Holographic approach to dense QCD and neutron star mergers

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

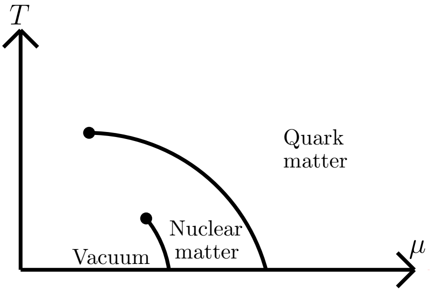
NRF
National Research Foundation of Korea

Outline

1. Introduction and motivation
2. Dense QCD matter in V-QCD
   - Both quark and nuclear matter
3. "Hybrid" Equations of State (EoSs)
   - Combining V-QCD with other approaches
   - Model at finite temperature and density
4. Application to neutron star mergers
   - Production of quark matter

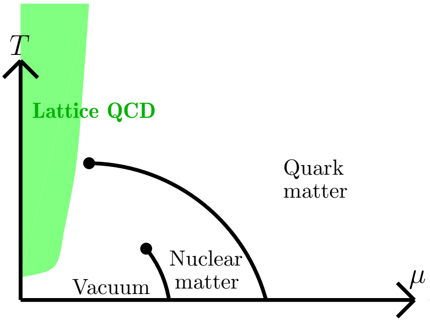
1. Introduction

QCD phase diagram: theoretical results



QCD phase diagram: theoretical results

- Lattice data only available at zero/small chemical potentials



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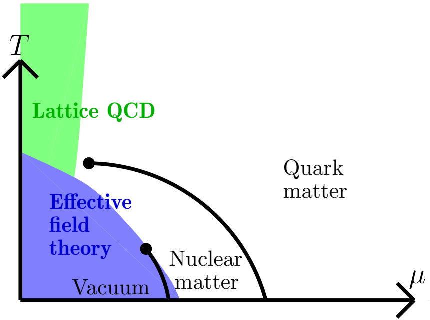

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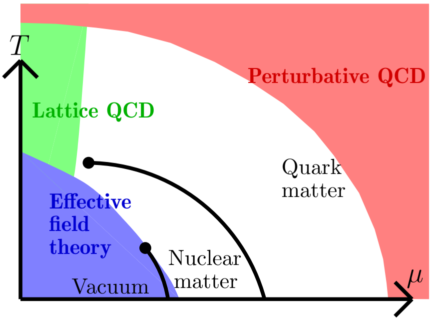
- Perturbative QCD: only at high densities and temperatures



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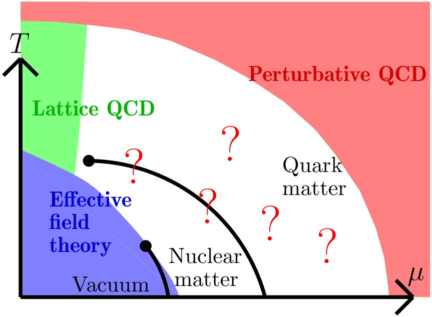

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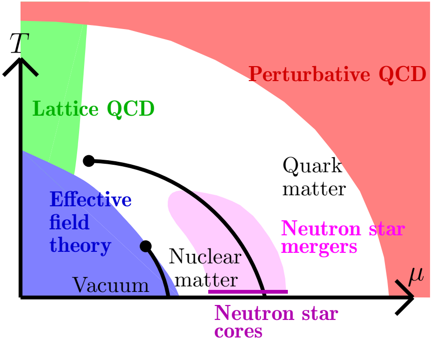

1. Improving theoretical predictions important!
2. Incoming experimental data from neutron star measurements!

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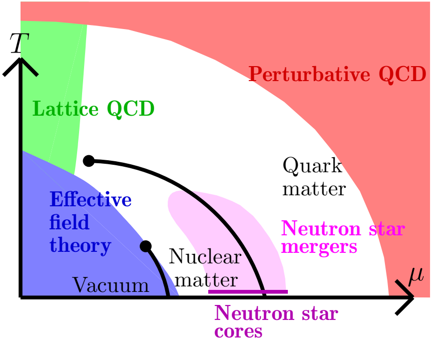


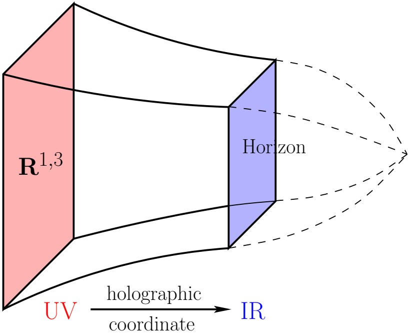
1. Improving theoretical predictions important!
2. Incoming experimental data from neutron star measurements!

White region strongly coupled $\Rightarrow$ use holography?

Interpolate between known results using holography?

Gauge/gravity duality for QCD

- Motivated by the original AdS/CFT correspondence for $\mathcal{N} = 4$ SYM
- Instead of conformality, confinement: non-AdS/non-CFT duality
- Field theory lives on the boundary of the 5D geometry



- Operators $O_i(x^\mu) \leftrightarrow$ classical bulk fields $\phi_i(x^\mu, r)$

$$Z_{\mathrm{grav}}(\phi_i|_{\mathrm{bdry}} = J_i(x^\mu)) = \int \mathcal{D}\, e^{iS_{QCD} + i\int d^4x J^i(x^\mu) O_i(x^\mu)}$$

  - E.g. $\bar{\psi}^j \psi^i \leftrightarrow \phi^{ij}$ $\quad T_{\mu\nu} \leftrightarrow g_{\mu\nu}$ $\quad J_\mu \leftrightarrow A_\mu$
- Thermodynamics of QCD $\leftrightarrow$ thermodynamics of a planar bulk black hole

2. Dense holographic QCD matter

Holographic V-QCD

A holographic model for QCD

- Bottom-up, but trying to follow principles from string theory closely [MJ, Kiritsis 1112.1261; Review MJ 2110.08281]

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 a D-brane setup [Klebanov,Maldacena; Bigazzi,Casero,Cotrone,Iatrakis,Kiritsis,Paredes]

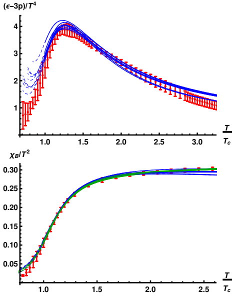
Two bulk scalars: $\lambda \leftrightarrow \mathrm{Tr}F^2$, $\tau \leftrightarrow \bar{q}q$

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

Effective model, many potentials V_g, V_{f0}, w, κ – essential to fix them by fitting QCD data $\to$ predictions for other observables

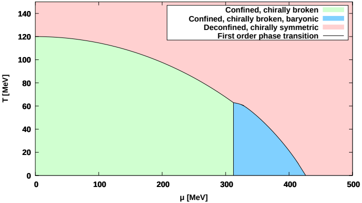
Quark matter:

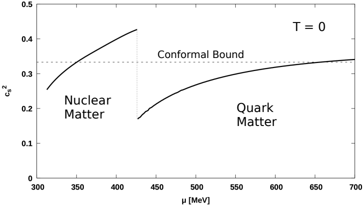
- Require agreement with confinement, asymptotic freedom ...
- (Good) fit to lattice data at $\mu \approx 0$
- Extrapolate to high μ and down to $T \approx 0$
- Extrapolated results consistent with pQCD and EFT! [MJ, Jokela, Remes, 1809.07770]



Nuclear matter:

- In holographic setups, baryons $\leftrightarrow$ solitons of gauge fields in the gravity dual [Talk and poster by Edwan Préau]
- However, solitons technically involved ... use a simple homogeneous approximation $\approx$ smeared solitons [Ishii, MJ, Nijs 1903.06169]
- Stiff EoS: "violation" of the conformal bound $c_s^2 = 1/3$!





3. Hybrid EoSs

Combining with other approaches

The V-QCD EoS as such is however not fully satisfactory:

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 for nuclear matter, use "traditional" nuclear theory results

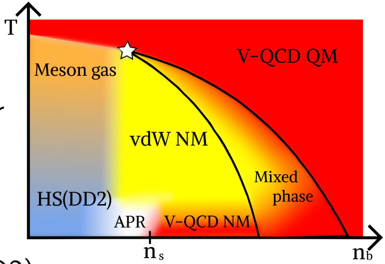
   ⇒ choose the Hempel-Schaffner-Bielich model with DD2 interactions (HS(DD2))

   [Typel et al. 0908.2344; Hempel, Schaffner-Bielich 0911.4073]
2. Since no reliable results available, borrow T dependence from basically the simplest reasonable model

   ⇒ use van der Waals (vdW) gas (protons, neutrons, electrons)

   [Ecker, MJ, Nijs, van der Schee 1908.03213]
   [Jokela, MJ, Nijs, Remes 2006:01141]
   [Demircik, Ecker, MJ 2112.12157]

Overview of the hybrid model

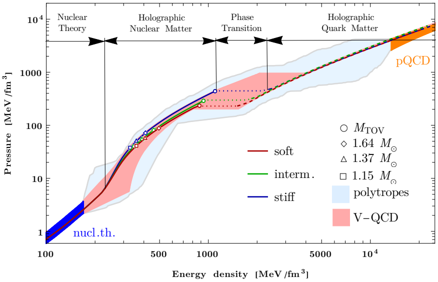


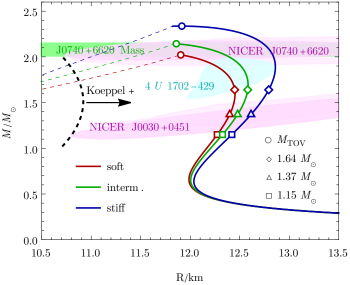
- V-QCD for quark matter and cold dense nuclear matter
- Van der Waals model extrapolates dense V-QCD nuclear matter to finite T
- At low density, choose HS(DD2)
- At medium density, use APR cold EoS (using only HS(DD2) would lead to tension with neutron star observations)
- Add QCD mesons to HS(DD2),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

[Demircik, Ecker, MJ 2112.12157]

Cold EoS and known constraints

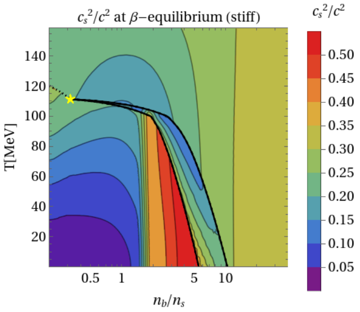
- Three choices of EoSs: soft, intermediate, and stiff $\leftrightarrow$ the degrees of freedom of V-QCD left free by fit to lattice data
- Compared to bands of all feasible cold matter EoS: Without and with holography

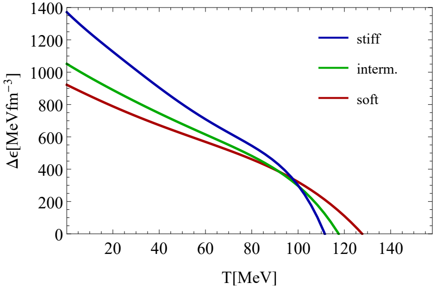




- Plug EoSs in TOV: neutron star $M(R)$ curves (left plot)
- Compares well with mass/radius observations

Results: phase transition 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
  $110\ \mathrm{MeV} \lesssim T_c \lesssim 130\ \mathrm{MeV}$
  $480\ \mathrm{MeV} \lesssim \mu_{bc} \lesssim 580\ \mathrm{MeV}$
- Close to results in other (simpler) holographic models
  [DeWolfe et al. 1012.1864; Knaute et al. 1702.06731; Critelli et al. 1706.00455]

4. (Holographic) Neutron Star Mergers

Simulating Binary Neutron Star Mergers

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

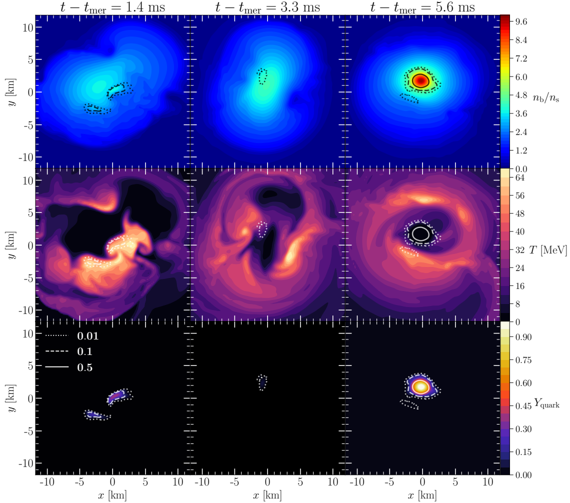
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G_N T_{\mu\nu} \,, \quad \nabla_\mu T^{\mu\nu} = 0 \,, \quad \nabla_\mu J^\mu = 0$$

with initial spacetime and fluid distribution modelling a NS binary system

- Equation of State $p = p(n_b, T, Y_e)$ as input – use V-QCD hybrid EoS
- Spectral code Frankfurt University/Kadath (FUKA) for initial data
  [Papenfort, Tootle, Grandclement, Most, Rezzolla 2103.09911]
- Frankfurt/Illinois (FIL) code for binary evolution with tabulated EoS
  [Most, Papenfort, Rezzolla 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

Hot, Warm and Cold Quarks

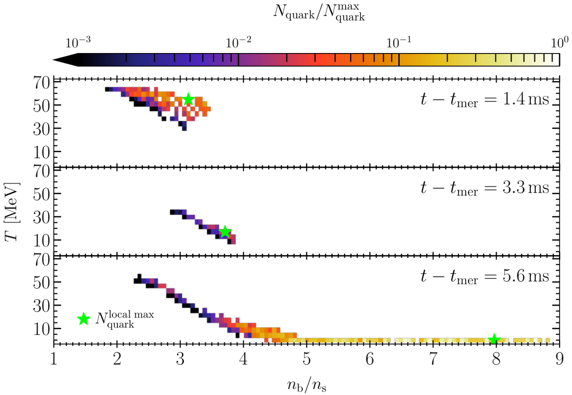
Simulations with parameters chosen to match with GW170817



Hypermassive neutron star after merger (soft EoS, $M_1/M_2 = 0.7$)

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

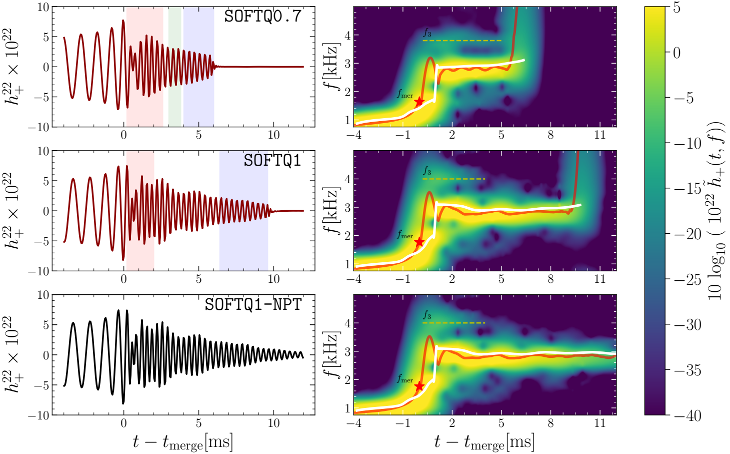
- Hot quarks: in the hottest region at early times
- Warm quarks: at intermediate times due to complicated post-merger dynamics
- Cold quarks: in the densest core at late times



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

details

Imprint on Gravitational Waves



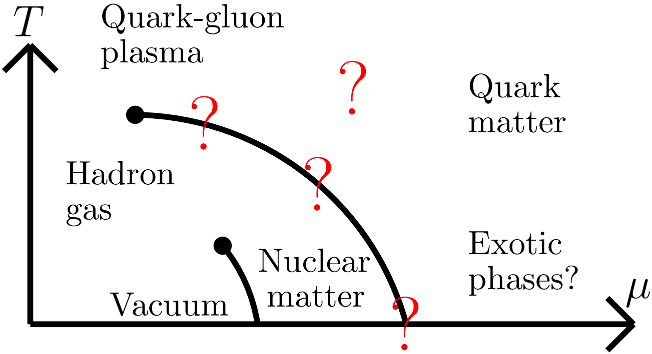
- Most significant signature of the phase transition: short lifetime of remnant
- Early collapse in tension with electromagnetic signal from GW170817 $\Rightarrow$ constrains the EoS – soft model disfavored

Summary

- (Effective) holography, 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

Thank you!

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

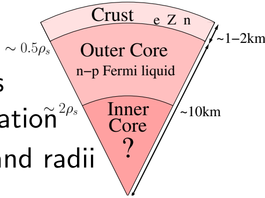
Laboratory experiments challenging ($T_{QCD} \sim 10^{12}$ K), in particular at high density – lots of effort

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

Neutron stars

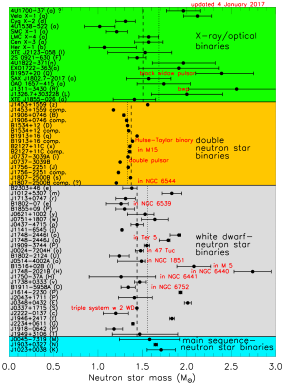
Neutron stars: extremely dense cold QCD matter

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



[Lattimer]

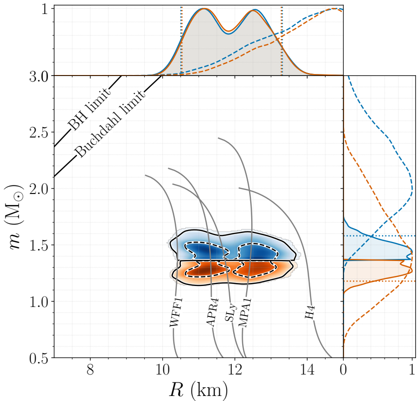
Radius measurements: more challenging, high uncertainties

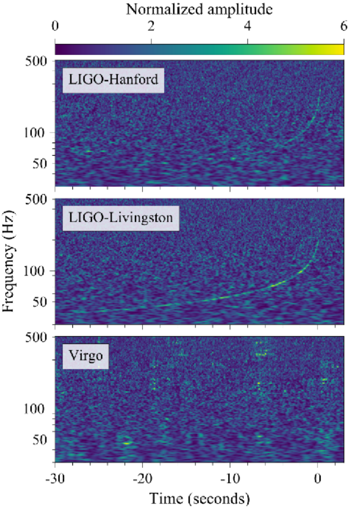
- Cooling after X-ray bursts ⇒ radii around 10-15 km

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

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

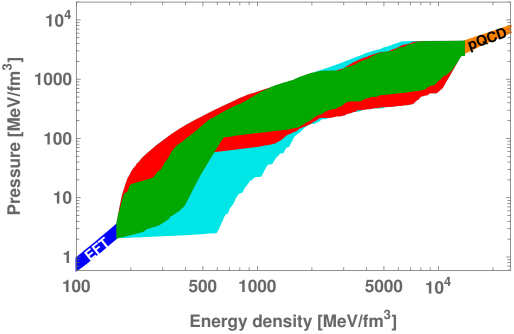




Constraints on equation of state (EoS)

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 1711.02644]

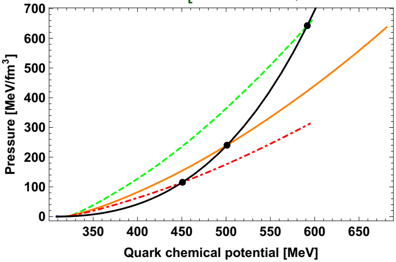
Source of uncertainties: physics at strong coupling ⇒
Can holographic methods be used to reduce uncertainties further?

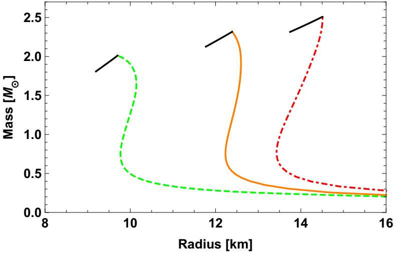
Recent progress on dense holographic QCD

For quark matter, use D3-D7 top down model: $\epsilon = 3p + \frac{\sqrt{3}m^2}{2\pi}\sqrt{p}$
[Karch, O'Bannon, 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 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 1603.02943]

Varying the quark mass m one can get quark stars and hybrid stars

[Annala, Ecker, Hoyos, Jokela, Rodriguez-Fernandez, Vuorinen 1711.06244]

- Sizeable deviations from universal I-Love-Q relations

[Yagi, Yunes, 1303.1528]

Including running of the quark mass + color superconductivity

[Bitaghsir Fadafan, Cruz Rojas, Evans, 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, 2006.09401]

(Largish) quark stars also studied in Witten-Sakai-Sugimoto and in D4-D6 models

[Burikham, Hirunsirisawat, Pinkanjanarod, 1003.5470
Kim, Shin, Lee, Wan, 1108.6139, 1404.3474]

This talk: towards more realistic model of quark matter?

Ansatz for potentials, $(x = 1)$

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

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

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

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

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

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 0707.1324; MJ, Kiritsis 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 0707.1349; MJ, Kiritsis 1112.1261; Arean, Iatrakis, MJ, Kiritsis 1309.2286, 1609.08922; MJ 1501.07272]

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

- Qualitative comparison to lattice/experimental data

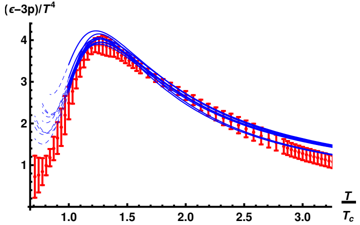
Constraining the model at $\mu \approx 0$

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

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

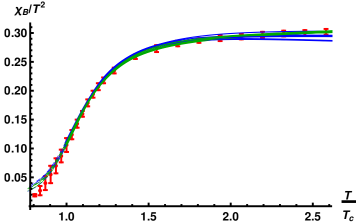
Interaction measure, 2+1 flavors

Lattice data: Borsanyi et al. 1309.5258



Baryon number susceptibility

Lattice data: Borsanyi et al. 1112.4416

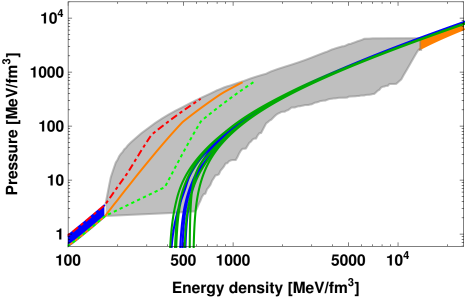


Extrapolated EoSs of cold quark matter

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

[MJ, Jokela, Remes, 1809.07770]

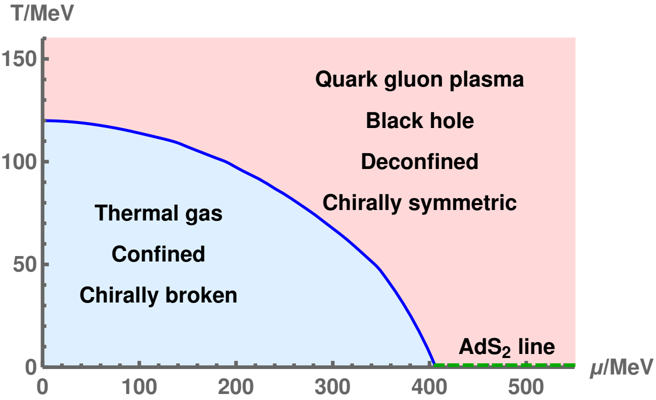
- Band of allowed equations of state (EoSs) (gray, polytropic interpolations)
- Stiff, intermediate, and soft nuclear EoSs [Hebeler, Lattimer, Pethick, Schwenk 1303.4662]



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, 1706.00455]

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

Nuclear matter in holographic models

Each baryon maps to a solitonic "instanton" configuration of gauge fields in the bulk

[Witten; Gross, Ooguri; ...]

- Such instantons have been studied in many models, including V-QCD (see the poster/talk by Edwan Préau)
- However, dense nuclear matter requires studying many-instanton solutions
- Extremely challenging!
- This talk: set $N_f = 2$ and try first a simple approximation scheme (homogeneous), reasonable at high densities?

[Rozali, Shieh, Van Raamsdonk, Wu 0708.1322]

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

[Li,Schmitt,Wang 1505.04886; Elliot-Ripley,Sutcliffe,Zamaklar 1607.04832]

[Kovensky, Poole, Schmitt, 2111.03374]

Homogeneous nuclear matter in V-QCD

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

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

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

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

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

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

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 0708.1322]

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

[Ishii, MJ, Nijs, 1903.06169]

Discontinuity and smeared instantons

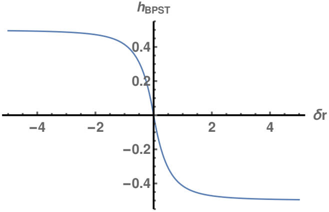
With the homogeneous Ansatz $A_i^a(r) = h(r)\delta_i^a$ baryon number vanishes for any smooth $h(r)$:

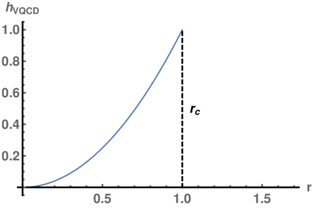
$$N_b \propto \int dr \frac{d}{dr}\,[\mathrm{CS}-\mathrm{term}] = 0$$

How can this issue be avoided?

- Smearing the BPST soliton in singular Landau gauge:

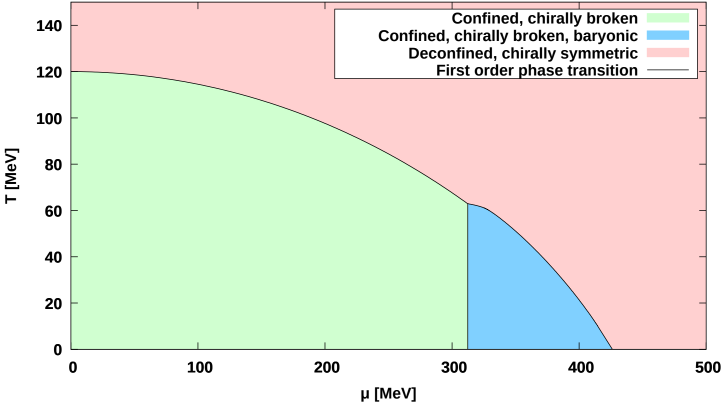
$$\langle A_i^a \rangle \sim \int \frac{d^3x \;\; \eta_{i4}^a \;\delta r}{(\delta r^2 + x^2 + \rho^2)(\delta r^2 + x^2)} \sim -\frac{\delta_i^a \;\delta r}{\sqrt{\delta r^2 + \rho^2} + |\delta r|}$$





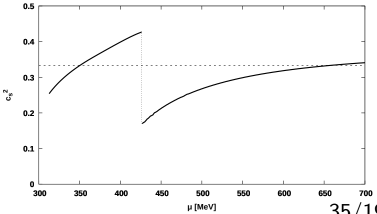
- This suggests a solution: introduce a discontinuity in $h(r)$ at $r = r_c$
- The discontinuity sources nonzero baryon charge!

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, 1903.06169]



Van der Waals model

Ideal gas of protons, neutrons and electrons with

- Excluded volume correction for nucleons

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

  $v_0 \sim$ volume of one nucleon

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

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

  schematically:

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

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

[Vovchenko, Gorenstein, Stoecker, 1609.03975]

[Vovchenko, Motornenko, Alba, Gorenstein, Satarov, Stoecker, 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, 0911.4073]

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

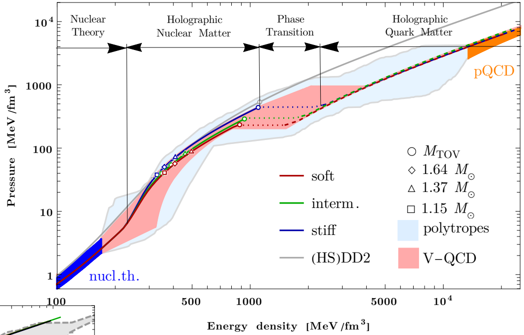
  [Typel, Ropke, Klahn, Blaschke, Wolter, 0908.2344]

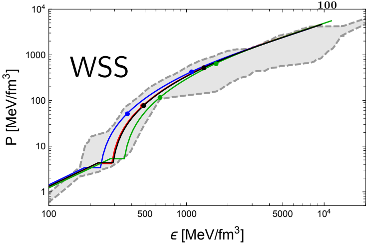
Results: Cold Hybrid Equations of State

- 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 1908.03213]
[Jokela, MJ, Nijs, Remes 2006:01141]





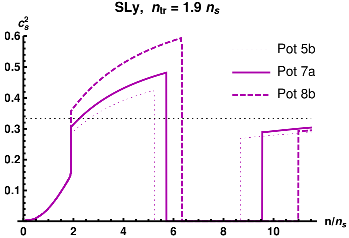
WSS with isospin asymmetry and holographic crust region

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

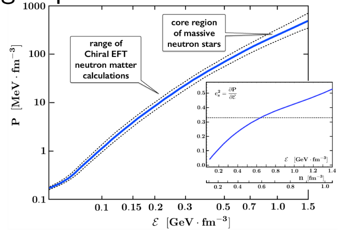
[Kovensky, Poole, Schmitt 2111.03374]

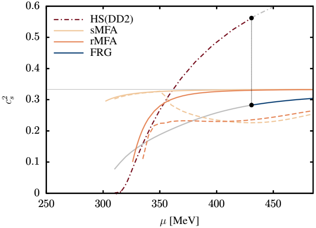
Speed of sound and comparison to FRG

Speed of sound (squared) as a function of density



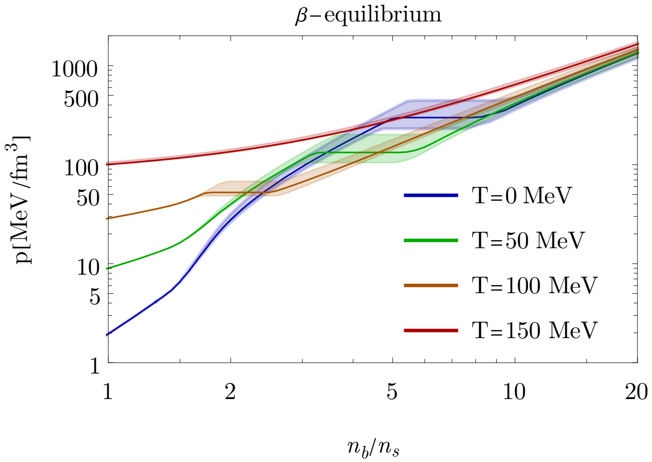
- Relatively mild dependence on model parameters
- Similar predictions as with the functional renormalization group method!





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

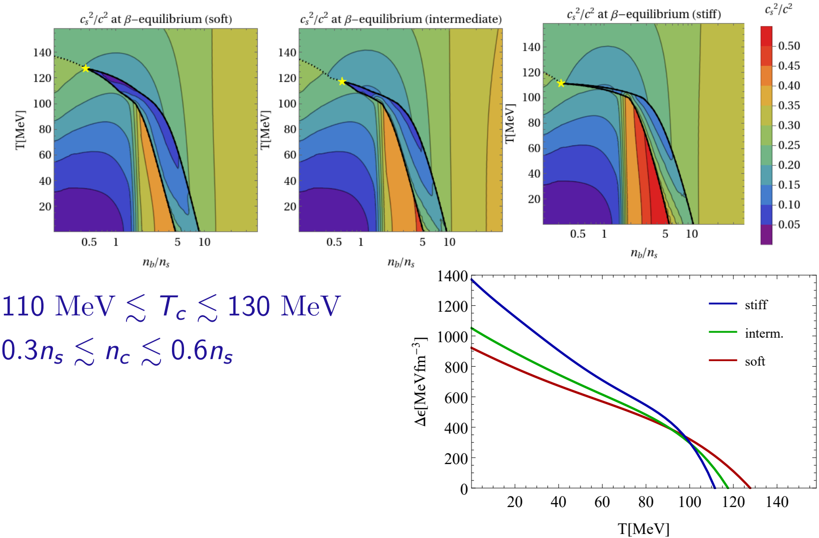
Results: EoS at Finite T



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

[Demircik, Ecker, MJ 2112.12157]

Results: critical point

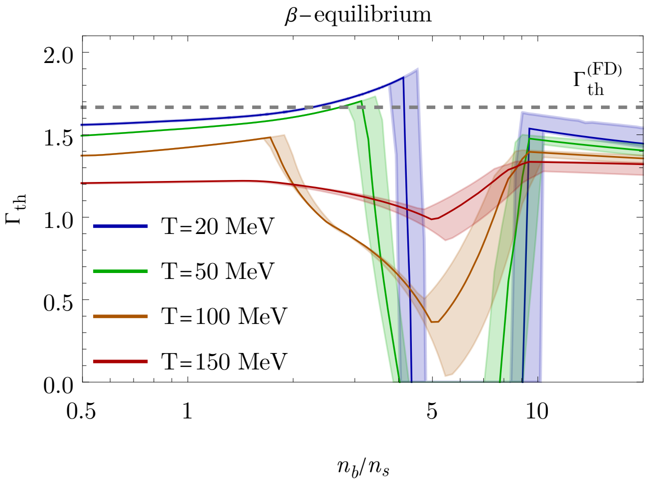


$110 \text{ MeV} \lesssim T_c \lesssim 130 \text{ MeV}$

$0.3 n_s \lesssim n_c \lesssim 0.6 n_s$

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

Results: thermal index



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

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

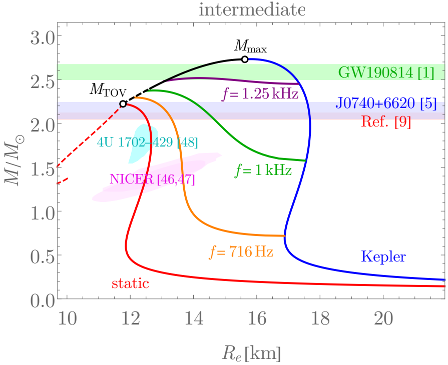
Rapidly spinning holographic neutron stars

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

[2006.12611]

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

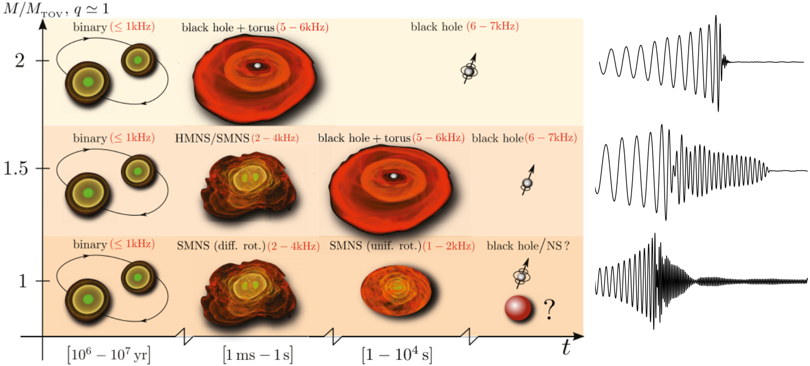
- Holographic EoSs easily compatible with the neutron star interpretation
- However requires fast rotation, $f \gtrsim 1$ kHz



[Demircik, Ecker, MJ, 2009.10731]

Neutron star mergers

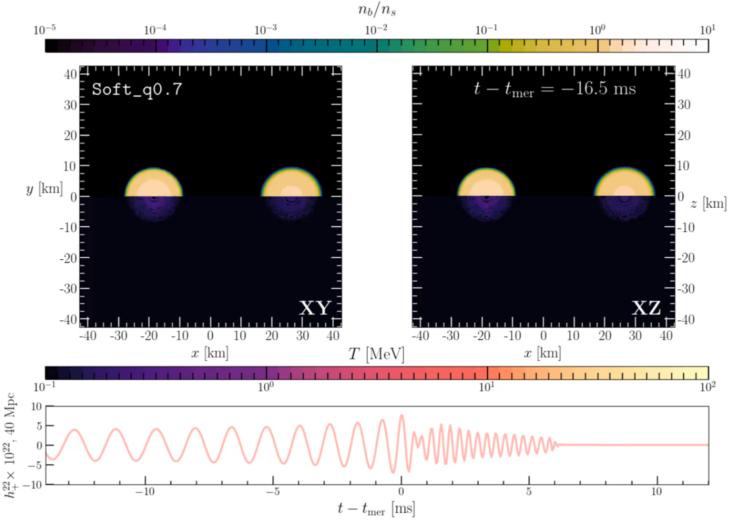
- Significant sources of gravitational radiation
- Microscopic properties of dense matter encoded in GW and EM signal



[picture: Baiotti, Rezzola 1607.03540]

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

Simulations with parameters chosen to match with GW170817

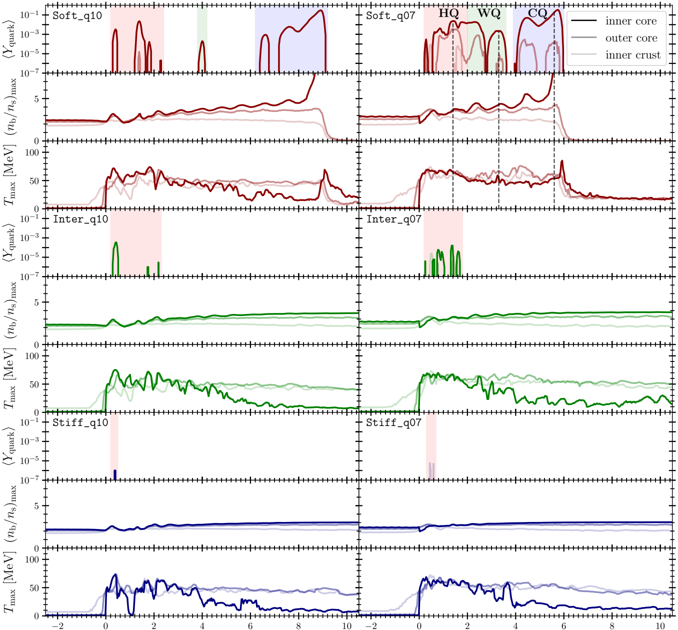


Soft EoS with $M_1/M_2 = 0.7$

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

[Movie by K. Topolski]

Details on quark formation



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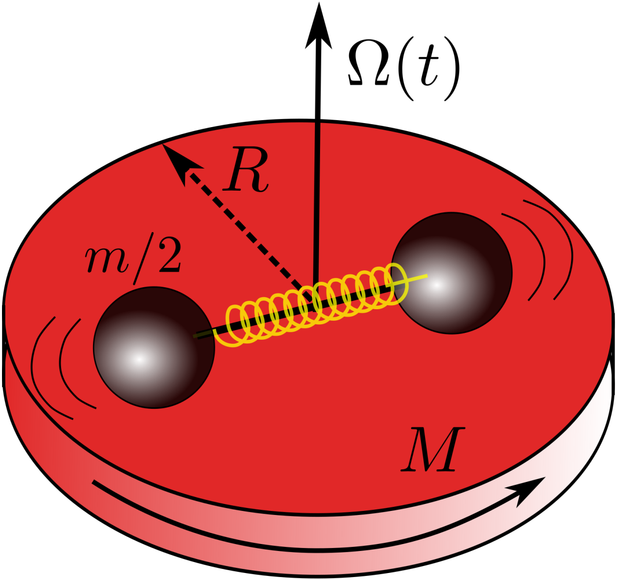
Mechanical Toy Model



[Takami, Rezzolla, Baiotti 1412.3240]