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# Gamma-Ray Burst Central Engines *with Binary Population Synthesis Models*

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# Gamma-ray burst requirements

Long-duration gamma-ray bursts (GRBs) arise from the collapse of massive, stripped envelope, rapidly spinning stars. We know this because…

Ic — low Z — Γ~100

### Stripped envelope supernova

They are associated with broad-line type Ic supernovae (~$10^{52}$ erg and lacking in hydrogen and helium) – *observational*

### Low metallicity environments

They prefer low-metallicity[1] host environments: implies faster spinning stars – *observational*

### Relativistic jets

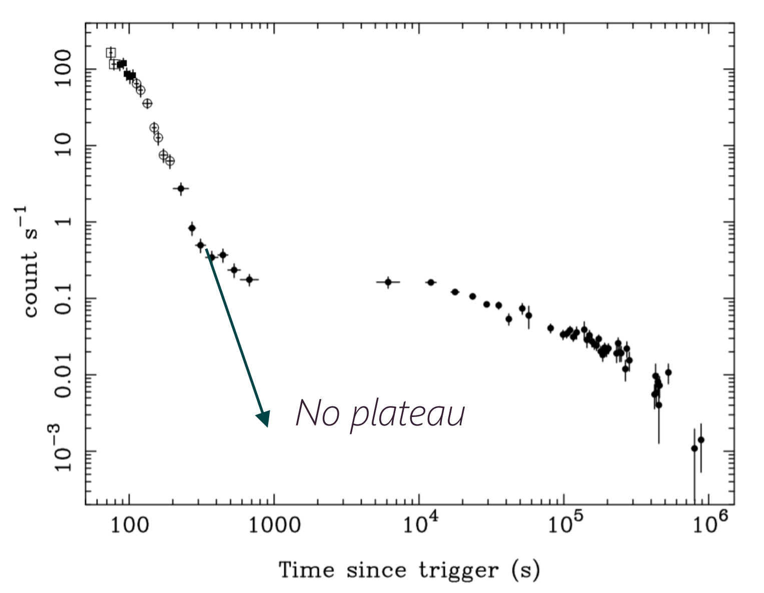
They launch relativistic jets (Γ~100), requiring a rotating central engine (see e.g. Blandford-Znajek mechanism) – *theoretical*

[1] *Metallicity Z: the fraction of stellar mass that is not hydrogen or helium*

# What are the central engines?

What powers the launch of relativistic jets in GRBs?

*Plateaus in GRB X-ray light curves (as in this example from Vaughan et al. 2006) are indicative of continued central engine activity*




Collapsar

**Black hole accretion disc**

Narayan et al. 1992, Woosley et al. 1993

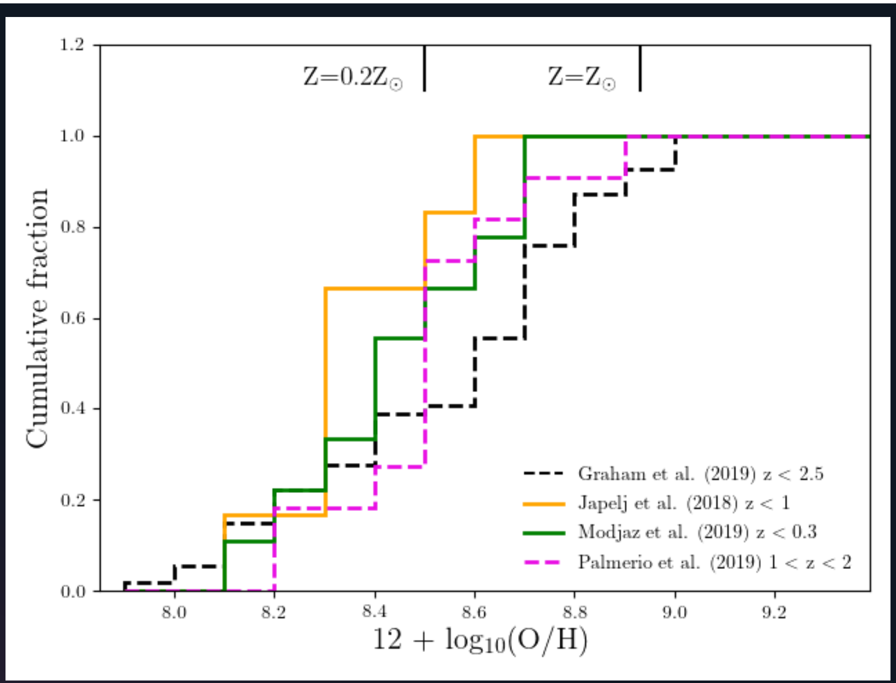
Accretion powered, requires specific angular momentum > $10^{16}$ cm$^2$s$^{-1}$ at ISCO

Magnetar

**Neutron star magnetic field**

Metzger et al. 2011, Mazalli et al. 2014

E.g. magnetic tower mechanism, requires a ms-period magnetar

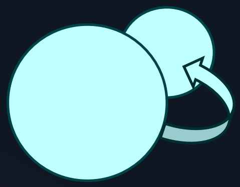



*The host galaxy metallicity distribution, as determined by various studies*

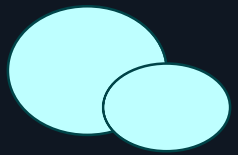
# What are the progenitor systems?

We need a model for long-duration, core-collapse GRBs that explains (i) the GRB prompt and afterglow emission (i.e., works with the collapsar or magnetar models) and (ii) the host galaxy properties.

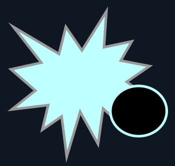
*Single stars: e.g. Wolf-Rayet, O stars (hard to maintain spin **and** lose envelope)*



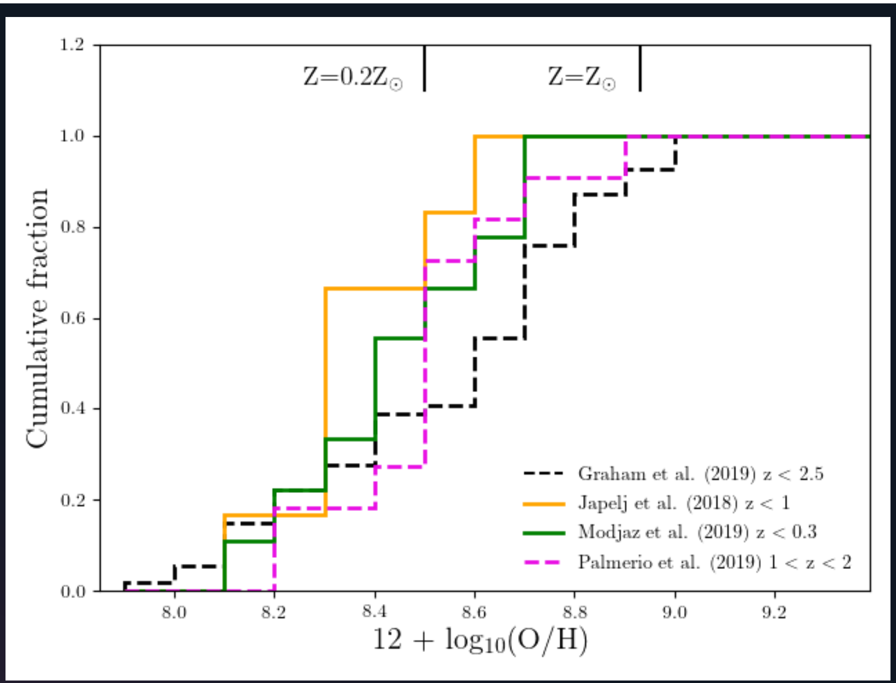
*Quasi Homogenous Evolution (QHE): accretion onto a secondary star spins it up to rotational speeds that mix the stellar interior.*



*Binary stars with tides: tidal interactions maintain spins, counteracting the effects of mass-loss*



*Other: e.g. binary driven hypernova where the GRB is launched by NS→BH collapse induced by the SN of a companion*

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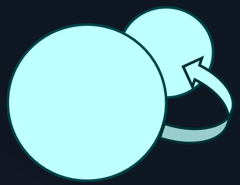

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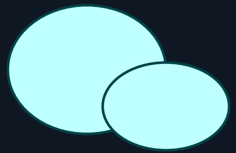

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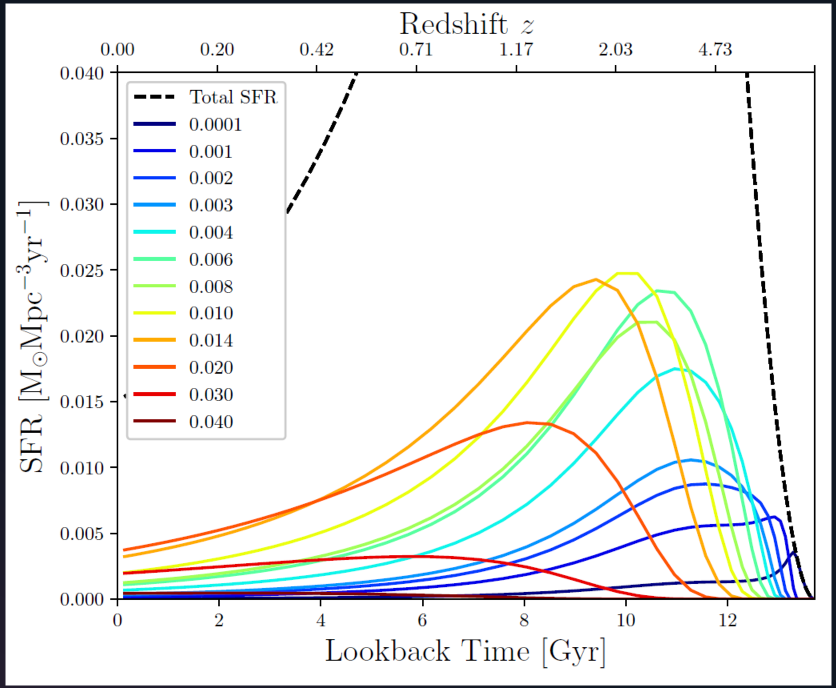
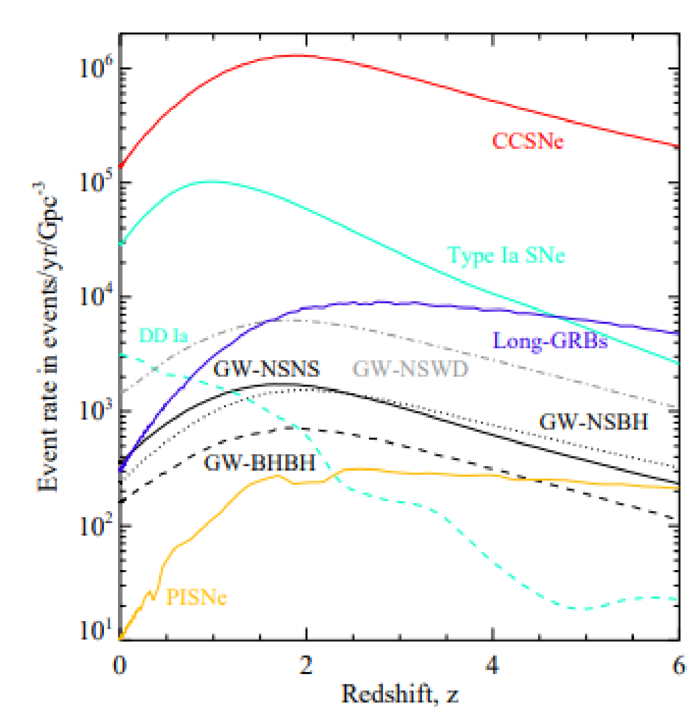



*Using **Langer & Norman 2006** distributions.*

*Eldridge et al. 2019 synthesised the rates of GW and EM transients using BPASS. Only the QHE pathway was considered for long-GRBs.*




# BPASS

## Binary Population and Spectral Synthesis

- Range of models, IMF, binary parameters – see **Eldridge et al. 2017** for a full description
- Each model is weighted according to it's frequency in a $10^6$ $M_0$ stellar population (at the chosen metallicity)
- Project to investigate the plausibility of non-QHE progenitor channels using BPASS – described in **Chrimes, Stanway & Eldridge 2019**
- Previous studies include Fryer et al. 2007, Trenti et al. 2015…

Total H mass > $5\times10^{-4}\,M_{\odot}$ → Type II

If type I:
He ejecta fraction > 0.2 → Type Ib

# Model selection

The first step is to select models which

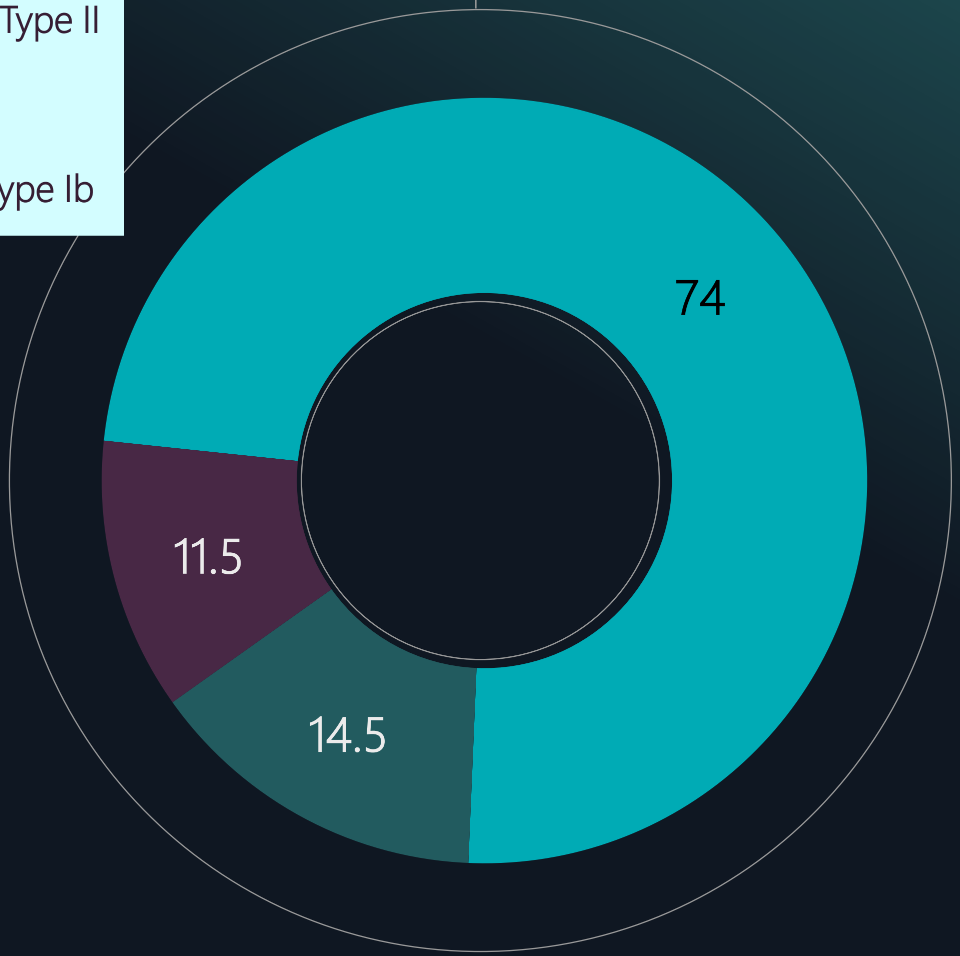
(a) produce black holes or neutron star remnants, and

(b) are H and He poor (Ic SN progenitors)

**Type II**
*H & He rich*

**Type Ib**
*H poor & He rich*

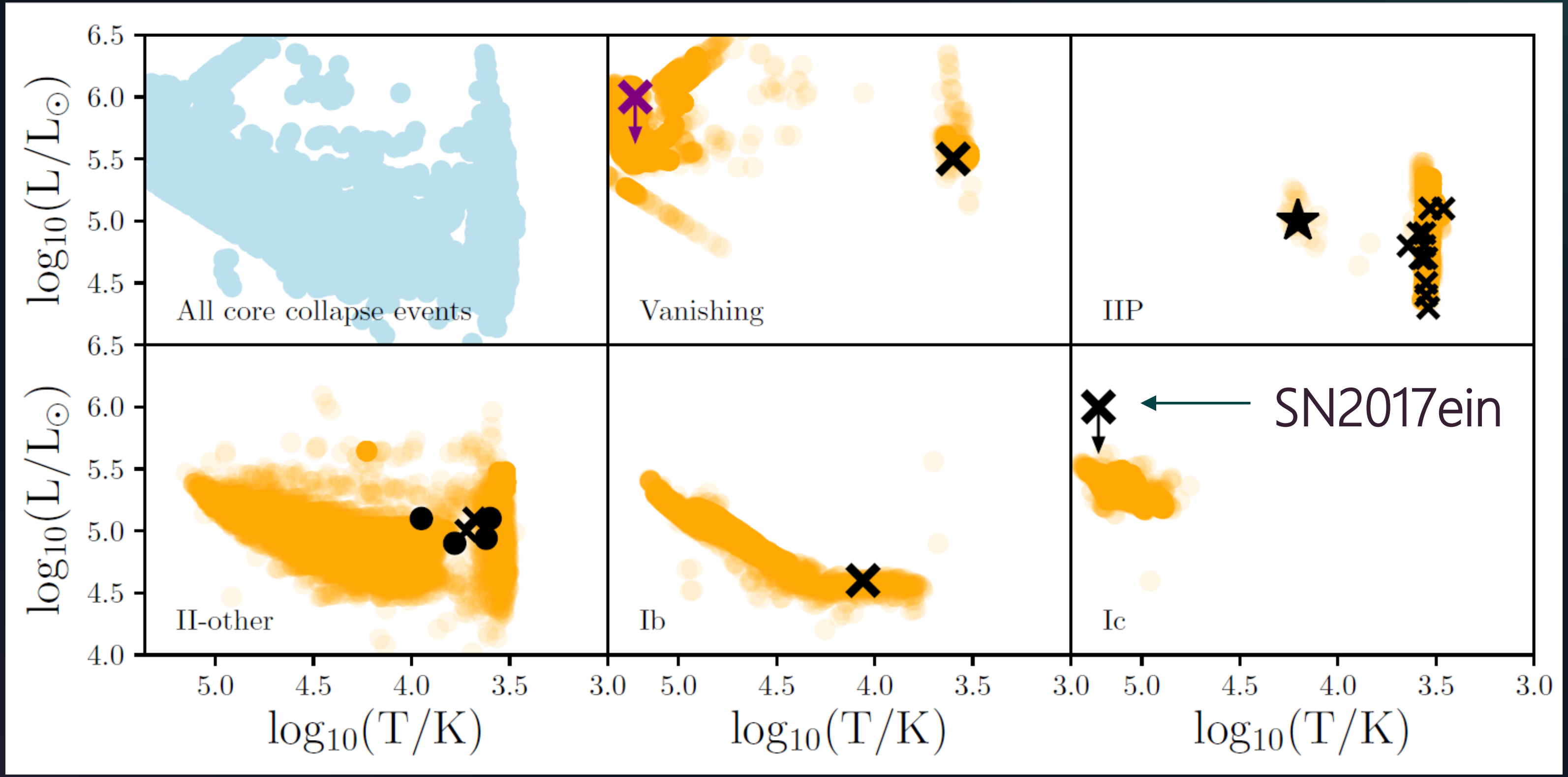
**Type Ic**
*H & He poor*




*Based on Eldridge et al. 2013 and Shivvers et al. 2017 rates*

# Progenitors on the HRD

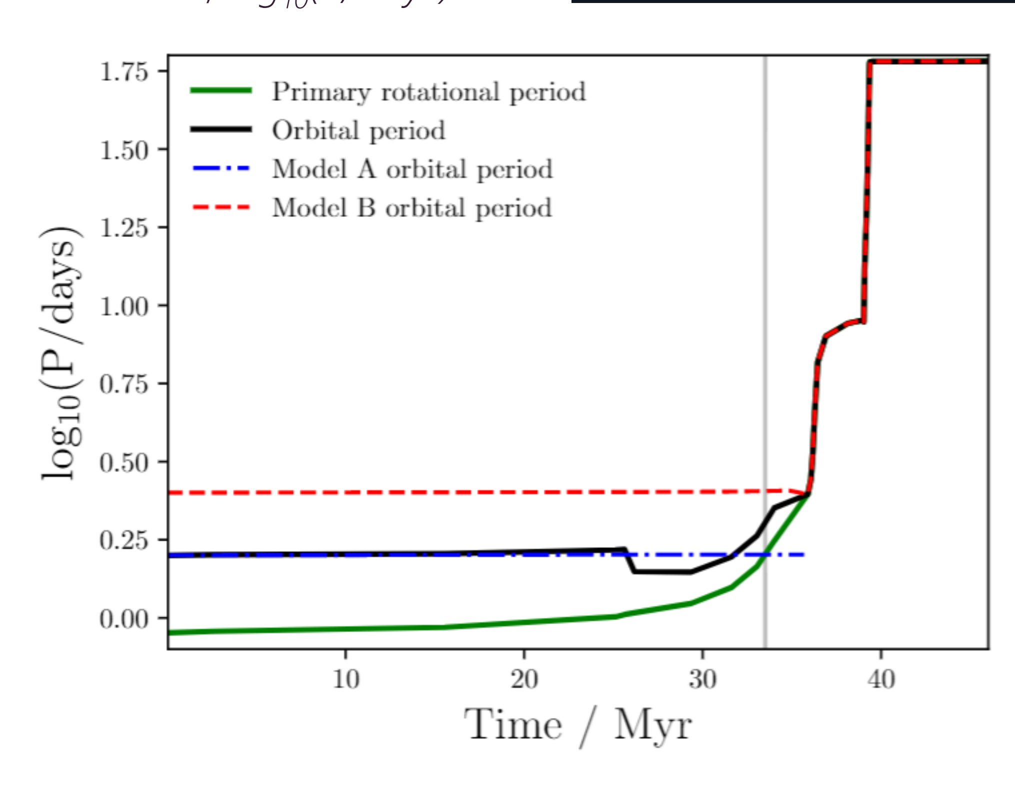
- BPASS models
- Pre-explosion progenitor imaging




*See Walborn et al. 1987, Adams et al. 2017, Smartt et al. 2015, Van Dyk et al. 2018, Kilpatrick et al. 2018…*

# Tidal post-processing

*$8M_{\odot}$, 0.9 mass ratio, $\log_{10}(P/days)=0.2$*




We need to consider stellar spins: the models are post-processed to include tidal interactions[1].

Binaries are synchronised upon primary envelope expansion, and kept tidally locked after that.

[1] *Using radiative damping of the dynamical tide as in Zahn 1975, Hurley et al. 2002*

# MCMC

Four parameters are varied to fit the observed GRB rate as a function of redshift.

$$J_{cut} = J_{cut,\theta} \times \left(\frac{Z}{Z_{\odot}}\right)^{n}$$

Choosing GRB models

**$J_{cut,\theta}$** The minimum angular momentum required for GRB production.

**$Z^n$** The dependence of $J_{cut}$ on metallicity. The index $n$ is varied.

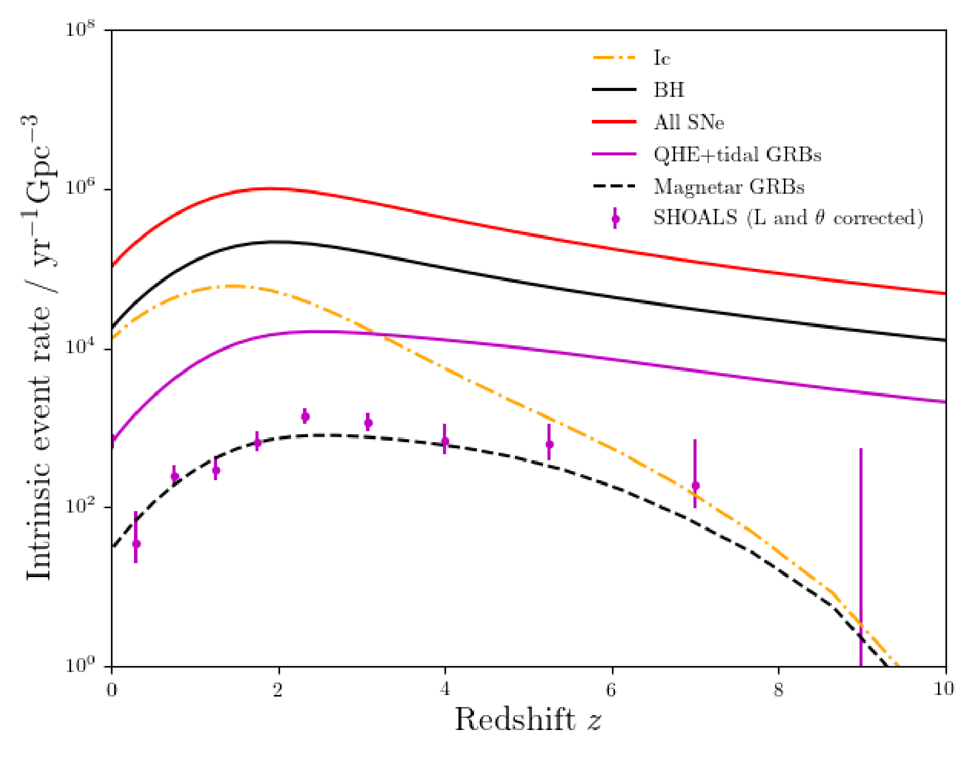
Intrinsic to observed

**$\theta$** The jet opening angle. Corrects the intrinsic rate by a factor $[1-\cos(\theta)]^{-1}$.

**$E_{min}$** The minimum energy that GRBs release. A luminosity function is assumed with $E_{min}$ as the lower bound.

Using the Python module emcee (Foreman-Mackey et al. 2013)

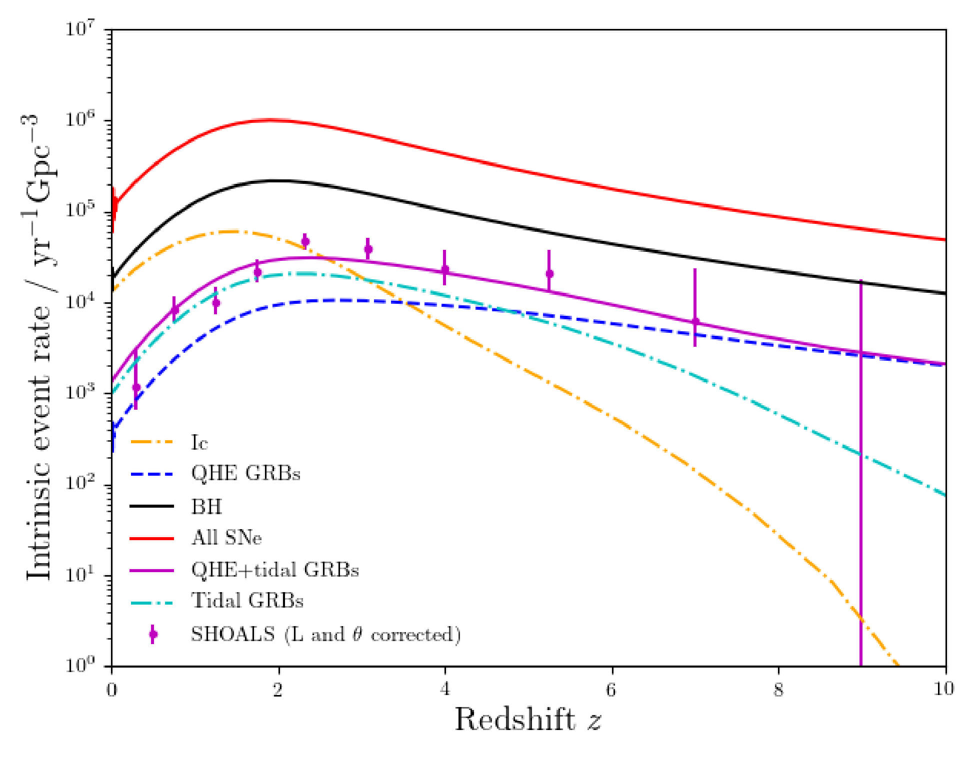
# MCMC Results - Magnetars




| | Median |
|---|---|
| θ /deg | $12.8 \pm^{6.4}_{4.6}$ |
| $Log_{10}(E_{min}/erg)$ | $49.6 \pm^{0.6}_{0.5}$ |
| $Log_{10}(j_{cut,\theta}/cm^2 s^{-1})$ | $18.8 \pm^{0.3}_{0.4}$ |
| $Z^n$ index | $2.2 \pm^{1.0}_{1.3}$ |

*Fitted rates from Perley et al. 2016 (SHOALS), >$10^{51}$ erg LGRBs*

# MCMC Results - Collapsars




| | Median |
|---|---|
| θ /deg | $9.9\pm^{8.9}_{6.8}$ |
| $Log_{10}(E_{min}/erg)$ | $48.1\pm^{1.2}_{0.7}$ |
| $Log_{10}(j_{cut,\theta}/cm^2s^{-1})$ | $18.7\pm^{0.4}_{0.6}$ |
| $Z^n$ index | $3.8\pm^{2.1}_{2.4}$ |

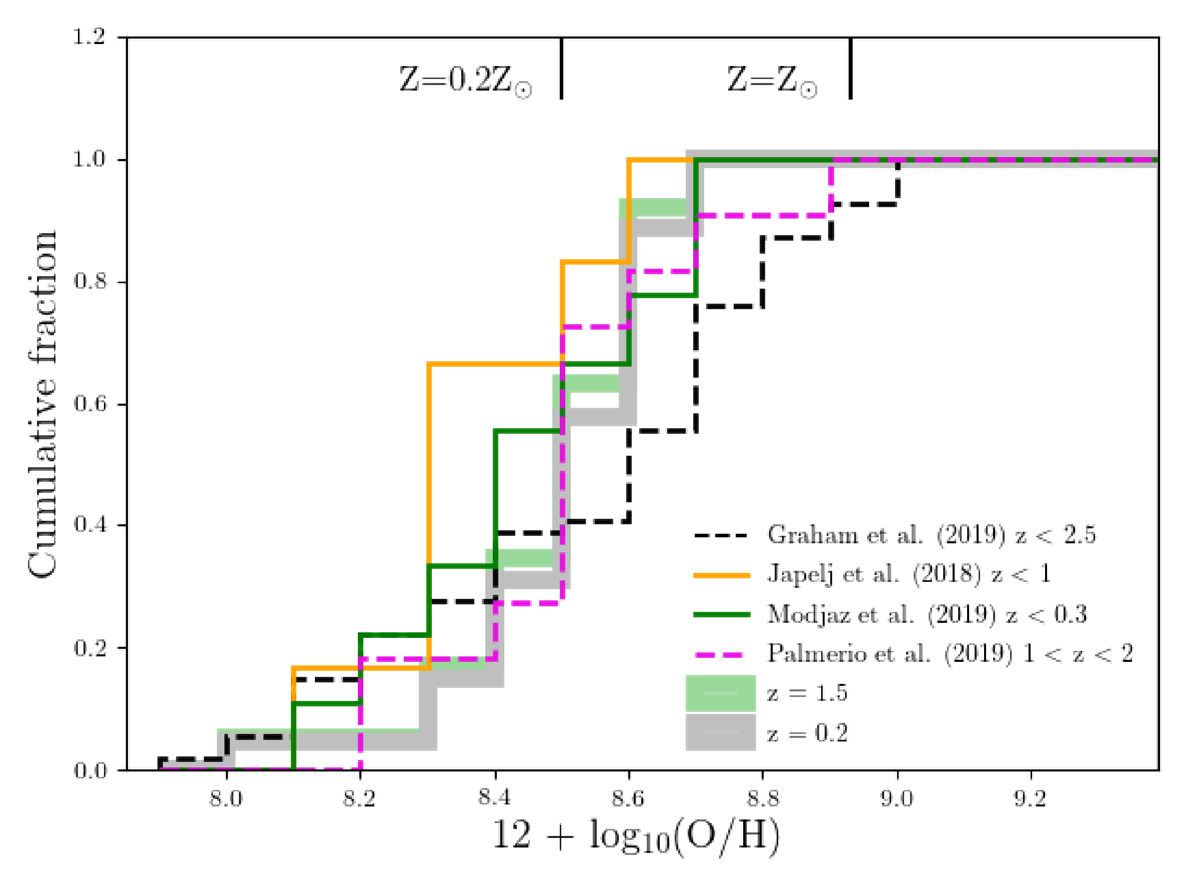
*Fitted rates from Perley et al. 2016 (SHOALS), >$10^{51}$ erg LGRBs*

Still allows for ~10% magnetars

# Metallicity distribution

The metallicity distribution, assuming collapsars and an n=3.8 metallicity dependence.

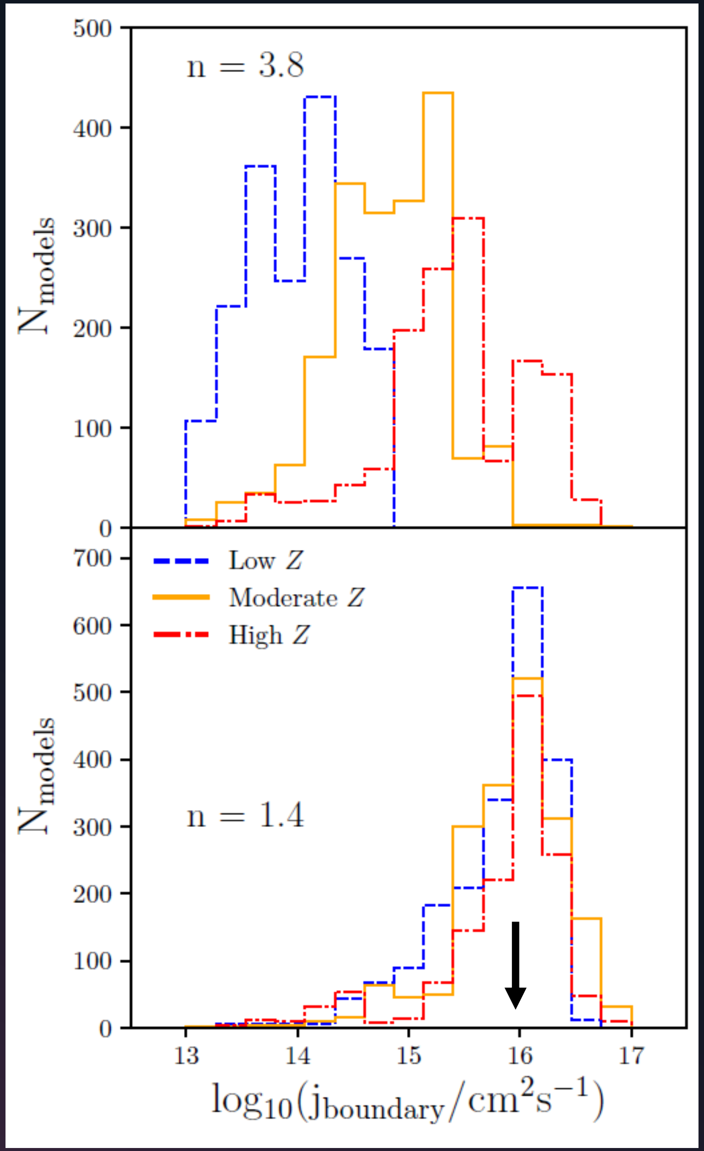
We can also predict the *T* and *L* of the progenitor stars prior to core-collapse.



# Core angular momentum

Using the STARS model outputs, the accretion disc *j* can be calculated assuming rigid body rotation, and that the accretion disc forms at the radius enclosing the subsequent remnant mass.

$$J_{cut} = J_{cut,0} \times \left(\frac{Z}{Z_\odot}\right)^n$$




*If the 1σ lower bound for n is used, the core j required agrees across the range of metallicities (no reason why that should be Z dependent?)*

*~$10^{16}$ $cm^2s^{-1}$ is the minimum required in the collapsar model!*

*→ $Z^n$ where n~1 is also approximately how opacity scales due to metals in a stellar envelope – higher opacity – higher $j_{cut}$ required*

# SUMMARY

## Binary population synthesis with BPASS can reproduce the long GRB rate and host galaxy properties if:

- There are two channels, QHE and tidally spun-up,
- Black holes are the dominant engines,
- There is a metallicity dependence on the escape of relativistic jets from the stellar envelope once they are launched

# Any questions?

*Email:*
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