Modeling of matter ejection and kilonova emission from binary NS mergers

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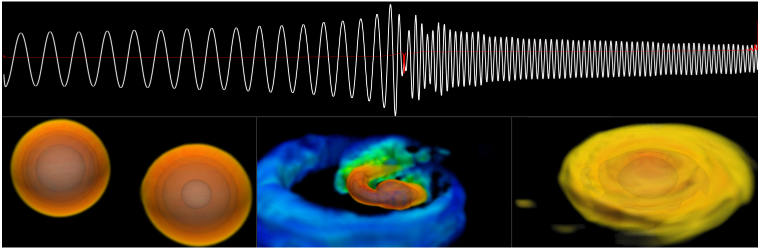
BNS mergers and their aftermath

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

- coalescence phase
- merger aftermath



GW and matter distribution from NR simulations of BNS merger

Credit: S. Bernuzzi & T. Dietrich

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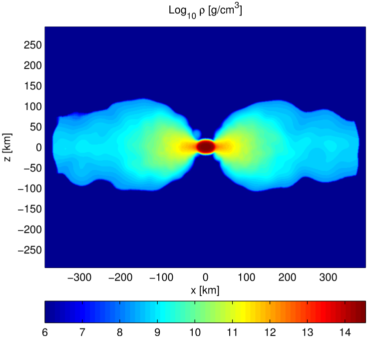


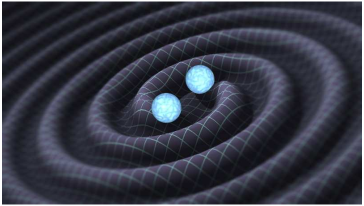
slice from 3D matter density (Perego+2014)

- 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
  $L_{\nu,\mathrm{tot}} \sim 10^{53} \mathrm{erg\,s^{-1}}$
  $E_{\nu} \gtrsim 10\,\mathrm{MeV}$
  $L_{N,\nu,\mathrm{tot}} \sim 10^{57} \mathrm{particles\,s^{-1}}$

Astrophysical relevance

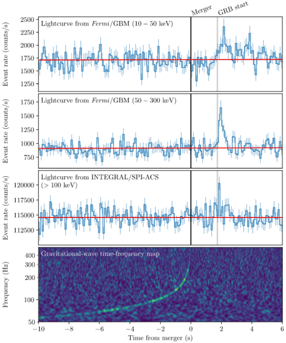
dynamical encounter of neutron-rich, stellar compact object

- intense emitter of GWs and ν's e.g., Peters 64, Eichler+ 87
- ejecta and heavy elements nucleosynthesis Lattimer & Schramm 74



www.ligo.caltech.edu

- short GRBs progenitors Paczynski 86, Eichler+ 87
- kilonova/macronova powered by radioactive decay Li & Paczynski98



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

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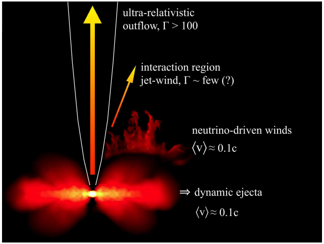
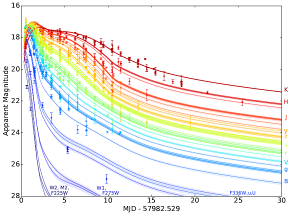


Rosswog 12



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

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

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

  $N + N \rightarrow N + N + \nu + \bar{\nu}$
- scattering:

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

Neutrino production rates:

production boosted by high temperatures & densities

Neutrino absorption rates:

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

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

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

Role of ν's in BNS mergers

Role of ν's

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

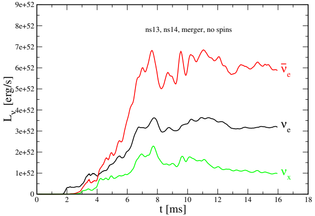
ν luminosities

- ν gas formation and diffusion
- n-richness $\rightarrow L_{\bar{\nu}_e} \gtrsim L_{\nu_e}$
- EOS dependence e.g. Sekiguchi+15

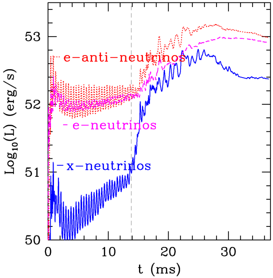
ν modelling: extremely challenging

- multi-D, GR radiation hydro
- leakage schemes, moment schemes, MC schemes?

Shibata+11,Foucart+15,18; Perego+15, Radice+16,...

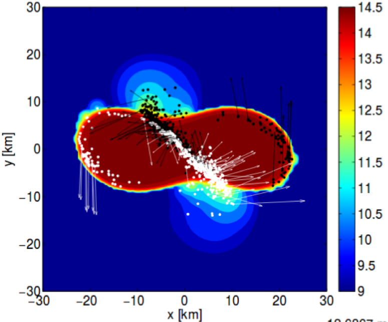


Rosswog+13 (up), Neilsen+15 (down)

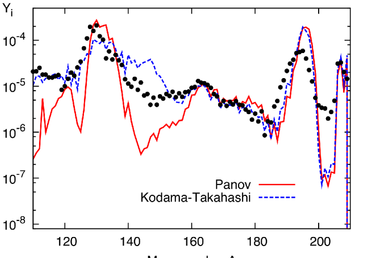


Dynamic ejecta from BNS merger

- $t_{\mathrm{ej,dyn}} \sim$ few ms and $v_{\mathrm{ej,dyn}} \sim$ few $0.1\,c$
- $M_{\mathrm{ej,dyn}} \sim 10^{-4} - 10^{-2} M_{\odot}$
- tidal: equatorial, low $\mathrm{Y_e}$, high opacity ($\sim 10\,\mathrm{cm^2 g^{-1}}$)
- shock: equatorial+polar, higher entropy
  larger $\mathrm{Y_e}$ due to weak interactions, at high latitudes (lower opacities: $\sim 1\,\mathrm{cm^2 g^{-1}}$)



Bauswein+13



Korobkin+12

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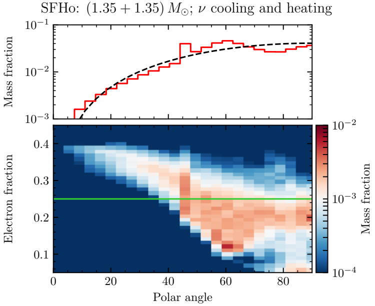
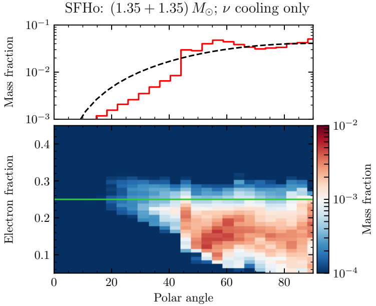


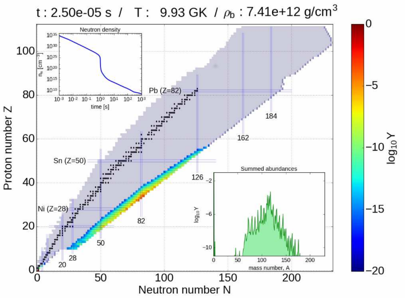


Perego, Radice, Bernuzzi 17, Radice+ in prep

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 and/or high entropy
  $\rightarrow t_{\mathrm{n-capture}} < t_{\beta}$ 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
- more than 5800 nuclei
- huge system of ODEs with stiff source terms
- outcomes: $Y_{(A,Z)}(t)$ 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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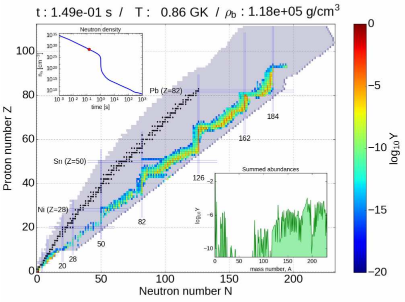

(n,γ)-(γ,n) equilibrium

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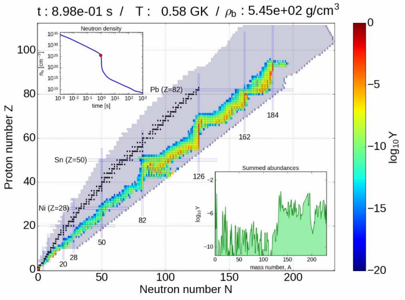

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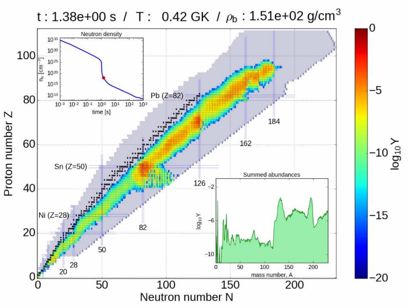

end of r-process: β-decays

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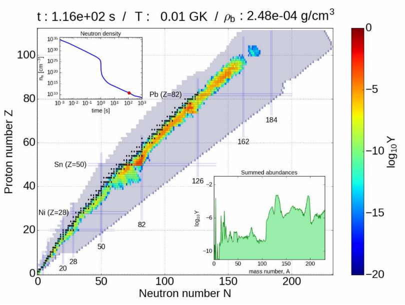

long term nuclear decays

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

r-process nucleosynthesis in BNS mergers

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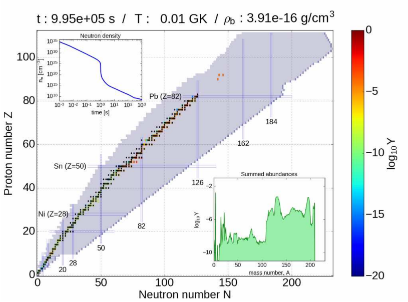

nuclei reach valley of stability

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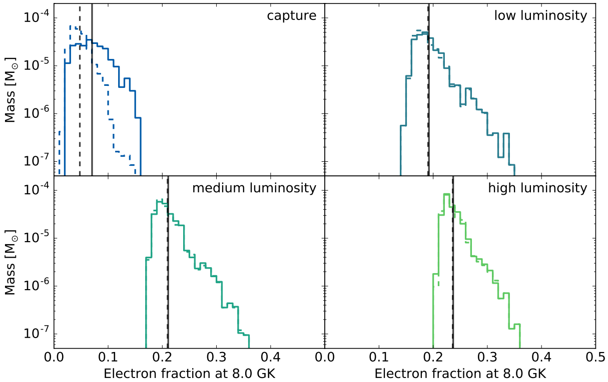
How robust are dynamic ejecta propeties?

Martin, Perego, Kastaun, Arcones 17, CQG; cf. Goriely+ 15, MNRAS

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



Martin+ 18, CQG

[isotropic ν emission with increasing intensity]

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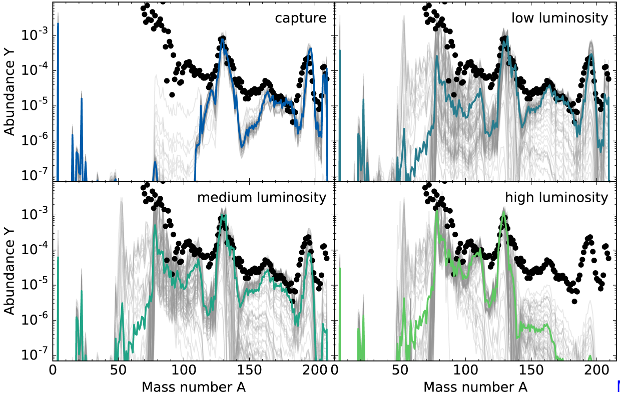
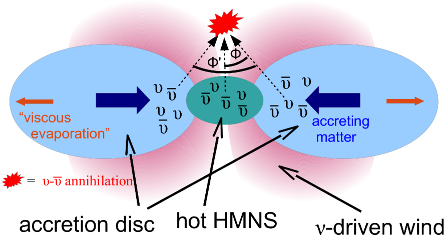


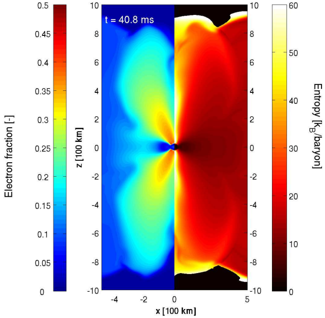
Martin+ 18, CQG

[isotropic ν emission with increasing intensity]

Wind ejecta from BNS merger

- due to neutrino absorption inside the disk
- $t_{\rm ej,wind}$ ~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+14, MNRAS; Martin,AP+ 15, ApJ

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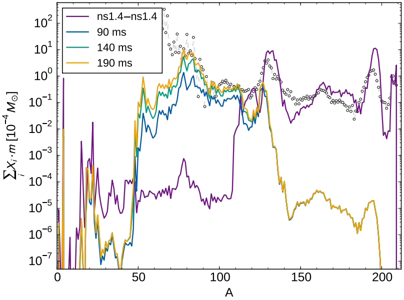
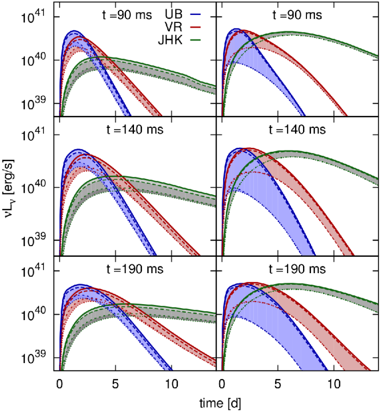


nucleosynthesis (dynamic + wind)

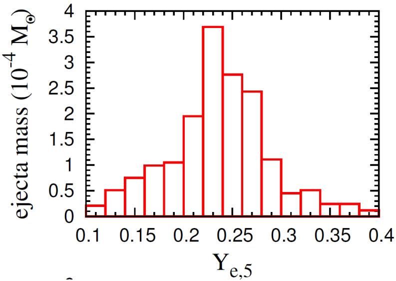


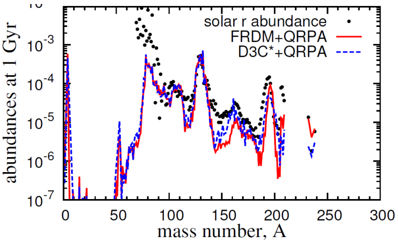
Martin, AP+ 15, ApJ

broadband light curves (L: wind, R: dynamic + wind)

Viscous (secular) ejecta from BNS merger

- due to viscosity and nuclear recombination in the disk
- $t_{\rm ej,sec} \sim$ few 100's ms and $v_{\rm ej,sec} \sim$ few $0.01c$
- broad distribution of n-rich matter $(0.1 \lesssim {\rm Y_e} \lesssim 0.4)$
- $M_{\rm ej,sec} \sim (0.2 - 0.4)\, M_{\rm disk}$
- all solid angle ejection, intermediate opacity $1 - 10\,{\rm cm^2 g^{-1}}$



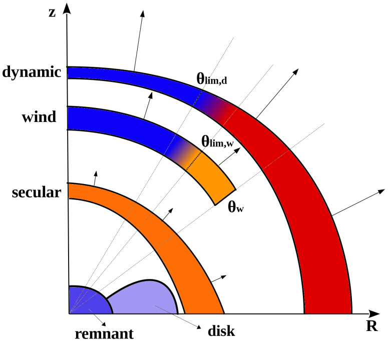


Wu+16, see e.g. Just+15,Lippuner+17, Siegel& Metzger 17

Anisotropic & multi-component MKN model

- Macro-kilonova model that includes our present knowledge about ejecta
- different ejection channels $\rightarrow$ multi-component
- explicit dependency on polar angle $\rightarrow$ 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

Kilonova model

see Grossman+ 14, Martin+ 15

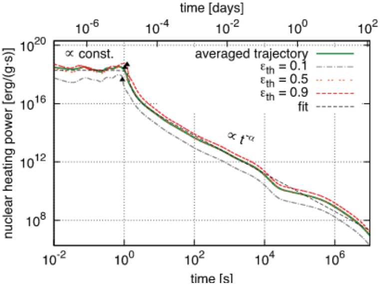
- homologous expansion (from long term simulations)

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

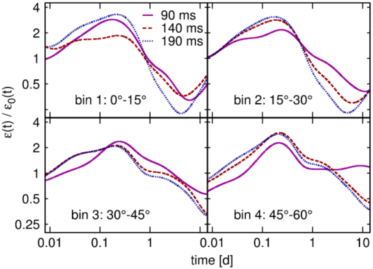
- nuclear heat (computed by nuclear network)

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

- 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

Interpretation of AT2017gfo

AT2017gfo, EM counterpart of GW170817

- light curve properties:
  - bright, UV/O component, with a peak @ $\sim 1\mathrm{day}$
  - rather bright, IR component, with a peak @ $\sim 4\mathrm{day}$
- possible interpretation: macro/kilonova (MKN) 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

MKN parameter exploration

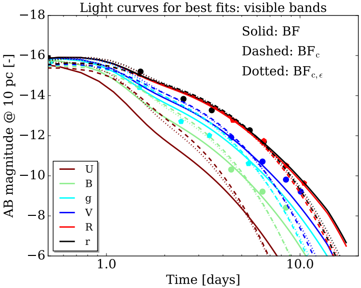
	Main parameter ranges
$M_{\rm disk}$ $[M_\odot]$	$\{0.01;\ 0.08;\ 0.1;\ 0.12;\ 0.15;\ 0.2\}$
$m_{\rm ej,dyn}$ $[10^{-2} M_\odot]$	$\{0.05;\ 0.5;\ 1.0;\ 2.0;\ 5.0\}$
$\xi_{\rm wind}$	$\{0.001;\ 0.05;\ 0.1;\ 0.15;\ 0.2\}$
$\xi_{\rm sec}$	$\{0.001;\ 0.1;\ 0.2;\ 0.3;\ 0.4\}$
$v_{\rm rms,dyn}$ $[c]$	$\{0.1;\ 0.13;\ 0.17;\ 0.2;\ 0.23\}$
$v_{\rm rms,wind}$ $[c]$	$\{0.033;\ 0.05;\ 0.067\}$
$v_{\rm rms,sec}$ $[c]$	$\{0.017;\ 0.027;\ 0.033;\ 0.04\}$
$\kappa_{\rm dyn}$ $[{\rm cm\,g^{-1}}]$	$\{(0.5, 30);\ (1, 30)\}$
$\kappa_{\rm wind}$ $[{\rm cm\,g^{-1}}]$	$\{(0.5, 5);\ (0.1, 1)\}$
$\kappa_{\rm sec}$ $[{\rm cm\,g^{-1}}]$	$\{1;\ 5;\ 10;\ 30\}$
$\theta_{\rm obs}$	$n\,\pi/36$ for $n = 0 \ldots 11$
$\epsilon_o[10^{18}{\rm erg\,g^{-1}\,s^{-1}}]$	$\{2;\ 6;\ 12;\ 16;\ 20\}$

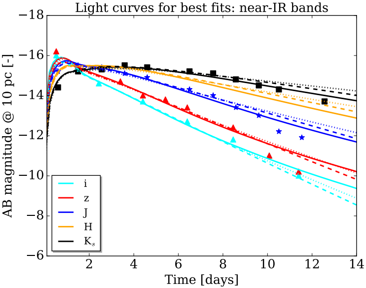
Our procedure:

- fix a parameter set
- produce a model (lightcurves in different filters)
- compare with observations

Pian, D'Avanzo +17, Tanvir+17

Best-fit models





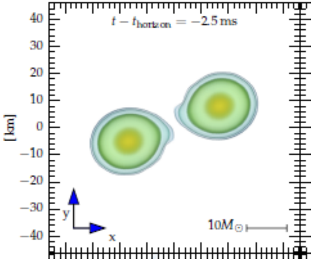
- 2 component (dyn+sec) model (BF)
  - low opacity secular ejecta (long-lived MNS?)
- 3 component (dyn+wind+sec) model (BF_c)
  - low opacity wind, medium opacity secular
- global properties for AT2017gfo
  - anisotropic and multicomponent ejecta
  - $M_{\rm ej,tot} \sim 0.05 M_\odot$, $\theta_{\rm obs} \approx 30^o$, $M_{\rm disk} \sim 0.1 M_\odot$
  - low-opacity material at high latitude! neutrinos @ work!

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

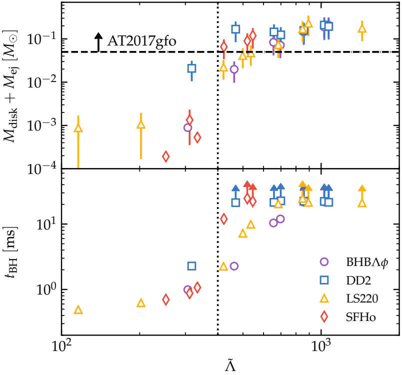
$$\tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\Lambda_2^{(A)}}{(M_A+M_B)^5} + (A \leftrightarrow B)\right] = \tilde{\Lambda}(\mathrm{EOS}, \mathcal{M}_{\mathrm{chirp}}, q)$$

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

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



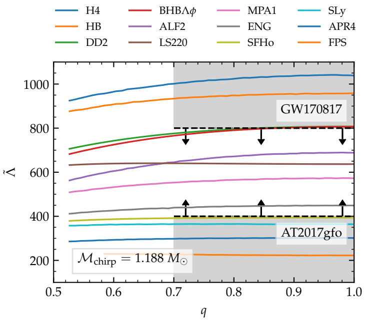
Radice, Perego, Zappa 2017

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

$M_{\rm ej,tot} \gtrsim 0.05 M_\odot$ 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

Summary and outlook

- weak reactions and neutrinos play a central role in BNS mergers, matter ejection and kilonova modelling
- multi-component, anisotropic MKN model for AT2017gfo, including influence of weak reactions
- genuine multi-messenger constraints on nuclear EOS from GW and EM counterpart

Outlook:

- detailed inclusion of ν's in BNS mergers
- accurate KN models
- jointed GW and KN analysis