Predictions for neutron star mergers from the gauge/gravity duality

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POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

XVIth Quark Confinement and the Hadron Spectrum

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National Research Foundation of Korea

Outline

1. Introduction and motivation
2. Holographic equation of state
   - Holographic quark matter
   - Holographic nuclear matter
3. Holographic neutron star mergers
   - Production of quark matter
   - Prompt collapse to a black hole
4. Conclusion

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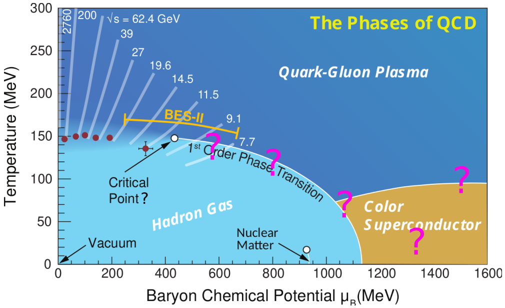

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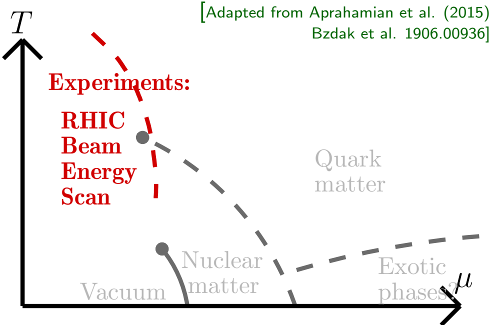

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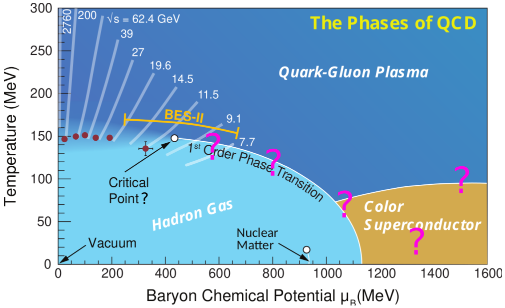

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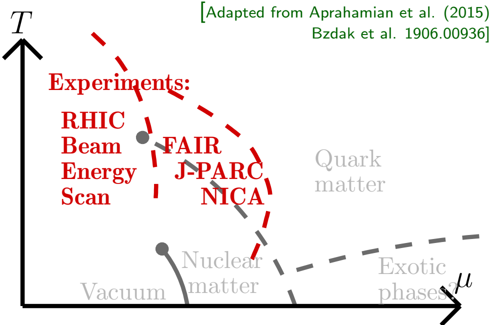

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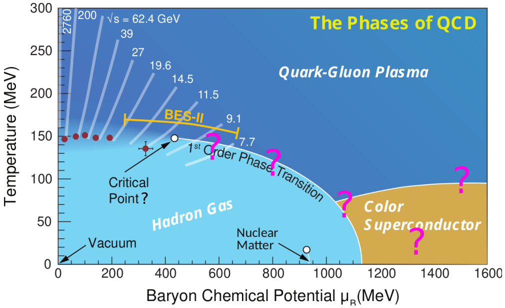

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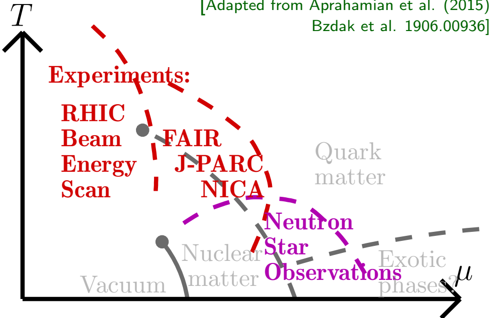

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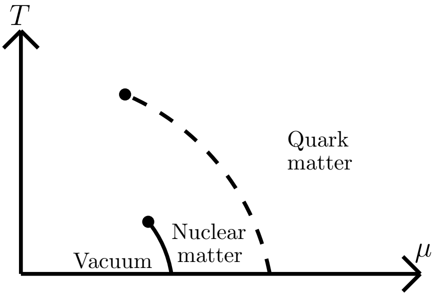

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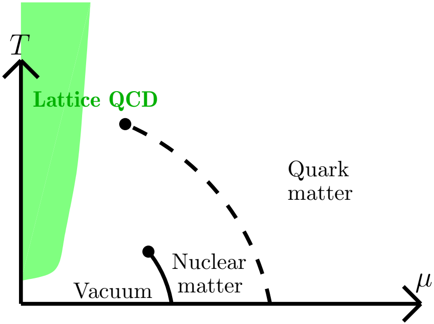

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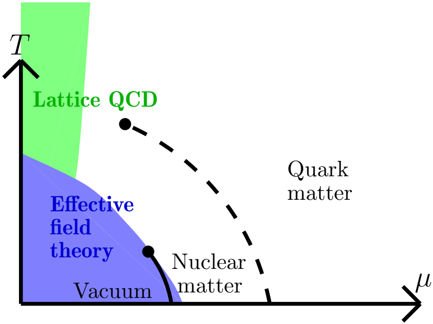

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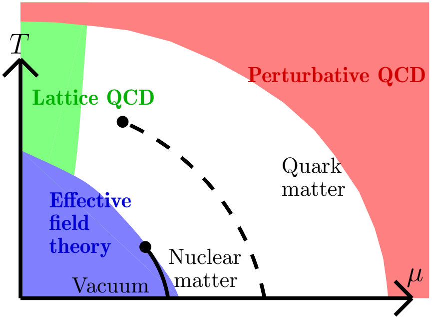

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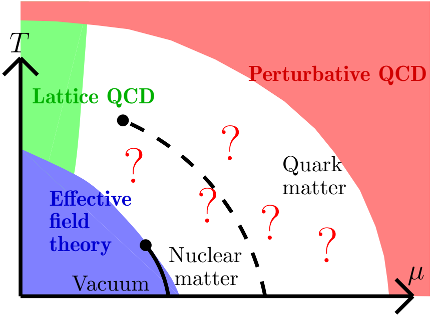

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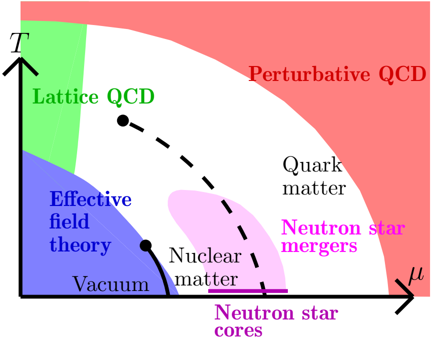

- This region is highly relevant for neutron star physics!
- Improving theoretical predictions important!
- Strongly coupled physics – use the gauge/gravity duality?

Gauge/gravity duality for QCD

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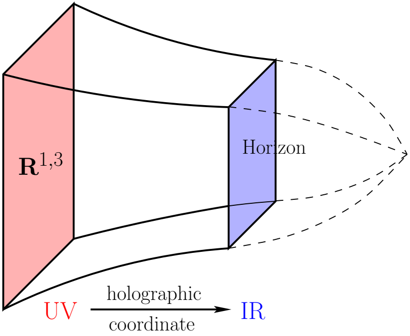

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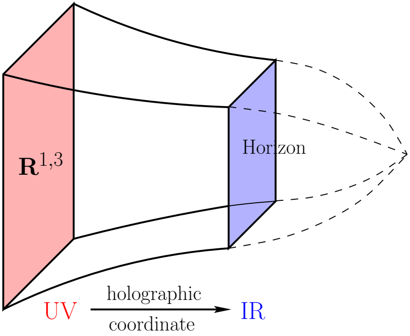

- Operators $O_i(x^\mu) \leftrightarrow$ classical bulk fields $\phi_i(x^\mu, r)$

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

- Thermodynamics of QCD $\leftrightarrow$ thermodynamics of a planar bulk black hole

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There is however strong motivation for this approach:

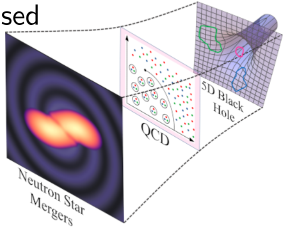
- Strongly coupled physics: holography may work better than many other approaches
- Different phases (quark, nuclear, color superconducting, quarkyonic . . .) in the same footing or even in a single model
  - Typically not achieved in the literature
  - Gives rise to predictions for phase transitions
- As it turns out, predictions do make sense!
  - Highly nontrivial – as the precise holographic dual for QCD is not known, these model cannot be derived
  - I will show examples later in this talk

Outline

The approach

Goal: construct a state-of-the-art EOS, to be used

1. to describe (isolated) neutron stars
2. in simulations of neutron star mergers
3. in simulations of core collapse supernovae
4. when analyzing heavy-ion collisions (?)



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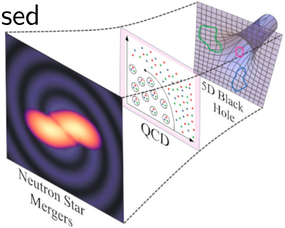

I choose a specific holographic model (V-QCD)

- Many other approaches available, I will cover only this one
- Some parts could also be covered using simpler models (e.g. quark matter using Einstein-Maxwell-dilaton)

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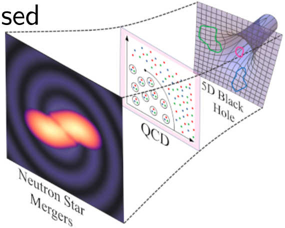

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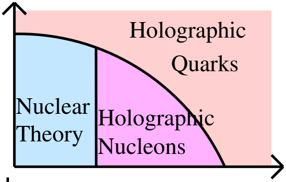
Main ingredients are

1. Holographic model for quark matter
2. (Slightly adjusted) holographic model for nuclear matter
3. Nuclear theory model for hadronic phase – at low density holography not very useful



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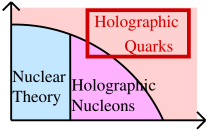
Model for quark matter

V-QCD: a holographic bottom-up model for QCD with backreacted quarks

- Combines model for glue (IHQCD) with flavor (brane action) [Gürsoy, Kiritsis, Nitti] [Bigazzi,Casero,Cotrone,Kiritsis,Paredes] [MJ, Kiritsis 1112.1261]



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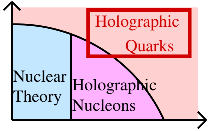

$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right] - N_f N_c M^3 \int d^5x \; V_{f0}(\lambda) \sqrt{-\det(g_{ab} + w(\lambda) F_{ab})}$$

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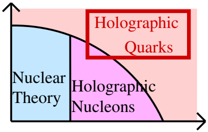

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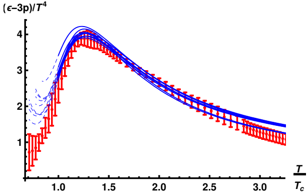
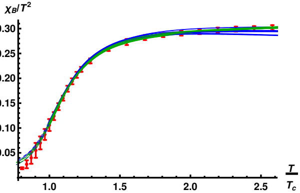
Effective model: choose potentials by comparing to QCD at $\mu \approx 0$





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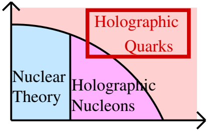

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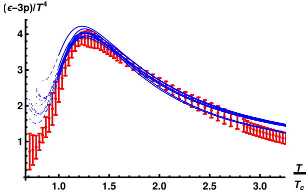
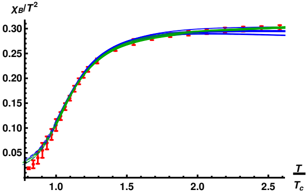
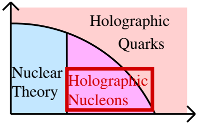




Equation of state obtained numerically from black hole thermodynamics of charged black holes

Model for nuclear matter

Standard method for baryons in holographic models: Each baryon maps to a solitonic 5D "instanton" of gauge fields



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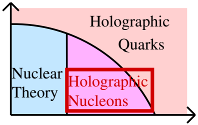

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- Our approach: V-QCD with two flavors and a homogeneous gauge field, mimicking dense solitons: $A^i = h(r)\sigma^i$

[Rozali, Shieh, Van Raamsdonk, Wu 0708.1322]
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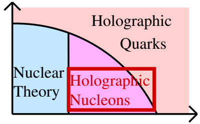

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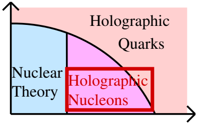

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Our solution: we extrapolate the holographic nuclear matter EOS to nonzero T by a using a van der Waals approach

- Gas of protons, neutrons and electrons with an excluded volume correction and a potential term

[Demircik, Ecker, MJ 2112.12157]

Combining the building blocks: the hybrid model

- For low density nuclear matter, Hempel-Schaffner-Bielich DD2
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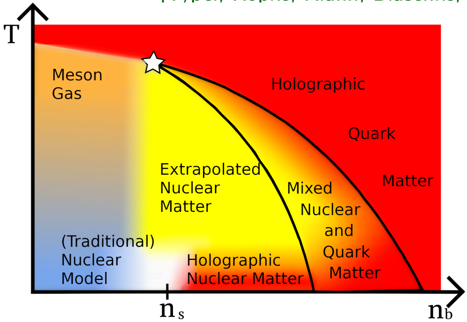

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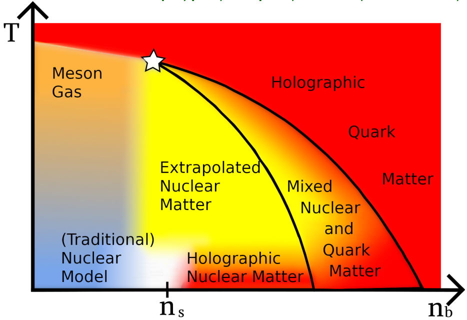

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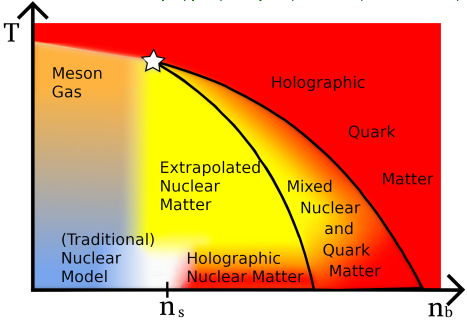

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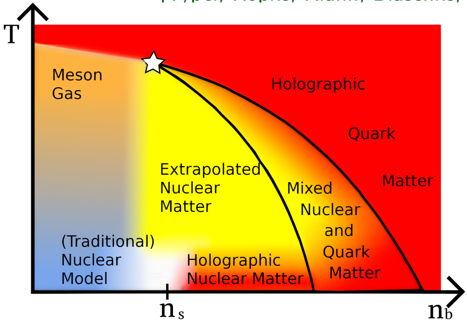

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- One of the most ambitious attempts to describe the QCD EOS to date, in any approach
- Consistent with theoretical and observational constraints
- Pick three variants (soft, intermediate, stiff) – different fits of the holographic model to lattice data – published in the CompOSE database of EOSs [http://compose.obspm.fr]

Advantages of the model

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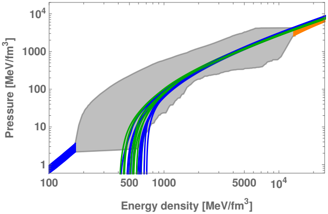

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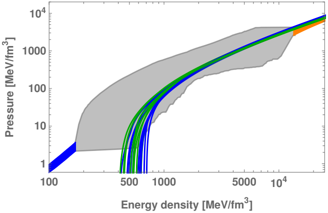

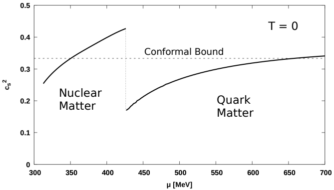

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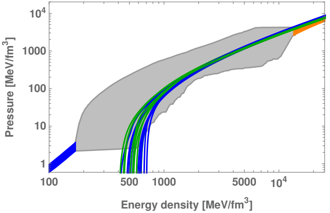
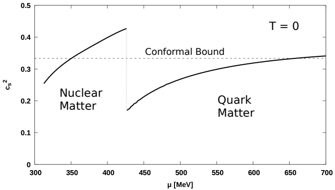
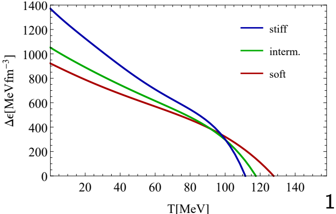
4. Simultaneous modeling of nuclear and quark matter phases
   - Predictions for the phase transition
   - Btw no stable quark cores inside neutron stars







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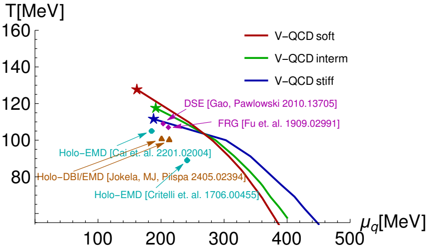

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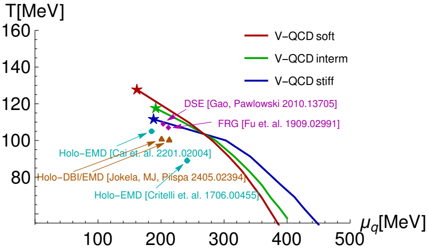

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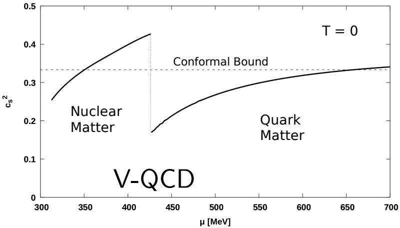
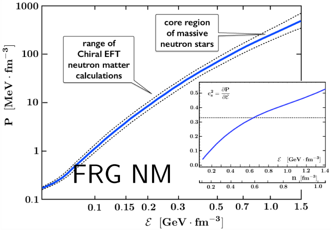
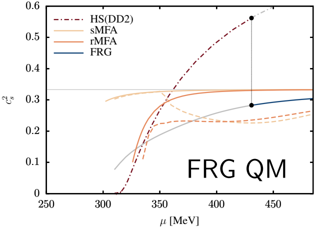


- Speed of sound at $T = 0$





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

A digression: instability in quark matter phase

Any holographic model for QCD must include Chern-Simons terms

- Required by the anomalies of QCD
- Known to give rise to spatial instabilities at finite density

[Nakamura, Ooguri, Park 0911.0679;
Ooguri, Park 1011.4144]

[Cruz Rojas, Demircik, MJ 2405.02399; Demircik, Jokela, MJ, Piispa 2405.02392]

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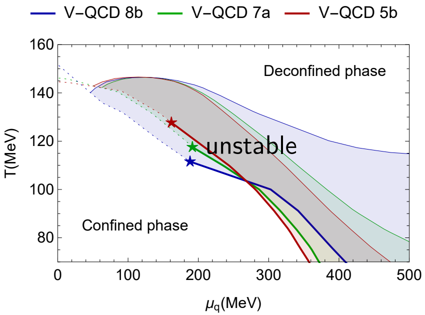

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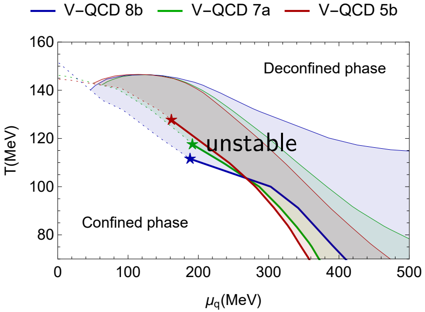

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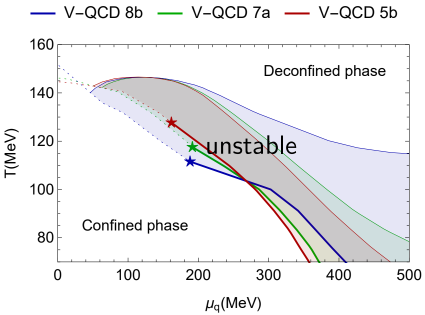
- Result largely model-independent
- However, might be sensitive to strange quark mass – requires further study



[Cruz Rojas, Demircik, MJ 2405.02399; Demircik, Jokela, MJ, Piispa 2405.02392]

Outline

Neutron star mergers

- Significant sources of gravitational radiation
- Microscopic properties of dense matter encoded in the gravitational waves and the electromagnetic signal

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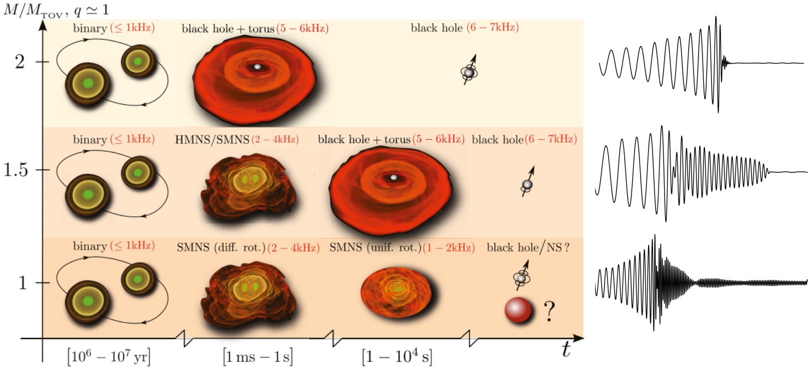

[picture: Baiotti, Rezzola 1607.03540]

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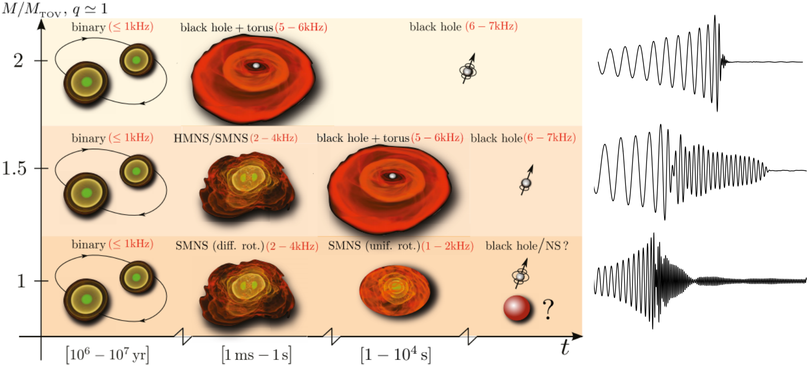

[picture: Baiotti, Rezzola 1607.03540]

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

Simulating 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 state modelling a neutron star binary system

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  [Papenfort, Tootle, Grandclement, Most, Rezzolla 2103.09911]
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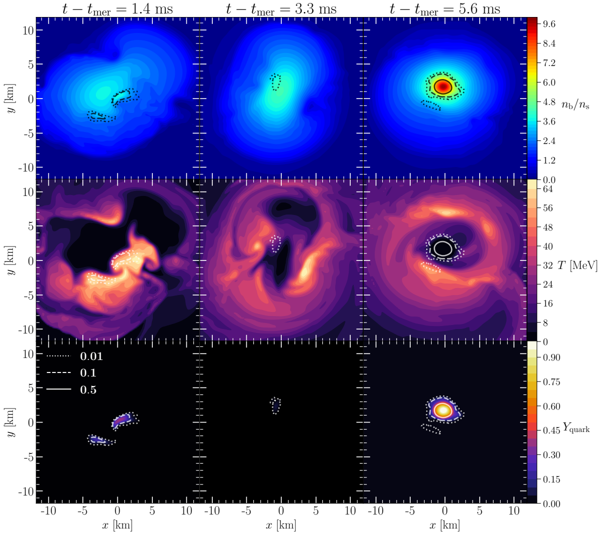
- Need supercomputing!

Hot, warm and cold quarks

Quark matter formation in the hypermassive neutron star stage:

Hot quarks   Warm quarks   Cold quarks



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

Threshold mass of prompt black hole formation

Analysis of mergers at high mass where the system collapses to a black hole

- Idea: use curvature invariants for precise classification of "prompt" collapse

[CE, Topolski, Järvinen, Stehr 2402.11013]

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$$K_1 = R_{abcd}\, R^{abcd}$$

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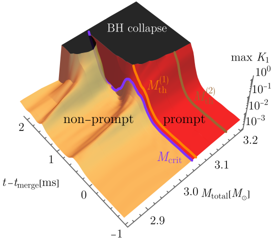

Motivated by simulations, in particular dependence of K_1 on t and M_{total}, we define

1. The critical mass

$$M_{crit} = \min(M) : \frac{dt_{crit}}{dM_{total}} < 0 \quad \forall\, M_{total} > M\,,$$

where t_{crit} is the time of formation of an apparent horizon

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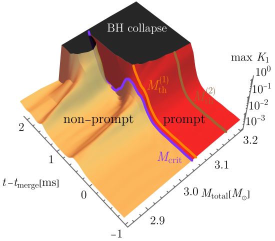

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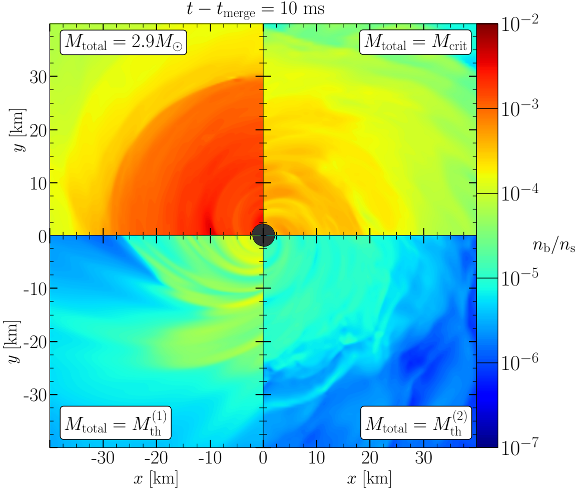
2. Threshold masses of promptness p

$$\left\{ M_{th}^{(p)} = \min(M_{total}) : \frac{d^p}{dt^p}\max(K_1) \geq 0\ \forall\ t > t_{merge} \right\}$$

[CE, Topolski, Järvinen, Stehr 2402.11013]

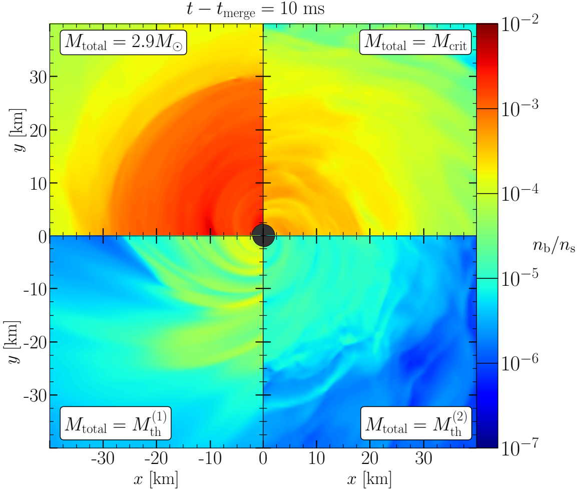
Residual matter

- Significant drop in residual matter outside horizon at M_{crit}



Residual matter

- Significant drop in residual matter outside horizon at $M_{\rm crit}$



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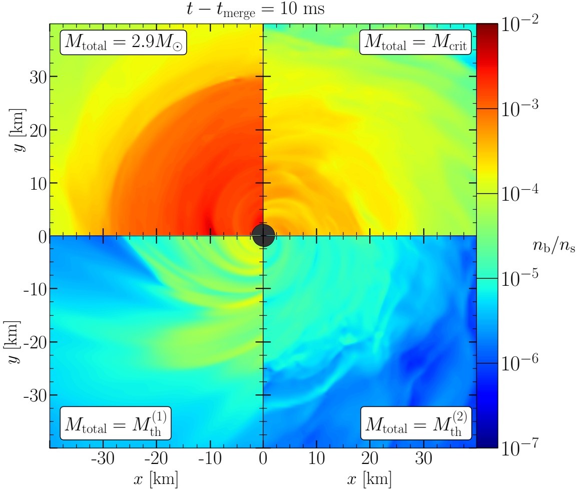

- Enhanced by the transition to quark matter
- So M_{crit} can potentially be measured precisely by observing the EM counterpart

Outline

1. Introduction and motivation
2. Holographic equation of state
   - Holographic quark matter
   - Holographic nuclear matter
3. Holographic neutron star mergers
   - Production of quark matter
   - Prompt collapse to a black hole
4. Conclusion

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- Holographic description of dense QCD works well:
  - ✓ Precise fit of lattice thermodynamics at $\mu \approx 0$
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  - ✓ Simultaneous model for nuclear and quark matter
  - ✓ Stiff EOS for nuclear matter

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- Predictions for binary neutron star mergers from state-of-the-art simulations using our model
- Recent/ongoing/future improvements: turning on strange quark mass, transport (e.g. viscosities and neutrino transport), isospin asymmetry, color superconducting phases, improving predictions for spatial modulation ...

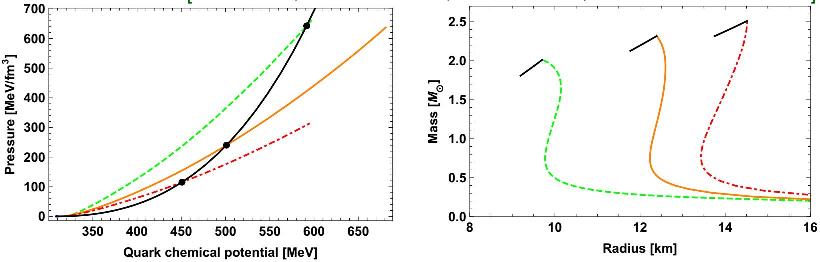
Thank you!

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?

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

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 model at $\mu \approx 0$

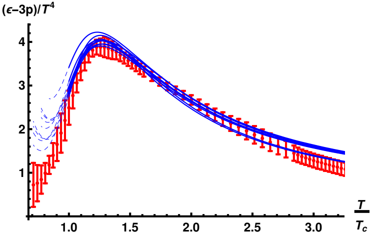
Standard recipe (charged black holes) $\Rightarrow$ lots of numerical work
$\Rightarrow$ description of hot and dense quark matter

Fit to lattice data near $\mu = 0$ [MJ, Jokela, Remes, 1809.07770]

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

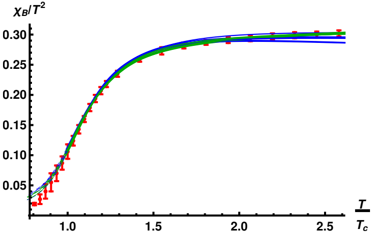
Interaction measure $\frac{\epsilon - 3p}{T^4}$, 2+1 flavors

[Data: Borsanyi et al. 1309.5258]



Baryon number susceptibility $\chi_B = \frac{d^2 p}{d\mu^2}\Big|_{\mu=0}$

[Data: Borsanyi et al. 1112.4416]

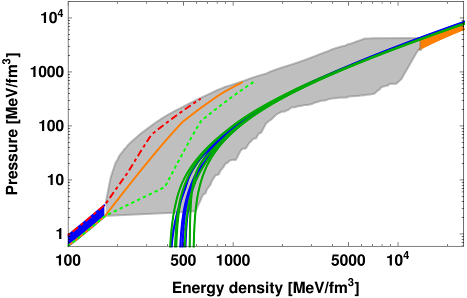


Extrapolated EOSs of cold quark matter

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

[MJ, Jokela, Remes, 1809.07770]

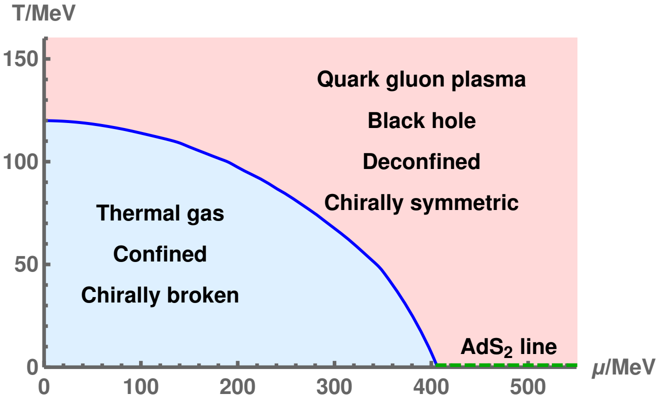
- Band of allowed equations of state (EOSs) (gray, polytropic interpolations)
- Stiff, intermediate, and soft nuclear EOSs [Hebeler, Lattimer, Pethick, Schwenk 1303.4662]



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; Cai, He, Li, Wang 2201.02004]

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 constraints

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]

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

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

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

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 0708.1322]

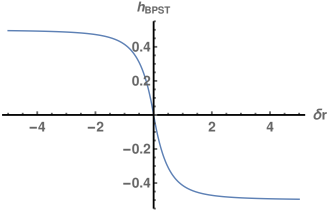
$$A_L^i = -A_R^i = h(r) \sigma^i$$

[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 $h(r)$:

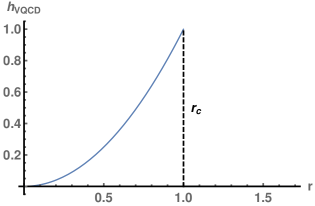
$$N_b \propto \int dr \frac{d}{dr}\,[\mathrm{CS-term}] = 0$$



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!

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:

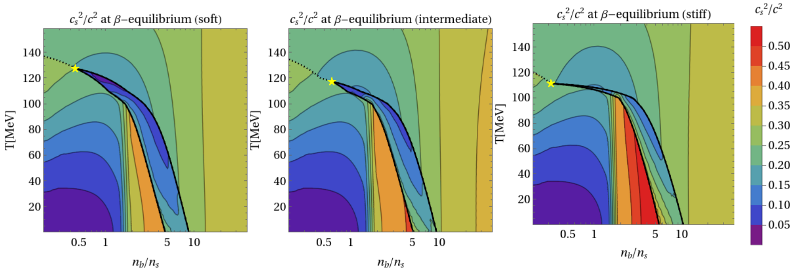
$$\Delta p(\{\mu_i\}) = p_{\rm V-QCD}(T=0,\{\mu_i\}) - p_{\rm ex}(T=0,\{\mu_i\})$$

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

[Vovchenko, Gorenstein, Stoecker, 1609.03975]

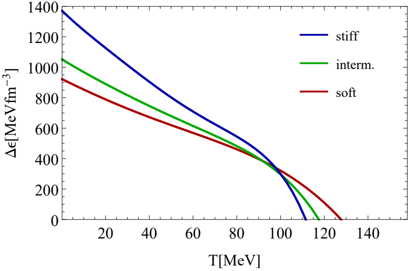
[Vovchenko, Motornenko, Alba, Gorenstein, Satarov, Stoecker, 1707.09215]

Results: critical point



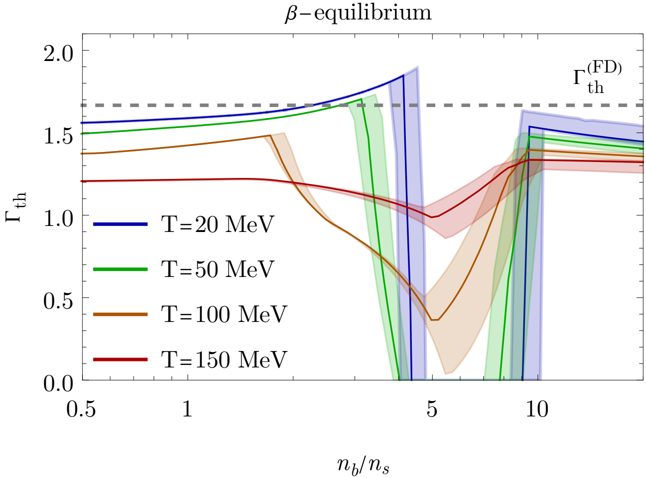
$110\ \mathrm{MeV} \lesssim T_c \lesssim 130\ \mathrm{MeV}$

$0.3 n_s \lesssim n_c \lesssim 0.6 n_s$



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

Results: thermal index



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

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

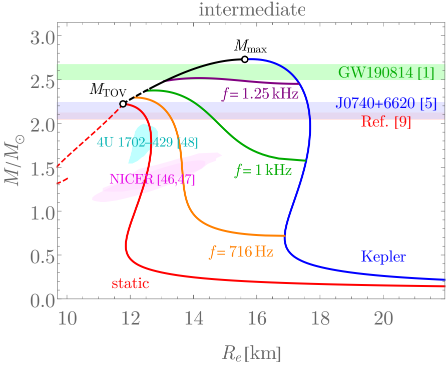
Rapidly spinning holographic neutron stars

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

[2006.12611]

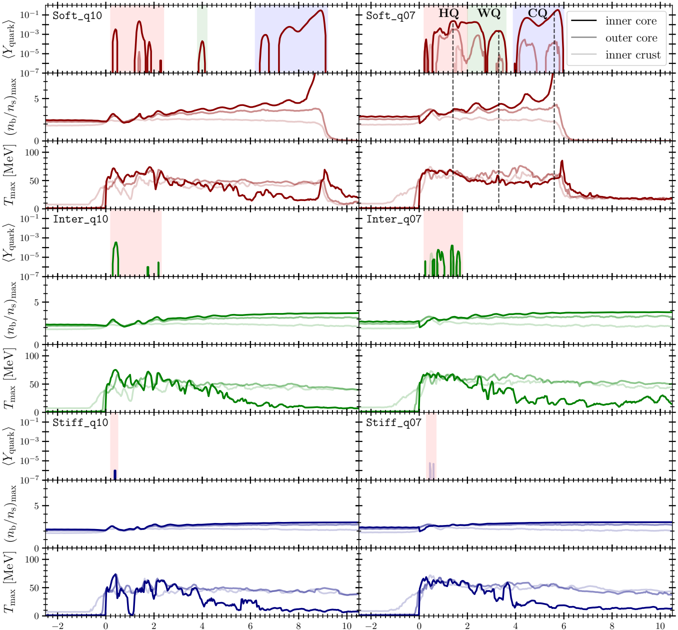
- $2.6M_\odot$ falls in the "gap": a black hole or a neutron star?

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



[Demircik, Ecker, MJ, 2009.10731]

Details on quark formation



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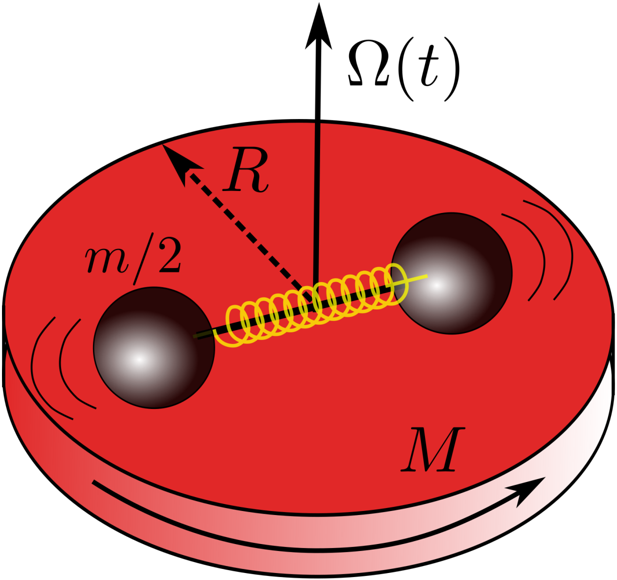
Mechanical Toy Model



[Takami, Rezzolla, Baiotti 1412.3240]