Supported by ERC through Starting Grant no. 759253 and Synergy Grant no. 101071865

European Research Council
Established by the European Commission

SFB 1245

ELEMENTS

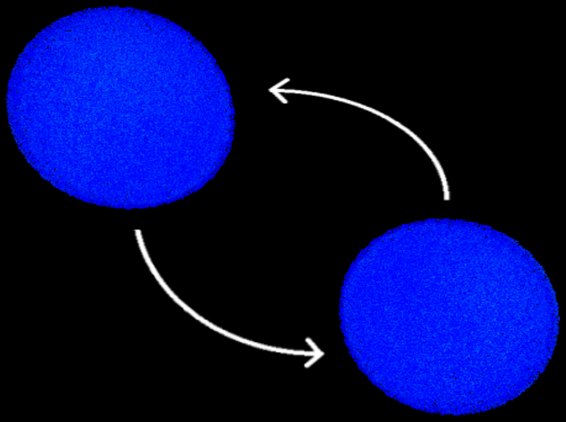
GSI

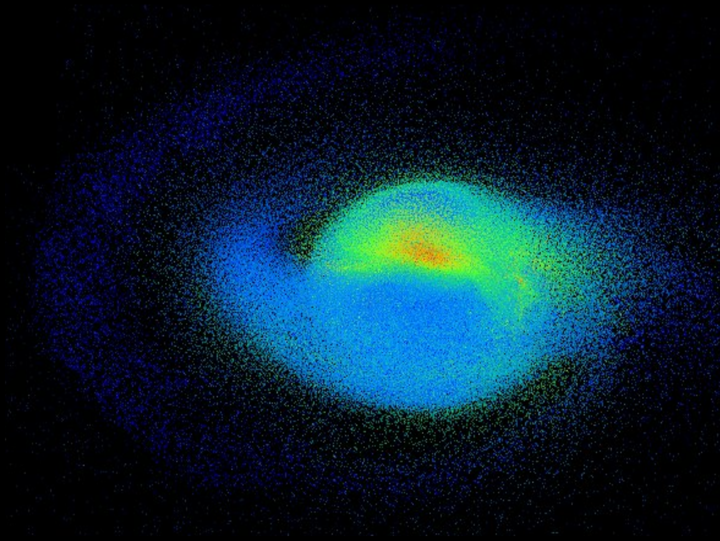
Pions, hyperons and quark matter in neutron star mergers

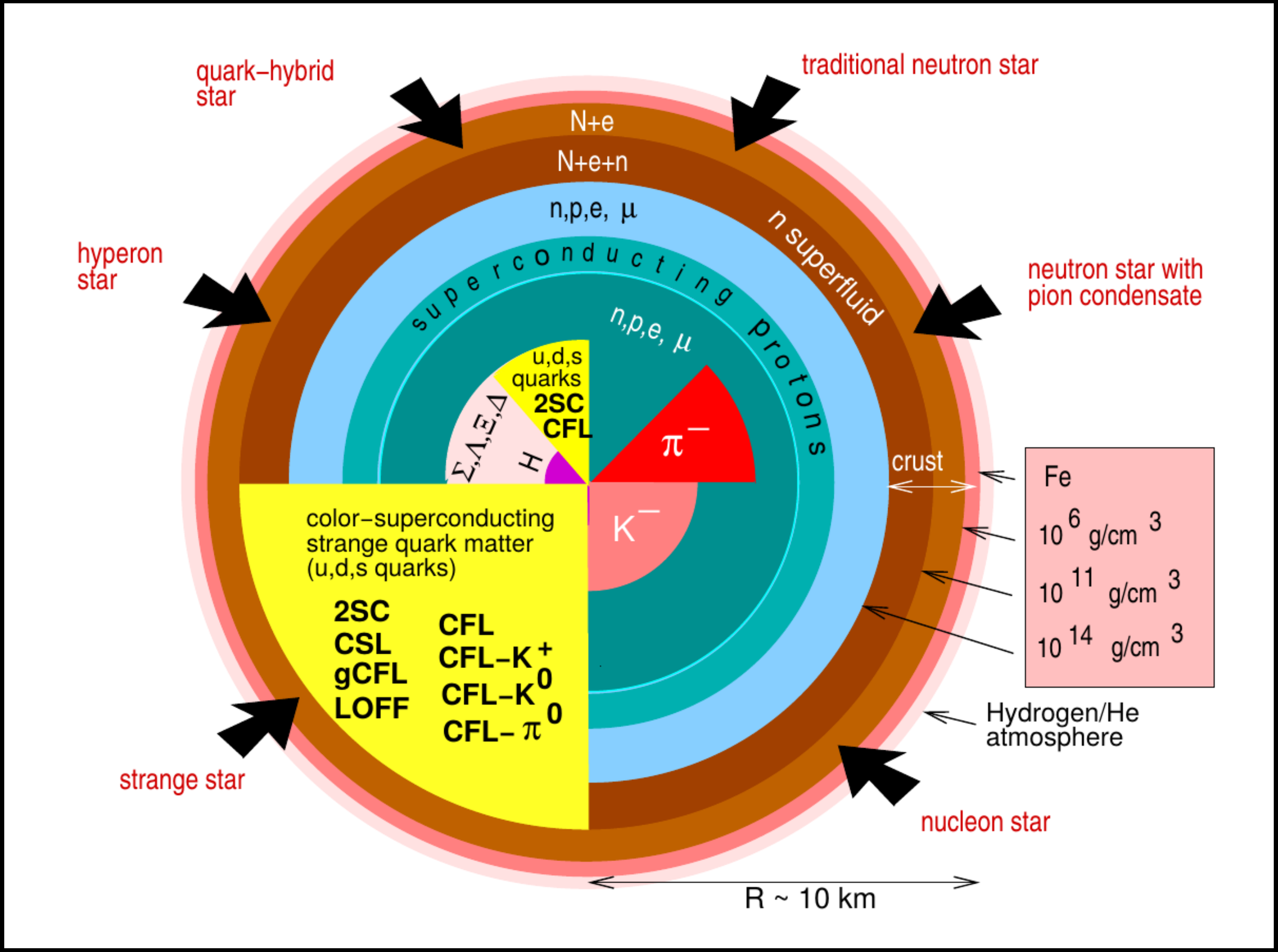
GraSP23, PISA, 16/10/2023

Andreas Bauswein

(GSI Darmstadt, HFHF)







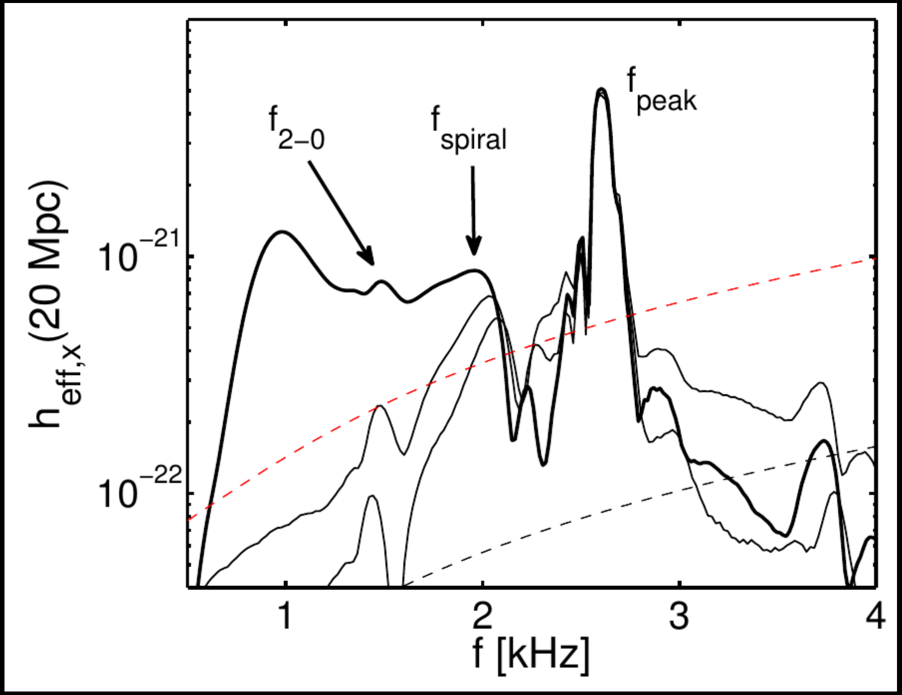
quark–hybrid star
traditional neutron star
hyperon star
neutron star with pion condensate
strange star
nucleon star
N+e
N+e+n
n,p,e, μ
n superfluid
superconducting protons
n,p,e, μ
u,d,s quarks
2SC
CFL
Σ,Λ,Ξ,Δ
H
π⁻
K⁻
color–superconducting strange quark matter (u,d,s quarks)
2SC
CSL
gCFL
LOFF
CFL
CFL–K+
CFL–K0
CFL–π0
crust
Fe
10 6 g/cm 3
10 11 g/cm 3
10 14 g/cm 3
Hydrogen/He atmosphere
R ~ 10 km

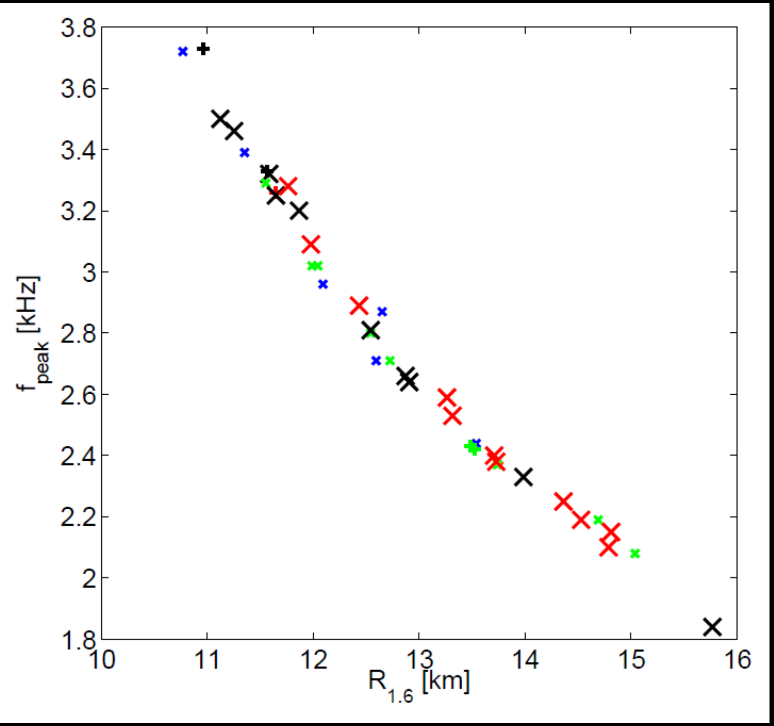
Weber 2004

Empirical relations

- To determine NS properties and EoS
- For postmerger GW emission, ejecta properties, threshold mass for black-hole formation etc.

Bauswein et al. 2012





Bauswein et al. 2016

Do non-nucleonic degrees of freedom lead to deviations from empirical relations?

Impact of pions in NS mergers

Vimal Vijayan, Ninoy Rahman, AB, Gabriel Martinez-Pinedo, Ignacio Arbina

arXiv: 2302.12055

Including pions

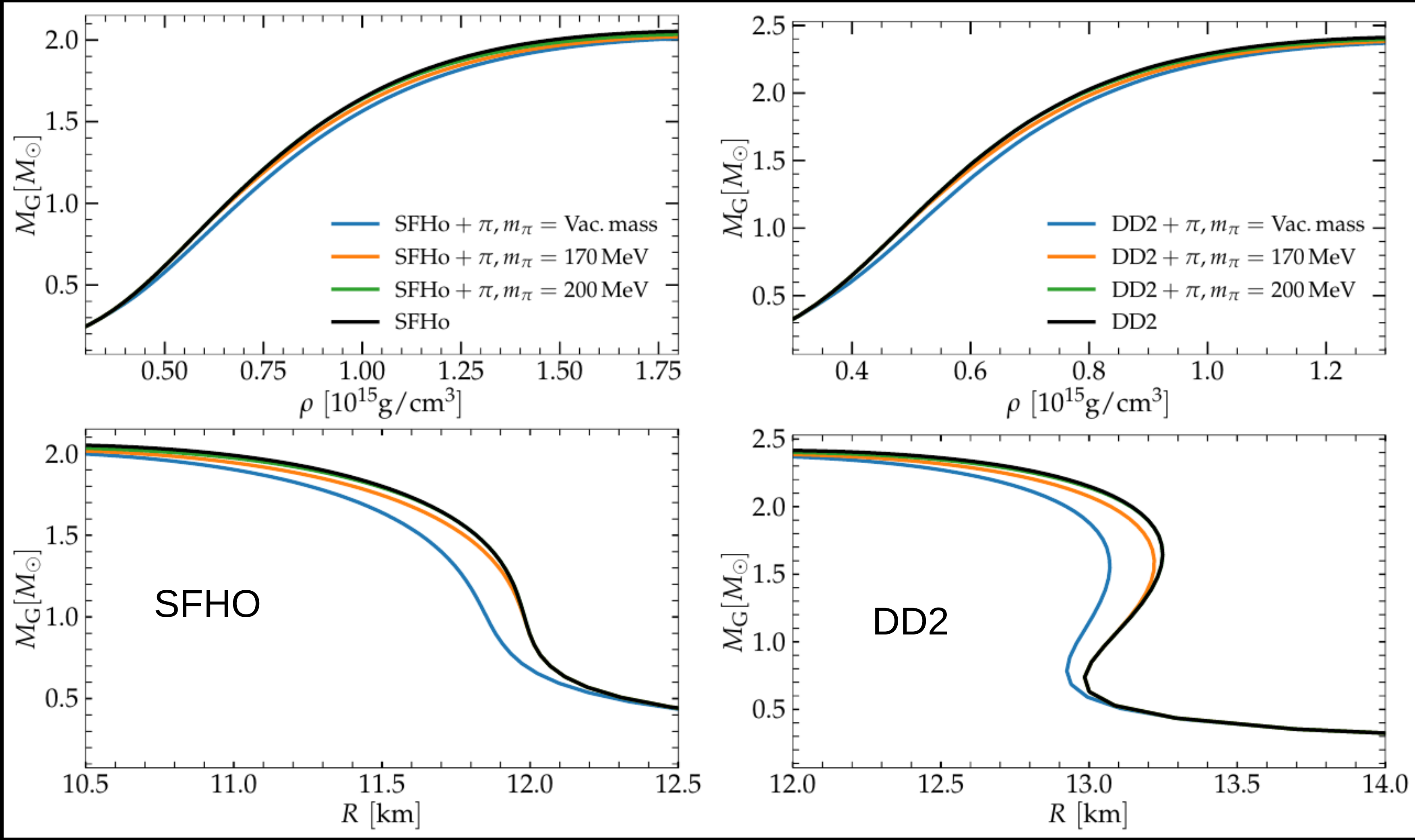
- $\pi^{\pm}, \pi^{0}$ mesons with rest mass of about 140 MeV in vacuum
- Impact on NS matter already discussed for decades but neglected in basically all EoS tables used in merger simulations
- Simple model to include pions as non-interacting Bose gas with chosen effective mass

  → pion condensation (ground state) and thermal pions
- Two base EoSs (DD2 and SFHO) and chosen constant effective mass

Pion condensation discussed since decades, e.g. Sawyer+ 1972, Migdal 1973, Baym & Flowers 1974, …; more recently thermal pions Oertel+ 2012, Fore & Reddy 2020

Impact on stellar structure

- Stronger impact for smaller pion mass (earlier condensation)
- Radius decrease by 200 m; Mmax slightly reduced



Vijayan et al 2023

Merger simulations

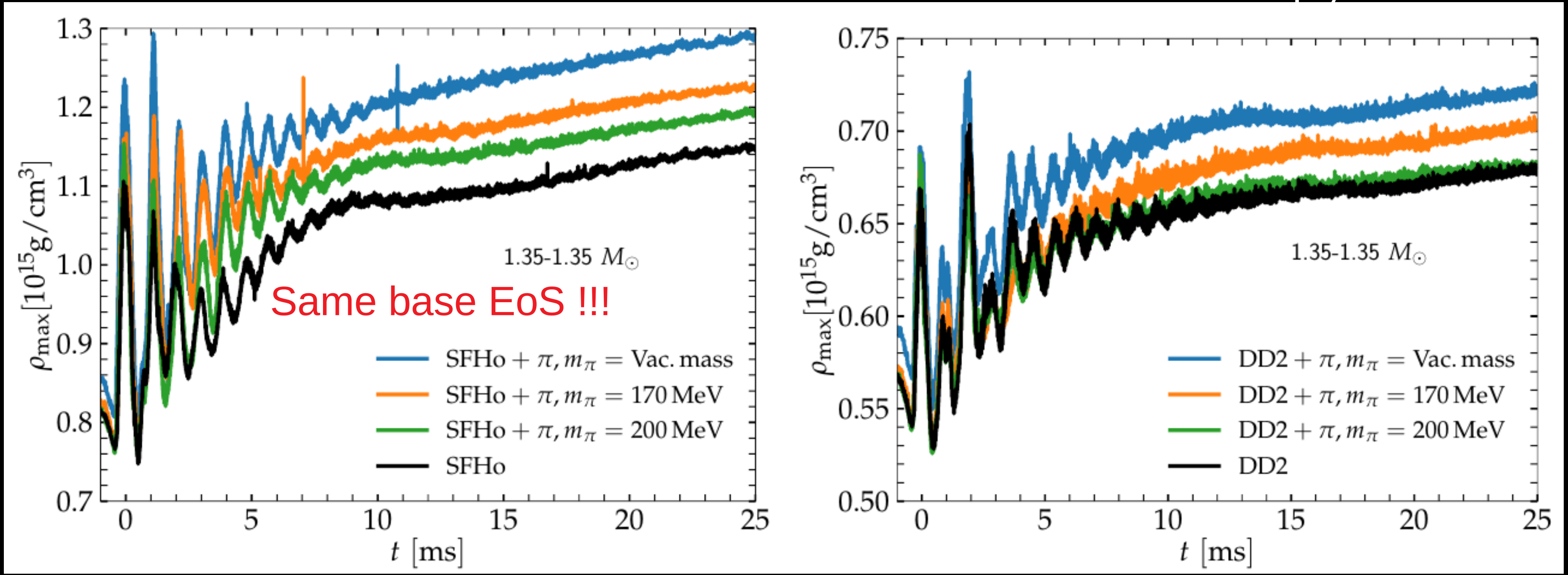
Motivation:

- Possibly combined effects condensate and thermal pions
- Empirical relations of merger observables often expressed by TOV properties

  → to which extend to those relations hold when pions are included ?

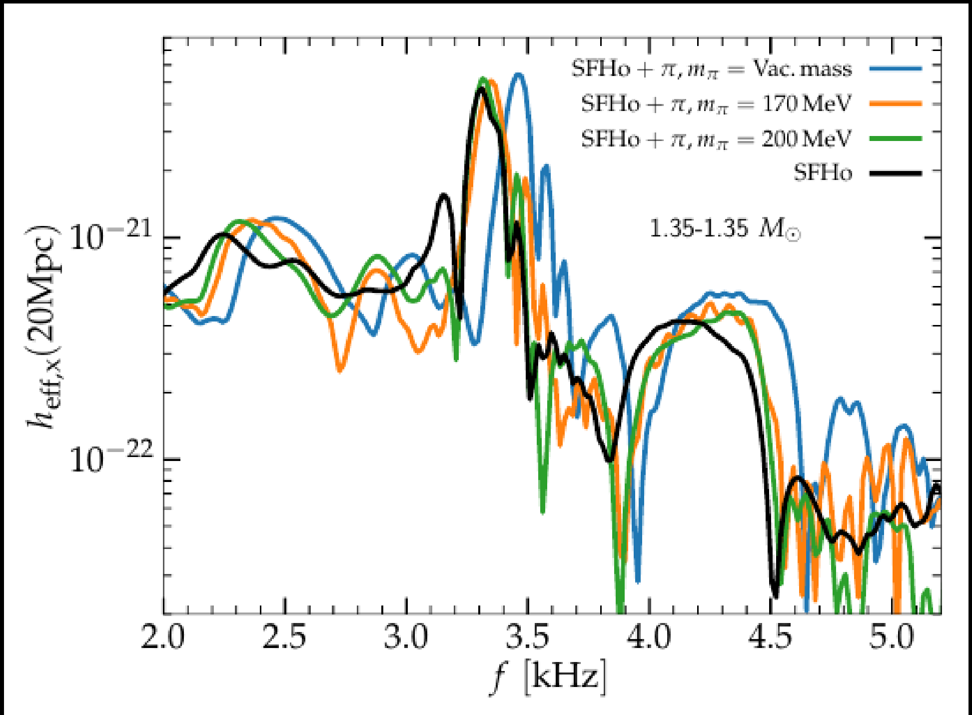
- SPH merger simulations in CFC with modified EoS tables compared to originals
- Electron fraction advected (okaish for high-density part where pions occur)

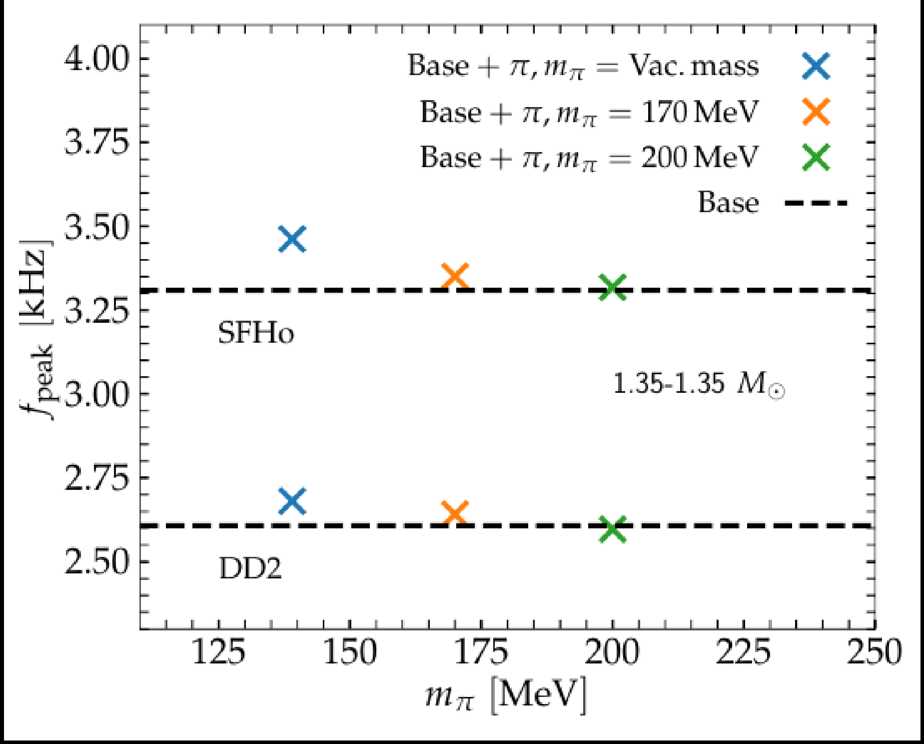
Vijayan et al 2023



Postmerger GWs

- Inspiral: Tidal deformability reduced by 10 per cent (for mpi close to vac mass)
  → potentially problematic if nuclear parameters are deduced and pis neglected
- Postmerger: frequency shifts up to 150 Hz

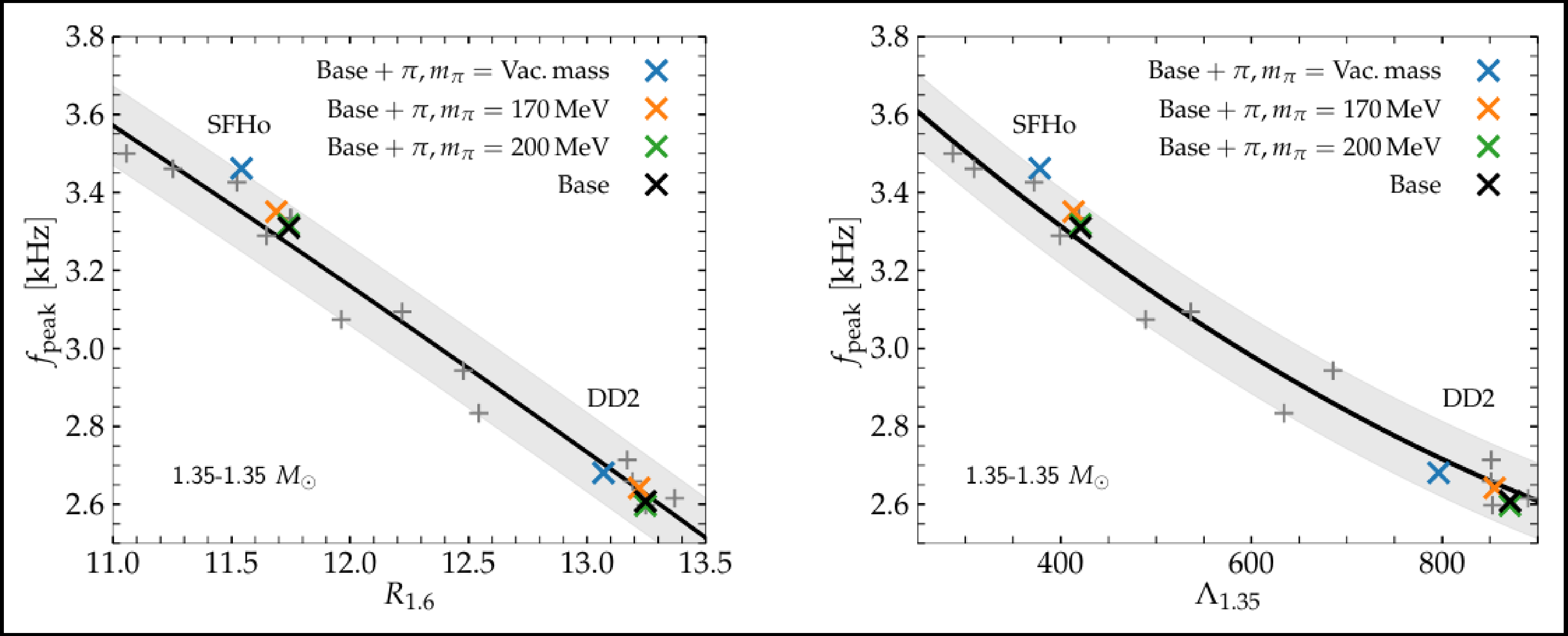




Vijayan et al 2023

Empirical relations for dominant postmerger frequency

- Empirical relations build without pions remain approximately valid
- For softer SFHO model possibly stronger shifts for m_π = vac. mass

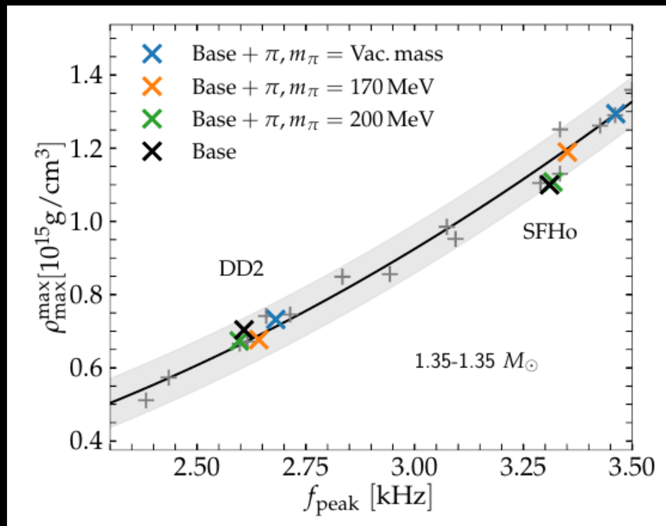


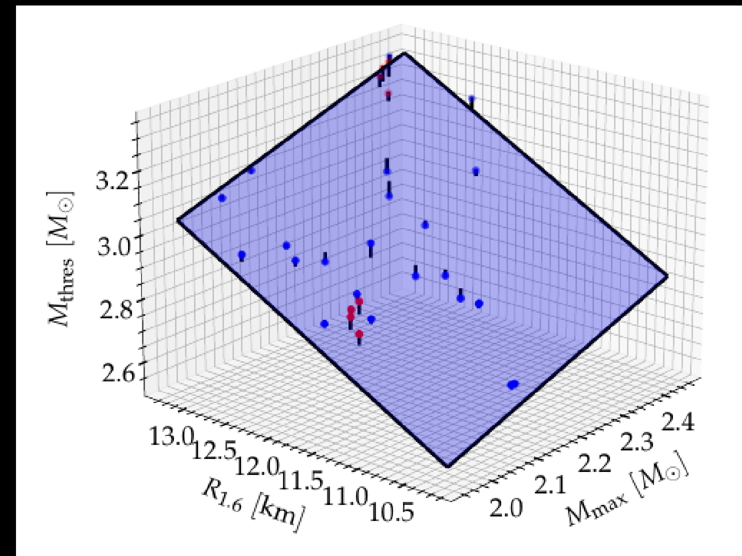
Grey data points EoS models **without** pions (black curve fit to those)

Vijayan et al 2023

Threshold mass for prompt collapse

Vijayan et al 2023





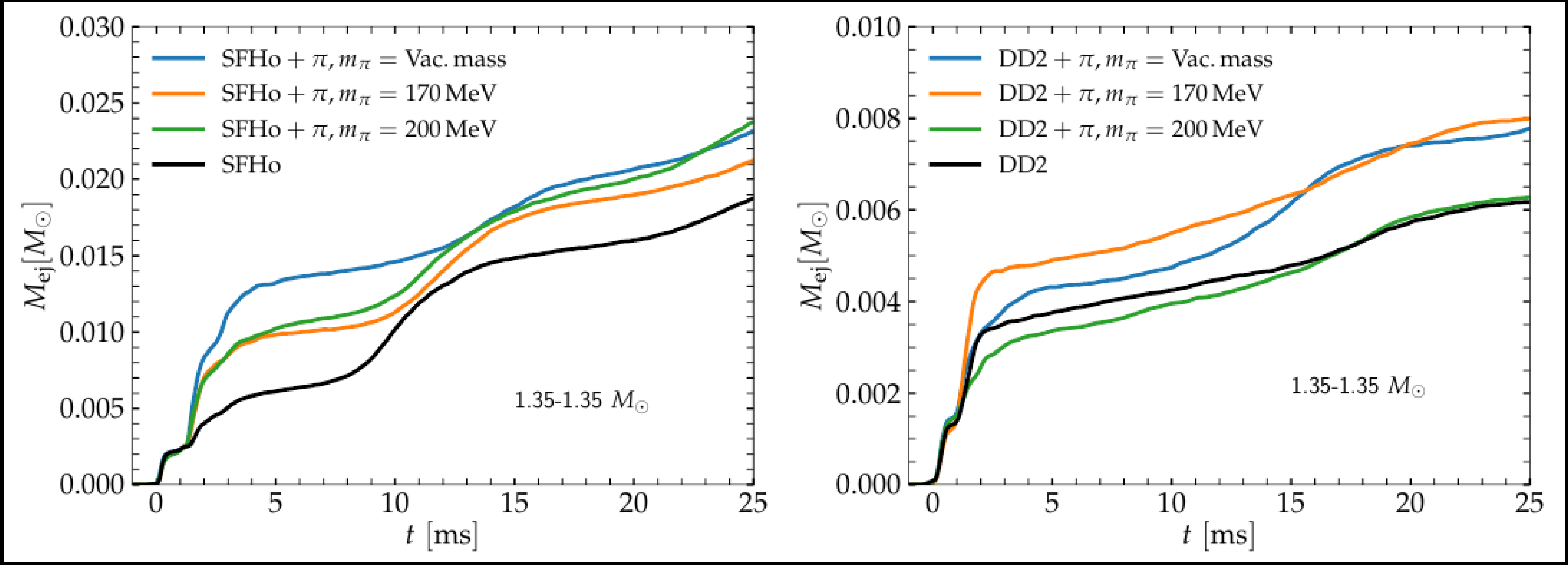
Model (Max. dev./$M_\odot$)	M_{thres} [$M_\odot$]	M_{max} [$M_\odot$]	$R_{1.6}$ [km]	R_{max} [km]	$\Lambda_{1.4}$	$\tilde{\Lambda}_{thres}$	M_{thres}^{fit} ($Y = R_{1.6}$) (0.042) [$M_\odot$]	M_{thres}^{fit} ($Y = R_{max}$) (0.059) [$M_\odot$]	M_{thres}^{fit} ($Y = \Lambda_{1.4}$) (0.056) [$M_\odot$]	M_{thres}^{fit} ($Y = \tilde{\Lambda}_{thres}$) (0.085) [$M_\odot$]
SFHo + π, Vac. mass	2.810	2.017	11.542	10.085	296.937	290.362	2.806(0.004)	2.804(0.006)	2.784(0.026)	2.796(0.014)
SFHo + π, 170 MeV	2.845	2.026	11.688	10.212	324.561	292.701	2.835(0.010)	2.832(0.013)	2.811(0.034)	2.816(0.029)
SFHo + π, 200 MeV	2.855	2.038	11.741	10.277	332.950	291.953	2.851(0.004)	2.850(0.005)	2.825(0.030)	2.832(0.023)
SFHo Base	2.870	2.056	11.743	10.285	332.970	282.036	2.861(0.009)	2.859(0.011)	2.835(0.035)	2.830(0.040)
DD2 + π, Vac. mass	3.250	2.381	13.069	11.692	639.278	256.841	3.257(-0.007)	3.271(-0.021)	3.271(-0.021)	3.228(0.022)
DD2 + π, 170 MeV	3.290	2.390	13.220	11.791	699.649	261.744	3.287(0.003)	3.294(-0.004)	3.325(-0.035)	3.256(0.034)
DD2 + π, 200 MeV	3.310	2.403	13.246	11.865	700.166	256.079	3.298(0.012)	3.314(-0.004)	3.333(-0.023)	3.259(0.051)
DD2 Base	3.322	2.417	13.246	11.899	700.146	250.548	3.306(0.016)	3.327(-0.005)	3.341(-0.019)	3.263(0.059)

- Mthres reduced by up to 0.08 M_{sun} (for m_π~vac mass)
- But empirical relations remain valid (within scatter) - combined effect on M_{thres} and TOV properties

Mass ejection

- Inclusion of pions leads to (tentatively) more ejecta
- Increase stronger than expected from TOV properties (employing common fit formulae, see e.g. Henkel et al 2022)

  → potentially problematic of EoS inference
- Torus mass similar effects



Vijayan et al 2023

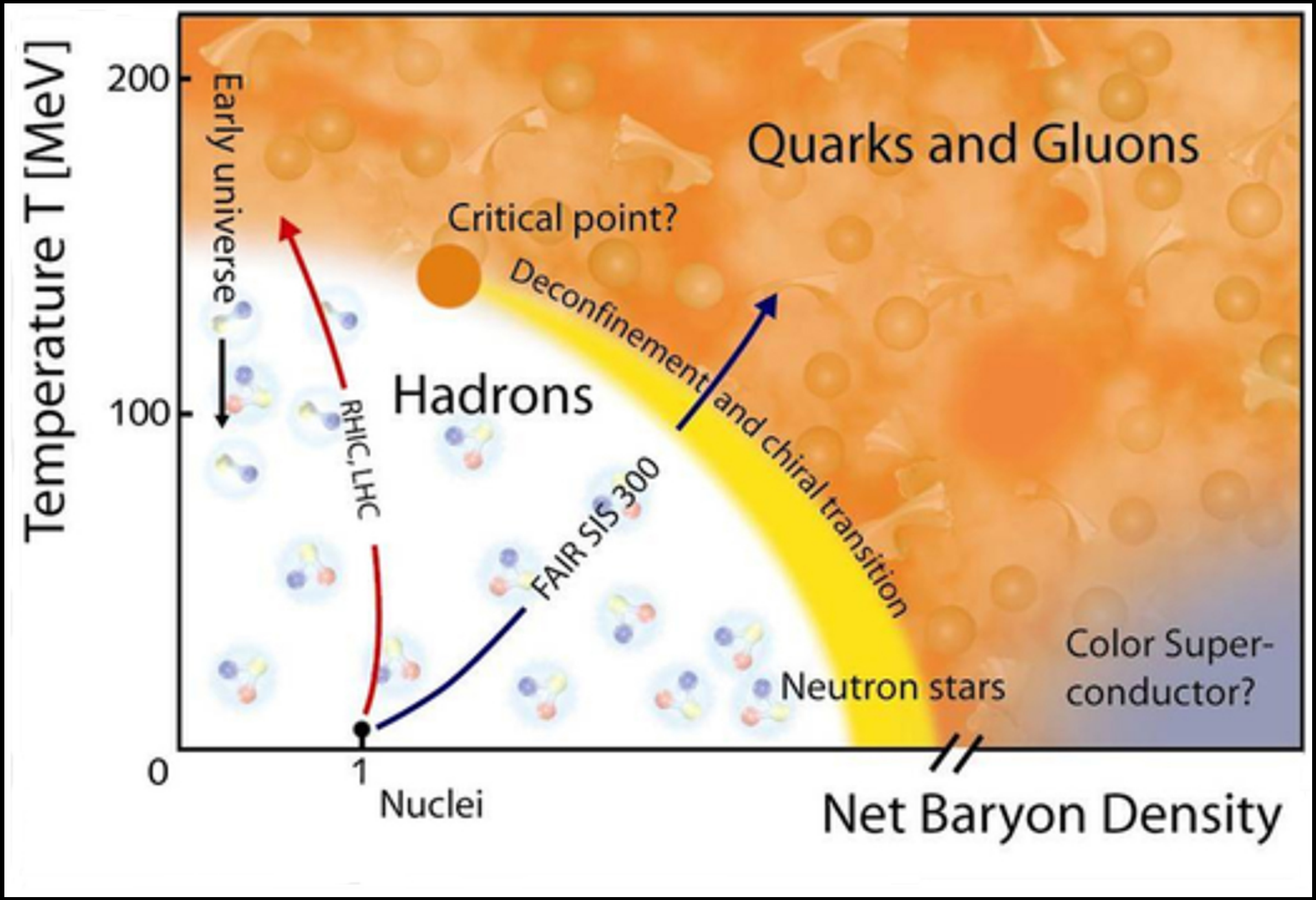
Quark matter in NS mergers

Bauswein et al 2019, Bauswein & Blacker 2020,
Bauswein et al 2020, Blacker et al. 2020, Blacker et al. 2023

Phase diagram of matter of strongly interacting matter

High T, low μ:
experiments and
lattice QCD

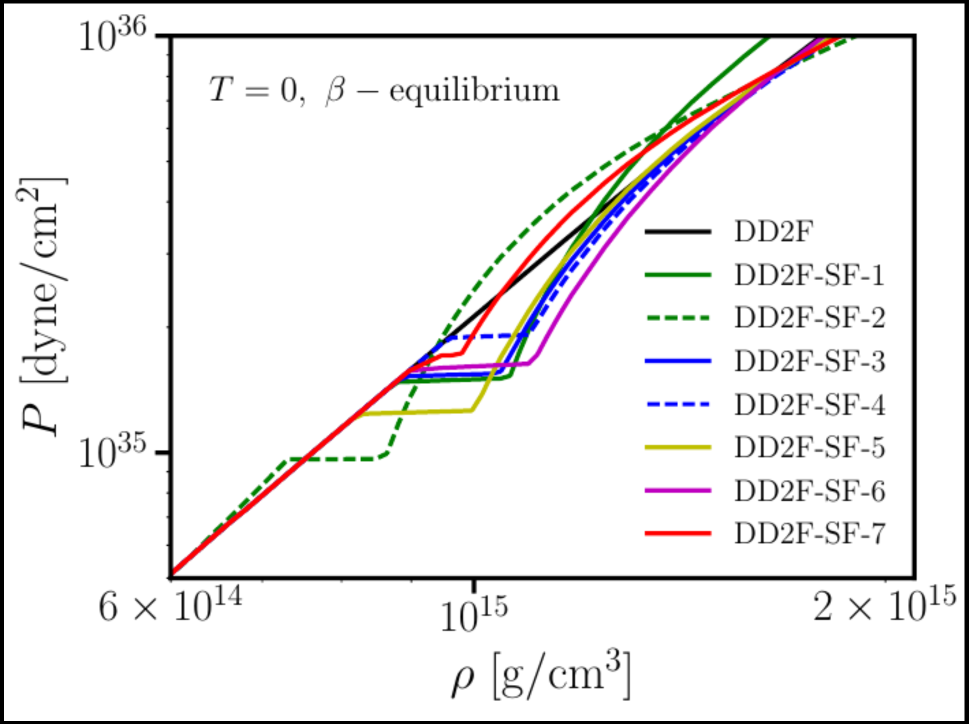
GSI/FAIR

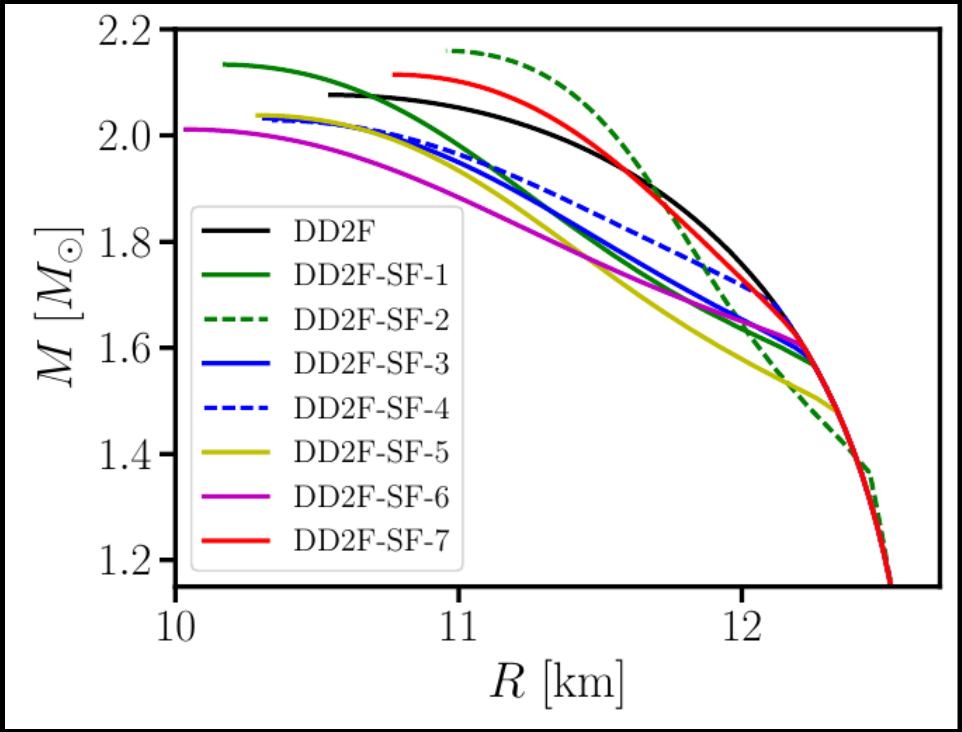


Does the phase transition to quark-gluon plasma occur (already) in neutron stars or only at higher densities?

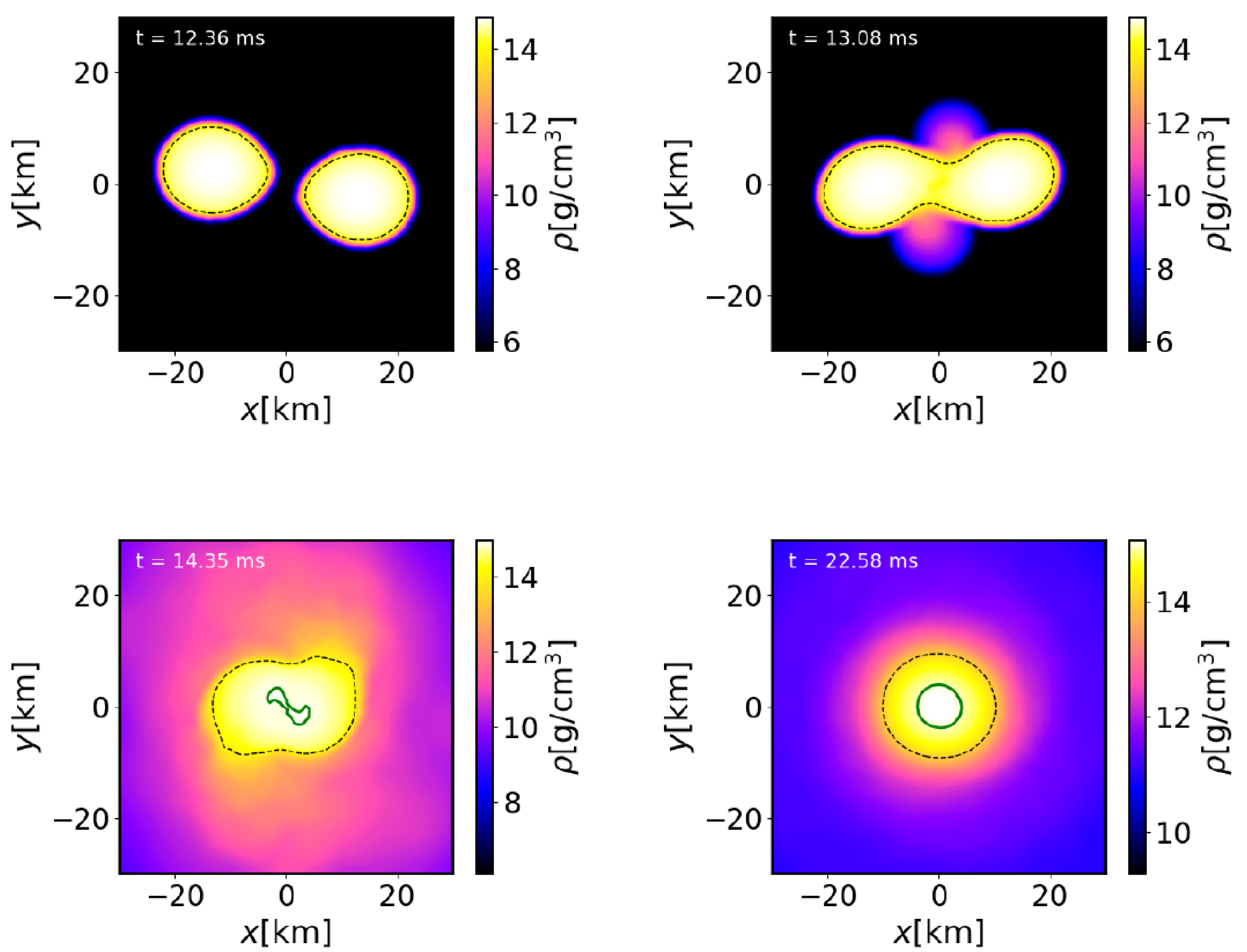
(low T, high rho not accessible by experiments or ab-initio models)

- 7 different models for quark matter: different onset density, different density jump, different stiffness of quark matter phase



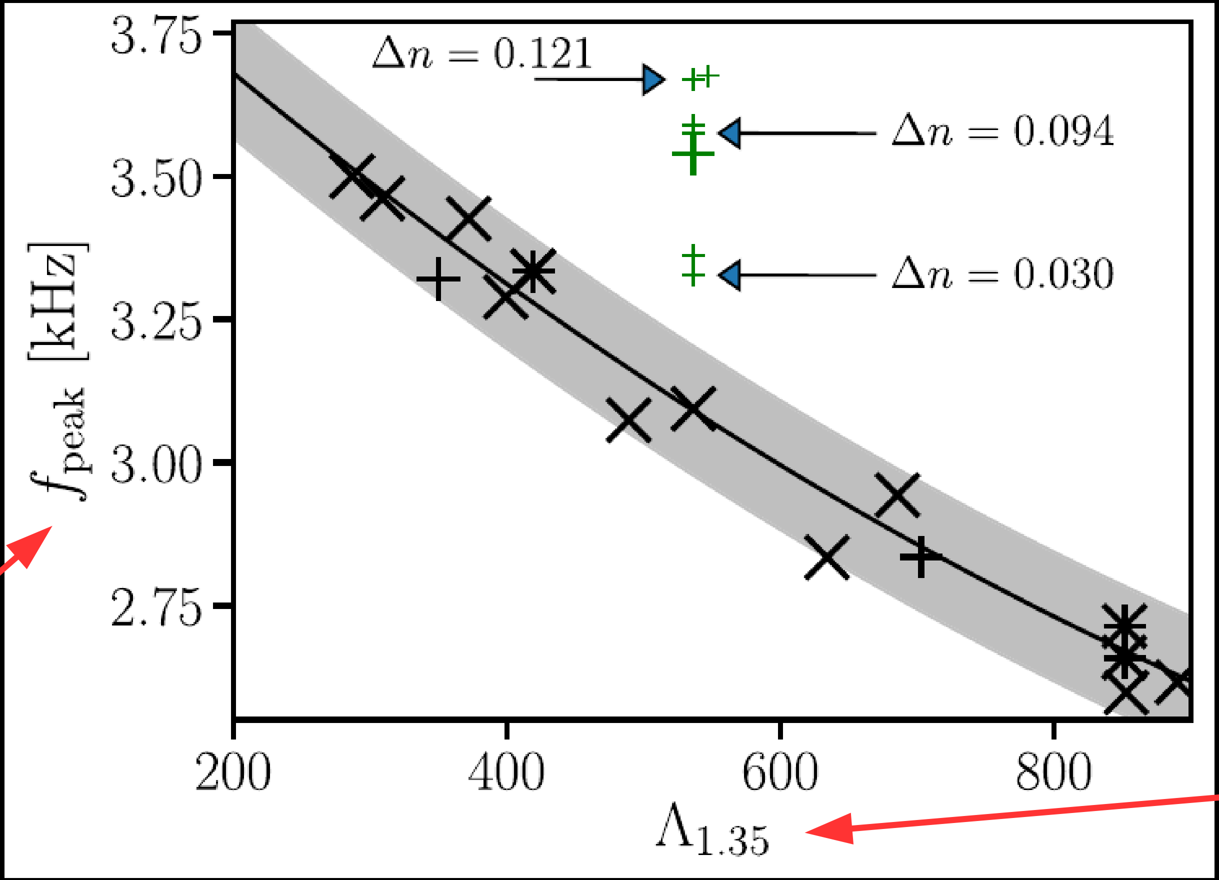


Bauswein et al. 2019, Bastian 2020



Bauswein et al. 2019

Signature of phase transition



from postmerger

from the inspiral

Bauswein et al., PRL 122 (2019)

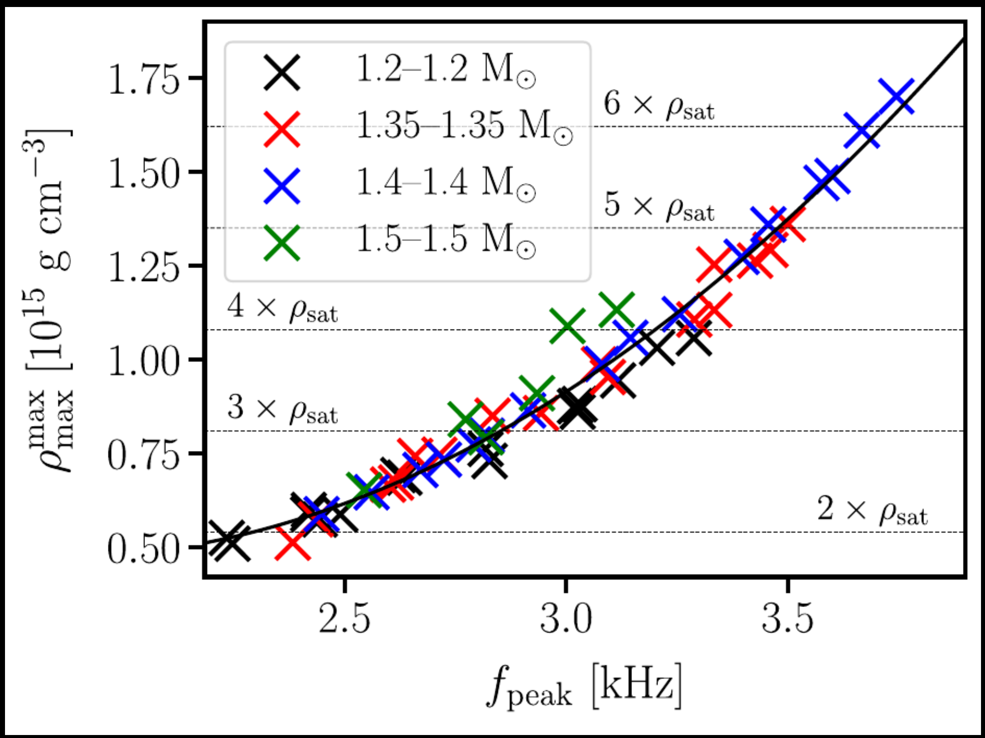
- Tidal deformability from inspiral
- Postmerger frequency measurable to within a few 10 Hz @ a few 10 Mpc (eg by Adv. Ligo upgrade, e.g. Chatziioannou+2017, Torres-Riva+2019, Wijngaarden+ 2022)

See also Most+ 2019, Blacker+ 2020, Weih +2020, Bauswein+2020, Prakash+ 2021, Liebling+ 2021, Hanauske+ 2021, Fujimoto+2022, Tootle+ 2022, Huang+ 2022, ...

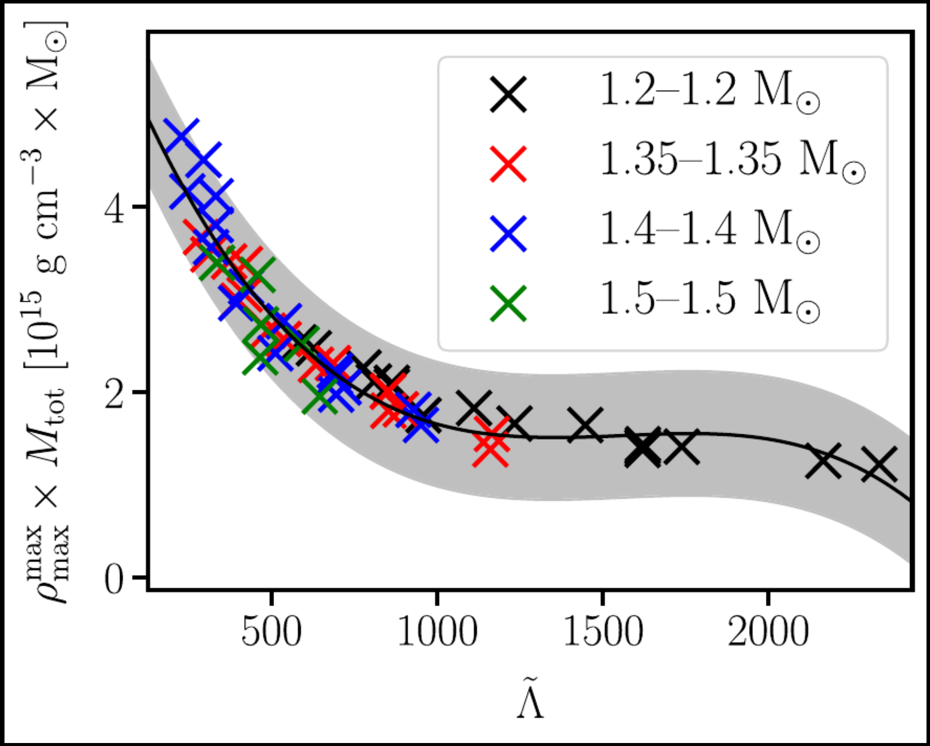
- GWs inform about highest density in the remnant

  → constraint on onset density (if PT is identified/excluded)

Blacker et al. 2020



Postmerger frequency fpeak

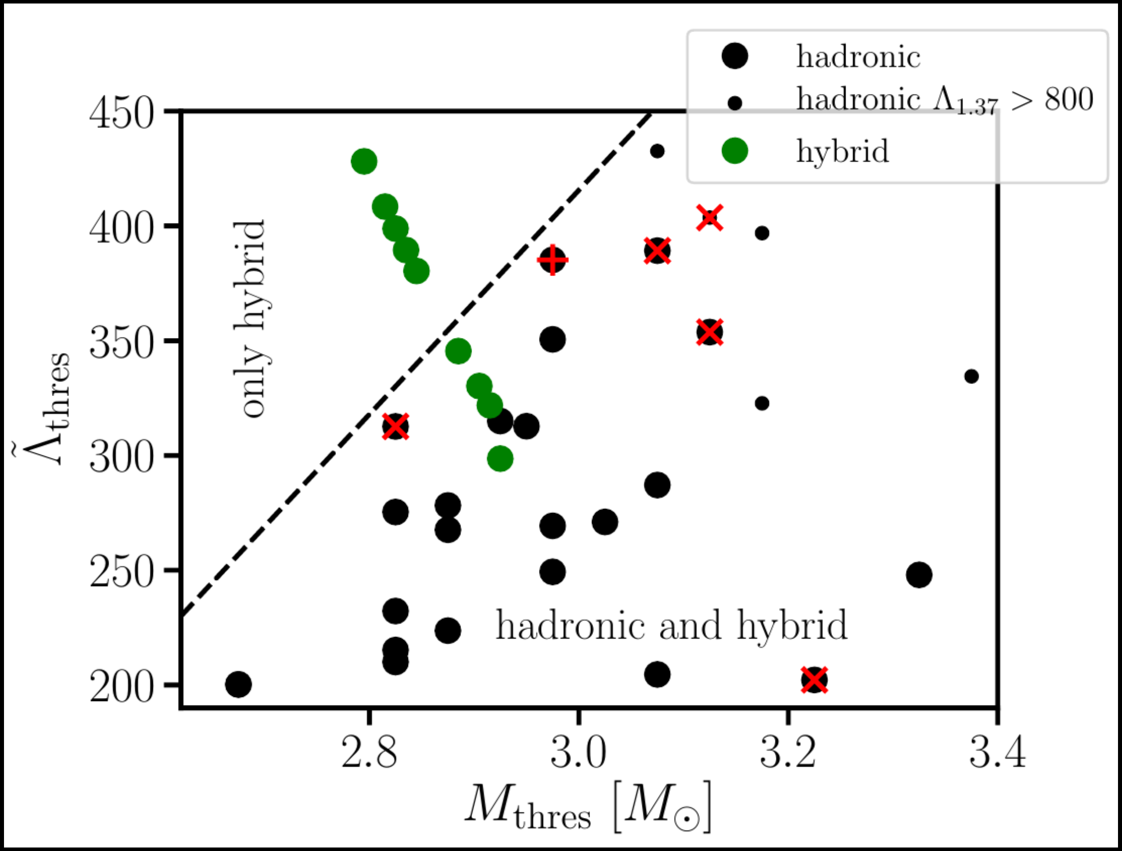


tidal deformability from inspiral

QCD phase transition from collapse behavior

- Directly measurable from events around M_{thres}
- Already single events yielding constraints may indicate presence of quark matter

With M_{max} > 1.97 !!



Bauswein et al., PRL 125 (2020)

Measurable from GW inspiral

Measurable from inspiral + information on merger product

$$\tilde{\Lambda}_{\rm thres} = \Lambda(M_{\rm thres}/2) \ \ \text{for} \ \ q = 1$$

QCD phase transition from collapse behavior

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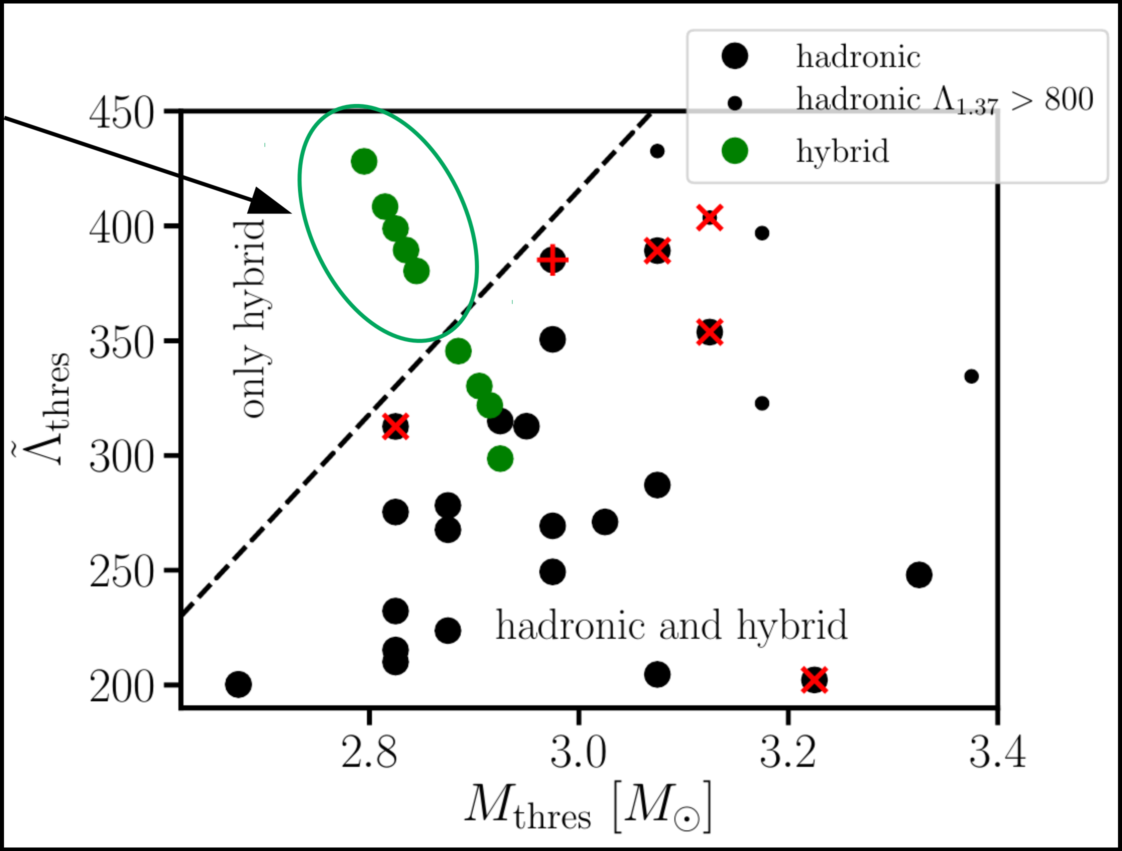
Evidence for quark matter

With M_{max} > 1.97 !!



Bauswein et al., PRL 125 (2020)

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Hyperons in NS mergers

Blacker, Kochankovski, Bauswein, Ramos, Tolos, arXiv:2307.03710

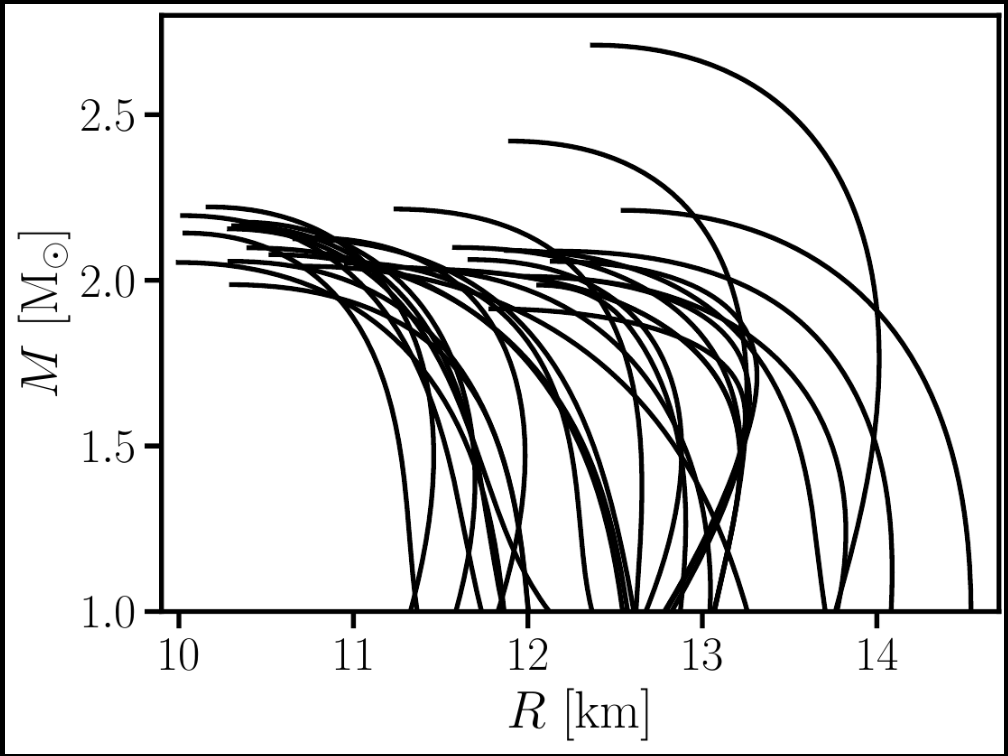
See Sekiguchi et al. 2011, Raice et al 2017 for early studies of individual EoS models

Hyperon puzzle

- Natural to expect that nucleons are converted to hyperons once chemical potential reaches hyperon mass
- Hyperon puzzle: Hyperons would soften the EoS which is in tension (?) with 2 Msun NSs
- Several modern hyperonic EoS fulfill the 2 Msun constraint

→ hyperon puzzle unsolved – interacting Fermi gas with unknown interactions

→ generally hyperons leave weak impact on NS structure – indistinuishable MR



Blacker et al. 2023

Hyperon puzzle

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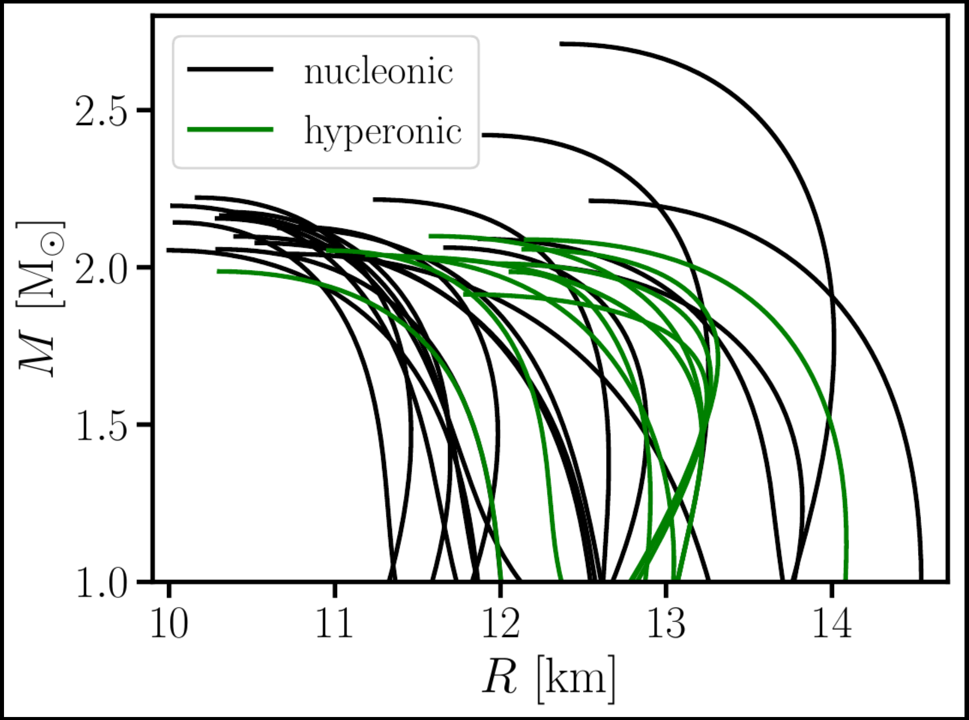


Blacker et al. 2023

Thermal behavior as indicator for hyperons

- A nucleonic EoS could mimic T=0 behavior of any hyperonic EoS !

  → Comprehensive study of hyperonic EoSs in NS mergers

- Isolate thermal behavior of hyperons

  - Idea: assume T=0 EoS do not contain any information and adopt hyperonic EoS to be purely nucleonic (obviously incorrect assumption but necessary)

  - supplement with approximate thermal pressure treatment to mimic "nucleonic" thermal behavior

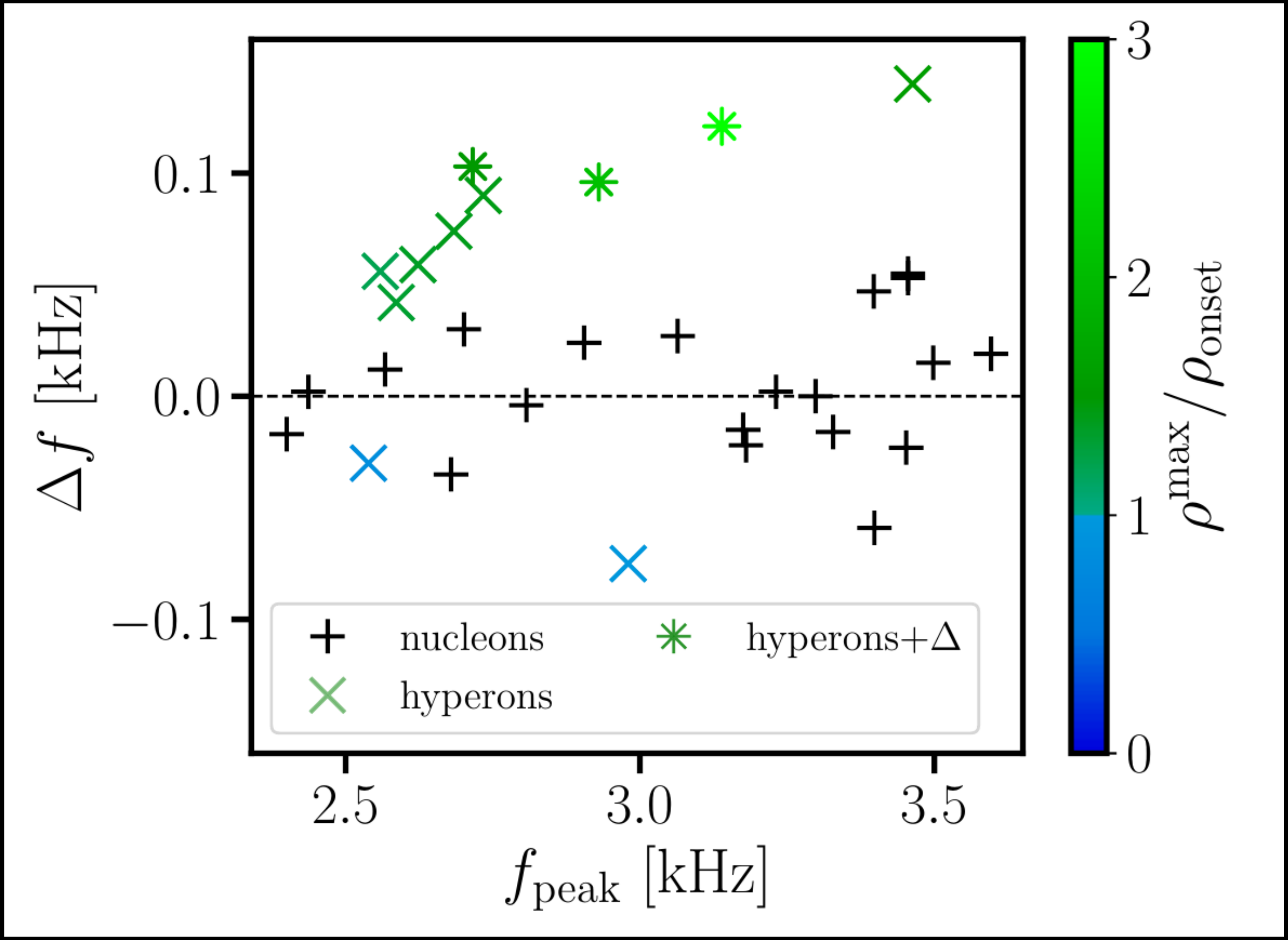
$$P_{th} = (\Gamma_{th} - 1)\epsilon\rho$$

$\Gamma_{th} = 1.75$ found to reproduce nucleonic EoSs

Compare $\Gamma_{th} = 1.75$ runs vs. full T-dependent simulations → thermal behavior of hyperons

Thermal behavior as indicator for hyperons

- Delta f describes impact of hyperons on thermal behavior → in principle measurable !!



Blacker et al. 2023

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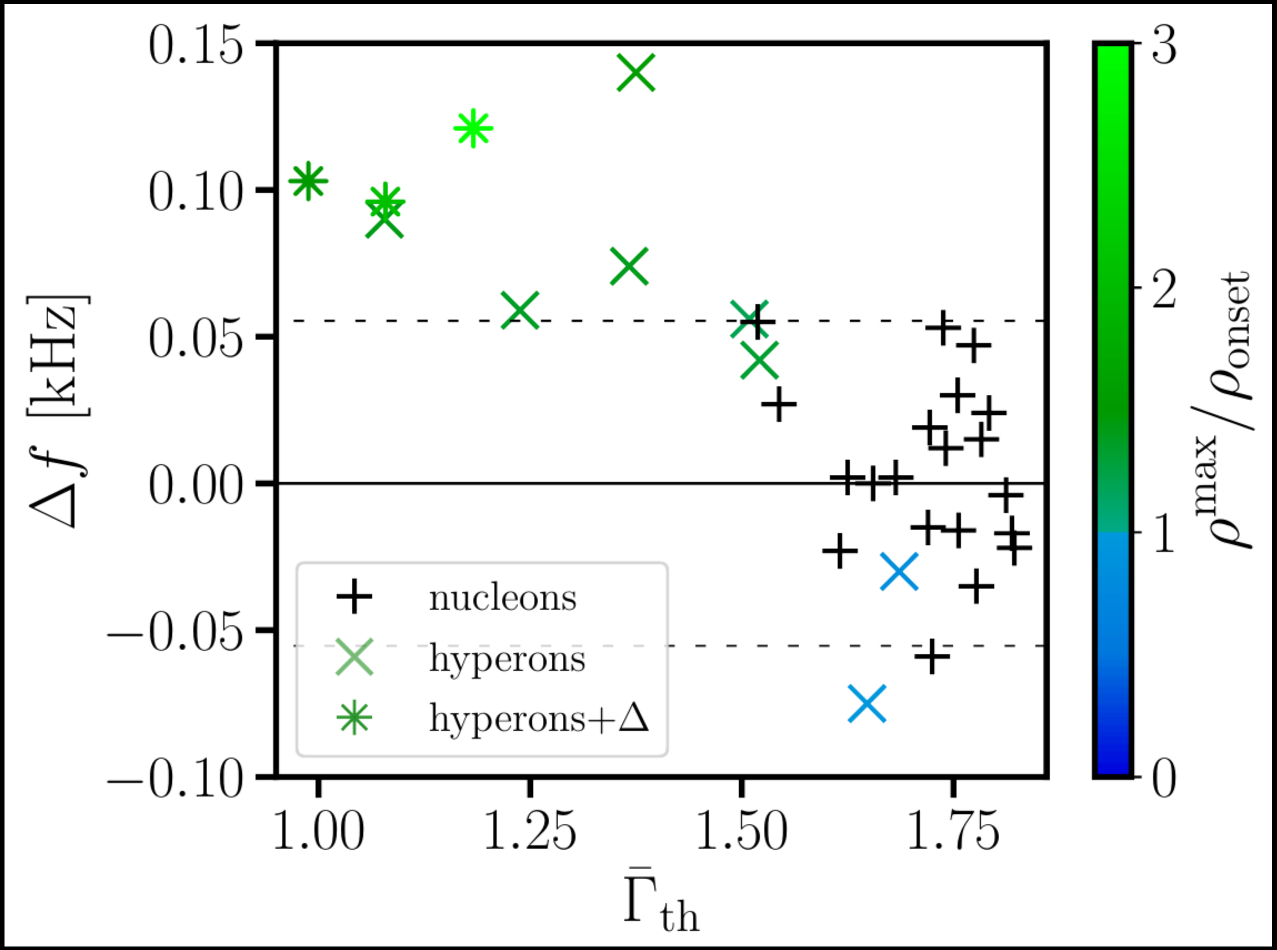

Blacker et al. 2023

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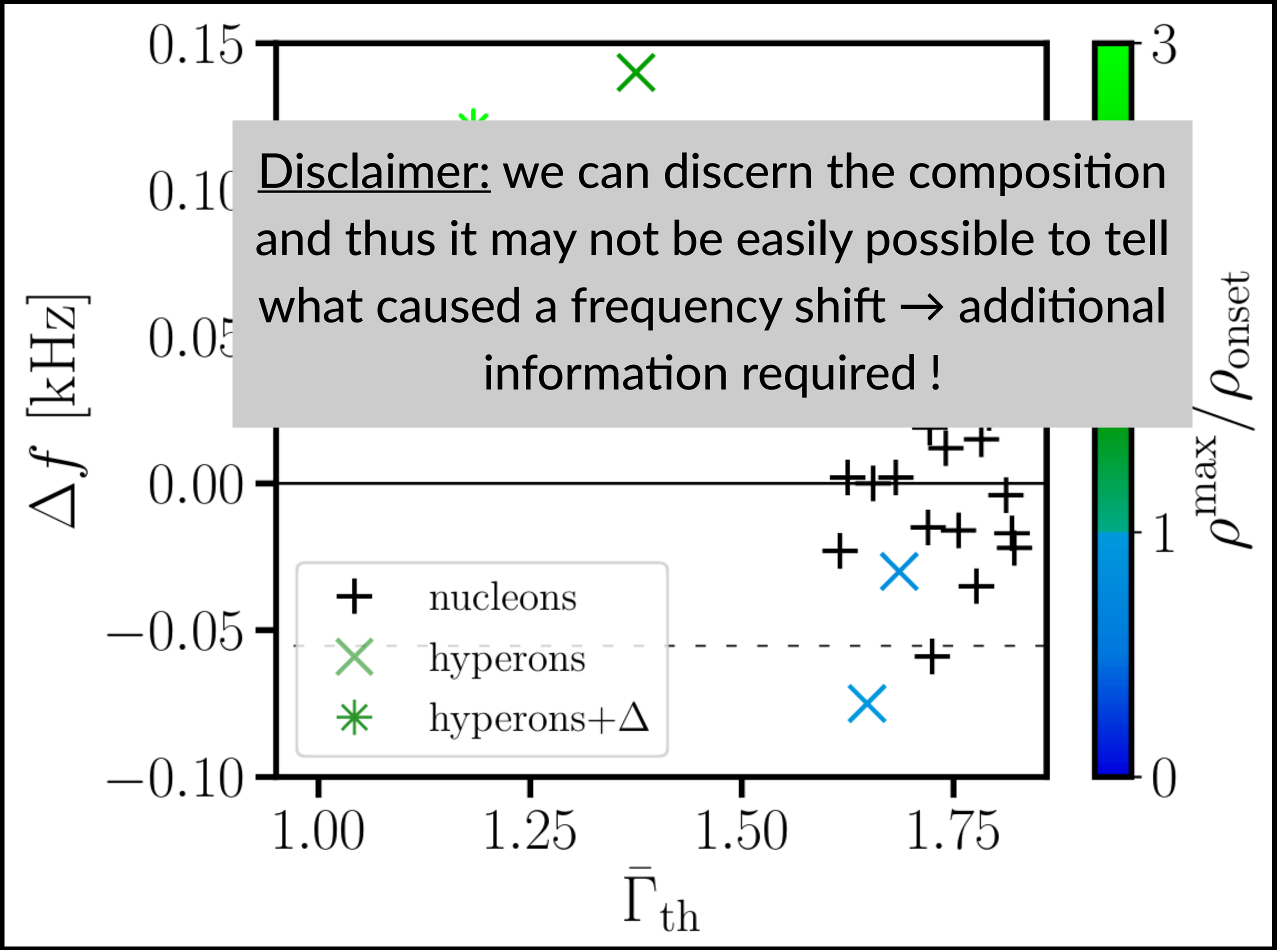
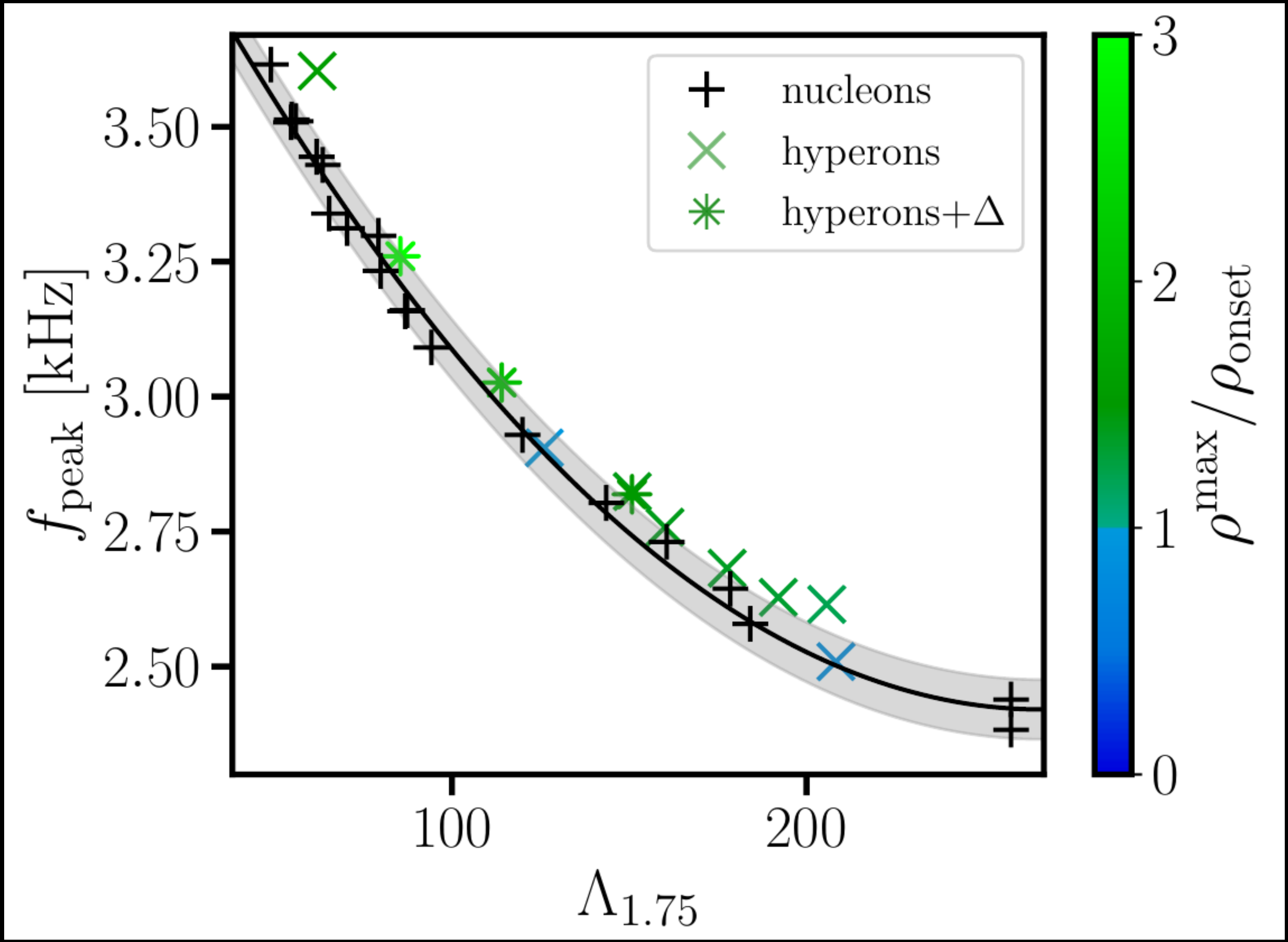


Disclaimer: we can discern the composition and thus it may not be easily possible to tell what caused a frequency shift → additional information required !

Blacker et al. 2023

- Concrete scenario: hyperonic models have tendency to yield increased fpeak



Blacker et al. 2023

Summary

- Pions may affect stellar structure and merger dynamics

  → empirical relations still hold (cancelation effect)

  - but should be considered for certain applications (systematic bias)
- Quark matter can lead to a characteristic shift of postmerger frequency

  - by compactification of remnant

  - also threshold mass affected
- Hyperons modify thermal behavior of EoS → only minor frequency shift