Accreting supermassive BH

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Overview

- AGN; what are they
- The power source
- Accretion: the “standard” model
- Accretion: high and low accretion rates
- The SED: radio quiet – radio loud
- The X-ray spectrum radio quiet
- Relativistic beaming
- The X-ray spectrum radio-loud

Overview

Black hole accreting systems:

Active Galactic Nuclei

Black Hole Binary Systems/ Microquasars

Gamma-Ray Bursts

☐ AGN: what are they?

☐ The `paradigm': black hole
accretion
jets
+ torus, line emitting gas, ….

AGN: what are they?

Ac

mma

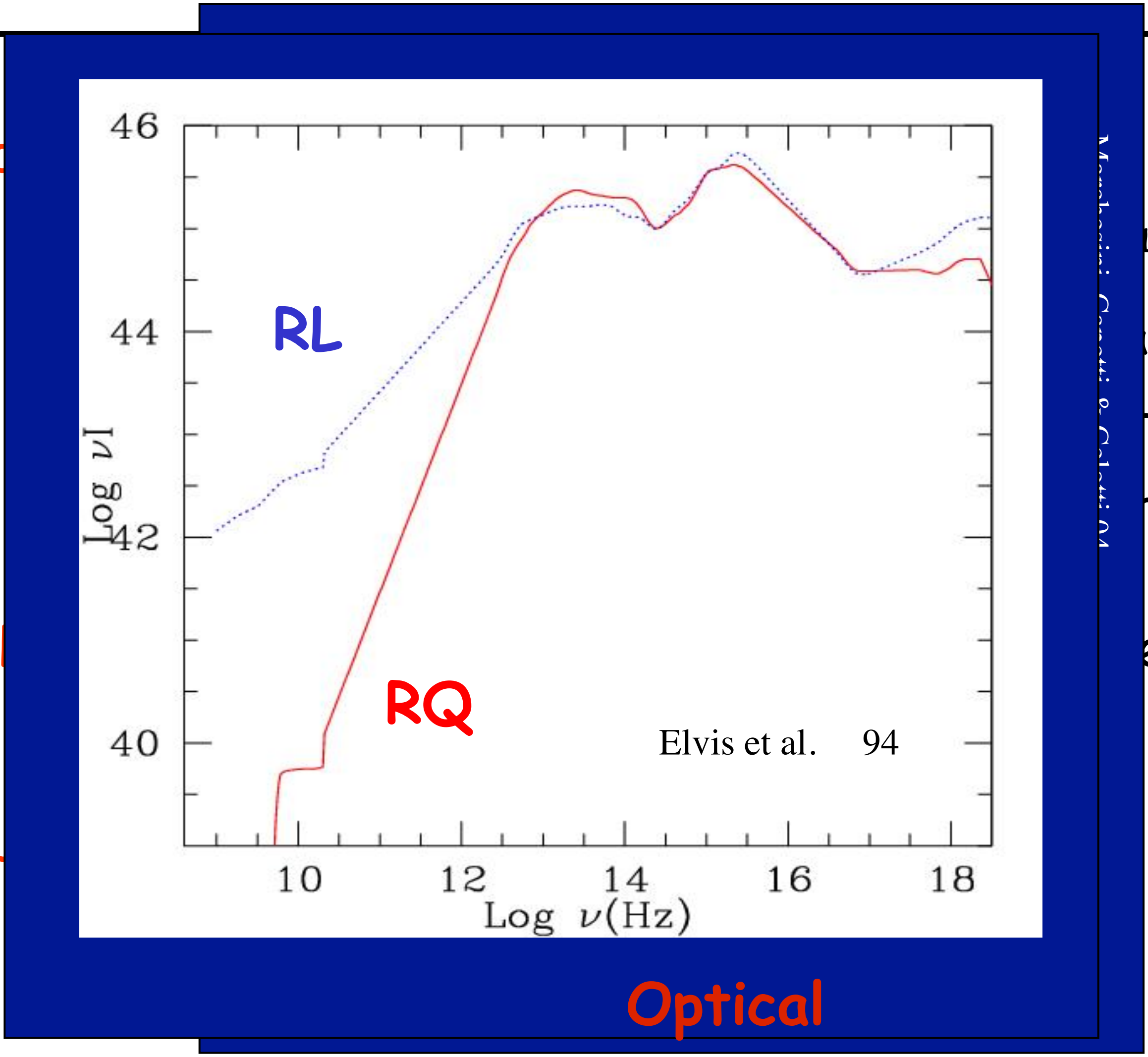
~ 100 s

n lines…

Gal

es

Nu



Black holes (1)

Large luminosity from small volume

efficiency $\varepsilon = E/ Mc^2$

$\varepsilon_{chem} = 1\ eV / 10\ m_p \sim 10^{-10}$

$\varepsilon_{nucl} = 8$ MeV/nucleon $\sim 8 \times 10^{-3}$

$\varepsilon_{grav} = G M / R\ m_p c^2 \sim 6 \times 10^{-2}$ Schwarzchild

0.3-0.4 max Kerr

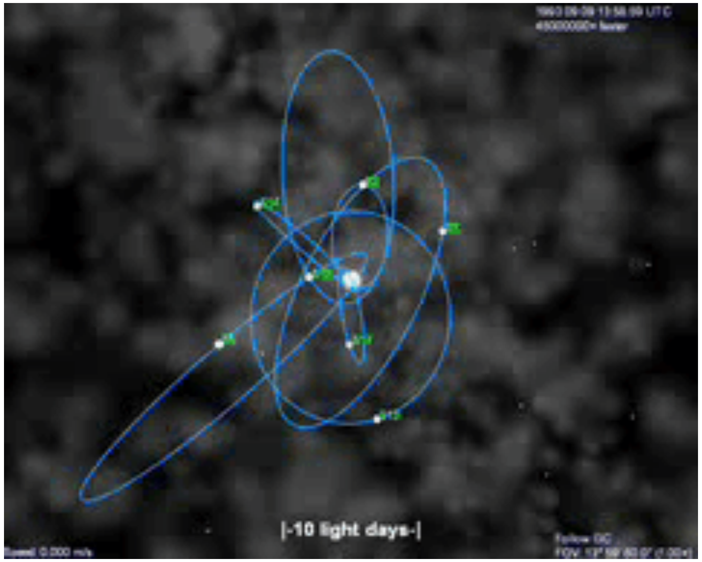
→ Black holes

→ compactness L/R → High photon density

Black holes (2)

Masses? L~ 10^{46} erg s^{-1} → M 10^{8} M

E ~ 10^{60} erg,



Direct estimates of BH mas

stellar dynar

gas dynamic

reverberation mapping

Fe Kα X-ray line

> Most (all?) galaxies host a supermassive BH

Accretion (1)

Energy = potential energy of gas in the BH gravitational field

How is it converted into radiation?

`Accretion'
- ~~Low angular momentum ➔ free fall~~
- High angular momentum ➔ disc

Loss of angular momentum ➔ loss of energy
➔ dissipation heats gas
➔ radiation

due to 'viscosity' (MRI)

Accretion (2)

Reference (o.m.) values of physical parameters:

$L \sim L_{Edd} = (4p\ G m_p\ c\ /\ \sigma_T\ )\ M \sim 1.5 \times 10^{46}\ M_8\ \mathrm{erg\ s^{-1}}$

$R \sim R_s = (2\ G/c^2)\ M \sim 1.5 \times 10^{13}\ \ M_8\ \mathrm{cm}$

$M_8 = 10^8\ M_{sun}$

$t \sim R_s/c^2 \sim 500\ M_8\ \mathrm{s}$

$\dot{M} \sim L_{Edd}/c^2 \sim 10^{25}\ \mathrm{gr\ s^{-1}} \sim 0.2\ M_8\ \mathrm{yr^{-1}}$

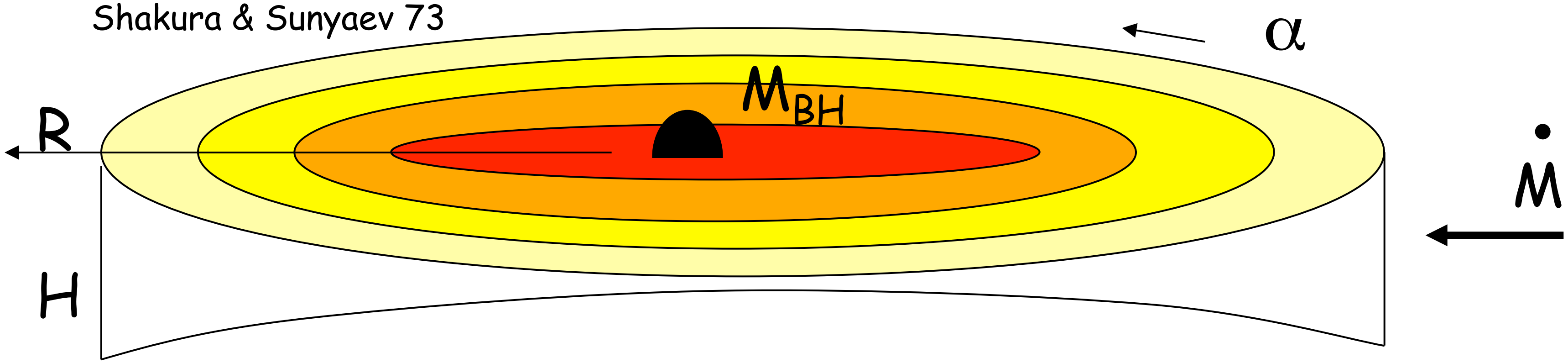
$T_E \sim (L_{Edd}/\pi\ \sigma\ R_s)^{1/4}\ \sim 5 \times 10^5\ \ M_8^{1/4}\ \mathrm{K}$

$T_{vir} \sim G\ m_p M\ /\ R_s \sim 5 \times 10^{12}\ \mathrm{K}$

$B_E = 8\pi\ (L_{Edd}/4\pi\ R_s^2\ c)^{1/2} \sim 4 \times 10^4\ M_8^{-1/2}\ \ \mathrm{G}$

Accretion (3)

Shakura & Sunyaev 73



Keplerian orbits

H/R << 1 – 'cold' disc

Optically thick ➔ blackbody

Local dissipation

Stationary

Pseudo Newtonian potential – relevant close to R_s

verified a posteriori ⟷ $\dot{M} < 0.2\ \dot{M}_{Edd}$

Energy, momentum, mass conservation (vertically integrated)

Accretion (4)

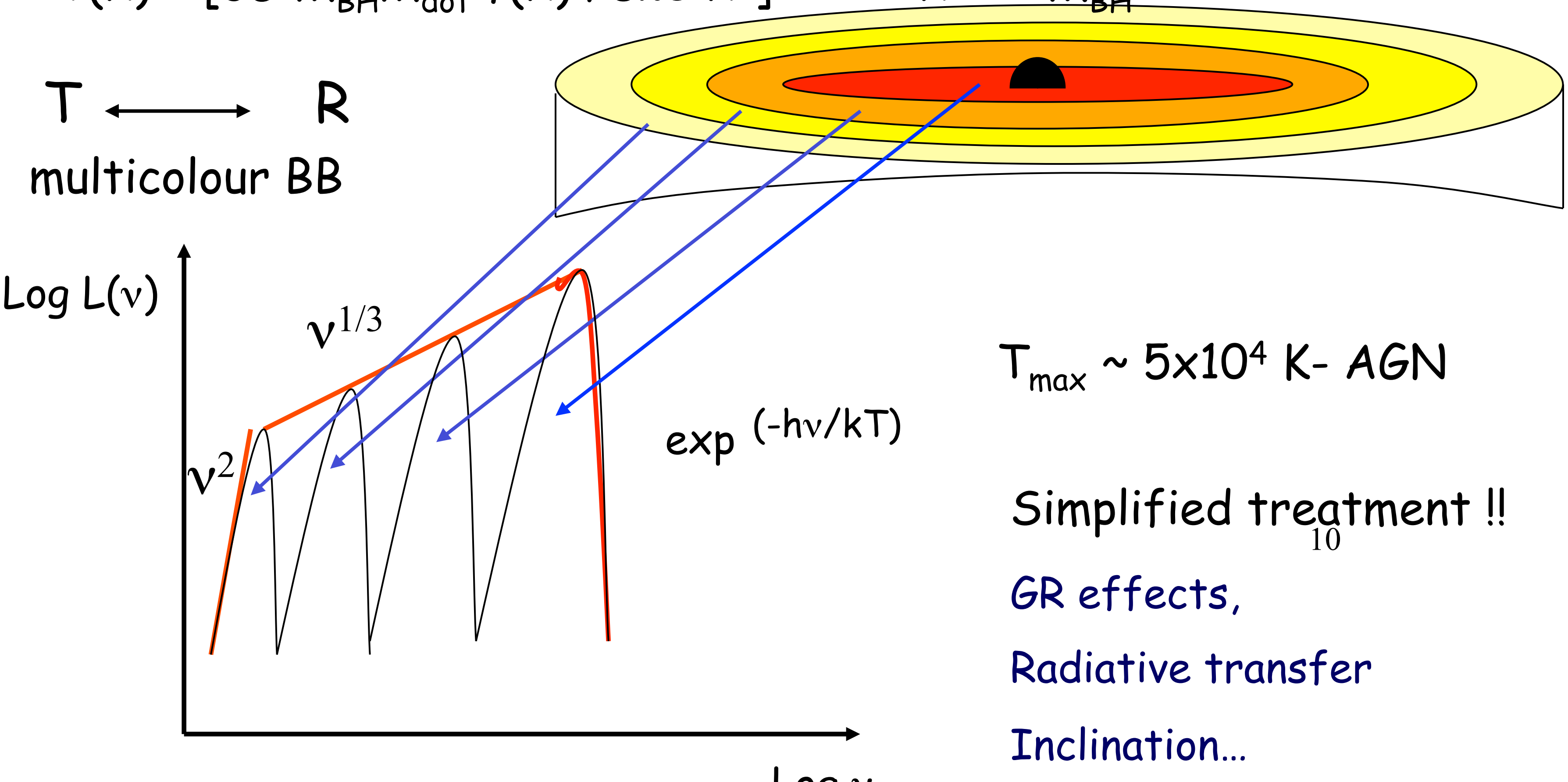
Input parameters: M_{BH}, M_{dot} , viscosity α

➔ Analytic solutions for Q^{-}_{rad} (R), T(R), H(R), …

$$T(R) = [3G\, M_{BH} M_{dot}\, f(R)\, /8\pi\sigma\, R^3]^{1/4} \sim R^{-3/4}\, M_{BH}^{1/4}$$

T ⟷ R

multicolour BB



$T_{max} \sim 5\times10^4$ K- AGN

Simplified treatment !!

GR effects,

Radiative transfer

Inclination…

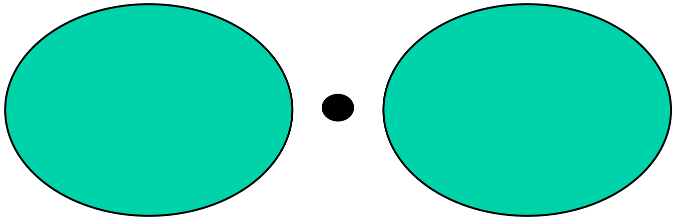
Accretion (5)

$\dot{M} \ll \dot{M}_{Edd}$ ➔ $t_{coul} < t_{infall}$

➔ Ion supported torii

Radiative inefficient accretion flows

`Inactive' galaxies ?



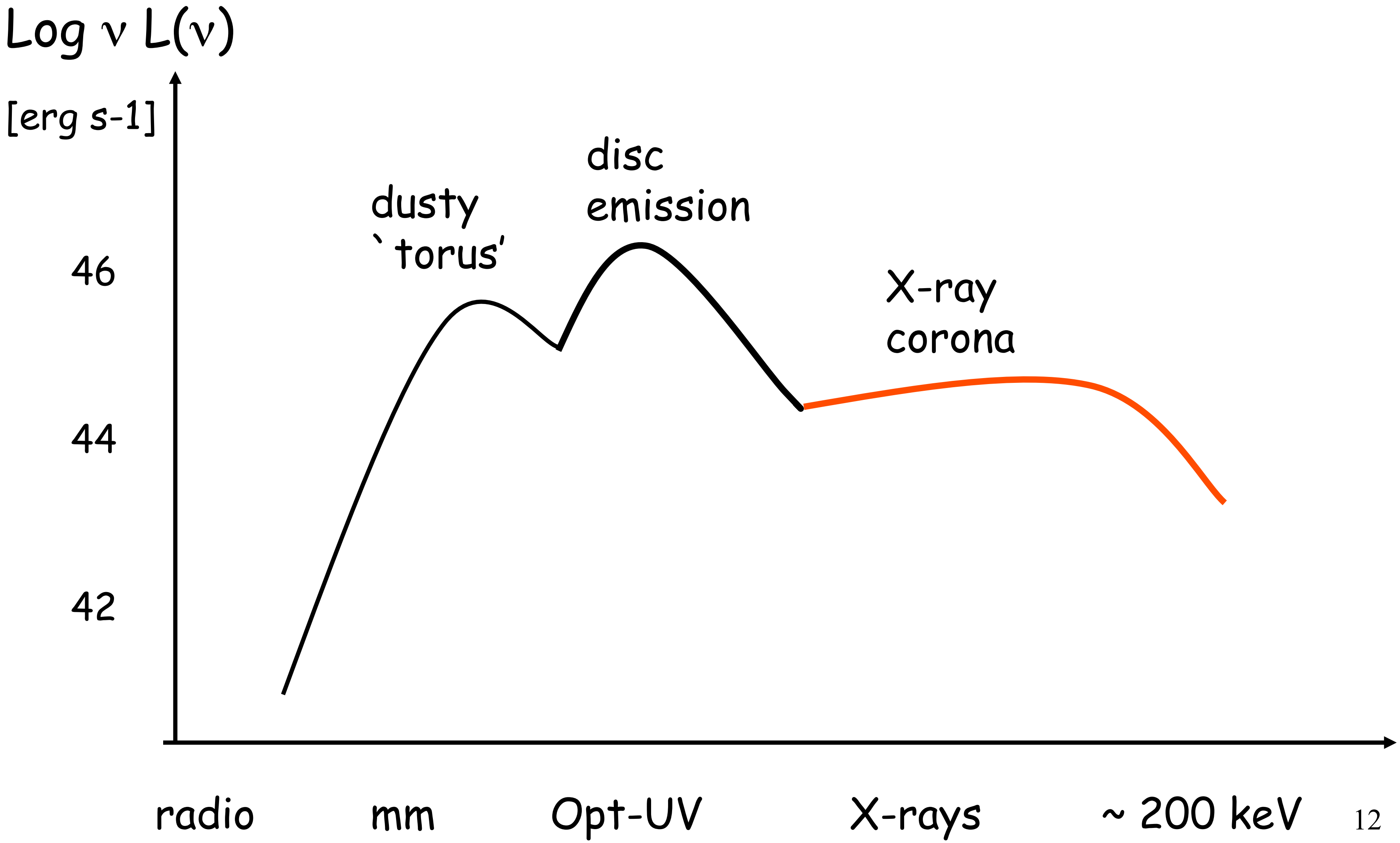
$\dot{M} \gg \dot{M}_{Edd}$ ➔ $t_{esc} < t_{infall}$

➔ Radiation trapping

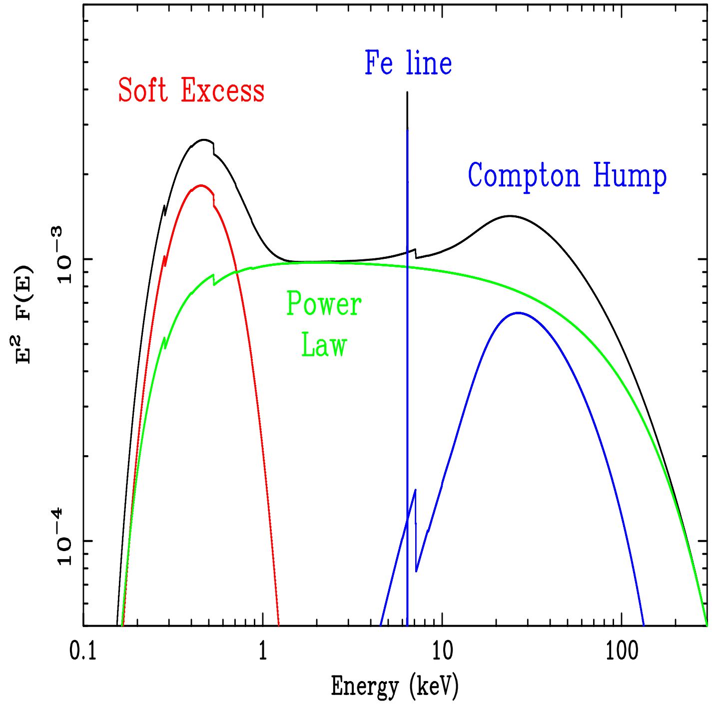
Radiation supported torii

Early accretion phase ?

X-ray emission (1)



X-ray emission (1)



Exponential cutoff ~ 40-300 keV
Emission line ~6.4-6.7 keV
Hump peak ~ 30 keV ➔ α_x ~ 0.9-1

Fabian & Miniutti 2005

X-ray emission (2)

Spectrum = superposition of Compton scattering spectra

Different spectra depending on τ_T and T

Hot corona? Where does the energy come from?

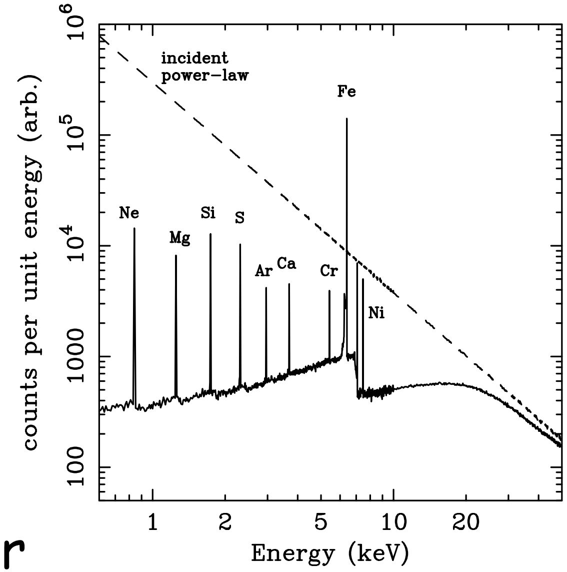
X-ray emission (3)

Reflection: coronal photons impinging on cold disk

Photoelectric absorption $\sigma_{ph} \sim E^{-2-3}$

Compton scattering σ_T ~const + KN

$\sigma_{ph} \sim \sigma_T$ at 30-40 keV ➔ bump



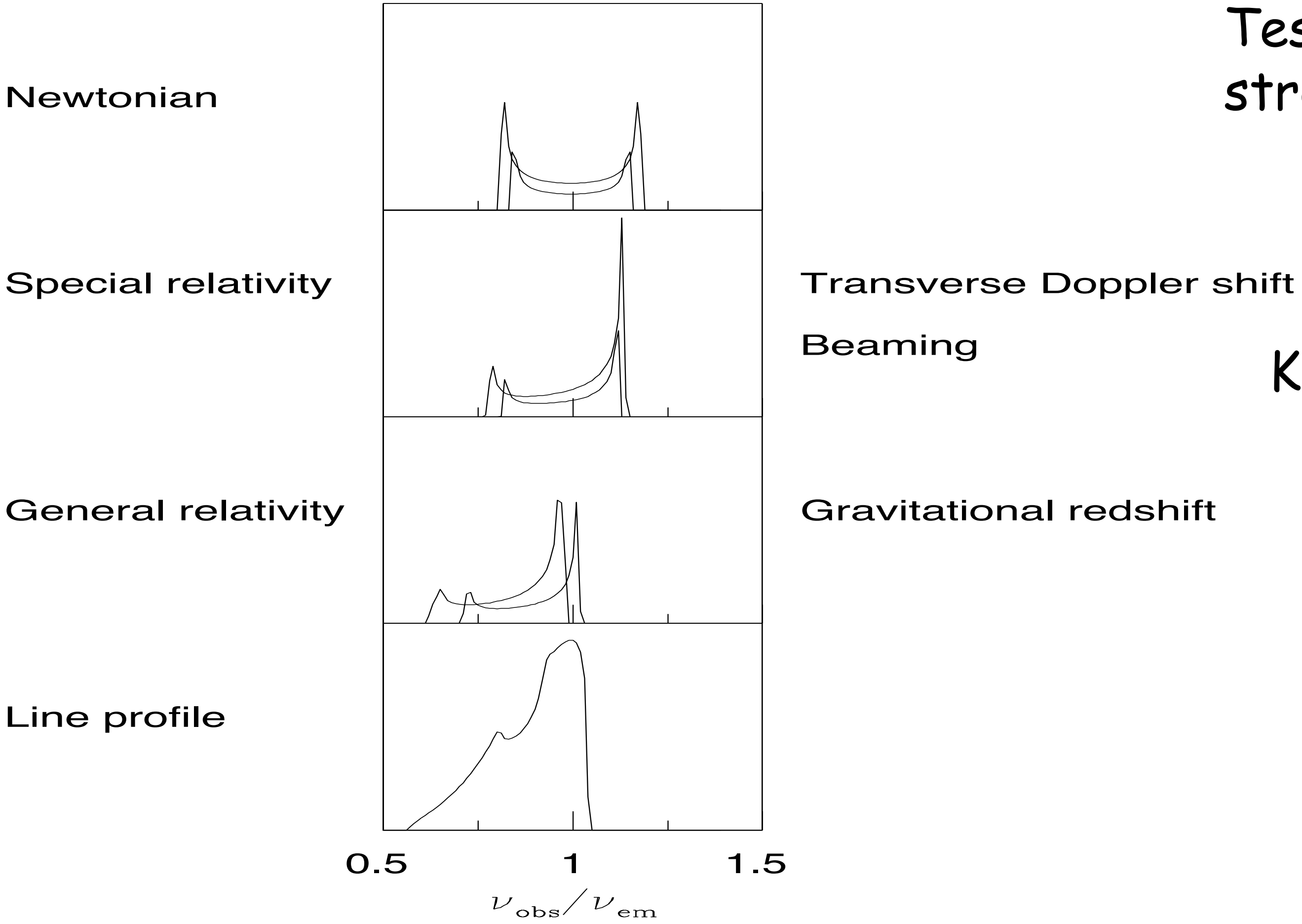
Inner e^- kicked out of cold atom➔ Auger
➔ Fluorescence

Strongest line = High abundance x Fluorescent yield

➔ Ka Iron line – energy depends on ionization state

X-ray Emission (3)

Fe Kα line is often broad



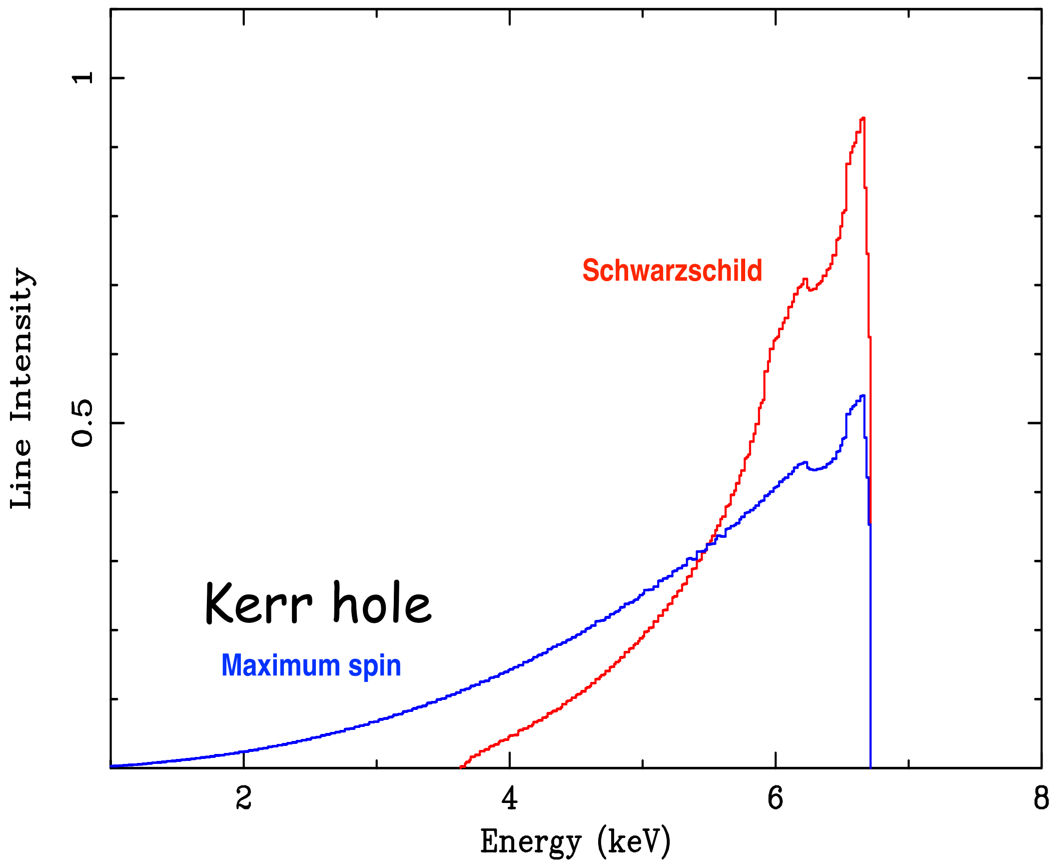
Test of GR in strong field

Kerr hole

Fabian & Miniutti 2005

X-ray emission (4)

Estimate of BH spin



Fabian & Miniutti 2005

Relativistic beaming with photons (1)

Lorentz transformations: $\vec{v}$ along x

$x' = \Gamma(x - vt)$

$y' = y$

$z' = z$

$t' = \Gamma(t - v\,x/c^2)$

$x = \Gamma(x' + vt')$

$y = y'$

$z = z'$

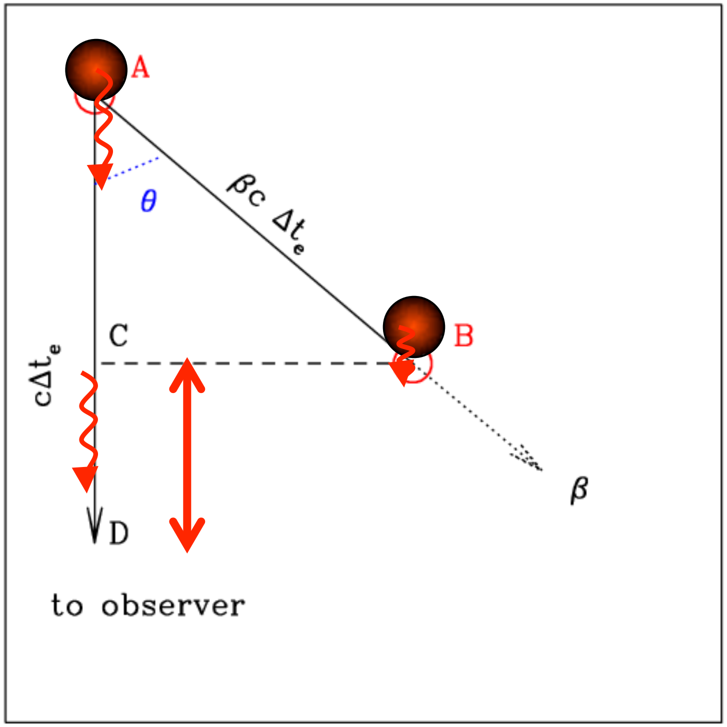
$t = \Gamma(t' + v\,x'/c^2)$

for $\Delta t = 0 \Rightarrow \Delta x = \Delta x'/\Gamma$ contraction of length

for $\Delta x' = 0 \Rightarrow \Delta t = \Gamma\,\Delta t'$ time dilation

Relativistic beaming with photons (2)

I.e. from rulers and clocks to photographs and frequencies
Or : from elementary particles to extended objects



Δt_e = emission time in lab frame

$\Delta t_e'$ = emission time in comov. frame

$\Delta t_e = \Delta t_e' \, \Gamma$

$CD = c\Delta t_e - c\Delta t_e \beta\cos\theta \rightarrow$

$\Delta t_A = \Delta t_e \,(1-\beta\cos\theta)$

$\rightarrow \Delta t_A = \Delta t_e' \, \Gamma(1-\beta\cos\theta)$

Relativistic beaming with photons (2)

Relativistic Doppler factor

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

"standard' relativity – change of frame

Doppler factor - no change of frame

2Γ for $\theta=0^o$

Γ for $\theta=1/\Gamma$

$1/\Gamma$ for $\theta=90^o$

Eg $\Delta t_A = \Delta t_e ' / \delta$

High β and small θ → Doppler "wins" over special relativity

Relativity with photons (3)

$\nu = \delta\, \nu'$

$\int$

$I(\nu)$ $[\mathrm{erg\ s^{-2}\ cm^{-2}\ Hz^{-1}\ sr^{-1}}]$

$$I(\nu) = dN\, h\nu \,/\, dt\, d\nu\, d\Omega\, dA =$$

$$= dN'\, (h\nu'\, \delta) \,/\, (dt'/\delta) \,/\, (d\nu'\, \delta)\, (d\Omega'/\delta^2)\, dA'$$

$$= I'(n')\, \delta^3$$

aberration

Relativistic motion $\beta=0.995$ $\Gamma=10$

$$\int I(\nu)\, d\nu \;=\; \underset{\updownarrow}{\delta^4} \int I'(\nu')\, d\nu'$$

$\sim 10^4$

Relativity with photons (5)

$t_{obs} = t\,\delta^{-1}$

$R_{obs} = R\,\delta$

$\nu_{obs} = \nu\,\delta$

$I_{obs}(\nu_{obs}) = I(\nu)\,\delta^3$

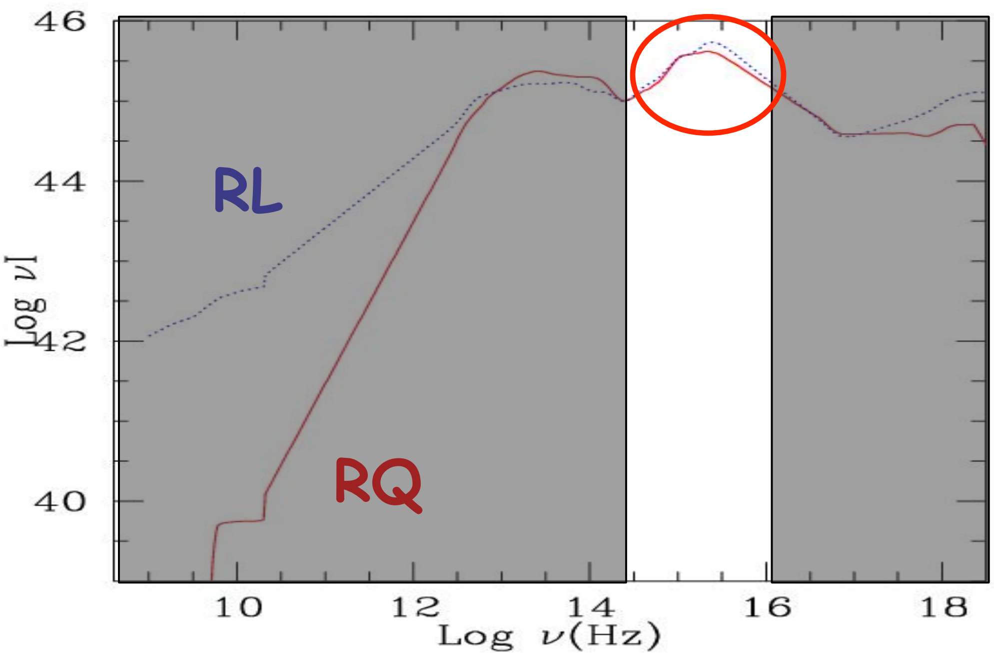
$T_{b,obs}(\nu_{obs}) = T_b(\nu)\,\delta$

$\mu_{obs}(\nu_{obs}) = \mu(\nu)\,\delta^{-1}$ absorption coefficient

$j_{obs}(\nu_{obs}) = j(\nu)\,\delta^2$ emissivity

$F_{obs}(\nu_{obs}) = \int I_{obs}(\nu_{obs})\,d\Omega = \delta^{2+\alpha} \int dV_{obs}\,j(\nu) / d_L^2$

Emission Radio-loud AGN (1)



~ 10% radio loud :

> stronger radio
> GeV-TeV energies
> Flatter (harder) X-ray spectru

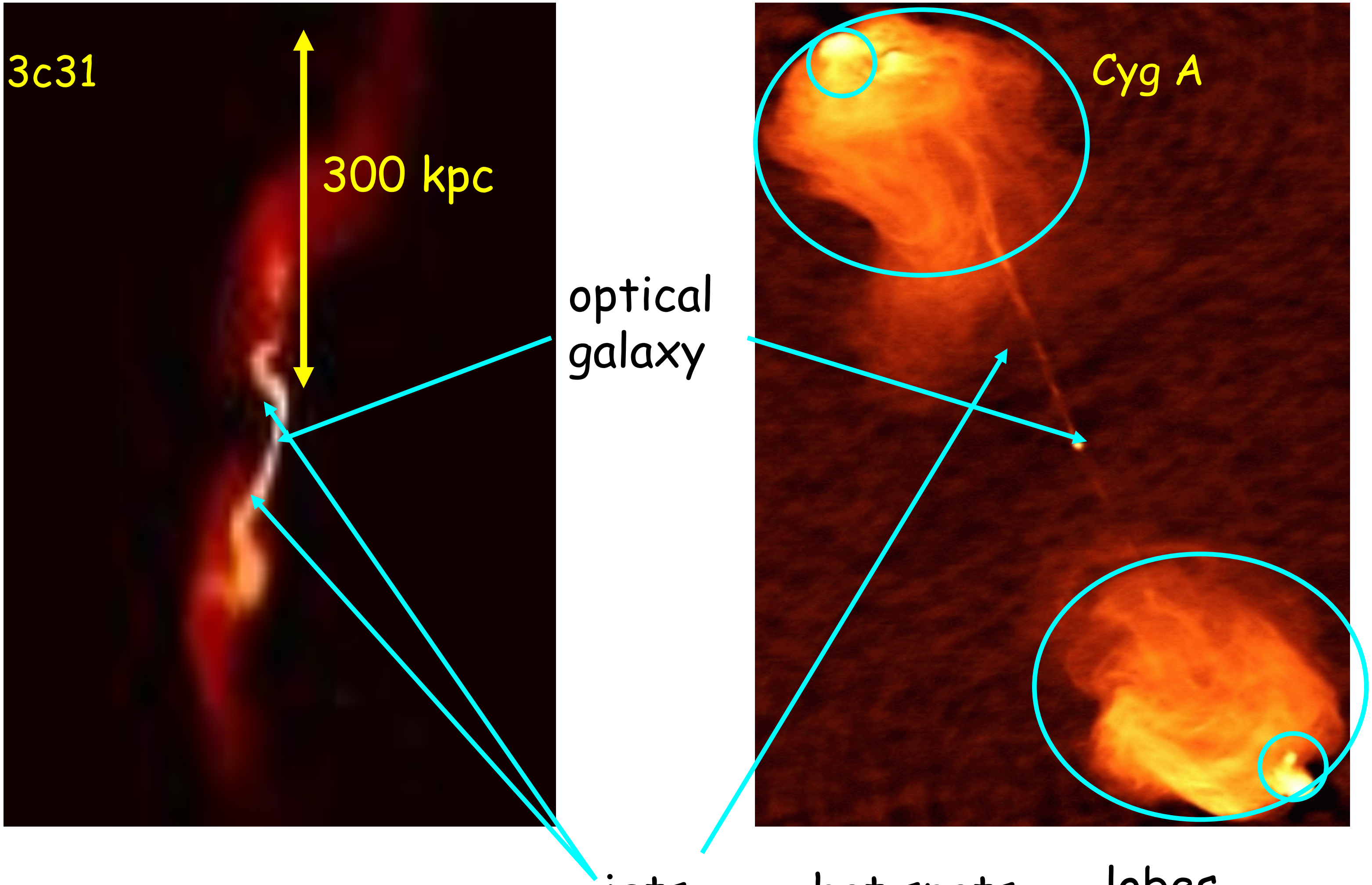
Radio Power

Radio-to-optical ratio:

$$R^* \equiv F_r/F_{4400A} \qquad \nu_r L_r/L_{opt} = 1.5\ 10^{-6}\ \nu_{GHz} R^*$$

AGN dichotomy???

Emission Radio-loud AGN (3)



optical galaxy

jets

hot spots

lobes

Images courtesy of NRAO/AUI

Jets on all scales

Compact - flat α_r

Extended - up to Mpc

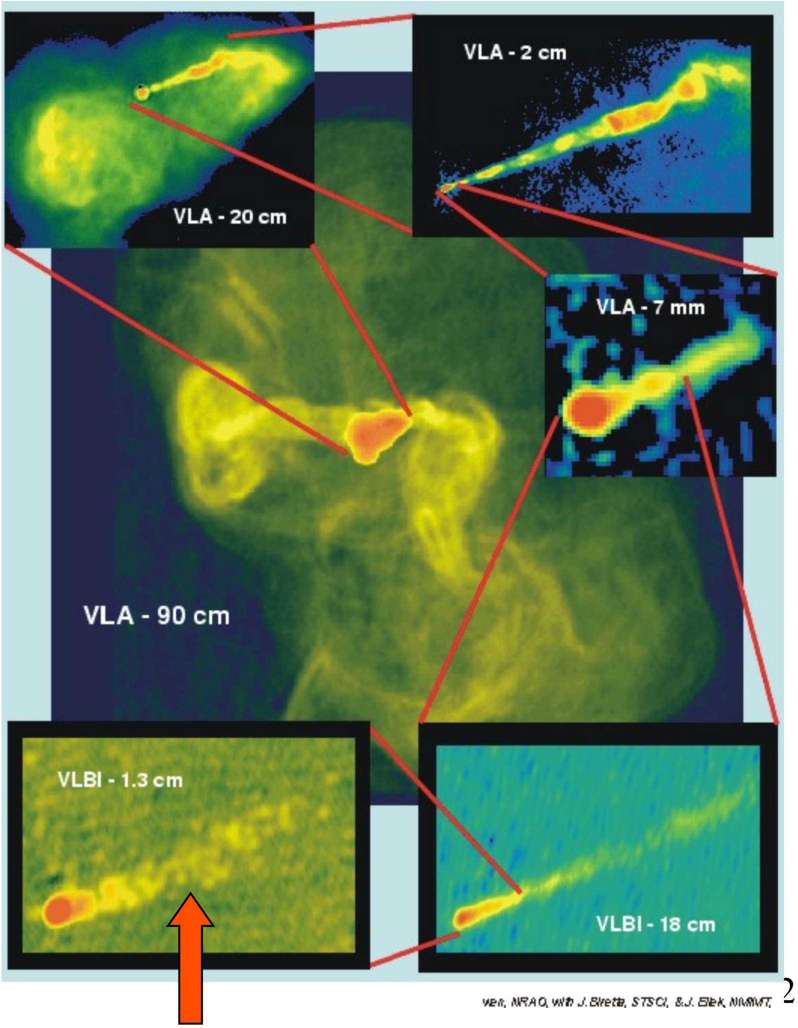
- steep α_r ~0.8

Continuous (?) flows

Different particle ageing

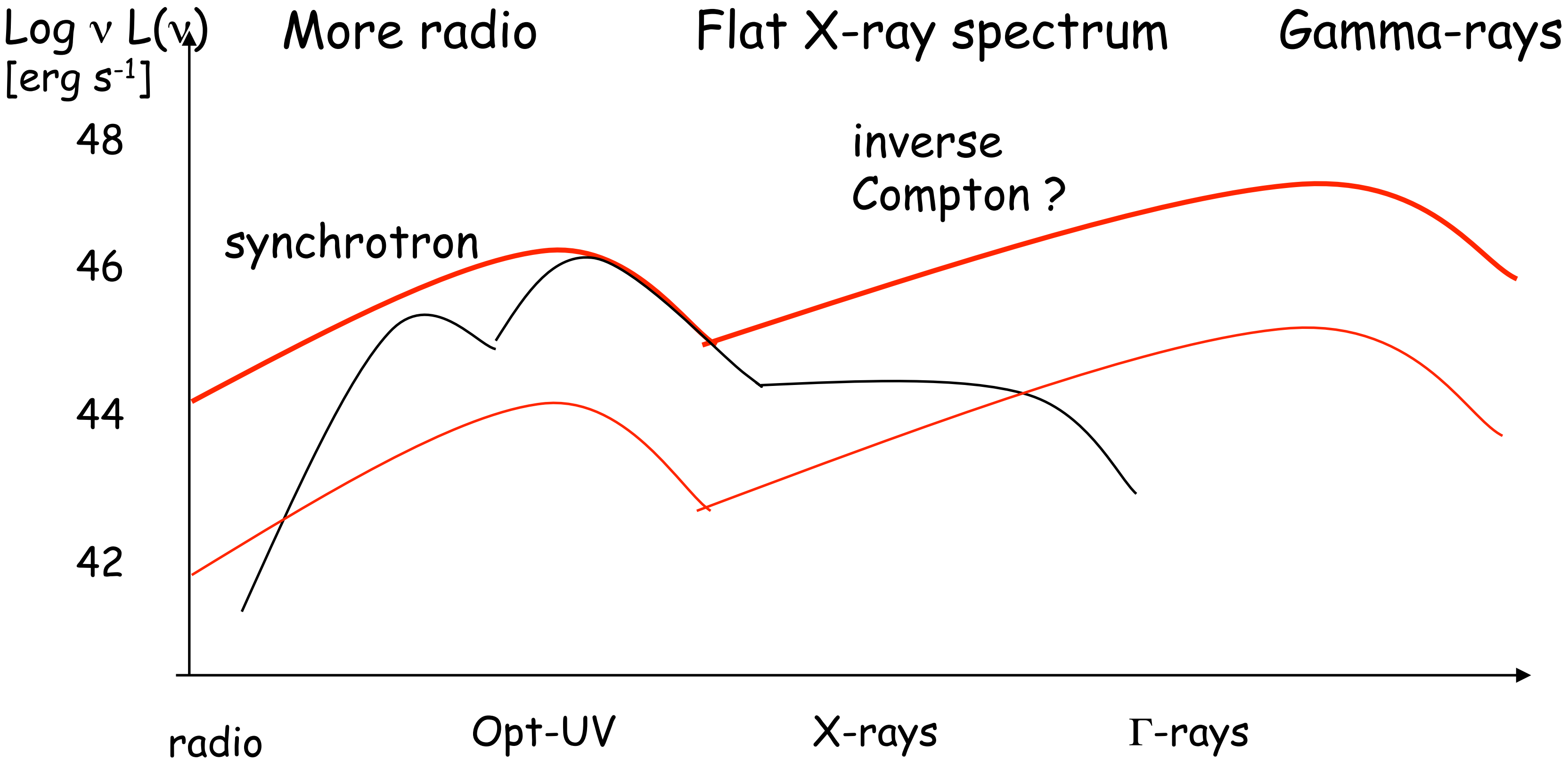
200.000 ⟶ 0.2 l.y.

M87



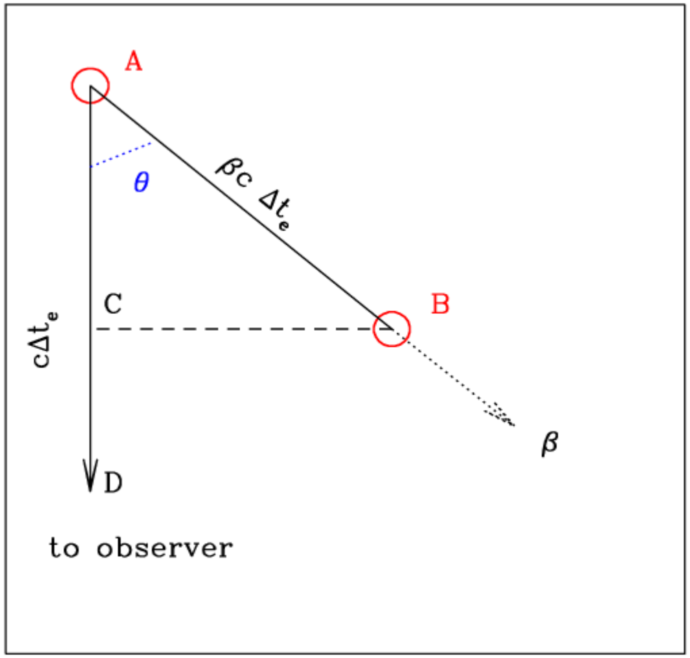
ven, NRAO, with J. Biretta, STScI, & J. Eilek, NMIMT,

Emission Radio-loud AGN (4)



Intermediate objects – radio gal with broad lines…

Emission Radio-loud AGN (5)



$$\Delta t_{obs} = \Delta t - \beta \Delta t \cos\theta$$

$$\beta_{app} = \frac{\beta \sin\theta}{1 - \beta \cos\theta}$$

$\beta \sim 1 - 1/2\gamma^2$ $\cos\theta \sim 1 - \theta^2/2$

$$\beta_{app} \sim 2\theta/(\theta^2 + \gamma^{-2})$$

$$\begin{cases} \theta \ll 1/\gamma & \beta_{app} \rightarrow 2\gamma^2\theta \\ 1/\gamma < \theta < 1 & \beta_{app} \sim 2/\theta \end{cases}$$

No Γ factor in β_{app}
Correct ???

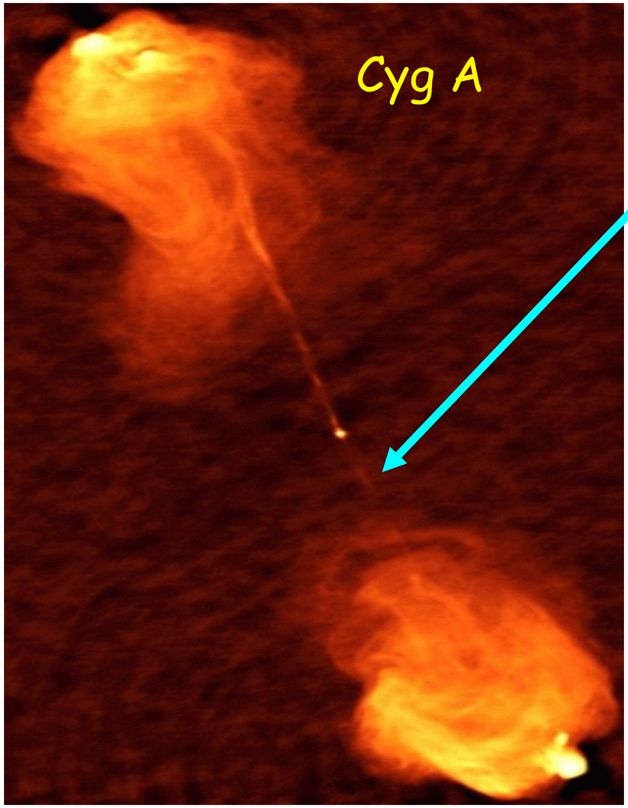
<u>NOTE</u>: β_s vs β_j

pattern vs bulk speed

$v \leq c$: relativistic motion

θ small

Emission Radio-loud AGN (6)



Where is the jet?

Current dynamic range $\geq$ 1000

$L_j/L_{cj} \sim [(1+\beta \cos \theta)/(1-\beta \cos \theta)]^{(2+a)}$

Consistent with relativistic motion

An elegant explanation…

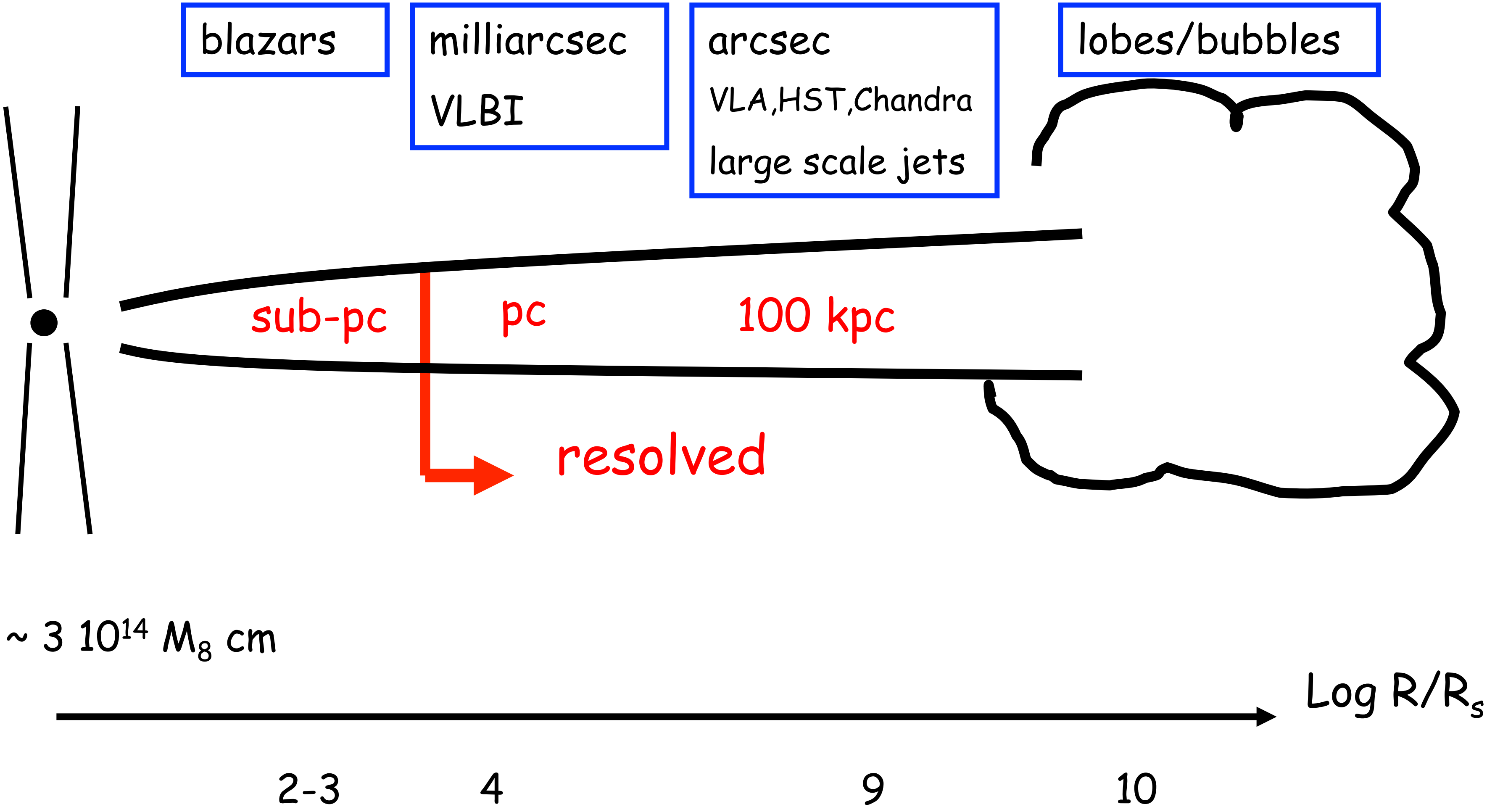
- Superluminal motion
- $T_b > 10^{12}$ K - IDV
- Excess Compton flux (ν_t, F_t, θ): SSC >> observed
- Pair opacity $\tau_{\gamma\gamma} >> 1$
- Efficiency limit ΔL_x vs Δt
- Jet one-sidedness in double sources
- Very curved jets
- Laing-Garrington effect
- Efficiency energy transport
- Unification
- Core and lobe dominated sources

Relativistic motion

$\Gamma \sim 3 - 50$

GRB ~ 300

Jet “scales”



blazars

milliarcsec

VLBI

arcsec

VLA,HST,Chandra

large scale jets

lobes/bubbles

sub-pc

pc

100 kpc

resolved

$R_s \sim 3\ 10^{14}\ M_8$ cm

Log R/R_s

2-3

4

9

10

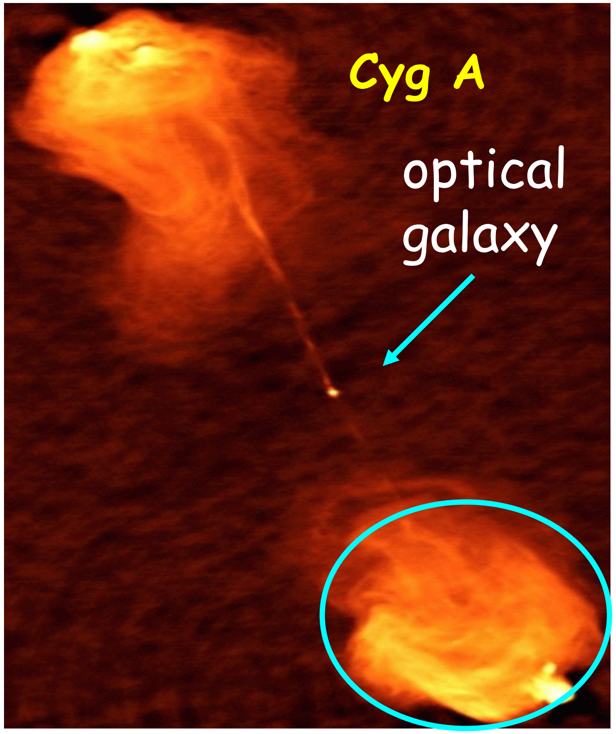
Jets: what are they?

$$\begin{cases} t_{adiab}\,(\gamma) < t_{ife} \\ t_{rad}\,(\gamma) < t_{life} \end{cases}$$

in hot spots

&

total energetics



➔ Jets: - morphological definition = elongated flows

- physically = energy and momentum carriers from active nucleus to ISM ICM

Emission: lobes

Power-law spectrum ➔ non thermal process

+

High linear polarization

⇨ synchrotron emission: e^{+-}, B

Timescales

$B_{eq} \sim \mu$ G in extended structures

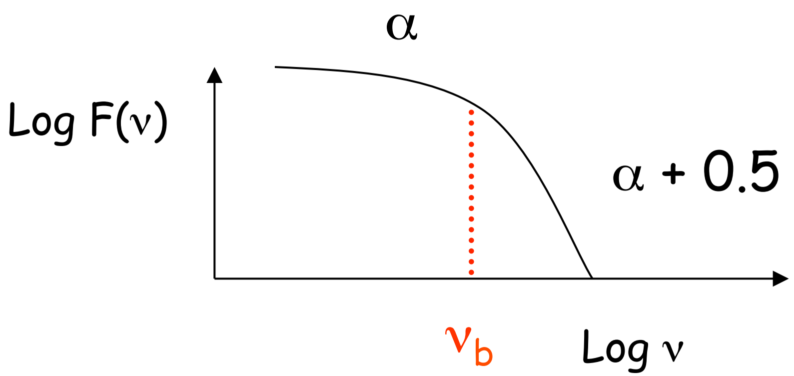
$\nu_{1GHz} = 1.2 \times 10^6 B_{eq} \gamma^2 \rightarrow \gamma \sim 10^4$

$t_{cool} \sim 2.4 \times 10^9 \gamma_4^{-1} B_{\mu G}^{-2}$ yr

- Spectral ageing

  $t_{cool}(\gamma_b) \sim B^{-3/2} \nu_b^{1/2}$

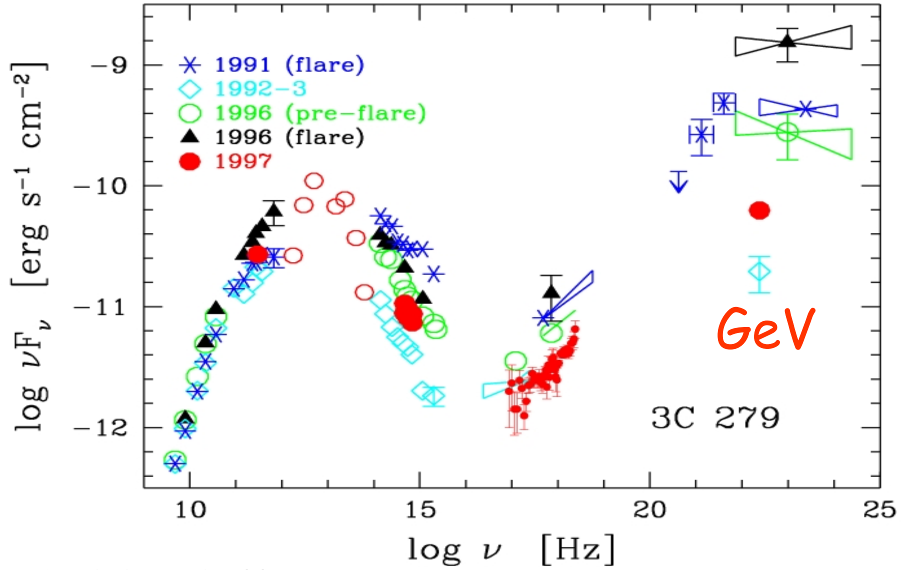
  $t_{life} = t_{dyn} = D/v$



- X-ray emission in hot spots: $t_{cool} \ll t_{life}$ → in situ reacceleration
- Incomplete cooling → $L_j \gg L_r$

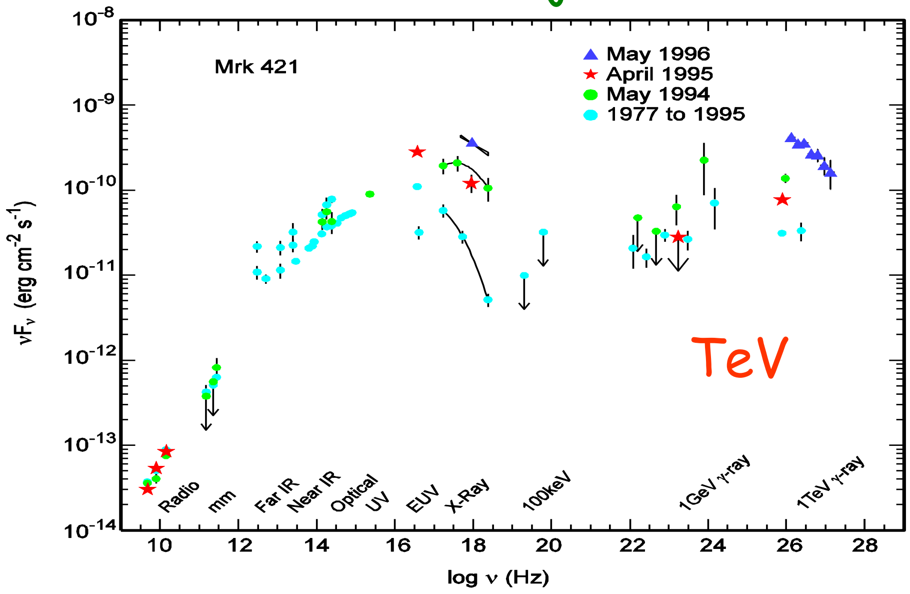
Emission Radio-loud AGN (7)

Log ν F(ν) FSRQ



(Wehrle et al. 1998)

Log ν F(ν) BL Lac object

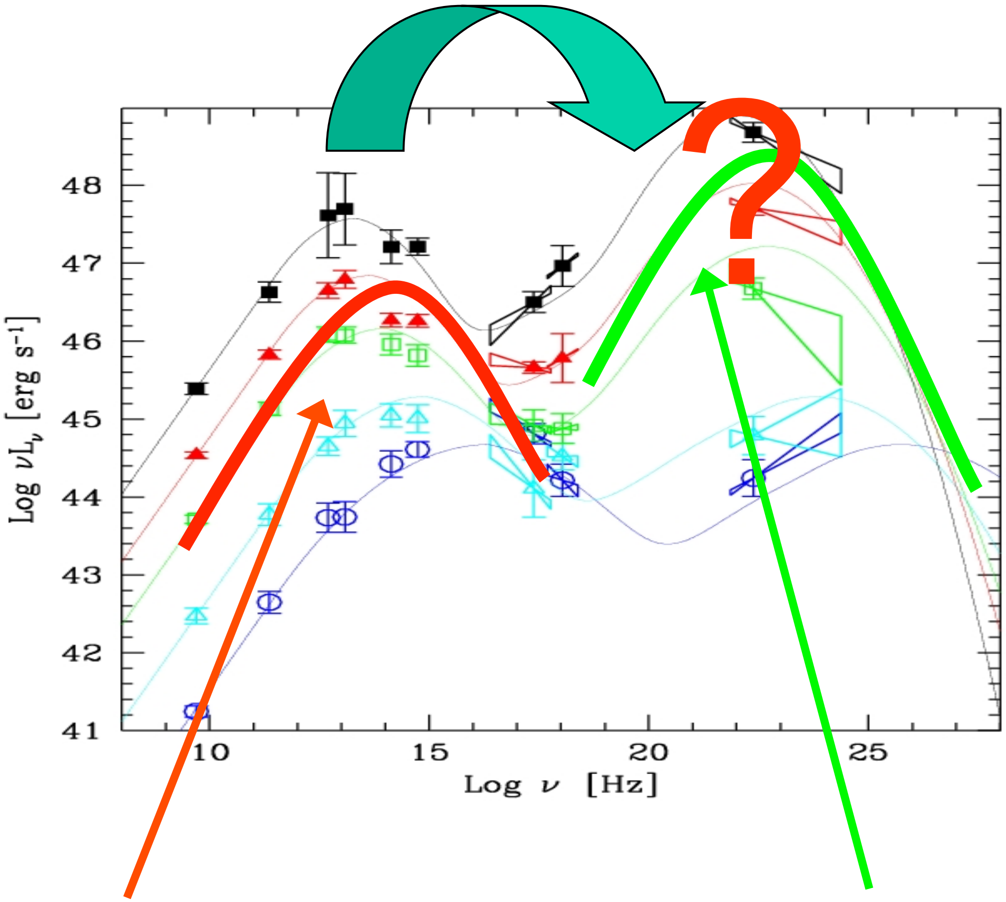


(Macomb et al. 1995)

1 - Broadband SED: radio-TeV - 20 decades
non thermal equilibrium
two broad peaks [in νF(ν)]

2- Highly polarized radio (several 10%) and optical emission

Simplest model: same e^- produce both peaks



IR-X

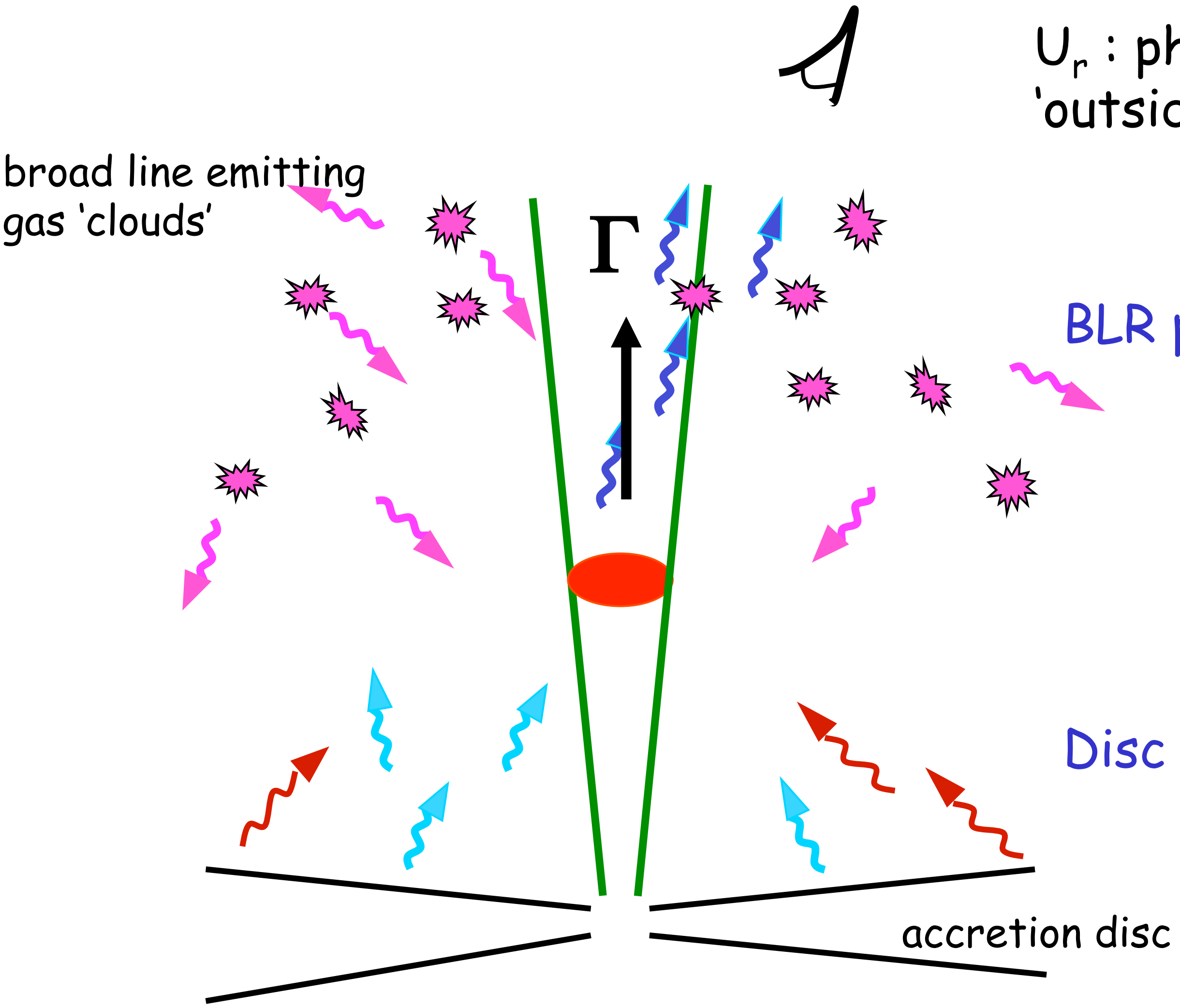
Gev-TeV

often dominates the emission

Synchrotron

Synchrotron self-Compton ? Not enough...

External Compton

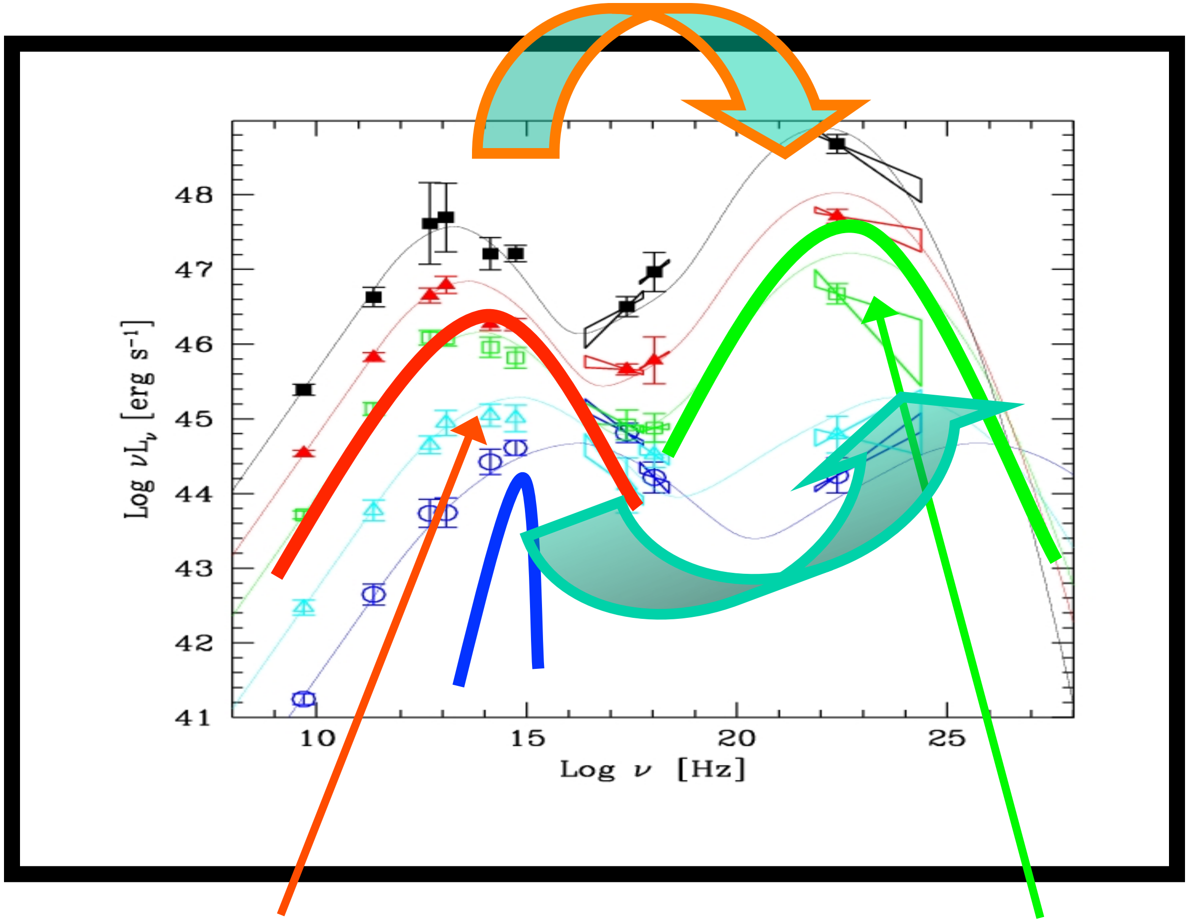


U_r : photon field produced 'outside' the jet

BLR photons ~ isotropic

Disc photons ~ anisotropic

Simplest model: same e^- produce both peaks

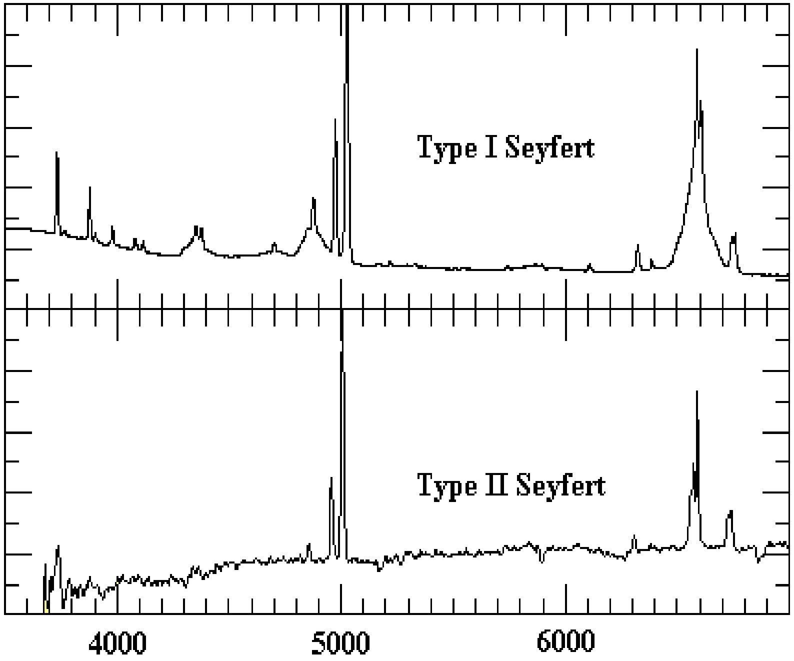


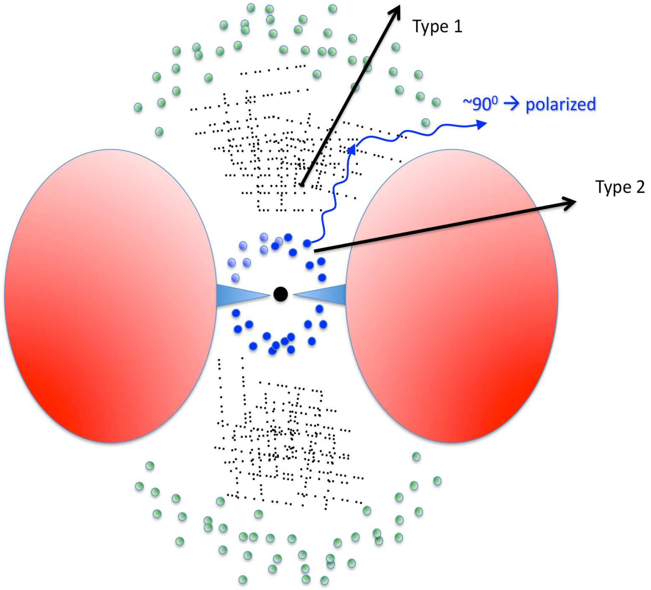
Synchrotron

SSC +
External Compton on BLR, disc, torus,…

NOTE: Hadronic models: some difficulties, but not ruled out

Unification Type 1 and Type 2





In rough agreement with N_H

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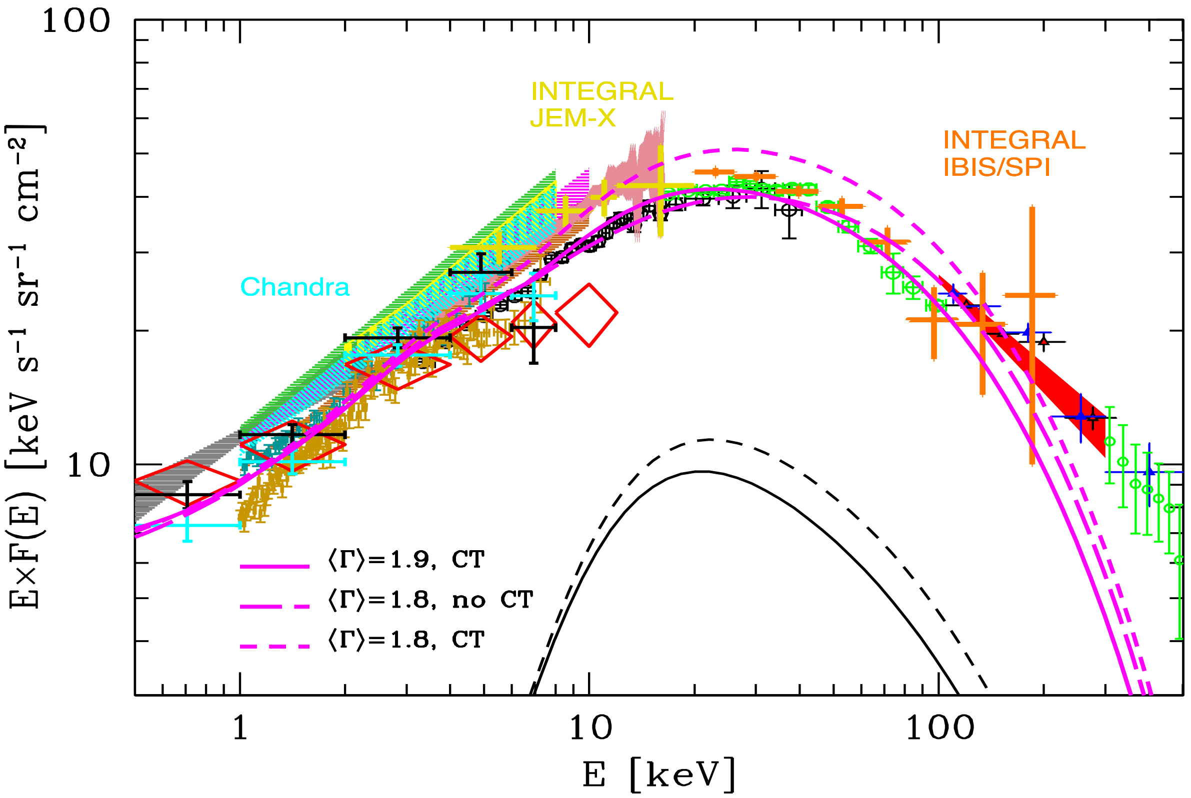
X-ray background



Sum Sey 1 and Sey 2

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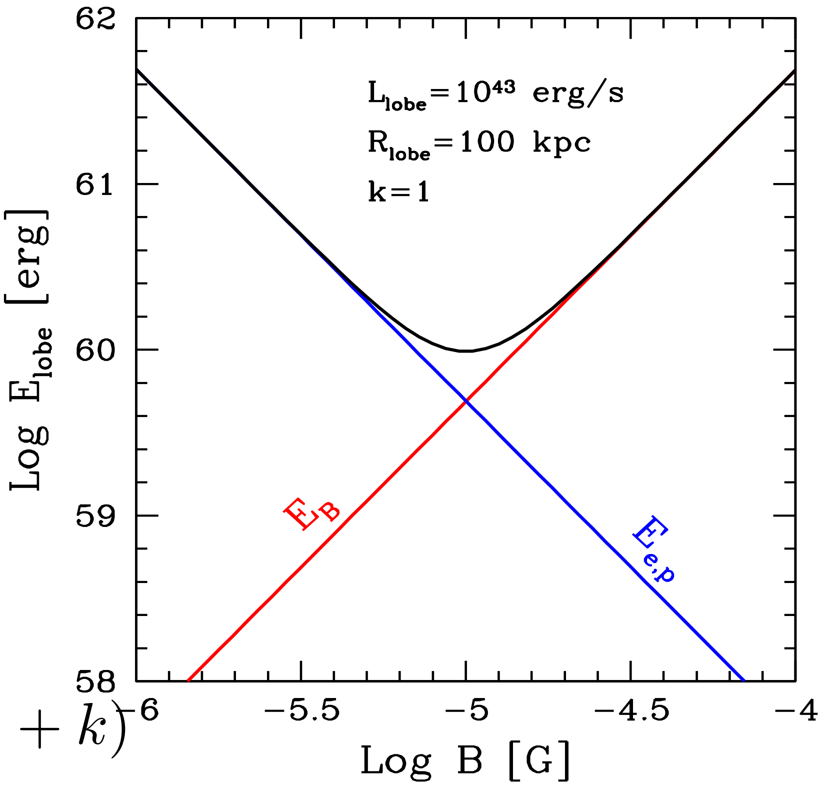
Jet energetics

$$P_{\rm i} = \pi R^2 \Gamma^2 \beta\, c\, U'_{\rm i}$$ >= $P_{\rm disk}$



$$E_{\rm B} = \frac{4\pi}{3} R^3_{\rm lobe} \frac{B^2}{8\pi}$$

$$\begin{aligned} E_{\rm e,p} &= \frac{4\pi}{3} R^3_{\rm lobe} \langle\gamma\rangle\, n_{\rm e} m_{\rm e} c^2\, (1+k) \\ &= 6\pi\, \frac{\langle\gamma\rangle m_{\rm e} c^2}{\langle\gamma^2\rangle}\, \frac{L_{\rm lobe}}{\sigma_{\rm T} c\, B^2}\, (1+k) \end{aligned}$$

Ghisellini 2015

THE END