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Absorption features in gamma-ray spectra of BL Lac objects

L. Foffano, V. Vittorini, M,. Tavani, E. Menegoni

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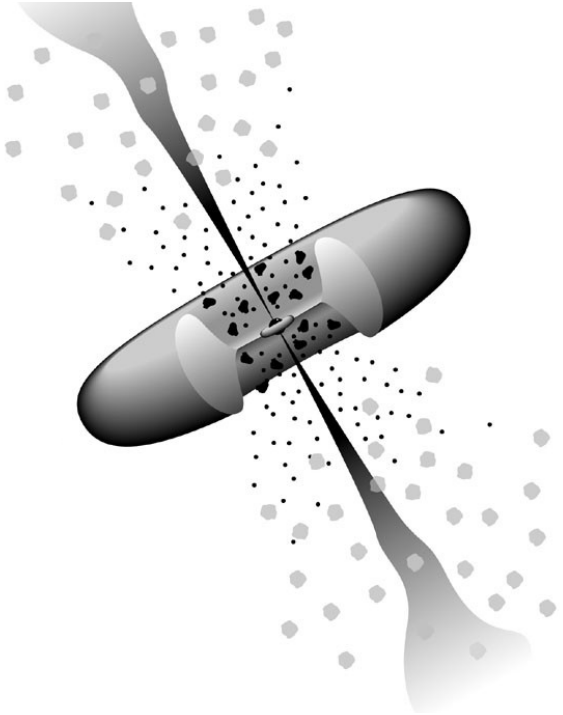
AGNs and their large-scale structures

A simplified view



Adapted from Urry&Padovani+1995

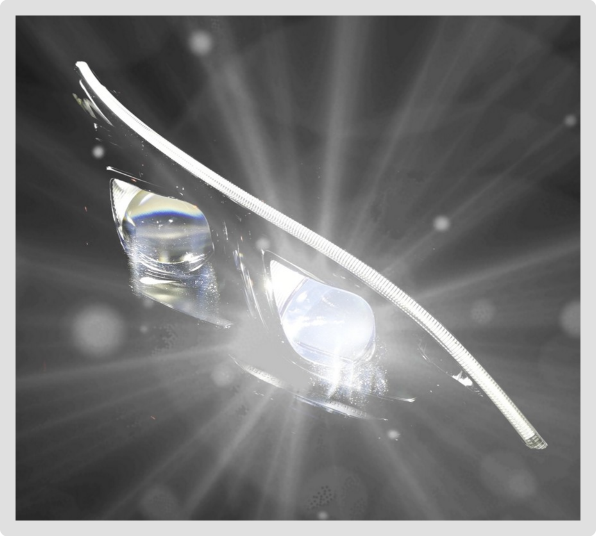
The **main components and large-scale structures** of an active galactic nucleus (AGN) are, for example:

- Central supermassive black hole (BH)
- Accretion disk
- Dusty torus
- Broad-line region (BLR)
- **Narrow-line region** (NLR, or extended narrow-line region, ENLR)

The zoology of AGNs is very complex:
some of these structures change with the evolution history of the AGN

Blazars

Blazars are AGNs with a relativistic jet pointing towards the line of sight of the observer.



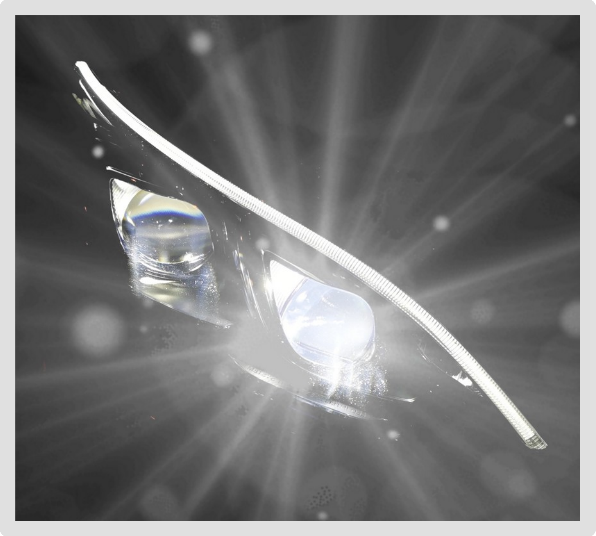
They are subdivided in:

- **Flat Spectrum Radio Quasars (FSRQs)**
  - Young evolution stage, rich environment,
  - High accretion rate $\dot{M} \gtrsim 1$
  - High electromagnetic output
  - Detectable optical absorption / emission lines

- **BL Lac objects**
  - Late evolution stage, scarce environment, with a slow population evolution
  - Low accretion rate $\dot{M} \ll 1$
  - Energy extracted from the rotational energy
  - Non-thermal continuum overwhelms the thermal emission

e.g. Cavaliere&D'Elia+02

The evolution of BL Lac objects and their large-scale structures



BL Lac objects: non-thermal continuum overwhelms the thermal emission

Some standard methods investigating the optical spectra do not always work, due to the dominant radiation of the jet

→ **An indirect method may do the work!**

Question 1:

Which large-scale structures are present in BL Lac objects?

Question 2:

Do the large-scale structures survive to the evolution in BL Lac objects?

Absorption features in gamma-ray spectra of BL Lac objects

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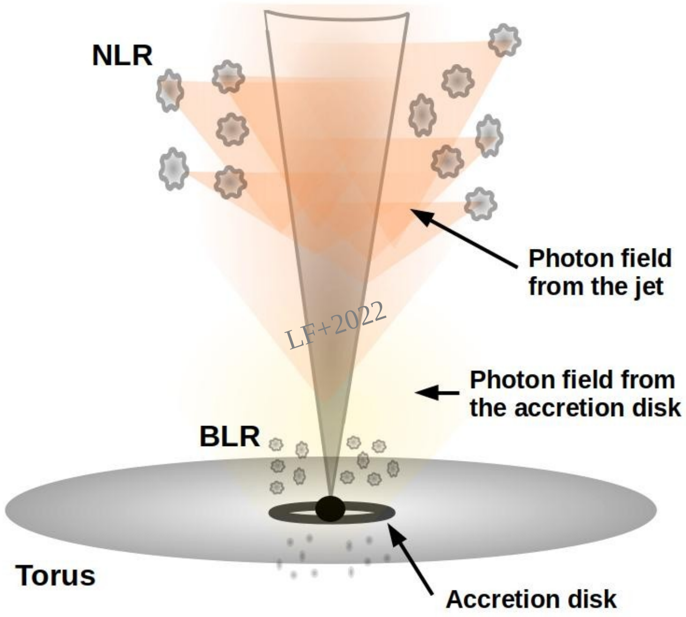


Let’s assume the presence of a NLR in a BL Lac object.

The NLR may be *illuminated* by the relativistic jet and produce a local bath of optical-UV **seed photons**.

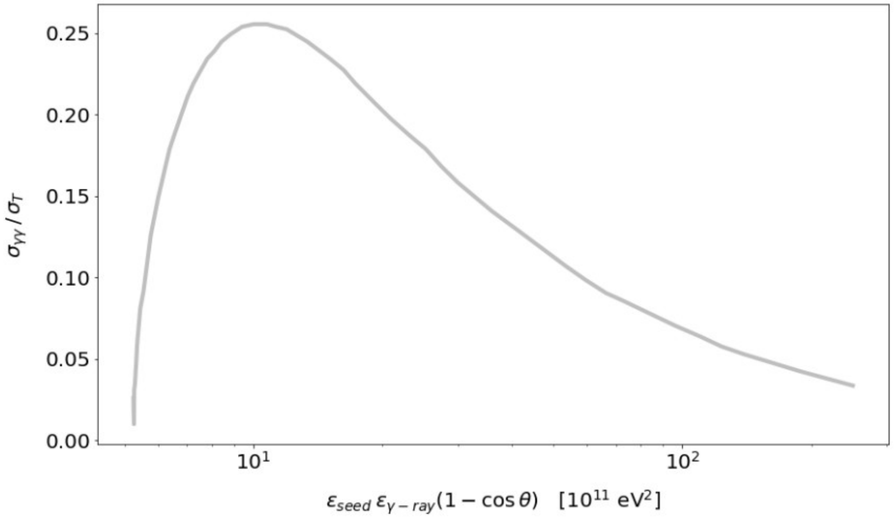
Gamma rays of the jet may interact with these seed photon field via ɣ-ɣ pair production, producing **absorption features** in the ɣ-ray spectrum of the BL Lac object.

Gamma-gamma pair production

The γγ interaction takes place when two photons collide and produce an electron-positron pair.

In our case, we will consider a **gamma-ray photon of the jet γ_{gamma}** interacting with a **seed photon γ_{seed}** at ~optical-UV energies:

$$\gamma_{gamma} + \gamma_{seed} \rightarrow e^{+} + e^{-}$$



γγ cross section as a function of the energy of the incoming photons, in units of the Thomson cross section

Important features:

- Precise threshold

$$\epsilon_{\rm seed}\cdot\epsilon_{\gamma\text{-ray}} \geq \frac{2\left(m_e c^2\right)^2}{1-\cos\theta} \sim \frac{5.2\cdot 10^{11}\ {\rm eV}^2}{1-\cos\theta}$$

- Maximum cross-section very *close* to the energy threshold
- Extension appreciable over less than 2 orders of magnitute in energy

Assumption: mono-energetic isotropic seed photon field

→ see F.Aharonian – VHE Cosmic Gamma Radiation

Absorption features in gamma-ray spectra of BL Lac objects

The interaction reduces the observed flux

$$I_{\rm out} = I_{\rm in}\, e^{-\tau_{\gamma\gamma}}$$

Where the absorption factor

$$\tau_{\gamma\gamma} = n_{\rm seed} \cdot \sigma_{\gamma\gamma} \cdot R \simeq 0.68 \cdot n_{\rm seed,4} \cdot (R/100 \text{ pc})$$

depends on:

- **average photon density $\mathbf{n_{seed}}$** of the seed photons
- **size R** of the path of gamma rays into the seed photon field
- cross-section, and then on the **energy of the interacting photons**

We may indirectly constrain the physical properties of the NLR of the BL Lac object!

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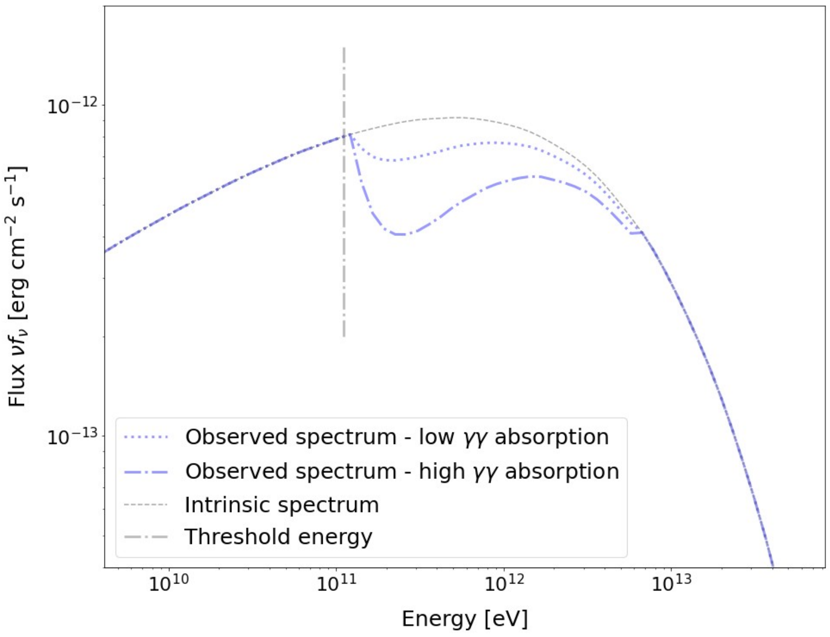
Theoretical absorption feature



Experimental application

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Experimentally, we may apply the inverse procedure:

- **Identify a possible absorption feature** that can be explained by the ɣ-ɣ cross section with

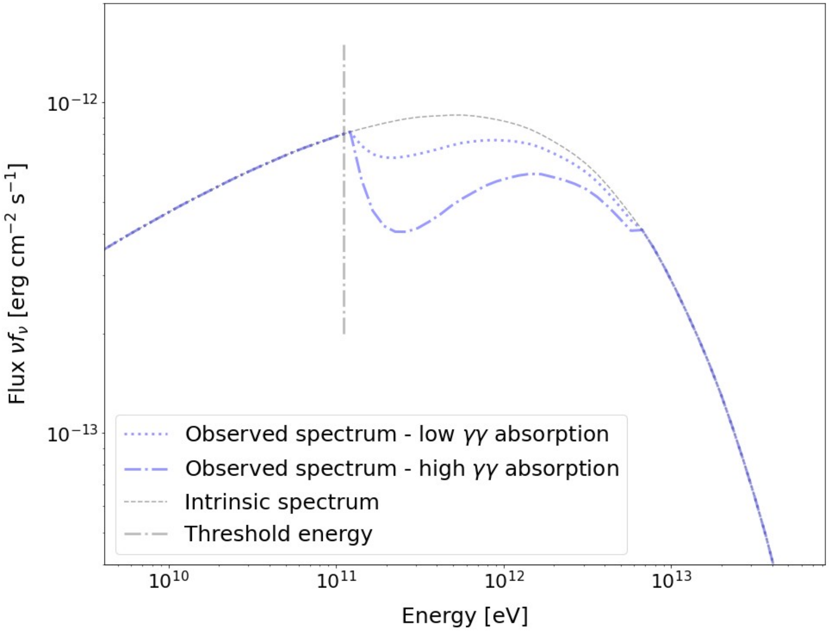
$$I_{\text{out}} = I_{\text{in}}\, e^{-\tau_{\gamma\gamma}}$$

- Extract the product of the **energy of the interacting photons** **from the maximum of the interaction**

- **Extract the photon column density,** that is the **product** between:
  - **average photon density $\mathbf{n_{seed}}$** of the seed photons
  - **size R** of the path of gamma rays into the seed photon field

$$\tau_{\gamma\gamma} = n_{\text{seed}} \cdot \sigma_{\gamma\gamma} \cdot R \simeq 0.68 \cdot n_{\text{seed},4} \cdot (R/100\ \text{pc})$$

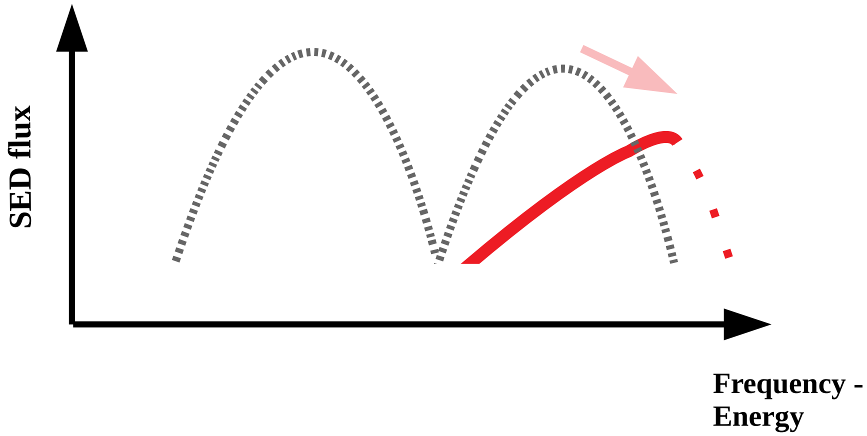
Theoretical absorption feature



Best candidates to detect absorption features at gamma rays

The best targets to detect gamma-ray absorption features are sources that:

1) are **well detected in gamma rays**
   (especially from 100 GeV up to ~TeV)
2) show ~**hard intrinsic spectra** extending up to hundreds GeV
   (EBL absorption)
3) show a ***clean* spectral shape** in that band,
   (without contamination of other spectral features)
4) and show a ***relatively stable* flux** at those energies
   (at least during the observations)



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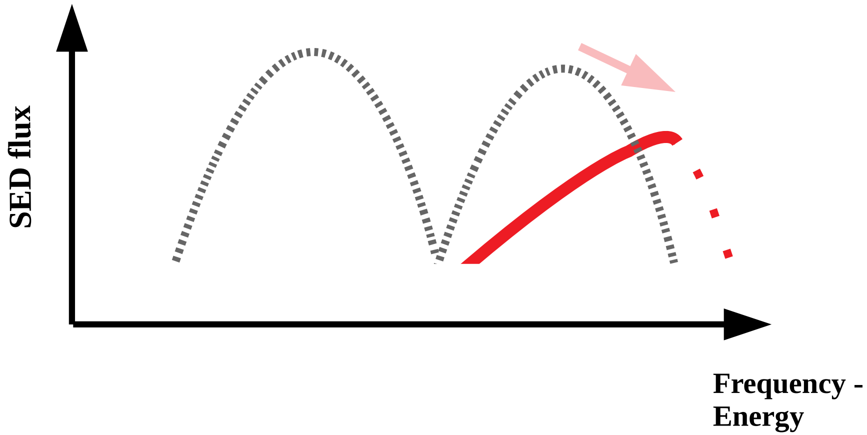
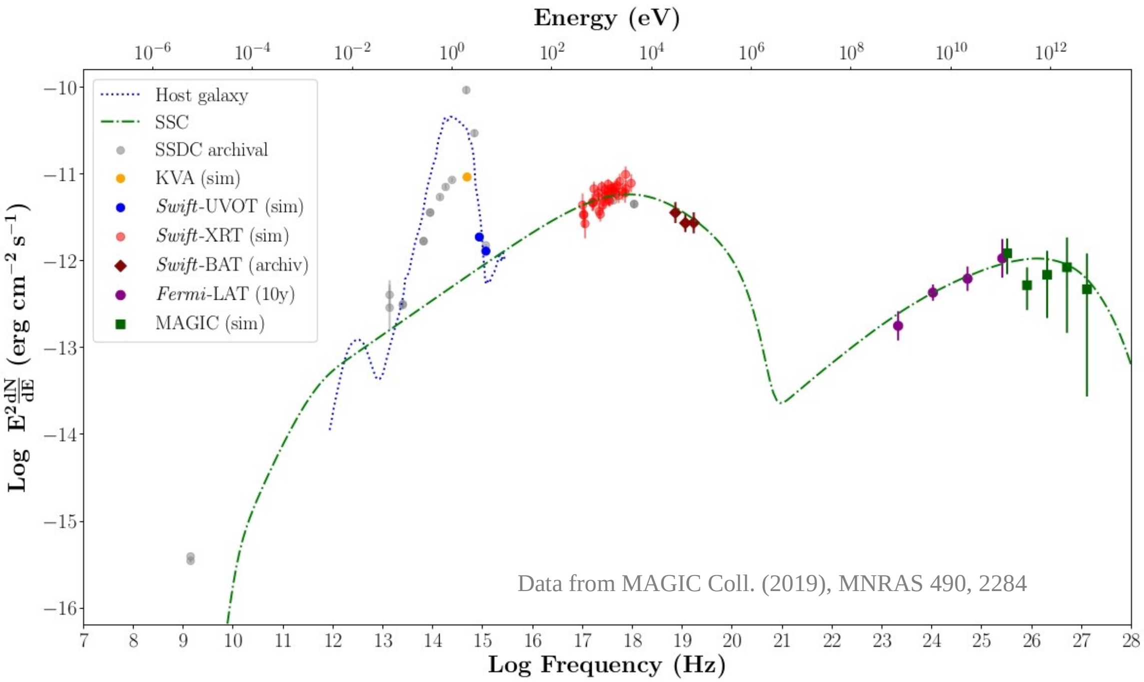


High-synchrotron peaked BL Lac objects **HBLs** and extreme HBLs (**EHBLs**, or extreme blazars) are the best candidates!

Our first candidate

Name	**PGC 2402248** or 2WHSP J073326.7+515354
Type	extreme blazar (EHBL)
Redshift	0.065 Becerra+2020
VHE detection	MAGIC MAGIC Coll. (2019), MNRAS 490, 2284
Principal investigators	L.Foffano, J.G.Becerra



Theory vs real data

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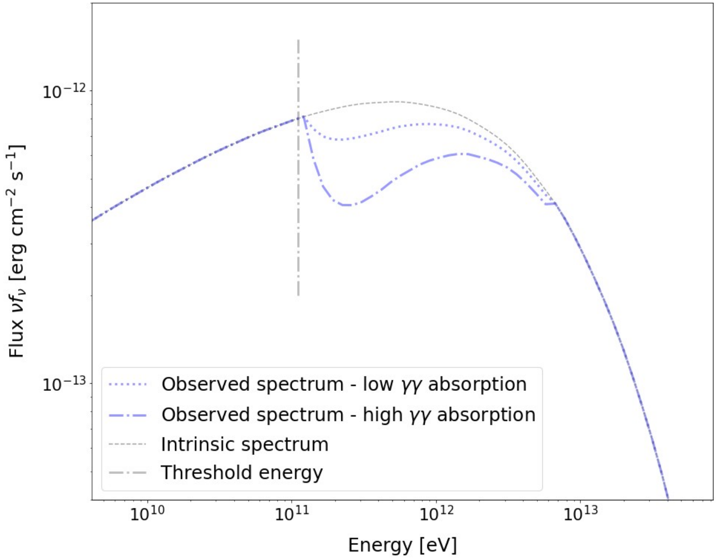
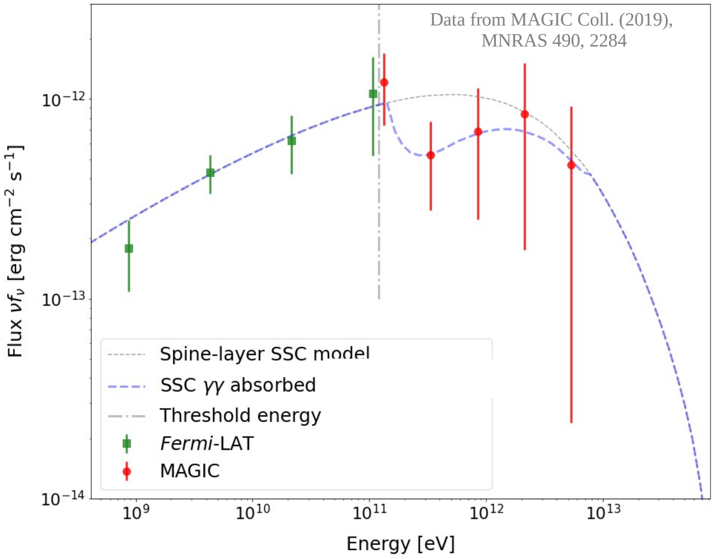
Theoretical absorption feature



Real data of PGC 2402248



The real data are compatible with the absorption produced by a NLR/ENLR

photon column density $K_{seed} = 130 \cdot 10^4$ pc/cm^3

Open points

This phenomenon may be temporary

- The clouds of material creating the seed photon fields may change over time
- The luminosity of the accretion disk / jet may change over time
- The gamma-ray emission of the jet may change over time

→ change the absorption factor

→ verify variable sources!

It may be more complex:

- If the seed photon field is not **mono-energetic**, the absorption feature may be more difficult to be identified in the BL Lac spectrum. → change the absorption feature *shape*

It may be not detectable:

- If the opacity of the absorbing region is not strong enough, the low-resolution of the gamma-ray spectral points of the current observatories may not allow for the identification of such a feature

Conclusions

Context:

The identification of large-scale structures (e.g. a narrow-line region, NLR) in BL Lac objects is complicated by the overwhelming non-thermal continuum in the optical spectrum

→standard methods are usually not appliable

Method:

We apply the ɣ-ɣ pair production interaction to propose a new **indirect method** to suggest the presence of large-scale structures in BL Lac objects.

The presence of a hypothetical NLR on the trajectory of the relativistic jet would eventually cause a reduction of the observed flux of gamma rays in the spectrum of the BL Lac object. The corresponding **absorption feature** provides indirect estimations on the properties of the NLR.

Results:

- Promising application to real data of an extreme blazar named PGC 2402248
- Further studies ongoing to confirm this hypothesis in other sources → LF+ in preparation
- May it be related to **neutrino production**? → under investigation

Notes:

- The best candidates to apply this method are **HBLs and EHBLs**
- This phenomenon may be temporary and/or **depend on the activity state** of the source
- It may be identified in **archival data**!

More details in: Foffano L., Vittorini V., Tavani M., Menegoni E., 2022, ApJ, 926, 95