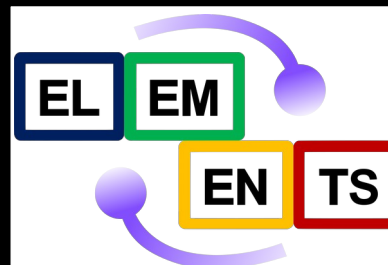




European Research Council
Established by the European Commission

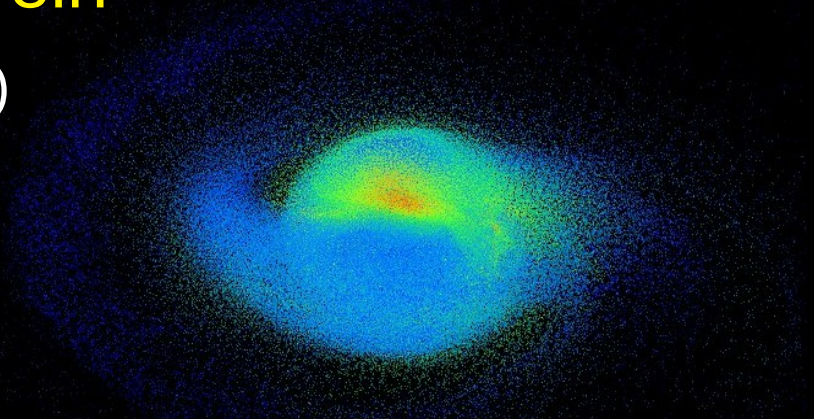
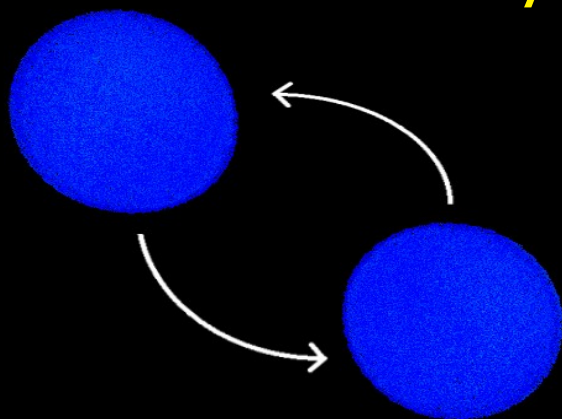


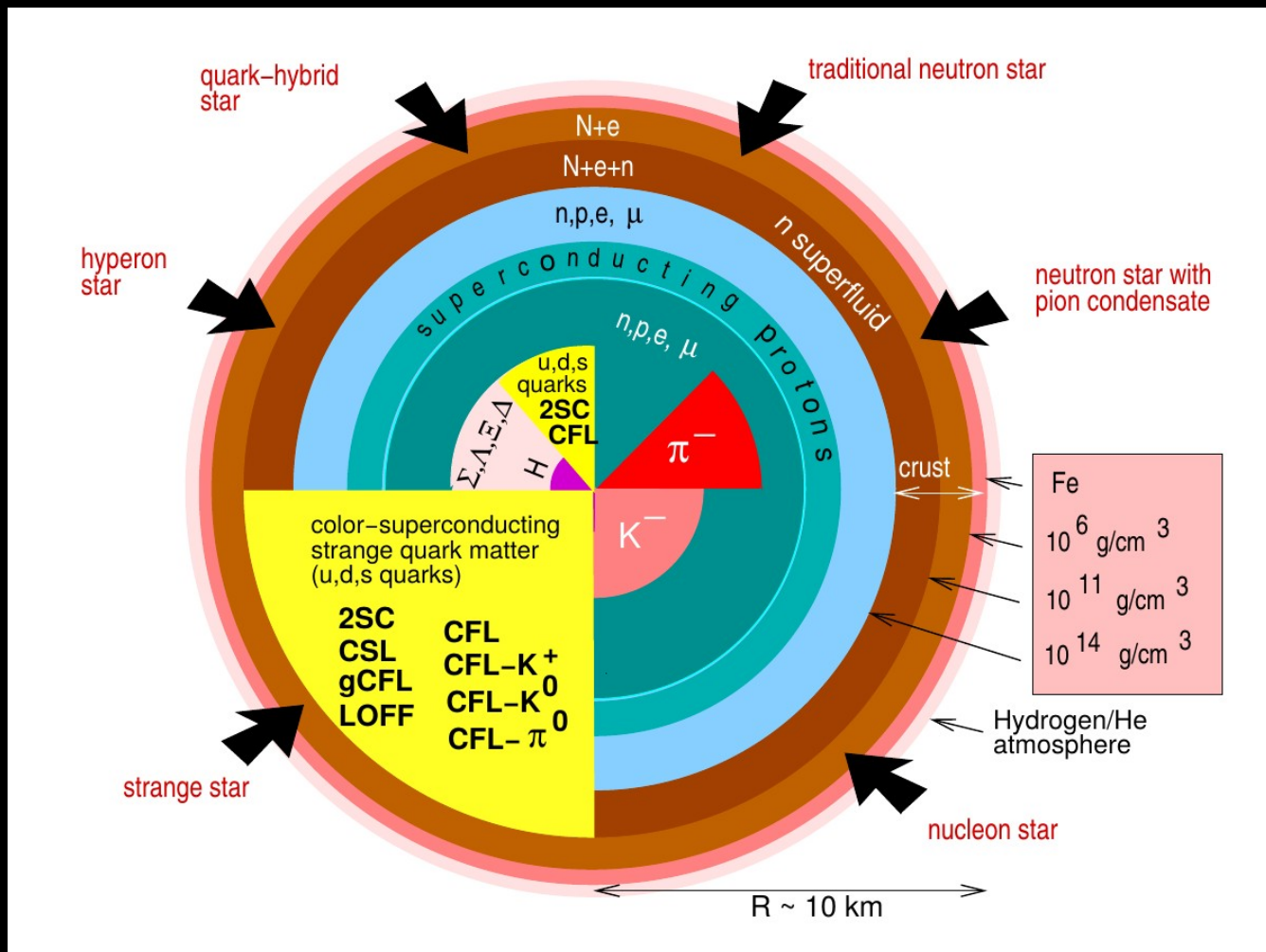
Pions, hyperons and quark matter in neutron star mergers

JENAS Initiative “Gravitational wave probes of fundamental physics”,
Rome, 12/02/2024

Andreas Bauswein

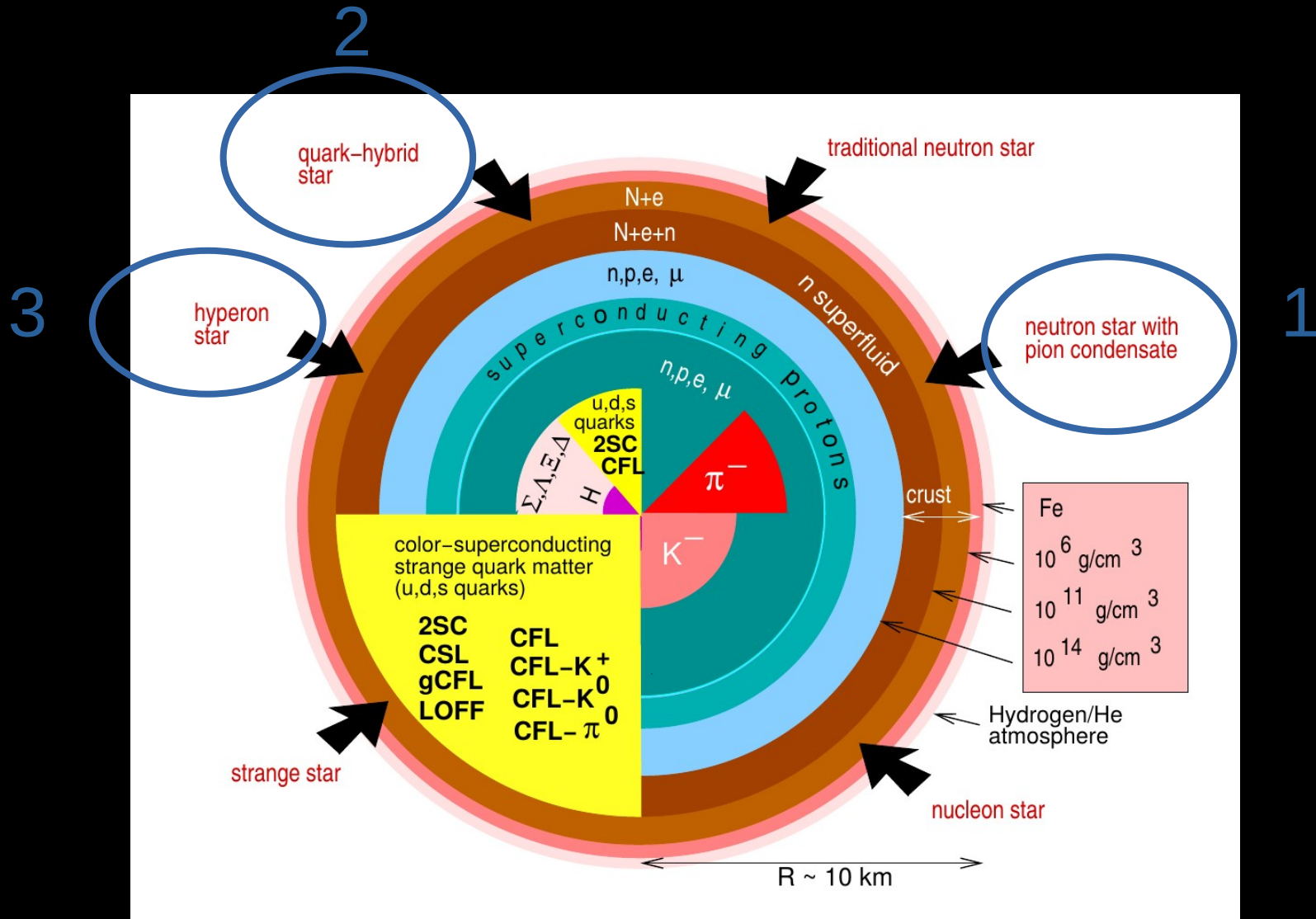
(GSI Darmstadt)





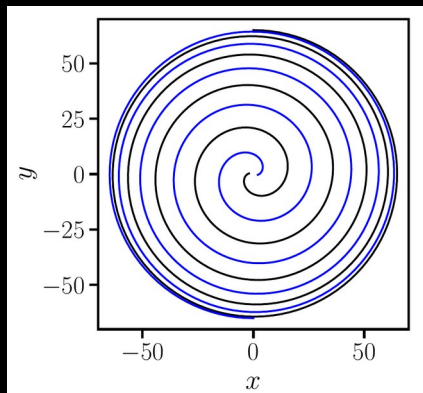
Weber 2004

- EoS of NS matter incompletely known \rightarrow stellar structure (mass-radius relation)



Weber 2004

- EoS of NS matter incompletely known → stellar structure (mass-radius relation)



$P_{orb} \sim 10 h$

Inspiral of NS binary

~ 100 Myrs

$P_{orb} \sim 1 ms$

Neutron star merger

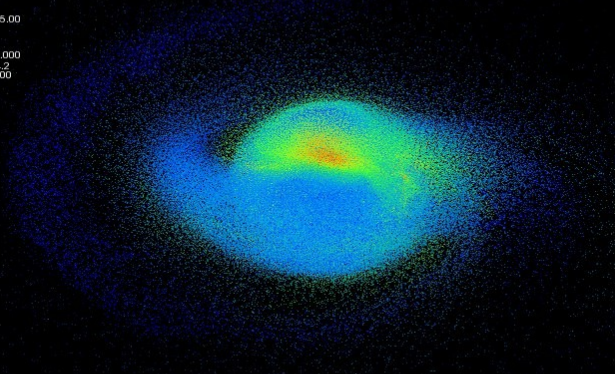
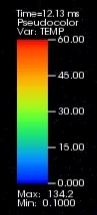
dependent on
 EoS, M_{tot}

ms

Prompt formation of a
BH + torus

ms

Formation of a differentially
rotating massive NS

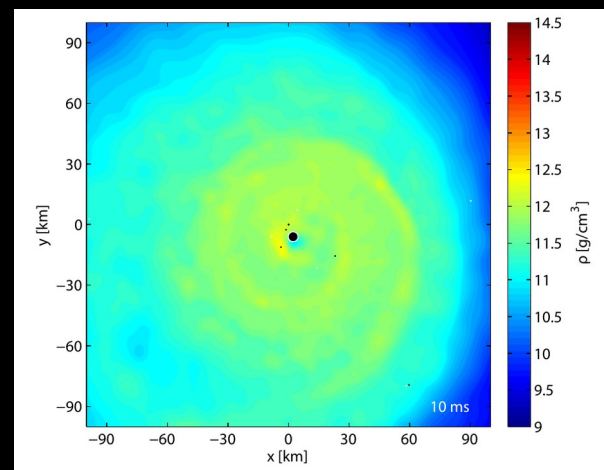


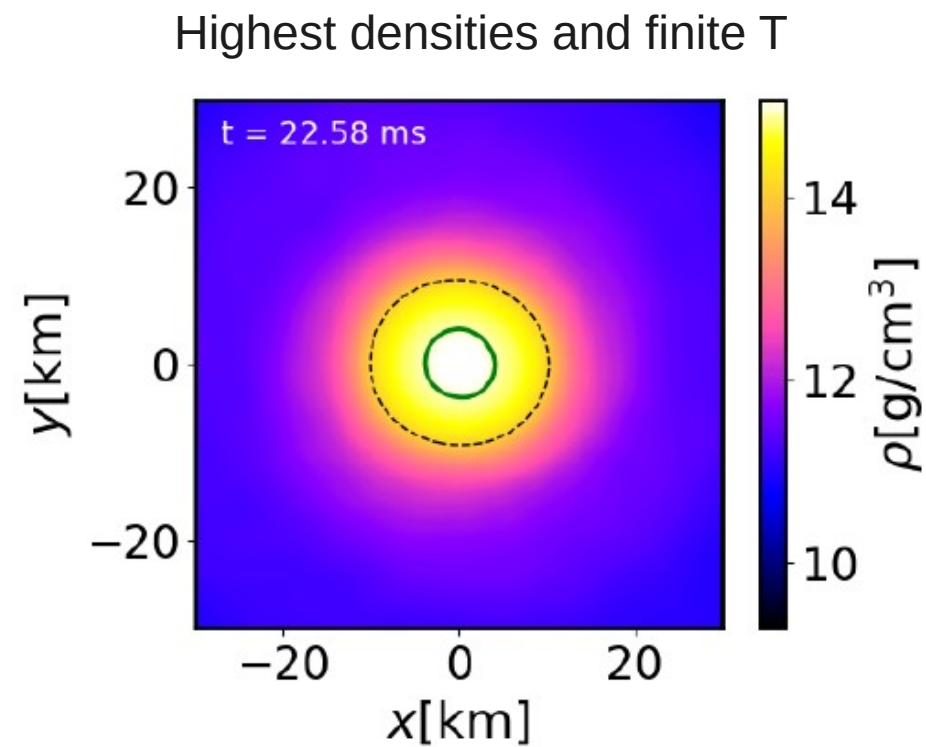
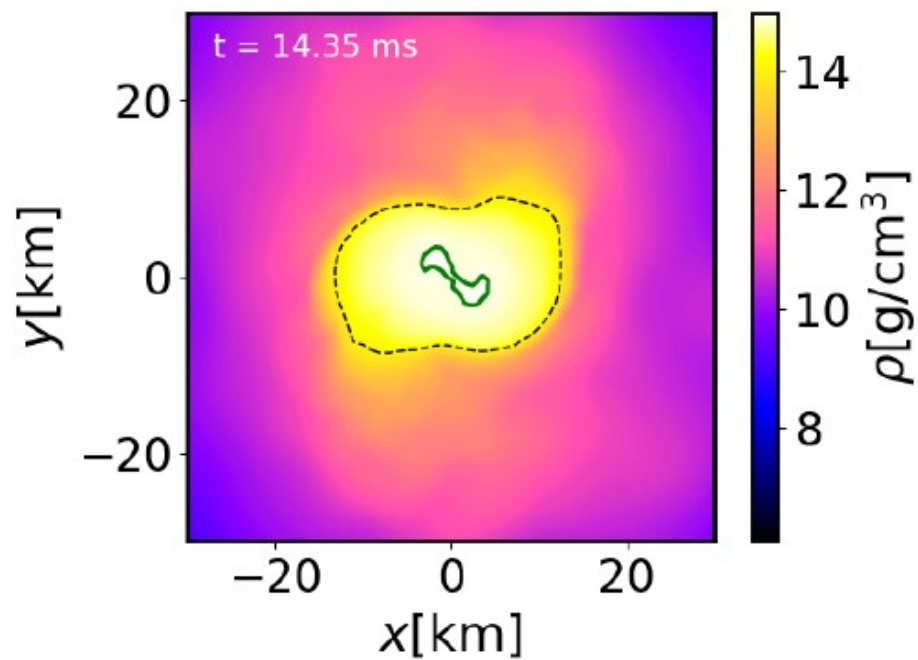
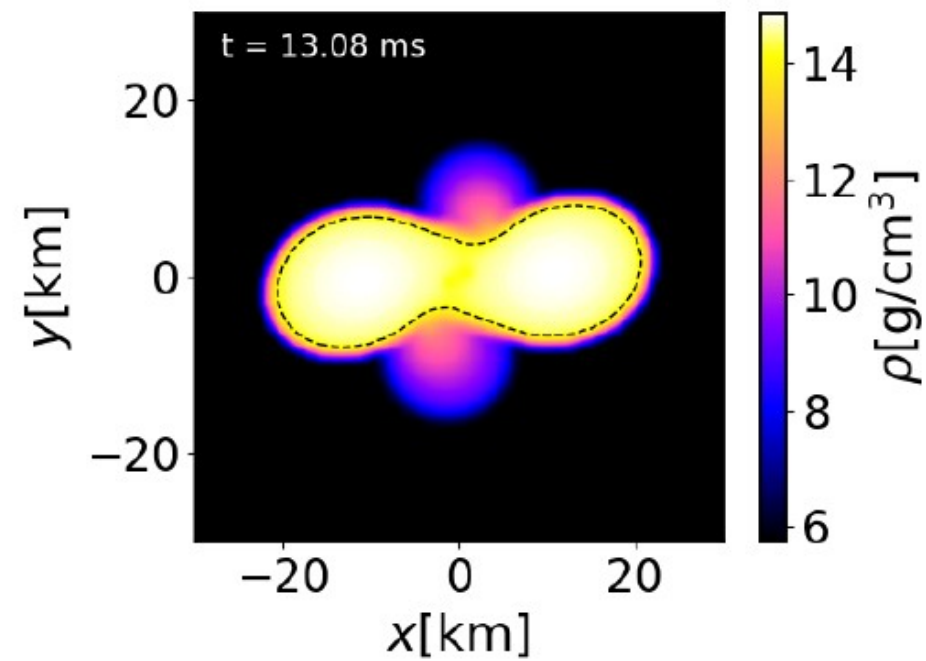
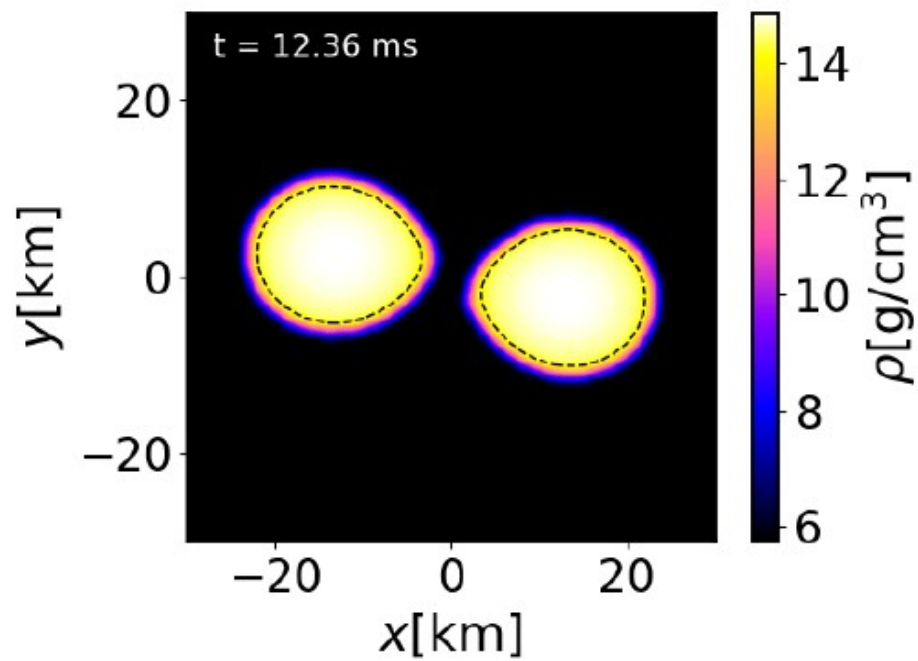
dependent on
 EoS, M_{tot}

10-100 ms

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

Delayed collapse
to a BH + torus

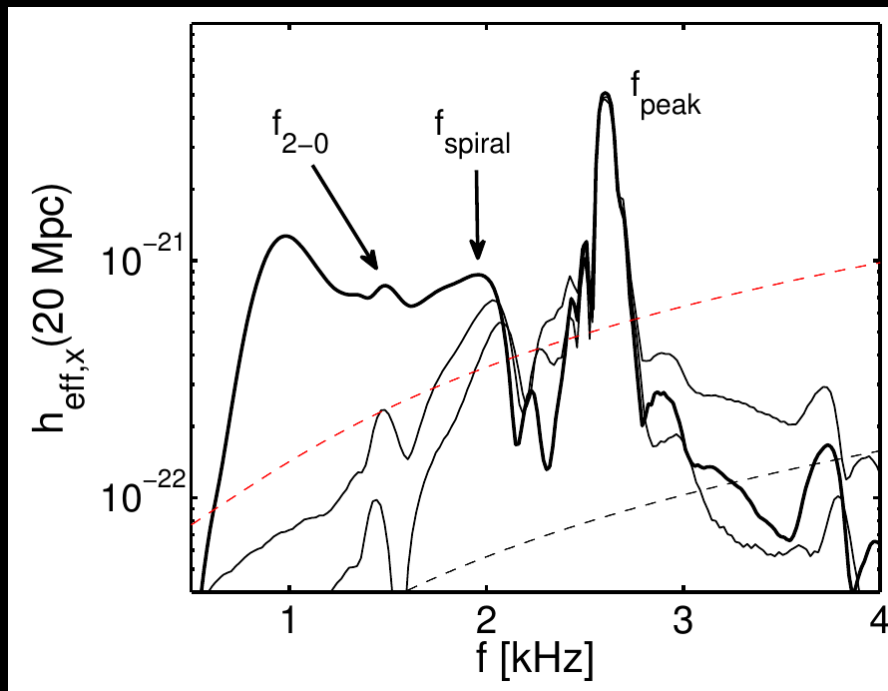




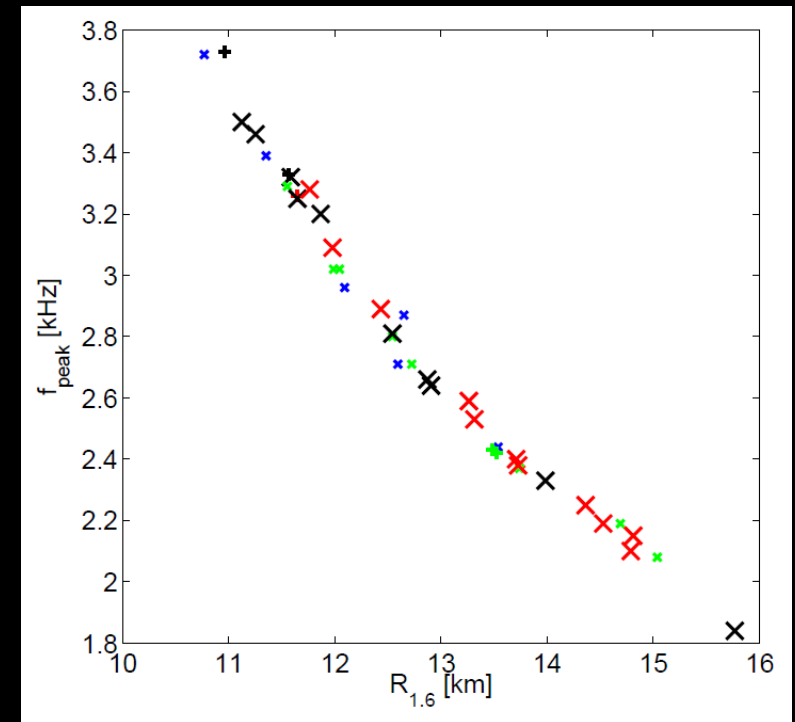
Empirical relations

- ▶ 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

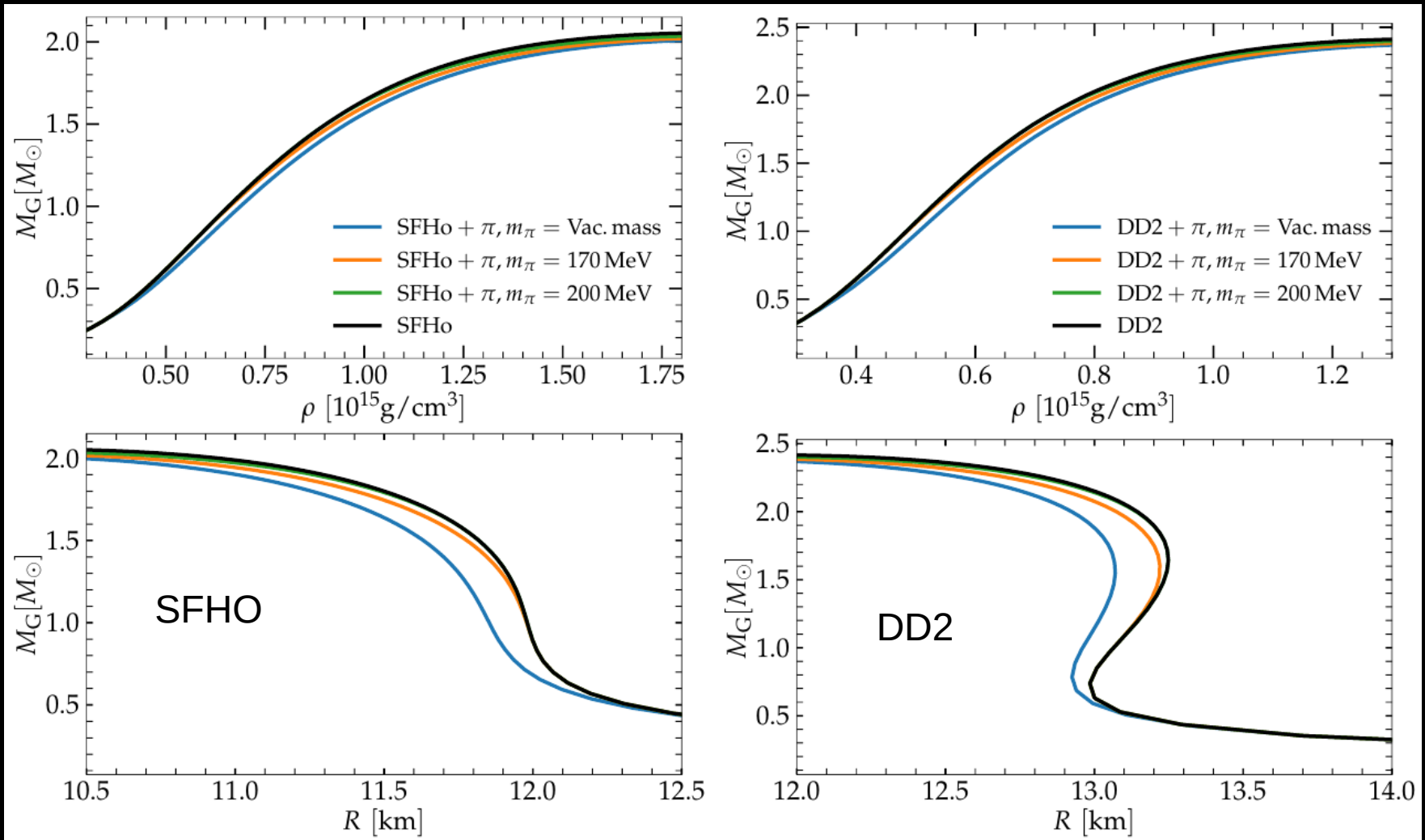
Including pions

- ▶ π^\pm, π^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

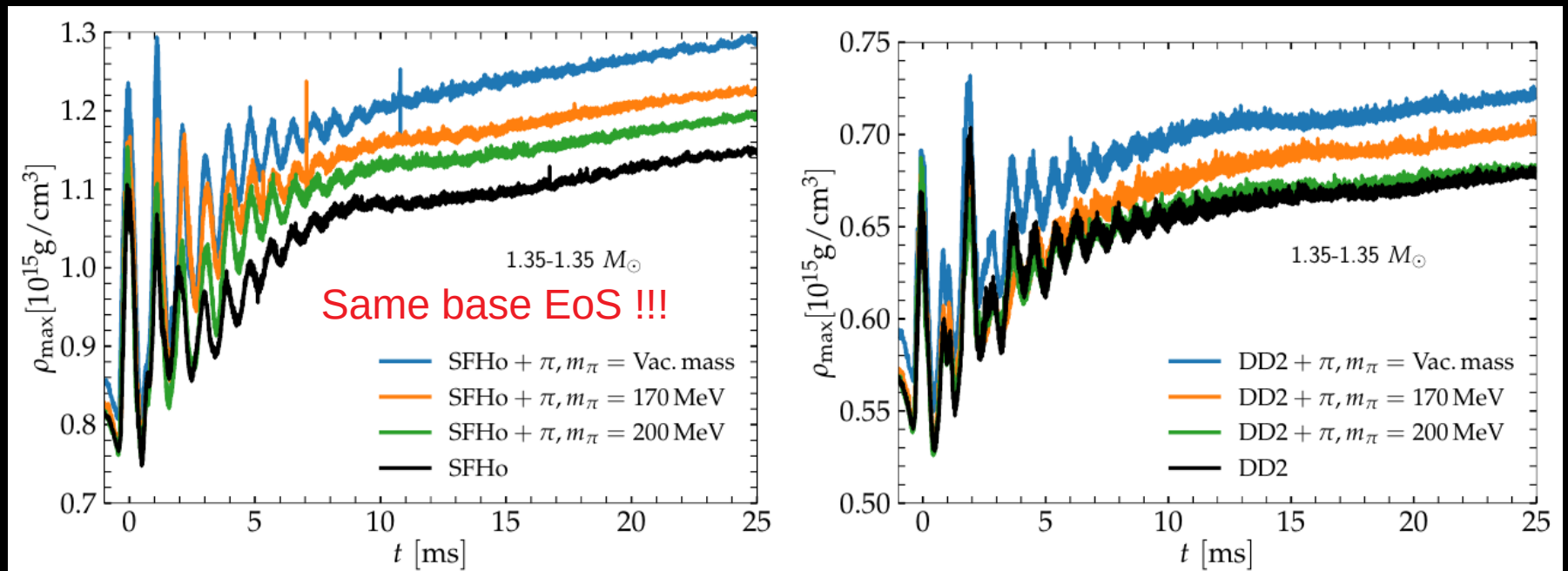
- ▶ Stronger impact for smaller pion mass (earlier condensation)
- ▶ Radius decrease by 200 m; Mmax slightly reduced



Merger simulations

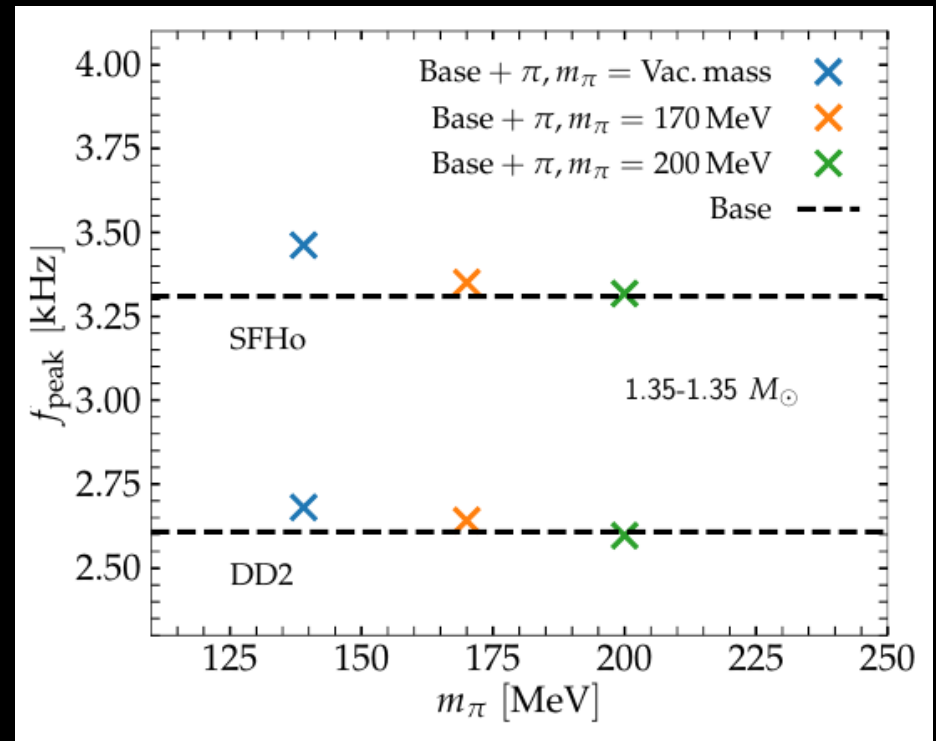
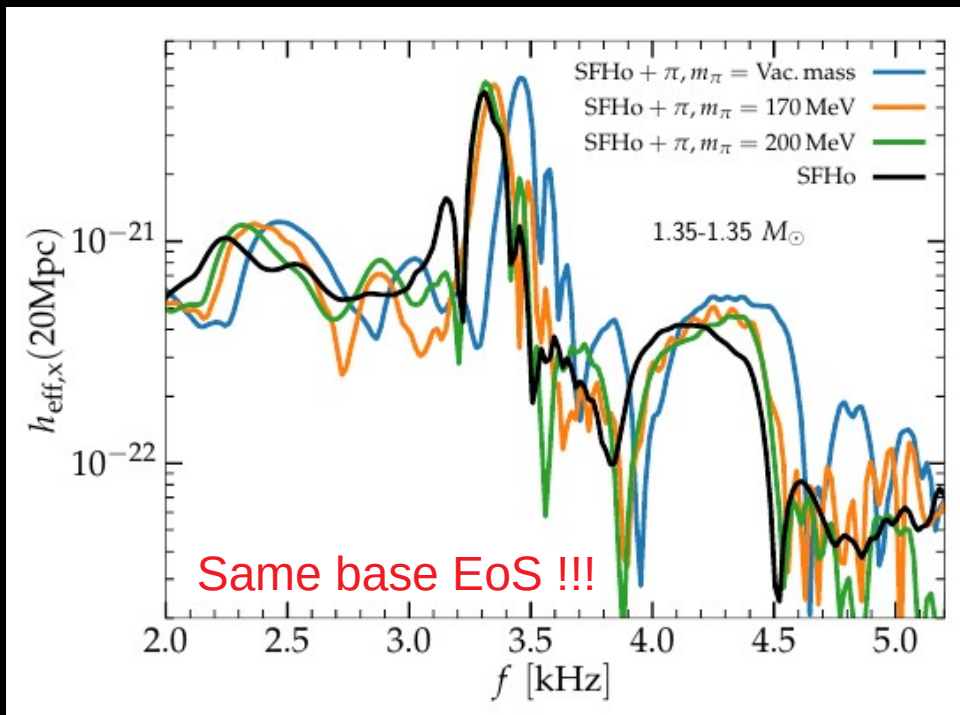
Motivation:

- ▶ Possibly combined effects condensate and thermal pions
- ▶ Empirical relations of merger observables often expressed by TOV properties
→ to which extent do those relations hold when pions are included ?
- ▶ SPH merger simulations in CFC with modified EoS tables compared to originals
- ▶ Electron fraction advected (ok-ish for high-density part where pions occur)
Vijayan et al 2023



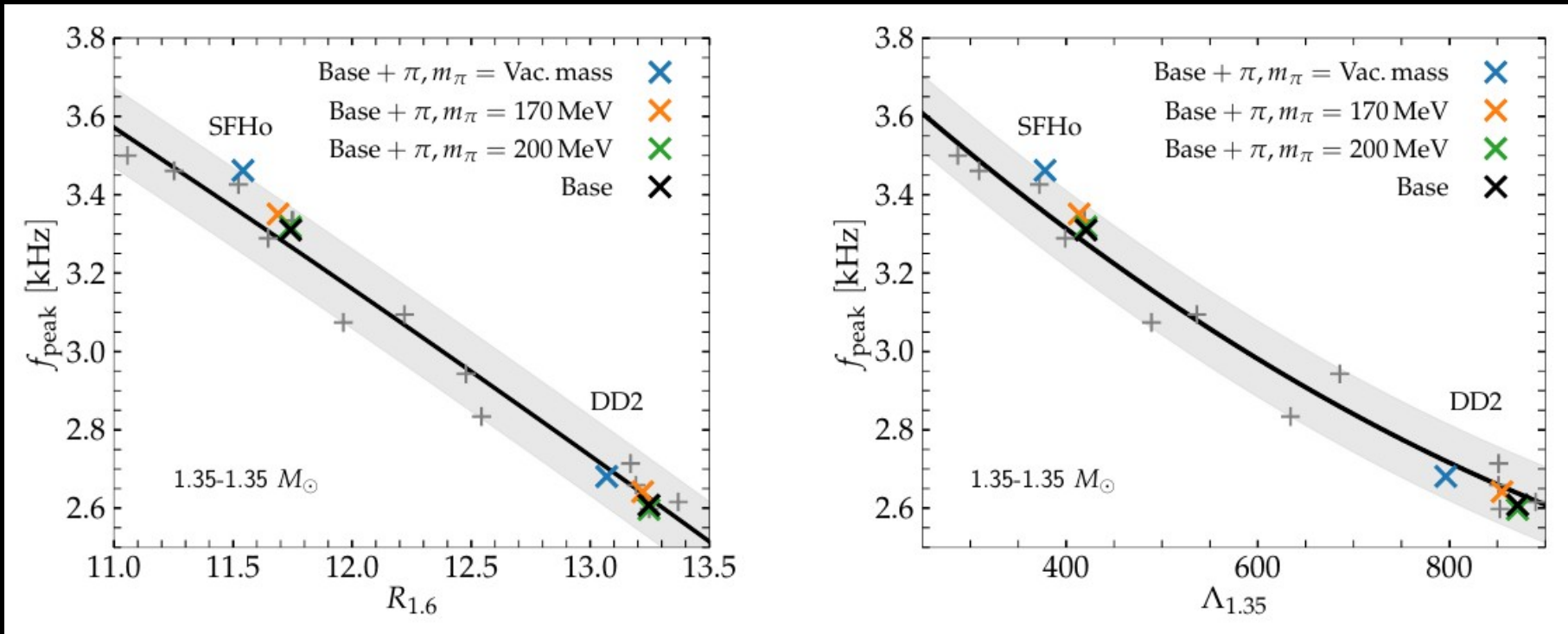
Inspiral and Postmerger GWs

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



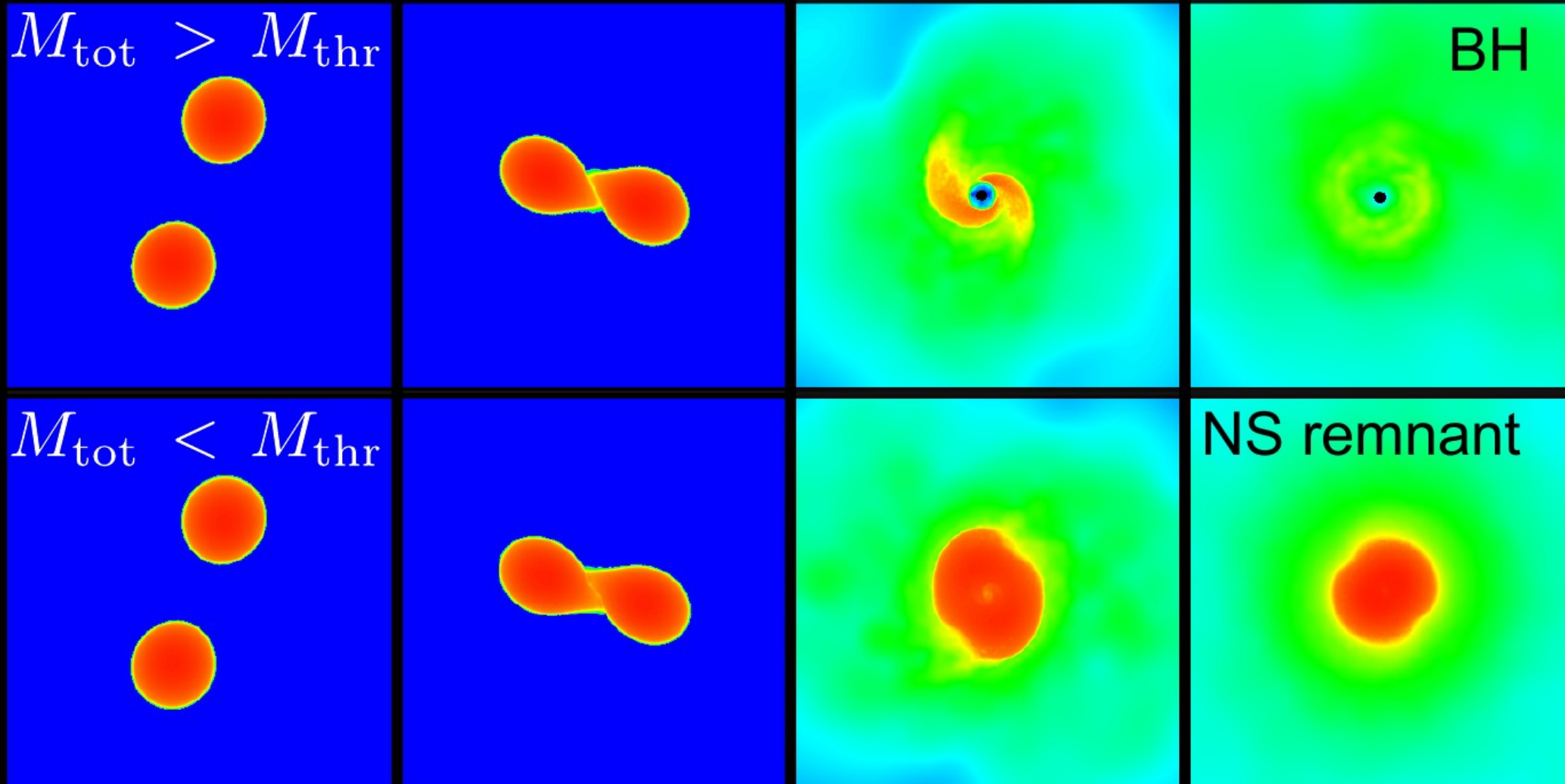
Empirical relations for dominant postmerger frequency

- ▶ Empirical relations build without pions remain approximately valid
- ▶ For softer SFHO model possibly stronger shifts for $m_\pi = \text{vac. mass}$



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

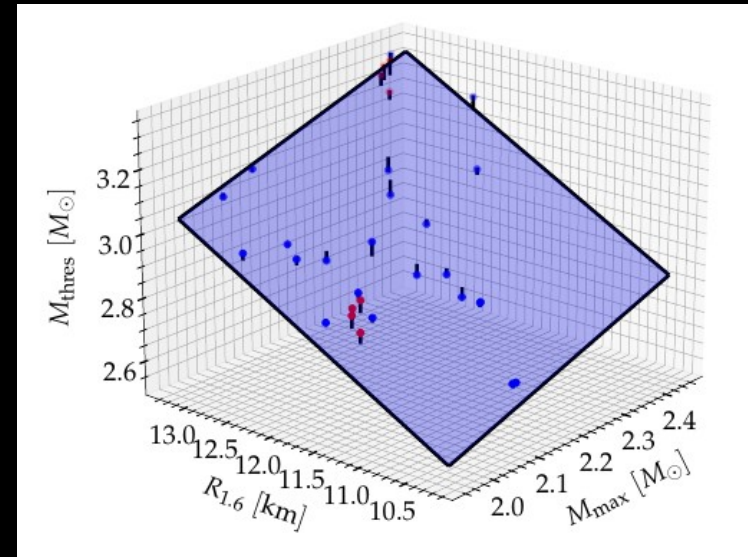
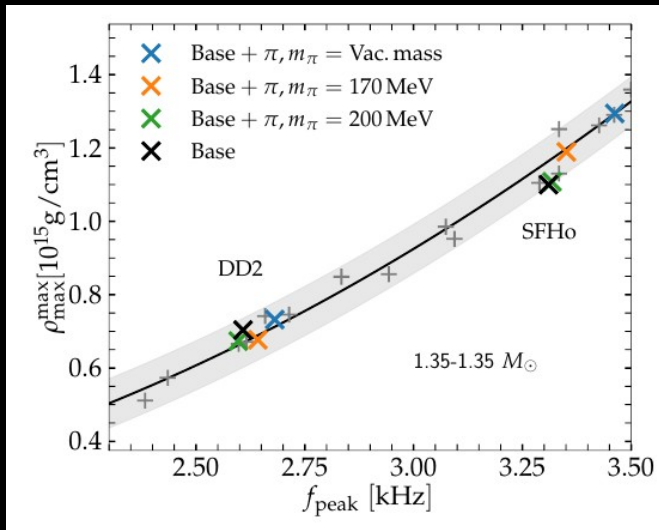
Collapse behavior – M_{thres} measurable




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, Koepfel 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

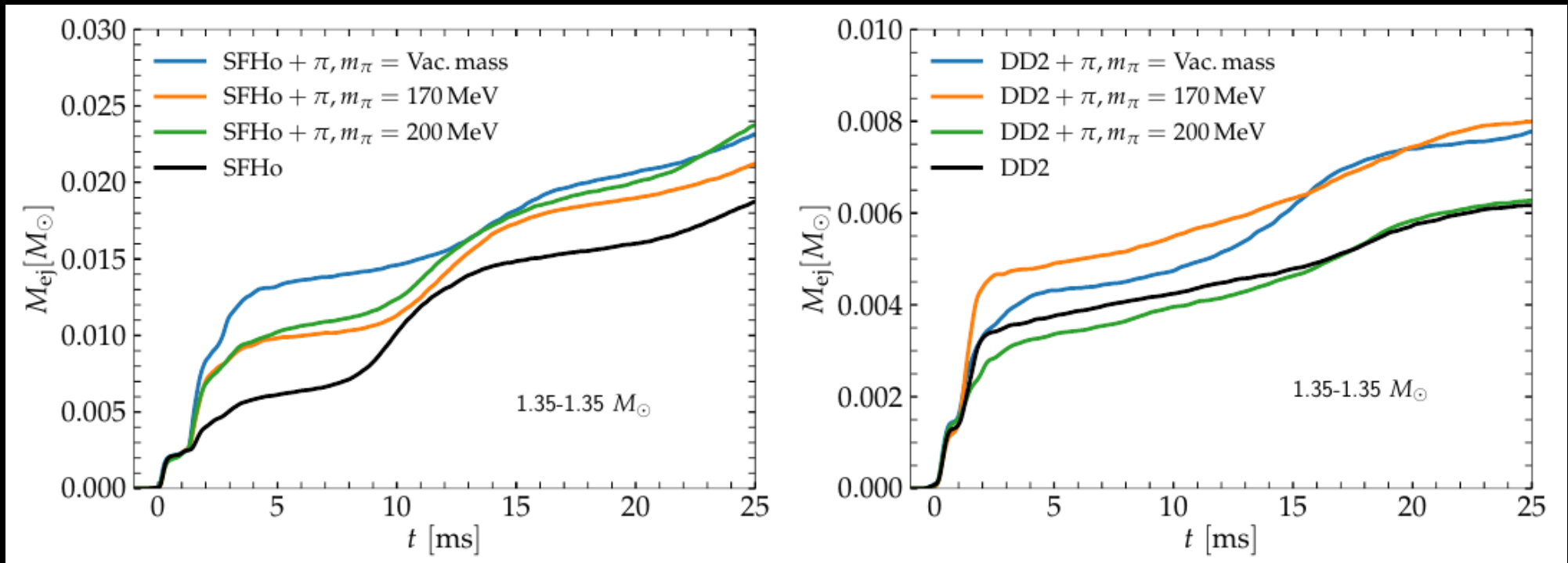


Model	M_{thres}	M_{max}	$R_{1.6}$	R_{max}	$\Lambda_{1.4}$	$\tilde{\Lambda}_{\text{thres}}$	$M_{\text{thres}}^{\text{fit}}$ ($Y = R_{1.6}$)	$M_{\text{thres}}^{\text{fit}}$ ($Y = R_{\text{max}}$)	$M_{\text{thres}}^{\text{fit}}$ ($Y = \Lambda_{1.4}$)	$M_{\text{thres}}^{\text{fit}}$ ($Y = \tilde{\Lambda}_{\text{thres}}$)
(Max. dev./ M_{\odot})							(0.042)	(0.059)	(0.056)	(0.085)
	[M_{\odot}]	[M_{\odot}]	[km]	[km]			[M_{\odot}]	[M_{\odot}]	[M_{\odot}]	[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)

- ▶ M_{thres} reduced by up to $0.08 M_{\text{sun}}$ (for $m_{\pi} \sim \text{vac mass}$)
- ▶ But empirical relations remain valid (within scatter) - combined effect on M_{thres}

Mass ejection \rightarrow 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 multi-messenger analysis)
 - \rightarrow potentially problematic of EoS inference
- ▶ Torus mass similar effects

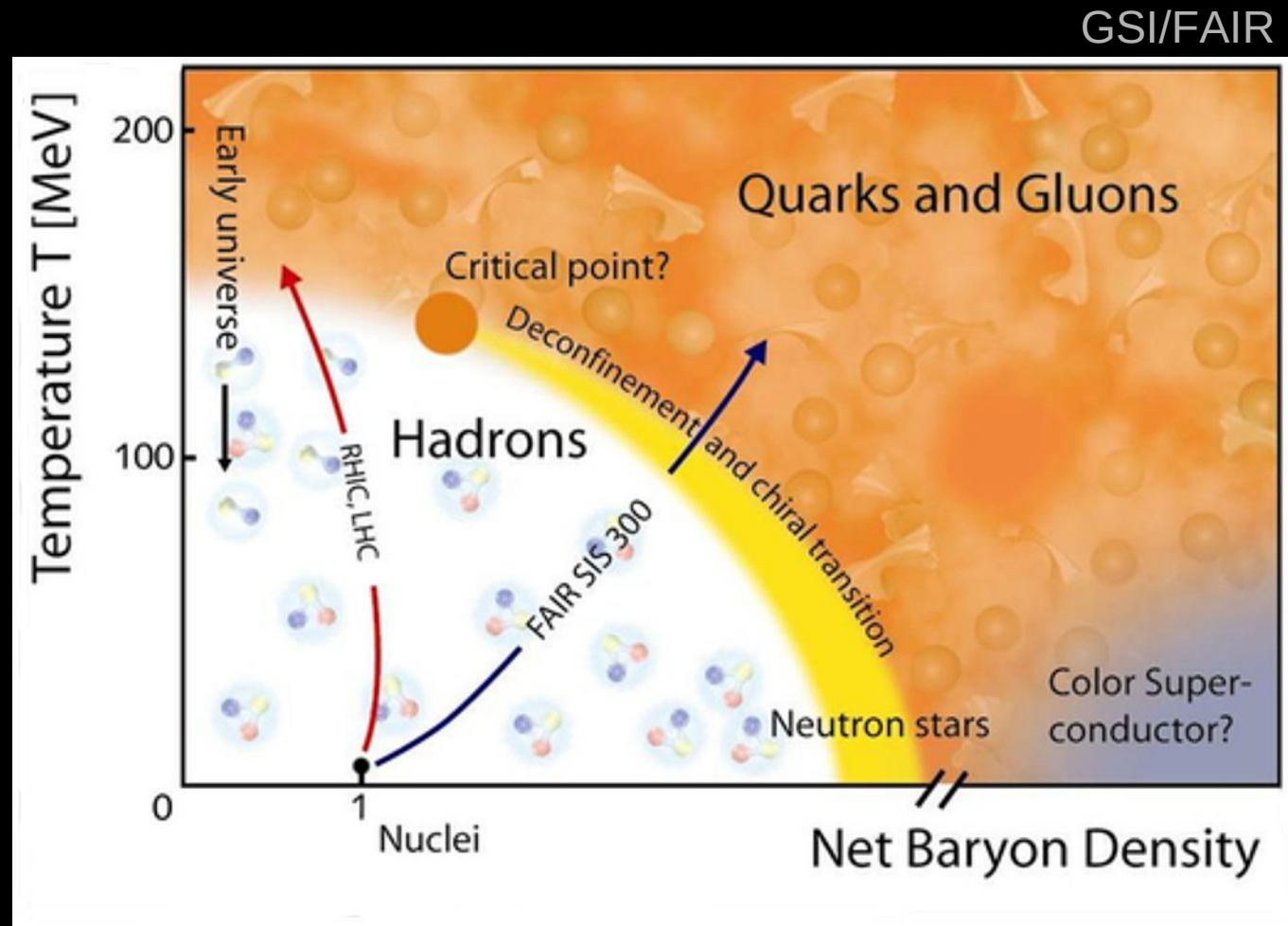


Quark matter in NS mergers

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

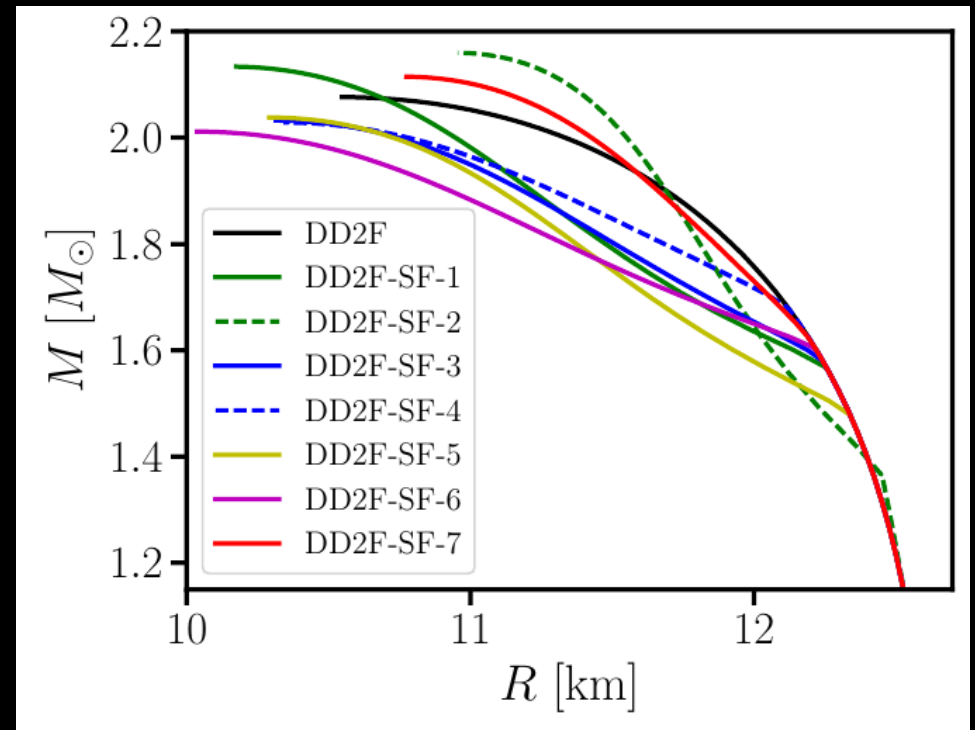
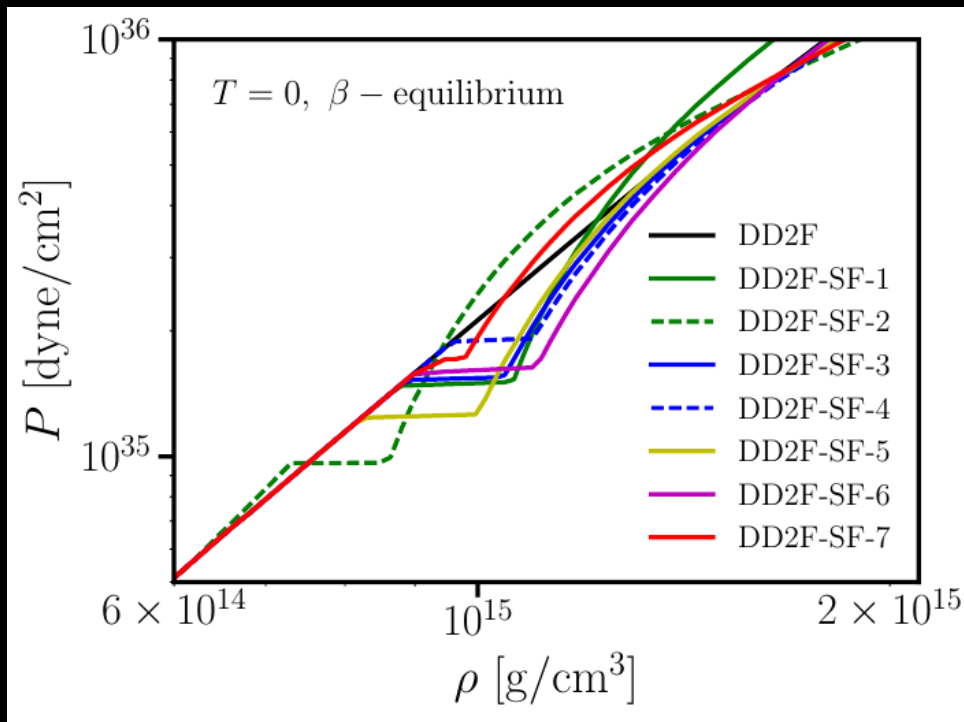
Phase diagram of matter of strongly interacting matter

High T , low μ :
experiments and
lattice QCD

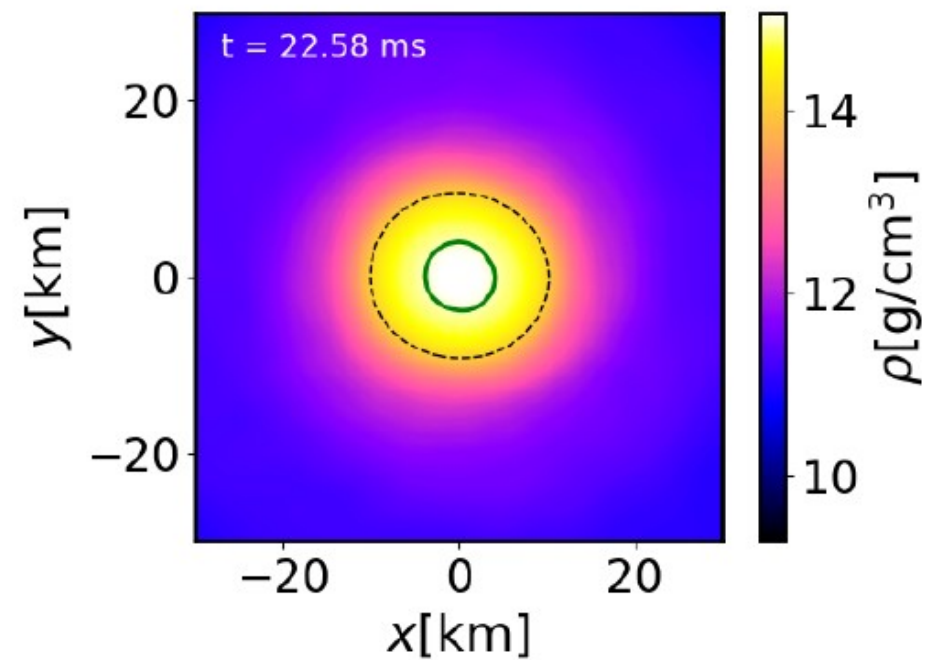
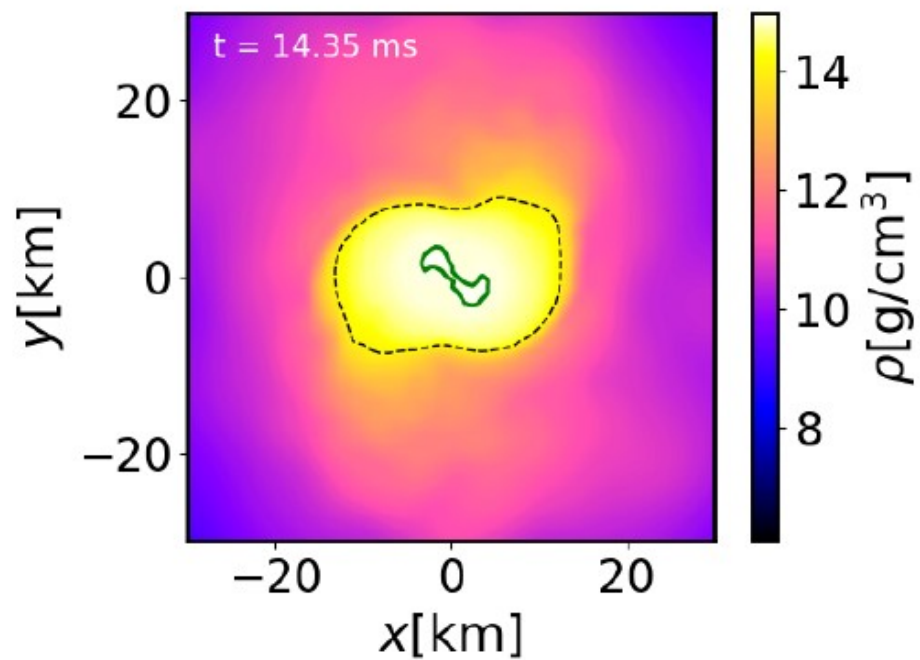
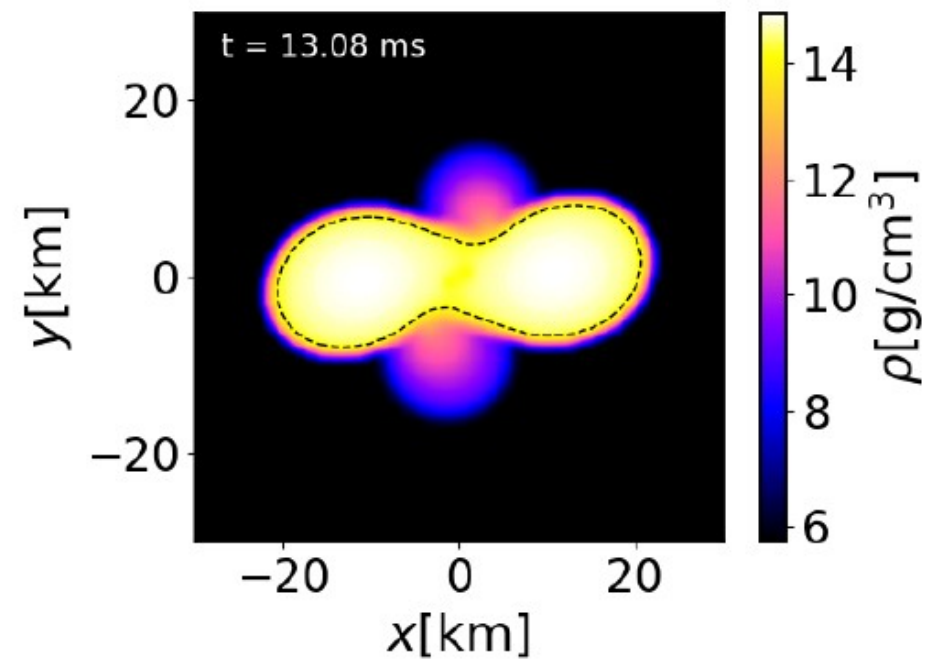
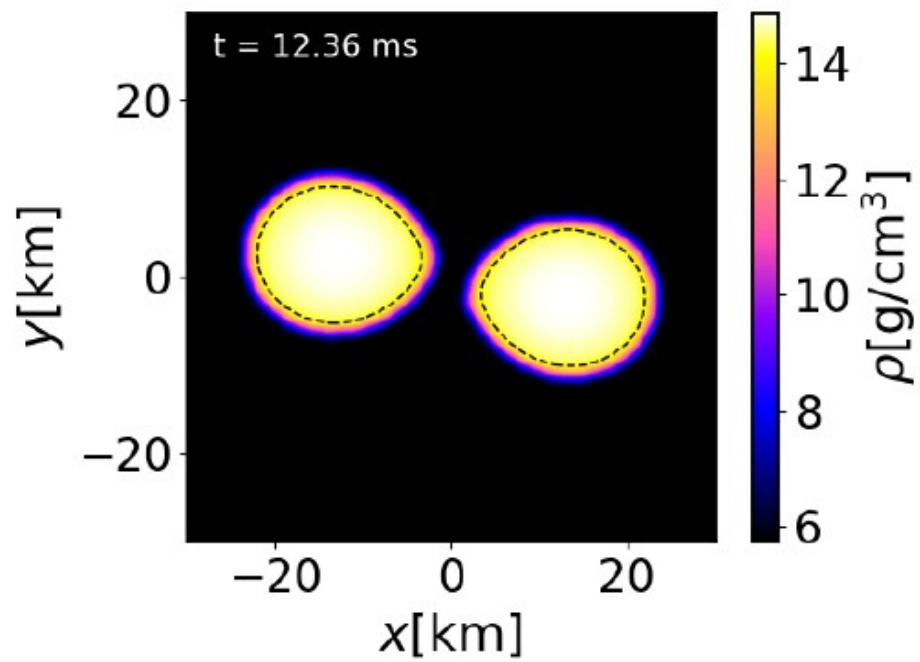


Does the phase transition to quark-gluon plasma occur (already) in neutron stars or only at higher densities?
(low T , high ρ not accessible by experiments or ab-initio models)

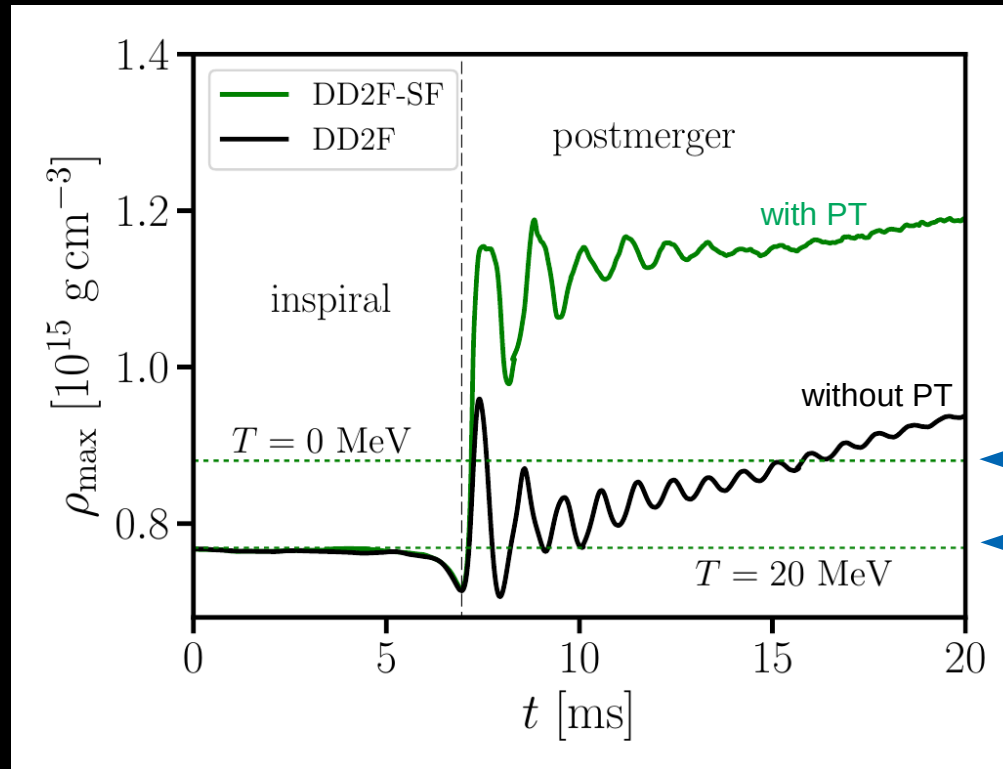
- ▶ 7 different models for quark matter: different onset density, different density jump, different stiffness of quark matter phase



Bauswein et al. 2019, Bastian 2020



Merger simulations

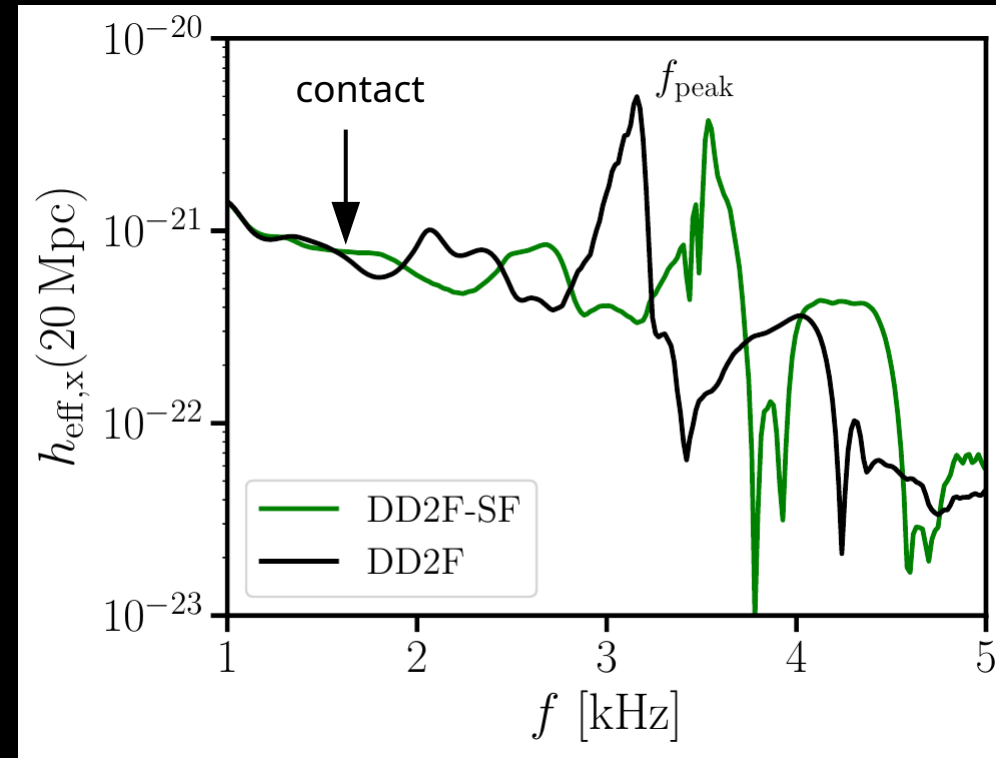
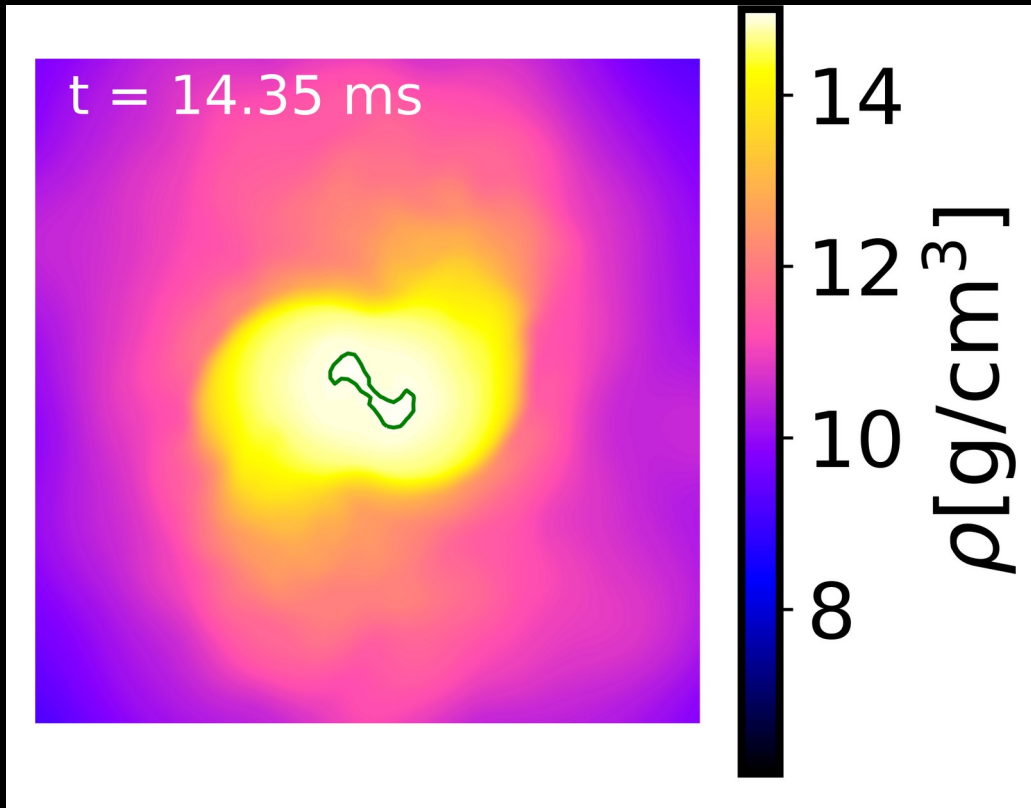


Bauswein et al. 2019

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

Merger simulations with quark matter core

► GW spectrum 1.35-1.35 Msun

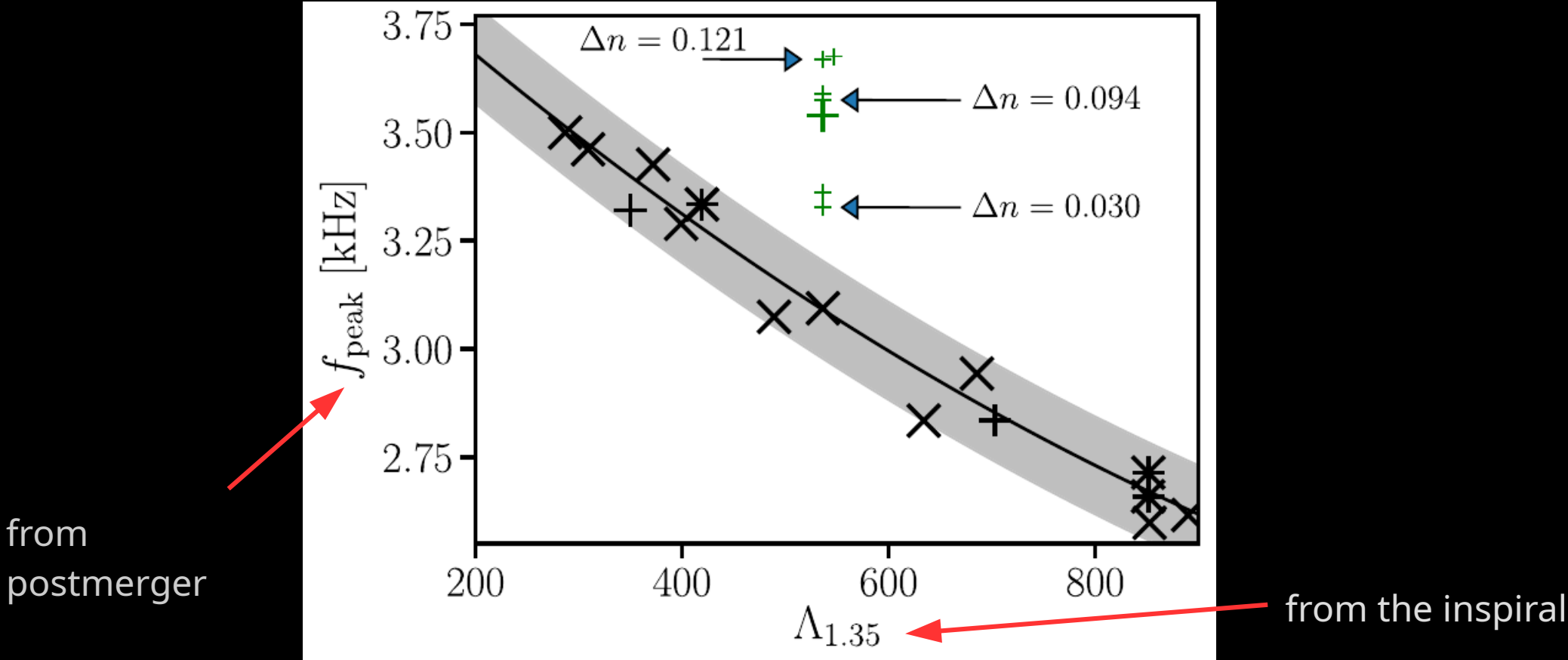


A.B. et al. 2019

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

→ unambiguous signature

Signature of 1st order phase transition



A.B. et al 2019

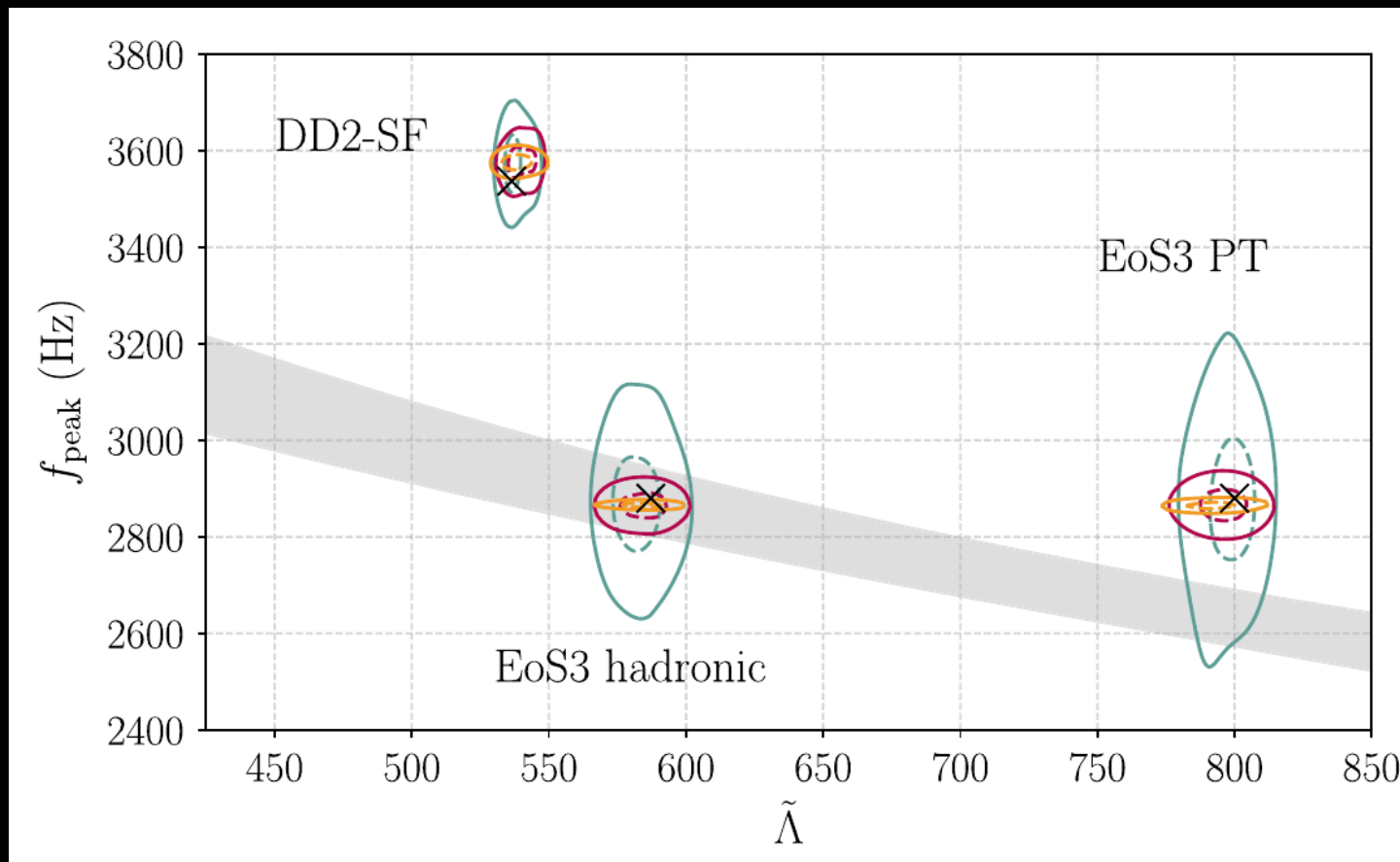
- ▶ Characteristic increase of postmerger frequency compared to tidal deformability
 - evidence of presence of quark matter core
 - in any case constraint on onset density/properties of hadron-quark phase transition

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

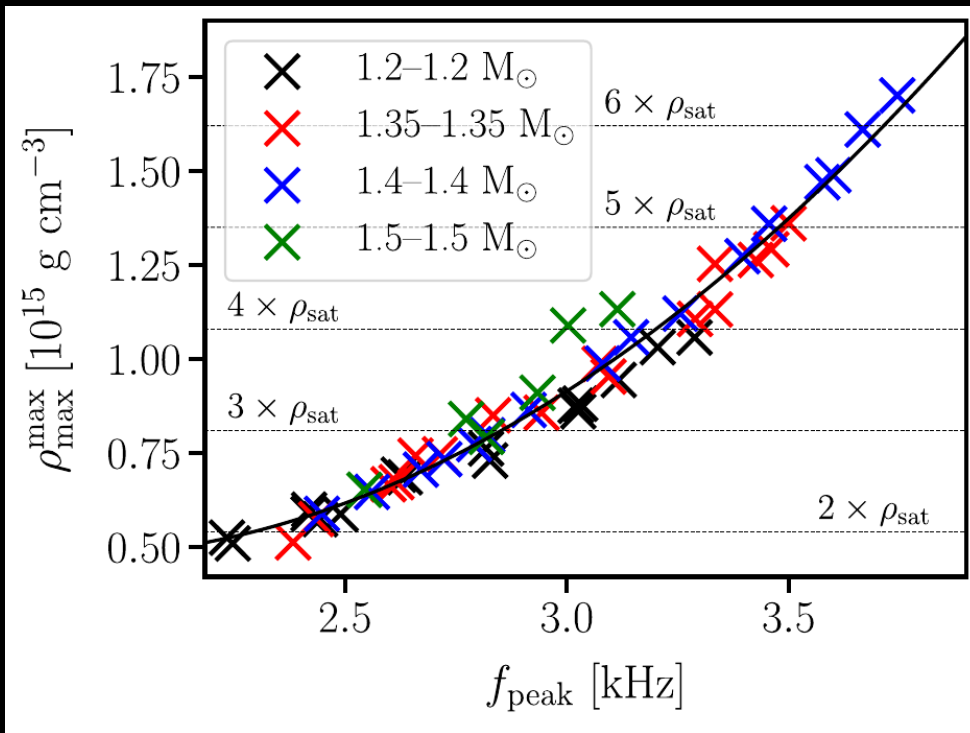


Wijngaarden et al., PRD 2022

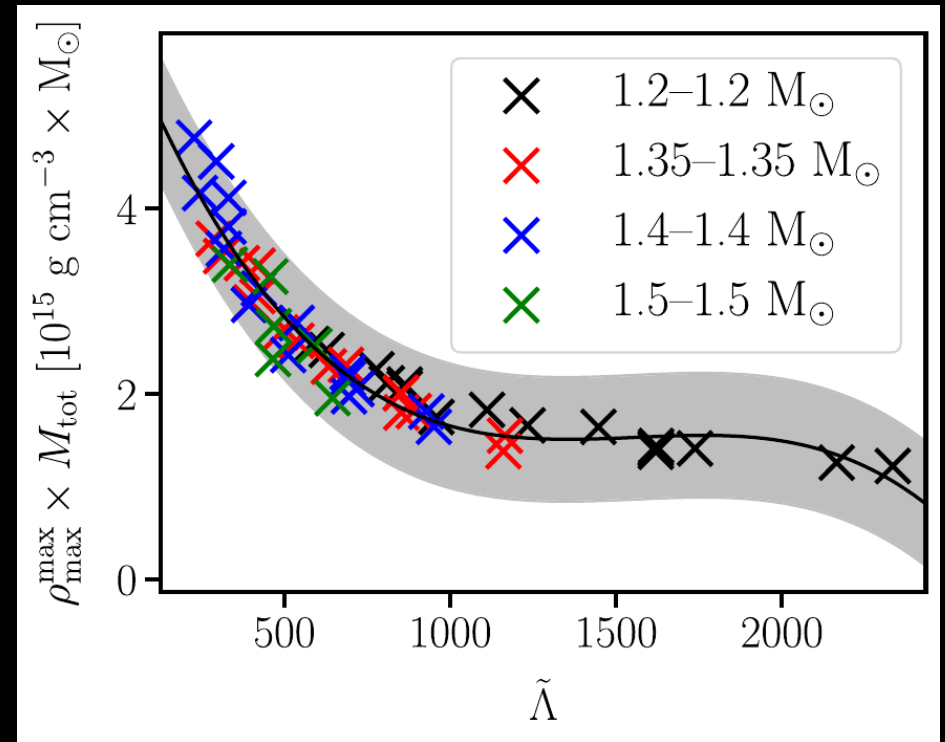
40 Mpc, 2x, 4x, 6x design sensitivity

- ▶ GWs inform about highest density in the remnant
 - constraint on onset density (if PT is identified/excluded)

Blackmer et al. 2020



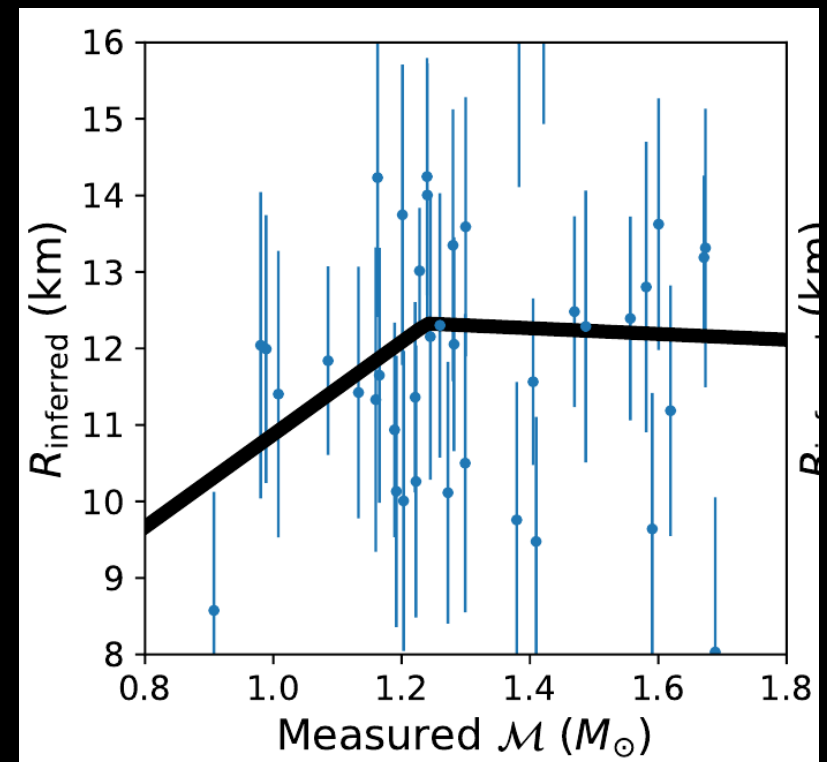
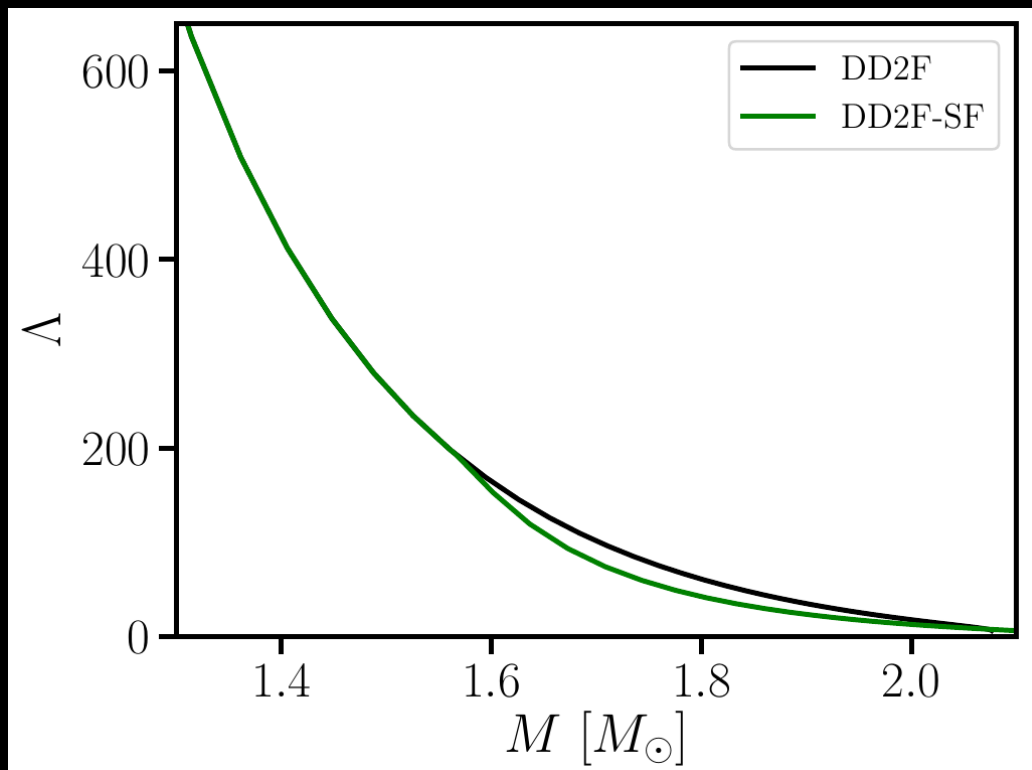
Postmerger frequency f_{peak}



tidal deformability from inspiral

Phase transition and the GW inspiral

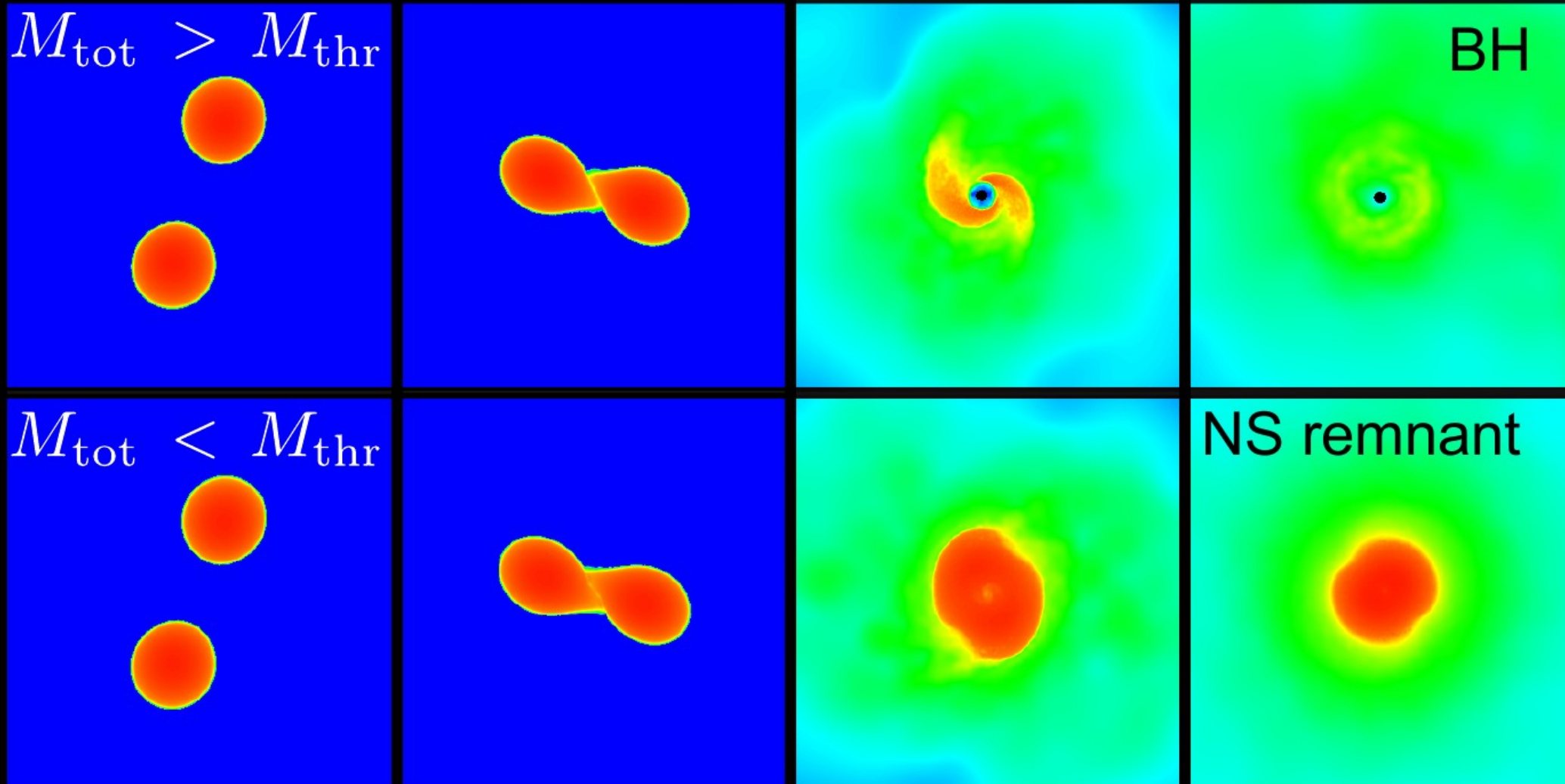
- ▶ Even strong phase transitions leave relatively weak impact on tidal deformability
 - challenging to measure transition in mergers through inspiral: Kink weak, Lambda generally very small, high mass star possibly less frequent



Chen et al 2020

→ see e.g. Chen et al. 2020, Chatzioannou & Han 2020 using multiple (~100) events

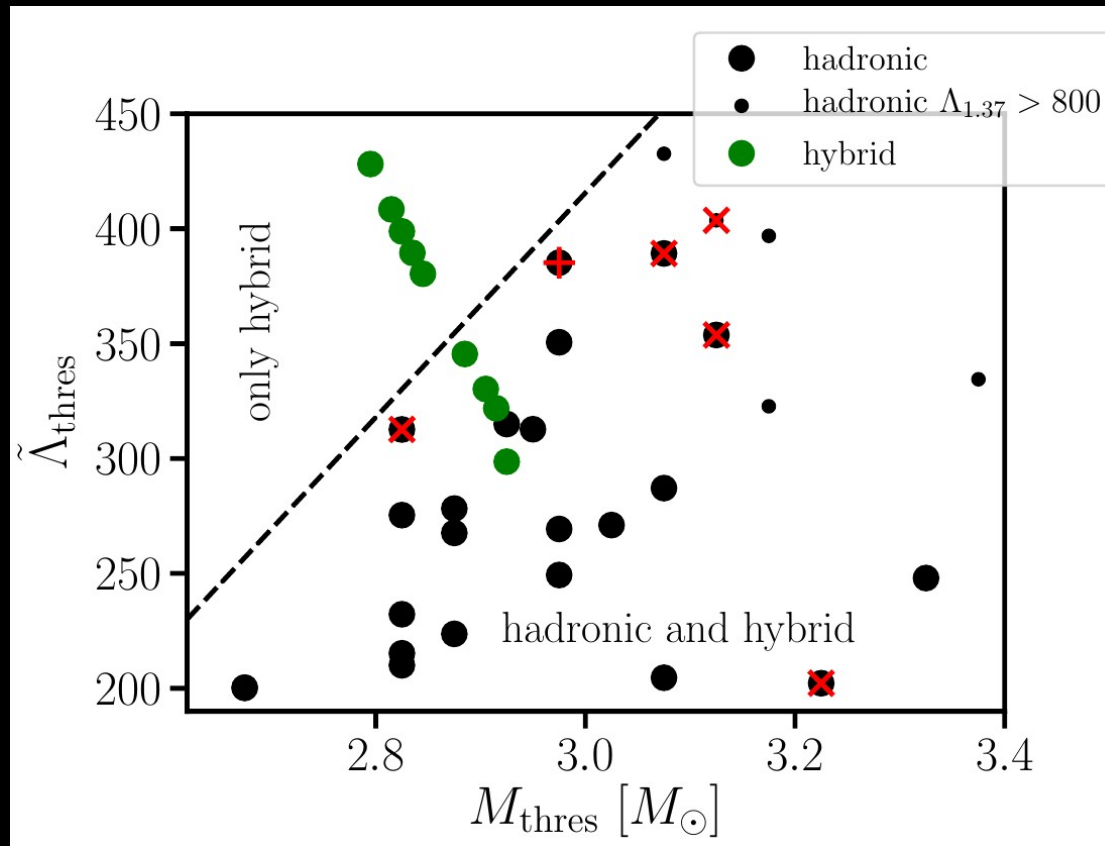
Collapse behavior – M_{thres} measurable



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, Koepfel 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]

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 $M_{\text{max}} > 1.97$!!

Measurable from GW inspiral

Bauswein et al., PRL 125 (2020)

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

Measurable from inspiral + information on merger product

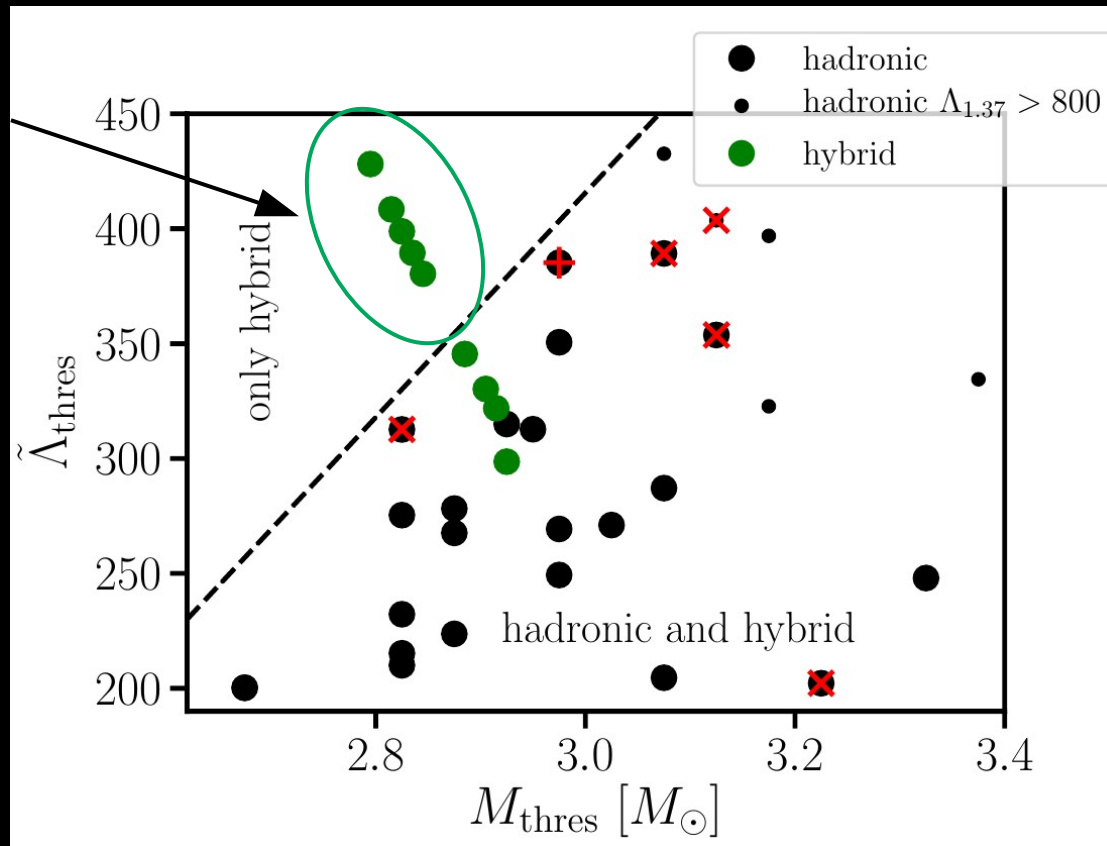
QCD phase transition from collapse behavior

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Evidence for quark matter

With $M_{\text{max}} > 1.97$!!

Measurable from GW inspiral



Bauswein et al., PRL 125 (2020)

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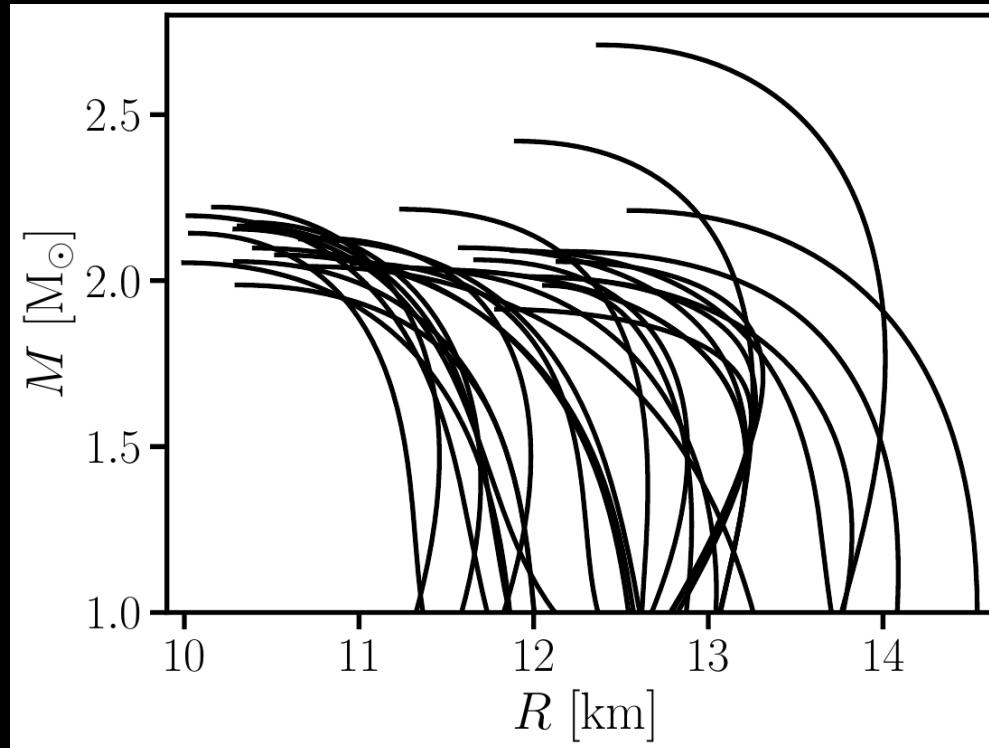
Hyperons in NS mergers

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

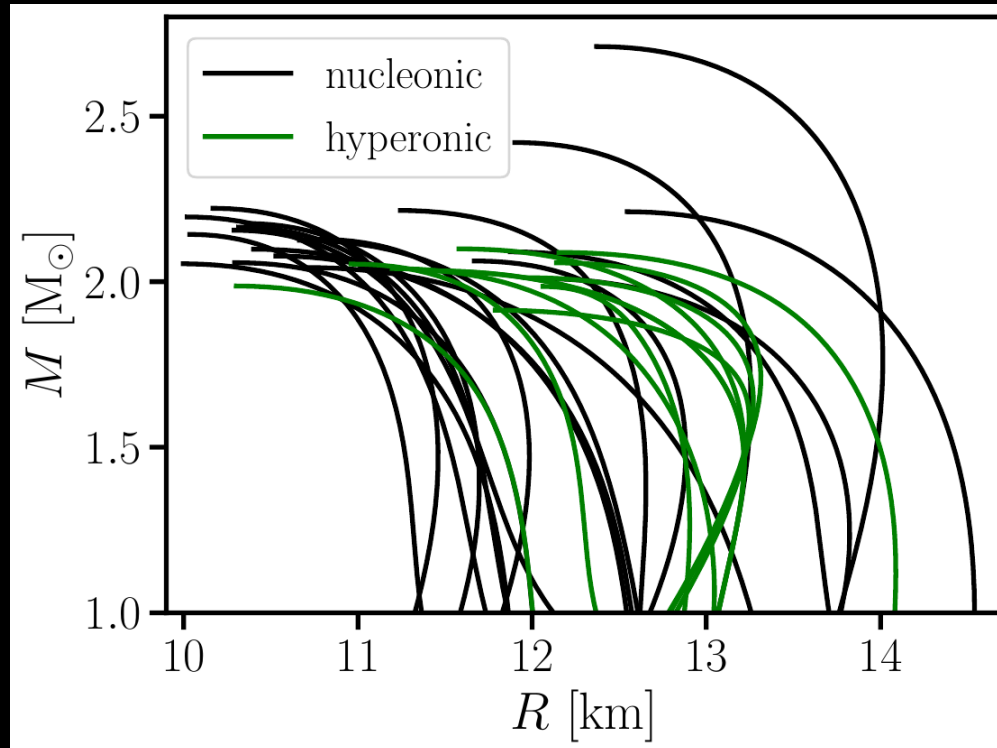
Hyperon puzzle

- ▶ 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 $2 M_{\text{sun}}$ NSs
- ▶ Several modern hyperonic EoS fulfill the $2 M_{\text{sun}}$ constraint
 - hyperon puzzle unsolved – interacting Fermi gas with unknown interactions
 - generally hyperons leave weak impact on NS structure – indistinguishable MR



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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

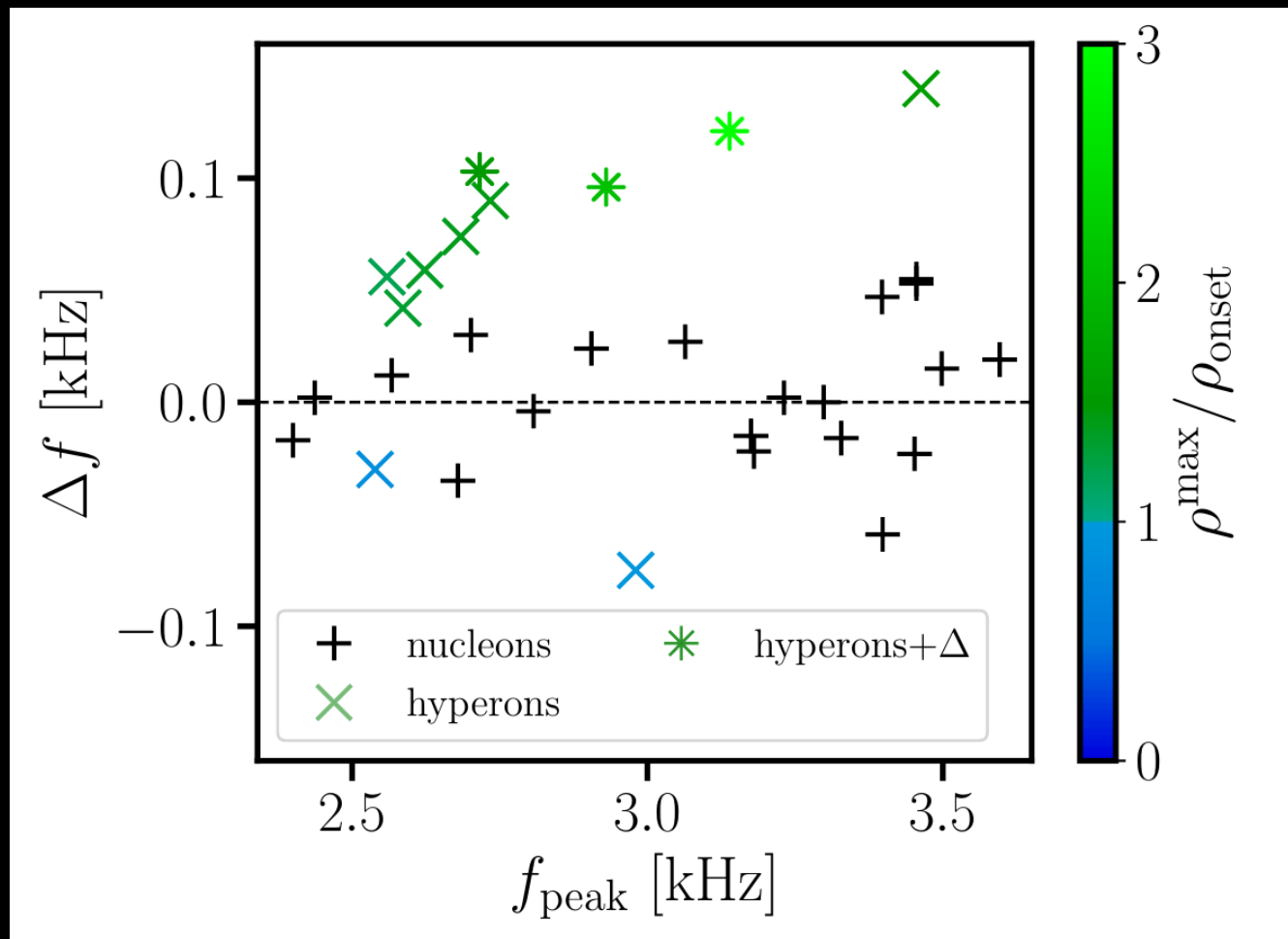
Compare $\Gamma_{th} = 1.75$ runs vs. full T-dependent simulations

→ thermal behavior of hyperons

Thermal behavior as indicator for hyperons

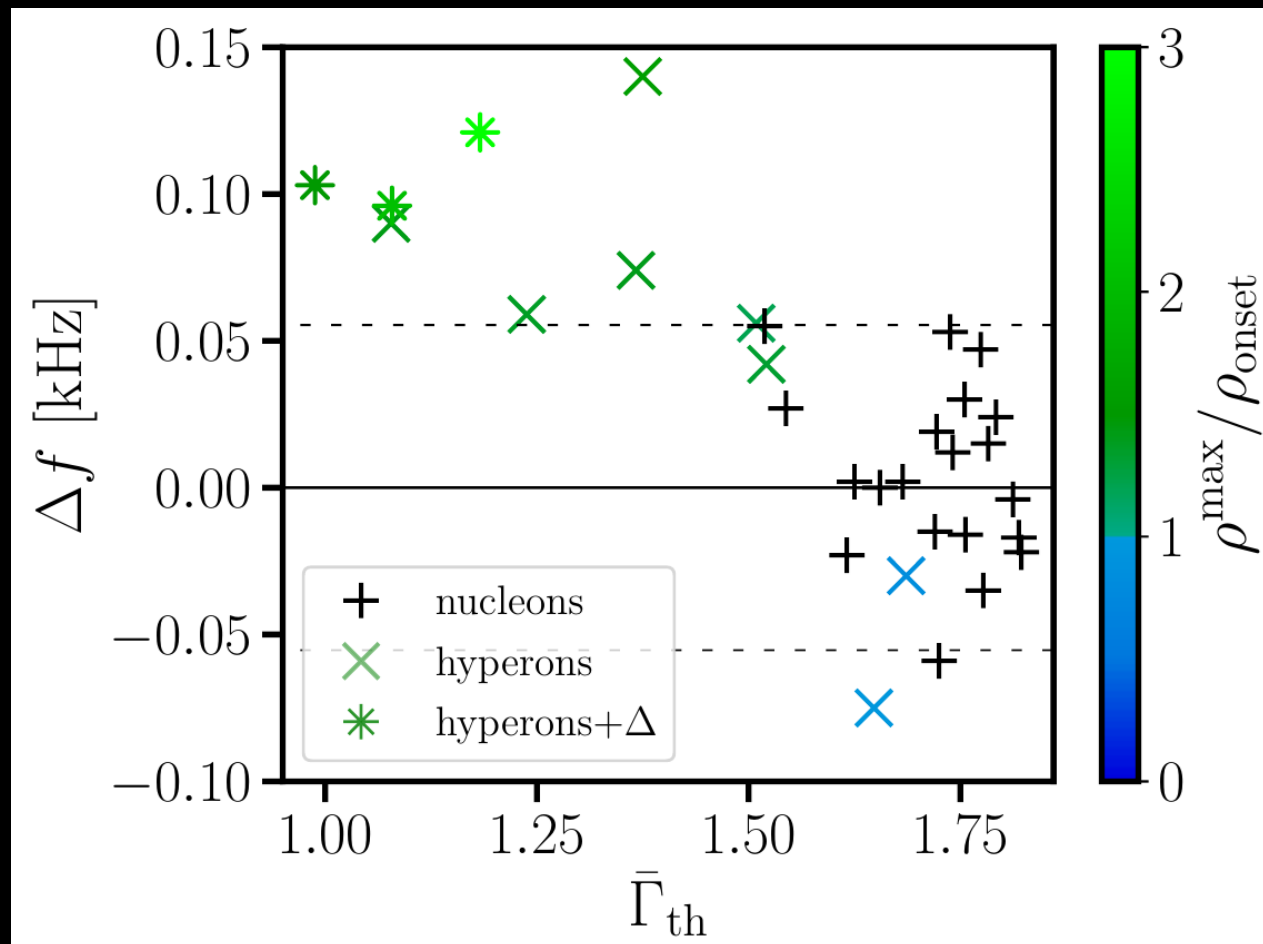
- ▶ Delta f describes impact of hyperons on thermal behavior → in principle measurable !!

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



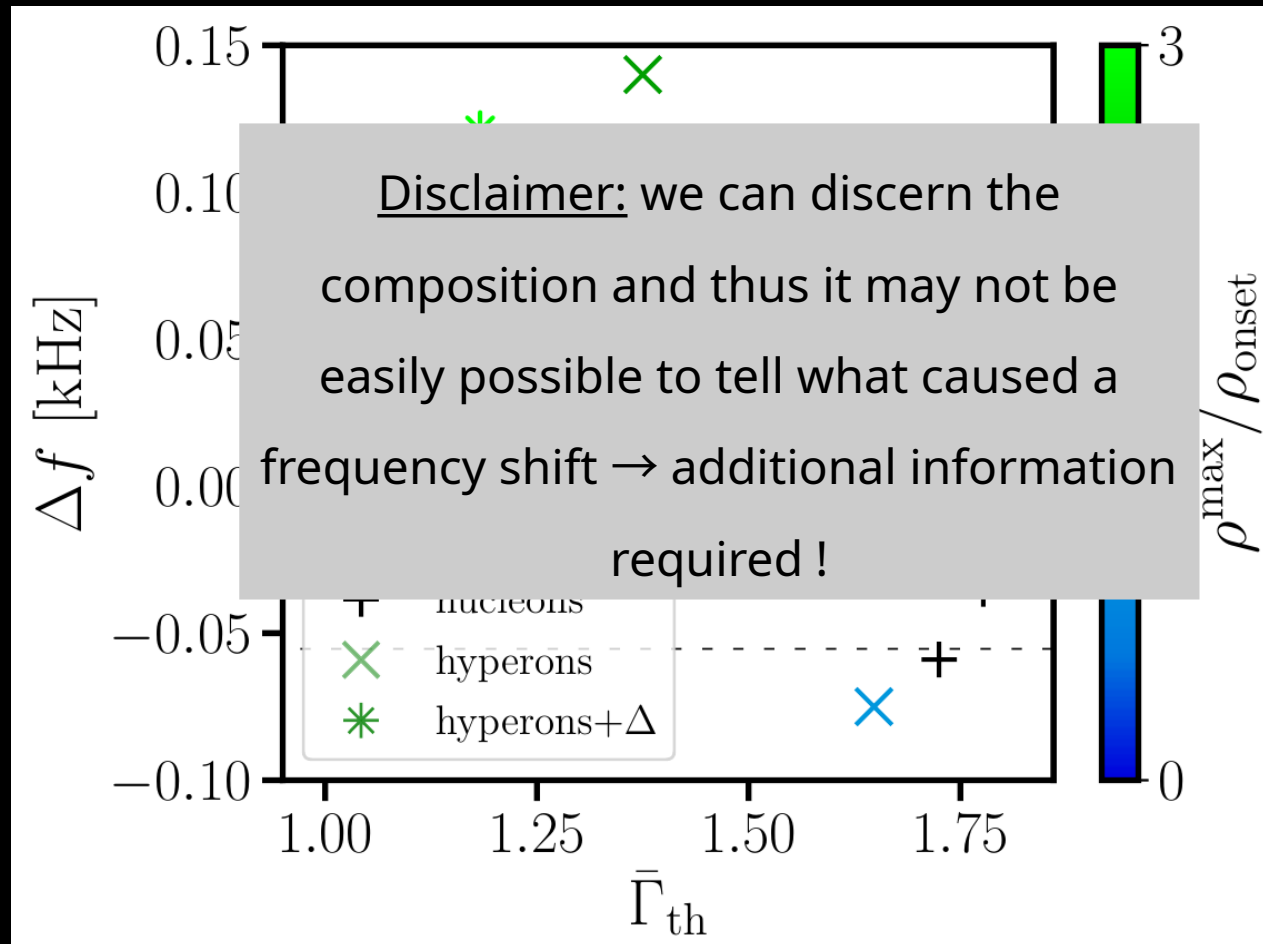
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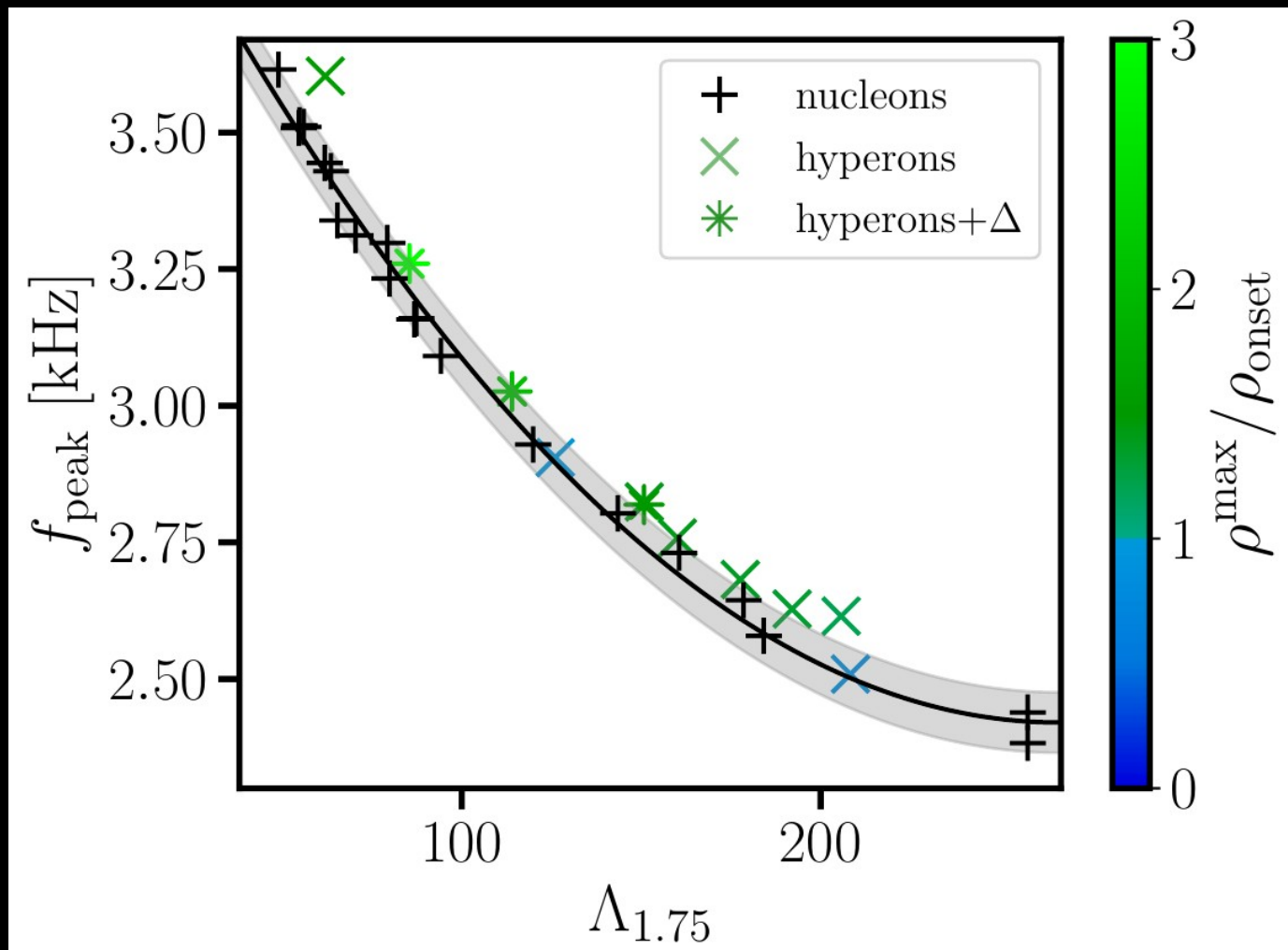


Thermal behavior as indicator for hyperons

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



- Concrete scenario: hyperonic models have tendency to yield increased f_{peak}



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)