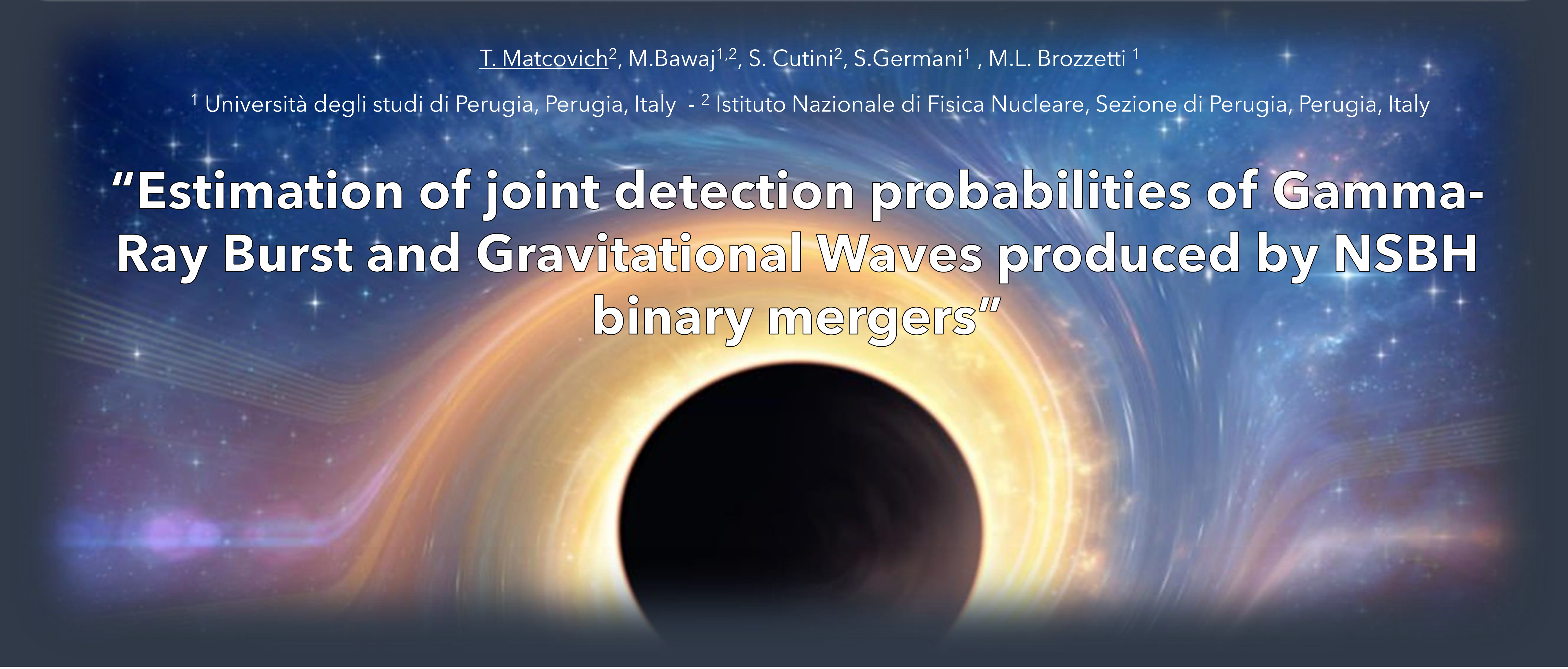


T. Matcovich[2], M.Bawaj[1,2], S. Cutini[2], S.Germani[1] , M.L. Brozzetti [1]

[1] Università degli studi di Perugia, Perugia, Italy - [2] Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Perugia, Italy

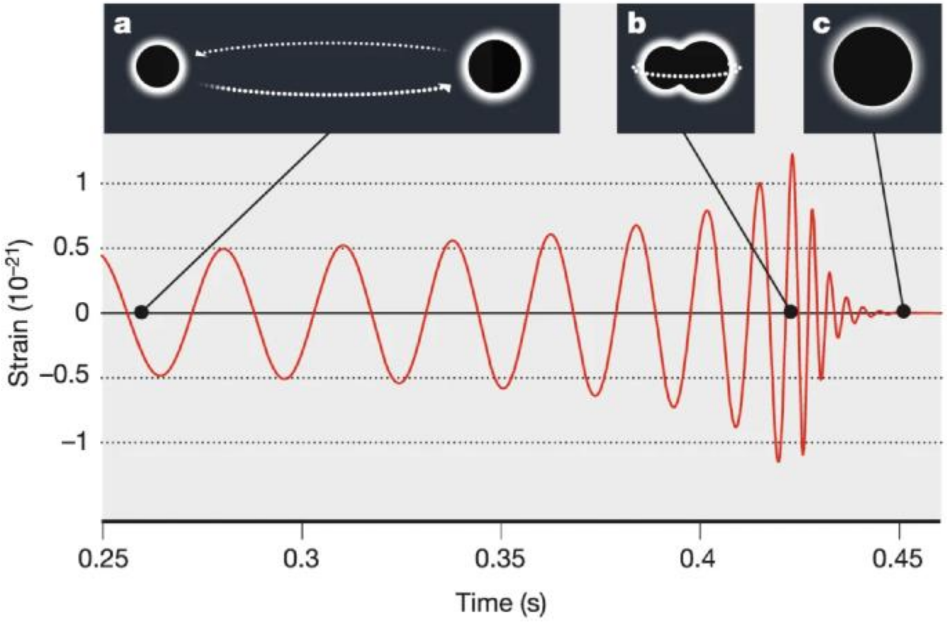
"Estimation of joint detection probabilities of Gamma-Ray Burst and Gravitational Waves produced by NSBH binary mergers"

Introduction:

Compact Binary objects Coalescence:

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

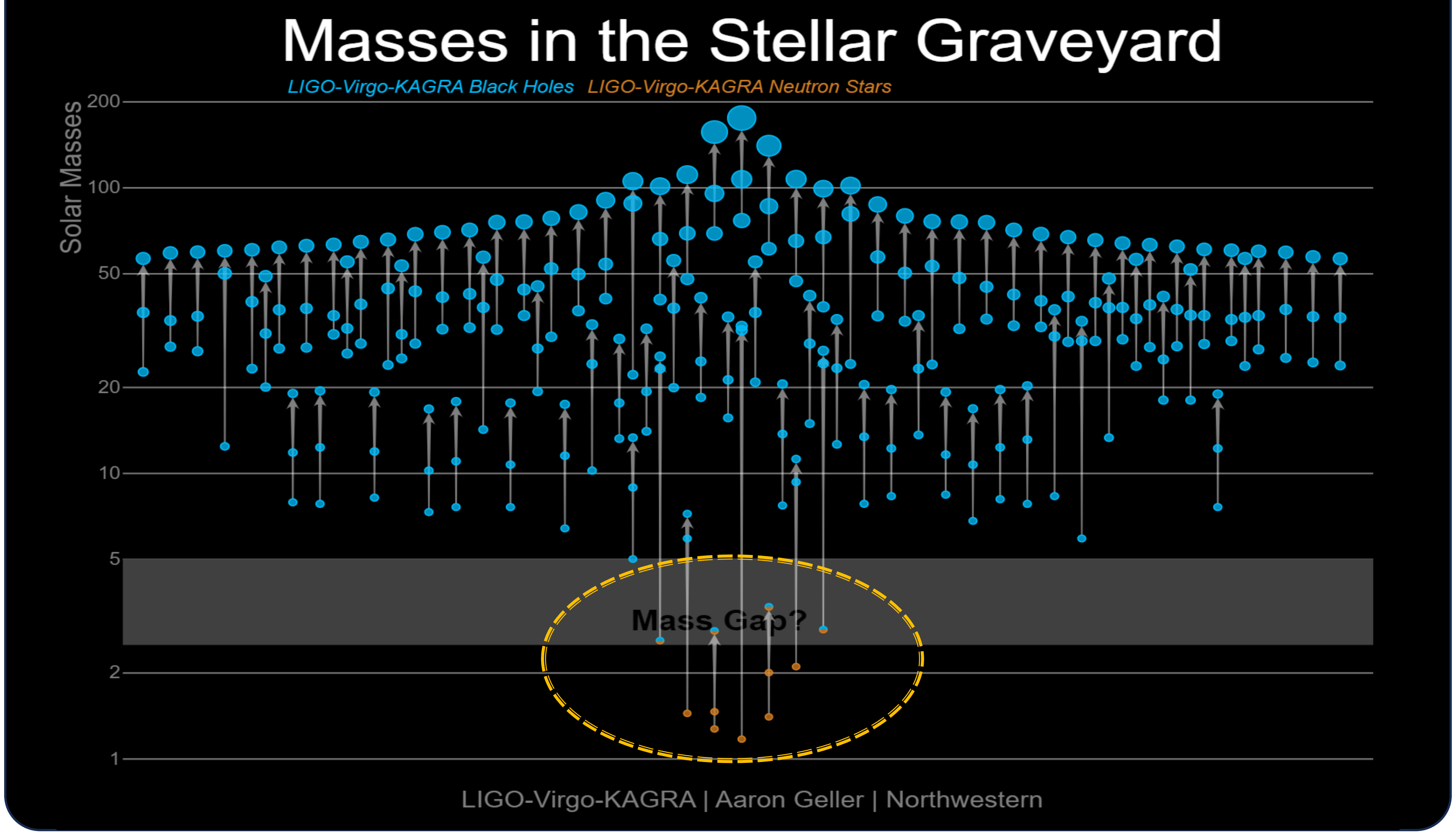
Disruptive binary mergers (**Tidal disruption**) → Why are weinterested? → Possible **EM counterpart**



1. **Formation** and **inspiral**
   - Trilions- 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:

Before O4 run



Simulations

↓

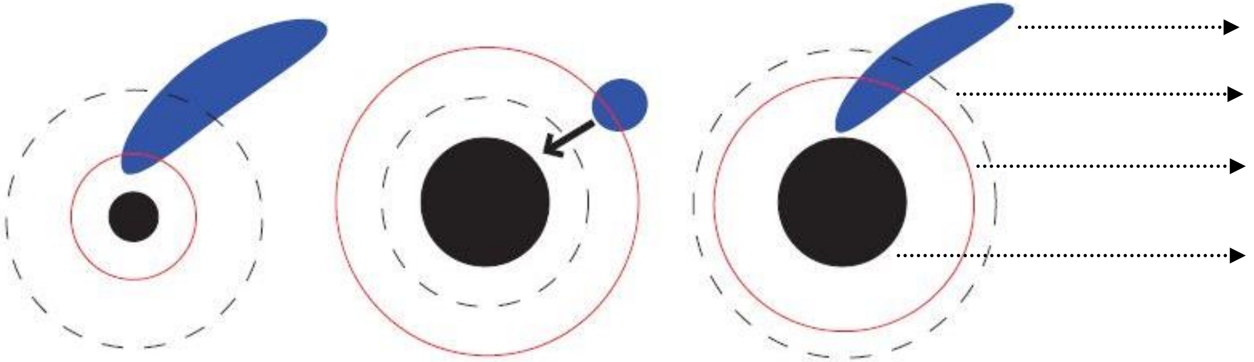
Expected events in the future

$Rivelatore$	$NS\text{-}BH$
$AdLIGO$	$1.2 - 9.3$
A+	3.2-26
ET + CE	2.4×10^3- 2.2×10^4

In O4 run

- 140 Events
- ~ 130 BBH
- ~ 6-8 NSBH

Introduction:



Tidal disruption

Plunge

Tidal disruption

Neutron Star

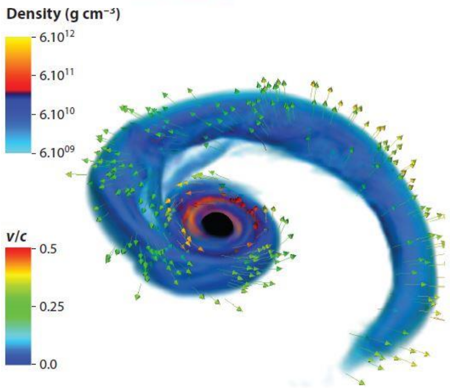
d_{tidal}

R_{ISCO}

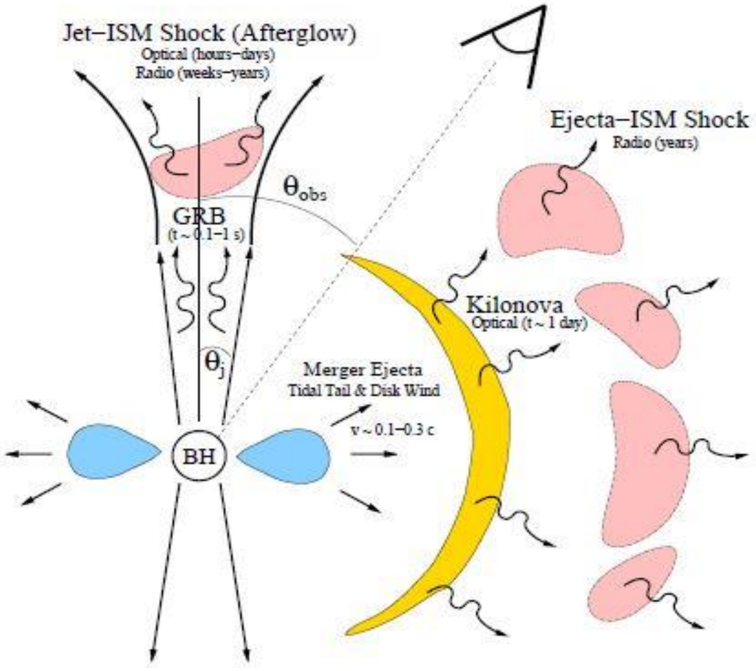
Black Hole (Event Horizon)

Spins

NS Equation of State (**EoS**) o λ



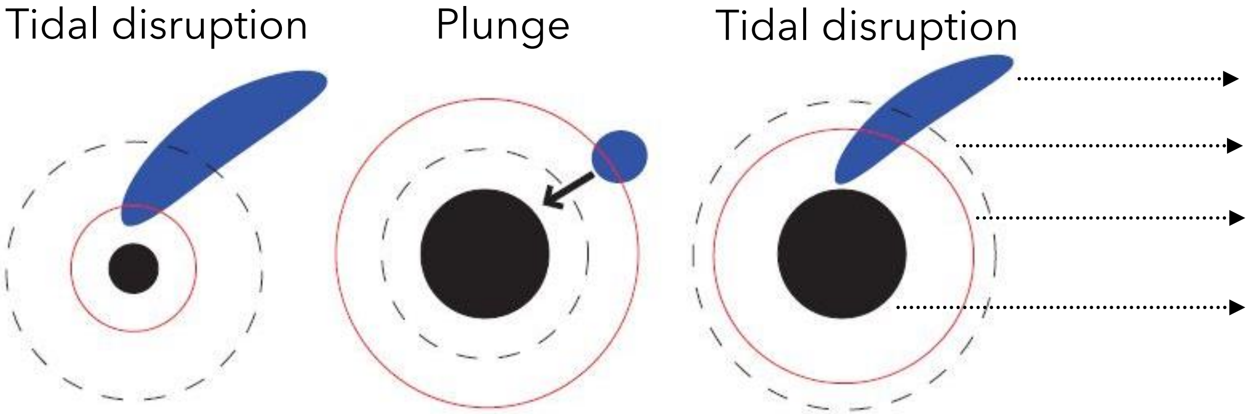
- Dynamical ejecta
- Wind ejecta
- Viscous ejecta
- Getto relativistico



Different emission for every component:

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

Introduction:



Neutron Star

d_{tidal}

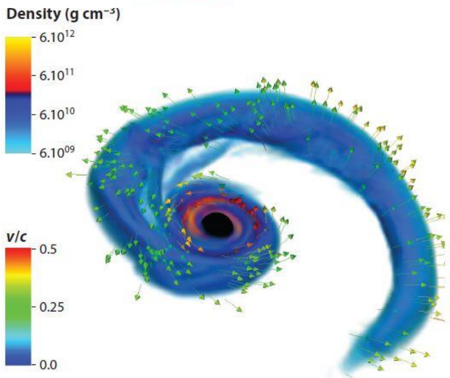
R_{ISCO}

Black Hole (Event Horizon)

Spins

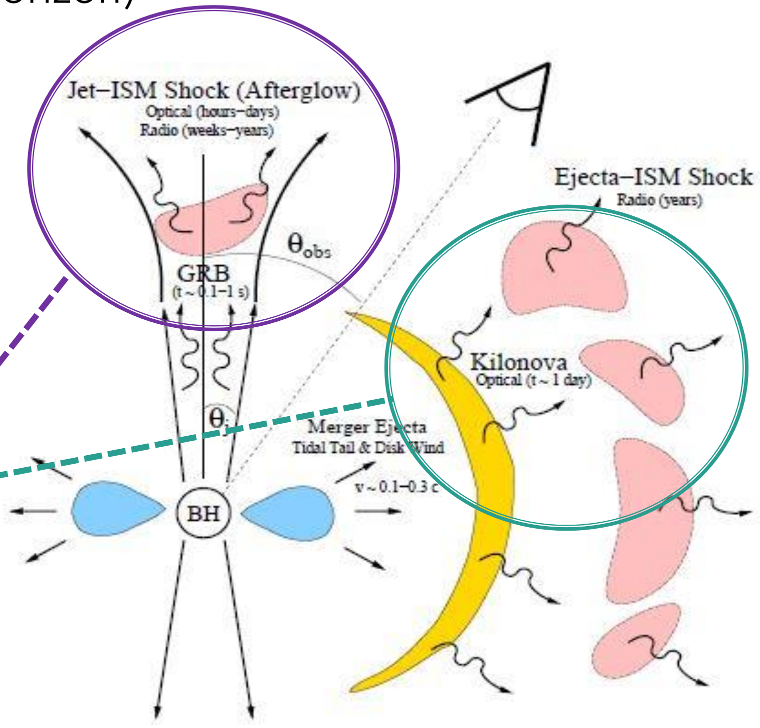
NS Equation of State (**EoS**) o λ

- Dynamical ejecta
- Wind ejecta
- Viscous ejecta
- Getto relativistico



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 **NSBH multimessenger** 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

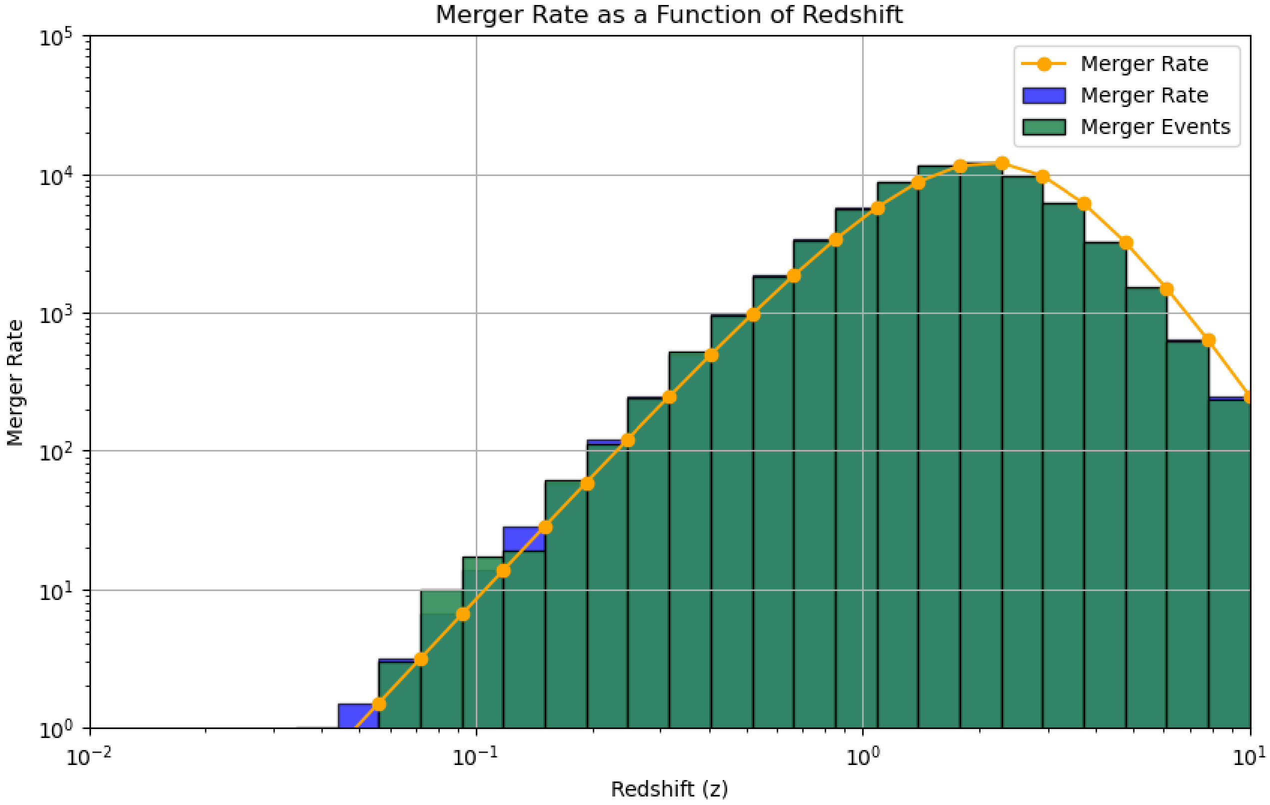


Fig. 1: Merger rate of NSBH merger events a as a function of redshift (z) vs the number of expected events in z shells.

2

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)

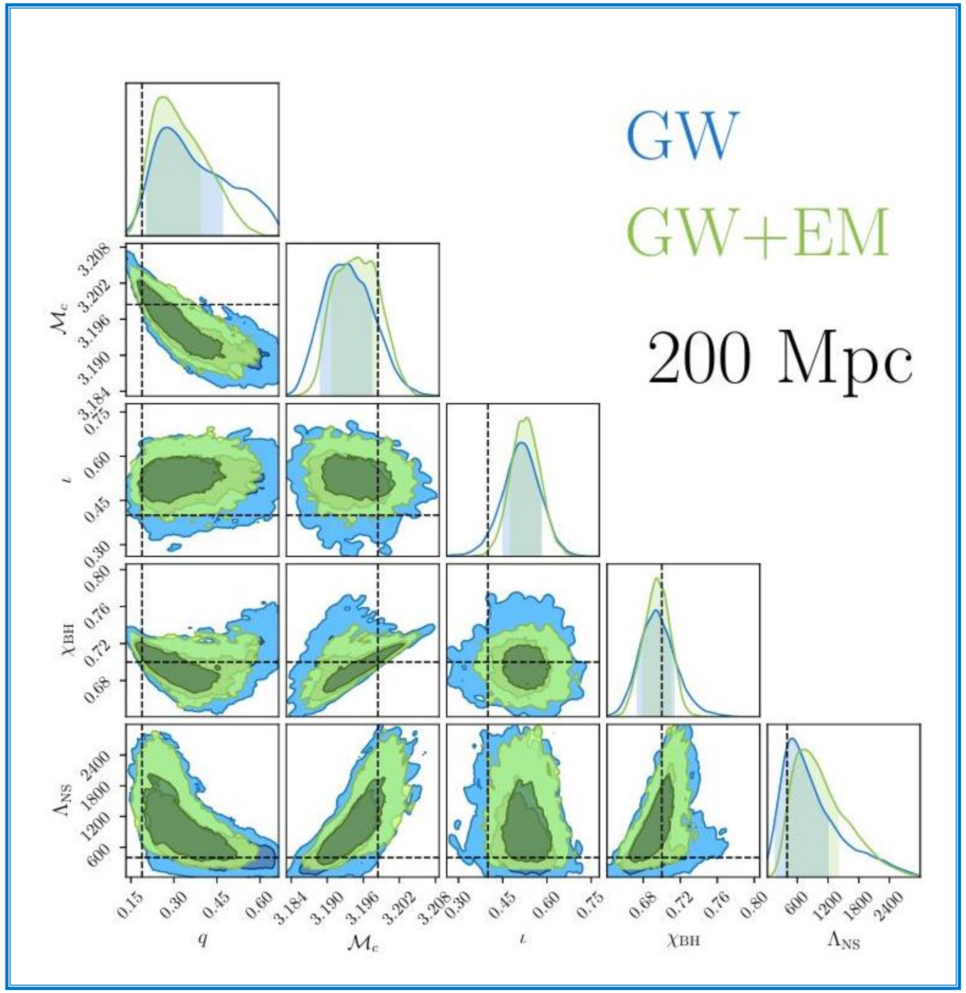


Fig. 2: Corner plot of the parameter estimation (O.M. Boersma e J.van Leeuwen 2022)

2

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.

- 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)

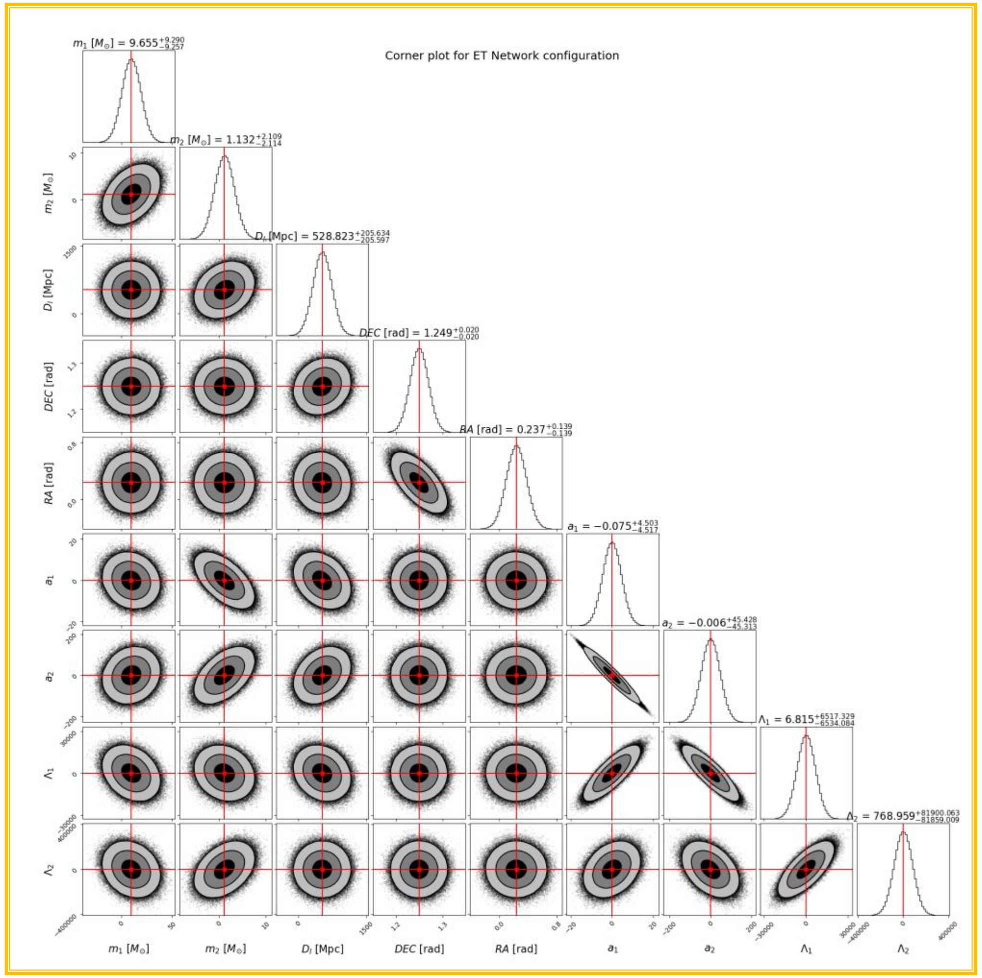


Fig. 3: Corner plot of della parameter estimation .

3 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 build 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

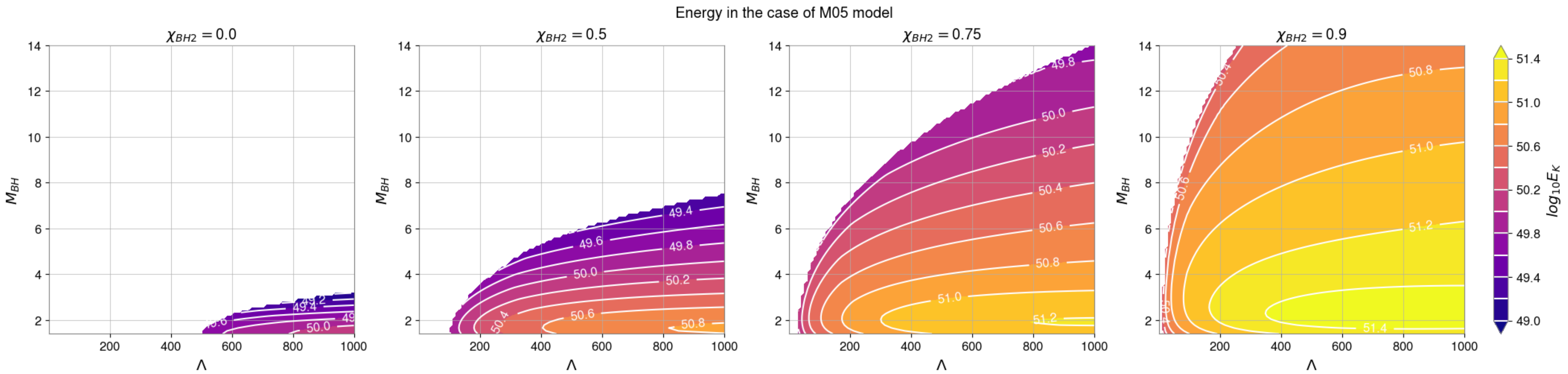
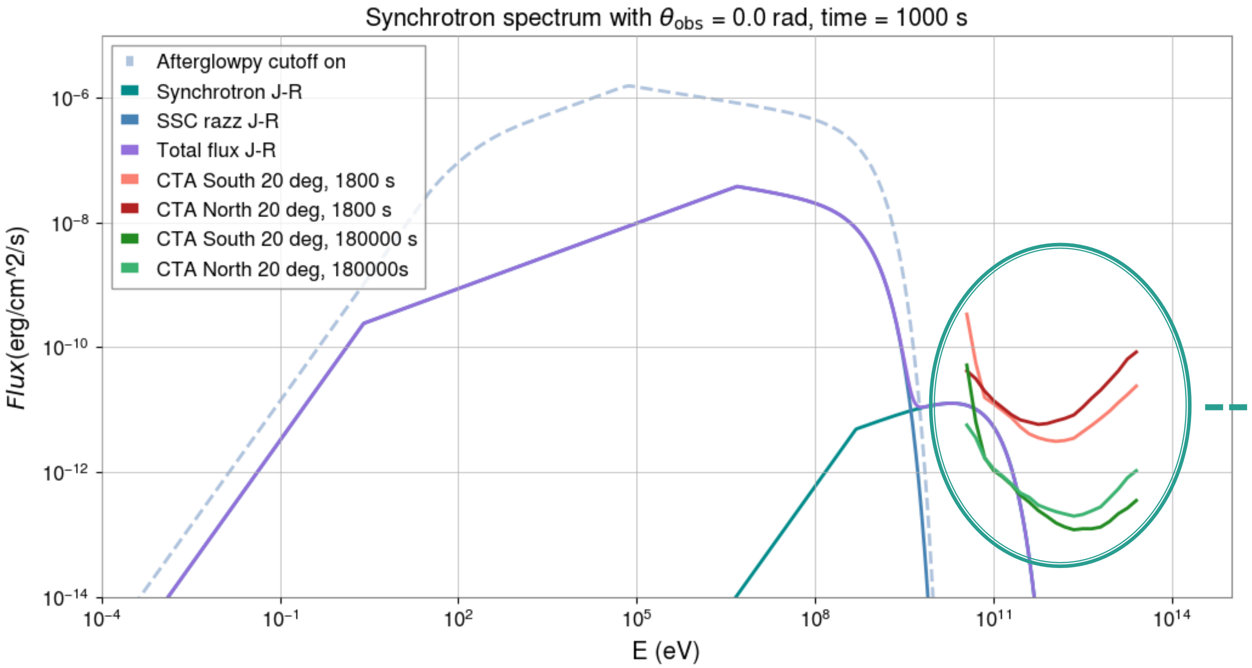


Fig. 4: Countour plots of kinetic Energy (E_k) in function of BH mass, spin a_{BH} and Λ.

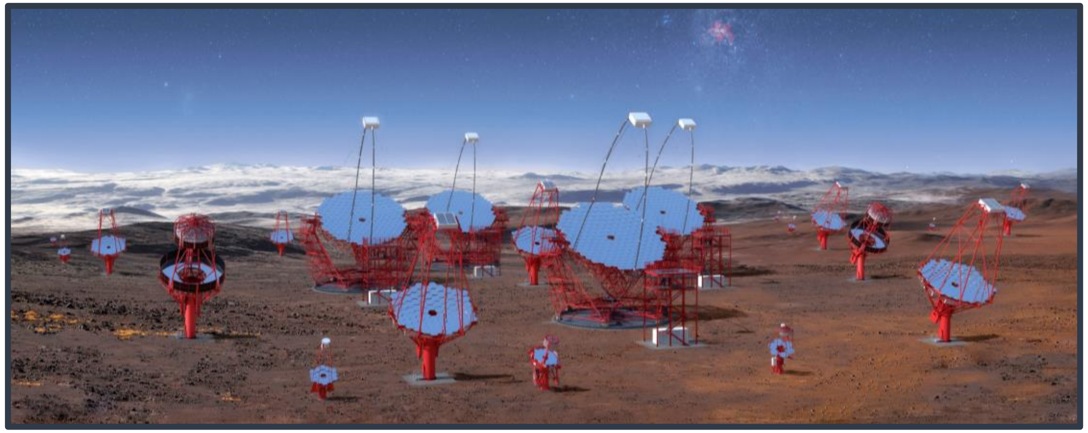
4 Methods and analysis : Very High energy afterglow evaluation

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).

Making a comparison from the expected flux with the sensitivity of the considered telescope in several configurations we can 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.

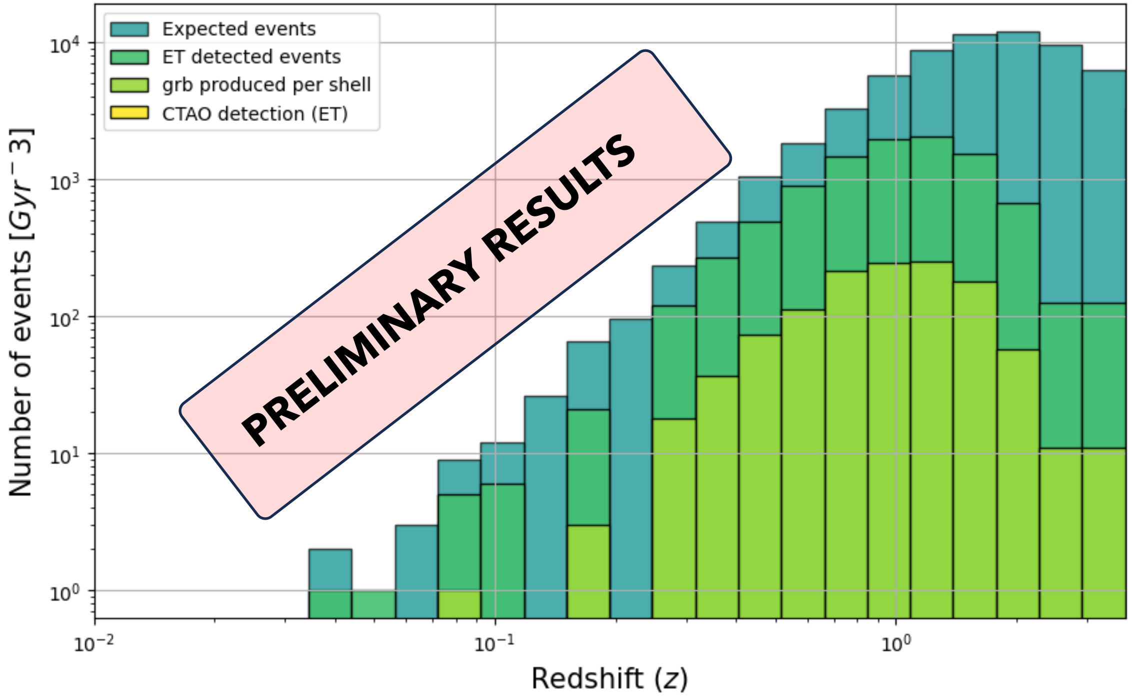


- $n_0 = 10^{-5} cm^{-3}$ (density)
- $\epsilon_e = 0.2$ (e field density)
- $\epsilon_B = 0.01$ (magnetic density)
- $b = 6$ (power law index)
- $p = 2.3$ (electron energy index)
- $\theta_{core} = 0.05\, rad$

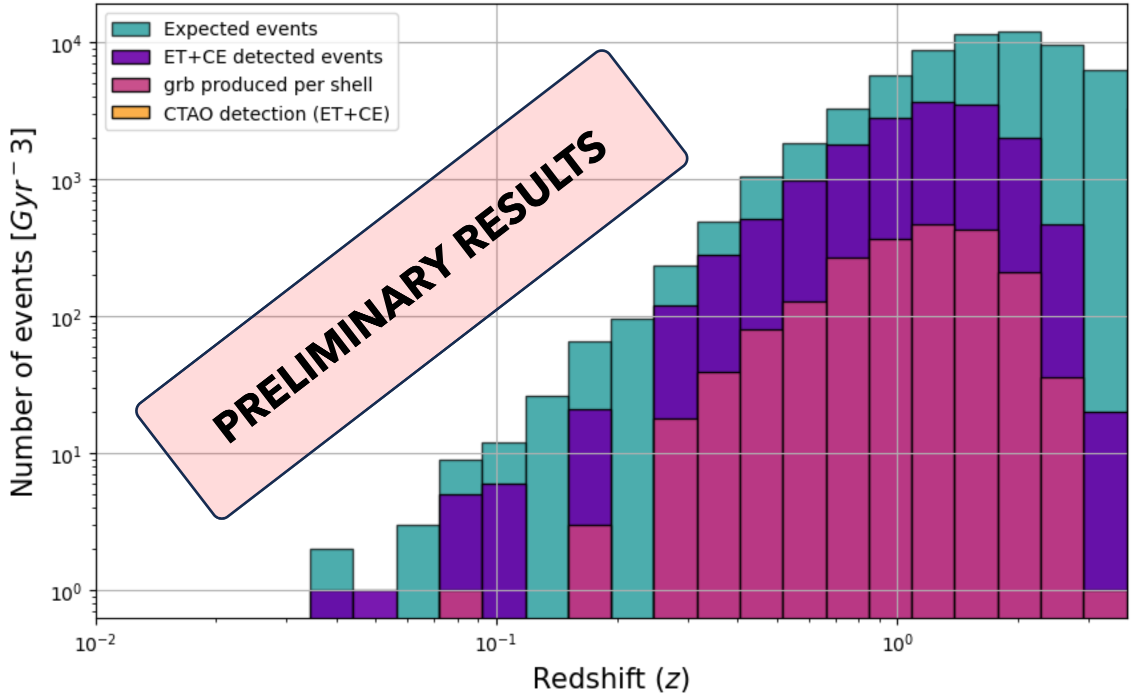


4 Methods and analysis : Expected probability of detection for **NSBH** events

ET



ET + Cosmic Explorer



ERRORS? BUGS?

Next steps and developments

→ Make a better estimation of the **number of detectable events** with that multimessenger approach (CTAO + interferometers) with respect to the total amount of events.

→ Study how results change considering **other instruments**.

Next steps and developments

→ Make a better estimation of the **number of detectable events** with that multimessenger approach (CTAO + interferometers) with respect to the total amount of events.

→ Study how results change considering **other instruments**.

CTA (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. 5: https://www.to.infn.it/attivita-scientifica

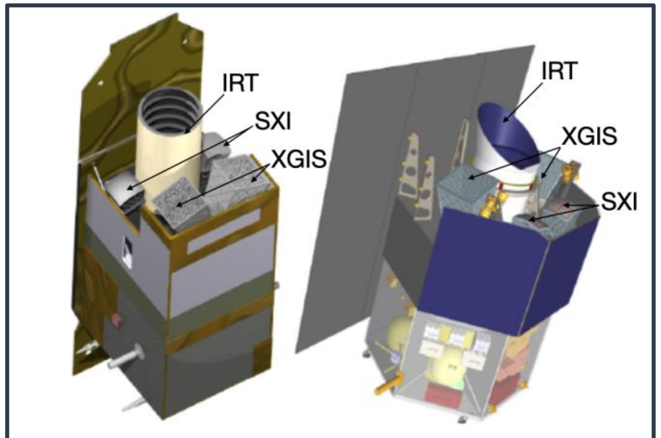
Next steps and developments

→ Make a better estimation of the **number of detectable events** with that multimessenger approach (CTAO + interferometers) with respect to the total amount of events.

→ Study how results change considering **other instruments**.

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 pochi secondi; ~1″ in pochi minuti)
- Range: 0.3 keV – 20 MeV



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

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

Next steps and developments

→ Make a better estimation of the **number of detectable events** with that multimessenger approach (CTAO + interferometers) with respect to the total amount of events.

→ Study how results change considering **other instruments**.

Main open questions:

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

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

Future outlook

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

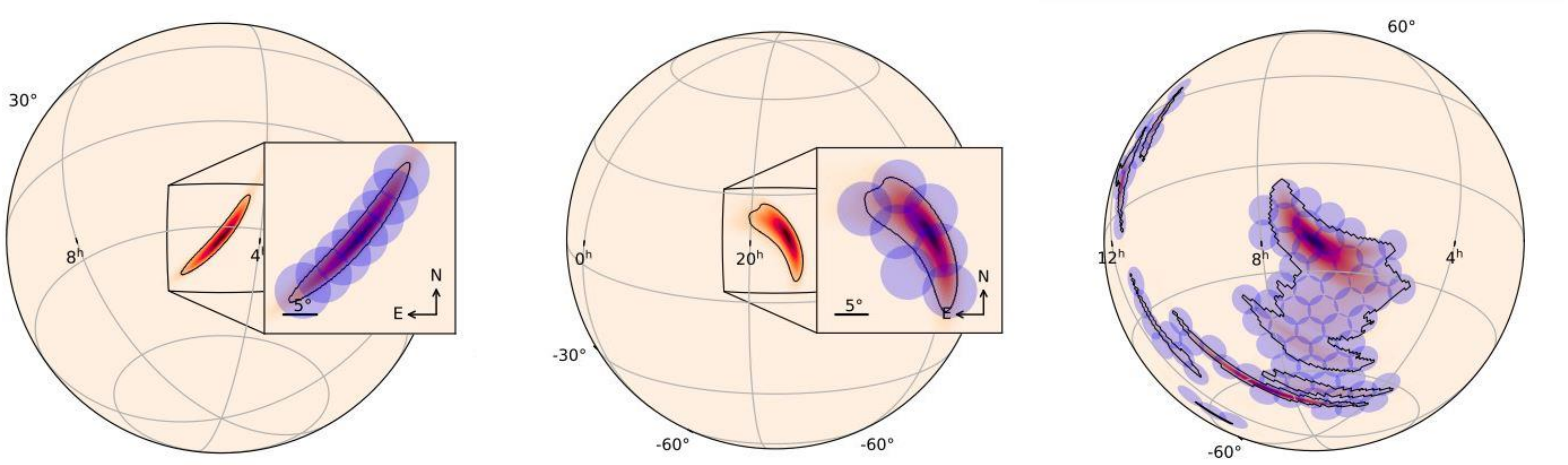


Fig. 5: Strategie osservative per CTAO (Bartos et al. 2019)

Future outlook

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

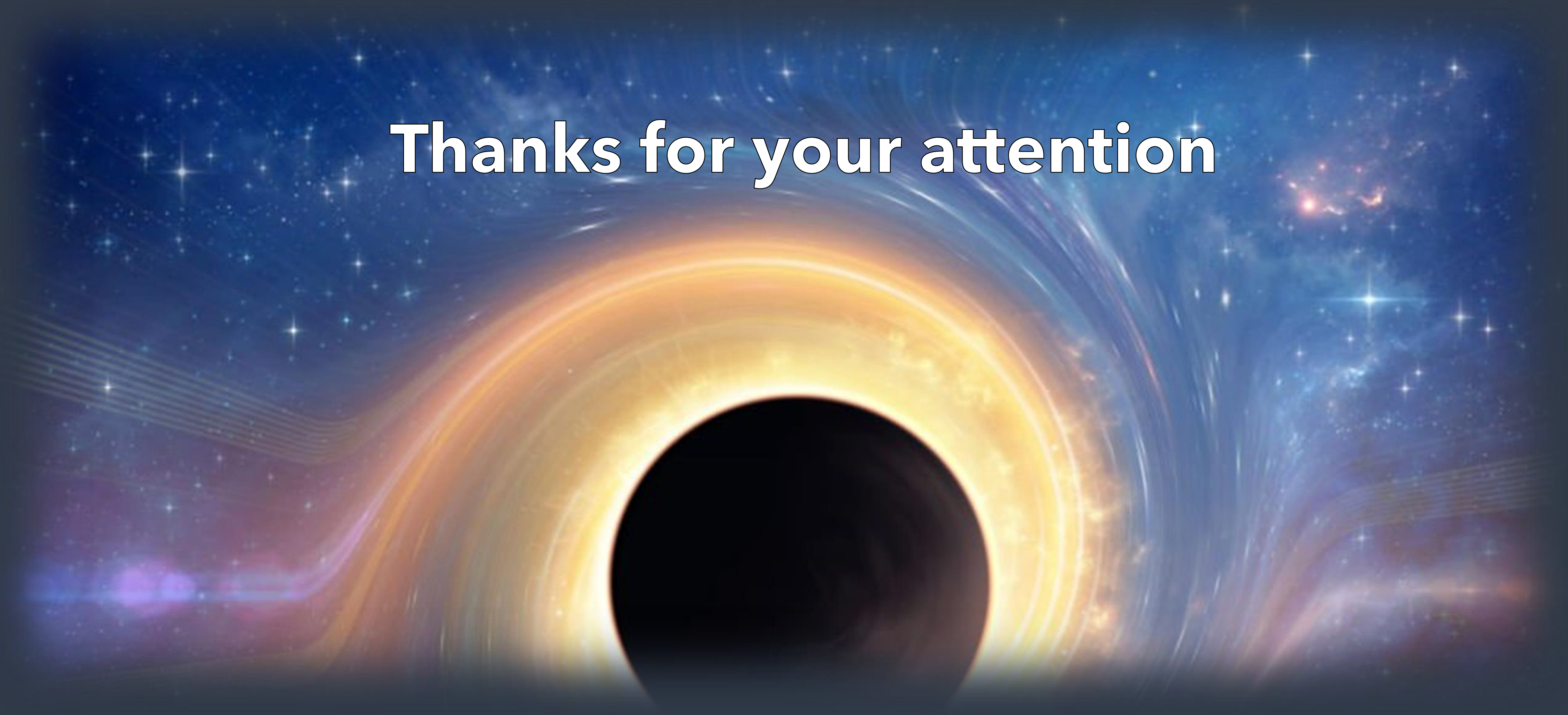
2. Study the **observational strategies** for considered telescopes for a faster more efficient follow-up.

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

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

T. Matcovich[2], M.Bawaj[1,2], S. Cutini[2], S.Germani[1] , M.L. Brozzetti [1]

[1] Università degli studi di Perugia, Perugia, Italy - [2] Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Perugia, Italy



Thanks for your attention