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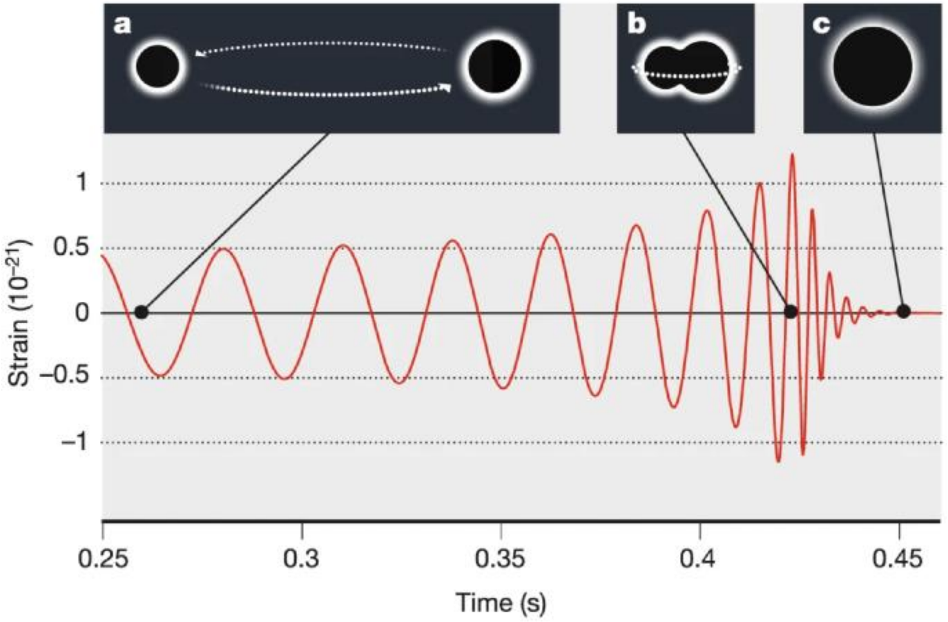
"Estimation of joint detection probabilities of Gamma-Ray Burst and Gravitational Waves produced by NSBH binary mergers"

Introduction

Compact Binary objects Coalescence:

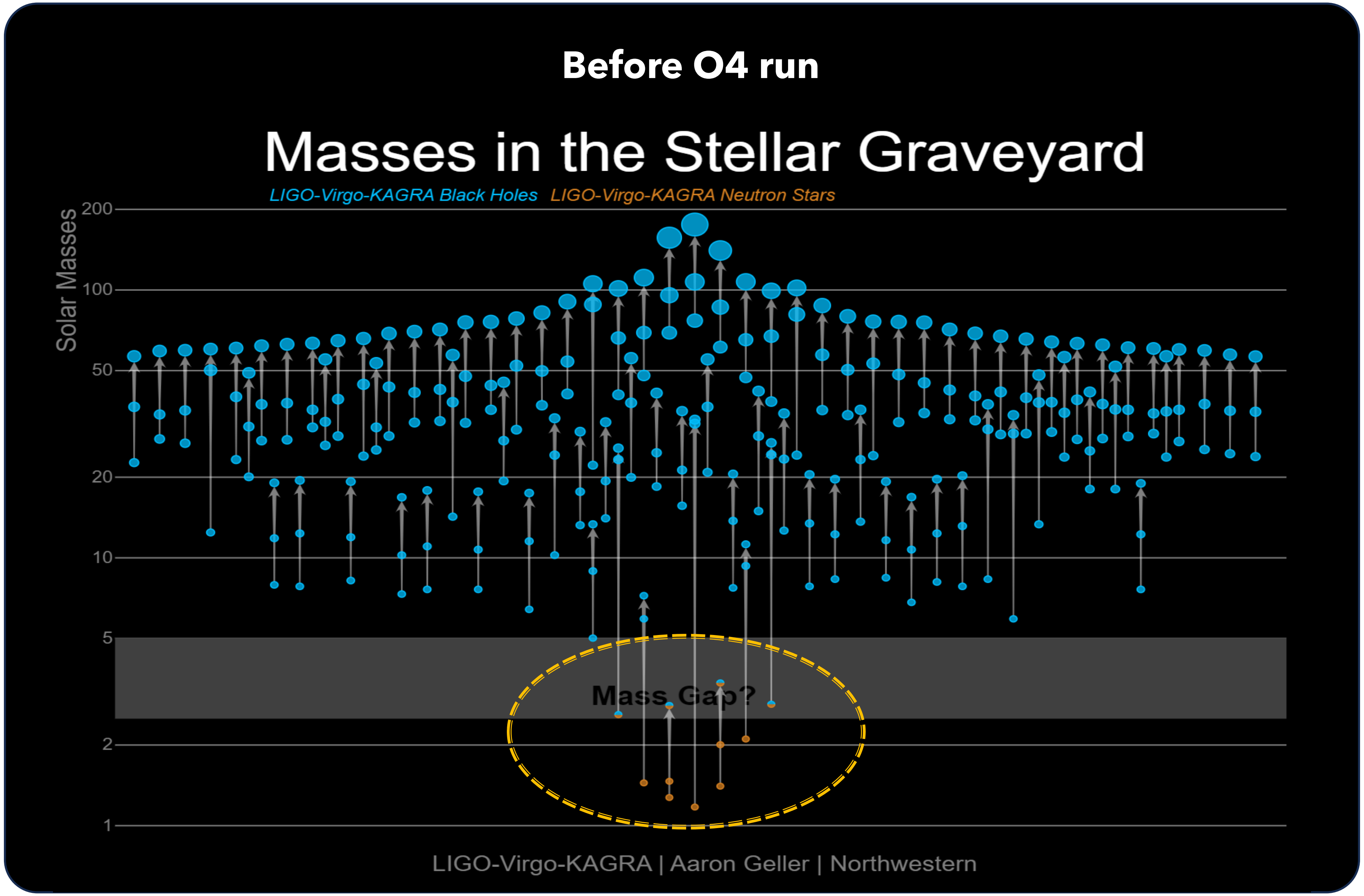
- Binary Black Hole (BBH)
- Binary Neutron Star (BNS)
- Neutron Star – Black Hole (NS-BH)

Disruptive binary mergers (**Tidal disruption**) ⟶ Possible **EM counterpart**



1. **Formation** and **inspiral** — Trillions - Billions years; Energy loss for GW emission
2. **Merging** phase — Lasts ~ ms; From two objects to one
3. **Ringdown** and post merger phase — Lasts ~ seconds; Settle down of final object and emissions

Introduction



Simulations

Expected events in the future / year

Detector	*NS-BH*
AdLIGO	$1.2 - 9.3$
A+	3.2-26
ET + CE (next gen.)	2.4×10^3-2.2×10^4

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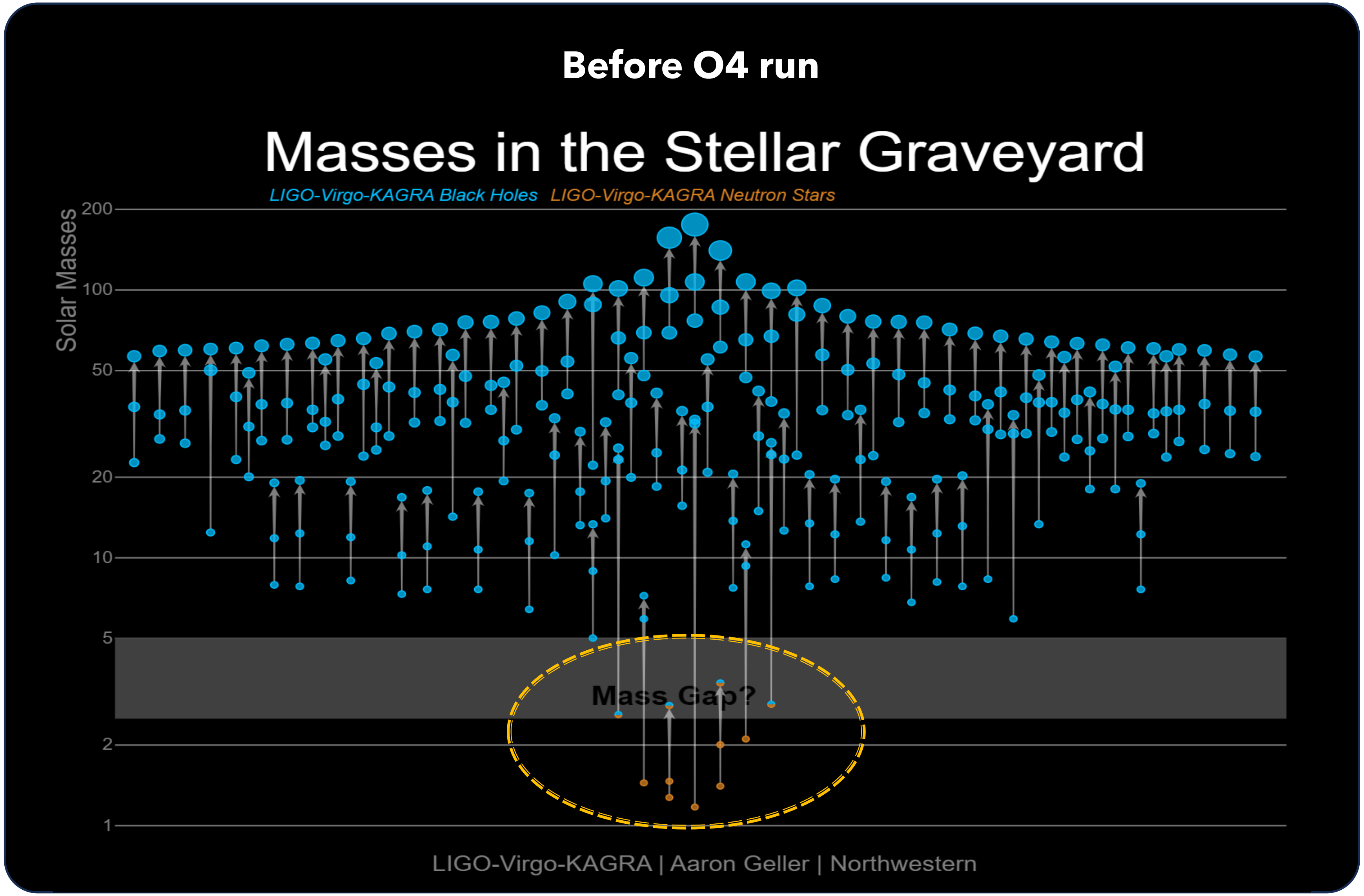

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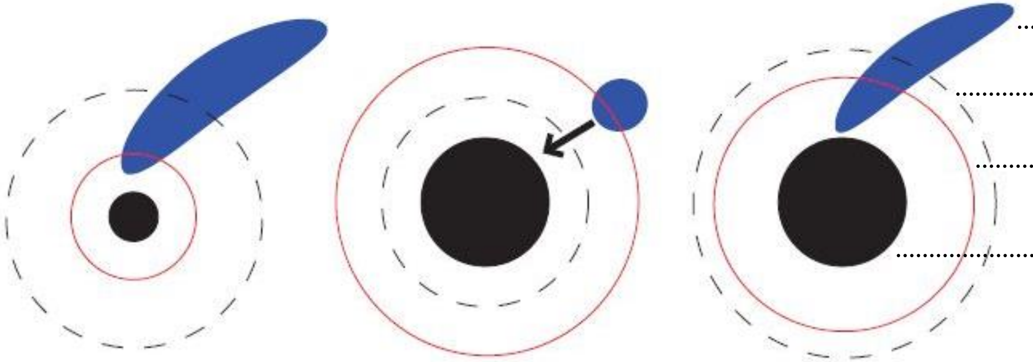
In O4 obs. run

(May 2023 to Feb 2025)

- 196 Events
- ~ 186 BBH
- ~ 8-10 NSBH

Introduction

Tidal disruption   Plunge   Tidal disruption



Neutron Star

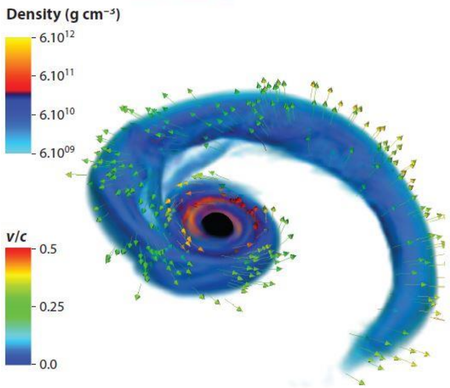
d_{tidal}

R_{ISCO}

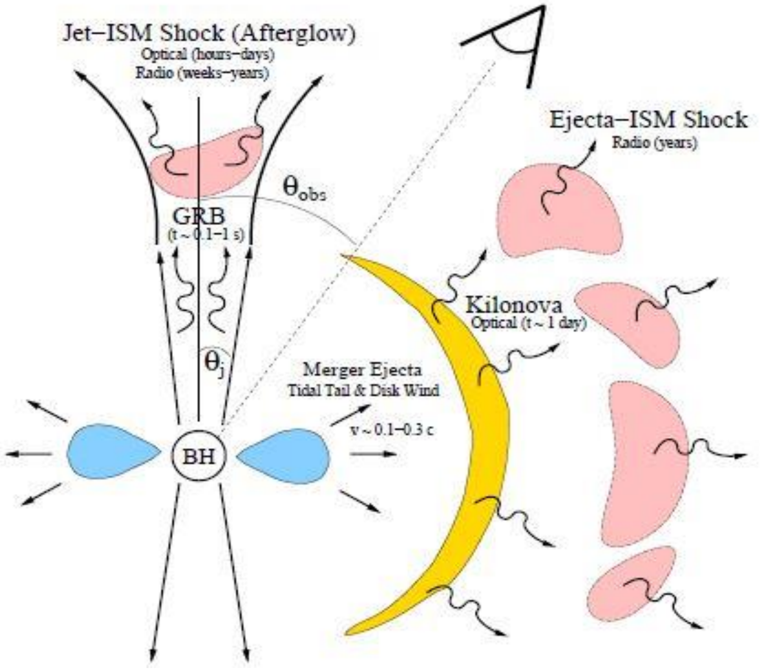
Black Hole (Event Horizon)

Spins

NS Equation of State (**EoS**) o λ



- Dynamical ejecta
- Wind ejecta
- Viscous ejecta
- Relativistic jet

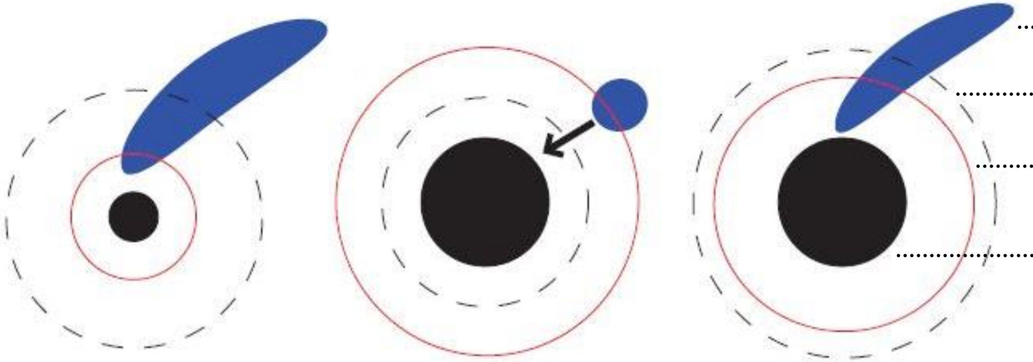


Different emission for every component:

- **Kilonova**: r process, β decay
- **Gamma-Ray Burst**: Prompt and Afterglow emission

Introduction

Tidal disruption Plunge Tidal disruption



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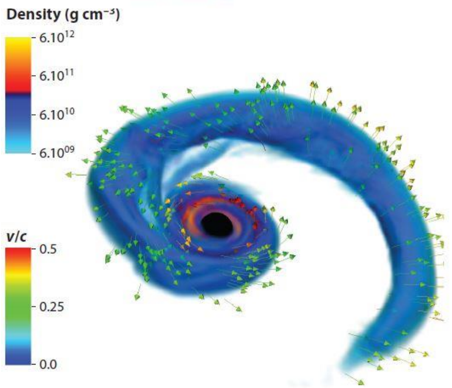

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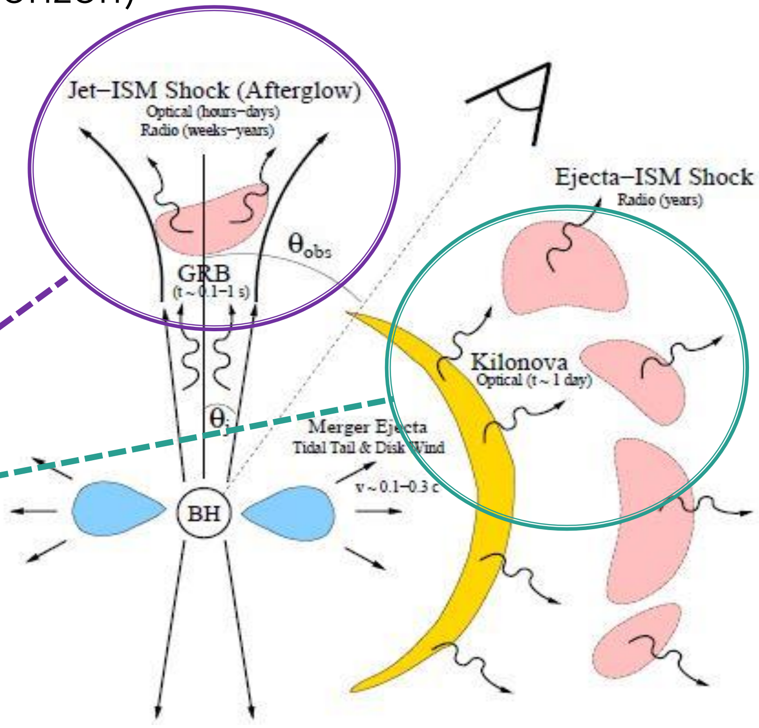

Different emission for every component:

- **Kilonova**: r process, β decay
- **Gamma-Ray Burst**: Prompt and Afterglow emission

Methods and Analysis

1. Expected **merger rate** throughout the universe
2. **Simulation** of **G**ravitational **W**aves **detection** with GWFish tool
3. Mass **remnant** and kinetic **energy model** for GRB production
4. Very High energy **afterglow evaluation**
5. Expected probability of detection for **NSBH multi messenger** events

1 Methods and Analysis: exepected event rate estimation

The first step consists of estimating the number of expected NSBH events in the Redshift function.

The models have to be normalized to the local event rate, this is affected by big uncertainties.

Using the same method of Ish Gupta et al. to compute the merging rate and fixing the local merger rate as $\dot{n}(0) = 45 Gpc^{-3} yr^{-1}$, we obtain a distribution like this.

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

Madau-Dickinson model

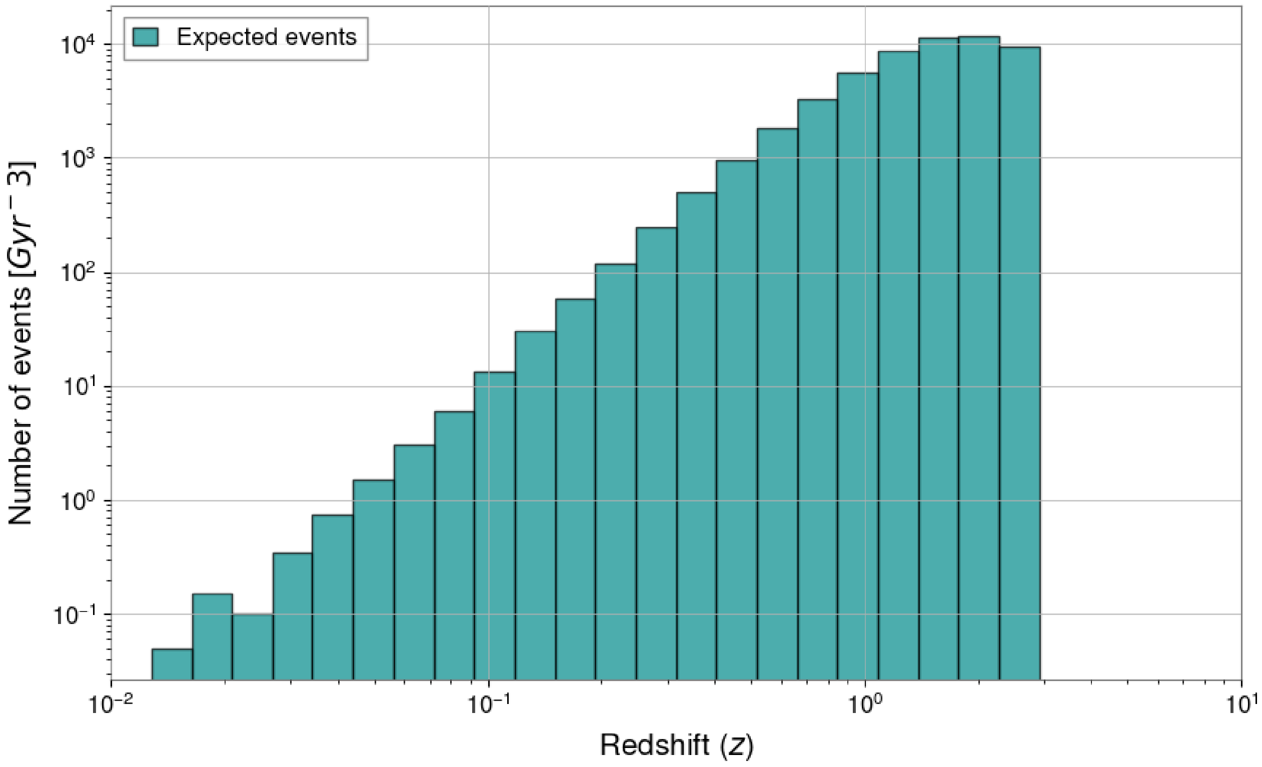

Fig. 1: Merger rate of NSBH merger events a as a function of redshift (z) vs the number of expected events in z shells.

Methods and Analysis : GW detection simulation

To simulate the detection we can use two different approaches:

- **Bayesian** approach with **Bilby** (or pyCBC): More precise but very slow

We can build a dataframe with all the coalescence parameters and compute the SNR, parameters values and the corresponding errors for every event. We can study different network configurations of interferometers.

- 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)

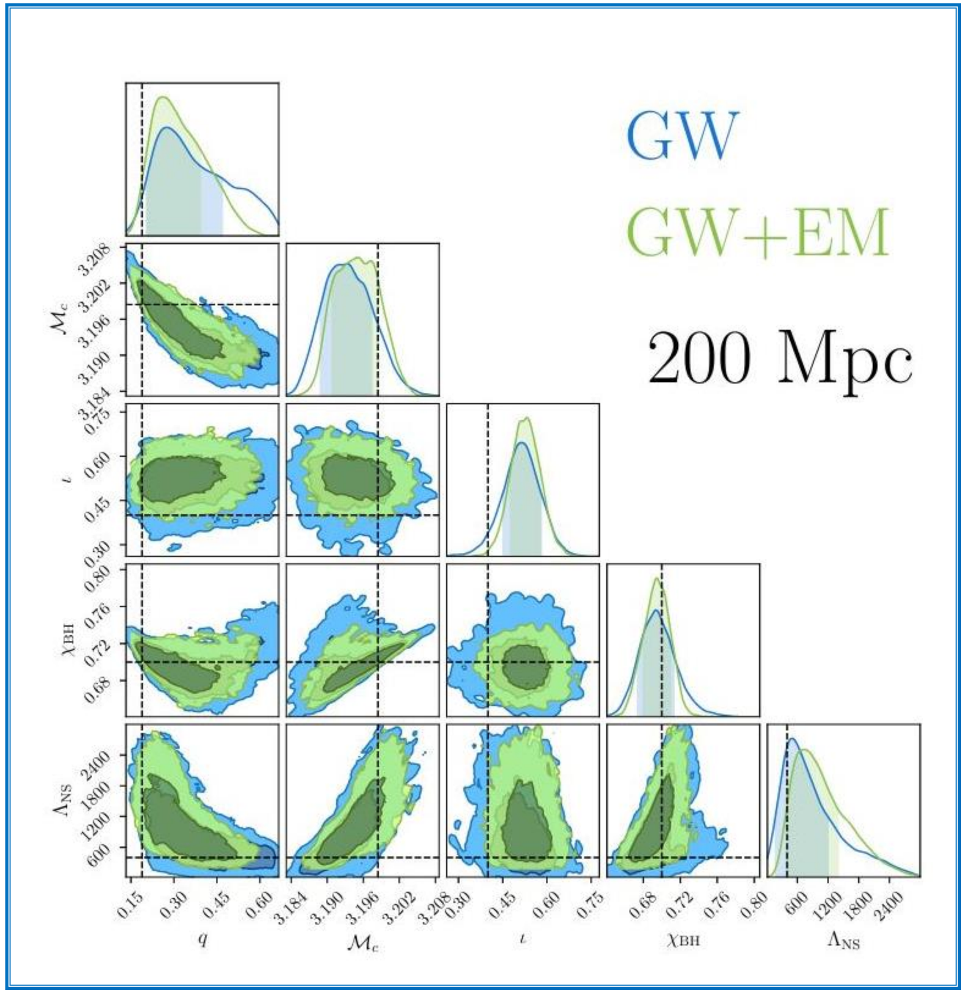

Fig. 2: Parameter estimation
(O.M. Boersma e J.van Leeuwen 2022)

Methods and Analysis : GW detection simulation

To simulate the detection we can use two different approaches:

- **Fisher Matrix** approach con **GWFish** (o GWFast): less precise but faster

We can build a dataframe with all the coalescence parameters and compute the SNR, parameters values and the corresponding errors for every event. We can study different network configurations of interferometers.

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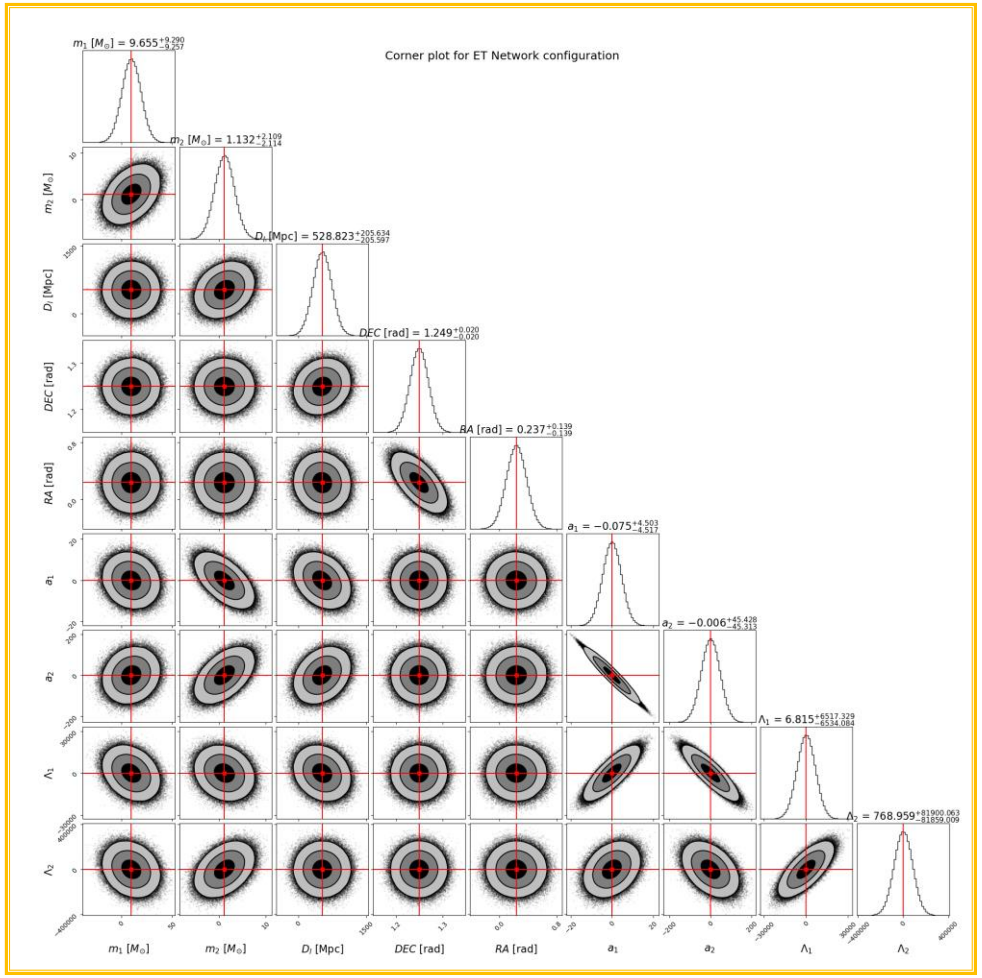


Fig. 3: Parameter estimation with GWFish.

Methods and Analysis : Mass remnant and kinetic energy model for GRB production

We need to choose the model in order to estimate the amount of mass in the accretion disk (M_{acc}) and the energy of the produced jet (E_k).

These models are built on complex relativistic magnetohydrodynamic simulations and their parameters are affected by big uncertainties.

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

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

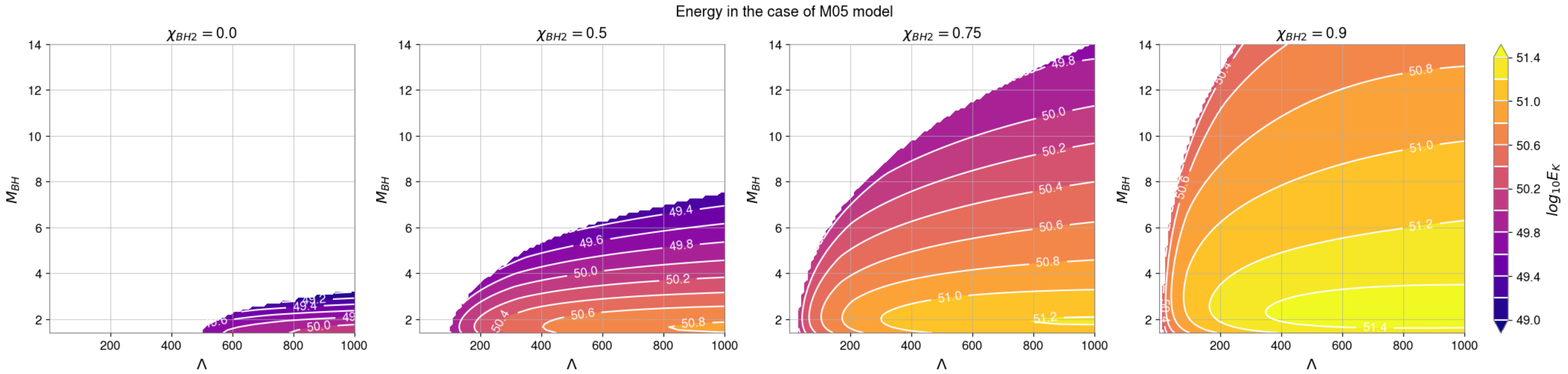
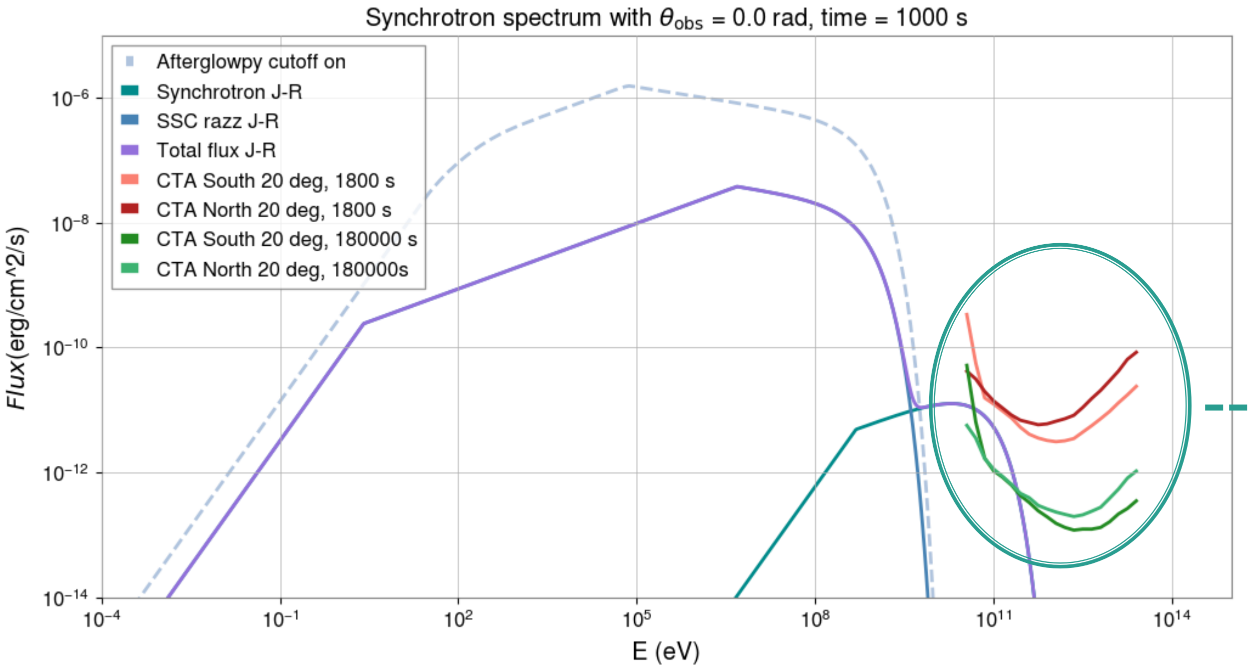


Fig. 4: Countour plots of kinetic Energy (E_k) in function of BH mass, spin a_{BH} and Λ.

4 Methods and Analysis : Very High energy afterglow evaluation

Using proper models or tools (Afterglowpy) we can study what happens at very high energies, in that band of the spectrum dominated by di Synchrotron Self Compton (SSC). We use Joshi-Razzaque model (2021)

Making a comparison from the expected flux with the sensitivity of the considered telescope in several configurations we can (roughly) estimate the detectability of a certain event with that instrument. In this work, we started considering CTAO, a Cherenkov telescope planned for the next decade, in the North and South configuration.



- $n_0 = 10^{-5} cm^{-3}$ (ISM density)
- $\epsilon_e = 0.2$ (e field density)
- $\epsilon_B = 0.02$ (magnetic density)
- $b = 6$ (power law index)
- $p = 2.3$ (electron energy index)
- $\theta_{core} = 0.05\, rad$

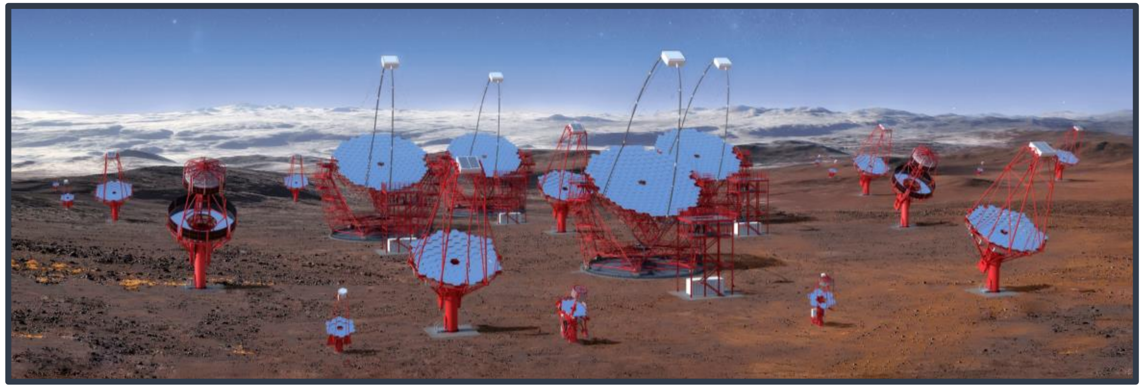


Fig. 5: CTAO picture of the planned configuration.

Methods and Analysis : Expected probability of detection for **NSBH** events

Einstein Telescope + CTAO

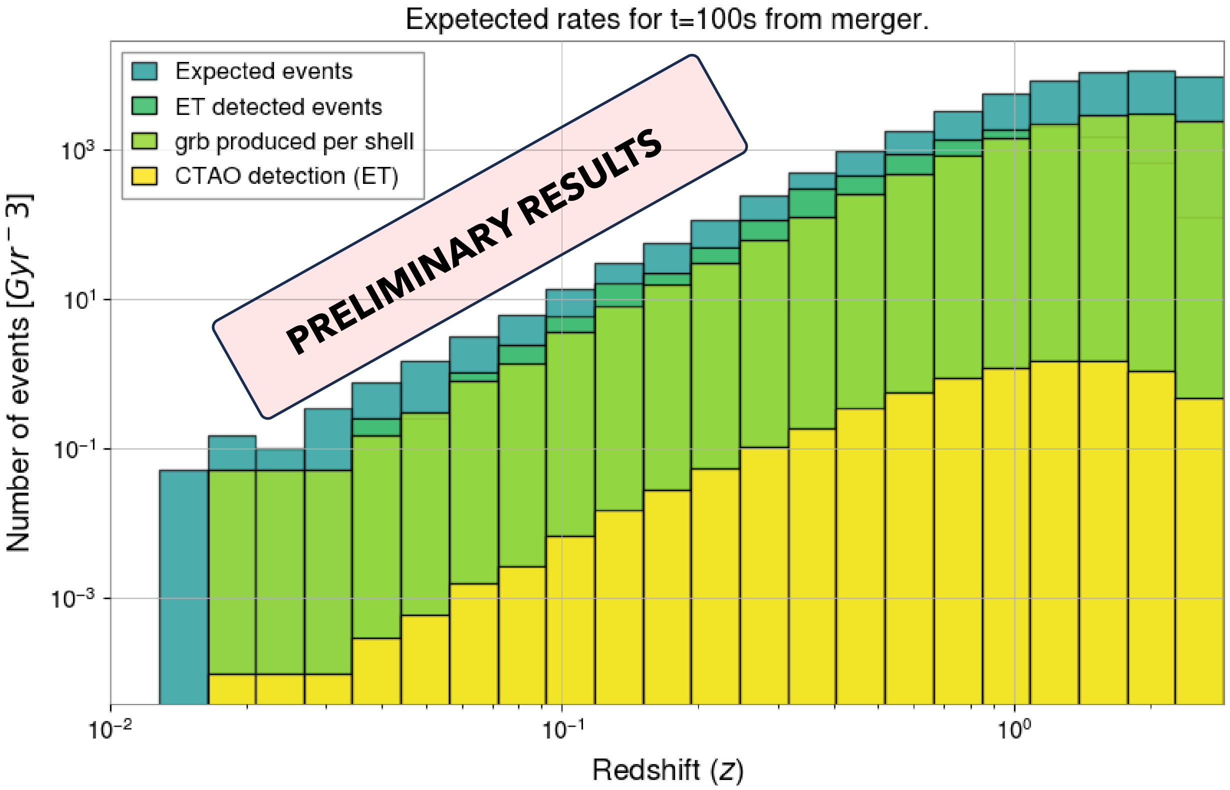


Fig. 6: Histogram of the expected events versus the number of NSBH events detected by ET, the number of GRB produced in every redshift (z) (up to z=2.7) and the number of possible detections with CTAO.

The number of possible detections with CTAO is very low, **Why?**

Possible reasons:

- The **model for the VHE** part of the flux is not the best one: higher flux
- The model used for **the number of expected events is too conservative**: we have more events (especially for low z)
- **Energy conversion** model too conservative

Methods and Analysis : Expected probability of detection for **NSBH** events

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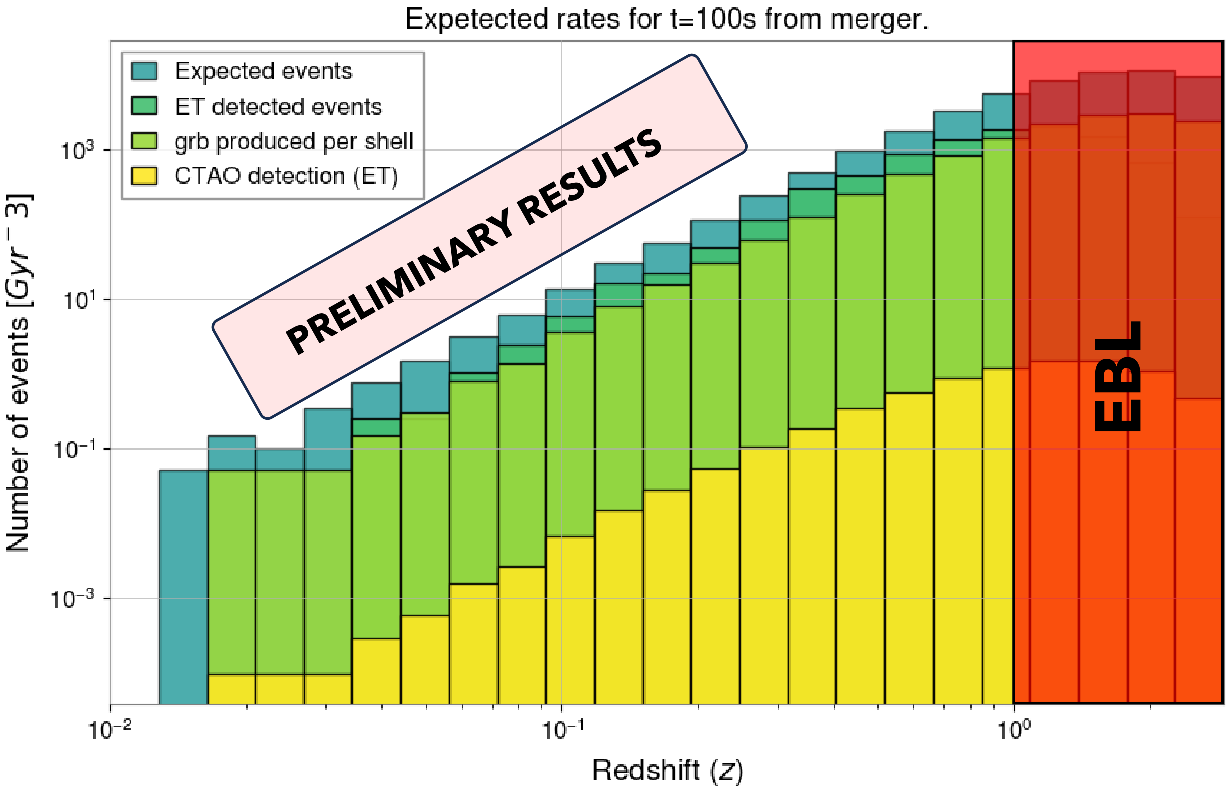

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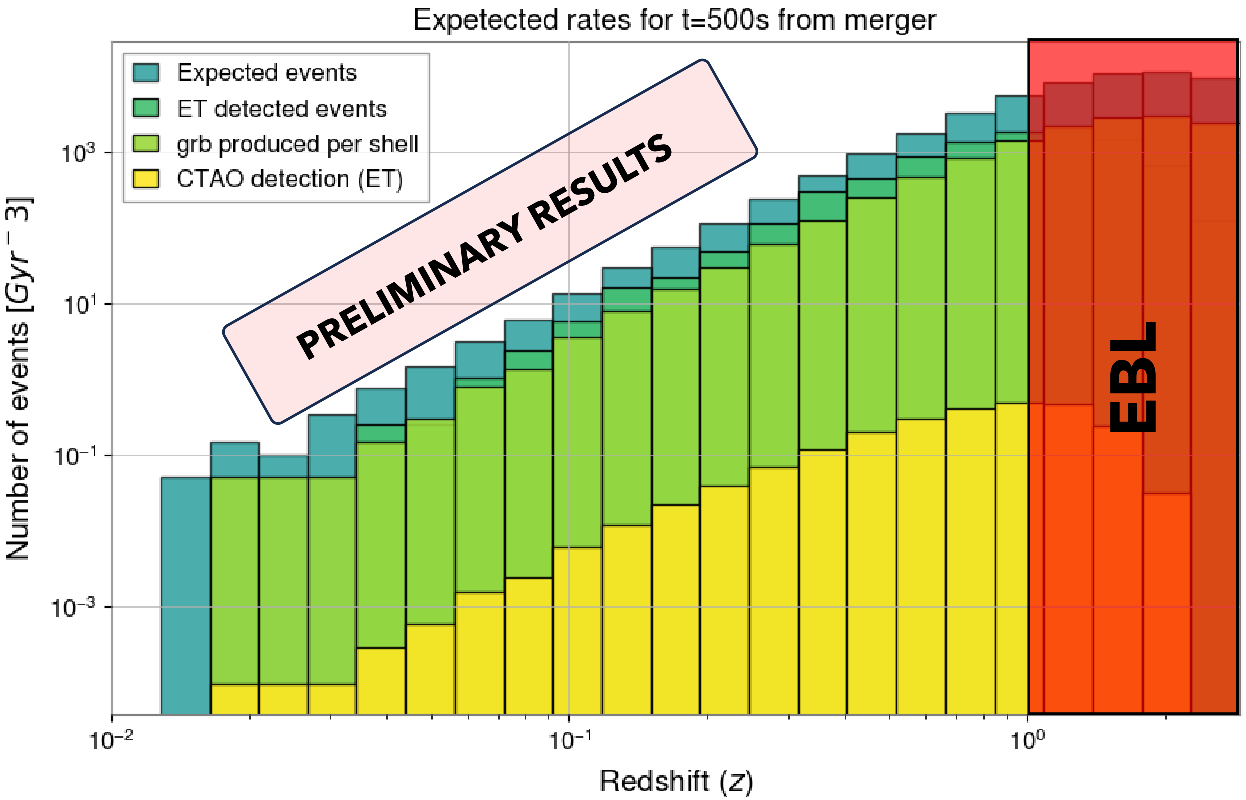

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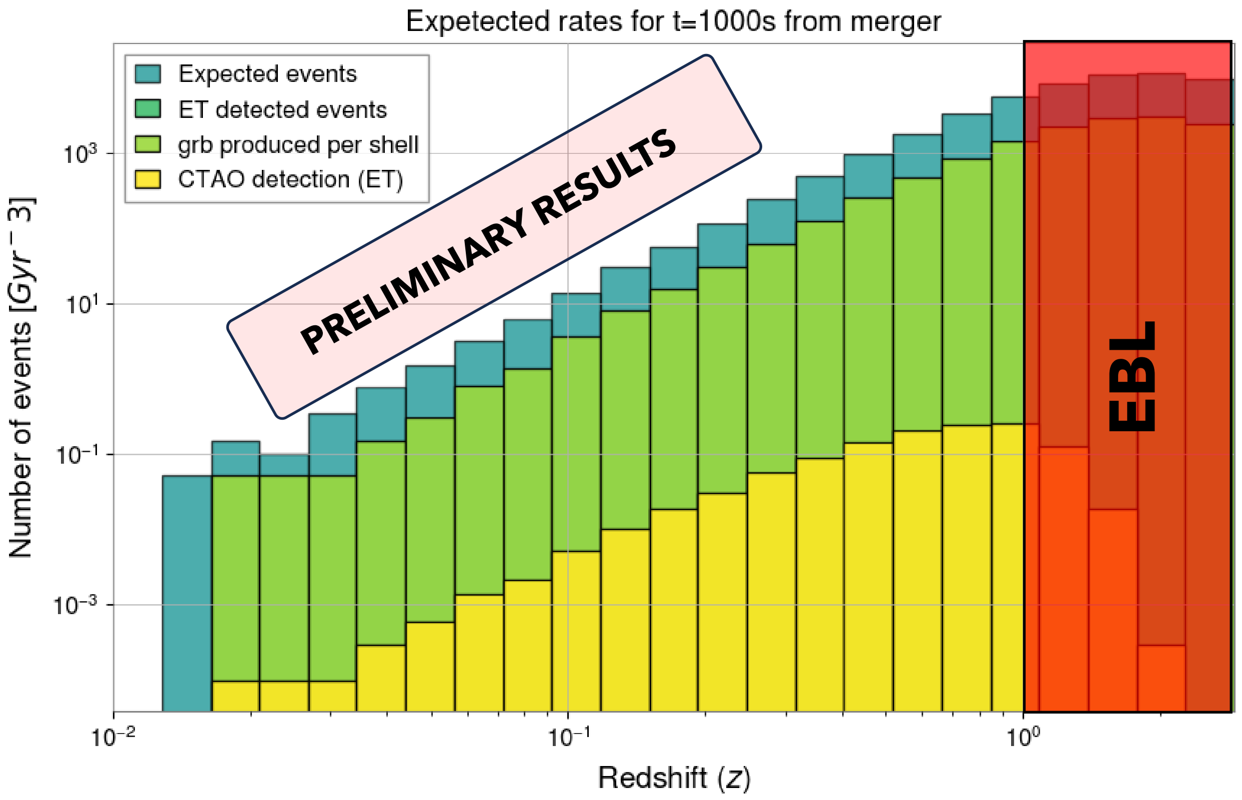

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Next Steps and Developments

→ Check for possible reasons in order to have better estimation of the **number of detectable events** with that multi messenger approach (CTAO + interferometers).

→ We are now working on **a numerical model** similar to the approach used by NAIMA code (not semi-analytical approach):

- We will have **more control** on expected spectrum and on the parameter space
- We expect a **bigger flux for IC** part of the spectrum
- We will use a more precise way to **handle the jet structure**

Next Steps and Developments

→ Study how results change considering **other instruments** expanding the energy range of interest.

CTAO (Cherenkov Telescope Array)

- It is sensible to the Cherenkov light produce by EM showers
- More than 60 telescopes, south and north emisphere, different scales
- Range: 20 GeV- 5 TeV

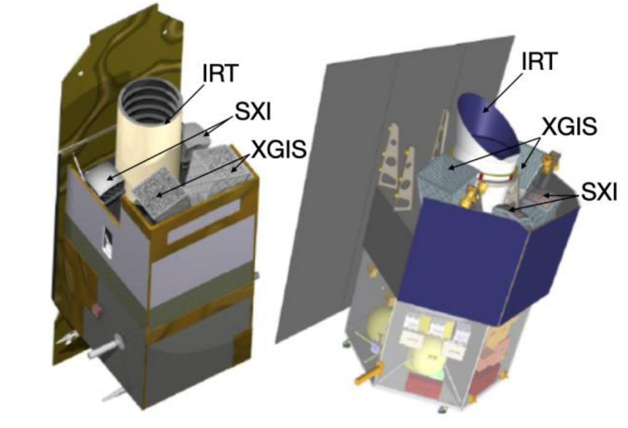
Fig. 7: https://www.to.infn.it/attivita-scientifica

Next Steps and Developments

⟶ Study how results change considering **other instruments** expanding the energy range of interest.

THESEUS (*Transient High Energy Sky and Early Universe Surveyor*)

- ESA telescope programmed to be launched in 2032
- Complete census of GRBs in the universe's first billion years, deep monitoring of cosmic X-ray transients
- Providing accurate triggers in real-time (~1′ in few seconds; ~1″ in few minutes)
- Range: 0.3 keV – 20 MeV



THESEUS Phase A industrial study configuration from ADS (left) and TAS (right)

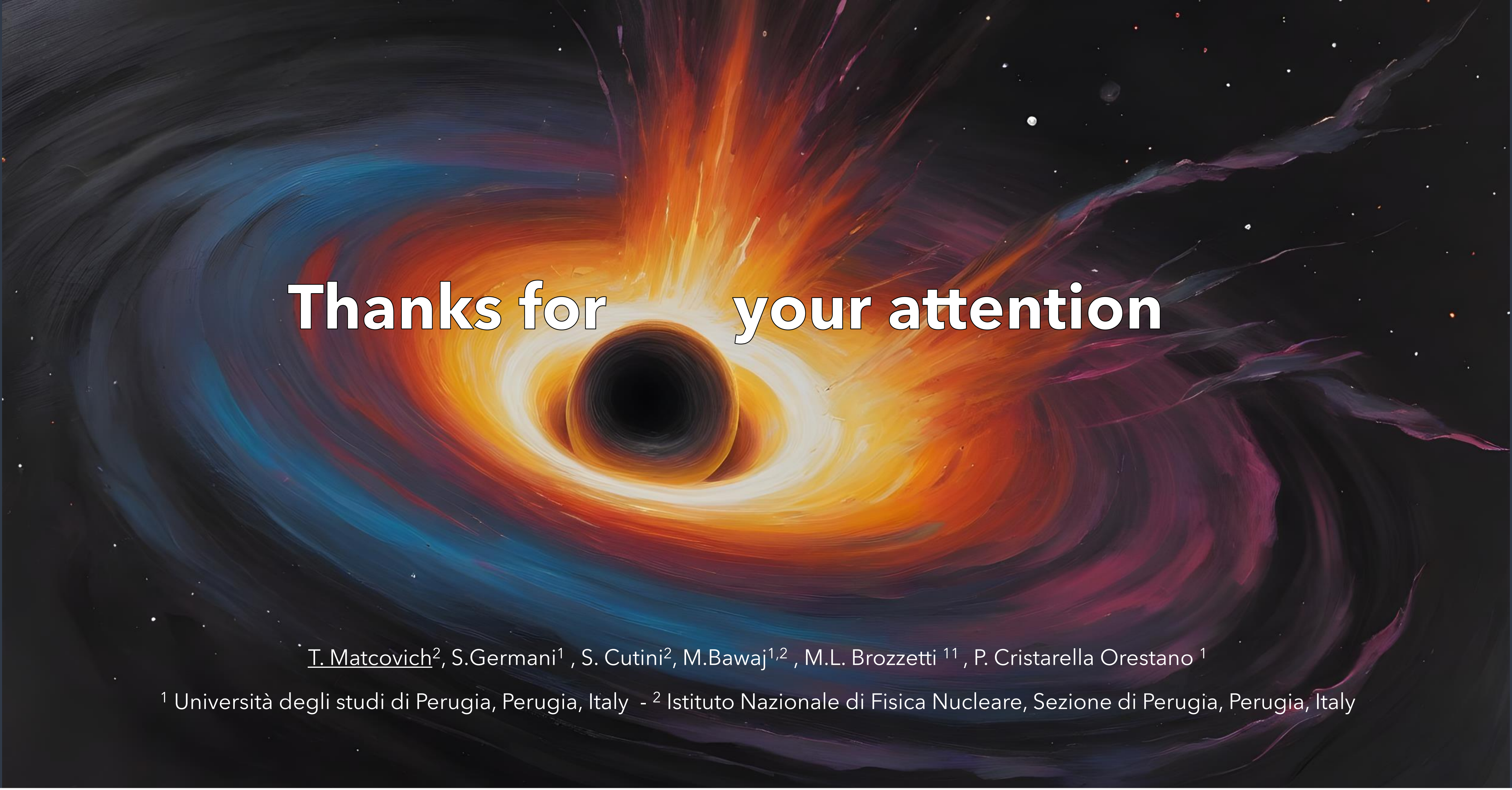
Fig 8: https://www.oas.inaf.it/it/progetti/theseus-it/

Next Steps and Developments

⟶ Study how results change considering **other instruments** expanding the energy range of interest.

Main open questions:

- How much these results depends on **fixed parameters** we used in selected models?
- How much the expected number of multi messenger events and the quality of the parameter estimation changes if we use **different models** (for the jet energy, for the merging rate …) ?



Thanks for your attention

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Future Outlook

1. Study the **optimal conditions** of observing for the selected telescopes

2. Study the **observational strategies** for considered telescopes for a faster and more efficient follow-up

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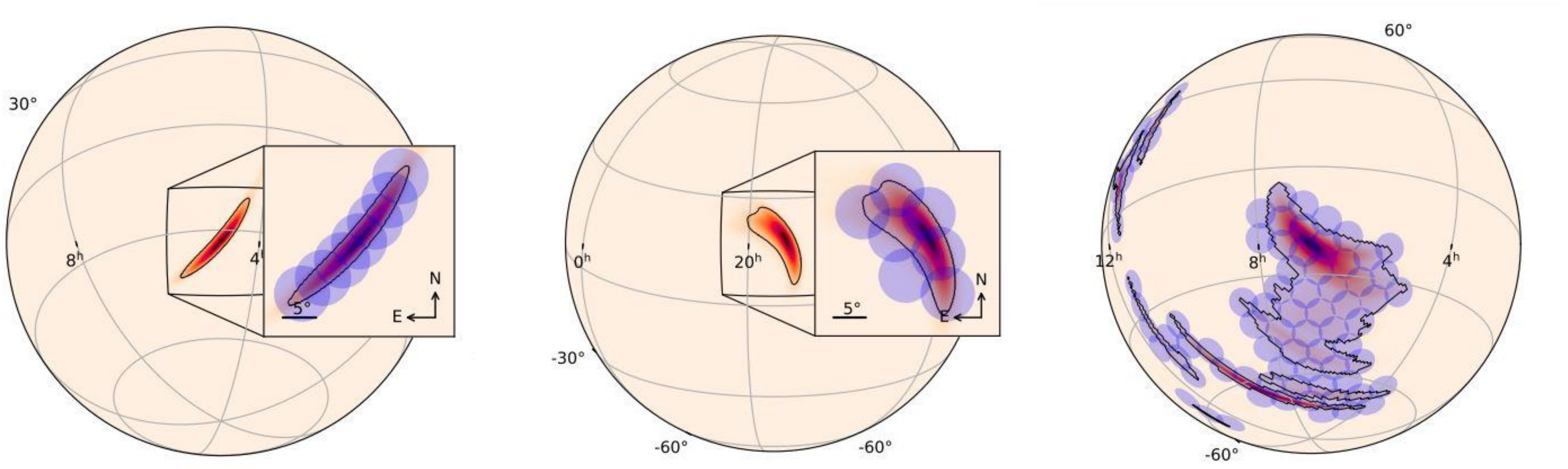

Fig. 5: Strategie osservative per CTAO (Bartos et al. 2019)

Future Outlook

1. Study the **optimal conditions** of observing for the selected telescopes.

2. Study the **observational strategies** for considered telescopes for a faster more efficient follow-up.

3. Make a precise comparison between **Bayesian** and **Fisher Matrix** approach.

4. Use upgraded and more precise **models** for the waveforms (precession)