Holographic Dense QCD and Neutron Star Mergers

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POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Gauge Topology, Flux Tubes and Holographic Models
Trento – 26 May 2022

[Tuna Demircik, Christian Ecker, MJ arXiv:2112.12157]
[Samuel Tootle, Christian Ecker, Konrad Topolski, Tuna Demircik, MJ, Luciano Rezzolla arXiv:2205.05691] + [earlier work]

National Research Foundation of Korea

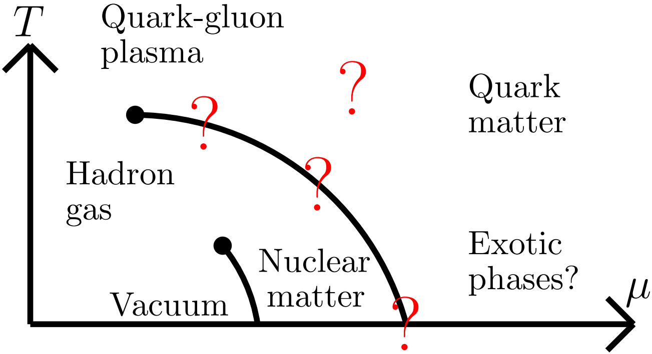
STRONG 2020

Outline

1. Introduction and motivation
2. Dense QCD matter in V-QCD
   - Dense holographic quark matter
   - Dense holographic nuclear matter
3. "Hybrid" equations of state
   - Model at finite temperature and density
4. Application to neutron star mergers
   - Production of quark matter

1. Introduction

The QCD phase diagram



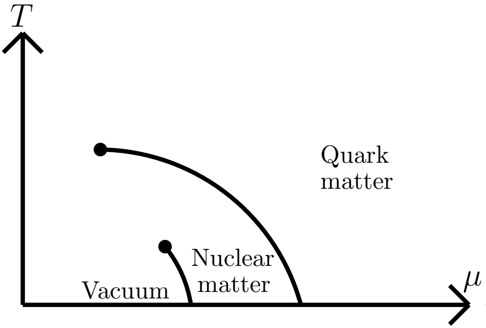
Focus in this talk: phases at high density

- Nuclear matter: dense liquid of protons and neutrons – density $\gtrsim$ density of large nuclei
- Quark matter: densely packed phase of free quarks and gluons

Laboratory experiments challenging ($T_{QCD} \sim 10^{12}$ K), in particular at high density – lots of effort

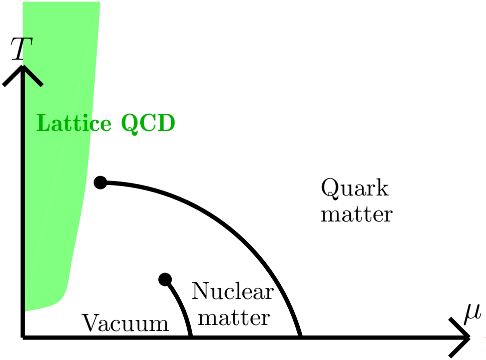
- Recent and future progress: LHC, RHIC, FAIR, NICA, ...

Theoretical results for the phase diagram



Theoretical results for the phase diagram

- Lattice data only available at zero/small chemical potentials



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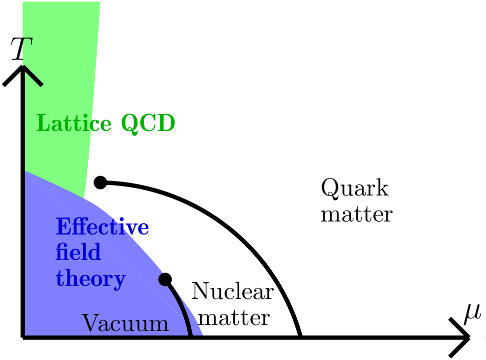
- Effective field theory works at small densities



Theoretical results for the phase diagram

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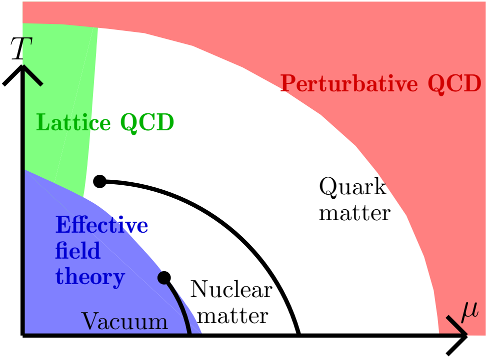
- Effective field theory works at small densities
- Perturbative QCD: only at high densities and temperatures



Theoretical results for the phase diagram

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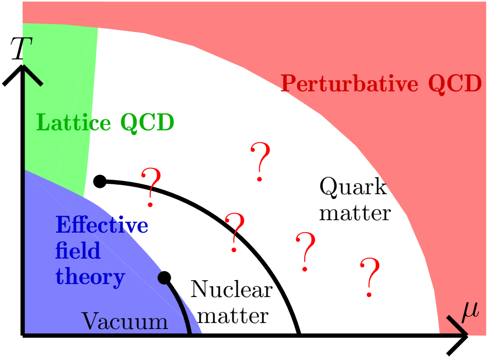
- Perturbative QCD: only at high densities and temperatures
- Open questions at intermediate densities



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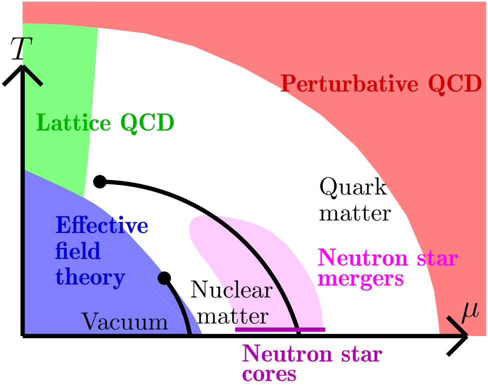
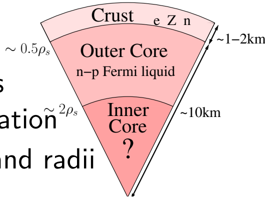


1. Improving theoretical predictions important!
2. Incoming experimental data from neutron star measurements!
3. White region strongly coupled $\Rightarrow$ use holography?

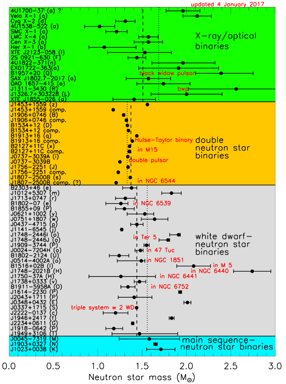


Neutron stars: extremely dense cold QCD matter

- Tolman-Oppenheimer-Volkoff (TOV) equations map equation of state (EoS) to mass-radius relation
- 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: $M_{\max} \gtrsim 2M_\odot$ [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

Modeling dense QCD using holography?

Plenty of studies in the literature, using various different models (D3-D7, Witten-Sakai-Sugimoto, ...)

[Kobayashi, Mateos, Matsuura, Myers, Thomson; ...
Bigazzi, Cotrone, Mas, Mayerson, Tarrio ... Horigome, Tanii;...]

Recently several studies in connection to neutron star physics

- Using D3-D7 for quark matter + exotic phases
  [Hoyos, Rodriguez, Jokela, Vuorinen; Bitaghsir Fadafan, Cruz Rojas, Evans]
- Witten-Sakai-Sugimoto, including nuclear matter
  [Kovensky, Poole, Schmitt]
- In bottom-up models (Einstein-Maxwell-dilaton, enhanced hard-wall models)
  [Mamani, Flores, Zanchin; Ghoroku, Kashiwa, Nakano, Tachibana, Toyoda;
  Bartolini, Gudnason, Leutgeb, Rebhan]
- Various studies using the V-QCD model (this talk + Edwan Preau's talk on Monday)

2. Dense holographic QCD matter

(Quark Matter in) 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 [See Edwan Preau's talk]

- Bottom-up, but trying to follow principles from string theory as closely as possible [MJ, Kiritsis arXiv:1112.1261]

The model is obtained through a fusion of two building blocks:

1. IHQCD: model for glue inspired by string theory [Gürsoy, Kiritsis, Nitti; Gubser, Nellore]
2. Adding flavor and chiral symmetry breaking via space filling $D4 - \overline{D4}$ branes and Sen-like tachyon condensation [Klebanov,Maldacena; Bigazzi,Casero,Cotrone,Iatrakis,Kiritsis,Paredes]

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

$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g}\left[R - \frac{4}{3}\frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda)\right]$$
$$-N_f N_c M^3 \int d^5x\, V_{f0}(\lambda) e^{-\tau^2}\sqrt{-\det(g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab})}$$

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

Effective model, many potentials V_g, V_{f0}, w, κ – essential to fix them by comparing to QCD data

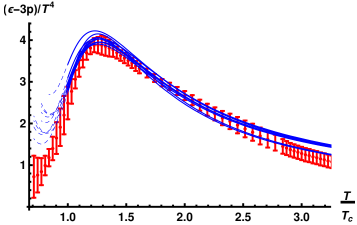
Constraining the model at $\mu \approx 0$

Stiff fit to lattice data near $\mu = 0$ (many parameters, but results insensitive to them) [Gürsoy, Kiritsis, Mazzanti, Nitti arXiv:0903.2859; MJ, Jokela, Remes, arXiv:1809.07770]

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

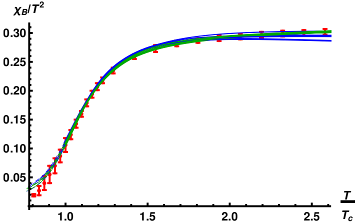
Interaction measure, 2+1 flavors

Lattice data: Borsanyi et al. arXiv:1309.5258



Baryon number susceptibility

Lattice data: Borsanyi et al. arXiv:1112.4416

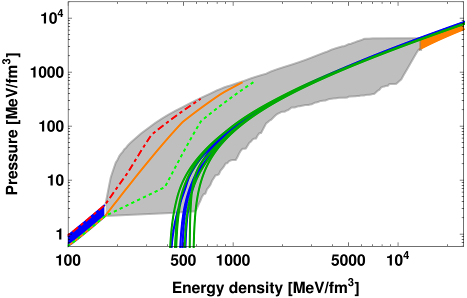


Extrapolated EoSs of cold quark matter

The V-QCD cold quark matter result compares nicely to known constraints:

[MJ, Jokela, Remes, arXiv:1809.07770]

- Band of allowed equations of state (EoSs) (gray, polytropic interpolations)
- Stiff, intermediate, and soft nuclear EoSs
  [Hebeler, Lattimer, Pethick, Schwenk arXiv:1303.4662]



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]

Nuclear matter in holographic models

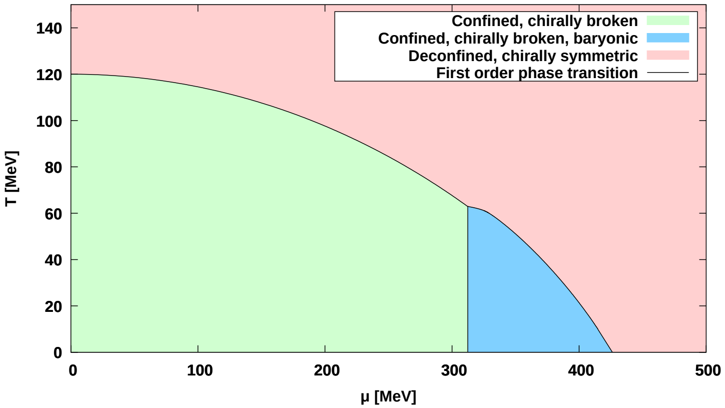
Each baryon maps to a solitonic "instanton" configuration of gauge fields in the bulk [Witten; Gross, Ooguri; ...]
[Talk of Edwan Preau]

- 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; Kim, Sin, Zahed; Preis, Schmitt;...]
  - Baryonic phase has soliton crystals with nontrivial transitions
    [Kaplunovsky, Melnikov, Sonnenschein; ...]
    [MJ, Kaplunovsky, Sonnenschein]
- Solution constructed in "hard-wall" models [Pomarol, Wulzer]
  - and also in V-QCD [See Edwan's talk]
- This talk: instanton solutions are hard...set $N_f = 2$ and try first a simple approximation scheme (homogeneous), reasonable at high densities?
  [Rozali, Shieh, Van Raamsdonk, Wu arXiv:0708.1322]

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

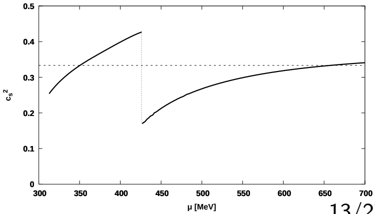
[Li,Schmitt,Wang arXiv:1505.04886; Elliot-Ripley,Sutcliffe,Zamaklar arXiv:1607.04832]
[Kovensky, Poole, Schmitt, arXiv:2111.03374]

Phase diagram at zero quark mass



Stiff EoS (high c_s^2) in the nuclear matter phase ⇒ helps to pass the bounds from neutron star observations!

[Ishii, MJ, Nijs, arXiv:1903.06169]



3. Hybrid EoSs

Fixing the shortcomings

We want to use our EoS in neutron star merger simulations, however there are some issues:

1. Our (homogeneous) approach for nuclear matter only works at high densities
2. Temperature dependence is trivial in the confined phases, and therefore also for holographic nuclear matter
   - This is a large N_c issue, T dependence would arise from loops

Solutions:

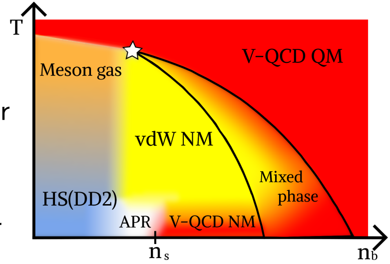
1. At low densities, use "traditional" nuclear theory results (e.g. chiral effective theory)
2. Since no reliable results available, borrow T dependence from basically the simplest reasonable model
   - $\Rightarrow$ use van der Waals (vdW) gas (protons, neutrons, electrons)

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

[Jokela, MJ, Nijs, Remes arXiv:2006:01141]

[Demircik, Ecker, MJ arXiv:2112.12157]

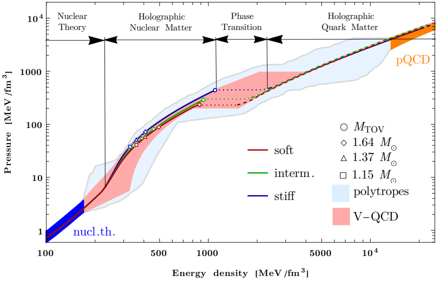
Overview of our approach

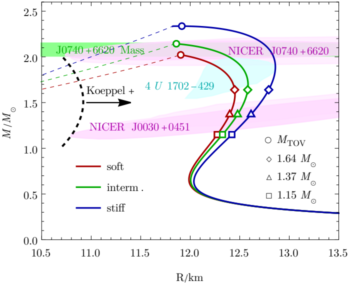


- Use V-QCD for quark matter and cold dense nuclear matter (+electrons and photons)
- Van der Waals model extrapolates dense V-QCD nuclear matter to finite T
- At low density, use Hempel-Schaffner-Bielich model with DD2 interactions (HS(DD2))
- At medium density, use APR cold EoS (using only HS(DD2) would lead to issues with neutron star observations)
- Add QCD mesons to HS(DD2), important to describe the critical point

[Demircik, Ecker, MJ arXiv:2112.12157]

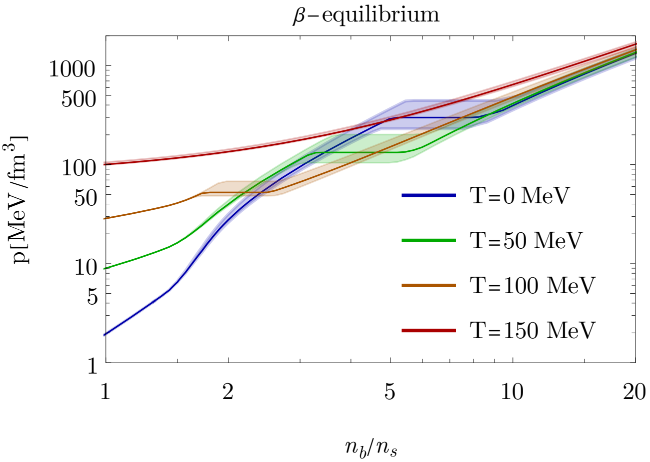
- Three choices of EoSs: soft, intermediate, and stiff $\leftrightarrow$ the degrees of freedom of V-QCD left free by fit to lattice data
- Compared to bands of all feasible cold matter EoS: Without and with holography





- Plug EoSs in TOV: neutron star $M(R)$ curves (left plot)
- Compares well with mass/radius observations

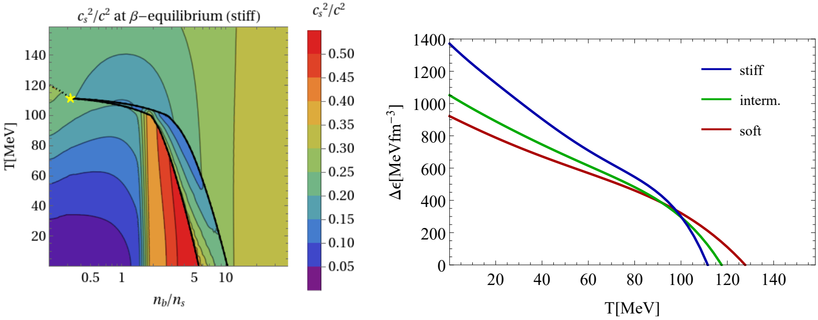
Results: EoS at Finite T



- Bands: variation of the V-QCD model (soft/intermediate/stiff)
- With increasing T, weaker transition at lower pressure

[Demircik, Ecker, MJ arXiv:2112.12157]

Results: phase diagram and critical point

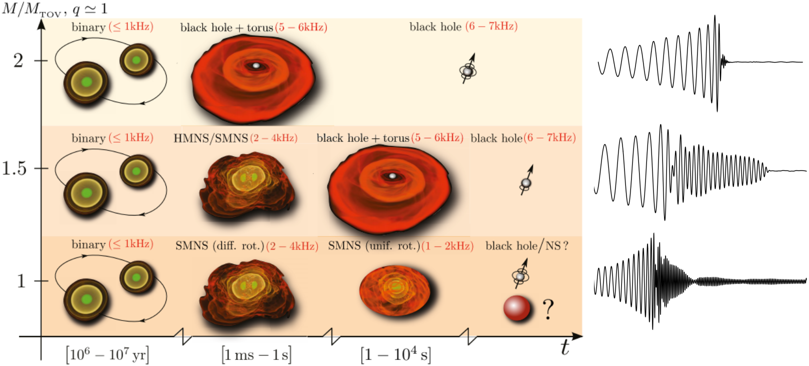


- Low T: strong 1st order nuclear to quark matter transition and mixed phase
- High T: weak first order transition $\approx$ crossover
- Critical point with $110 \text{ MeV} \lesssim T_c \lesssim 130 \text{ MeV}$

4. (Holographic) Neutron Star Mergers

Neutron star mergers

- Significant sources of gravitational radiation
- Microscopic properties of dense matter encoded in GW and EM signal



[picture: Baiotti, Rezzola arXiv:1607.03540]

One good event (GW170817) and a few other events already observed! [LIGO/Virgo, arXiv:1710.05832]

Simulating Binary Neutron Star Mergers

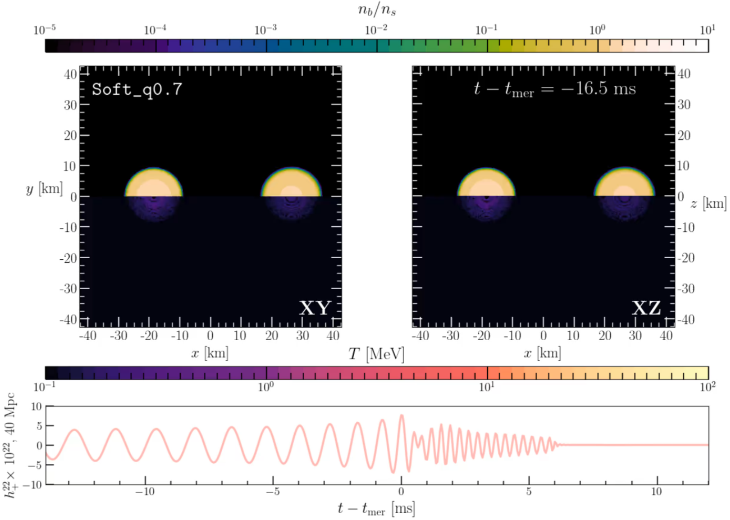
Have to solve the 3+1D General Relativistic hydrodynamics equations:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G_N T_{\mu\nu}\,, \quad \nabla_\mu T^{\mu\nu} = 0\,, \quad \nabla_\mu J^\mu = 0$$

with initial spacetime and fluid distribution modelling a NS binary system

- Equation of State $p = p(n_b, T, Y_e)$ as input required
- Spectral code Frankfurt University/Kadath (FUKA) for initial data
  [Papenfort, Tootle, Grandclement, Most, Rezzolla arXiv:2103.09911]
- Frankfurt/Illinois (FIL) code for binary evolution with tabulated EoS
  [Most, Papenfort, Rezzolla arXiv:1907.10328]
- Implemented in the Einstein Toolkit
  [http://einsteintoolkit.org]
- Need supercomputing: Project BNSMIC with 100 million core-hours on HAWK at the High-Performance Computing Center Stuttgart

Simulations with parameters chosen to match with GW170817

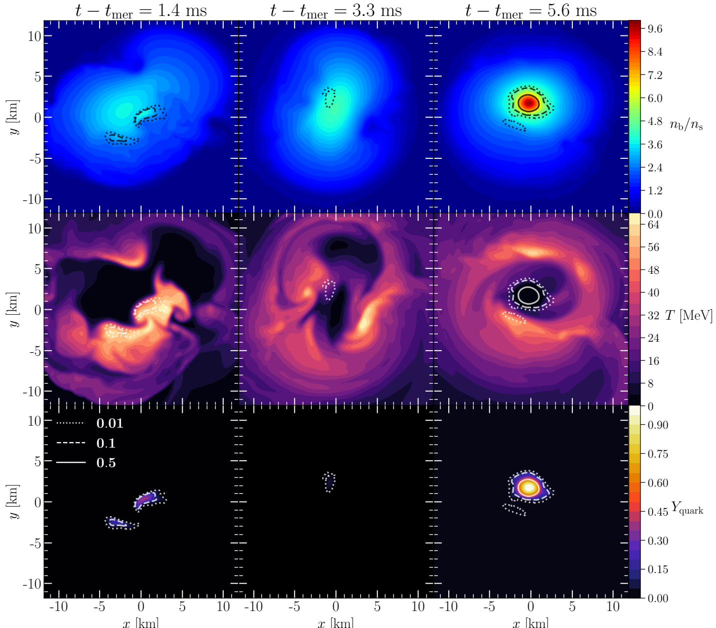


Soft EoS with $M_1/M_2 = 0.7$

[Tootle, Ecker, Topolski, Demircik, MJ, Rezzolla arXiv:2205.05691]

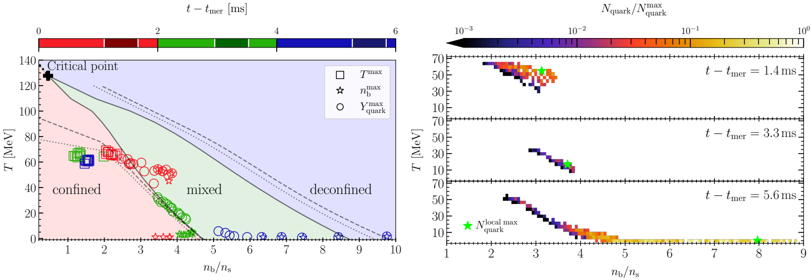
[Movie by K. Topolski]

Hot, Warm and Cold Quarks



Phase Diagram and Quark Formation

- Hot quarks: in the hottest region at early times
- Warm quarks: at intermediate times due to complicated post-merger dynamics
- Cold quarks: in the densest core at late times

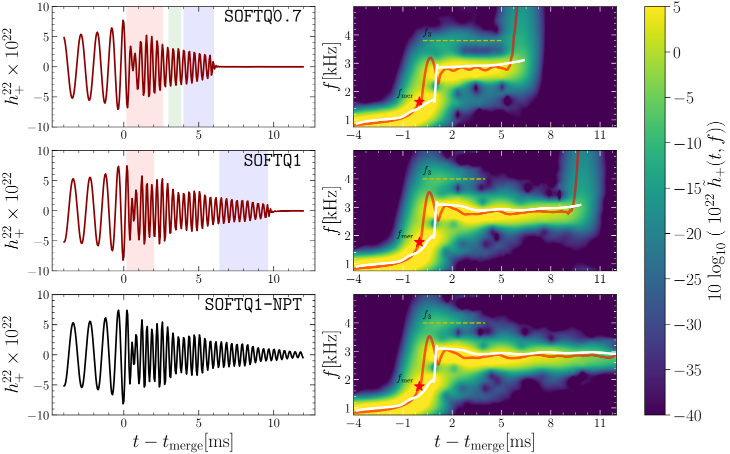


- Intermediate and stiff EoSs lead to significantly suppressed quark formation

[Tootle, Ecker, Topolski, Demircik, MJ, Rezzolla arXiv:2205.05691]

details

Imprint on Gravitational Waves



- Most significant signature of the phase transition: short lifetime of remnant
- Early collapse with soft EoS in tension with electromagnetic signal from GW170817 $\Rightarrow$ a new constraint for the EoS

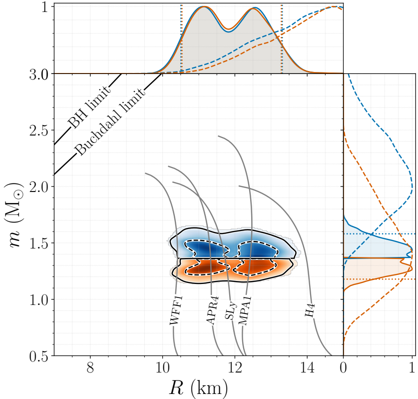
Conclusions

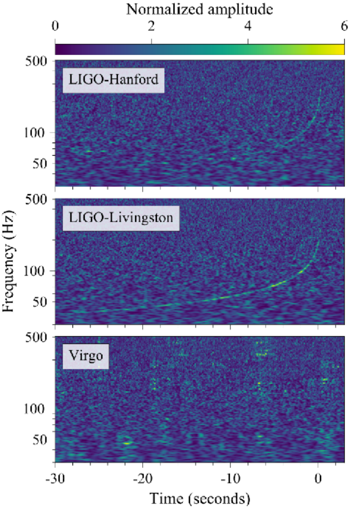
- Gauge/gravity duality (combined with other approaches) is useful to study dense QCD
- Using V-QCD with simple approximations, many details work really well:
  - ✓ Precise fit of lattice thermodynamics at $\mu \approx 0$
  - ✓ Extrapolated EoS for cold quark matter reasonable
  - ✓ Simultaneous model for nuclear and quark matter
  - ✓ Stiff EoS for nuclear matter
- We constructed an EoS at finite temperature and density using V-QCD (+other models)
  - Predictions for the critical point
  - Input for merger simulations
- State-of-the-art binary neutron star merger simulations with our EoS
  - Production of hot, warm and cold quark matter

Backup slides

LIGO/Virgo constraints from GW170817

- The tidal deformability Λ measures how strongly neutron stars deform in gravitational field
- Inspiral phase GW signal gives an upper bound $\Lambda \lesssim 580$
- Implies a rough upper bound for neutron star radius: $R \lesssim 13.5$ km

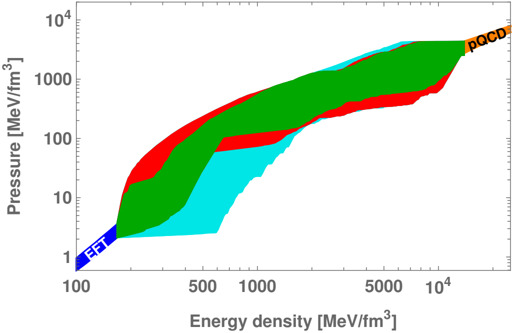




Constraints on equation of state (EoS)

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

1. Mass bound $M_{\mathrm{max}} > 2M_{\odot}$ (excludes cyan area)
2. LIGO constraint from GW170817: (excludes red area)



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

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

Recent progress on dense holographic QCD

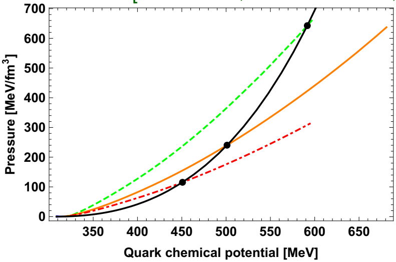
For quark matter, use D3-D7 top down model: $\epsilon = 3p + \frac{\sqrt{3}m^2}{2\pi}\sqrt{p}$

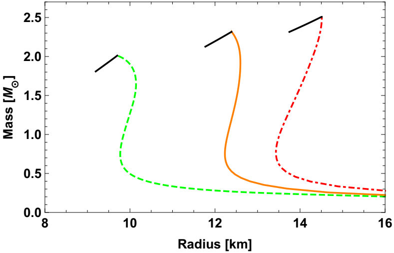
[Karch, O'Bannon, arXiv:0709.0570]

- $\mathcal{N} = 4$ 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 + color superconductivity

[Bitaghsir Fadafan, Cruz Rojas, Evans, arXiv:1911.12705; 2009.14079]

- Possibility of an intermediate χSB deconfined phase
- Stiffer holographic equations of state (high speed of sound)
- Quark matter cores

Using Einstein-Maxwell-dilaton for quark matter

[Mamani, Flores, Zanchin, arXiv:2006.09401]

(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:1108.6139, 1404.3474]

This talk: towards more realistic model of quark matter?

Ansatz for potentials, $(x = 1)$

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

$$V_{f0}(\lambda) = W_0 + W_1\lambda + \frac{W_2\lambda^2}{1+\lambda/\lambda_0} + W_{\rm IR}\, e^{-\lambda_0/\lambda}(\lambda/\lambda_0)^2$$

$$\frac{1}{w(\lambda)} = w_0\left[1 + \frac{w_1\lambda/\lambda_0}{1+\lambda/\lambda_0} + \bar{w}_0\, e^{-\lambda_0/\lambda w_s}\frac{(w_s\lambda/\lambda_0)^{4/3}}{\log(1+w_s\lambda/\lambda_0)}\right]$$

$$V_1 = \frac{11}{27\pi^2}\ , \qquad V_2 = \frac{4619}{46656\pi^4}$$

$$W_1 = \frac{8 + 3\,W_0}{9\pi^2}\ ; \qquad W_2 = \frac{6488 + 999\,W_0}{15552\pi^4}$$

Fixed UV/IR asymptotics $\Rightarrow$ fit parameters only affect details in the middle

Constraining the potentials

In the UV ($\lambda \to 0$):

- UV expansions of potentials matched with perturbative QCD beta functions $\Rightarrow$ asymptotic freedom and logarithmic flow of the coupling and quark mass, as in QCD

[Gürsoy, Kiritsis arXiv:0707.1324; MJ, Kiritsis arXiv:1112.1261]

In the IR ($\lambda \to \infty$): various qualitative constraints

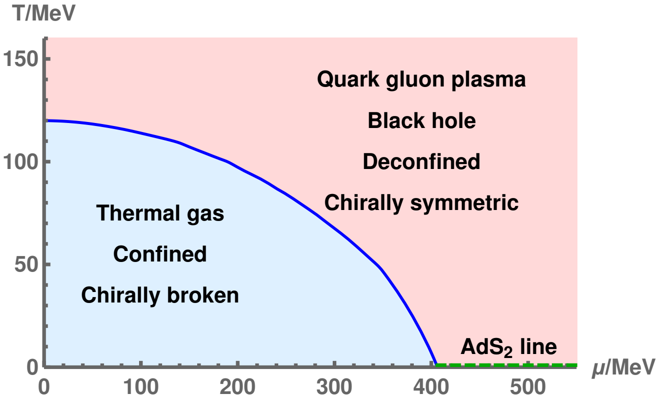
- Linear confinement, discrete glueball & meson spectrum, linear radial trajectories
- Existence of a "good" IR singularity
- Correct behavior at large quark masses
- Working potentials often string-inspired power-laws, multiplied by logarithmic corrections (i.e, first guesses usually work!)

[Gürsoy, Kiritsis, Nitti arXiv:0707.1349; MJ, Kiritsis arXiv:1112.1261; Arean, Iatrakis, MJ, Kiritsis arXiv:1309.2286, arXiv:1609.08922; MJ arXiv:1501.07272]

Final task: determine the potentials in the middle, $\lambda = \mathcal{O}(1)$

- Qualitative comparison to lattice/experimental data

Phase diagram with quark matter



- With quark matter only, expected phase diagram
- Cold QM equation of state (EoS) and location of the $T = 0$ phase transition agree with contraints

Homogeneous nuclear matter in V-QCD

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

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

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

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

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

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 arXiv:0708.1322]

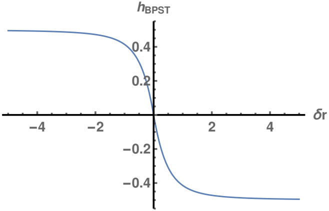
$$A^i_L = -A^i_R = h(r) \sigma^i$$

[Ishii, MJ, Nijs, arXiv:1903.06169]

Discontinuity and smeared instantons

With the homogeneous Ansatz $A_i^a(r) = h(r)\delta_i^a$ baryon number vanishes for any smooth $h(r)$:

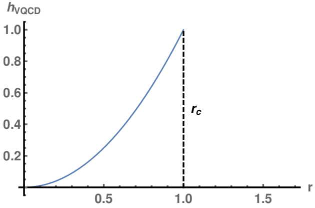
$$N_b \propto \int dr \frac{d}{dr} [\mathrm{CS-term}] = 0$$



How can this issue be avoided?

- Smearing the BPST soliton in singular Landau gauge:

$$\langle A_i^a \rangle \sim \int \frac{d^3\mathrm{x} \;\; \eta_{i4}^a \; \delta r}{(\delta r^2 + \mathrm{x}^2 + \rho^2)(\delta r^2 + \mathrm{x}^2)}$$
$$\sim -\frac{\delta_i^a \; \delta r}{\sqrt{\delta r^2 + \rho^2} + |\delta r|}$$



- This suggests a solution: introduce a discontinuity in $h(r)$ at $r = r_c$
- The discontinuity sources nonzero baryon charge!

Van der Waals model

Ideal gas of protons, neutrons and electrons with

- Excluded volume correction for nucleons

$$p_{\rm ex}(T,\{\mu_i\}) = p_{\rm id}(T,\{\tilde\mu_i\})$$
$$\tilde\mu_i = \mu_i - v_0 p_{\rm ex}(T,\{\mu_i\}) \qquad (i = p,\, n)$$

  $v_0 \sim$ volume of one nucleon

- (Mostly) attractive potential term to match with (APR and) V-QCD at $T = 0$

$$p_{\rm vdW}(T,\{\mu_i\}) = p_{\rm ex}(T,\{\mu_i\}) + \Delta p(\{\mu_i\})$$

  schematically:

$$\Delta p(\{\mu_i\}) = p_{\rm V-QCD}(T=0,\{\mu_i\}) - p_{\rm ex}(T=0,\{\mu_i\})$$

[Rischke, Gorenstein, Stoecker, Greiner, Z Phys. C 51, 485 (1991)]

[Vovchenko, Gorenstein, Stoecker, arXiv:1609.03975]

[Vovchenko, Motornenko, Alba, Gorenstein, Satarov, Stoecker, arXiv:1707.09215]

Hempel-Schaffner-Bielich DD2 model

A widely used general purpose model for the EoS

- Parameters: temperature, density, charge fraction Y_q

Combines two approaches (in thermodynamically consistent way):

- For $n < n_s$, statistical method with excluded volume corrections and interactions, including light and heavy nuclei

  [Hempel, Schaffner-Bielich, arXiv:0911.4073]

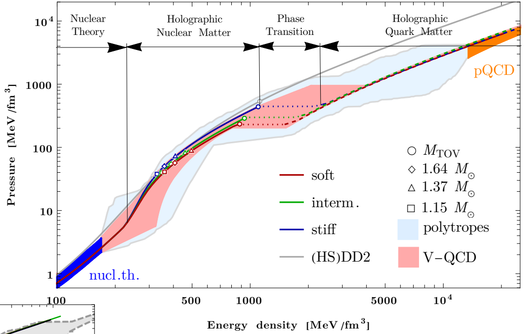
- For $n > n_s$, relativistic mean field theory of nucleons interacting with σ, ρ, and ω mesons (DD2)

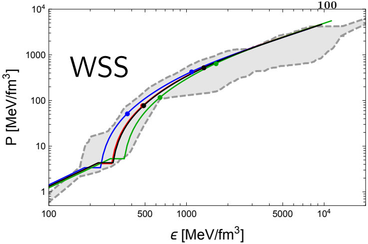
  [Typel, Ropke, Klahn, Blaschke, Wolter, arXiv:0908.2344]

- Variations in model parameters give rise to the band
- Same (holographic) model for dense nuclear and quark matter phases!

Without and with holography

[Ecker, MJ, Nijs, van der Schee arXiv:1908.03213] [Jokela, MJ, Nijs, Remes arXiv:2006:01141]





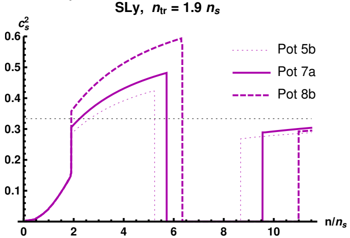
WSS with isospin asymmetry and holographic crust region

- Similar EoS for dense nuclear matter as V-QCD!

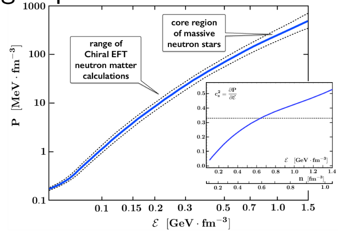
[Kovensky, Poole, Schmitt arXiv:2111.03374]

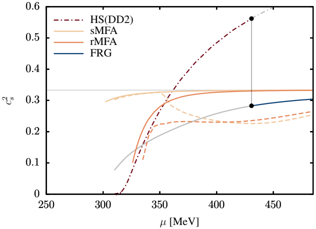
Speed of sound and comparison to FRG

Speed of sound (squared) as a function of density



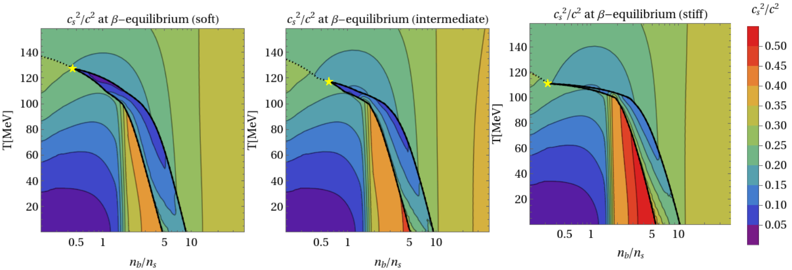
- Relatively mild dependence on model parameters
- Similar predictions as with the functional renormalization group method!





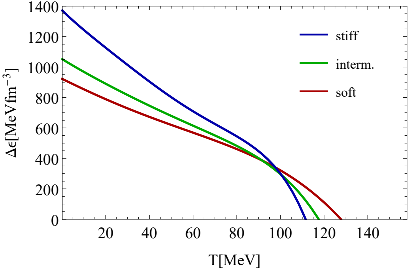
[Drews, Weise arXiv:1610.07568; Otto, Oertel, Schaefer arXiv:1910.11929]

Results: critical point



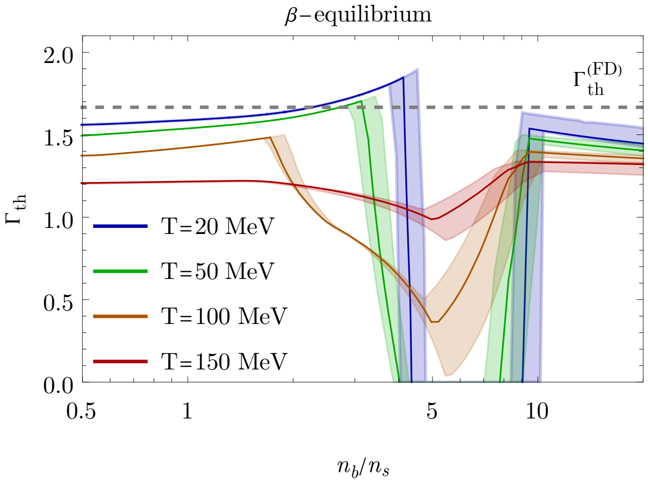
$110\ \mathrm{MeV} \lesssim T_c \lesssim 130\ \mathrm{MeV}$

$0.3 n_s \lesssim n_c \lesssim 0.6 n_s$



Critical point is determined by fitting the latent heat in the region of strong phase transition and extrapolating

Results: thermal index



$$\Gamma_{\mathrm{th}}(n_b, T) = 1 + \frac{p(n_b,T)-p(n_b,0)}{e(n_b,T)-e(n_b,0)}$$

- Values in expected range
- Low values in the mixed phase

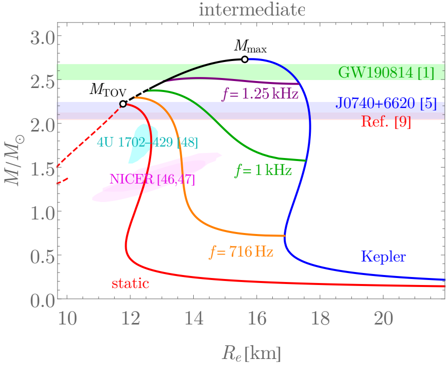
Rapidly spinning holographic neutron stars

GW190814: LIGO/Virgo observed a merger of a $23M_\odot$ black hole with a $2.6M_\odot$ compact object

[arXiv:2006.12611]

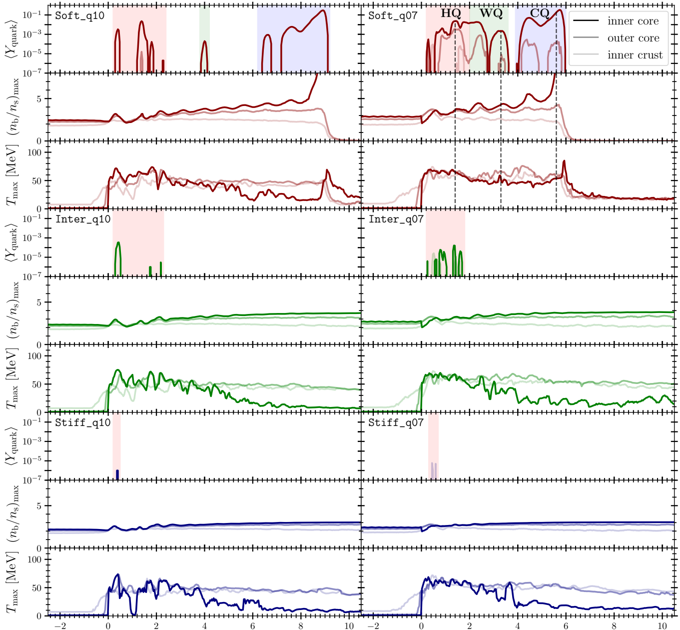
- $2.6M_\odot$ falls in the "gap": a black hole or a neutron star?

- Holographic EoSs easily compatible with the neutron star interpretation
- However requires fast rotation, $f \gtrsim 1$ kHz



[Demircik, Ecker, MJ, arXiv:2009.10731]

Details on quark formation



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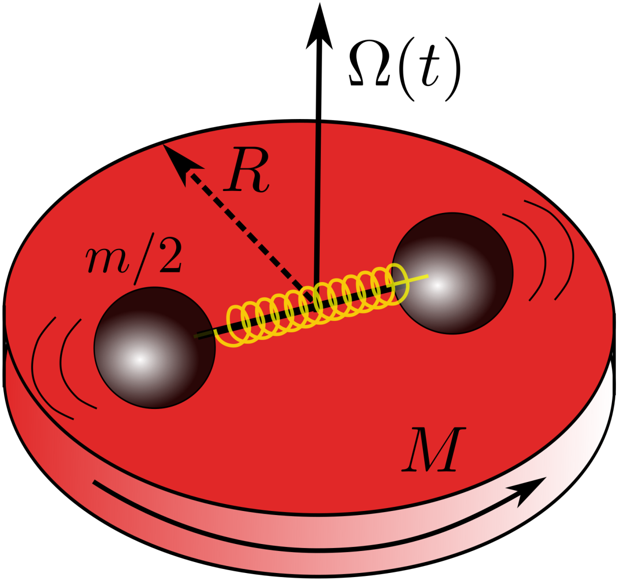
Mechanical Toy Model



[Takami, Rezzolla, Baiotti arXiv:1412.3240]