High-energy processes at the base of magnetized, baryon loaded jets

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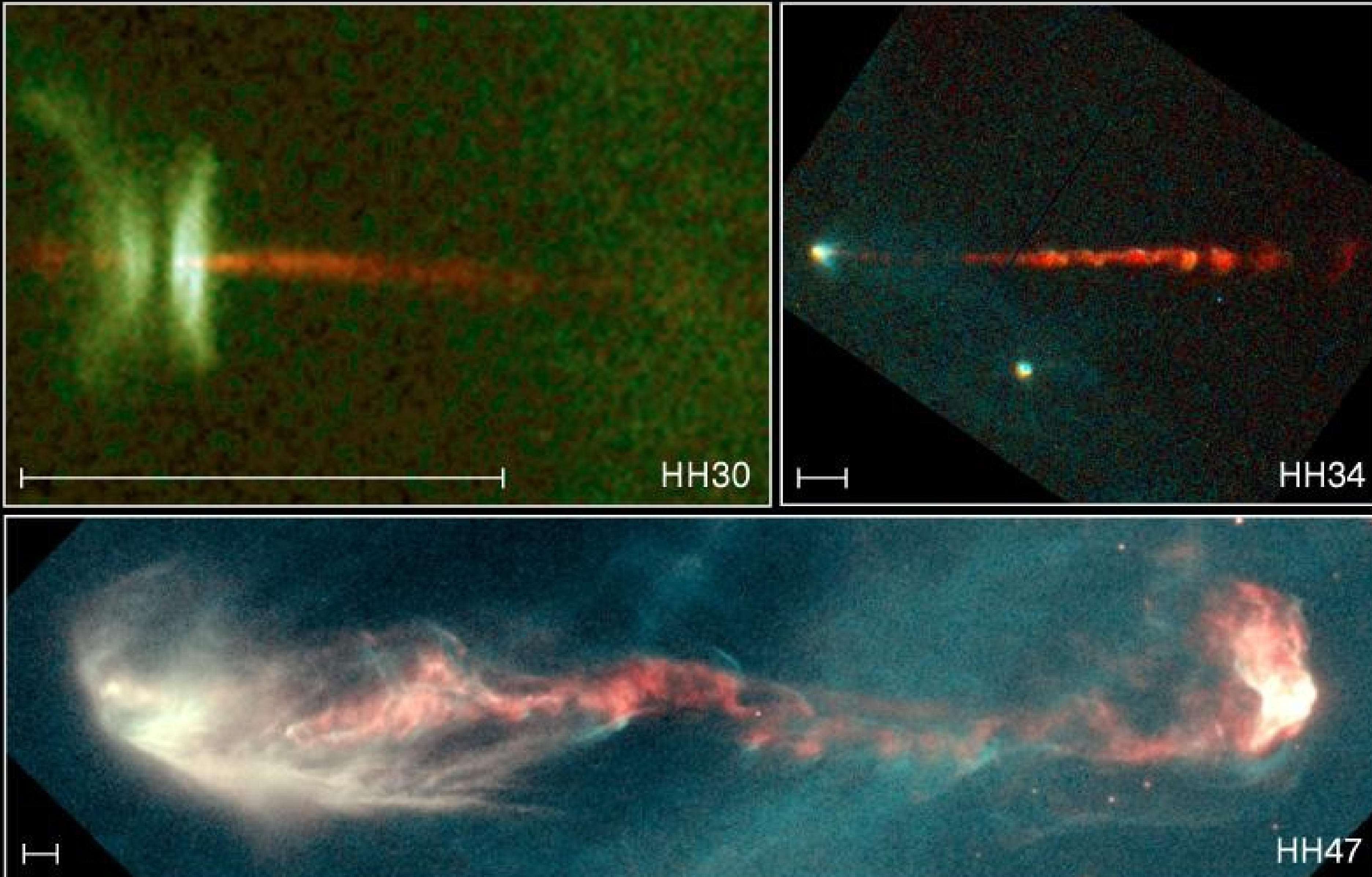
Jets at all scales

Gravitation + accretion + angular momentum + B → Jets

E.g. Young stellar objects, microquasars, AGNs, GRBs.

These jets can be thermal, non-thermal, mixed, poynting-flux dominated, matter-dominated, etc.

The basic ingredients are always present.

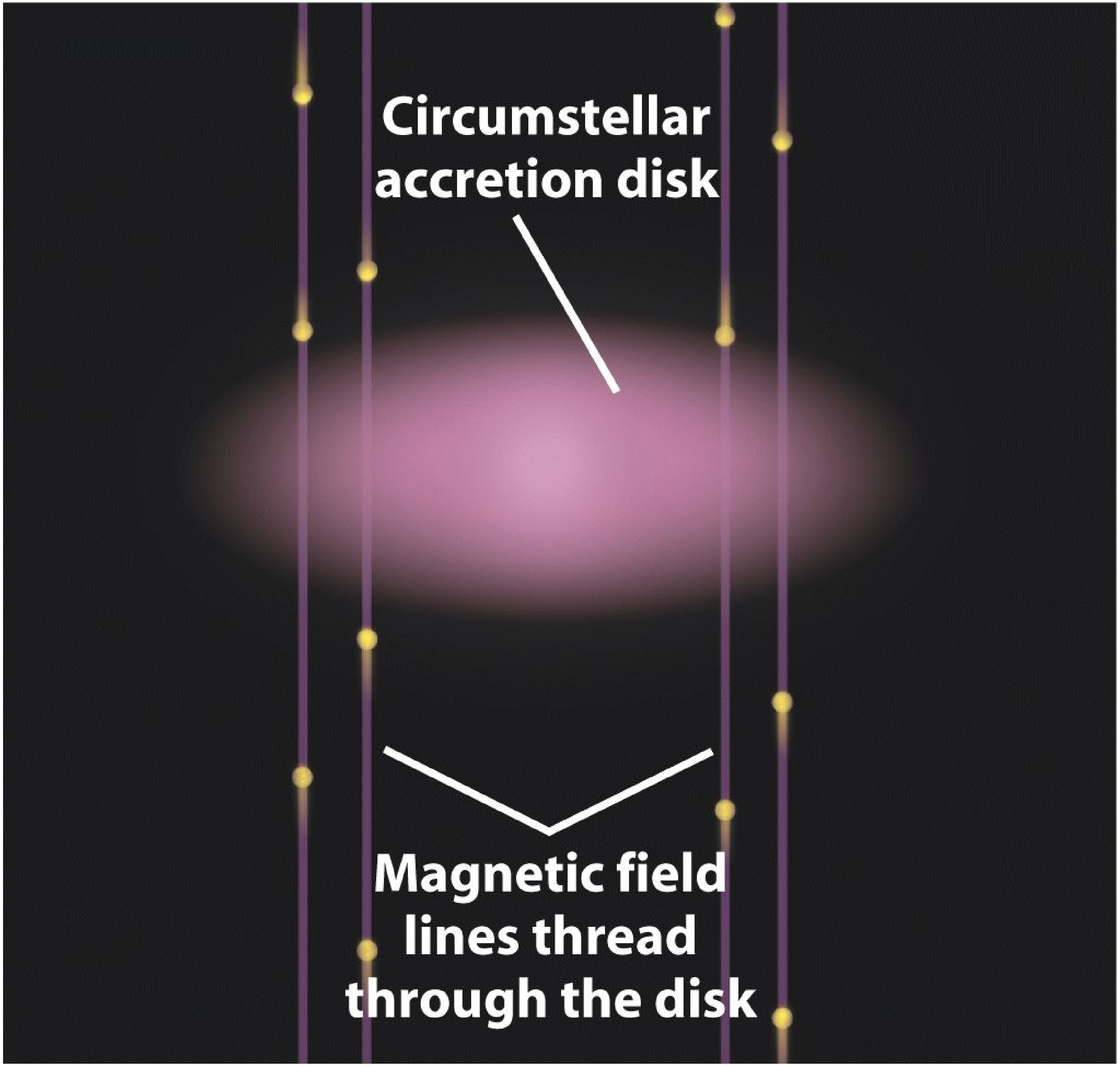


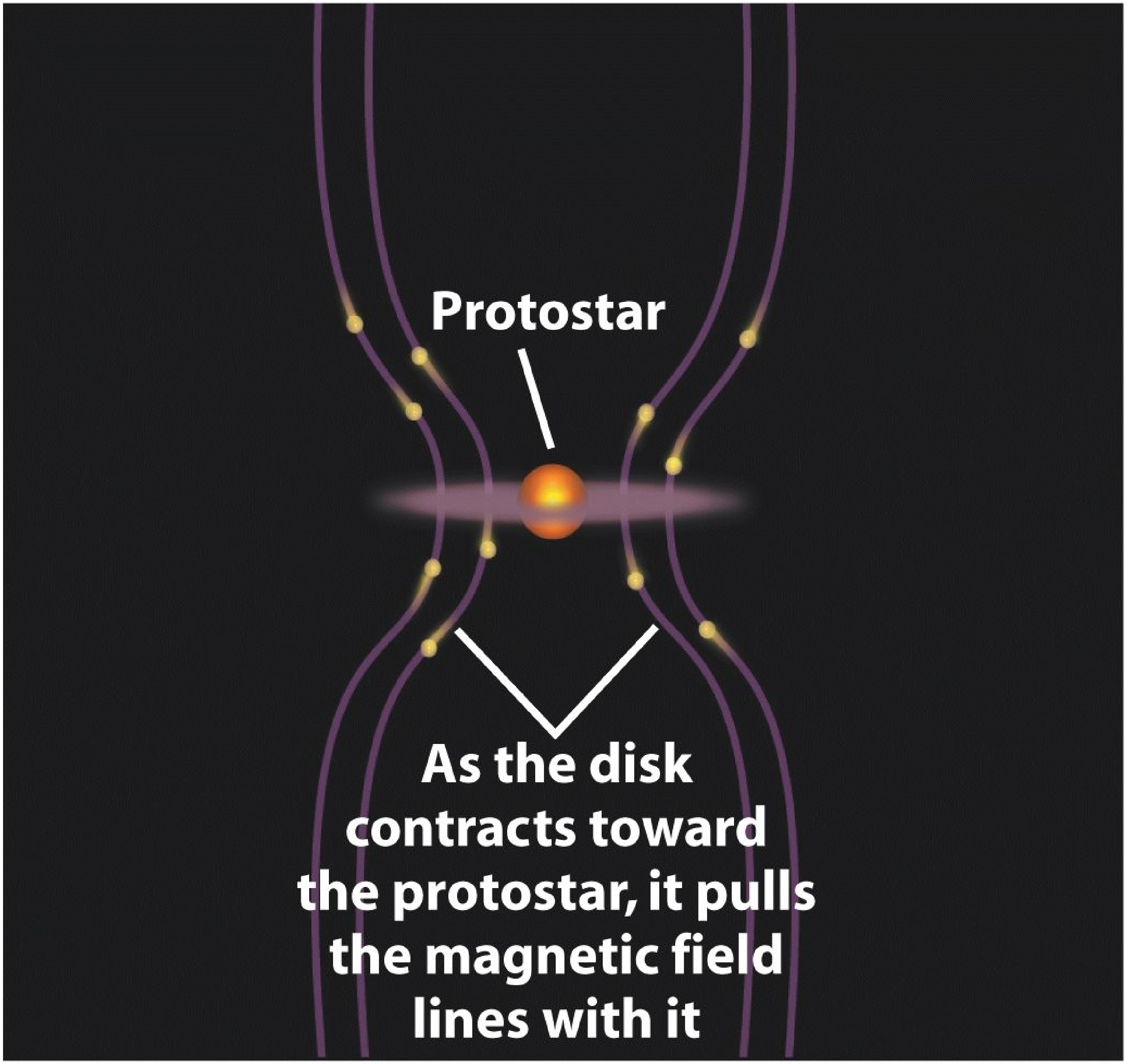
Jets from Young Stars

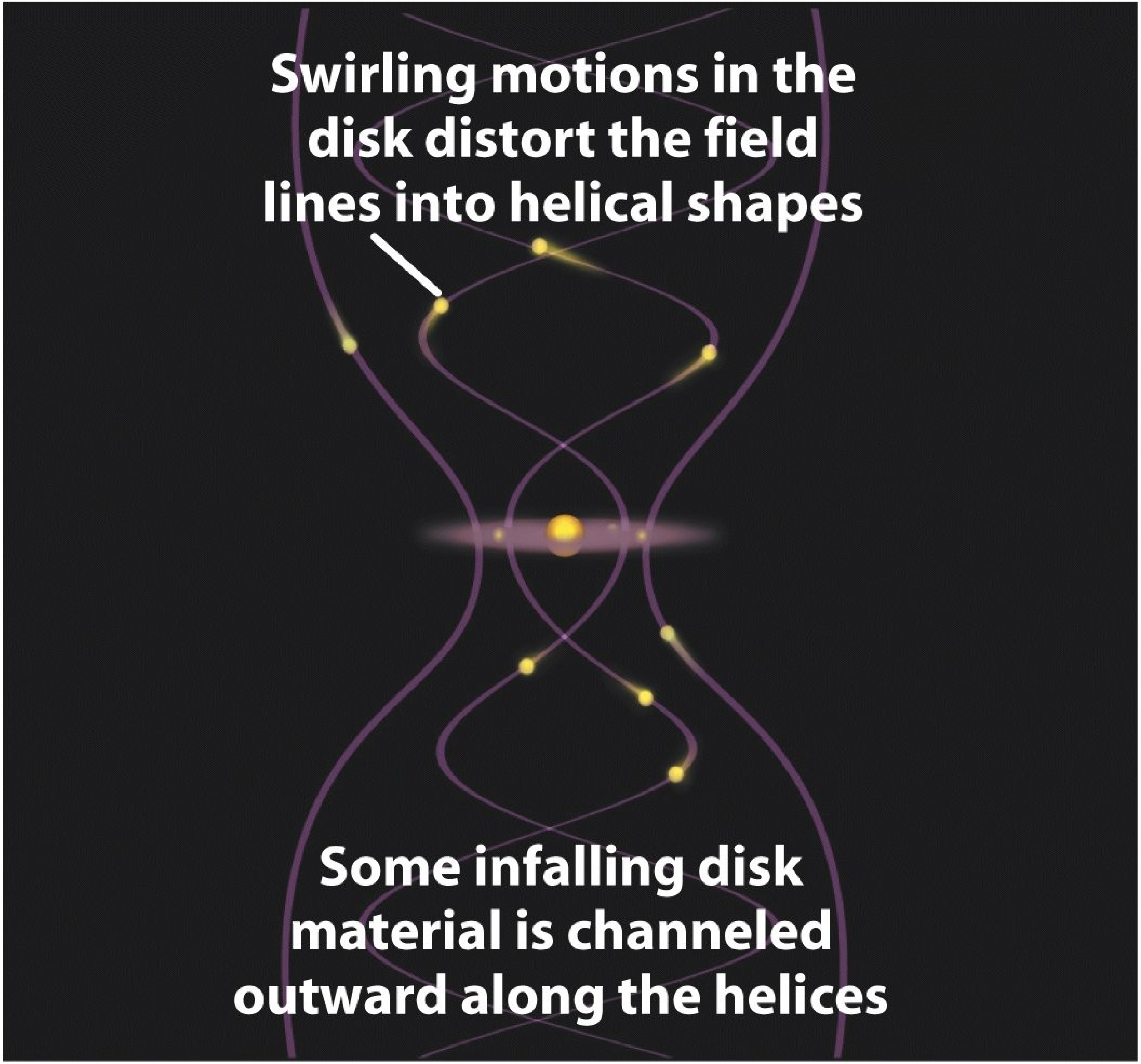
HST • WFPC2

PRC95-24a • ST ScI OPO • June 6, 1995

C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

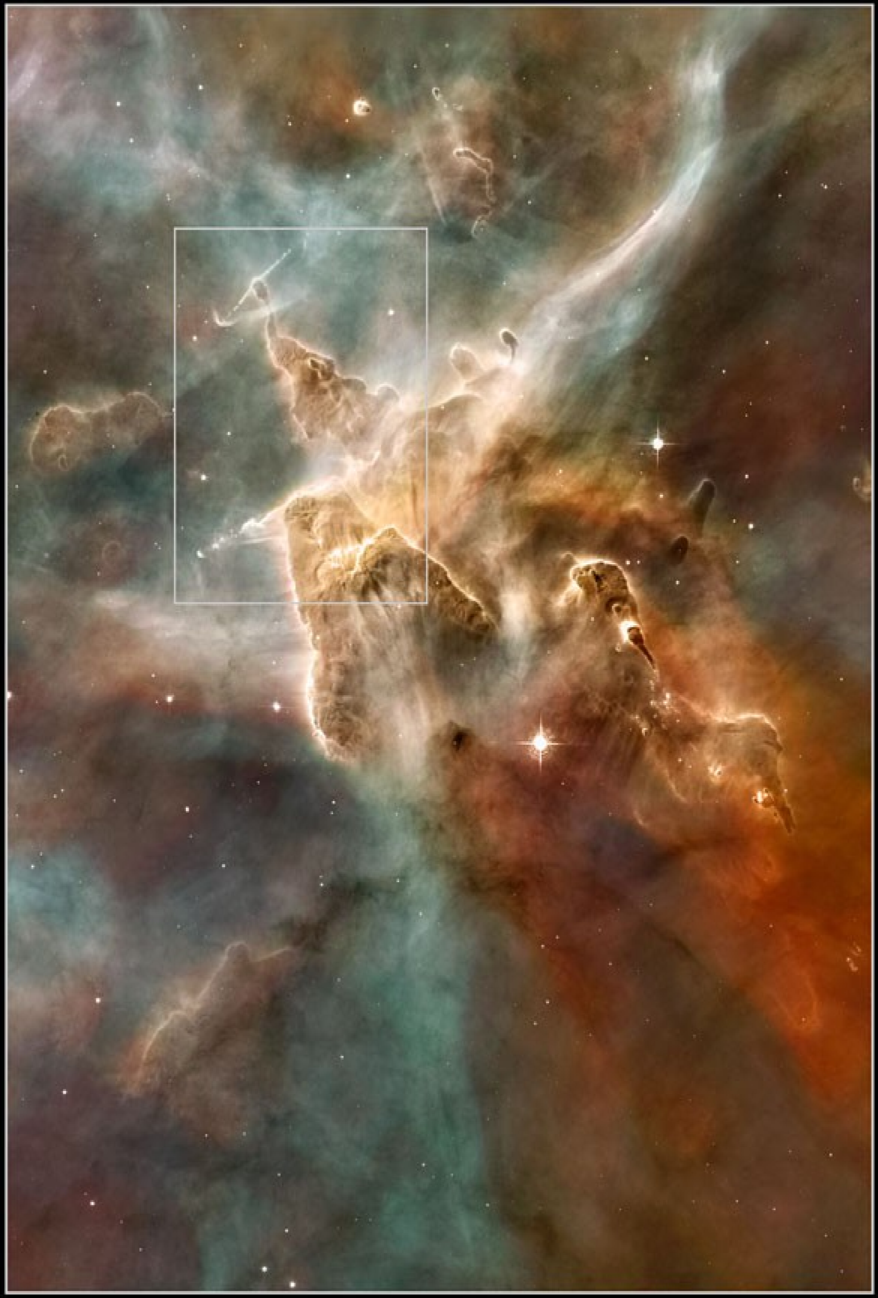

Circumstellar
accretion disk
Magnetic field
lines thread
through the disk


Protostar
As the disk contracts toward the protostar, it pulls the magnetic field lines with it


Swirling motions in the disk distort the field lines into helical shapes
Some infalling disk material is channeled outward along the helices

Starforming Region in the Carina Nebula

HST•ACS/WFC



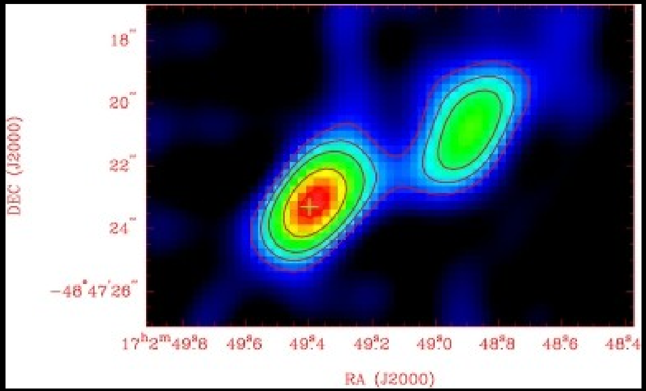
Microquasars

Microquasars (MQs) are accreting binaries formed by a compact object and a donor star. The compact object can be a neutron star (e.g. as in Sco X-1) or a black hole (e.g. Cygnus X-1). The donor star can be of an early type or a low-mass star.

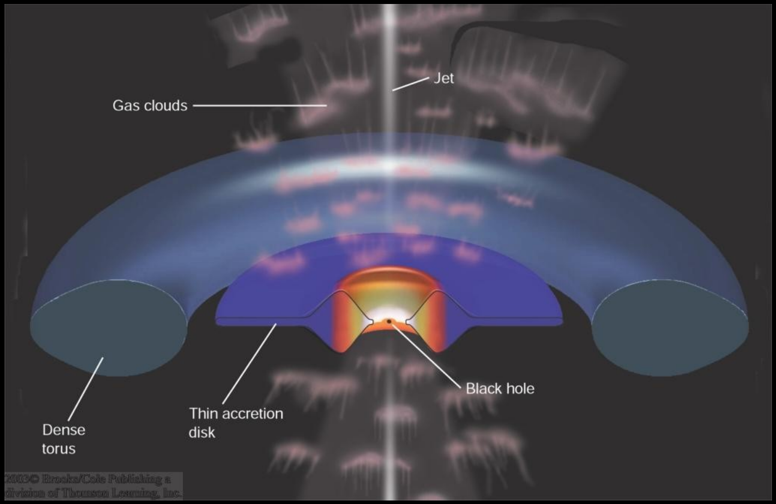
MQs present non-thermal jets. This means that there are relativistic particles in the jets.

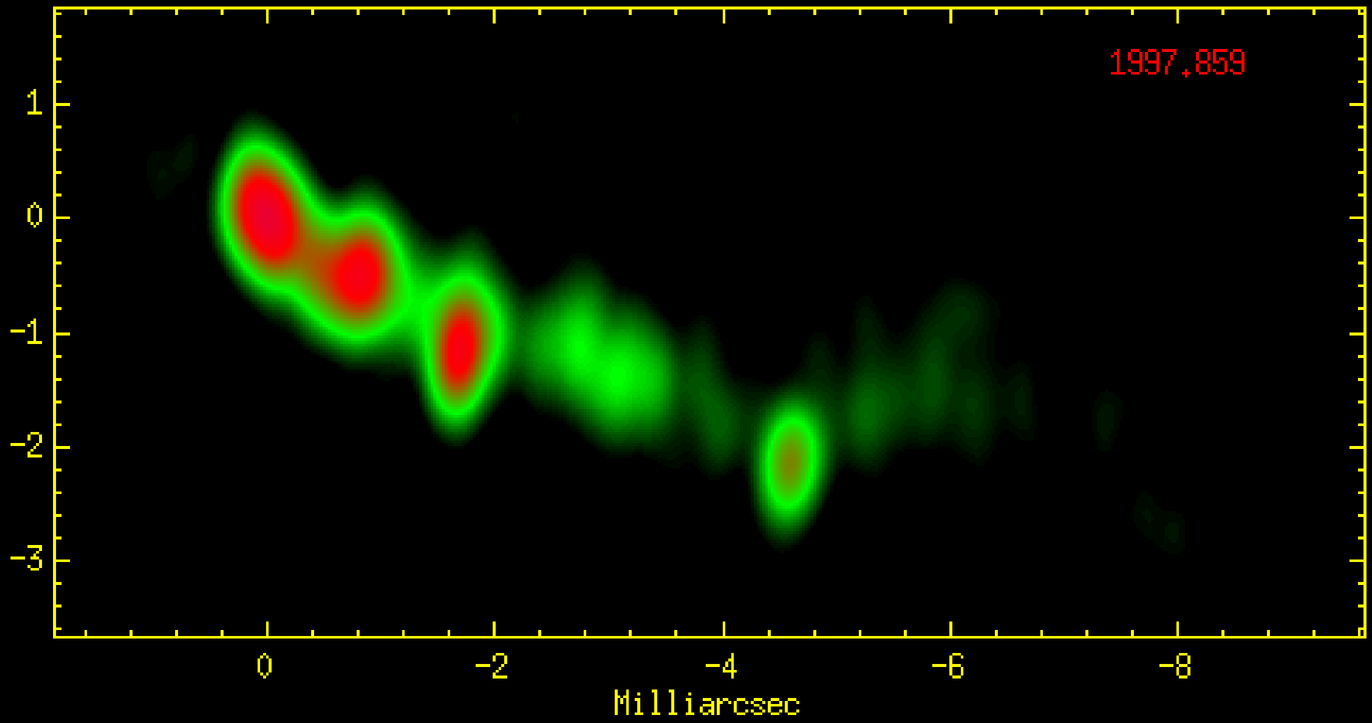
In the environment of a MQ the presence of relativistic particles can result in the production of detectable gamma-rays (Levinson & Blandford 1996).

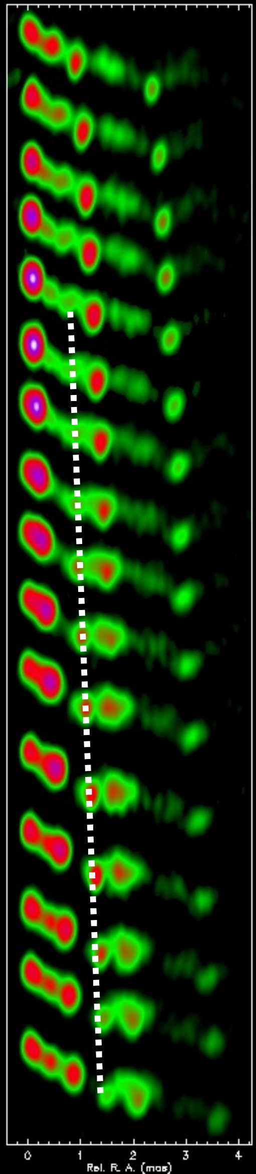
GX 339-4



AGNs (3C120)

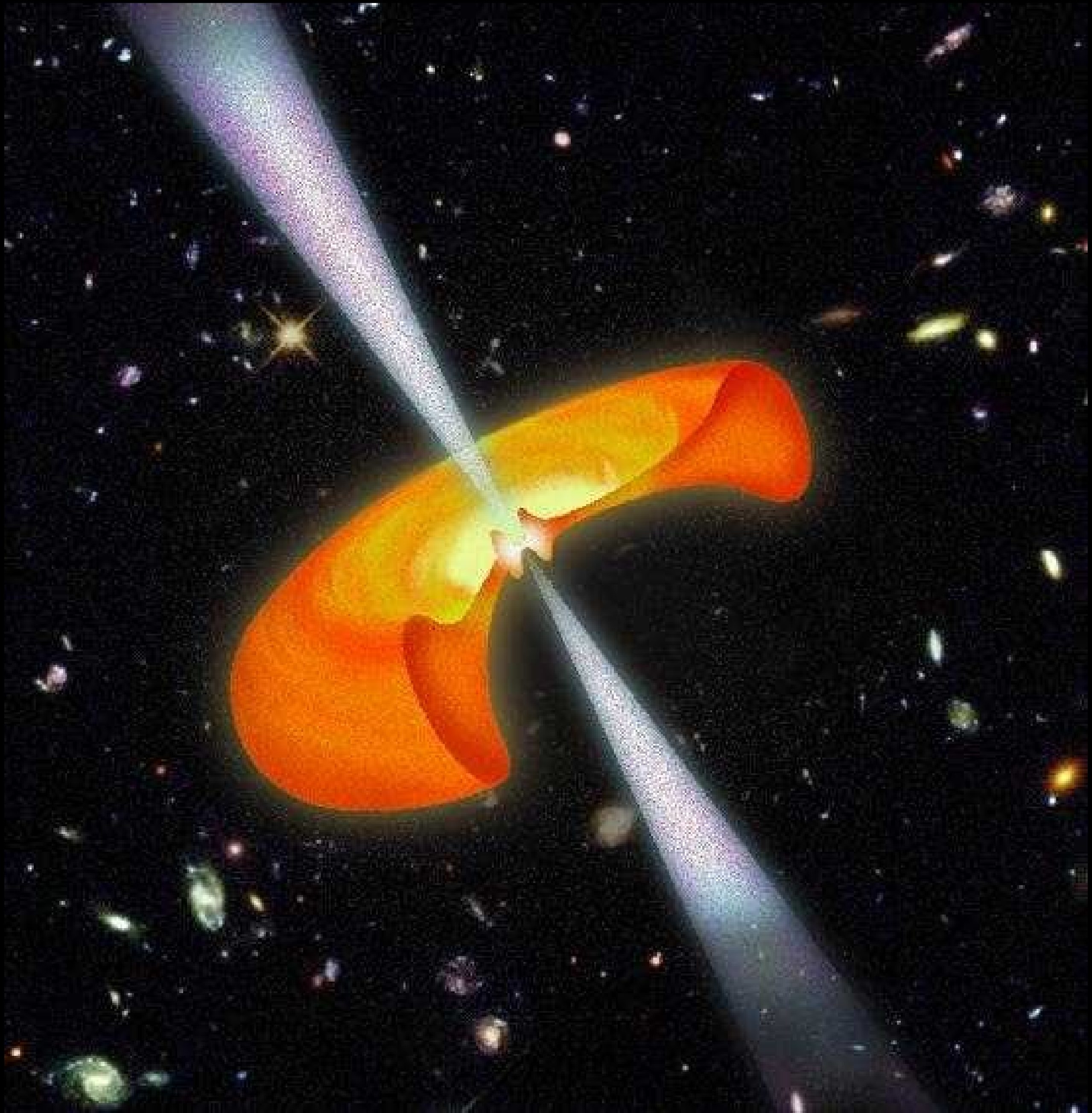




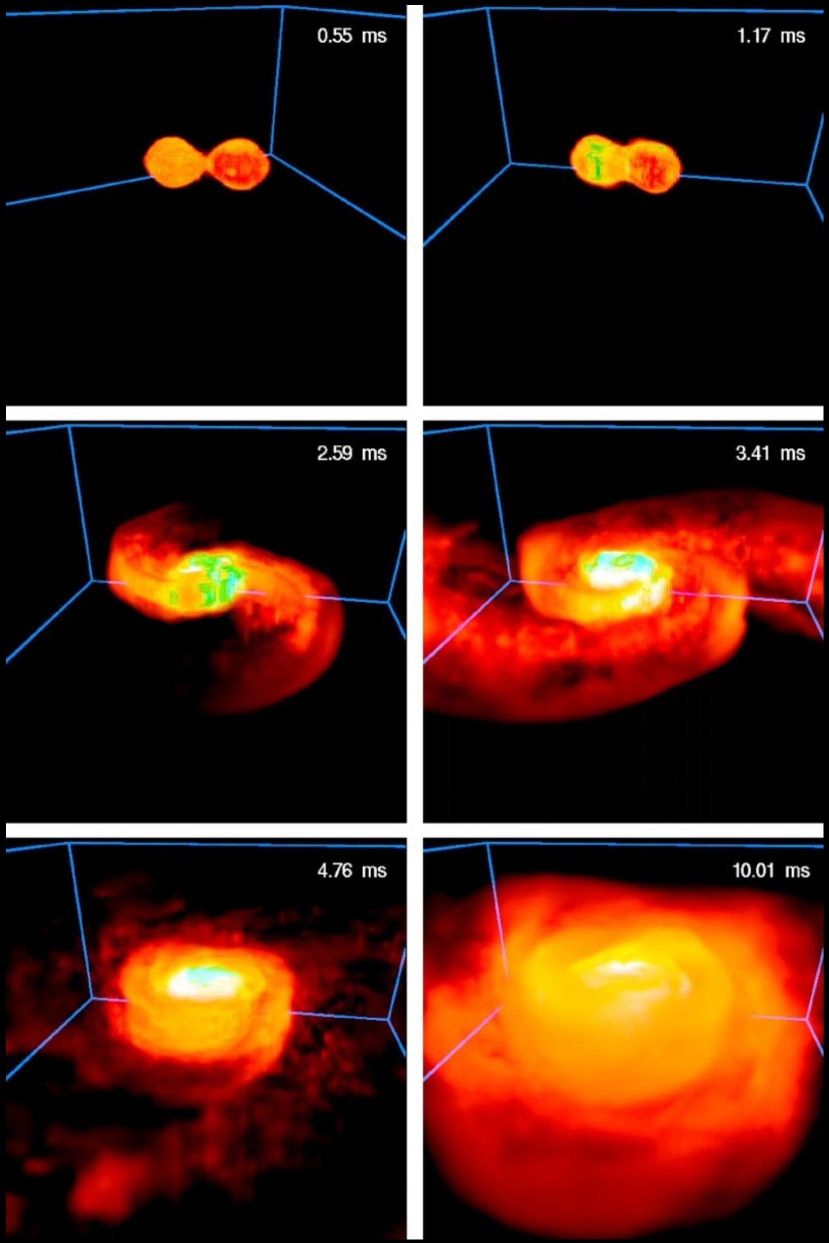


Gómez et al. (2000)

GRBs (long)



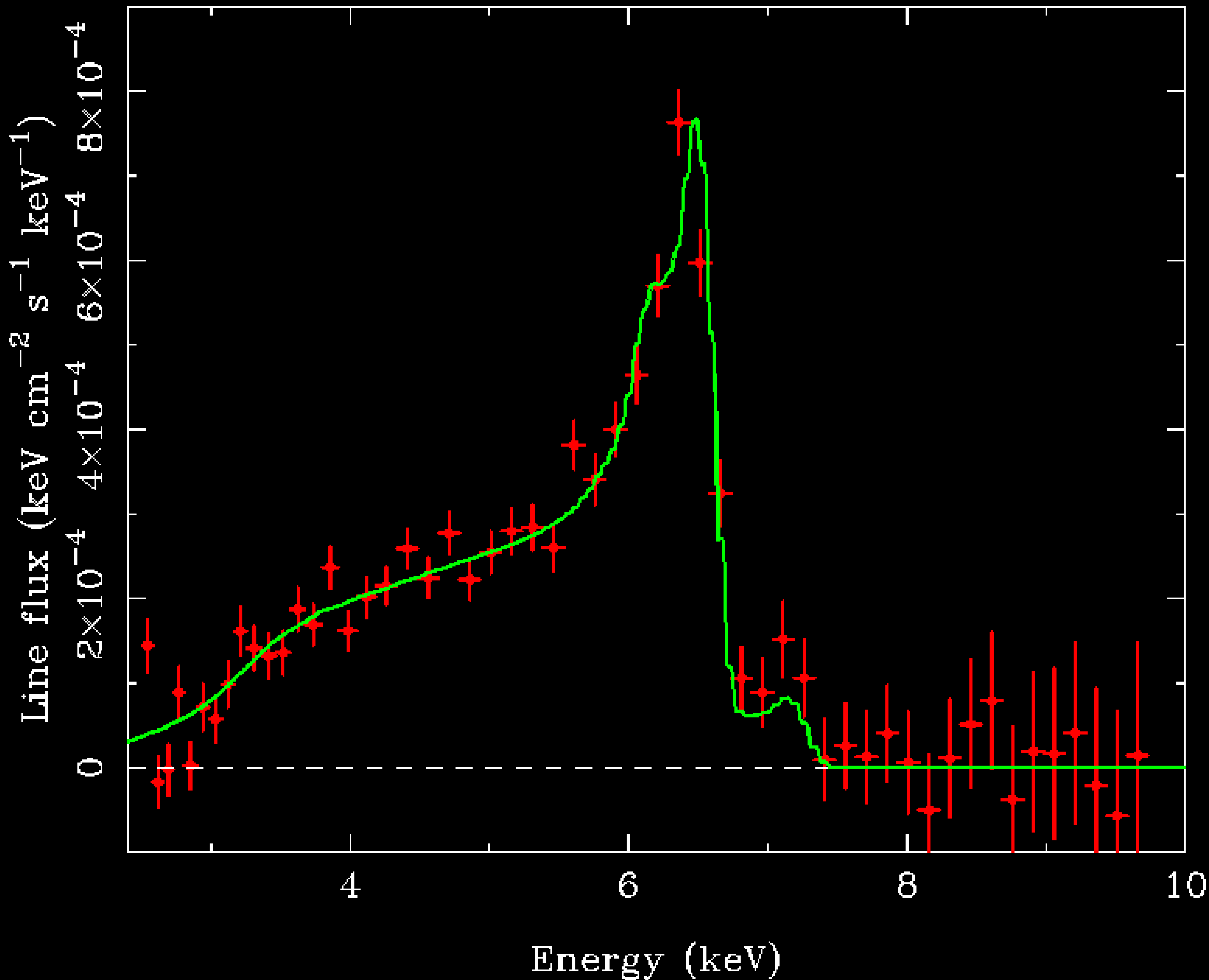
GRBs (short)



What are jets made of?

- Relativistic electron-positron plasma?
- Relativistic electrons plus cold protons?
- Relativistic electron-proton plasma plus cold barionic flow?

In the case of MQs and YSOs there is evidence for the presence of hadrons in the outflow. There is also evidence for the couplng of the accretion power and the jet power.



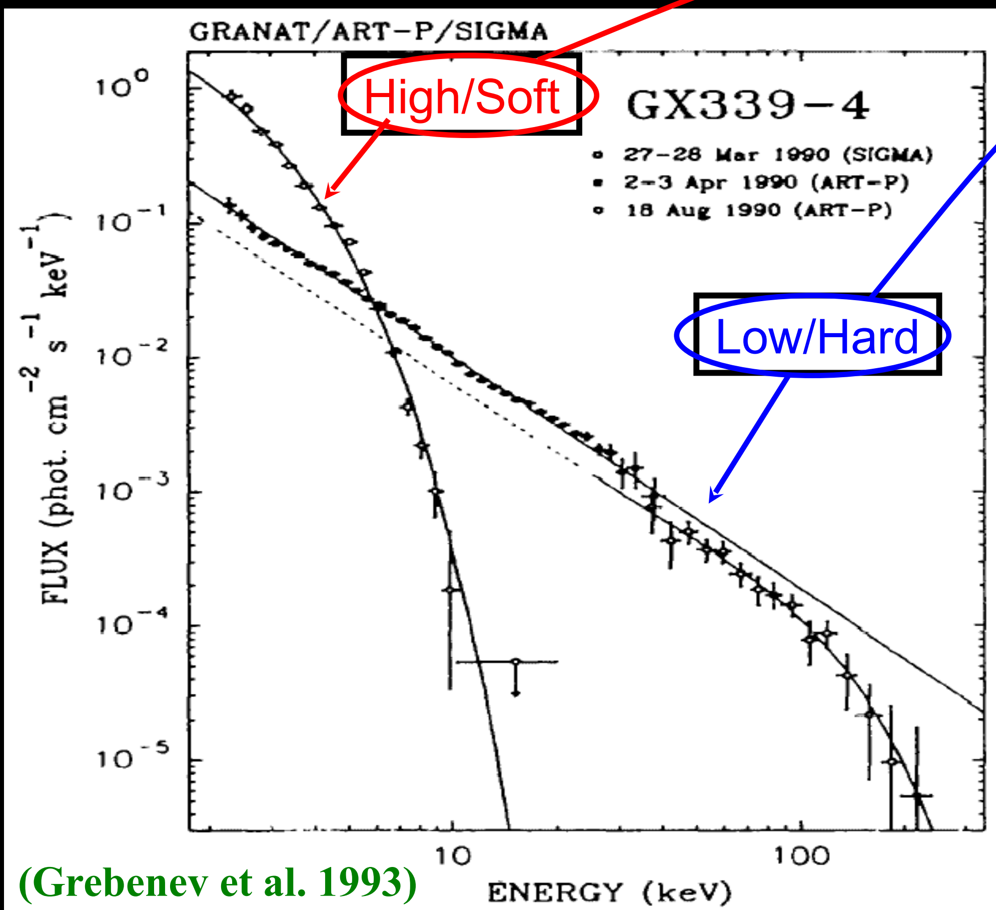
Line flux (keV cm^{-2} s^{-1} keV^{-1})
0
2×10^{-4}
4×10^{-4}
6×10^{-4}
8×10^{-4}
4
6
8
10
Energy (keV)

BLACK HOLE STATES

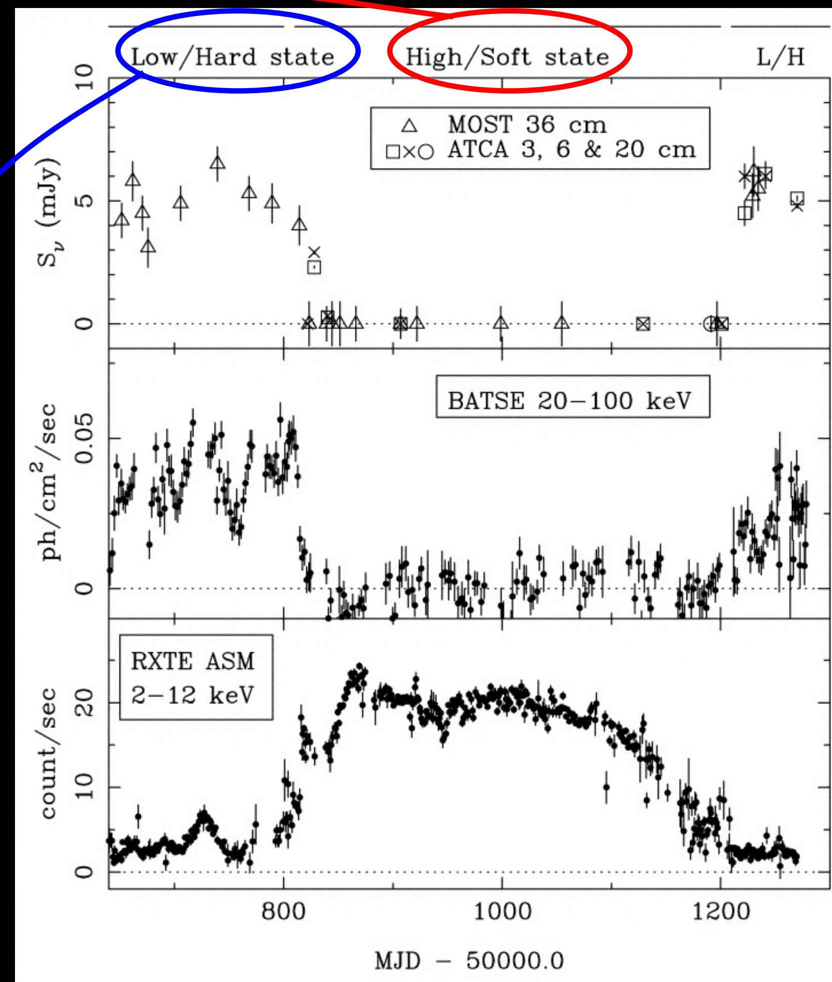
Accreting stellar black holes display different X-ray spectral states:

- **Low/hard** state (a.k.a. power-law state).
  High/soft state (a.k.a. thermal-dominant state).

(Fender et al. 1999)



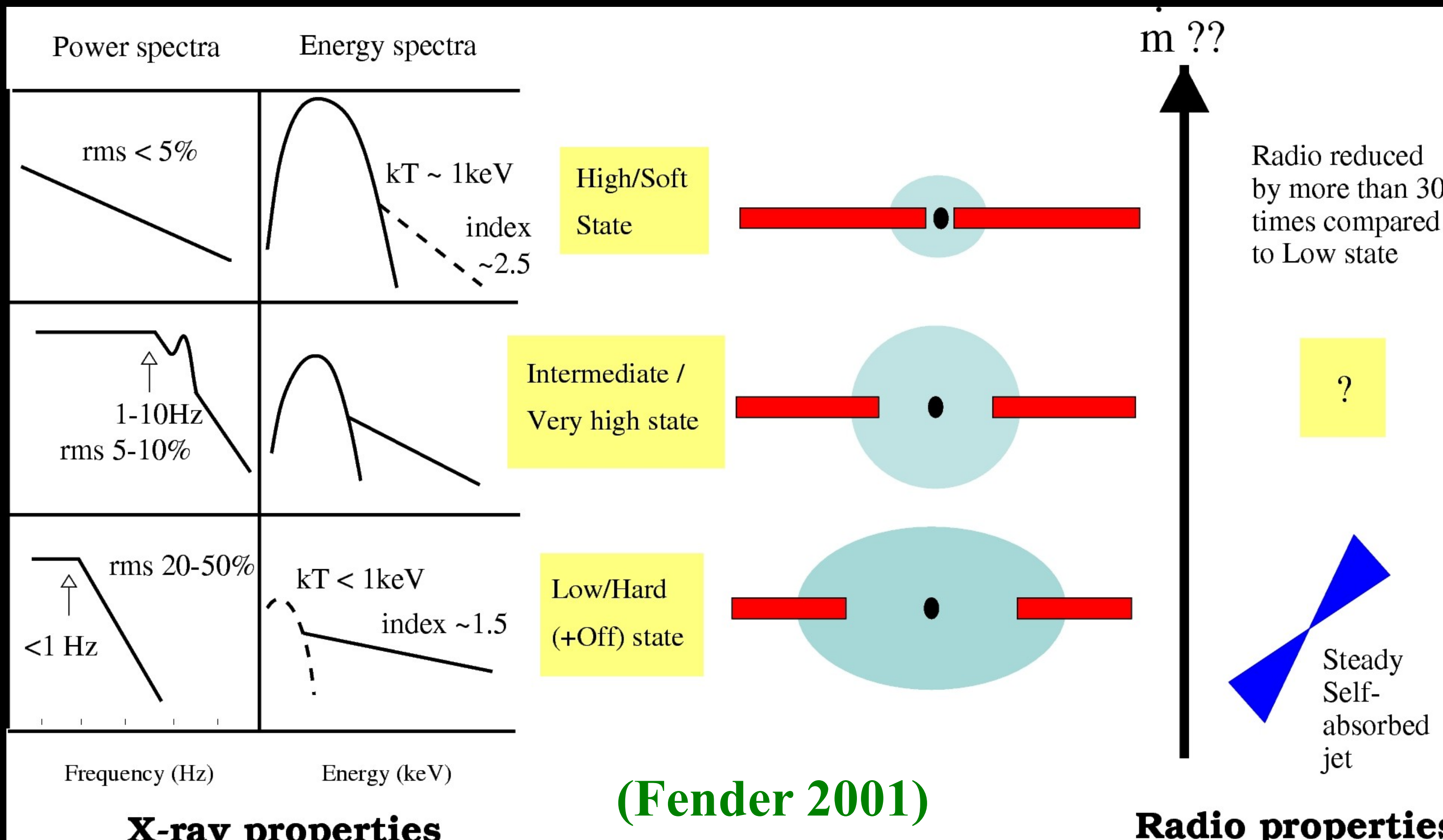
(Grebenev et al. 1993)



BLACK HOLE STATES AND DIFFERENT TYPES OF JETS

Black holes display different X-ray spectral states:

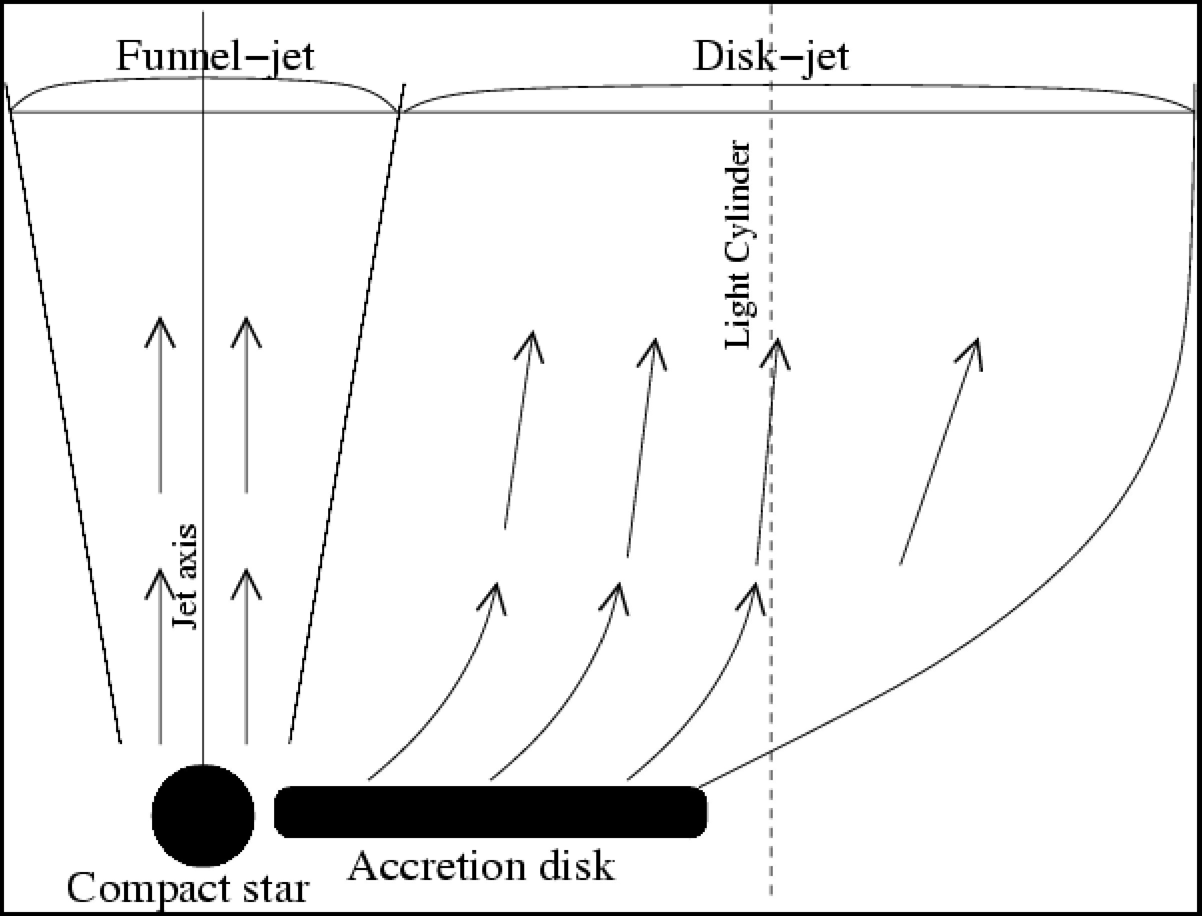
- **Low/hard** state (a.k.a. power-law state). **Compact radio jet.**
- **High/soft** state (a.k.a. thermal-dominant state). **No radio emission**
- **Intermediate** and **very high** states → transitions **Transient radio emission**



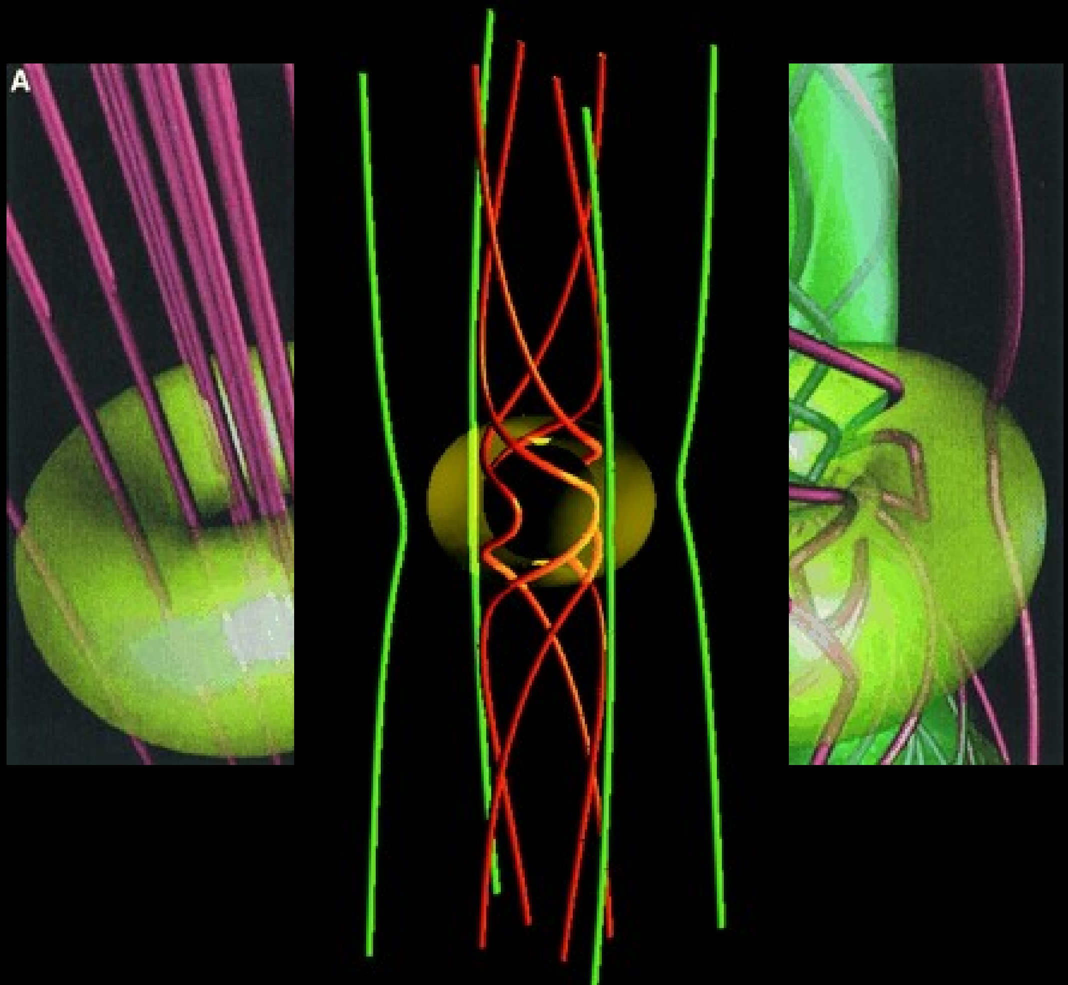
(Fender 2001)

Formation of relativistic jets

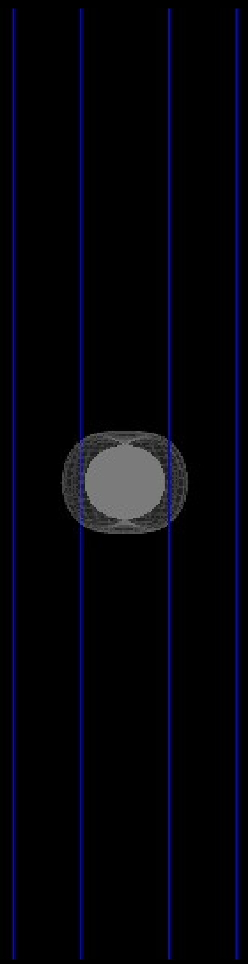
Evacuation of the corona plus a disc wind?



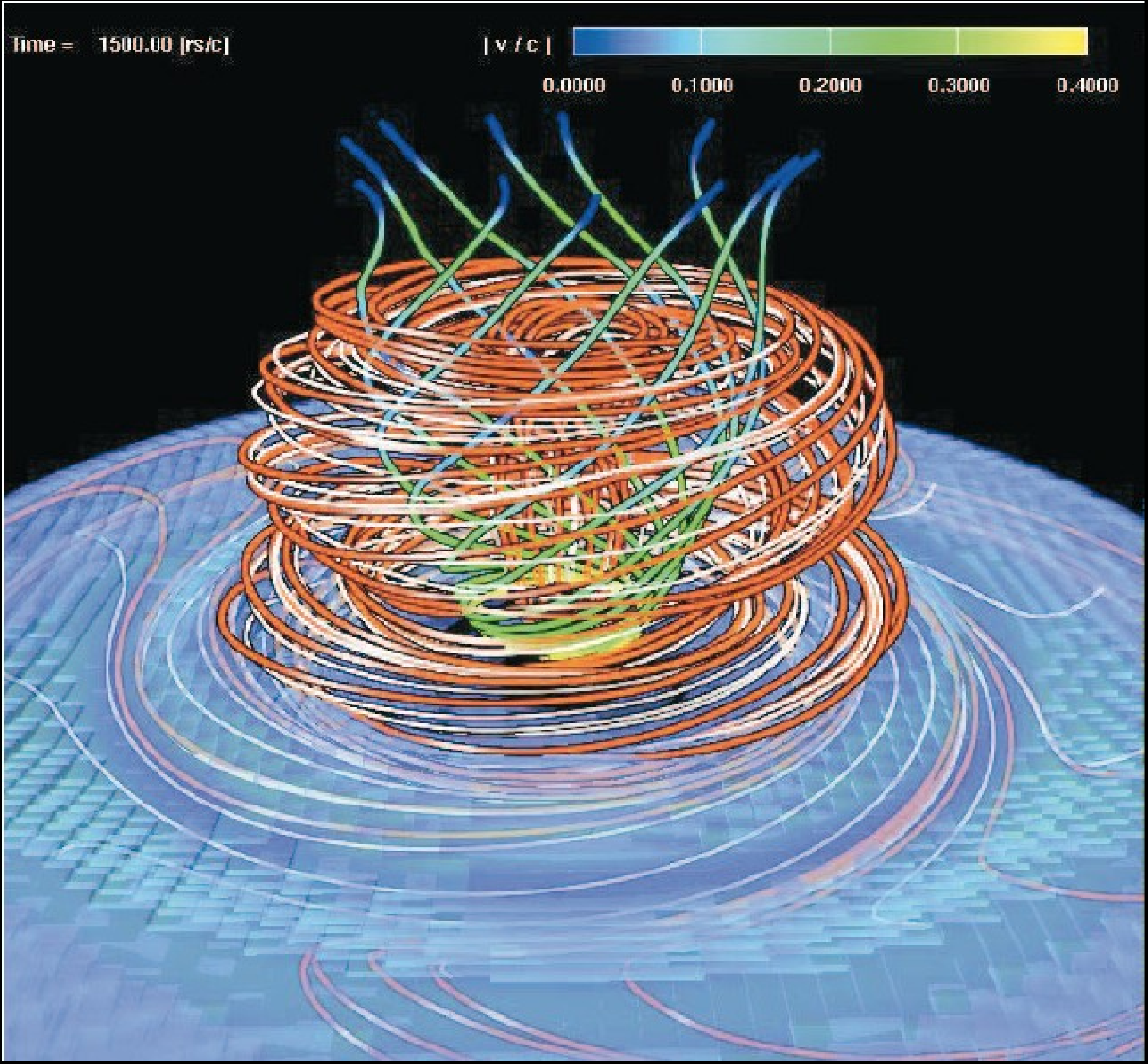
MHD model: differential rotation in the system creates a magnetic coil that simultaneously expels and pinches some of the infalling material. The model may explain the basic features of observed jets (**Meier et al. 2001**).



Effects of the ergosphere



Effects of the disc



Kato et al. 2004, 2006

A hadronic model for jets is a model that represents radiative processes triggered by protons or other nuclei. There is not such a thing as a *purely hadronic radiative model* in astrophysics. All models are actually lepto-hadronic, since relativistic hadronic interactions unavoidably lead to meson production and the subsequent injection of leptons in the system.

Proton-dominated jet models (e.g. Romero & Vila, A&A 485, 623, 2008, also Romero & Vila, A&A, submitted)

Interaction of relativistic *p* and *e*⁻ with

- magnetic field
- matter fields
- radiation fields

in the jet

• Synchrotron radiation $$p,\ e^- + B \rightarrow p,\ e^- + \gamma$$

• Inverse Compton (IC) $$e^- + \gamma \rightarrow e^- + \gamma$$

• Proton-proton inelastic collisions $$p + p \rightarrow p + p + a\,\pi^0 + b(\pi^+ + \pi^-)$$

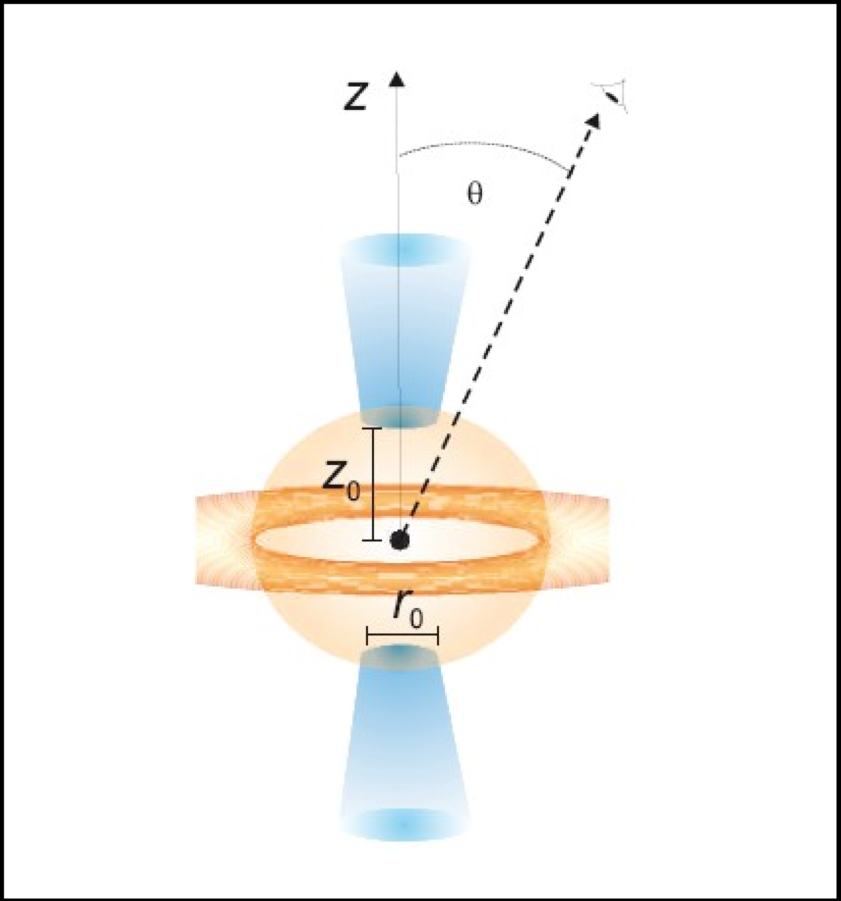
• Photohadronic interactions (*p*γ) $$p + \gamma \rightarrow p + e^+ + e^-$$

$$e^\pm + B \rightarrow e^\pm + \gamma$$

$$p + \gamma \rightarrow p + a\pi^o + b(\pi^+ + \pi^-) \qquad \pi^o \rightarrow 2\gamma$$

$$p + \gamma \rightarrow n + \pi^+ + a\pi^o + b(\pi^+ + \pi^-) \qquad \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \qquad \mu^\pm \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \bar{\nu}_\mu (\nu_\mu)$$

Proton-dominated jet models (Romero & Vila, A&A 485, 623, 2008, also Romero & Vila, A&A, submitted)



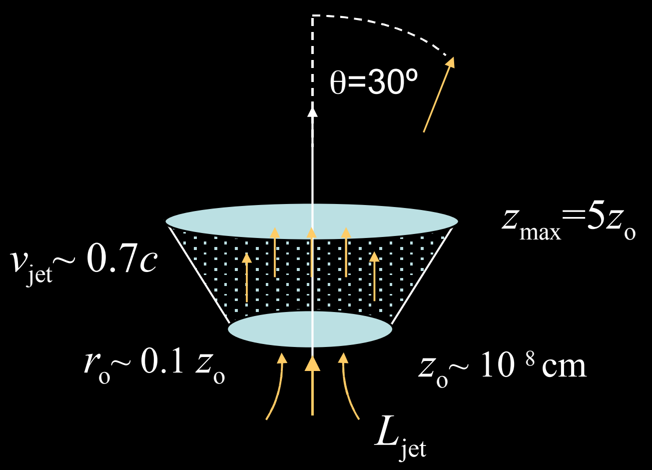
Jet model

Conical jet, perpendicular to binary orbit

Mildly relativistic outflow, Γ =1.5

Viewing angle θ=30º, moderate

Compact acceleration/emission region



✓ Content of relativistic particles

$$L_{jet} = 0.1 L_{acc}$$

Falcke & Biermann (1995)
Körding *et al.* (2006)

$$L_{rel} = 0.1 L_{jet} \approx 2\times 10^{37}\ \mathbf{erg\ s^{-1}}$$

$$L_{rel} = L_p + L_e \quad L_p = a L_e \quad a = 1 - 10^3$$

✓ Magnetic field ~ equipartition

✓ Particle distributions “one-zone” approximation (Khangulyan *et al.* 2007)

$$\frac{\partial}{\partial E}\frac{dE}{dt}N(E,z)+\frac{N(E,z)}{T_{\rm esc}}=Q(E,z) \quad\Rightarrow\quad N(E,z)\propto\begin{cases}E_p^{-\alpha}\\ E_e^{-(\alpha+1)}\end{cases}$$

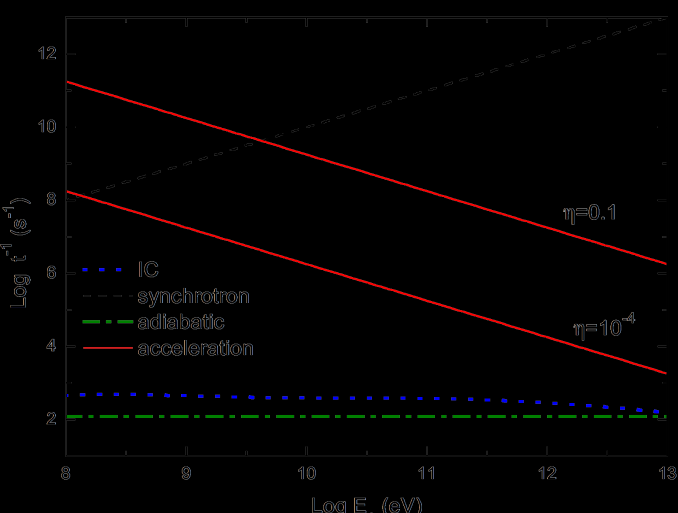
$$\left.\frac{dE}{dt}\right|_{\rm acc}=\left.\frac{dE}{dt}\right|_{\rm loss}\approx\left.\frac{dE}{dt}\right|_{\rm synchr}+\left.\frac{dE}{dt}\right|_{\rm ad}$$

$$T_{\rm esc}\approx\frac{z_{\rm max}}{v_{\rm jet}}$$

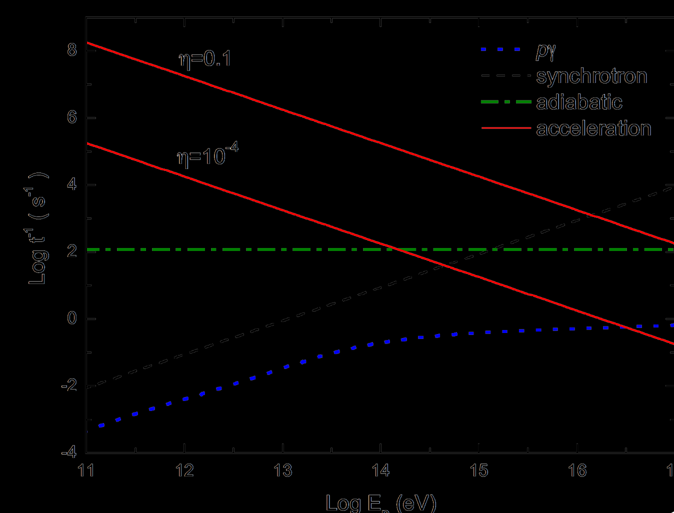
$$Q_{\rm e,p}=Q^{\rm o}_{\rm e,p}\frac{E_{\rm e,p}^{-\alpha}}{z}$$

α=1.5, 2.2

diffusive shock acceleration



$$E_e^{\rm max}\approx 3\times10^{10}\,\eta^{1/2}\,{\rm eV}$$



$$E_p^{\rm max}\approx 10^{17}\,\eta^{1/2}\,{\rm eV}$$

Particle losses

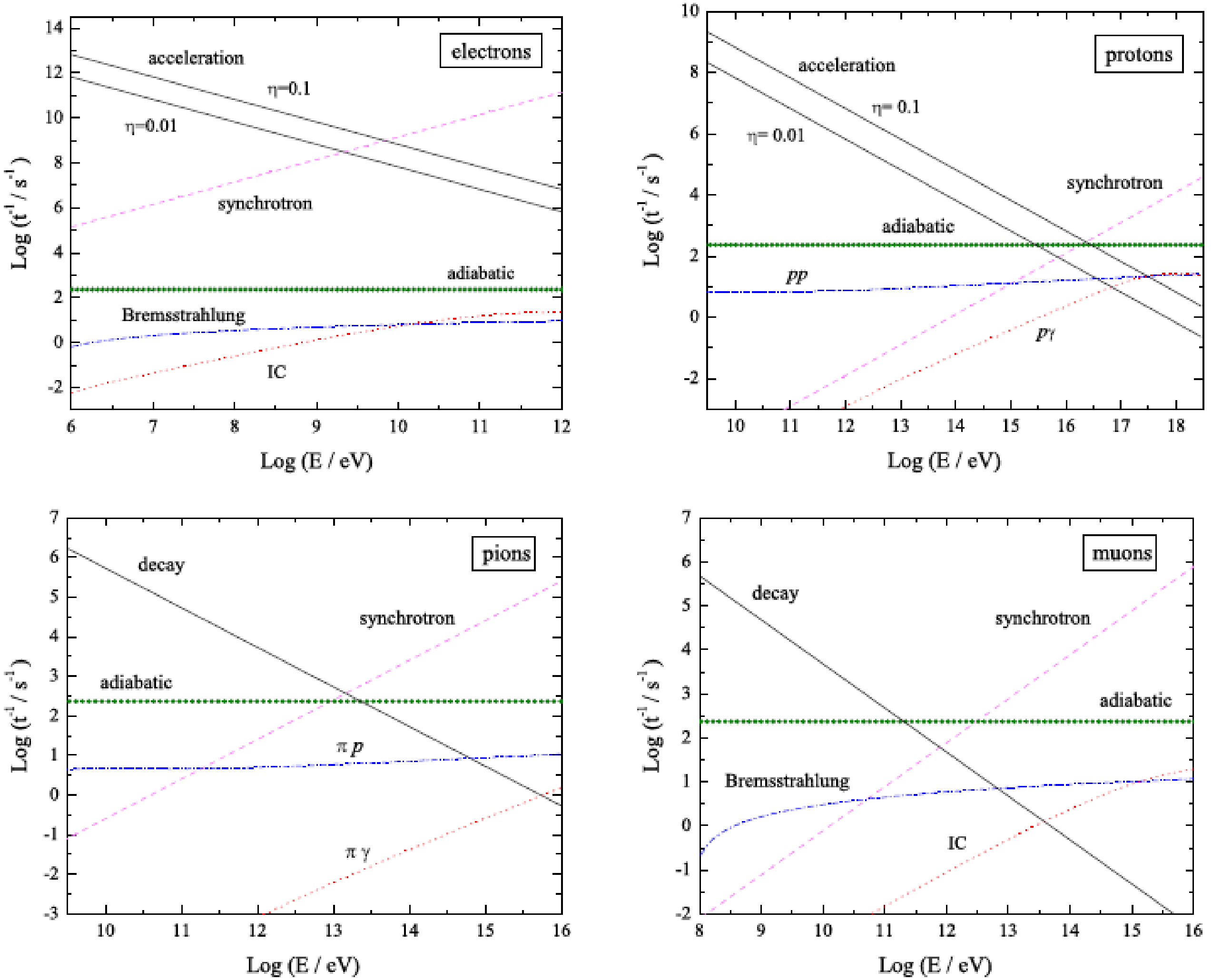
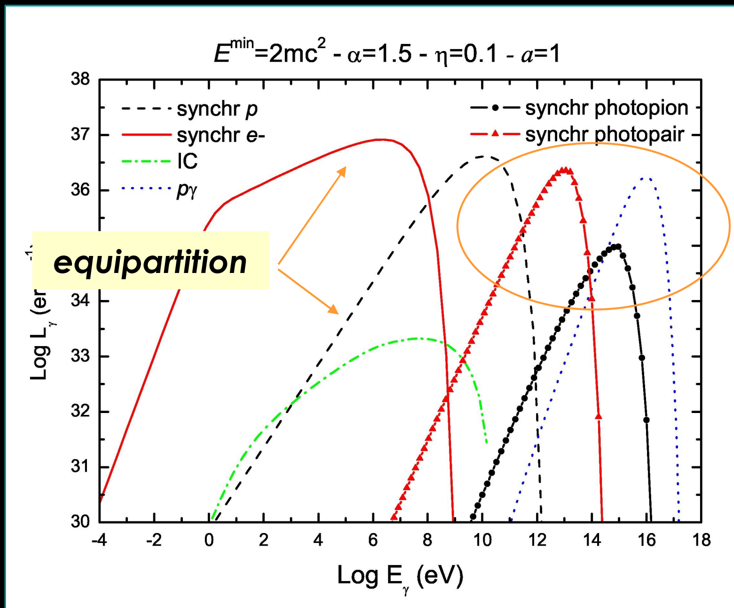
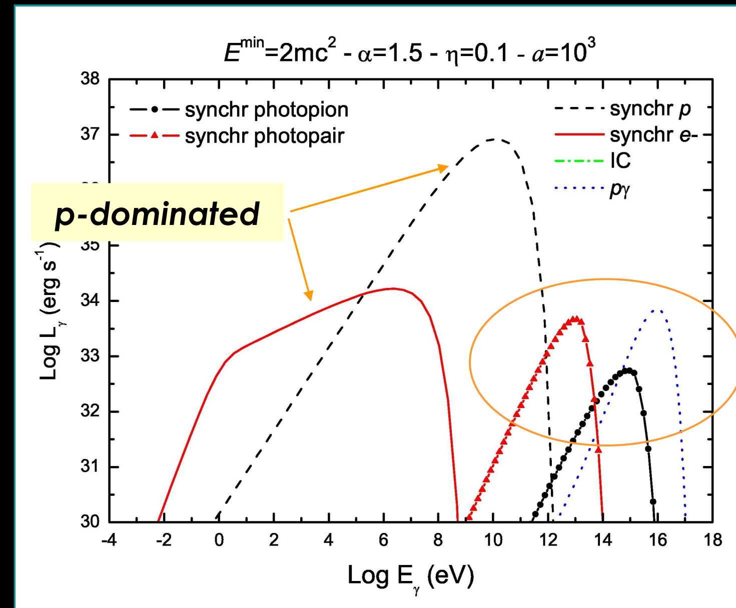
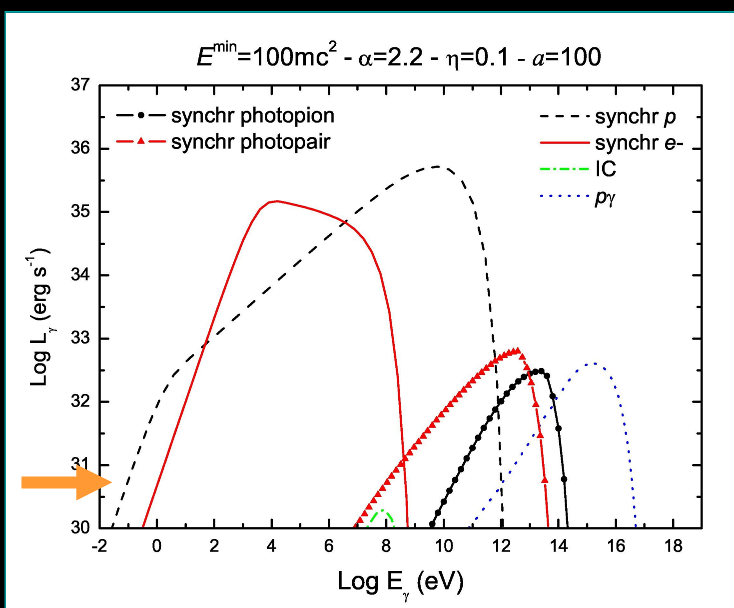


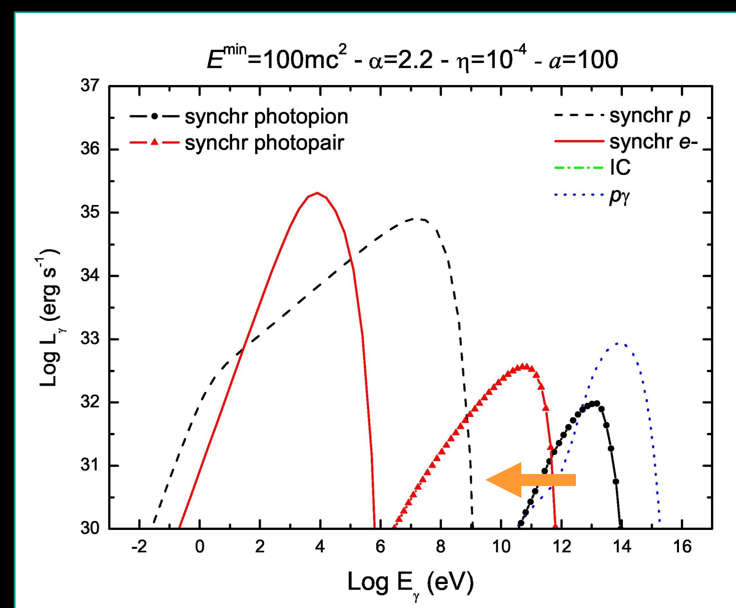
Fig. 1. Acceleration and cooling rates at the base of the jet for primary protons and electrons, and secondary pions and muons, calculated for representative values of the model parameters (proton-to-lepton energy ratio $a = 1000$, and primary injection spectral index $\alpha = 1.5$). The acceleration efficiency parameter η is indicated.

Spectral energy distributions

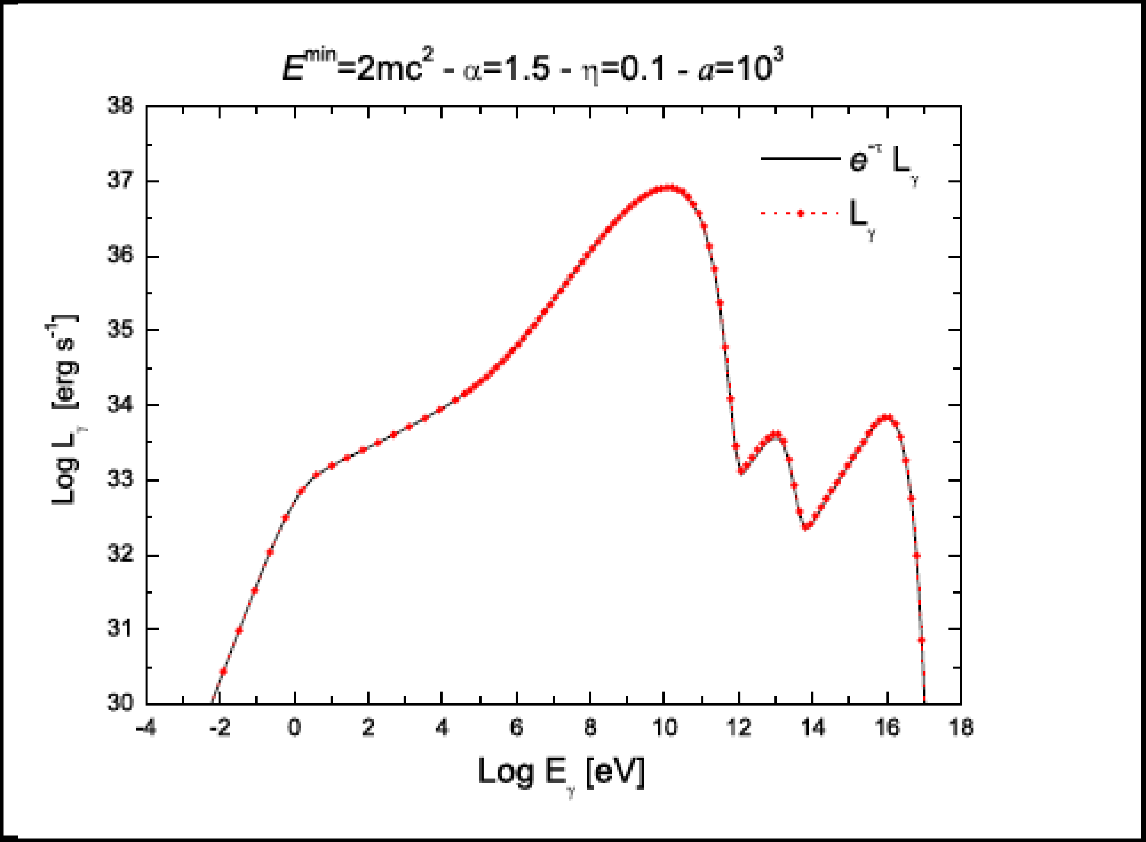








Internal absorption



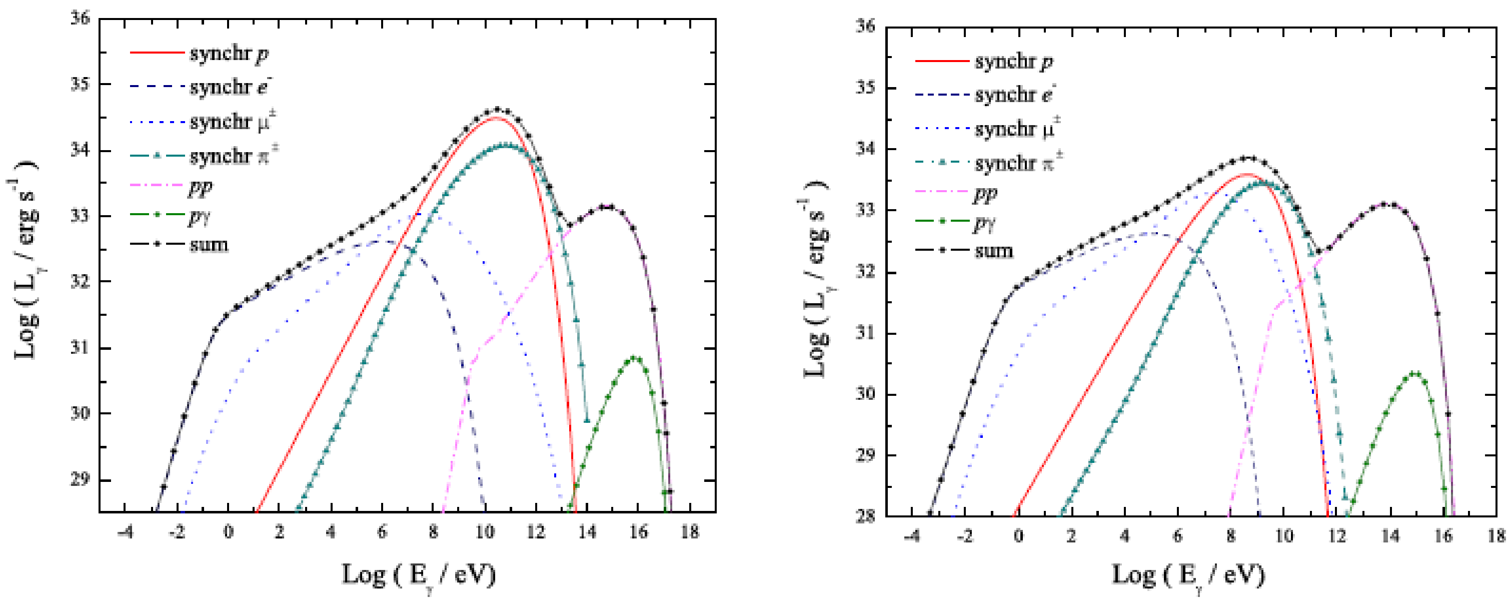
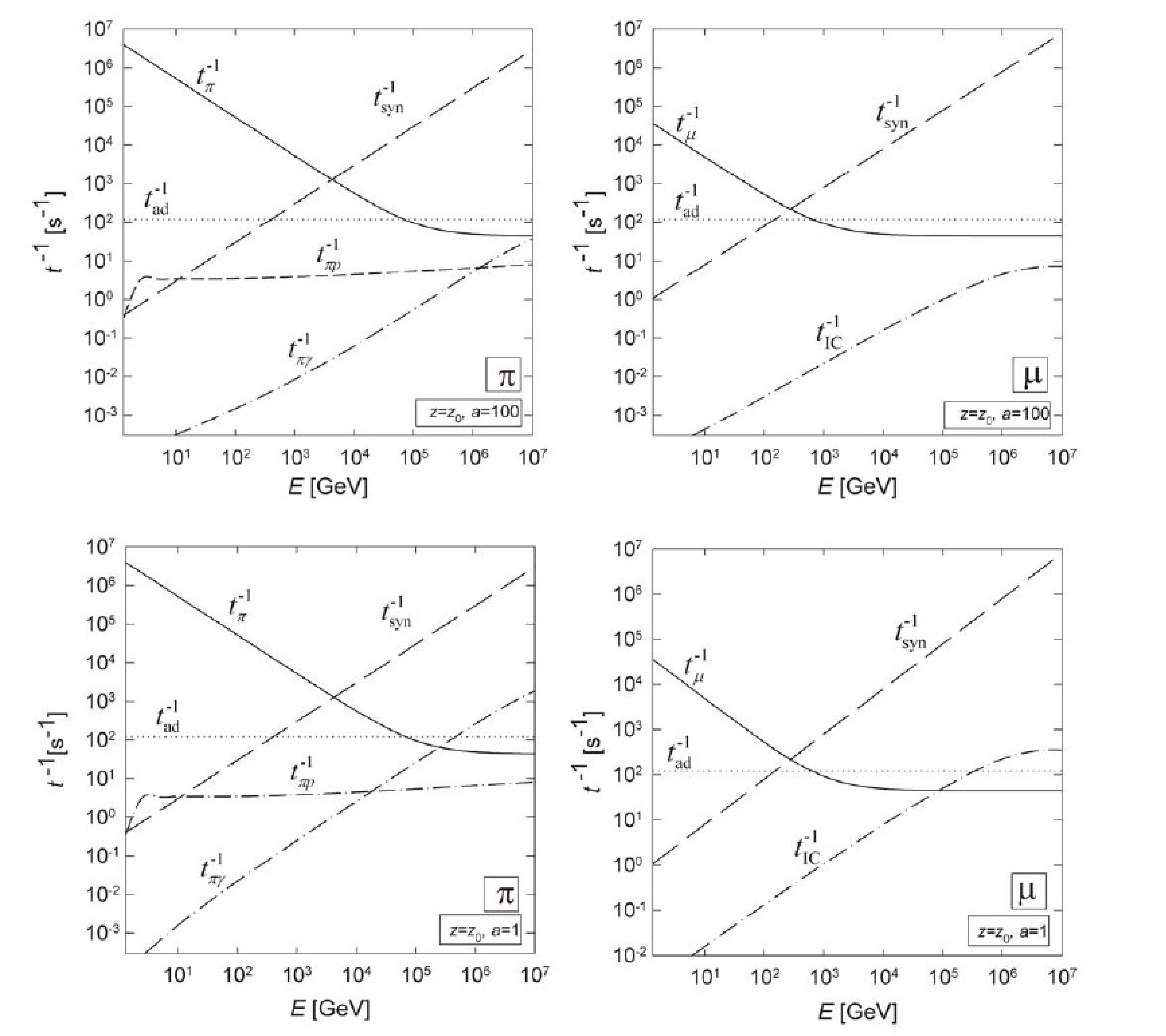


Fig. 2. Spectral energy distributions of a proton-dominated microquasar ($a = 1000$). Each panel corresponds to a different acceleration efficiency ($\eta = 0.1$ on the left, $\eta = 0.01$ on the right).

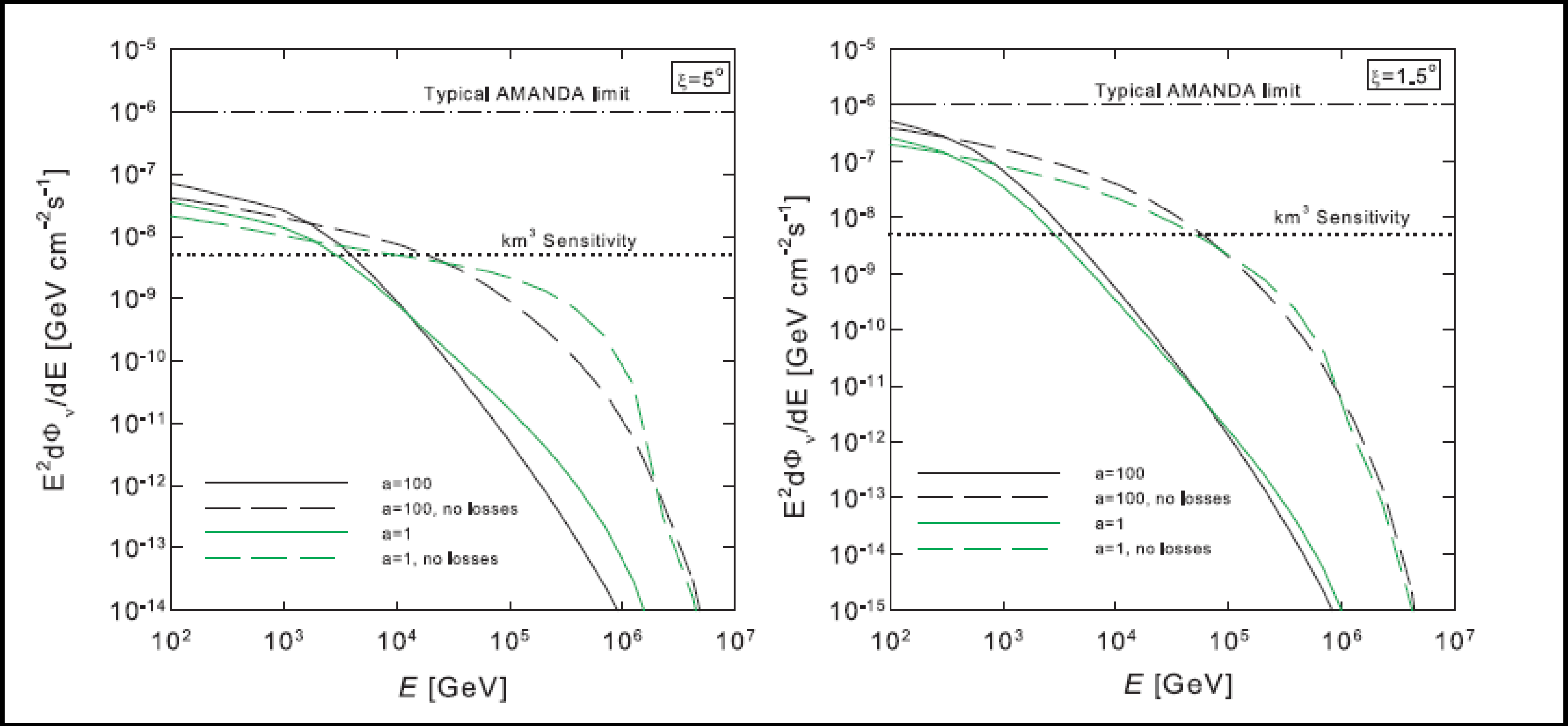
Romero & Vila, A&A, 2008, submitted

Magnetic field effects on neutrino production



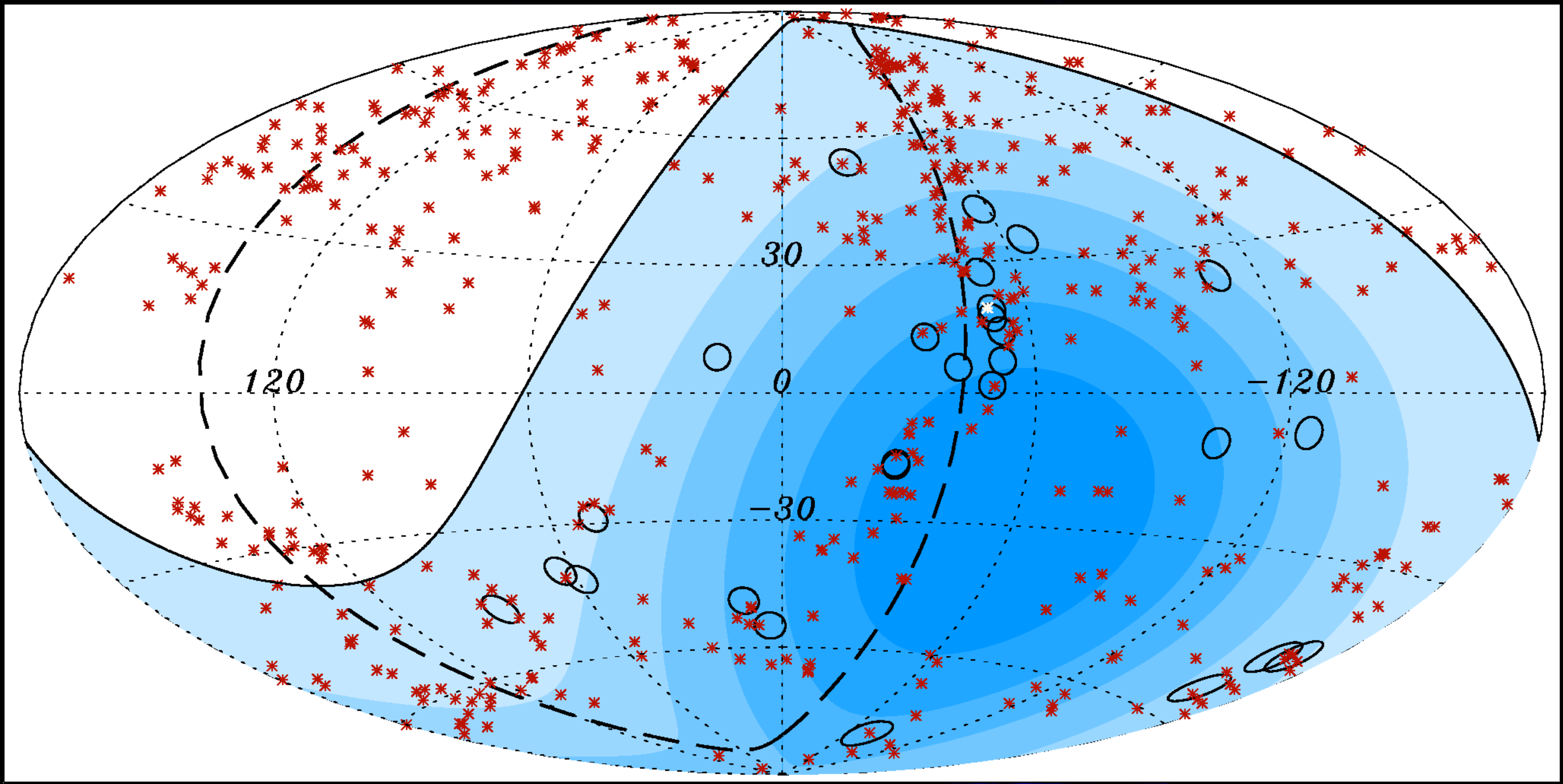
Reynoso & Romero (A&A, 2008, in press)

Magnetic field effects on neutrino production



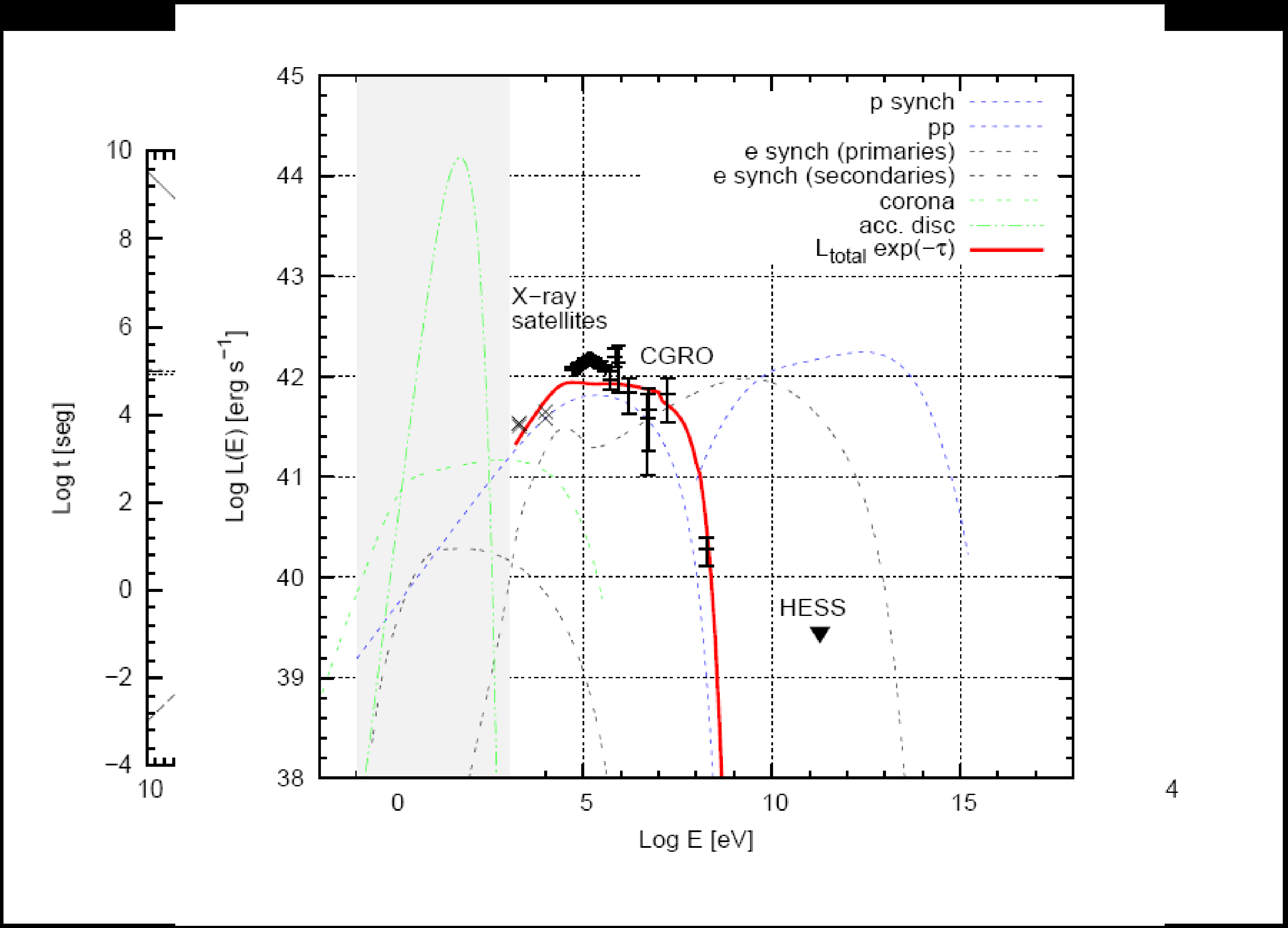
Reynoso & Romero (A&A, 2008, in press)

Application to extragalactic sources: Cen A



Auger coll., 2008

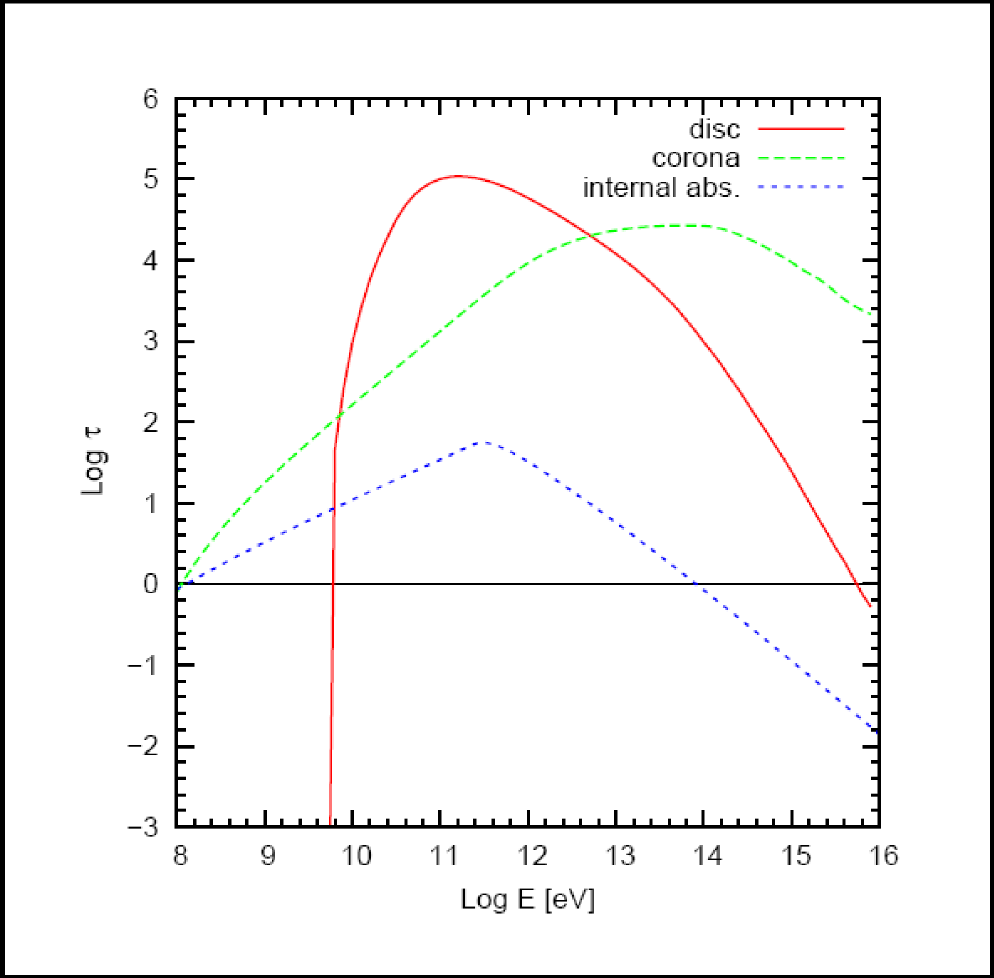
Application to extragalactic sources: Cen A



L_{jet}~10^{44} erg/s, B_0=10^4 G

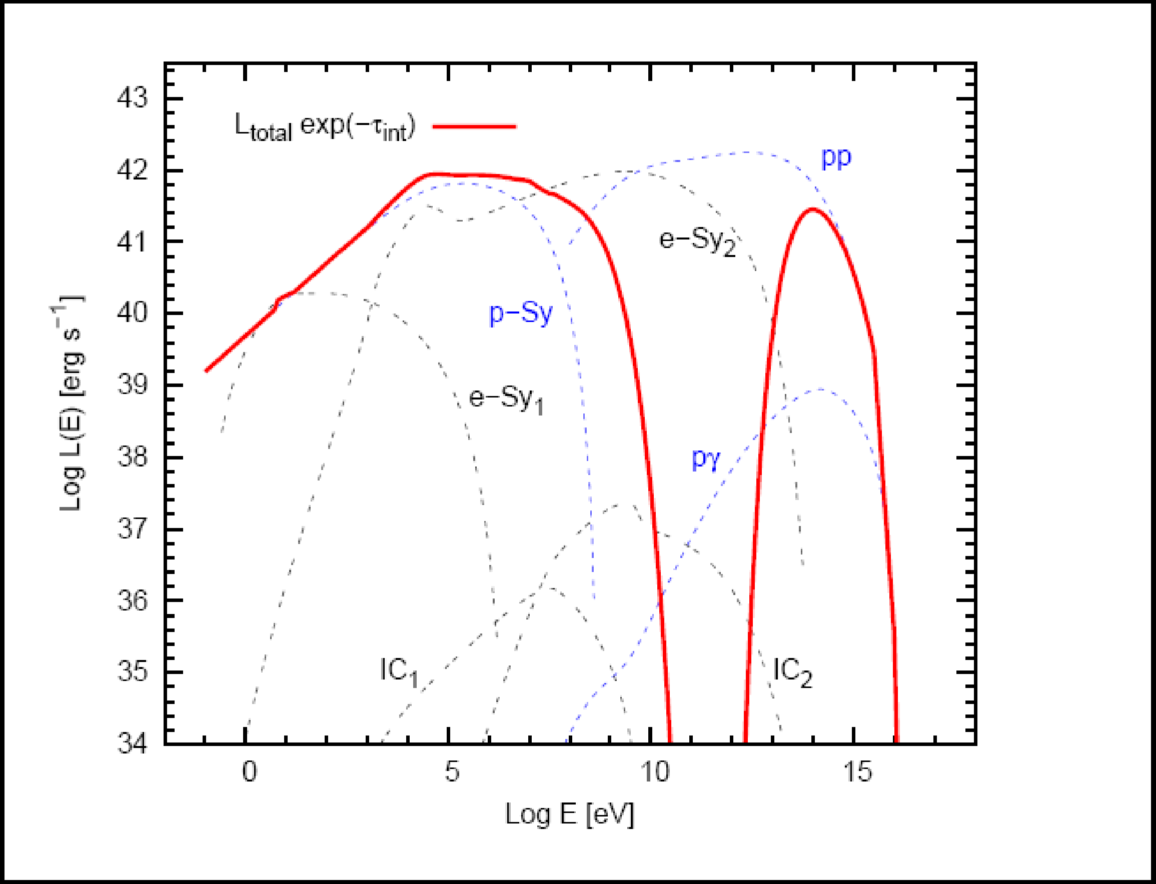
Orellana & Romero 2009

Application to extragalactic sources: Cen A



Orellana & Romero 2009

Application to extragalactic sources: Cen A



Summary

- **Jets are the result of the accretion of magnetized matter onto a massive, compact object.**
- **Relativistic jets seem to have structure, and baryonic content.**
- **Relativistic jets present non-thermal emission from radio to very high-energy gamma rays.**
- **To launch a jet magnetic energy must be converted into kinetic energy of the outflowing plasma.**
- **Shocks at the base of the jet are expected to accelerate charged particles to high energies.**

* **Gamma-rays can be produced by lepto/hadronic processes, but absorption can be important depending on the geometry and the ambient fields.**

- **Neutrinos are a necessary by-product of hadronic interactions. In some cases where the jet has a high content of relativistic protons the neutrino signal can be detectable by km^3 detectors. However, pay attention to the magnetic field effects!**

Thank you!

Additional slides