Automatic Quenching of High Energy γ-ray Sources by Synchrotron Photons

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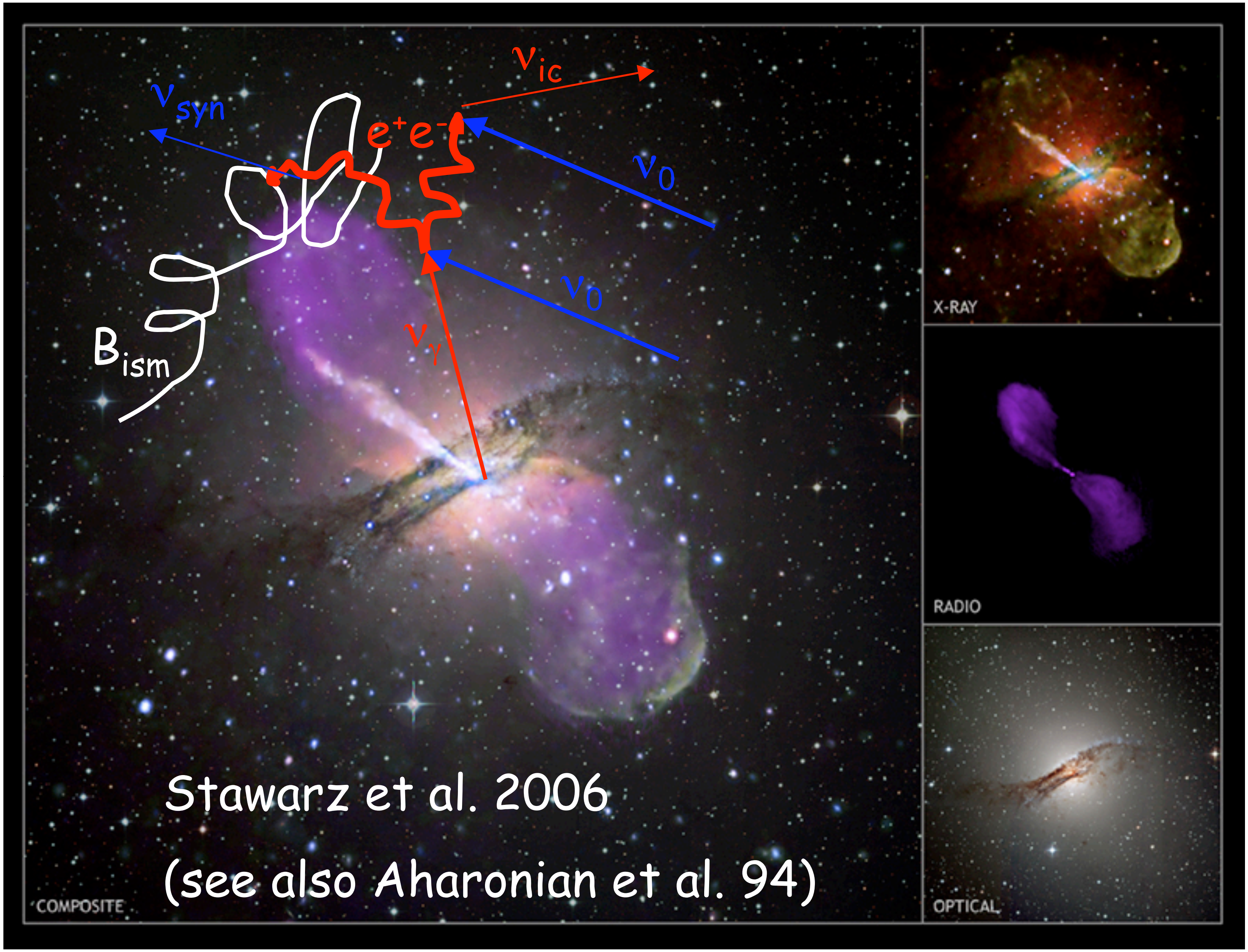
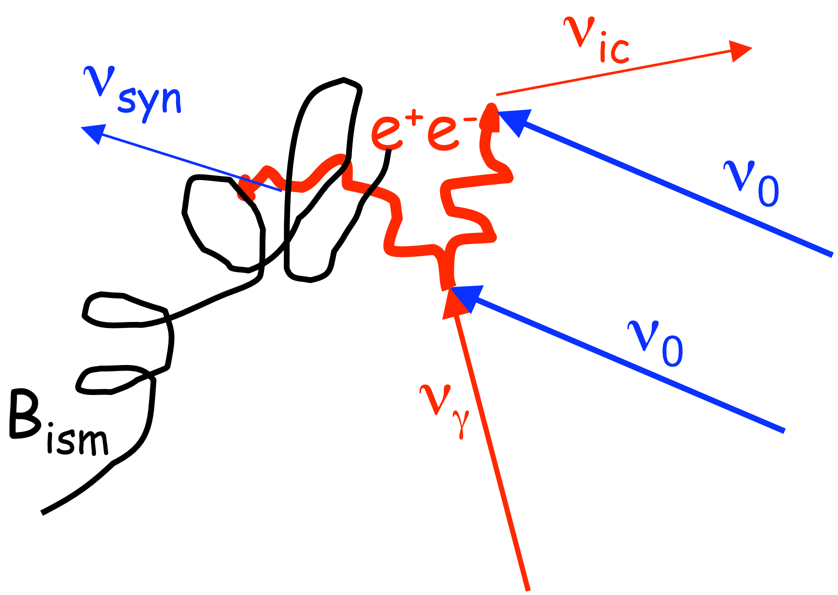
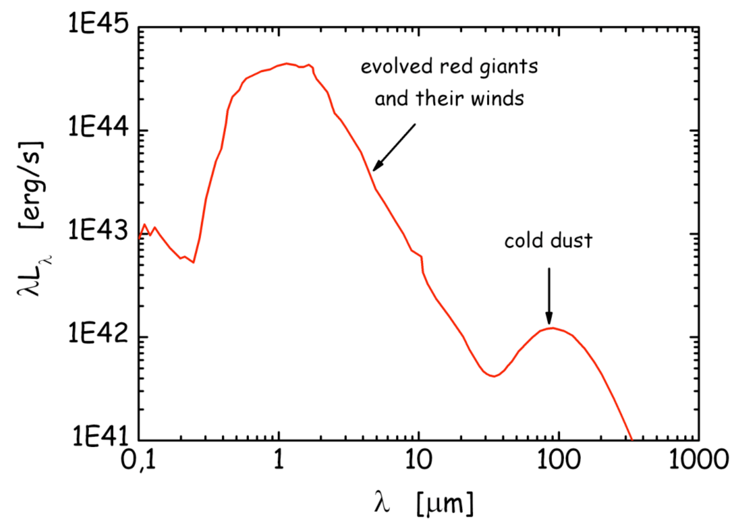
(Stawarz & Kirk, 2007, ApJL, 661, L17)

Giant Pair Halo in Centaurtus A



Giant Pair Halos in Ellipticals





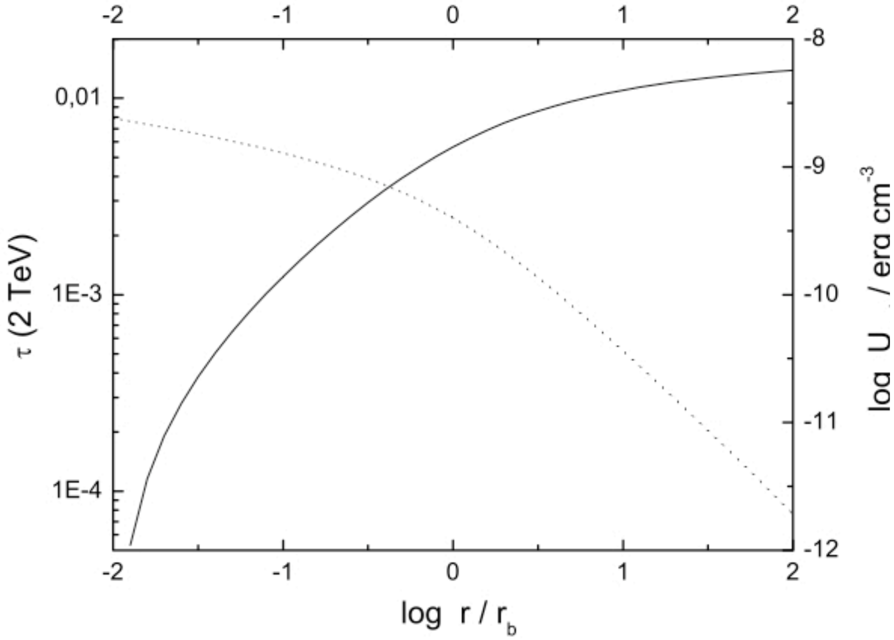
Interestingly, for the typical parameters of a giant elliptical galaxy (host of Centaurus A radio source),

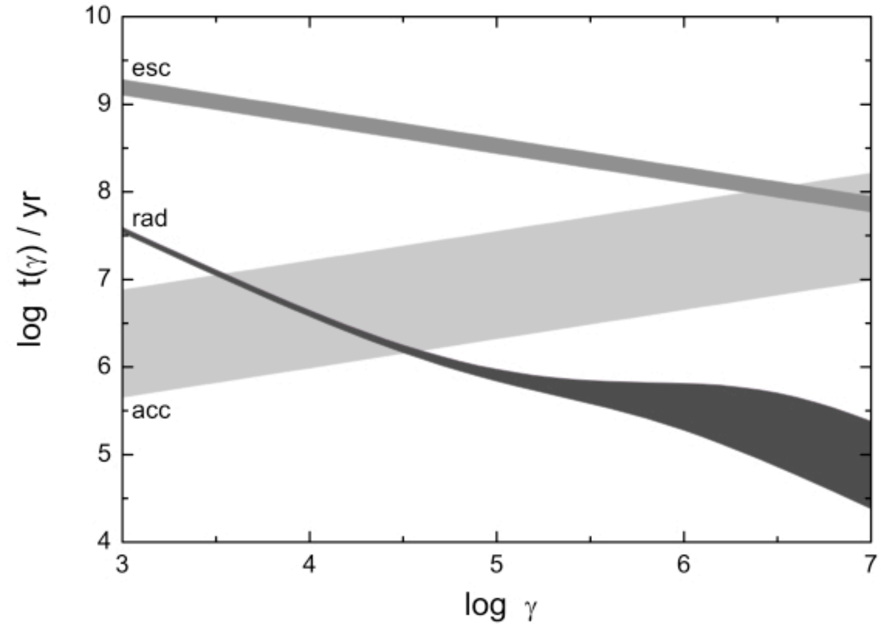
$\nu_0 \sim 10^{14}$ Hz and $B_{ism} \sim$ few μG

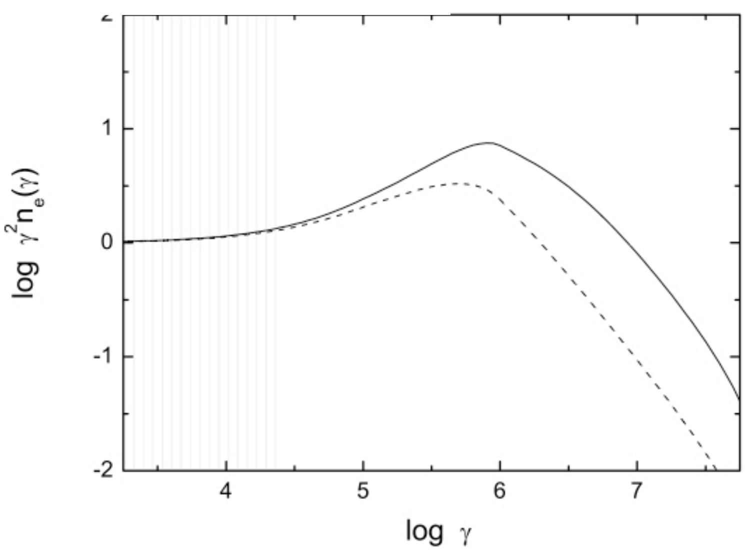
and TeV emission of the nuclear jet ("misaligned", or Doppler-hidden blazar of the BL Lac type), we have

$\nu_{ic} \sim \nu_\gamma$ and $\nu_{syn} \sim \nu_0$

Some Calculations







$\varepsilon_0\, \varepsilon_\gamma = 2\, m_e^2 c^4$

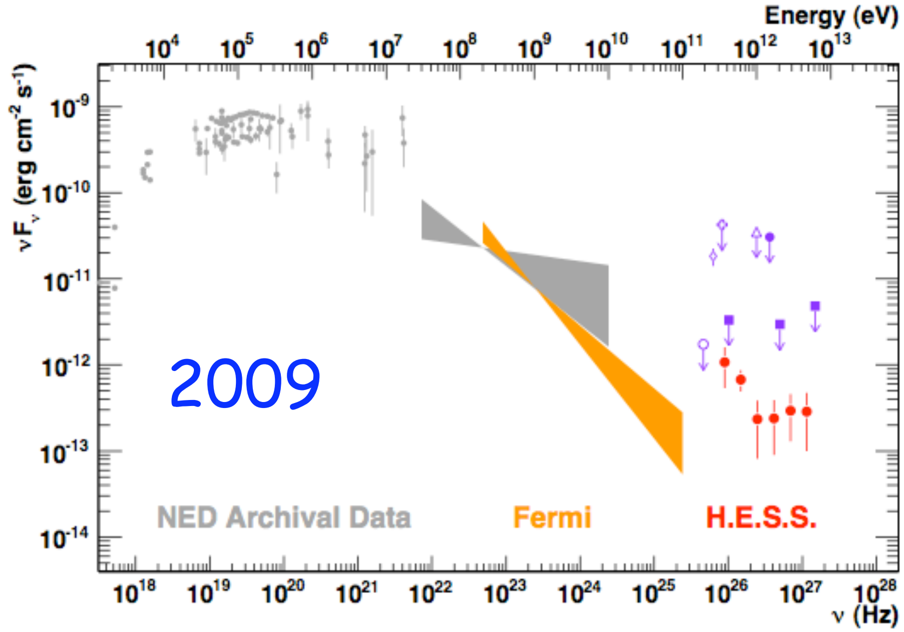
$E_e = \varepsilon_\gamma / 2$

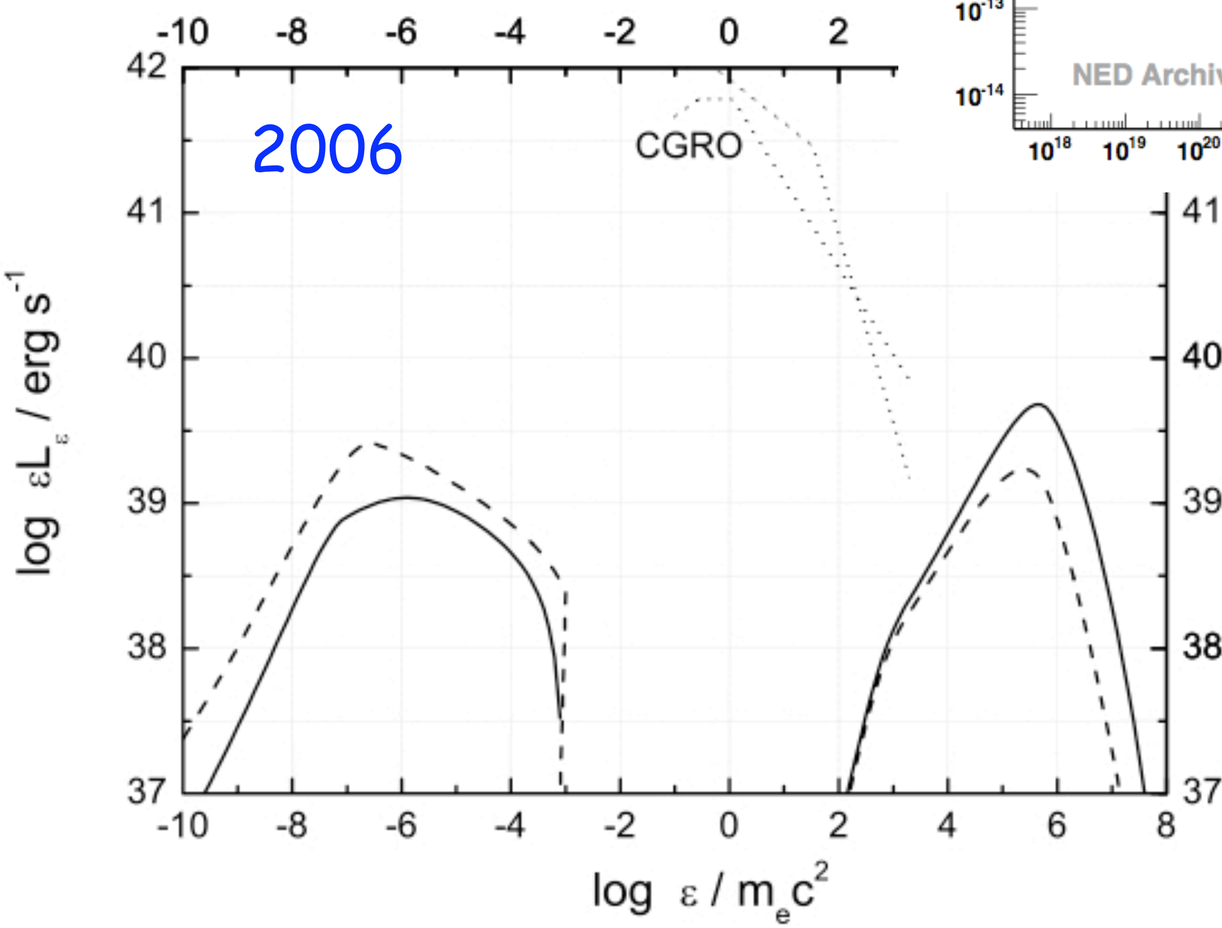
for $\varepsilon_0 \sim 0.5$ eV

$\varepsilon_\gamma \sim$ TeV,

$E_e \sim 0.5$ TeV

Detection (?)





Centaurus A system has been detected by FERMI/LAT and H.E.S.S.

TeV flux is consistent with being steady.

Non-linear Effects

Stawarz & Kirk 07: We investigate a magnetized plasma in which injected high energy gamma-rays annihilate on a soft photon field, that is provided by the synchrotron radiation of the created pairs.

$$B = 6\, B_{cr}\, (h\nu \,/\, m_e c^2)^{-3}$$

$$= 35\, (h\nu \,/\, \mathrm{TeV})^{-3}\ \mu\mathrm{G}$$

That is, for the magnetic field B ~ nG - MG, gamma-rays with energies $h\nu$ ~ 0.3 GeV - 30 TeV are involved.

We derive a simple dynamical system for this process, analyze its stability to runaway production of soft photons and pairs, and find conditions for it to automatically quench by reaching a steady state with an optical depth to photon-photon annihilation larger than unity.

(Inspired by the work of Kirk & Mastichiadis 92, Stern & Poutanen 06)

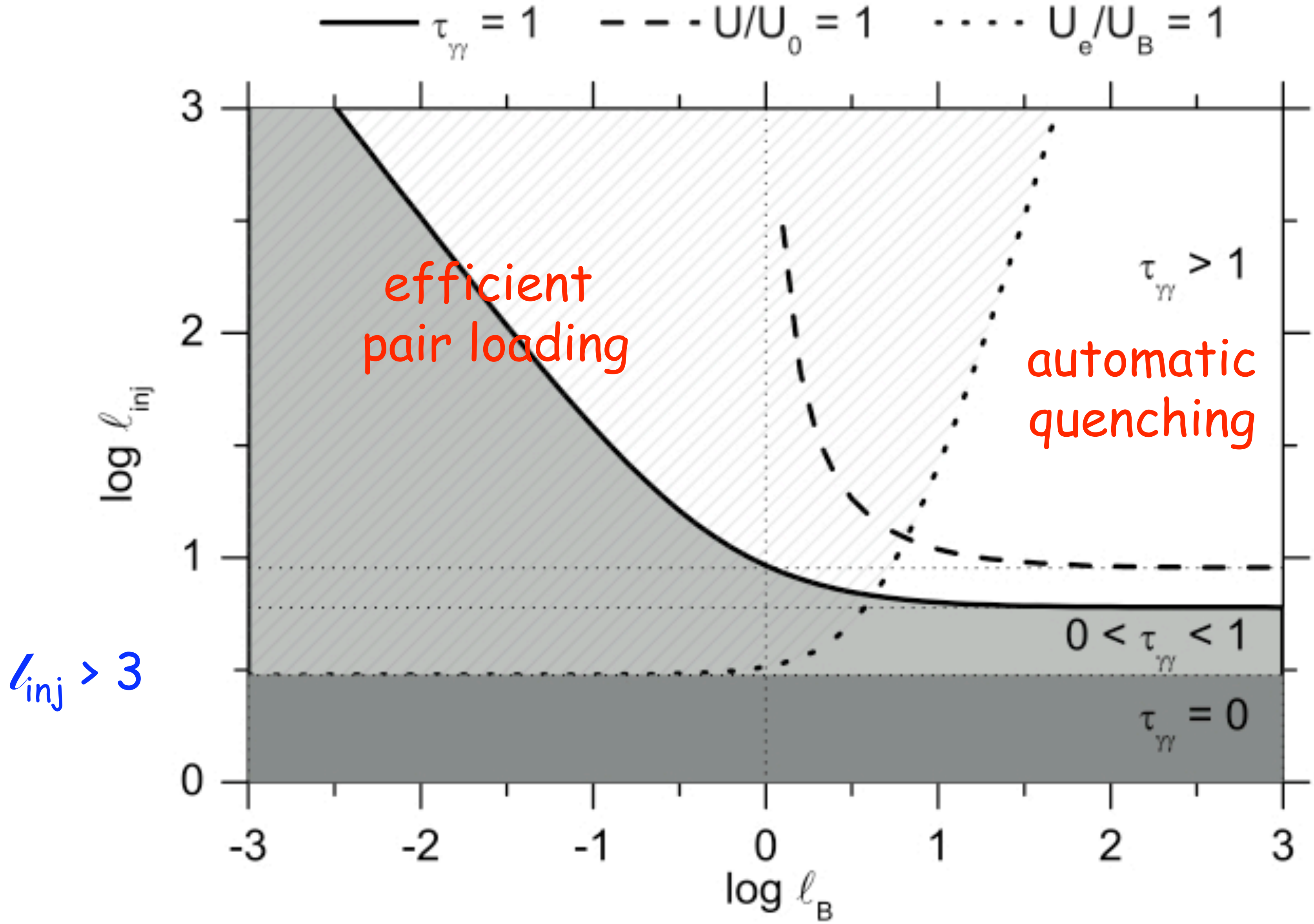
Simplified Dynamical System

$$\begin{aligned}
\frac{\mathrm{d}\mathcal{N}(\epsilon)}{\mathrm{d}t} &= \dot{\mathcal{N}}^{\gamma\gamma}(\epsilon) + \dot{\mathcal{N}}^{\rm esc}(\epsilon) + \mathcal{Q}(\epsilon) \quad , \\
\frac{\mathrm{d}\mathcal{N}_0(\epsilon_0)}{\mathrm{d}t} &= \dot{\mathcal{N}}_0^{\rm esc}(\epsilon_0) + \dot{\mathcal{N}}_0^{\rm syn}(\epsilon_0) \quad , \\
\frac{\mathrm{d}\mathcal{N}_{\rm e}(\gamma)}{\mathrm{d}t} &= \dot{\mathcal{N}}_{\rm e}^{\gamma\gamma}(\gamma) + \dot{\mathcal{N}}_{\rm e}^{\rm syn}(\gamma) + \dot{\mathcal{N}}_{\rm e}^{\rm ic}(\gamma)
\end{aligned}$$

$$\ell_{\rm inj} \equiv \frac{\epsilon\, L_{\rm inj}\, \sigma_{\rm T}}{4\pi\, m_{\rm e} c^3\, R} \quad \text{and} \quad \ell_{\rm B} \equiv \frac{\epsilon\, U_{\rm B}\, R\, \sigma_{\rm T}}{m_{\rm e} c^2} .$$

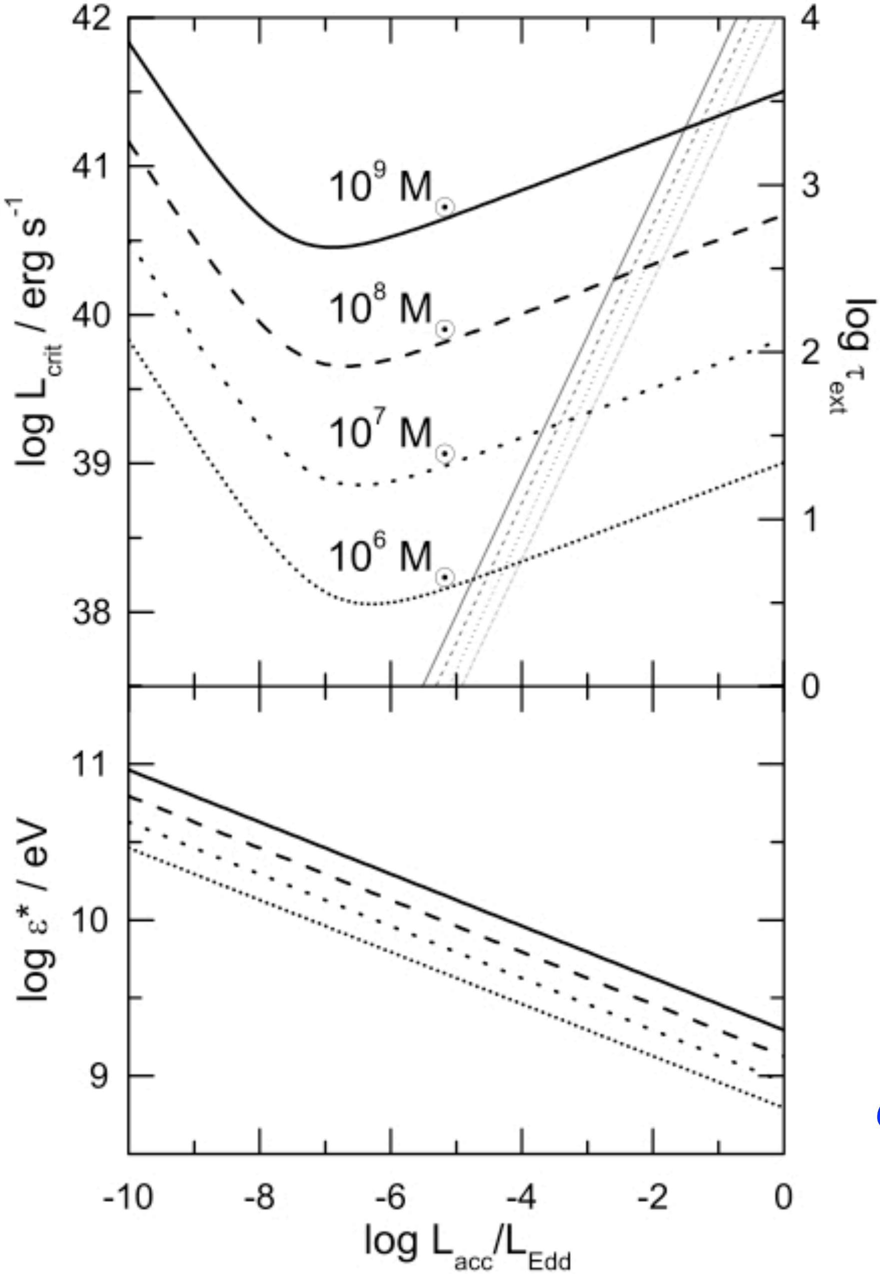
$$\begin{aligned}
\frac{\mathrm{d}\,n}{\mathrm{d}\tau} &= -n\,n_0 - n + \frac{2}{3}\,\ell_{\rm inj} \\
\frac{\mathrm{d}\,n_0}{\mathrm{d}\tau} &= -n_0 + \frac{1}{3}\,\ell_{\rm B}\,n_{\rm e} \\
\frac{\mathrm{d}\,n_{\rm e}}{\mathrm{d}\tau} &= n\,n_0 - \frac{2}{3}\,\ell_{\rm B}\,n_{\rm e} - \frac{4}{\eta}\,n_{\rm e}\,n_0 \quad .
\end{aligned}$$

The Results


τγγ = 1
U/U0 = 1
Ue/UB = 1
efficient pair loading
automatic quenching
τγγ > 1
0 < τγγ < 1
τγγ = 0
ℓinj > 3
log ℓinj
log ℓB
3
2
1
0
-3
-2
-1
0
1
2
3

Applications I

1) Vicinities of SMBHs



$B \sim$

$\sim (R/r_g)^{-1}(L_{acc}/L_{edd})^{1/2}(L_{edd}/r_g^{\,2}c)^{1/2}$

$\sim 10^4\ (\lambda/M_8)^{1/2}$ G

with

$R \sim 3\ r_g$

$\lambda = L_{acc}/L_{edd}$

$M_8 = M_{BH}/10^8\ M_{sol}$

$h\nu \sim \lambda^{-1/6}\ M_8^{\,1/6}$ GeV

$\ell_{inj} \sim 2\ \lambda^{-1/6}\ M_8^{\,-5/6}\ (L_{inj}/10^{40}\ \mathrm{erg\ s^{-1}})$

$\ell_B \sim 3 \times 10^5\ \lambda^{5/6}\ M_8^{\,1/6}$

➔ Possible quenching;
efficient pair loading only for low λ.

Applications II

2) Extended Sources (galaxies)

$B \sim \mu G$
$R \sim \mathrm{kpc}$

$h\nu \sim 3$ TeV
$\ell_{inj} \sim 4\,(L_{inj}/10^{45}$ erg s$^{-1})$
$\ell_B \sim 10^{-3}$

➔ No quenching (low ℓ_B)
but possibly efficient pair loading

3) GRB Afterglows ???

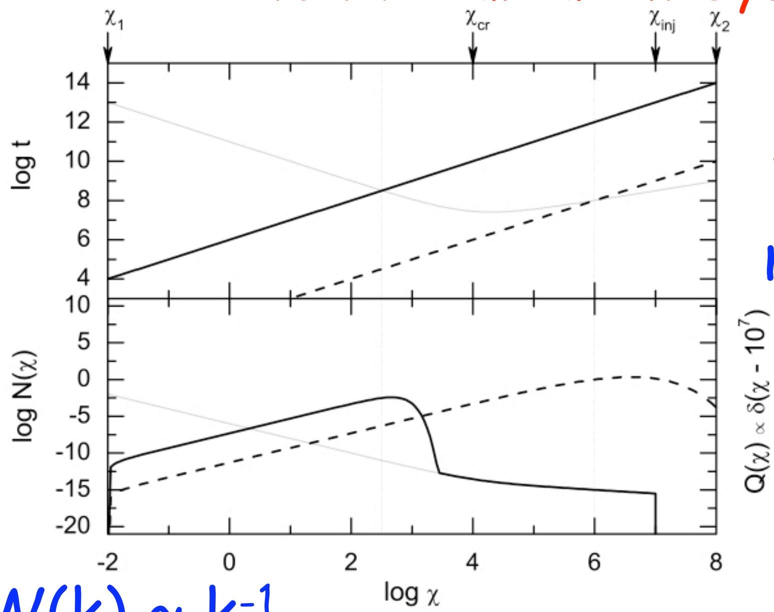
$B \sim G$
$R \sim 10^{17}$ cm

$h\nu' \sim 30$ GeV
$\ell_{inj} \sim (L'_{inj}/10^{42}$ erg s$^{-1})$
$\ell_B \sim 100$

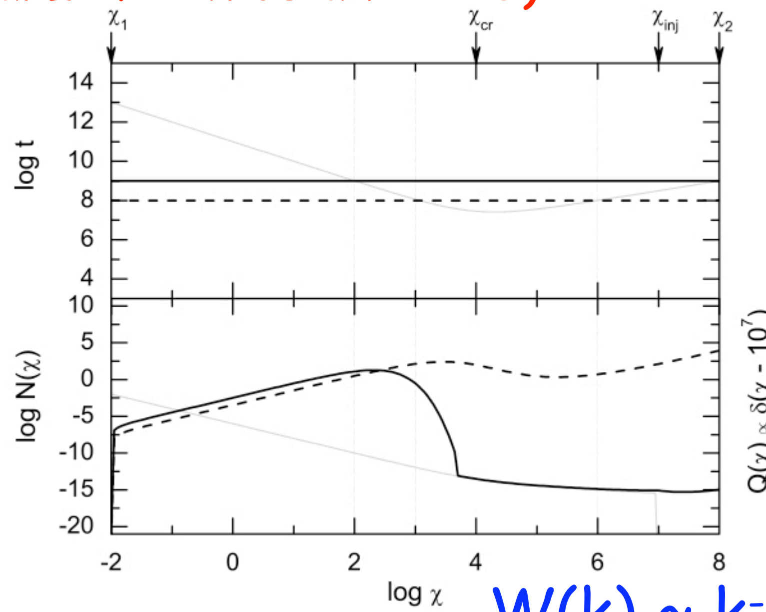
➔ Possible quenching
but no efficient pair loading (high ℓ_B)

(but plenty of $h\nu'_0 \sim 10$ eV emission expected to be generated in the system)

Realistic Situation: Injection of High Energy Electrons to the Turbulent System (Stawarz & Petrosian 2008)

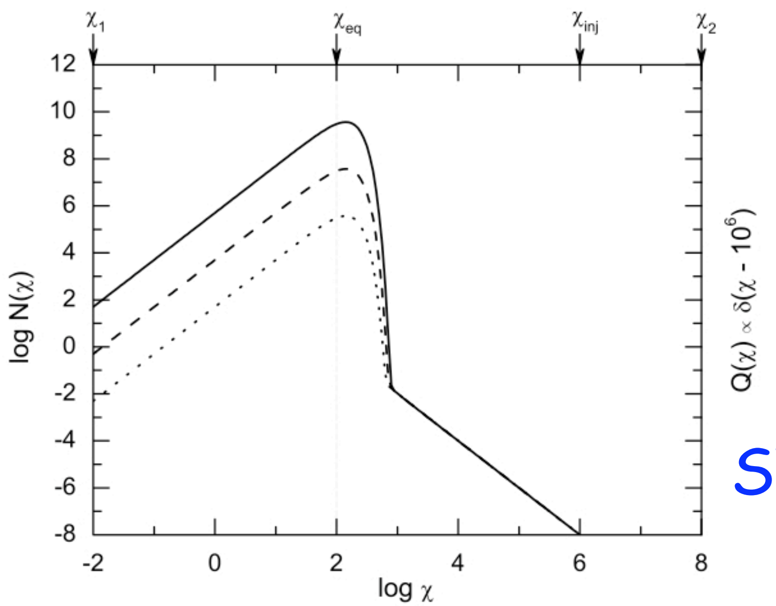


IC/T+KN
no escape



W(k) ~ k^{-1}

W(k) ~ k^{-2}



SYN or IC/T
no escape