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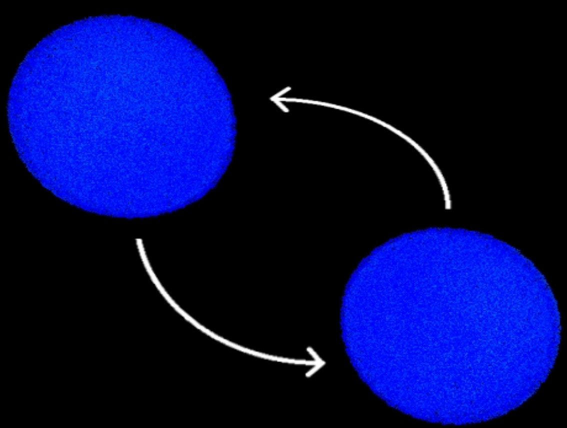
Neutron star merger simulations

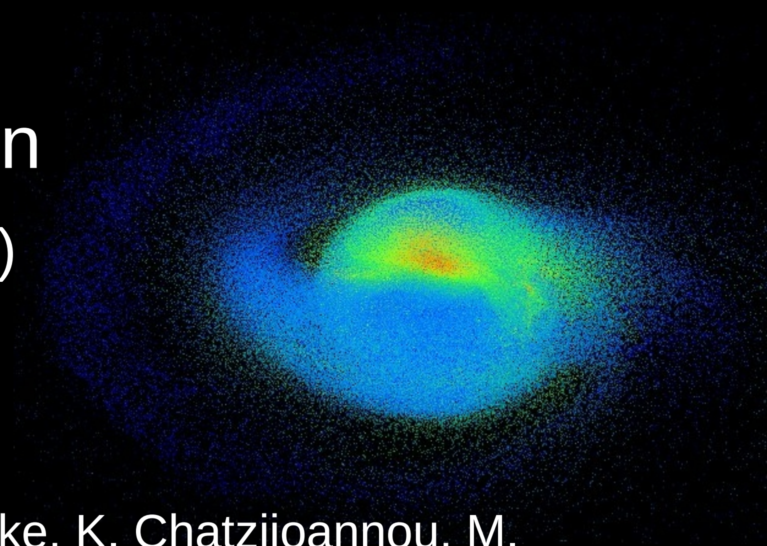
Pharos Compose Workshop

virtual, 24/02/2021

Andreas Bauswein

(GSI Darmstadt, HFHF)





with R. Ardevol, N. Bastian, S. Blacker, D. B. Blaschke, K. Chatziioannou, M. Cierniak, J. A. Clark, T. Fischer, S. Goriely, T. Janka, O. Just, G. Lioutas, M. Oertel, T. Soultanis, N. Stergioulas, S. Typel, V. Vijayan

Outline

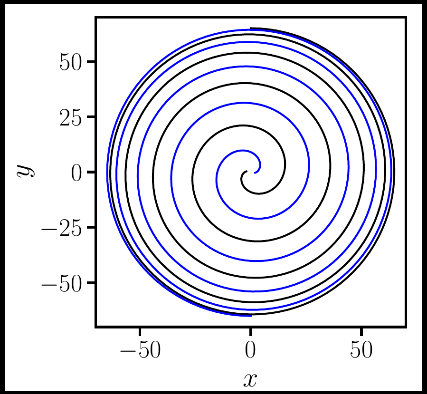
- Basic details of simulation code / EoS in mergers
- Studies based on availability of large EoS sample/repository

  → to motivate wish list / future needs

  - Phase diagram of matter from merger perspective and impact of hadron-quark phase transition in NS mergers

  - EoS dependence of BH formation

  - Correspondence between frequencies in postmerger remnants and isolated stars
- Secular ejecta in BH torus systems – systematic investigation
- Wish list



Inspiral of NS binary

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

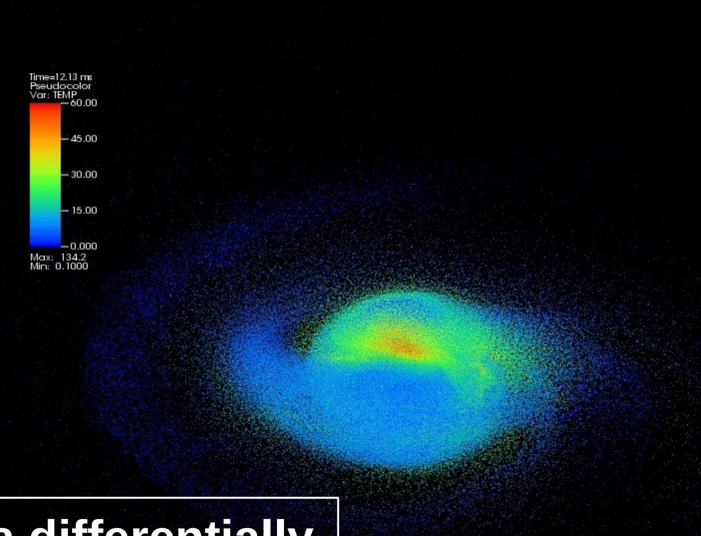
Mostly point-particle dynamics

~100 Myrs

Only last cycles affected by cold EoS

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

Neutron star merger



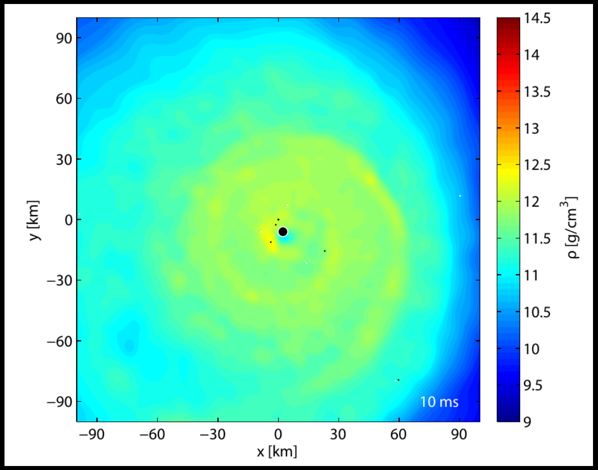
dependent on EoS, M_{tot}

ms

ms

Prompt formation of a BH + torus

Formation of a differentially rotating massive NS



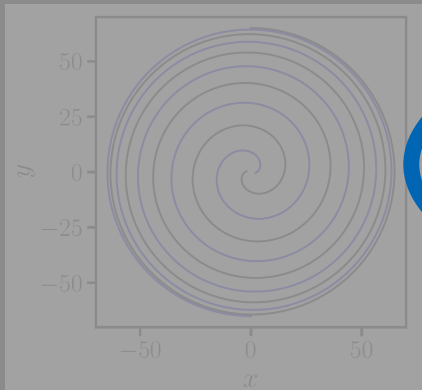
dependent on EoS, M_{tot}

10-100 ms

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

Delayed collapse to a BH + torus

Cold EoS in neutrinoless beta equilibrium



Inspiral of NS binary

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

~100 Myrs

Mostly point-particle dynamics

Only last cycles affected by cold EoS

Hot EoS – several 10 MeV

Weak interactions may affect certain features in particular ejecta

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

Neutron star merger

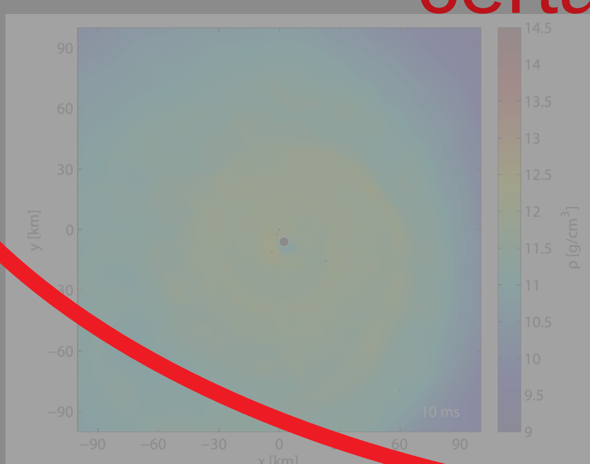
dependent on EoS, M_{tot}

ms

ms

Prompt formation of a BH + torus

Formation of rotating...



dependent on EoS, M_{tot}

10-100 ms

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

Delayed collapse to a BH + torus

EoS ingredients – tentative importance

- Binary inspiral: cold EoS in neutrinoless beta equilibrium, i.e. barotropic EoS sufficient (?)

- NS merger: hot, composition dependent EoS, weak interactions

  - postmerger GW signal: thermal pressure <10% effect, neutrinos marginal impact

  - prompt BH formation / Mthres: thermal pressure relevant, neutrinos marginal impact

  - life time sensitive to thermal pressure, neutrino cooling, B-fields but also resolution

  - ejecta properties: thermal pressure >10% effect on ejecta mass, neutrinos very relevant for mass and in particular composition

  - torus mass: thermal pressure ~10% effect, neutrino impact highly relevant for secular evolution of torus and its ejecta

- Note: additional, possibly stronger (!!) impact from modeling (e.g. resolution dependence, MHD, neutrino treatment, etc), viscosity; different effects of neutrinos

All just hand-waving numbers based on e.g. Gamma_th comparison, w/wo neutrinos

Some basic details about EoS implementation

- Specific to our relativistic smooth particle hydrodynamics code, but similar to other grid-based codes
- Baryon and energy conservation yield evolution equations for "conserved" variables (Lagrangian formulation)

$$\frac{d}{dt}\rho^* = \ldots$$
$$\frac{d}{dt}\hat{u}_i = \ldots$$
$$\frac{d}{dt}\tau = \ldots$$

- EoS required to close the system $P = P(\rho, u, Y_e)$

  + evolution eq. for Ye $\frac{d}{dt}Y_e = \ldots$

- Since "primitive" variables like P occur on RHS, con2prim is required in every step (next talk)
- Starting point for simplifications or sophistication

Some basic details about EoS implementation

- In practice we have rho, u and Ye from evolution equations
- But table in the form $P(\rho, T, Y_e)$ $u(\rho, T, Y_e)$ + arrays for e.g. chem potentials and entropy

  → in every EoS call inversion along T direction until u is found

Popular simplification

- Only barotropic relation available → treat thermal pressure in an approximate way
- Computationally cheaper and thus beneficial for large studies

$$P = P_{\mathrm{cold}} + P_{\mathrm{th}},$$

$$\epsilon = \epsilon_{\mathrm{cold}} + \epsilon_{\mathrm{th}}.$$

From energy and density evolution

$$\epsilon_{\mathrm{th}} = \epsilon - \epsilon_{\mathrm{cold}}(\rho),$$

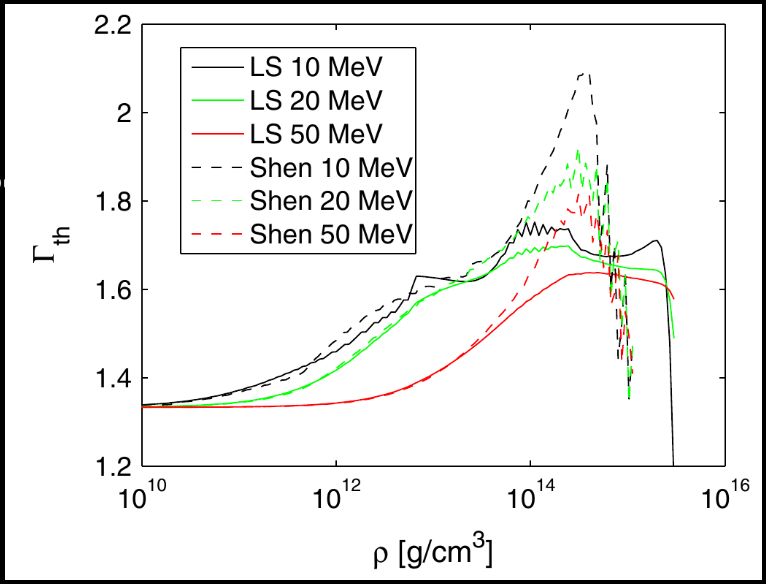
- Freedom to choose constant Gamma_th

  → simplification, but not too bad for GWs

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

- Subtle effect: we instantaneously reset Ye to value of neutrinoless b[…] equilibrium

  → Gamma_th should effectively capture both effects



Bauswein+ 2010

See e.g. Constantinou+ 2015,2017, Carbone & Schwenk 2019, ... for deep discussion of Gamma_th

Weak interactions

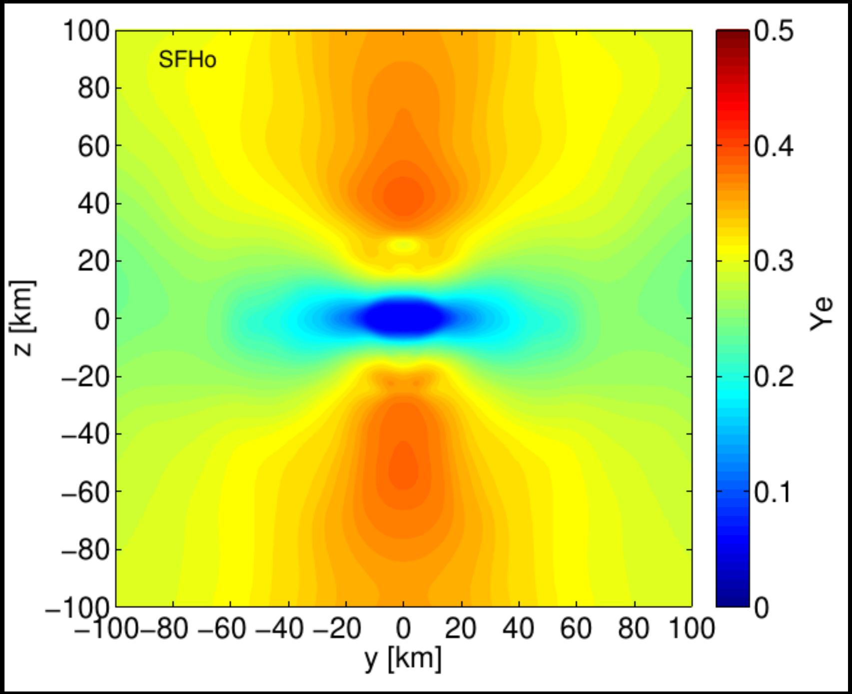
- Different schemes available (see talks on Friday)
- Improved leakage-equilibration-absorption scheme ILEAS (Ardevol-Pulpillo+ 2019)

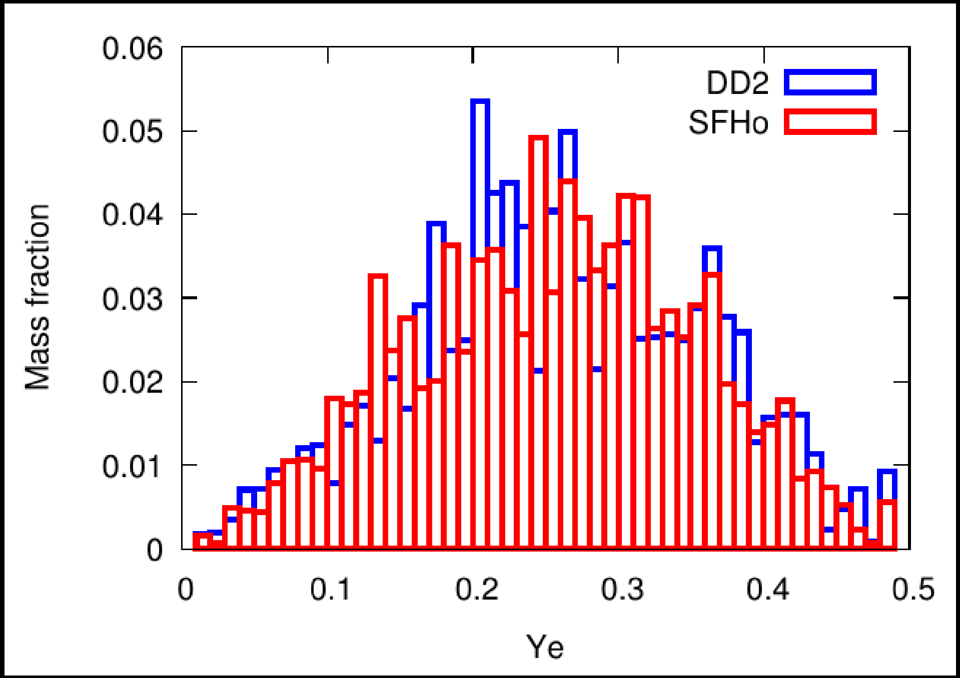
→ 3 modules implemented in relativistic SPH:

- leakage: loss of leptons and energy

- equilibration: treatment of optically thick regime (neutrinos trapped → corrections to pressure and energy → relevant for bulk properties, e.g. GWs)

- absorption: reabsorption of neutrinos in semi-transparent regime





SFHO 1.35-1.35 Msun, Ardevol+2019

Equilibration

- Simple to implement and should capture some main effects on stellar structure
- In optically thick regime trapped neutrinos in beta-equilibrium with matter

  → advect / evolve $Y_{lep} = Y_e + Y_{\nu_e}^{trap} - Y_{\bar{\nu}_e}^{trap}$

  → Automatic "reshuffling" of trapped neutrinos to be in equilibrium $\mu_{\nu_e} = \mu_e + \mu_p - \mu_n$

- However: now we need new table $P/u(\rho, T, Y_{lep})$ with neutrino pressure and energy to be used only in this regime
- In practice rebuild from original table by adding trapped neutrino contributions and inverting Ylep(Ye)

→ compose wish list?

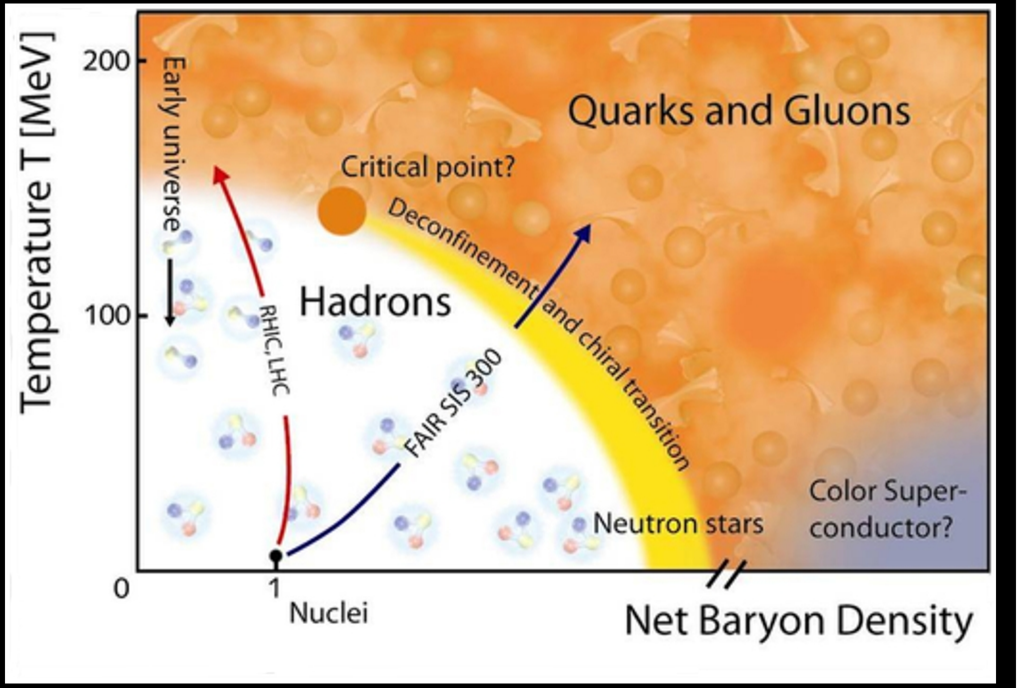
Equilibration region	Trapped ν species
1	$\nu_e,\ \bar{\nu}_e,\ \nu_x$
2	$\nu_e,\ \bar{\nu}_e$
3	$\nu_e,\ \nu_x$
4	$\bar{\nu}_e,\ \nu_x$
5	ν_e
6	$\bar{\nu}_e$
7	ν_x
8	none

Simpler hierachy possible 1,2,5,8

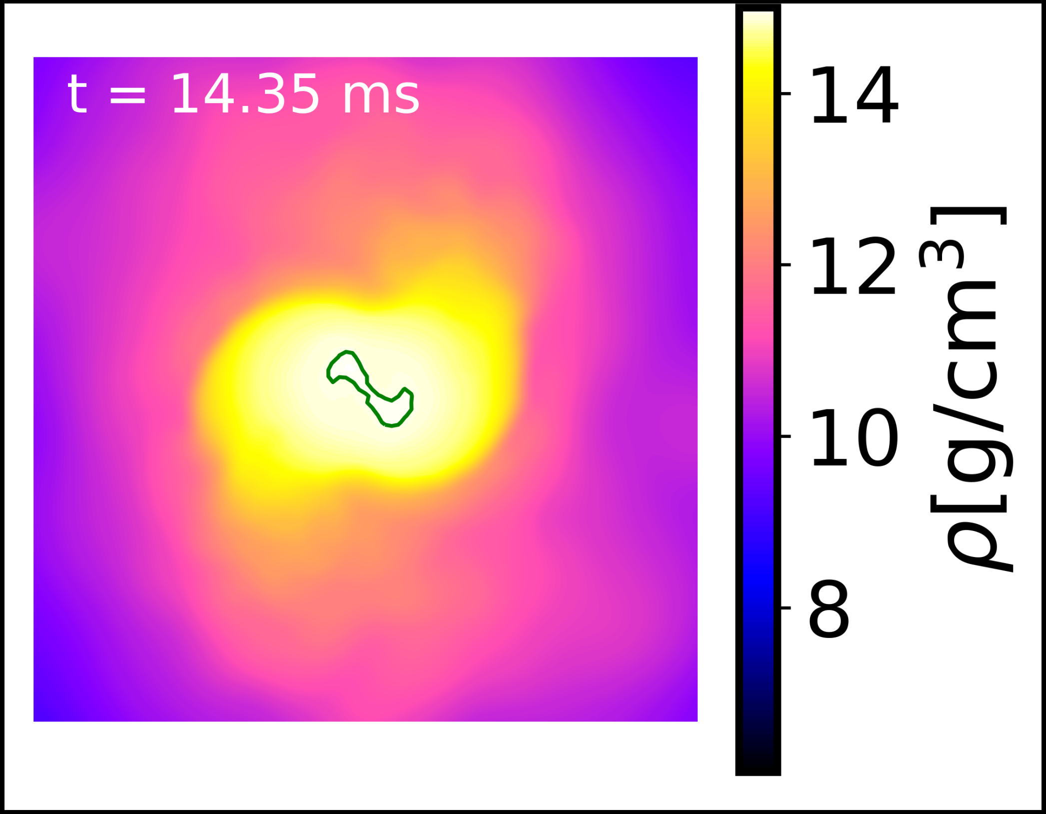
Some merger results where large and representative EoS sample is critical

Hadron-quark phase transition in NS mergers

- Can we constrain at which density quark occur?
- Based on sample of purely hadronic EoS in comparison to EoS with 1st order phase transition to deconfiend quark matter (provided by Wroclaw group: N.-U. Bastian, D. Blaschke, M. Cierniak, T. Fischer)
- PT → effective softening of EoS



GSI/FAIR



See also work by Frankfurt group (Dexheimer, Hanauske, Most, Rezzolla, Weih)

Hadron-quark phase transition in NS mergers

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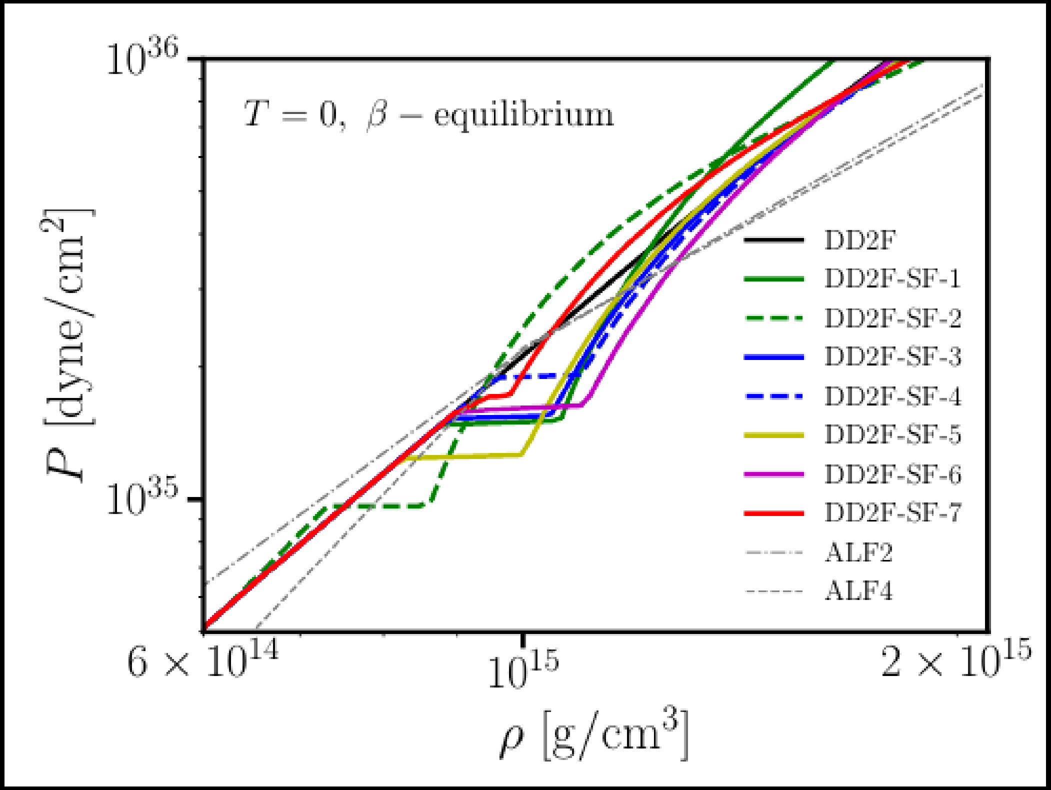
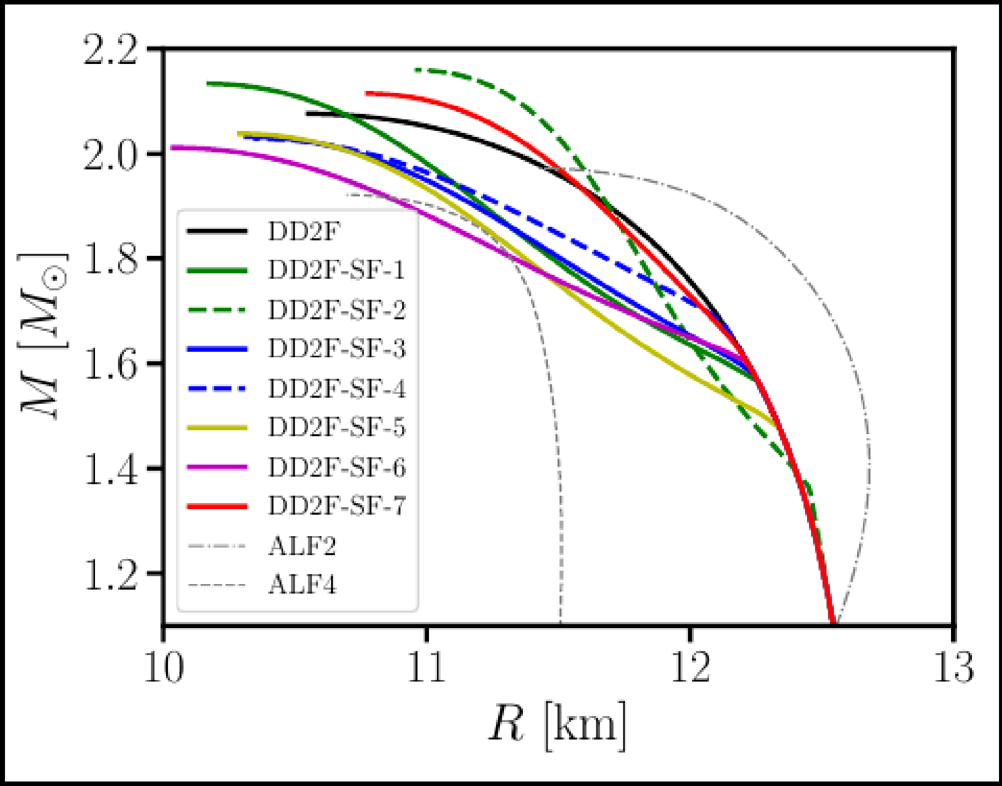
- PT → effective softening of EoS → kink in M-R relation



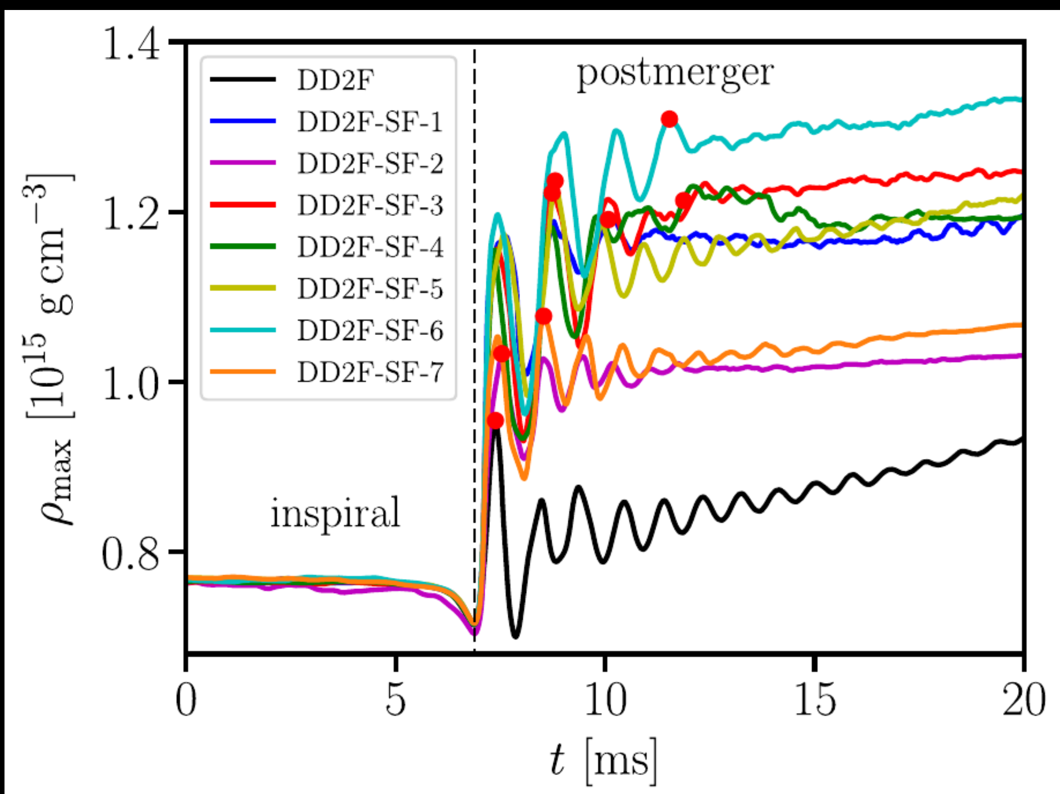


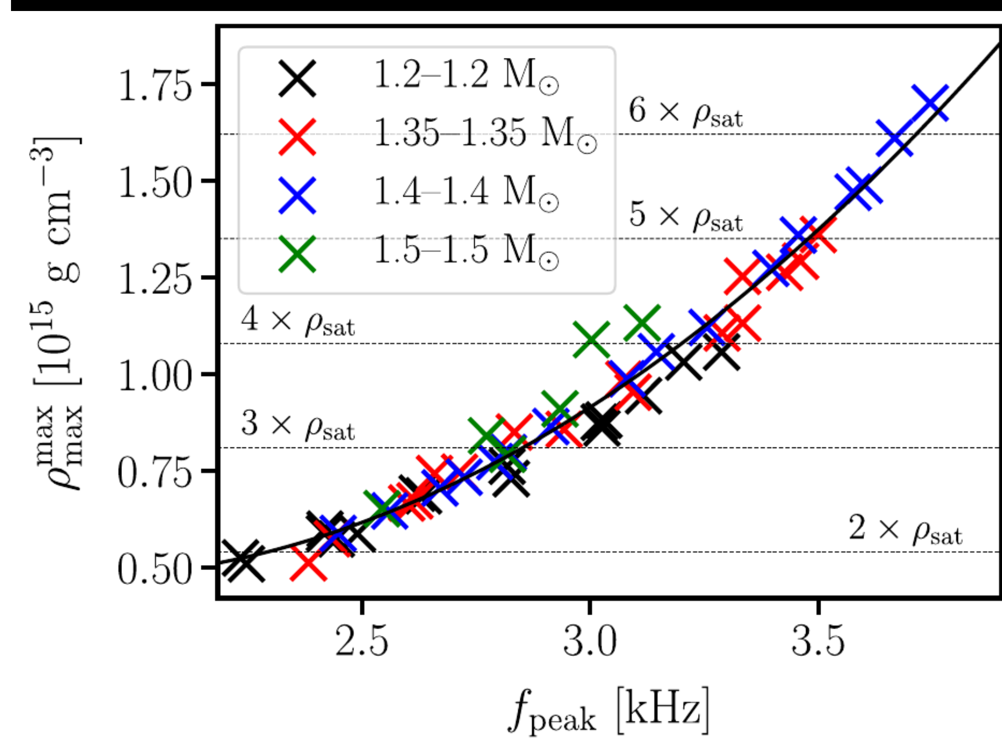
Bauswein+ 2019

Hadron-quark phase transition in NS mergers

Main results:

- EoS softening by PT leads to very compact remnant (oscillation frequency increased relative to tidal deformability of pre-merger stars)
- Strong phase transition leaves an unambiguous imprint on GWs of merger
- GWs carry information on density regime of remnant, i.e. which densities are probed → constraint on onset density of hadron-quark phase transition





→ compose wish list – importance to have a representative set of purely hadronic EoSs

Blacker+ 2020

Hadron-quark phase transition in NS mergers

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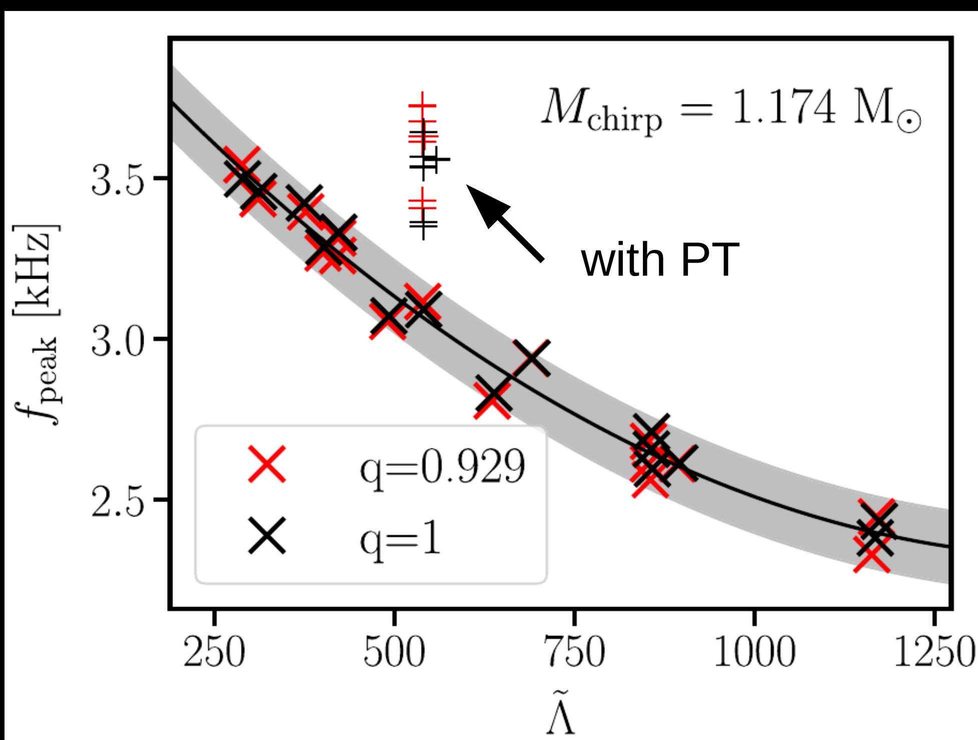
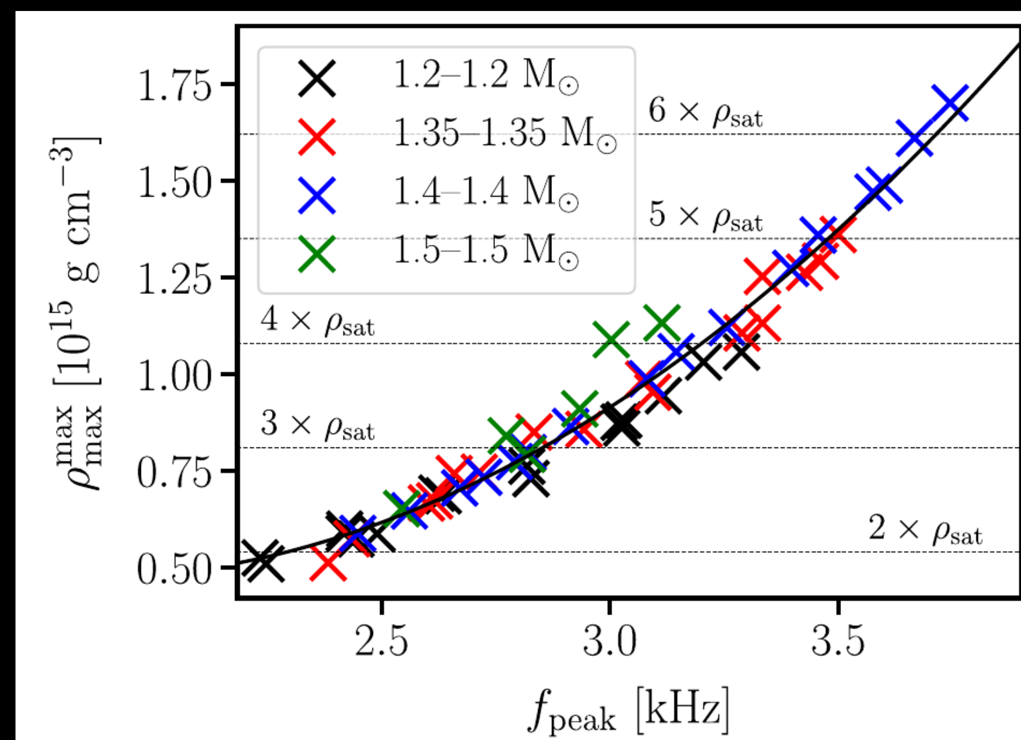


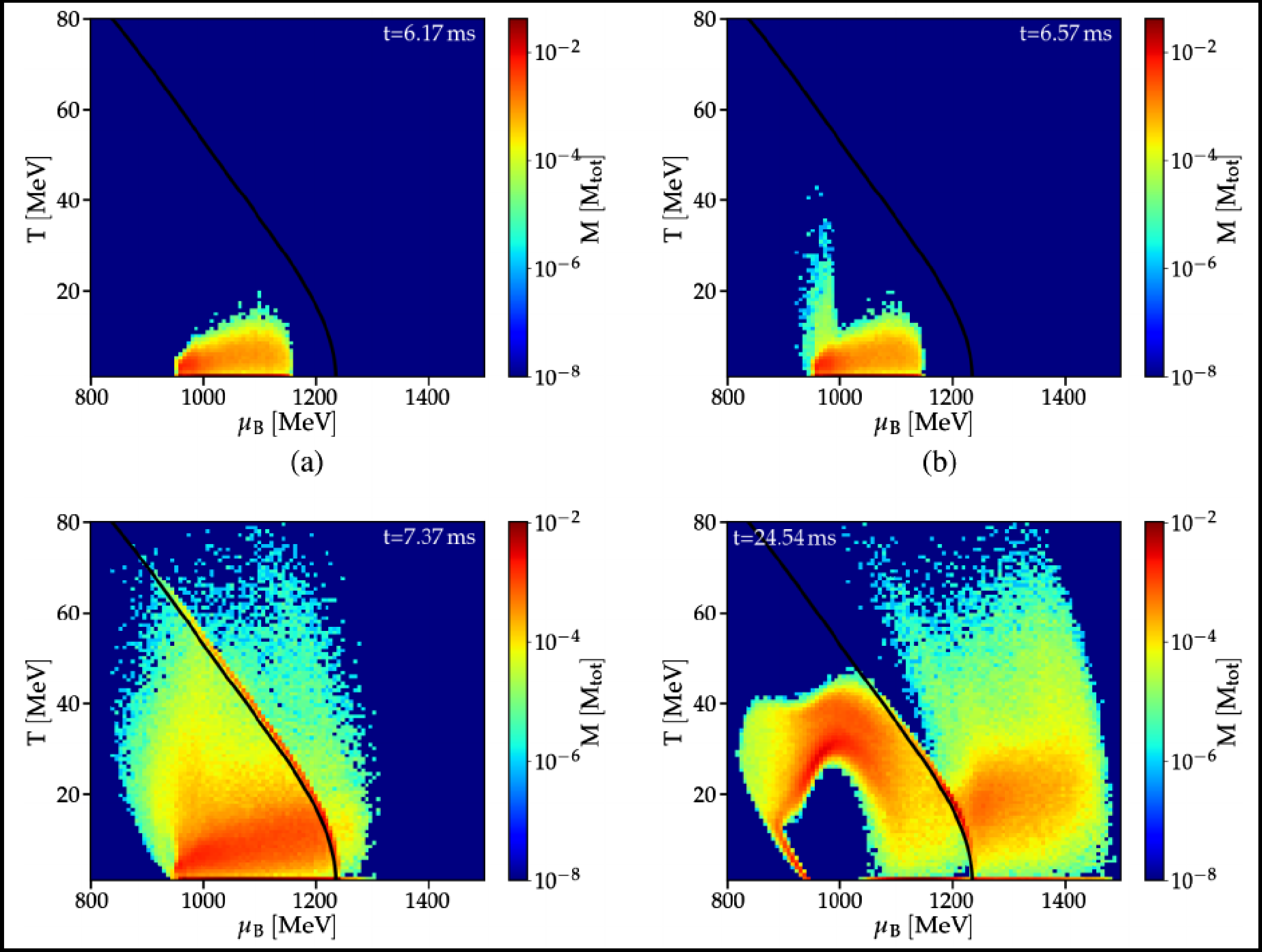


→ compose wish list – importance to have a representative set of purely hadronic EoSs

Blacker+ 2020

Hadron-quark phase transition in NS mergers

- Technical note: thermal effects very important – T dependent phase boundaries !!
- Cannot be well captured by Gamma_th

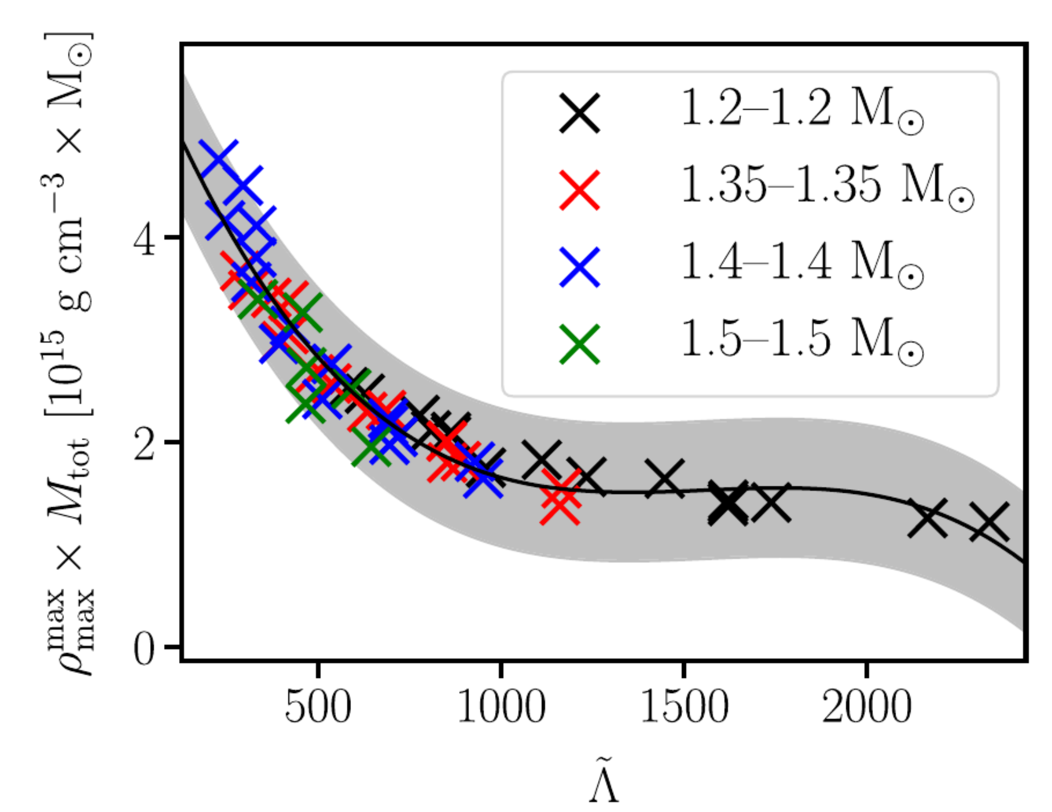


→ compose wish list

Blacker+ 2020

Density regime in mergers

- Generally interesting to understand density regime of NS mergers
- Compression factor during merging higher for softer EoSs



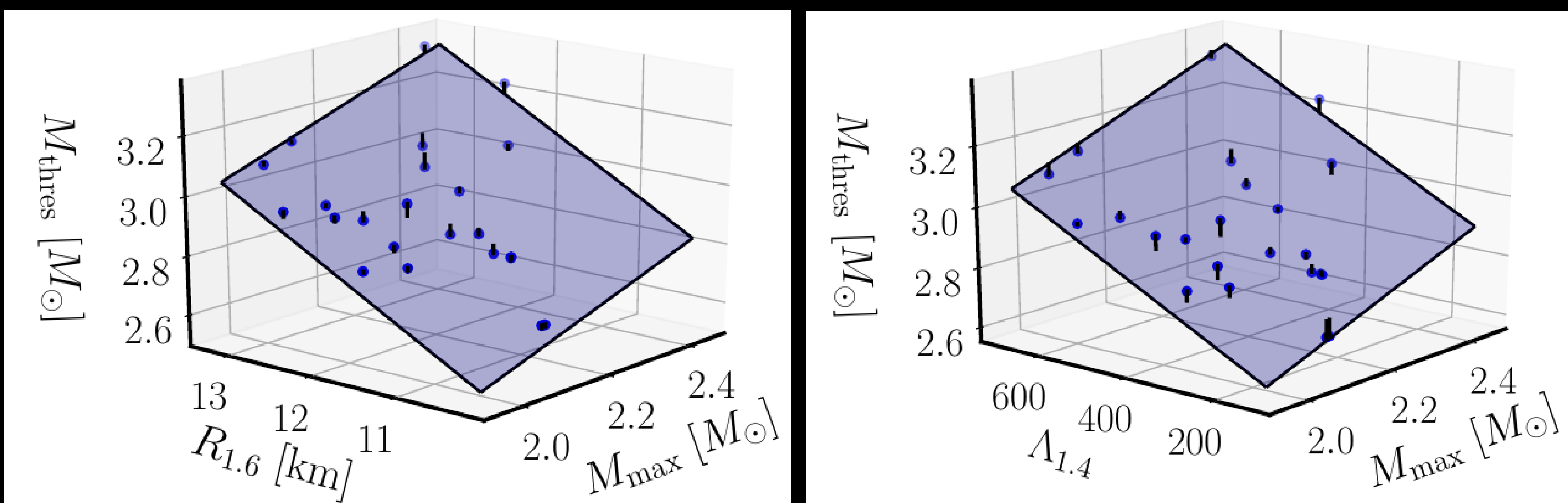
Blacker+2020

Prompt BH formation in NS mergers

- Again, critical to explore largest possible parameter space
- One of the most basic features of merger: BH - yes or no

  → quantified by threshold binary mass Mthres
- 40 different mostly hot EoS models
- 3 different binary mass ratios Mthres(q) ~ 400 simulations

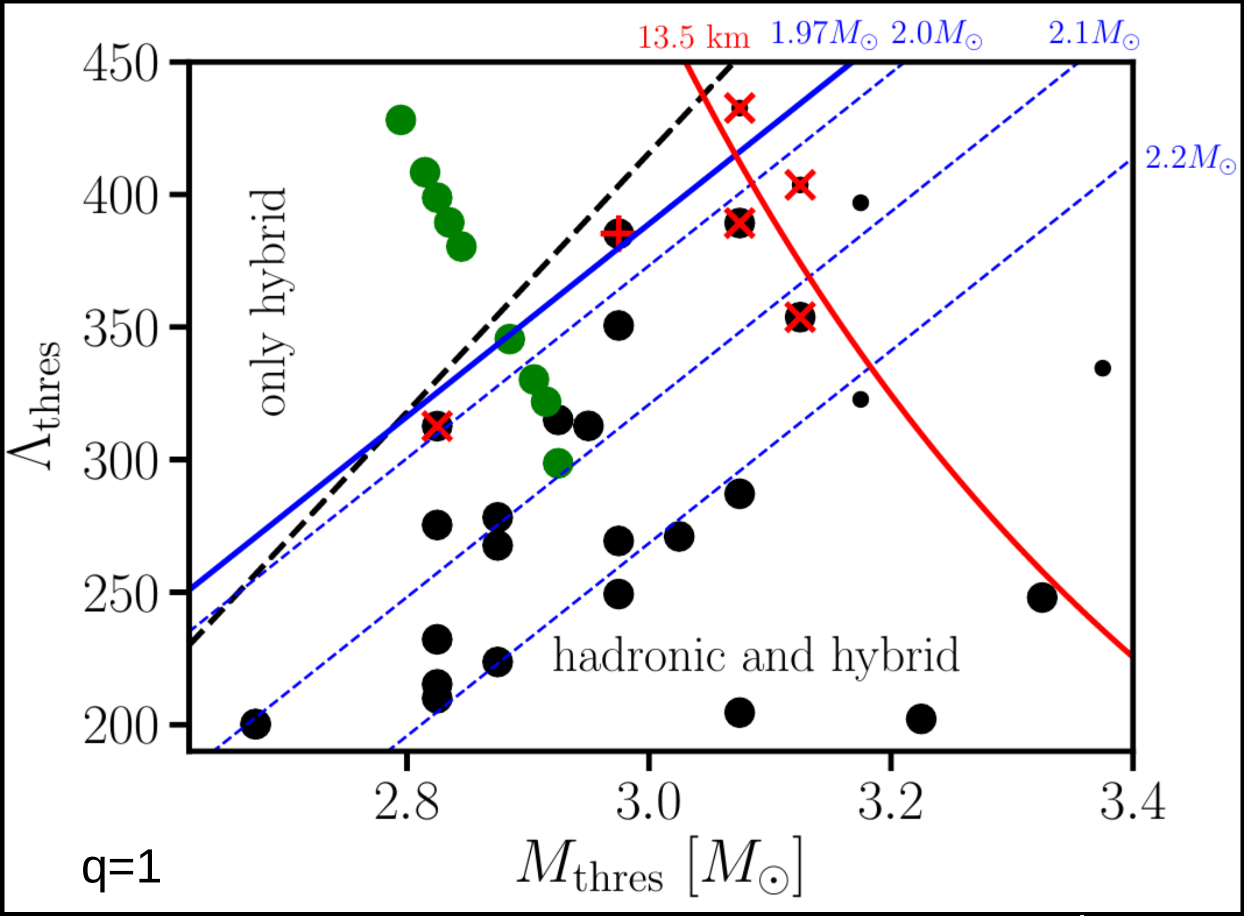
  → very tight expressions for Mthres(q)



Bauswein+ 2020

Prompt BH formation in NS mergers

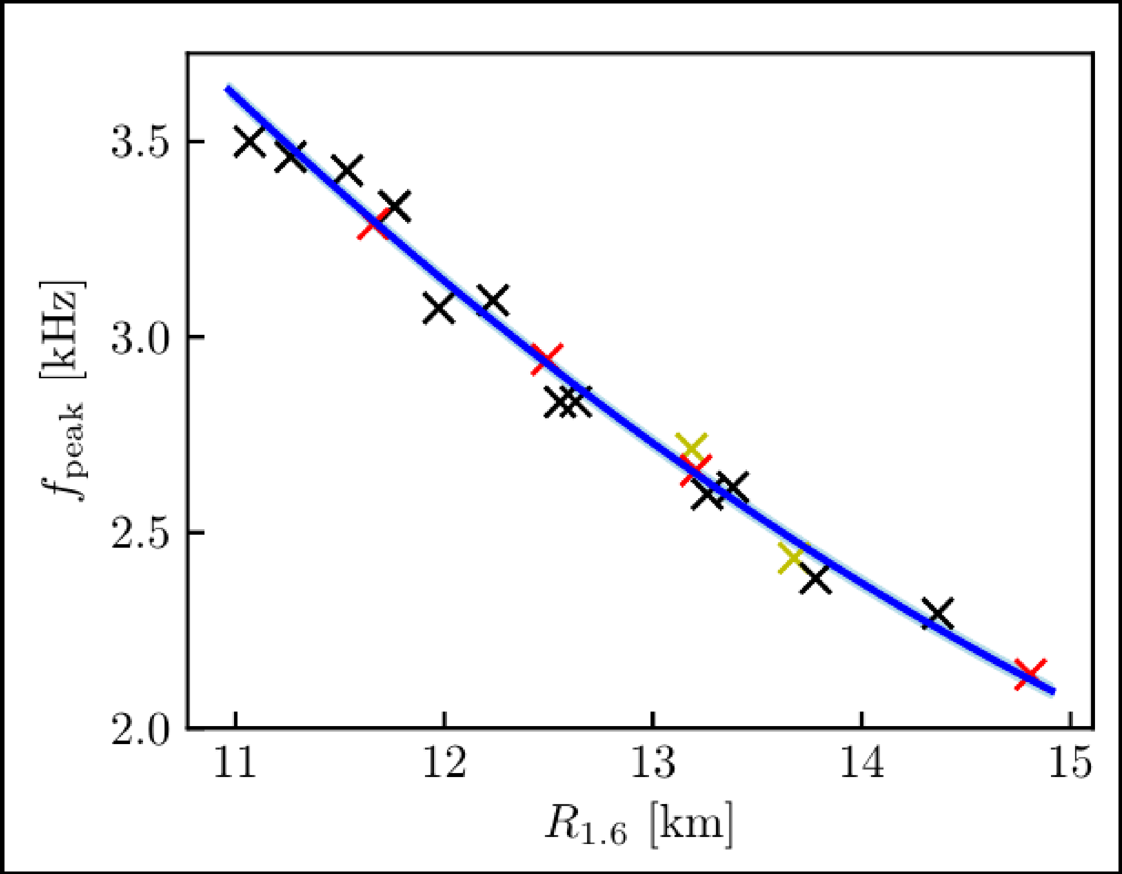
- Hadron-quark phase transition can lead to characteristic reduction of Mthres (and increase of Lambda_thres)
- For 0.7 < q=M1/M2 < 1:   200 < Lambda_thres < 650



Bauswein+ 2020

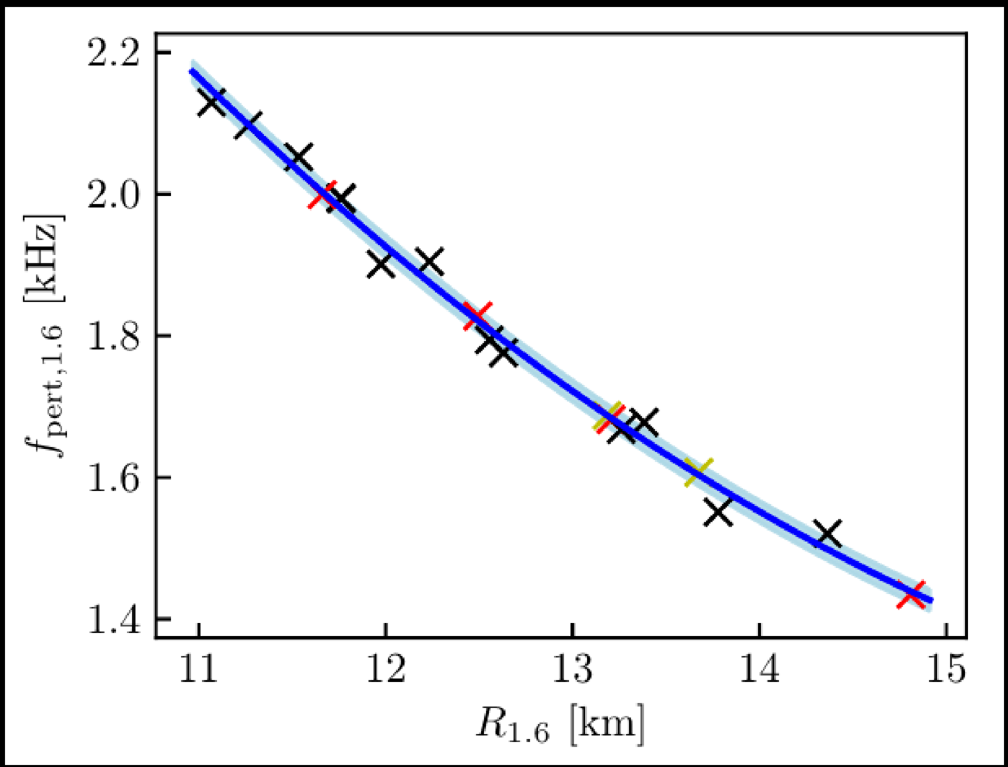
Postmerger GW frequency

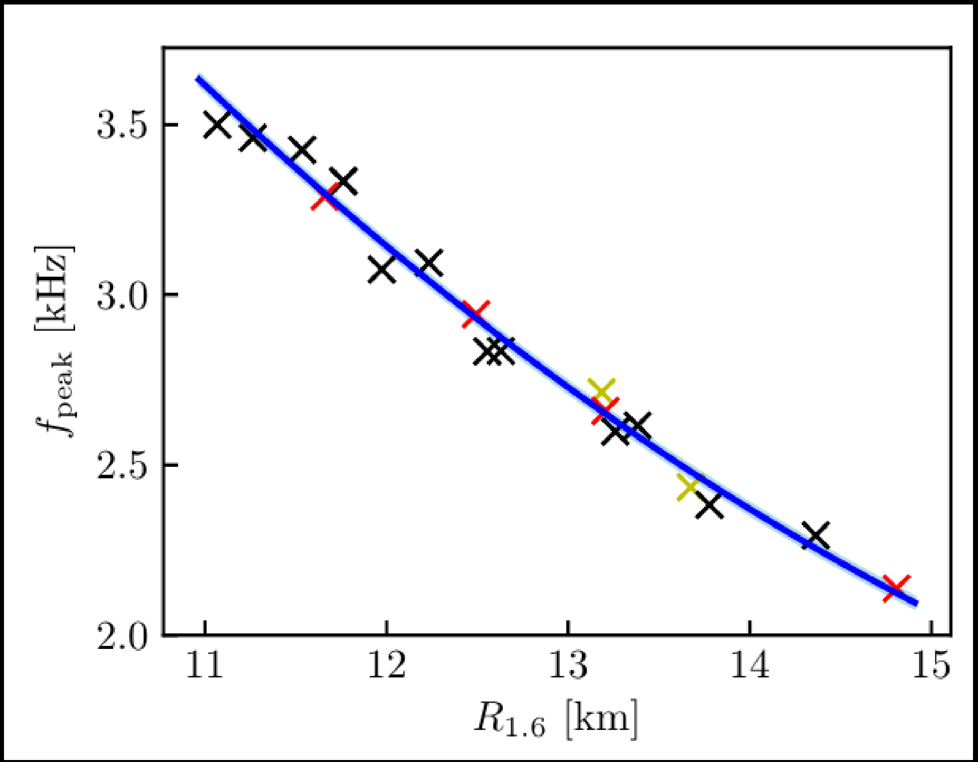
- Tight relations between dominant postmerger GW frequency and TOV properties
- Does the residual scatter mean anything?



Lioutas+ 2021, arXiv:2102.12455

- Compare f-mode frequency of isolated, nonrotating cold NS and oscillation of hot, massive, rapidly rotating, dynamically evolving merger remnant
- (as function of the same independent variable, i.e. TOV property to characterize EoS)
- Frequency deviations correlate – data point cluster in very similar way





Frequencies from perturbative calculation

frequency from messy 3d merger simulation

Also for other (binary) masses and other TOV properties, e.g. tidal polarizability

Lioutas+ 2021, arXiv:2102.12455

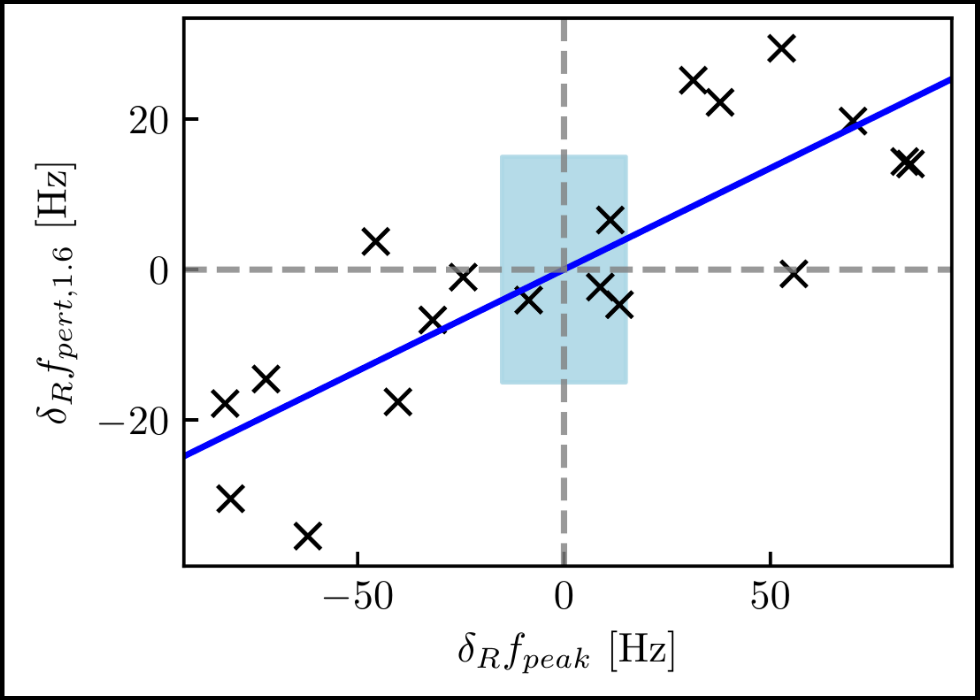
Frequency deviations in static stars and merger remnants

- Agreement of frequency deviations is very remarkable
- Hydro code is apparently able to resolve underlying physics with an accuracy of the frequency devations, i.e. ~10 Hz (not necessarily implying that this is the level of uncertainty, possibly even better trends in reality !)
- Only connection between both codes is EoS

→ frequency deviations encode additional information about EoS

→ e.g. k2 or slope of Lambda(M) – hard but at least in principle measurable

→ agreement corroborates that dominant postmerger oscillation is related to f-mode



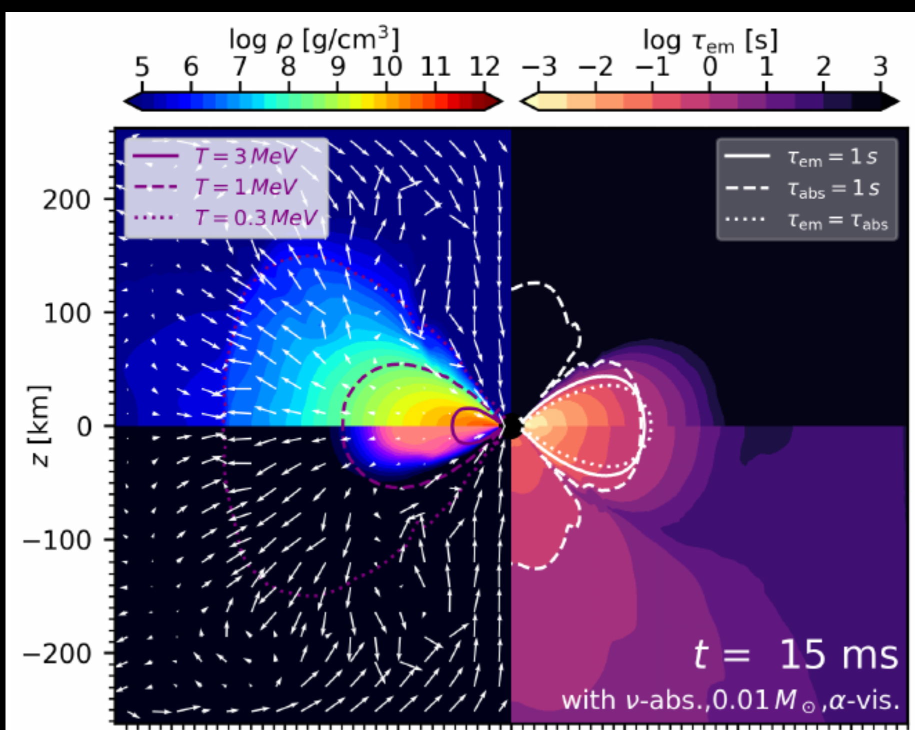
Compose-Note: for such type of study a consistent set of EoS models is critical !
→ may further reduce scatter

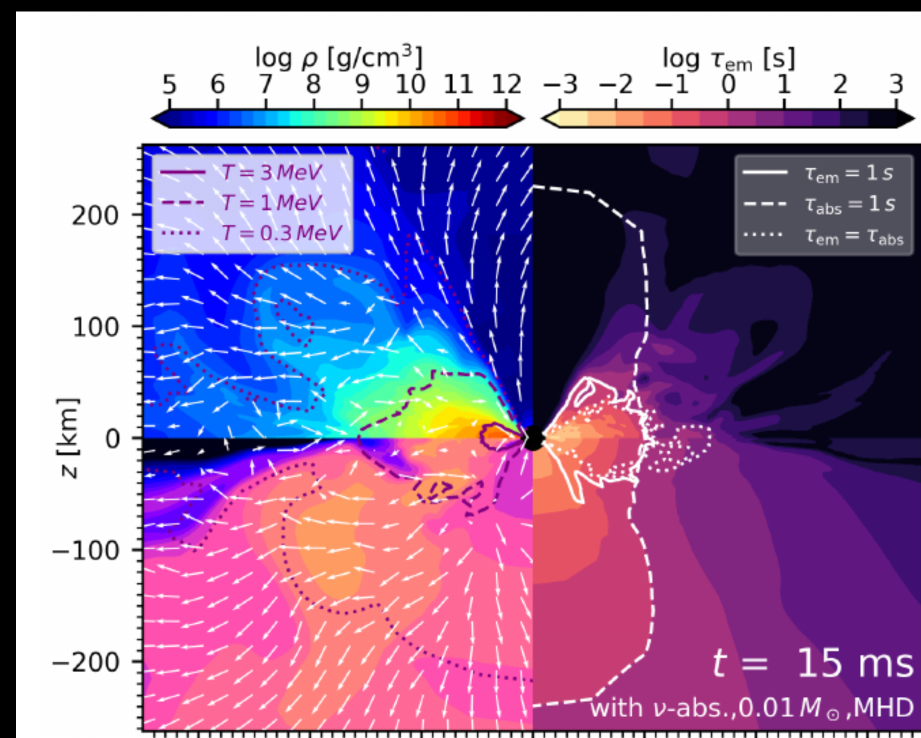
Lioutas+ 2021, arXiv:2102.12455

BH torus ejecta

- Systematic investigation of model ingredients (Just+ 2021)

  → assess impact on ejecta properties
- Truncated moments neutrino transport scheme, pseudo-Newtonian potential, alpha-viscosity / MHD, 2/3d, IC equilibrium torus configurations





Just+ 2021, arXiv:2102.08387

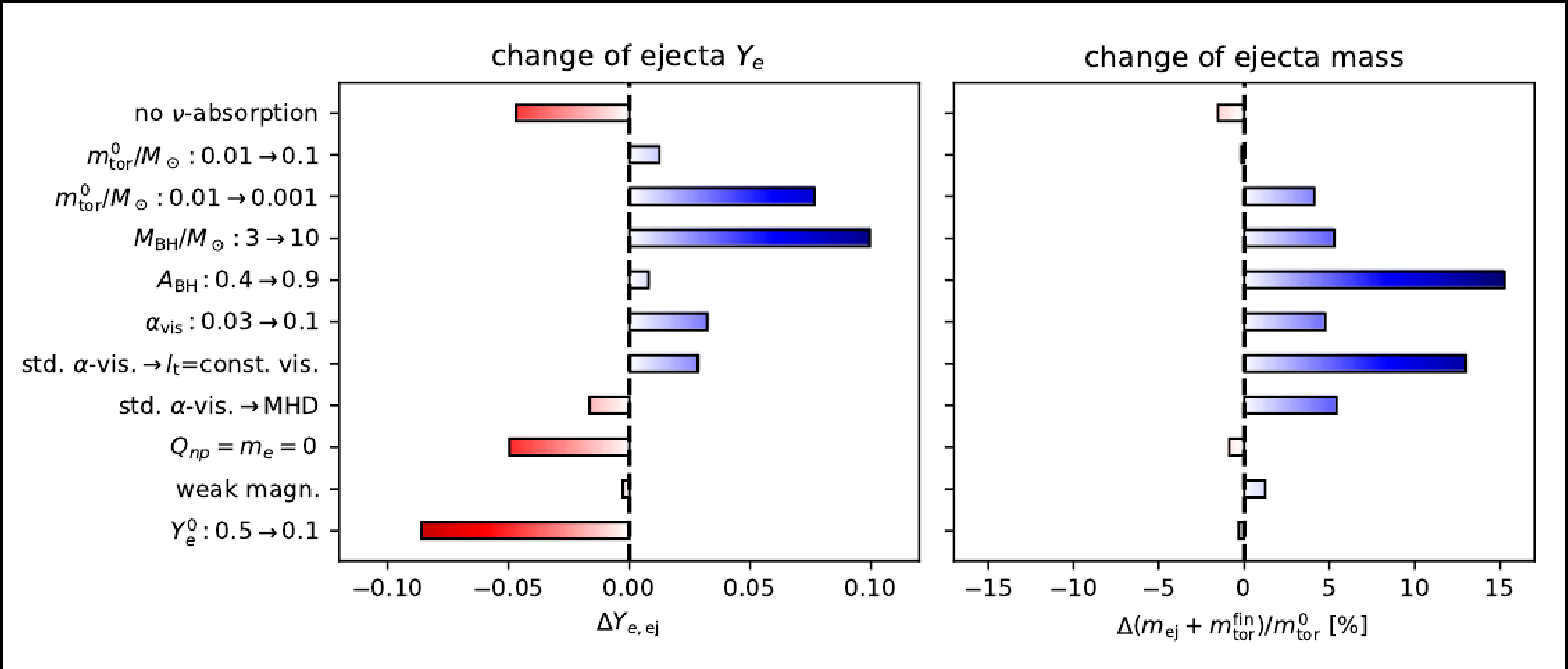
Reference	$m_{\rm tor}^0$ $[M_\odot]$	$M_{\rm BH}$ $[M_\odot]$	$A_{\rm BH}$	Y_e^0	viscosity treatment	neutrino treatment	Q_{np} and m_e included?	$Y_{e,\rm ej}$ [1]
Fernández et al. (2020)	0.03	3	0.8	0.1	std. α-vis.	leak.+abs.	yes	0.28
Fernández et al. (2019)	0.03	3	0.8	0.1	std. α-vis.	leak. ($Y_e^{\rm eq}$=$Y_e^{\rm eq,em}$)	no	0.20
Just et al. (2015a)	0.03	3	0.8	0.1	std. α-vis.	spectral M1	yes	0.27
m01M3A8 *(this work)*	0.01	3	0.8	0.5	std. α-vis.	spectral M1	yes	0.32
m01M3A8-noQm-noν *(this work)*	0.01	3	0.8	0.5	std. α-vis.	no abs. ($Y_e^{\rm eq}$=$Y_e^{\rm eq,em}$)	no	0.24
Fujibayashi et al. (2020a)	0.1	3	0.8	0.07-0.5	l_t=const. vis.	grey M1+leak.	yes	0.31
	0.1	3	0.8	0.07-0.5	l_t=const. vis.	no abs. ($Y_e^{\rm eq}$=$Y_e^{\rm eq,em}$)	yes	0.30
m01M3A8-vis2 *(this work)*	0.01	3	0.8	0.1	l_t=const. vis.	spectral M1	yes	0.35
m01M3A8-vis2-noν *(this work)*	0.01	3	0.8	0.1	l_t=const. vis.	no abs. ($Y_e^{\rm eq}$=$Y_e^{\rm eq,em}$)	yes	0.34
Siegel & Metzger (2018)	0.03	3	0.8	0.1	MHD	leakage	no	0.18
Siegel et al. (2019)	0.016	3	0.8	0.5	MHD	leakage	no	$\lesssim 0.25^{**}$
Fernández et al. (2019)	0.03		0.8	0.1	MHD	leak. ($Y_e^{\rm eq}$=$Y_e^{\rm eq,em}$)	no	0.16
Miller et al. (2019b)	0.12	2.58	0.69	0.1	MHD	Boltzmann	yes	$\sim 0.2 - 0.25^{**}$
Miller et al. (2019a)	0.02	3	0.8	0.5	MHD	Boltzmann	yes	0.36^{*}
m01M3A8-mhd *(this work)*	0.01	3	0.8	0.1	MHD	spectral M1	yes	0.31

model name	$m_{\rm tor}^0$ $[M_\odot]$	$M_{\rm BH}$ $[M_\odot]$	$A_{\rm BH}$	$Y_e(t=0)$	$\alpha_{\rm vis}$	viscosity treatment	mass corr. included?	weak magn. included?	$t^{\rm fin}$ [s]	$m_{\rm tor}^{\rm fin}/m_{\rm tor}^0$ [%]	dimensions
m01M3A8(-noν)	0.01	3	0.8	0.5	0.06	std. α-vis.	yes	no	10 (10)	<1 (<1)	2D
m1M3A8(-noν)	0.1								10 (10)	<1 (<1)	
m001M3A8(-noν)	0.001								10 (10)	<1 (<1)	
m01M5A8(-noν)	0.01	5							10 (10)	<1 (<1)	
m01M10A8(-noν)		10							20 (20)	<1 (<1)	
m01M3A4(-noν)		3	0.4						10 (10)	<1 (<1)	
m01M3A9(-noν)			0.9						10 (10)	<1 (<1)	
m01M3A8-α03(-noν)			0.8		0.03				10 (10)	<1 (<1)	
m01M3A8-α1(-noν)					0.1				10 (10)	<1 (<1)	
m01M3A8-vis2(-noν)					0.05	l_t=const. vis.			20 (20)	5.7 (6.81)	
m01M3A8-mhd(-noν)					–	MHD			2.1 (2.1)	12.5 (15.0)	3D
m01M3A8-noQm(-noν)					0.06	std. α-vis.	no		10 (10)	<1 (<1)	2D
m01M3A8-wm							yes	yes	10	<1	
m01M3A8-ye01(-noν)				0.1				no	10 (10)	<1 (<1)	

Just+ 2021, arXiv:2102.08387

Secular ejecta properties of BH tori

- Impact of physical parameters and modeling (neutrino treatment, angular momentum transport)
- Relative to reference model, Mtor=0.01 Msun, a_BH=0.8, alpha=0.06, nu absorption
- Helpful to assess literature results with different IC and model assumptions



→ compose wish list: appropriate EoS tables

Just+ 2021, arXiv:2102.08387

Summary: Compose wish list*

- More hot EoS models
- Systematic variation of parameters
- More models with phase transition (effectively more degrees of freedom)

  → David's comment earlier this morning (automatic PT construction?)

- Consistent tables with larger parameters space (higher Ye, lower densities, lower lower T)

  → (secular) ejecta and consistent simulations (+ rest mass of nuclei, blocking factors, ...)

- Higher temperatures (50 – 100 MeV is too less), extension to even lower T – in particular for secular ejecta / low density matter
- Tables for equilibration? (e.g. defined through transition densities → relatively simple implementation), i.e. including neutrinos, Ylep as independent quantity

* some aspects had already been mentions in questions/discussions