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Department of Physics
Section of Astrophysics, Astronomy & Mechanics

MHD Accretion Disk Winds and the Blazar Sequence

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Outline

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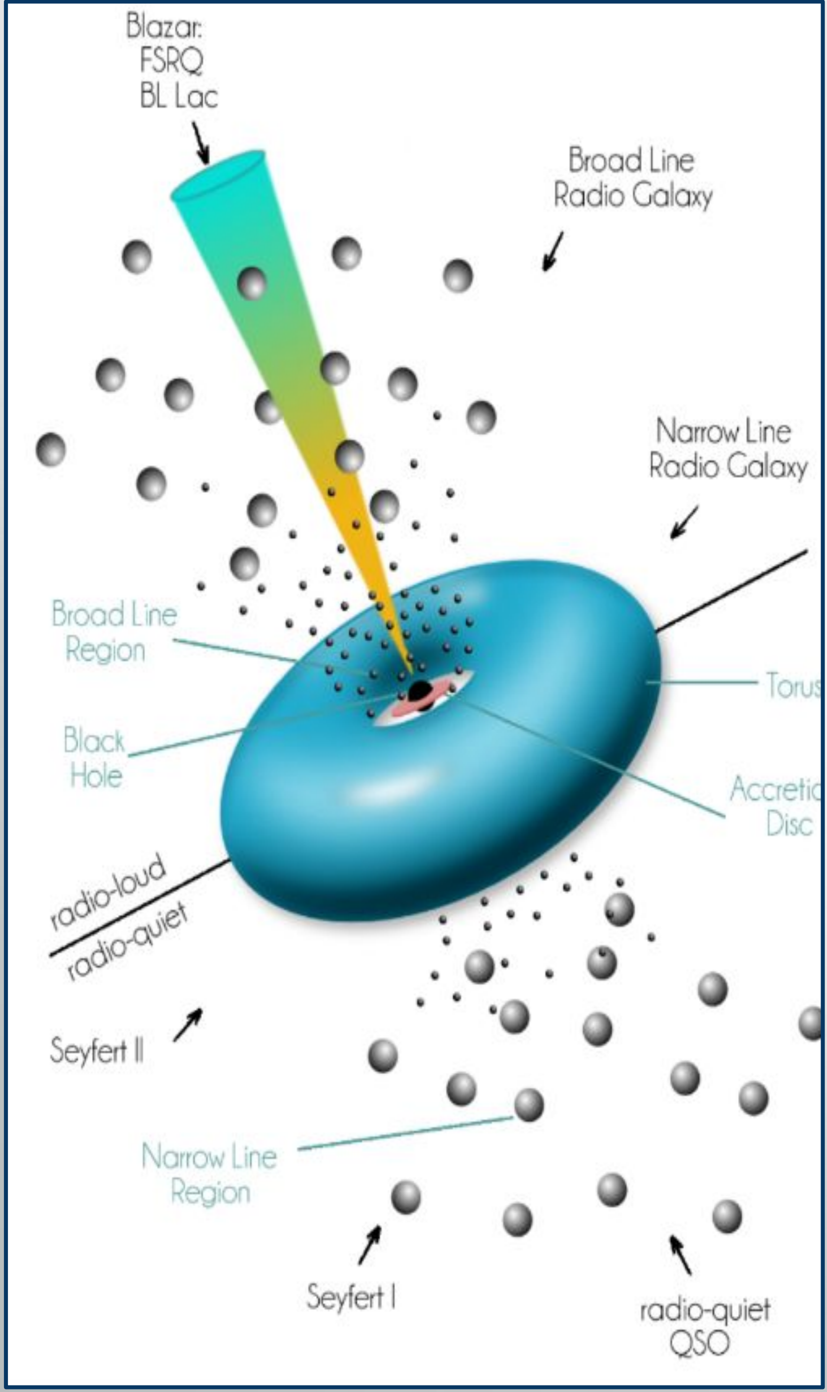
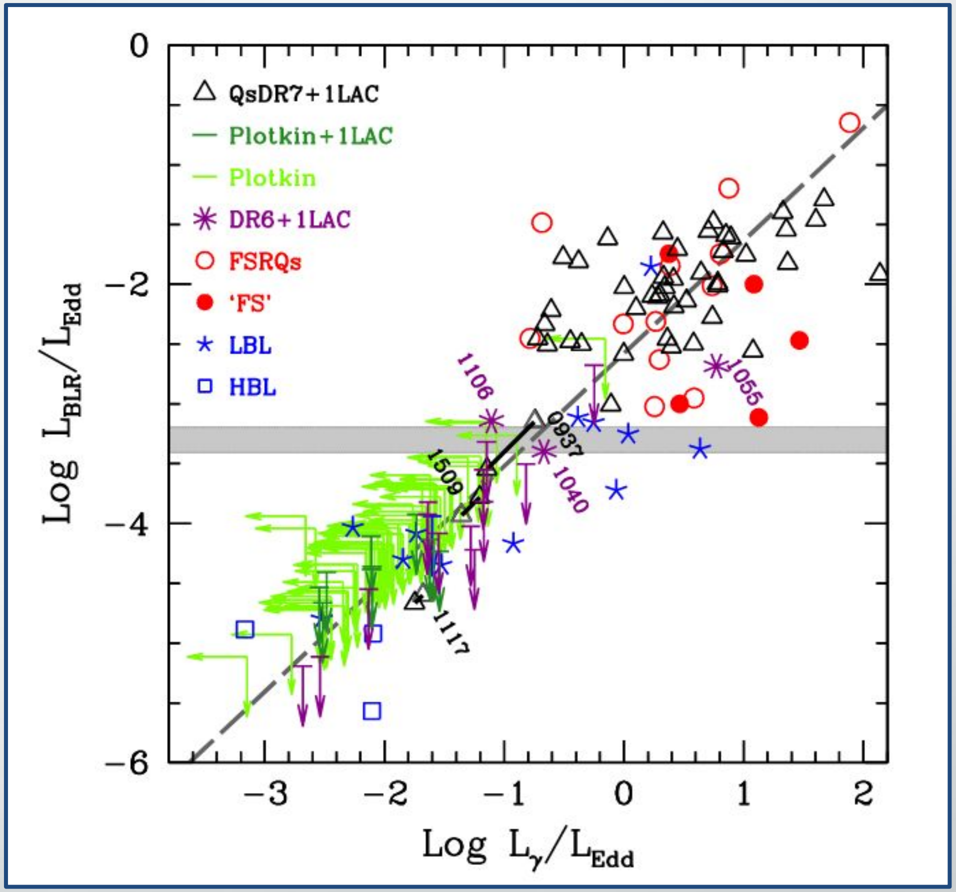
- Modelling the Non-Thermal Emission and External Photon Fields of Blazars
- MHD Accretion Disk Winds
- Blazar Sequence
- A Theoretical Model for the Blazar Sequence
- Results

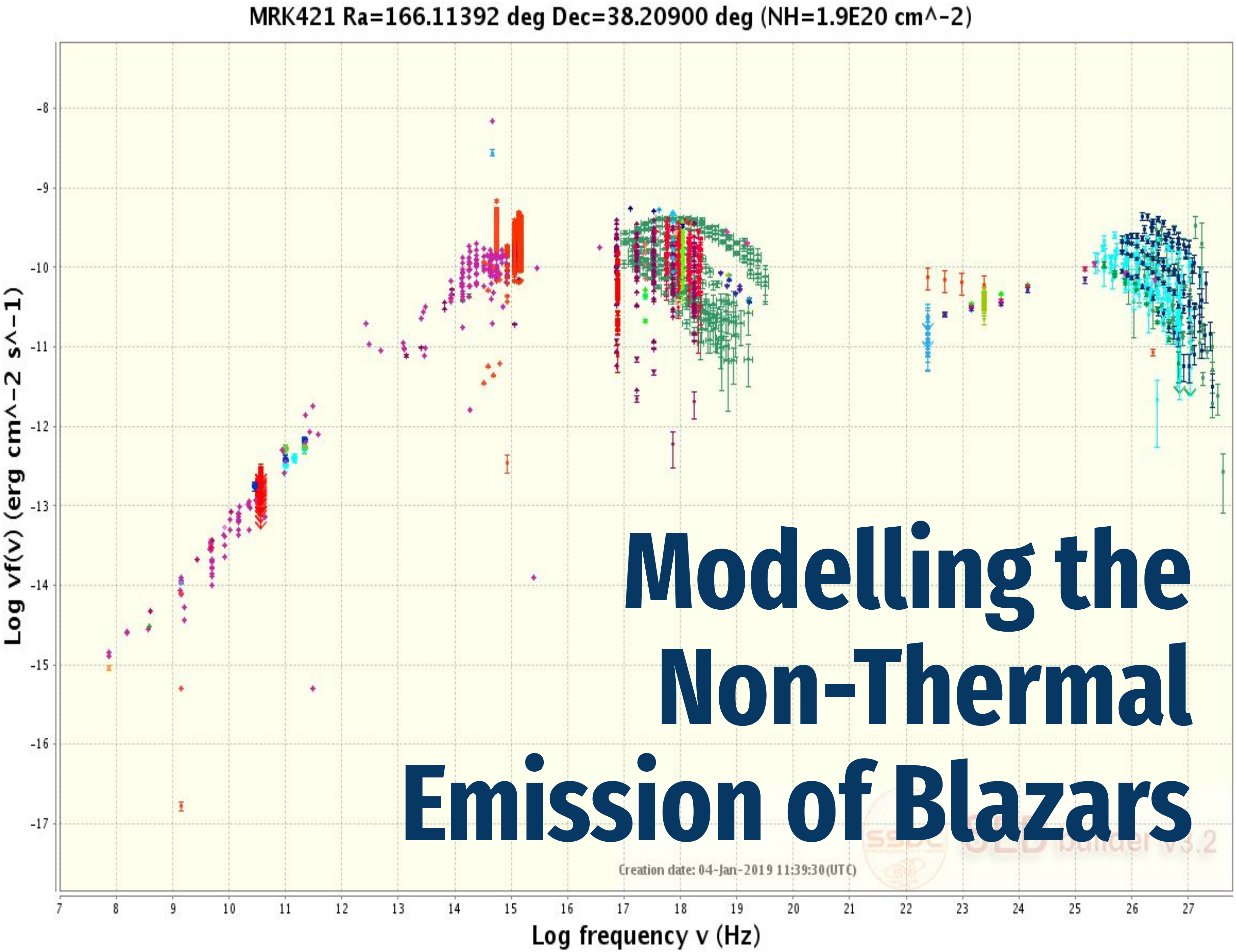




Sbarrato et al., 2012

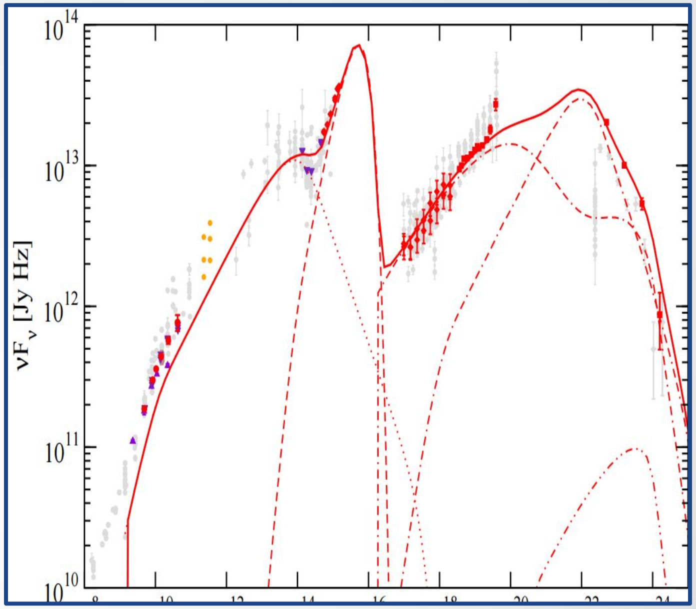
Credit: http://www.sternwarte.unierlangen.de/ krauss.

Modelling the Non-Thermal Emission of Blazars

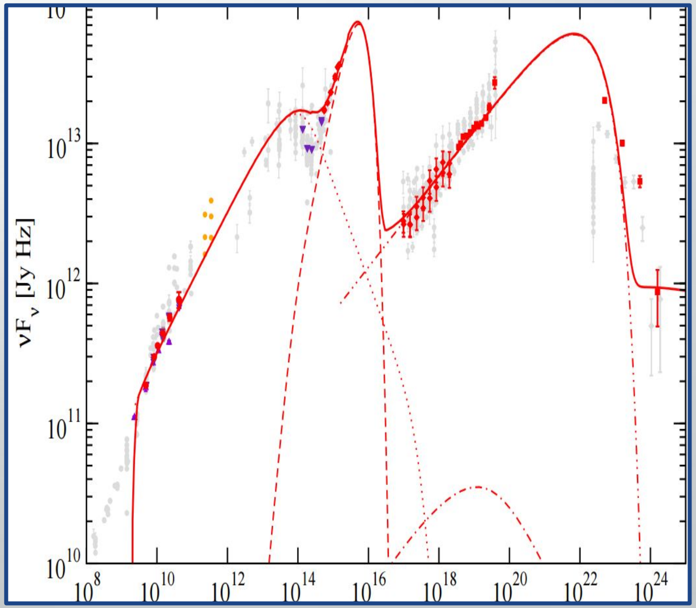


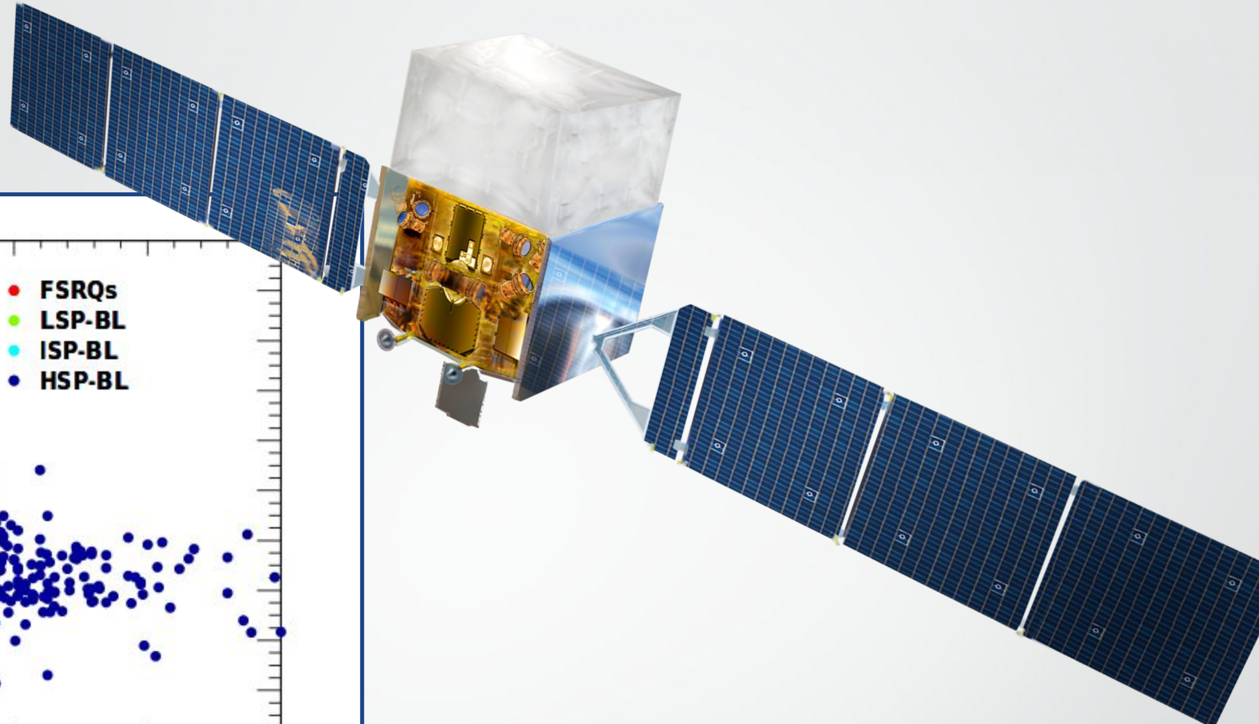
Leptonic (Mastichiadis and Kirk, 1997,Weidinger and Spanier, 2010, Kataoka et al., 2000, Krawczynski et al., 2002, Sikora et al., 2001, Bottcher and Chiang, 2002, Ghisellini and Tavecchio, 2009, Acciari and Aliu, 2009, ++)

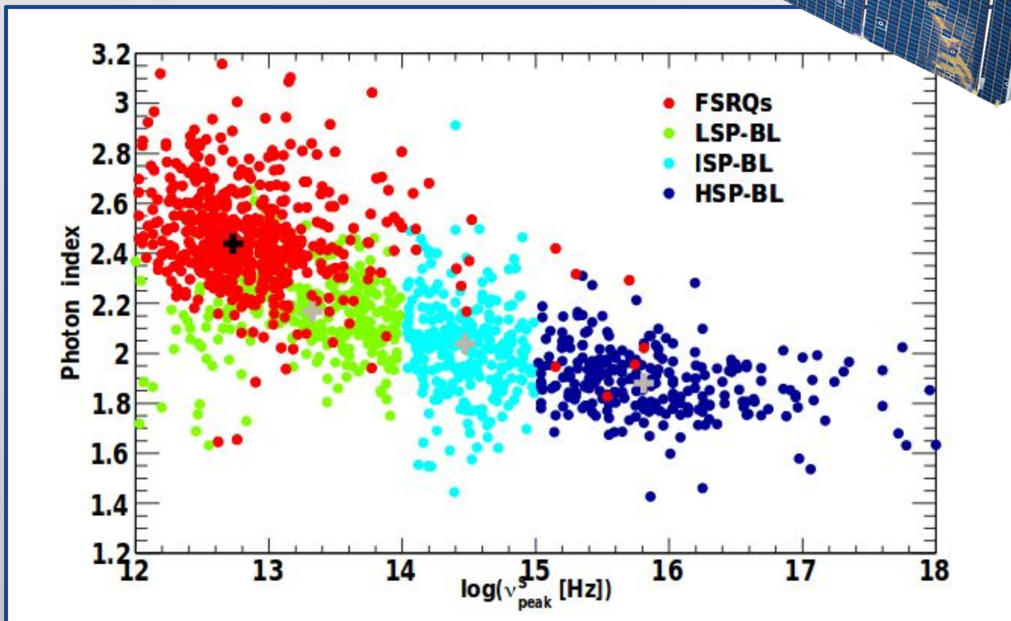
Hadronic (Mannheim and Biermann, 1992, Dimitrakoudis et al., 2014, Petropoulou et al., 2014, Padovani et al., 2015, Petropoulou et al., 2016, Zech et al., 2017, Padovani et al., 2018, Keivani et al., 2018 ++)

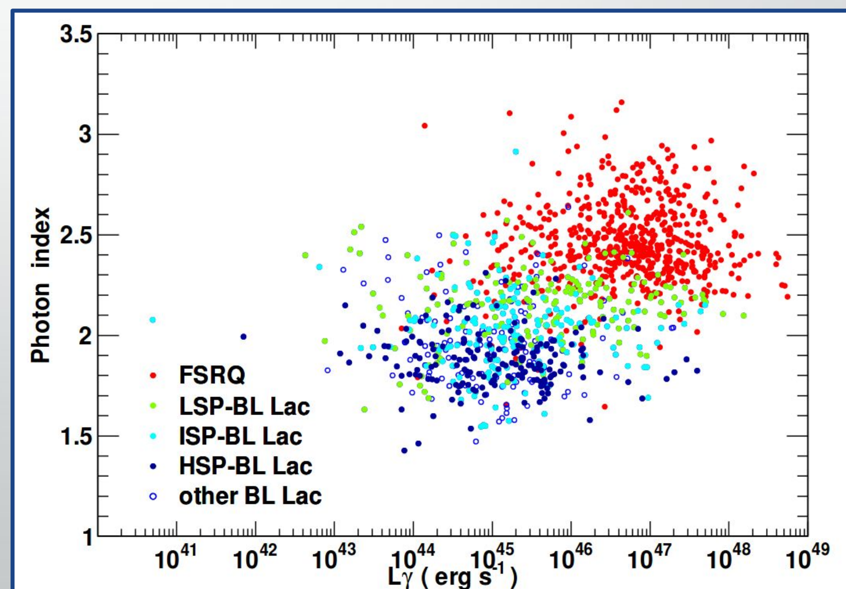


Bottcher et al, 2013



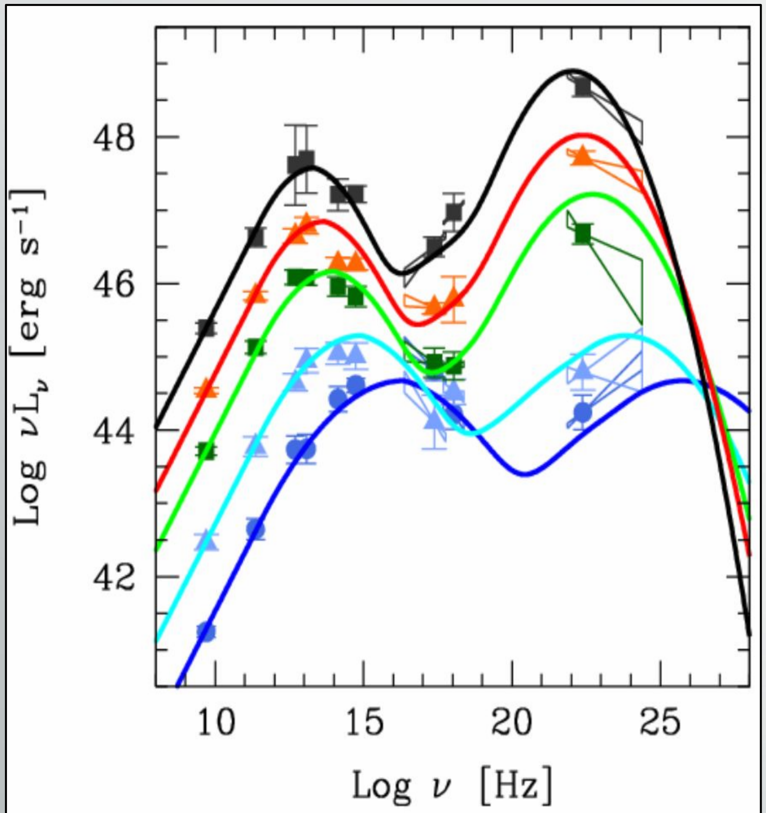



FSRQs
LSP-BL
ISP-BL
HSP-BL
Photon index
log(ν^{s}_{peak} [Hz])
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
12
13
14
15
16
17
18

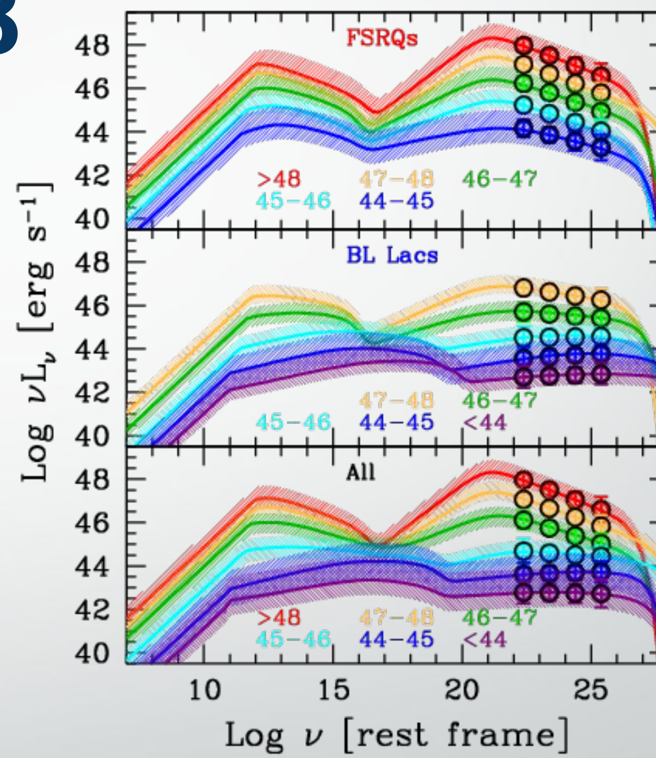

FSRQ
LSP-BL Lac
ISP-BL Lac
HSP-BL Lac
other BL Lac
Photon index
L_γ (erg s^{-1})
3.5
3
2.5
2
1.5
1
10^{41}
10^{42}
10^{43}
10^{44}
10^{45}
10^{46}
10^{47}
10^{48}
10^{49}

4th LAC, 2019

The Blazar Sequence circa 1998



Fossati et al, 1998



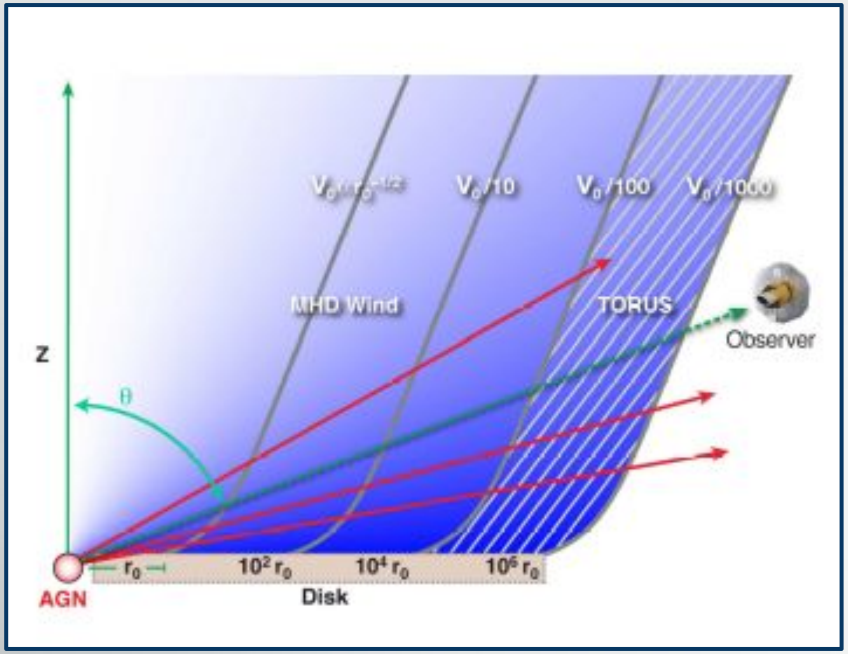
Ghisellini, 2017

(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)

Targets for ICS

- Accretion Disk Photons (Dermer et al., 1992, Dermer and Schlickeiser, 1993 ++)
- Broad Line Region Photons (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



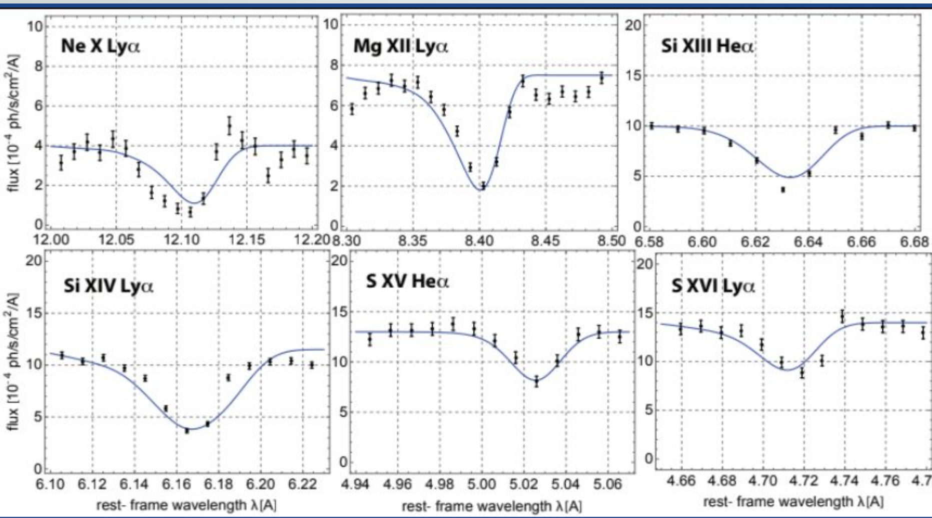
- Winds driven by an accretion disk threaded by a poloidal magnetic field.
- At latitudes above the Alfven point the field lines become toroidal and the flow is almost radially out.
- The magnetic field permeates the entire disk, out to ~10^6 R_s

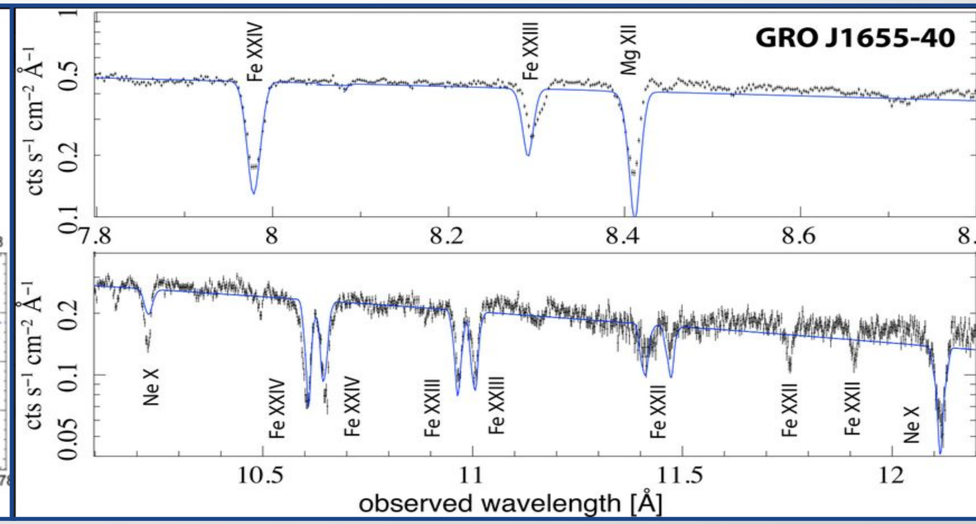
$$B(r,\theta) = x^{-(p+1)/2} B(\theta) B_0$$
$$V(r,\theta) = x^{-1/2} V(\theta) V_0$$
$$n(r,\theta) = x^{-p} n(\theta) B_0^2 V_0^{-2}$$

Contopoulos & Lovelace, 1994
Fukumura et al., 2010

Galactic and extragalactic applications of the wind

AGN





Fukumura et al., 2018,2019

Parameters of the Emission Model

- Magnetic Field Strength
- Injected electrons luminosity
- Electrons Distribution
- Energy Density of the External Photon Field

Related to the mass accretion rate

- Bulk Lorentz factor
- Doppler factor

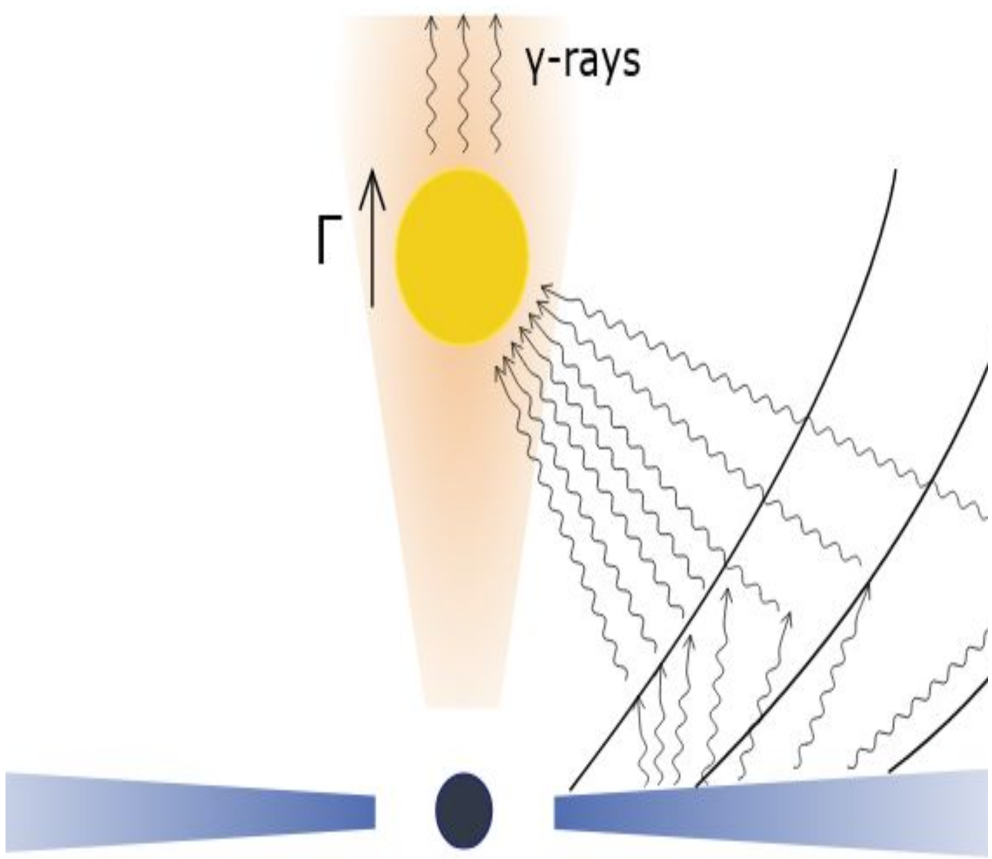


Image credit: S. Dimitrakoudis

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

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

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

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

External Photon Field :

Disk photons scattered on Wind

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

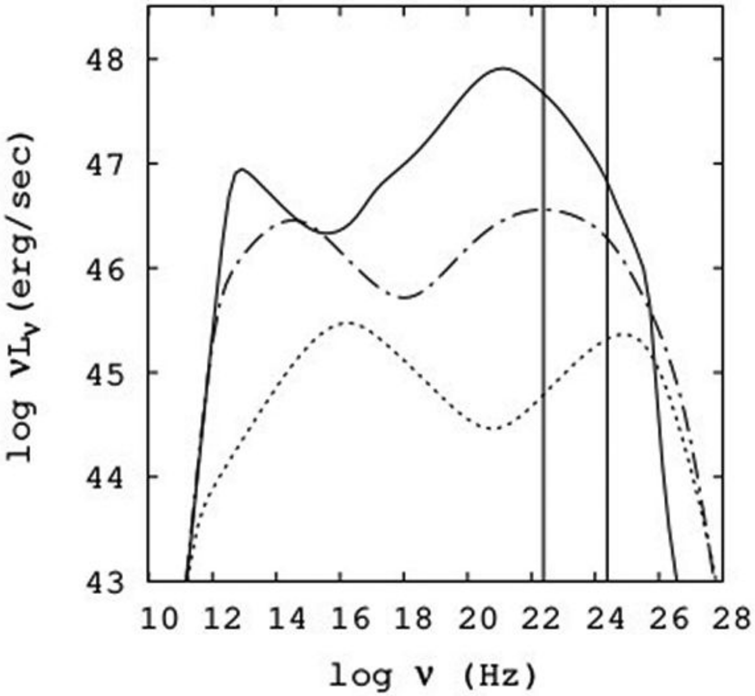
$$\tau_\tau(R_1, R_2) = \int_{R_1}^{R_2} n(r)\sigma_{\rm T}{\rm dr} = n_0\sigma_{\rm T} r_s \ln(R_2/R_1)$$

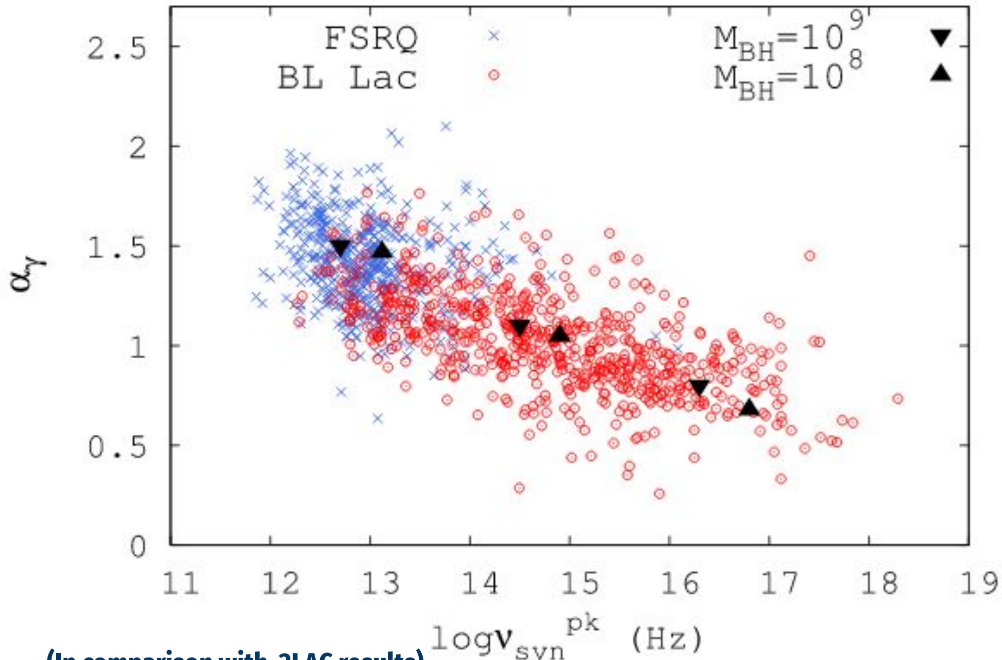
$$L_{\rm disc} = \begin{matrix} \epsilon\dot{m}\mathcal{M}L_{\rm Edd} & \text{for } \dot{m} \gtrsim 0.1 \\ \epsilon\dot{m}^2\mathcal{M}L_{\rm Edd} & \text{for } \dot{m} \lesssim 0.1 \end{matrix}$$

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

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

Results





(In comparison with 3LAC results)

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

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

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

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

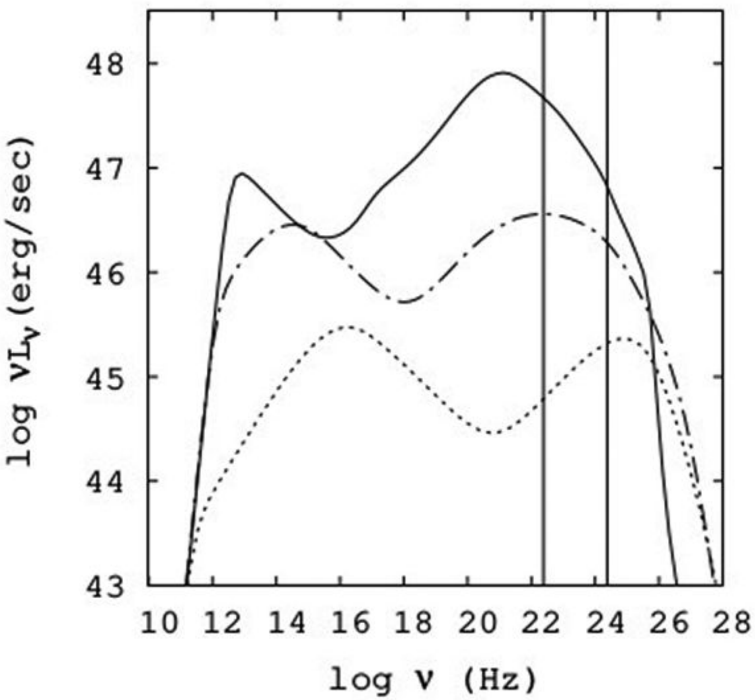
$$\nu_{\rm pk}^{\rm syn} \propto \mathcal{M}^{-1/2}\dot{m}^{-3/2}/(1+\dot{m}^{\alpha})^2$$

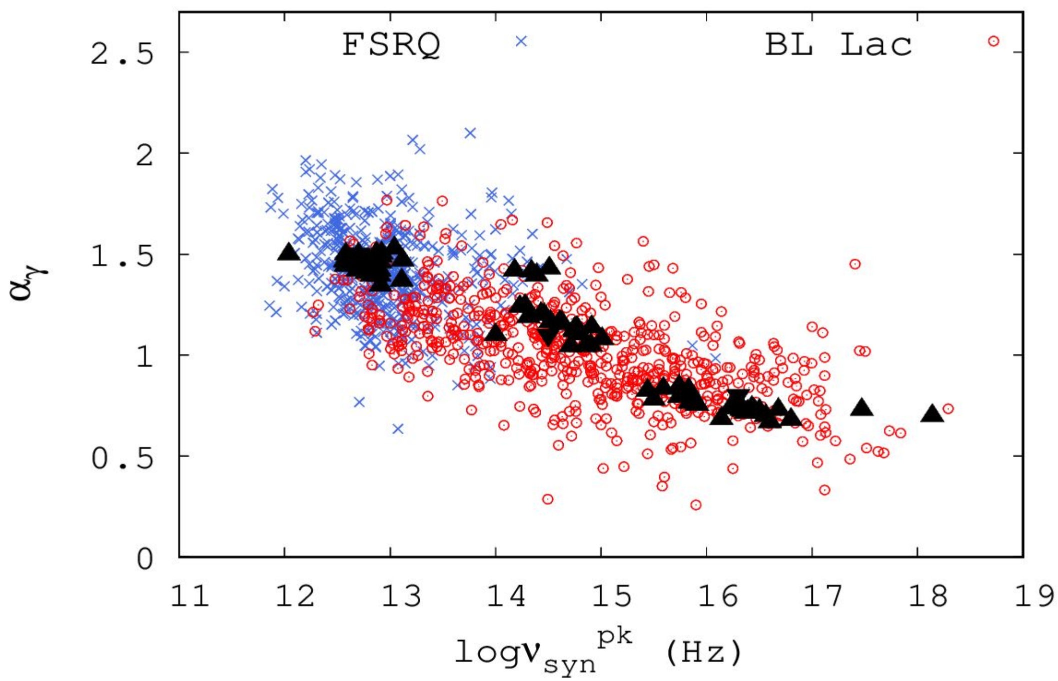
$\dot{m}$	B(G)	$U_{\rm ext}$ $\left(\frac{\rm erg}{\rm cm^3}\right)$	$L_{\rm e}^{\rm inj}$ $\left(\frac{\rm erg}{\rm sec}\right)$	$\gamma_{\rm br}$	Blazar class
−0.5	−0.3	−1.4	45.2	2.3	FSRQ
−1.5	−0.8	−4.6	44.2	3.3	LBL
−2.5	−1.3	−7.6	43.2	6.5	HBL

(logarithmic values)

Boula, Kazanas, Mastichiadis, 2019

Results





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

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

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

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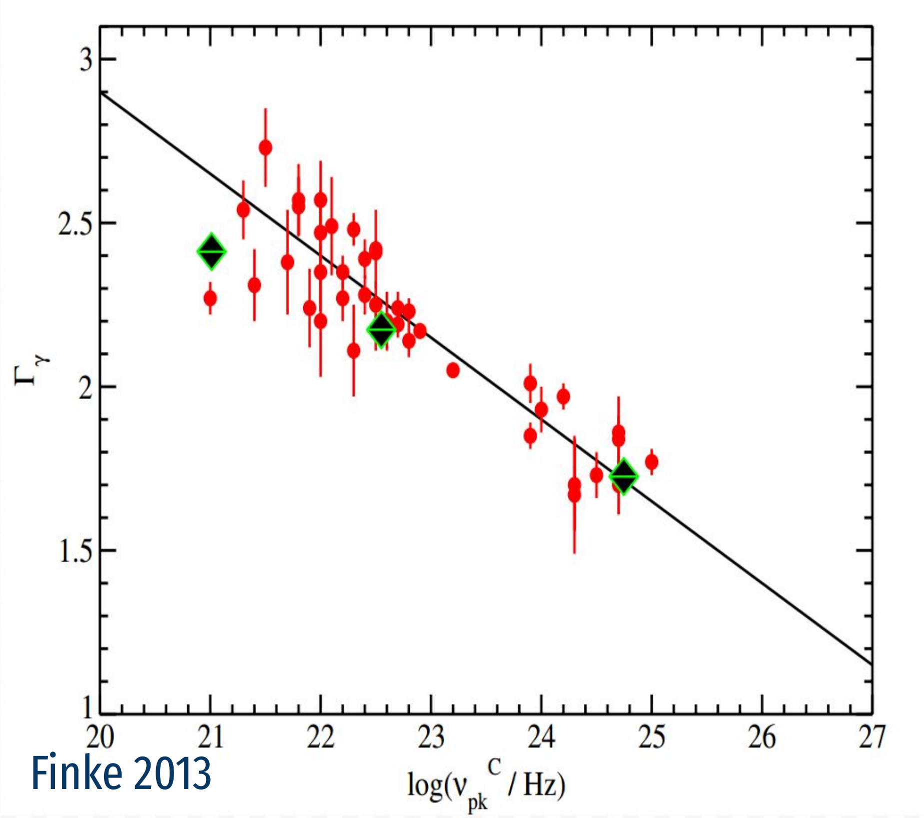
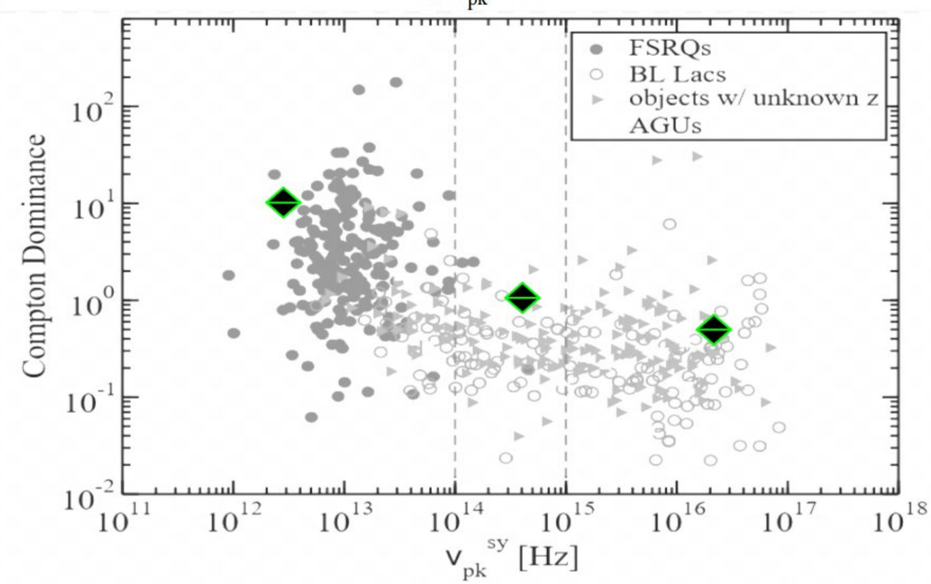
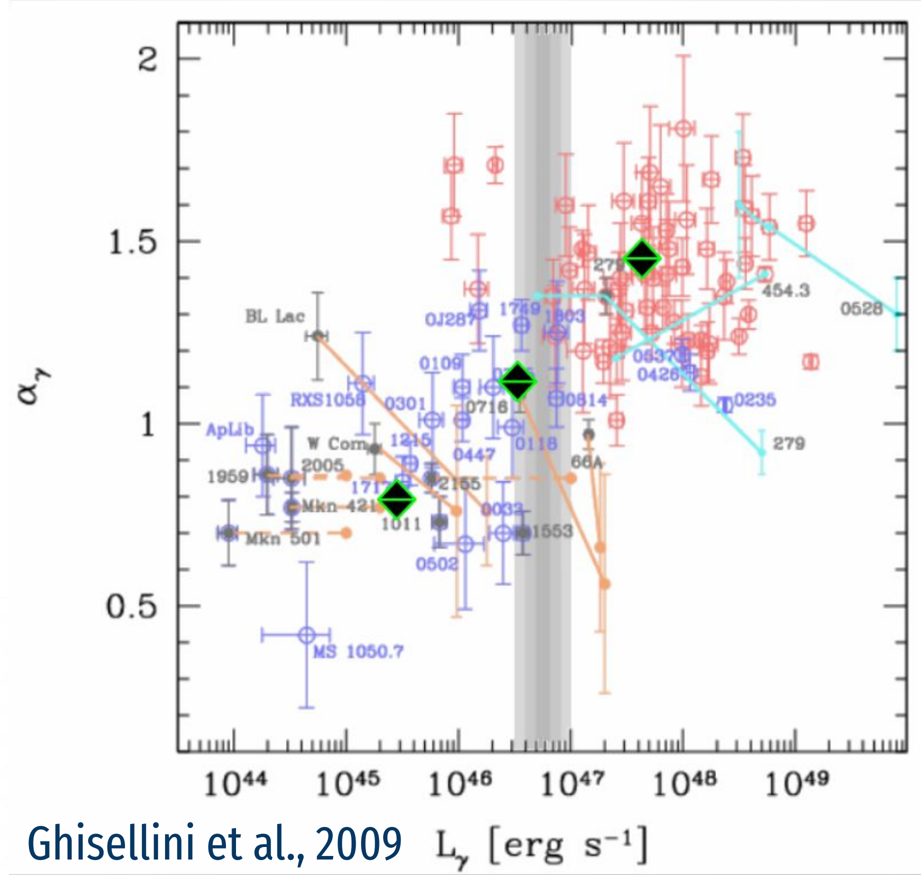
Boula, Kazanas, Mastichiadis, 2019



Finke 2013





Ghisellini et al., 2009

Take home messages

- 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.

Thank you!

stboula@phys.uoa.gr

Accretion Disk MHD Winds and Blazar Classification, Boula S., Kazanas D. and Mastichiadis A., Monthly Notices of the Royal Astronomical Society: Letters, Volume 482, Issue 1, 1 January 2019, Pages L80-L84

Back up Slide - Emission Lines

$Density$

$$n(x) = n_0 x^{-1},\ n_o \sigma_\tau R_S = \dot{m}_0$$

$$\dot{m}(x) = \dot{m}_0 x^{1/2},$$

$$n(x) = \frac{\dot{m}_0}{\sigma_\tau R_s} x^{-1}$$

$Total\ number\ of\ recombinations$

$$N = n^2(x) V \alpha(T),\ \alpha(T) \simeq 4 \cdot 10^{-13}\ cm^3/sec$$

$$N = \frac{\dot{m_0}^2}{\sigma_\tau^2 R_S^2} 4\pi x^{-2} R_S^3 x^3 \alpha(T) = \frac{\dot{m_0}^2}{\sigma_\tau^2} R_S 4\pi x_M \alpha(T)$$

$$N = 4 \cdot 10^{50} \dot{m_0}^2 M_8 x_M\ recombinations/sec$$