Gamma-rays, neutrinos, and positrons from galactic jets

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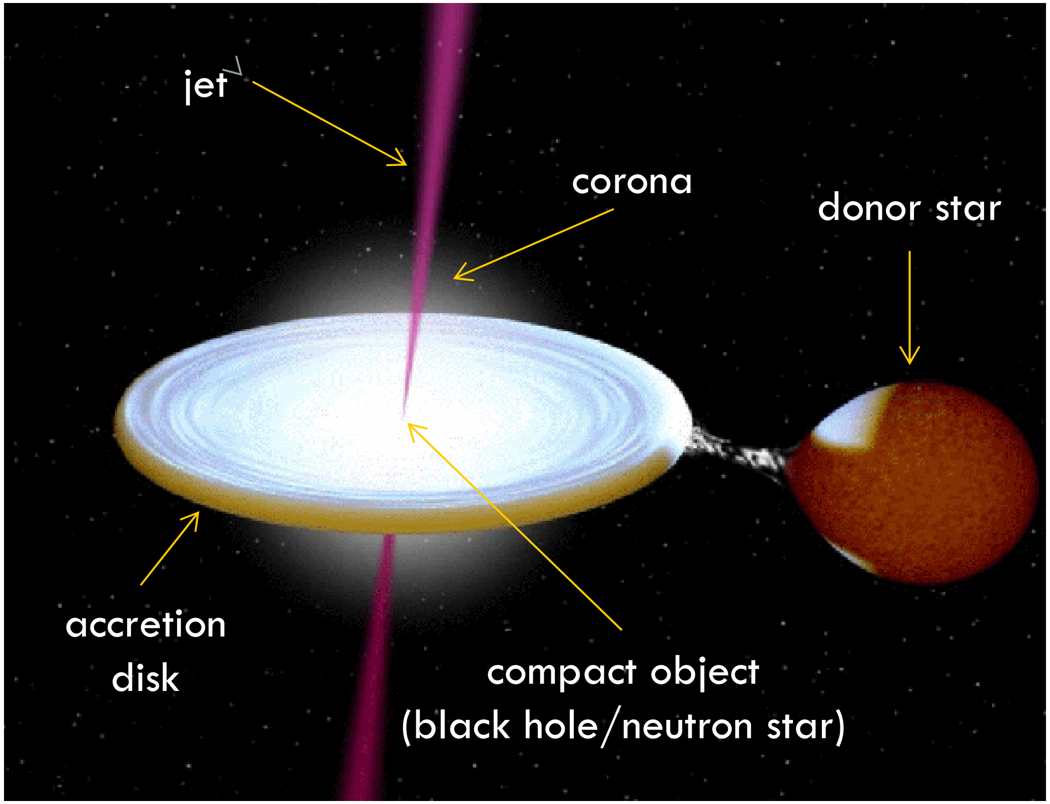
Microquasars: X-ray binaries with relativistic jets



Some characteristics of the jets

- Mildly relativistic

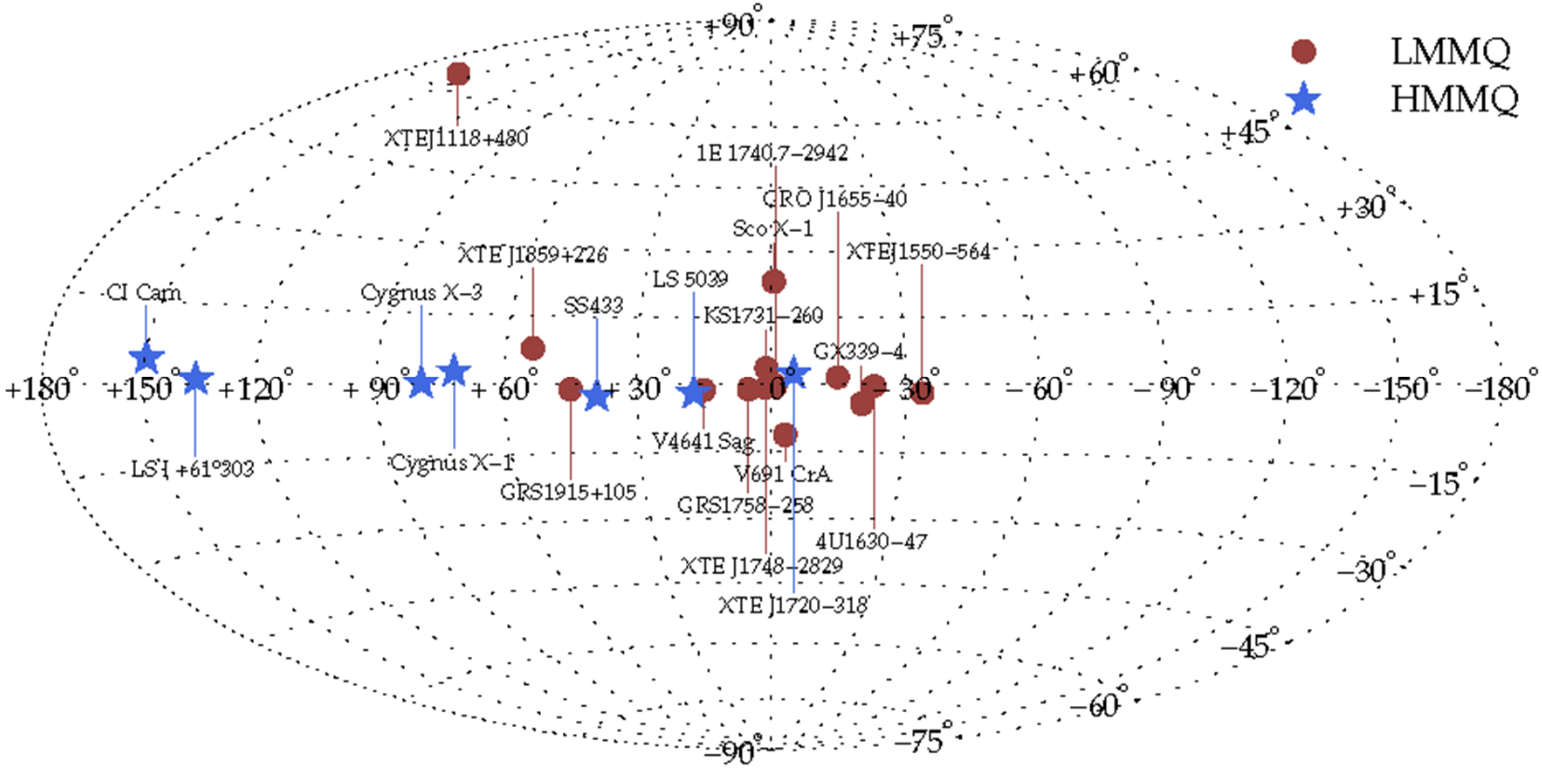
  $\Gamma_{jet} \approx 2 - 10$

- Typical luminosity

  $L_{jet} = 10^{36\text{-}40}$ erg s^{-1}

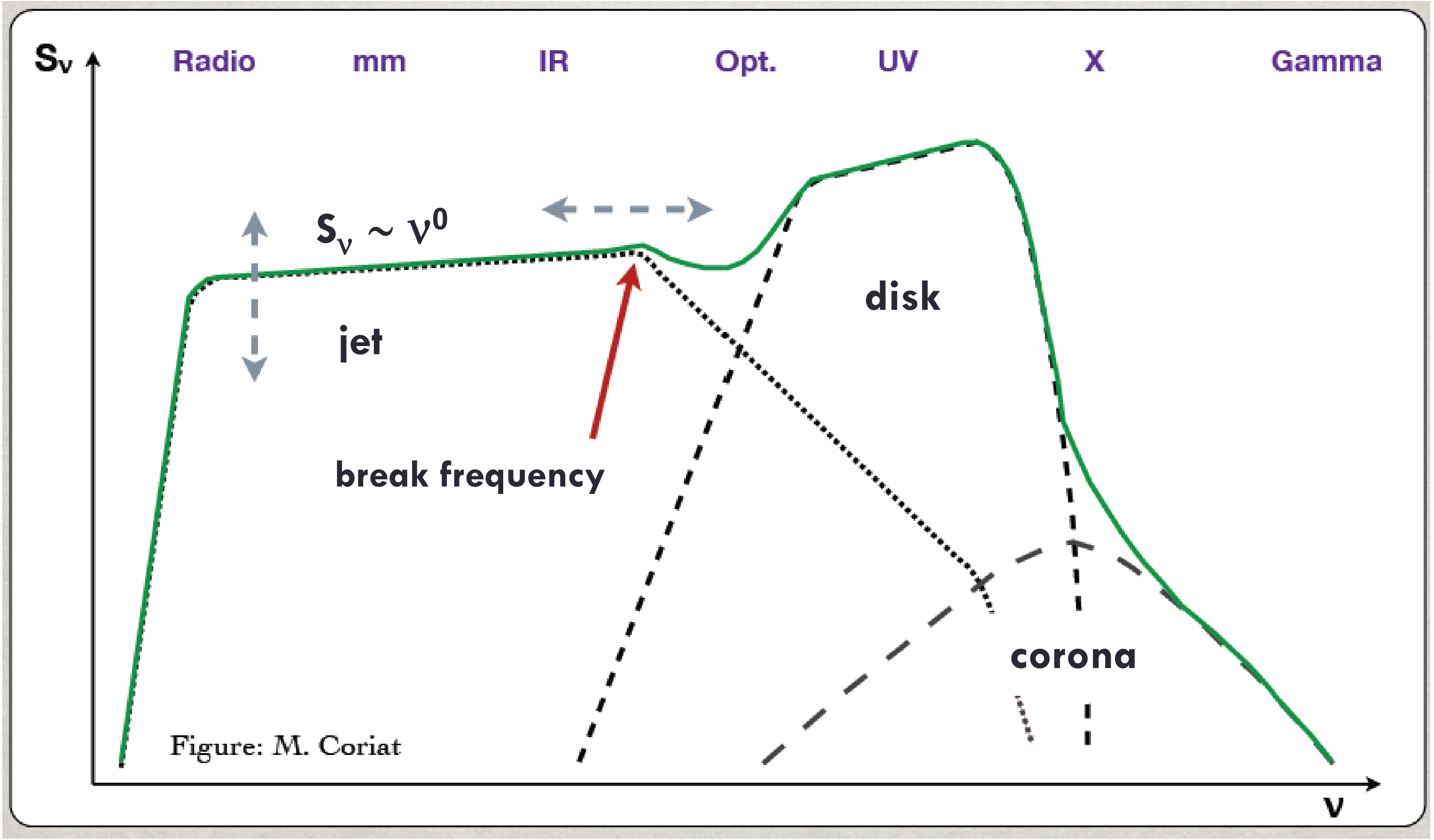
- Typical length $\ell_{jet} \leq 1$ pc

~20 known microquasars in the Galaxy



+1 MQ (S26) in NGC 7793

Microquasars emit at all wavelengths



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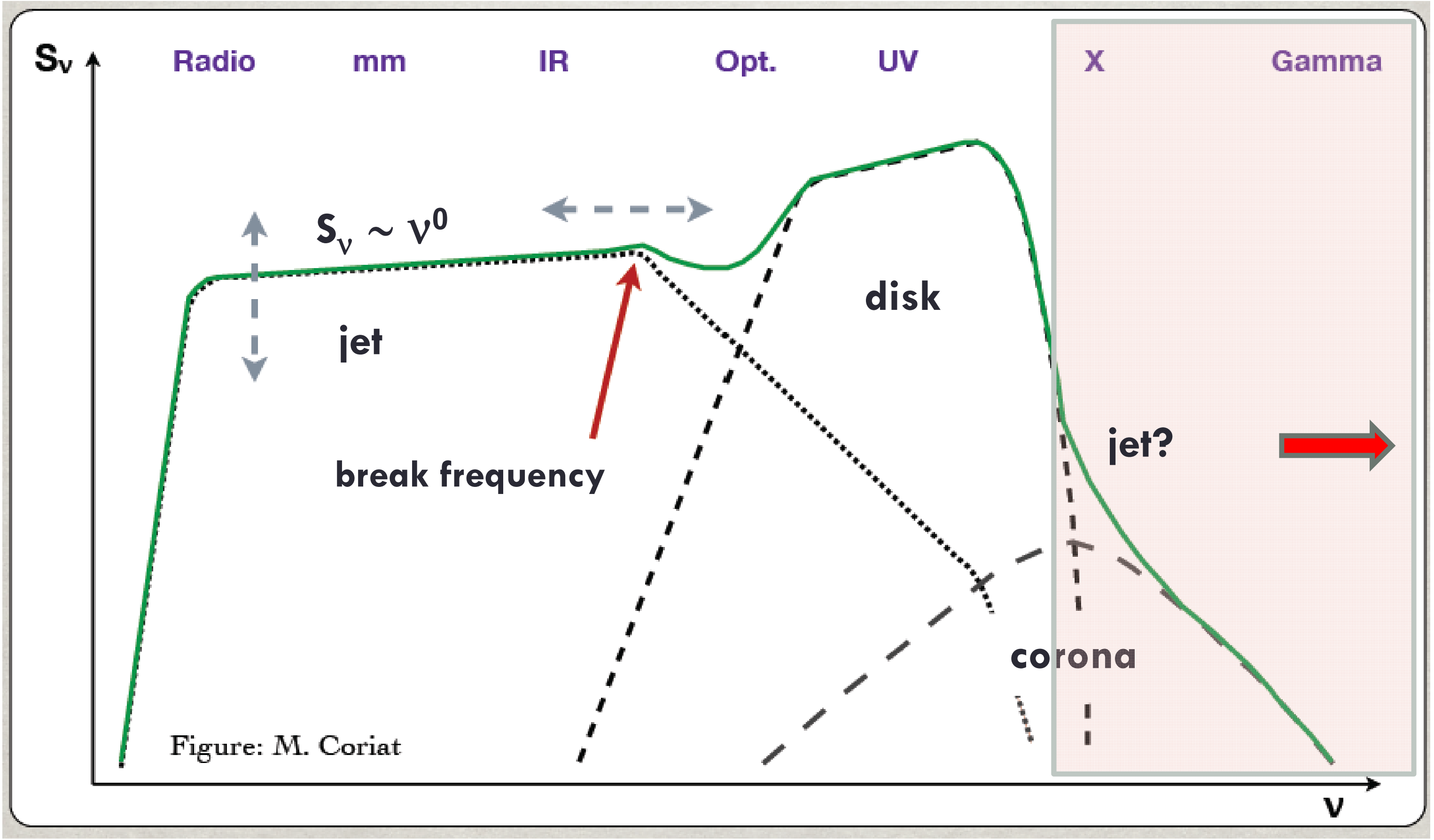
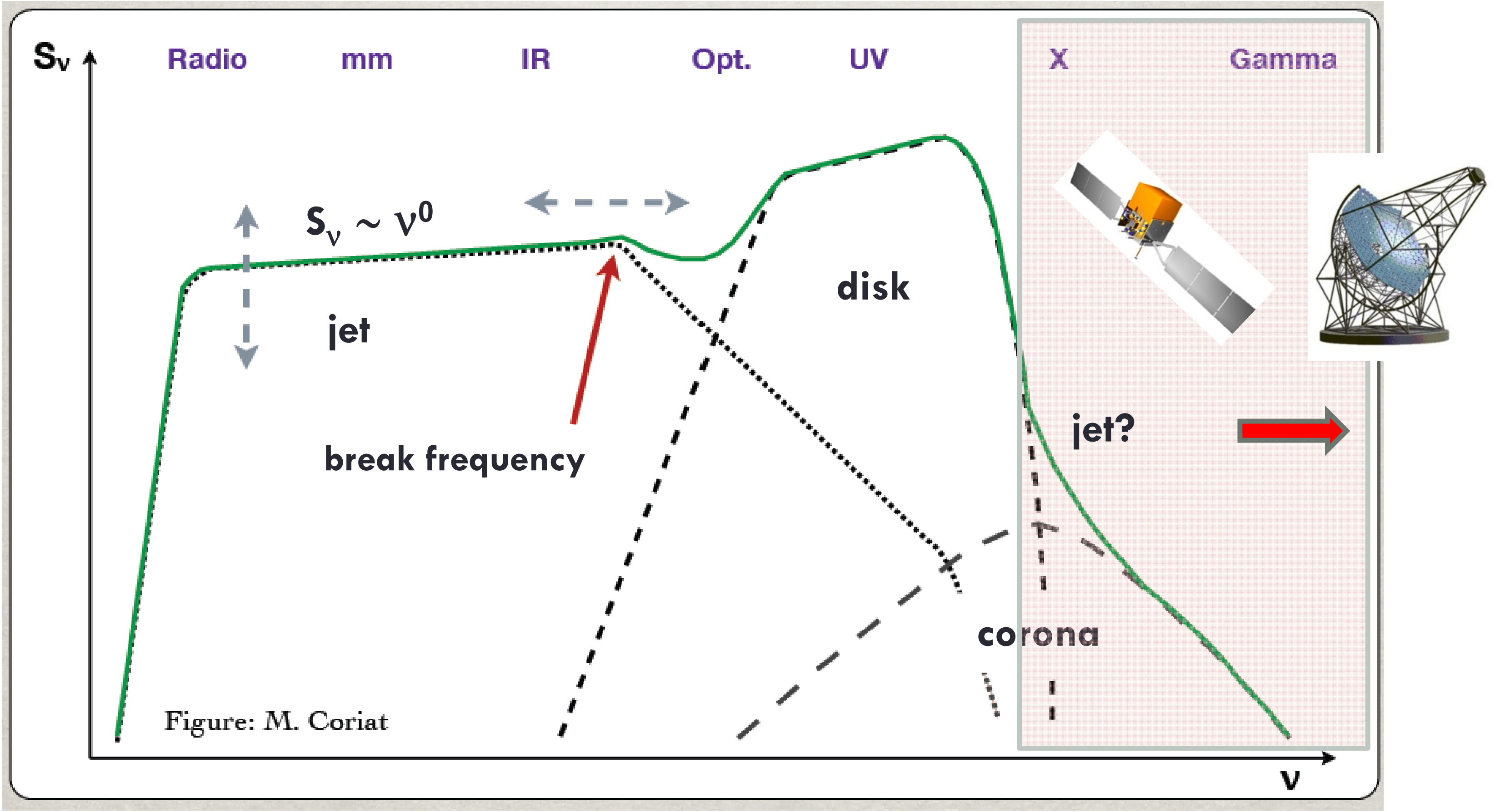
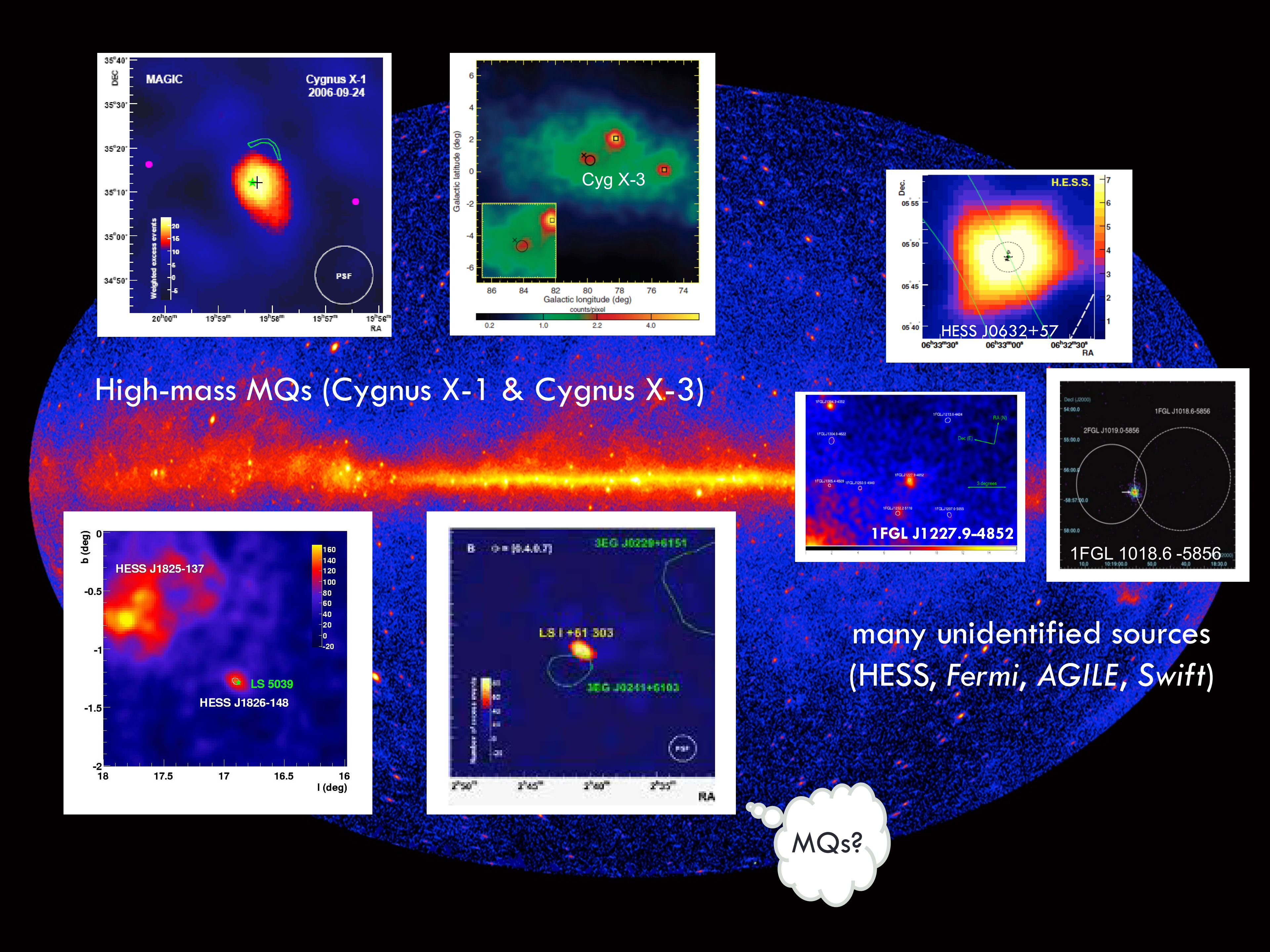


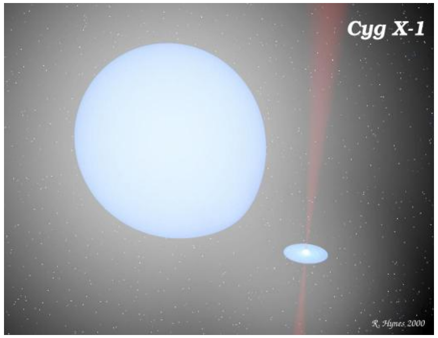
Microquasars emit at all wavelengths

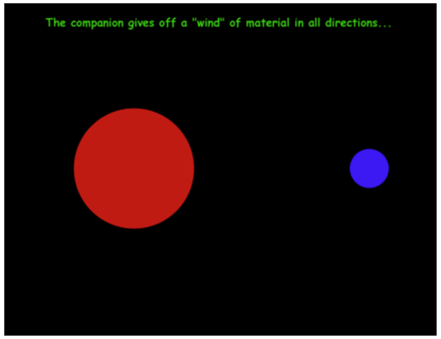



MAGIC
Cygnus X-1
2006-09-24
PSF
Weighted excess events
DEC
RA
Cyg X-3
Galactic latitude (deg)
Galactic longitude (deg)
counts/pixel
H.E.S.S.
HESS J0632+57
Dec.
RA
High-mass MQs (Cygnus X-1 & Cygnus X-3)
1FGL J1227.9-4852
2FGL J1019.0-5856
1FGL J1018.6-5856
1FGL 1018.6 -5856
HESS J1825-137
LS 5039
HESS J1826-148
b (deg)
l (deg)
3EG J0229+6151
LS I +61 303
3EG J0241+6103
PSF
RA
many unidentified sources
(HESS, *Fermi*, *AGILE*, *Swift*)
MQs?

Mechanisms of gamma-ray emission

- High-mass MQs



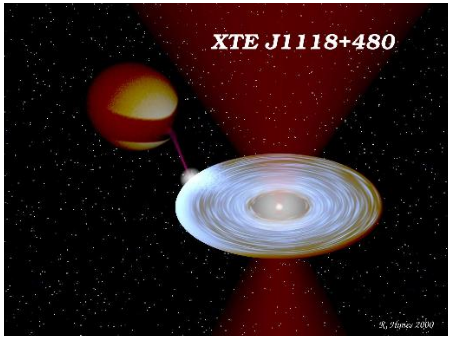


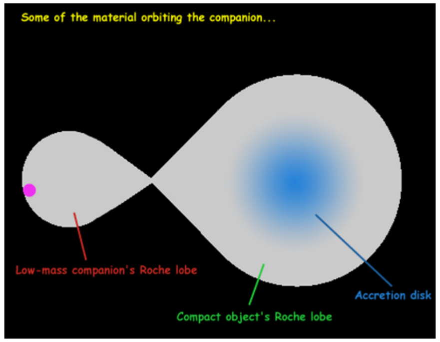
Interaction of relativistic particles in the jets with

- matter in the wind
- the radiation field

companion star

- Low-mass MQs





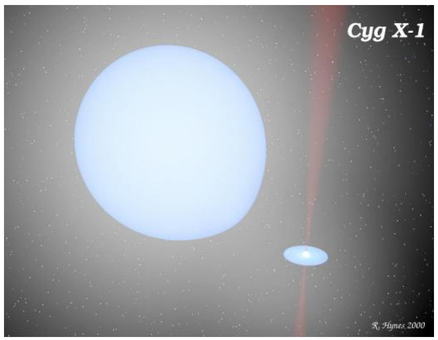
Interaction of relativistic particles in the jets with

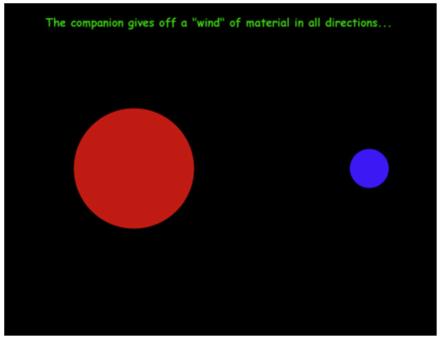
- magnetic field
- matter
- radiation

internal to the jet

Mechanisms of gamma-ray emission

- High-mass MQs





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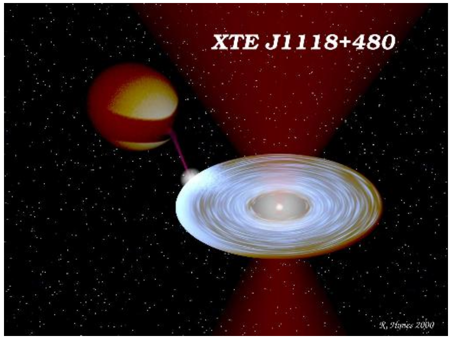

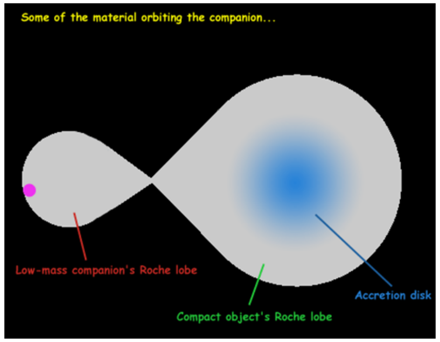

Interaction of relativistic particles in the jets with

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internal to the jet

Jet content of relativistic particles

- Largely unknown. For sure relativistic electrons (synchroton emission).
- If the jet is fed from accretion flow there could be protons as well. Evidence from Doppler-shifted iron lines in the MQ SS 433 (e.g. Migliari et al. 2002).

We adopt the prescription

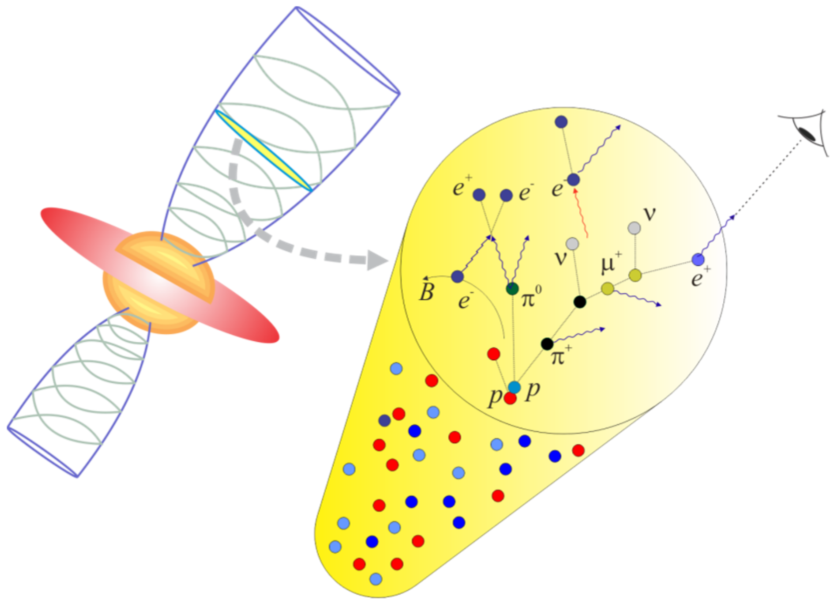
$$L_{\rm rel} = q\, L_{\rm jet} \qquad L_{\rm rel} = L_e + L_p \qquad L_p = a L_e \qquad a \geq 1$$

$a \approx 100$ typical CR composition

Diffusive shock acceleration

- Power-law energy distribution of accelerated particles $n(E) \propto E^{-\alpha}$ $\alpha \sim 1.4 - 2.4$
- Acceleration rate $t^{-1} \propto B\, E^{-1}$ $B \sim 10^5 - 10^6$ G

Relativistic particles lose energy and radiate by interacting with matter, photons, and the magnetic field in the jet



- Relativistic Bremsstrahlung

$$q + N \rightarrow q + N$$

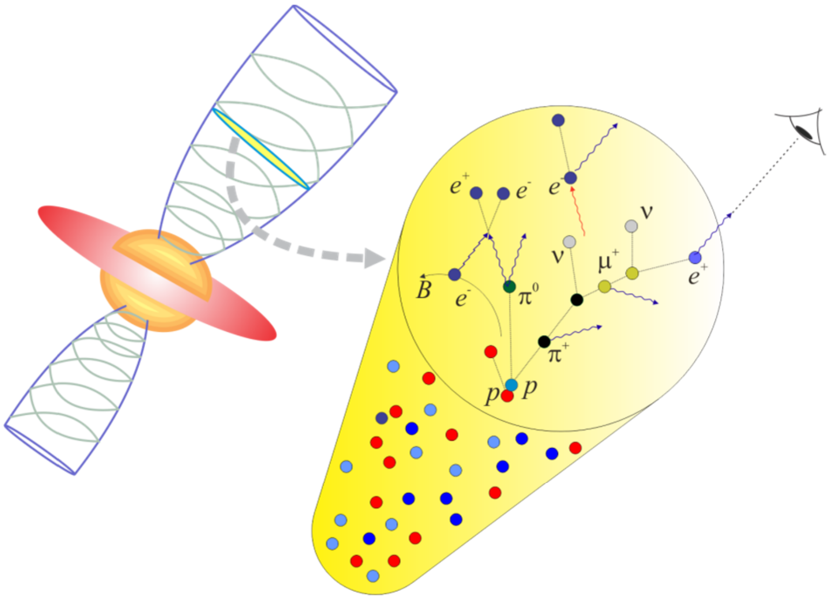
- Inverse Compton effect (IC)

$$q + \gamma \rightarrow q + \gamma$$

- Synchrotron radiation

$$q + B \rightarrow q + B + \gamma$$

Relativistic protons have other efficient cooling channels



- Proton-proton inelastic collisions (pp)

$$p + p \longrightarrow p + p + \; a\pi^0 + b(\pi^+ + \pi^-)$$

- Proton-photon inelastic collisions (pγ)

$$p + \gamma \longrightarrow p + a\pi^0 + b(\pi^+ + \pi^-)$$

$$p + \gamma \longrightarrow p + e^- + e^+$$

Radiation $\pi^0 \longrightarrow \gamma + \gamma$

$$e^\pm(\mu^\pm)(\pi^\pm) + B \longrightarrow e^\pm(\mu^\pm)(\pi^\pm) + B + \gamma$$

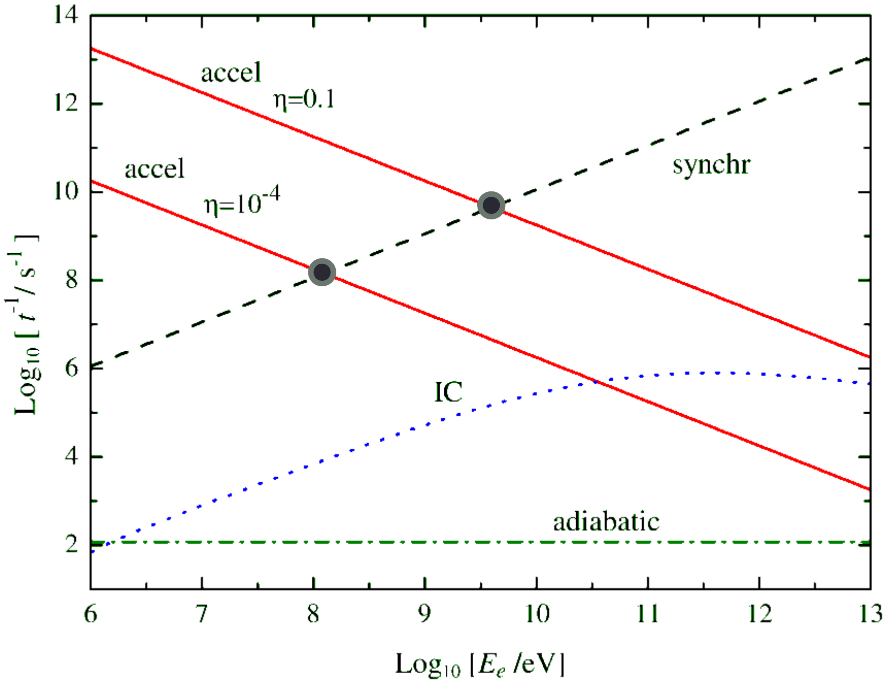
Charged particles and neutrinos

$$\pi^\pm \longrightarrow \mu^\pm + \upsilon_\mu(\bar{\upsilon}_\mu)$$

$$\mu^\pm \longrightarrow e^\pm + \upsilon_e(\bar{\upsilon}_e) + \upsilon_\mu(\bar{\upsilon}_\mu)$$

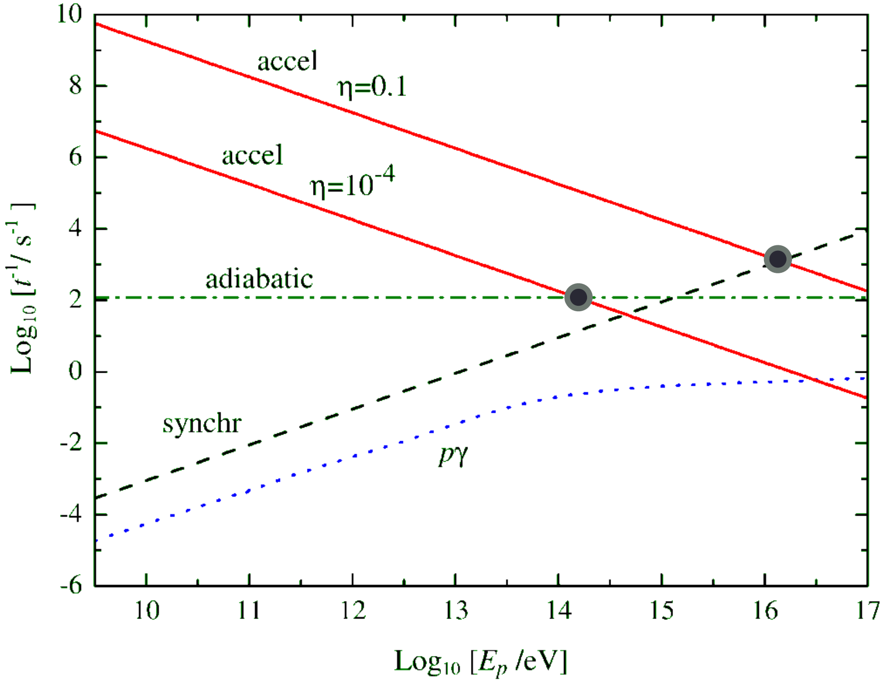
Cooling and acceleration rates and maximum energies

Electrons



$$E_{\max} \approx 0.1 - 5 \text{ GeV}$$

Protons

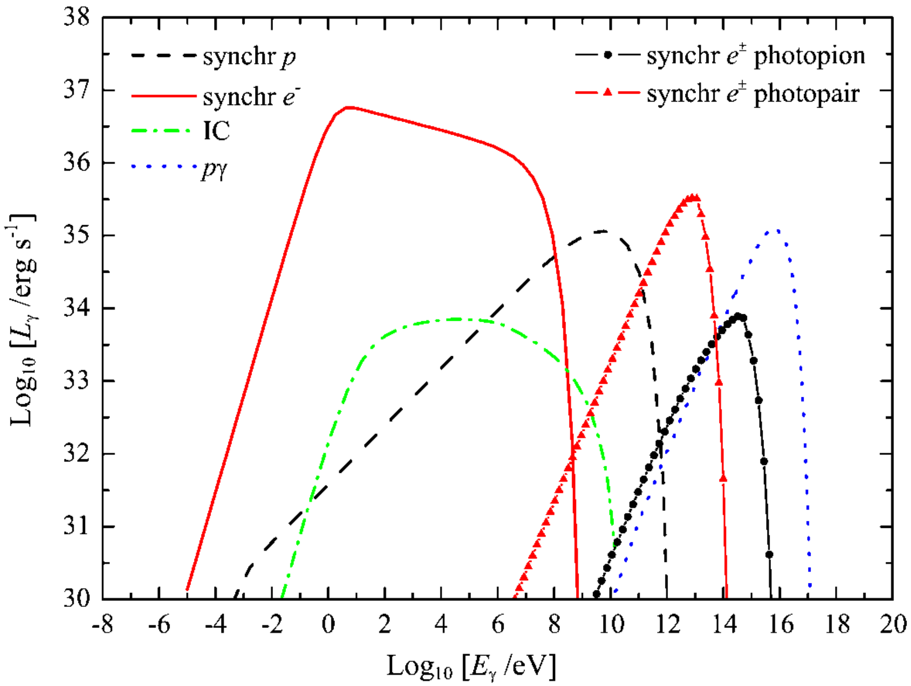


$$E_{\max} \approx 10^2 - 10^4 \text{ TeV}$$

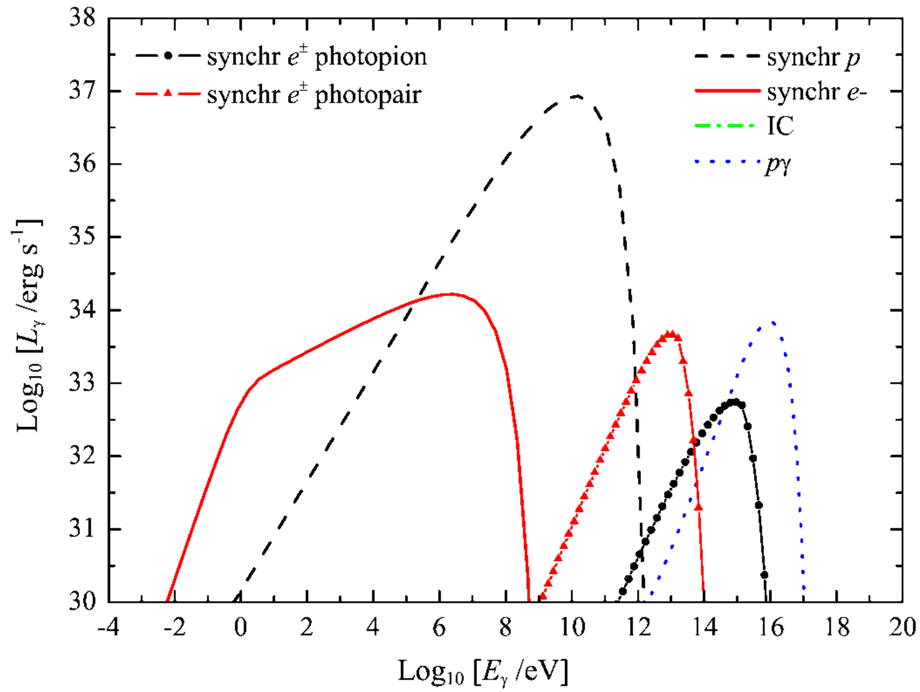
Romero & Vila (2008)

Espectral energy distributions (SEDs)

$L_p = L_e$



$L_p = 10^3 L_e$

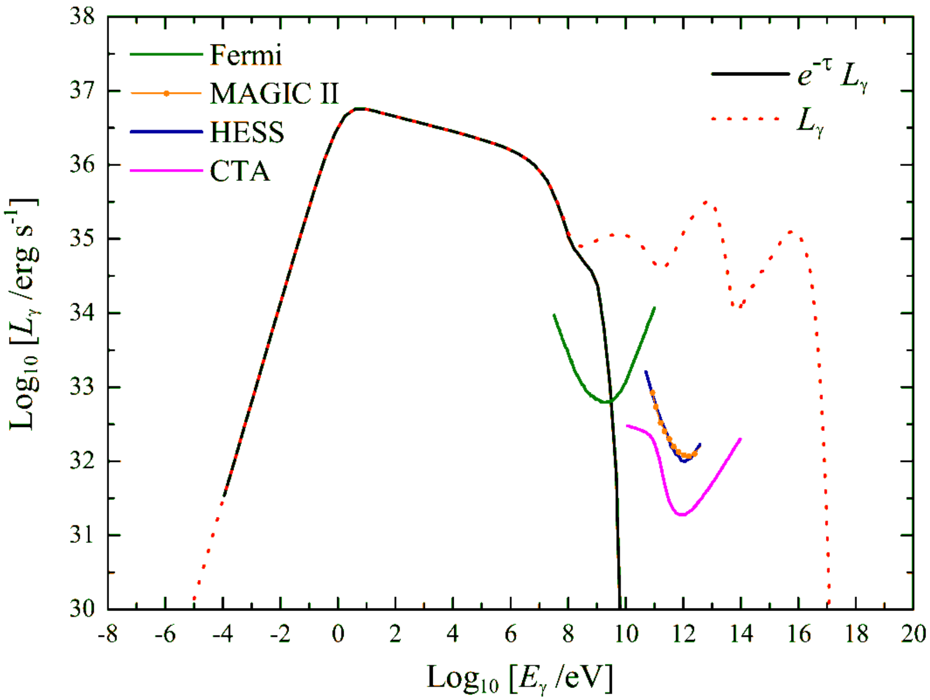


The efficiency of hadronic processes to produce gamma-rays depends on the content of electrons in the jet and their radiation at lower energies

Romero & Vila (2008)

Gamma-ray absorption by photon-photon annihilation $\gamma + \gamma \rightarrow e^- + e^+$

$L_p = L_e$



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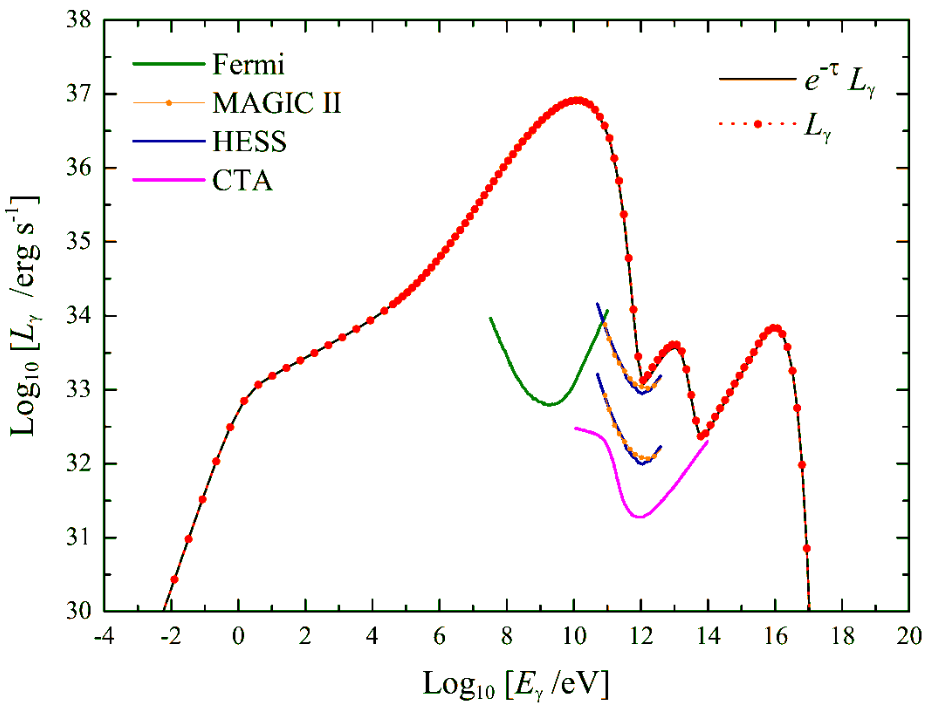

- The leptonic content also determines the importance of gamma-ray absorption
- Jets highly absorbed in gamma-rays may be strong neutrino sources

Romero & Vila (2008)

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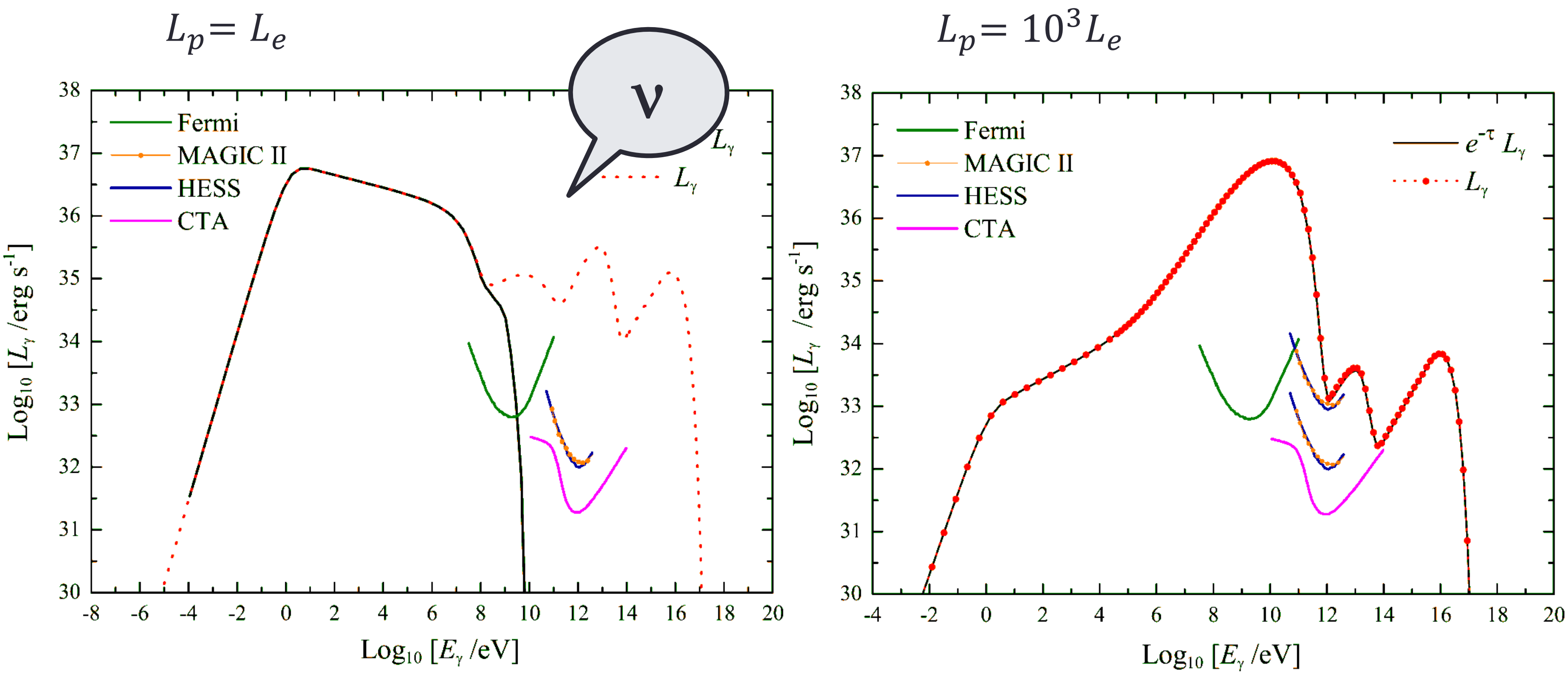

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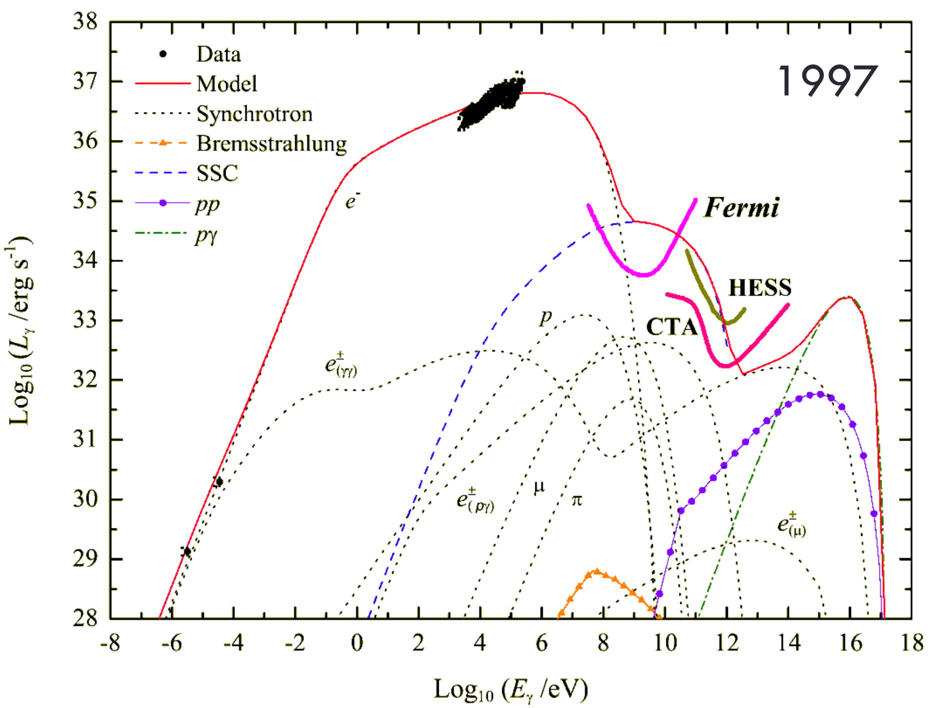
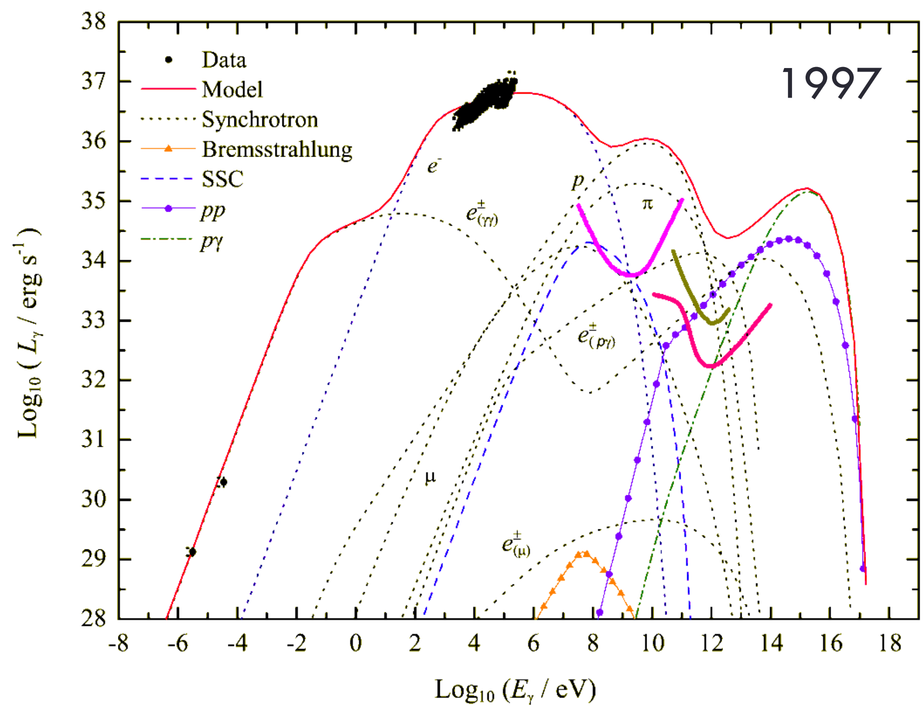
Romero & Vila (2008)

GX 339-4 (≥6 $M_\odot$ BH + ≤ $M_\odot$ star at d ≥ 6 kpc)

X-ray transient (months in outburst after years in quiescence)

High X-ray luminosity state $L_X \approx L_{Edd}$



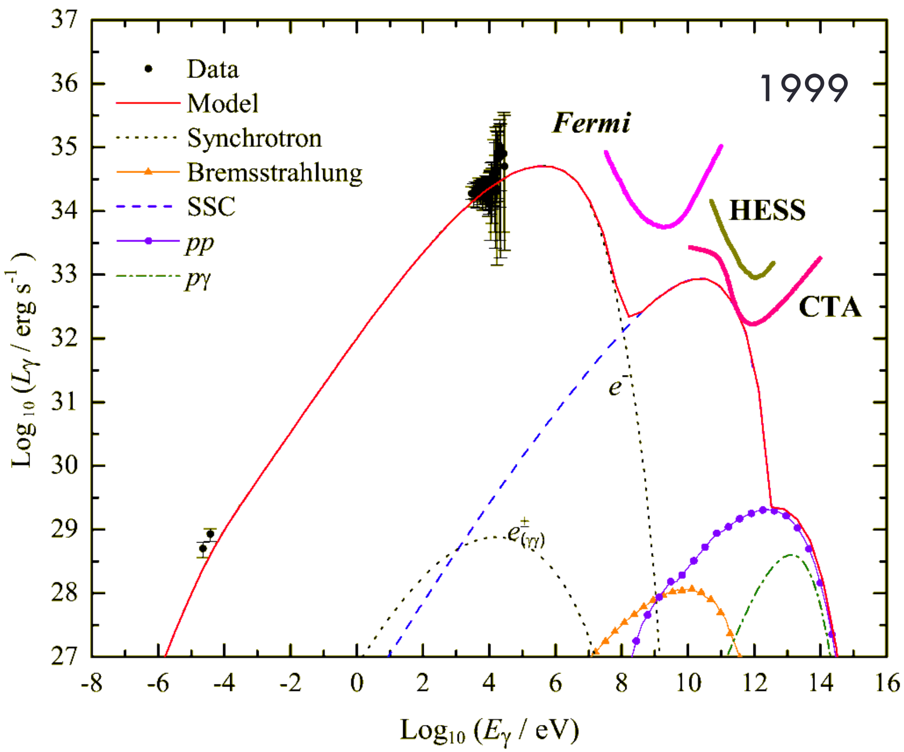


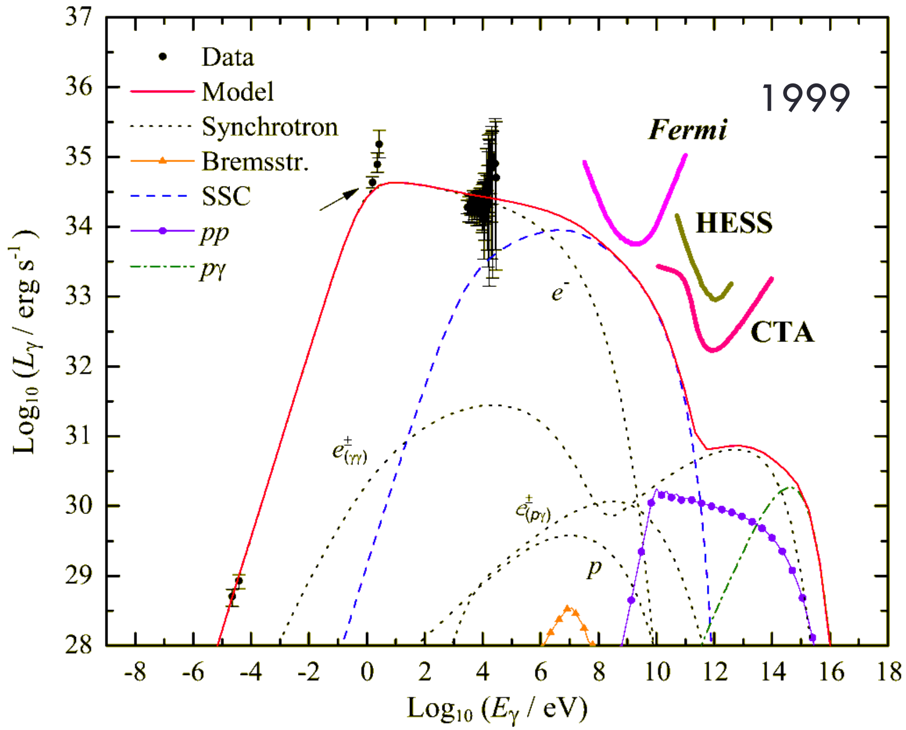
Different sets of parameters approximately reproduce the observed SED

Vila & Romero (2010)

GX 339-4 (≥6 $M_\odot$ BH + ≤ $M_\odot$ star at d ≥ 6 kpc)
X-ray transient (months in outburst after years in quiescence)

Low X-ray luminosity state $L_X \approx 10^{-3} L_{Edd}$

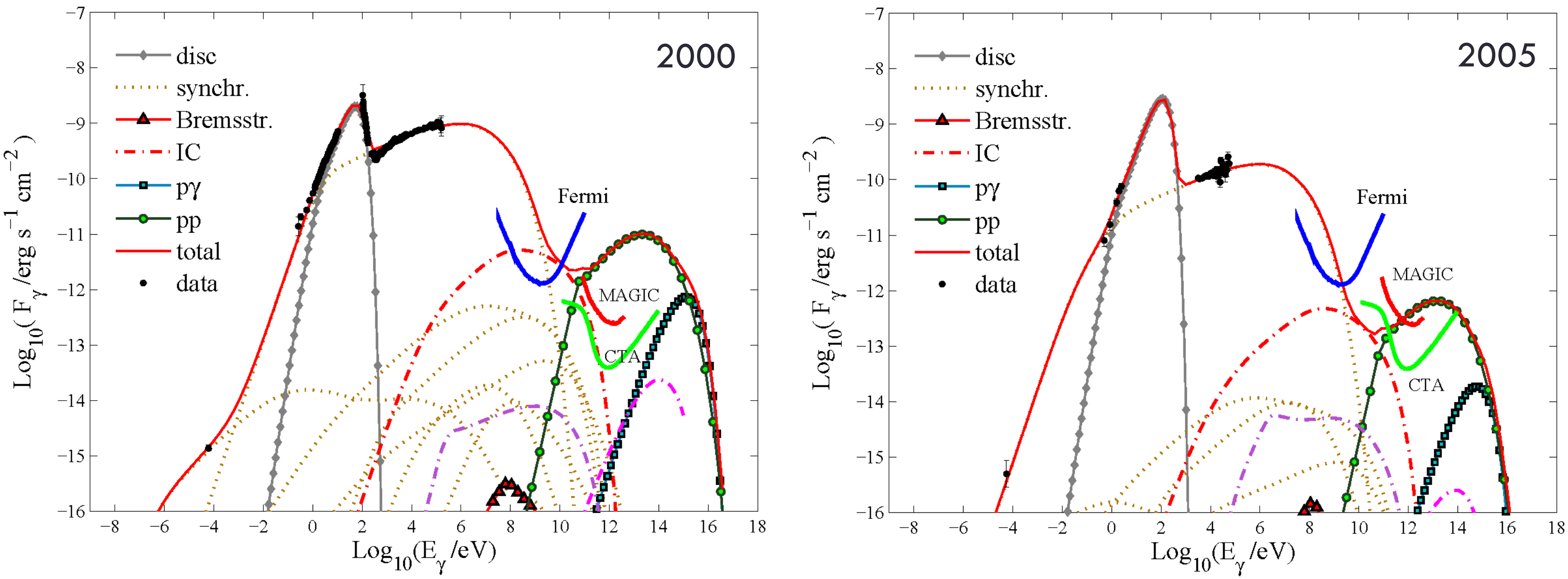




Different sets of parameters approximately reproduce the observed SED

Vila & Romero (2010)

XTE J1118+480 (≈ 8.5 $M_\odot$ BH + 0.37≈ $M_\odot$ star at d ≥ 1.72 kpc)
X-ray transient (months in outburst after years in quiescence)



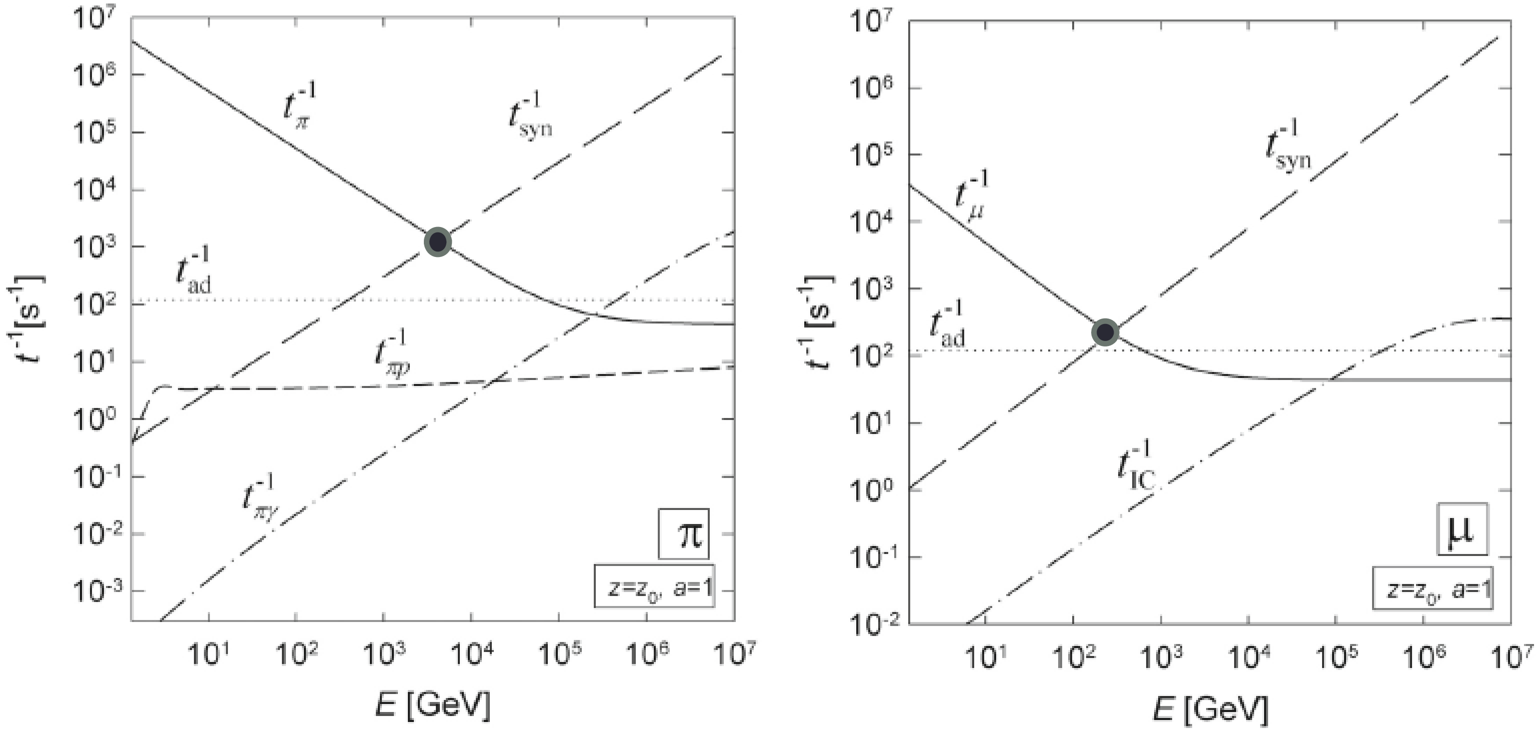
Vila et al. (2012)

Neutrinos are a product of hadronic interactions

$$p + \gamma \rightarrow \pi^{\pm} + X$$

$$p + p \rightarrow \pi^{\pm} + X$$

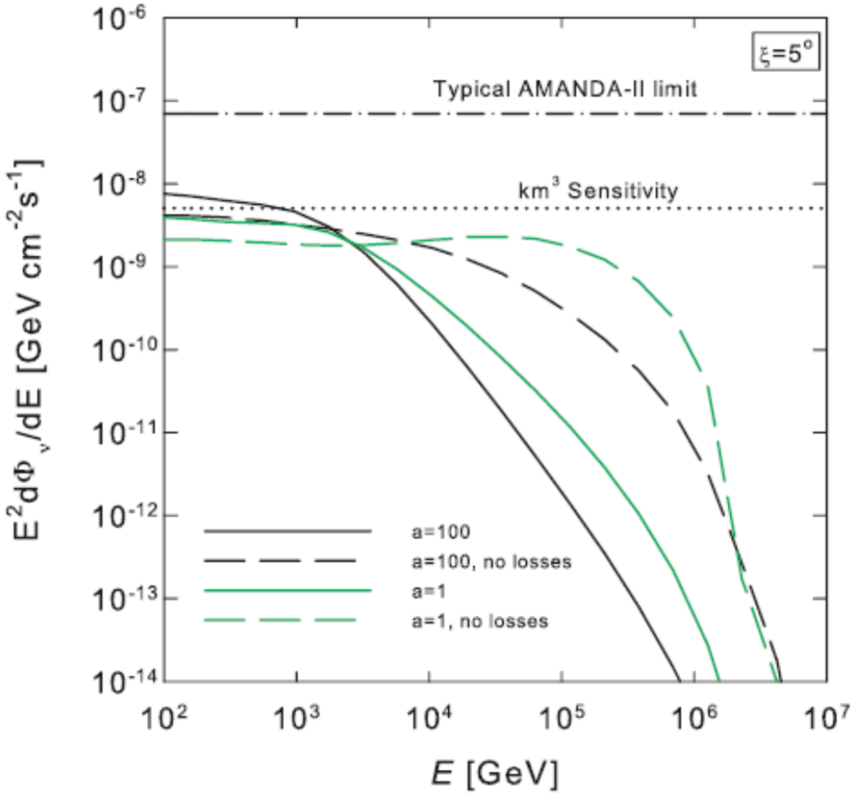
$$\Longrightarrow \quad \pi^{\pm} \longrightarrow \mu^{\pm} + \upsilon_{\mu}(\bar{\upsilon}_{\mu}) \quad \Longrightarrow \quad \mu^{\pm} \longrightarrow e^{\pm} + \upsilon_{e}(\bar{\upsilon}_{e}) + \upsilon_{\mu}(\bar{\upsilon}_{\mu})$$

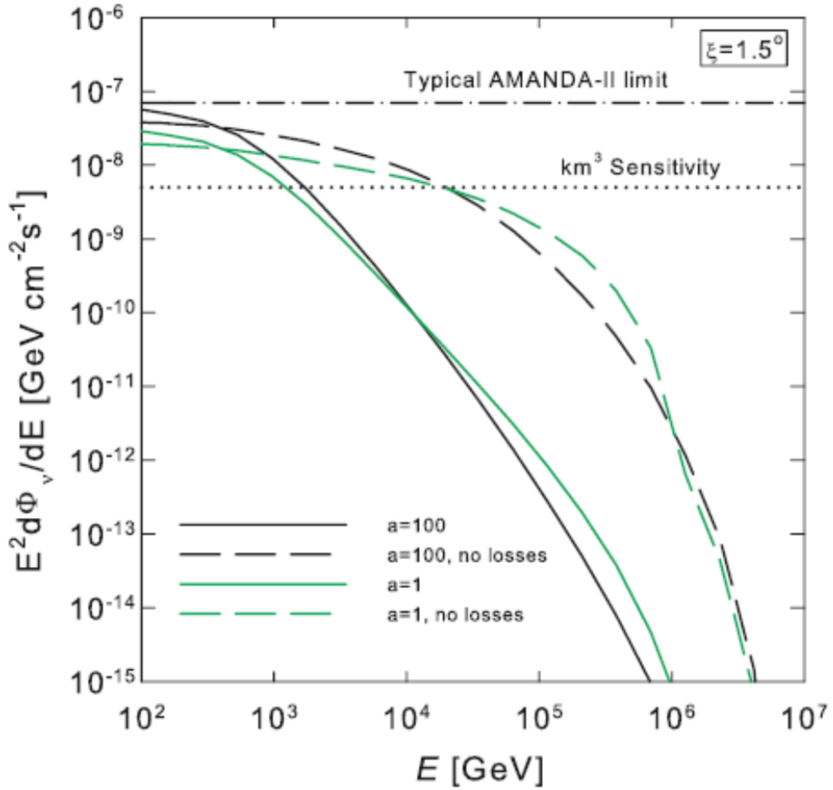


If the $\pi^{\pm}$ and $\mu^{\pm}$ are very energetic they may cool substantially before decaying

Reynoso & Romero (2009)

Cooling of $\pi^{\pm}$ and $\mu^{\pm}$ reduces the emission of very high-energy neutrinos

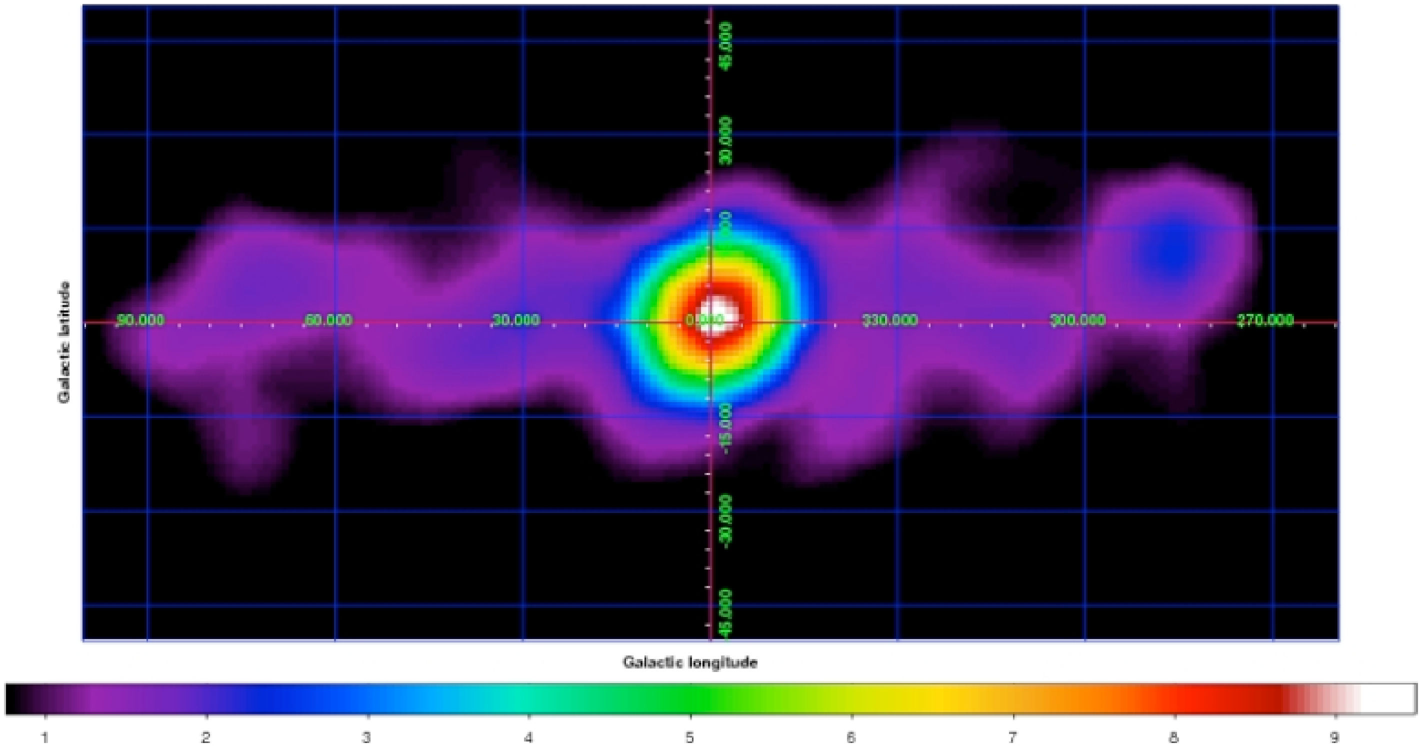




Detection of neutrinos from MQs is still difficult, but not impossible with the new telescopes

Reynoso & Romero (2009)

Spatial distribution of annihilation line at 511 keV as seen by *INTEGRAL*-SPI



Winkler et al. (2011)

Bouchet et al. (2010)

Diffuse (no point sources detected), no variability

Bright central bulge + extended disk ($|l| < 200°$, $|b| < 10°$)

Bulge-to disc flux ratio ≈ 0.25 – 0.7 (1.7 -2.1)

Positron production (annihilation) rate ≈ 1.1 – 0.8 x10^{43} s^{-1}

Different origins for the e^+e^- have been proposed

- Annihilation or decay of dark matter
- Pulsars and magnetars
- Ancient nearby gamma-ray bursts
- β^+ decay of nuclei (e.g. ^{26}Al, ^{44}Ti) from SNR and massive stars
- Galactic center blak hole
- MICROQUASARS

Low-mass MQs and the annihilation line 511 keV emission

Interesting possibility since…

- spatial distribution of low-mass XRB ~ observed distribution of 511 keV line
- several mechanisms of pair production in the jets (but also in the corona)

Some general estimations from global energetics and population analysis

- $\gamma + \gamma \rightarrow e^+e^-$ in the inner disk; pairs channeled by the jet into the ISM (Guessoum et al. 2006).

Assume "canonical" value $\dot{N}_{e^+} \approx 10^{41}\ \mathrm{s}^{-1}$ for a single MQ

$\Longrightarrow$ enough if ~100 MQs in the Galaxy (reasonable)

- Summed emission from ~300-3000 low-mass XRB with very low luminosity lepto-hadronic jets (Bandyopadhyay et al. 2008).

$$\Longrightarrow \dot{N}_{e^+\,\mathrm{total}} \approx 10^{43}\ \mathrm{s}^{-1}$$

An estimation of the e^+e^- production rate in the MQ GX 339-4

$$p + \gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$$

$$p + p \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$$

$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

$$\dot{N}_{e^{\pm}} \approx \frac{L_{e^{\pm}}}{2\Gamma_{\mathrm{jet}}\bar{\gamma}_{e^{\pm}} m_e c^2}$$

$$\bar{\gamma}_{e^{\pm}} \sim \Gamma_{\mathrm{jet}} = 2$$

Heinz (2008)

Depending on the model parameters we obtain

Low luminosity X-ray state ← $\dot{N}_{e^{\pm}} \approx 10^{38}\ \mathrm{s}^{-1}$ - $10^{42}\ \mathrm{s}^{-1}$ → High luminosity X-ray state

If there are ≥100 low-mass XRB in the Galaxy, and most of them probably MQs…

⟹ the added e^+e^- production rates might account for the observed 511 keV emission

Vila & Romero (2010)

Some conclusions

- The radiation from jets in microquasars likely covers the whole electromagnetic spectrum.
- At low energies (from radio to probably X-rays) the emission is of leptonic origin, whereas at high and very high energies models predict it originates in proton interactions.
- Highly absorbed sources in gamma-rays may be strong neutrino emitters.
- Charged secondaries might contribute to the SED in some cases. Cooling of these particles must be considered when calculating neutrino emissivities.
- Detailed models predict that detection of neutrinos from MQs is presently difficult.
- MQs might contribute significantly to the injection of electron-positron pair that yield the 511 keV line emission detected by *INTEGRAL*.
- Observations at high and very high energies will be fundamental to improve models, and reveal the composition of jets in MQs among other unknowns.