

Neutronsterne als Labor für dichte Kernmaterie

Christian Ecker

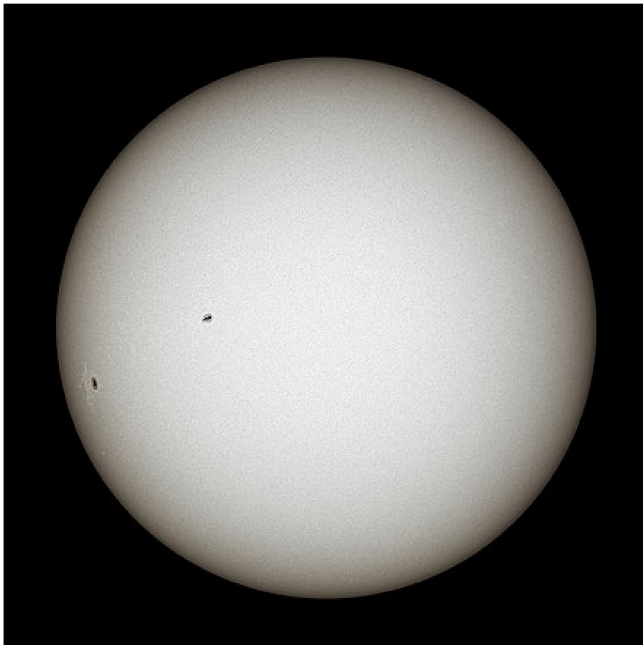


DPG-Fortbildung: Gravitationswellen-Astronomie
28 Juni 2023, Bad Honnef

Überblick

1. Neutronensterne
2. Gravitation
3. Stark Wechselwirkende Materie
4. Zustandsgleichung
5. Neutronensternmerger
6. Beispiel

1. Neutronensterne



$$M = 1 M_{\odot} \approx 2 \cdot 10^{30} \text{ kg}$$

$$R \approx 700.000 \text{ km}$$

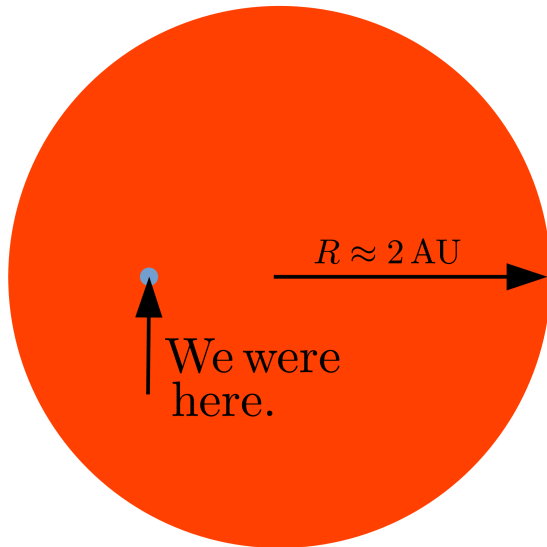


$H + \text{Gravitation}$

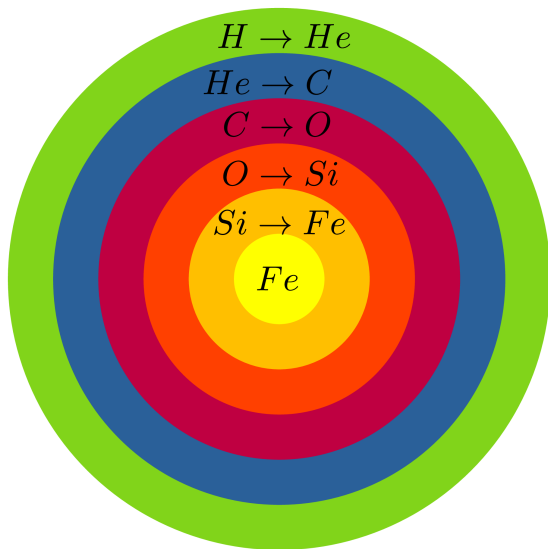


$He + \text{Wärme}$

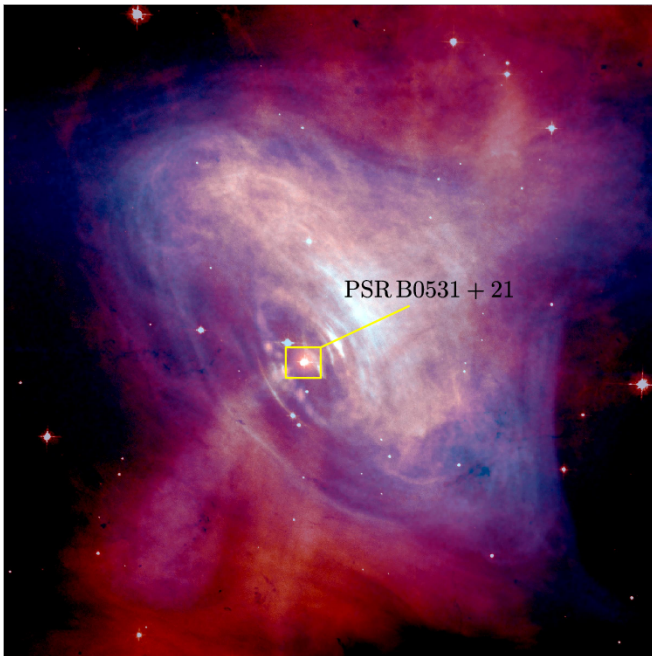
5 Milliarden Jahre Später

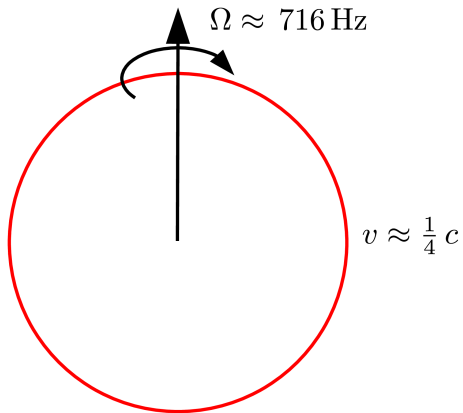


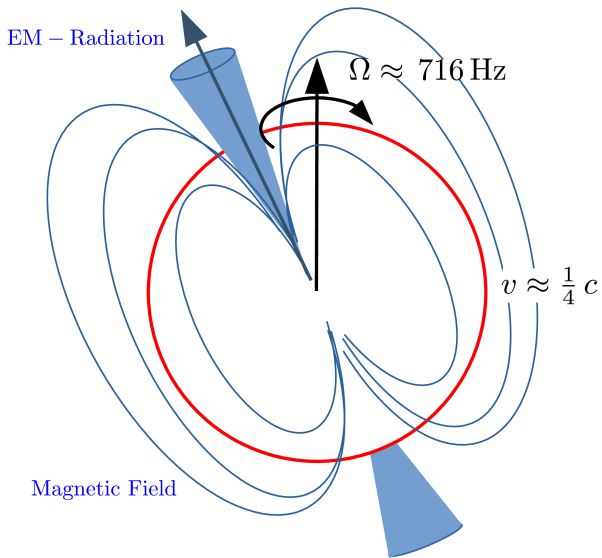
$$M = 8 - 25 M_{\odot}$$

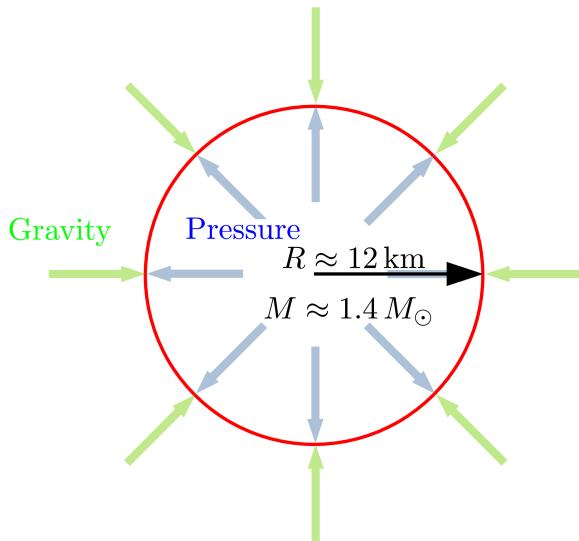




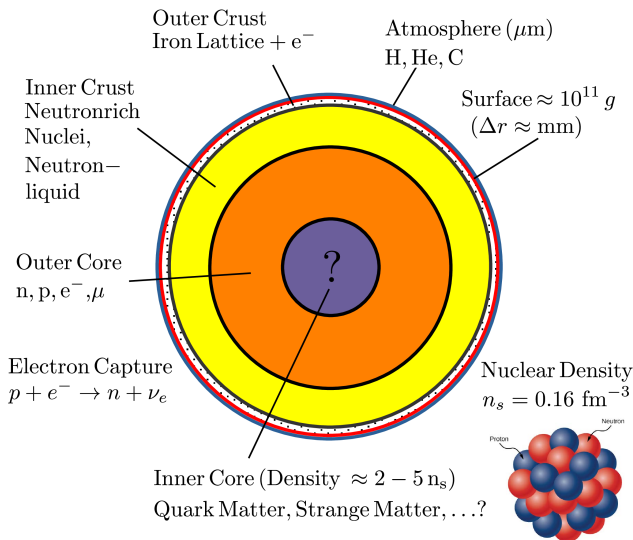


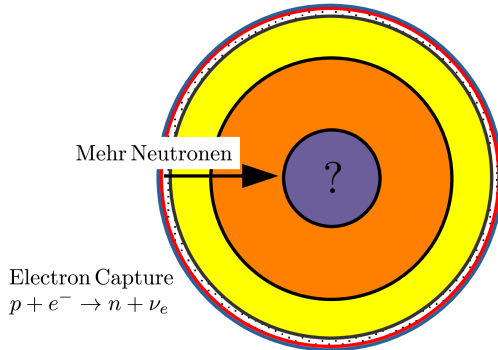




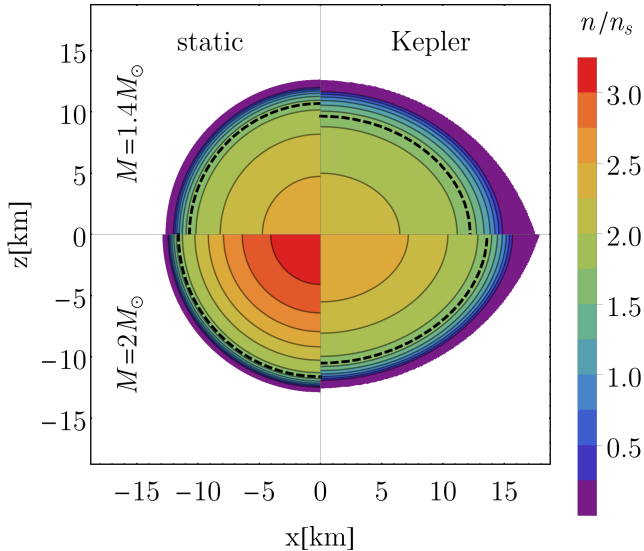






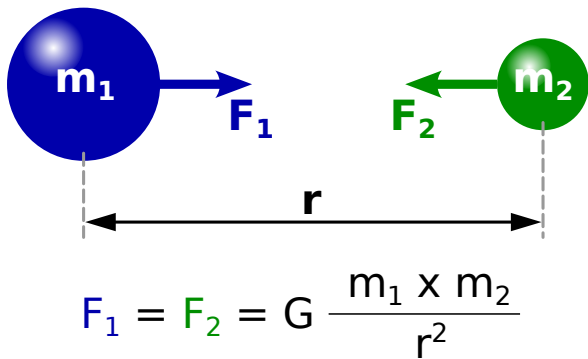


Dichteprofil



2. Gravitation

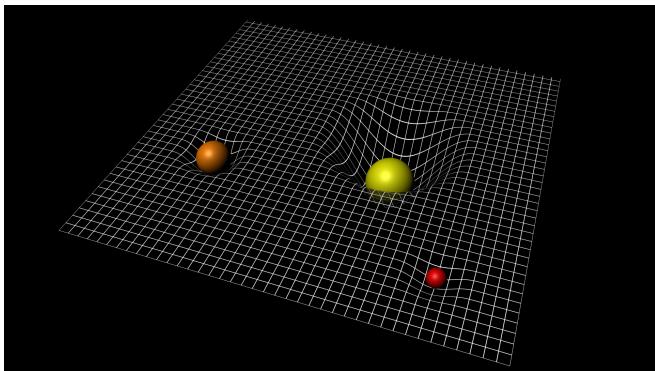
Newton's Gravitation (1687)



Einsteins Allgemeine Relativitätstheorie (1915)

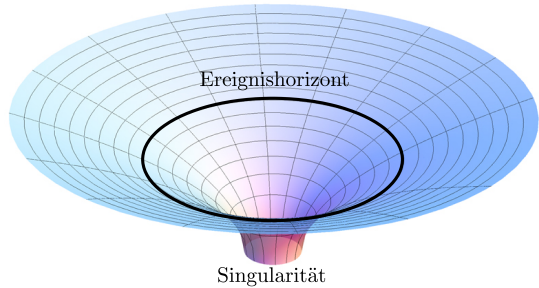
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G_N T_{\mu\nu} .$$

Verteilung von *Materie* bestimmt wie sich Raumzeit krümmt, *Krümmung* der *Raumzeit* bestimmt wie sich *Materie* verteilt.

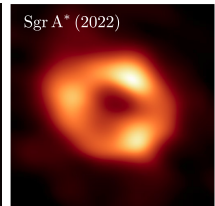
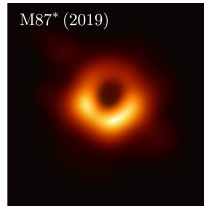
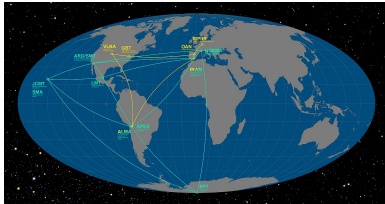


Schwarze Löcher

Karl Schwarzschild

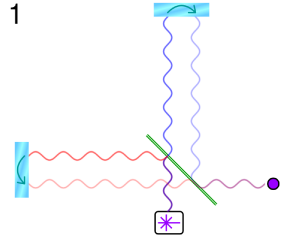
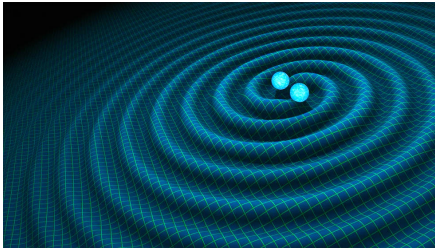
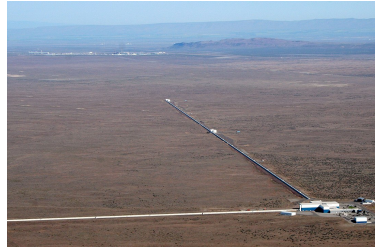


Event Horizon Telescope



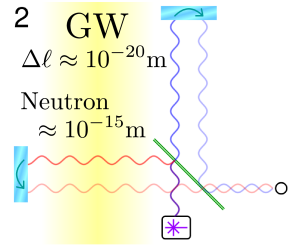
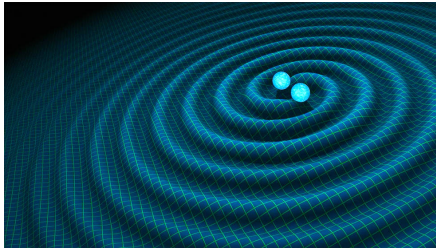
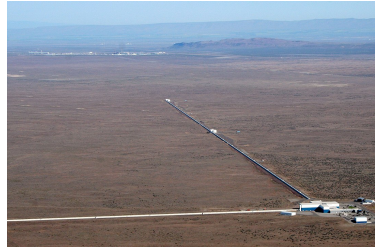
Gravitationswellen

LIGO: Laser Interferometer Gravitational-Wave Observatory



Gravitationswellen

LIGO: Laser Interferometer Gravitational-Wave Observatory



Hulse-Taylor Binärpulsar: PSR B1913+16

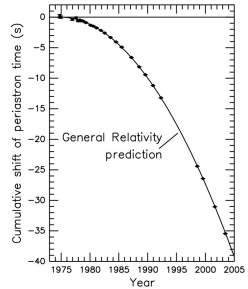
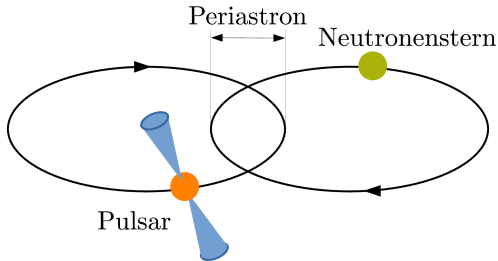


Photo from the Nobel
Foundation archive.
Russell A. Hulse
Prize share: 1/2



Photo from the Nobel
Foundation archive.
Joseph H. Taylor Jr.
Prize share: 1/2



Hulse-Taylor Binärpulsar: PSR B1913+16

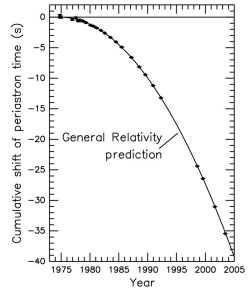
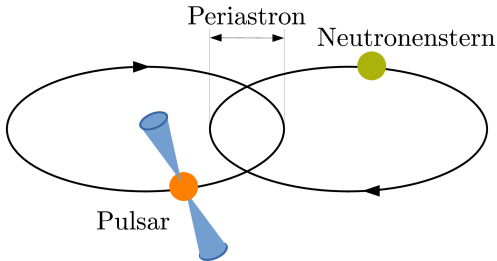


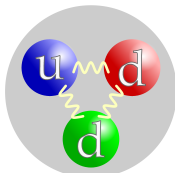
Photo from the Nobel
Foundation archive.
Russell A. Hulse
Prize share: 1/2



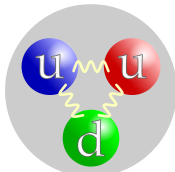
Photo from the Nobel
Foundation archive.
Joseph H. Taylor Jr.
Prize share: 1/2



3. Stark Wechselwirkende Materie



Neutron



Proton

Standard Model of Elementary Particles

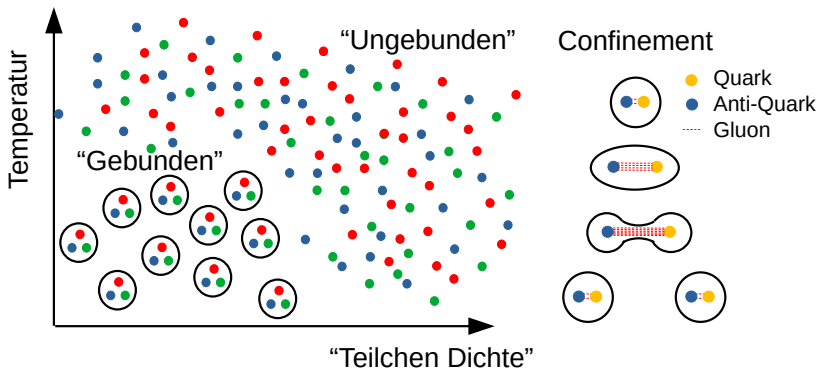
	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
QUARKS	mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ up	mass $\approx 1.28 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ charm	mass $\approx 173.1 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ top	mass 0 charge 0 spin 1 gluon	mass $\approx 124.97 \text{ GeV}/c^2$ charge 0 spin 0 higgs
	mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ down	mass $\approx 96 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ bottom	mass 0 charge 0 spin 1 photon	
	mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ electron	mass $\approx 105.66 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ tau	mass $\approx 91.19 \text{ GeV}/c^2$ charge 0 spin 1 Z boson	
LEPTONS	mass $< 1.0 \text{ eV}/c^2$ charge 0 spin $\frac{1}{2}$ electron neutrino	mass $< 0.17 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ charge ± 1 spin 1 W boson	
				mass $\approx 80.39 \text{ GeV}/c^2$ charge ± 1 spin 1 W boson	

SCALAR BOSONS

Gauge Bosons
Vector Bosons

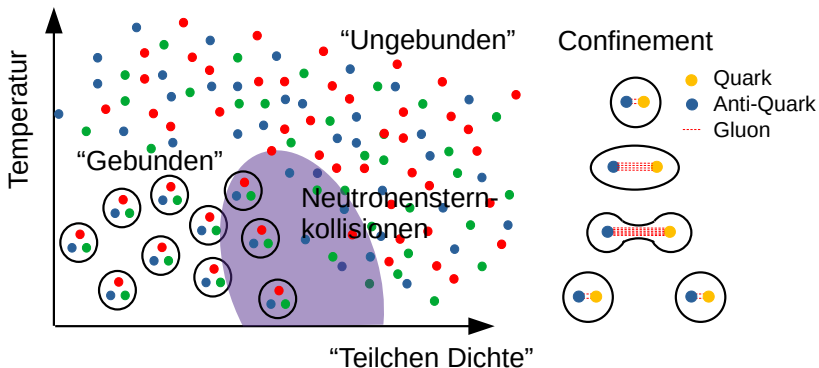
Das QCD Phasen Diagramm

Theorie der Starken Wechselwirkung: Quantenchromodynamik (QCD)
Abstoßung/Anziehung durch Gluonenaustausch farbgeladener Quarks.

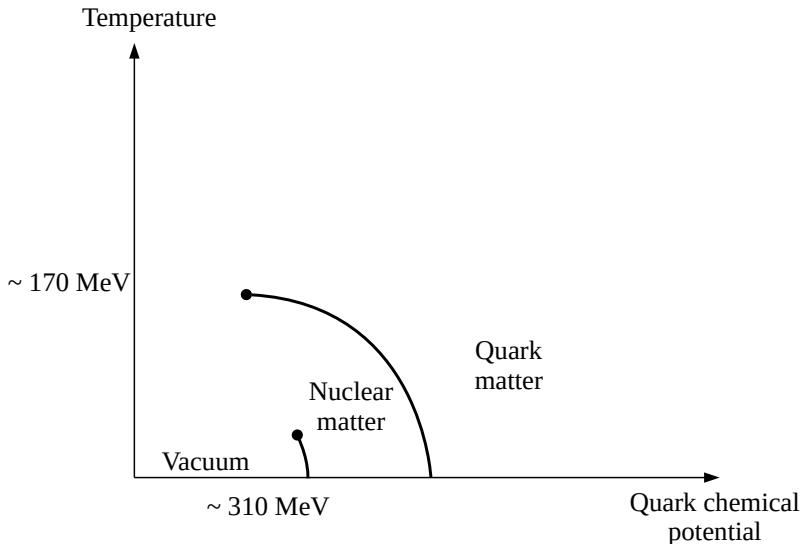


Das QCD Phasen Diagramm

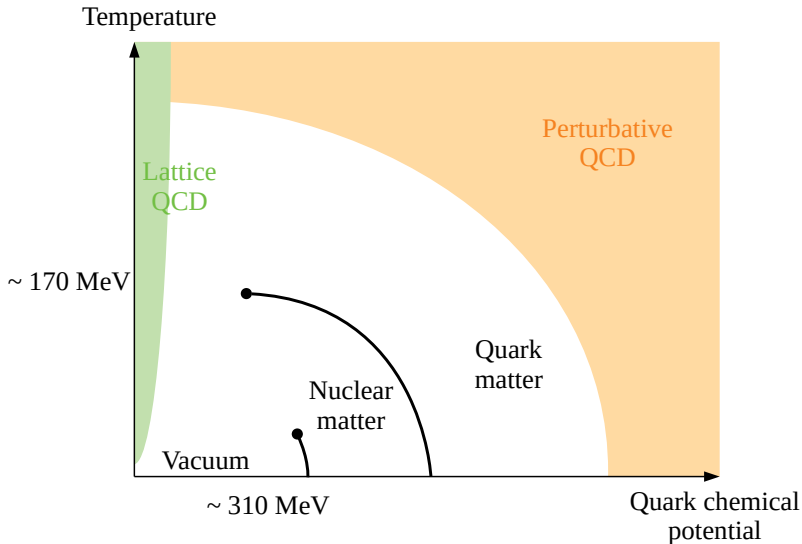
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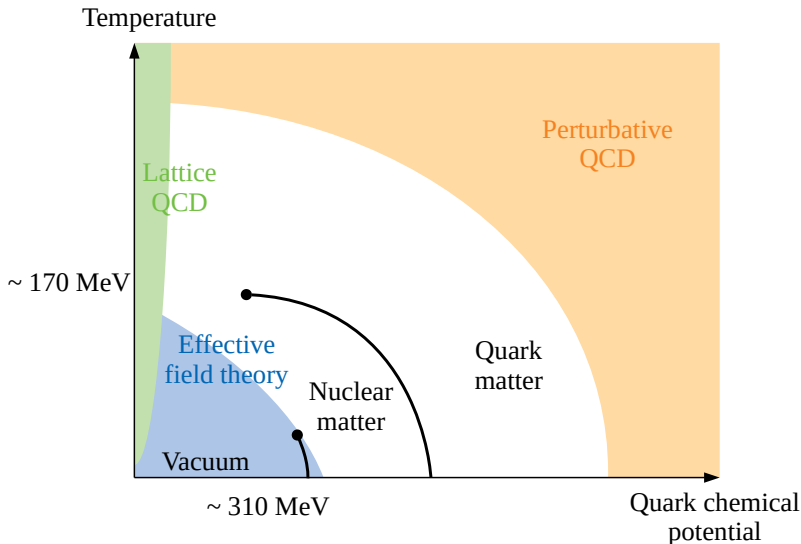
Was man (nicht) über QCD weiss



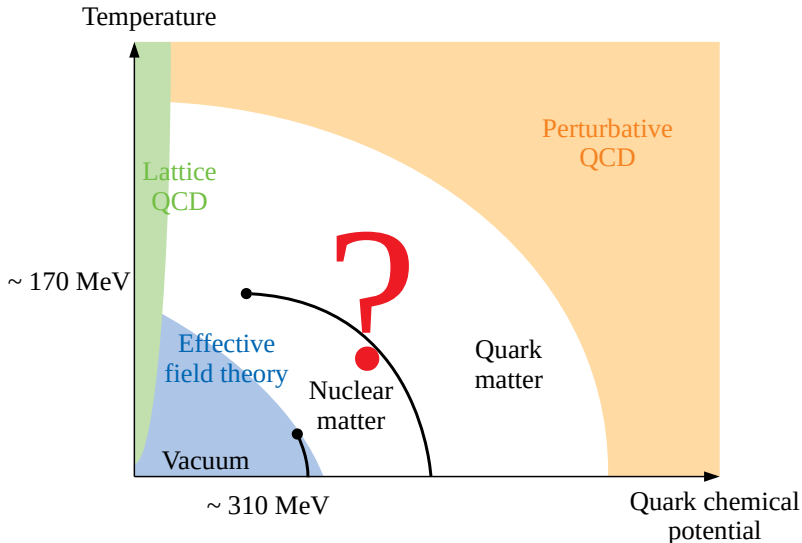
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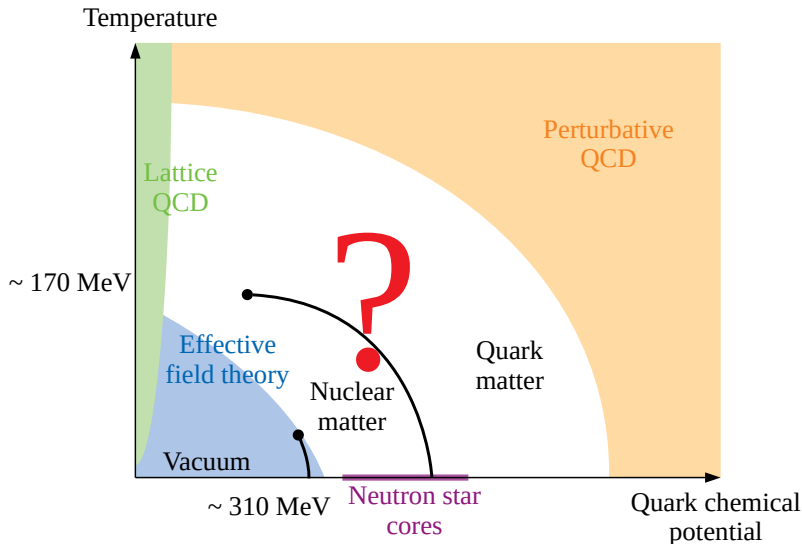
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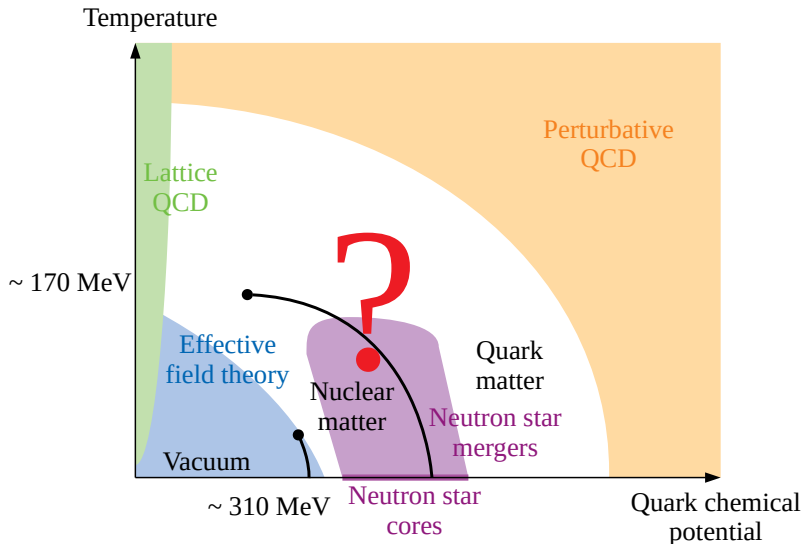
Was man (nicht) über QCD weiss



Was man (nicht) über QCD weiss



Was man (nicht) über QCD weiss



4. Zustandsgleichung

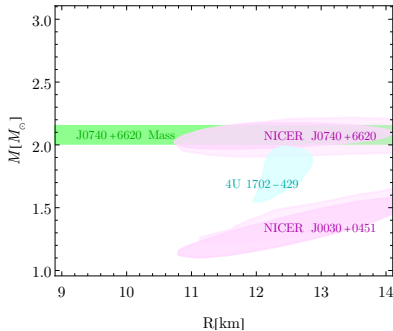
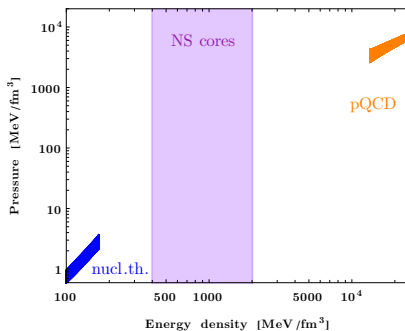
Equation of State

Relates properties of dense matter to properties of neutron stars.

$$p = p(e, \dots) \xrightarrow{\text{Einstein Eq.}} M(R)$$

Constrained by theory and neutron star observations:

- ▶ Causality & thermodynamic stability: $0 < c_s^2 = \frac{dp}{de} < 1$
- ▶ Direct mass and radius measurements: $M_{\text{TOV}} \gtrsim 2 M_{\odot}$, $11 \text{ km} \lesssim R \lesssim 14 \text{ km}$
- ▶ First GW detection from a BNS merger GW170817: $\tilde{\Lambda} \lesssim 720$



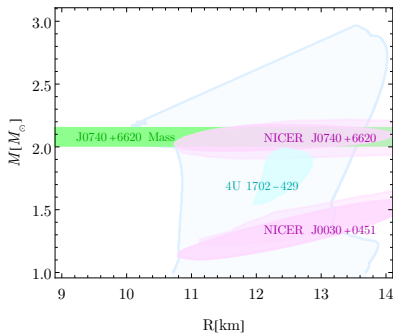
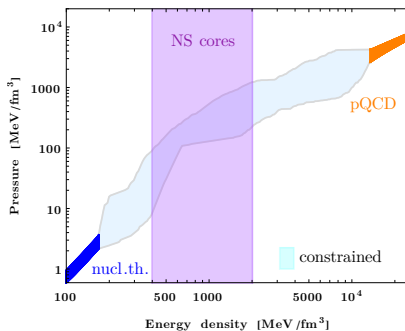
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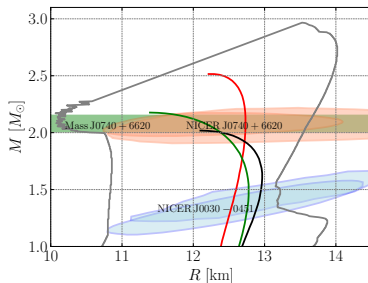
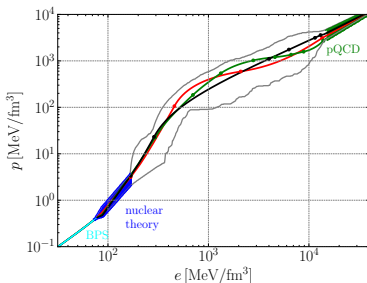
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Altıparmak, CE, Rezzolla arXiv:2203.14974 (ApJL)

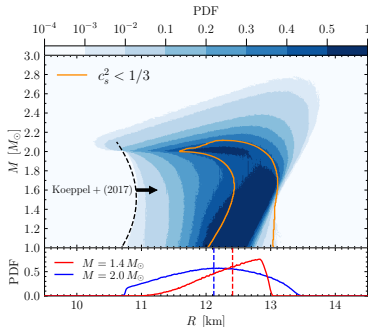
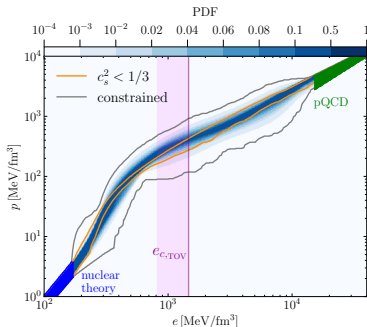
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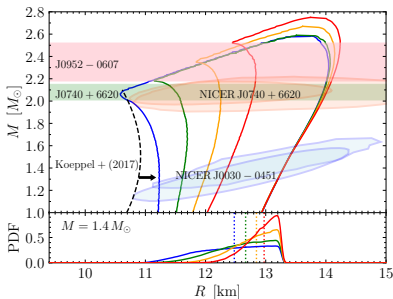
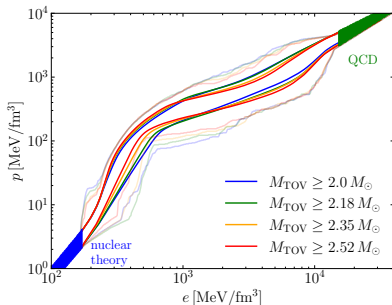
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Black-Widow Binary Pulsar PSR J0952-0607

- Massereichster bekannter NS: $M = 2.35 \pm 0.17 M_{\odot}$ (hohe Ungenauigkeit!)

Romani, Kandel, Filippenko, Brink, Zheng arXiv:2207.05124 (ApJL),
 PSR J2215+5135 ($M = 2.27^{+0.17}_{-0.15} M_{\odot}$) Linares, Shahbaz, Casares arXiv:1805.08799 (ApJ)



CE, Rezzolla arXiv:2209.08101 (MNRAS)

Schallgeschwindigkeit in Neutronensternmaterie

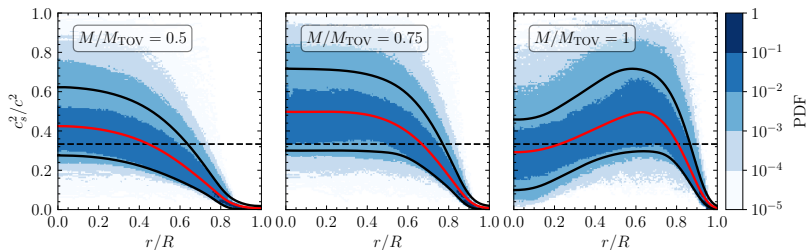
- Die Schallgeschwindigkeit ist ein Mass für die Steifigkeit von Materie:

hohe (geringe) Schallgeschwindigkeit

=

hoher (geringer) Widerstand gegen Gravitationsanziehung

$$c_s^2 = \left(\frac{\partial p}{\partial e} \right)_s . \quad (1)$$



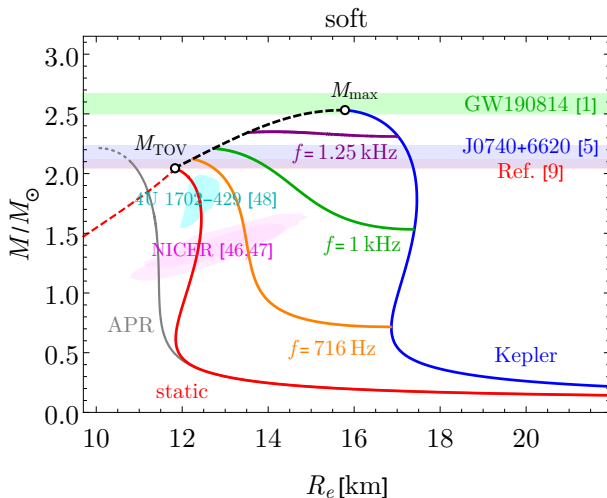
- Leichte Sterne:** harter Kern, weiche Hülle.
- Typische Sterne:** großer harter Kern.
- Massive Sterne:** weicher Kern, harte Hülle.

CE, Rezzolla arXiv:2207.04417 (ApJL)

Masse-Radius Beziehung Rotierender Sterne

Universelles Verhältnis: $\frac{M_{\max}}{M_{\text{TOV}}} \approx 1.2$

Breu, Rezzolla arXiv:1601.06083 (MNRAS)

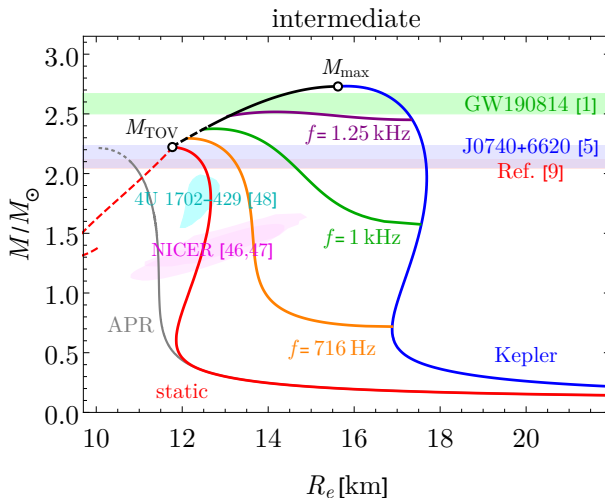


Demircik, CE, Järvinen arXiv:2009.10731 (ApJL)

Masse-Radius Beziehung Rotierender Sterne

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Breu, Rezzolla arXiv:1601.06083 (MNRAS)

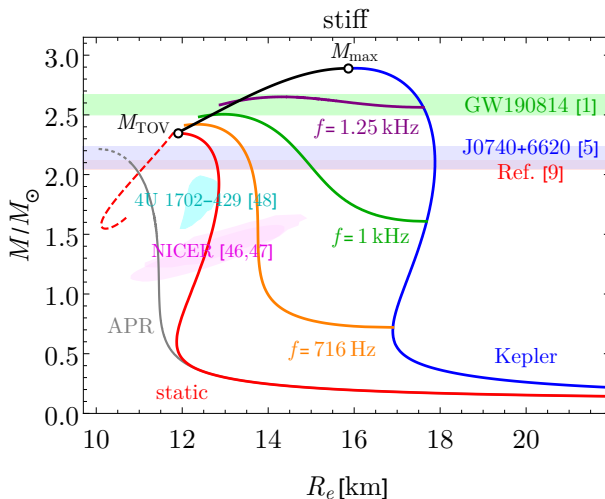


Demircik, CE, Järvinen arXiv:2009.10731 (ApJL)

Masse-Radius Beziehung Rotierender Sterne

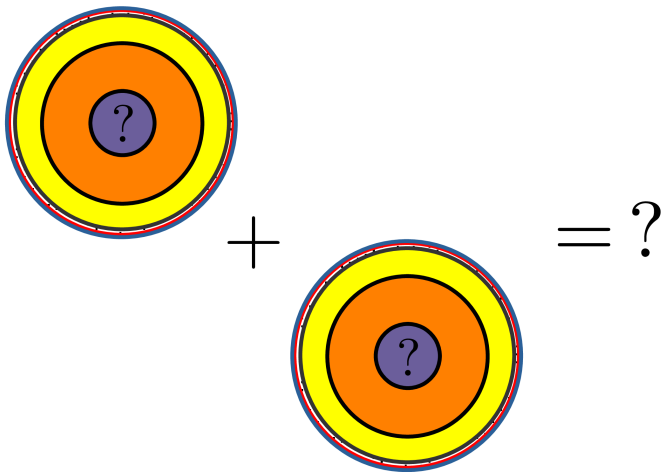
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Breu, Rezzolla arXiv:1601.06083 (MNRAS)



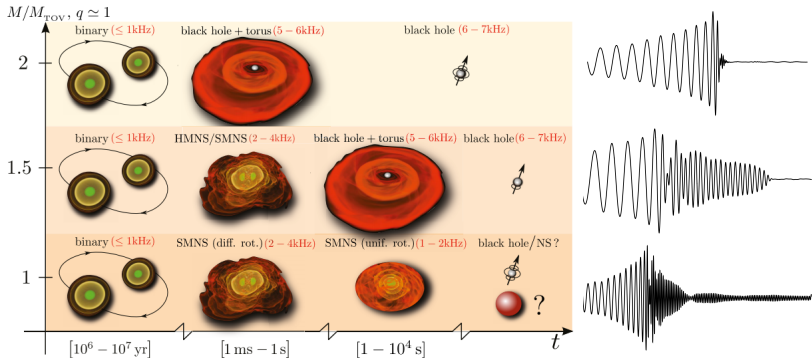
Demircik, CE, Järvinen arXiv:2009.10731 (ApJL)

5. Neutronenstermerger



Neutronensternkollisionen

- Quelle für Gravitationswellen.
- Information über dichte Kernmaterie in GW and EM Signal.
- Wahrscheinlicher Ursprung von Short Gamma-Ray Bursts
- und schwerer Elemente wie Gold, Platin, Uranium, ...

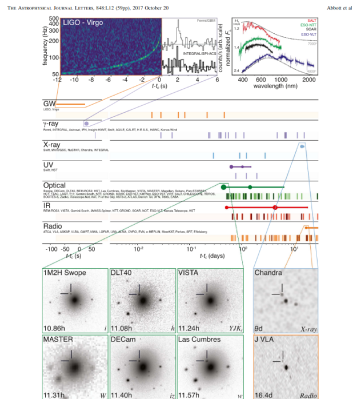
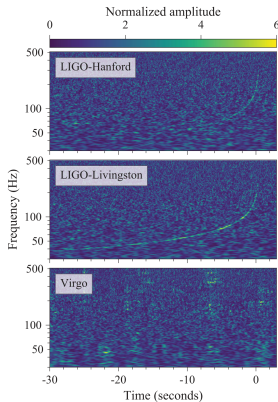


Picture: Baiotti, Rezzola 1607.03540 (Rept.Prog.Phys.)

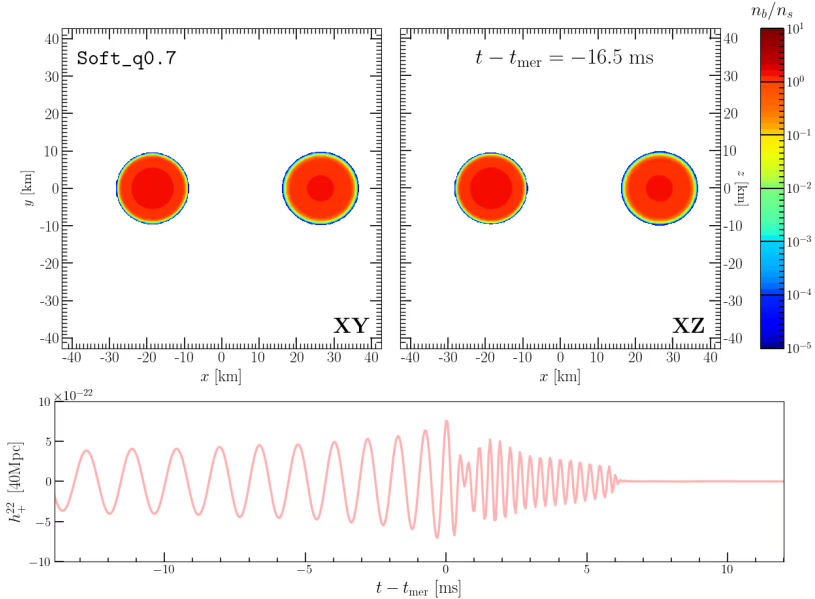
GW170817

- Seen on multiple wavelengths and time-scales: GW, optical, X-ray, γ , UV, IR
- $d \approx 40$ Mpc, $\mathcal{M}_{\text{chirp}} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} = 1.188^{+0.004}_{-0.002} M_{\odot}$, $q = M_2/M_1 > 0.73$.
- Inspiral (but no post-merger) waveform: $\tilde{\Lambda} \lesssim 720$

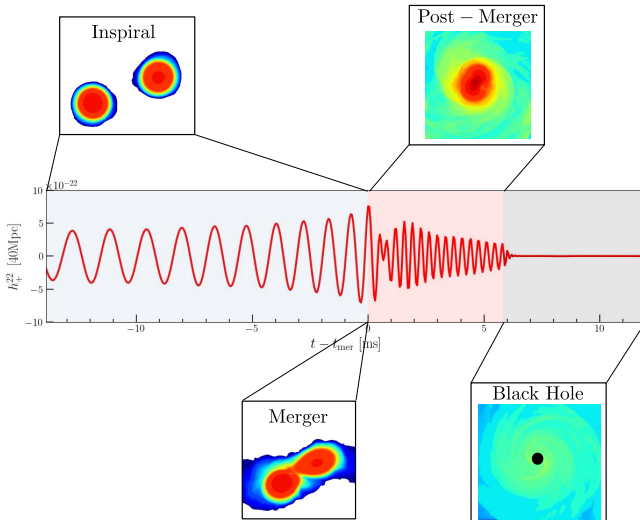
LIGO/Virgo arXiv:1805.11579 (PRX)



LIGO/Virgo arXiv:1710.05832 (PRL), arXiv:1710.05834 (ApJL)

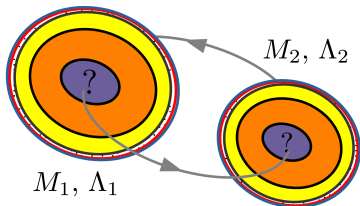


Movie by Konrad Topolski with data from [arXiv:2205.05691](https://arxiv.org/abs/2205.05691) (SciPost).



- ▶ Inspiral: $f \approx 100\text{s Hz}$.
- ▶ Post-Merger: $f \approx \text{kHz}$.
- ▶ Black Hole: exponentieller "ring-down" $f \rightarrow 0$.

Inspiral: Chirp Mass and Binary Tidal Deformability



- Chirp mass can be extracted accurately from inspiral GW strain frequency

$$\mathcal{M}_{chirp} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} = \left(\frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right)^{3/5}.$$

- Binary tidal deformability encodes EOS properties via Λ_i

$$\tilde{\Lambda} = \frac{16}{13} \frac{(12M_2 + M_1) M_1^4 \Lambda_1 + (12M_1 + M_2) M_2^4 \Lambda_2}{(M_1 + M_2)^5}, \quad \Lambda_i = \frac{2}{3} k_2 (R_i/M_i)^5.$$

- GW170817 only “good” event so far:

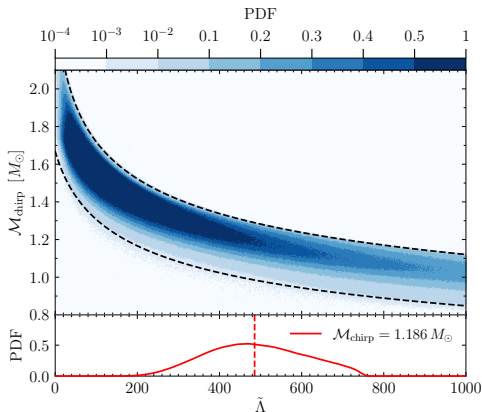
$$\mathcal{M}_{chirp} = 1.188^{+0.004}_{-0.002} M_{\odot}, \quad q = M_2/M_1 > 0.7, \quad \tilde{\Lambda} \lesssim 720.$$

Binary Tidal Deformability

- More than 10^8 binary configurations with $M_{1,2} \in [0.5M_\odot, M_{\text{TOV}}]$.

$$\tilde{\Lambda}_{\min(\max)} = a + b \mathcal{M}_{\text{chirp}}^c \longrightarrow \tilde{\Lambda}_{1.186} = 485_{-211}^{+225},$$

$$a = -50(-20), \quad b = 500(1800), \quad c = -4.5(-5.0).$$



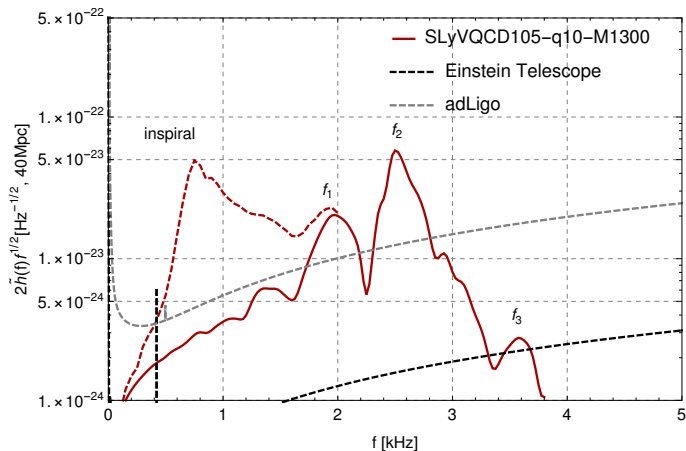
Altiparmak, CE, Rezzolla arXiv:2203.14974 (ApJL)

Post-Merger: Power Spectral Density

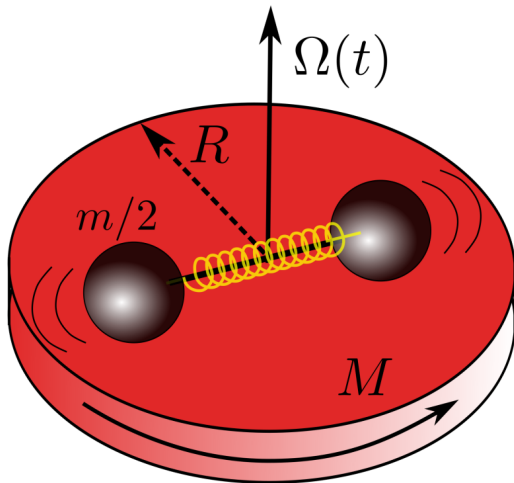
Post-merger power spectral density (PSD) has typical three peak structure

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

Characteristic frequencies f_1 , f_2 , f_3 encode information about EOS.

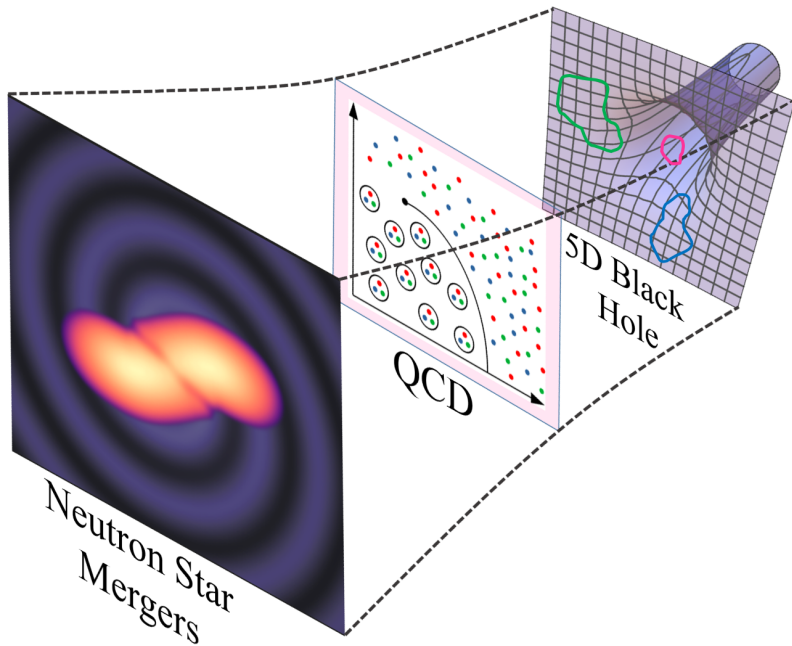


Mechanical Toy Model



Takami, Rezzolla, Baiotti [arXiv:1412.3240](https://arxiv.org/abs/1412.3240)

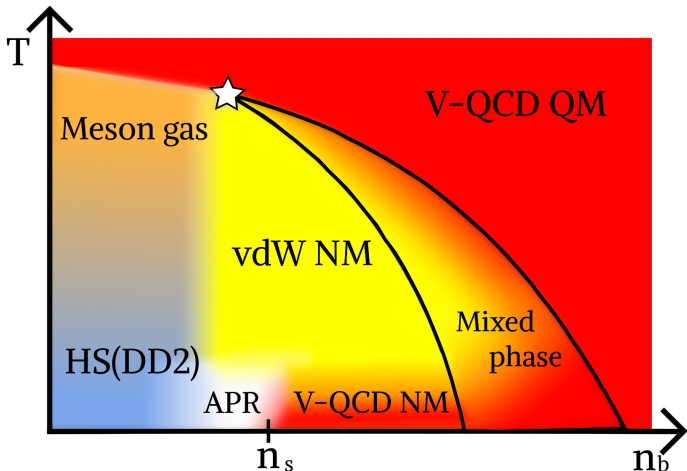
6. Beispiel



Phasendiagramm

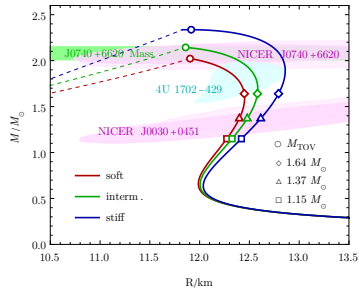
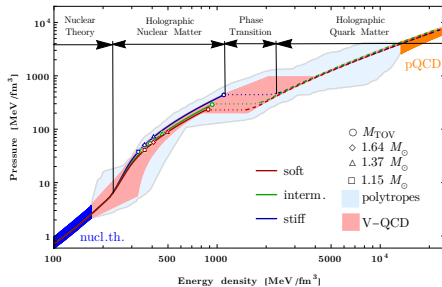
Beschreibung dichter Kern- und Quarkmaterie mit holographischer QCD.

YouTube: <https://www.youtube.com/watch?v=Lv3AJtlaRI0>

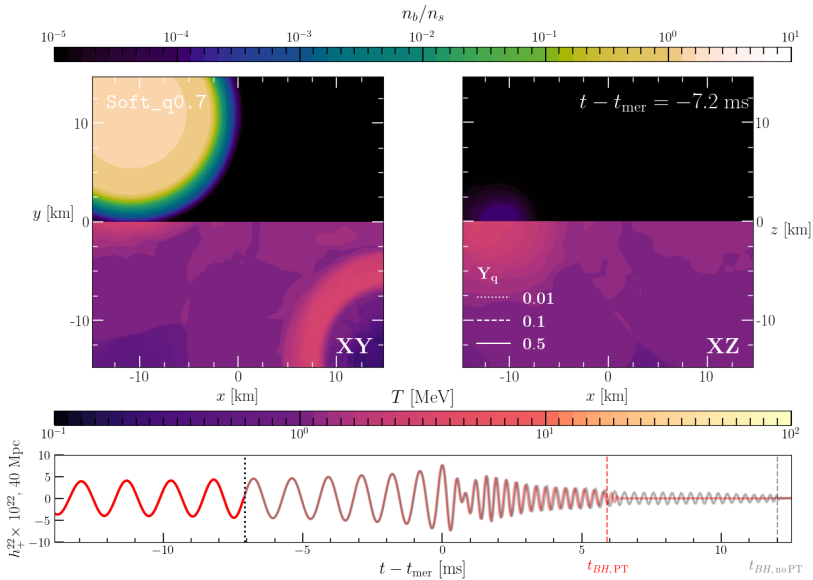


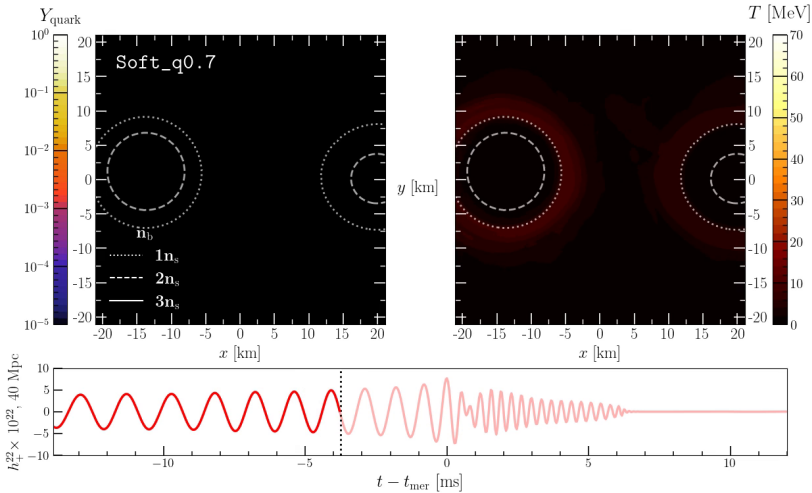
Zustandsgleichung und Masse-Radius Beziehung

- ▶ Zustandsgleichung mit Phasenübergang zwischen Kern- und Quarkmaterie.
- ▶ Eingeschränkt durch Kernphysik/QCD und Neutronensternmessungen.



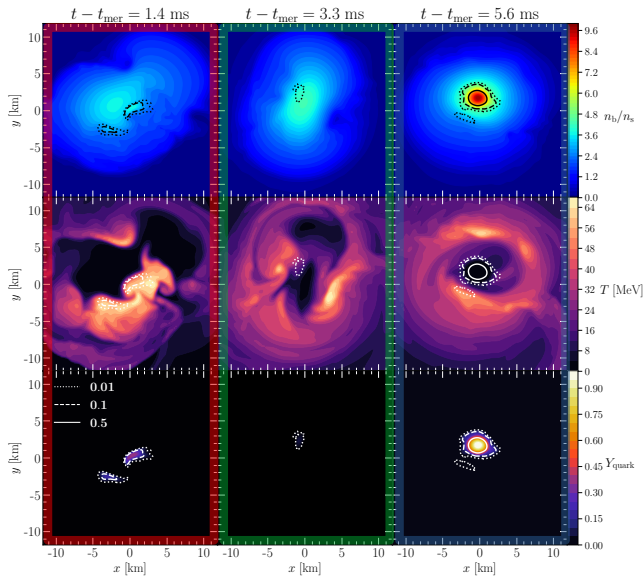
CE, Järvinen, Nijs, van der Schee arXiv:1908.03213 (PRD);
 Jokela, Järvinen, Nijs, Remes arXiv:2006.01141 (JHEP); Demircik, CE, Järvinen arXiv:2112.12157 (PRX)





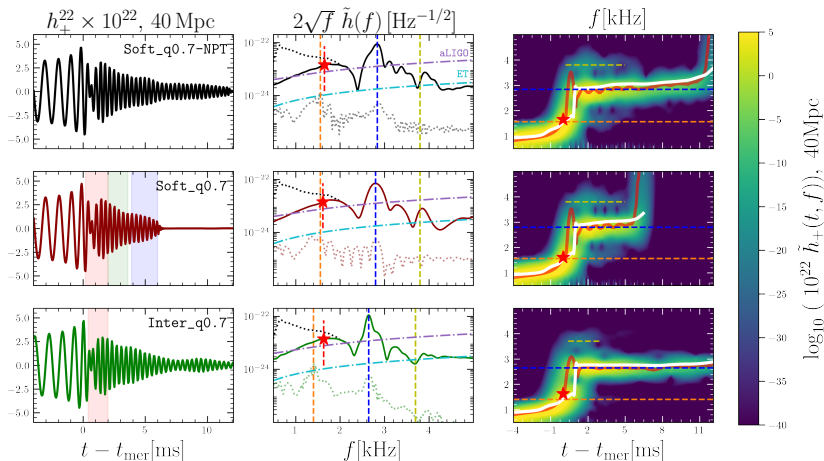
Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla arXiv:2205.05691 (SciPost)

Hot, Warm and Cold Quarks



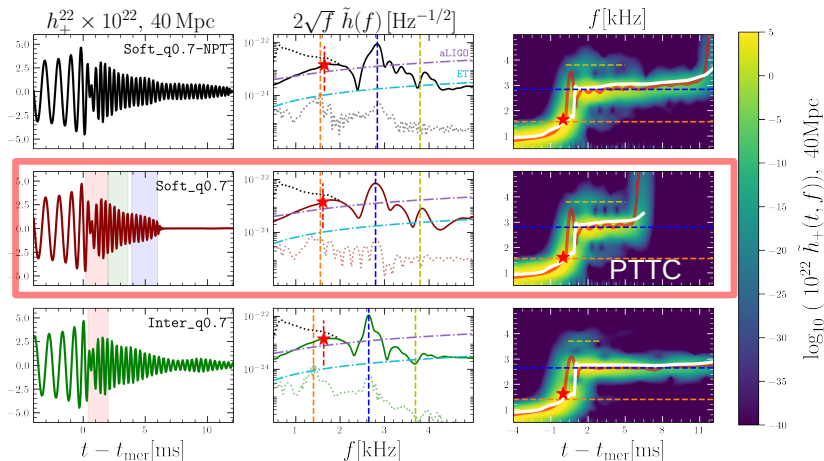
Waveforms and Frequency Spectra

- Small impact of quark matter on post-merger frequencies.



Waveforms and Frequency Spectra

- ▶ Small impact of quark matter on post-merger frequencies.
- ▶ Phase transition triggered collapse (PTTC) leads to shorter lifetime of the hyper massive neutron star (HMNS).



Zusammenfassung

- ▶ Viele Eigenschaften dichter Kernmaterie sind zur Zeit unbekannt: QCD Phasendiagramm, Zustandsgleichung, ...?
- ▶ Messungen von Massen und Radien von Neutronensternen ermöglichen es die Ungewissheit der Zustandsgleichung einzuschränken.
- ▶ Gravitationswellenmessungen von Neutronensternmergern erlauben Einblicke in den dichten und heißen Teil des QCD Phasendiagramms.
- ▶ Mit numerische Simulationen dieser Ereignisse kann man Vorhersagen für diese Gravitationswellen und deren Spektrum machen.
- ▶ Beispiel: holographische Modell für das QCD Phasendiagramm und die Zustandsgleichung.
- ▶ Es kann kalte, warme und heiße Quarkmaterie in Neutronensternkollisionen entstehen.
- ▶ Kleiner Einfluss auf die Post-merger Frequenz aber früherer Kollaps zu einem Schwarzen Loch.