Binary neutron star mergers: connecting strong field dynamics with multimessenger observations

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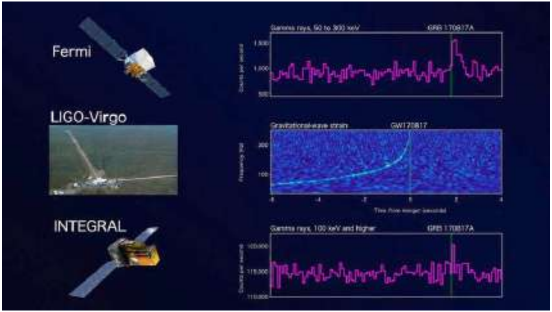
GW170817: first MM detection from a BNS merger



- GWs from an event compatible with BNS merger reported by LVC

  LVC PRL 119 2017

- ∼1.7 seconds after, γ-ray signal compatible with short GRB

  LVC, Fermi, Integral ApJ 848 L13 2017

- 11 hrs after, kilonova emission from NGC 4993 (40 Mpc): AT2017gfo

  e.g., LVC+ many other astronomy and astroparticle collaborations ApJ 848 L2 2017

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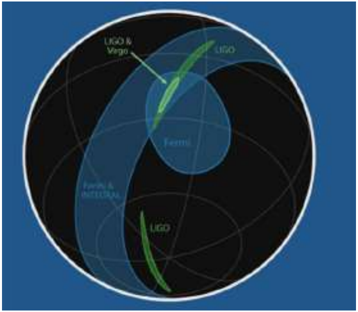

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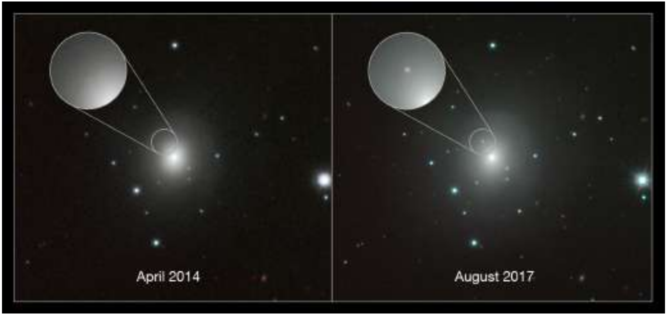

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Challenges in BNS merger modelling

- relevance:
  - BNS mergers as cosmic laboratory for fundamental physics
  - prototype of MM astrophysics sources
- challenge: quantitative statements require sophisticated numerical models

multi-physics

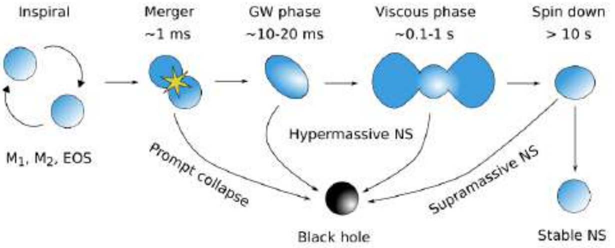
- GR
- strong nuclear interaction
- weak nuclear interactions
- magnetic fields & EM interactions

multi-scale

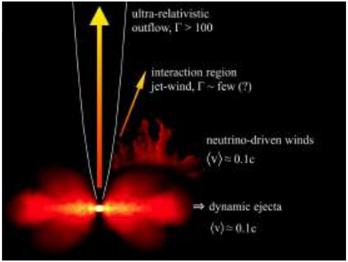
- strong field dynamics
  - small-size (100 km)
  - short timescale (1 ms – 1 s)
- EM counterpart emission
  - large-scale (10^6 km – 10^{12} km)
  - long timescale (1 s – 10 days)

different scales and different interactions are intimately related

BNS merger in a nutshell



Credit: D. Radice; see Rosswog IJMP 2015 for a recent review



- Massive NS (→ BH)
  $\rho \gtrsim 10^{12} \mathrm{g\,cm^{-3}}$, $T \sim$ a few 10 MeV
- thick accretion disk
  $M \sim 10^{-2} - 0.2 M_{\odot}$, $\mathrm{Y_e} \lesssim 0.20$
  $T \sim$ a few MeV
- intense ν emission
  $L_{\nu,\mathrm{tot}} \sim 10^{53} \mathrm{erg\,s^{-1}}$, $E_\nu \gtrsim 10\,\mathrm{MeV}$

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

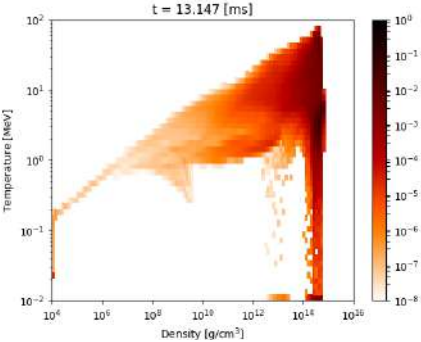
BNS mergers on thermodynamics diagrams

Which are the thermodynamics conditions of matter during the merger?

Perego,Bernuzzi,Radice 2019 arXiv:1903.07898

- set of BNS merger simulations in NR: different NS masses and microphysical EOSs (DD2, LS220, SFHo)
- ν-physics: leakage scheme (optically thick) + M0 transport (opt. thin)
- possibly, turbulent viscosity (GRLES)

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



WhiskyTHC NR code

Radice+ 12,14,15

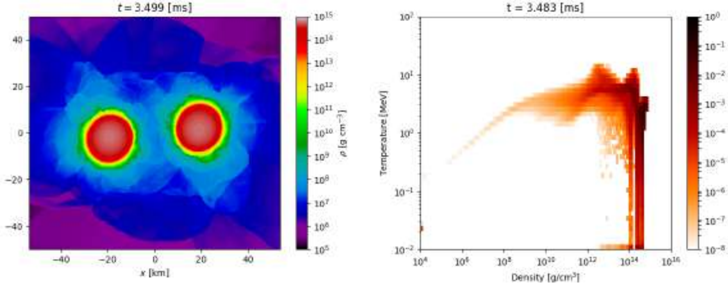
$M_1 = M_2 = 1.364\ M_\odot$

DD2 EOS

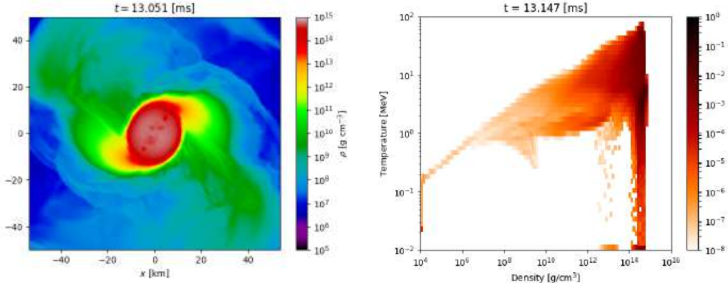
movies at
www.youtube.com/channel/
UChmn-JGNa9mfY5H5938jnig

BNS mergers on thermodynamics diagrams II

inspiral



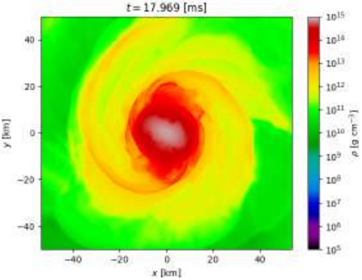
$t(T_{\rm peak})$

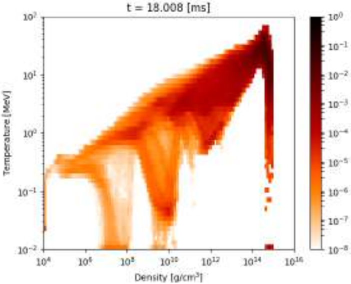


Perego,Bernuzzi,Radice 2019 arXiv:1903.07898

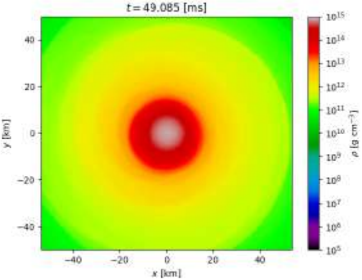
BNS mergers on thermodynamics diagrams III

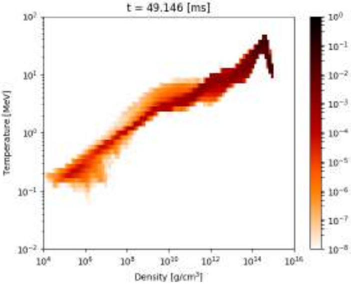
$t \gtrsim t_{\rm dyn}$





$t \gg t_{\rm dyn}$





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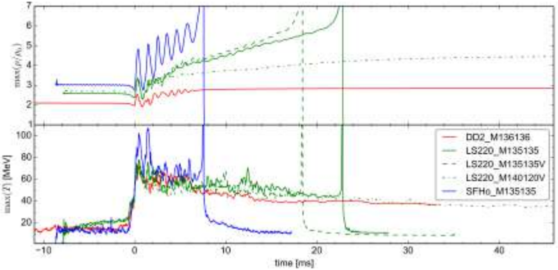
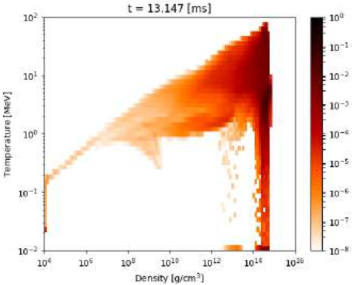
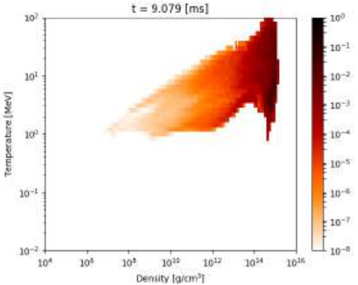
Thermodynamics diagrams: soft VS stiff EOS



DD2 (stiff), $M_1 = M_2 = 1.364 M_\odot$ SFHo (soft),, $M_1 = M_2 = 1.35 M_\odot$

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





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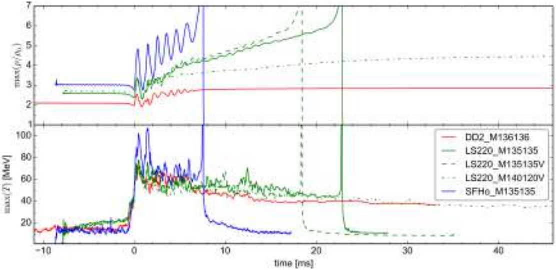
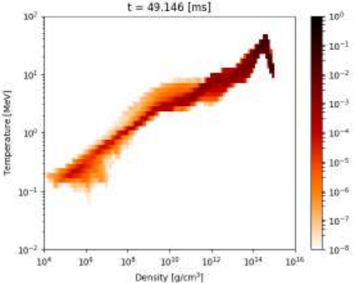
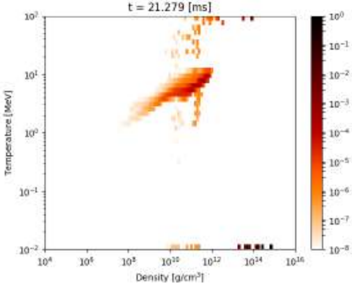


DD2 EOS (stiff)

SFHo EOS (soft)

$t \gg t_{\rm dyn}$

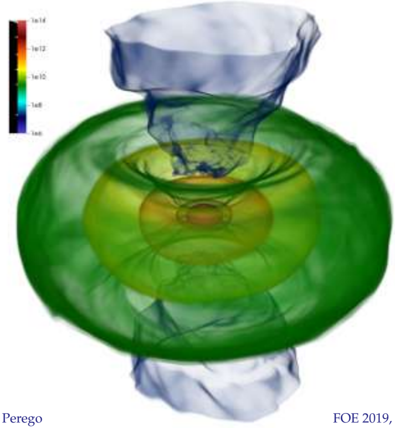




Disk properties: BH vs MNS remnant

Disk harboring a MNS are …

- …less compact
- …less entropic ($\Delta s \approx 2\, k_{\mathrm{B}}$)
- …more neutron rich



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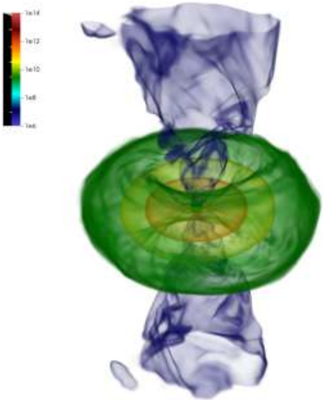

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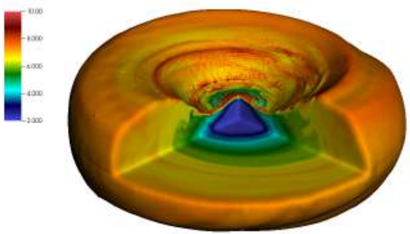
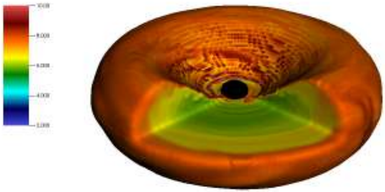


Disk harboring a BH are …

- …more compact
- …more entropic ($\Delta s \approx 2\,k_{\mathrm{B}}$)
- …less neutron rich



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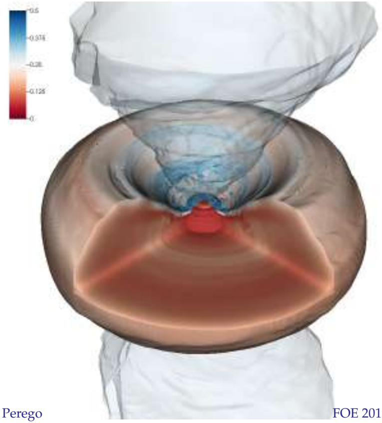
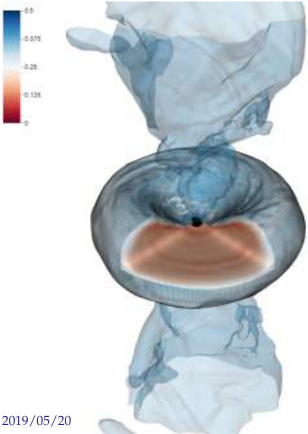
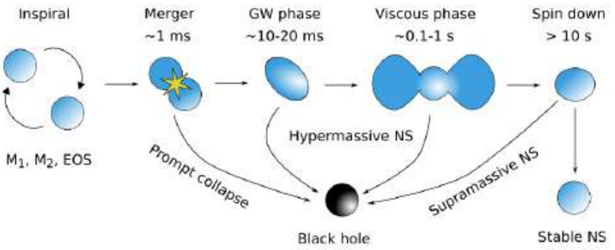
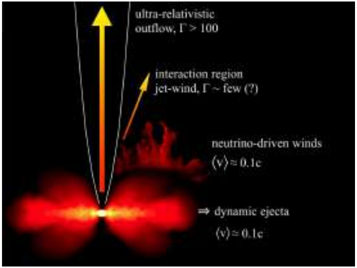




BNS merger in a nutshell (II)



Credit: D. Radice



Rosswog 2015

- ejection of *n*-rich matter
  - a few % of $M_{\rm tot}$
  - different ejection mechanisms
  - *r*-process nucleosynthesis

$$E_{\rm kin} \approx 1.35 \times 10^{51} {\rm erg} \left(\frac{M_{\rm ej}}{0.05 M_{\odot}} \right) \left(\frac{v_{\rm ej}}{0.1\ c} \right)^2$$

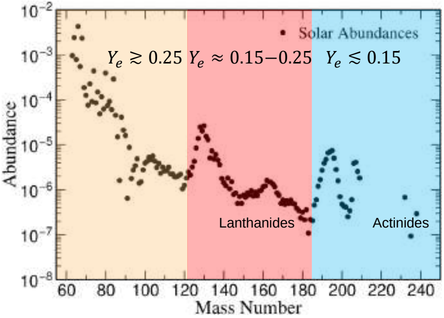
e.g. Lattimer & Schramm ApjL 73, for a recent review: Thielemann+ ARAA 17

r-process nucleosynthesis: yields

at low entropy ($s \lesssim 30 k_b$/baryon), Y_e dominant parameter

e.g., Hoffman+ ApJ 98

- $Y_e > 0.5$: no *r*-process
- $0.25 \lesssim Y_e < 0.5$: weak *r*-process
- $Y_e \lesssim 0.25$: strong *r*-process



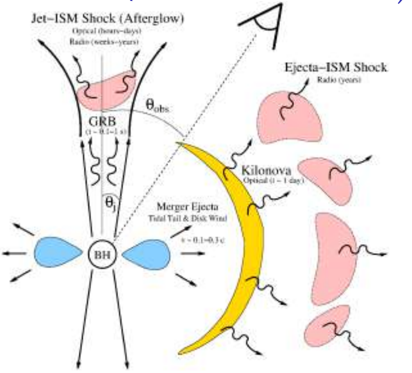
Courtesy of G. Martinez-Pinedo

Production of lanthanides dramatically changes photon opacity

- no lanthanides: low opacity ($\kappa_\gamma \lesssim 1\,\mathrm{cm}^2/\mathrm{g}$)
- presence of lanthanides: increased opacity ($\kappa_\gamma \gtrsim 10\,\mathrm{cm}^2/\mathrm{g}$)

κ_γ: effective gray opacity

Kilonova (aka Macronova) emission



e.g., Li & Paczenski 98, Rosswog+ 05, Metzger+ 10, see Fernandez & Metzger 2016, Metzger LRR 2017 for recent reviews

- radioactive decay of freshly sinthetized *r*-process elements in ejecta: release of nuclear energy
- photon thermalization & diffusion
- emission of photons at photosphere
- non-trivial, energy-dependent photon-matter interaction in atmosphere

What does influence kilonova emission?
In other words, how different can kilonovae be?

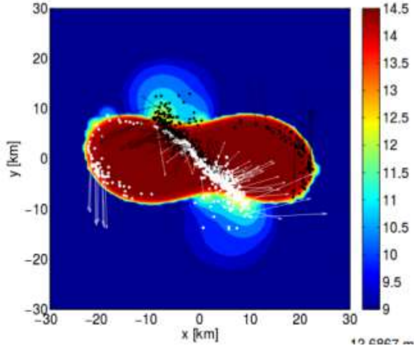
- m_{ej}
- v_{ej}
- k_{ej} → nucleosynthesis → Y_e

⇒ numerical models for matter ejection & including weak interactions

Dynamical ejecta from BNS merger

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

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



Bauswein+13

- tidal component
  - first to develop
  - equatorial
  - cooler (lower entropy)
- shocked component
  - due to (H)MNS bounces
  - equatorial & polar
  - higher entropy

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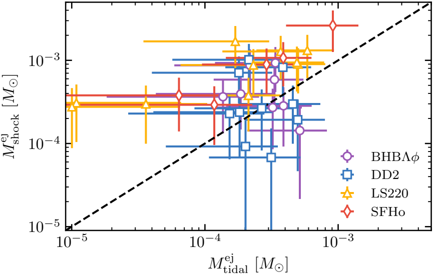

Radice, Perego, Hotokezaka *et al* ApJ 2018

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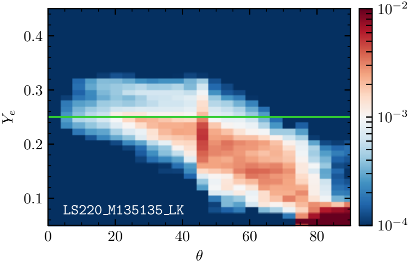
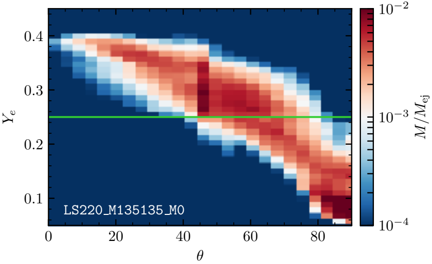
Impact of ν absorption on dynamical ejecta

- in the past, ν-matter interactions assumed to be negligile:
  - ejecta had always and everywhere $Y_e < 0.1$
  - robust *r*-process
- however, ν-matter interactions increase Y_e at polar latitudes
  - most relevant reaction: $n + \nu_e \rightarrow p + e^-$
  - possible angular dependence in *r*-process nucleosynthesis

w/o neutrino absorption



w neutrino absorption

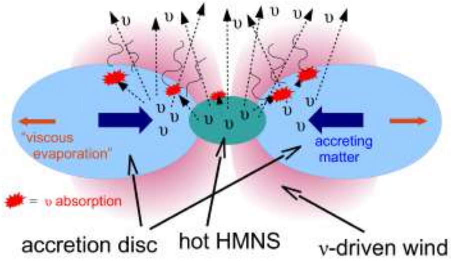


Perego, Radice, Bernuzzi ApJL 17; Radice, Perego, Hotokezaka *et al* ApJ 2018

see also e.g. Wanajo+ ApJL 2014' Sekiguchi+ PRD 2015; Martin, Perego, Kastaun & Arcones CQG 2018, Ardevol-Pulpillo *et al* 2019

Baryonic winds from BNS merger

- due to secular and thermal evolution of the remnant and of the disk
- $t_{\rm ej,wind}$ ~few 10's-100's ms and $v_{\rm ej,wind} \lesssim 0.1\,c$
- $M_{\rm ej,wind}$ up to a few 0.01 $M_\odot$



- neutrino absorption
- turbulent angular momentum transport
- nuclear recombination

- several works for BH+disk systems e.g. Metzger&Fernandez 13 MNRAS, Just+15 MNRAS, Fernandez+17, CQG, Siegel+ 2018, Fernandez+ 19
- several works for BNS remnants e.g. Fernandez&Metzger 14 MNRAS, Perego+14 MNRAS, Martin+15 ApJ, Lippuner+ 16 MNRAS, Fujibayashi+ 17,18 ApJ, Shibata+17 PRD, Radice+18 ApJ, Perego+18 JPhg, Fahlman & Fernandez 18 …

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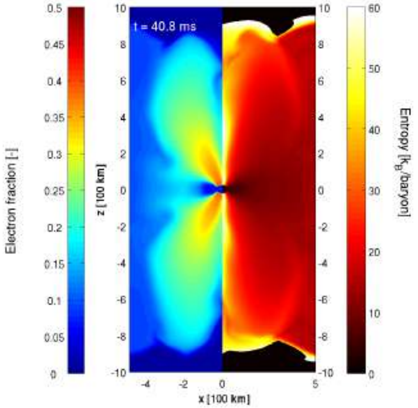
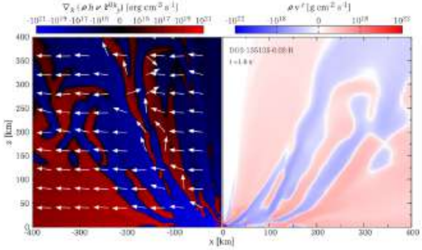


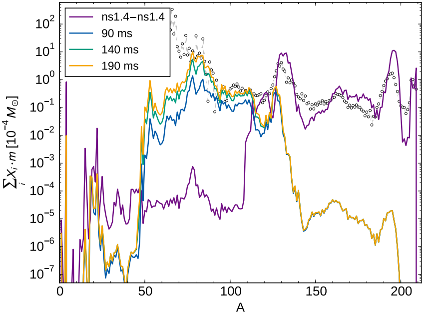


Fujibayashi+18, ApJ

Perego+14, MNRAS

Ejecta properties and kilonovae

- electron fraction
  - polar regions: $\mathrm{Y_e} \gtrsim 0.25$
  - equatorial regions: $\mathrm{Y_e} < 0.25$
- nucleosynthesis
  - polar regions
    - I *r*-process peak
    - $\kappa_\gamma \lesssim 1 \mathrm{cm}^2 \mathrm{g}^{-1}$
  - equatorial regions
    - II-III *r*-process peaks
    - $\kappa_\gamma \gtrsim 10 \mathrm{cm}^2 \mathrm{g}^{-1}$
- EM counterparts
  kilonova: early blue + later red



Nucleosynthesis from dynamical ejecta & wind

Perego, Rosswog, Cabezon *et al* MNRAS 2014; Martin,Perego, Arcones *et al* ApJ 15

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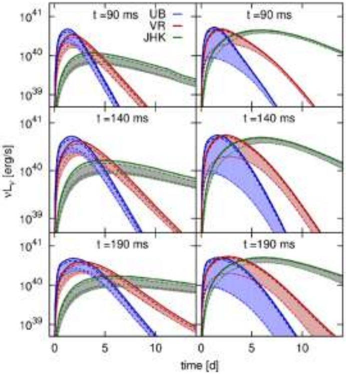


Broadband light curves from wind only (left)

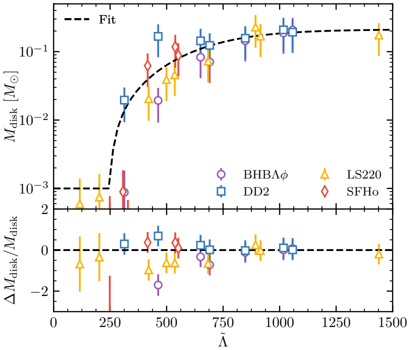
and from wind+dynamical ejecta (right)

Perego, Rosswog, Cabezon *et al* MNRAS 2014; Martin,Perego, Arcones *et al* ApJ 15

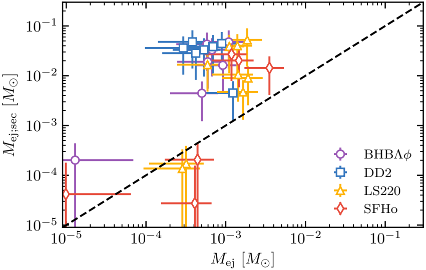
Disk masses and baryonic winds

- independent works suggest that

$$M_{\rm ej,wind} = \xi\, M_{\rm disk} \quad \text{with} \quad 0.1 \lesssim \xi \lesssim 0.4$$



$$\frac{M_{\rm disk}}{M_\odot} \approx 0.084 + 0.13\ \tanh\left(\frac{\tilde\Lambda - 567}{405}\right)$$



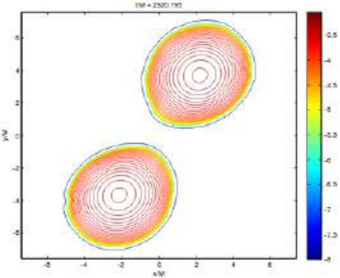
Radice,Perego,Hotokezaka et al ApJ 2018

- here, $M_{\rm ej,wind} = 0.2\, M_{\rm disk}$
- $\rightarrow$ mostly, $M_{\rm ej,wind} > M_{\rm ej,dyn}$

see also, e.g., Just+ MNRAS 2015, Wu+ MNRAS 2016

Tidal deformation during the inspiral phase

NS in external, inhomegeneous gravitational field ⇒ tidal deformation



Bernuzzi et al PRD 2012

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

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

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

- tidal deformation enhances GW emission
- $\geq 5^{th}$ PN order correction to point particle dynamics
- leading term $\propto \tilde{\Lambda}(M_A, M_B, \mathrm{EOS})$

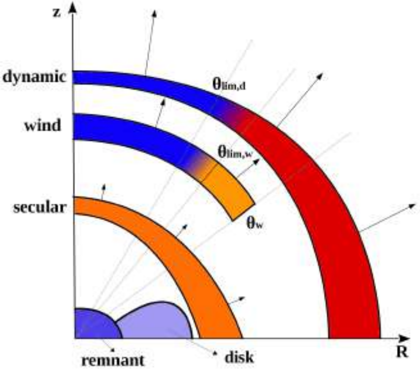
$$\tilde{\Lambda} = \frac{16}{13} \left[\frac{(M_A + 12 M_B) M_A^4 \Lambda_2^{(A)}}{(M_A + M_B)^5} + (A \leftrightarrow B) \right] ; \ \Lambda_2^{(i)} = \left(\frac{c^2}{M_i} \right)^5 \lambda_{(i)} ; \quad i = A, B$$

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

Multi-Component Anisotropic Kilonova Model

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

Perego, Radice, Bernuzzi 17, ApjL



- $M_{\rm ej}(\theta)$, $v_{\rm ej}(\theta)$, $\kappa_{\rm ej}(\theta)$
- 1D models along each ray
- homologous mass expansion
- time scale argument for γ-diffusion
- black-body emission at photosphere Grossman+14 MNRAS; Martin+15 ApJ

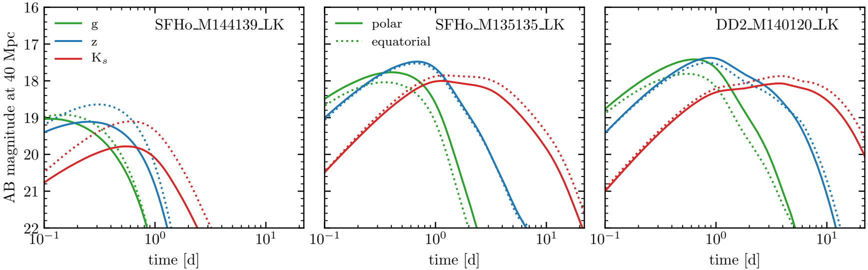
Representative kilonova emission

- light curves in relevant photometric bands (UV, Optical, NIR) for a broad set of BNS
- dynamical ejecta directly extracted from simulations
- wind and viscous ejecta: fraction of the disk mass (0.03 and 0.20, respectively) with properties obtained from AT2017gfo best-fit model

prompt BH
small $\tilde{\Lambda}$

short-lived MNS
intermediate $\tilde{\Lambda}$

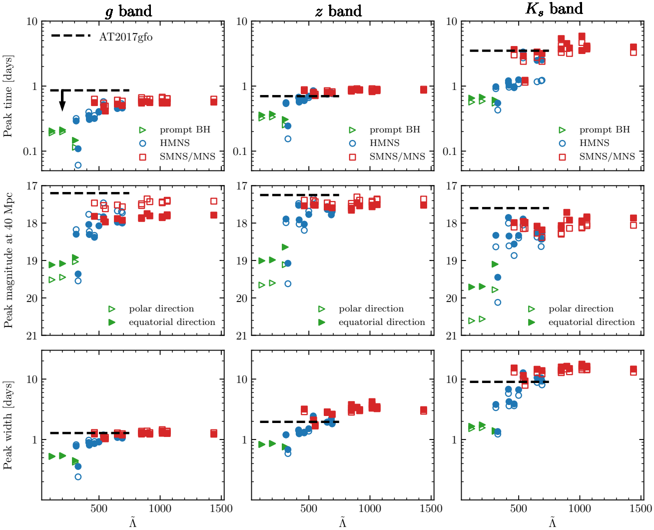
long-lived MNS
large $\tilde{\Lambda}$



Radice,Perego,Hotokezaka *et al* 2018 ApJ

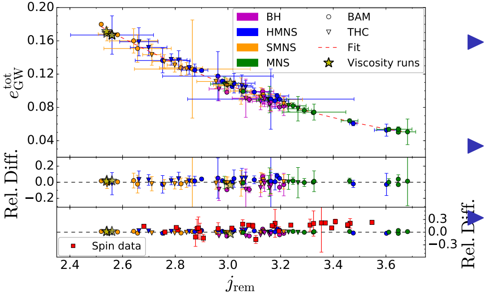
Systematics of kilonova peaks

Peak time, magnitude and time width ($\Delta M = 1\,\mathrm{mag}$) VS $\tilde{\Lambda}$



Radice,Perego,Hotokezaka *et al* 2018 ApJ

Super-Keplerian Long-Lived Remnant

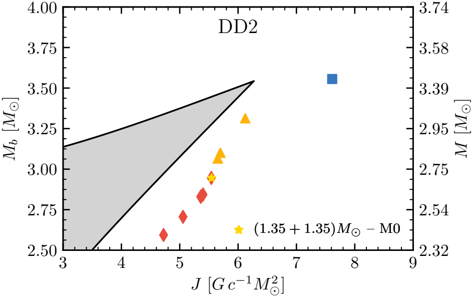


- quantitative merger prediction require Numerical Relativity (NR) simulations
- NR BNS database

CoRe collaboration, Dietrich+ 2018 CQGL

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

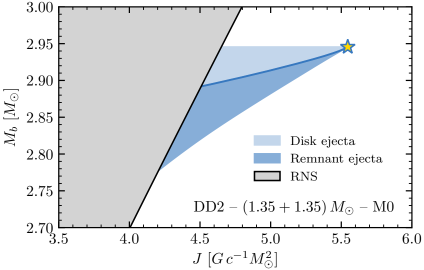
Zappa+ PRL 2018



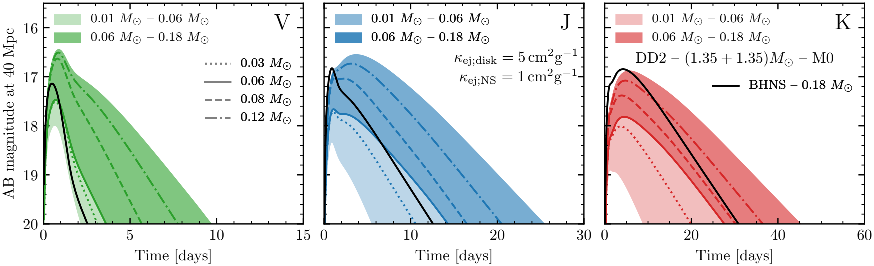
- (S)MNS are super-Keplerian
- robust and EOS independent feature

Radice,Perego,Bernuzzi, Zhang 2018 MNRAS

Possible Signatures of long-lived Remnant



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

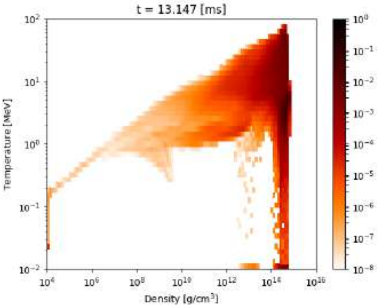


bright visible and IR peak: possible signature of stable MNS

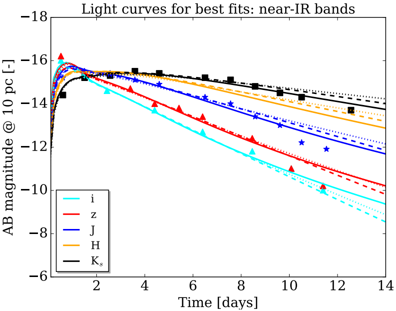
Radice,Perego,Bernuzzi, Zhang 2018 MNRAS

Conclusions

- BNS modelling: fundamental to make the most of MM astrophysics
- BNS merger as sites where matter reaches most extreme density and temperature conditions
- relevance of weak interaction, especially for ejecta properties and nucleosynthesis
- kilonovae: possibly large intrinsic variability and $\tilde{\Lambda}$-correlation



Perego,Bernuzzi,Radice arXiv:1903.07898



Perego,Radice,Bernuzzi ApjL 2017

INFN Post-Job position at ECT*

- INFN post-doc position at the European Center for Theoretical Studies in Nuclear Physics and Related Areas (ECT*)
- topic: Multimessenger Physics of Neutron Star Mergers
- duration: 2(+1) years
- position advertised in ∼ weeks
- start: ≥ fall 2019
- where: (beautiful) Trento
- infos: albino.perego@unitn.it or Prof. Wambach: jwambach@ectstar.eu

ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

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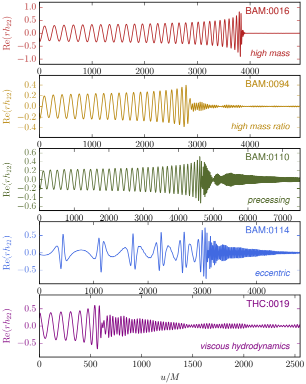
Observables from BNS: GW waveforms

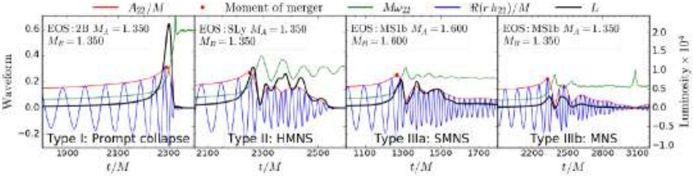
`CoRe` collaboration: catalogue of 367 merger simulations in NR from 164 BNS configurations

`www.computational-relativity.org`

- largest waveform catalogue
- inclusion in NR-calibrated EOB models
- (long) hybrid GW waveforms models & GW analysis pipelines



Dietrich+ 2018 CQG Letter



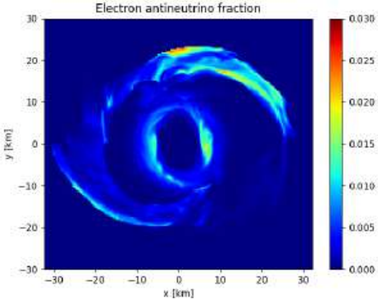
Zappa, Bernuzzi, Radice, Perego, Dietrich PRL 2018

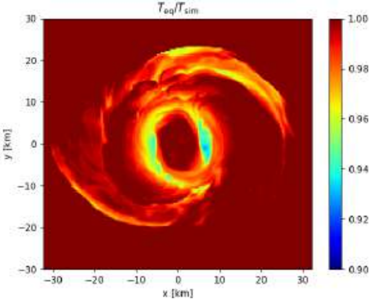
Influence of trapped neutrinos

- BNS simulations did not include trapped neutrinos
- post processing analysis: $Y_e \to Y_l = Y_e + Y_\nu \quad e \to u = e + e_\nu$

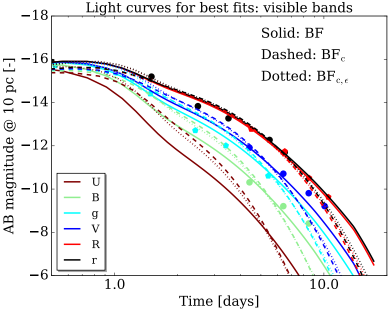
$$\begin{aligned} Y_l &= Y_{e,\mathrm{eq}} + Y_{\nu_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) - Y_{\bar{\nu}_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) \\ u &= \quad e(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \frac{\rho}{m_b}\left[Z_{\nu_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \right. \\ &\qquad \left. + Z_{\bar{\nu}_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + 4 Z_{\nu_x}(T_{\mathrm{eq}})\right] \\ 0 &= \quad \eta_{\nu_e}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) - \eta_e(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \\ &\qquad -\eta_{\mathrm{p}}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) + \eta_{\mathrm{n}}(Y_{e,\mathrm{eq}}, T_{\mathrm{eq}}) . \end{aligned}$$

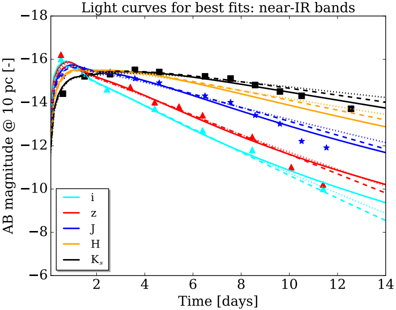
- baryon degeneracy favors $\bar{\nu}_e$ over ν_e, but overall small effect
- $\delta T/T \lesssim 8\%$, $\delta P/P \lesssim 5\%$





Application to AT2017gfo: model calibration


Light curves for best fits: visible bands


Light curves for best fits: near-IR bands

- multi-components (2 or 3) models reproduce major observed features of AT2017gfo
- fast ($v \sim 0.3c$), low opacity ($\kappa \sim 1\,\mathrm{cm}^2\mathrm{g}^{-1}$) material essential
- global properties for AT2017gfo
  - anisotropic and multicomponent ejecta
  - $M_{\mathrm{ej,tot}} \sim 0.05 M_\odot$, $\theta_{\mathrm{obs}} \approx 30^o$, $M_{\mathrm{disk}} \sim 0.1 M_\odot$
  - low-opacity material at high latitude: neutrinos @ work

on multi-component kilonova nature and on relevance of multi-D see e.g. Villar+17, Shibata+17, Kasen+17, Smartt+17, Tanvir+17, Pian, D'Avanzo+ 17, Tanaka+17 etc.