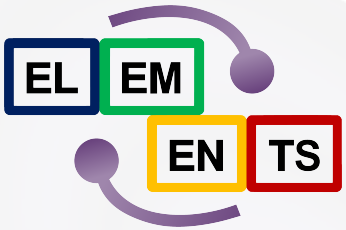
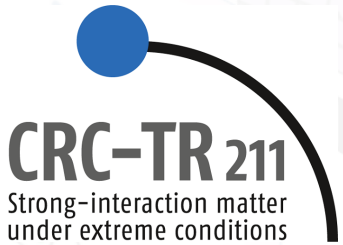
From DKPI to Neutron Star Research

Christian Ecker





DKPI Final Event
28 September 2023

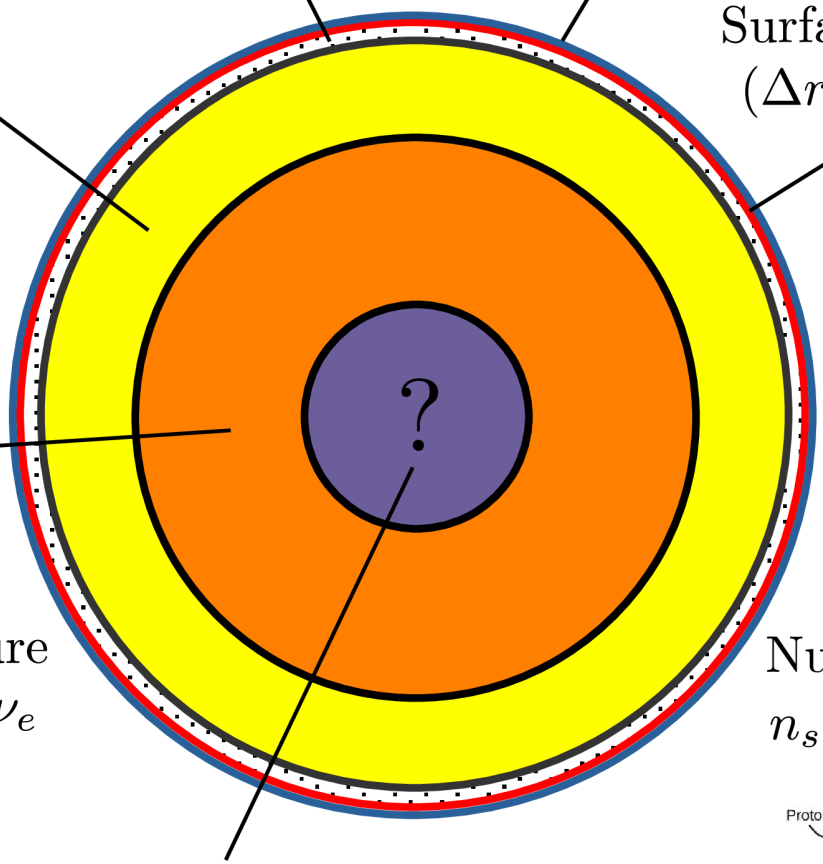
Based on
2009.10731 (ApJL), 2112.12157 (PRX) and 2205.05691 (SciPost) with
Tuna Demircik, Matti Järvinen, Luciano Rezzolla, Samuel Tootle and Konrad Topolski

and

2203.14974 (ApJL), 2207.04417 (ApJL) and 2209.08101 (MNRAS) with
Sinan Altiparmak and Luciano Rezzolla

- **2014:** Full member of DKPI, supervisor Daniel Grumiller.
- **2016, 2017:** Research stays at University of Helsinki and Barcelona.
- **2018:** Graduation with thesis on numerical relativity and holography.
- **2018-2020:** Postdoc at Utrecht and Leiden University, holographic QCD.
- **2019:** Invited lecture at DKPI Summer School in Zwettl.
- **since 2020:** Postdoc at Goethe University, Theoretical Astrophysics.
- **since 2021:** Member of the Hessian research cluster ELEMENTS.
- **2020-2022:** Main Campus Educator Program, scientific group leadership.
- **since 2022:** Member of the Collaborative Research Center for Strong-Interaction Matter under Extreme Conditions.

Neutron Stars



Outer Crust
Iron Lattice + e^-

Atmosphere (μm)
H, He, C

Inner Crust
Neutronrich
Nuclei,
Neutron−
liquid

Surface $\approx 10^{11}\ g$
($\Delta r \approx$ mm)

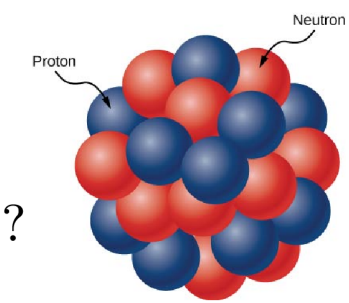
$M \approx 1.4 M_\odot$
$R \approx 12.5$km

Outer Core
n, p, e^-,μ

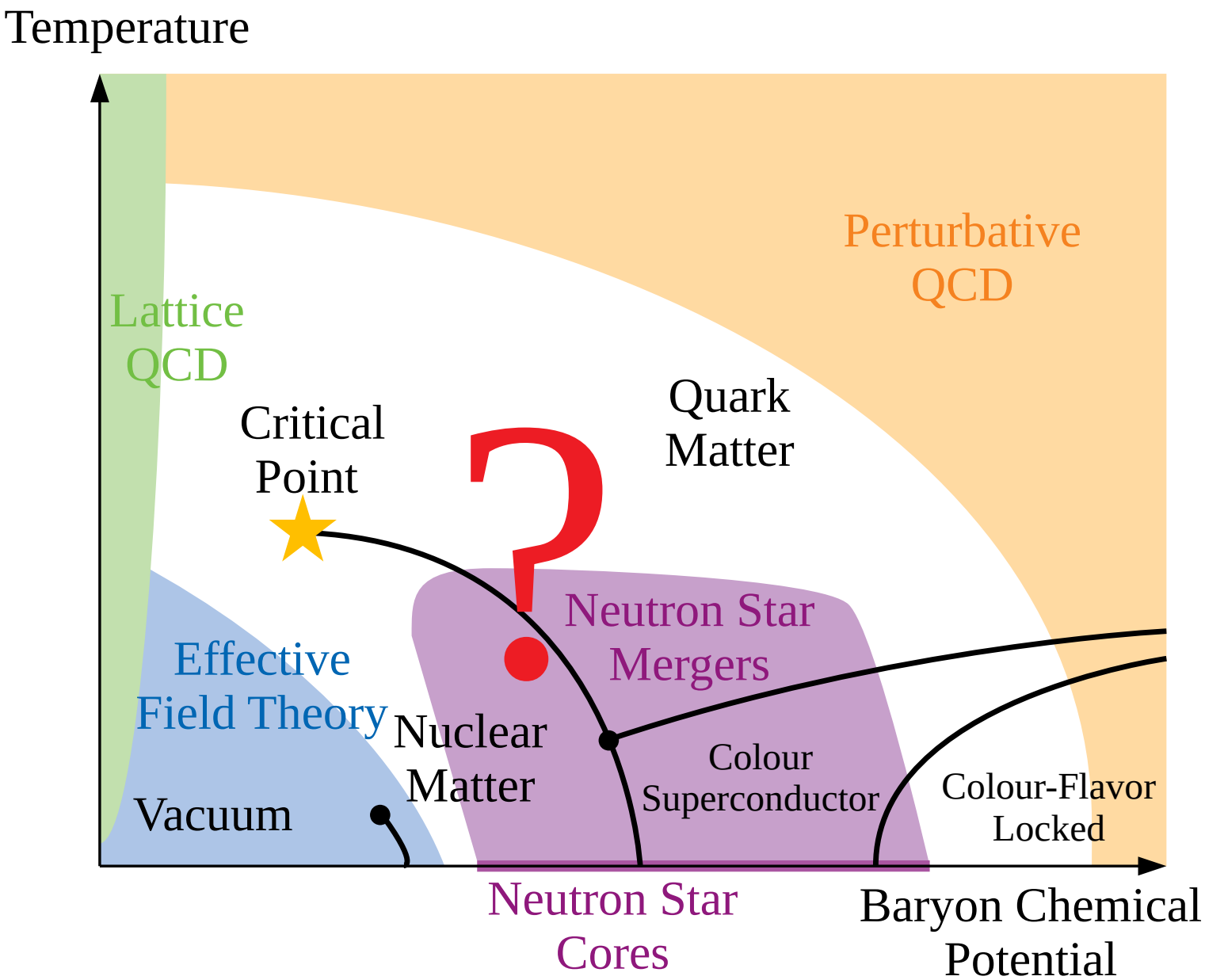
Electron Capture
$p + e^- \rightarrow n + \nu_e$

Nuclear Density
$n_s = 0.16\ \mathrm{fm}^{-3}$

Inner Core (Density $\approx 2 - 5\,\mathrm{n_s}$)
Quark Matter, Strange Matter, . . .?



What we (don't) know about QCD



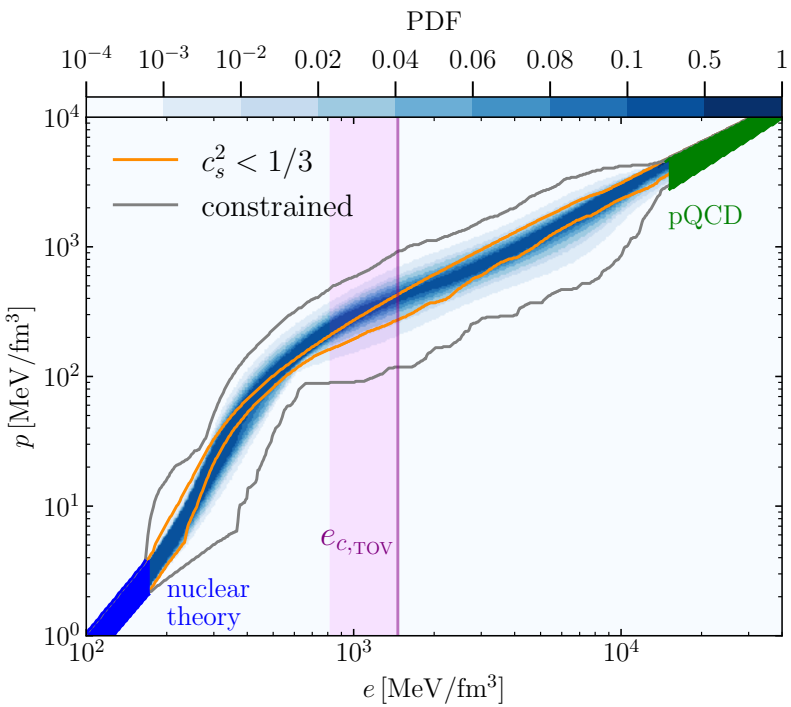
Equation of State and Mass-Radius Relation

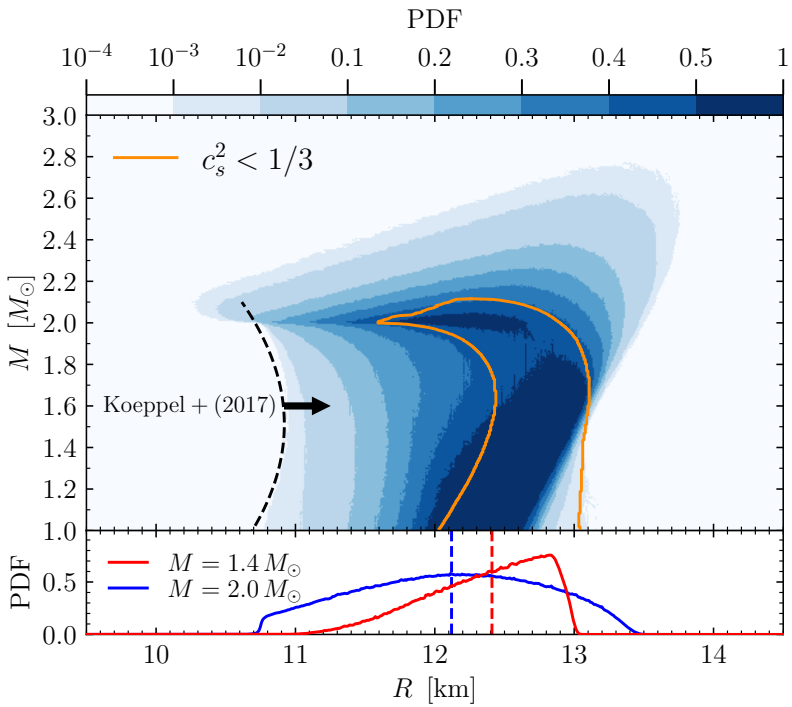
Relates properties of dense matter to properties of neutron stars.

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

Constrained by theory and neutron star observations:

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





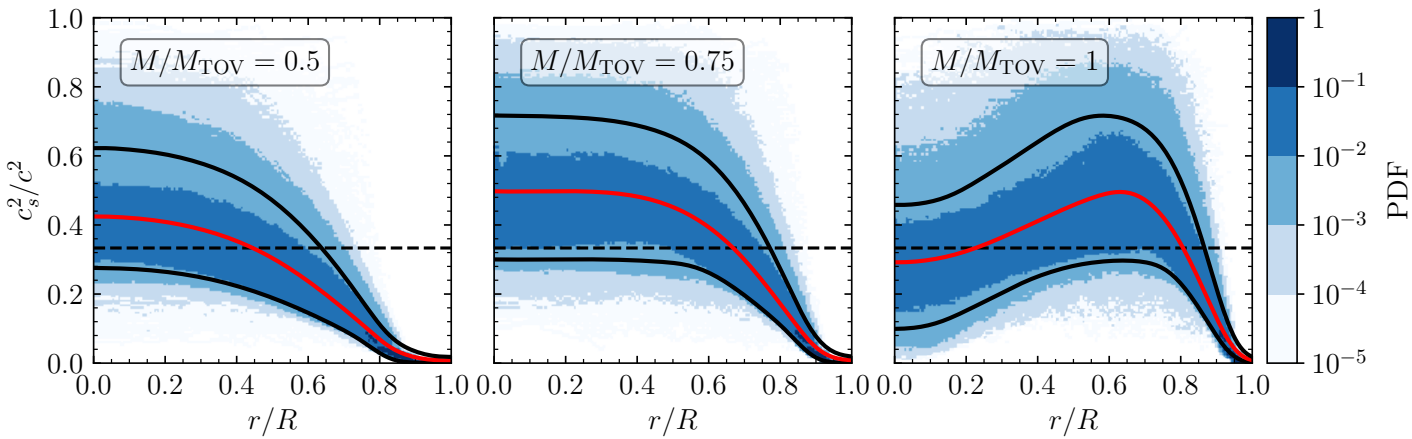
Altiparmak, CE, Rezzolla 2203.14974 (ApJL)

Sound Speed Inside Neutron Stars

- Adiabatic speed of sound provides a measure for the stiffness of matter

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

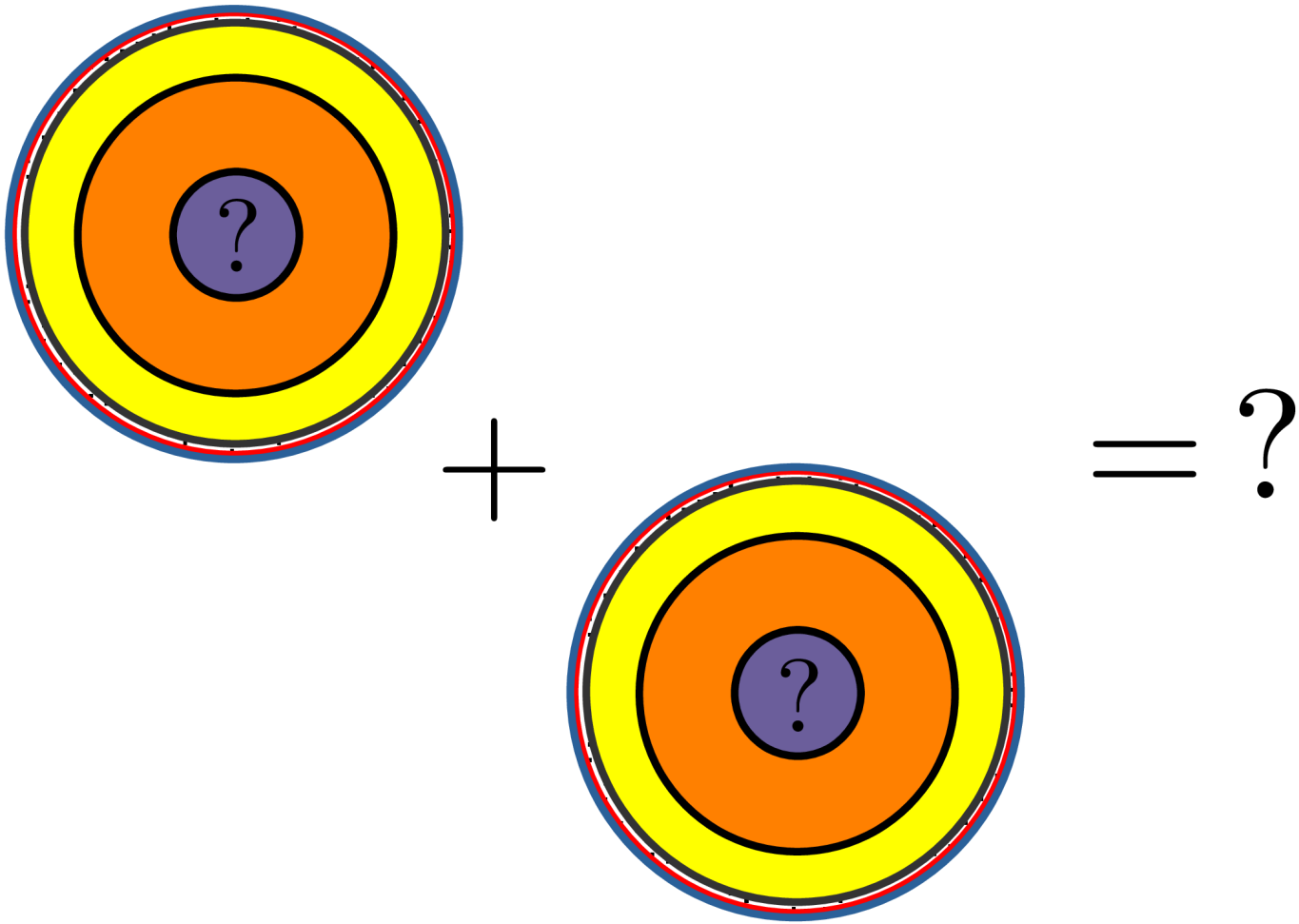
- Relevant for neutron star properties: stiff (soft) matter has large (small) sound speed and results in large (small) maximal mass and radius.
- Difficult open problem: What is $c_s^2(n)$ in QCD at neutron star densities?

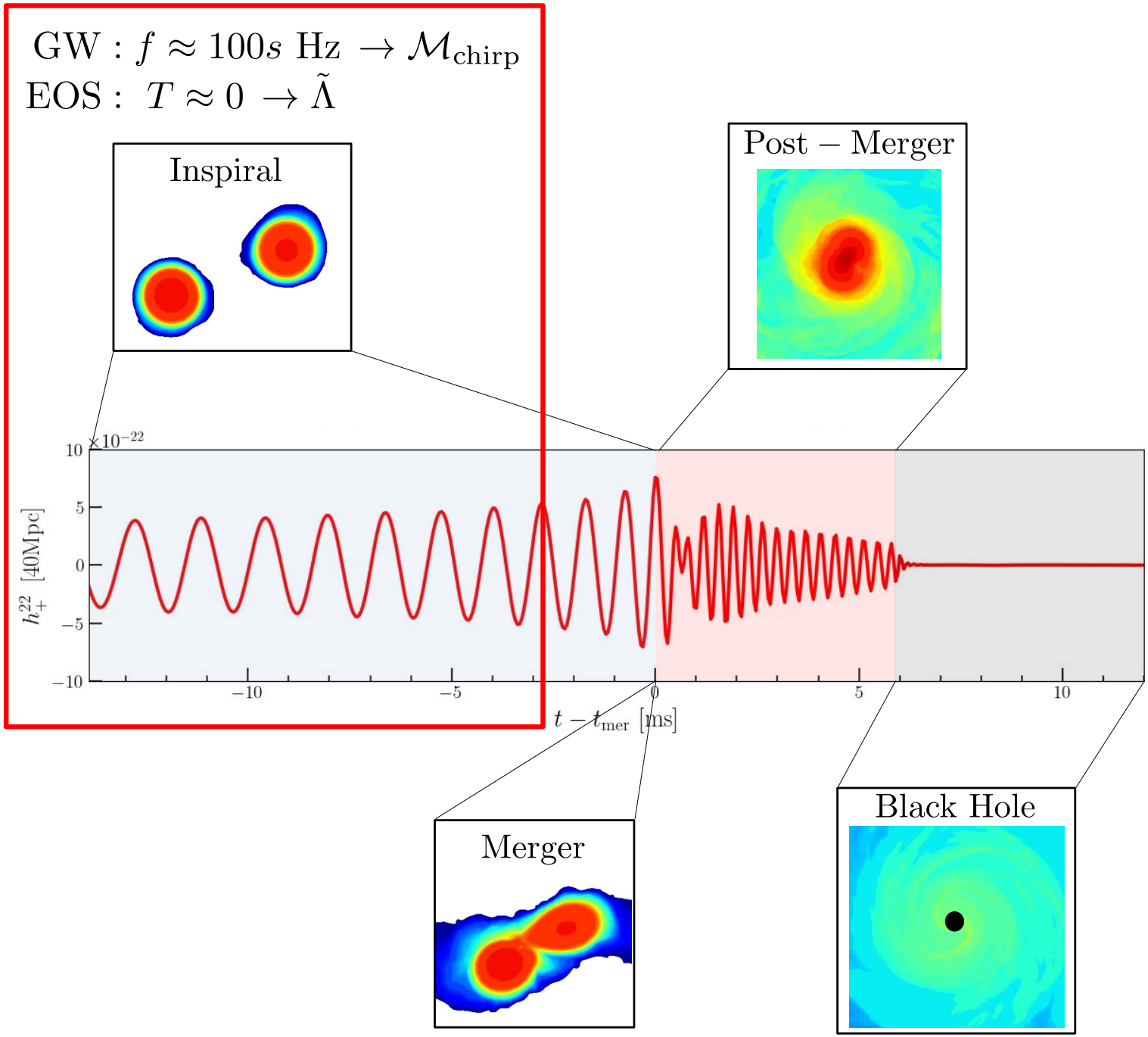


- **Light Stars:** stiff core, soft outer layer.
- **Typical Stars:** large stiff core.
- **Massive Stars:** soft core, stiff outer layer.

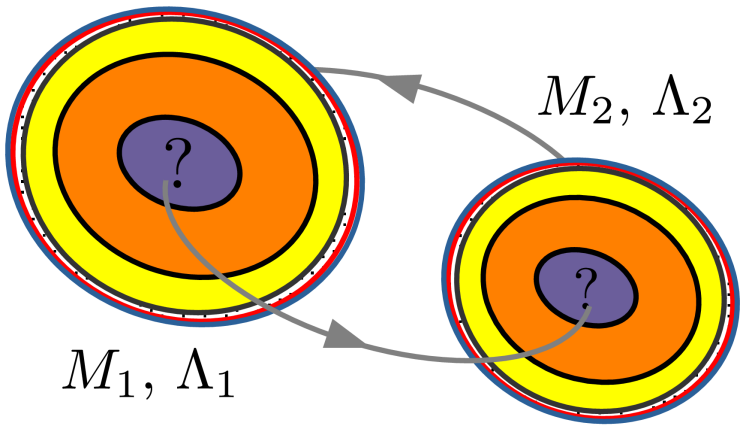
CE, Rezzolla 2207.04417 (ApJL);

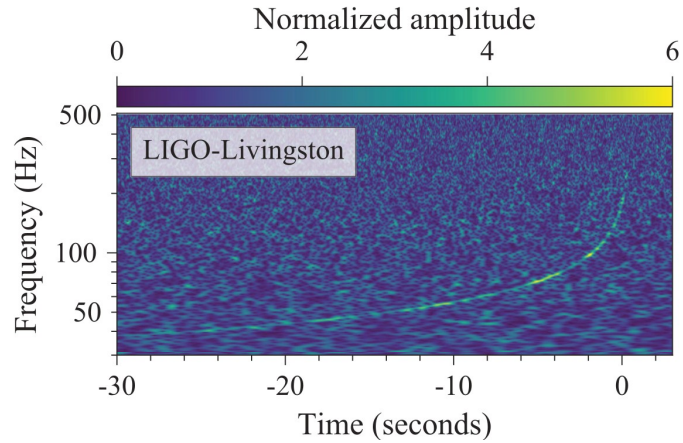
Outreach: idw award for science communication, featured in Frankfurter Allgemeine Zeitung, etc.




GW : $f \approx 100s$ Hz $\rightarrow \mathcal{M}_{\rm chirp}$
EOS : $T \approx 0 \rightarrow \tilde{\Lambda}$
Inspiral
Post − Merger
Merger
Black Hole
$\times 10^{-22}$
10
5
0
−5
−10
h_+^{22} [40Mpc]
−10
−5
0
5
10
$t - t_{\rm mer}$ [ms]

Chirp Mass and Binary Tidal Deformability





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

$$\frac{\mathrm{d}f_{GW}}{\mathrm{d}t} = \frac{96}{5}\pi^{8/3}\mathcal{M}_{chirp}^{5/3} f_{GW}^{11/3}\,, \quad \mathcal{M}_{chirp} = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}\,.$$

Cutler, Flanagan arXiv:gr-qc/9402014 (PRD)

- Binary tidal deformability encodes EOS properties via Λ_i

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

- GW170817 "best" event so far:

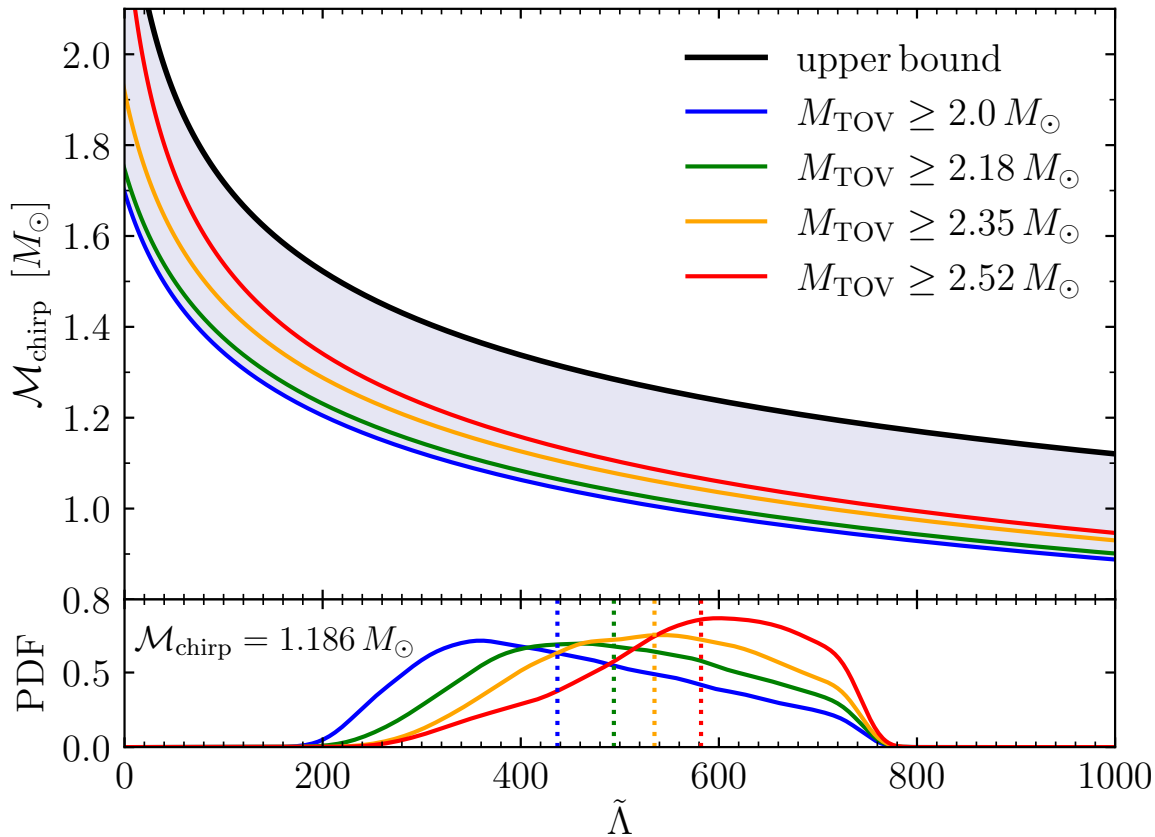
$$\mathcal{M}_{chirp} = 1.188^{+0.004}_{-0.002}M_\odot, \quad q = M_2/M_1 > 0.7, \quad \tilde{\Lambda} \lesssim 720\,.$$

LIGO/Virgo: arXiv:1805.11579 (PRX)

Binary Tidal Deformability

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

$$\tilde{\Lambda}_{min(max)} = a + b\,\mathcal{M}_{chirp}^{c} \longrightarrow \tilde{\Lambda}_{1.186}^{\rm min} \in [236, 301]\,,\; M_{\rm TOV} > [2.18, 2.52]\; M_\odot\,.$$

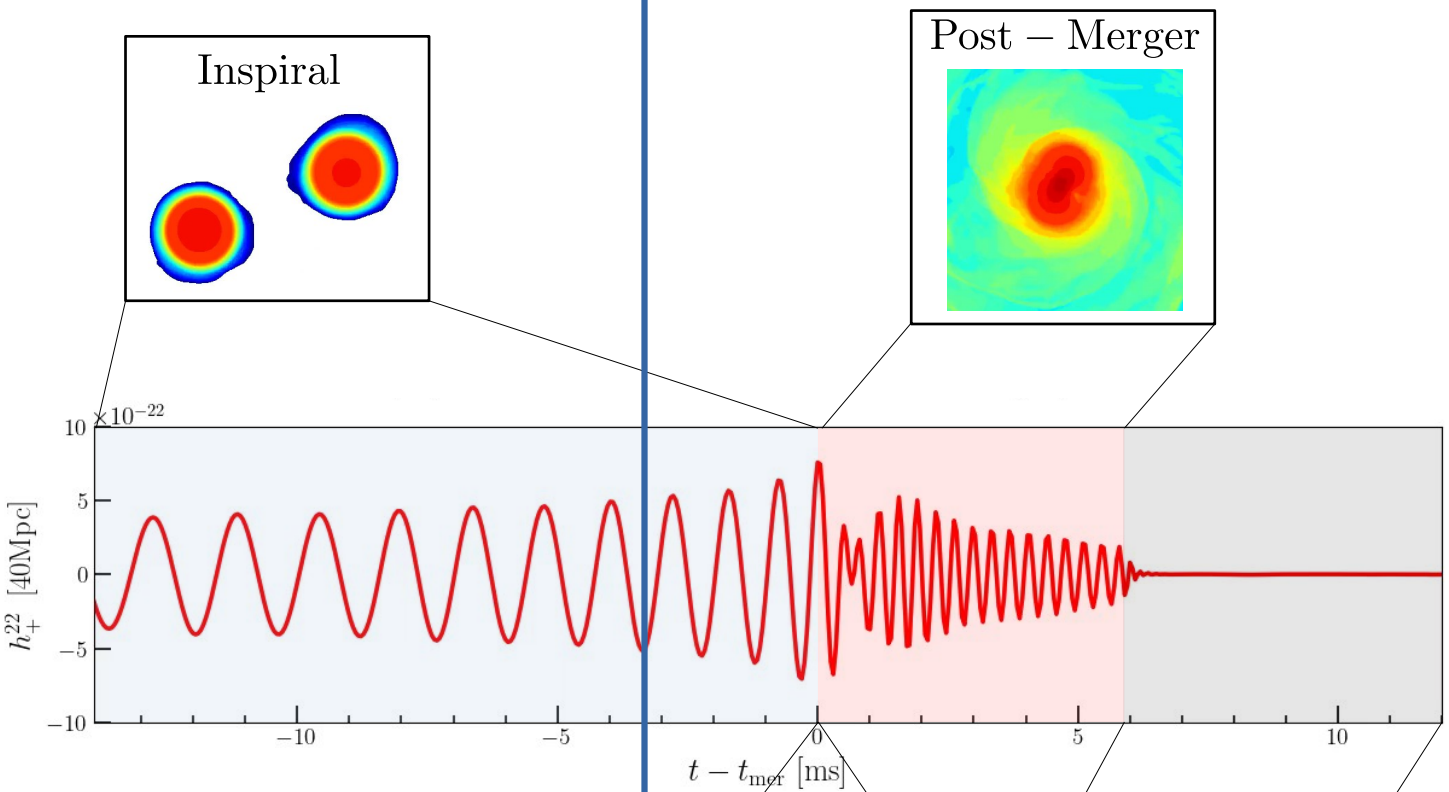


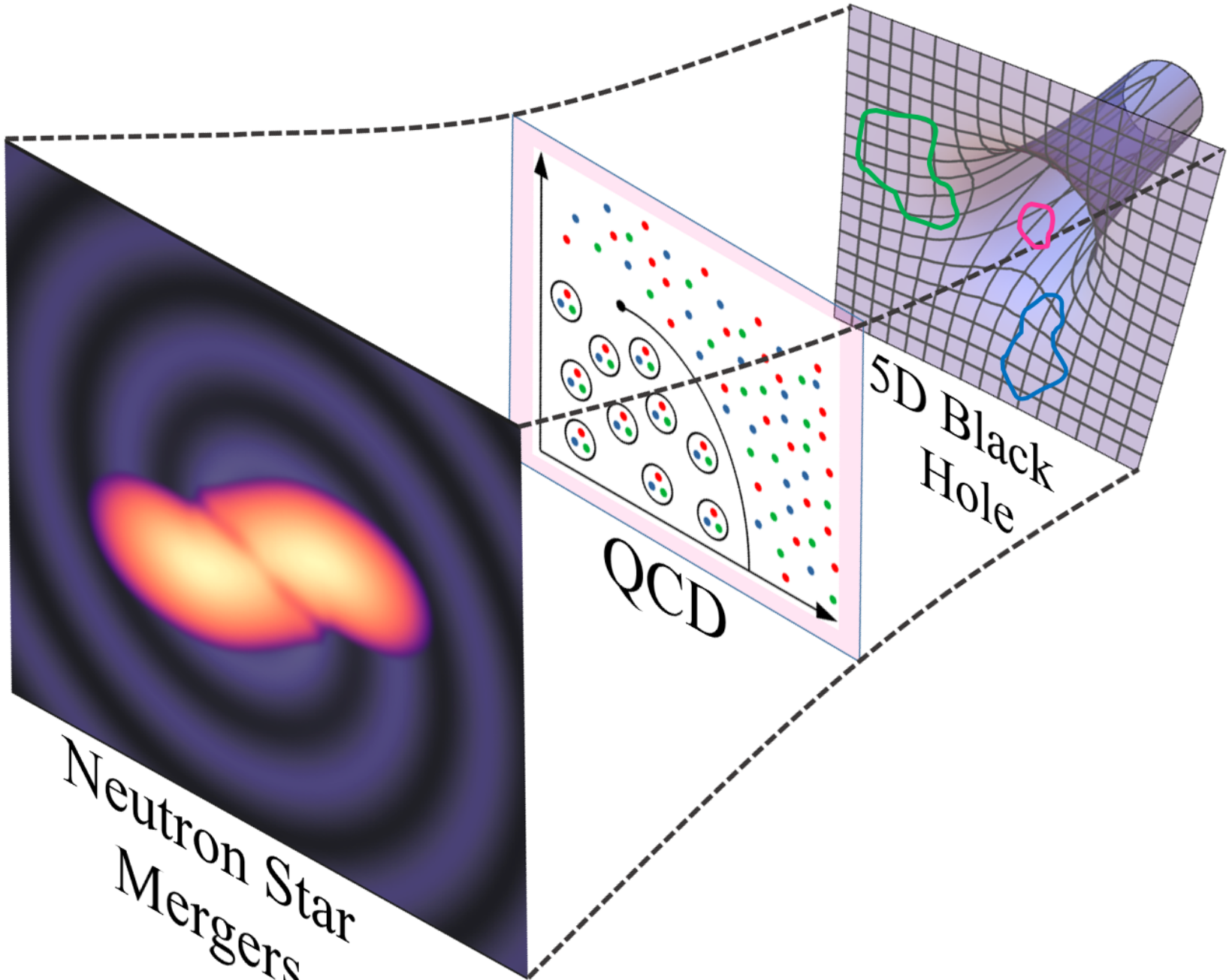
CE, Rezzolla 2209.08101 (MNRAS), see also Altiparmak, CE, Rezzolla 2203.14974 (ApJL)

$\mathrm{GW}: f \approx \mathrm{kHz} \rightarrow f_1, f_2, f_3, \ldots$

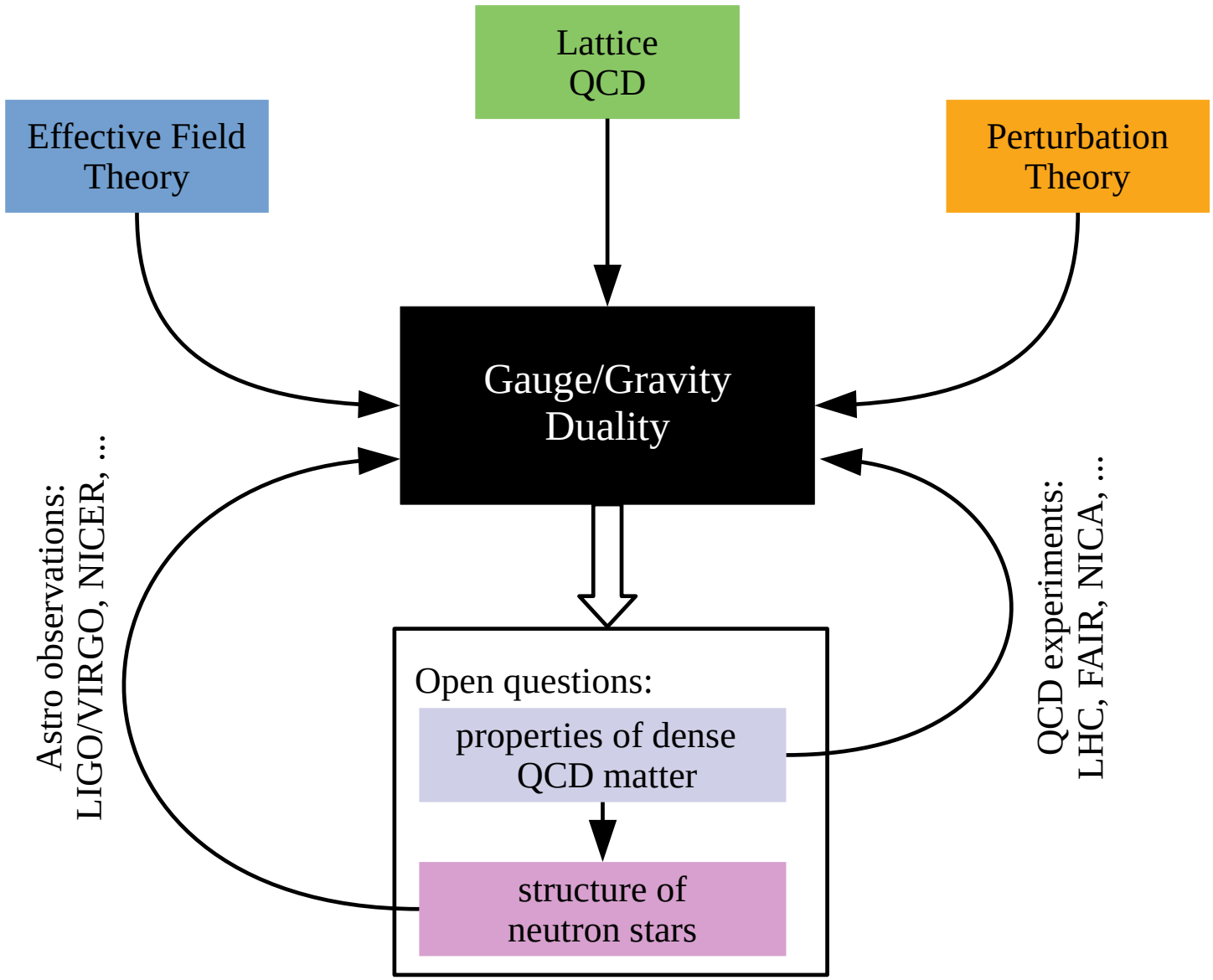
$\mathrm{EOS}: \ T \gg 0$

lifetime?, composition?, ejecta?, ...



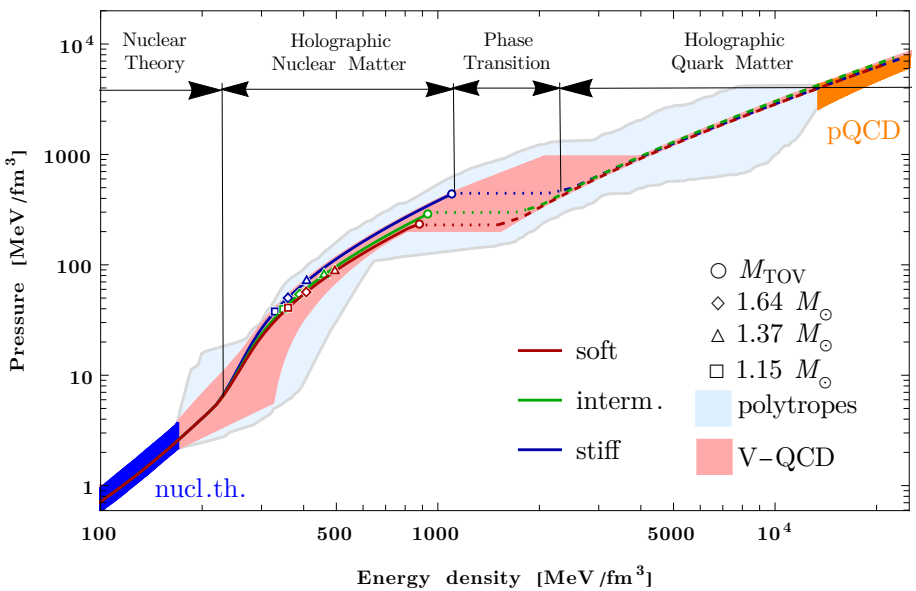

Neutron Star
Mergers
QCD
5D Black
Hole

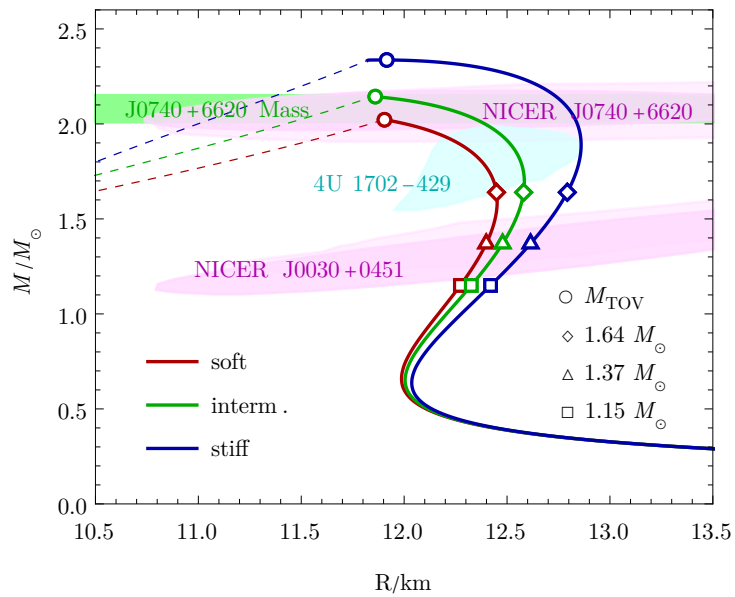
A Holographic Approach to Dense QCD Matter



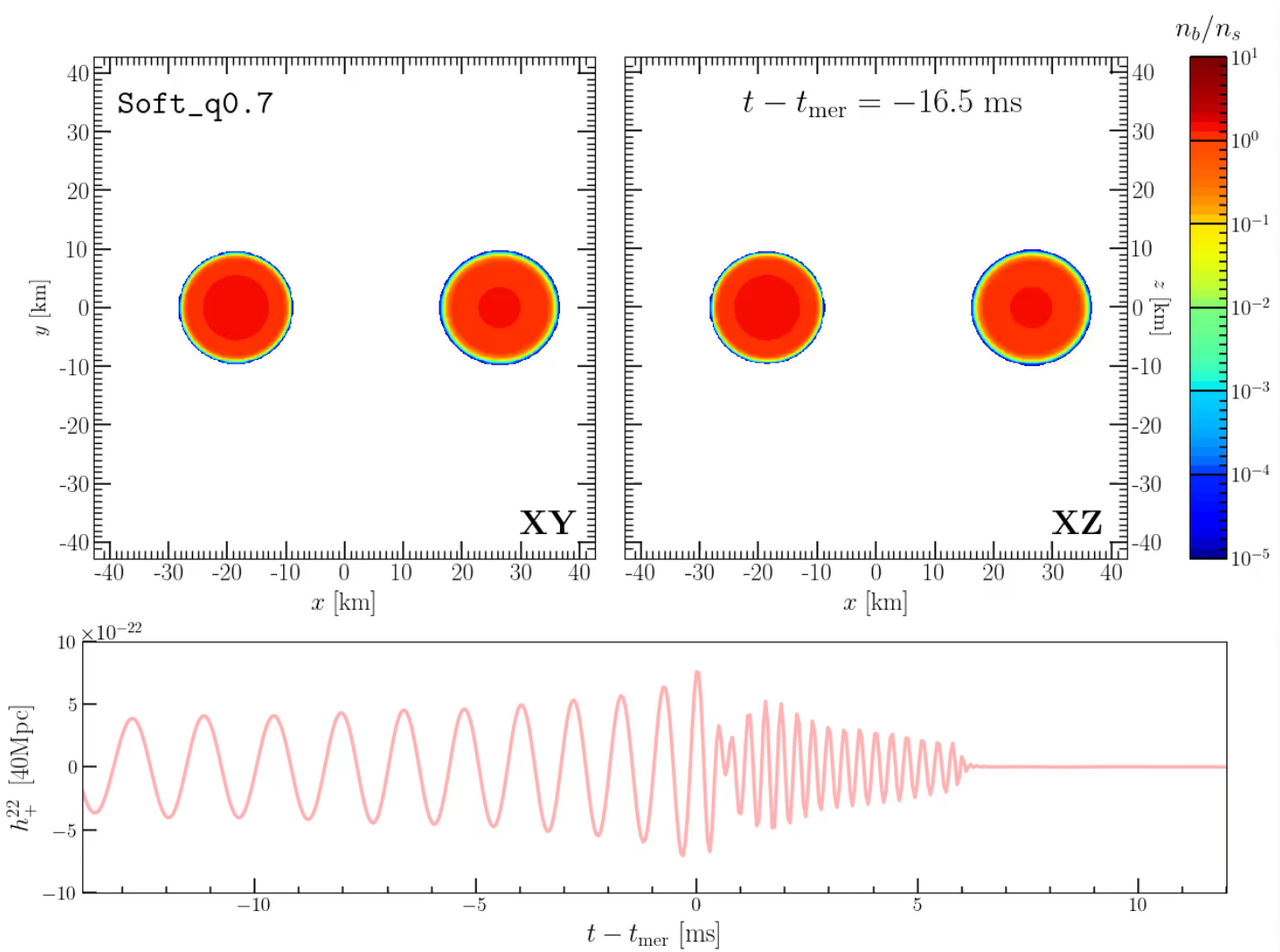
V-QCD Hybrid Equation of State

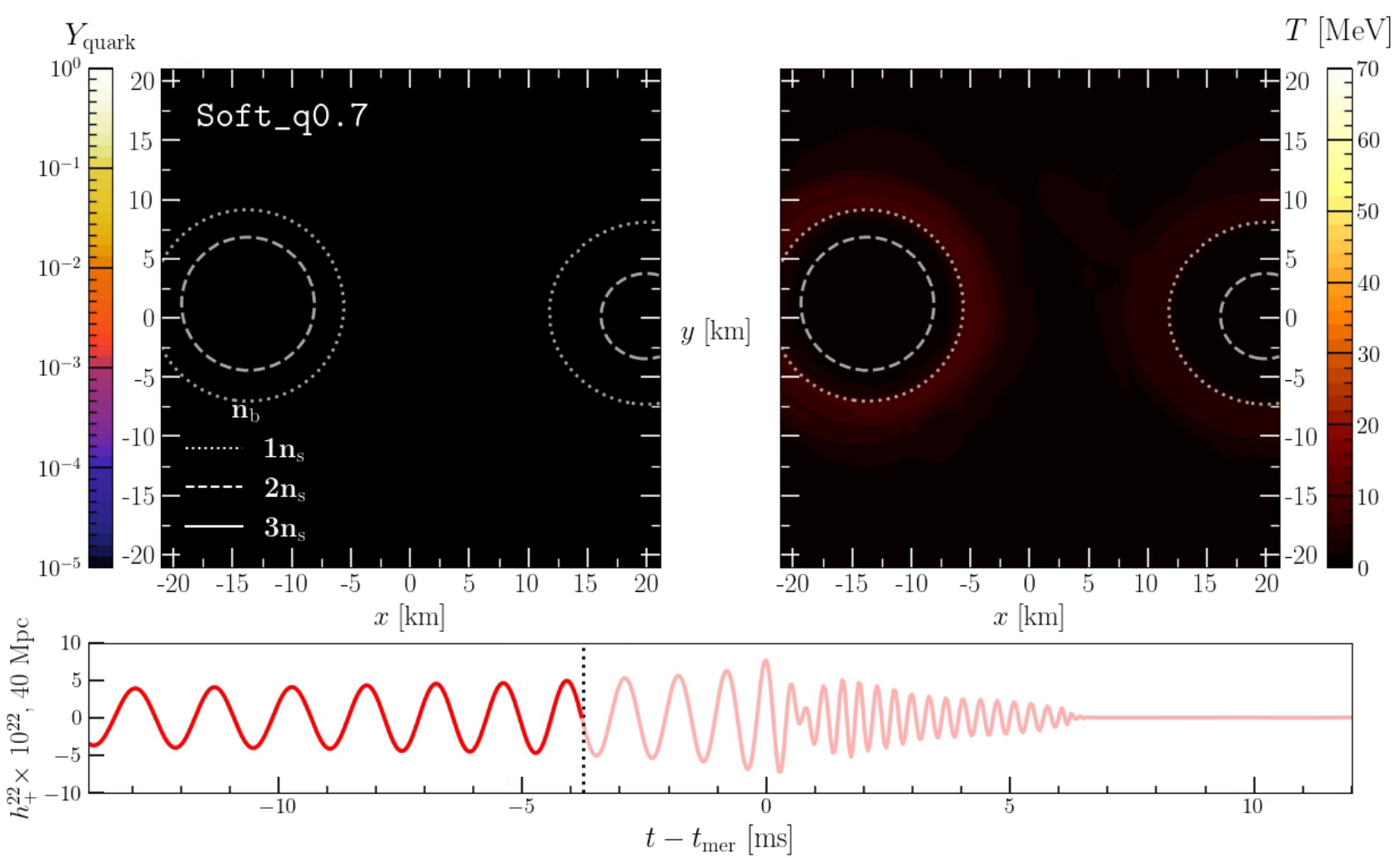
- Hybrid EOSs: nuclear theory model at lowest densities + V-QCD model for dense baryonic and quark matter at large densities.
- By construction consistent with nuclear theory and perturbative QCD.
- Predicts strong first-order deconfinement phase transition.
- Provides estimates for the QCD critical point.



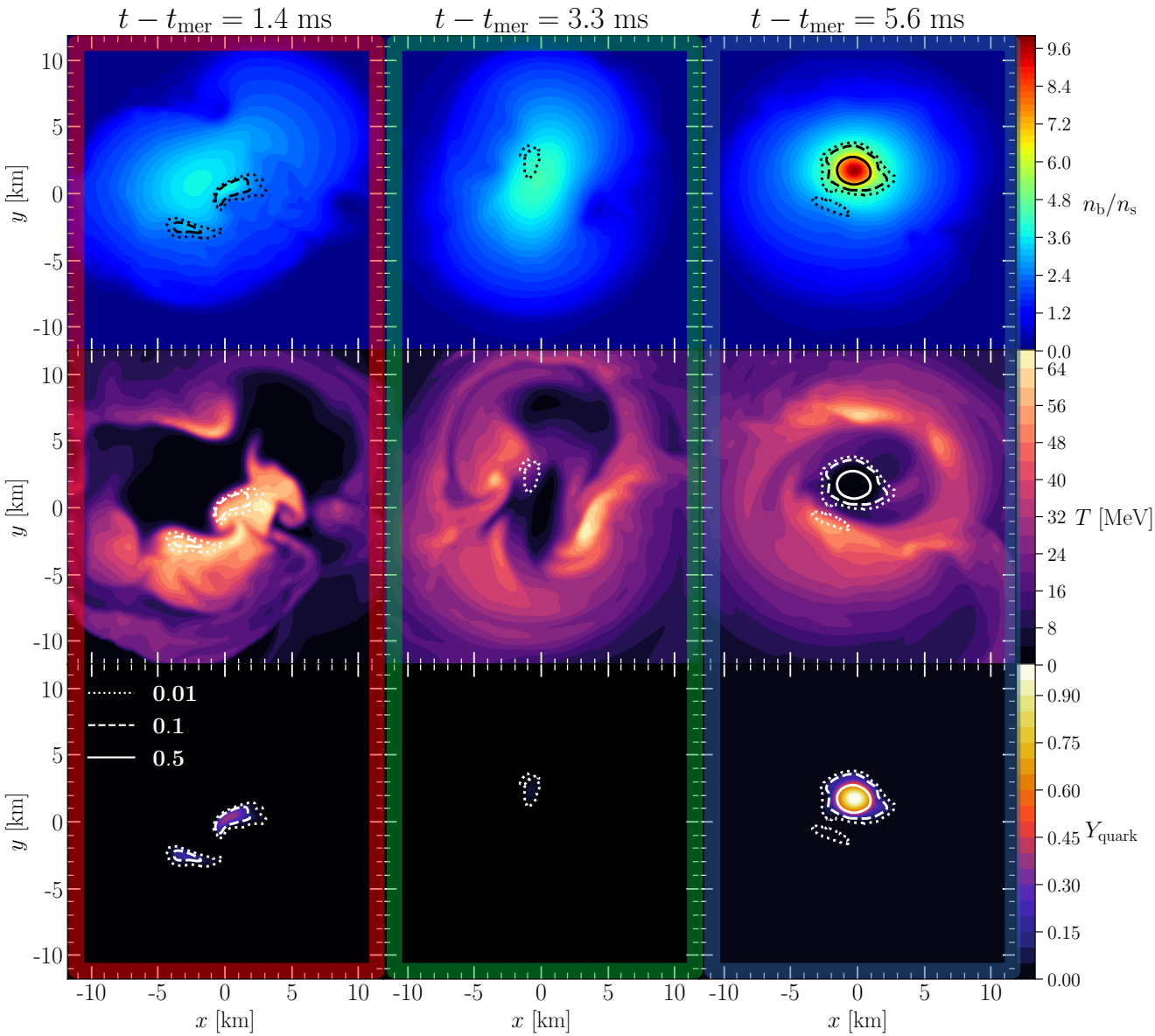


Demircik, CE, Järvinen 2112.12157 (PRX);
see also CE, Järvinen, Nijs, van der Schee 1908.03213 (PRD);
Jokela, Järvinen, Nijs, Remes 2006.01141 (JHEP);


Soft_q0.7
XY
XZ
$t - t_{\rm mer} = -16.5$ ms
n_b/n_s
y [km]
z [km]
x [km]
$\times 10^{-22}$
h_+^{22} [40Mpc]
$t - t_{\rm mer}$ [ms]


$Y_{\rm quark}$
Soft_q0.7
$\rm n_b$
$1\rm n_s$
$2\rm n_s$
$3\rm n_s$
y [km]
x [km]
T [MeV]
$h_+^{22} \times 10^{22}$, 40 Mpc
$t - t_{\rm mer}$ [ms]

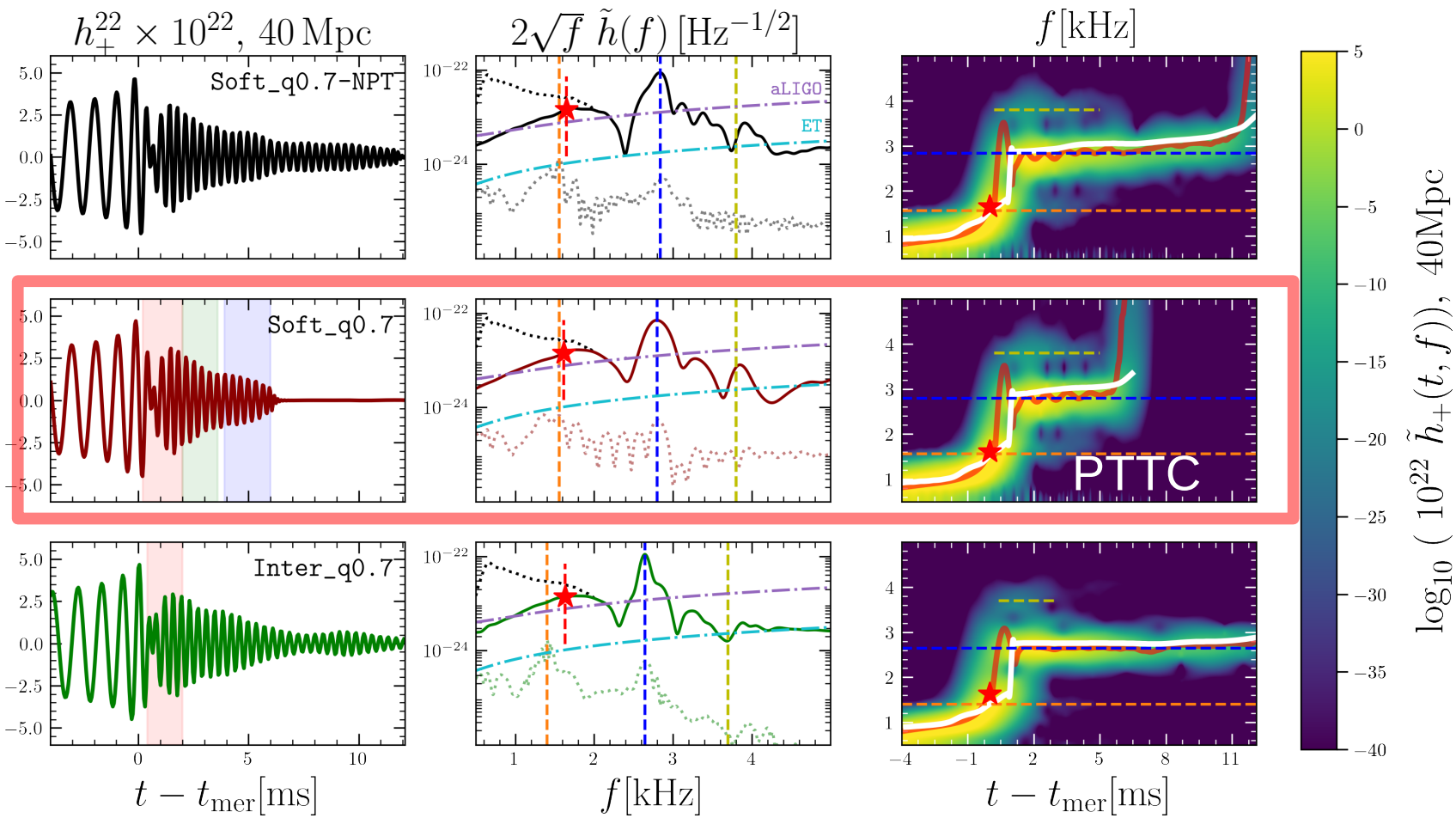
Hot, Warm and Cold Quarks



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

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).



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

Thank you DKPI!

I would like to thank:

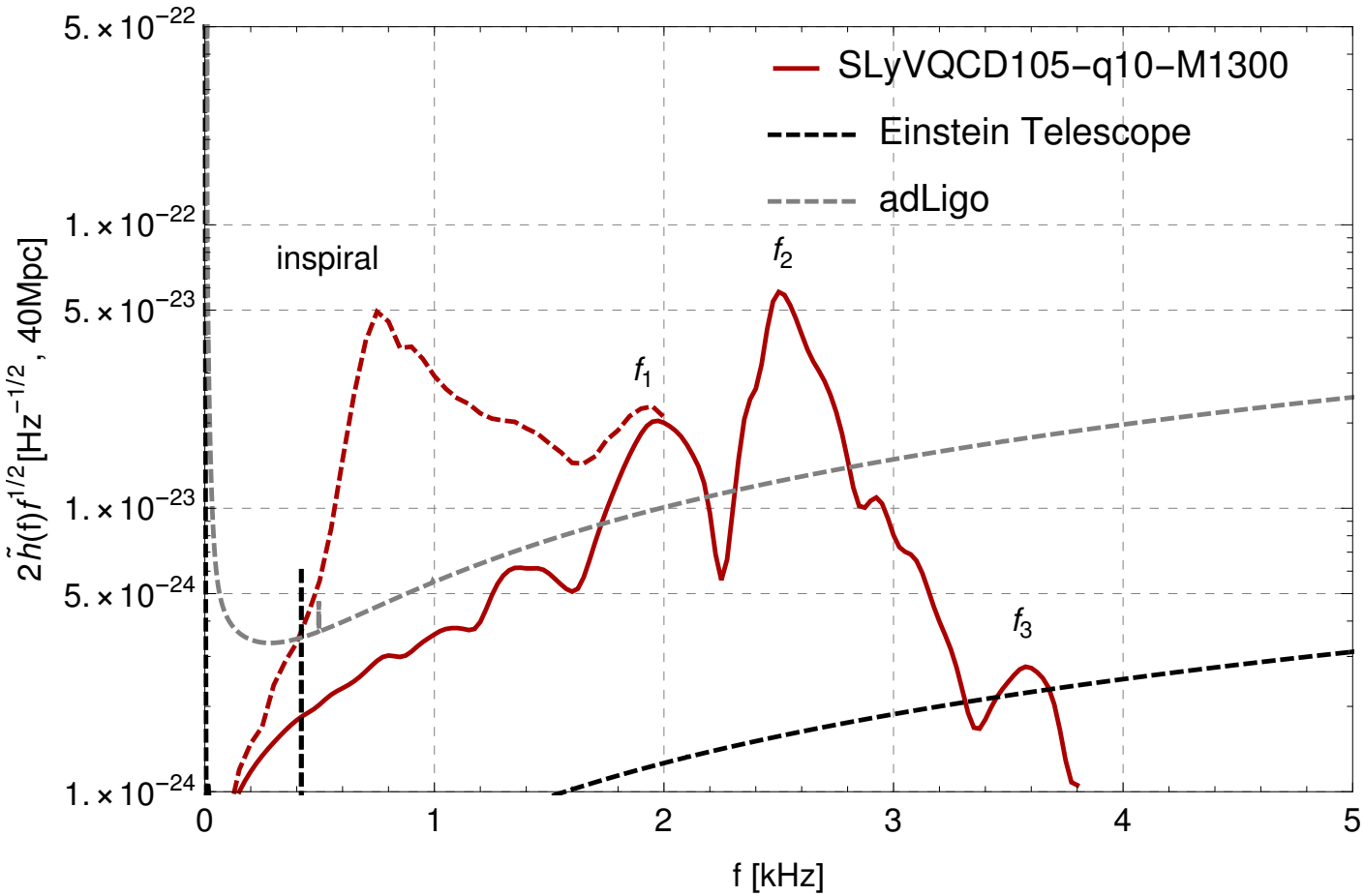
- the FWF and the ÖAW for funding the DKPI,
- Daniel Grumiller and Anton Rebhan for their mentorship,
- Andreas Ipp, Andrea Smith-Stachowski, Simone Krüger and Ingrid Unger for the excellent coordination and organization of the program,
- all other faculty members and fellow DKPI students for providing a wonderful scientific environment.

Power Spectral Density

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

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

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



Holographic Veneziano QCD

Holographic bottom-up model for QCD with many parameters that are tuned to mimic QCD and that are constrained by lattice QCD data.

Järvinen, Kiritsis 1112.1261 (JHEP)

Gluons: Improved holographic QCD (Einstein-dilaton gravity)

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

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

Gürsoy, Kiritsis 0707.1324 (JHEP); Gürsoy, Kiritsis, Nitti 0707.1349 (JHEP)

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

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

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

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

Bigazzi et al. 0505140 (JHEP); Casero et al. 0702155 (Nucl.Phys.B)

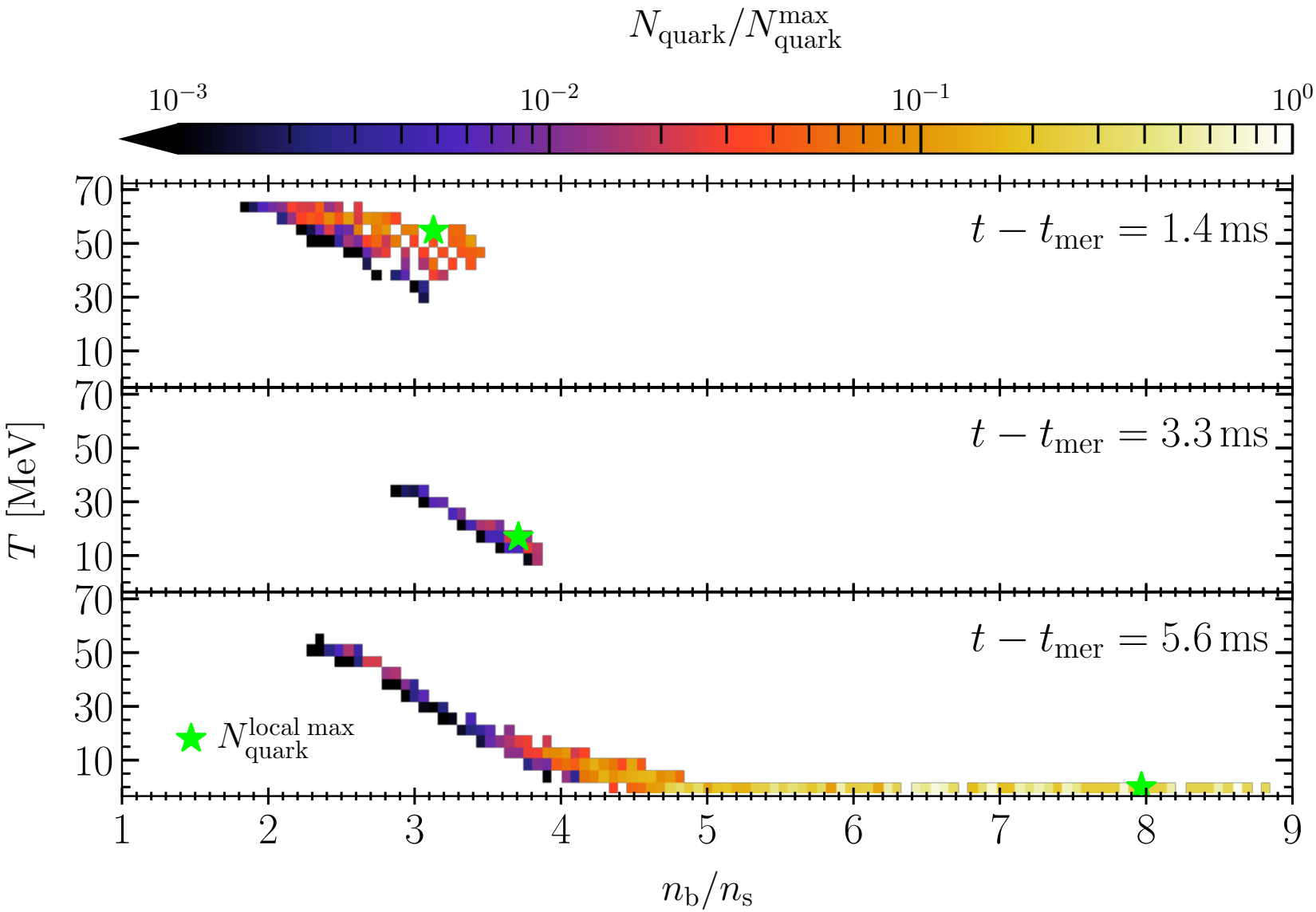
Baryons: homogeneous solution of non-Abelian DBI + Cern–Simons action.

Ishii, Järvinen, Nijs 1903.06169 (JHEP)

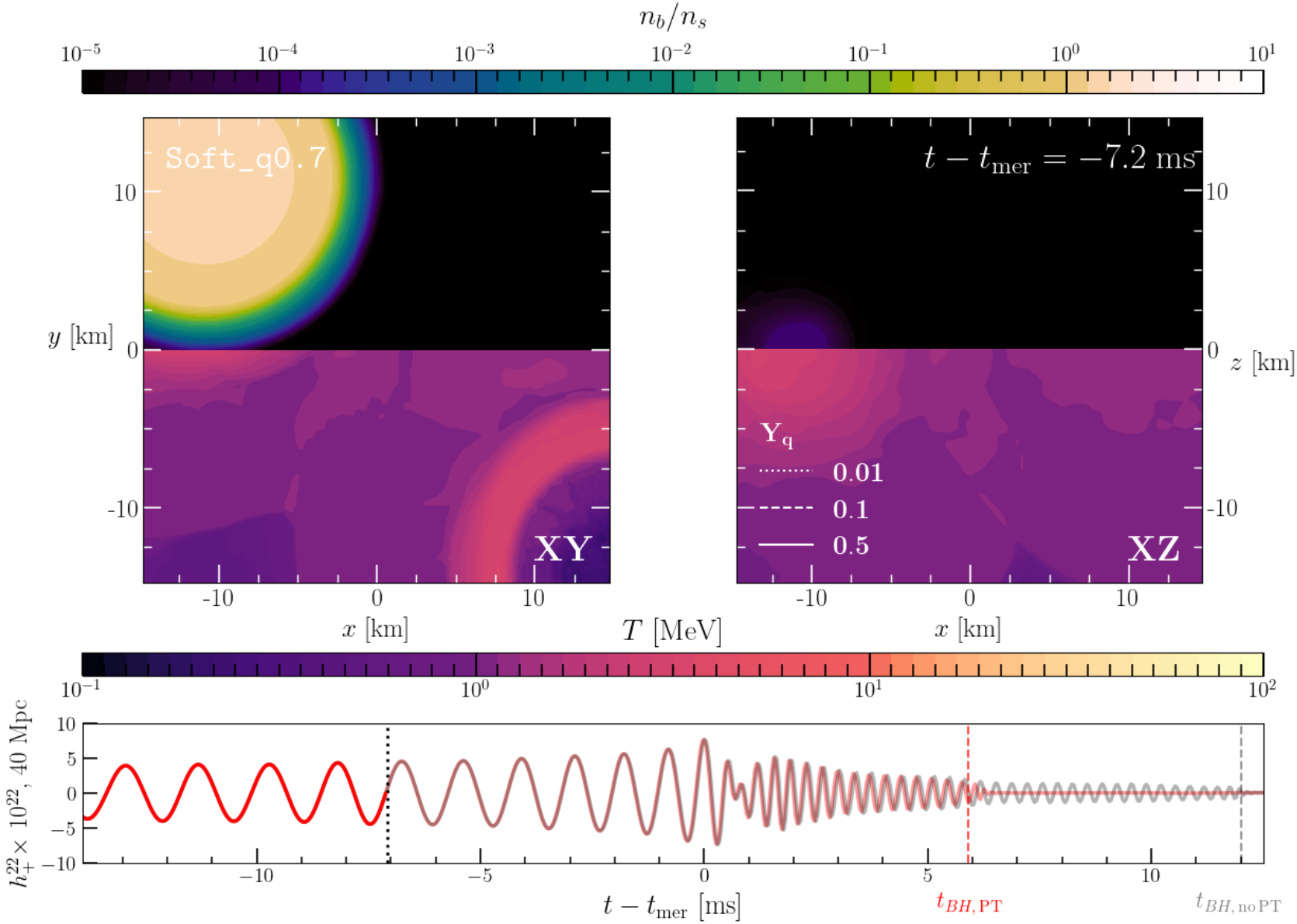
Veneziano limit: $N_c \to \infty$ and $N_f \to \infty$ with $N_f/N_c = \mathcal{O}(1)$ fixed

Järvinen, Kiritsis 1112.1261 (JHEP)

Quark Abundance

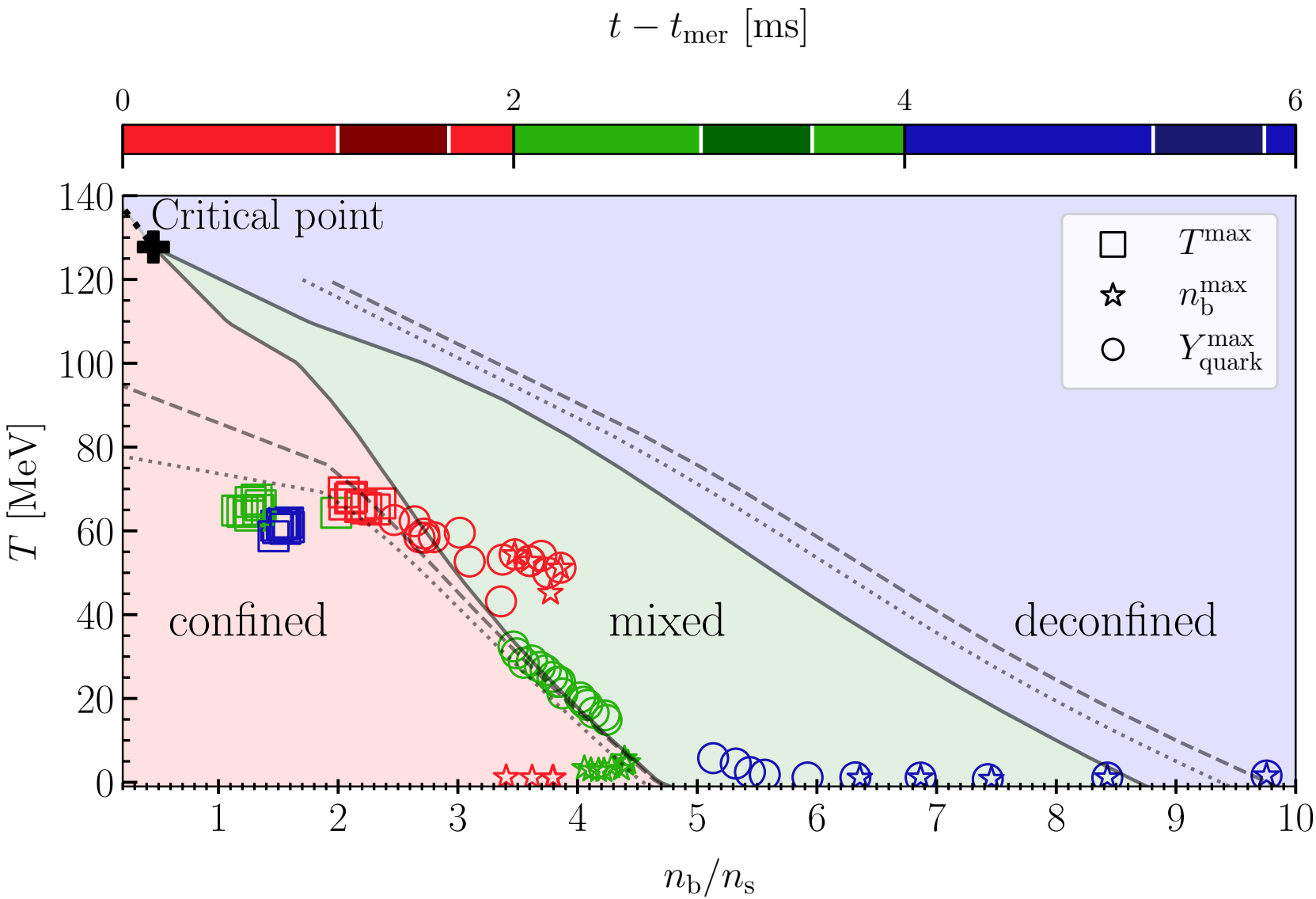


Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)



Movie by Konrad Topolski with data from 2205.05691 (SciPost).

Phase Diagram

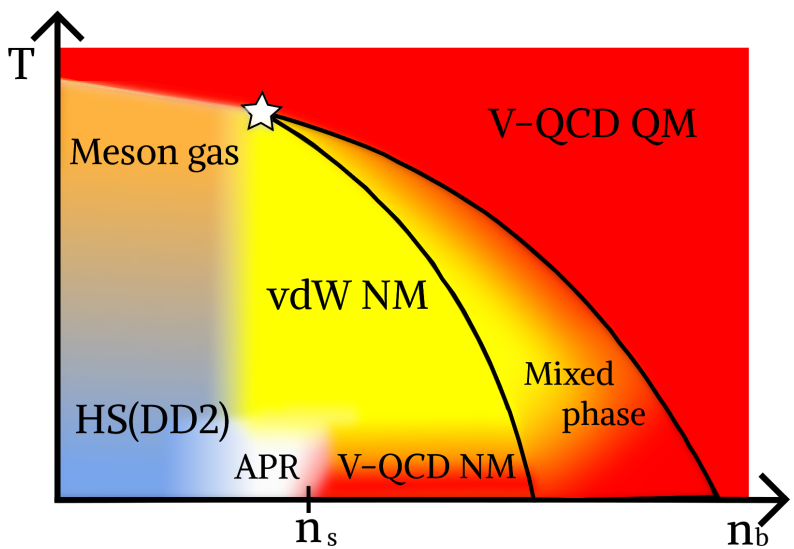


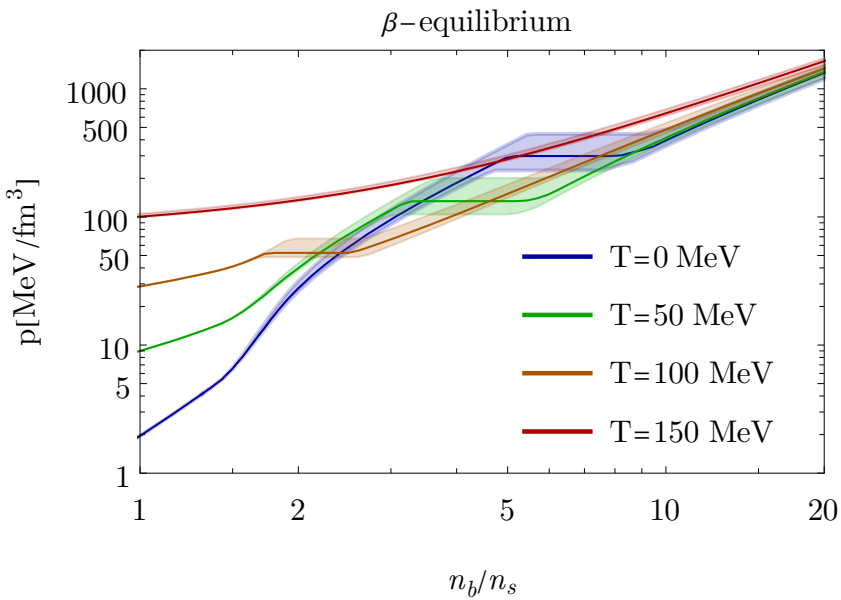
Tootle, CE, Topolski, Demircik, Järvinen, Rezzolla 2205.05691 (SciPost)

Hot V-QCD Hybrid Equation of State

- Low density part: Hemple-Schaffner-Bielich model (HS)DD2 + Particle Data Group (PDG) mesons. Hempel, Schaffner-Bielich 0911.4073 (Nucl.Phys.A); Zyla et al. (Particle Data Group 2020)
- (HS)DD2 too stiff around n_s, replace with APR model. Akmal, Pandharipande, Ravenhall 9804027 (PRC)
- Van der Waals construction to extend cold V-QCD baryons to finite-T. Vovchenko, Motornenko, Alba, Gorenstein, Satarov, Stoecker 1707.09215 (PRC)
- Mixed baryon and quark matter phase from mech. and chem. equilibrium:

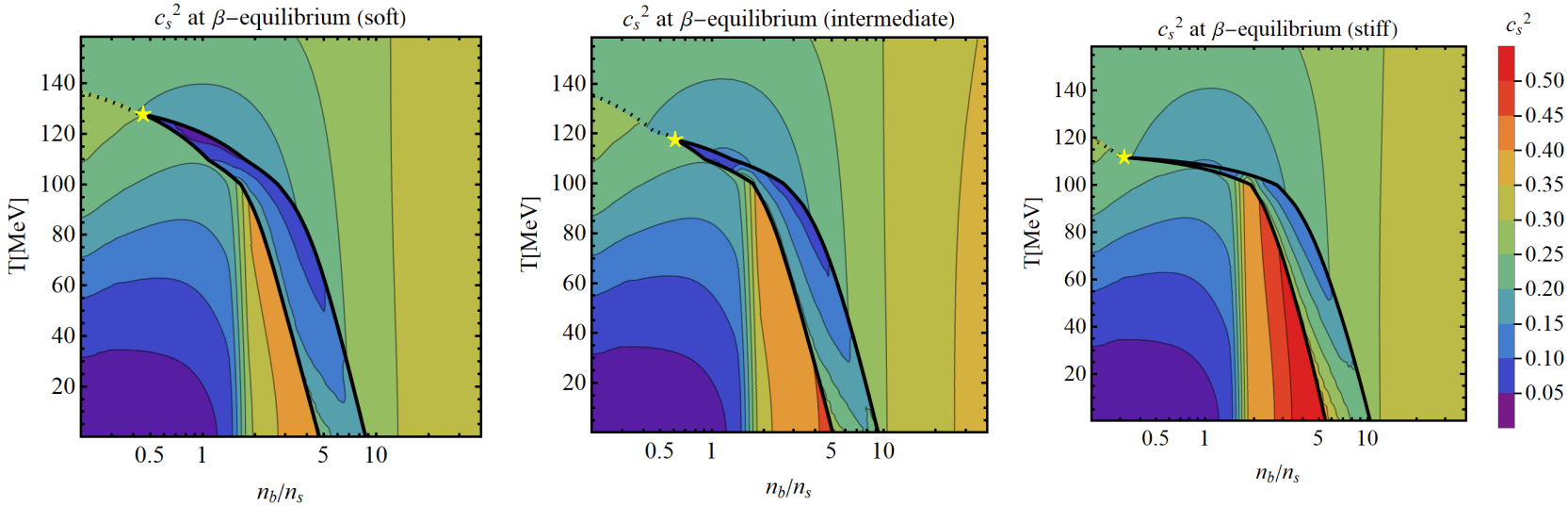
$$X_{NM}(T, n_b^{(1)}, Y_q^{(1)}) = X_{QM}(T, n_b^{(2)}, Y_q^{(2)}), \quad X = \{p, \mu_b, \mu_{Ie}\}.$$





Demircik, CE, Järvinen 2112.12157 (PRX)

V-QCD Critical Point

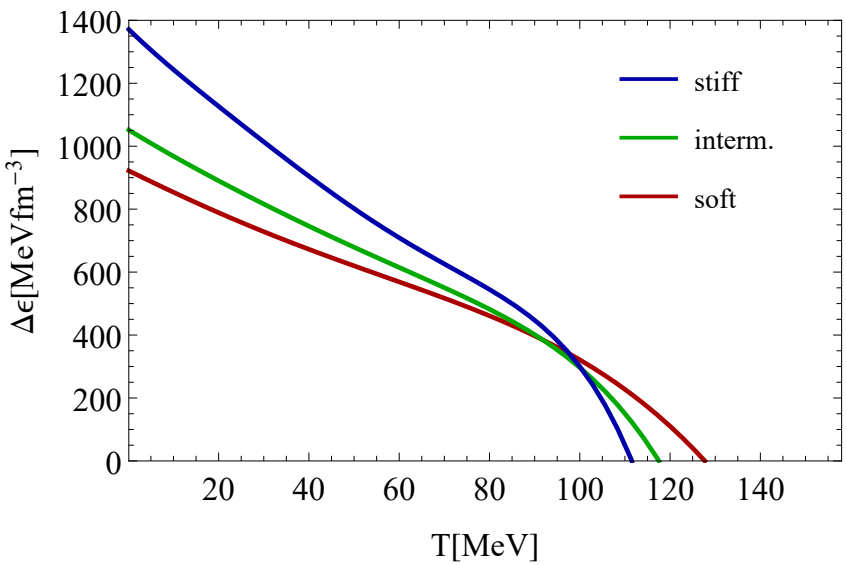


Estimates for the critical point:

$$110\ \text{MeV} \lesssim T_c \lesssim 130\ \text{MeV}$$
$$0.3\ n_s \lesssim n_c \lesssim 0.6\ n_s$$

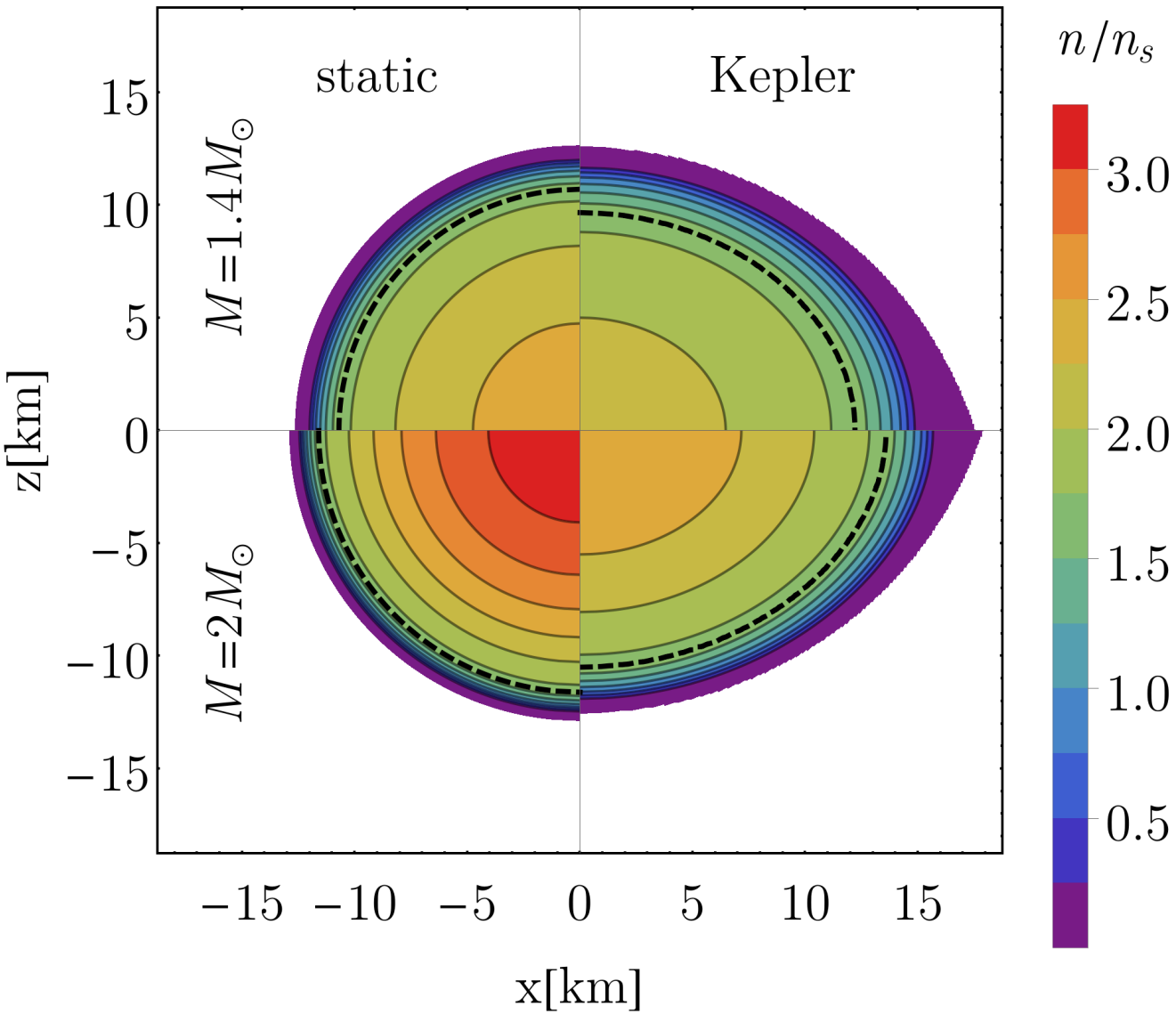
model	$\frac{n_{bc}}{n_s}$	$\frac{\mu_{bc}}{\text{MeV}}$	$\frac{T_c}{\text{MeV}}$
soft	0.46	485	128
interm.	0.62	575	118
stiff	0.32	565	112

(Same ballpark as seen in Nicolas talk.)



Demircik, CE, Järvinen 2112.12157 (PRX)

Density Profile

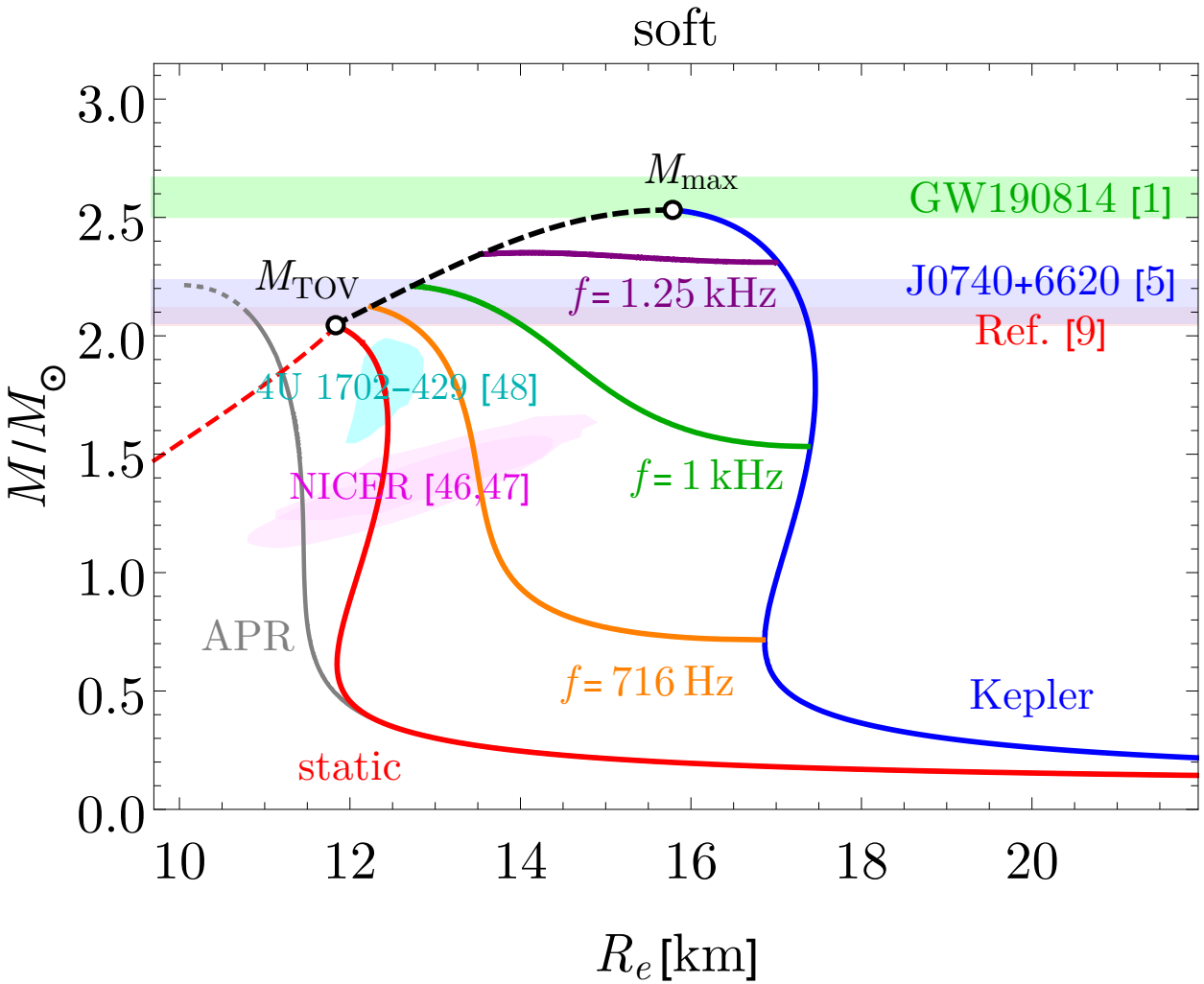


Demircik, CE, Järvinen 2009.10731 (ApJL)

Mass-Radius Relation of Rotating Stars

Universal Ratio: $\frac{M_{\max}}{M_{\mathrm{TOV}}} \approx 1.2$

Breu, Rezzolla arXiv:1601.06083 (MNRAS)



Demircik, CE, Järvinen arXiv:2009.10731 (ApJL)

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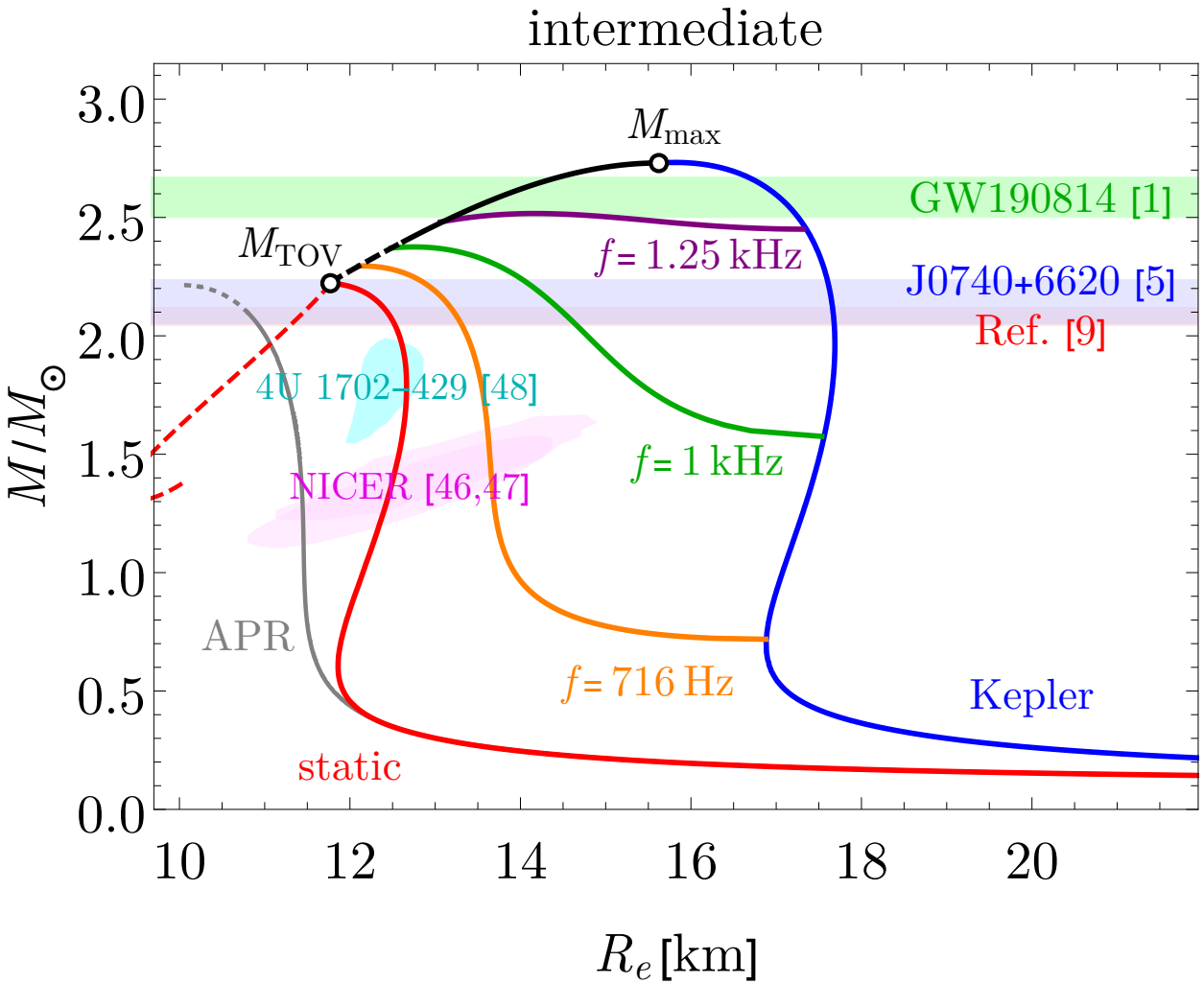

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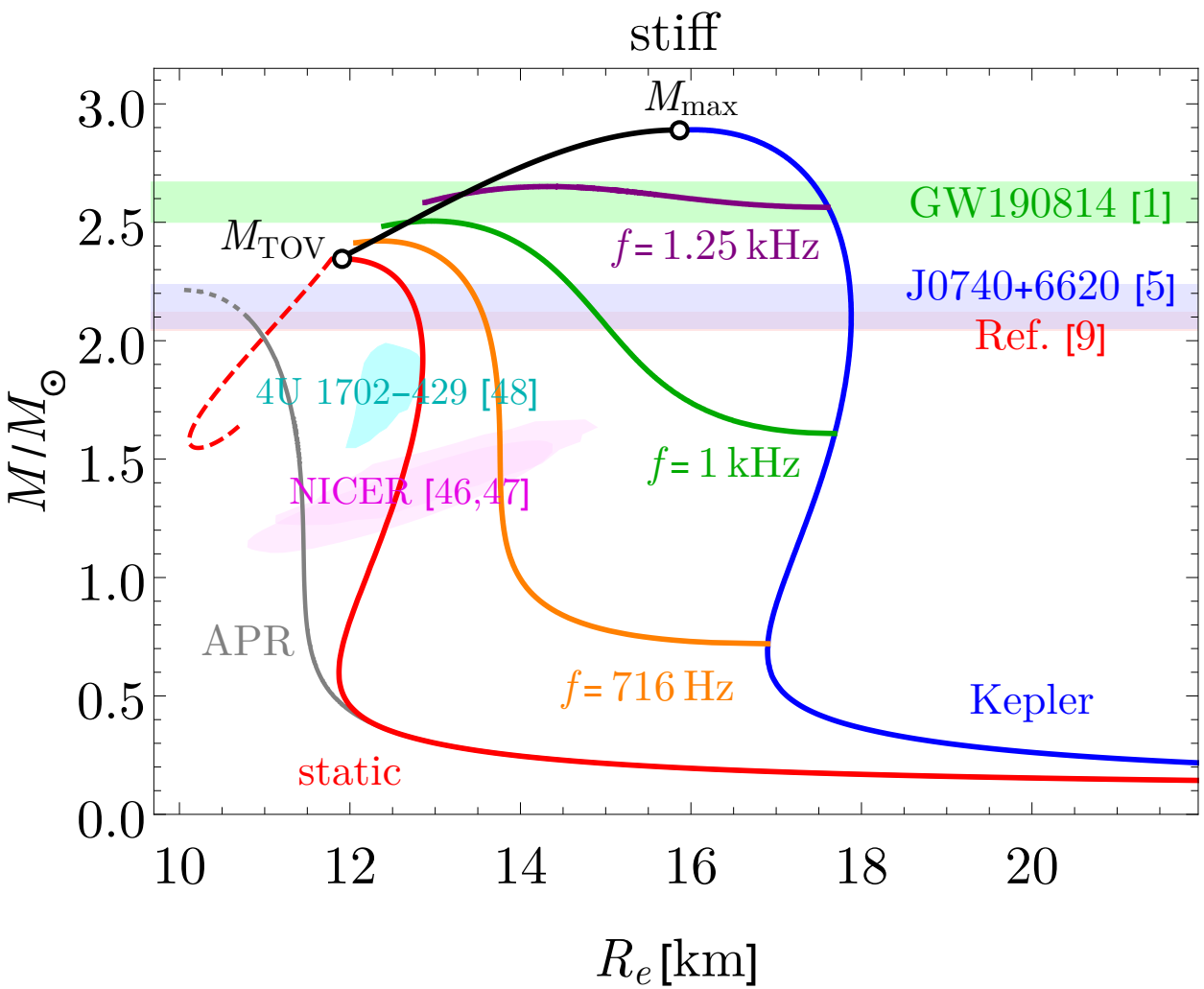
Universal Ratio: $\frac{M_{\rm max}}{M_{\rm TOV}} \approx 1.2$

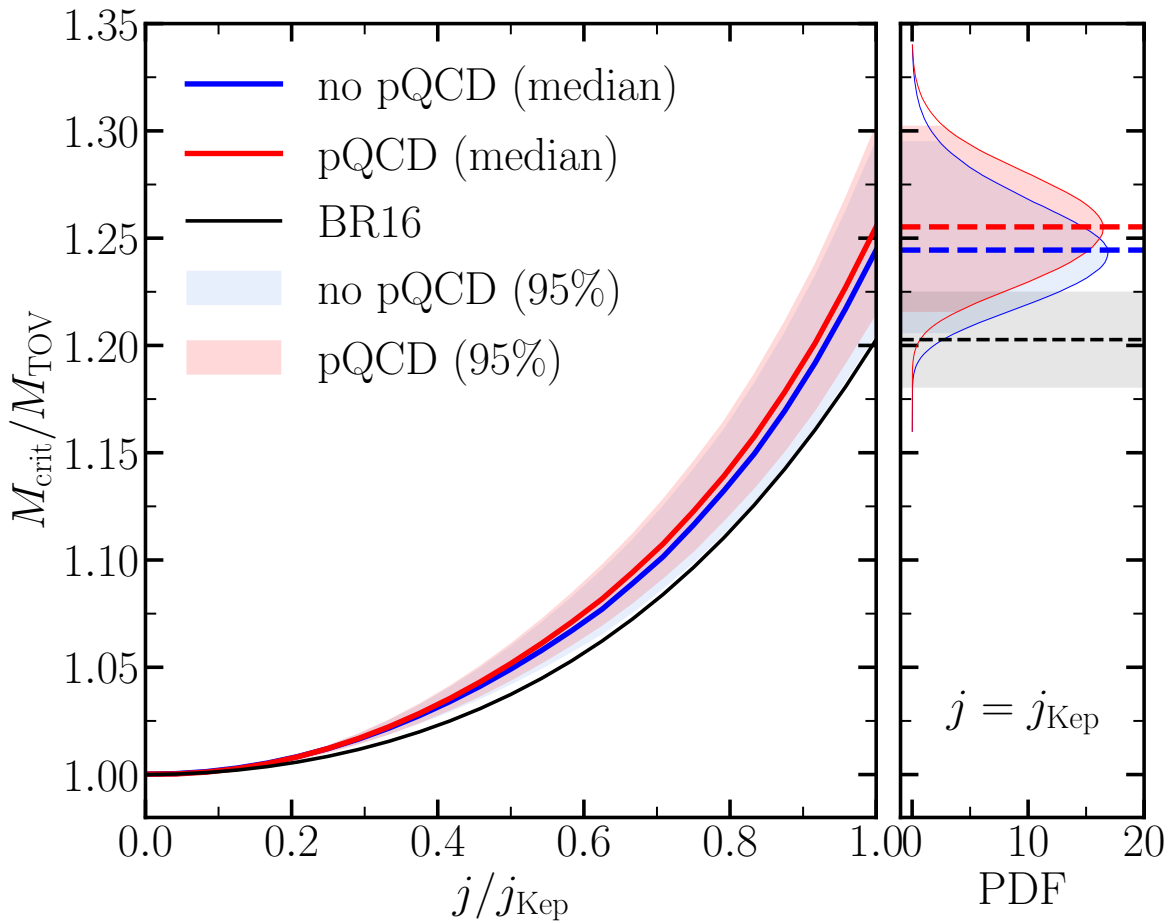
Breu, Rezzolla arXiv:1601.06083 (MNRAS)



Demircik, CE, Järvinen arXiv:2009.10731 (ApJL)

Quasi-Universal Relations for Rotating Stars

$$\frac{M_{\rm max}}{M_{\rm TOV}} = 1.255^{+0.047}_{-0.040}, \quad \left(1.244^{+0.050}_{-0.039}, 1.203^{+0.022}_{-0.022}\right) \qquad (2)$$



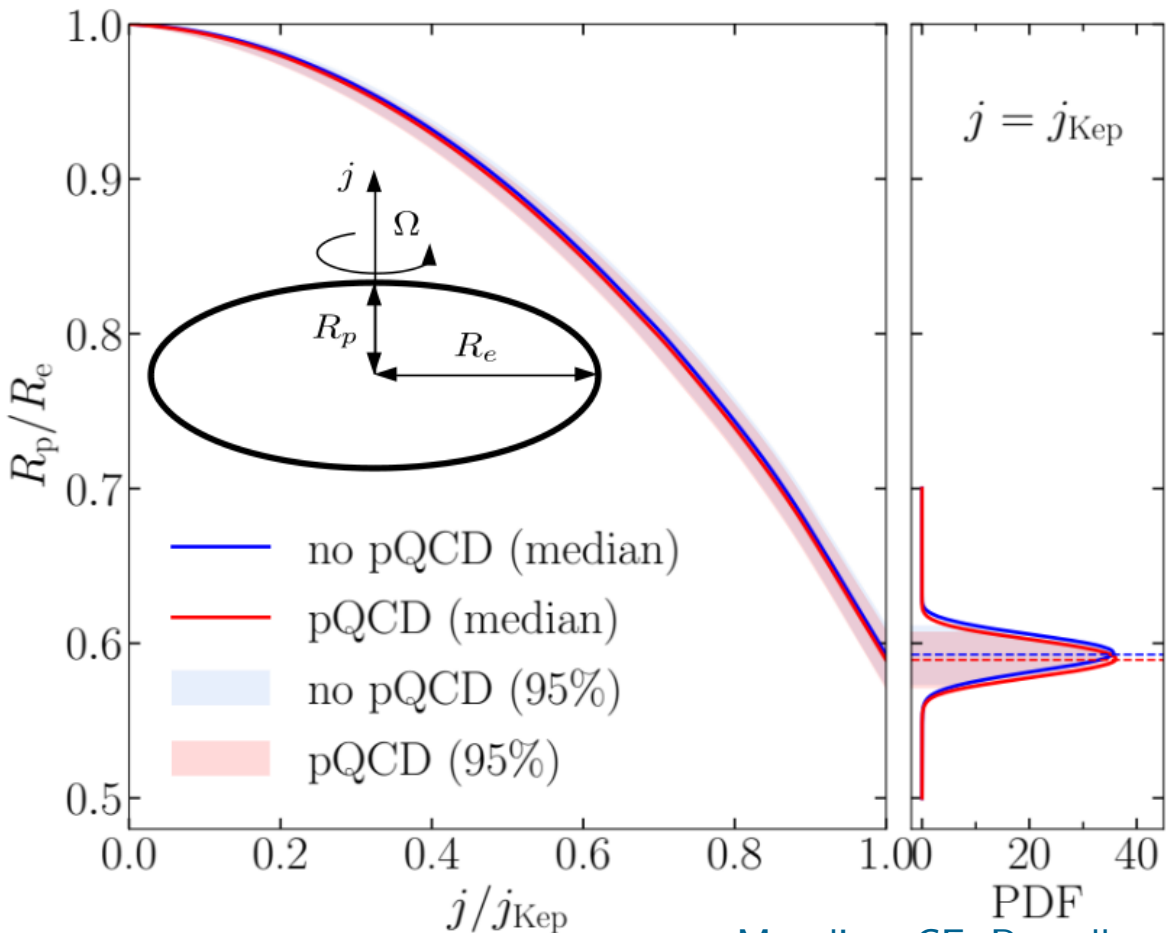
Musolino, CE, Rezzolla arXiv:2307.03225

Quasi-Universality of Neutron Star Oblateness

Oblateness: ratio of polar radius (R_p) and equatorial radius (R_e).

$$\frac{R_p}{R_e} = 1 - b_2 \left(j/j_{\rm Kep}\right)^2 \ , \ b_2 = 0.41^{+0.02}_{-0.02} \left(0.40^{+0.02}_{-0.02}\right) \ . \qquad (3)$$

Lower bound depends only (mildly) on crust: $0.6 \lesssim \frac{R_p}{R_e} \leqslant 1$.



Musolino, CE, Rezzolla arXiv:2307.03225