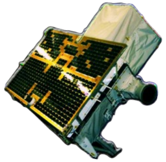
INAF
ISTITUTO NAZIONALE DI ASTROFISICA



AGILE Satellite
Bruno Rossi Prize 2012

Partially funded also by
AHEAD 2020 HIGH ENERGY ASTROPHYSICS
Funded by the Horizon 2020 Framework Programme of the European Union Grant Agreement No. 871158

Neutrinos from interactions between the relativistic jet and large-scale structures of BL Lac objects investigated through their gamma-ray spectrum

Luca Foffano, M. Cerruti, V. Vittorini

TeVPA 2023

TeVPA2023 conference – Naples (Italy) – 11/09/2023

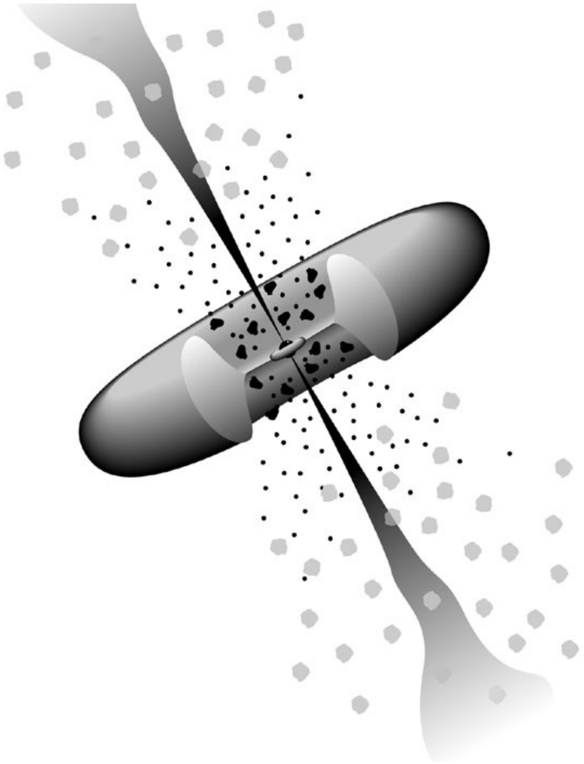
Overview

Context on large-scale structures of AGNs

Phase 1
Study ɣɣ interactions between the relativistic jet and large-scale structures of BL Lac objects

Phase 2
Investigate pɣ interactions producing neutrinos

Active galactic nuclei and their large-scale structures

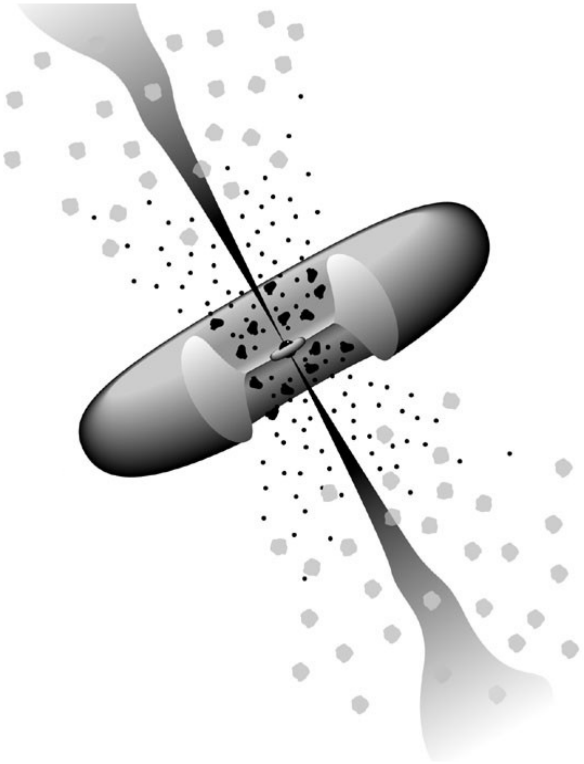


Adapted from Urry&Padovani+1995

The environment around jets of active galactic nuclei is supposed to form medium- to large-scale structures such as:

- Broad-line region (BLR)
- **Narrow-line region** (NLR)

Active galactic nuclei and their large-scale structures



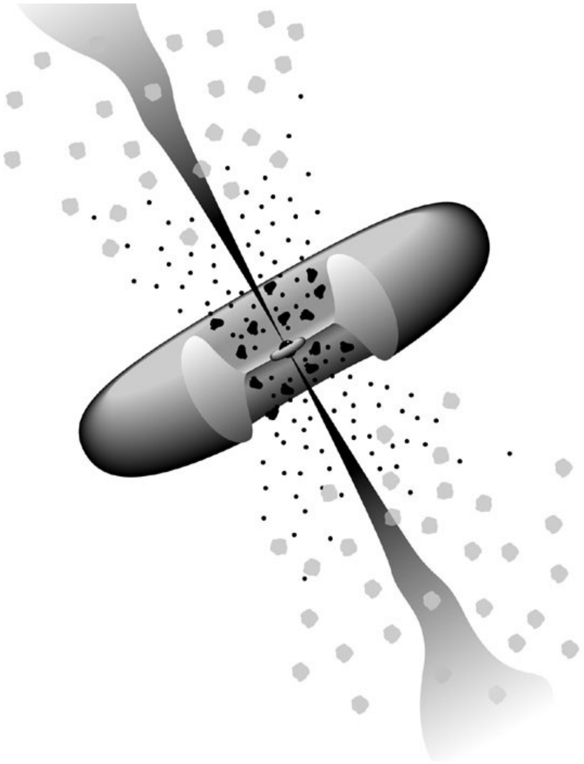
Adapted from Urry&Padovani+1995

The environment around jets of active galactic nuclei is supposed to form medium- to large-scale structures such as:

- Broad-line region (BLR)
- **Narrow-line region** (NLR)
- Further / intermediate regions (Intermediate or extended narrow-line region, ENLR) in specific types of AGNs, depending on matter state and physical conditions

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

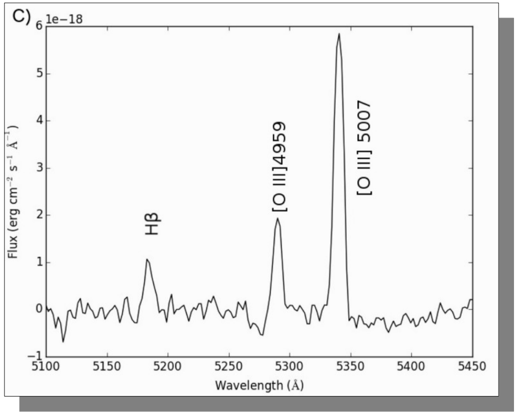
Active galactic nuclei and their large-scale structures



Adapted from Urry&Padovani+1995

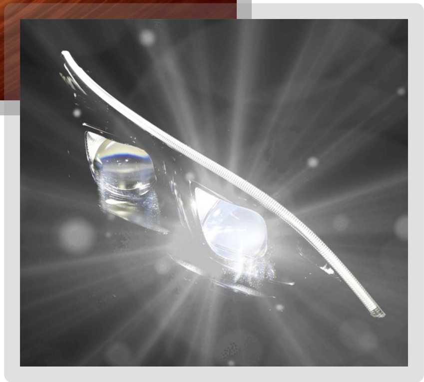
How do we detect medium- and large-scale structures in AGNs?

Standard methods to detect large-scale structures in AGNs are based on their **optical spectra**



Large-scale structures in BL Lac objects

Credit: NASA JPL/Caltech



In **BL Lac objects**, the relativistic jet points directly to the observer.

The non-thermal continuum of the relativistic jet overwhelms any thermal emissions emitted from large-scale structures

- ❌ standard methods can not be applied
- ✓ **an indirect method may do the work!**

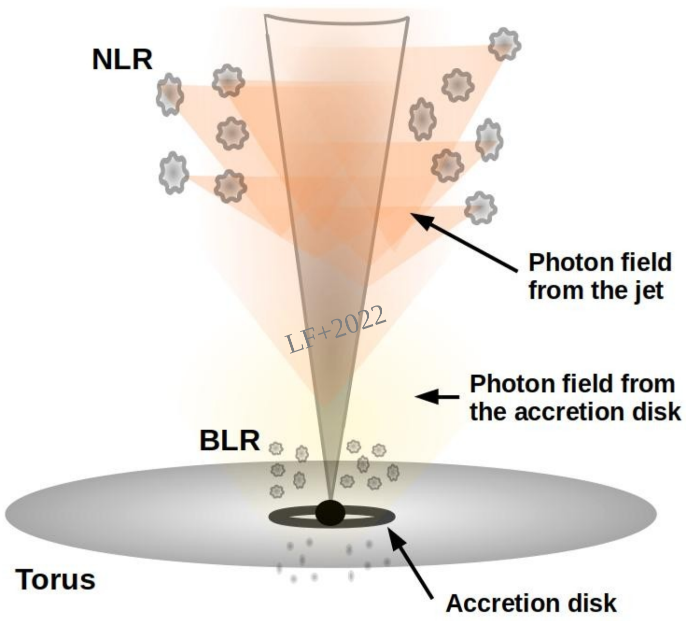
Which large-scale structures are present in BL Lac objects?

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

Absorption features in gamma-ray spectra of BL Lac objects

Foffano L., Vittorini V., Tavani M., Menegoni E., 2022, ApJ, 926, 95

Phase 1



Let's assume the presence of a narrow-line region (NLR) in a BL Lac object.

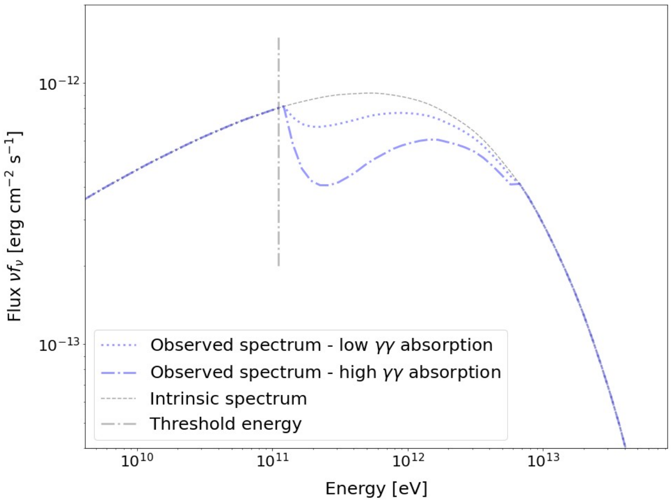
The NLR may be *illuminated* by the relativistic jet and produce a local bath of optical-UV **seed photons**.

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.

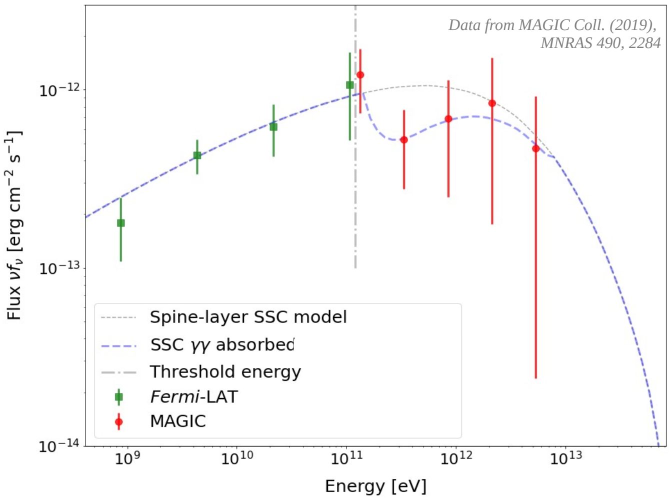
Theory vs real data

Foffano L., Vittorini V., Tavani M., Menegoni E., 2022, ApJ, 926, 95

Theoretical absorption feature



Real data of an extreme blazar named PGC 2402248



A possible case study?

A sistematic analysis of gamma-ray spectra of BL Lac objects is being performed

Dual action

Phase 2

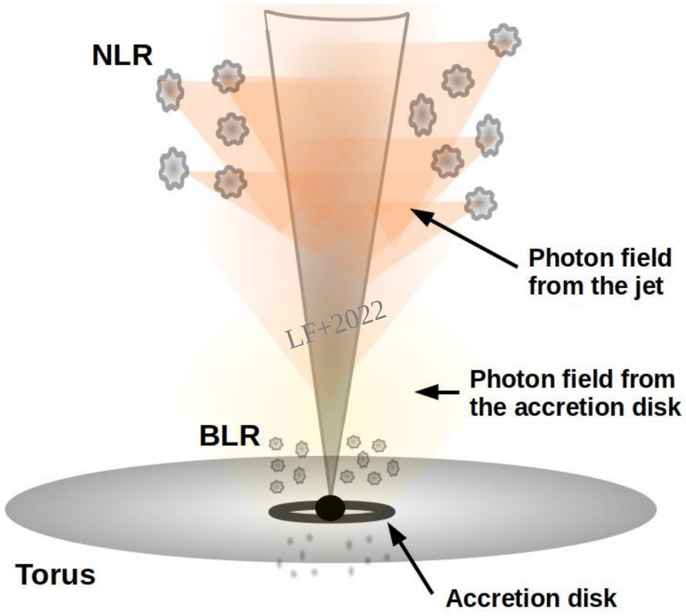
The target photon field on the relativistic jet trajectory may cause:

ɣ **ɣ-ɣ interactions** → absorption feature in the gamma-ray spectrum

p Assuming relativistic protons in the jet → **p-ɣ interactions** → **neutrinos**!

$$p + \gamma \rightarrow p_0 + \pi_0$$
$$p + \gamma \rightarrow n + \pi^+$$
$$p + \gamma \rightarrow p_0 + \pi^+ + \pi^-$$

$$\pi_0 \rightarrow \gamma\gamma$$
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_\mu + \bar{\nu}_\mu$$



Power-law distribution:

$$N(\gamma_p) = N_0\, \gamma_p^{-s} \qquad \gamma_{min} < \gamma_p < \gamma_{max}$$

Model parameters of the proton distribution: normalization N_0, γ_{min} and γ_{max}, spectral index

Main target of the project:

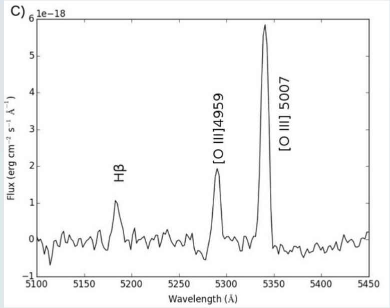
correlation of the gamma-ray absorption features with the possible corresponding neutrino flux

Main target of the project:

correlation of the gamma-ray absorption features with the possible corresponding neutrino flux

Approach 1

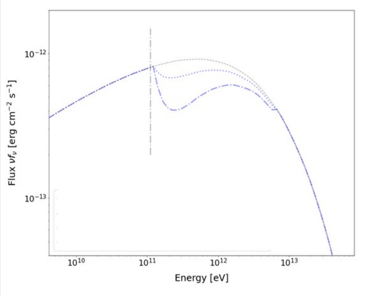
Correlation of a hypothetical optical emission of the large-scale structure with the possible corresponding neutrino flux



Neutrino Flux computation

Approach 2

Direct correlation of the gamma-ray absorption feature with the possible corresponding neutrino flux



Approach 1

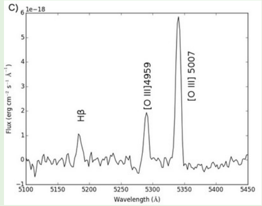
Correlation of a hypothetical optical emission of the large-scale structure with the possible corresponding neutrino flux

We assume the presence of
an optical emission of the NLR
of the BL Lac object

→ may be hidden by the relativistic jet radiation

→ may be temporary

e.g. masquerading BL Lac objects [Padovani+19, …]



Approach 1

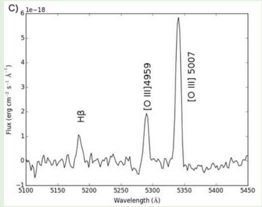
Correlation of a hypothetical optical emission of the large-scale structure with the possible corresponding neutrino flux

We assume the presence of an optical emission of the NLR of the BL Lac object

→ may be hidden by the relativistic jet radiation

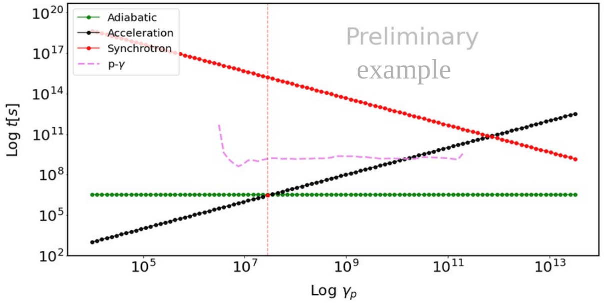
→ may be temporary

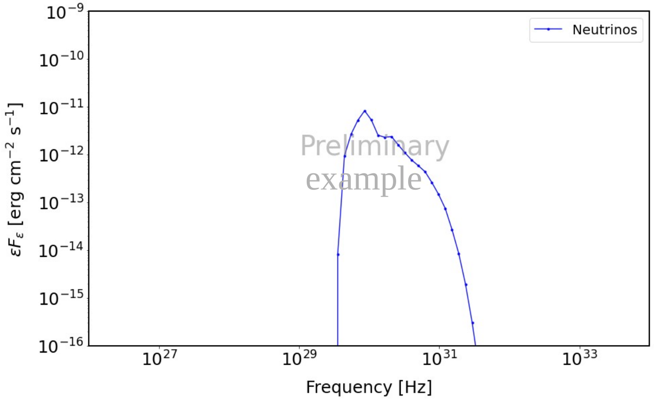
e.g. masquerading BL Lac objects [Padovani+19, …]



We compute the **neutrino flux and spectrum** from the interaction between the protons in the relativistic jet and the target photon field producing such an optical spectrum

Redshift	B [Gauss]	r [cm]	eta	Gamma bulk
0.15	0.01	1e+17	10	10



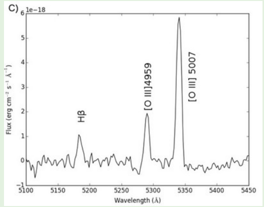


Approach 1

Correlation of a hypothetical optical emission of the large-scale structure with the possible corresponding neutrino flux

We assume the presence of
an optical emission of the NLR
of the BL Lac object
→ may be hidden by the relativistic jet radiation
→ may be temporary

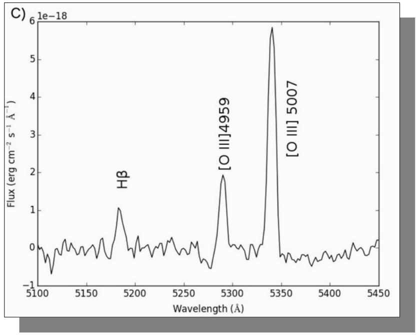
e.g. masquerading BL Lac objects [Padovani+19, …]

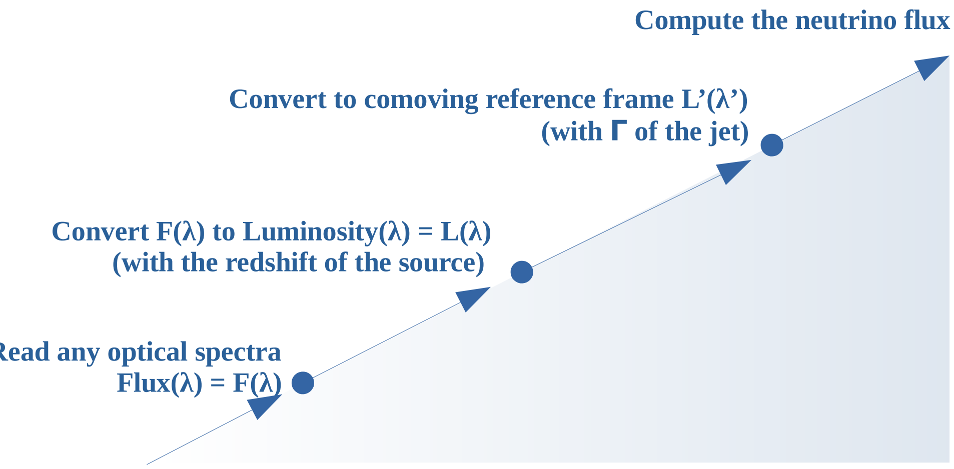


We compute the **neutrino flux and spectrum** from the interaction between the protons in the relativistic jet and the target photon field producing such an optical spectrum

We perform **simulations** with semi-analytical formulae scanning over a wide parameter space describing the photon field and the blazar properties

Parameters





Foteini+19, Murase+06 among others

Parameters describing blazar and dynamics:

- z: redshift of the source
- Γ: bulk Lorentz factor of the relativistic jet
- R: size of the emitting region
- B: magnetic field
- η: proton acceleration efficiency

Parameters describing photon field:

- Photon column density (photon density x size interaction region)
- Energy

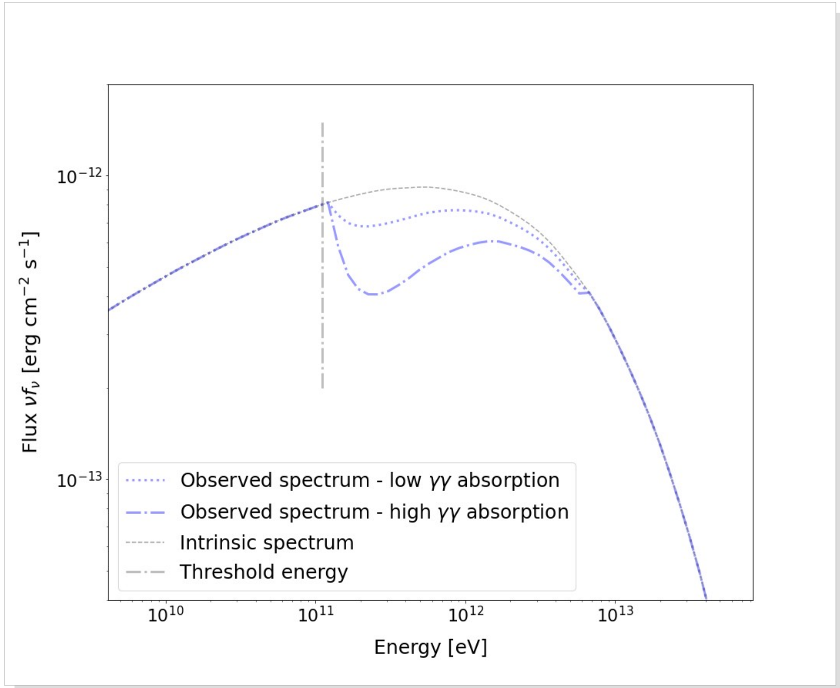
Parameters describing proton distribution:

- Normalization
- Spectral index
- Energy extremes
- Total luminosity

→ simulations to find the best conditions to produce neutrinos

Approach 2

Direct correlation of the gamma-ray absorption feature with the possible corresponding neutrino flux



- Assume the presence of an absorption feature in the gamma-ray spectrum of the BL Lac object
- This absorption effect is supposed to be due to the ɣɣ interaction between the relativistic jet and the NLR
- The absorption factor may correlate with the efficiency of neutrino production from pɣ reactions following:

$$\tau_{\gamma\gamma}(\epsilon_\gamma^c) \simeq 10 \left(\frac{f_{p\gamma}(\epsilon_p)}{0.01} \right)$$

e.g. Murase+05, +16, +18, ...

The stronger the absorption due to ɣɣ interaction,
the higher the pɣ efficiency

Conclusions

Context:

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

→ standard methods usually cannot be applied

This work:

- **Phase 1:** a new indirect method may provide indirect estimations on the properties of the NLR looking at possible **absorption features in the gamma-ray spectrum of the BL Lac object,** produced by the **ɣɣ interaction** between the relativistic jet and the photon fields produced by the NLR itself.
- **Phase 2:** the same physical configuration should produce also **pɣ interactions** leading to production of **neutrinos from BL Lac objects**

We are studying **two main approaches**:

1) extracting the neutrino flux from the possible **optical spectrum** of the NLR (possibly partially/temporarily hiddenby the BL Lac jet)
2) extracting the neutrino flux directly from the **absorption feature** in the gamma-ray spectrum of the BL Lac object

This is performed with **simulations** over several sets of parameters describing the interacting region, the relativistic jet properties, and the AGN properties.

Thank you!