Compact stars made of holographic QCD matter

Christian Ecker

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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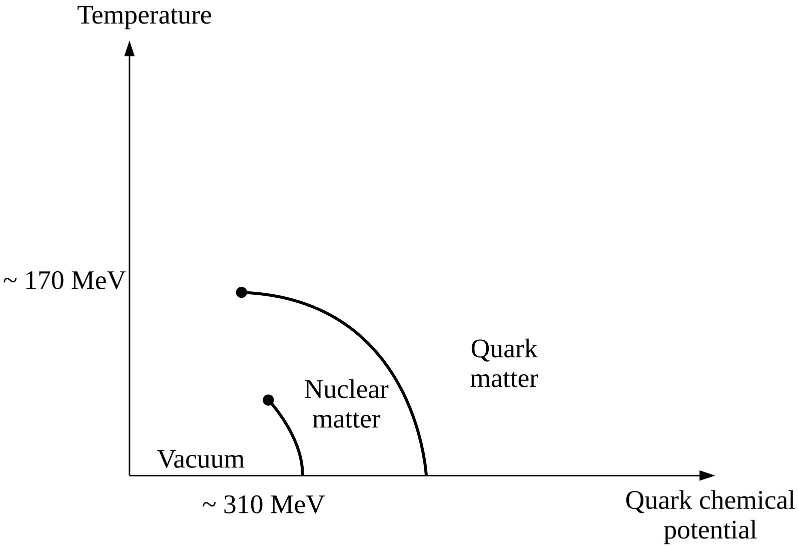
Based on
2009.10731 with Tuna Demircik and Matti Järvinen
&
1908.03213 with Matti Järvinen, Govert Nijs and Wilke van der Schee

What is known about the QCD phase diagram?



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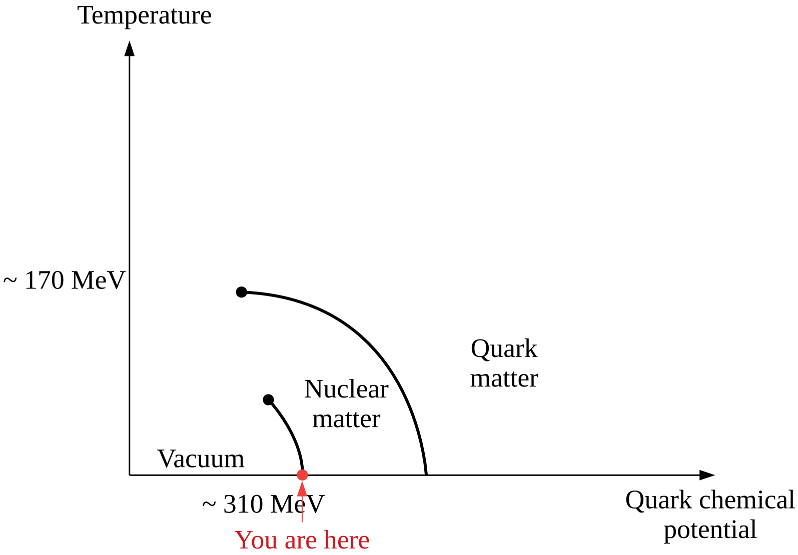

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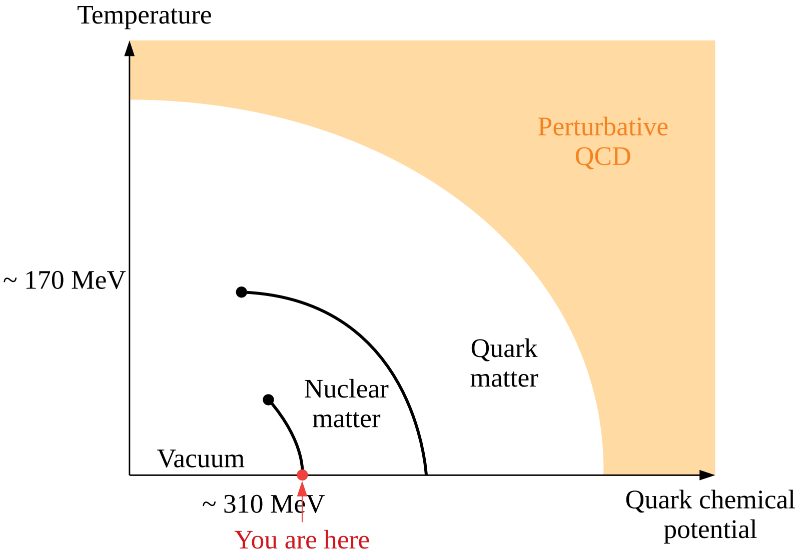

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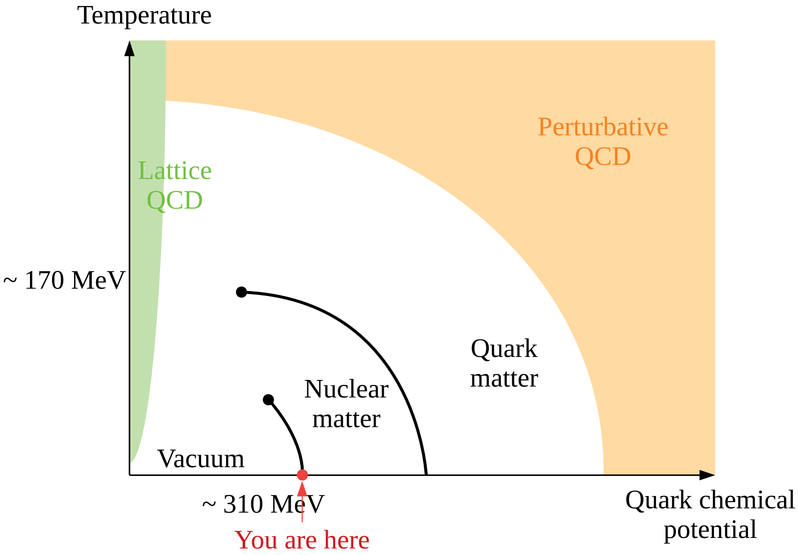

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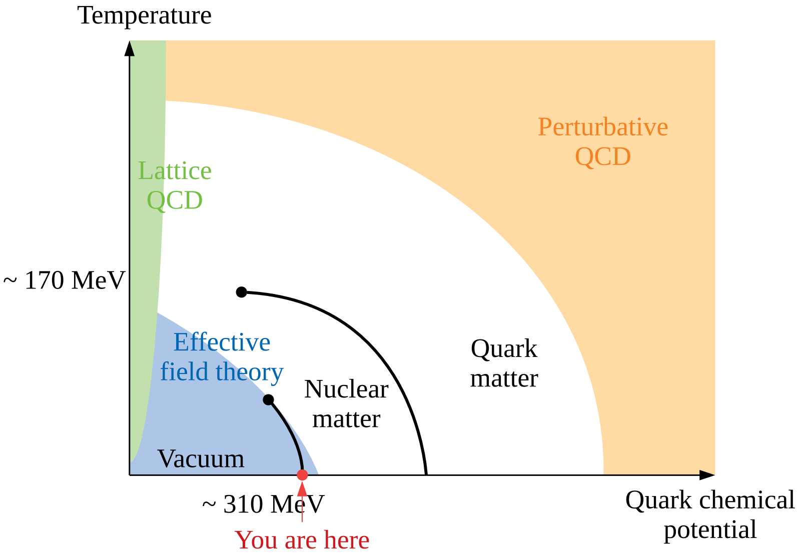

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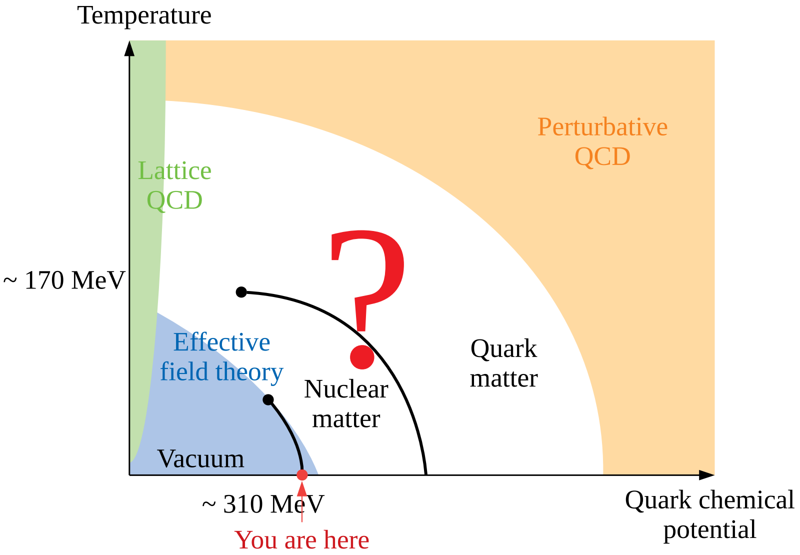

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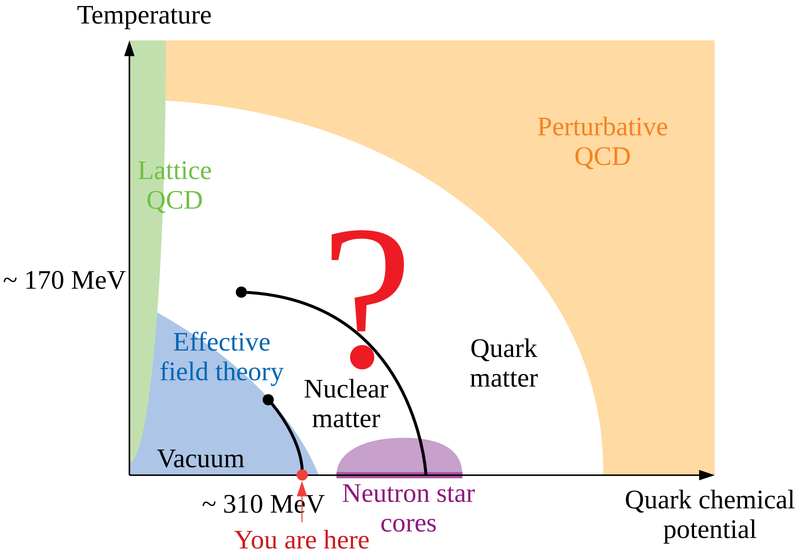
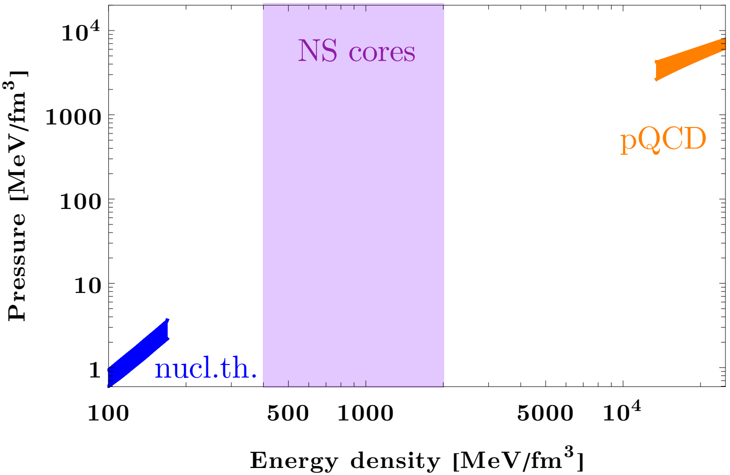


Equation of State



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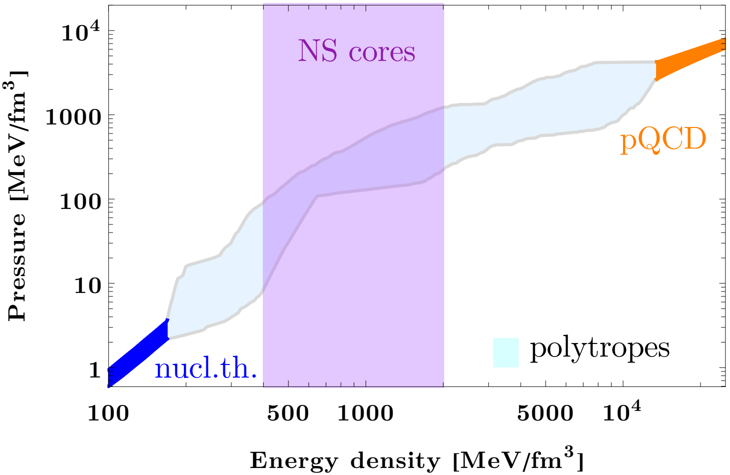

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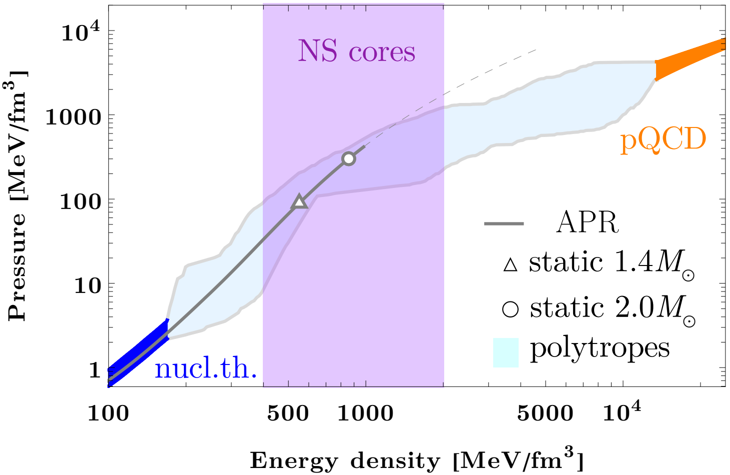
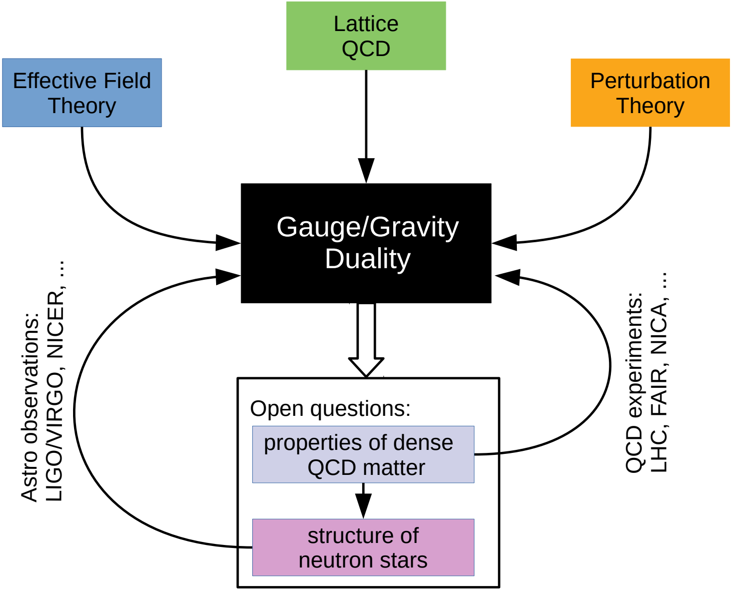



Lattice QCD
Effective Field Theory
Perturbation Theory
Gauge/Gravity Duality
Astro observations: LIGO/VIRGO, NICER, ...
QCD experiments: LHC, FAIR, NICA, ...
Open questions:
properties of dense QCD matter
structure of neutron stars

Gauge/Gravity Duality

- Mathematical relation between gauge theories and higher dimensional gravity theories found in string theory.
- Strong-weak duality: if gauge theory is strongly coupled then gravity theory is weakly coupled and vice versa.
- Observables in a strongly coupled field theory (hard) can be obtained from a classical gravity calculation (easy).

Gravity Side	Gauge Theory Side
on-shell action $S_{\rm grav}$	free energy f
black hole area $\mathcal{A}$	thermal entropy $S_{\rm th}$
surface gravity at horizon κ	temperature T
metric near boundary $g^{(4)}_{\mu\nu}$	stress tensor $\langle T^{\mu\nu}\rangle$, p, ϵ
gauge field A_μ	global sym. current $\langle J^\mu\rangle$, μ
...	...

- Gravity dual of QCD is not known. Bottom-up approach: construct a gravity model that mimics the relevant features of QCD.

Holographic Veneziano QCD

Gluons: Improved holographic QCD (Einstein-dilaton gravity)

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

$\lambda \equiv e^{\phi} \leftrightarrow \mathrm{Tr} F^2$ sources the 't Hooft coupling in YM theory

[Gürsoy, Kiritsis arXiv:0707.1324; Gürsoy, Kiritsis, Nitti arXiv:0707.1349]

Quarks: Tachyonic Dirac-Born-Infeld (DBI) action

$$S_{\mathrm{f}} = -N_f N_c M^3 \int d^5x V_{f0}(\lambda) e^{-\tau^2} \sqrt{-\det \left[g_{ab} + \kappa(\lambda) \partial_a \tau \partial_b \tau + w(\lambda) F_{ab} \right]}$$

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

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

[Bigazzi et al. arXiv:0505140; Casero et al. arXiv:0702155]

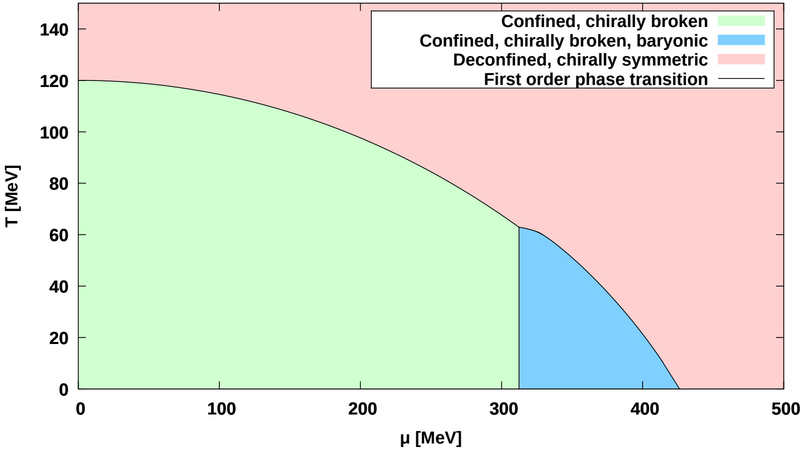
Baryons: homogeneous solution of non-Abelian DBI + Cern–Simons action.

[Ishii, Järvinen, Nijs arXiv:1903.06169]

Veneziano limit: $N_c \to \infty$ and $N_f \to \infty$ with $N_f/N_c = x$ fixed

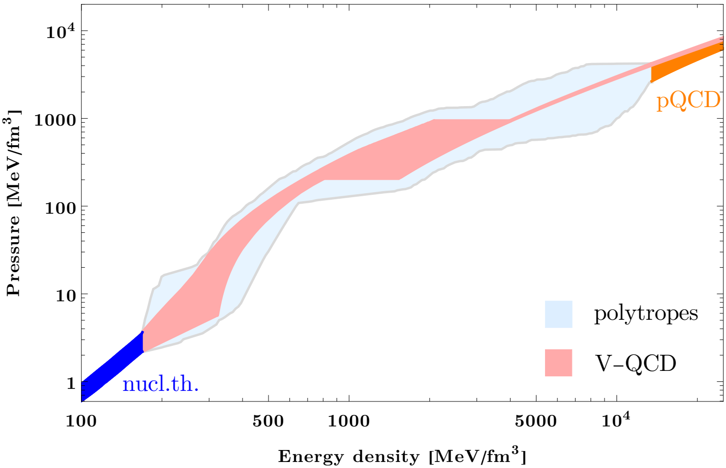
[Järvinen, Kiritsis arXiv:1112.1261]

Phase Diagram



[Ishii, Järvinen, Nijs arXiv:1903.06169]

Hybrid Equations of State



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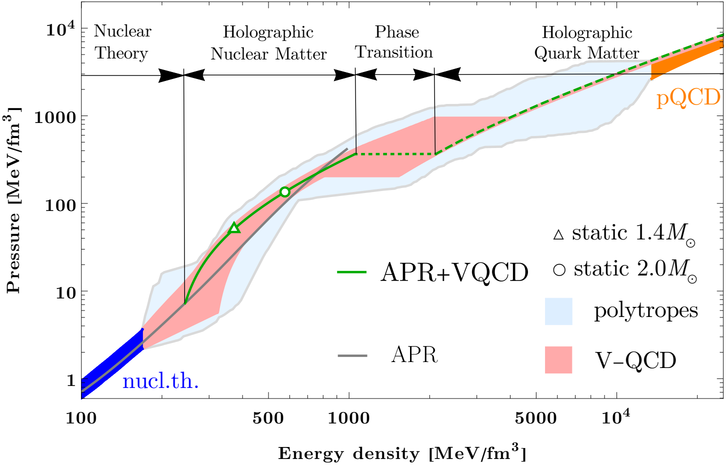

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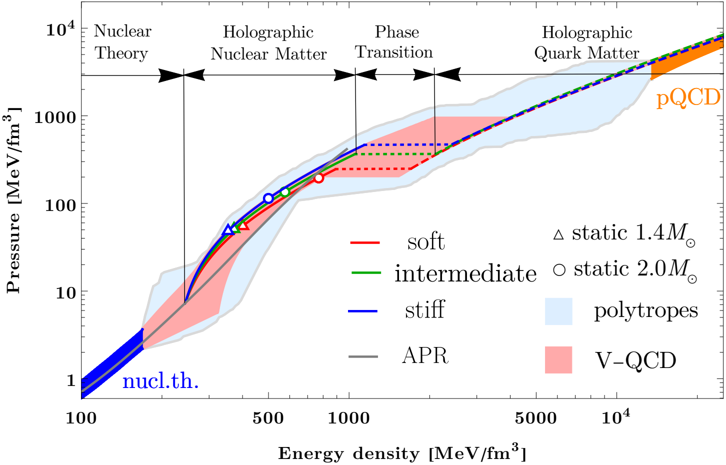
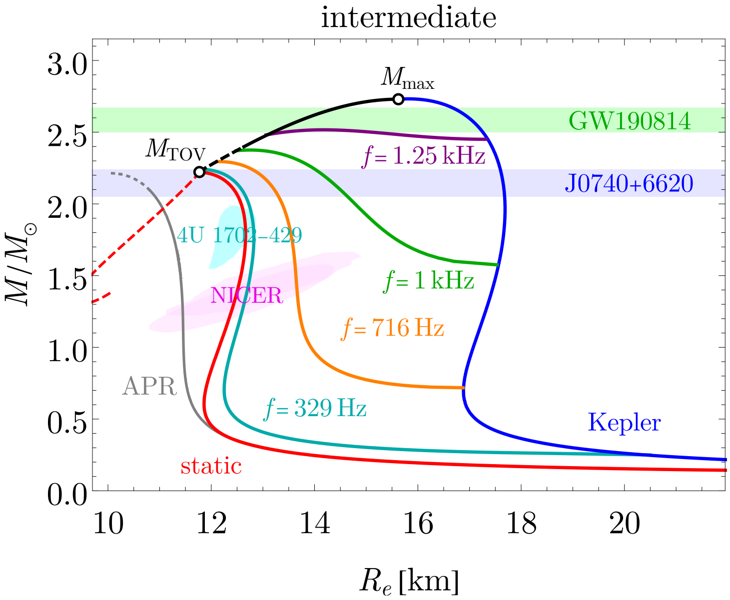
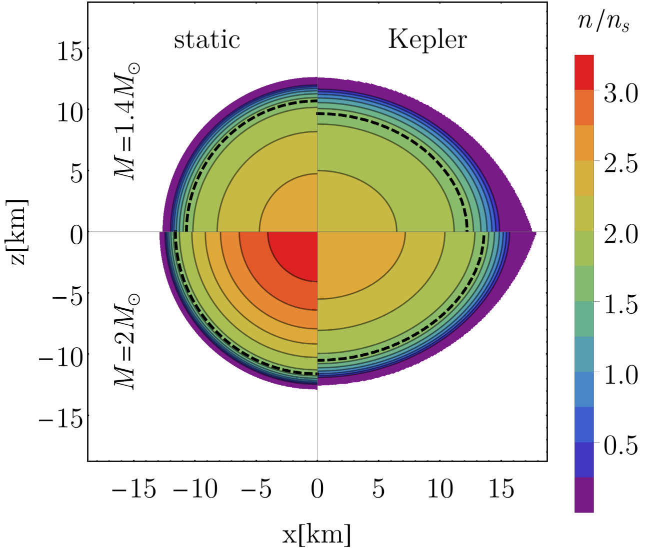


Mass Radius Relation



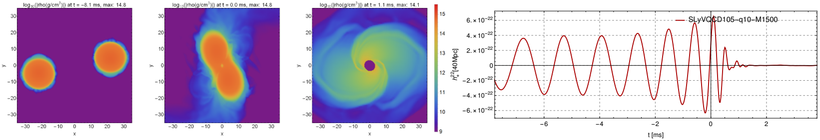
Density Profile



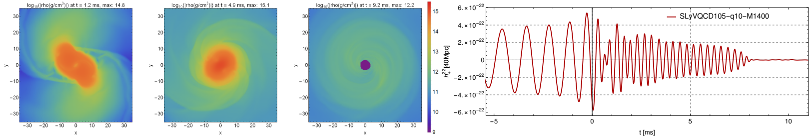
$M = 1.4\,M_\odot$: $R_{\rm match}/R_e = 0.85$, $\quad M = 2\,M_\odot$: $R_{\rm match}/R_e = 0.90$

Merger Dynamics and Waveforms

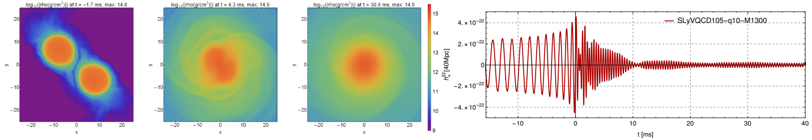
- $M = 1.5 + 1.5 M_{\odot}$: Prompt collapse to BH with dilute matter torus.



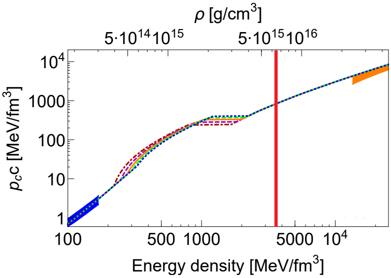
- $M = 1.4 + 1.4 M_{\odot}$: Formation of a short lived ($\approx 7.8 ms$) HMNS.

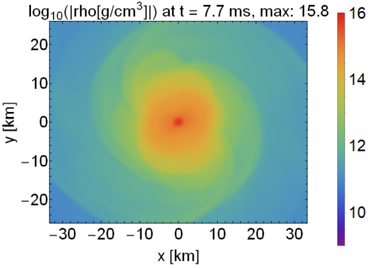


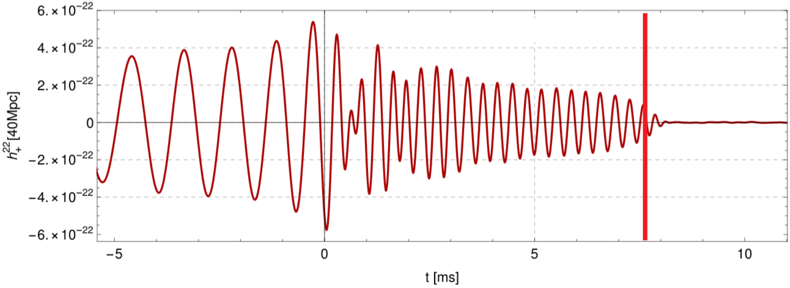
- $M = 1.3 + 1.3 M_{\odot}$: Formation of a long lived ($> 40 ms$) SMNS.



Phase Transition Induced Collapse

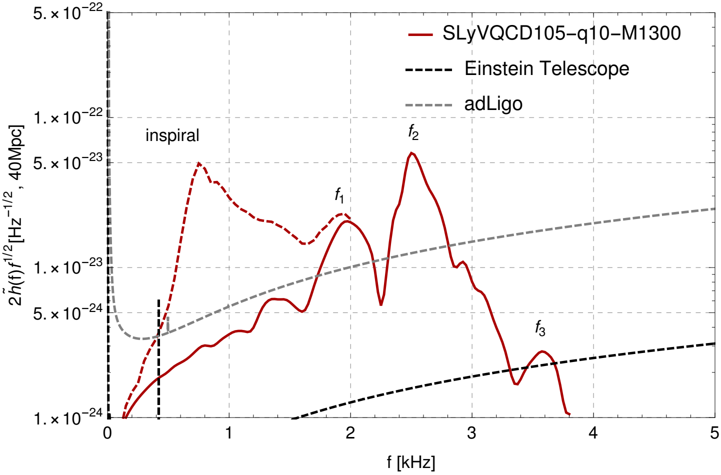




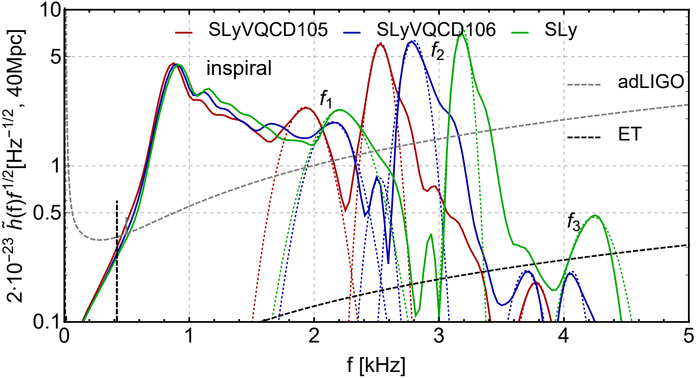


Power Spectral Density

$$\tilde{h}(f) \equiv \sqrt{\frac{|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2}{2}}, \quad \tilde{h}_{+,\times}(f) \equiv \int h^{22}_{+,\times}(t) e^{-i2\pi f t} dt$$



EoS dependence of the Power Spectral Density



EoS	$\Lambda_{1.4}$	f_1[kHz]	f_2[kHz]	f_3[kHz]
SLyVQCD105	550	1.93	2.53	3.77
SLyVQCD106	410	2.15	2.80	3.70 (4.06)
SLy	300	2.21	3.19	4.24

Summary & Prospect

- Gauge/gravity duality is used to build hybrid equations of state that satisfy known theoretical and observational constraints.
- Non-perturbative: deconfinement phase transition within one model.
- Strong first order PT: V-QCD disfavours stable quark matter cores.
- Slightly higher $\frac{M_{\mathrm{max}}}{M_{\mathrm{TOV}}}$ than nuclear matter models without PT:

$$\left.\frac{M_{\mathrm{max}}}{M_{\mathrm{TOV}}}\right|_{\mathrm{V-QCD}} = 1.227^{+0.031}_{-0.016} \quad \text{vs.} \quad \left.\frac{M_{\mathrm{max}}}{M_{\mathrm{TOV}}}\right|_{\mathrm{nucl.}} = 1.203^{+0.022}_{-0.022}$$

[Breu, Rezzolla arXiv:1601.06083]

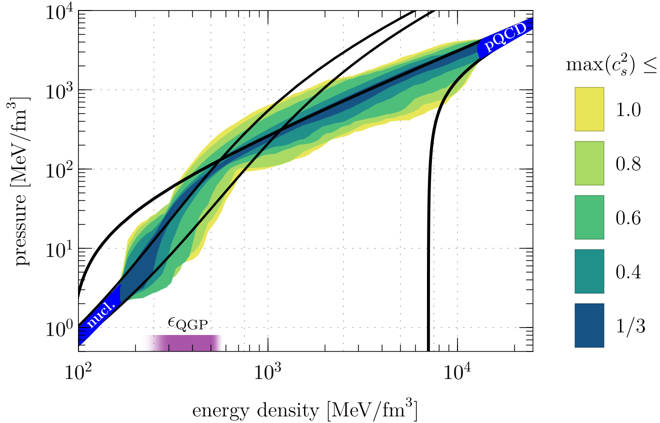
- **Work in progress:** holographic baryons at finite T by matching hardron resonance gas + finite volume corrections.
- **Future:** improve (e.g. finite quark masses, CSC phases, etc.) and constrain (GWs, lattice QCD, FAIR, etc.) the V-QCD model.
- **Useful side product:** transport coefficients (viscosities, susceptibilities, resistivities, etc.)

[Hoyos, Jokela, Järvinen, Subils, Tarrio arXiv:2005.14205]

Backup

Constraints from Theory

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



[Annala, Gorda, Kurkela, Nättila, Vuorinen arXiv:1903.09121]

Constraints from Astrophysical Observations

- NS-white dwarf binary PSR J0348+0432 (MSP J0740+6620)

$$M_{\max} > 2.01^{+0.04}_{-0.04}\,(2.14^{+0.1}_{-0.09})M_{\odot}.$$

[Antoniadis et al. arXiv:1304.6875, (Cromartie et al. arXiv:1904.06759)]

- LIGO/Virgo: constrains on tidal deformability from GW170817

$$\Lambda_{1.4} = 190^{+390}_{-120}\,, \quad \text{where} \quad \Lambda_M = \tfrac{2}{3}k_2\left(c^2 R/(G\,M)\right)^5$$

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

- NICER: constrain on radius of PSR J0030+0451 ($f \approx 205$Hz)

$$M = 1.34^{+0.15}_{-0.16}\,(1.44^{+0.15}_{-0.14})M_{\odot}\,, \quad R = 12.71^{+1.14}_{-1.19}\,(13.02^{+1.24}_{-1.06})\text{km}$$

[Riley et al. arXiv:1912.05702, (Miller et al. arXiv:1912.05705)]

- From X-ray bursts of accreting neutron star 4U1702-429

$$M = 1.9^{+0.3}_{-0.3}\,M_{\odot}\,, \quad R = 12.4^{+0.4}_{-0.4}\text{km}$$

[Nättilä et al. arXiv:1709.09120]

V-QCD without baryons (I)

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

$$S^{(0)}_{\mathrm{V-QCD}} = S_{\mathrm{glue}} + S^{(0)}_{\mathrm{DBI}}\,.$$

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

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

where $\lambda \equiv e^{\phi} \leftrightarrow \mathrm{Tr}F^2$ ($\approx g^2 N_c$ near the boundary) sources the 't Hooft coupling in YM theory, the dilaton potential is chosen[1] to mimic QCD

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

Finite T is implemented by homogeneous+isotropic black brane metric

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

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

V-QCD without baryons (II)

The flavor part is modelled by the tachyonic DBI-action[2]

$$S_{\rm DBI}^{(0)} = -N_f N_c M^3 \int d^5x\, V_{f0}(\lambda) e^{-\tau^2} \sqrt{-\det\left[g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab}\right]}\,,$$

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

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

Several potentials: $\{V_g(\lambda), V_{f0}(\lambda), w(\lambda), \kappa(\lambda)\}$, chosen to match pQCD in UV ($\lambda \to 0$), qualitative agreement with QCD in IR ($\lambda \to \infty$) and tuned to lattice QCD in the middle ($\lambda \sim \mathcal{O}(1)$).

[For details see Appendix B of Ishii, Järvinen, Nijs arXiv:1903.06169]

Different solutions:

without/with horizon $\leftrightarrow$ confined/deconfined phase
without/with tachyon $\leftrightarrow$ chirally symmetric/chirally broken phase

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

Probe baryons in V-QCD

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

[Witten; Gross, Ooguri; ...]

Consider the full non-Abelian brane action $S = S_{\rm DBI} + S_{\rm CS}$ 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.
The Cern-Simons term sources the baryon number for the solitions

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

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

Homogeneous Baryon Ansatz

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

[Rozali, Shieh, Van Raamsdonk, Wu]

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

Immediate consequence: baryon charge integrates to zero?

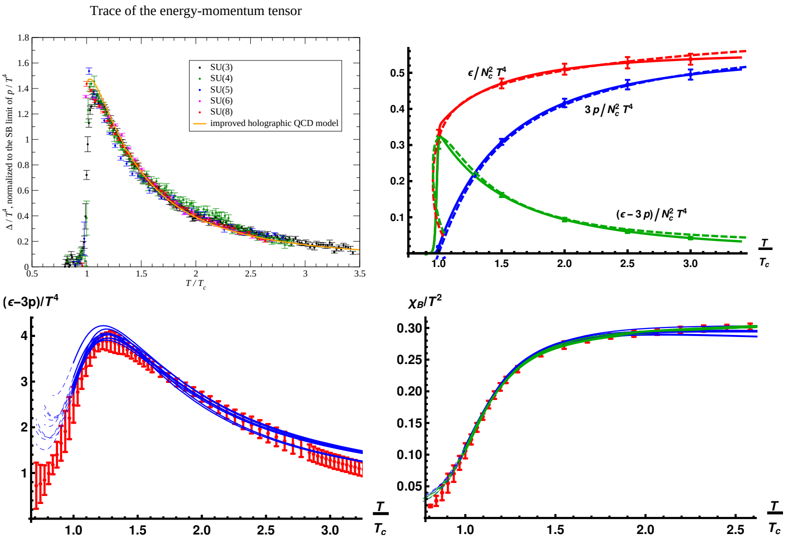
$$N_b \propto \int dr \frac{d}{dr}\left[e^{-b\tau^2} h^3 (1 - 2b\tau^2)\right] \stackrel{?}{=} 0$$

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

[Ishii, Järvinen, Nijs, arXiv:1903.06169]

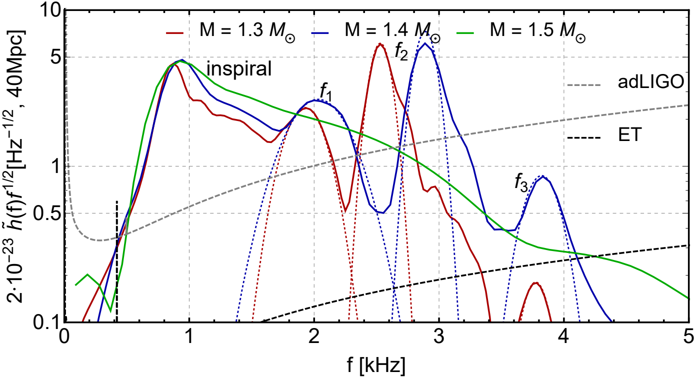
The free parameter b of the model is used to tune the baryon onset to its physical value in QCD.

Matching to Lattice QCD



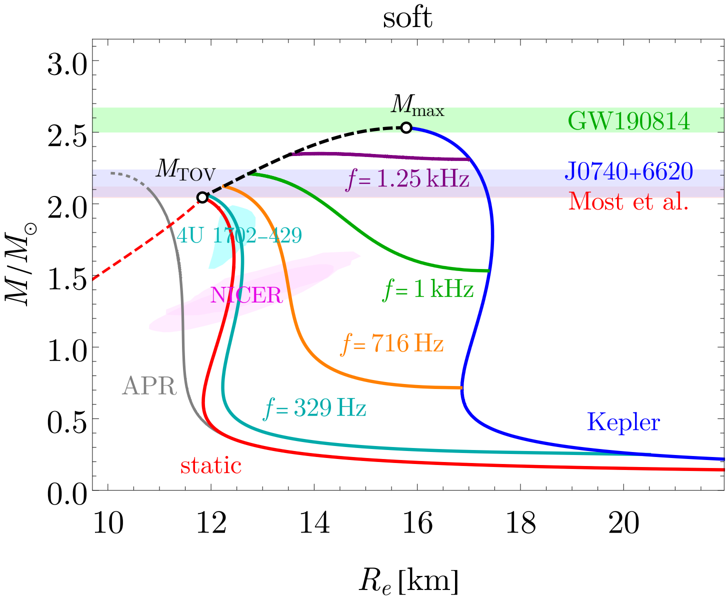
[Panero arXiv:0907.3719; Jokela, Järvinen, Remes arXiv:1809.07770]

Mass dependence of the Power Spectral Density



$M[M_\odot]$	EoS	b	f_1[kHz]	f_2[kHz]	f_3[kHz]
1.30	SLyVQCD105	10.5	1.93	2.53	3.77
1.35	SLyVQCD105	10.5	1.95	2.60	3.53 (3.90)
1.40	SLyVQCD105	10.5	2.03	2.89	3.82
1.50	SLyVQCD105	10.5	–	–	–

Mass Radius Relation



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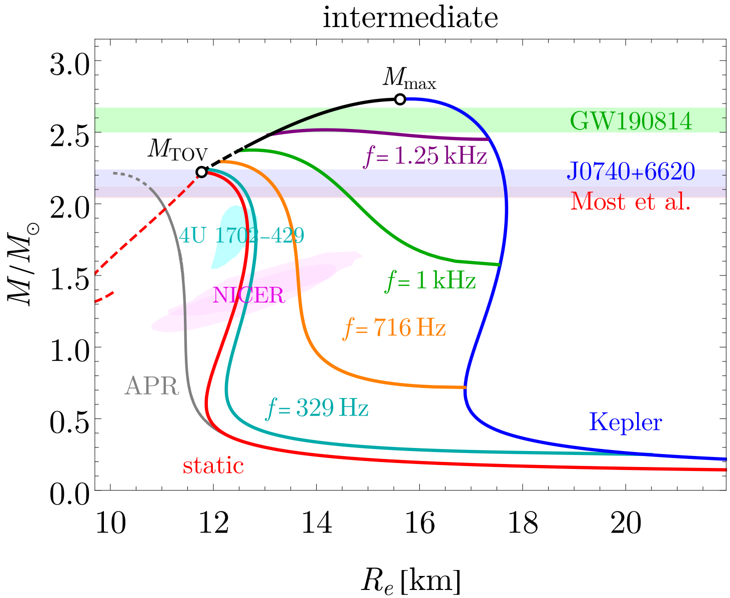
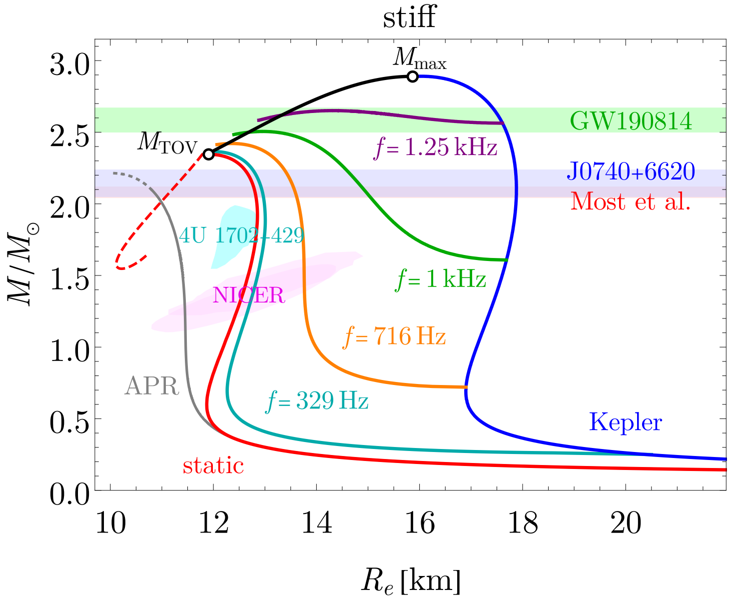
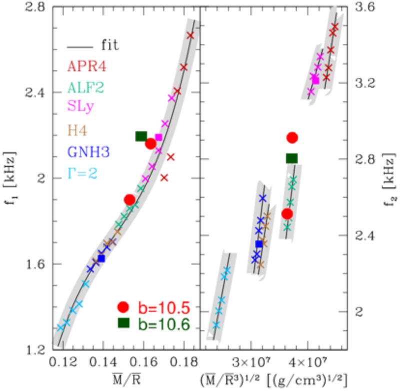


Mass Radius Relation

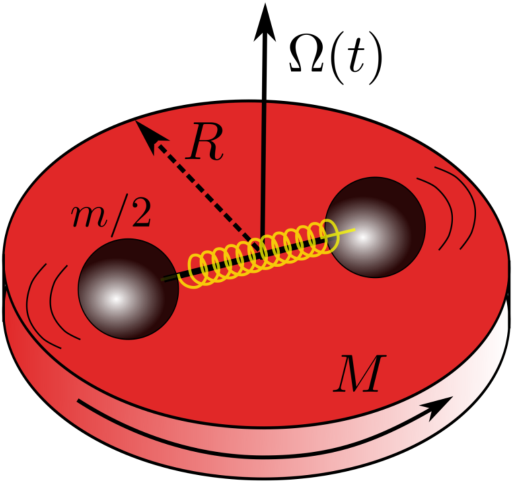


Universality



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

Mechanical Toy Model

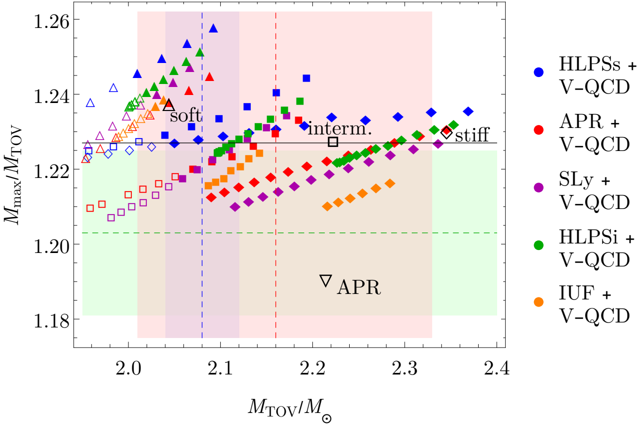


[Takami, Rezzolla, Baiotti arXiv:1412.3240]

Maximum Mass

Using a large number of viable V-QCD hybrids with phase transition gives

$$\frac{M_{\max}}{M_{\mathrm{TOV}}} = 1.227^{+0.031}_{-0.016}\,, \quad \mathrm{Max}(M_{\mathrm{TOV}}) \approx 2.4 M_\odot\,, \quad \mathrm{Max}(M_{\max}) \approx 2.9 M_\odot$$



(red band) Upper bound from GRB 170817A: $M_{\mathrm{TOV}}/M_\odot \lesssim 2.16^{+0.17}_{-0.15}$.
[Rezzolla, Most, Weih arXiv:1711.00314]

(blue band) Lower bound assuming NS in GW190814: $M_{\mathrm{TOV}}/M_\odot > 2.08^{+0.04}_{-0.04}$.
[Most, Papenfort, Weih, Rezzolla arXiv:2006.14601]

GW190814

- Binary merger of a black hole and compact secondary object:

$$m_1 = 23.2^{+1.1}_{-1.0}\,\mathrm{M}_\odot\,, \quad m_2 = 2.59^{+0.08}_{-0.09}\,\mathrm{M}_\odot\,.$$

[The LIGO Scientific Collaboration, the Virgo Collaboration arXiv:2006.12611]

- Secondary component falls into so-called mass-gap region: either the heaviest NS or the lightest BH ever observed.
- m_2 is likely too large to be non-rotating, cf. V-QCD: $M_{\mathrm{TOV}}^{\mathrm{max}} \approx 2.4 M_\odot$.
- Does the V-QCD model allow it to be a spinning NS?
- If this is the case, how fast does it need to rotate?