The quest for r-process cosmic forges

Albino Perego

Trento University & INFN-TIFPA

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s-, i-, r- Element Nucleosynthesis (sirEN) Conference
Giulianova, 09-13 June 2025

r-process nucleosynthesis sites: the shopping list

(yes, it is getting longer and longer)

How to make an r-process?

r-process requires

- high neutron densities: $n \gtrsim 10^{24}$g cm^{-3}
- high temperatures ($T \gtrsim 1$ GK, but cold r-process also possible)
- explosive environment

uncertainties in r-process calculations

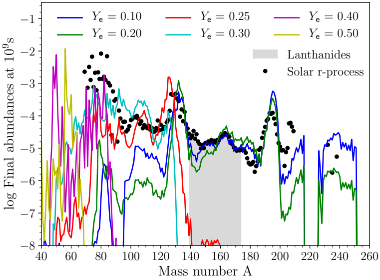
- nuclear: input physics
- astrophysical: matter conditions & evolution

see Cowan *et al* 2021 RMP for a recent review

- nucleosynthesis yields mostly depend on (Y_e, s, τ) Hoffman *et al* 1998 ApJ
- for $s \lesssim 50 k_B$/baryon, Y_e leading parameter

left: abundances for $s = 10 k_B$/baryon, $\tau = 10$ ms and several Y_e

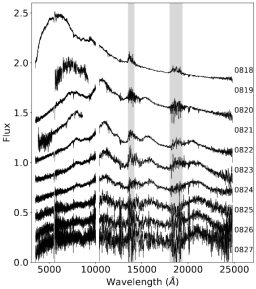
Perego, Thielemann & Cescutti 2021; Courtesy of D. Vescovi

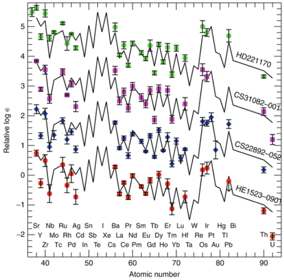


question: where does the r-process occur?

Observational constraints on r-process

- spectral & light curve from EM transients powered by r-process elements
  - smoking gun evidence
  - several limitations
    - horizon: local & present Universe
    - statistics: relatively rare events
- abundances observed in stars and on Earth
  - Solar system abundances, including meteorites and sediments
  - stellar abundances in MW $\rightarrow$ metal poor stars
  - stars in nearby (ultra-faint) dwarf galaxies
  - local Universe, but through cosmic history $\rightarrow$ GCE

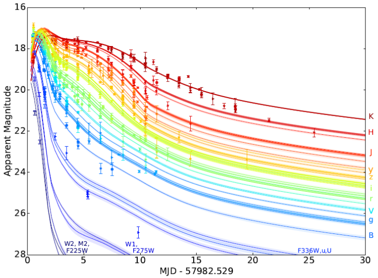




Pian it et al 2017, Nature

Frebel & Norris 2013

GW170817 (and other recent surprices)

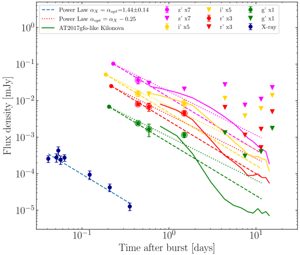


Villar *et al* 2017 ApJL

- GW170817: BNS merger producing GWs, a short GRB and a kilonova
- a few nearby sGRBs with KN-like excess in afterglow

- population of long GRBs with KN-like features in the afterglow,
  e.g. 230307A (Te emission line?), 211211A, 191019A

Mei *et al* 2022 Nat, Dalessi *et al* 2025 ApJ, Stratta *et al* 2025 ApJ



Stratta *et al* 2025 ApJ

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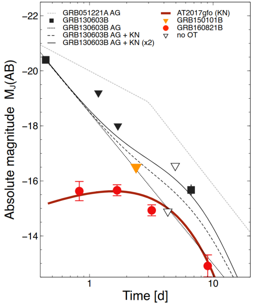

Troja 2023 Universe

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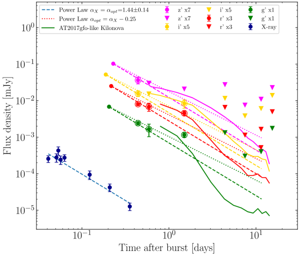

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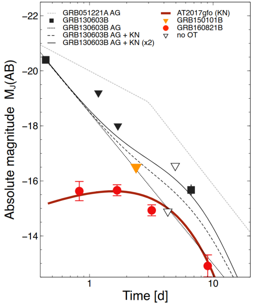

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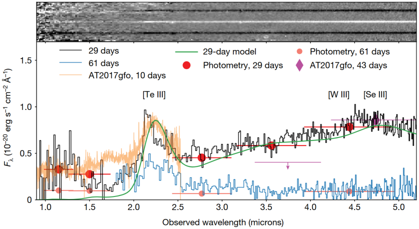

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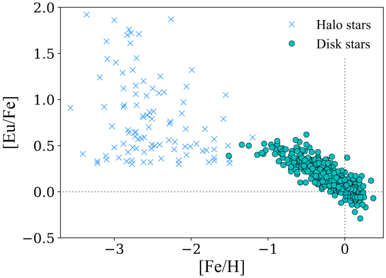
Levan *et al* 2024 Nature

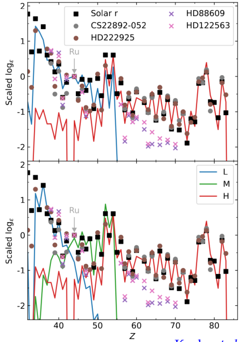
Constraints from stellar abundances



Côté *et al* 2019 ApJ

- large spread of r-process elements at low metallicity: rare events with large yields
- heavy r-process elements in metal poor stars and (ultra) faint dwarf galaxies: r-process active at low metallicity

- large set of conditions produce pattern between II and III peaks: robustness
- different conditions produce significant variety in I peak
- variety necessary to explain observations

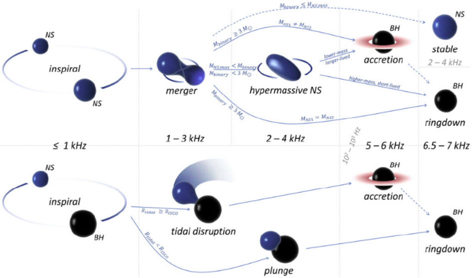


Kuske *et al* arxiv2606.00092

Compact binary mergers with neutron stars

Binary neutron star (BNS) and BH-NS binaries as plausible sites

Lattimer & Schramm 1973 ApJ, Symbalisty & Schramm ApJL 1982



tight BNS or BH-NS: shrinking driven by GW emission:

Credit: Bartos *et al* 2013

$$t_{\mathrm{inspiral}} \sim 3.24\,\mathrm{Gyr} \left(\frac{M}{2.8M_{\odot}}\right)^{-\frac{2}{3}} \left(\frac{\mu}{0.7M_{\odot}}\right)^{-1} \left(\frac{\mathcal{T}}{10\mathrm{h}}\right)^{-\frac{8}{3}} \left(1-e^2\right)^{-\frac{7}{2}}$$

- $M = M_A + M_B$: total mass
- $\mu = (M_A M_B)/M$: reduced mass
- $\mathcal{T}$: binary period
- e: binary eccentricity

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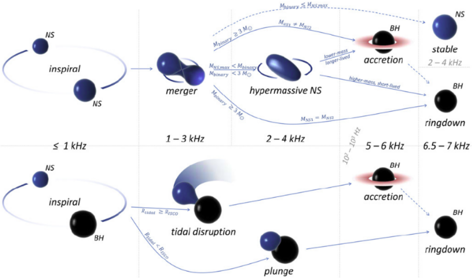


Credit: Bartos *et al* 2013

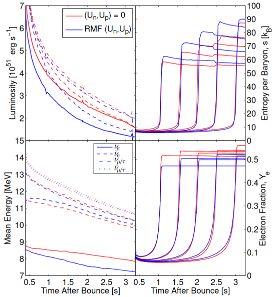
Inspiral-merger-postmerger

- strong GW emitter in LVK (→ ET & CE) bands ($L_{\rm GW} \sim 10^{55}$erg/s)
- BH/MNS+magnetized disk
  - engine of (short) GRBs ($t_{\rm acc} \sim t_{\rm cool} \sim 1 sec$)
  - strong neutrino emitter, $L_\nu \sim 10^{53}$erg/s
- merger dynamics and disk evolution: n-rich ejecta → r-process nucleosynthesis → kilonova

Core-collapse supernovae?

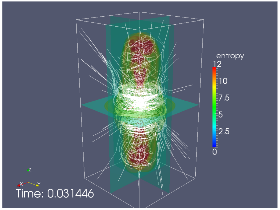
- standard CCSNe: disfavored sites
  - detailed explosion models predict *p*-rich conditions
  - rate and yields incompatible with observations e.g. Hotokezaka *et al* 2015 NatPhys
  - possible contribution to light r-process

    Wanajo ApJ 2013, see e.g. Arcones & Thielamnn 2013 JPhG



Martinez-Pinedo *et al* 2012 PRL

- MHD-driven CCSNe: rare classes of CCSNe requiring fast rotating cores and high polar magnetic fields
  - early, neutron-rich ejecta
  - potential issues: full r-process requires extreme conditions



Winteler *et al* 2012 ApJL

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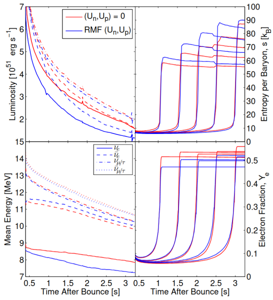

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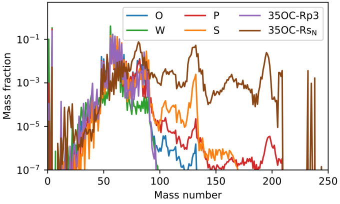


Reichert *et al* 2023 MNRAS

Collapsar?

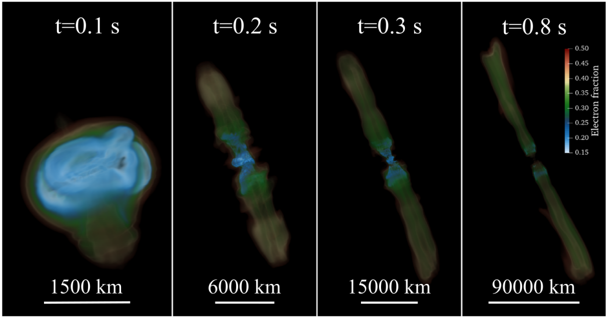
Collapsar: favored central engine of long GRBs

- supernova-triggering collapse of rapidly rotating massive stars, resulting in spinning BH + magnetized torus
- neutronization process inside the disk: similar to BNS merger?

Siegel & Metzger 2018 ApJ

- is n-rich matter ejected? still debated
  - if $\dot{M} \sim 0.1 - 1 M_{\odot}/s$, $Y_e \gtrsim 0.3$
  - if $\dot{M} \gtrsim \mathrm{few} M_{\odot}/s \to 1 M_{\odot}$ ejecta with $Y_e \lesssim 0.25$

Issa *et al* 2025 ApJL, but see Miller *et al* PRD, Just *et al* 2022



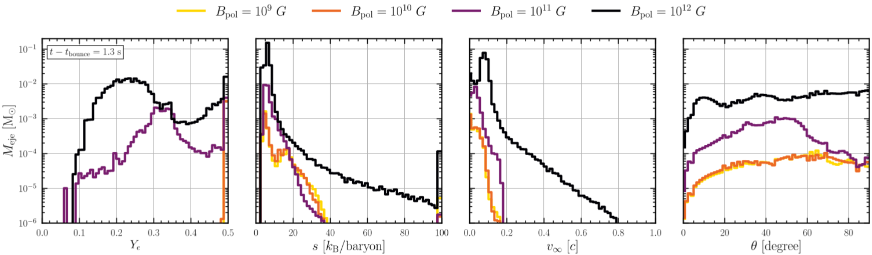
Issa *et al* 2025 ApJL

Accretion induced collapse of white dwarfs?

Collapse of an accreting massive WD to NS: alternative scenario to explain long-GRBs with kilonova-like emission

- ONe WD ($M \gtrsim 1.2 M_\odot$) with slow accretion rates $\Rightarrow$ massive WD
- accretion in single or double degenerate scenario: $M_{\rm WD} \to M_{\rm Ch}$ & WD collapses to NS
- strong magnetic fields and rapid rotation could produce
  - relativisitc jet along the pole
  - n-rich ejecta from middle & low latitudes

e.g. Cheong *et al* 2025 ApJL, Batziou *et al* ApJ 2025



Cheong *et al* 2025 ApJL

ejecta properties from 2D GR ν-radiation MHD simulation rapidly rotating, strongly magnetized super-Chandrasekhar WDs

Magnetar Giant Flares?

r-process Nucleosynthesis and Radioactively Powered Transients from Magnetar Giant Flares

Anirudh Patel[1], Brian D. Metzger[1,2], Jared A. Goldberg[2], Jakub Cehula[3], Todd A. Thompson[4,5,6], and Mathieu Renzo[7]

[1] Department of Physics and Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA; anirudh.p@columbia.edu
[2] Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY 10010, USA
[3] Institute of Theoretical Physics, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, Prague, 180 00, Czech Republic
[4] Department of Astronomy, Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA
[5] Center for Cosmology & Astro-Particle Physics, Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210, USA
[6] Department of Physics, Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210, USA
[7] Steward Observatory and Department of Astronomy, University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721, USA
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Abstract

We present nucleosynthesis and light-curve predictions for a new site of the rapid neutron capture process (*r*-process) from magnetar giant flares (GFs). Motivated by observations indicating baryon ejecta from GFs, J. Cehula et al. proposed that mass ejection occurs after a shock is driven into the magnetar crust during the GF. We confirm using nuclear reaction network calculations that these ejecta synthesize moderate yields of third-peak *r*-process nuclei and more substantial yields of lighter *r*-nuclei, while leaving a sizable abundance of free neutrons in the outermost fastest expanding ejecta layers. The final *r*-process mass fraction and distribution are sensitive to the relative efficiencies of α-capture and n-capture freeze-outs. We use our nucleosynthesis output in a semianalytic model to predict the light curves of novae breves, the transients following GFs powered by radioactive decay. For a baryonic ejecta mass similar to that inferred of the 2004 Galactic GF from SGR 1806-20, we predict a peak UV/optical luminosity of $\sim 10^{39}$–10^{40} erg s^{-1} at $\sim$10–15 minutes, rendering such events potentially detectable to several Mpc following a gamma-ray trigger by wide-field transient monitors such as ULTRASAT/UVEX. The peak luminosity and timescale of the transient increase with the GF strength due to the larger ejecta mass. Although GFs likely contribute 1%–10% of the total Galactic *r*-process budget, their short delay-times relative to star formation make them an attractive source to enrich the earliest generations of stars.

Ejecta from BNS mergers

A biased overview

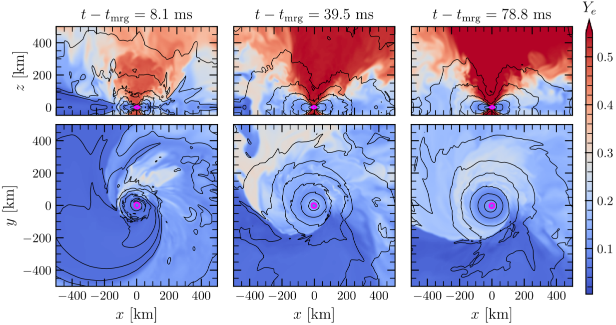
Modeling of BNS mergers and their ejecta

State of the art (still far from completeness)

- simulations in Numerical Relativity evolving spacetime & matter
- nuclear EOS: finite T, composition-dependent simulations
- neutrino transport: moment schemes & detailed rates
- MHD or effective viscosity models

Additional challenges:

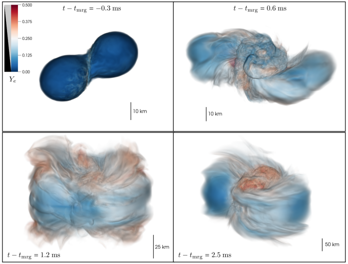
- large parameter space: total mass and mass ratio
- consistent evolution from inspiral to remnant cooling timescale



Bernuzzi *et al* 2024.18185

Dynamical ejecta

Matter ballistically expelled by merger dynamics, $t \sim 1 - 10\text{ms}$

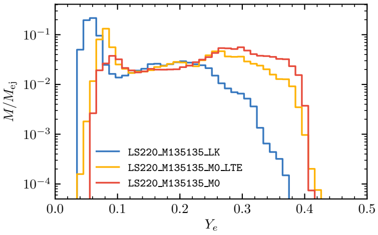


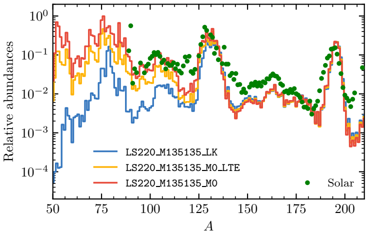
Radice *et al* ApJ 2018

Properties:

- tidal & shock heated ejecta
- $\langle v \rangle \sim 0.2 - 0.3c$
- $M_{\rm ej} \sim 10^{-4} - 10^{-2} M_\odot$
- entropy: $\langle s \rangle \sim 10 - 20 k_{\rm B}/\text{baryon}$
- larger (smaller) Y_e along poles (equator)

Y_e distribution & nucleosynthesis:





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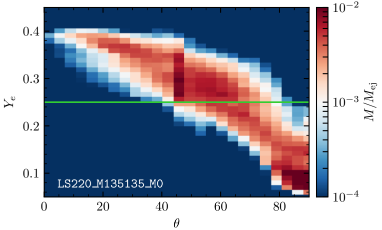

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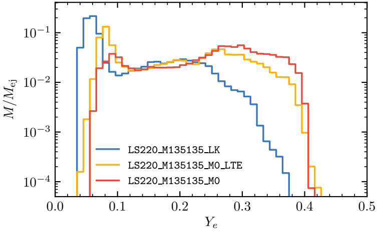
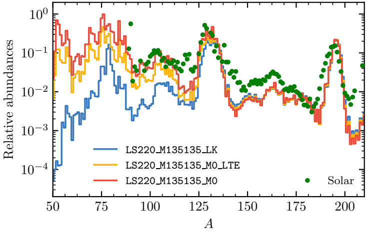




Disk-winds ejecta

Matter expelled by disk secular evolution, $t \sim 10\text{ms} - 10\text{s}$

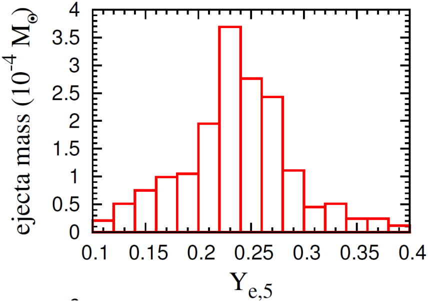
- very efficient

$$M_{\rm ej} \sim (0.1 - 0.4)\, M_{\rm disk}$$

- several possible dependences:
  - nature of the remnant: BH VS NS
  - magnetization degree
  - ν radiation & physics

Viscous ejecta from BH-torus:

- MHD-turbulent viscosity inflates the disk
- nuclear recombination releases $\sim$ 8MeV/baryon
- matter ejection
- weak interaction sets Y_e
- full r-process nucleosynthesis



Wu *et al* 2016 MNRAS

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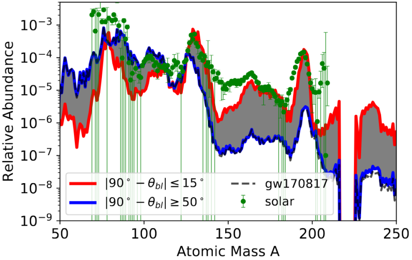
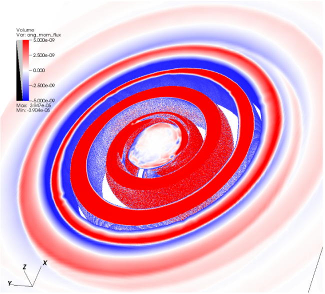


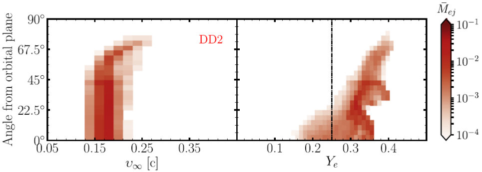
Miller *et al* 2019 PRD

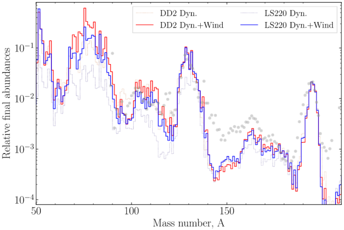
Disk-winds ejecta: massive NS

Spiral-wave wind

- $m = 1, 2$ spiral mode in the remnant
- $\langle v \rangle \sim 0.15 - 0.2\,c$
- $\dot{M} \sim 0.1\,M_{\odot}/\mathrm{s}$
- mostly equatorial: $(\theta - \pi/2) \lesssim \pi/4$
- broad Y_e distribution, with significant contribution $\gtrsim 0.25$







Nedora *et al* 2019 ApJL

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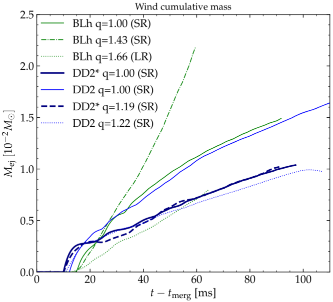

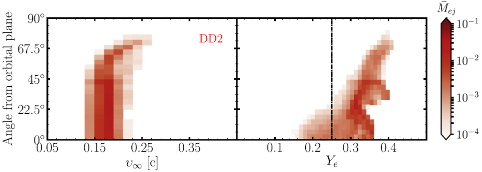

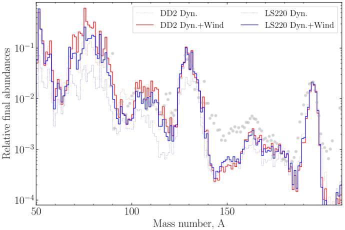

Nedora *et al* 2019 ApJL

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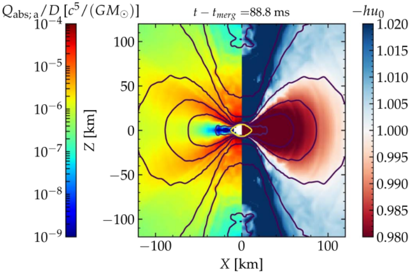
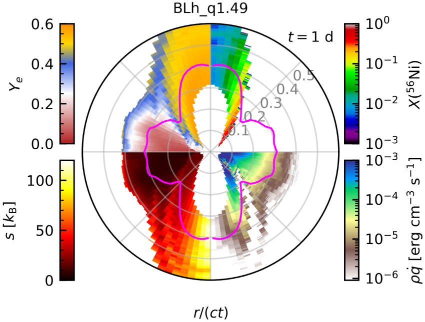


Nedora *et al* ApJ 2021

Neutrino-driven winds

- ν (re)absorption in the remnant
- $\langle v \rangle \sim 0.1 - 0.2\,c$
- mostly polar: $(\theta - \pi/2) \gtrsim \pi/4$
- strong ν-irradiation: $Y_e \sim 0.3 - 0.55$



- ejecta w $Y_e \gtrsim 0.4$ produce Ca, He and iron group elements
- possibly observable in light curves and spectra

Domoto *et al* 2021 ApJ, Perego *et al* 2022 ApJ, Sneppen *et al* 241103427S,

Jacobi *et al* 2025 arXiv 250317445 (left figure)

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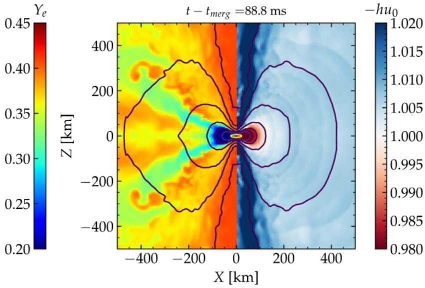

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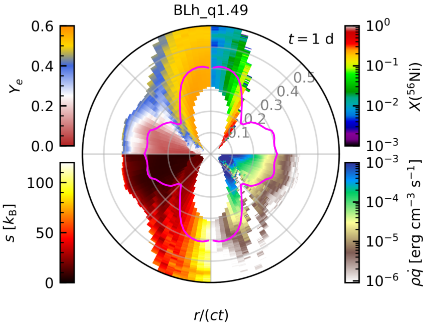


- ejecta w $Y_e \gtrsim 0.4$ produce Ca, He and iron group elements
- possibly observable in light curves and spectra

Domoto *et al* 2021 ApJ, Perego *et al* 2022 ApJ, Sneppen *et al* 241103427S, Jacobi *et al* 2025 arXiv 250317445 (left figure)

Theory meets observations

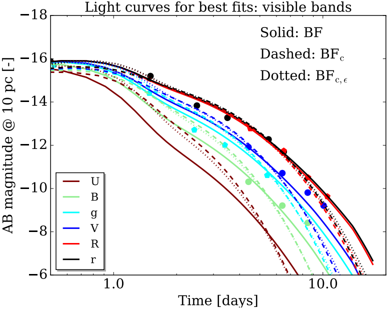
...or at least we try

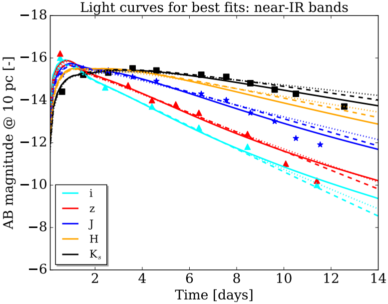
Light curves and spectra from AT2017gfo

AT2017gfo: bright light curves compatible with

- $m_{\rm ej} \sim 0.01 - 0.05 M_\odot$
- multi-component, anisotropic ejecta: an early blue emission followed by a red emission → *broadly* consistent with strong-field models

⇒ absence of prompt collapse





Perego *et al* 2017, ApJ

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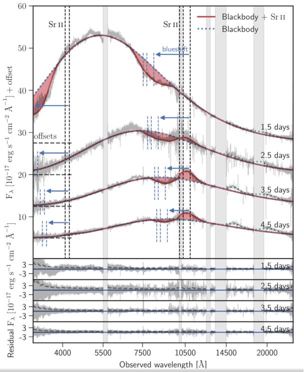


observed spectra at 1.5-4.5 day: identification of strontium

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

Watson+ 18 Nature, Gillanders+ 22 MNRAS

- is Sr an expected element?
- is the inferred amount telling us something about the remnant?

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

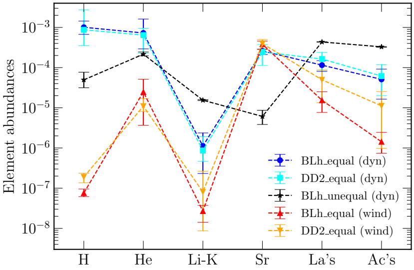
From strong field dynamics to kilonova emission

Analysis of a large sample of BNS merger simulations

- targeted to GW170917
- including microphysics EOSs and neutrino physics

nucleosynthesis yields from dynamical and spiral wave wind ejecta

- 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



Perego *et al*, ApJ 2022

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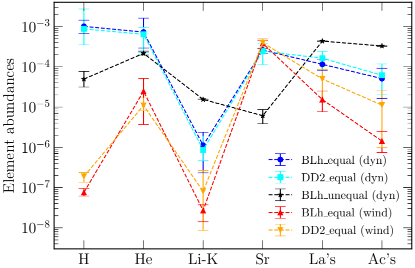


Perego *et al*, ApJ 2022

our results suggest GW170817 remnant survived only a few ms after merger!

confermed by more recent simulations: prospects for Ca & He production in long-lived remnant

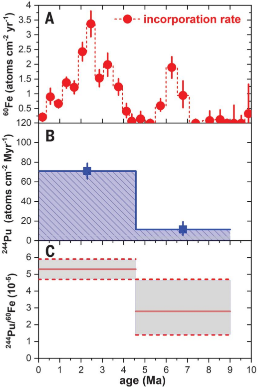
Jacobi *et al* 2503.17445, Sneppen *et al* 2411.03427

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

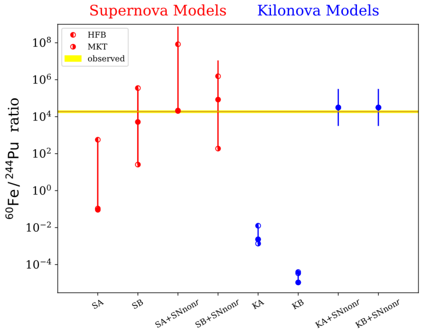


How can we interpret the more recent peaks?

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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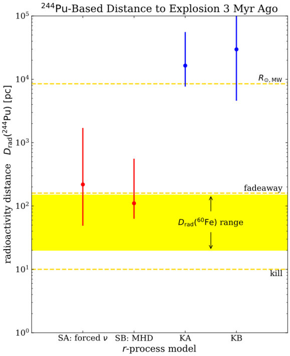

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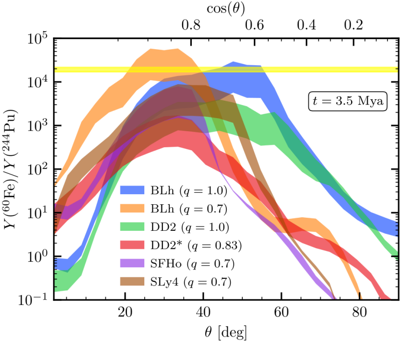
Iron to plutonium ratio from simulations

Analysis of ejecta from long lived BNS merger simulations w microphysics



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

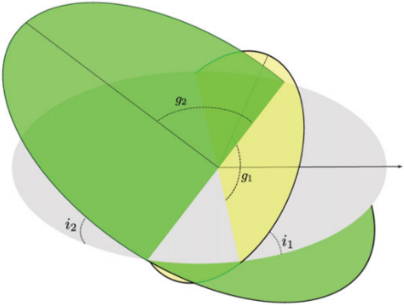
Chiesta *et al.* ApJL 2024

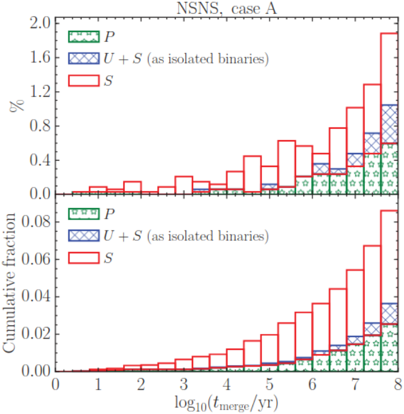
- similar trend for all simulations
- 2 models match observed ratio
- crucial presence of spiral wave wind and neutrino effects to produce also iron group nuclei

Fast mergers in triple systems

Is it possible for BNS and BH-NS to merge within 8 Myr?

- Kozai-Lidov resonance in hierarchical triple systems excites eccentric binaries
- $\times \gtrsim 2$ fast coalescing BNS and BH-NS in hierarchical triple systems

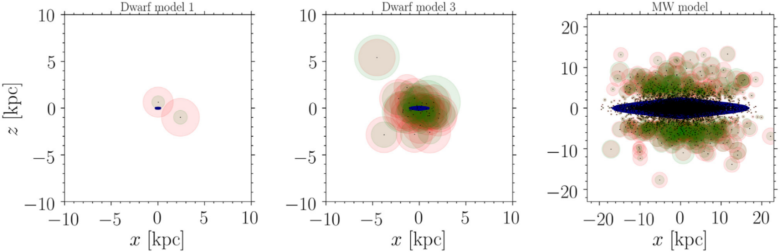




Bonetti *et al* 2018 PASA

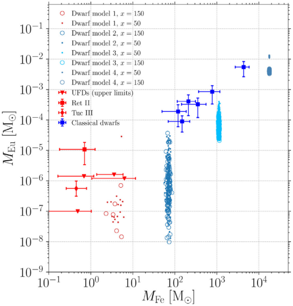
R-process source in dwarf galaxies

Can BNS mergers explain observed r-process elements in dwarf galaxies?



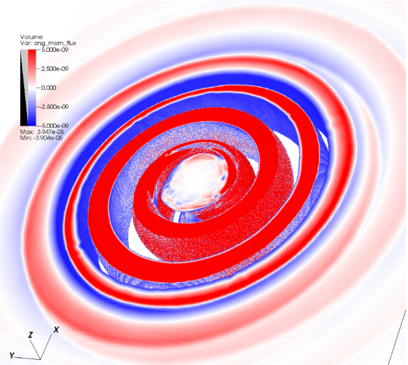
- BNSs have significant kick velocities at birth
- in dwarf galaxies, compact binaries spend most of the time *outside* the galaxy
- enrichment has dilution factor

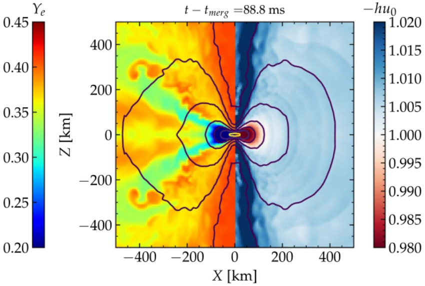
Bonetti *et al* 2019 MNRAS



Conclusions

- r-process nucleosynthesis requires extreme conditions
- several explosive events could host r-process
- theretical modeling crucial to provide reliable astrophysical conditions
- comparison with observatons necessary to discriminate and define relevance
- present tendencies
  - more sophisticated models of robust sites, e.g. compact binary mergers & core-collapse SNe
  - exploration of novel sites: e.g. collapsar. AIC of WD, magnetar flares …



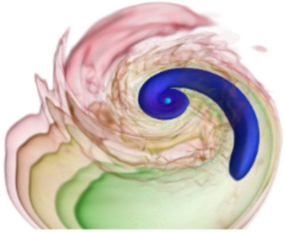


Modeling of long lived BNS mergers

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

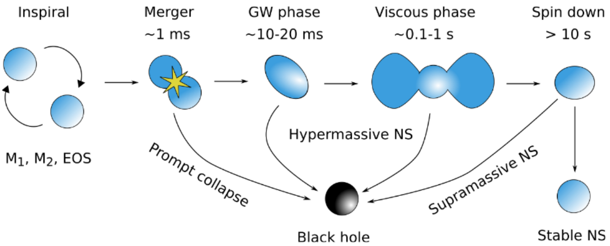
- 6 distinct binaries
  - $q = M_A/M_B \in [0.7, 1.]$
- GRHD (WhiskyTHC code) Radice+ 2011,13,14
- finite-T, composition dependent nuclear EOSs: HS(DD2), SFHo, BLh, SRO(Sly4)

  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: $\mathrm{d}x = 185$m



Bernuzzi *et al.* MNRAS 2020

BNS merger in a nutshell: inspiral & merger



Credit: D. Radice; Radice, Bernuzzi, Perego 2020 ARNPS

- inspiral: driven by GW emission

$$t_{\text{inspiral}} \sim 3.24\,\text{Gyr} \left(\frac{M}{2.8M_\odot}\right)^{-\frac{2}{3}} \left(\frac{\mu}{0.7M_\odot}\right)^{-1} \left(\frac{\mathcal{T}}{10\text{h}}\right)^{-\frac{8}{3}} \left(1-e^2\right)^{-\frac{7}{2}}$$

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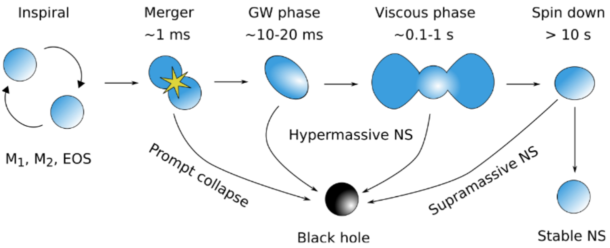

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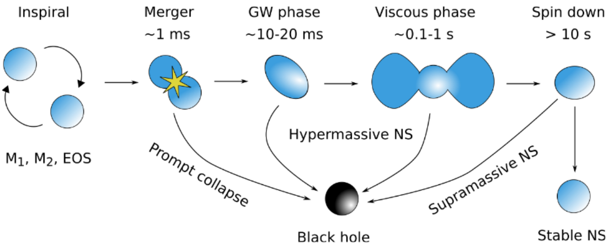
- merger:
  - $L_{\rm GW} \sim 10^{55} {\rm erg/s} \sim 10^{-4} L_{\rm P}$ — e.g. Zappa *et al* 2018 PRL
  - $v_{\rm orb}/c \sim \sqrt{\mathcal{C}} \approx 0.39\,(\mathcal{C}/0.15)^{1/2}$
  - $t_{\rm dyn} \sim 1.5{\rm ms} \left(\frac{M}{2.8 M_\odot}\right)^{-3/2} \left(\frac{\mathcal{C}}{0.15 M}\right)^{-1/2}$
  - NS collision: $E_{\rm kin} \to E_{\rm int} \Rightarrow \langle T\rangle \sim 30{\rm MeV} \gtrsim T_{\rm Fermi}$

BNS merger in a nutshell: post-merger



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  - GW emission dominant, $L_{\rm GW} \sim 10^{54}$erg/s, but rapidly faiding
  - hot & dense matter $\rightarrow$ copious ν production with $L_\nu \sim 10^{53}$erg/s

Eichler+ 89, Ruffert+ 97, Rosswog & Liebendoerfer 03

  - disk formation, $M_{\rm disk} \sim 10^{-3}$- $0.1 M_\odot$
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- viscous phase
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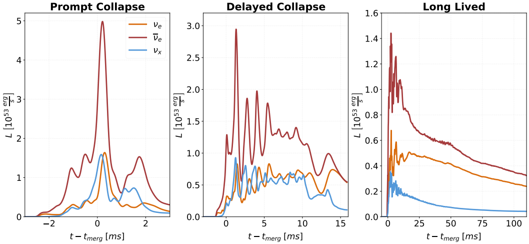
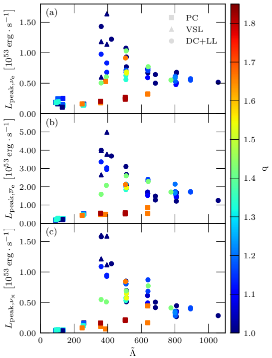
Neutrino emission



Cusinato *et* al EPJA 2022



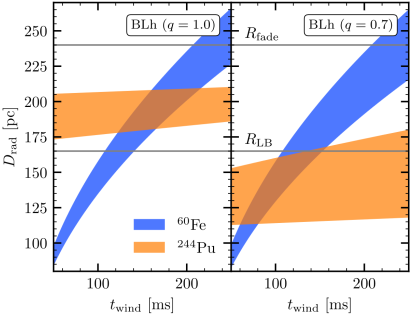
- ν's exchange energy and momentum with matter
- set n-to-p ratio $\rightarrow \mathrm{Y_e}$
  $p + e^- \leftrightarrow n + \nu_e$ (EC)
  $n + e^+ \leftrightarrow p + \bar{\nu}_e$ (PC)
- n-richness $\rightarrow L_{\bar{\nu}_e} \gtrsim L_{\nu_e} \sim L_{\nu_x}$
- EOS and q dependence
- thermal neutrinos

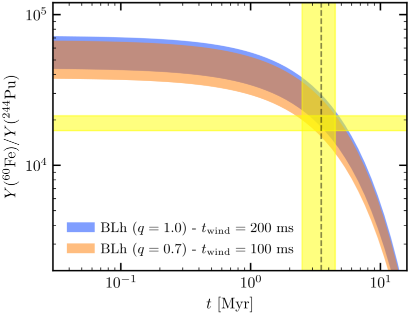
  $\langle E_\nu \rangle \sim 10\ (\nu_e) - 20\ (\nu_{\mu,\tau})$ MeV

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

Ejecta and nucleosynthesis

- Ejecta: unbound matter from a BNS merger
  - Lagrangian approach: tracer particles
  - Eulerian approach: flux across surfaces
- ejecta identification: geodesic VS Bernoulli criterion
- expelled by different mechanisms, acting on different timescales
  - broad range of properties, including ρ, Y_e, s and $\mathbf{v}$
- quantitative outcome:
  - a few percent of $M = M_A + M_B$
  - usually, neutron rich, i.e. $Y_e < 0.5$ and typically $Y_e \ll 0.5$

Nucleosynthesis calculations on the ejecta:

- tracer particles: $\rho(t)$ input for nuclear network calculations
- matter flows: distribution of ejecta properties, to be convolved with network calculations along parametrized tracers

Neutron stars in isolation or in binaries

- mass and radii

$$\frac{M}{M_\odot} \sim 1.4 \in [M_{\rm min} \lesssim 1.2, M_{\rm max} \gtrsim 2.1]$$

$$R \approx 11\text{--}12\text{km}$$

- compact

$$\mathcal{C} \equiv \frac{GM}{Rc^2} \approx 0.173 \left(\frac{M}{1.4M_\odot}\right)\left(\frac{R}{12\text{km}}\right)^{-1}$$

- dense

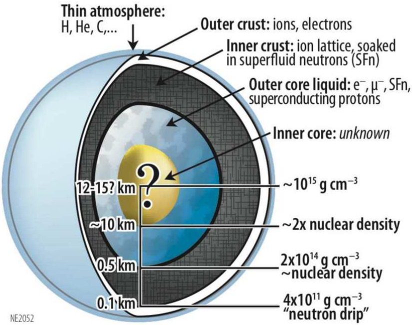
$$\langle\rho\rangle \approx 3.8 \times 10^{14}\text{g cm}^{-3}\left(\frac{M}{1.4M_\odot}\right)\left(\frac{R}{12\text{km}}\right)^{-3}$$

- cold

$$T \lesssim T_{\rm Fermi} \sim 30\text{MeV}(\rho/10^{14}\text{g cm}^{-3})$$

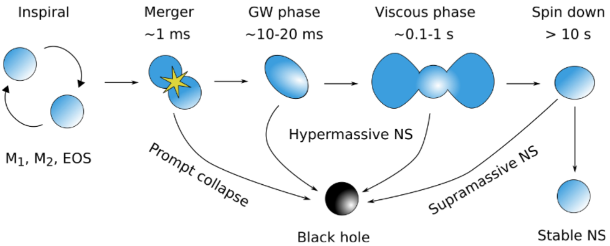
- β-equilibrated

$$p + e^- \leftrightarrow n + (\nu_e) \Rightarrow Y_e \equiv n_e/n_{\rm B} = n_p/(n_n + n_p) \lesssim 0.1$$



https://heasarc.gsfc.nasa.gov/

BNS merger in a nutshell: inspiral & merger



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  - $M = M_A + M_B$, total mass
  - $\mu = (M_A M_B)/M$, reduced mass
  - $\mathcal{T}$, binary period
  - e, binary eccentricity

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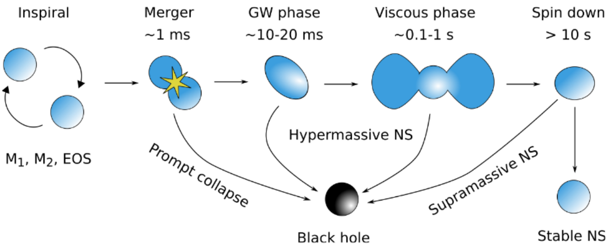

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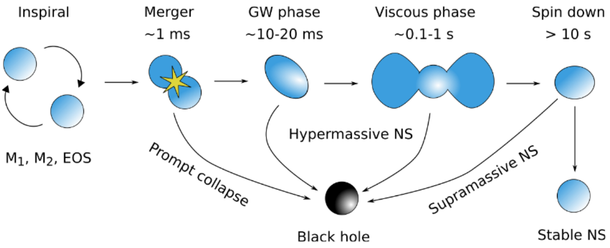

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BNS mergers on the thermodynamics plane

Which are the thermodynamics conditions of matter during the merger?

Perego,Bernuzzi,Radice 2019 EPJ A 2019

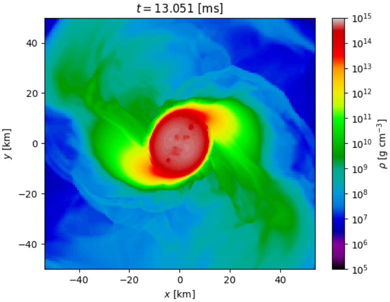
movies at www.youtube.com/channel/UChmn-JGNa9mfY5H5938jnig

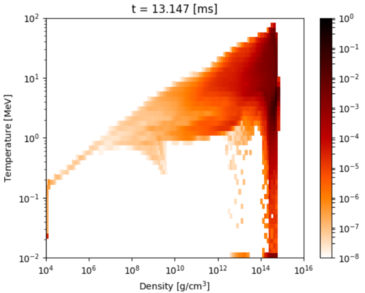
BNS simulation performed with `WhiskyTHC` code — Radice+ 12,14,15

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

DD2 EOS, leakage+M0 scheme for neutrinos

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

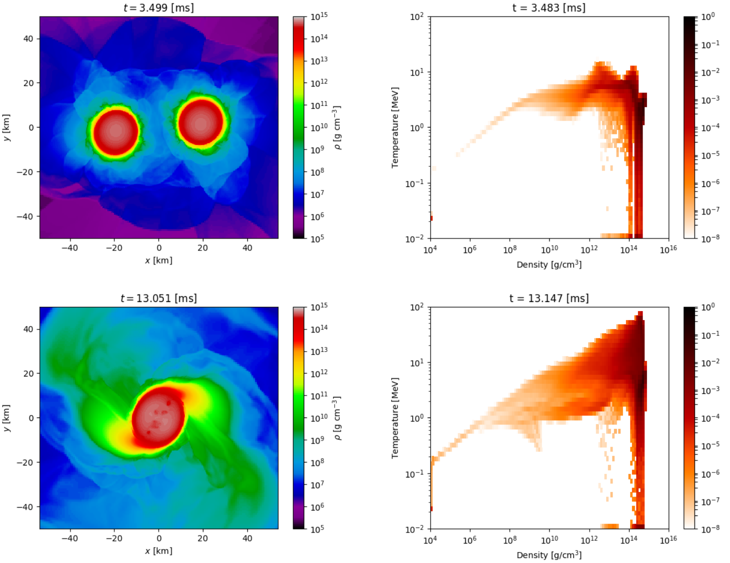




BNS mergers on the thermodynamics plane

inspiral

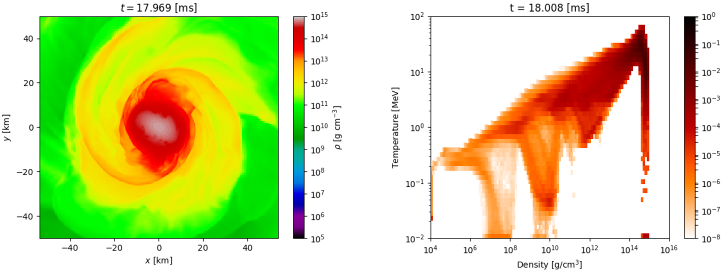
$t(T_{\text{peak}})$



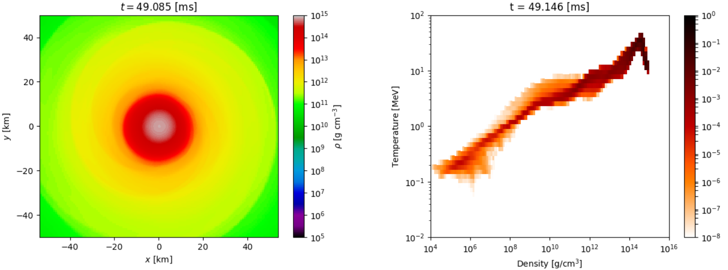
Perego,Bernuzzi,Radice EPJA 2019

BNS mergers on the thermodynamics plane

$t \gtrsim t_{\text{dyn}}$

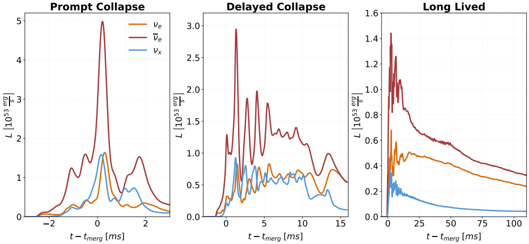


$t \gg t_{\text{dyn}}$

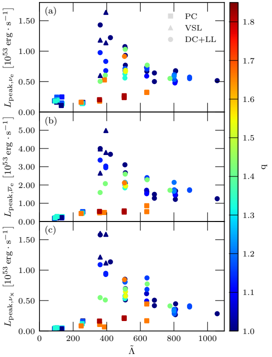


Perego,Bernuzzi,Radice EPJA 2019

Neutrino emission



Cusinato *et* al EPJA 2022



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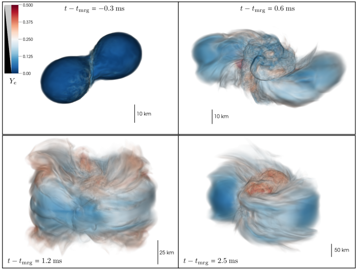
- neutron rich, i.e. $Y_e < 0.5$ and typically $Y_e \ll 0.5$
- expelled by different mechanisms, acting on different timescales

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

- remnant & disk winds ($t \sim 10$ms $- 1$s)
  - BH+torus:
    - MHD viscosity & nuclear recombination
  - massive remnant + disk:
    - spiral modes
    - neutrino absorption
    - MHD viscosity
  - very efficient: $M_{\rm ej} \sim 0.1 - 0.4 M_{\rm disk}$



Radice, Perego *et al* ApJ 2018

What is this matter relevant for?

Ejecta: unbound matter from BNS mergers

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

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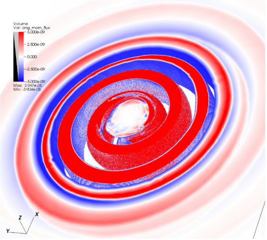
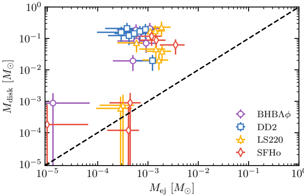




Nedora *et al* ApjL 2019, Radice *et al* ApJ 2018

What is this matter relevant for?

Production of heavy elements

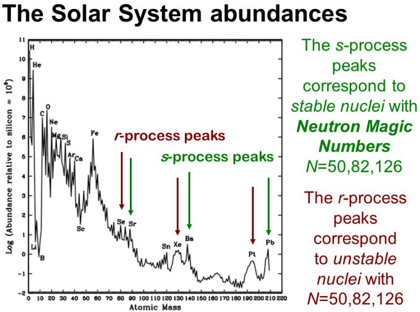
- the Universe is made of elements, from H to U (and beyond)
- elements appear with different abundances
- abundances evolve in time through the cosmic history

Where and how do elements form?
Why do elements show the abundaces they have?

- big bang produced H and He
- stars can forge elements up to iron group
- how do heavier elements form?

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

e.g. B^2FH RvMP 57



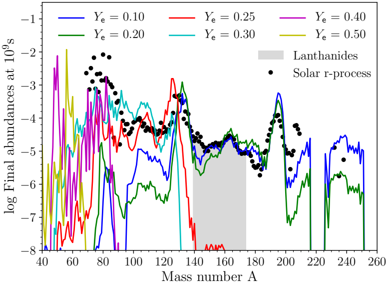
how and where can *n*-captures happen?

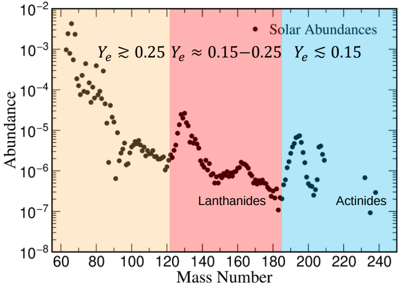
r-process nucleosynthesis in BNS ejecta

- at low entropy ($s \lesssim 40 k_b$/baryon), Y_e dominant parameter
- Y_e influenced by weak interactions involving neutrinos, e.g.

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

- lanthanides (and actanides) production dramatically changes photon opacity (atomic f-shell opening)





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

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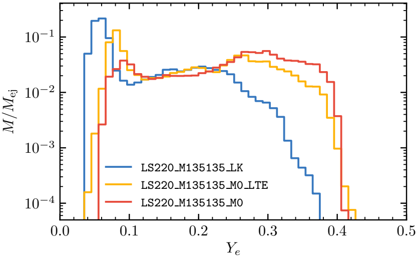
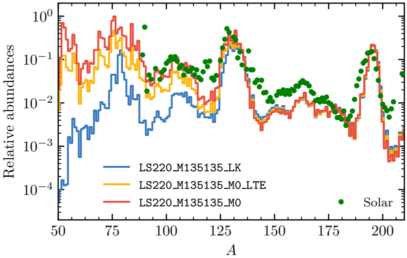
w/o neutrino absorption



w neutrino absorption



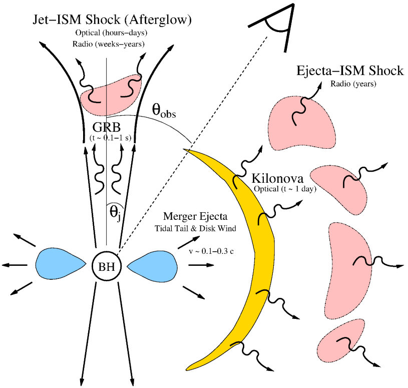
Radice *et al* 2018

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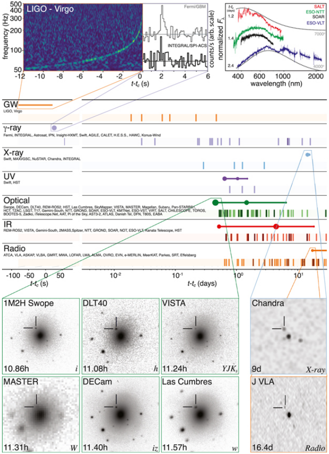


LVC PRL 2017

BNS as laboratory for fundamental physics

challenge:

quantitative statements require sophisticated numerical models

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 – 1 year)

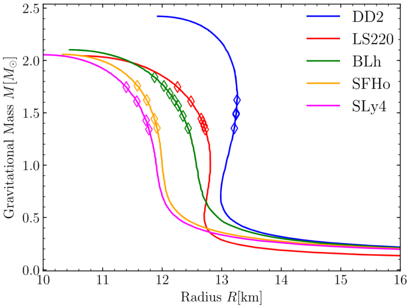
different scales & different interactions ⇒ intimately related

opportunity:

comparison between model and multimessenger observations can probe Nature in regimes otherwise unaccessible

What do we know about ultradense matter in NSs?

- cold nuclear matter:
  - $n \lesssim n_0$: decently described by nuclear χ-EFTs or nuclear potentials
  - $n \gtrsim 2n_0$: very uncertain
- hot, out-of-β equilibrium nuclear matter:
  - largely unknown, especially at high density
- relevant degrees of freedom (hyperons, quark-gluon plasma, π's, ...)



- cold nuclear matter $\sim n_0$ determines R_{NS} and tidal deformability (k_2 or Λ)
- cold nuclear matter at several n_0 sets M_{max}^{TOV}
- hot matter determines behavior and evolution of BNS merger remnant

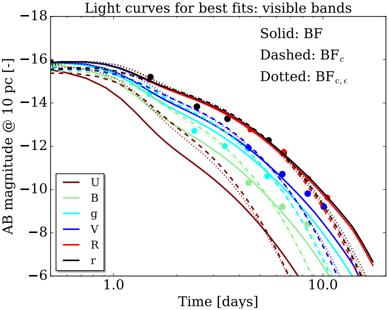
$\Rightarrow$ BNS merger observables (GWs, EM, ν, nucleosynthesis) can set constraints on nuclear EOS

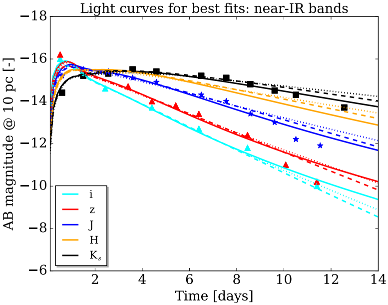
Light curves and spectra from AT2017gfo

AT2017gfo: bright light curves compatible with

- $m_{ej} \sim 0.01 - 0.05 M_\odot$
- multi-component, anisotropic ejecta: an early blue emission followed by a red emission $\rightarrow$ *broadly* consistent with strong-field models

$\Rightarrow$ absence of prompt collapse





Perego *et al* 2017, ApJ

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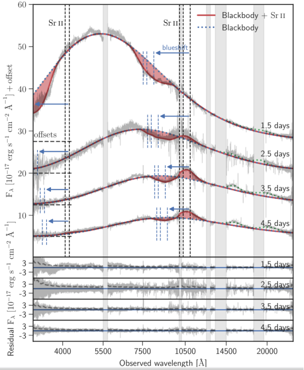


observed spectra at 1.5-4.5 day: identification of strontium

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

Watson+ 18 Nature, Gillanders+ 22 MNRAS

- is Sr an expected element?
- is the inferred amount telling us something about the remnant?

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

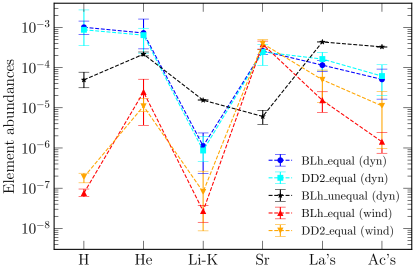
From strong field dynamics to kilonova emission

Analysis of a large sample of BNS merger simulations

- targeted to GW170917
- including microphysics EOSs and neutrino physics

nucleosynthesis yields from dynamical and spiral wave wind ejecta

- 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 $m_{\mathrm{Sr}} \sim 5 \times 10^{-5} M_{\odot}$, $\Delta t_{\mathrm{wind}} \lesssim 4$ ms



Perego *et al*, ApJ 2022

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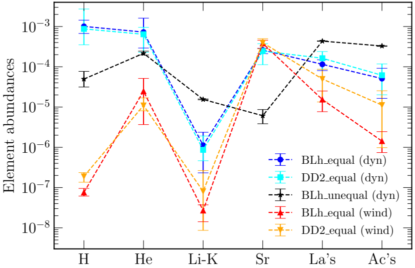


Perego *et al*, ApJ 2022

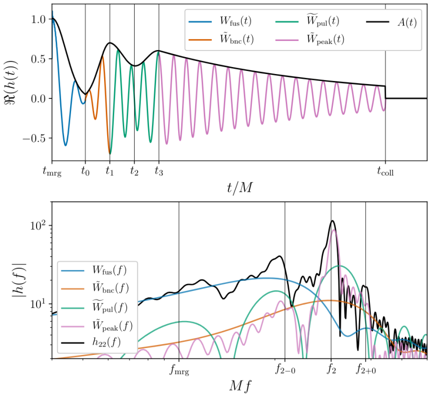
our results suggest GW170817 remnant survived only a few ms after merger!

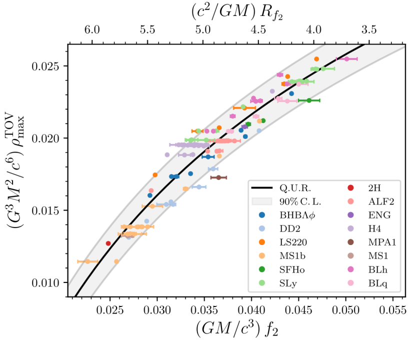
confermed by more recent simulations: prospects for Ca & He production in long-lived remnant

Jacobi *et al* 2503.17445, Sneppen *et al* 2411.03427

Probing supranuclear matter with post-merger GWs

Post-merger GW signal:





Breschi *et al*, PRD 2024

- dominant peak frequency, f_2
- f_2 EOS-sensitive: nuclear interaction, DOFs, phase transitions, thermal effects

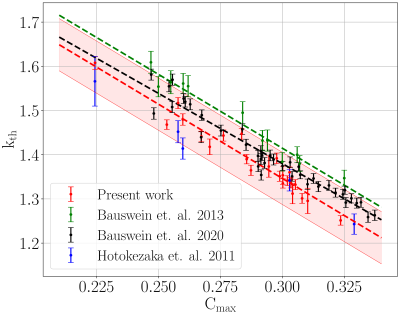
analysis of post-merger signals from different EOSs: empirical relation

$$f_2 \leftrightarrow \rho_{\rm max}^{\rm TOV}$$

single high S/N detection in ET could determine $\rho_{\rm max}$!

Probing supranuclear matter with prompt collapses

equal mass BNS mergers:
large simulation campaigns to determine $M_{\rm th}$ for prompt collapses



Kashyap+22 PRD

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

- $k_{\rm th}$ correlates with several EOS-dependent NS properties
  - $C_{\rm max}$
  - $R_{1.6}$

Hotokezaka+11 PRD 11, Bauswein+12 PRL

- combination of $k_{\rm th}$, GW170817 and massive NS information tighter constraints on $M_{\rm max}$, $\Lambda_{1.4}$ or $R_{1.4}$

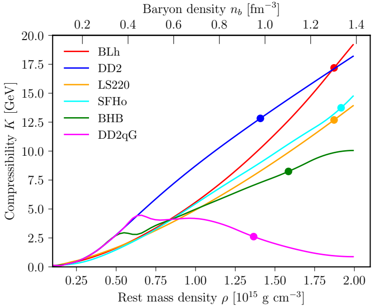
Probing supranuclear matter with prompt collapses

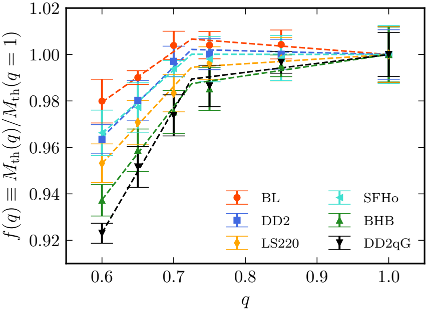
prompt collapse in the case of unequal mass mergers

Perego *et al* PRL 2022

- nuclear incompressibility:

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





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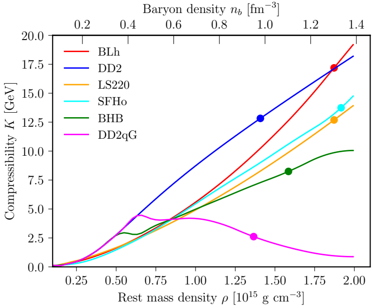

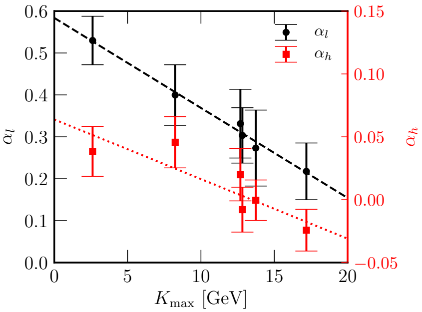

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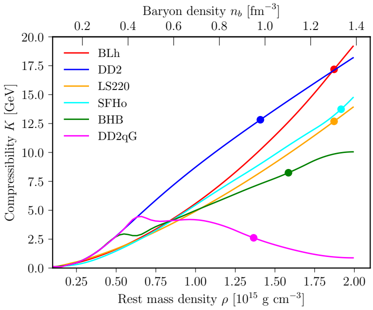
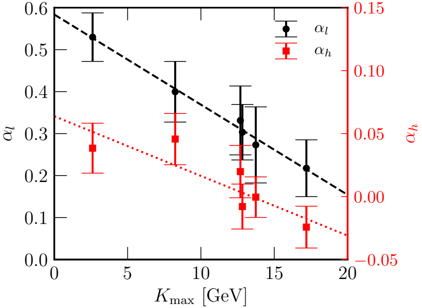




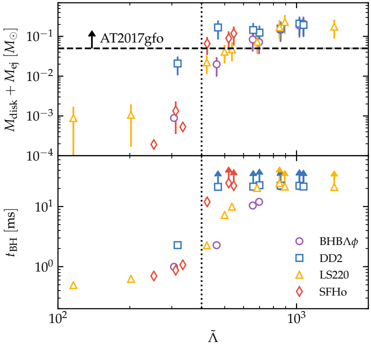
measurement of M_{th} at two q's directly provides $K_{\max}$

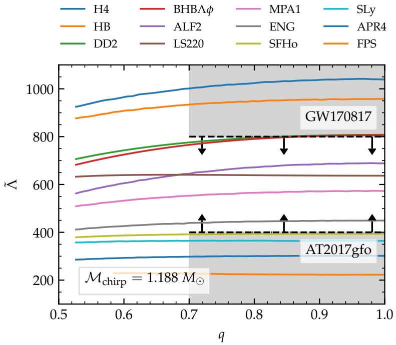
Constraining the nuclear EOS from MM astrophysics

Combination of GW and EM signals from the same event allows to extract stringent constraints

e.g. Radice *et al* ApJL 2017

Can information deduced from kilonova modelling be combined to NR results to constrain NS EOS?





Radice *et al* ApJL 2018

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

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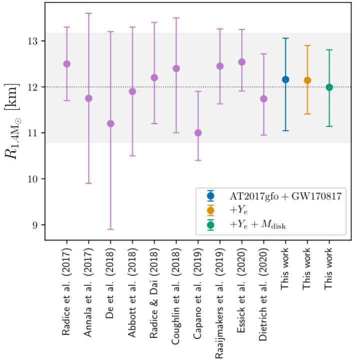
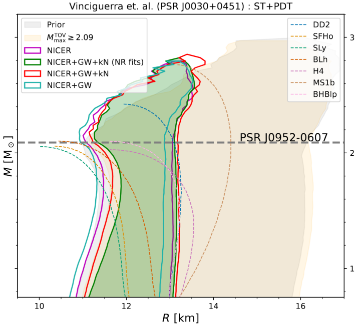
coherent GW+kilonova analysis within Bayesian framework, e.g. using `bajes` code



Breschi *et al* MNRAS 2021



Breschi *et al* A&A 2024

What's more?

- exotic neutron rich nuclei
  most of the *r*-process path layes in unexplored sector of the nuclear chart: mass, decay rates, cross section largely unknown
  - dedicated nuclear accelerators to explore neutron-rich side of valley of stability
    - RIKEN (JP)
    - FRIB (US - Michigan)
    - FAIR (DE)
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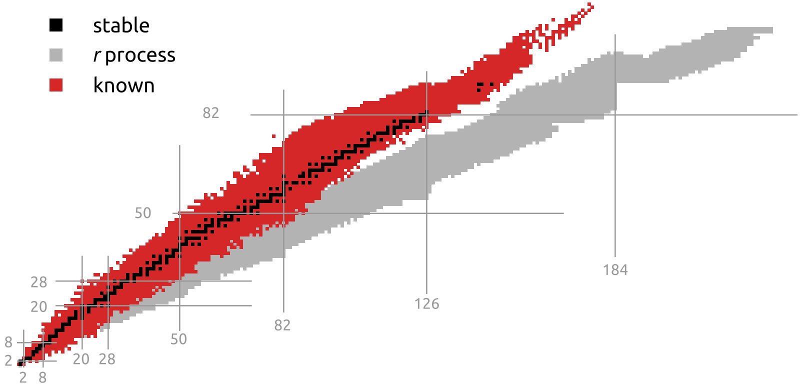

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- neutrino flavor evolution
  $m_\nu \neq 0$ translates into flavor oscillations and flavor changes due to
  - flavor instabilities, quantum many-body effects, or potential beyond standard model physics

$$i \frac{\mathrm{d}}{\mathrm{d}t} S = H\, S \qquad \text{where} \quad H = H_V + H_{\mathrm{mat}} + H_{\nu\bar{\nu}}$$

  - challenging quantum kinetic problem coupled to BNS radiation MHD

see e.g. Zhu *et al* PRD 2017 for MNR, Yi *et al* 2503.11758 for BNS simulations

Conclusions

- BNS mergers are fundamental laboratory for fundamental physics
- crucial comparison between theoretical prediction and observations
  - GWs
  - kilonova light curves and spectra
  - short GRB and its afterglow
- robust and reliable models are mandatory
  - microphysics (e.g. EOS and neutrinos) still very uncertain or approximated
- multiple messengers do provide tighter constraints
  - nuclear EOS constraints
  - neutrino physics
  - exotic nuclei and nuclar interaction