# Multi-messenger astronomy for white dwarf mergers – *a theorist's perspective*

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*with*

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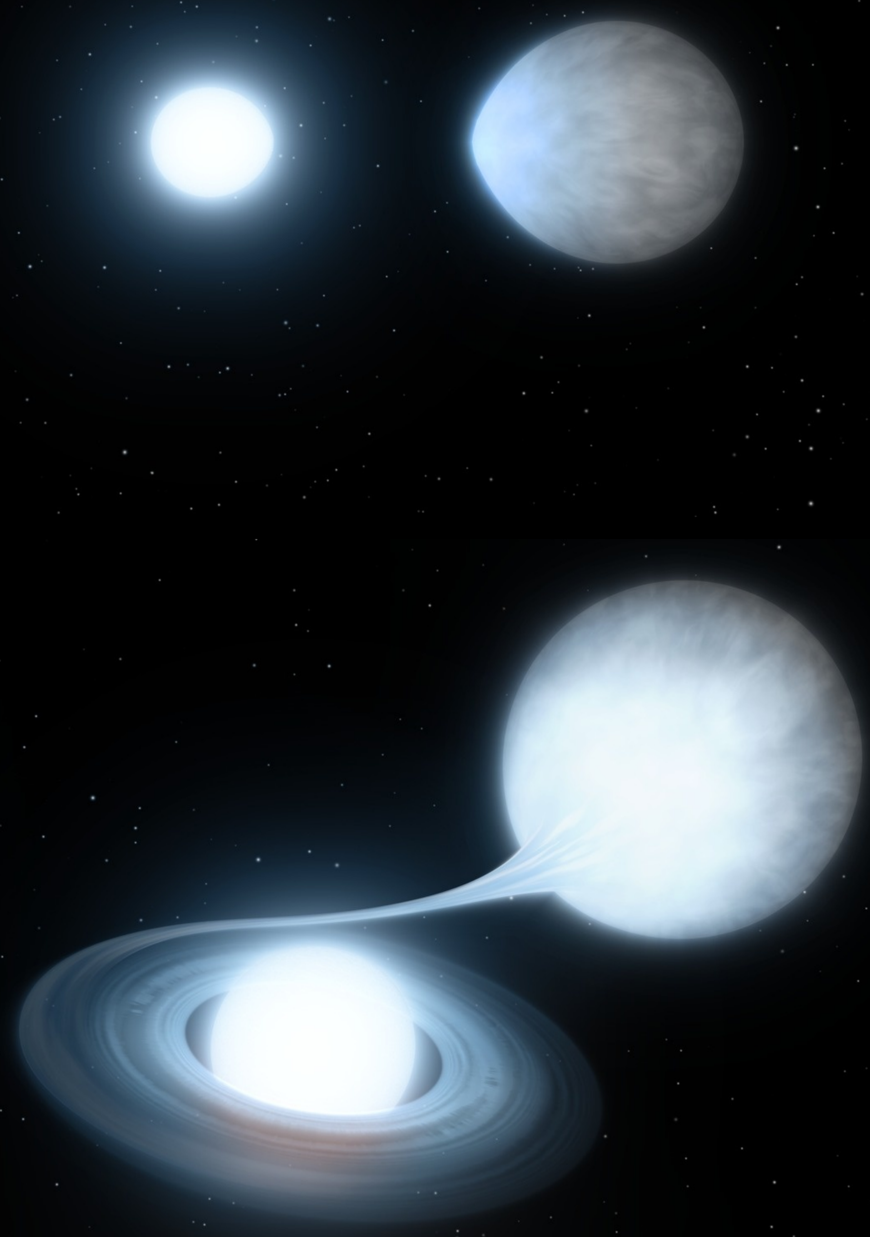
# Why would we be interested in WD mergers?

- How frequent are they?
- What do they result in?

Artwork credit: Caltech (ZTF)

# WD mergers are a common phenomenon

- about $10^{10}$ WDs in Galaxy
  (Napiwotzki 2009)
- about $2.5 \times 10^{8}$ of them in WD–WD binaries (Nelemans+ 2001)
  → most common DCOs
- about half of them close enough such that GW emission drives them into contact, most will merge
  (Nelemans+, 2001)

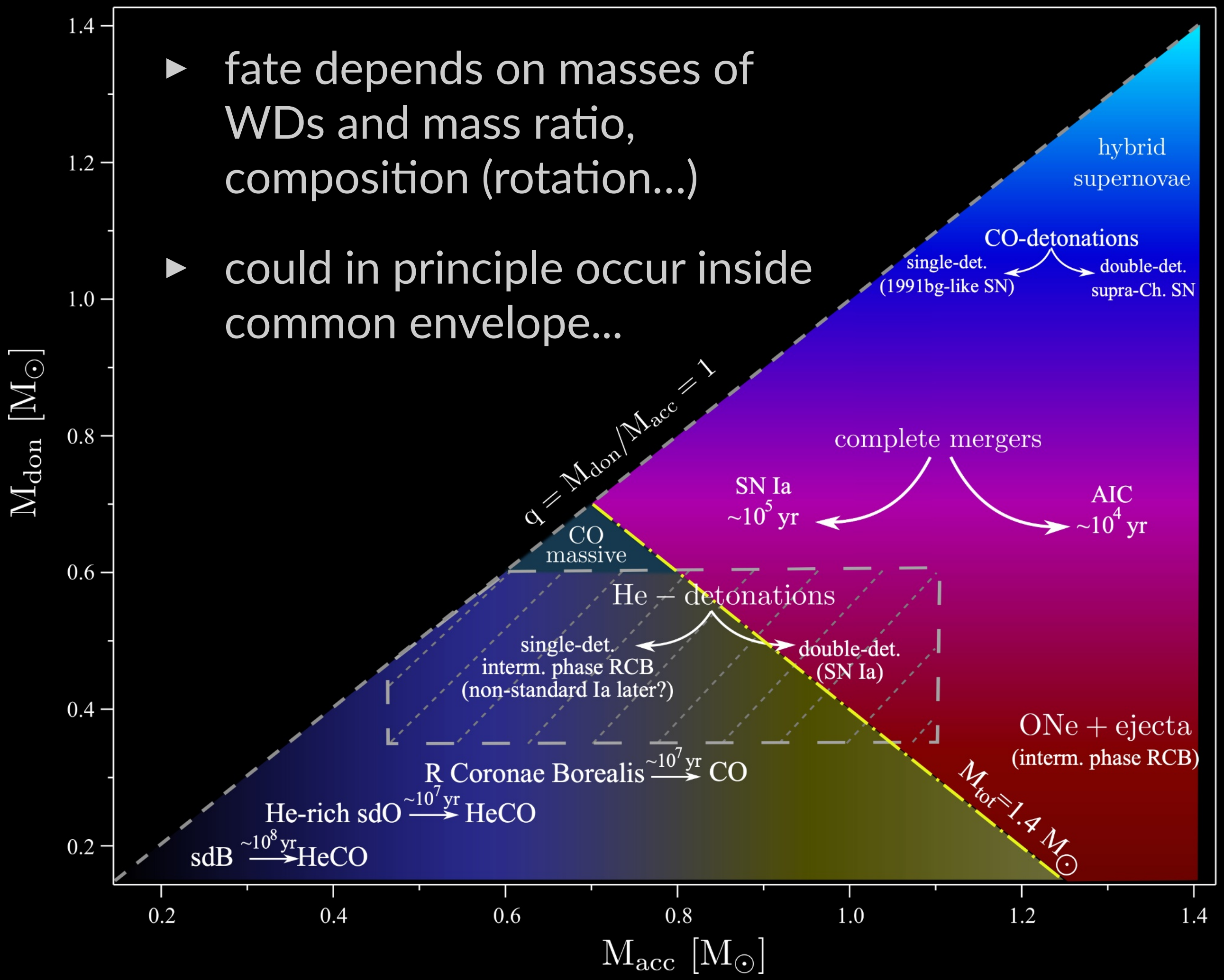


# WD mergers give rise to a zoo of astrophysical phenomena

- thermonuclear supernovae
- classical nova outbursts
- formation of R Coronae Borealis stars
- formation of He rich subdwarfs sdB and sdO
- accretion-induced collapse (AIC) to neutron star (or thermonuclear ECSN)
- ...

Dan+, 2014

- fate depends on masses of WDs and mass ratio, composition (rotation...)
- could in principle occur inside common envelope...



# What can we learn from studying WD mergers?

- determine the progenitor system and explosion mechanism of Type Ia supernovae (see also Benetti+, 2025)
- test hypothesized formation channels for RCB stars and hot subdwarfs
- understand how highly magnetized WDs form
- constrain mechanism CE interaction
- ...

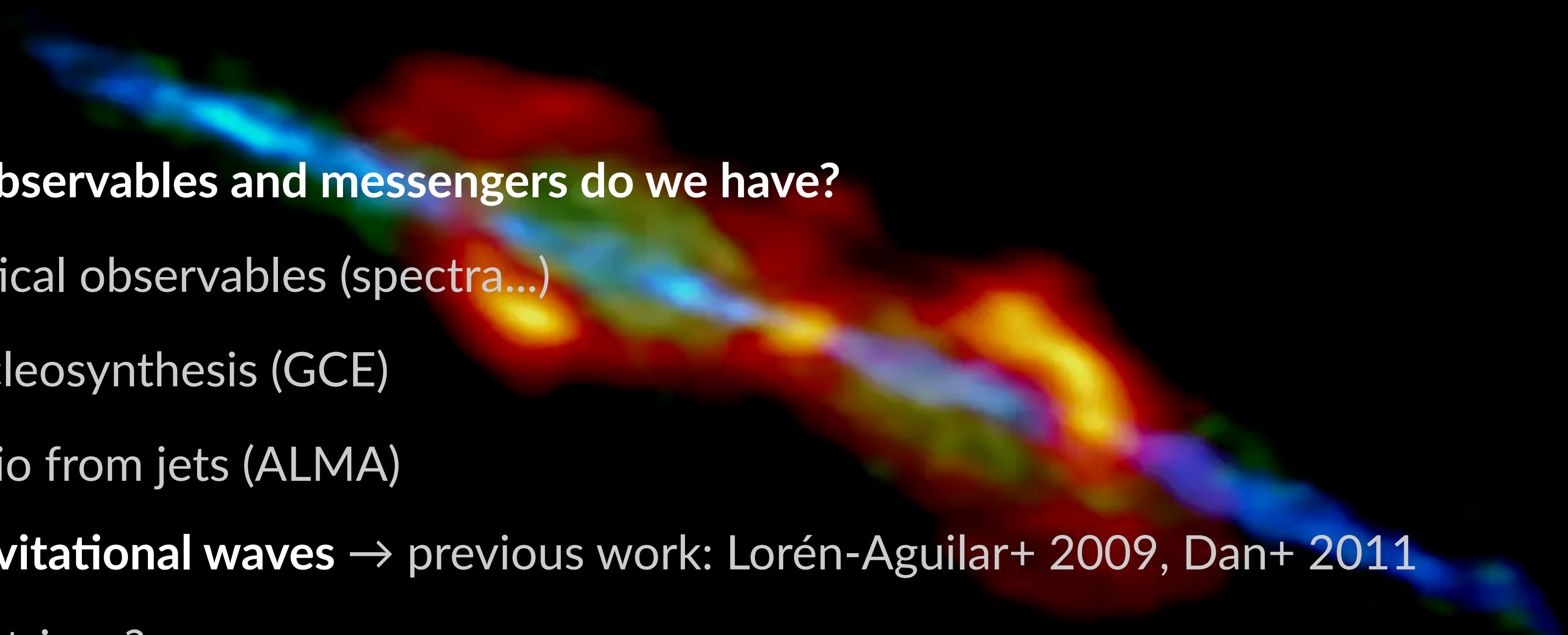
# Physical processes in merging WDs

- mass ejection
- mixing of composition near surface of more massive WD
- magnetic field amplification
- formation of jet-like outflow
- dynamic (in some cases explosive) thermonuclear burning
- gravitational collapse to NS
- **emission of gravitational waves**

# How can we make progress?

theorist's view: **simulate interaction/merger processes of WDs** and **derive multimessenger observables**

- why important? as usual in astronomy, signals are degenerate and it is hard to settle physical models with single observations...



**What observables and messengers do we have?**

- optical observables (spectra...)
- nucleosynthesis (GCE)
- radio from jets (ALMA)
- **gravitational waves** → previous work: Lorén-Aguilar+ 2009, Dan+ 2011
- neutrinos?

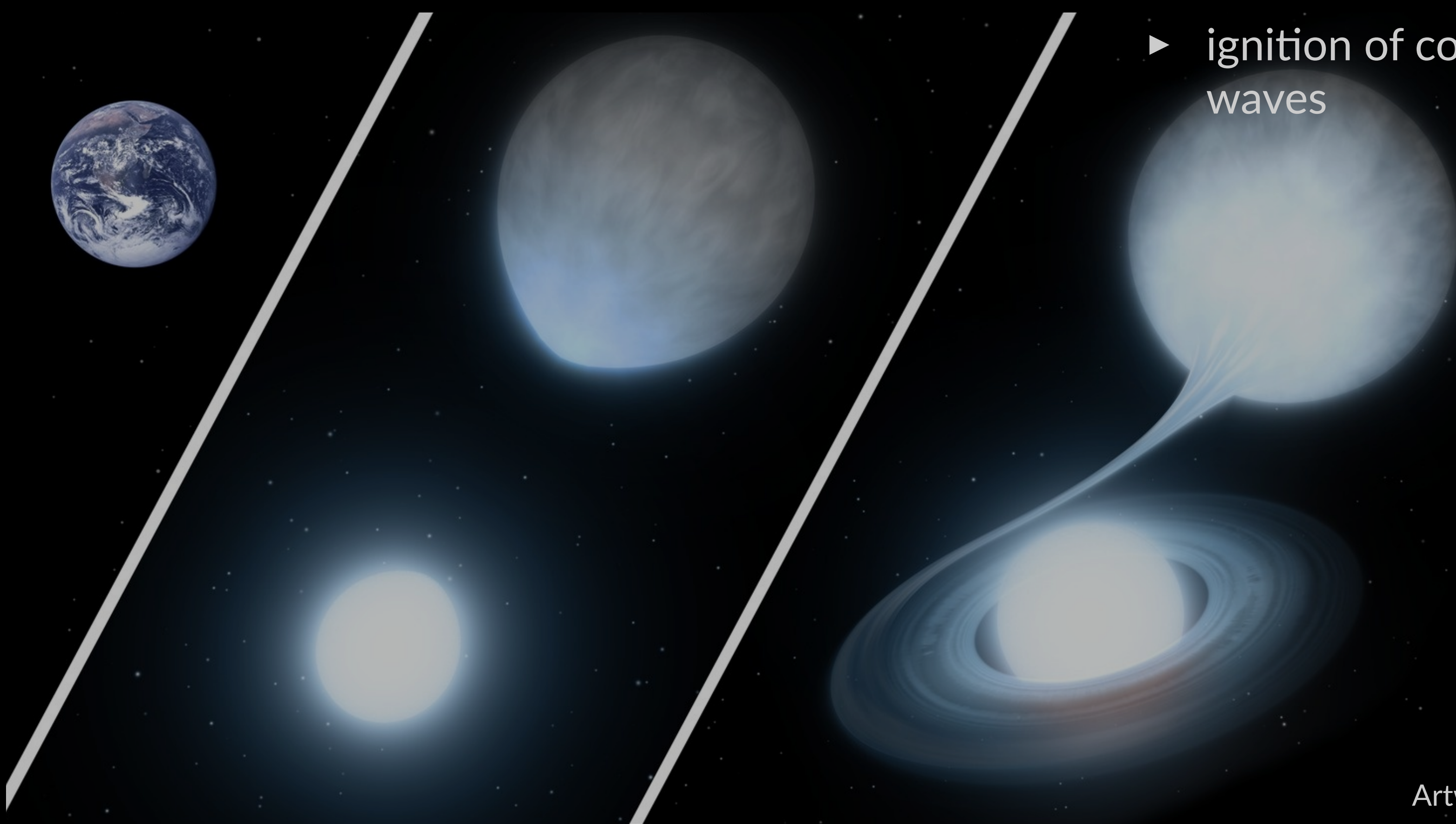
# Simulating WD mergers

**reasonably accessible to numerical simulations**

- spatial scales
- timescales

**limitations:**

- equilibration of remnant
- resolution of mixing and burning processes
- ignition of combustion waves



Artwork credit: Caltech (ZTF)

# Numerical approaches

Springel, 2010

- Smooth Particle Hydrodynamics

- moving mesh MHD
  → Arepo

# Derivation of the GW signal

- all our simulations are non-relativistic
- quadrupole radiation from Newtonian gravity (Morán Fraile+ 2023, Seitenzahl+ 2015, Blanchet+ 1990, Nakamura & Oohara 1989)
- usually written out as a “by-product” from all our simulations

# Common-envelope events

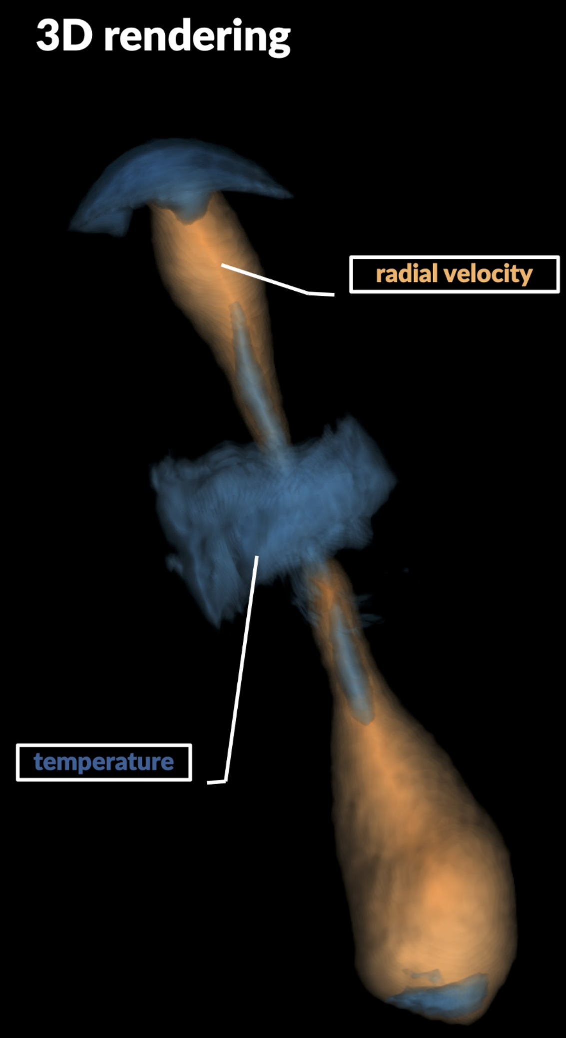
- example: 2 $M_\odot$ (49 $R_\odot$) RG primary star with 0.6 $M_\odot$ WD companion (Morán Fraile+ 2023)
- **if envelope ejected successfully → cores don't merge**
- rate of inspiral not determined by GW emission but by drag force in envelope (see also Ginat+ 2020, Renzo+ 2021)
- final orbital separation ~3.6 $R_\odot$ (orbit eccentric) → peak frequency $3.4 \times 10^{-5}$ Hz
- envelope contributes little (and only at very low frequencies) to GW emission

# Successful CE ejection

- Morán Fraile+, 2023 (assumed distance: 1 kpc)

# Formation of bipolar planetary nebulae

- two velocity components: toroidal slow ~10 – 30 km/s ejected envelope material and narrow polar magnetically driven outflow with ~ 90 – 130 km/s
- morphology of ejected material resembles structure of bipolar PNe





Calabash Nebula (OH 231.8+04.2)

# Common-envelope events

- example: 2 $M_\odot$ (49 $R_\odot$) primary star with 0.6 $M_\odot$ WD companion
- **core merger if envelope ejection fails**
- rate of inspiral initially dominated by drag force in envelope, later by mass transfer between cores and tidal interaction
- final phase of core merger simulated without envelope:

  $\rightarrow$ merger between 0.4 $M_\odot$ He WD and 0.6 $M_\odot$ CO WD

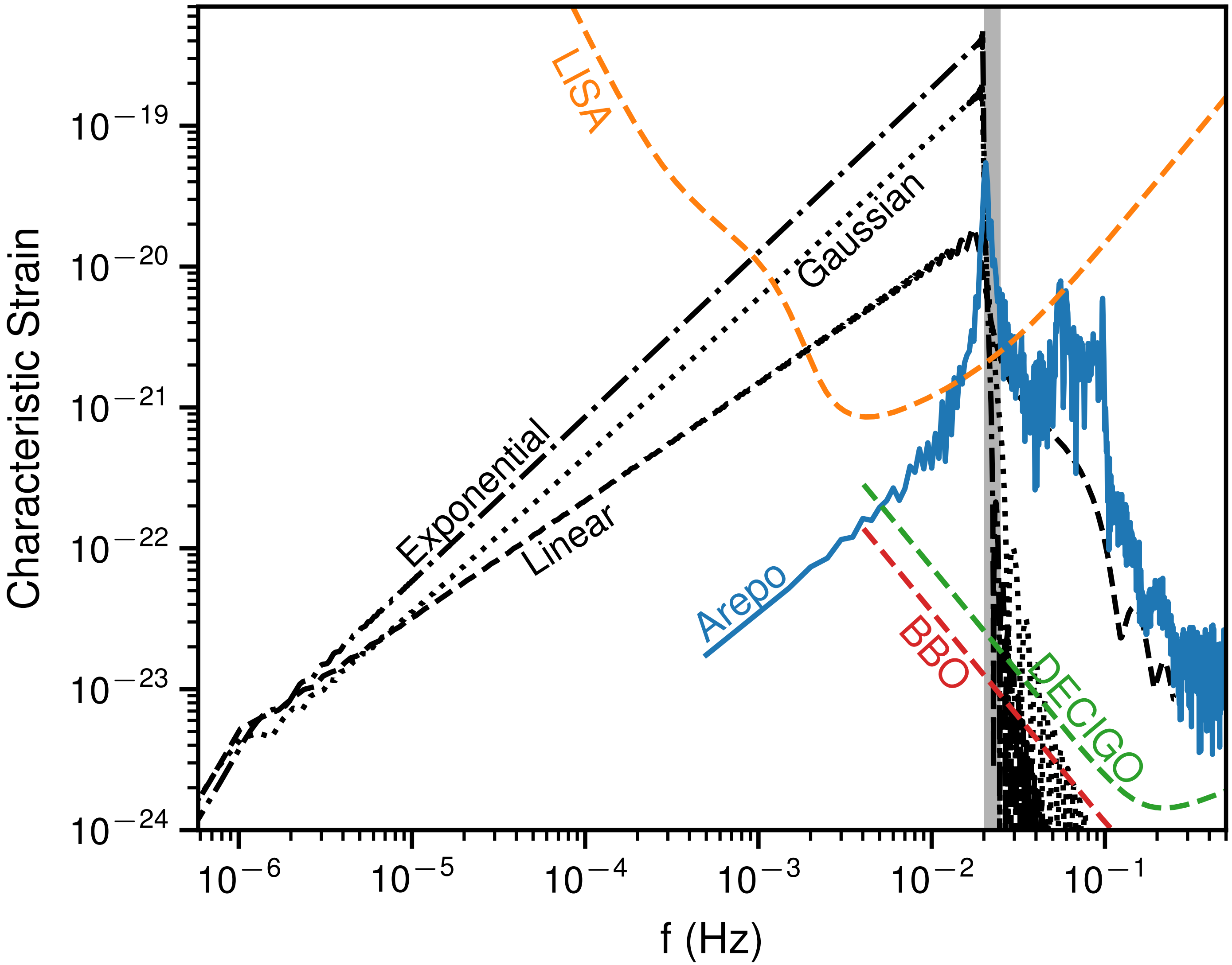
# CE merger

- Morán Fraile+, 2023

# Adding a CE inspiral phase

- simple analytic fits

  (Morán Fraile+, 2023)



# Magnetically driven jets in CE mergers or WD mergers

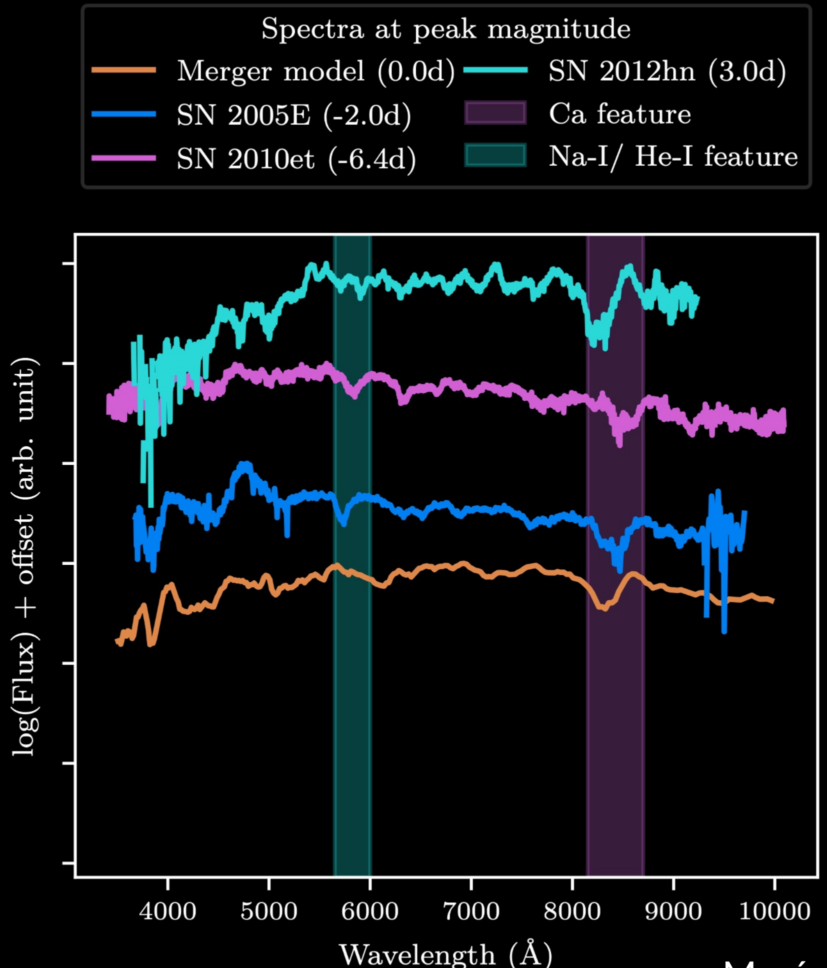
- Morán Fraile,
  unpublished

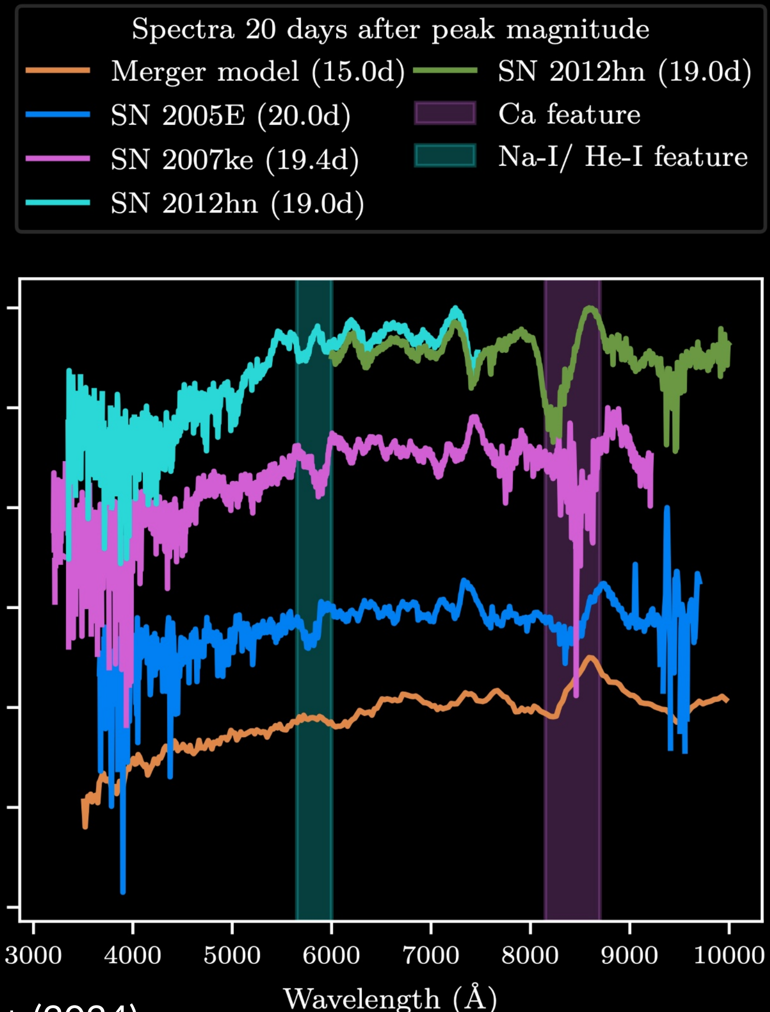
# Switching on nuclear reactions

- Morán Fraile+, 2023

# Optical observables

- $8\times10^{-3}$ $M_\odot$ of $^{56}$Ni, most He unburnt, rich in $^{40}$Ca → Ca-rich transient? (NLTE spectra: Callan+ subm.)

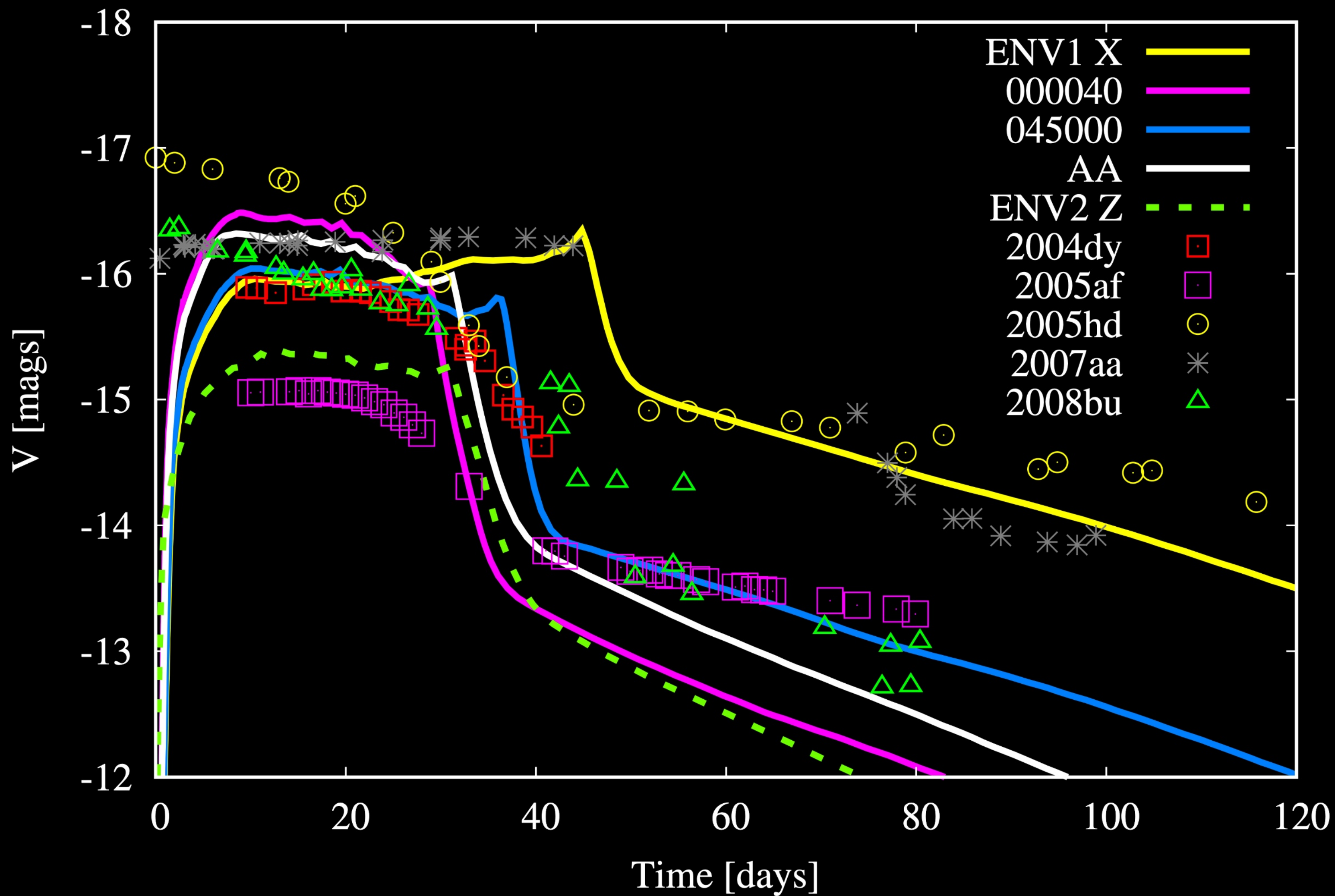



Morán-Fraile+ (2024)

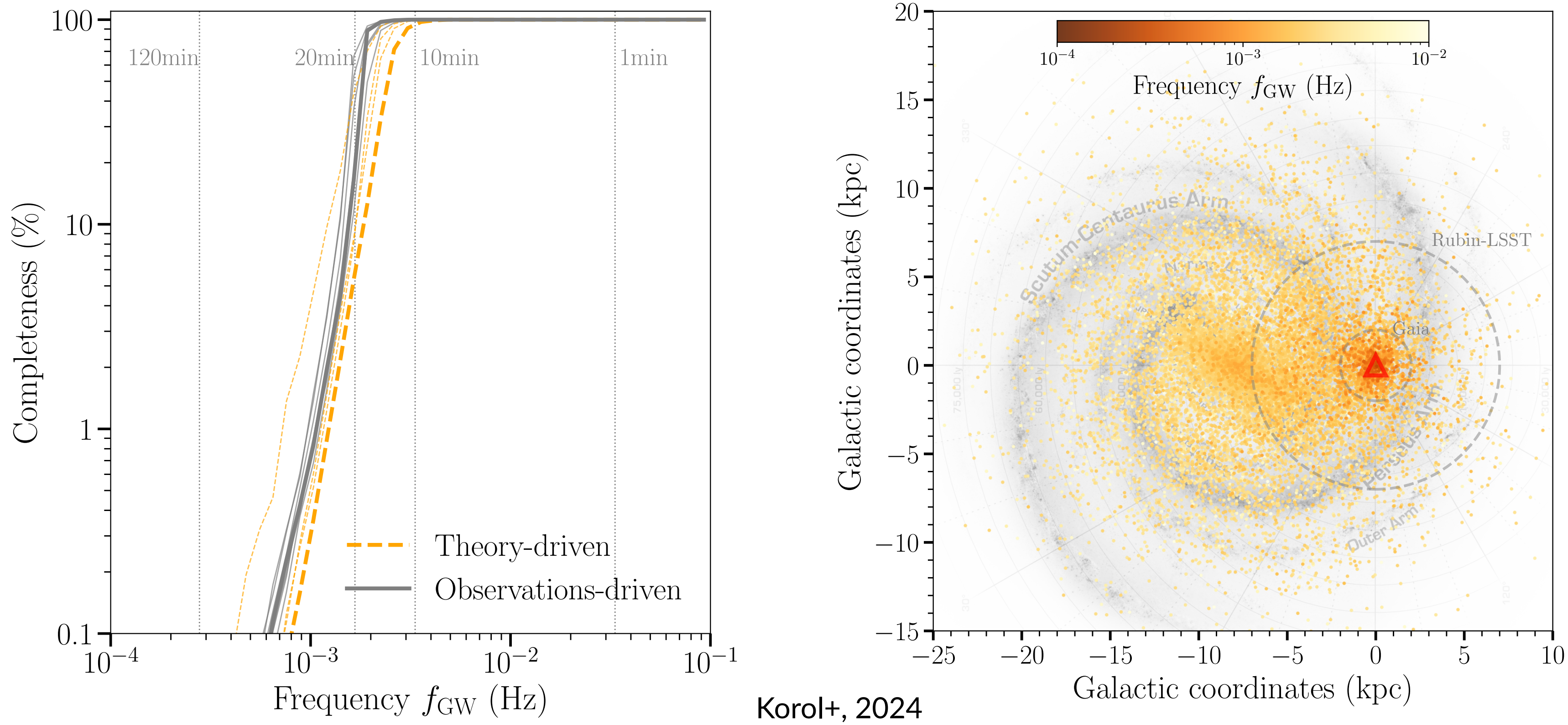
# Optical observables

- thermonuclear Type II supernova! → Kozyreva+, 2024



# GW signals of SNe Ia

- GW signals from $M_{Ch}$ WD explosion models (Falta+ 2011, Seitenzahl+ 2015)
- WD merger: explosion → disappearance of a nearly monochromatic wave (Seto 2023)
- Korol+, 2024: LISA provides complete sample of double WD SN Ia progenitors in the Galaxy; chirp masses put lower constraints on mass of primary WD




Korol+, 2024

# GW signals of SNe Ia

Korol+, 2024

- direct observation → likelihood 3-7% in 10 years (Korol+, 2024)
- target for multimessenger astronomy → combine with SN Ia electro-magnetic signal to validate explosion mechanism (Korol+, 2024)

# Non-explosive WD mergers

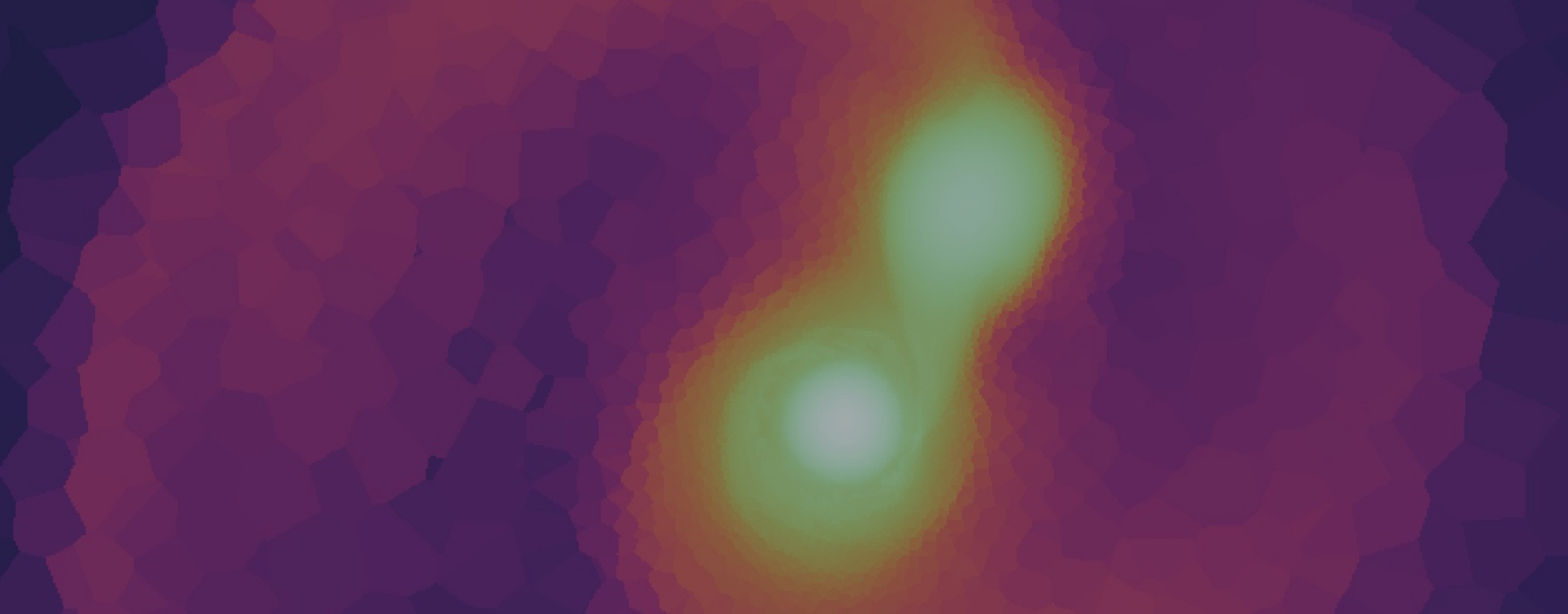
- merger between 0.3 $M_\odot$ He WD and 0.6 $M_\odot$ CO WD (Agaeva+ in prep.)
- potential formation channel of RCB stars
- observations show low $^{16}O/^{18}O$
- dynamic, but non-explosive He burning near the surface of the CO WD that can produce $^{18}O$ (Holas+, subm.)
- magnetic fields strongly amplified, polar (jet-like?) outflow

# Non-explosive WD mergers

- Agaeva+ in prep.

# Summary

- LGWA can make important contributions to understanding WD mergers
- interesting targets for multimessenger astronomy



- parameter space will be explored with numerical simulations → produce the GW signal as a standard result
- Would a data base of GW signals from our simulations be useful?

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