Estimation of detection probabilities of Gamma-Ray Burst and Gravitational Waves multimessenger events produced by disruptive binary mergers

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Presentation outline

Introduction

Introduction to the topic and motivation for the study

Disruptive binary mergers

- Disruptive binary mergers events description
- Detected events
- EM instruments

Parameters and models

Space parameter evaluation

Spectrums

- Afterglow spectrums model
- Comparison with instruments sensitivity

Detectability

Detectabilty evaluation in function of the parameters

Conclusions

Results and final considerations

Introduction : context and objectives

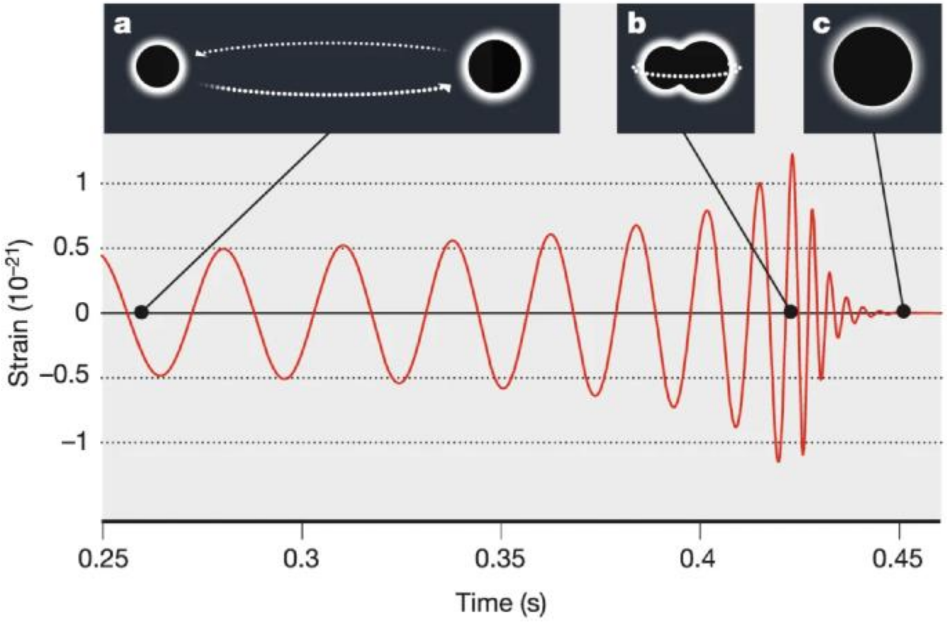
- GW150914 First detected GW event
- **GW170817** + **GRB170817A** First multimessenger detected event
- Only few events, we need to study these events in preparation for future detections
- **Future detections** (LIGO-Virgo-Kagra interferometers)
- **Future instruments**: Einstein Telescope, LISA

- **Models** study
- Gravitational **data analysis**
- Estimate the **electromagnetic counterpart** of the coalescence
- Estimation of the events **detectability**

Compact binary objects coalescence (CBC)

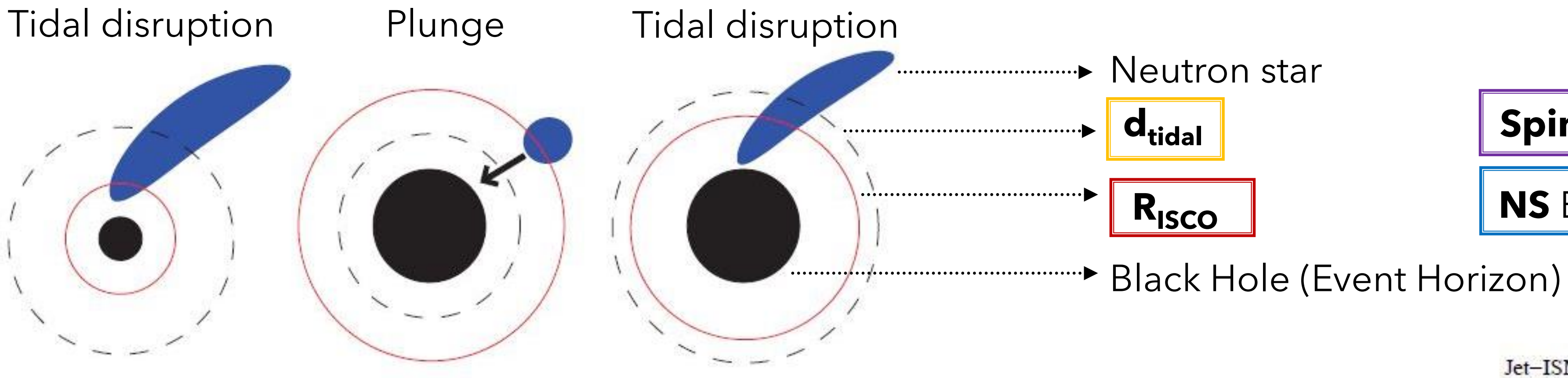
- Binary Black Hole (BBH)
- Binary Neutron Star (BNS)
- Neutron Star – Black Hole (**NS-BH**)

Distruptive binary mergers (**Tidal disruption**) → why are we interested? → Possible **EM counterpart**



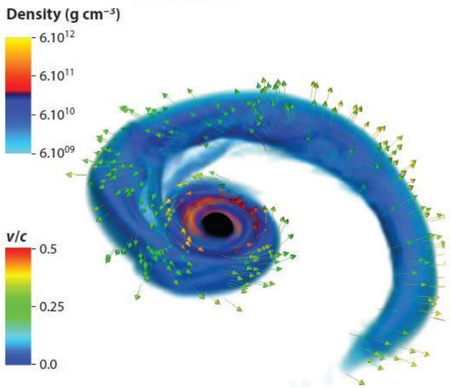
- **Formation** and **inspiral** — Billion-million years; Energy loss by GW emission
- **Merging** phase — lasts ~ ms; The two objects merges
- **Ringdown** and post-merger phase — lasts ~ seconds; Final object creation and emissions

NS-BH events: merging and EM emission

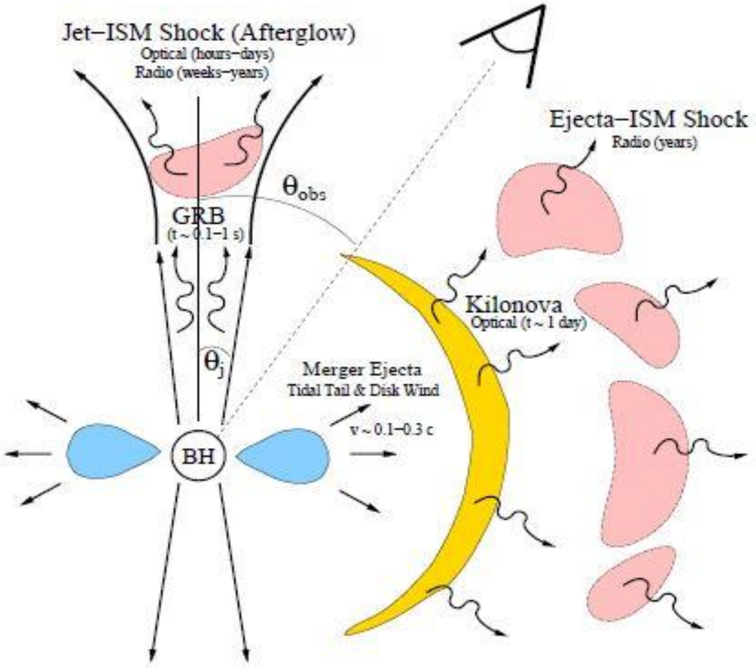


Spins

NS Equation of State (**EoS**) o λ



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

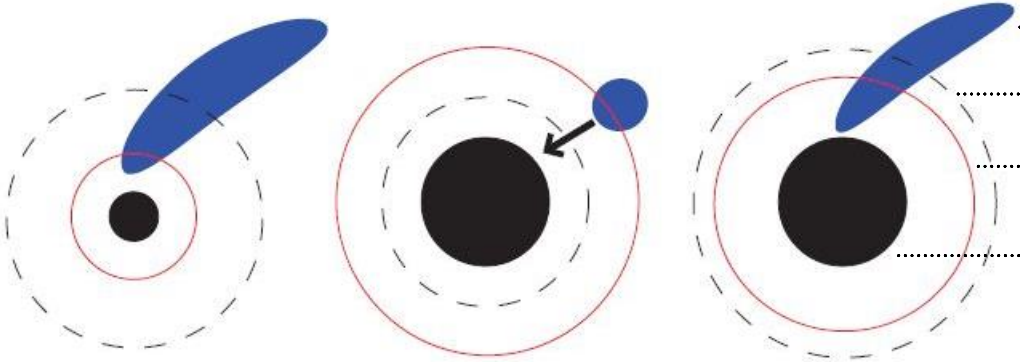


To these components corresponds different EM emissions:

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

NS-BH events: merging and EM emission

Tidal disruption | Plunge | Tidal disruption



Neutron star

d_{tidal}

R_{ISCO}

Black Hole (Event Horizon)

Spins

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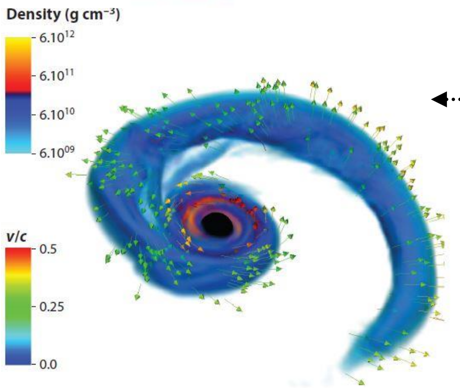

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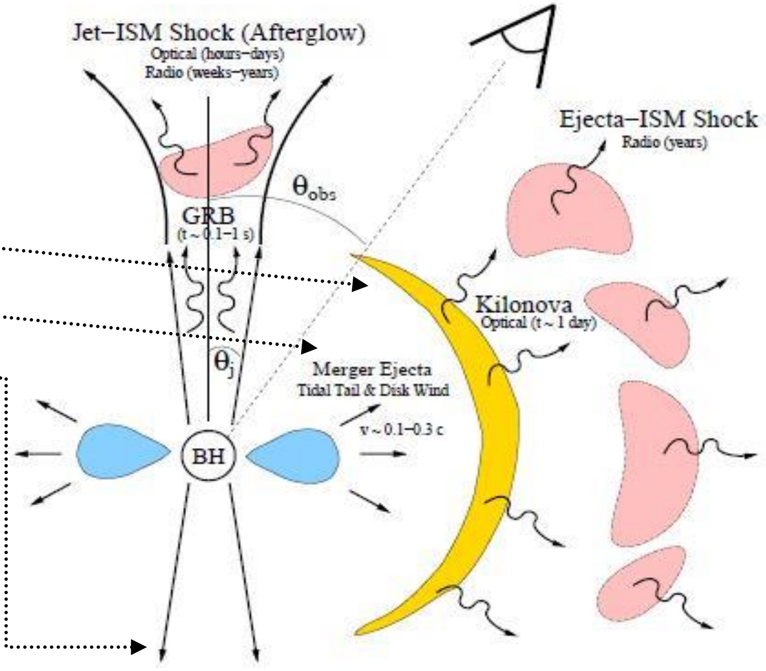

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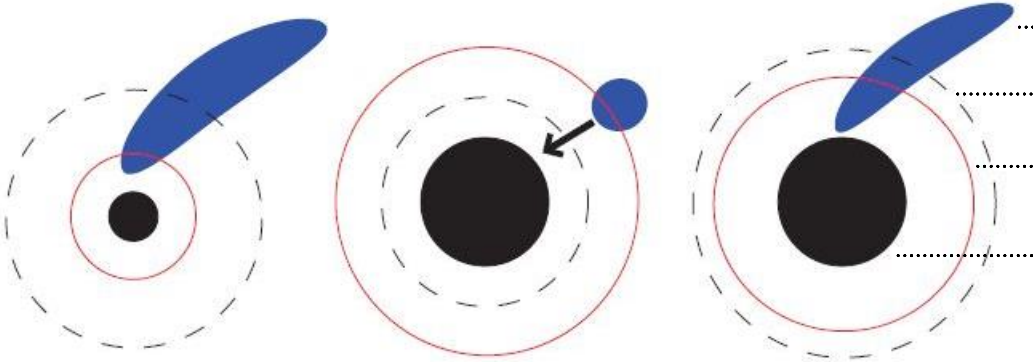

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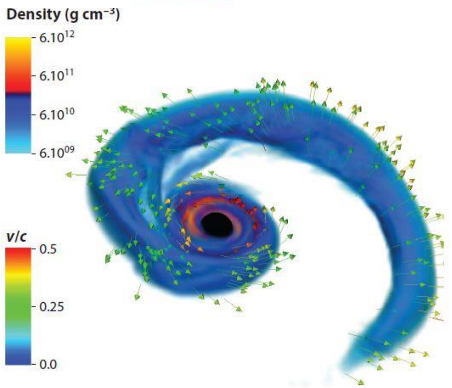

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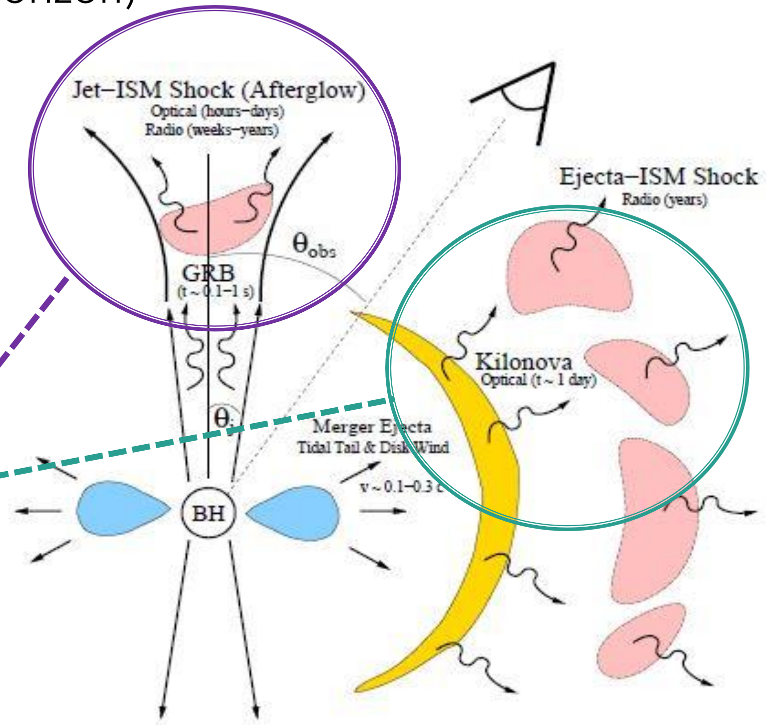

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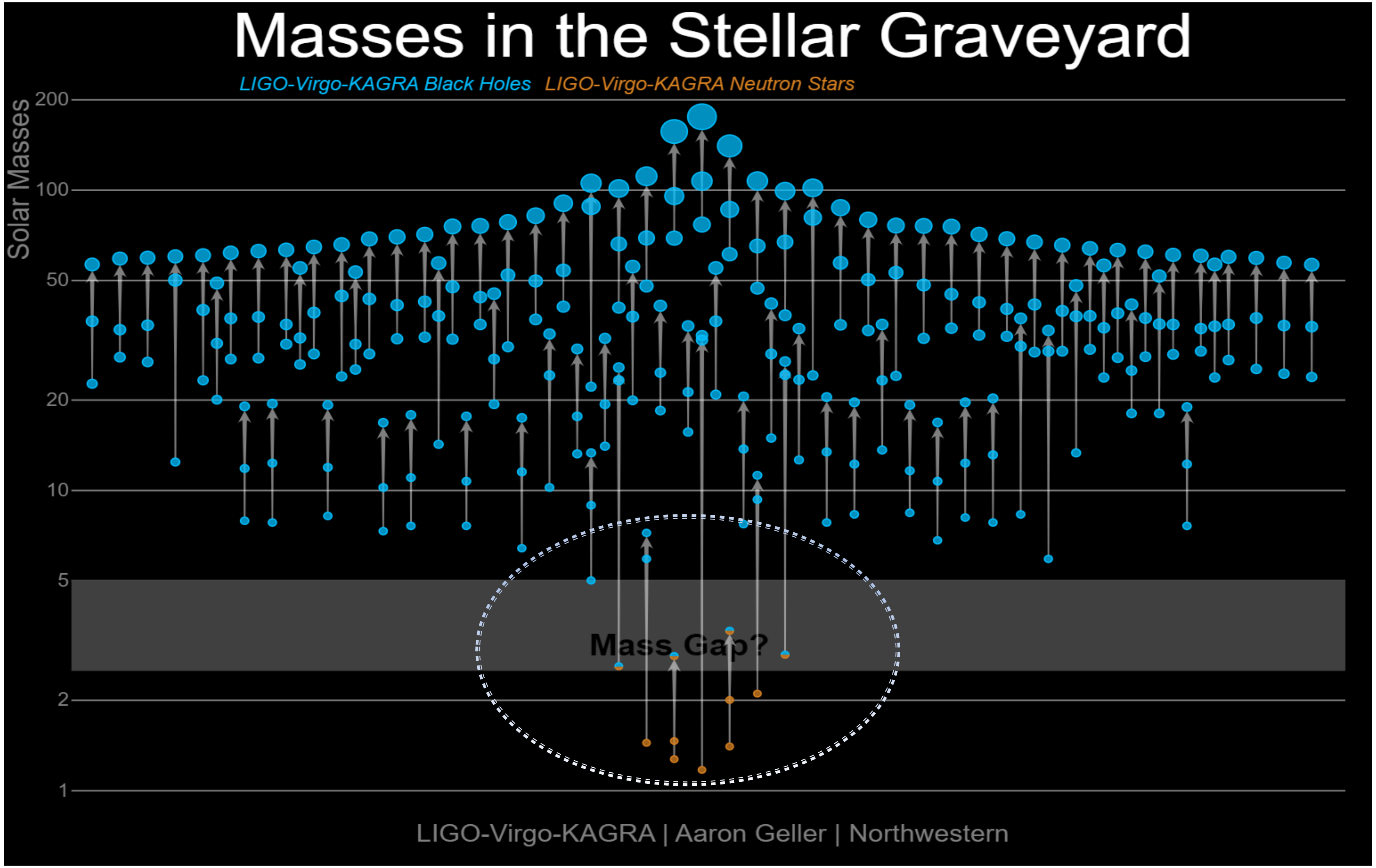
Detected events



Simulations + Sentitivity

Expected event for the future

Instrument	*NS-BH*
AdLIGO	1.2-9.3
A+	3.2-26
ET	2.4×10^3- 2.2×10^4

Baibhav et al. 2019

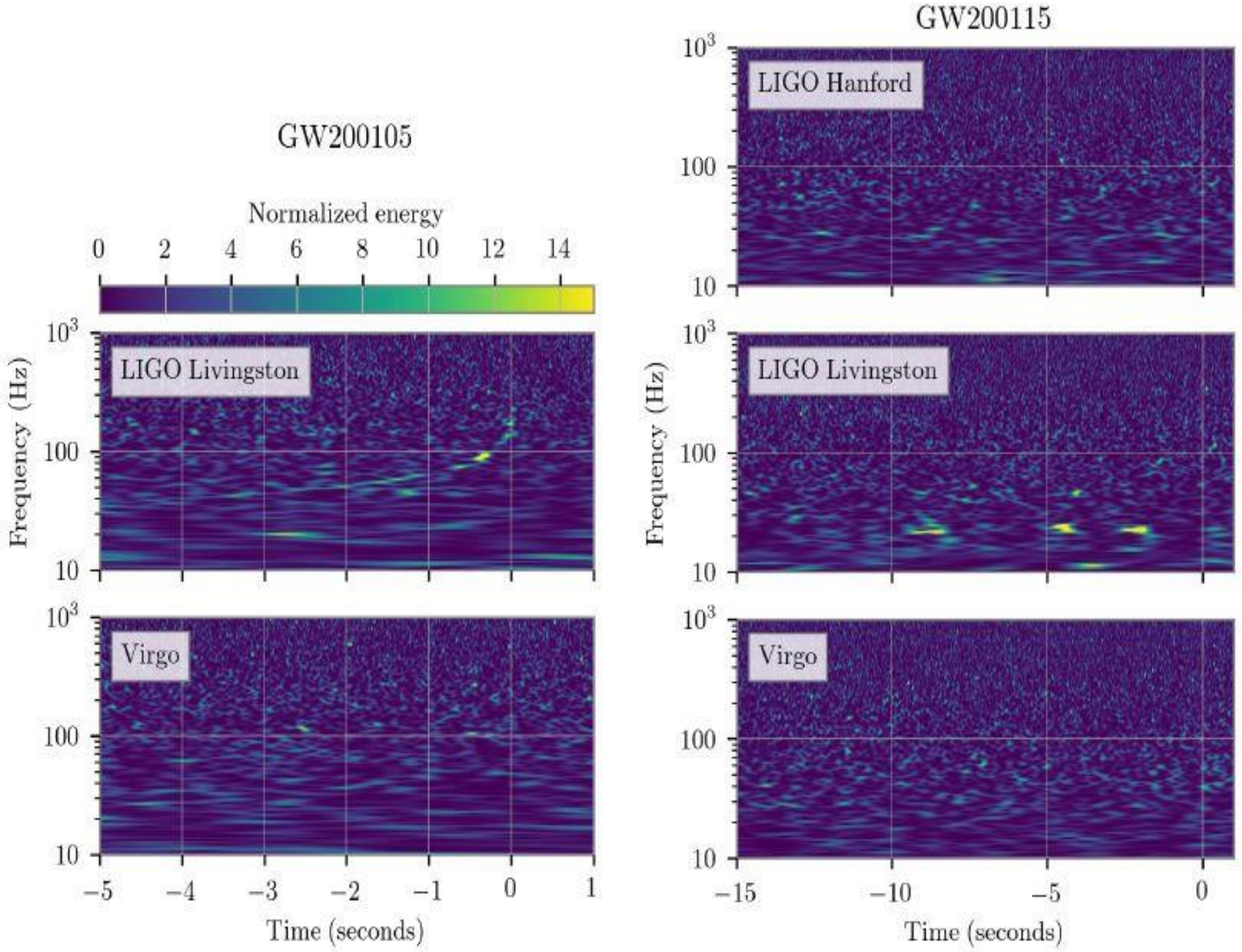
Detected events: GW200105 e GW200115

First two NS-BH type events confirmed ---------→ No EM counterpart detection

↓

It was not possible to constrain λ significantly

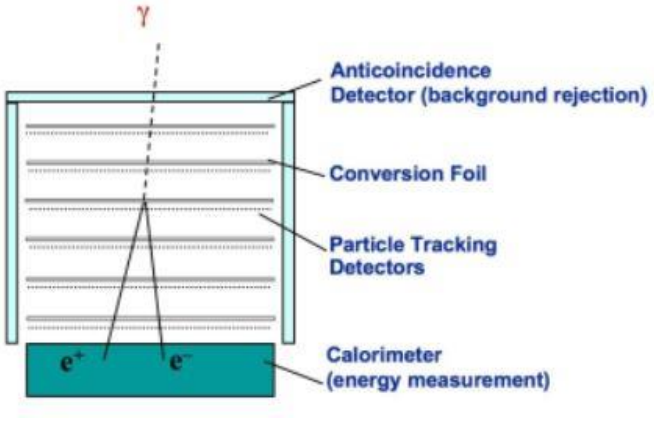
	GW200105		GW200115	
	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)
Primary mass $m_1/M_\odot$	$8.9^{+1.1}_{-1.3}$	$8.9^{+1.2}_{-1.5}$	$5.9^{+1.4}_{-2.1}$	$5.7^{+1.8}_{-2.1}$
Secondary mass $m_2/M_\odot$	$1.9^{+0.2}_{-0.2}$	$1.9^{+0.3}_{-0.2}$	$1.4^{+0.6}_{-0.2}$	$1.5^{+0.7}_{-0.3}$
Mass ratio q	$0.21^{+0.06}_{-0.04}$	$0.22^{+0.08}_{-0.04}$	$0.24^{+0.31}_{-0.08}$	$0.26^{+0.35}_{-0.10}$
Total mass $M/M_\odot$	$10.8^{+0.9}_{-1.0}$	$10.9^{+1.1}_{-1.2}$	$7.3^{+1.2}_{-1.5}$	$7.1^{+1.5}_{-1.4}$
Chirp mass $\mathcal{M}/M_\odot$	$3.41^{+0.08}_{-0.07}$	$3.41^{+0.08}_{-0.07}$	$2.42^{+0.05}_{-0.07}$	$2.42^{+0.05}_{-0.07}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$3.619^{+0.006}_{-0.006}$	$3.619^{+0.007}_{-0.008}$	$2.580^{+0.006}_{-0.007}$	$2.579^{+0.007}_{-0.007}$
Primary spin magnitude χ_1	$0.09^{+0.18}_{-0.08}$	$0.08^{+0.22}_{-0.08}$	$0.31^{+0.52}_{-0.29}$	$0.33^{+0.48}_{-0.29}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.01^{+0.08}_{-0.12}$	$-0.01^{+0.11}_{-0.15}$	$-0.14^{+0.17}_{-0.34}$	$-0.19^{+0.23}_{-0.35}$
Effective precession spin parameter χ_p	$0.07^{+0.15}_{-0.06}$	$0.09^{+0.14}_{-0.07}$	$0.19^{+0.28}_{-0.17}$	$0.21^{+0.30}_{-0.17}$
Luminosity distance D_L/Mpc	280^{+110}_{-110}	280^{+110}_{-110}	310^{+150}_{-110}	300^{+150}_{-100}
Source redshift z	$0.06^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$	$0.07^{+0.03}_{-0.02}$	$0.07^{+0.03}_{-0.02}$

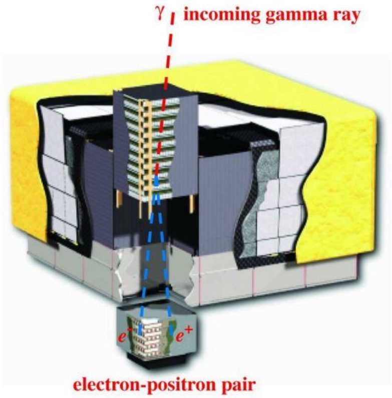


Fermi-LAT e CTA telescopes

- **Fermi-LAT** (Large Area Telescope)

  γ-ray wide field telescope :20 MeV-300 GeV

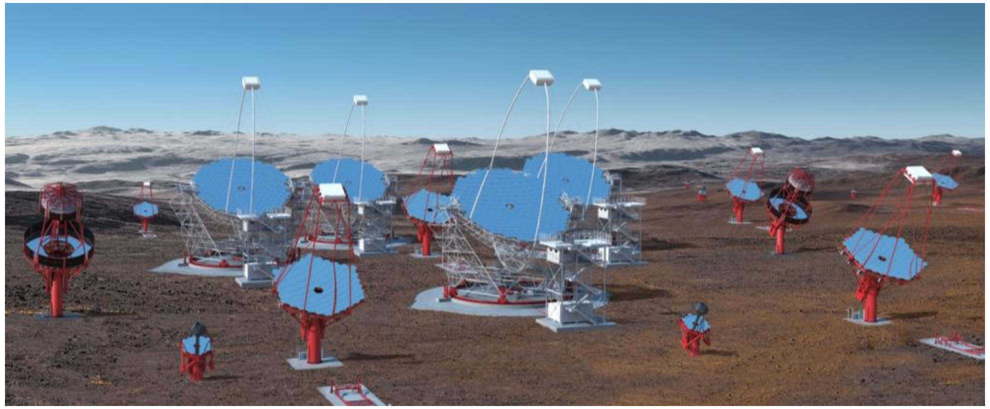




https://www-glast.stanford.edu/instrument.html

- **CTA** (Cherenkov Telescope Array)

  - It uses Cherenkov light generated by EM shower
  - These showers are very rare (1 photon $/m^2 \cdot$ yr for bright sources, 1 photon$/m^2 \cdot$ century for weak sources)
  - More then 60 telescopes, north e south hemisphere, differents sizes
  - Range: 20 GeV- 5 TeV



https://www.cta-observatory.org/

Our work: multimessenger analysis

In order to estimate the events detectability we followed these steps:

1. Study and application of **models** for the **remnant mass** and **jet** formation
2. Modelling the **afterglow spectrum**
3. Comparison of spectra obtained and **sensitivities** of Fermi-LAT and CTA instruments
4. Estimation of **event detectability** as a function of coalescence parameters

Parameter space evaluation: M_{rem} model

Through the models extracted from the simulations, we can study the parameter space that allows the creation of an observable EM counterpart

Faucart 2018 model

$$\hat{M}^{rem}_{model} = \left[Max\left(\alpha\frac{1-2C_{NS}}{\eta^{1/3}} - \beta\hat{R}_{ISCO}\frac{C_{NS}}{\eta} + \gamma, 0\right)\right]^{\delta}$$

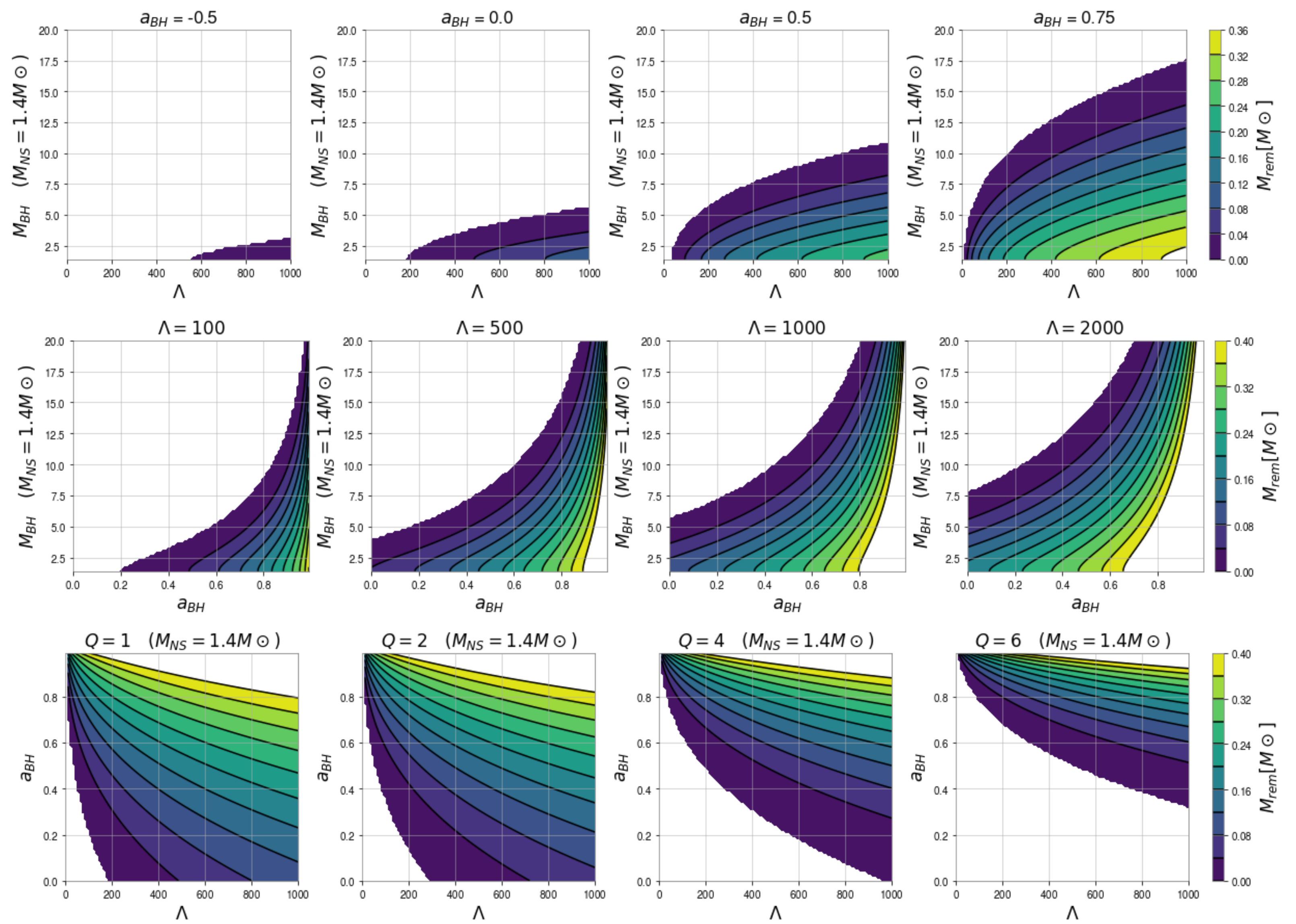
(Foucart, Hinderer and Nissanke 2018)

$Q = M_{BH}/M_{NS}$ Mass ratio

$\eta = Q/(1+Q)^2$ Symmetric mass ratio

$C_{NS} = \sum_{k=0}^{2} a_k(\log\lambda_{NS})^k$ Compactness

$\lambda = \frac{2}{3}(k_2/C_{NS}^5)$ Tidal deformability



Parameter space evaluation: jet energy model

This represents the main link between the gravitational part and the EM part

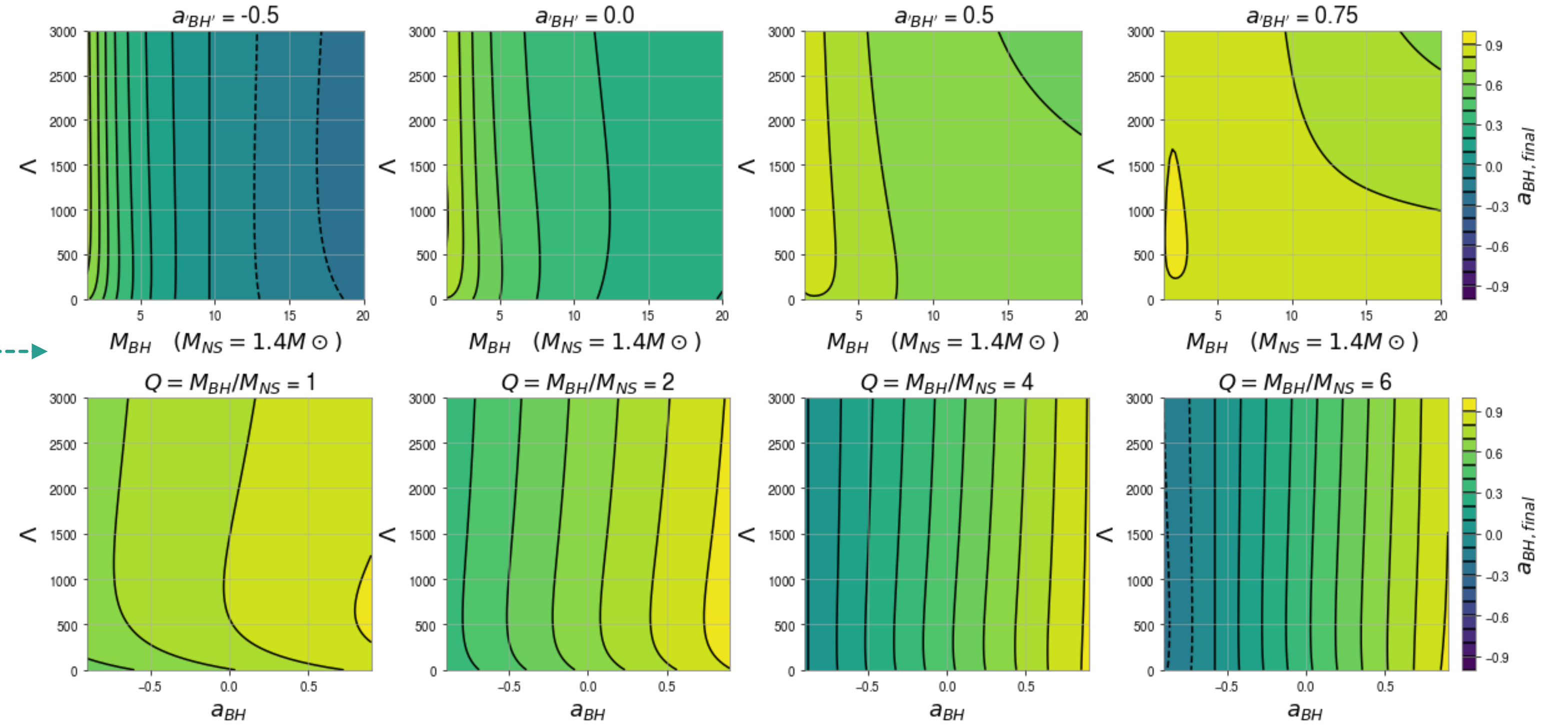
We assume the Blandford-Znajeck (BZ) mechanism

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

- $f_\gamma = 10\%$: Emission efficiency (Beniamini et al. 2016)
- η_{BZ}: Mass-energy conversion efficiency (Salafia and Giacomazzo 2021)
- $M_{acc} \geq 0.03 M_\odot$: accretion mass (Stone et al. 2016)

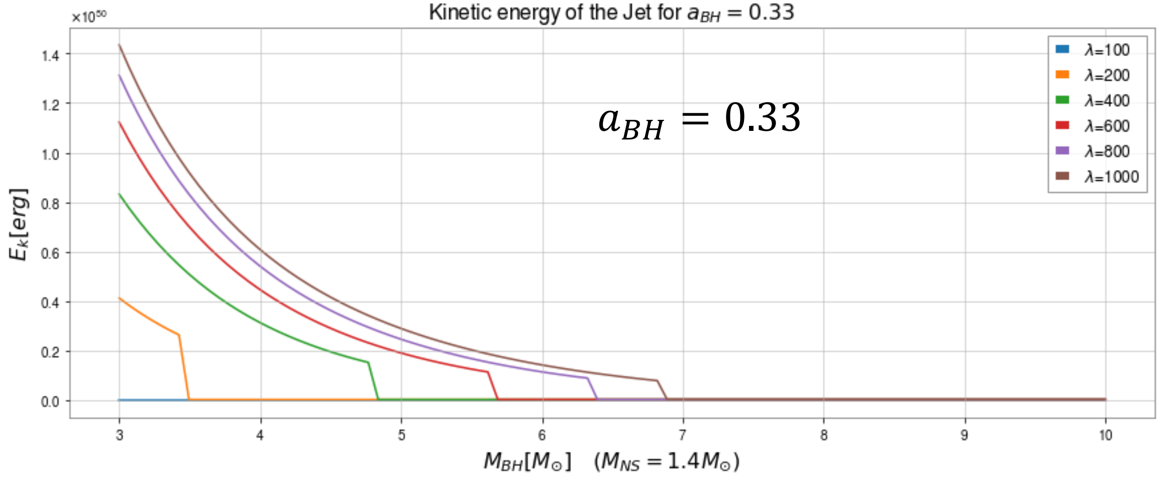
$$\eta_{BZ} = \begin{cases} 10^{-4} e^{(a^f_{BH} - 0.25)/0.06} & a^f_{BH} \leq 0.25 \\ 10^{-4} & 0.25 < a^f_{BH} \leq 0.505 \\ 0.068\Omega_H^5 & a^f_{BH} > 0.505 \end{cases}$$

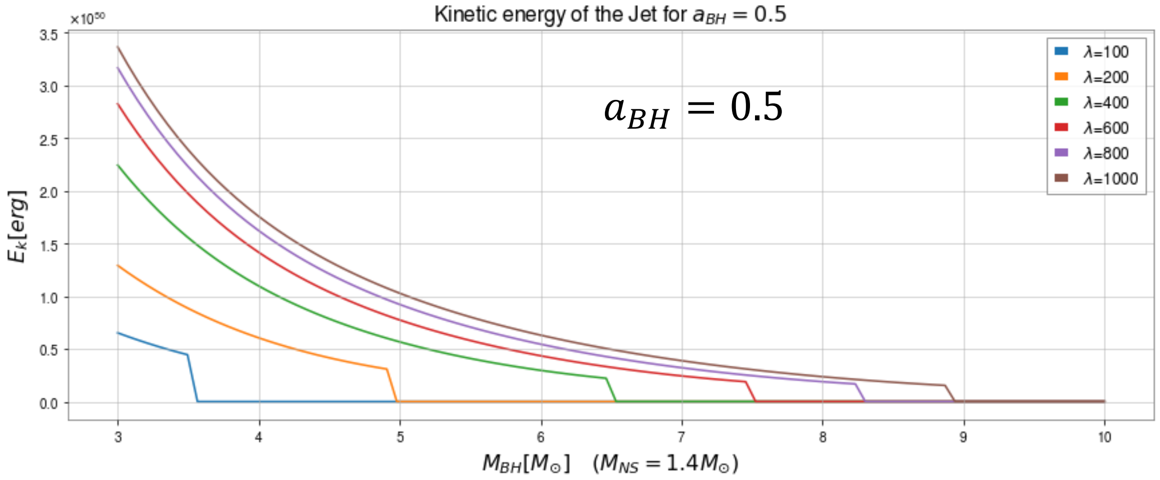
η_{BZ} depends from BH final spin a_{BH}
(models taken from Zappa et al. 2019)

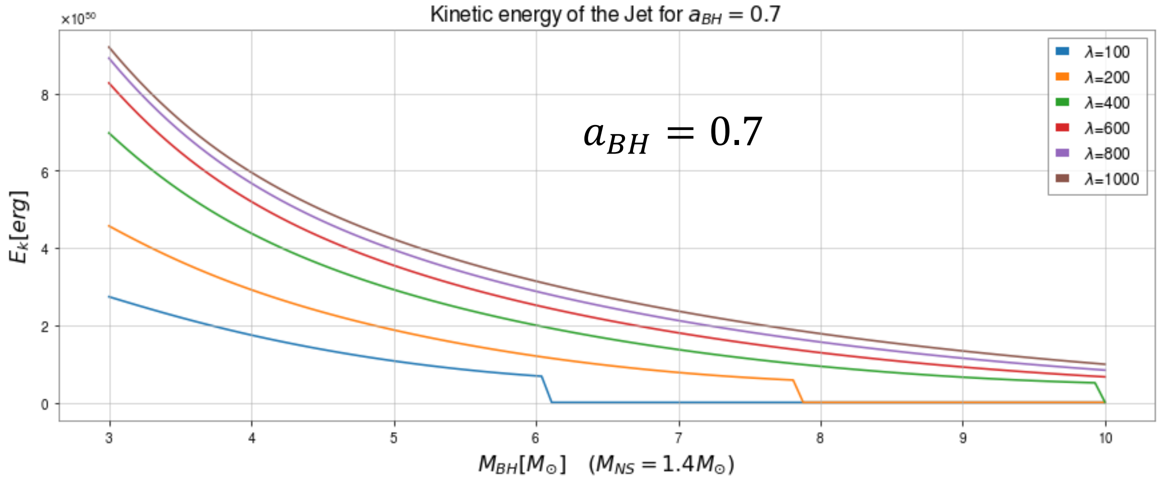


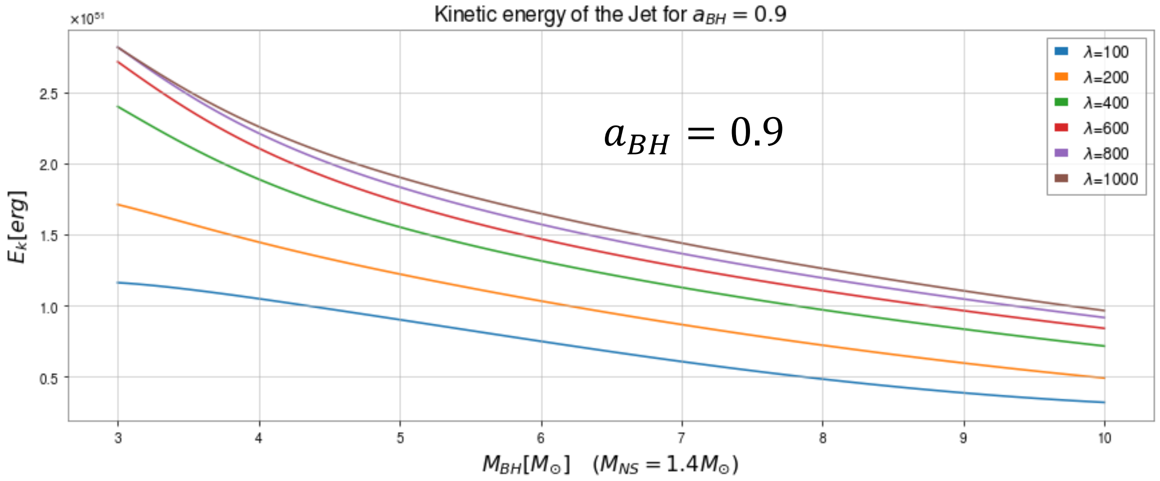
Parameter space evaluation: jet energy model

Plots of the trend of the kinetic energy of the jet Ek as a function of parameters:









Afterglow spectrum

To obtain the expected spectra, we used a newly formulated model for synchrotron and synchrotron-self-Compton (SSC) (Joshi e Razzaque 2021)

Expected flow in the case of **slow cooling** ⟶

$$F_{\nu,\text{slow}} = f_{\nu,max} \begin{cases} \left(\frac{\nu_a}{\nu_m}\right)^{1/3}\left(\frac{\nu}{\nu_a}\right)^2, & \nu < \nu_a \\ \left(\frac{\nu}{\nu_m}\right)^{1/3}, & \nu_a < \nu < \nu_m \\ \left(\frac{\nu}{\nu_m}\right)^{-(p-1)/2}, & \nu_m < \nu < \nu_c \\ \left(\frac{\nu_c}{\nu_m}\right)^{-(p-1)/2}\left(\frac{\nu}{\nu_c}\right)^{-p/2}, & \nu > \nu_c \end{cases}$$

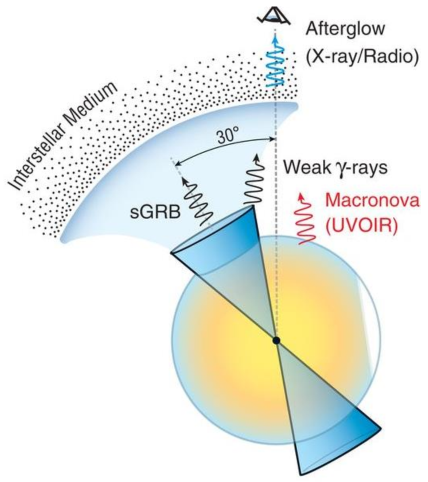
For parameter values we refer to those used in the analysis of GRB event 090510

n_0	p	ϵ_e	ϵ_B	$Y = L_{SSC}/L_{sy}$
$10^{-5} cm^{-3}$	2.3	0.2	0.02	$0.93 \cdot (t/10^2)^{-0.09}$

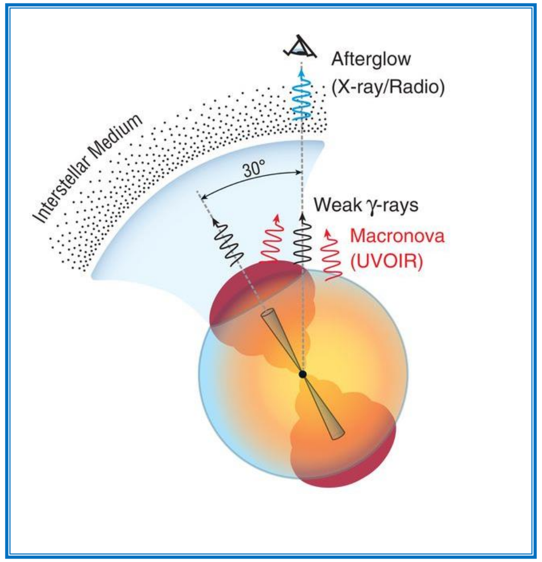
Hypothesis of a **structured jet**: we introduce the angular dependence for energy

$$E(\theta) = E_0\left(1 + \frac{\theta^2}{b\theta_{core}^2}\right)^{-\frac{b}{2}}$$

b	θ_{core}
6	$0.1\ rad$



(Kasliwal, Nakar et al. 2017)



Afterglow spectrum vs Fermi-LAT e CTA

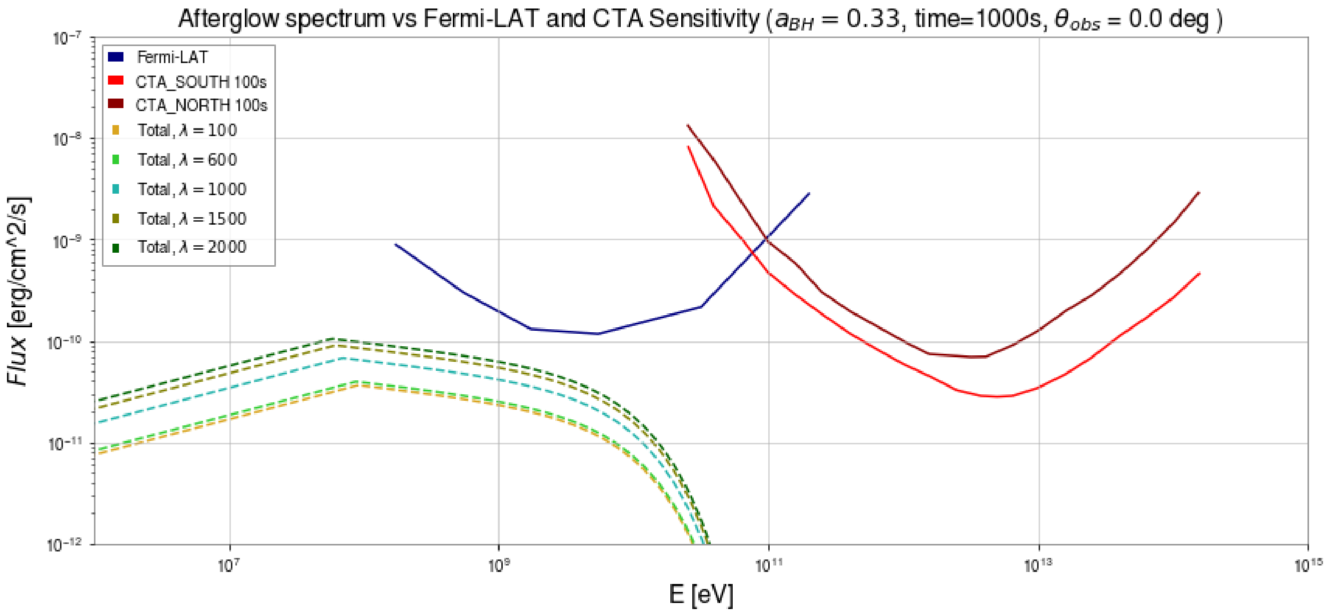
To estimate the probability of detection, we initially used the best parameter estimates of the **GW200115** event to obtain the expected EM spectrum

$M_{BH} = 5.7\ M_{\odot},\quad M_{NS} = 1.5\ M_{\odot},\quad a_{BH} = 0.33,\quad d_L = 300\ Mpc,\ \lambda = 400$ ----------→ The **jet cannot be created** because of the threshold imposed on Mrem

--------→ **Result:** event GW200115 does not have the necessary characteristics to create a jet and thus an EM counterpart if we impotize the reasonable value $\lambda = 400$

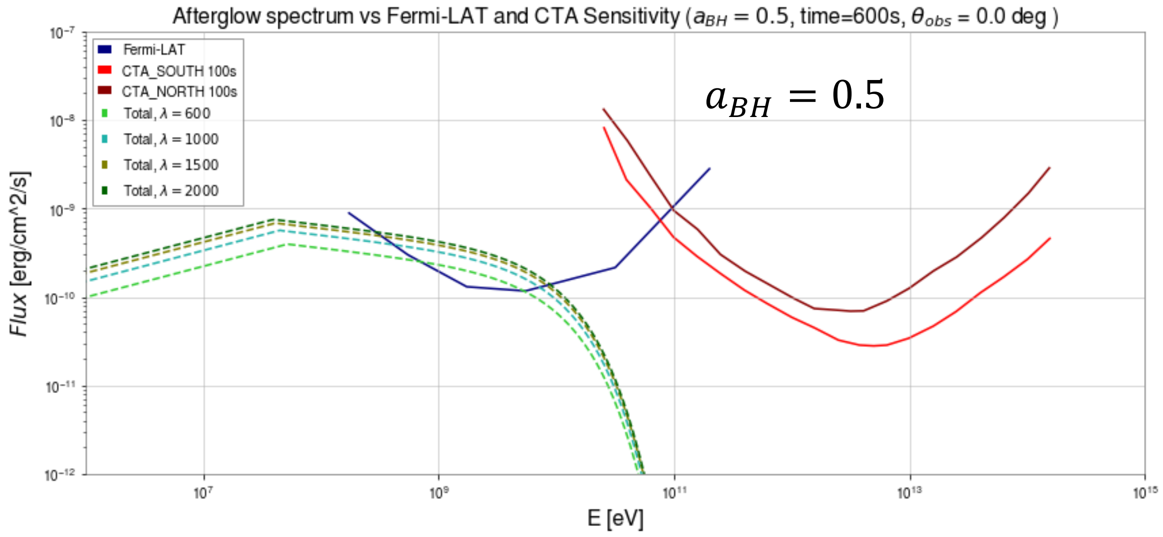
Depends on **spin** and $\boldsymbol{\lambda}$:

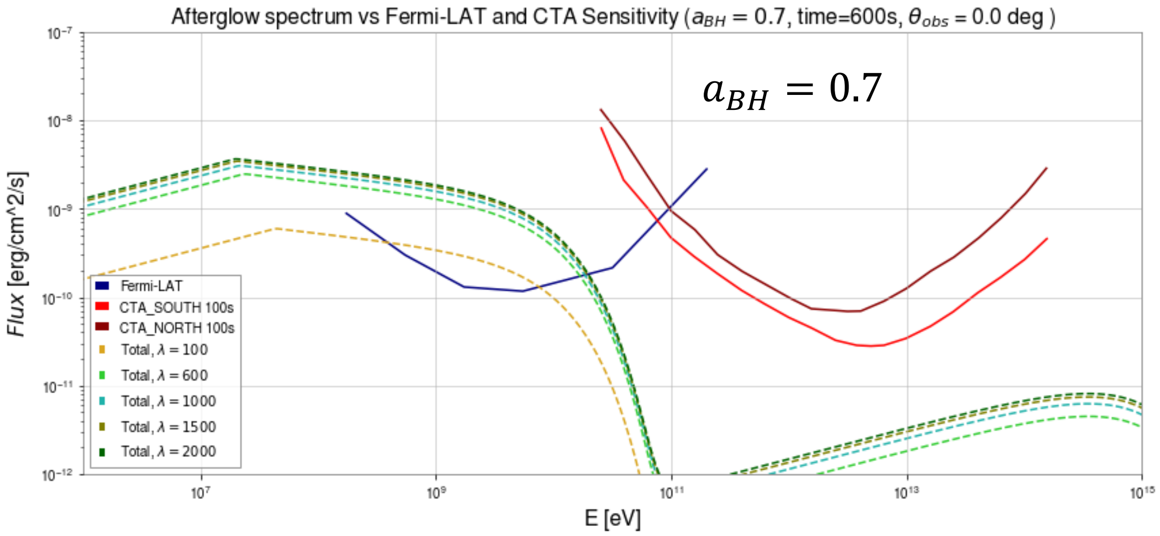
if we increase λ the jet is created but the flux intensity is too low --------→

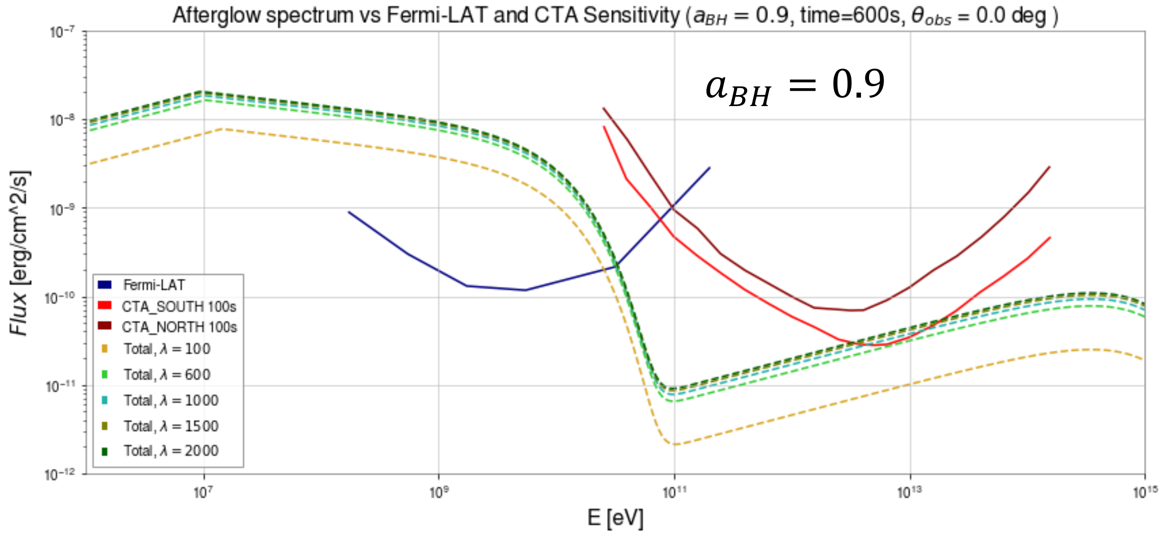


Afterglow spectrum vs Fermi-LAT e CTA

Let's see what happens if the BH spin was higher



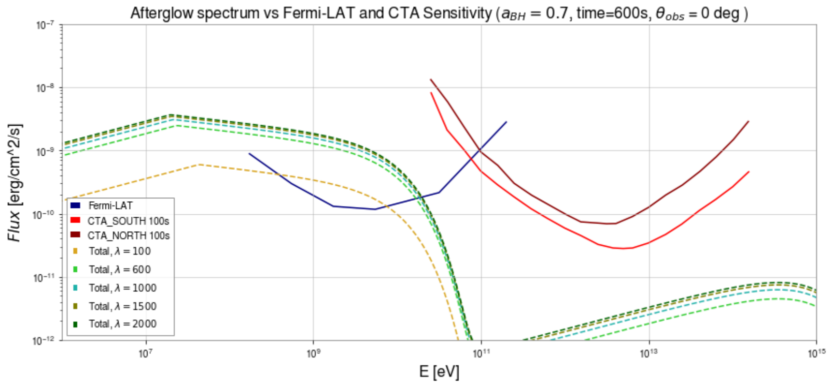




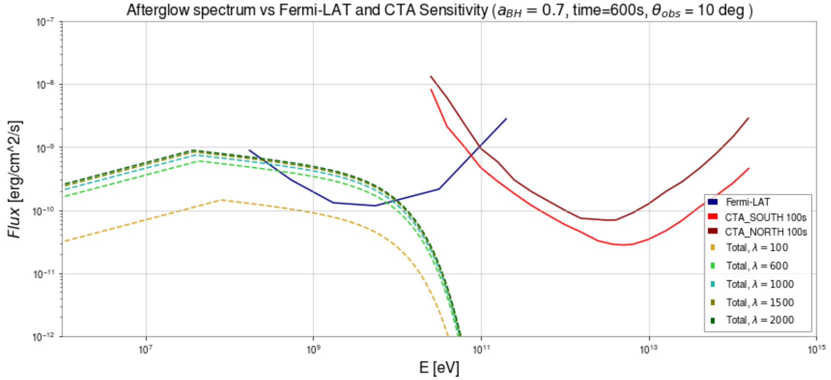
Afterglow spectrum vs Fermi-LAT e CTA

We varied one parameter at a time to study how the probability of detection changes

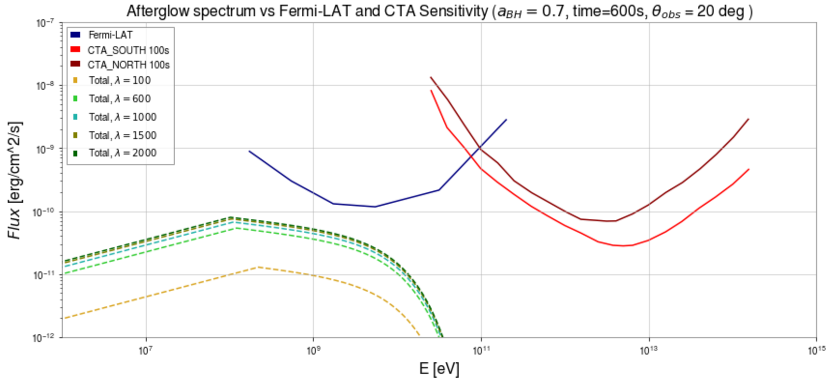
- Variation of observation angle $\boldsymbol{\theta_{obs}}$
- Variation in the mass of the black hole $\boldsymbol{M_{BH}}$
- Variation of the distance $\boldsymbol{D_L}$



$\theta_{obs} = 0°$



$\theta_{obs} = 10°$



$\theta_{obs} = 20°$

Afterglow spectrum vs Fermi-LAT e CTA

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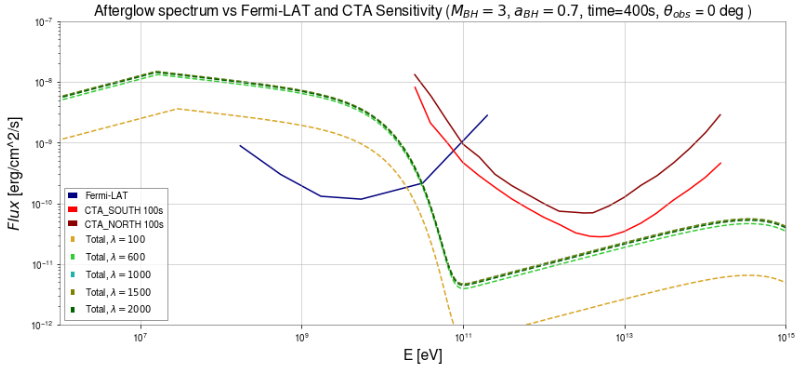
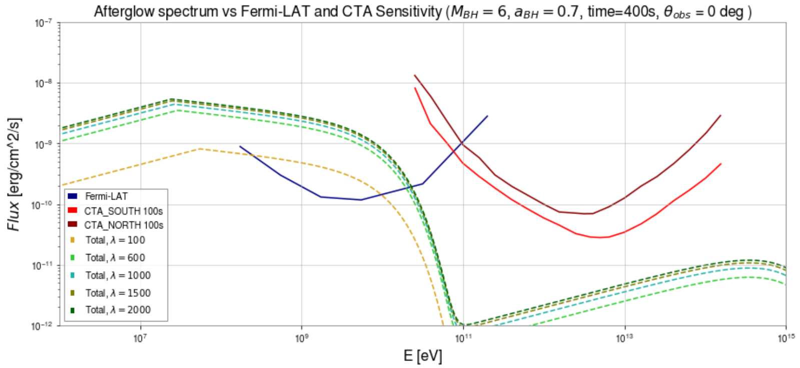
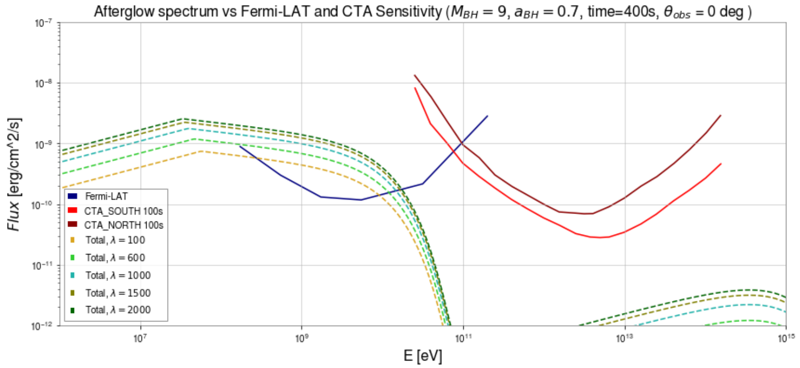


$M_{BH} = 3\ M_{\odot}$



$M_{BH} = 6\ M_{\odot}$



$M_{BH} = 9\ M_{\odot}$

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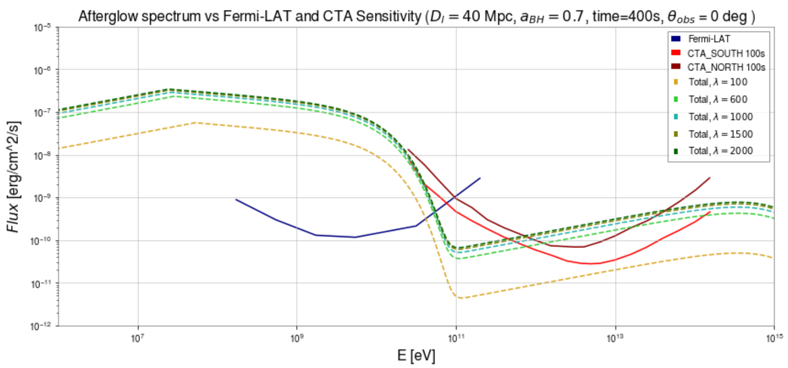
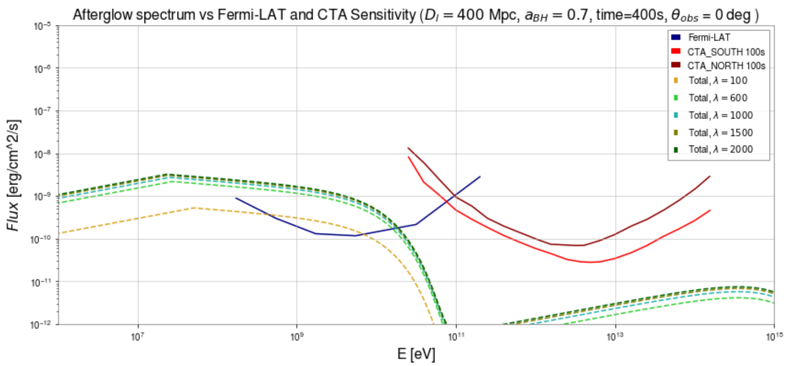
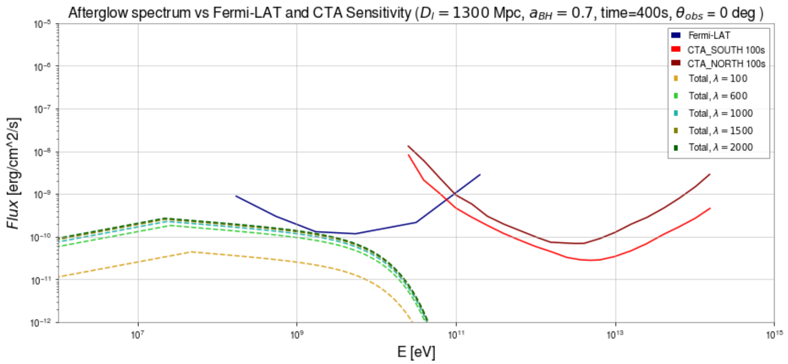


$D_L = 40\ Mpc$



$D_L = 400\ Mpc$

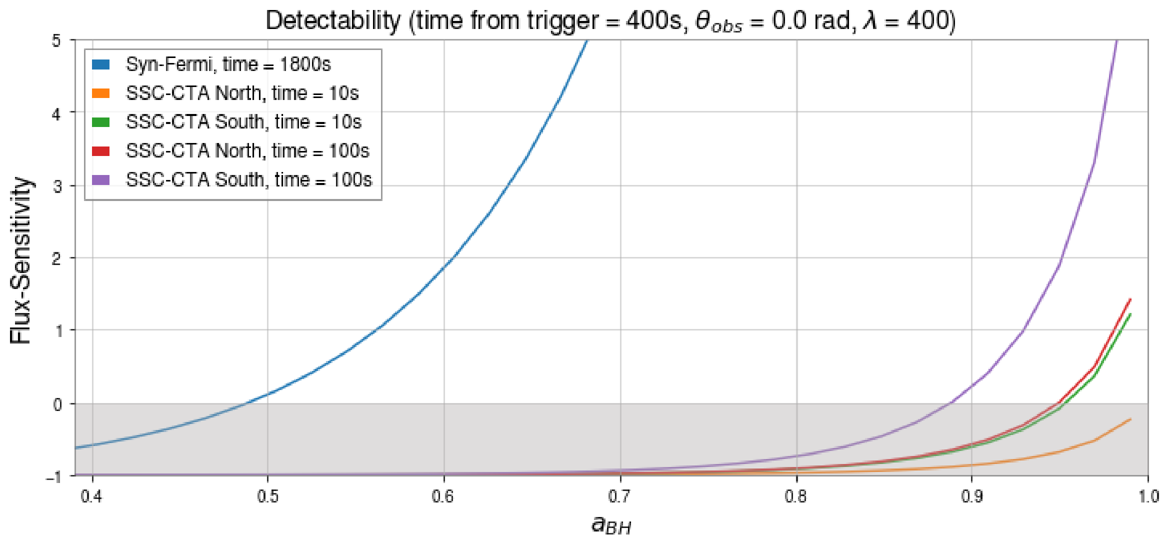


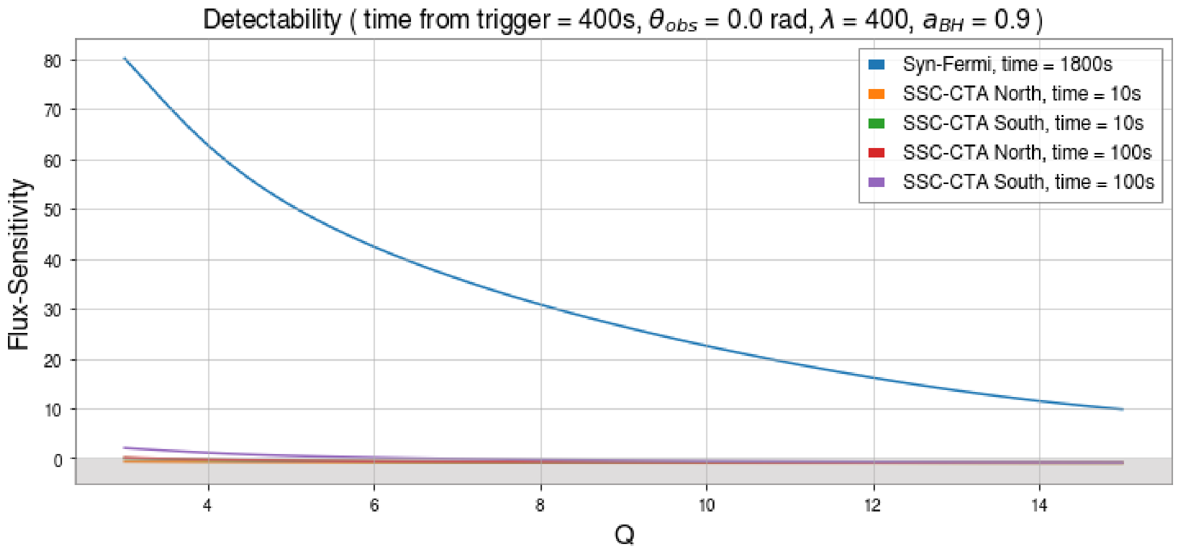
$D_L = 1300\ Mpc$

Detectability

To evaluate the **probability of detection** we defined a simple parameter

$$Detectability = \frac{Flux(\nu_{max,sens}) - \max\_sens}{\max\_sens}$$





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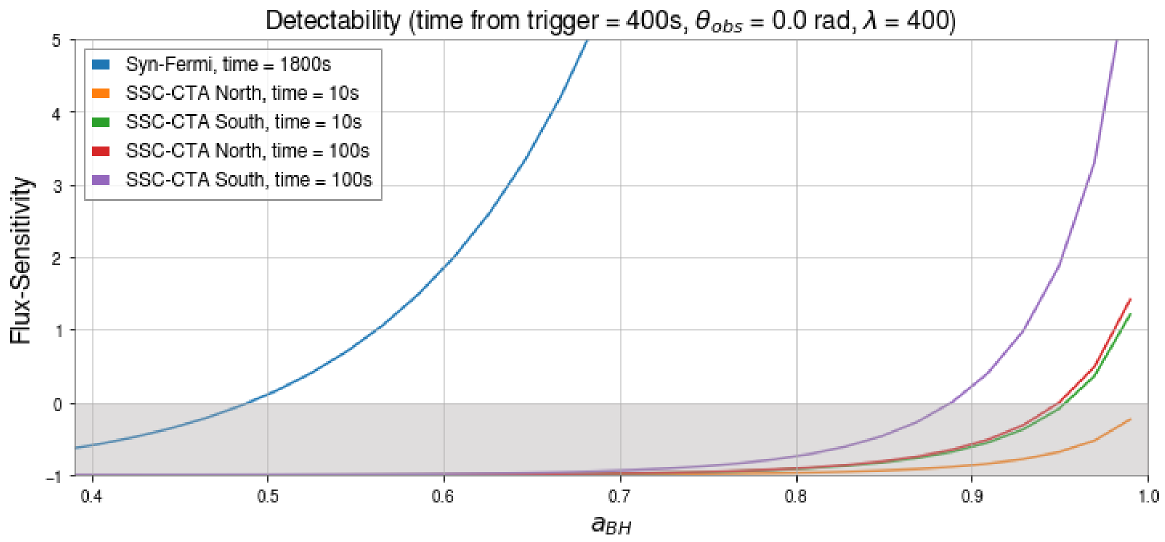

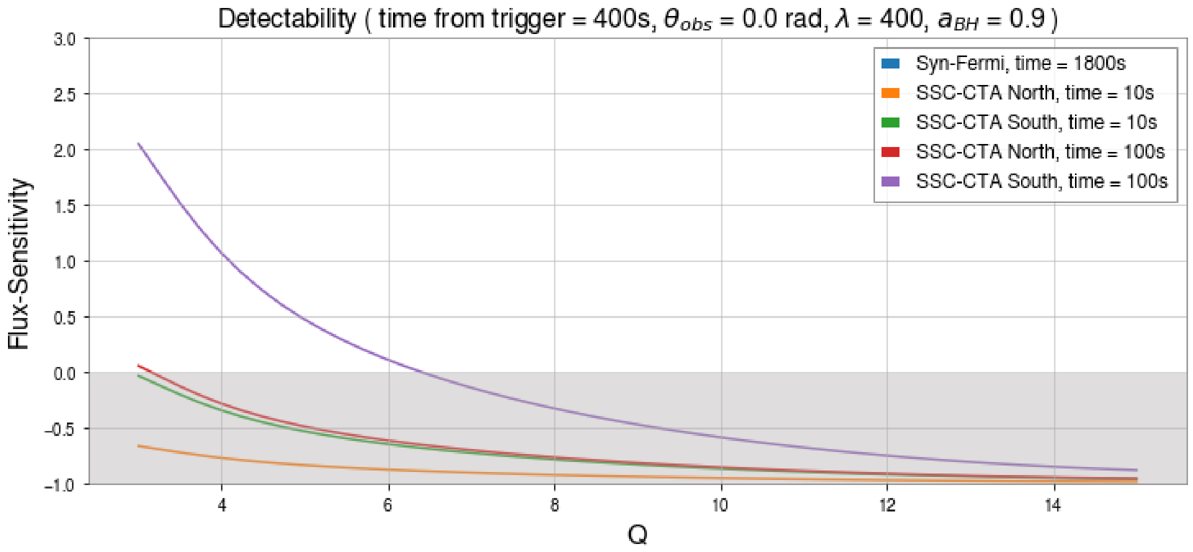

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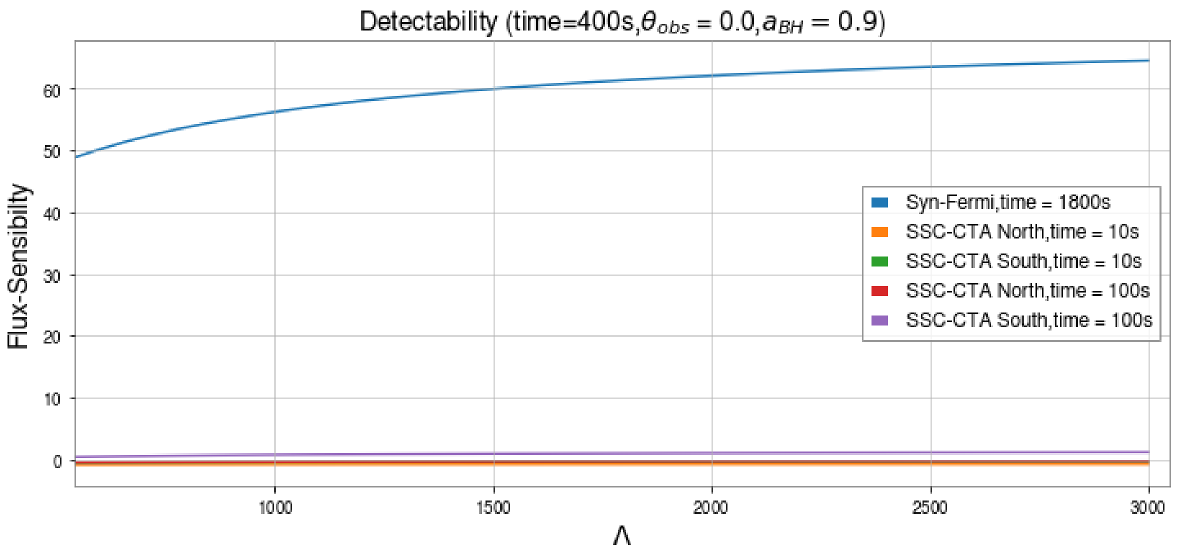

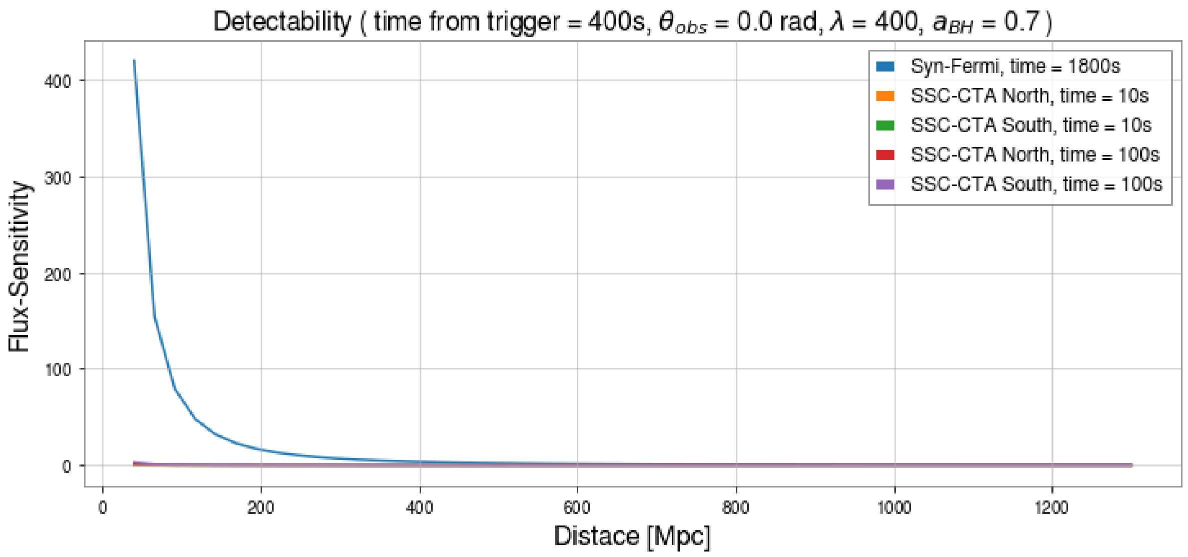

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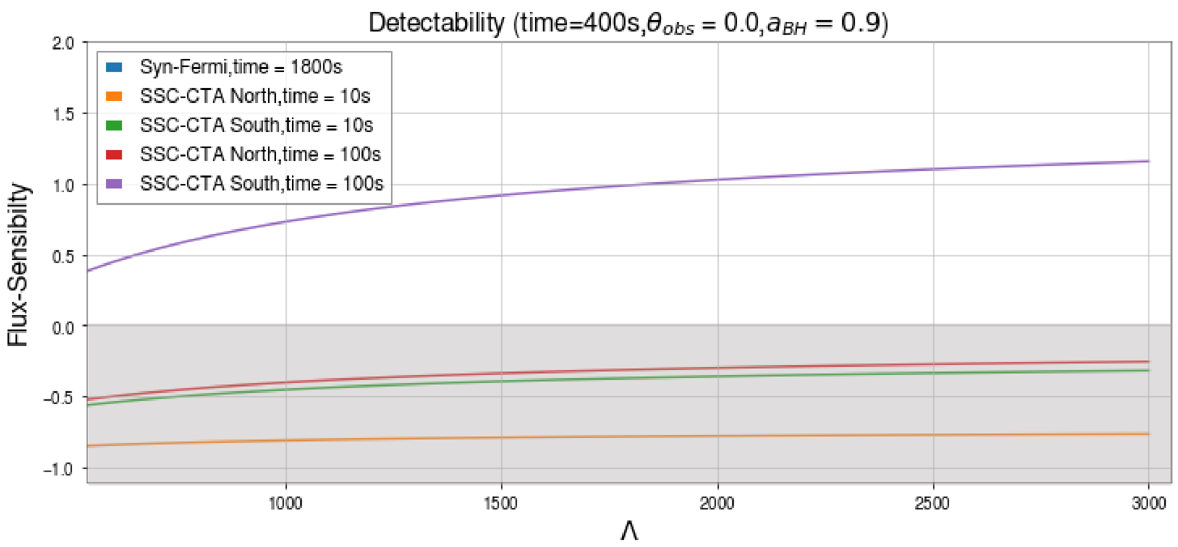
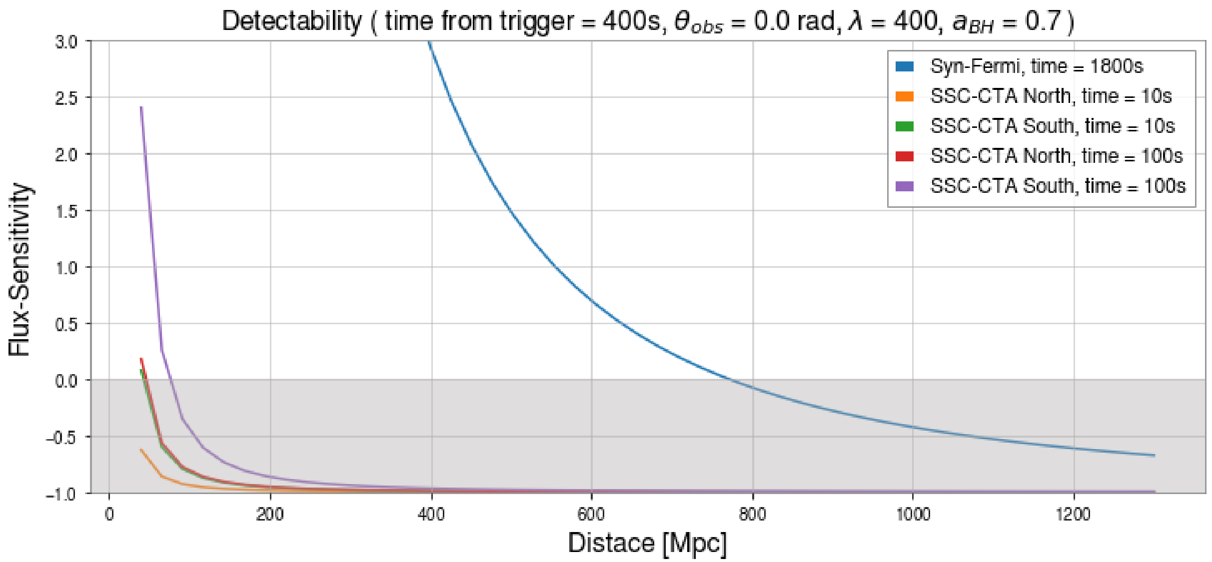
$$Detectability = \frac{Flux(\nu_{max,sens}) - \max\_sens}{\max\_sens}$$





Results and conclusions

- **Not all GRBs** produced can be detected
- If the **GW200115** event had had a higher spin and/or λ it would have been possible to see the GRB with Fermi-LAT
- The **parameters** that most influence detectability are a_BH and Q while λ introduces small differences
- **Synchrotron** emission shows **high detectability** and bodes well for the future
- In contrast, the detectability for the **SSC** component with **CTA is very low**

↓

It depends very much on the parameters and the models themselves: more in-depth analyses are needed in the future

Thanks for your attention

Tobia Matcovich

Supervisors:
Dr. M. Bawaj
Dr. S. Germani
Dr. S. Cutini

Backup Slides

Formazione e inspiral

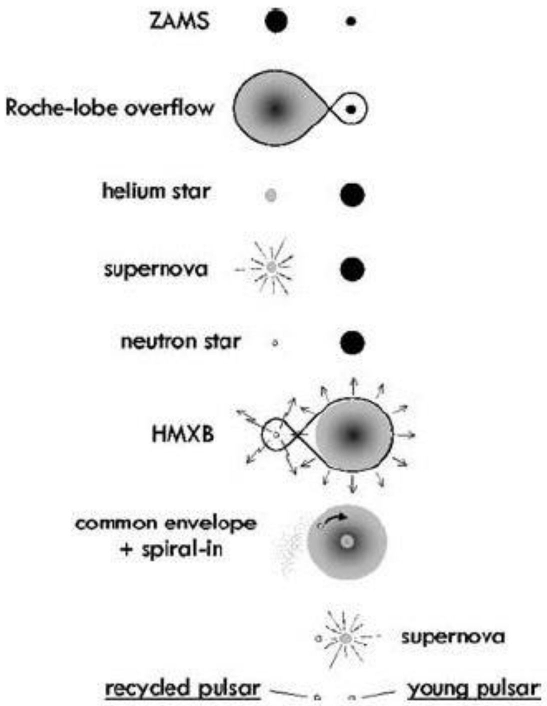
Gli eventi BNS e NS-BH sembrano condividere il canale di formazione → "**Standard evolution channel**"

↓

Necessarie simulazioni

↓

- $M \gtrsim 8 - 10\, M_{\odot}$ per gli oggetti neonati (ZAMS)
- Roche-lobe overflow
- Coppia di Supernovae
- Common envelope phase (CE)
- Inspiral



Ci sono ancora molte domande aperte:
- Efficenza CE
- Kick velocity?
- Massa massima della NS

Rate di formazione

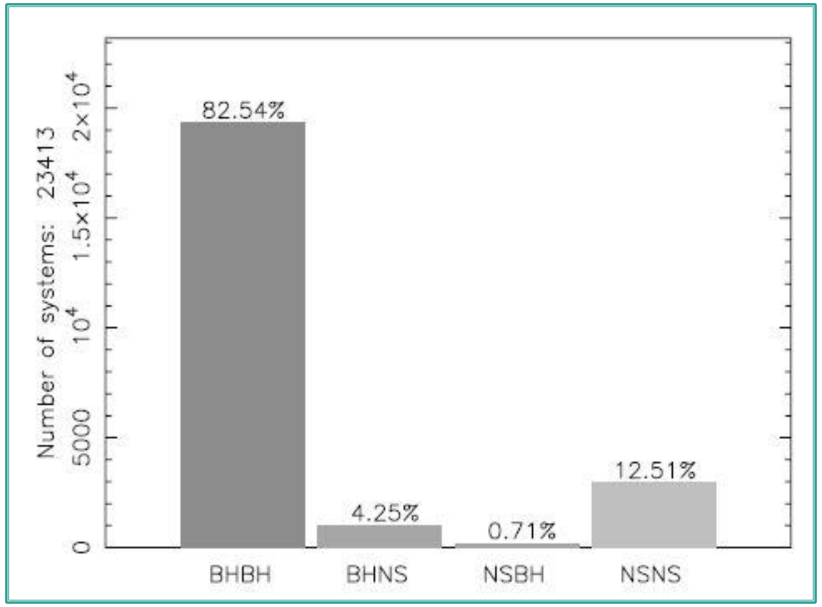
Siamo interessati agli oggetti che si incontrerrano in un tempo ~ minore della vita dell'Universo

$$t_{merge} = \frac{5}{256}\frac{c^5}{G^3}\frac{R^4}{(M_1 M_2)(M_1+M_2)} \approx 54 M_{yr}\left(\frac{1}{q(1+q)}\right)\left(\frac{R}{R_\odot}\right)^4\left(\frac{1.4M_\odot}{M_1}\right)^3$$

(Assumendo orbite quasi circolari)

$q = M_1/M_2$

Simulando il processo di formazione si ottengono stime sulla formazione dei differenti oggetti binari compatti

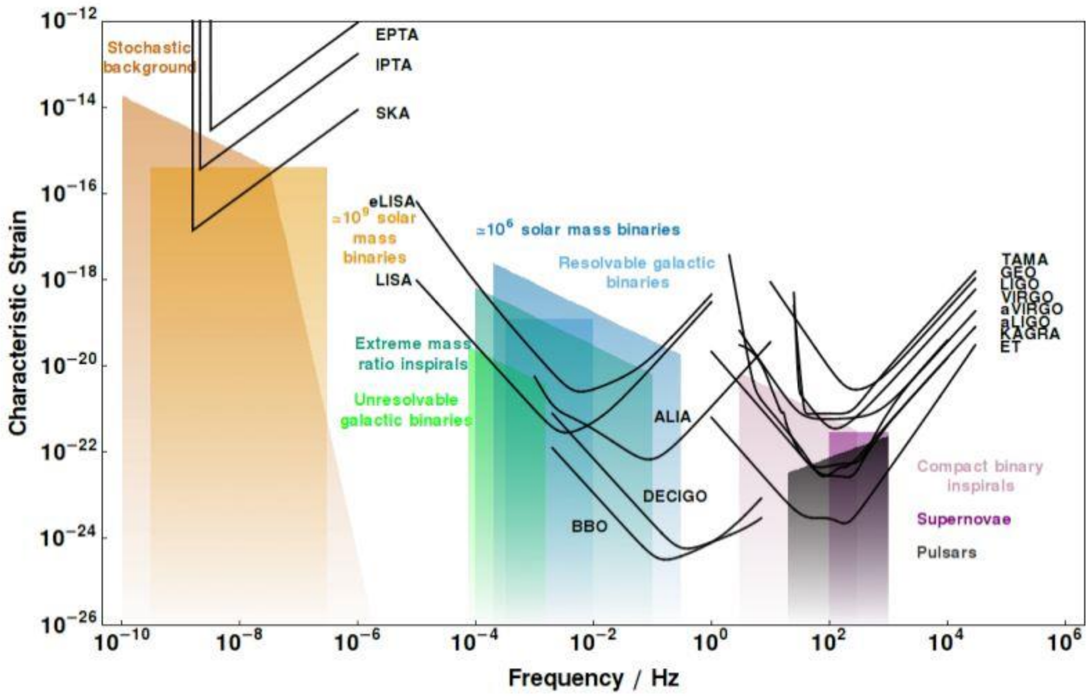


Tempo di coalescenza minore di 10 Gyr

R. Voss e T. M. Tauris 2003

Rate di detection

Utilizzando le simulazioni per la formazione e le sensibilità si può stimare il numero di eventi che ci aspettiamo di rivelare



Sensibilità degli strumenti attuali e futuri

→ Parametro fondamentale: **chirp mass** $\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$

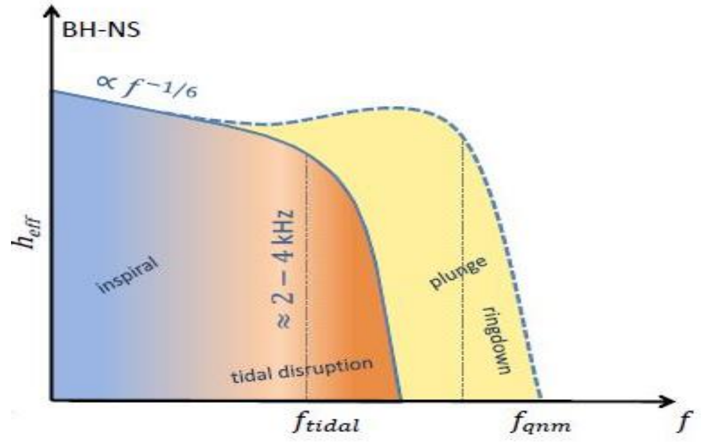
Detector	BNS	NSBH	BBH
O2	0.028 - 0.91	0.12 - 1.1	27 - 40
O3	0.11 - 3.4	0.46 - 3.9	94 - 1.5×10^2
AdLIGO	0.27 - 8.6	1.2 - 9.3	2.2×10^2 - 3.6×10^2
A+	0.88 - 28	3.2 - 26	5.6×10^2 - 9.7×10^2
A++	2.3 - 71	8.1 - 63	1.3×10^3 - 2.4×10^3
Voyager	32 - 9.4×10^2	1.0×10^2 - 7.8×10^2	9.7×10^3 - 2.7×10^4
ET-B	1.1×10^3 - 2.7×10^4	2.4×10^3 - 2.2×10^4	4.9×10^4 - 2.7×10^5
CE	1.6×10^4 - 2.7×10^5	1.6×10^4 - 1.4×10^5	8.6×10^4 - 5.4×10^5
Noiseless	2.8×10^4 - 4.5×10^5	2.0×10^4 - 1.8×10^5	9.2×10^4 - 5.7×10^5

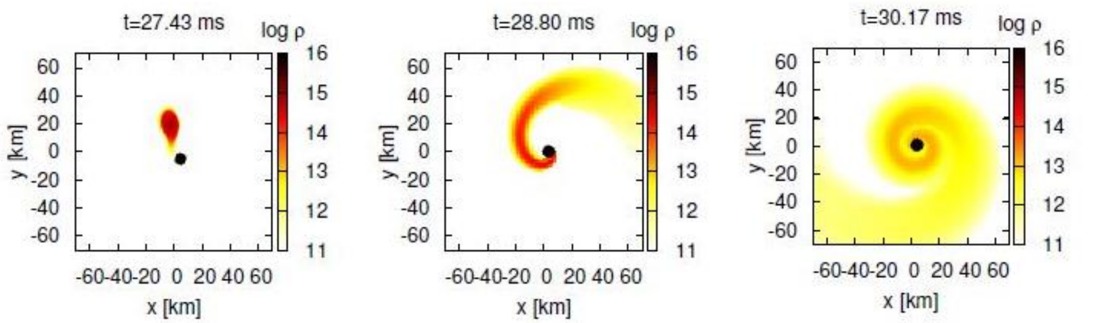
Ringdown e formazione del disco

É la fase più complicata da analizzare, sia teoricamente che strumentalmente

Relatività numerica e BH perturbation theory

Frequenze delle onde GW molto alte per le odierne sensibilità





Occorrono potenti simulazione per estrarre stime ragionevoli degli oggetti che ci interessano:

- **Massa** del disco di **accrescimento**
- Formazione del **getto**
- **Campi magnetici**

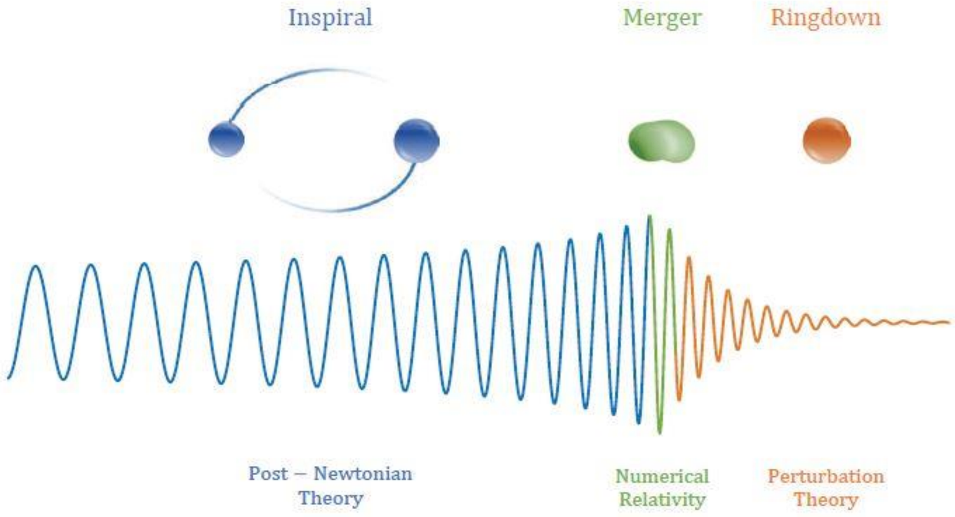
Descrizione completa del segnale chirp

Per descrivere tutto il segnale chirp abbiamo bisogno di più approcci

- **Teoria Post-Newtoniana**: ci consente di fare un espansione attorno al parametro $(v/c)^2$

- **Relatività numerica:** quando falliscono altri metodi, il problema è il tempo computazionale

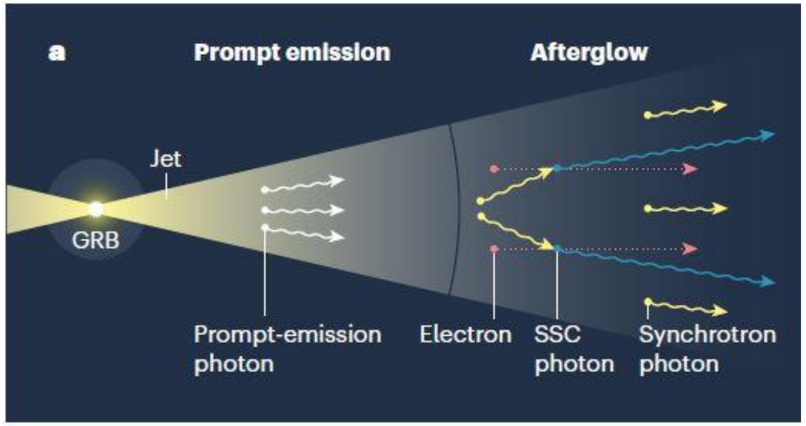
- **BH perturbation theory:** al primo ordire è costituita da una sovrapposizione di sinusoidi esponenzialmente decrescenti



Costruzione dei template:
- Approccio Effective One-Body (**EOB**)
- Approccio fenomenologico Inspiral Merger Ringdown (**IMRPhenom**)

Gamma-Ray Burst

Modello a **Jet** per il GRB : cono formato da più gusci che si espandono verso l'esterno



Lo scontro tra i vari gusci genera degli **shock**

Afterglow causato dagli shock **esterni** con il mezzo interstellare

- Emissione più regolare decrescente nel tempo
- Rivelabile anche mesi dopo la prompt
- Produzione a $R > 10^{15} - 10^{16}$cm

Più facile da usare per l'**analisi**

Prompt causato dagli shock **interni**

- ~~Impulsi rapidi e irregolari di raggi gamma~~
- ~~Durata < 1 minuto~~
- ~~Produzione a $R \sim 10^{13} - 10^{15}$cm~~

Classificazione

Long/soft: T_{90} ~ 20 sec

Short/hard: T_{90} ~ 0.2 sec

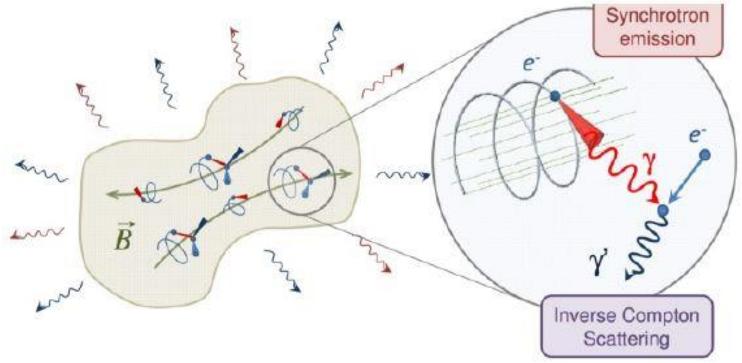
Processi radiativi: Synchron Self Compton (SSC)

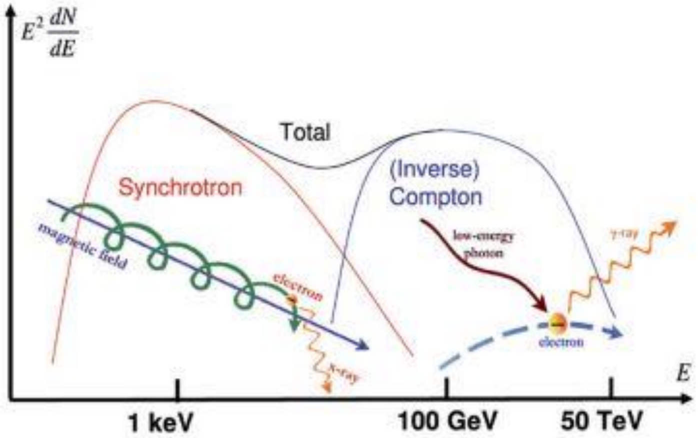
In presenza di forti campi magnetici e tante particelle relativistiche (elettroni) i processi di Sincrotrone e Compton Inverso avvengono insieme

Synchrotron Self Compton (SSC)

I fotoni prodotti per sincrotrone interagiscono con gli elettroni guadagnando energia

Otteniamo uno spettro caratteristico con due picchi raggiungendo **energie molto** elevate (GeV – TeV)





Afterglow spectrum

$$F_{\nu,\mathrm{slow}} = f_{\nu,max} \begin{cases} \left(\frac{\nu_a}{\nu_m}\right)^{1/3}\left(\frac{\nu}{\nu_a}\right)^2, & \nu < \nu_a \\ \left(\frac{\nu}{\nu_m}\right)^{1/3}, & \nu_a < \nu < \nu_m \\ \left(\frac{\nu}{\nu_m}\right)^{-(p-1)/2}, & \nu_m < \nu < \nu_c \\ \left(\frac{\nu_c}{\nu_m}\right)^{-(p-1)/2}\left(\frac{\nu}{\nu_c}\right)^{-p/2}, & \nu > \nu_c \end{cases}$$

n_0	p	ϵ_e	ϵ_B	$Y = L_{SSC}/L_{sy}$
$10^{-5} cm^{-3}$	2.3	0.2	0.02	$0.93 \cdot (t/10^2)^{-0.09}$

$$h\nu_{a,\mathrm{slow}} = 4.4 \times 10^{-4} \frac{(p+2)^{3/5}(p-1)^{8/5}}{(3p+2)^{3/5}(p-2)}(1+z)^{-1}\epsilon_{B,-1}^{1/5}\epsilon_{e,-1}^{-1}n_0^{3/5}E_{55}^{1/5}\ \mathrm{eV}$$

$$h\nu_c = 1.0\,(1+z)^{-1/2}\epsilon_{B,-1}^{-3/2}n_0^{-1}E_{55}^{-1/2}t_2^{-1/2}(1+Y)^{-2}\ \mathrm{eV}$$

$$h\nu_m = 41.3\left(\frac{p-2}{p-1}\right)^2 (1+z)^{1/2}\epsilon_{B,-1}^{1/2}\epsilon_{e,-1}^{2}E_{55}^{1/2}t_2^{-3/2}\ \mathrm{keV}$$

$$h\nu_{a,ssc,\mathrm{slow}} = 0.7\left[\frac{(p+2)^{3/5}(p-1)^{-2/5}(p-2)}{(3p+2)^{3/5}}\right](1+z)^{-1/4}\epsilon_{B,-1}^{1/5}\epsilon_{e,-1}n_0^{7/20}E_{55}^{9/20}t_2^{-3/4}\ \mathrm{MeV}$$

$$h\nu_{c,ssc} = 0.04\,(1+z)^{-3/4}\epsilon_{B,-1}^{-7/2}n_0^{-9/4}E_{55}^{-5/4}t_2^{-1/4}(1+Y)^{-4}\ \mathrm{MeV}$$

$$h\nu_{m,ssc} = 66.5\left(\frac{p-2}{p-1}\right)^4(1+z)^{5/4}\epsilon_{B,-1}^{1/2}\epsilon_{e,-1}^{4}n_0^{-1/4}E_{55}^{3/4}t_2^{-9/4}\ \mathrm{TeV}$$

$$f_{\nu,\mathrm{max}} = 377.1\,(1+z)^{-1}\epsilon_{B,-1}^{1/2}n_0^{1/2}E_{55}d_{28}^{-2}\ \mathrm{Jy}.$$

$$f_{\nu,\mathrm{max},ssc} = 7.7\times 10^{-4}(1+z)^{-5/4}\epsilon_{B,-1}^{1/2}n_0^{5/4}E_{55}^{5/4}t_2^{1/4}d_{28}^{-2}\ \mathrm{Jy}.$$

Inferenza Bayesiana con la libreria Bilby

L'obiettivo principale dell'inferenza Bayesiana è quello di ottenere la **distribuzione di probabilità a posteriori** per una certa variabile θ una volta noti i valori misurati per quella variabile

$p(\theta|d)$

- θ corrisponde al set di parametri (15 per un evento BBH)
- d corrisponde al flusso di dati degli interferometri

Dobbiamo aggiungere il modello H con cui interpretare I dati

Teorema di Bayes

$$p(\theta|d,H) = \frac{L(d|\theta,H)\pi(\theta,H)}{Z(d|H)}$$

Prior: informazioni a priori sui parametri

Normalizzazione $Z(d|H) = \int p(\theta|d,H)\pi(\theta,H)d\theta$

In BILBY solitamente è integrata la funzione log-likelihood gaussiana

$$\ln L(\mathrm{d}|\theta) = -\frac{1}{2}\sum_k \{\frac{[d_k - \mu_k(\theta)]^2}{\sigma_k^2} + \ln(2\pi\sigma_k^2)\}$$

μ é il template selezionato

σ è il rumore del rivelatore

Analysis of the NS-BH event GW200115

- Download the data from **Gra**vitational-Wave **C**andidate **E**vent **D**ata**b**ase (**GraceDB**)
- Selection of fixed injected **parameters**
- Selection of the a **priori distribution** for every parameter we want to evaluate
- Selection of the **GW model** and **generate the wave**
- **Likelihood** function definition
- Select the **sampler** we want to use: Nestle, Dynesty, Pymultinest….
- **Run** the bayesian analysis

```
ifo_list = bilby.gw.detector.InterferometerList([])
for det in detectors:
    logger.info("Downloading analysis data for ifo {}".format(det))
    ifo = bilby.gw.detector.get_empty_interferometer(det)

    data = TimeSeries.fetch_open_data(det, start_time, end_time)

    #data_filt = data.bandpass(46,51).notch(60).notch(100).notch(120).notch(150).notch(509)

    ifo.strain_data.set_from_gwpy_timeseries(data)

    logger.info("Downloading psd data for ifo {}".format(det))
    psd_data = TimeSeries.fetch_open_data(det, psd_start_time, psd_end_time)
    psd_alpha = 2 * roll_off / duration
    psd = psd_data.psd(
        fftlength=duration, overlap=0, window=("tukey", psd_alpha), method="median")

    ifo.power_spectral_density = bilby.gw.detector.PowerSpectralDensity(

        frequency_array=psd.frequencies.value, psd_array=psd.value
    )
    ifo.maximum_frequency = maximum_frequency
    ifo.minimum_frequency = minimum_frequency
    ifo_list.append(ifo)
```

```
injection_parameters = dict(mass_1=5.7,mass_2=1.5,a_1=0.5,a_2=0.02,tilt_1=0.0,
    tilt_2=0,phi_12=0,phi_jl=0.0,luminosity_distance=300.0,theta_jn=0.4,psi=2.659,
    phase=1.3,geocent_time=1263097407.7,ra=1.375,dec=-1.2108,
)
```

Analysis of the NS-BH event GW200115

- Download the data from **Gra**vitational-Wave **C**andidate **E**vent **D**ata**b**ase (**GraceDB**)
- Selection of fixed injected **parameters**
- Selection of the a **priori distribution** for every parameter we want to evaluate
- Selection of the **GW model** and **generate the wave**
- **Likelihood** function definition
- Select the **sampler** we want to use: Nestle, Dynesty, Pymultinest….
- **Run** the bayesian analysis

```
priors = bilby.gw.prior.PriorDict()
print(priors)

for key in ["a_2","tilt_1","tilt_2","phi_12","phi_jl","psi","ra","dec","geocent_time","phase"]:
    priors[key] = injection_parameters[key]
print(priors)


#priors['chirp_mass'] = bilby.core.prior.Gaussian(3.198, 0.1, name='chirp_mass', unit='$M_{\\odot}$')
#priors['mass_ratio'] = bilby.prior.Uniform(name='mass_ratio', latex_label='$q$', minimum=0.05, maximum=1.0

#priors['chirp_mass'] = bilby.core.prior.Gaussian(1.215, 0.1, name='chirp_mass', unit='$M_{\\odot}$')

priors['mass_1'] = bilby.prior.Uniform(name='mass_1', minimum=3, maximum=8)
priors['mass_2'] = bilby.prior.Uniform(name='mass_2', minimum=1.2, maximum=3)
priors['theta_jn'] = bilby.core.prior.Sine(name="theta_jn", minimum=0, maximum=1.0)
priors['a_1'] = bilby.core.prior.Uniform(name="chi_1", minimum=-0.5, maximum=0.5)
priors['luminosity_distance'] = bilby.core.prior.Uniform(name="luminosity_distance",
                                                         minimum=30, maximum=500)
```

```
waveform_arguments = dict(
    waveform_approximant="IMRPhenomXPHM",
    reference_frequency=50,
    minimum_frequency=25.0,
    maximum_frequency=300,
    catch_waveform_errors =False
)
```

```
waveform_generator = bilby.gw.WaveformGenerator(

                    duration=duration,
                    sampling_frequency=sampling_frequency,
                    frequency_domain_source_model=bilby.gw.source.lal_binary_black_hole,
                    parameter_conversion=bilby.gw.conversion.convert_to_lal_binary_black_hole_parameters,
                    waveform_arguments=waveform_arguments,
                )
```

Analysis of the NS-BH event GW200115

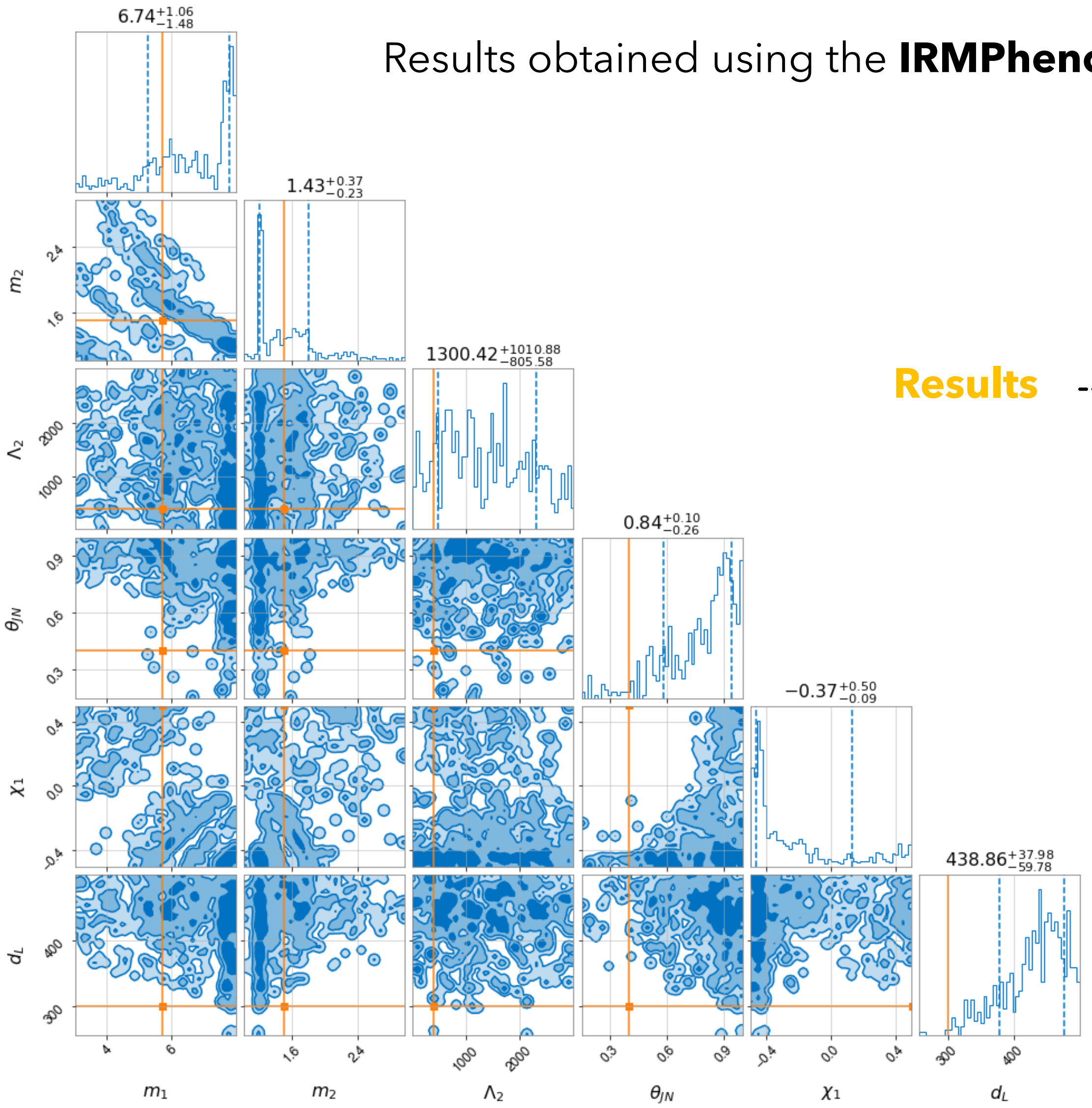
- Download the data from **Gra**vitational-Wave **C**andidate **E**vent **D**ata**b**ase (**GraceDB**)
- Selection of fixed injected **parameters**
- Selection of the a **priori distribution** for every parameter we want to evaluate
- Selection of the **GW model** and **generate the wave**
- **Likelihood** function definition
- Select the **sampler** we want to use: Nestle, Dynesty, Pymultinest….
- **Run** the bayesian analysis

```
likelihood = bilby.gw.GravitationalWaveTransient(
    interferometers=ifo_list,
    waveform_generator=waveform_generator,
    time_marginalization=False,
    phase_marginalization=False,
    distance_marginalization=False,
    priors=priors)
```

```
result = bilby.run_sampler(
    likelihood=likelihood,
    priors=priors,
    sampler='nestle',
    npoints=50,
    conversion_function=bilby.gw.conversion.generate_all_bbh_parameters)
```

Analysis of the NS-BH event GW200115

Results obtained using the **IRMPhenomNSBH** phenomenological model visualised in a corner plot



Results ---------→

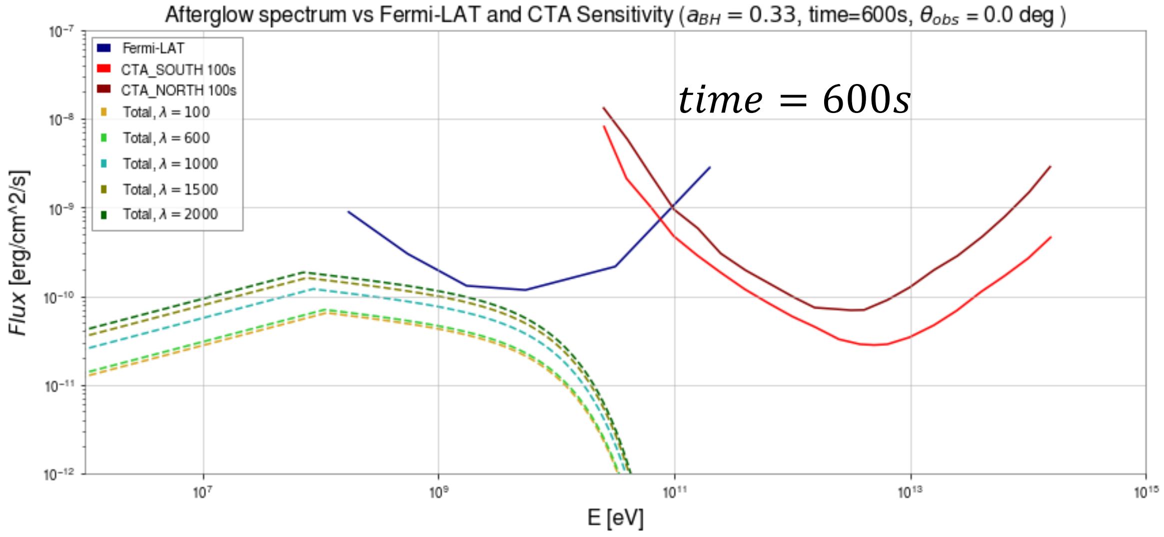
Model	m_{BH} $[M_\odot]$	m_{NS} $[M_\odot]$	a_{BH}	d_L[Mpc]	λ
Article	$5.7^{+1.8}_{-2.1}$	$1.5^{+0.7}_{-0.3}$	$0.33^{+0.48}_{-0.29}$	300^{+150}_{-100}	/
IRMPhenomXHPM	$7.4^{+0.38}_{-1.85}$	$1.30^{+0.81}_{-0.05}$	$-0.38^{+0.47}_{-0.08}$	$422.84^{+51.66}_{-60.75}$	/
IRMPhenomNSBH	$6.74^{+1.06}_{-1.48}$	$1.43^{+0.37}_{-0.23}$	$-0.37^{+0.50}_{-0.09}$	$438.86^{+37.98}_{-59.78}$	$\lambda = 1300.42^{+1010.88}_{-805.58}$

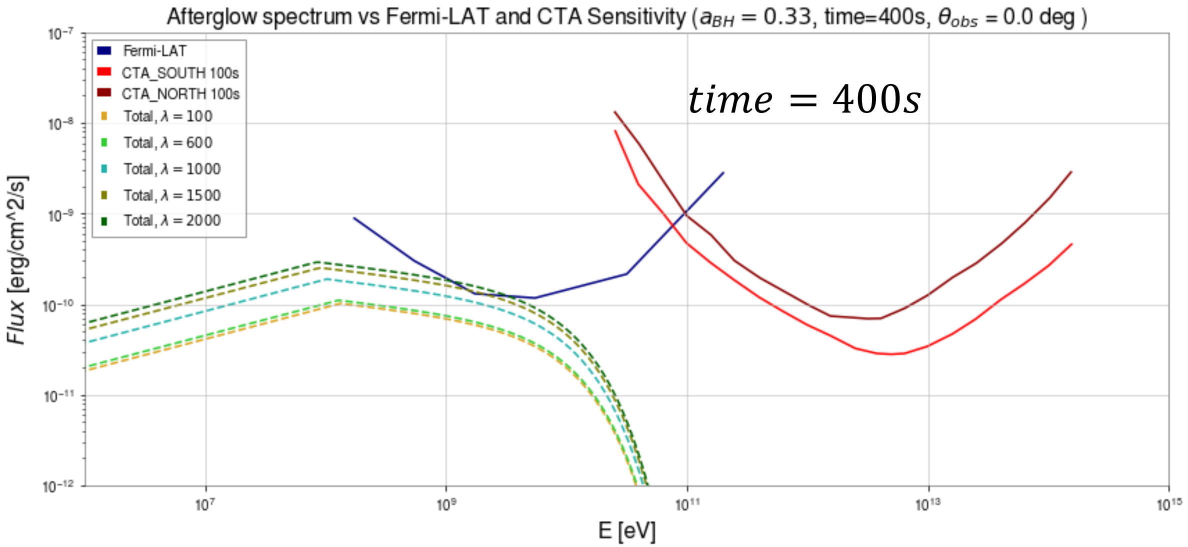
Conclusions:

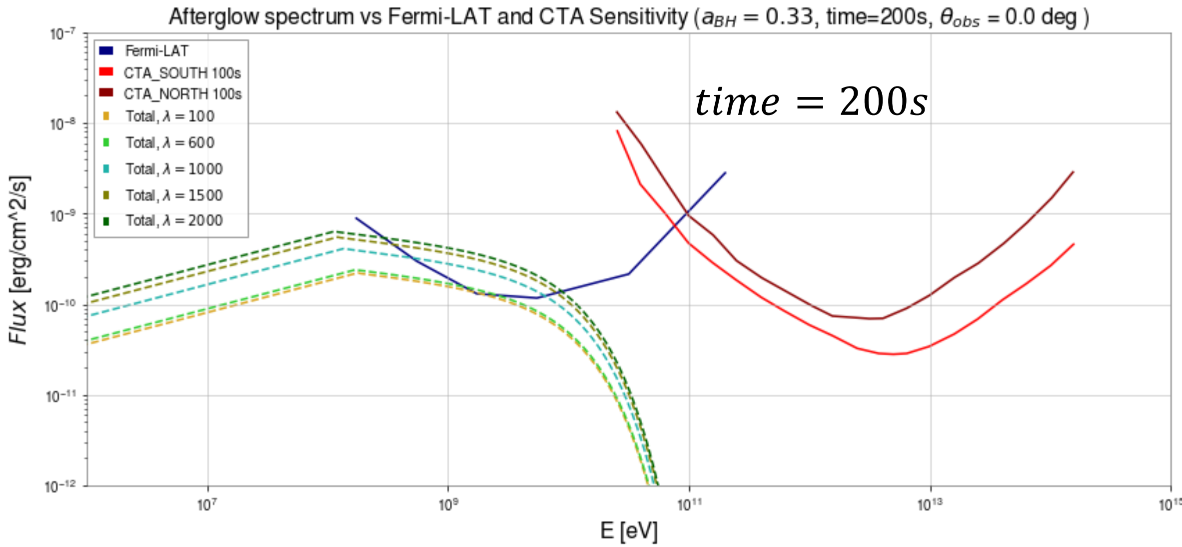
- Error-compatible parameter values
- λ parameter difficult to estimate

Afterglow spectrum vs Fermi-LAT e CTA

Let's see what happens if we observe the emission at a time closer to the trigger







Spettro afterglow vs Fermi-LAT e CTA

Per valutare la probabilità di rivelazione abbiamo definito un semplice parametro

$$Detectability = \frac{Flux(\nu_{max,sens}) - \max\_sens}{\max\_sens}$$