Supported by ERC through Starting Grant no. 759253

European Research Council

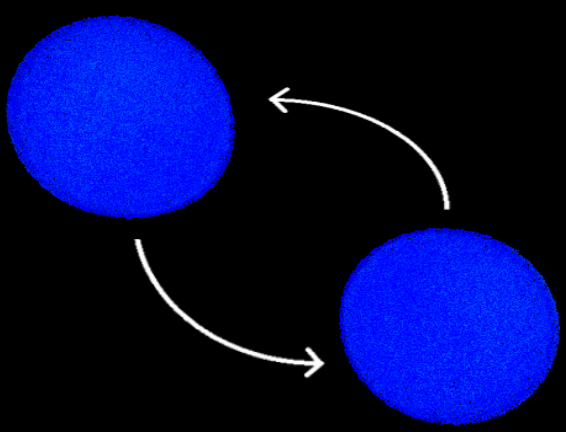
Established by the European Commission

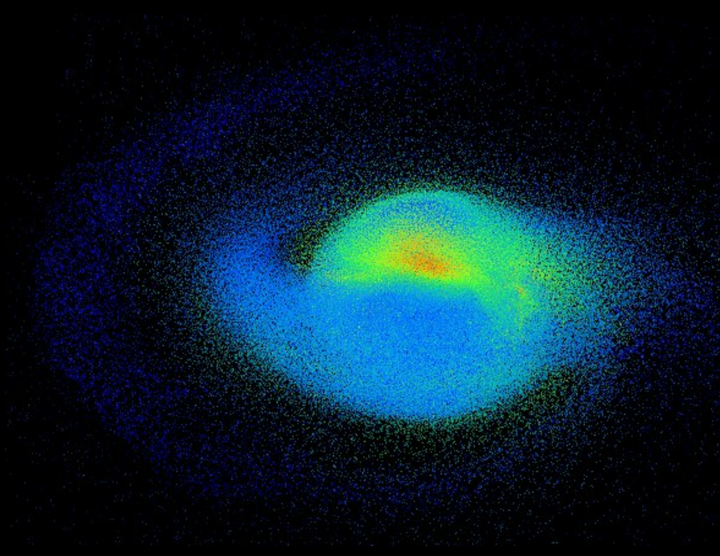
Neutron star mergers: black hole formation, hadron-quark phase transition and gravitational waves

½ EMMI day, GSI, virtual, 02/02/2022

Andreas Bauswein

(GSI Darmstadt, HFHF)





First detection of a NS merger

= gravitational wave event on August 17, 2017

- GW170817 first unambiguously detected NS merger
- Multi-messenger observations: gravitational waves (GWs), gamma, X-rays, UV, optical, IR, radio

Detection August 17, 2017 by LIGO-Virgo network

→ GW data analysis providing approximate sky location

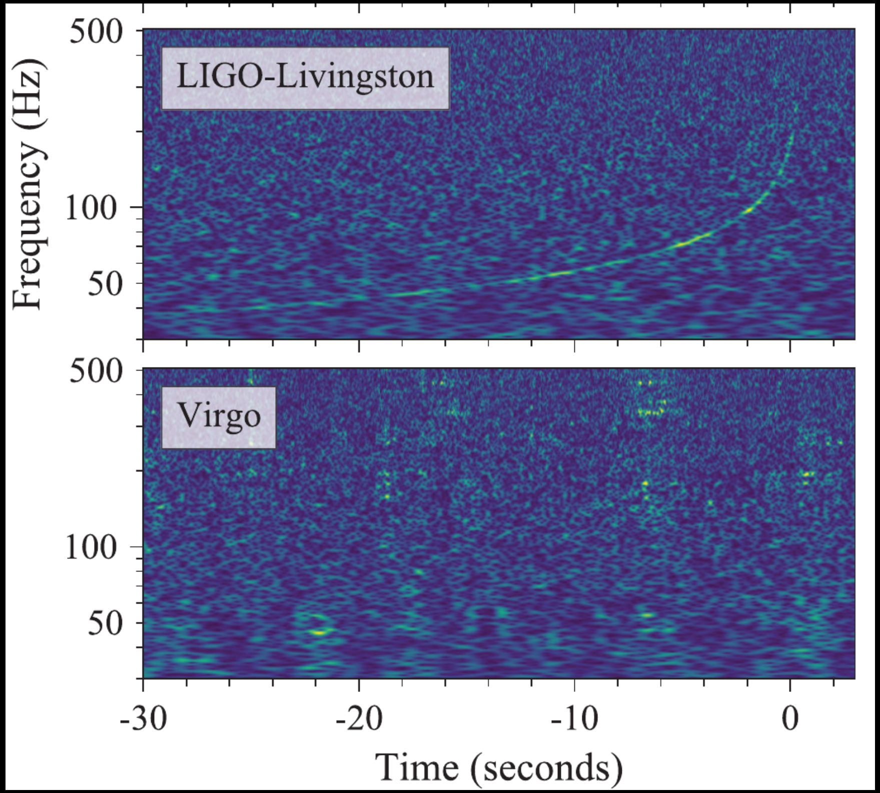
→ follow-up observations - triggered by GW signal providing sky location starting immediately after – in X-rays and radio even years after

→ settled many open/tentative/speculative ideas in the context of NS mergers !!!

- meanwhile a few more mergers with NSs but at larger distance (including NS-BH)

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- ... !!!



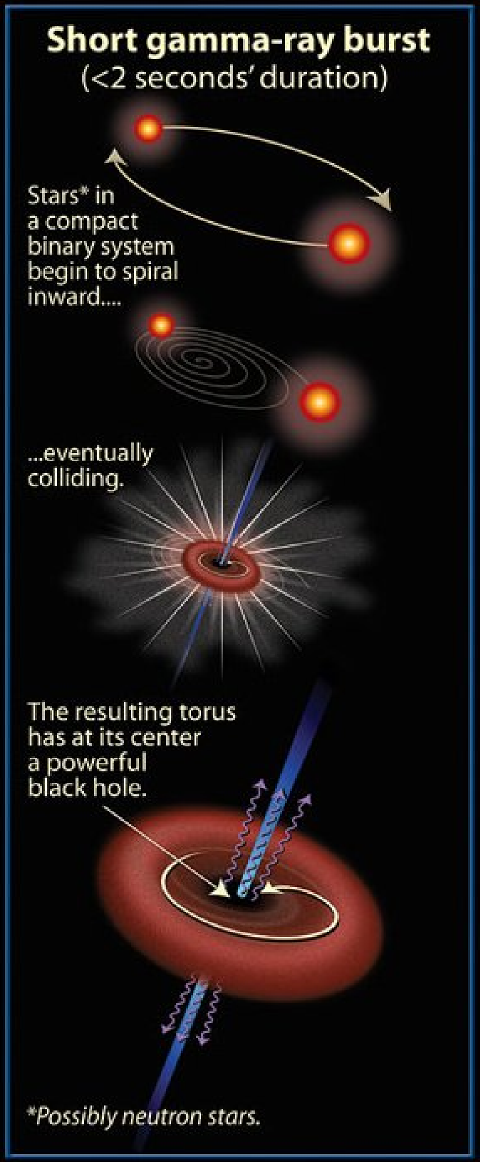
Time-frequency map; Abbott et al 2017

- GWs reveal masses and distances
- Roughly sky location

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

- Intense flashes of gamma-rays with < 2s
- Produced by beamed relativistic outflow (jet)



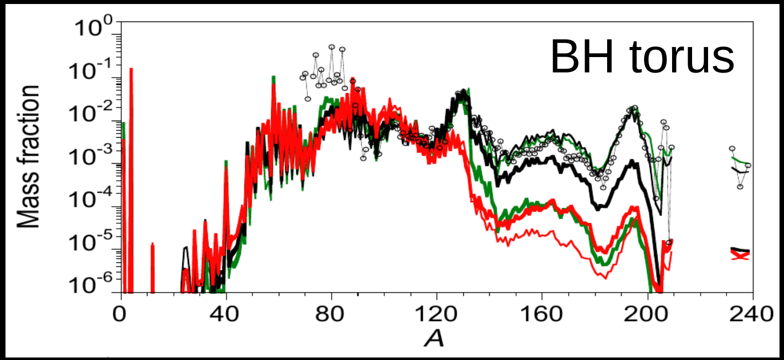
Covino 2007

NS mergers as probes for fundamental physics

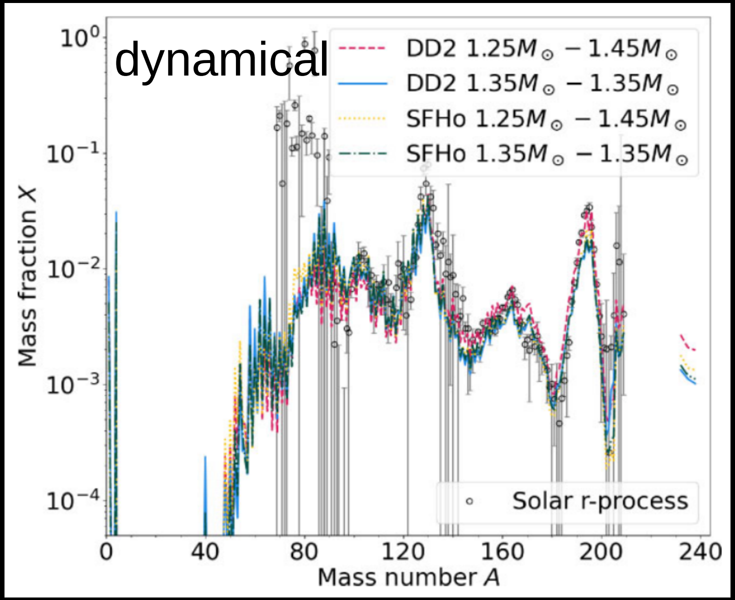
- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- ... !!!

> - First and only confirmed site of rapid neutron-capture process
> - Mej * rate = mergers compatible with dominant source

Just et al. 2022



Kullmann et al. 2022

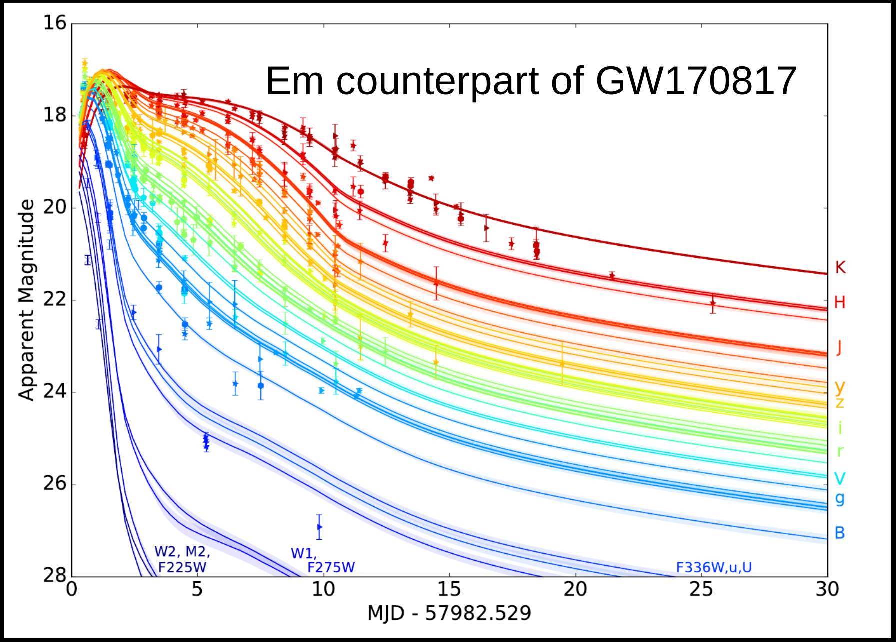


Btw, similar results before 2017

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

Light curve → estimate of ejecta properties
→ compatible with r-process heated outflow



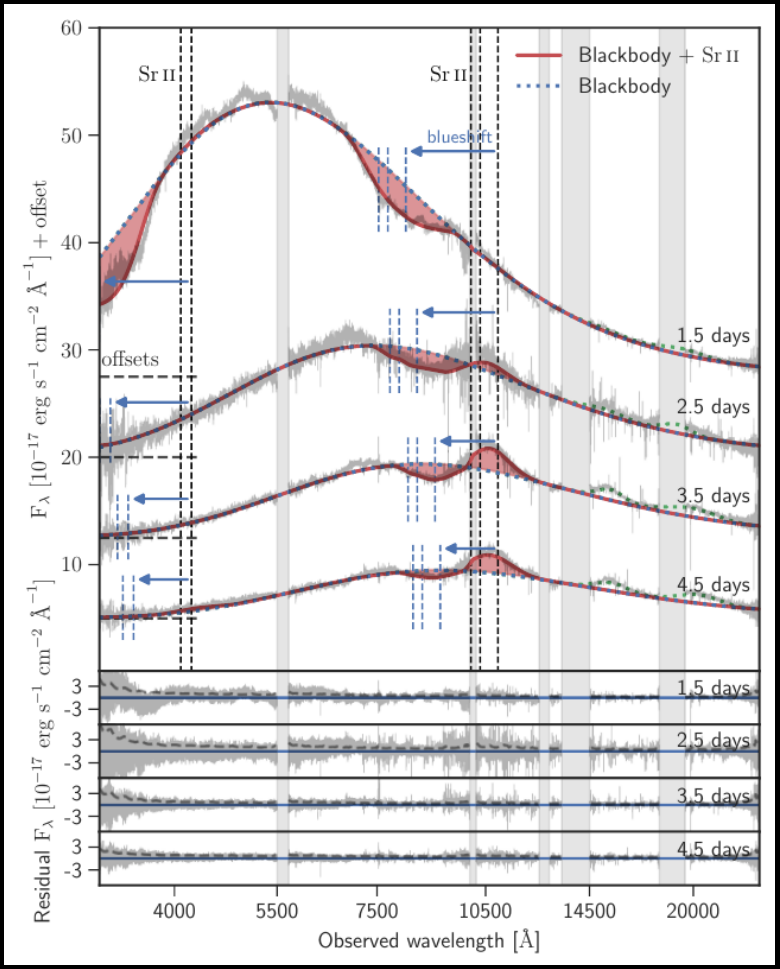
Villar et al. 2017

- Thermal emission in optical/IR
- Targets of "time-domain" astronomy (evolution on time scales of h/d)

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

Spectroscopic idenitifcation of Sr
Watson et al. 2019



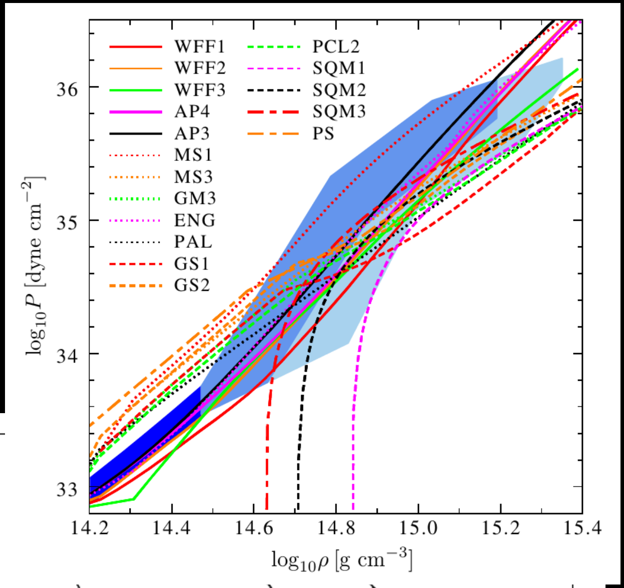
- First and only confirmed site of rapid neutron-capture process
- Mej * rate = mergers compatible with dominant source

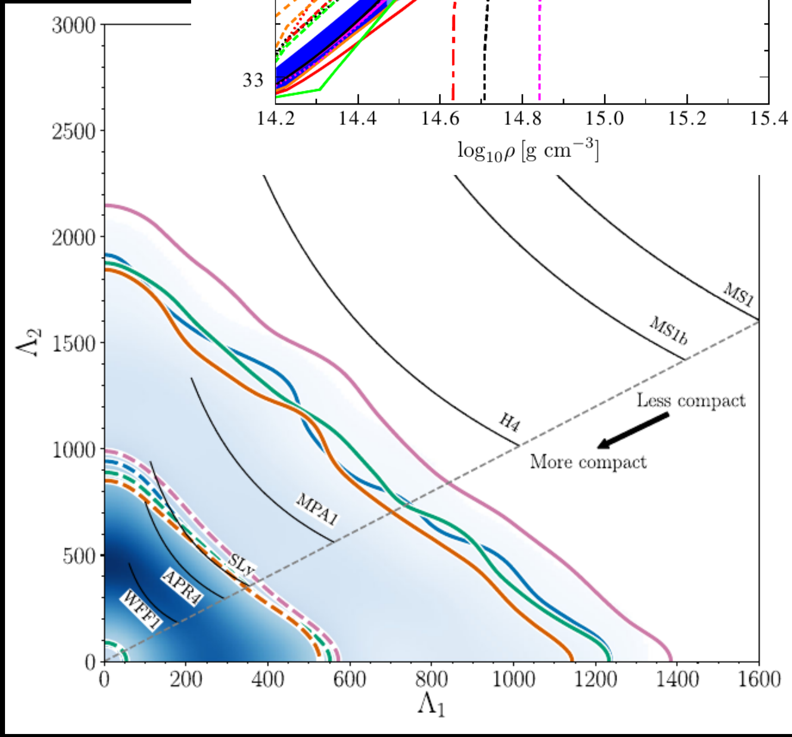
NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

- EoS affects dynamics and thus all observables of merger

Hebeler & Schwenk 2014



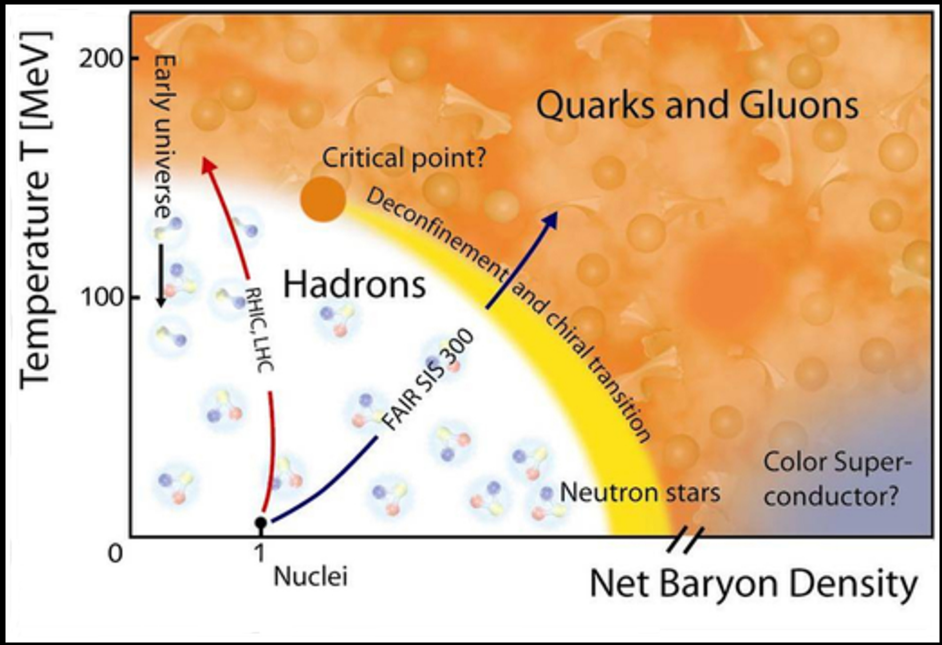


Finite-size effects during late inspiral
→ R < 13.5 km – Abbott et al. 2019

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

> • EoS affects dynamics and thus all observables of merger

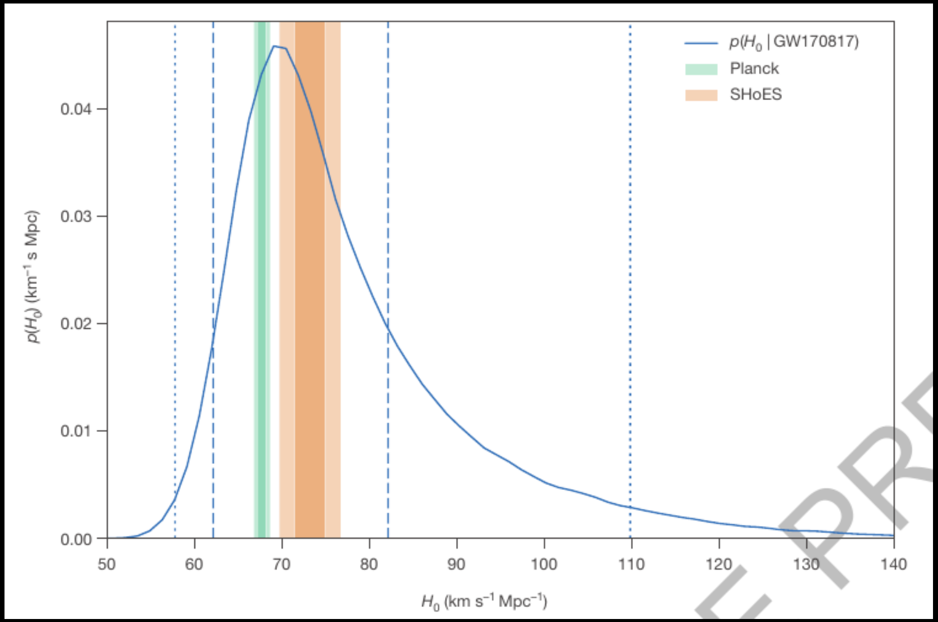


GSI

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

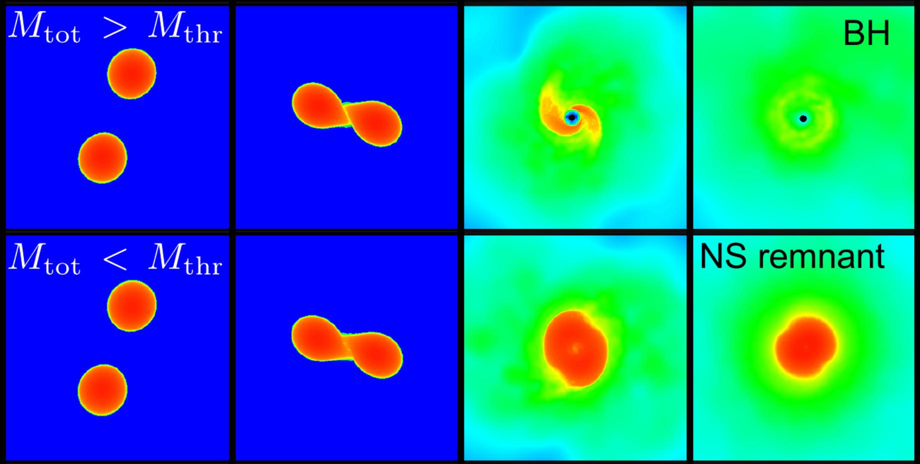
Abbott et al 2017



- Distance from GW amplitude
- Plus redshift from host galaxy → H0

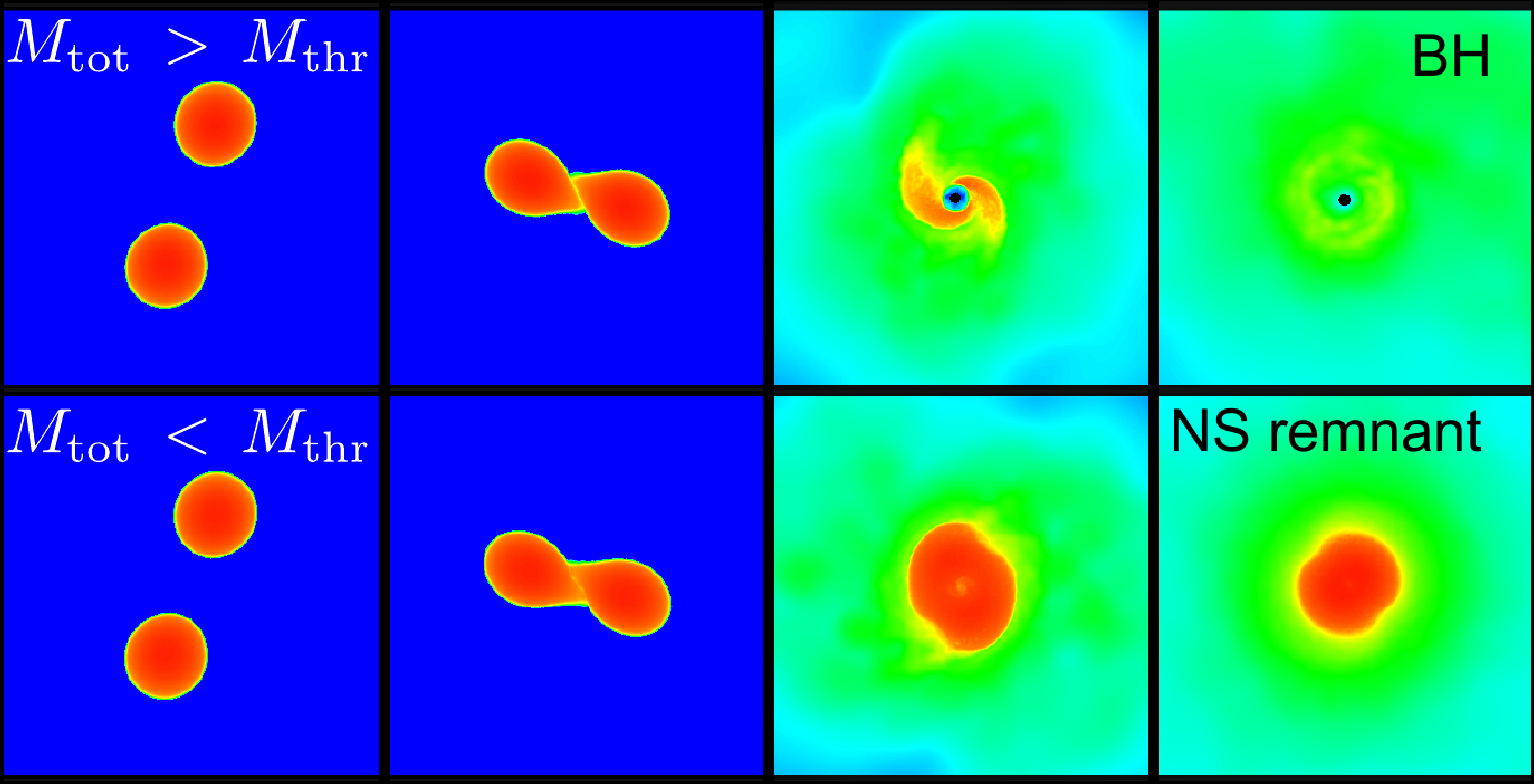
Outline

- Black hole formation in neutron star mergers
- Quark matter in neutron star mergers
- Postmerger gravitational wave emission



- Many interesting and important aspects of NSMs cannot be covered in great detail: GRBs, element formation through rapid neutron capture process, kilonovae, binary population, Hubble constant, ...

Collapse behavior – prompt black hole formation



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, Agathos et al. 2020, Bauswein et al. 2020, 2021]

Collapse behavior - motivation and context

- Merger outcome as most basic feature of a NS merger !

- BH formation leaves strong impact on observables:

  - mass ejection → kilonova properties (dim for prompt collapse)

  - presence of postmerger GW emission from oscillating NS remnant

  - conditions for gamma-ray burst

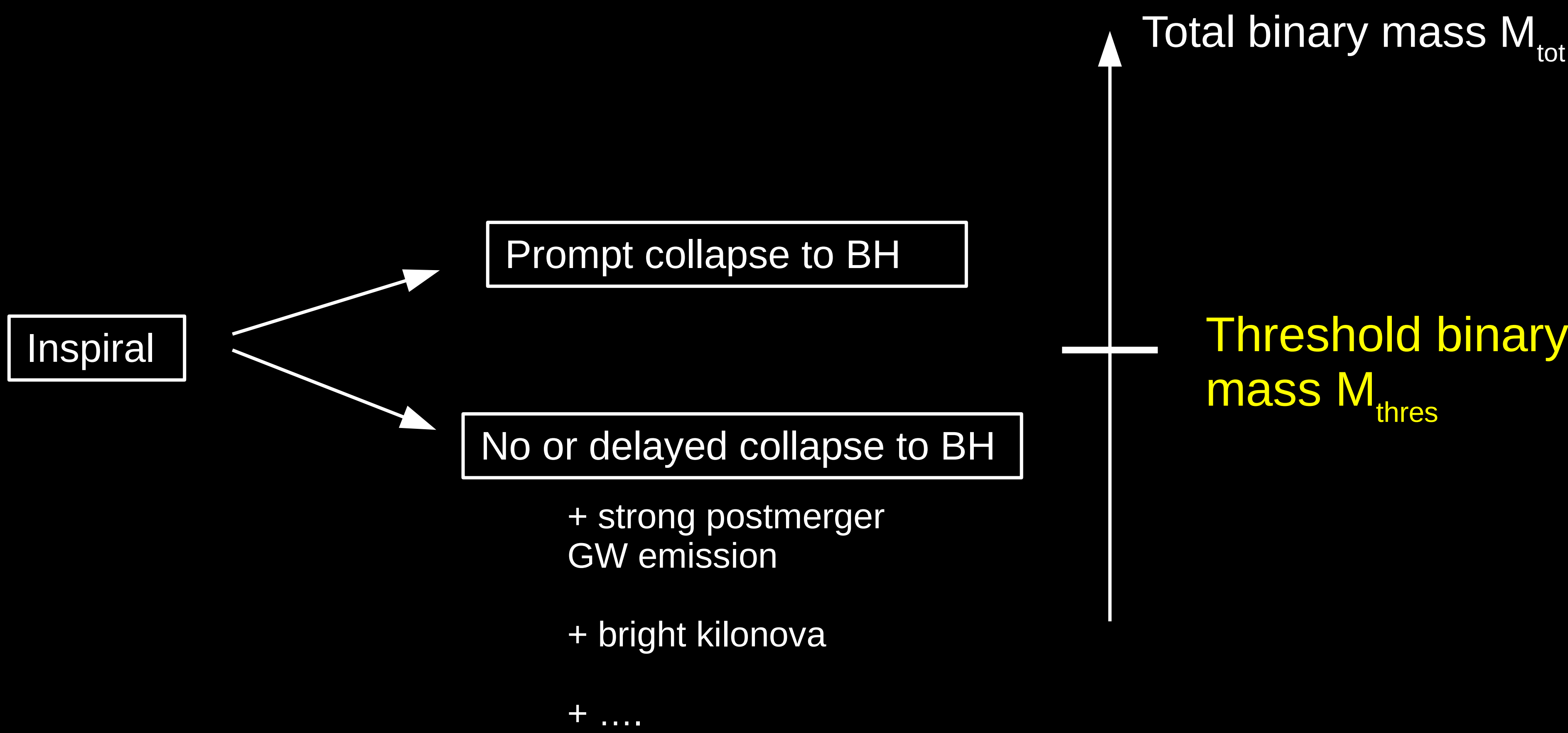
  - ...

  → M_{thres} measurable *

- M_{thres} critical for the interpretation of merger events (e.g. to predict outcome and adapt possible search strategies for em counterparts and postmerger GW)
- Constraints on M_{thres} → EoS of high-density matter (high-density regime)

* Binary masses measurable from GW inspiral

Collapse behavior



M_{thres} - EoS dependent !!!

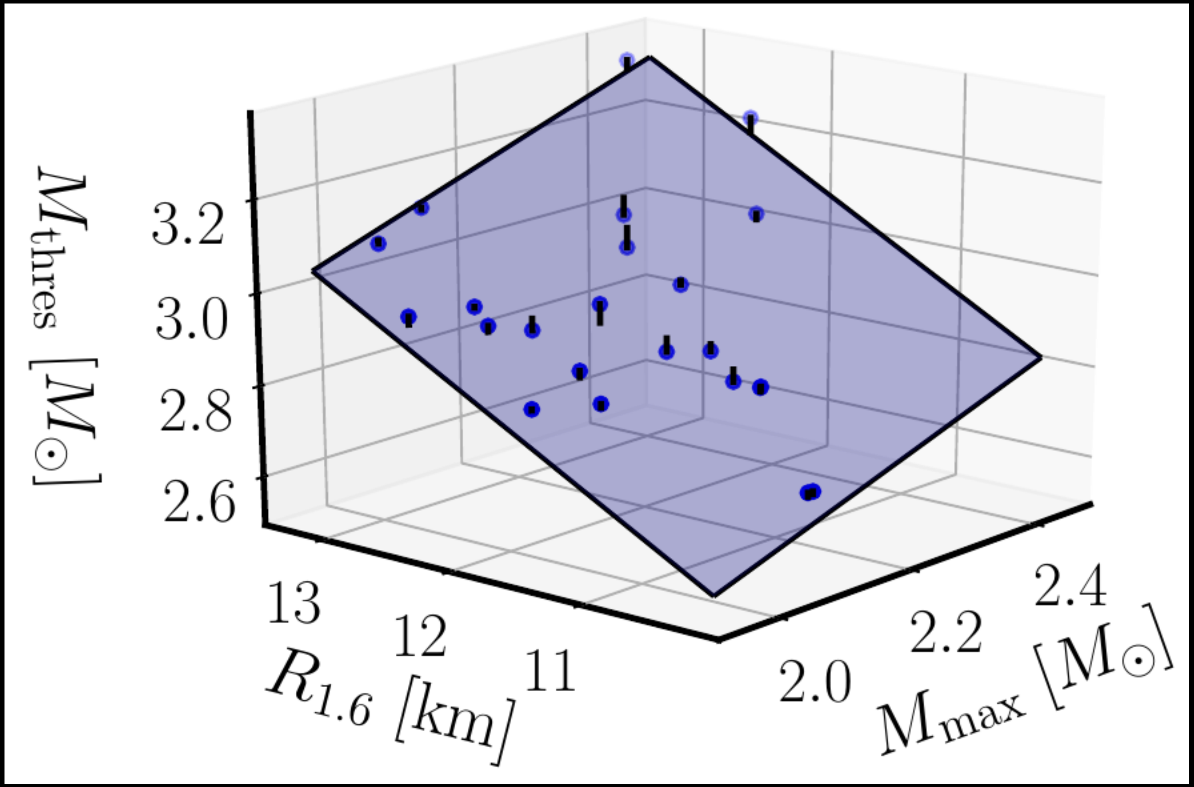
- Essence of ~ 400 relativistic hydrodynamics simualtions
- Relativistic hydrodynamics simulations
- Mostly T-dependent EoSs

EoS	T/B	$M_{\max}$ ($M_\odot$)	$R_{1.6}$ (km)	$\Lambda_{1.4}$	$M_{\rm thres}$ $q=1$ ($M_\odot$)	$\tilde{\Lambda}_{\rm thres}$ $q=1$	$M_{\rm thres}$ $q=0.85$ ($M_\odot$)	$\tilde{\Lambda}_{\rm thres}$ $q=0.85$	$M_{\rm thres}$ $q=0.7$ ($M_\odot$)	$\tilde{\Lambda}_{\rm thres}$ $q=0.7$	sample	Ref.
BHBLP	T	2.100	13.203	696.1	3.125	356.4	3.075	400.9	2.975	516.8	b	[67]
DD2Y	T	2.033	13.182	695.7	3.075	392.2	3.025	440.2	2.875	626.2	b	[68, 69]
DD2	T	2.421	13.258	699.5	3.325	249.7	3.325	255.3	3.275	302.5	b	[70, 71]
DD2F	T	2.079	12.232	426.3	2.925	317.5	2.925	327.4	2.850	430.9	b	[71–73]
APR	B	2.189	11.263	247.5	2.825	233.9	2.862	220.4	2.825	262.1	b	[74]
BSK20	B	2.167	11.658	319.6	2.875	269.5	2.875	276.5	2.875	302.5	b	[75]
eosUU	B	2.191	11.066	229.5	2.825	216.8	2.825	222.3	2.825	242.8	b	[76]
LS220	T	2.043	12.491	541.1	2.975	353.5	2.975	366.7	2.875	523.2	b	[77]
LS375	T	2.711	13.776	957.4	3.575	225.1	3.575	230.4	3.575	250.2	e	[77]
GS2	T	2.091	13.381	722.3	3.175	325.3	3.075	410.8	3.025	491.0	e	[78]
NL3	T	2.789	14.807	1369.4	3.775	230.2	3.812	221.7	3.775	259.7	e	[70, 79]
Sly4	B	2.045	11.533	294.6	2.825	277.4	2.825	285.8	2.775	355.5	b	[81]
SFHO	T	2.058	11.761	333.9	2.875	280.3	2.875	288.2	2.825	355.5	b	[82]
SFHOY	T	1.988	11.758	333.9	2.825	315.0	2.825	323.4	2.725	444.7	b	[68, 69]
SFHX	T	2.129	11.972	395.8	2.975	271.3	2.975	277.0	2.925	330.7	b	[82]
TM1	T	2.212	14.361	1150.8	3.375	337.1	3.325	386.9	3.225	529.1	e	[80, 90]
TMA	T	2.010	13.673	935.3	3.175	400.3	3.125	461.7	2.975	703.6	e	[80, 91]
BSK21	B	2.278	12.552	515.0	3.075	289.2	3.125	266.8	3.075	319.9	b	[75]
GS1	T	2.753	14.877	1402.3	3.775	231.2	3.775	237.7	3.775	262.3	e	[78]
eosAU	B	2.127	10.365	150.9	2.675	201.6	2.712	189.2	2.675	223.7	b	[76]
WFF1	B	2.120	10.370	151.0	2.675	201.6	2.688	199.9	2.675	221.5	b	[76, 87]
WFF2	B	2.188	11.057	223.9	2.825	211.5	2.800	229.5	2.825	236.9	b	[76, 87]
MPA1	B	2.456	12.458	479.1	3.225	203.7	3.225	208.4	3.225	226.1	b	[83, 87]
ALF2	B	1.975	12.628	569.4	2.975	388.2	2.938	428.0	2.875	513.9	b	[84, 87]
H4	B	2.012	13.731	853.2	3.125	407.1	3.025	524.2	2.925	704.9	e	[87, 88]
DD2F-SF-1	T	2.136	12.158	426.3	2.845	383.3	2.845	394.4	2.770	502.0	h	[58, 60–62, 92]
DD2F-SF-2	T	2.162	12.071	426.2	2.925	300.9	2.925	318.4	2.870	402.2	h	[58, 60–62, 92]
DD2F-SF-3	T	2.034	12.205	426.3	2.825	401.9	2.788	451.1	2.720	574.9	h	[58, 60–62, 92]
DD2F-SF-4	T	2.031	12.232	426.3	2.835	392.5	2.797	440.6	2.725	571.2	h	[58, 60–62, 92]
DD2F-SF-5	T	2.040	11.943	426.3	2.815	411.5	2.777	456.8	2.725	543.6	h	[58, 60–62, 92]
DD2F-SF-6	T	2.013	12.231	426.3	2.795	431.4	2.757	483.9	2.675	640.2	h	[58, 60–62, 92]
DD2F-SF-7	T	2.117	12.232	426.3	2.905	332.8	2.868	374.2	2.825	454.6	h	[58, 60–62, 92]
DD2F-SF-8	T	2.026	12.232	426.3	2.915	325.0	2.877	365.6	2.810	471.4	h	[58, 60–62, 92]
VBAG	T	1.932	12.214	422.3	2.885	345.5	2.848	388.4	2.775	505.4	h	[59]
ENG	B	2.238	11.909	370.0	2.975	251.2	2.975	257.6	2.975	281.6	b	[85, 87]
APR3	B	2.365	11.963	367.2	3.075	206.0	3.075	211.0	3.075	229.6	b	[74, 87]
GNH3	B	1.961	13.772	857.8	3.075	436.7	2.975	577.0	2.875	806.1	e	[87, 89]
SAPR	T	2.196	11.474	267.9	2.875	225.5	2.913	213.2	2.875	256.9	b	[86]
SAPRLDP	T	2.247	12.369	449.3	3.025	271.0	3.062	257.4	3.025	309.4	b	[86]
SSkAPR	T	2.028	12.304	442.6	2.950	312.7	2.938	331.6	2.875	420.8	b	[86]

Simulation results

EoS/TOV properties

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



$$M_{\rm thres} = M_{\rm thres}(M_{\rm max}, R_{1.6}) = aM_{\rm max} + bR_{1.6} + c$$

Very clear dependence on stellar properties – several other relations discovered

(Maximum residual 0.04 M_{sun}, on average 0.02 M_{sun} deviation!)

Example: NS radius constraint from GW170817

- If GW170817 did not directly form BH as indicated by relatively bright kilonova
- NSs cannot be too small/ EoS too soft because this resulted in a prompt collapse
- Relatively simple and robust: Quantitatively based on threshold binary mass for prompt collapse

  → better constraints in future, in particular on Mmax

Soares-Santos et al 2017

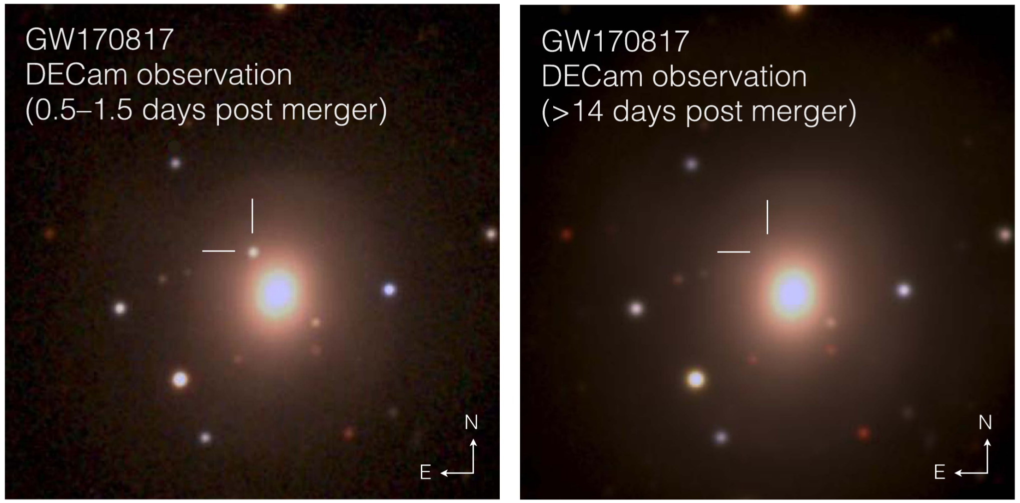
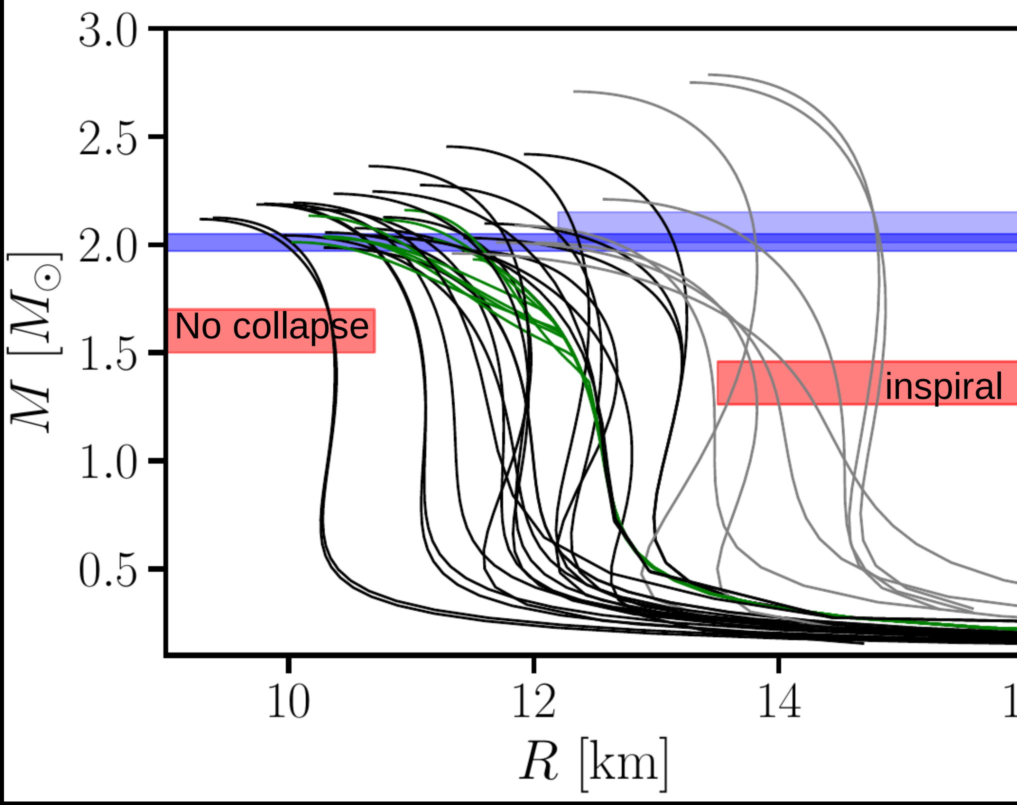


Figure 1. NGC4993 *grz* color composites (1.′5 × 1.′5). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same area two weeks later.

$$L_{\mathrm{bol}} \propto \sqrt{M_{\mathrm{ejecta}}}$$

→ Inferred ejecta mass 0.02-0.05 Msun



Bauswein et al. 2017, 2020

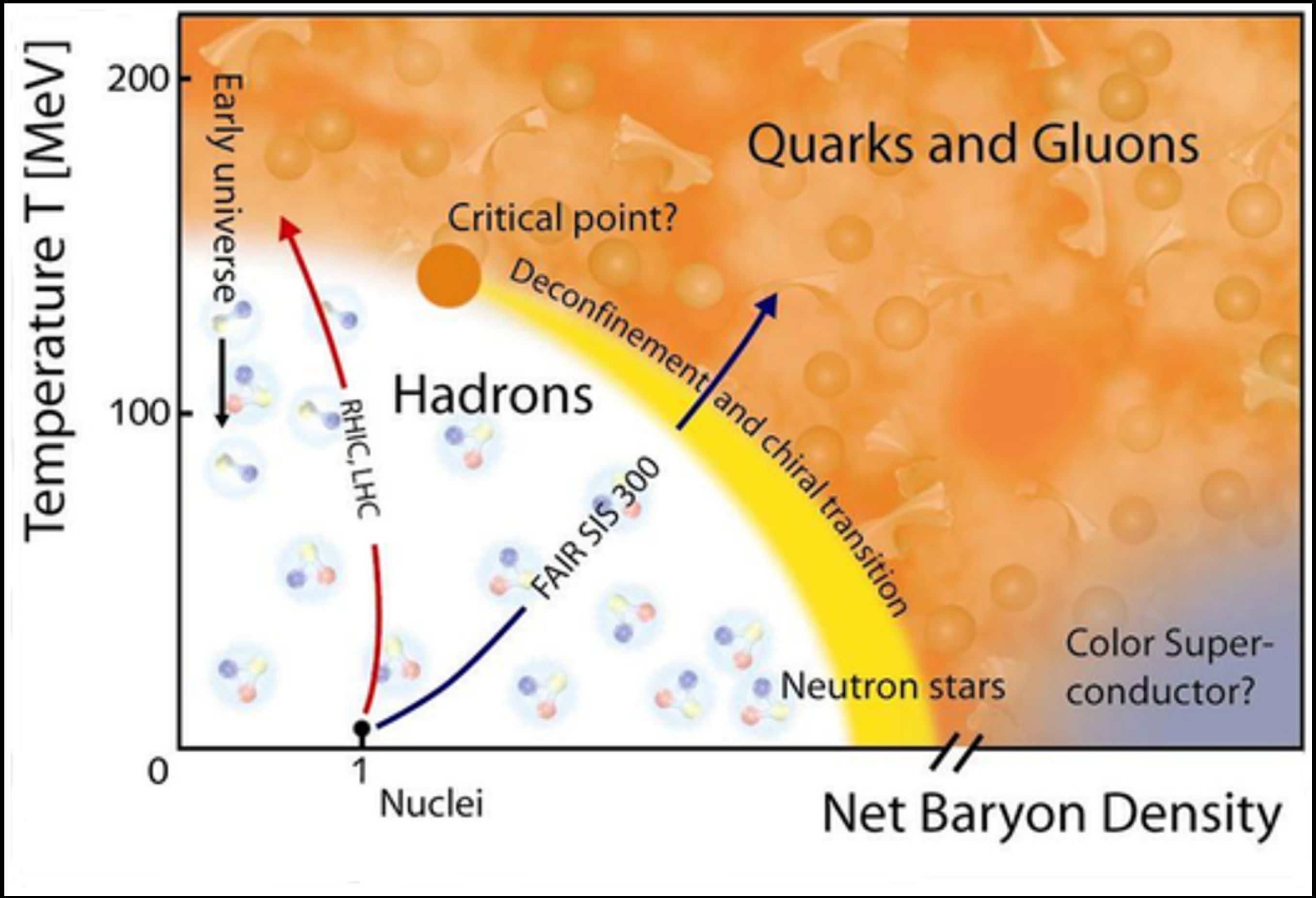
Quark matter in NS mergers ?

→ focus on postmerger phase (not yet detected)

Phase diagram of matter of strongly interacting matter

GSI/FAIR

High T, low μ: experiments and lattice QCD

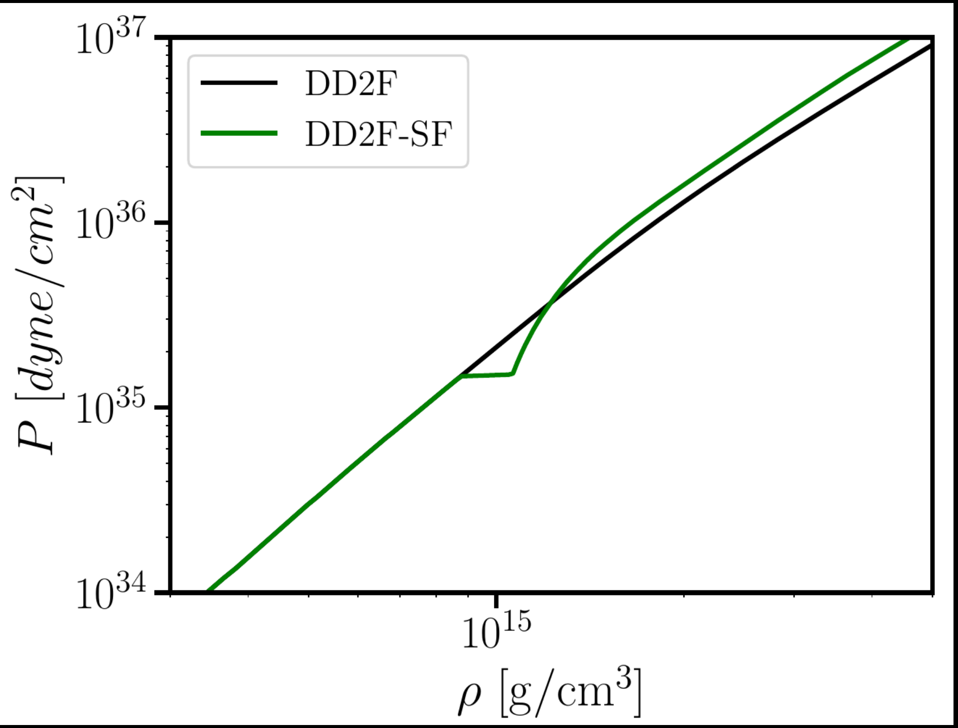


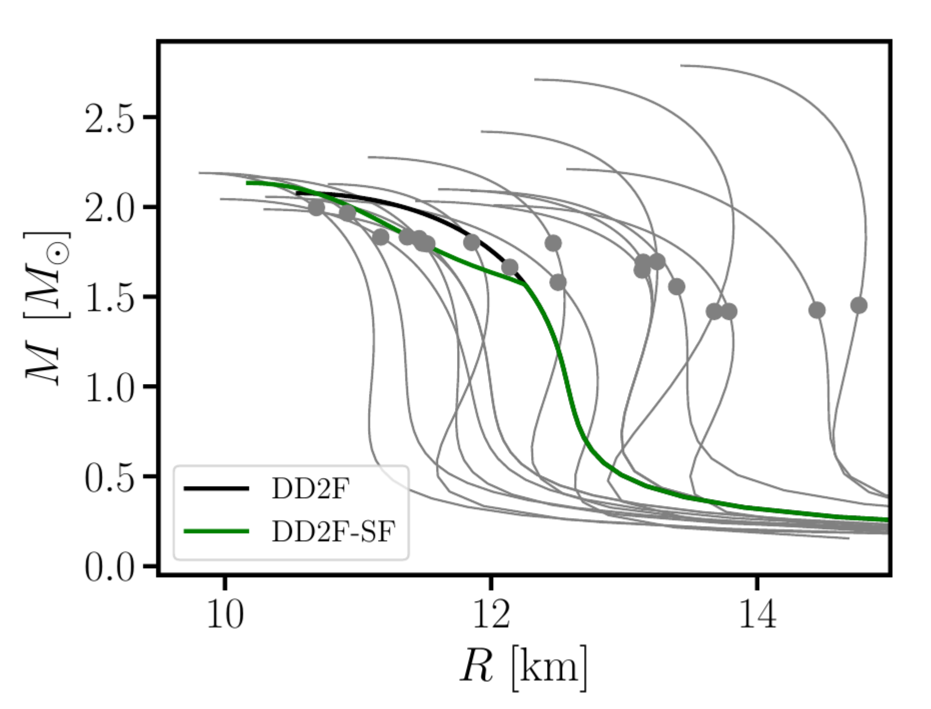
Does the phase transition to quark-gluon plasma occur (already) in neutron stars or only at higher densities?

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

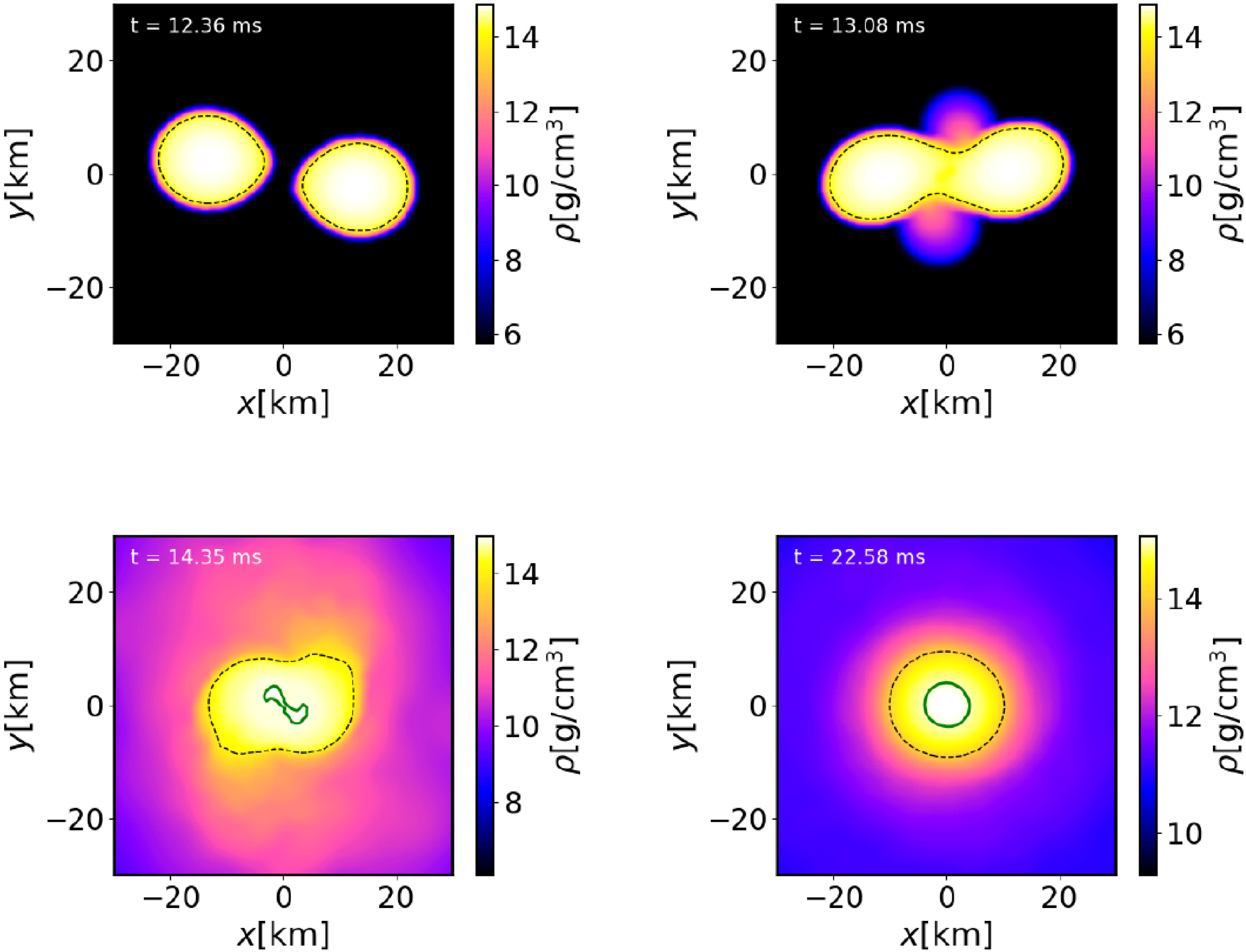
Impact of quark matter on stellar structure

- Phase transition → strong softening of EoS
- Phase transition leads to a characteristic kink in M-R relation !!





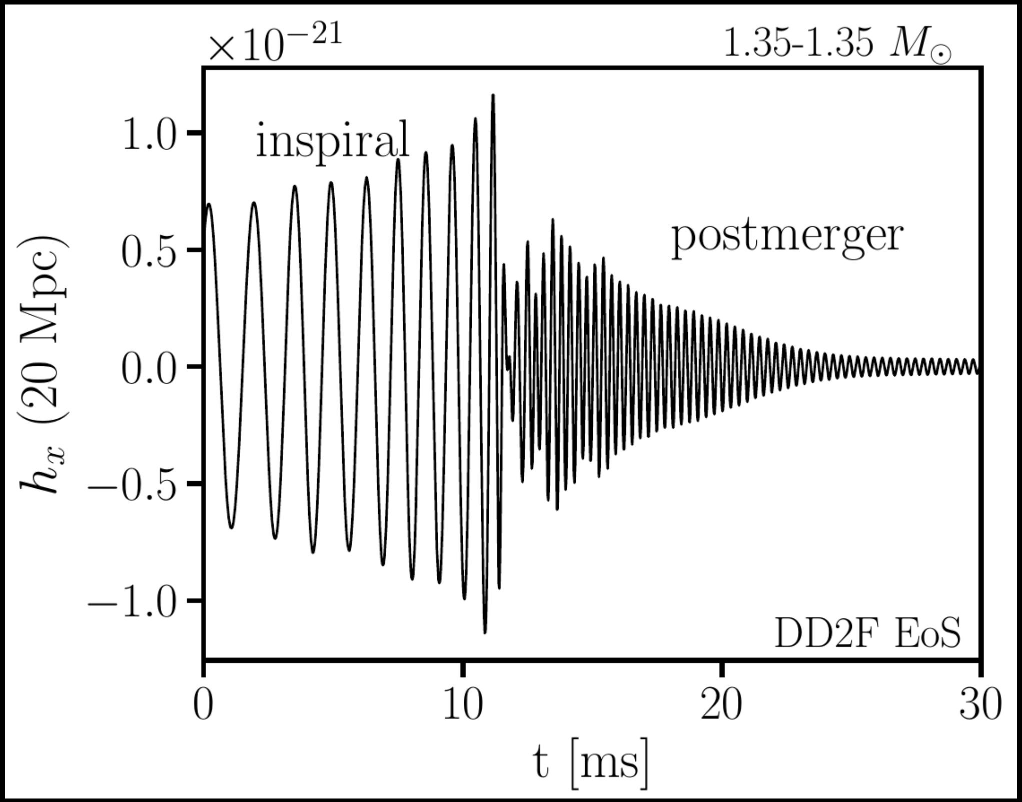
EoSs from Wroclaw group (Fischer et al. 2018, Bastian et al 2018, Bastian 2020)

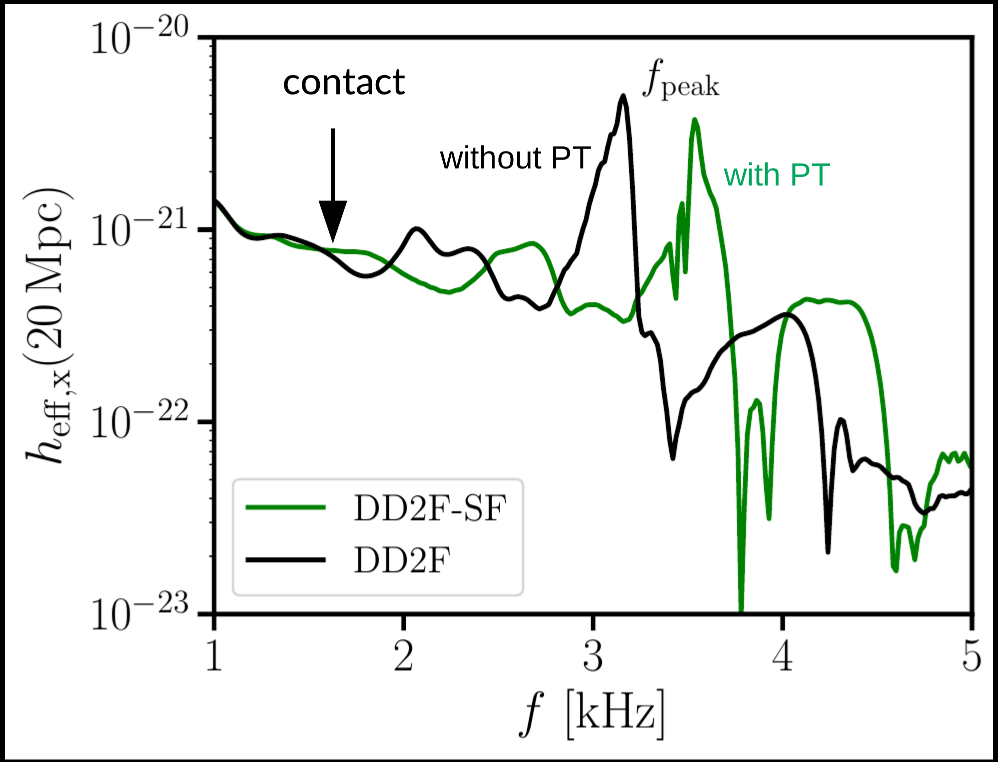


Bauswein et al. 2019

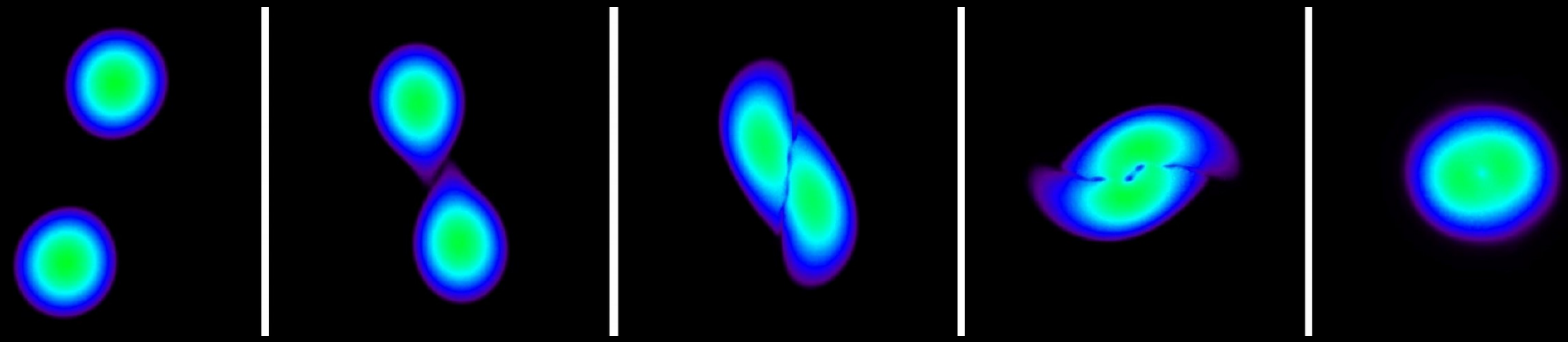
Merger simulations

- GW spectrum 1.35-1.35 Msun



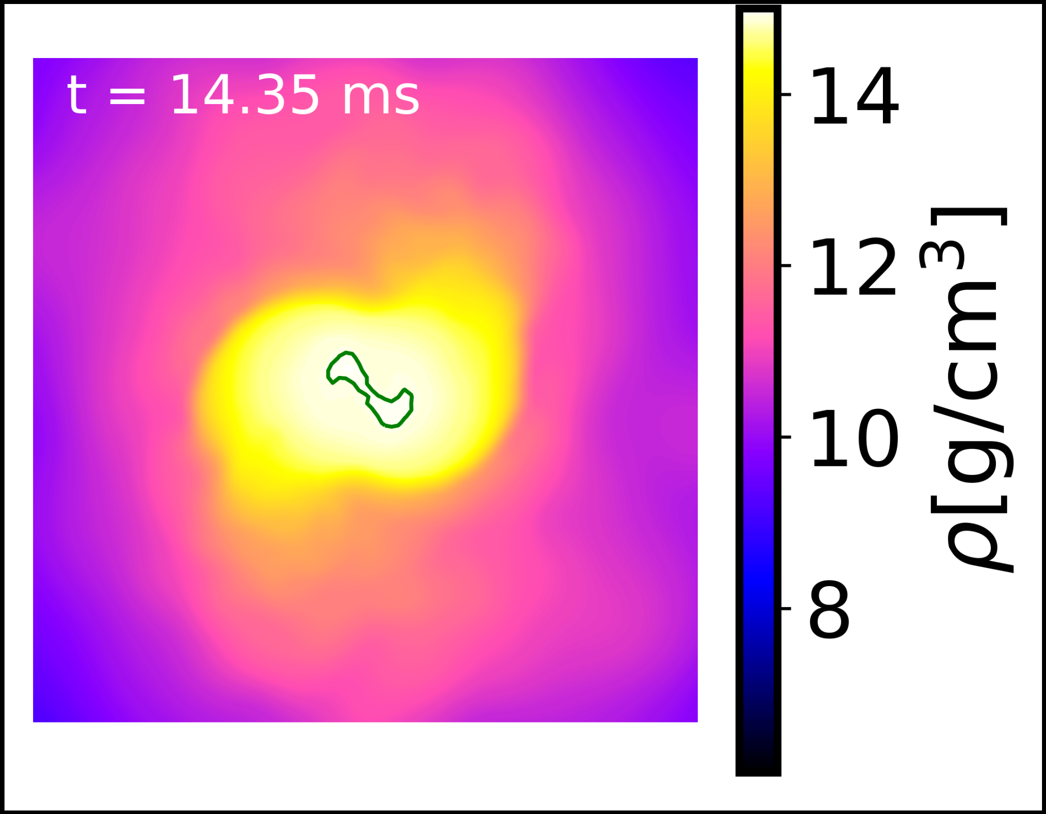


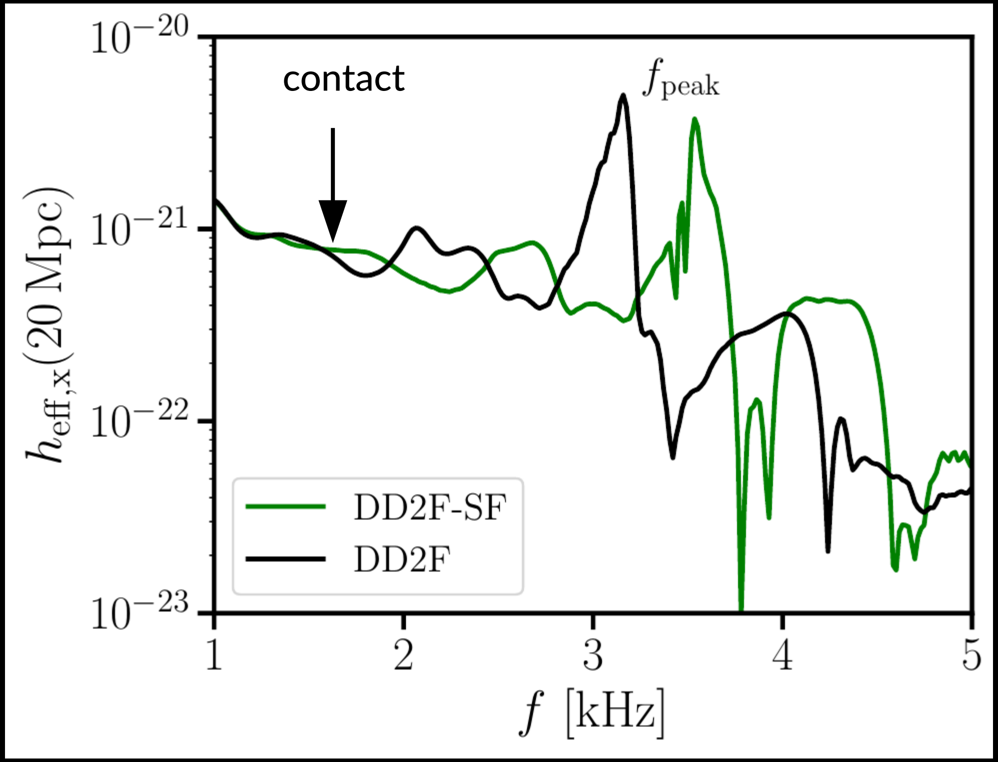
Bauswein et al. 2019



Merger simulations with quark matter core

- GW spectrum 1.35-1.35 Msun



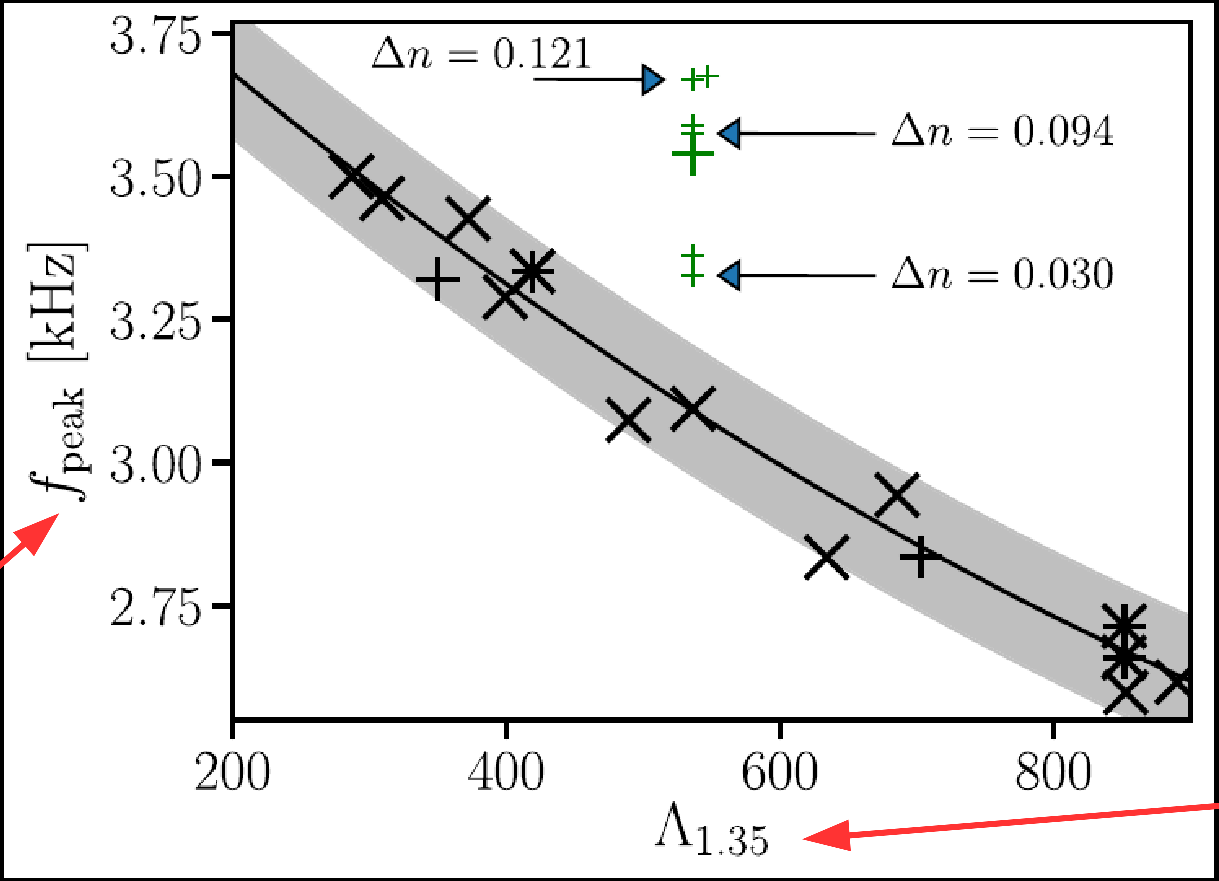


A.B. et al. 2019

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

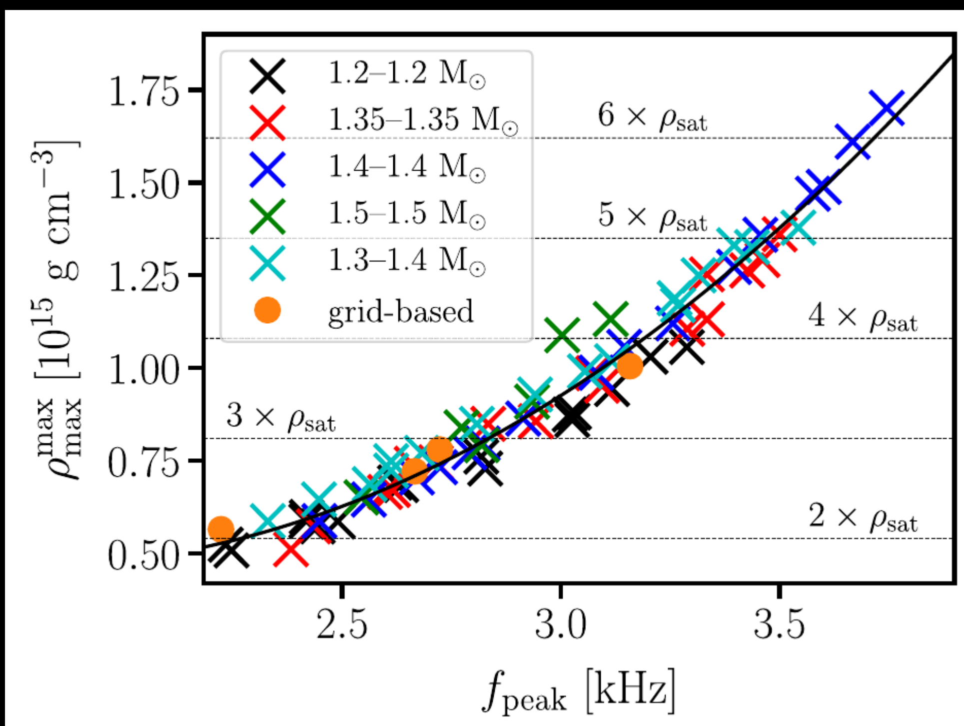
  → evidence of presence of quark matter core

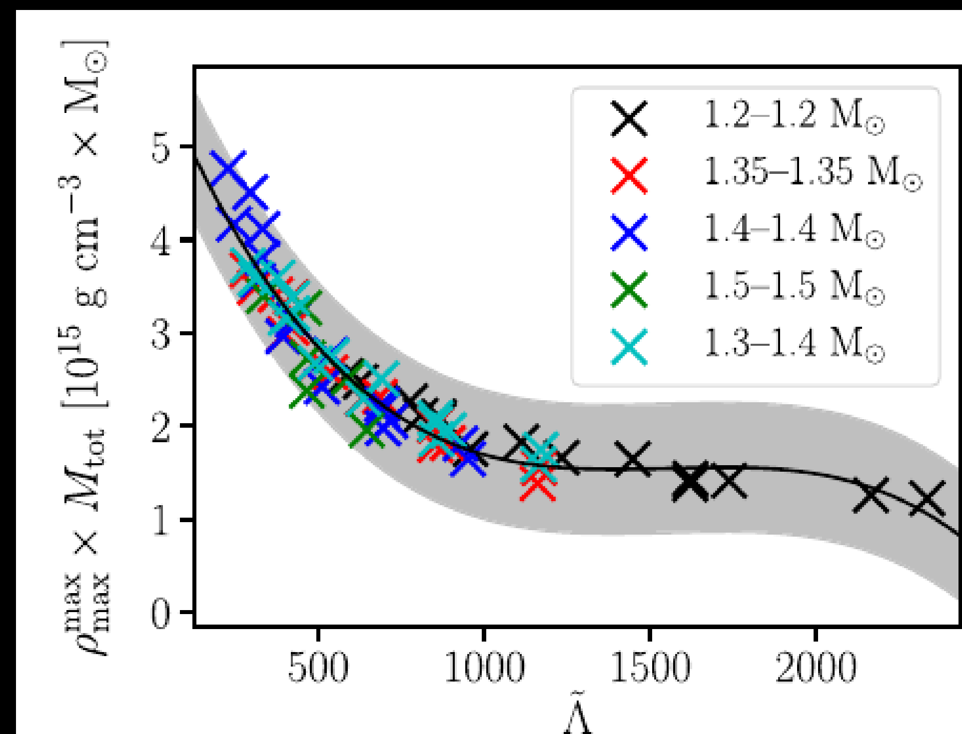
  → in any case constraint on onset density of hadron-quark phase transition

Constraining onset density of hadron-quark phase transition

- Frequency shift can inform about presence of PT
- Universal relations link GW parameters with probed density

  → constrains onset of phase transition



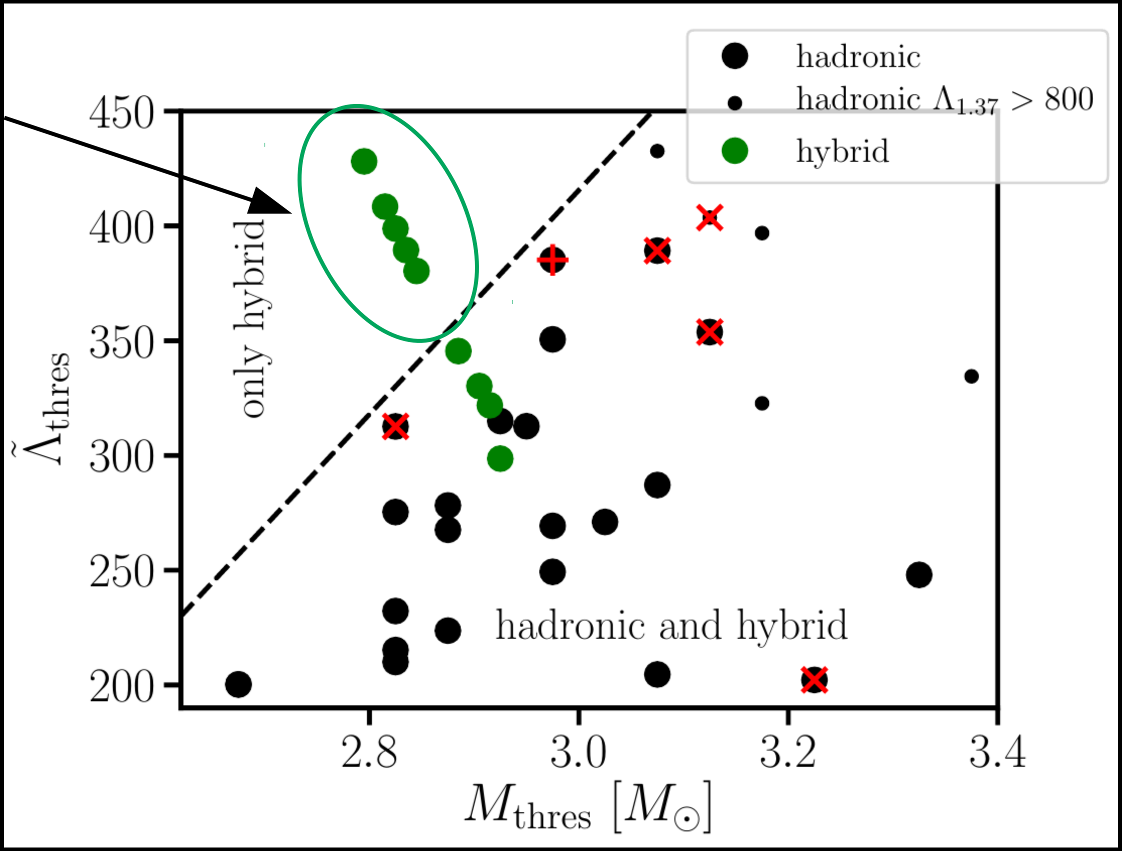


Blacker et al. 2020

QCD phase transition from collapse behavior

- Quark matter may lead to characteristic reduction of M_{thres}
- Already single events may indicate presence of quark matter

Evidence for quark matter



A.B. et al 2020

Measurable from GW inspiral

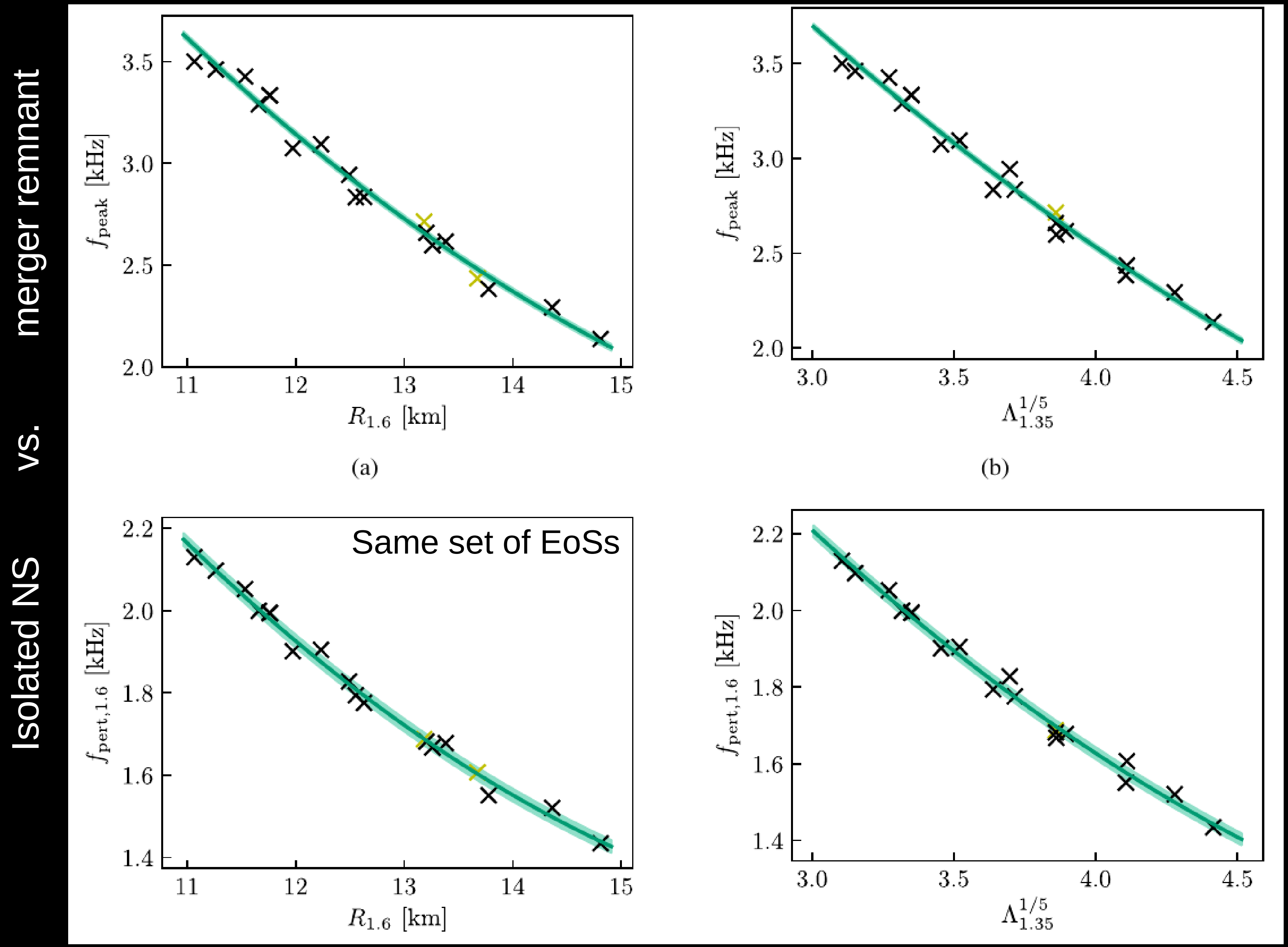
Measurable from inspiral + information on merger product

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

Postmerger GW emission

Frequency deviations – purely hadronic EoSs

- Relations between GW frequency and NS parameter → EoS constraints
- Study f-mode in mergers and NSs (purely hadronic models) – Lioutas et al 2021



Frequency deviations

- Remarkable similarity between oscillations of isolated NSs and merger remnants

  → frequency deviations encode additional EOS information → tidal Love number

  → in principle measurable – break degeneracy between R and Λ

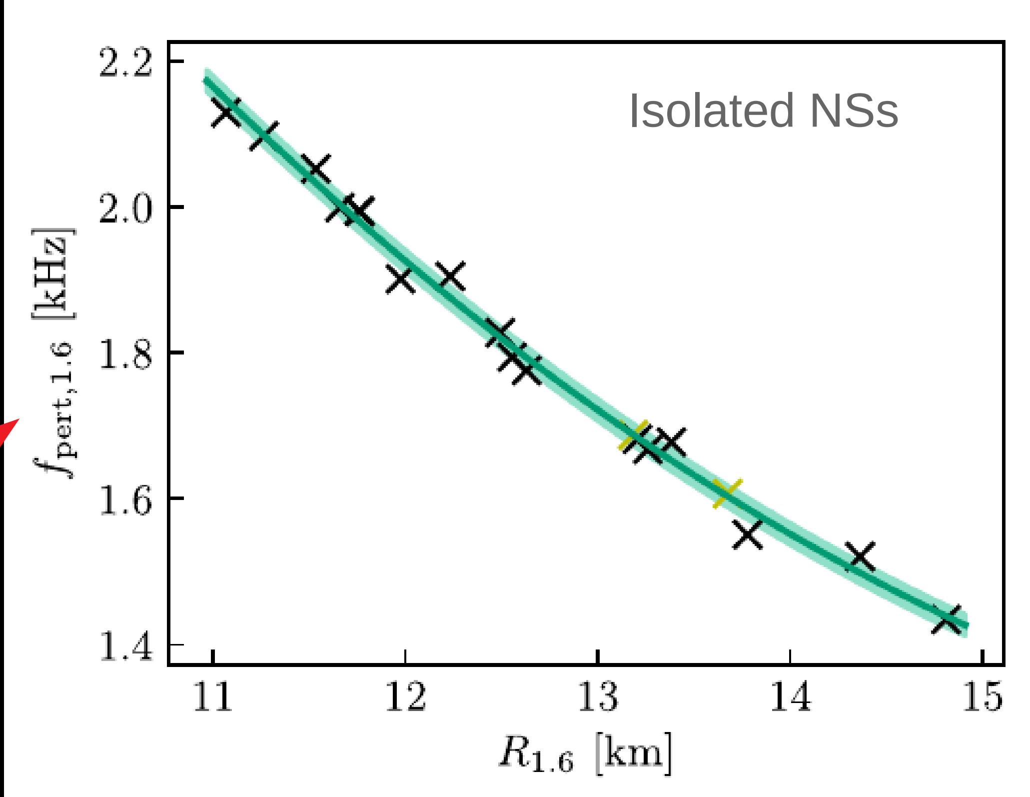
- modeling approach complementary: perturbative vs dynamical calculation

  → reliability of dynamical simulations

  → new way to study oscillations (robust and efficient)

$$\Lambda(M) = \frac{2}{3} k_2(M) \left(\frac{c^2 R}{G\, M} \right)^5$$

Lioutas et al 2021

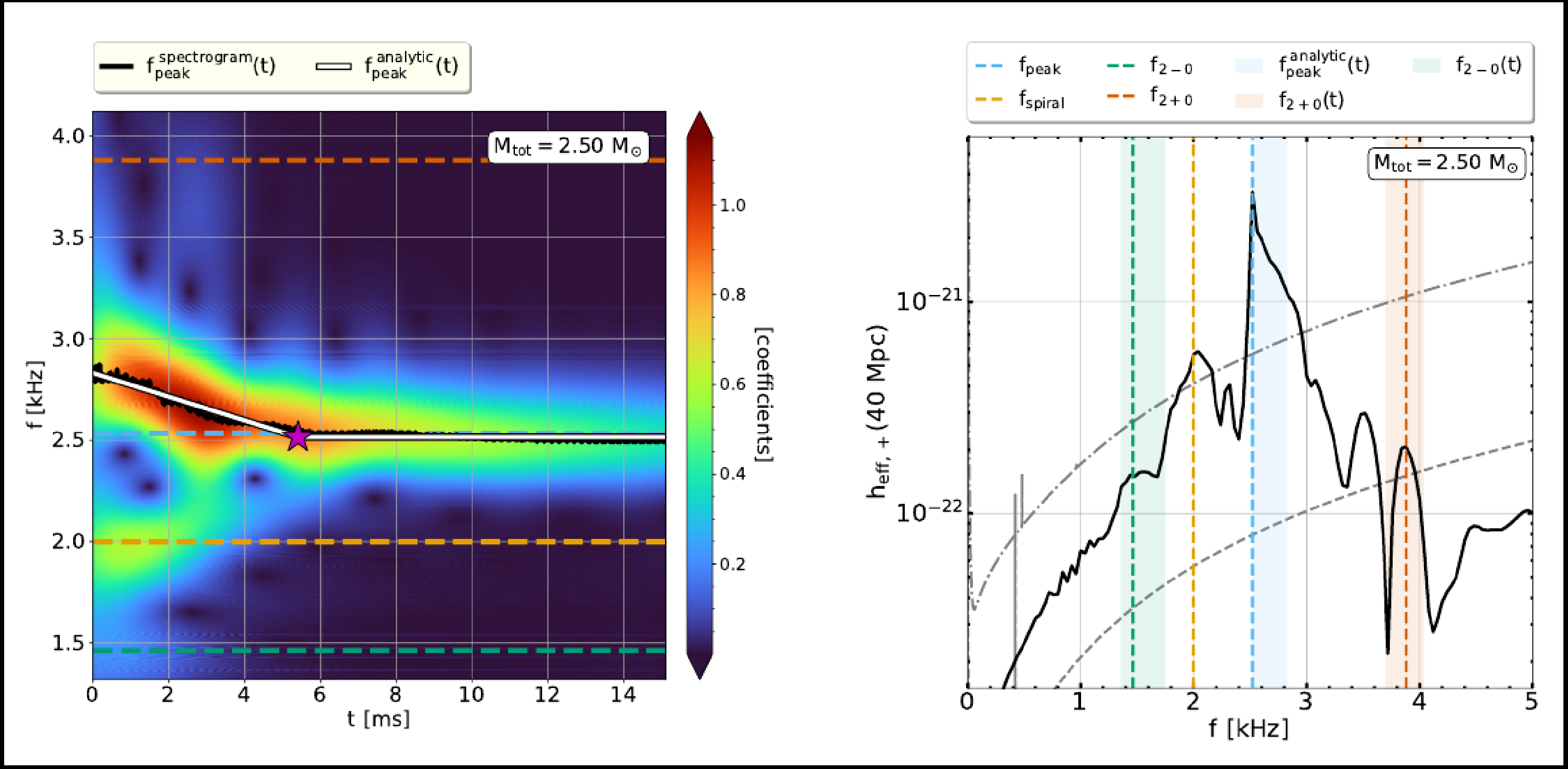


Scales perfectly with Λ, i.e. interchangable

Analytic models of postmerger GW emission

- GW data analysis can be performed with unmodeled searches or using templates
- Templates require analytic models which fit signal very well – otherwise loss of detection rate / incorrect parameter estimation

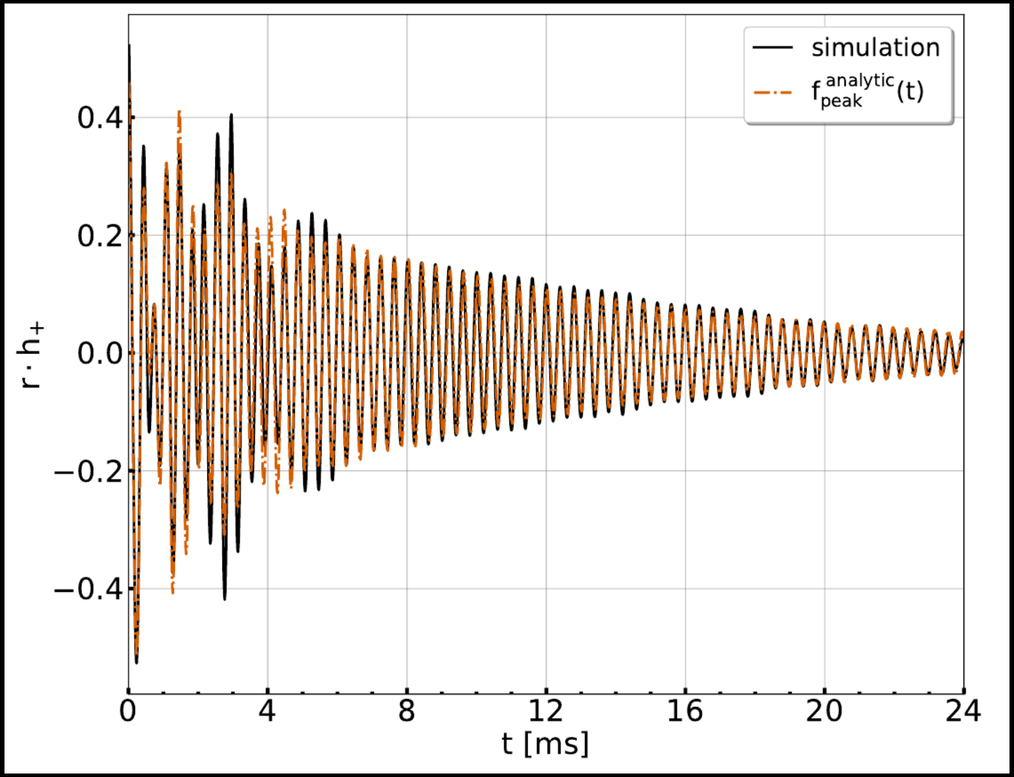
  → model subdominant frequency peaks and frequency evolution of main peak

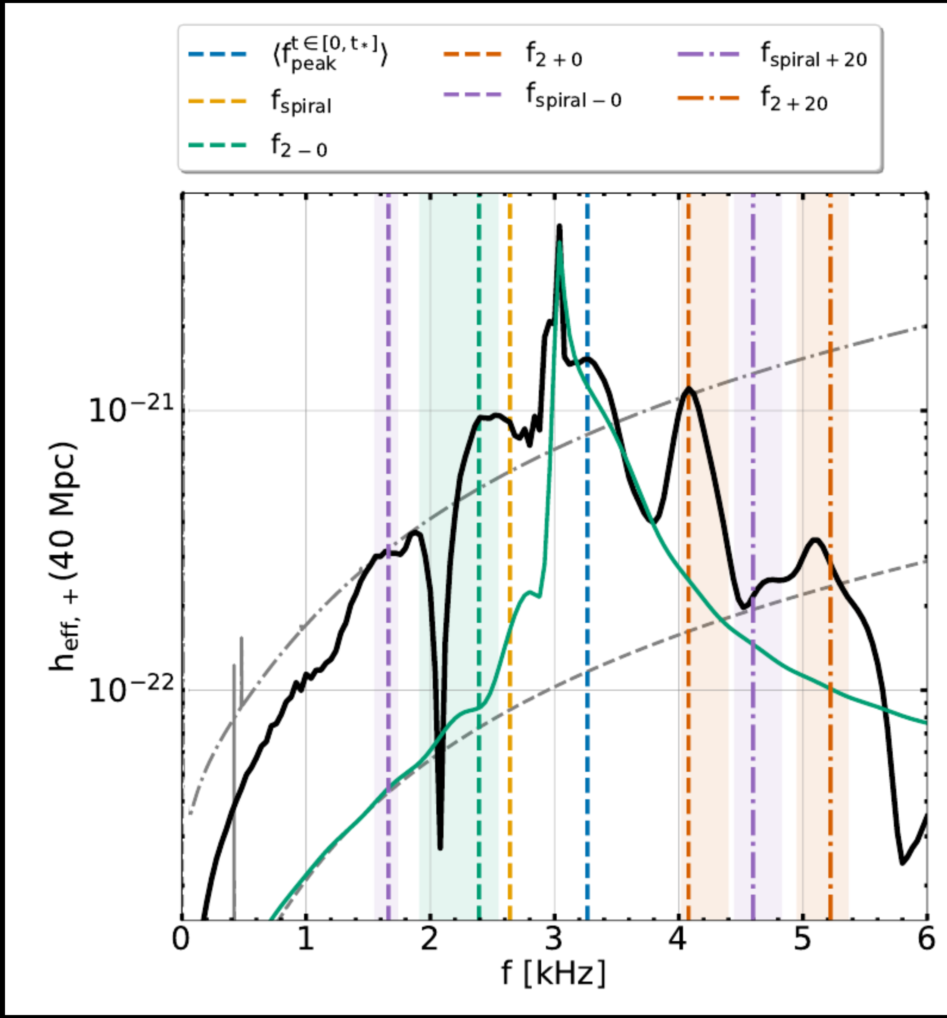


Soultanis et al 2022

Analytic models of postmerger GW emission

- Model achieves very high “fitting factors”, i.e. suitale for GW data analysis
- Analysis reveals and explains additional features of GW spectrum





Soultanis et al 2022

Summary

- Mergers linked with different aspects of fundamental physics
- Black hole formation important characteristic that affects observables

  → EoS / NS constraints: EoS not too soft + future measurements
- Frequency deviations in universal relations follow systematic behavior

  → encodes detailed EoS information
- Postmerger GW emission → EoS constraint

  → phase transition yields characteristic frequency shift

  → constraint on onset density of hadron-quark pahse transition
- Analytic model to describe postmerger GW signal
- GW spectra with many subdominat features

  → understanding important for modeling to increase match

  → additional EoS constraints
- Many new and better facilities will become operational for better and more data !!
- ...

Deadline for abstract submission:

February 15th !!!!

webpage:

https://indico.gsi.de/event/13960/