Estimation of joint detection probabilities of Gamma-Ray Burst and Gravitational Waves produced by NSBH binary mergers

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Abstract

Black hole-neutron star (NSBH) coalescence events are regarded as highly significant phenomena within the current multimessenger framework of gravitational waves, and they are poised to assume an increasingly prominent role in the foreseeable future. To date, only a handful of such events have been observed, with GW200105 and GW200115 being the most noteworthy among them. However with the prospective implementation of next-generation instruments such as the Einstein Telescope (ET) , we anticipate a substantial increase in the detection rate of these events.

The study of NSBH coalescences, is pivotal due to their status as prime multimessenger candidates capable of producing a wide range of electromagnetic counterparts, including Gamma-ray Bursts (GRBs) and Kilonovae. By conducting joint analyses of both the gravitational and electromagnetic signals, it becomes feasible to derive more precise insights into the myriad processes occurring during and subsequent to the merger, including the neutron star's stiffness and the mechanisms underlying GRB generation.

Here we present preliminary results of our work in which we try to provide an estimation of the joint detection capability, GW and GRB afterglow . We compare the LVK interferometers with ET employing the GWFish software, while for evaluating the detectability of GRBs, particularly focusing on the afterglow component, we primarily reference Fermi and the prospective CTA array telescope.

Methods and Analyses

1. Expected merger rate
2. Simulation of Gravitational Waves detection with GWFish tool
3. Mass remnant and kinetic energy model for GRB production
4. Very High energy afterglow evaluation
5. Expected detected probabilities

1 Expected event rate

First we need to estimate the number of expected events as a function of redshift. Different groups have given various estimates using different approaches, some from cosmological considerations alone, others recourse to computationally intensive numerical simulations for stellar evolution [1] [2] .

In addition to this, the models must somehow be normalized to the local event rate, which itself is still very uncertain.

By adopting the methodology proposed by Ish Gupta et al. [1] for the merger rate R and stipulating a local event frequency of $\dot{n}(0) = 45 Gpc^{-3} yr^{-1}$, we partitioned the universe up to a redshift of z=10 into 10 logarithmically scaled shells.

$$R = \int_0^z \frac{\dot{n}(z')}{(1+z')} \frac{dV}{dz'} dz'$$

Madau-Dickinson model

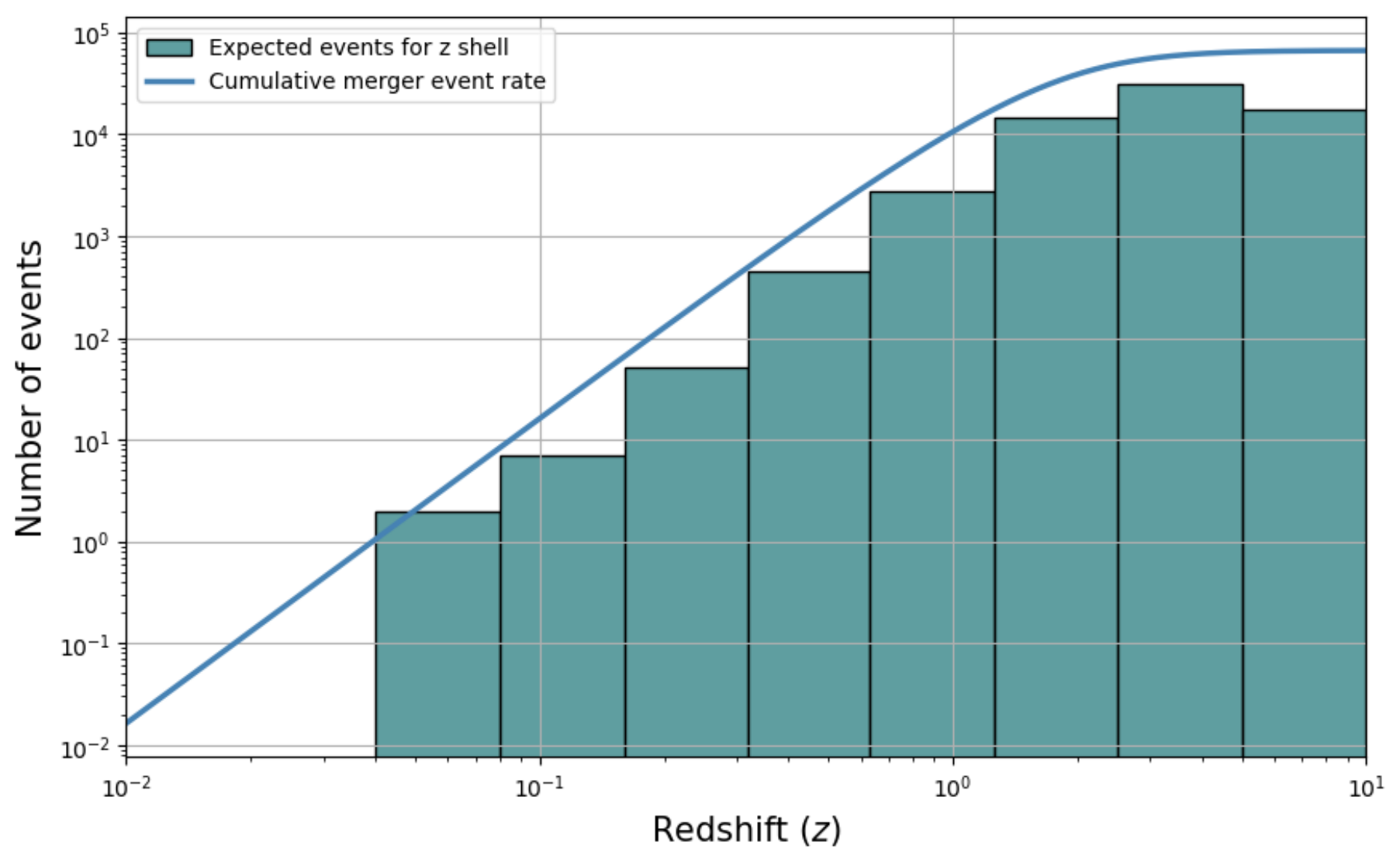

Fig. 1: Merger rate of NSBH merger events a as a function of redshift (z) vs the number of expected events in z shells.

2 Simulation of Gravitational Waves detection with GWFish

In order to simulate the detection of the GW signals we used the GWFish tool [3], which allows to perform the parameter estimation much faster than other tools (such as for example bilby or pyCBC) because it does not use a Bayesian approach but uses Fisher matrices to calculate errors.

We then constructed a dataframe for all the parameters needed to describe the merger and we calculated the SNRs and errors for each event considering three detector networks:

- LIGO-VIRGO-KAGRA (planned for O5 run)
- Einstein Telescope (ET)
- ET coupled with Cosmic Explorer (CE).

Waveform model: IMRPhenomNSBH (LAL suite)

Minimum SNR = 8.0 (Signal to Noise Ratio)

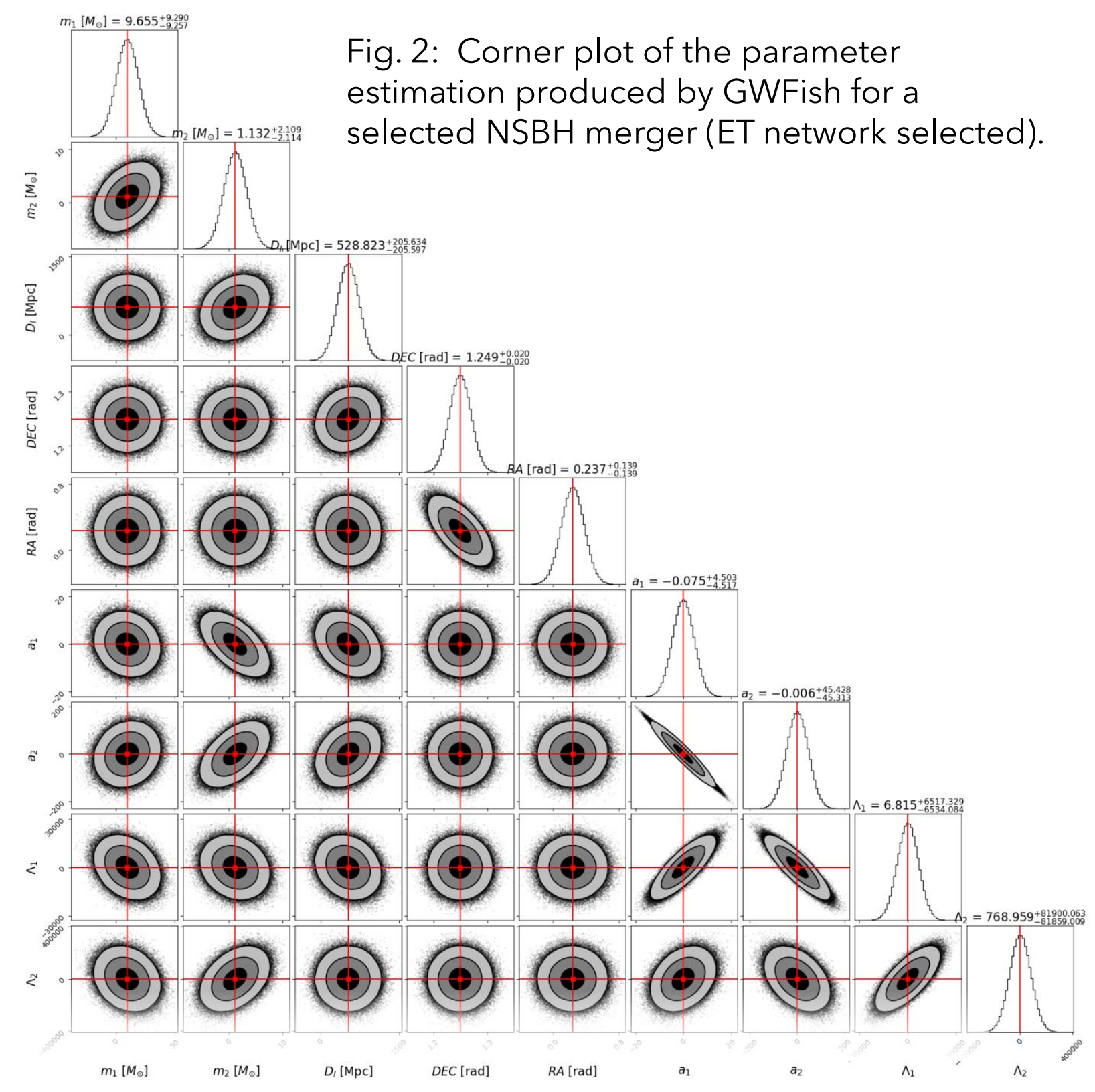

Fig. 2: Corner plot of the parameter estimation produced by GWFish for a selected NSBH merger (ET network selected).

3 Mass remnant and kinetic energy model for GRB production

To assess the productionof the GRB and the resulting characteristics of its afterglow component, it is first necessary to define the model used to estimate the amount of mass available in the accretion disk as a result of the merger (M_{acc}) and the energy of the resulting jet (E_k).

The models we use rely on complex relativistic magnetohydrodynamics simulations and contain within them various parameters affected by large uncertainty. In our work we use the Foucart 2018 [4] for the mass computation and the approach proposed by [5] for the GRB ignition energy .

$$E_k = \frac{1}{2}(1 - f_\gamma)\eta_{BZ} M_{acc} c^2$$

- $f_\gamma = 10\%$: Emission efficiency [6]
- η_{BZ}: Mass-energy conversion efficiency
- $M_{acc} \geq 0.03 M_\odot$: accreted mass [7]

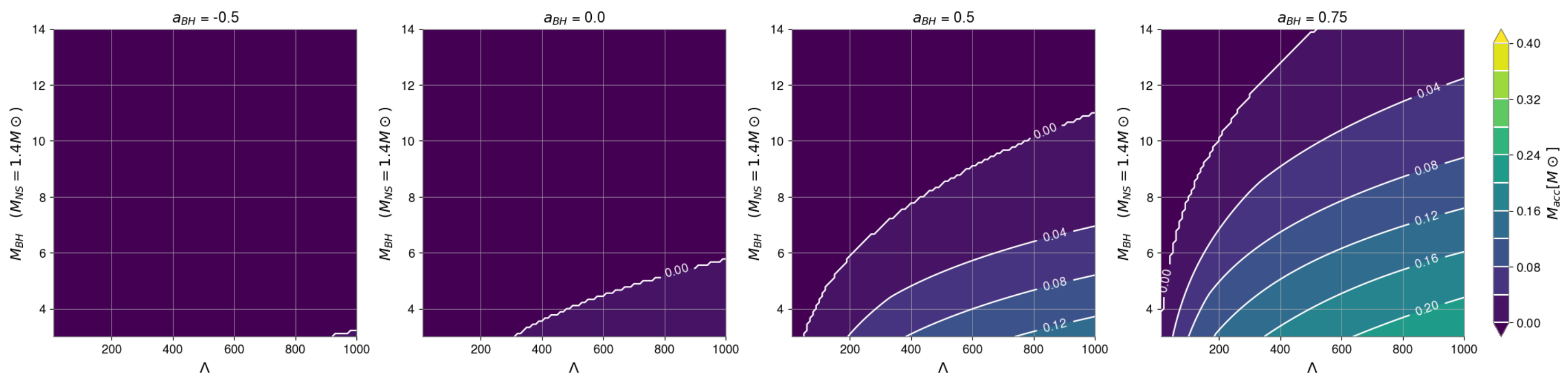

Fig. 3: Countour plots of accreted disk mass in solar masses as a function of BH mass, BH dimensionless spin a_{BH},and tidal deformability Λ of the Neutron Star.

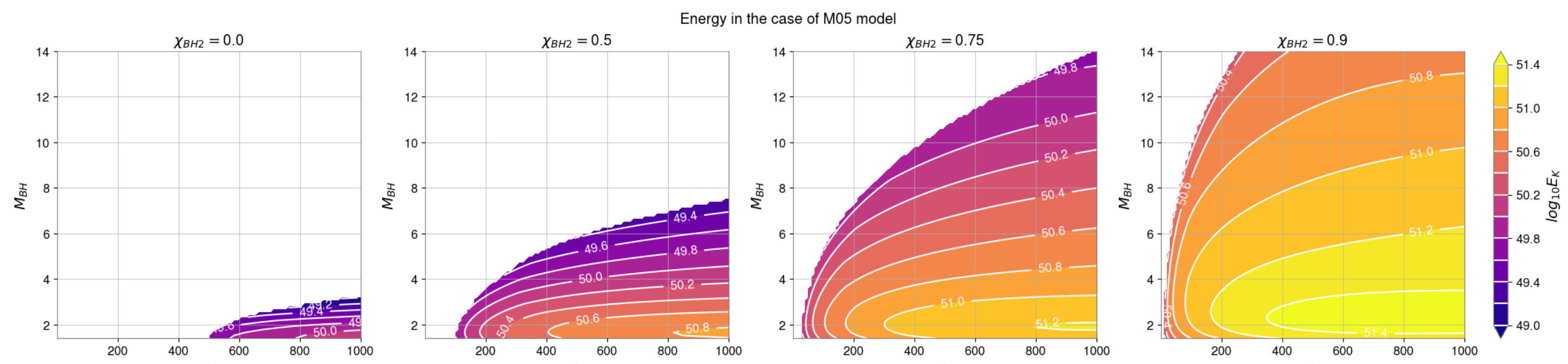

Fig. 4: Countour plots of Kinetic Energy (E_k) as a function of BH mass, BH dimensionless spin a_{BH},and tidal deformability Λ of the Neutron Star.

4 Very High energy afterglow evaluation for CTAO

As mentioned we are studying the Afterglow component of the GRB and in particular we want to see what happens at very high energies in the part of the spectrum dominated by the Synchrotron Self Compton (SSC) component.

To evaluate this component we use a recent method developed by Joshi-Razzaque [8] and go to compare the emission spectrum with the most recent estimates of the CTAO future sensitivity, in the North and South configurations.

We set this parameter values:

- $n_0 = 10^{-5} cm^{-3}$ (density)
- $\epsilon_e = 0.2$ (e field density)
- $\epsilon_B = 0.01$ (magnetic density)
- $b = 6$ (power law index)
- $p = 2.3$ (elctron energy index)
- $\theta_{core} = 0.05\, rad$

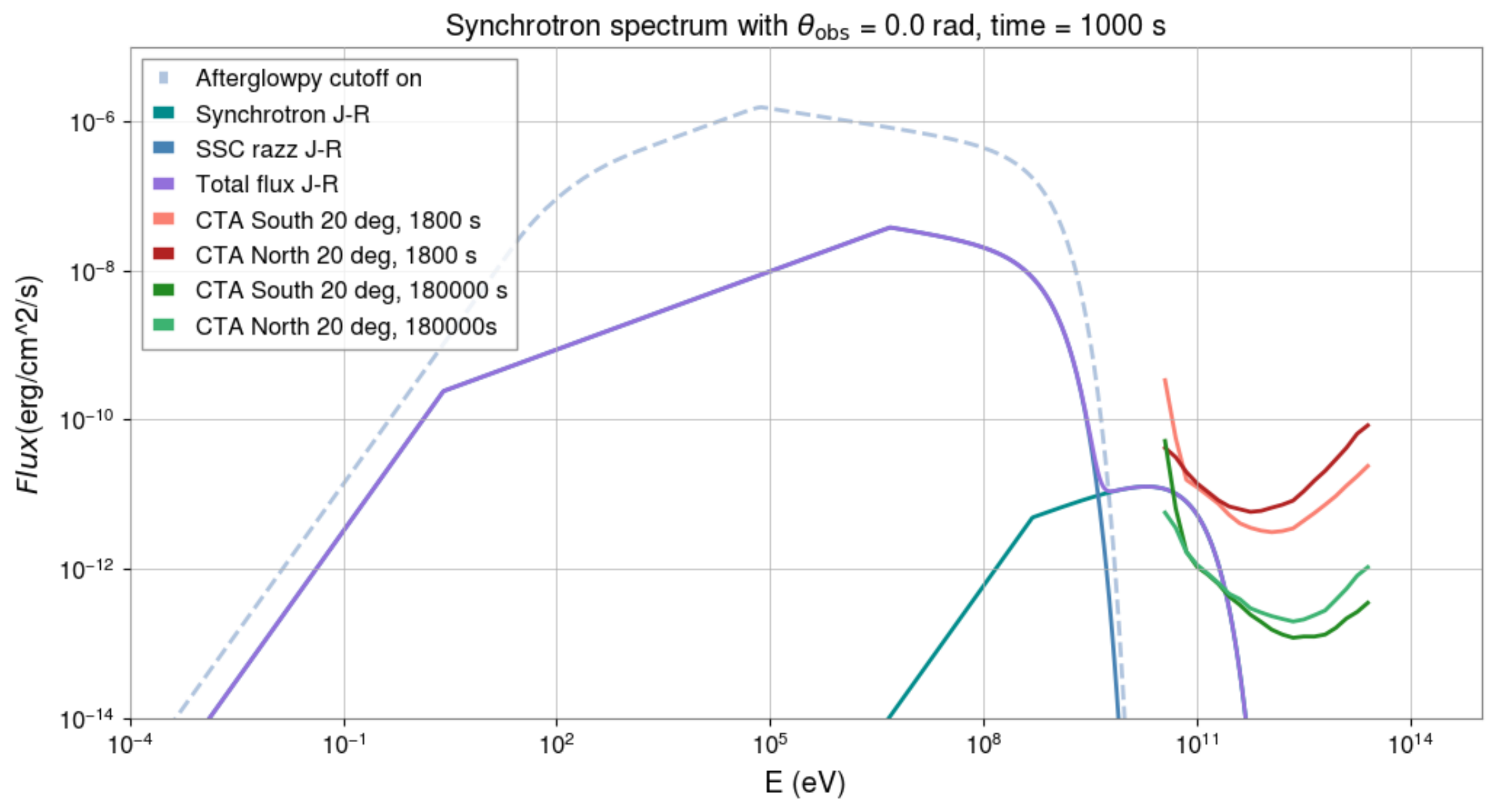

Fig. 5: Emitted flux of the afterglow emission with boh the Syncrotron and the SSC components vs CTA sensitivity. Here we set an observing angle of $\theta = 0\, deg$ and a time after the emission t=18000 s for both South 20 deg and North 20 deg.

Preliminary results and future prospects

To give a preliminary estimate of possible detections, we computed the number of events whose resulting produced SSC flux is above the sensitivity threshold, considering CTA configurations at 18000 s.

In Figures 6 and 7 we show the number of events detected by the ET and ET+ CE1 networks vs. the expected number of events already shown up to a redshift z=2.1. In the same plots we report the number of GRBs produced for each shell according to our model and the number of events above threshold considering CTAO. As can be deduced there appear to be a good number of EM counterparts produced but none appear to be above threshold.

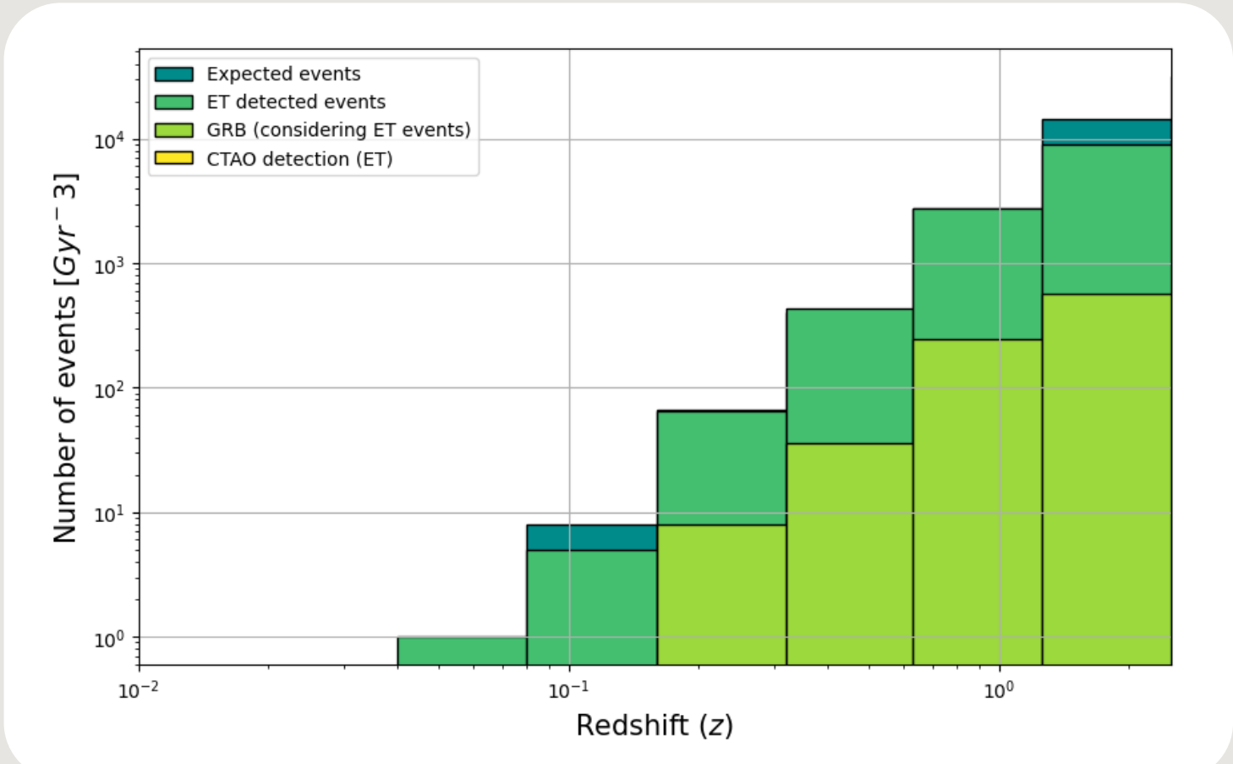

Fig. 6: Preliminary results for ET network configuration.

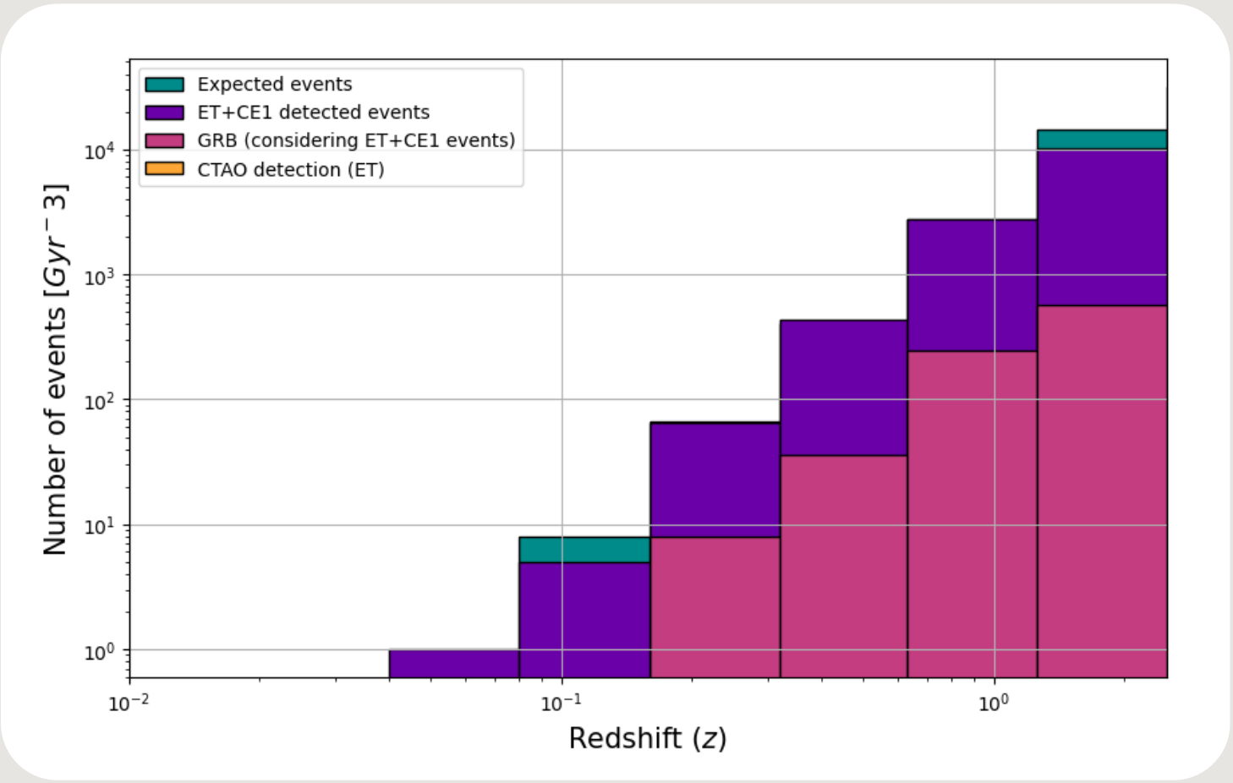

Fig. 7: Preliminary results for ET+CE1 network configuration.

- Check for possible unexpected error sources in the code that could give this result.
- Study how much the result depends on the values of the fixed parameters chosen for the several models.
- Explore alternative models (for merger rate, energy production...) and see if we get more events and more energy, and thus supra-threshold events in significant numbers.

References

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ETSYMP2024 - Maastricht

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