National and Kapodistrian University of Athens
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Department of Physics
Section of Astrophysics, Astronomy & Mechanics

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Modelling the non-thermal emission from Active Galactic Nuclei

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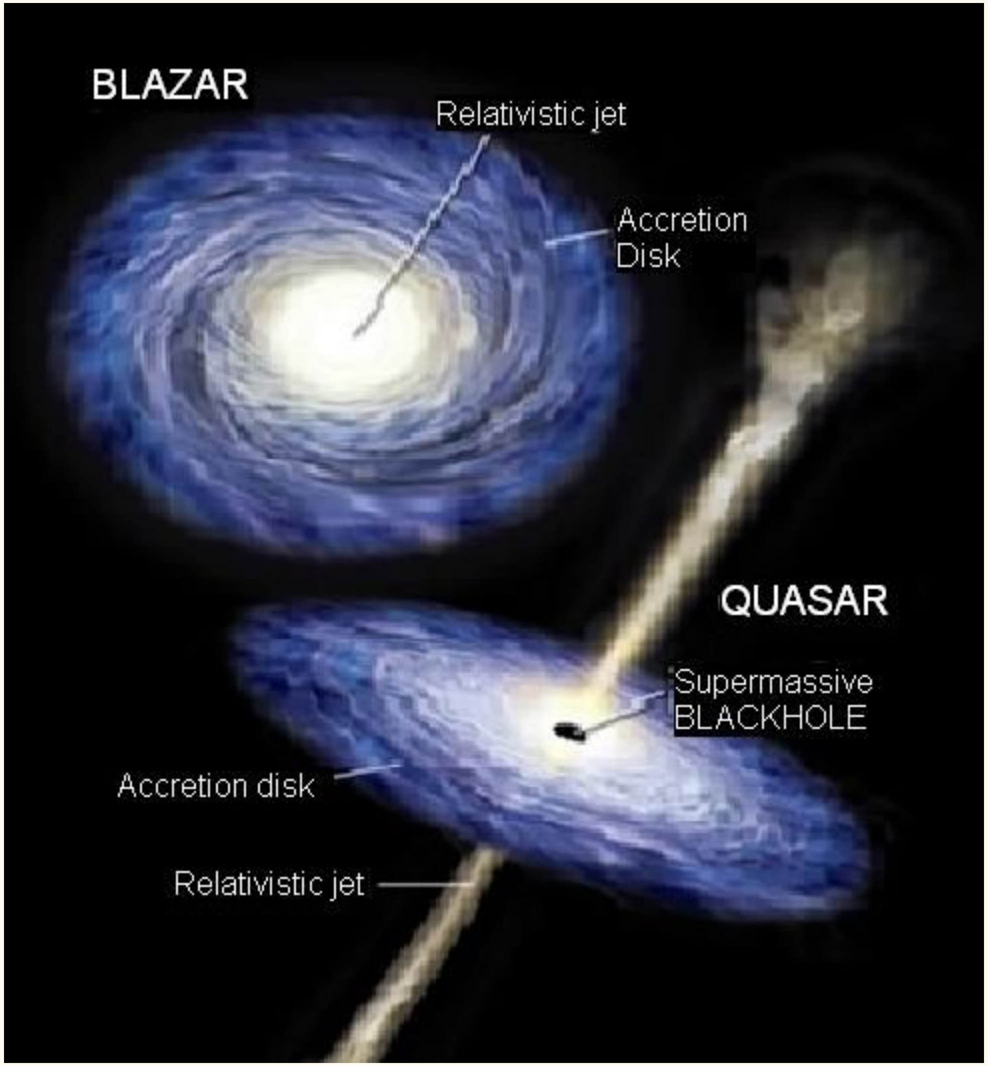
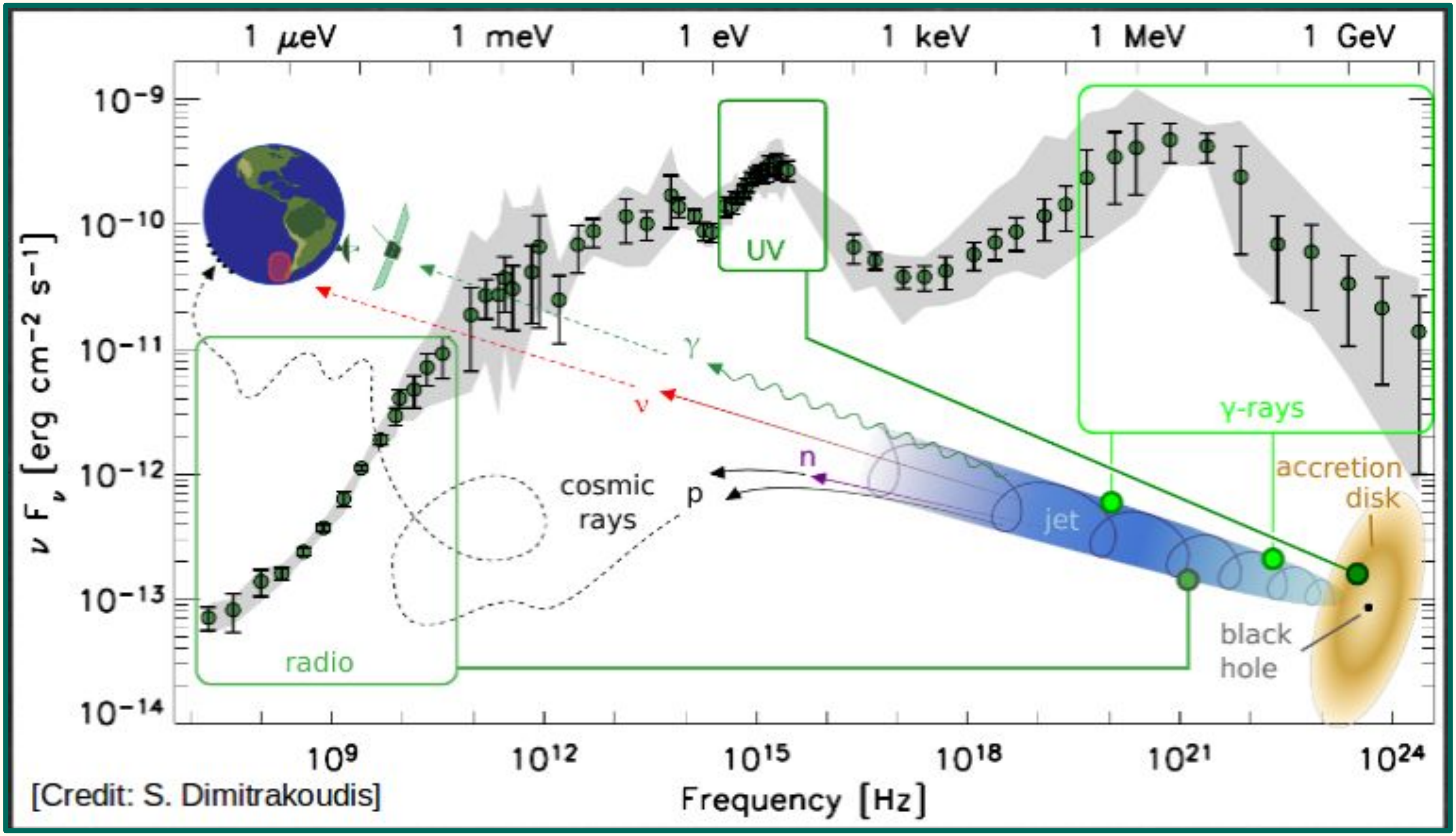
Outline

- Introduction
- Models
- Some Open Questions
- Results

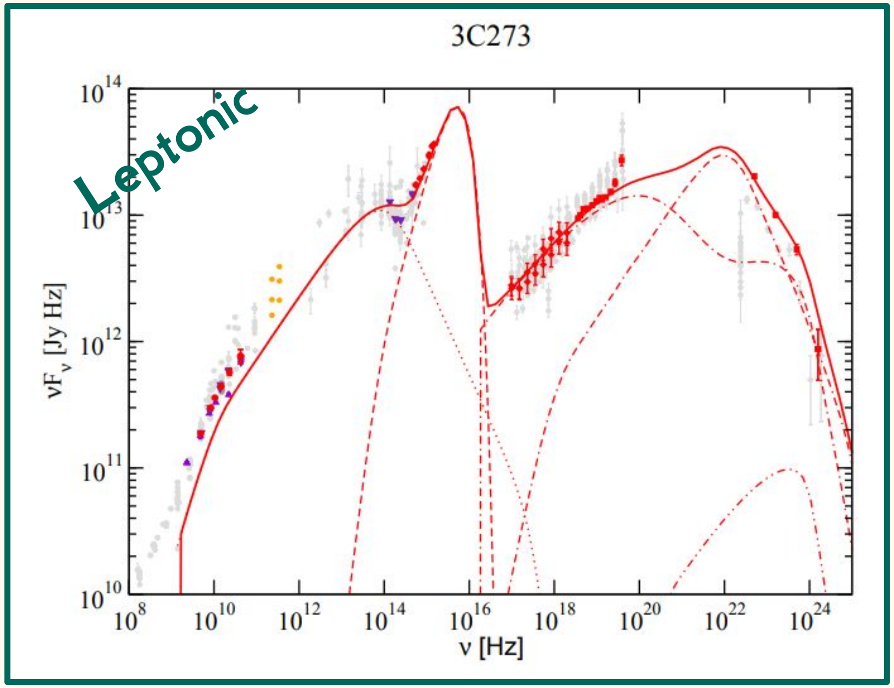


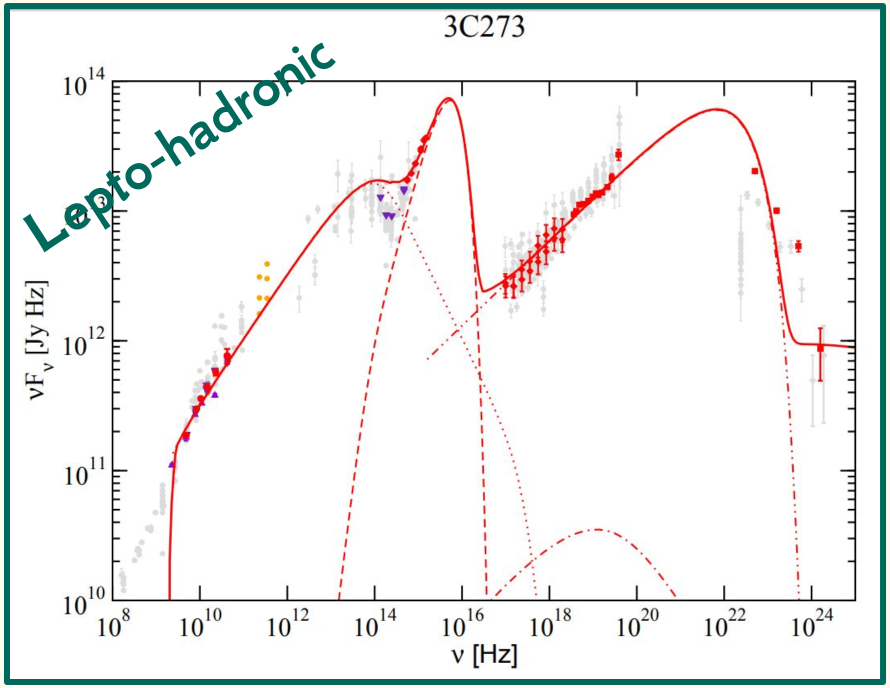
https://ruffletheteacher.files.wordpress.com/2011/07/blazar-and-quasar1.jpg



Bindu et al., 2019

Radiation models



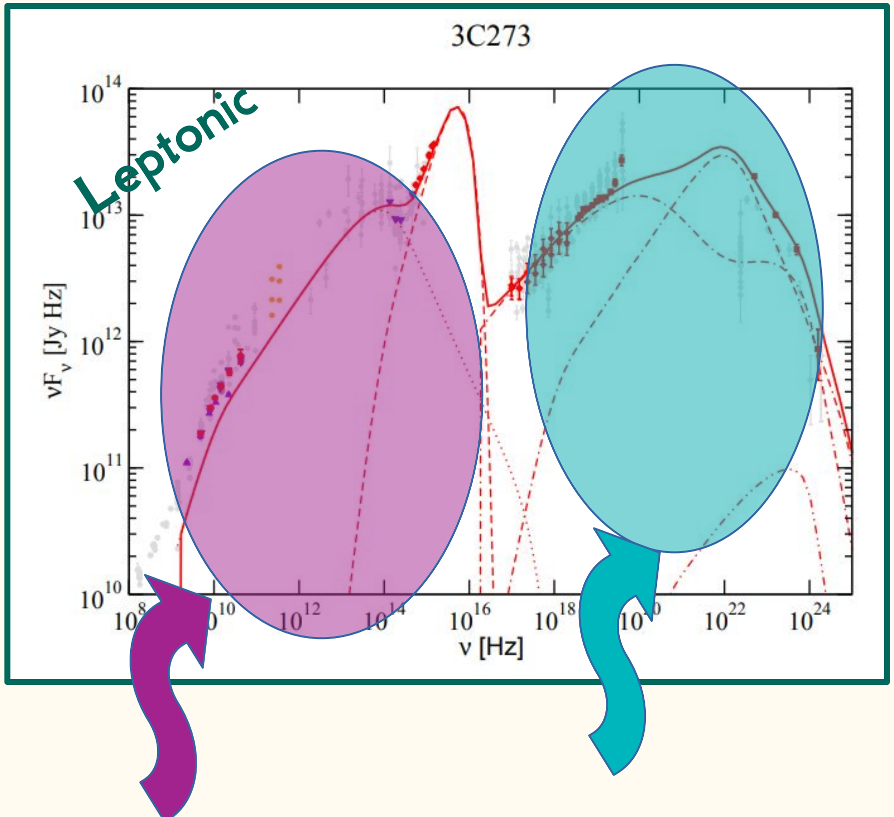


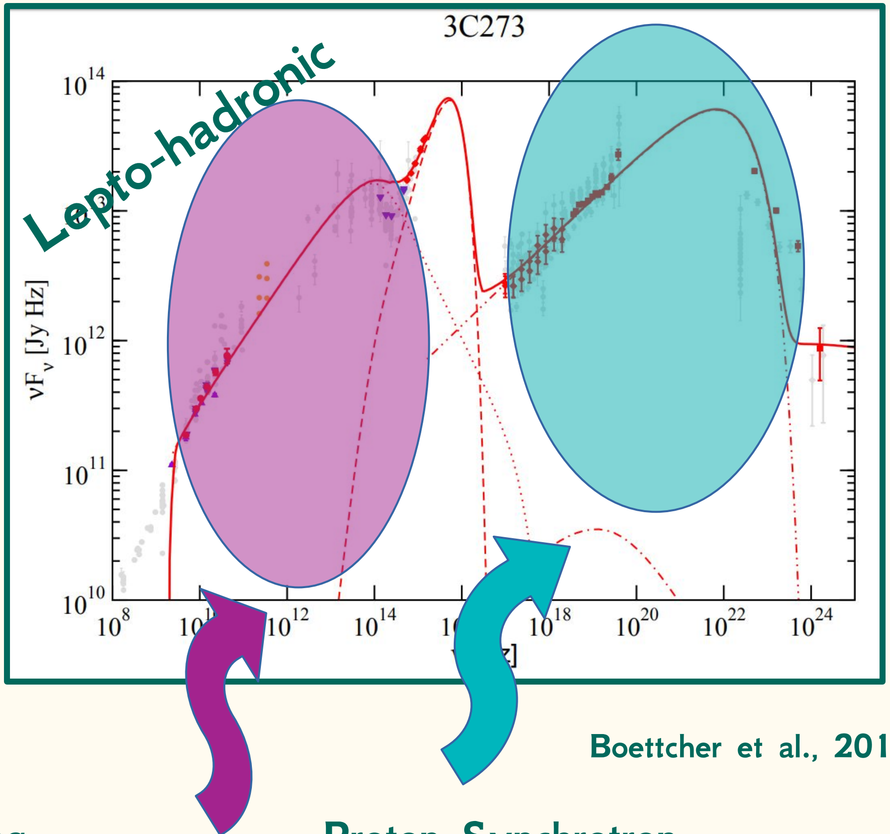
Boettcher et al., 2013

Leptonic (Mastichiadis and Kirk, 1997,Weidinger and Spanier, 2010, Kataoka et al., 2000, Krawczynski et al., 2002, Sikora et al., 2001, Bottcher and Chiang, 2002, Ghisellini and Tavecchio, 2009, Acciari and Aliu, 2009, ++)

Hadronic (Mannheim and Biermann, 1992, Dimitrakoudis et al., 2014, Petropoulou et al., 2014, Padovani et al., 2015, Petropoulou et al., 2016, Zech et al., 2017, Padovani et al., 2018, Keivani et al., 2018 ++)

Radiation models





Boettcher et al., 2013

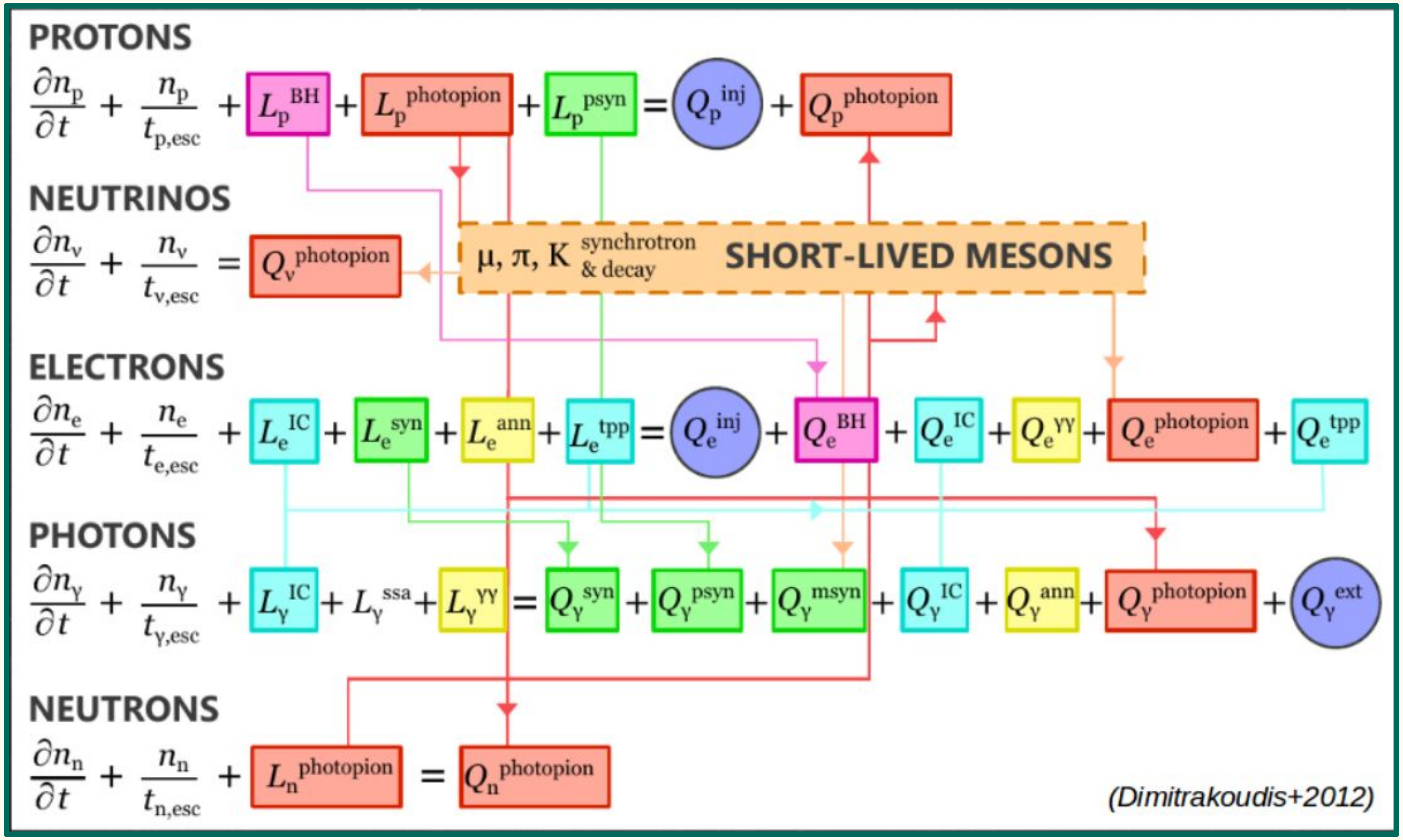
Inverse Compton Scattering

Proton Synchrotron

Electron Synchrotron

Electron Synchrotron

Kinetic equations of particles and photons



Based on the numerical code:
Mastichiadis & Kirk, 1995, A&A

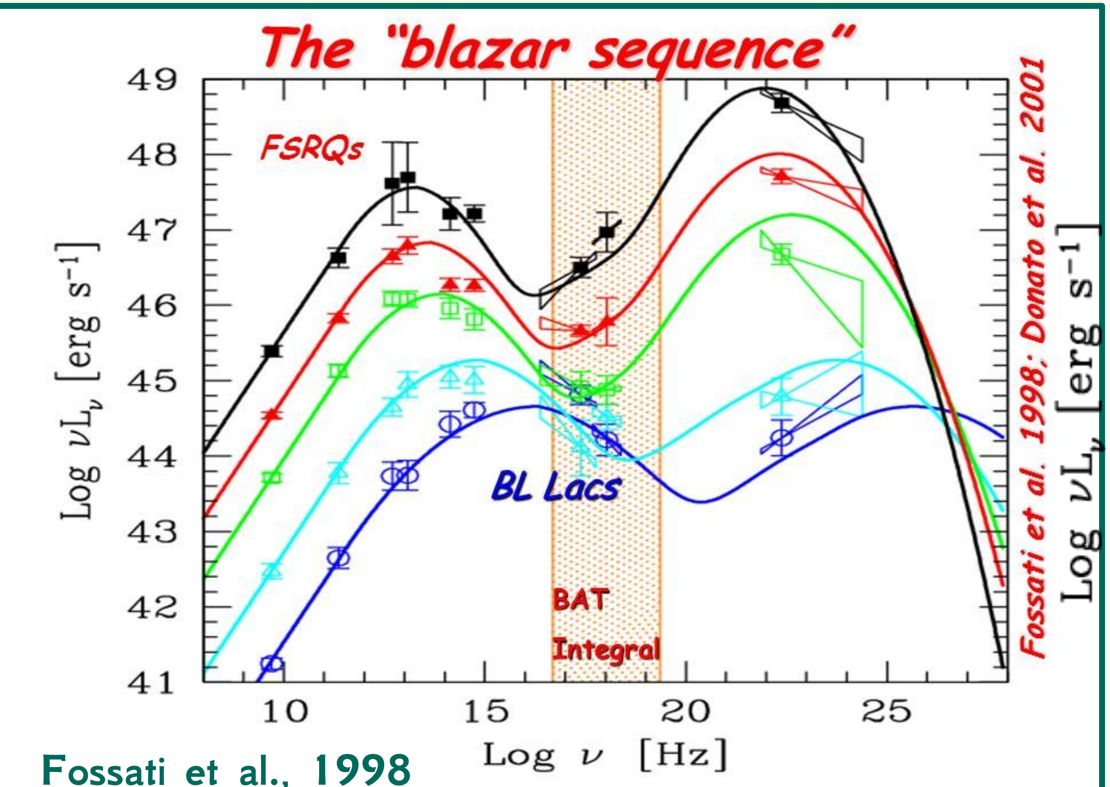
Some Open Questions

1. Blazar Sequence

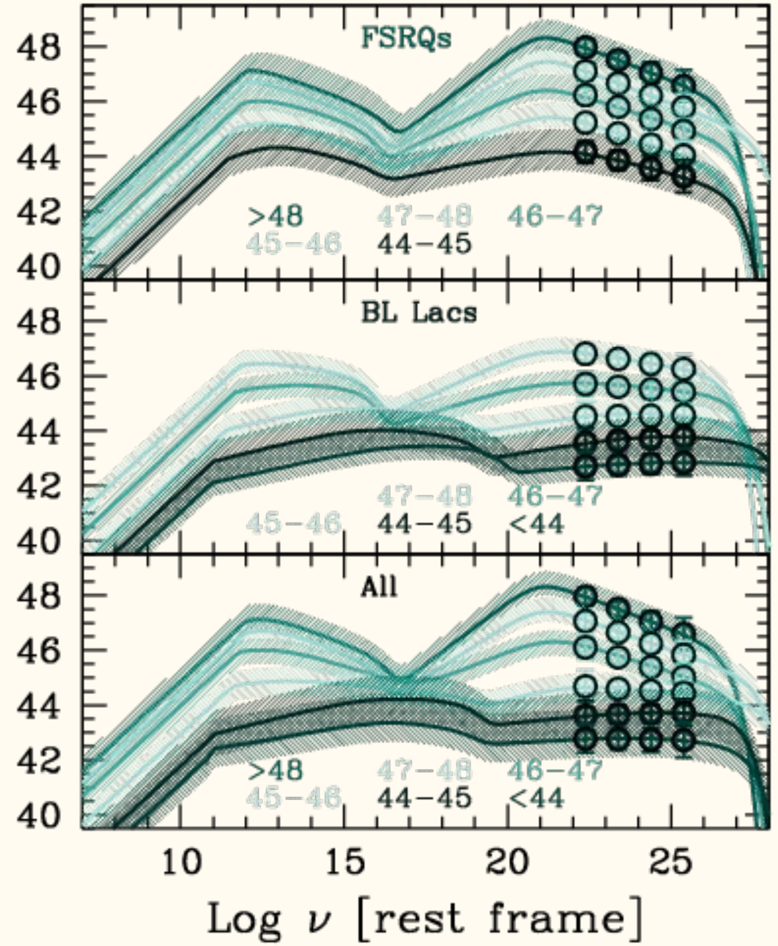
2. Localization of radio emission

3. Flares

1. Blazar Sequence

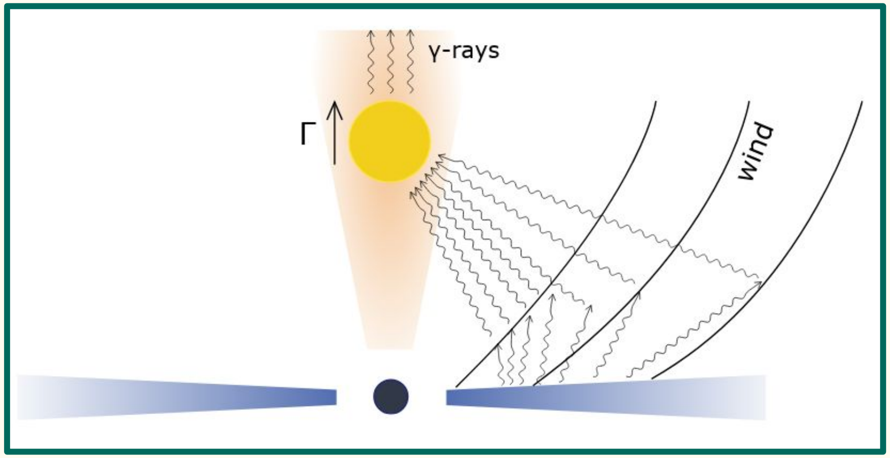


Fossati et al., 1998

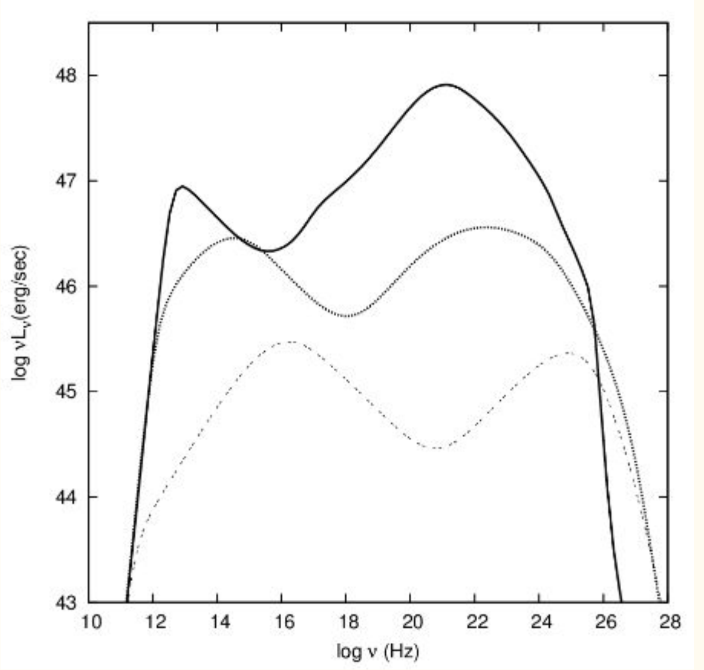


Ghisellini, 2017

(Giommi et al., 1999, Georganopoulos et al., 2001, Cavaliere and D'Elia, 2002, Padovani et al., 2003, Maraschi and Tavecchio, 2003, Nieppola et al., 2006, Padovani, 2007, Nieppola et al., 2008, Xie et al., 2007, Padovani 2007, Ghisellini and Tavecchio, 2008, Ghisellini and Tavecchio, 2009, Meyer et al., 2011, Chen and Bai, 2011, Giommi et al., 2012, Finke, 2013, Xiong et al., 2015, Xiong et al., 2015b, Raiteri and Capetti, 2016, Ghisellini et al., 2017, Boula et al., 2019).



Credit: S. Dimitrakoudis



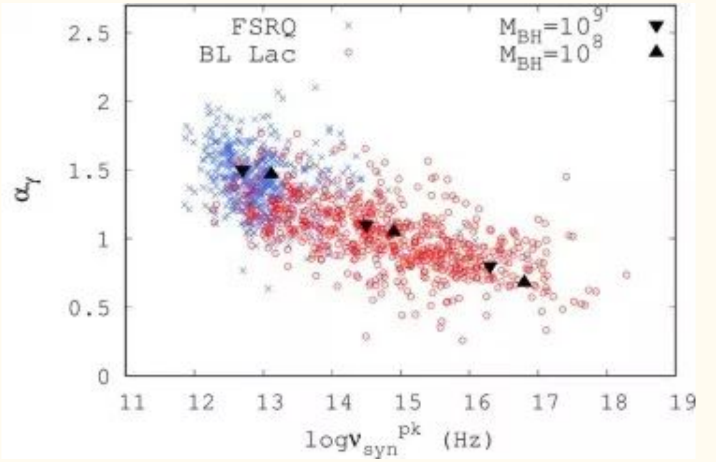
$$U_{\rm B} \propto \frac{\dot{m}}{\mathcal{M}},$$

$$U_{\rm ext} \propto U_{\rm sc} \propto \frac{\dot{m}^{\alpha+1}}{\mathcal{M}} \quad (\alpha = 1 \text{ for } \dot{m} \geq 0.1 \text{ and } \alpha = 2 \text{ for } \dot{m} < 0.1),$$

$$\gamma_{\rm br} \propto \dot{m}^{-1}(1+\dot{m}^{\alpha})^{-1},$$

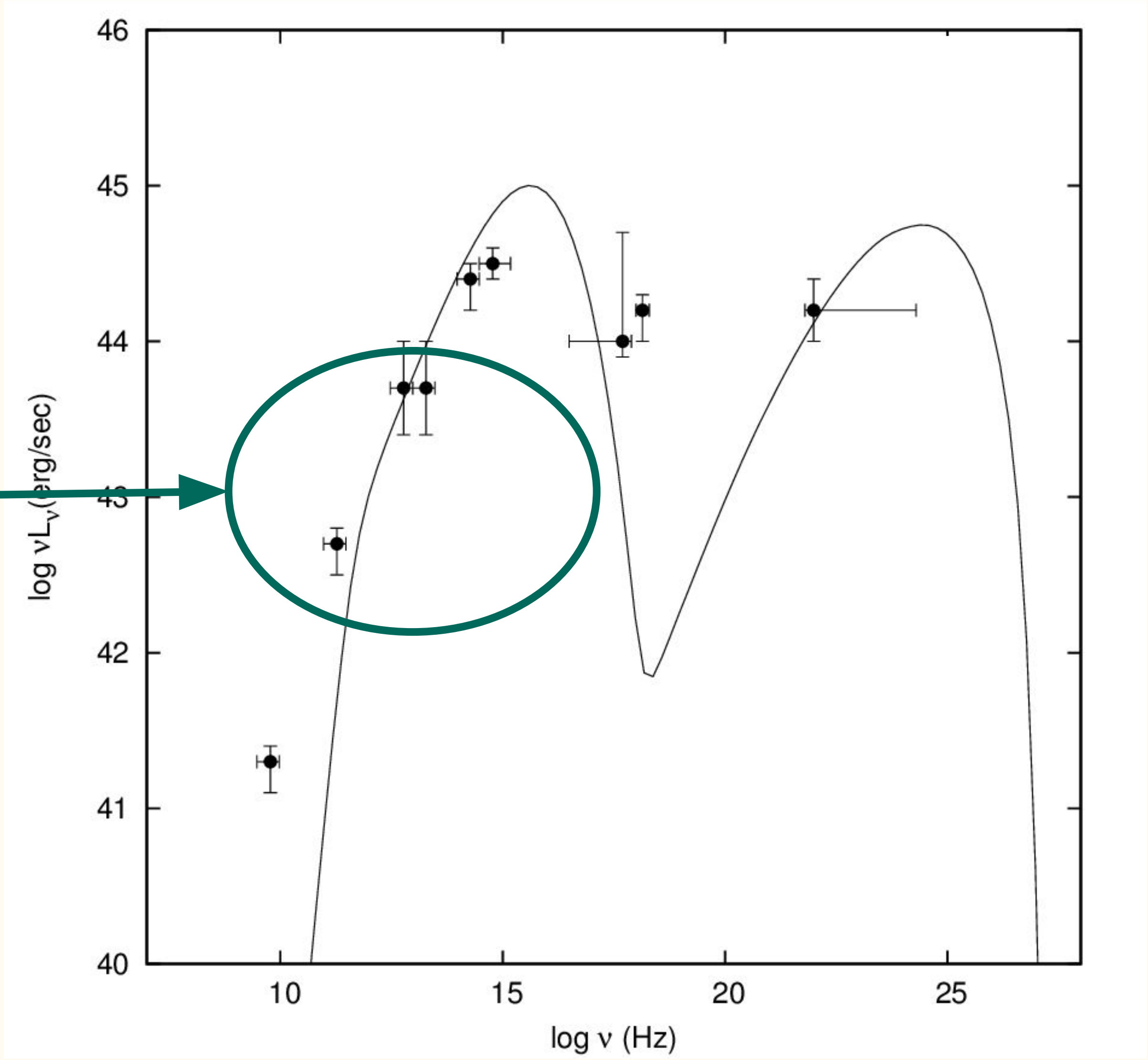
$$L_{\rm e}^{\rm inj} \propto \dot{m}\mathcal{M}$$

$$\nu_{\rm pk}^{\rm syn} \propto \mathcal{M}^{-1/2}\dot{m}^{-3/2}/(1+\dot{m}^{\alpha})^2$$



Boula, Kazanas & Mastichiadis, 2019

2. Localization of radio emission



Synchrotron Self-Absorption

Synchrotron Self - Absorption

The synchotron self-absorption frequency is defined as ν_{ssa} and it has the form:

$$\nu_{ssa} = \left[\frac{\sqrt{3}q^3}{8\pi m} \left(\frac{3q}{2\pi m^3 c^5}\right)^{\frac{p}{2}} C (B \sin\alpha)^{\frac{p+2}{2}} \Gamma\left(\frac{3p+2}{12}\right) \Gamma\left(\frac{3p+22}{12}\right) R \right]^{\frac{2}{p+4}}$$

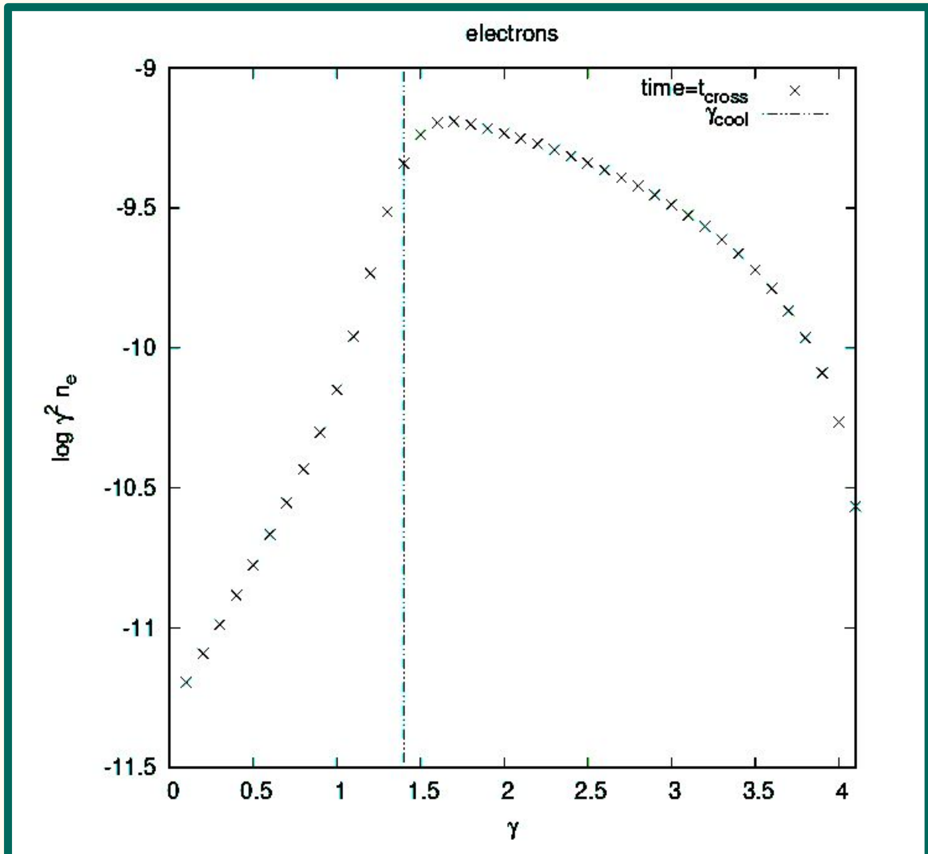
The units of C are $\left[\frac{erg}{cm^3}\right]$.

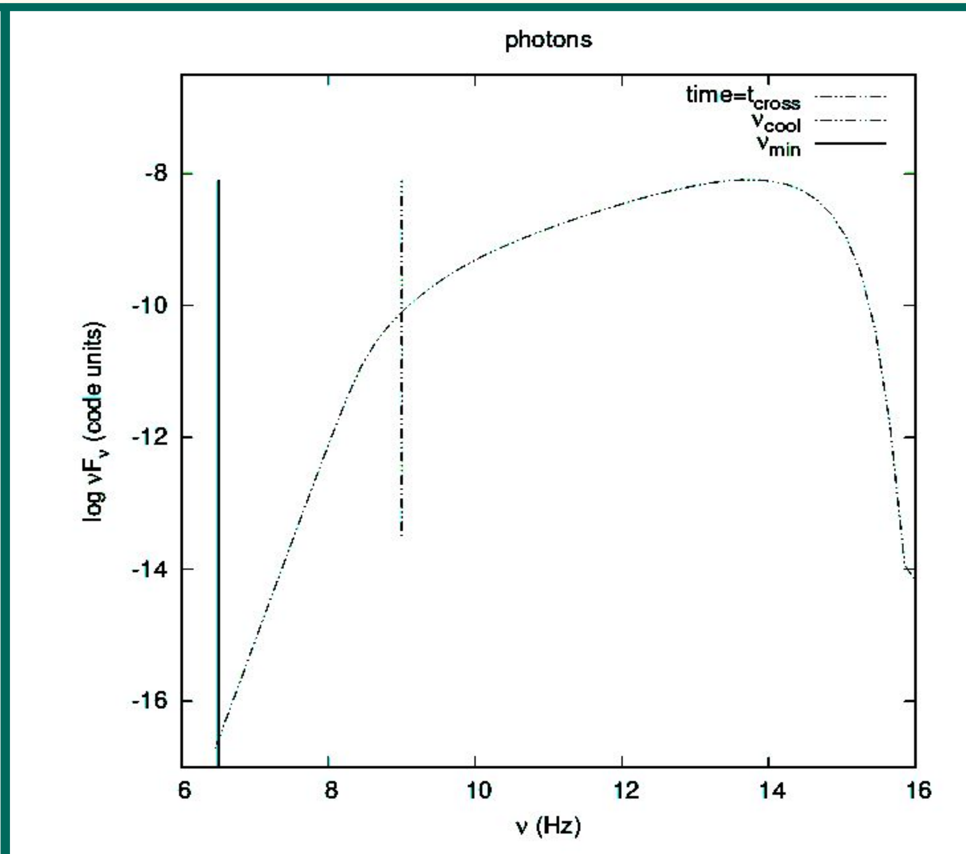
C is related to the code by: C= $(\mathrm{n}_{e,c} mc^2)/(\sigma_\tau R)$

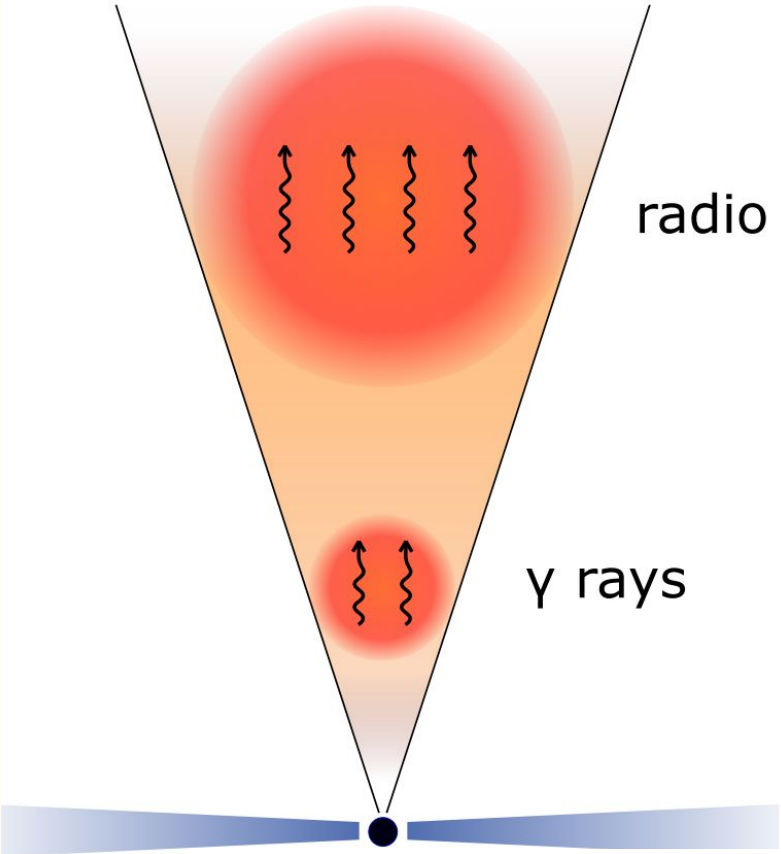
Example:

$R = 10^{18}\ cm,\ B = 1\ Gauss,\ p = 1,\ L_e = 10^{40}\ \frac{erg}{sec}$ at time $t = t_{cross}$ the synchrotron self absorption frequency has the value $\nu_{ssa} \simeq 10^6\ Hz$.

At the same time the electrons cooling Lorentz factor is $\gamma_{cool} \simeq 10^{1.4}$ and the cooling frequency is $\nu_{cool} \simeq 10^9\ Hz$. For $\gamma_{min} = 10^{0.1} \rightarrow \nu_{min} = 10^{6.5}\ Hz$


electrons
time=t_{cross}
γ_{cool}
log $\gamma^2 n_e$
-9
-9.5
-10
-10.5
-11
-11.5
0
0.5
1
1.5
2
2.5
3
3.5
4
γ


photons
time=t_{cross}
ν_{cool}
ν_{min}
log νF_ν (code units)
-8
-10
-12
-14
-16
6
8
10
12
14
16
ν (Hz)



Credit: S. Dimitrakoudis

$$R(t) = R_0 + u_{exp} t,$$

$$B = B_0 \left(R_0/R\right)^s$$

$$Q_e(\gamma, R) = q_e(R)\gamma^{-p} = q_{e_0} \left(\frac{R_0}{R}\right)^{\chi} \gamma^{-p}, \quad \gamma_{min} \leq \gamma \leq \gamma_{max},$$

$$\frac{\partial N(\gamma, R)}{\partial R} + \frac{\partial}{\partial \gamma} \left[\left(A_{syn}(\gamma,\ R) + A_{ICS}(\gamma,\ R) + A_{exp}(\gamma,\ R) \right) N(\gamma, R) \right] = Q_e(\gamma,\ R),$$

A proposed model for a uniform conical jet can be found at Potter & Cotter series of papers.

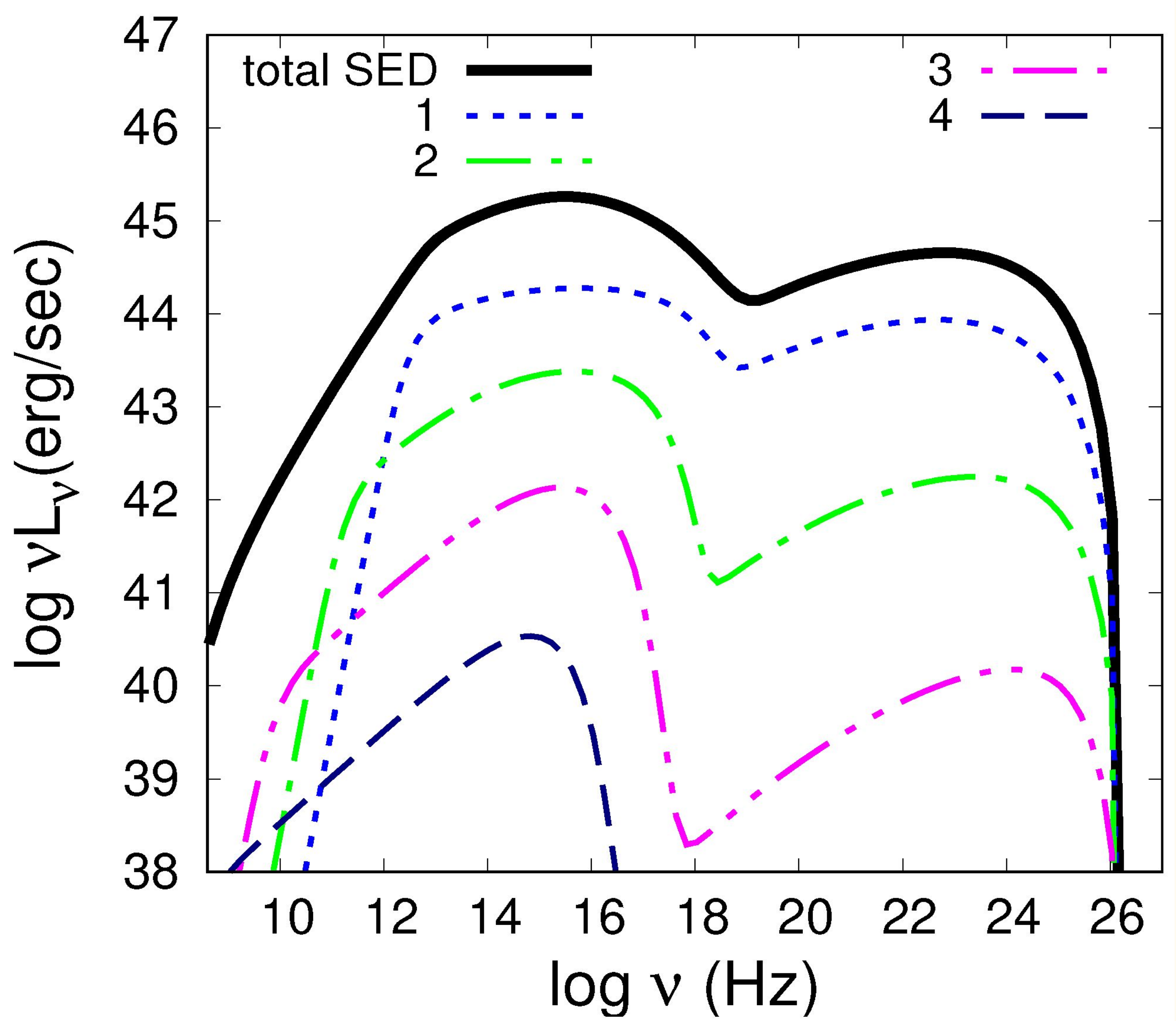
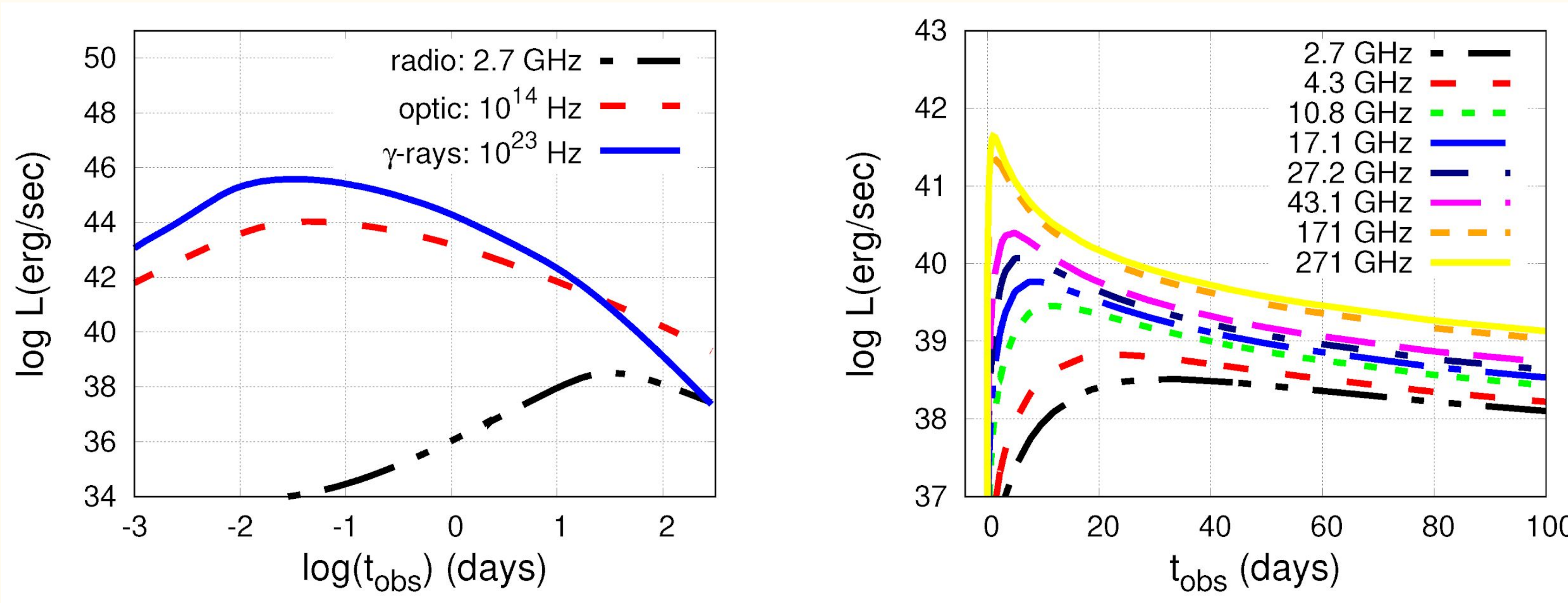


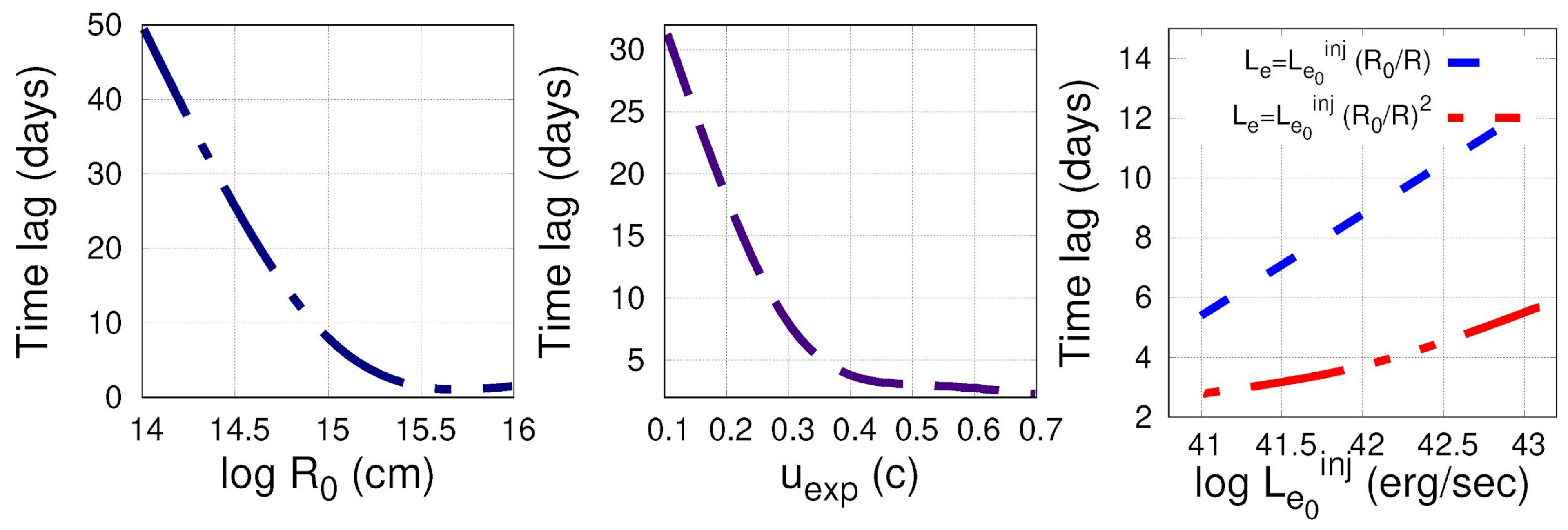
Figure 1. Steady-state SED of a fiducial BL Lac source (thick black line), computed by superimposing the emission of 10^4 blobs that are produced continuously at distance $z_0 = 10^{-3}$ pc from the central engine. For illustration purposes, we show the spectra of a few indicative blobs ($1 : R_1 = 10^{15.5}$ cm, $z_1 = 1.6 \times 10^{-3}$ pc; $2 : R_2 = 10^{16.5}$ cm $z_2 = 7 \times 10^{-3}$ pc; $3 : R_3 = 10^{17.5}$ cm, $z_3 = 6 \times 10^{-2}$ pc; $4 : R_4 = 10^{18.5}$ cm, $z_4 = z_{final} = 6 \times 10^{-1}$ pc). All blobs are initialized with the same parameters: $B_0 = 10$ G, $R_0 = 10^{15}$ cm, $L_{e_0}^{inj} = 10^{42}$ erg s^{-1}, $u_{exp} = 0.3$ c, $\gamma_{min} = 1$, $\gamma_{max} = 10^5$, $p = 2$, $\Gamma = 5$ and $\delta = 10$. The magnetic field and electron injection luminosity decrease linearly with radius.

Boula, Petropoulou & Mastichiadis, 2019

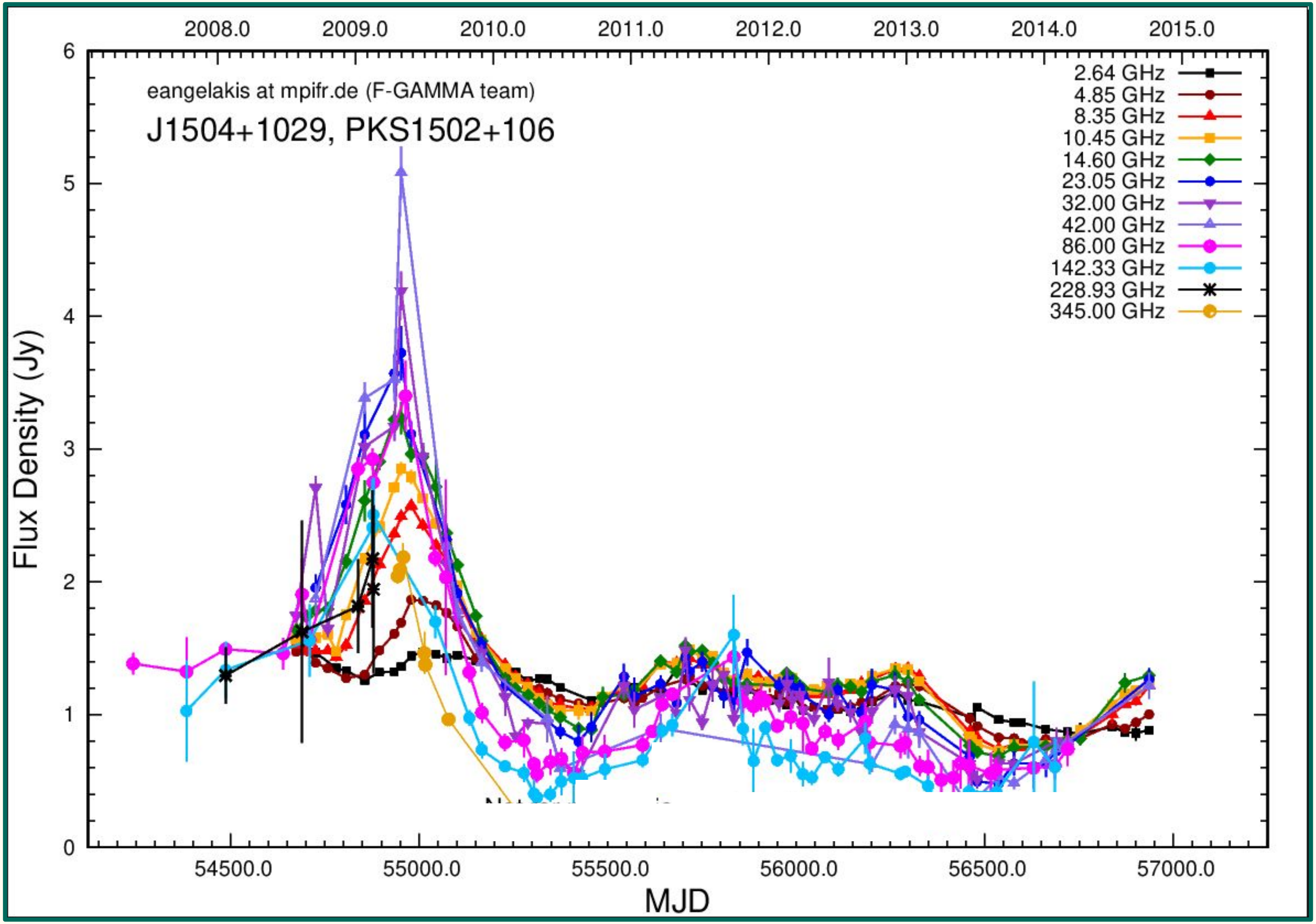
3. Flares



Boula, Petropoulou & Mastichiadis, 2019

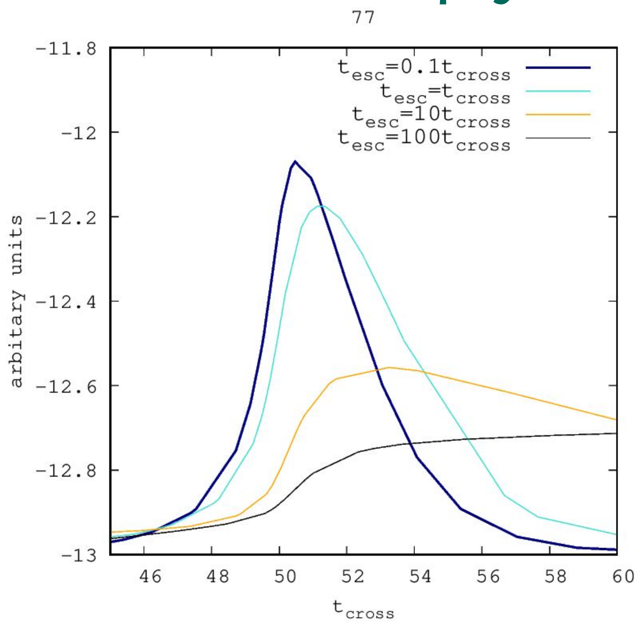


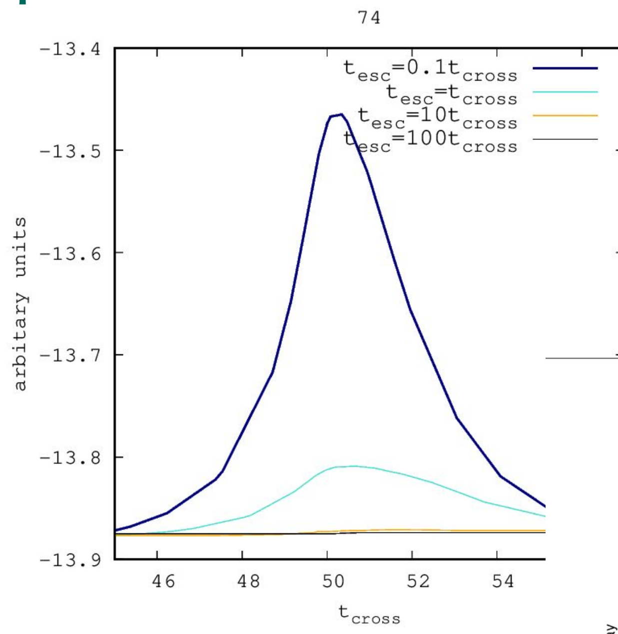
Boula, Petropoulou & Mastichiadis, 2019

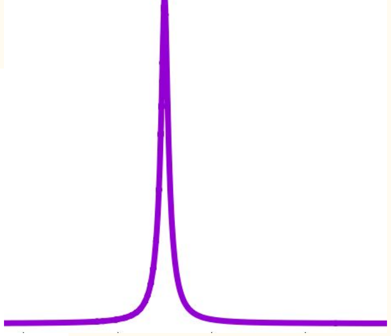


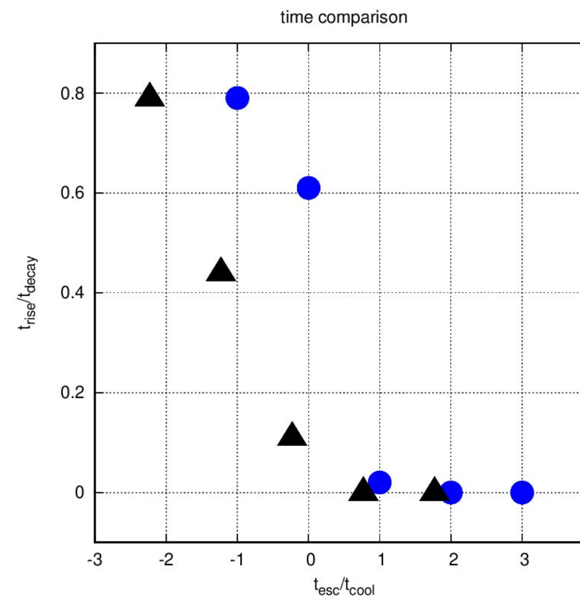
2008.0
2009.0
2010.0
2011.0
2012.0
2013.0
2014.0
2015.0
eangelakis at mpifr.de (F-GAMMA team)
J1504+1029, PKS1502+106
2.64 GHz
4.85 GHz
8.35 GHz
10.45 GHz
14.60 GHz
23.05 GHz
32.00 GHz
42.00 GHz
86.00 GHz
142.33 GHz
228.93 GHz
345.00 GHz
Flux Density (Jy)
0
1
2
3
4
5
6
54500.0
55000.0
55500.0
56000.0
56500.0
57000.0
MJD

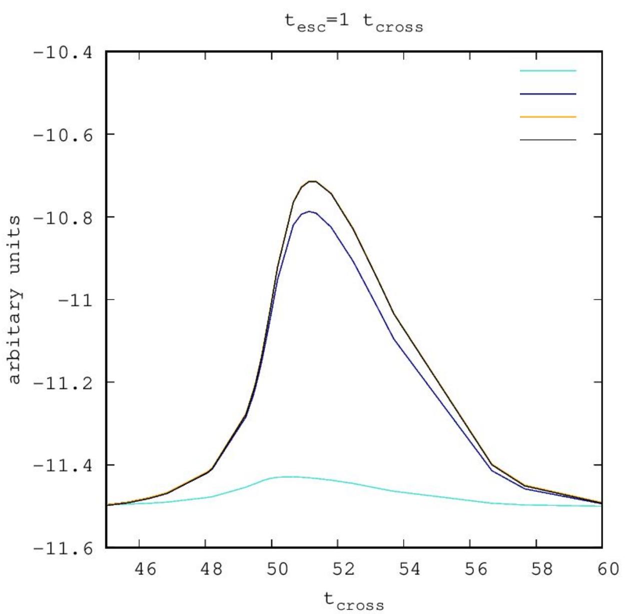
The role of the physical escape time

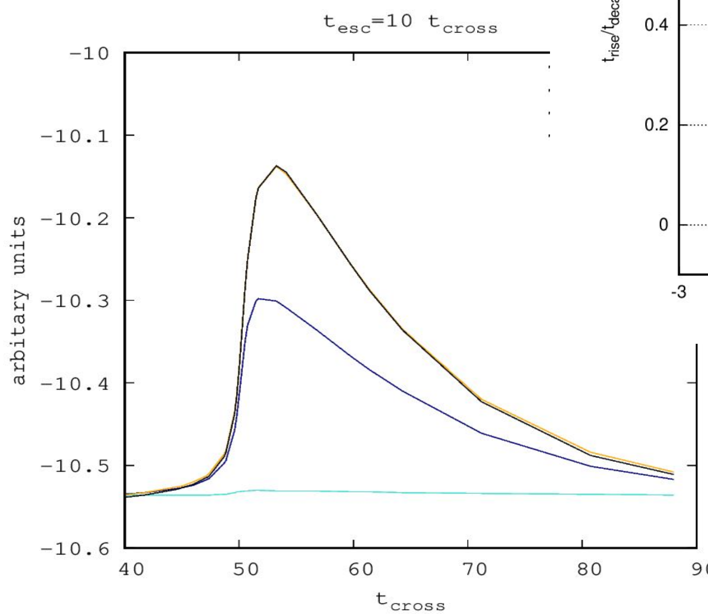


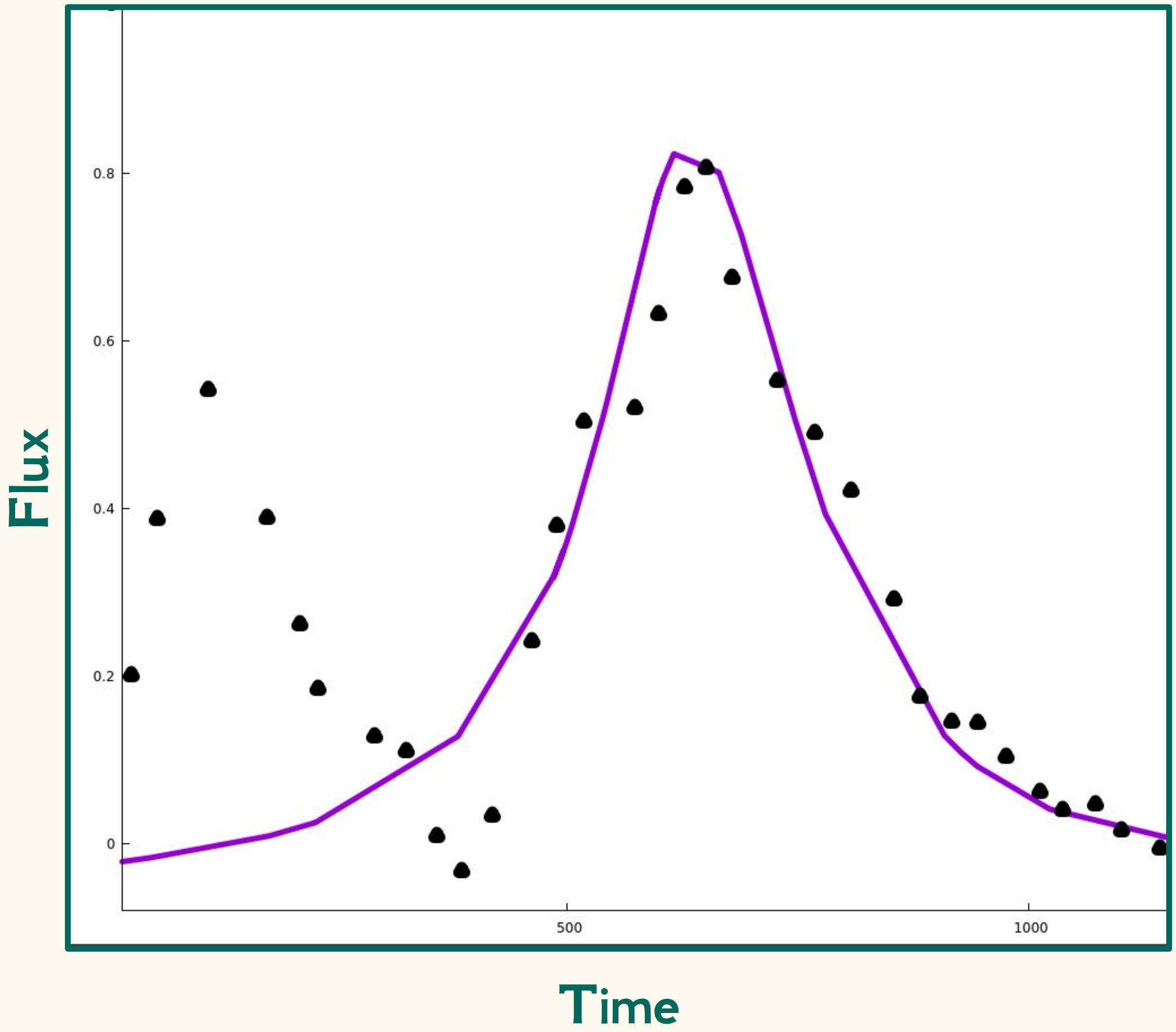











Flux
0.8
0.6
0.4
0.2
0
500
1000
Time

We are working on...

- searching the parameter space for the expanding model
- properties of flaring episodes
- the parameter space for the Blazar Sequence
- particles accelaration

Thank you!

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Back up Slides

Photon Fields

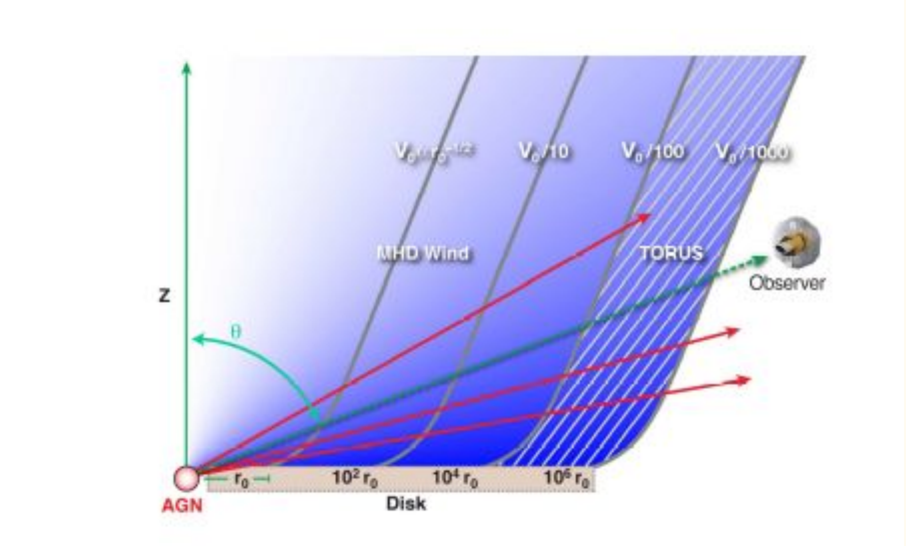
- Accretion Disk Photons (Dermer et al., 1992, Dermer and Schlickeiser, 1993 ++)
- Broad Line Region (Sikora et al., 1994, Blandford and Levinson, 1995, Ghisellini and Madau, 1996, Dermer et al., 1997, Finke, 2013 ++)
- Photons from torus (Blazejowski et al., 2000)
- Synchrotron emission from other regions of the jet (Georganopoulos and Kazanas, 2003, Ghisellini and Tavecchio, 2008)
- Photons which are scattered on Accretion Disk Wind particles (Boula et al., 2019)

- Synchrotron Photons (Marscher and Gear, 1985, Maraschi et al., 1992, Bloom and Marscher, 1996 ++)

MHD Accretion Disk Winds

- Winds driven by an accretion disk threaded by a poloidal magnetic field.
- At latitudes above the Alfven point the field lines become toroidal and the flow is almost radially out.
- The magnetic field permeates the entire disk, out to ~10^6 R_s, so these winds extend across many decades in R along the disk surface.

$$
\begin{aligned}
\mathbf{B}(\mathbf{r},\theta) &\equiv x^{-(s+1)/2}\tilde{\mathbf{B}}(\theta)B_o\ , \\
\mathbf{v}(\mathbf{r},\theta) &\equiv x^{-1/2}\tilde{\mathbf{v}}(\theta)v_o\ , \\
p(r,\theta) &\equiv x^{-(s+1)}\mathcal{P}(\theta)B_o^2\ , \\
n(r,\theta) &\equiv x^{-s}\tilde{n}(\theta)B_o^2 v_o^{-2}\ ,
\end{aligned}
$$



Fukumura et al., 2010 (based on Contopoulos & Lovelace, 1994)

A Theoretical Emission Model

Basic Parameters of a Leptonic Model

- Magnetic Field Strength
- Electrons luminosity
- Electrons Distribution
- Energy Density of the External Photon Field
- Bulk Lorentz factor
- Doppler factor

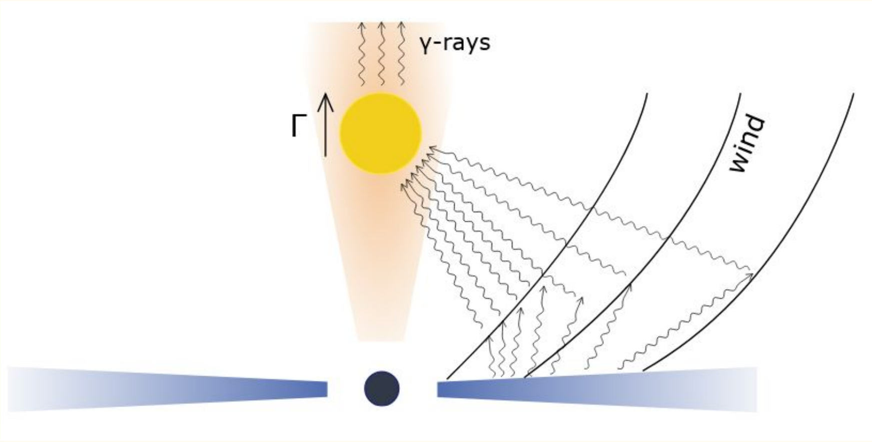


Image credit: S. Dimitrakoudis

Theoretical Emission Model

Basic Parameters of a Leptonic Model

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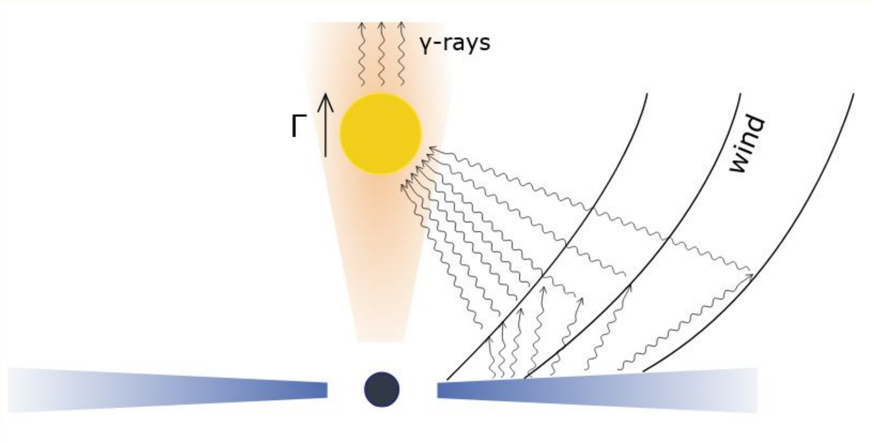


Image credit: S. Dimitrakoudis

Related to the mass accretion rate

Accretion Power of the source:

$$P_{\text{acc}} = \dot{m}\mathcal{M}L_{\text{Edd}}$$

Magnetic Field

$$U_{\text{B}_0} = \frac{\eta_b P_{\text{acc}}}{4\pi(3r_{\text{s}})^2 c},\ B = B_0(\frac{z_0}{z})$$

Electron Injection

$$Q_{\text{e}} = \begin{cases} k_{\text{e}_1}\gamma^{-s} & \text{for } \gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{br}}, \\ k_{\text{e}_2}\gamma^{-q}e^{-\gamma/\gamma_{\text{max}}} & \text{for } \gamma_{\text{br}} \leq \gamma \leq \gamma_{\text{max}}, \end{cases}$$

$$\gamma_{\text{br}} = \frac{3m_{\text{e}}c^2}{4\sigma_\tau c t_{\text{dyn}} U_{\text{tot}}}$$

$$L_{\text{inj}}^e = m_{\text{e}}c^2 \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} Q_{\text{e}}(\gamma)\gamma \text{d}\gamma = \eta_{\text{e}} P_{\text{acc}}$$

External Photon Field

$$n(r,\theta) = n_0 (r_s/r)^p \, e^{5(\theta-\pi/2)} \quad n_0 = \frac{\eta_w \dot{m}}{2\sigma_{\mathrm{T}} r_{\mathrm{s}}}$$

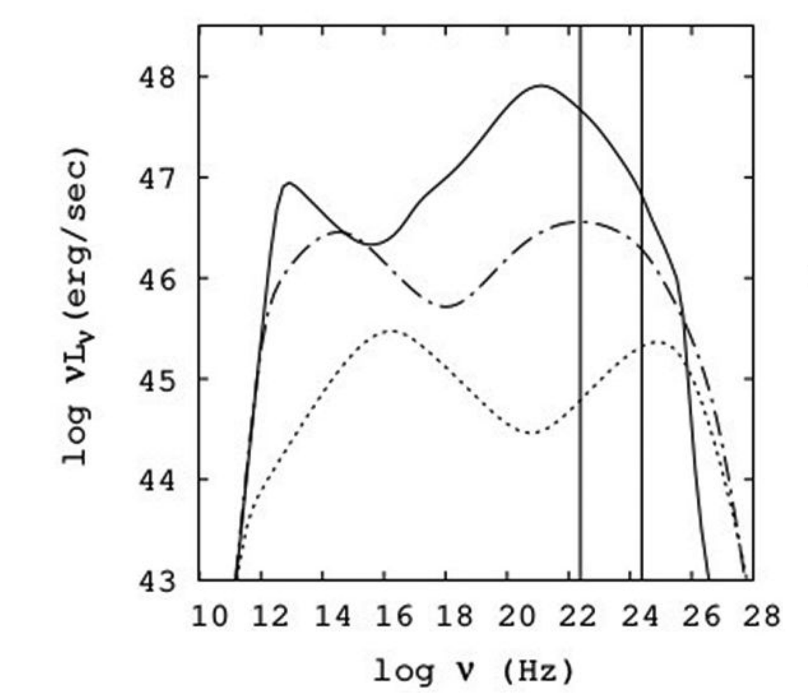
$$\tau_\tau(R_1, R_2) = \int_{R_1}^{R_2} n(r)\sigma_{\mathrm{T}} \mathrm{dr} = n_0 \sigma_{\mathrm{T}} r_s \ln(R_2/R_1)$$

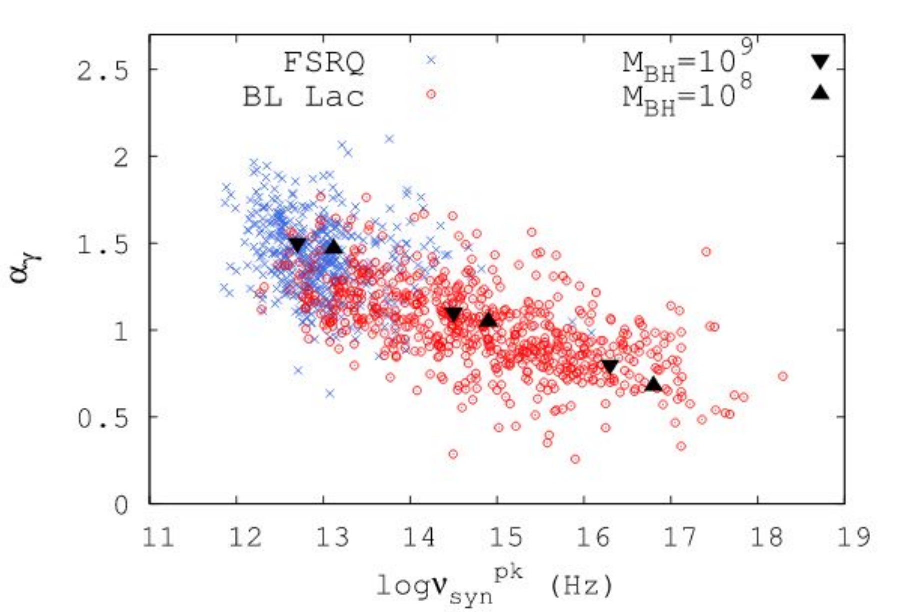
$$L_{\mathrm{disc}} = \begin{cases} \epsilon \dot{m} \mathcal{M} L_{\mathrm{Edd}} & \text{for } \dot{m} \gtrsim 0.1 \\ \epsilon \dot{m}^2 \mathcal{M} L_{\mathrm{Edd}} & \text{for } \dot{m} \lesssim 0.1 \end{cases}$$

$$U_{\mathrm{sc}} = \frac{L_{\mathrm{disc}} \tau_{\mathrm{T}}}{4\pi R_2^2 c}$$

$$U_{\mathrm{ext}} = \Gamma^2 U_{\mathrm{sc}}$$

Results





(In comparison with 3LAC results)

$$U_B \propto \frac{\dot{m}}{\mathcal{M}}$$

$$U_{ext} \propto U_{sc} \propto \frac{\dot{m}^{\alpha+1}}{\mathcal{M}}$$ $\alpha = 1$ for $\dot{m} \geq 0.1$ and $\alpha = 2$ for $\dot{m} < 0.1$

$$L_e^{inj} \propto \dot{m}\mathcal{M}$$

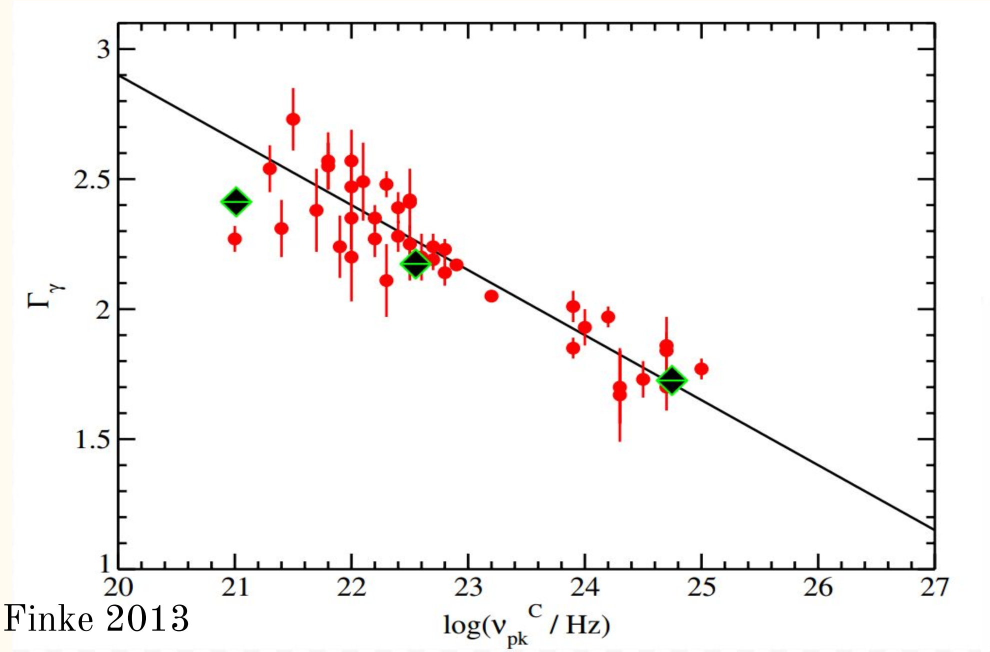
$$\gamma_{br} \propto \dot{m}^{-1}(1+\dot{m}^{\alpha})^{-1}$$

$$\nu_{pk}^{syn} \propto \mathcal{M}^{-1/2}\dot{m}^{-3/2}/(1+\dot{m}^{\alpha})^2$$

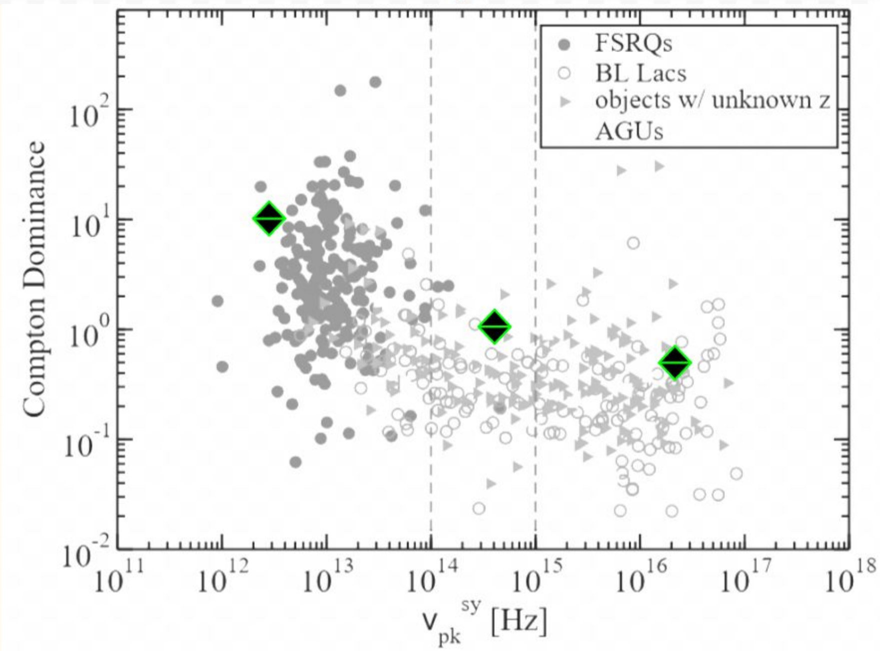
$\dot{m}$	B(G)	U_{ext} $\left(\frac{erg}{cm^3}\right)$	L_e^{inj} $\left(\frac{erg}{sec}\right)$	γ_{br}	Blazar class
−0.5	−0.3	−1.4	45.2	2.3	FSRQ
−1.5	−0.8	−4.6	44.2	3.3	LBL
−2.5	−1.3	−7.6	43.2	6.5	HBL

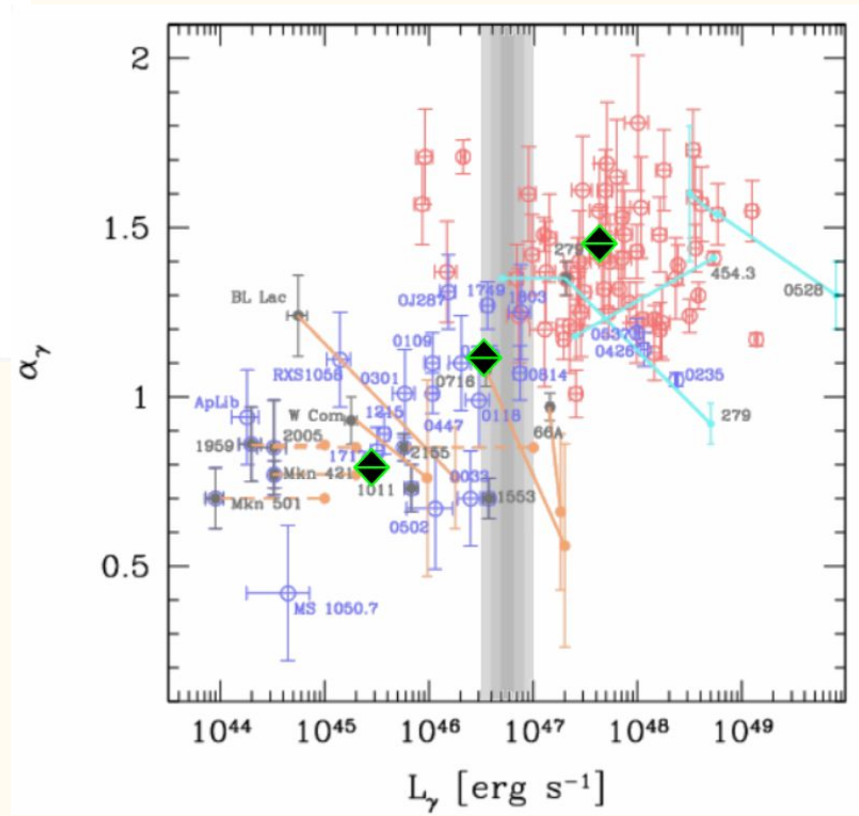
(logarithmic values)

Boula, Kazanas, Mastichiadis, 2019



Finke 2013





Ghisellini et al., 2009