Numerical Relativity informed kilonova models

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In collaboration with
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Outline

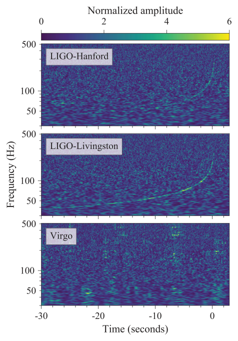
- GW170717 – GRB 170817 – AT2017gfo
- Kilonova (observations and models)
- Binary Neutron Star merger dynamics
- Ejecta mechanisms
- Examples
- Conclusion

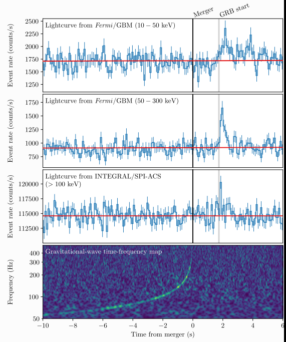
GW170717 – GRB 170817 – AT2017gfo

17th August 2017: GW detection from elliptical galaxy NGC 4993.

GW signal 100 seconds.

GRB170817A of ≈ 2 seconds duration





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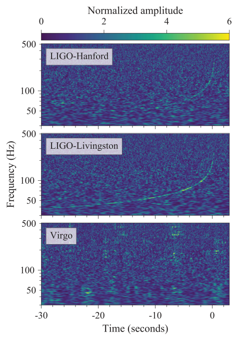

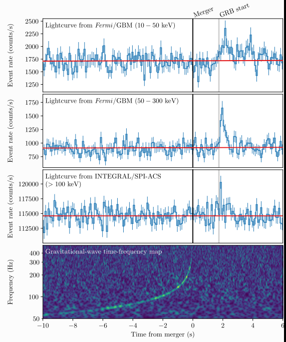

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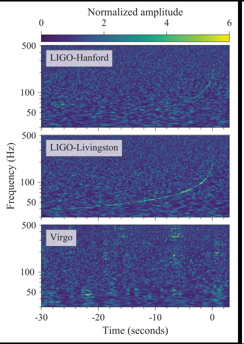

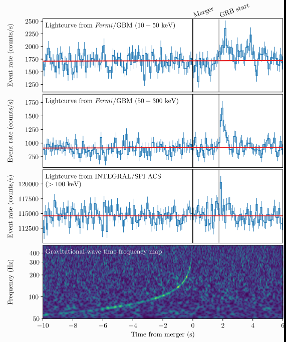

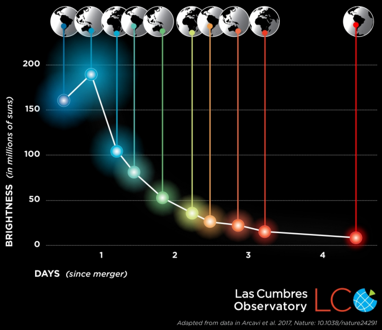

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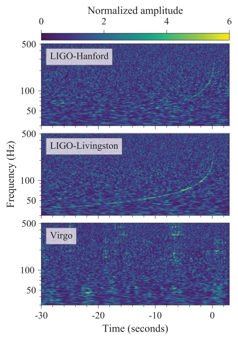
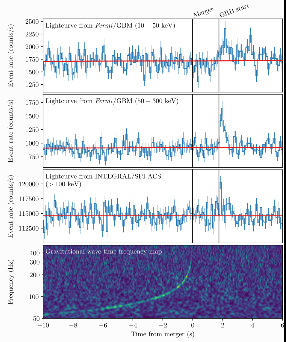
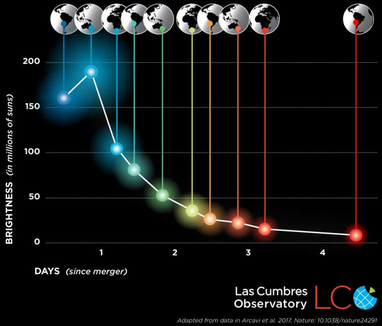
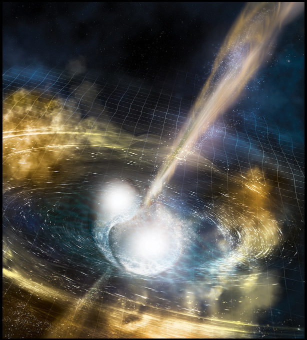
Kilonova







Kilonova - EM counterpart to the merger, powered by the radioactive decay of newly-produced heavy nuclei.



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- Blue component: early, low photon opacity
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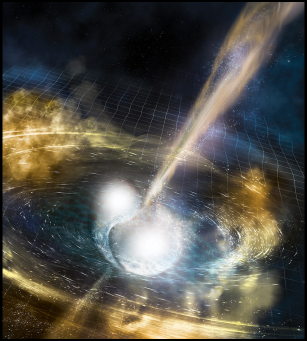

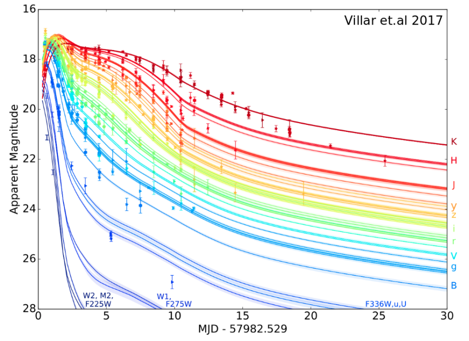

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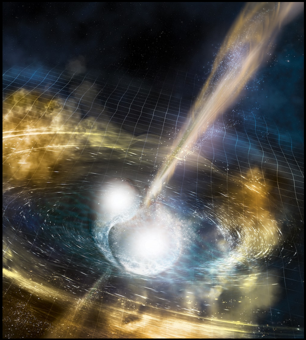
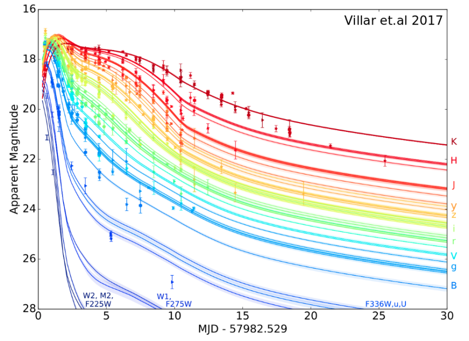
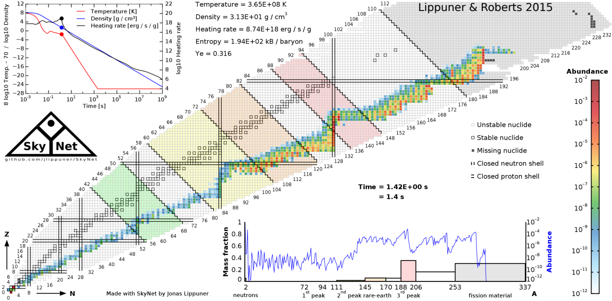
r-process nucleosynthesis (source of the heaviest elements)
Chemical Evolution of the Universe







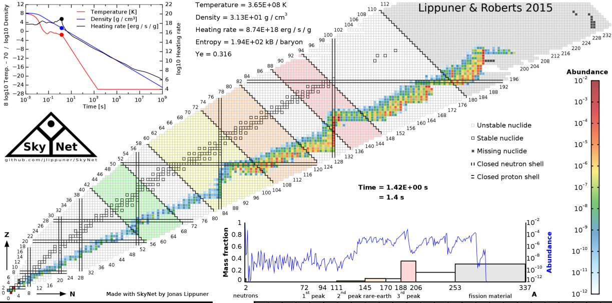
$r-$**process nucleosynthesis**

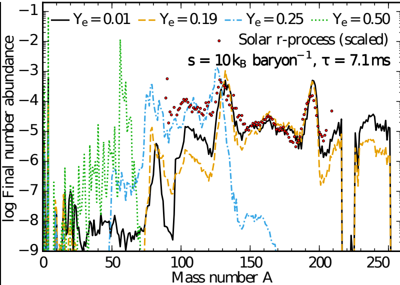
Formation elements heavier than iron

Requarements: $T > 10^9$K $n_n > 10^{22}$ cm^{-3}

Produces: unstable n-rich nuclei

Radioactive decay can power an EM transient





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Fission and Opacities

$r-$prcess forms Lanthanides & Actinides

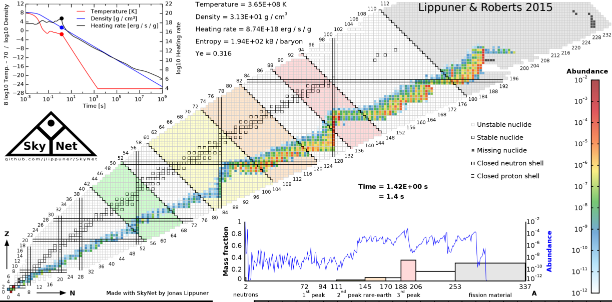
Complex atomic structure. High opacities $\propto 10$ & $\propto 30$ cm^{2}g^{-1}

Ejecta Composition

Electron Fraction

$$Y_e = \frac{n_{e^-} - n_{e^+}}{n_b}$$

$$Y_e = \frac{1}{(1+N_n/N_p)}$$



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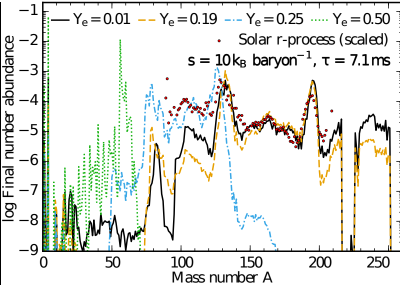

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$Y_e > 0.25$ - Low κ - Blue

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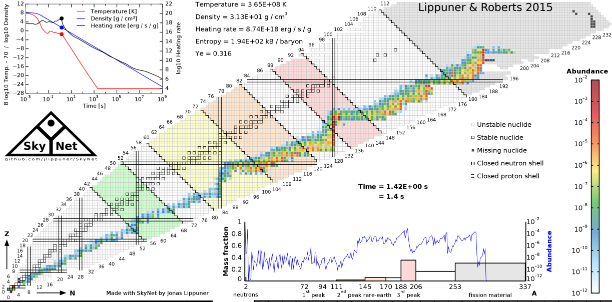

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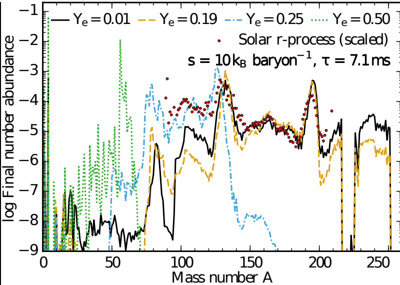

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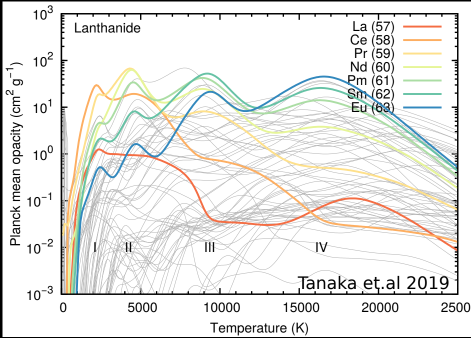

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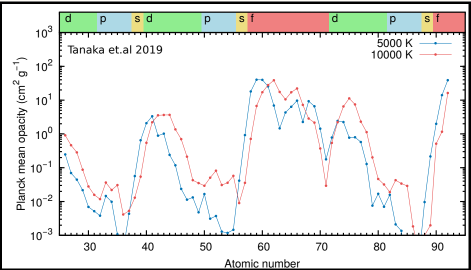

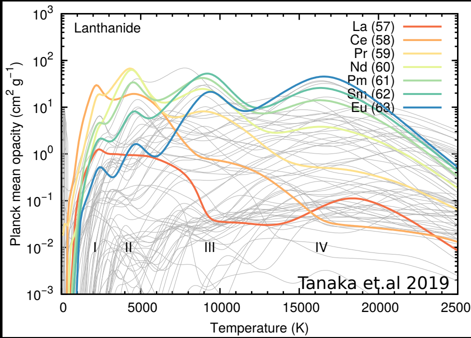

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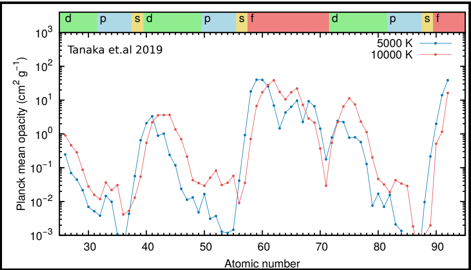
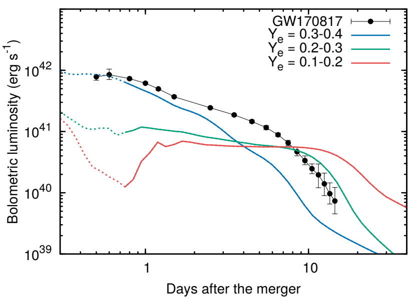
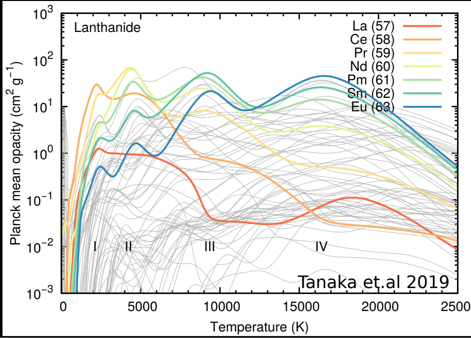
Kilonova
Monte-Carlo radiative transfer code
simple one-dimensional ejecta model,
power-law density structure $\rho \propto r^{-3}$,
$< v > \propto 0.1$c, $M_{\mathrm{ej}} = 0.03 M_{\odot}$







Kilonova models

Radiative transfer simulations $\rightarrow$ Spectra (detailed composition).

Semi-analitic models $\rightarrow$ bolometric lightcurves (energy evolution & the amount of radioactive nuclides produced)

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Axisymmetric ejecta components, Polar angle split into bins with radial model for each ejecta component of Grossman et al. (2014).

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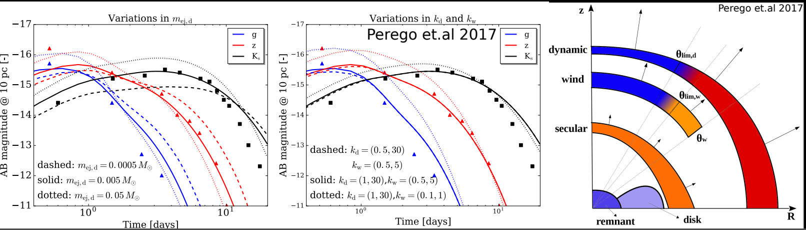
$m^i_{\rm ej}(\theta)$, $v^i_{\rm rms}(\theta)$, $\kappa^i_{rmej}(\theta)$



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$2-3$ components (Blue and Red)

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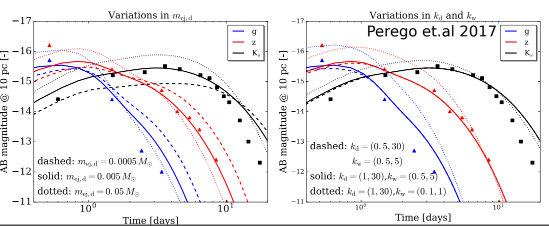

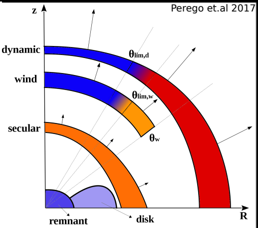

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Merger simulations...

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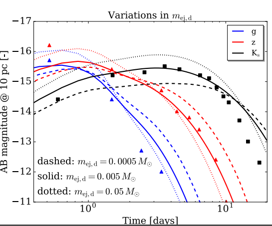
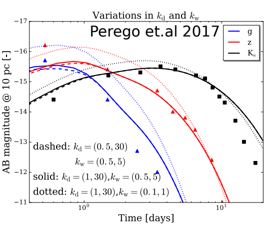
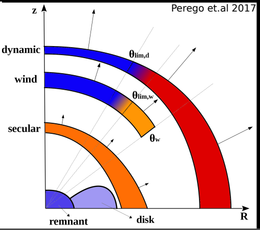
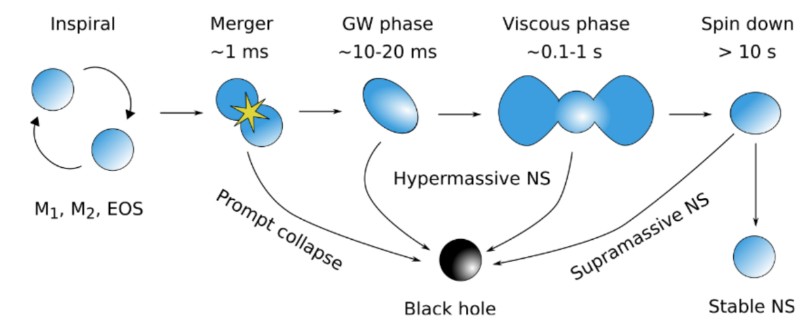


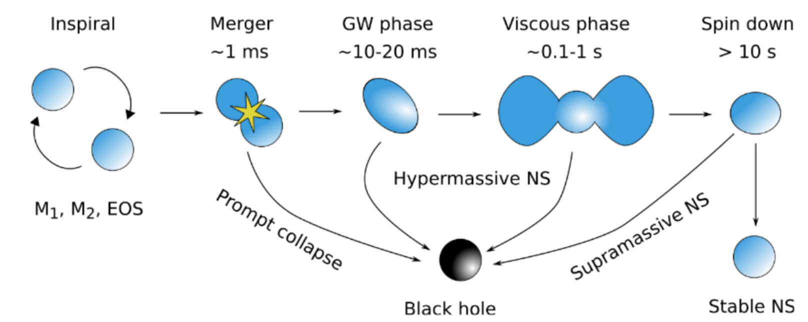




Binary Neutron Star merger dynamics



courtesy of David Radice



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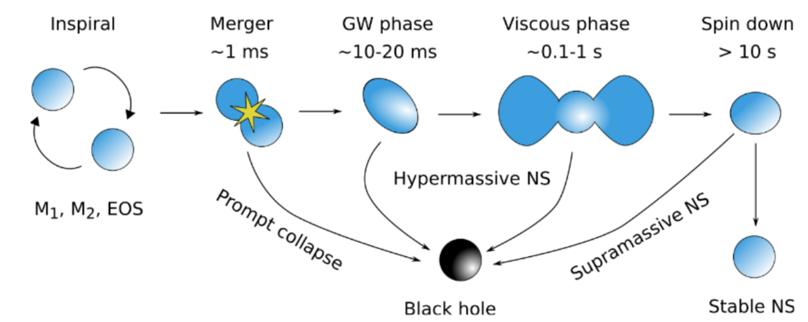
Geodesic Criterion

$u_t \leq -1$

(u_t is the covariant time component of the fluid element 4-velocity)

Simplicity (Nuetonian$\rightarrow v_\infty > 0$)

Independent of EOS.



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Bernoulli criterion

$hu_t \leq -1$,

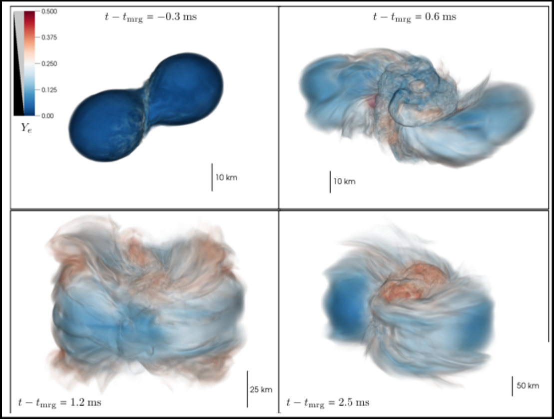
(h - enthalpy)

thermal energy of the fluid is transformed into kinetic one.

Dynamical Ejecta

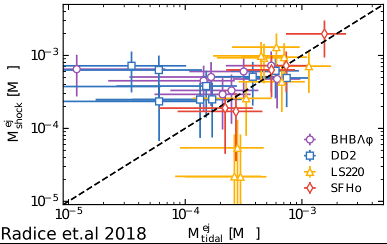
Components

- Tidal : Orbital plane, Low Y_e
- Shocked : Polar, High Y_e



Dynamical ejecta average properites

$M_{\rm rj} \propto 10^{-3}$, $v_\infty \propto 0.2$, $Y_e \propto 0.2$



Radice et.al 2018

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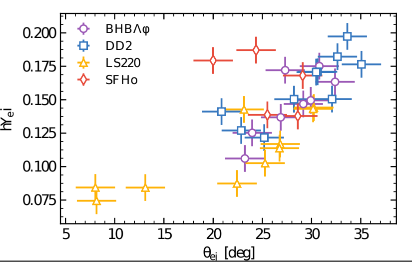

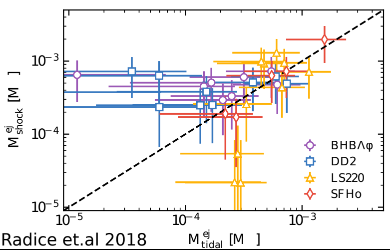

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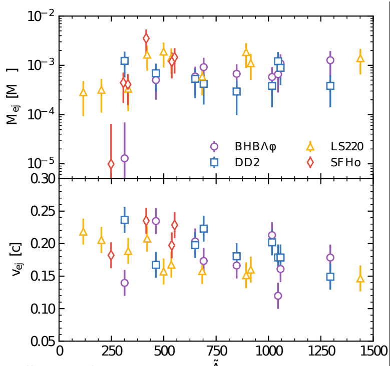

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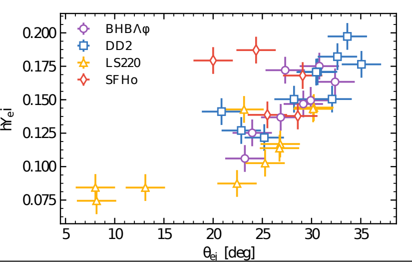

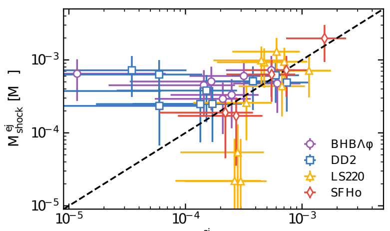

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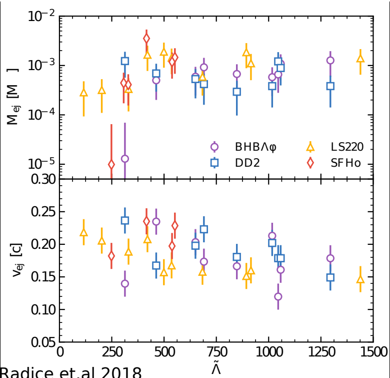
For kilonova:

$Y_e \propto 0.2 \rightarrow$ Red component

$M_{\mathrm{ej}} <$ needed.



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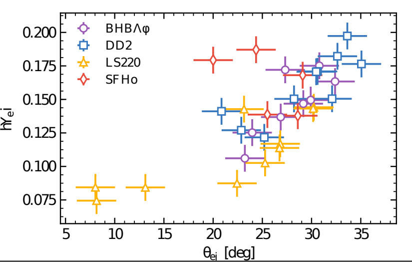

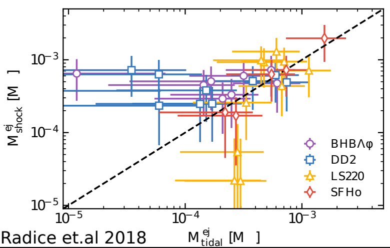

Radice et.al 2018

Secular Ejecta

- Remnant is born with excess in angular momentum and mass.
- Disk colling & heating via outflows.
- Neutrino cooling,
- neutrino re-absorption [Perego+2014].
- Magnetic stresses & turbulence [Siegel+2014].
- Nuclear recombination energy unbind matter & $r-$process heating [Fernandez&Metzger 2013.

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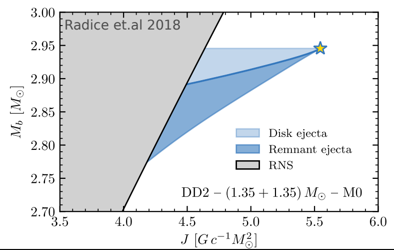

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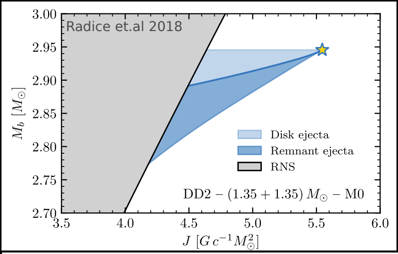

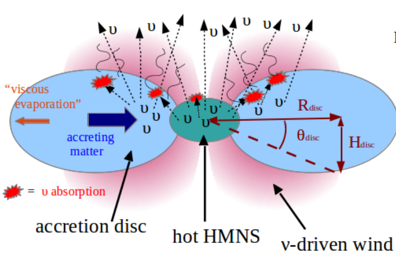

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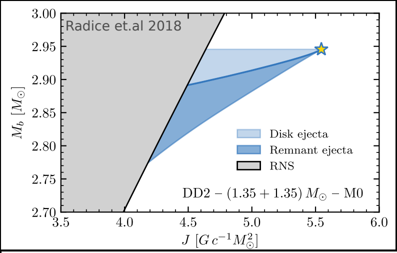
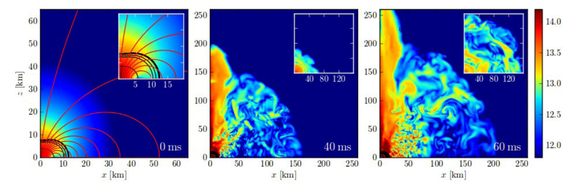
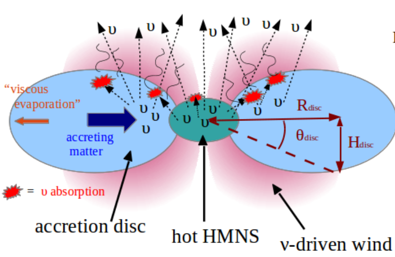




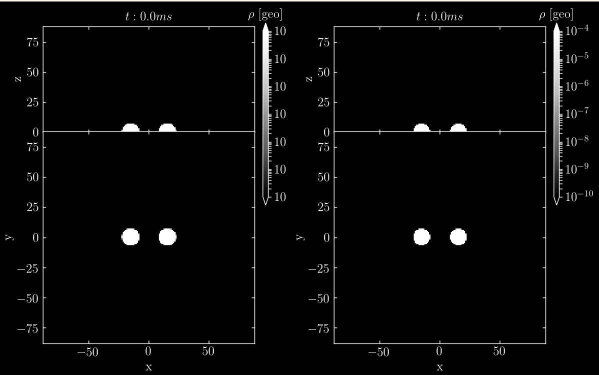


Goal: construct a numeral relativity informed kilonova model

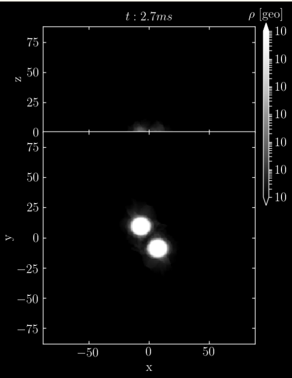
- **GRHD** – `WhiskyTHC`
  (Radice & Rezzolla 2012; Radice+2014a,b, Radice+2015)
- **Spacetime** – `z4c` **of the** `Einstein Toolkit`
  (Bernuzzi & Hilditch 2010)
- **Neutrinos** – Leakage + M0 (gray)
  (Galeazzi+2013; Radice+2016b)
- **Viscosity** – subgrid-scale turbulent angular momentum transport.
  GRLES (Radice+2017)
- **Kilonova** – semi-analytical anisotropic NR informed kilonova model
  (Perego+2017)

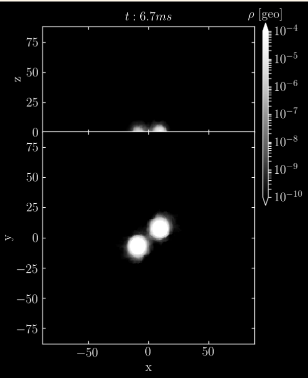
Setup

DD2 M13641364 LS220 M13641364



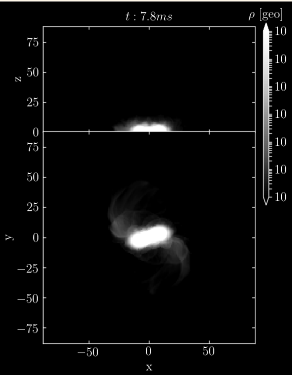
DD2 M13641364 LS220 M13641364



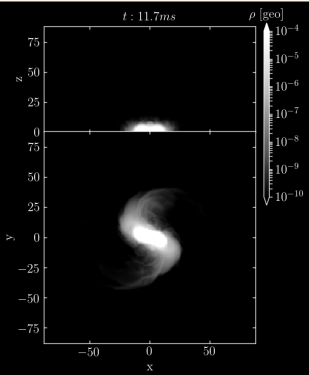


Merger

DD2 M13641364



LS220 M13641364



Merger

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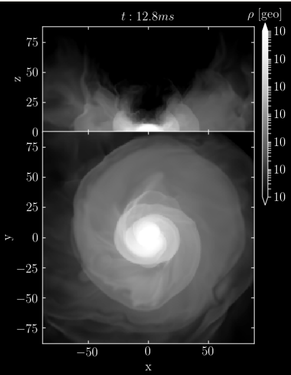
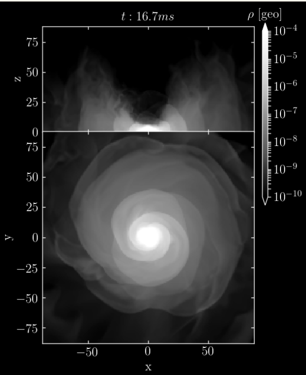
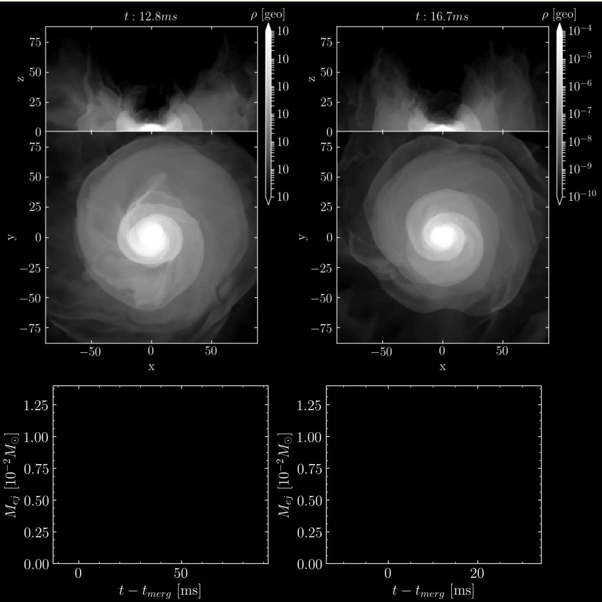
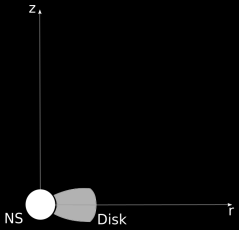


LS220 M13641364



DD2 M13641364 LS220 M13641364

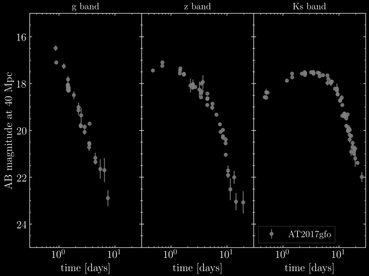


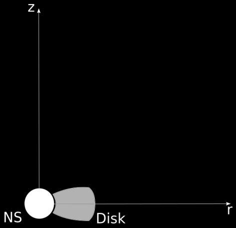


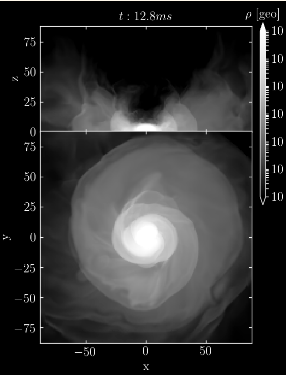
Merger

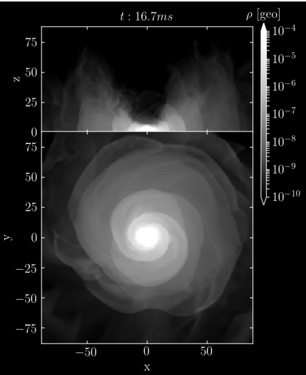
DD2 M13641364 — LS220 M13641364

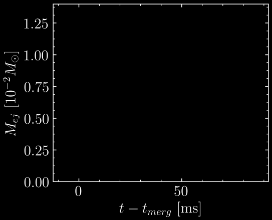
The AT2017gfo data is from Pian+17, Tanvir+17

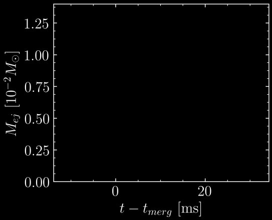






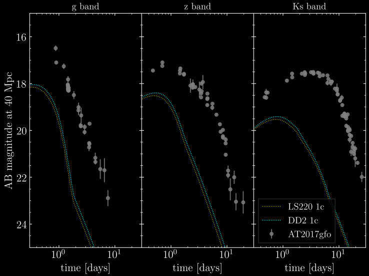


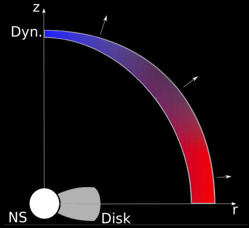


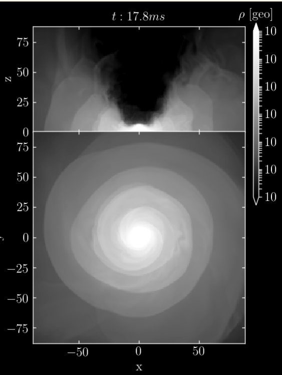


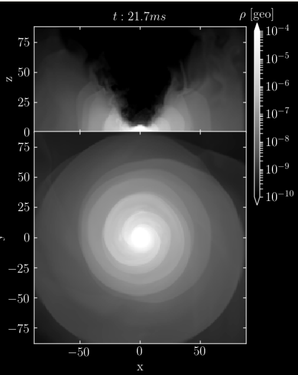
DD2 M13641364 LS220 M13641364

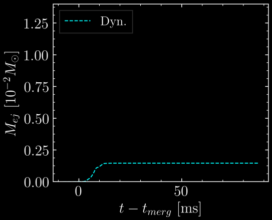
Semi-analytical, anisotropic, kilonova model, Perego+17a)

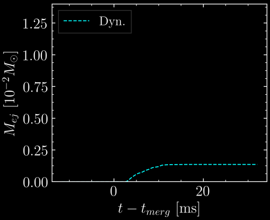






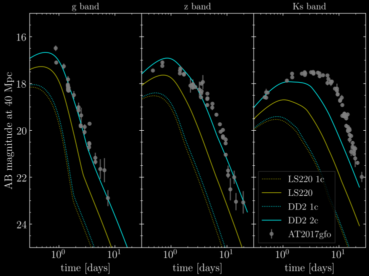


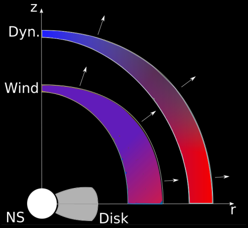




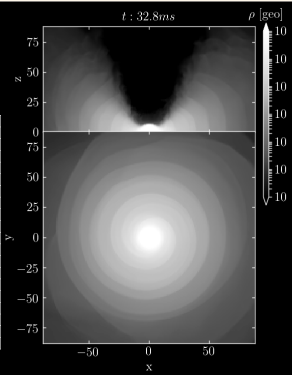
Spiral Wave Wind

[arXiv:1907.04872]

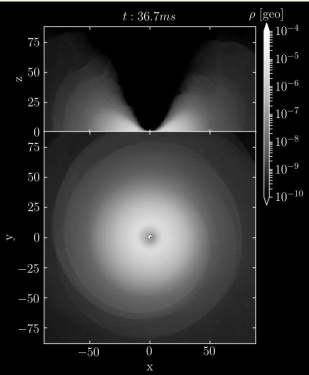


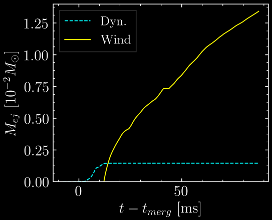


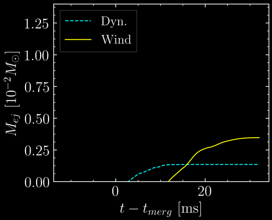
DD2 M13641364



LS220 M13641364



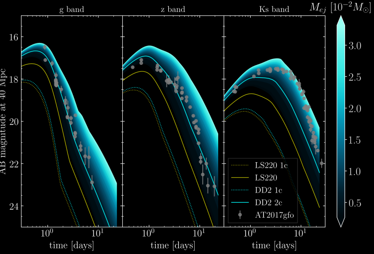


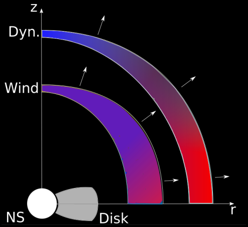


Spiral Wave Wind

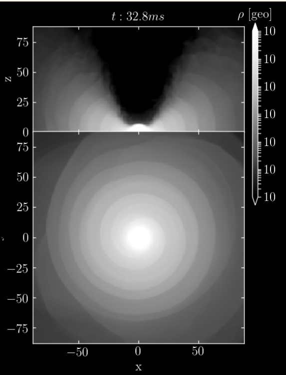
[arXiv:1907.04872]

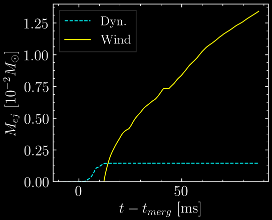
Assuming that DD2 does not collapse in 250ms



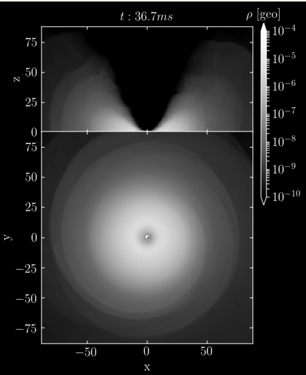


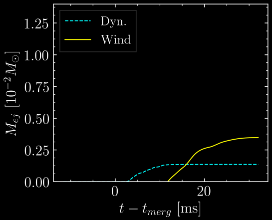
DD2 M13641364





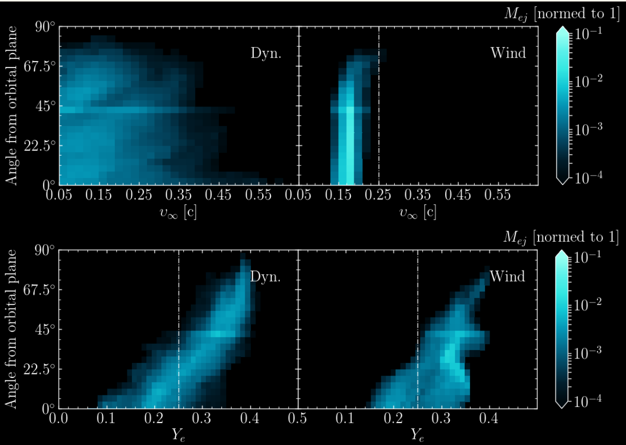
LS220 M13641364





Properties of the wind:

- **Confined to the plane of the binary**
- $v_\infty \approx 0.2$
- $Y_e \geq 0.25$



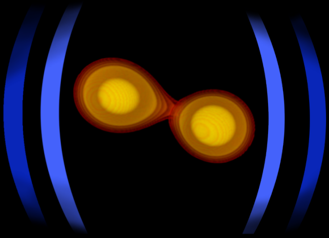
Idea: construct a numeral relativity informed Kilonova model

Extracting NR data allows us to improve physical interpretation of the Kilonova model

Future work

- Longer runs (100+ ms)
- High resolution runs
- Add more physics (MF, neutrino treatment)
- More observed events

Thank you for your attention



Computational Relativity Group

http://www.computational-relativity.org/

DD2

- based on nuclear statistical equilibrium with a finite volume correction coupled, to a relativistic mean field theory for treating high density,
- contains neutrons, protons, light nuclei such as deuterons, helions, tritons and alpha particles and heavy nuclei,
- support masses up to $\approx 2.4 M_{\odot}$

LS220

- is based on the single nucleus approximation for heavy nuclei where the thermal distribution of different nuclear species is replaced by a single representative heavy nucleus,
- contains neutrons, protons, alpha particles and heavy nuclei.
- support masses up to $\approx 2.05 M_{\odot}$

Geodesic $u_t < -1$

- u_t – constant of motion for a geodesics (stationary space-time)
- $W = -u_t$ for asymptotically flat space at ∞.
- assuming, flow is made of isolated particles, following the geodesic, metric is time-independent,
- neglecting pressure and $r-$process heating,

Bernoulli, $hu_t < -1$

- stationary relativistic fluid flow, hu_t constant along fluid world lines.
- thermal energy of the fluid is now assumed to be transformed into kinetic energy as the fluid decompresses.

Semi-analytic anisotropic kilonova model (Perego et.al 2017)

- multiple ejecta components (Dynamical, secular)
- Ejecta properties: $m^i_{\rm ej}(\theta)$, $v^i_{\rm rms}(\theta)$, $\kappa^i_{rmej}(\theta)$
- Axisymmetry, 12 θ bins.
- Radial model inside each bin (Grossman et.al 2014)
- energy is reprocessed and reimetted at the photosphere, $Q = M_{\rm env}\epsilon_{\rm nuc}$. Heating rates (Korobkin et al. 2012)

GR Hydro: `WhiskyTHC` for n_p and n_n evolution (Radice & Rezzolla 2012; Radice+2014a,b, Radice+2015)

- NS matter is a perfect fluid
- high resolution shock-capturing (HRSC) schemes

P5 scheme for primitive variables reconstruction

Atmosphere is set to $\rho_0 = 6 \times 10^4$g com^{-3}

Z4c formulation of Einstein's equations for spacetime evolution ((Bernuzzi & Hilditch 2010)

Grid: 3.024 km in diameter. `Carpet` module of the `Einstein Toolkit` (Berger-Oliger conservative AMR)