Binary neutron star mergers: highlights and perspectives from modeling

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Albino Perego, Progetto EMERGE

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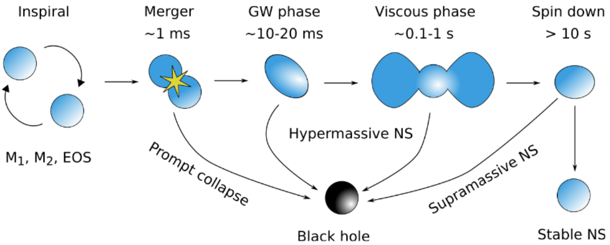
A brief overview about BNS mergers

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 merger in a nutshell: ejecta

- a few percent of $M = M_A + M_B$
- neutron rich, i.e. $Y_e < 0.5$ and typically $Y_e \ll 0.5$
- expelled by different mechanisms, acting on different timescales

$\mathrm{Y_e = n_e/n_B \approx n_p/\left(n_p + n_n\right)}$: electron fraction

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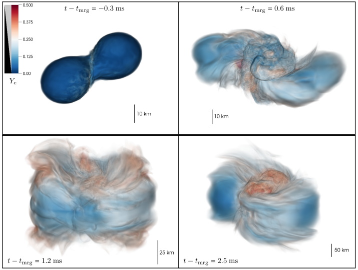
- dynamical ejecta ($t \sim 1 - 5$ms)
  - tidal & shock heated ejecta
  - $\langle v \rangle \sim 0.2 - 0.3c$
  - $M_{\rm ej} \sim 10^{-4} - 10^{-2} M_\odot$



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

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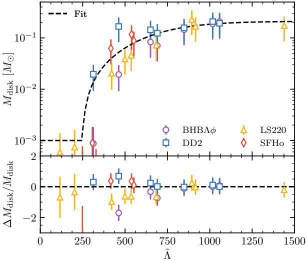

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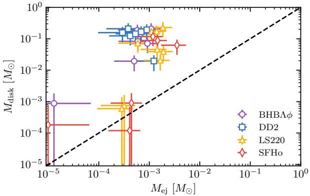
- disk winds ($t \sim 0.05 - 10$s)
  - neutrinos, MHD
  - $\langle v \rangle \sim 0.1c$
  - up to $M_{\rm ej} \sim 0.1 - 0.4 M_{\rm disk}$



Radice+ ApJ 2018

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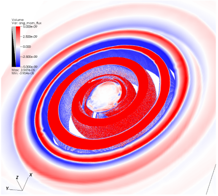
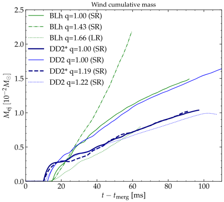
- spiral wave winds ($t \sim 0.01 - 1$s)
  - $m = 1, 2$ spiral mode in the remnant
  - $\langle v \rangle \sim 0.2c$
  - $\dot{M} \sim 0.1 M_\odot/$s
  - acting until BH formation



top: ϕ-angular momentum radial flux

bottom: spiral wind ejecta mass



Nedora *et al* ApjL 2019

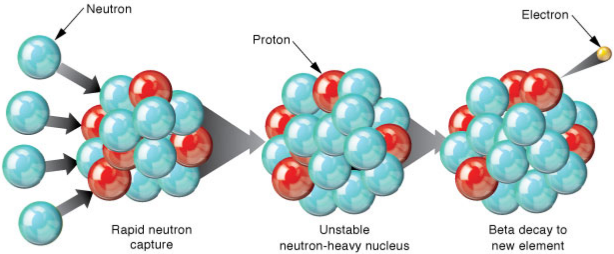
r-process nucleosynthesis: basic ideas

- how do heavy elements ($>$ Fe group) form? n-capture e.g. $\mathrm{B^2FH}$ 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

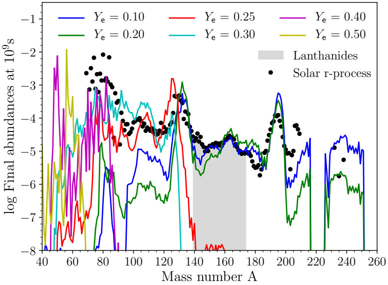
Hoffman+ ApJ 98,Lippuner & Roberts ApJ 17

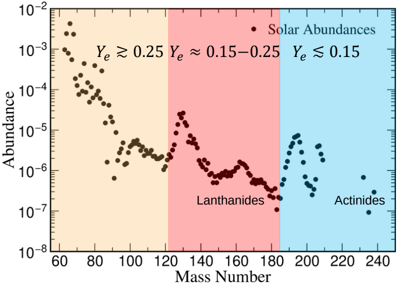


r-process nucleosynthesis in BNS ejecta

- 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.

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



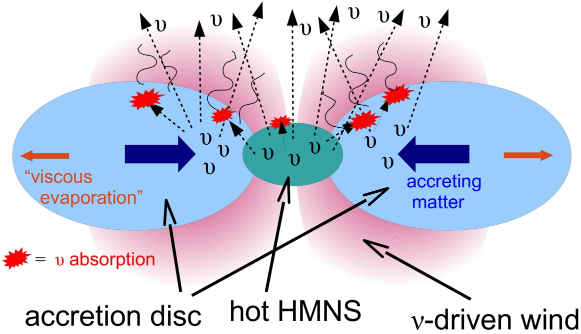


left: Perego, Thielemann & Cescutti 2021; right: Courtesy of G. Martinez-Pinedo

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

Impact of ν processes on BNS merger ejecta

- if ν absorption is neglected (e.g., for BH-NS mergers)
  - $Y_e \lesssim 0.1 \Rightarrow$ robust *r*-process ($Y_e = n_e/n_B = n_p/(n_n + n_p)$)
- however, ν-matter interactions increase Y_e, e.g. at polar latitudes
  - most relevant reaction: $n + \nu_e \rightarrow p + e^-$
  - possible angular dependence in *r*-process nucleosynthesis



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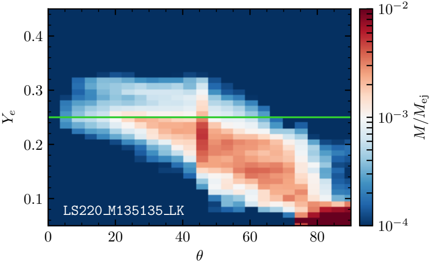

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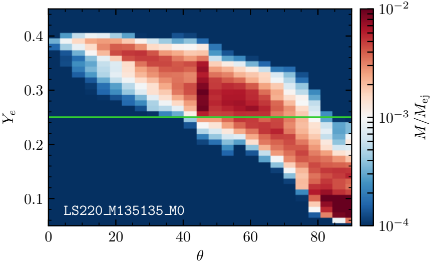

Perego, Radice, Bernuzzi ApJL 17; Radice, Perego, Hotokezaka *et al* ApJ 2018

see also e.g. Wanajo+ ApJL 2014' Sekiguchi+ PRD 2015; Martin, Perego, Kastaun & Arcones CQG 2018

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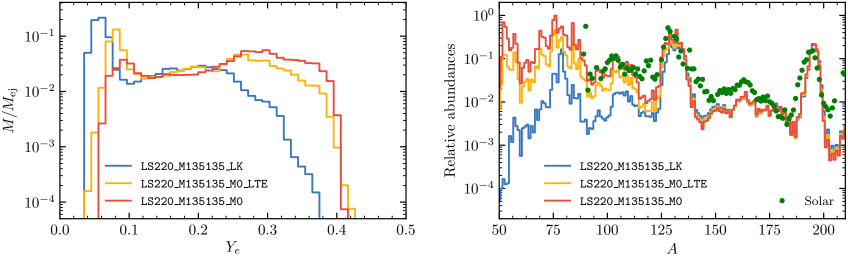
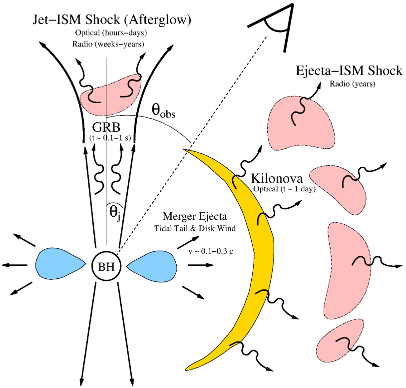


Electromagnetic counterparts

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
- 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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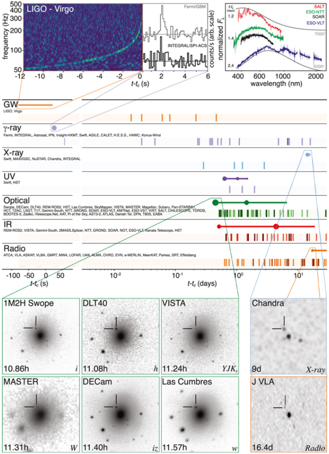

LVC PRL 2017

Relevance & Challenges in NS merger modelling

- relevance:
  - astrophysical key players
    - primary GW sources
    - major source of *r*-process elements → kilonova emission
    - central engine of short/hard GRBs
  - BNS mergers as cosmic laboratory for fundamental physics
  - prototype of MM astrophysics sources
- challenge:
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multi-physics

- General Relativity
- strong nuclear interaction
- weak nuclear interactions
- magnetic fields (MHD) & EM interactions

multi-scale

- strong field dynamics
  - small-size (100 km)
  - short timescale (1 ms – 1 s)
- EM counterpart emission
  - large-scale (10^6 km – 10^{12} km)
  - long timescale (1 s – 10 days)

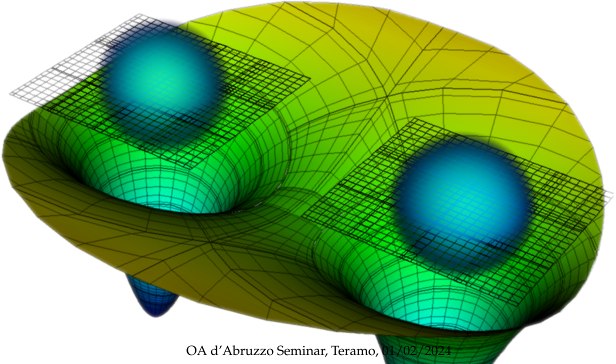
different scales & different interactions ⇒ intimately related

State-of-the-art of BNS merger modeling

BNS merger: computer simulations in Numerical Relativity

- solution of Einstein's equations coupled with relativistic (magneto)hydrodynamics
- relevant input physics:
    - finite-T, composition dependent NS EOS
    - source terms: ν radiation
- simulations often containing subset of necessary physics

Shibata & Hotokezaka 2019, Radice,Bernuzzi & Perego ARNPS 2020 for recent reviews



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BNS counterparts: Radiative transfer simulations

- photon diffusion in radioactive material
- relevant input physics:
  - r-process element opacity, heating rate, thermalization efficiency
  - non-trivial, asymmetric geometry
- simulations often containing simplifications

e.g. Kawaguchi *et al* 2020 ApJ, Kasen *et al* Nature 2017, Tanaka *et al* 2018 PASJ, Wollaeger *et al* 2018 MNRAS, Miller *et al* PRD 2019, …

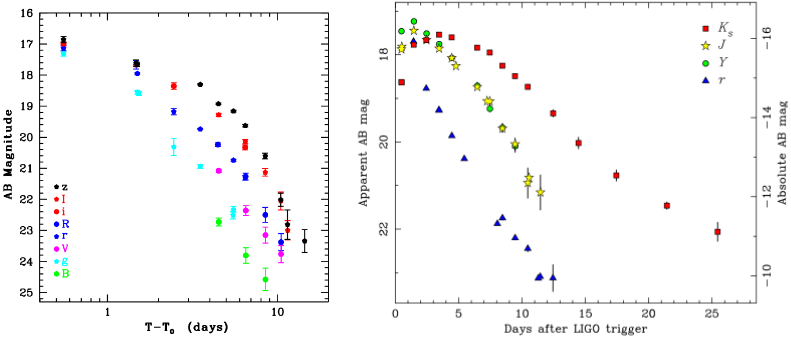
Toward end-to-end modeling of observed events:

GW170817

Properties of AT2017gfo

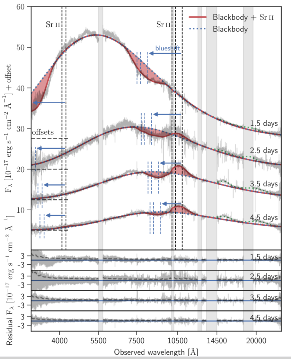
AT2017gfo: kilonova associated to GW170817

- bright, UV/O component, with a peak @ $\sim$ 1day (blue component)
- rather bright, nIR component, with a peak @ $\sim$ 5day (red component)



Light curves; Pian, D'Avanzo+2017 (left); Tanvir+2017 (right)

Strontium (or Helium) in AT2017gfo early spectra?



Sr in AT2017gfo spectra: Watson *et al* Nature 2018

- observed spectra from AT2017gfo
  - 1.5-4.5 day: identification of Strontium (Sr) P-Cygni lines in spectrum
- spectra modeling to estimate Sr mass in GW170817 ejecta
  - Watson *et al*, Nature, 2018:

$$1 - 5 \times 10^{-5} M_\odot$$

  - Gillanders *et al* MNRAS 2022:

$$\gtrsim 1.2 \times 10^{-5} M_\odot$$

- SrII line in overlap with HeII line

- do we expect Sr in GW170817 ejecta? If yes, how much? Does this say something about this event?
- Is it possible that we are observing He in the ejecta?

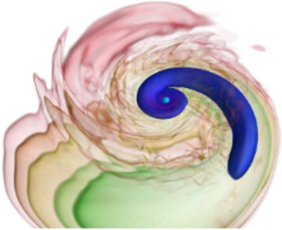
Modeling GW170817 through simulations

Simulations targeted to GW170817 ($\mathcal{M}_{\rm chirp} = 1.188 M_\odot$):

Nedora+ 2021 ApJ, Bernuzzi+2020 MNRAS

- 2 distinct binaries, $q = M_B/M_A = [1, 0.56]$
- GRHD (WhiskyTHC code) Radice+ 2011,13,14
- finite-T, composition dependent nuclear EOSs: HS(DD2) & BLh

  CompOse & stellarcollapse websites, Logoteta *et al* 2021
- neutrino treatment Radice 2016 MNRAS
  - leakage in opt. thick conditions
  - M0 in opt. thin conditions
- w and w/o effective treatment for turbulent viscosity (GRLES) Radice 2018 ApJL
- multiple resolutions

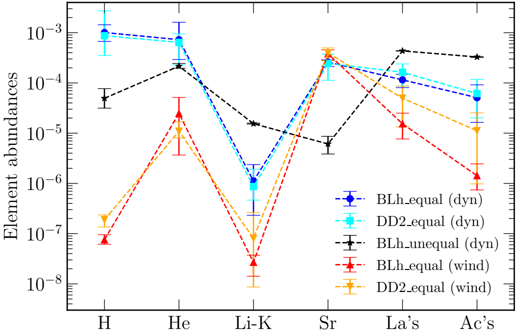


Bernuzzi *et al.* MNRAS 2020

Nucleosynthesis in the ejecta

- all models produce dynamical ejecta
- $q = 1$ models produce long-lived remnant & spiral wave wind ejecta
- extraction of dynamical and spiral wave wind ejecta properties
- calculation of expected nucleosynthesis yields using `Skynet`

Lippuner & Roberts ApJSS 2017



Perego *et al*, ApJ 2022

A constraint on GW170817 remnant survival time?

How much Sr is produced in targeted simulations?

- dynamical ejecta
  - for symmetric BNS, $m_{\rm Sr,dyn} \approx 3 \times 10^{-5} M_\odot$
  - for very asymmetric BNS, $m_{\rm Sr,dyn} \approx 3 \times 10^{-6} M_\odot$
- spiral-wave wind ejecta
  - only in symmetric BNS,

$$X_{\rm Sr,dyn} \sim 3.4 \times 10^{-2} \quad \& \quad \dot{M}_{\rm spiral-wave} \approx 1.6 \times 10^{-1} M_\odot/{\rm s}$$

Where does it come from and what could we infer from it?

- Sr robustly produced for $0.2 \lesssim Y_e \lesssim 0.4$
- unequal mass BNS model seems to be disfavored
- $q = 1$ dynamical ejecta seems to account for a large fraction of Sr
- assuming $m_{\rm Sr} \sim 5 \times 10^{-5} M_\odot$, $\Delta t_{\rm wind} \lesssim 4$ ms
- our results suggest GW170817 remnant survived only a few tens of ms

H and He in kilonova spectra?

H:

- β-decay of unburned free n
- $m_{\mathrm{H,dyn}} \approx 0.5\text{-}1.4 \times 10^{-6} M_{\odot}$
  - interesting for UV KN precurson, but lower than initially expected

    Metzger *et al* 2015 MNRAS
  - no visible spectral features using `TARDIS`

    Kerzendorf & Sim MNRAS 2014

He:

- β-decay of n, producing $d \rightarrow t \rightarrow\ ^{4}$He + α-decay of very heavy elements
- or α-rich freeze-out
- $m_{\mathrm{He,dyn}} \approx 3\text{-}8 \times 10^{-6} M_{\odot}$
  - no visible signature using `TARDIS` in LTE or NLTE tuned to SNIa

    Vogl *et al* 2020 A&A
  - He spectral features require strong NLTE effects

    see Tarumi *et al* 2023

Did a kilonova set off in our neighborhood, $\sim$ 3Myrs ago?

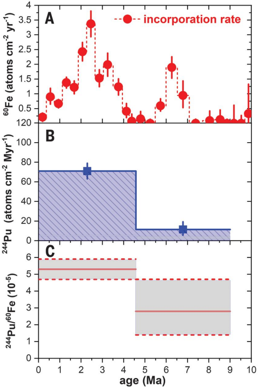
^{60}Fe and ^{244}Pu detection in crust sediments

- observation of r-process abundance patterns traceable to single events has the potential to shed light on their production site
- detection of live radioactive isotopes in sediments features a non-trivial temporal dependence from their decay profile

analysis of deep-sea crust sample delivered to Earth within the past few million years

- identification of (175 ± 15) ^{244}Pu ($\tau = 116.3$Myr) atoms
- simultaneous signal of ^{60}Fe ($\tau = 3.8$Myr)
- $^{244}\mathrm{Pu}/^{60}\mathrm{Fe} = (53 \pm 6) \times 10^{-6}$

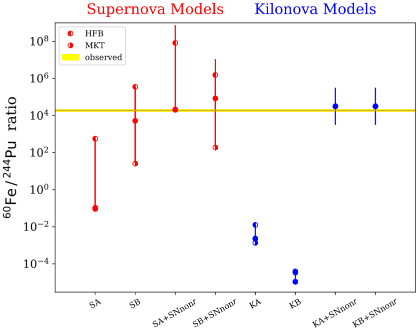
How can we interpret the more recent peaks?



Wallnet+21 Science

Supernova VS kilonova origin?

- ^{60}Fe usually synthesized in (standard) CCSNe
- ^{244}Pu synthesized in rare events
  - kilonovae from compact binary mergers
  - special CCSN?
- single source or multiple sources?



- explosive event(s) in Local Bubble
- previous analysis seem to exclude a nearby KN as possible single source

Wang+21 ApJ

Wang+21 used i) BNS modelels forming a BH & ii) isotropized ejecta

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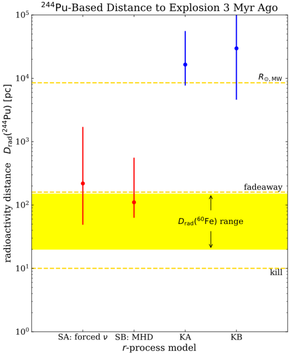

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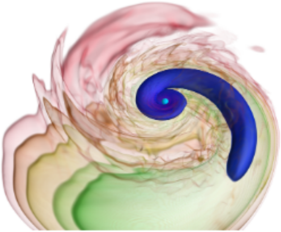
Modeling of long lived BNS mergers

Selection of simulations targeted to GW170817 ($\mathcal{M}_{\rm chirp} = 1.188 M_\odot$), producing a long lived remnant:

- 6 distinct binaries
  - $q = M_A/M_B \in [0.7, 1.]$
- GRHD (WhiskyTHC code) Radice+ 2011,13,14
- finite-T, composition dependent nuclear EOSs: HS(DD2), SFHo, BLh, SRO(Sly4)

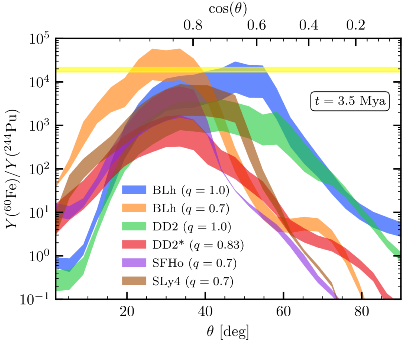
  CompOse & stellarcollapse websites, Logoteta *et al* 2021
- neutrino treatment Radice 2016 MNRAS
  - leakage in opt. thick conditions
  - M0 in opt. thin conditions
- effective treatment for turbulent magnetic viscosity (GRLES) Radice 2018 ApJL
- single maximum resolution: dx = 185m



Bernuzzi *et al.* MNRAS 2020

Iron to plutonium ratio from simulations

$$\frac{Y_i}{Y_j}(\tilde{\theta}, t_{\rm wind}) = \frac{A_j}{A_i}\frac{m_{{\rm ej},i}(\tilde{\theta}, t_{\rm wind})}{m_{{\rm ej},j}(\tilde{\theta}, t_{\rm wind})}e^{t(1/\tau_j - 1/\tau_i)}$$



Chiesta *et al.* ApJL 2024 accepted

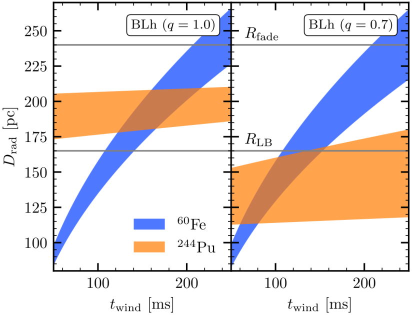
- ^{60}Fe and ^{244}Pu from dynamical ejecta & spiral-wave wind
- polar angle dependence: inefficient mixing assumption
- color band: spiral wave wind duration $t_{\rm wind} \in [50, 200]$ms
- BNS merger occurring 3.5 Myr ago

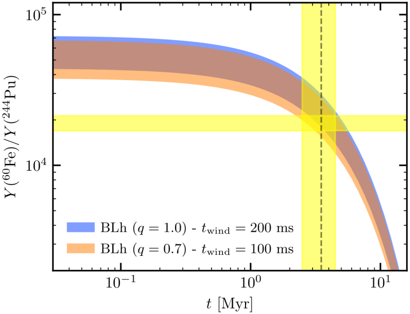
- similar trend for all simulations
- 2 models match observed ratio
- crucial presence of spiral wave wind and neutrino effects to produce also iron group nuclei

Do distance and time matters?

$$\mathcal{F}_i = f_{\mathrm{dust},i} \frac{m^{\mathrm{iso}}_{\mathrm{ej},i}(\tilde{\theta}, t_{\mathrm{wind}}) / (A_i m_u)}{4\pi D^2_{\mathrm{rad},i}} e^{-t/\tau_i}$$

- $\mathcal{F}$: measured fluence on Earth
- $f_{\mathrm{dust},i} \approx 0.5$: fraction of atoms forming dust





Chiesta *et al.* ApJL 2024 accepted

- radioactivity distance compatible with local bubble and fading radius
- no fine tuning wrt time within ± 1 Myr

How to solve the puzzle?

Detection of other live isotopes can break scenario degeneracy

Isotope	τ	BLh	BLh
$\ldots/^{244}$Pu	[Myr]	$q = 1.0$	$q = 0.7$
^{93}Zr	2.32	$8.68^{+6.22}_{-4.49} \times 10^{3}$	$1.22^{+1.00}_{-0.70} \times 10^{4}$
^{107}Pd	9.38	$2.14^{+1.71}_{-1.21} \times 10^{4}$	$2.80^{+3.33}_{-1.95} \times 10^{4}$
^{129}I	22.65	$7.63^{+5.93}_{-4.77} \times 10^{3}$	$1.75^{+2.59}_{-1.45} \times 10^{4}$
^{135}Cs	1.92	$6.68^{+1.55}_{-1.29} \times 10^{1}$	$1.06^{+0.26}_{-0.22} \times 10^{2}$
^{182}Hf	12.84	$3.24^{+0.43}_{-0.37} \times 10^{1}$	$5.25^{+0.80}_{-1.07} \times 10^{1}$
^{236}U	33.76	$1.98^{+0.08}_{-0.08}$	$2.04^{+0.14}_{-0.06}$
^{237}Np	3.09	$5.26^{+0.17}_{-0.17} \times 10^{-1}$	$5.42^{+0.38}_{-0.17} \times 10^{-1}$
^{247}Cm	22.51	$3.19^{+0.10}_{-0.09} \times 10^{-1}$	$3.03^{+0.06}_{-0.07} \times 10^{-1}$

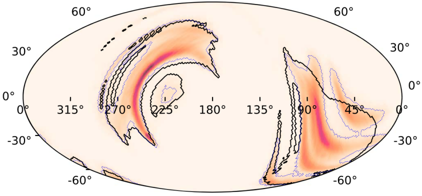
- recent detection of ^{53}Mg in sediments
- but negligible ^{53}Mg in our simulation
- a killer or a new challenge for a nearby BNS merger?

toward end-to-end modeling of observed events:

GW190425

GW190425 GW detection

- GW190425
    - second BNS merger detected by LVC, $\mathcal{M} = (1.44 \pm 0.02) M_\odot$
    - heaviset BNS ever observed: $M_{\rm tot} = (3.3 \pm 0.1) M_\odot$
- poor sky localization
- large field of view searches ($\sim 1/3$ coverage), but no detected EM counterparts



Skymap from GW190425: Abbott *et al* ApJL, 892(1) 2018

assuming a good enough sky coverage, does the lack of EM counterpart say something?

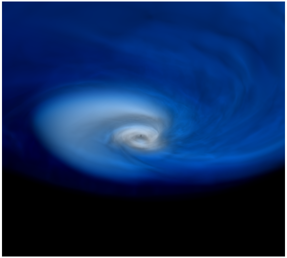
- based on NR simulations (polytropic EOS, no ν's) and rad transfer KN code, Duti *et al* PRD ()2022 excluded face-on BNS with $q \gtrsim 1.2$
- Raaijmaker *et al* ApJ (2021) computed GW190425-like KN light curves using GW posteriors + GW170817-inferred EOS + NR fitting formulae and found that ZTF could have detected GW190425 KN at peak

Modeling of GW190425

How does KN light curves depend on microphysics in modeling of GW190425-like BNS events?

Simulations targeted to GW190425 ($\mathcal{M}_{\rm chirp} = 1.44 M_\odot$):

- 3-4 distinct binaries, $q = M_B / M_A \in [1, 1.67]$
- GRHD (WhiskyTHC code) Radice+ 2011,13,14
- 2 resolutions: $\Delta x = [180, 246]$m



Courtesy of D. Radice

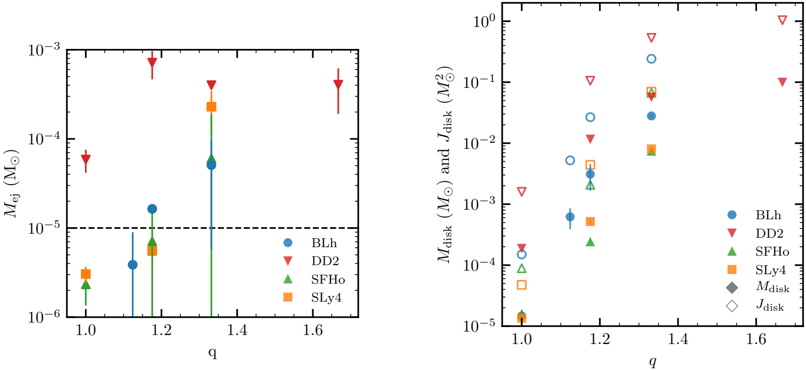
What's new?

- 4 finite-T, composition dependent nuclear EOSs: HS(DD2), BLh, SFHo & SLy4

  CompOse & stellarcollapse websites, Logoteta *et al* 2021
- neutrino treatment Radice 2016 MNRAS
  - leakage in opt. thick conditions
  - M0 in opt. thin conditions

  Radice 2018 ApJL

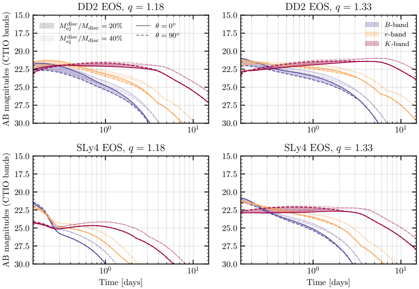
Dynamical ejecta and disk masses



Camilletti et al 2022 MNRAS

- all simulations resulted in prompt BH formation
- overall, small $M_{\rm ej}$ and $M_{\rm disk}$, unless very asymmetric BNS
- dependence on q and on (EOS-dependent) compactness
- $J_{\rm disk}/M_{\rm disk} \sim (8-10) G M_\odot / c$, over several orders of magnitude

Expected kilonova signal

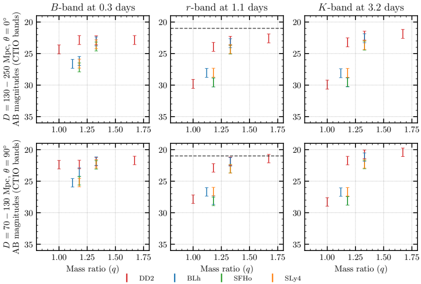


- KN signal computed with improved version of multicomponent, anisotropic KN light curve model

Wu *et al* MNRAS 2022

- small $M_{\rm ej}$ & $M_{\rm disk}$: faint KNe

- r-band AB mag at peak below ZTF sensitivity threshold
- possible exception: very stiff EOS & high asymmetry
- no robust constraints on EOS & q, once microphysics is taken into account



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A FRB associated to GW190425?

It is commonly believed that GW190425 promptly collapsed to BH.

Abbott *et al 2020* ApJL, Agathos *et al* 2020

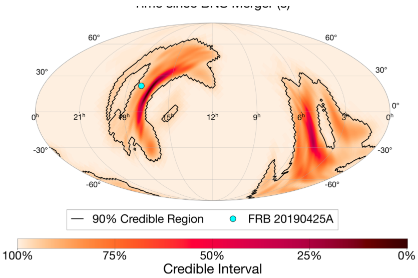
However …

FRB 20190425A was a fast radio burst happening

- 2.5 hours after GW190425 merger
- in the GW sky localization area

⇒ a possible association between GW190425 and FRB 20190425A?

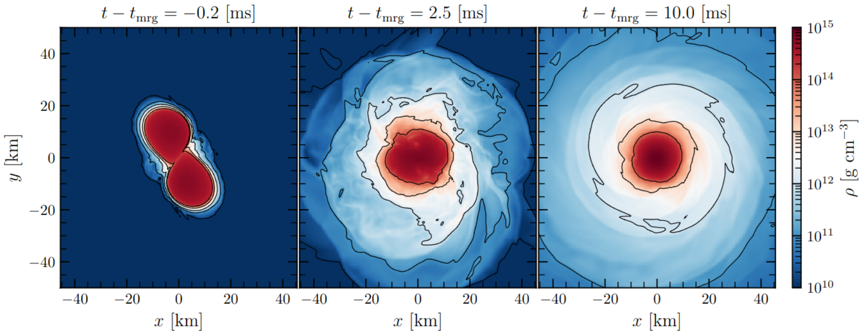
Moroianu *et al* 2023, Nat Astr.



Interesting consequences:

- confirmation of "blitzar" mechanism
- need of long lived remnant → very stiff nuclear EOS

Simulating non-collapsing GW190425 mergers

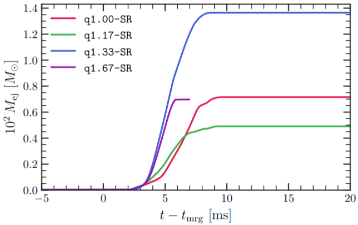


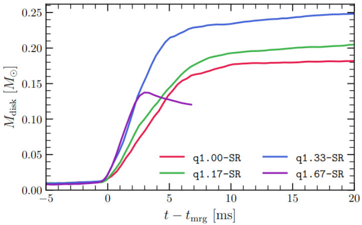
- simulations using Big Apple (BA) EOS do not produce BH, unless the 2 NSs have very different masses
- $M_{\rm NS,max} = 2.6 M_\odot$ for BA EOS

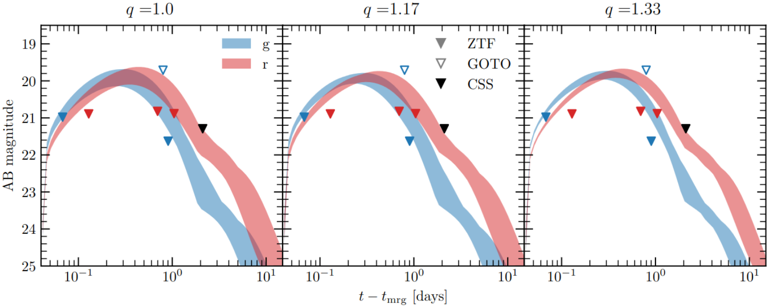
Fattoyev *et al* 2020

- caveat: no neutrinos and approximated finite temperature effects

Ejecta and kilonova light curves

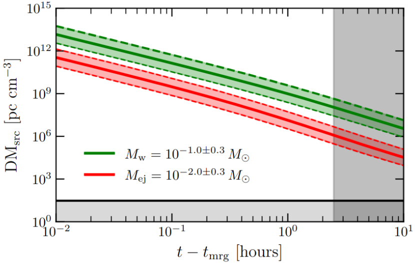






Radice *et al* arxiv 2309.15195

Constraints on dispersion measure



- ejected mass should have provided a bright kilonova
- ejected mass should have prevented radio emission during the first hours

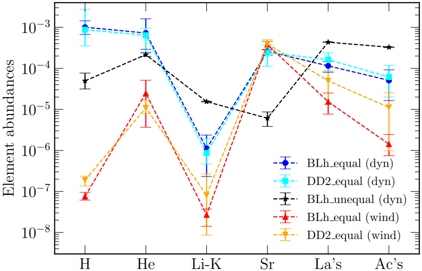
Radice *et al* arxiv 2309.15195

⇒ association with FRB seems ruled out

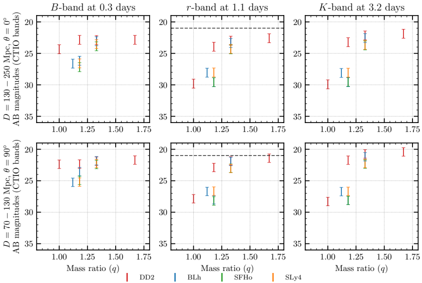
⇒ assuming good sky coverage, long lived remnant is unlikely if BNS merger happened $d_L \lesssim 150$ pc

Summary & Conclusions I

- BNS merger as sites where matter reaches most extreme gravity, density and temperature conditions
- BNS modeling: fundamental to make the most of MM astrophysics
- numerical simulations have dramatically improved over the last few years, but much work still needed
- large number of extractable information



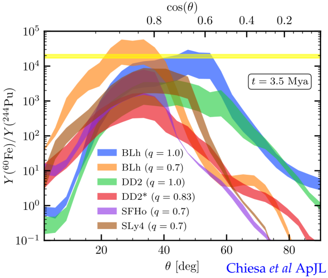
Perego, Vescovi *et al*, ApJ 2022



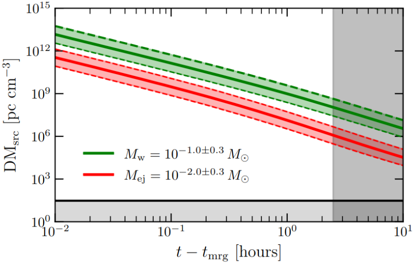
Camilletti *et al* MNRAS 2022

Summary & Conclusions II

- EM counterparts provide unique and complementary inforation to GW signals
- combination of detailed merger & counterpart models necessary to produce faithful predictions and analysis
- sophisticated models can highlight BNS merger potential as unique laboratories in the sky
- however, several uncertainties still remain, both on the physics and on the modelling side



Chiesa *et al* ApJL accepted



Radice *et al* arxiv 2309.15195