



Gamma-rays and neutrinos from black hole coronae

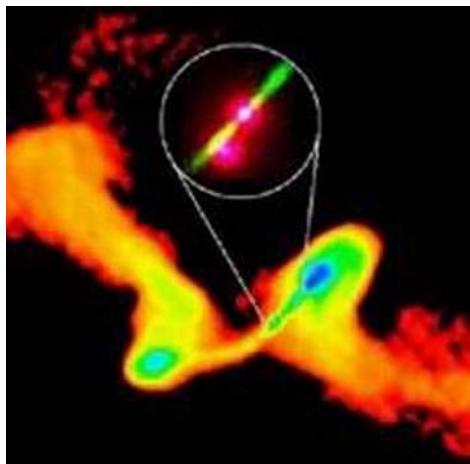
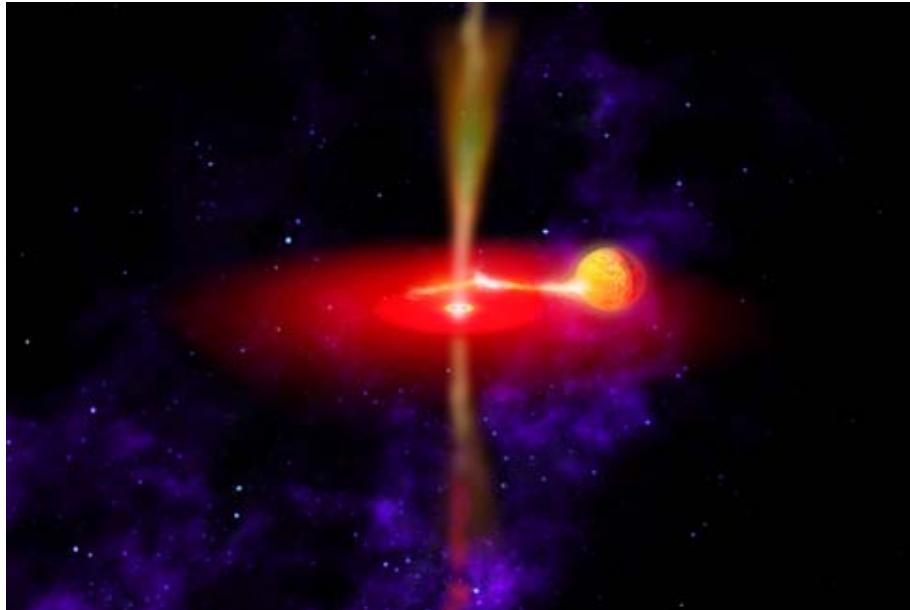
Gustavo E. Romero^{(1,2)*}

* romero@iar-conicet.gov.ar

1 Instituto Argentino de Radioastronomía (CCT- La Plata, CONICET), C.C.5, 1894 Villa Elisa, Buenos Aires, Argentina.

2 Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, paseo del Bosque, 1900, La Plata, Argentina.

Accreting black holes



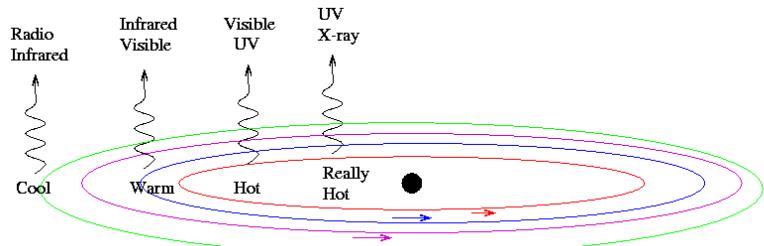
X-ray binary

← → AGN

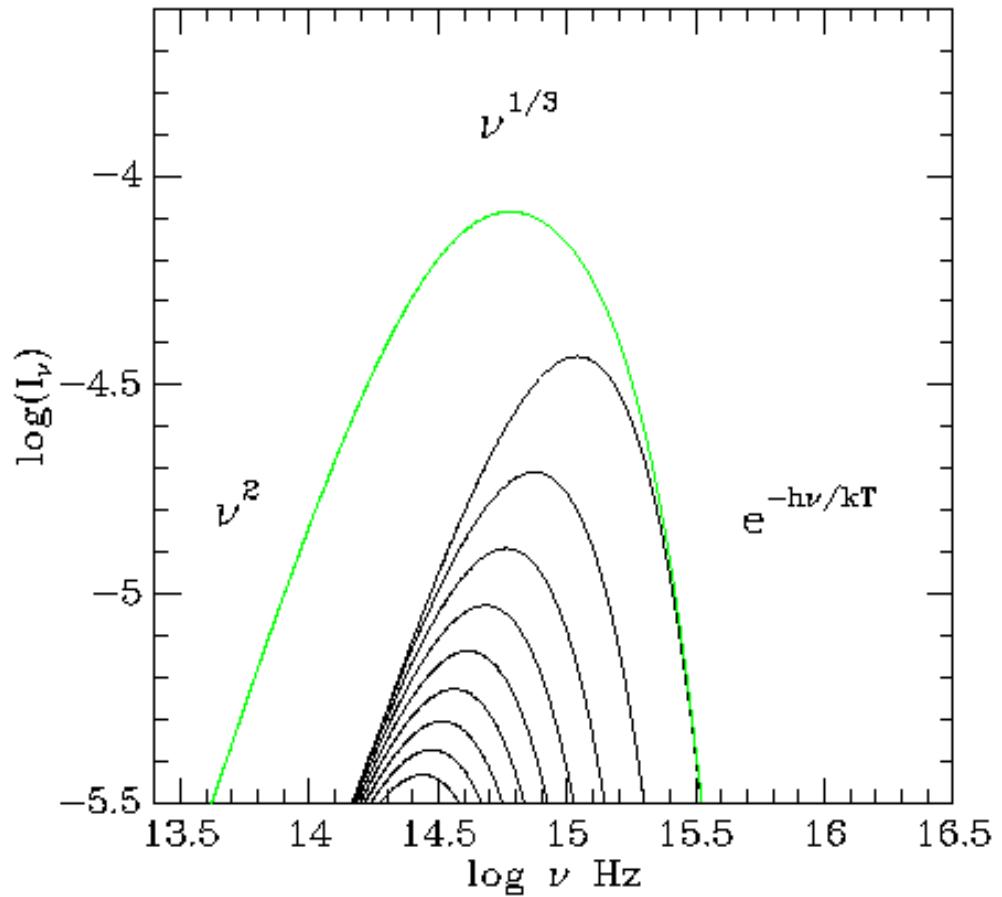


Gamma-ray bursts/Collapsars

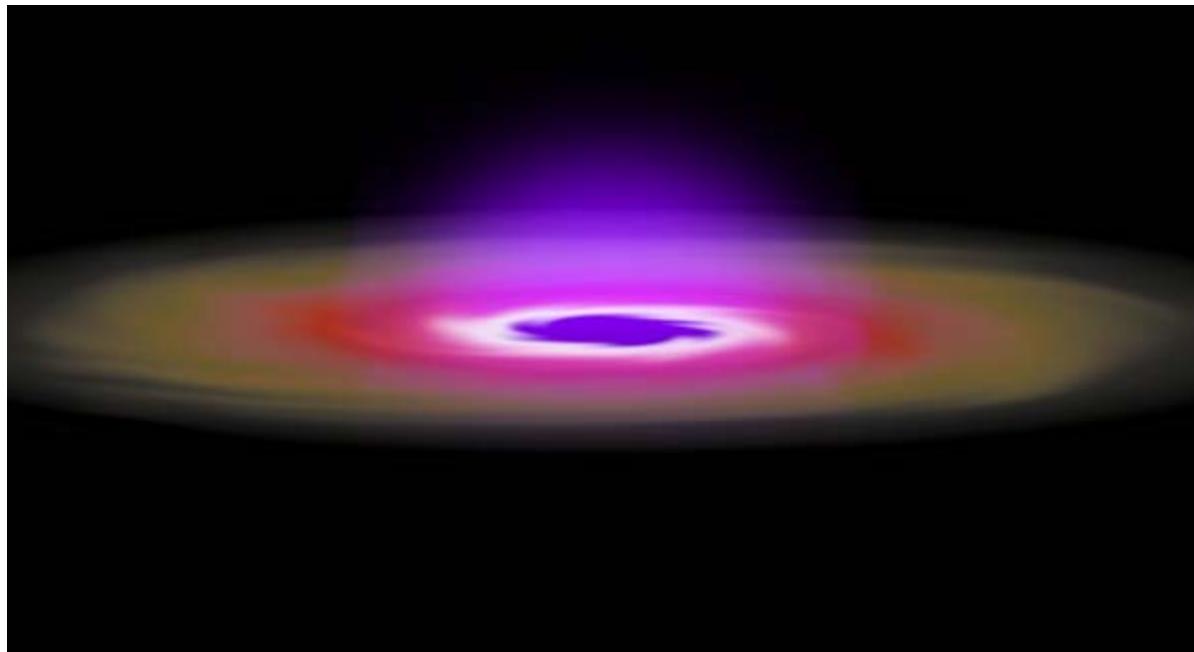
Accretion disk



Accretion disk spectra

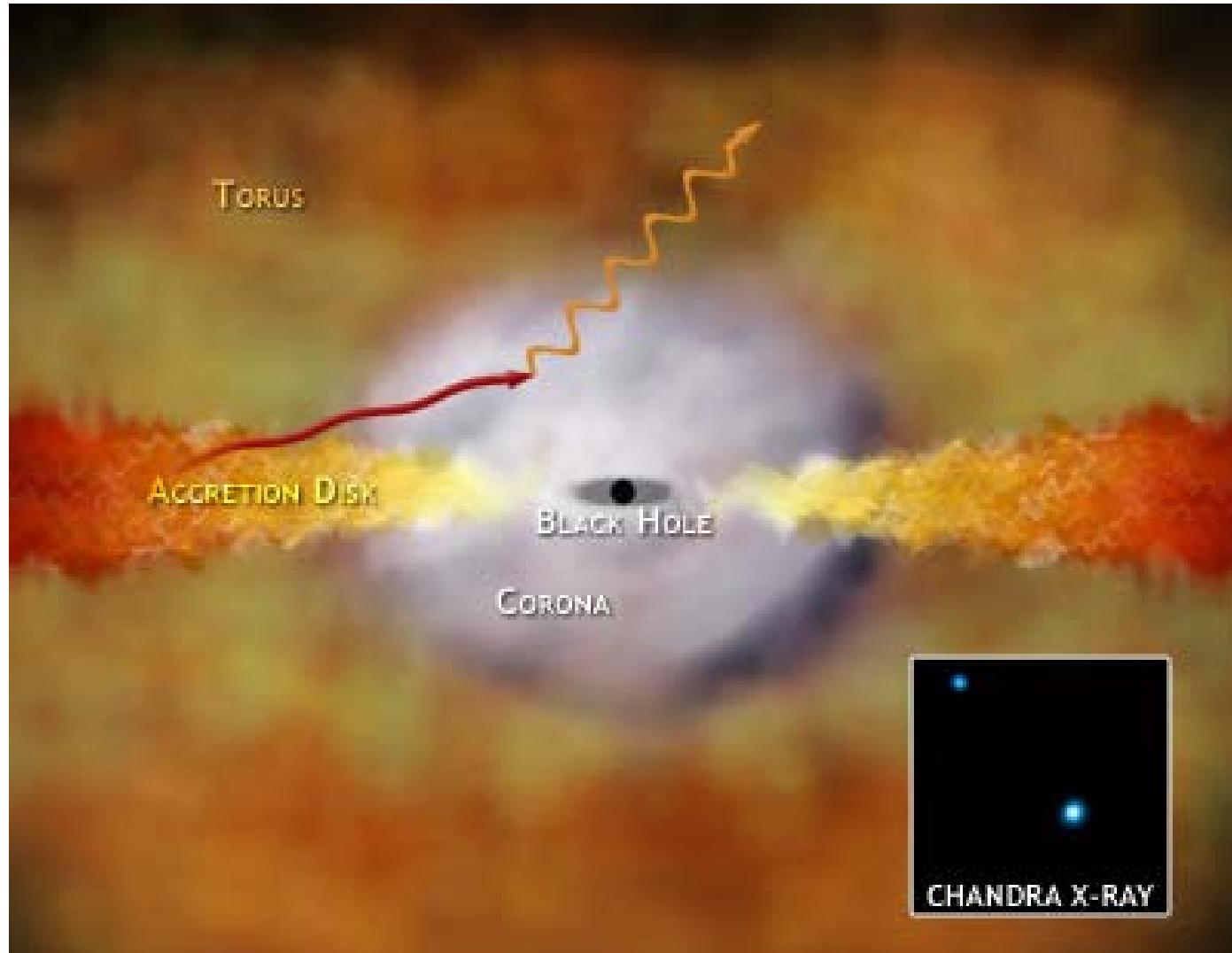


Corona

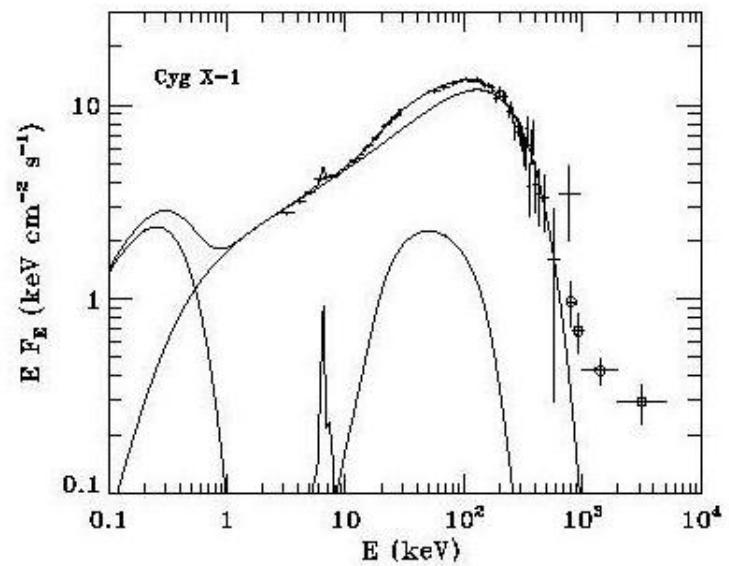
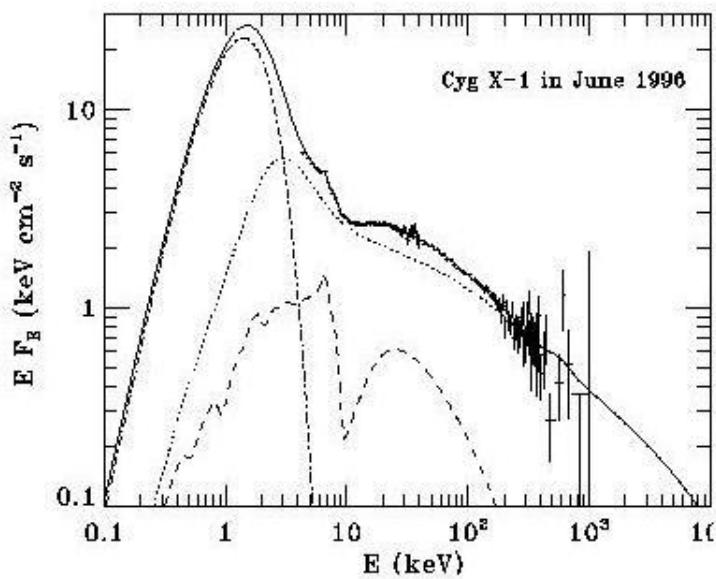


Bisnovatyi-Kogan & Blinnikov (1976)

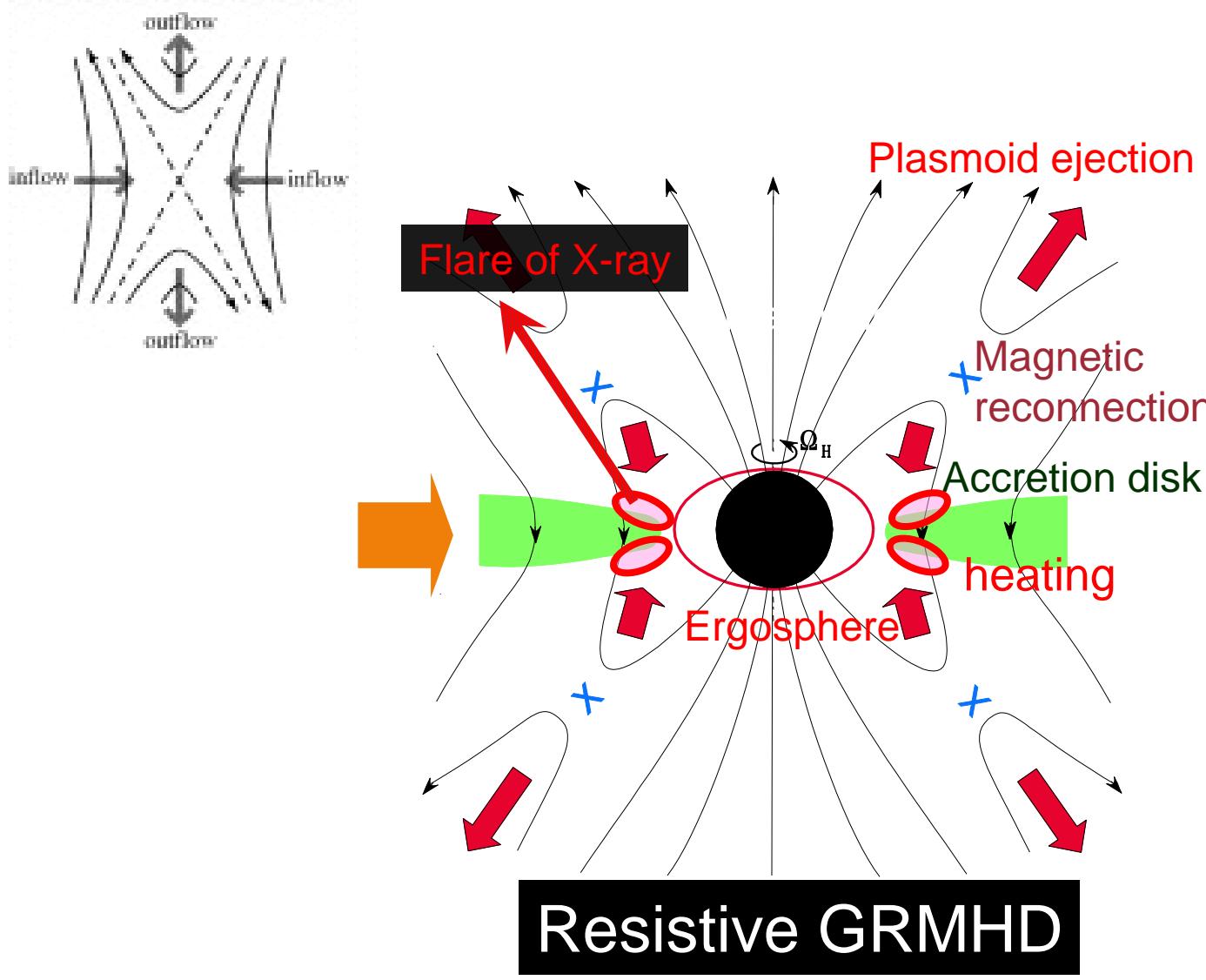
The structure of coronae around black holes



Spectral states

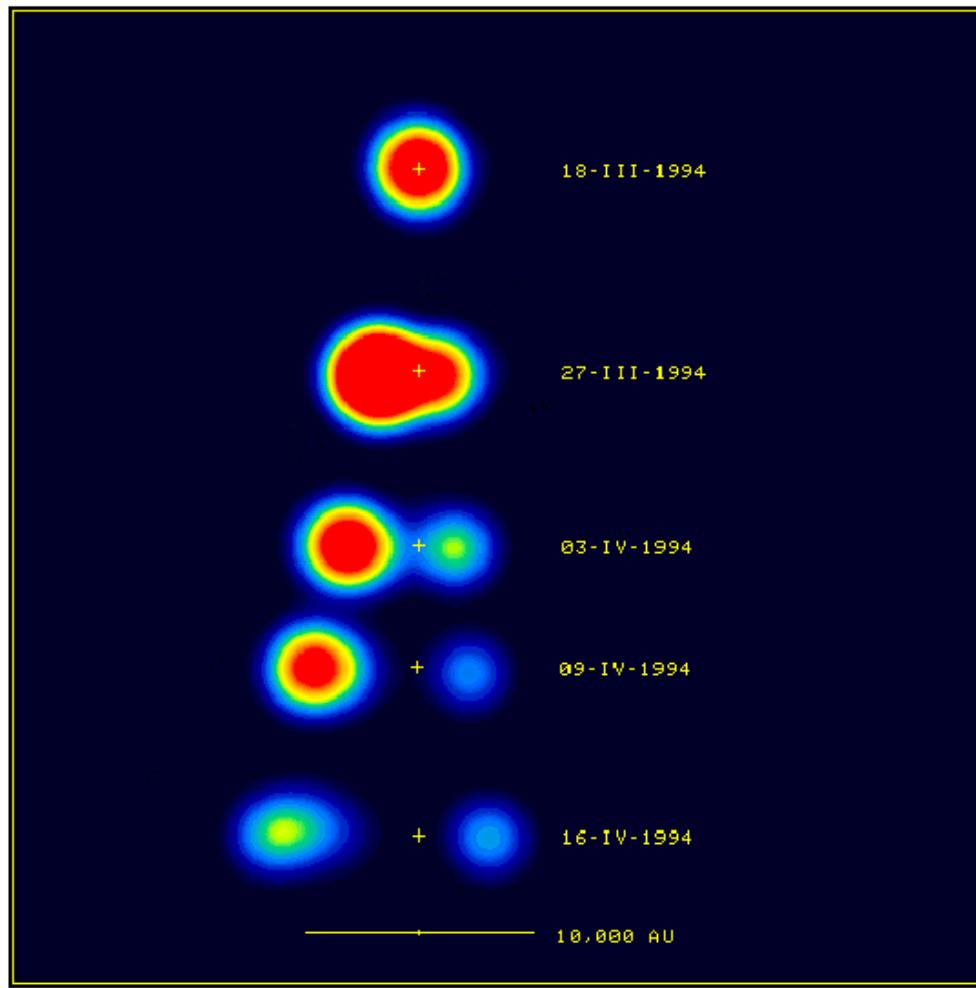


- Cygnus X-1 states



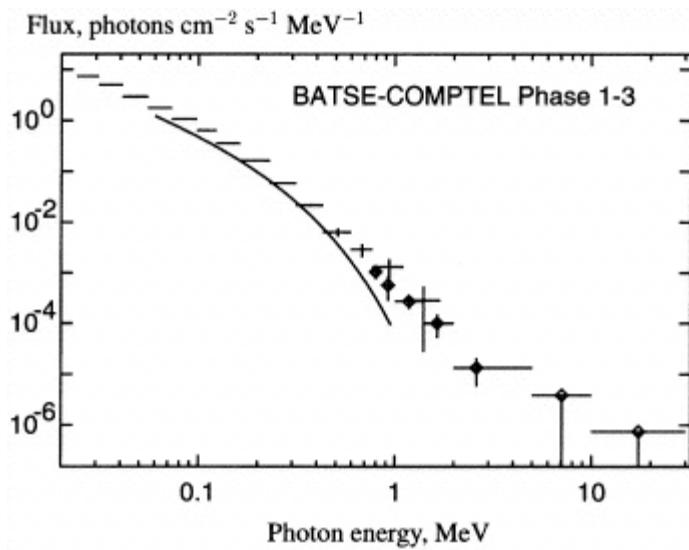
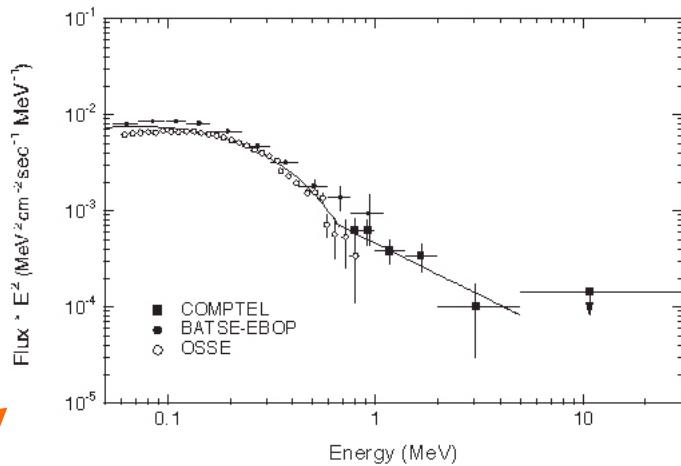
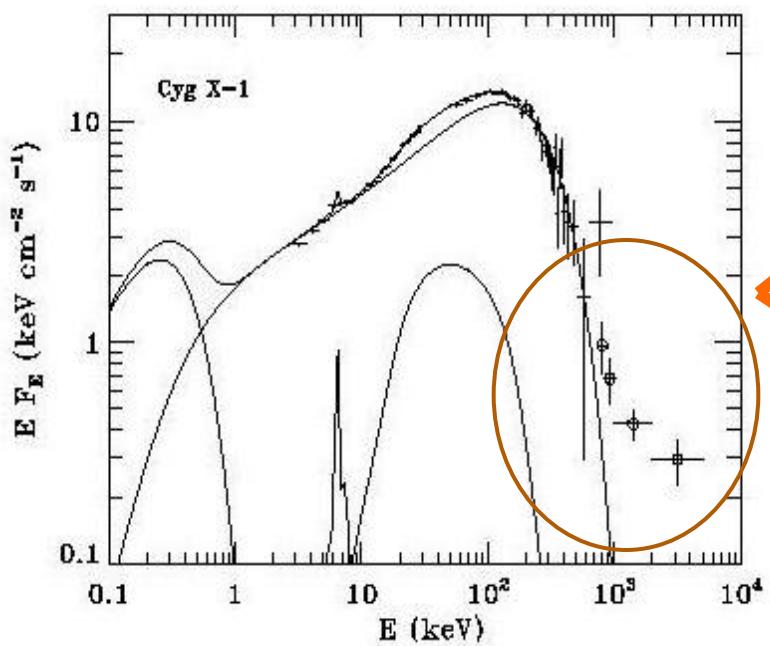
Magnetic reconnection happens

Koide



Mirabel & Rodríguez 1994

MeV non-thermal tail



Non-thermal processes around black holes

Injection of non-thermal relativistic
electrons and protons



Interactions with
different fields



Radiative output

Magnetized astrophysical plasmas

Two basic approaches

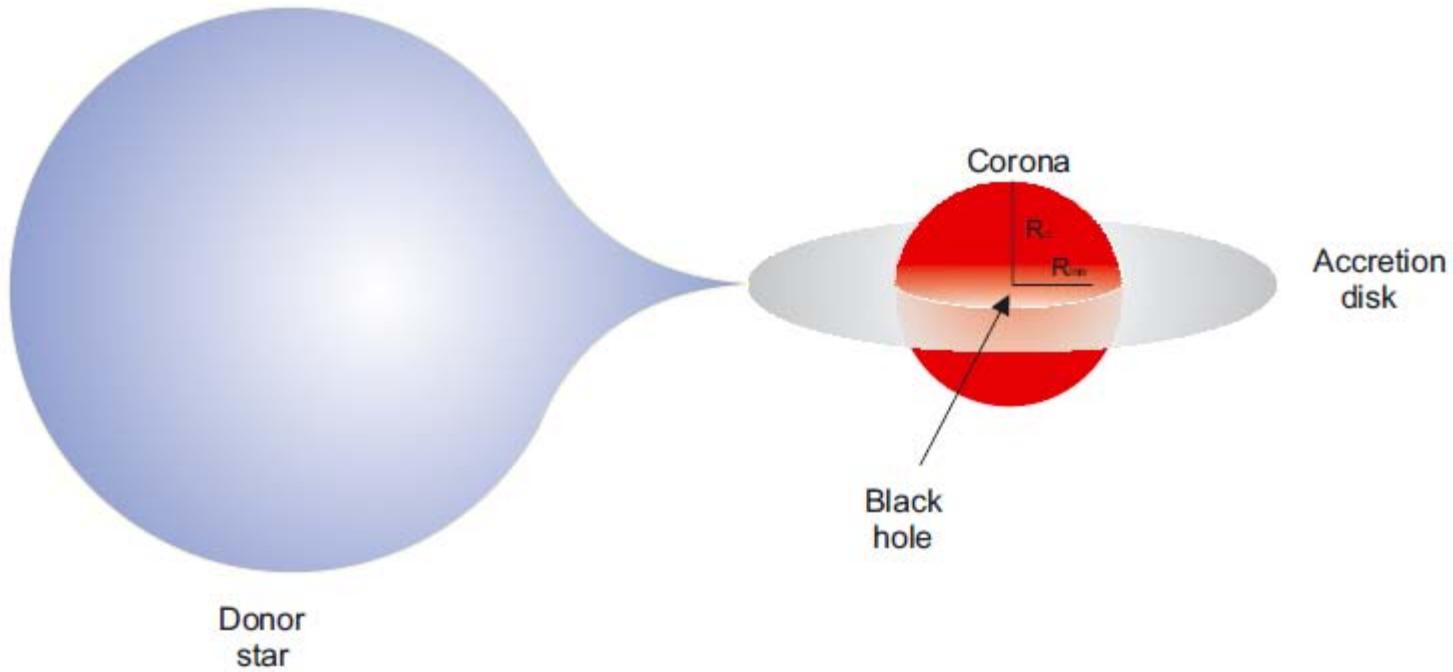
MonteCarlo
method

Solving kinetic
equations

- Easy treatment of radiative processes
- Poor photon statistics (e.g., Aharonian et al. 1985; Stern et al. 1995; Pilla & Shaham 1997, Pellizza, Orellana & Romero 2010)
- Photon statistics not an issue
- Solving integro-differential equation (e.g., Zdziarski 1988, Coppi 1992; Vurm & Poutanen 2009; Pe'er & Waxman 2005)

Model setup

- Spherical geometry: corona + disk
- $M_{\text{BH}} = 14.8 M_{\odot}$ (Orosz et al. 2011)
- $R_c = 35 R_g \approx 5 \times 10^7 \text{ cm}$
- $L_c = 10^{-2} L_{\text{Edd}} = 1.6 \times 10^{37} \text{ erg/s}$
- Temperature plasma $T_e = 10^9 \text{ K}$
- Magnetic field: $B = 5.7 \times 10^5 \text{ G}$
- Plasma density: $n_{e,i} = 6.2 \times 10^{13} \text{ cm}^{-3}$
- Acceleration efficiency: $\eta = 10^{-2}$



- Static corona: $t_{\text{diff}}^{-1} = \frac{2D(E)}{R_c^2}$, $D(E) \approx \frac{1}{3} r_g \nu$
- X-ray emission of the corona
 - $n_{\text{ph}}(E) = A_{\text{ph}} E^{-\alpha} e^{-E/E_c}$
 - Spectral index: $\alpha \sim 1.6$
 - Cutoff energy: $E_c = 150 \text{ keV}$
 - Normalization: $\frac{L_c}{4\pi R_c^2 c} = \int E n_{\text{ph}}(E) dE$
- Photon field from the disk
 - Black body with temperature $kT = 0.1 \text{ keV}$

Particle injection

- Primary injection of relativistic electrons and protons
 - $Q(E) = Q_0 E^{-\alpha} e^{-E/E_{\max}}$, $\alpha = 2.2$
 - $L_p = a L_e$
 - $L_p = a L_e$, $a = 100 - 1$
- Injection of charged pions
 - Proton-proton inelastic collisions (Kelner et al. 2006)
 - Proton-photon interactions (Atoyan & Dermer 2003)
- Muons
 - Charged pions decay (Lipari et al. 2007)
- Electron/Positron pairs
 - Muons decay
 - Bethe-Heitler process
 - Photon-photon annihilation (Vila & Aharonian 2009;
Boettcher & Schlickeiser 1997)

Radiative losses

- Electron/positron pairs

$$b(E) = -\frac{dE}{dt} \Big|_{Synchr} - \frac{dE}{dt} \Big|_{IC} - \frac{dE}{dt} \Big|_{Bremsstr} - \frac{dE}{dt} \Big|_{e^\pm \rightarrow \gamma\gamma}$$

- Protons and charged pions

$$b(E) = -\frac{dE}{dt} \Big|_{Synchr} - \frac{dE}{dt} \Big|_{p\gamma} - \frac{dE}{dt} \Big|_{pp}$$

- Muons

$$b(E) = -\frac{dE}{dt} \Big|_{Synchr} - \frac{dE}{dt} \Big|_{IC} - \frac{dE}{dt} \Big|_{Bremsstr}$$

Kinetic equation for relativistic particles

- Steady state
- Isotropy and homogeneity
- Particle injection $Q(E)$
- Radiative losses $b(E) = -\frac{dE}{dt}$

$$\frac{\partial}{\partial E} (N(E) \cdot b(E)) + \frac{N(E)}{t_{esc}} = Q(E)$$

Kinetic equation for photons

$$\frac{N_{ph}(E_\gamma)}{t_{esc}^\gamma} = Q_\gamma^{rp}(E_\gamma) + Q_\gamma^{e^\pm \rightarrow \gamma\gamma}(E_\gamma) - Q_\gamma^{\gamma\gamma \rightarrow e^\pm}(E_\gamma)$$

- $Q_\gamma^{rp}(E_\gamma)$ Synchrotron, IC, hadronic collision, and photohadronics interactions
- $Q_\gamma^{e^\pm \rightarrow \gamma\gamma}(E_\gamma)$ Photon emissivity produced by pair annihilation (Coppi & Blandford 1990)
- $Q_\gamma^{\gamma\gamma \rightarrow e^\pm}(E_\gamma)$ Photopair production (Vila & Aharonian 2009)

Set of coupled equation

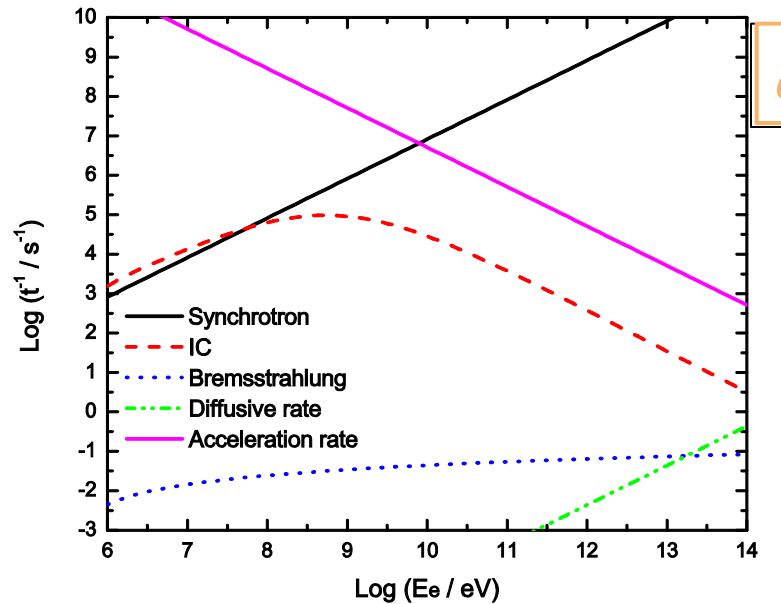
$$\frac{N_{ph}(E_\gamma)}{t_{esc}} = Q_\gamma^{rp}(E_\gamma) + Q_\gamma^{e^\pm \rightarrow \gamma\gamma}(E_\gamma) - Q_\gamma^{\gamma\gamma \rightarrow e^\pm}(E_\gamma) \quad \left. \right\} \text{Photons}$$

$$\frac{\partial}{\partial E} (N(E).b(E)) + \frac{N(E)}{t_{esc}} = Q(E) \quad \left. \right\} \begin{array}{l} \text{Electrons} \\ \text{Protons} \\ \text{Pairs} \end{array}$$

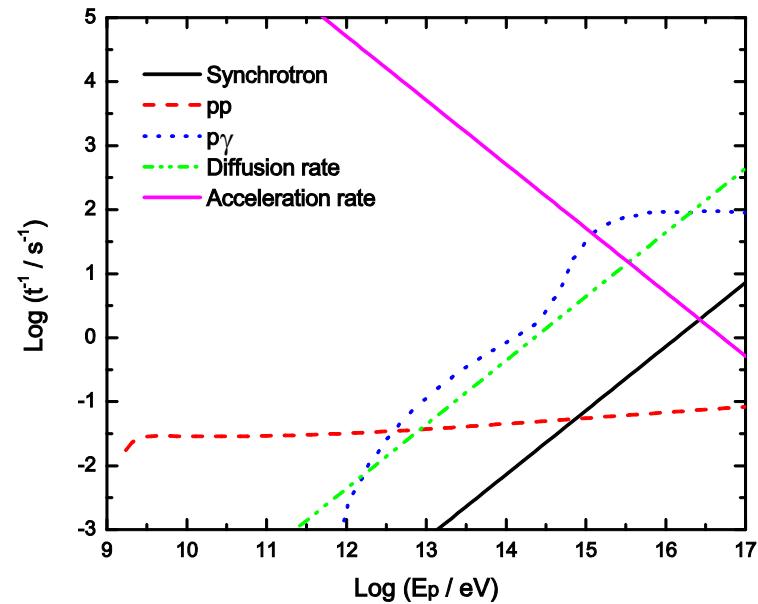
$$\frac{\partial}{\partial E} (N(E).b(E)) + \frac{N(E)}{t_{esc}} + \frac{N(E)}{t_{dec}} = Q(E) \quad \left. \right\} \begin{array}{l} \text{Pions} \\ \text{Muons} \end{array}$$

Adams-Moulton method (implicit multiple-step integration procedure)

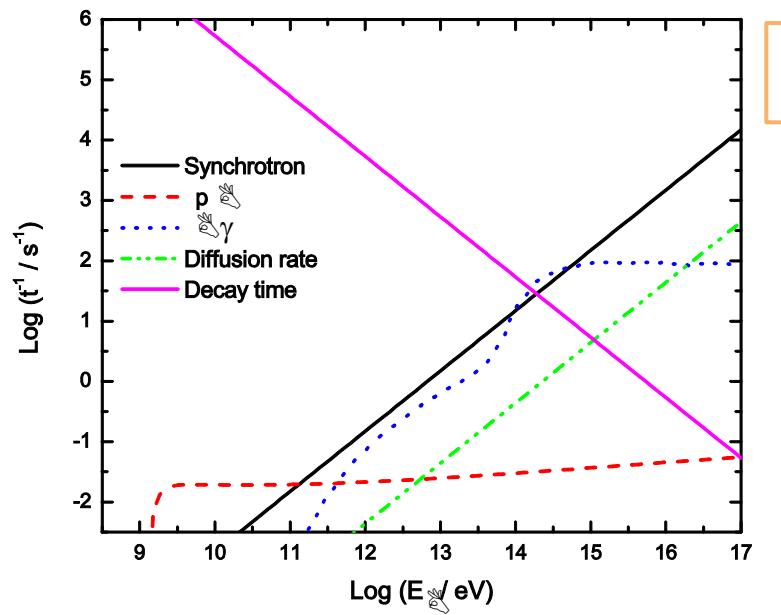
Radiative losses



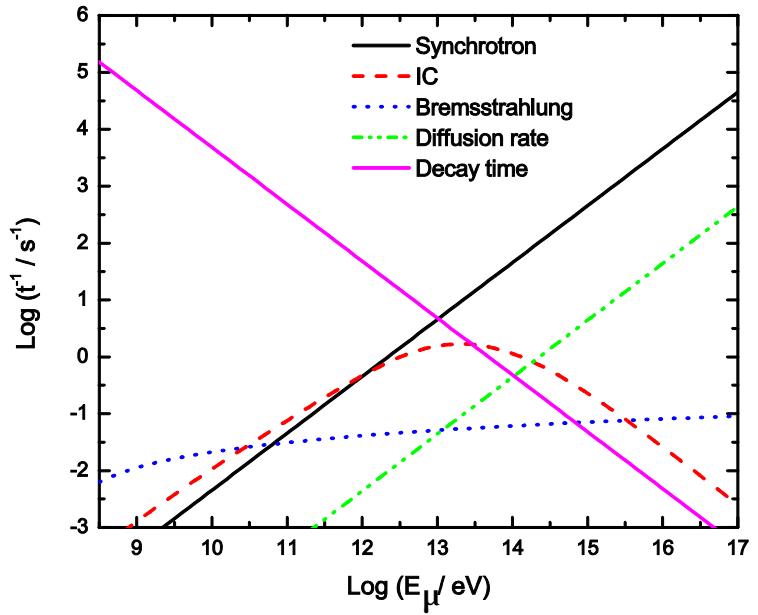
e



p

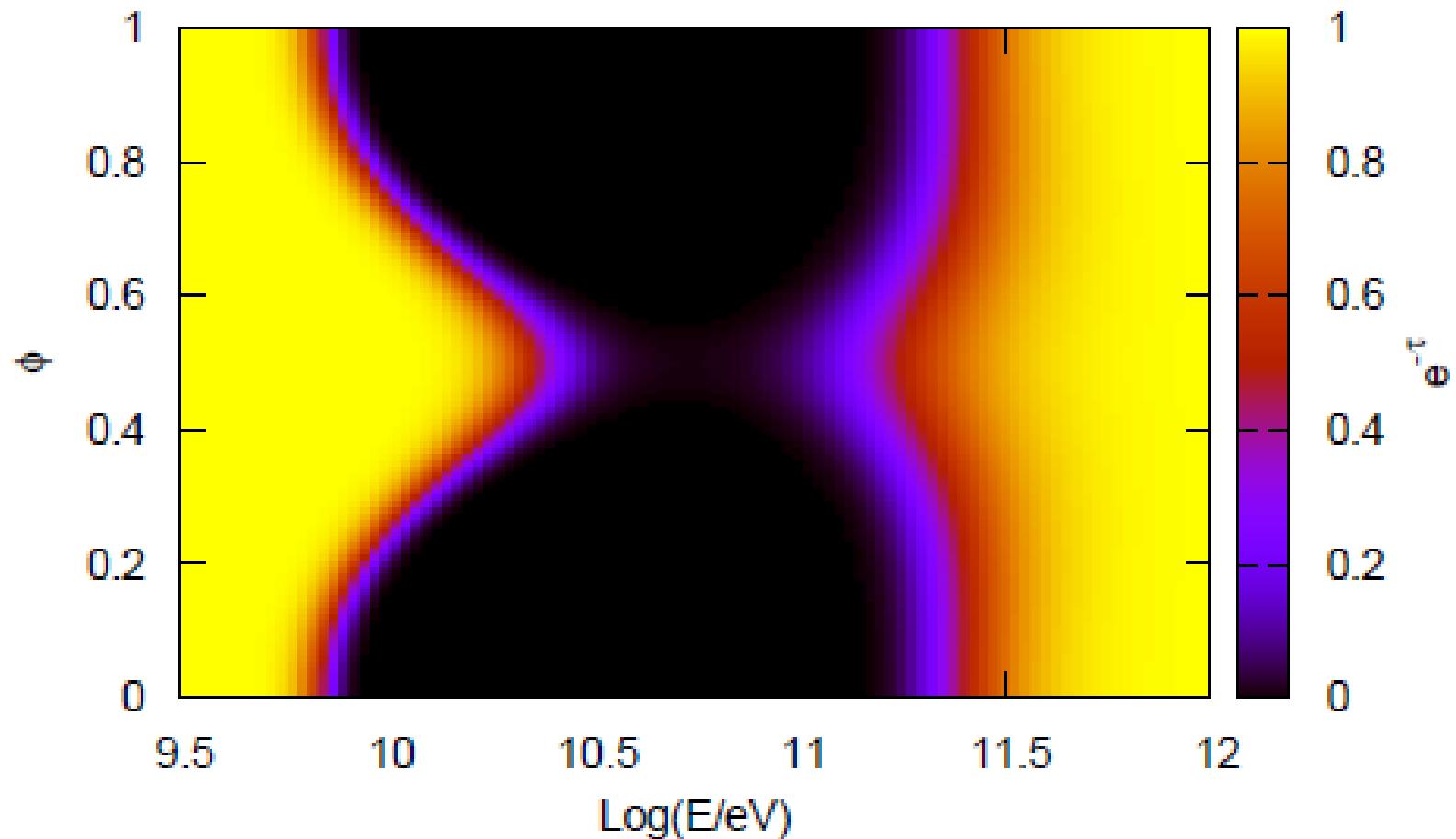


π



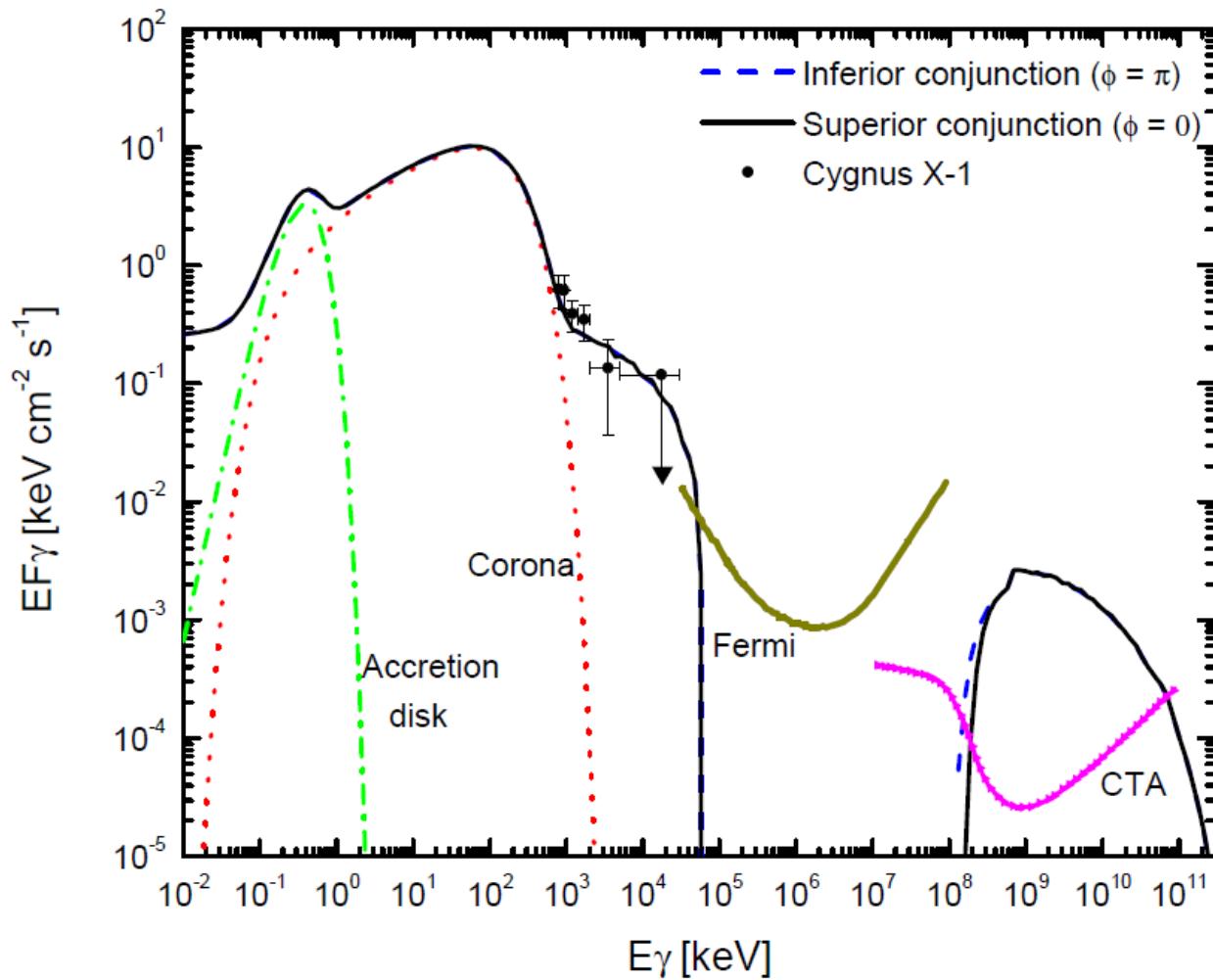
μ

External absorption in Cyg X-1



SED (Vieyro & Romero, A&A 2012)

a=1

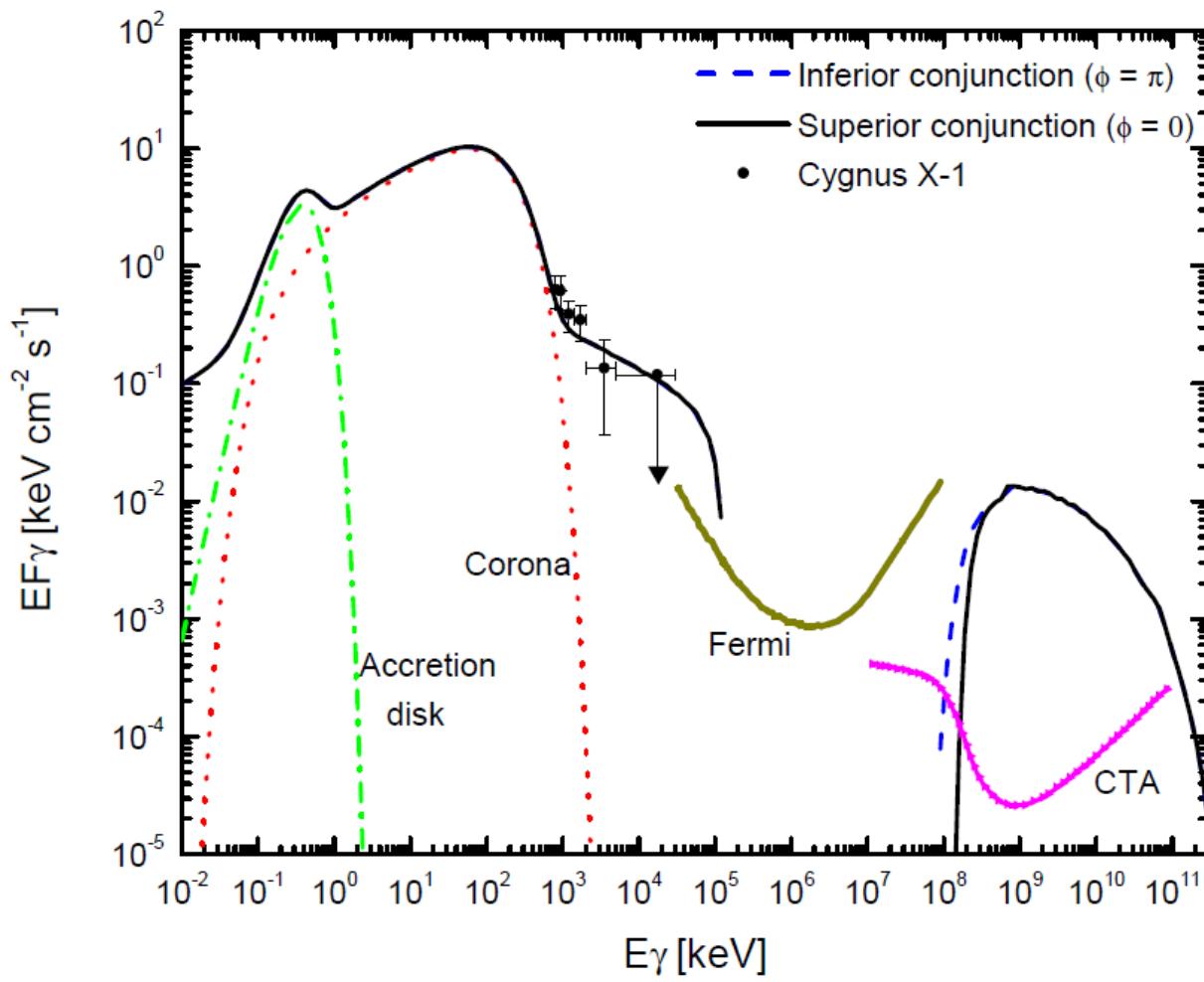


Cygnus X-1

D=1.8 kpc (Reid et al. 2011)

SED (Vieyro & Romero, A&A 2012)

$a=100$

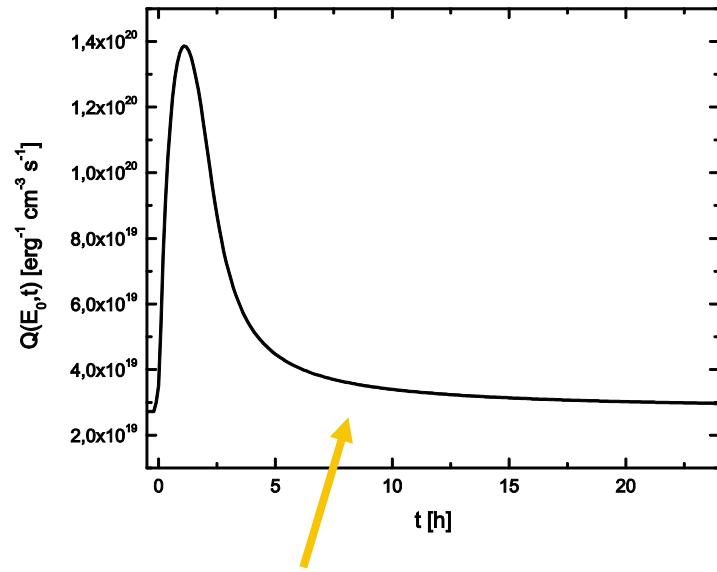


Cygnus X-1

D=1.8 kpc (Reid et al. 2011)

Flares

Particle injection: $Q(E, t)$

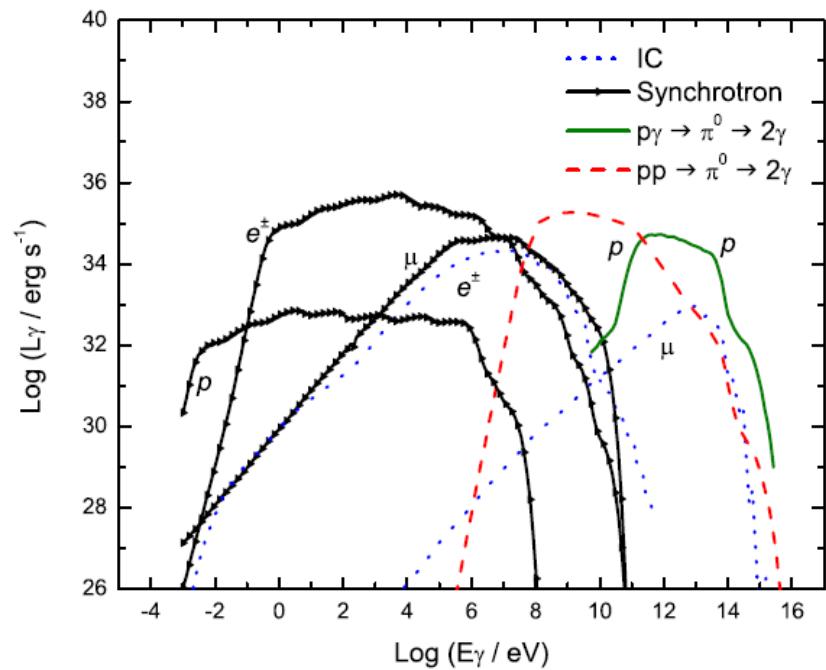
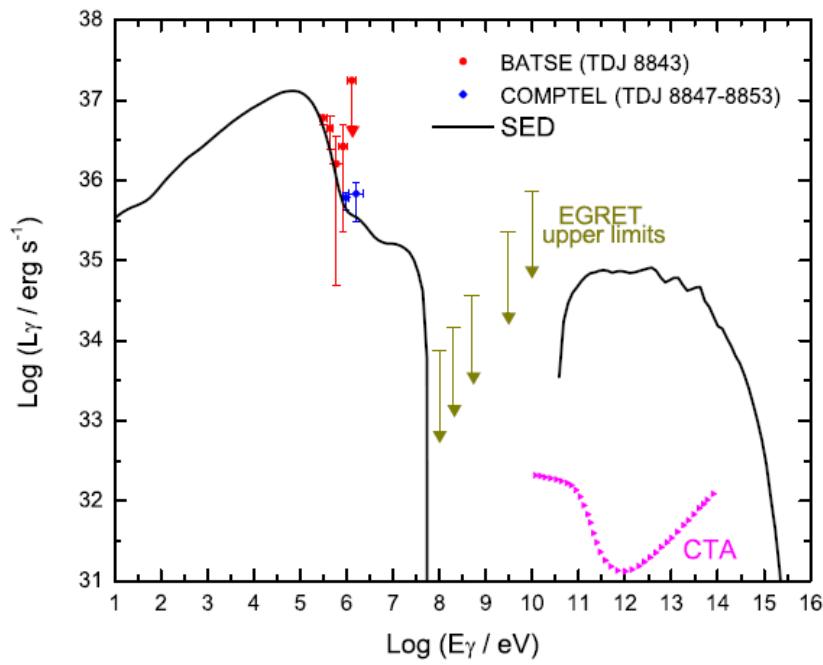


Electron injection at $E=10^7$ eV

$$\frac{\partial}{\partial t} N(E, t) + \frac{\partial}{\partial E} [N(E, t) \cdot b(E)] + \frac{N(E, t)}{t_{esc}} = Q(E, t)$$

Time-dependent transport equation

A transient source: GRO J0422+32



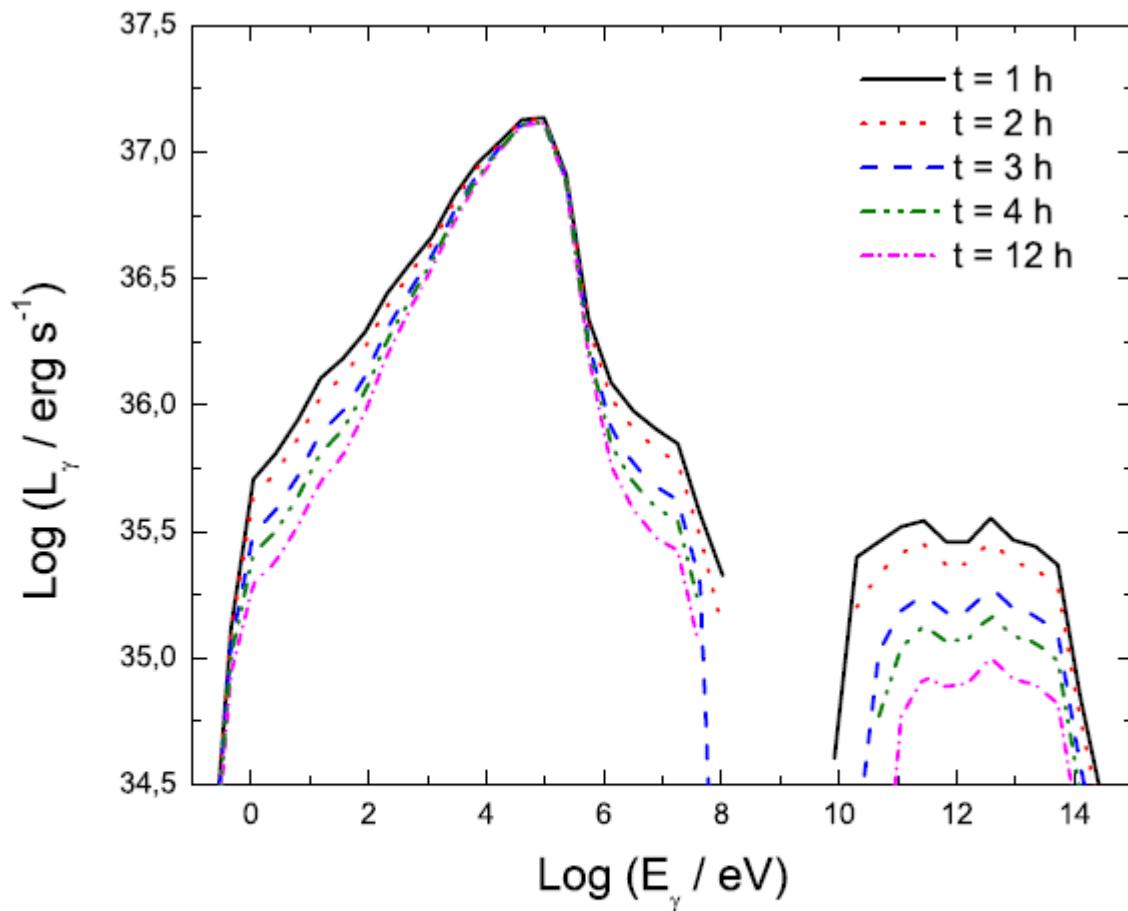


Fig. 7. Evolution of the luminosity during a flare of ~ 2 h of duration. Since the cooling time scales in the corona are significantly shorter than flare time scales, the shape of the spectrum does not change and just shows decreasing luminosity levels as the flare evolves.

Neutrino emission of GRO J0422+32

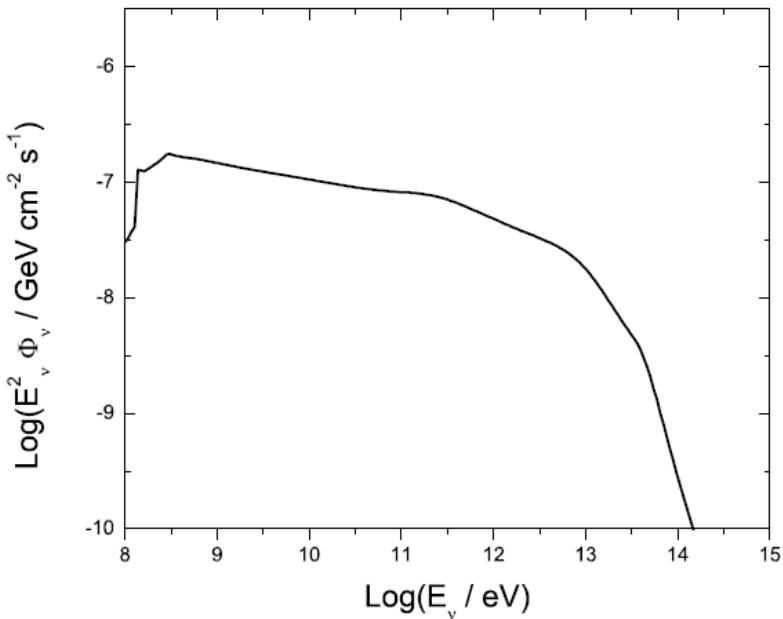


Fig. 8. Differential flux of muon neutrinos produced in the hard state of GRO J0422+32 arriving at the Earth. The effects of neutrino oscillations are included.

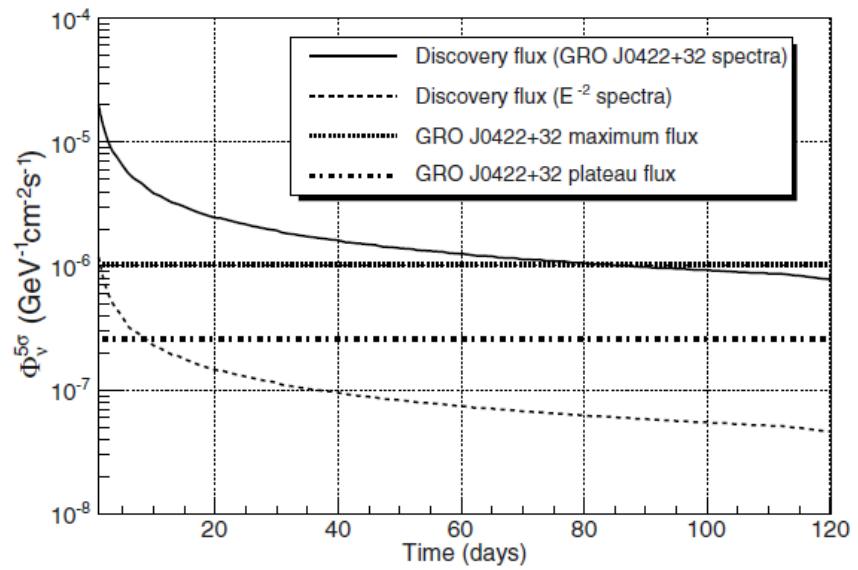
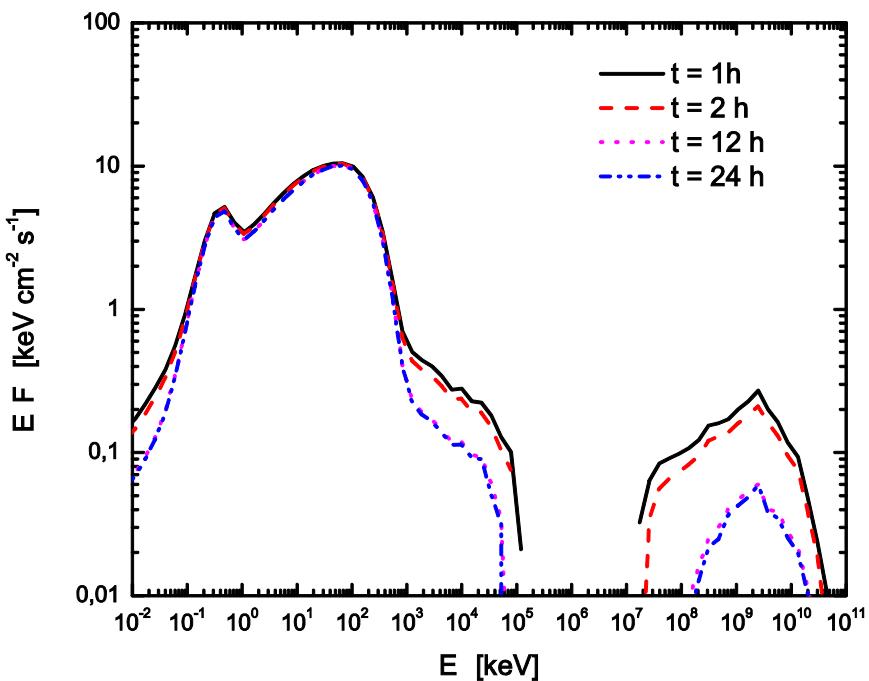
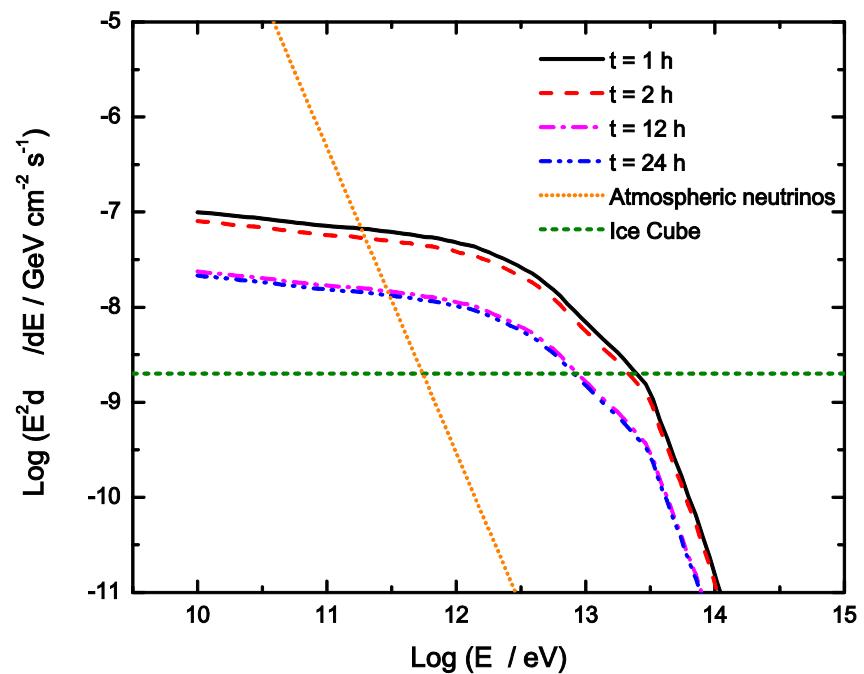


Fig. 11. Discovery Flux Φ_0 , where $\Phi_\nu = \Phi_0 E^{-2.16} \exp(-(E/8 \text{ TeV})^{-0.52})$ for the case of GRO J0422+32 and an unbroken spectrum $\Phi_\nu = \Phi_0 E^{-2}$ used for comparison.

Flares: Cygnus X-1



Gamma-ray flare



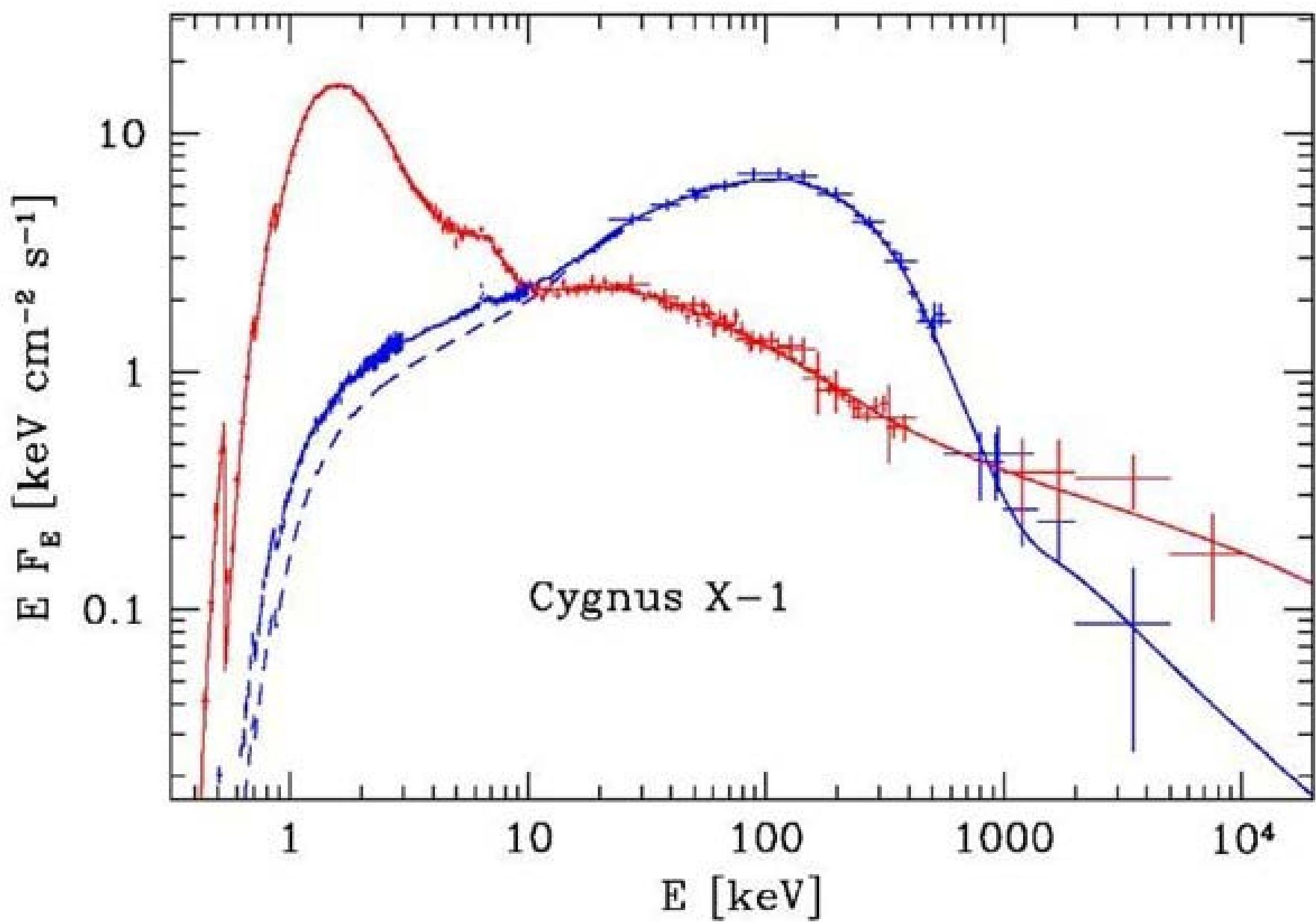
Neutrino flare

Conclusions

- Consistent treatment of non-thermal emission from a magnetized corona can be implemented solving the set of coupled differential equations for all particles species.
- The application to Cygnus X-1 yields a good fit of the observational data and leads to interesting predictions for very high energy and neutrino instruments
- The methods develop in this work can be useful for the study of radiative processes in the uncorking region of long GRBs (collapsars).



Thanks!



3.3. Numerical method

We use an Adams-Moulton method (see, e.g., Press et al. 1992) to solve the differential equations in Eqs. (15)-(16). This is an implicit multi-step integration method that can reach higher orders than other numerical algorithms; we use in particular a second order method.

Following the scheme described in Vurm & Poutanen (2009), we define an equally spaced grid on a logarithmic scale for the energy of particles

$$\ln E_i = \ln E_{\min} + i \cdot \Delta E, i \in [0, i_m], \quad (23)$$

$$\ln E_l^\gamma = \ln E_{\min}^\gamma + l \cdot \Delta E^\gamma, l \in [0, l_m]. \quad (24)$$

We then obtain a system of linear algebraic equations of the form

$$\sum_{j=1}^{i_m} A_{ij} \cdot N_j = Q_i, \quad (25)$$

with the boundary condition that $N_{i_m} = 0$, which represents $N(E_{\max}) = 0$. The matrix A_{ij} contains the particle

losses, whereas particle injection is included in the vector Q_i

$$Q_i = \begin{pmatrix} \frac{1}{2}h_1(Q_1 + Q_2) \\ \frac{1}{2}h_1(Q_1 + Q_2) \\ \frac{1}{2}h_2(Q_2 + Q_3) \\ \vdots \\ \frac{1}{2}h_{m-1}(Q_{i_{m-1}} + Q_m) \\ 0 \end{pmatrix}, \quad (26)$$

where $h_j = E_{j+1} - E_j$ is the energy step.

We first solve the transport equations and obtain the particle distributions. These are used to estimate to first order the non-thermal luminosity. Once we know the non-thermal photon injection, we solve Eq. 17. An important property of the photon transport equation (17) is its non-linearity. This is because the cross-section of photopair pro-

duction ($Q_{\gamma\gamma \rightarrow e^\pm}(N_\gamma, E_\gamma)$) depends explicitly on the photon distribution. We use the approximation discussed in Poutanen & Vurm (2009), which consists in taking the photon distribution from a previous step, j , to obtain the current injection (step $j + 1$) of electron/positron pairs. Since we firstly consider a steady state, the way to solve the photon transport equation is then reduced to a simple iterative scheme given by

$$N_\gamma^{j+1}(E_\gamma) = t_{\text{esc}}^\gamma \left(Q_\gamma^{j+1}(E_\gamma) + Q_{e^\pm \rightarrow \gamma}^{j+1}(N_{e^\pm}^j, E_\gamma) - Q_{\gamma\gamma \rightarrow e^\pm}^{j+1}(N_\gamma^j, E_\gamma) \right). \quad (27)$$

The updated photon distribution is then added to the background photon fields (corona power-law plus emission of the disk)¹ to compute the IC scattering and hadronic interactions. We calculate the radiative losses and injection of particles where appropriate. The transport equations of massive particles are then solved, and the new distributions are used to compute the luminosity to second order. The process is repeated until all particle distributions converge to a stationary value.

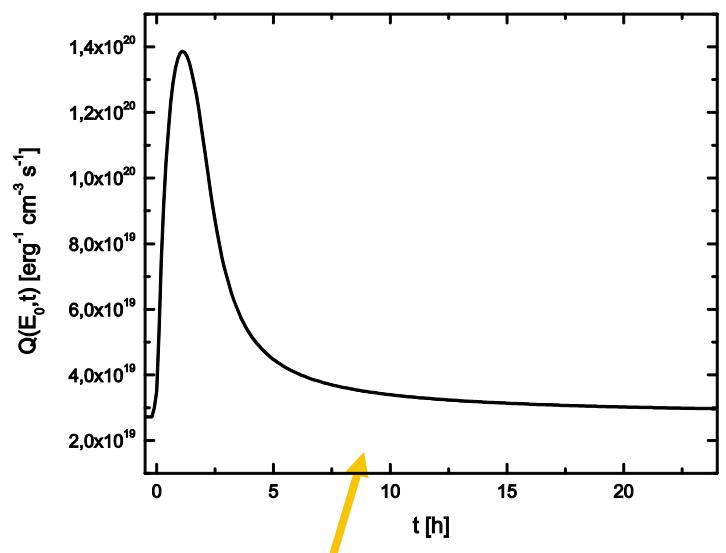
Flares

- In 2006 Cyg X-1 is detected at 4.2 sigma during a possible transient event (Albert et al. 2007). Previous detections at MeV energies.
- Recently, the AGILE satellite confirmed the flaring nature of Cygnus X-1 (Sabatini et al, 2010)
- Four gamma-ray flares detected in the X-ray binary Cyg X-3 (Tavani et al., 2009)

Particle injection

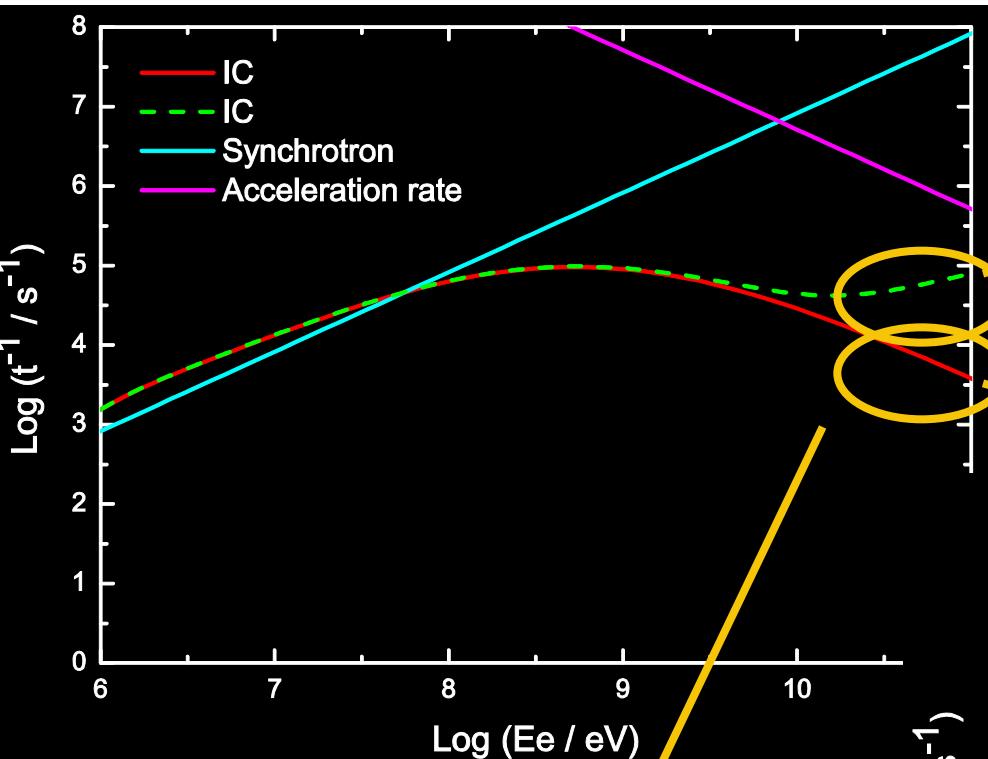
- Electron and proton injection:

- $Q(E,t) = Q_0 E^{-\alpha} e^{-E/E_{\max}} (1 - e^{-t/\tau_{\text{rise}}}) \left[\frac{\pi}{2} - \arctan \left(\frac{t - \tau_{\text{plat}}}{\tau_{\text{dec}}} \right) \right]$
- $\tau_{\text{rise}} = 30^{\text{min}}$, $\tau_{\text{dec}} = 1^{\text{h}}$, $\tau_{\text{plat}} = 2^{\text{h}}$
- $\alpha = 2.2$
- $L_{\text{rel}} = 10^{-1} L_{\text{c}}$
- $L_p = a L_e$, and $a = 1 - 100$



Electron injection at $E=10^7$ eV

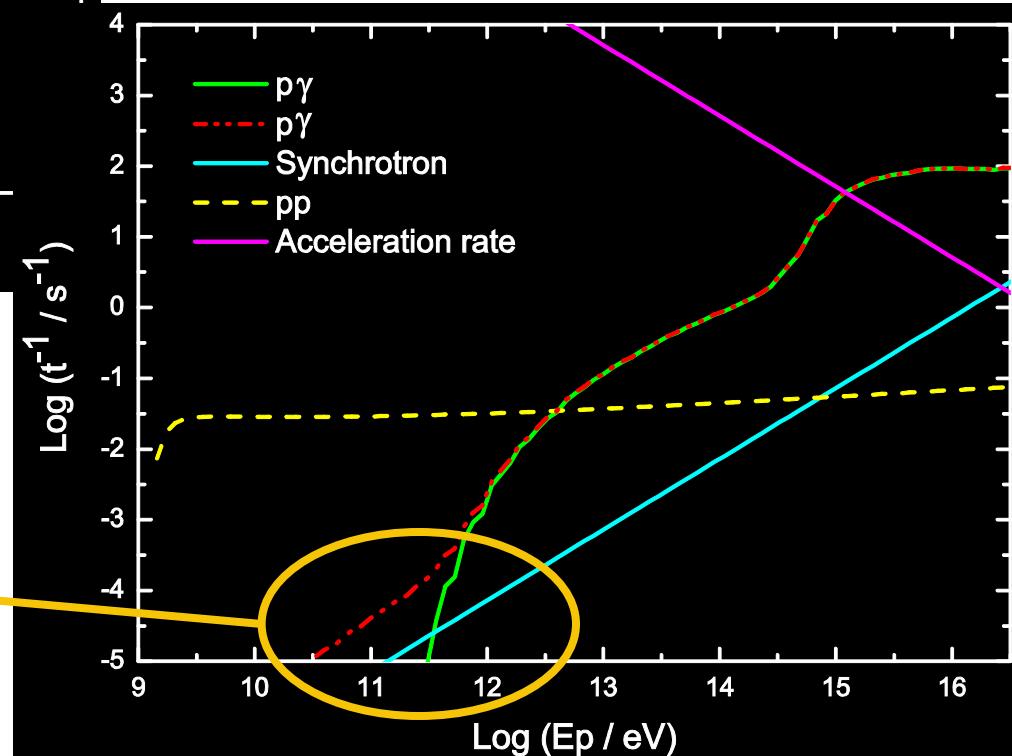
Different target photon fields



IC against disk+corona
power-law+non-thermal
luminosity

IC against disk+corona
power-law

Negligible
differences



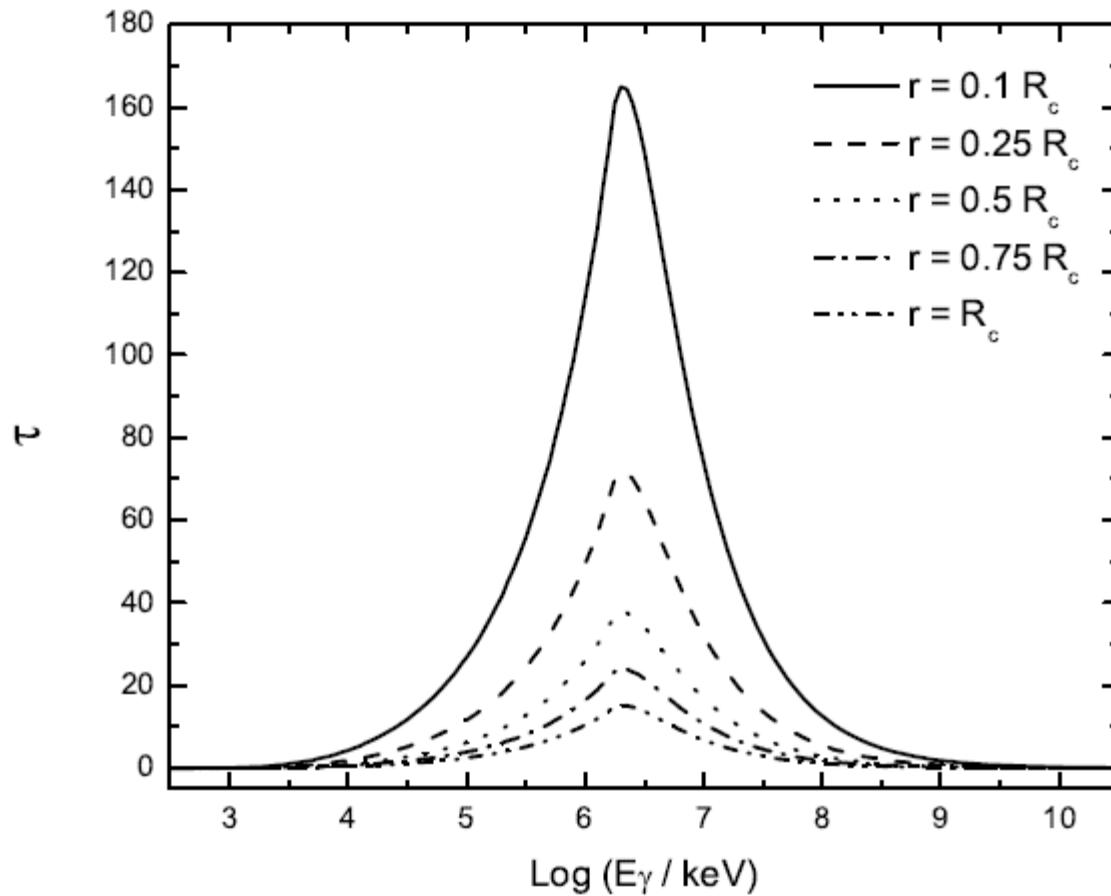
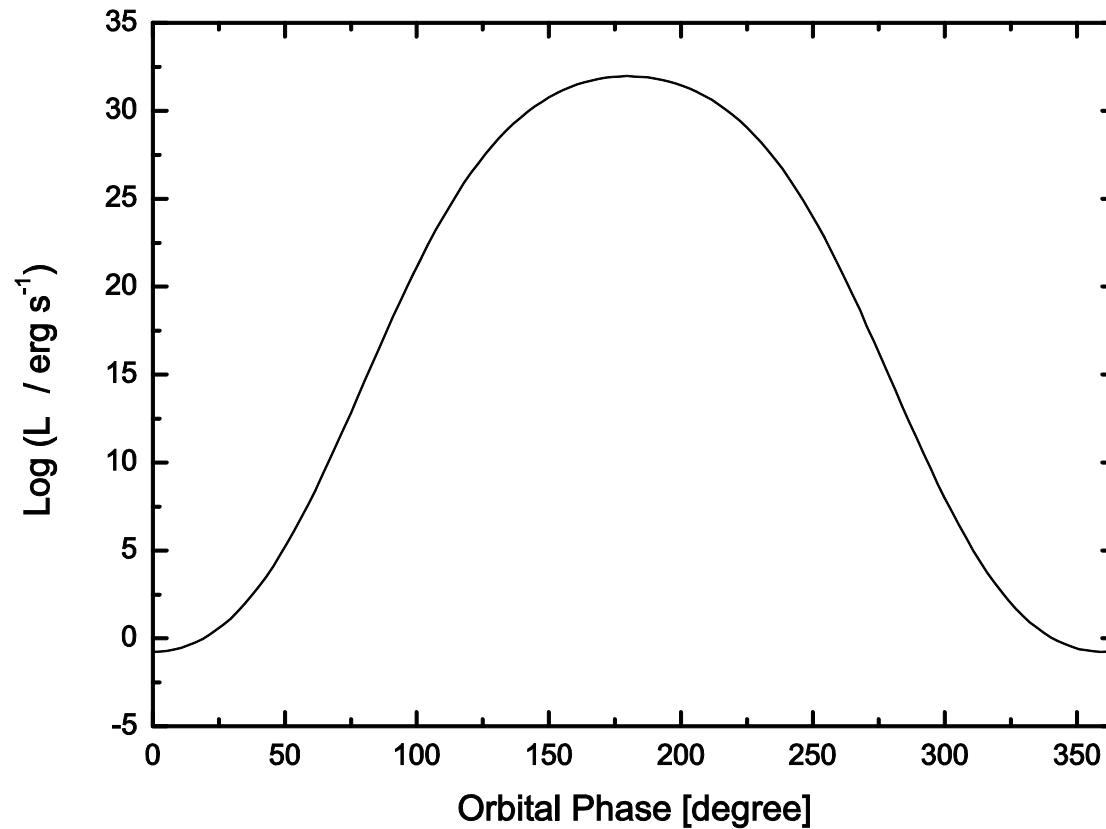


Fig. 7. Internal absorption due to photopair production in the soft photon field of the corona and the accretion disk.

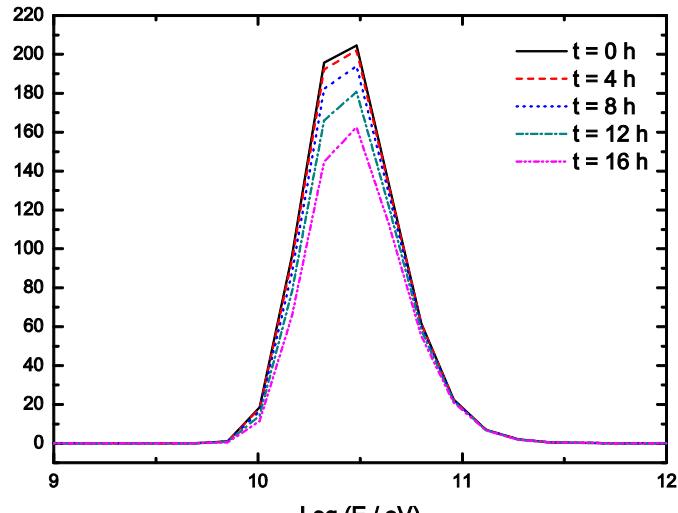
Orbital modulation



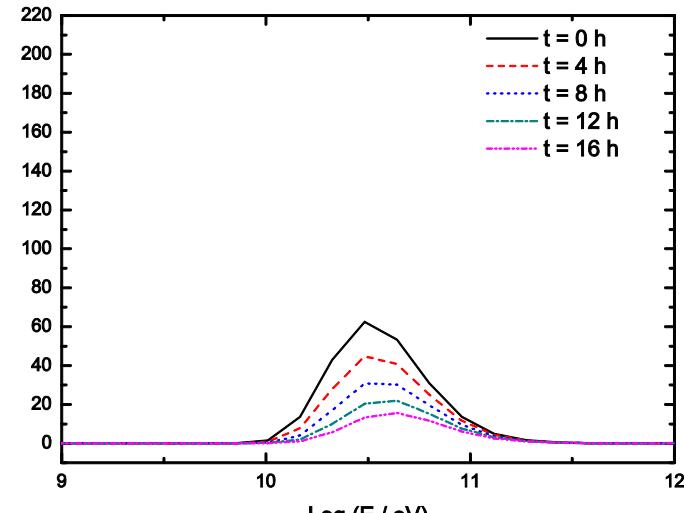
- Gamma-ray emission in steady state at E ~ 50 GeV

External absorption in Cyg X-1

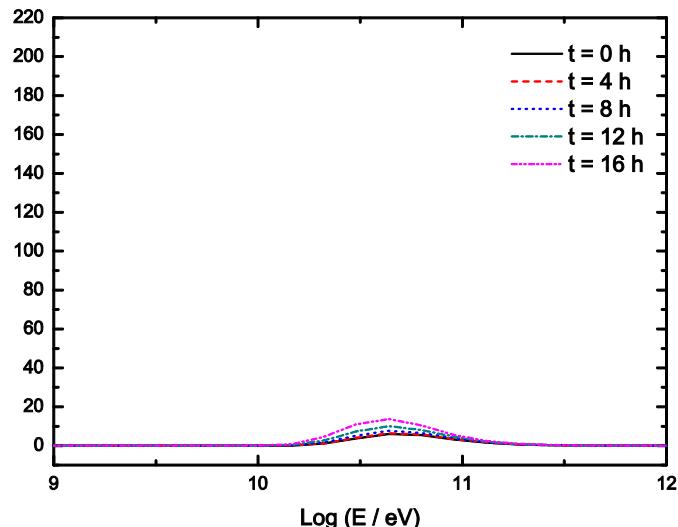
τ



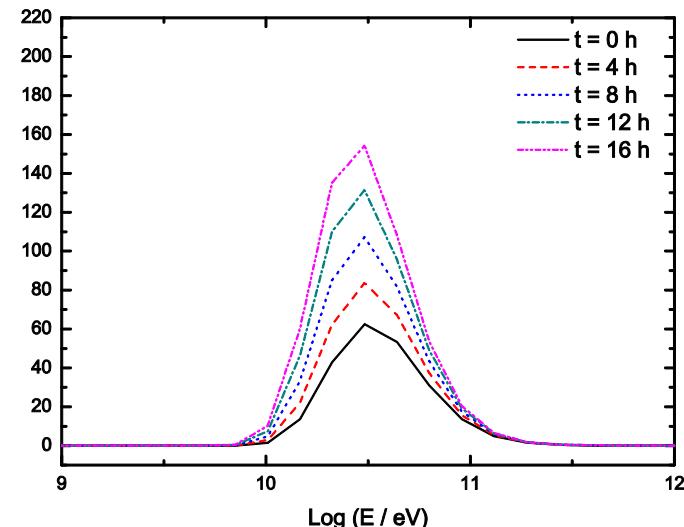
$$\phi = 0$$



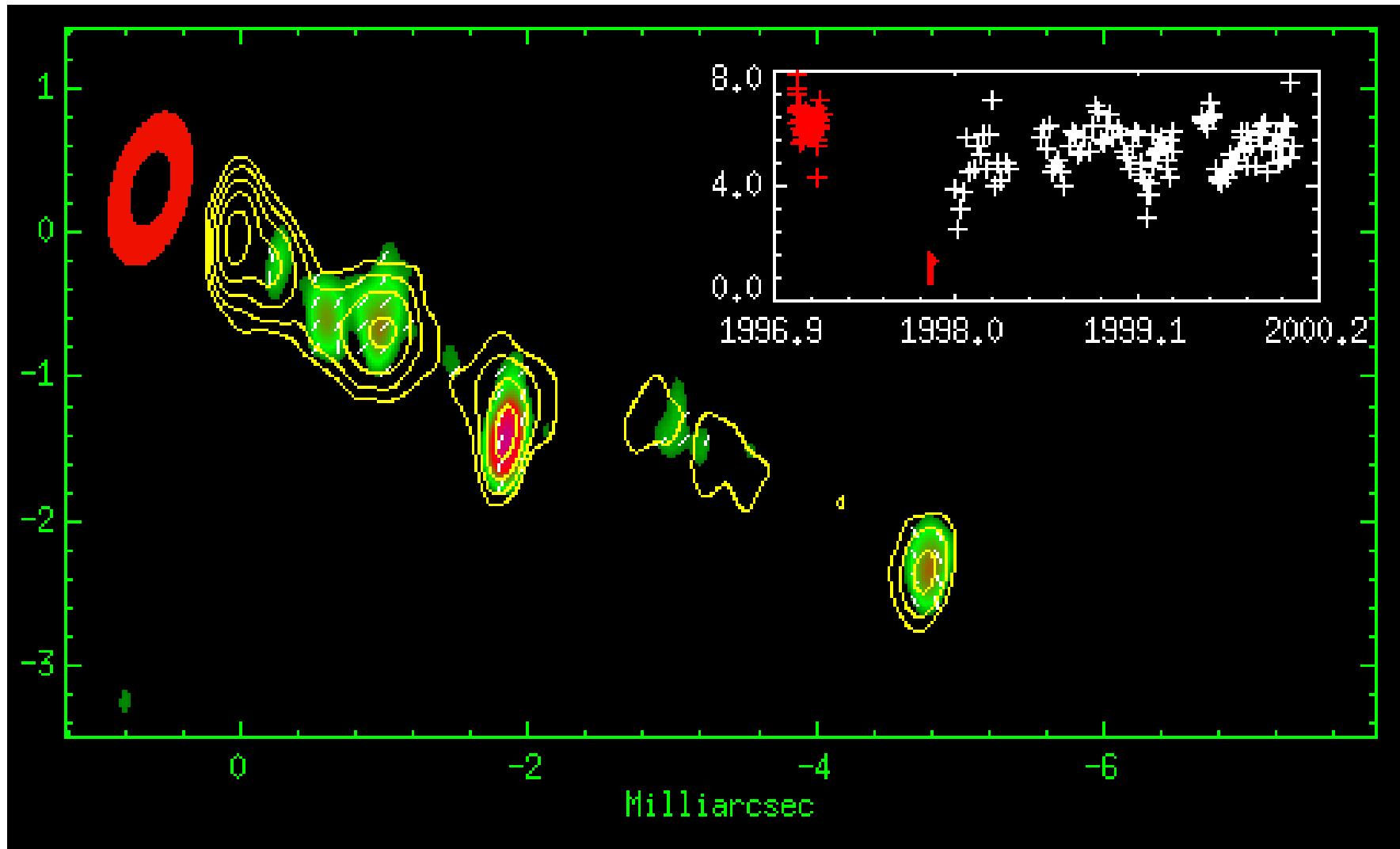
$$\phi = \pi/2$$



$$\phi = \pi$$



$$\phi = 3\pi/2$$



3C120