Astrophysical jet around compact objects: A source for HEN and GW ?

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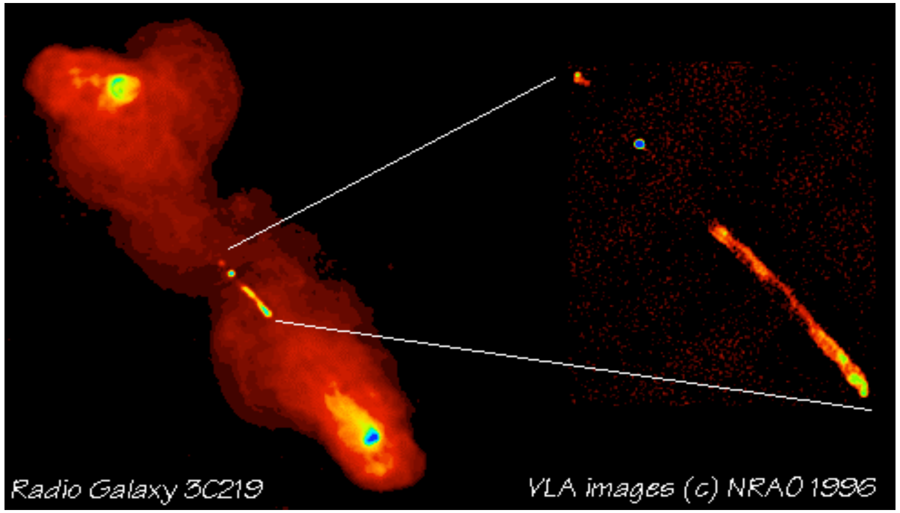
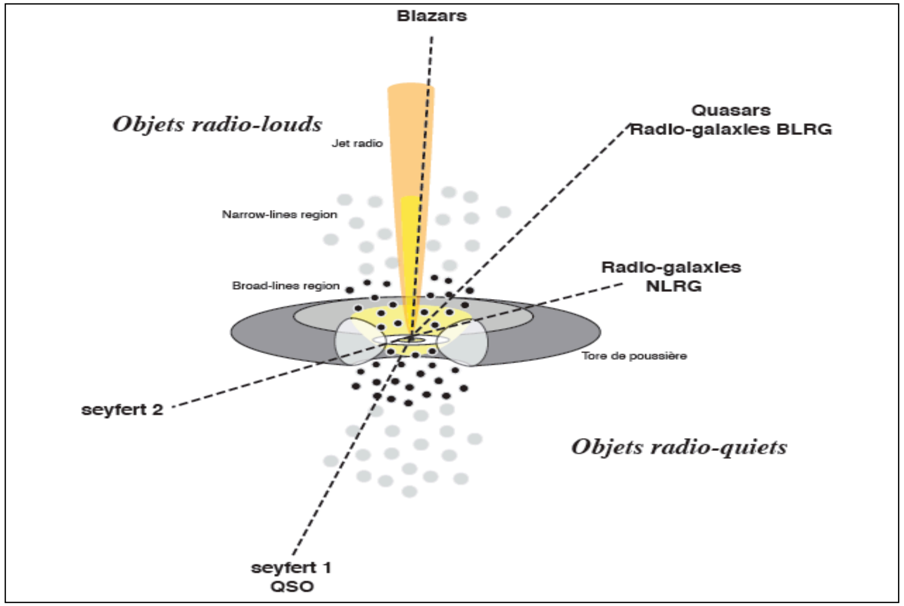
Active Galactic Nuclei

- The core of the AGN is a black hole surrounded by an accretion disk.
- Various classes of AGN with different characteristics (FR 1 and FR 2).
- FR2 AGN are the most powerful high-energy emitters among AGN.
- Low emitting jets ending into bright, extended "hotspots".
- "Blazars" seems to be interesting objects for the production of HE astroparticles (TeV emission).
- Search for HE neutrinos is linked to the search of UHECR sources.
- Recent Auger results suggest that UHE cosmic rays come from AGN (real source or last scattering centers for CR from GRBs? See e.g. Kotera & Lemoine 2008).





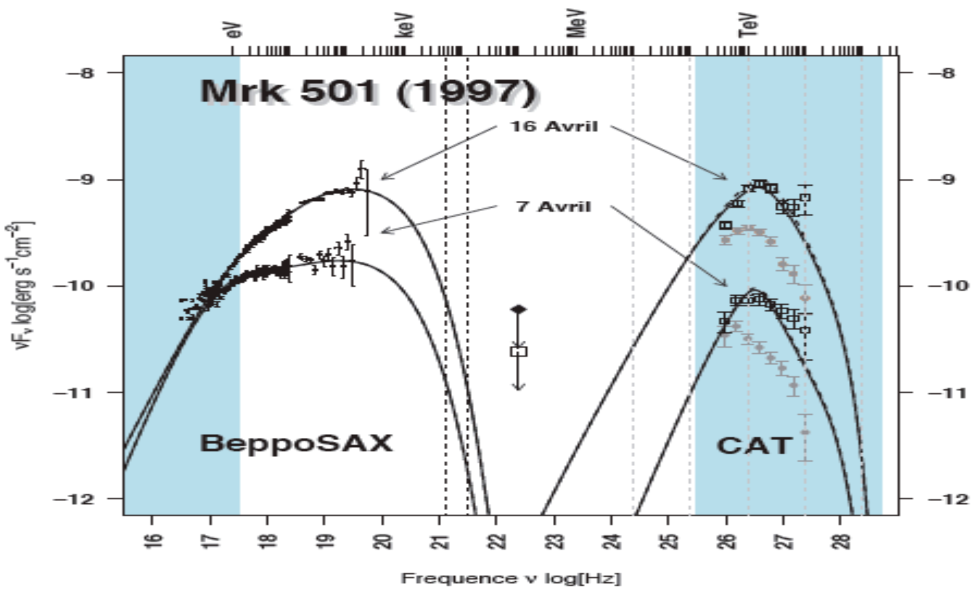
Urry & Padovani (1995)

Blazars

- Blazars are believed to be FR2 jets aligned with our line of sight.
- Powerful emission ranging from VLBI up to TeV γ-rays.
- The variability of the source shows that the emitting region has a size of $\leq 10^{13}$cm.
- The emitting region is a small region containing relativistic particles --> Relativistic beaming enhances the radiative emission.
- The first hump feature is believed to arise from synchrotron emission by relativistic electrons --> presence of significant magnetic field.
- The nature of the second hump is still a matter of debate..

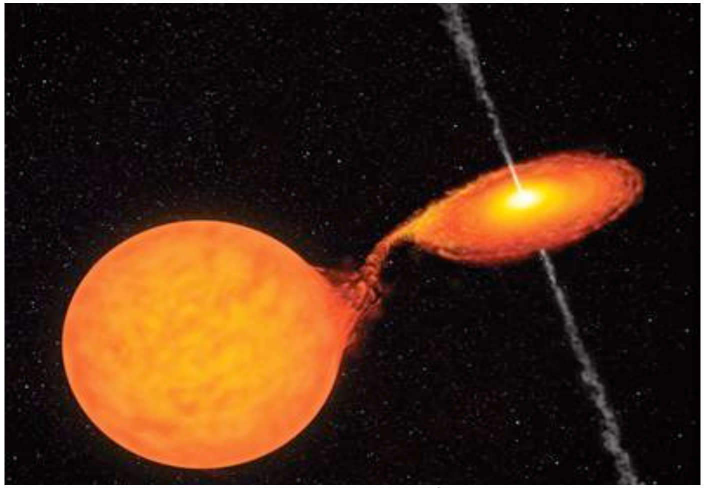
• <u>Leptonic models</u>: the second hump produced by SSC emission of a relativistic pair plasma.

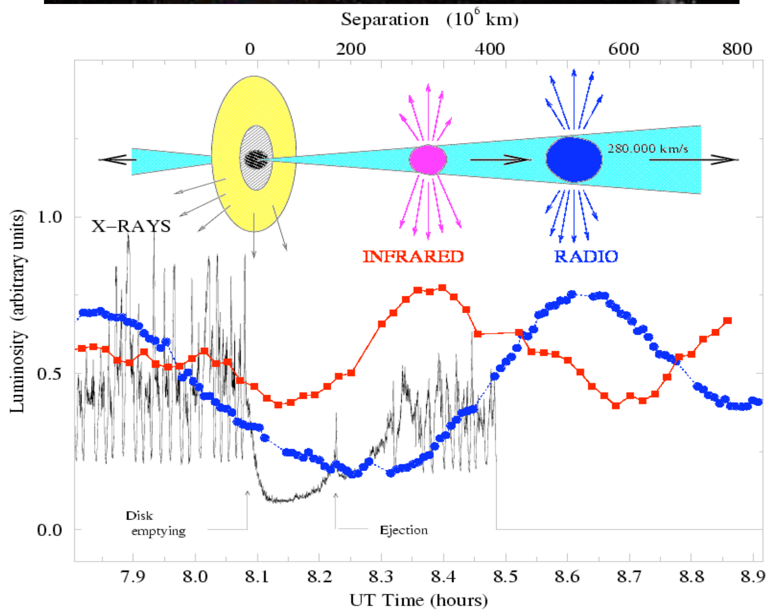
• <u>Hadronic models</u>: the HE bump is created by proton induced cascades (pp collision or pγ photo-desintegration via Δ-resonance).



Microquasars

- Binary compact objects (BH or NS) surrounded by an accretion disk.
- Compact objects likely to be stellar black hole (M ~3-10 $M_\odot$).
- Binary systems located in our close environnement (d~ few kpc).
- Angular resolution is quite poor compared to AGN !
- Mildly relativistic large-scale jet which velocity ranges from V_{jet}~0.1 to 0.95c.
- Multi-wavelength (Radio to X-ray) emission from both the disk and jets.
- Composition of the jet is still an issue (except for SS433 -> baryonic).
- Quasi-Periodic Oscillations (QPO) in X-rays emission question the accretion process.





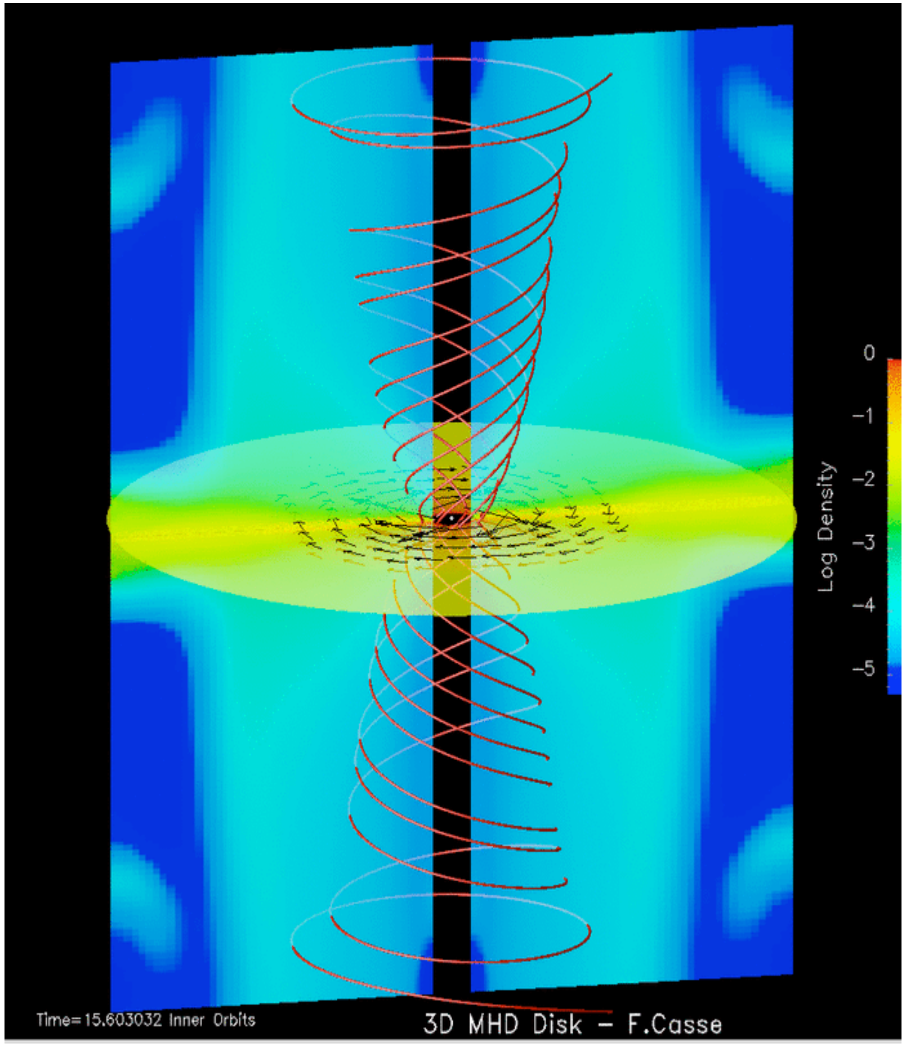
Chaty et al. (1998)

Compact objects & Jets

- What is the energy source able to power the jets ?
  - Rotation energy of a spinning black hole: $$\frac{P_{BZ}}{L_{Ed}} \simeq 10^{-4} a_s^2 \left(\frac{B}{10^4 G}\right)^2 \left(\frac{M}{10^8 M_\odot}\right)$$
  - Energy released by accretion of mass: $$P_a = \varepsilon_a \dot{M}_a c^2 \ ,$$
- Accretion is the most likely reservoir of energy.
- Still need to have an extra mechanism to give birth to relativistic particles able to radiate non-thermal emission..
- What about cosmic ray acceleration ? $$\epsilon_{max} \simeq 10^{20} \Gamma Z \left(\frac{M}{10^8 M_\odot}\right)^{1/2} eV$$
  - AGN: E_{max} ~ 10^{21} eV
  - Microquasars: E_{max} ~10^{17} eV

Accretion disks & Jets

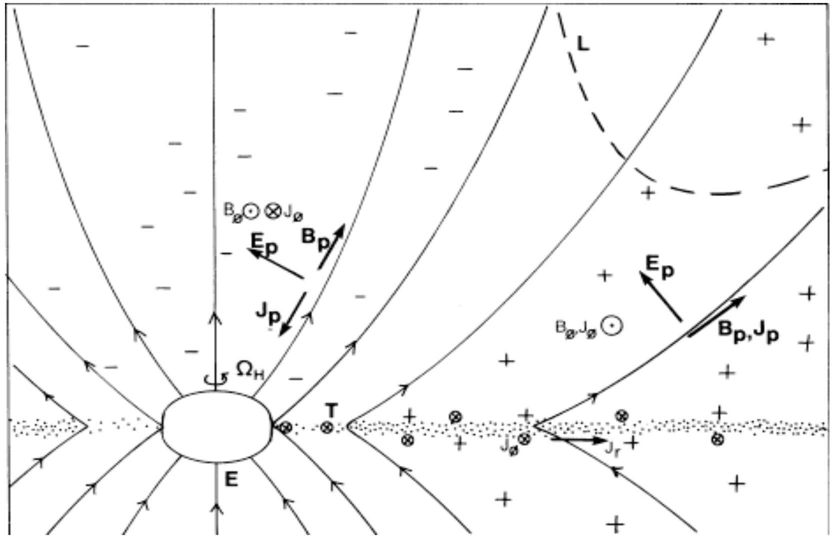
- Jets can be launched from accretion disks thank to a MHD energy transfer (Blandford & Payne 1982).
- Collimation is ensured by the pinching effect of the toroidal magnetic field.
- Jets launched by disks cannot reach relativistic bulk velocities !
- Hollow structure enables additional non-thermal particle acceleration to take place along the jet axis.

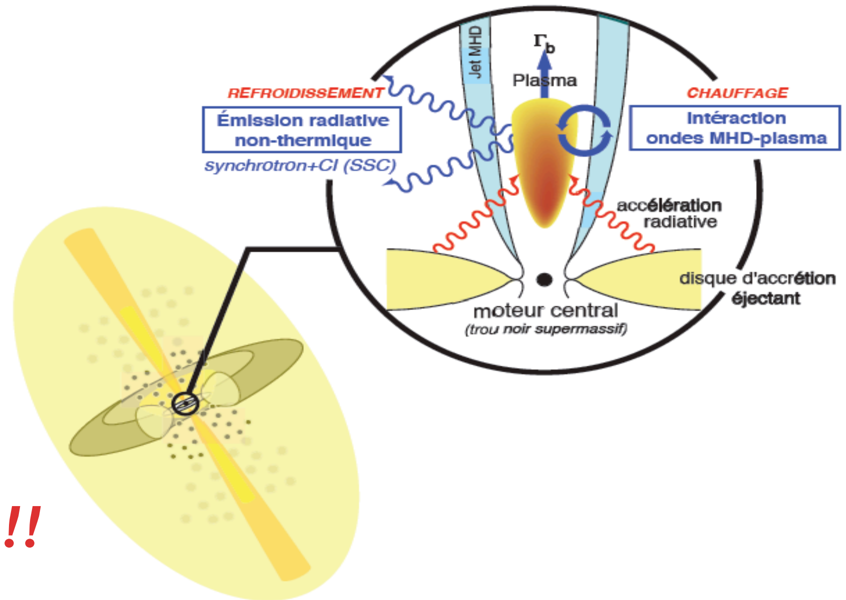


Casse & Keppens (2004)

Leptonic models

- These models are based on the birth of a dense, relativistic pair plasma in a strongly magnetized region.
- The pair plasma is either produced by:
  - Interaction of the rotating massive black hole with a surrounding magnetic field (Blandford-Znajek 1977) *-> works only if the accretion disk is underluminous..*
  - The comptonization of the accretion disk photons (up to UV/X rays) with external jet electrons (e.g. Henri & Pelletier 1991).
- The acceleration of the pair plasma is sustained by interaction with MHD wave turbulence from external jet (Γ ~10).
- Small fraction of protons seems able to be accelerated by the e^+-e^- pairs.





No significant neutrino emission expected !!

Hadronic models

- The sub-pc relativistic jet is made of proton-electron plasma.
- The relativistic electrons produce the low energy synchrotron emission.
- The collisions of relativistic protons with ambient matter and photon field generate secondary particles

$$p + p \longrightarrow p + n + a(\pi^+ + \pi^-) + \pi^0,$$
$$\pi^0 \longrightarrow \gamma + \gamma$$
$$\pi^\pm \longrightarrow \mu^\pm + \left\{ \begin{array}{l} \bar{\nu}_\mu \\ \nu_\mu \end{array} \right. \longrightarrow e^\pm + \nu_e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu .$$

$$p + \gamma \longrightarrow \Delta^+ \left\{ \begin{array}{l} \xrightarrow{2/3} \; p + \pi^0 \longrightarrow p + \gamma + \gamma \\ \xrightarrow{1/3} \; n + \pi^+ \longrightarrow \ldots \longrightarrow p + e^\pm + \nu_e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \end{array} \right.$$

- High energy γ-rays and neutrinos will be produced altogether !
- Several types of model:
  - Pp collisions: require very large ambient plasma density ($n_p > 10^9 cm^{-3}$) --> leads to (too) large total energy in AGN jets but may be alright in microquasar jets..
  - Photohadronic model: take into account either the internal synchrotron emission or the photon field produced by the accretion disk or both of them !

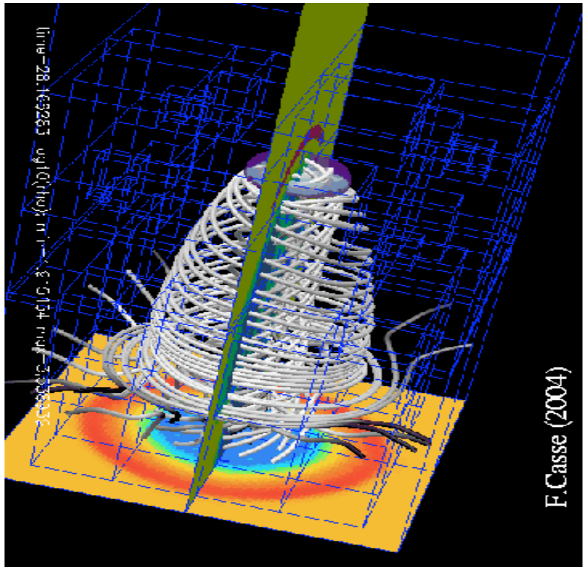
Neutrinos emission from jets

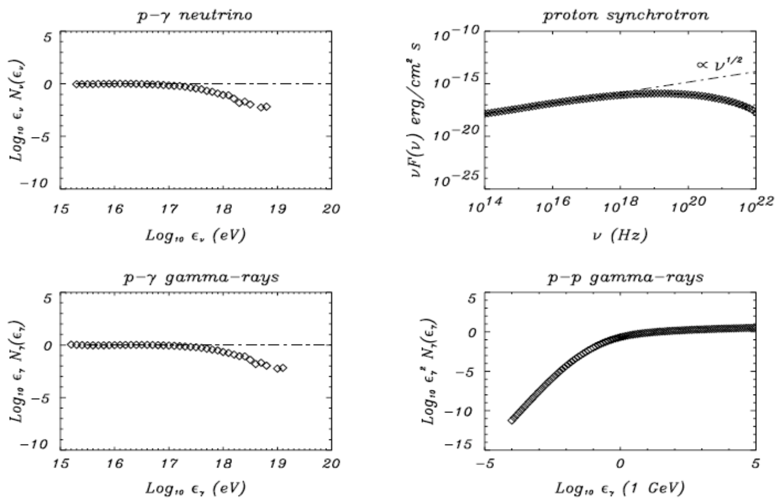
- Various authors have addressed the issue of UHE neutrino production doing different assumptions:
  - Heavy jets (high density protons) leading to dominant p+p collisions (e.g. Atoyan & Dermer, Schuster et al.,Heinz, Romero et al., etc..) --> the surrounding plasma density has to be large which is quite challenging for the jet launching in AGN..
  - Relativistic jet encountering a dense photon field (Stecker et al., Levinson & Waxman, Mannheim et al., Bednarek & Protheroe, Aharonian et al.,etc…).
- Both AGN and microquasars jets are believed to be optically thin to cosmic ray production, thus prone to the Waxman-Bahcall limit.
- Studies generally provides upper neutrinos flux around $E^2 \Phi_\nu \sim 10^{-8}$ *GeV/ cm*^{2} *s sr* which may be detectable by km^3 neutrino observatories --> stretching the parameters of the acceleration model and/or physical environnement ..
- Recent study have highlighted the impact of the jet strong magnetic field upon neutrino production attenuation (Reynoso & Romero 2009) --> Synchrotron cooling may affect π^{+-} and thus lead to strong attenuation of neutrino spectrum beyond 10 TeV in microquasars.

What about AGN hotspots ?

- AGN jet hotspots are quite large (L>1kpc), magnetized (B>0.1 mG) region emitting strong X-ray radiations in the vicinity of a shock.
- Computations linking MHD simulations to Fokker-Planck calculations provide cosmic ray and electron spectra with secondary particles produce by pp and pγ collisions.
- Some hotspots (e.g. 3C273A) are able to accelerate particle up to 10^{20} eV.
- Neutrinos (up to 10^{18} eV) can be produce altogether with γ-rays.
- Nevertheless, hotspots are very diluted (n_p~$2x10^{-7}cm^{-3}$) and remote objects (> 50 Mpc) leading to a very weak neutrino flux

--> $E^2\Phi_\nu \sim 10^{-15}$ GeV/ cm² s





Casse & Marcowith (2005)

GW and microquasars

- Sudden accretion onto a black hole or a neutron star can lead to GW whose amplitude is

$$h \sim 10^{-20}\left(\frac{\delta m}{10^{-6}M_{\oplus}}\right)^{1/2}\left(\frac{f}{1kHz}\right)^{-1/2}\left(\frac{d}{1kpc}\right)^{-1}$$

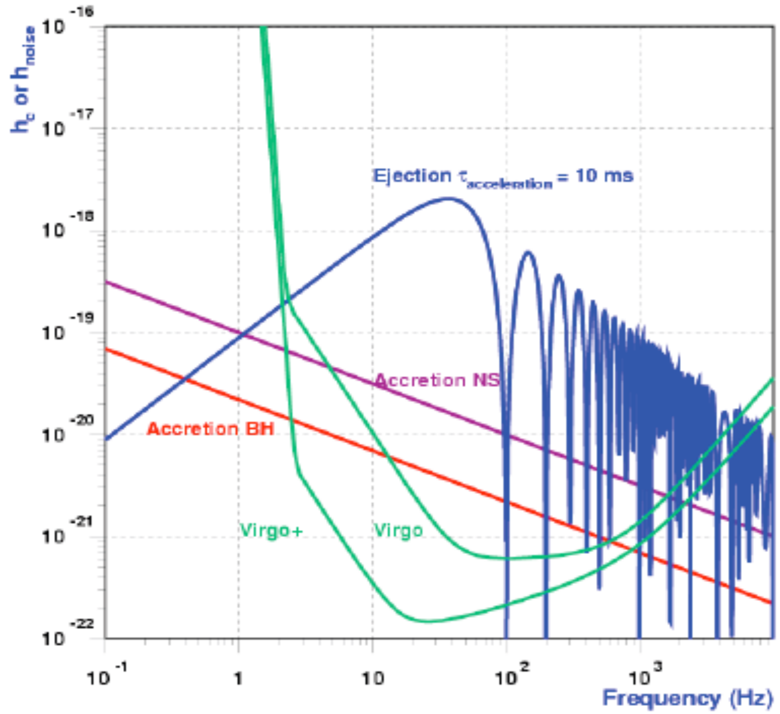
Price (1972)
Nagar et al.(2007)

- Such signal would be associated with extremely powerful outburst from the accretion disk (P_{ACC} ~ 10^{47} erg/s!!).
- Ejection of mass from a black hole can also generate GW whose amplitude is

$$h \sim 10^{-22}\left(\frac{\Gamma}{10}\right)\left(\frac{\delta m}{10^{-6}M_{\oplus}}\right)$$

Segalis & Ori (2001)

- Ejection must come from the black hole itself, which seems doubtful…



Pradier (2008)

Summary

- Detection of HE neutrinos coming from AGN and/or microquasars would have a tremendous impact on models dealing with the physics of ejection (nature of the relativistic flow, constraints on acceleration, magnetic field, etc…).
- It would also be a "smoking gun" for cosmic ray acceleration within these structures.
- The variability of the HE neutrino emission would also help to characterize the accretion process occurring near black hole (especially in microquasars where variability scales over short periods).
- Non-detection of HE neutrinos coming from AGN and/or microquasars would not be conclusive as it might be either because relativistic jets are leptonic or because the neutrino flux is too weak.
- GW detection from microquasars would be a huge surprise since it would imply accretion parameters far beyond what is expected -->It would also imply finding brand new ideas to explain the related catastrophic accretion onto black hole.