Extragalactic X-ray and Gamma sources

Active Galactic Nuclei

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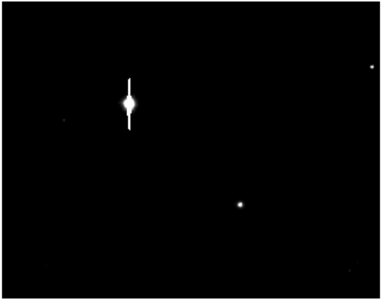
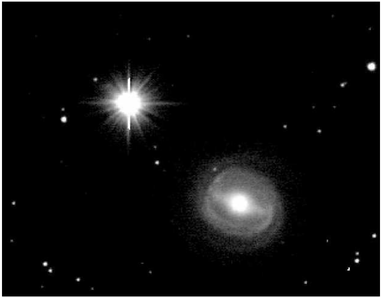
Universität Erlangen-Nürnberg

24th June 2010

1. General Characteristics
2. Classification, Unified Model
3. Energy Gain
4. SED
5. Further Jet Physics
6. research



NGC3783 linear intensity scale



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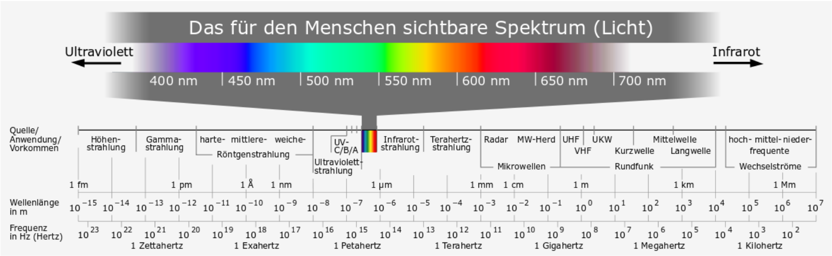
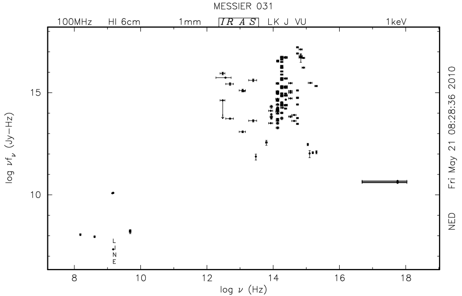
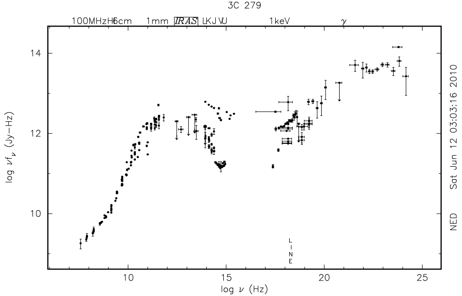

Das für den Menschen sichtbare Spektrum (Licht)
Ultraviolett
Infrarot
400 nm
450 nm
500 nm
550 nm
600 nm
650 nm
700 nm
Quelle/ Anwendung/ Vorkommen
Höhen-strahlung
Gamma-strahlung
harte- mittlere- weiche-
Röntgenstrahlung
UV-C/B/A
Ultraviolett-strahlung
Infrarot-strahlung
Terahertz-strahlung
Radar
MW-Herd
Mikrowellen
UHF
VHF
UKW
Kurzwelle
Mittelwelle
Langwelle
Rundfunk
hoch- mittel- nieder-frequente
Wechselströme
1 fm
1 pm
1 Å
1 nm
1 µm
1 mm
1 cm
1 m
1 km
1 Mm
Wellenlänge in m
10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
Frequenz in Hz (Hertz)
10^{23} 10^{22} 10^{21} 10^{20} 10^{19} 10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2}
1 Zettahertz
1 Exahertz
1 Petahertz
1 Terahertz
1 Gigahertz
1 Megahertz
1 Kilohertz

Wikipedia





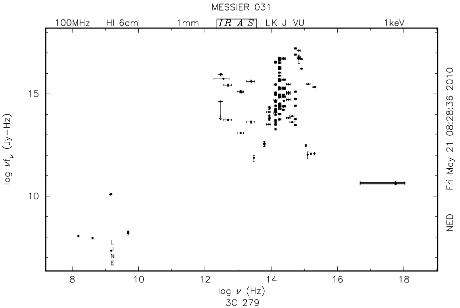
normal galaxies, e.g. M31 - Infrared:

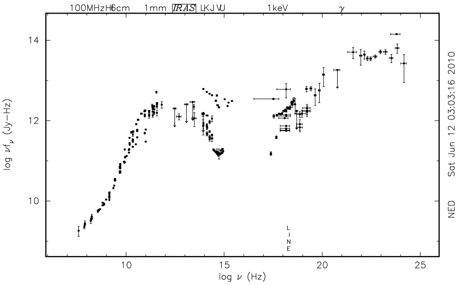
- concentrated thermal emission at IR and optical wavebands
- diameter ~ 43 kpc
- integrated luminosity $\sim 10^{44}\ \frac{\mathrm{erg}}{\mathrm{s}}$

AGN:

- broad, mainly non-thermal continuum emission
- diameter $\sim$ pc
- integrated luminosity $\sim 10^{42}\text{-}10^{48}\ \frac{\mathrm{erg}}{\mathrm{s}} \approx 10^{10}\ L_\odot$

[0] http://nedwww.ipac.caltech.edu/





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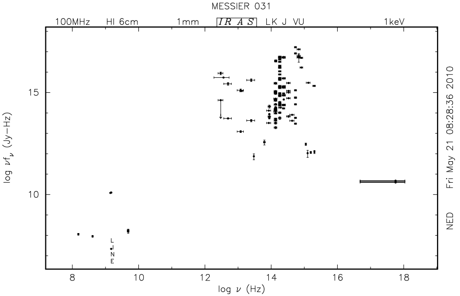

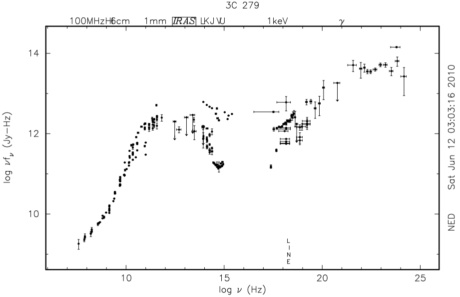

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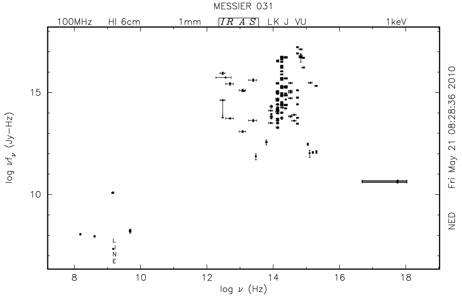

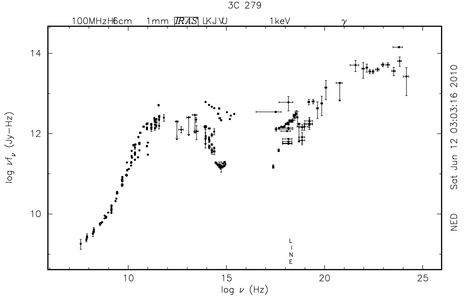

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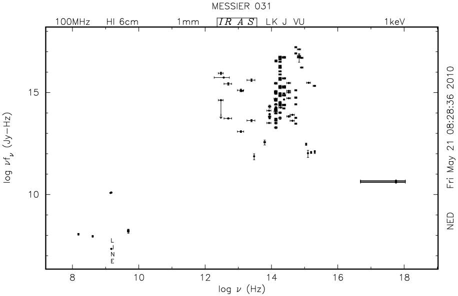

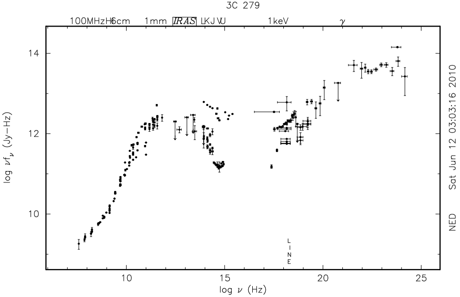

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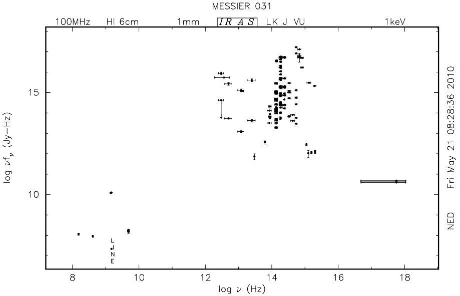

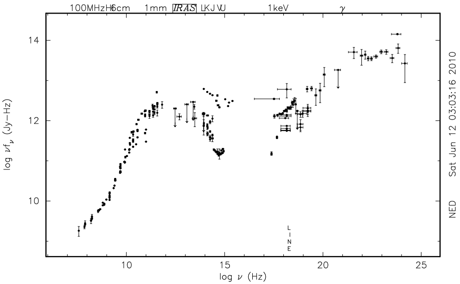

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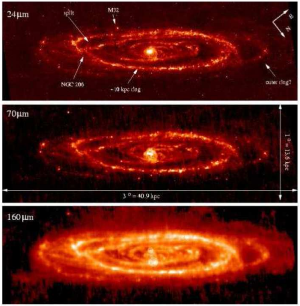
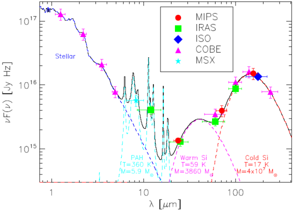
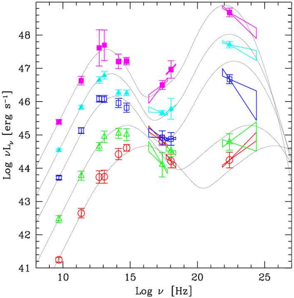
M31

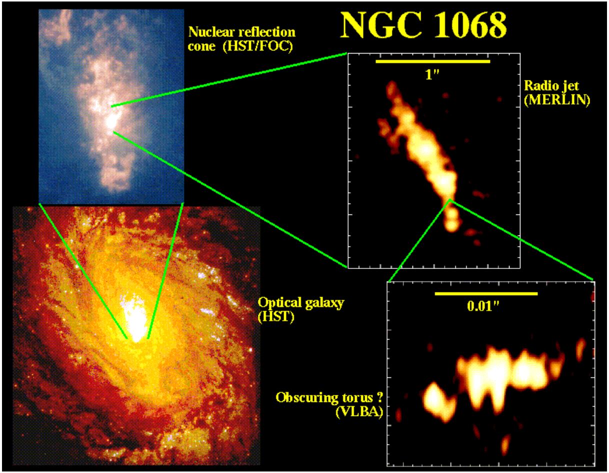




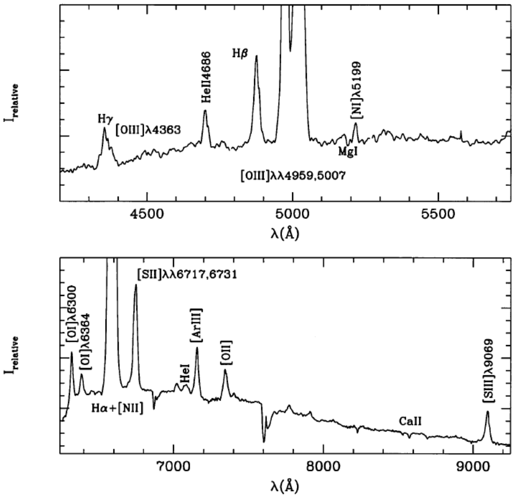
averaged SED of many blazars



[0] [5], [3], [10], [15], [18]

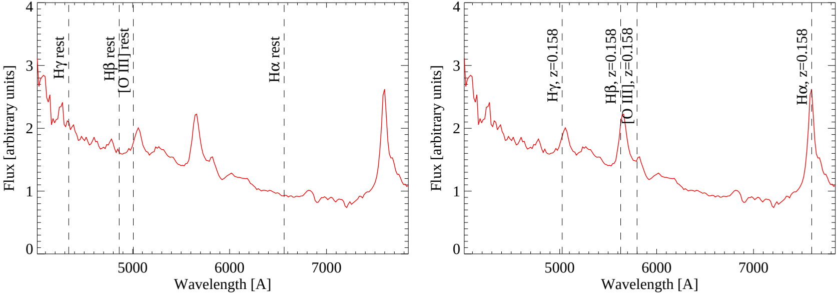


[0] www.astr.ua.edu/keel/agn/



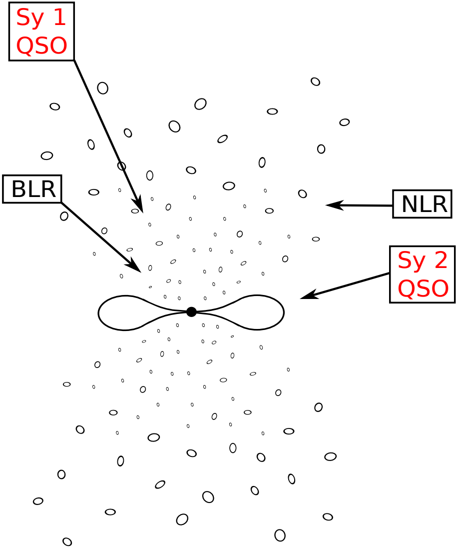
Optical spectrum of the central region of NGC 1068. Fath (1908): comparable to planetary nebula spectra, but with broad emission lines

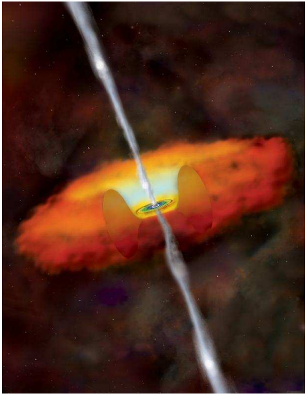
[0] [4]



Maarten Schmidt (1962): redshift of lines ⇒ distance using Hubble's law $v = HD$ ⇒ absolute magnitude over distance modulus ⇒ luminosity by comparing M_{abs} with $M_{\odot}$ ⇒ $L_{\textbf{quasar}} \approx 50 \cdot L_{\textbf{brightest galaxy}} = 4.8 \cdot 10^{12}\ L_{\odot}$ **for 3C 273**

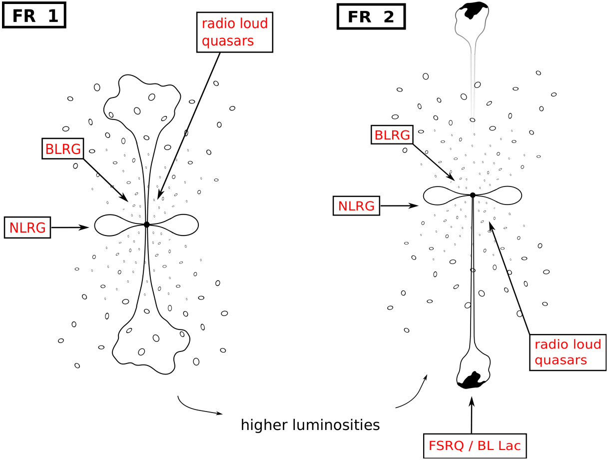
[0][18], Falke (MPIfR), [13]



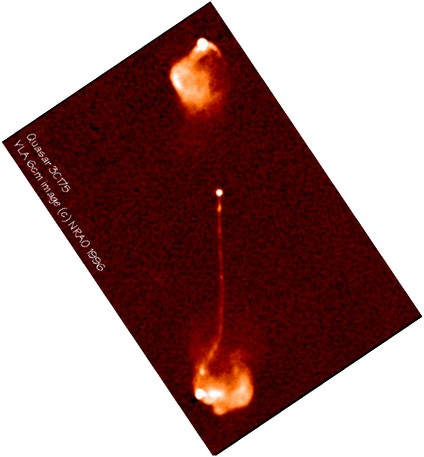


Unified model for radioquiet AGN

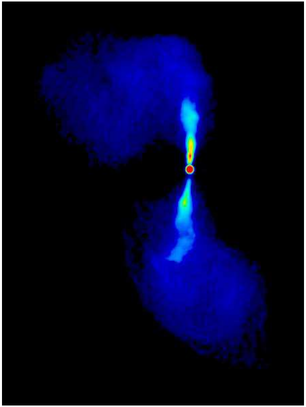
[0] http://www.obspm.fr/actual/nouvelle/jul04



Unified model for radioloud AGN



FR II Type, Quasar 3C175, VLA image at 6cm (http://www.cv.nrao.edu/~abridle/3c175.htm)



FR I Type, 3C271.1, M84 (http://nedwww.ipac.caltech.edu/)

[0] [13]

energy source

Which process of gaining energy is the most efficient one?

Nuclear Fusion

$$E = \epsilon m c^2 \tag{1}$$

$L \approx 10^{47}$ erg/s over 10^7 yrs ($\approx 3.2 \cdot 10^{61}$ erg) requires:

$$m = \frac{E}{\epsilon c^2} \approx 2.2 \cdot 10^9\ \mathrm{M}_\odot \tag{2}$$

$(1-\epsilon)m \Rightarrow$ "fusion-waste"!
Schwarzschildradius of that mass:

$$r_s = \frac{2Gm}{c^2} \approx 6.6 \cdot 10^{12}\ \mathrm{m} \tag{3}$$

$\rightarrow \epsilon = 0.008 \Rightarrow$ energy yield $\approx 7.2 \cdot 10^{18}$ erg/g

Gravitation $\Rightarrow \epsilon \approx 0.1 \Rightarrow$ energy yield $\approx 10^{20}$ erg/g

[0][15], [18]

accretion process I

optical thick accretion disc

$\Rightarrow$ balance between **radiation** and **gravitation**

- angular momentum $\rightarrow$ no accretion
- frictional force $F_{fr} \ll F_{grav} \Rightarrow$ Kepler orbits
- differential rotation $\Rightarrow$ heating $\Rightarrow$ outward loss of angular momentum $\Rightarrow$ accretion

Radiation

$$\Delta E = \frac{GM_\bullet m}{r} - \frac{GM_\bullet m}{r+\Delta r} \approx \frac{GM_\bullet m}{r^2}\Delta r \tag{4}$$

virial theorem: $E_{kin} = -1/2 E_{pot} = -1/2 \Delta E$
$\Delta E - E_{kin} = E_i \Rightarrow$heating $\Rightarrow$ radiation
Using $[L] =$erg/s:

$$\Delta L = \frac{GM_\bullet \dot{m}}{2r^2}\Delta r \tag{5}$$

with **accretion rate** $\dot{m}$.

Eddington Luminosity

condition for matter being accreted (optically thick discs)

$$\frac{dp_{grav}}{dr} \overset{!}{>} \frac{dp_{rad}}{dr} \tag{6}$$

$\Rightarrow$ upper luminosity (**Eddington Luminosity** $L_{\mathbf{Edd}}$, see handout)

$$L \overset{!}{<} L_{\rm Edd} = \frac{GM_\bullet m_{\rm H} c}{\sigma_{\rm T}} \approx 1.3 \cdot 10^{38}\ \text{erg/s} \cdot \frac{M_\bullet}{M_\odot} \tag{7}$$

upper **accretion rate** $\dot{M}_{\rm Edd}$:

$$L_{\rm Edd} = \eta \dot{M}_{\rm Edd} c^2 \tag{8}$$

$$\Rightarrow \dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\eta c^2} \approx 2\ M_\odot/\text{yr} \tag{9}$$

With an efficiency η of $\gtrsim 0.12$ due to high optical depth as “resistance” for photons.

[0] [12], [7]

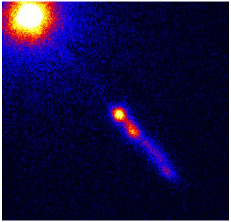
Temperature Profile

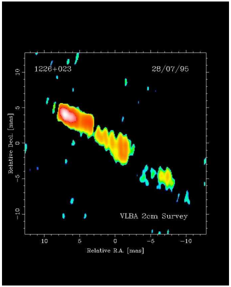
Black body radiation (optical thick) → temperature layer with **Planck Law**
$\Delta L = 4\pi r \Delta r \sigma T^4$

$$T(r) = \left(\frac{L}{4\pi r^3 \sigma_{SB}}\right)^{-1/4} = \left(\frac{GM_\bullet \dot{m}}{8\pi r^3 \sigma_{SB}}\right)^{-1/4} \overset{r_s = 2GM_\bullet/c^2}{=} \left(\frac{c^6}{64\pi \sigma_{SB} G^2}\right)^{1/4} \dot{m}^{1/4} M_\bullet^{-1/2} \left(\frac{r}{r_s}\right)^{-3/4} \tag{10}$$

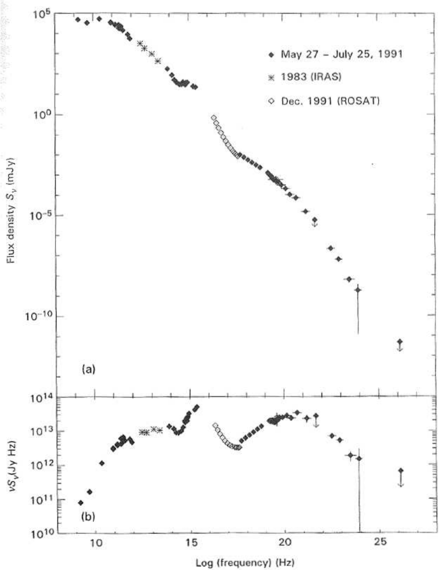
→ r fixed, $\dot{m}$ ↑ ⇒ T ↑
→ $M_\bullet$ ↑, reached temperatures ↓

0[15]

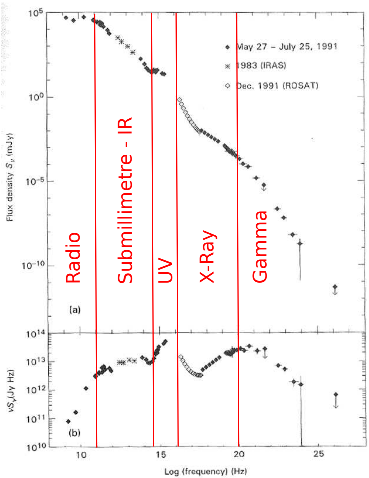




top: 3C273 in X-Rays (NASA/CXS/SAO, 2003), bottom: Jet of 3C273 in 2cm, VLBA (NRAO, Kellermann 1998)



Spectral Energy Distribution (SED) of 3C273 ([13], p.149)



- need many instruments on earth and in orbit measuring "simultaneous" if possible
- units: $[S_\nu] = \text{erg}/\text{m}^2\text{sHz} = \text{W}/\text{m}^2\text{Hz}$
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- $(\log \nu S_\nu - \log \nu)$: equal energy at all frequencies $\rightarrow$ flat spectrum with $\alpha = 0 \Rightarrow$ good indicator for above-average flux (bumps...)
- overall radiation follows powerlaws like $S_\nu \sim \nu^{-\alpha}$

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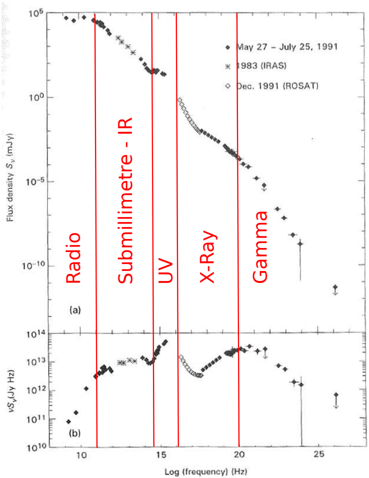

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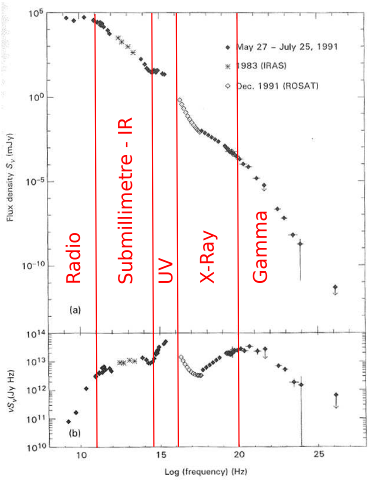

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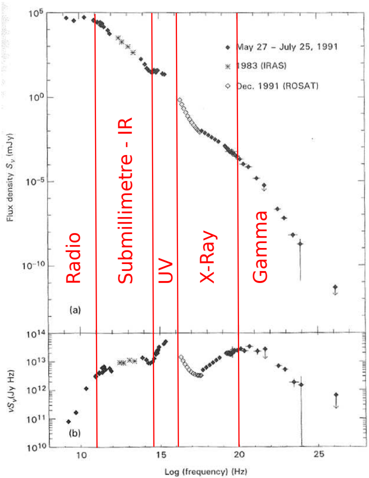

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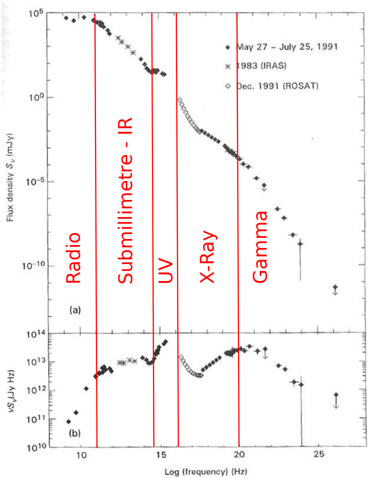

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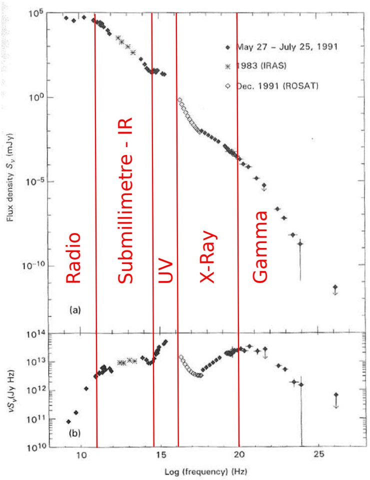

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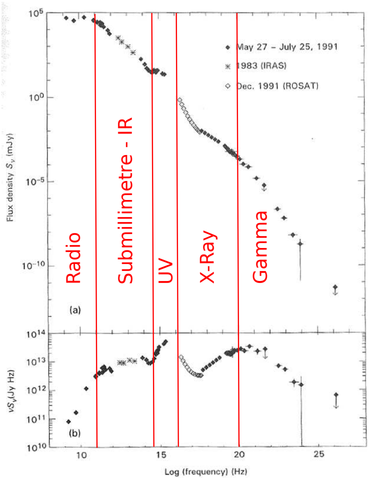

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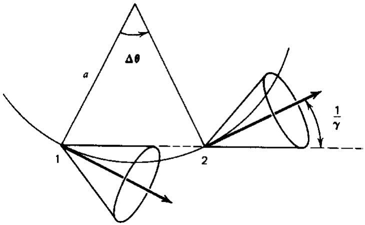
- $(\log S_\nu - \log \nu)$: equal energy at all frequencies $\rightarrow$ spectrum with $\alpha = -1$
- $(\log \nu S_\nu - \log \nu)$: equal energy at all frequencies $\rightarrow$ flat spectrum with $\alpha = 0 \Rightarrow$ good indicator for above-average flux (bumps...)
- overall radiation follows powerlaws like $S_\nu \sim \nu^{-\alpha}$

[0] [13]

Radio - synchrotron emission (circular orbits)



→ high degree of linear **polarization**.

→ Electron **frame of rest**: **radial symmetric emission**

whole emitted power:

$$\boxed{I = \frac{4}{3}\sigma_T c \gamma^2 U_{mag}} \quad (11)$$

“cooling time” (energy decreased by factor 2):

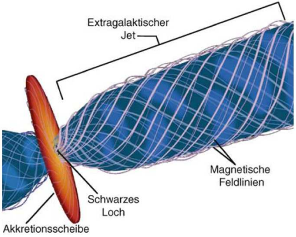
$$t = \frac{3}{2}\frac{m^4 c^7}{e^4 B^2 E_0} \quad (12)$$

[0] `http://www.cv.nrao.edu/~abridle/3c175.htm`, [13], [7], [11], [2], Falke, [14]

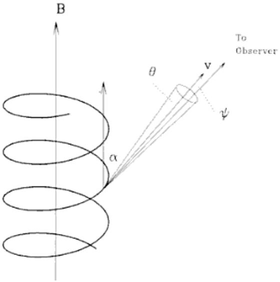
Radio - synchrotron emission (realistic conditions)

less massive particles (electrons) ⇒ most efficient energy loss ⇒ seem to form a leptonic plasma

More realistic conditions (see handout):



theoretical model of an AGN



helical trajectory of electrons around H-fieldlines

0[13], [7], [11], [2], [?]

Radio - synchrotron emission (ensemble of electrons)

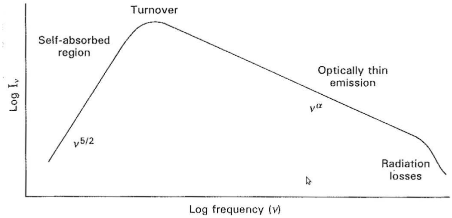
→ powerlaw-distribution of electrons in jet plasma: $\boxed{N(E)dE \sim E^{-s}dE}$

gained energy by radiation $=$ **lost energy** through emission

$=$ **particle distribution** $\cdot$ **synchrotron emission**

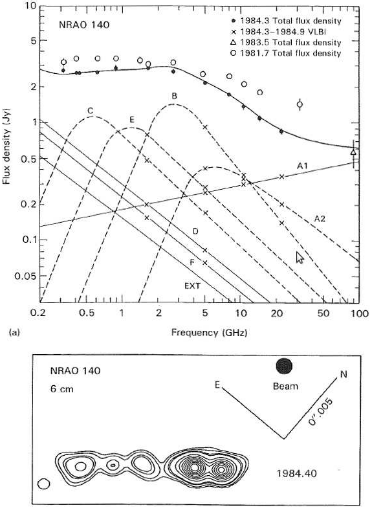
$$I_\nu d\nu = \eta(E)dE = N(E)dE \cdot \frac{dE}{dt}$$

$$I_\nu \sim \begin{cases} B^{-1/2}\,\nu^{5/2} & \nu < \nu_c \quad \text{synchrotron self absorption} \\ \nu^{-(p-1)/2} & \nu > \nu_c \quad \text{optical thin} \end{cases} \tag{13}$$



[0] [13], [7], [11], [2]

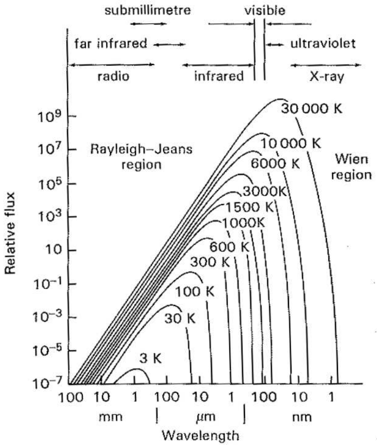
Radio - synchrotron emission (ensemble of electrons)



(a)

(b)

Submillimetre - IR (thermal black body radiation)



black body emission at different temperatures

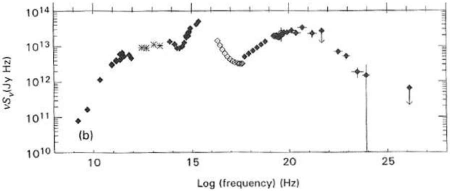
- most likely: thermal BB emission from central parts of AGN (Torus, gas, dust)
- temperatures for dust: $\approx 20 - 80$ K
- **no polarization → thermal emission**!
- Planck's law:

$$B_\nu(T) = \frac{8\pi h\nu^3}{c^3 e^{\frac{h\nu}{kT}} - 1} \tag{14}$$

---

[0] [13]

IR - UV (thermal black body radiation)



IR Bump

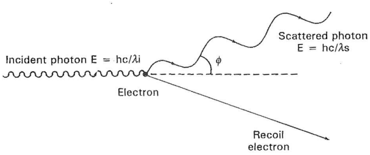
- near $\approx 10^{13}$ keV
- thermal emission of warm dust (T > 2000 K) near black hole

UV Bump

- in general: strong, broad line emission from BLR/NRL $\rightarrow$ continuum more difficult to model than in IR!
- Big Blue Bump (**BBB**) from hot accretion disc or free-free emission (bremsstrahlung)
- thermal BB emission of the temperature-profile

[0] [13], [7], [15]

X-Ray - Compton scattering



Compton scattering: energy transfer **photon → electron**
inverse Compton scattering: energy transfer **electron → photon**

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta) \quad (15)$$

$$E'_e = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)} \quad (16)$$

$$\frac{\Delta E}{E} \approx -\frac{E}{m_e c^2} \qquad (E \ll m_e c^2) \quad (17)$$

From Eq.16 for many scattering events (cf. Eq.11):

$$\boxed{I = \frac{dE}{dt} = \frac{4}{3}\sigma_T c \gamma^2 U_{el}} \quad (18)$$

[0] [13], [7], [18]

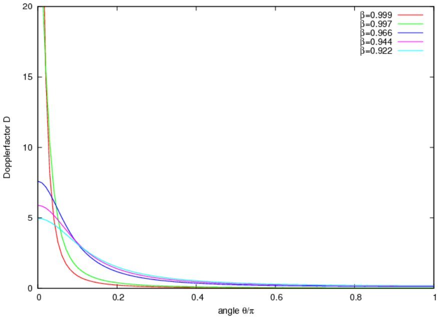
relativistic boosting

Time dilatation causes **relativistic Doppler effect** with

$$\nu_{\rm obs} = \frac{\nu_{\rm em}}{\gamma(1-\beta\cos\theta)} \qquad (19)$$

with the relativistic **Doppler factor**

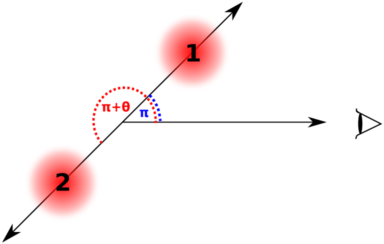
$$\mathcal{D} = \frac{\sqrt{1-\beta^2}}{(1-\beta\cos\theta)} \qquad (20)$$



relativistic boosting - jet one sideness

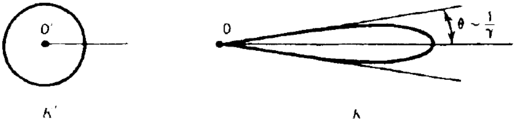
One can show, that $\frac{I_\nu^{\text{obs}}}{\nu_{\text{obs}}^3} = \frac{I_\nu^{\text{em}}}{\nu_{\text{em}}^3} \Rightarrow I_\nu^{\text{obs}} = \mathcal{D}^3 I_\nu^{\text{em}}$

power law $I_\nu \sim A\nu^\alpha \Rightarrow I_\nu^{\text{obs}} = \mathcal{D}^{3-\alpha} I_\nu^{\text{em}}$

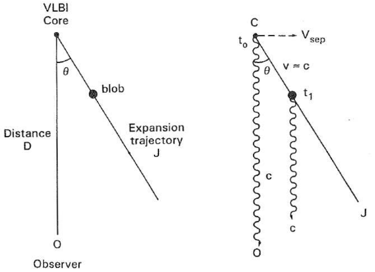


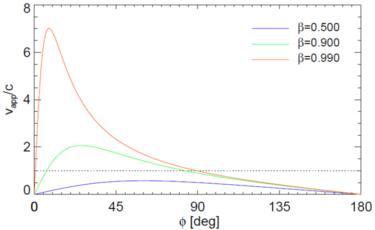
$$\frac{I_1}{I_2} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{3-\alpha} \tag{21}$$

In addition: **relativistic abberation**



Superluminal Motion





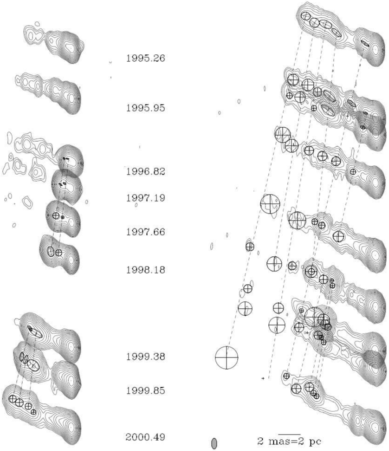
apparent speed of a blob:

$$v_{app} = \frac{v \sin\theta}{1 - \beta\cos\theta} \qquad (22)$$

"superluminal" only for relativistic blob-speeds (large β) at small viewing angles Φ

0[18], [13]

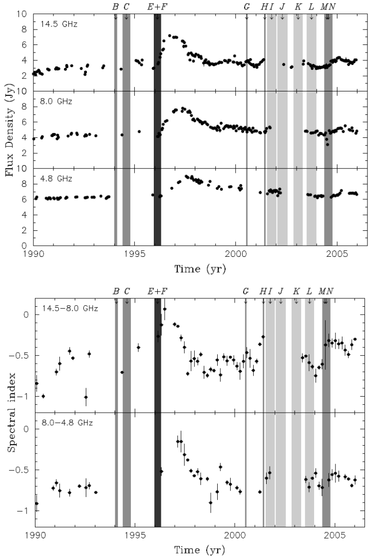
tracking flares of 3C111



VLBA monitoring at 2cm

[0] [6]

tracking flares of 3C111



[0][6], [16], [8]

radio lightcurve (top figure)

- blob first visible at high frequencies (synchrotron self absorption mainly at lower frequencies)
- blob expands $\Rightarrow$ less dense electron plasma $\Rightarrow$ less synchrotron self absorption

spectral indices (bottom figure)

- spectral indices α from $I_\nu \sim \nu^\alpha$
- compact blobs in plateau-state $\Rightarrow$ flat radio spectrum ($\alpha \approx 0$)
- decay state: blob expands $\Rightarrow$ radio spectrum steepened ($\alpha < 0$)

Relationship between frequency bands

relationship radio - gamma ([17])

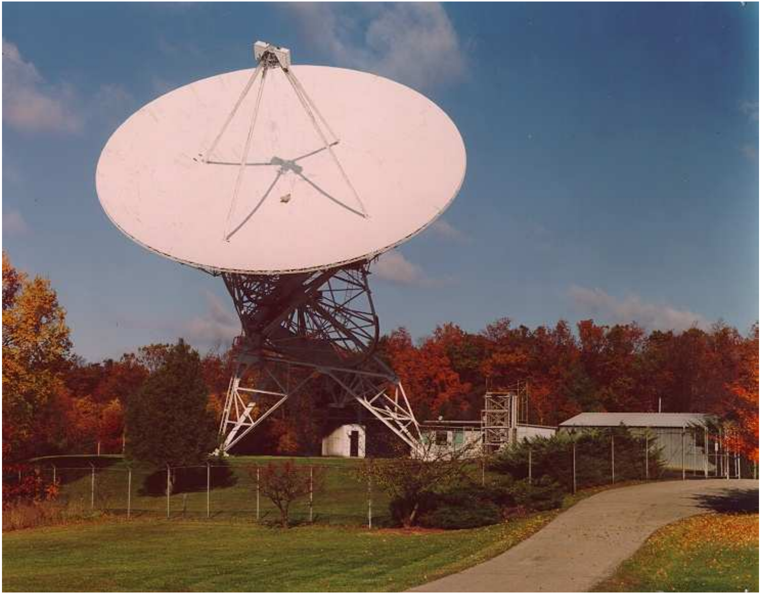
- comparison radio (22 GHz and 37 GHz, Metsähovi Obs.) - gamma (EGRET)
- radio emission several month after gamma emission
- coupling gamma - radio: both originate in same flare $\leftrightarrow$ gamma rays from SSC-upscattering of synchrotron seed photons (from accelerated relativistic electrons)

relationship optical - radio ([16]: Generalized Shock Model)

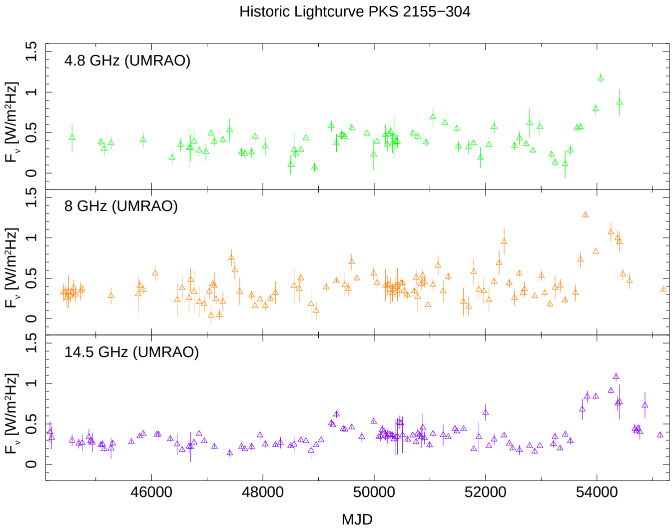
- connection: **accreted matter** ($\rightarrow$ optical thermal emission) - **radio-flare**
- strong delay between accretion and radio-flare expected
- or: optically thin slope of synchrotron spectrum reaches optical waveband $\rightarrow$ no delay!

[0] [16], [17], [9]

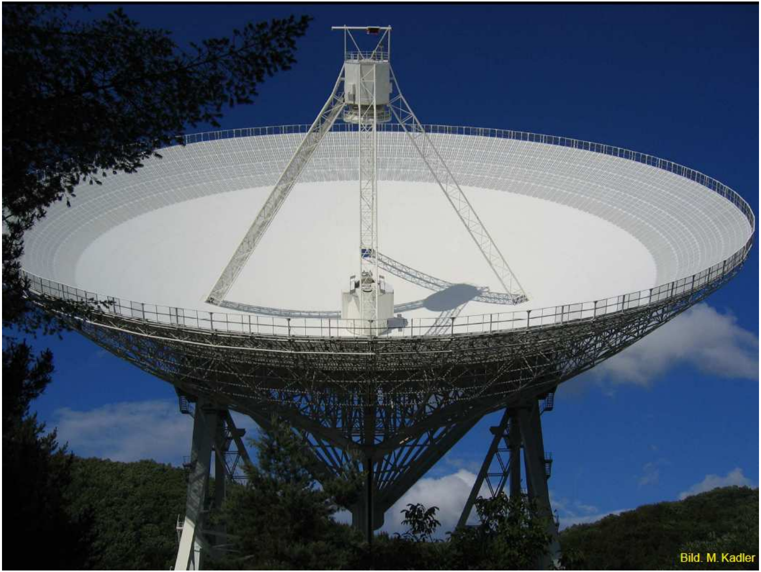
UMRAO Radio Observatory



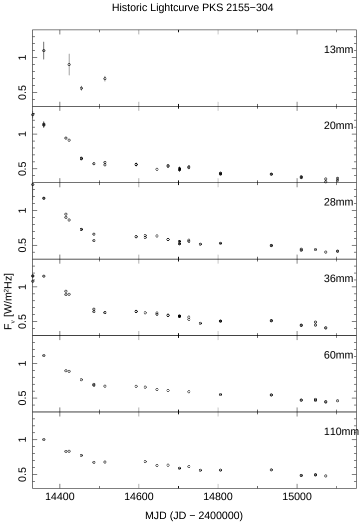
UMRAO lightcurve of PKS 2155-304



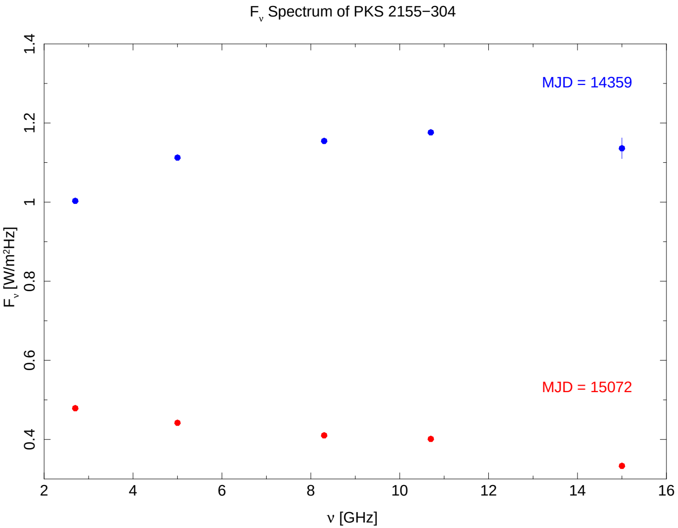
Effelsberg Radio Telescope



Effelsberg lightcurves of PKS 2155-304

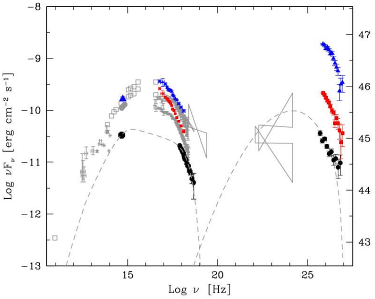


Effelsberg lightcurves of PKS 2155-304



Multiwavelength observations of the 2006 flare of PKS 2155-304

simultanious observation of the flare with HESS (gamma), Chandra (X-ray), RossiXTE (X-ray), Bronberg Obs. (optical)



SED of PKS 2155-304 with highest and lowest states during this observation

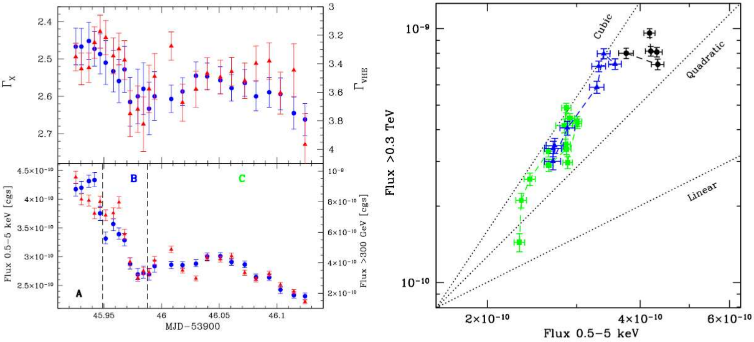
- first peak, right slope: X-Ray (Synchrotron emission)
- second peak: Gamma (inverse Compton emission)
- flare not moving though frequencies with time

Why X-Ray through Synchrotron emission??

- **“blue blazars”**
  $\rightarrow$ less external photons $\rightarrow$ less Compton cooling of electrons $\rightarrow$ overall higher photon energies due to synchrotron or inverse Compton recoil
- **“red blazars”**
  $\rightarrow$ higher photon density $\rightarrow$ lower photon energies

0[1], HESS-collaboration (2009)

Multiwavelength observations of the 2006 flare of PKS 2155-304



plot of spectral index' and flux variability

- strong correlation between X-ray and γ-ray flux (synchrotron and inverse Compton emission → as already shown)
- γ-ray flux decreases approximately with cube of X-ray flux ($F_\gamma \sim F_X^3$)

[0]HESS-collaboration (2009)

[1] J.M. Bay et al. Existence of large-scale synchrotron x-ray jets in radio-loud active galactic nuclei. paper, 2001.

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[18] Kadler Wilms. Active galactic nuclei, 2010. Lecture ST 2010 University Erlangen-Nürnberg.