Holographic dense QCD and neutron stars

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Frontiers of holographic duality
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Outline

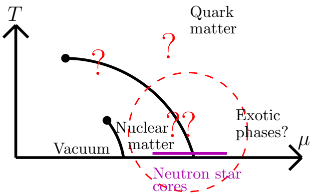
1. Introduction and motivation
2. Holographic models for dense QCD
3. Holographic nuclear matter and hybrid equations of state
4. Merging holographic neutron stars

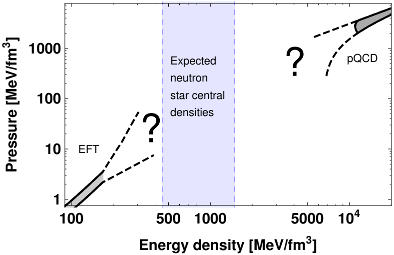
1. Introduction and motivation

Motivation

Computing theoretical predictions from QCD is particularly hard at intermediate densities and small temperatures:

- Lattice data only available at zero/small chemical potentials
- Perturbative QCD works only at asymptotically high densities
- Effective field theory works at small densities



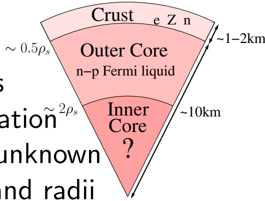


This region is relevant for neutron stars (which have $T \ll \Lambda_{\mathrm{QCD}}$)

Experimental data coming in from measurement of neutron stars and neutron star mergers!

Neutron stars

Neutron stars: extremely dense cold QCD matter

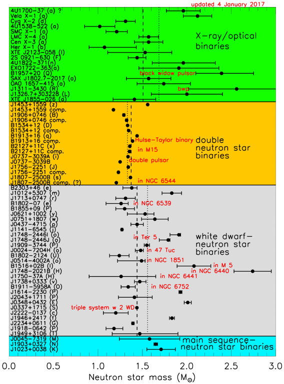


- Tolman-Oppenheimer-Volkoff (TOV) equations map equation of state (EoS) to mass-radius relation
- Uncertainty in EoS ⇒ inner core composition unknown
- EoS can be constrained by measuring masses and radii

Mass measurements: dozens of results using various methods

- Highest masses from Shapiro delay measurement of NS – white dwarf binaries J0348+0432 and J0740+6620:

$M_{\max} \gtrsim 2 M_\odot$ [Antoniadis et al arXiv:1304.6875 Cromartie et al arXiv:1904.06759]



[Lattimer]

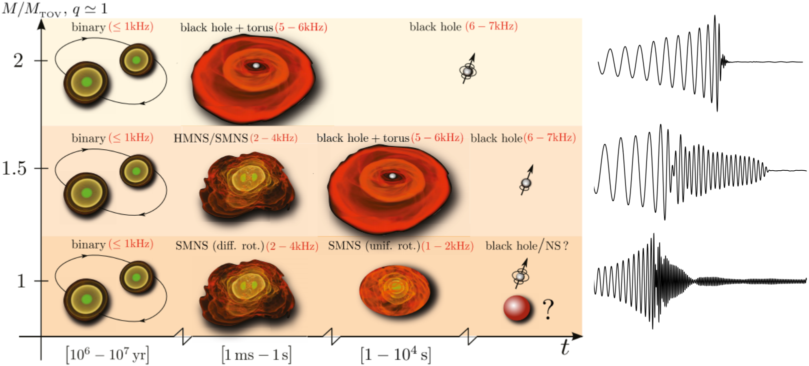
Radius measurements: more challenging, high uncertainties

- Cooling after X-ray bursts ⇒ radii around 10-15 km

More and better results expected in near future! E.g. NICER

Neutron star mergers

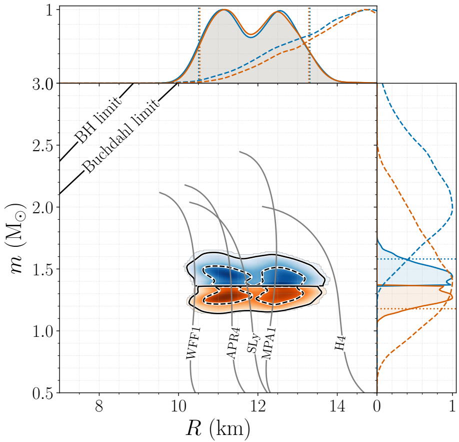
- Significant sources of gravitational radiation
- Microscopic properties of dense matter encoded in GW and EM signal
- Likely the origin of short gamma-ray-bursts and heaviest elements

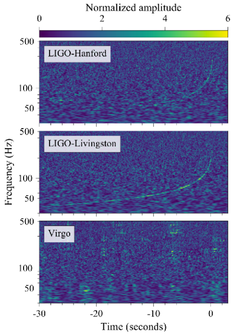


[picture: Baiotti, Rezzola arXiv:1607.03540]

LIGO constraints from GW170817

- Inspiral phase GW signal gives an upper bound for the tidal deformability $\Lambda \lesssim 580$
- Rough upper bound for neutron star radius





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

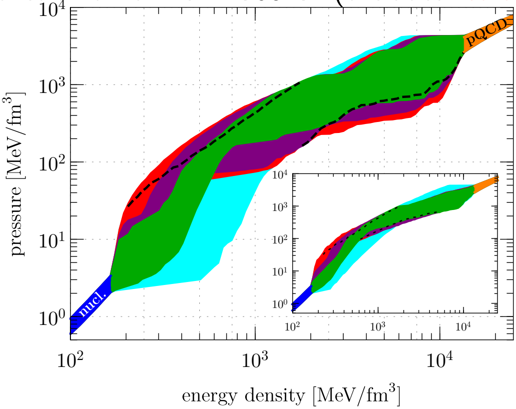
LIGO has enhanced sensitivity since this event!

Constraints on equations of state

State of the art for QCD EoS at $T = 0$: interpolations between nuclear EoS and pQCD, constrained by

[Annala, Gorda, Kurkela, Vuorinen arXiv:1711.02644]

- Mass bound $M_{\max} > 1.97 M_{\odot}$ (excludes cyan area)
- LIGO constraint from GW170817: (excludes red area)



Source of uncertainties: physics at strong coupling. $\Rightarrow$
Can holographic methods be used to reduce uncertainties further?

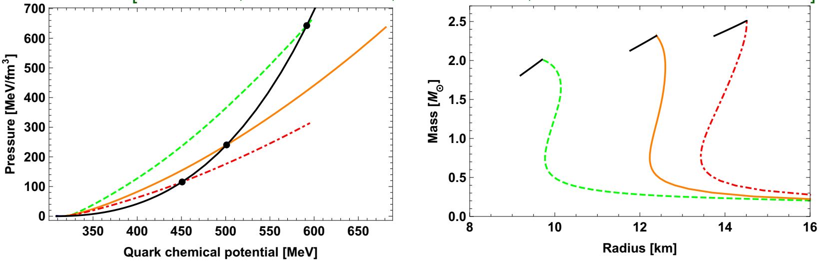
2. Holographic models for dense QCD

$\mathcal{N} = 4$ SYM and probe matter

For quark matter, use D3-D7 top down model: $\epsilon = 3p + \frac{\sqrt{3}m^2}{2\pi}\sqrt{p}$
[Karch, O'Bannon, arXiv:0709.0570]

- $\mathcal{N} = 4$ SYM + $N_f = 3$ probe hypermultiplets in the fundamental representation

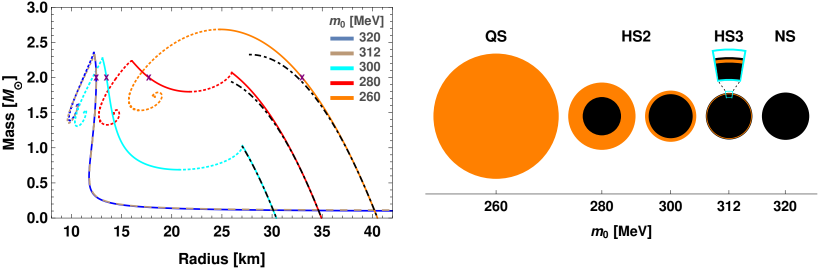
For nuclear matter use with stiff, intermediate, and soft "extrapolations" of EFT results
[K. Hebeler, J. M. Lattimer, C. J. Pethick, A. Schwenk arXiv:1303.4662]



- Strong first order nuclear to quark matter transitions
- Neutron stars with "holographic" quark matter core (black curves) are unstable

[Hoyos, Rodriguez, Jokela, Vuorinen arXiv:1603.02943]

Varying the quark mass *m* one can get quark stars and hybrid stars
[Annala, Ecker, Hoyos, Jokela, Rodriguez-Fernandez, Vuorinen arXiv:1711.06244]



- Sizeable deviations from universal I-Love-Q relations
[Yagi, Yunes, arXiv:1303.1528]

Including running of the quark mass
[Bitaghsir Fadafan, Cruz Rojas, Evans, arXiv:1911.12705]

- Stiffer equations of state (high speed of sound)
- Hints of twin stars with quark matter cores?

(Largish) quark stars also studied in Witten-Sakai-Sugimoto and in D4-D6 models [Burikham, Hirunsirisawat, Pinkanjanarod, arXiv:1003.5470 Kim, Shin, Lee, Wan, arXiv:1404.3474]

Holographic V-QCD

A holographic bottom-up model for QCD in the Veneziano limit (large N_f, N_c with $x = N_f/N_c$ fixed): V-QCD

- Bottom-up, but trying to follow principles from string theory as closely as possible
- Many parameters: effective description of QCD
- Comparison with QCD data essential
- One of the most realistic models available
- Works surprisingly well! (I will show examples)

The model is obtained through a fusion of two building blocks:
[MJ, Kiritsis arXiv:1112.1261]

1. IHQCD: model for glue inspired by string theory (dilaton gravity)
[Gursoy, Kiritsis, Nitti; Gubser, Nellore]
2. Adding flavor and chiral symmetry breaking via tachyon brane actions
[Klebanov,Maldacena; Bigazzi,Casero,Cotrone,Iatrakis,Kiritsis,Paredes]

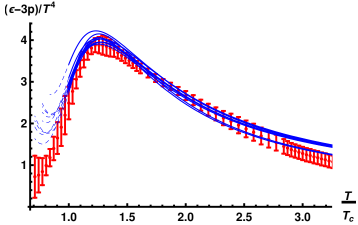
Constraining the model at $\mu \approx 0$

Stiff fit to lattice data near $\mu = 0$ (many parameters, but results insensitive to them) [MJ, Jokela, Remes, arXiv:1809.07770]

- Many parameters already fixed by requiring qualitative agreement with QCD
- Good description of lattice data – nontrivial result!

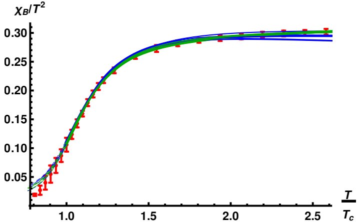
Interaction measure

Lattice data: Borsanyi et al. arXiv:1309.5258



Baryon number susceptibility

Lattice data: Borsanyi et al. arXiv:1112.4416

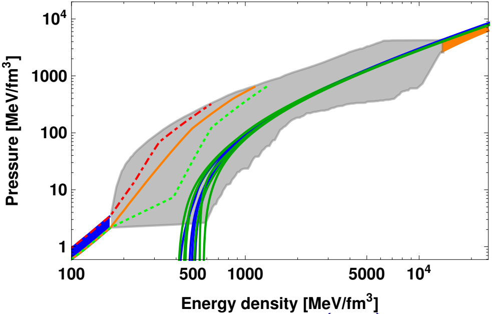


Extrapolated EoSs of cold QCD

The V-QCD quark matter result compares nicely to

[MJ, Jokela, Remes, arXiv:1809.07770]

- Interpolated EoSs (gray band)
- Stiff, intermediate, and soft nuclear EoSs [Hebeler, Lattimer, Pethick, Schwenk arXiv:1303.4662]



Holographic curves do not intersect nuclear models on (ϵ, p) plane

$\Rightarrow$ Strongly first order transitions

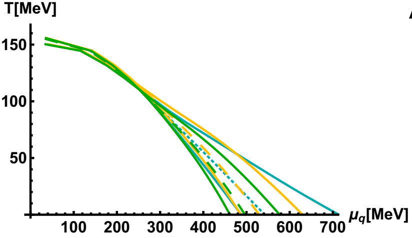
- Agrees qualitatively with the simplest D3-D7 model
- In some constrast to Witten-Sakai-Sugimoto model where the transition appears smoother [Bitaghsir Fadafan, Kazemian, Schmitt, arXiv:1811.08698]

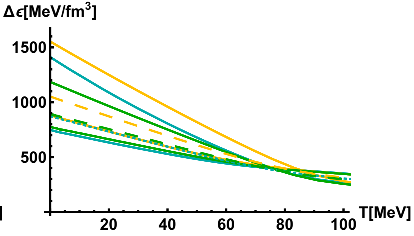
Approach similar in spirit to studies of the QCD critical point [DeWolfe,Gubser,Rosen 1012.1864; Knaute,Yaresko,Kämpfer 1702.06731; Critelli, Noronha, Noronha-Hostler, Portillo, Ratti, Rougemont, arXiv:1706.00455]

EoSs of hot and dense QCD

EoS of V-QCD quark matter (with various potential choices) combined with DD2, SFHx, and IUF nuclear matter EoSs

[Chesler, Jokela, Loeb, Vuorinen, arXiv:1906.08440]





- Reasonable EoS at all μ and T
- Sizable latent heat, decreases with T

3. Holographic nuclear matter and hybrid EoSs

Nuclear matter in holographic models

Each baryon maps to a solitonic "instanton" configuration of gauge fields in the bulk [Witten; Gross, Ooguri; ...]

- Studied a lot in Witten-Sakai-Sugimoto model [Sakai, Sugimoto; Kim, Sin, Zahed; Hong, Rho, Yee, Yi; Hata, Sakai, Sugimoto, Yamato; Hashimoto, Sakai, Sugimoto;...]
  - Rough model for physics of QCD at finite density [Bergman, Lifschytz, Lippert; Rozali, Shieh, Van Raamsdonk,Wu; Preis,Schmitt;...]
  - Baryonic phase has soliton crystals with nontrivial transitions [Kaplunovsky, Melnikov, Sonnenschein; ...]
  - Quarkyonic phase possible? [de Boer, Chowdhury, Heller,Jankowski]
- Solution also constructed in "hard-wall" models [Pomarol, Wulzer]

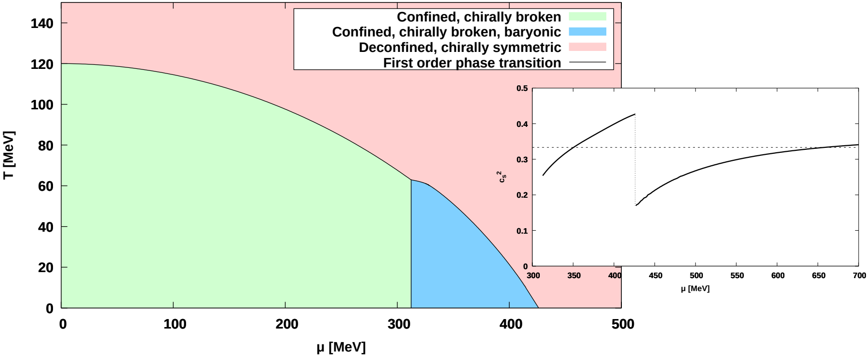
This talk: add baryons in richer bottom-up model (V-QCD) $\Rightarrow$ more realistic results?

- Set $N_f = 2$ and use a simple approximation scheme (homogeneous) [Rozali, Shieh, Van Raamsdonk, Wu, arXiv:0708.1322]

$$A^i = h(r)\sigma^i$$

[Li,Schmitt,Wang arXiv:1505.04886; Elliot-Ripley,Sutcliffe,Zamaklar arXiv:1607.04832]
[Ishii, MJ, Nijs, arXiv:1903.06169]

Phase diagram at zero quark mass



- Baryons appear at medium μ in the confined phase
- Nontrivial nuclear and quark matter EoS from the same model
- Stiff EoS (high c_s^2) in particular in the nuclear matter phase
  $\Rightarrow$ exactly what needed to pass the astro bounds!

[Ishii, MJ, Nijs, arXiv:1903.06169]

A stiff nuclear matter EoS also obtained in the holographic Witten-Sakai-Sugimoto model

[Bitaghsir Fadafan, Kazemian, Schmitt, arXiv:1811.08698]

Hybrid Equations of State ($T = 0$)

V-QCD nuclear matter description not reliable at low densities
$\Rightarrow$ use traditional models (effective field theory) instead

- Match nuclear models (low densities) with V-QCD (high densities)
- Easy to pass astrophysical constraints thanks to stiffness of V-QCD EoS
- Same (holographic) model for nuclear and quark matter phases!

[Ecker,MJ,Nijs,van der Schee arXiv:1908.03213; Jokela,MJ,Nijs,Remes, to appear]

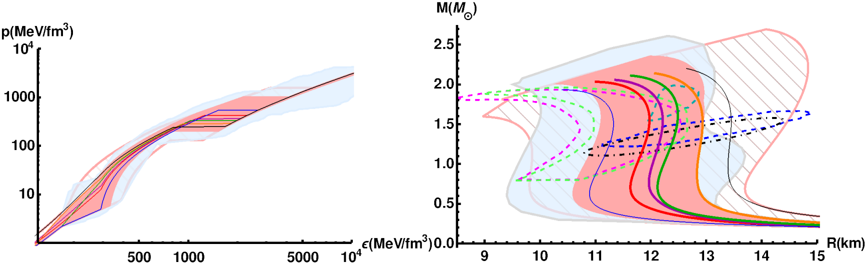
Construct "all possible" hybrid EoSs, depending on

1. The nuclear matter EoS: different models with varying stiffness
2. Parameters of the holographic model still free after lattice fit
3. The matching density between nuclear matter/holography

Constraining the EoS with gauge/gravity duality

All viable hybrid EoSs (light red) compared to interpolated EoSs (light blue), both passing constraints on $M_{\rm max}$ and Λ

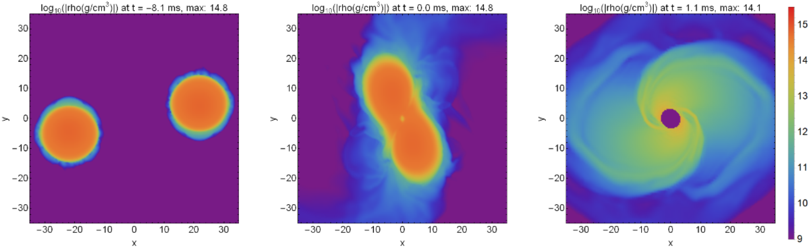
[Jokela,MJ,Nijs,Remes, to appear]



- Results disfavor stiff models for low density and soft models for high density nuclear matter
- Again strong first order nuclear to quark matter phase transitions: $\Delta\epsilon \gtrsim 500$ MeV/fm^3
- Large radii of neutron stars preferred

4. Merging holographic neutron stars

Neutron star mergers with holographic EoS

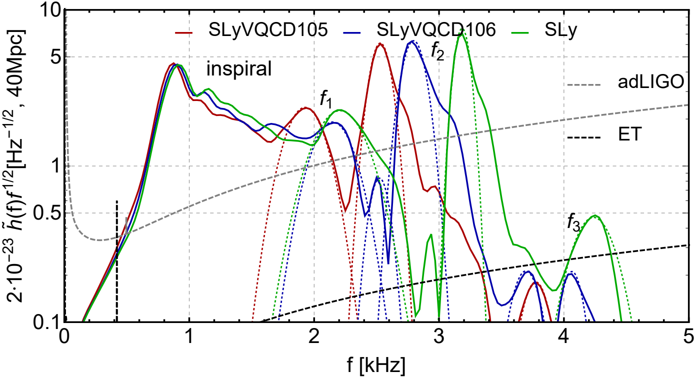


[Ecker, MJ, Nijs, van der Schee arXiv:1908.03213]

- Use the hybrid SLy+VQCD EoS as input
  [SLy: Haensel, Pichon nucl-th/9310003, Douchin, Haensel astro-ph/0111092]
- Have to evolve the 4D general relativistic hydrodynamics equation: use LORENE + Einstein Toolkit with WhiskyTHC
  [Gourgoulhon et al, arXiv:gr-qc/0007028]
  [Löfler et al, arXiv:1111.3344, http://einsteintoolkit.org]
  [Radice, Rezzolla arXiv:1206.6502]
- To simulate neutron stars one needs supercomputing: Pilot project (500.000 CPUh) on Dutch supercomputer Cartesius
  [https://userinfo.surfsara.nl/systems/cartesius]
- We thank Helvi Witek and Elias Most for help with the code

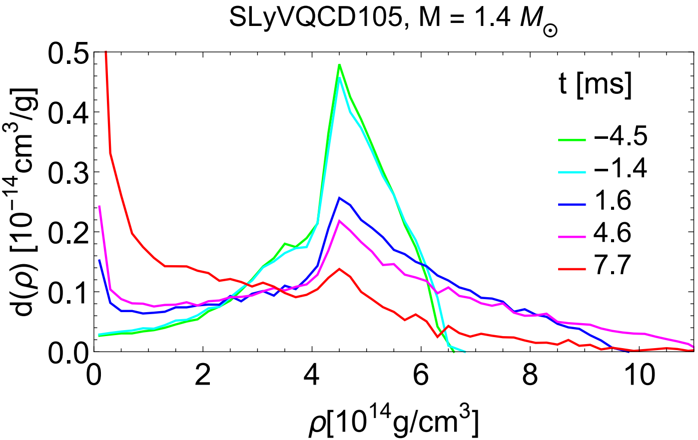
Power spectral densities of gravitational waves

- At high mass, immediate collapse to a black hole induced by the transition to quark matter
- At lower mass, remnant is hypermassive neutron star: power spectral density of the GW carries the imprint of the EoS



- Holographic EoSs predict low frequencies f_2 of the strongest peak
- Signal will be visible at advanced LIGO for nearby mergers

Density distributions



Evolution of density in the merger: no quark matter produced (outside possible horizon): transition at $\sim 17 \times 10^{14} g/cm^3$

Conclusions

- Gauge/gravity duality (combined with other approaches) is useful to study dense QCD
- D3-D7 and V-QCD predict strong first order transitions: no quark matter cores
- Using V-QCD with simple approximations, many details work really well:
  - ✓ Precise fit of lattice thermodynamics at $\mu \approx 0$
  - ✓ Extrapolated EoS for cold quark matter reasonable
  - ✓ Simultaneous model for nuclear and quark matter
  - ✓ Stiff EoS for nuclear matter
- Predictions for gravitational wave spectrum in neutron star mergers $\Longrightarrow$ new connection between holography and experiment!
- Ongoing work: transport in dense quark matter

Extra slides

V-QCD at finite T and μ: model for quark matter

Two bulk scalars: $\lambda \leftrightarrow \mathrm{Tr}F^2$ ($\lambda \approx g^2 N_c$ near boundary), $\tau \leftrightarrow \bar{q}q$

$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g} \left[R - \frac{4}{3}\frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$

$$-N_f N_c M^3 \int d^5x \; V_{f0}(\lambda) e^{-\tau^2}$$

$$\times \sqrt{-\det(g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab})}$$

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

[Alho, Kajantie, Kiritsis, MJ, Tuominen arXiv:1210.4516;
Alho, Kajantie, Kiritsis, MJ, Rosen, Tuominen arXiv:1312.5199]

Effective model: choose potentials by comparing to QCD data

- Many potentials V_g, V_{f0}, w, κ – however need to be “simple” functions – still lot of predictivity!
- Constrained asymptotically by properties of QCD
- Remaining degrees of freedom fitted to lattice data

Homogeneous nuclear matter in V-QCD

Baryons in the probe limit: consider full brane action
$S = S_{\text{DBI}} + S_{\text{CS}}$ where

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

$$S_{\text{DBI}} = -\frac{1}{2} M^3 N_c \, \mathbb{T}r \int d^5x \, V_{f0}(\lambda) e^{-\tau^2} \left(\sqrt{-\det \mathbf{A}^{(L)}} + \sqrt{-\det \mathbf{A}^{(R)}} \right)$$
$$\mathbf{A}_{MN}^{(L/R)} = g_{MN} + \delta_M^r \delta_N^r \kappa(\lambda) \tau'(r)^2 + \delta_{MN}^{rt} w(\lambda) \Phi'(r) + w(\lambda) F_{MN}^{(L/R)}$$

gives the dynamics of the solitons (will be expanded in $F^{(L/R)}$) and

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

sources the baryon number for the solitons

- Extra parameter, $b > 1$, to ensure regularity of solutions

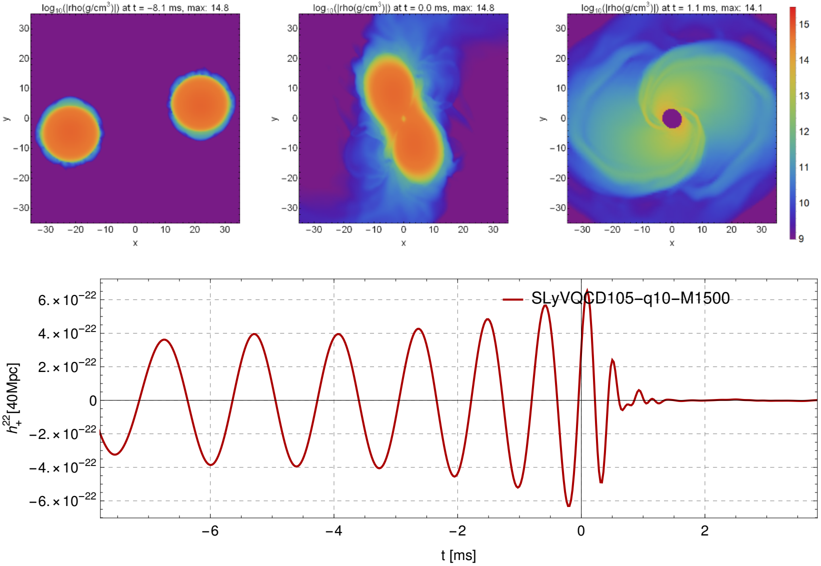
Set $N_f = 2$ and consider the homogeneous SU(2) Ansatz

[Rozali, Shieh, Van Raamsdonk, Wu]

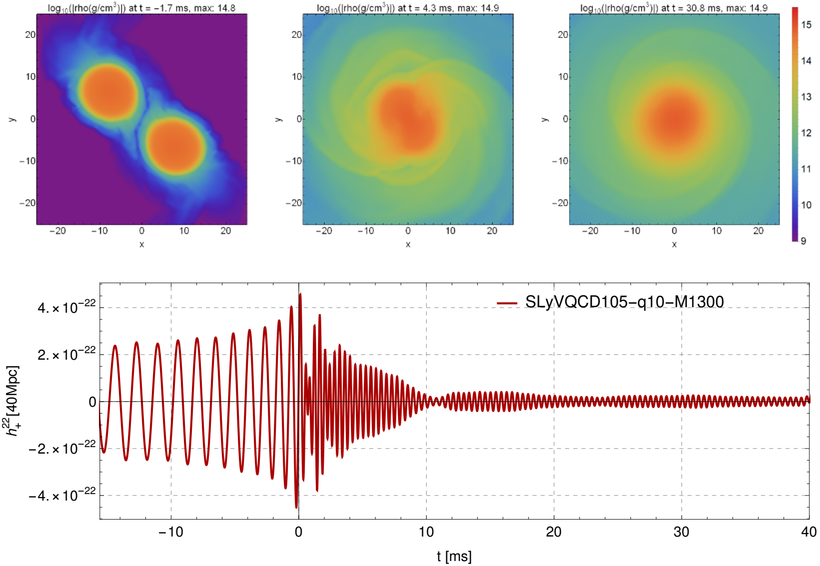
$$A_L^i = -A_R^i = h(r)\sigma^i$$

[Ishii, MJ, Nijs, arXiv:1903.06169]

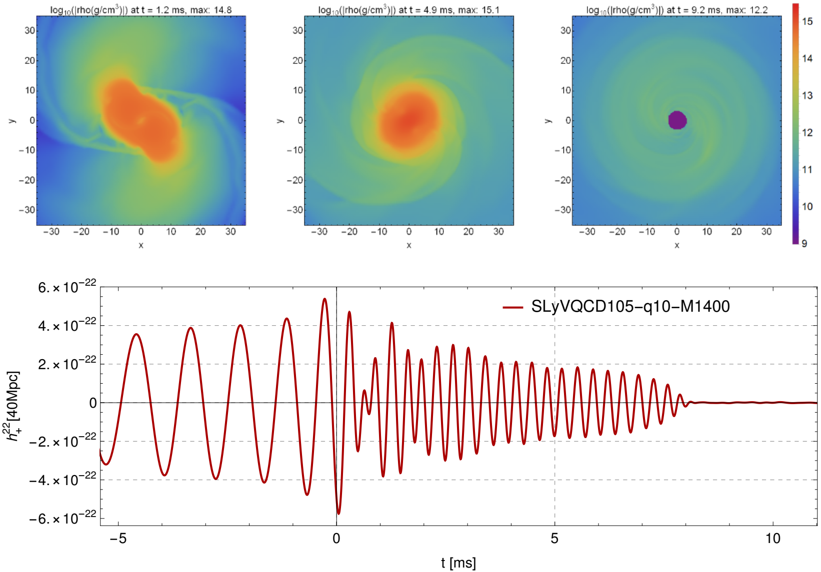
High mass binary



Low mass binary



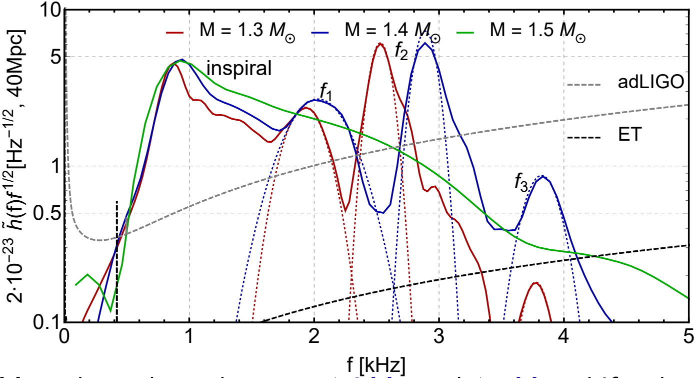
Intermediate mass binary



Power Spectral Density: Mass dependence

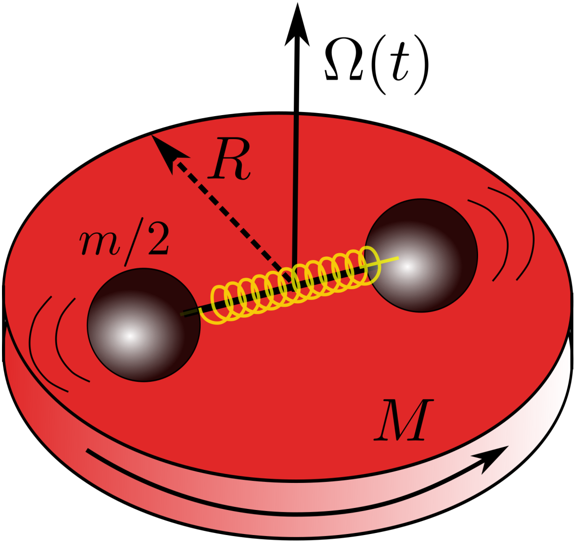
PSD of the gravitational waveform carries information on

- Initial conditions (masses, spins)
- EoS (mostly the high frequency post-merger part)



- Mass dependence between $1.3M_\odot$ and $1.4M_\odot$: shifts the characteristic frequencies f_1 and f_2
- f_3 peak potentially accessible by 3rd generation detectors

Mechanical toy model



[Takami, Rezzolla, Baiotti arXiv:1412.3240]