

Modeling of binary neutron star mergers: challenges and recent results

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ray bursts**

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A bit of history: the seminal works

BSN merger modeling has seen a blooming phase in the past few years

- ▶ 1974-1982: compact binary mergers as sources of r -processes

Lattimer & Schramm ApJ 1974 & 1976, Symbalisty & Schramm ApJ 1982

- ▶ 1989: BNS mergers as sources of GWs, neutrinos, r -process nucleosynthesis and GRBs

Eichler, Livio, Piran, Schramm Nature 1989

- ▶ 1995-2005: kilonova emission

Li & Paczynski ApJ 1995, Kulkarni 2005

Abstract

NEUTRON-STAR collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors¹. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant². However, the rate of these neutron-star collisions is highly uncertain³. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r -process)⁴. Furthermore, these collisions should produce neutrino bursts⁵ and resultant bursts of γ -rays; the latter should comprise a subclass of observable γ -ray bursts. We argue that observed r -process abundances and γ -ray-burst rates predict rates for these collisions that are both significant and consistent with other estimates.

Abstract from Eichler *et al* 1989

A bit of history: simulation breakthroughs

- ▶ **1994-2003**: first simulations in Newtonian-gravity

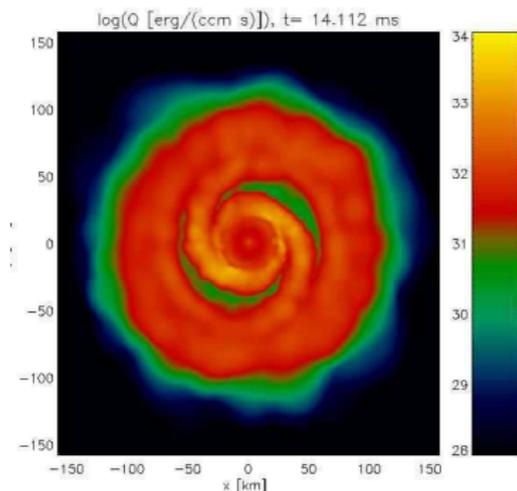
Davis et al 1994, Freiburghaus et al 1999, Ruffert et al 1996-1999, Rosswog et al 1999-2003

- ▶ **2000**: first BNS mergers in full GR

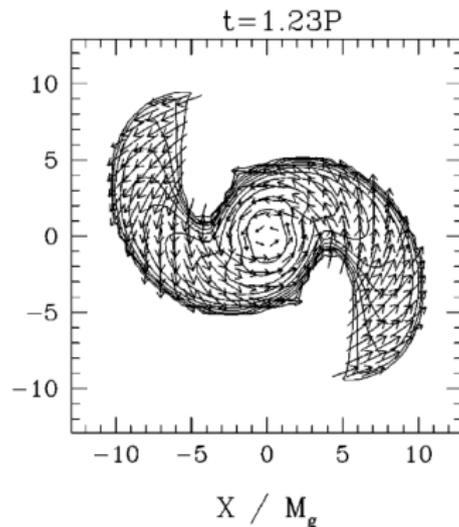
Shibata & Uryu PRD 2000

- ▶ **2014-2016**: first BNS mergers in full GR w/ neutrinos

Wanajo et al ApJL 2014, Sekiguchi et al PRD 2015, Radice et al 2016 MNRAS, Foucart et al 2016 PRD



Rosswog & Liebendoerfer MNRAS 2003

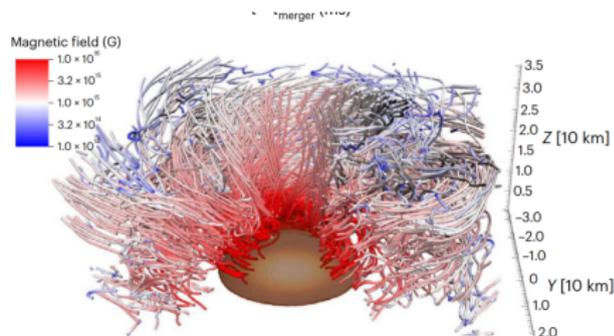


Shibata & Uryu PRD 2000

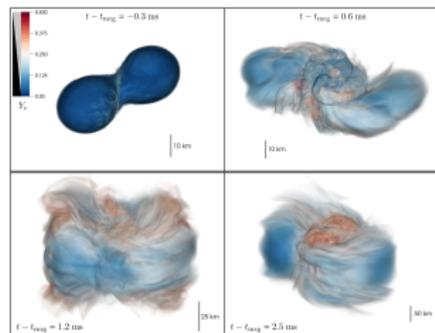
A bit of history: recent developments

Since then, our BNS models (incl. counterparts & nucleosynthesis) have gained several ingredients/aspects:

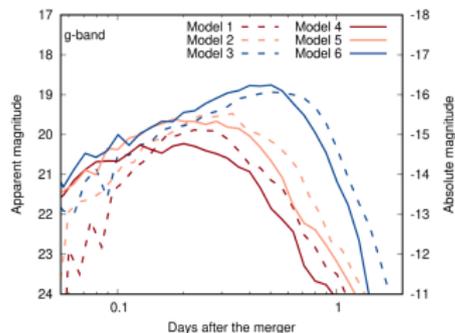
- ▶ relativistic MHD
- ▶ nuclear EOS
- ▶ neutrino radiation
- ▶ detailed nucleosynthesis
- ▶ radiative transfer kN
- ▶ detailed atomic opacities



Kiuchi *et al* Nature 2024

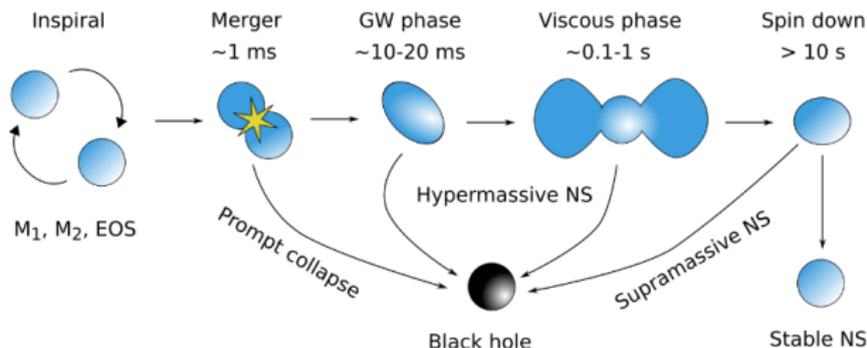


Radice *et al* ApJ 2018



Banerjee *et al* ApJ 2024

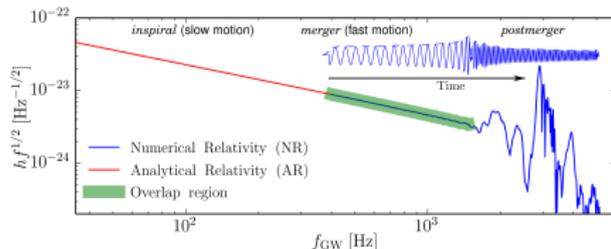
What can we (reasonably) say?



Radice, Bernuzzi, Perego 2020 ARNPS; see also Bernuzzi 2020

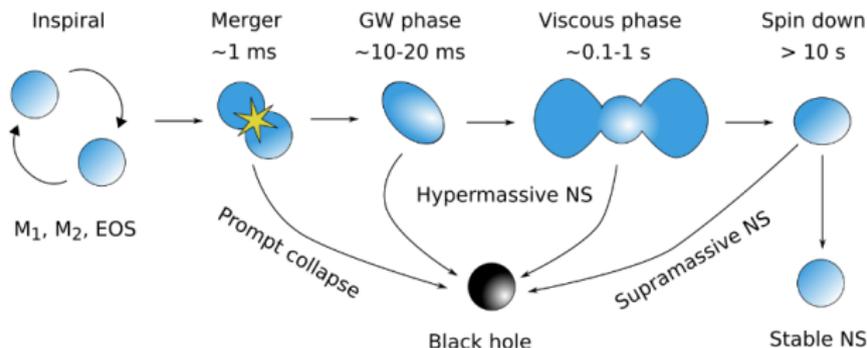
GW emission

- ▶ inspiral signal
 - ▶ sensible to NS tidal deformation
 - ▶ constraining NS EOS up to $\sim 2\text{-}3\rho_0$
- ▶ post-merger signal
 - ▶ characteristic f_2 peak in frequency
 - ▶ sensible to physics at $\rho \lesssim \rho_{\text{max}}$
 - ▶ sensible to additional degrees of freedom



Credit: S. Bernuzzi, see also Dietrich's Jacobi's talk, G. Huez poster

What can we (reasonably) say?

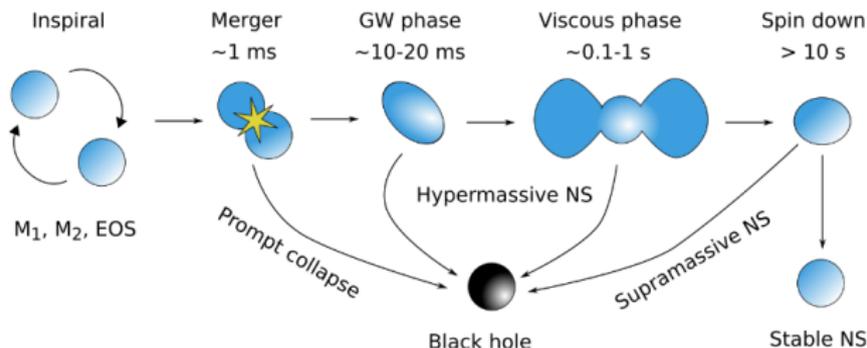


Radice, Bernuzzi, Perego 2020 ARNPS; see also Shibata & Hotokezaka ARNPS 2019

Matter ejection

- ▶ up to several $0.01's M_{\odot}$, depending on mass, mass ratio and EOS
- ▶ subdominant dynamical mass ejection
 - ▶ tidal+shock-driven
- ▶ disk as (usually) dominant ejecta source
 - ▶ driven by viscosity, ν 's, spiral modes, MHD processes

What can we (reasonably) say?



Radice, Bernuzzi, Perego 2020 ARNPS; see also Perego, Thielemann, Cescutti 2021

Nucleosynthesis

- ▶ potential production of full r -process pattern
- ▶ sensible to remnant lifetime through ν 's

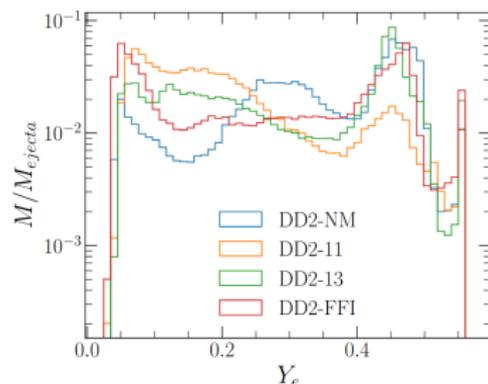
Kilonova

- ▶ color evolution, light curves and spectral features reflecting ejecta composition: blue & red kilonova
- ▶ crucial role of detailed opacity, nuclear energy/rates & thermalization

Which are the still open/new issues?

- ▶ **Quantitative outcome** still uncertain, mostly due to:
 - ▶ accuracy of input physics
 - ▶ numerical convergence
 - ▶ multiscale nature of the problem
 - ▶ large parameter space
- ▶ this prevents to fully address **long-standing issues**:
 - ▶ actual role of BNS mergers in GCE
 - ▶ properties of high density EOS
 - ▶ mechanism for GRB production
 - ▶ role of magnetic field and turbulence for matter ejection

- ▶ **new challenges** have appeared, e.g.
 - ▶ role of ν flavor conversions see Qiu's and Wu's talks
 - ▶ LTE VS NLTE conditions for kilonova emission see e.g. Just's talk



Outline of the talk

- ▶ neutrino modeling
 - ▶ qualitative overview of neutrino emission
 - ▶ uncertainties in the transport and in the rates
- ▶ EOS constraints
 - ▶ PC and the supra-dense EOS
- ▶ remnant properties
 - ▶ characterizing disks from BNS mergers
- ▶ toward our discussion: nucleosynthesis & kilonovae
 - ▶ nucleosynthesis signatures in kilonovae and BNS mergers
 - ▶ some modeling developments

Neutrino modeling:
emission overview & uncertainties

Transport in BNS merger simulations

- ▶ state of the art: **energy-integrated two-moment (M1) scheme** including Doppler effects at all orders in v/c , and all ν -matter coupling terms
 - ▶ ✓ accurate methods
 - ▶ ✓ consistent solution in optically thin/thick regimes
 - ▶ ✗ computationally expensive
 - ▶ ✗ closure-related artifacts

e.g. Foucart *et al* 16a,b PRD, Radice *et al* 22 MNRAS, Musolino *et al* 24 MNRAS, Schianchi *et al* 24 PRD

- ▶ for several years, **energy-integrated hybrid leakage (opacially thick) + M0 (optically thin) scheme**
 - ▶ conceptually easier than M1
 - ▶ ✓ computationally cheaper → several tens of simulations
 - ▶ ✗ more approximate
 - ▶ ✗ lack of trapped neutrinos

e.g. Sekiguchi *et al* 15 PRD, Radice *et al* 16 MNRAS, Radice *et al* 18 ApJ

▶ **future directions:**

- ▶ energy-dependent moment schemes e.g. Cheong *et al* ApJ 2024
- ▶ Monte Carlo transport Foucart *et al* 2020 ApJ, 2023 PRD; see Kawaguchi's talk
- ▶ S_N or full Boltzmann transport

How to characterize neutrino luminosities?

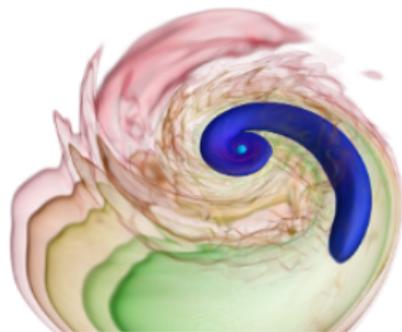
Large (66) sample of BNS merger simulations:

- ▶ broad mass ($M \in [2.6, 3.44] M_{\odot}$) & mass ratio ($q \in [0.55, 1]$) ranges
- ▶ 6 finite T , composition dependent EOSs
- ▶ different resolutions: $\delta x \in [123, 246]$ m
- ▶ different outcomes:
long-lived VS delayed collapse VS short-lived VS PC

2nd release of CoRe database, Gonzales *et al* 2023 CQG

Homogeneous numerical setup:

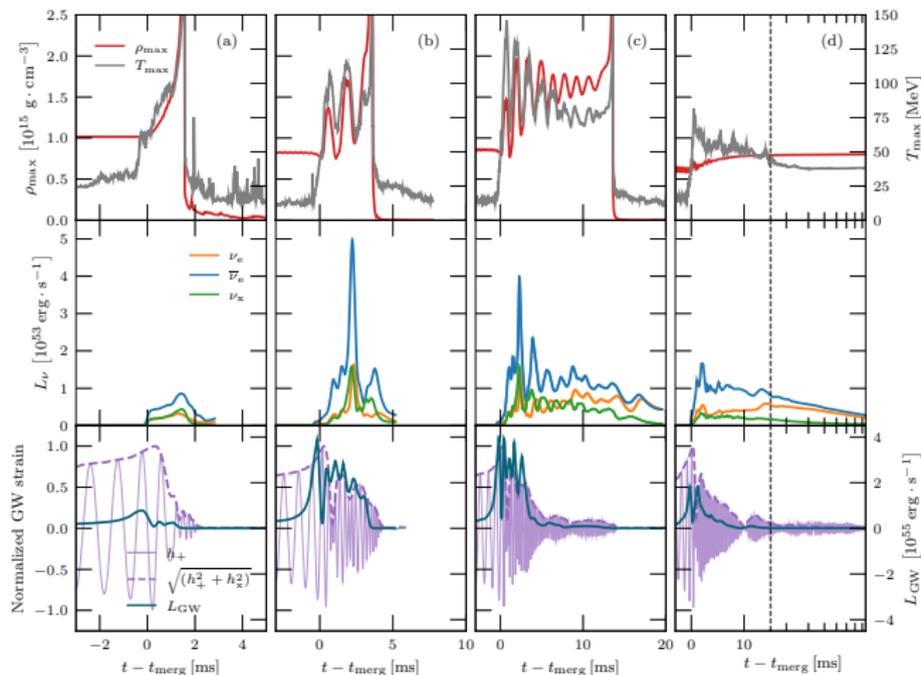
- ▶ GRHD (WhiskyTHC code)
Radice et al 2011,13,14 CQG, MNRAS
- ▶ neutrino treatment: leakage (optically thick)+ M0 (optically thin) scheme
Radice 2016 MNRAS
- ▶ effective treatment for turbulent viscosity (GRLES)
Radice et al 2018 ApJL



Bernuzzi et al. MNRAS 2020

Free streaming neutrinos: overview

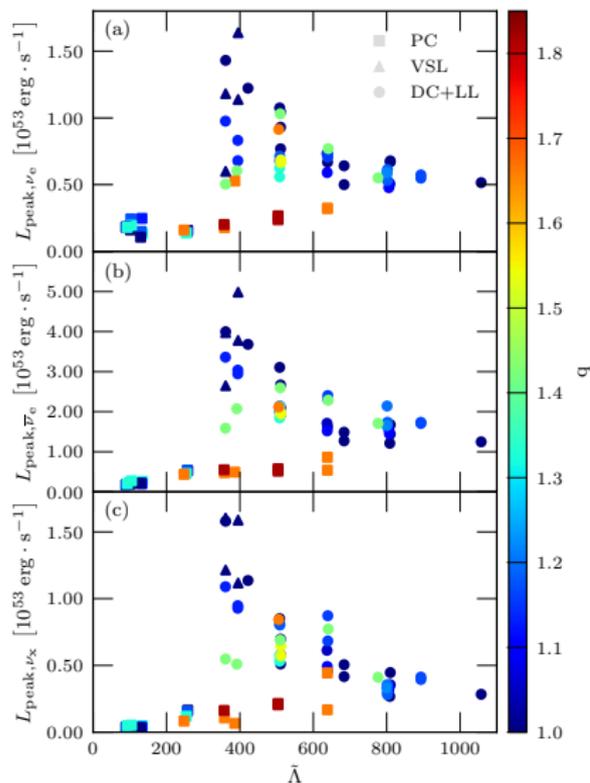
- ▶ outside the remnant ($\rho \lesssim 10^{13} \text{ g cm}^{-3}$): $\lambda_\nu \gg R$ and $\tau_\nu \lesssim 1$



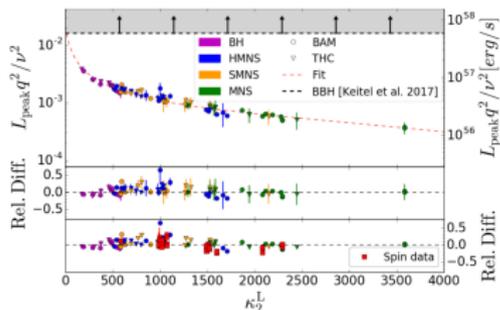
Cusinato et al, EPJA 2022

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

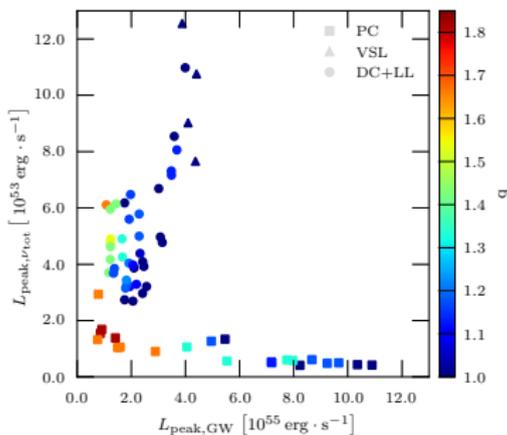
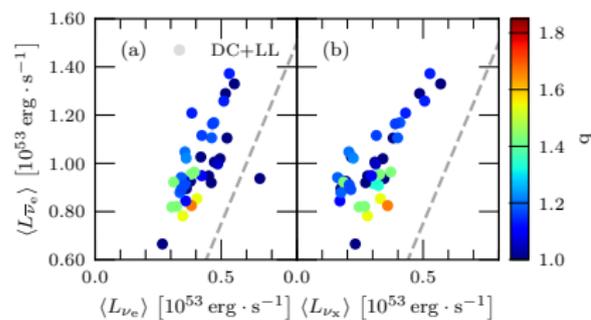
Neutrino emission: peak luminosity



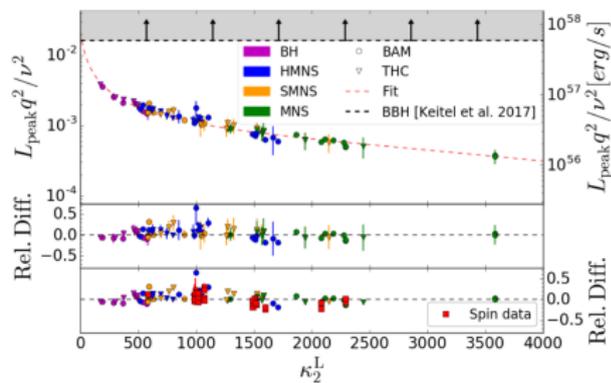
- ▶ non-PC BNS mergers
 - ▶ main $\tilde{\Lambda}$ dependence: for $q \gtrsim 1$, L_{peak} decreases for increasing $\tilde{\Lambda}$
 - ▶ further influence on q
- ▶ PC mergers
 - ▶ separated branch with weaker dependence on $\tilde{\Lambda}$
 - ▶ $L_{\nu, \text{peak}}$ increases for increasing $\tilde{\Lambda}$,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



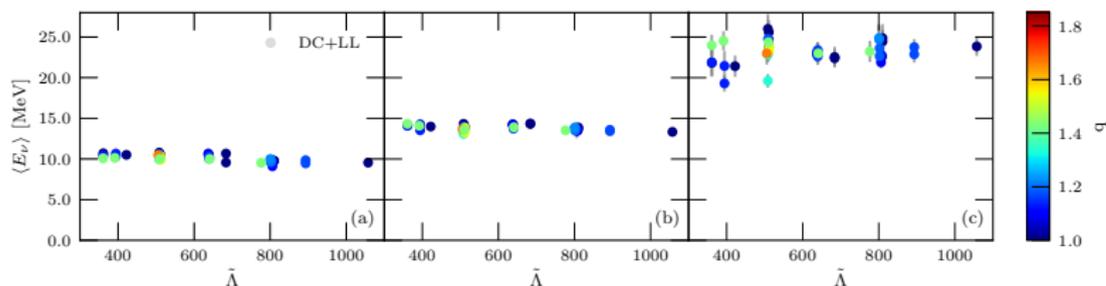
Neutrino emission: correlations



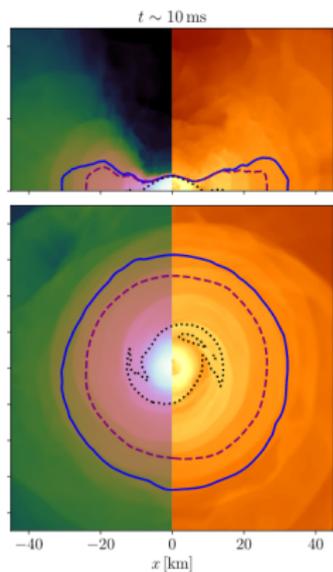
- ▶ (initial) $\bar{\nu}_e$ dominance over the other flavors
- ▶ good correlation between luminosities in different flavors
- ▶ partial correlation between L_{ν} and L_{GW} , mitigated by q and broken by PC binaries



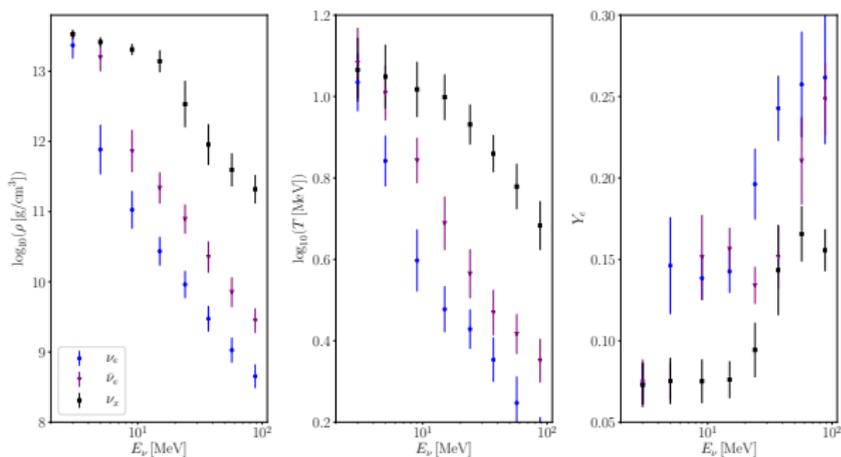
Neutrino emission: mean energies



Cusinato *et al*, EPJA 2022



matter density at thermal neutrino decoupling



Endrizzi *et al*, EPJA 2021

How to characterize neutrino transport uncertainties?

Common simulation setup:

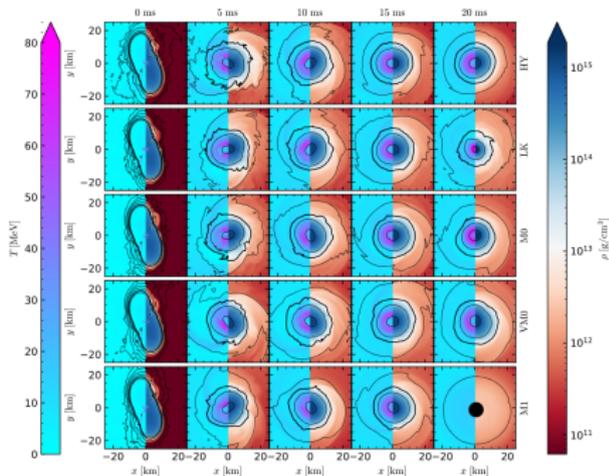
- ▶ $M = (1.30-1.30)M_{\odot}$
- ▶ SLy4 EOS
- ▶ GRHD (WhiskyTHC code)

Schneider *et al* ApJ 2017

Radice *et al* CQG & MNRAS 2011,13,14

comparison of BNS models with different ν transport, viscosity, resolution:

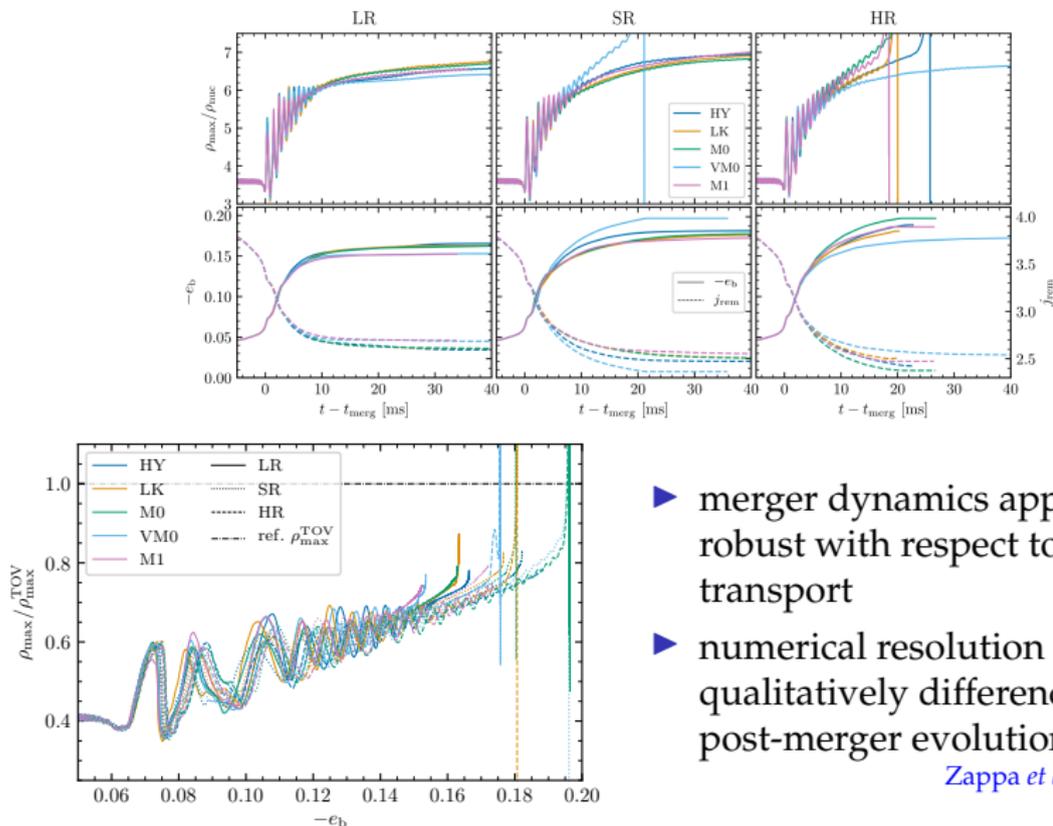
- ▶ 3 different resolutions (LR, SR, HR): $\delta x \in [123, 246]$ m
- ▶ neutrino physics and viscosity
 - ▶ pure hydro (HD)
 - ▶ leakage (LK)
 - ▶ LK+M0 (M0)
 - ▶ (LK+M0) + effective turbulent viscosity (M0V)
 - ▶ M1



Zappa *et al* MNRAS 2023

Influence on merger dynamics

Impact of ν transport, resolution & viscosity on merger dynamics

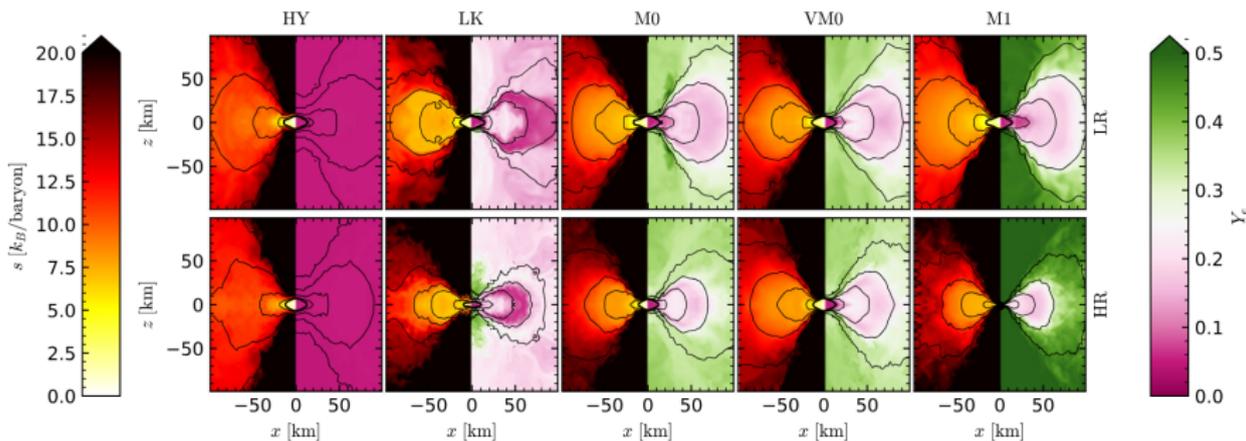
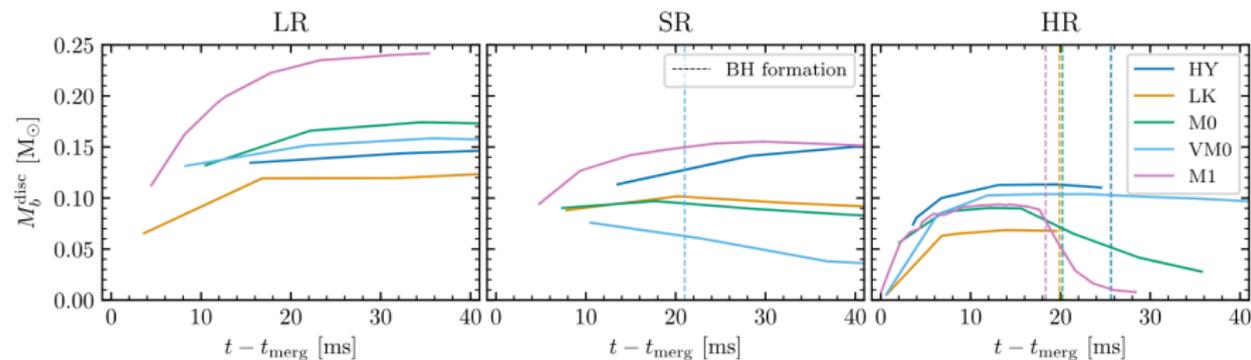


- ▶ merger dynamics appears robust with respect to neutrino transport
- ▶ numerical resolution introduces qualitatively differences in post-merger evolution

Zappa *et al* 2023 MNRAS

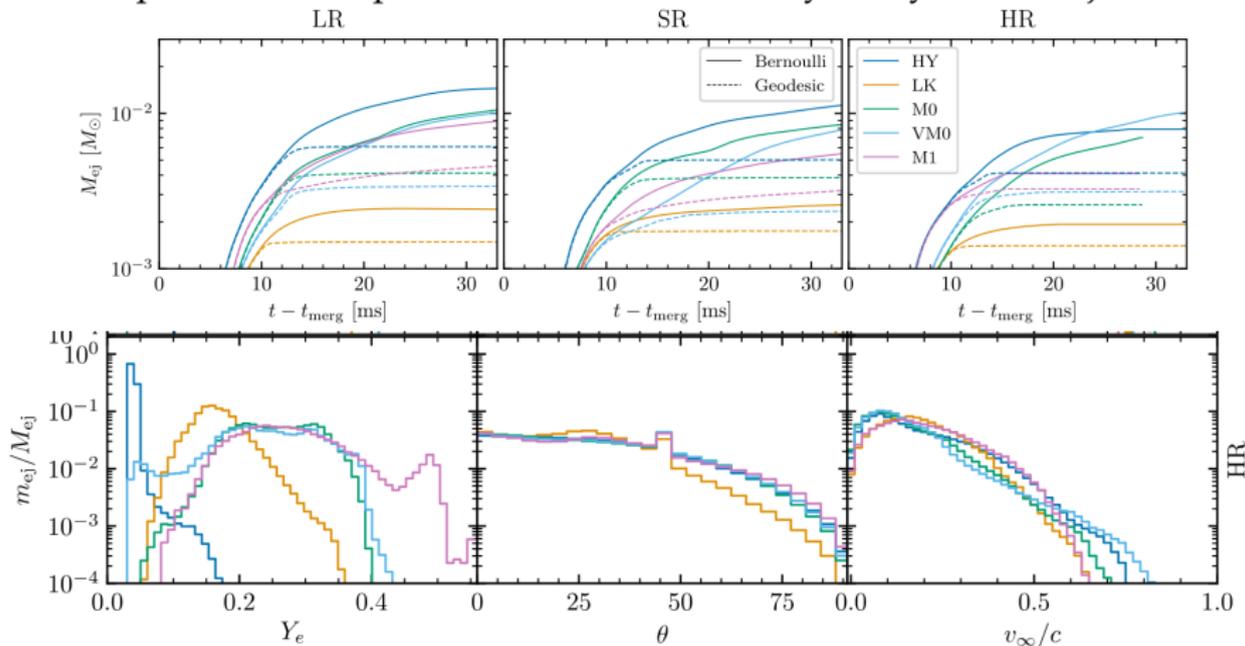
Influence on remnant properties

Impact of ν transport, resolution & viscosity on M_{disc} & thermodynamics



Influence on ejecta properties

Impact of ν transport, resolution & viscosity on dynamical ejecta:



Zappa *et al* 2023 MNRAS

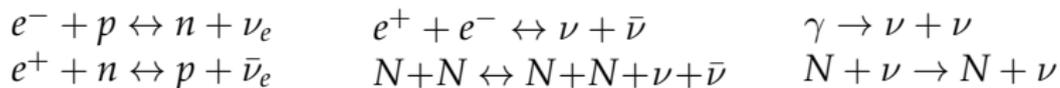
- ▶ ν 's introduce quantitative differences in M_{ej} , θ and v_{∞} distributions
- ▶ ν 's introduce qualitative differences in Y_e distribution

Reactions and rates in BNS merger simulations

- ▶ collision integral for the gray M1 ν transport:

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

- ▶ η : energy emissivity,
 - ▶ κ_{ab} : stimulated absorption opacity
 - ▶ κ_{sc} : scattering opacities
- ▶ basic set of reactions



- ▶ some commonly used approximations:

- ▶ energy integrated, analytical expressions from simplified reaction kernels
e.g. Radice *et al* 16 MNRAS using Ruffert+ 97 A&A or Rosswog & Liebendoerfer +03 MNRAS
- ▶ pre-computed, energy integrated detailed rates in tabulated form
e.g. Foucart+ 16 PRD, Ho-Yin Ng *et al* ApJL 2025, P. Cheong *et al* 2025 PRD
- ▶ E integration: LTE conditions + correction for optically thin conditions
see e.g. Foucart+ 16 PRD or Radice+ 22 MNRAS

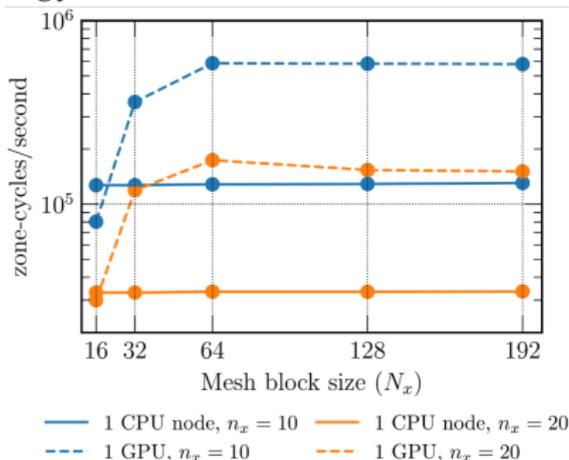
do η & κ presently contain the relevant reactions and physical accuracy?

BNS_nurates: a portable neutrino library

What is it?

- ▶ open-source numerical library for efficient on-the-fly computation of neutrino interaction rates
- ▶ both spectral & energy integrated η 's and κ 's
- ▶ energy integration based on f_ν at equilibrium or reconstructed from local neutrino number and energy

- ▶ performance portable codes, fully integrated with Kokkos \Rightarrow run efficiently both on CPUs and GPUs
- ▶ consistent & careful coupling for GRHD codes



Chiesa, Bhattacharyya *et al* 2025

https://github.com/RelNucAs/bns_nurates

BNS_nurates: a portable neutrino library

Which reactions and physics are included?

$$e^- + p \leftrightarrow n + \nu_e$$

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

$$n \leftrightarrow p + e^- + \nu_e$$

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

▶ NR nucleons & zero-momentum transfer

▶ weak magnetism, recoil & phase space

▶ in-medium effects: $\Delta U_{n,p}$ & $m_{n,p}^*$

$$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$$

$$N + N \leftrightarrow N + N + \nu + \bar{\nu}$$

▶ monopole terms of Legendre kernel expansion

▶ N-N interaction at one-pion exchange level & in-medium effects or chiral EFT description

$$N + \nu \rightarrow N + \nu$$

▶ 0-th & 1-st terms of Legendre kernel expansion

▶ weak magnetism, recoil & phase space

$$e^\pm + \nu \rightarrow e^\pm + \nu$$

▶ 0-th term of Legendre kernel expansion

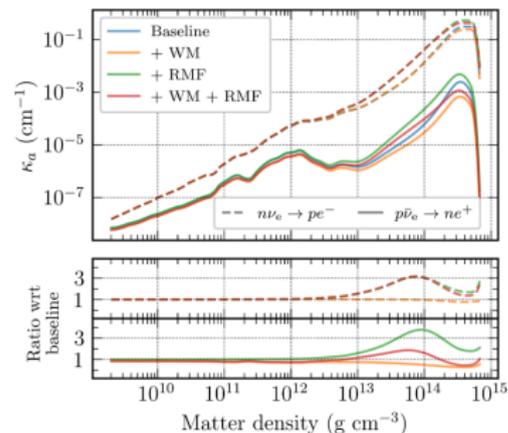
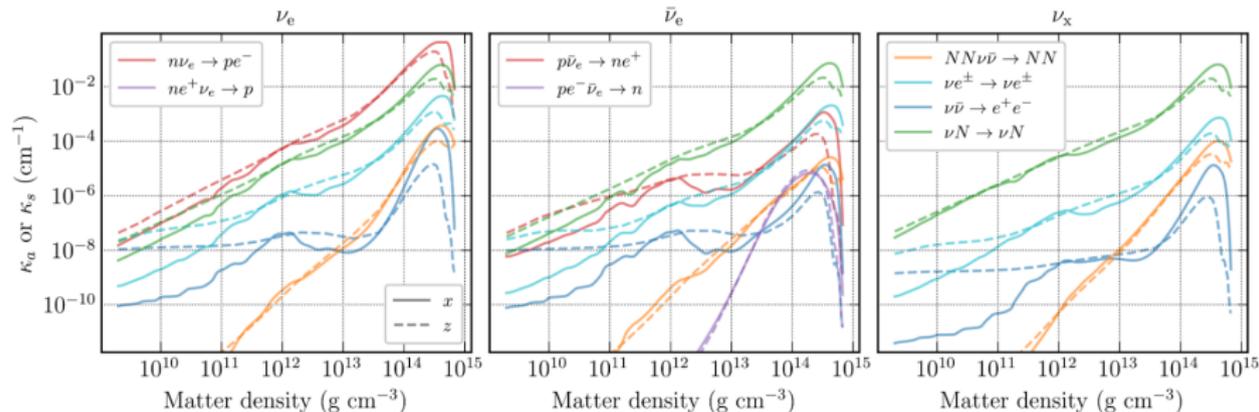
▶ $m_e \approx 0$ limit

Chiesa, Bhattacharyya *et al* 2025 PRD,

see also Bruenn 1985 ApJS, Pons *et al* 1998 A&A, Hannestad & Raffelt 1998 A&A, Horowitz 2002 PRD,

Hempel 2015 PRC, Fischer *et al* 2016, Oertel *et al* 2020 PRC, Guo & Martinez Pinedo 2019 ApJ

BNS_nurates: a portable neutrino library



- ▶ variety of conditions
- ▶ significant differences wrt ν flavor
- ▶ relevant impact of detailed reaction physics

Constraining the high density EOS through prompt collapses

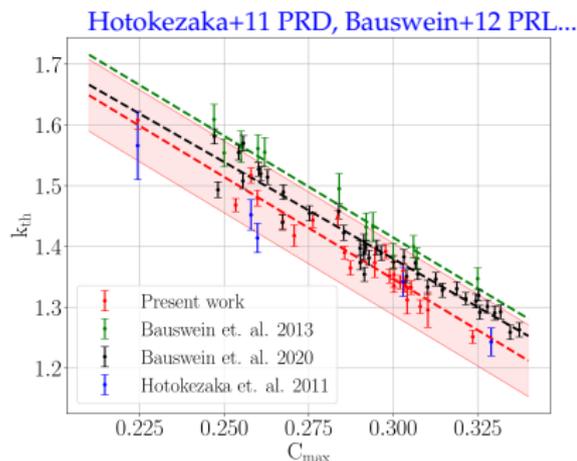
When does PC occur?

$q = 1$, non spinning BNSs:

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

k_{th} correlates with EOS-dependent NS properties, e.g.

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



Kashyap+22 PRD

When does PC occur?

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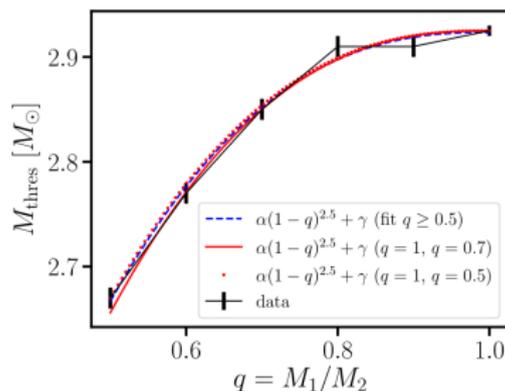
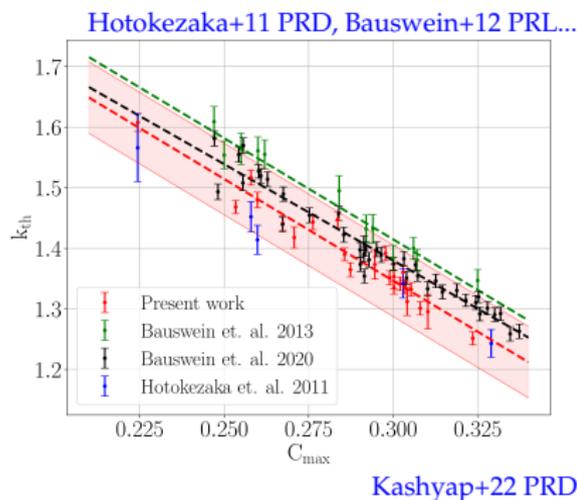
$$k_{\text{th}} = a C_{\text{max}} + b$$

what about $q \neq 1$ BNSs?

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

- ▶ M_{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



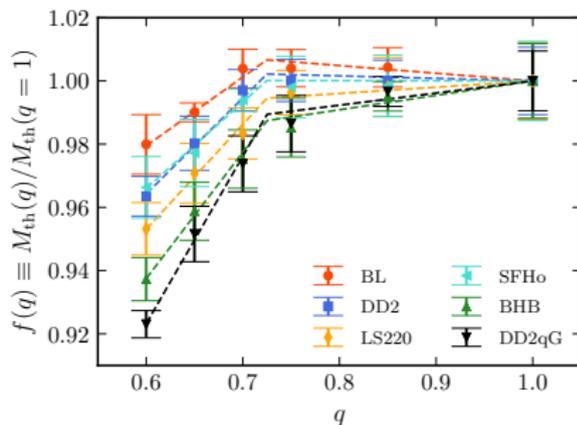
PC in asymmetric, irrotational BNSs

large simulation campaign (~ 250) to determine $M_{\text{th}}(q)$

- ▶ 6 EOSs and 6 mass ratios: $q \in [0.6, 1]$
- ▶ GRHD (WhiskyTHC code) at 2 or 3 resolutions

$$f(q) \equiv \frac{M_{\text{th}}(q)}{M_{\text{th}}(q=1)}$$

- ▶ 2 regimes, $\tilde{q} \approx 0.725$
- ▶ global decrease for decreasing q
 - ▶ non-trivial EOS dependence
 - ▶ non-monotonic behavior for $q > \tilde{q}$ for some EOSs



Perego *et al* PRL 2022

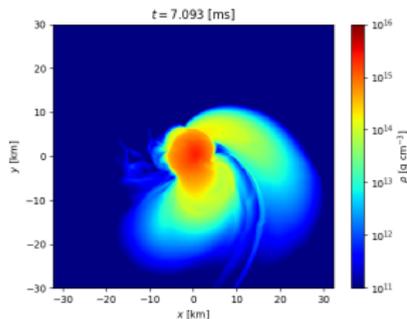
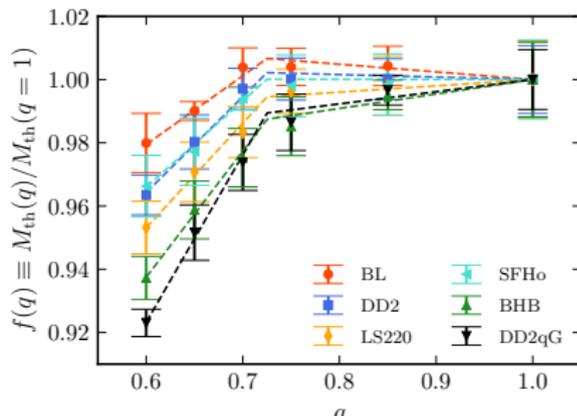
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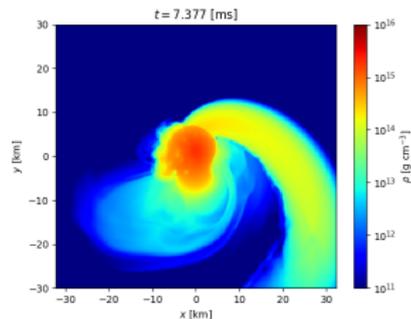
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$\leftarrow q = 0.85$
 $q = 0.6 \rightarrow$



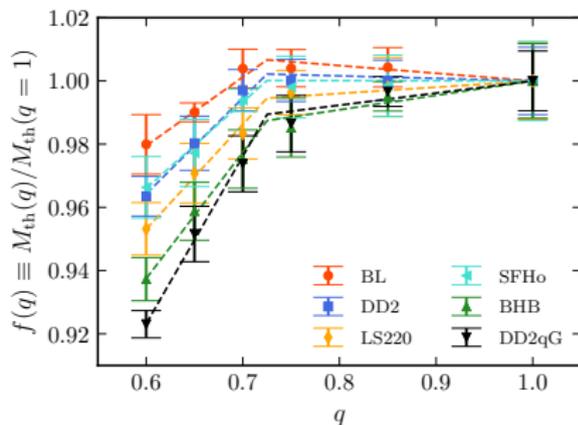
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Perego et al PRL 2022

- ▶ double linear fit

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

The role of nuclear incompressibility

How to interpret these results?

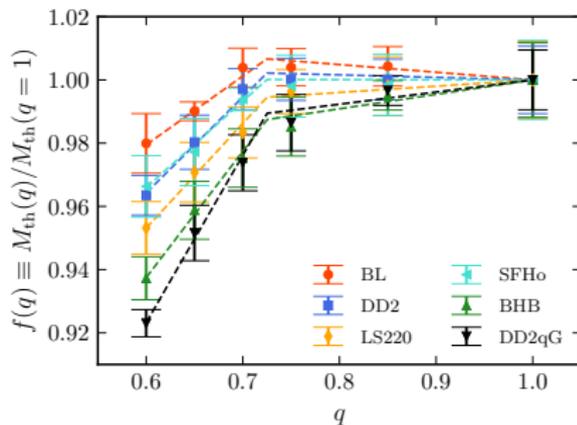
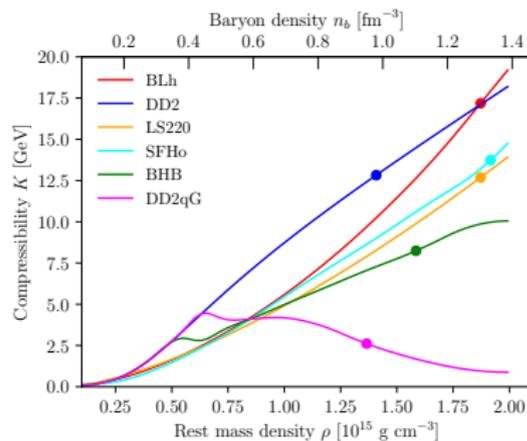
- ▶ (prompt) collapse: competition between gravity and matter incompressibility
- ▶ nuclear incompressibility:

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

- ▶ clear correlation of α 's with

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

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



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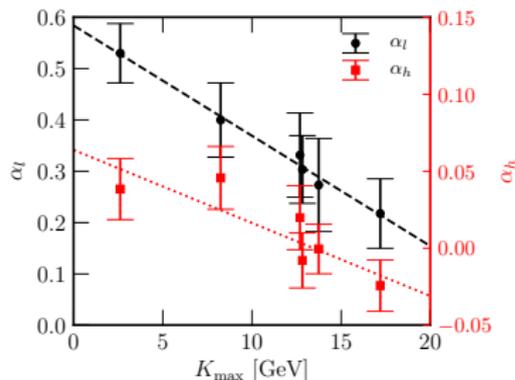
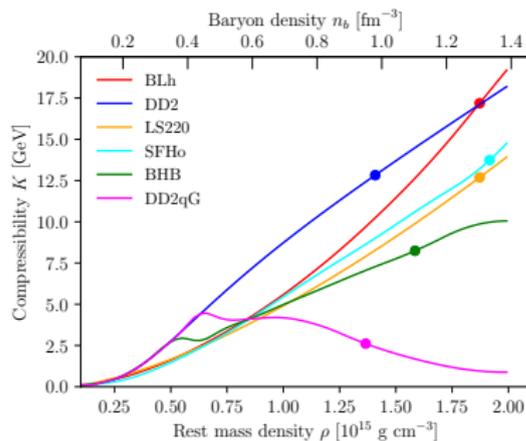
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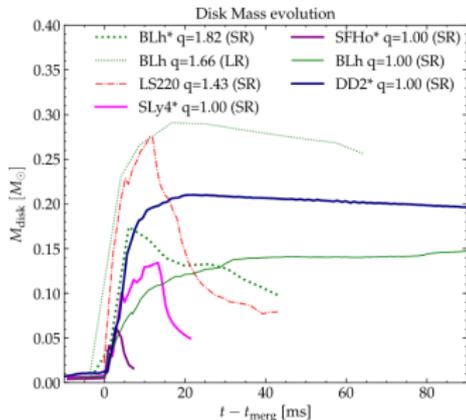
- ▶ measurement of M_{th} at two q 's directly provide K_{max}



Characterizing disks from BNS mergers

Disks in BNS merger remnants

- ▶ disk formation is a common features of BNS merger remnants
 - ▶ tidal tails
 - ▶ hot matter ejection
 - ▶ angular momentum conservation



- ▶ formation timescale: 10-20ms
- ▶ strongly affected by BH formation
- ▶ relevant sources of ejecta

Nedora+ ApJ 906, 2,2021

long-term post-merger simulations: often initialized with idealized disks

How different can disks be? How much can they differ?

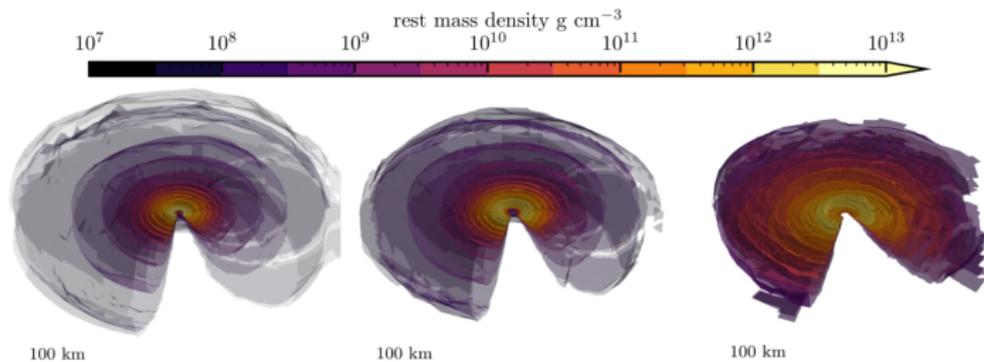
How to characterize disk properties?

Large (38) sample of BNS merger simulations:

- ▶ different outcomes: long-lived (20) VS short-lived (9) VS PC (9)
- ▶ different resolutions: $\delta x \in [123, 246]$ m
- ▶ 5 different finite-temperature, composition dependent EOSs
- ▶ broad mass ($M \in [2.6, 3.3] M_{\odot}$) & mass ratio ($q \in [0.6, 1]$) ranges

Homogeneous numerical setup:

- ▶ GRHD (WhiskyTHC code) Radice *et al* 2011,13,14 CQG & MNRAS
- ▶ neutrino treatment: leakage+M0 scheme Radice 2016 MNRAS
- ▶ effective treatment for turbulent viscosity (GRLES) Radice 2018 ApJL



Camilletti *et al.* PRD 2024

Scales and aspect ratios

- ▶ broad range of disk masses:

$$M_{\text{disk}} \sim 10^{-4} M_{\odot} - \text{a few } 0.1 M_{\odot}$$

- ▶ typical lengthscale

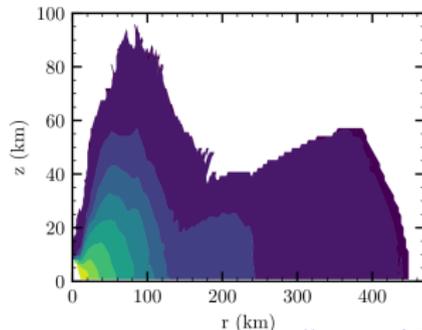
$$R_{\text{disk}} \sim \text{several } 100 \text{ km}$$

- ▶ thick disks \rightarrow thermal support

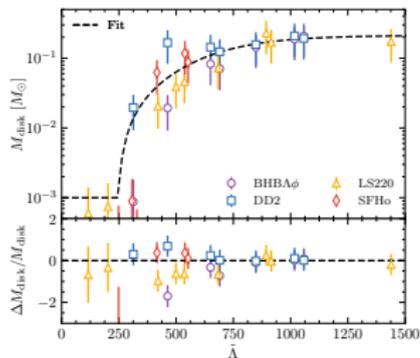
$$\frac{H}{R} \sim \frac{c_s}{v_{\text{orb}}} \sim 0.2 - 0.7$$

$$\langle \rho \rangle_{\phi} \text{ (g cm}^{-3}\text{)}$$

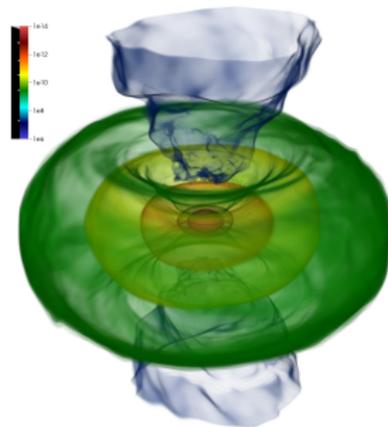
$$10^9 \quad 10^{10} \quad 10^{11} \quad 10^{12} \quad 10^{13}$$



Camilletti *et al* PRD 2024



Radice+ ApJ 2018



Perego, Bernuzzi, Radice EPJA 2019

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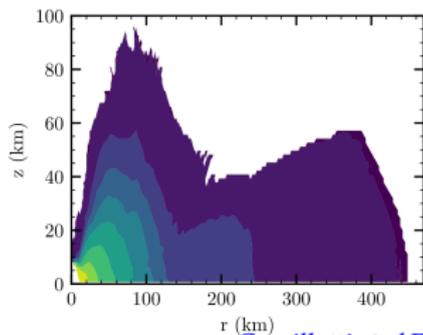
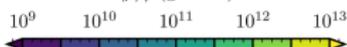
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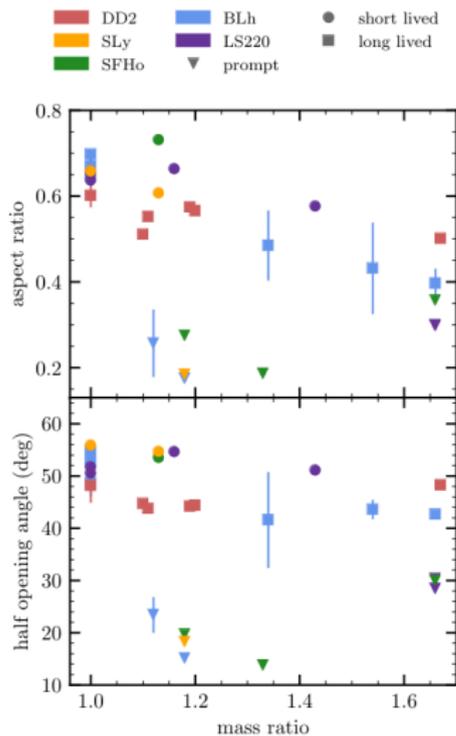
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Camilletti et al PRD 2024



Camilletti et al. PRD 2024

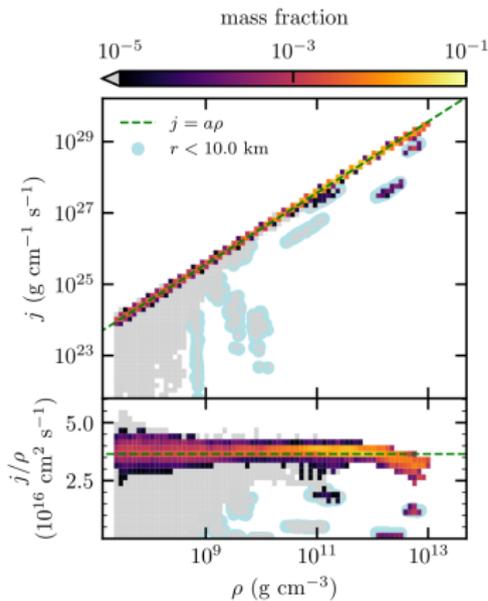
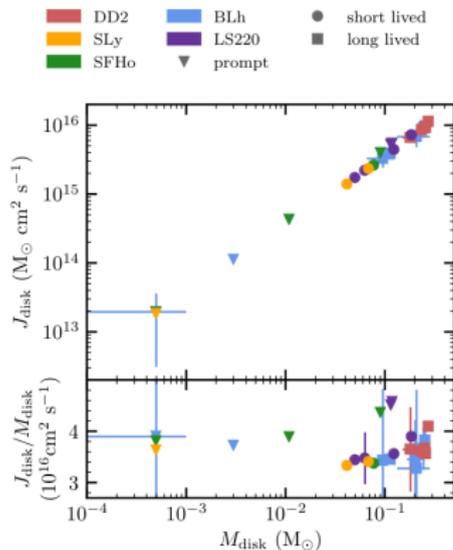
BNS merger in a nutshell: angular momentum

J_{disk} proportional to M_{disk} :

$$J_{\text{disk}} \sim 7 - 10 \left(\frac{G}{c} M_{\odot} \right) M_{\text{disk}}$$

specific angular momentum:

$$\frac{j}{\rho} \approx \text{const} = 3.5 - 5 \times 10^{16} \text{ cm}^2 \text{ s}^{-1}$$



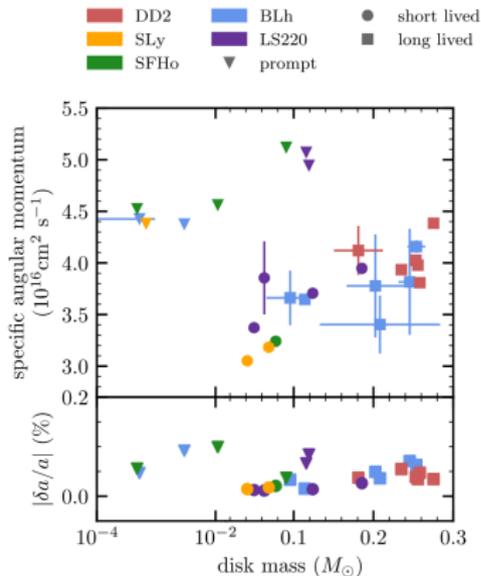
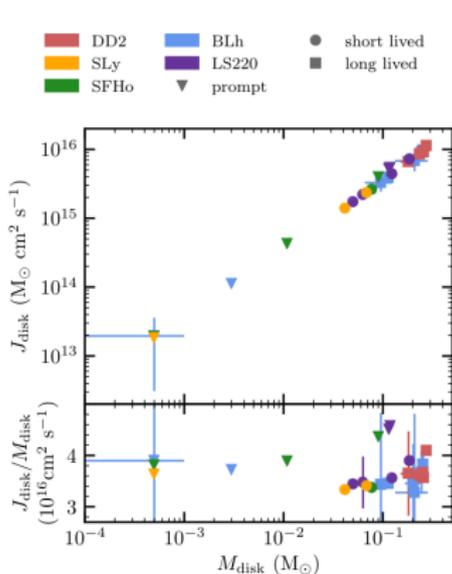
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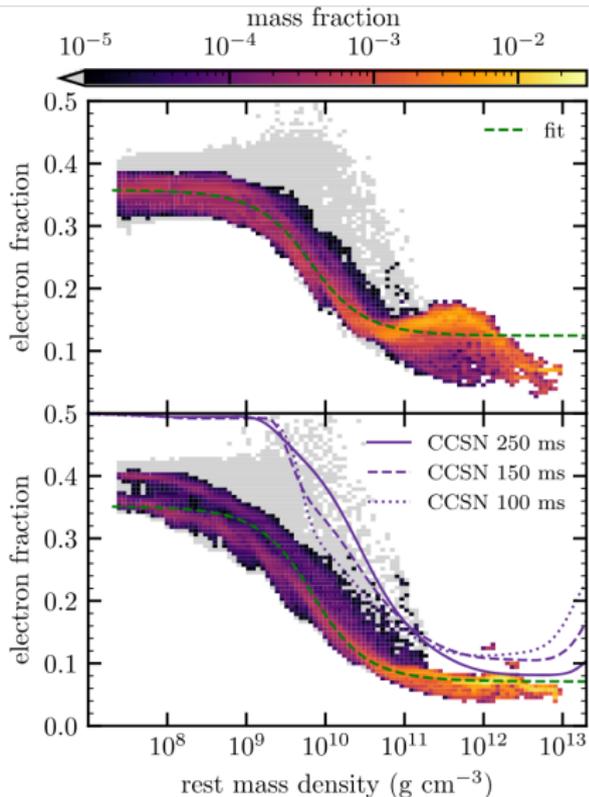
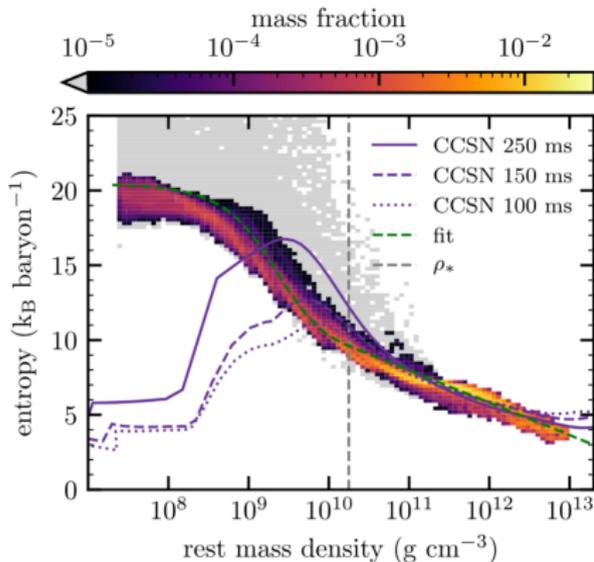
Camilletti *et al.* PRD 2024

BNS merger in a nutshell: entropy and Y_e

for long-lived remnant,

- ▶ specific entropy
- ▶ Y_e

have robust profiles



Camilletti et al. PRD 2024

Toward our discussion:
kilonova-nucleosynthesis
connections

Nucleosynthesis and kilonova modeling

Ambitious goal:

toward end-to-end simulations of BNS mergers and their counterparts

e.g. Just *et al* ApJL 2023, Kawaguchi *et al* 2024, Just's & Longo Micchi's talks

- ▶ method:
 - ▶ sequentially connect different phases/scales of the merger
 - ▶ search for key observational features and relations
- ▶ potential:
 - ▶ provide complementary information
 - ▶ ejecta properties → binary intrinsic and fundamental physics
- ▶ challenges:
 - ▶ long term evolution
 - ▶ combination of different scales & codes
- ▶ open questions:
 - ▶ LTE VS NLTE regimes
 - ▶ relevant elements (in Lanthanides rich/poor conditions)

Strontium in AT2017gfo early spectra

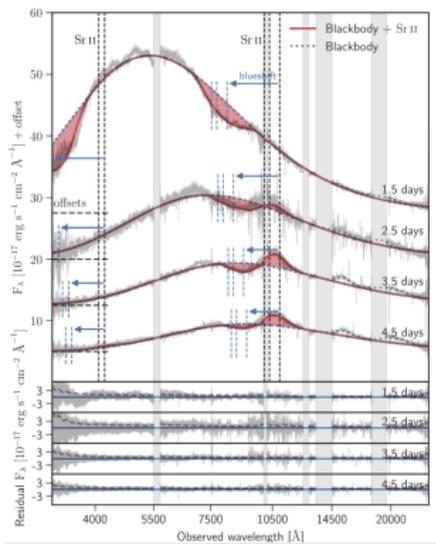
observed spectra from AT2017gfo at 1.5-4.5 day: identification of strontium

- ▶ LTE conditions: $M_{\text{Sr}} \sim 1 - 5 \times 10^{-5} M_{\odot}$ [Watson+ 18 Nature](#), [Gillanders+ 22 MNRAS](#)
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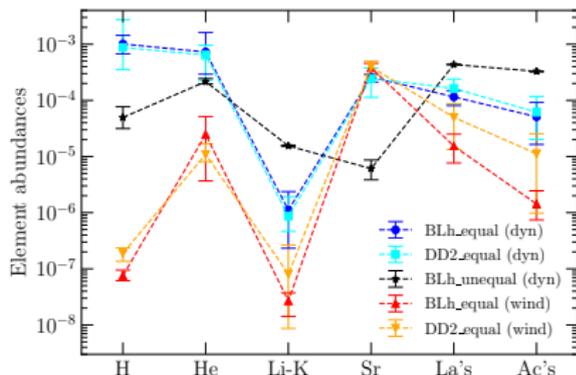
Sr in AT2017gfo spectra: [Watson et al Nature 2018](#)

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- ▶ nucleosynthesis yields from targeted simulations including neutrinos (leakage+M0 scheme)
 - ▶ Sr robustly produced for $0.2 \lesssim Y_e \lesssim 0.4$
 - ▶ $q \ll 1$ BNS model disfavored
 - ▶ $q = 1$ dynamical ejecta account for a possibly large fraction of Sr: $m_{\text{Sr}} \approx 3 \times 10^{-5} M_{\odot}$



[Perego et al, ApJ 2022](#)

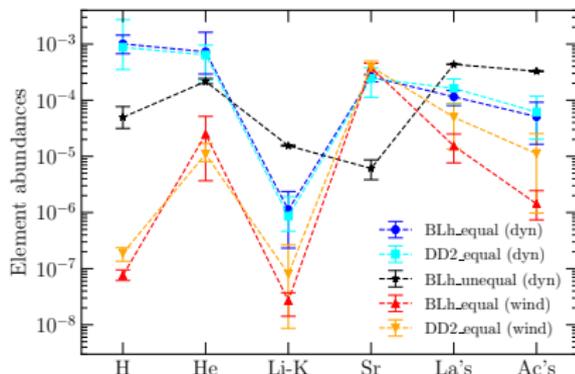
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[Perego et al, ApJ 2022](#)

- ▶ spiral wave wind:

$$M_{\text{spiral}} \approx 0.16 M_{\odot} \text{ s}^{-1} \text{ \& } X_{\text{Sr}} \approx 2 - 3.5 \times 10^{-2}$$

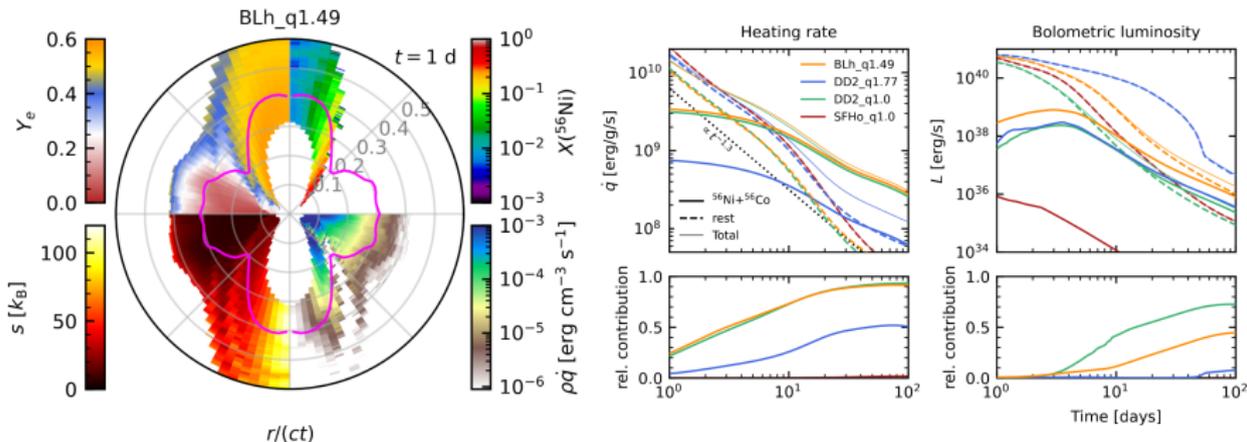
- ▶ LTE conditions: $\Delta t_{\text{wind}} \lesssim 5 \text{ ms}$
- ▶ NLTE conditions: if $M_{\text{Sr,NLTE}} \approx 10 \times (M_{\text{Sr,LTE}})$, $\Delta t_{\text{wind}} \sim 100 \text{ ms}$

Impact of detailed neutrino transport

BNS mergers with long lived remnants:

- ▶ $Y_e \gtrsim 0.4 - 0.5 \rightarrow$ production of ^{48}Ca & ^{56}Ni & ^4He
- ▶ observable features in light curves & spectrum

Domoto *et al* ApJ 2021 2022, Tarumi *et al* arXiv:2302.13061, Perego *et al* ApJ 2022, Sneppen *et al* A&A 2024, arXiv:2411.03427, see also Just's and Jacobi's talks



Jacobi *et al*, arXiv:2503.17445

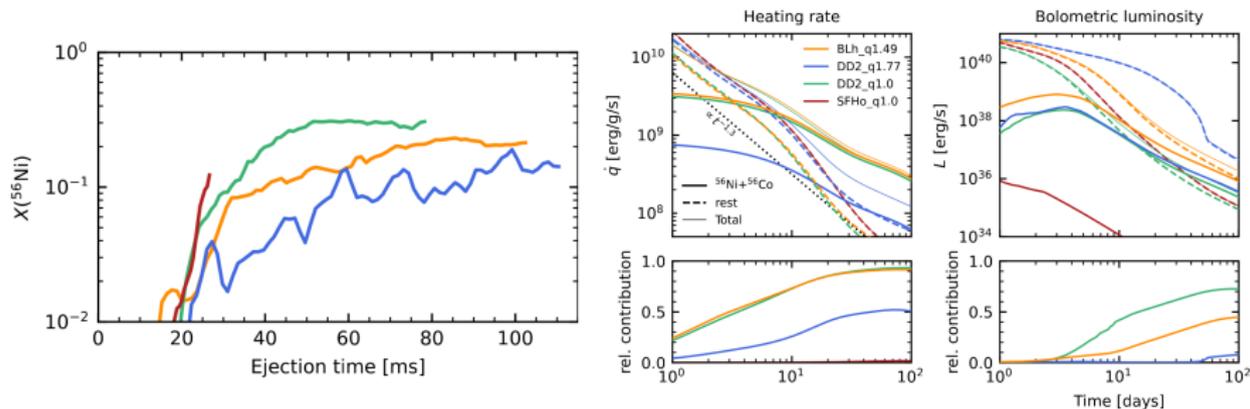
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- ▶ astrophysical relevance (depending on EOS and masses)
- ▶ potential role in EOS constraints

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Toward consistent nucleosynthesis and kilonova modeling

matter ejection \leftrightarrow nucleosynthesis \leftrightarrow kilonova

Common approaches:

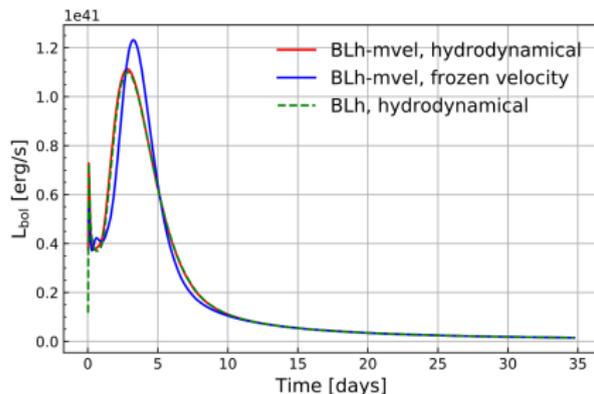
- ▶ BNS simulations in NSE
- ▶ perform nucleosynthesis calculation on homogeneously
- ▶ compute kilonova light curves and spectra on stationary or pre-defined profiles

Questions:

- ▶ how does radiation hydrodynamics influence kilonova light curves and matter expansion?
- ▶ how does consistent and fully coupled modeling of radiation hydrodynamics and nuclear reactions combine?

Radiation hydrodynamics modeling of kilonovae

- ▶ Lagrangian radiation-hydrodynamics code, SNEC Morozova *et al* 2015 ApJ
- ▶ time- & composition-dependent heating rates
- ▶ simplified, Y_e -dependent gray opacity
- ▶ ejecta from NR BNS merger simulations

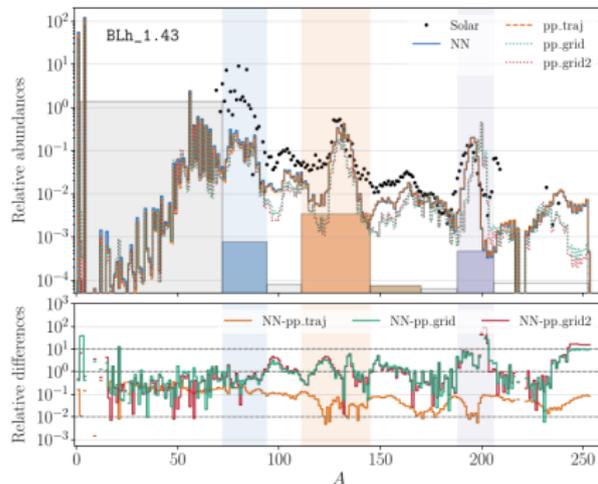


- ▶ density profile is impactful
- ▶ for simulation-driven profiles, homologous expansion is a very good approximation
- ▶ pressure forces can amplify nuclear physics uncertainties by changing very early phase

Wu, Ricigliano *et al* MNRAS 2022

Radiation HD with in-situ nucleosynthesis

- ▶ Lagrangian rad-HD (SNEC) coupled to nuclear network (NN, SkyNet)
- ▶ 2D ray-by-ray approach
- ▶ nuclear energy & composition-dependent thermalization from NN
- ▶ gray VS energy dependent opacities
- ▶ ejecta from NR BNS merger simulations



- ▶ RHD+in-situ NN crucial for precise reliable nucleosynthesis & kN predictions
- ▶ first 100's ms impactful for nucleosynthesis calculations.
- ▶ composition-dependent thermalization and frequency-dependent, atomic-physics-based opacities necessary for ejecta temperature evolution, of kN brightness & color evolution

Magistrelli *et al* A&A 2024, arXiv:2512.11032, see also
Magistrelli's poster

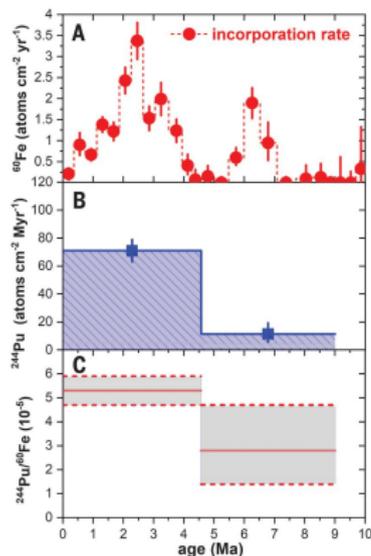
^{60}Fe and ^{244}Pu detection in crust sediments

- ▶ 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

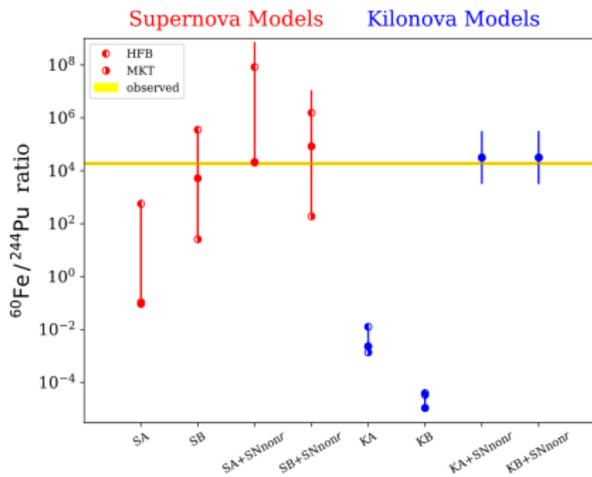
- ▶ identification of $(175 \pm 15) ^{244}\text{Pu}$ ($\tau = 116.3\text{Myr}$) atoms
- ▶ simultaneous signal of ^{60}Fe ($\tau = 3.8\text{Myr}$)
- ▶ $^{244}\text{Pu}/^{60}\text{Fe} = (53 \pm 6) \times 10^{-6}$

How can we interpret the more recent peaks?



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?



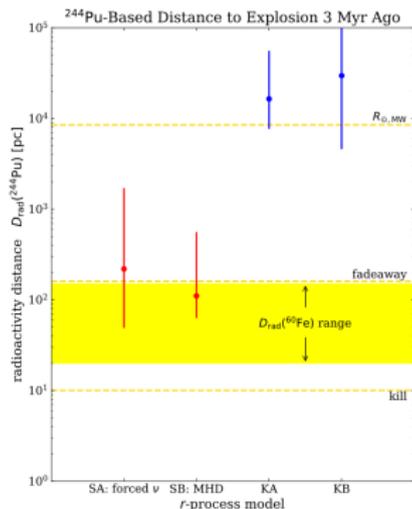
- ▶ explosive event(s) in Local Bubble
- ▶ previous analysis seem to exclude a nearby KN as possible single source

Wang+21 ApJ

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

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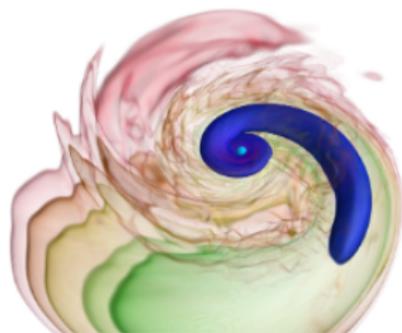
Wang+21 ApJ

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Modeling of long lived BNS mergers

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

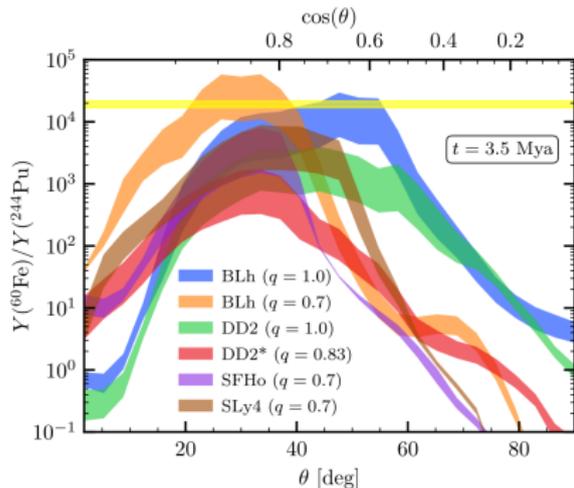
- ▶ 6 distinct binaries
 - ▶ $q = M_A/M_B \in [0.7, 1.]$
- ▶ GRHD (WhiskyTHC code) Radice+
2011,13,14
- ▶ finite- T , composition dependent nuclear EOSs:
HS(DD2), SFHo, BLh, SRO(SLy4)
CompOSE & stellarcollapse websites, Logoteta *et al* 2021
- ▶ neutrino treatment Radice 2016 MNRAS
 - ▶ leakage in opt. thick conditions
 - ▶ M0 in opt. thin conditions
- ▶ effective treatment for turbulent magnetic viscosity (GRLES) Radice 2018
ApJL
- ▶ single maximum resolution: $dx = 185\text{m}$



Bernuzzi *et al.* MNRAS 2020

Iron to plutonium ratio from simulations

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



Chiesta *et al.* ApJL 2024

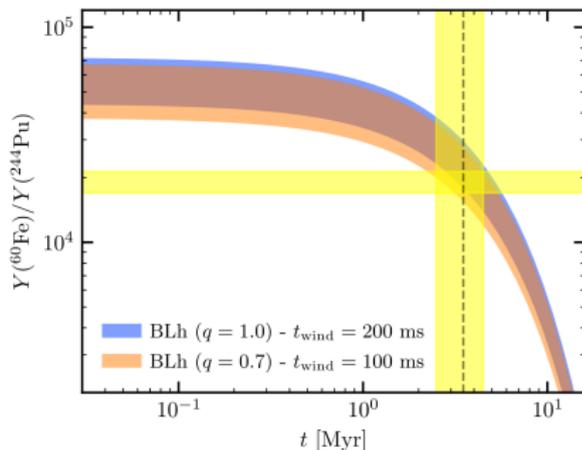
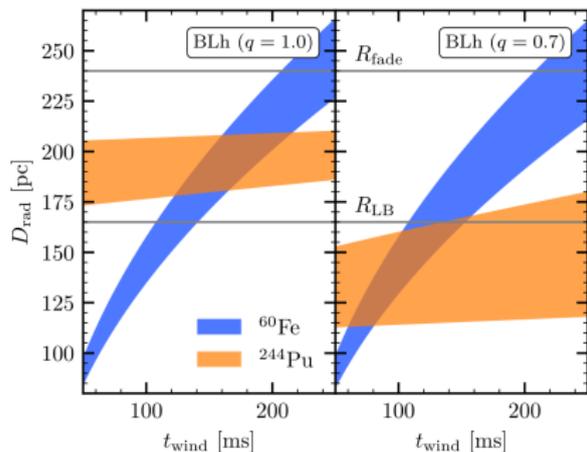
- ▶ ^{60}Fe and ^{244}Pu from dynamical ejecta & spiral-wave wind
- ▶ polar angle dependence: inefficient mixing assumption
- ▶ color band: spiral wave wind duration $t_{\text{wind}} \in [50, 200]\text{ms}$
- ▶ BNS merger occurring 3.5 Myr ago

- ▶ 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 matter?

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

- ▶ \mathcal{F} : measured fluence on Earth
- ▶ $f_{\text{dust},i} \approx 0.5$: 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

Conclusions

Microphysics (nuclear \rightarrow atomic physics) crucial for BNS merger modeling and multimessenger astrophysics

- ▶ ν transport
 - ▶ challenging problem
 - ▶ significant recent progresses on transport (e.g. M1 and Monte Carlo)
 - ▶ space for improvements, e.g. rates & flavor conversion & numerical convergence
- ▶ MM observations have the potential to unveil fundamental physics (e.g. NS EOS)
 - ▶ prompt collapse
 - ▶ identification of key observable features
 - ▶ accurate nucleosynthesis
 - ▶ more consistent kilonova models: RHD w/ nuclear network

