Radiation Processes in Active Galactic Nuclei

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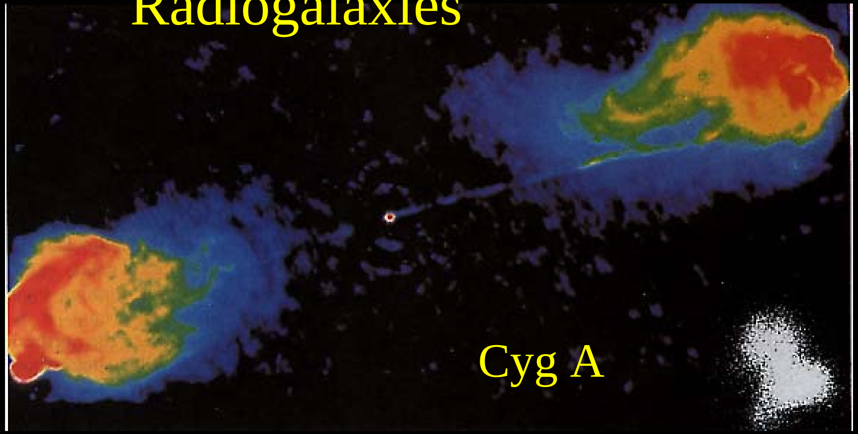
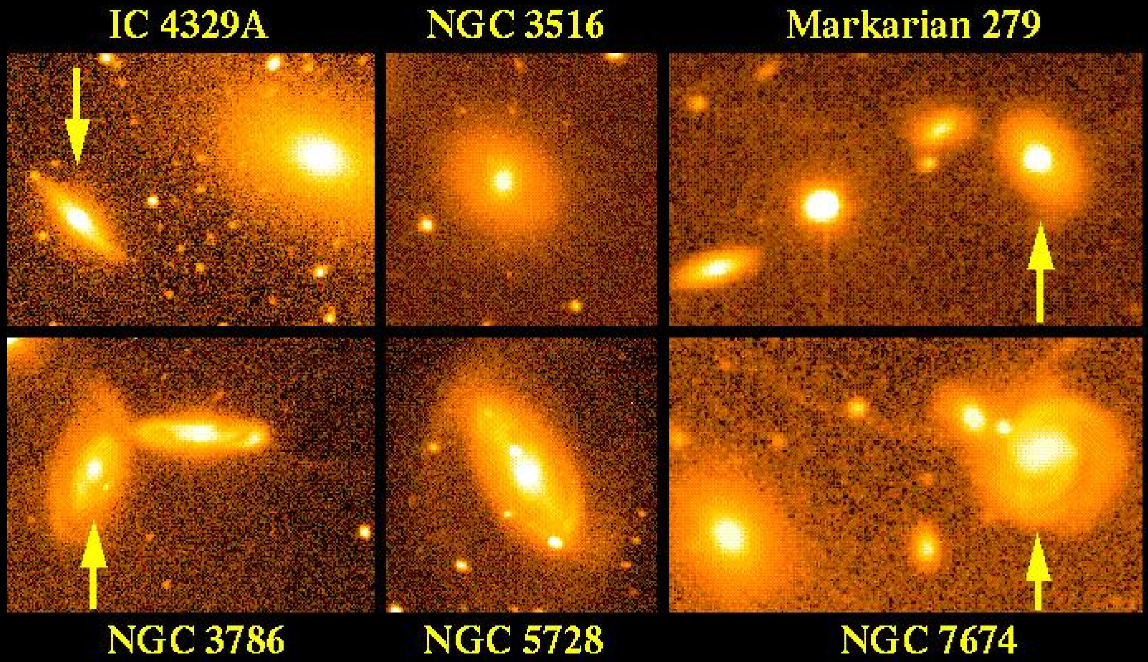
Radiogalaxies

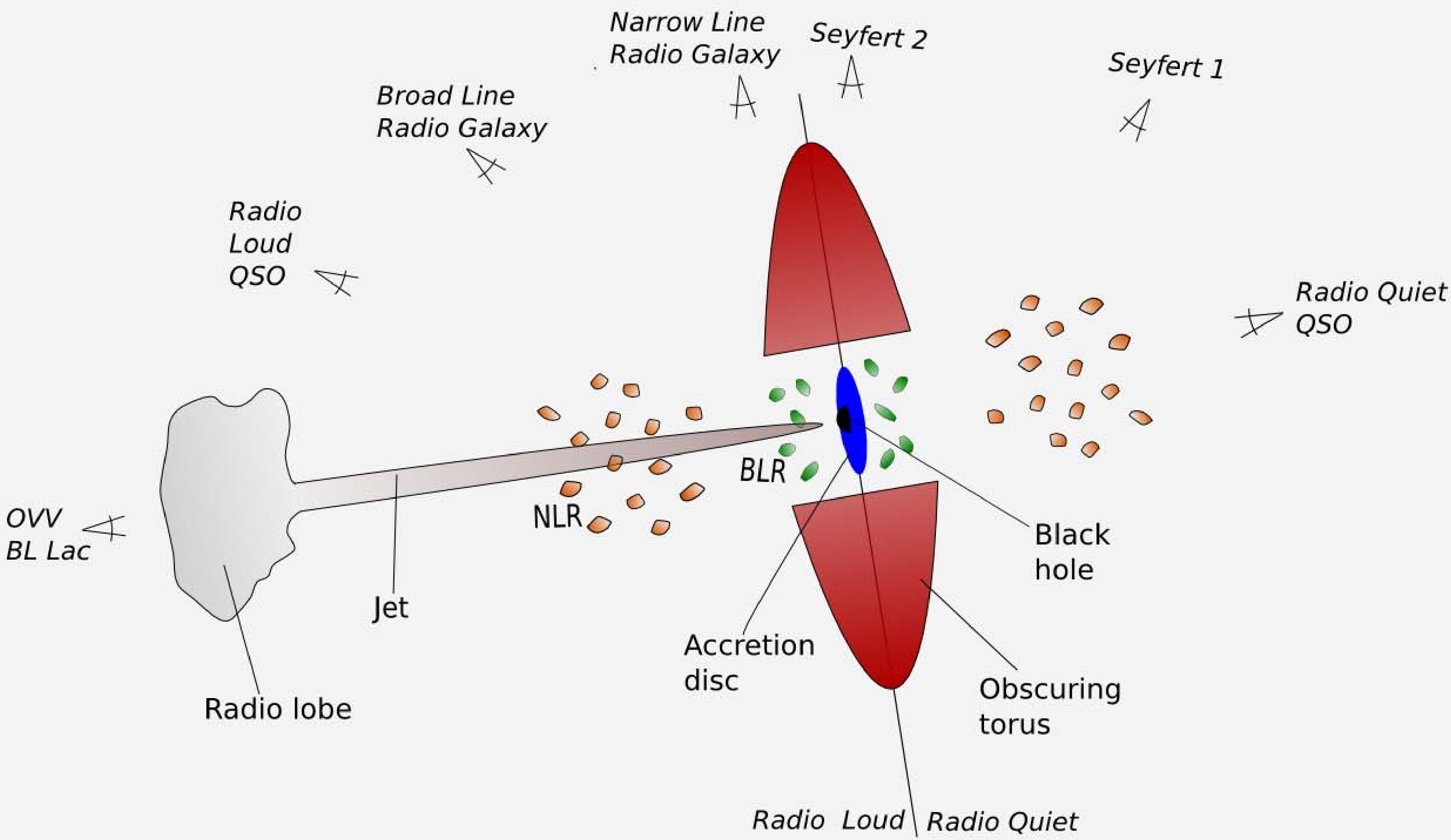


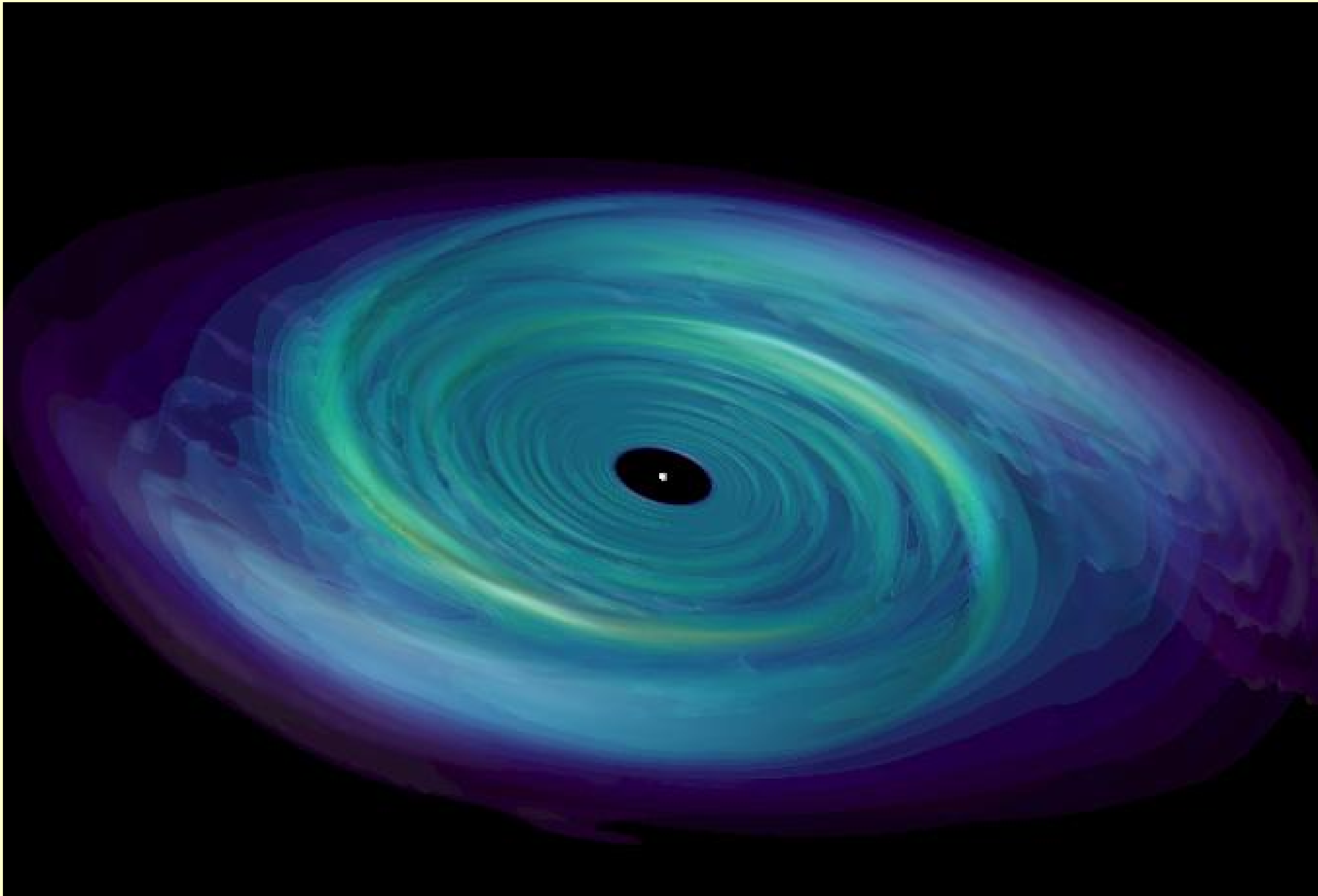
Seyfert Galaxies



AGN TAXONOMY

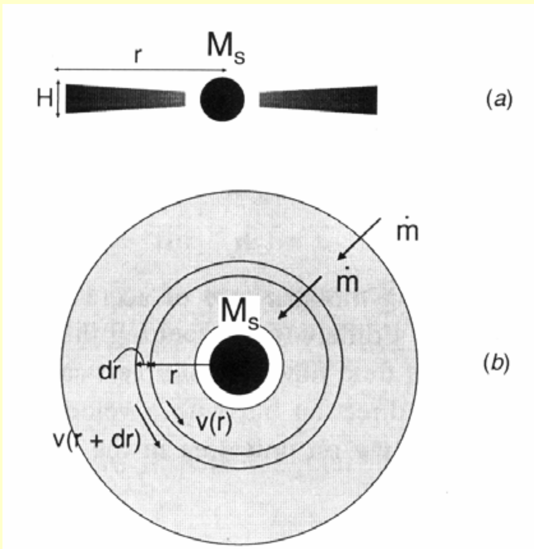
	Type 2 (Narrow Line)	Type 1 (Broad+Narrow Line)	Type 0 (Irregular)
RADIO QUIET	**Seyferts 2**	**Seyferts 1** **QSO**	
RADIO LOUD	**NLRG**	**BLRG** **QSR**	**BL Lacs** **Blazars**


Narrow Line
Radio Galaxy
Seyfert 2
Seyfert 1
Broad Line
Radio Galaxy
Radio
Loud
QSO
Radio Quiet
QSO
NLR
BLR
OVV
BL Lac
Black
hole
Jet
Accretion
disc
Obscuring
torus
Radio lobe
Radio Loud
Radio Quiet



High Resolution 3D Hydrodynamic Simulations of Accretion Disks in Close Binaries -- M.P.Owen

ACCRETION DISCS-1



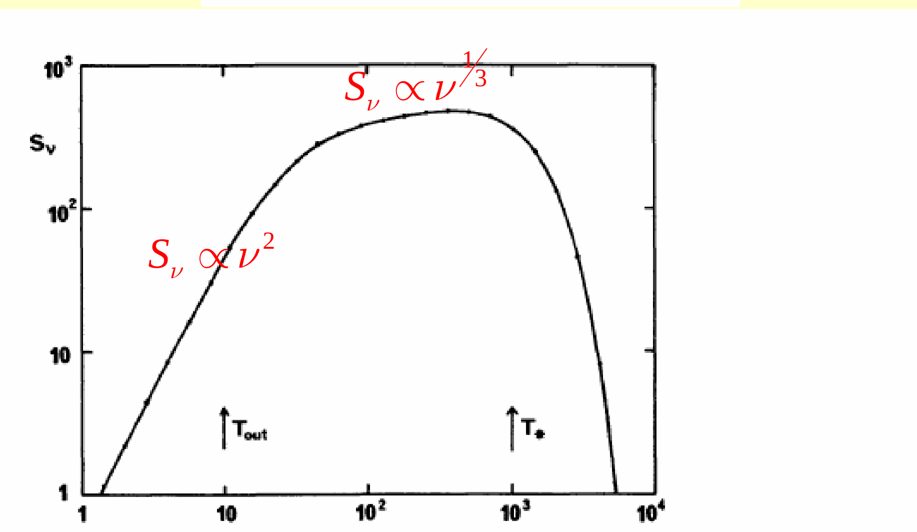
Standard steady state, geometrically thin, optically thick disks

Gravitational binding energy → Heating → Radiation

Central Mass ⇑

Luminosity $$L_{acc} = \frac{GM\dot{m}}{2R}$$ ⇒ Mass accretion rate

Temperature $$T(r) = \left(\frac{GM\dot{m}}{8\pi\sigma R^3}\right)^{1/4}\left(\frac{R}{r}\right)^{3/4}$$



Spectrum $$S_\nu = \int B_\nu(T_s(r))\,dA(r)$$

Can accretion disks explain the X-ray emission in AGN?

$$T_{disk} \equiv T(R) = \left(\frac{GM\dot{m}}{8\pi\sigma R^3} \right)^{1/4}$$

Mass $\quad M = 10^8 M_8 M_\odot$

Inner radius $\quad R \simeq 3R_s = \frac{6GM}{c^2} \simeq 10^{14} M_8 \text{ cm}$

Luminosity $\quad L \equiv L_E = \frac{4\pi G M m_p c}{\sigma_T} = 1.3 \times 10^{46} M_8 \text{ erg/sec}$

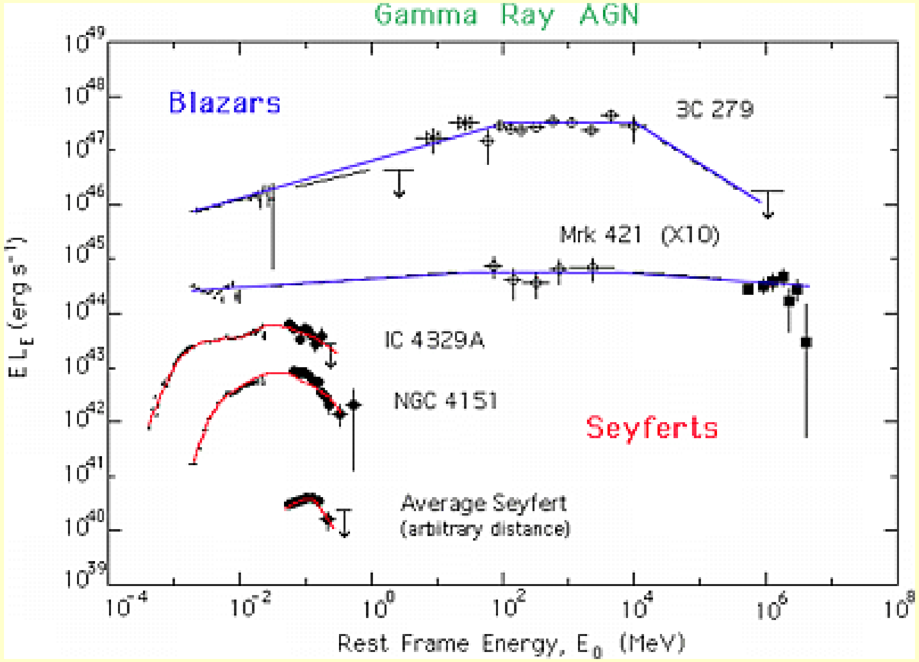
Eddington accretion rate:

$$L = \frac{GM\dot{m}_{Edd}}{2R} = L_{Edd} \Rightarrow \dot{m}_{Edd} = \frac{8\pi m_p c}{\sigma_T} 3R_s = 2.3 M_8 M_\odot / yr$$

$$\therefore \quad T_{disk} = 3 \times 10^5 \left(\dot{m} / \dot{m}_{Edd} \right)^{1/4} M_8^{-1/4} \text{ K}$$

Max at UV

BLAZARS vs SEYFERTS: HIGH ENERGY SPECTRA



Blazars: Emission extends to GeV and (sometimes) to TeV regimes

Seyferts: Emission extends up to ~100 keVs

HIGH ENERGY RADIATION FROM AGNs: RADIO LOUD vs RADIO QUIET OBJECTS

X- and gamma-rays from radio-loud AGNs + blazars

- Non-thermal in origin: Power-laws extending for many decades in frequency
- Sometimes extends to VHE (Very High Energies) ~ TeV

X-ray and gamma-rays from radio-quiet AGNs

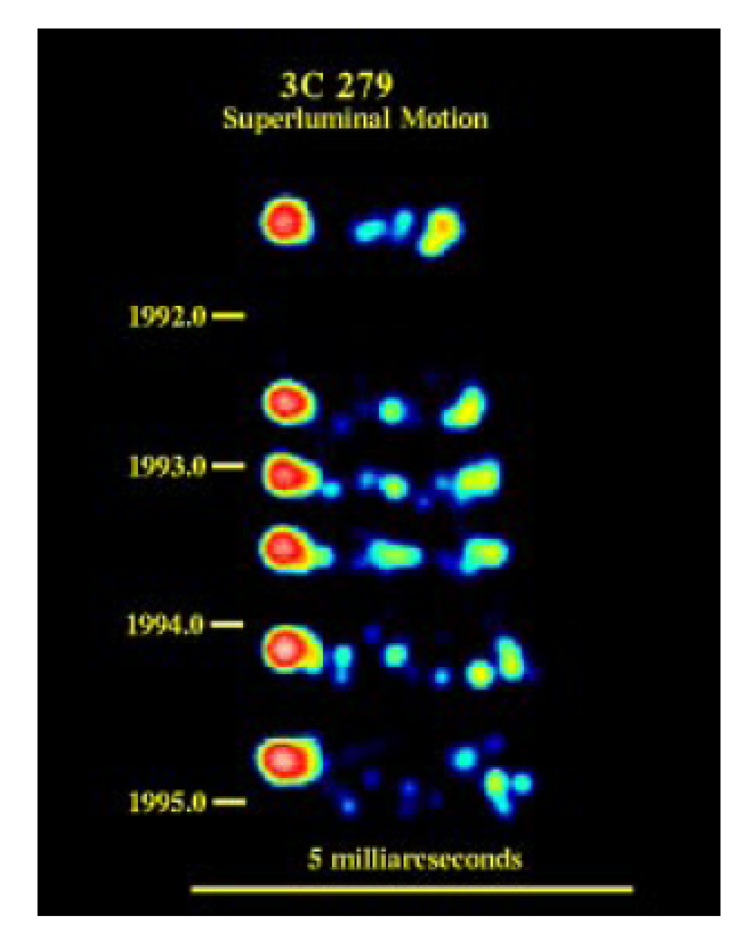
- Power laws in X-rays (keV)+ cutoffs ~100 keV
- No High Energy gamma-rays
- Fe Ka line

What are the radiation mechanisms responsible for this very different type of emission?

(X-RAY AND GAMMA-RAY) RADIATION PROCESSES IN RADIO-LOUD AGNs / BLAZARS

- Evidence and consequences of relativistic bulk motion
- Synchrotron radiation
- Compton scattering
- Modelling

Assume a spherical source moving with velocity u making an angle θ with our line of sight



Apparent velocity $\beta_{\perp,app} = \dfrac{\beta\cos\theta}{1-\beta\sin\theta}$

For $\beta_{\perp,app} > 1 \Rightarrow$ both $\beta \simeq 1$ and $\cos\theta \simeq 1$ required

$$\beta_{\perp,app} \approx \frac{2\theta}{\Gamma^{-2}+\theta^2}$$

e.g. if $\Gamma^{-1} < \theta \ll 1 \Rightarrow \beta_{\perp,app} \approx 2\theta^{-1} \gg 1$

$\beta_{\perp,app}^{max} = \dfrac{\beta}{\sqrt{1-\beta^2}}$ for $\cos\theta \simeq \beta$

β	$\beta_{\perp,app}$
.99	7
.999	22

DOPPLER BOOSTING-1

- Assume (again) a spherical source moving with velocity $\upsilon = \beta c$ making an angle θ with our line of sight
- If the source has a luminosity L' in its rest frame, what is the luminosity an observer infers?

- Observed flux $S_\nu = \int I_\nu d\Omega$, where I_ν is the specific intensity of radiation
- Use
  - $d\Omega = dA / D^2$, dA the area, D the distance to the source
  - $I_\nu = j_\nu s$ (optically thin source, j_ν the emission coefficient)
  - $dV = dA.s$

$$\rightarrow \quad S_\nu = \int j_\nu dV / D^2$$

→ Need to know how j_ν (O.F.) and $j'_{\nu'}$ (R.F. of the flow) are related

DOPPLER BOOSTING-2

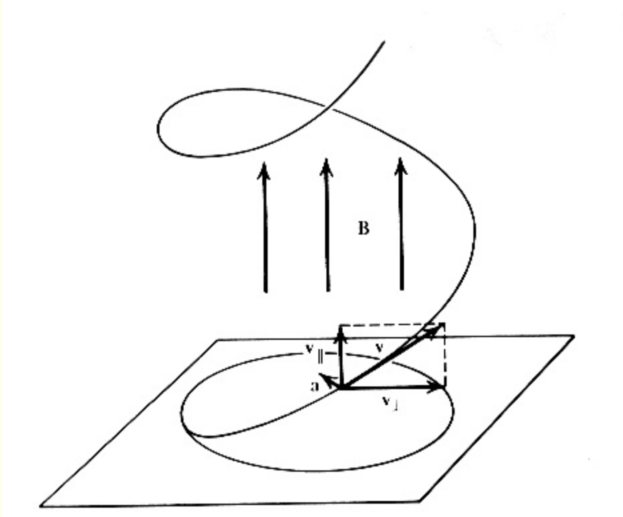
- Emission coefficient $j_\nu \equiv n \frac{dW}{dt\,d\Omega\,d\nu}$ where n is the density of emitters
- Define the Doppler factor $\delta = \Gamma^{-1}(1-\beta\cos\theta)^{-1}$ where Γ is the bulk Lorentz factor of the flow
- Transformations
  - o Frequency $d\nu' = \delta^{-1} d\nu$ (Doppler formula)
  - o Energy $dW' = \delta^{-1} dW$
  - o Time $dt' = \Gamma^{-1} dt$ → $j'_{\nu'} = \delta^{-2} j_\nu$
  - o Density $n' = \Gamma^{-1} n$
  - o Solid angle $d\Omega' = \delta^2 d\Omega$
- Then $S_\nu = \delta^3 \int j'_{\nu'} dV' / D^2$
- If $j'_{\nu'} \propto (\nu')^{-\alpha} \Rightarrow S_\nu = \delta^{3+\alpha} \int j'_{\nu'}{}' dV' / D^2$
- Luminosity $L = \delta^4 L'$

DOPPLER BOOSTING-3

- Doppler factor $\delta = \Gamma^{-1}(1-\beta\cos\theta)^{-1}$
  - o For $\theta < \Gamma^{-1}$ $\rightarrow \delta \sim \Gamma$
  - o For $\Gamma^{-1} < \theta \ll 1$ $\rightarrow \delta \sim \Gamma\theta^2$
  - o For $1 \ll \theta$ $\rightarrow \delta \sim \Gamma^{-1}$
- Relativistically moving sources are boosted when moving towards the observer.
- For AGN jets: $\Gamma \simeq 10$ (typically)
  - o For $\theta < 5^o \rightarrow \delta \sim \Gamma \simeq 10$
  - o Since $L = \delta^4 L' \rightarrow$ observer infers a luminosity higher by a factor of $\sim 10^4$

SYNCHROTRON RADIATION: GENERAL

- Radiation from relativistic electrons accelerated in magnetic fields



- If $\upsilon / c << 1$: Cyclotron motion
- Lorentz force $\frac{d}{dt}(\gamma m \vec{\upsilon}) = \frac{e}{c} \vec{\upsilon} \times \vec{B}$
- No acceleration parallel to B-field → circular motion

$$ma_{\perp} = \frac{\gamma m \upsilon_{\perp}^2}{R} = \frac{e}{c} \upsilon_{\perp} B$$

$$\frac{\upsilon_{\perp}}{R} = \frac{\upsilon \sin\alpha}{R} = \frac{eB}{\gamma mc} = \frac{\omega_L}{\gamma} = \omega_B$$

- $\omega_L = 2\pi\nu_L$ - Larmor frequency
- $R = \frac{\gamma \upsilon_{\perp}}{\omega_L} \simeq 10^7 \frac{E_{GeV}}{B_{Gauss}}$ cm - gyroradius
- $\alpha = \angle(\upsilon, B)$ - pitch angle

SYNCHROTRON RADIATION: ENERGY LOSSES

From relativistic Larmor formula $P = \frac{2e^2}{3c^3}\gamma^4\left(a_\perp^2 + \gamma^2 a_{//}^2\right)$ →

radiated power of a single electron $P = \frac{2}{3}\frac{e^2}{m^2c^3}B^2\beta^2\gamma^2\sin^2\alpha$

Total radiated power (averaged over pitch angles – isotropic distn)

$$P = \frac{4}{3}\sigma_T c\beta^2\gamma^2 U_B$$

where σ_T the Thomson cross section, γ the electron Lorentz factor

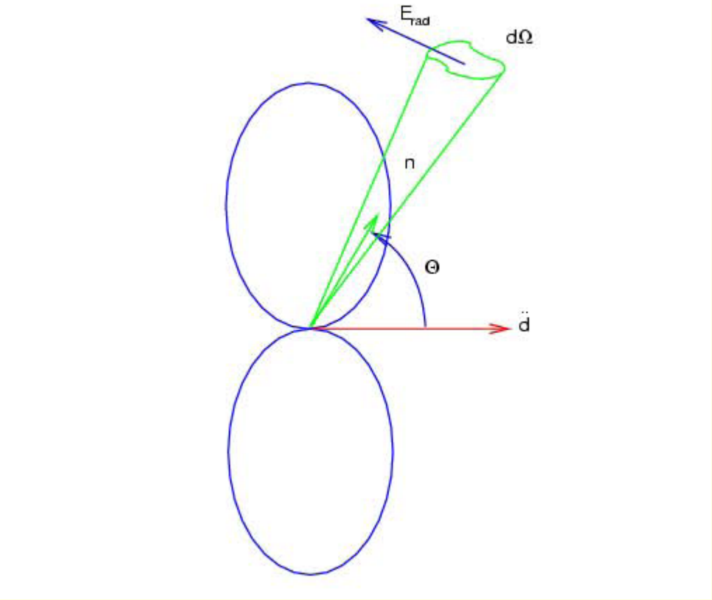
and $U_B = \frac{B^2}{8\pi}$ the magnetic energy density.

Loss timescale

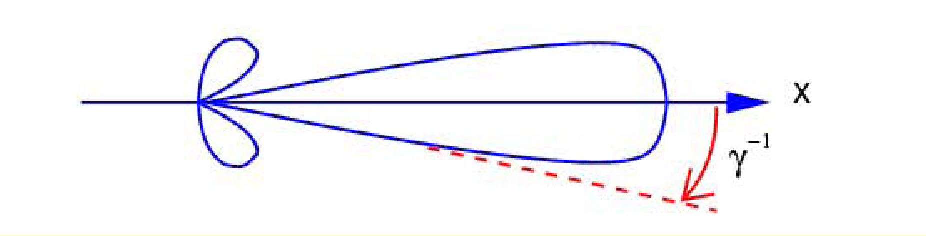
$$\tau_{syn} = \frac{E_e}{P} = \frac{\gamma mc^2}{\frac{4}{3}\sigma_T c\gamma^2 u_B} = 7.7\times10^8\gamma^{-1}B^{-2}\,\sec$$

→ Higher energy electrons lose energy faster

SYNCHROTRON RADIATION: BEAMING

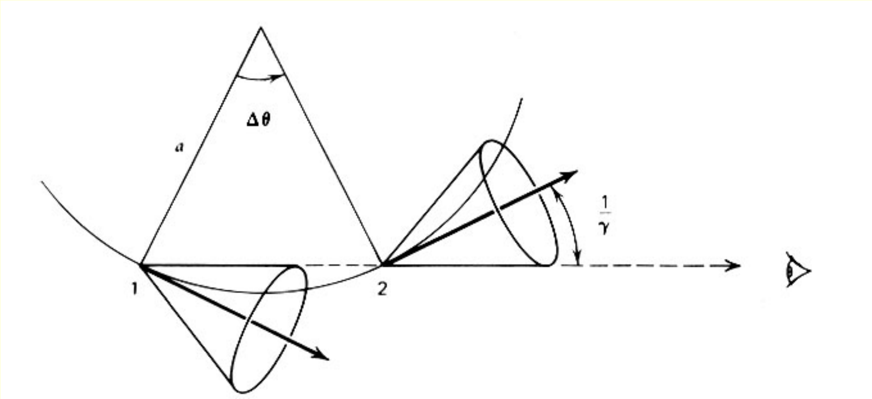


ERF: Emitted spectrum is dipole



Lab Frame:
Forward beaming
Opening angle
$\Delta\theta \approx \gamma^{-1}$

SYNCHROTRON RADIATION: CHARACTERISTIC FREQUENCY



In ERF, observer sees beam during time $\Delta t = \frac{\Delta\theta}{\omega_B} \approx \frac{1}{\omega_L}$

Doppler effect shortens the duration of the pulse

$$\Delta t_{obs} = (1-\beta)\Delta t = \frac{\Delta t}{\gamma^2}$$

Characteristic synchrotron frequency $\omega_c = \gamma^2 \omega_L \sin\alpha = \frac{eB}{mc}\gamma^2 \sin\alpha$

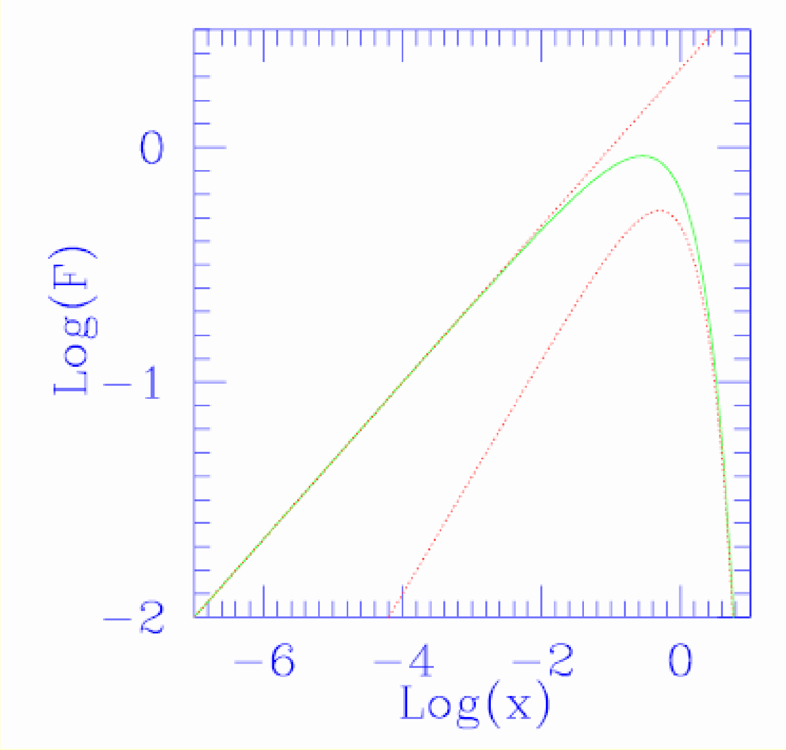
Numerically $\nu_c \simeq 4.10^6 B_{Gauss} \gamma^2 \sin\alpha \ \text{Hz}$

For X-rays

- $\nu_X \simeq 10^{18}$ Hz → $\gamma \approx 5.10^5 B_{Gauss}^{-1}$ → $E \approx 250 B_{Gauss}^{-1} \text{GeV}$
- $\tau_{syn} \simeq 0.5 B_{Gauss}^{-2} \text{hr} \quad (!)$

→ particles need to be replenished → **ACCELERATION**

SYNCHROTRON RADIATION: SINGLE PARTICLE EMISSIVITY



$$\frac{dL_{s.p.}}{d\nu} = j_{syn}(\nu) = \frac{\sqrt{3}e^3 B \sin\alpha}{mc^2} F\left(\frac{\nu}{\nu_c}\right)$$

where

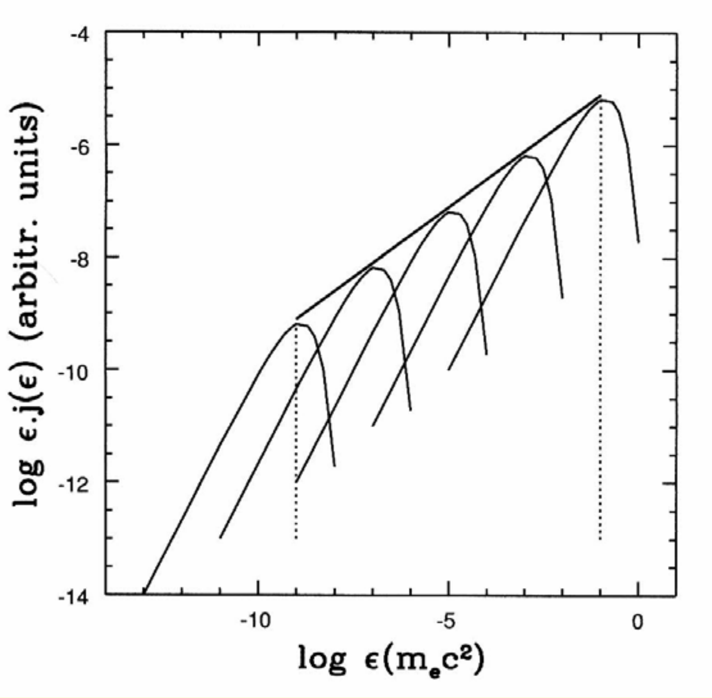
$$F(x) \equiv x \int_x^{\infty} K_{5/3}(\xi) d\xi$$

- Maximum at $x = 0.29$

Asymptotic forms

- $F(x) \approx \frac{4\pi}{\sqrt{3}\Gamma(1/3)} \left(\frac{x}{2}\right)^{1/3} (x \ll 1)$
- $F(x) \approx \sqrt{\frac{x\pi}{2}} \exp(-x) (x \gg 1)$

SYNCHROTRON RADIATION: POWER LAW EMISSION



Important special case: $N_e(\gamma) = k_e \gamma^{-p}$ for $\gamma_{min} \leq \gamma \leq \gamma_{max}$

Photon spectrum obtained from a convolution over single electron emissivity

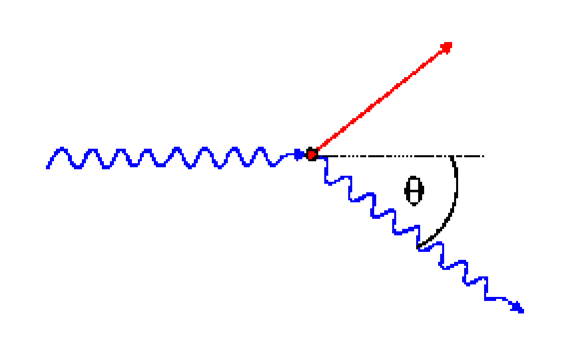
$$I^{pl}_{syn}(\nu) = \int_{\gamma_{min}}^{\gamma_{max}} d\gamma N_e(\gamma) j_{syn}(\nu)$$

$$\Rightarrow I^{pl}_{syn}(\nu) = \frac{2}{3} c \sigma_T k_e \frac{U_B}{\nu_L} \left(\frac{\nu}{\nu_L} \right)^{-\frac{p-1}{2}}$$

provided $\gamma^2_{min} \ll \nu/\nu_L \ll \gamma^2_{max}$

A power-law in electrons results in a power-law photon spectrum

- Thomson scattering (scattering of a photon by an electron at rest) applies at low photon energies $h\nu \ll mc^2$ - Classical approach



- Differential cross section

$$\frac{d\sigma}{d\Omega} = \frac{3}{16\pi}\sigma_T\left(1+\cos^2\theta\right)$$

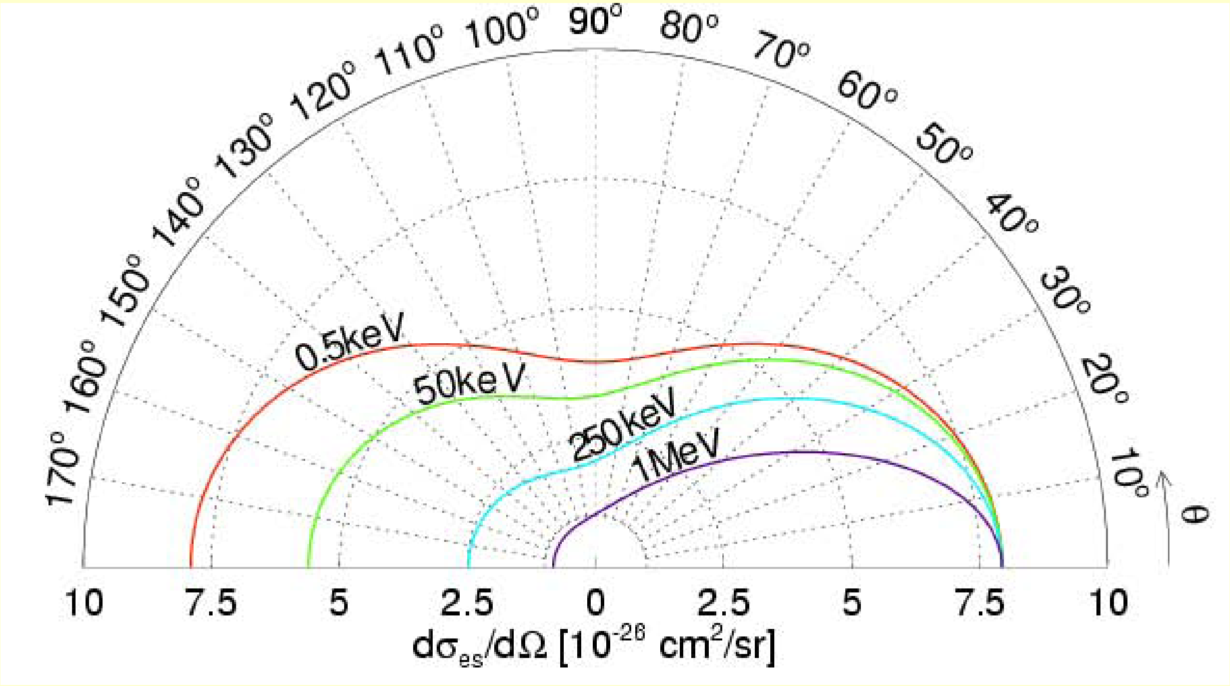
- Photon frequency after scattering

$$\nu_1 = \frac{\nu}{1+\frac{h\nu}{mc^2}(1-\cos\theta)}$$

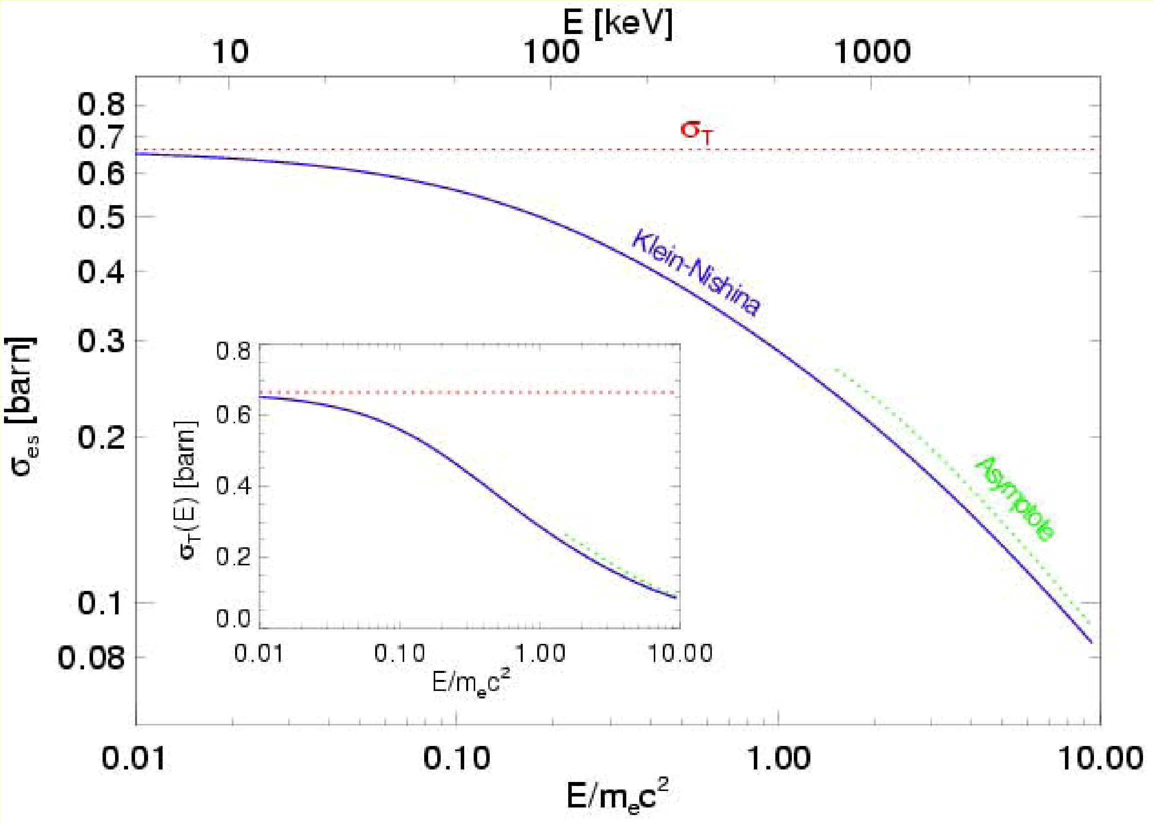
$$\approx \nu \quad (\text{for } h\nu \ll mc^2)$$ → elastic scattering

- For $h\nu \sim mc^2$ recoil important → Thomson formula breaks down and QED has to be used
- Klein-Nishina formula $\frac{d\sigma}{d\Omega} = \frac{3}{16\pi}\sigma_T\left(\frac{\nu_1}{\nu}\right)^2\left(\frac{\nu_1}{\nu}+\frac{\nu}{\nu_1}-\sin^2\theta\right)$

→ Thomson for $\nu_1 \rightarrow \nu$



COMPTON SCATTERING: TOTAL CROSS SECTION

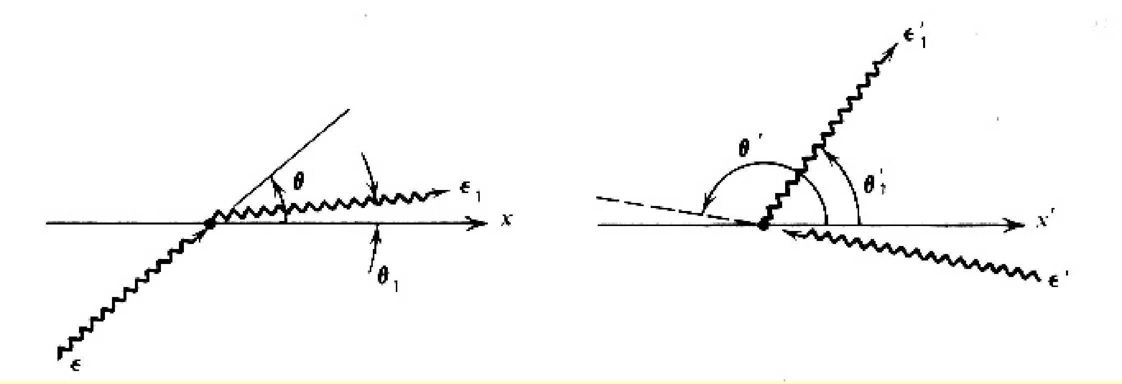


Total cross section: $\sigma_{es} = \int d\Omega \frac{d\sigma}{d\Omega}$

Asymptotes

- $\sigma_{es} = \sigma_T$ for $x = \frac{h\nu}{mc^2} \ll 1$
- $\sigma_{es} = \frac{3}{8}\sigma_T \frac{1}{x}\left(\ln 2x + \frac{1}{2}\right)$ for $x = \frac{h\nu}{mc^2} \gg 1$

INVERSE COMPTON SCATTERING



K (lab frame) K′ (electron frame)

Electron energy $E = \gamma mc^2 >> \varepsilon$ photon energy

Energy is transferred from electrons to photons

Photon energy in ERF $\varepsilon' = \gamma\varepsilon(1-\beta\cos\theta)$

- o If $\frac{\varepsilon'}{mc^2} \ll 1$ → Thomson limit
- o If $\frac{\varepsilon'}{mc^2} \gg 1$ → Klein-Nishina limit

ICS: SCATTERED PHOTON ENERGIES

- Photon energies after and before scattering

$$\frac{\varepsilon_1}{\varepsilon} = \frac{1-(\upsilon/c)\cos\theta}{\left[1-(\upsilon/c)\cos\theta_1 + \left(\varepsilon/\gamma m_e c^2\right)(1-\cos\alpha)\right]}$$

In Thomson regime

- Max energy possible ($\theta=\pi$ -- head-on collision and $\theta_1 = 0$)

$$\varepsilon_1^{max} = 4\gamma^2\varepsilon$$

- Average energy (after angle average)

$$<\varepsilon_1> = \frac{4}{3}\gamma^2\varepsilon = \frac{1}{3}\varepsilon_1^{max}$$

→ ICS can boost photons to high energies

(e.g. for $\gamma = 10^4$ radio $10^{10}\,\mathrm{Hz}$ → X-rays $10^{18}\,\mathrm{Hz}$)

- Forward beaming

$$\cos\theta_1 = \frac{\cos\theta_1' - \beta}{1-\beta\cos\theta_1'} \approx -1 - \frac{1}{\gamma^2(1-\cos\theta_1')}$$

→ scattered photon has (almost) the direction of the electron

ICS: ENERGY LOSSES

- Single electron energy losses $-\left(\frac{dE}{dt}\right) = P = \sigma_T c U'_{ph}$
- Relation between photon energy densities $U'_{ph} = \frac{4}{3} U_{ph} \left(\gamma^2 - \frac{1}{4}\right)$

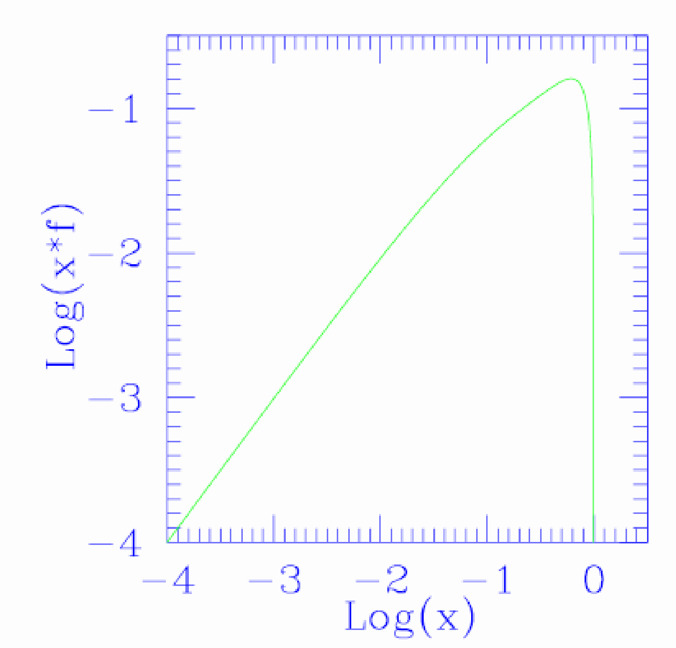
$$-\left(\frac{dE}{dt}\right) = P = \frac{4}{3} \sigma_T c U_{ph} \beta^2 \gamma^2$$

Close analogy to synchrotron radiation: Losses $U_{ph} \rightarrow U_B$

Ratio of emitted powers $\frac{P_{syn}}{P_{ics}} = \frac{U_B}{U_{ph}}$

- If $U_B > U_{ph}$ → synchrotron dominates
- If $U_B < U_{ph}$ → ics dominates

ICS: SINGLE ELECTRON AND POWER LAW EMISSIVITY



Photon spectrum emitted by an electron in an isotropic soft photon field $I(\varepsilon_1) = 3\sigma_T c \int d\varepsilon . n_{ph}(\varepsilon) \frac{\varepsilon_1}{\varepsilon_{ic}} f\left(\frac{\varepsilon_1}{\varepsilon_{ic}}\right)$

where $\varepsilon_{ic} = 4\gamma^2\varepsilon$,

$f(x) = 2x\ln x + x + 1 - 2x^2$ for $x < 1$

For $x > 1$ (i.e. $\varepsilon_1 > 4\gamma^2\varepsilon$)

→ $f(x) = 0$ (kinematics!)

As in synchrotron: A power-law of electrons gives a power-law photon spectrum

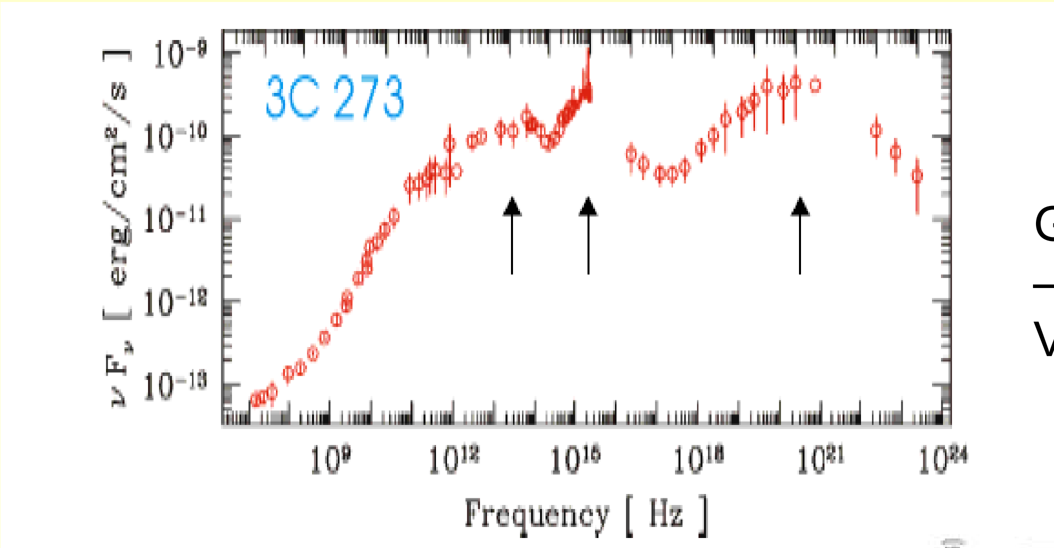
$$N_e(\gamma) = k_e \gamma^{-p} \Rightarrow I_{ics}^{pl}(\varepsilon_1) = \frac{2}{3} c\sigma_T k_e \frac{U_{ph}}{\varepsilon}\left(\frac{\varepsilon_1}{\varepsilon}\right)^{-\frac{p-1}{2}} \text{ provided } \gamma_{min}^2 \ll \varepsilon_1/\varepsilon \ll \gamma_{max}^2$$

SYNCHRO SELF-COMPTON

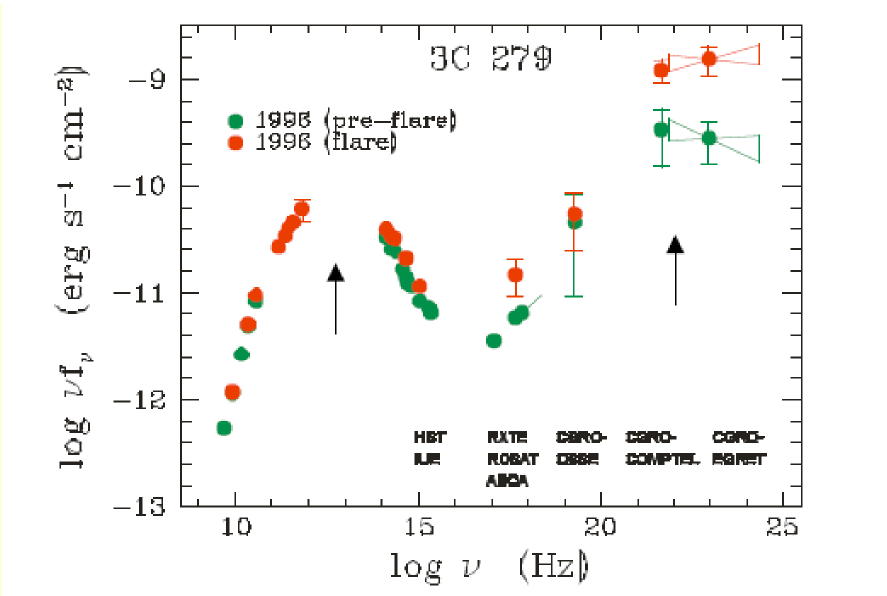
- In compact sources → electrons lose energy via ics on their own synchrotron photons → Synchro self-Compton (SSC)
- As $j_s \propto n_e$ and $j_c \propto n_e n_{ph}$ → $j_{ssc} \propto n_e^2$, i.e, a non-linear process
- For $N_e(\gamma) = k_e \gamma^{-p}$ $(\gamma_{min} \le \gamma \le \gamma_{max})$ → SSC emissivity

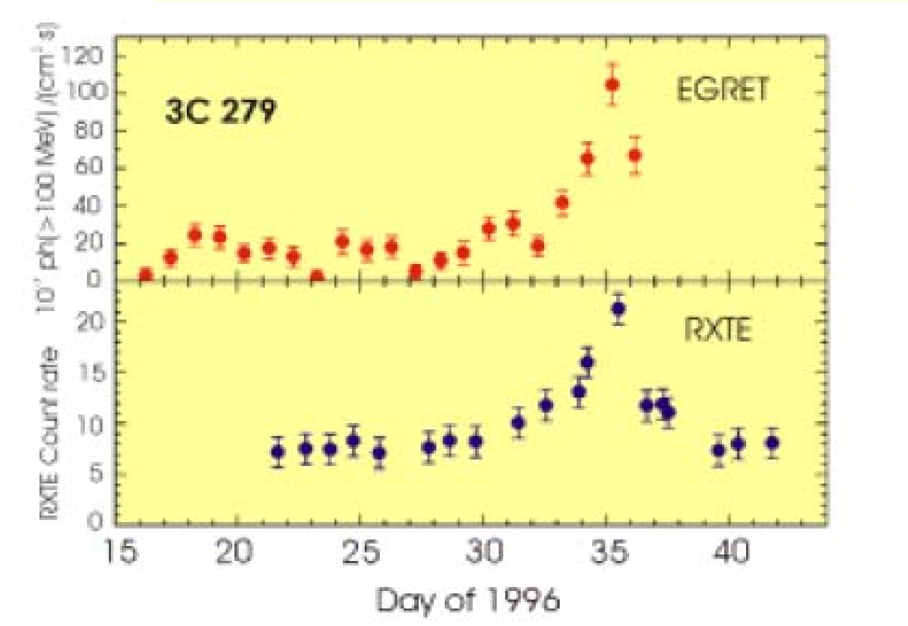
$$I_{ssc}^{pl}(\nu) \propto k_e^2 \left(\frac{\nu}{\nu_L}\right)^{-\frac{p-1}{2}} \ln \Sigma_G \quad \text{for } \nu_L \gamma_{min}^4 \ll \nu \ll \nu_L \gamma_{max}^4$$

- If $U_B < U_{syn}$ → electrons will lose energy not by synchrotron but by ssc → higher order Compton scatterings → a loop leading to **Compton Catastrophe**



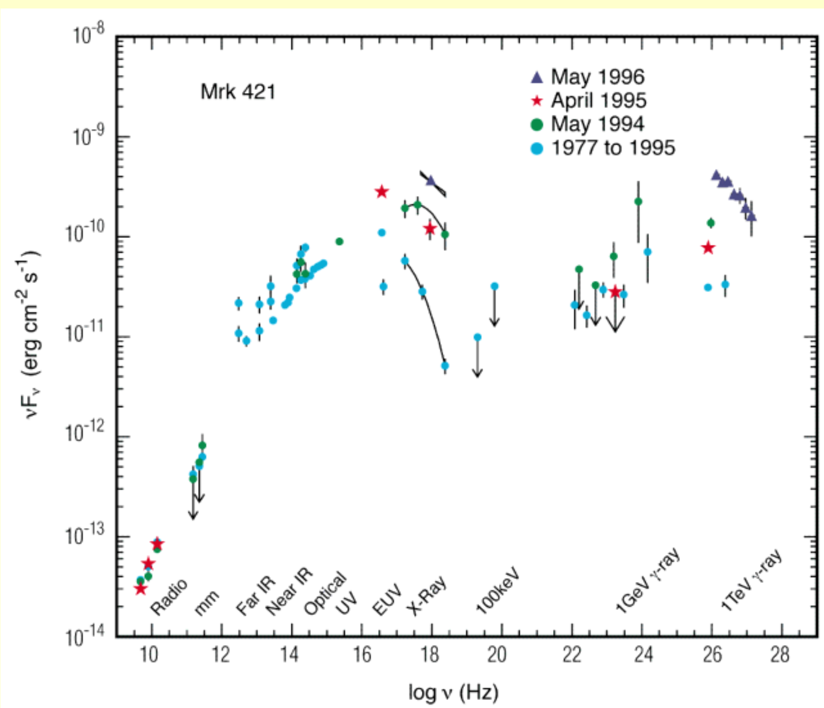
Gamma-ray luminosity ~1.e47 – 1.e49 erg/sec
Variability timescales ~ days

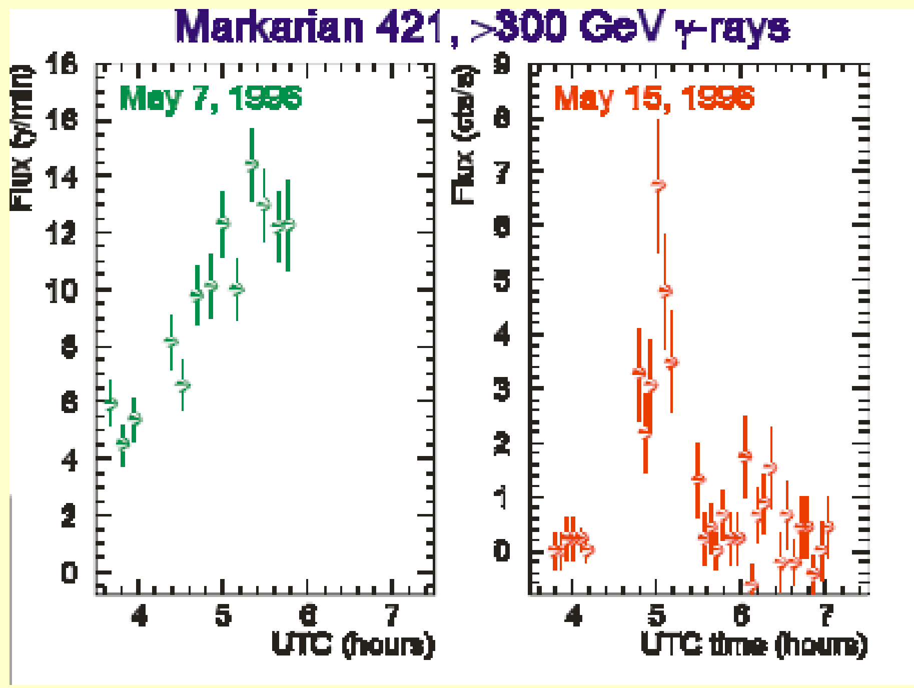




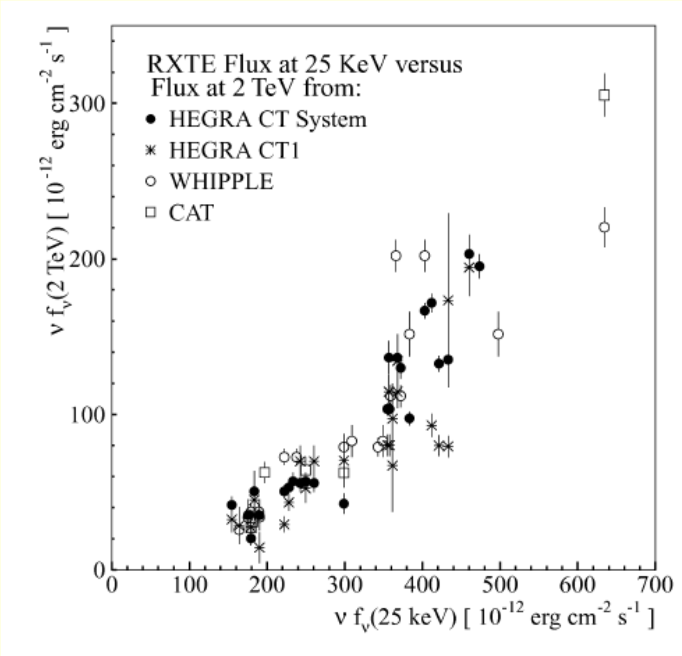
TeV BLAZARS

An expanding list!
Mostly nearby objexts
Gamma-ray luminosity ~1.e44 – 1.e45 erg/sec
Variability timescales ~ hrs
In 2005: Mkn501 varied in mins !



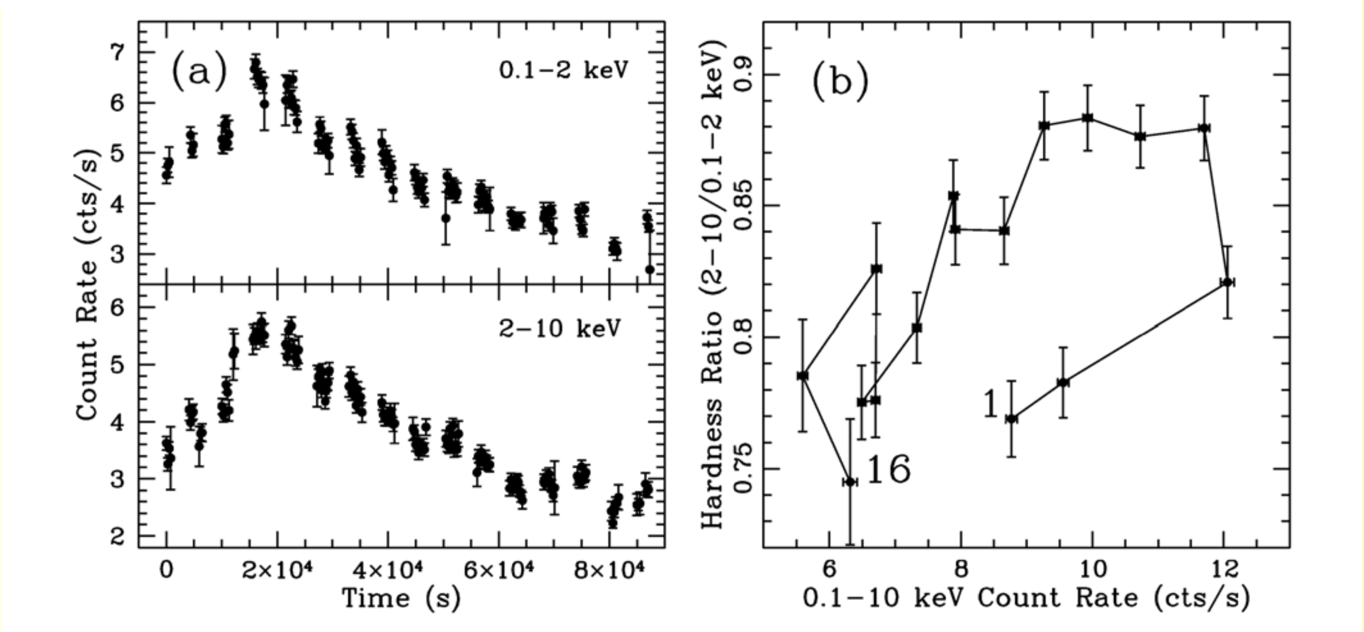


CORRELATIONS AND LOOPS



X-ray – TeV correlation during a flare
In Mkn 421: synchrotron and ics from
the same population of relativistic electrons?

Loop in X-rays during a flare: synchrotron
cooling or particle acceleration?



BLAZAR EMISSION: THE COMMON WISDOM

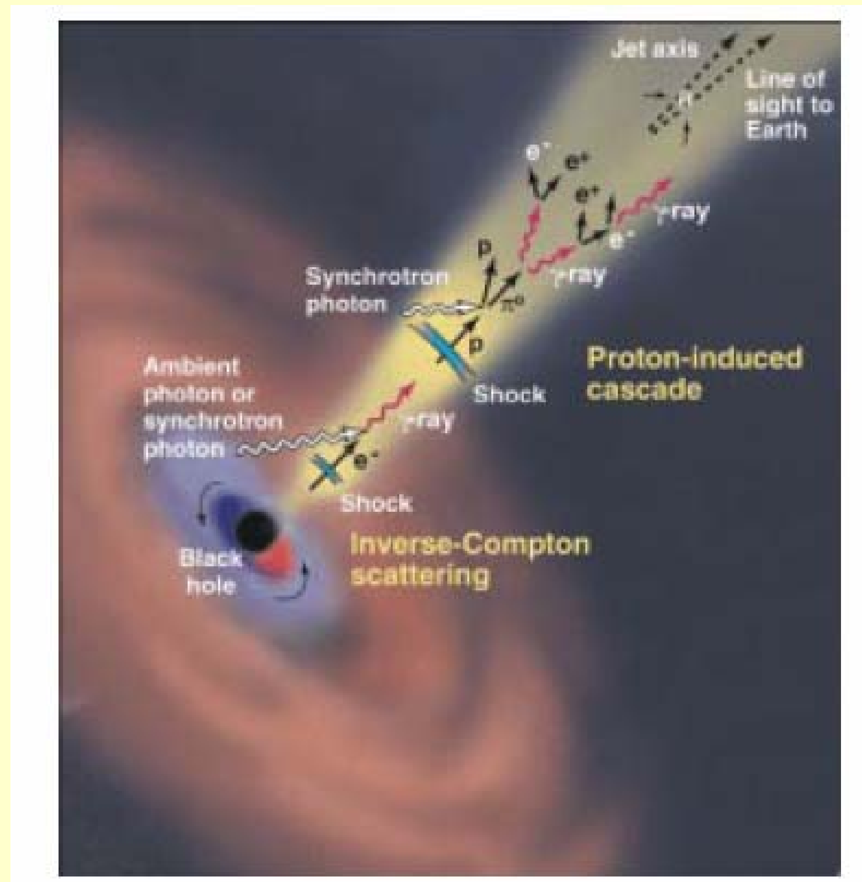
- Collimated outflows of high Lorentz factors → jets
- Conversion of the internal energy to random through shocks
- Particle acceleration and radiation

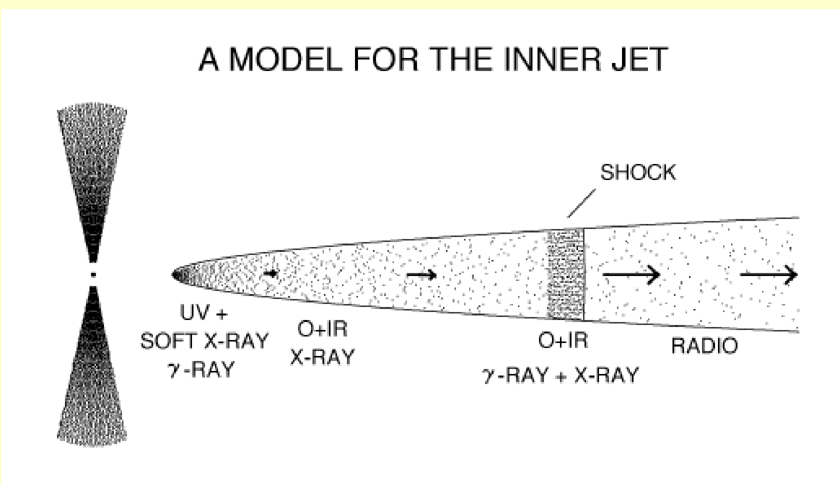
→Gamma-rays: ICS

→X-rays: synchrotron or ICS

The usual questions

- Where?
- How?
- Why?



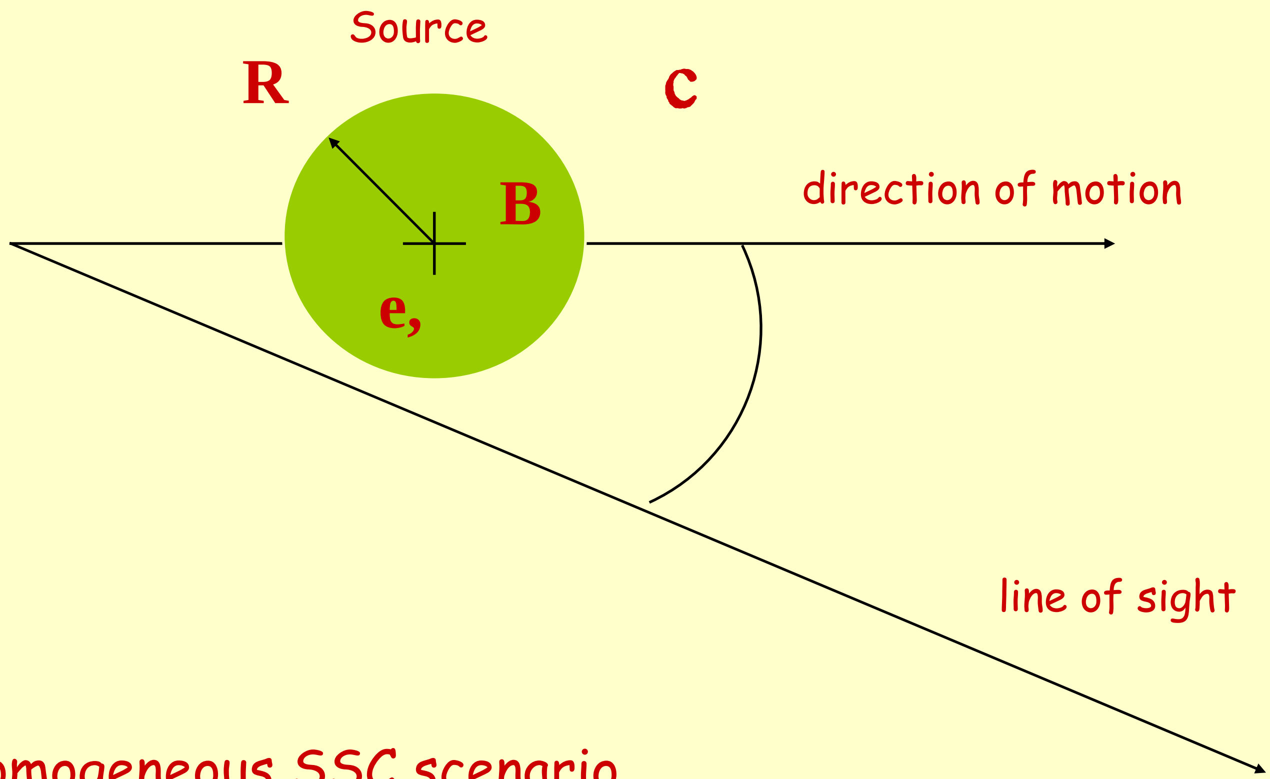


Electrons:

$$\dot{n}_e(\gamma,t) + L_e(n_e,n_\gamma,\gamma,t) + Q_e(n_e,n_\gamma,\gamma,t) = 0$$

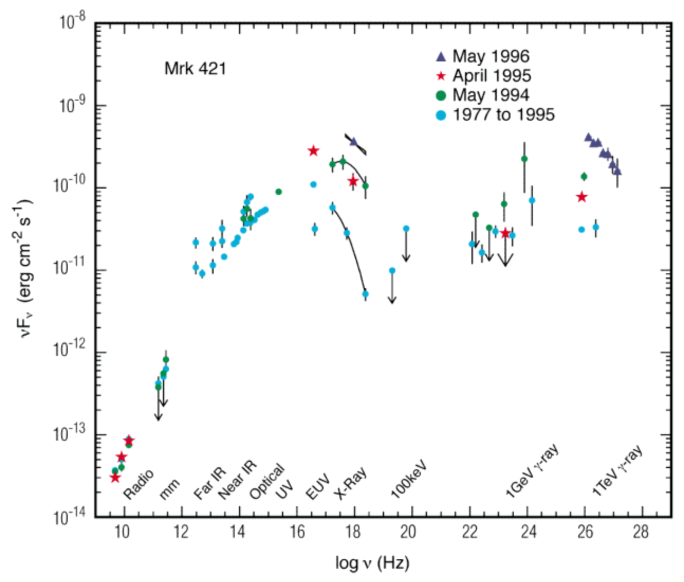
Photons:

$$\dot{n}_\gamma(x,t) + L_\gamma(n_e,n_\gamma,x,t) + Q_\gamma(n_e,n_\gamma,x,t) = 0$$



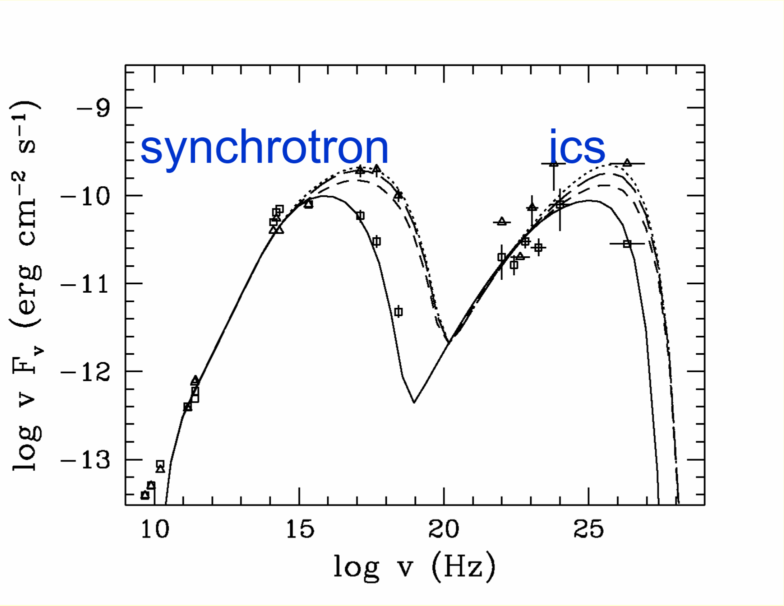
Homogeneous SSC scenario

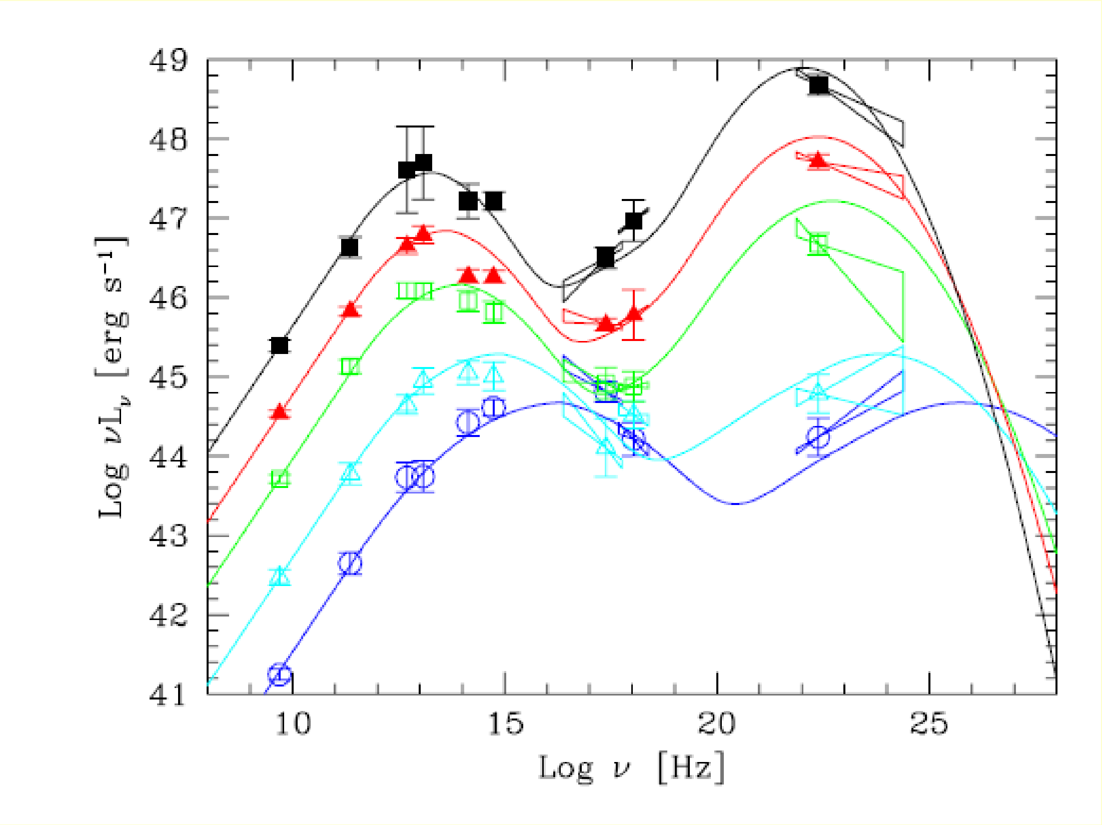
MODELS FOR BLAZARS-1



Multi-wavelength spectrum of TeV blazar Mkn 421

Fit of the above source → seven observables and seven parameters → estimates on the Doppler factor, the size of the source, the magnetic field and the specifics of relativistic electrons (high energy cut-off, spectral index)





Multiwavelength specta (and fits) of gamma-ray blazars:

X-rays in the less luminous AGNs→ synchrotron radiation from the high energy end of the relativistic electron population.

X-rays in the more luminous AGNs→ ics radiation from the low energy end of the relativistic electron population.

(X-RAY) RADIATION PROCESSES IN RADIO-QUIET AGNs

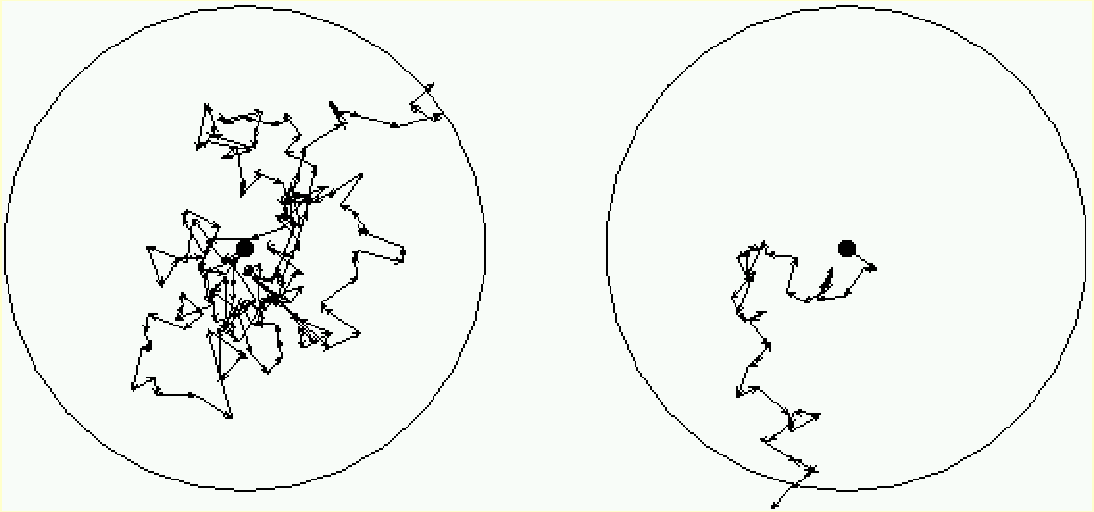
- Comptonization
- Bremsstrahlung
- Photoabsorption
- Modelling

COMPTONIZATION: THE FRAMEWORK

- Assume an 'electron' cloud
- Input photon spectrum → Repeated Compton scatterings → Final photon spectrum?
- Of central importance: Compton y parameter

$$y = \begin{pmatrix} \text{energy} \\ \text{change/} \\ \text{scattering} \end{pmatrix} \times \begin{pmatrix} \text{number} \\ \text{of} \\ \text{scatterings} \end{pmatrix}$$

- $y > 1$: Significant modification of input spectrum



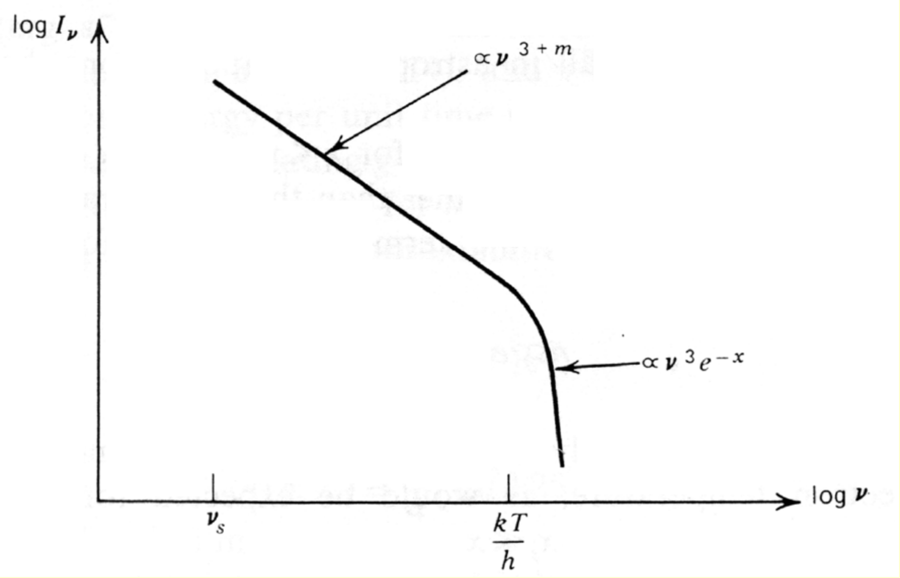
- Spherical region of radius R containing electrons with number density n_e.
- Optical depth to Compton scattering (Thomson regime):

$$\tau_T = n_e \sigma_T R$$

- Probability for photons (emitted at the center) escaping without interacting $P_{esc} = \exp(-\tau_T)$
- The rest will undergo one or more isotropic scatterings → Diffusion in space → Random walk
- Average number of scatterings before escape $N_{esc} \approx \max(\tau_T, \tau_T^2)$

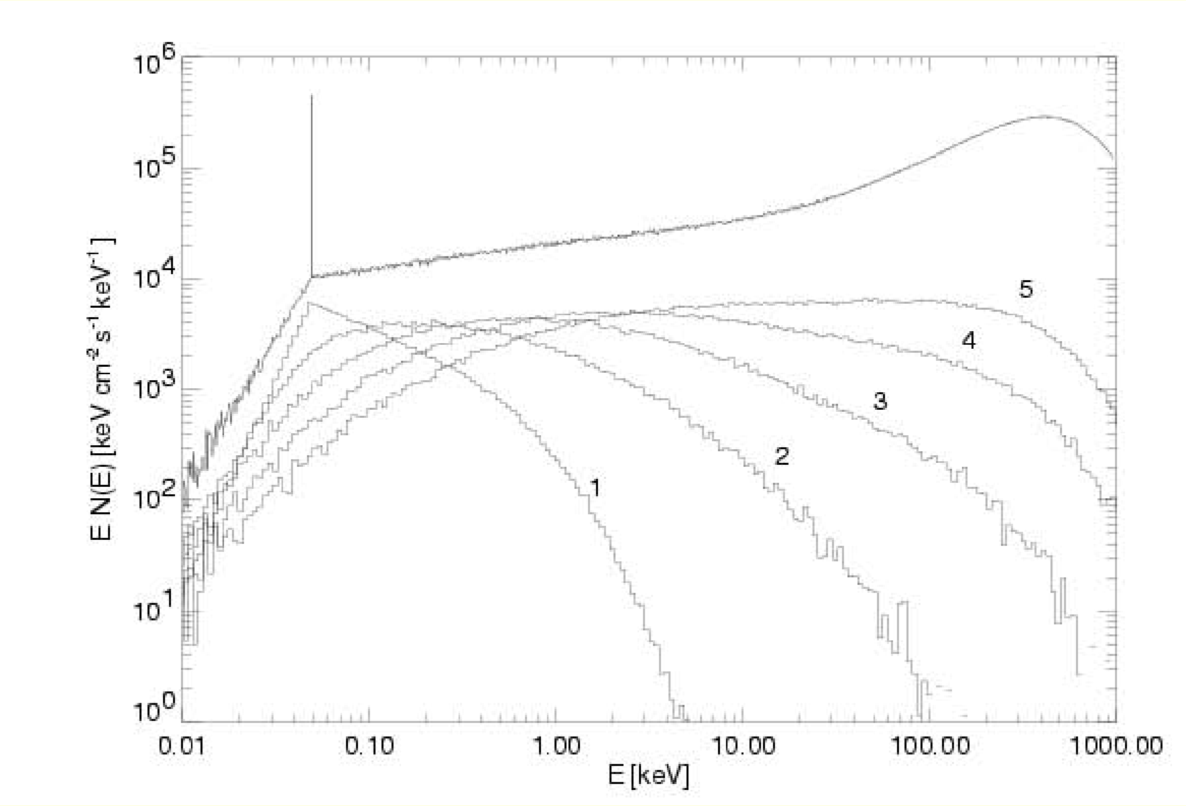
COMPTONIZATION: ENERGY EXCHANGE

- Assume that electrons have temperature T_e
- If electrons 'colder' than the photons: Compton formula $\frac{\Delta\varepsilon}{\varepsilon} = -\frac{\varepsilon}{mc^2}$
- If electrons 'hotter' than the photons: $\frac{\Delta\varepsilon}{\varepsilon} = \frac{4kT_e}{mc^2}$
- Overall $\frac{\Delta\varepsilon}{\varepsilon} = -\frac{\varepsilon}{mc^2} + \frac{4kT_e}{mc^2}$
    - If $\varepsilon < 4kT_e$ → energy is transferred to the photons
    - If $\varepsilon > 4kT_e$ → energy is transferred to the electrons
    - $\varepsilon = 4kT_e$ EQUILIBRIUM
      → Photons diffuse in energy
- Compton parameter (for photon gain) $y = \frac{4kT}{mc^2} \max(\tau_T, \tau_T^2)$



- To obtain Comptonized photon spectrum → Kompaneets equation
- Solution for special cases ($x = h\nu/kT_e$)
  - $I_\nu \propto x^{3+p}$ for x<<1
  - $I_\nu \propto x^3 e^{-x}$ for x>>1 (Wien)
  - Index $p = -\frac{3}{2} \pm \sqrt{\frac{9}{4} + \frac{4}{y}}$
    - For y>>1 → keep the (+) root → $I_\nu \propto x^3$ (low frequency Wien limit)
    - For y<<1 → keep the (–) root → $I_\nu \propto x^{-1/y}$ (steep power law)
    - For $y \geq 1$ → $p > -4$ → energy amplification

COMPTONIZATION: MONTE CARLO

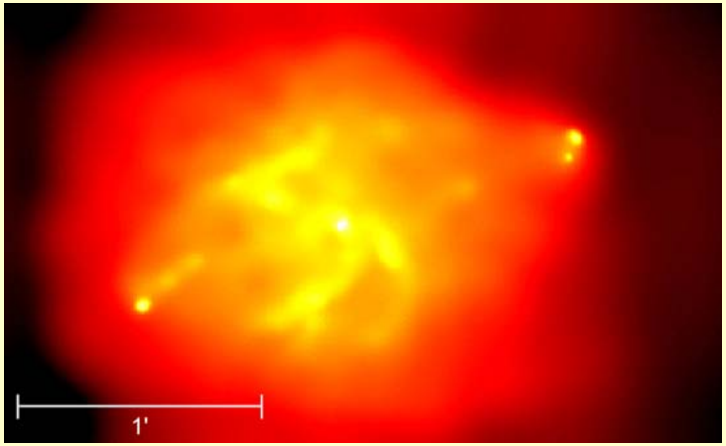


- For general cases: Monte Carlo approach → good agreement with analytical solutions (where available)

COMPTONIZATION: CONCLUSIONS

Hot electrons can upscatter soft photons to high energies
Spectrum characterized by a power law continuum and an exponential turnover
Photon spectral index depends on the Compton parameter y, i.e. a combination of the optical depth and the temperature of the electrons
For $kT_e \simeq 100$ keV, photon spectrum extends up to hard X-rays (however relativistic effects start becoming important!)
Spectral fits to observations?
Source of hot electrons and geometry?

BREMSSTRAHLUNG IN A NUTSHELL



Radiation due to acceleration of a charge in the Coulomb field of another charge

Electrons of velocity υ and density n_e emit a photon spectrum

$$\frac{dW}{d\omega dt dV} = \frac{16e^6}{3c^3 m^2 \upsilon} n_e n_i Z^2 g_{ff}(\upsilon, \omega)$$

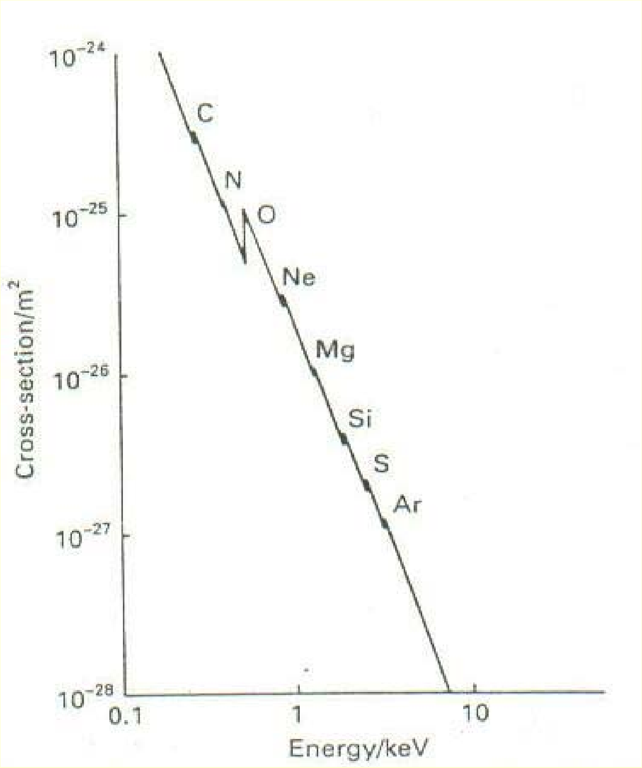
where g_{ff} is the Gaunt factor, a slowly varying function of υ and ω

If electrons have a thermal distribution →

$$j_{ff} \propto T^{-1/2} n_e n_i Z^2 e^{-h\nu/kT} \bar{g}_{ff}$$

Thermal bremsstrahlung has a flat spectrum $I_\nu \propto j_{ff} \propto \text{const}$ up to an exponential cut-off characteristic of the gas temperature

PHOTOABSORPTION-1



If matter not fully ionized → photons can be absorbed by atoms → line emission at $\varepsilon = E_1$ (photoelectric effect)

Cross section (QED) for $\varepsilon > E_1$ (i.e. above the absorption edge) $\sigma_p \propto \varepsilon^{-3}$

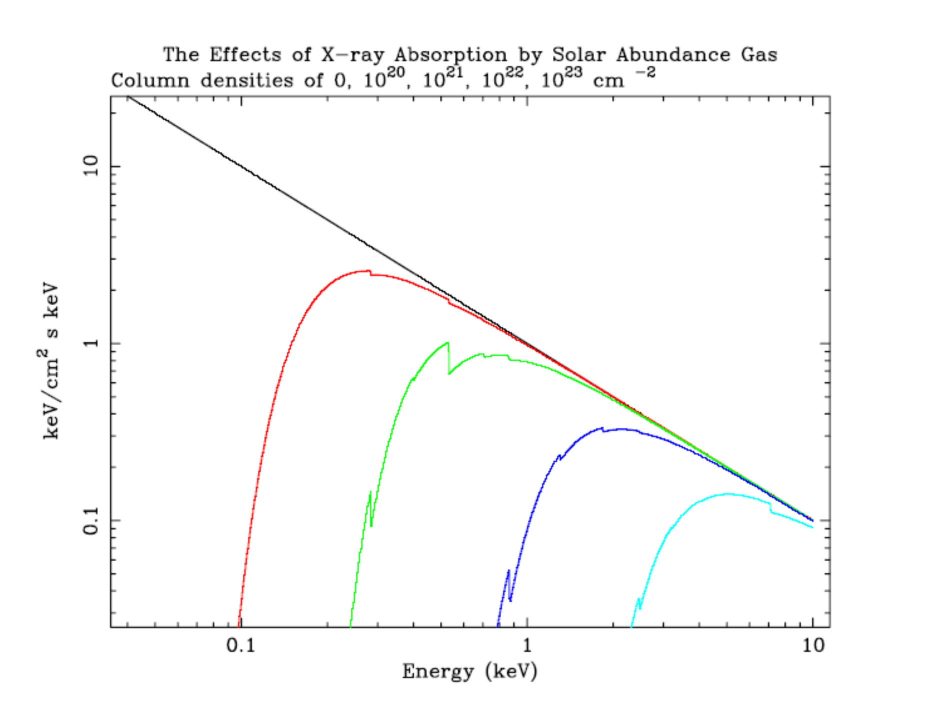
Optical depth for species i

$$\tau_{pi} = \int dl \sigma_{pi}(\varepsilon) n_i$$

Total optical depth for matter consisting of various elements

$$\tau_p = \sum \tau_{pi}$$

PHOTOABSORPTION-2



Column density $N_H = \int dl . \sum n_i$ (units cm^{-2})

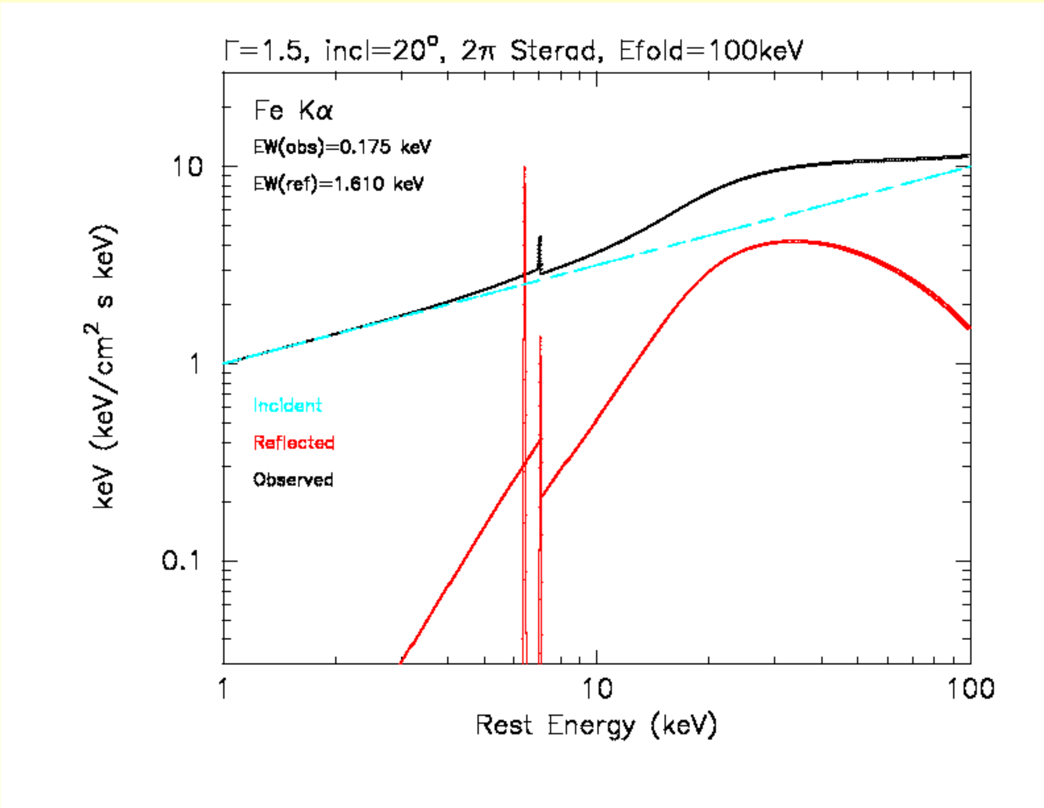
If X-rays of energy ε pass through a 'screen' of matter of column density N_H, only a fraction $\exp\{-\tau_p(\varepsilon)\} = \exp\{-N_H \sigma_p(\varepsilon)\}$ will escape

As $\tau_p \propto \sigma_p \propto \varepsilon^{-3} \rightarrow \tau_p$ increases steeply with decreasing ε →

efficient absorption of X-rays below a certain energy $\varepsilon_b\left(N_H, Z/Z_\odot\right)$

Important consequence: line emission (Fe K-a at 6.4 keV)

REFLECTION

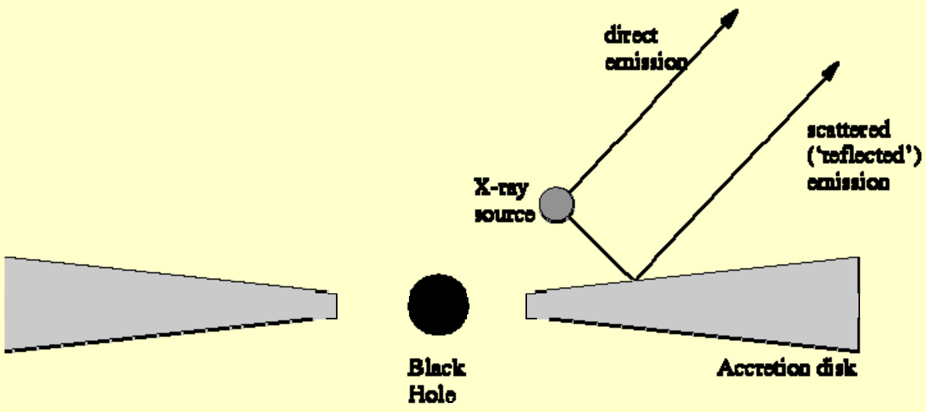


- Assume a power-law of X-rays illuminating cold material
- At low energies X-rays will be absorbed by photoabsorption
- At high energies X-rays have higher penetration and also lose substantial fraction of their energy in collisions with electrons

$$\left(\frac{\Delta\varepsilon}{\varepsilon} = -\frac{\varepsilon}{mc^2}\right)$$

(little photoabsorption + almost elastic scattering)

MODEL FITS TO X-RAYS FROM RADIO QUIET AGNs

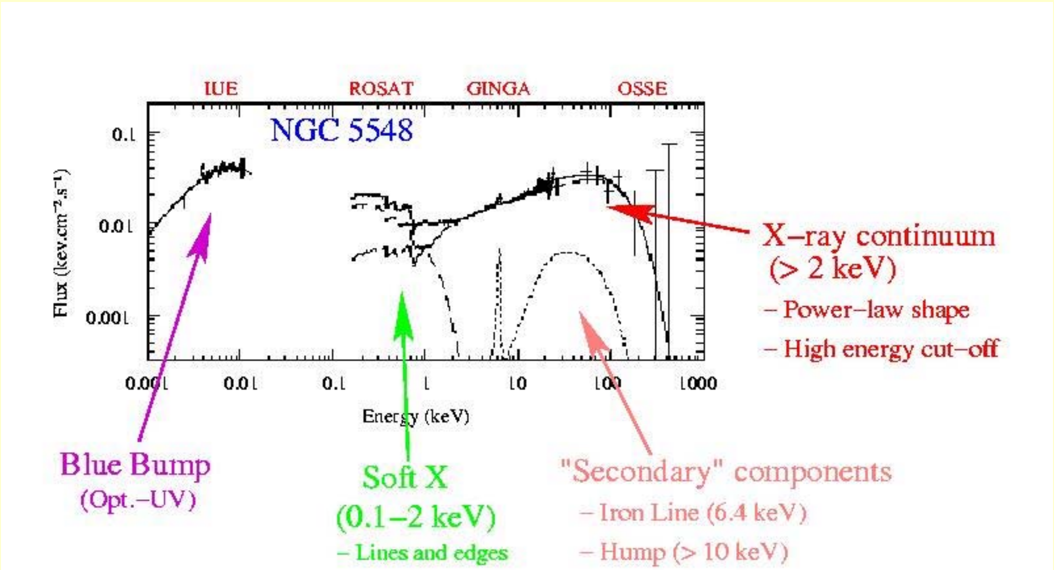


X-ray corona of hot electrons Comptonizes accretion disk photons

Part of X-rays escape and are observed

Part of X-rays hit the disk and are reprocessed → reflection component

Questions:
- Energetics
- Geometry
- Feedbacks



CONCLUSIONS

X- and gamma-rays from blazars

- Are produced from synchrotron radiation (X) and inverse Compton scattering (gamma).
- Their flux is well correlated (multi-wavelength campaigns)
- Require particle acceleration to very high energies + relativistic beaming → jet related phenomena

X-rays from radio-quiet AGNs

- Are produced from mildly relativistic electrons close to the central black hole
- To understand their spectra we need to add various components which absorb and reflect the radiation
- Fe Ka line is an important diagnostic tool

Unified model of active galactic nucleai