THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

Modeling the non-thermal emission from blazars

Stella S. Boula

Collaborators:
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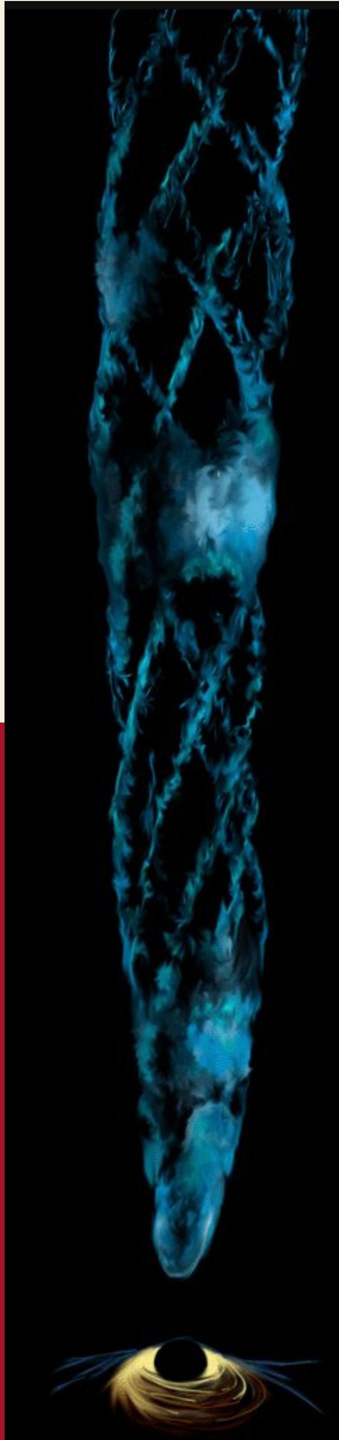
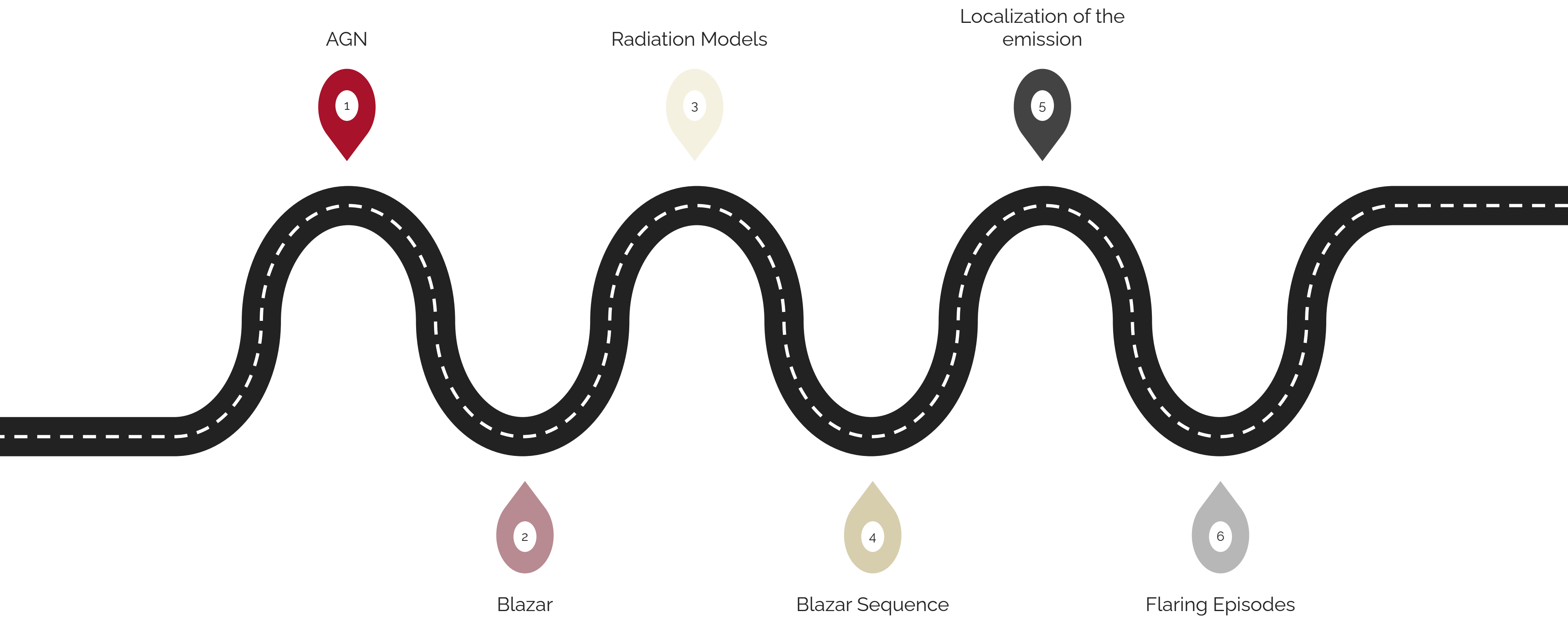
Demosthenes Kazanas (NASA)



Outline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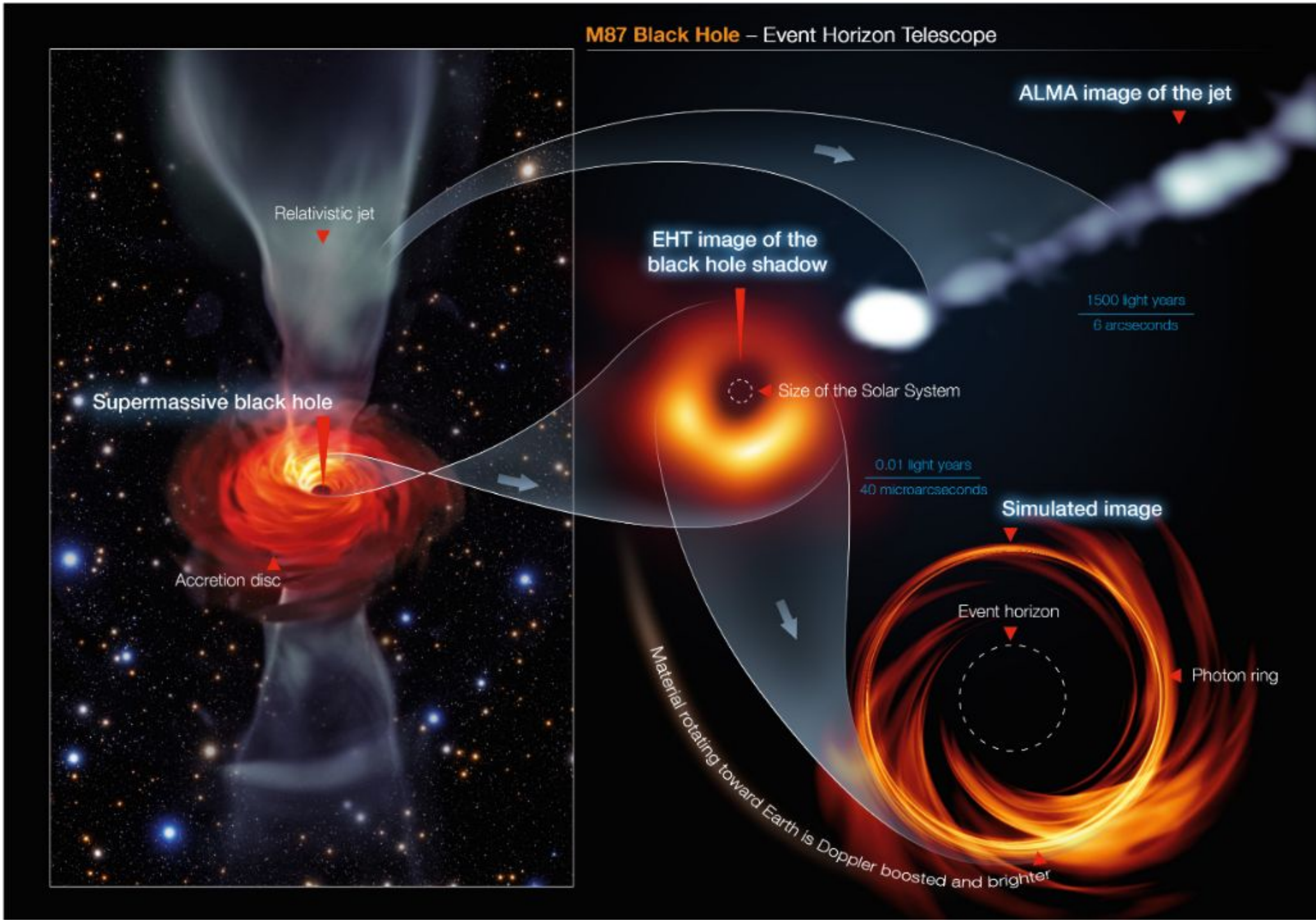
Introduction

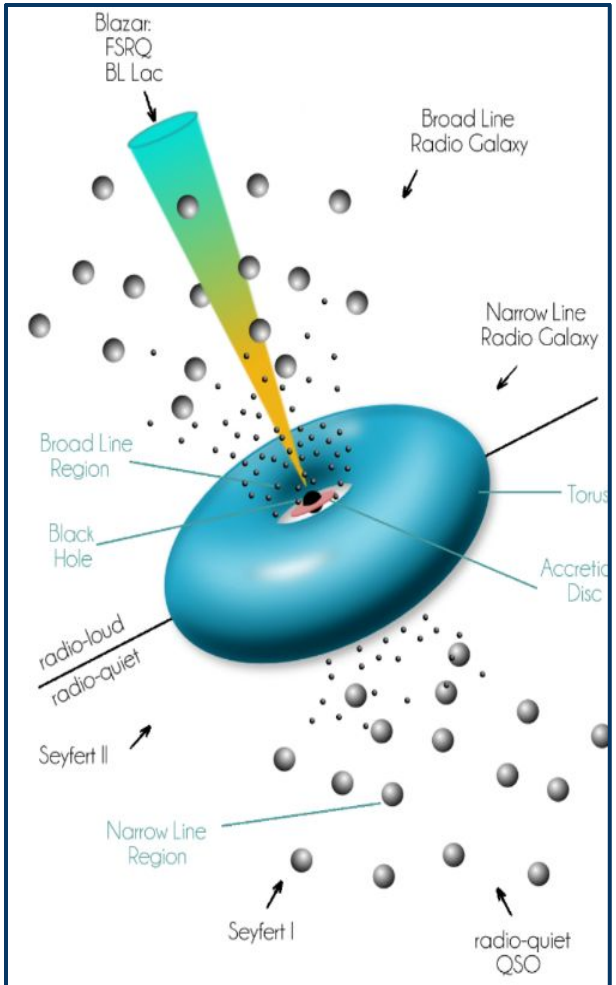
Active Galactic Nuclei

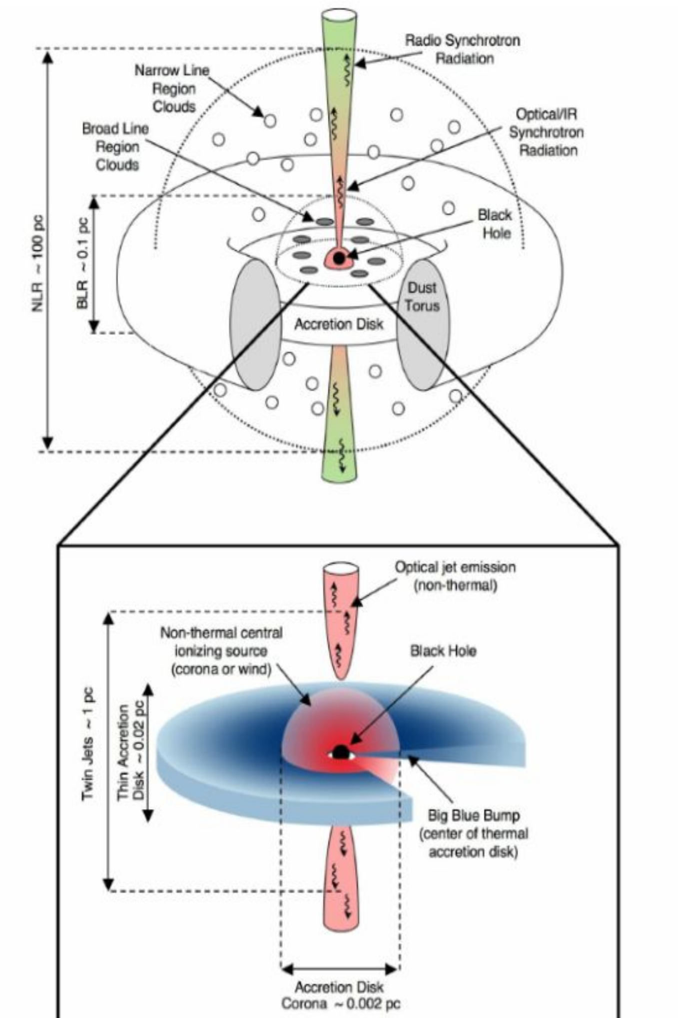


Credit: EHT Collaboration

Active Galactic Nuclei

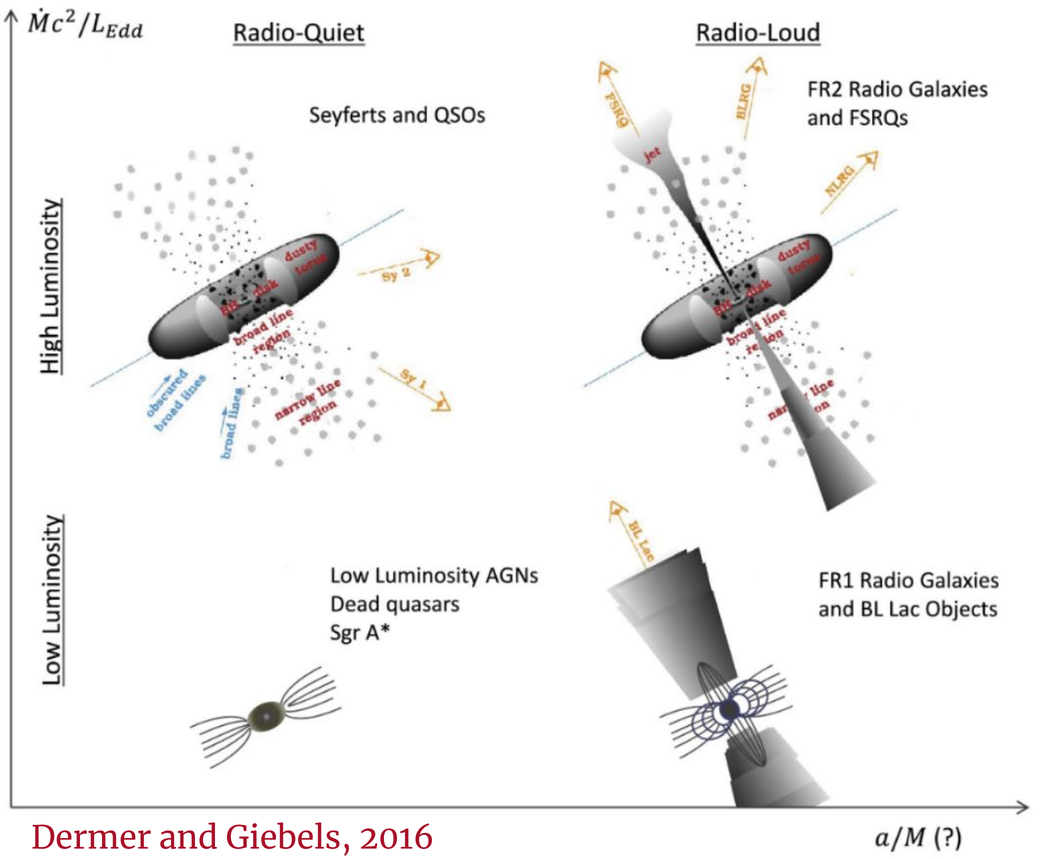
Urry and Padovani, 1995



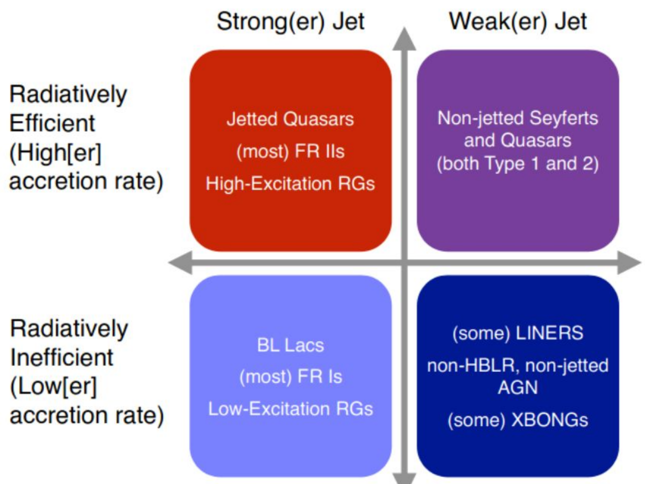


Credit: http://www.sternwarte.unierlangen.de/krauss.

Credit: Unwin et. al, 2008



Dermer and Giebels, 2016



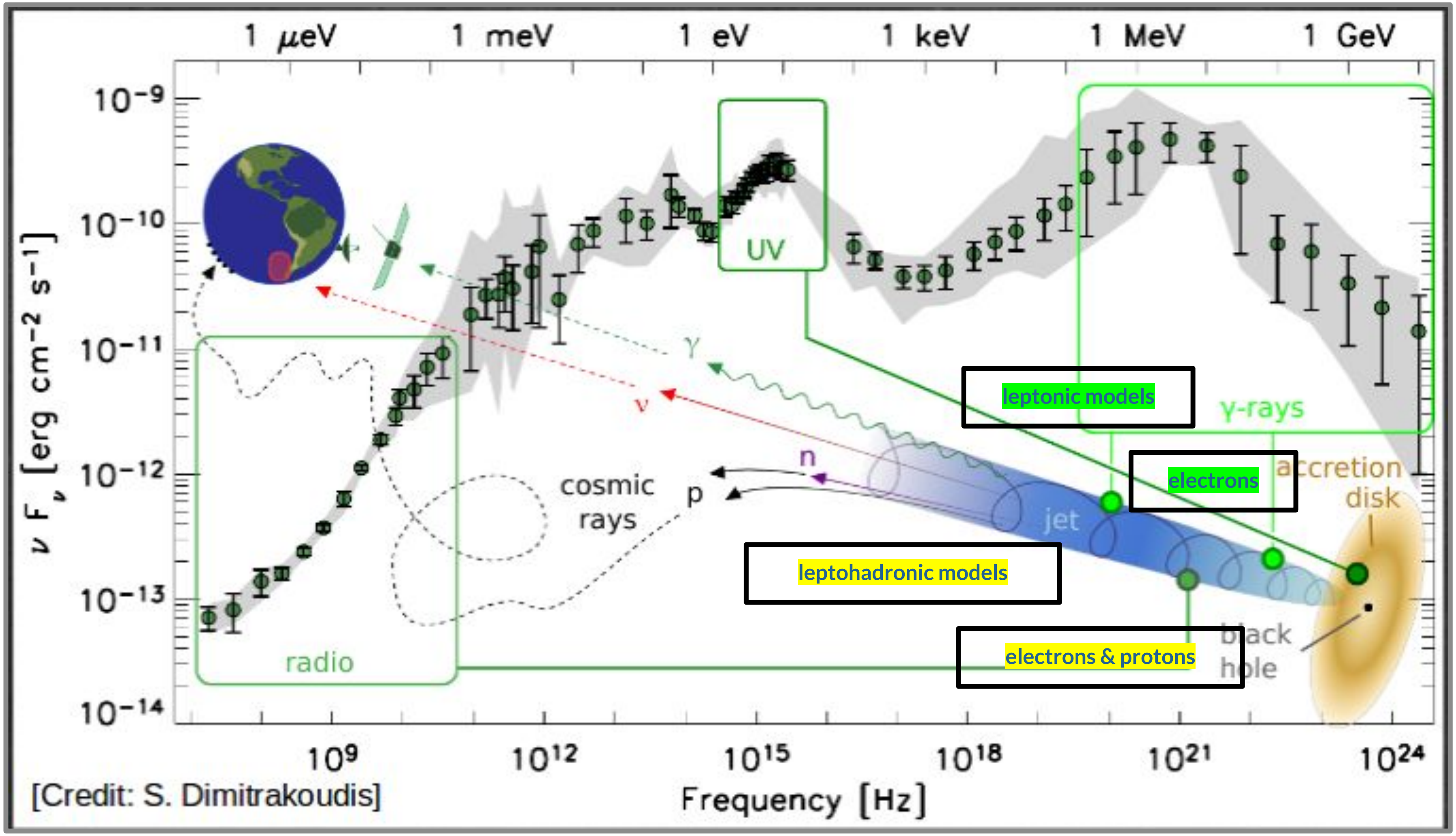
Padovani et. al, 2017

Introduction

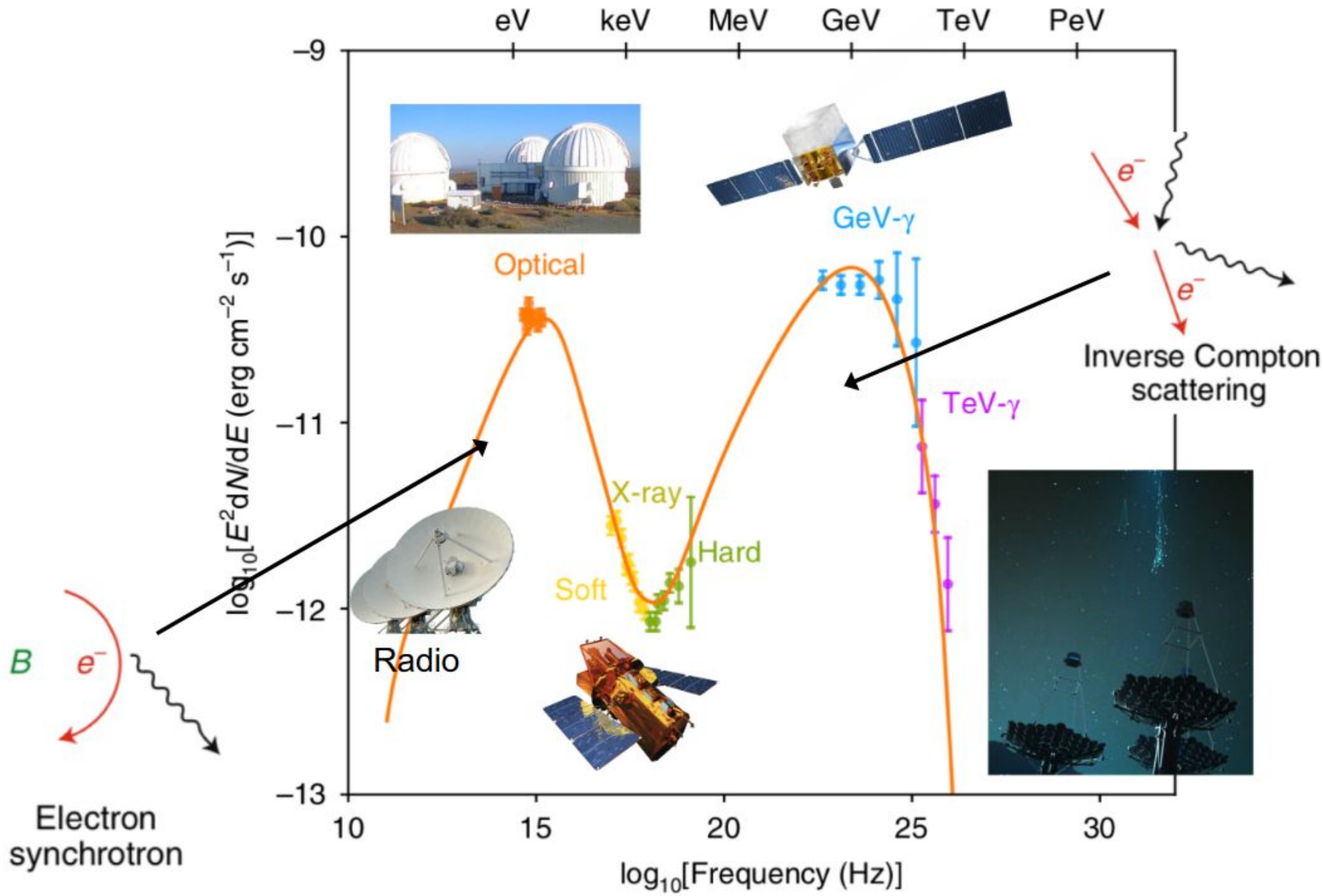
Blazars

Credit: DESY

Blazar

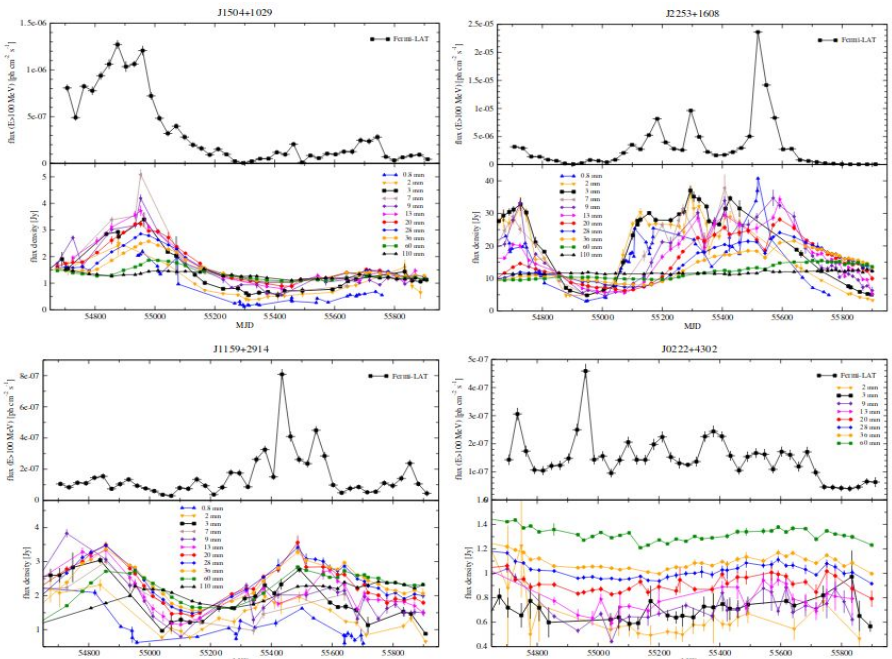


Rani et al., 2019



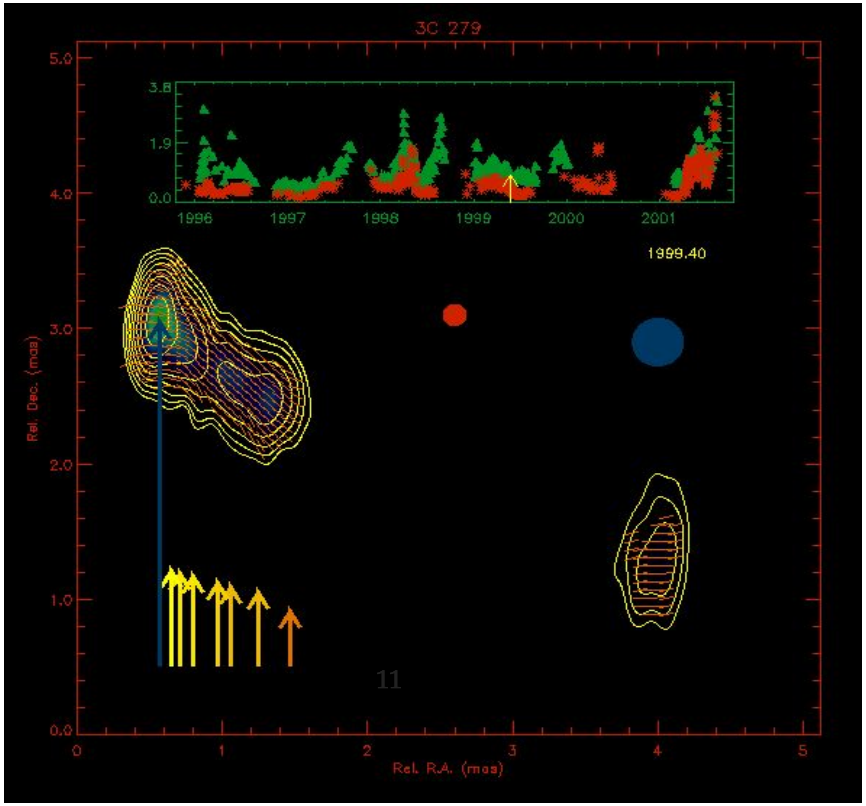
Credit: Walter

Blazars Monitoring Programs



F-gamma project

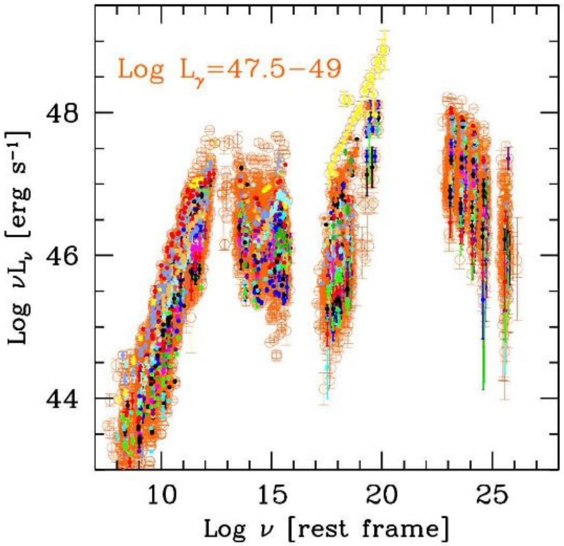
Boston University
Blazar Group



You can find a list of Blazars Monitoring Programs at MOJAVE page:
https://www.physics.purdue.edu/MOJAVE/blazarprogramlist.html

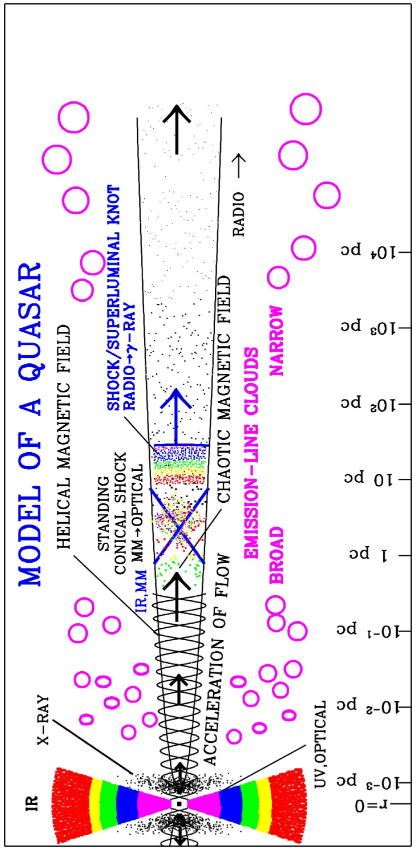
Subjects of present talk

Blazar Sequence

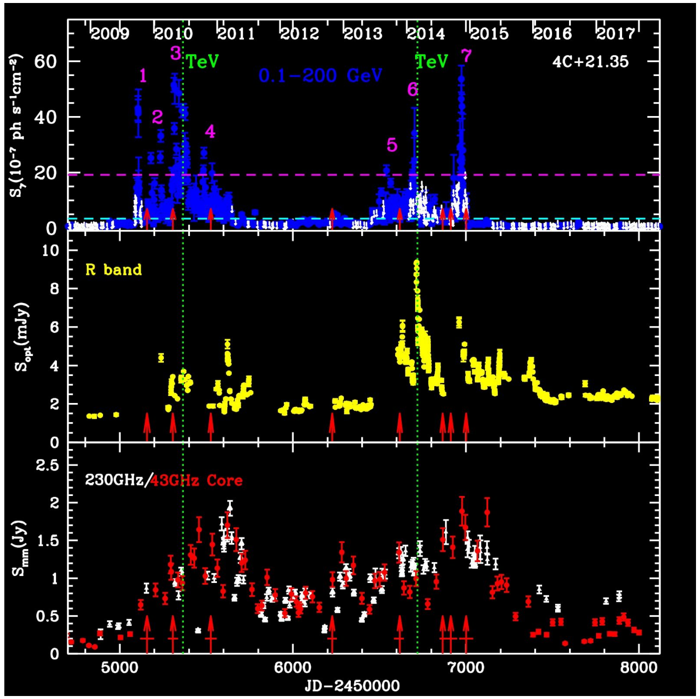


Ghiselini 2017

Localization of the Emission



Flaring activity



Credit: BU blazar group

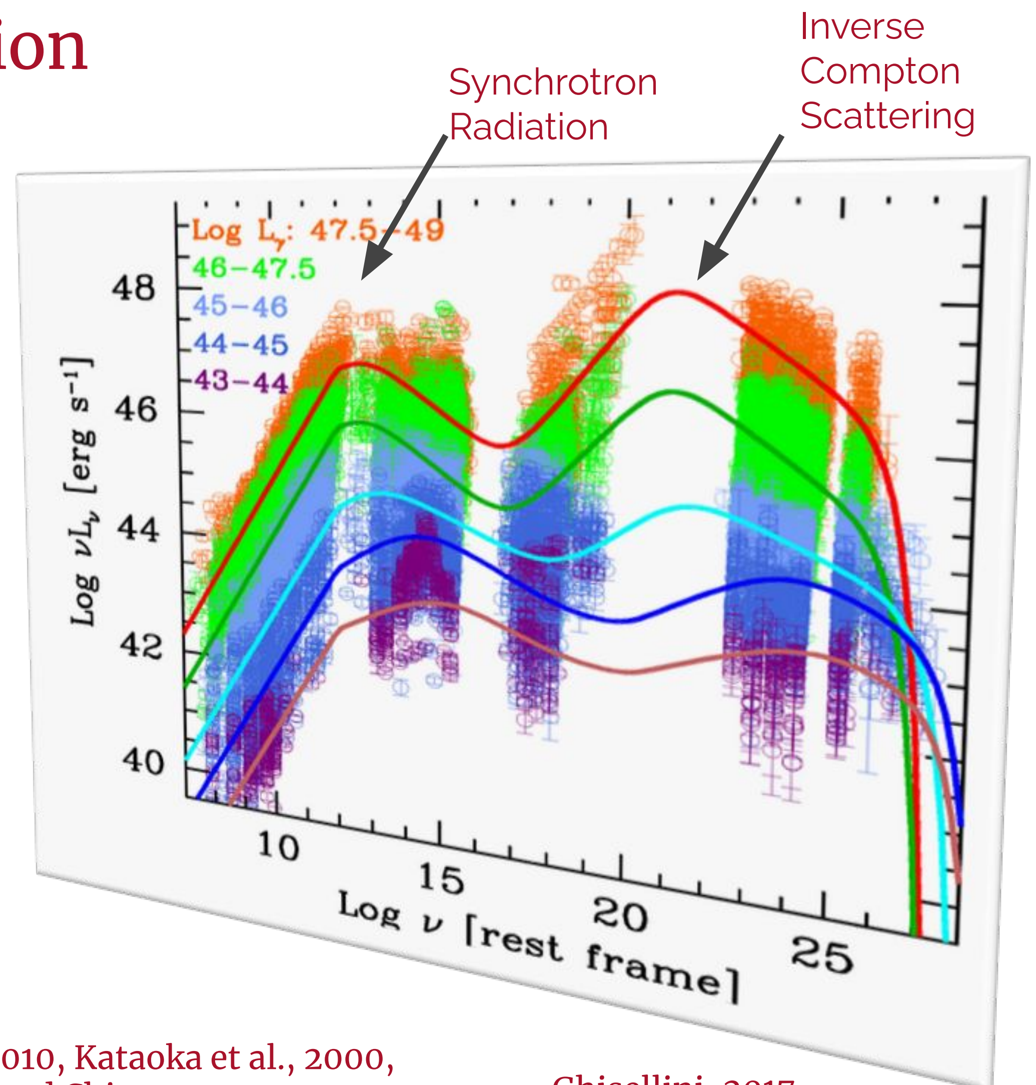
Introduction

Radiation Models

Modeling the blazar emission

Parameters of the Leptonic Model :

- Radius of the source
- Magnetic Field Strength
- Electrons Energy Distribution
- External photon fields
- Bulk Lorentz factor
- Doppler factor



Ghisellini, 2017

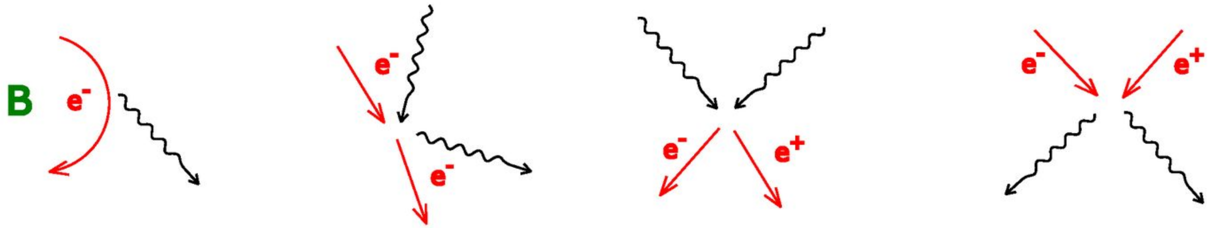
Leptonic Models:
Mastichiadis and Kirk, 1997,Weidinger and Spanier, 2010, Kataoka et al., 2000, Krawczynski et al., 2002, Sikora et al., 2001, Bottcher and Chiang, 2002, Ghisellini and Tavecchio, 2009, Acciari and Aliu, 2009, Boula et al., 2019 ++

Numerical Approach

Kinetic Equations

Electrons

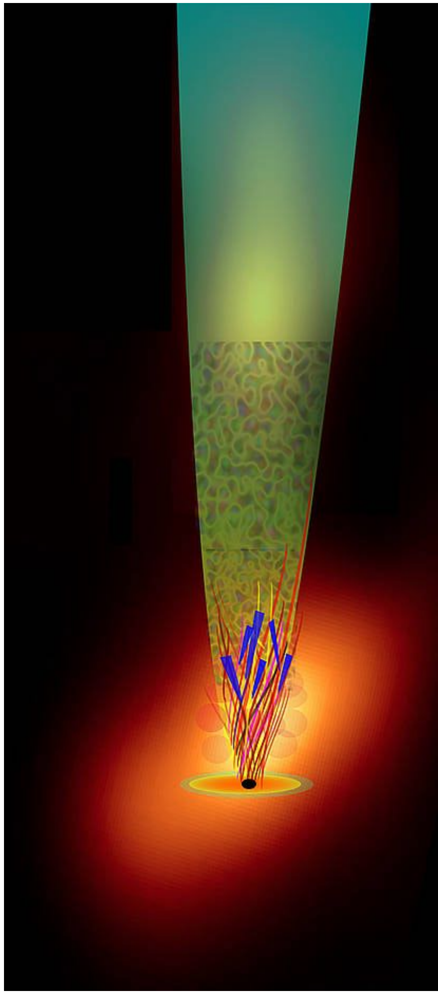
$$\frac{\partial N_e(\gamma,t)}{\partial t} + \sum \mathcal{L}_i^e N_e(\gamma,t) + \frac{N_e}{t_{e_{esc}}} = \sum Q_e(\gamma,\ t)$$



electron synchrotron — Inverse Compton scattering — photon-photon pair production — electron-positron annihilation

Photons

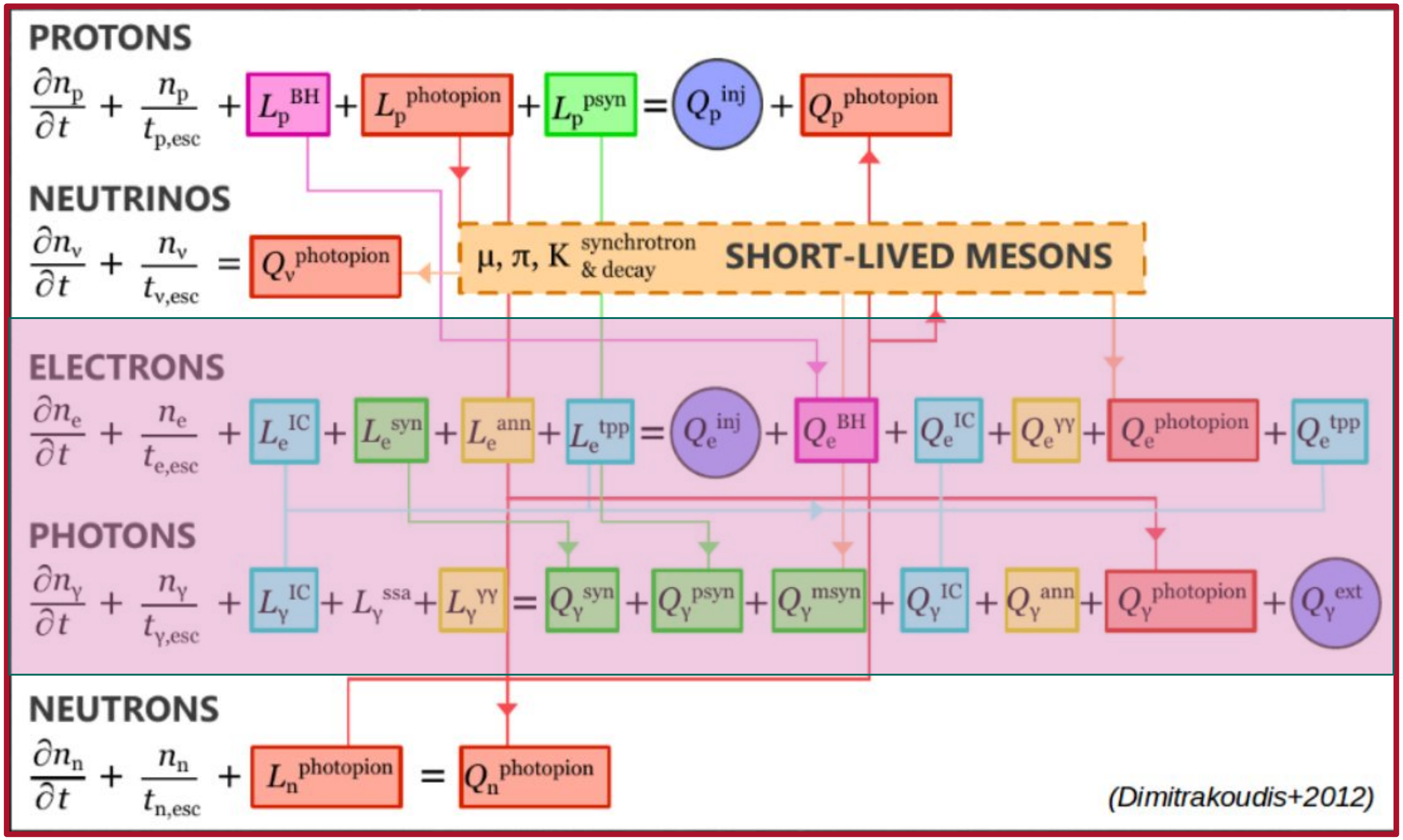
$$\frac{\partial N_\gamma(x,t)}{\partial t} + \frac{N_\gamma(x,t)}{t_{\gamma_{esc}}} + \sum \mathcal{L}_\gamma^i(N_\gamma x,t) = Q_\gamma^{inj}(x,\ t)$$



Kinetic Equations

Numerical Approach

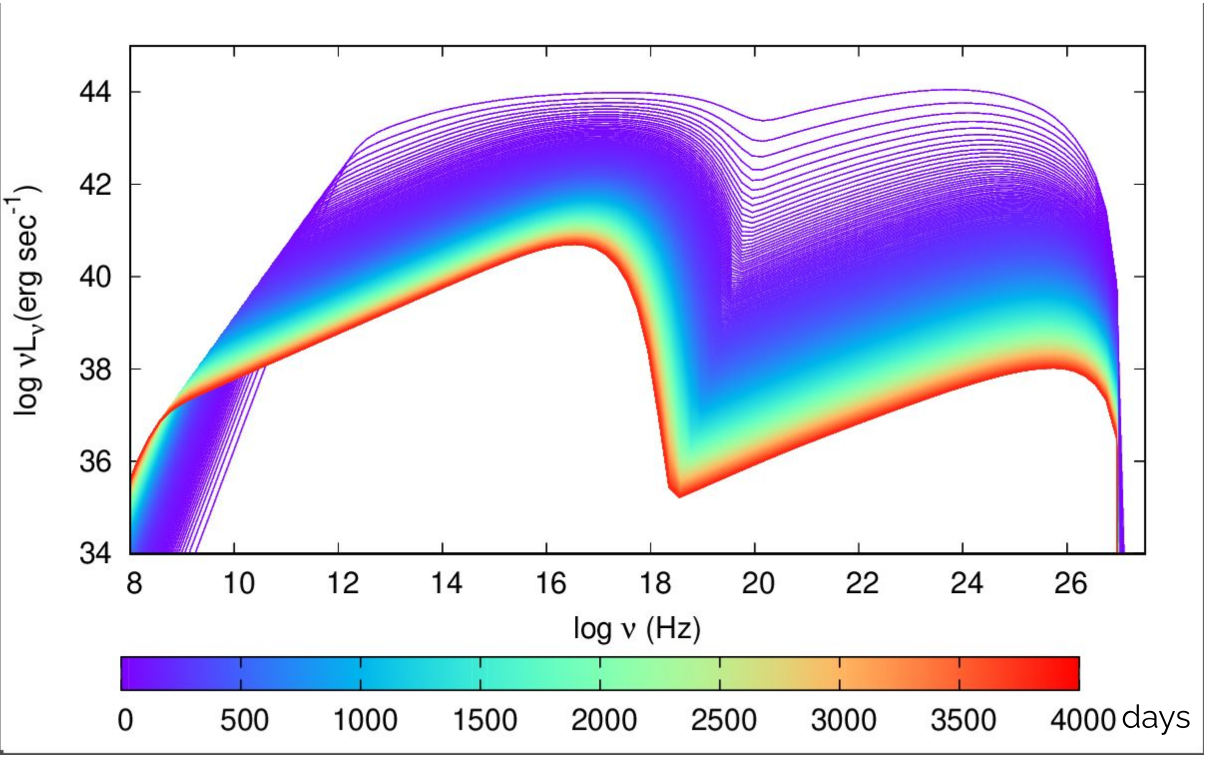
Numerical Code



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

A new numerical approach:

A one-zone **expanding** model



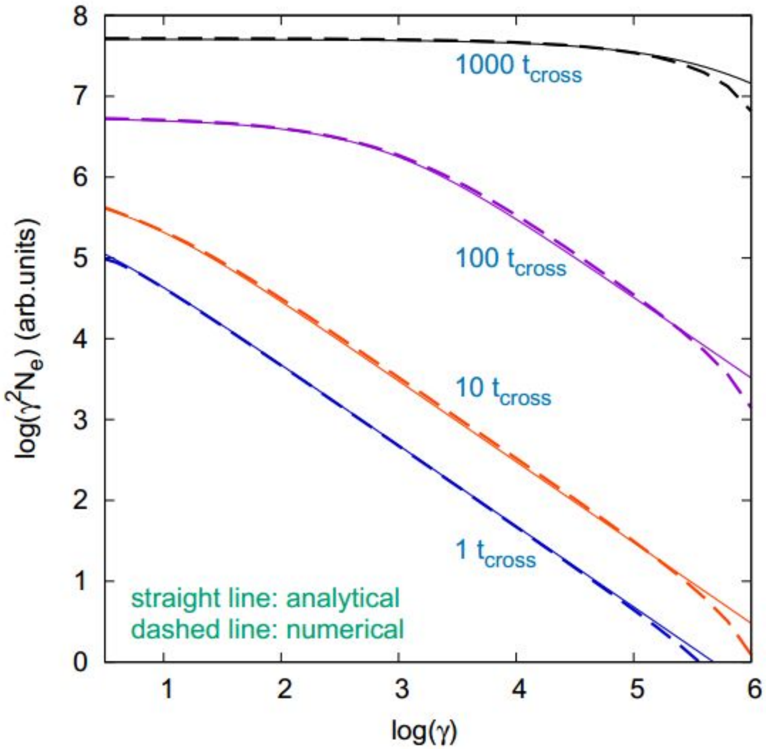
- Synchrotron Radiation
- Inverse Compton Scattering
- Synchrotron Self Absorption
- Photon-Photon Absorption
- Adiabatic Losses

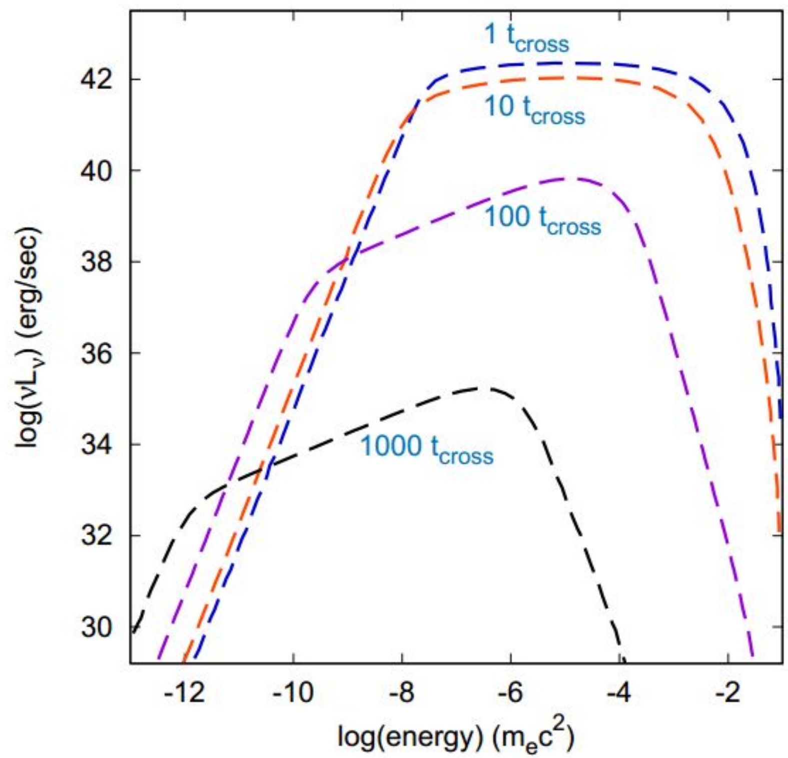
in an **expanding** source

A new numerical code based on Mastichiadis & Kirk, 1995, 1997; see also Boula et al. , 2019, Boula & Mastichiadis, 2021

Comparison of Analytical and Numerical solutions

The case of Synchrotron and Adiabatic losses

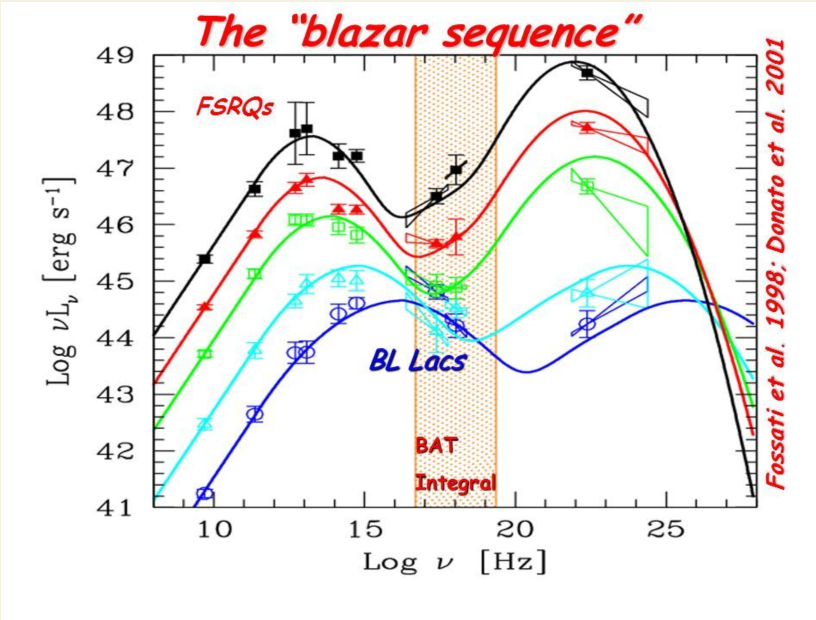


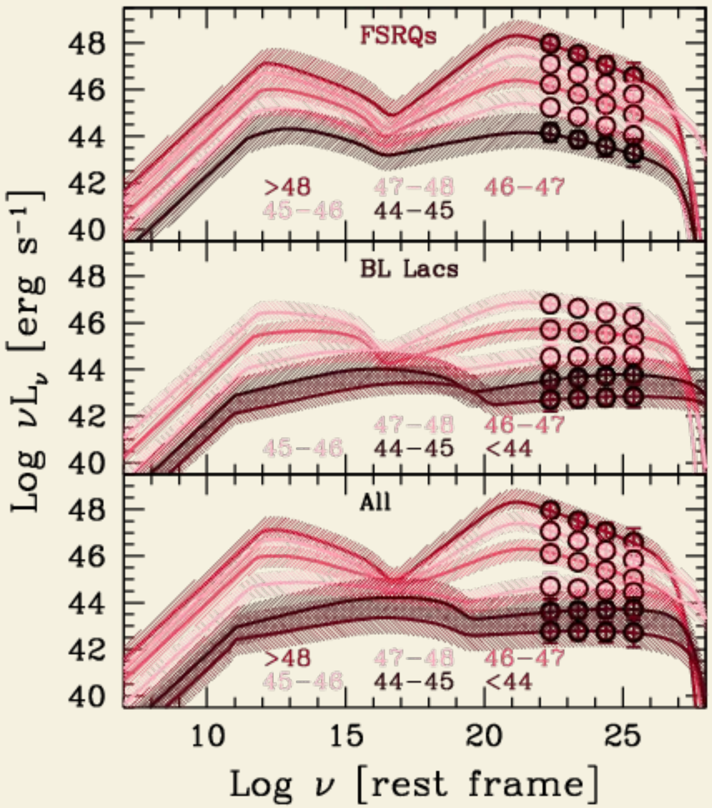


Boula & Mastichiadis, 2021

Topic No 1

Blazar Sequence

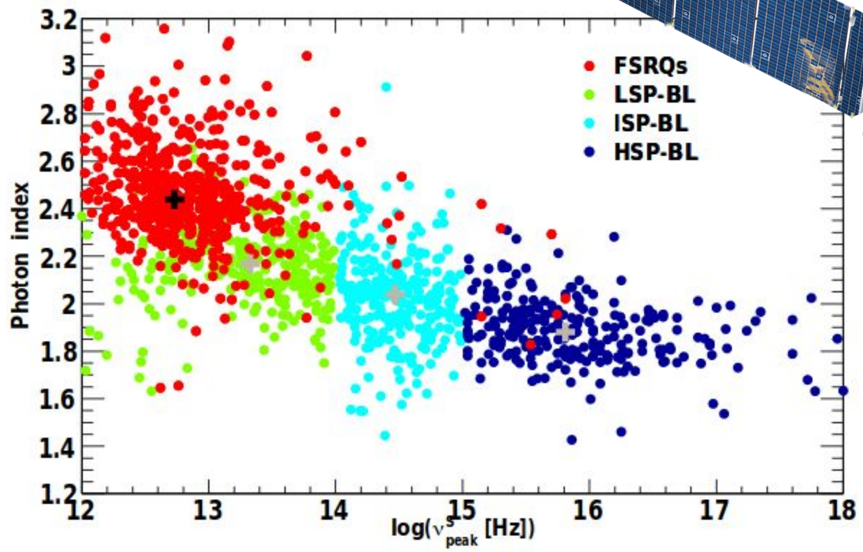


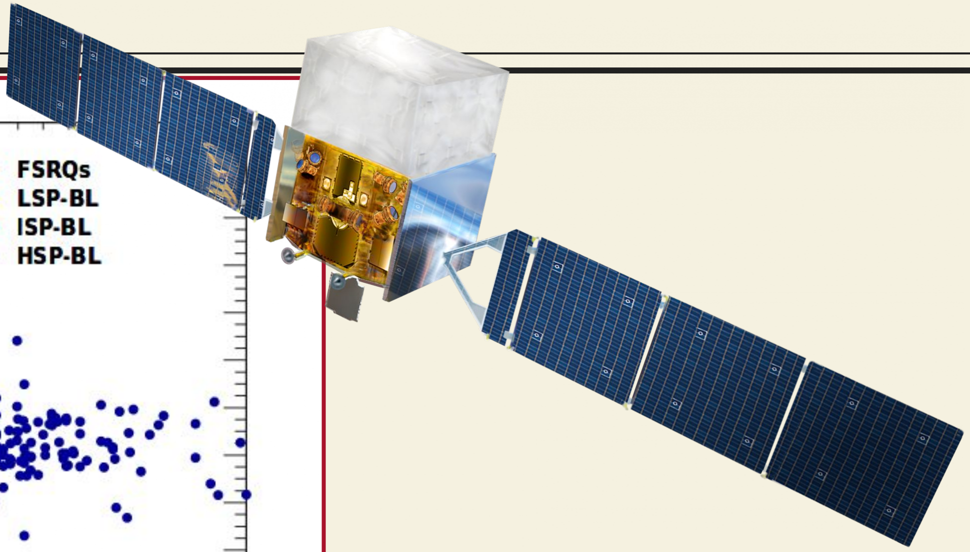


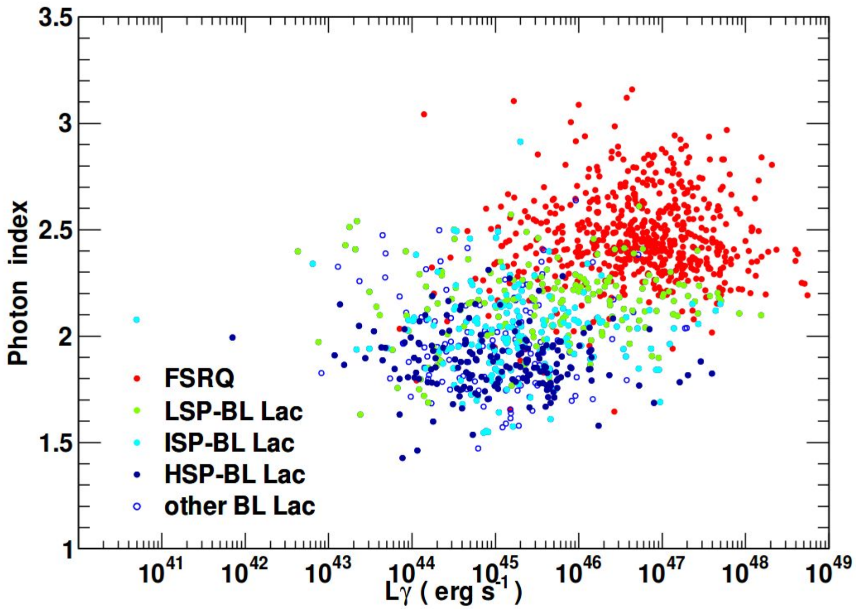
Fossati et al., 1998

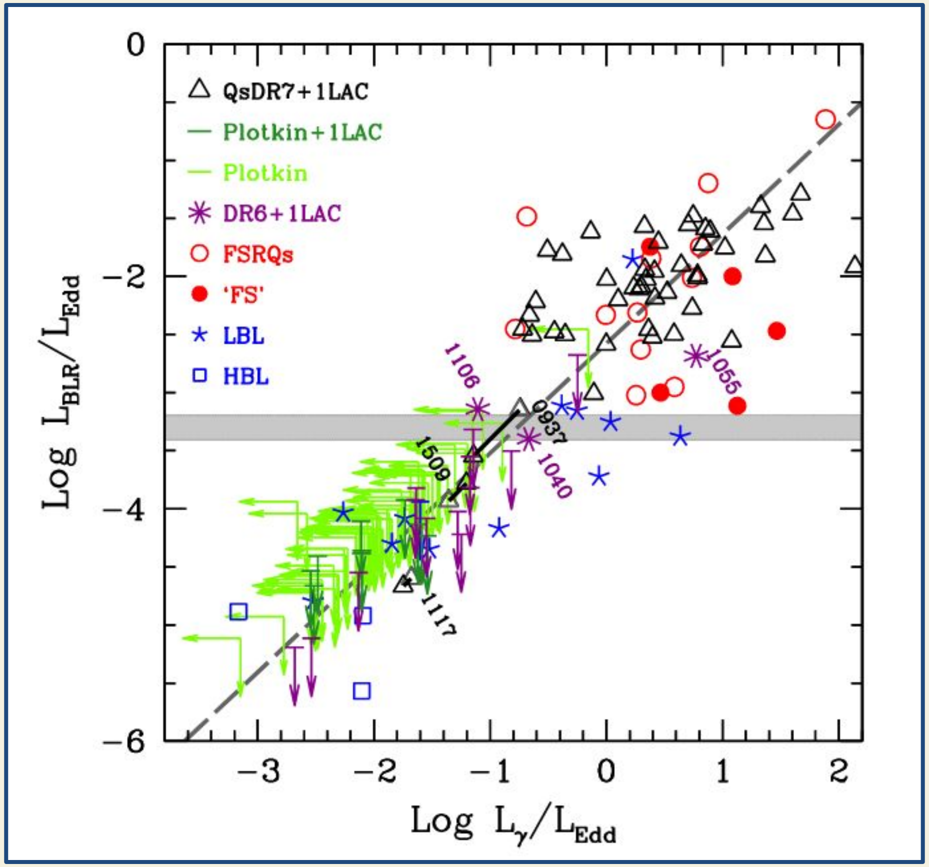
Ghisellini, 2017

(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).


FSRQs
LSP-BL
ISP-BL
HSP-BL
Photon index
log(ν^s_{peak} [Hz])

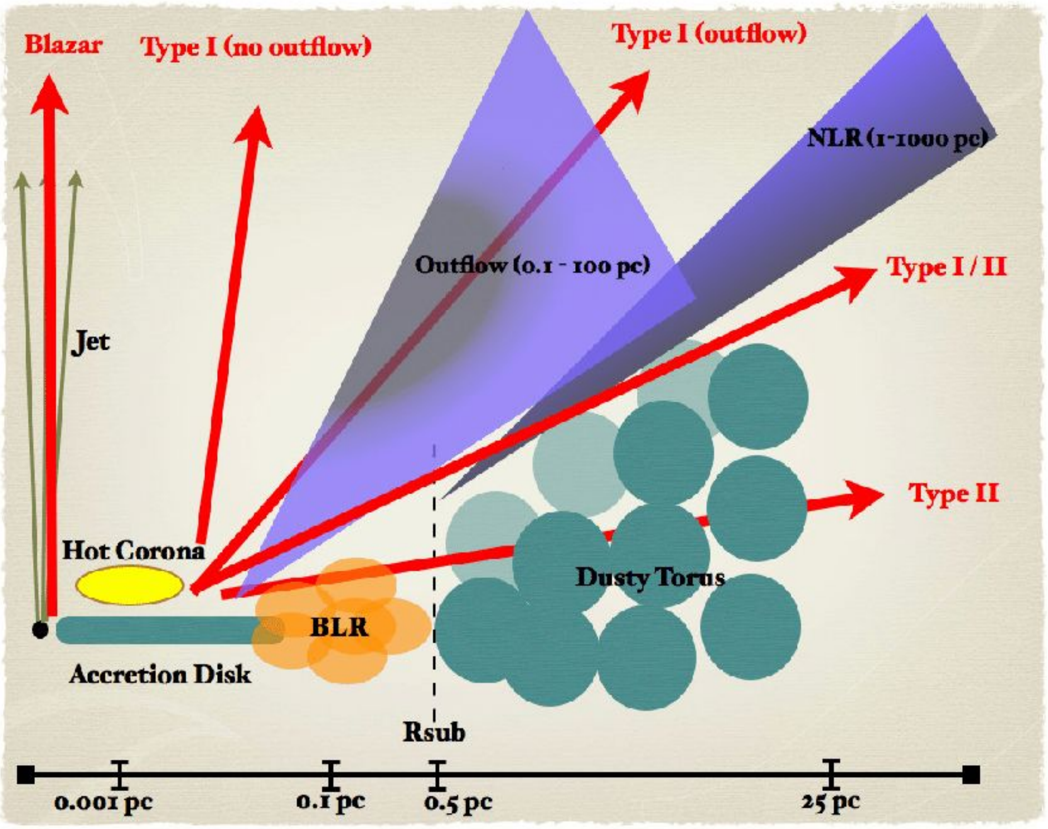



FSRQ
LSP-BL Lac
ISP-BL Lac
HSP-BL Lac
other BL Lac
Photon index
Lγ (erg s^{-1})



Sbarrato et al., 2012

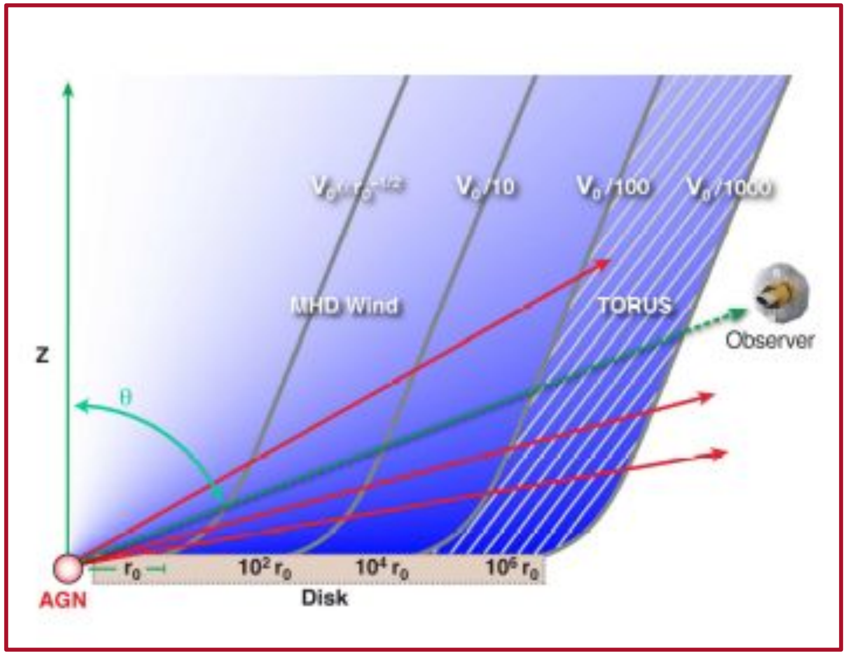
- Accretion Disk Photons (Dermer et al., 1992, Dermer and Schlickeiser, 1993 ++)
- Broad Line Region (Sikora et al., 1994, Blandford and Levinson, 1995, Ghisellini and Madau, 1996, Dermer et al., 1997, Finke, 2013 ++)
- Photons from torus (Blazejowski et al., 2000)
- Synchrotron emission from other regions of the jet (Georganopoulos and Kazanas, 2003, Ghisellini and Tavecchio, 2008)
- Photons which are scattered on Accretion Disk Wind particles (Boula et al., 2019)
- Self-Synchrotron Photons (Marscher and Gear, 1985, Maraschi et al., 1992, Bloom and Marscher, 1996 ++)



Credit: Detmers

Photon Fields

Accretion Disk Winds

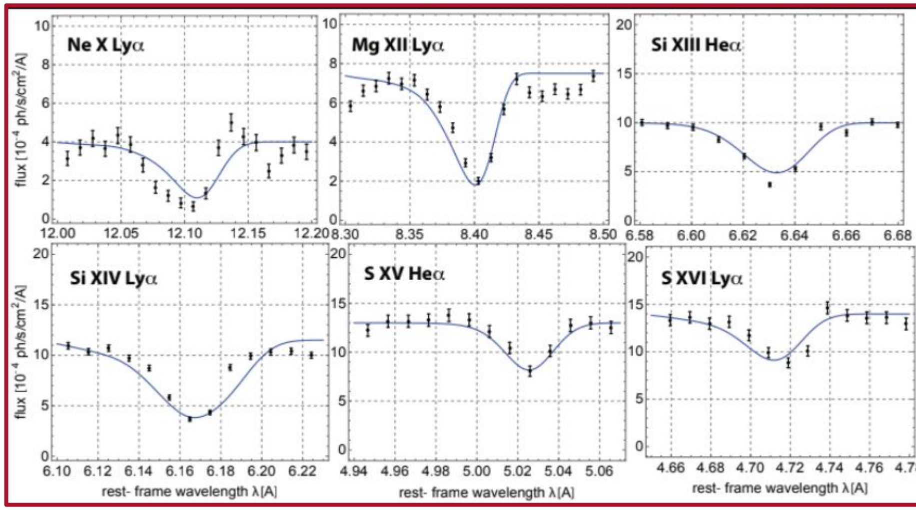


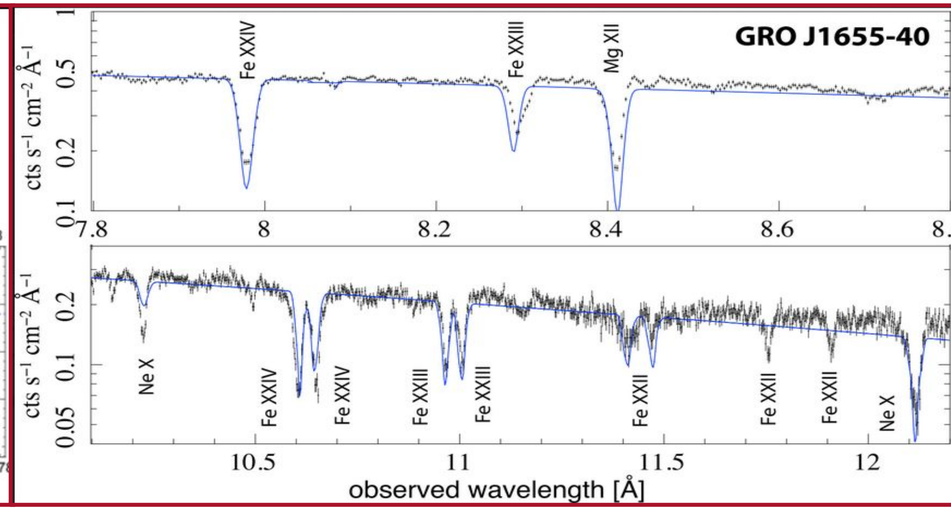
Contopoulos & Lovelace, 1994
Fukumura et al., 2010

- 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

Galactic & Extragalactic Applications

AGN





Fukumura et al., 2018,2019

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 $\Gamma = (1-\beta^2)^{-1/2}$
- Doppler factor $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$

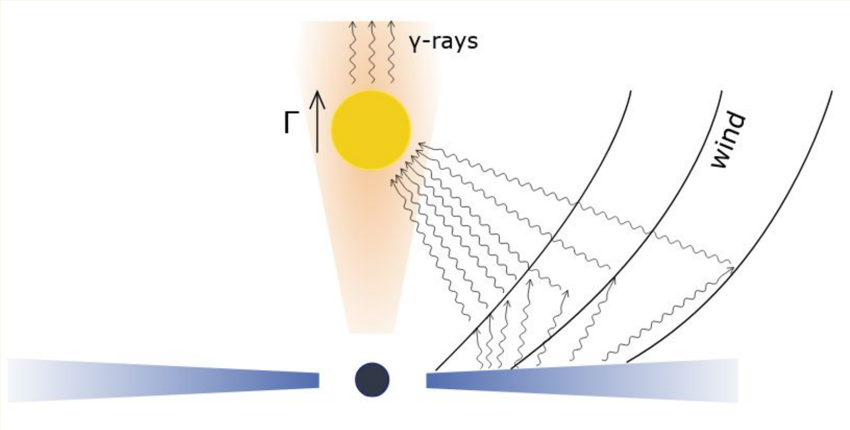


Image credit: S. Dimitrakoudis

Related to the mass accretion rate

External Photon Field

$$n(r,\theta) = n_0 (r_s/r)^p \; e^{5(\theta-\pi/2)} \qquad n_0 = \frac{\eta_w \dot{m}}{2\sigma_T r_s}$$

$$\text{for } p = 1, \; n(r) = n_0 (r_s/r)$$

$$\tau_T(R_1, R_2) = \int_{R_1}^{R_2} n(r)\sigma_T \mathrm{d}r = n_0 \sigma_T r_s \ln(R_2/R_1)$$

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

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

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

Accretion Power of the source:

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

Magnetic Field

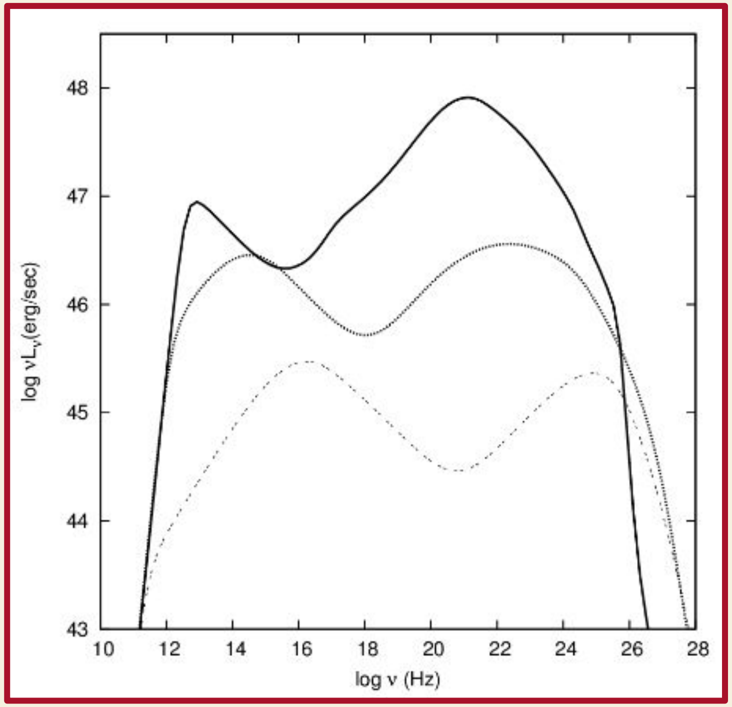
$$U_{\rm B_0} = \frac{\eta_b P_{\rm acc}}{4\pi(3r_{\rm s})^2 c}, \; B = B_0\left(\frac{z_0}{z}\right)$$

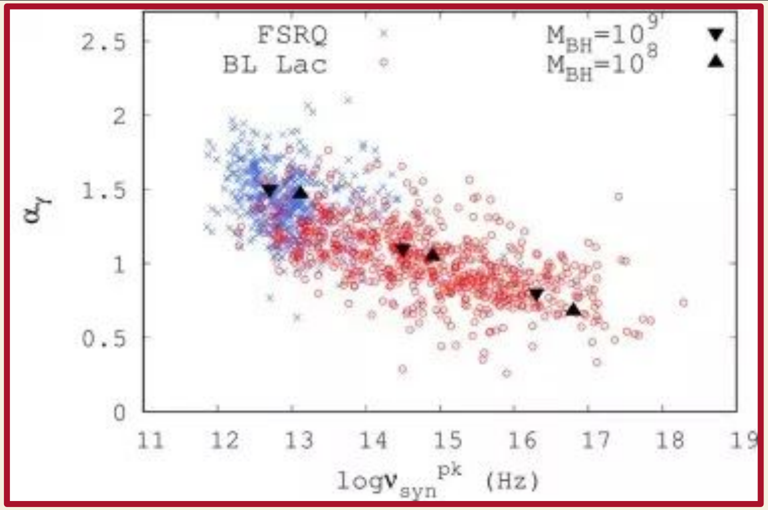
Electron Injection

$$Q_{\rm e} = \begin{cases} k_{\rm e_1}\gamma^{-s} & \text{for } \gamma_{\rm min} \le \gamma \le \gamma_{\rm br}\,, \\ k_{\rm e_2}\gamma^{-q}e^{-\gamma/\gamma_{\rm max}} & \text{for } \gamma_{\rm br} \le \gamma \le \gamma_{\rm max}\,, \end{cases}$$

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

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





$\dot{m}$	B(G)	$U_{\rm ext}$ $\left(\frac{\rm erg}{\rm cm^3}\right)$	$L_{\rm e}^{\rm inj}$ $\left(\frac{\rm erg}{\rm sec}\right)$	$\gamma_{\rm br}$	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

values are in logarithmically scale

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

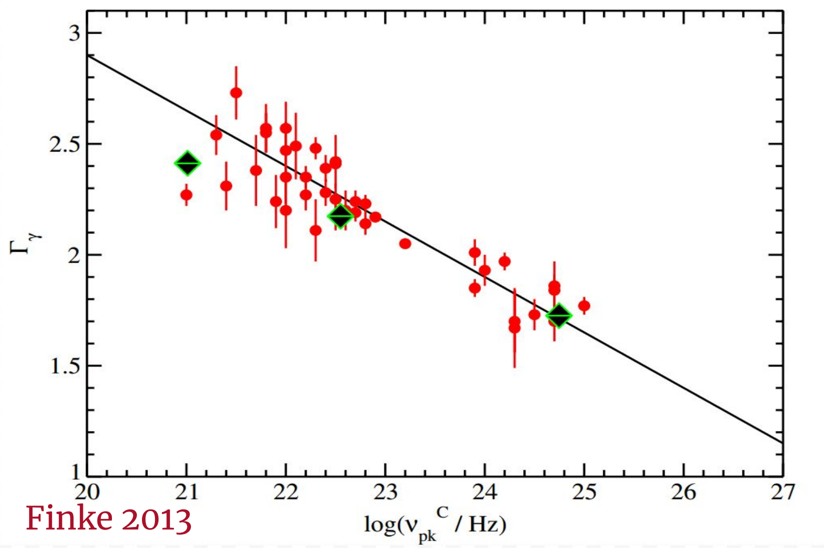
$$U_{\rm ext} \propto U_{\rm sc} \propto \frac{\dot{m}^{\alpha+1}}{\mathcal{M}} \quad (\alpha = 1 \text{ for } \dot{m} \geq 0.1 \text{ and } \alpha = 2 \text{ for } \dot{m} < 0.1),$$

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

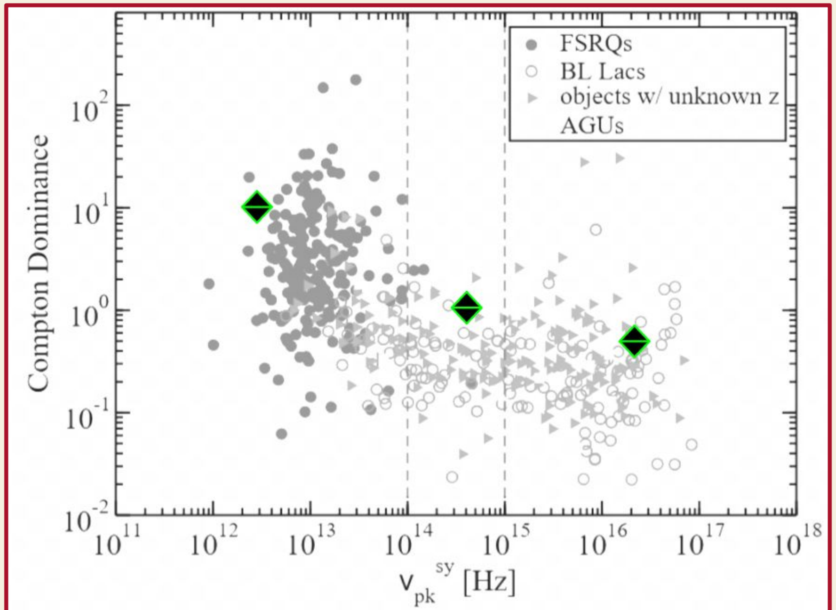
$$L_{\rm e}^{\rm inj} \propto \dot{m}\mathcal{M}$$

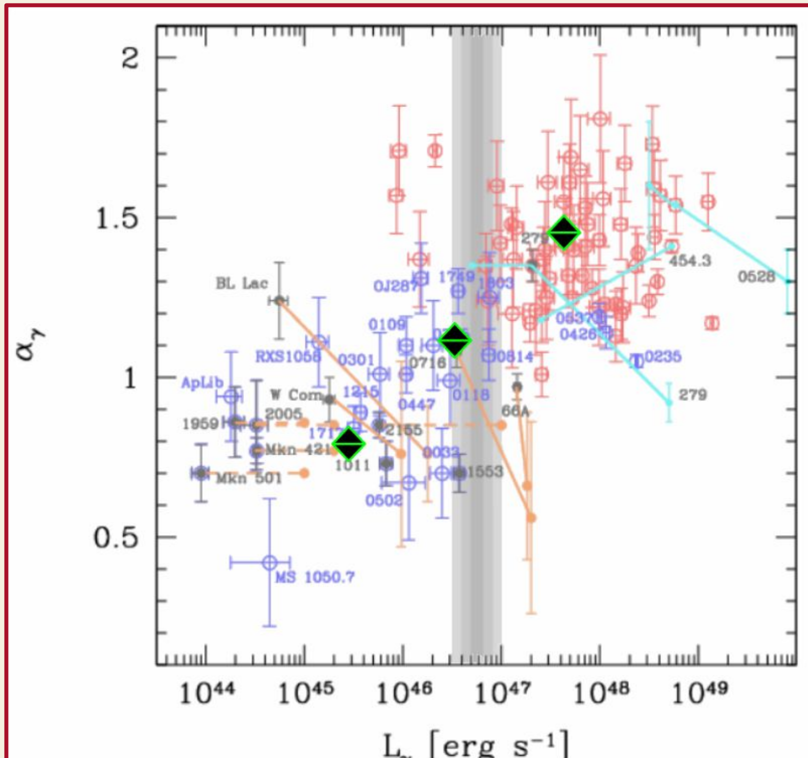
$$\nu_{\rm pk}^{\rm syn} \propto \mathcal{M}^{-1/2}\dot{m}^{-3/2}/(1+\dot{m}^{\alpha})^2$$

Boula, Kazanas & Mastichiadis, 2019 (MNRASL), 2020(PoS)



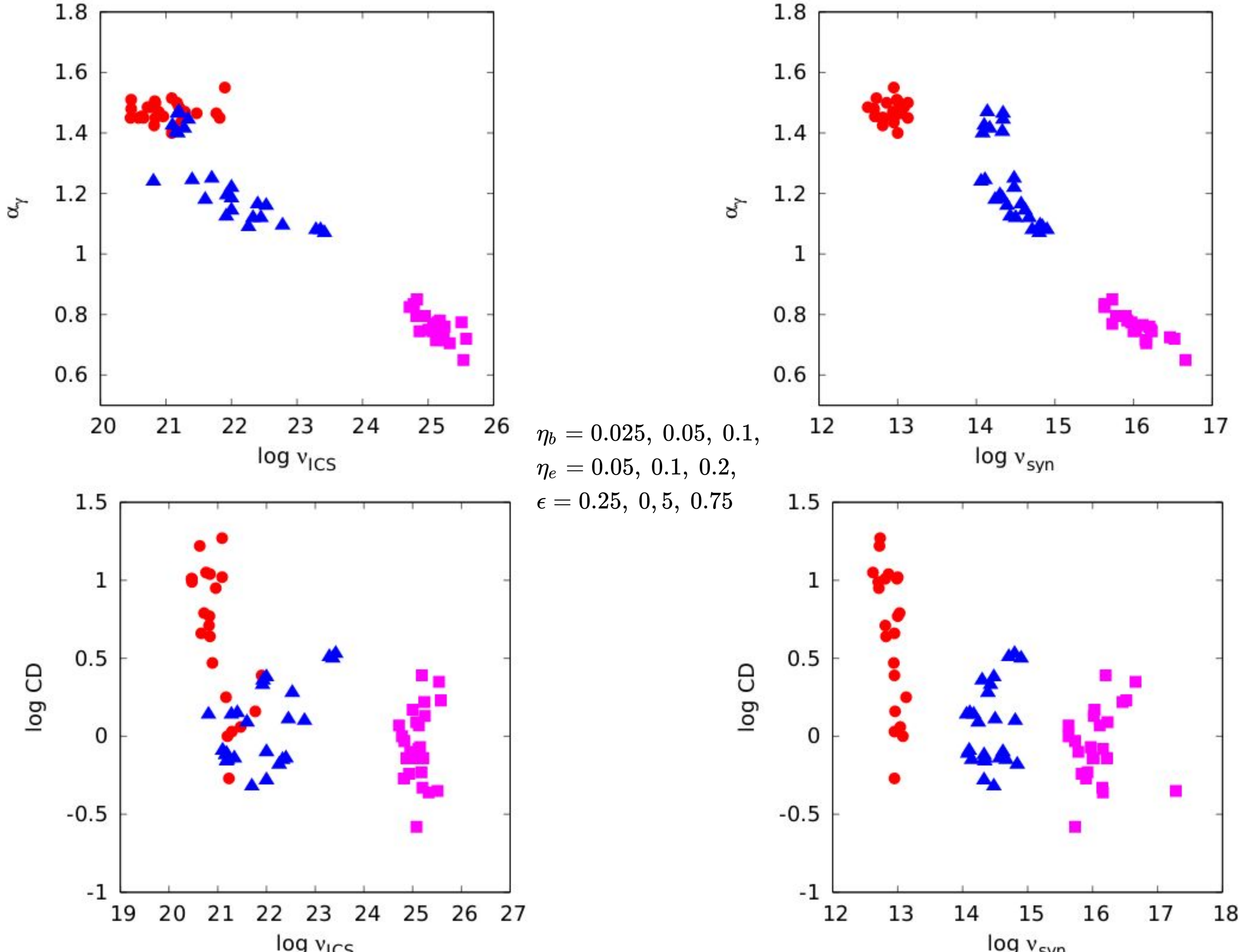
Finke 2013





Ghisellini et al., 2009

$$CD = \frac{L^{pk}_{Compton}}{L^{pk}_{synchrotron}}$$



$\eta_b = 0.025,\ 0.05,\ 0.1,$
$\eta_e = 0.05,\ 0.1,\ 0.2,$
$\epsilon = 0.25,\ 0,5,\ 0.75$

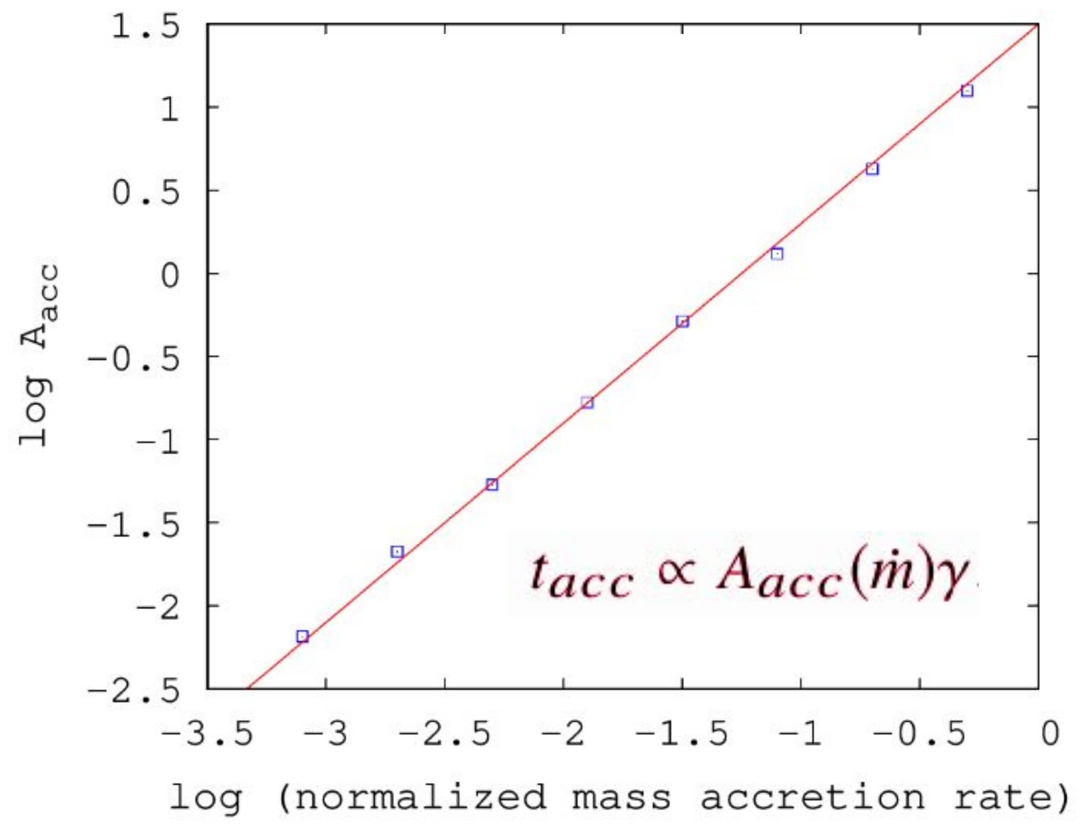
Particle Acceleration

Boula, Mastichiadis & Kazanas, in prep.

$$\frac{\partial n_e(\gamma,t)}{\partial t} + \frac{n_e(\gamma,t)}{t_{esc}(\gamma)} + \frac{\partial}{\partial \gamma}\left(\frac{\gamma}{t_{acc}(\gamma)} n_e(\gamma,t)\right) = \mathcal{L}_e(\gamma,t)$$

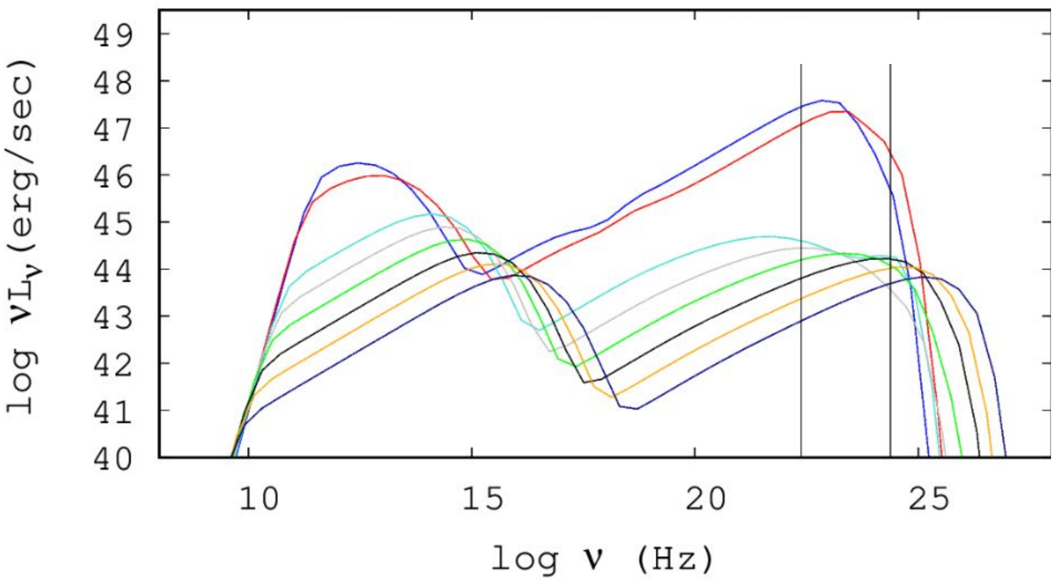
$$t_{acc_{FI}} \geq 6\left(\frac{c}{u_s}\right)^2 \frac{\lambda}{c} \simeq 6\frac{r_g c}{u_s^2}$$

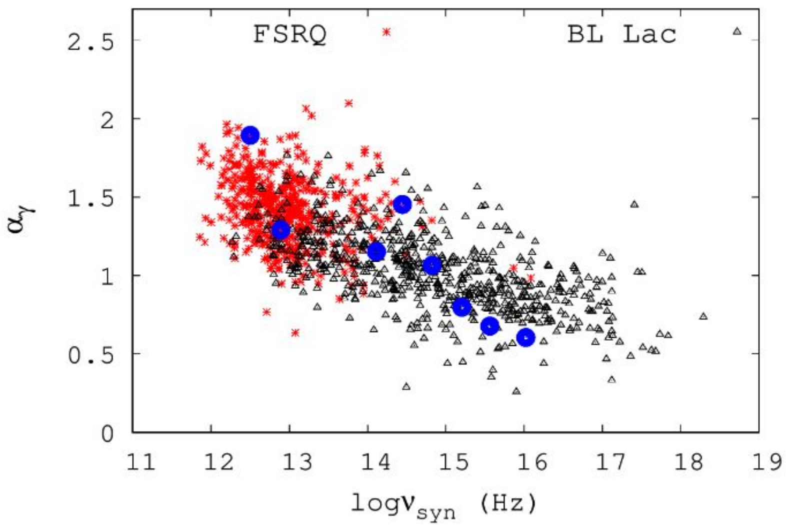
$$r_g = \frac{\gamma m c^2}{eB}$$



We assume next that the particles gain energy and the electrons energy distribution is calculated self-consistently

Boula et al., 2021 (ICRC2021)

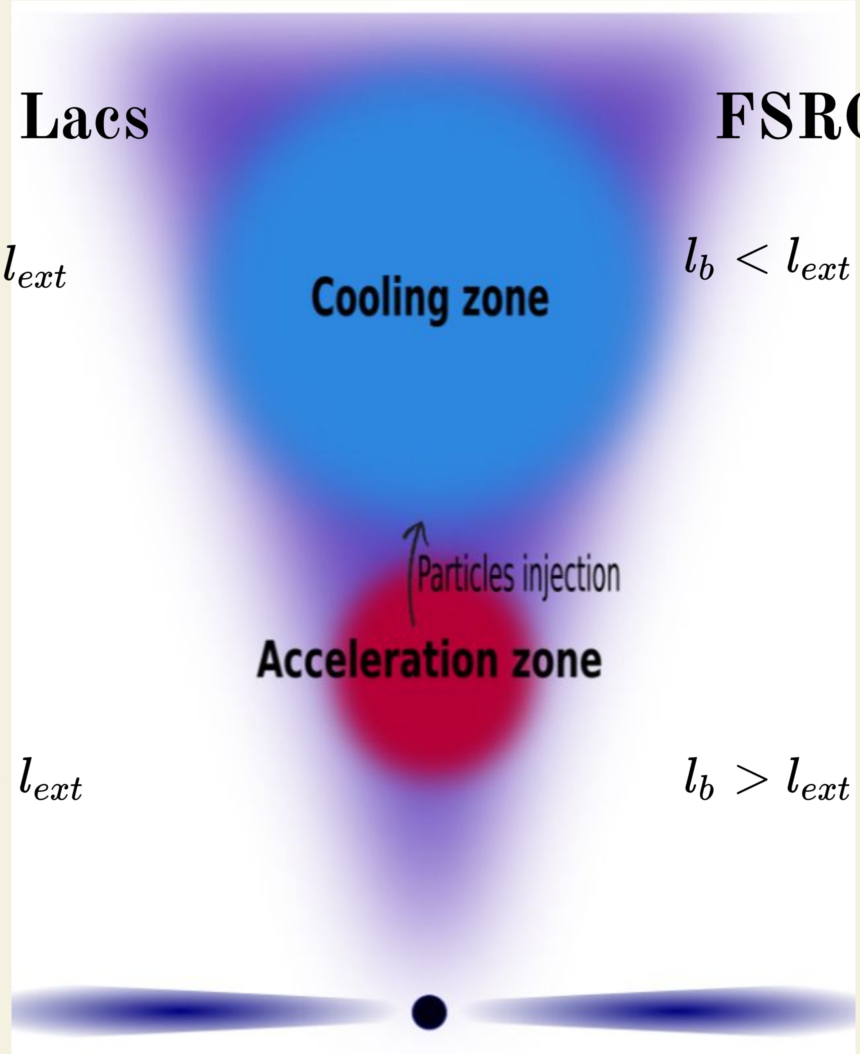

49
48
47
46
45
44
43
42
41
40
10
15
20
25
log νL_ν (erg/sec)
log ν (Hz)


FSRQ
BL Lac
2.5
2
1.5
1
0.5
0
11
12
13
14
15
16
17
18
19
α_γ
logν_syn (Hz)

Next step:

BL Lacs | **FSRQs**

$l_b > l_{ext}$ | $l_b < l_{ext}$

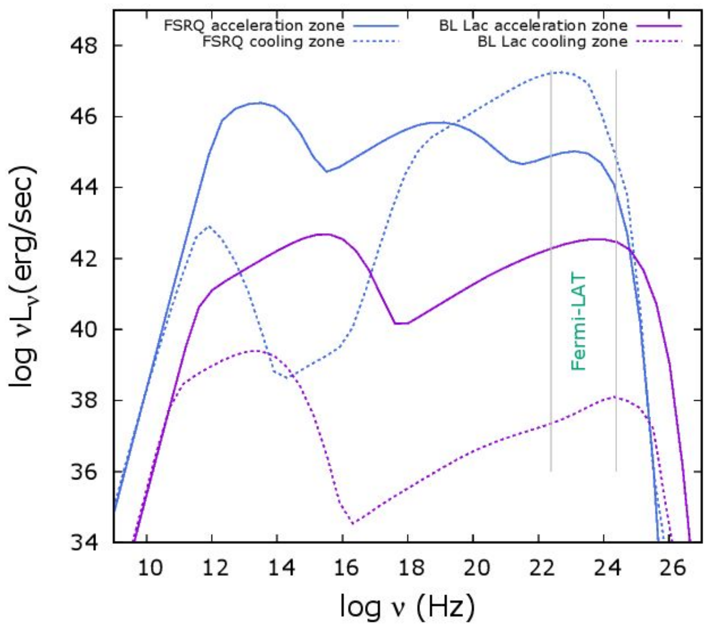


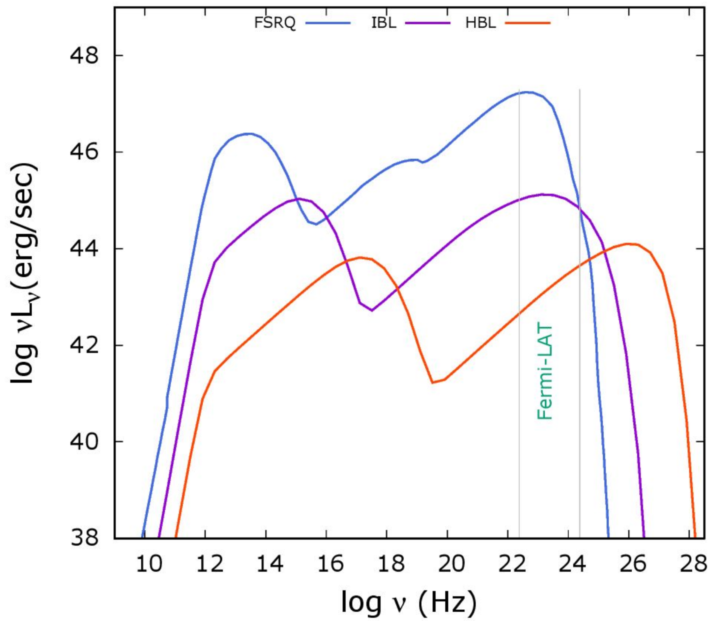
$l_b > l_{ext}$ | $l_b > l_{ext}$

Boula et al., 2021 (ICRC2021)

$$l_b = \frac{\sigma_T R_b U_b}{m_e c^2}, l_{ext} = \frac{\sigma_T R_b U_{ext}}{m_e c^2}$$

$$B \propto 1/z, \; U_{ext} = constant$$



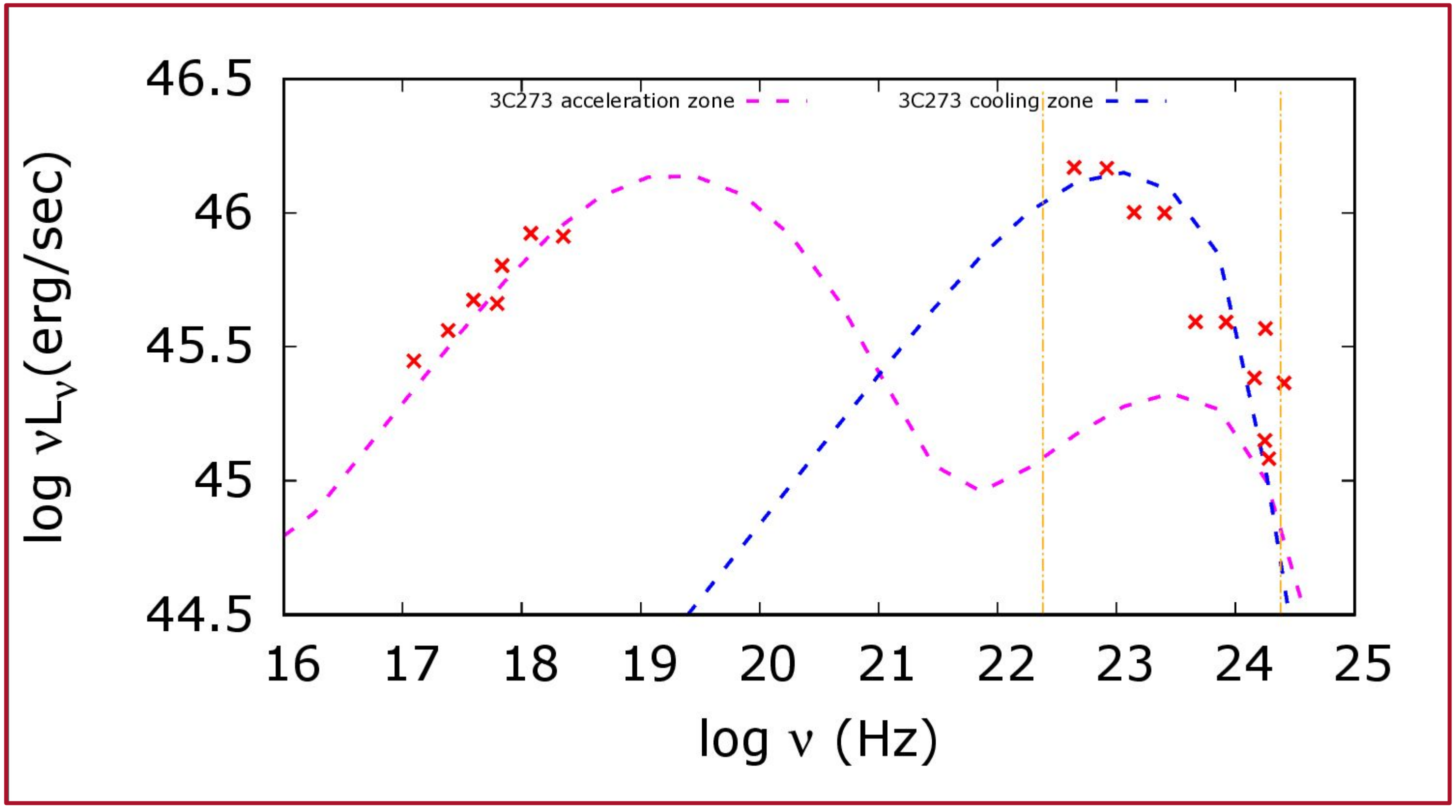


Boula et al.,2021 (ICRC 2021)

$\dot{m}$	B(G)	U_{ext} $\left(\frac{erg}{cm^3}\right)$	A_{acc}	Blazar Class
-0.5	1	-2.6	-4	FSRQ
-1.5	0	-5.6	-5	LBL
-2.5	-1	-8.6	-6	HBL

Application to 3C273

$z = 10^{-2}$ pc
$R_1 = 10^{15}$ cm
$R_2 = 3 \times 10^{18}$ cm
$B = 1$ G
$R = 8 \times 10^{15}$ cm
$A_{acc} = 10^{-4}$
$U_{ext} = 2.5 \times 10^{-3}\ \frac{erg}{sec}$
$T_{disk} = 3 \times 10^5 K$
$\Gamma = 30$
$\delta = 15$

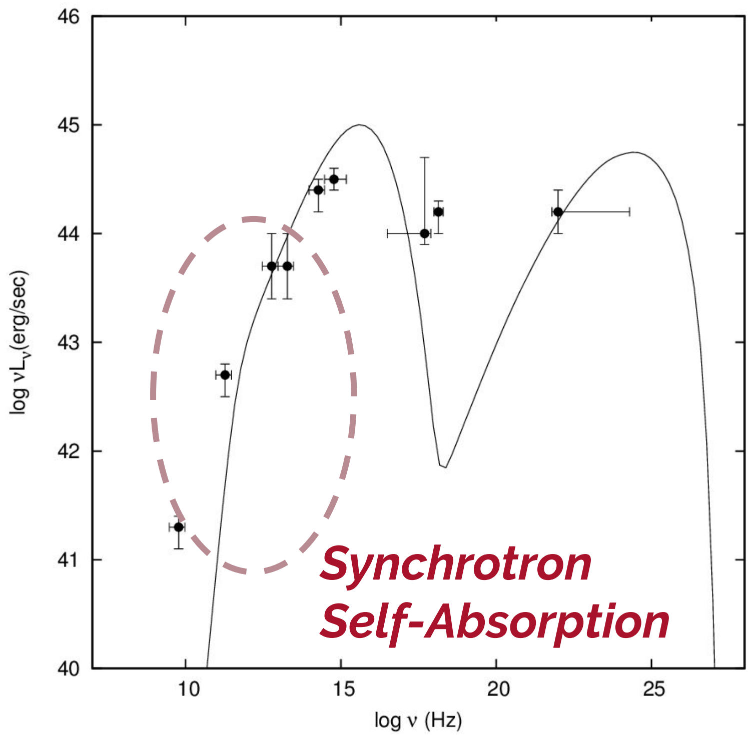


Boula et al., 2021 (ICRC2021)

Topic No 2

Localization of the emission

Where the radio photons are produced?



Numerical code:
Mastichiadis & Kirk, 1995, A&A

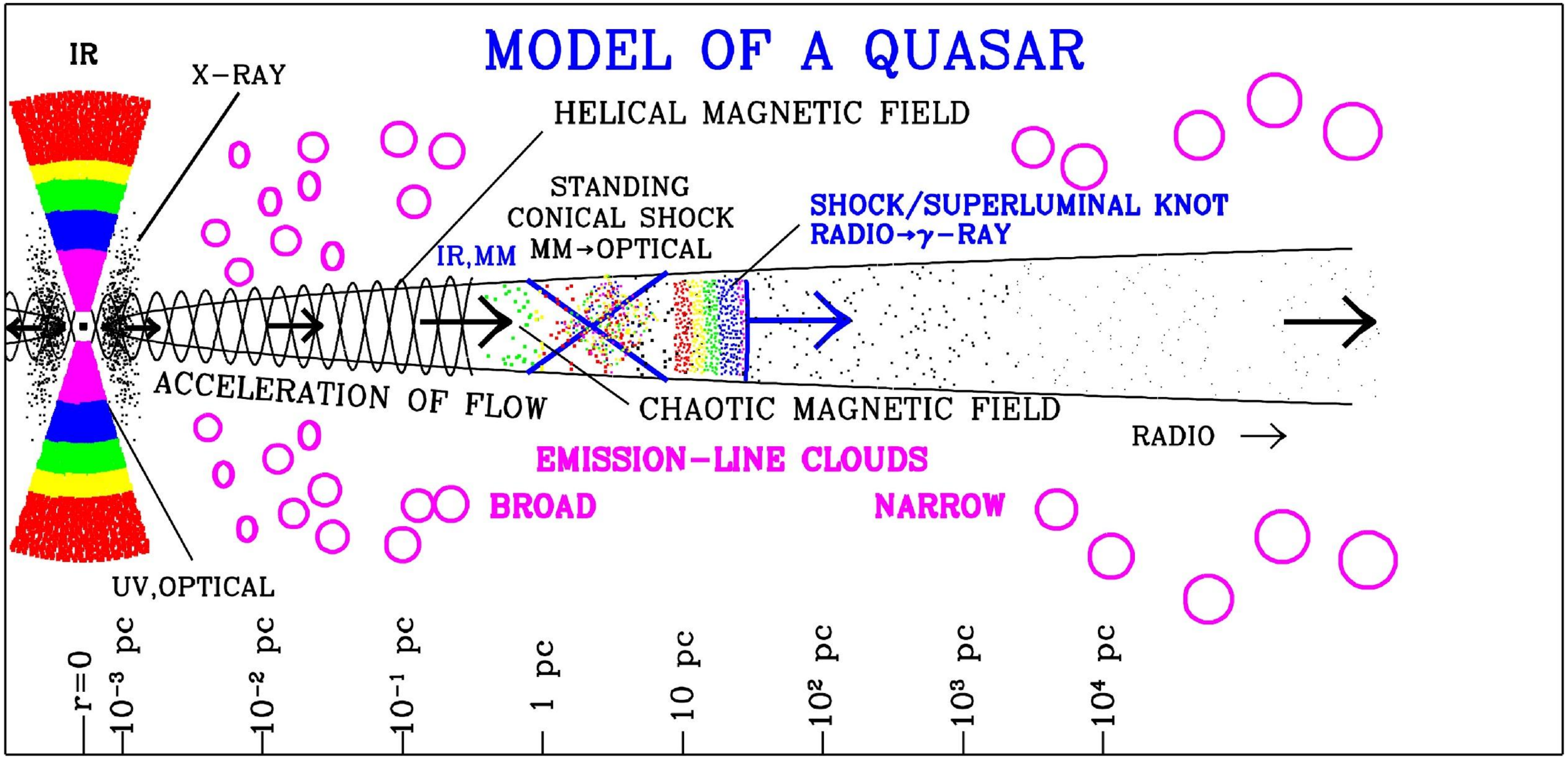
$$\nu_{ssa} = \left[\frac{\sqrt{3}q^3}{8\pi m}\left(\frac{3q}{2\pi m^3 c^5}\right)^{\frac{p}{2}} C (B \sin\alpha)^{\frac{p+2}{2}} \Gamma\left(\frac{3p+2}{12}\right)\Gamma\left(\frac{3p+22}{12}\right) R\right]^{\frac{2}{p+4}}$$

Rybicki & Lightman, 1974

Jet Models:

Blandford & Königl, A, 1979 , Marscher & Gear, 1985, Ghisellini, Maraschi & Treves, 1985, Georganopoulos & Marscher , 1998, Katarzynski, Sol & Kus, 2003, Potter & Cotter, 2012, Hervet, Boisson & Sol, 2015, Richter & Spanier, 2016 +++

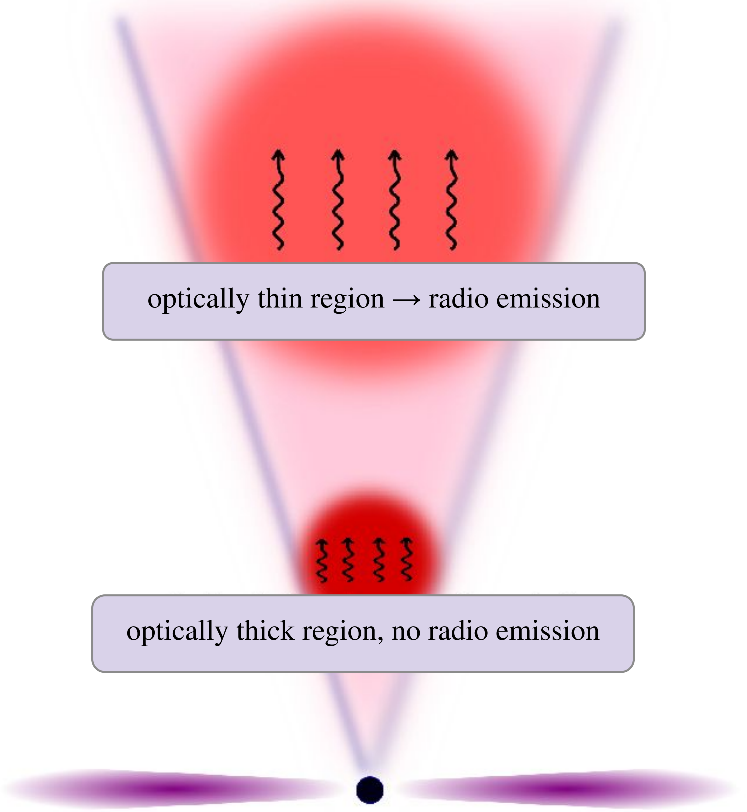
Standard Jet Model



Credit: Marscher

Our model for the continuous jet

- Spherical regions of accelerated particles, that move along the jet and at the same time are expanding.
- Superposition of the emission of these blobs leads to a continuous jet emission.



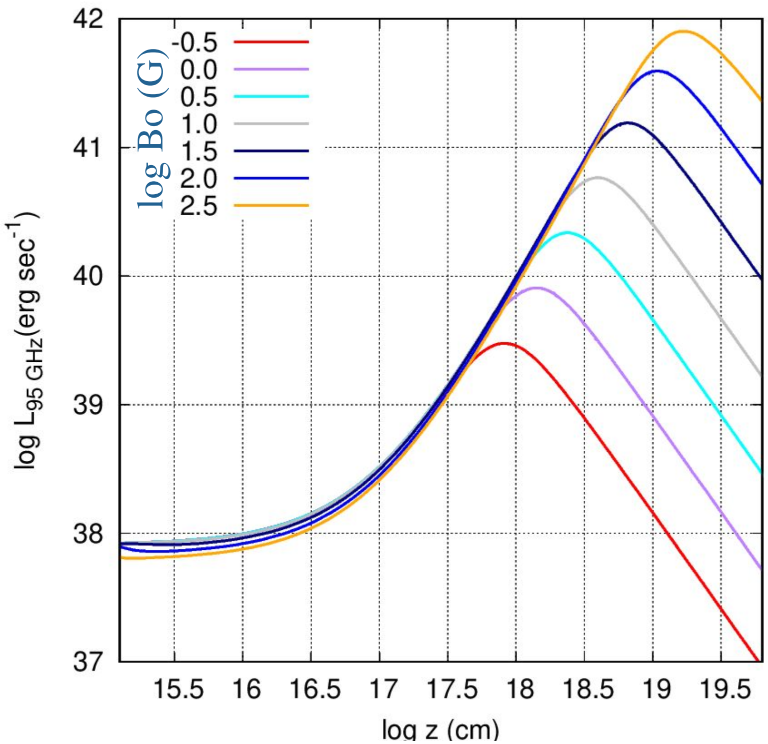
$$R(t) = R_0 + u_{exp} t, \qquad B = B_0 \left(R_0/R\right)^s$$

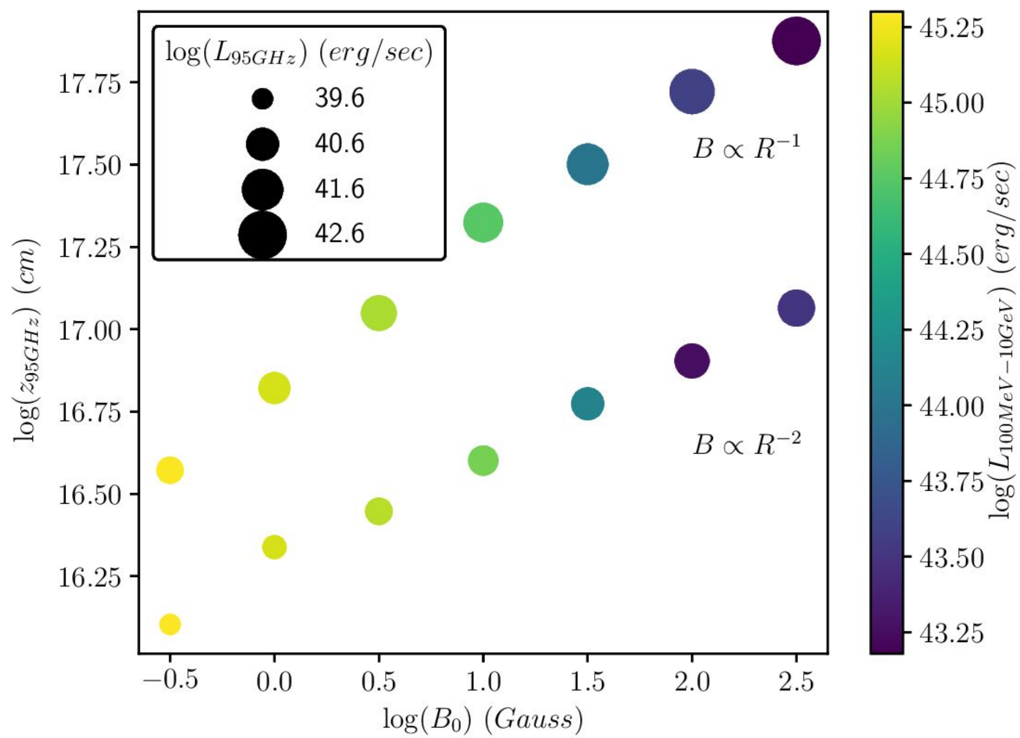
$$\frac{\partial N(\gamma, R)}{\partial R} + \frac{\partial}{\partial \gamma}\left[\left(A_{syn}(\gamma, R) + A_{ICS}(\gamma, R) + A_{exp}(\gamma, R)\right) N(\gamma, R)\right] = Q_e(\gamma, R),$$

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

The role of the initial Magnetic Field on ν_{ssa}

Boula & Mastichiadis, 2021





The values of the rest parameters:

R_o = 1.e15 cm, $L_{inj\ eo}$ = 1.e42 erg/s, u_{exp} = 0.01c,

γ_{min} = 1, γ_{max} = 1.e6, slope index= -2, δ = 10.

The magnetic field strength and electron injection luminosity decrease linearly with radius

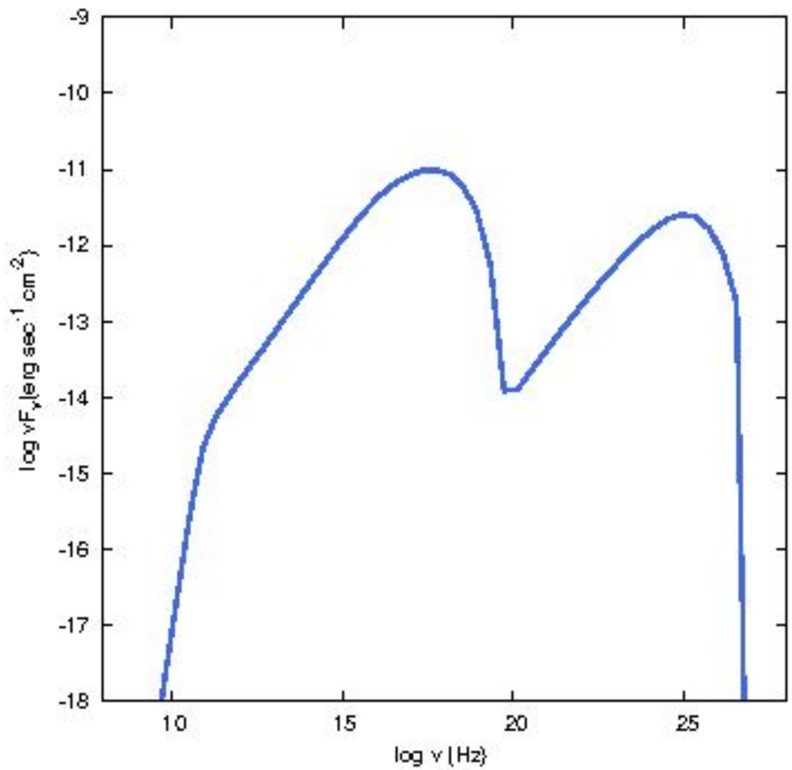
The values of the rest parameters:

R_o = 1.e15 cm, $L_{inj\ eo}$ = 1.e42 erg/s, u_{exp} = 0.1c,

γ_{min} = 1, γ_{max} = 1.e6, slope index= -2, δ = 10.

The electron injection luminosity decrease linearly with radius

Steady State Emission of Mrk 421



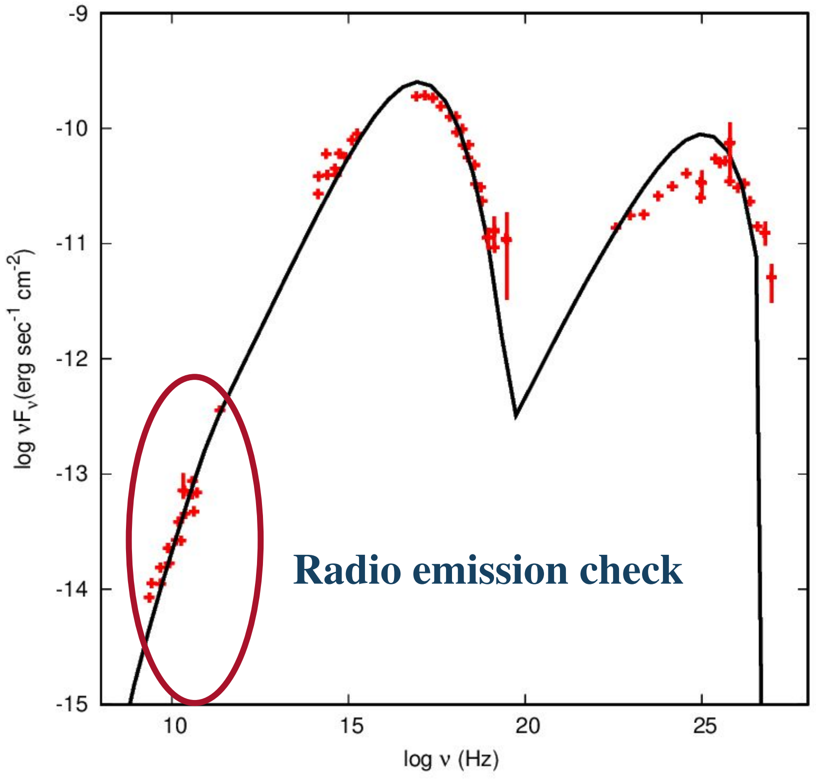
Produced by supeposition of expandinhg blobs injected at z_o = 0.01 pc with the following properties:

B_o = 0.3 G, R_o = 1.e16 cm, $L_{inj\ eo}$ = 3.e41 erg/s, u_{exp} = 0.2c, γ_{min} = 1, γ_{max} = 1.e6,

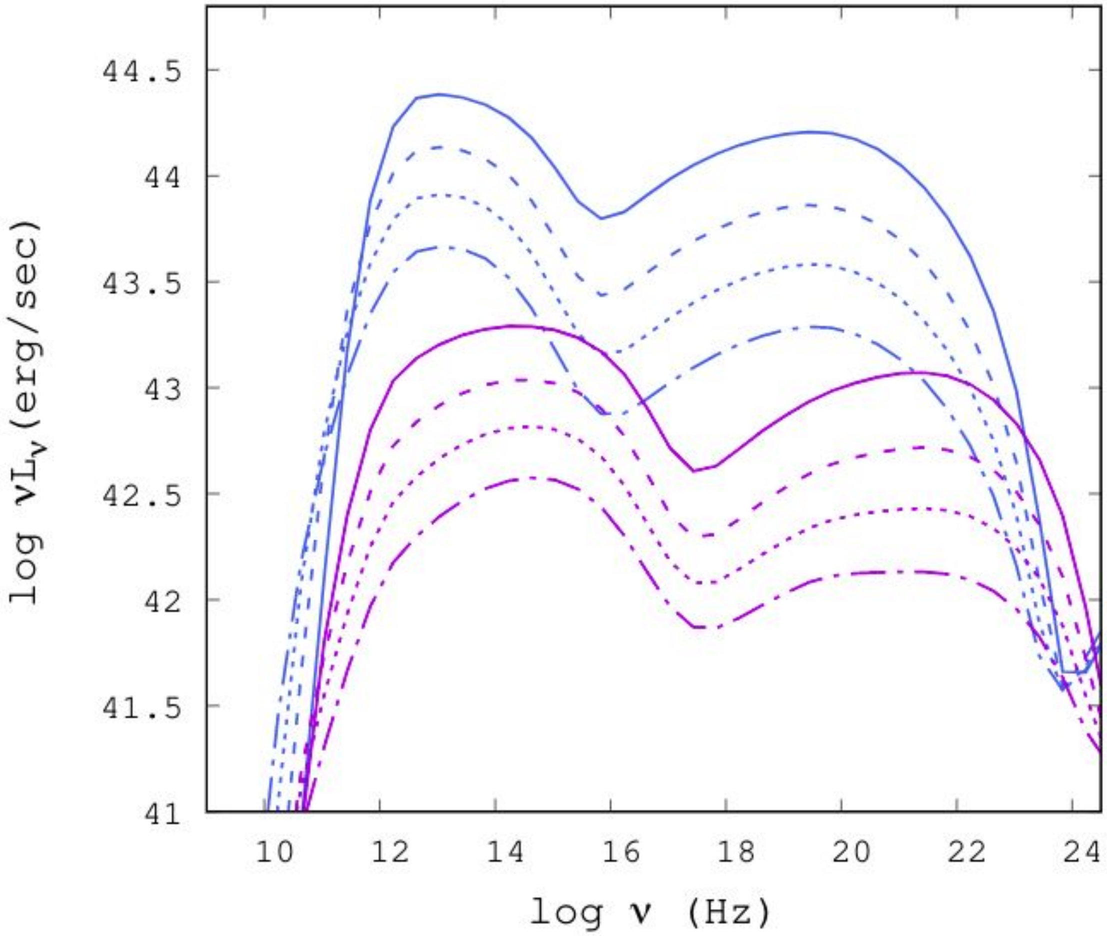
slope index= -2, δ = 10.

The magnetic field and electron injection luminosity decrease linearly with radius

Steady State Emission of Mrk 421



Different mass accretion rates and expansion velocities

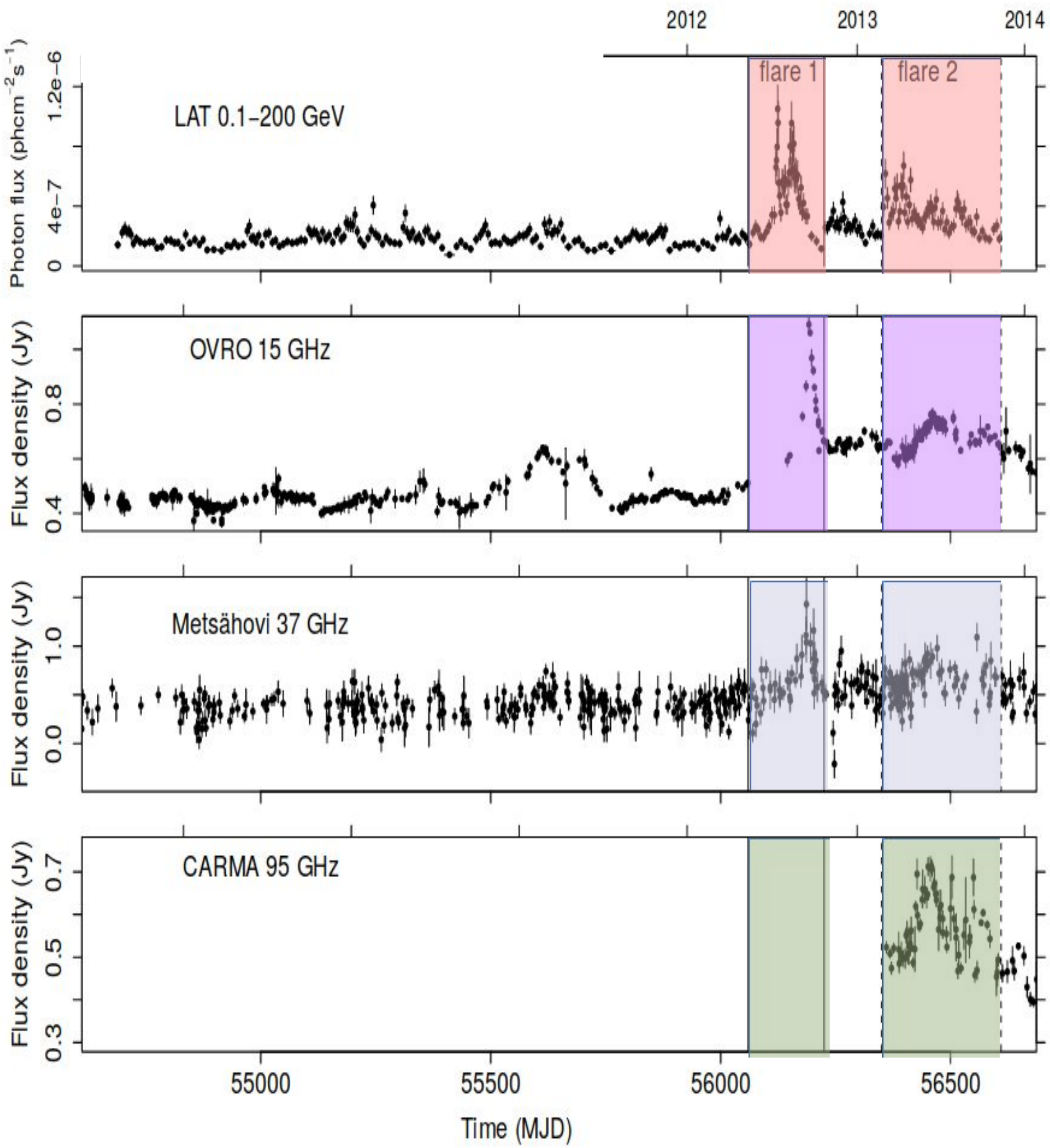


B_0(G)	$L_{e_0}^{inj}$ $\left(\frac{erg}{sec}\right)$	γ_{max}	Blazar Class
1.5	43.5	4	LBL
1.0	42.5	5	HBL

u_{exp} = 0.010, 0.025, 0.050, 0.100

Topic No 3

Flaring Episodes

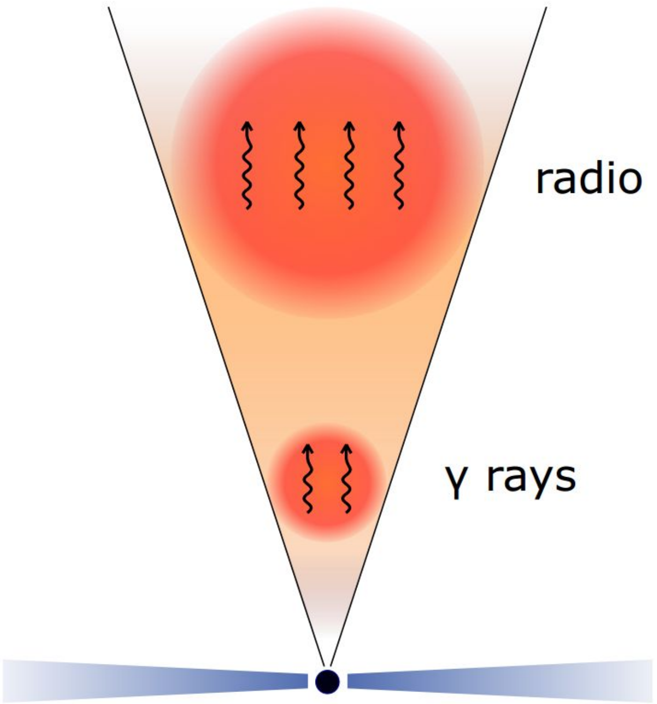


A combined radio and GeV gamma-ray view of the 2012 and 2013 flares of Mrk 421 (Hovatta et al., 2015)

Challenge: The connection of γ-ray and radio flare

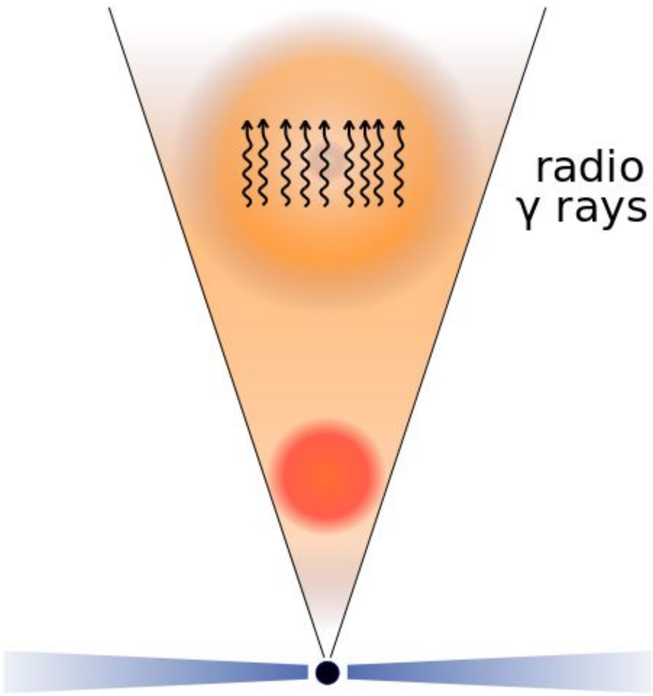
- Is there a causal connection between γ-ray and radio flares?
- What drives the time-lag between radio and γ-ray flares?

Modeling Flaring Episodes



Case 1

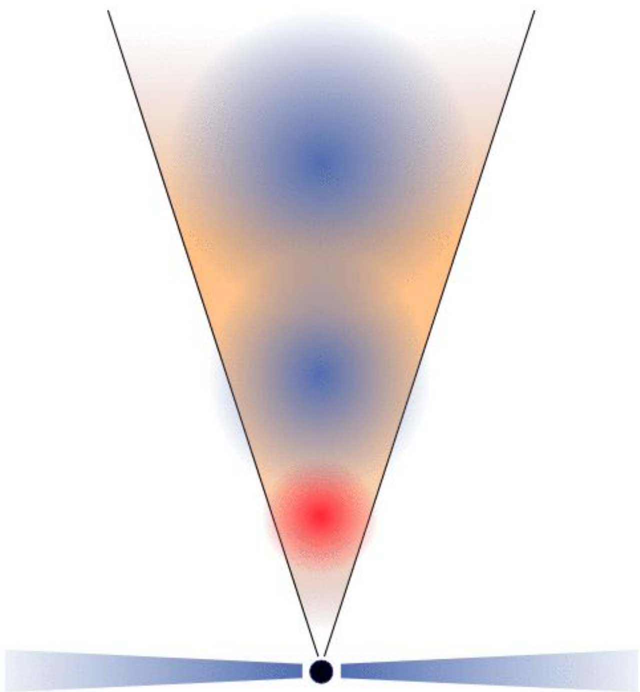
Blob with different initial properties → flare

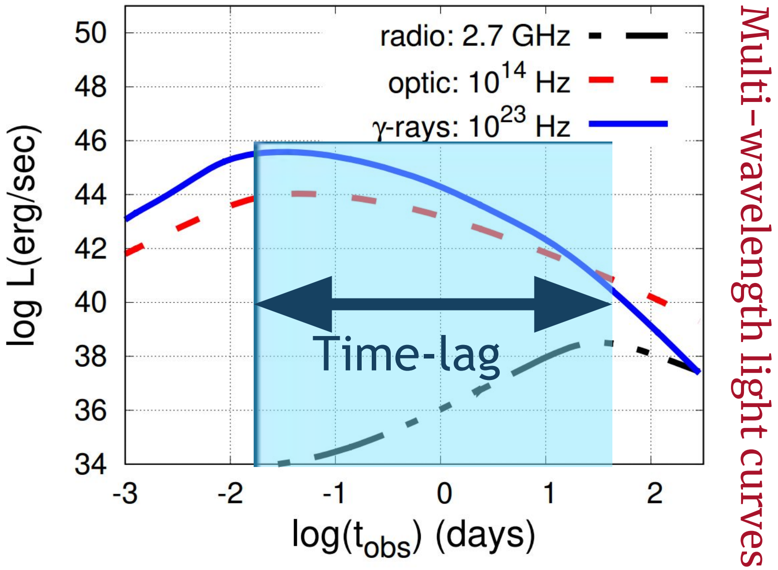


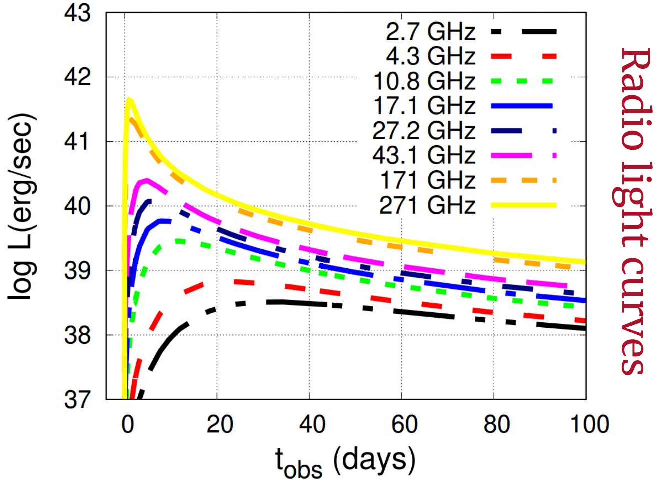
Case 2

Particle re-acceleration at a distance z → flare

Case 1







Produced by a single blob injected at z_o = 0.001 pc with the following properties:

B_o = 1 G, R_o = 1.e15 cm, $L_{inj\ eo}$ = 1.e43 erg/s, u_{exp} = 0.4c, γ_{min} = 1, γ_{max} = 1.e5, p = 2, δ = 10.

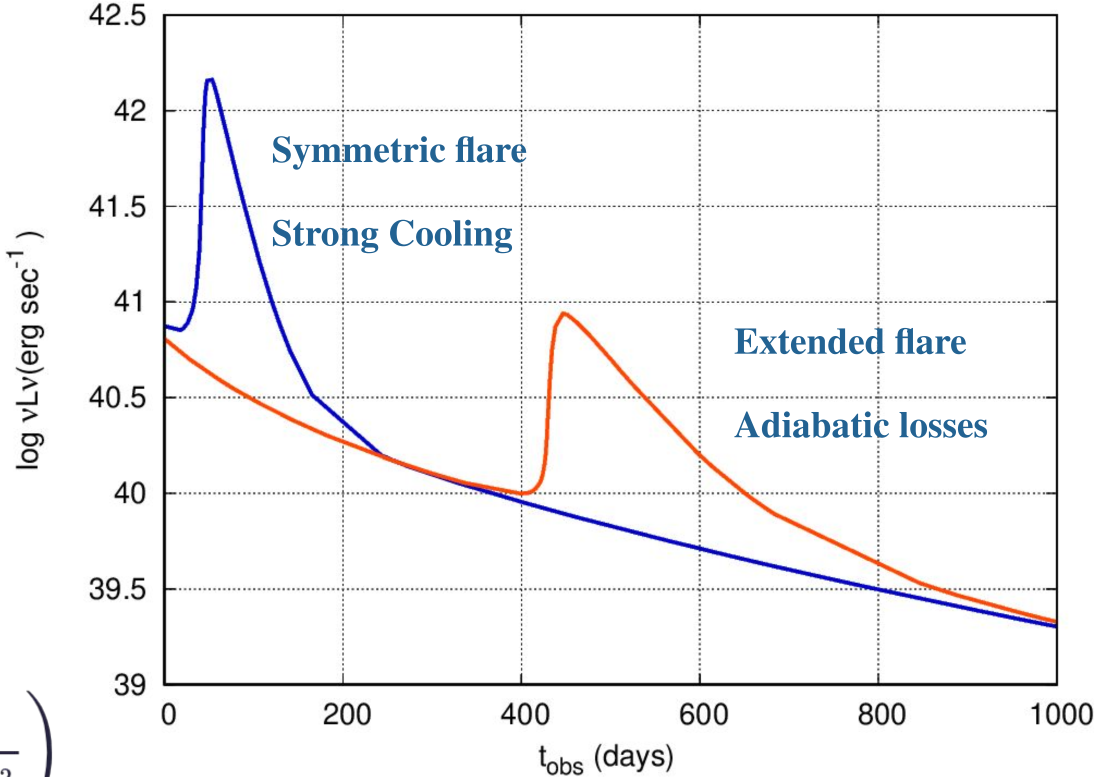
The magnetic field and electron injection luminosity decrease linearly with radius

Boula et al., 2019

Case 2

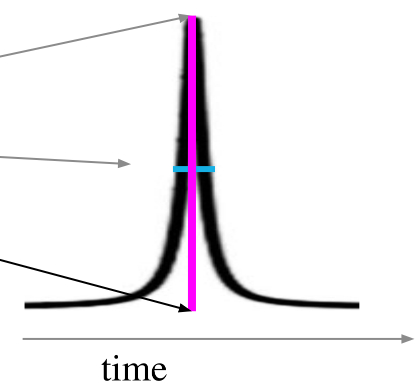
A particle re-acceleration episode “somewhere”into the jet could produce a photon flare.

Here we use the assumption that this injection has the form of a lorentzian distribution.



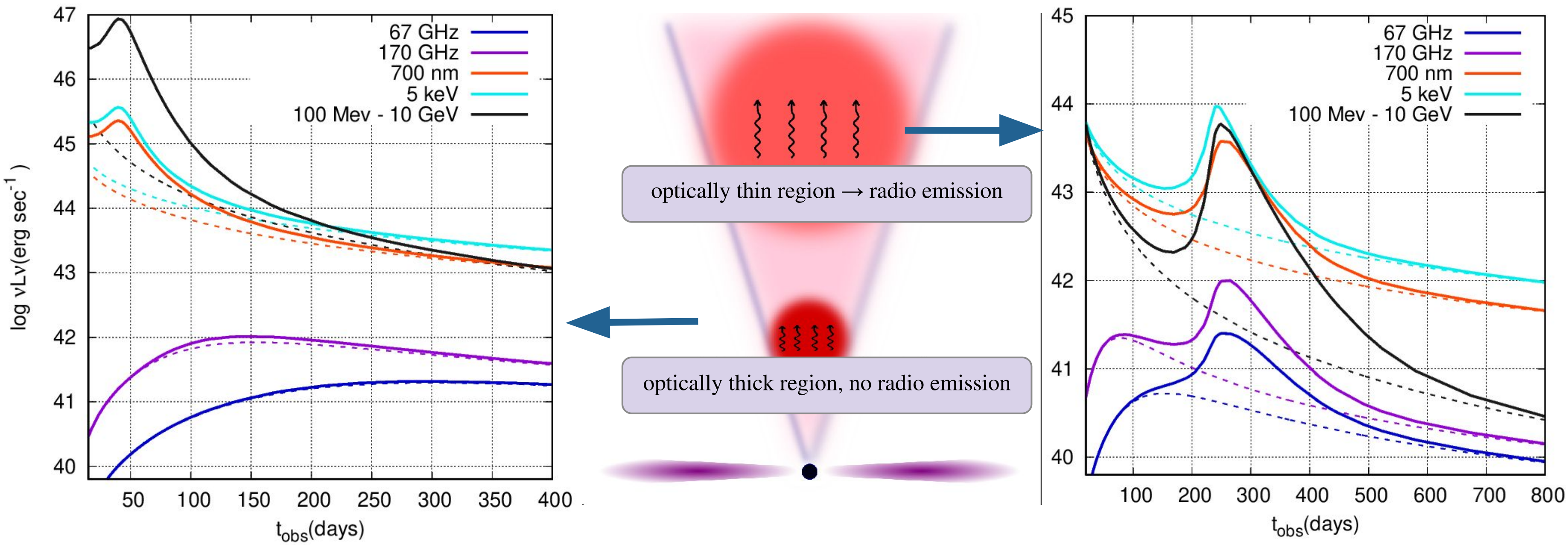
$$Q_e(\gamma,t) = q_e(t)\gamma^{-p}\left(1+\frac{\alpha w^2}{4(t-t_0)^2+w^2}\right)$$

α=the value of the luminosity at the peak
w=the width of the injection
t_o=the time of the injection at the peak



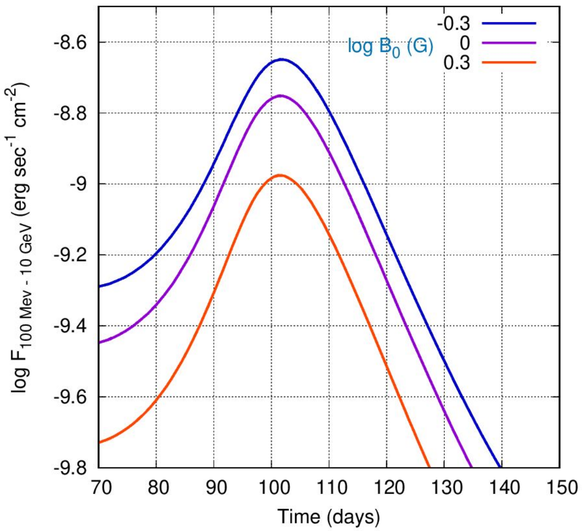
Boula & Mastichiadis, 2021

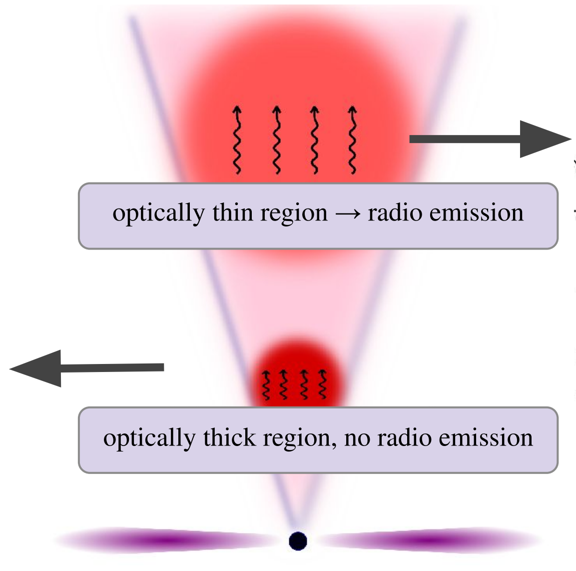
For modeling the production of flares in gamma-ray quasars e.g. Sikora et al., 2001

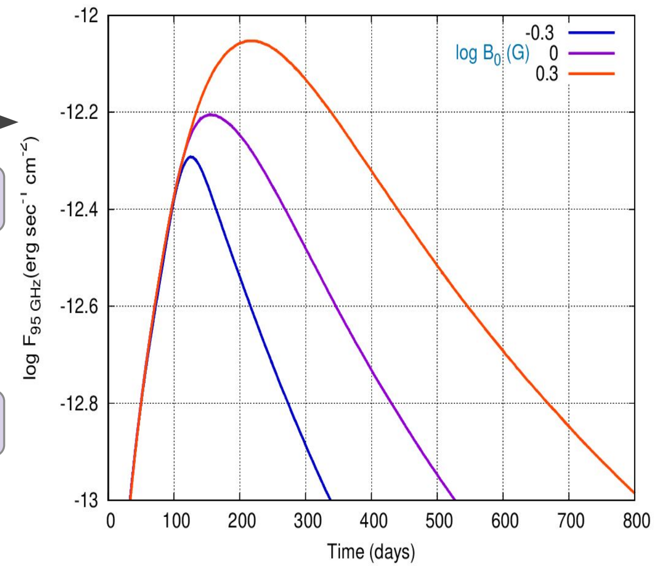


optically thick region **optically thin region**

Boula & Mastichiadis, 2021





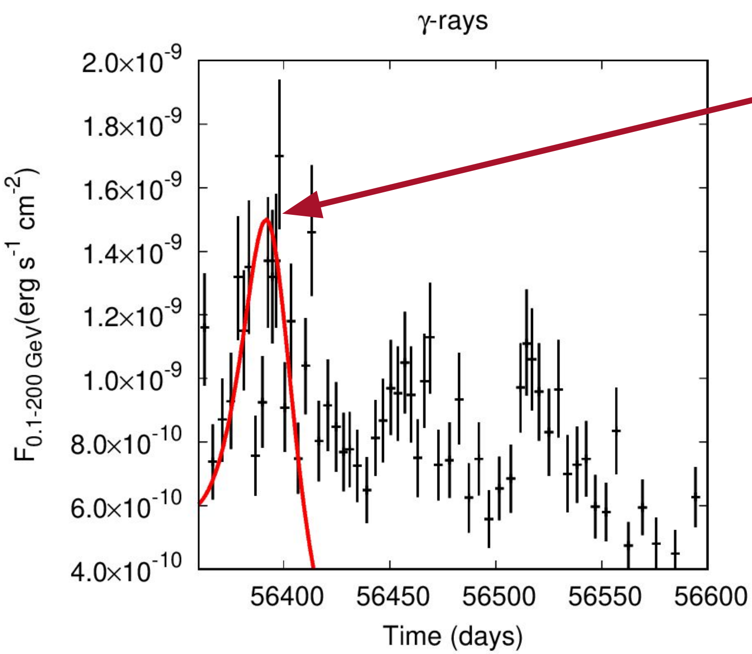


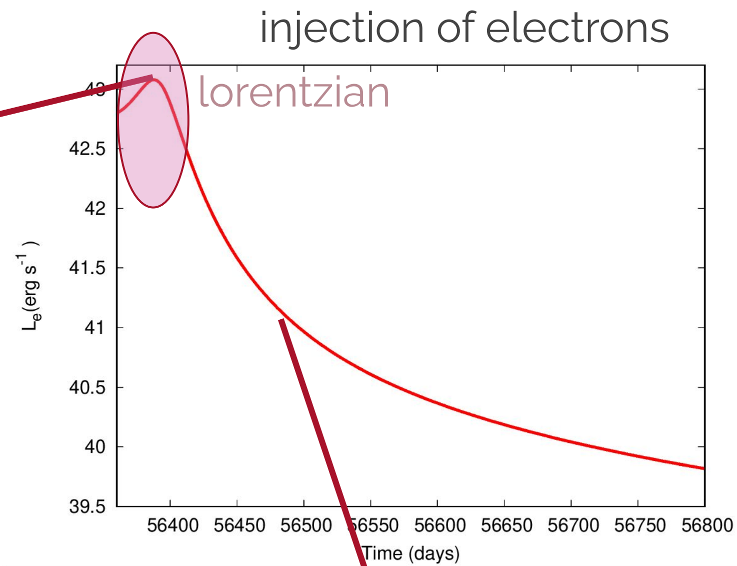
optically thick region
γ-ray flare

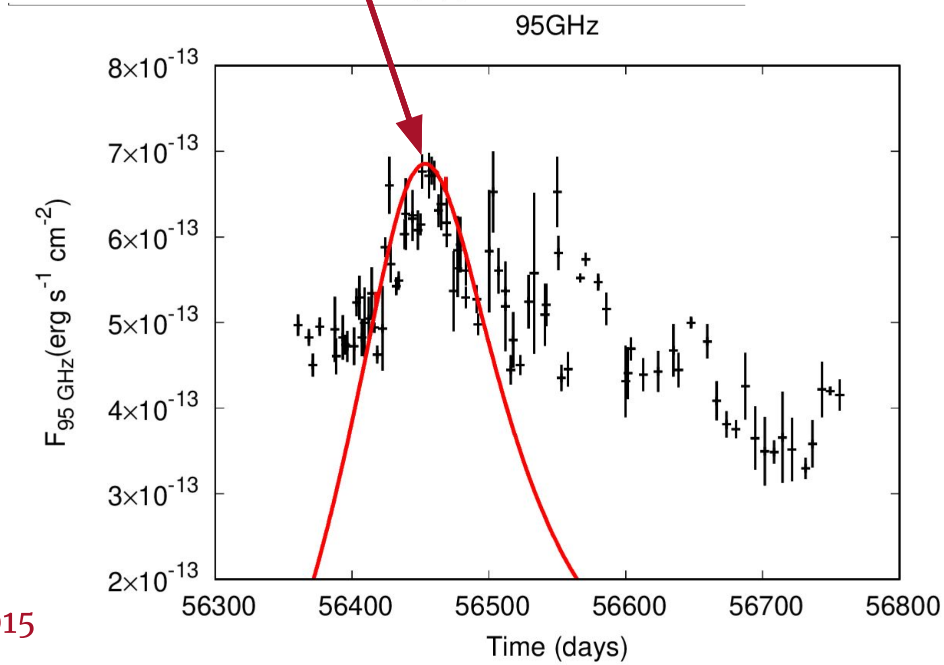
optical thin region
radio flare

Gamma-ray flare is produced by a re-acceleration episode close to the central engine and radio flare is produced by the transition from the optical thick to the optically thin region

Application to Mrk 421 2013 flaring episode







B_o = 1,25 G, R_o = 4.e16 cm, $L_{inj\ eo}$ = 1.58e42 erg/s,

u_{exp} = 0.05c, γ_{min} = 1, γ_{max} = 1.e5, p = 2,

δ = 10.

t_{inj}=40t_{cross}, α = 60, w= 22t_{cross}

$B \propto R^{-1}$

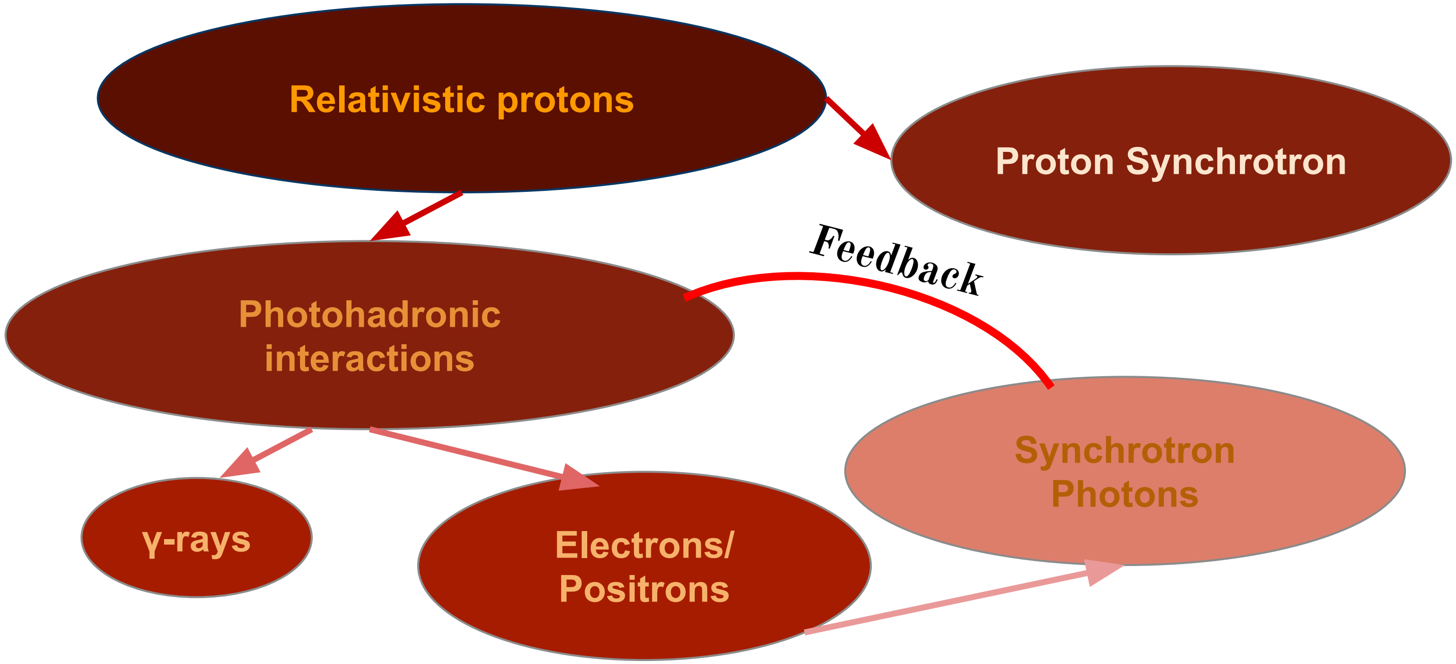
$L_e \propto R^{-2}$

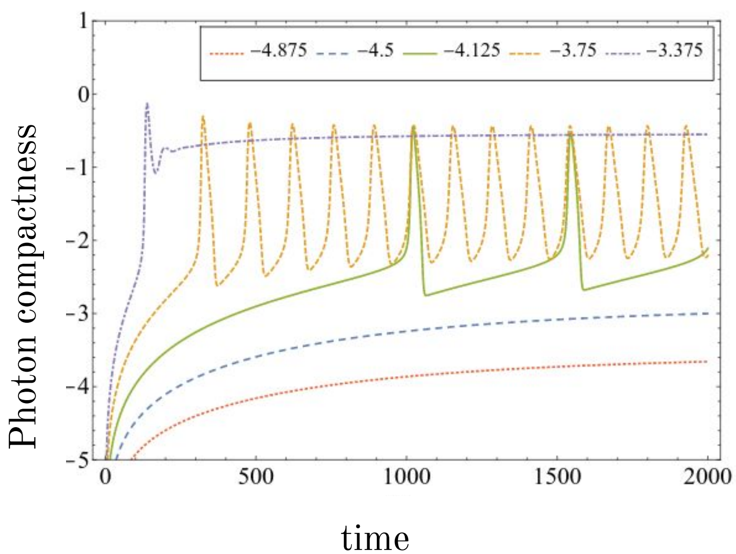
Boula & Mastichiadis, 2021
Data by Hovatta et al., 2015

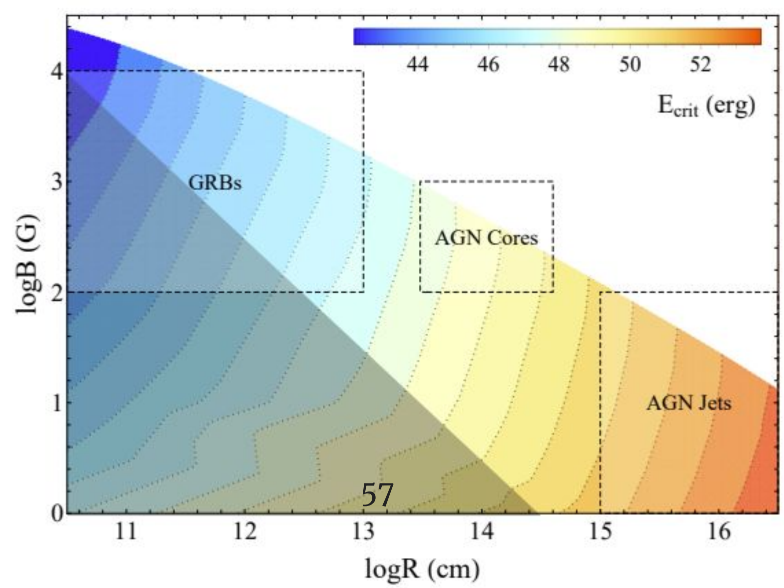
Topic No 3

Flaring Episodes & Hadronic Supercriticalities

Hadronic Supercriticalities: A nonlinear system

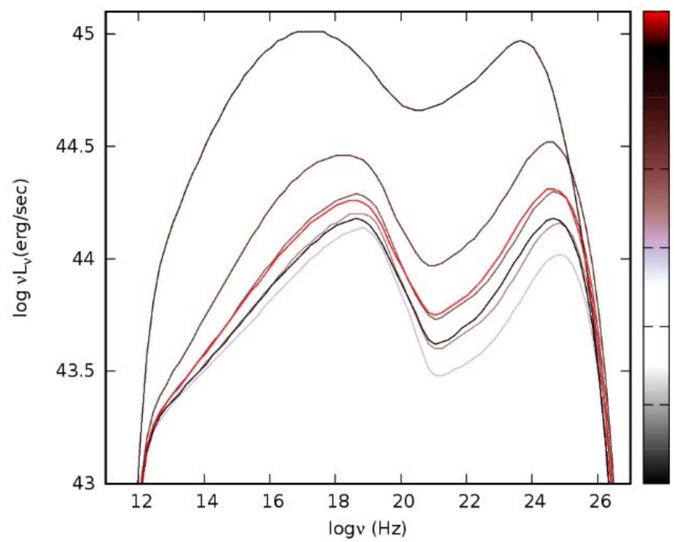


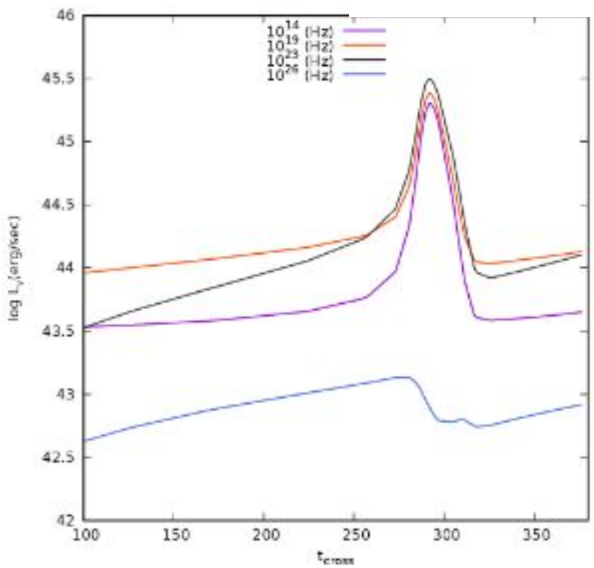


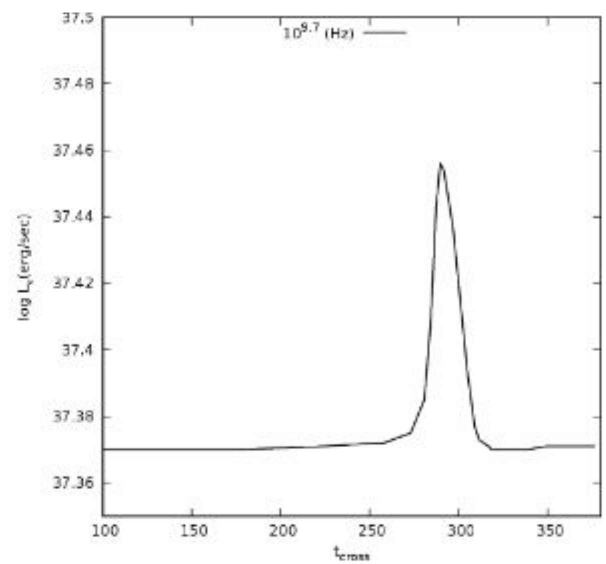


Mastichiadis, ..., SB et. al, 2020

Supercriticality and Blazars







Summary ☺

Take Home Messages

Topic No 1

- MHD Accretion Disk Winds are fundamental in reproducing the LAT Blazar phenomenology (Blazar Sequence) which appears to be a one parameter family.
- We obtain the theoretical Blazar Sequence by varying only one parameter, the mass accretion rate .
- The spread of the distribution depends on the other parameters.

Topic No 2

- Development of a new one-zone expanding radiation.
- The localization of radio emission depends on the properties of the jet.
- Production of a continuous jet by superposition of expanding blobs across the axis of the jet.

Topic No 3

- Prediction of zero or positive time lags, i.e., the γ-rays come first and the radio follow.
- Flares in radio and γ-rays with a wide range of time-lags may be produced my re-acceleration of electrons.
- Correlations between γ-rays and radio flares are studied.

Dziękuję