Transients following WDs mergers

Lyutikov & Toonen 2019 (model for Fast Blue Optical Transients)

Lyutikov 2022 (a number of confirmed predictions)

WD-WD mergers are the most frequent unobserved catastrophic events

- Rates (per WD, per stellar mass, per Galaxy, per Gpc^3…):
  - the rates of WD-WD mergers are huge
  - ~10% of all WDs ever formed merged with another WD (Maoz+ 2018)
  - The DWD merger rate is 4.5-7 times the Milky Way's specific Type-Ia
- FBOTs - rare but bright results of WD-WD merger, followed by AIC ~ 10^4 yrs later, with small remaining envelope $M_{ej} \leq 0.1 M_{\odot}$
- central engine (NS) powered

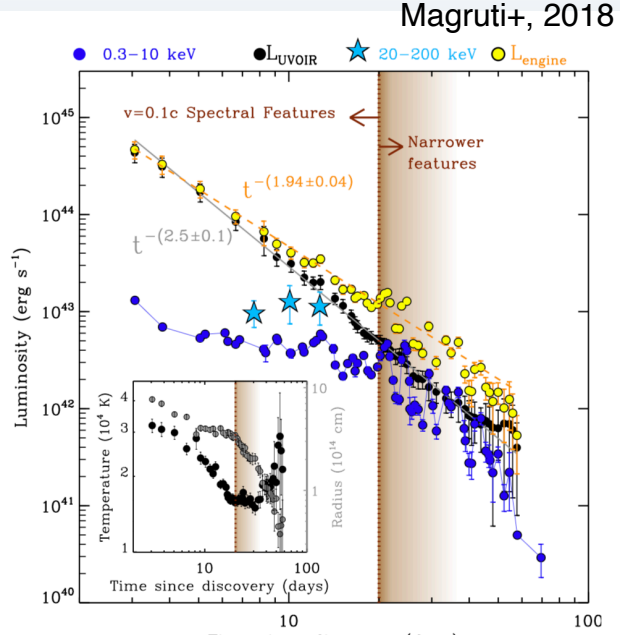
DBH	$23.9^{+14.3}_{-8.6}$	$2.1^{+1.2}_{-0.7} \times 10^{-4}$	(Abbott et al. 2021)

- Most WD-WD mergers are not observed directly
  - except, perhaps, DD Ia - small fraction
- There is a large room for many interesting transients after the merger, especially with super-Ch

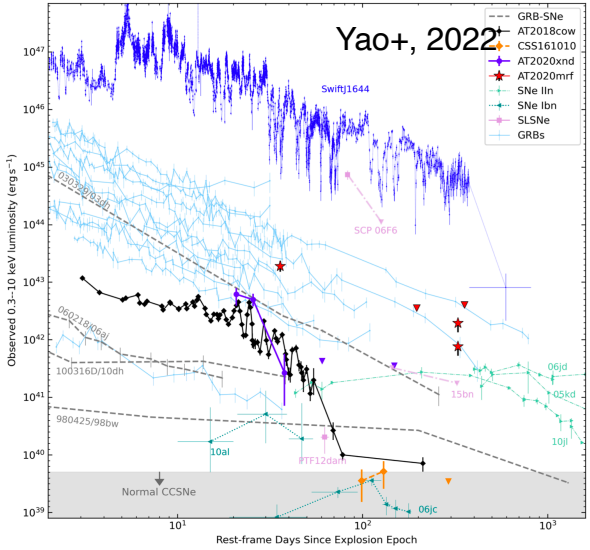
FBOTs - Fast Blue Optical Transients
AT2018cow & AT2020mrf

- rise-time of ≤ 3 days, peak at 5 days
- peak luminosity ~ 4 × 10^{44} erg s^{-1}
- Similar optical and X-ray luminosities
- Change of properties of the emission at ~ 30 days, H & He lines appear
- rising IR component at t ≥ 30 days
- Bright radio emission t ≥ 80 day
- AT2020mrf:
  - X-ray flash at ~35 day
  - dominant X-ray emission a year after E ~ few 10^{49} erg

Magruti+, 2018



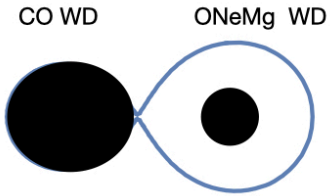
Yao+, 2022

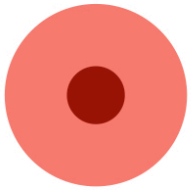


Quick conclusions

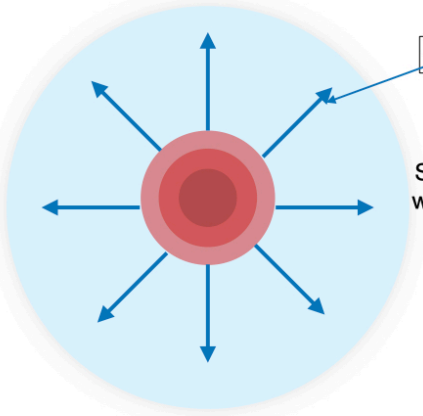
- Peak time: few days:
  - not Ni-powered - central engine
  - **small** $M_{ej} \leq 0.1 M_{\odot}$ (or energy through the roof):
  - $$t_{FBOT} = \left(\frac{3}{4\pi} \frac{M_{ej}\kappa}{c V_{ej}} \right)^{1/2} = 4.6\, m_{ej,-1}^{1/2}\, V_{ej,4}^{-1/2}\ \mathrm{days}$$
    - this is photon diffusion ahead of the shock, not full transparency
    - **How to make** $M_{ej} \leq 0.1 M_{\odot}$**?**
- Energy:
  - $E_{opt} \sim 10^{49}$ erg
  - $E_X \sim 3 \times 10^{49}$ erg, 1yr after (!) -AT2020mrf
  - **Internal engine** with $L_0 \sim 10^{43}$ erg/s a year after - not too bad, $E_{tot} \sim 10^{50}$ erg

The idea

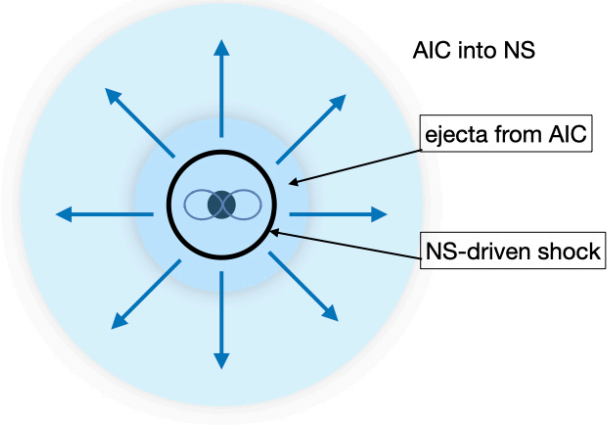


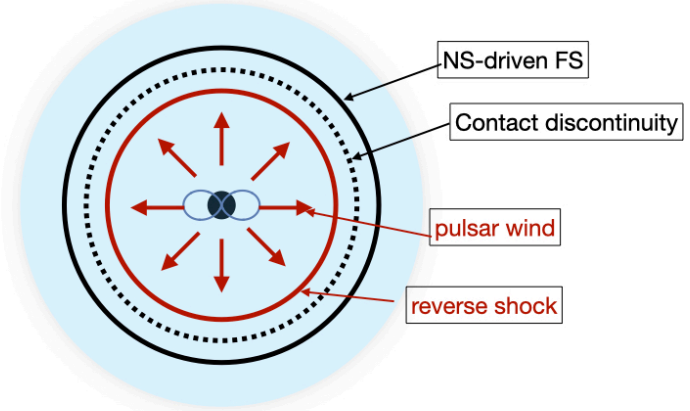


ONeMg core +
non-degenerate shell

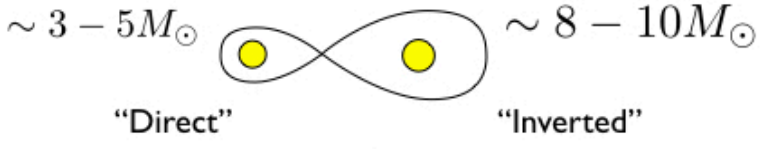


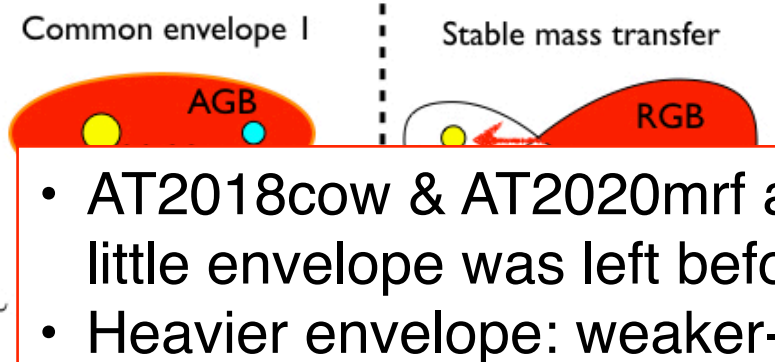
Shell material is lost to the
wind and added to the core





- Initial binary ~ 5+8 M_{Sun}





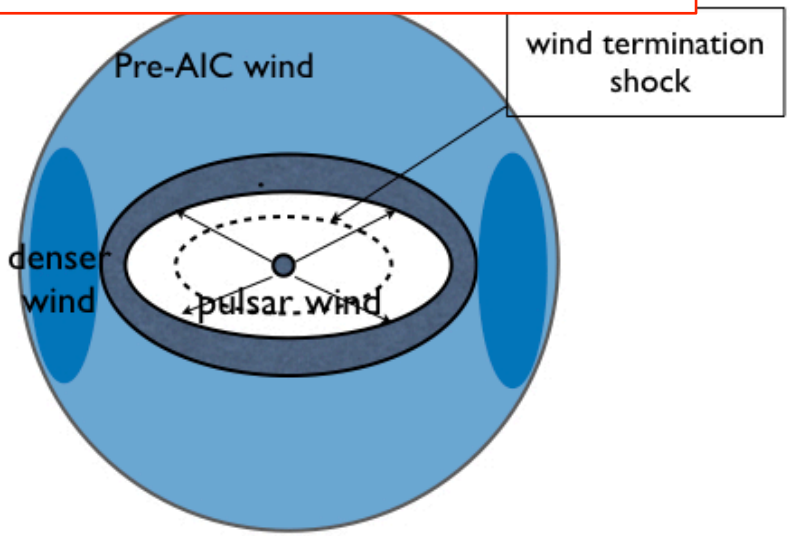
unstable GW-driven mass transfer, secondary disrupted,

- q> 0.25 - Unstable Roch lobe overflow

- AT2018cow & AT2020mrf are the lucky ones of FBOTs - very little envelope was left before AIC
- Heavier envelope: weaker-longer

- Central NS drives relativistic wind
- Termination shock: X - IR in fast
- Small Ejecta mass
- H in the wind
  - change at ~ 20 days
  - hydrogen from wind (DA WDs, 10-4 of H)

- Fast rotating NS, B-field is amplified

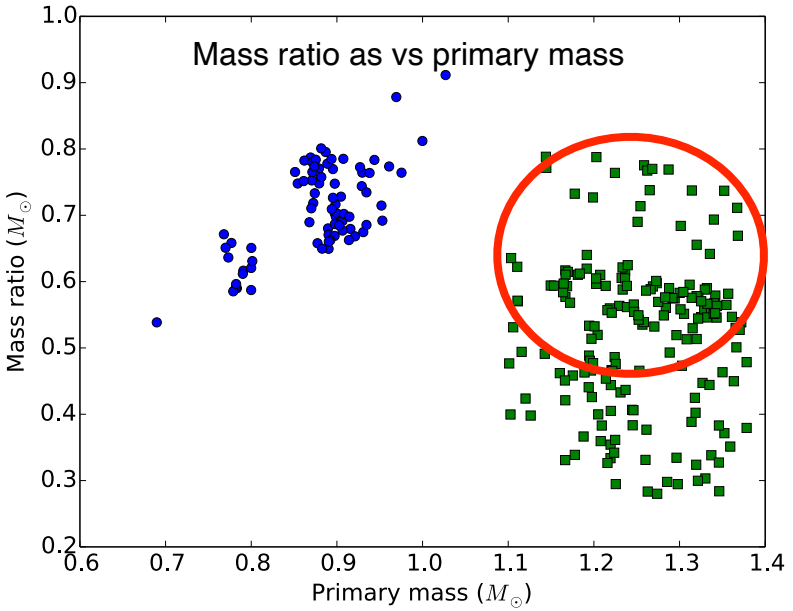


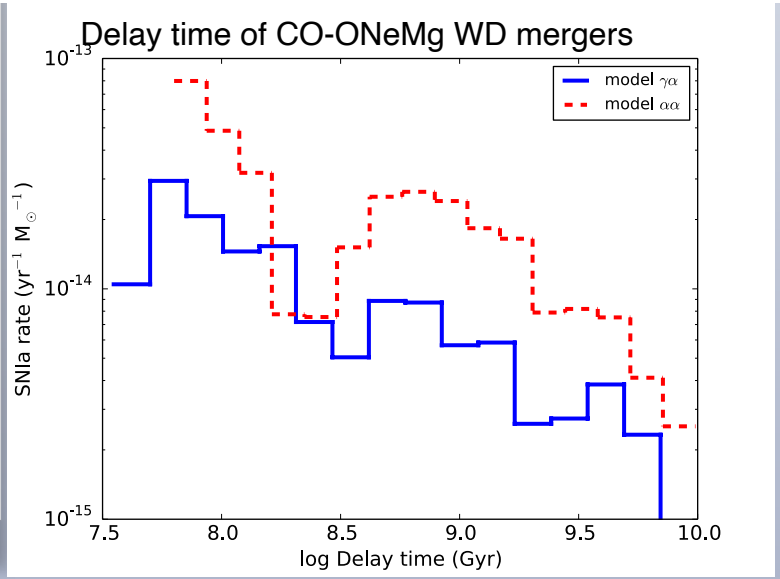
- Two evolutionary channels:

ONeMg + CO WDs

Population synthesis

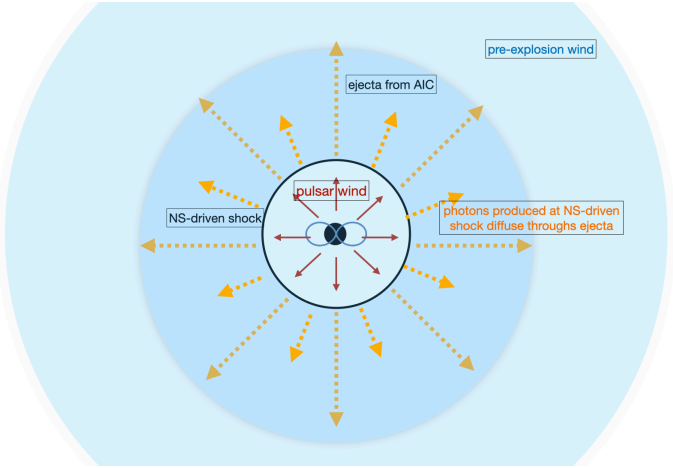
- Initial binary ~ 5+8 M_{Sun}
- Two distinct evolutionary channel (direct and inverted)
- CO-ONeMg WD mergers rate (q> 0.25) ~ $5 \cdot 10^{-5}$ per Solar mass, consistent with the lower limit of the FBOT rate.
- Host galaxies: merger delays ~ 100s Myrs -fairly fast

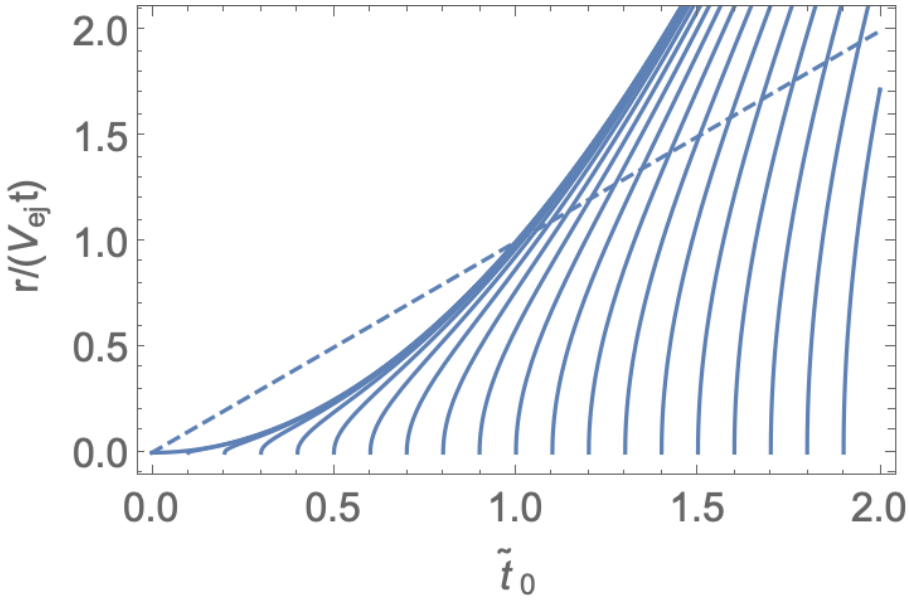




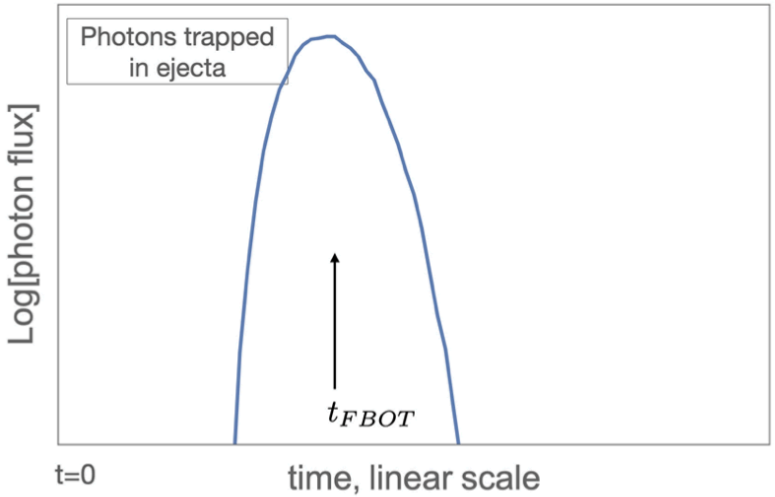
“Diffusive caustic”

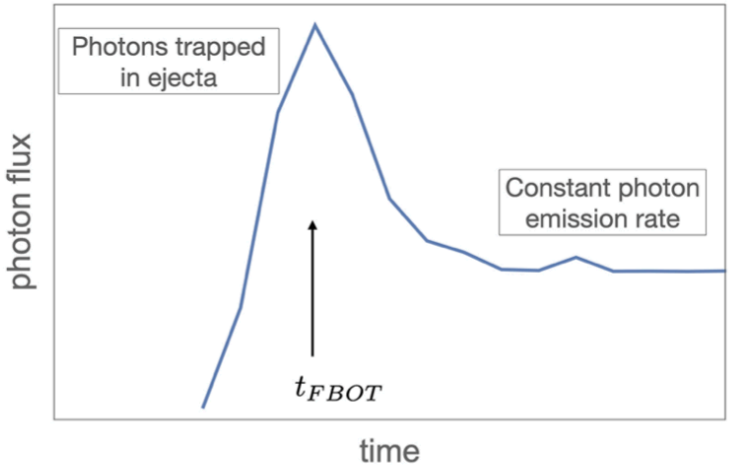
- Central engine: shock in the expanding ejecta
- ready-set-go: photons first trapped, all escape at once
- photon flux (not energy - photons got ~2 degraded)
  - Green’s func., $G(r,t) = \frac{1}{8(\pi\kappa_0)^{3/2}t^6} e^{-r^2/(\kappa_0 t^4)}$,etc

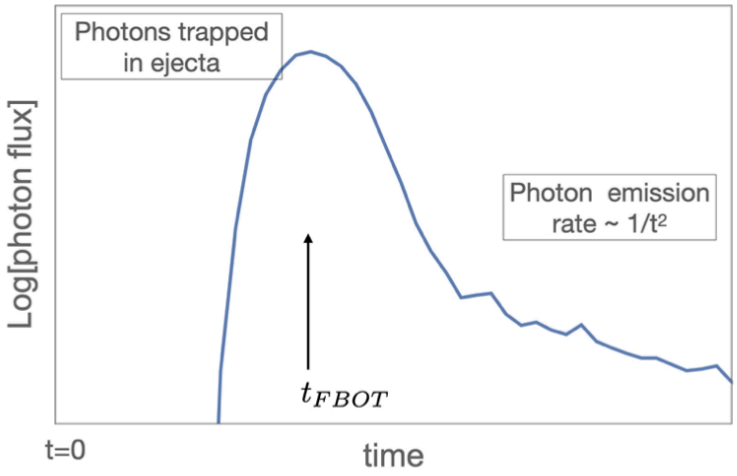


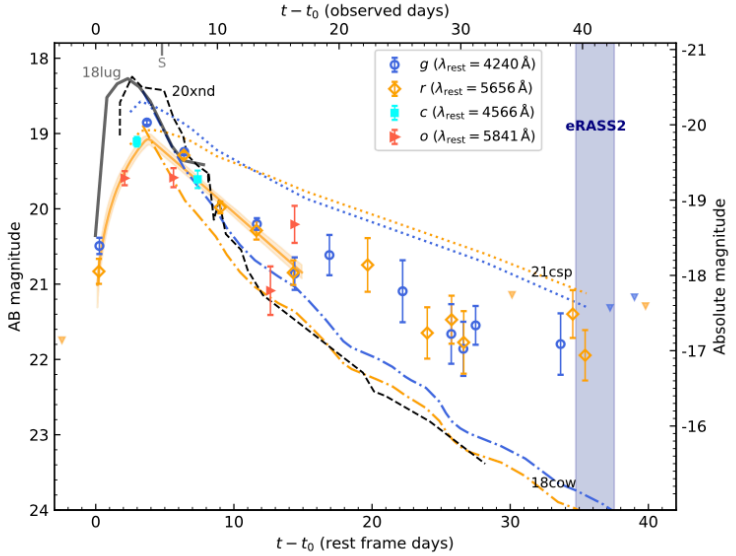


Light curves (photons)

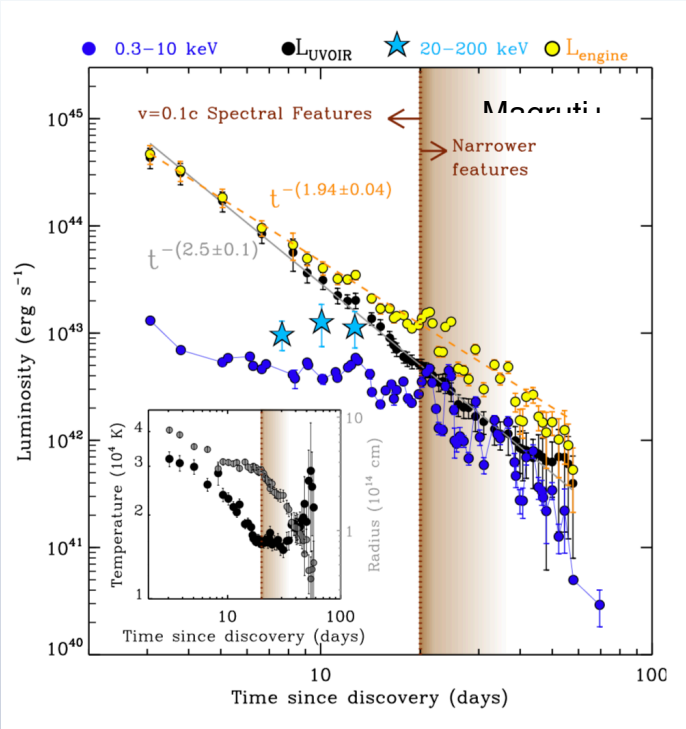




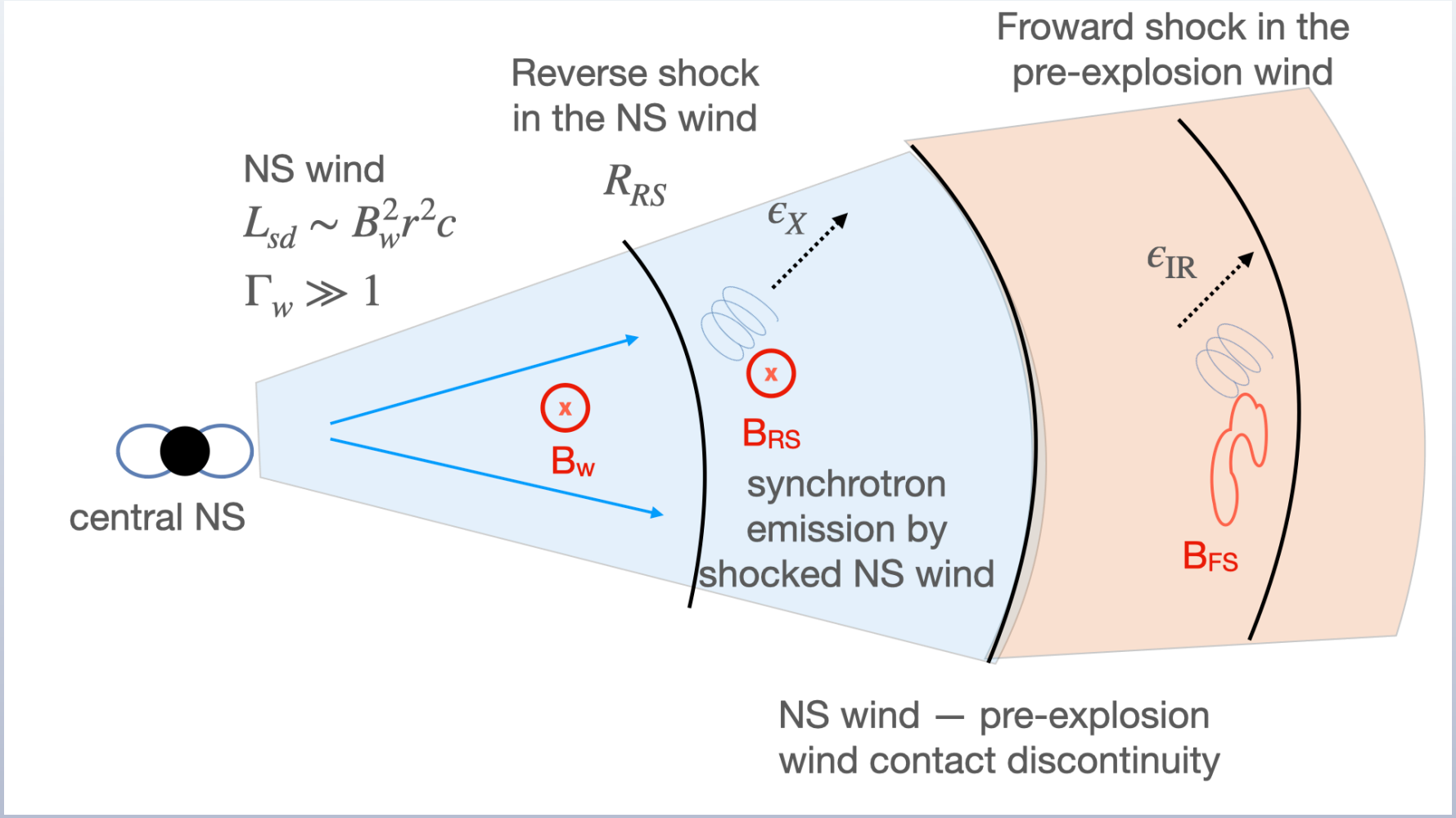




- They are blue (T ~ 40000K)
  - radiation-dominated shock within the ejecta
  - $\frac{4}{c}\sigma_{SB}T^4 \sim \rho_{ej}V_s^2$
  - $T = 4\times10^4 L_{X,42}^{1/10}\epsilon_{X,-1}^{-1/10}V_{ej,4}^{-9/20}\,K$
- Change of properties at 30 days
  - full transparency through ejecta
  - breaking out of the shock from the eject into preceding wind
- eRosita bump in AT2020mrf (predicted) - shock break-out from ejecta into wind
  - $t_{br} = \epsilon_e\frac{E_{ej}}{L_X} = 46\epsilon_{e,-1}V_{ej,4}^2L_{X,42}^{-1}\,\mathrm{days}$



Late: like pulsar winds (reverse shock)



X-rays: synchrotron from termination shock: PWN-like

- Peak synch. frequency at TS: $\epsilon_s \approx 50\mathrm{keV}\, t_d^{-5/4}$
- Radiative cooling in decreasing B-field: pile-up in IR
- In fast cooling regime: most wind power radiated, $L_X \sim L_w$
- NS s

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t_Ω

$= 8 \times 10^{14}$ G

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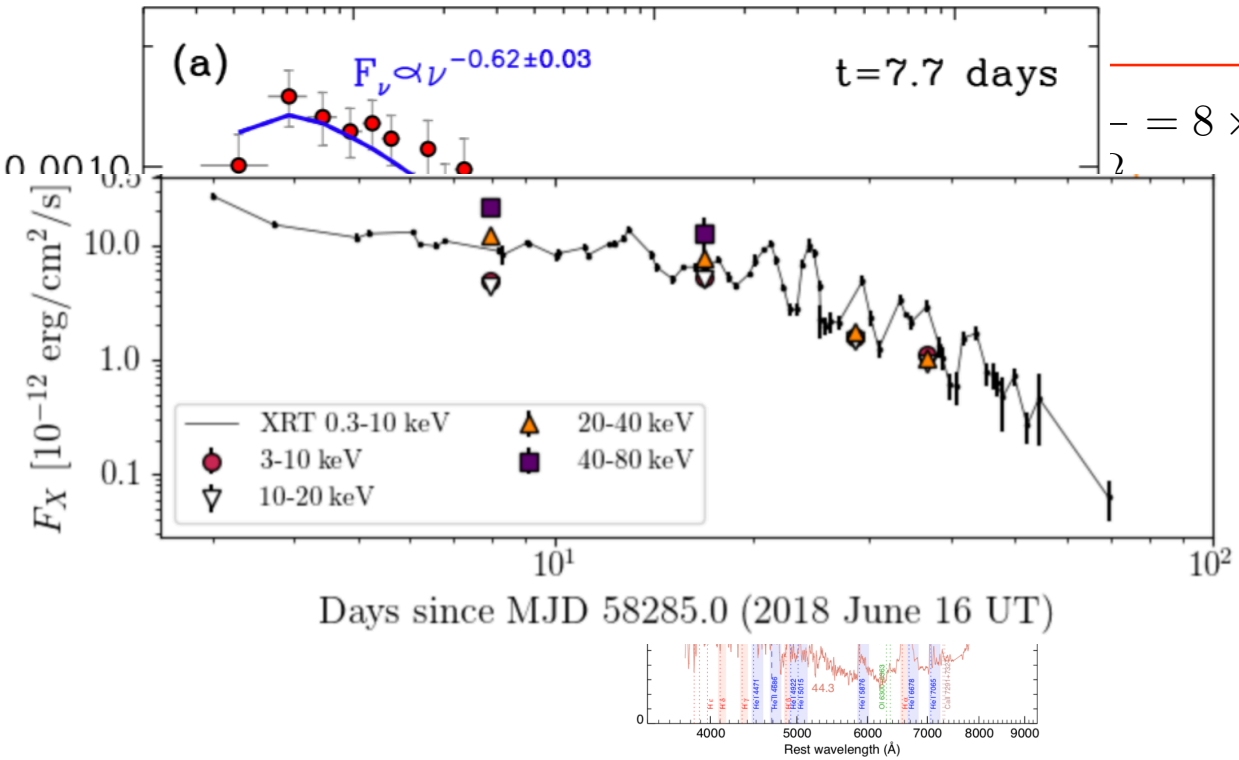
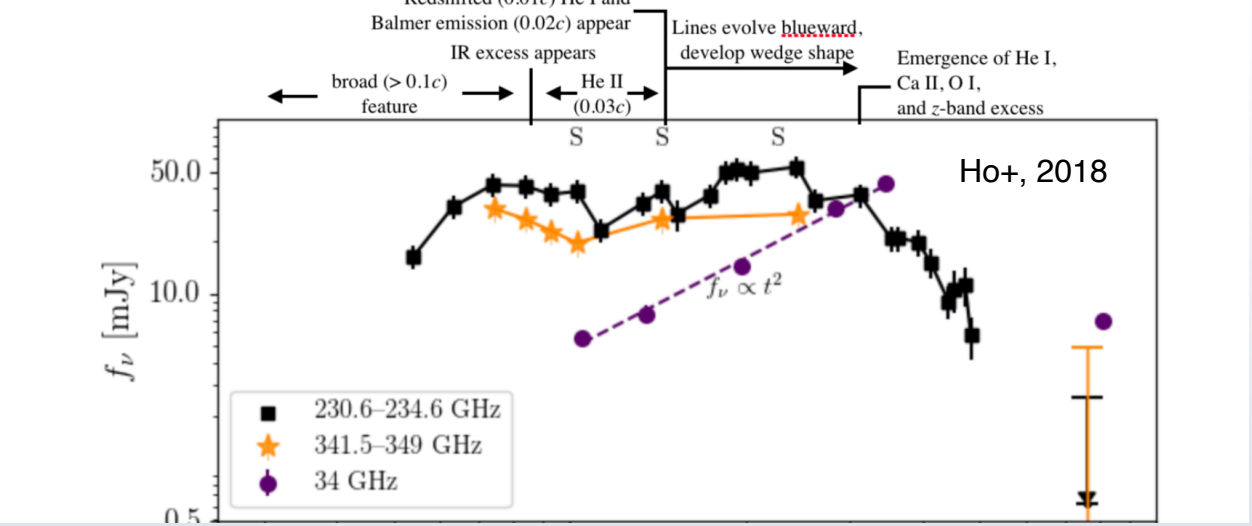


IR



- Ejecta contributes a lot to free-free absorption

$$\tau_{ff,ej} = 2 \times 10^{20} \nu_{GHz}^{-4.2} T_4^{-2.7} t_d^{-10}$$

- Thin for

$$\nu_{GHz} > 7 \times 10^4 t_d^{-2.4}$$

- High frequencies, 341 and 230 GHz, are transparent all along, while lower frequency, 34 GHz traces expanding τ = 1 surface.
- In radio and far IR ejecta thick until the shock breakout from the ejecta, ~ month
- Pile-up in mm range

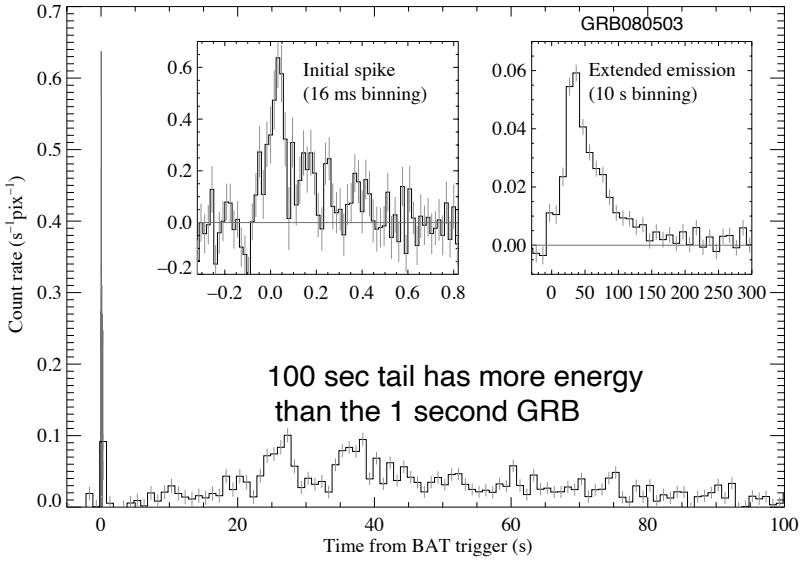
Related(?)

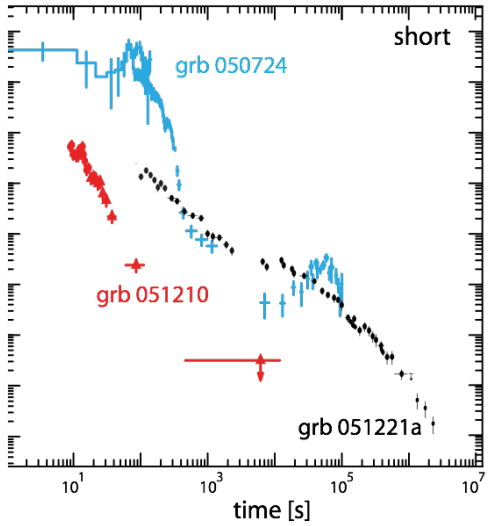
- IRAS 00500+6713: a hot, ~ 200, 000K, luminous ~ $10^{4.5} L_{\odot}$ star within a mid-infrared nebula (Oskinova + 2021). Both the star and the nebula appear to be free of hydrogen and helium. The wind velocity is exceptionally high, ~ 16,000 km s^{-1}.
- A highly magnetized and rapidly rotating white dwarf as small as the Moon (Caiazzo et al. 2021) is the remnant of the merger. It was on the verge of electron-capture collapse, but run out of the material in the envelope and remained intact.
- Ultra H-poor WD J055134.612+413531.09: doubly-burnt ashes
- Iax may be the results of AICs with larger ejecta mass $M_{ej} \geq 0.1$; Type Ibn may be the result of merger with a He WD

Predictions

- Merger proper:
  - grav. energy goes into puffing-up the envelope
  - must be some optical signature… (~10^{48} ergs over few hours, optical - surveys are not designed for such short events)
- FBOTs are H-poor, ~ WD composition, $\leq 10^{-3} M_{\odot}$ of H.
  - too hot in the beginning
  - some H is seen, not clear how much: most advanced radiative modeling needed
- one expects evidence (e.g., spectral) of shock interaction with fast and dense pre-explosion wind
- anisotropy is expected: both the ejection of the envelope during AIC, as well as neutron star-driven winds are expected to be anisotropic.
- pre-FBOT archival data should show a bright persistent hydrogen-poor source, possibly surrounded by a nebula (similar to IRAS 00500+6713)
- in the case when AIC does not occur, a hydrogen poor envelope around the central (massive) WD is expected (< 10000 yr)

Connection to Short GRBs: there are problems with NS+NS scenario, not seen in GW170817





Active stage of NS-NS merger takes 10-100 msec, then collapse into BH. Very little mass is ejected.

Many short GRBs have long 100 sec tails, energetically comparable/dominant to the prompt spike.

Many GRBs have late time flares, 10^5 sec

Would be good to have an active object remaining, but $M_{tot} > 2.5\ M_{Sun}$

AIC of merged WDs: bounce-off may produce a short GRB - eg. if jet is produced and observer is on the axis (Lyutikov & Toonen 2017)

Main points

- small ejecta mass: competition between the wind and added ashes to the core
- overall energetics is dominated in AT2020mrf by long-term X-ray emission: central engine.
- Fast cooling - all wind energy emitted
- the duration of the FBOTs is determined by the diffusion of photons from the central engine
  - nearly all the photons escape at the same time
- break through ejecta - SRG/eROSITA X-ray bump
- Merger proper: optical transient of ~ few hours, 10^{48} ergs