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Compact Binaries: NS– WD mergers Formation and Outcomes

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AND

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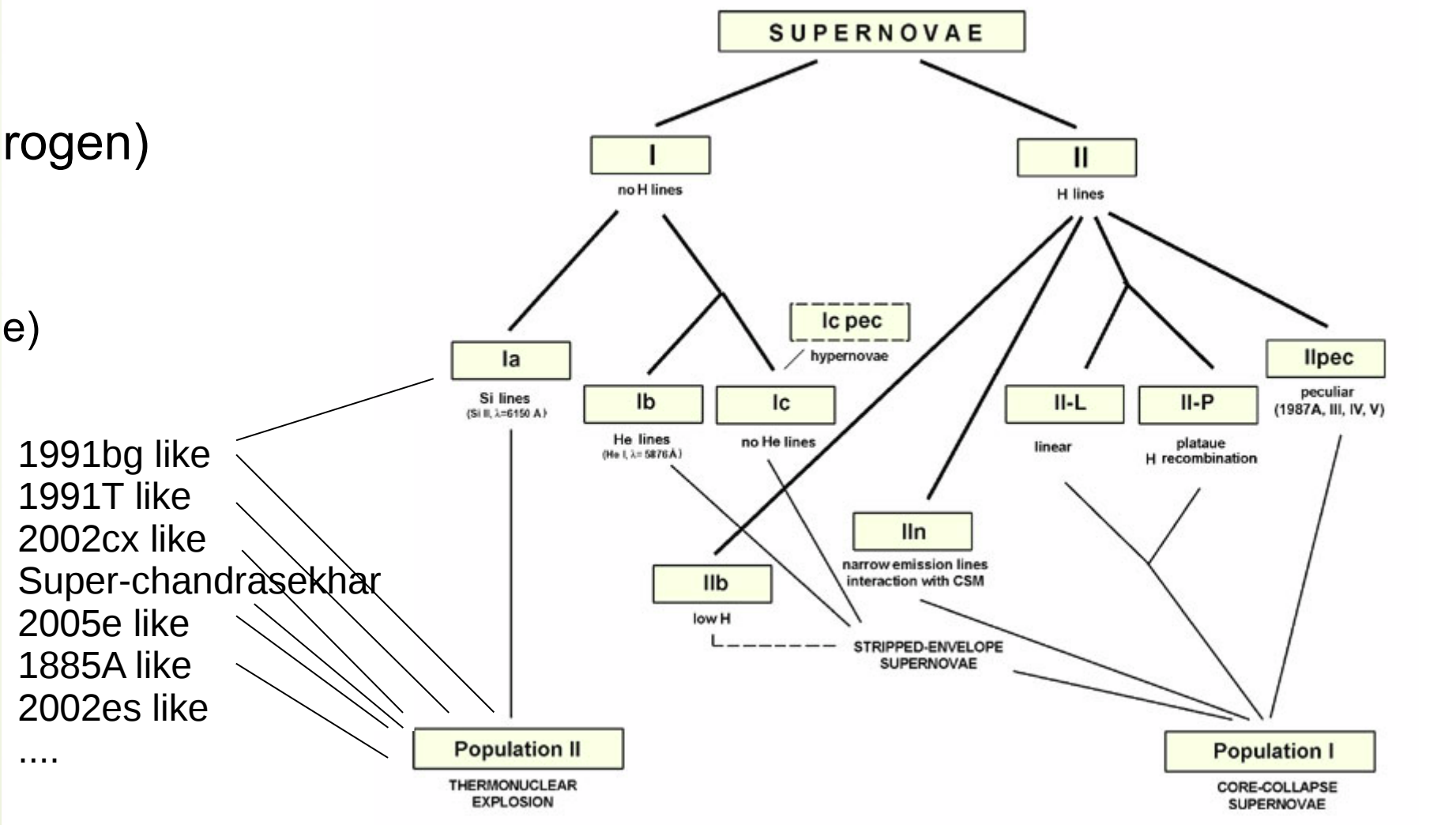
There are many sub-types of SNe

Type I (no hydrogen)

- Ia (Si, no He)
- Ib (He, no Si)
- Ic (no Si; no He)

1991bg like
1991T like
2002cx like
Super-chandrasekhar
2005e like
1885A like
2002es like
....



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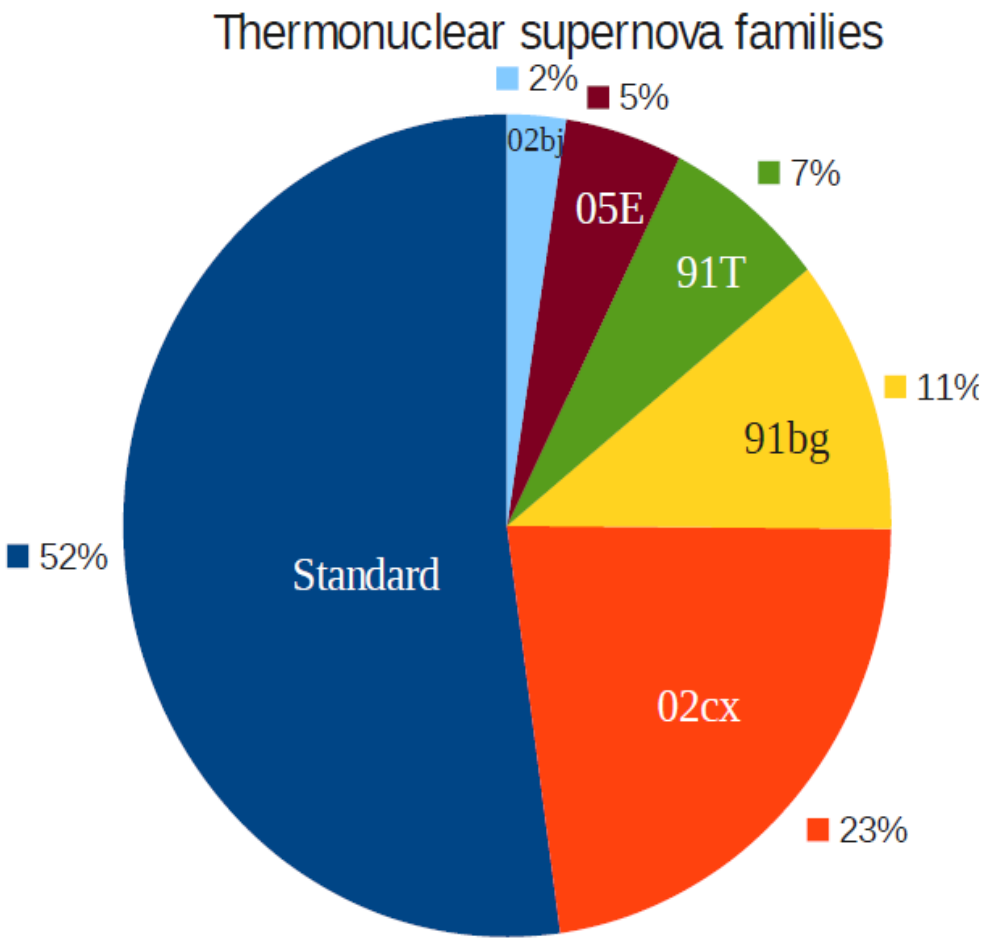
Many types of – thermonuclear SNe exist

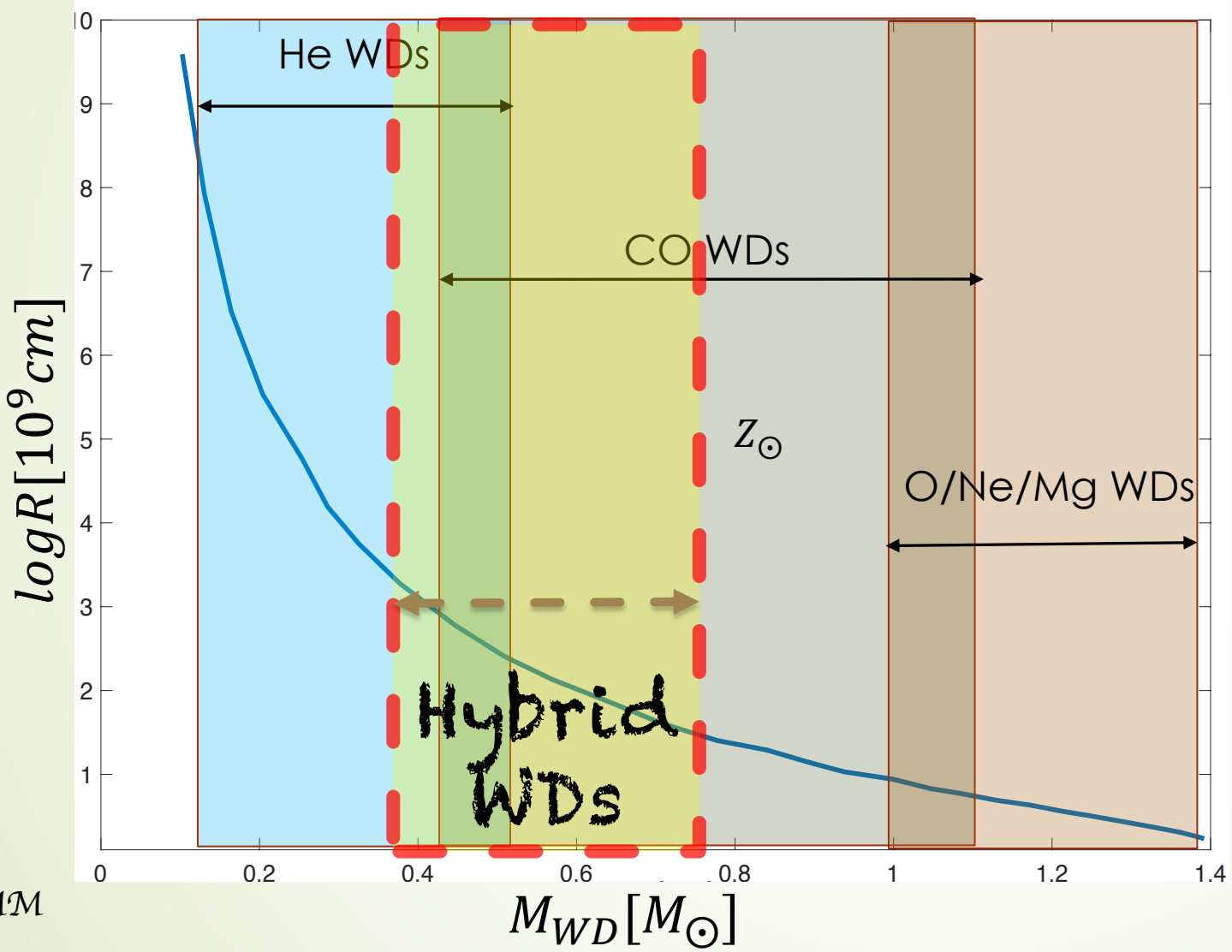
- lax (31 % +17 -13) - Foley et al. (13), Li et al.
- 1885A/02bj-like(3.4 %) - Hartwig (1885), Cheve et al. 10, HP et al. (11a).
- **05E-like (7 %)** - HP et al. 10, Kasliwal et al 94%) !!
- SN2019hek (?%)- Jacobson-Galan+21,22
- Fast and furious SNe (10X,05ek) (10-20 %) - Kasliw (+HP 13), Drout et al (14).
- 91bg-like (15%) - Fillipenko et al. (1992a).
- 91T-like (>9%) – Fillipenko et al. (1992b).
- Super-Chandrasekhar- Howell et a. (06).
- PTF 10ops,02es-like (2.5%) - Maguire et al. 11,



Ca-rich could be Ia or Ib

- Intermediate luminosity $M_{Bol} < -16.5$mag
- Small Ni56 amount $\lesssim 0.1 M_{\odot}$
- Faster photometric evolution than normal Sne $\Delta m_{15}(B) < 1.8 - 2.8$
- Photospheric velocities 6000–11000 $km \cdot s^{-1}$
- Rapid evolution to the nebular phase. $B \approx -15 - -14$mag
- Nebular spectrum dominated by calcium emission
- The ejecta Mass $\lesssim 0.3 - 0.7 M_{\odot}$
- S0 or elliptical hos galaxies (not PTF09dav).

The masses of hybrid-WDs overlap with both He and CO WDs



Hybrid-WDs are composed of significant fractions of both CO and He.

In binaries $M_{HeCO\ WD} \gtrsim 0.33\ M_\odot$
(Prada Moroni & Straniero 2009)

Iben & Tutukuv 1985
Tutukov & Yugelson 1992
Drirble et al. 1998
YZ+18

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Unstable mass transfer and disc formation

- **NS-WD binaries** – initially wide binary with intermediate- mass $\sim 8 - 10 M_{\odot}$- WD evolution scenario (van den Heuvel & Bonsdema 84).
- **Debris disk around the NS**
  - NS-WD binary - J_z loss (GW emission)→ period < 1 min → RLOF → Mass transfer -
    - Unstable systems → WD tidally disrupted **(~few t_{dyn})**→ NS- disc (WD)→ $\dot{M} \sim 10^{-4} - 10^{-1} M_{\odot} s^{-1}$ → ? (Paschalidis et al. 2009)
    - Stable systems → wide system $\frac{da}{a}$ ↑. → UCXB.
  - Collisions event- in centres of galaxies and GC. (Sigurdsson & Rees 1997).

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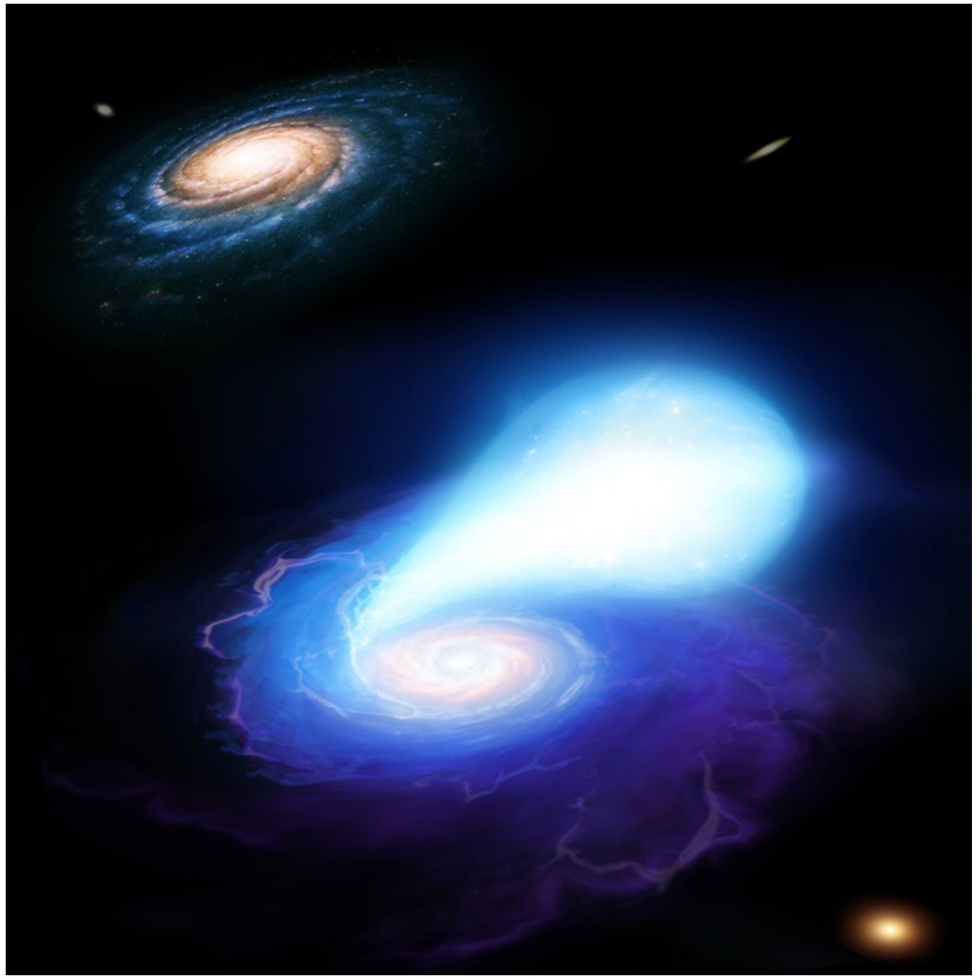
Ultra-Compact x-ray Binary (UCXB)

$$M_{\rm WD} = 0.067\, M_\odot$$
$$\text{Age} \lesssim 2\,\text{Myr}$$
$$P_{\rm orb} = 11.4\,\text{min}$$

Transient UCXBs spend almost all the time in a quiescent state with little or no accretion- depend on $\dot{M}, t_{dyn}$.

Evolution of UCXB - Nelemans & Jonker 2010, Toonen et al 2018.



4U 1820-30 (Stella et al. 1987)

Image credit: Mark A.Garlick

Ultra-Compact x-ray Binary **(UCXB,ULXs)**

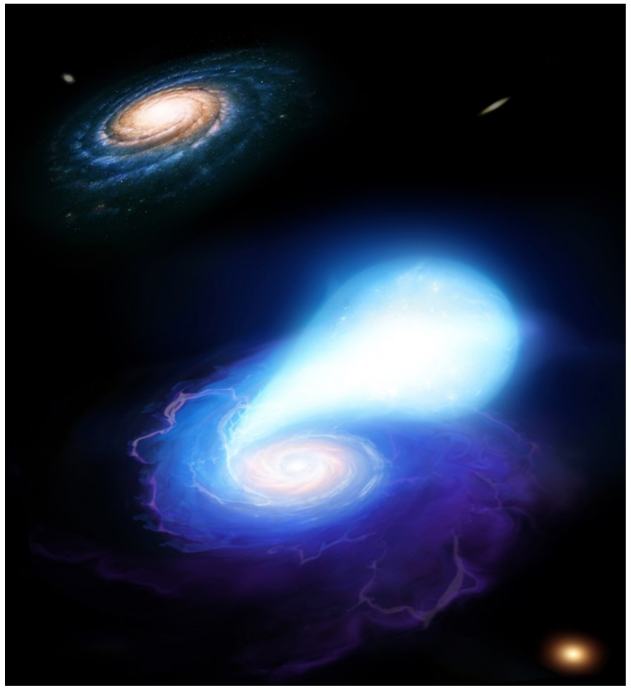
- First optical spectroscopy 4U 1626-67, 4U 0614+09- clearly lack **H, He lines**, but exhibit **C/O lines**, →**C/O WD donors.** (Nelemans et al 04,06 and Werner et al 06)

- Systems observed in our galaxy- wide range WD mass. (Edwards & Bailes 18, Kim el al 2010, Bailes et al. 2003, Kaspi et al 2000, van Kerkwijk & Kulkarni 1999, ATNF catalogue).
  - PSR J1738−0333 – $M_{WD} = 0.67 M_{\odot}$
  - PSR J1141−6545 – $M_{WD} = 0.99 M_{\odot}$
  - PSR J1757−5322 - $M_{WD} = 0.2 M_{\odot}$

$M_{\rm WD} = 0.067\, M_{\odot}$

$\mathrm{Age} \lesssim 2\,\mathrm{Myr}$

$P_{\rm orb} = 11.4\,\mathrm{min}$



4U 1820-30 (Stella et al. 1987)

Image credit: Mark A.Garlick

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Observations and Evolution

Detached WD-NS Binaries
(>150 observed, ATNF cat.)

(van Kerkwijk & Kulkarni 1999)

GW Emission $(a_{\rm bin} \lesssim 4\,R_\odot)$

Spiral into Contact (10 objects, ATNF cat.)

$M_{\rm WD,crit} = 0.82\,M_\odot$

Low-mass WD

Ultra-Compact X-ray Binaries (15 observed)

E.g. (Heinke et al. 2013)

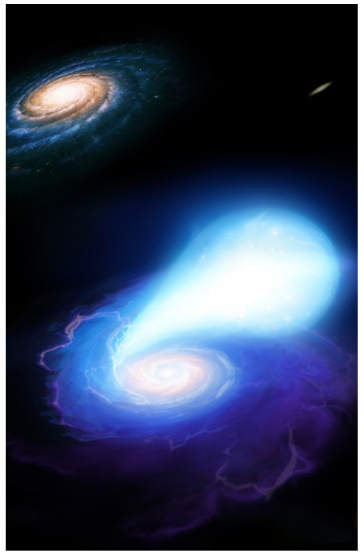
High-mass WD

Tidal Disruptions, Faint Rapid Transients

(Metzger, 2010; Drout et al. 2014)

E.g. (Hurley et al. 2002; van Haaften et al. 2013)

Standard value



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NS-WD Rates

Hydrodynamic Simulations

Independent of eccentricity

$M_{\rm WD,crit} = 0.82\,M_\odot$ ⟶ $M_{\rm WD,crit} = 0.2\,M_\odot$

E.g. (Hurley et al. 2002; van Haaften et al. 2013)

E.g. (Toonen et al. 2018; Eldridge et al. 2019)

Inspiral rates of binary pulsars with He WD companion:

$$\text{MW rate} \approx 0.72\,\text{Myr}^{-1}$$

He UCXB formation rate:

$$\text{MW rate} \approx 0.07 - 0.23\,\text{Myr}^{-1}$$

CO UCXBs must have formed in some other way (e.g. He star channel)

Rates for unstable systems match those of observed rapid faint SNe (e.g. Drout et al. 2014)

(Ritter & King 2002)
(Bobrick et al. 2017)

NS-WD mergers about 6–20% of the type Ia SNe rate.

BPS Model	Synthetic time-integrated merger rate ($M_\odot^{-1}$)		
	NS–WD	WD–WD	Super-Ch WD–WD
$\alpha\alpha$	$(4.7–18)\times10^{-5}$	3.2×10^{-3}	5.5×10^{-4}
$\alpha\alpha2$	$(3.8–8.1)\times10^{-5}$	5.9×10^{-5}	2.1×10^{-5}
$\gamma\alpha$	$(3.7–12)\times10^{-5}$	3.2×10^{-3}	4.2×10^{-4}
	Observed time-integrated rate ($M_\odot^{-1}$)		
Supernova Type Ia[a]	$(1.3\pm0.1)\times10^{-3}$, $(1.6\pm0.3)\times10^{-3}$		
Calcium-rich transients[b]	33–94% of the SNIa rate		

SNe Ia in field galaxies$\sim10^{-3}M_\odot$

Maoz et al. 2014, Maoz & Graur 2017

Simulations should include both hydrodynamics and thermonuclear reactions

- BH-WD merger –during the merger, the WD is tidally disrupted and sheared into accretion disk. (Papaloizou et al 83,Fryer et al 1998 and Metzger 2012).
- Paschalidis et al. (2011) & Bobrick et al. (2017) have explored the disruption and the disk formation process with time-dependent simulations.
- Thermonuclear processes can also play an important role on the dynamics of accretion following the TD of WD. (Metzger12, Fernandes&Metzger13, YZ+20).
- NS-WD mergers could be modeled in 2D using accretion disk. (Fernandes&Metzger13, Bobrick et al 2016, Margalit&Metzger16, and YZ+19, 21).

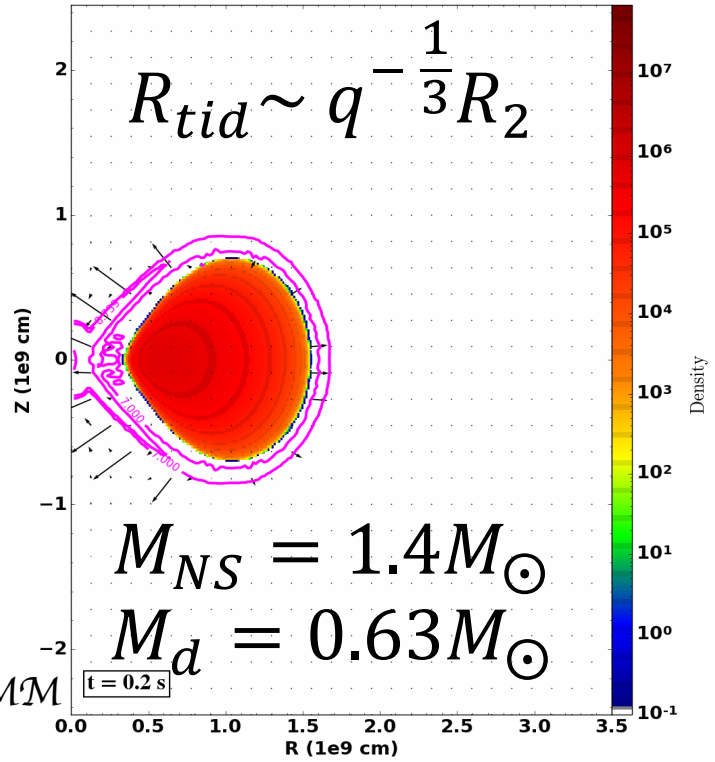
$$t_{\rm visc} \simeq \alpha^{-1}\left(\frac{R_0^3}{GM_{\rm c}}\right)^{1/2}\left(\frac{H_0}{R_0}\right)^{-2}$$
$$\sim 2600\,{\rm s}\left(\frac{0.01}{\alpha}\right)\left(\frac{R_0}{10^{9.3}{\rm cm}}\right)^{3/2}\left(\frac{1.4M_\odot}{M_{\rm c}}\right)^{1/2}\left(\frac{H_0}{0.5R_0}\right)^{-2}$$

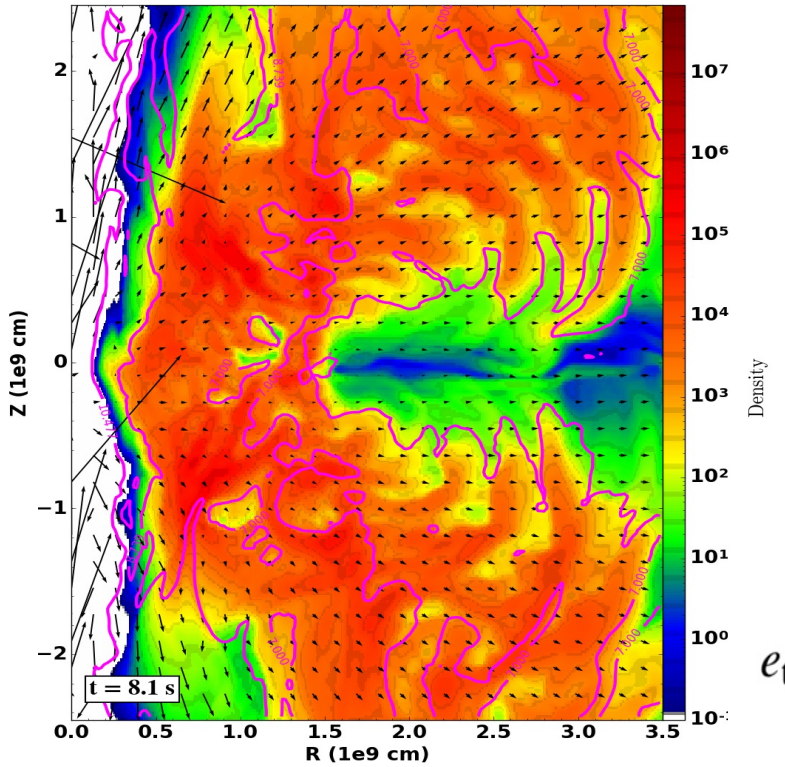
$$\rho_{\rm disk} = \rho_{\rm max}\left[\left(\frac{2{\rm H}}{{\rm R}_0}\right)\frac{2{\rm d}}{{\rm d}-1}\left(\frac{{\rm R}_0}{r}-\frac{1}{2}\left(\frac{{\rm R}_0}{{\rm r}\sin\theta}\right)^2-\frac{1}{2{\rm d}}\right)\right]^{7/2} \quad (3)$$

$$\frac{\rm P}{\rho} = \frac{2{\rm GM}}{5{\rm R}_0}\left[\frac{{\rm R}_0}{\rm r}-\frac{1}{2}\left(\frac{{\rm R}_0}{{\rm r}\sin\theta}\right)^2-\frac{1}{2{\rm d}}\right] \quad (4)$$

Simulation should include both hydrodynamics and thermonuclear reactions

- Nuclear burning on accretion have been explored in. (Taam&Fryxell 1985, Chakrabarti et al 1987).
- Thermonuclear process can play an important role also on the dynamics of accretion following the TD of WD. (Metzger 11+12,FM13,YZ et al 19,20,21,22).





Virial Temperature

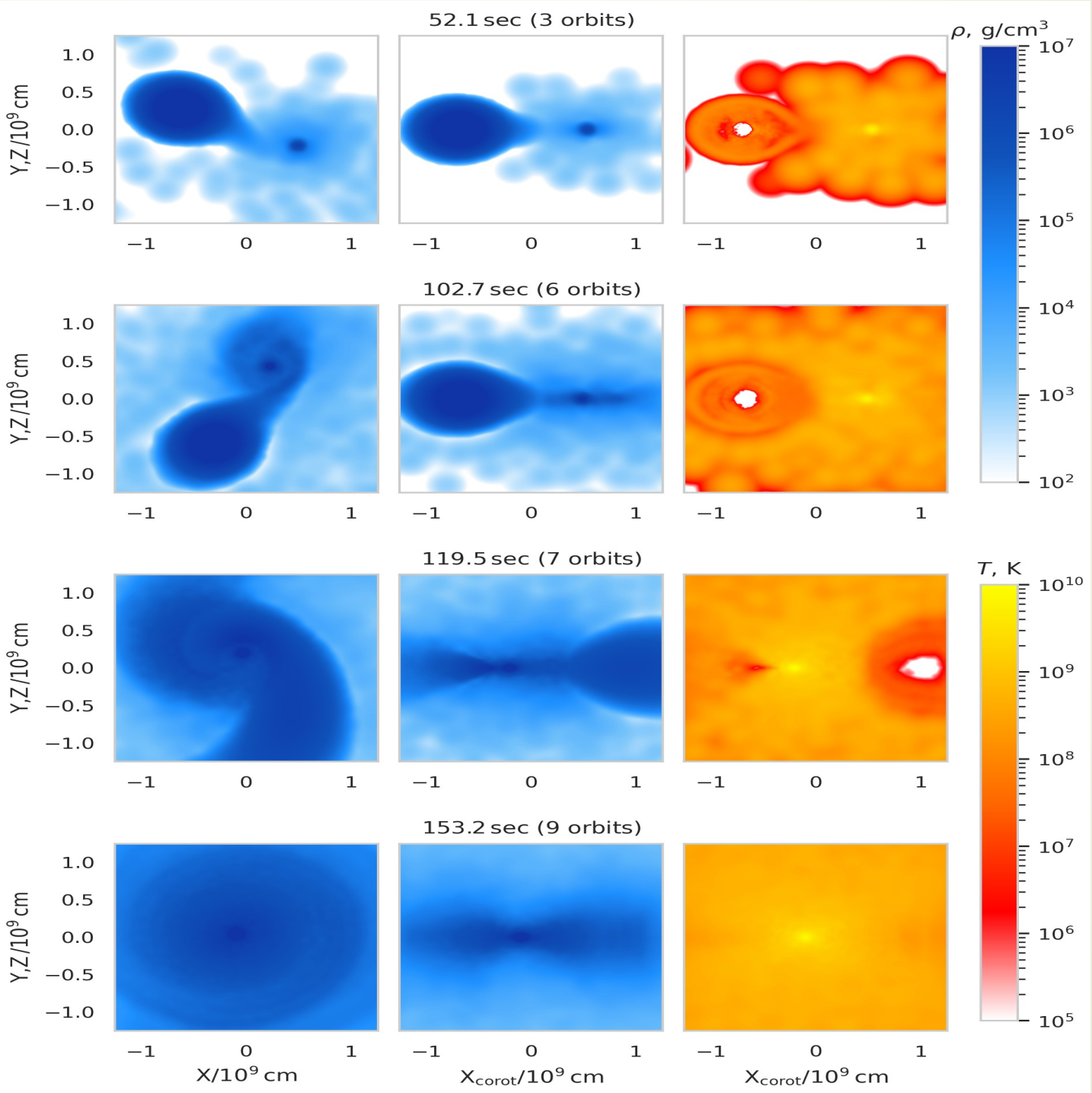
$$T(R_{tid}) \geq 6\times10^8 K$$

Midplane Density

$$\rho(R_{tid}) \approx 10^7 g cm^{-3}$$

$$e_{\rm tot} = \frac{1}{2}\left[v_r^2 + v_\theta^2 + \frac{\ell_z^2}{(r\sin\theta)^2}\right] + e_{\rm int} - \frac{GM_c}{r}$$

WD- NS simulation



TDAMM
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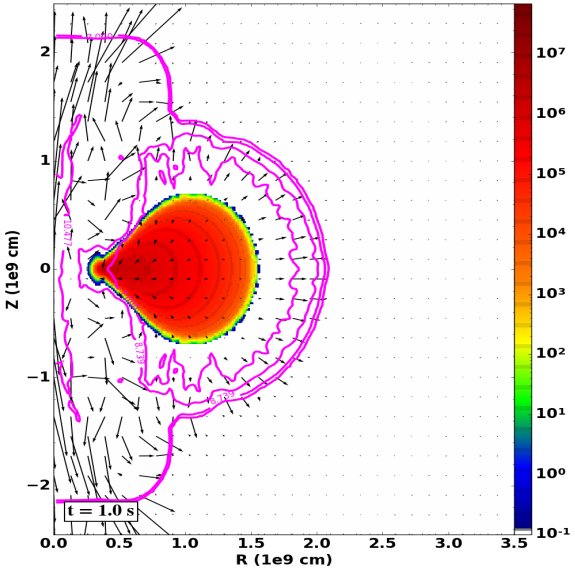
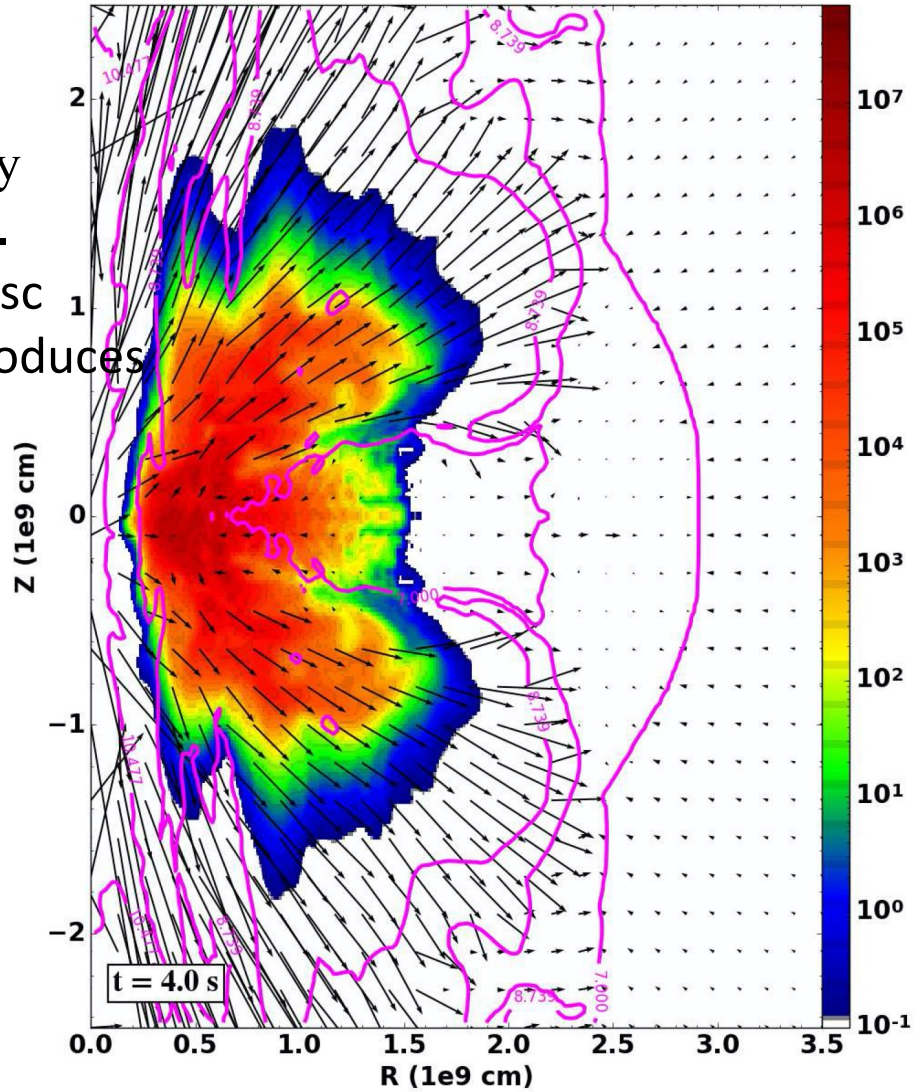
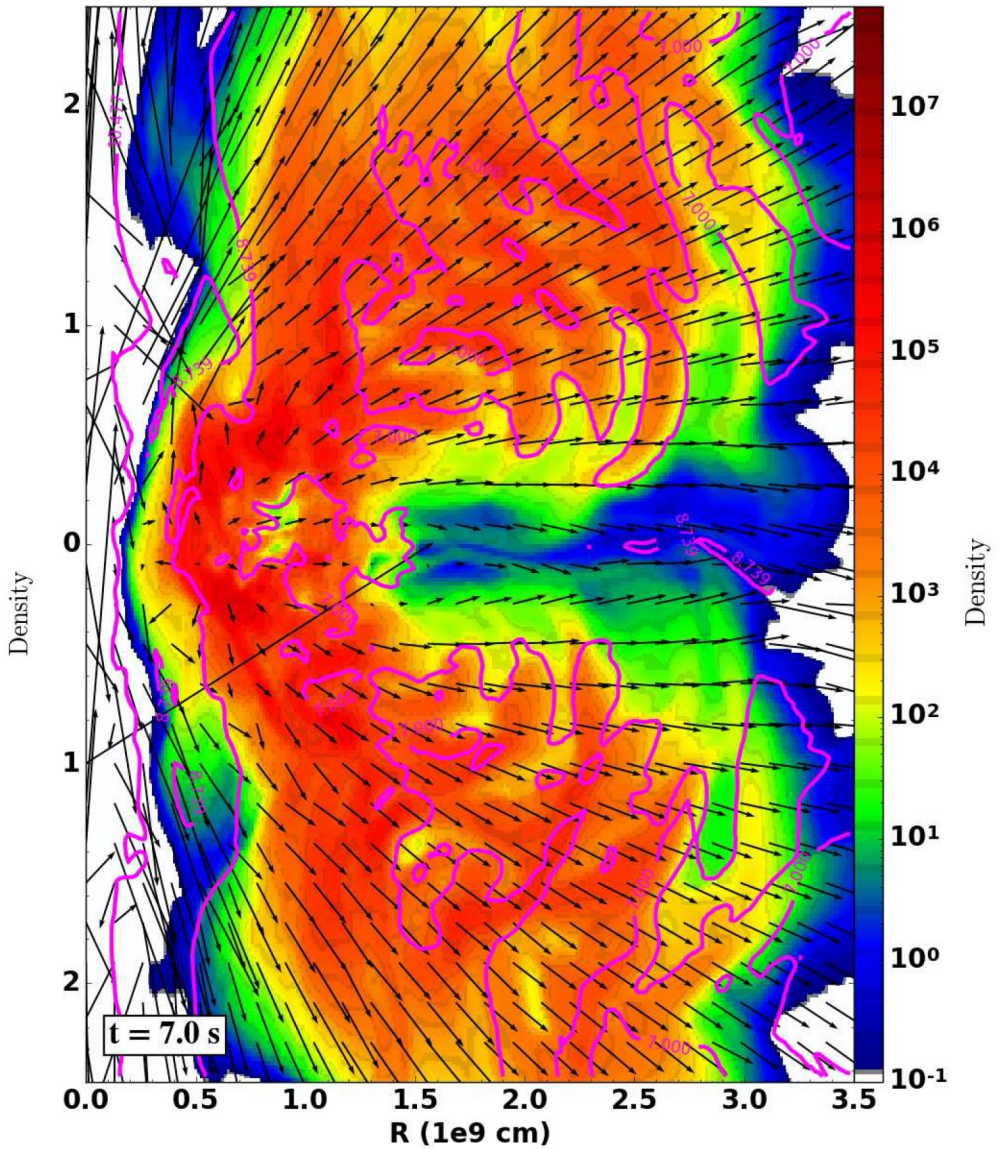
Self-gravity changes the structure of the disk

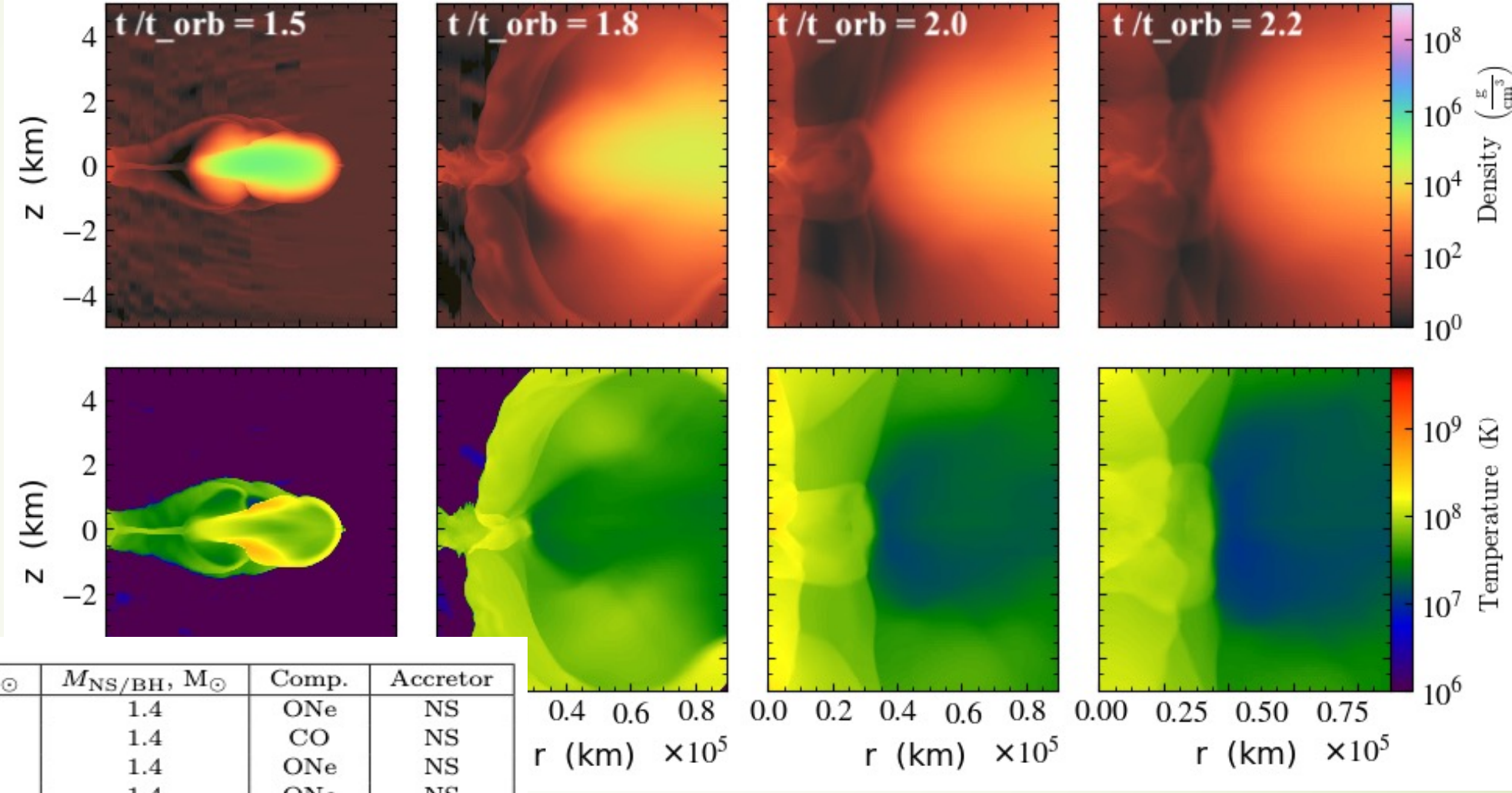
- The time is normalized by $0.25\ t_{orb}(\sim 9-14 sec)$.
- Nuclear burning in the disc proceeds steadily and produces small amounts of 56Ni







ONe WD- NS hydro-nuclear challenge



Model	M_{WD}, $M_\odot$	$M_{NS/BH}$, $M_\odot$	Comp.	Accretor
U	0.9	1.4	ONe	NS
U_2	0.9	1.4	CO	NS
V	1.0	1.4	ONe	NS
W	1.1	1.4	ONe	NS
X	1.2	1.4	ONe	NS
X_2	1.2	2.0	ONe	NS
X_3	1.2	5.0	ONe	BH
Y	1.3	1.4	ONe	NS

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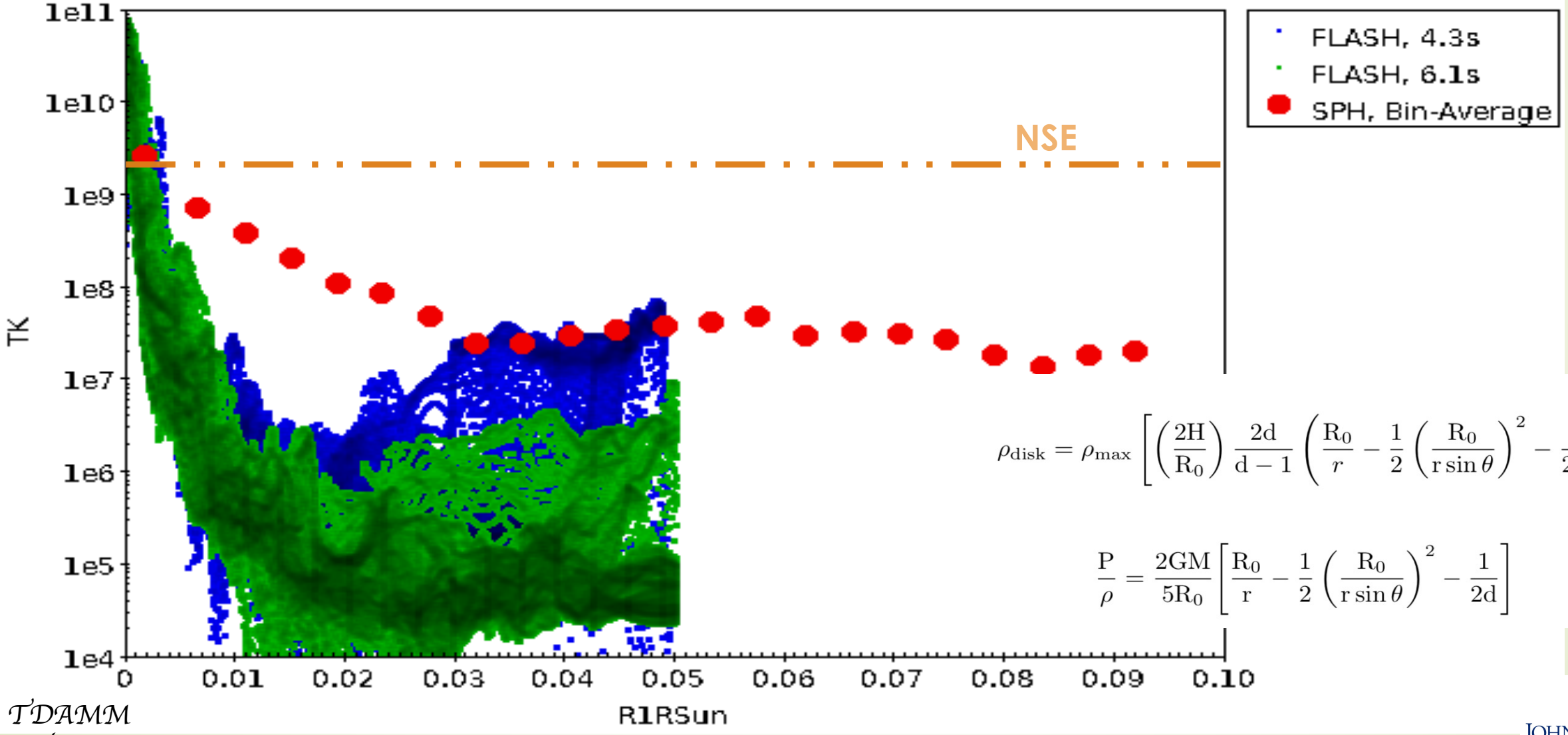
Initial density and temperature - SPH and FLASH



$$\rho_{\rm disk} = \rho_{\rm max}\left[\left(\frac{2H}{R_0}\right)\frac{2d}{d-1}\left(\frac{R_0}{r}-\frac{1}{2}\left(\frac{R_0}{r\sin\theta}\right)^2-\frac{1}{2d}\right)\right]^{7/2} \quad (3)$$

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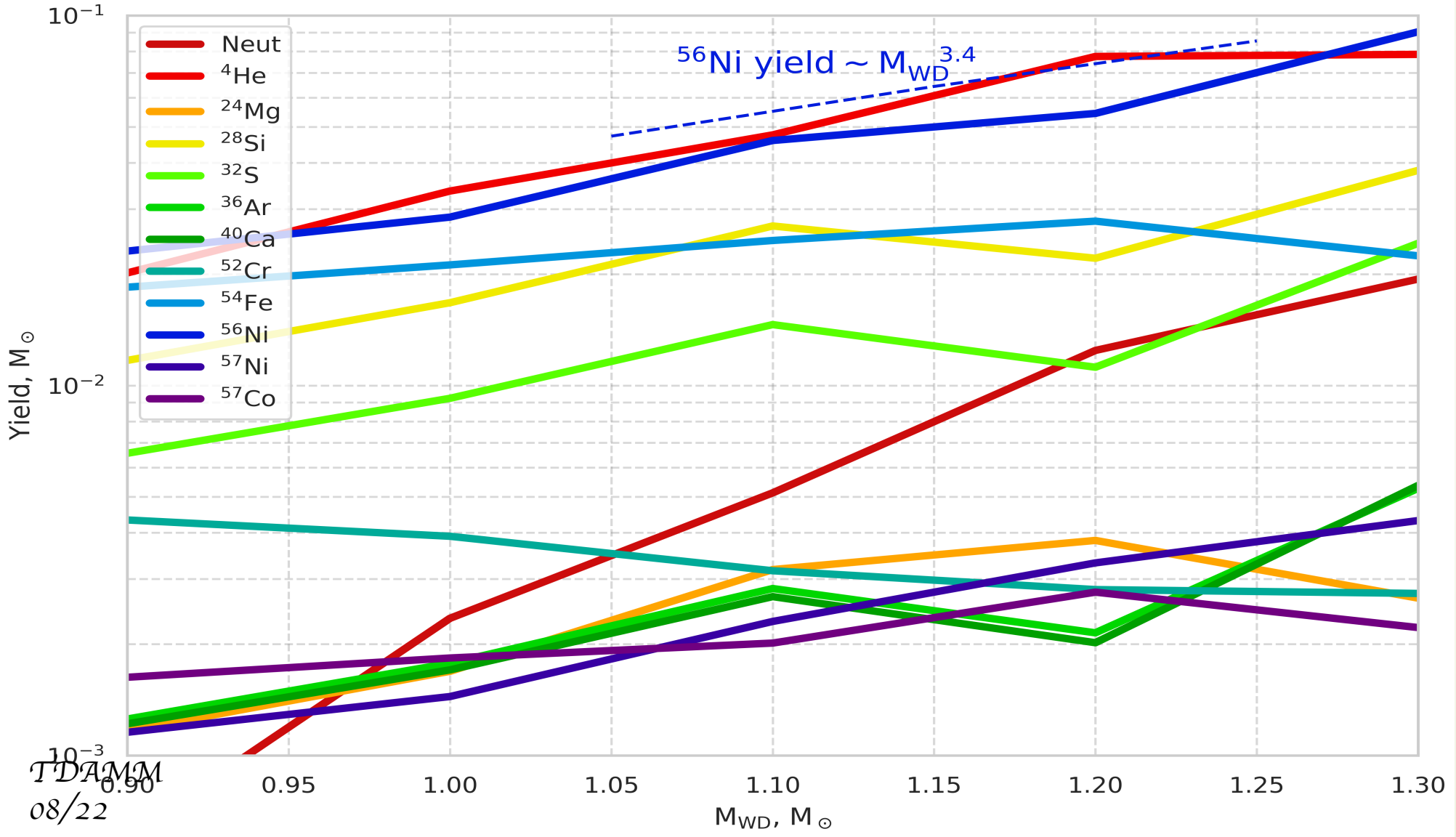
The nuclear energy is a strong function of the WD [ONe WD-NS]



Nuclear yields –
up to few 0.05 - 0.1$M_\odot$

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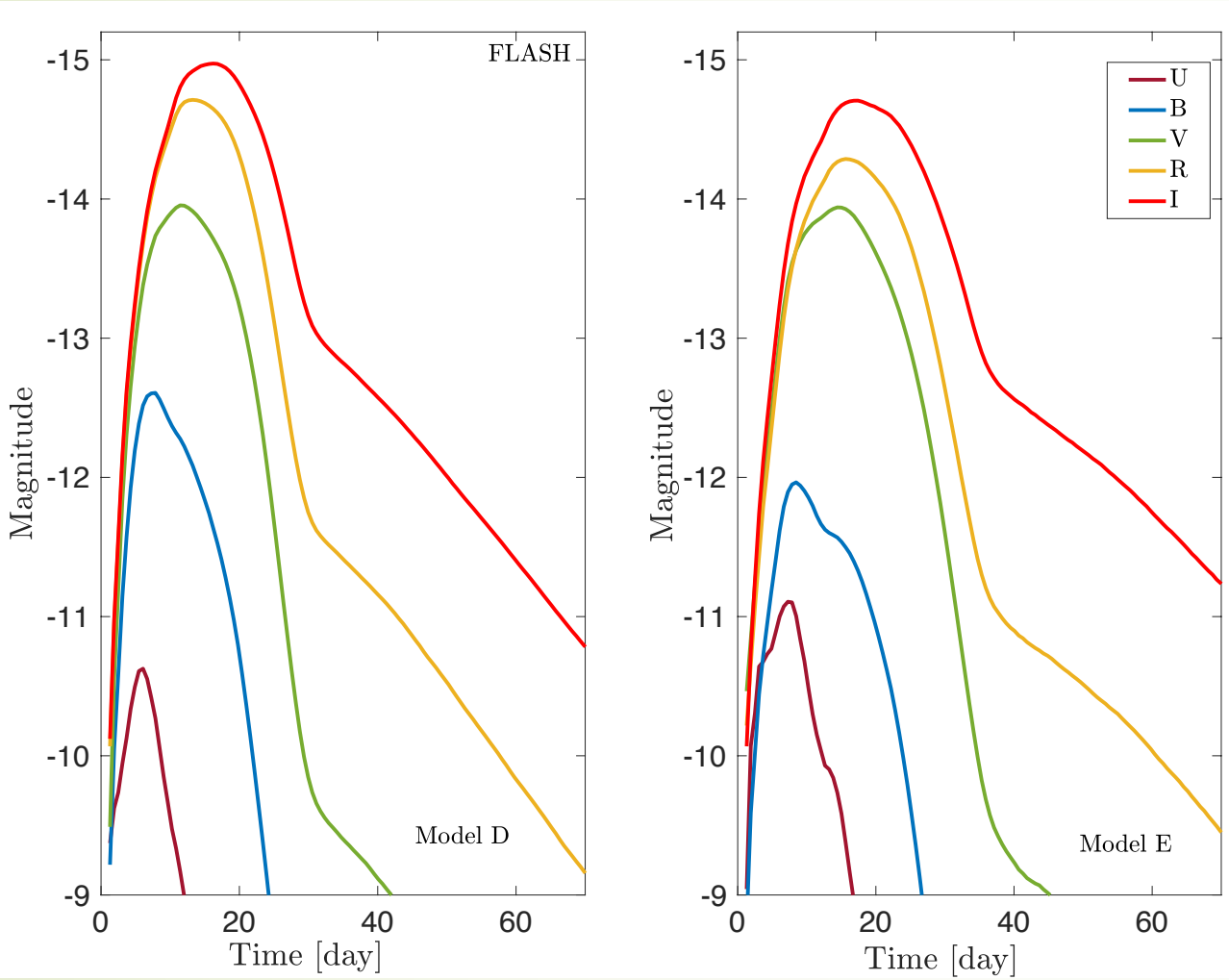
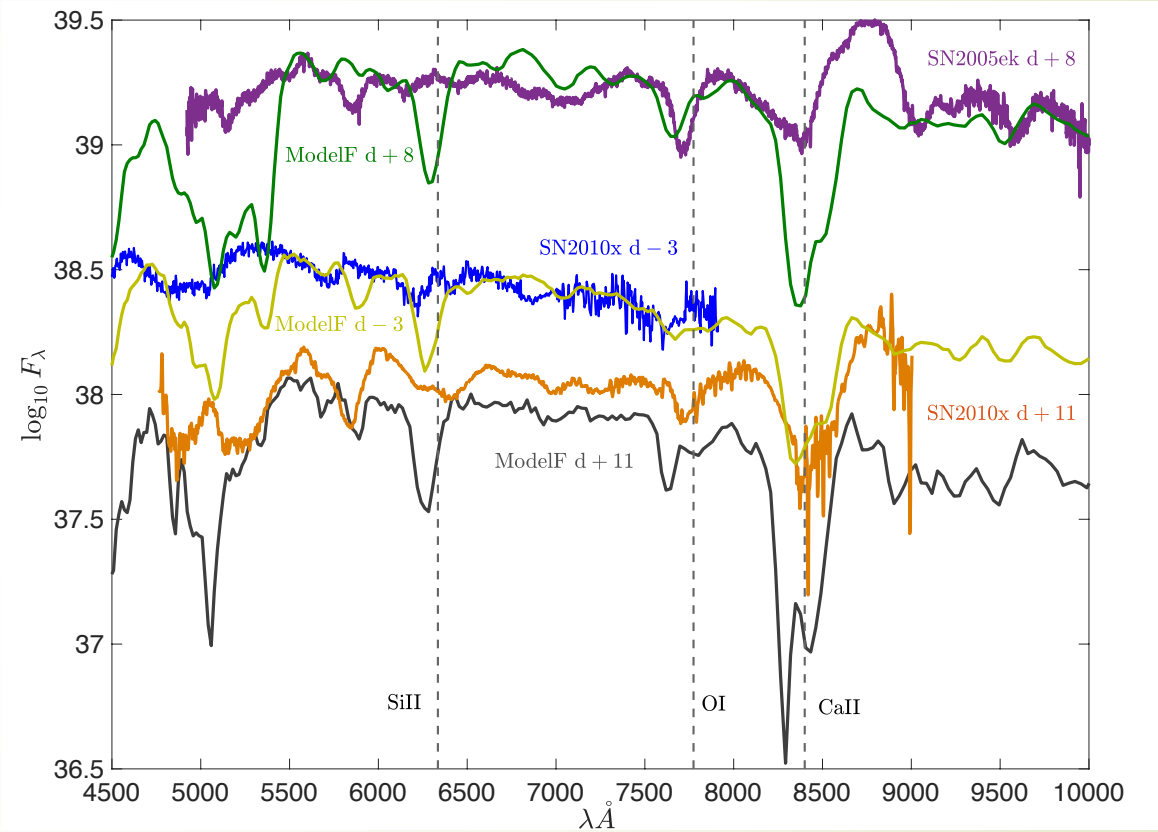
Rapid Red Transients





- Radiative Transfer (SuperNu code) Lightcurves - faint,
- few weeks duration Spectra - new transient
- Few 10s per year with LSST

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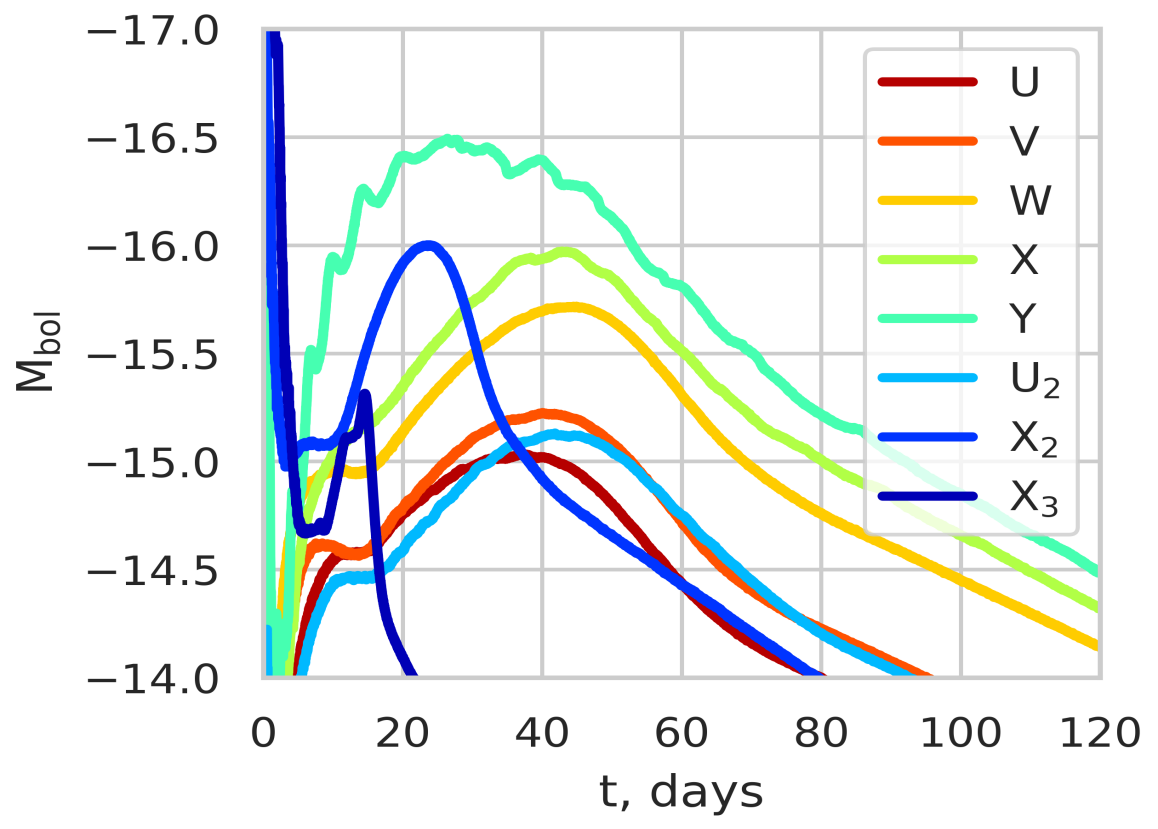
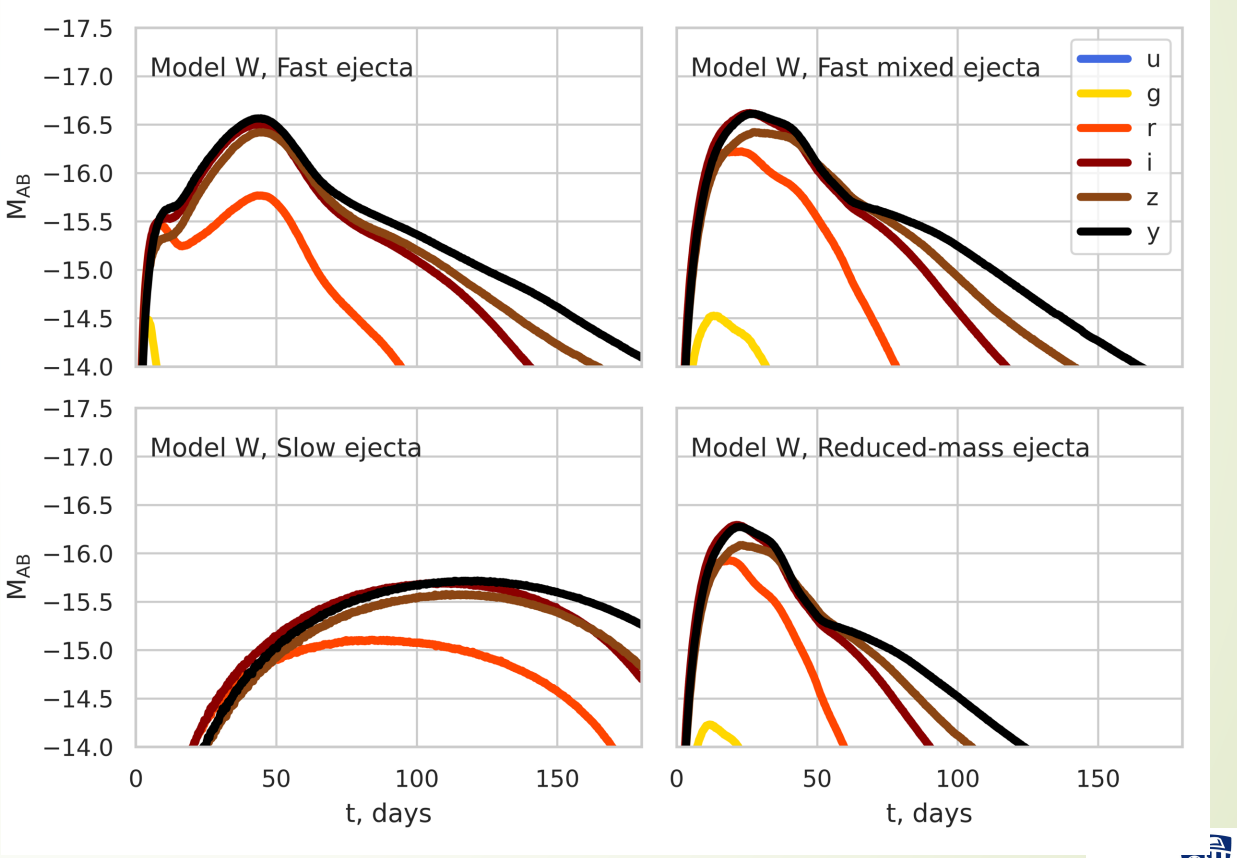
Could be faint Iax or Ic

The transients from ONe WD-NS binaries $\mathbf{10^{41.5} - 10^{42}}$**erg/s**, the fainter transients from CO WD-NS binaries ($\mathbf{10^{41.1} - 10^{41.5}}$**erg/s** (YZ et al 20, 21)





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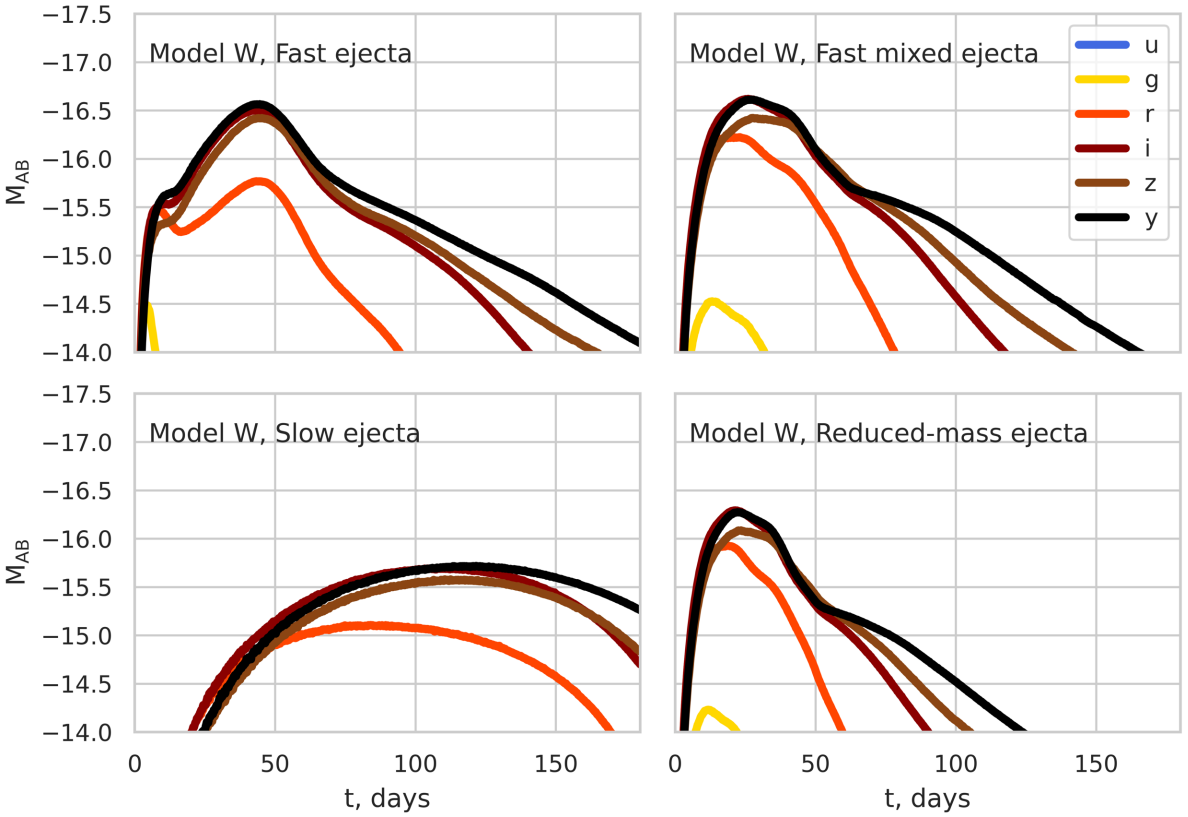

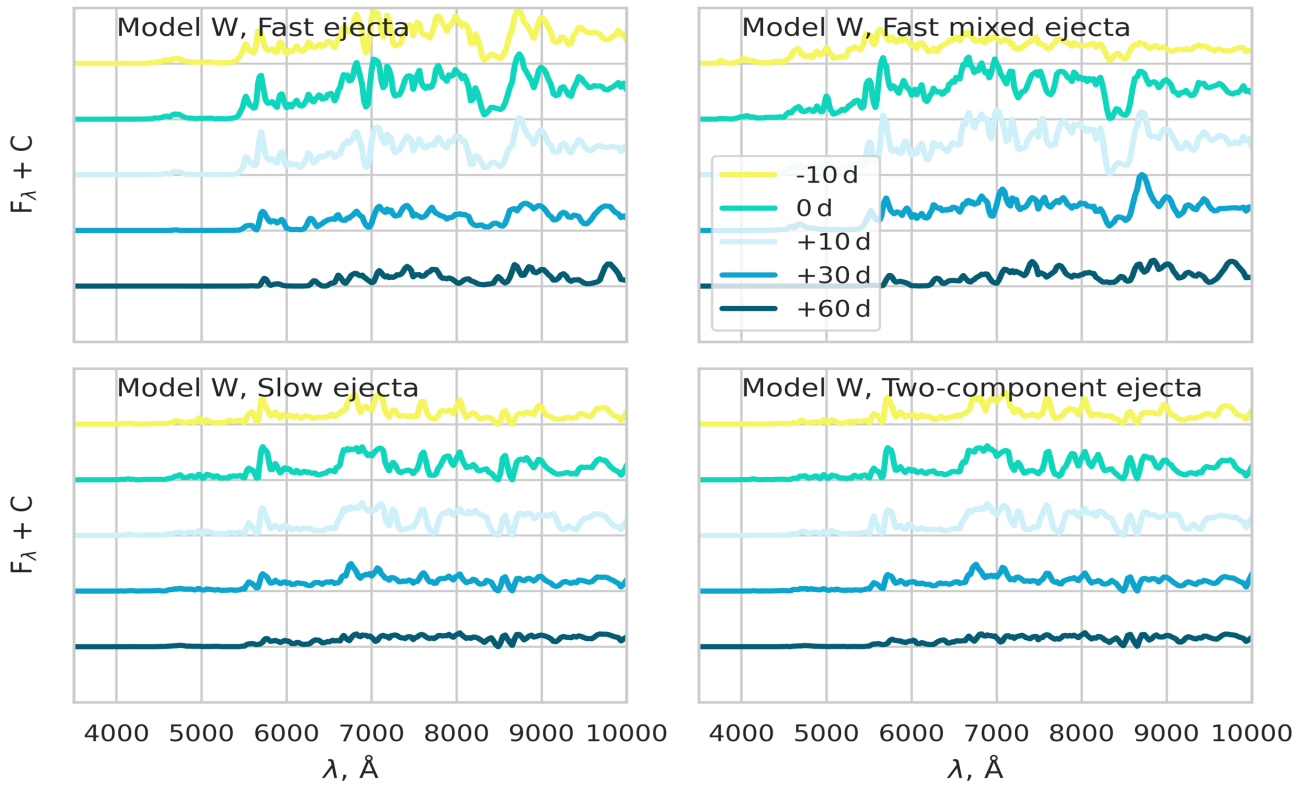

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Summary

- Hybrid HeCO WDs can form robustly.
- **CO WD-NS mergers give rise to ultra-faint, rapidly evolving reddened transients (RRTs).**
- **ONe WD-NS mergers are dominantly red/infrared, best agree with faint type 1ax supernovae.**
- **ONe WD-BH transients agree well with the recently proposed candidate event SN AT2019kzr.**
- Ca-rich 2005E-like SNe or SN 2008ha-like SNe are still much brighter in the blue bands.