CTA-Oz workshop
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Accreting white dwarfs as CTA sources

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This talk features some results from Alex Kemp (PhD Student, Monash) based on Kemp, Karakas, Casey, Izzard, Ruiter, Agrawal, Broekgaarden, & Temmink 2021 (under review)

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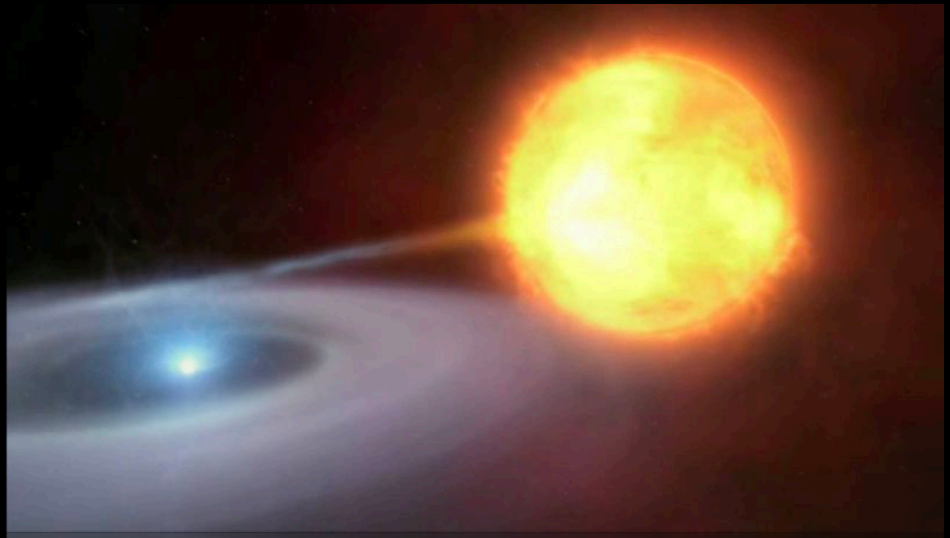
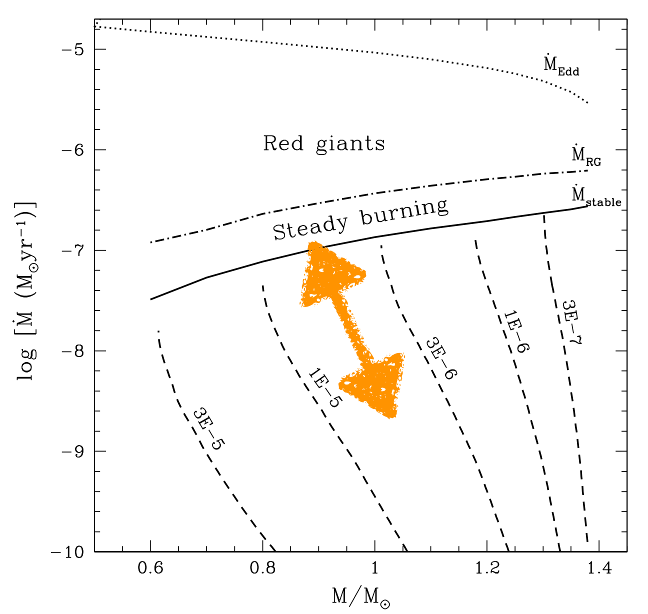
Accreting white dwarfs are responsible for some very energetic phenomena - e.g. Type Ia supernovae. But more commonly, novae (flashes on white dwarfs).

- Depending on the rate of mass transfer from a companion star to a white dwarf (and the mass of the white dwarf), you may end up with a Chandrasekhar mass scenario Type Ia supernova. But more likely, you get a nova explosion(s). ***Most nova systems never become supernovae***.

- Novae occur in cataclysmic variables; a class of accreting white dwarfs in binary star systems. There are the more typical 'hydrogen novae', but there is also a population of 'helium novae' (less common, e.g. V445 Pup). These different novae have different progenitors types and population age.



Chandrasekhar mass scenario for Type Ia supernovae; sometimes called 'single degenerate' or delayed detonation scenario. These supernova progenitors are expected to undergo a nova phase before the final explosion.



nova/flash regime

Figure: *Hydrogen accretion on WDs*; Nomoto et al. 2007

image credit: Fermilab. https://arstechnica.com/science/2017/08/we-may-have-caught-supernova-debris-slamming-into-neighboring-stars/

Usually, accreting white dwarfs don't self-destruct in a SN… they accrete material and undergo a number of outbursts (novae) over Myr or Gyr…

Some novae have been seen to emit gamma rays >100 MeV! 🤔

- *Classical novae* erupt infrequently (e.g. every 10,000 yrs); *recurrent novae* are observed to have more frequent eruptions (~every <100 yrs). However, probably all classical novae would be 'recurrent', if we live long enough!

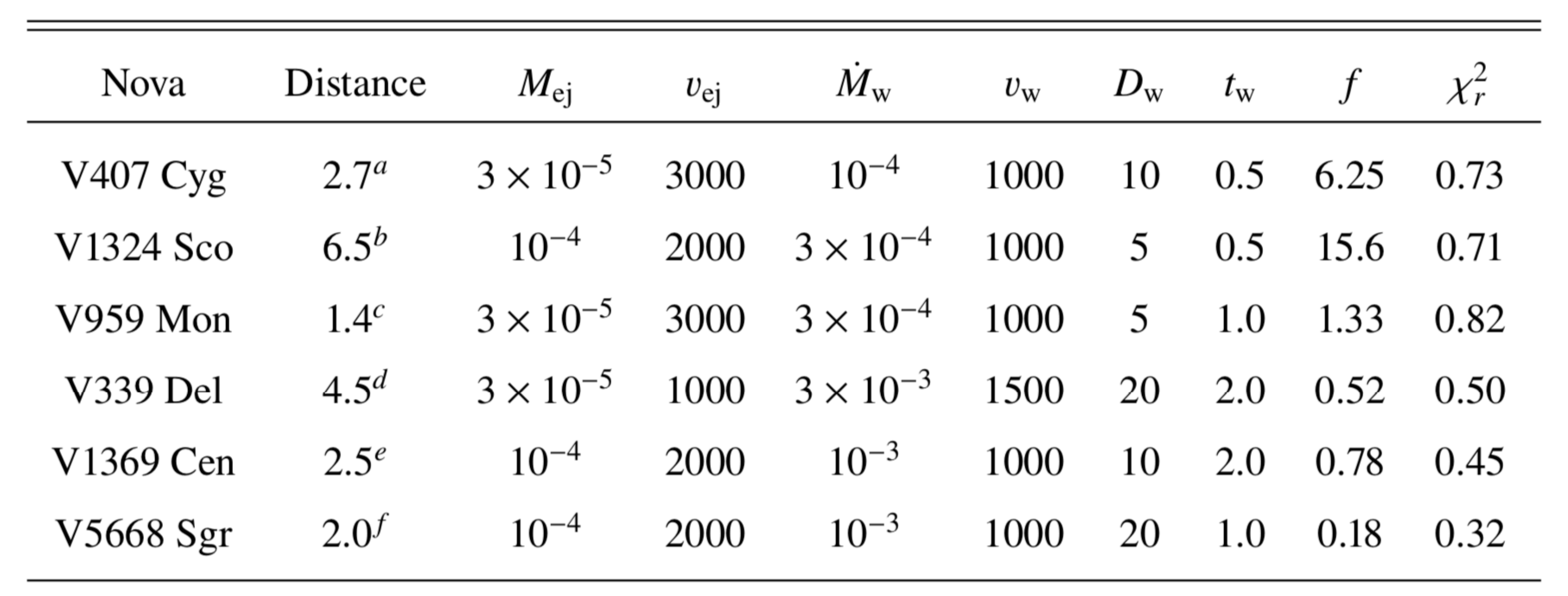
- Out of the handful of novae that have been detected in gamma rays with Fermi LAT (see Martin et al. 2018, A&A 612, A38), most have been of the classical type, with a main sequence donor star (see also Prialnik 1986 for theoretical background).

- Exactly what causes the high energy gamma ray emission is still a puzzle (see also Aydi et al. 2020), but a promising model involves a fast white dwarf wind colliding with slower-moving ejecta material, resulting in shocks and hadronic interactions. >100 MeV γ from pion decay; >100 GeV is predicted for >3000 km/s winds.

Novae and gamma ray emission with future CTA

- Gamma ray emission observed in ~10 novae with Fermi LAT (Martin et al. 2018 performed hydrodynamical and shock modelling based on Martin and Dubus (2013); i.e. below table).

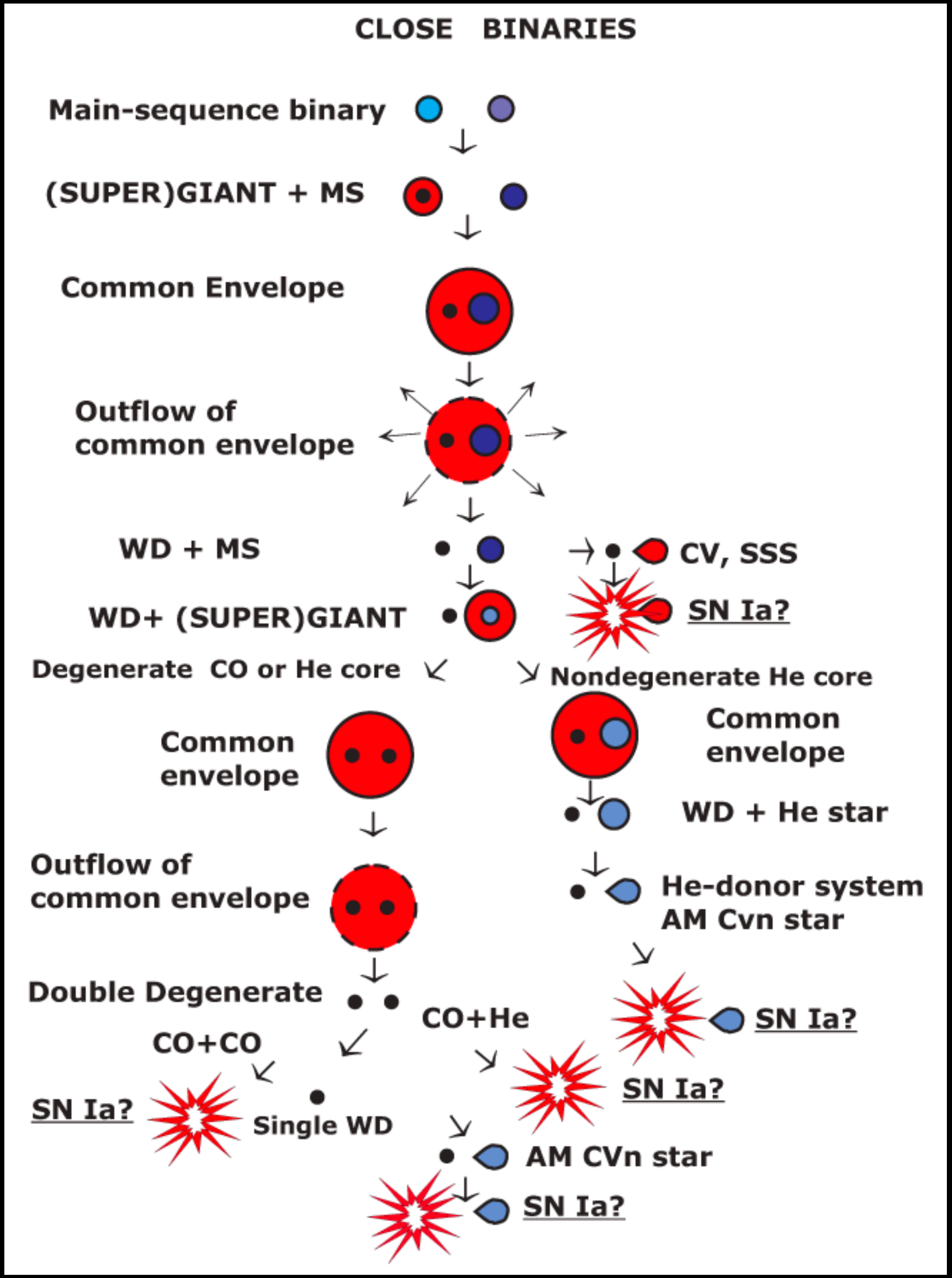
- CTA will likely be able to detect accelerated particles in the reverse shocks of nova systems that harbour high-velocity winds (>1500 km/s) with relatively large (~>10^{-4} M_{sun}) amounts of ejecta. In such cases, >100 GeV signals could be observed from these novae, in addition to features at different wavelengths (e.g. optical, X-ray synergies).



Nova	Distance	M_{ej}	v_{ej}	$\dot{M}_{\mathrm{w}}$	v_{w}	D_{w}	t_{w}	f	χ_r^2
V407 Cyg	2.7^{a}	3×10^{-5}	3000	10^{-4}	1000	10	0.5	6.25	0.73
V1324 Sco	6.5^{b}	10^{-4}	2000	3×10^{-4}	1000	5	0.5	15.6	0.71
V959 Mon	1.4^{c}	3×10^{-5}	3000	3×10^{-4}	1000	5	1.0	1.33	0.82
V339 Del	4.5^{d}	3×10^{-5}	1000	3×10^{-3}	1500	20	2.0	0.52	0.50
V1369 Cen	2.5^{e}	10^{-4}	2000	10^{-3}	1000	10	2.0	0.78	0.45
V5668 Sgr	2.0^{f}	10^{-4}	2000	10^{-3}	1000	20	1.0	0.18	0.32

Martin et al. 2018
Table 2

How to quantify numbers? Binary star evolution pathways to accreting white dwarfs

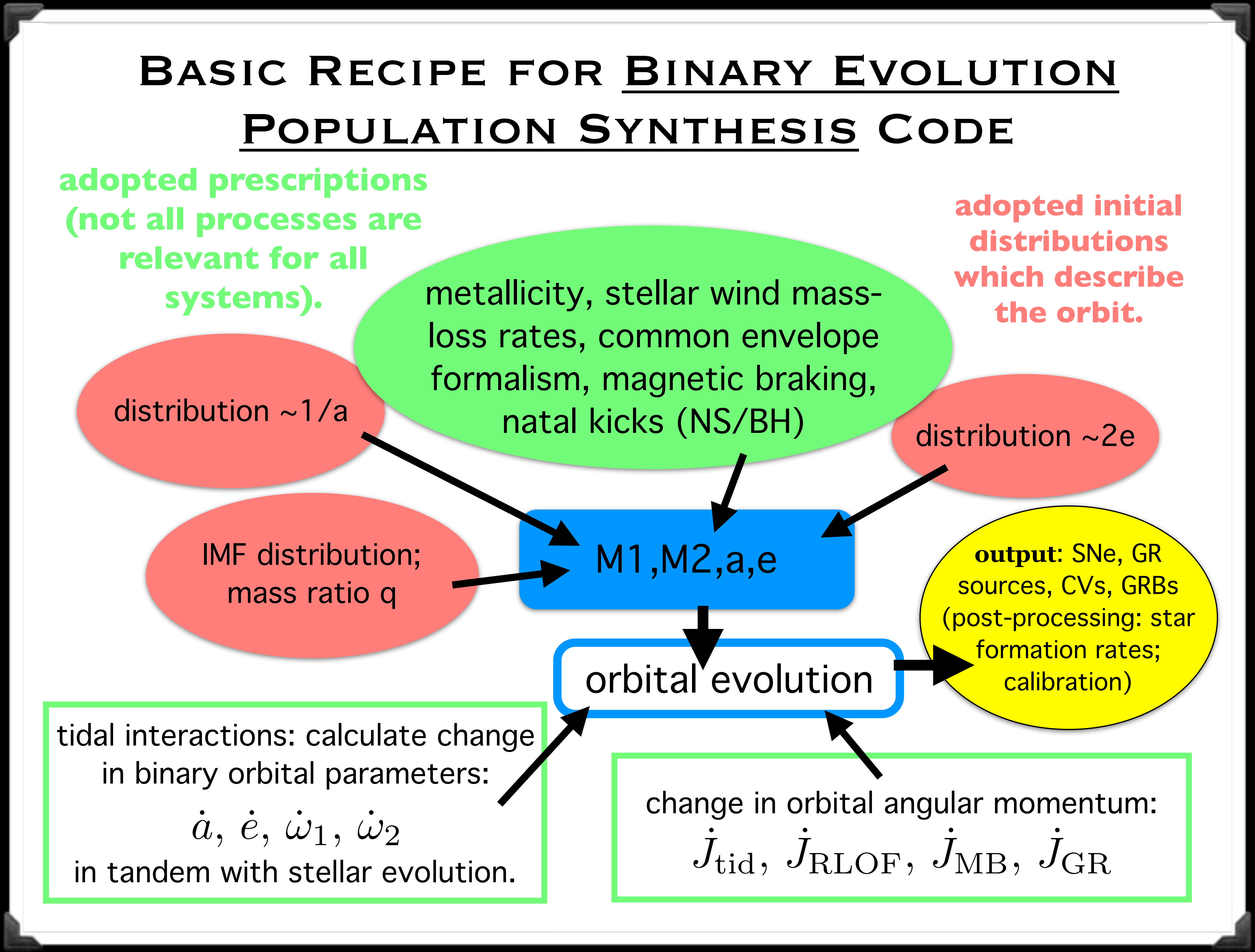


Left: different evolutionary pathways (formation channels) that might lead to the formation of explosive binaries (from Postnov and Yungelson, Living Reviews, "The Evolution of Compact Binary Star Systems".

We figure out which formation channels are viable and/or common using numerical methods, through rapid binary evolution population synthesis, or BPS. **Obtaining a rate** is relatively easy for supernovae or kilonovae etc., but hard for novae since one system may undergo a few, or 100s of nova eruptions…

https://www.emis.de/journals/LRG/Articles/lrr-2014-3/articlese7.html

StarTrack BPS code (e.g. Belczynski et al. 2008).
Orbital equations evolved in tandem with stellar evolution.



Basic Recipe for Binary Evolution Population Synthesis Code

adopted prescriptions (not all processes are relevant for all systems).

adopted initial distributions which describe the orbit.

distribution ~1/a

metallicity, stellar wind mass-loss rates, common envelope formalism, magnetic braking, natal kicks (NS/BH)

distribution ~2e

IMF distribution; mass ratio q

M1,M2,a,e

output: SNe, GR sources, CVs, GRBs (post-processing: star formation rates; calibration)

orbital evolution

tidal interactions: calculate change in binary orbital parameters:

$$\dot{a},\ \dot{e},\ \dot{\omega}_1,\ \dot{\omega}_2$$

in tandem with stellar evolution.

change in orbital angular momentum:

$$\dot{J}_{\rm tid},\ \dot{J}_{\rm RLOF},\ \dot{J}_{\rm MB},\ \dot{J}_{\rm GR}$$

Orbital separation ‘a’, eccentricity ‘e’, Initial Mass Function (IMF) of stars: chosen via Monte Carlo from probability distribution functions that are based on observational data.

Rapid binary evolution population synthesis (BPS): orbital evolution in tandem with stellar evolution.

a_i, e_i, q_i, M_{1zams}, M_{2zams} -> a_f, e_f, q_f, M_{1f}, M_{2f}

Assumptions about **common envelope** evolution, etc.

$$\alpha(\frac{-GM_{rem}M_2}{2a_f} + \frac{GM_{giant}M_2}{2a_i}) = -\frac{GM_{giant}M_{env}}{\lambda R_{giant}}$$

Thomas Reichardt

The orbital separation decreases more rapidly now...

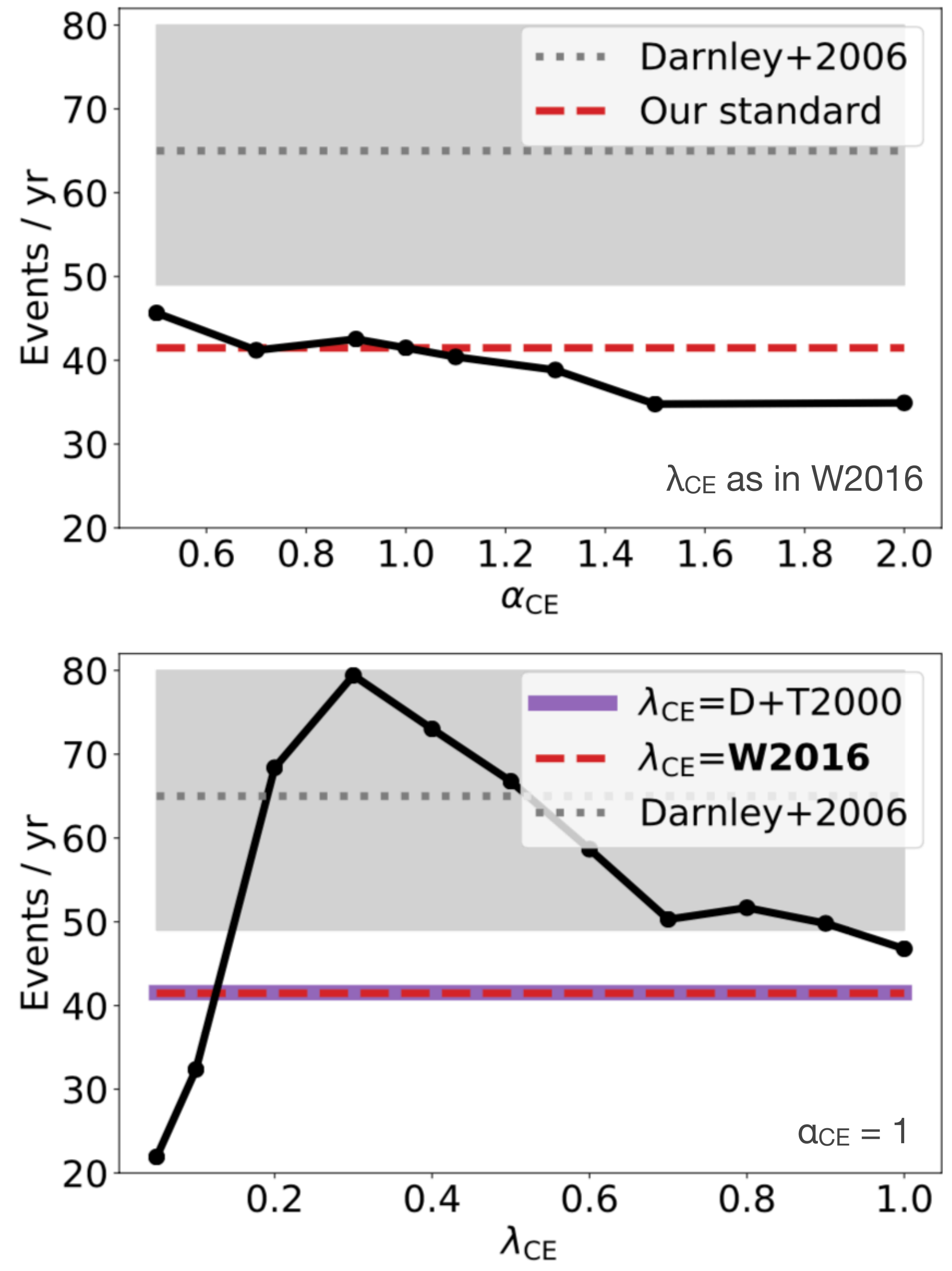
Common Envelope (CE): When a star overfills its Roche lobe and transfers mass to a companion star so rapidly such that the companion cannot adjust (thermal timescale is too long), both stars become engulfed in the envelope of the mass-losing star. This is a **common envelope**. Due to friction/other energy losses, both stars spiral in to one another, sometimes merging. Or, mass transfer may resume, but be 'stable' (no CE). **α & λ determine the outcome**.

Example: Nova rates in M31 (new prediction)

M31 is a great test-bed for our population models

- Right (from Kemp et al. 2021): predicted event rates for hydrogen novae in M31 using the Binary_C BPS code. Black line represents how the event rate changes as a function of common envelope phase physics (λ, α). Greyscale shows currently-estimated nova rate from Darnley et al.

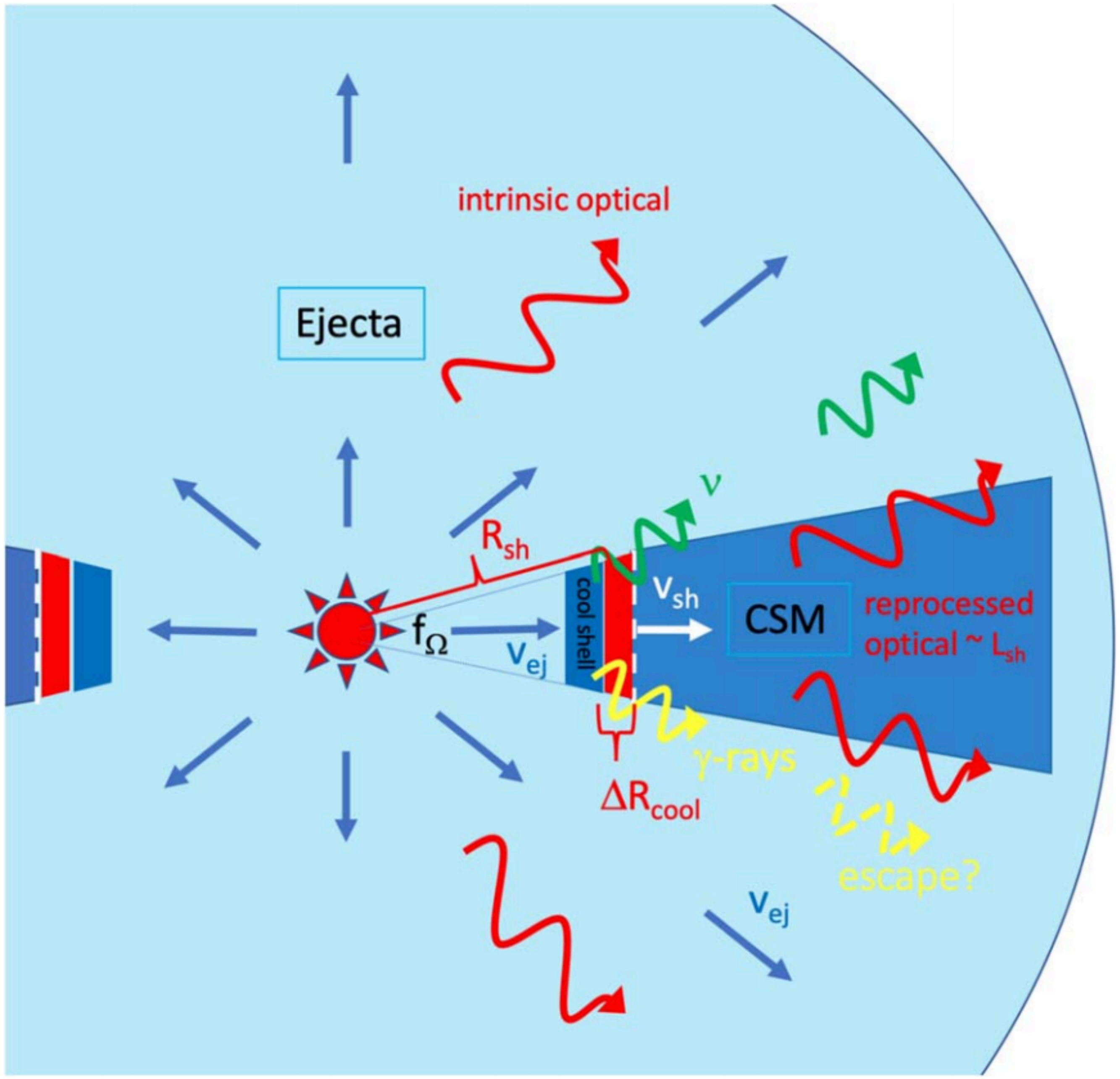
- Galactic novae will likely be less frequent but will be brighter. It would be great to try to find them with CTA. Synergies with Vera Rubin or other surveys (cf. Gavin's talk after lunch).



(a) H Novae

Extra Slides

From Fang et al. 2020



(slower-moving ejected material)

(from the WD)

Figure 1. Schematic diagram illustrating the generic scenario for shock-powered emission from explosive nonrelativistic transients. The explosion ejecta collides with a dense external medium (e.g., circumstellar medium, CSM) of radial density profile $n(r)$ and effective wind mass-loss rate parameter $A \equiv \dot{M}/(4\pi v_w)$, which covers a fractional solid angle $f_\Omega < 1$. The ejecta of mean velocity $\bar{v}_{ej}$ collides with the CSM, driving a shock into the latter with a velocity v_{sh} and kinetic luminosity L_{sh}. UV/X-ray emission from the thin cooling layer behind the shocks is absorbed and reprocessed by the surrounding gas into optical radiation of luminosity $L_{opt} \approx L_{sh}$. The shock also accelerates relativistic ions that collide with background ions, generating π^0 and $\pi^\pm$, which decay into gamma rays and neutrinos, respectively. The optical light curve peaks, and the bulk of particle acceleration occurs, when the optical depth surrounding the shock first obeys the condition $\tau_{opt} \lesssim c/v_{sh}$, similar to that required for the formation of a collisionless shock capable of particle acceleration. At this epoch of peak emission, both thermal particles (which emit via free–free emission) and nonthermal particles (undergoing p–p interactions) are radiative, such that the emitted nonthermal gamma-ray/neutrino emission is proportional to the shock-powered optically radiated energy. The thickness of the postshock region as set by thermal cooling, ΔR_{cool}, is much smaller than the shock radius R_{sh}, limiting the maximum particle energy achievable via diffusive shock acceleration (Equation (16)).

A bit about my institution

- UNSW Canberra is a faculty of the University of New South Wales. I am at the School of Science at UNSW Canberra located at the Australian Defence Force Academy. Our School research includes Mathematics, Chemistry, Human and Environmental Geography, Oceanography and Atmospheric Science, Material Physics and **Astrophysics**!

- Our astrophysics group (myself, Ivo Seitenzahl, Warrick Lawson, and PhD students starting soon) interests lie in **stellar astrophysics**, in particular evolution of interacting binaries, explosive nucleosynthesis, supernova remnants, supernova progenitors and other transients (i.e. connections with the Vera C. Rubin observatory/LSST), and Galactic gravitational wave sources (e.g. LISA).

2020 ANITA summer school and workshop
(Australian National Institute for Theoretical Astrophysics)

https://unsw.adfa.edu.au/our-research/astronomy-and-astrophysics