Amal Abdulrahman [1]

Guide: Prof. P. A Subha [1]

Collaborator: Dr. Sunder Sahayanathan [2]

[1] Farook College (Autonomous), Calicut, Kerala, India.
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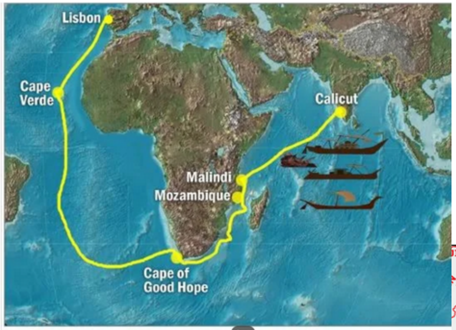
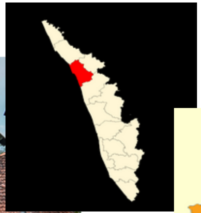
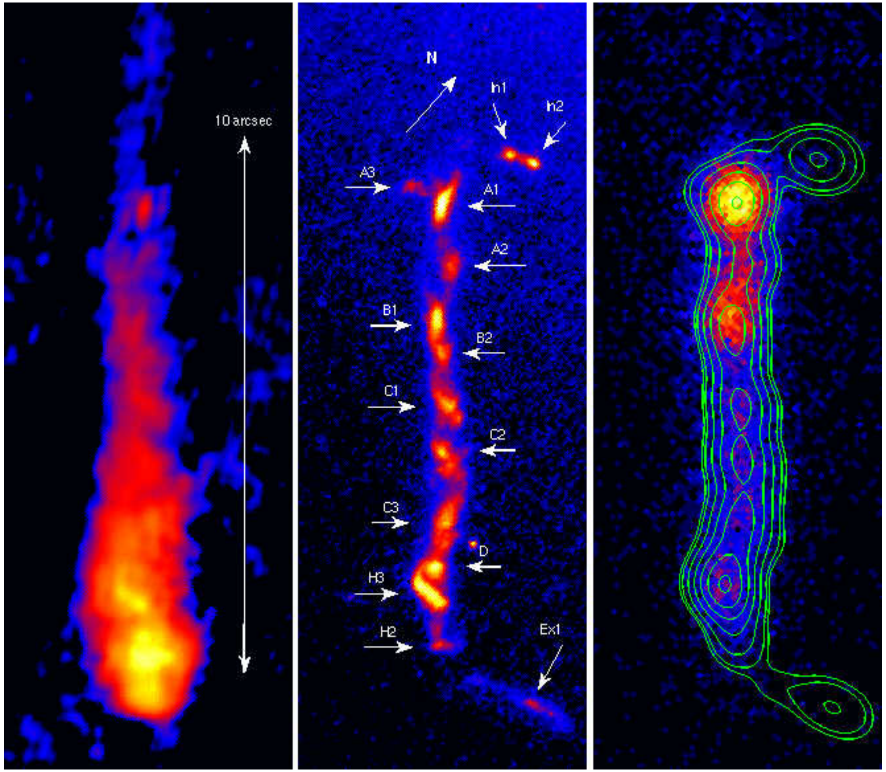


Route taken by Vasco da Gama to reach India from Portugal



Understanding the high energy emission and multi-wavelength morphology of the knots in kilo-parsec scale jets of Active Galactic Nuclei

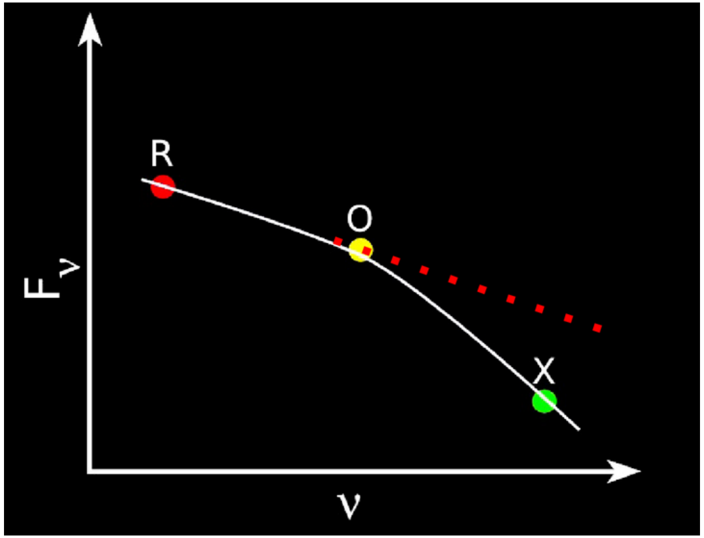
- **The large scale AGN jets (kpc/Mpc)**
- **X-ray emissions from jets/knots**
- **Their multiwavelength emission & morphology**

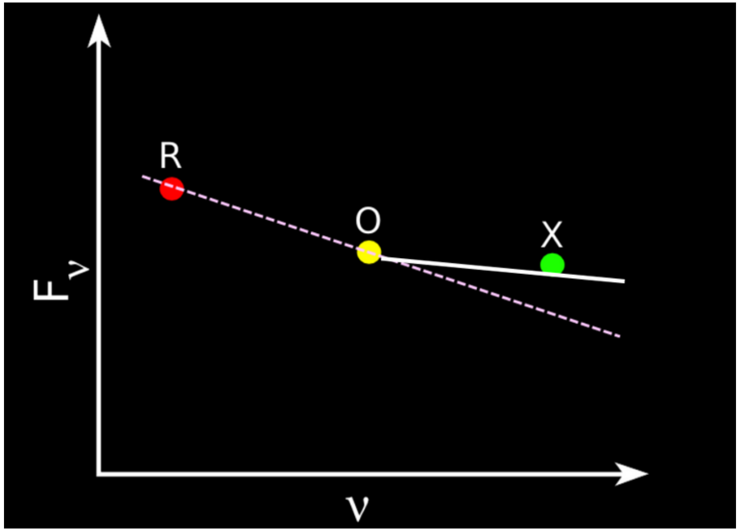


3C 273 , Marshall et. al 2001

High energy emissions from kpc knots/jets?

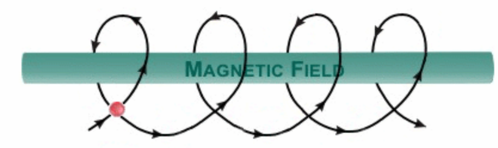
Two scenarios

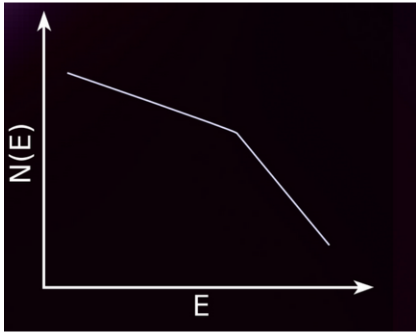


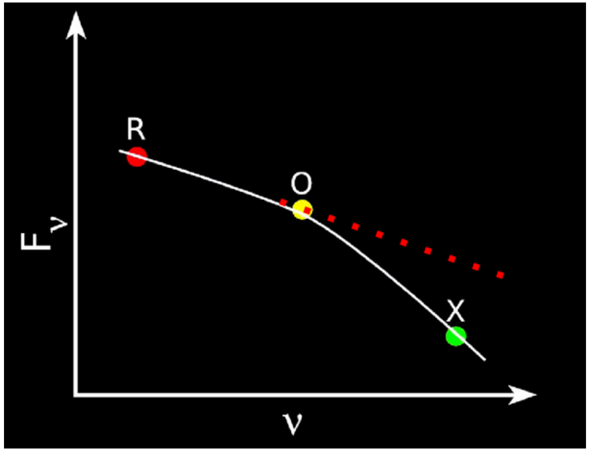


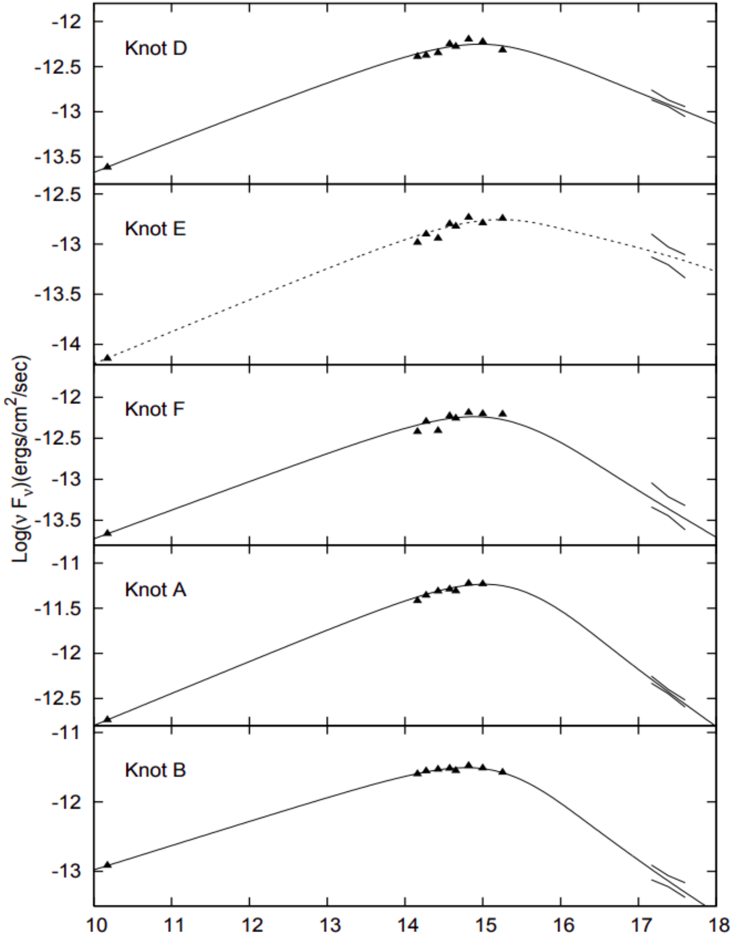
High energy emissions from k-pc knots/jets?

Synchrotron emission from a broken power-law distribution particles



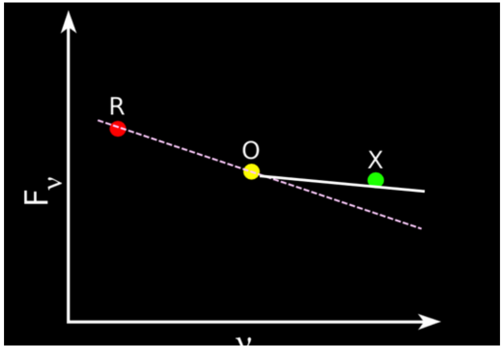




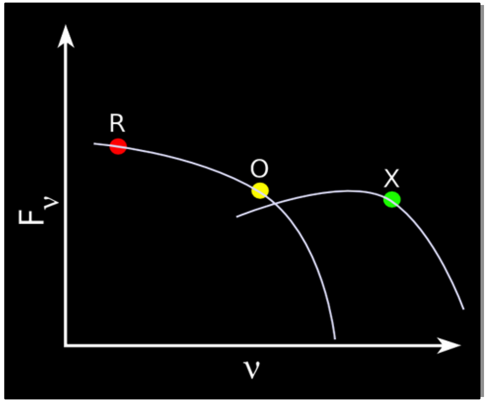


M 87, S. Sahayanathan 2008

High energy emissions from kpc knots/jets?



Suggest two emission mechanisms



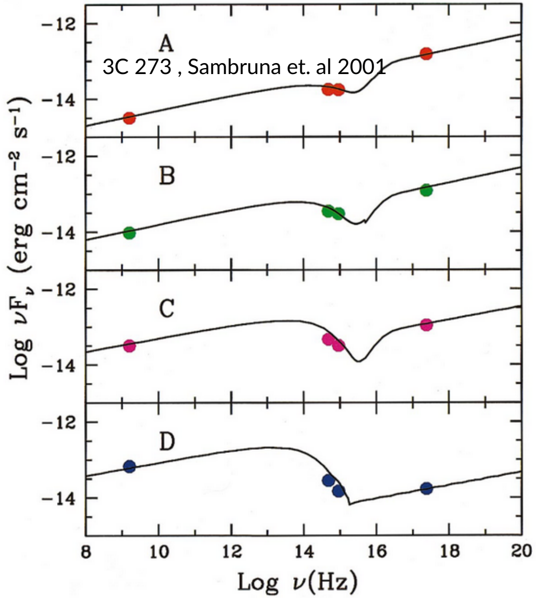
Possible mechanisms

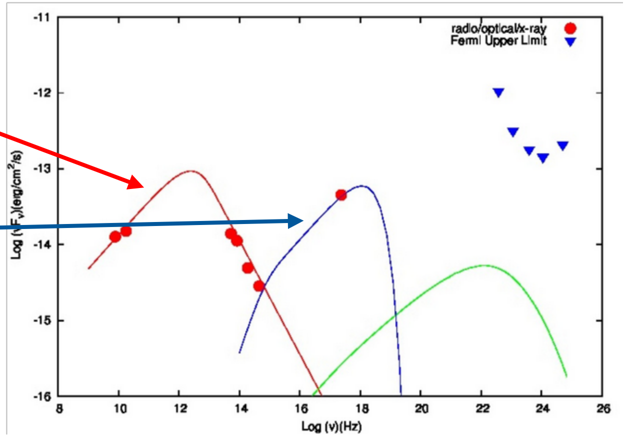
Synchrotron + IC/CMBR

eg:Tavecchio et al. 2000;
Celotti et al. 2001

Synchrotron(low energy electron distribution)
+
Synchrotron(high energy electron distribution)

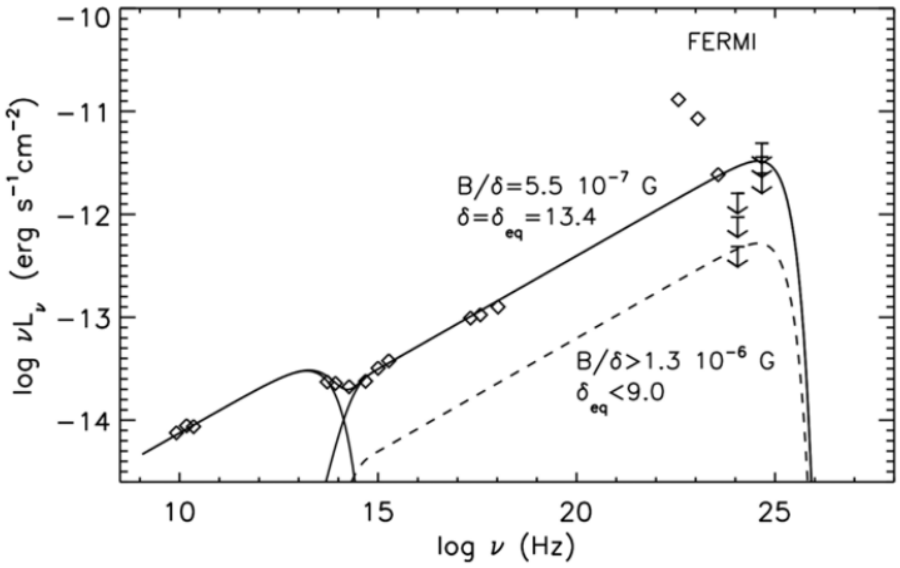
eg: Harris & Krawczynski 2002; Jester et al. 2002; Georganopoulos et al. 2006





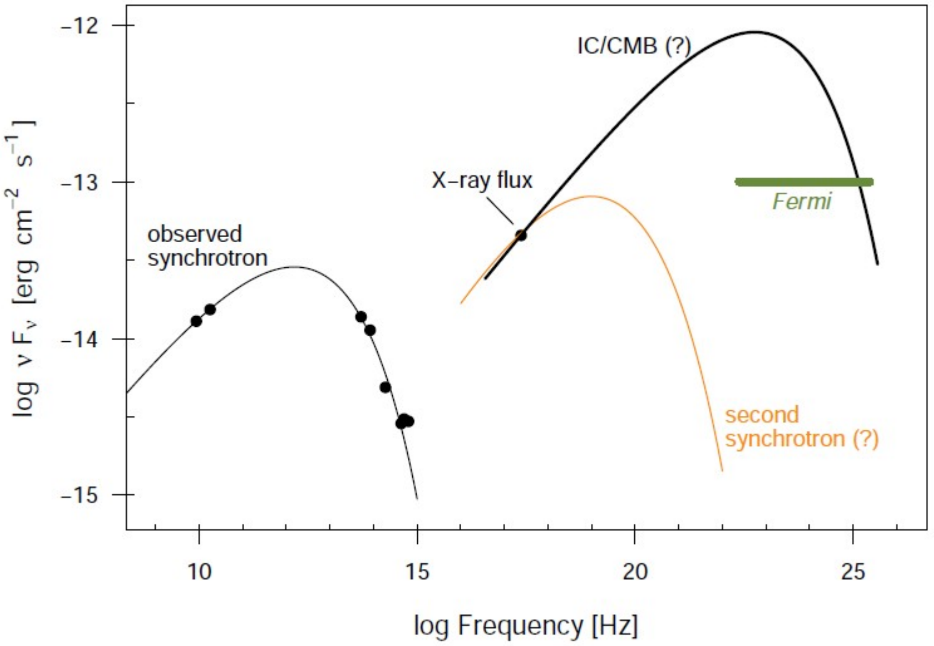
Case 1 : Synchrotron + IC/CMBR

X-ray Knots : IC/CMBR Failure!!!



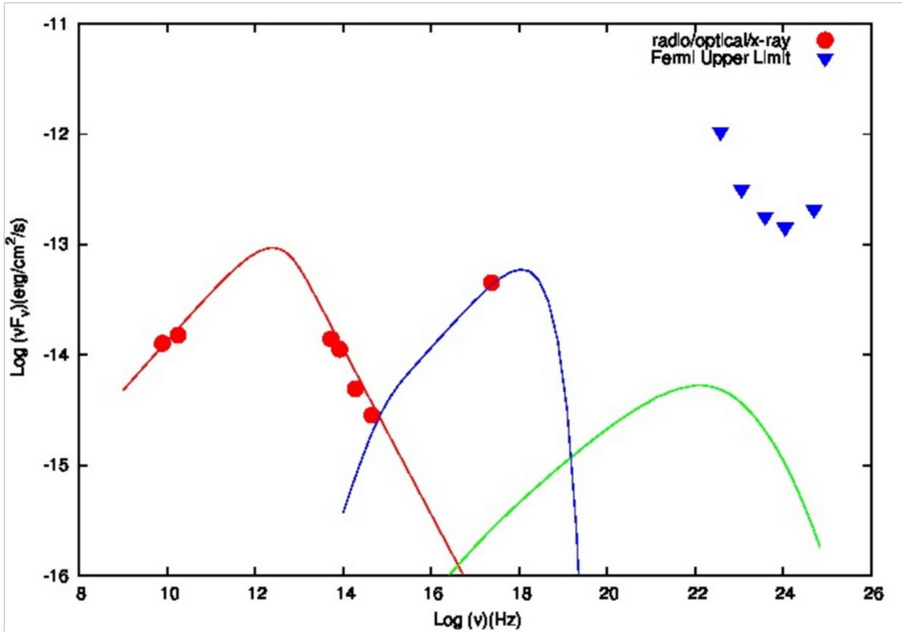
3C 273, Meyer & Georganopoulos 2014

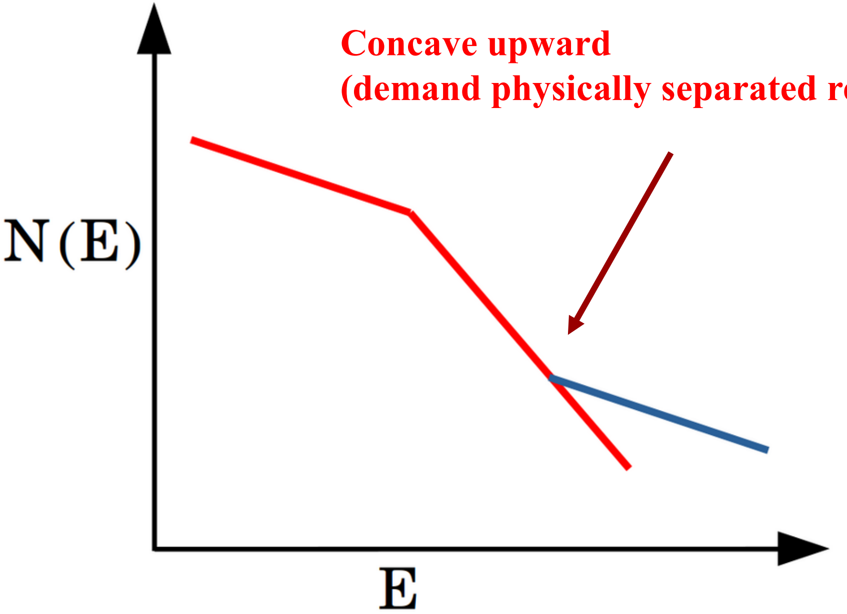
PKS 0637-752, Meyer et. al 2015



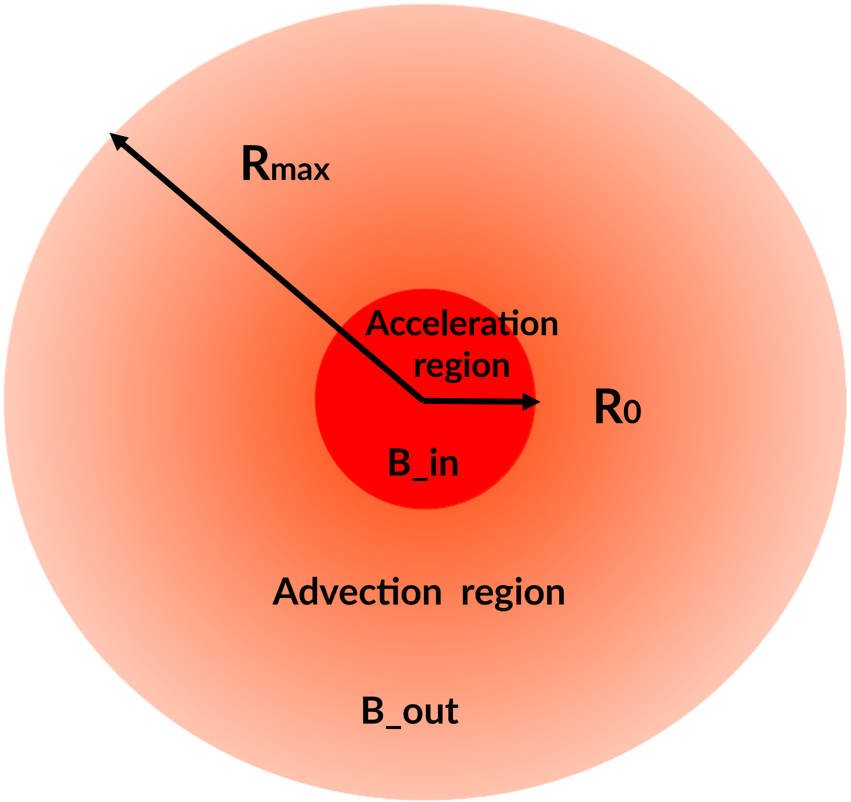
3C 273, PKS 0637-752, PKS 1136-135, PKS 1229-021, PKS 1354+195 and PKS 2209+080 and many more.. (Meyer et. al 2015, Meyer & Georganopoulos 2014, Breiding, Peter et. al 2023 etc..)

Case 2 : Synchrotron (low energy particle distribution) + Synchrotron(high energy particle distribution)

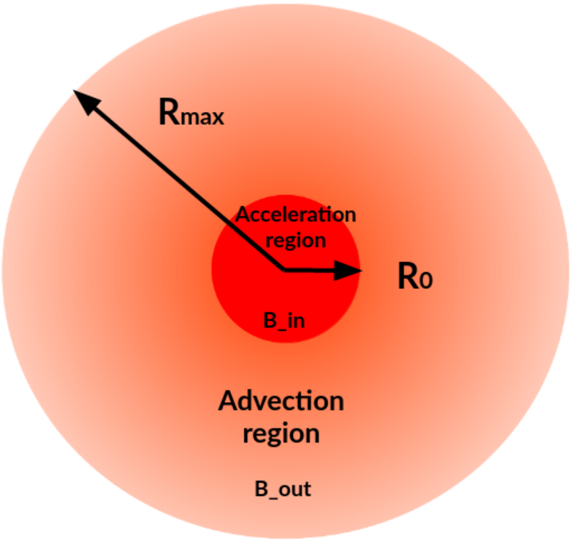




Physically separated two population model



The two population model



- **Acceleration region**: bpl particle distribution (multiple acceleration processes ; Sahayanathan 2008)

- **Advection region**: (Ginzburg & Sirovatskii 1964)

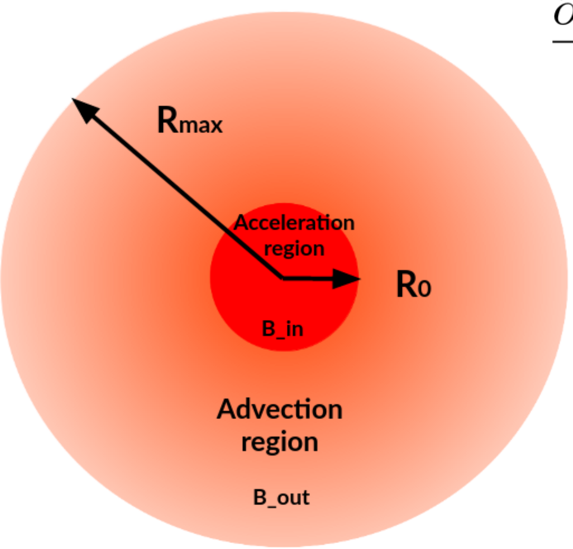
$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial \gamma}(PN) - \frac{N}{\tau} + Q$$

- Delta function injection of particles at R0 - green's function method (Kardashev 1962; Atoyan & Aharonian 1997)

$$\frac{\partial \bar{n}(\gamma, R, R_0)}{\partial R} = \frac{\partial}{\partial \gamma}\left[\bar{P}(\gamma, R)\, \bar{n}(\gamma, R, R_0)\right] - \frac{\bar{n}(\gamma, R, R_0)}{R_*(R)} + n_0(\gamma)\, \delta(R - R_0)$$

$$\bar{P}(\gamma, R) = \frac{d\gamma}{dR} = \xi\gamma^2 + \frac{\gamma}{R}$$

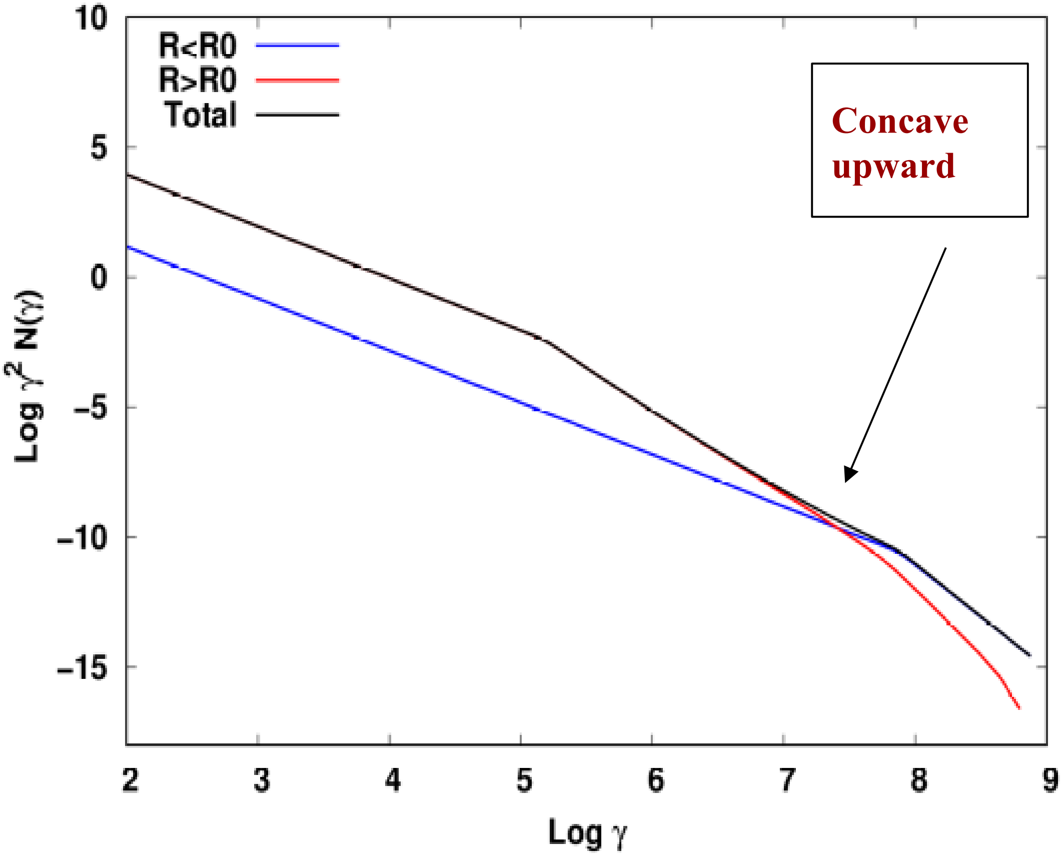
The two population model

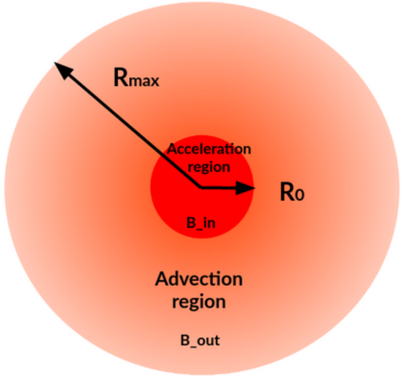


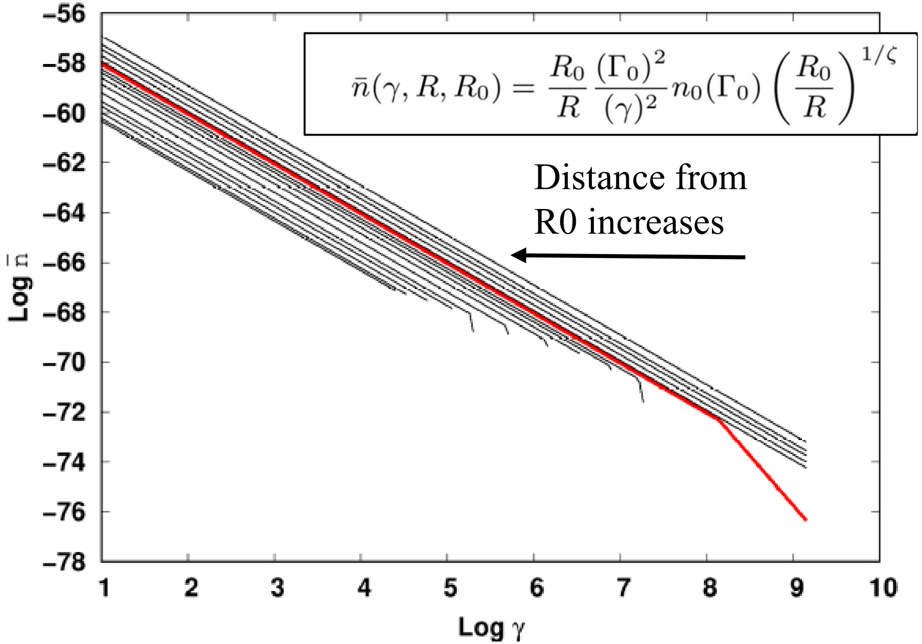
$$\frac{\partial \bar{n}(\gamma, R, R_0)}{\partial R} = \frac{\partial}{\partial \gamma}\left[\bar{P}(\gamma, R)\,\bar{n}(\gamma, R, R_0)\right] - \frac{\bar{n}(\gamma, R, R_0)}{R_*(R)} + n_0(\gamma)\,\delta(R - R_0)$$

$$\bar{n}(\gamma, R, R_0) = \frac{R_0}{R}\frac{(\Gamma_0)^2}{(\gamma)^2} n_0(\Gamma_0)\left(\frac{R_0}{R}\right)^{1/\zeta}$$

$$n_0(\gamma)\,\mathrm{d}\gamma = \begin{cases} K\gamma^{-p}\,\mathrm{d}\gamma & \gamma_{\min} < \gamma < \gamma_{\mathrm{b}}, \\ K\gamma_{\mathrm{b}}^{q-p}\gamma^{-q}\,\mathrm{d}\gamma & \gamma_{\mathrm{b}} < \gamma < \gamma_{\max}. \end{cases}$$

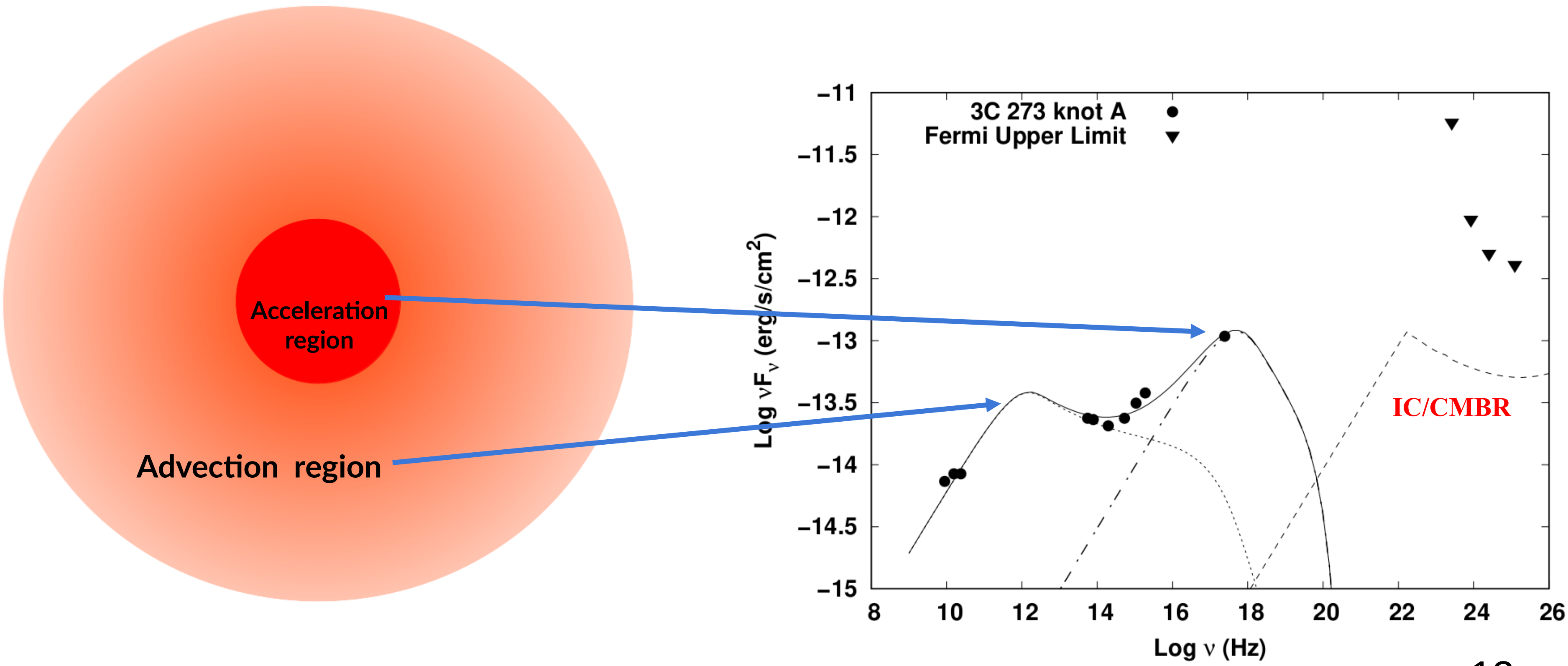


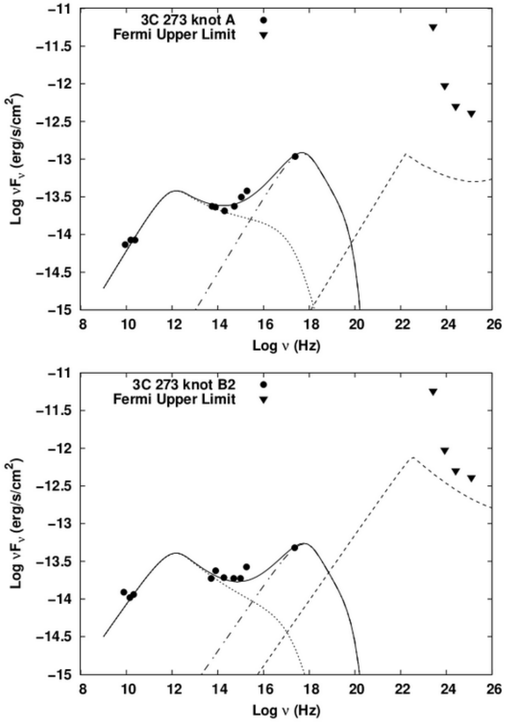




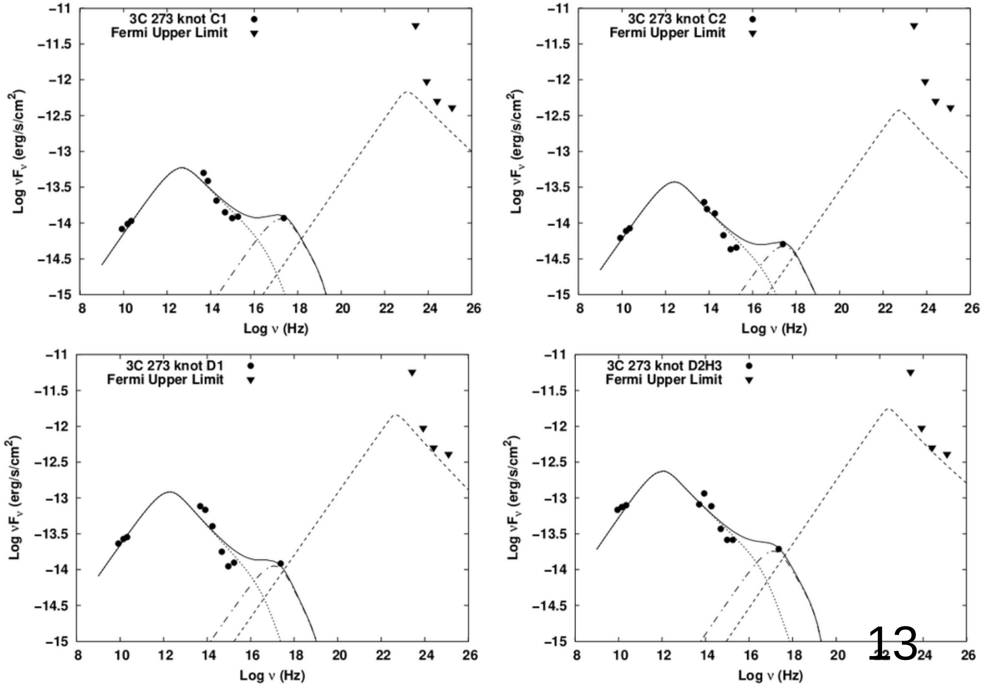
$$\bar{n}(\gamma, R, R_0) = \frac{R_0}{R}\frac{(\Gamma_0)^2}{(\gamma)^2} n_0(\Gamma_0)\left(\frac{R_0}{R}\right)^{1/\zeta}$$

The two population model:





Knot	R_0 (kpc)	R_{size} (kpc)	B_{in} (10^{-5} G)	$\omega = \frac{B_{in}}{B_{out}}$	γ_b (10^7)	v_{ad} ($10^{-2}c$)	p	q	Γ	ζ
A	0.12	2.9	1.5	2.08	7.5	2.0	2.0	4.0	1.3	7.0
B1	0.10	5.5	1.8	3.3	6.5	1.6	2.13	4.0	2.0	7.0
B2	0.10	5.50	2.0	3.6	6.18	1.6	2.13	4.0	2.0	7.0
B3	0.09	5.5	1.3	2.4	4.85	1.6	2.13	4.0	2.0	7.0
C1	0.08	8.0	1.9	3.45	3.64	9.0	2.12	4.0	1.7	5.5
C2	0.05	6.0	1.9	3.17	4.70	5.0	2.13	4.2	1.7	9.5
D1	0.05	6.0	1.5	3.0	3.58	4.0	2.13	4.2	1.6	9.5
D2H3	0.05	6.5	1.1	2.4	4.62	2.5	2.11	4.0	1.3	9.5

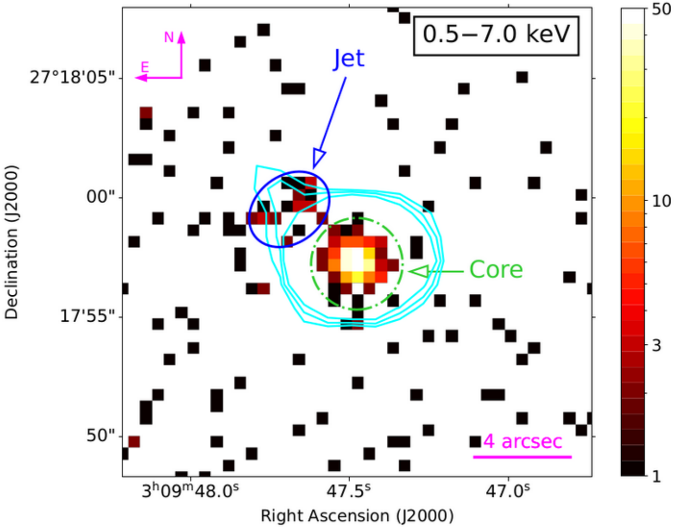


Rahman et al, 2022, MNRAS

X-ray emissions from large scale jets of AGN at high redshifts

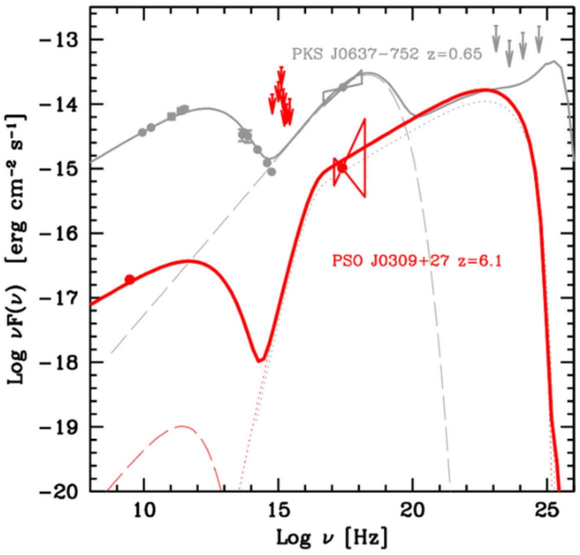
$$U_{CMB} \propto (1+z)^4$$

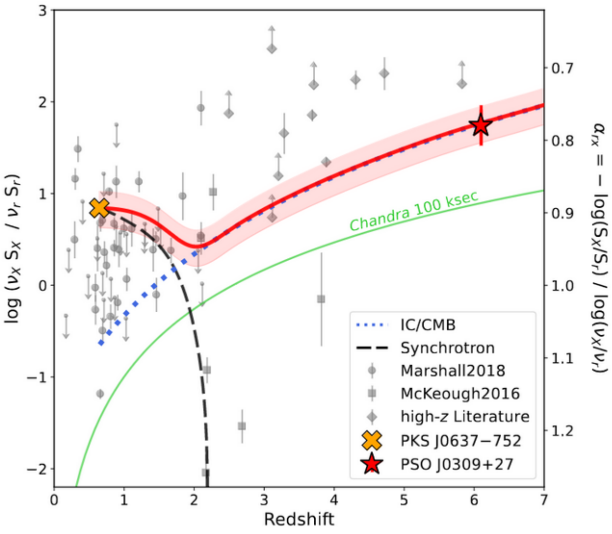
PSO J0309+27



Direct observation of an extended X-ray jet at z=6.1

L. Ighina[1,2], A. Moretti[1], F. Tavecchio[3], A. Caccianiga[1], S. Belladitta[1,2], D. Dallacasa[4,5], R. Della Ceca[1], T. Sbarrato[3], and C. Spingola[5]





At high redshift, IC/CMB cooling time < shear acceleration timescale

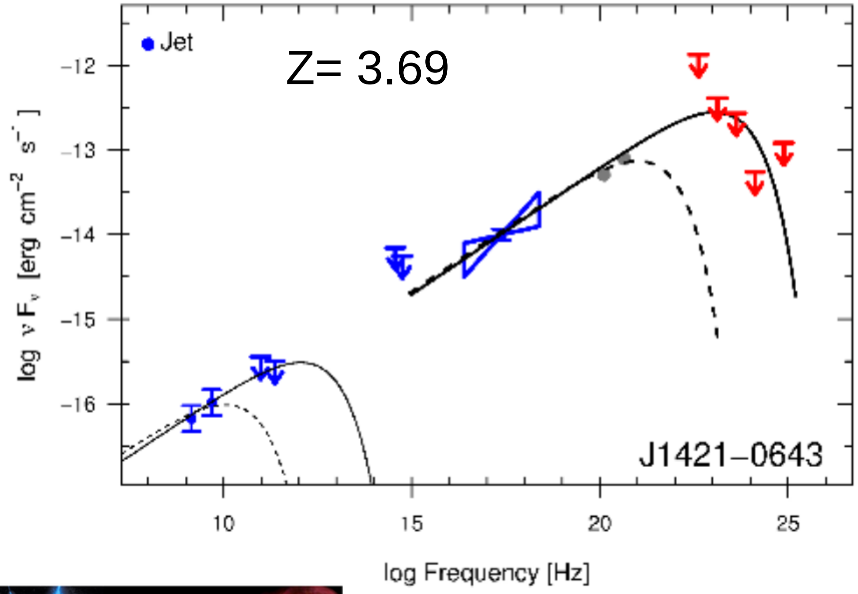
X-ray emissions from large scale jets of AGN at high redshifts

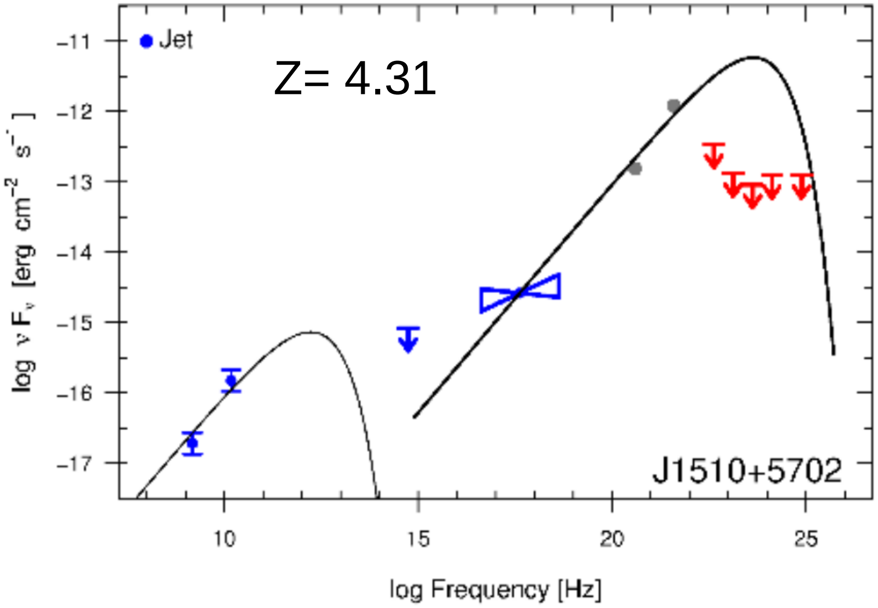
A Multi-Wavelength Study of Multiple Spectral Component Jets in AGN: Testing the IC/CMB Model for the Large-Scale-Jet X-ray Emission

Peter Breiding,[1★] Eileen T. Meyer,[2] Markos Georganopoulos,[2,3] Karthik Reddy,[2] Kassidy E. Kollmann,[2,4] and Agniva Roychowdhury[2]

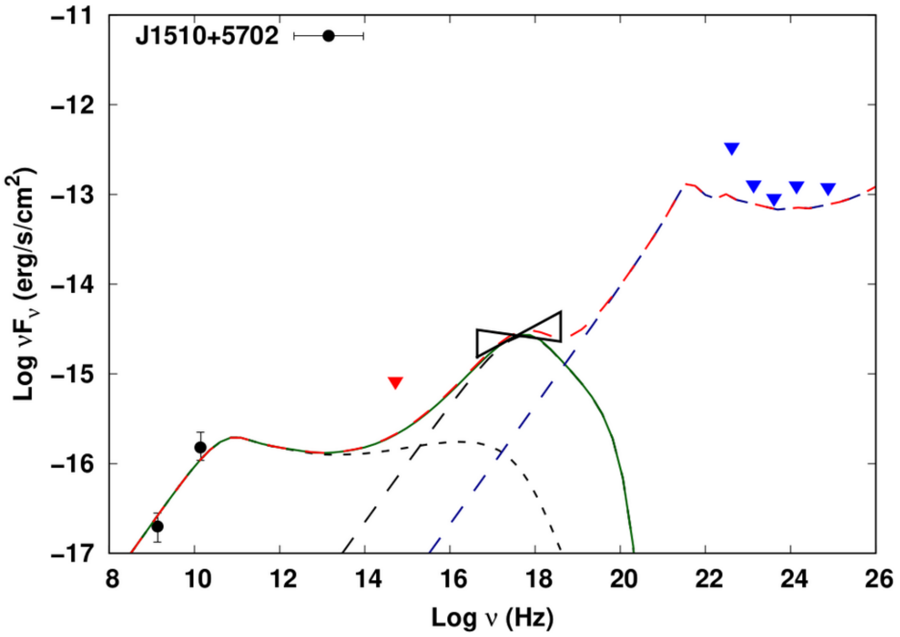
Test the IC/CMB model in 45 extragalactic X-ray jets

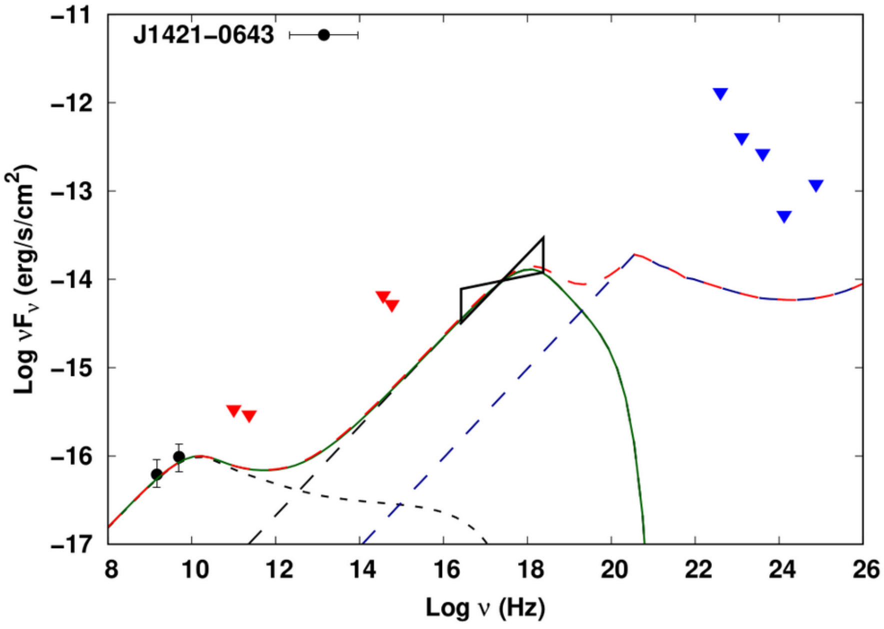
Two sources at z > 3.5





X-ray emissions from large scale jets of AGN at high redshifts

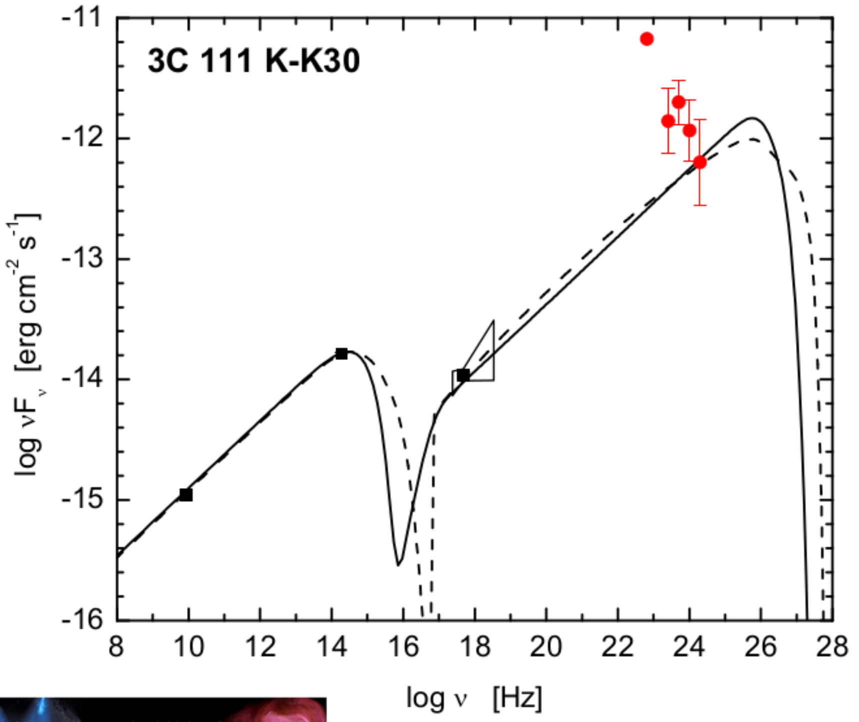




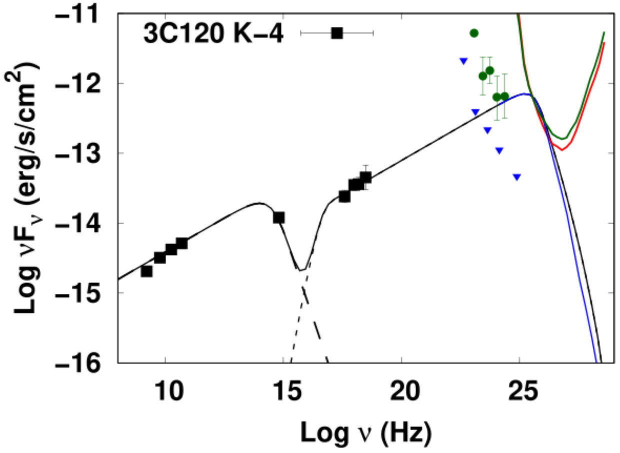
Under preparation...

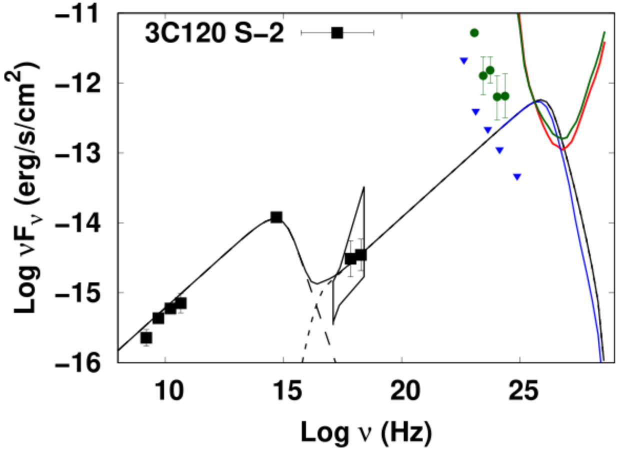
Probing the IC/CMB interpretation: VHE observations???

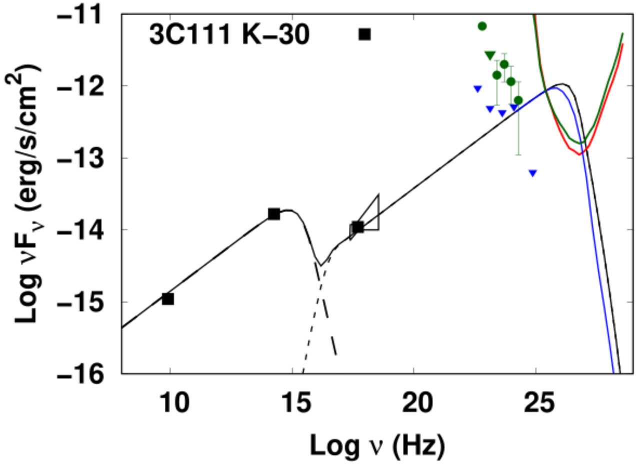
IC/CMB: not ruled out by Fermi observations (studies until 2023) →



Source	Type	Knot	z
3C 15	FR-I	K C	0.073
3C 17	Hybrid	S 3.7	0.22
3C 17	Hybrid	S 11.3	0.22
3C 111	FR-II	K 22	0.049
3C 111	FR-II	K 30	0.049
3C 111	FR-II	K 61	0.049
3C 120	FR-I	K 4	0.033
3C 120	FR-I	S 2	0.033
PKS 1354+195	CDQ	S 4.0	0.720
PKS 1354+195	CDQ	S 5.3	0.720
3C 346	FR-I	K C	0.161
3C 454.3	CDQ	K A	0.859
3C 454.3	CDQ	K B	0.859
PKS 2101−490	CDQ	K 6	1.040
PKS B0106+013	CDQ	K 1	2.11
PKS B0106+013	CDQ	K 2	2.11
PKS B0106+013	CDQ	K 3	2.11
PKS 1045−188	CDQ	K C	0.590







Rahman et al, 2023, MNRAS

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3C 454.3	CDQ	K A	0.859
3C 454.3	CDQ	K B	0.859
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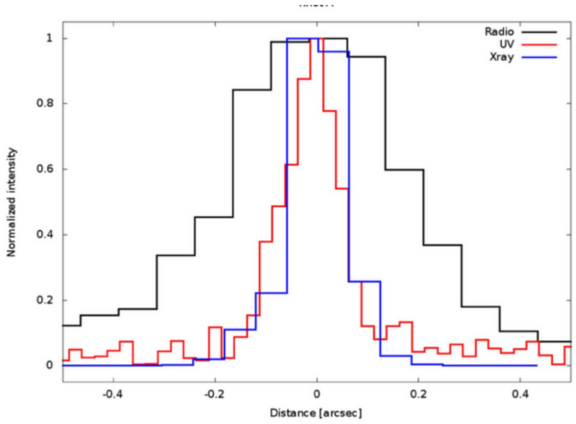
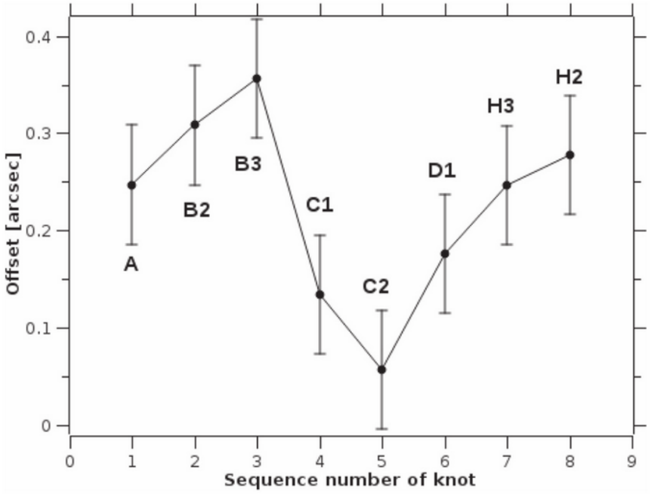
PKS B0106+013	CDQ	K 3	2.11
PKS 1045−188	CDQ	K C	0.590

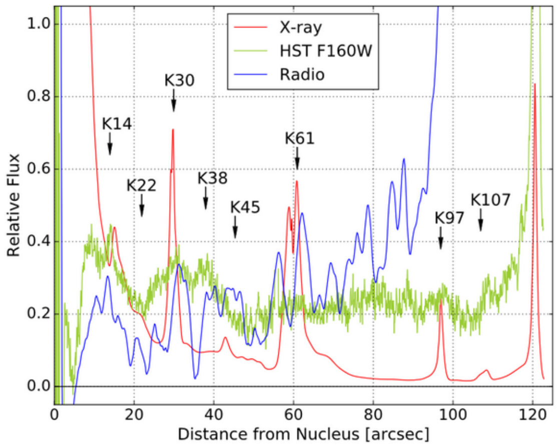
X-ray/ radio offsets in jet emissions

Are emitting regions CO-SPATIAL or not???

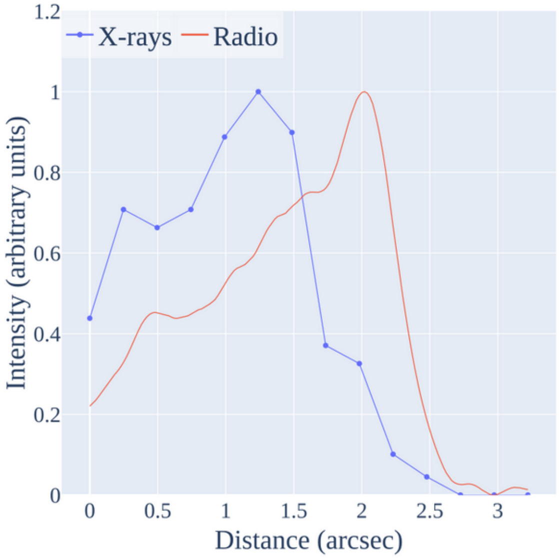


Offset measurements in 3C 273
Marchenko, Volodymyr et al, 2017 (ApJ)





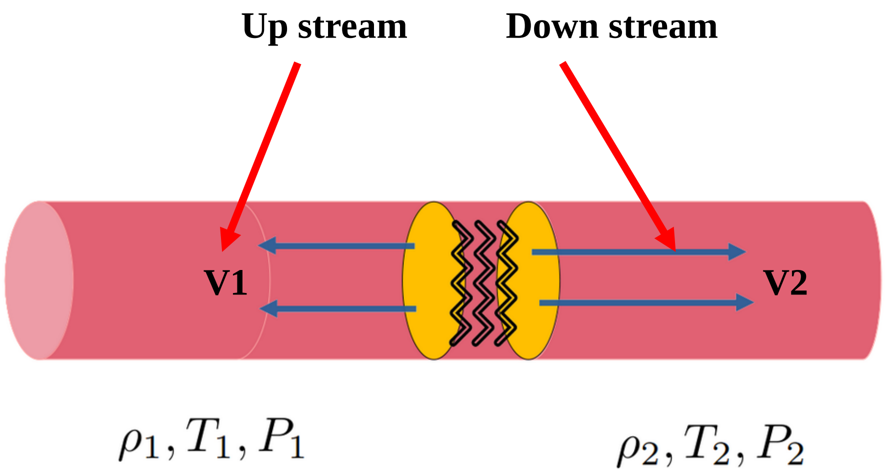
Clautice, Devon et. al, 2016 (ApJ))



PKS 0605–08
Reddy, Karthik et al., 2021 (ApJ)

X-ray/ radio offsets in jet emissions

- Cylindrical jet
- Difference in thermodynamic conditions at upstream/downstream of the shock.
- The Synchrotron cooling time scale – extension of region
- The advection velocity + cooling time scale: nature of the offset (Xf/Rf)



under construction....

- **Electron acceleration & advection model:**

  production of physically separated two population explain multiwavelength emission of 3C 273.

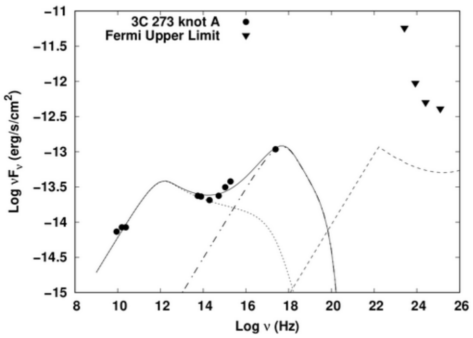
- **IC/CMB ruled out for high z jets (J1510+5702 & J1421-0643)**

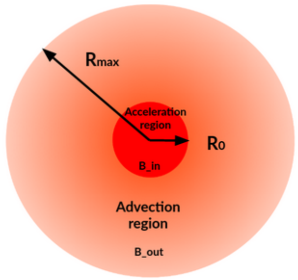
  The model explains radio/optical/X-ray emissions.

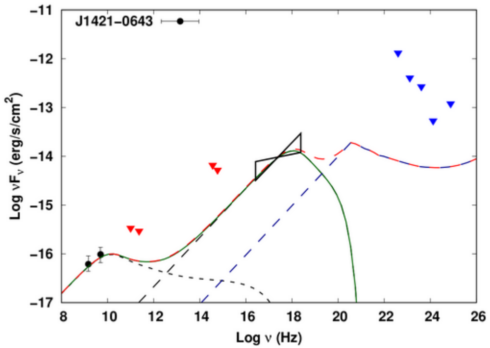
- **The scope of VHE observations - additional tool**

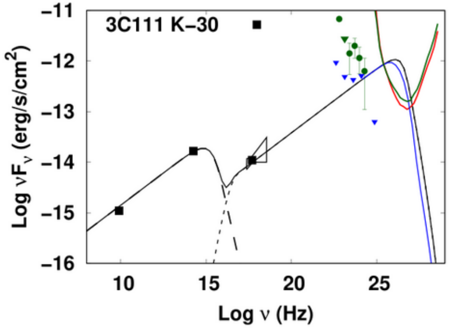
  3C 111 & 3C 120

- **Digging out the physics of offsets!!**



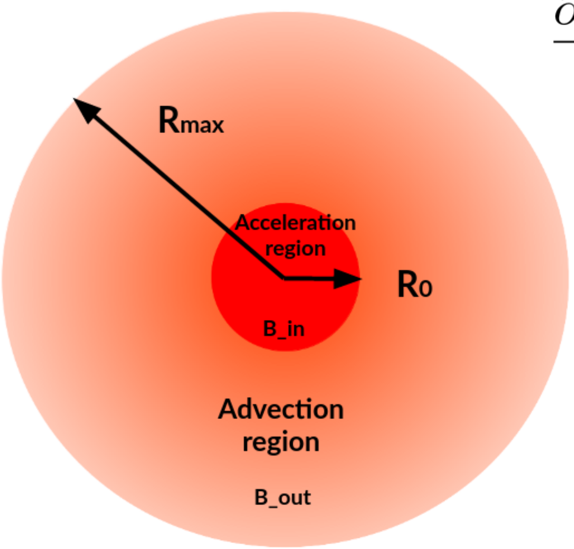






- LOC/SOC – HEPRO VIII
- Science & Engg Research Board, Govt. Of India
- University Grants Commission, Govt of India
- Farook College & BARC Mumbai.

The two population model



$$\frac{\partial \bar{n}(\gamma, R, R_0)}{\partial R} = \frac{\partial}{\partial \gamma}\left[\bar{P}(\gamma, R)\,\bar{n}(\gamma, R, R_0)\right] - \frac{\bar{n}(\gamma, R, R_0)}{R_*(R)} + n_0(\gamma)\,\delta(R - R_0)$$

$$\bar{P}(\gamma, R) = \frac{d\gamma}{dR} = \xi\gamma^2 + \frac{\gamma}{R}$$

$$\bar{n}(\gamma, R, R_0) = \frac{R_0}{R}\frac{\Gamma_0^2}{\gamma^2} n_0(\Gamma_0) \exp\left[-\int_{R_0}^{R}\frac{dx}{R_*(x)}\right]$$

$$\Gamma_0(\gamma, R) = \frac{\gamma\frac{R}{R_0}}{1 - \xi\gamma R \ln\frac{R}{R_0}} \qquad R_*(R) = \zeta R^\alpha$$

$$R_{\max}(\gamma) \leq R_0 + \frac{1}{\xi}\left(\frac{1}{\gamma} - \frac{1}{\gamma_{\max}}\right) \qquad \frac{R_{max}}{R_0} = \frac{\gamma_{max}}{\gamma}\left[1 - \xi\gamma R_{max}\ln\left(\frac{R_{max}}{R_0}\right)\right]$$

$$\bar{n}(\gamma, R, R_0) = \frac{R_0}{R}\frac{(\Gamma_0)^2}{(\gamma)^2} n_0(\Gamma_0)\left(\frac{R_0}{R}\right)^{1/\zeta}$$