GW signals from 3DMHD simulations of white dwarf mergers

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October 28th, 2024

Uncertainties in binary physics?

- Despite *many* uncertainties in rapid population synthesis
    - We always see 3 peaks
    - The relative peak heights shift with the assumed physics
    - Gap at ~10 $M_\odot$ is always present…
- …Except in the traditional (non-bimodal) BH formation models

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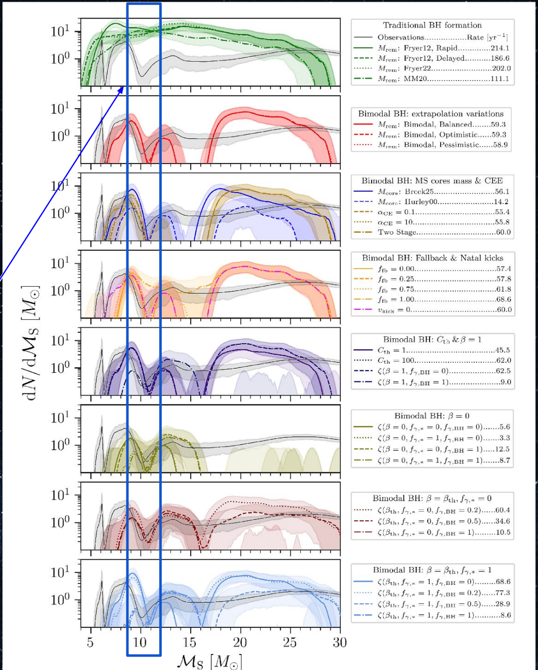
Willcox et al. 2025



RW+ (2025b)

Mergers involving white dwarfs: motivation

- Most frequent compact object merger
- **Potential origin of many transients**
- Multi-messenger astronomy (?)

Very challenging to model

- Merger NOT driven by GW emission
- Many different physics acting on different scales
- 3D magneto-hydrodynamics (MHD) simulations needed to capture most of them

SNR G299.2-2.9 as seen by Chandra observatory

Mergers involving white dwarfs: motivation

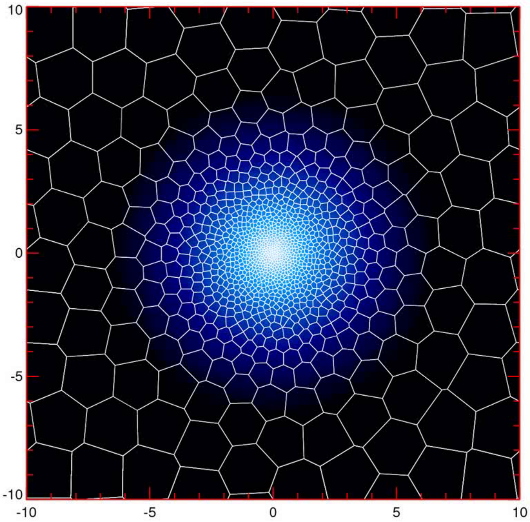
- Most frequent compact object merger
- **Potential origin of many transients**
- Multi-messenger astronomy (?)

Two main unexplored types

- Neutron star - White dwarf
- Binary white dwarf

SNR G299.2-2.9 as seen by Chandra observatory

AREPO



AREPO Code (Springel 2010)

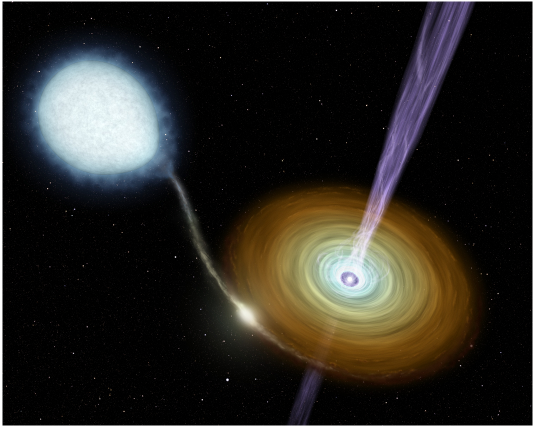
- 3D MHD code
- Unstructured, moving Voronoi mesh
- Mesh moves with local speed (quasi-Lagrangian)
- Automatic and continuous refining
- Coupling to nuclear networks
- Can use GR and SR
- Computation of GW signal on the fly

NS-WD binaries

- 2nd most common type of DCO
- As binaries $\rightarrow$ LISA targets
- if $q < q_{crit}$ UCXRB
- if $q > q_{crit}$ $\rightarrow$ merger

Outcome of the merger?

- Magnetars
- Collapse to a BH
- Long gamma-ray bursts (GRBs)
- Fast radio bursts (FRBs)
- Fast blue optical transients (FBOTs)
- ...



Artist impression of XRB (NASA/JPL-Caltech)

Moran-Fraile 2024a

3DMHD NS-WD merger

Setup

- $1 M_\odot$ COWD
- $1.4 M_\odot$ NS (point mass)
- >8 million voronoi cells
- Magnetic field seed: 10^5G
- No nuclear reactions

Self-consistent magnetohydrodynamic simulation of jet launching in a neutron star - white dwarf merger

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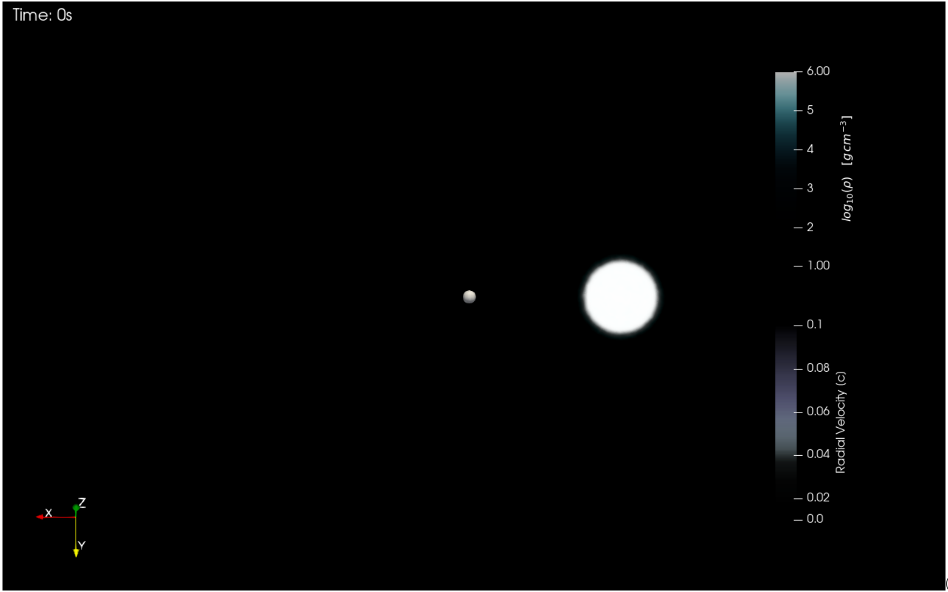
ABSTRACT

The merger of a white dwarf (WD) and a neutron star (NS) is a relatively common event that produces an observable electromagnetic signal. Furthermore, the compactness of these stellar objects makes them an interesting candidate for gravitational wave (GW) astronomy, potentially being in the frequency range of LISA and other missions. To date, three-dimensional simulations of these mergers have not fully modeled the WD disruption or have used lower resolutions and have not included magnetic fields even though they potentially shape the evolution of the merger remnant. In this work, we simulated the merger of a $1.4\,M_\odot$ NS with a $1\,M_\odot$ carbon oxygen WD in the magnetohydrodynamic moving mesh code AREPO. We find that the disruption of the WD forms an accretion disk around the NS, and the subsequent accretion by the NS powers the launch of strongly magnetized, mildly relativistic jets perpendicular to the orbital plane. Although the exact properties of the jets could be altered by unresolved physics around the NS, the event could result in a transient with a larger luminosity than kilonovae. We discuss possible connections to fast blue optical transients (FBOTs) and long-duration gamma-ray bursts. We find that the frequency of GWs released during the merger is too high to be detectable by the LISA mission, but suitable for deci-hertz observatories such as LGWA, BBO, or DECIGO.

Key words. Stellar Merger — Gravitational Waves — Magnetohydrodynamics — White Dwarf — Neutron Star

3D render


Time: 0s
6.00
5
4
3
2
1.00
$log_{10}(\rho)$ $[g\,cm^{-3}]$
0.1
0.08
0.06
0.04
0.02
0.0
Radial Velocity (c)
X
Y
Z

Results

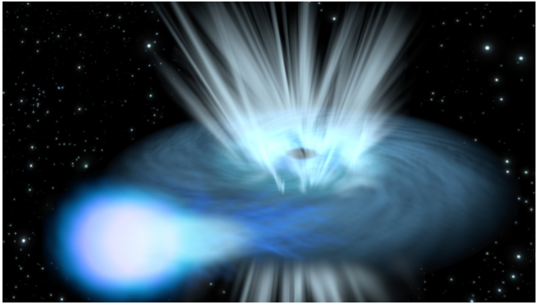
Potential transients?

- UV / Xray flash resembling some FBOTs
- If collapse into a BH $\rightarrow$ long/ultra-long GRBs
- Still uncertain

Next steps

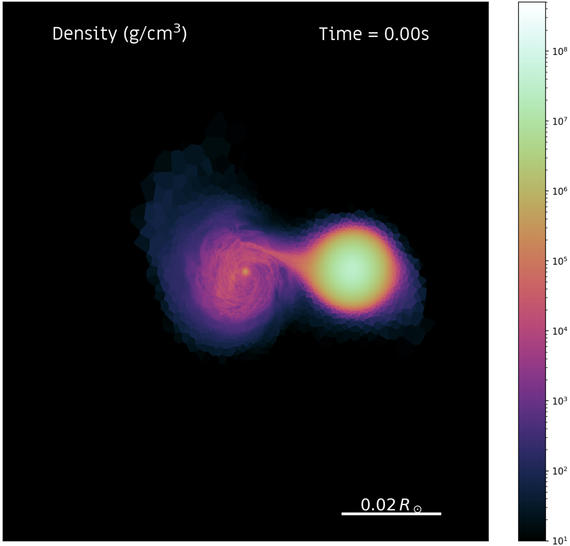
- Radiative transfer simulations

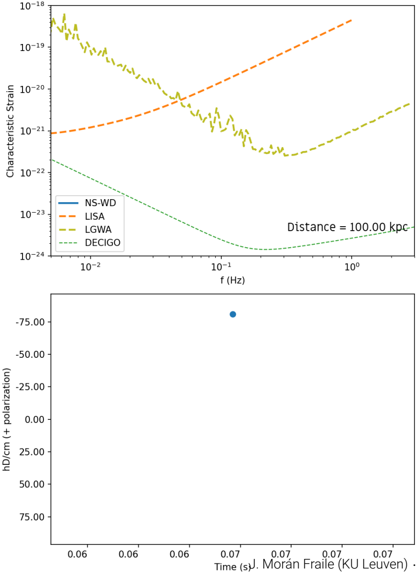
Can GW help?



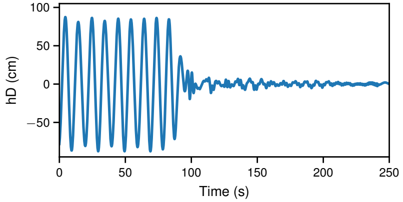
Artist impression of UCXRB (ESA-C. Carreau)

Gravitational wave signal

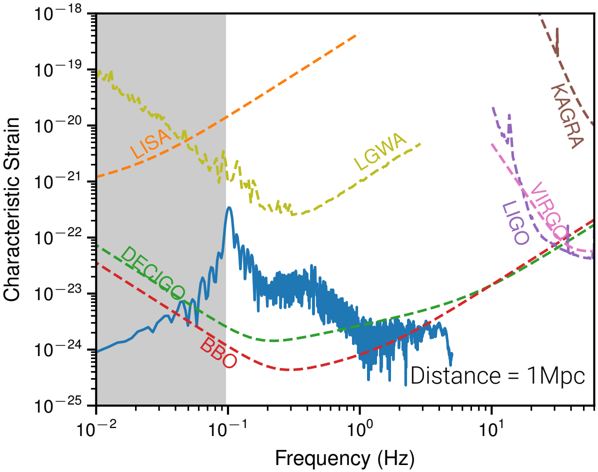




Gravitational wave signal

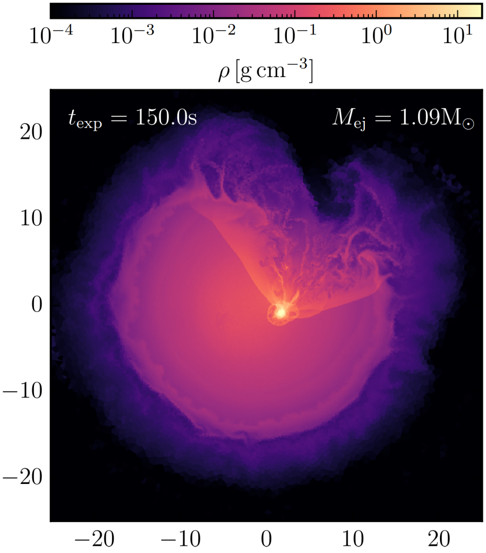


- Signal shuts down after disruption
- Merger signal peaks at 0.1Hz
- Only in range of deci-Hertz observatories

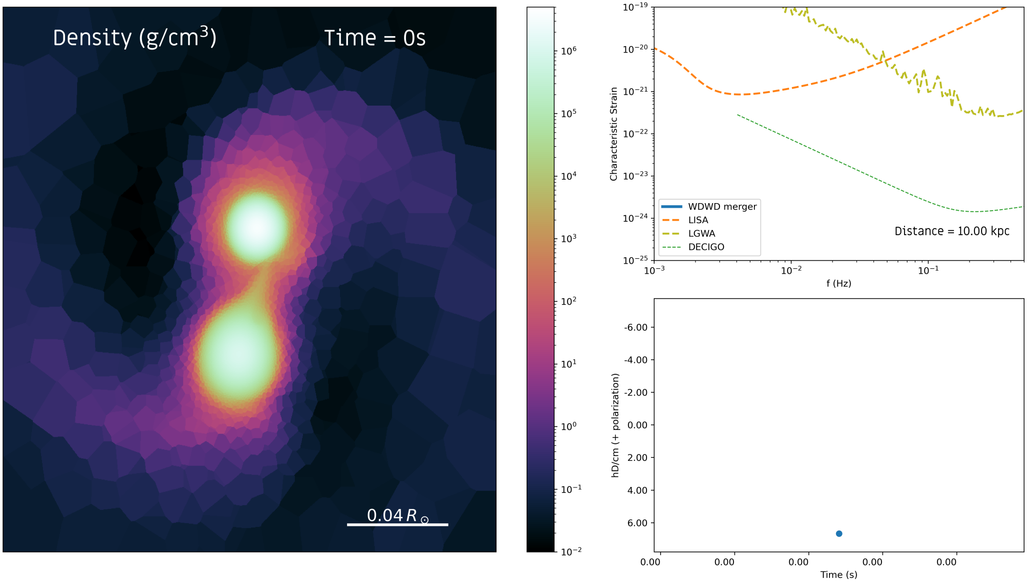


WD - WD binaries

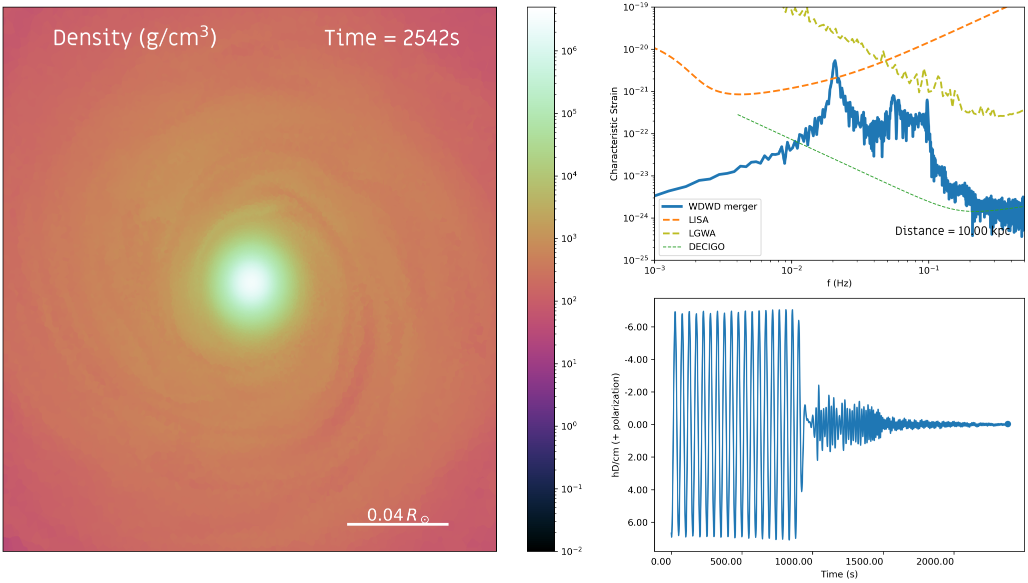
- Most common type of DCO
- Targets for GW astronomy (LISA)
- Interaction can have many different outcomes
- Hot subdwarf stars
- Type Ia SNe
- Ca-strong transients
- Faint Type Ia-like transients ...



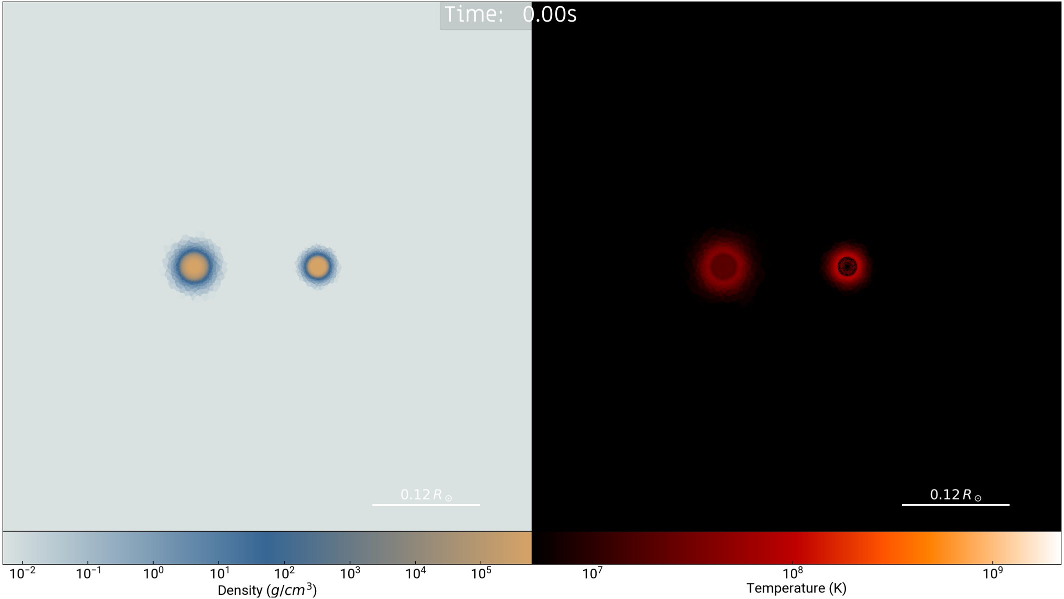
Pakmor et al. 2022

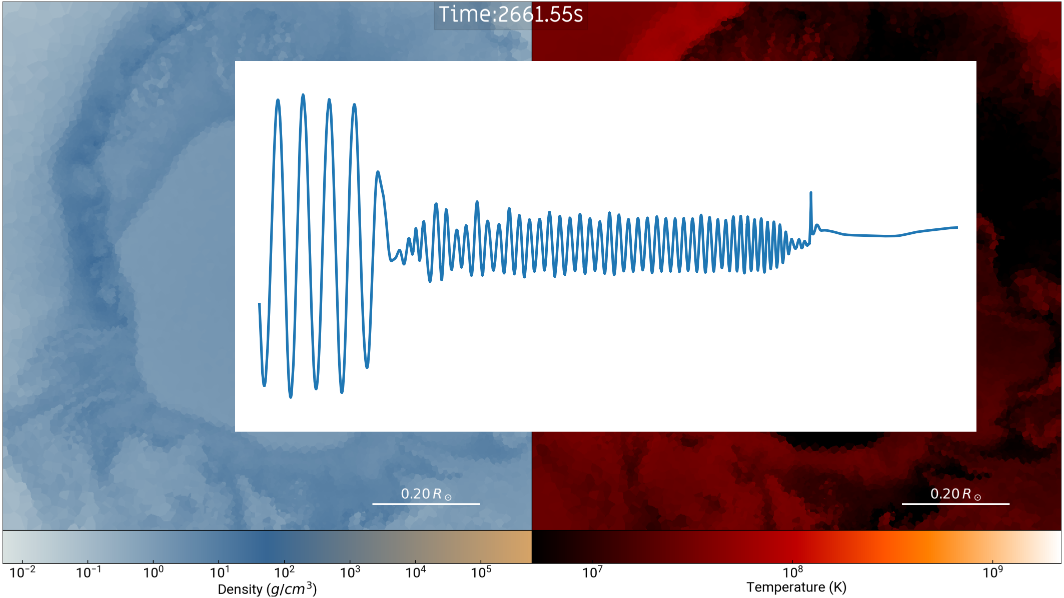


Density (g/cm³)
Time = 0s
0.04 R☉
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
Characteristic Strain
WDWD merger
LISA
LGWA
DECIGO
Distance = 10.00 kpc
f (Hz)
hD/cm (+ polarization)
Time (s)



Density (g/cm^3)
Time = 2542s
$0.04\,R_\odot$
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
Characteristic Strain
f (Hz)
WDWD merger
LISA
LGWA
DECIGO
Distance = 10.00 kpc
hD/cm (+ polarization)
Time (s)


Time: 0.00s
$0.12\,R_\odot$
$0.12\,R_\odot$
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
Density (g/cm^3)
10^{7} 10^{8} 10^{9}
Temperature (K)



Time:2661.55s
0.20 $R_\odot$
0.20 $R_\odot$
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
Density (g/cm^3)
10^{7} 10^{8} 10^{9}
Temperature (K)

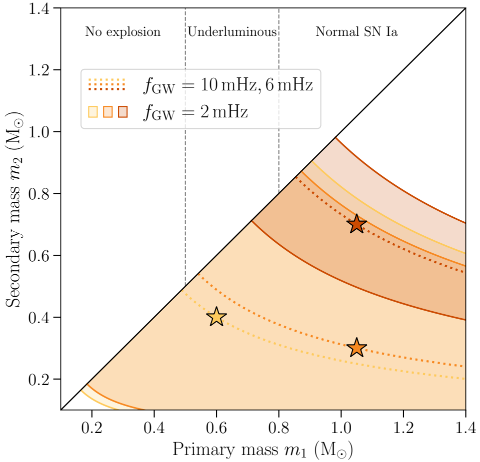
When do WD mergers explode?

How can GWs help?

Korol et al. 2024

- LISA will provide a complete sample of galactic WD binaries
- Constrains on merger rates
- Constrains on merger masses

Indirect constrains on which WD mergers can result in bright transients



Korol et al. 2024

Thank you!

Summary

- There is a myriad of potential transients arising from WD mergers. (GRBs, SNIa, Ca-strong transients, FBOTS, FRBs ...)
- WD mergers are GW sources mostly in the cHz-dHz range
- Multimessenger approach in this regime would be huge!
- 4th generation GW detectors (or with LISA if very close)
- LISA can help constrain the outcomes of WDWD mergers
- 3D simulations are already producing the first templates for these systems

Discussion points

- How important will be templates for next-gen GW detectors?
- What else can 3D simulations provide?

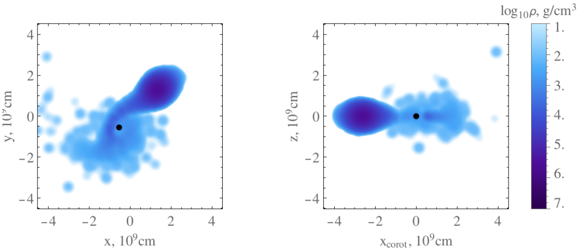
NS-WD mergers

Main Challenges

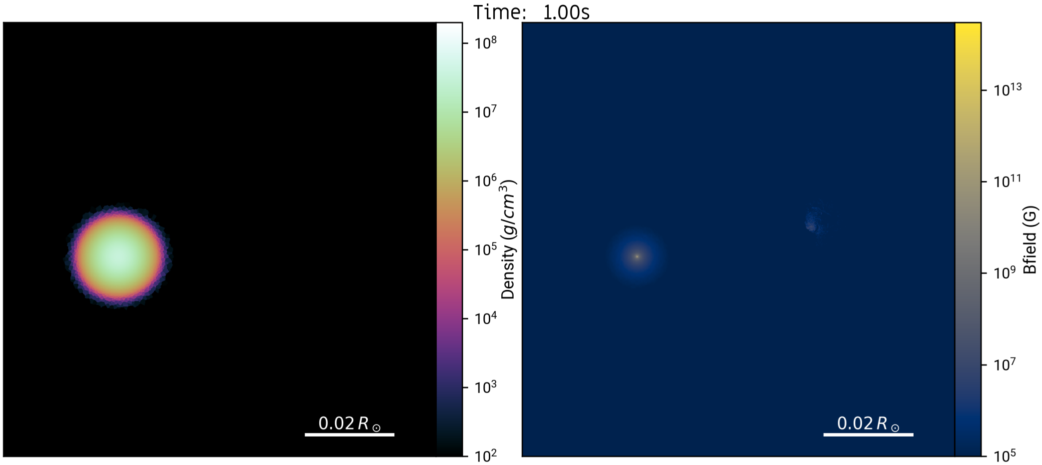
- Vast range of time and length scales:
  - NS radius: $\sim$ 10km
  - WD radius: $\sim$ 6000km
  - NS $t_{dyn} \sim 10^{-5}$ s
  - WD $t_{dyn} \sim 1$ s
  - Merger timescale $> 10^2$ s
- Very steep density gradients

Previous works in 3D

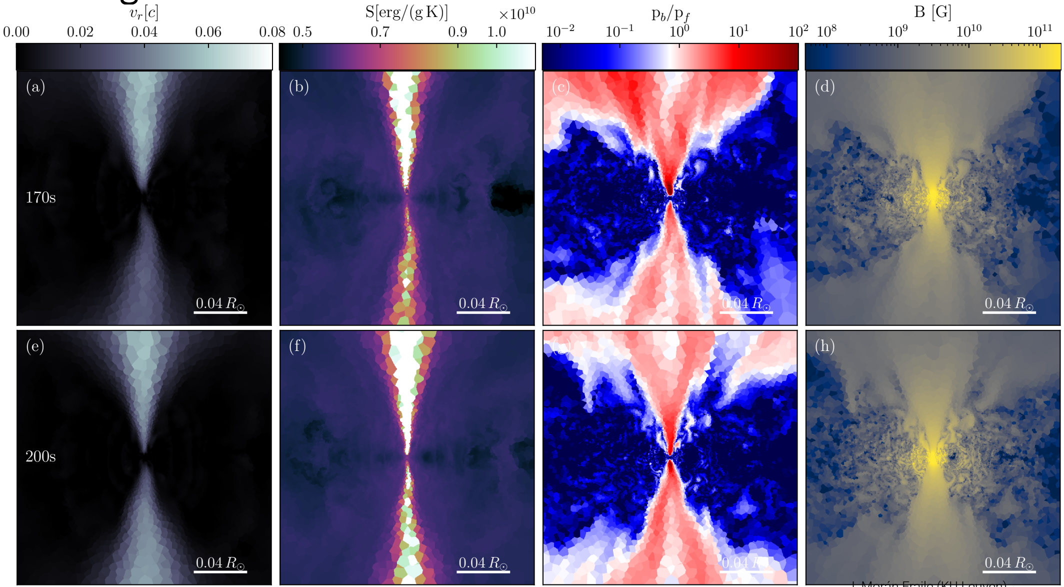
- Paschalidis et al. 2011: GRHD merger using "pseudo-WD"
- Zenati et al. 2020, Bobrick et al. 2023: 3D SPH



Zenati et al. 2020


Time: 1.00s
0.02 $R_\odot$
Density (g/cm^3)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
0.02 $R_\odot$
Bfield (G)
10^{13}
10^{11}
10^9
10^7
10^5

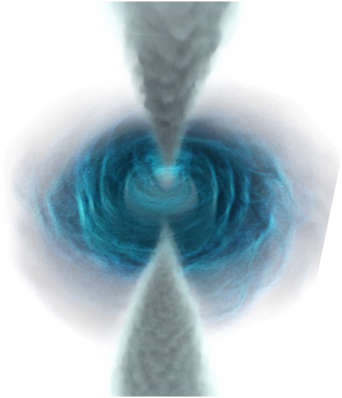
Jet magnitudes



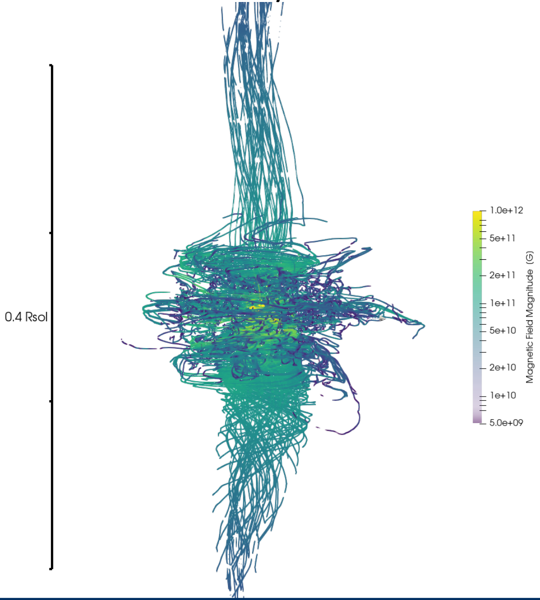
NS-WD Jet

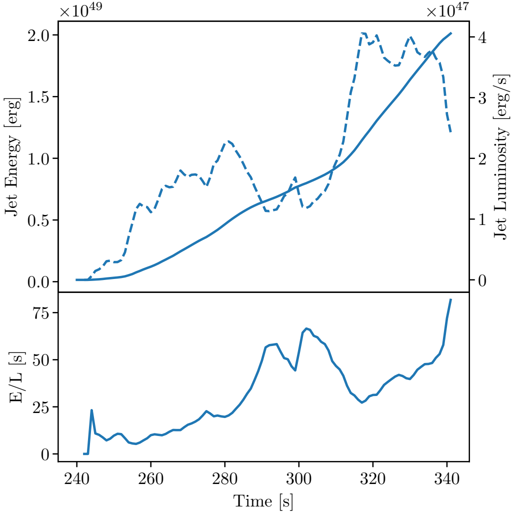
Summary

- Max. radial velocity ~ 0.1c.
- Opening half-angle $\theta \sim 20\,\mathrm{deg}$
- Peak Luminosity $= 4 \times 10^{47}$erg/s.
- Jet Energy $= 2 \times 10^{49}$erg.
- Mass ejection rate $\sim 3 \times 10^{-4} M_{\odot}$/s.



Jet luminosity





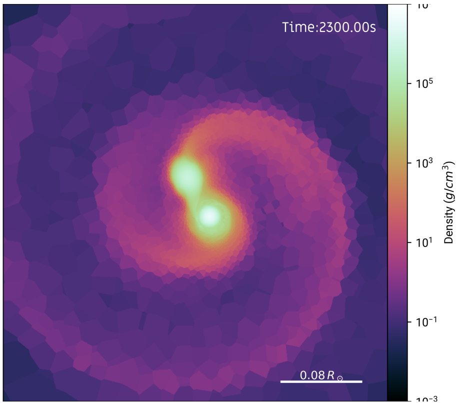
WD mergers

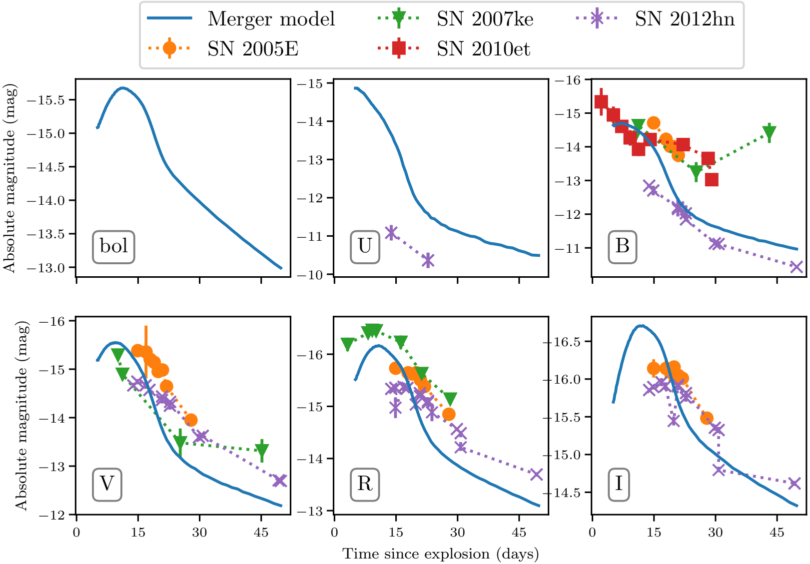
Moran-Fraile 2024b

- $0.4M_\odot$ HeWD (RG core) + $0.6M_\odot$ CO-WD as companion
- Initial separation $0.05R_\odot$
- No nuclear reactions

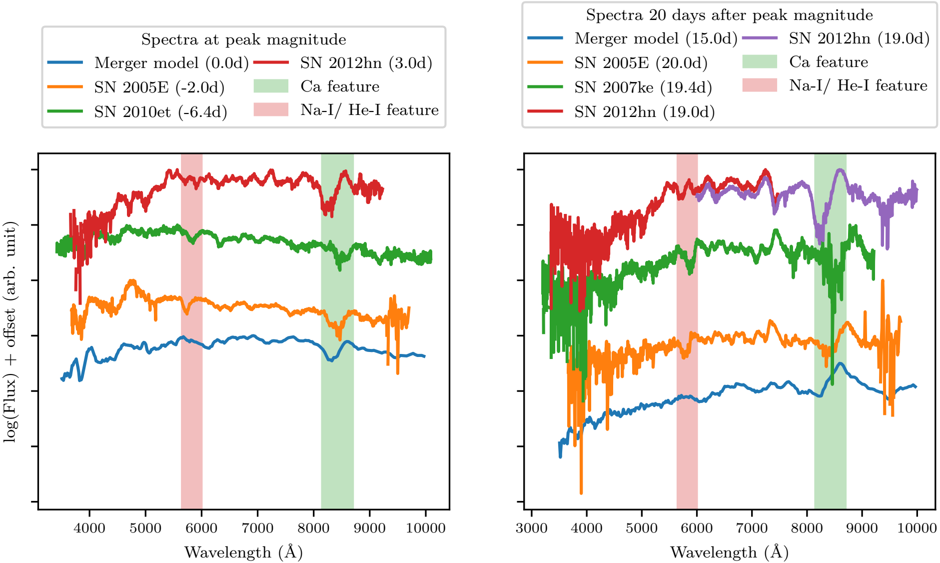
Outcome

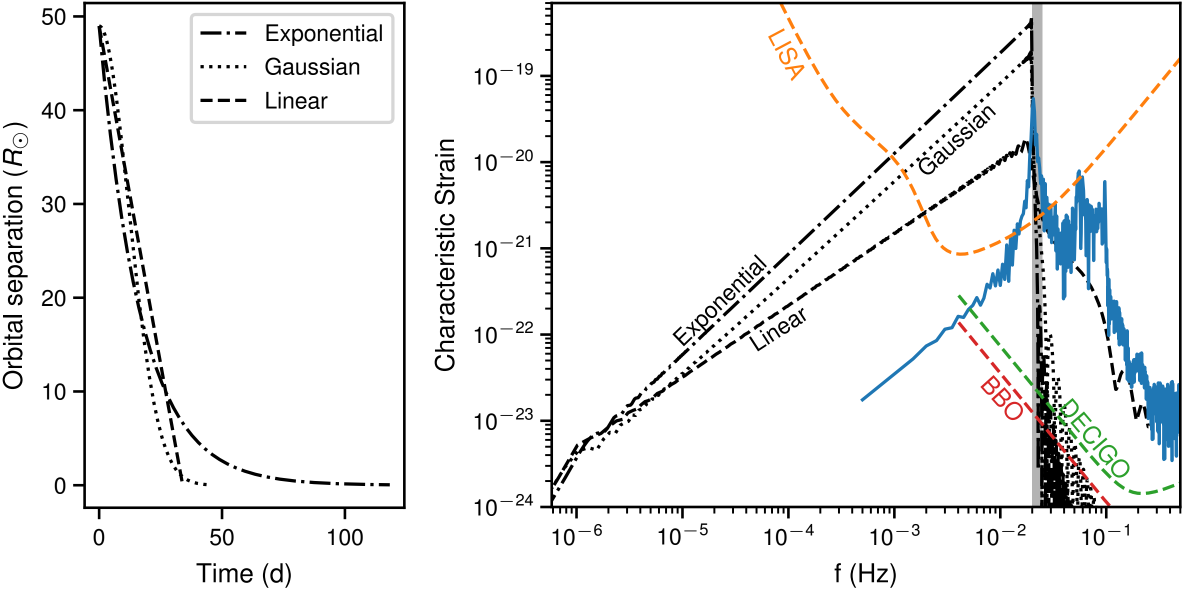
- Tidal disruption of core
- $0.11M_\odot$ accreted
- Disk-like structure





Merger model
SN 2005E
SN 2007ke
SN 2010et
SN 2012hn
bol
U
B
V
R
I
Absolute magnitude (mag)
Time since explosion (days)


Spectra at peak magnitude
Merger model (0.0d)
SN 2012hn (3.0d)
SN 2005E (-2.0d)
Ca feature
SN 2010et (-6.4d)
Na-I/ He-I feature
log(Flux) + offset (arb. unit)
4000
5000
6000
7000
8000
9000
10000
Wavelength (Å)
Spectra 20 days after peak magnitude
Merger model (15.0d)
SN 2012hn (19.0d)
SN 2005E (20.0d)
Ca feature
SN 2007ke (19.4d)
Na-I/ He-I feature
SN 2012hn (19.0d)
3000
4000
5000
6000
7000
8000
9000
10000
Wavelength (Å)



Orbital separation ($R_\odot$)
Time (d)
Exponential
Gaussian
Linear
Characteristic Strain
f (Hz)
LISA
BBO
DECIGO
Exponential
Gaussian
Linear