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

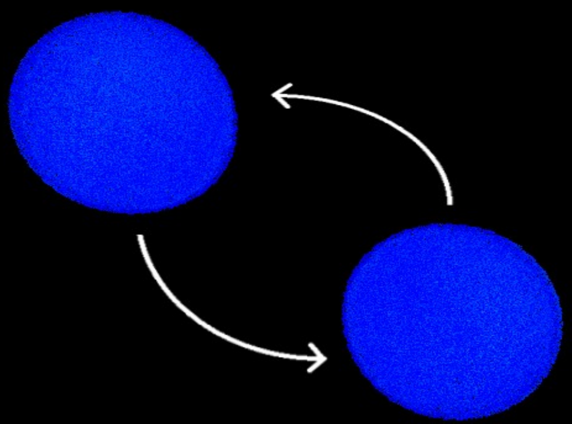
Non-nucleonic degrees of freedom in neutron star mergers

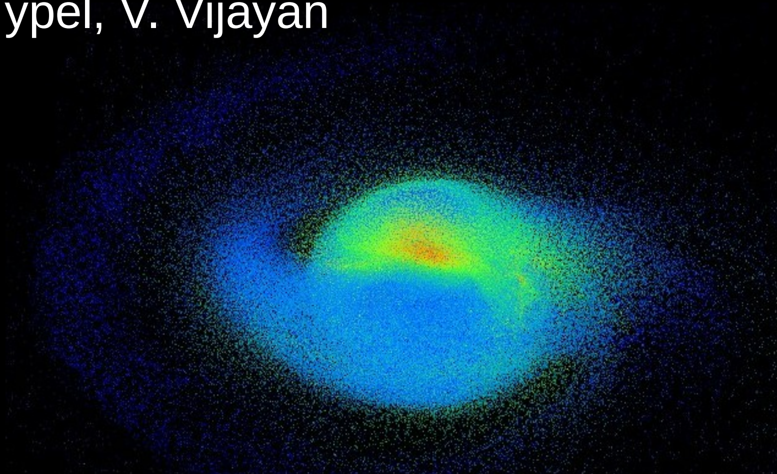
ECT* workshop “The physics of strongly interacting matter: neutron stars, cold atomic gasess, and related areas”, Trento 26/04/2024

Andreas Bauswein

(GSI Darmstadt)

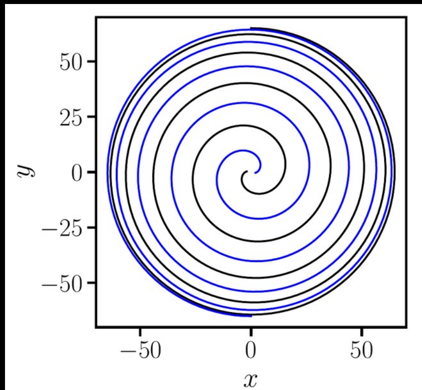
with N. Bastian, S. Blacker, D. B. Blaschke, K. Chatziioannou, T. Fischer, H. Kochankovski, G. Lioutas, G. Martinez-Pinedo, M. Oertel, N. Rahman, A. Ramos, T. Soultanis, N. Stergioulas, L. Tolos, S. Typel, V. Vijayan





Outline

- Intro
- Pions
- Quark matter
- Hyperons
- Conclusions



$P_{orb} \sim 10\,h$

Inspiral of NS binary

~100 Myrs

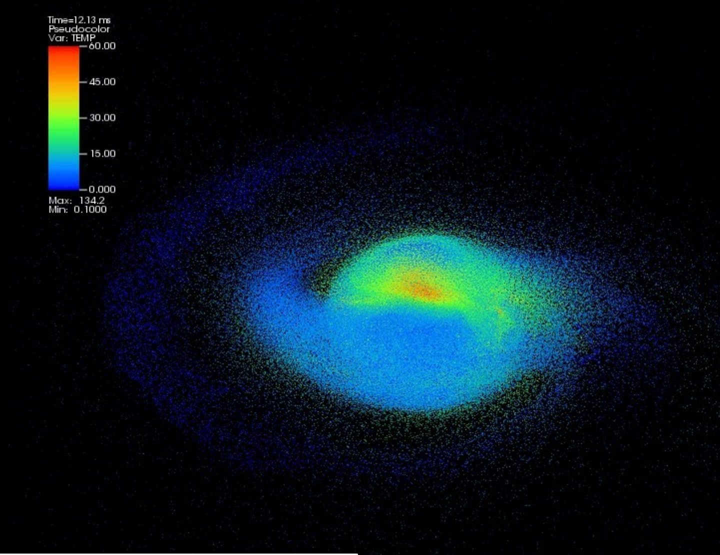
$P_{orb} \sim 1\,ms$

Neutron star merger

dependent on EoS, M_{tot}

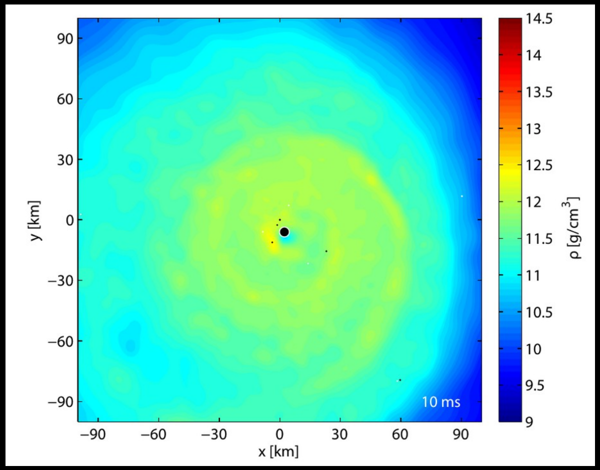
ms

ms



Prompt formation of a BH + torus

Formation of a differentially rotating massive NS



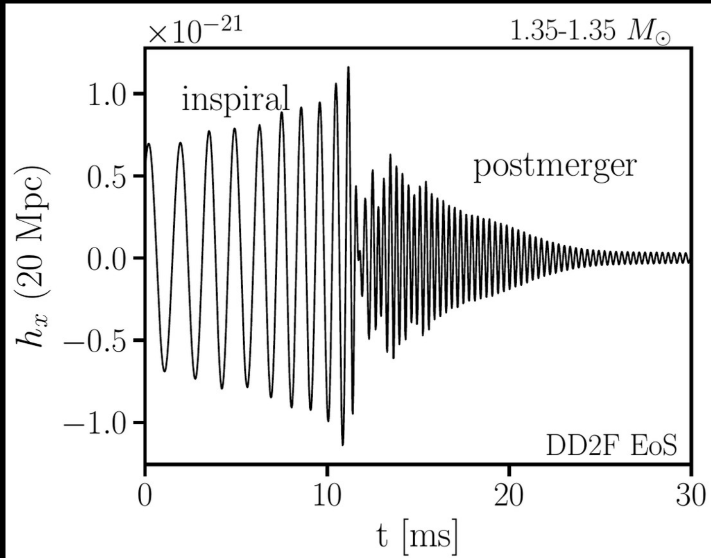
dependent on EoS, M_{tot}

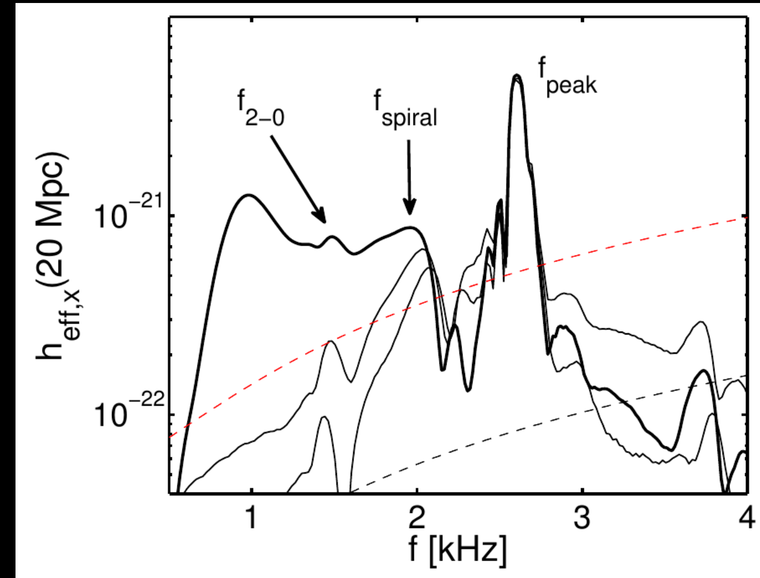
10-100 ms

Rigidly rotating (supermassive) NS (stable or long-lived)

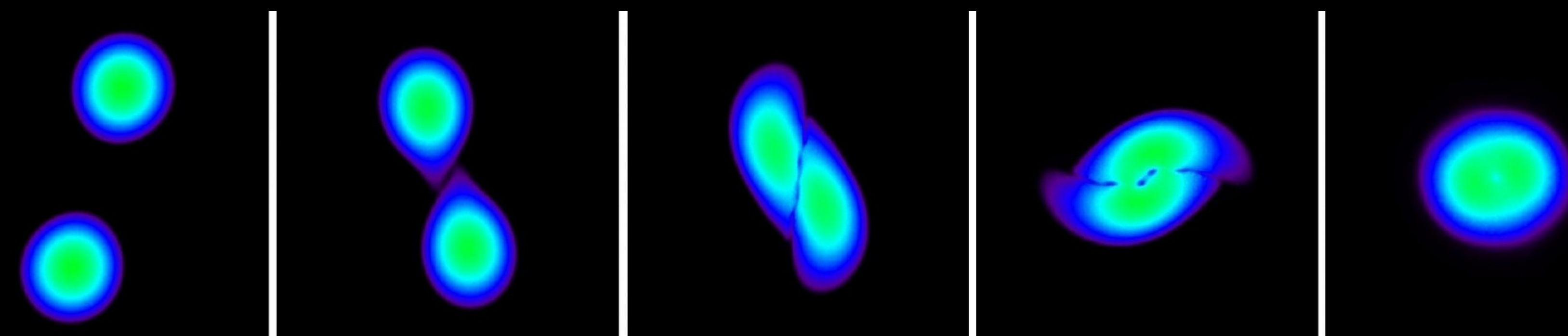
Delayed collapse to a BH + torus

Simulations





Bauswein et al. 2016



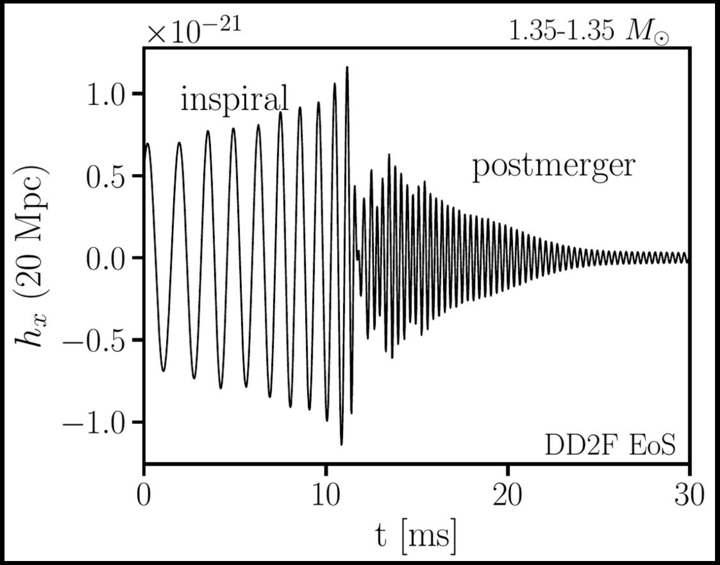
Finite-size effects, i.e. EOS impact, during insprial described by tidal deformability Λ

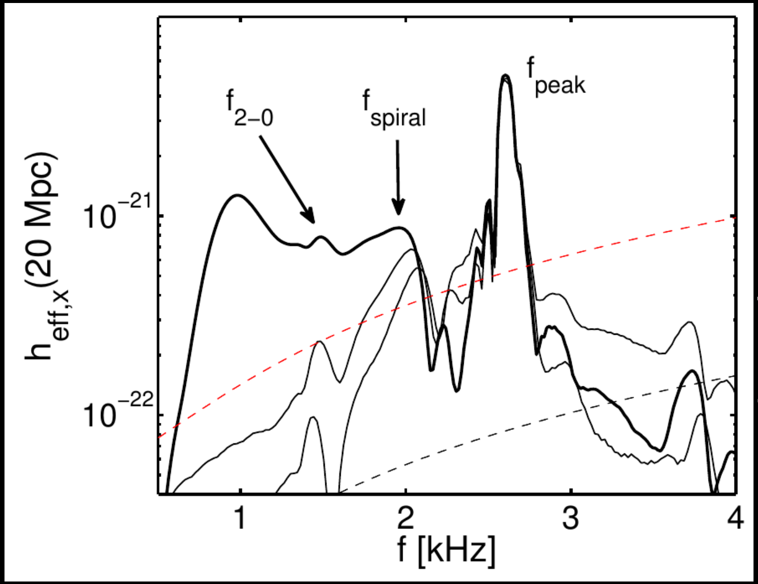
Larger stars /stiffer EOS accelerate inspiral

Dominant remnant oscillation generates pronounced GW peak f_{peak}

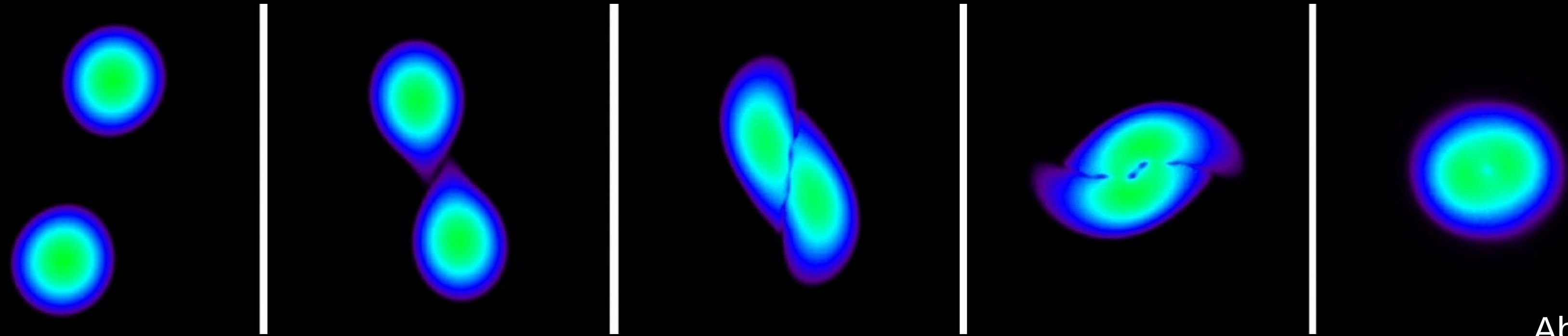
More compact remnants/softer EOS higher f_{pe}

Simulations



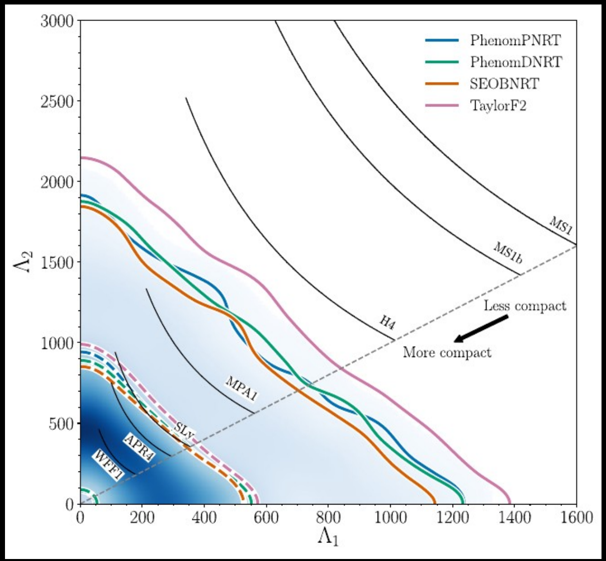


Bauswein et al. 2016



Abbott et al. 2019

Observations



Abbott et al. 2019

GW170817:

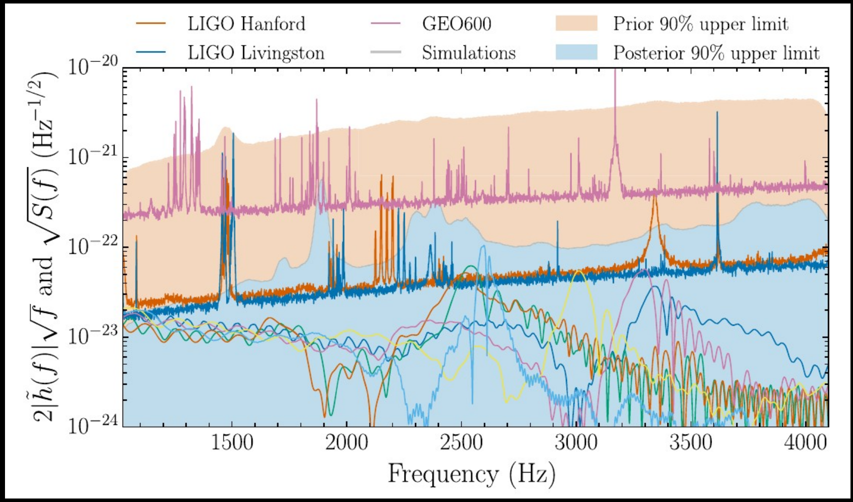
EoS constraint

from GW inspiral:

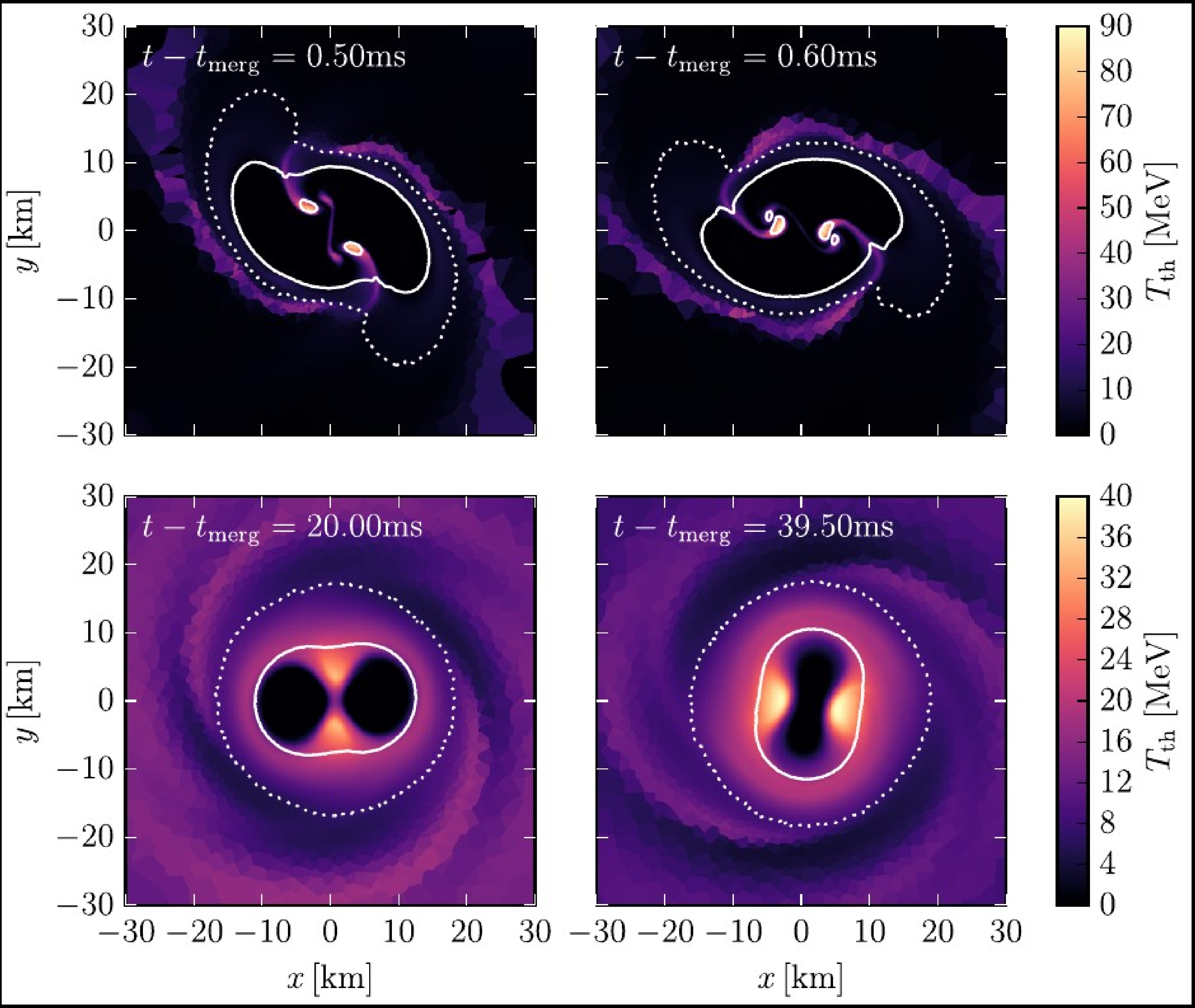
tidal

deformability

Λ<650; R<13.5 km



GW170817: postmerger not yet measured but within

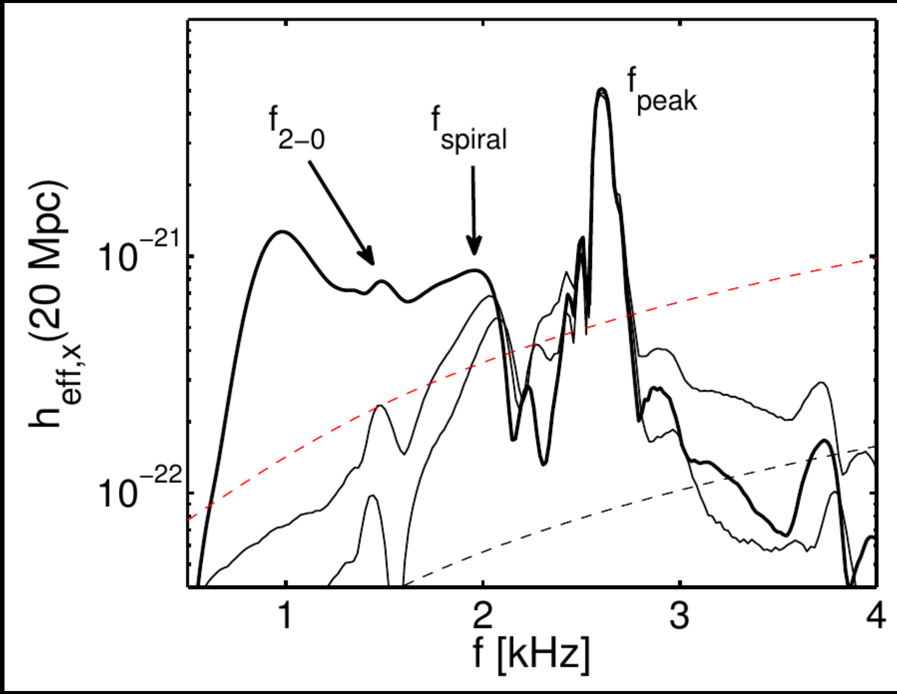


Moving-mesh hydrodynamics – Lioutas et al. 2024

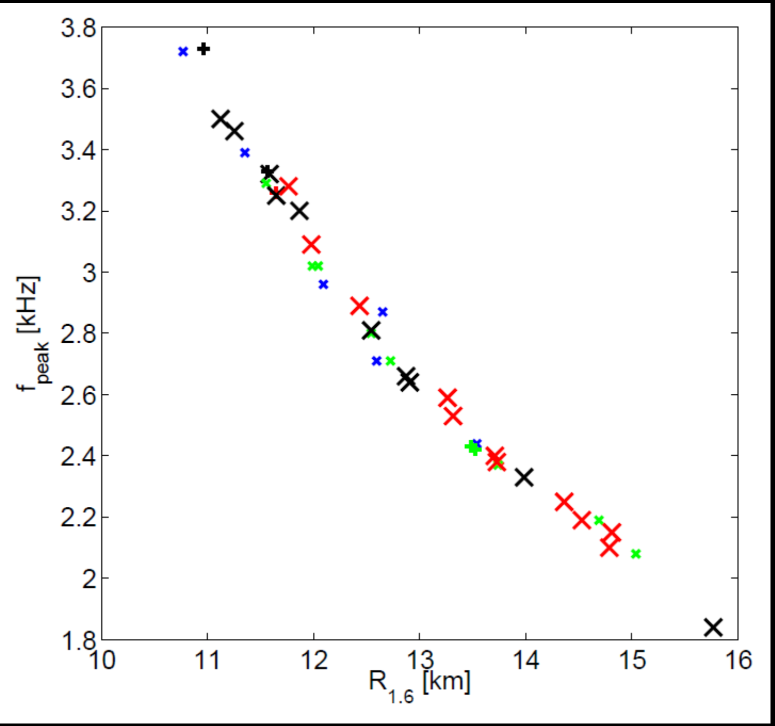
Empirical relations

- To determine NS properties and EoS from some merger observable
- For postmerger GW emission, ejecta / kilonova 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

PRD 108 (2023); 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

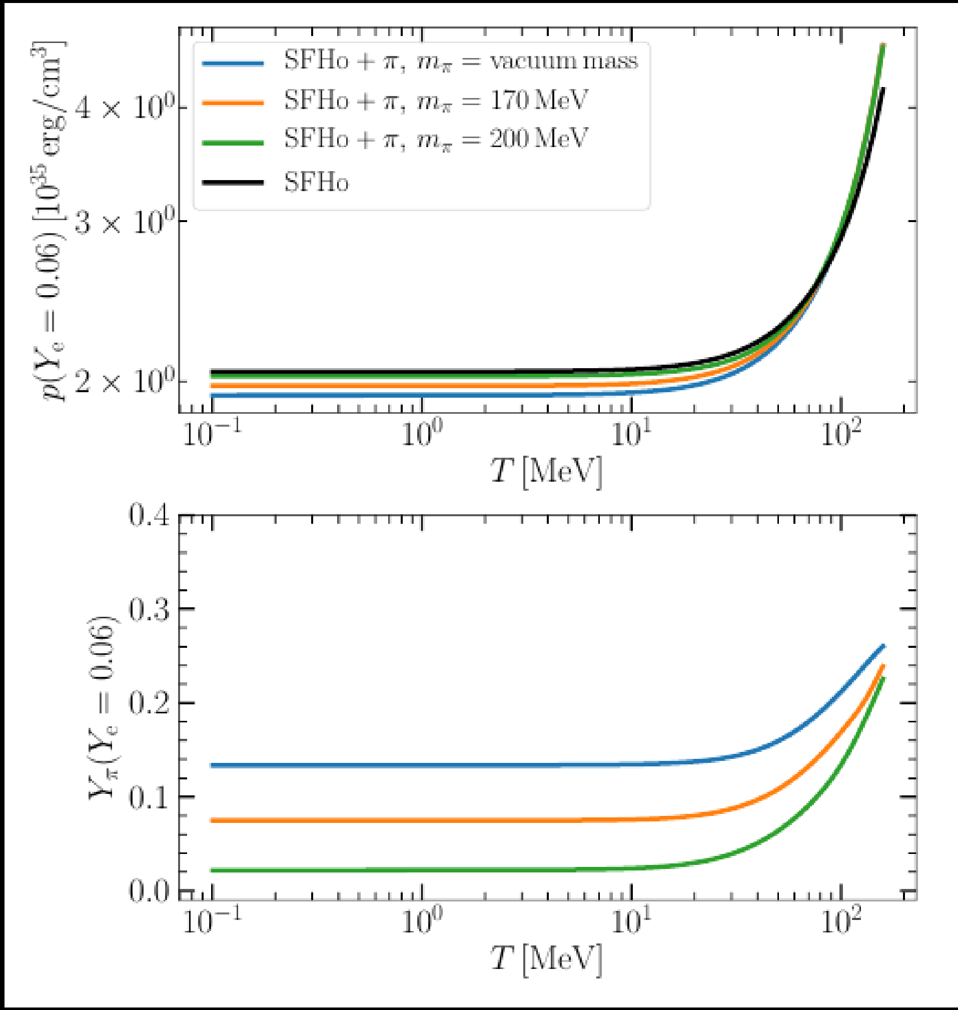
  $\rightarrow$ pion condensation (ground state) and thermal pions
- Two base EoSs (DD2 and SFHO) and chosen constant effective mass

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

Effect of pions on EoS

- SFHo, m_π=vac mass → neutral and thermal pions become relevant at several 10 MeV
- Condensation softens EoS
- (chosen) pion mass determines magntitude of effect – higher m_π smaller impact
- Similar for DD2, other Ye

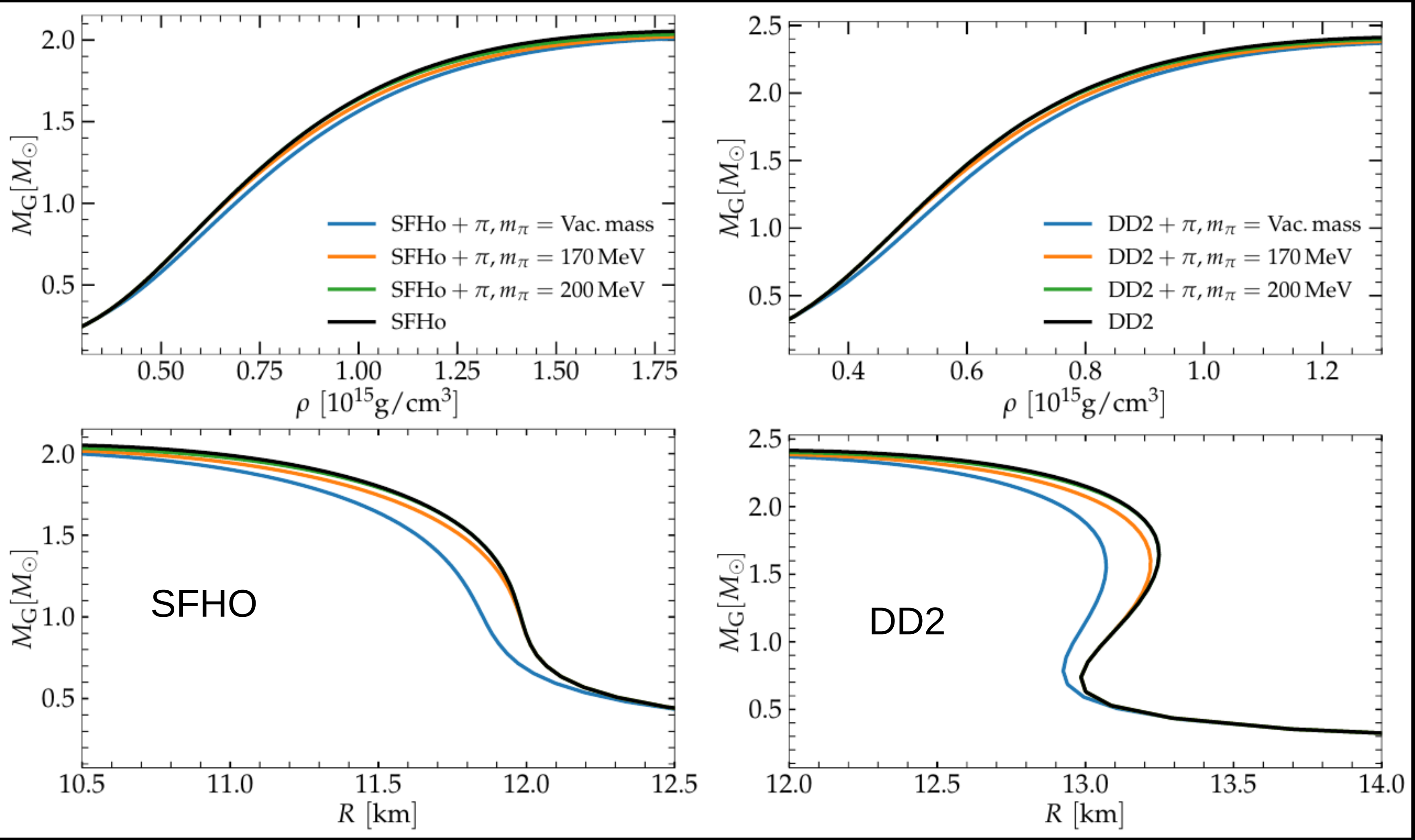
$$\rho = 10^{15} \text{ g/cm}^3$$



Vijayan et al 2023

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

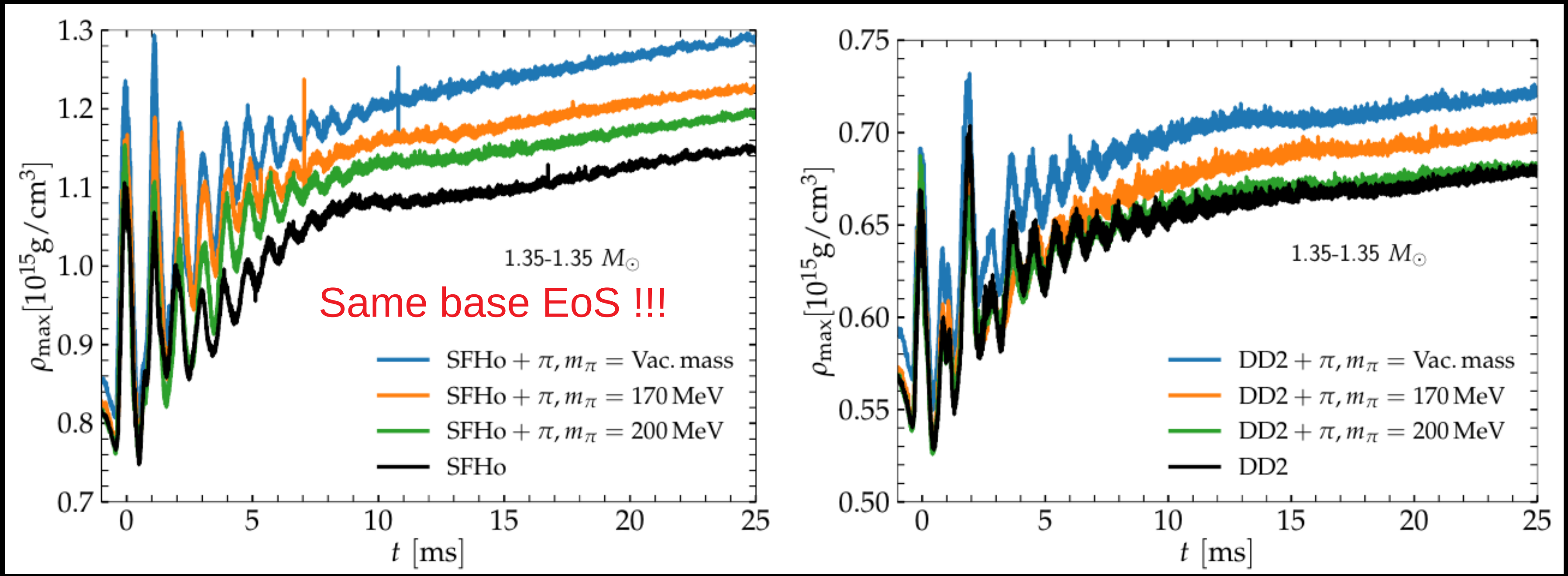
Motivation:

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

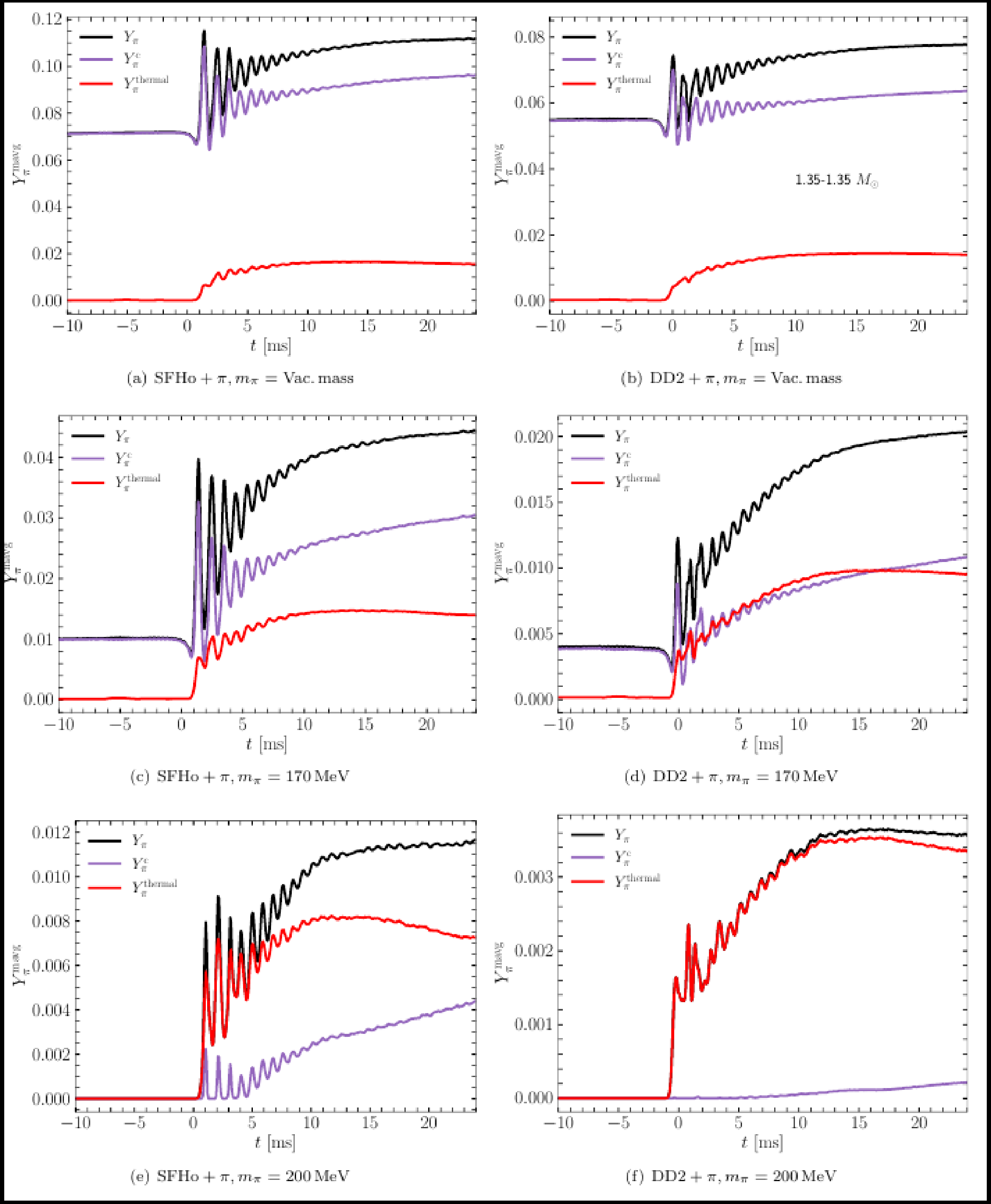
  → to which extend to those relations hold when pions are included ?

- 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



- Mass averaged pions fractions
- Only for 200MeV thermal dominates – but overall small contributions



(a) SFHo + π, m_π = Vac. mass

(b) DD2 + π, m_π = Vac. mass

(c) SFHo + π, m_π = 170 MeV

(d) DD2 + π, m_π = 170 MeV

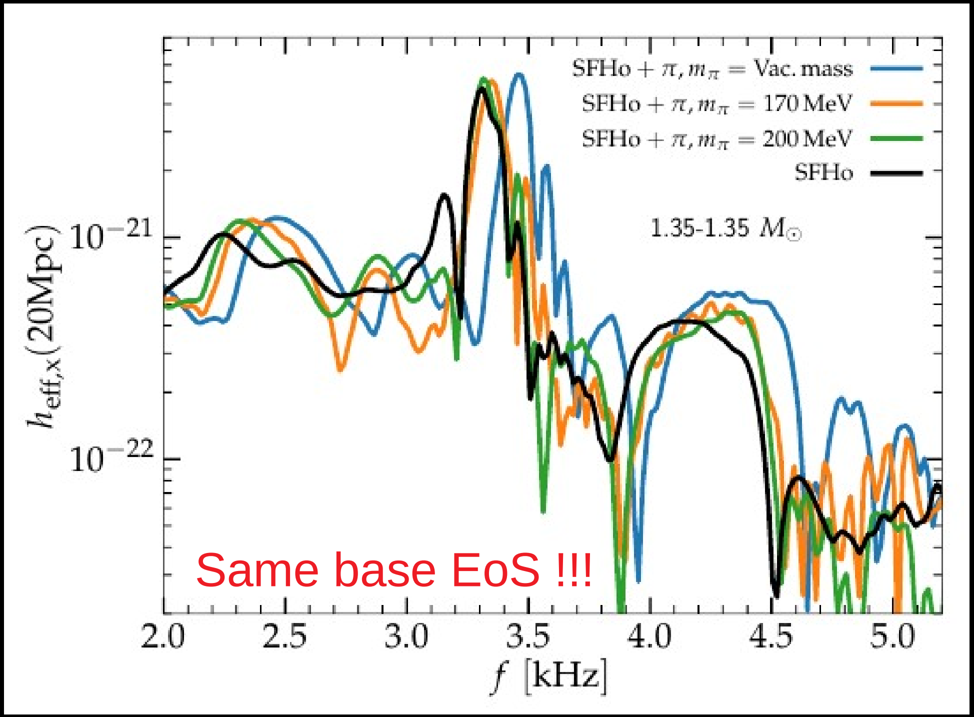
(e) SFHo + π, m_π = 200 MeV

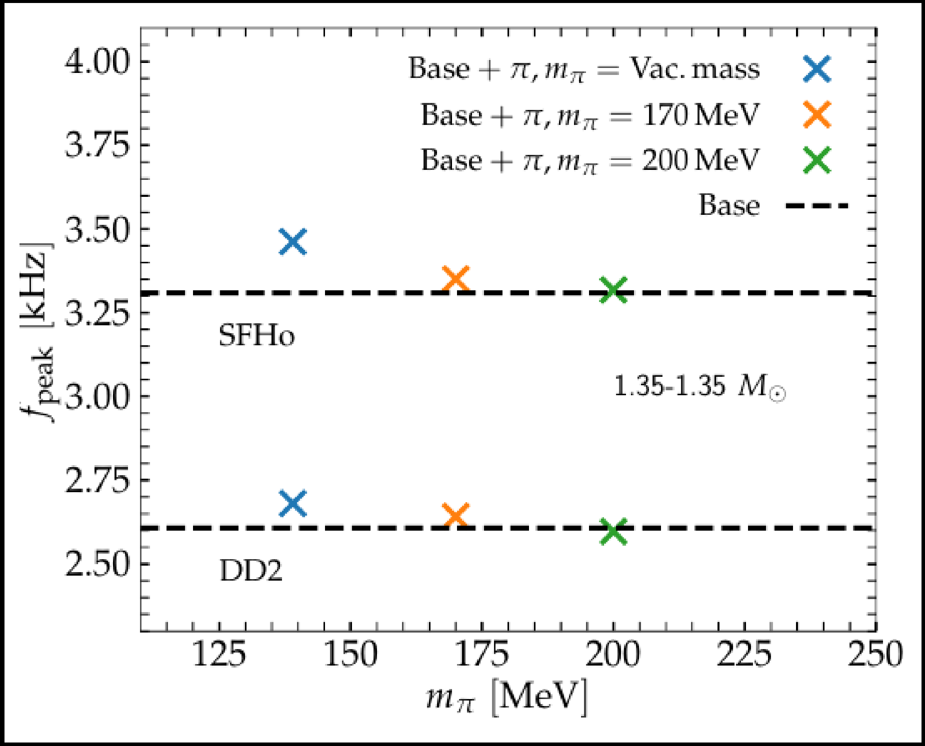
(f) DD2 + π, m_π = 200 MeV

Inspiral and Postmerger GWs

- Inspiral: Tidal deformability reduced by 10 per cent (for m_pi close to vac mass) !

  → potentially problematic if nuclear parameters are deduced and pis neglected
- Postmerger: frequency shifts up to 150 Hz

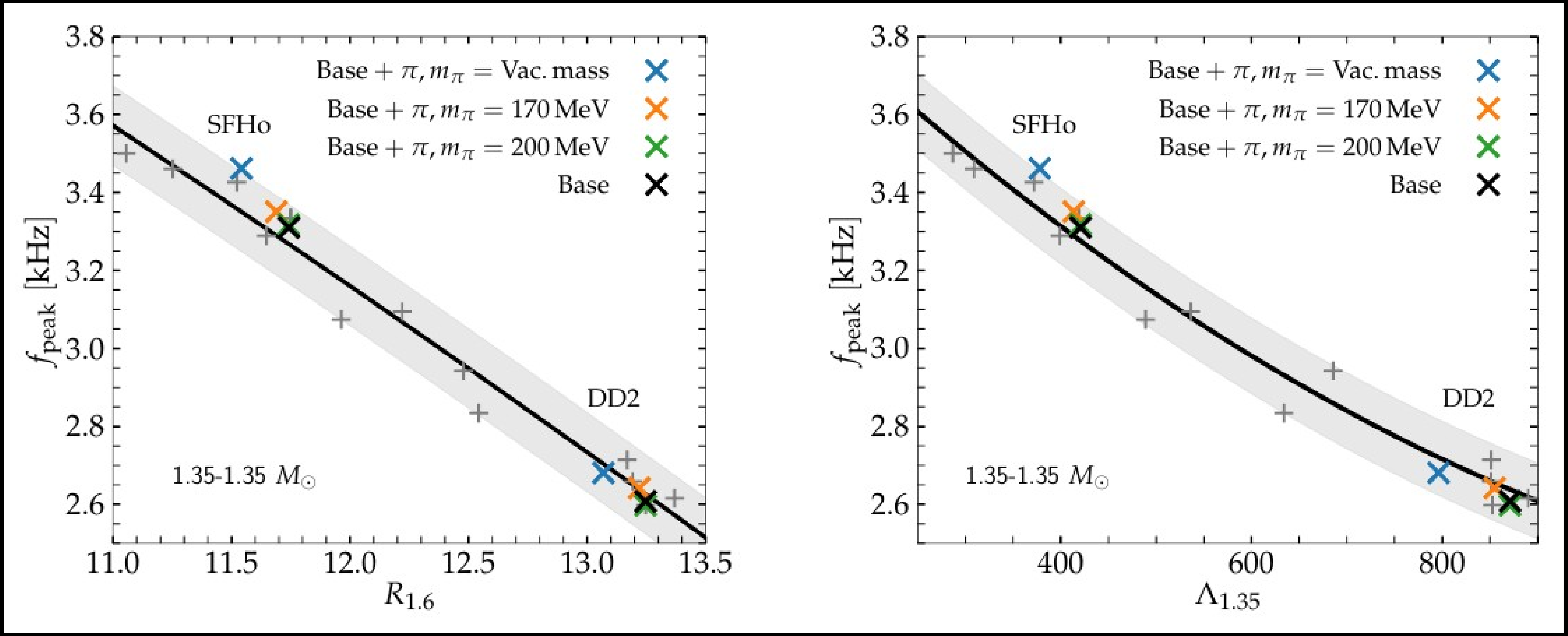




Vijayan et al 2023

Empirical relations for dominant postmerger frequency

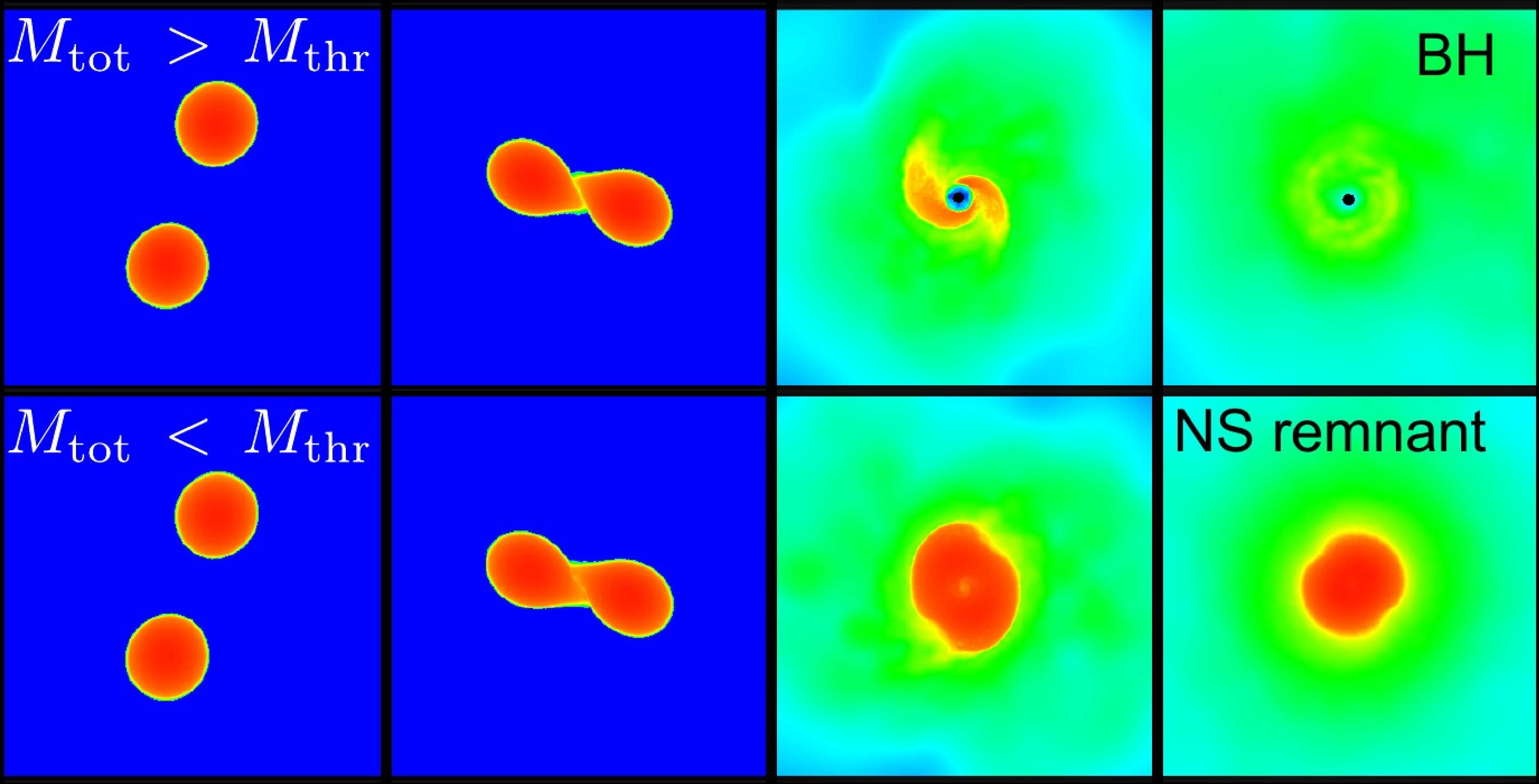
- Empirical relations build without pions remain approximately valid
- For softer SFHO model possibly stronger shifts for m_π = vac. mass



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

Vijayan et al 2023

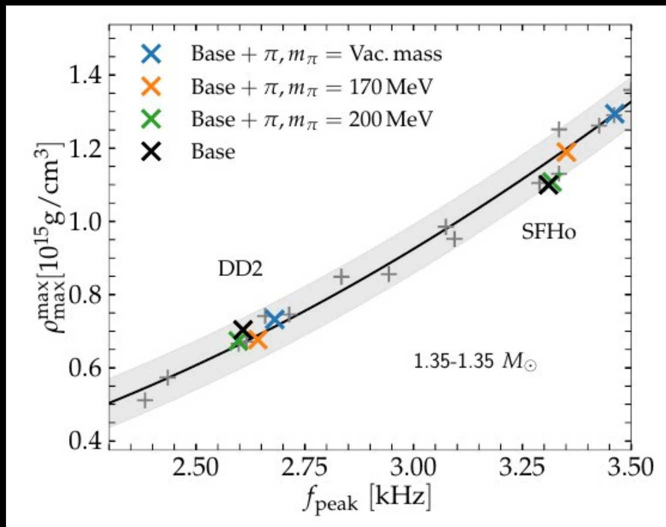
Collapse behavior – M_{thres} measurable

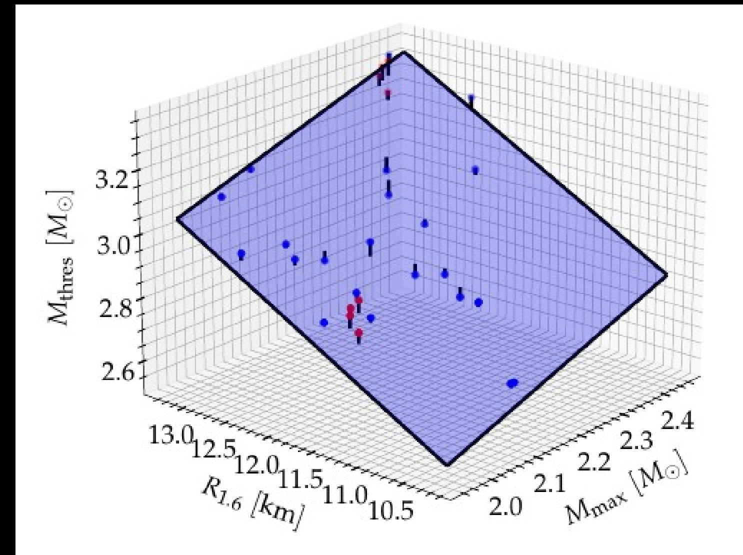


Understanding of BH formation in mergers [e.g. Shibata 2005, Baiotti et al. 2008, Hotokezaka et al. 2011, Bauswein et al. 2013, Bauswein et al 2017, Koeppel et al 2019, Agathos et al. 2020, Bauswein et al. 2020, Bauswein 2021, Kashyap et al 2022, Perego et al 2022, Koelsch et al 2022]

Threshold mass for prompt collapse

Vijayan et al 2023





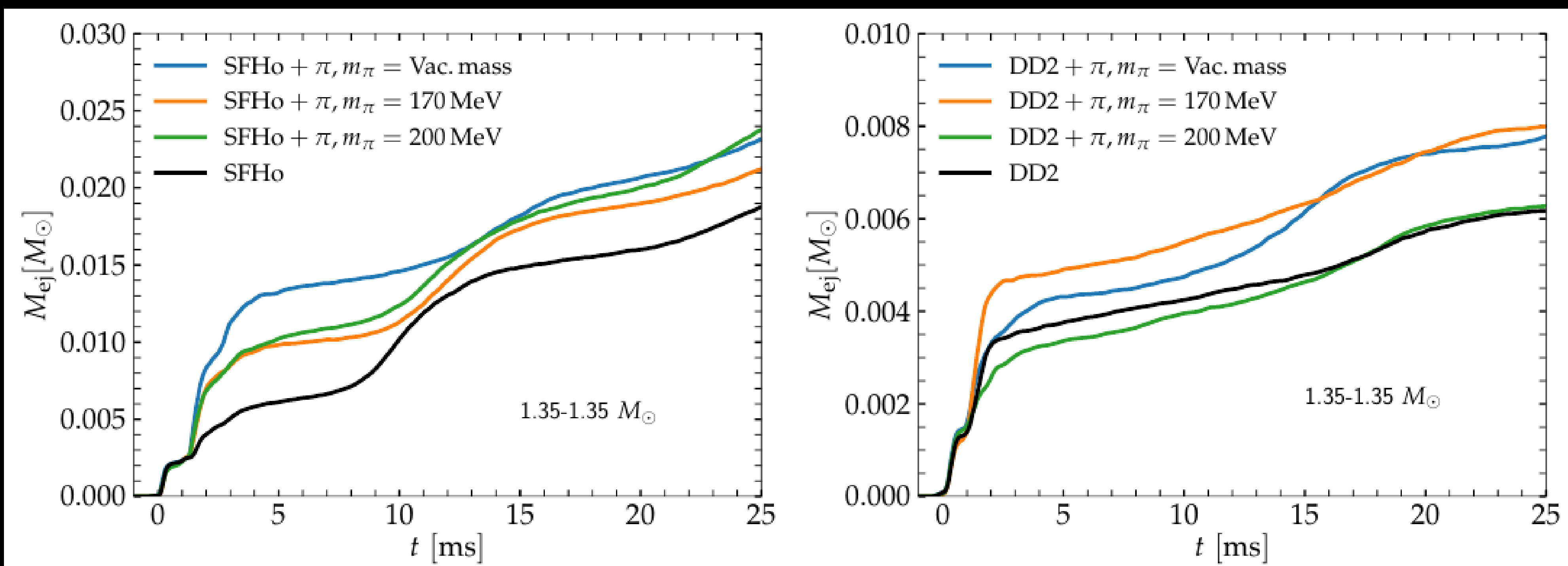
Model (Max. dev./$M_\odot$)	M_{thres} $[M_\odot]$	M_{max} $[M_\odot]$	$R_{1.6}$ [km]	R_{max} [km]	$\Lambda_{1.4}$	$\tilde{\Lambda}_{thres}$	M^{fit}_{thres} ($Y = R_{1.6}$) (0.042) $[M_\odot]$	M^{fit}_{thres} ($Y = R_{max}$) (0.059) $[M_\odot]$	M^{fit}_{thres} ($Y = \Lambda_{1.4}$) (0.056) $[M_\odot]$	M^{fit}_{thres} ($Y = \tilde{\Lambda}_{thres}$) (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}

Mass ejection → kilonovae

- 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 – often used in mutli-messenger analysis)

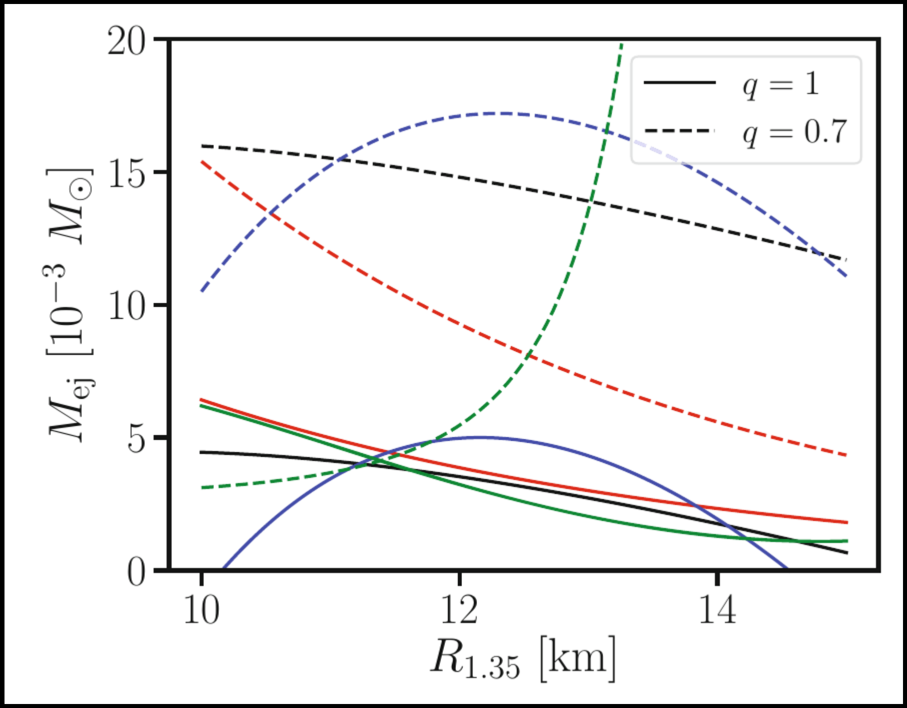
  → potentially problematic of EoS inference
- Torus mass similar effects

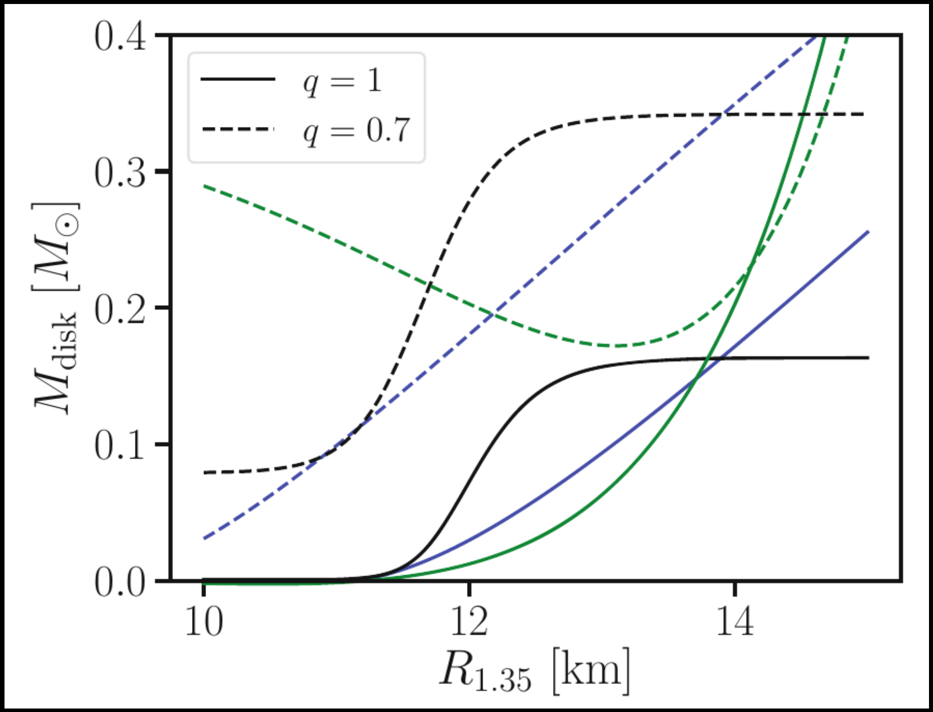


Vijayan et al 2023

EoS inference through kilonova properties

- Fit formulae compiled from the literature





Janka & Bauswein 2023

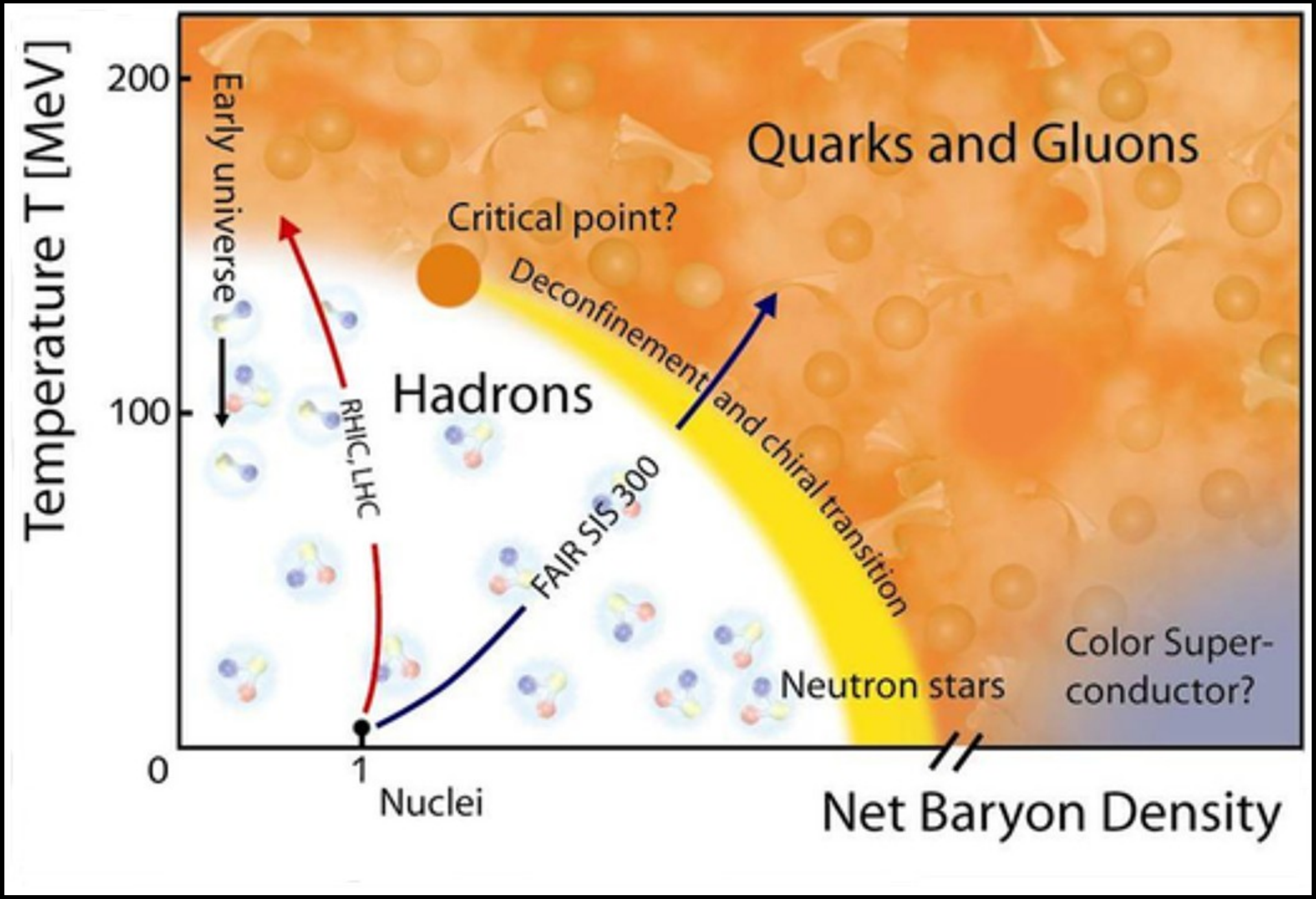
Quark matter in NS mergers

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

GSI/FAIR

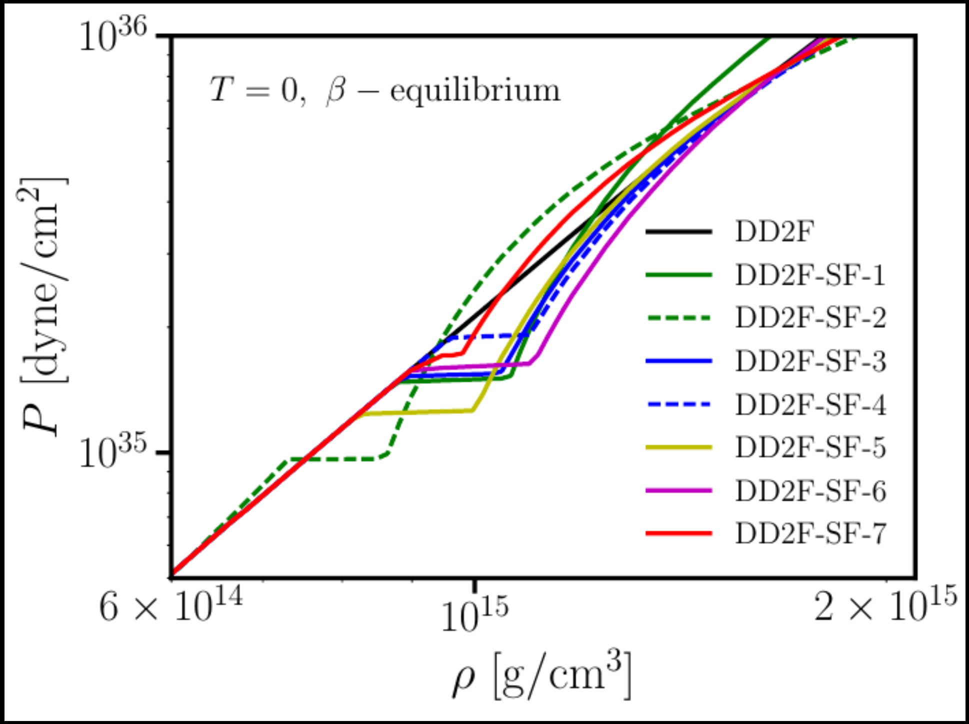
High T, low μ: experiments and lattice QCD

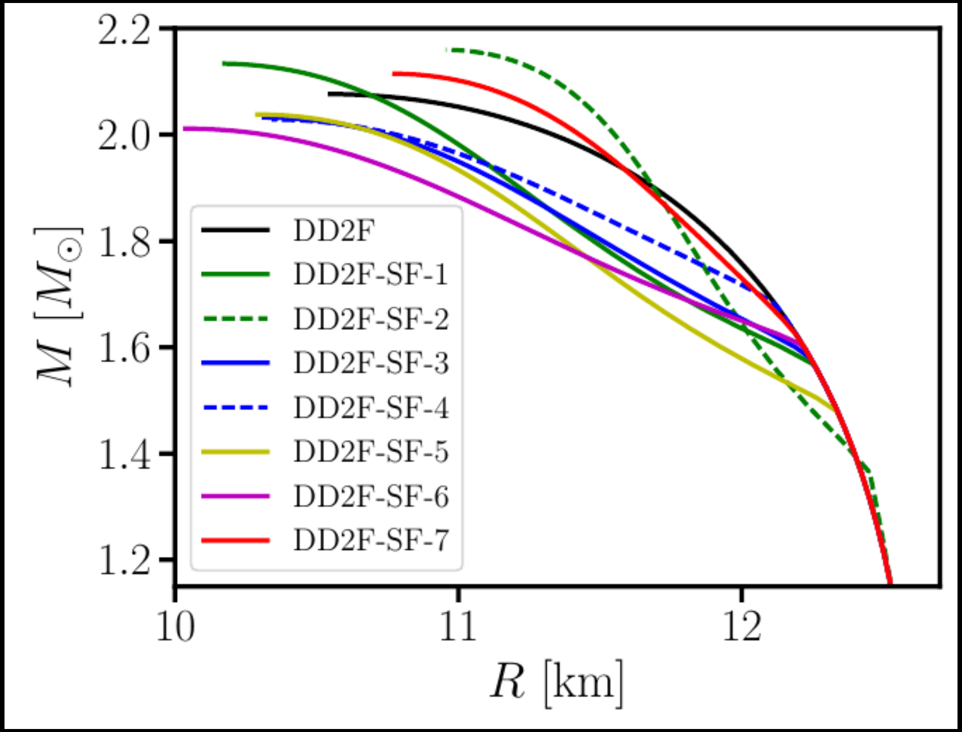


Does the phase transition to quark-gluon plasma occur (already) in neutron stars or only at higher densities?

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

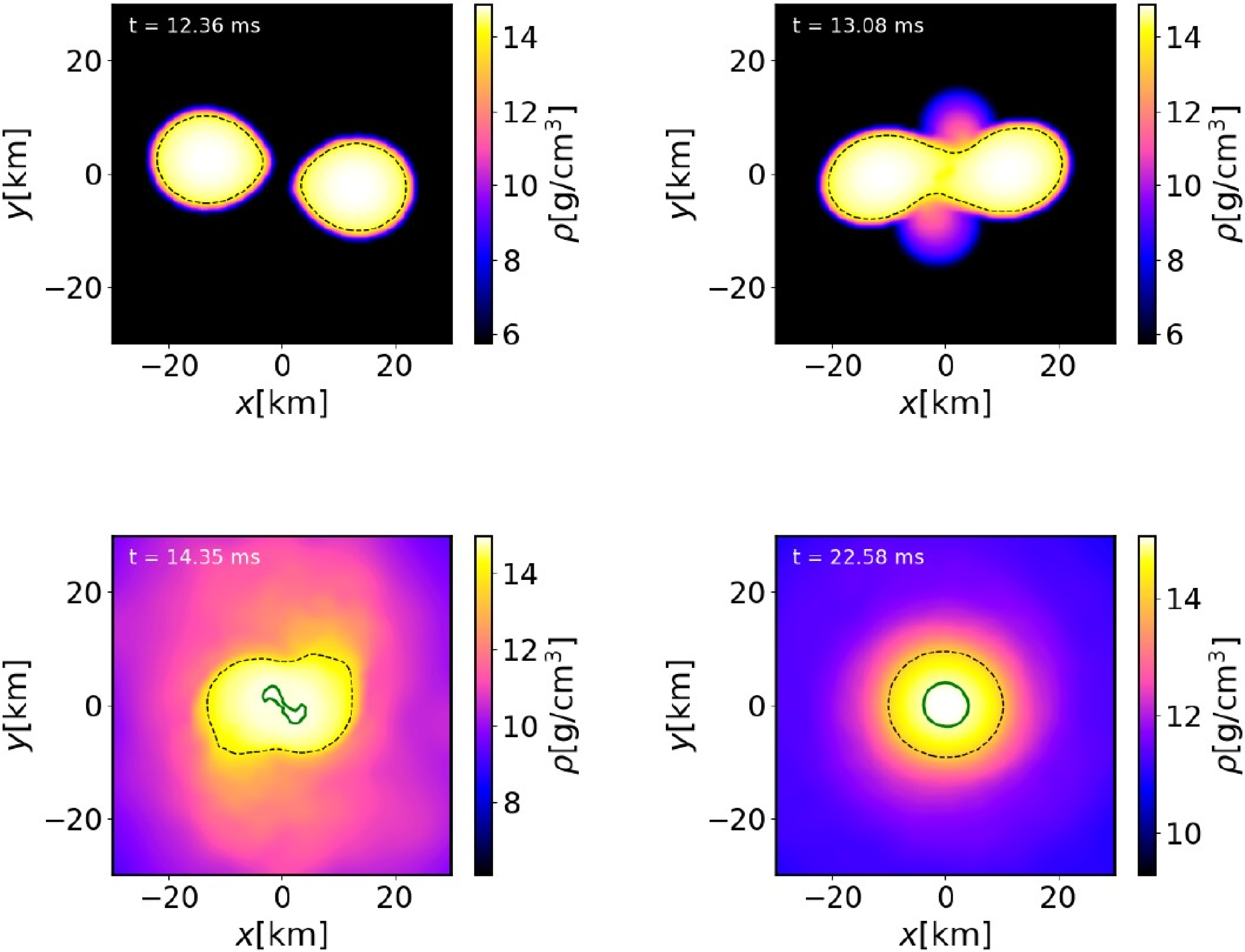
- 7 different models for quark matter: different onset density, different density jump, different stiffness of quark matter phase



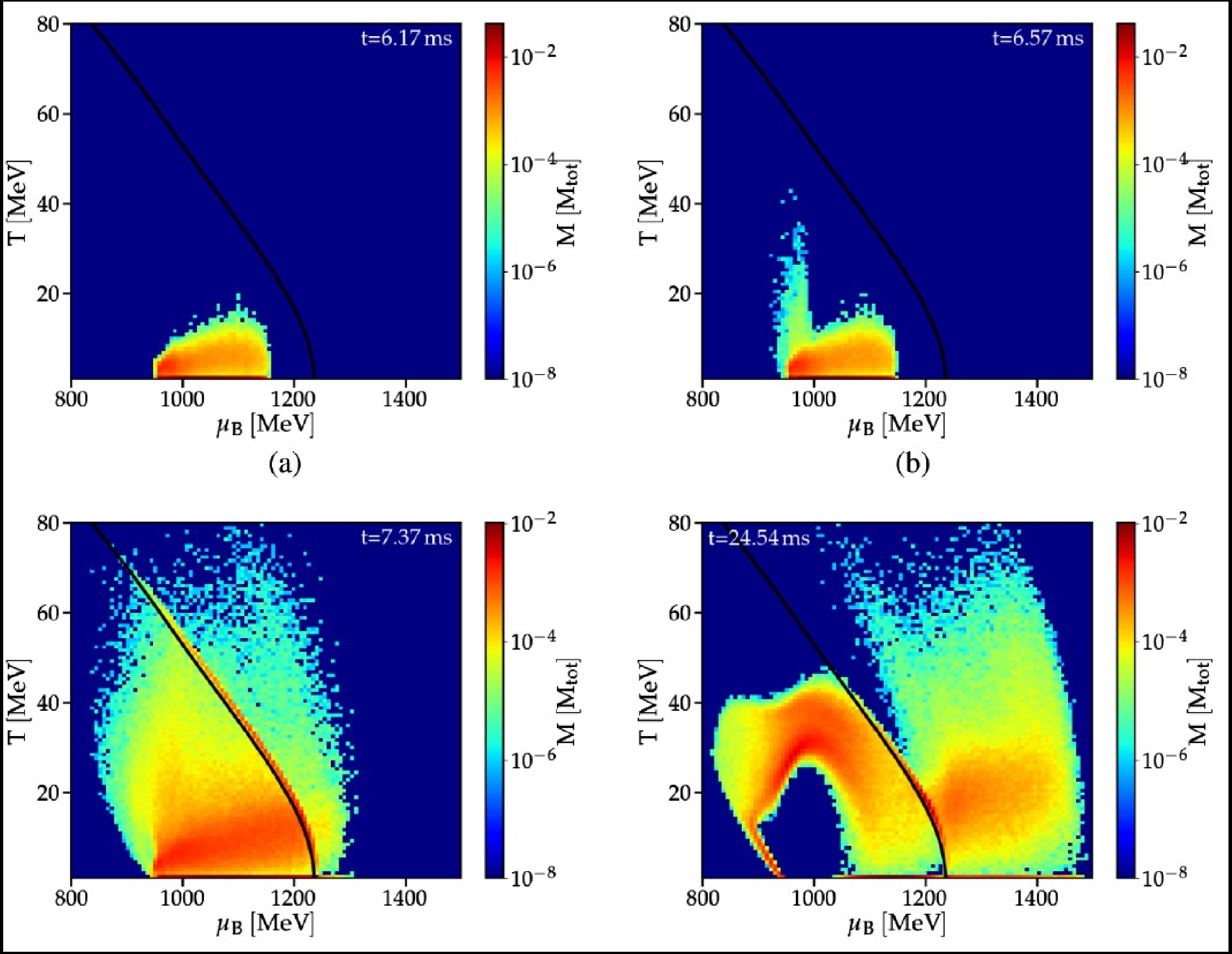


Bauswein et al. 2019, Bastian 2020

EOS	$\sqrt{D_0}$ (MeV)	α (fm^6)	a ($\mathrm{MeV\,fm}^3$)	b ($\mathrm{MeV\,fm}^9$)	c (fm^6)	ρ_1 ($\mathrm{MeV\,fm}^3$)	n_{onset} (fm^{-3})	Δn (fm^{-3})	M_{onset} ($M_\odot$)	M_{max} ($M_\odot$)	f_{peak} (kHz)
DD2-SF-1	265	0.39	-4.0	1.6	0.025	80.0	0.533	0.106	1.57	2.13	3.54
DD2-SF-2	250	0.60	10.0	0.0	0.000	80.0	0.466	0.057	1.37	2.16	3.68
DD2-SF-3	240	0.36	1.0	0.5	0.015	80.0	0.538	0.094	1.58	2.03	3.58
DD2-SF-4	240	0.34	1.0	0.5	0.015	80.0	0.580	0.082	1.68	2.03	3.36
DD2-SF-5	240	0.38	1.0	0.5	0.015	80.0	0.499	0.108	1.48	2.04	3.59
DD2-SF-6	240	0.30	-3.0	0.8	0.015	80.0	0.545	0.121	1.60	2.01	3.67
DD2-SF-7	240	0.47	7.0	0.2	0.015	80.0	0.562	0.030	1.62	2.11	3.33

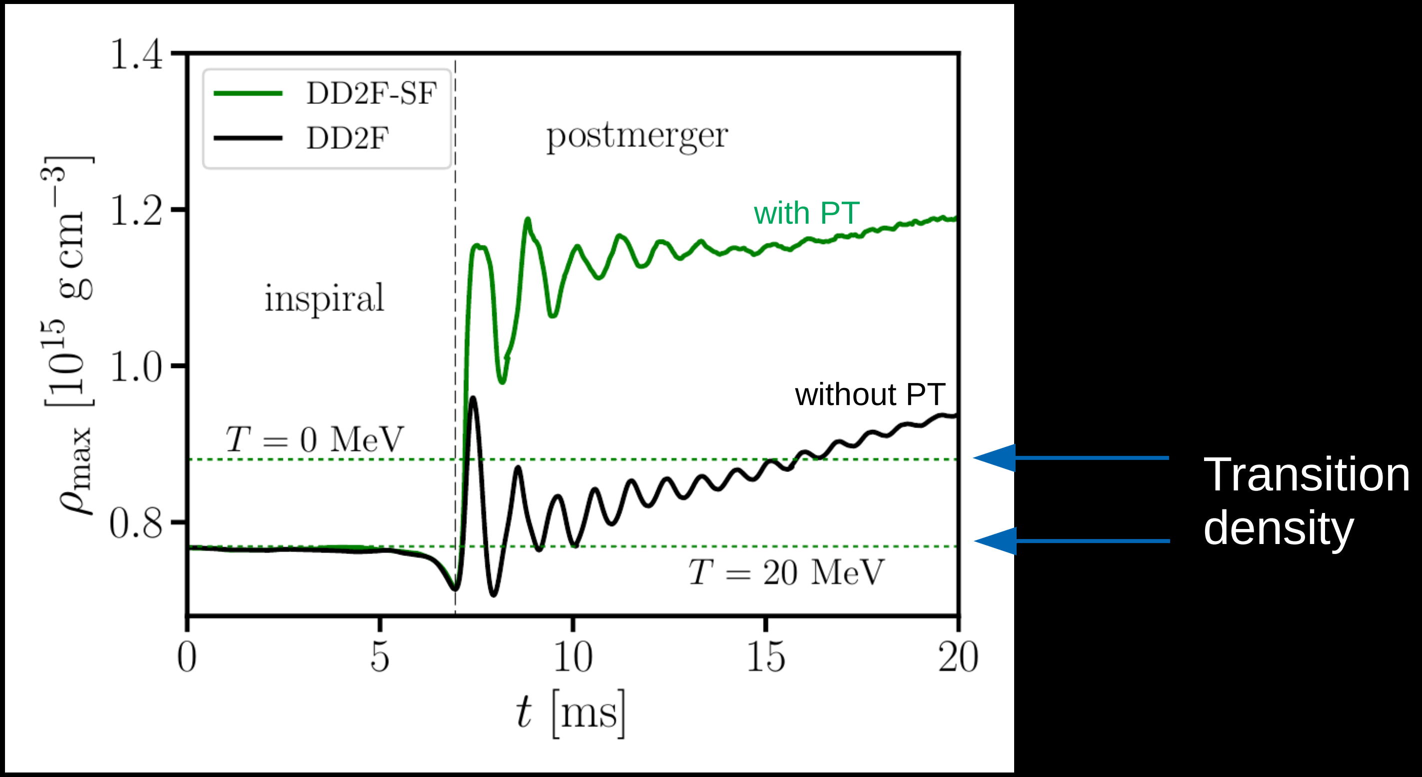


Bauswein et al. 2019



Blacker et al. 2020

Merger simulations

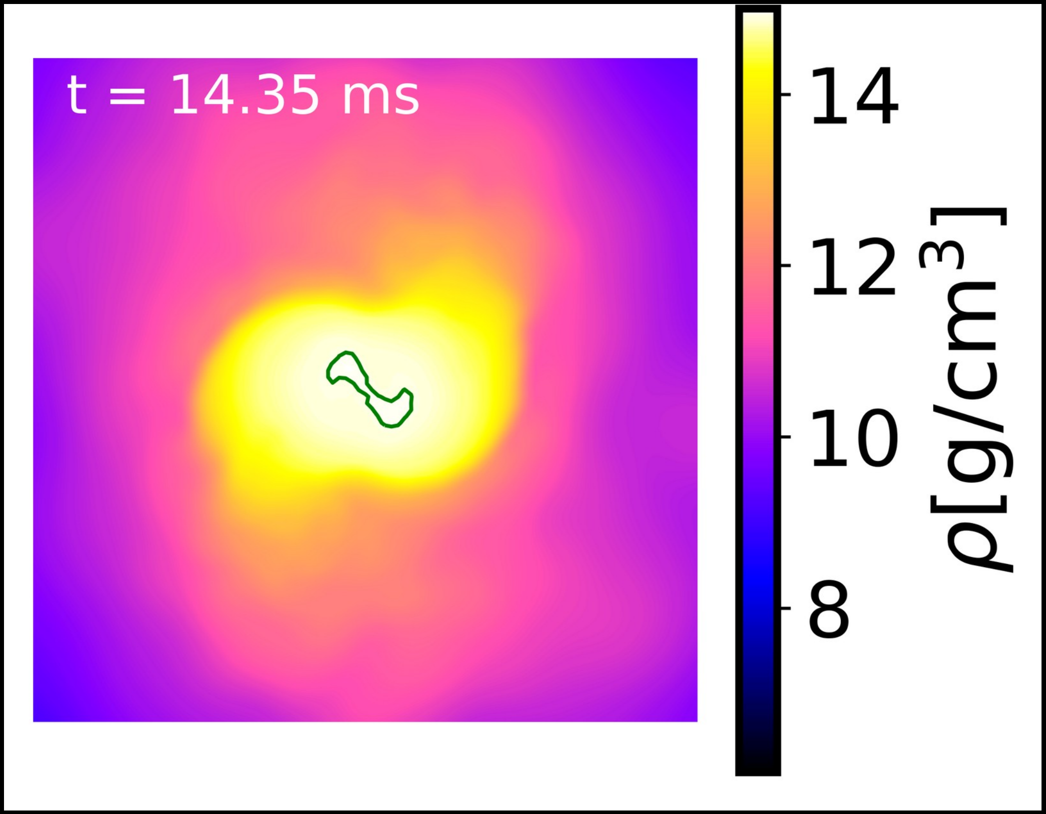


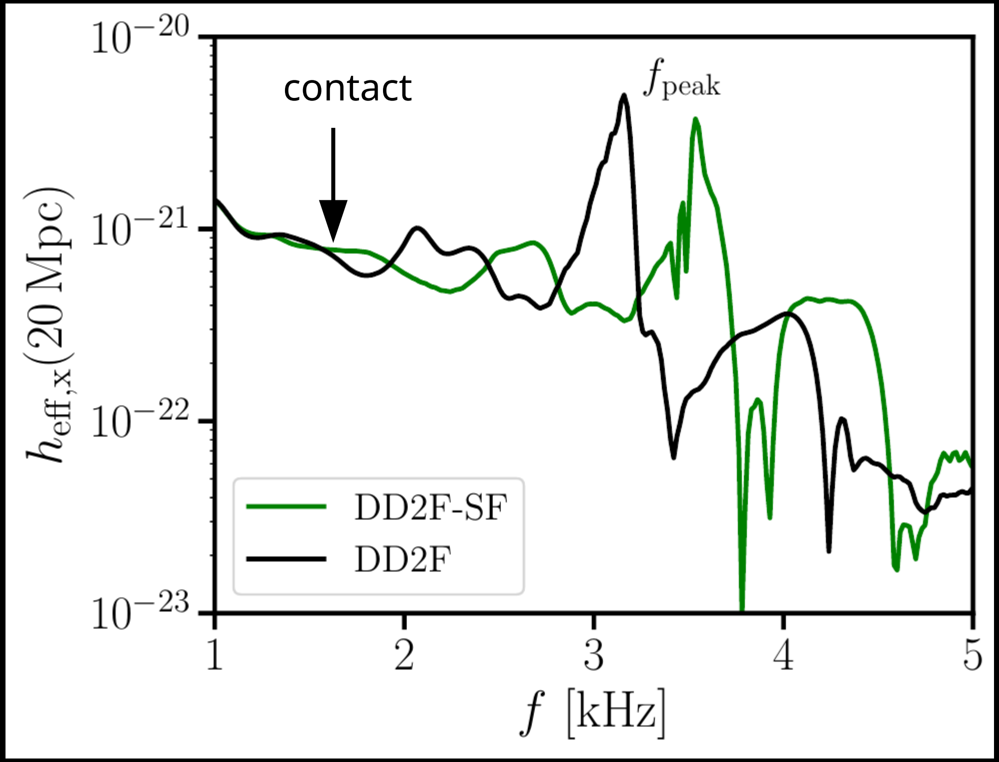
Bauswein et al. 2019

- Softer EoS “needs more density” to provide sufficient pressure support

Merger simulations with quark matter core

- GW spectrum 1.35-1.35 Msun



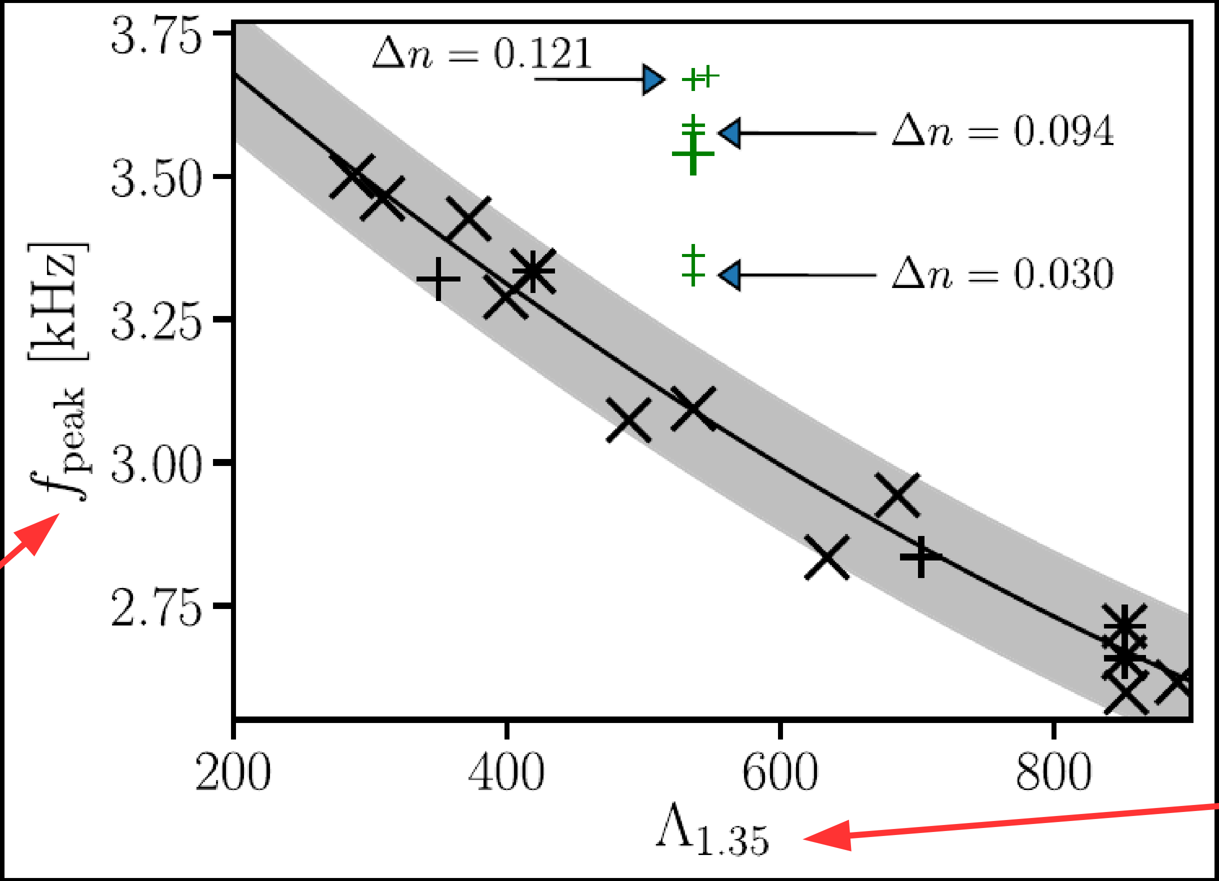


A.B. et al. 2019

But: a high frequency on its own may not yet be characteristic for a phase transition

→ unambiguous signature

Signature of 1st order phase transition



from postmerger

from the inspiral

A.B. et al 2019

- Characteristic increase of postmerger frequency compared to tidal deformability

  → evidence of presence of quark matter core

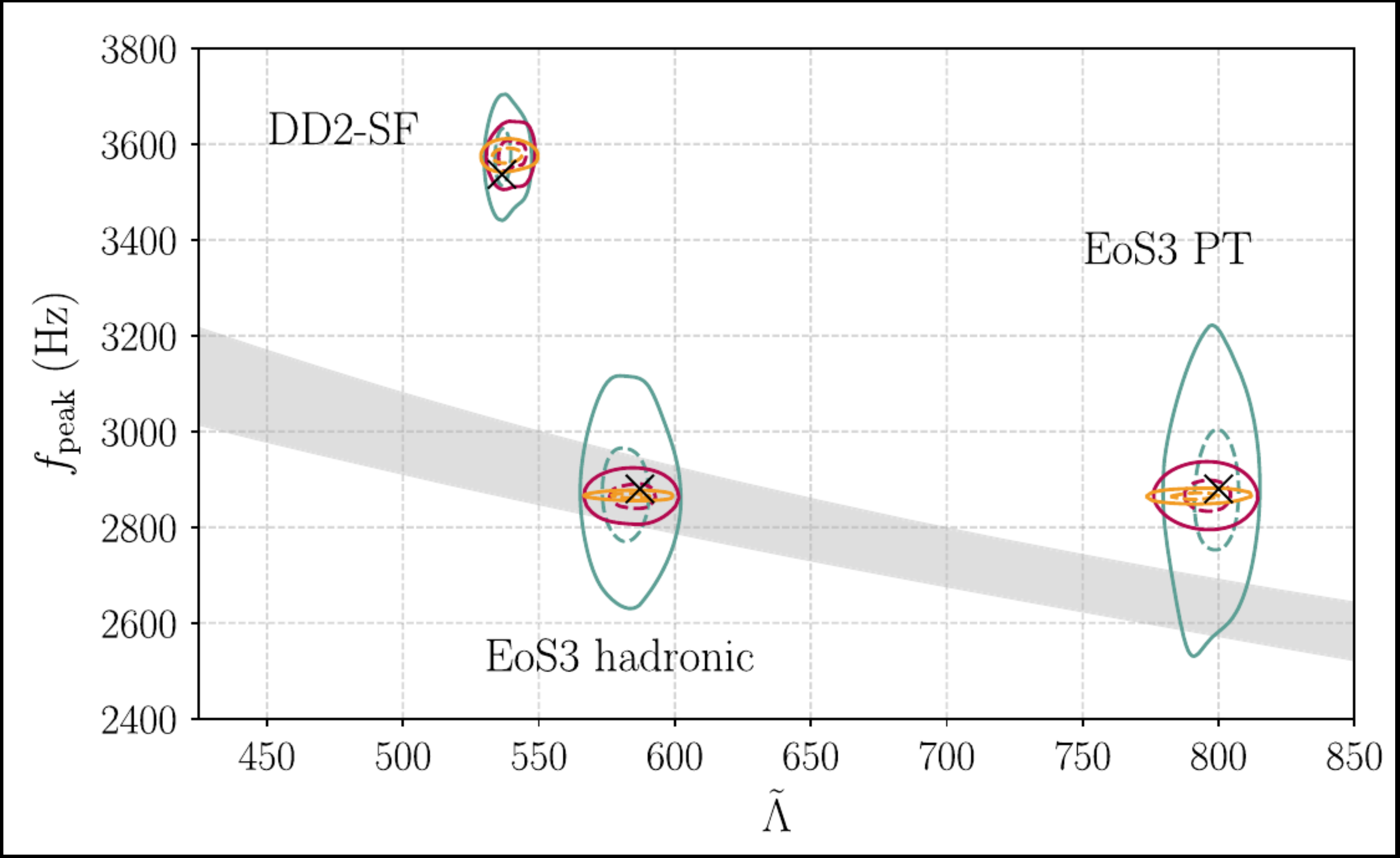
  → in any case constraint on onset density/properties of hadron-quark phase transition

See also Most+ 2019, Blacker+ 2020, Weih +2020, Bauswein+2020, Prakash+ 2021, Liebling+ 2021, Hanauske+ 2021, Fujimoto+2022, Tootle+ 2022, Huang+ 2022, Blacker+ 2023,...

GW data analysis

- Recovery of injected waveforms as proof of principle for GW data analysis with BayesWave, i.e. morphology-independent search, combined with pre-merger templates

  → signature of quark matter measurable

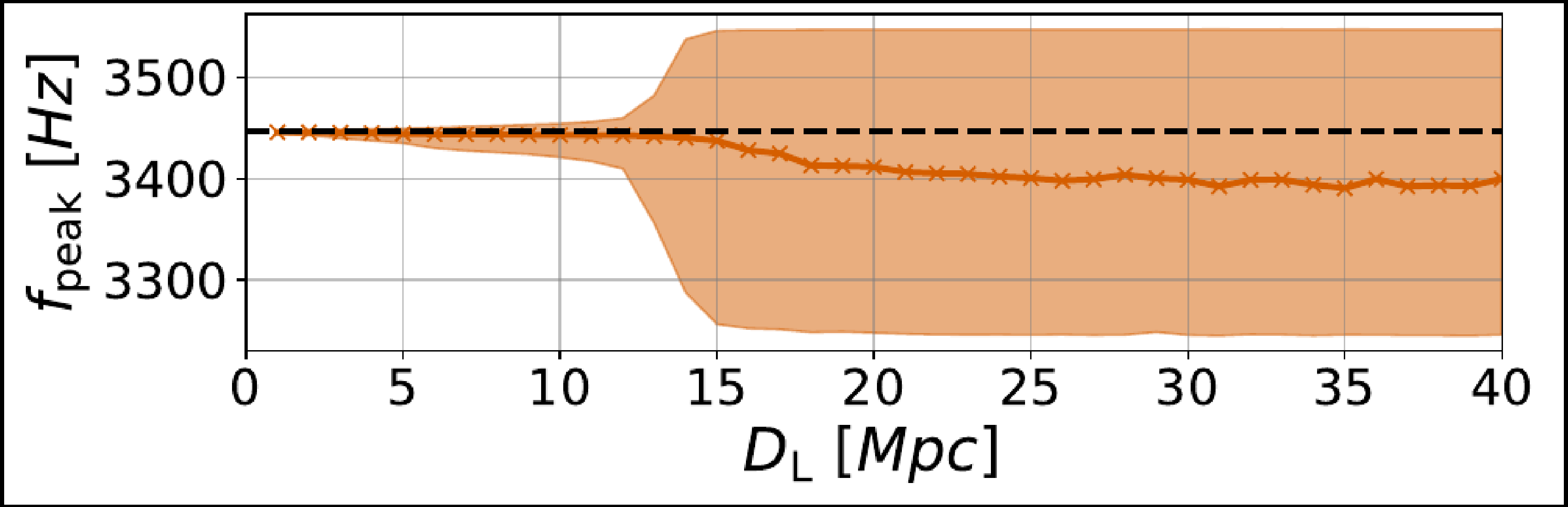


Wijngaarden et al., PRD 2022

40 Mpc, 2x, 4x, 6x design sensitivity

GW data analysis

- Use simulations to train machine learning template construction
- Successfully recovers injected signal and its main frequency



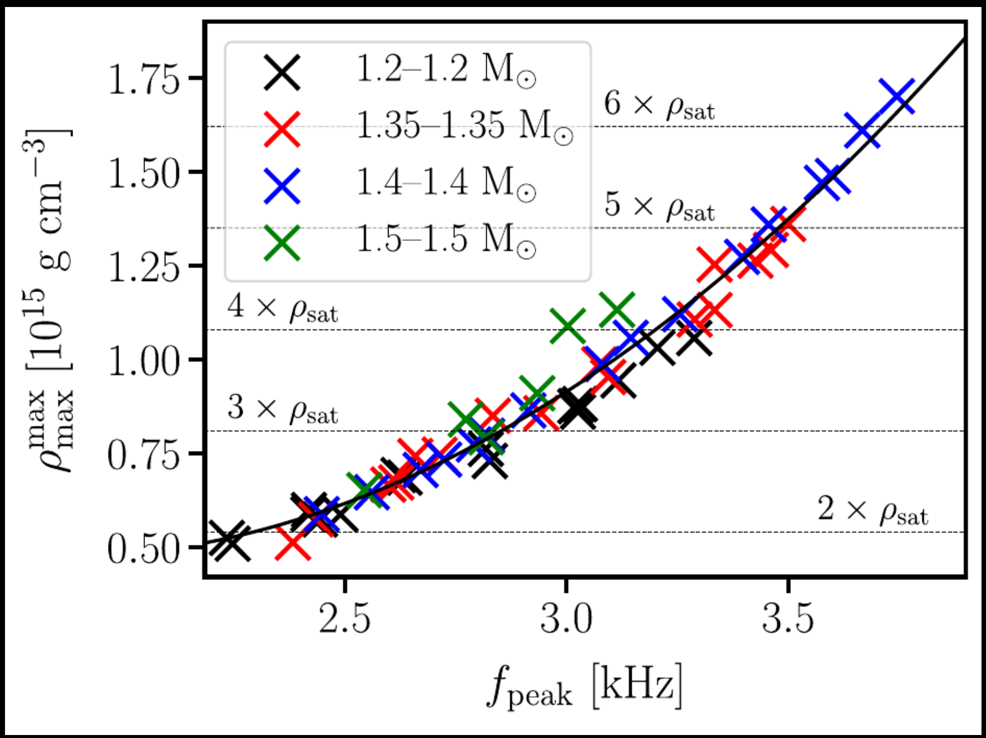
Ad. Ligo/Virgo network at design sensitivity

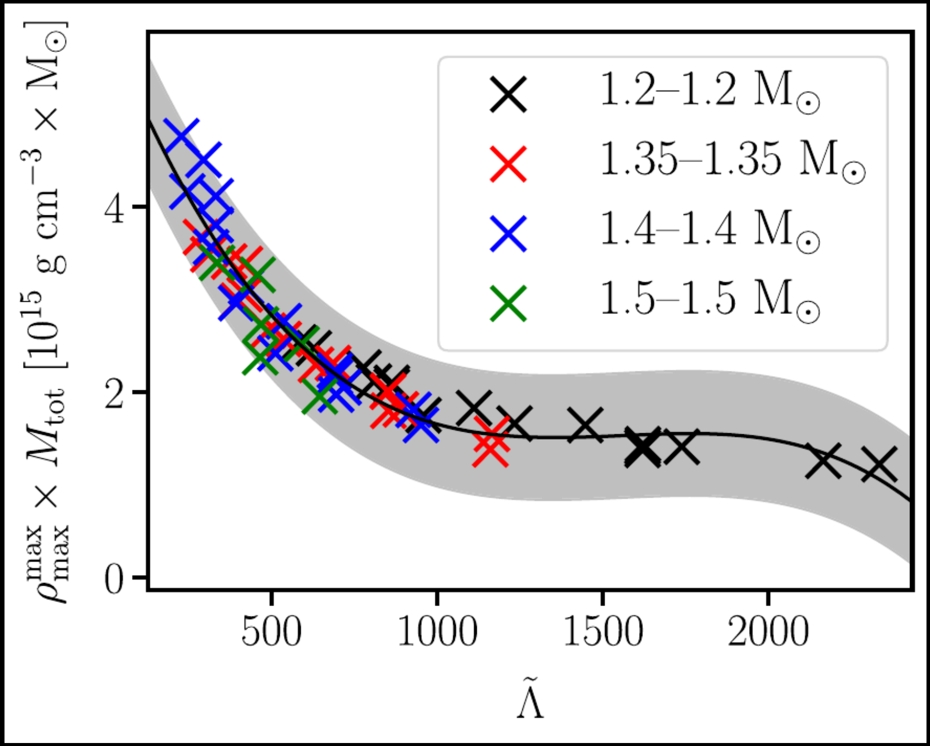
Soultanis et al 2024 (in prep)

- GWs inform about highest density in the remnant

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

Blacker et al. 2020

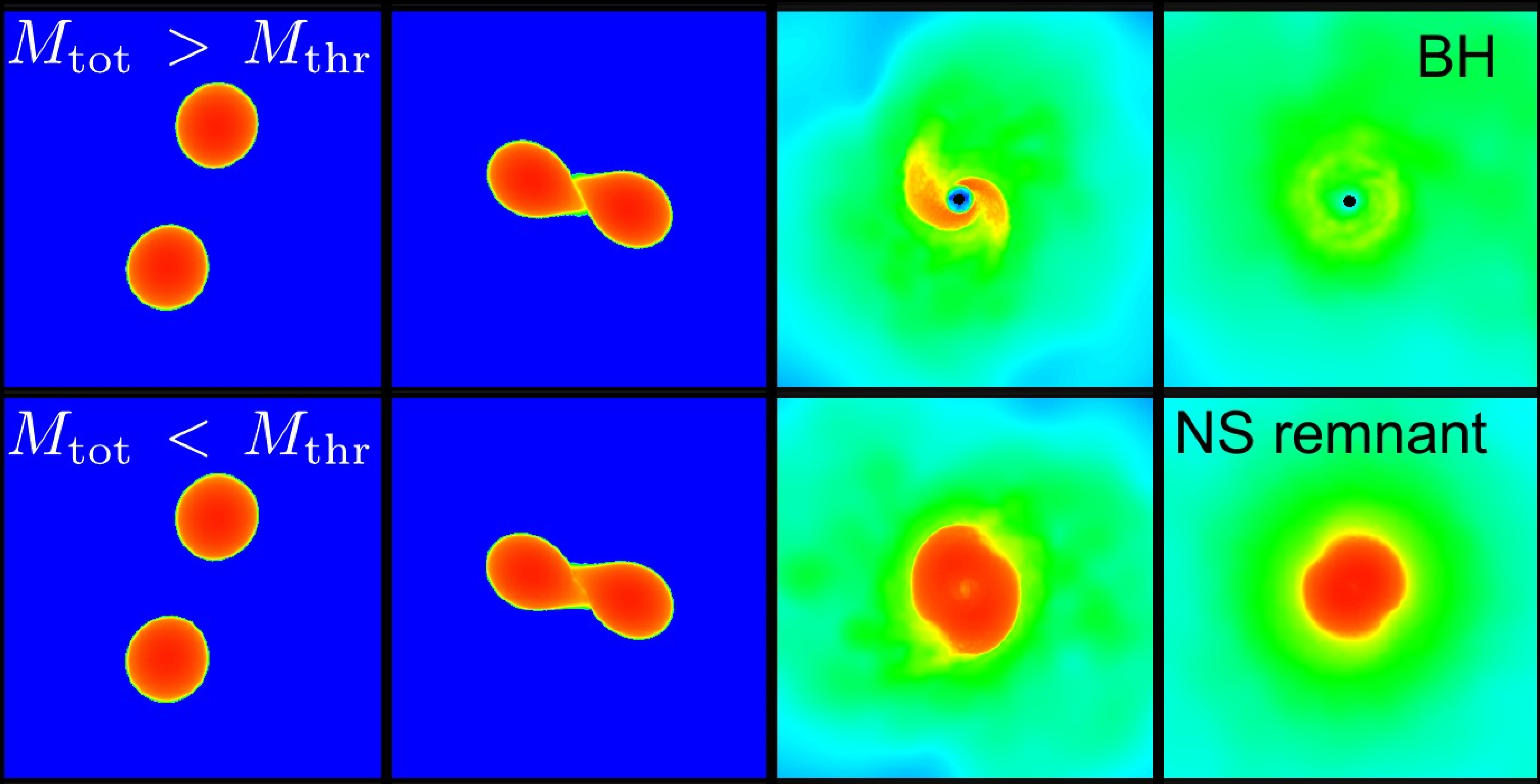




Postmerger frequency fpeak

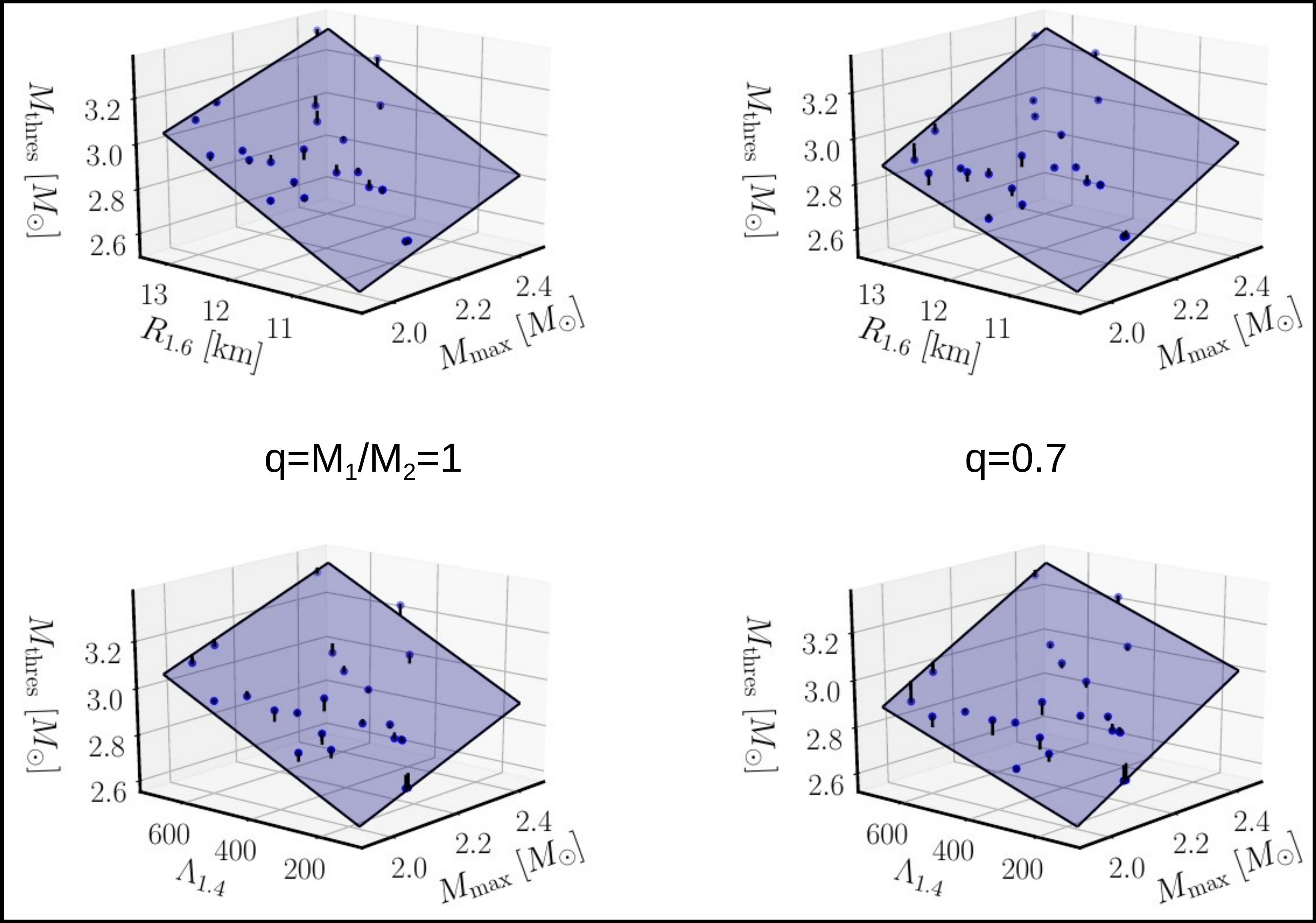
tidal deformability from inspiral

Collapse behavior – M_{thres} measurable



Understanding of BH formation in mergers [e.g. Shibata 2005, Baiotti et al. 2008, Hotokezaka et al. 2011, Bauswein et al. 2013, Bauswein et al 2017, Koeppel et al 2019, Agathos et al. 2020, Bauswein et al. 2020, Bauswein 2021, Kashyap et al 2022, Perego et al 2022, Koelsch et al 2022]

$$M_{\rm thres} = M_{\rm thres}(X, Y) = aX + bY + c$$



Bauswein et al 2021

- Similarly tight fits for asymmetric mergers

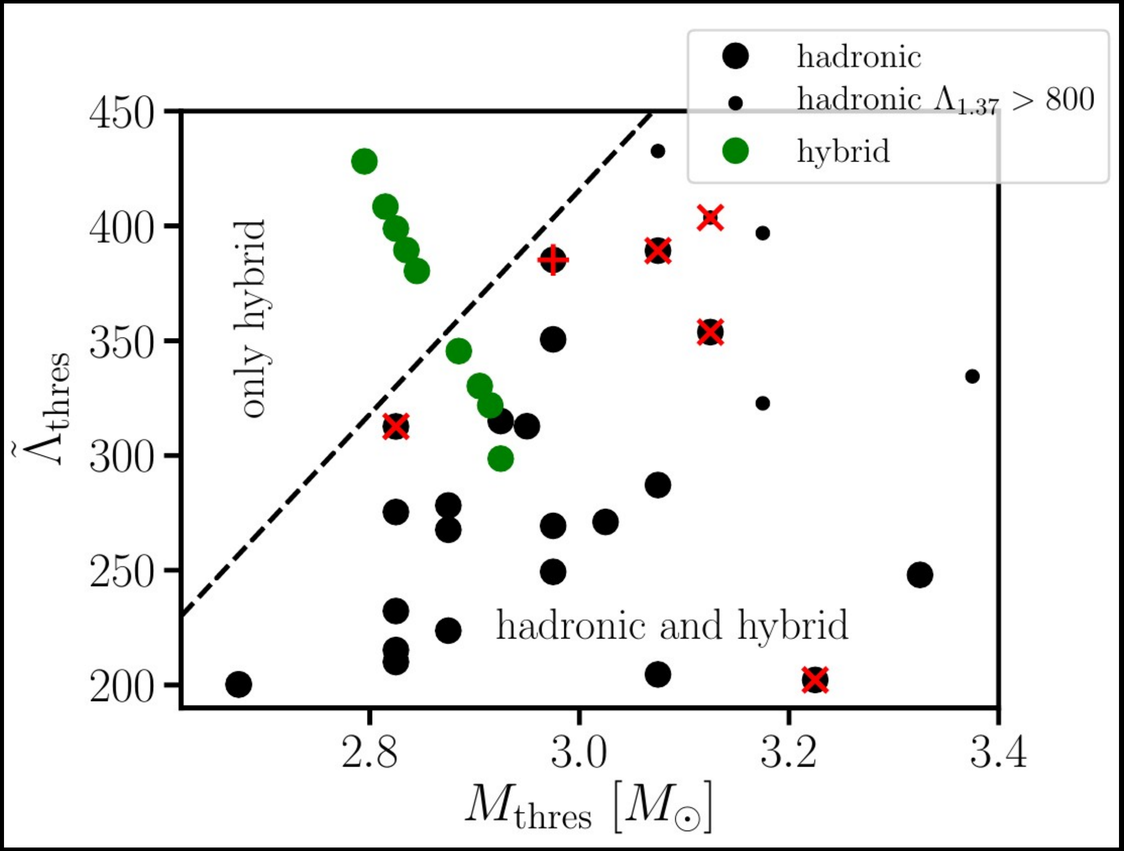
Other independent variables like Λ(1.4), R_{max}, Λ_thres

- Bi-linear relations → simple to invert → useful for EoS constraints
- Similar relations for chirp mass

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

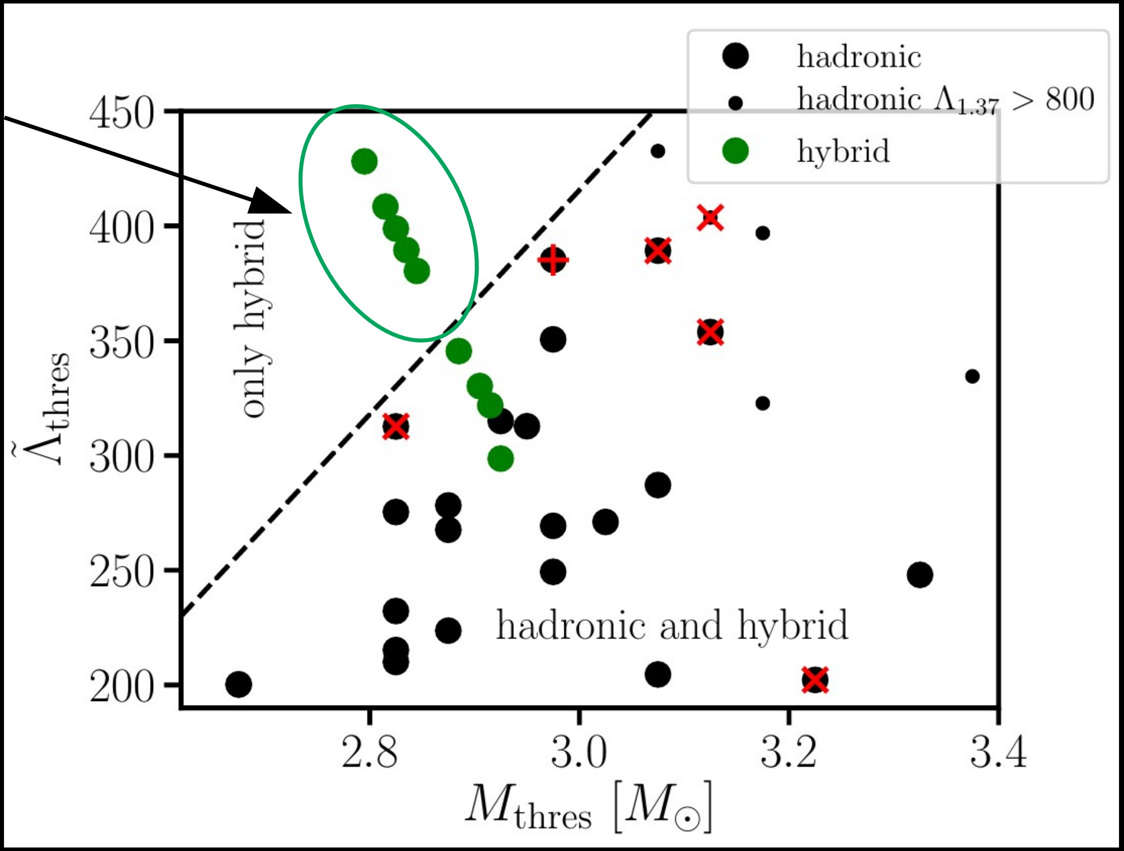
$$\tilde{\Lambda}_{\rm thres} = \Lambda(M_{\rm thres}/2) \ \text{ for } \ q = 1$$

QCD phase transition from collapse behavior

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

Evidence for quark matter

With M_{max} > 1.97 !!



Bauswein et al., PRL 125 (2020)

Measurable from GW inspiral

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

Measurable from inspiral + information on merger product

Hyperons in NS mergers

Blacker, Kochankovski, Bauswein, Ramos, Tolos, PRD 109 (2024); arXiv:2307.03710

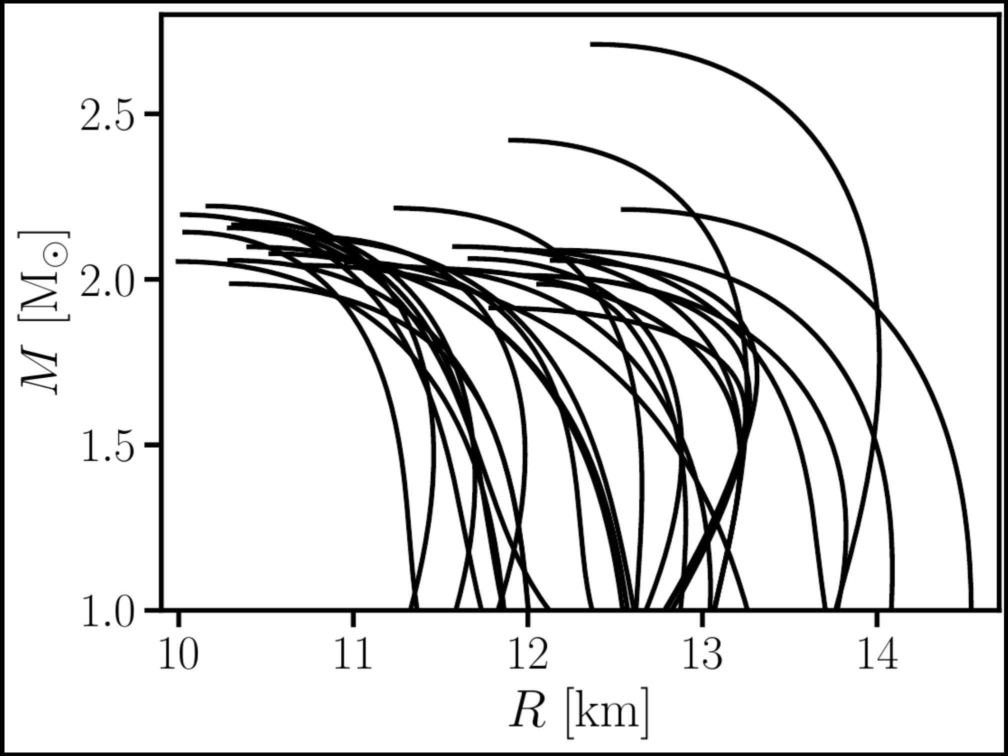
See Sekiguchi et al. 2011, Radice et al 2017 for early studies of individual EoS models

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 M_{sun} 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



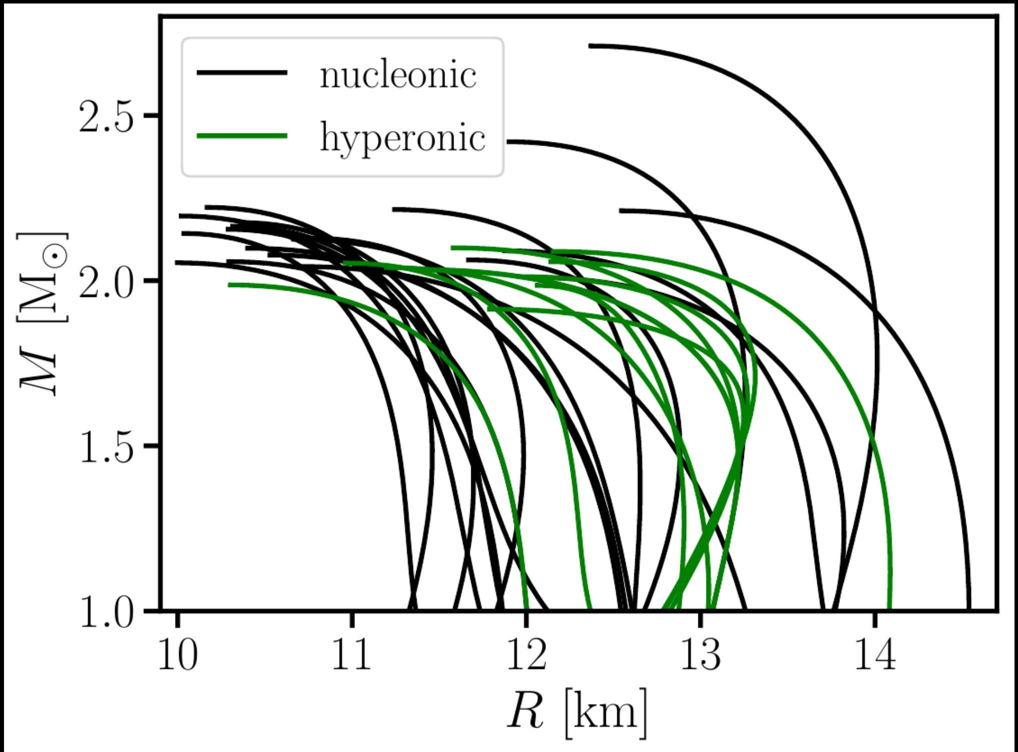
Blacker et al. 2024

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 M_{sun} NSs
- Several modern hyperonic EoS fulfill the 2 Msun constraint

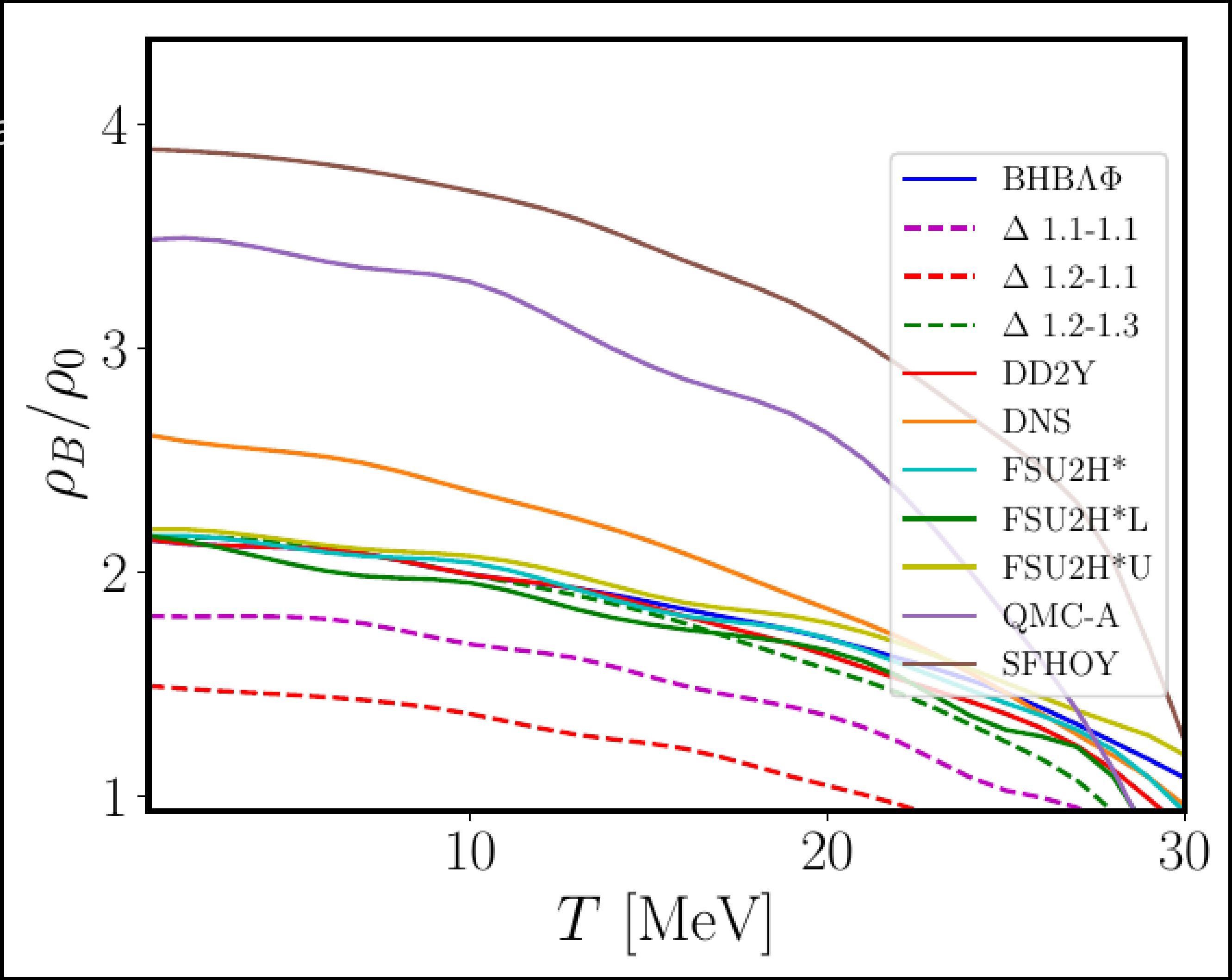
→ hyperon puzzle unsolved – interacting Fermi gas with unknown interactions

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



Blacker et al. 2024

▸ Phase dia



ρ_B/ρ_0
4
3
2
1
10
20
30
T [MeV]
BHBΛΦ
Δ 1.1-1.1
Δ 1.2-1.1
Δ 1.2-1.3
DD2Y
DNS
FSU2H*
FSU2H*L
FSU2H*U
QMC-A
SFHOY

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

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

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

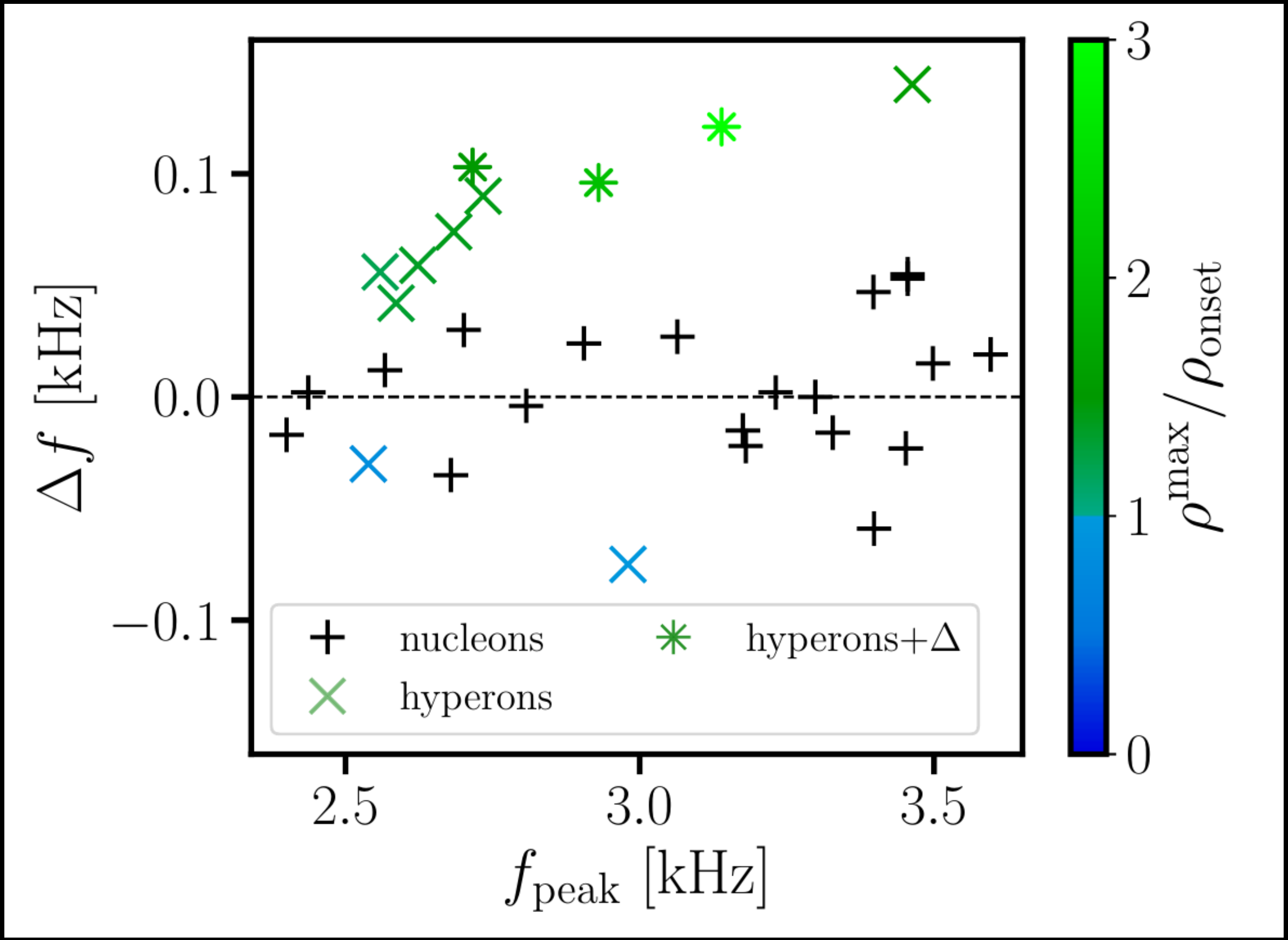
Compare $\Gamma_{th} = 1.75$ runs vs. full T-dependent simulations

→ thermal behavior of hyperons

Thermal behavior as indicator for hyperons

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

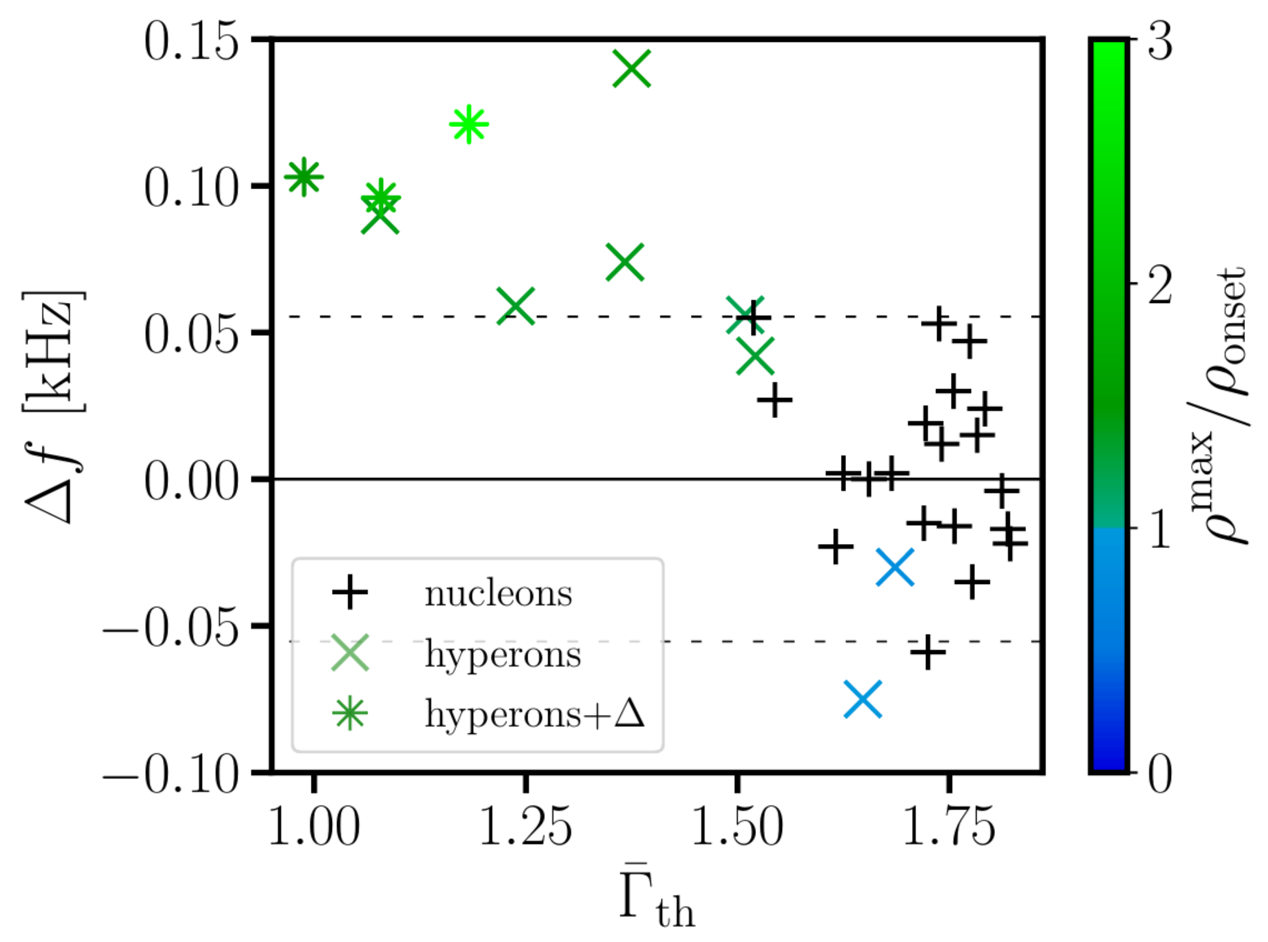
$$\Delta f_{\mathrm{peak}} = f_{\mathrm{peak}} - f_{\mathrm{peak}}^{\Gamma_{\mathrm{th}}=1.75}$$



Blacker et al. 2024

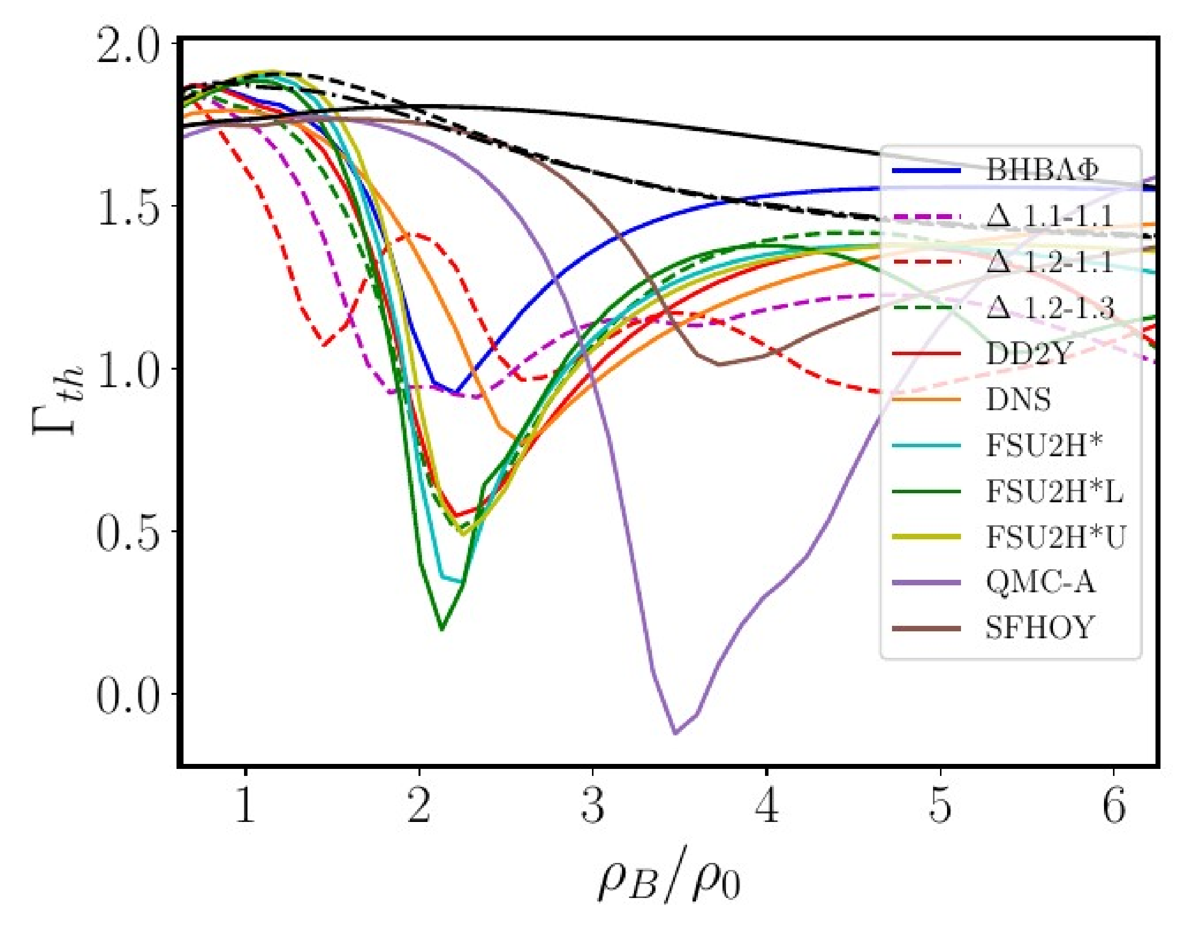
Thermal behavior as indicator for hyperons

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



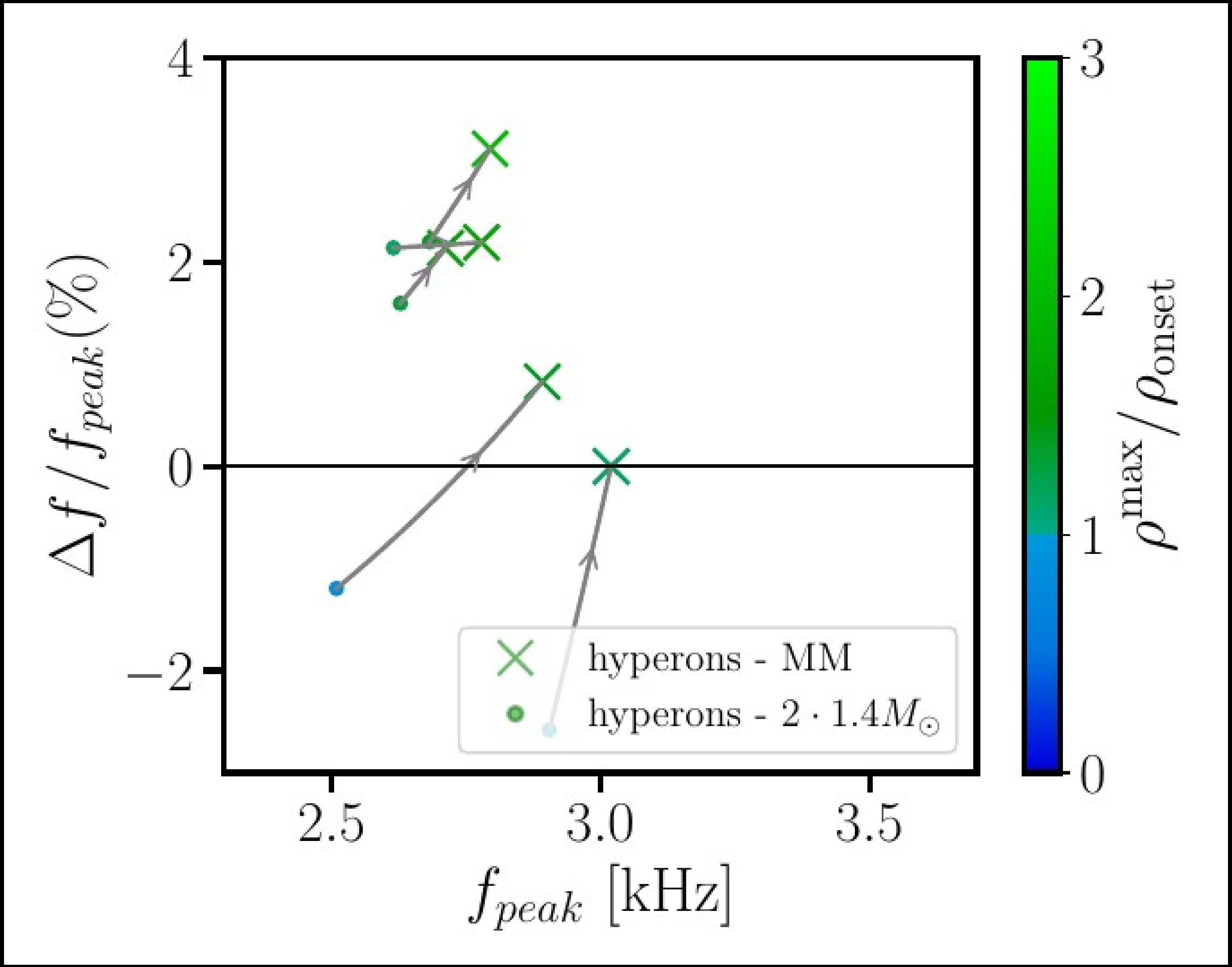
Blacker et al. 2024

- Quantify thermal pressure support (at 25MeV) $P_{th} = (\Gamma_{th} - 1)\epsilon_{th}\rho$



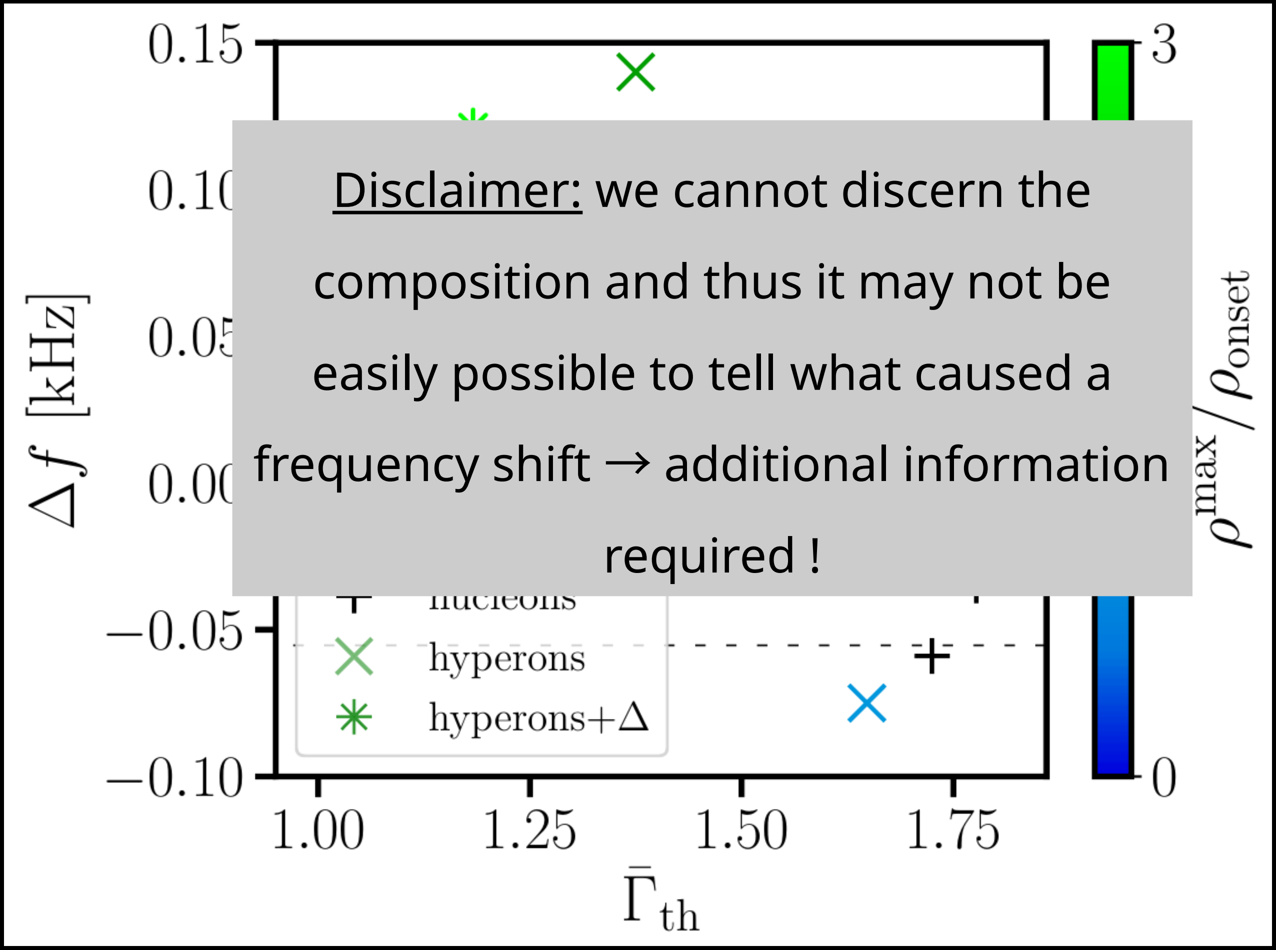
Black curves are purely nucleonic

- More massive bianries → stronger effect



Thermal behavior as indicator for hyperons

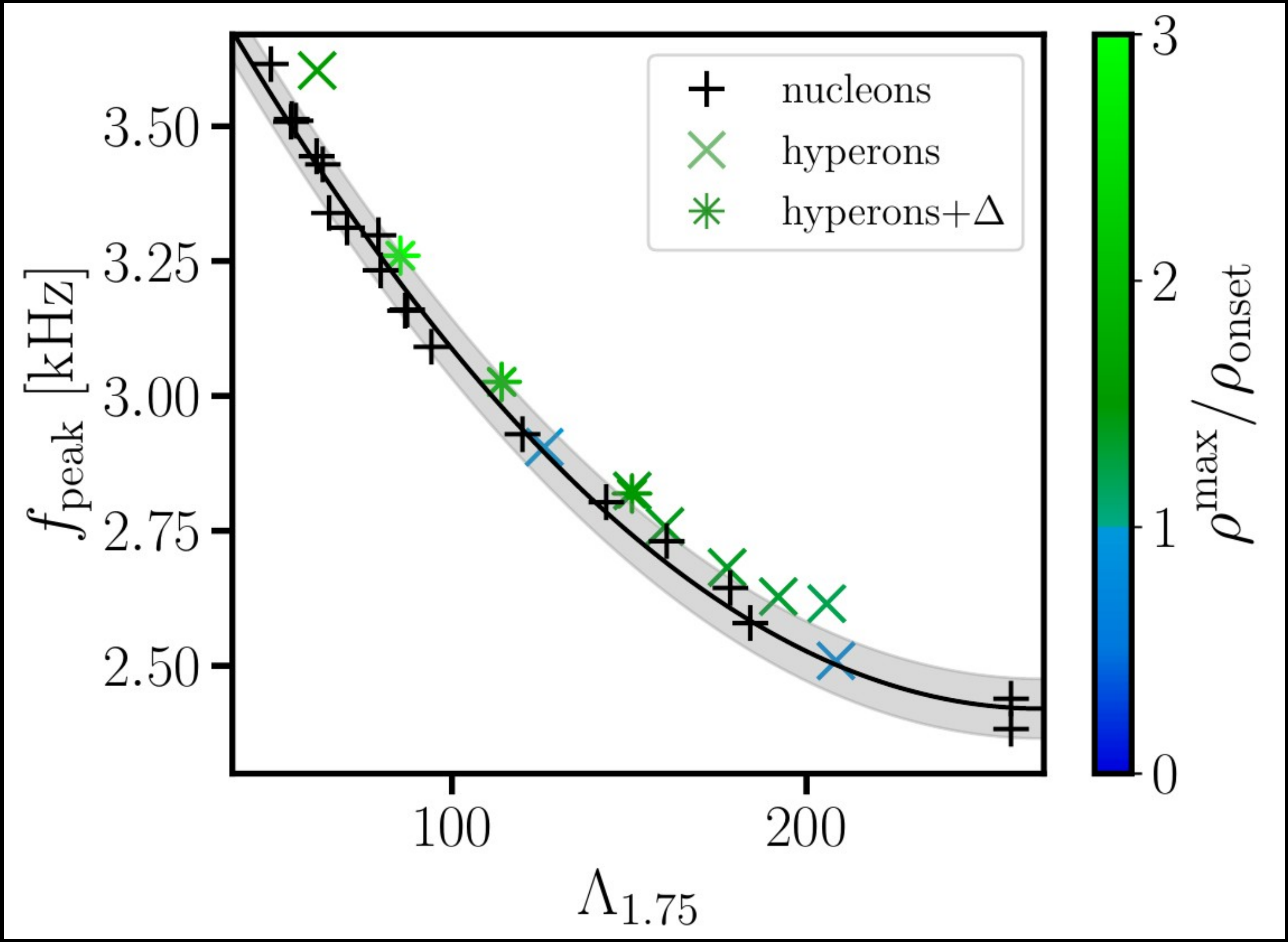
- Delta f describes impact of hyperons on thermal behavior → in principle measurable !!



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

Blacker et al. 2024

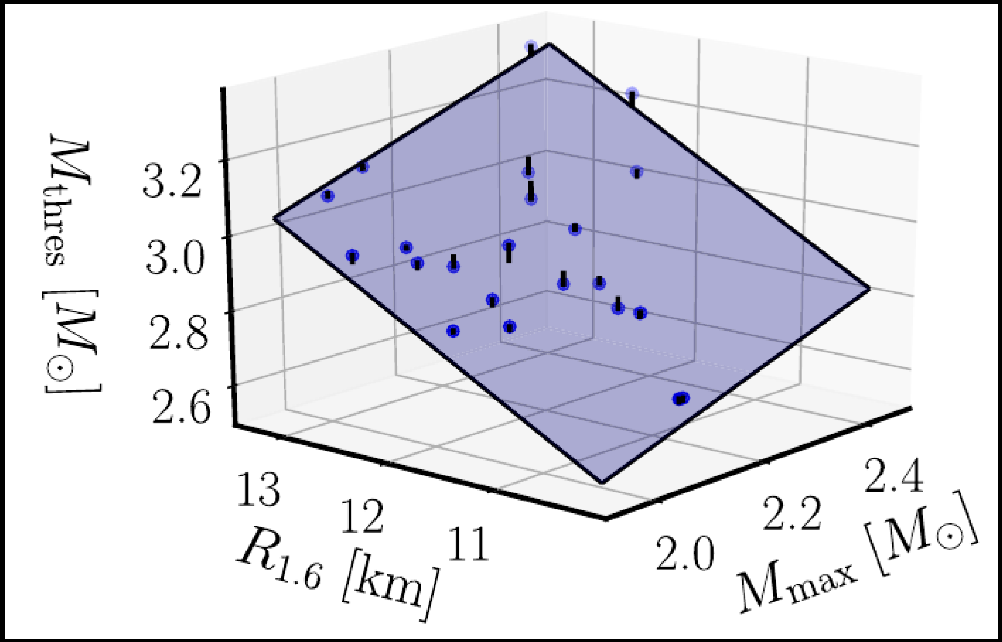
- Concrete scenario: hyperonic models have tendency to yield increased fpeak

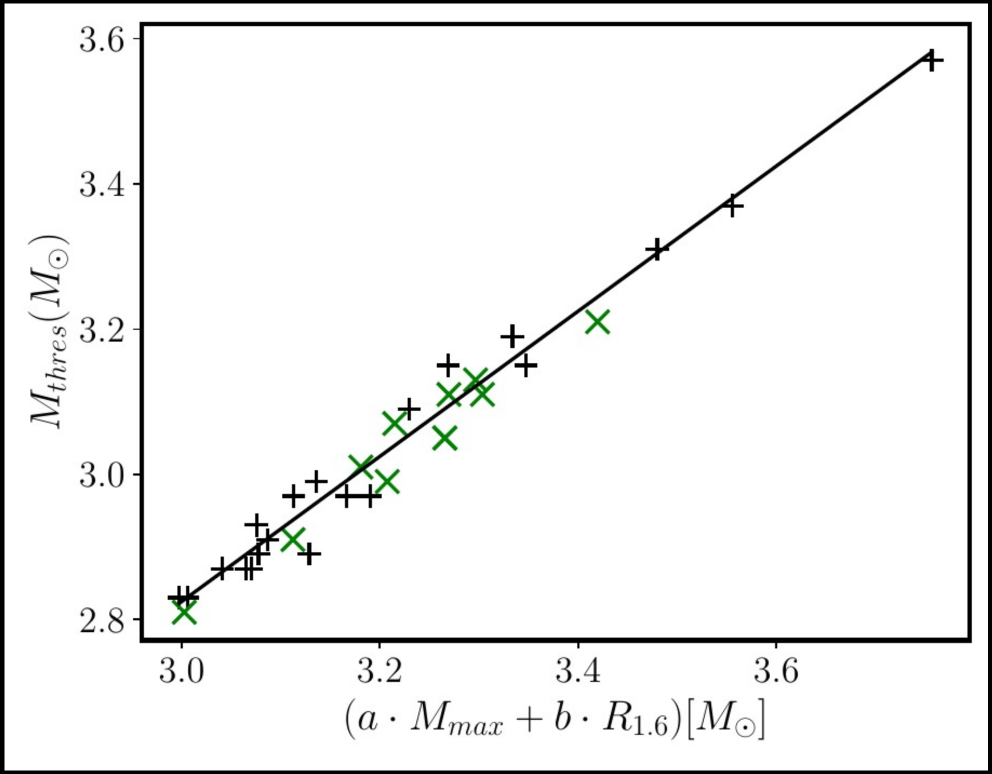


Blacker et al. 2024

Black hole formation

- Marginal reduction of M_thres





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 in comparison to nucleonic systems

  → small frequency shift (challenging but in principle measurable)
- (Generally NS mergers probe bulk properties of EoS – microphysics only accessible through combined effort with theory and experiment)