Microphysics in BNS mergers: status and challenges

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Albino Perego, Progetto EMERGE

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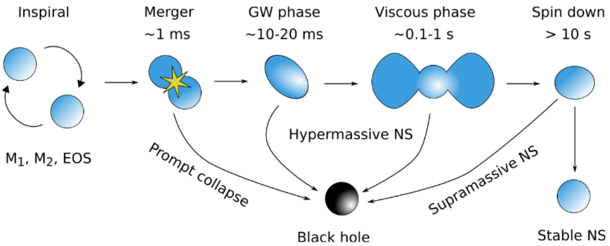
A brief overview about BNS mergers and their microphysics

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

BNS merger in a nutshell: ejecta

ejecta:

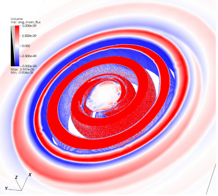
- a few percent of $M = M_A + M_B$
- neutron rich, i.e. $Y_e < 0.5$ and typically $Y_e \ll 0.5$
- expelled by different mechanisms, acting on different timescales

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

BNS merger in a nutshell: ejecta

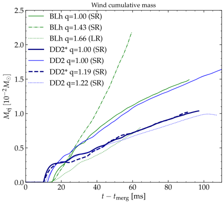
ejecta:

- 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
- dynamical ejecta ($t \sim 1 - 5\text{ms}$)
  - tidal & shock heated ejecta
  - $\langle v \rangle \sim 0.2 - 0.3c$
  - $M_{\text{ej}} \sim 10^{-4} - 10^{-2} M_\odot$
- disk winds ($t \sim 0.05 - 10\text{s}$)
  - neutrinos, MHD
  - $\langle v \rangle \sim 0.1c$
  - up to $M_{\text{ej}} \sim 0.1 - 0.4 M_{\text{disk}}$
- spiral wave winds ($t \sim 0.01 - 1\text{s}$)
  - $m = 1, 2$ spiral mode in the remnant
  - $\langle v \rangle \sim 0.2c$
  - $\dot{M} \sim 0.1 M_\odot/\text{s}$
  - acting until BH formation



top: ϕ-angular momentum radial flux

bottom: spiral wind ejecta mass



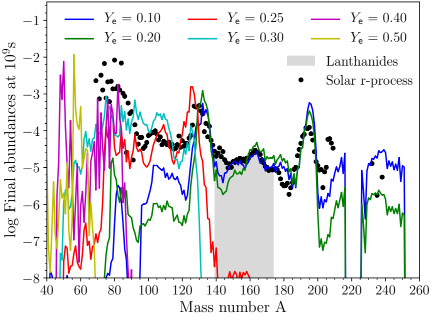
Nedora *et al* ApjL 2019

r-process nucleosynthesis in BNS ejecta

- ejecta: ideal site for r-process nucleosynthesis
- at low entropy ($s \lesssim 40 k_b$/baryon), Y_e dominant parameter
- Y_e influenced by weak interactions involving neutrinos, e.g.

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

- observable in
  - kilonova: light curve (opacity) and spectra (absorption lines)
  - chemical enrichment



Perego, Thielemann & Cescutti 2021

Microphysics in BNS merger simulations: EoS

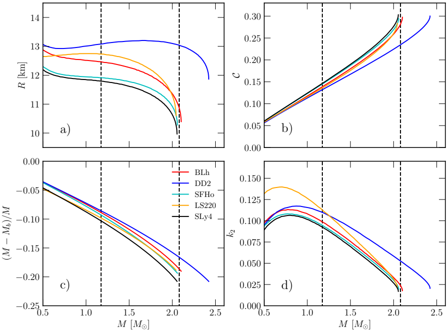
finite temperature, composition dependent Equation of State (EoS), in nuclear statistical equilibrium

- relevant degrees of freedom

$$\text{minimal set}: \quad n, p, e^{\pm}, \gamma$$

some present challenges:

- nuclear interaction above saturation density
- finite temperature treatment
- are we including all the relevant species?
  - hyperons, quarks $\rightarrow$ phase transition?
  - pions
  - muons



for pions and muons: Vijayan+ PRD 23, Fore & Reddy 20

PRD

Microphysics in BNS merger simulations: neutrinos

Radiation transport

- non trivial GR radiation hydrodynamics
- state of the art: energy-integrated two-moment (M1) scheme with analytic closure for energy density and fluxes
  - supplemented by fenomenological transport eq for number density
  - ✓ accurate methods
  - ✓ consistent solution in optically thin/thick regimes
  - ✗ computationally expensive
  - ✗ closure-related artifacts

e.g. Foucart+ 16a,b PRD, Radice+ 22 MNRAS, Musolino+ 24 MNRAS, Schianchi+ 24 PRD

- for several years, energy-integrated hybrid leakage (opacially thick) + M0 (optically thin) scheme
  - supplemented by fenomenological transport eq for number density
  - conceptually easier than M1
  - ✓ computationally cheaper $\rightarrow$ several tens of simulations
  - ✗ more approximate
  - ✗ lack of trapped neutrinos

e.g. Sekigichi+ 15 PRD, Radice+ 16 MNRAS, Radice+ 18 ApJ

Microphysics in BNS merger simulations: reactions

- collision integral for the radiation HD equations

$$\mathcal{S}^\mu = (\eta - \kappa_a J)\, u^\mu - (\kappa_a + \kappa_s)\, H^\mu$$

j: emissivities, $\kappa_{a,s}$: absorption & scattering (stimulated) opacities

- starting from ”standard set” of reactions

$$p + e^- \to n + \nu_e$$
$$n + e^+ \to p + \bar{\nu}_e$$
$$N + \nu \to N + \nu$$
$$e^- + e^+ \to \nu + \bar{\nu}$$
$$N + N \to N + N + \nu + \bar{\nu}$$

  - energy integrated, analitycal expressions from simplified reaction kernels

    Radice+ 16 MNRAS using Ruffert+ 97 A&A or Rosswog & Liebendoerfer +03 MNRAS

  - energy integarted tabulated rates

    Foucart+ 16 PRD using *NuLib* O'Connor& Ott 10 CQG

  - E integration: LTE conditions + correction for optically thin conditions

    see e.g. Foucart+ 16 PRD or Radice+ 22 MNRAS

  - detailed balance necessary to predict correct equilibrium
    $\to$ how to do it with approximated, energy-integrated rates?

Outline of the talk

Accurate microphysics & neutrino modeling in BNS mergers is crucial.

Why?

- direct neutrino detection: implausible
- however, microphysics & neutrinos impact on many aspects/observables related to mergers
- key input to study detailed nuclear and neutrino physics

- what do we know about neutrino emission from BNS mergers?
  - characterizing neutrino luminosities and mean energies in BNS mergers

Cusinato et al 2022 EPJA

- where can neutrinos have an impact on merger observables?
  - e.g. nucleosynthesis → Sr in kilonova spectra, ^{60}Fe and ^{244}Pu in ocean sediments

Perego et al 2022 ApJ; Chiesa et al 2024 ApJL

- are we including all the relevant species in the EOS?
  - the potential impact of muons

Loffredo *et al* 2023 A&A

- are we including all the relevant reactions and reaction physics?

Neutrino luminosities from BNS mergers

Simulation sample

66 BNS merger simulations (51 BNS models) from the CoRe database

Gonzales *et al* arxiv:221016366

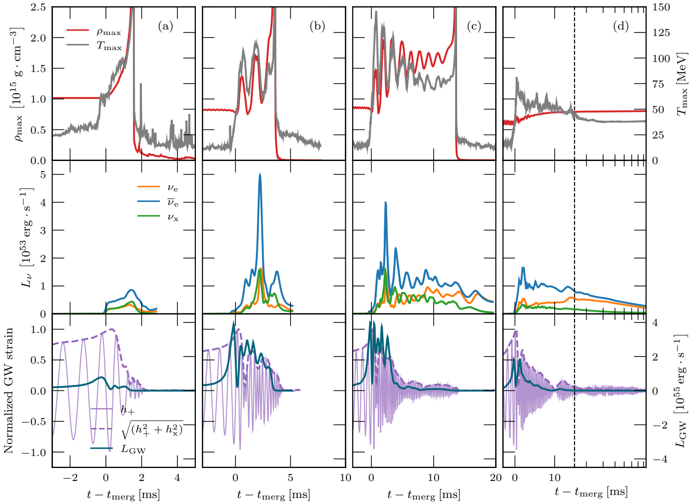
- $M_{\rm tot} \in [2.6, 3.438] M_\odot$
- 6 different finite T, composition depedent EOS
- $q \in [1.0, 1.82]$
- different resolutions:
  - mostly, $\Delta x = 185$ m
  - 15: $\Delta x = 246$ m
  - 2: $\Delta x = 123$ m

homogeneous numerical setup

- WhyskyTHC code — Radice+ 2011,13,14
- neutrino treatment:
  - leakage+M0
  - extraction of ν emission properties at the edge of computational domain: luminosities, number luminosity, mean energies

Radice+ 16 MNRAS, Radice+ 18 ApJ

Neutrino emission: qualitative overview

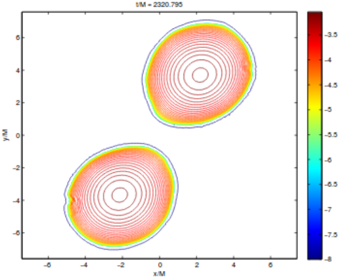


Cusinato *et al*, EPJA 2022

a) PC b) short lived c) delayed collapse d) long lived

Tidal deformation during the inspiral phase

NS in external, inhomegeneous gravitational field ⇒ tidal deformation



Bernuzzi et al PRD 2012

$$Q_{i,j} = -\lambda \mathcal{E}_{i,j}$$

$$\lambda = \left(\frac{2}{3} \frac{R^5}{G} k_2 \right)$$

- $Q_{i,j}$ quadrupolar moment
- $\mathcal{E}_{i,j} = \partial^2_{i,j} \Phi$ tidal field
- k_2 quadrupolar tidal polarizability
- R radius of the star

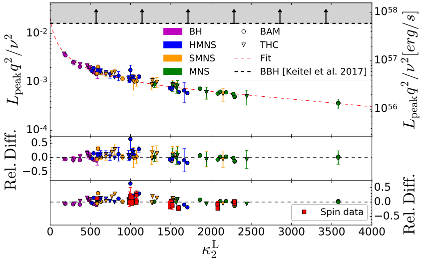
Tidal effect in GW signal encoded in linear combinations of λ's: $\tilde{\Lambda}$ and κ_2

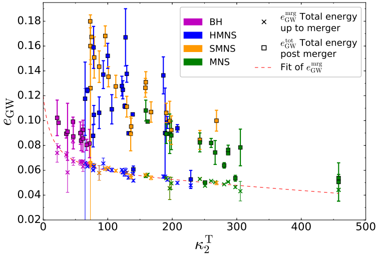
$$\tilde{\Lambda} = \frac{16}{13} \left[\frac{(M_A + 12 M_B) M_A^4 \Lambda_2^{(A)}}{(M_A + M_B)^5} + (A \leftrightarrow B) \right] ; \; \Lambda_2^{(i)} = \left(\frac{c^2}{M_i} \right)^5 \lambda_{(i)} ; \quad i = A, B$$

$$\kappa_2^T = \kappa_2^A + \kappa_2^B \, . \, \kappa_2^i = \frac{1}{3} x_i^4 (1 - x_i) \Lambda_2^{(i)} \, , x_i = M_i / M_{\rm tot} \quad i = A, B$$

see, e.g., Damour, Les Houches Summer School on Gravitational Radiation 1982; Flanagan & Hinderer PRD 77 2008, Bernuzzi et al PRD 2012

GW luminosities and energetics of BNS



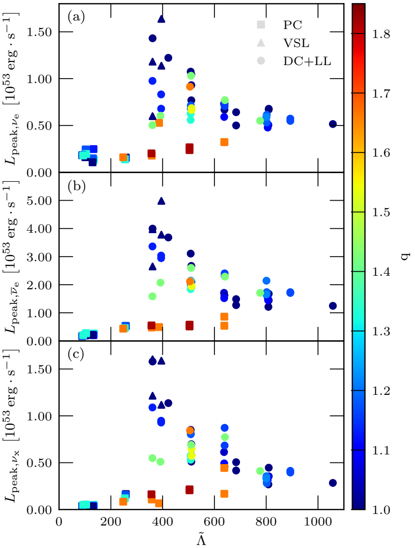


Zappa, Bernuzzi, Radice, Perego, Dietrich PRL 2018

how luminous/energetics are BNS at merger?

- $L_{\rm GW,peak} \lesssim 10^{-3} L_P$ with $L_P = c^5/G \approx 3.63 \times 10^{59} \rm erg\, s^{-1}$
- significantly smaller than BBH
- prompt collapses: largest $L_{\rm GW,peak}$
- $L_{\rm GW,peak}(q^2/\nu^2)$ correlates with κ_2^L
    - κ_2^L: combinations of quadrupolar tidal polarizabilities
    - $\nu = M_A M_B/(M_A + M_B)^2 \leq 1/4$

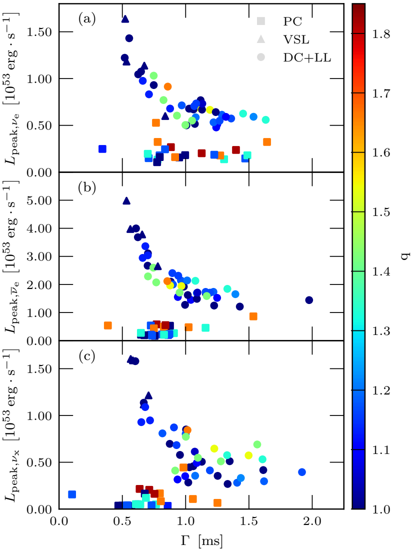
Neutrino emission: peak luminosity



- non-PC BNS mergers
  - main $\tilde{\Lambda}$ dependence: for $q \gtrsim 1$, L_{peak} decreases for increasing $\tilde{\Lambda}$
  - further influence on q
- PC mergers
  - separated brench with weaker dependence on $\tilde{\Lambda}$
  - $L_{\nu,\mathrm{peak}}$ increases for increasing $\tilde{\Lambda}$, probably related with q
- similar dependence for $\langle L_\nu \rangle_{10\ \mathrm{ms}}$

Cusinato *et al*, EPJA 2022

Neutrino emission: peak luminosity VS peak width



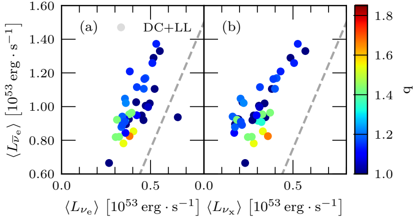
- first (main) peak: well described by Gaussian profile of FWHM $\Delta t_{\mathrm{peak}} \sim \Gamma = 2\sqrt{2\ln 2}\,\sigma$

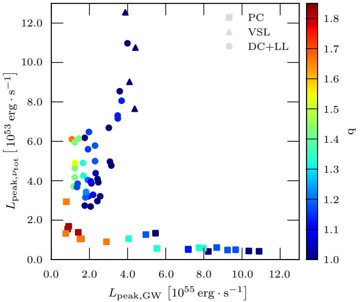
$$L = L_{\mathrm{peak}} \exp\left(-\frac{(t - t_{\mathrm{peak}})^2}{2\sigma^2}\right)$$

- Γ behaves similar to L_{peak}
- $\Rightarrow \Delta E_{\mathrm{peak}} \approx L_{\mathrm{peak}}\Gamma \approx$ constant

Cusinato *et al*, EPJA 2022

Neutrino emission: correlations

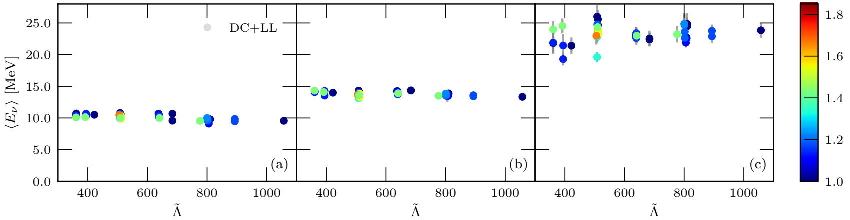




Cusinato *et al*, EPJA 2022

- (initial) $\bar{\nu}_e$ dominance over the other flavors
- good correlation between luminosities in different flavors
- partial correlation between L_ν and L_{GW}, mitigated by q and broken by PC binaries

Neutrino emission: mean energies



Cusinato *et al*, EPJA 2022

- results compatible with previous outcomes

  e.g. Ruffert+97 A& A, Rosswog & Liebendoerfer 03 MNRAS, Foucart+ 16 PRD

- mean ν energy at infinity: robust behavior wrt BNS parameters
- robust hierarchy, reflecting ν's decoupling conditions

  e.g. Endrizzi *et al* 2021 EPJA

- indication that post-merger remnant partially looses memory of the merging binary (for non-PC)

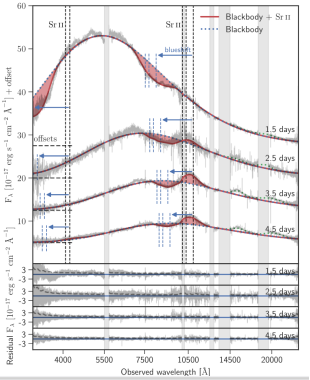
Nucleosynthesis in BNS mergers and their observables

Strontium in AT2017gfo early spectra

observed spectra from AT2017gfo at 1.5-4.5 day: identification of strontium

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

Watson+ 18 Nature, Gillanders+ 22 MNRAS



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

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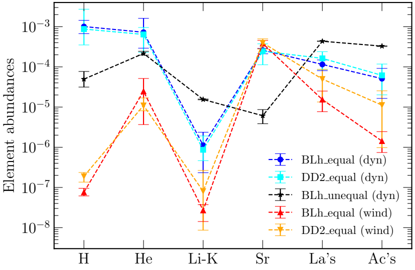
$$M_{\rm Sr} \sim 1 - 5 \times 10^{-5} M_\odot$$

Watson+ 18 Nature, Gillanders+ 22 MNRAS

- nucleosynthesis yields from targeted simulations including neutrinos (leakage+M0 scheme)
  - Sr robustly produced for $0.2 \lesssim Y_e \lesssim 0.4$
  - unequal mass BNS model disfavored
  - $q = 1$ dynamical ejecta 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



Perego *et al*, ApJ 2022

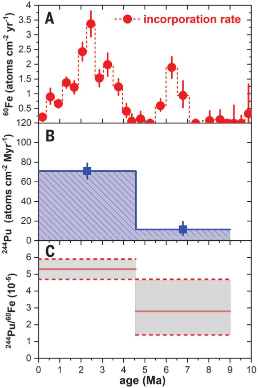
^{60}Fe and ^{244}Pu detection in crust sediments

- 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)
- $^{244}\mathrm{Pu}/^{60}\mathrm{Fe} = (53 \pm 6) \times 10^{-6}$

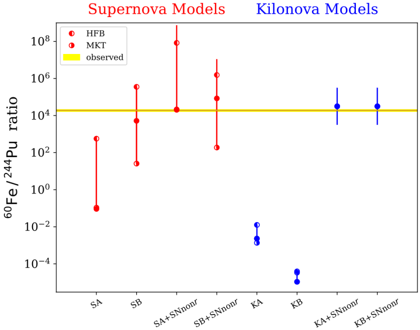
How can we interpret the more recent peaks?



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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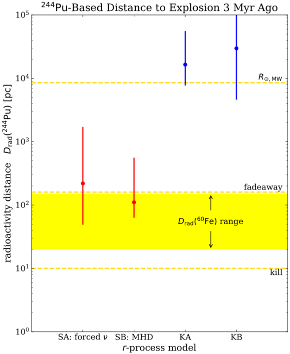

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Wang+21 ApJ

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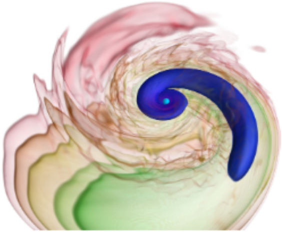
Modeling of long lived BNS mergers

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)

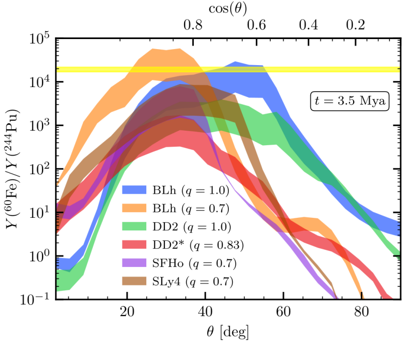
  CompOse & stellarcollapse websites, Logoteta *et al* 2021
- neutrino treatment Radice 2016 MNRAS
  - leakage in opt. thick conditions
  - M0 in opt. thin conditions
- effective treatment for turbulent magnetic viscosity (GRLES) Radice 2018 ApJL
- single maximum resolution: $dx = 185$m



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

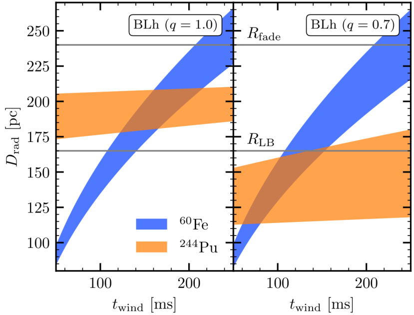
- ^{60}Fe and ^{244}Pu from dynamical ejecta & spiral-wave wind
- polar angle dependence: inefficient mixing assumption
- color band: spiral wave wind duration $t_{\rm wind} \in [50, 200]$ms
- BNS merger occurring 3.5 Myr ago

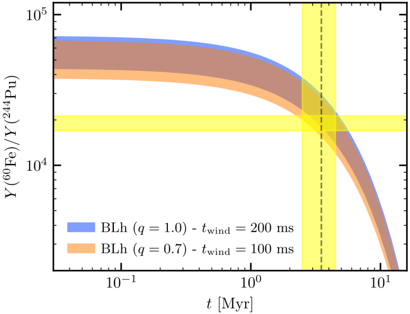
- similar trend for all simulations
- 2 models match observed ratio
- crucial presence of spiral wave wind and neutrino effects to produce also iron group nuclei

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





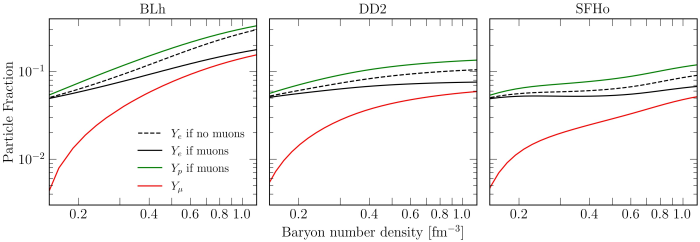
Chiesta *et al.* ApJL 2024 accepted

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

Impact of muons

in BNS merger remnants

Muons in NSs and BNS mergers



- muons are relevant in cold NSs

$$\mu_e\,[\mathrm{MeV}] \sim 131.5 \left(\frac{Y_e}{0.05}\right)^{1/3} \left(\frac{n_b}{0.2\,\mathrm{fm}^{-3}}\right)^{1/3} \qquad \mu_\mu\,[\mathrm{MeV}] \sim 106 + 28 \left(\frac{Y_\mu}{0.01}\right)^{2/3} \left(\frac{n_b}{0.2\,\mathrm{fm}^{-3}}\right)^{2/3}$$

and cold, β-equilibrated NS EOS usually include muons

- CCSN and BNS merger conditions allows (anti)muon presence

Bollig+ PRL 2017, Bollig+ PRL 2020, Fischer+ 2020 PRD

- however, state-of-the-art BNS simulations do not include muons

Estimating the impact of muons

Our aim:
to estimate the impact of muons on the merger remnant and on the trapped neutrino component in post-processing

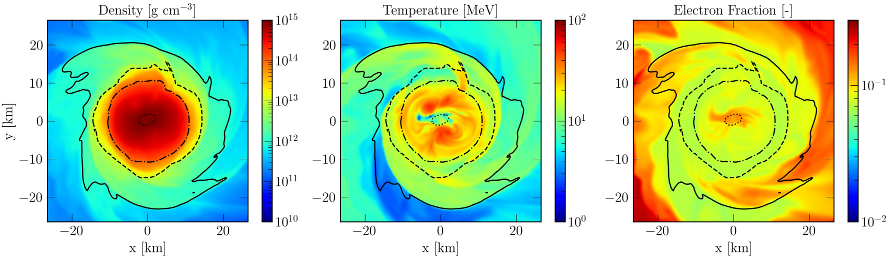
Our post-processin method:

- consider early post-merger outcome of 4 GW170817 simulations
  - neutrino radiation: leakage+M0 scheme
  - muons and trapped neutrinos not included
- include (anti)muons in the EOS
- from the simulations output, infer $(Y_{l,e}, Y_{l,\mu}, u)$
- solve the system:

$$\begin{cases} Y_{l,e} &= Y_e + Y_{\nu_e} - Y_{\bar{\nu}_e} \\ Y_{l,\mu} &= Y_\mu + Y_{\nu_\mu} - Y_{\bar{\nu}_\mu} \\ u &= \sum_i e_i \qquad i = \{N's, e^\pm, \mu^\pm, \gamma, \nu\} \end{cases}$$

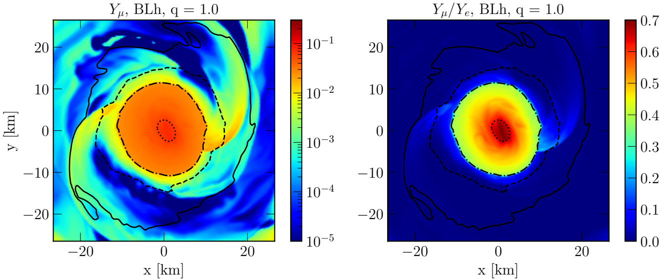
w.r.t. (Y_e, Y_μ, T)

Muons in the remnant



- muons present for $\rho \gtrsim 10^{13}$g cm^{-3}
- bulk of muons from the cold NSs
- muons also created during merger via thermal processes and weak reactions
- net muon fraction: $\sim 30\% \div 70\%$ of net electron fraction, depending on the nuclear EOS

Muons in the remnant



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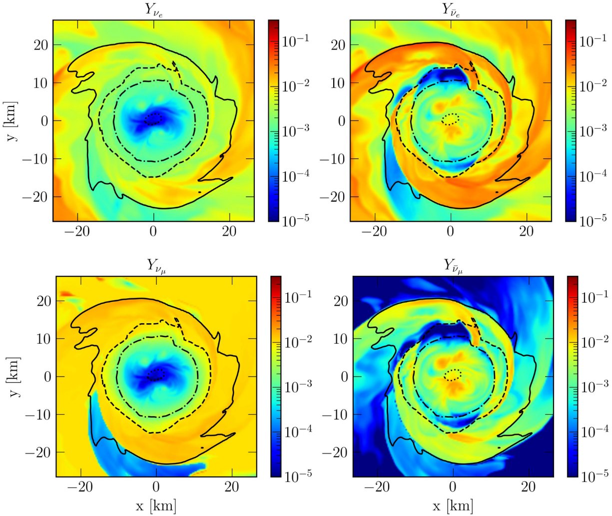
Trapped neutrinos in the remnant

- $\rho > 10^{14}$g cm^{-3}: $\bar{\nu}$'s dominate $\Rightarrow$ $\bar{\nu}_\mu$ most abundant, followed by $\bar{\nu}_e$
- $\rho \sim 10^{13\div14}$g cm^{-3}: ν's dominate $\Rightarrow$ ν_μ most abundant, followed by ν_e



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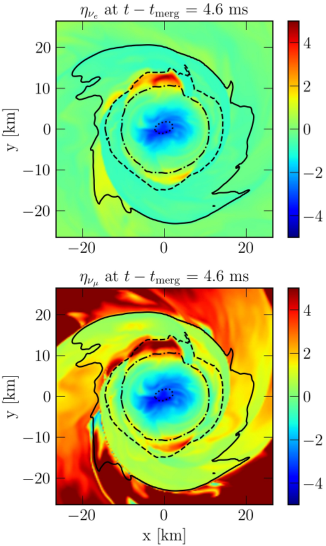
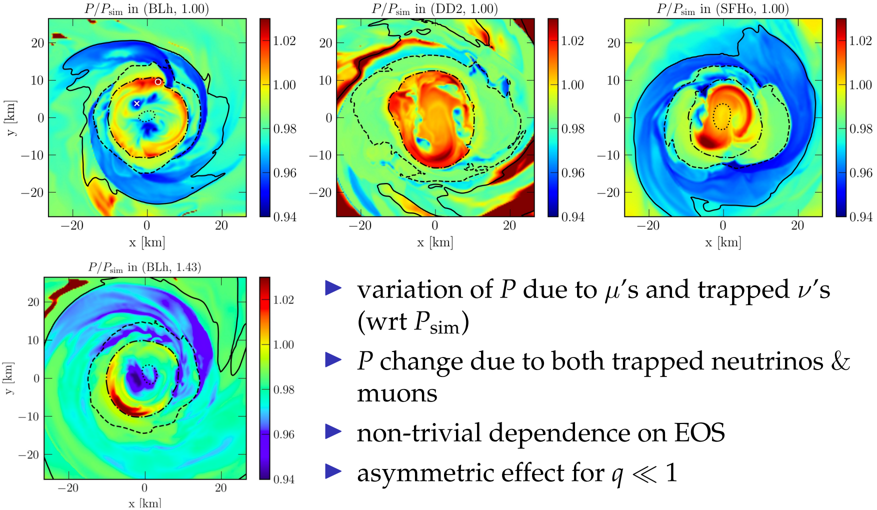


- ν gas properties determined by equilibrium μ_ν's ($\rightarrow$ degeneracy parameter $\eta_\nu = \mu_\nu / T$)
- decompression of cold n-rich matter: matter leptonization $\rightarrow$ $\bar{\nu}$ dominance
- possible non-trivial dependence on EOS: larger Y_ν for BLh due to larger symmetry energy

Influence on remnant pressure

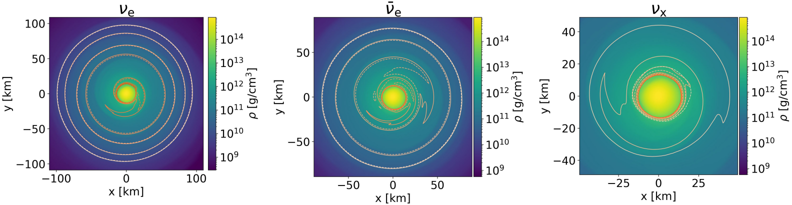


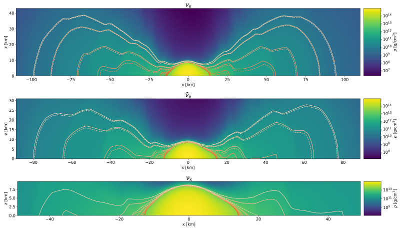
- variation of P due to μ's and trapped ν's (wrt $P_{\rm sim}$)
- P change due to both trapped neutrinos & muons
- non-trivial dependence on EOS
- asymmetric effect for $q \ll 1$

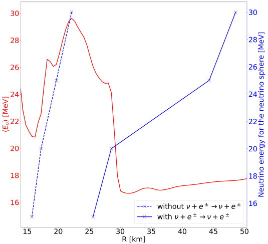
What's next?

Are we including all the relevant reactions?

- $\nu + e^{\pm} \to \nu + e^{\pm}$
- very relevant in core collapse and PNS spectra
- $\lambda_{\rm en} = \sqrt{\lambda_{\rm tot}\lambda_{\rm inel}} \to \tau_{\rm en} \to$ neutrino-surfaces: $\tau_{\rm en} = 2/3$



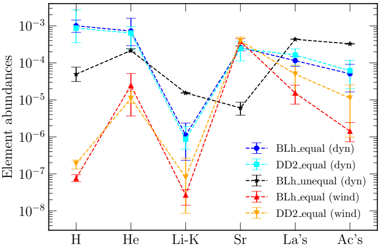




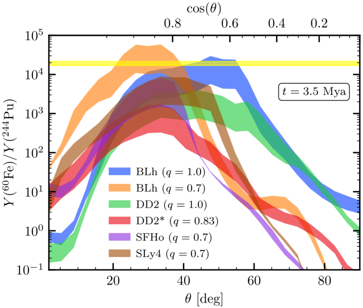
Courtesy of F. Mazzini (Master Student)

Summary & Conclusions

- neutrinos are key players in BNS mergers
- accurate neutrino modeling necessary to interpret BNS observables
  - nucleosynthesis
  - kilonovae and sediments
- numerical simulations have dramatically improved over the last few years, but much work still needed
  - relevant EoS degrees of freedom
  - relevant reactions and accurate/consistent physics
- necessary input for future studies, including neutrino oscillation



Perego *et al*, ApJ 2022



Chiesta *et al.* ApJL 2024