Numerical relativity simulations of the neutron star merger GW190425

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(arXiv:2204.05336)

In collaboration with

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ECT* Workshop

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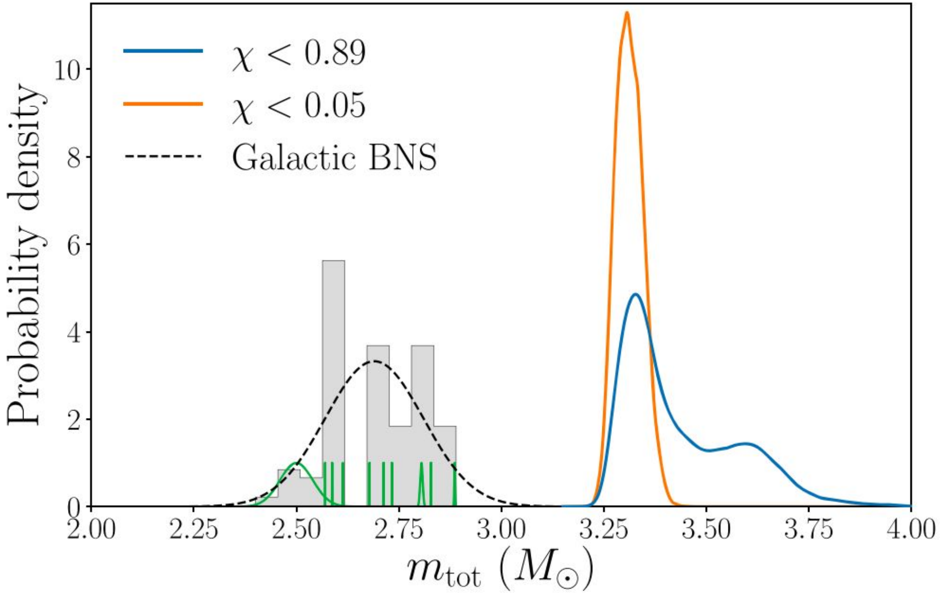
- GW190425 -

Observation Summary

- High total mass
- Population Outlier
- (Almost) only one detector
- Broad sky Location
- No observed EM counterpart

	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	1.60–1.87 $M_\odot$	1.61–2.52 $M_\odot$
Secondary mass m_2	1.46–1.69 $M_\odot$	1.12–1.68 $M_\odot$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02}$ $M_\odot$	$1.44^{+0.02}_{-0.02}$ $M_\odot$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}$ $M_\odot$	$1.4873^{+0.0008}_{-0.0006}$ $M_\odot$
Mass ratio m_2/m_1	0.8 – 1.0	0.4 – 1.0
Total mass m_{tot}	$3.3^{+0.1}_{-0.1}$ $M_\odot$	$3.4^{+0.3}_{-0.1} M_\odot$



From Abbott et al. 2019, Astrophys. J. Lett. 892

- GW190425 -

Observation Summary

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LIGO
@LIGO

Here's the @LIGO & @ego_virgo skymap [...] The map isn't too precise, covering about 18% of the sky

- AIM OF THE WORK -

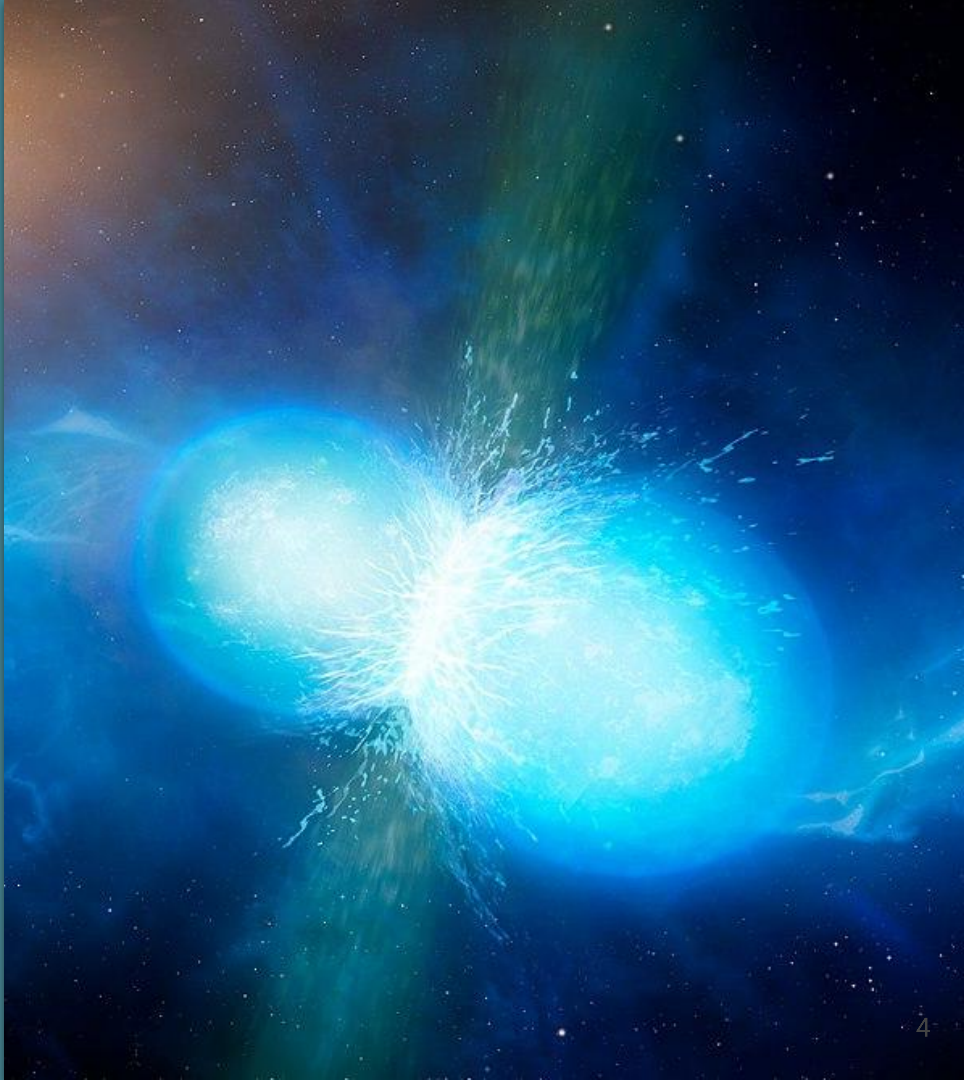
What are the peculiarities of such type of events? What is the expected magnitude of the Kilonova?

Characterize the:

- Remnant
- Dynamical Ejecta
- Nucleosynthesis
- Kilonova

Using:

- Simulations in NR with detailed microphysics
- Nucleosynthesis and kilonova models



- METHODS -

- BNS SIMULATIONS -

Setup and Code

28 simulations targeted to GW190425:

- 2 resolutions (246 m, 185 m)
- 4 NS EOS
- 3 - 4 mass ratios

Code:

- Metric: EinsteinToolkit (Z4c)
- Hydrodynamics: THC *(Radice et al. 2012)*
- Cartesian grid with 7 MR levels

$$M_{\rm chirp} = 1.44\ M_\odot$$

$$M \in [3.307, 3.438]\ M_\odot$$

$$q \in [1, 1.67]$$

q	M_A ($\mathrm{M}_\odot$)	M_B ($\mathrm{M}_\odot$)
1.00	1.654	1.654
1.12	1.557	1.750
1.18	1.527	1.795
1.33	1.437	1.914
1.67	1.289	2.149

- MICROPHYSICS -

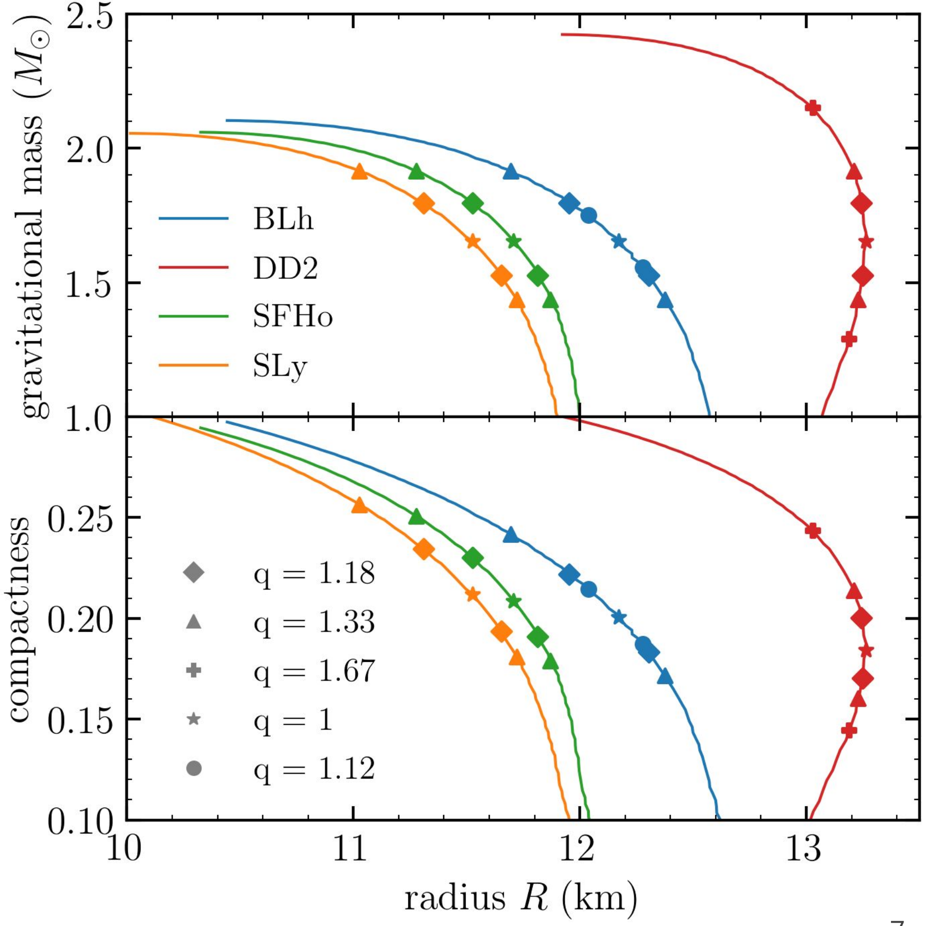
EOS and Neutrinos

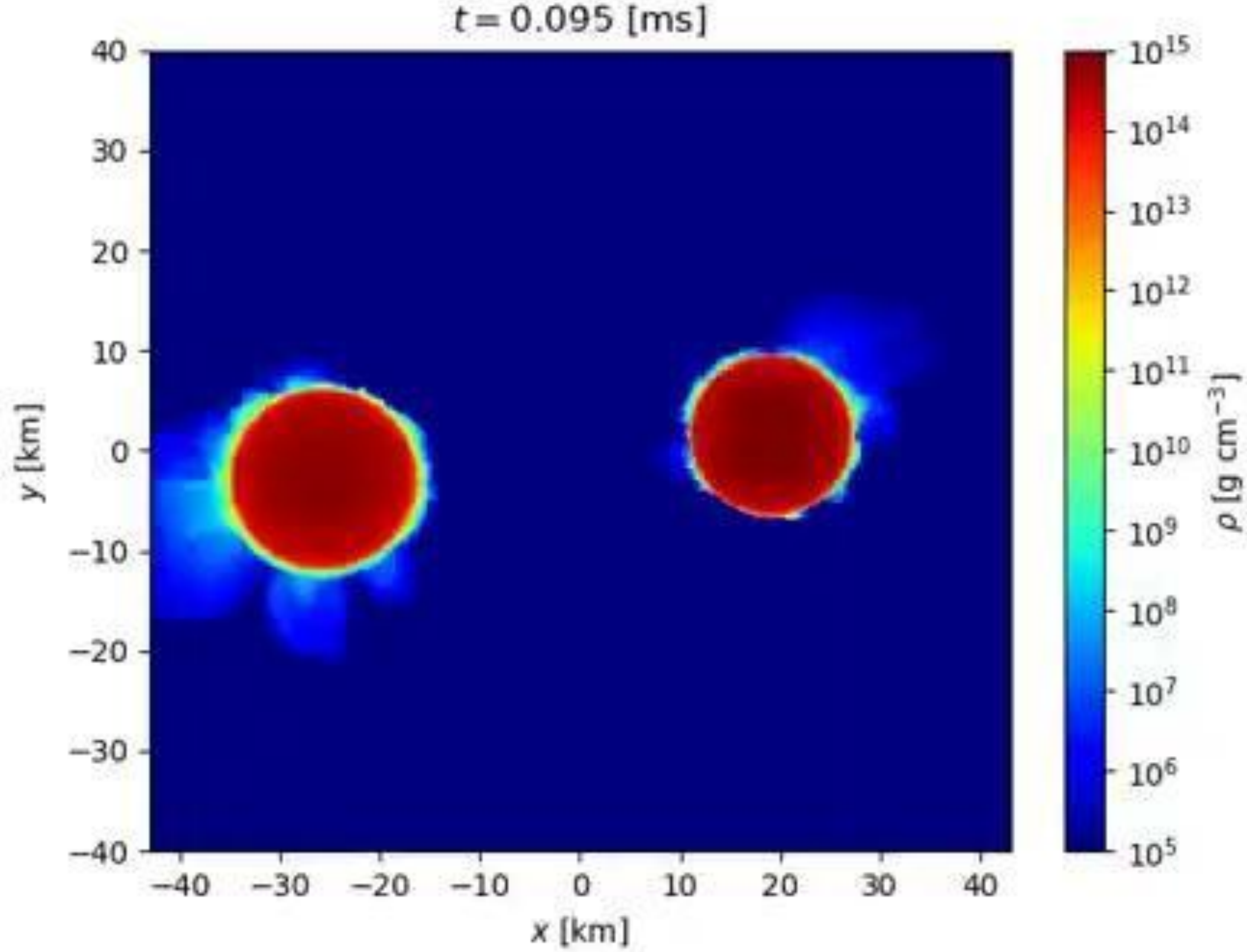
Finite-temperature, composition dependent EOS

- BLh, DD2, SFHo, SLy
- Compatible with astro/nuclear constraints
- Broad range of compactness

3 flavor, gray neutrino scheme

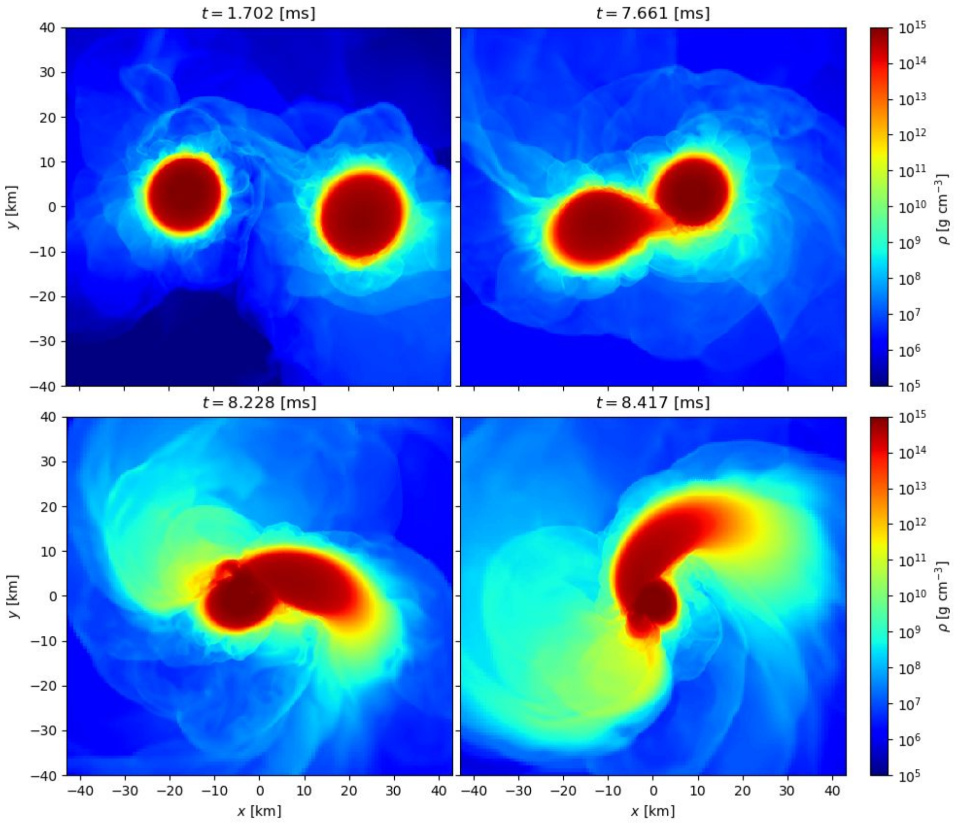
- Emission: Leakage
- Optically thin transport: M0




$t = 0.095$ [ms]
y [km]
x [km]
40
30
20
10
0
−10
−20
−30
−40
−40
−30
−20
−10
0
10
20
30
40
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
ρ [g cm^{-3}]

ANALYSIS PROCEDURE

- Inspiral: last 2.5 - 3 orbits
- Merger
- Post-merger: up to ~ 4 - 10 ms



ANALYSIS PROCEDURE

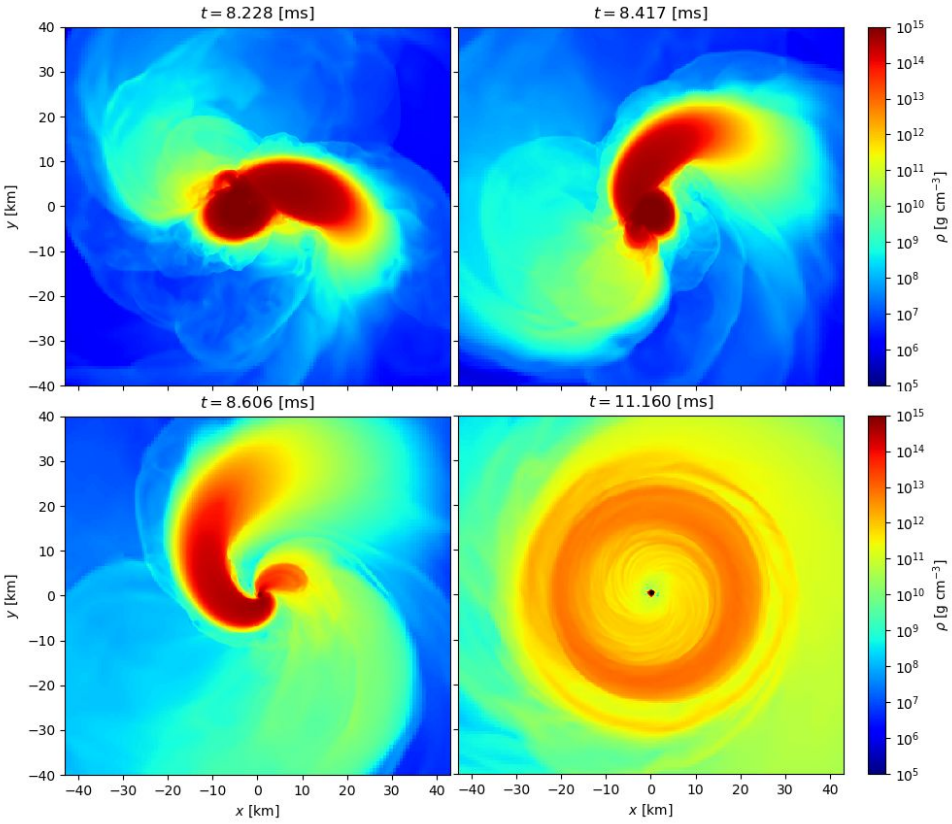
BH and disk

Black Hole:

- AH finder: estimate $M_{\rm BH}$ and $a_{\rm BH}$

Disk:

- Outside the horizon
- Density ≤ 10^{13} g cm^{-3}
- Estimate $M_{\rm disk}$ and $J_{\rm disk}$

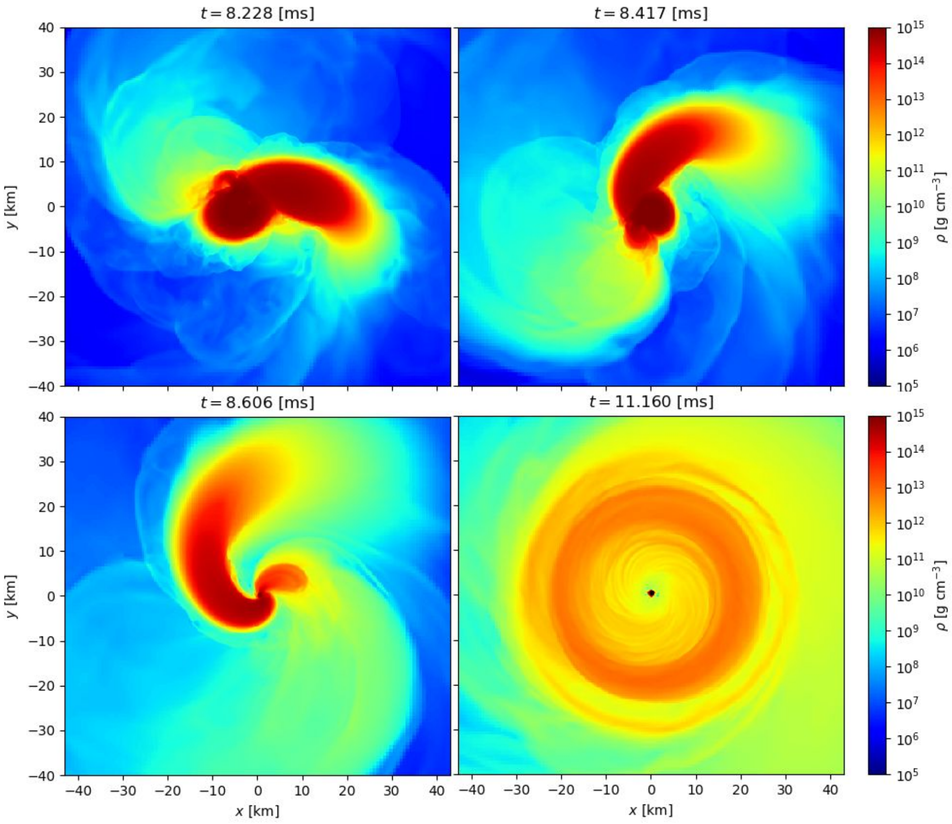


ANALYSIS PROCEDURE

Dynamical Ejecta

- Matter that unbound during the merger and up to ~ 5 ms post-merger
- Geodetic criterion ($u_t \leq -1$)
- Properties extracted at 294 km from the center of mass

Dynamical Ejecta and Disk are input for Nucleosynthesis and Kilonova



ANALYSIS PROCEDURE

Nucleosynthesis

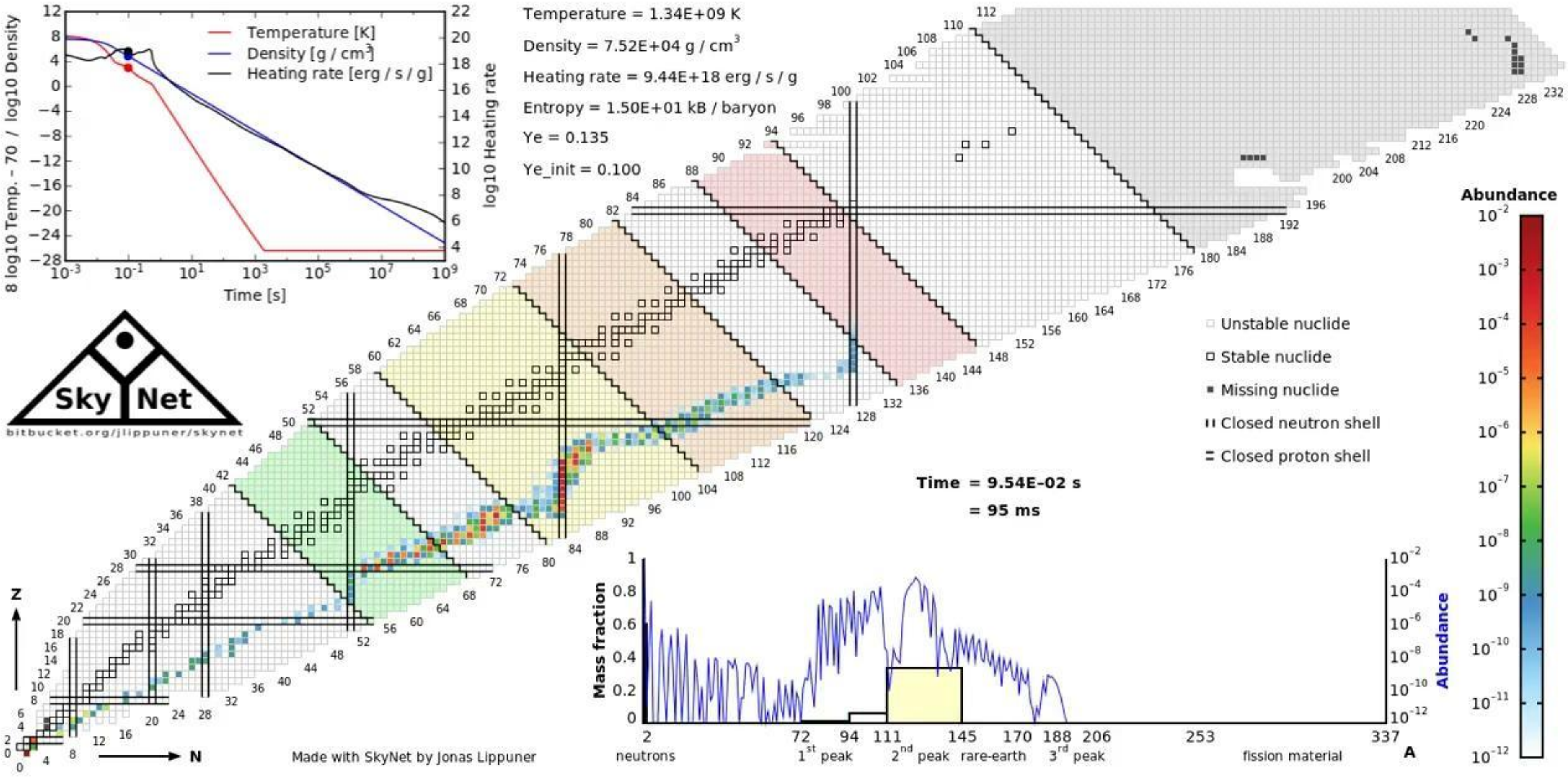
Nuclear Reaction Network Solver:

- Initial Conditions
  - Lagrangian particles with given $(s,\ Y_e = n_e/n_B,\ \tau)$ *(Hoffman ApJ 1998)*
  - Nuclear Statistical Equilibrium (NSE)

- Evolution:
  - Homologous expansion
  - Nuclear reactions

$$\text{Most relevant reactions for r-process nucleosynthesis}$$
$$(A,Z) + \gamma \longleftrightarrow (A-1,Z) + n$$
$$(A,Z) \longrightarrow (A,Z+1) + e^- + \bar{\nu}_e$$

$$\rho(t) \sim \rho_0 \left(\frac{\tau}{t}\right)^3$$



Courtesy of L. Chiesa

ANALYSIS PROCEDURE
Kilonova

(Perego et al. 2017, ApJ L.)

Anisotropy:

- Axial symmetry
- Discretized polar angle: 1D Kilonova model for each slice

Multicomponent:

- Dynamical ejecta:
  - $M_{\mathrm{ej}}(\theta),\ s(\theta),\ Y_e(\theta),\ v(\theta)$
  - $\kappa = \kappa(Y_e)$
- Disk wind:
  - 20% of the disk mass
  - uniform density
  - opacity $\kappa = 5\ \mathrm{cm}^2\ \mathrm{g}^{-1}$

- KILONOVA 1D MODEL -

(Wu, Ricigliano et al. 2021)

Components:

- Inner optically-thick sphere enclosed by photosphere
  (*Wollaeger et al. 2018, Roy. Astron. Soc.478*)
- Outer optically-thin layers

Radiative model:

- Optically-thick:
  - Semi-analytic solution of diffusion equation
  - Black body radiation with T_{ph}
- Optically-thin: Local Thermodynamic equilibrium

Nuclear Heating Rate

$$\dot{\epsilon}_r = At^{-\alpha}$$

Thermalization efficiency

$$\epsilon_{\mathrm{th}} = \epsilon_{\mathrm{th}}(\rho)$$

(Barnes et al. 2016)

- RESULTS -
Outline

From Numerical Simulations

- Remnant Properties
  - BH
  - Disk
- Ejecta properties

From Post Processing

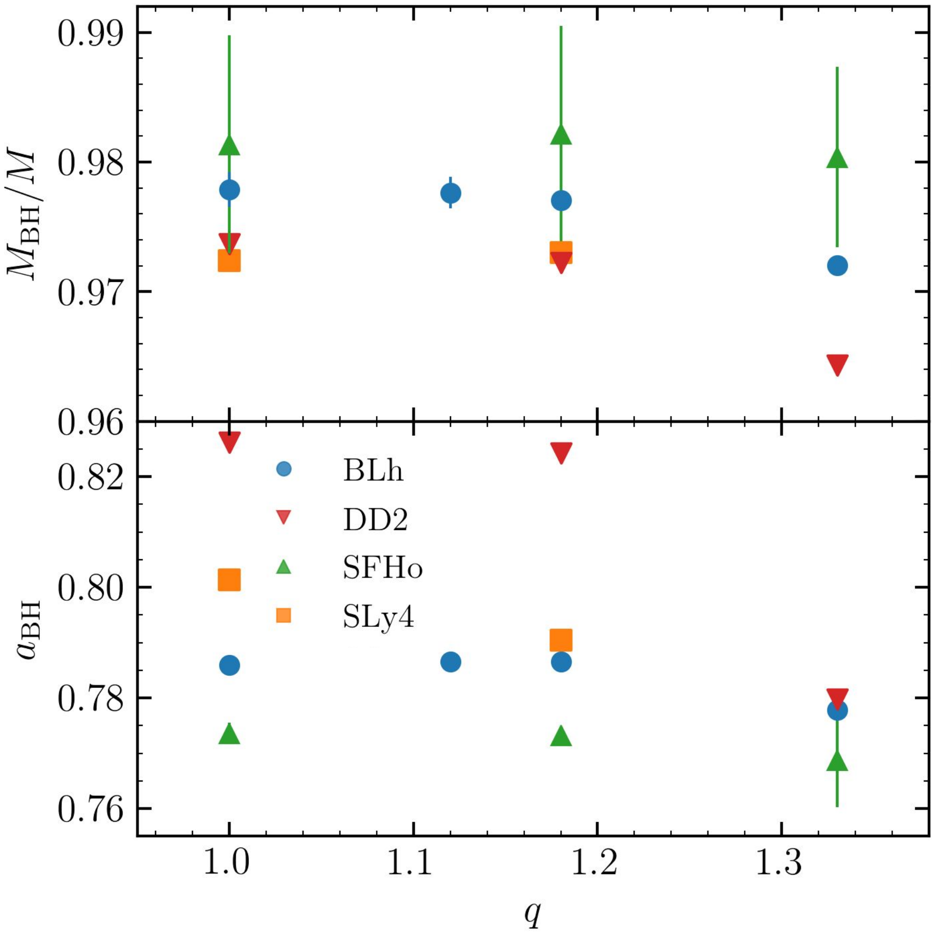
- Nucleosynthesis
- Kilonova

- BLACK HOLE -

Mass and Spin Parameter

Prompt Black Hole: increase of $\rho_{\max}$ without core bounces

- M_{BH}/M is slowly decreasing.
- Small decrease of the spin parameter with the mass ratio

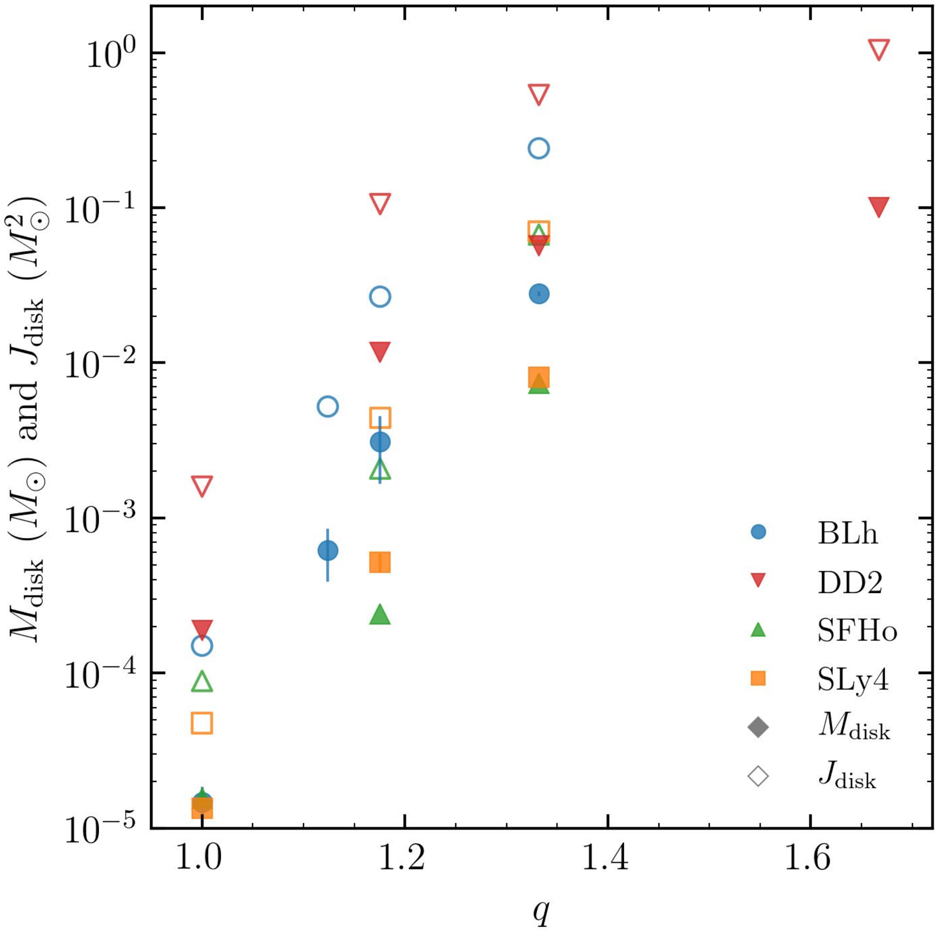


- DISKS -

Mass and Angular Momentum

Mass and angular momentum increase with:

- Mass ratio
- Stiffness of the EOS

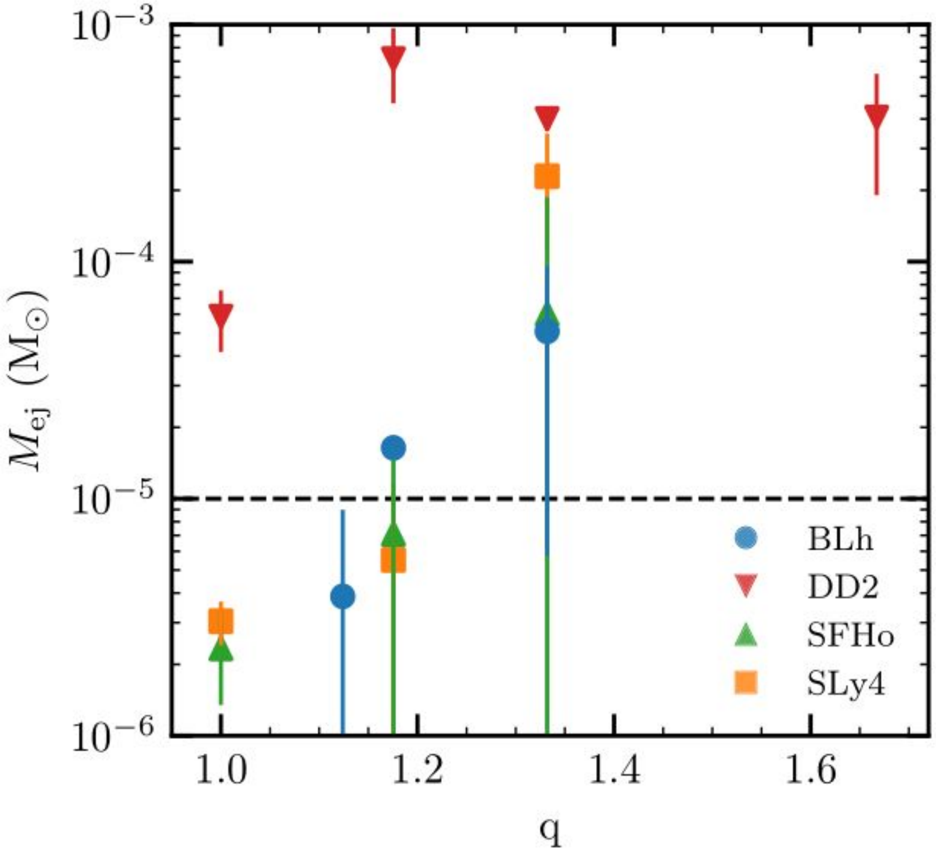


- DYNAMICAL EJECTA -

Unbound mass formed during and up to ~ 5 ms after the merger

Properties:

- P-BH ⇒ Small Shocked component
- Small ejected mass
- Mass increases with the mass ratio



- DYNAMICAL EJECTA -

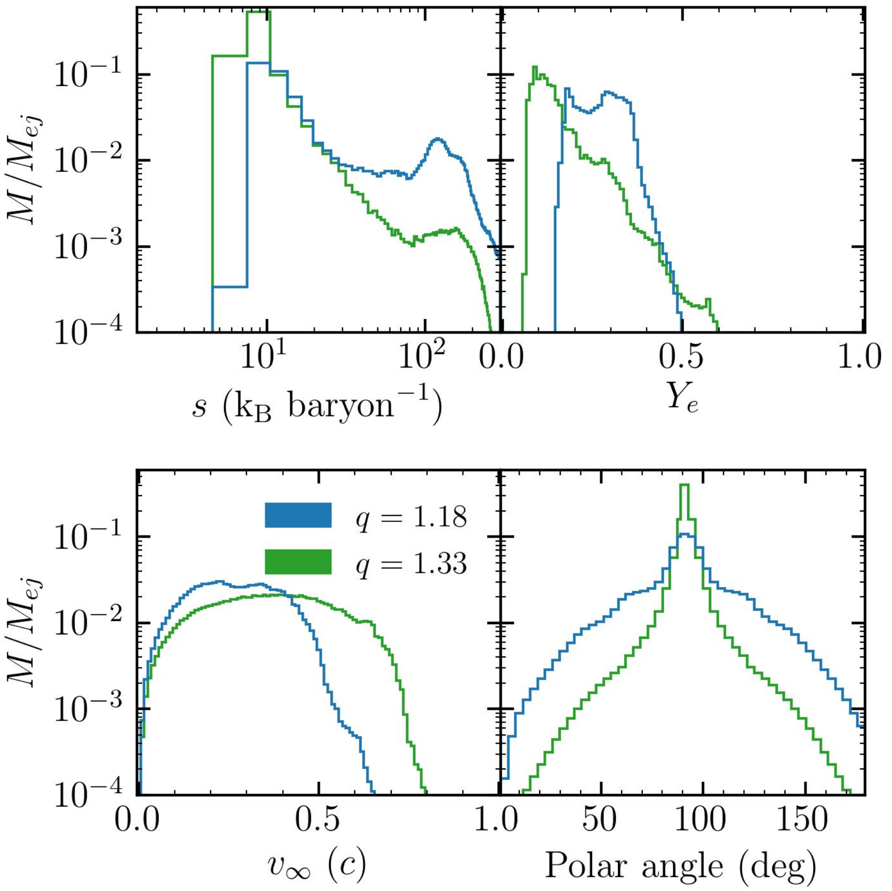
Distributions

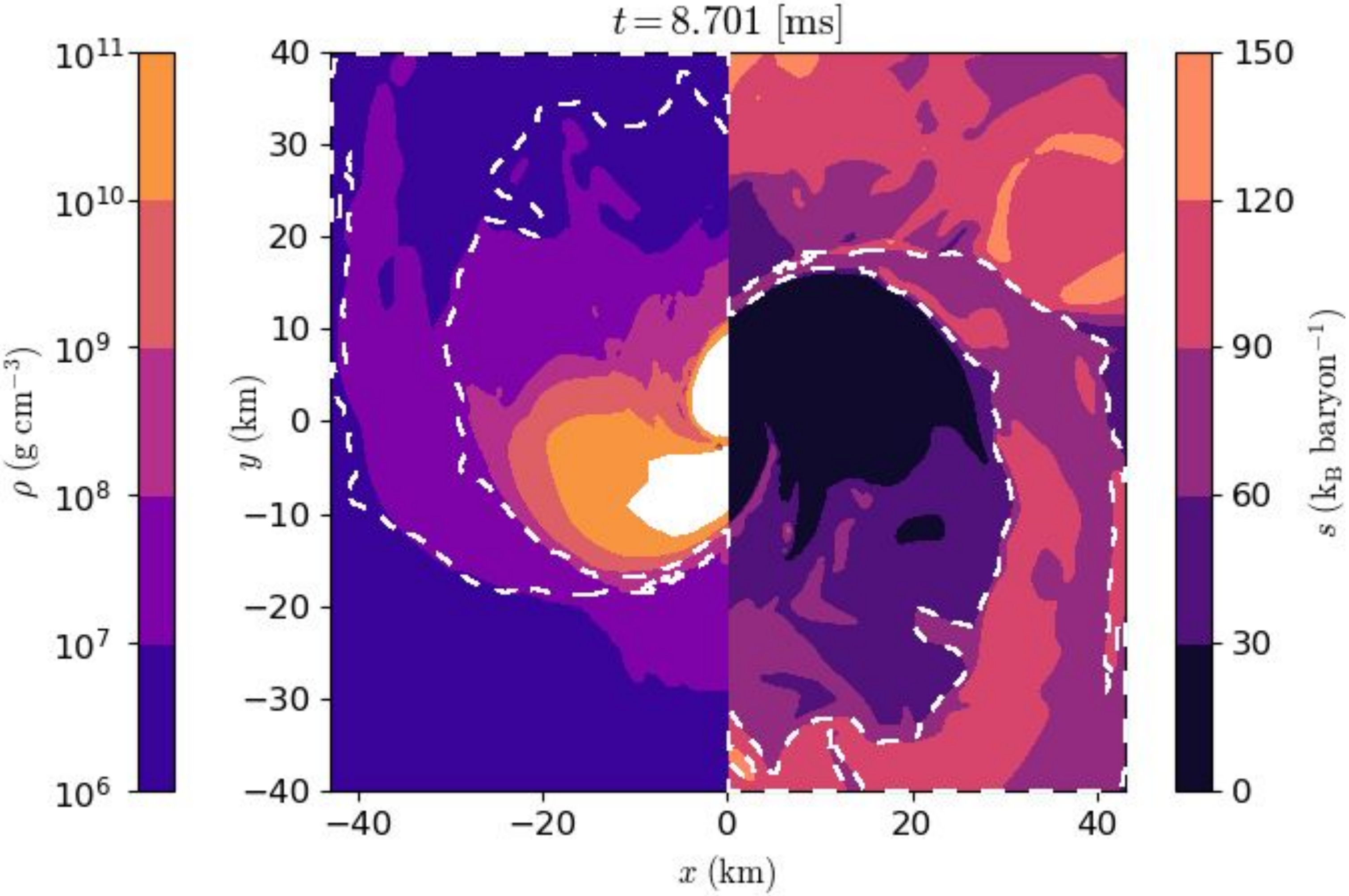
Only $M_{\rm ej} > 10^{-5}\ M_{\odot}$

Second peak in the entropy: 1 - 0.1% highly shocked component (110 k_B)

Medians range (all simulations):

$$s^{\rm med} \in [6, 80]\ {\rm k_B\ baryon^{-1}}$$
$$Y_e^{\rm med} \in [0.2, 0.3]$$
$$v_\infty^{\rm med} \in [0.13, 0.4]\ c$$
$$\theta^{\rm sd} \in [9, 26]\ {\rm deg}$$





$t = 8.701$ [ms]
$\rho\ (\mathrm{g\ cm^{-3}})$
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
y (km)
40
30
20
10
0
−10
−20
−30
−40
x (km)
−40
−20
0
20
40
$s\ (\mathrm{k_B\ baryon^{-1}})$
150
120
90
60
30
0

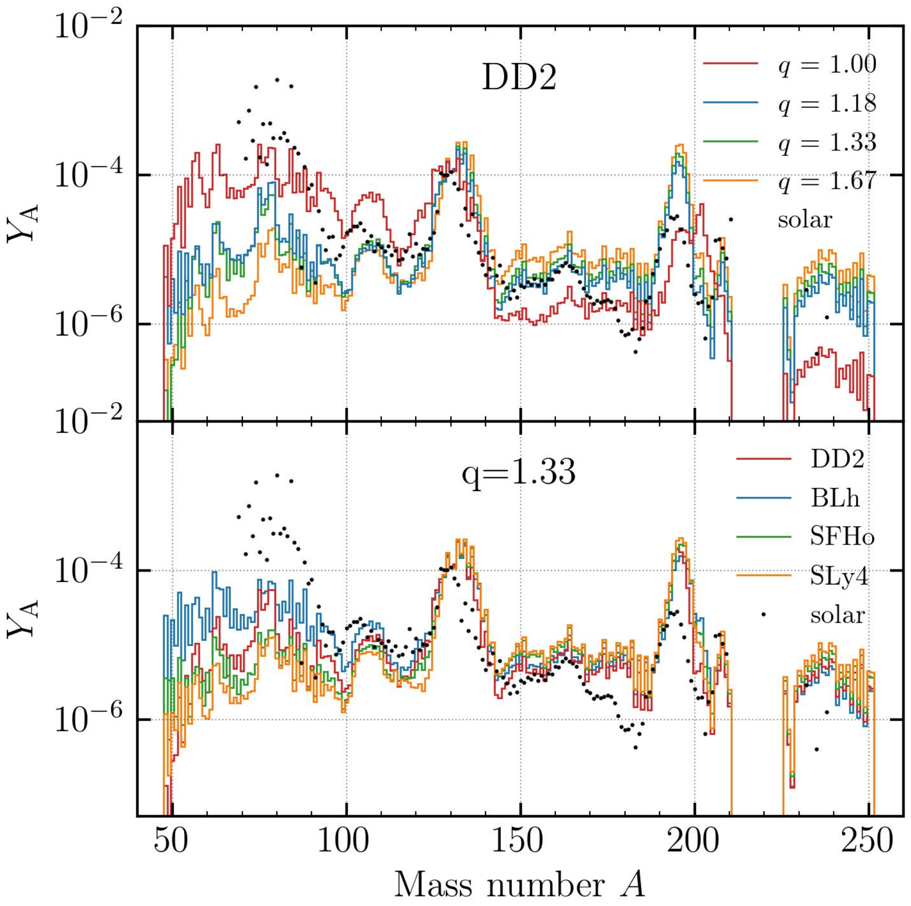
- NUCLEOSYNTHESIS -

Upper panel: fixed EOS (DD2)

- Equal mass ratio: higher production of first peak
- Higher mass ratio: more production above the second peak

Lower Panel: fixed mass ratio (1.33)

- First peak: less abundances for softer EOS!



- KILONOVA RESULTS -

Light Curves

Observer position:

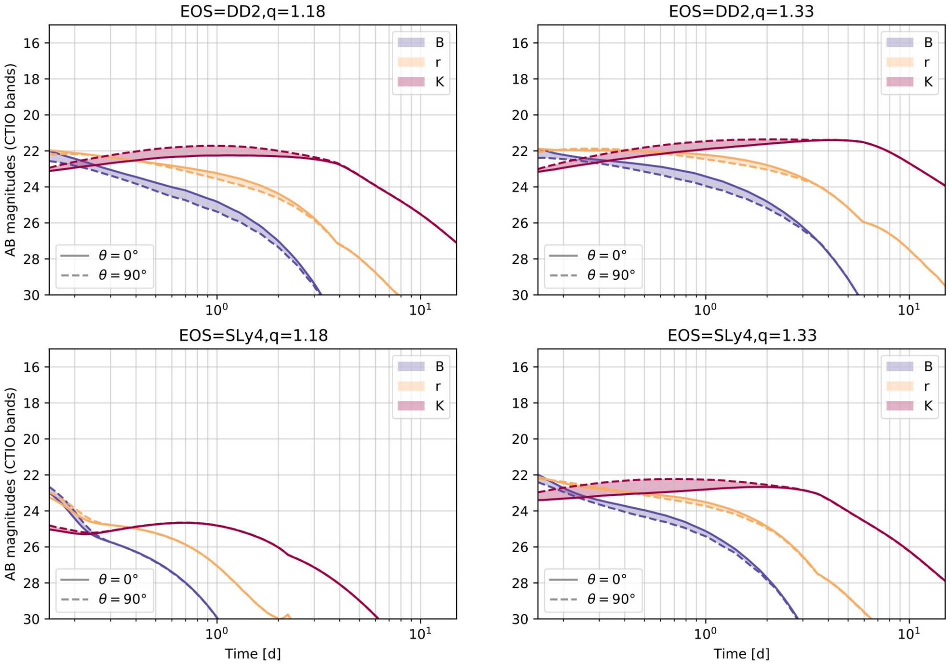
- Distance of 130 Mpc
- Angle from pole to equator

Peaks:

- infrared band: around 1 to 5 days
- red/blue band: within the first few hours

Infrared bands are higher along the equator. The opposite for blue/red.

Detection: No curves below 21 mag



- KILONOVA RESULTS -

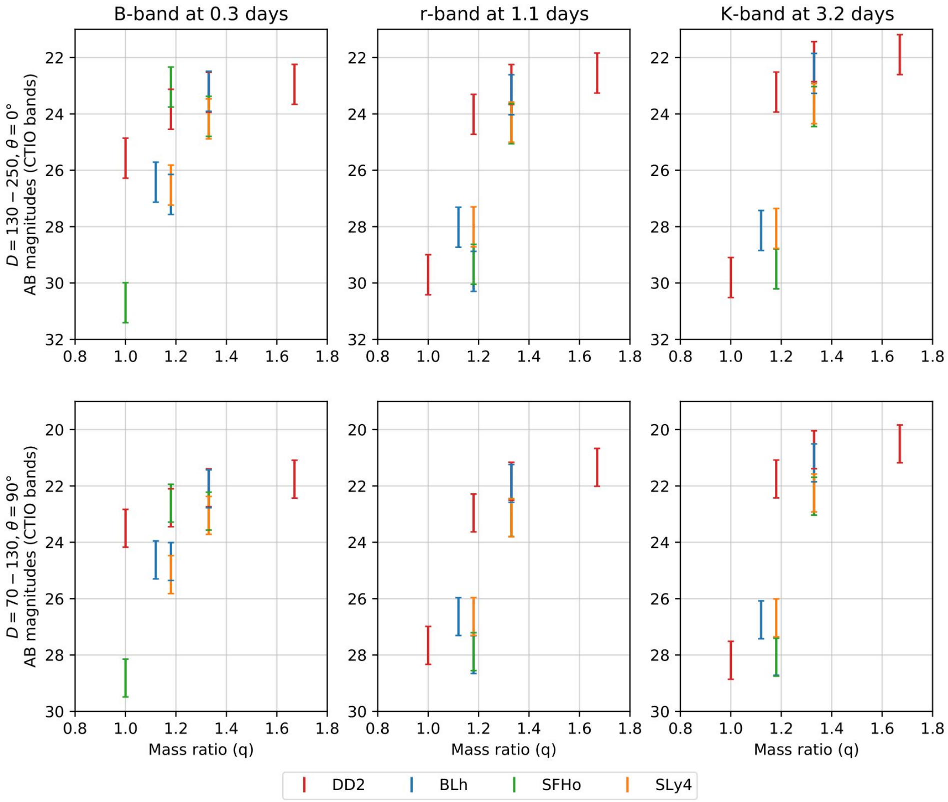
EOS and mass ratio

Top panel: observer at 130 - 250 Mpc along the pole

Bottom panel: observer at 70 - 130 Mpc along the equator

Luminosity (magnitude)

- increase (decrease) with the mass ratio
- It’s higher for BNS with stiffer EOS



- KILONOVA PREDICTIONS -

Fitting Formulae and Calibration

Disk:

Fitted on 57 numerical simulations from *Radice et al. 2018* and *Kiuchi et al. 2019*

Ejecta:

Fitted on 200 numerical simulations from *Dietrich et al.* and *Kiuchi et al. 2019*

$$M_{\rm disk} = M_1 \max\left\{5 \times 10^{-4}, (aC_1 + c)^d\right\}$$

$$\frac{M_{\rm dyn}}{10^{-3} M_\odot} = \left(\frac{a}{C_1} + b\frac{M_2^n}{M_1^2} + cC_1\right) M_1 + (1 \longleftrightarrow 2)$$

From Kruger and Foucart 2020

- KILONOVA PREDICTIONS -

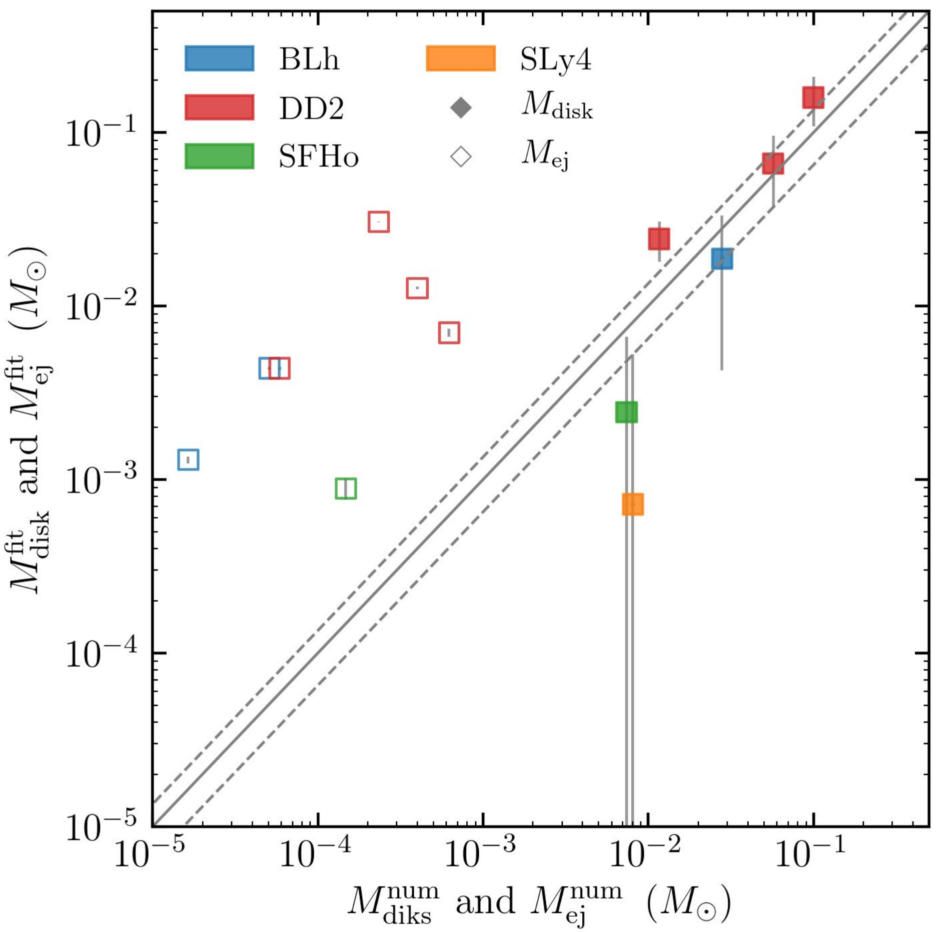
Range of validity: extrapolation

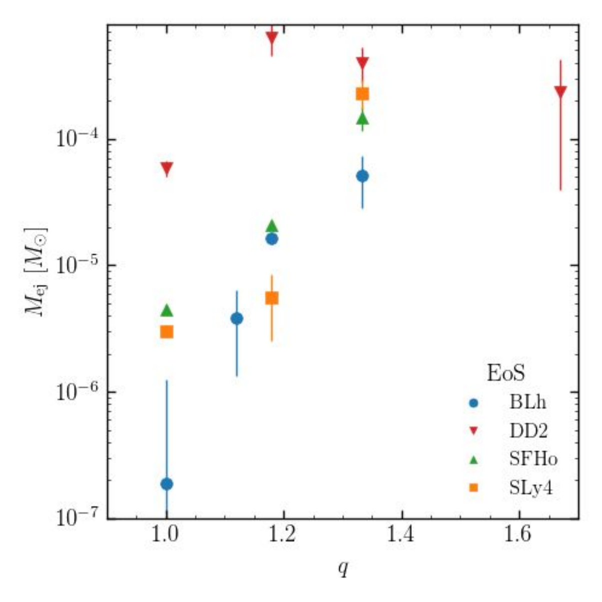
Disk:

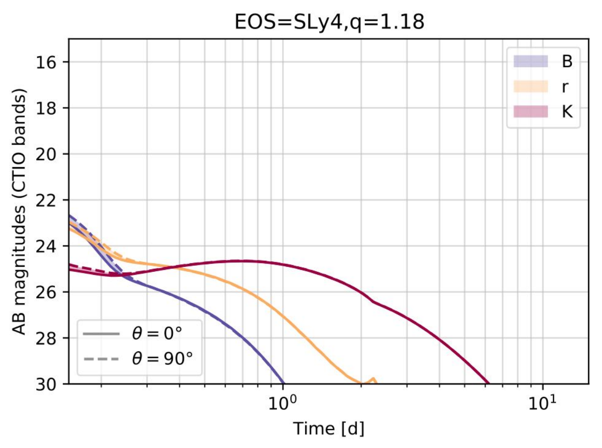
Consistency within 35% error (dashed lines)

Ejecta:

Disagreement outside the calibration dataset







- CONCLUSIONS -

Scope of the work: Characterize events like GW190425 for future detections and investigates the detectability of GW190425

Conclusions

- Prompt-BH
- Small values for the mass of
  - Dynamical ejecta
  - Disks
- Kilonova hard to detect with current wide-field facilities