Synchrotron Self-Compton code for multi-messenger study of Black Hole-Neutron Star coalescence events

Speaker:
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Supervisors:
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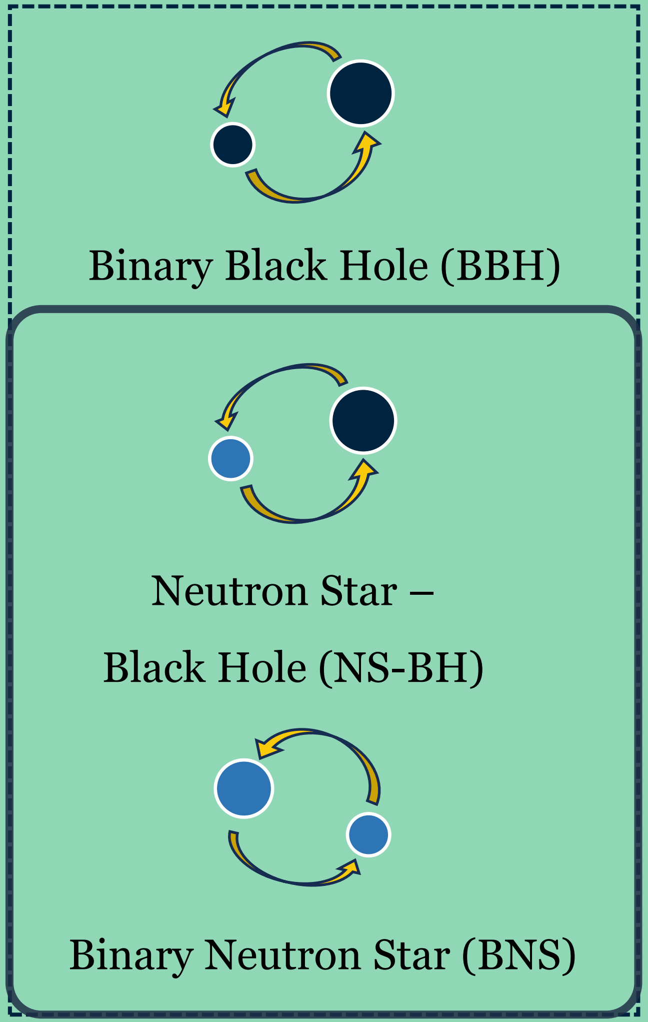
Sara Cutini

Compact Binary objects coalescence:



Binary Black Hole (BBH)

Neutron Star –

Black Hole (NS-BH)

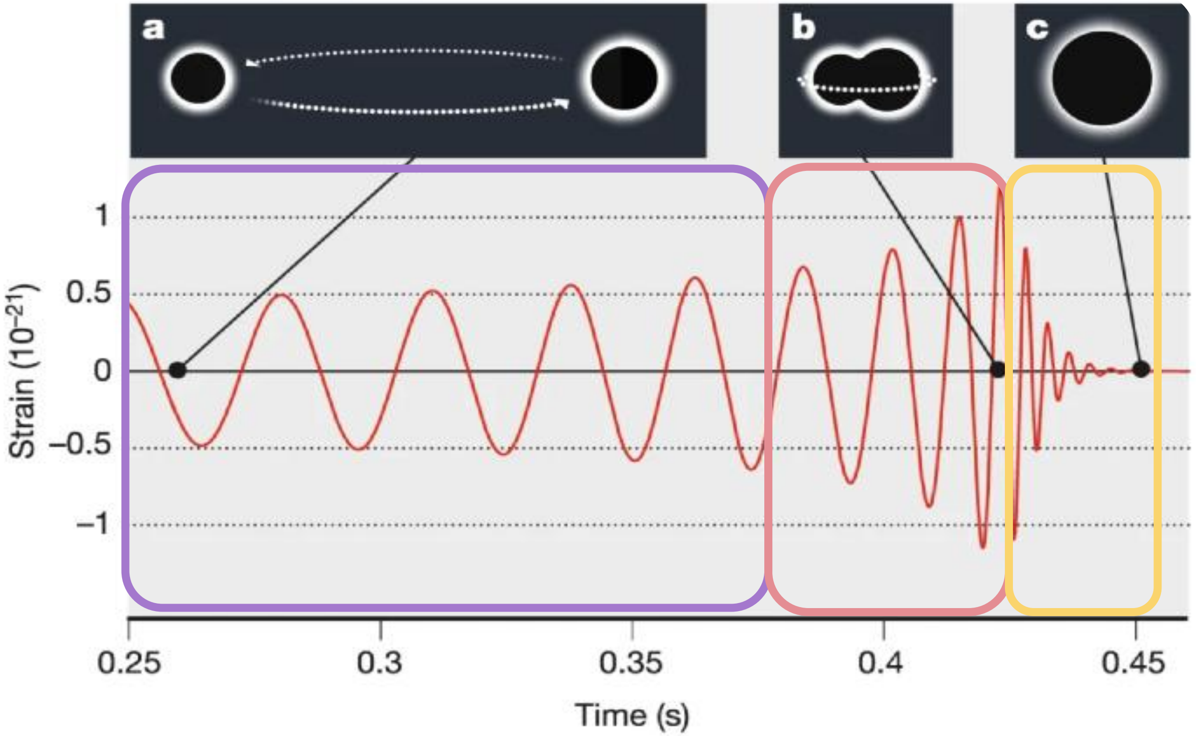
Binary Neutron Star (BNS)

Tidal disruption (Mass Remnant)

↓

Multi-messenger Astrophysics

1) Gravitational Wave signal



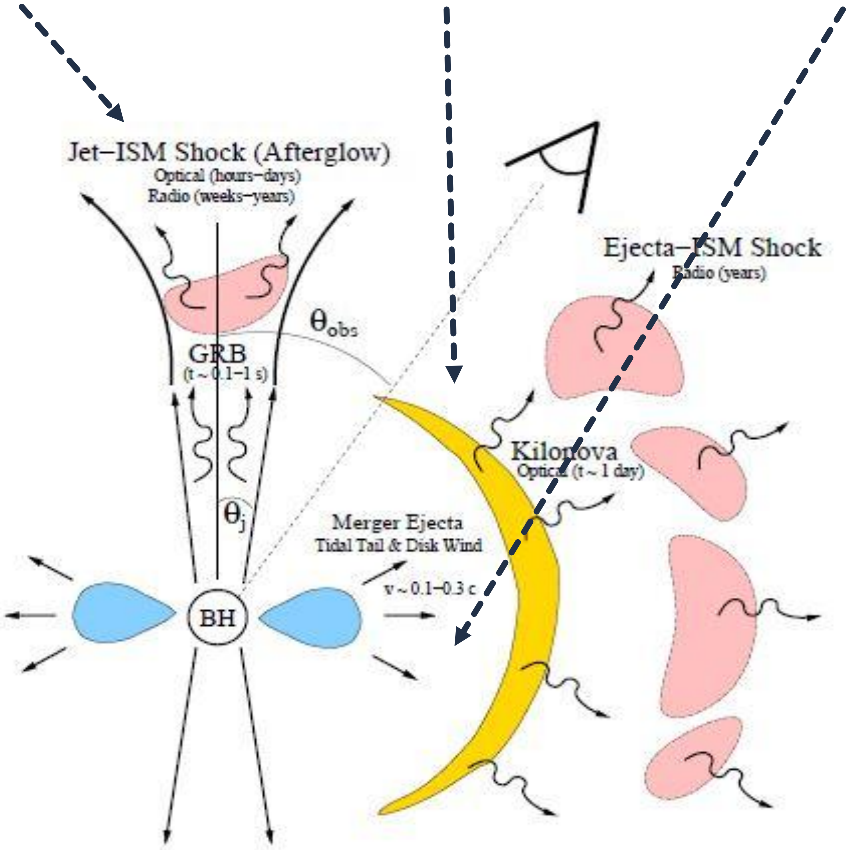
Formation *and* ***inspiral***

Merging phase

Ringdown and post-merger phase

2) EM counterpart: Different emissions

- **Relativistic jet**
- **Dynamical ejecta**
- **Wind ejecta**



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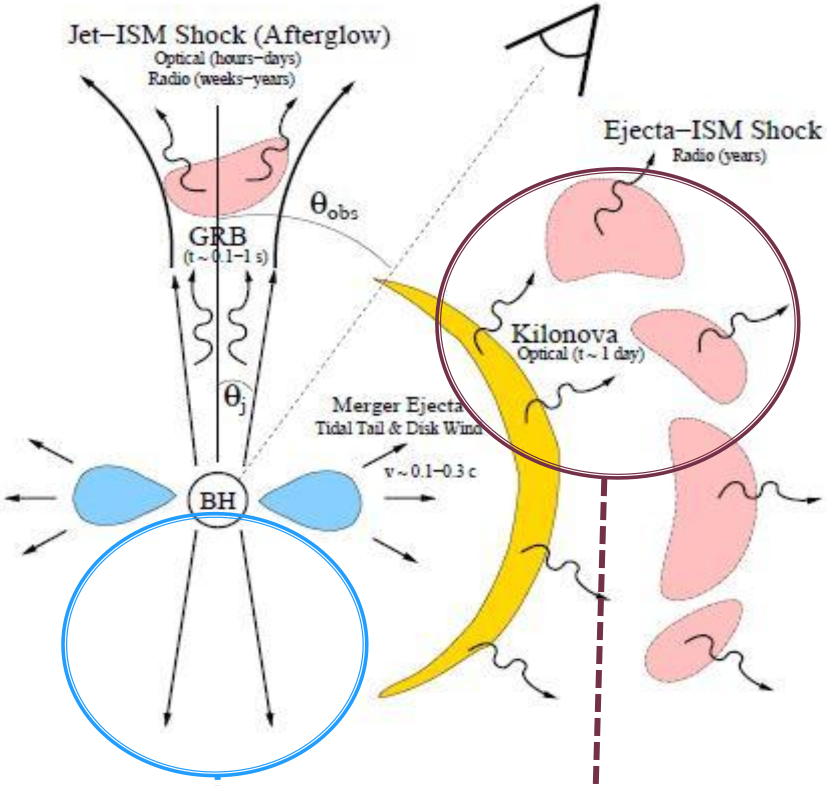
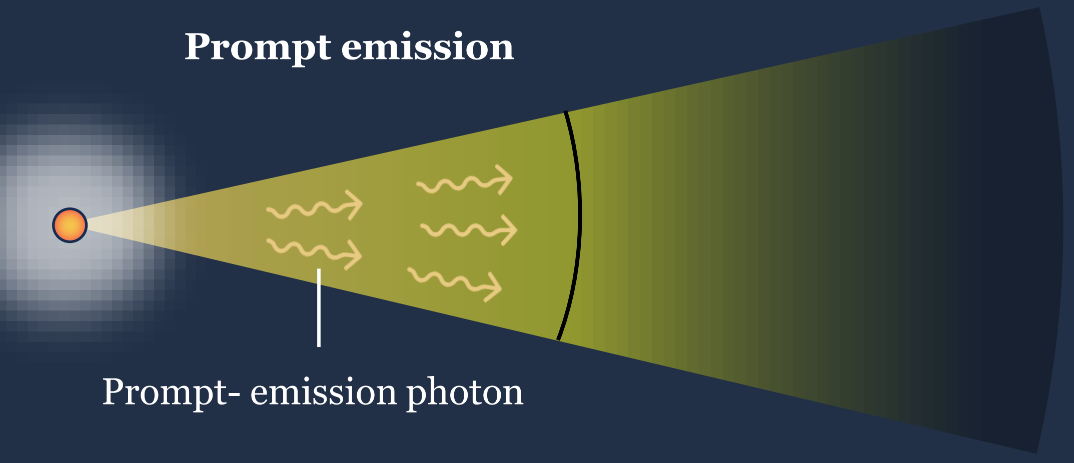


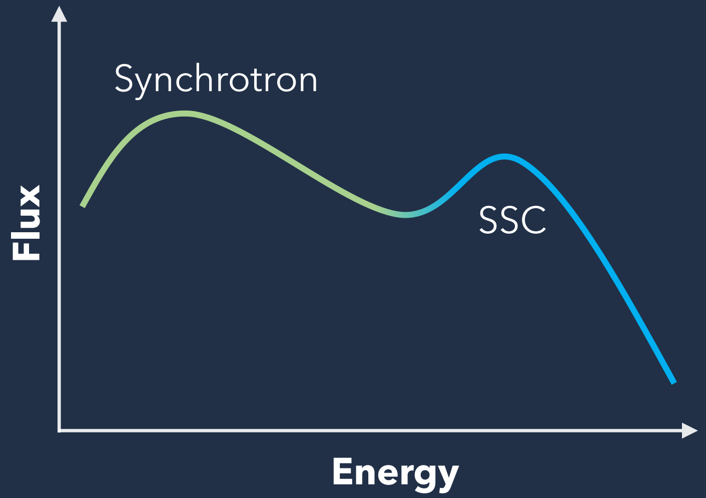
- **Kilonova**: r process

- **Gamma-Ray Burst**: Prompt and Afterglow emission

2) EM counterpart: Different emissions

Mass Remnant





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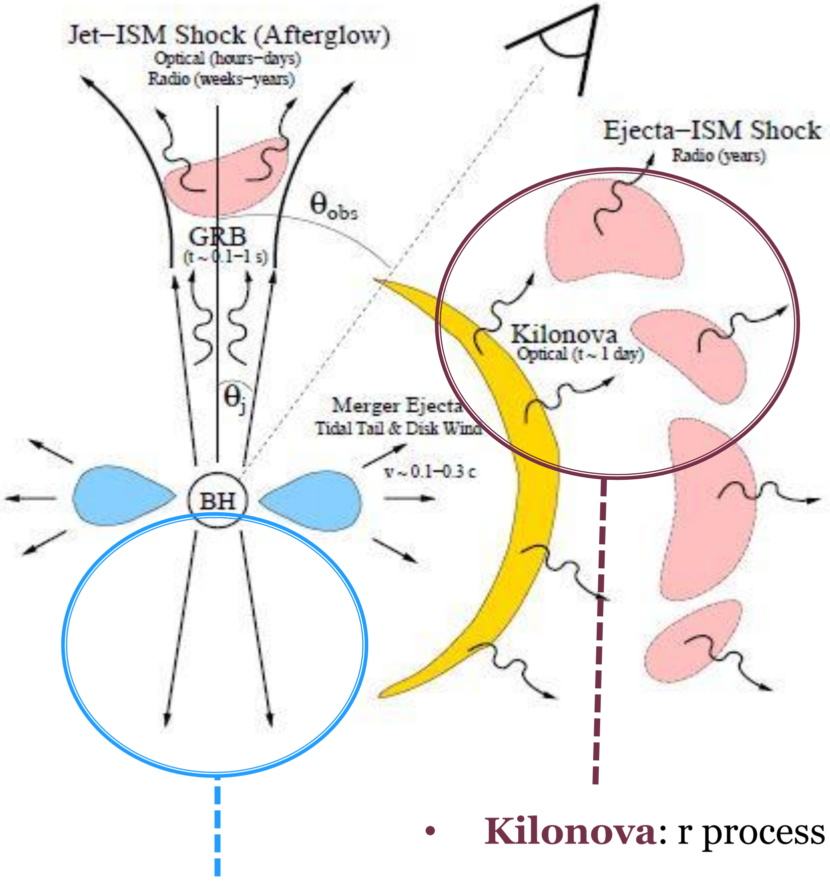

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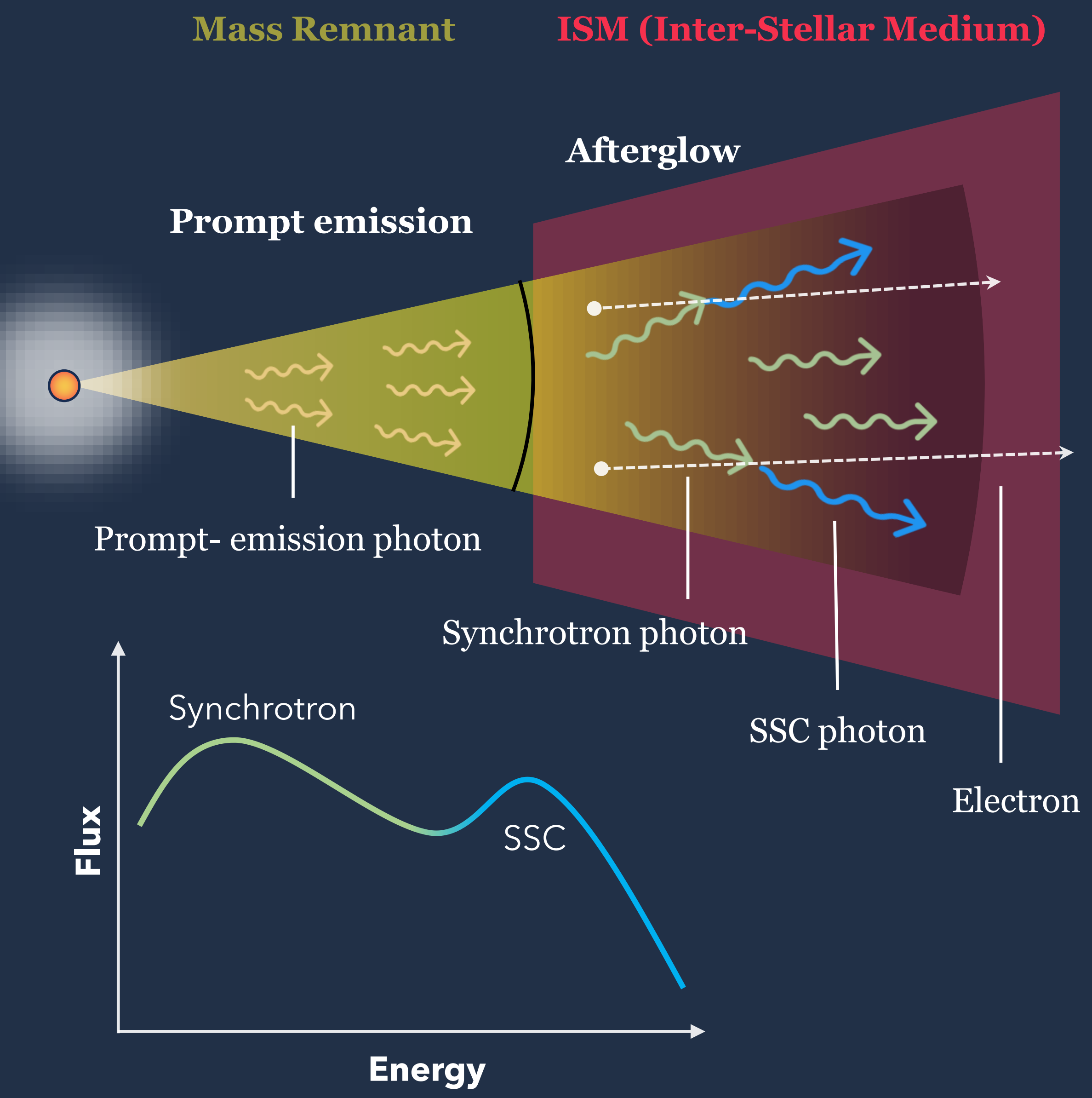
- **Gamma-Ray Burst**: Prompt and Afterglow emission



Mass Remnant

ISM (Inter-Stellar Medium)

Afterglow

Prompt emission

Prompt- emission photon

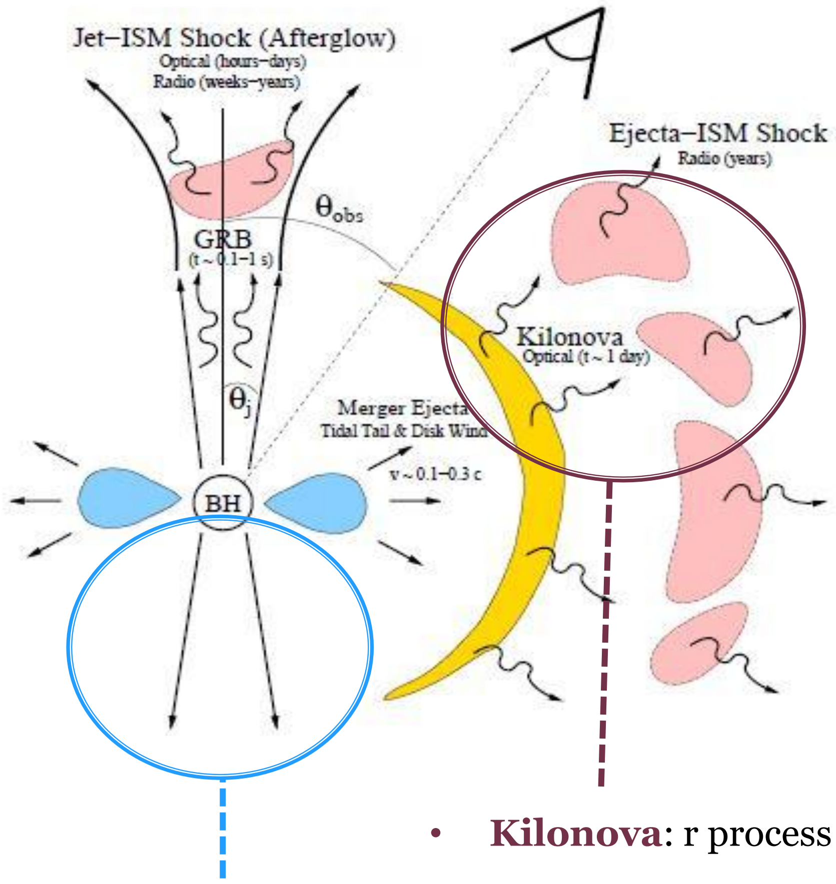
Synchrotron photon

SSC photon

Electron

2) EM counterpart: Different emissions

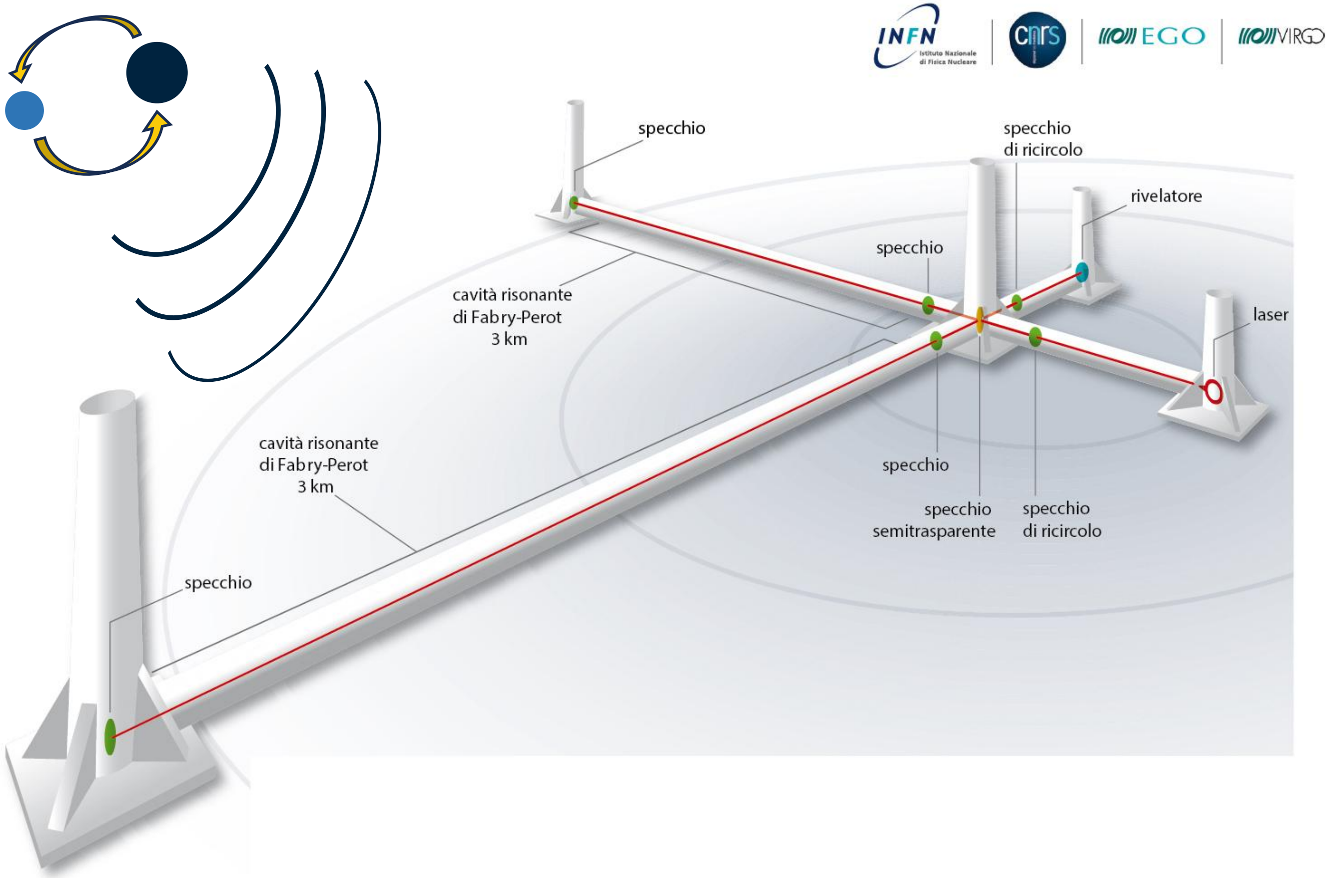
- **Relativistic jet**
- **Dynamical ejecta**
- **Wind ejecta**



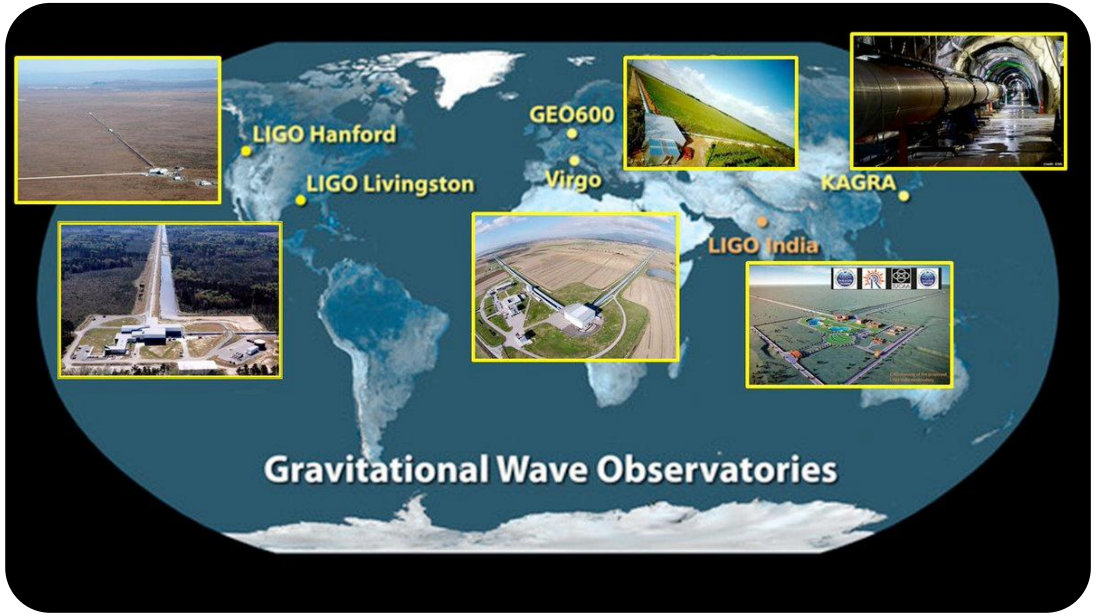
- **Kilonova**: r process

- **Gamma-Ray Burst**: Prompt and Afterglow emission

GW detectors

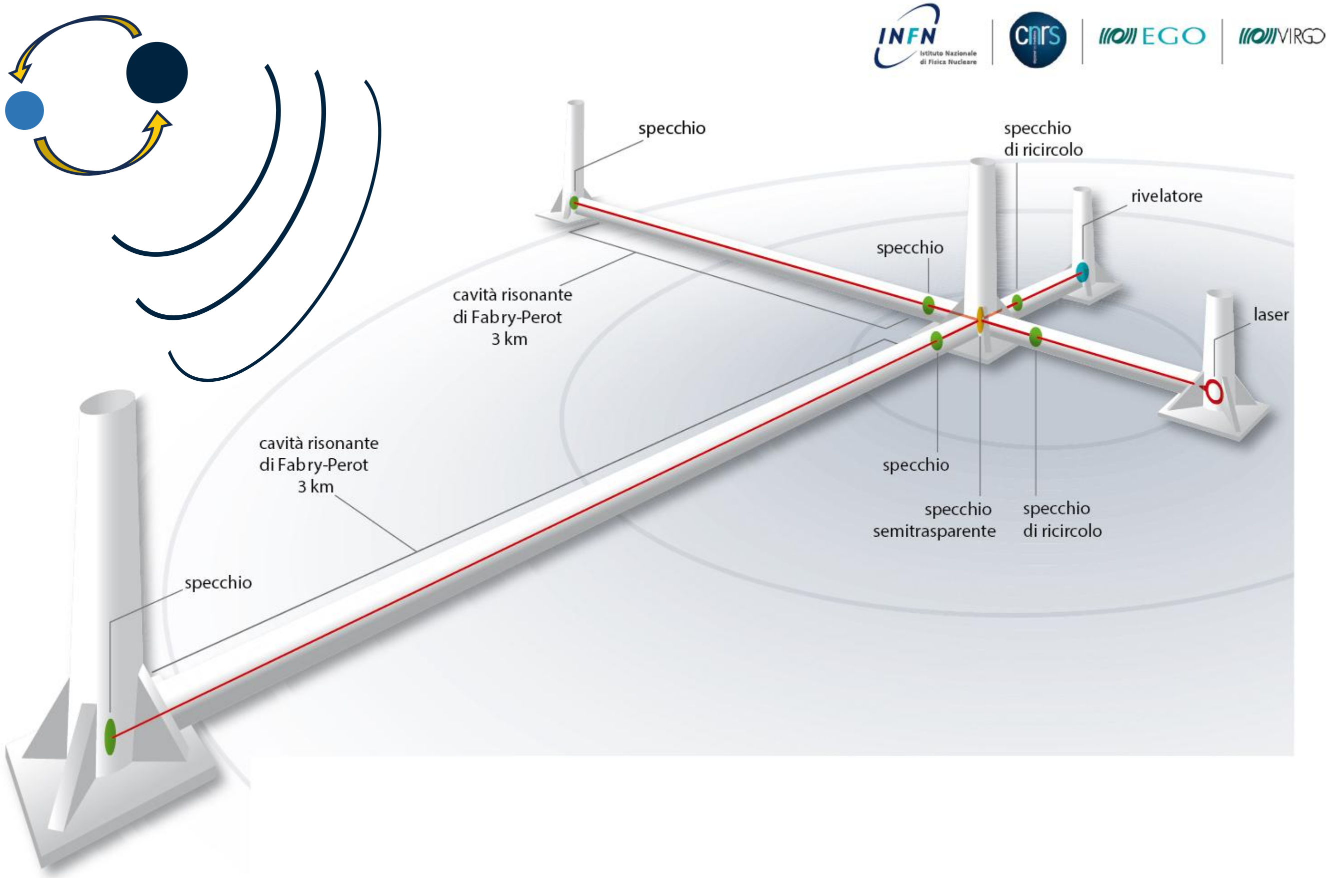


Schematic representation of the LIGO – VIRGO - KAGRA detectors



***GW** Interferometers LVK **community** around the world*

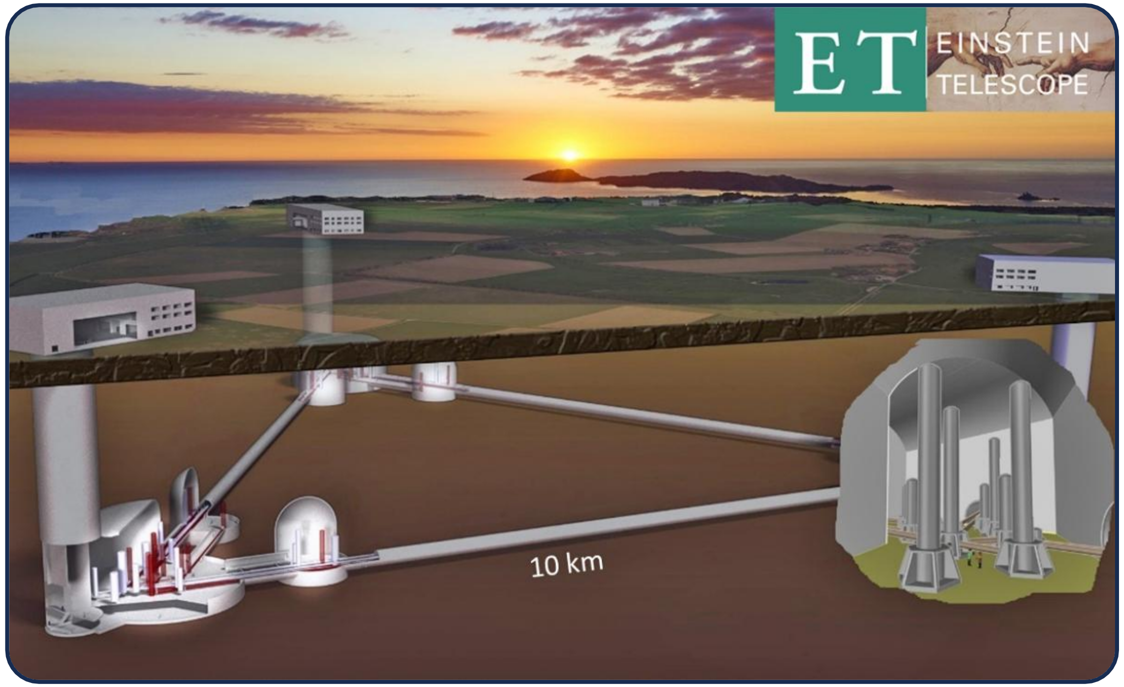
GW detectors



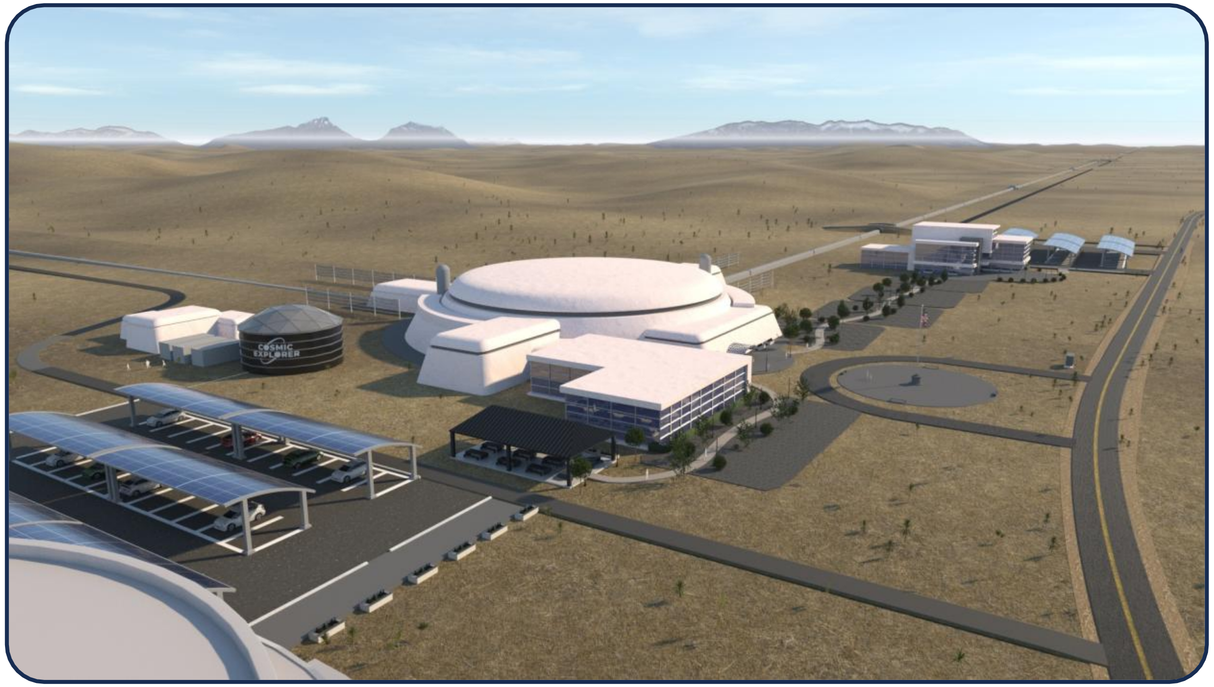
Schematic representation of the LIGO – VIRGO - KAGRA detectors

***VIRGO** (Cascina- Italy)*

GW Future Detectors



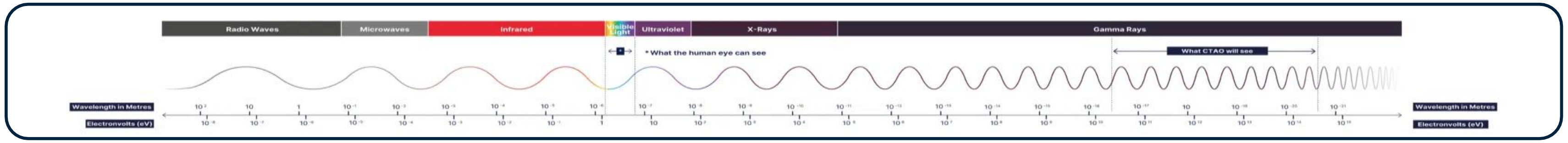
Schematic representation of the ***Einstein Telescope (ET)*** *detector*



Schematic representation of the ***Cosmic Explorer (CE)*** *detector*

Cherenkov Telescopes Array Observatory

- It catches the **Cherenkov light** from EM showers
- **Energy** range: 20 GeV- 300 TeV



Cherenkov Telescopes Array Observatory

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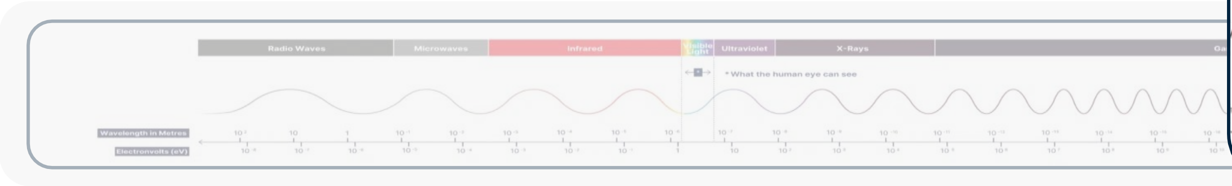
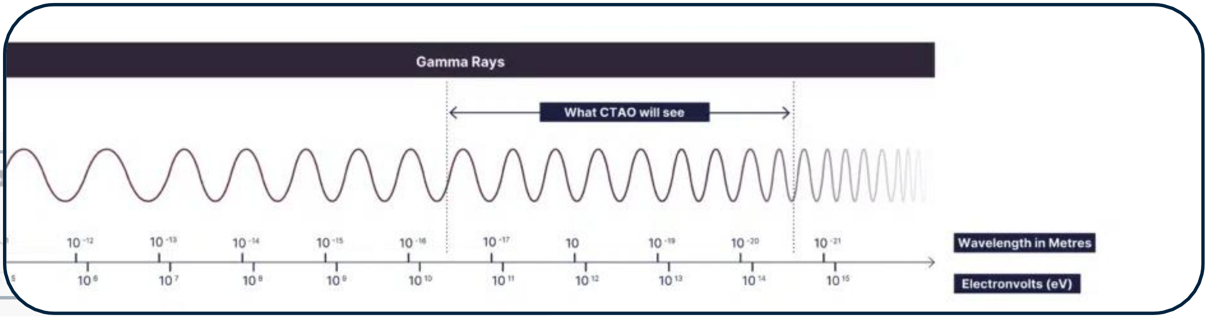
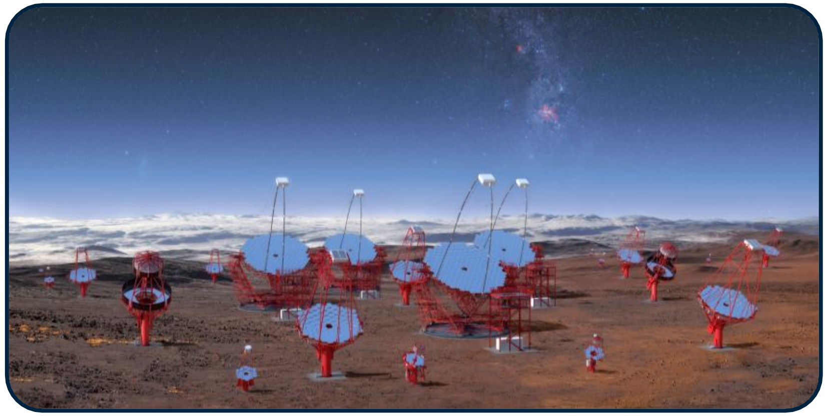
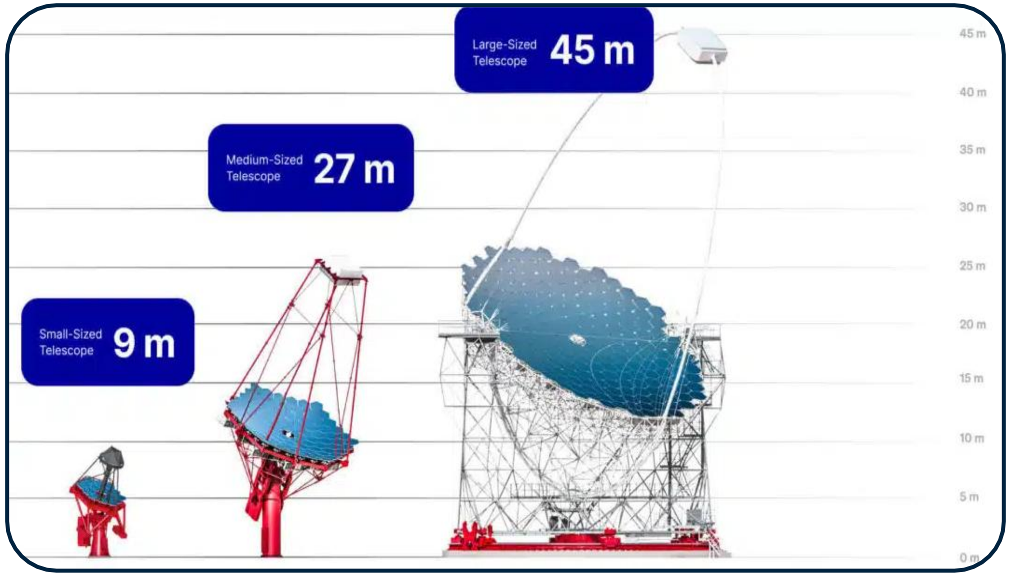


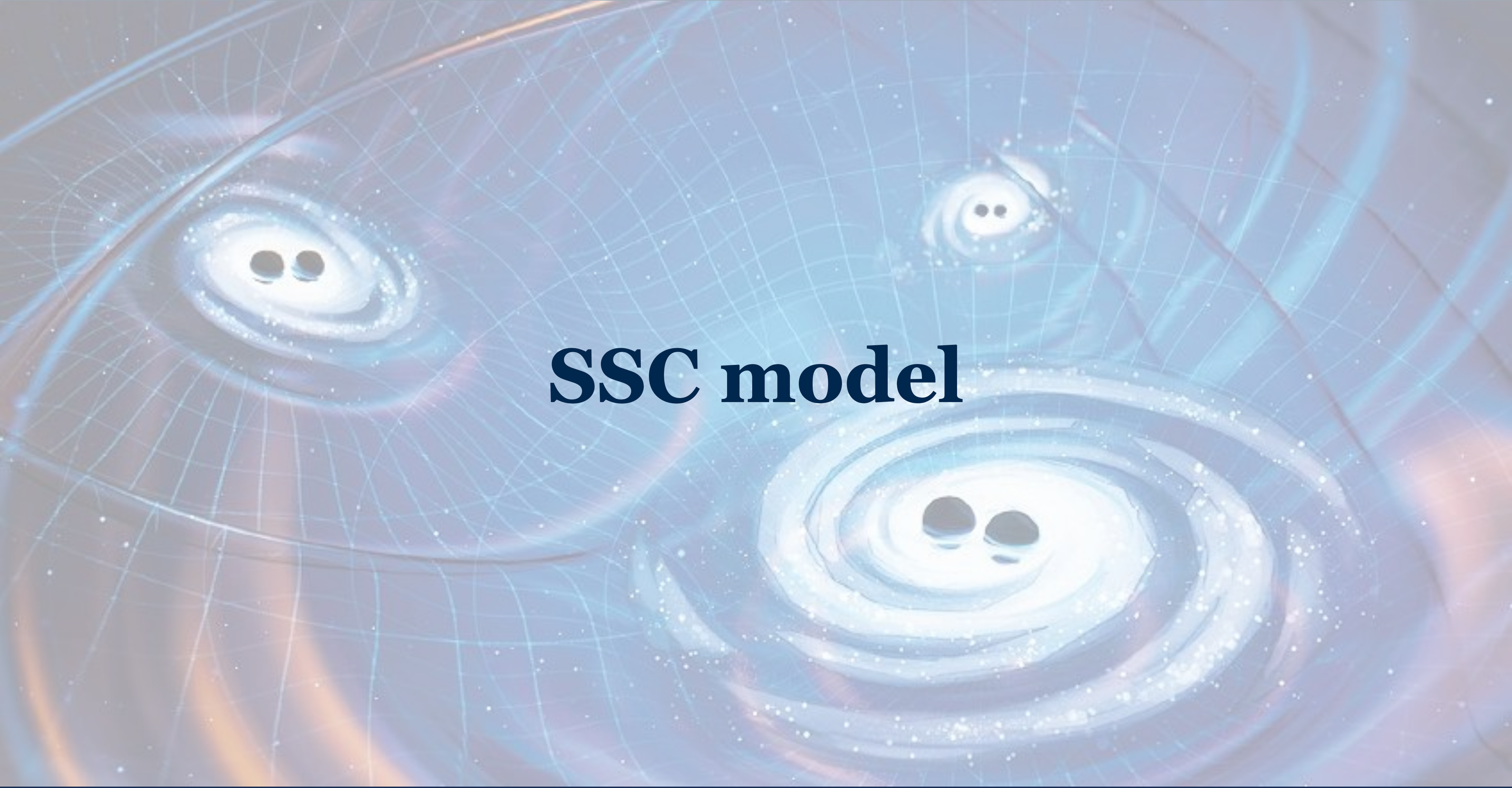


- More than **60** telescopes of different **sizes** in the north and south hemisphere:

  - **Large**-Sized, low-energy range (**20 to 150 GeV**).
  - **Medium**-Sized, core energy range (**150 GeV to 5 TeV**).
  - **Small**-Sized above **5 TeV**.







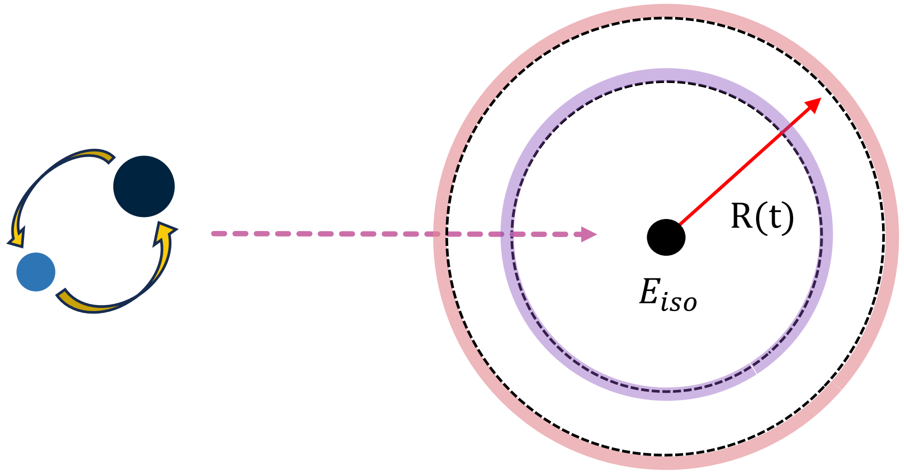
SSC model

Blandford & McKee solutions

R. Blandford & C. McKee (1976) – *Self-Similar Solutions for Relativistic Blast Waves*

- Ultra-relativistic spherical blast wave enclose by a strong shock
- Fixed amount of Energy in a uniform medium

Sedov-Taylor solution in relativistic regime: $\Gamma \gg 1$ (We consider $\Gamma > 5$ in this work)



merger

expanding spheric blast wave

$$\Gamma^2 = \frac{E_{iso}}{Mc^2} \qquad M(R) = \frac{4\pi R^3 n m_p}{3}$$

M = mass of the explosion products

$$\Gamma = \left(\frac{3E_{iso}}{4\pi n\, m_p\, R^3 c^2}\right)^{1/2}$$

$$\Big\downarrow \quad \textit{Full computation}$$

$$\Gamma = \left(\frac{17E_{iso}}{16\pi n\, m_p R^3\ c^2}\right)^{1/2}$$

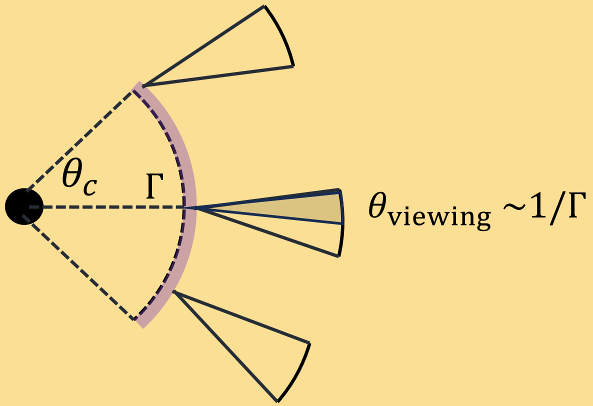
From Sphere to expanding cone

Opening angle θ_c ↓ $\theta_{\text{viewing}} \sim 1/\Gamma$

No lateral expansion until

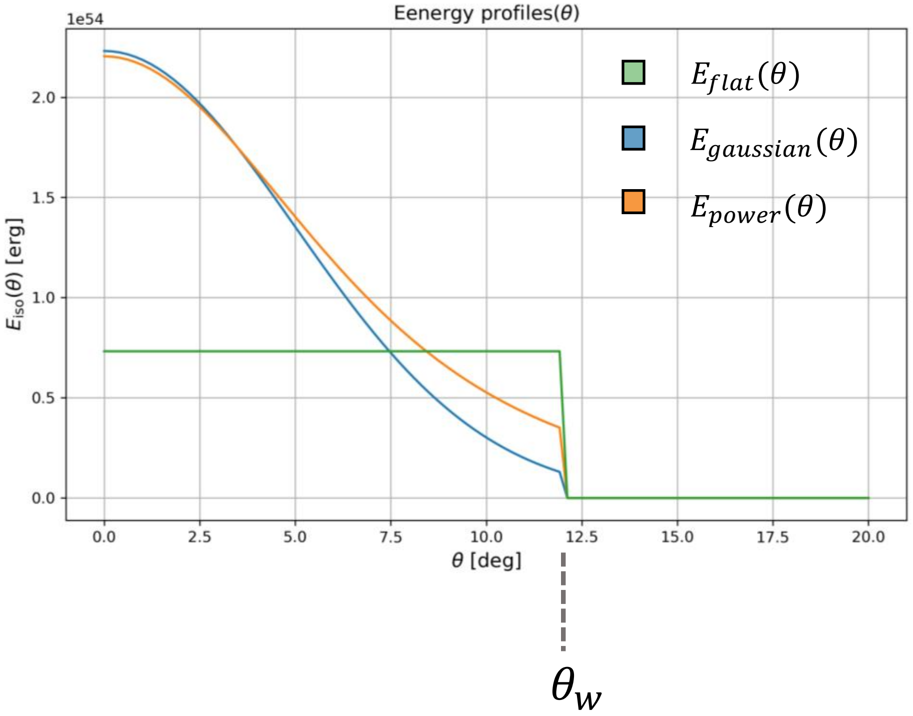
$\Gamma \gg 1/\theta_c$

We can consider every portion of the jet is like a mini spheric blast wave



Structured jet model: θ dependence

Strucured jet model $\boldsymbol{E_{isotropic} = E(\theta)}$



Top hat model

$$E_{flat}\begin{cases} E_{iso,0}\,, & \theta \le \theta_w \\ 0, & \theta > \theta_w \end{cases}$$

↓

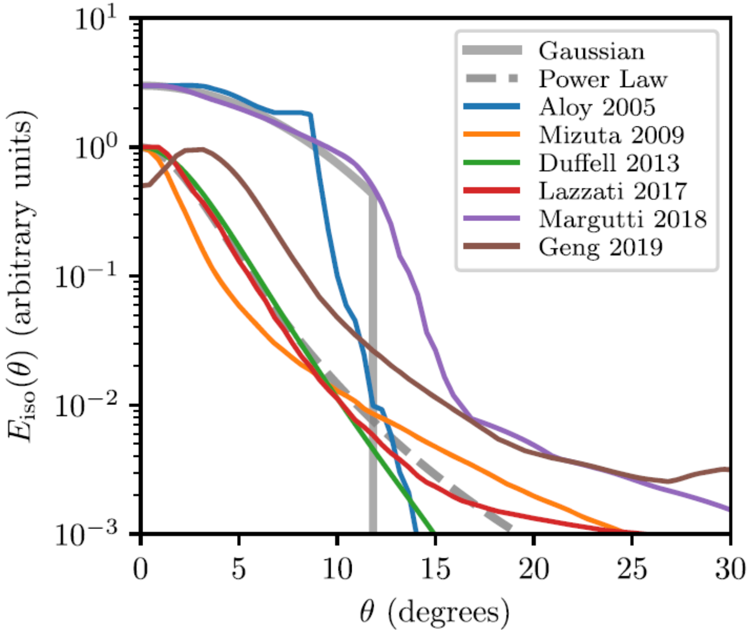
Gaussian model

$$E(\theta)\begin{cases} E_{iso,0}\exp\left(-\frac{\theta^2}{2\theta_c^2}\right), & \theta \le \theta_w \\ 0, & \theta > \theta_w \end{cases}$$

Power law model

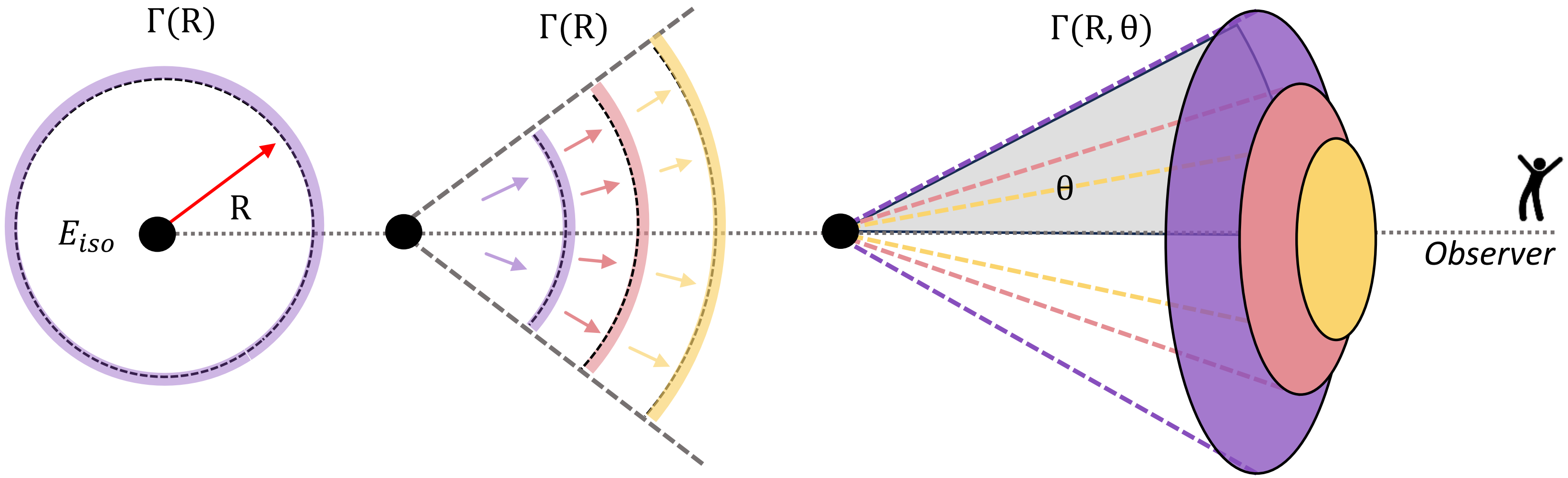
$$E(\theta)\begin{cases} E_{iso,0}\left(1+\frac{\theta^2}{b\theta_c^2}\right), & \theta \le \theta_w \\ 0, & \theta > \theta_w \end{cases}$$

Ryan et al. 2020



Structured jet model: θ dependence

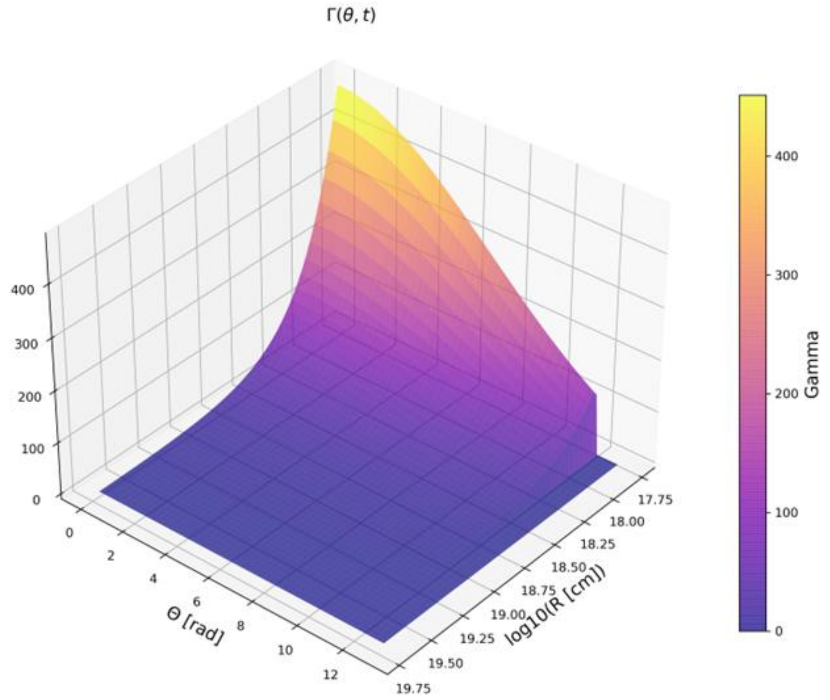
In the second step we build a structured jet model: **expanding shells (θ)** • $E_{isotropic} = E(\theta)$



expanding spheric blast wave

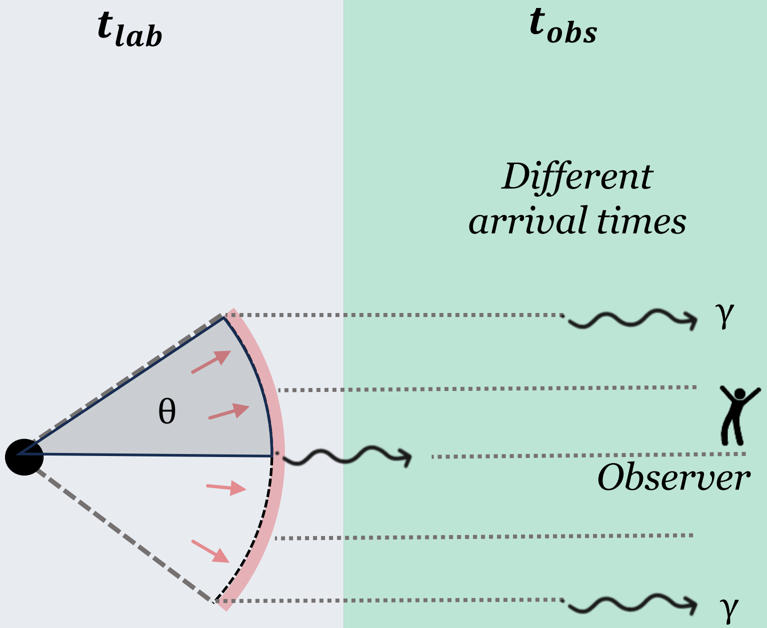
expanding cone blast wave

expanding shells (θ)



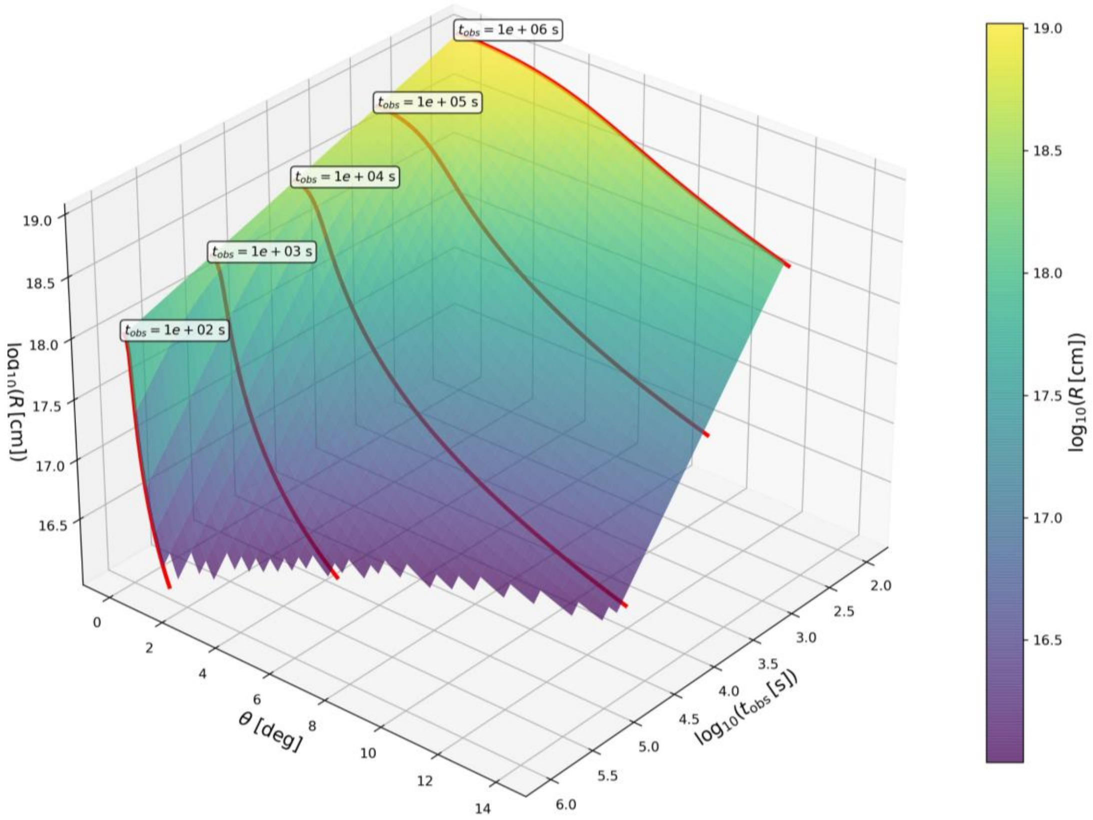
$$\Gamma = \left(\frac{17E_{iso}(\theta)}{16\pi n\, m_p R^3\ c^2}\right)^{1/2}$$

Arrival times: On Axis



$$t_{obs} = (1+z)\left[t_{lab}(R) - \frac{R\cos\theta}{c}\right]$$

$$t_{obs} = (1+z)\left[\int_0^R \frac{dR'}{2c\Gamma^2(R')}\right] + \frac{R\theta^2}{2c}$$



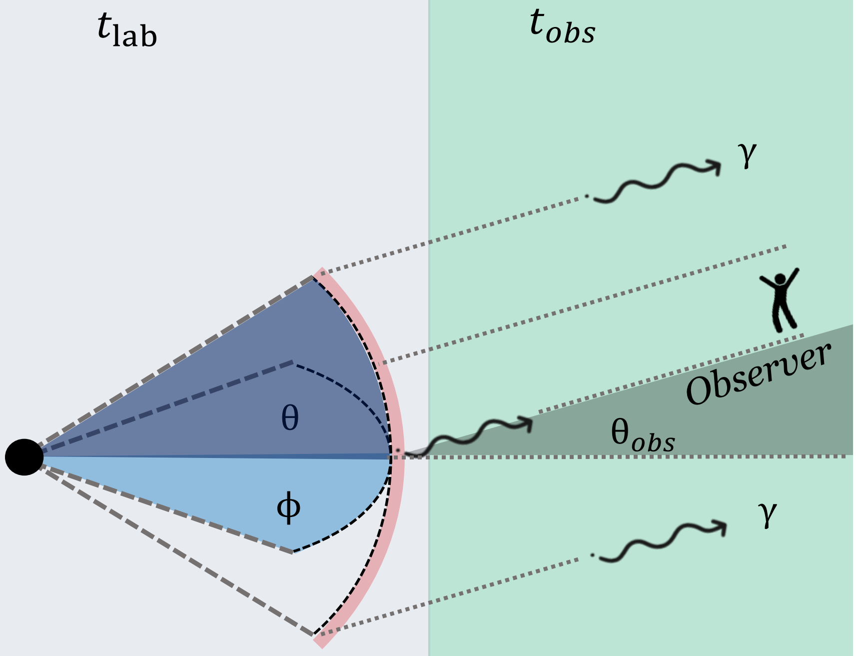
Solution Condition

$t_{obs}(\mathrm{R},\theta) = \text{constant}$

Equal Arrival Time Surface

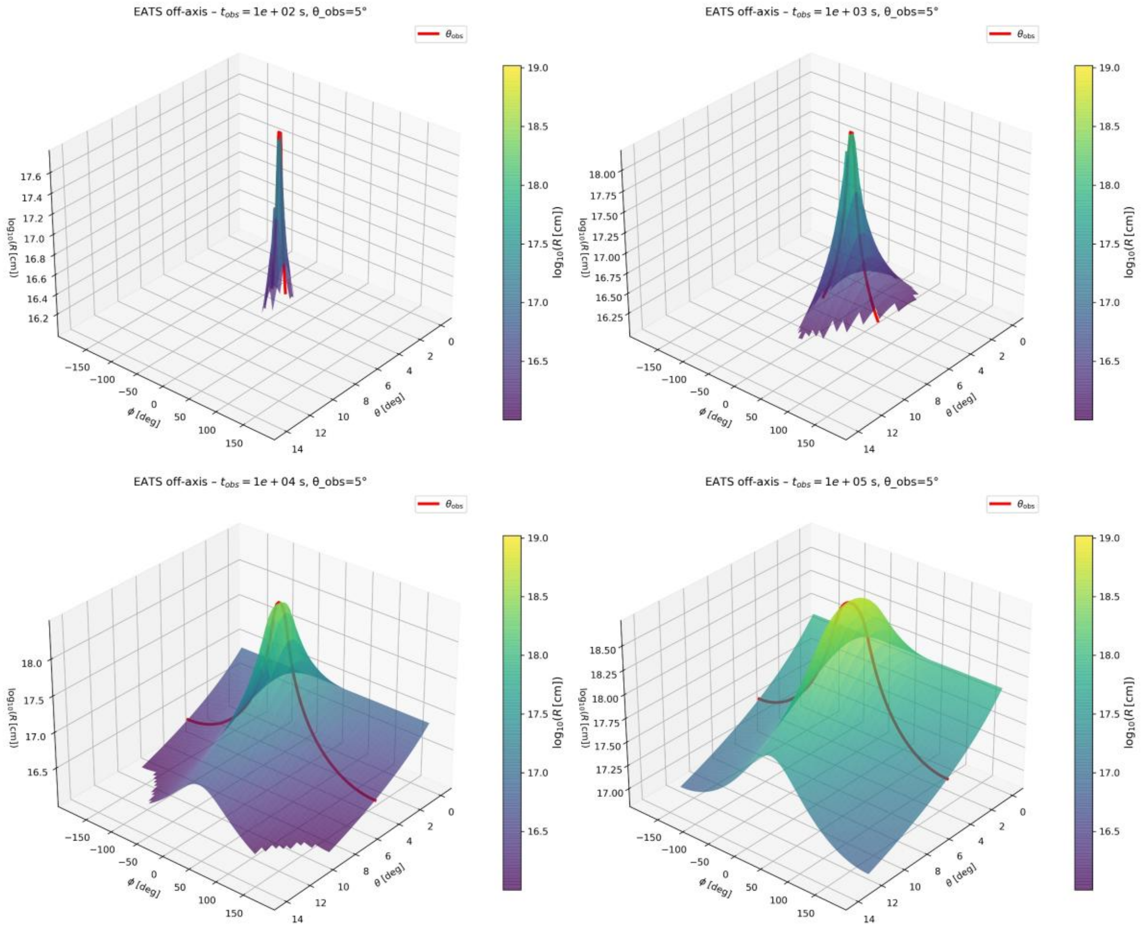
$\mathrm{R}(\theta, t_{obs})$

Arrival times: Off Axis



$$t_{obs} = (1+z)\left[t_{lab}(R) - \frac{\mathrm{R(t)\mu(\theta,\phi)}}{\mathrm{c}}\right]$$

$$\mu(\theta,\phi,\theta_{obs})) = \cos\theta\,\cos\theta_{obs} + \sin\theta\,\sin\theta_{obs}\,\cos\phi$$



Solution Condition

$$t_{obs}(\mathrm{R},\theta,\phi,\theta_{obs}) = \text{constant}$$

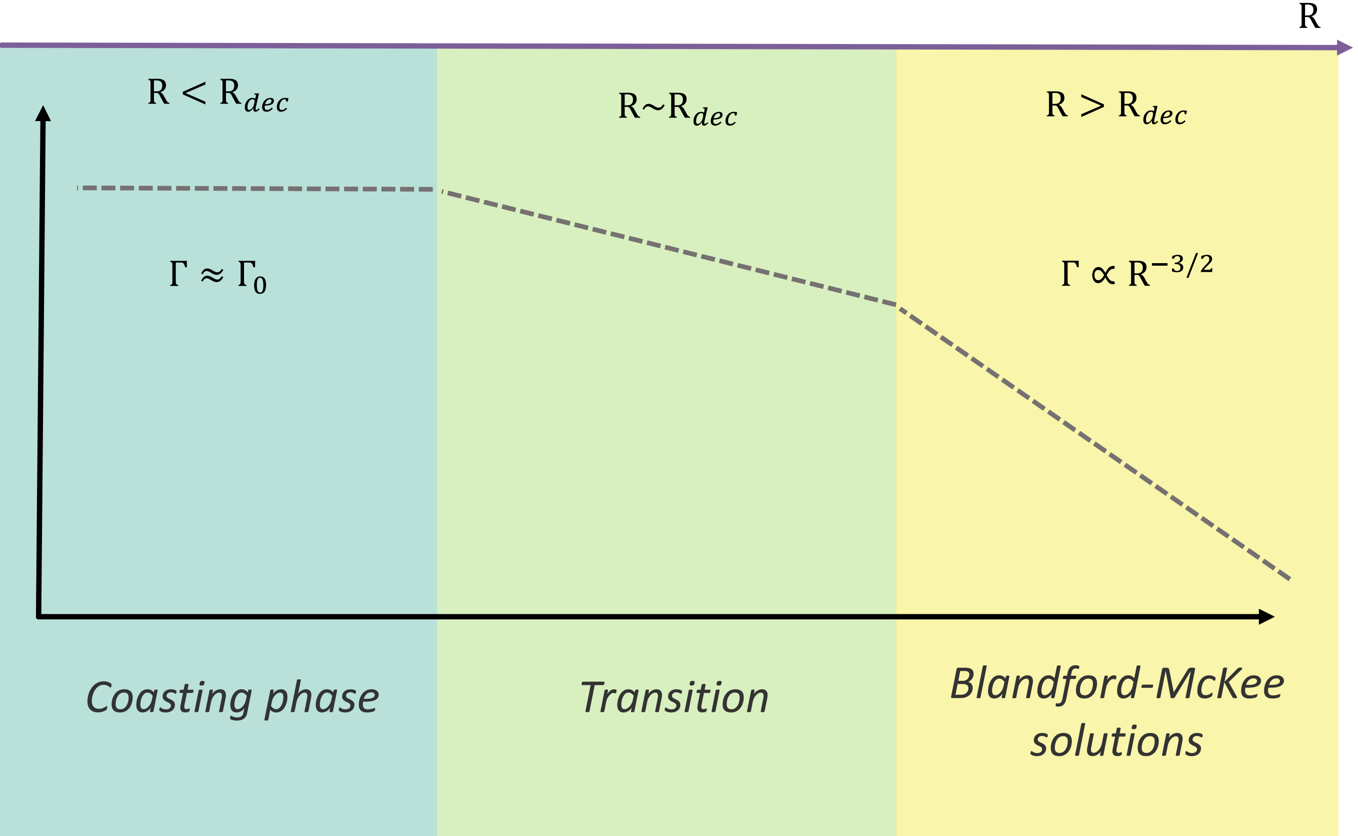
Equal Arrival Time Surface

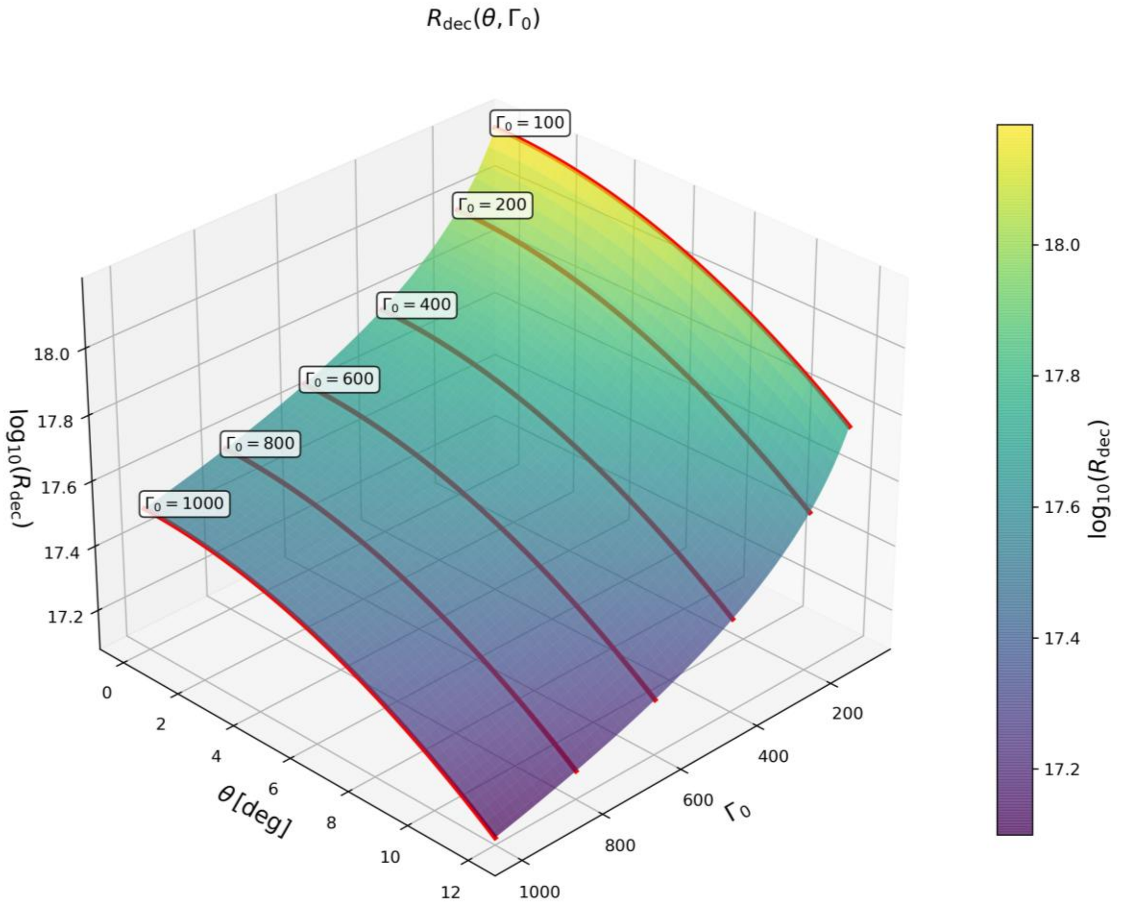
$$\mathrm{R}(\theta,\phi,\theta_{obs},t_{obs})$$

Deceleration Radius

Not every *R* of the *EATS* is valid*: R* must be > *deceleration Radius* (R_{dec})

$$R_{dec} = \left(\frac{3E(\theta)}{4\pi n m_p c^2 \Gamma_0^2}\right)^{1/3}$$

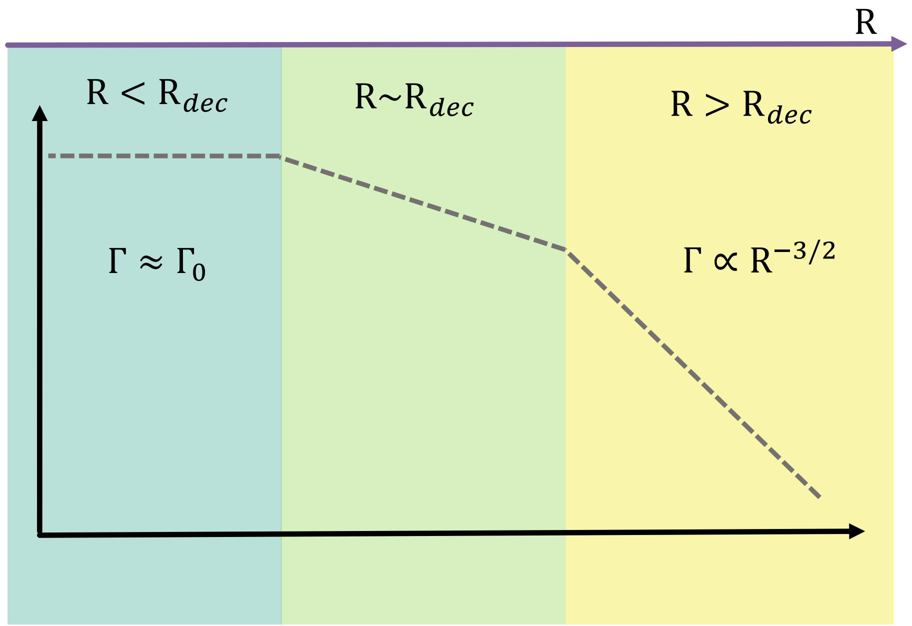


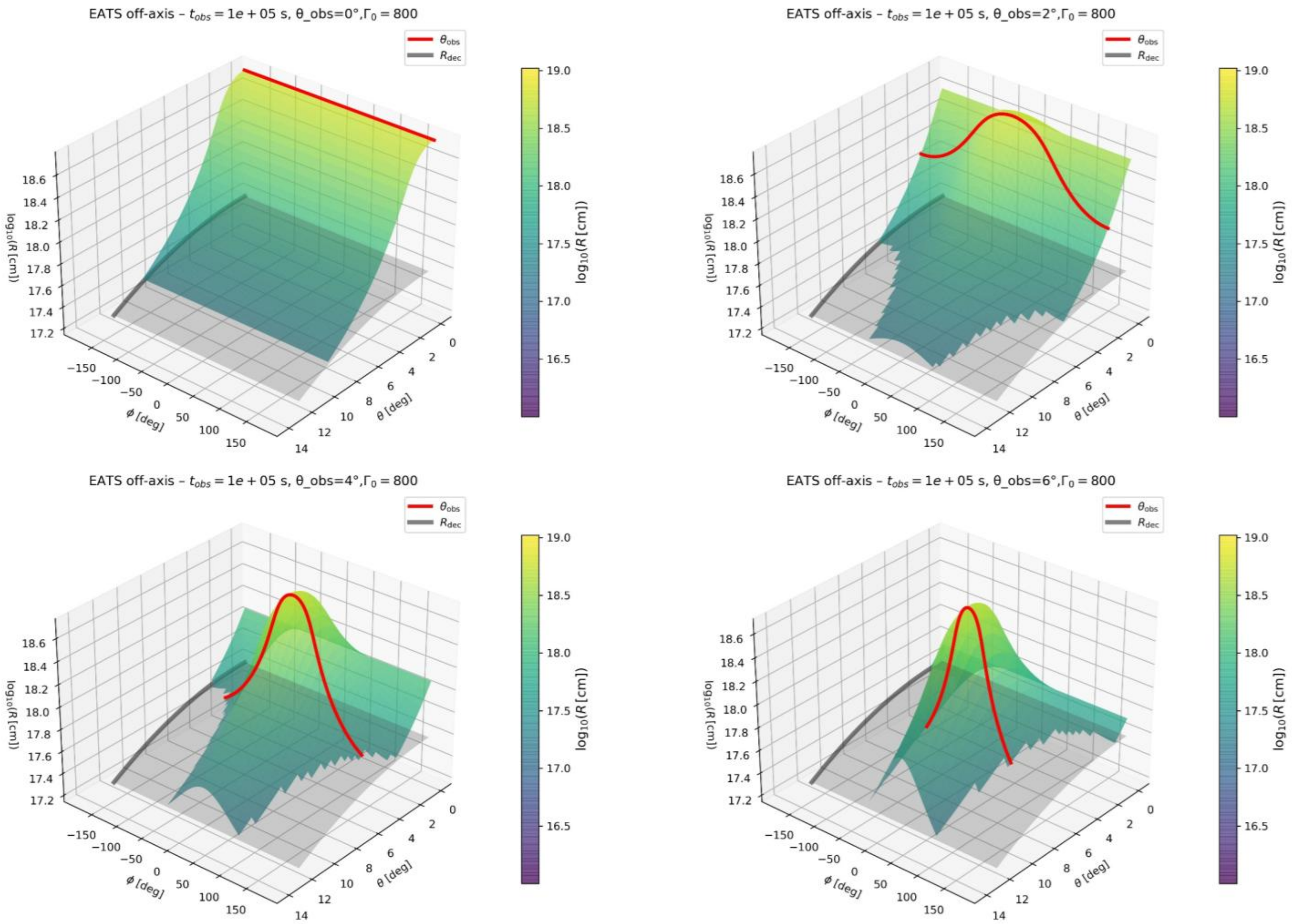


Valid EATS

Not every *R* of the *EATS* is valid: *R* must be > *deceleration Radius* (R_{dec})

$$R_{dec} = \left(\frac{3E}{4\pi n m_p c^2 \Gamma_0^2}\right)^{1/3}$$




EATS off-axis – $t_{obs} = 1e+05$ s, θ_obs=0°,$\Gamma_0 = 800$

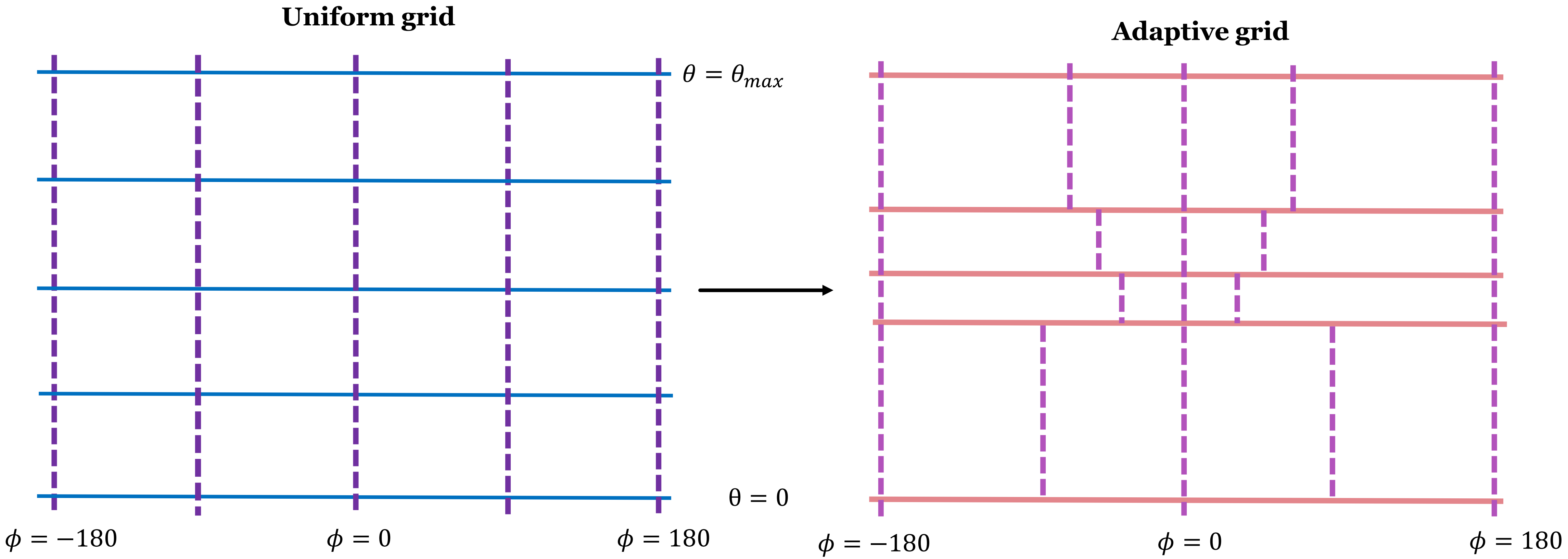
EATS off-axis – $t_{obs} = 1e+05$ s, θ_obs=2°,$\Gamma_0 = 800$

EATS off-axis – $t_{obs} = 1e+05$ s, θ_obs=4°,$\Gamma_0 = 800$

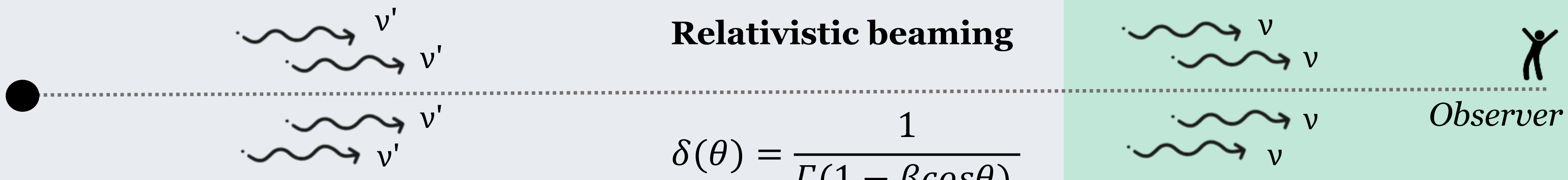
EATS off-axis – $t_{obs} = 1e+05$ s, θ_obs=6°,$\Gamma_0 = 800$

Building the grid

We want to build up a proper grid for the angles: **Shells number ($N_\theta = N_\phi$)**



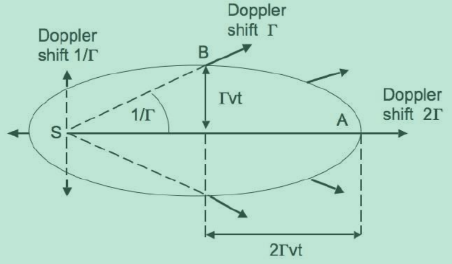
Doppler beaming



Relativistic beaming

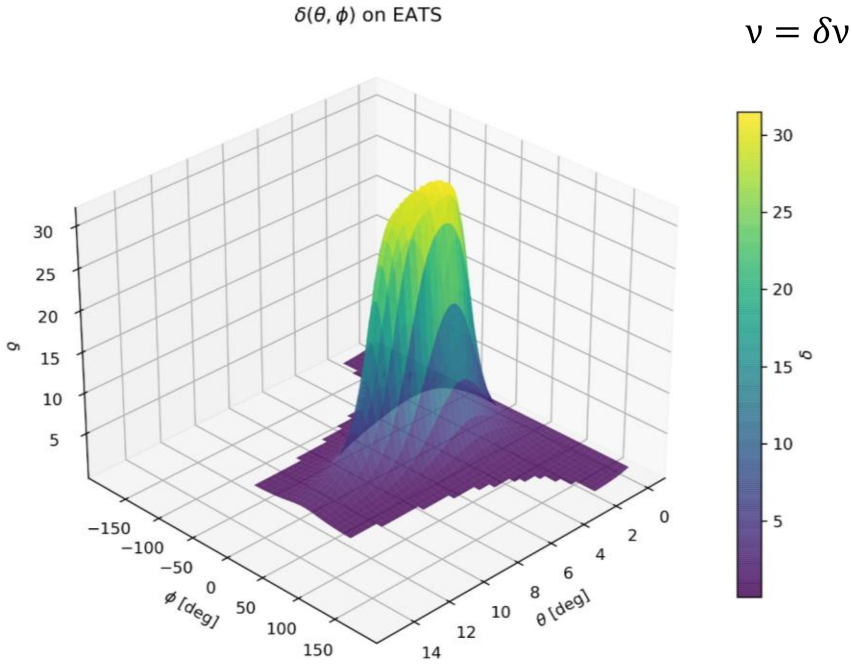
$$\delta(\theta) = \frac{1}{\Gamma(1-\beta cos\theta)}$$

Observer



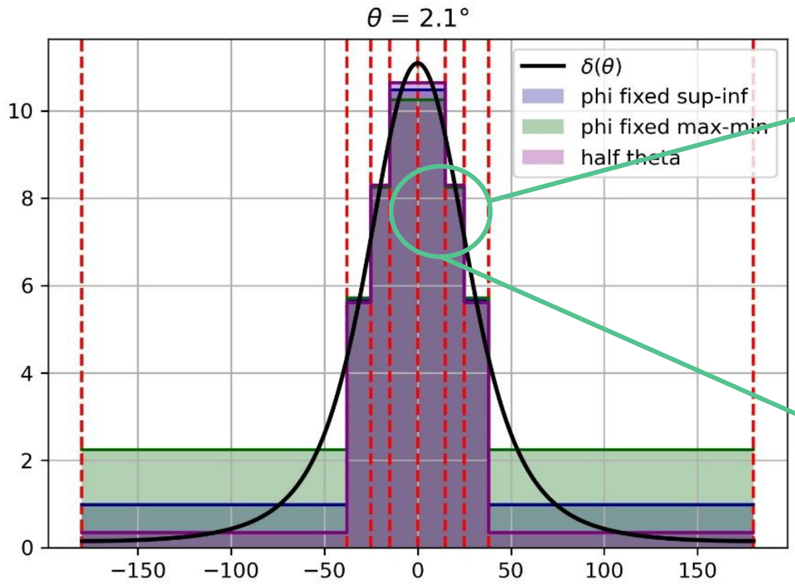
P. Mészàros 2006 «Gamma-Ray Bursts»

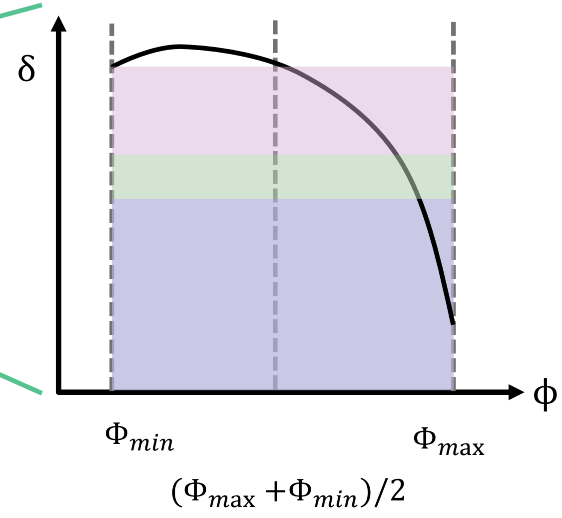
$$\nu = \delta\nu' \qquad d\Omega = \delta^{-2}d\Omega' \qquad dV = \delta dV' \qquad j_{\nu}(\nu) = \delta^2 j_{\nu'}(\nu')$$



$$\delta(\theta, \phi, \theta_{obs}) = \frac{1}{\Gamma(1-\beta\mu(\theta,\phi,\theta_{obs}))}$$

The grid matters!





Synchrotron Self Compton emission

$$\frac{dN_\gamma}{dE_\gamma dt} = \frac{\sqrt{3}}{2\pi}\frac{e^3 B}{m_e \hbar E_\gamma} F\left(\frac{E_\gamma}{E_c}\right)$$

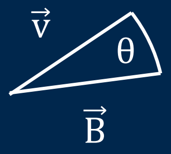
$$F(x) = x\int_x^\infty K_{5/3}(\tau)d\tau$$

$$E_c = \frac{3e\hbar B\gamma^2}{2m_e c}$$

↓

Over directions of magnetic field

Taking $B\perp = B\sin\theta$



we come to :

$$G(x) = \int_0^\pi F\left(\frac{x}{\sin\theta}\right)\sin^2\theta d\theta \approx \tilde{G}(x)$$

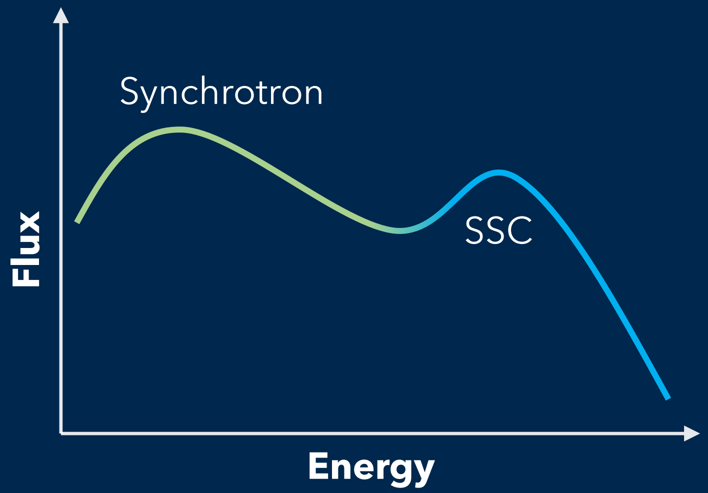
+

$N_e(\gamma)$

Electronic distribution (Broken power law)

↓

$$\frac{dN_\gamma}{dEdt} = \int N_e(\gamma)\frac{dN_\gamma}{dE_\gamma dt}d\gamma$$



F.A. Aharonian, S.R. Kelner, and A.Y. Prosekin 2010

Flux computation

$$F_\nu(t_{obs},\nu_{obs}) = \frac{1+z}{4\pi {d_L}^2}\int d\Omega\, R^2\, \Delta R\, \delta^2\, \epsilon'_{\nu'}$$

Ryan et al. 2020

$z =$ *redshift*

$d_L =$ *distance luminosity*

↓

Computation on the grid

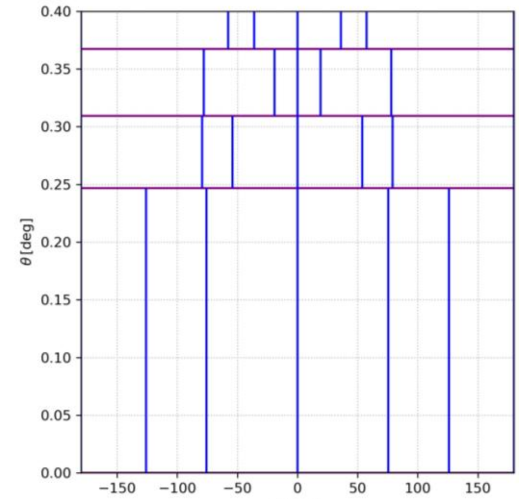
$$F_\nu(t_{obs},\nu_{obs}) = \frac{1+z}{4\pi {d_L}^2}\sum_{i=1}^{N\theta}\sum_{j=1}^{N\phi}\Delta\theta\Delta\phi\, \sin\theta_{ij} R_{ij}^2 \Delta R_{ij} {\delta_{ij}}^2 \epsilon'_{\nu'}$$

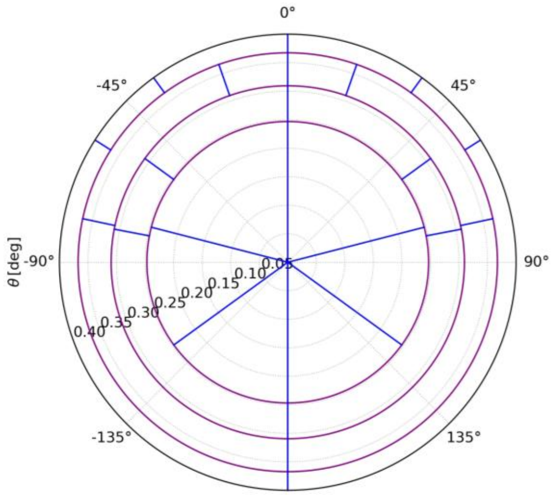
Grid selection: $\boldsymbol{N_\theta = N_\phi}$

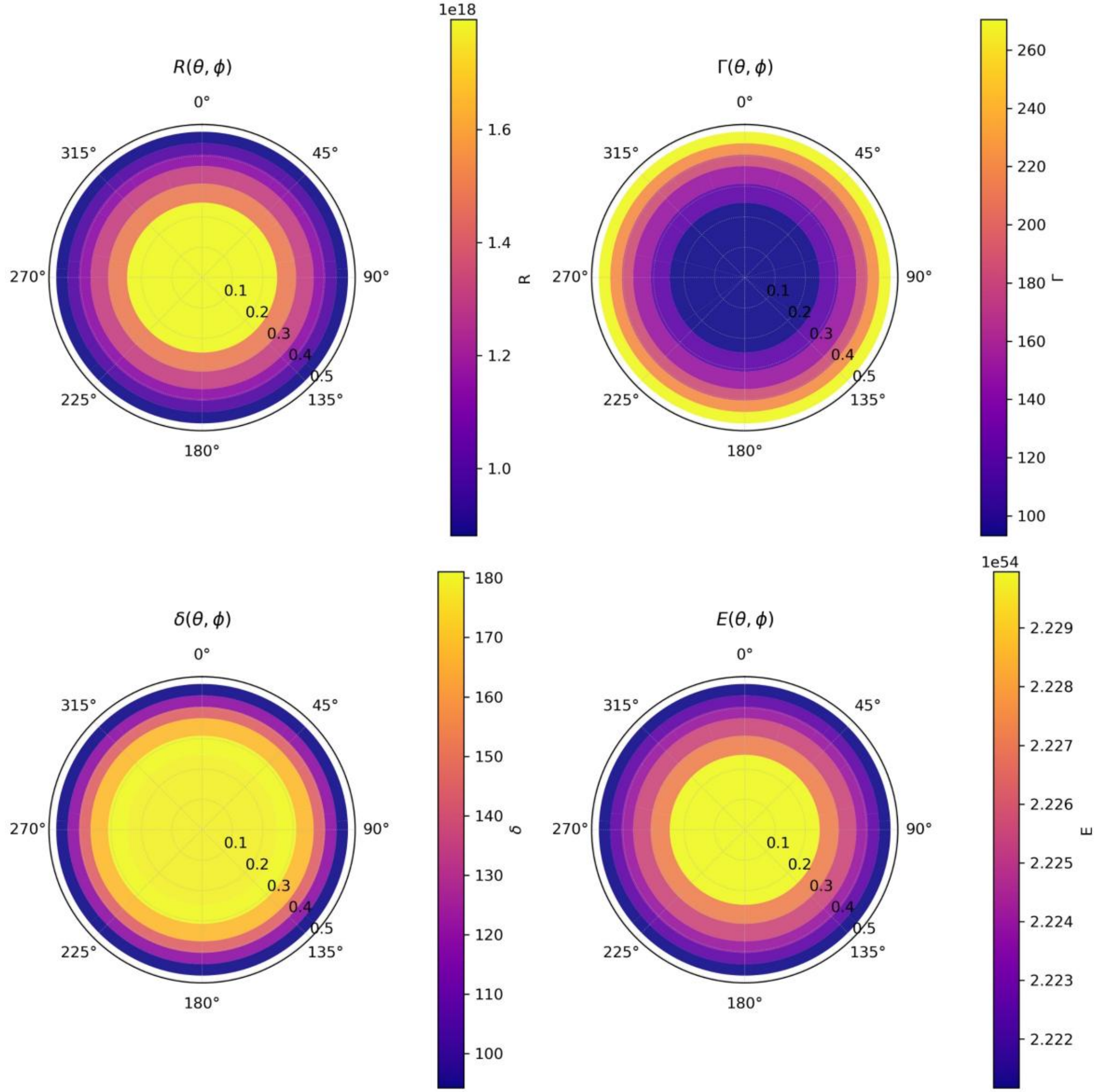
$$\nu_{obs} = \frac{\delta}{1+z}\nu'$$

$$t_{obs} = (1+z)\left[t_{lab}(R) - \frac{R\mu(\theta,\phi)}{c}\right]$$

Main functions on grid (θ, ϕ): On Axis

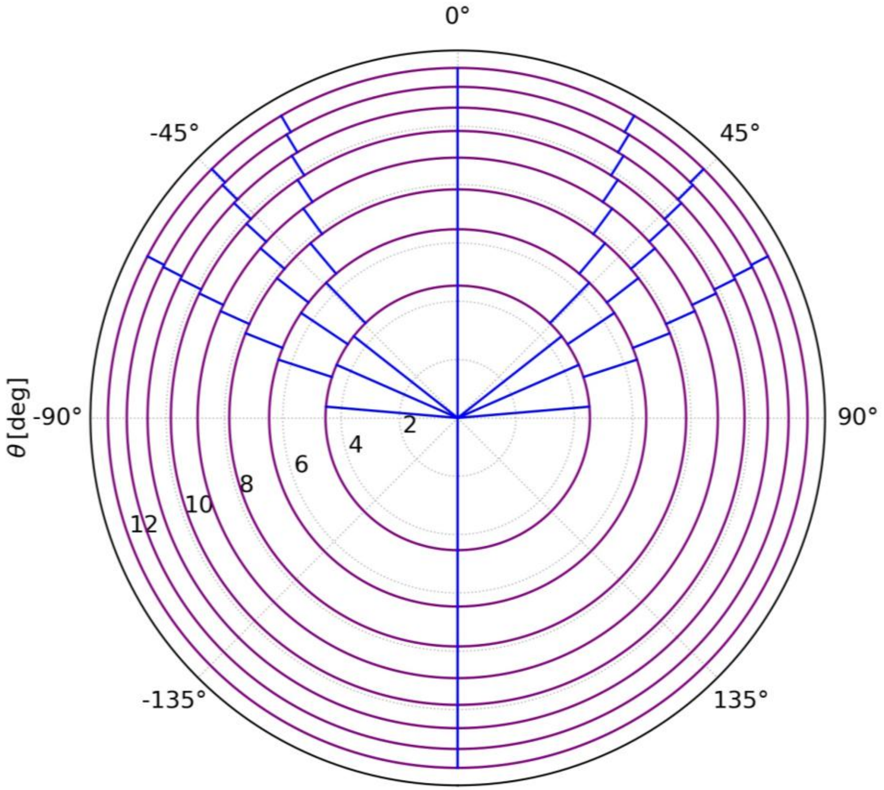


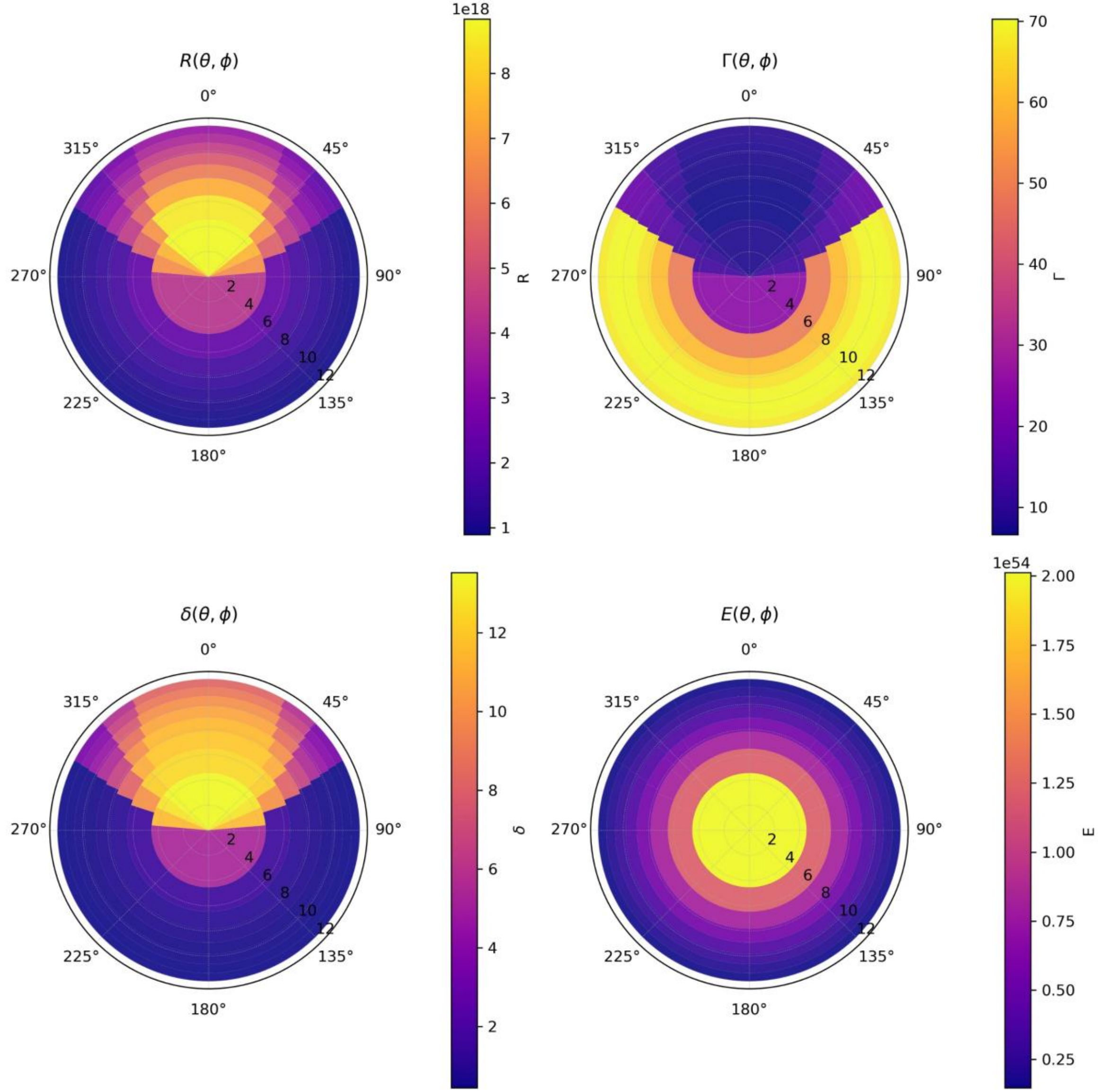




E_k	$10^{51}\ erg$
z	0.01
n_0	0.01 cm^{-3}
B	0.25 gauss

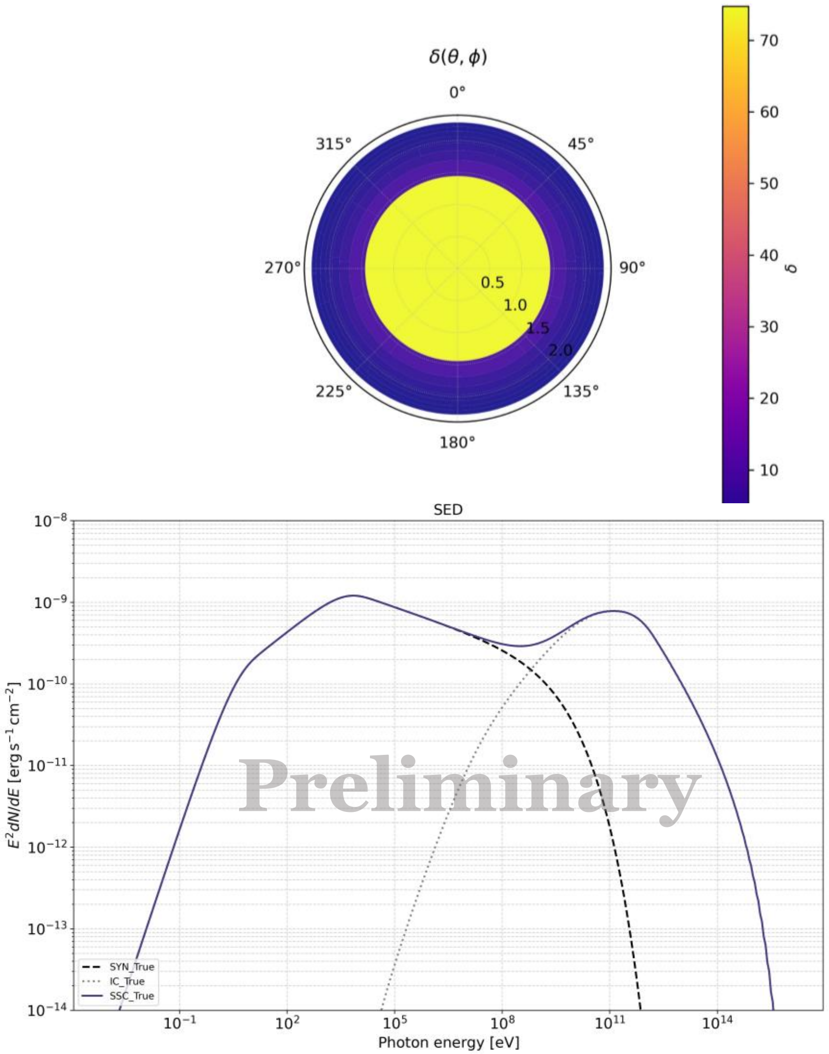
Main functions on grid (θ, ϕ): Off Axis



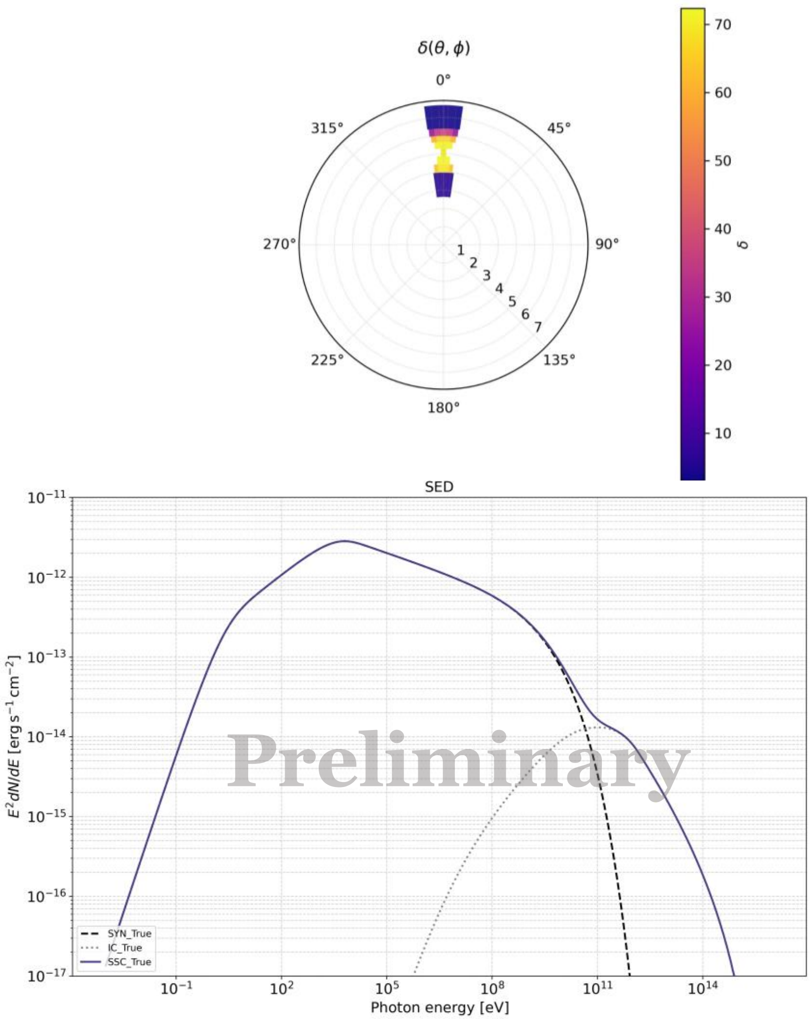


Spectral Energy Density (t_{obs} = fixed)

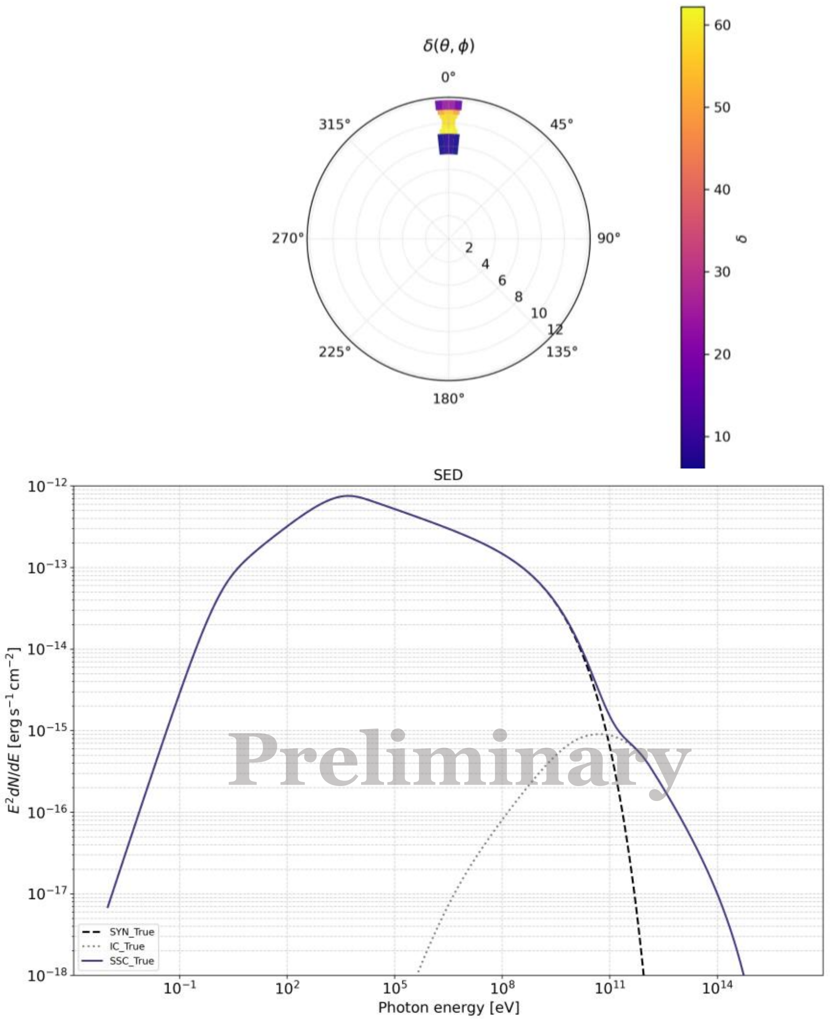
$t_{obs} = 10^4 \mathrm{s}\ \theta_{obs} = 0°$



$t_{obs} = 10^4 \mathrm{s}\ \theta_{obs} = 5°$

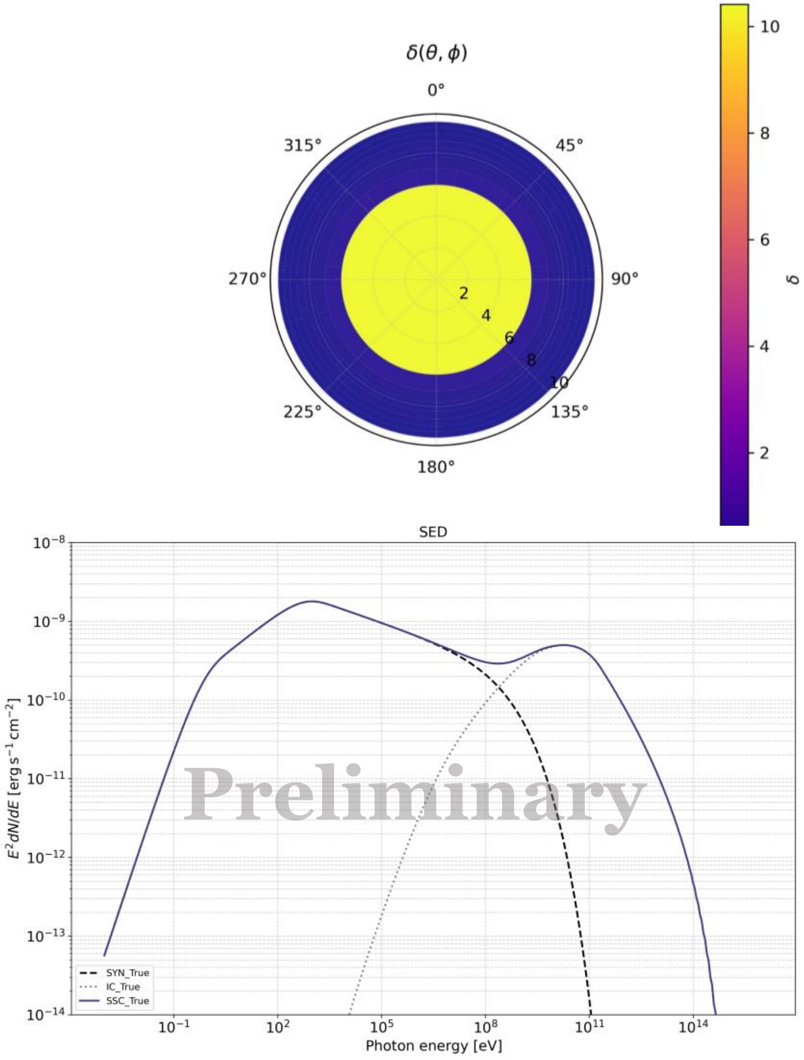


$t_{obs} = 10^4 \mathrm{s}\ \theta_{obs} = 10°$

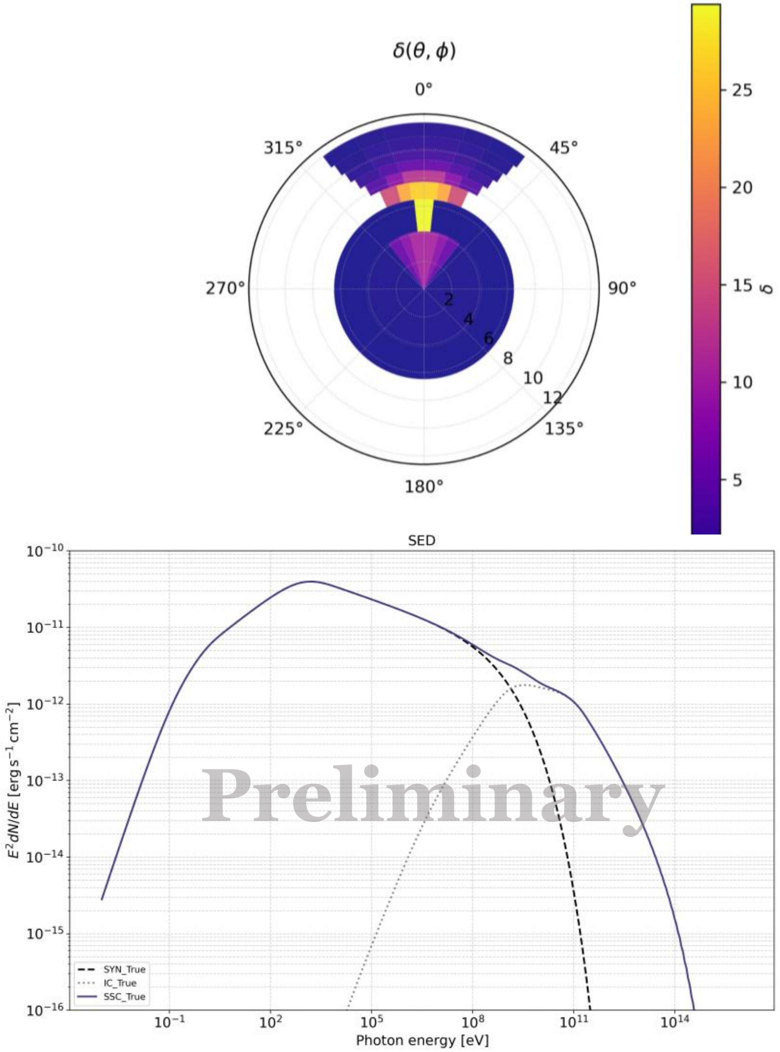


Spectral Energy Density (t_{obs} = fixed)

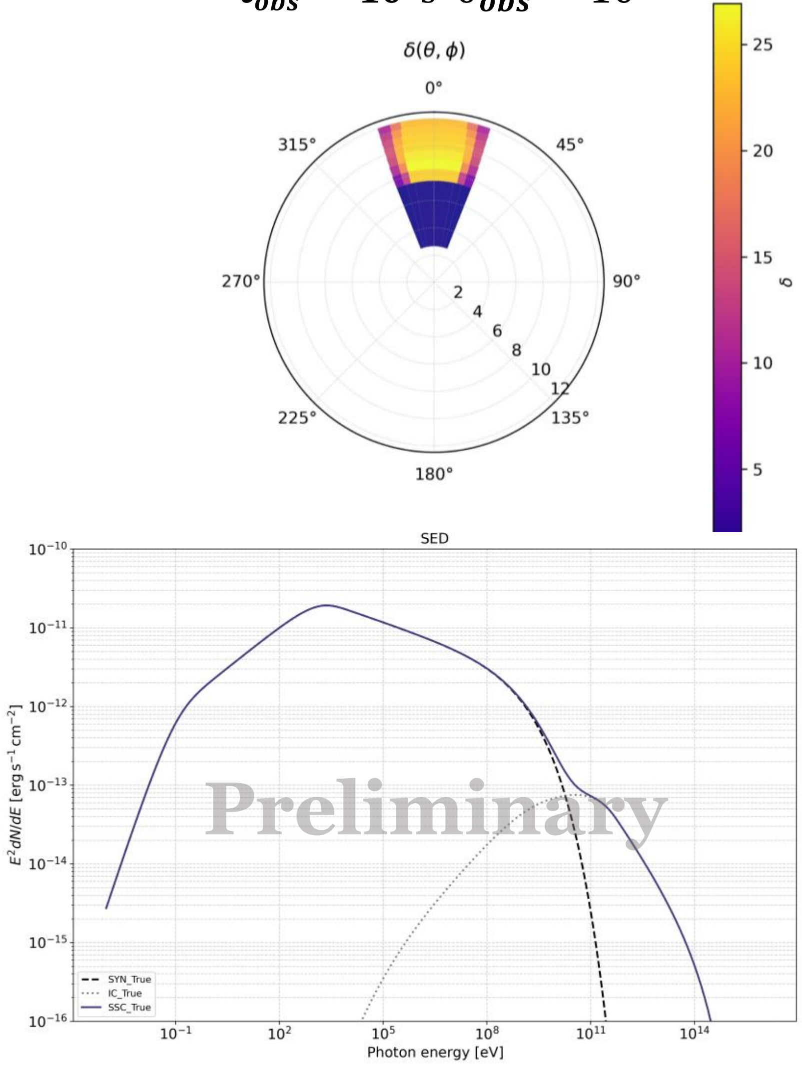
$\mathbf{t}_{obs} = \mathbf{10}^5\mathrm{s}\ \theta_{obs} = 0°$



$\mathbf{t}_{obs} = \mathbf{10}^5\mathrm{s}\ \theta_{obs} = 5°$

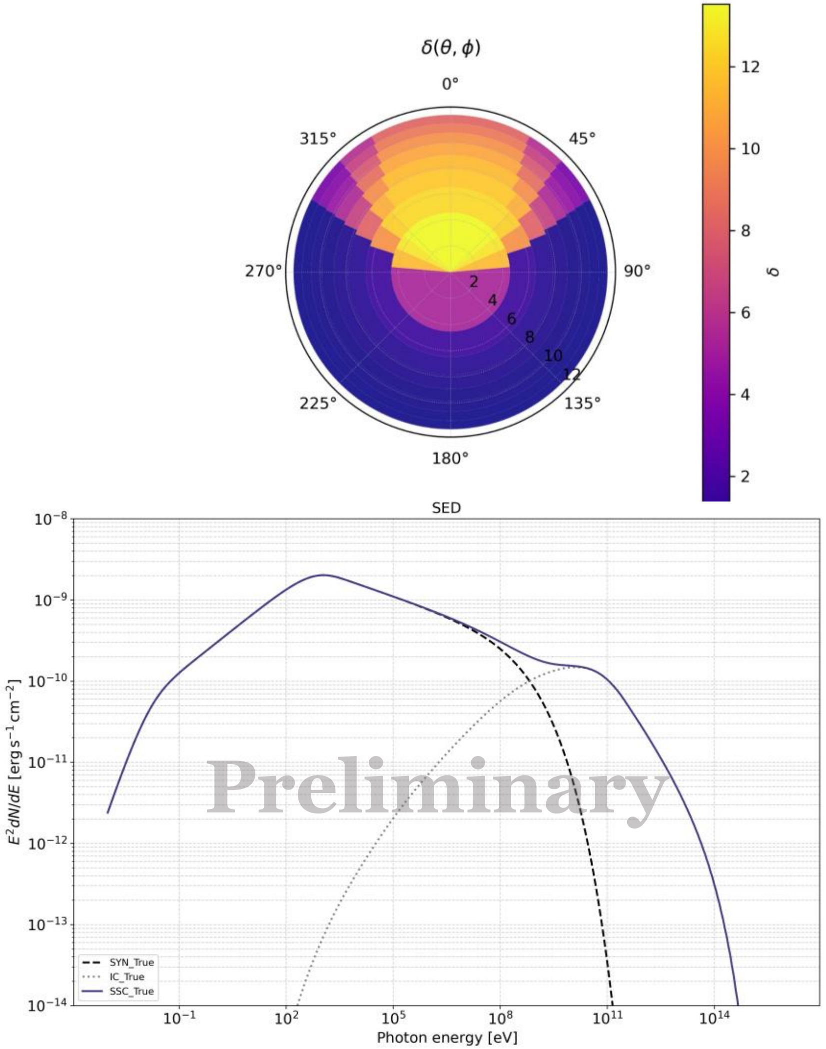


$\mathbf{t}_{obs} = \mathbf{10}^5\mathrm{s}\ \theta_{obs} = 10°$

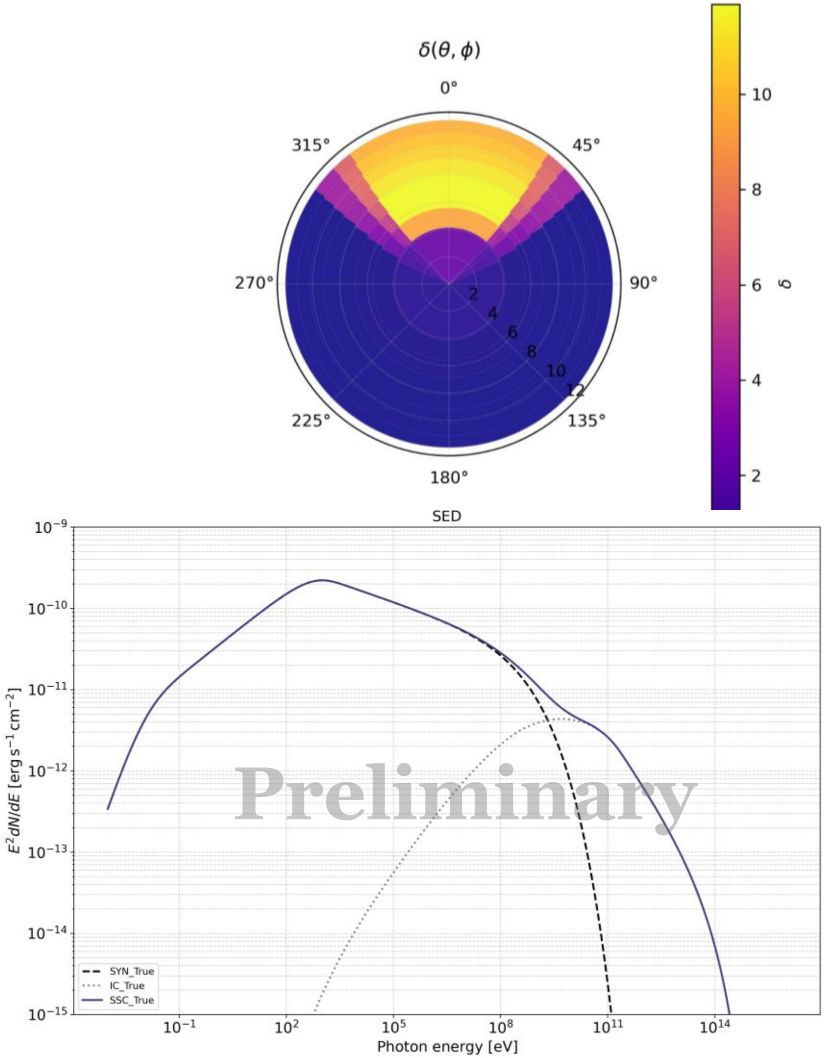


Spectral Energy Density (t_{obs} = fixed)

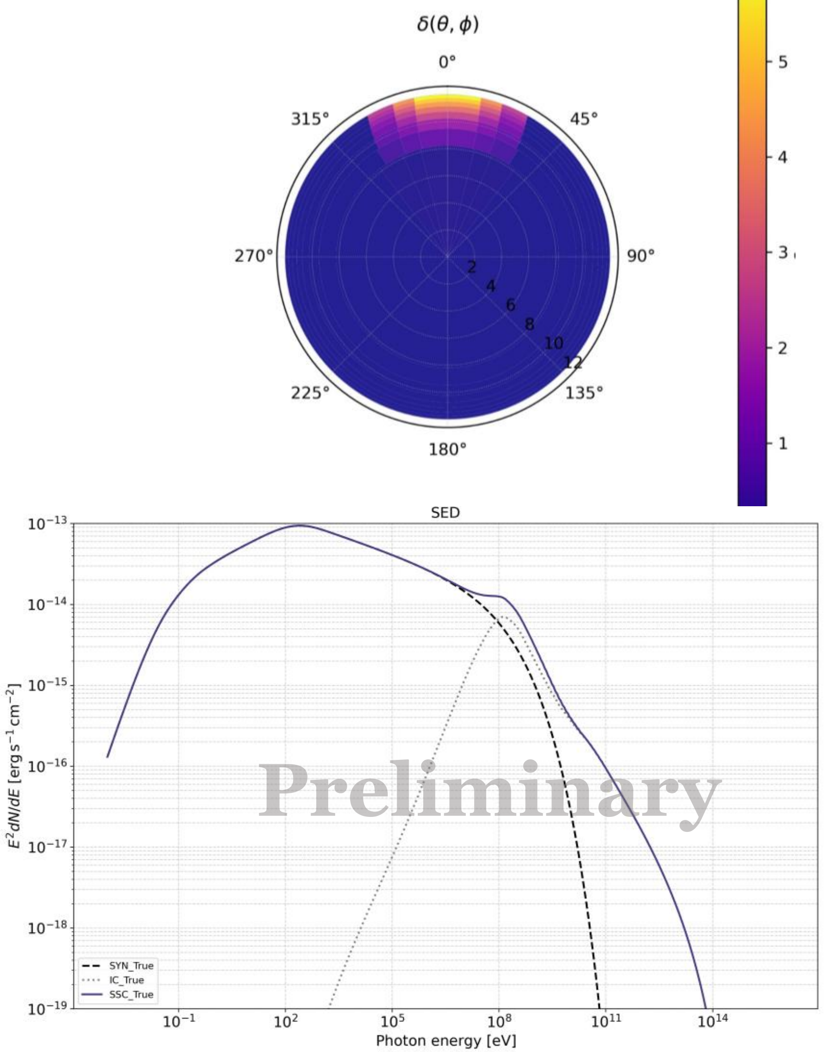
$\mathbf{t}_{obs} = \mathbf{10}^6\mathrm{s}\ \theta_{obs} = 0°$



$\mathbf{t}_{obs} = \mathbf{10}^6\mathrm{s}\ \theta_{obs} = 10°$



$\mathbf{t}_{obs} = \mathbf{10}^6\mathrm{s}\ \theta_{obs} = 20°$



Final Summary and future Goals

Summary

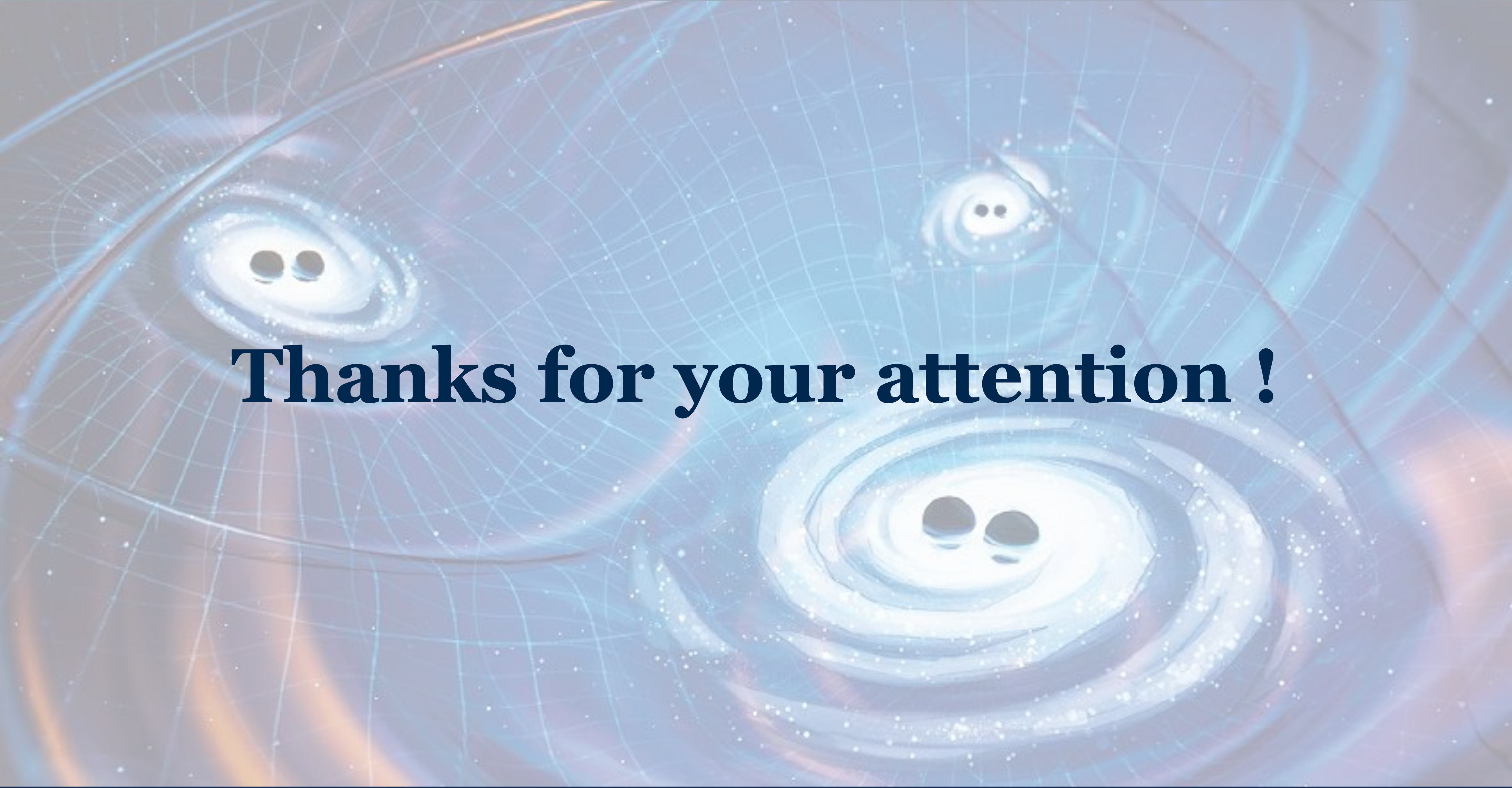
- We ended the first phase of the **SSC code** development: **good off axis behavior**

- **Preliminary flux** results on different observing times: **checking the code**

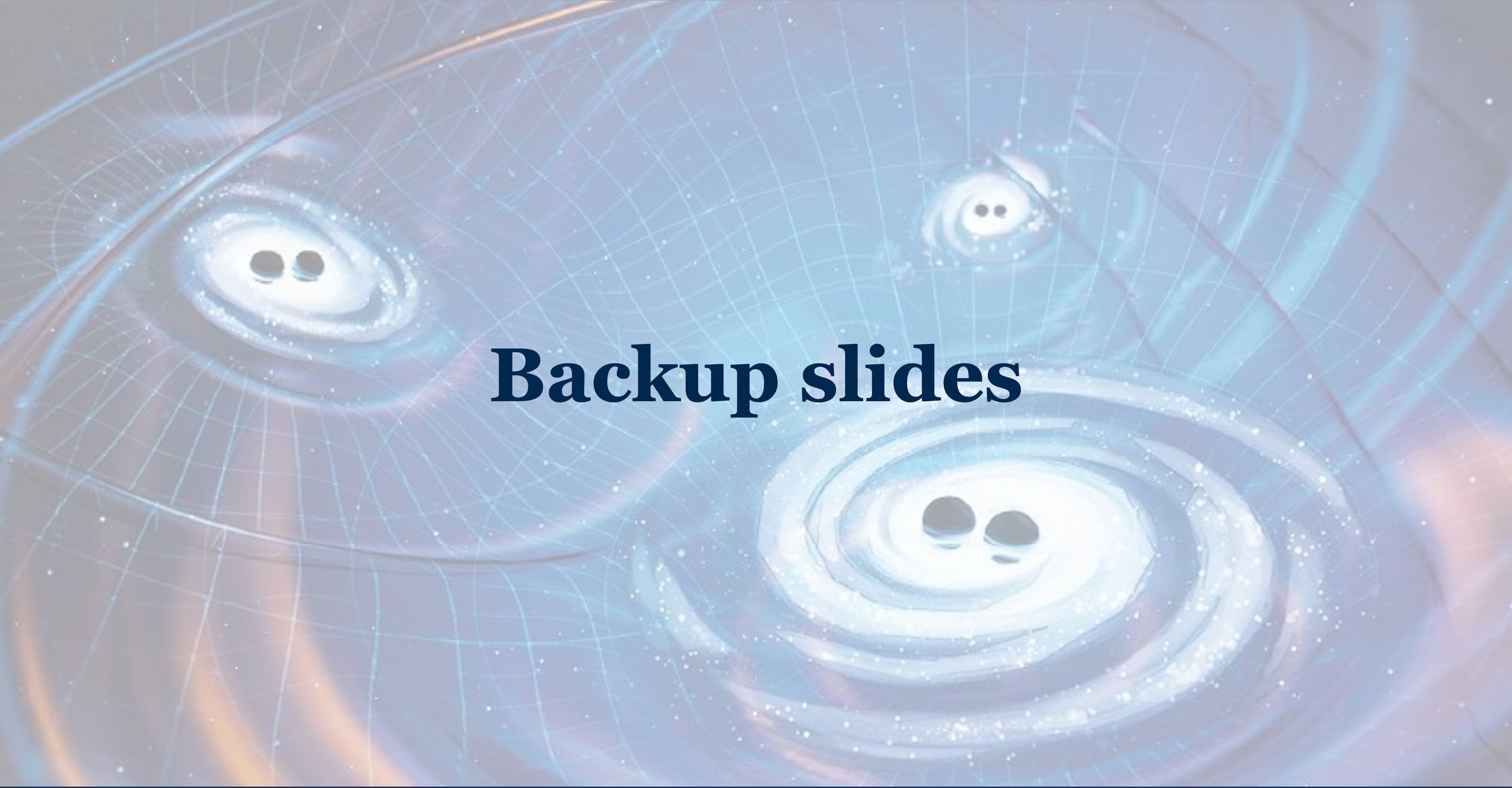
Future Goals

- Implementetion of **lightcurves** generation: **ongoing**

- Start to test the code in the **full analysis process:**
  computation of the expected detection probability for **NSBH multi messenger events**



Thanks for your attention !



Backup slides

Methods and Analysis

1. Expected **merger rate** throughout the universe
2. **Simulation** of **G**ravitational **W**aves **detection**
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 Expected Merger Rate Estimation

Number of expected NSBH events in the Redshift function.

Local merger rate as $\dot{n}(0) = 45 Gpc^{-3} yr^{-1}$

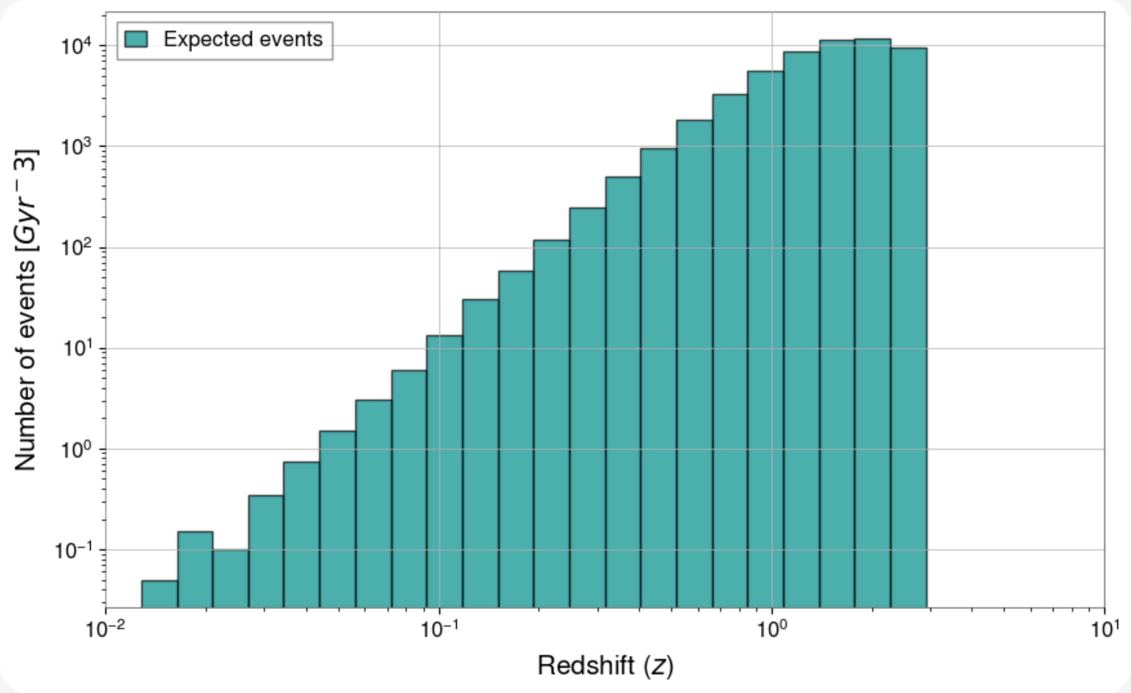


Fig 1. Merger rate of NSBH merger events a as a function of redshift (z) vs the number of expected events in z shells.

2 GW Detection Simulation

To simulate the detection we use the **Fisher Matrix** approach using **GWFish** (o GWFast): fast but not precise like the Bayesian approach

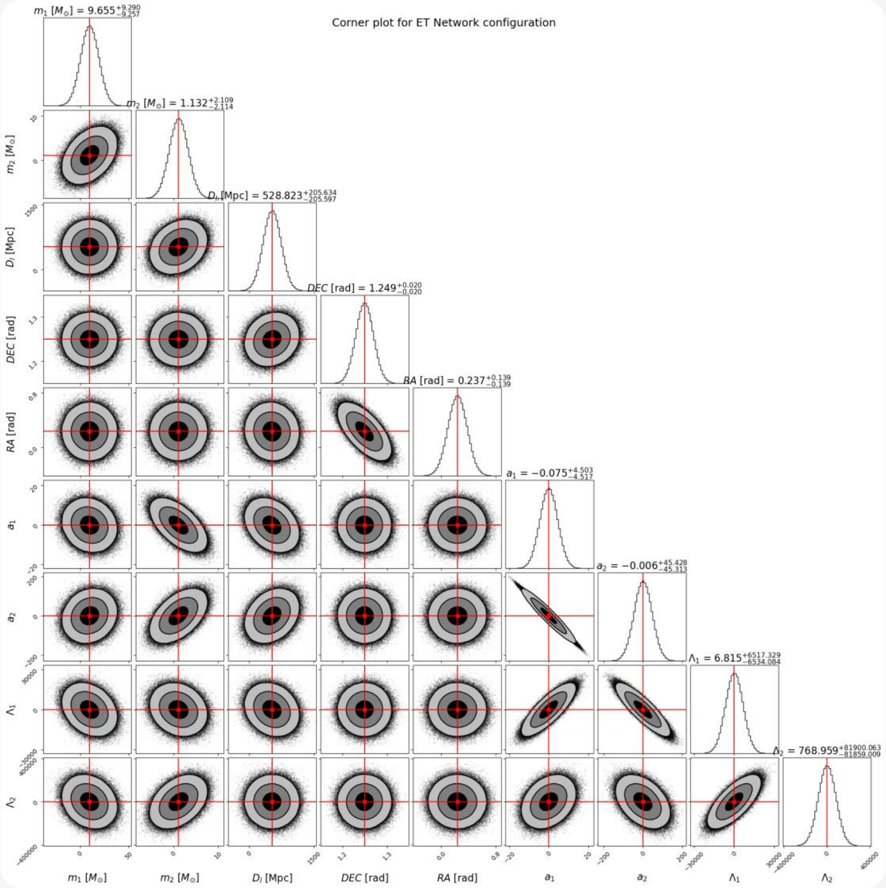


Fig. 2: Parameter estimation with GWFish.

3

Mass Remnant and Kinetic Energy

Choose the models:

- Amount of mass in the accretion disk (M_{acc})
- Energy of the produced jet (E_k)

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

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

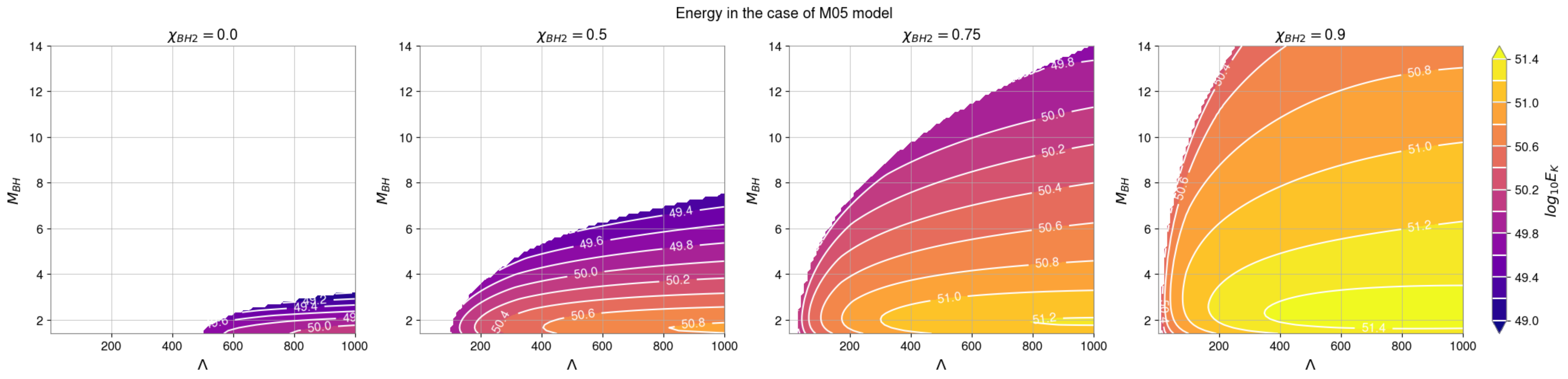


Fig. 3: Countour plots of kinetic Energy (E_k) in function of BH mass, spin a_{BH} and Λ.

4

Very High Energy Afterglow Evaluation

Afterglow Synchrotron + Compton components = **Synchrotron Self Compton (SSC)**

→ Here we use **semi analitycal model** (Joshi-Razzaque model 2021).

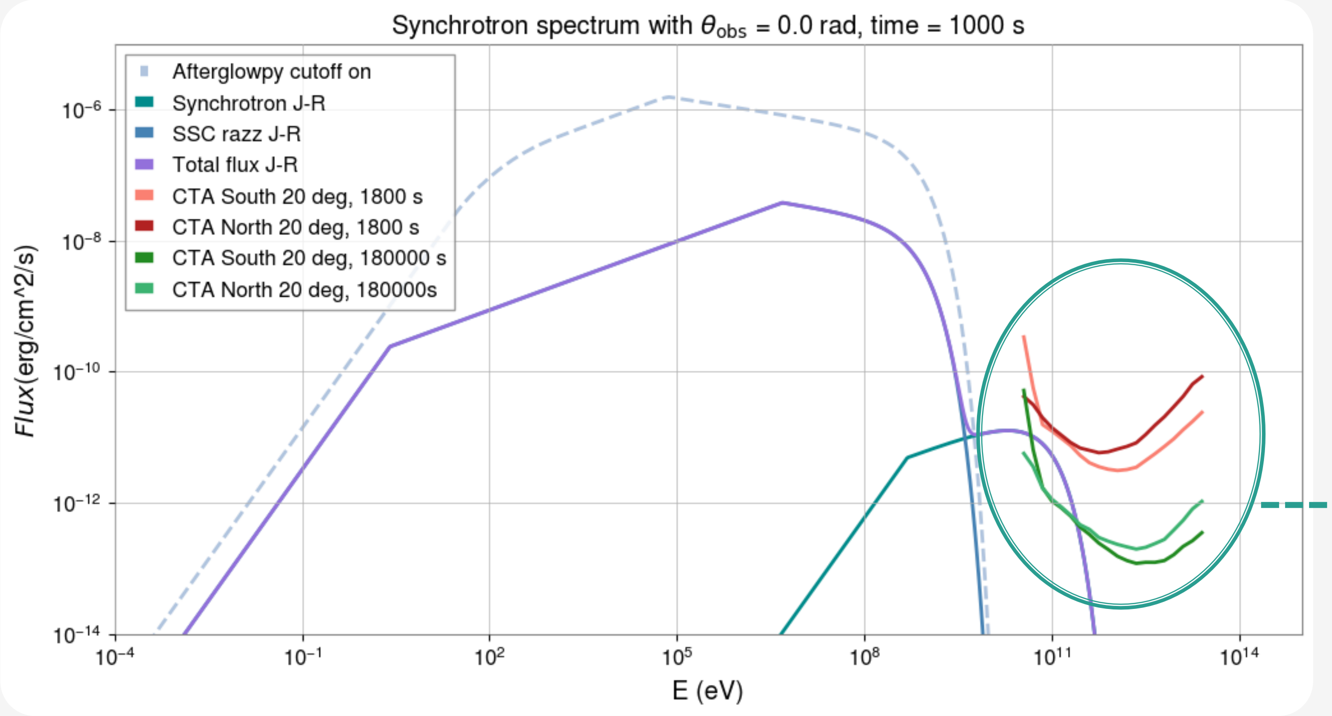
Parameters:

Intrinsic:

- Isotropic Energy: E_{iso}
- ISM density: n_0
- E field density: ϵ_e
- Magnetic density: ϵ_B
- Electronic distribution index: p
- $\theta_{core} = 0.05\, rad$

Extrinsic

- Redshift: z
- Time: t
- Observing angle: θ_{obs}



Sensitivity curves for CTAO, North and South configuration

Fig. 4: CTAO picture of the planned configuration.

Expected Probability of Detection for NSBH Events

Einstein Telescope + CTAO

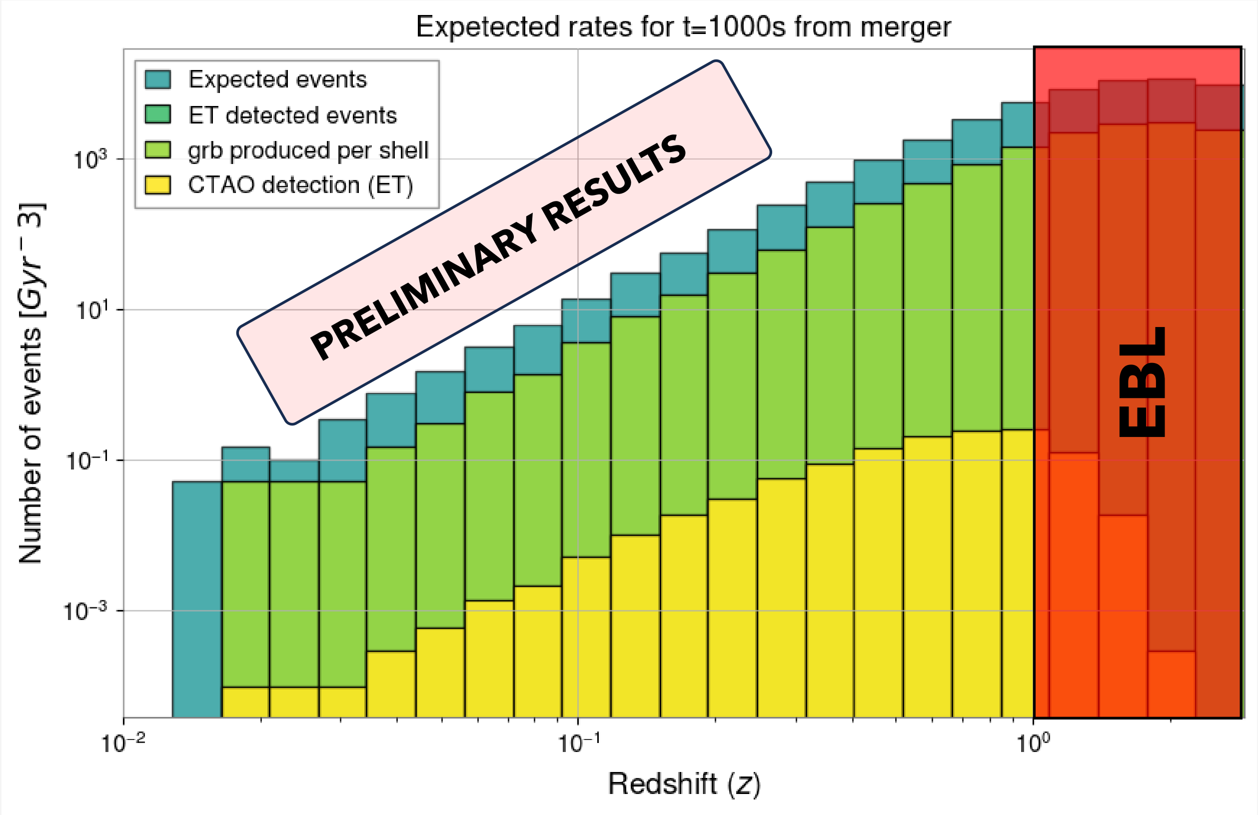


Fig. 5: Histogram of the expected events versus the number of NSBH events detected by ET, the number of GRB produced in every redshift (z) (up to z=2.7) and the number of possible detections with CTAO.

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

Possible reasons:

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

↓

Develop a numerical code for SSC Flux

Synchrotron Self Compton emission

$$\frac{dN_\gamma}{dE_\gamma dt} = \frac{\sqrt{3}}{2\pi}\frac{e^3 B}{m_e \hbar E_\gamma}\mathrm{F}\left(\frac{E_\gamma}{E_c}\right) \qquad F(x) = x\int_{\mathrm{x}}^{\infty} K_{5/3}(\tau)d\tau \qquad E_c = \frac{3e\hbar B\gamma^2}{2m_e\, c}$$

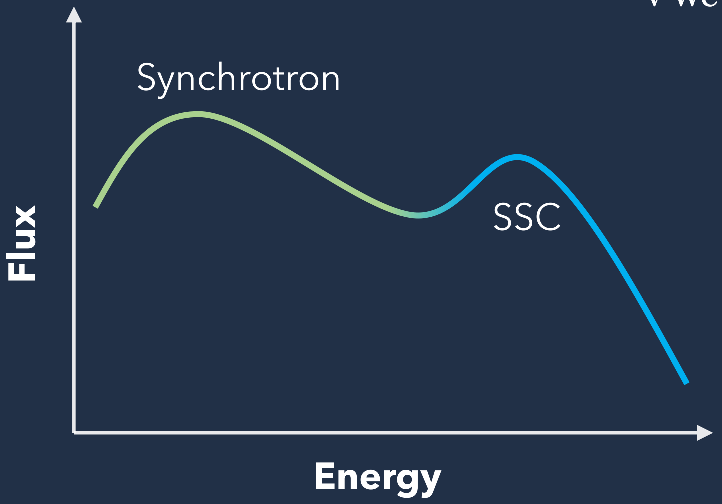
Over directions off magnetic field

Taking $B\perp=\sin\theta$, where θ is angle between B and v we come to the following double integral:

$$G(x) = \int \sin\theta\, F\left(\frac{x}{\sin\theta}\right)\frac{d\Omega}{4\pi}$$

$$= \int_0^{\pi} F\left(\frac{x}{\sin\theta}\right)\sin^2\theta d\theta \approx \tilde{\mathrm{G}}(x)$$

$$\mathrm{G}(x) = x\int_{\mathrm{x}}^{\infty} K_{5/3}(\omega)\sqrt{1-\frac{x^2}{\omega^2}}\,d\omega$$



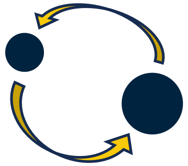
F.A. Aharonian,[*] S.R. Kelner,[†] and A.Y. Prosekin 2010

$$\frac{dN_\gamma}{d\mathrm{E}dt} = \int N_{\mathrm{e}}\,(\gamma)\frac{dN_\gamma}{dE_\gamma dt}d\gamma$$

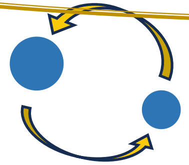
Multimessenger Transient Objects

Compact Binary objects coalescence:

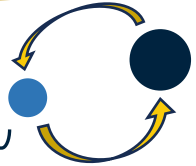
Binary Black Hole (BBH)



Binary Neutron Star (BNS)

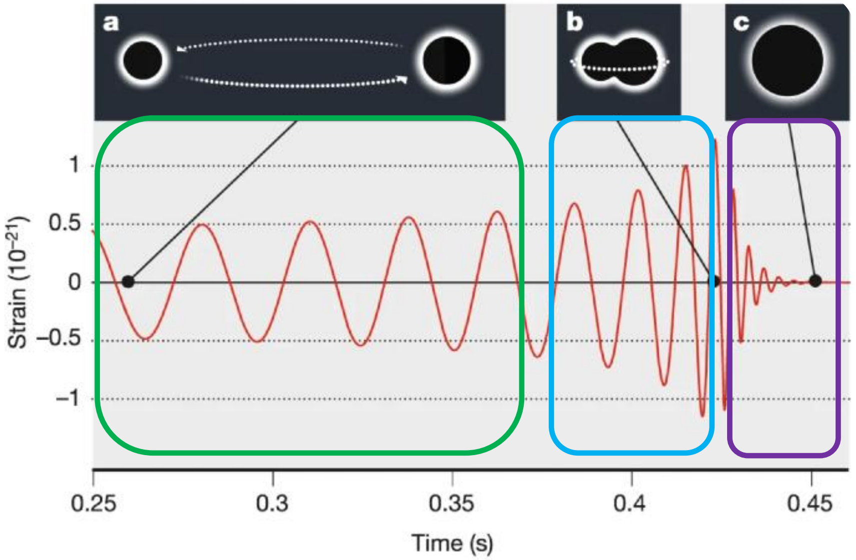


Neutron Star – Black Hole (NS-BH)



Disruptive binary mergers (**Tidal disruption**) -------→ **Multimessenger Astrophysics**

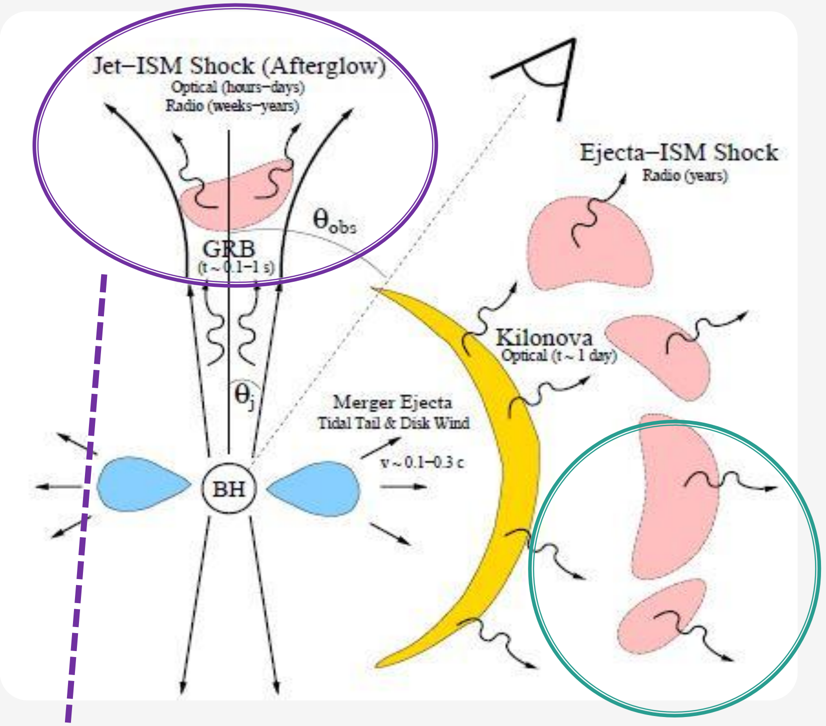
1) Gravitational Wave signal



- **Formation** and **inspiral** -----→ Energy loss for GW emission
- **Merging** phase -----→ From two objects to one
- **Ringdown** and post-merger phase -----→ Settle down of final object and emissions

Possible EM counterpart

Multimessenger Transient Objects



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

2) EM signal

Different emissions for every component --------> **Merger parameters**

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

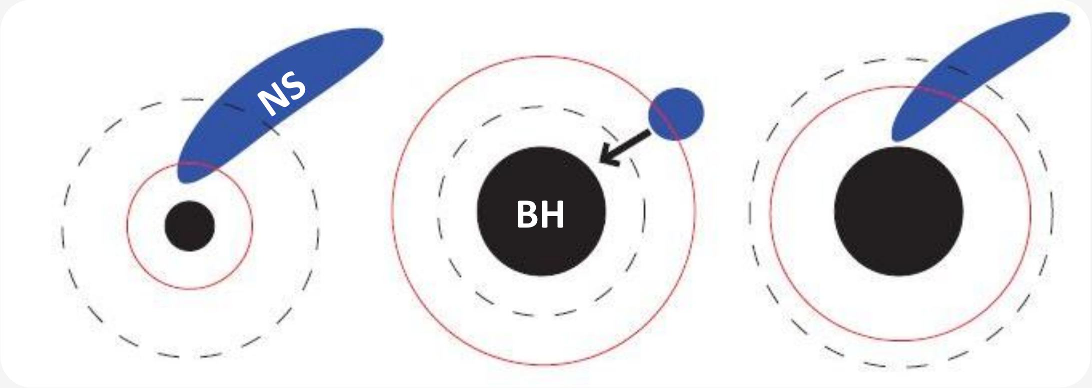
Spins

NS Equation of State (**EoS**) o λ

R_{ISCO}

d_{tidal}

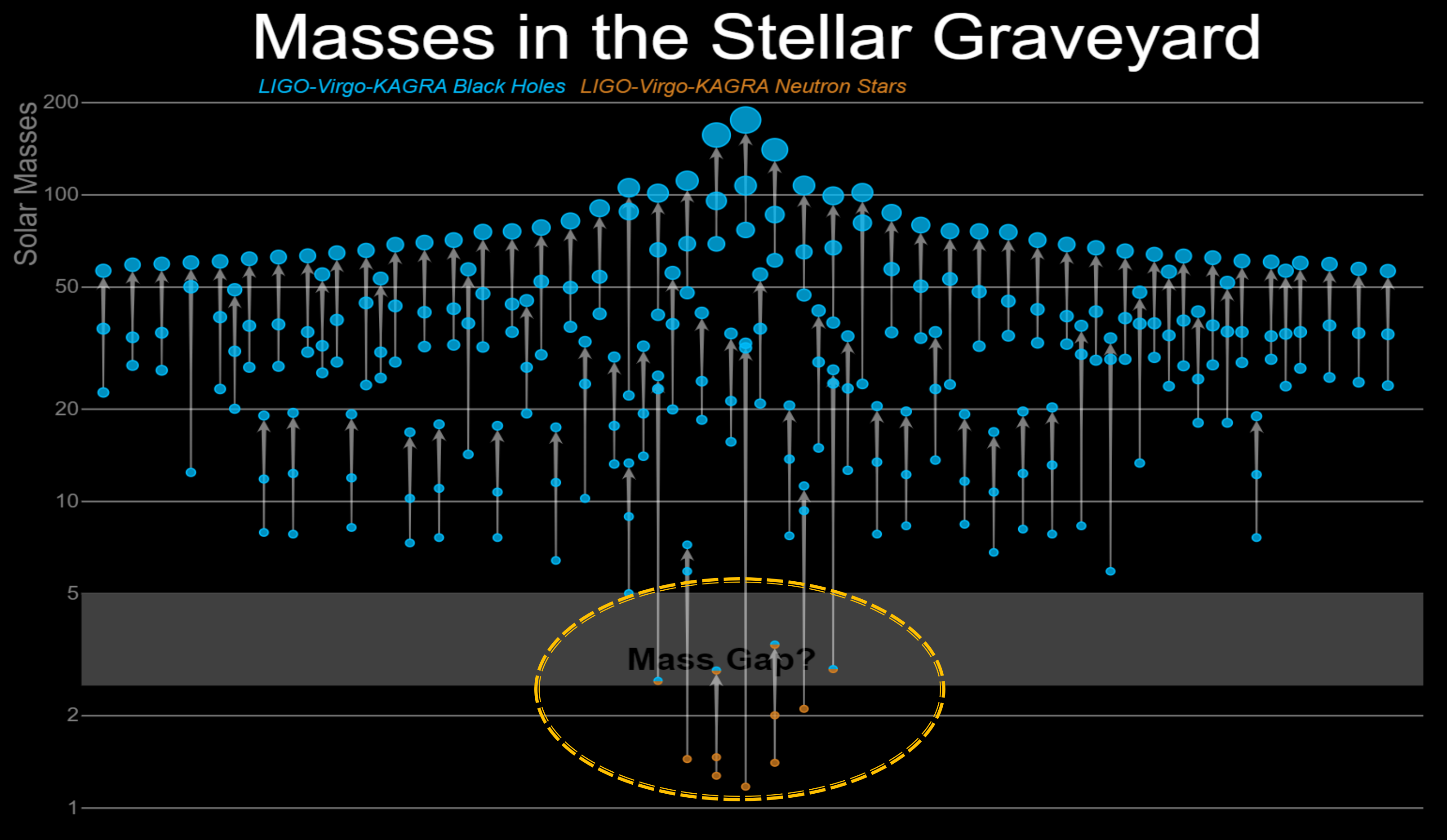
Masses



Tidal disruption Plunge Tidal disruption

The present and the future

Before O4 run



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Simulations

↓

Expected events in the future

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

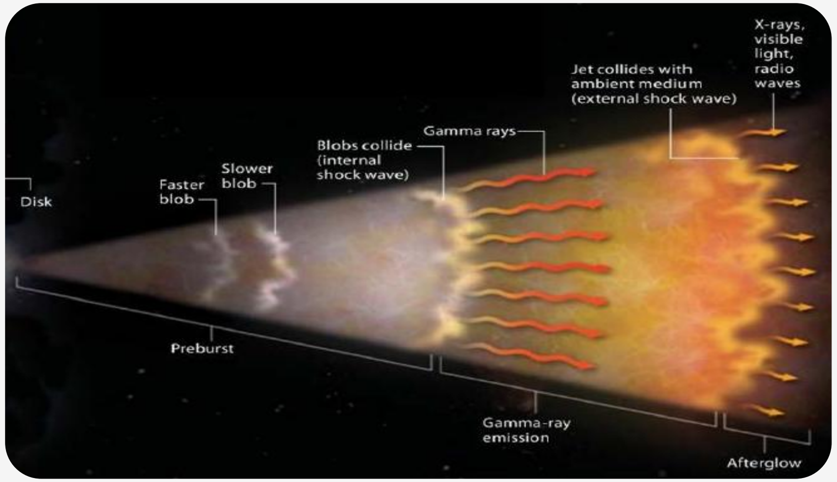
In O4 obs. run

(May 2023 to Feb 2025)

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

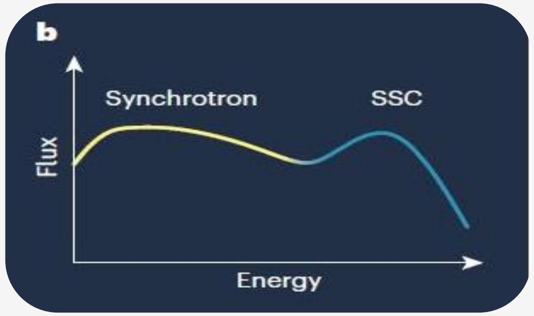
Main goals

Using proper models or tools we can study what happens at very high energies, in that band of the spectrum dominated by Synchrotron Self Compton (SSC).



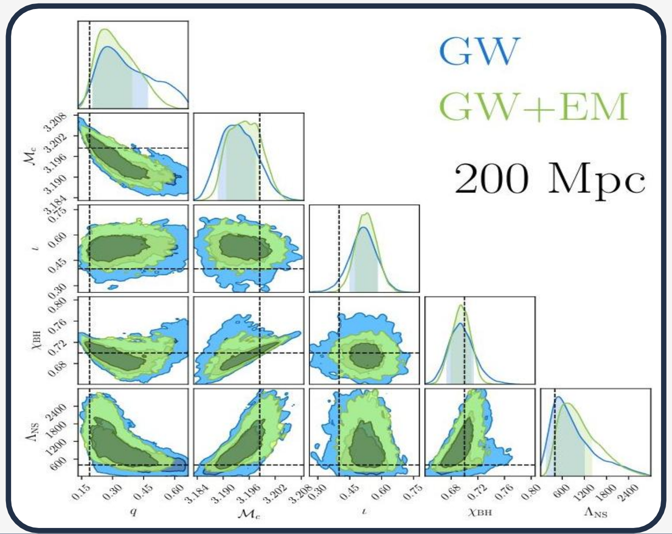
We need more precise models for the Very High Energy spectrum

1) Develop a **model for the SSC** and use it to predict the event rate with **CTAO**



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

3) **GW and EM joint** analysis to study the **event rate** and the goodness of the **parameter estimation**



2

GW Detection Simulation

To simulate the detection we use the **Fisher Matrix** approach using **GWFish** (o GWFast): fast but not precise like the Bayesian approach

- Build a dataframe with all the coalescence parameters
- Compute the SNR, parameters values and errors.
- Different network configurations of interferometers.

Einstein Telescope (ET) / ET plus Cosmic Explorer (CE).

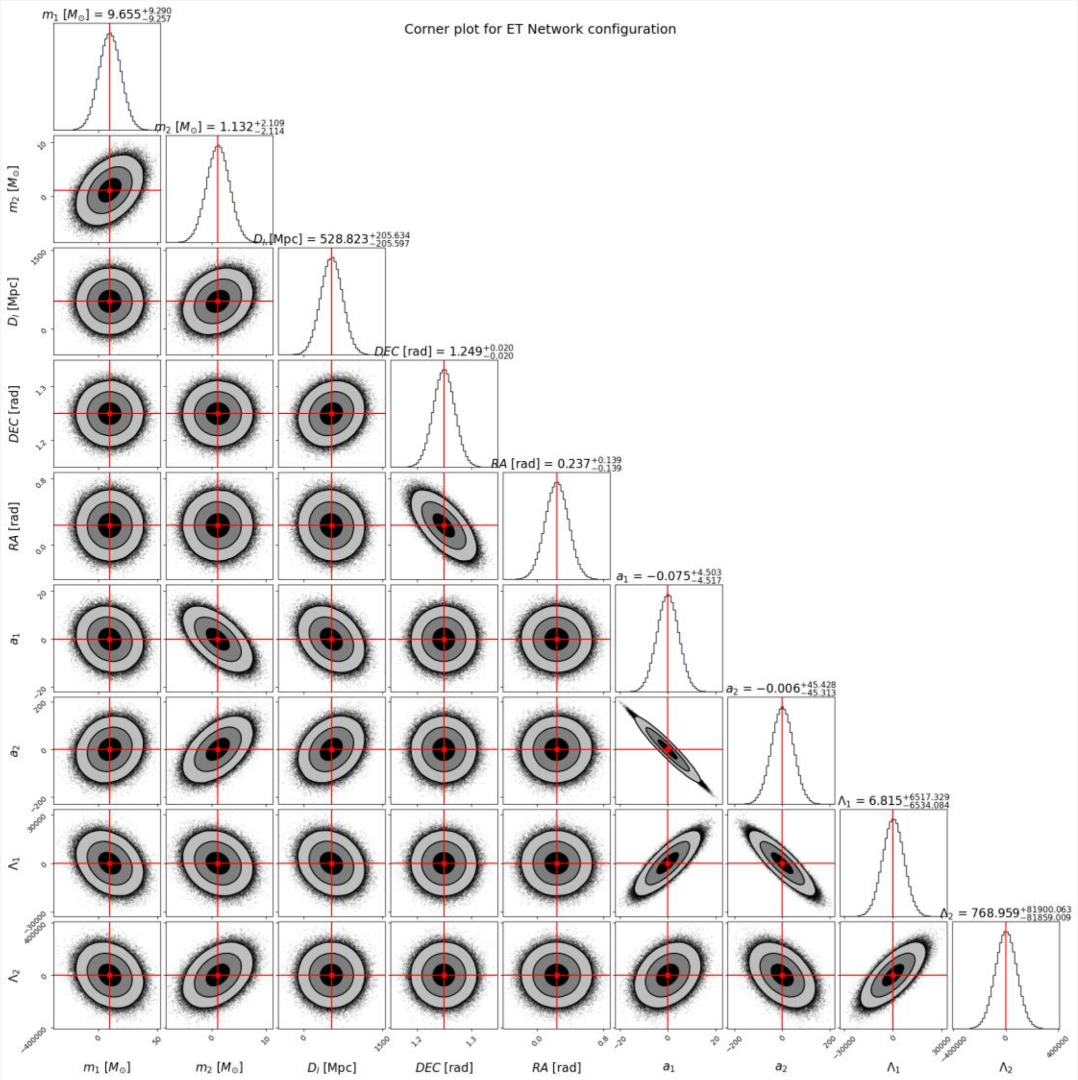


Fig. 3: Parameter estimation with GWFish.

2

GW Detection Simulation

To simulate the detection we use :

- **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)

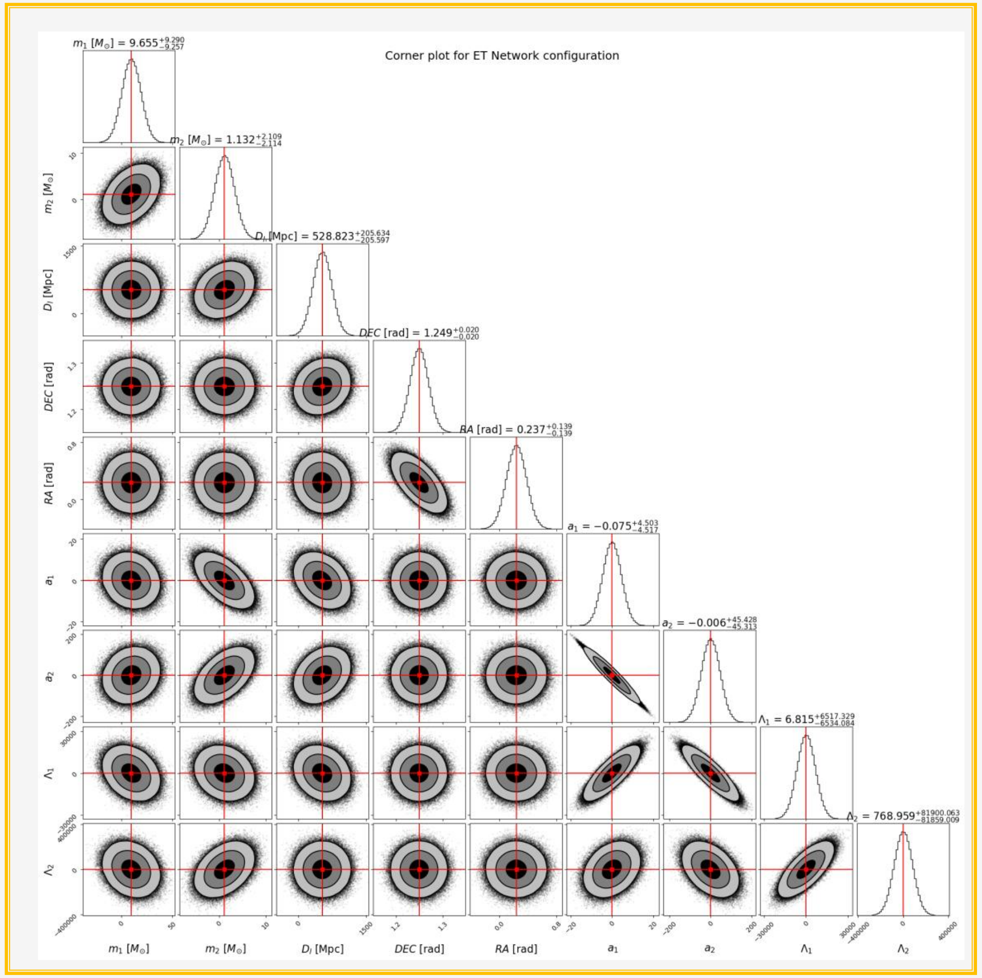
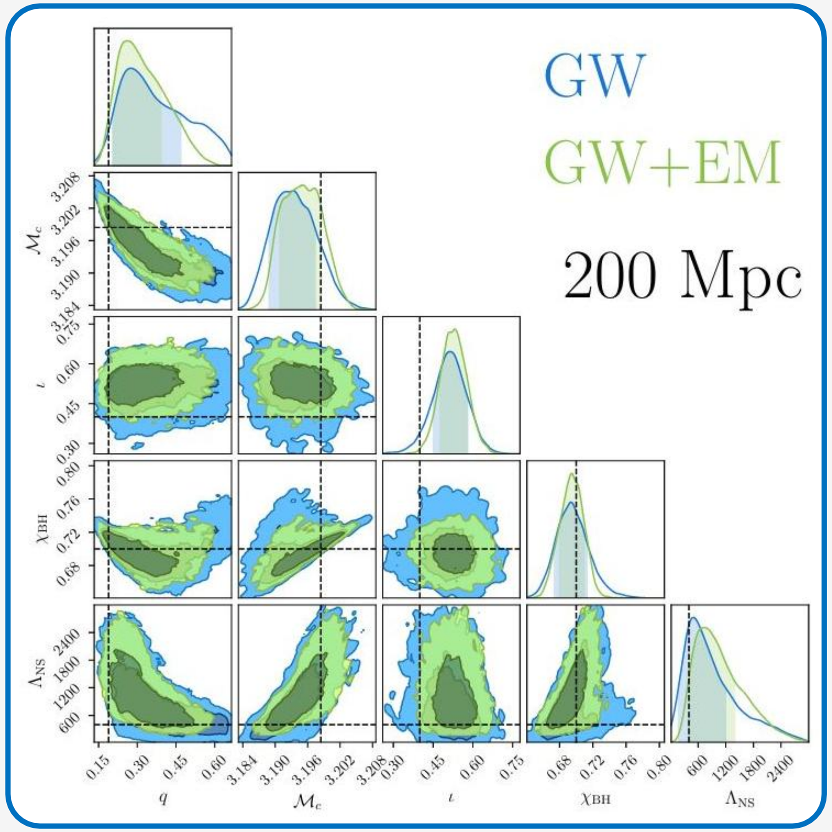


Fig. 3: Parameter estimation with GWFish.

Gravitational Wave detection

To simulate the detection we can use two different approaches:

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



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