Strangeness in binary neutron star mergers and its signature

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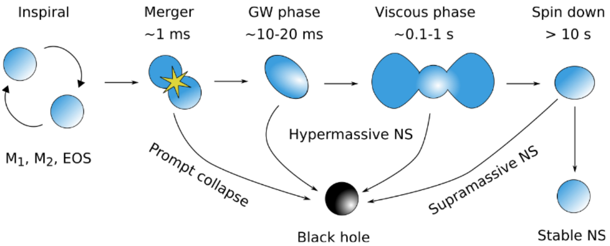
Introduction

BNS merger in a nutshell: dynamics



Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS, Bernuzzi 2020 for recent reviews

- inspiral: driven by GW emission
- GW-dominated phase:
  - $L_{\rm GW} \sim 10^{55}$erg/s — e.g. Zappa *et al* 2018 PRL
  - at merger
    - for $q \sim 1$, $v_{\rm orb}/c \approx \sqrt{\mathcal{C}} \sim 0.39\,(\mathcal{C}/0.15)^{1/2}$ ($\mathcal{C} \equiv M/R$) and $q = M_1/M_2$
    - NS collision $E_{\rm kin} \to E_{\rm int}$
    - copious ν production: $L_\nu \sim 10^{53}$erg/s — Eichler+ 89, Ruffert+ 97, Rosswog & Liebendoerfer 03
- viscous phase: MHD viscosity + ν emission

BNS mergers on thermodynamics diagrams

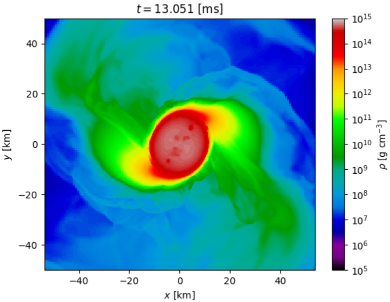
BNS simulation performed with the WhiskyTHC code

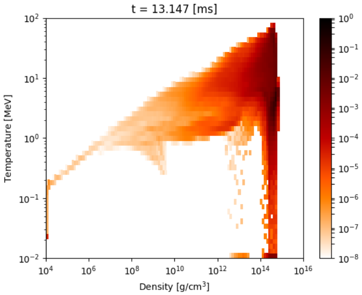
Radice+ 12,14,15

$$M_1 = M_2 = 1.364\, M_\odot$$

DD2 EOS, leakage+M0 scheme for neutrinos

at each time, mass weighted histograms in the ρ-T-Y_e or ρ-s-Y_e plane

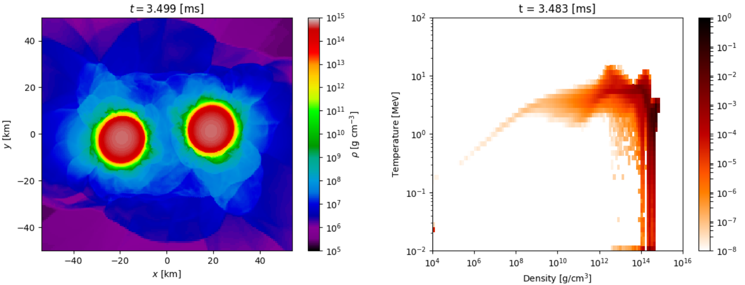




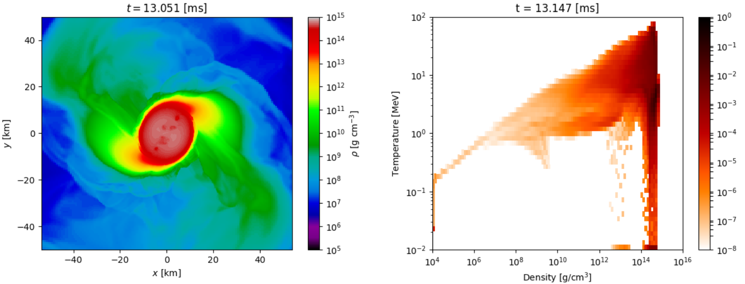
movies at www.youtube.com/channel/UChmn-JGNa9mfY5H5938jnig

BNS mergers on thermodynamics diagrams

inspiral



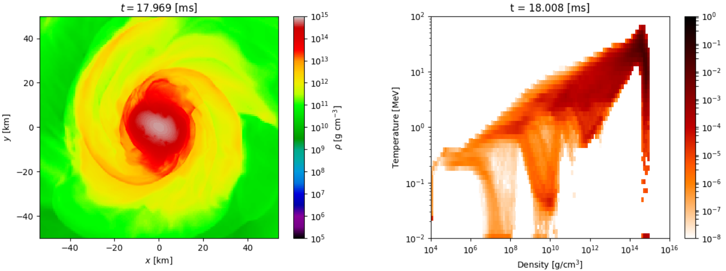
$t(T_{\rm peak})$



Perego,Bernuzzi,Radice EPJA 2019

BNS mergers on thermodynamics diagrams

$t \gtrsim t_{\rm dyn}$



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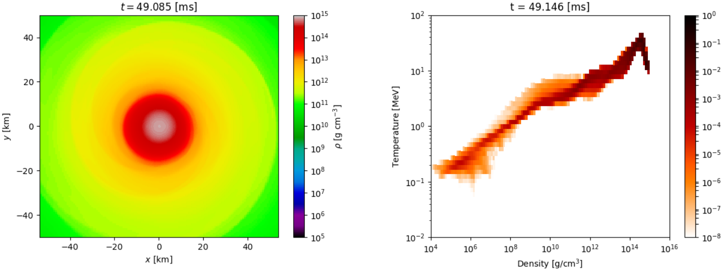


Perego,Bernuzzi,Radice EPJA 2019

Which EOSs for BNS merger simulations?

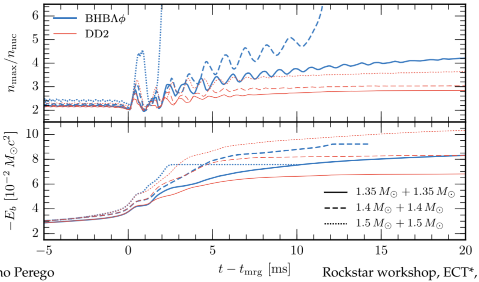
finite-T, composition dependent EOSs in Nuclear Statistical Equilibrium

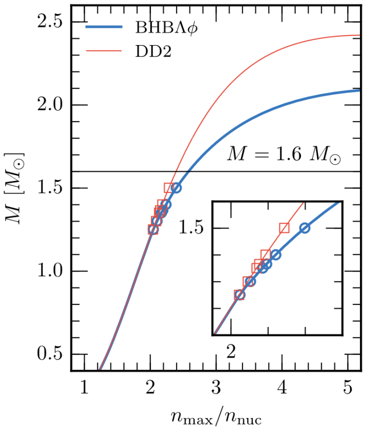
- relevant ranges
  - baryon density
  $$10^{-12} n_0 \lesssim n_b \lesssim 10 n_0$$
  ($n_0 \approx 0.16 \text{ fm}^{-3} \rightarrow \rho_0 \approx 2.6 \times 10^{14} \text{g cm}^{-3}$)
  - temperature:
  $$0.1 \text{ MeV} \lesssim T \lesssim 150\text{MeV}$$
  - isospin asymmetry:
  $$0.01 \lesssim Y_p \lesssim 0.5$$
- relevant particle content
  - minimal content:
  $$n \quad p \quad e^{\pm} \quad \gamma$$
  - additional (possibly relevant) content:
  $$\text{hyperons} \quad \text{quarks} \quad \mu^{\pm} \quad \pi^{\pi,0}$$
- usually, in tabulated form

What is the effect of strangeness in BNS mergers?

strangeness implies appearance of additional degrees of freedom

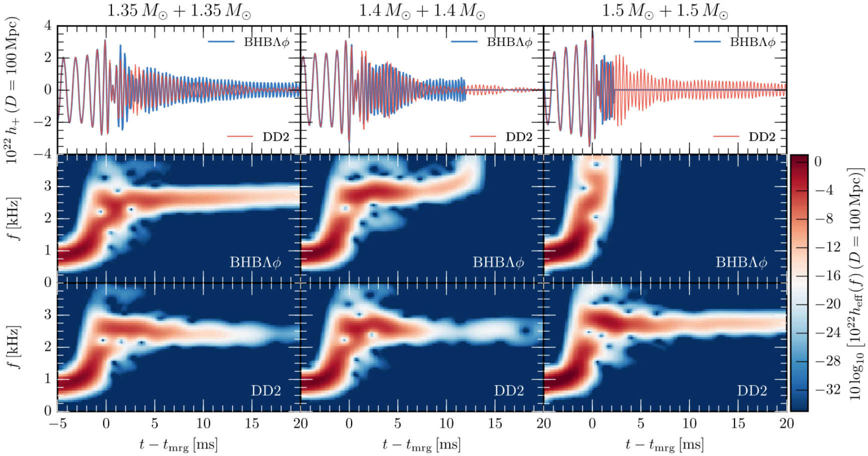
- EOS softening
- lower maximum NS mass ($T = 0$, β-equilibrated matter)
- remnant of BNS merger
  - cold, i.e. $s \sim 1 - 2k_b$/baryon
  - slower rotating core + fast rotating envelope
  - more prone to collapse





Radice et al ApJL 2017, see also Sekiguchi et al PRL 2011

Is there a signature in the GW signal?



hyperons soften the EOS …

- …inducing more remnant oscillations, at high frequency
- …producing more unstable remnants

Radice et al ApJL 2017, see also Sekiguchi et al PRL 2011

Can strangeness be detected in BNS observables?

Recent works investigated on the appearance of hyperons and/or quark have address their impact on BNS merger observables

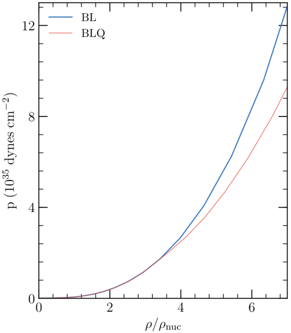
- Most *et al* PRL 2019, EPJA 2020:
  - hyperons and I order phase transition w quark have similar effects
  - quark appearance produces sudden BH formation and small dephasing in GWs
- Bauswein *et al* PRL 2019, EPJA 2020; Blacker *et al* PRD 2020:
  - extended mix phase of quark & hadrons producing hybrid remnants
  - quark appearance produces significantly larger post-merger peak frequency and violates quasi-universal relations of hadronic EOSs
- Weih *et al* PRL 2020, Liebling *et al* CQG 2021:
  - shift in post-merger GW most visible for non-collapsing remnants
  - if quarks appear post-merger with delay, 2 post-merger peaks
- Blacker *et al* arxiv 2023:
  - EOSs w hyperons at finite T
  - thermal production of hyperons soften the EOS and produce a slighly larger GW frequency in post-merger signal

Signature of deconfined quark matter in BNS mergers

. . . mostly based on Prakash, Radice, Logotate, Perego *et al* PRD 2021

The models

EOSs



- BLh EOS: BHF microscopic EOS, with Bethe-Goldstone extention to $T \neq 0$ Logoteta+ A&A 2021
- BLQ EOS: BLh + I-order phase transition to quarks (*uds*) (Gibbs construction)

BNS models

M_1 $[M_\odot]$	M_2 $[M_\odot]$	M $[M_\odot]$	q	ν	Λ_1	Λ_2	$\widetilde{\Lambda}$	ξ
1.3	1.3	2.6	1.0	0.25	696	696	696	130
1.3325	1.3325	2.67	1.0	0.25	595	595	595	111
1.365	1.365	2.73	1.0	0.25	510	510	510	95
1.4	1.4	2.8	1.0	0.25	432	432	432	81
1.45	1.45	2.9	1.0	0.25	341	341	341	63
1.475	1.475	2.95	1.0	0.25	303	303	303	56
1.5	1.5	3.0	1.0	0.25	269	269	269	50
1.6	1.6	3.2	1.0	0.25	168	168	168	31
1.4	1.2	2.6	1.17	0.25	432	1137	711	133
1.482	1.259	2.74	1.18	0.25	293	849	510	95
1.856	1.02	2.88	1.82	0.23	46	2896	505	92

- evolved in full GR through the NR code WhiskyTHC
- 2 different resolutions

The models

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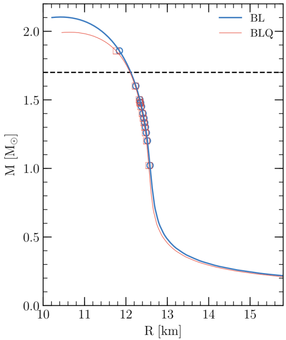

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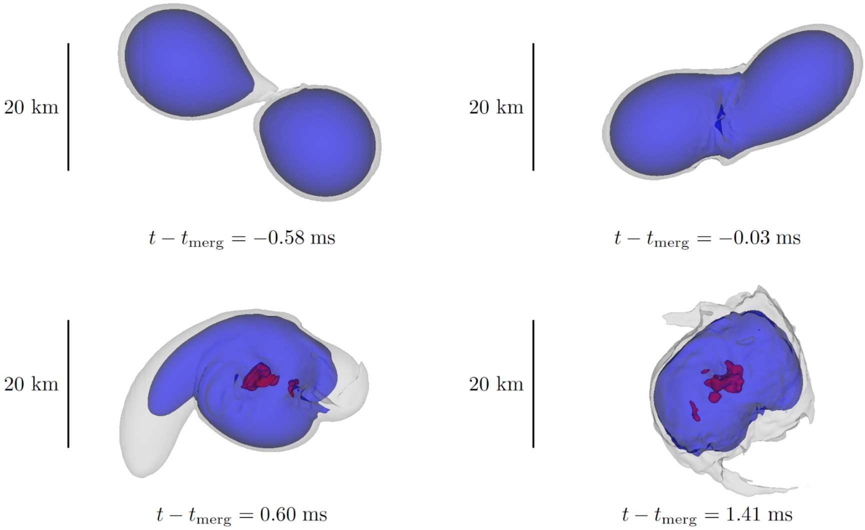
Dynamics of the phase transition



red areas: transition to quark matter

Prakash+ PRD 2021

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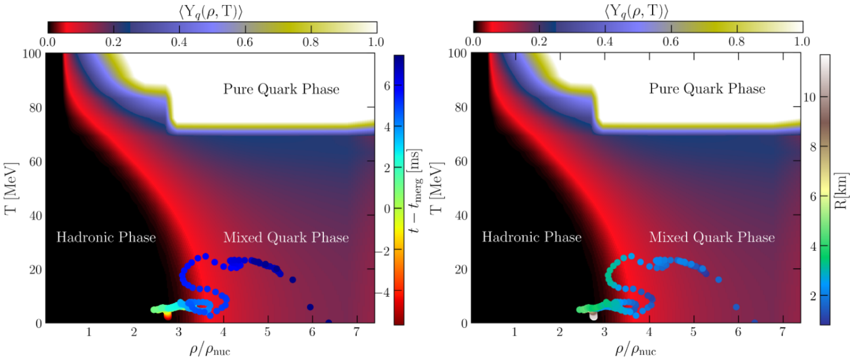
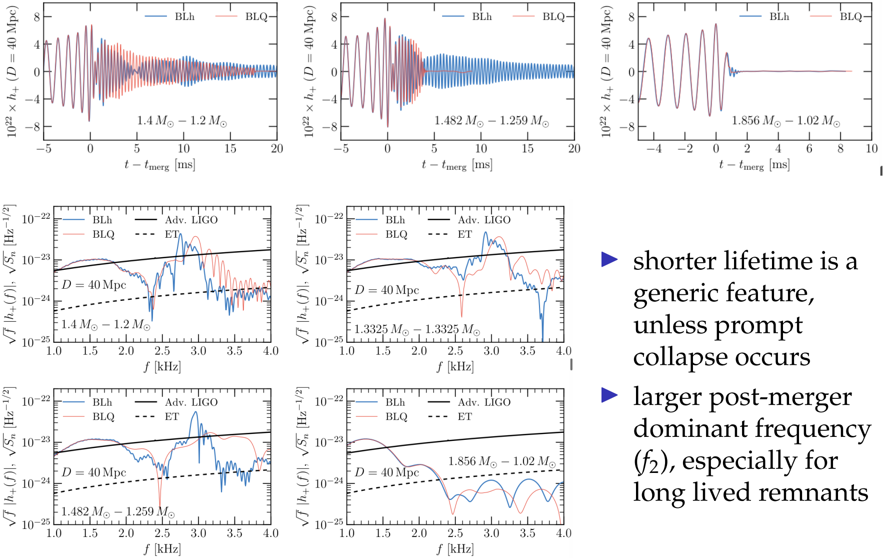


- fluid elements undergo multiple transitions
- oscillations in quark fraction correlates with density oscillations
- transition triggered by density *and* temperature

Prakash+ PRD 2021

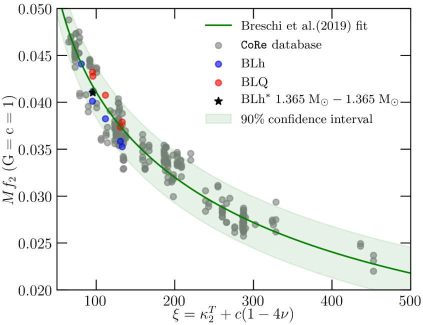
Impact on the GW signal



Prakash+ PRD 2021

- shorter lifetime is a generic feature, unless prompt collapse occurs
- larger post-merger dominant frequency (f_2), especially for long lived remnants

Is the GW shift detectable?



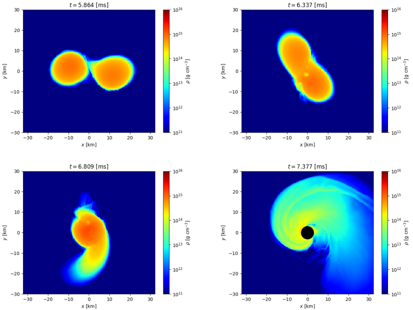
Prakash+ PRD 2021

- $\Delta f_2 \lesssim 0.2$ kHz
- significantly lower than previously reported variations, $0.2\ \text{kHz} \lesssim \Delta f_2 \lesssim 1.0\ \text{kHz}$
- signal more detectable (by Adv-LIGO, adv-Vrigo and KAGRA, and by 3rd generation GW telescopes) for a long lived remnant
- no significant deviation in EOS quasi-universal relation

Probing nuclear incompressibility through prompt collapses

The relevance of prompt collapse (PC)

- PC: sudden BH formation at merger
  - absence of remnant bounce: GW-quiet post merger
  - peculiar EM counterparts
    - symmetric BNS: EM quiet
    - highly asymmetric BNS: BHNS-like kilonova
- very likely …
  - …GW170817 was not a PC
  - …GW190425 was a PC



snapshots around merger for 1.305 $M_\odot$-1.535 $M_\odot$ simulation with SFHo EOS

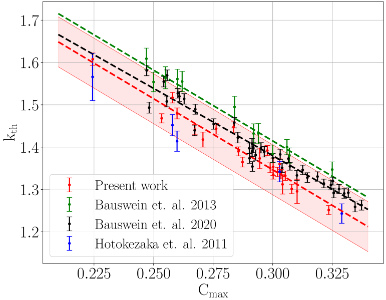
When does PC occur?

$q = 1$, non-spinning ($\chi = 0$) BNSs:

$$M > M_{\rm th} = k_{\rm th} M_{\rm max}^{\rm TOV}$$

$k_{\rm th}$ correlates with several EOS-dependent NS properties, e.g. $C_{\rm max}$ or $R_{1.6}$

Hotokezaka+11 PRD, Bauswein+12 PRL, Koeppel+19 ApJL, Kashyap+22 PRD



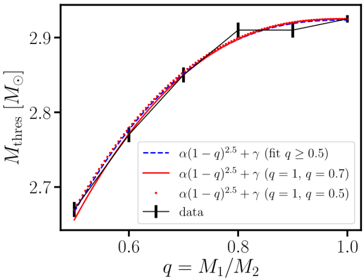
Kashyap+22 PRD

$q \neq 1, \chi \neq 0$ BNSs

$$M > M_{\rm th}(q,\chi) = k_{\rm th}(q,\chi) M_{\rm max}^{\rm TOV}$$

- $M_{\rm th}$ decreases for small q & χ, due to lower rotational support
- quasi-universal behavior?
- non-monotonicity at $q \lesssim 1$?

Bauswein+20,21 PRL & PRD; Tootle+21 ApJL, Kölsch+22 PRD

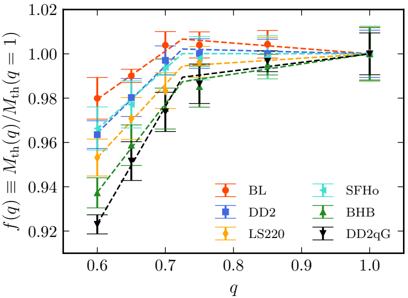


Bauswein+21 PRD

PC in asymmetric, irrotational BNSs

- large simulation campaign (~ 250) to determine $M_{\rm th}(q)$
- 6 EOSs and 6 mass ratios
- two regimes: $\tilde{q} \approx 0.725$
- global decrease for decreasing q
  - non-trivial EOS dependence
  - clear non-monotonic behavior for $q > \tilde{q}$ for some EOSs
- double linear fit

$$f(q) = \begin{cases} \alpha_l q + \beta_l & \text{if } q < \tilde{q}\,, \\ \alpha_h q + \beta_h & \text{if } q \geq \tilde{q}\,. \end{cases}$$



Perego et al PRL 2022

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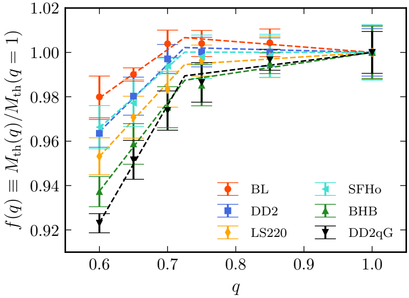

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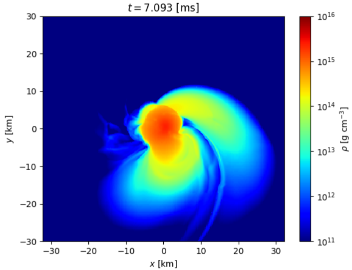

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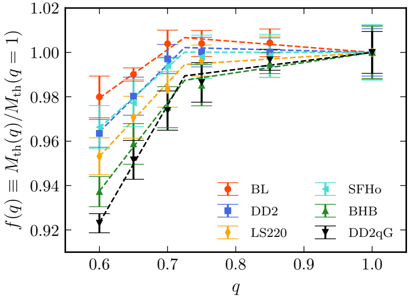

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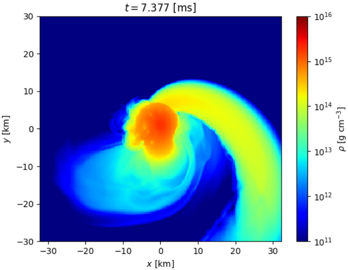


The role of nuclear incompressibility

What is missing?

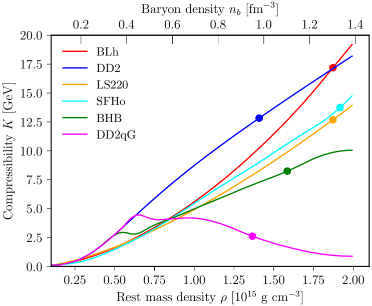
- (prompt) collapse: competition between gravity and matter incompressibility
- nuclear incompressibility:

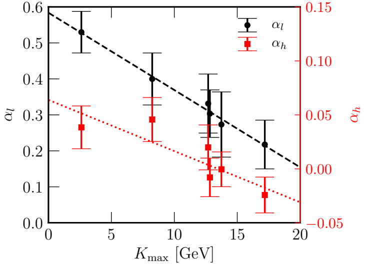
$$K(n_b, \delta) \equiv 9 \frac{\partial P}{\partial n_b}\bigg|_{T=0,\delta=\mathrm{const}} .$$

- clear correlation of α's with

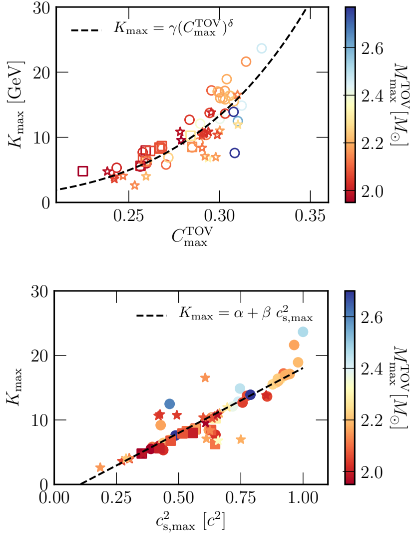
$$K_{\mathrm{max}} = K(n_{b,\mathrm{max}}^{\mathrm{TOV}}, \delta_{\mathrm{eq}})$$

- measurement of M_{th} at two q's directly provide K_{max}





Quasi-universal relations involving incompressibility

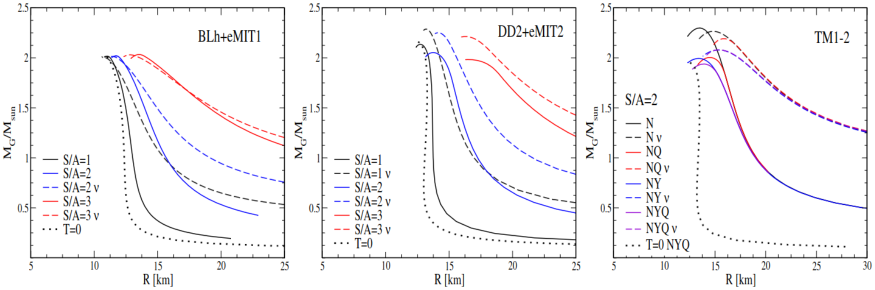


- $K_{\rm max}$ correlates with NS and EOS properties, e.g.
  - $C_{\rm max}$
  - $c^2_{\rm s,max}$
- $K_{\rm max}$ possibly provides information on high density composition:
  - $K_{\rm max} \gtrsim 15$GeV points to purely hardonic EOSs
  - possibly, $K_{\rm max} \gtrsim 12$GeV

The non-trivial effect of neutrinos with hyperons

Neutrinos in strange matter

- BNS remnants host also trapped neutrino gas
- also neutrinos are expected to soften the EOS
- however
  - in the presence of hyperons and/or quarks, trapped neutrinos make the EOS stiffer (than w/o them)
  - trapped neutrinos shift the onset of quark phase transition



Logoteta, Bombaci, Perego EPJA 2022

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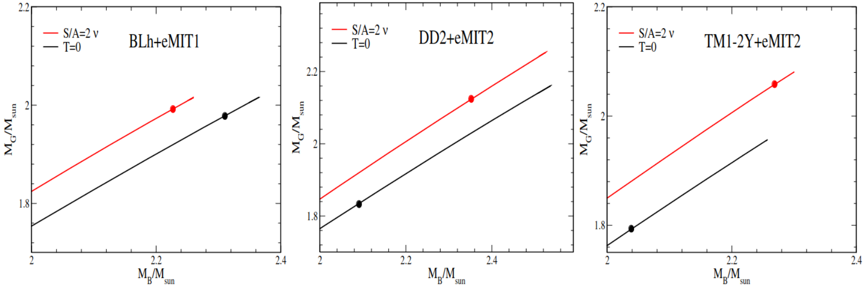


Logoteta, Bombaci, Perego EPJA 2022

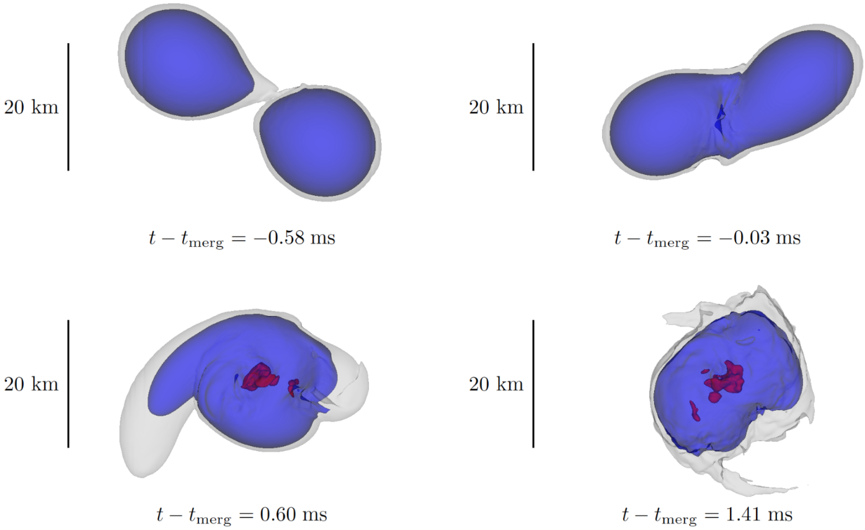
Conclusions and outlook

- strangeness has a (potential) significant impact on BNS merger, especially in the post-merger phase
- main effects:
  - remnant stability
  - post merger peak frequency
- however, effects on GWs (and other observables, e.g. kilonova) are ...
  - ... possibly small
  - ... degenerate among them (hyperons VS quark VS thermal ...)

Outlook:

- to quantify in a more firm way the impact and the onset of strangeness
- to explore systematics (e.g., construction in mixed phase)
- to provide finite T, composition dependent EOSs
- to include missing relevant physics: e.g. neutrinos and muons

Dynamics of the phase transition



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Prakash+ PRD 2021

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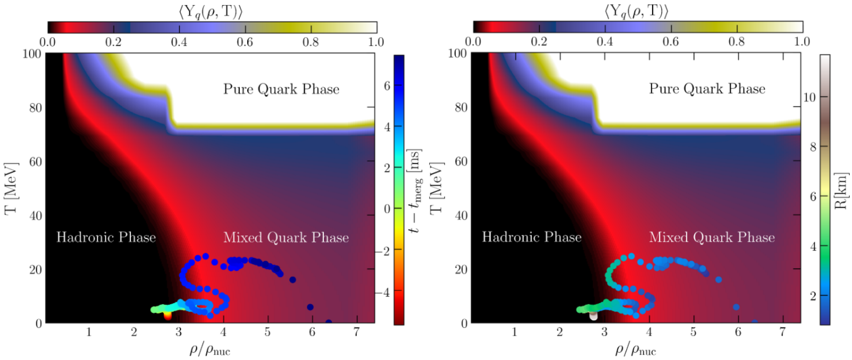

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- oscillations in quark fraction correlates with density oscillations
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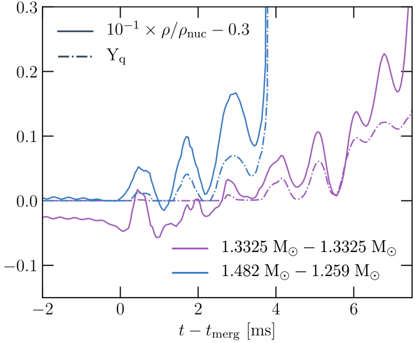

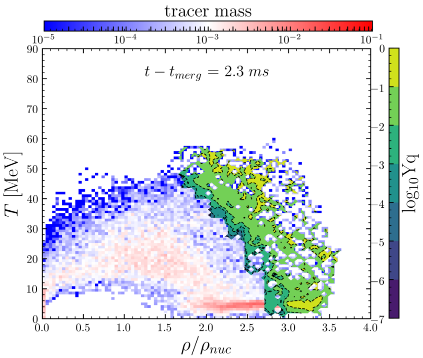

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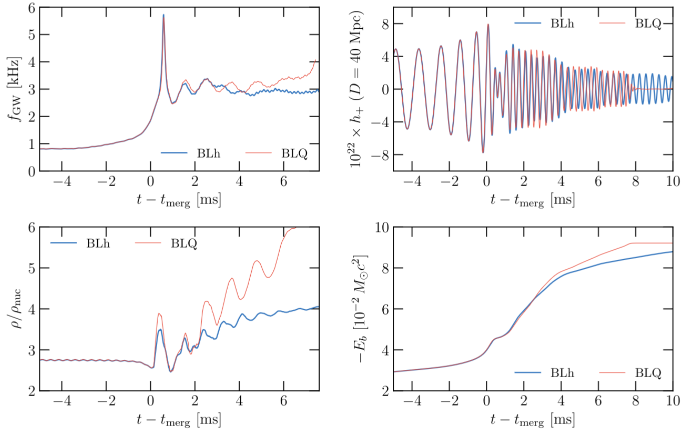
Pure hadronic VS quark phase transition



$1.3325 M_\odot - 1.3325 M_\odot$ BNS merger

BLQ shows …

- … larger density oscillations
- … shorter remnant lifetime
- … larger $f_{\rm GW}$