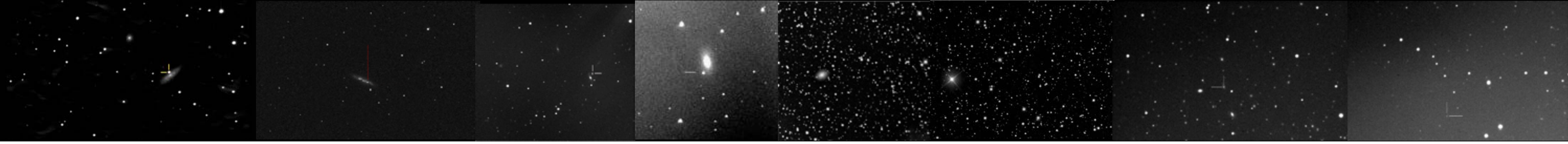

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White dwarf close encounters with SPH simulations

Gabriela Aznar-Siguan, Pablo Lorén-Aguilar, Enrique García-Berro

ESAC, 26/02/2015

Related news

The double-degenerate, super-Chandrasekhar nucleus of the planetary nebula Henize 2-428

M. Santander-García[1,2], P. Rodríguez-Gil[3,4], R. L. M. Corradi[3,4], D. Jones[3,4], B. Miszalski[5,6], H. M. J. Boffin[7], M. M. Rubio-Díez[8] & M. M. Kotze[5]

The planetary nebula stage is the ultimate fate of stars with masses one to eight times that of the Sun ($M_\odot$). The origin of their complex morphologies is poorly understood[1], although several mechanisms involving binary interaction have been proposed[2,3]. In close binary systems, the orbital separation is short enough for the primary star to overfill its Roche lobe as the star expands during the asymptotic giant branch phase. The excess gas eventually forms a common envelope surrounding both stars. Drag forces then result in the envelope being ejected into a bipolar planetary nebula whose equator is coincident with the orbital plane of the system. Systems in which both stars have ejected their envelopes and are evolving towards the white dwarf stage are said to be double degenerate. Here we report that Henize 2-428 has a double-degenerate core with a combined mass of $\sim$1.76$M_\odot$, which is above the Chandrasekhar limit (the maximum mass of a stable white dwarf) of 1.4$M_\odot$. This, together with its short orbital period (4.2 hours), suggests that the system should merge in 700 million years, triggering a type Ia supernova event. This supports the hypothesis of the double-degenerate, super-Chandrasekhar evolutionary pathway for the formation of type Ia supernovae[4].

The hypothesis of binarity as being essential to producing bipolar plan-

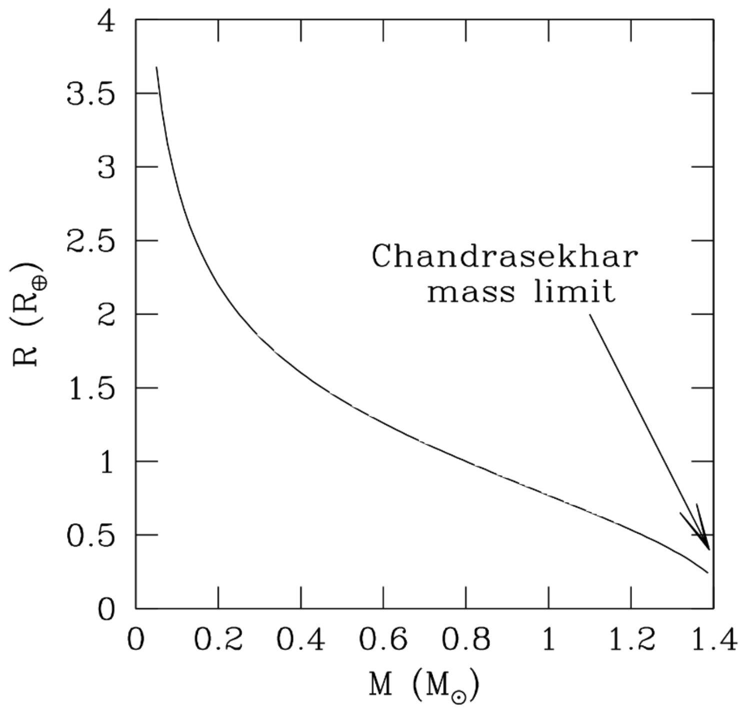
(GTC). Gaussian fitting of the absorption-line profiles followed by sinusoidal fitting to the data 'folded' (that is, the time of the data is converted into orbital phase) on the orbital period indicates that both radial velocity amplitudes are identical, with values of 206 ± 8 km s^{-1} and 206 ± 12 km s^{-1}, respectively. The very similar depths of the light-curve minima, intensities of the He II 541.2 nm stellar absorption lines, and velocity amplitudes indicate that the two stars have nearly identical masses and effective temperatures. The latter can be constrained by the presence of the photo-ionized nebula and by the lack of He II emission lines in the spectrum of the nebula. The effective temperatures of the stars have therefore been kept between 20,000 K and 40,000 K in our modelling.

The combined analysis of the light curves and radial-velocity curves[12,13] yields the orbital parameters of the system (Table 1). The result is a double-degenerate binary in 'overcontact', that is, both stars are overfilling their Roche lobes. The total luminosity of the system, 845$L_\odot$, where $L_\odot$ is the solar luminosity, is compatible with the 690$L_\odot$ reported in the literature[14].

The inclination of the orbital plane is confined to a narrow range between 63.4° and 66.1° (see Table 1), close to the $\sim$68°-inclined equa-

White dwarfs

- Stellar remnants of MS stars between $0.5M_\odot$ and $10M_\odot$.
- 97% of the stars in the Milky Way are going to end up as WD.
- Composed mostly of electron-degenerate matter.



Supernovae Type Ia

- Thermonuclear explosion of a WD, most likely CO.
- Initial consensus model: accreting WD before reaching M_{Ch} explodes.
- Very usefully used as standardisable distance candles and have provided the first indication for an accelerating Universe.

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- Thermonuclear explosion of a WD, most likely CO.
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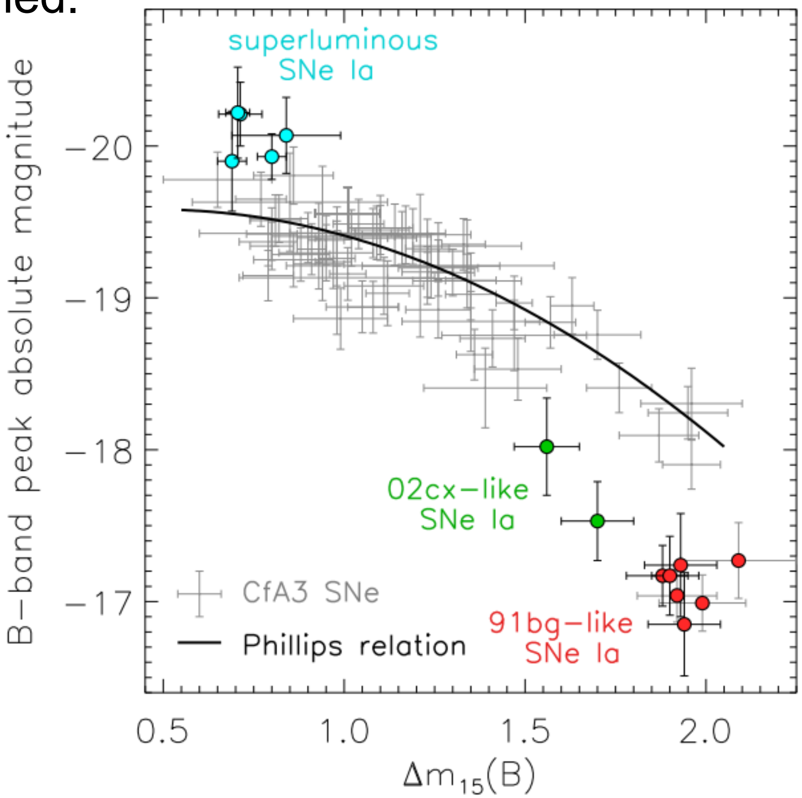
- Subclasses identified.

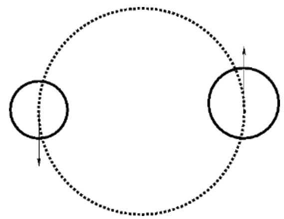


Hillebrandt et al 2013

Different progenitor scenarios and explosion mechanisms. Linked?

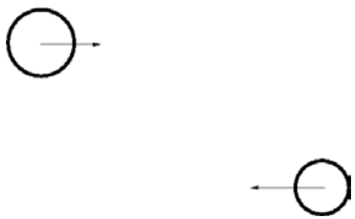
Ways to explode WDs

…involving two WDs



merger in WD binary

(e.g. Iben & Tutukov 1984, Webbink 1984)



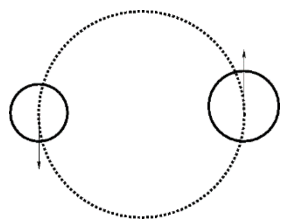
WD collision

(Rosswog et al. 2009)

When is the explosion triggered?

Ways to explode WDs

…involving two WDs



merger in WD binary

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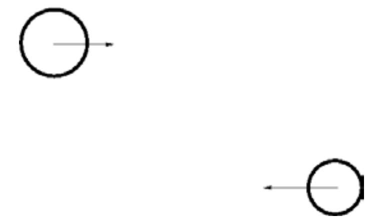


WD collision

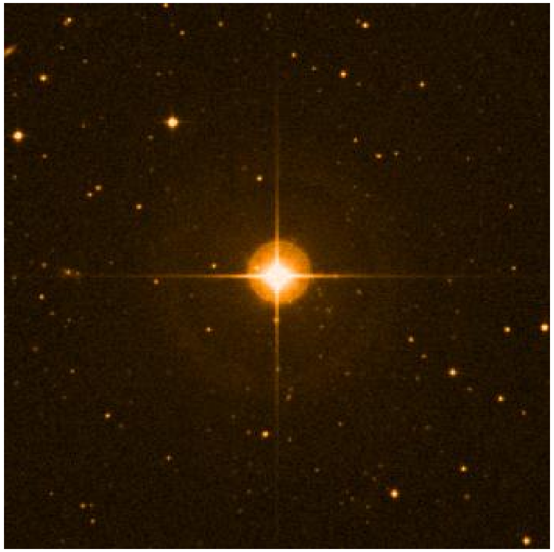
(Rosswog et al. 2009)

- During merging process in violent mergers (e.g. Pakmor et al. 2011).
- During collision (e.g. Rosswog et al. 2009, Raskin et al. 2009, Kuschnir et al 2013).
- Depending on the post evolution of the merger product (e.g. Saio & Nomoto 1998).

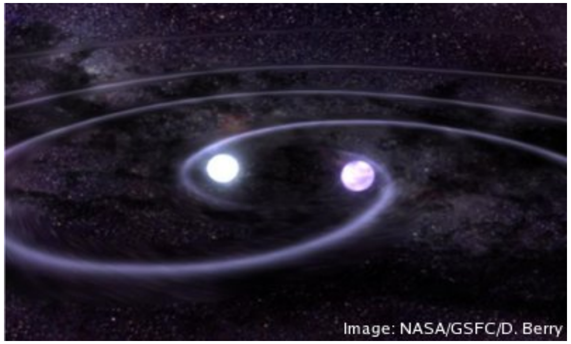
Other possible outcomes

- Non-explosive stellar objects that have been related to white dwarf interactions.

Anomalous X-ray pulsar



R Corona Borealis



White dwarf binaries

WD collisions

- Where? Old and dense stellar systems

Globular clusters:

- 10^6 stars pc^{-3} >> 1 star pc^{-3} (solar environs)
- Number density WDs 10^4 pc^{-3}
- Typical velocity dispersion 5 km/s
- 10^2-10^4 per galaxy

$\Rightarrow$ WD collision rate ~ 0.01 SN Ia rate

Galactic nuclei:

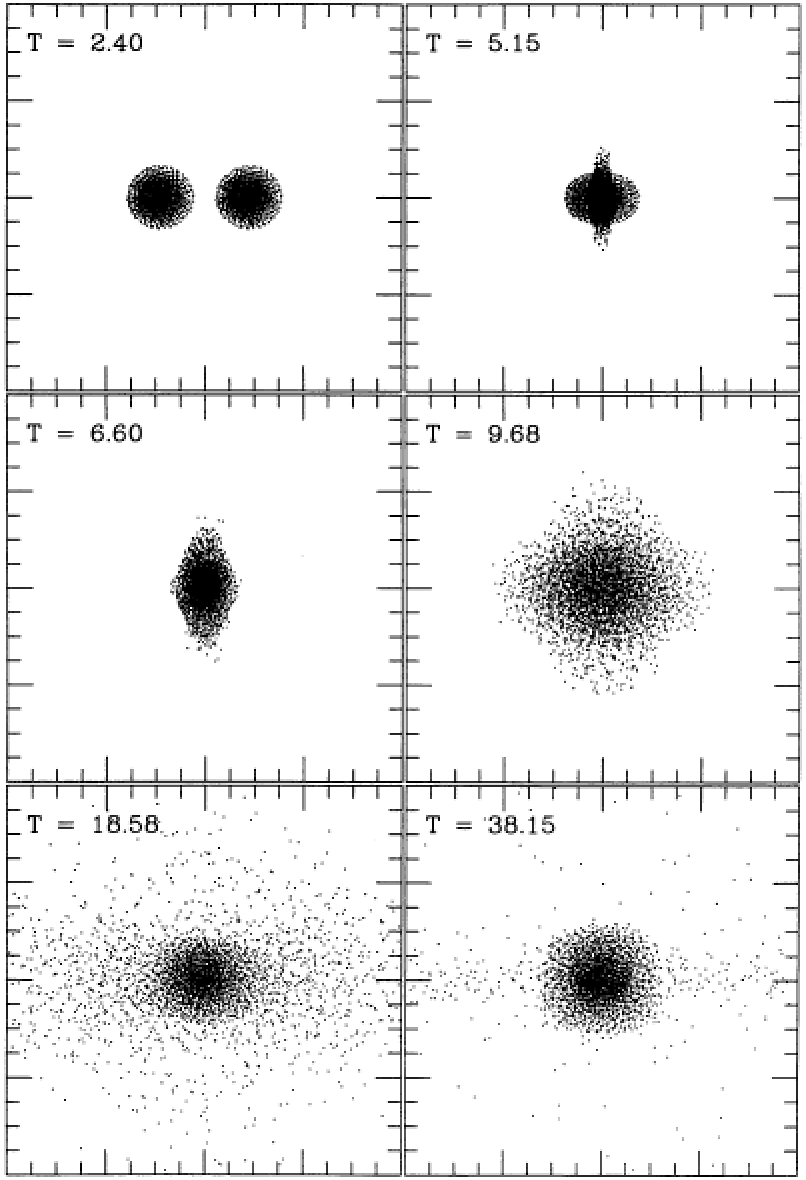
- Higher stellar densities ~ 10^8 stars pc^{-3}
- Greater velocity dispersions ~ 200 km/s

$\Rightarrow$ increased collision rates

- Also in perturbed multiple stellar systems (Kushnir et al. 2013)

Previous simulations

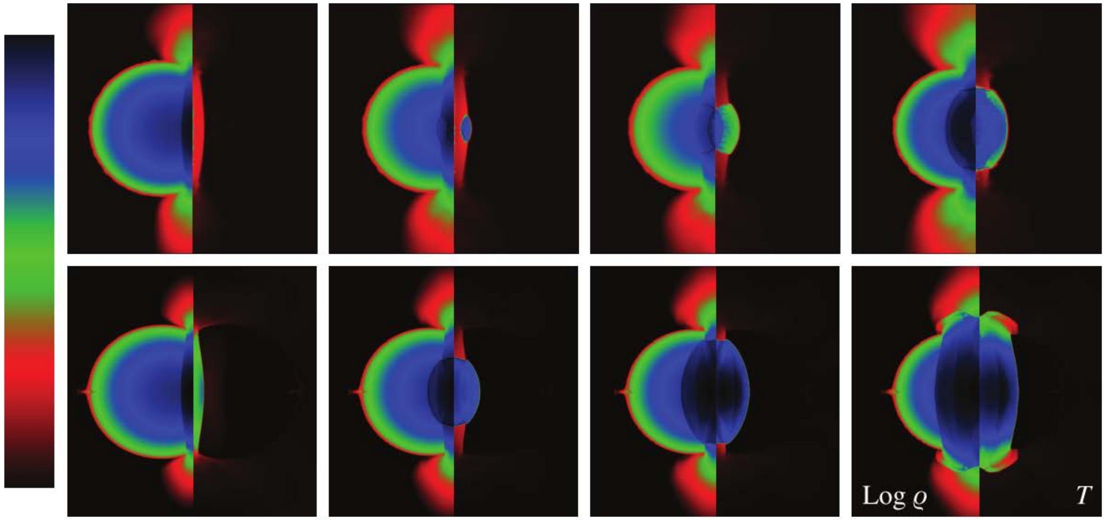
- Benz et al. 1989
  - Lagrangian: SPH
  - 5000 particles
  - Parabollic trajectories
  - No explosions



Benz et al 1989

Previous simulations

- Benz et al. 1989
- Rosswog et al. 2009
  - Lagrangian: SPH
  - Eulerian: FLASH
  - ~10^6 particles
  - Parabollic trajectories
  - Shock-triggered explosions

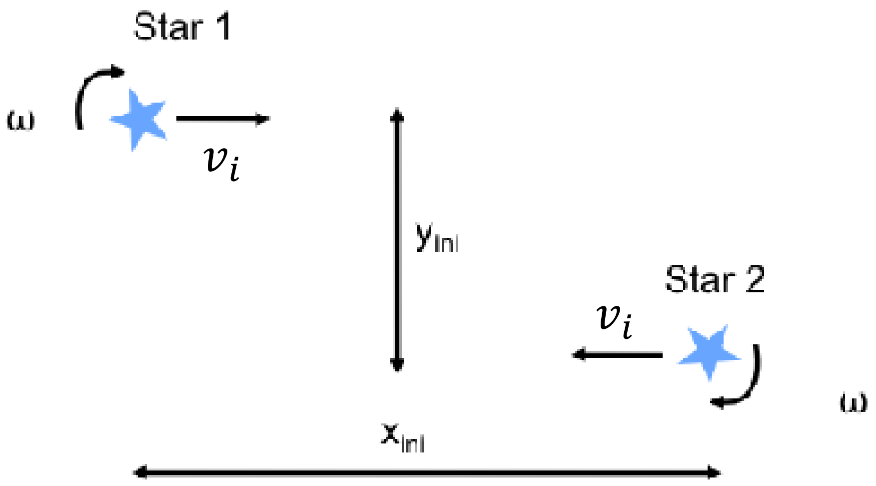


Rosswog et al 2009

- Raskin et al. 2009
- Lorén-Aguilar et al. 2009
- Hawley et al. 2012
- Kushnir et al.2013

Our approach

- Increase parameter space of Lorén-Aguilar et al. 2009:
  - Broader range of WD masses:
    $0.2\ M_{\odot},\ 0.4\ M_{\odot}, 0.6\ M_{\odot}, 0.8\ M_{\odot}, 1.0\ M_{\odot}, 1.2\ M_{\odot}$
  - Elliptical trajectories: post-capture scenario



$x_{ini} = 0.2\ R_{\odot}$

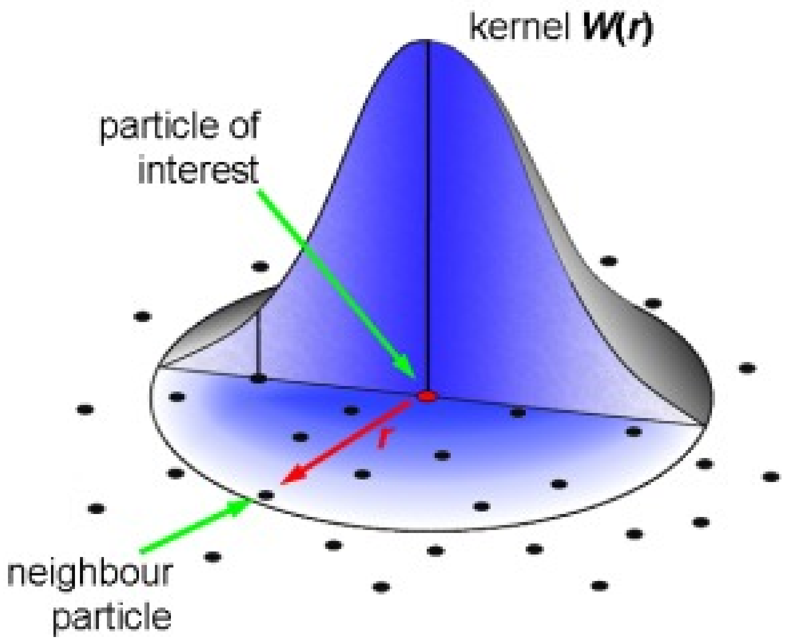
$y_{ini} \in \{0.3,\ 0.4\}\ R_{\odot}$

$v_i \in [75, 300]\ km/s$

- Compute different observational signatures.

SPH

- Smoothed Particle Hydrodynamics (SPH)
- Computing a continuos density field from a collection of point mass particles.



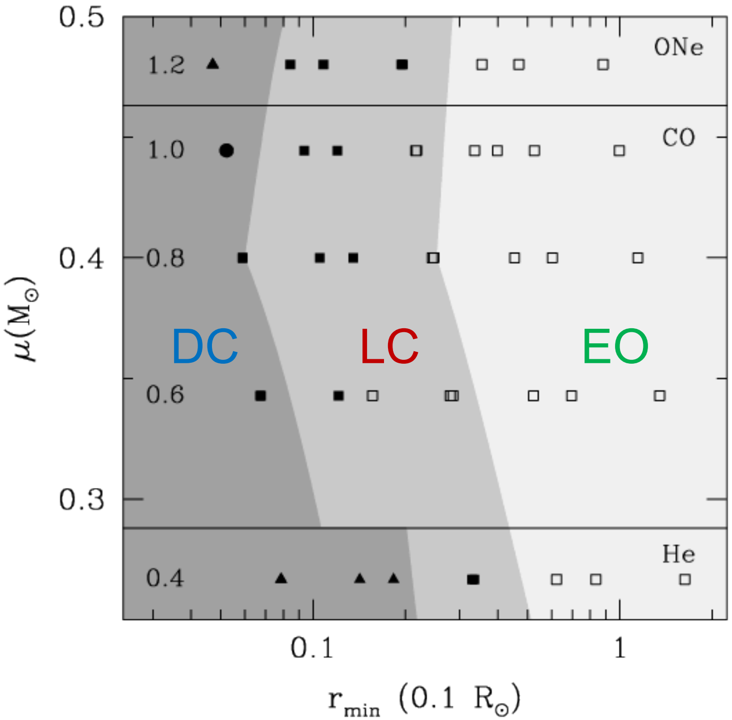
www.nuigalway.ie

Our SPH code

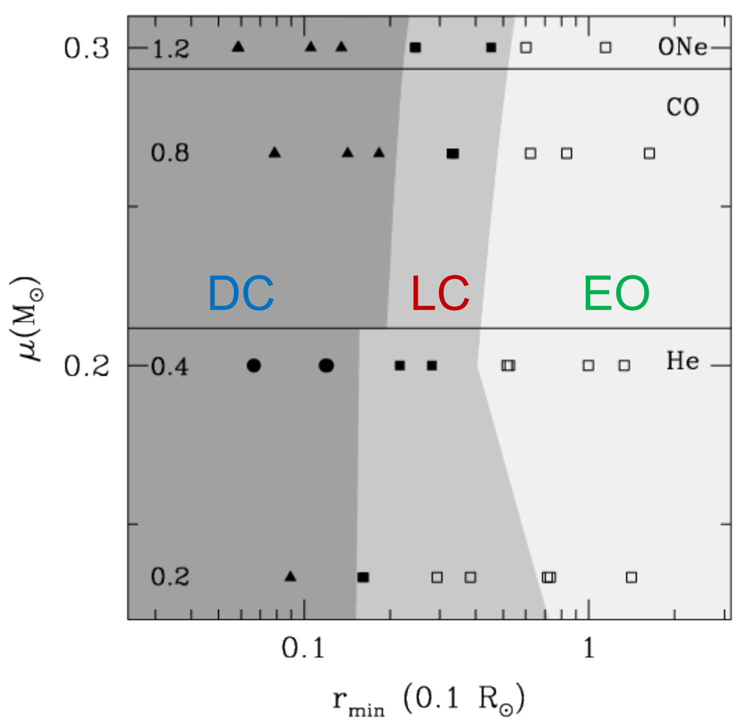
- Kernel: cubic spline of Monaghan & Lattanzio (1985).
- Tree: of Barnes & Hut (1986) to search neighbors and compute gravitational forces.
- Smoothing lengths: iteration method of Price & Monaghan (2007).
- Artificial viscosity: based on Riemann solvers (Monaghan 1997), variable viscosity parameters of Morris & Monaghan (1997) and switch of Balsara (1995).
- Double evolution of internal energy and temperature.
- EOS: Timmes & Swesty (2000).
- Nuclear network:
  - 14 nuclei : He, C, O, Ne, Mg, Si, S, Ar, Ca, Ti, Cr, Fe, Ni, Zn
  - Reactions: captures of α particles, associated back reactions, fusion of two C nuclei, reaction between C and O nuclei and between O and O.

Outcomes of the encounters

$0.8\ M_\odot$ +

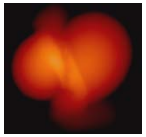


$0.4\ M_\odot$ +

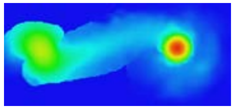


Aznar-Siguan et al 2013

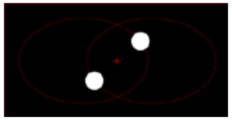
- Direct Collision (DC): one mass transfer



- Lateral Collision (LC): several mass transfers

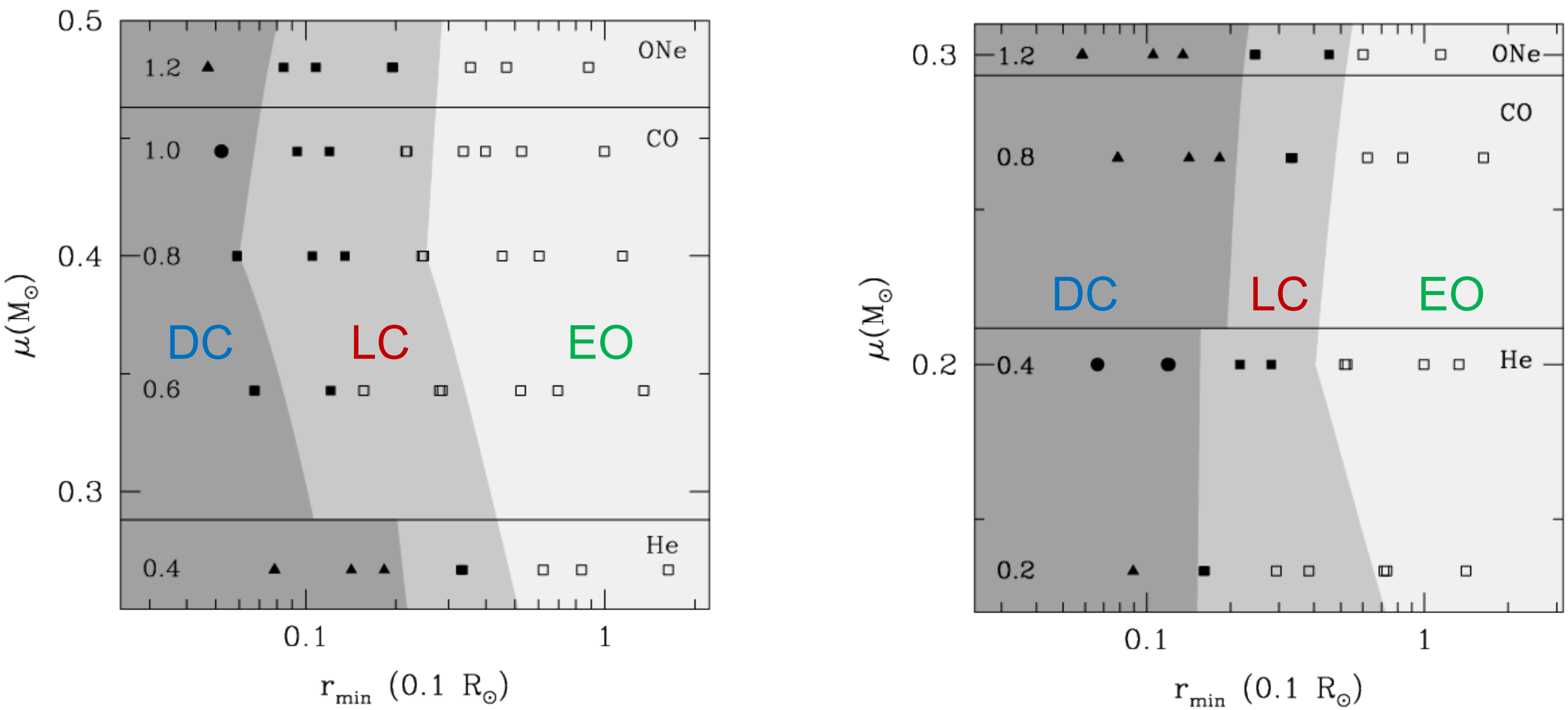


- Eccentric binary (EO): formation of eccentric binary



Outcomes of the encounters

$0.8\ M_{\odot}$ + $\qquad\qquad$ $0.4\ M_{\odot}$ +

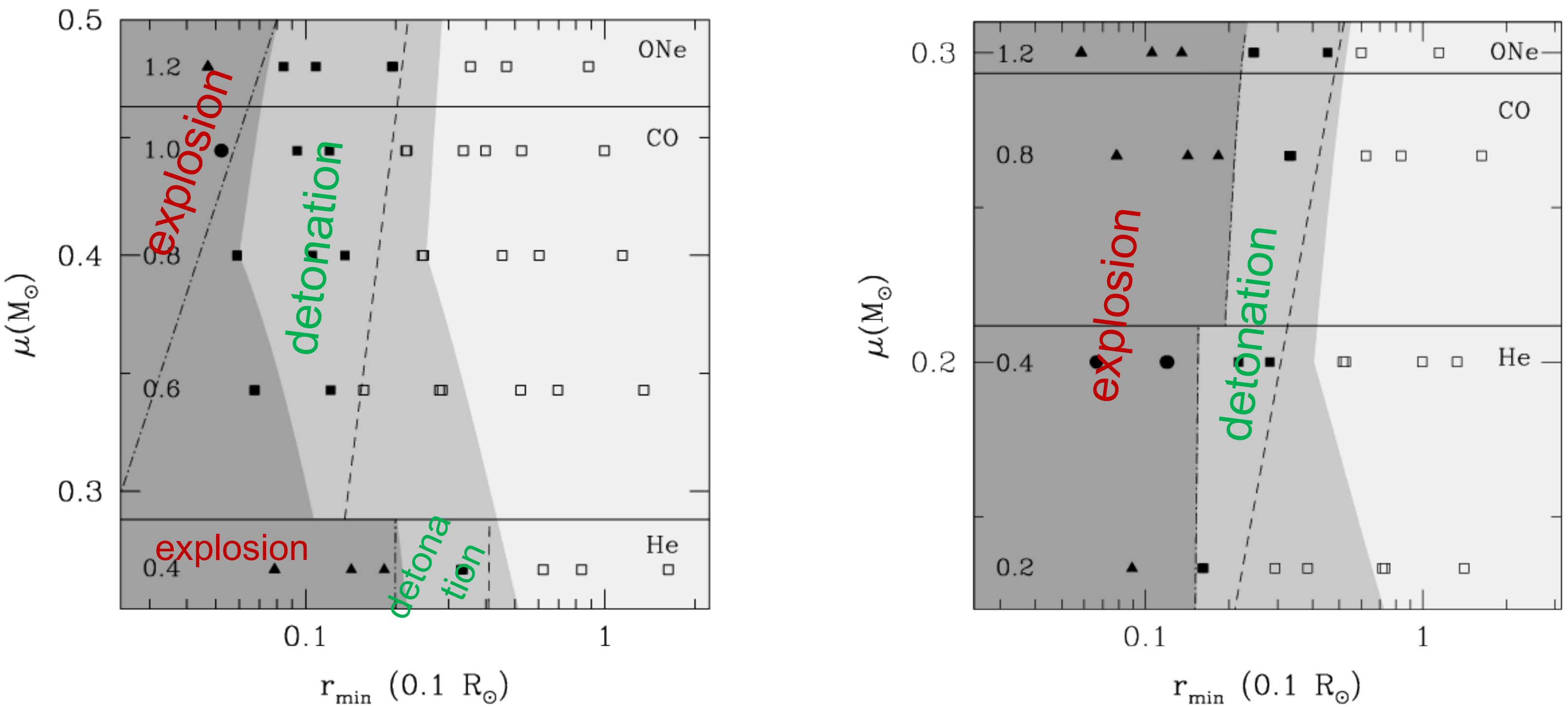


Aznar-Siguan et al 2013

- Direct Collision (DC): $r_{min} <$ -0.35R_1 +R_2 (without He)
- Lateral Collision (LC): $R_2 >$ 0.95 R_L, R_L Roche lobe
- Eccentric binary (EO)

Outcomes of the encounters

$0.8\ M_\odot$ + $0.4\ M_\odot$ +

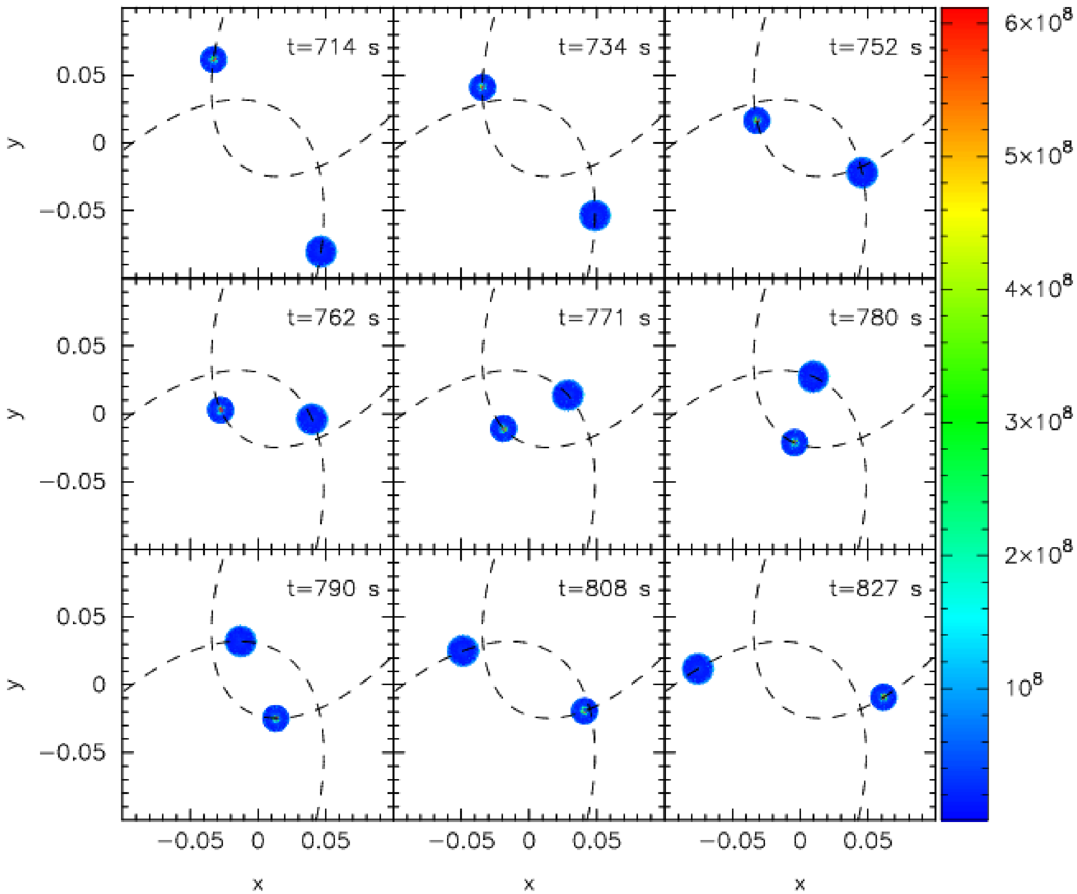


Aznar-Siguan et al 2013

- ● 2 WD ejected
- ▲ 1 WDs ejected
- ■ detonation: - in CO: $\rho > 2\ \times 10^6\ g/cm^3$ and $T > 2.5\ \times 10^9\ K$ (Seitenzahl et al. 2009)
  - in He: $\tau_{nuc} < \tau_{dyn}$
- □ no detonation

Eccentric orbits

$0.8\,M_\odot + 0.6\,M_\odot$



Lorén-Aguilar et al 2009

- No mass transfer nor strong tidal deformations at periastron
- Formation of an eccentric orbit

Eccentric orbits: GW

- Detection of the eccentric WD orbits formed with eLISA

$$f_{\rm c} = \left[\int_0^\infty \frac{\left\langle \left|\tilde{h}(f)\right|^2 \right\rangle}{S_{\rm n}(f)} f\, df\right] \left[\int_0^\infty \frac{\left\langle \left|\tilde{h}(f)\right|^2 \right\rangle}{S_{\rm n}(f)} df\right]^{-1}$$

$$h_{\rm c} = \left[3 \int_0^\infty \frac{S_{\rm n}(f_{\rm c})}{S_n(f)} \left\langle \left|\tilde{h}(f)\right|^2 \right\rangle f\, df\right]^{1/2}$$

h GW emission in the slow-motion, weak-field quadrupole approximation

$$\tilde{h}(f) = \int_{-\infty}^{\infty} e^{2\pi i f t} h(t) dt$$

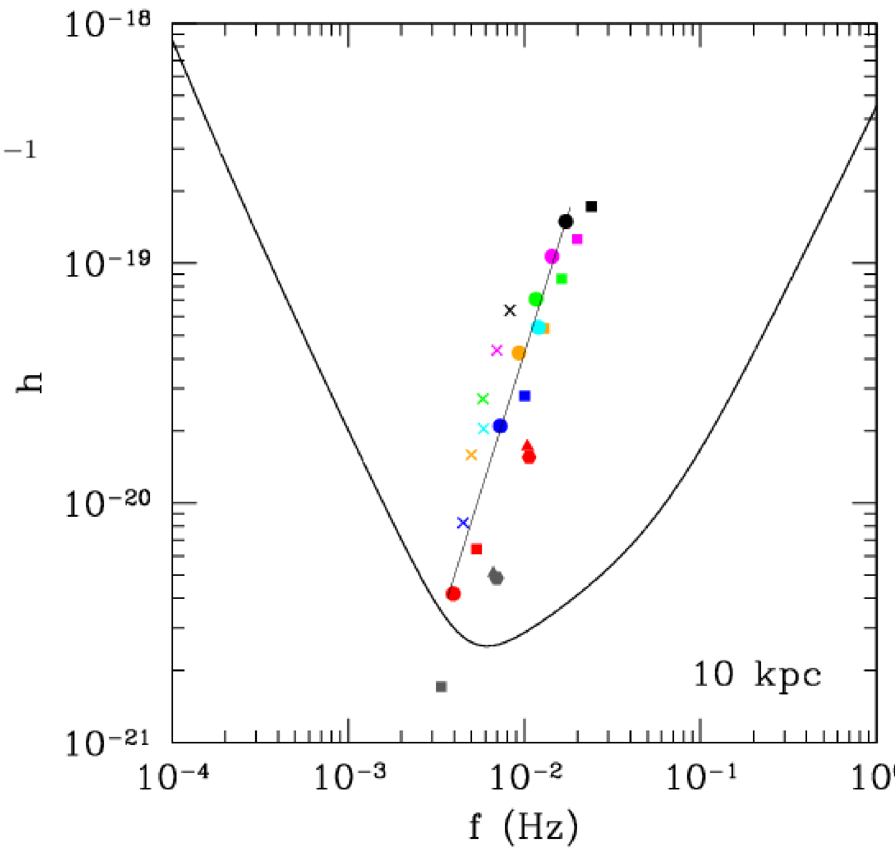
S_n from Amaro-Seoane et al. 2013

Eccentric orbits: GW

- Detection of the eccentric WD orbits formed with eLISA

$$f_c = \left[\int_0^\infty \frac{\left\langle \left|\tilde{h}(f)\right|^2 \right\rangle}{S_n(f)} f\, df\right] \left[\int_0^\infty \frac{\left\langle \left|\tilde{h}(f)\right|^2 \right\rangle}{S_n(f)} df\right]^{-1}$$

$$h_c = \left[3 \int_0^\infty \frac{S_n(f_c)}{S_n(f)} \left\langle \left|\tilde{h}(f)\right|^2 \right\rangle f\, df\right]^{1/2}$$

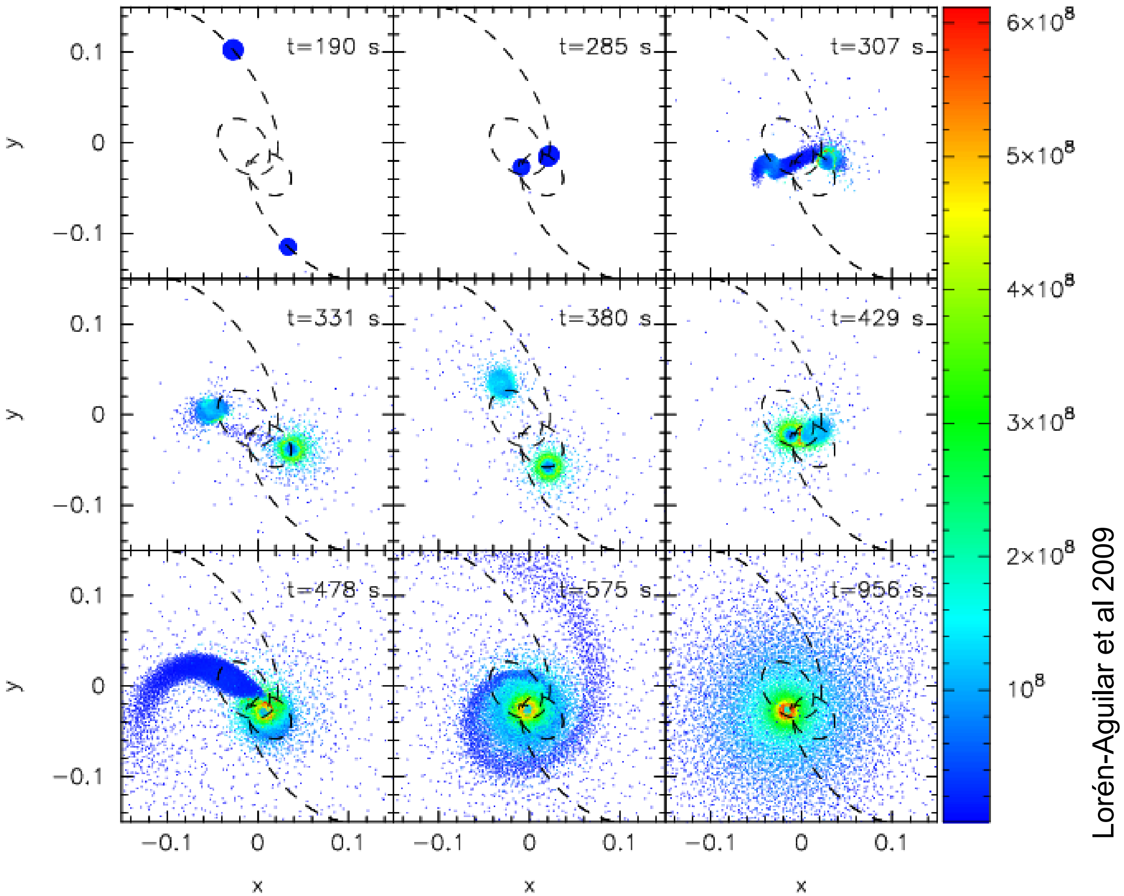


Aznar-Siguan et al 2014

- SNR > 1 for all the orbits, except for one $0.4\ M_\odot$ + $0.2\ M_\odot$ orbit.

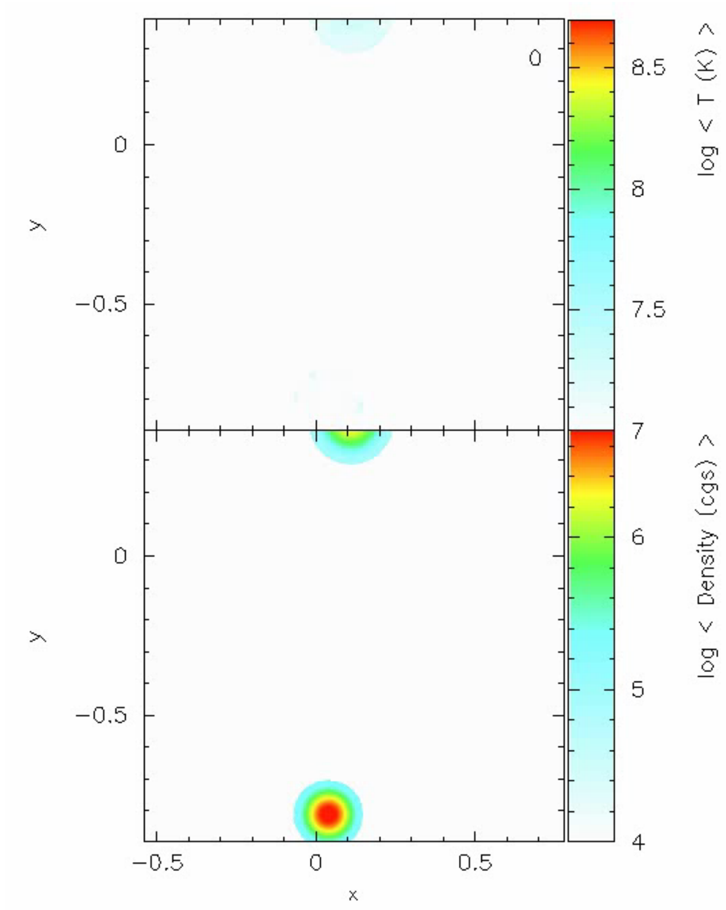
Lateral collisions

$0.8\ M_{\odot} + 0.6\ M_{\odot}$



- Secondary survives periastron.
- Several mass transfers episodes before merger.

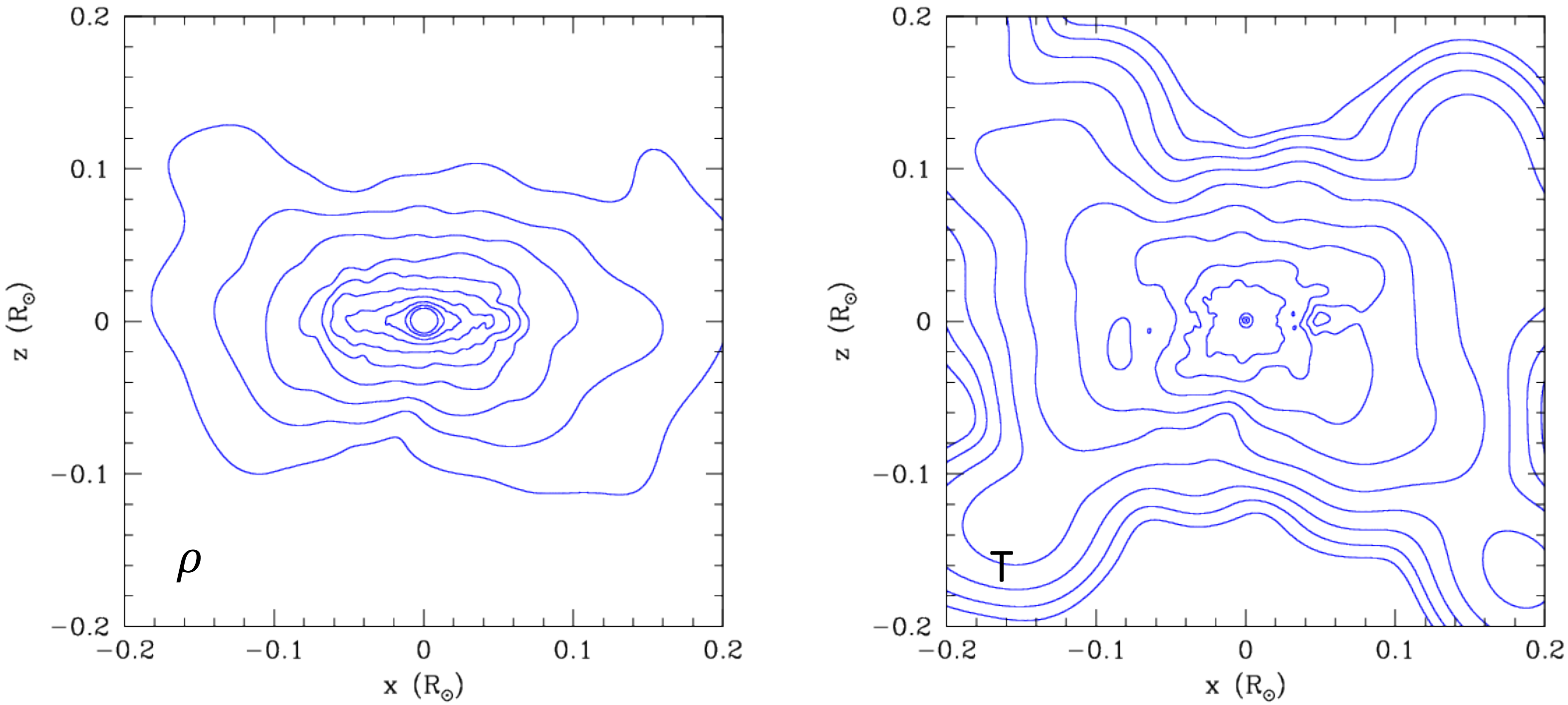
Lateral collisions



$0.8\ M_{\odot}$ + $0.6\ M_{\odot}$ LC where detonation conditions during mass transfer are met.

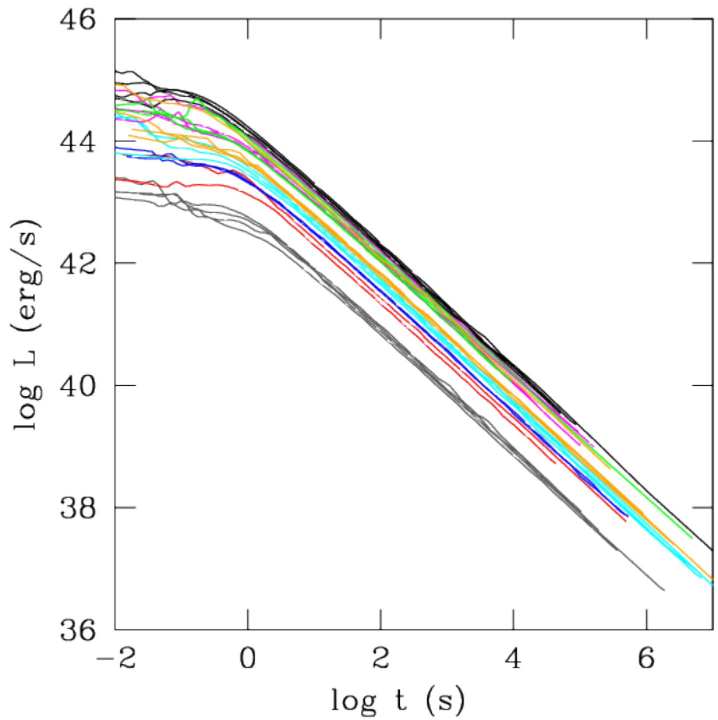
Lateral collisions: Remnants

- Structure of the merger remnants, similar to WD binary mergers:
    - Central compact object.
    - Hot envelope.
    - Accretion disk.
    - Debris region.
    - Ejected material.



Lateral collisions: Fallback luminosities

- Merger remnant: X-ray photons from the interaction of the material with high eccentric orbits and the disk.



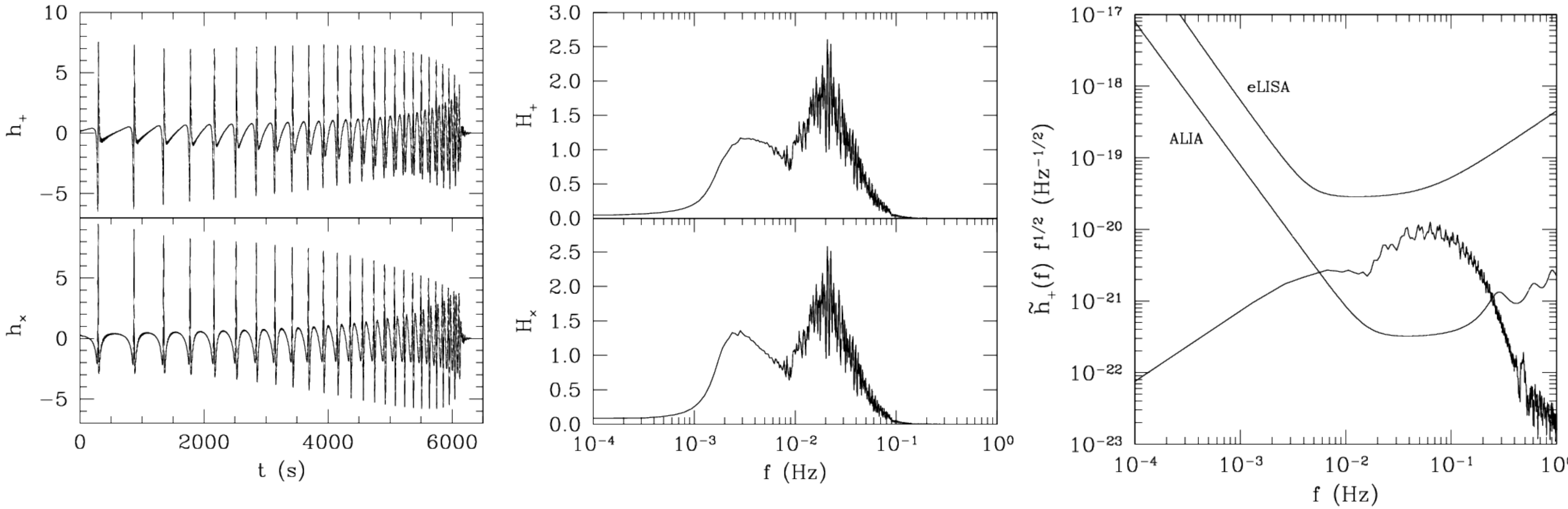
Aznar-Siguan et al 2014

$0.8\,M_\odot + 1.2\,M_\odot$ | $0.8\,M_\odot + 0.8\,M_\odot$ | $0.8\,M_\odot + 0.6\,M_\odot$ | $0.4\,M_\odot + 0.4\,M_\odot$

$0.8\,M_\odot + 1.0\,M_\odot$ | $0.4\,M_\odot + 1.2\,M_\odot$ | $0.8\,M_\odot + 0.4\,M_\odot$ | $0.4\,M_\odot + 0.2\,M_\odot$

Lateral collisions: GW

$0.8\ M_\odot + 0.6\ M_\odot$

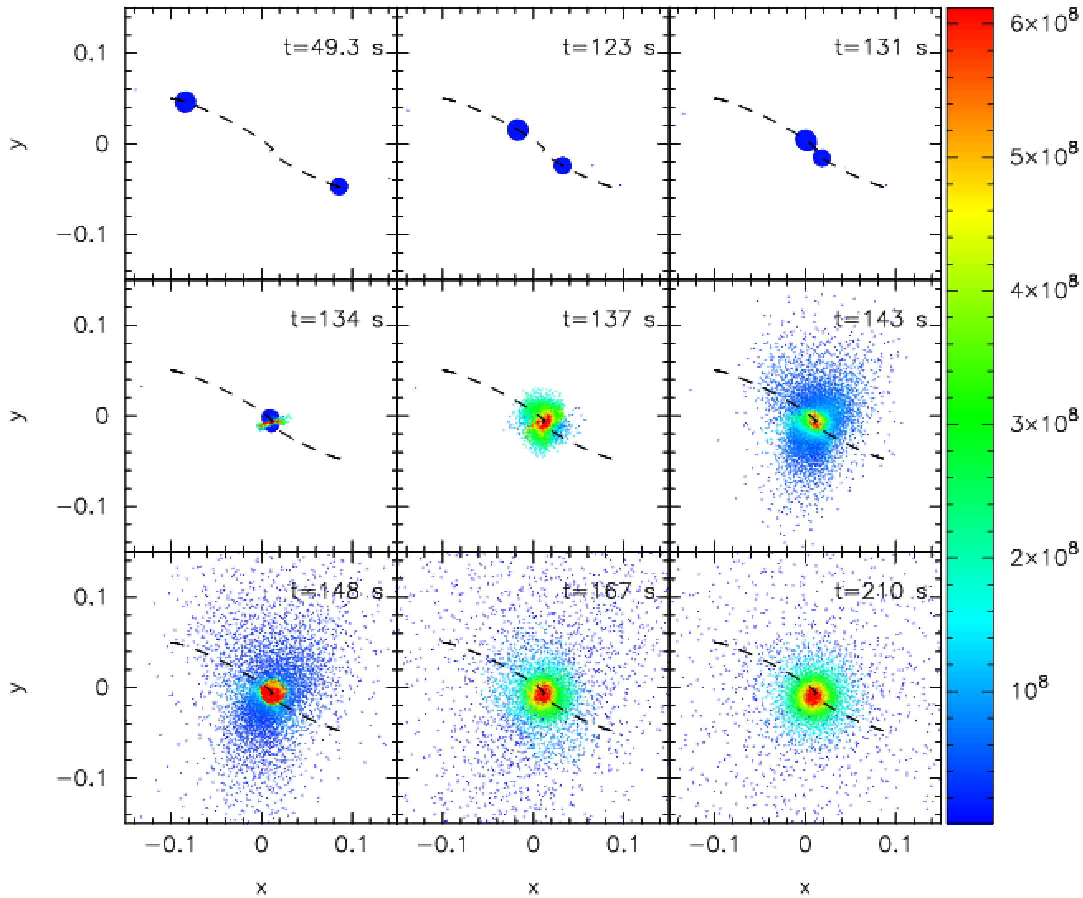


Aznar-Siguan et al 2014

- Not detectable by eLISA.

Direct collisions

$0.8\ M_{\odot} + 0.6\ M_{\odot}$

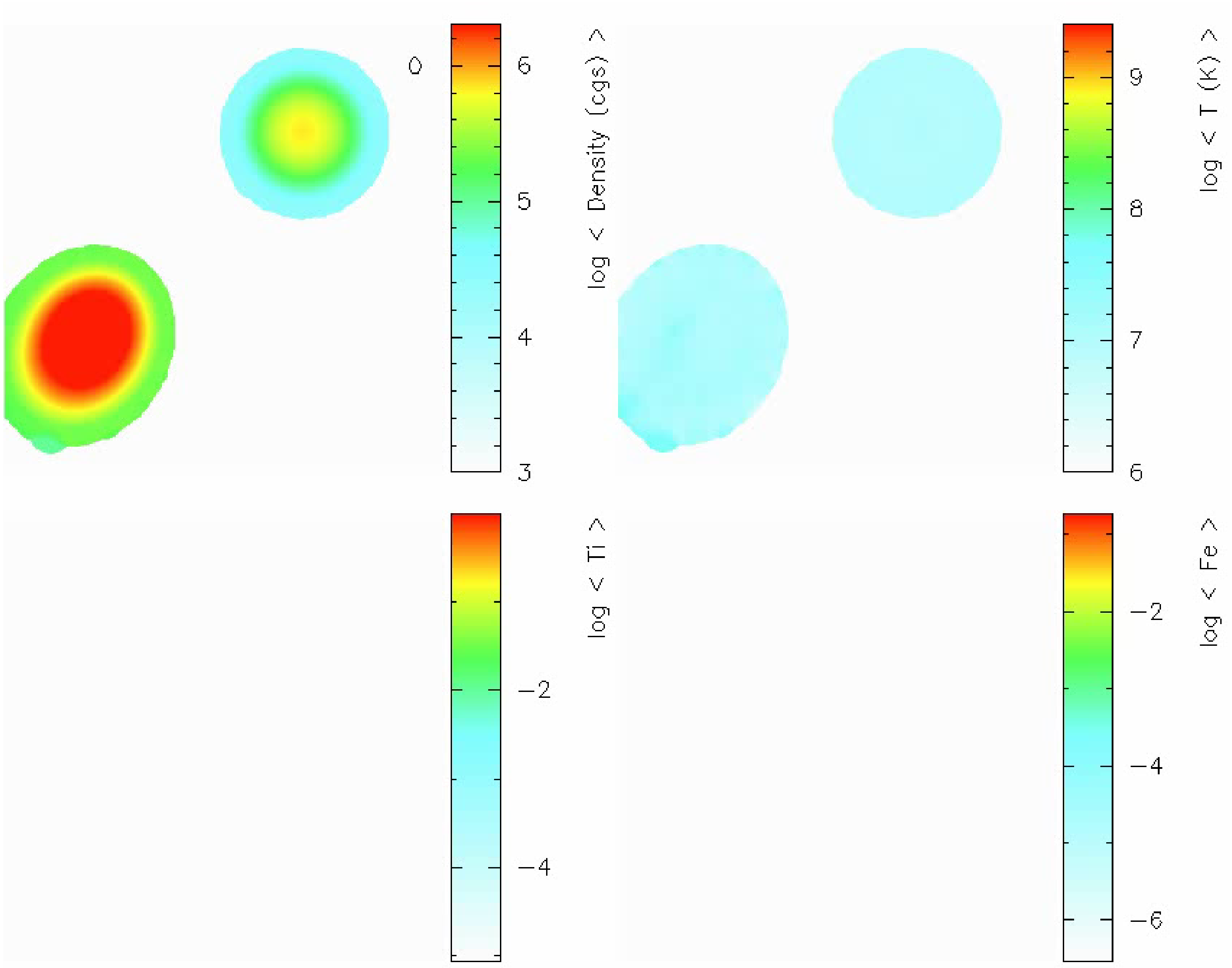


Lorén-Aguilar et al 2009

- Secondary destroyed at first periastron.
- Many explosive outcomes. If not, merger remnant similar to the LC ones.

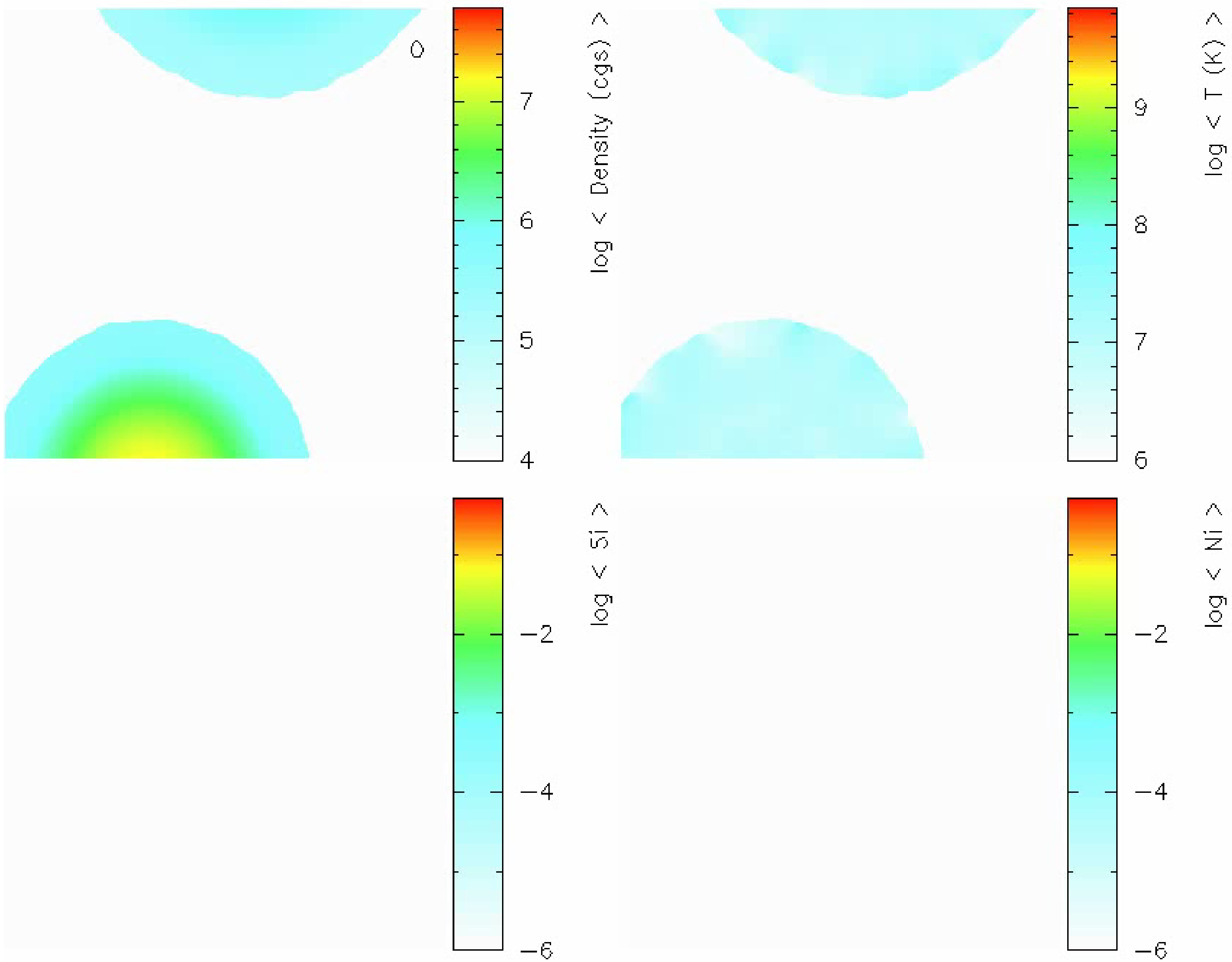
Direct collisions

$0.4\ M_{\odot} + 0.8\ M_{\odot}$



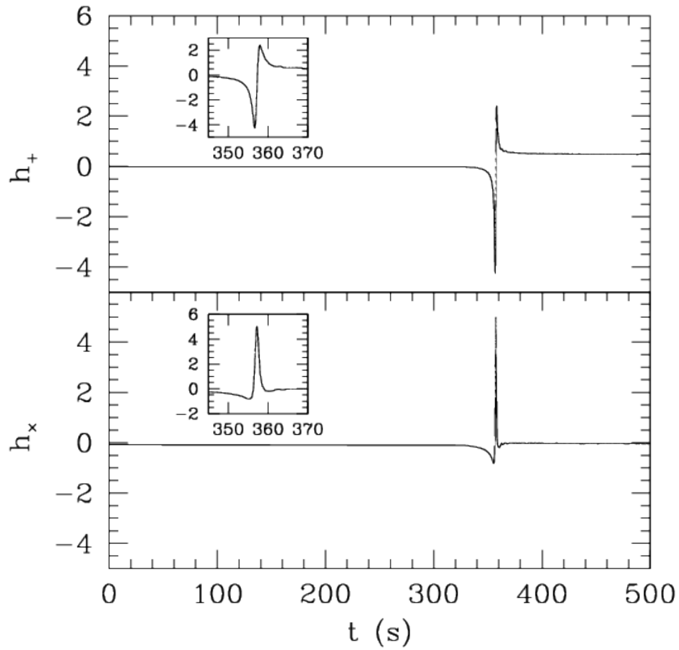
Direct collisions

$0.8\ M_{\odot} + 1.0\ M_{\odot}$



Direct collisions: GW

$0.8\ M_{\odot} + 1.2\ M_{\odot}$



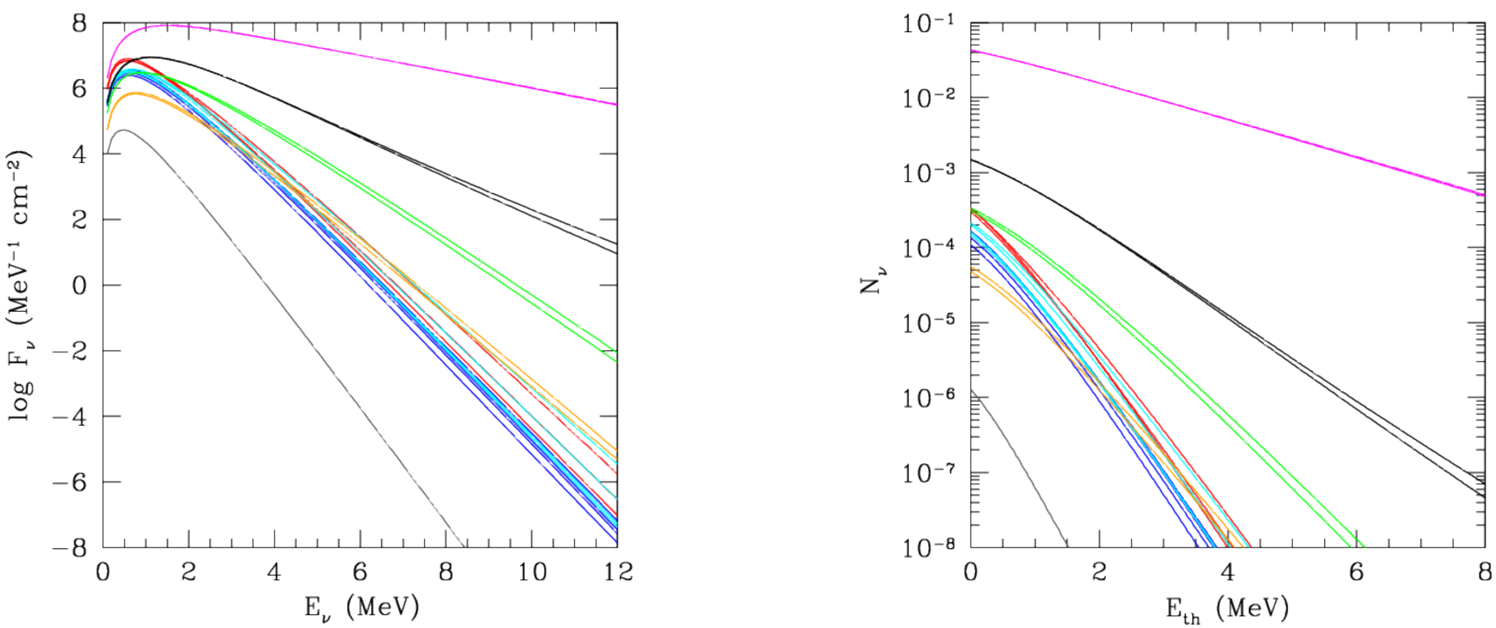
Aznar-Siguan et al 2014

- Just one pulse with not enough high frequency to be detected with current detectors.

Direct collisions: Neutrinos

- Thermal neutrino emission: electron-positron annihilation, plasmon decay, photoemission, neutrino brehmsstrahlung, neutrino recombination (Itoh et al.1996).

- Super-Kamiokande detector: max. ~0.04 neutrinos at 1kpc.



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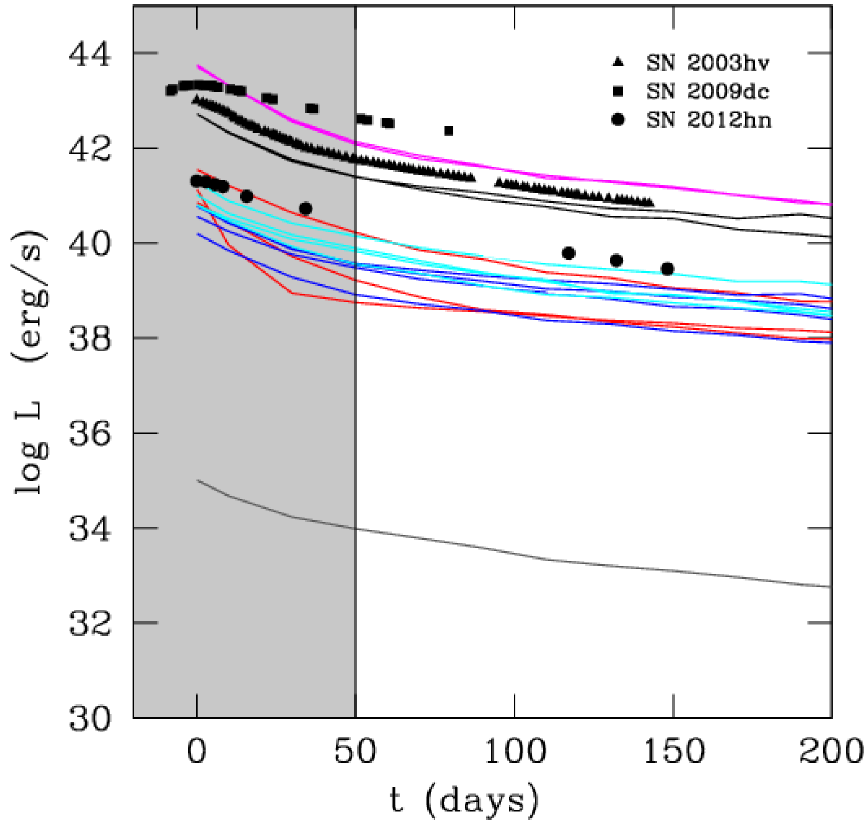
$0.8\,M_\odot + 1.2\,M_\odot$ (black) $0.8\,M_\odot + 0.8\,M_\odot$ (green) $0.8\,M_\odot + 0.6\,M_\odot$ (orange) $0.4\,M_\odot + 0.4\,M_\odot$ (red)

$0.8\,M_\odot + 1.0\,M_\odot$ (magenta) $0.4\,M_\odot + 1.2\,M_\odot$ (cyan) $0.8\,M_\odot + 0.4\,M_\odot$ (blue) $0.4\,M_\odot + 0.2\,M_\odot$ (grey)

Direct collisions: Light curves

- Late-time bolometric light curve is computed numerically using a Monte Carlo algorithm (Kushnir et al. 2013).
- The algorithm solves the transport of photons and the injection of energy by the γ-rays produced by the ^{56}Ni and ^{56}Co decays.



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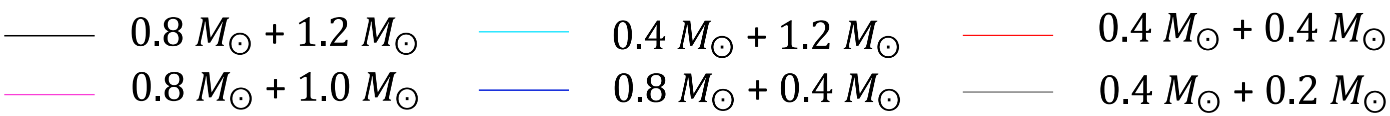

Summary

- White dwarf close encounters result in three different outcomes: DC, LC and EO.
- We have characterized for which initial conditions and WD masses conditions for a detonation to develop are met and when the explosion is powerful enough to result in the ejection of one or both WDs.
- Most of the eccentric orbits formed in the interactions would be detectable by eLISA.
- The late-time bolometric light curves of the explosive outcomes show a broad range of variation. Only when two rather massive WD collide the light curve assimilates to those of Type Ia supernovae.
- The chances of detecting thermal neutrinos emitted in these events are very low for current detectors.
- The accretion luminosity follows a characteristic power law of index -5/3, like in the neutron star mergers. The typical peak luminosities are of $10^{44}\,\mathrm{erg\,s^{-1}}$.