Asymmetrical supernovae triggered by the tidal disruption of white dwarfs
...
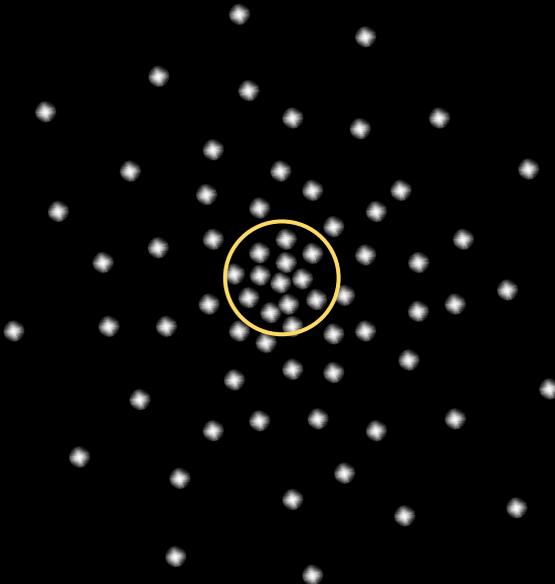
Pavan Vynatheya
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CITA Postdoctoral Fellow

Collaborators:
Luc Dessart, Taeho Ryu, Rüdiger Pakmor

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Types of tidal disruption events (TDEs) in dense star clusters

Object

Disruptor

Star

White dwarf

Intermediate-mass BH

Stellar-mass BH
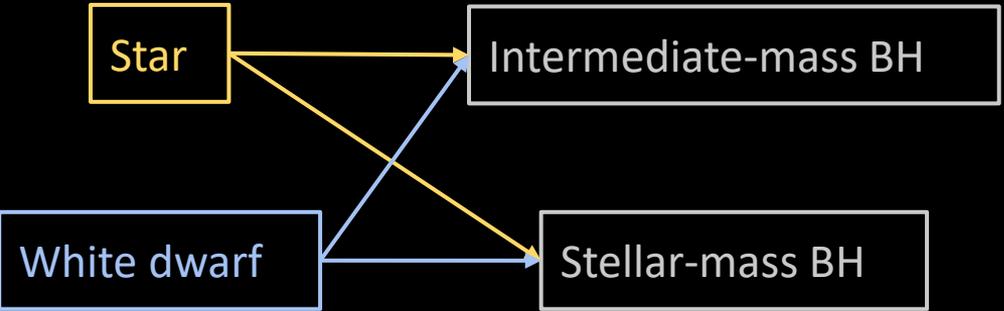
Intermediate-mass black holes

- Masses $10^2\ M_\odot$ – $10^5\ M_\odot$
- Theorized to reside in the centers of globular clusters and dwarf galaxies
- Few potential observations, one conclusive candidate (*Häberle et al. 2024*)
- WD TDEs can be indicators of the presence of IMBHs

Article

Fast-moving stars around an intermediate-mass black hole in ω Centauri

Maximilian Häberle[1✉], Nadine Neumayer[1], Anil Seth[2], Andrea Bellini[3], Mattia Libralato[4,5], Holger Baumgardt[6], Matthew Whitaker[2], Antoine Dumont[1], Mayte Alfaro-Cuello[7], Jay Anderson[3], Callie Clontz[1,2], Nikolay Kacharov[8], Sebastian Kamann[9], Anja Feldmeier-Krause[1,10], Antonino Milone[11], Maria Selina Nitschai[1], Renuka Pechetti[9] & Glenn van de Ven[10]

Black holes have been found over a wide range of masses, from stellar remnants with masses of 5–150 solar masses ($M_\odot$), to those found at the centres of galaxies with $M > 10^5 M_\odot$. However, only a few debated candidate black holes exist between $150 M_\odot$ and $10^5 M_\odot$. Determining the population of these intermediate-mass black holes is an important step towards understanding supermassive black hole formation in the early universe[1,2]. Several studies have claimed the detection of a central black hole in ω Centauri, the most massive globular cluster of the Milky Way[3-5]. However, these studies have been questioned because of the possible mass contribution of stellar mass black holes, their sensitivity to the cluster centre and the lack of fast-moving stars above the escape velocity[6-9]. Here we report the observations of seven fast-moving stars in the central 3 arcsec (0.08 pc) of ω Centauri. The velocities of the fast-moving stars are significantly higher than the expected central escape velocity of the star cluster, so their presence can be explained only by being bound to a massive black hole. From the velocities alone, we can infer a firm lower limit of the black hole mass of about $8,200 M_\odot$, making this a good case for an intermediate-mass black hole in the local universe.

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Parameter space of WD TDEs

Rosswog et al. (2009)

Closer encounters

Wider encounters

BH enters WD

WD enters BH

No disruption

$m_{WD} = 0.2\ M_\odot$

$m_{WD} = 1.4\ M_\odot$

Tidal radius

Periapsis

Black hole mass (solar masses)
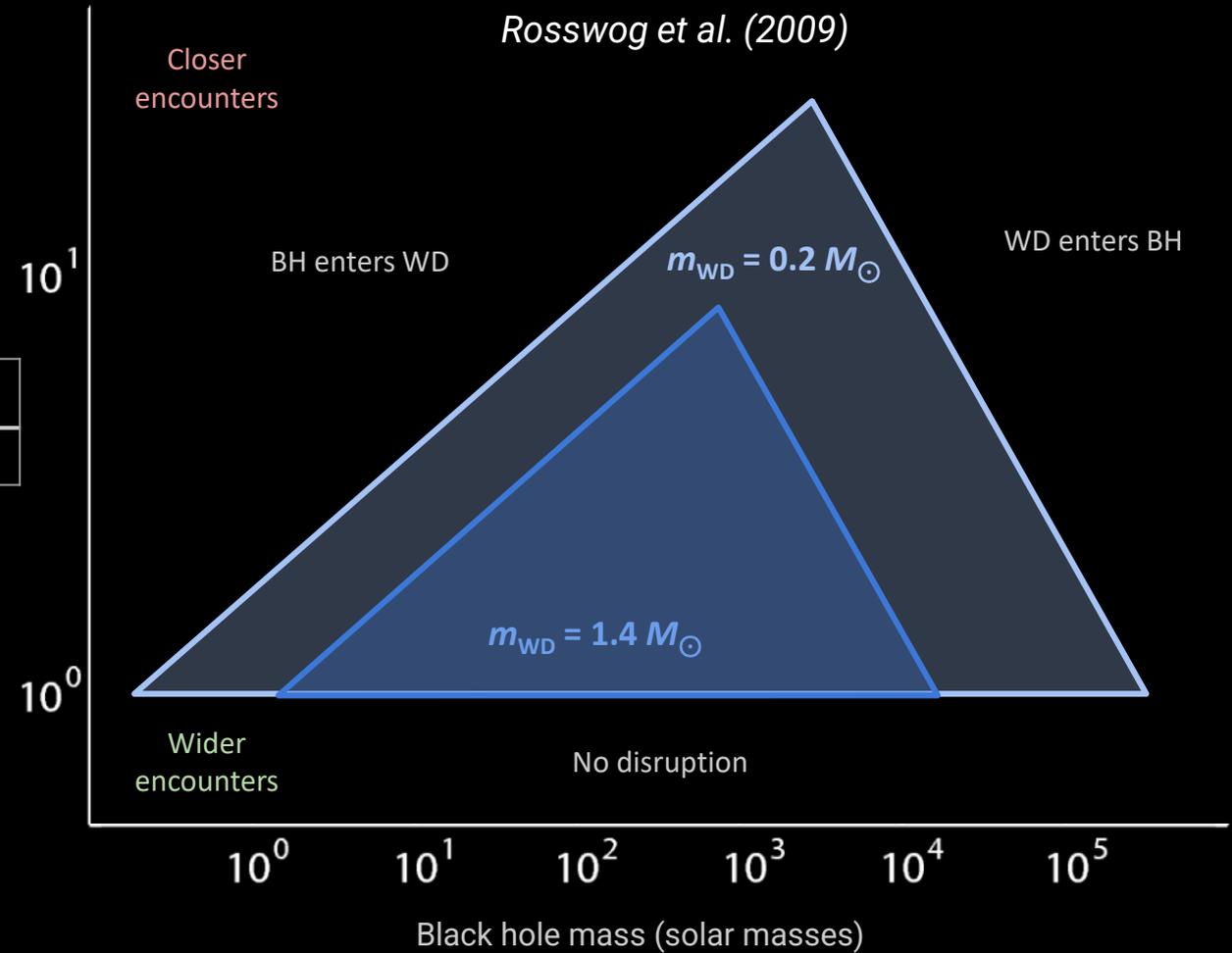
Observational prospects of WD TDEs

Swift spectra of AT2018cow: A White Dwarf Ti...
Disruption Event?

...SIENT NEAR M 86
...NELEMANS [2,7]

...ND OF EXP
N. Paul M. Kuin [1★]

A fast powerful X-ray transient from possible tidal disruption of a white dwarf

Tidal Disruptions of White Dw...
Models and Observational Pros...

Kate Maguire · Michael F...
Peter G. Jonker · Mc...
Stephan Rosswo...

...te Mass

...Search for Thermonuclear Transients

SEBAS...

Can GRB 250702B be explained as the tidal disruption of a white dwarf by an intermediate mass black hole? Yes.

Rob A. J. Eyles-Ferris, [1★] Andrew King, [1,2,3] Rhaana L. C. Starling, [1] Peter G. Jonker, [4] Andrew J. Levan, [4] Antonio Martin-Carrillo, [5] Tanmoy Laskar, [6,4] Jillian C. Rastinejad, [7,8] Nikhil Sarin, [9,10] Nial R. Tanvir, [1] Benjamin P. Gompertz, [11,12] Nusrin Habeeb, [1] Paul T. O'Brien [1] and Massimiliano De Pasquale [13]

Dongyue Li [1★], Wenda Zhang [1★†], Jun Yang [2★], Jin-Hong Chen [3,4,5★], Weimin Yuan [1,6‡], Huaqing Cheng [1], Wei-hua Lei [11], Xinwen Shu [7], Rong-Feng Shen [8,9], Ning Jiang [10], Jiazheng Zhu [10], Chang Zhou [11], Wei-hua Lei [11], Hui Sun [1], Chichuan Jin [1,6,12§], Lixin Dai [3,4¶], Bing Zhang [3,4], Yu-Han Yang [13], Wenjie Zhang [1], Hua Feng [14], Bifang Liu [1,6], Hongyan Zhou [10,15], Haiwu Pan [1], Mingjun Liu [1], Stéphane Corbel [16], Sitha K. Jagan [17], Maria Cristina Baglio [18], Christopher R. Burns [19], Floriane Cangemi [20], Chun Chen [8,9,21], Yehao Cheng [22], Alexis Coleiro [20], Francesco Coti Zelati [23,24], Sourya R. Das [16], Zhongnan Dong [8,20,1], Luis Galbany [23,24], Noa Grollimund [16], Daniel Kelson [19], Dong Lai [1,6], Xia Li [8,9], Yuan Liu [1], Alessio Marino [23,24], Brenna Mockler [19], Paul O'Brien [27], Erlin Qiao [1,6], Nanda ...24], Resmi [17], Jérome Rodriguez [16], Richard Saxton [28], Luming Sun [7], Lian Tao [13], Tinggui ...ong [1,23,24], Xuefeng Wu [29], Dong Xu [1], Yijia Zhang [30], Guoying Zhao [8], Con-...hai Chen [31], Yong Chen [14], Bertrand Cordier [32], Chenzhou Cui [1], ...Giancarlo Ghirlanda [18,34], Ju Guan [14], Dawei Han [14], Ste-...1], Yong-Feng Huang [35,36], Shumei Jia [14], Ge Jin [37], ...Ling [1,6,12], Congzhan Liu [14], Heyang Liu [1], Huaqiu Liu [31], ...ve Ness [40], Arne Rau [39], Jeremy Sanders [39], Liming Song [14], ...ojin Sun [43], Yunyin Tan [44], Eleonora Troja [13], Sixiang Wen [1], ...quan Xue [10], Yi-Han Iris Yin [3,4], Chen Zhang [1], Shuang-Nan

Haitao Xu [44], Yonghe Zhang ...
...Zhang [14], Yonghe Zhang ...

Consequences of extreme tidal forces on WDs   (see also *Rosswog et al. 2009*)
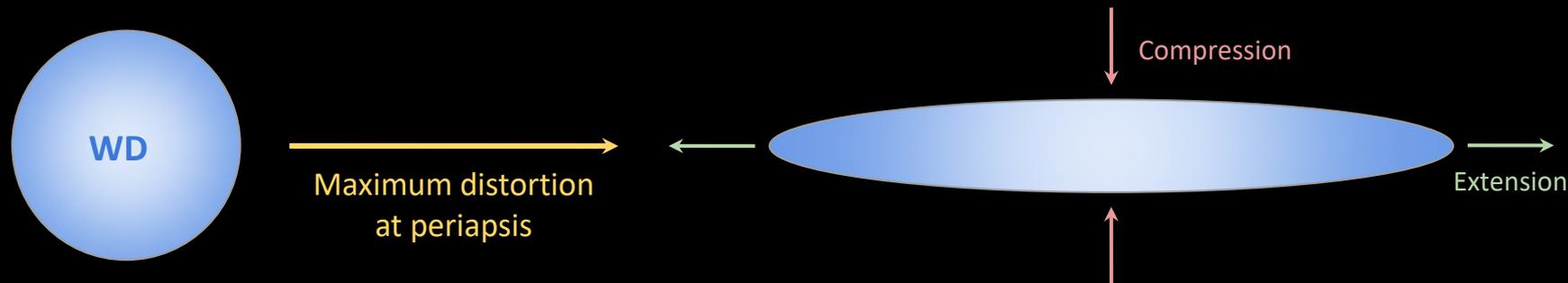
- Tidal compression → Very high densities → Very high temperatures
- C-burning ($T > 5 \times 10^8$ K) → Ne-burning ($T > 1.2 \times 10^9$ K) → O-burning ($T > 1.5 \times 10^9$ K) → Si-burning ($T > 3 \times 10^9$ K) producing isotopes up to Ni
- Very short time spent at maximum compression (< 1 s)

Outline

*Vynatheya, Dessart et al.
(2026)*

❖ Perform hydrodynamics simulations of WD TDEs using the `AREPO` code

❖ Simulations include an on-the-fly nuclear reaction network

❖ m_{WD} = 0.6 $M_\odot$ (C/O) and m_{BH} = 500 $M_\odot$ for different impact parameters

❖ Follow up with 1D and 2D radiative transfer using codes `CMFGEN` and `LONGPOL`, respectively

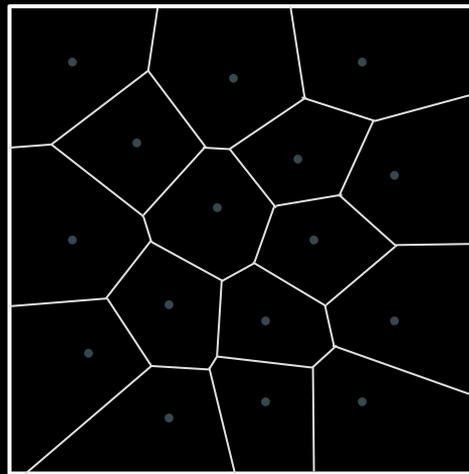❖ Generate synthetic light curve and spectra

AREPO - an unstructured mesh MHD code
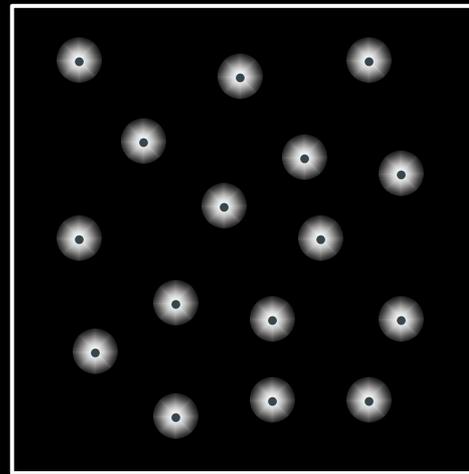
Springel (2010),
Pakmor et al. (2016)

**Finite-volume,
static mesh/grid**
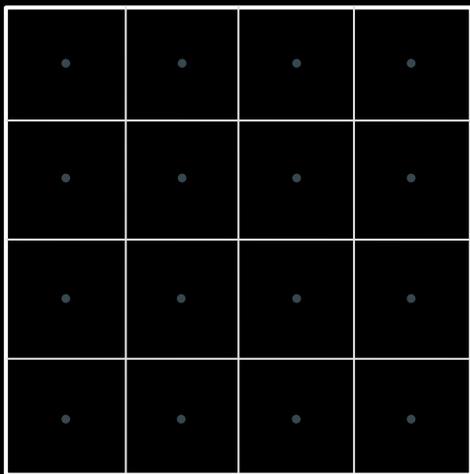
**Moving, unstructured
mesh**

**Smoothed particle
hydrodynamics**

Equation of state (EoS) and nuclear reaction network (NRN)

- `Helmholtz` **EoS** (*Timmes & Swesty 2000*) which accounts for arbitrarily degenerate and relativistic material
- `JINA REACLIB` nuclear reaction rates (*Cyburt et al. 2010*) and **weak interaction** rates (*Langanke & Martínez-Pinedo 2001*) for 55 isotopes
- Important isotopes: ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca, ^{52}Fe, ^{56}Ni
- **Hydro & gravity timestep → NRN integrated → Cell compositions & energies updated → ...**

Tidal disruption of a white dwarf can lead to a supernova!

Scaled impact parameter $b = r_p / r_t$ (ratio of periapsis distance to tidal radius)
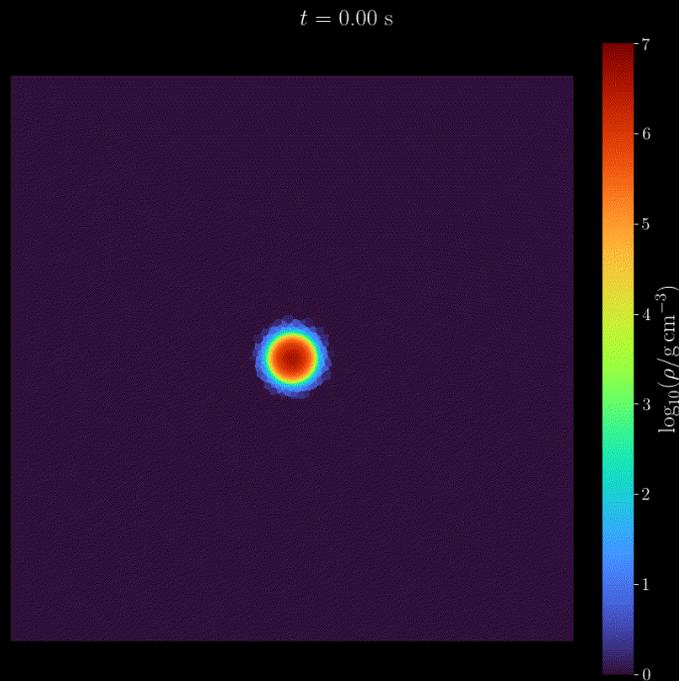
$t = 0.00$ s

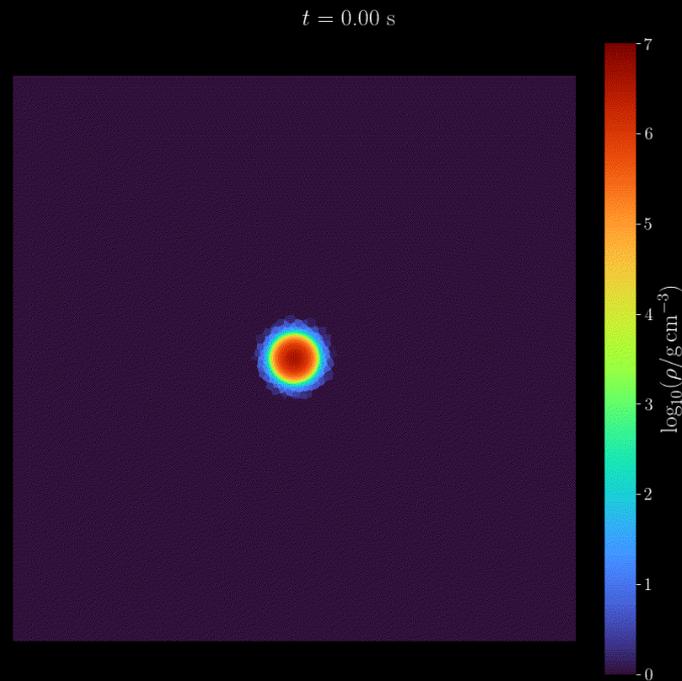$t = 0.00$ s

Farther approach distance ($b = 0.20$)

Closer approach distance ($b = 0.15$)

Tidal disruption of a white dwarf can lead to a supernova!

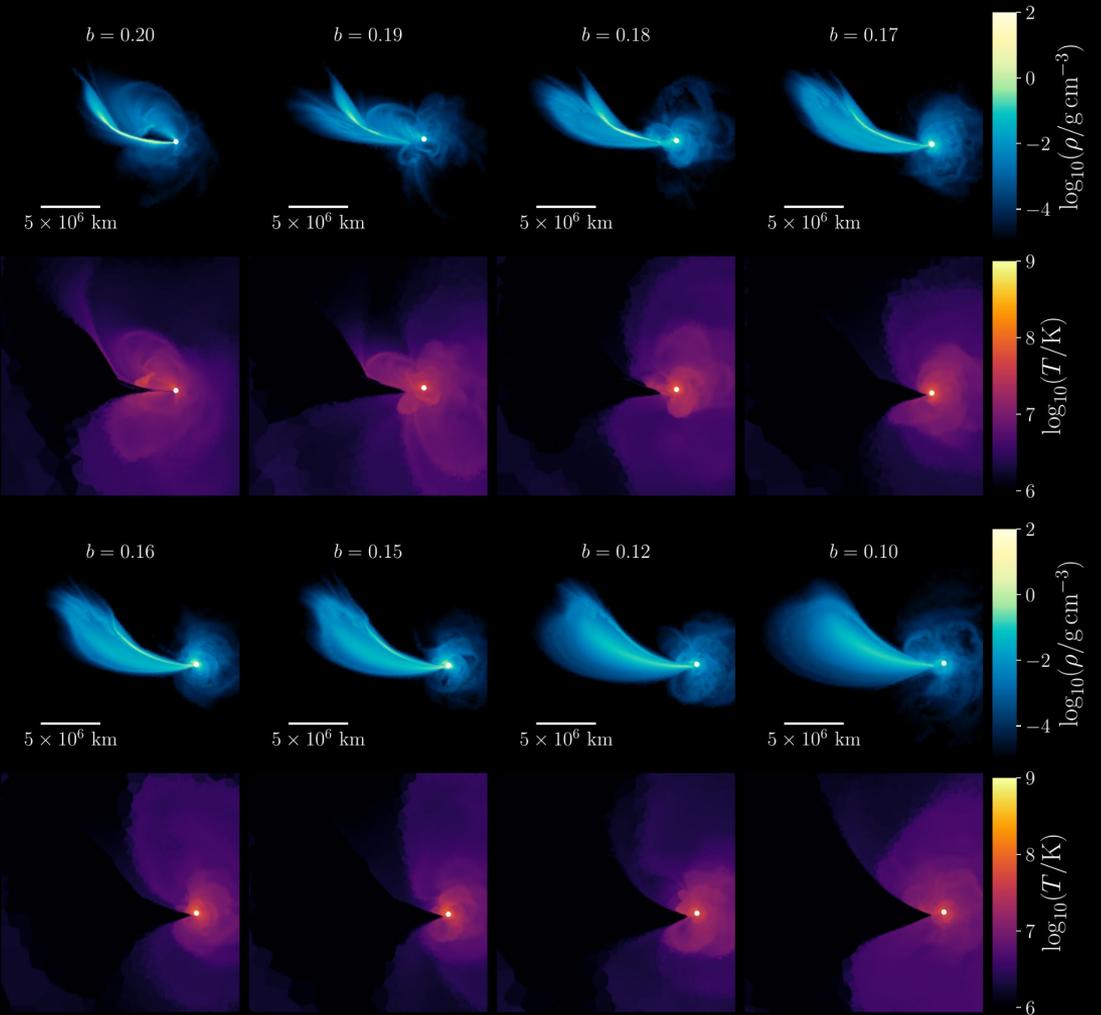Farther approach distance (b = 0.20)

Closer approach distance (b = 0.15)

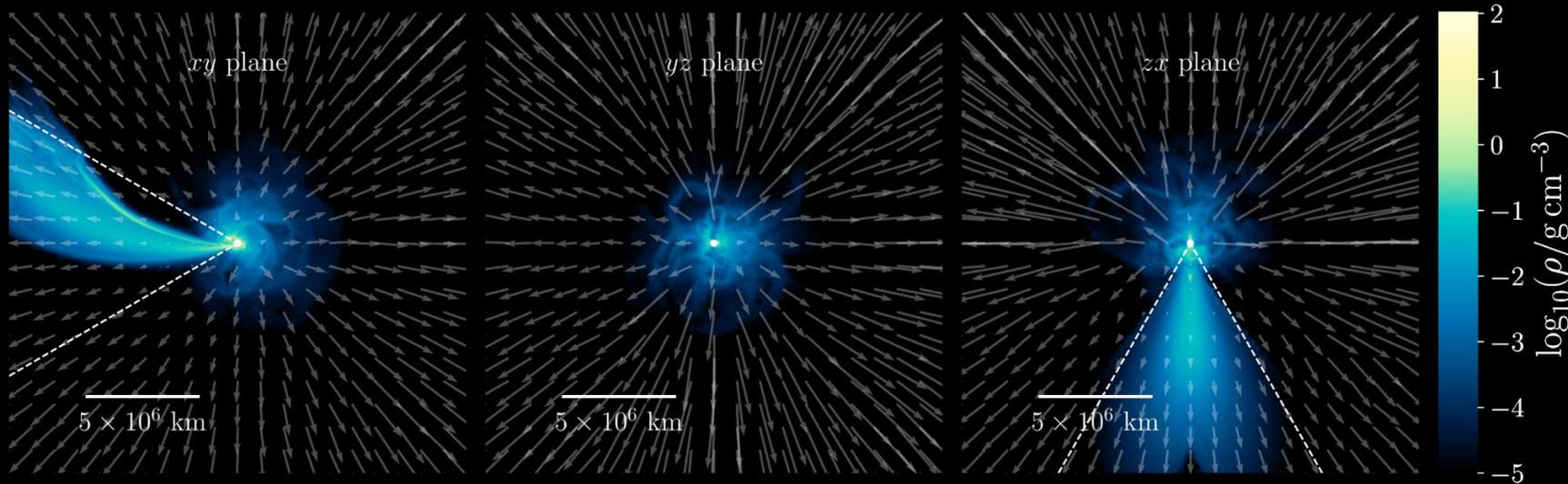# WD-TDEs (plus thermonuclear SNe) for different impact parameters b

$m_{\mathrm{WD}} = 0.6\ \mathrm{M}_{\odot}$, $m_{\mathrm{BH}} = 500\ \mathrm{M}_{\odot}$, $t = 502.66\ \mathrm{s}$

Vynatheya, Dessart et al. (2026)

Radial velocities in different planes

$m_{\mathrm{WD}} = 0.6\ \mathrm{M_\odot},\ m_{\mathrm{BH}} = 500\ \mathrm{M_\odot},\ b = 0.15,\ t = 502.66\ \mathrm{s}$

Vynatheya, Dessart et al. (2026)

Takeaway: Most of the ejecta are contained within (roughly) a cone of 30°. This is the considered region in our radiative transfer calculations.
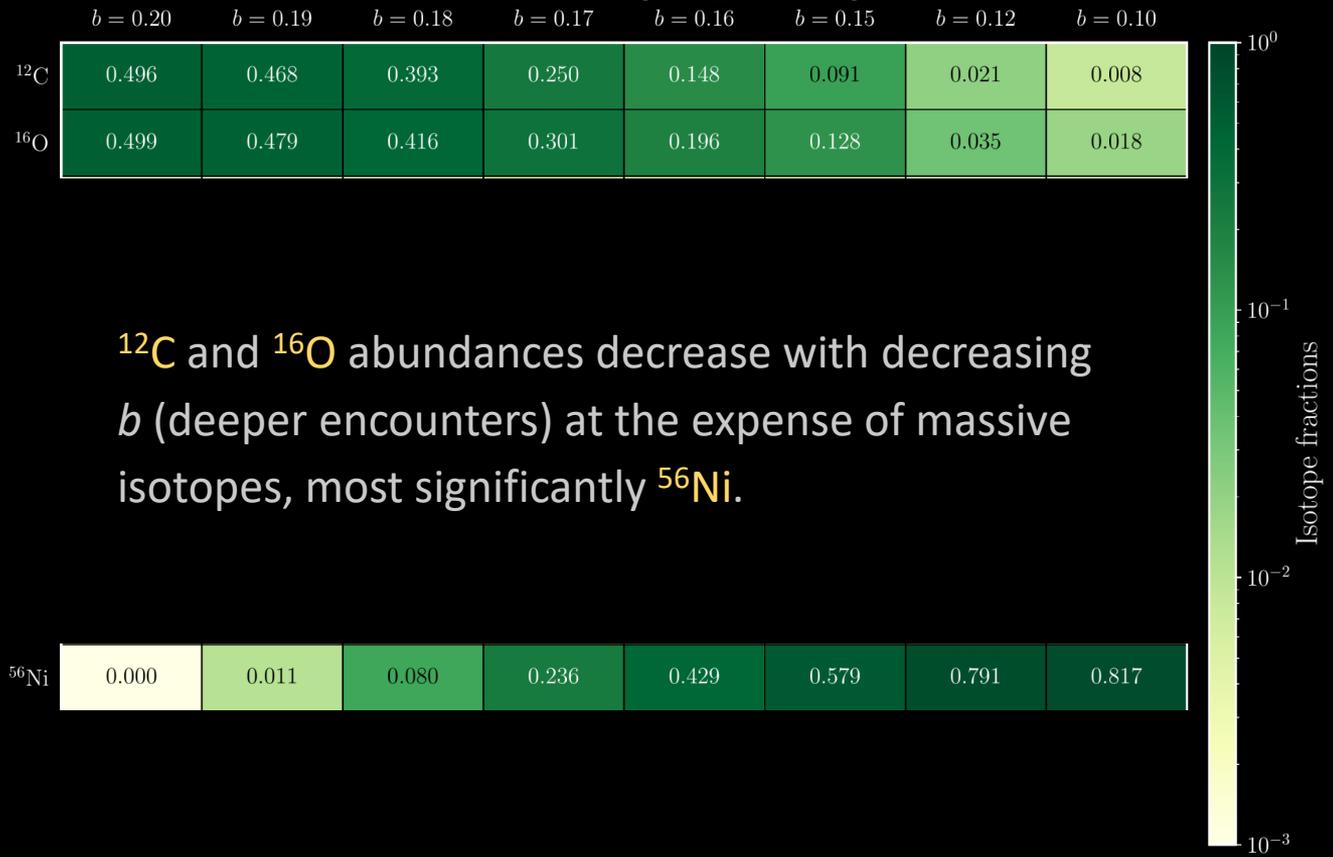
Isotope fractions as a function of TDE impact parameter

$m_{\mathrm{WD}} = 0.6\ \mathrm{M}_\odot,\ m_{\mathrm{BH}} = 500\ \mathrm{M}_\odot$

	$b = 0.20$	$b = 0.19$	$b = 0.18$	$b = 0.17$	$b = 0.16$	$b = 0.15$	$b = 0.12$	$b = 0.10$
^{12}C	0.496	0.468	0.393	0.250	0.148	0.091	0.021	0.008
^{16}O	0.499	0.479	0.416	0.301	0.196	0.128	0.035	0.018

^{12}C and ^{16}O abundances decrease with decreasing b (deeper encounters) at the expense of massive isotopes, most significantly ^{56}Ni.

^{56}Ni	0.000	0.011	0.080	0.236	0.429	0.579	0.791	0.817

Isotope fractions

Vynatheya, Dessart et al. (2026)

WD-TDEs (plus thermonuclear supernovae) chemical abundances

$m_{\mathrm{WD}} = 0.6\ \mathrm{M_\odot}$, $m_{\mathrm{BH}} = 500\ \mathrm{M_\odot}$, $t = 502.66$ s
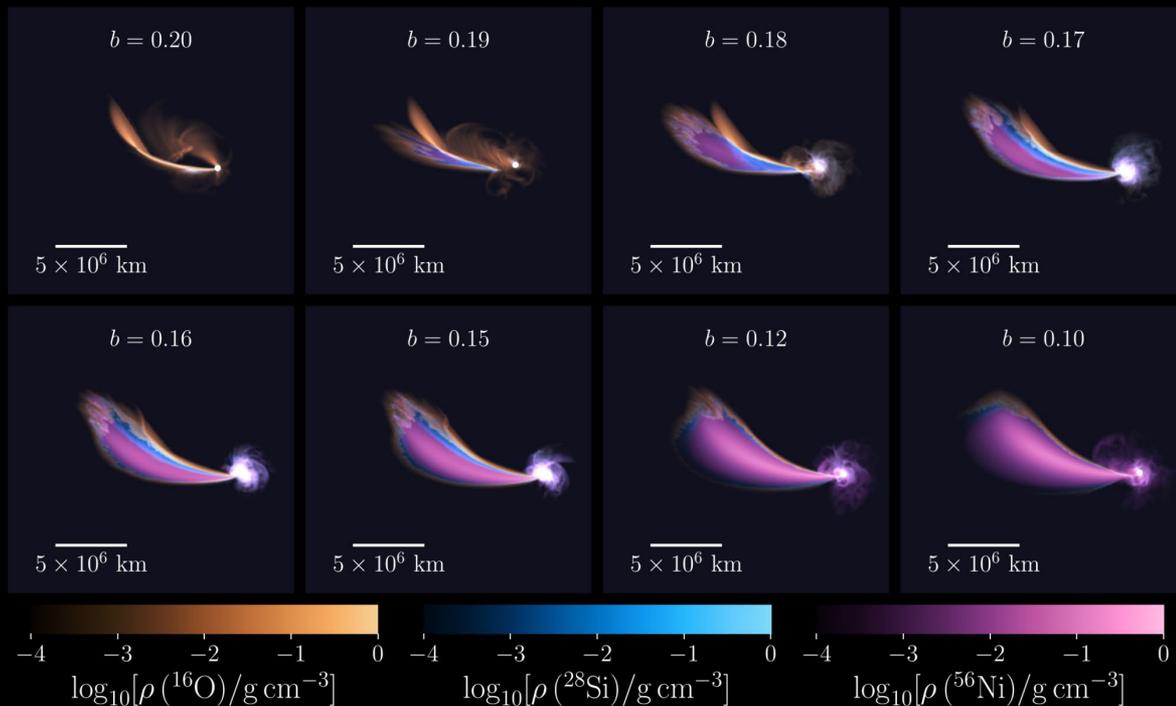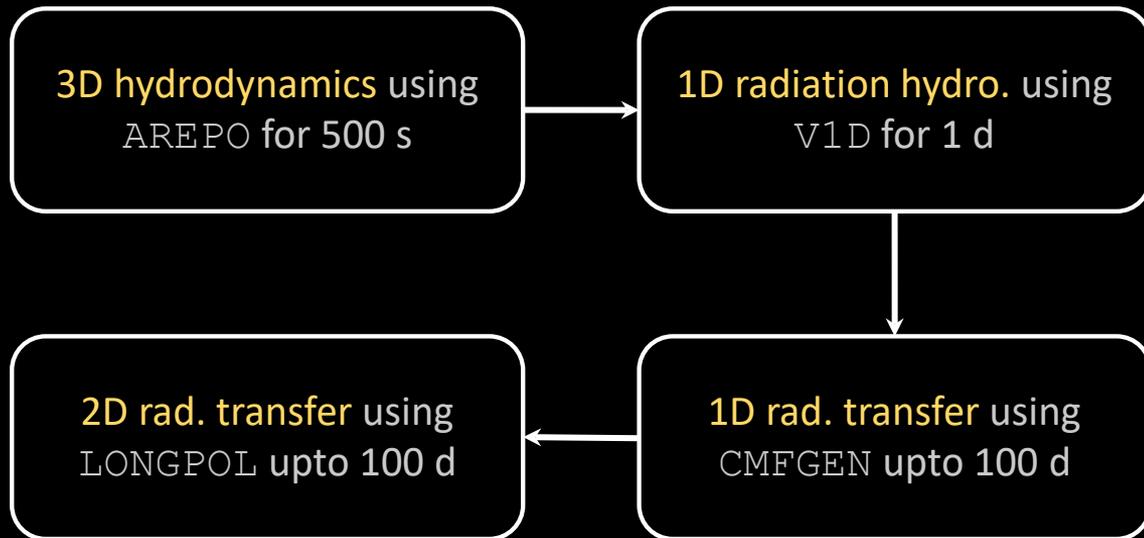
Vynatheya, Dessart et al. (2026)

Takeaway 1: As approaches get closer (lesser b), higher fractions of massive isotopes are produced.

Takeaway 2: The ejecta isotope profiles are onion-like, with heavier isotopes on the inside and lighter isotopes on the outside (w.r.t the ejecta center of mass and not the IMBH).

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1D and 2D Radiative transfer

V1D: *Livne (1993)*
CMFGEN: *Hillier & Miller (1994)*
LONGPOL: *Hillier (1994,1996)*

> **3D hydrodynamics** using `AREPO` for 500 s

→

> **1D radiation hydro.** using `V1D` for 1 d

↓

> **1D rad. transfer** using `CMFGEN upto 100 d`

←

> **2D rad. transfer** using `LONGPOL upto 100 d`

Timescales:

~ **1 d**: Homologous expansion reached

~ **40 d**: Photospheric phase (optically thick)

~ **100 d**: Nebular phase (optically thin)

Note: For the radiative transfer, only the (averaged) ejecta within the cone of 30° is considered. Additionally, the luminosity only from nuclear fusion is considered, not from accretion/fallback.
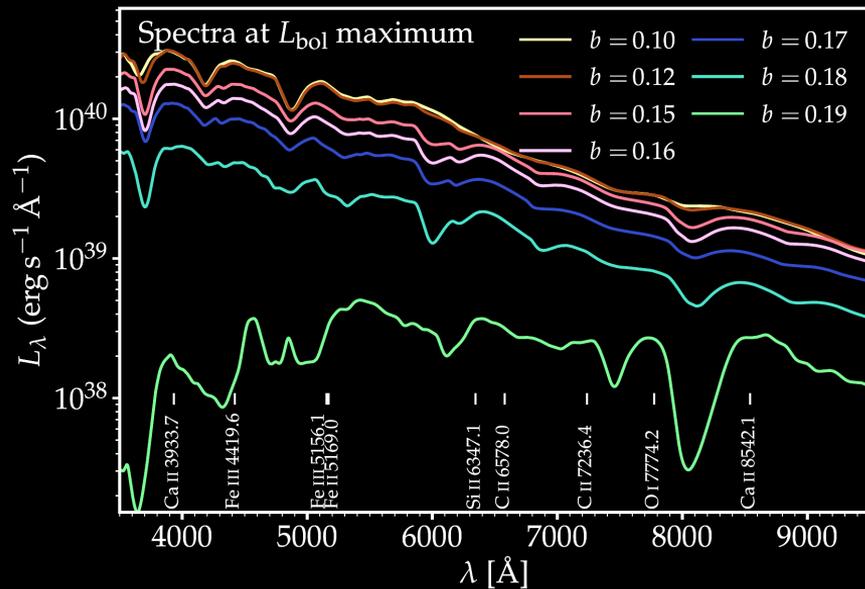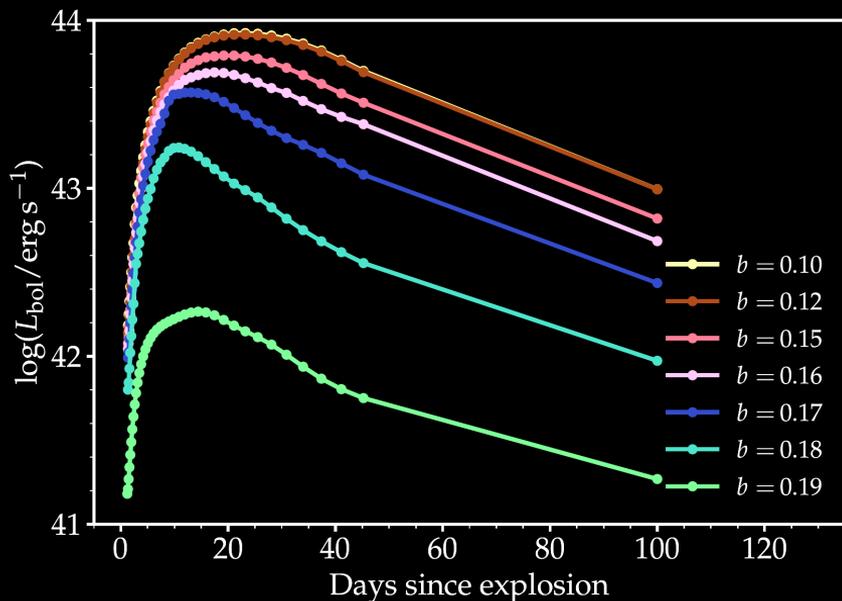
Source of luminosity for thermonuclear supernovae

- The initial rise to peak and decline is powered by the decay of ^{56}Ni to ^{56}Co. The half-life of ^{56}Ni is ~6 days.
- The later flattening in the light curve is powered by decay of ^{56}Co to ^{56}Fe. The half-life of ^{56}Co is ~77 days.
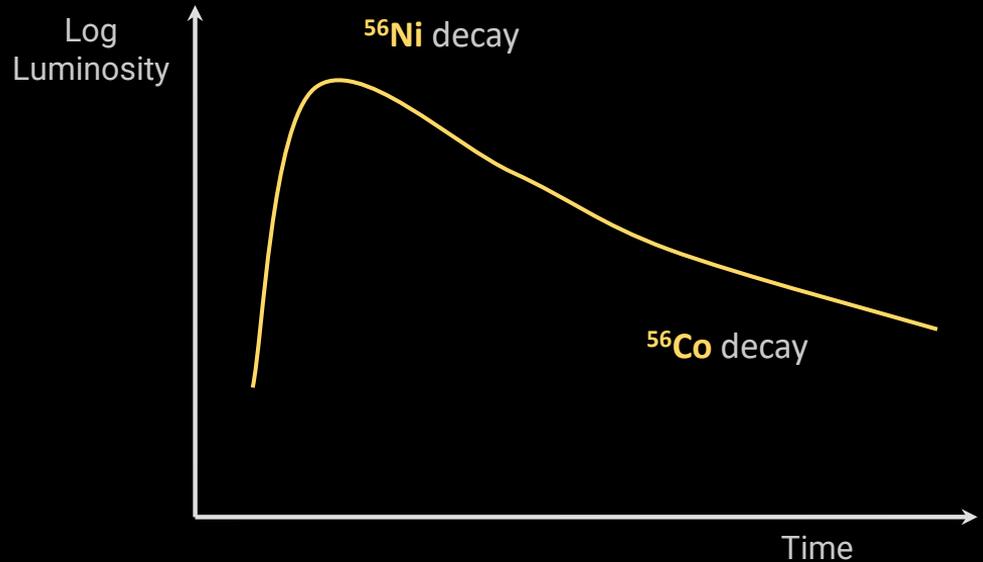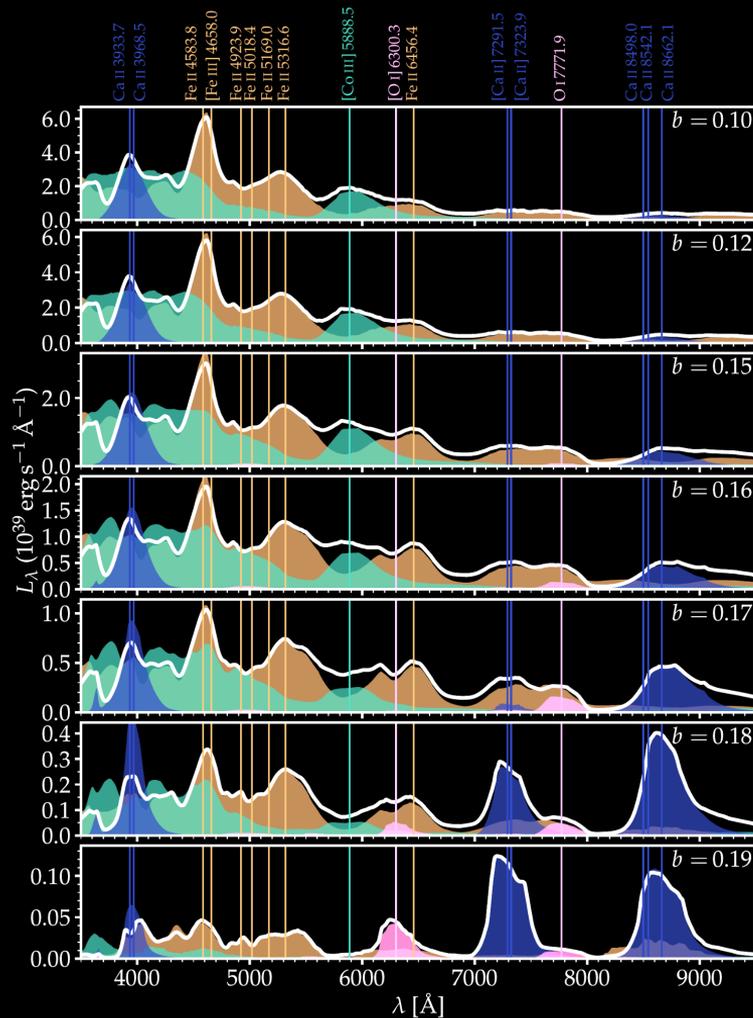
1D spherically-extrapolated luminosities and spectra

Vynatheya, Dessart et al. (2026)

Takeaway: Closer encounters are brighter and exhibit stronger Fe III lines, while wider ones show stronger O I, Si II and Ca II lines. All lines are blueshifted.
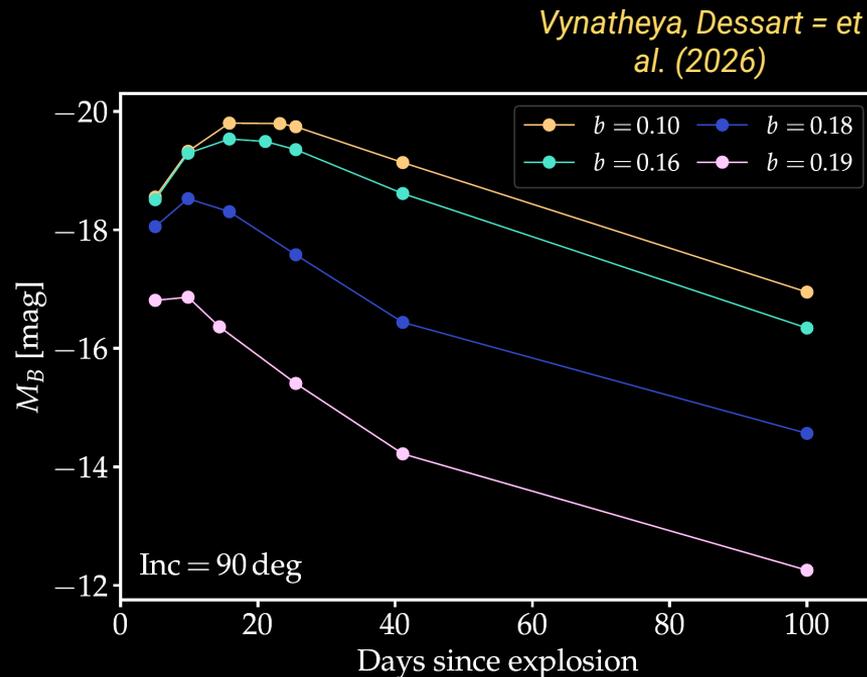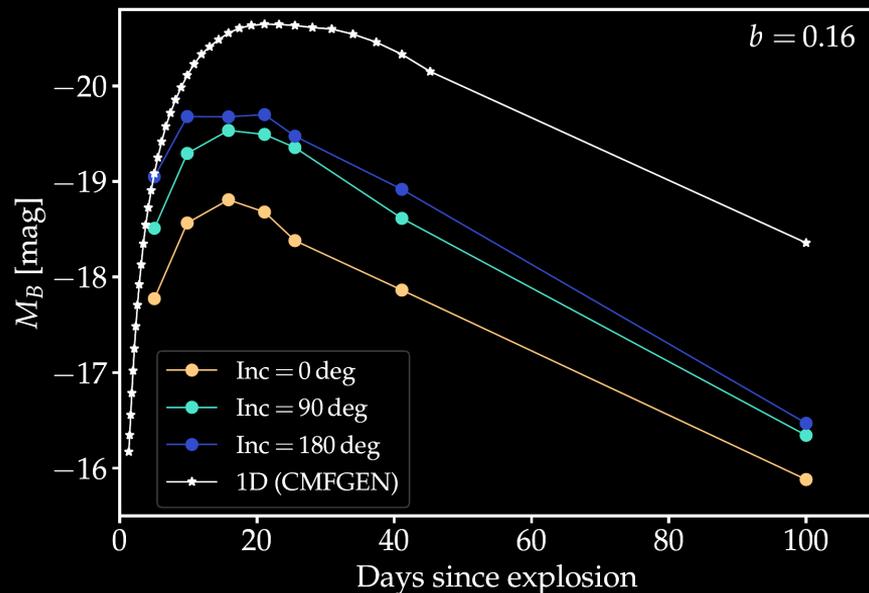
1D spectra at 100 d (nebular phase)

Vynatheya, Dessart et al. (2026)

Takeaway: As encounters get closer, **Fe III** and **Co III** lines increase in strength, while **O I** and **Ca II** lines decrease in strength. Thus, a wide range of transients are covered by WD TDEs.
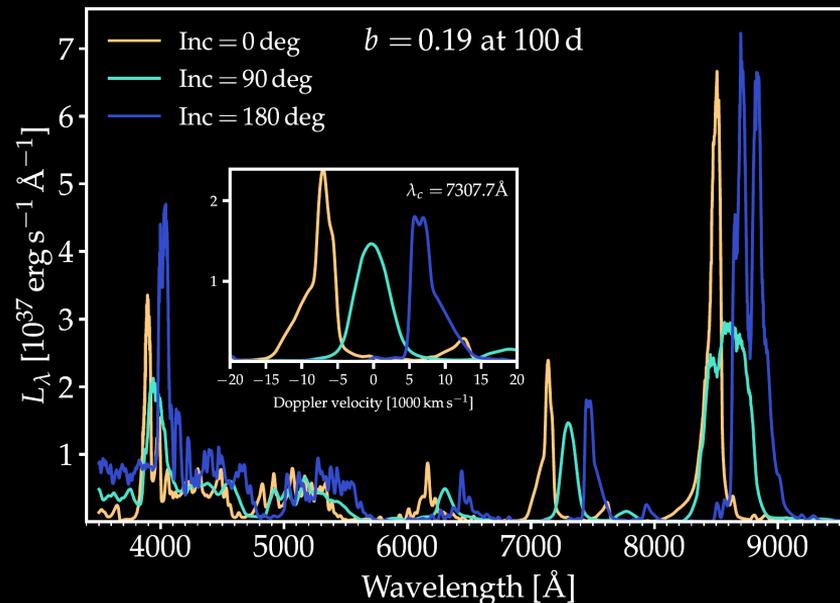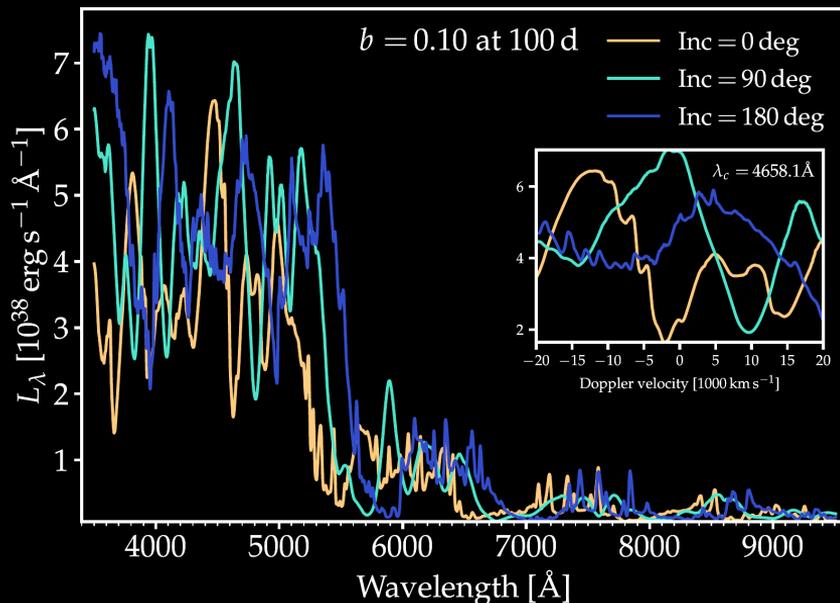
2D *B*-band magnitudes for different viewing angles

Vynatheya, Dessart = et al. (2026)

Takeaway: B-band magnitudes are highest for viewers opposite to the direction of the ejecta and for closer encounters, and vice versa.

2D spectra for different viewing angles at 100 d

Vynatheya, Dessart et al. (2026)

Takeaway: Spectral lines are strongly displaced and skewed by many 1000 km s⁻¹ at nebular times. They are blueshifted for viewers in the direction of ejecta, and vice versa.

Summary and future work

Vynatheya, Dessart et al. (2026)

- ❖ **Hydrodynamics** simulations of **WD TDEs**, followed by 1D and 2D **radiative transfer**

- ❖ Very close encounters lead to **runaway fusion**, with ^{56}**Ni fractions** up to **82%**

- ❖ **Highly asymmetric** ejecta, most of it (roughly) confined within a **cone of 30°**

- ❖ Spectra of **closer encounters** have strong **Fe and Co lines**, while those of **wider encounters** have strong **O and Ca lines**

- ❖ Spectra are **highly blueshifted** for viewers **in the direction of ejecta** and vice versa

- ❖ *Future work:* 3D Monte Carlo radiative transfer for better accuracy

The end

...

Classical tidal radius

Black hole

Stellar object

More
attracted

Less
attracted

Center of mass

The classical tidal radius is the (approximate) distance at which the tidal force on the stellar object that pulls it apart is comparable to the self-binding force that holds it together.

Tidal force: $f_t(r) \sim Gm_{BH}r_\star/r^3$

Binding force: $f_b \sim Gm_\star/r_\star^2$

$\longrightarrow$

$$r_t \sim (m_{BH}/m_\star)^{\frac{1}{3}} \, r_\star$$

r_t: Tidal radius
m_{BH}: Black hole mass
$m_\star$: Stellar object mass
$R_\star$: Stellar object radius

(Partial) Tidal disruption event

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