STUDY ON FUTURE GW - VHE GRB DETECTION SYNERGIES WITH THE CTAO

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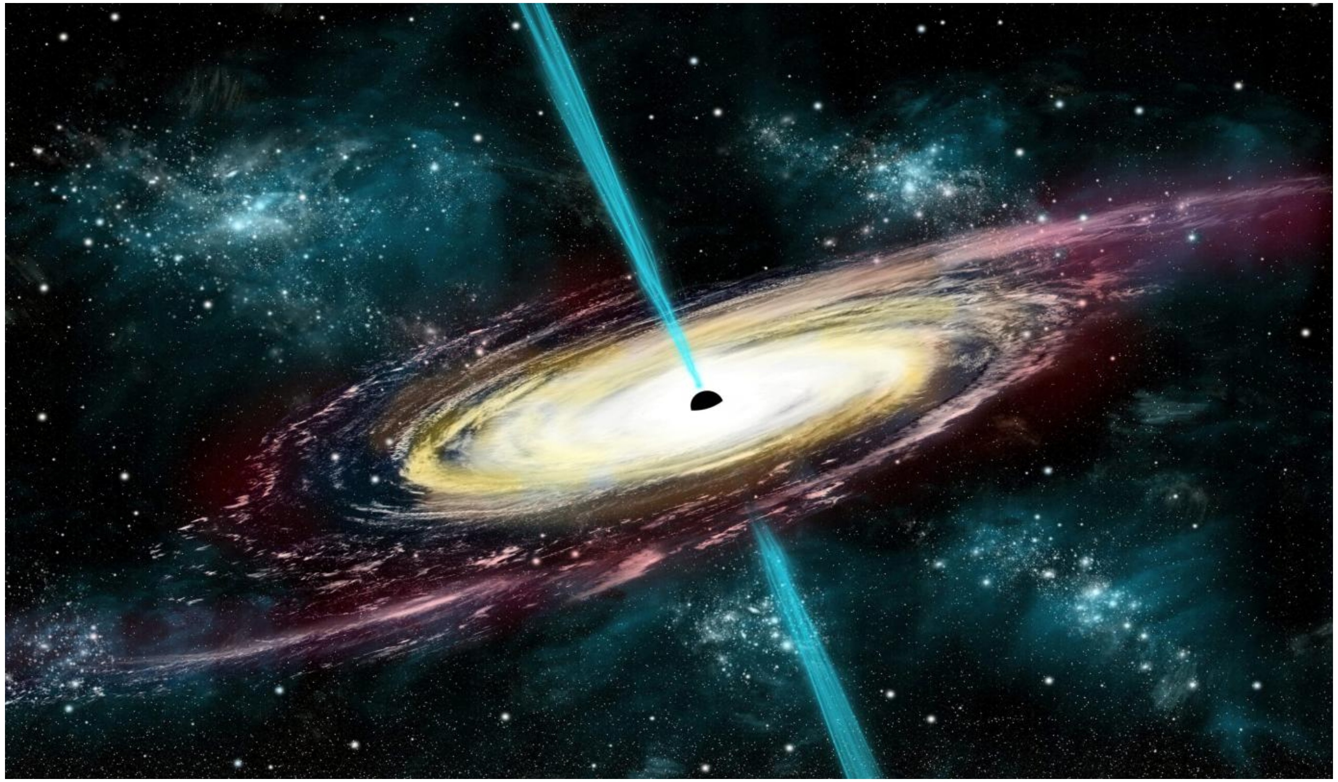
2nd VHEgam Meeting

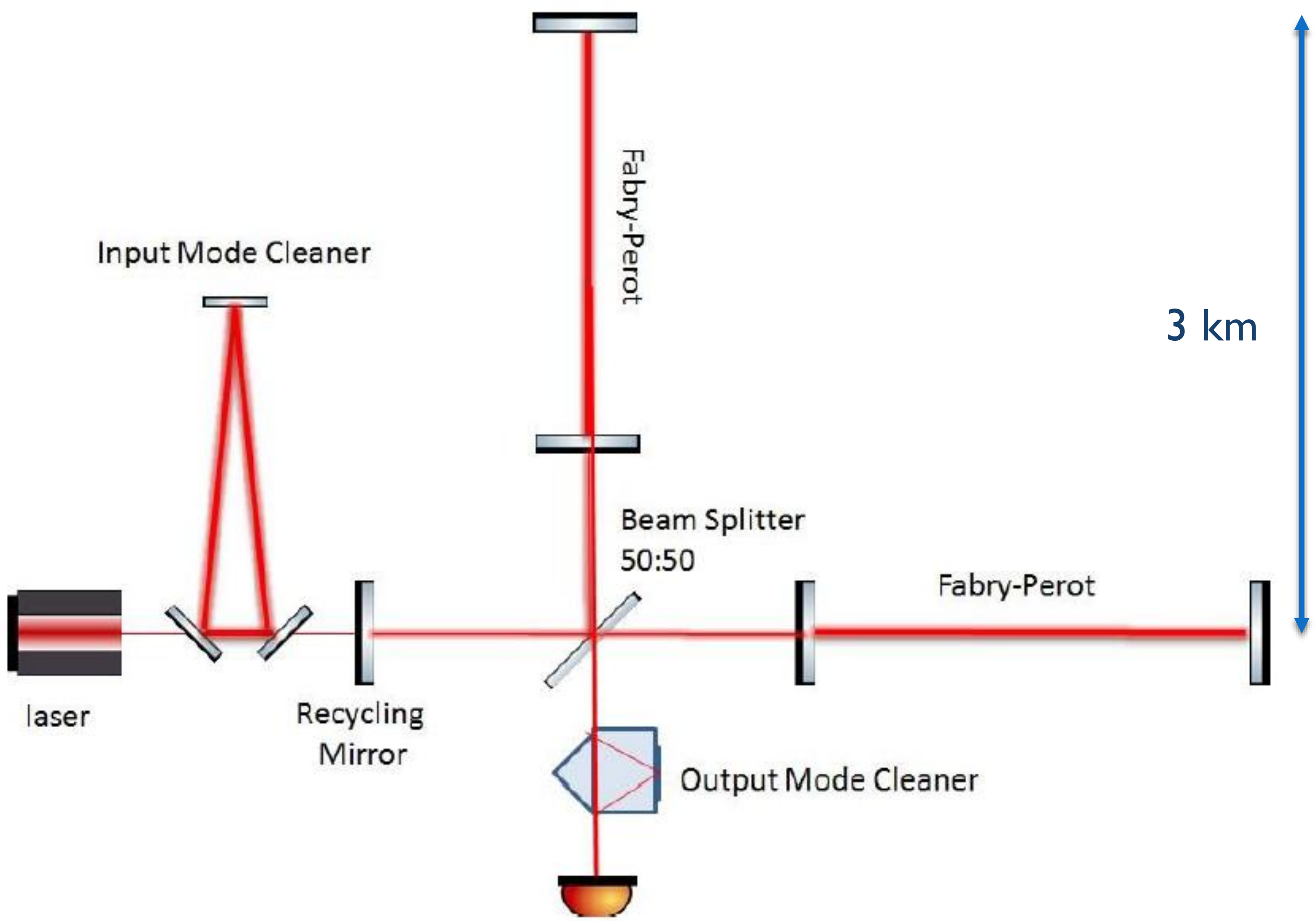
OUTLINE

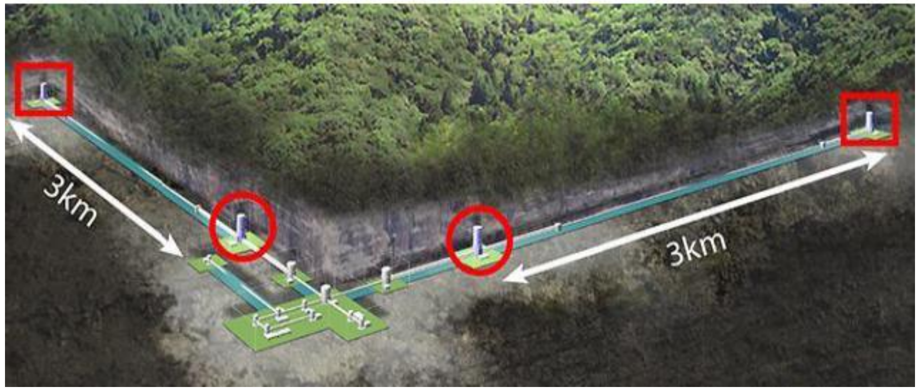
- Introduction on GW detectors
- Pipeline description
- BNS population and GW analysis
- GRB model
- GRB analysis
- Joint detection prospects
- Future improvements



2G Gravitational Waves Detectors: LVK

- Michelson Interferometer



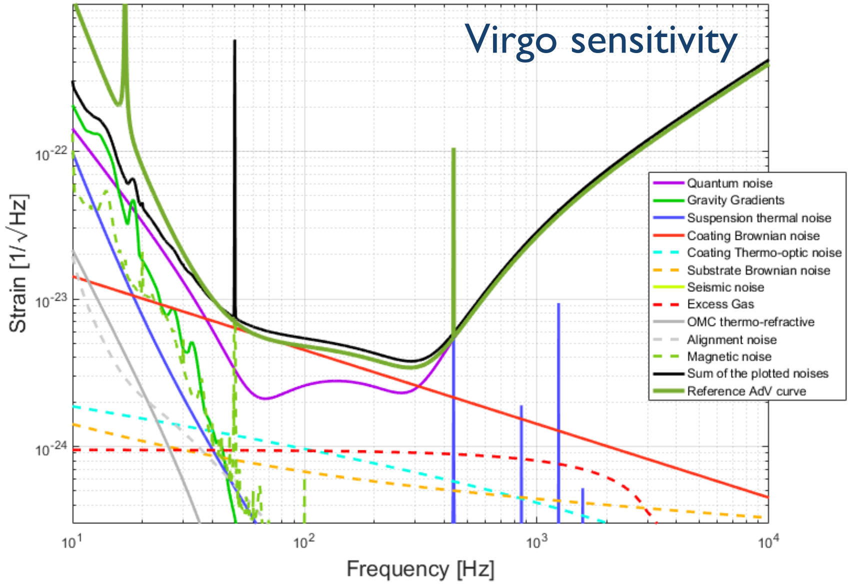


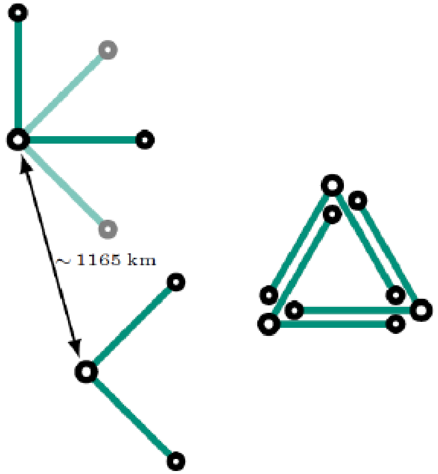
Masses in the Stellar Graveyard

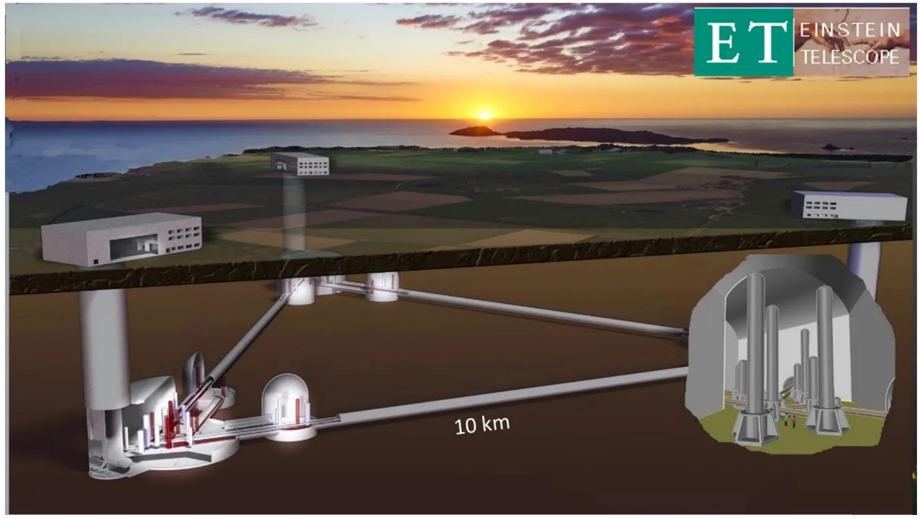
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

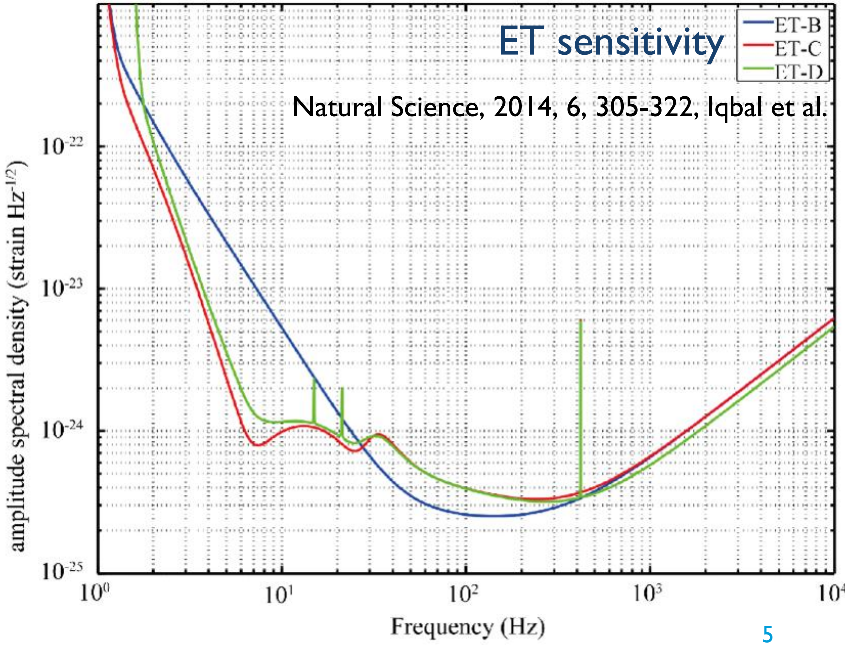
3rd Gen Detector: Einstein Telescope

- Proposed sites: Sardinia, Euro-region Meuse-Rhine, Lusatia (Germany)
- Underground
- Cryogenic optical components
- Detection radius: 10× *wrt* Virgo → 1000× events!









Pipeline

- Our aim is to understand how to run a future multimessenger analysis between GWs and VHE GRBs in preparation of future improvements, such as Virgo_nEXT or Einstein Telescope

- Simulation of the CBC BNS population

- Association to each event of a GW
- Definition of the detector network: SNR
- GW detection rate

- Association to each event of a GRB
- *Astroplan*: visibility of each event for CTAO-N
- Definition of the GRB model
- *Gammapy*: analysis of the GRBs
- GRB detection rate

Joint prospects!

BNS GW Population

https://ler.readthedocs.io/en/latest/index.html

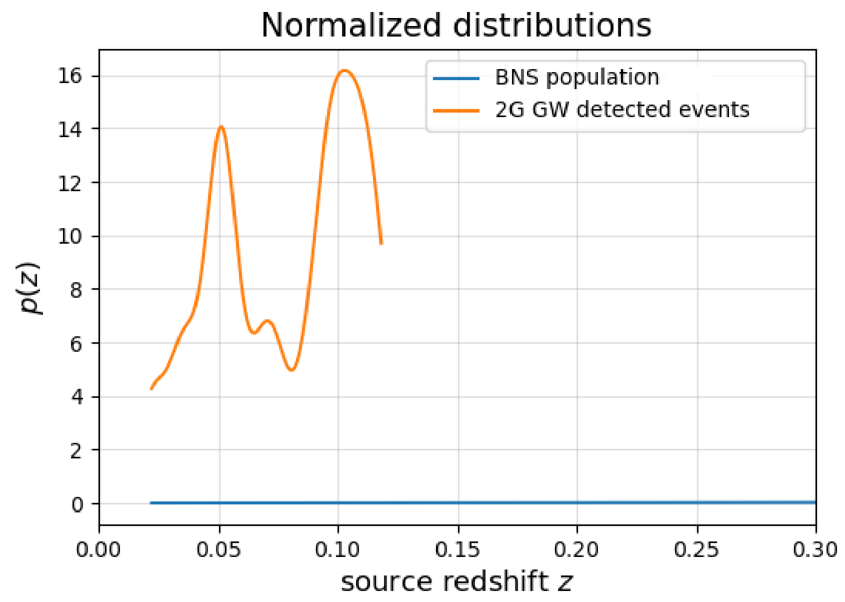
- **LER (LVK Event Rate calculator and simulator)**
  Statistical based Python package designed for simulation and forecasting of GW events

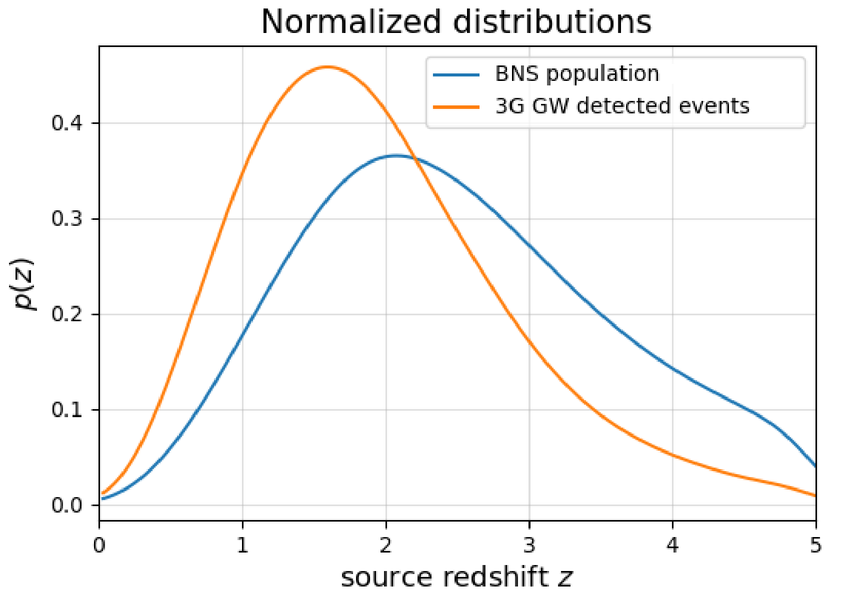
- **BNS population:**
  z in (0, 5) in a ΛCDM cosmology
  Mass in (1, 2.3) Msol (z corrected)

  Farr, Chatziioannou - Res. Notes AAS 4, 65 (2020)
  Renske, Wierda - ApJ 921, 154 (2021)

https://github.com/hemantaph/gwsnr

- **Detectability: LER makes use of the *gwsnr* python package for the calculation of the SNR**
- **Detected events: SNR > 8**
- **2G detectors expected rate: $\sim 10/\mathrm{yr}$**
- **3G detectors expected rate: $\sim 1.6 \cdot 10^5/\mathrm{yr}$**





GRB Temporal Model

Light Curve: From our previous GRB-focused work
(CG et al., RICAP-24 proceedings)

- Numerical model: *Miceli, Nava – Galaxies 2022, 10, 66*
- LCs produced varying a set of *physical* parameters: →

εe = electron energy fraction
εb = magnetic energy fraction
$\Gamma 0$ = bulk Lorentz factor
n0 = ISM density [cm^{-3}]
p = injected electrons index

- Analytical description: we can define a smoothly BPL:

$$F(t) = \Phi \left(\frac{t}{\tau}\right)^{a_1} \left[\frac{a_1\left(\frac{t}{\tau}\right)^{1/s} + a_2}{a_1 + a_2}\right]^{-(a_1+a_2)s}$$

Depending on some *fit* parameters:

τ = peak time
Φ = peak flux
a_1 = low time PL index
a_2 = high time PL index
s = smoothing parameter

Workflow

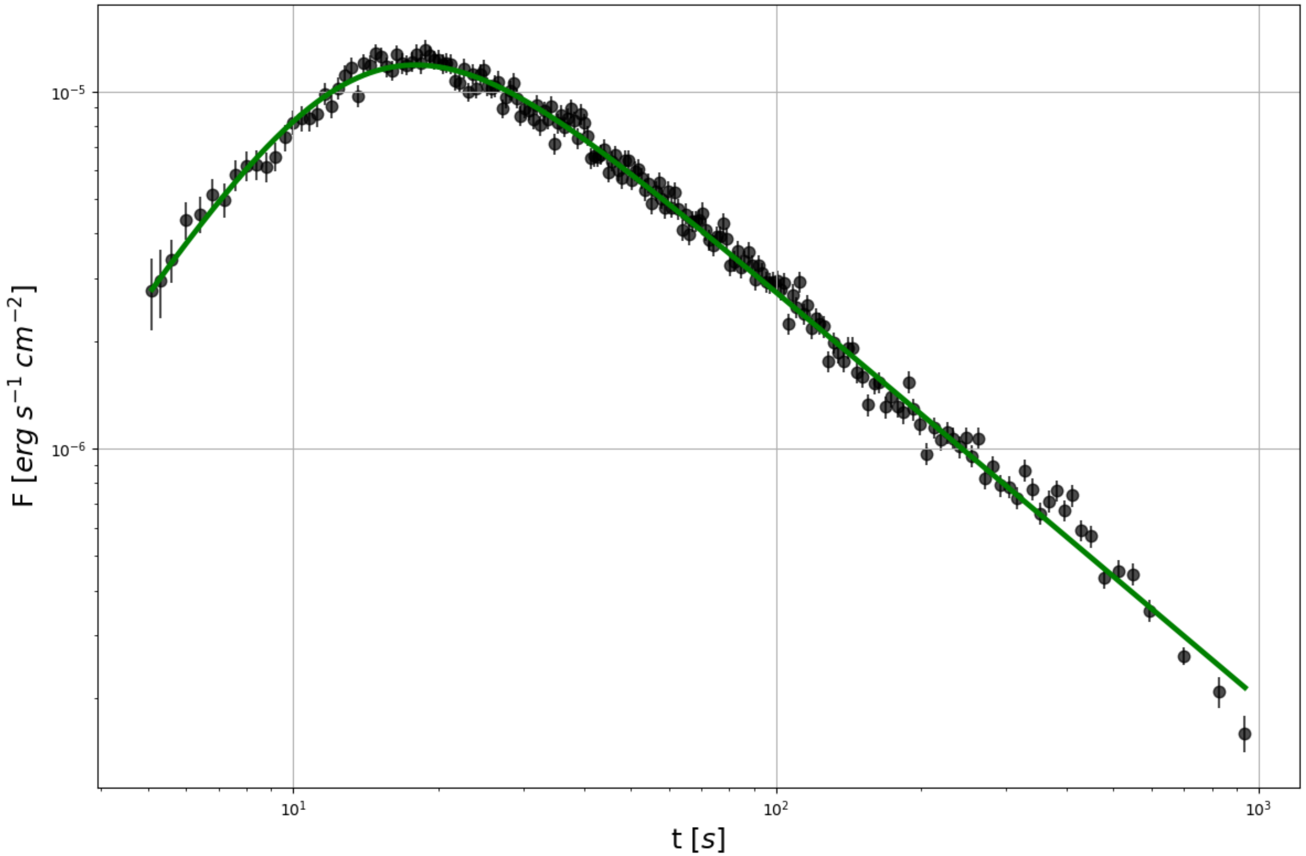
1. Production of curves with the numerical model
2. Variations of the parameters around some initial values
3. Link each fit par to each phys par through: $y = A\ x^b$
4. Description of the fit par as a combination of the phys par: $(fit\ par) = A \left(\frac{\epsilon_e}{\overline{\epsilon_e}}\right)^{b_e} \left(\frac{\epsilon_b}{\overline{\epsilon_b}}\right)^{b_b} \left(\frac{\Gamma_0}{\overline{\Gamma_0}}\right)^{b_\Gamma} \left(\frac{n_0}{\overline{n_0}}\right)^{b_n} \left(\frac{p}{\overline{p}}\right)^{b_p}$
5. Fast determination of parameters through a Maximum Likelihood Estimation

GRB Temporal Model

- Flux now expressed as function of the *physical* parameters!
- Log-likelihood:

$$\ln P\,(y \mid t, \sigma, \epsilon_e, \epsilon_b, \Gamma_0, n_0, p) = -\frac{1}{2}\sum_n \left[\frac{(y_n - F(phys))^2}{\sigma^2} + \ln(\sigma^2)\right]$$

- Through a Maximum Likelihood Estimation, we get a value for the parameters



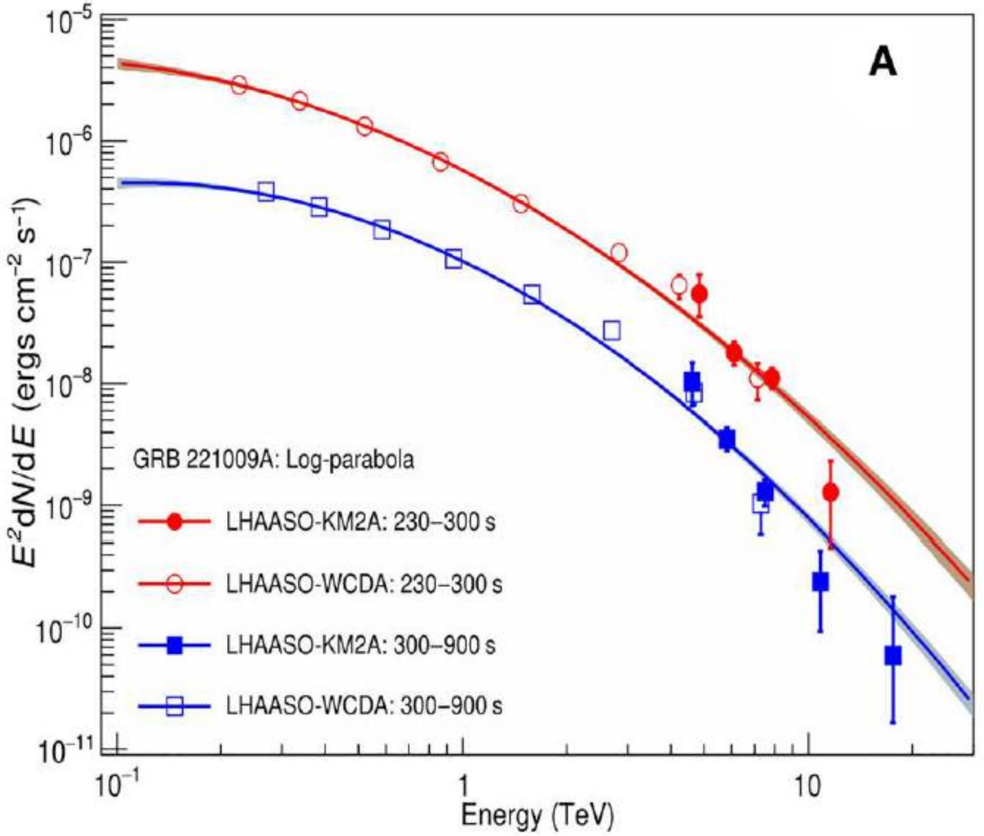
ϵ_e^{ML}	0.1
ϵ_b^{ML}	0.024
Γ_0^{ML}	580
n_0^{ML}	2.1 cm^{-3}
p^{ML}	2.0

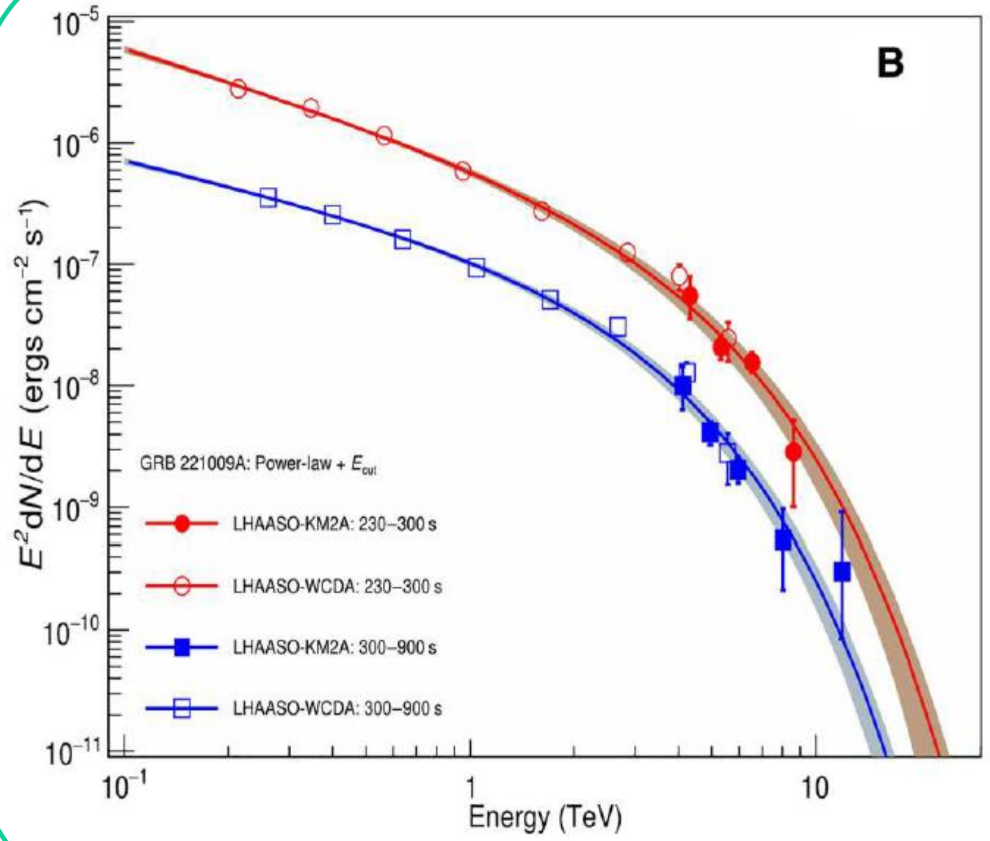
Data: LHAASO Collab. *Science* **380 (2023)**

LHAASO-WCDA
E = (0.3 – 5 TeV)

GRB Spectral Model

- **Spectrum** (**LHAASO Collab.** ***Science Advances*** **9, 46 (2023)**)





- No EBL attenuation
- Spectral model: Exponential cut-off Power Law

GRB Analysis

https://astroplan.readthedocs.io/en/stable/

***Astroplan*:**

Open-source Python package designed to help astronomers plan observations

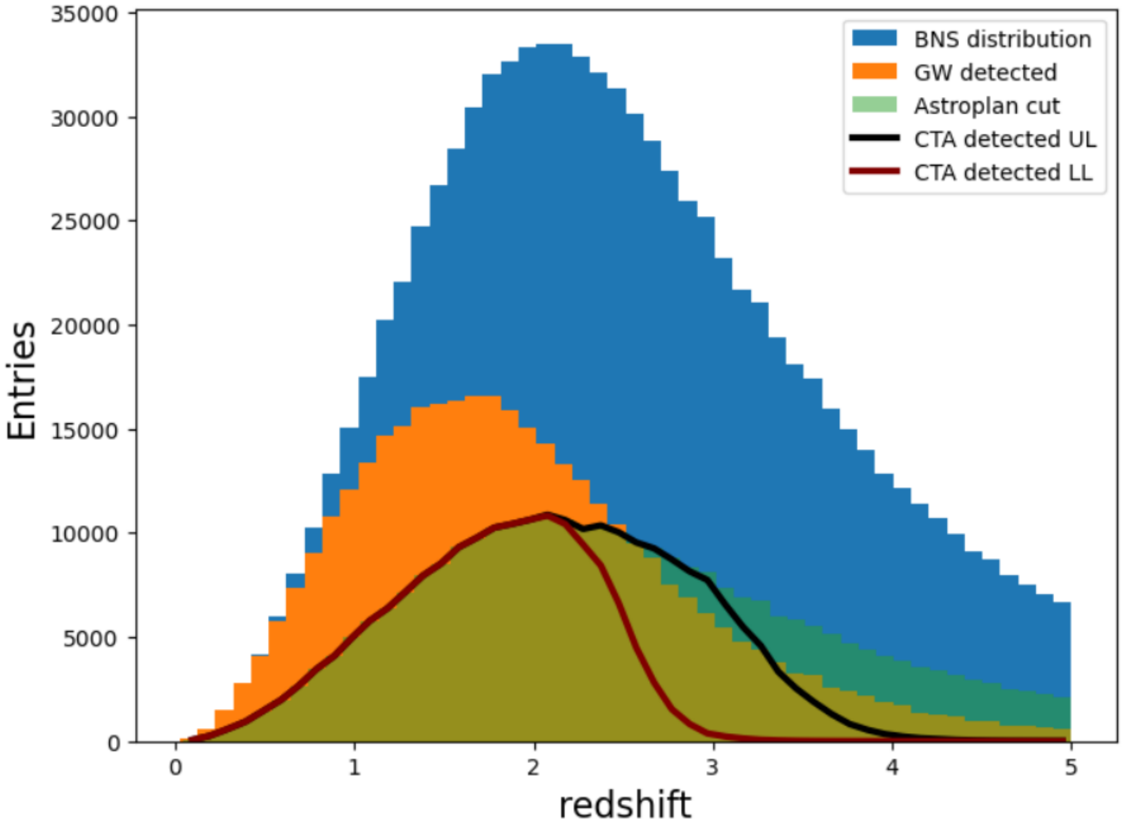
- Location of the observatory **(CTAO-N, Roque de los Muchachos)**
- Takes care of: **day/night, moon… visibility conditions**
- Gets the **visible sources**

https://gammapy.org

***Gammapy*:**

Open-source Python package for γ-ray astronomy, core library for the Science Analysis tools of the CTAO

- Defined: spectral model, temporal profile
- IRF (prod5 v0.1)
- We defined two possible situations:
  - the follow up starts immediately
  - the follow up starts after 1 min
- **We find the detected events!**



Joint detection prospects

To conclude: joint detection prospects

For the moment, we have considered independent the two results

- We see how the joint detection probability for 3G detectors is quite high
- For 2G detectors, the joint probability is basically negligible

Joint detection rate

2G detectors

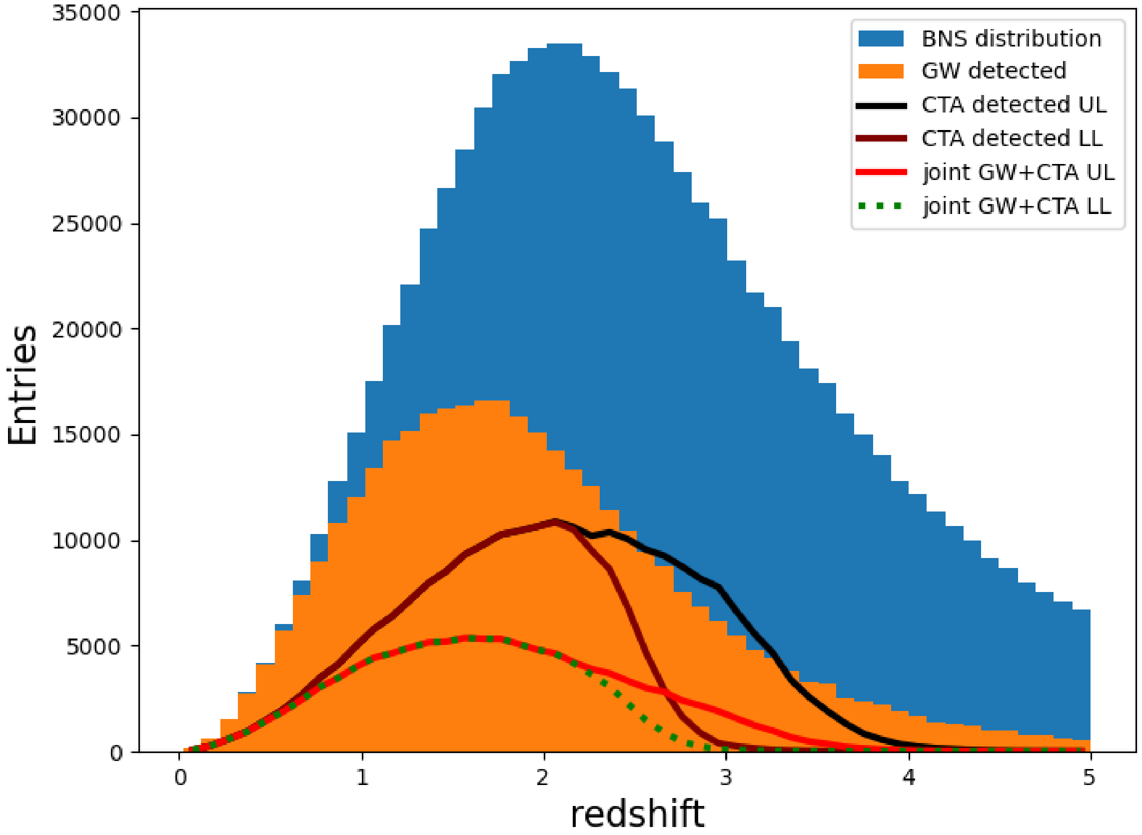
Upper limit: $\sim 1/10^5$ yr

Lower limit: $\sim 8/10^6$ yr

3G detectors

Upper limit: $\sim 1900/\text{yr}$

Lower limit: $\sim 1600/\text{yr}$



In such a plot, 2G detected events would not be visible

Future Improvements

- Once available, usage of the sensitivity of Virgo_nEXT
- Usage of other GW analysis softwares (e.g. PyCBC)
- Adding the BH-NS contribution
- Randomizing temporal and spectral profiles of GRBs (the one we have used is from an exceptional event – not even from a BNS)
- Adding the EBL attenuation
- In general, more realistic assumptions on GRBs
- Adding CTAO-S (and eventually more VHE observatories)
- More realistic dependencies between GWs and GRBs

Thank you!