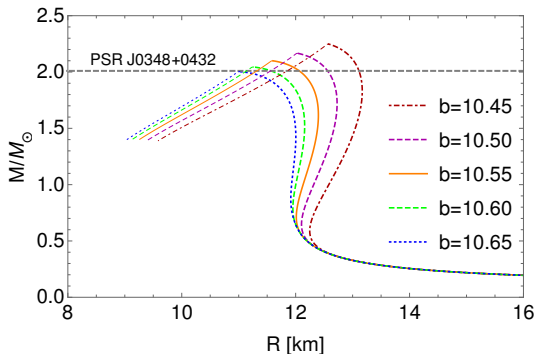
³The latent heat at the transition is sizable (for $b = 10.5$: $\Delta\epsilon = 920 \text{ MeV/fm}^3$).

Mass-radius relation

- Large values of $b \gtrsim 10.65$ are ruled out by $2.01 M_{\odot}$ -bound from PSR J0348+0432 and PSR J1614-2230.

[Demorest et. al. arXiv:1010.5788, Antoniadis et. al. arXiv:1304.6875]

- Allowed values in the holographic model: $10.45 \lesssim b \lesssim 10.65$.



b	$\frac{R_{1.4}}{\text{km}}$	$\frac{M_{\text{max}}}{M_{\odot}}$
10.45	13.0	2.25
10.50	12.6	2.17
10.55	12.3	2.10
10.60	12.1	2.04
10.65	12.0	2.00
SLy	11.7	2.05

3. Merger Simulations

Simulating neutron star mergers (I)

Have to evolve the 4D general relativistic hydrodynamics equations:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G_N T_{\mu\nu}, \quad \nabla_\mu T^{\mu\nu} = 0, \quad \nabla_\mu J^\mu = 0, \quad p = p(\epsilon),$$
$$ds^2 = -(\alpha^2 - \beta^i \beta_i) dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j,$$

with initial conditions (spacetime and fluid distribution) modelling a NS binary system:

- ▶ Use pseudo spectral code LORENE⁴ to generate initial data.
[Gourgoulhon, Grandclement, Taniguchi, Marck, Bonazzola arXiv:gr-qc/0007028]
- ▶ Assumes helical symmetry = circularity of the BNS orbit, no GWs.
- ▶ Use non-spinning ICs for the fluid distribution.
- ▶ Initial distance D must be sufficiently large to justify circular orbit approximation, but not too large (reasonable inspiral time).
Use $D = 45\text{km}$, gives between three ($1.4M_\odot$) and six ($1.3M_\odot$) orbits.

⁴Langage Objet pour la RELativite Numerique, see <http://www//lorene.obspm.fr>

Simulating neutron star mergers (II)

Einstein equations need to be solved in strongly hyperbolic⁵ form.

- ▶ Use Conformal and Covariant Z4 (CCZ4) formulation
[Alic, Bona-Casas, Bona, Rezzolla, Palenzuela]
- ▶ Lapse α and shift β^i fixed by singularity avoiding gauge conditions.
- ▶ Implemented in the Einstein Toolkit.
[Löffler et. al., arXiv:1111.3344, <http://einstein toolkit.org>]
- ▶ Hydro equations solved with WhiskyTHC⁶.
[Radice, Rezzolla arXiv:1206.6502]

⁵The weakly hyperbolic ADM formulation (metric γ_{ij} and the extrinsic curvature K_{ij} as dynamical variables) does not lead to stable time evolution.

⁶see D. Radices homepage: <https://www.astro.princeton.edu/~dradice/index.html>

Spacetime discretization

- ▶ Grid must be large enough to extract GW in "asymptotic" region.
- ▶ Fine enough to resolve the NS, merger dynamics and BH formation.
⇒ Adaptive mesh refinement (AMR) required.
- ▶ We use a cubic grid of $\approx 3025\text{km}$ ($\approx 70D$) side length.
- ▶ Reflection symmetry about xy -plane.
- ▶ Six "refinement levels":
Coarse mesh ($\Delta h_0 \approx 23.5\text{km}$) in the asymptotic region.
Finest meshes ($\Delta h_6 \approx 365\text{m}$) centered at the neutron stars.
⇒ $\approx 5 \cdot 10^6$ gridpoints and $\approx 5 \cdot 10^5$ time steps!

Supercomputing

- ▶ To simulate neutron stars one needs supercomputing.
- ▶ Pilot project (500.000 CPUh) on Dutch supercomputer Cartesius.
[<https://userinfo.surfsara.nl/systems/cartesius>]
- ▶ Typical simulation costs 10.000 CPUh on 100 CPUs and takes $\approx$ 4 days.



Extracting Waveforms

- ▶ Extract Newman-Penrose scalar ψ_4 from simulation

$$\psi_4 := C_{\mu\nu\rho\sigma} k^\mu \bar{m}^\nu k^\rho \bar{m}^\sigma, \quad \text{null tetrad: } \{l^\mu, k^\mu, m^\mu, \bar{m}^\mu\}.$$

- ▶ The GW polarization amplitudes (h_+ , $h_\times$) are related to ψ_4 via
[see e.g. book by M. Alcubierre (2005)]

$$\ddot{h}_+ - i\ddot{h}_\times = \psi_4 = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} \psi_4^{\ell m} {}_{-2}Y_{\ell m}(\theta, \varphi).$$

- ▶ Consider only the dominant $\ell = m = 2$ mode

$$h_{+, \times} = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} h_{+, \times}^{\ell m} {}_{-2}Y_{\ell m}(\theta, \varphi) \approx h_{+, \times}^{22} {}_{-2}Y_{22}(\theta, \varphi),$$

and assume optimal orientation (${}_{-2}Y_{22}(0, 0) = \frac{1}{2}\sqrt{5/\pi}$) of the merger with respect to the detector.

- ▶ Extrapolate signal to detector, assume distance of 40Mpc, i.e. same luminosity distance as GW170817.

Power Spectral Density

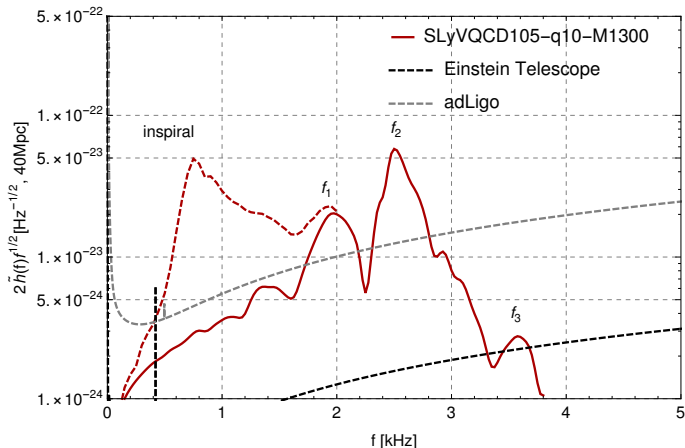
Post-merger power spectral density (PSD) has typical three peak structure.

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

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

[Takami, Rezzolla, Baiotti arXiv:1403.5672]

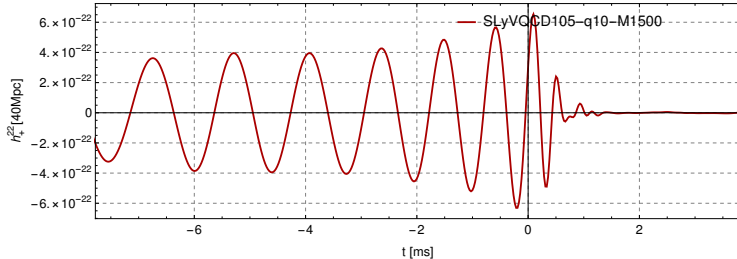
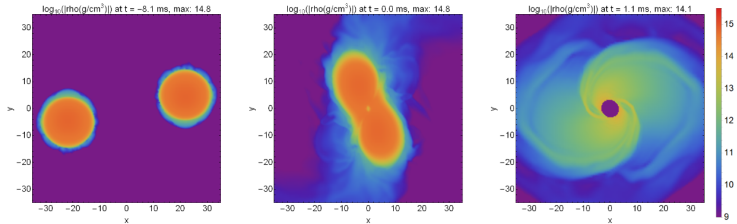
Strategy: simulate predictions for f_1 , f_2 , f_3 and compare to future observations.



4. Results

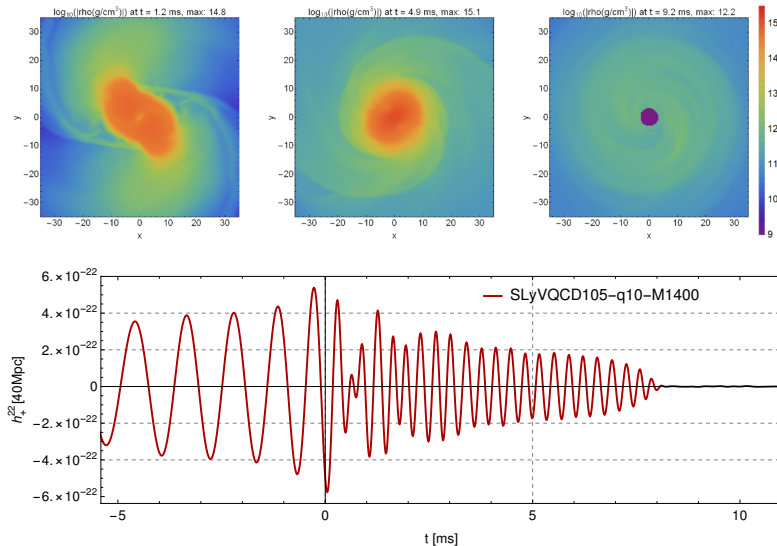
High mass binary

- ▶ Equal mass binary $M_1 = M_2 = 1.5M_\odot$ with $b = 10.5$ SLy+VQCD EoS.
- ▶ Prompt collapse to BH with dilute matter torus $\rightarrow$ trivial post-merger PSD.
- ▶ Densities are not high enough to create quark matter outside BH.



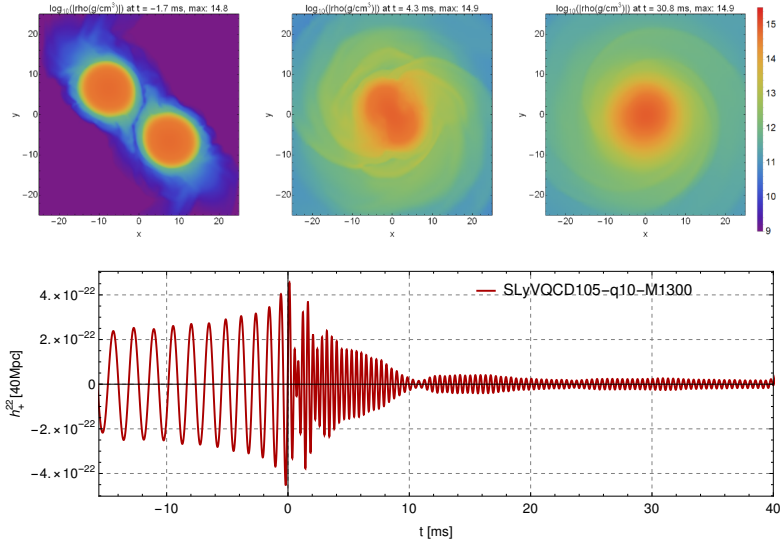
Intermediate mass binary

- ▶ Equal mass binary $M_1 = M_2 = 1.4M_\odot$ with $b = 10.5$ SLy+VQCD EoS.
- ▶ Formation of a short lived ($\approx 7.8\text{ms}$) HMNS $\rightarrow$ non-trivial PSD.

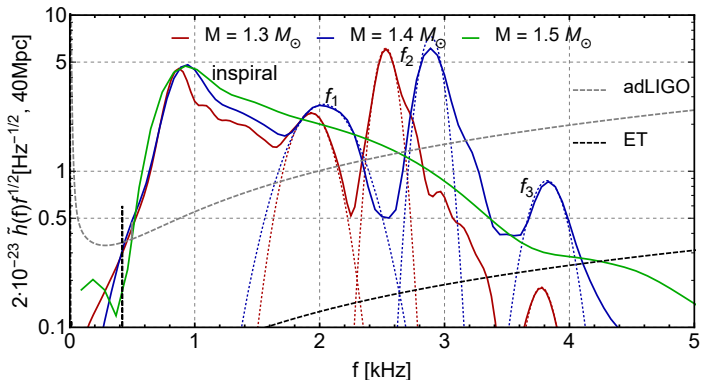


Low mass binary

- ▶ Equal mass binary $M_1 = M_2 = 1.3M_\odot$ with $b = 10.5$ SLy+VQCD EoS.
- ▶ Formation of a long lived ($> 40ms$) HMNS $\rightarrow$ non-trivial PSD.

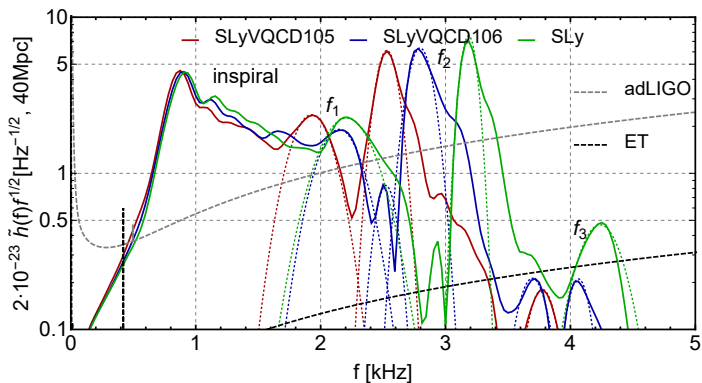


Mass dependence of the Power Spectral Density



$M[M_{\odot}]$	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	—	—	—

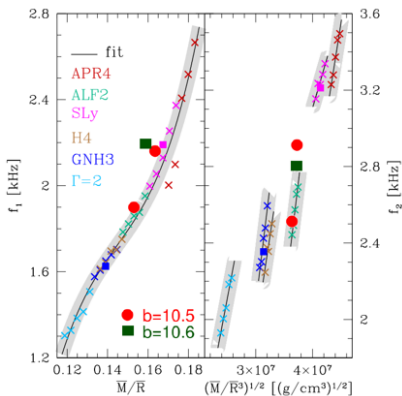
EoS dependence of the Power Spectral Density



$M[M_{\odot}]$	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

Universality

- Frequency f_1 as function of compactness $\mathcal{C} = M/R$ shows universal behaviour, i.e. results for different EoS fall on one universal curve.
- V-QCD EoS for $b = 10.5$ gives f_1 close to universal curve, $b = 10.6$ slightly off (?) $\implies$ more analysis needed.



[plot from Takami, Rezzolla, Baiotti arXiv:1403.5672]

5. Summary and Outlook

Summary

- ▶ Constructed “realistic” hybrid holographic EoS that satisfies all currently known theoretical and observational constraints.
- ▶ First NS merger simulations using input from holography.
- ▶ No (meta-)stable quark matter outside a BH horizon
 - ⇒ phase transition leads to prompt collapse.
- ▶ Predictions for characteristic peaks in power spectral densities
 - ⇒ new connection between holography and observation!
- ▶ Features in post merger power spectral densities (location of peaks) expected to be accessible by 3rd generation detectors.

Outlook

- ▶ Increase resolution to improve accuracy of waveforms and PSD (costly!).
- ▶ Include finite T effects in EoS $\rightarrow$ temperature driven de-confinement phase transition.
- ▶ Spin, non-equal mass binaries, NS-BH merger, magnetic fields.
- ▶ Improve holographic model:
 - ▶ go beyond homogeneous baryon ansatz: numerical solutions for inhomogeneous solitons.
 - ▶ include magnetic field dependence in the EoS.
 - ▶ systematic study with different nuclear matter EoSs at low density.
- ▶ Only first step towards holographic GW model building, lots of possibilities and challenges!

6. Backup

V-QCD without baryons (I)

Consider first the non-baryonic V-QCD action, whose solutions will serve as background for the probe baryons

$$S_{\text{V-QCD}}^{(0)} = S_{\text{glue}} + S_{\text{DBI}}^{(0)}.$$

The gluon part is given by the IHQCD (dilaton gravity) action

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

where $\lambda \equiv e^\phi \leftrightarrow \text{Tr} F^2$ ($\approx g^2 N_c$ near the boundary) sources the 't Hooft coupling in YM theory, the dilaton potential is chosen⁷ to mimic QCD

$$V_g(\lambda) = 12 \left[1 + V_1 \lambda + \frac{V_2 \lambda^2}{1 + \lambda/\lambda_0} + V_{\text{IR}} e^{-\lambda_0/\lambda} (\lambda/\lambda_0)^{4/3} \sqrt{\log(1 + \lambda/\lambda_0)} \right].$$

Finite T is implemented by homogeneous+isotropic black brane metric

$$ds^2 = e^{2A(r)} (-f(r) dt^2 + d\vec{x}^2 + f^{-1}(r) dr^2).$$

⁷E.g. V_1 and V_2 are fixed by requiring the UV RG flow of the 't Hooft coupling to be the same as in QCD up to two-loop order.

V-QCD without baryons (II)

The flavor part is modelled by the tachyonic DBI-action⁸

$$S_{\text{DBI}}^{(0)} = -N_f N_c M^3 \int d^5x V_{f0}(\lambda) e^{-\tau^2} \sqrt{-\det [g_{ab} + \kappa(\lambda) \partial_a \tau \partial_b \tau + w(\lambda) F_{ab}]},$$
$$F_{rt} = \Phi'(r), \quad \Phi(0) = \mu,$$

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

Several potentials: $\{V_g(\lambda), V_{f0}(\lambda), w(\lambda), \kappa(\lambda)\}$, chosen to match pQCD in UV ($\lambda \rightarrow 0$), qualitative agreement with QCD in IR ($\lambda \rightarrow \infty$) 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]

Different solutions:

without/with horizon $\leftrightarrow$ confined/deconfined phase

without/with tachyon $\leftrightarrow$ chirally symmetric/chirally broken phase

⁸Without baryons we have a vectorial flavor singlet gauge field $A^{(L/R)} = \mathbb{I}_f \Phi(r) dt$ giving nonzero charge density and chemical potential.

Probe baryons in V-QCD

Each baryon maps to a solitonic “instanton” configuration of non-Abelian gauge fields in the bulk.

[Witten; Gross, Ooguri; . . .]

Consider the full non-Abelian brane action $S = S_{\text{DBI}} + S_{\text{CS}}$ where

[Bigazzi, Casero, Cotrone, Kiritsis, Paredes; Casero, Kiritsis, Paredes]

$$S_{\text{DBI}} = -\frac{1}{2}M^3N_c \mathbb{T}r \int d^5x V_{f0}(\lambda) e^{-\tau^2} \left(\sqrt{-\det \mathbf{A}^{(L)}} + \sqrt{-\det \mathbf{A}^{(R)}} \right),$$

$$\mathbf{A}_{MN}^{(L/R)} = g_{MN} + \delta_M^r \delta_N^r \kappa(\lambda) \tau'(r)^2 + \delta_{MN}^{rt} w(\lambda) \Phi'(r) + w(\lambda) F_{MN}^{(L/R)}$$

gives the dynamics of the solitons.

The Cern-Simons term sources the baryon number for the solitons

$$S_{\text{CS}} = \frac{N_c}{8\pi^2} \int \Phi(r) e^{-b\tau^2} dt \wedge \left(F^{(L)} \wedge F^{(L)} - F^{(R)} \wedge F^{(R)} + \dots \right).$$

Non-Abelian DBI action only known to first few orders in $F^{(L/R)}$: expand to second order on top of solution $(g_{MN}, \Phi, \lambda, \tau)$ obtained from $S_{V-QCD}^{(0)}$.

Homogeneous Baryon Ansatz

Set $N_f = 2$ and consider the SU(2) Ansatz

[Rozali, Shieh, Van Raamsdonk, Wu]

$$A_L^i = -A_R^i = h(r)\sigma^i$$

Immediate consequence: baryon charge integrates to zero?

$$N_b \propto \int dr \frac{d}{dr} \left[e^{-b\tau^2} h^3 (1 - 2b\tau^2) \right] \stackrel{?}{=} 0$$

However finite baryon number may can be realized by discontinuity of h
 $\leftrightarrow$ smeared solitons in singular gauge.

[Ishii, Järvinen, Nijs, arXiv:1903.06169]

The free parameter b of the model is used to tune the baryon onset to its physical value in QCD.