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GSI

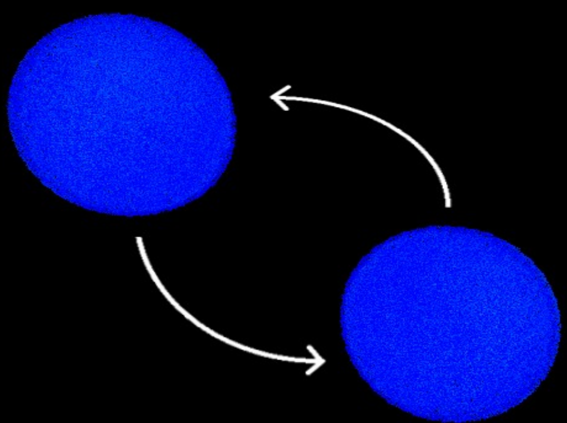
Systematics of prompt black-hole formation in neutron star mergers

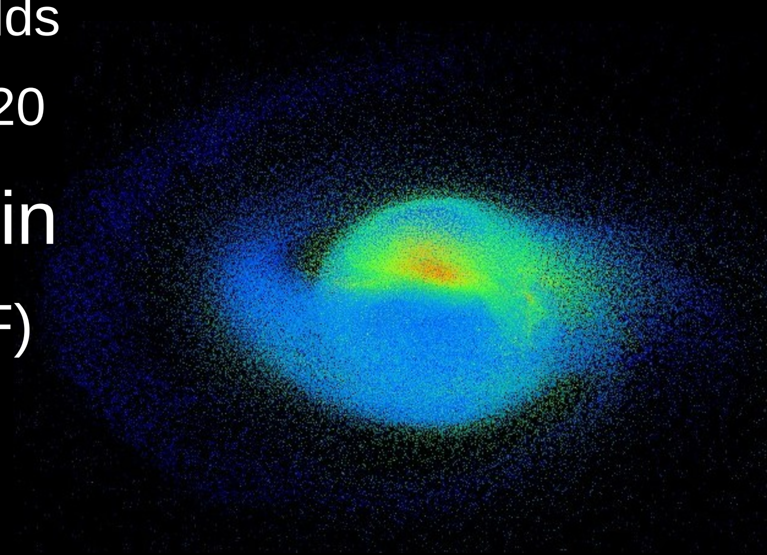
Mathematical and Computational Approaches for the Einstein Field Equations with Matter Fields

ICERM, virtual, 29/10/2020

Andreas Bauswein

(GSI Darmstadt, HFHF)





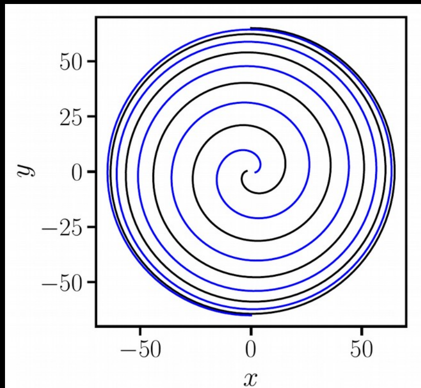
with N. Bastian, S. Blacker, D. B. Blaschke, K. Chatziioannou, M. Cierniak, J. A. Clark, T. Fischer, G. Lioutas, T. Soultanis, N. Stergioulas, V. Vijayan

Outline

- Overview and motivation
- Collapse behavior and simulations
- EoS dependence of threshold binary mass

  → constraints on EoS/NS parameters
- Impact of binary mass ratio
- QCD phase transition in NS mergers

  → signature in collapse behavior
- Summary and conclusions



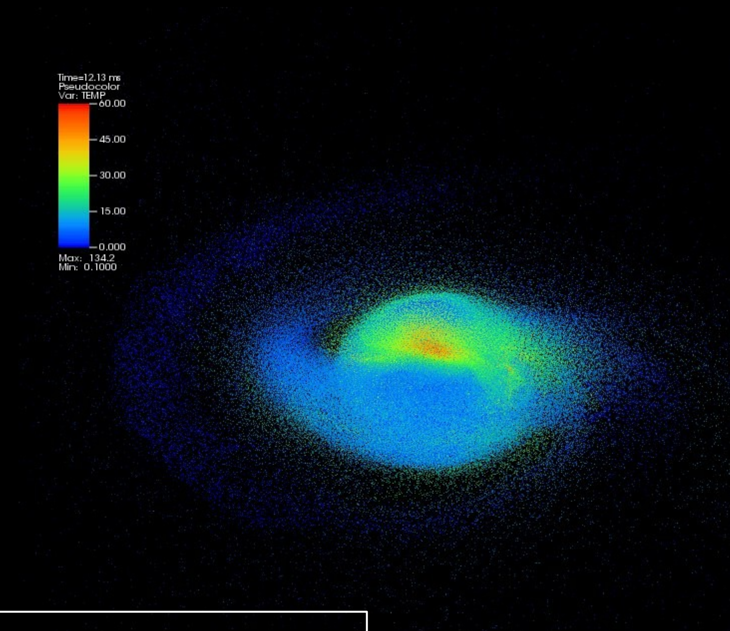
$P_{orb} \sim 10\,h$

Inspiral of NS binary

~100 Myrs

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

Neutron star merger



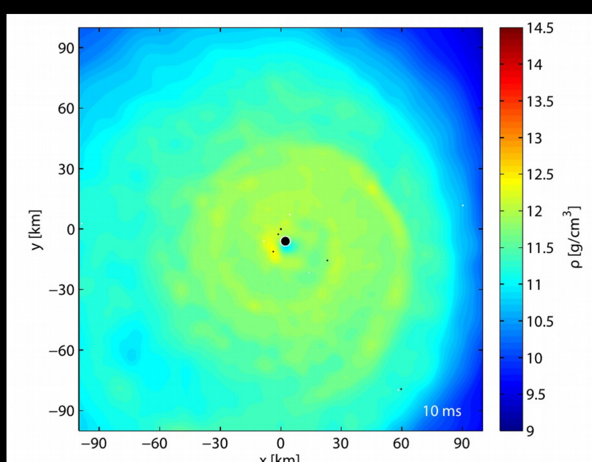
dependent on
EoS, M_{tot}

ms

ms

Prompt formation of a BH + torus

Formation of a differentially rotating massive NS

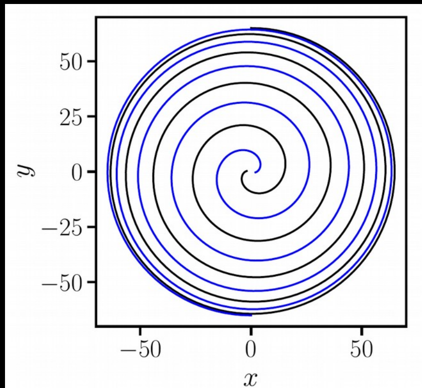


dependent on
EoS, M_{tot}

10-100 ms

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

Delayed collapse to a BH + torus



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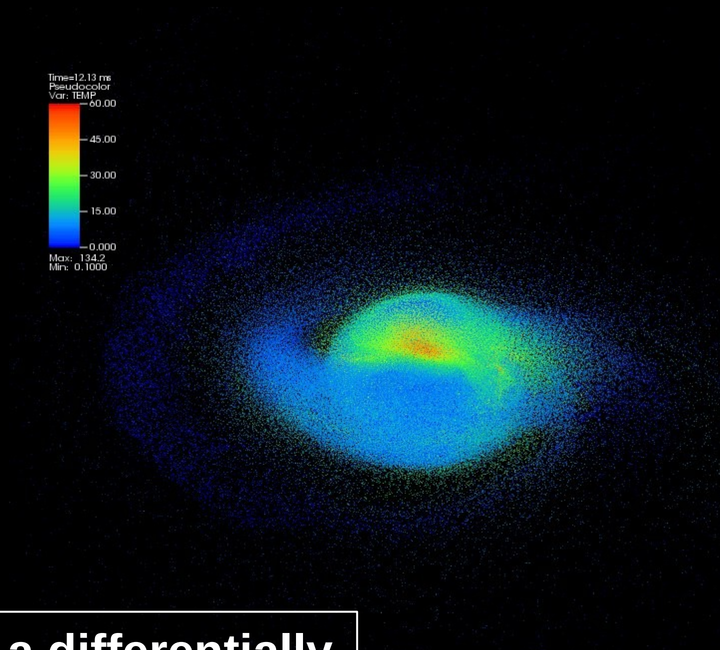
Neutron star merger



?

ms

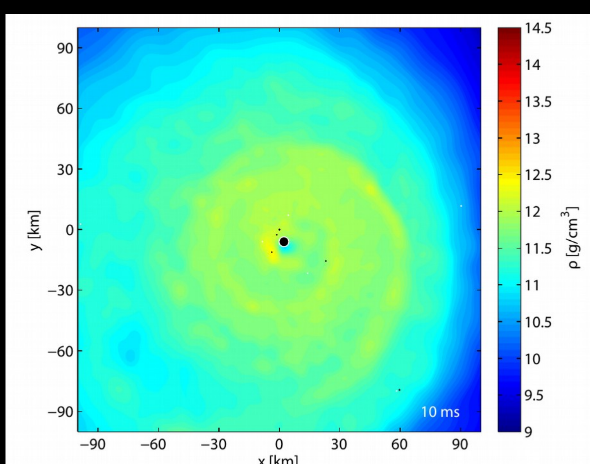
ms

Prompt formation of a BH + torus

Formation of a differentially rotating massive NS

dependent on EoS, M_{tot}

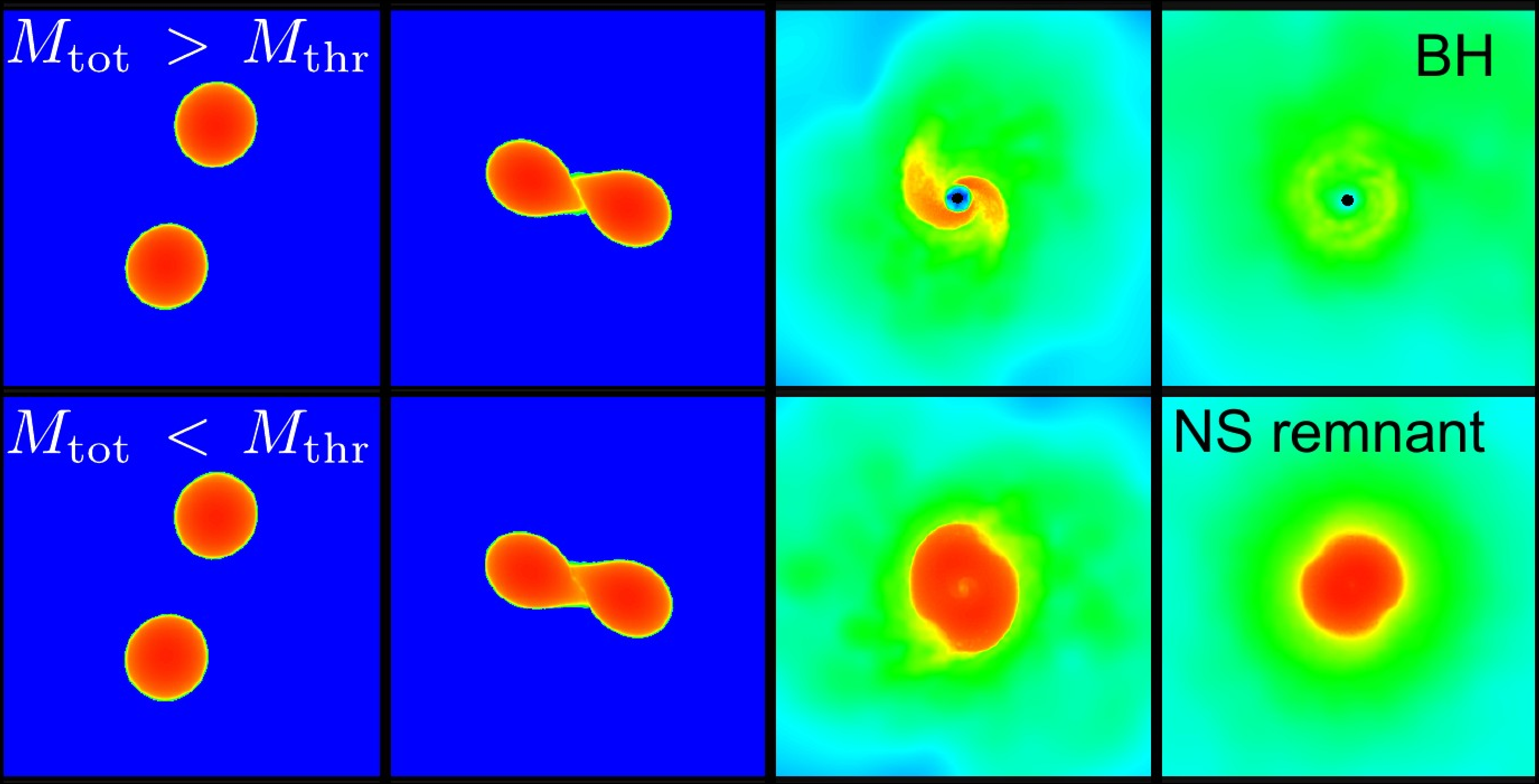
10-100 ms



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

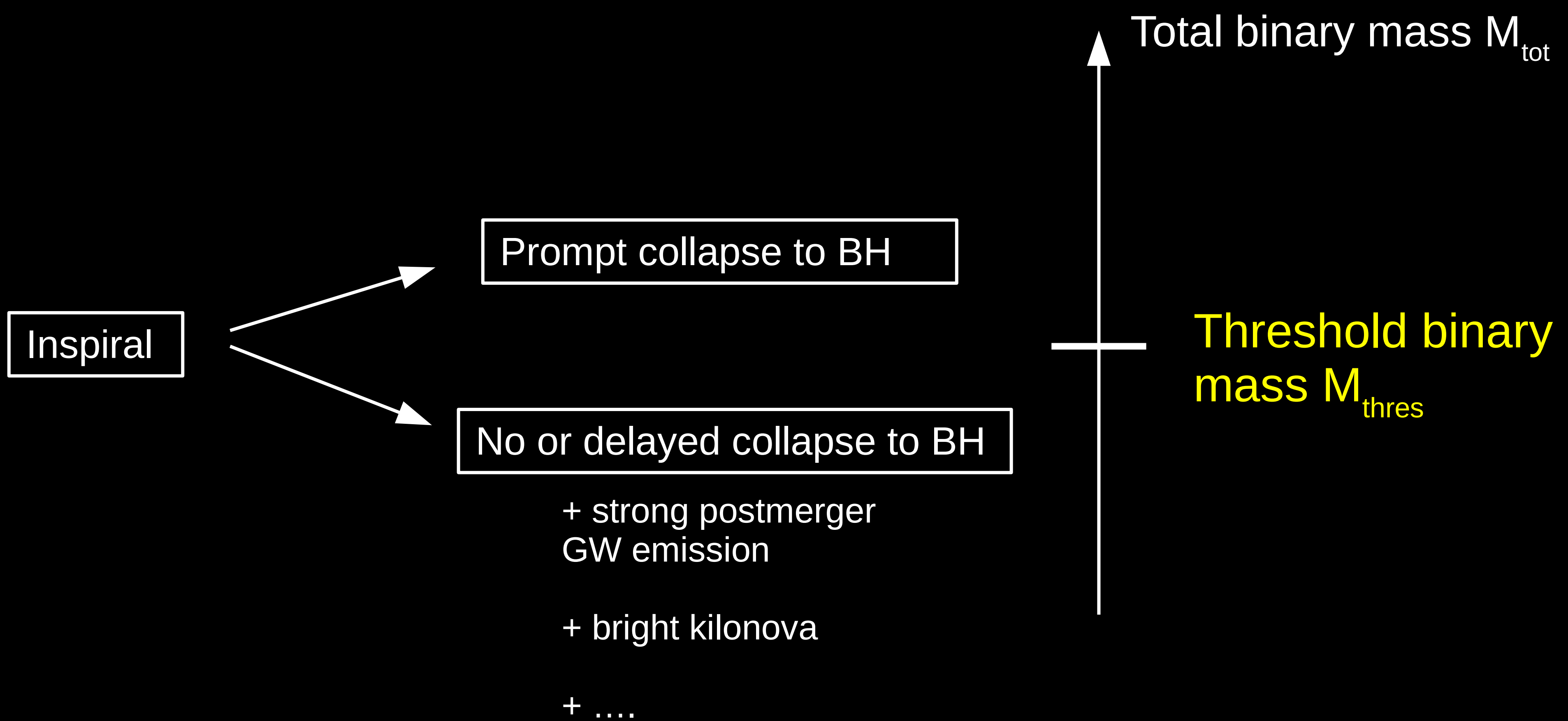
Delayed collapse to a BH + torus

Collapse behavior



Understanding of BH formation in mergers [e.g. Shibata et al. 2005, Baiotti et al. 2008, Hotokezaka et al. 2011, Bauswein et al. 2013, Bauswein et al 2017, Koeppel et al. 2019, Kiuchi 2019, Agathos et al. 2020, Bernuzzi et al. 2020, Bauswein et al. 2020]

Collapse behavior

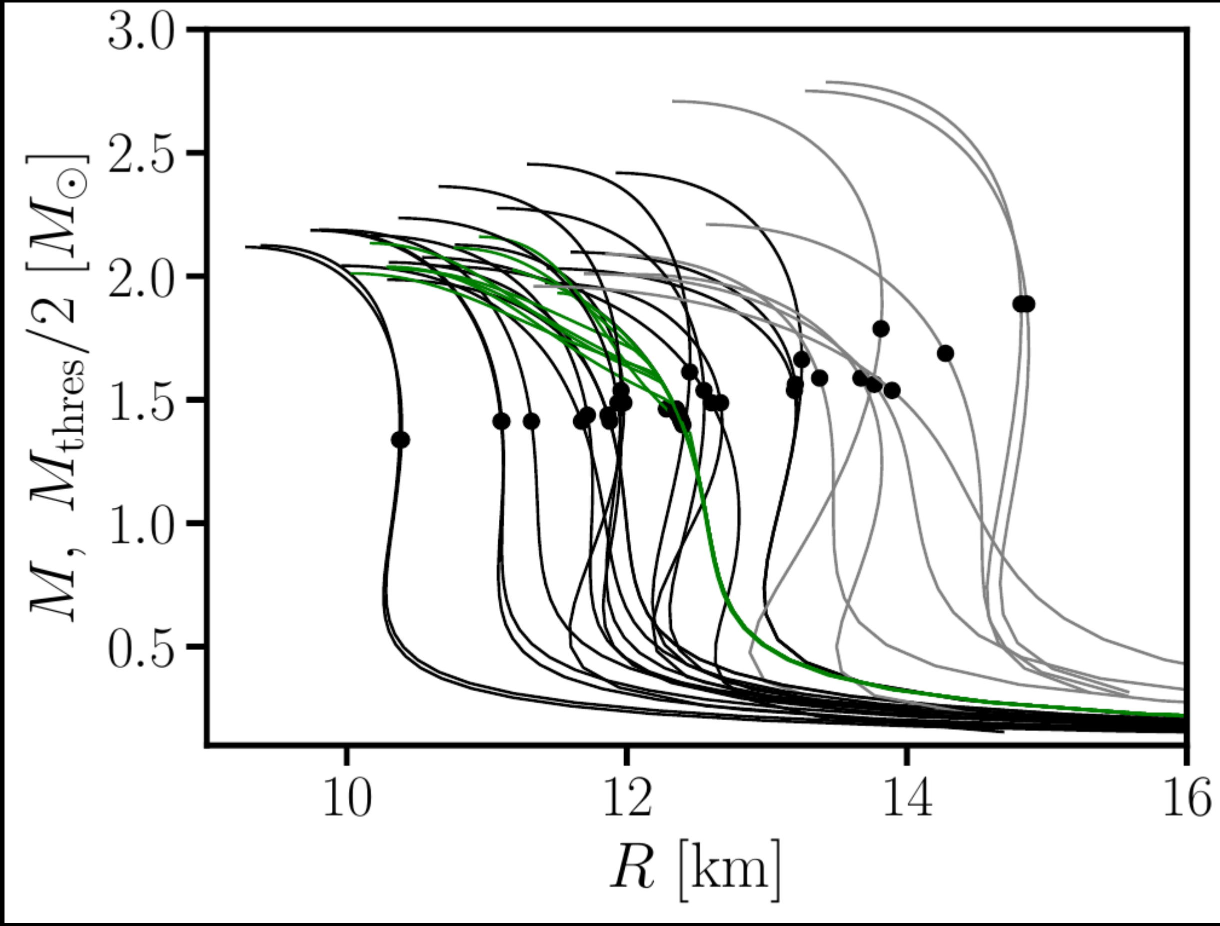


M_{thres} - EoS dependent (weakly on mass ratio) !!!

Which (binary) mass can be supported against gravitational collapse ?

High-density EoS and NS properties

- Stellar properties of NSs uniquely determined by incompletely known high-density EoS
- Maximum mass (of non-rotating!) NSs, i.e. threshold for BH formation, not precisely known (but above ~1.95 Msun)
- In turn, NS observations constrain EoS and thus inform about fundamental constituents and interactions of matter



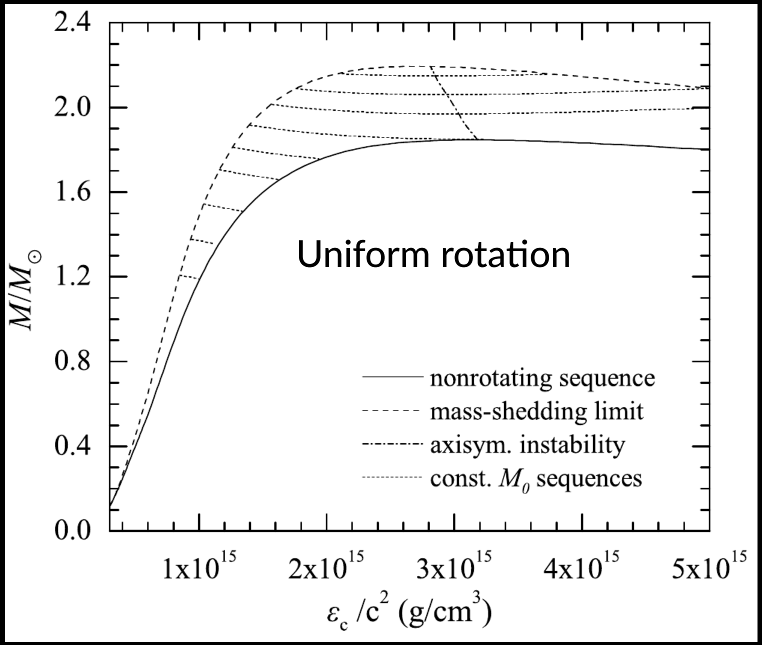
Some constraints on radius available e.g. from GW170817 ruling out very large NS radii

Bauswein et al., PRL 2020

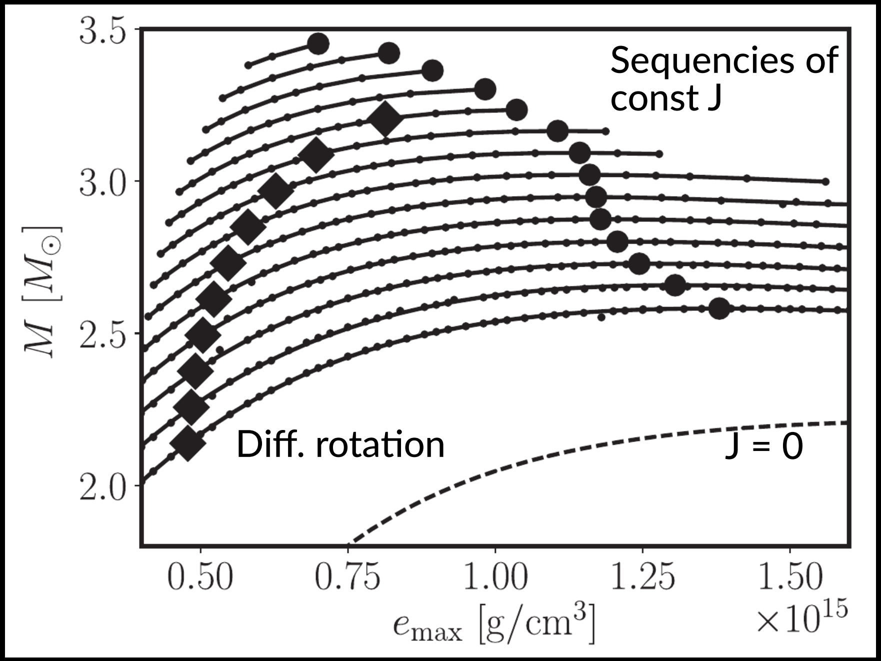
Mmax and rotation

- Centrifugal support increases stability: - supermassive – hypermassive NSs
- Uniform rotation → about 20% (limited by mass shedding), e.g. Lasota et al. 1996
- Differential rotation much more (depending on rotation law), e.g. Morrison et al. 2004

e.g. with RNS stellar equilibrium code (Stergioulas & Friedman 1995)



Friedman & Stergioulas 2013



Bauswein & Stergioulas 2017

- Complex velocity field in merger remnants → a priori maximum mass unclear and has to be determined by hydrodynamical simulations
- Maximum mass in mergers ≡ Mthres in the following

Motivation and context

- Binary inspiral: chirp mass and mass ratio → Mtot typically well measured, q less accurate
- Merger outcome leaves strong impact on observables:

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

  - presence of postmerger GW emission from oscillating NS remnant

  - gamma-ray burst (?)

  - ...

  → Mthres measurable
- Mthres important to predict outcome and possible search strategies for em counterparts and postmerger GW and their interpretation
- Constraints on Mthres → EoS of high-density matter (high-density regime) - later

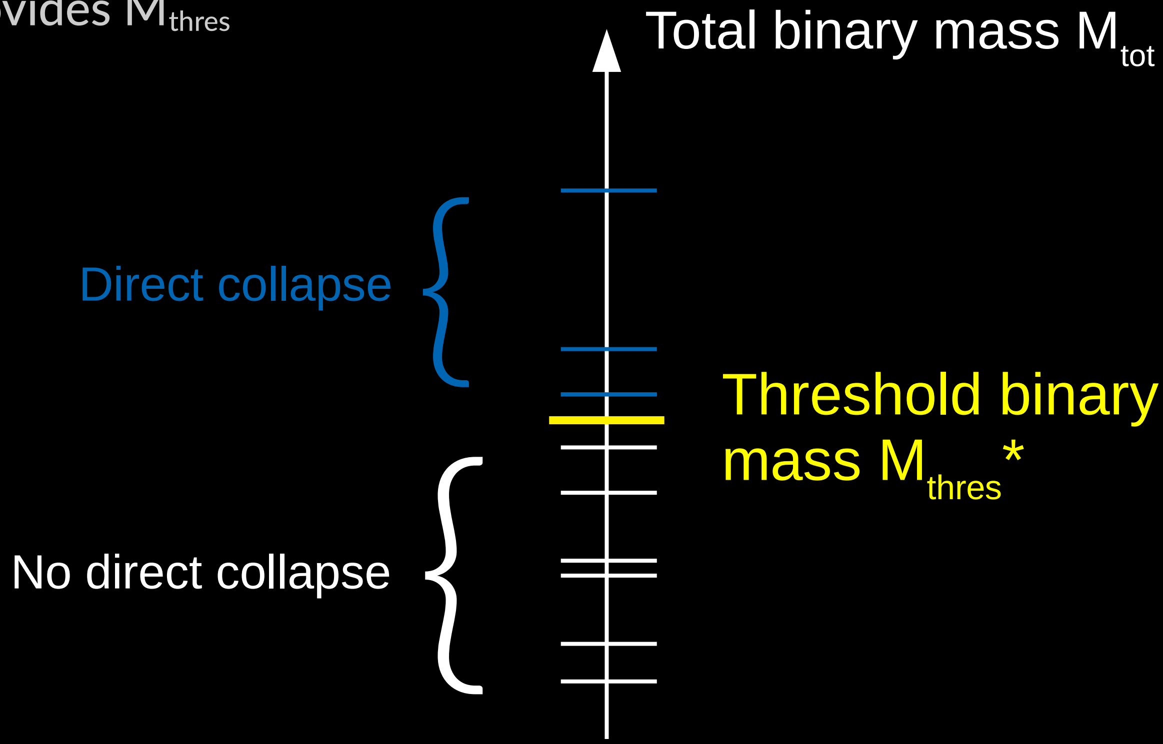
Future determination of M_{thres}

- M_{tot} accurately measured during inpiral

  (from chirp mass and mass ratio q)
- Combing several detections provides M_{thres}
- Merger product NS vs BH

  - kilonova properties

  - postmerger GWs



* determined by highest binary mass with no collapse and lowest mass with direct collapse

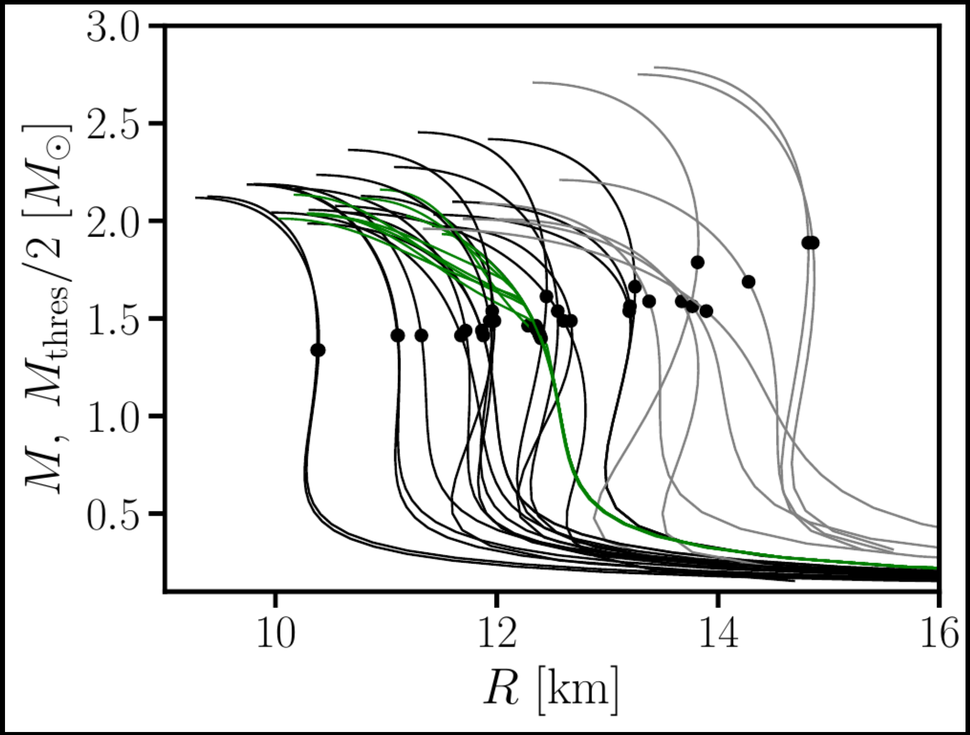
- Important questions:

  How does Mthres depend on binary mass ratio ?

  How does Mthres depend on EoS ?

Simulations and data

- 40 different EoS models (grouped in 3 classes depending on possible assumptions about a priori EoS knowledge: w/wo phase transition, “excluded” EoSs); most models temperature dependent
- 300-400 simulations with relativistic smoothed particle hydrodynamics code (conformal flatness approximation, temperature dependent EoSs – some EoS models with approximate thermal treatment, no initial spin)
- Calculations for different total masses to check outcome for fixed binary mass ratio (q=1 and q=0.7) → Mthres* within at least ± 0.025 Msun



Bauswein et al., PRL 2020

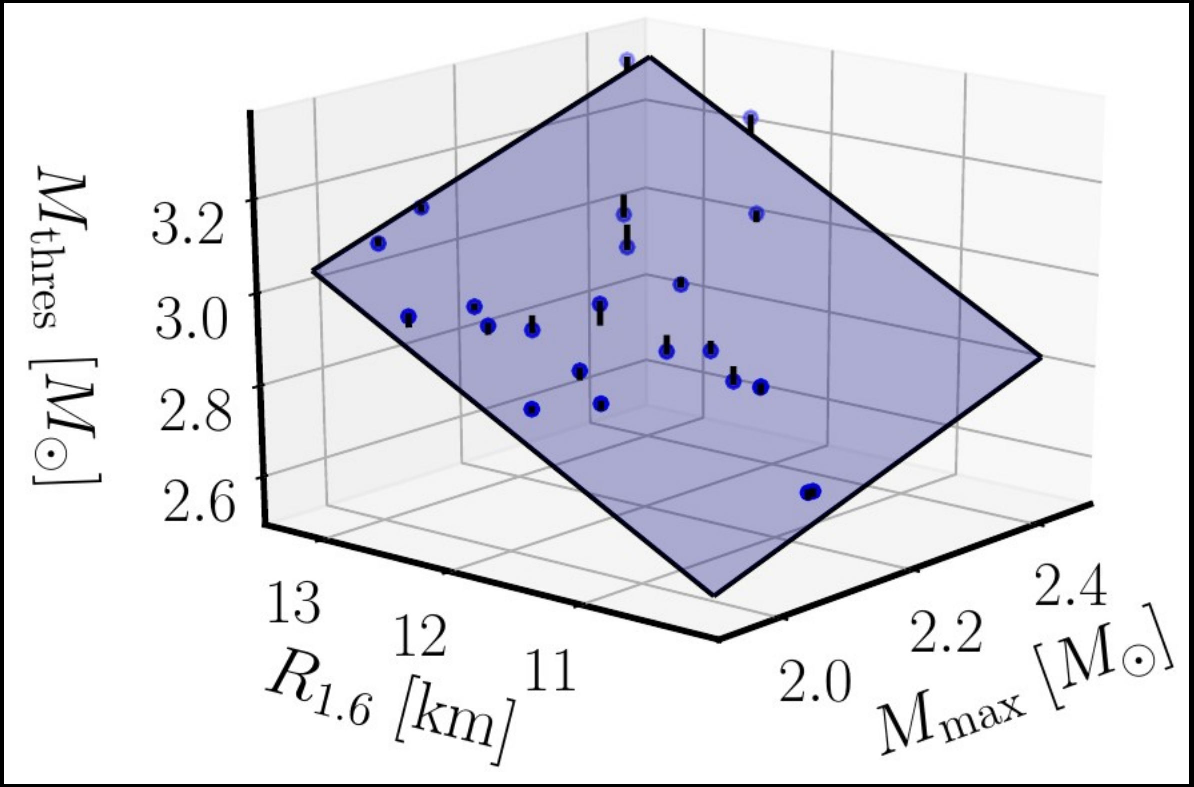
* determined by highest binary mass with no collapse and lowest mass with direct collapse

EoS	T/B	$M_{\max}$ ($M_\odot$)	$R_{1.6}$ (km)	$\Lambda_{1.4}$	$M_{\mathrm{thres}}(q=1)$ ($M_\odot$)	$\tilde{\Lambda}_{\mathrm{thres}}(q=1)$	$M_{\mathrm{thres}}(q=0.7)$ ($M_\odot$)	$\tilde{\Lambda}_{\mathrm{thres}}(q=0.7)$	sample	Ref.
BHBLP	T	2.098	13.192	691.0	3.125	353.8	2.975	512.8	b	[18]
DD2Y	T	2.031	13.169	691.0	3.075	389.2	2.875	622.1	b	[19, 20]
DD2	T	2.419	13.247	694.8	3.325	248.0	3.275	300.3	b	[14, 15]
DD2F	T	2.077	12.220	423.1	2.925	315.0	2.850	427.7	b	[15, 21, 22]
APR	B	2.187	11.253	245.9	2.825	232.2	2.825	260.2	b	[23]
BSK20	B	2.165	11.648	317.4	2.875	267.6	2.875	300.3	b	[24]
eosUU	B	2.189	11.057	227.9	2.825	215.2	2.825	241.1	b	[25]
LS220	T	2.041	12.478	537.0	2.975	350.6	2.875	519.0	b	[26]
LS375	T	2.709	13.767	950.8	3.575	223.5	3.575	248.5	e	[26]
GS2	T	2.089	13.369	717.2	3.175	322.7	3.025	487.3	e	[27]
NL3	T	2.787	14.795	1360.3	3.775	228.5	3.775	257.9	e	[14, 28]
Sly4	B	2.043	11.523	292.4	2.825	275.4	2.775	352.8	b	[29]
SFHO	T	2.056	11.751	331.5	2.875	278.2	2.825	352.9	b	[30]
SFHOY	T	1.986	11.748	331.5	2.825	312.6	2.725	441.5	b	[19, 20]
SFHX	T	2.127	11.963	393.1	2.975	269.3	2.925	328.3	b	[30]
TM1	T	2.210	14.347	1142.0	3.375	334.5	3.225	525.0	e	[16, 31]
TMA	T	2.008	13.660	928.0	3.175	396.9	2.975	698.1	e	[16, 32]
BSK21	B	2.276	12.543	511.4	3.075	287.1	3.075	317.7	b	[24]
GS1	T	2.750	14.864	1392.1	3.775	229.6	3.775	260.4	e	[27]
eosAU	B	2.125	10.357	149.9	2.675	200.3	2.675	222.2	b	[25]
WFF1	B	2.118	10.362	150.0	2.675	200.2	2.675	220.1	b	[25, 33]
WFF2	B	2.186	11.048	222.4	2.825	210.0	2.825	235.3	b	[25, 33]
MPA1	B	2.454	12.448	475.9	3.225	202.2	3.225	224.6	b	[33, 34]
ALF2	B	1.973	12.616	565.1	2.975	385.2	2.875	510.1	b	[33, 35]
H4	B	2.010	13.716	846.4	3.125	403.6	2.925	699.6	e	[33, 36]
DD2F-SF-1	T	2.134	12.141	423.1	2.845	380.4	2.770	497.8	h	[9, 10, 37, 38]
DD2F-SF-2	T	2.160	12.061	421.2	2.925	298.6	2.870	399.3	h	[9, 10, 37, 38]
DD2F-SF-3	T	2.032	12.189	423.1	2.825	398.8	2.720	570.1	h	[9, 10, 37, 38]
DD2F-SF-4	T	2.029	12.220	423.1	2.835	389.5	2.725	566.9	h	[9, 10, 37, 38]
DD2F-SF-5	T	2.038	11.928	423.1	2.815	408.4	2.725	539.2	h	[9, 10, 37, 38]
DD2F-SF-6	T	2.012	12.219	423.1	2.795	428.1	2.675	635.5	h	[9, 10, 37, 38]
DD2F-SF-7	T	2.115	12.220	423.1	2.905	330.2	2.825	451.2	h	[9, 10, 37, 38]
DD2F-SF-8	T	2.025	12.216	422.3	2.915	321.9	2.810	467.3	h	[9, 10, 37, 38]
VBAG	T	1.932	12.214	422.3	2.885	345.5	2.775	505.4	h	[39]
ENG	B	2.236	11.899	367.5	2.975	249.3	2.975	279.7	b	[33, 40]
APR3	B	2.363	11.954	364.8	3.075	204.6	3.075	228.1	b	[23, 33]
GNH3	B	1.959	13.756	850.4	3.075	432.6	2.875	799.3	e	[33, 41]
SAPR	T	2.194	11.462	265.7	2.875	223.7	2.875	254.5	b	[42]
SAPRLDP	T	2.247	12.369	449.3	3.025	271.0	3.025	309.4	b	[42]
SSkAPR	T	2.028	12.304	442.6	2.950	312.7	2.875	420.8	b	[42]

Bauswein et al., PRL 2020

Simulation results → EoS/TOV properties

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



arXiv:2010.04461

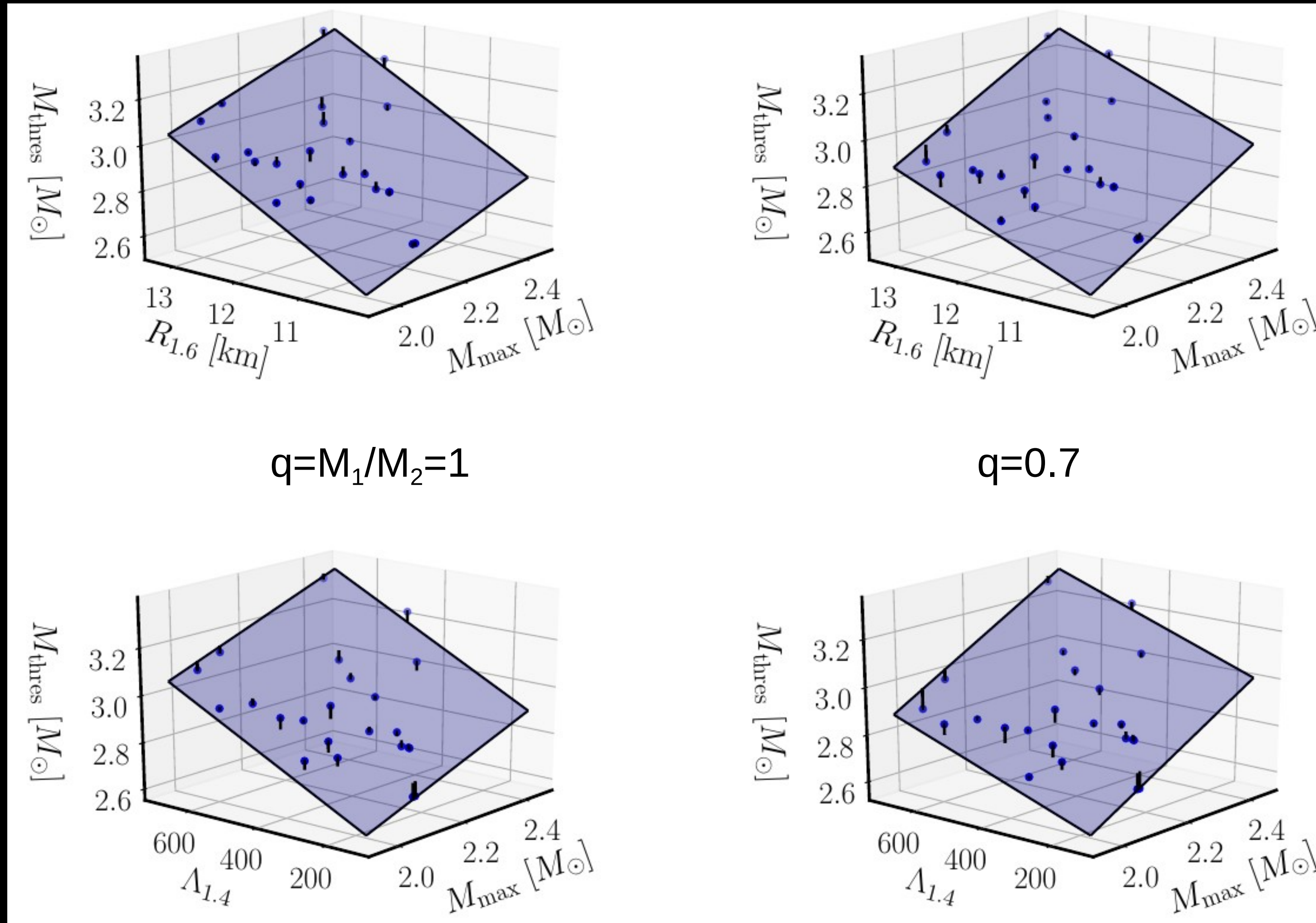
$$M_{\mathrm{thres}} = M_{\mathrm{thres}}(M_{\mathrm{max}}, R_{1.6}) = aM_{\mathrm{max}} + bR_{1.6} + c$$

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

Compatible but better than older relation
A.B., Baumgarte, Janka, PRL 111 (2013)

$$M_{\mathrm{thres}} = \left(-3.6 \frac{G\, M_{\mathrm{max}}}{c^2\, R_{1.6}} + 2.38 \right) M_{\mathrm{max}}$$

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



arXiv:2010.04461

- Similarly tight fits for asymmetric mergers

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

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

EoS constraints, i.e. NS TOV parameter

measurable

Unknown EoS/TOV properties

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

$$\text{e.g.}\quad M_{\rm thres} = M_{\rm thres}(M_{\rm max}, R_{1.6}) = aM_{\rm max} + bR_{1.6} + c$$

- Either measure X as well and get Y
- Or impose a relation between X and Y

$$X = M_{\rm max}; \quad Y = \{R_{1.6}, R_{\rm max}, \Lambda_{1.4}, \tilde{\Lambda}_{\rm thres}, ...\}$$

- From causality or large set of EoSs:

$$M_{\mathrm{max}} < M_{\mathrm{max}}^{\mathrm{up}} = w_1 R + w_2$$

- Measured binary mass and NO collapse:

$$\begin{aligned} M_{\mathrm{tot}} &< a M_{\mathrm{max}} + bR + c \\ &< a M_{\mathrm{max}}^{\mathrm{up}} + bR + c \\ &< a w_1 R + a w_2 + bR + c \end{aligned}$$

as arguably for GW170817 with 2.73 Msun

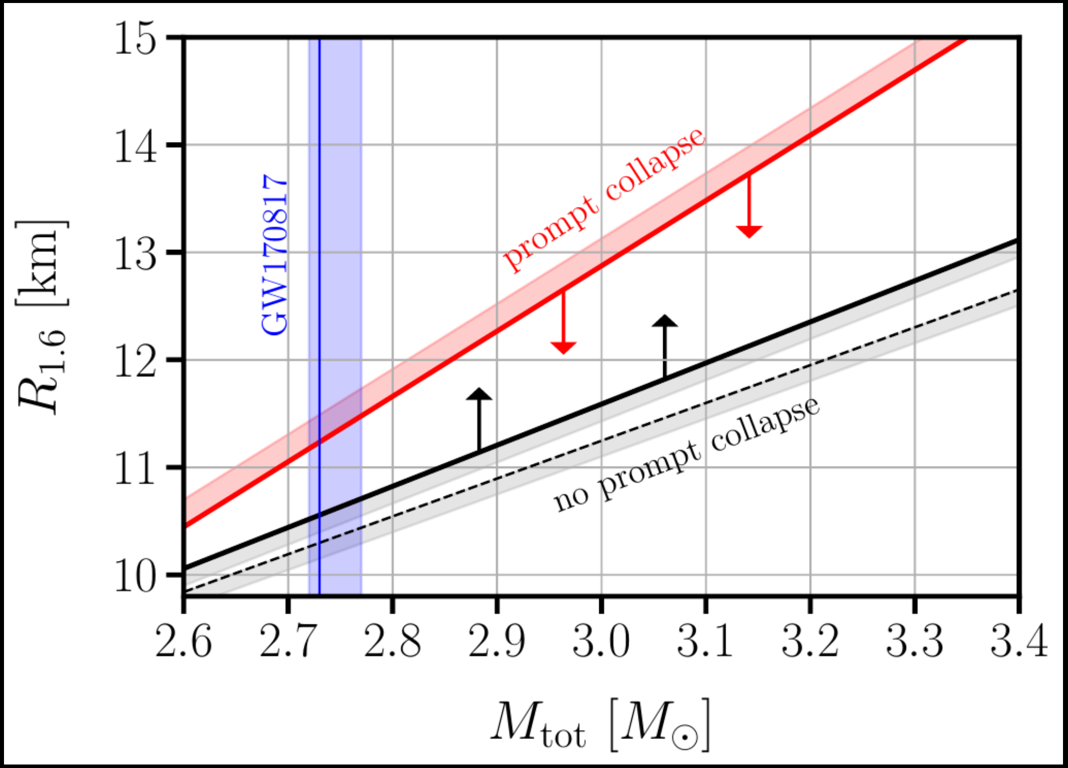
(Margalit & Metzger 2017, Bauswein et. al 2017, Radice et al. 2018, ...)

$$R > \frac{M_{\mathrm{tot}} - c - a w_2}{a w_1 + b}$$

Current and future multi-messenger constraints

- For GW170817 we obtain R > 10.6 km
- Applicable to any new observation with information on the outcome

  → a lot of potential for future – complementary and independent of inspiral finite-size effects



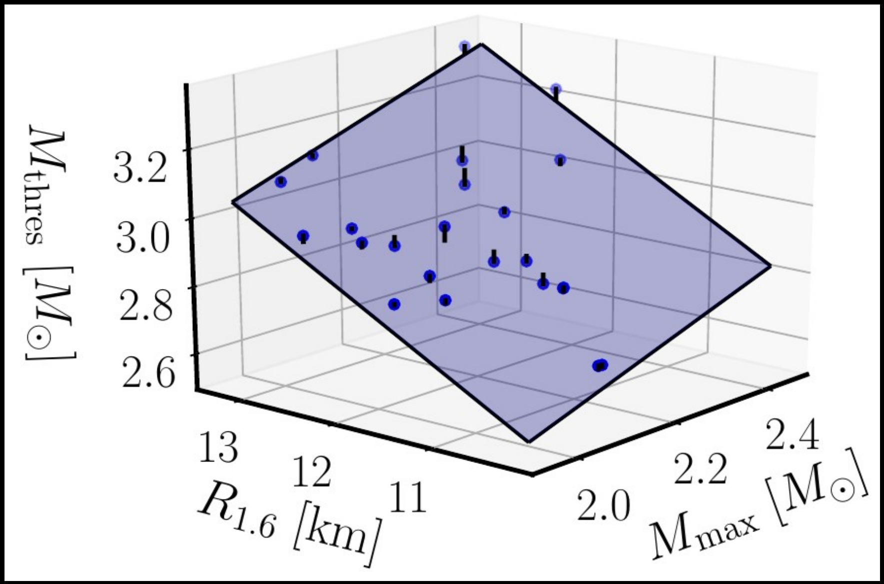
arXiv:2010.04461

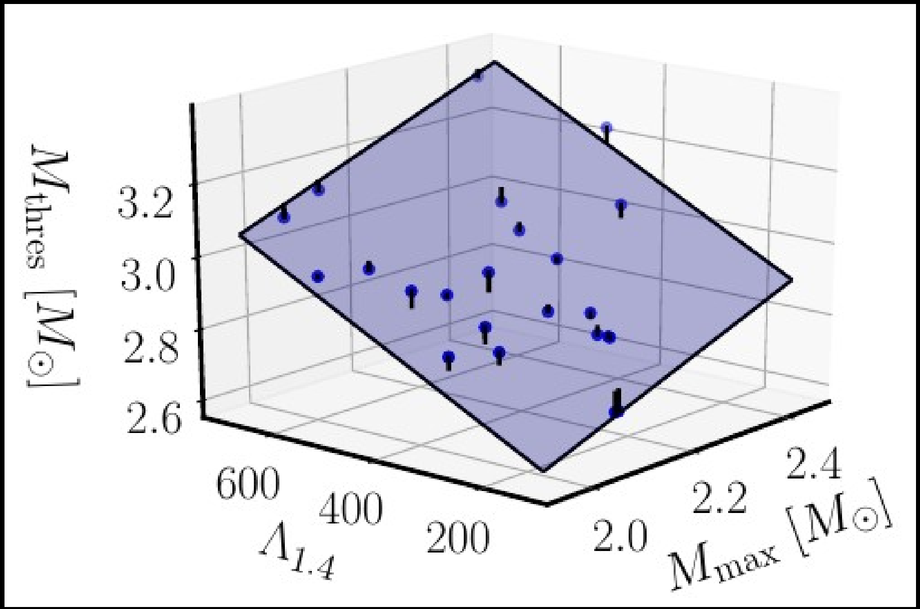
(cf. R /Λ limits from Bauswein et al. 2017, Radice et. al 2018, Most et al. 2018, Koeppel et al. 2019, Bauswein et al. 2019, Capano et al. 2020, ...)

M_{max} from M_{thres}

- M_{thres} + another NS property (radius or Lambda from other observations)

  → very accurate and robust M_{max}





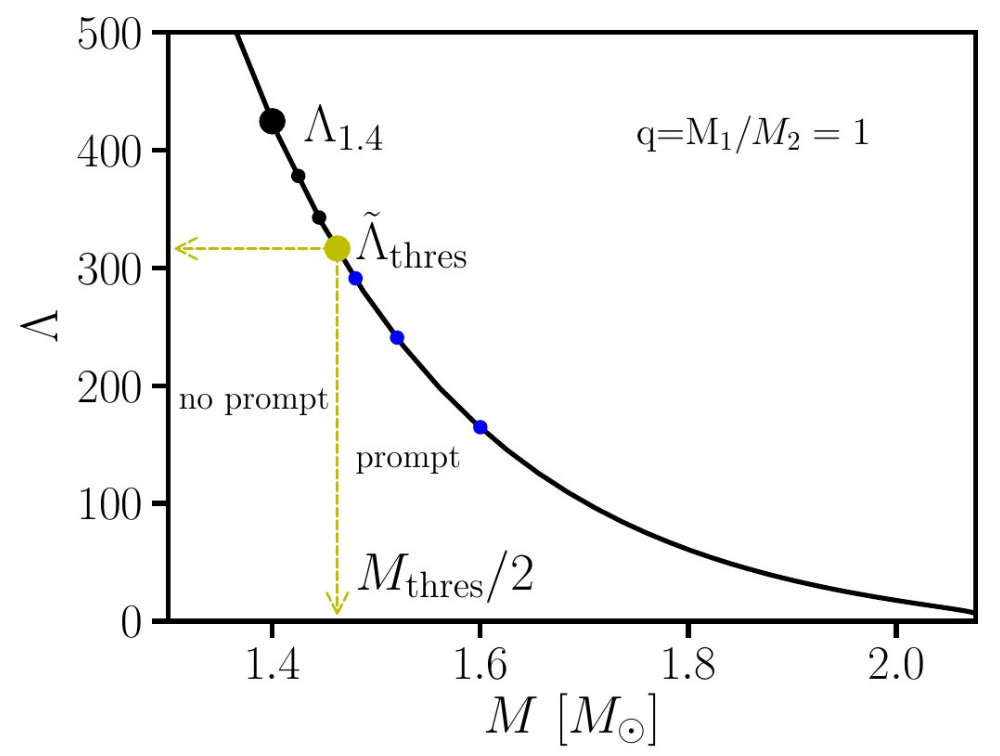
$$M_{\rm thres} = M_{\rm thres}(X, Y) = aX + bY + c$$

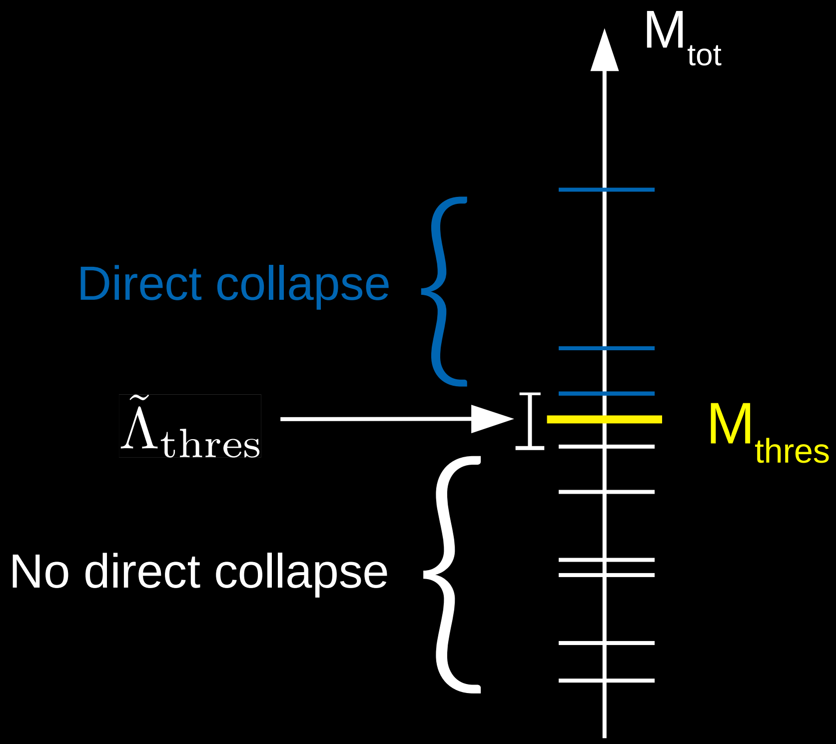
arXiv:2010.04461

see also current estimates e.g. by Margalit & Metzger 2017, Shibata et al. 2017, Rezzolla et al 2018, Ruiz & Shapiro 2018, Shibata et al. 2019, … (employing GW170817) and Lawrence et al 2015, Fryer et al. 2015, …

Λ_{thres} and Mthres

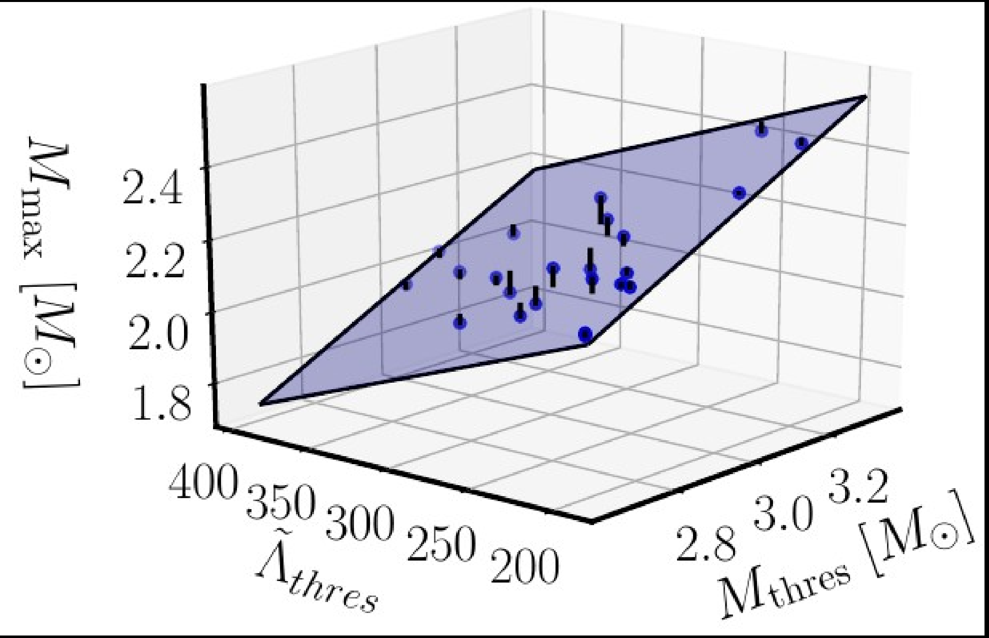
$$\tilde{\Lambda}_{\rm thres} = \tilde{\Lambda}(M_{\rm thres}/2, M_{\rm thres}/2) = \Lambda(M_{\rm thres}/2) \quad \text{for } q = 1$$





- Instead of $R_{1.6}$ or $\Lambda_{1.4}$ $\tilde{\Lambda}_{\mathrm{thres}} = \tilde{\Lambda}(M_{\mathrm{thres}}/2, M_{\mathrm{thres}}/2) = \Lambda(M_{\mathrm{thres}}/2) \quad \text{for } q = 1$
- Most direct determination via **Lambda @ M_{thres}**, i.e. combined tidal deformability of events which determine M_{thres}
- Directly measurable with the same events which determine M_{thres} (with sufficient SNR)
- Already a single detection with information on merger product or poorly constrained parameters can yield interesting constraint

$$M_{\mathrm{max}} = 0.632 M_{\mathrm{thres}} - 0.002\tilde{\Lambda}_{\mathrm{thres}} + 0.802$$



Bauswein et al., PRL 2020

$M_{\mathrm{tot}} > M_{\mathrm{thres}}, \ \ \tilde{\Lambda} < \tilde{\Lambda}_{\mathrm{thres}} \ \ \Rightarrow M_{\mathrm{max}} < M_{\mathrm{max}}(M_{\mathrm{tot}}, \tilde{\Lambda})$ for prompt collapse

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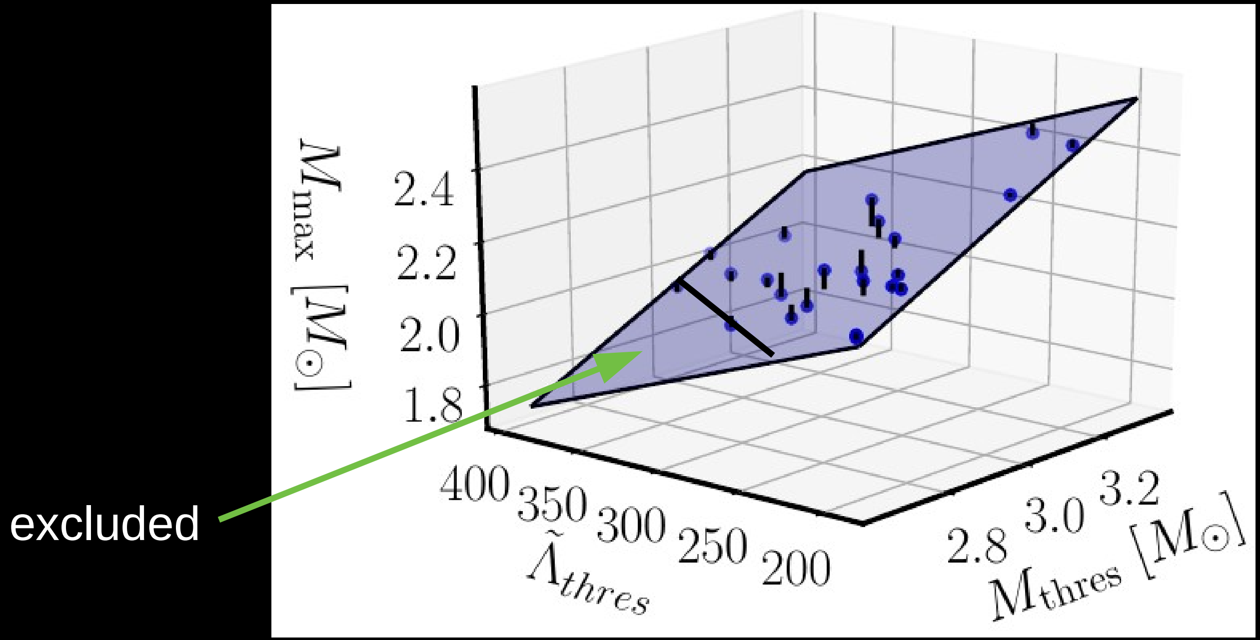


$$M_{\mathrm{tot}} > M_{\mathrm{thres}}, \quad \tilde{\Lambda} < \tilde{\Lambda}_{\mathrm{thres}} \quad \Rightarrow M_{\mathrm{max}} < M_{\mathrm{max}}(M_{\mathrm{tot}}, \tilde{\Lambda})$$ for prompt collapse

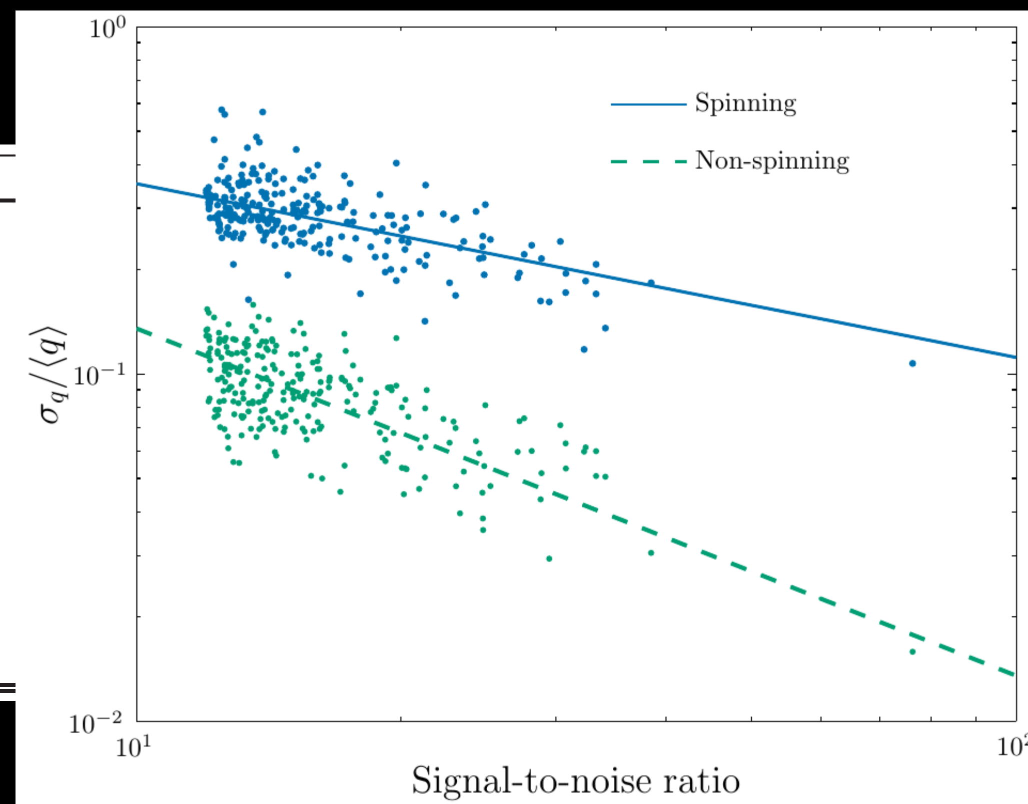
Impact of the binary mass ratio

- Mass ratio may be well measurable for near-by events / but less accurate in more distant mergers

  → for both cases we need to understand how Mthres depends on q

Low-spin prior, $\chi_i \leq 0.05$	TaylorF2
Binary inclination θ_{JN}	146^{+24}_{-28} deg
Binary inclination θ_{JN} using EM distance constraint [108]	149^{+13}_{-10} deg
Detector-frame chirp mass $\mathcal{M}^{\rm det}$	$1.1975^{+0.0001}_{-0.0001}$ $M_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}$ $M_\odot$
Primary mass m_1	$(1.36, 1.61)$ $M_\odot$
Secondary mass m_2	$(1.16, 1.36)$ $M_\odot$
Total mass m	$2.73^{+0.05}_{-0.01}$ $M_\odot$
Mass ratio q	$(0.72, 1.00)$
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$
Primary dimensionless spin χ_1	$(0.00, 0.02)$
Secondary dimensionless spin χ_2	$(0.00, 0.02)$
Tidal deformability $\tilde{\Lambda}$ with flat prior (symmetric/HPD)	$340^{+580}_{-240}/340^{+490}_{-290}$

@~40 Mpc →



GW170817, Abbott et al 2019

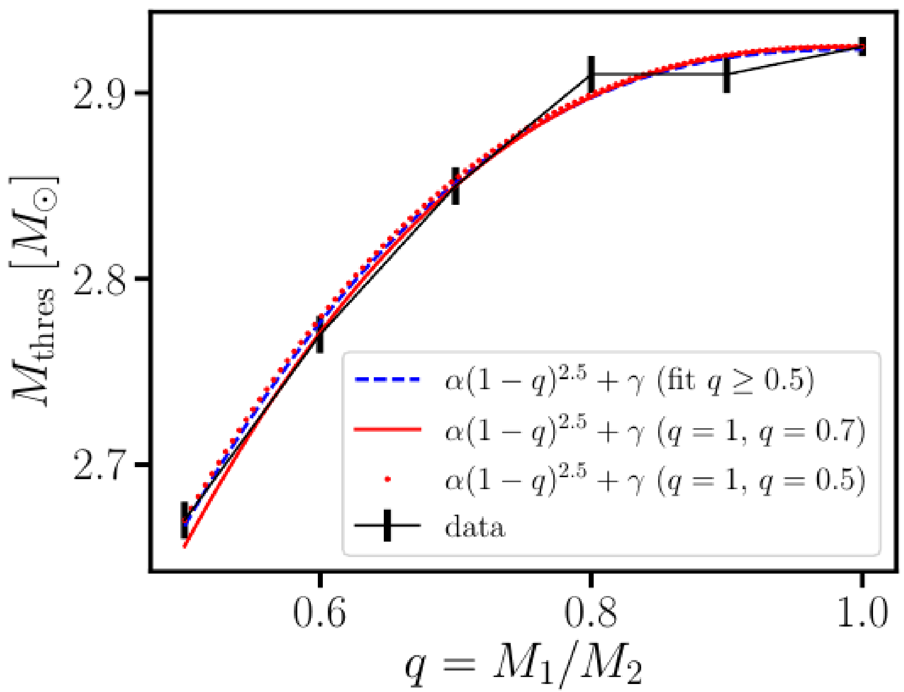
Similar q range for GW190425

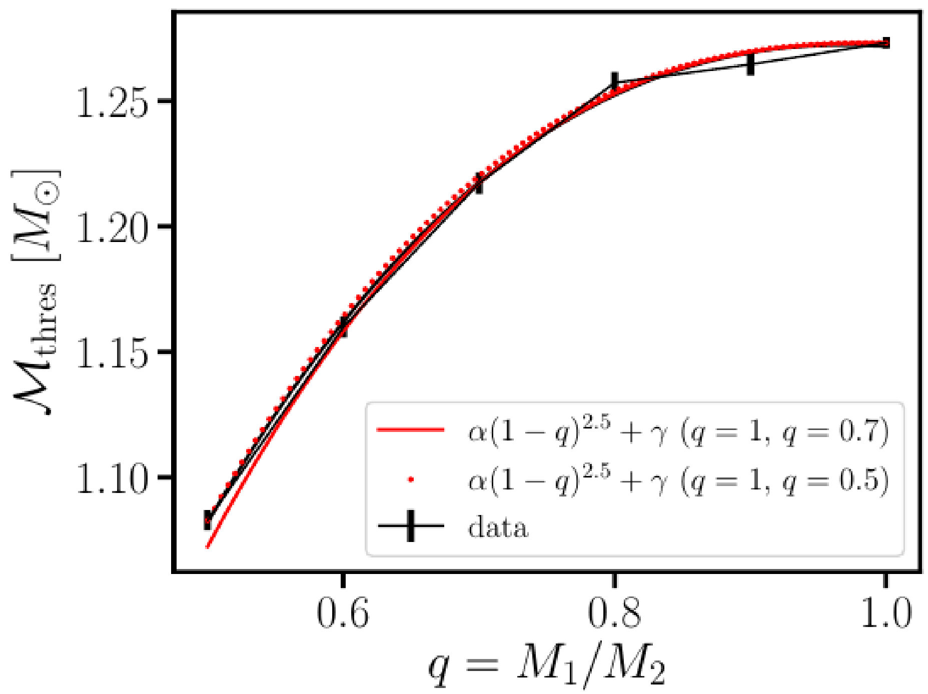
Farr et al. 2016

Mass ratio effect on Mthres

- For a selected subset of EoSs determine Mthres(q)
- Typically decrease with binary asymmetry – understandable by Newtonian toy model
- Mthres roughly constant for 0.85 <= q <= 1
- Higher-order polynomials provide decent description

  → power of 3 works well for most (tested) EoSs





DD2F EoS

arXiv:2010.04461

Mass ratio effect on Mthres: EOS dependent!

Mthres for q=1   and q=0.7

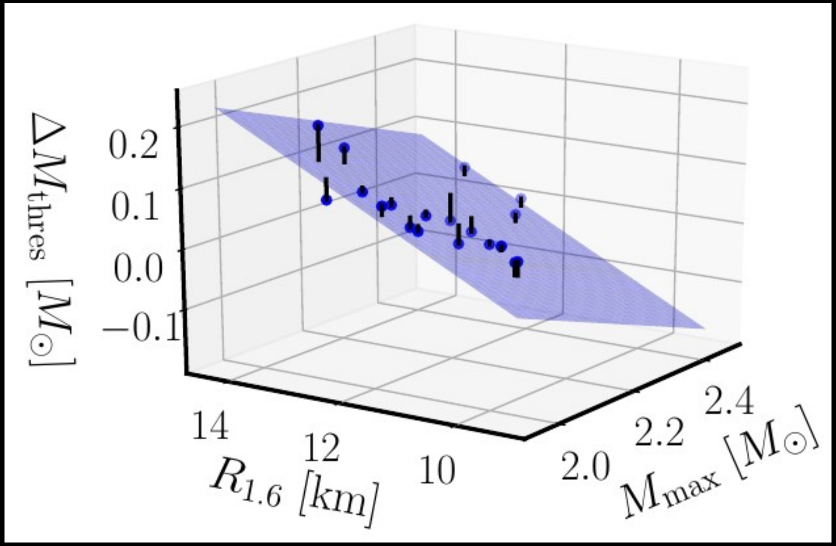
EoS	T/B	$M_{\max}$ ($M_\odot$)	$R_{1.6}$ (km)	$\Lambda_{1.4}$	$M_{\rm thres}(q=1)$ ($M_\odot$)	$\tilde{\Lambda}_{\rm thres}(q=1)$	$M_{\rm thres}(q=0.7$ ($M_\odot$)	$\tilde{\Lambda}_{\rm thres}(q=0.7)$	sample	Ref.
BHBLP	T	2.098	13.192	691.0	3.125	353.8	2.975	512.8	b	[18]
DD2Y	T	2.031	13.169	691.0	3.075	389.2	2.875	622.1	b	[19, 20]
DD2	T	2.419	13.247	694.8	3.325	248.0	3.275	300.3	b	[14, 15]
DD2F	T	2.077	12.220	423.1	2.925	315.0	2.850	427.7	b	[15, 21, 22]
APR	B	2.187	11.253	245.9	2.825	232.2	2.825	260.2	b	[23]
BSK20	B	2.165	11.648	317.4	2.875	267.6	2.875	300.3	b	[24]
eosUU	B	2.189	11.057	227.9	2.825	215.2	2.825	241.1	b	[25]
LS220	T	2.041	12.478	537.0	2.975	350.6	2.875	519.0	b	[26]
LS375	T	2.709	13.767	950.8	3.575	223.5	3.575	248.5	e	[26]
GS2	T	2.089	13.369	717.2	3.175	322.7	3.025	487.3	e	[27]
NL3	T	2.787	14.795	1360.3	3.775	228.5	3.775	257.9	e	[14, 28]
Sly4	B	2.043	11.523	292.4	2.825	275.4	2.775	352.8	b	[29]
SFHO	T	2.056	11.751	331.5	2.875	278.2	2.825	352.9	b	[30]
SFHOY	T	1.986	11.748	331.5	2.825	312.6	2.725	441.5	b	[19, 20]
SFHX	T	2.127	11.963	393.1	2.975	269.3	2.925	328.3	b	[30]
TM1	T	2.210	14.347	1142.0	3.375	334.5	3.225	525.0	e	[16, 31]
TMA	T	2.008	13.660	928.0	3.175	396.9	2.975	698.1	e	[16, 32]
BSK21	B	2.276	12.543	511.4	3.075	287.1	3.075	317.7	b	[24]
GS1	T	2.750	14.864	1392.1	3.775	229.6	3.775	260.4	e	[27]
eosAU	B	2.125	10.357	149.9	2.675	200.3	2.675	222.2	b	[25]
WFF1	B	2.118	10.362	150.0	2.675	200.2	2.675	220.1	b	[25, 33]
WFF2	B	2.186	11.048	222.4	2.825	210.0	2.825	235.3	b	[25, 33]
MPA1	B	2.454	12.448	475.9	3.225	202.2	3.225	224.6	b	[33, 34]
ALF2	B	1.973	12.616	565.1	2.975	385.2	2.875	510.1	b	[33, 35]
H4	B	2.010	13.716	846.4	3.125	403.6	2.925	699.6	e	[33, 36]
DD2F-SF-1	T	2.134	12.141	423.1	2.845	380.4	2.770	497.8	h	[9, 10, 37, 38]
DD2F-SF-2	T	2.160	12.061	421.2	2.925	298.6	2.870	399.3	h	[9, 10, 37, 38]
DD2F-SF-3	T	2.032	12.189	423.1	2.825	398.8	2.720	570.1	h	[9, 10, 37, 38]
DD2F-SF-4	T	2.029	12.220	423.1	2.835	389.5	2.725	566.9	h	[9, 10, 37, 38]
DD2F-SF-5	T	2.038	11.928	423.1	2.815	408.4	2.725	539.2	h	[9, 10, 37, 38]
DD2F-SF-6	T	2.012	12.219	423.1	2.795	428.1	2.675	635.5	h	[9, 10, 37, 38]
DD2F-SF-7	T	2.115	12.220	423.1	2.905	330.2	2.825	451.2	h	[9, 10, 37, 38]
DD2F-SF-8	T	2.025	12.216	422.3	2.915	321.9	2.810	467.3	h	[9, 10, 37, 38]
VBAG	T	1.932	12.214	422.3	2.885	345.5	2.775	505.4	h	[39]
ENG	B	2.236	11.899	367.5	2.975	249.3	2.975	279.7	b	[33, 40]
APR3	B	2.363	11.954	364.8	3.075	204.6	3.075	228.1	b	[23, 33]
GNH3	B	1.959	13.756	850.4	3.075	432.6	2.875	799.3	e	[33, 41]
SAPR	T	2.194	11.462	265.7	2.875	223.7	2.875	254.5	b	[42]
SAPRLDP	T	2.247	12.369	449.3	3.025	271.0	3.025	309.4	b	[42]
SSkAPR	T	2.028	12.304	442.6	2.950	312.7	2.875	420.8	b	[42]

Bauswein et al., PRL 2020

- 40 EoS models – consider difference

$$\Delta M_{\rm thres} = M_{\rm thres}(q=1) - M_{\rm thres}(q=0.7)$$

→ Reduction by asymmetry itself EoS dependent



Only hadronic models

Qualitative dependence understandble by semi-analytic Newtonian toy model !!

Generalized formula for Mthres

- We found for fixed q $M_{\mathrm{thres}} = M_{\mathrm{thres}}(M_{\mathrm{max}}, R_{1.6})$

  and for difference $\Delta M_{\mathrm{thres}} = \Delta M_{\mathrm{thres}}(M_{\mathrm{max}}, R_{1.6})$

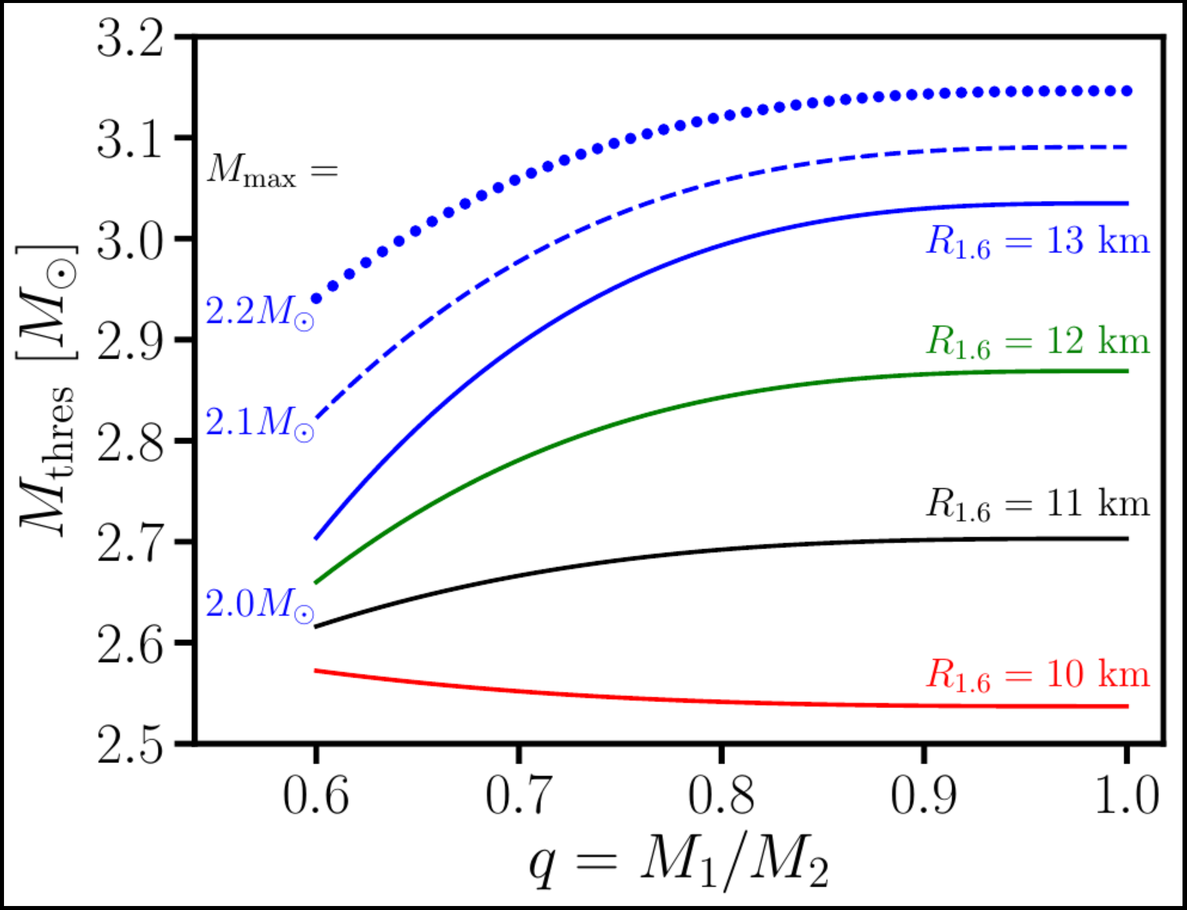
  → suggest to try a combined fit to the q=1 and q=0.7 data:

$$M_{\mathrm{thres}}(q, M_{\mathrm{max}}, R_{1.6}) = c_1 M_{\mathrm{max}} + c_2 R_{1.6} + c_3 + c_4 \delta q^3 M_{\mathrm{max}} + c_5 \delta q^3 R_{1.6} + c_6 \delta q^3.$$

$$\delta q \equiv 1 - q$$

- (nearly) as tight as fits for fixed mass ratio q (average deviation 0.017 Msun)
- Useful for applications with a range of q
- Similar relations for threshold chirp mass
- Similar relations for other R or Lambda (check paper for fit paramters)
- Valid somewhat below q=0.7

- Impact of EoS on Mthres(q)



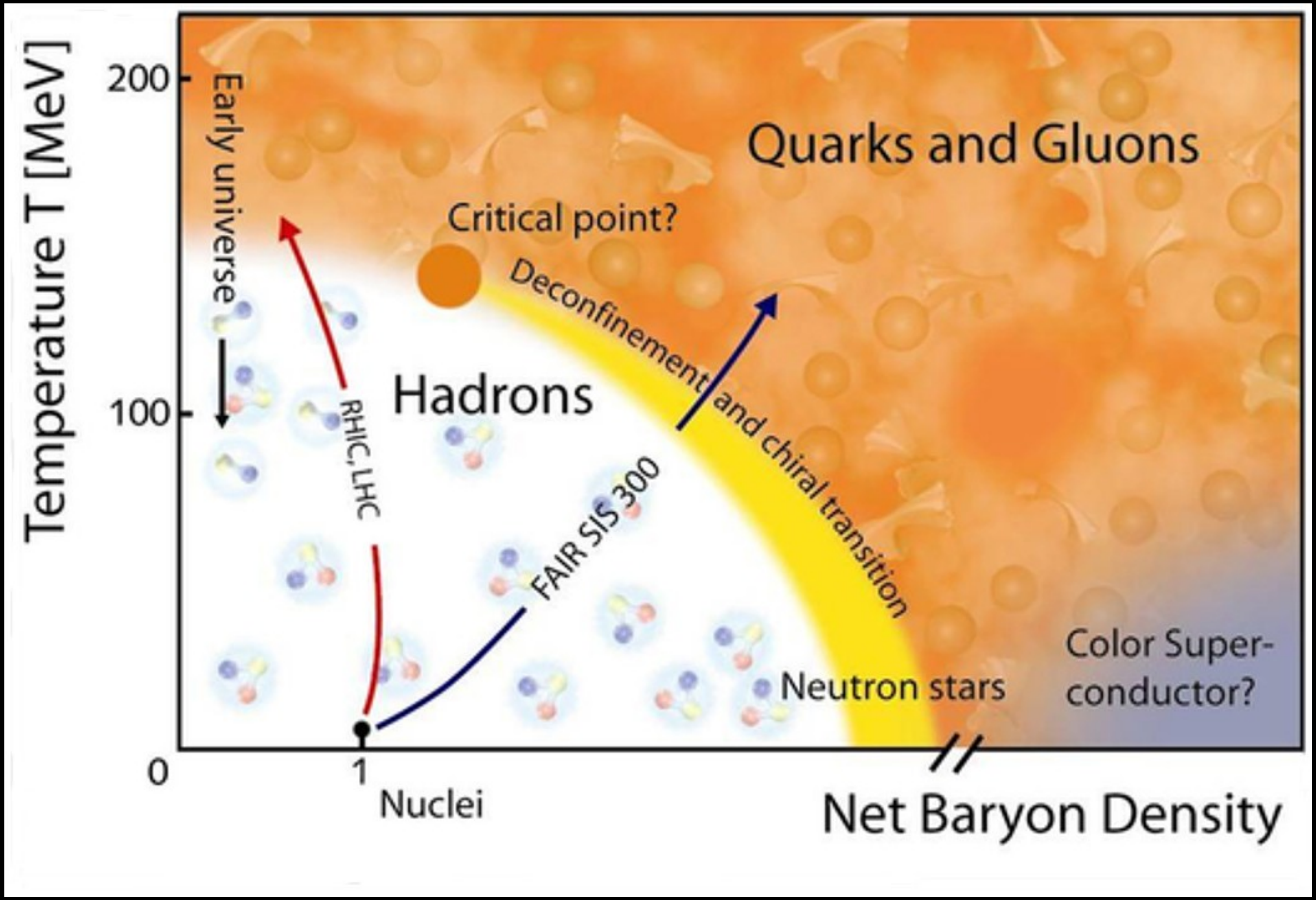
arXiv:2010.04461

Compatible with early tentative assessments of mass ratio effect on stability of remnants, e.g. Bauswein et al. 2013, Bauswein & Stergioulas 2017, Kiuchi et al. 2019, Bernuzzi et al. 2020

Phase diagram of 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)

Does a phase transition have an impact on the collapse behavior ?

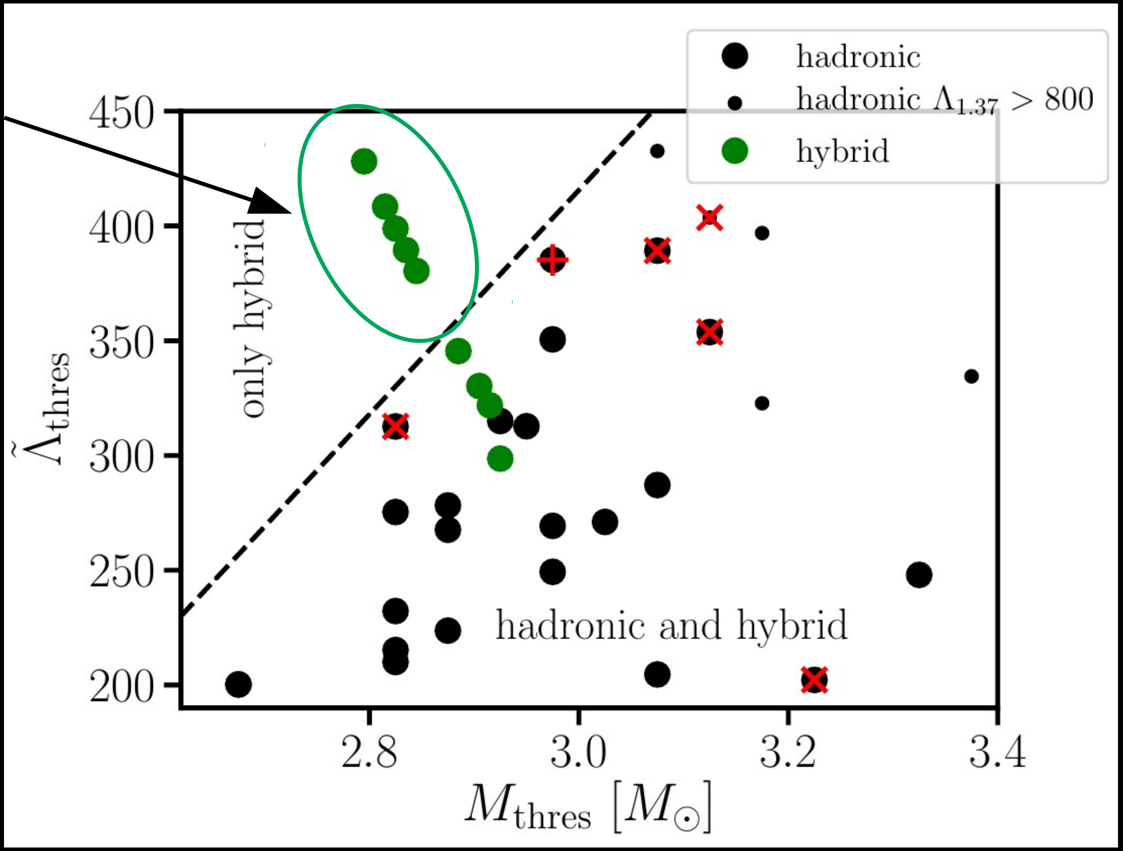
- Consider additional set of hybrid EoSs (with PT to deconfined quark matter) in comparison to purely hadronic EoSs

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 2020

Measurable from GW inspiral

Measurable from inspiral + information on merger product

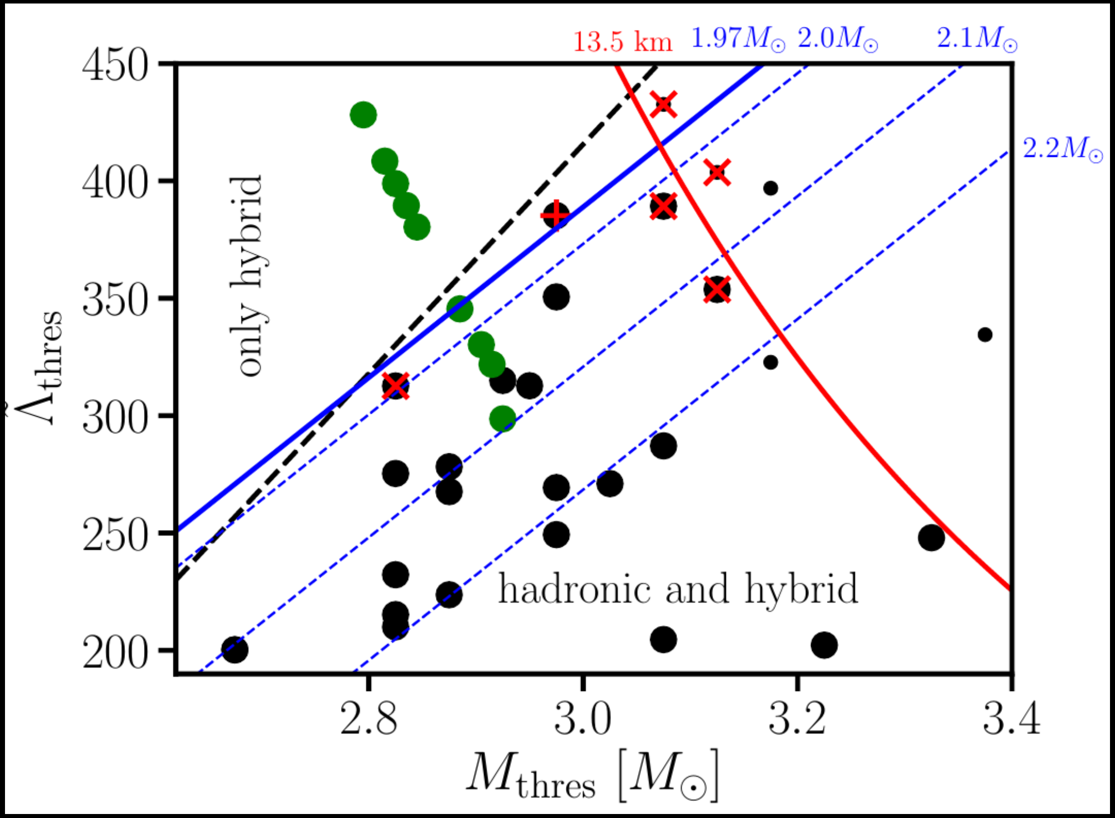
$$\tilde{\Lambda}_{thres} = \Lambda(M_{thres}/2) \text{ for } q = 1$$

- Note: Important that a signature is unambiguously related to a PT, i.e. all possible hadronic EoS should behave differently
- Overplotting $M_{\rm thres} = aM_{\rm max} + b\tilde{\Lambda}_{\rm thres} + c$

→ no hadronic EoS can occur in the "hybrid" regime because this would require a lower Mmax, which is excluded by pulsar observations

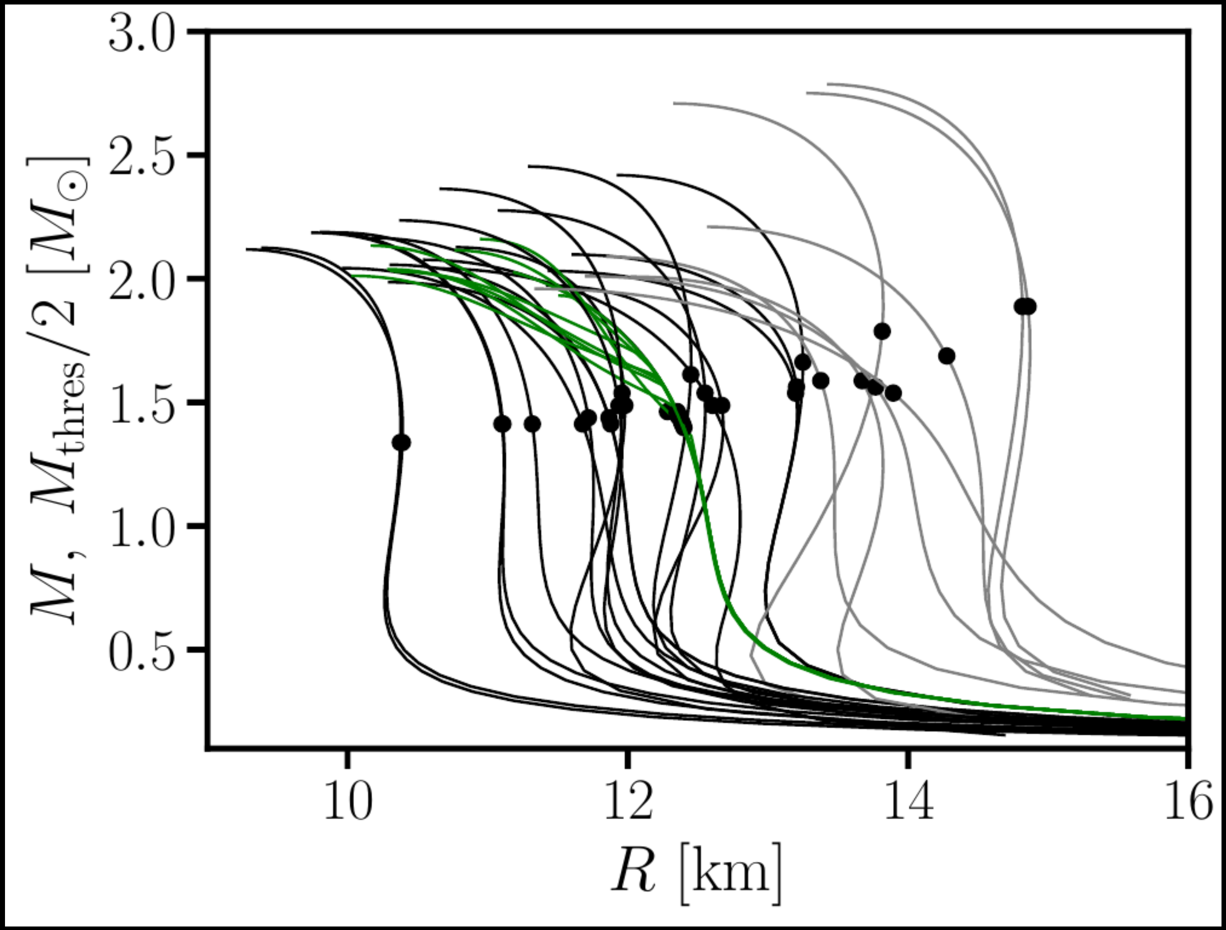
→ hybrid models can violate this relation and occur at relatively low Mthres for the given Lambda_thres

Lambda_thres probes moderate densities, i.e. hadronic regime, and does not know yet about the softening of the EoS at higher densities which leads to a "earlier" collapse



arXiv:2010.04461

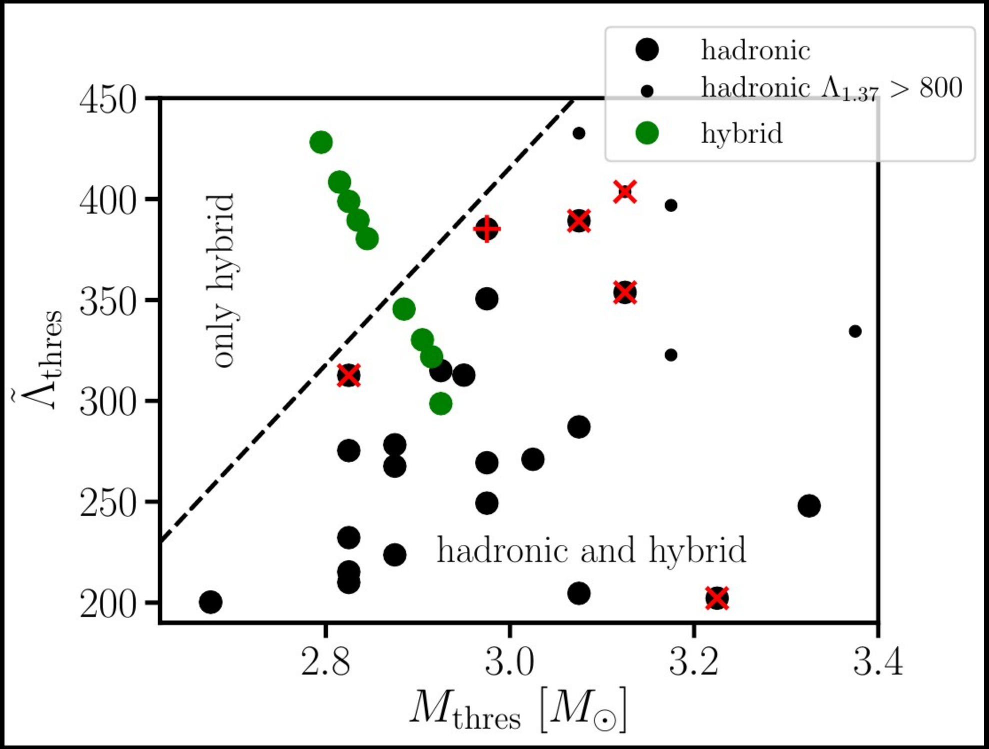
- Dots show Mthres/2 → phase transition occurs after merger



Bauswein et al., PRL 2020

QCD phase transition from collapse behavior

- In other words, if there is evidence for a prompt collapse although the tidal deformability suggest there shouldn't → points to a strong phase transition
- Already a single measurement may provide interesting insights
- Also $\Lambda_{1.4}$ - M_{thres} diagram reveals hadron-quark phase transition (less clear)



Bauswein et al., PRL 2020

Collapse behavior – general considerations

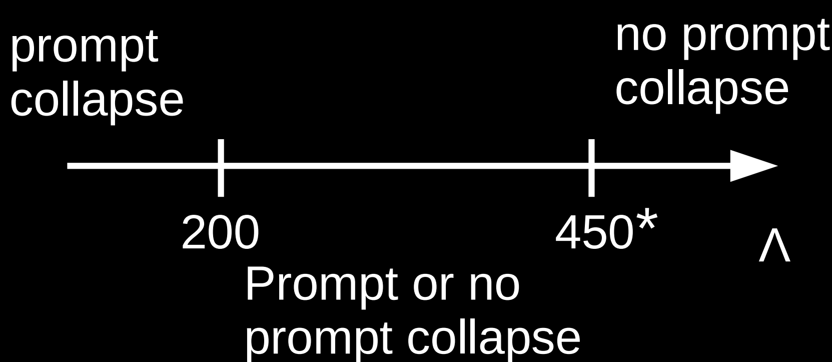
- General consideration for all EoSs
- General range: 200 < Λ_{thres} < 450* (cf. Zappa et al 2018)

→ only for Λ_{thres} < 200 we can safely assume a prompt collapse

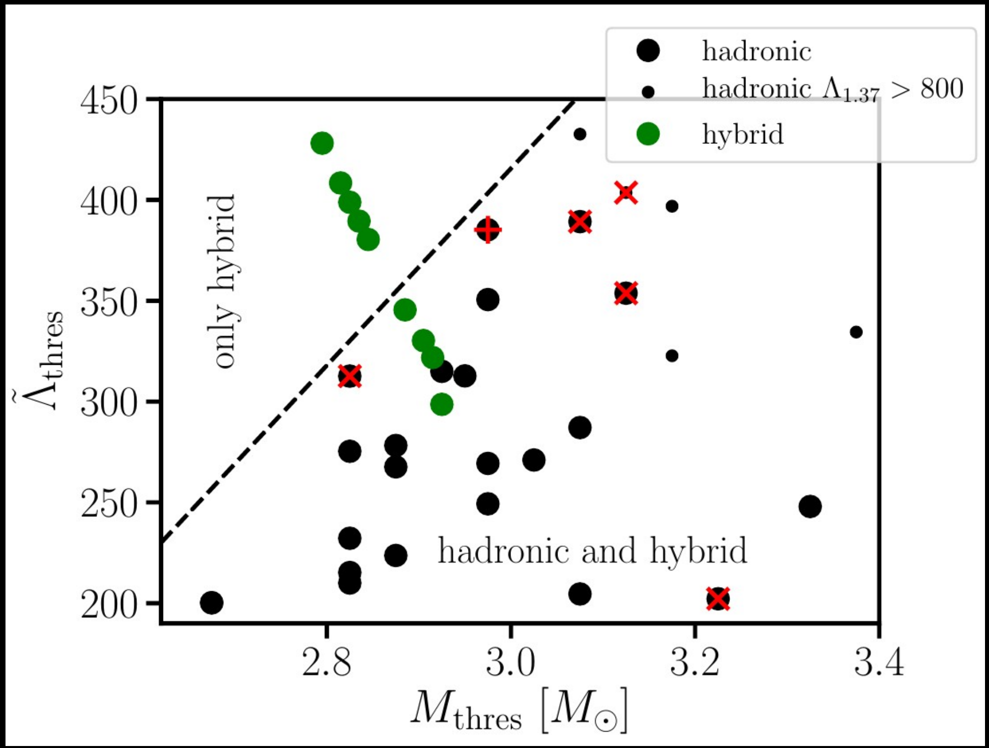
→ only for Λ_{thres} > 450 / 650 we can safely assume that there was no direct collapse

→ GW17087: **$\Lambda_{1.37}$ > 200** (if no direct collapse, i.e. M_{thres} > 2.73 M_{sun})

(cf. R /Λ limits from Bauswein et al. 2017, Radice et. al 2018, Most et al. 2018, Koeppel et al. 2019, Bauswein et al. 2019, Capano et al. 2020, ...)

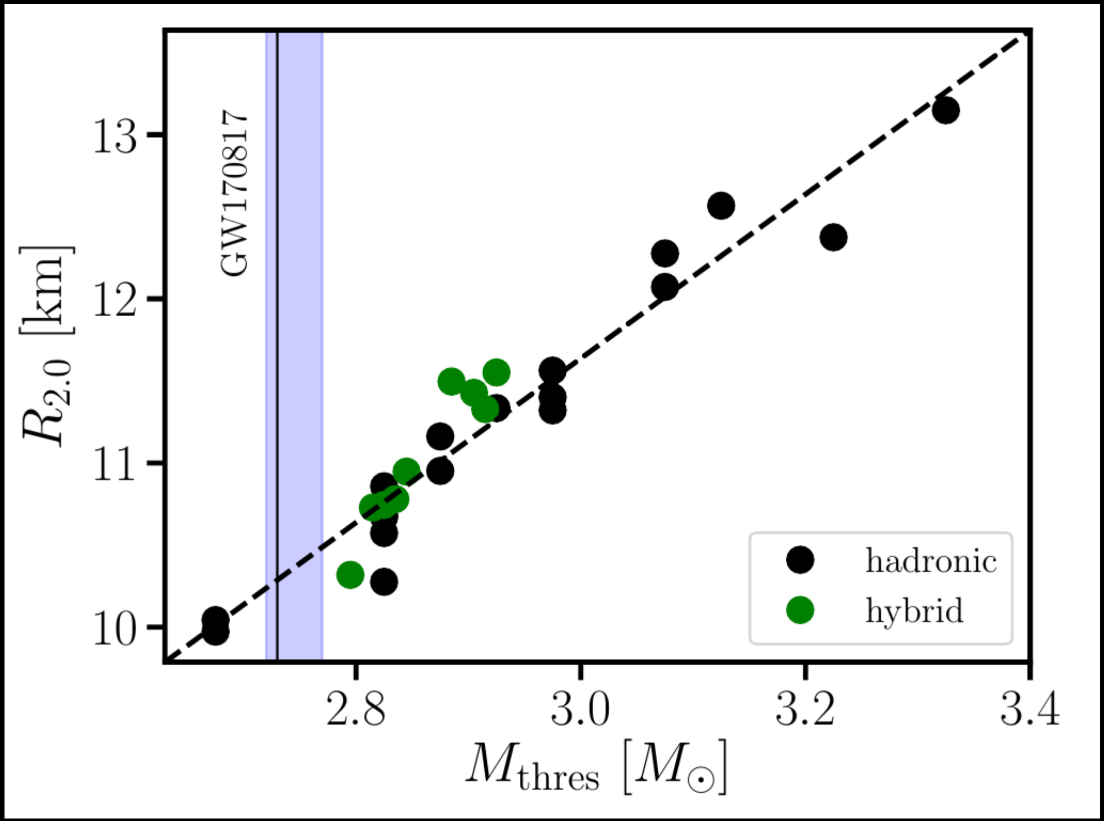


* 650 for q=0.7



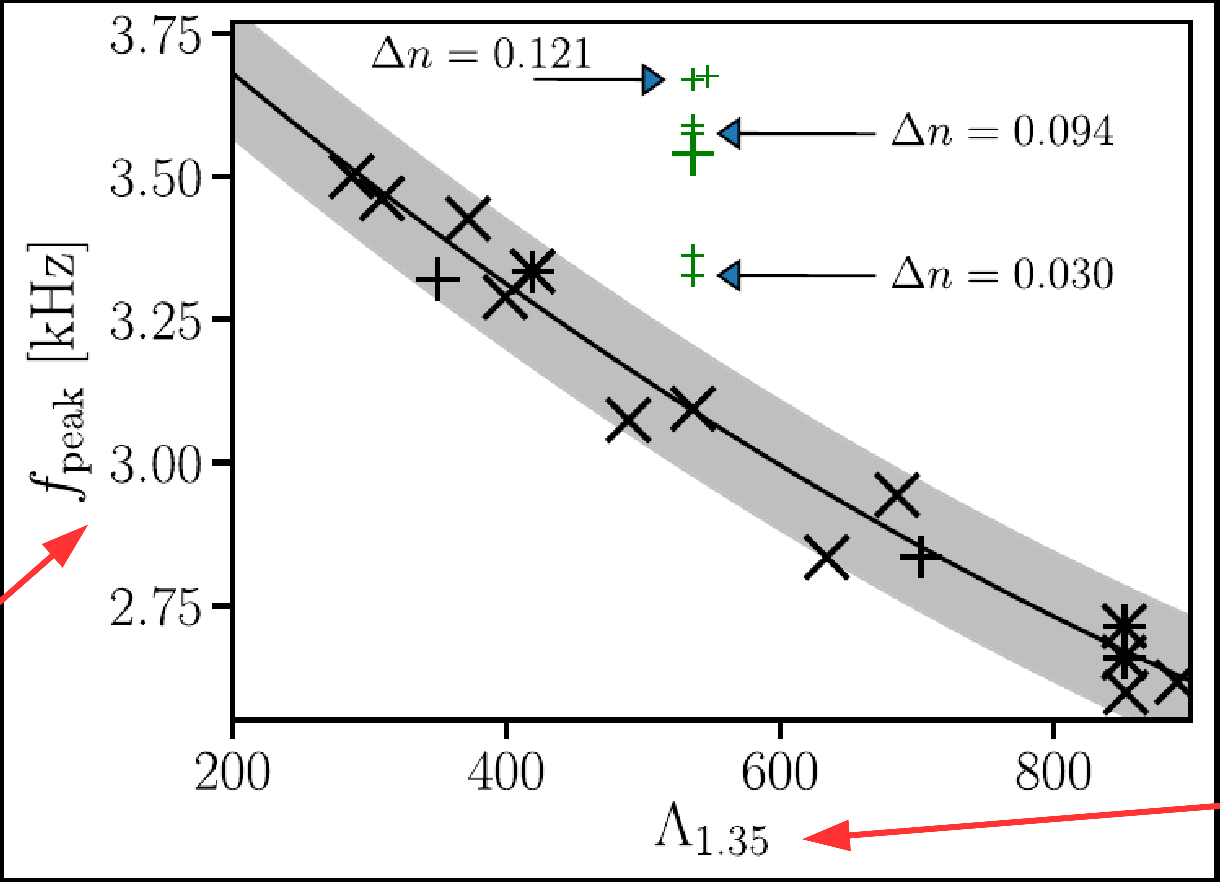
Bauswein et al., PRL 2020

- Univariate relations between Mthres and high-mass NS properties (R and Lambda)
- Insensitive to presence of phase transition



arXiv:2010.04461

Alternative signature of 1st order phase transition



Green models with phase transition to quark matter [Fischer et al. 2018]

from postmerger

from the inspiral

A.B. et al, PRL 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

Summary and conclusions

- Outcome one of the most basic characteristics of a merger – quantified by Mthres
- Tight relations describing Mthres as function of stellar parameters (for fixed q)
- Allows constraints on these parameters, e.g. Mmax

  → probed the very high density regime of EoS (which may be hard to access otherwise)

  → interesting radius constraints from current and future multi-messenger observations
- Binary mass asymmetry typically leads to lower Mthres (less stability) – in systematic dependencies
- Generalized tight (!) fit formulae for Mthres with explicit q dependence
- Phase transition to deconfined quark matter can lead to reduction of Mthres

  → unambiguous signature in Mthres-Lambda_thres plane

  → importance of instruments and search strategies for follow-up in GW and em