GW detections from neutron star mergers in the ET era

Albino Perego

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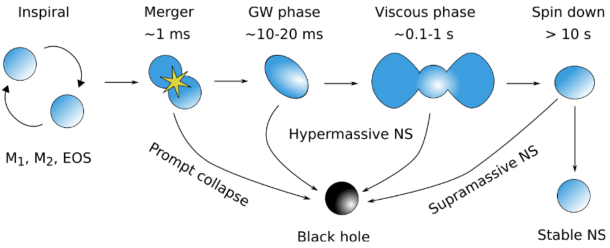
GRASS 2024 Symposium, Trento

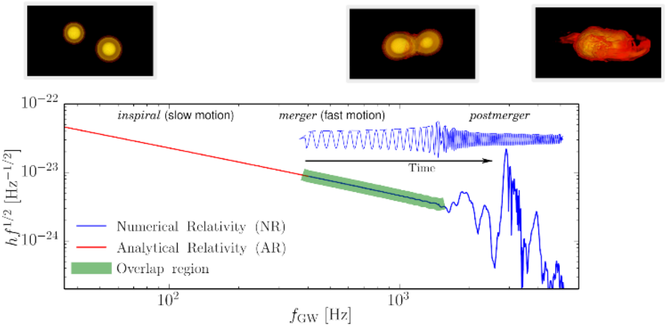
BNS merger in a nutshell: dynamics



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 $E_{\rm kin} \rightarrow E_{\rm int}$
    - copious ν production: $L_\nu \sim 10^{53}$erg/s — Eichler+ 89, Ruffert+ 97, Rosswog & Liebendoerfer 03
- viscous phase: MHD viscosity + ν emission

GWs from coalescing neutron star binaries



Courtesy of S. Bernuzzi

- inspiral: chirp signal ($\mathcal{M}_{\mathrm{chirp}}, q$)
- late inspiral and merger: matter effects (reduced tidal parameter $\tilde{\Lambda}$)
- post-merger:
  - remnant as loud source of kHz GWs with rich phenomenology
  - dominant feature (f_2 or f_{peak}) directly related to the remnant angular velocity (dominant $\ell = m = 2$ mode)
  - peak location and amplitudes depend on EOS of NSs and possibly reveal microphysics features (e.g. QCD phase transitions)

Modelling of GWs from BNS mergers

CoRe database

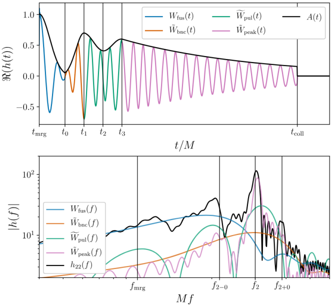
- largest GW database from Numerical Relativity (NR) simulations
  - 254 BNS configurations
  - 590 distinct simulations
  - NS masses, EOS, spins, eccentricity, microphysics
- GW strains and Weyl multipoles up to $(\ell, m) = (4, 4)$ mode

I release: Dietrich+ CQG 2018, II release: Gonzalez+ 2023 CQG

NRPMw: post-merger model

Breschi+ 2019,2024 PRD

- kHz frequency realm
- it complements EOB inspiral-merger models
- calibrated against 618 NR simulations



Breschi+ PRD 2023

BNS merger in a nutshell: ejecta

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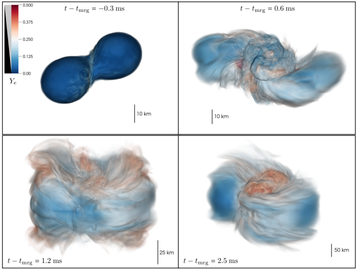
  - $M_{\rm ej} \sim 10^{-4} - 10^{-2} M_{\odot}$



Radice, Perego, Hotokezafa, Fromm, Bernuzzi, Roberts ApJ 2018

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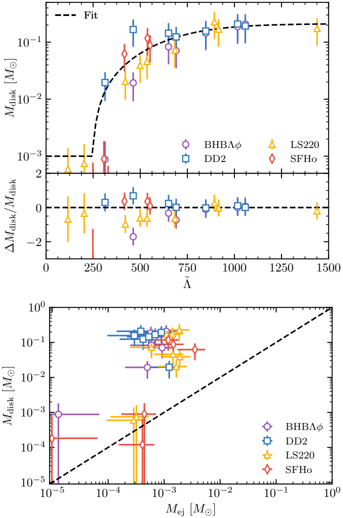

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  - neutrinos, MHD
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  - up to $M_{\rm ej} \sim 0.1 - 0.4 M_{\rm disk}$

Radice+ ApJ 2018

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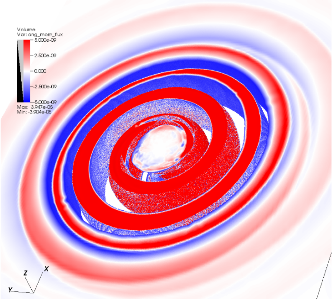
  - $m = 1, 2$ spiral mode in the remnant
  - $\langle v \rangle \sim 0.2c$
  - $\dot{M} \sim 0.1 M_\odot/$s
  - acting until BH formation



Nedora *et al* ApjL 2019

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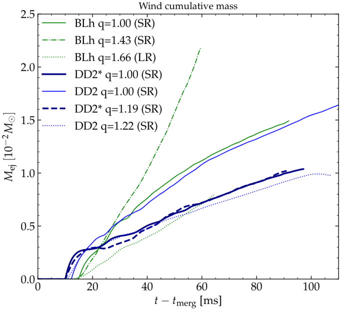
top: ϕ-angular momentum radial flux

bottom: spiral wind ejecta mass

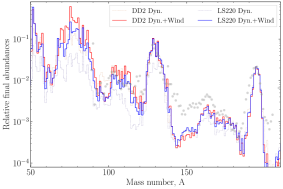


Nedora *et al* ApjL 2019

Nucleosynthesis and EM counterparts

r-process nucleosynthesis

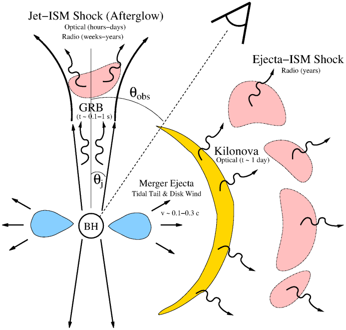
- ejecta: ideal place for *r*-process nucleosynthesis
- production of all *r*-process elements once neutrinos are taken into account



Nedora+ ApJ 2022

EM counterparts

- kilonova:
  - UV/optical/IR transient
  - 1-10 day timescale
  - powered by radioactive decay of *r*-process elements
- short-GRB
  - relativistic jet produced by the remnant
  - precise mechanism still elusive



Berger+ 2015

BNS mergers in ET era

III generation GW detectors will allow to access not only inspiral, but also post-merger signals, as well as good sky localization

great opportunity:

- to extract the most from GW detections, for example in extracting EOS information
- to enable multi-messenger detections, for example in combination with kilonova observation

great challenge:
strong need for ...

- ...detailed and reliable models
- ...sophisticated data analysis techniques
- ...effective multimessenger strategies

see the talks of this section, as well as Anna's and Eleonora's talk from tomorrow morning!

Detection of BH formation in BNS mergers

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- invaluable information about dense and hot nuclear matter (EOS)
- key information for EM counterpart interpretation and understanding

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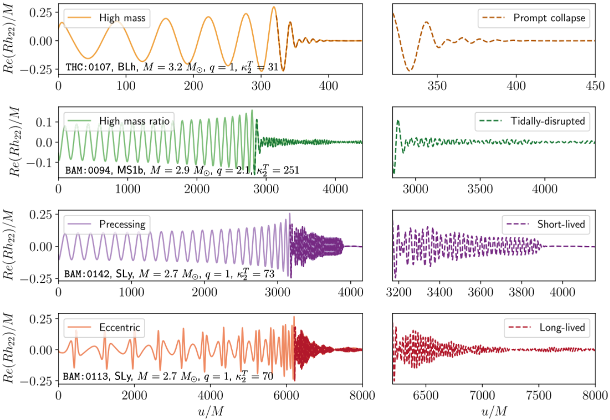

Gonzalez+ CQG 2023

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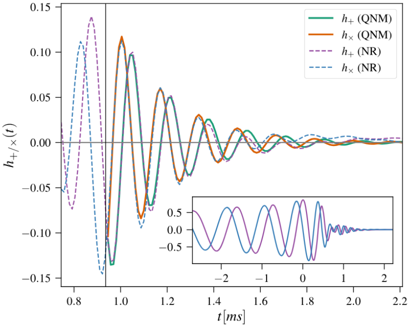
A possible way to do it: searching for termination of post-merger GW

however:

- time-domain analysis of weak signal
- it provides only lower limit for remnant lifetime

Ring down from BH formation

- Detailed analysis of GW post-merger signal from 190 Numerical Relativity BNS merger simulations
- all performed with `THC` code, at multiple resolutions
- promptly collapsing, short lived, or long-lived remnants



- post-collapse signal: exponential dumping of quasi-normal ring down

$$h_{\mathrm{QNM}} = \mathcal{C} \exp\left(-i\omega(t - t_{\mathrm{start}})\right)$$

- postmerger GW spectrum of a long-lived remnant has greatly reduced power at $f \gtrsim f_{\mathrm{peak}}$, for $f \gtrsim 4$ kHz & $f_{\mathrm{peak}} \in [2.5, 4]$kHz

Dhani+ 2024, PRD

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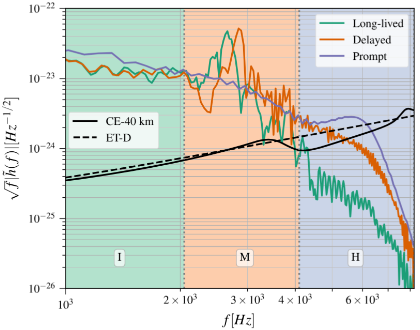

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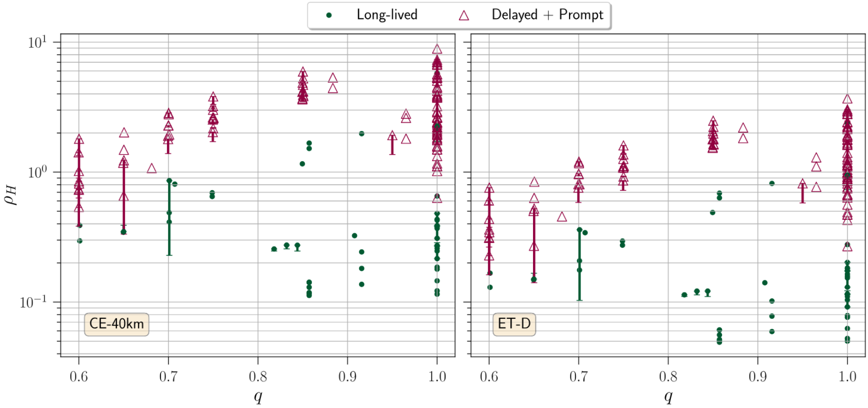
Is it something we can detect?

- Calculation of SNR in the high portion of the spectrum
- optimally oriented BNS at 40 Mpc



Dhani+ 2024, PRD

What can we learn from promptly collapsing BNS mergers?

1. Testing GR in strong field regime

2. Measuring nuclear incompressibility at the highest densities

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Do black holes remember what they are made of?

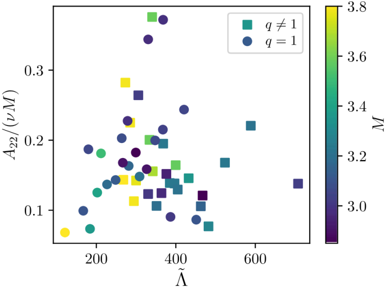
- Bandyopadhyay+ 2024, CQG
- analysis of post-collapse ring-down signal from 49 NR simulations
- QNM-fit of ℓ, m =(2,2) and (2,1) spherical armonics decomposition

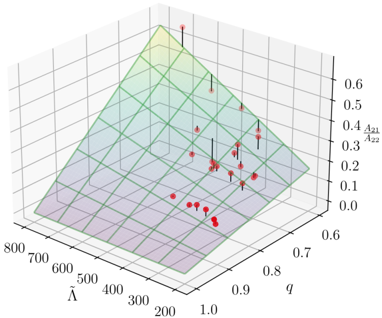
$$h_{(\ell,m)} = \mathcal{A}_{(\ell,m)} \exp\left(-i\omega_{(\ell,m)}(t - t_{\rm start})\right)$$

- $\mathcal{A}_{(\ell,m)}$'s seem not to correlated …
- …while $\mathcal{A}_{(2,1)}/\mathcal{A}_{(2,2)}$ seem to correlate with $q = M_1/M_2$ and $\tilde{\Lambda}$

$$\frac{\mathcal{A}_{(2,1)}}{\mathcal{A}_{(2,2)}} = (1-q)\left(\frac{a}{1+q} + \frac{b}{\tilde{\Lambda}}\right)$$

- $b \neq 0$: direct imprint of matter ($\tilde{\Lambda}$)





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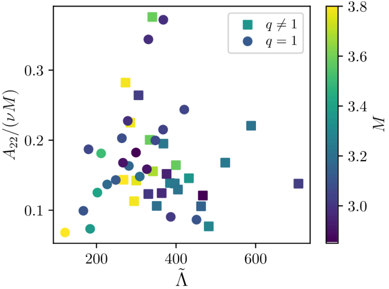

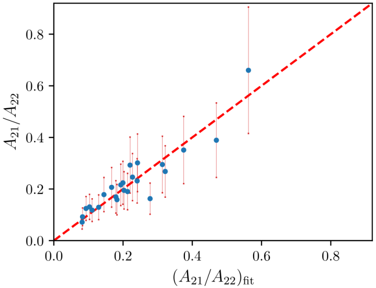

Testing GR with prompt collapse mergers

Some preliminary considerations:

- no-hair theorem: while final BH is only characterized by mass & spin, ringdown mode amplitudes depend on the properties of the progenitor BNS
- results on post-merger QNM analysis derived assuming GR
- post-merger QNM analysis requires high enough SNR in the post-merger $\rightarrow$ very high SNR in inspiral: q and $\tilde{\Lambda}$ well measured during the inspiral

How can we use these results to test GR?

by comparing $\left(\mathcal{A}_{(2,1)}/\mathcal{A}_{(2,2)}\right)_{\rm data}$ VS $\left(\mathcal{A}_{(2,1)}/\mathcal{A}_{(2,2)}\right)_{\rm fit}(q,\tilde{\Lambda})_{\rm data}$ one could test consistency of GR between inspiral and post-merger

Caveat:

- for SNR$\gtrsim$ 3, systematics error dominates
- strong need for high resolution simulations

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When does PC occur?

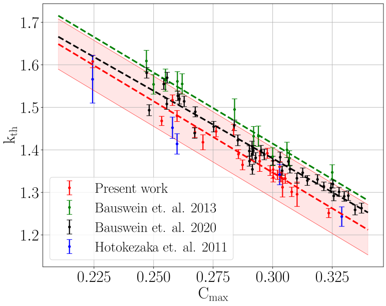
$q = 1$, non spinning BNSs:

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

and $k_{\rm th}$ correlates with EOS-dependent NS properties

$$k_{\rm th} = a C_{\rm max} + b$$

Hotokezaka+11 PRD, Bauswein+12 PRL, Koeppel+19 ApJL...



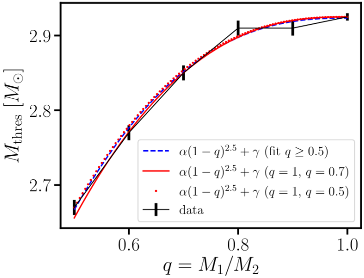
Kashyap+22 PRD

what about $q \neq 1$ BNSs?

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

- $M_{\rm th}$ decreases for small q 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

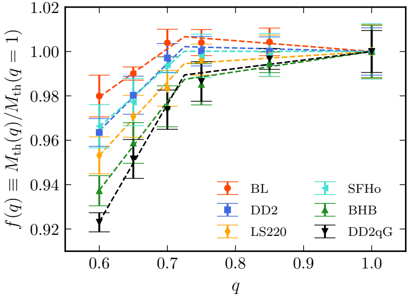


Bauswein+21 PRD

PC in asymmetric, irrotational BNSs

- large simulation campaign (~ 250) to determine $M_{\rm th}(q)$
- 6 EOSs and 6 mass ratios
- two regimes, separated by $\tilde{q} \approx 0.725$
- global decrease for decreasing q, but
  - 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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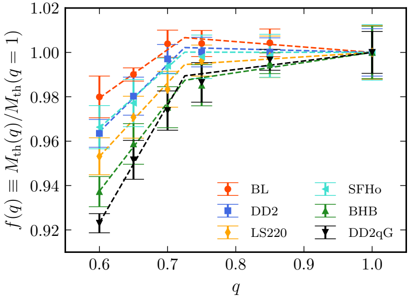
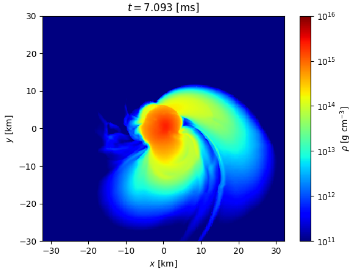


Perego et al PRL 2022



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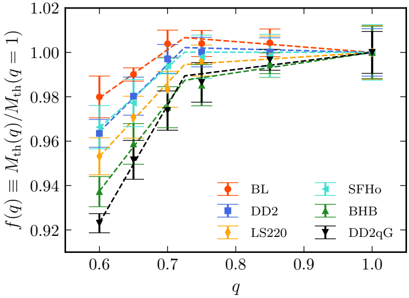

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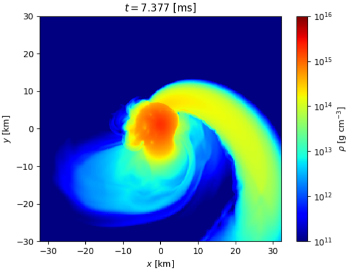


The role of nuclear incompressibility

What is missing?

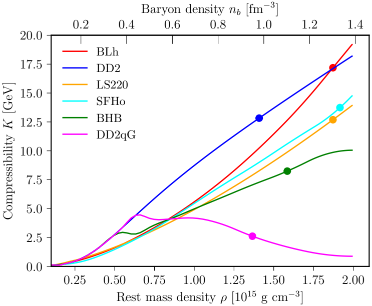
- (prompt) collapse: competition between gravity and matter incompressibility
- nuclear incompressibility:

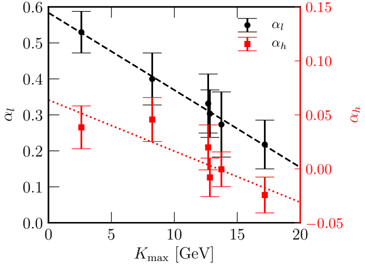
$$K(n_b, \delta) \equiv 9 \frac{\partial P}{\partial n_b}\bigg|_{T=0,\delta=\mathrm{const}} .$$

- clear correlation of α's with

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

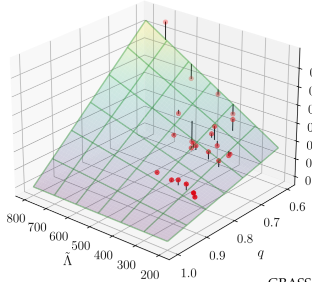
- measurement of M_{th} at two q's directly provide K_{max}

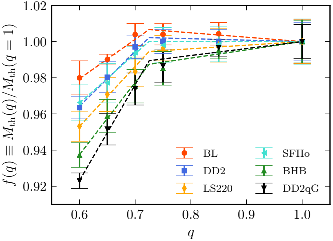




Conclusions

- We live in exciting times, thanks to GWs and multimessenger astrophysics
- (Advanced) Ligo and Virgo have opened new fields and unveiled the potential of multi-messenger detections
- III generation detectors will enable detections from BNS merger remnants
- remnant is ideal playground for theoretical physics and multimessenger signals will provide valuable insights on several topics, including
  - properties of nuclear matter — e.g. Perego+ 2023 PRL
  - properties of spacetime — e.g. Dhani+ 2024 PRD, Bandyopadhyay+ 2024 CQG





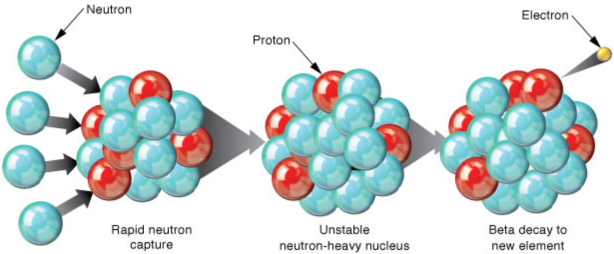
r-process nucleosynthesis: basic ideas

- how do heavy elements (> Fe group) form? n-capture — e.g. B[2]FH RvMP 57

$$(A, Z) + n \leftrightarrow (A+1, Z) + \gamma$$

- if n density high enough, $t_{n-\mathrm{capt}} \ll t_{\beta-\mathrm{decay}}$
- ejecta properties, i.e. $(s, Y_e, \tau_{\mathrm{exp}})$ at NSE freeze-out ($T \lesssim 6\mathrm{GK}$) determine final nucleosynthesis yields

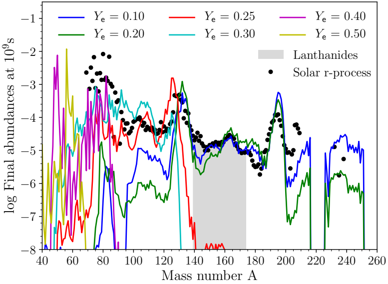
Hoffman+ ApJ 98,Lippuner & Roberts ApJ 17

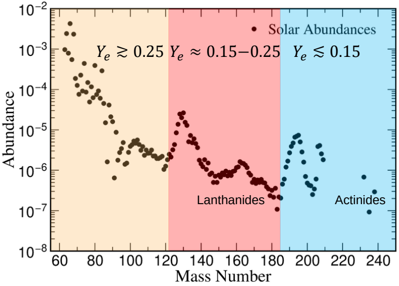


r-process nucleosynthesis in BNS ejecta

- at low entropy ($s \lesssim 40 k_b$/baryon), Y_e dominant parameter
- lanthanides (and actanides) production dramatically changes photon opacity (atomic f-shell opening)
- Y_e influenced by weak interactions involving neutrinos, e.g.

$$p + e^- \leftrightarrow n + \nu_e \qquad n + e^+ \leftrightarrow p + \bar{\nu}_e$$





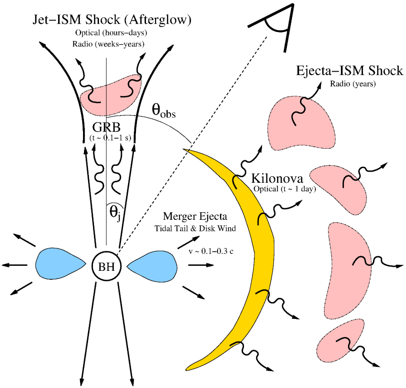
left: Perego, Thielemann & Cescutti 2021; right: Courtesy of G. Martinez-Pinedo

$Y_e = n_e/n_B \approx n_p/(n_p + n_n)$: electron fraction

Electromagnetic counterparts

BNS mergers (possibly) produce several transient EM emissions: e.g.,

- (short/hard) gamma-ray burst
  - accretion of magnetized matter on compact object producing a relativistic jet
  - prompt emission:
    - γ-rays
    - $T_{90} \lesssim 2$ sec
  - afterglow emission
    - from X-rays to radio
    - $t \sim$ days-weeks
- kilonova
  - r-process nucleosynthesis produces unstable nuclei
  - quasi-thermal, nuclear powered
    - from UV to NIR
    - $t \lesssim 0.1 - 10$ days
  - afterglow emission
    - from X-rays to radio
    - $t \sim$ months $-$ years



Berger+ 2015

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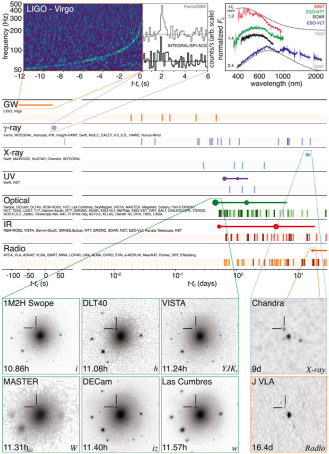
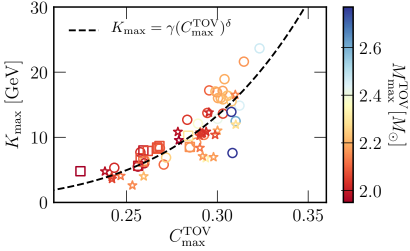
BNS mergers (possibly) produce several transient EM emissions: e.g.,

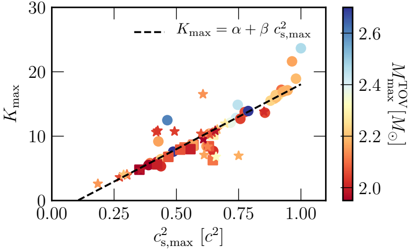
- (short/hard) gamma-ray burst
  - accretion of magnetized matter on compact object producing a relativistic jet
  - prompt emission:
    - γ-rays
    - $T_{90} \lesssim 2$ sec
  - afterglow emission
    - from X-rays to radio
    - $t \sim$ days-weeks
- kilonova
  - r-process nucleosynthesis produces unstable nuclei
  - quasi-thermal, nuclear powered
    - from UV to NIR
    - $t \lesssim 0.1 - 10$ days
  - afterglow emission
    - from X-rays to radio
    - $t \sim$ months – years



LVC PRL 2017

Quasi-universal relations involving incompressibility

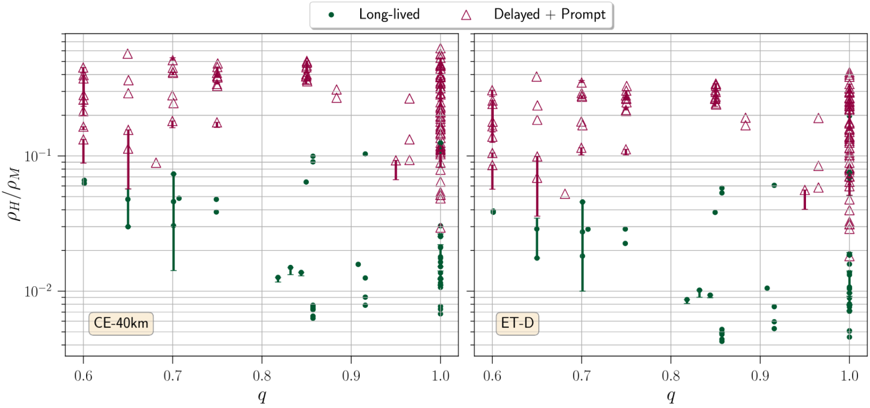




- $K_{\max}$ correlates with NS and EOS properties, e.g.
  - $C_{\max}$
  - $c^2_{s,\max}$
- $K_{\max}$ possibly provides information on high density composition:
  - $K_{\max} \gtrsim 15$GeV points to purely hardonic EOSs
  - possibly, $K_{\max} \gtrsim 12$GeV

Is it something we can detect?

Calculation of SNR in the high (H) and medium (M) portion of the spectrum for optimally oriented BNS at 40 Mpc



Is it something we can detect?

Calculation of SNR in the high (H) and medium (M) portion of the spectrum for optimally oriented BNS at 40 Mpc