Neutrinos in binary NS mergers: ejecta, nucleosynthesis and EM counterparts

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In collaboration with A. Arcones, S. Bernuzzi, O. Korobkin, D. Martin, D. Radice, S. Rosswog, F-K Thielemann, . . .

INFN, Milano-Bicocca & Gruppo collegato di Parma

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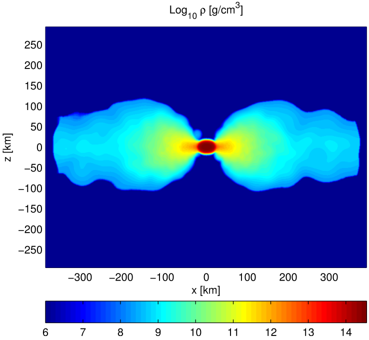
BNS mergers and their aftermath

Final stage of a binary NS (BNS) system evolution:

- coalescence phase
- merger aftermath



slice from 3D matter density (Perego+2014)

- Massive NS ($\rightarrow$ BH)
  $M \sim 2.2 - 2.8 M_\odot$,
  $\rho \gtrsim 10^{12}\,\mathrm{g\,cm^{-3}}$
  $T \sim$ a few 10 MeV
- thick accretion disk
  $M \sim 10^{-2} - 0.4 M_\odot$
  $\mathrm{Y_e} \lesssim 0.20$
  $T \sim$ a few MeV
  $\left(\mathrm{Y_e} = \frac{n_e}{n_B} \approx \frac{n_p}{n_p + n_n} \right)$
- intense ν emission
  $L_{\nu,\mathrm{tot}} \sim 10^{53}\,\mathrm{erg\,s^{-1}}$
  $E_\nu \gtrsim 10\,\mathrm{MeV}$
  $L_{N,\nu,\mathrm{tot}} \sim 10^{57}\,\mathrm{particles\,s^{-1}}$

Neutrino-matter interaction in BNS merger remnants

- ν's are weakly interacting particles (NC & CC processes)
- production (and possibly absorption):
  $p + e^- \to n + \nu_e$ (EC)
  $n + e^+ \to p + \bar{\nu}_e$ (PC)
  $e^- + e^+ \to \nu + \bar{\nu}$
  $N + N \to N + N + \nu + \bar{\nu}$
- scattering:
  $N + \nu \to N + \nu$ $\quad$ $e^\pm + \nu \to e^\pm + \nu$

Neutrino production rates:
production boosted by high temperatures & densities

- $R_{EC} \propto n_p T^5 F_4(\mu_e/T)$

- $R_{PC} \propto n_n T^5 F_4(-\mu_e/T)$

e.g. Rosswog & Liebendörfer 03

Neutrino-matter interaction in BNS merger remnants

- ν's are weakly interacting particles (NC & CC processes)
- production (and possibly absorption):

$$p + e^- \to n + \nu_e \text{ (EC)} \qquad e^- + e^+ \to \nu + \bar{\nu}$$
$$n + e^+ \to p + \bar{\nu}_e \text{ (PC)} \qquad N + N \to N + N + \nu + \bar{\nu}$$

- scattering:

$$N + \nu \to N + \nu \qquad e^\pm + \nu \to e^\pm + \nu$$

Neutrino production rates:
production boosted by high temperatures & densities

Neutrino absorption rates:
neutrino opacity $\leftrightarrow$ neutrino mean free path, $\lambda_\nu \ll R_{\rm NS}$

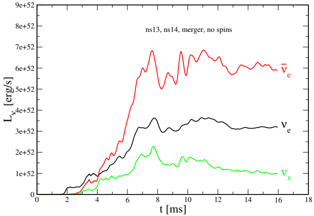
$$\sigma_\nu \sim \sigma_0 \left(\frac{E_\nu}{m_{\rm e} c^2} \right)^2 \qquad \sigma_0 = \frac{4 G_F^2 (m_e c^2)^2}{\pi (\hbar c)^4} \approx 1.76 \times 10^{-44}\,{\rm cm}^2 \approx 2.6 \times 10^{-20} \sigma_t$$

$$\lambda_\nu \approx \frac{1}{n_{\rm target} \sigma_\nu} \sim 2.36 \times 10^3 {\rm cm} \left(\frac{\rho}{10^{14}\,{\rm g/cm^3}} \right)^{-1} \left(\frac{E_\nu}{10\,{\rm MeV}} \right)^{-2}$$

Basic ν features in BNS mergers

Role of ν's

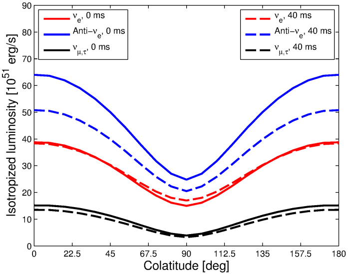
- exchange energy and momentum with matter
- set n-to-p ratio (i.e. Y_e)
  $p + e^- \rightarrow n + \nu_e$ (EC)
  $n + e^+ \rightarrow p + \bar{\nu}_e$ (PC)
- influence nucleosynthesis



Rosswog+13 (up), Perego+14 (down)

ν luminosities

- ν gas formation and diffusion
- n-richness $\rightarrow L_{\bar{\nu}_e} \gtrsim L_{\nu_e}$



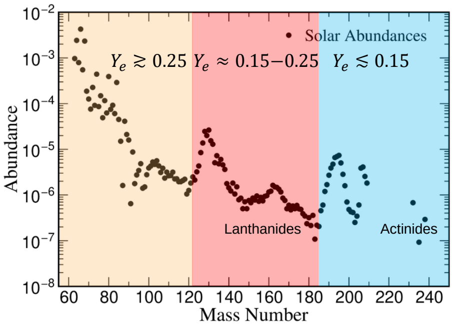
anisotropic ν emission, due to the presence of the disk:

- $F_{\nu,\mathrm{equator}} \approx (1/3) F_{\nu,\mathrm{pole}}$

Dessart+09; Perego+14, Just+15,...

Matter Ejection Channels

- why different ejection channels?
  - different physical origins and timescales
- which implications from different channels?
  - different M_{ej} and v_{ej}
  - different Y_e → composition → photon opacity, κ_γ
- ejecta properties affect EM emission



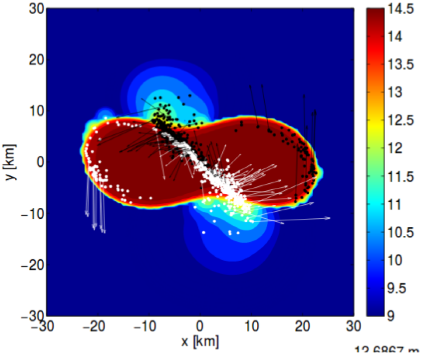
- no lanthanides: low opacity ($\kappa \lesssim 1\,\mathrm{cm}^2/\mathrm{g}$)
- presence of lanthanides: high opacity ($\kappa \sim 10\,\mathrm{cm}^2/\mathrm{g}$)

← Courtesy of G. Martinez-Pinedo

Dynamic ejecta from BNS merger

- $t_{\rm ej,dyn} \sim$ few ms
- $v_{\rm ej,dyn} \sim$ few $0.2 - 0.3\,c$
- $M_{\rm ej,dyn} \sim 10^{-4} - 10^{-2} M_{\odot}$, depending on q and EOS

Korobkin+12,Hotokezaka+13,Bauswein+13,Wanajo+14,Sekiguchi+15,Radice+16,Bovard+17,...



- tidal component
  - equatorial
  - low Y_e
- shocked component
  - equatorial & polar
  - higher entropy
  - larger Y_e at high latitudes

Bauswein+13

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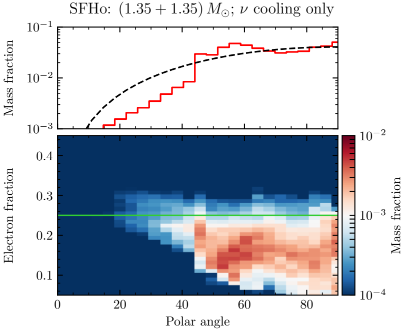

$e^{\pm}$ captures but no ν absorption

Simulation: D.Radice; Perego,Radice,Bernuzzi ApJL 17

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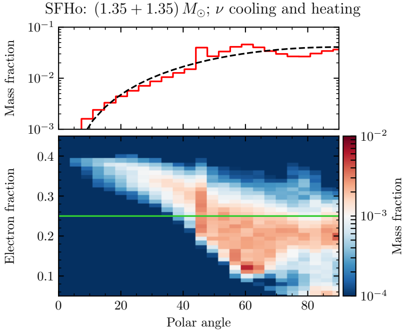

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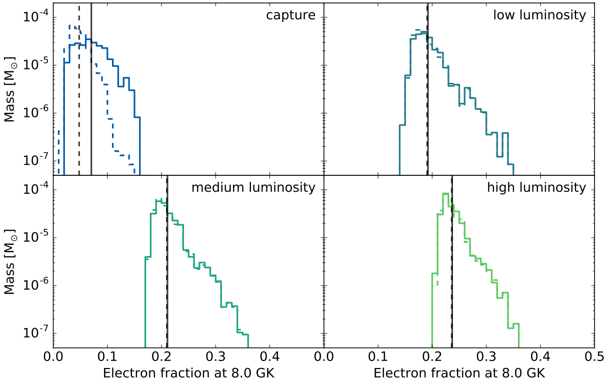

Martin+ 18, CQG

[increasing ν flux: higher total luminosity or anisotropic emission: smaller along the equator, larger along the poles]

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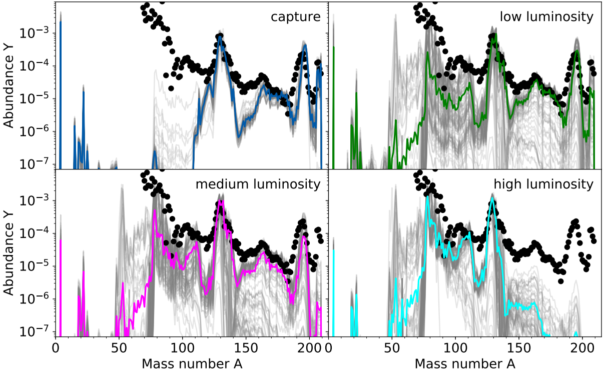

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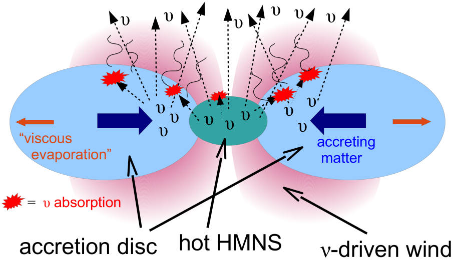
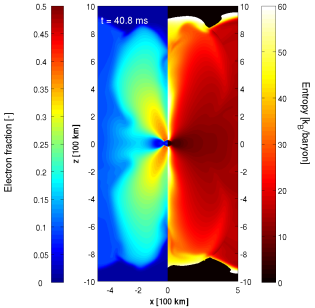
Wind ejecta from BNS merger

- due to neutrino absorption inside the disk
- enhanced by the presence of central MNS
- $t_{\rm ej,wind}$ ~few 10's ms and $v_{\rm ej,wind} \lesssim 0.1\,c$
- $M_{\rm ej,wind} \lesssim 0.05 M_{\rm disk}$
- polar character, with low opacity ($\lesssim 1\ {\rm cm^2 g^{-1}}$)



Perego,Rosswog,Cabezon+14, MNRAS



see also Dessart+2009,Metzger & Fernandez 14, Fujibayashi+18

Martin,AP,Arcones+ 15, ApJ

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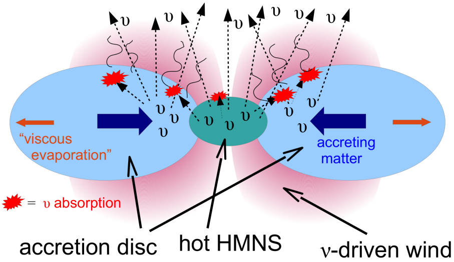
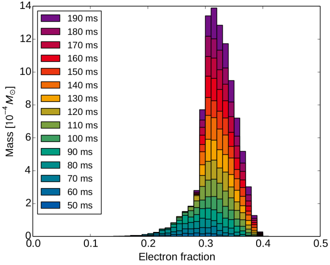


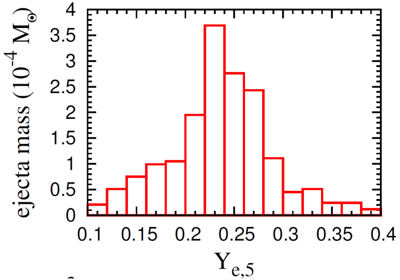


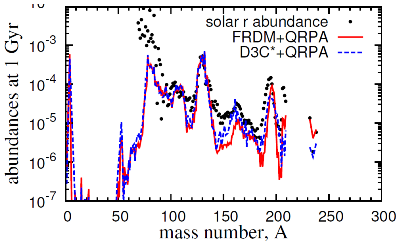
Perego,Rosswog,Cabezon+14, MNRAS; Martin,AP,Arcones+ 15, ApJ

see also Dessart+2009,Metzger & Fernandez 14, Fujibayashi+18

Viscous ejecta from BNS merger

- due to viscosity and nuclear recombination in the disk
- $t_{\mathrm{ej,sec}} \sim$ few 100's ms and $v_{\mathrm{ej,sec}} \lesssim 0.1c$
- broad distribution of n-rich matter ($0.1 \lesssim \mathrm{Y_e} \lesssim 0.4$)
- long-lived MNS $\rightarrow$ larger Y_e
- $M_{\mathrm{ej,sec}} \sim (0.2 - 0.4)\, M_{\mathrm{disk}}$
- all solid angle ejection, intermediate opacity $1 - 10\,\mathrm{cm^2 g^{-1}}$





Wu+16, see e.g. Metzger+10,Fernandez&Metzger+13,Just+15,Lippuner+17, Siegel& Metzger 17,...

Interpretation of AT2017gfo

AT2017gfo, EM counterpart of GW170817

- light curve properties:
  - bright, UV/O component, with a peak @ $\sim$ 1day
  - rather bright, IR component, with a peak @ $\sim$ 4day
- possible interpretation: (macro)kilonova associated with a BNS and powered by radioactive decay of *r*-process material ejected into ISM by the merger
- light curve properties depends on the properties of the ejecta (e.g., mass, velocity, composition $\rightarrow$ opacity)

can we explain the observed light curve properties in terms of the ejecta properties?

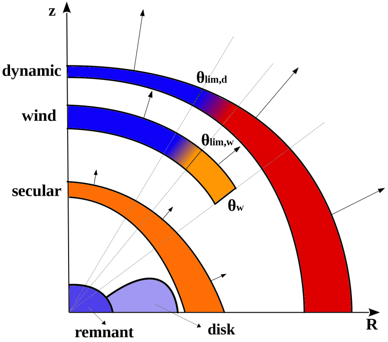
Perego,Radice,Bernuzzi 17, ApJL

see also, e.g., Abbott+ 17 (ApjL), Tanvir+ 17, Villar+ 17, Murguia-Bertier+ 17, Tanaka+2017, Kasen+2017, Shibata+2017...

Multi-Component Anisotropic Kilonova Model

- (macro)kilonova model that includes our present knowledge about ejecta
- different ejection channels → multi-component
- explicit dependency on polar angle → anisotropic
  - multi-angle (polar angle discretization)
  - explicit dependence on observer viewing angle

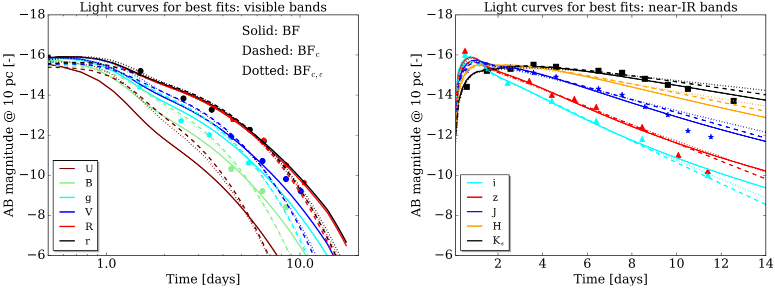
Perego, Radice, Bernuzzi 17, ApjL



- $M_{ej}(\theta)$, $v_{ej}(\theta)$, $\kappa_{ej}(\theta)$
- 1D models along each ray
- homologous mass expansion

Grossman+14

Analysis of AT2017gfo signal

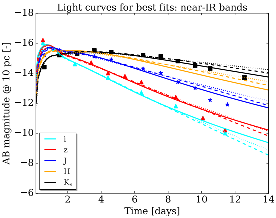


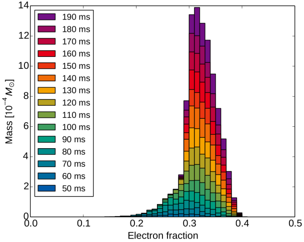
observations: Pian,D'Avanzo+17,Tanvir+17

- global properties for AT2017gfo
  - anisotropic and multicomponent ejecta
  - $M_{\mathrm{ej,dyn}} \sim 0.005 - 0.01\ M_\odot$
  - $M_{\mathrm{ej,winds}} \sim 0.03 - 0.045\ M_\odot$
  - $M_{\mathrm{ej,tot}} \sim 0.05 M_\odot$, $\theta_{\mathrm{obs}} \approx 30^o$, $M_{\mathrm{disk}} \sim 0.1 M_\odot$
  - low-opacity material at high latitude! neutrinos @ work!

Summary

- weak reactions and neutrinos play a central role in BNS mergers, matter ejection and kilonova modelling
- matter ejection: anisotropic and multi-component
- multi-component, anisotropic KN model for AT2017gfo, including influence of weak reactions compatible with observations
- BNS can eject a few times $0.01 M_\odot$ of r-process elements, with broad chemical composition ($A > 70$)





Astrophysical relevance

dynamical encounter of neutron-rich, stellar compact object

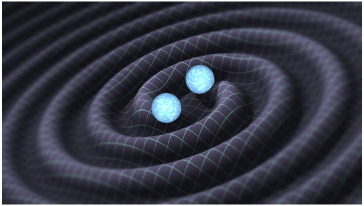
- intense emitter of GWs and ν's e.g., Peters 64, Eichler+ 87
- ejecta and heavy elements nucleosynthesis

Lattimer & Schramm 74

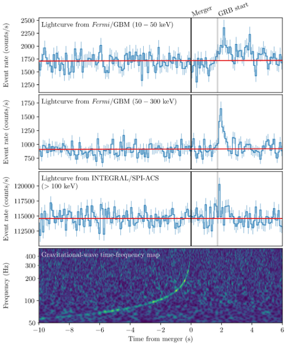
- short GRBs progenitors

Paczynski 86, Eichler+ 87

- kilonova/macronova powered by radioactive decay Li & Paczynski98



www.ligo.caltech.edu



Jointed γ-ray and GW detections, Abbott+17, ApJL

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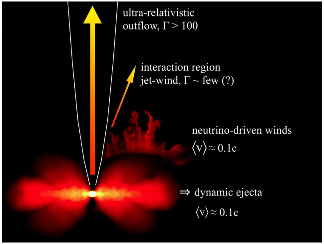
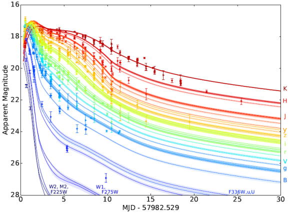


Rosswog 12



Villar+17, see also Pian+17, Tanvir+17, Abbott+ 17, Coulter+ 17; Nicholl+ 2017; Chornock+ 17

How robust are dynamic ejecta propeties?

Martin, Perego, Kastaun, Arcones CQG 2018; cf. Goriely+2015

- shock heated dynamic ejecta from GR simulation — Kastaun+17
- postprocessing of tracer particles to include ν's feedback

$$\frac{dY_e}{dt} = (\lambda_{\nu_e} + \lambda_{e^+}) Y_n - (\lambda_{\bar{\nu}_e} + \lambda_{e^-}) Y_p$$

$$\frac{ds}{dt} = \left(\frac{ds}{dt}\right)_{\rm hydro} + \frac{1}{T}\left[\left(\frac{dQ}{dt}\right)_{\nu} - (\mu_e - \mu_n + \mu_p)\left(\frac{dY_e}{dt}\right)_{\nu}\right]$$

- optically thin conditions ($\rho < 10^{12}\,{\rm g/cm^3}$)
- consistent ν emission, $\lambda_{e\pm}$ — Bruenn 1985 + Horowitz 2002
- parametrized ν flux for ν absorption, $F_\nu \propto L_\nu / \left(\langle E_\nu \rangle R^2\right)$

Name	$L_{\nu_e,\max}$ [10^{53} erg/s]	$L_{\bar{\nu}_e,\max}$ [10^{53} erg/s]	$E_{\nu_e,\max}$ [MeV]	$E_{\bar{\nu}_e,\max}$ [MeV]
capture	0.0	0.0	0.0	0.0
low	0.86	1.0	11.5	16.2
medium	1.0	1.5	12.0	16.3
high	1.2	2.4	13.0	16.7

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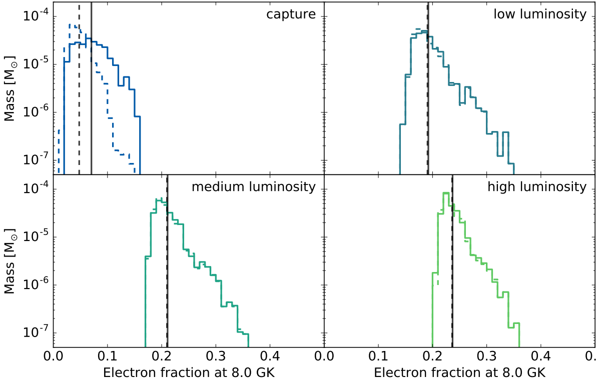

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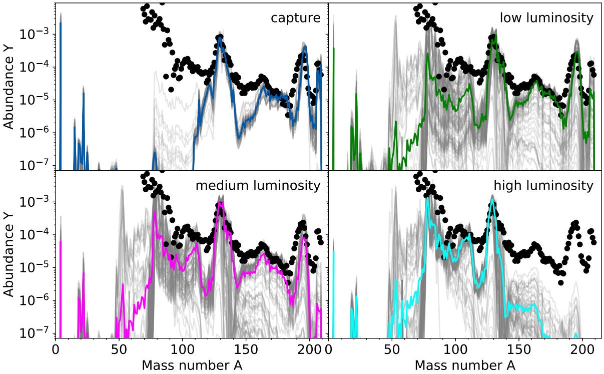

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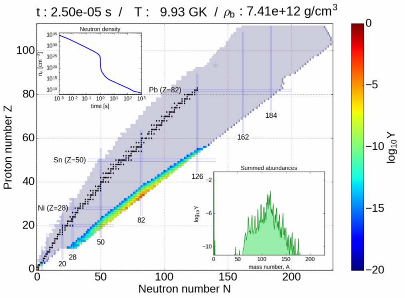
r-process nucleosynthesis in BNS mergers

Where and how do heavy elements form (above Fe group)?

- n-capture processes (rapid (r) or slow (s))
- conditions for r-process: n-rich matter (possibly at high entropy): high n-to-seed ratio $\rightarrow t_{\mathrm{n-capture}} < t_\beta$ e.g., Hoffman+ 98
- verified in BNS merger ejecta e.g., Korobkin+12, Bauswein+13, Hotokezaka+13, Wanajo+14, Fernandez&Metzger 13, Just+14, Perego+14, Martin+15, Radice+2016, Bovard+17, Wu+17 ...



NSE freeze-out: high n-to-seed ratio

- detailed nuclear network (e.g., `WINNET`) Winteler+12
- large ODE system (5800 nuclei)
- $\Rightarrow Y_{(A,Z)}(t)$ and $Q_{\mathrm{nuc}}(t)$

(snapshots from network movie, courtesy of D Martin and O Korobkin. Mass model: FRDM from Möller+ 1995)

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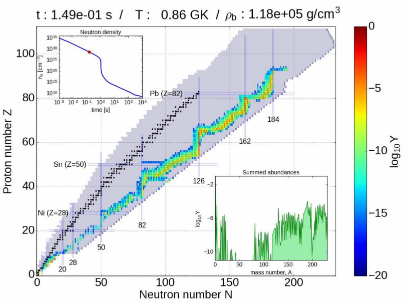

(n,γ)-(γ,n) equilibrium

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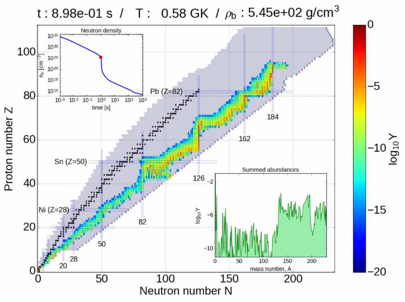

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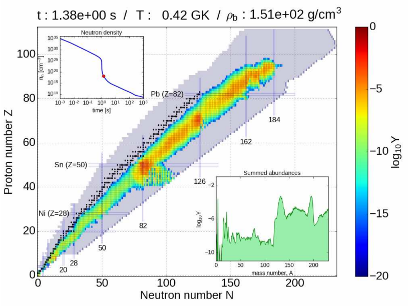

end of r-process: β-decays

- detailed nuclear network (e.g., WINNET) Winteler+12
- large ODE system (5800 nuclei)
- $\Rightarrow Y_{(A,Z)}(t)$ and $Q_{\text{nuc}}(t)$

(snapshots from network movie, courtesy of D Martin and O Korobkin. Mass model: FRDM from Möller+ 1995)

r-process nucleosynthesis in BNS mergers

Where and how do heavy elements form (above Fe group)?

- n-capture processes (rapid (r) or slow (s))
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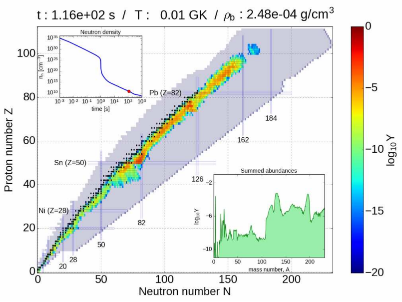

long term nuclear decays

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- large ODE system (5800 nuclei)
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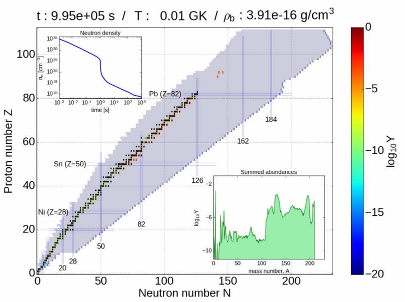

nuclei reach valley of stability

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- $\Rightarrow Y_{(A,Z)}(t)$ and $Q_{\mathrm{nuc}}(t)$

(snapshots from network movie, courtesy of D Martin and O Korobkin. Mass model: FRDM from Möller+ 1995)

Kilonova model

see Grossman+ 14, Martin+ 15

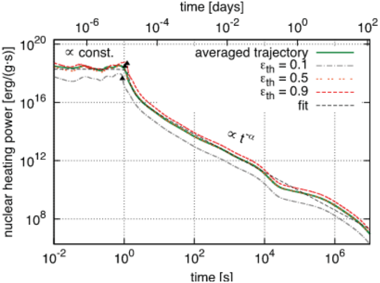
- homologous expansion (from long term simulations)

$$M_{ej} = \int_0^{\pi} \left(\int_0^{v_{max}} \xi(v,\theta)\, dv \right) d\theta \qquad \xi(v,\theta) = \left(1 - \left(\frac{v}{v_{max}(\theta)}\right)^2\right)^3$$

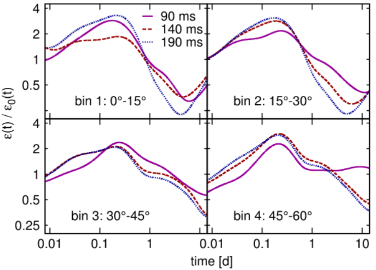
- nuclear heat (computed by nuclear network)

$$Q_{heat} \approx Q_0 (t_{days})^{-1.3}$$

- impact of weak r-process nucleosynthesis: shorter β decays lifetimes
- opacity due to r-process elements? e.g.,Tanaka+13,Kasen+13,Wollaeger+17



Korobkin+ 12; see also Metzger+ 10



Martin+ 15

Modelling of BNS Mergers

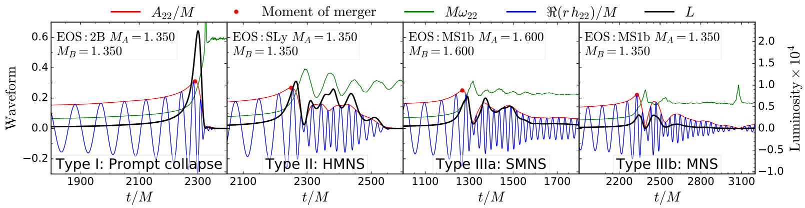
BNS inspiral & merger modelling: Numerical Relativity (NR)

- NR: the art of solving Einstein's equations on a computer
- large computing resources, parallel and HPC codes
- large parameter space:
  M_A, M_B, $\mathbf{S}_A$, $\mathbf{S}_B$, e + uncertainties on NS EOS

- largest database of BNS mergers in NR ($\sim$ 164 configuration, $>$ 300 simulations)
- 2 different NR codes
  - `BAM` — Thierfelder, Bernuzzi, Brügmann PRD 2011
  - `WhiskyTHC` — Radice, Rezzolla, Galeazzi MNRAS 2013
- $q \leq 2.06\,, \quad 2.4 \leq M_A + M_B \leq 3.4\,,$ 8 different EOS
  $(q \equiv M_A/M_B \geq 1)$
- different numerical resolutions and schemes

CoRe collaboration: Dietrich+2018 submitted

BNS remnant properties



Zappa, Bernuzzi, Radice, Perego, Dietrich PRL 2018

- NS masses and EOS → direct impact on remnant fate and imprint on GW signal

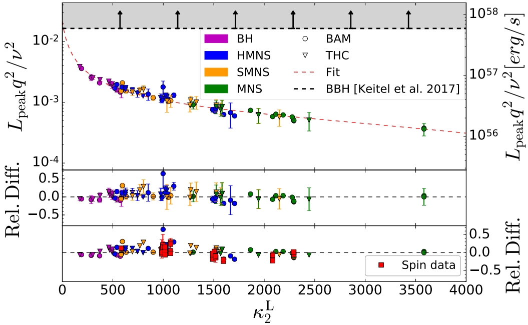
possible remnant fate:

- prompt collapse to BH
- hypermassive NS (HMNS)
- supramassive NS (SMNS)
- massive MNS

however, post-merger signal not detectable by Advanced Ligo and Advanced Virgo

LVC ApJL 851 2017

GW luminosities of BNS

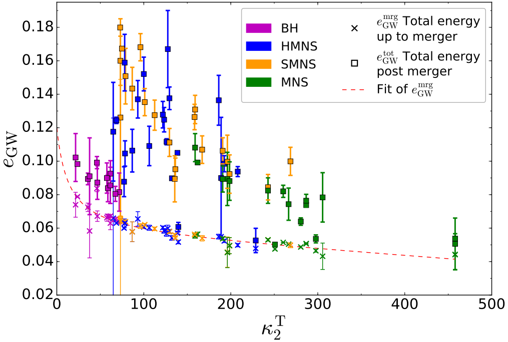


how luminous are BNS at peak?

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

Zappa, Bernuzzi, Radice, Perego, Dietrich PRL 2018

GW energies of BNS

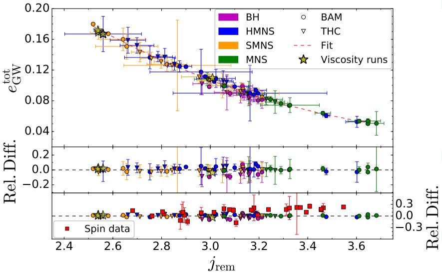


how energetic are BNS?

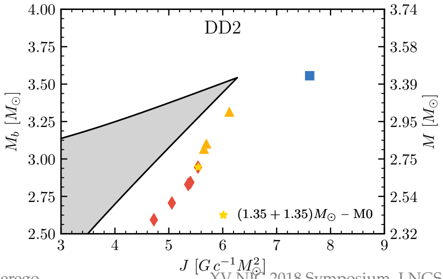
- $e_{\rm GW} = E_{\rm GW}/(M_A + M_B) \lesssim 0.2$
- $E_{\rm GW} \lesssim 0.126\, M_\odot c^2\, (M_A + M_B)/(2.8 M_\odot)$
- HMNS: largest $e_{\rm GW} \sim L_{\rm GW,peak} t_{GW}$
- $e_{\rm GW}$ weakly correlates with κ_2^T
  - κ_2^T: combinations of quadrupolar tidal polarizabilities

Zappa, Bernuzzi, Radice, Perego, Dietrich PRL 2018

Super-Keplerian Long-Lived Remnant



Zappa+ PRL 2018



- quantitative merger prediction require Numerical Relativity (NR) simulations
- NR BNS database

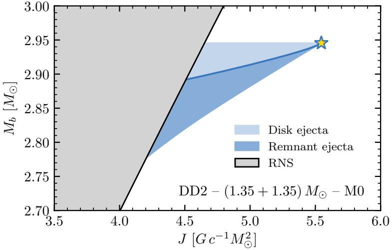
CoRe collaboration, Dietrich+ submitted

- $e_{\rm GW}$ and $j_{\rm rem}$ correlate: GW emission is driving mechanism during merger

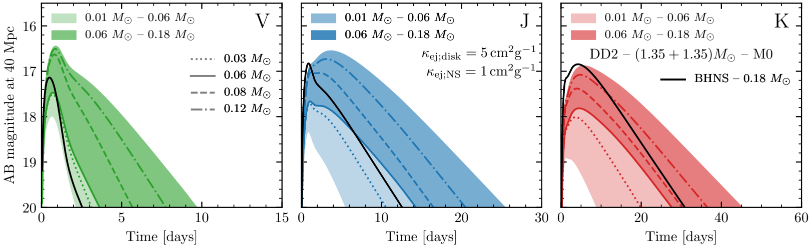
- (S)MNS are super-Keplerian
- robust and EOS independent feature

Radice, AP + submitted

Possible Signatures of long-lived Remnant



- $t_{\mathrm{GW}} \gg t_{\mathrm{visc}}$
- removal of angular momentum through viscous processes
- disk viscous evaporation
- additional viscous processes from the central NS?

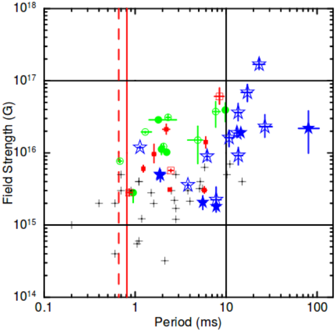


bright visible and IR peak: possible signature of stable MNS

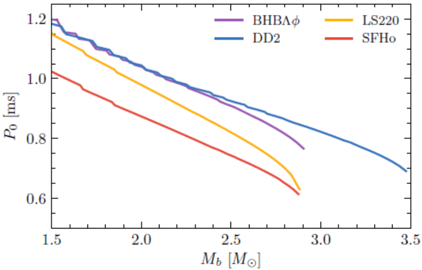
Radice, AP+ submitted

Magnetar Model for SGRBs?

how do MNS spins compare with spins required by magnerat models of SGRB?



Gompertz+ 2013



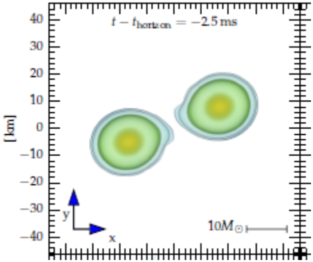
Radice, AP + submitted

Tidal deformation in BNS mergers

Neutron star in an external, inhomegeneous gravitational field becomes tidally deformed

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

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



Haas+16

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

λ depends on EOS and mass of the star $(M, R = R(\mathrm{EOS}, M))$

Multimessenger constraints on nuclear EOS

- GW signal has encoded information about k_2 and M of both stars
- GW170817: $\tilde{\Lambda} < 800$ (90 % CL, Abbott+17)
  i.e. exclusion of very stiff EOS

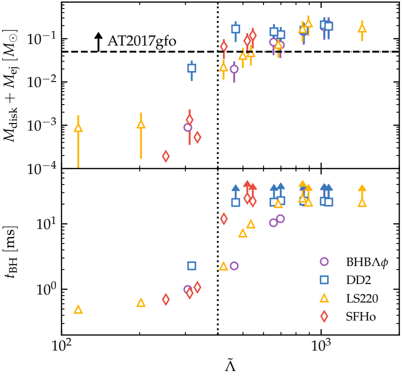
$$\tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\Lambda_2^{(A)}}{(M_A+M_B)^5} + (A \leftrightarrow B)\right] = \tilde{\Lambda}(\mathrm{EOS}, \mathcal{M}_{\mathrm{chirp}}, q)$$

$$\Lambda_2^{(i)} = \frac{2}{3}k_2^{(i)}\left[\left(\frac{c^2}{G}\right)\left(\frac{R_i}{M_i}\right)\right]^5 \quad i = A, B \quad \& \quad q \equiv M_A/M_B$$

can EM signature, in combination with NR simulations of BNS, set a lower bound on $\tilde{\Lambda}$?

Radice,Perego,Zappa,Bernuzzi 17

Constraints from BNS simulations in NR



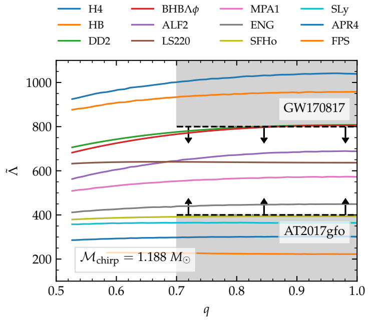
Radice, Perego, Zappa 2017

- for $M_{ej,dyn}$, hard to find correlations
- M_{disk}: clear correlation with $\tilde{\Lambda}$ that reflects correlation of t_{BH} with $\tilde{\Lambda}$
- for $M_{disk} \gtrsim 0.02 M_\odot$, $M_{ej,dyn}$ subdominant

$M_{ej,tot} \gtrsim 0.05 M_\odot$ suggests a lower limit on $\tilde{\Lambda}$:

$$\tilde{\Lambda} \gtrsim 400$$

GW and EM constraints on NS EOS



Radice, Perego, Zappa 2017

- $\tilde{\Lambda}(\mathrm{EOS}, \mathcal{M}_{\rm chirp} = 1.118 M_\odot, q)$
  Abbott+2017
- calculation of $\tilde{\Lambda}$ for different EOSs
- constraints from interpretation of EM observations exclude very soft EOS

- genuine multi-messenger approach
- caveats: still large uncertanties, several approximations and a few hypothesis
- valuable proof of principle