Radiative processes in high-energy astrophysics (with a focus on jetted AGN)

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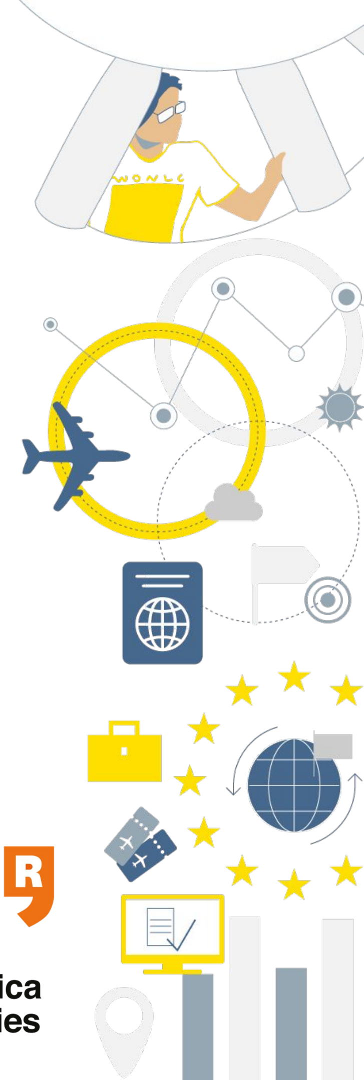
Astrophysics Data Camp at the University of Padova
Shaping a World-class University
Padova, 25-29 September 2023

Institut de Física d’Altes Energies



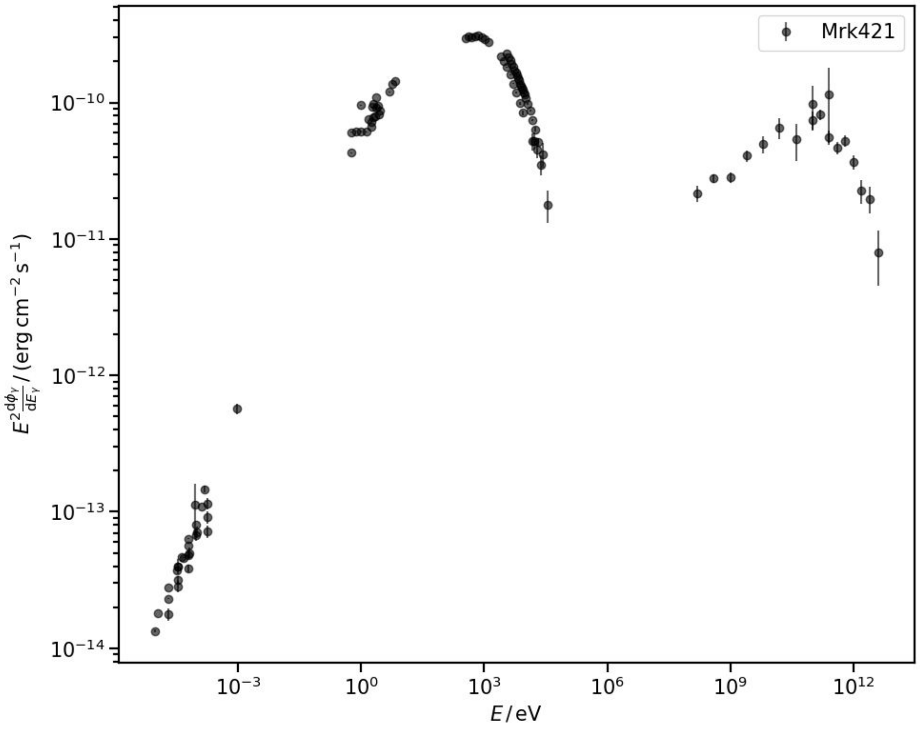
Overview and aim

This talk and the following hands-on session aim at:

> make you familiar with the state of matter in astrophysical environments and with the mechanism of particle acceleration (**Part I**);

> make you aware of the possible emission mechanisms of particles accelerated in astrophysical environments (**Part II**);

> apply the previous notions to a particular class of sources: active galaxies with jets, and identify the particle populations and the emission mechanisms generating its broad-band emission from radio to gamma-rays (**Part III**).



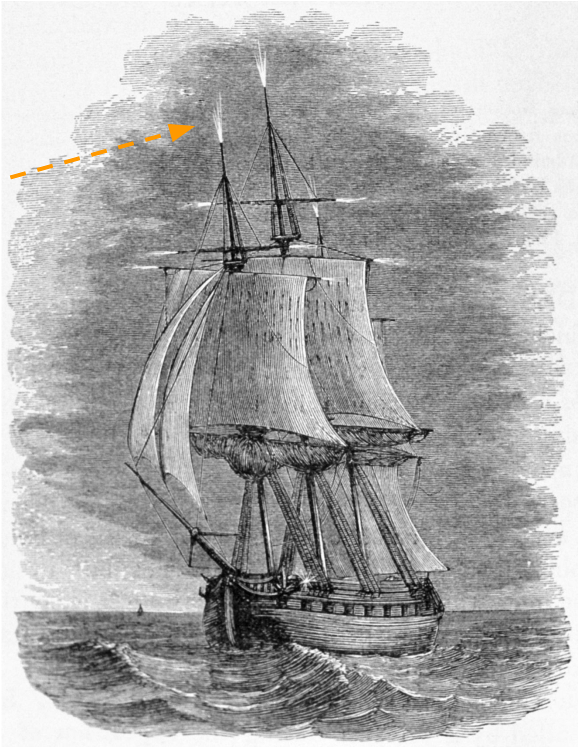
PROSPERO

Hast thou, spirit,
Perform'd to point the tempest that I bade thee?

ARIEL

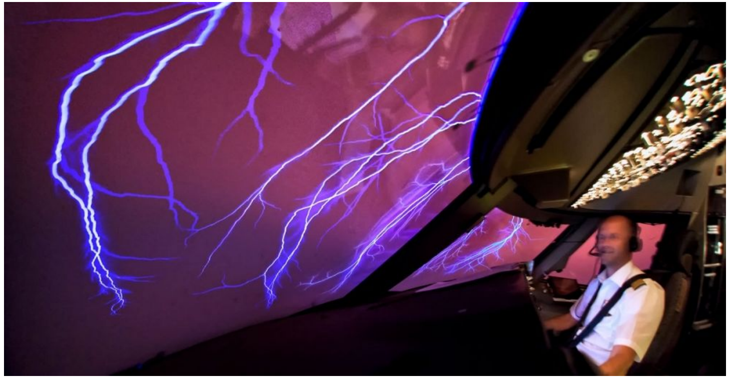
To every article.
I boarded the king's ship; now on the beak,
Now in the waist, the deck, in every cabin,
I flamed amazement: sometime I'd divide,
And burn in many places; on the topmast,
The yards and bowsprit, would I flame distinctly,
Then meet and join.

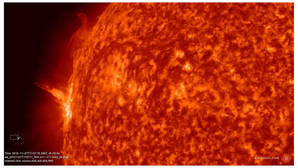
—Act I, Scene II, *The tempest*

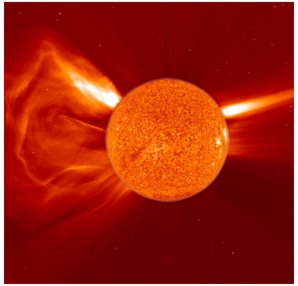


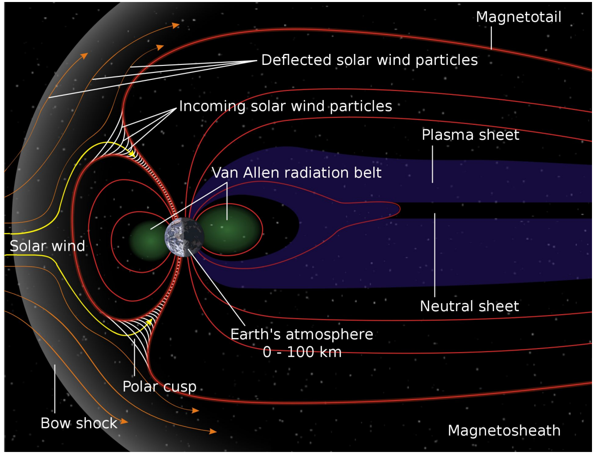
Part I
Plasma and particle acceleration

Plasma









> A plasma is an electrified gas with the atoms dissociated into positive ions and negative electrons:

$$\mathrm{H} \leftrightarrow \mathrm{p} + \mathrm{e}$$

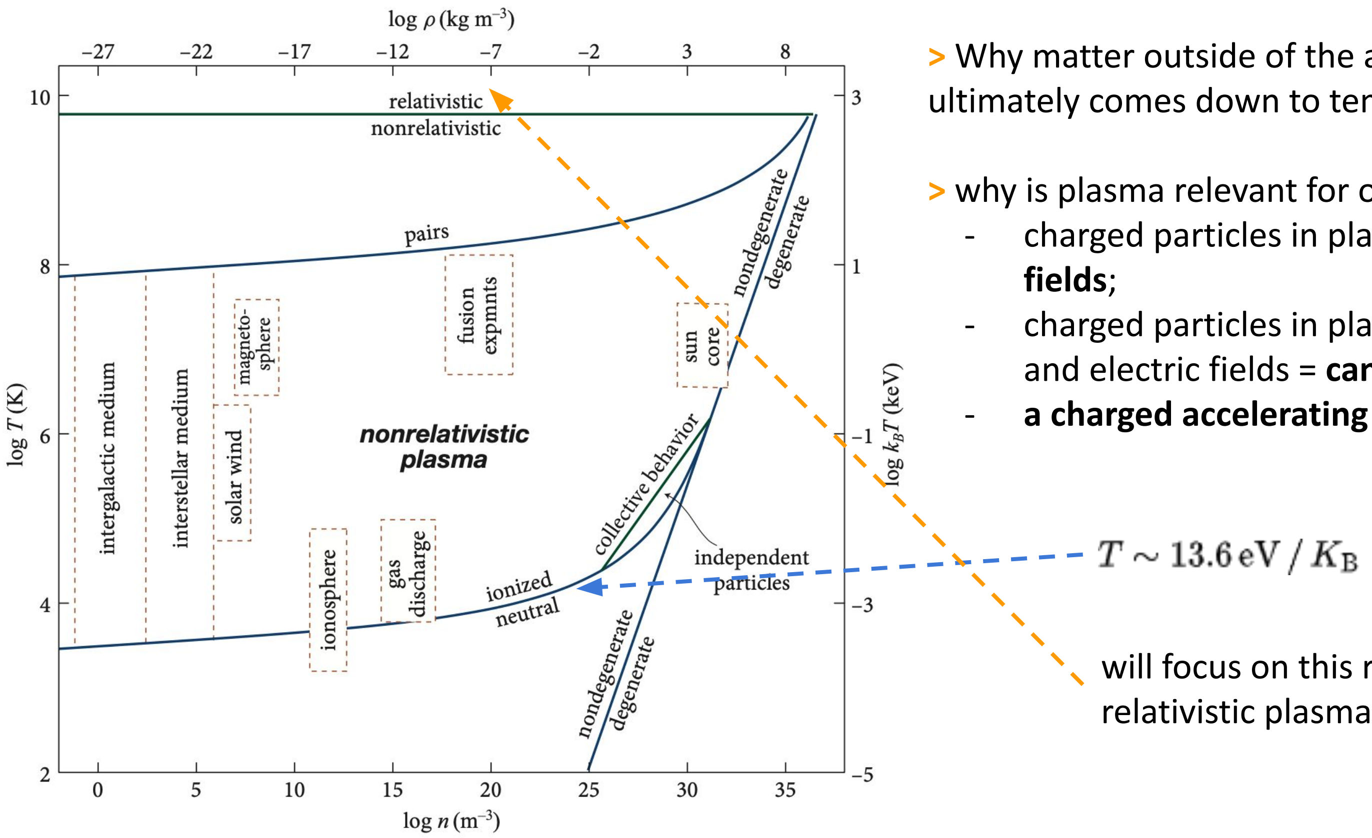
> **Question**: in the case of the hydrogen atom, how much energy do we need to separate p and e?

> On Earth, there are several natural occurrences of plasma (St. Elmo's fire, lightning, aurorae);

> leaving Earth's atmosphere we encounter **more and more matter in the state of plasma**: Earth's ionosphere and magnetosphere, solar winds, the sun and the stars, the interstellar and intergalactic medium;

> ultimately, **99% of the matter in the universe is in the state of plasma**.

Plasma

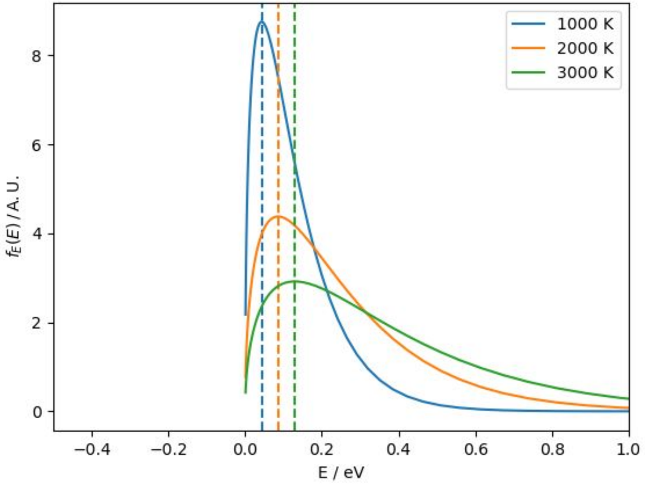


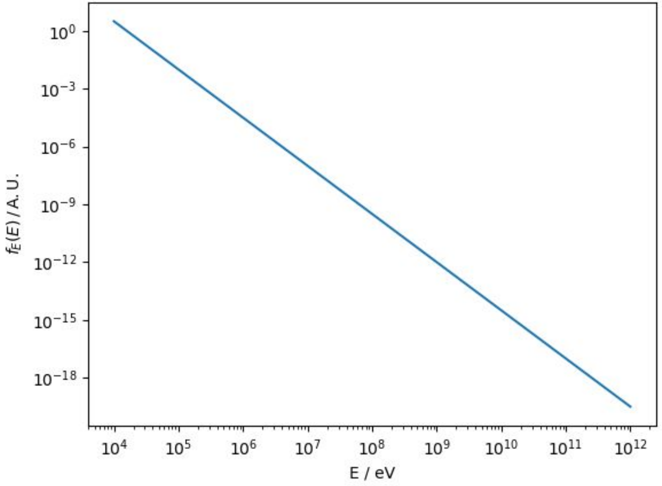
> Why matter outside of the atmosphere is ionised? It all ultimately comes down to temperature and density;

> why is plasma relevant for our astrophysical discussion?
- charged particles in plasma **can generate magnetic fields**;
- charged particles in plasma are subject to magnetic and electric fields = **can be accelerated**;
- **a charged accelerating particle radiates**;

will focus on this regime: relativistic plasma

Non-thermal particles distribution





> Thermal particles follow the Maxwell-Boltzmann distribution. T determines both the peak of the energy distribution and its width (rigorously in the velocity space)

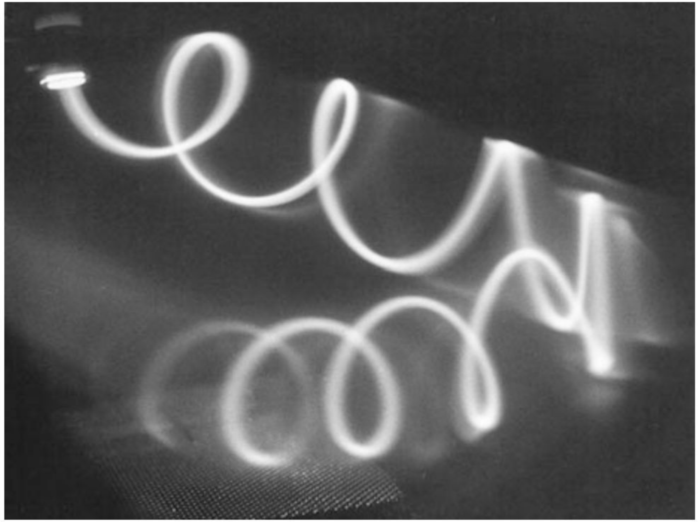
$$f_E(E) = 2\sqrt{\frac{E}{\pi}}\left[\frac{1}{kT}\right]^{\frac{3}{2}} \exp\left(-\frac{E}{kT}\right)$$

> relativistic particles accelerated in astrophysical sources display instead a power-law energy distribution

$$f_E(E) = k\left(\frac{E}{E_0}\right)^{-\Gamma}$$

> **Question**: which experimental evidence do we have of astrophysical power-law of particles?

Particle acceleration



reflection of an electron beam in a magnetic field converging (increasing) to the right

> Fermi's acceleration theory is **canonical as it naturally produces a power-law spectra for accelerated particles**;

> particles are accelerated by bouncing off "magnetic mirrors", regions, clouds, of plasma with increased B values;

> let us start with N_0 particles, each with energy E_0, that undergo *n* collisions. For each collision the energy of a particle increases of a factor ξ. At each collision the particles has a probability *P* to remain in the acceleration region. After *n* collision:

$$N = N_0 P^n \Rightarrow \ln(N/N_0) = n \ln(P)$$

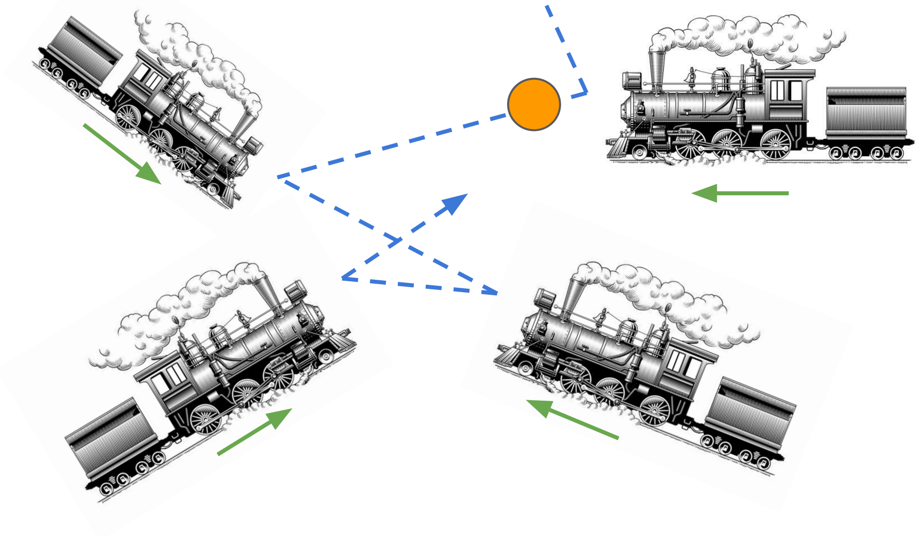
$$E = E_0 \xi^n \Rightarrow \ln(E/E_0) = n \ln(\xi)$$

dividing and manipualting the two: $N = N_0 \left(\frac{E}{E_0}\right)^{\ln(P)/\ln(\xi)}$

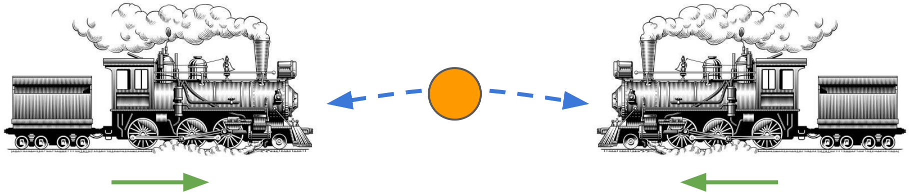
> the spectral index of the power-law will depend on the average energy gain and the containment (or escape) probability.

Particle acceleration

> **II order Fermi acceleration**



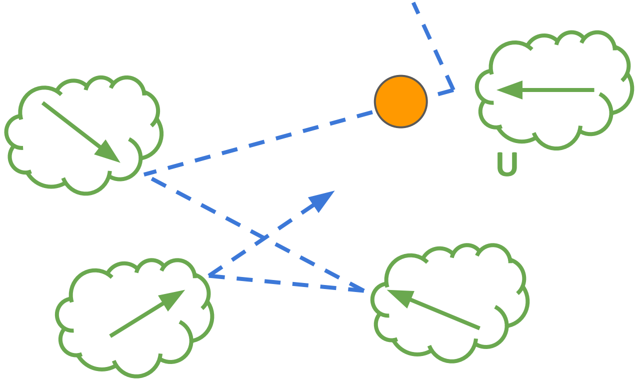
> **I order Fermi acceleration**



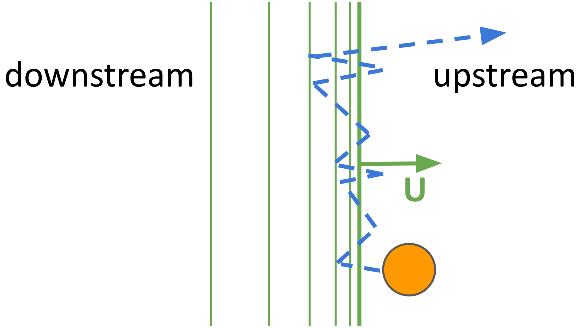
> **Question**: Let us consider this analogy from mechanics. Which of the two balls is more efficiently accelerated?

Particle acceleration

> **II order Fermi acceleration (clouds)**



> **I order Fermi acceleration (shock)**



> For a particle of velocity ***v***, colliding at an angle θ with a scatterer of velocity ***U***, we obtain in the reference frame of the observer:

$$\Delta E = E - E_0 = \left[2\frac{Uv}{c^2}\cos\theta + 2\left(\frac{U}{c}\right)^2\right]E_0$$

<u>II order</u>: the first term goes to 0 (we average cosine over all angles) and we obtain

$$\frac{\Delta E}{E} \approx \frac{8}{3}\left(\frac{U}{c}\right)^2$$

<u>I order</u>, we only have head-on collisions ($\cos\theta$ > 0). For v=c the first term dominates: we obtain

$$\frac{\Delta E}{E} \approx \frac{4}{3}\frac{U}{c}$$

> e.g. for a scatterer moving at U=10 km/s, the ΔE/E~10^{-7} for the I order and ΔE/E~10^{-4}.

> shock acceleration is more efficient and the velocities of the shocks are even higher than this example ~10^4 km/s

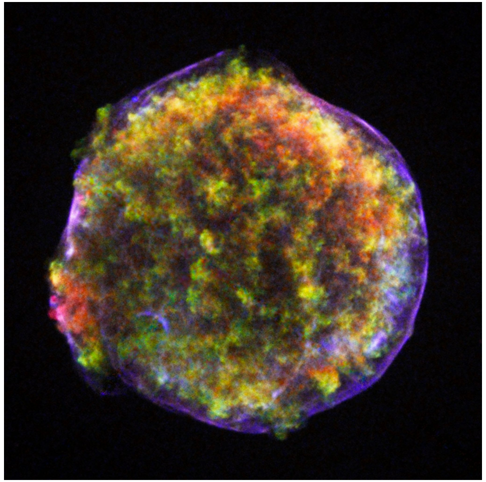
Recap of part I:

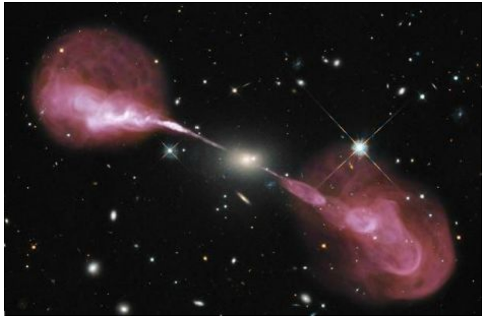
Let us write it together in a few points:

> **plasma as electrified gas in astrophysical sources**

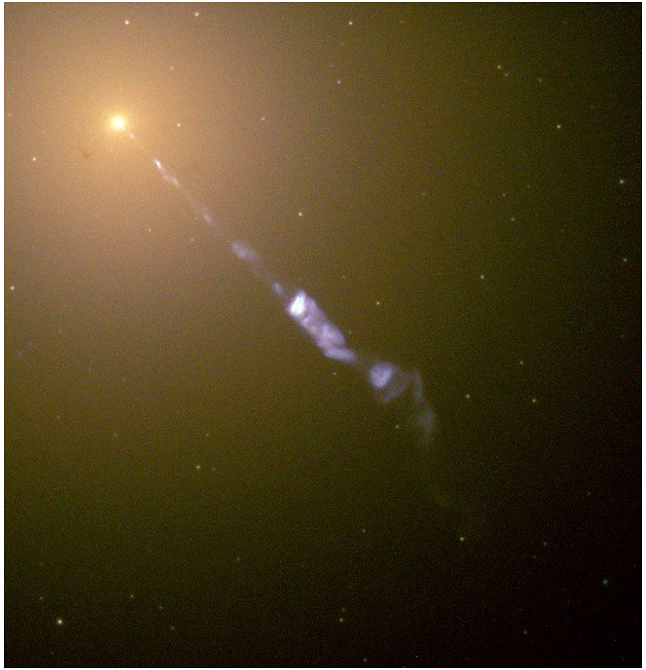
> **power-law distributions of particles in astrophysical sources, derived it**

> **acceleration by magnetic scattering**

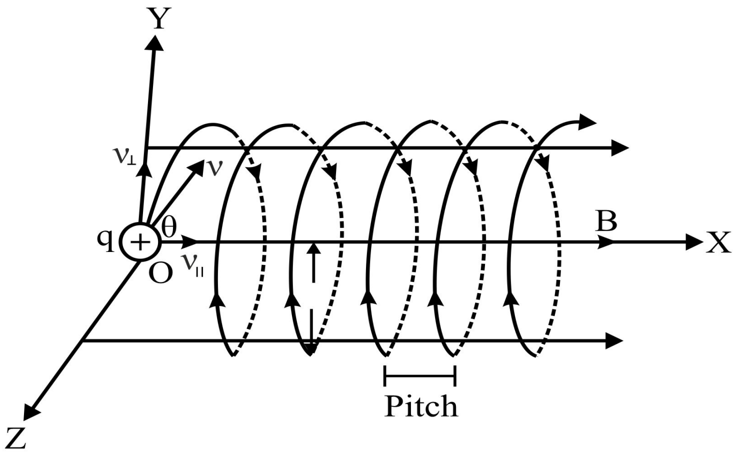


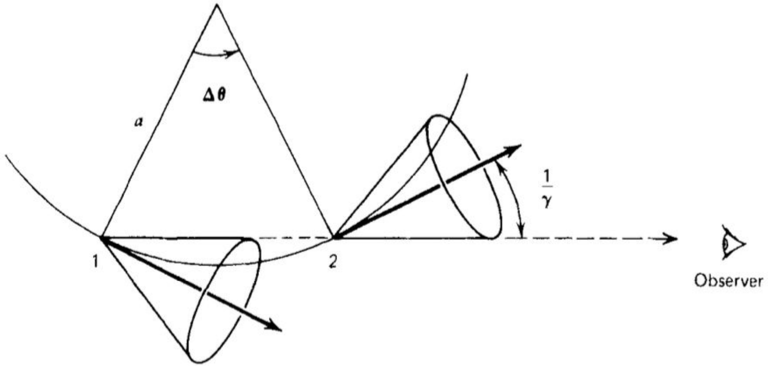


Part II
Radiation of accelerated particles



Synchrotron radiation





> A particle with velocity ***v*** enters a region of magnetic field ***B***, which frequency can we associate to this motion?

$$\frac{\mathrm{d}}{\mathrm{d}t}(\gamma m\vec{v}) = \frac{q}{c}\vec{v} \times \vec{B}$$

$$\frac{\mathrm{d}v_\perp}{\mathrm{d}t} = \frac{qB}{\gamma mc}v_\perp \Rightarrow \frac{\mathrm{d}v_\perp}{\mathrm{d}t} = \omega_\mathrm{L} v_\perp$$

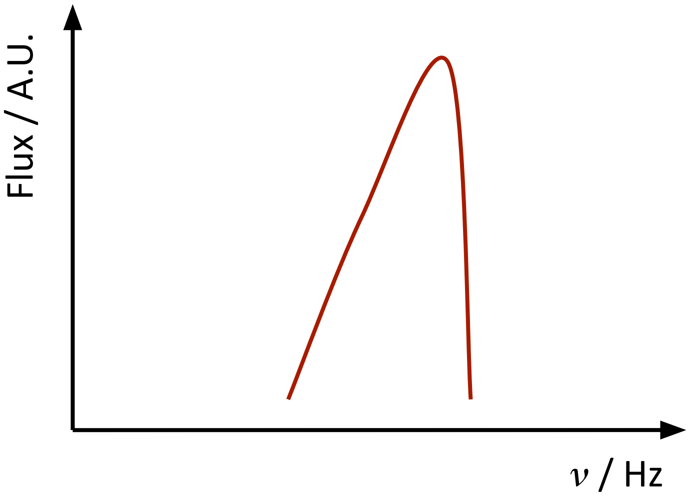
> where ω_B is the **Larmor** or **gyrofrequency**. **Question:** What type of motion does this equation on v describe? We can use the Larmor formula to compute the power:

$$P_\mathrm{synch} = -\langle\frac{\mathrm{d}E}{\mathrm{d}t}\rangle = \frac{4}{3}Z^4\left(\frac{m_e}{m}\right)^3 c\sigma_\mathrm{T}\left(\frac{B^2}{8\pi}\right)\beta^2\gamma^2 = \frac{4}{3}c\sigma_\mathrm{T}U_B\beta^2\gamma^2$$

> The radiation is relativistically beamed at an angle θ~$1/\gamma$, the resulting frequency of emission is Doppler-boosted, in case of electrons most of the emission will happen at:

$$\nu_\mathrm{synch\ peak} = \frac{eB}{2\pi m_e c}\gamma^2$$

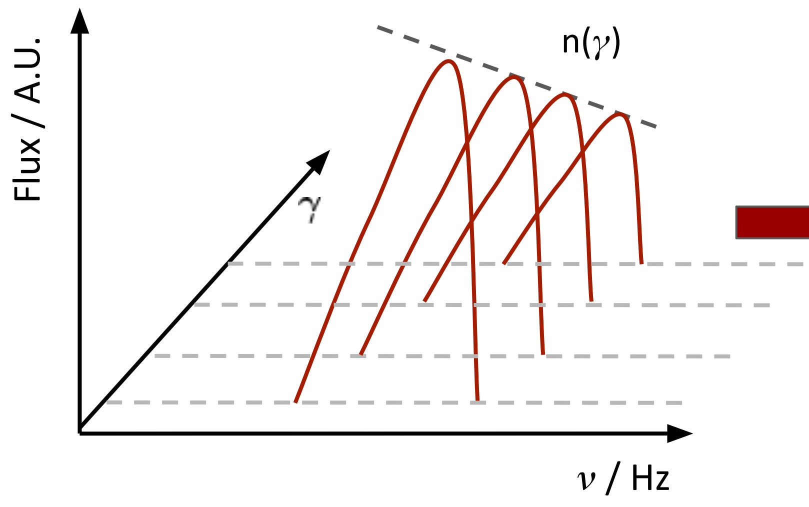
Synchrotron radiation

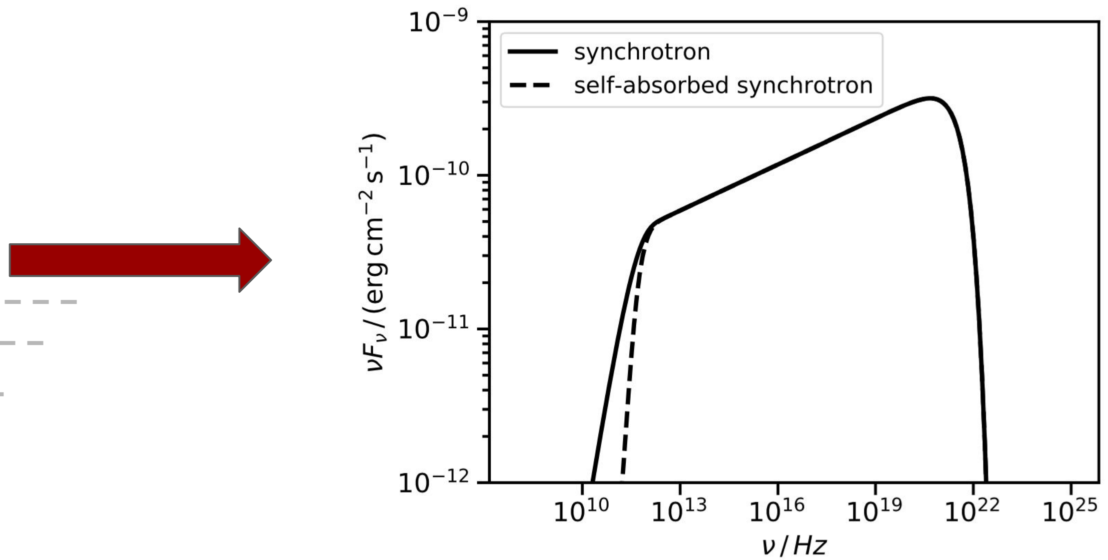


> Of course, a single particle will not emit at a single frequency, but will emit a synchrotron spectrum

$$P_{\text{synch s.p.}}(\nu, \gamma)$$

Synchrotron radiation





> Of course, a single particle will not emit at a single frequency, but will emit a synchrotron spectrum

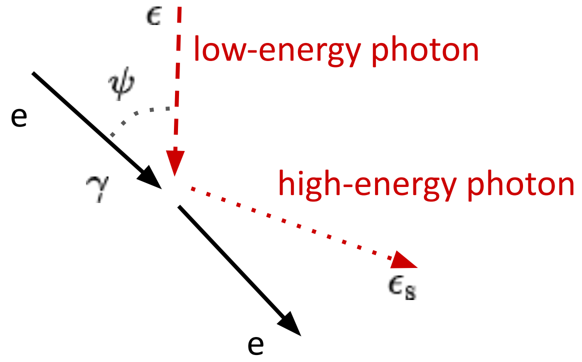
$$P_{\mathrm{synch\,s.p.}}(\nu, \gamma)$$

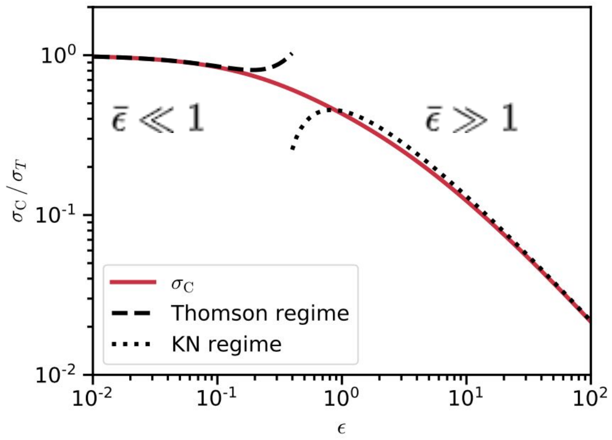
> But the Fermi acceleration gives us an <u>energy distribution</u> $n(\gamma)$, what should we do to obtain the synchrotron emission of the whole power-law of particles? Convolution:

$$P_{\mathrm{synch}}(\nu) \propto \int_0^\infty P_{\mathrm{synch\,s.p.}}(\nu, \gamma)\, n(\gamma)\, \mathrm{d}\gamma$$

(Inverse) Compton scattering

note, for photons: $\epsilon = E/(m_e c^2)$





> Reverse of the classical Compton scattering: a high-energy electron scatters a photon to higher energies (and loses its own energy in the process). The energy of the photon in the reference frame in which the electron is at rest is:

$$\bar{\epsilon} = \gamma\epsilon(1 - \cos\psi) \approx \gamma\epsilon$$

> this parameter defines two regimes of the Compton scattering

$\bar{\epsilon} \ll 1$

In the Thompson regime, we have basically Thomson (elastic) scattering. The photon is - in average - scattered with energy

$$\langle\epsilon_s\rangle = \gamma\bar{\epsilon} = \gamma^2\epsilon(1 - \cos\psi) \approx \gamma^2\epsilon$$

$\bar{\epsilon} \gg 1$

In the Klein-Nishina regime, the cross section is very low, the interaction has low probability, and the energy of the scattered photon is

$$\langle\epsilon_s\rangle = \gamma$$

(Inverse) Compton scattering

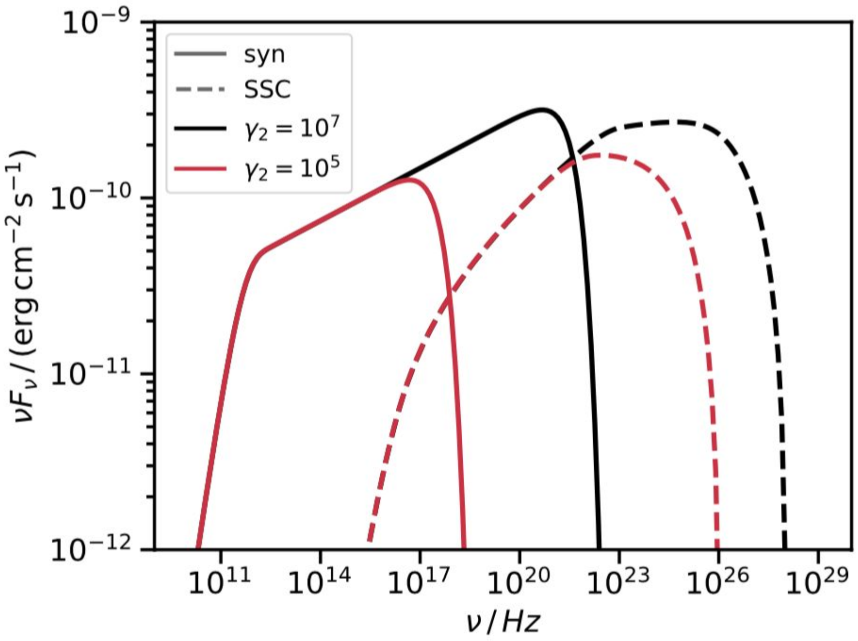
> But, in an astrophysical source, we have don't have a single electron scattering a single photon, we have a distribution of both

$$P_{\rm IC}(\epsilon, \epsilon_{\rm s}, \gamma) \propto \int {\rm d}\epsilon \, n_{\rm ph}(\epsilon) \int {\rm d}\gamma \, n_{\rm e}(\gamma) \frac{{\rm d}\sigma_{\rm C}}{{\rm d}\epsilon_{\rm s}}$$

> as an example, we can see as the synchrotron radiation is scattered by the very same electrons that produced it: *Synchrotron Self-Compton* scenario.

> in the Thomson regime, the energy losses have the same formula as the synchrotron ones, but changing the energy density in magnetic field with that in target radiation.

$$P_{\rm IC} = -\langle \frac{{\rm d}E}{{\rm d}t} \rangle = \frac{4}{3} c \sigma_{\rm T} u_{\rm rad} \beta^2 \gamma^2$$



Exercise:

> Consider an electron of energy 1 TeV scattering three different photons with energies 1 meV, 1eV, and 1 keV, respectively. Determine the following:

- in which regime each interaction is occurring (KN or Thomson);
- what is the energy of the scattered photon in each case.

You can use astropy to speed-up the calculations.

Hadronic models (pp)

> Gamma rays can of course be produced also by hadronic interactions

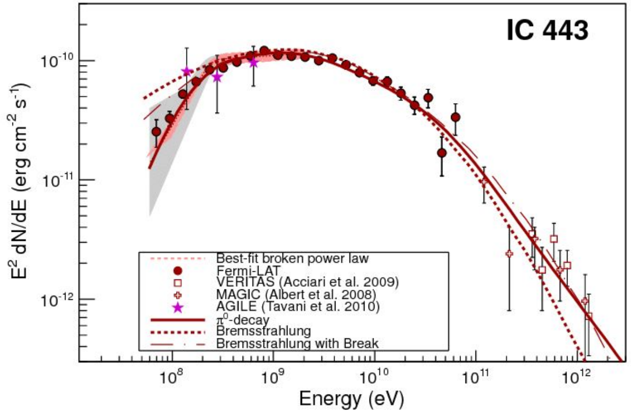
$$p + p \rightarrow \pi^{\pm}, \pi^0, K^{\pm}, K^0, \ldots$$

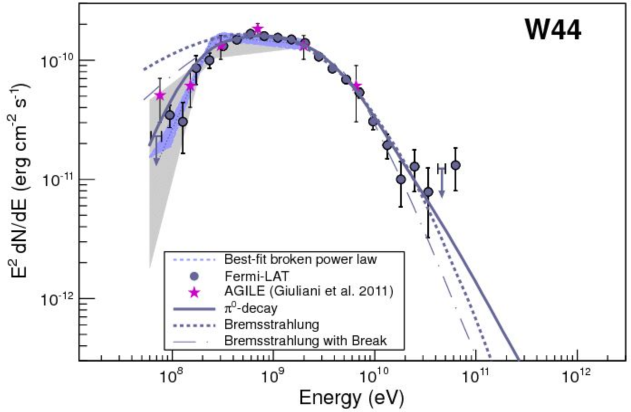
> pions then decay in 2 gammas:

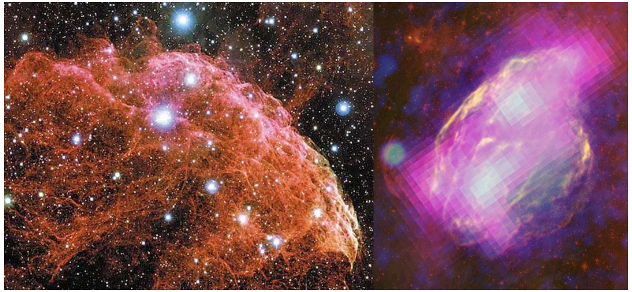
$$\pi^0 \rightarrow 2\gamma$$

> a major result of Fermi-LAT was the demonstration that the spectra of two SNR could be fitted with a π0-decay model;

> this works very well in SNR, which are surrounded by their dense ejecta. There is not enough matter around AGN to consider this interaction.







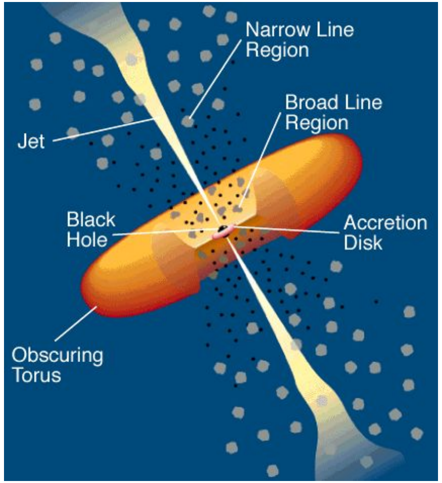
Hadronic models (pγ)

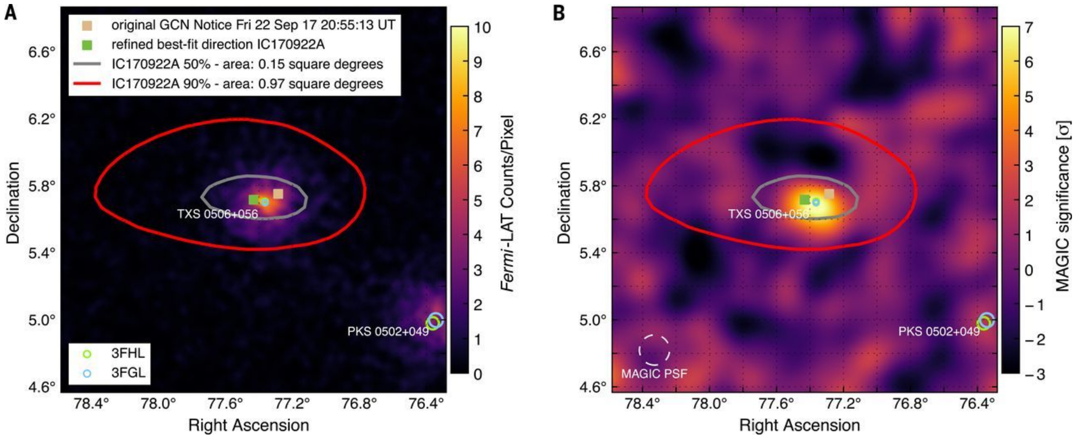
> The environment around jetted active galaxies is rich in photons, so pγ interactions are more often considered

$$p + \gamma \rightarrow \begin{cases} \text{photo-pion} & \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} & \sqrt{s} = (m_p + m_\pi)\, c^2, \\ \text{Bethe-Heitler} & p + e^+ + e^- & \sqrt{s} = (m_p + 2\, m_e)\, c^2, \end{cases}$$

> at the end of the decay chain of pions there are neutrinos. These models were re-discovered when an astrophysical neutrino was observed in coincidence with a flaring blazar.

Plenty of line/thermal emission





Recap of part II:

Let us write it together in a few points:

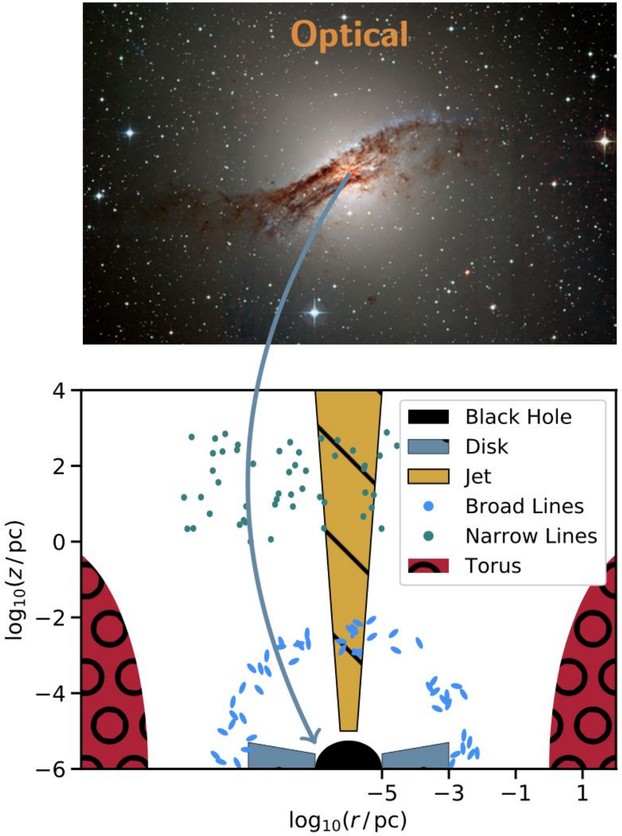
> two types of emission models: leptonic (electrons emission) + hadronic (proton emission);

> leptonic: synchrotron + inverse compton
Hadronic: pp, p-gamma (+neutrinos)

>

Part III
Broad-band emission of jetted AGN

Structure of a jetted AGN



> **Central Engine**

black hole, $M_{BH} > 10^5\ M_\odot^\dagger$

accretion disk ⇝ UV-peaking black body

$^\dagger M_\odot = 2 \times 10^{30}\,\mathrm{kg}$

> **Reprocessing Material**

central engine photoionisation ⇝ broad and narrow line regions

dust torus ⇝ IR-peaking black body

> **Jet**

relativistic plasma outflow ⇝ non-thermal emission, radio - gamma rays

→ $L_{\mathrm{obs}} = \delta_D^4\, L_{\mathrm{em}}$

→ maximum $\delta_D^\dagger$ $(\theta < 10°)$: *blazar*

$^\dagger \delta_D = [\Gamma_{\mathrm{jet}}(1 - \mathcal{B}_{\mathrm{jet}} \cos\theta)]^{-1}$

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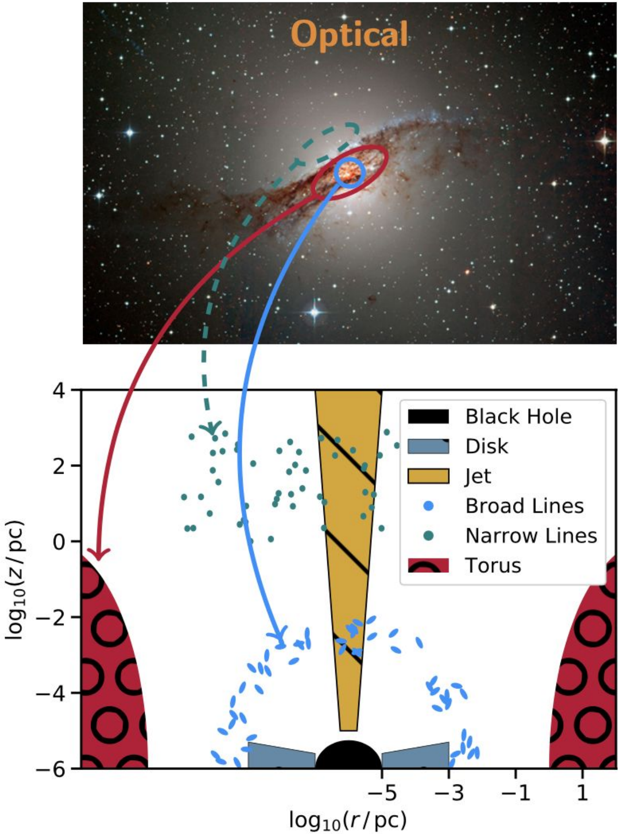

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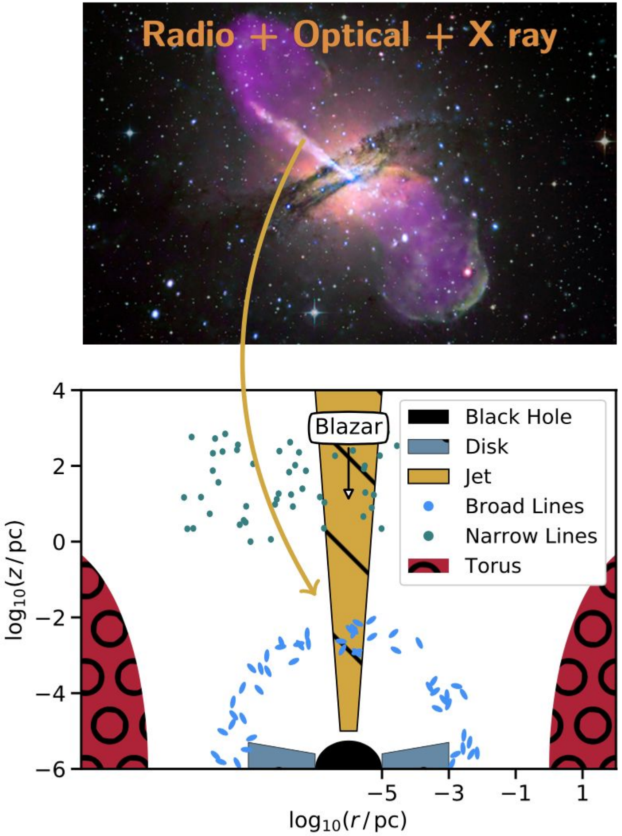

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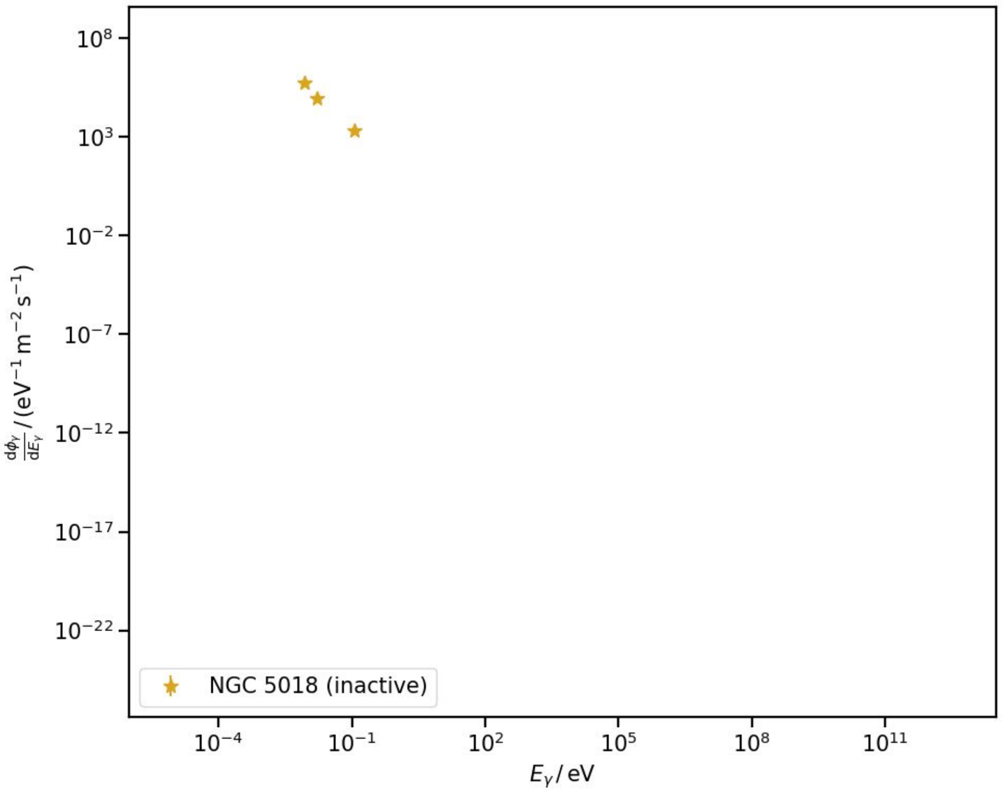
Broad-band emission of galaxies

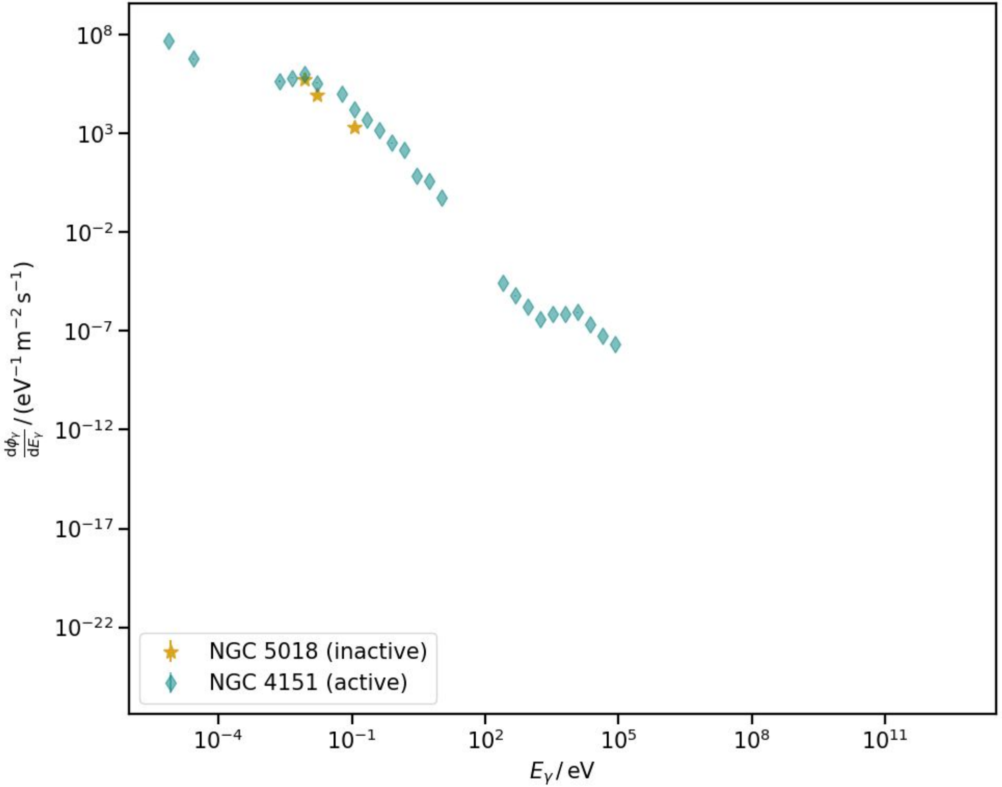


Normal galaxy:

> L < 10^{45} erg/s (10^{38} W);

> **thermal emission** (mostly in optical), cumulative emission of stars.

Broad-band emission of active galaxies



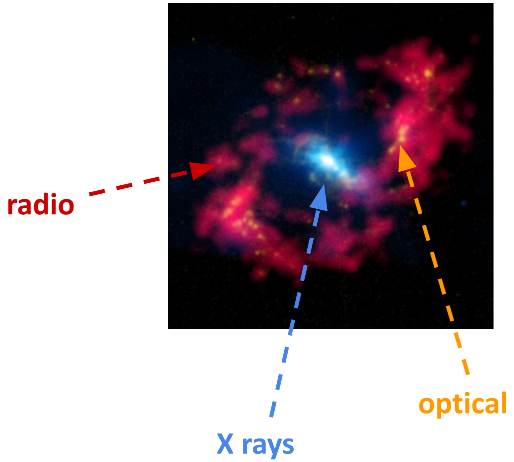
Active galactic nucleus (AGN):

> L ~ 10^{44}-10^{49} erg/s;

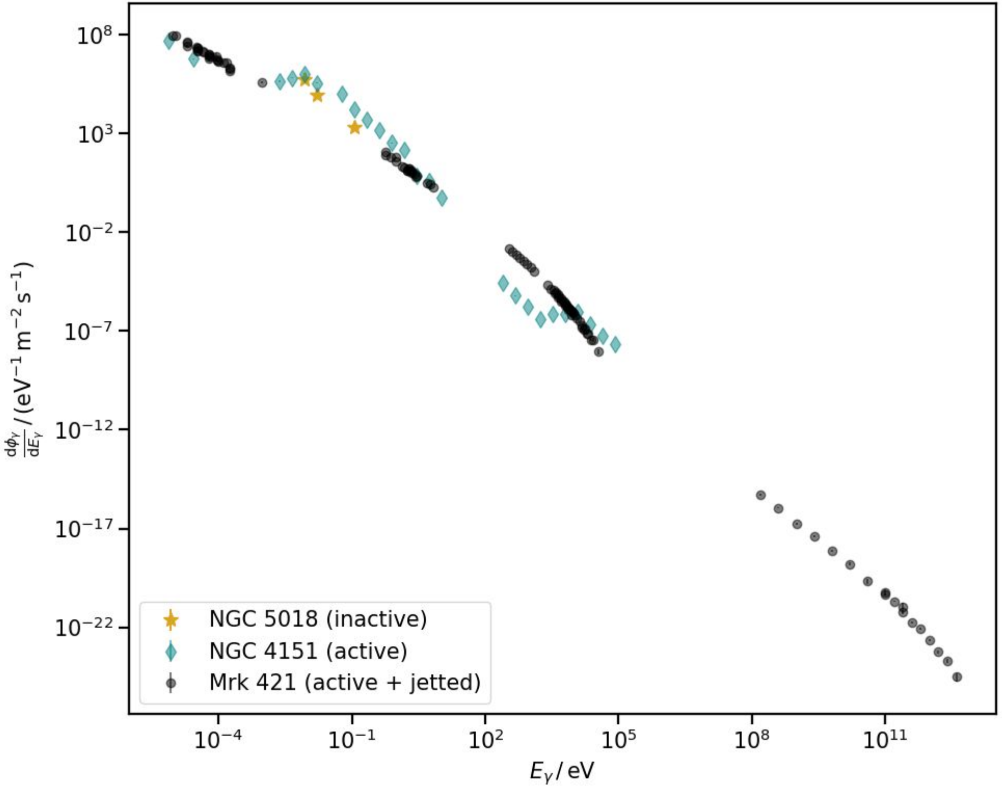
> **thermal emission** from black hole's (BH) accretion disk;

> **line emission** from ionised material orbiting BH;

> broadband emission from radio to X rays.



Broad-band emission of jetted active galaxies



Jetted AGN:

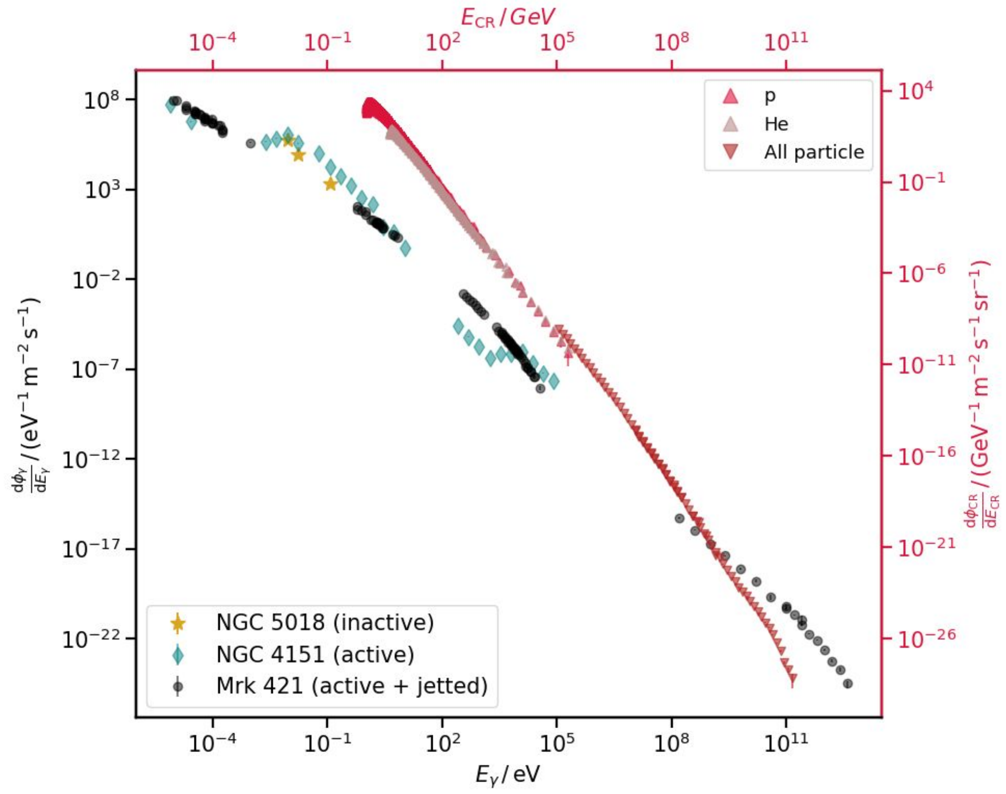
> $L \sim 10^{44}$-10^{49} erg/s;

> broadband **non-thermal emission** from the jet from radio to X rays;

> power-law emission $d\phi/dE \sim E^{-\Gamma}$;

radio optical X rays γ rays

Broad-band emission of jetted active galaxies



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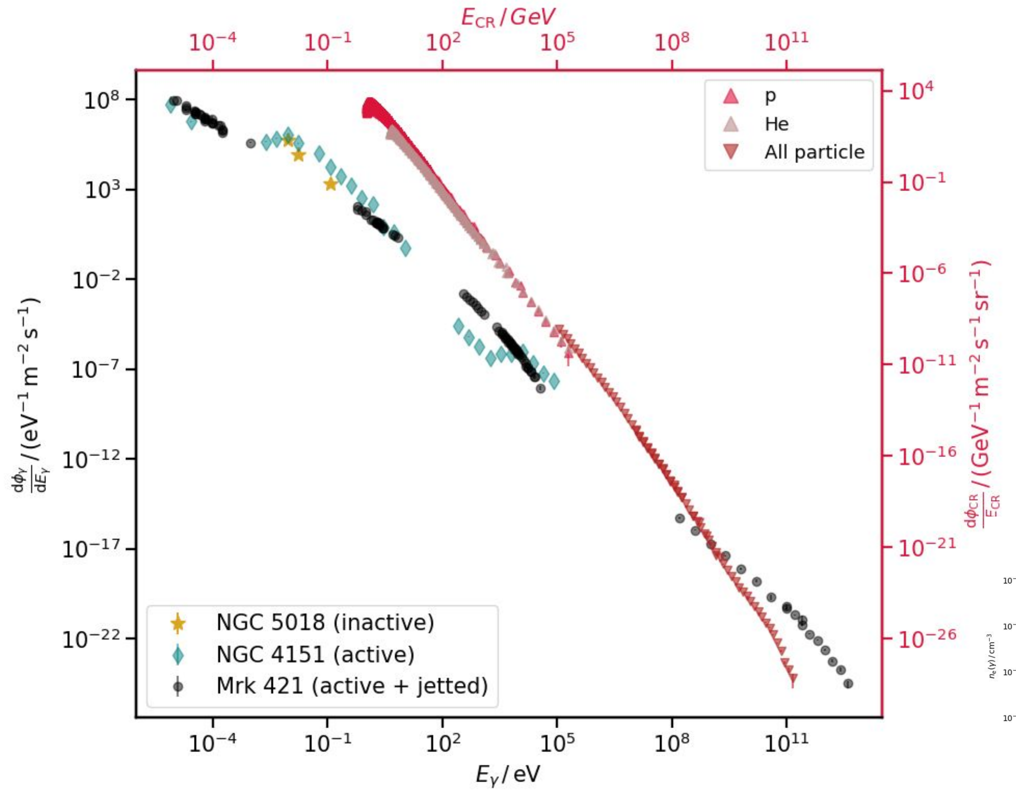

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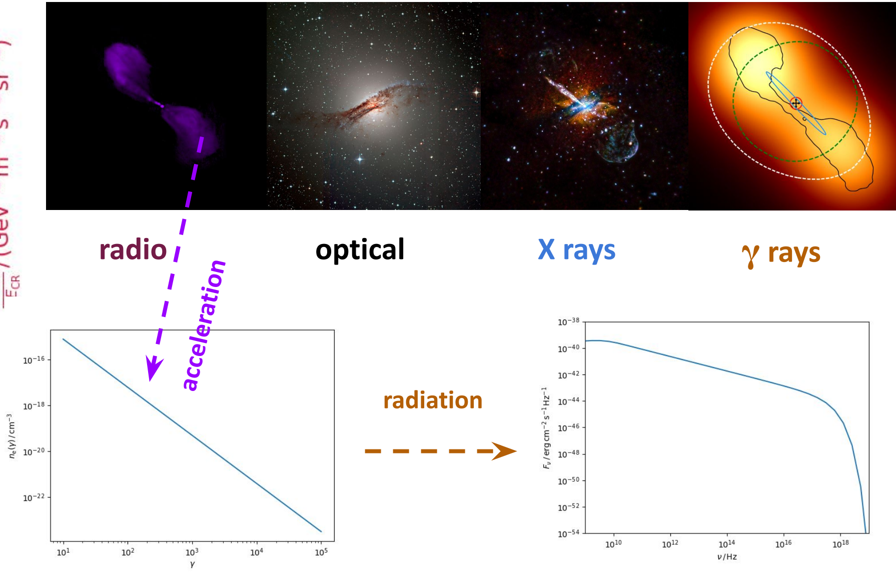
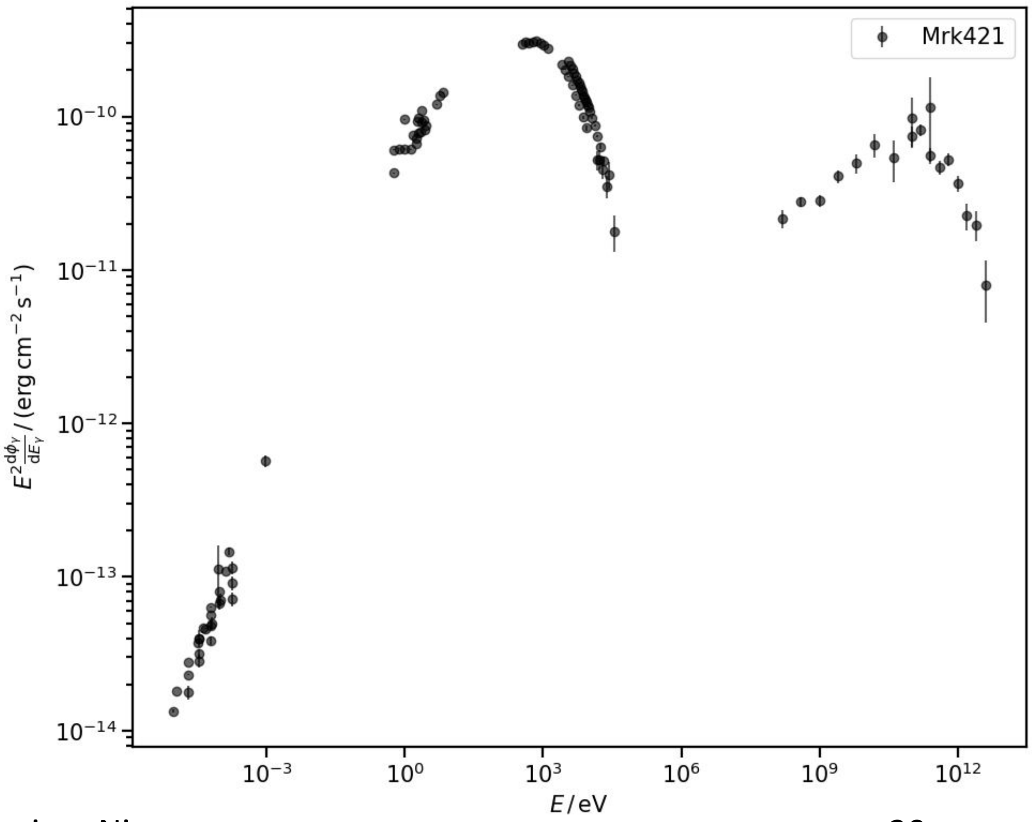
> broadband **non-thermal emission** from the jet from radio to X rays;

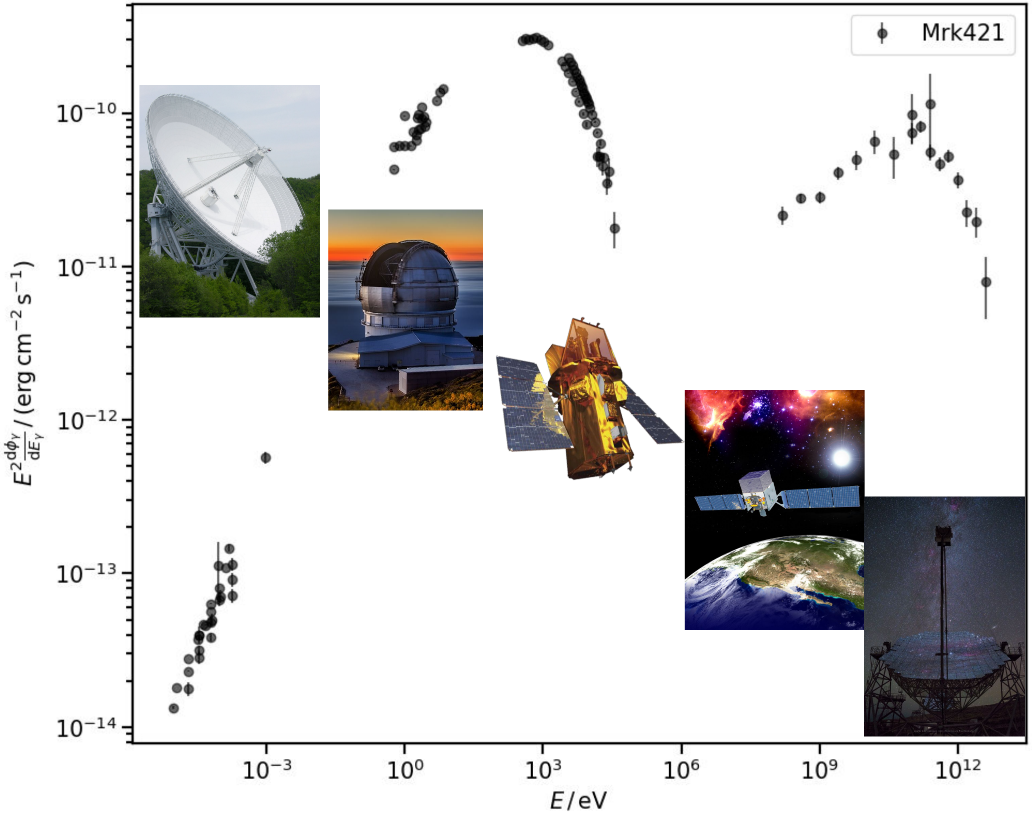
> power-law emission $d\phi/dE \sim E^{-\Gamma}$;



How do we measure their emission?

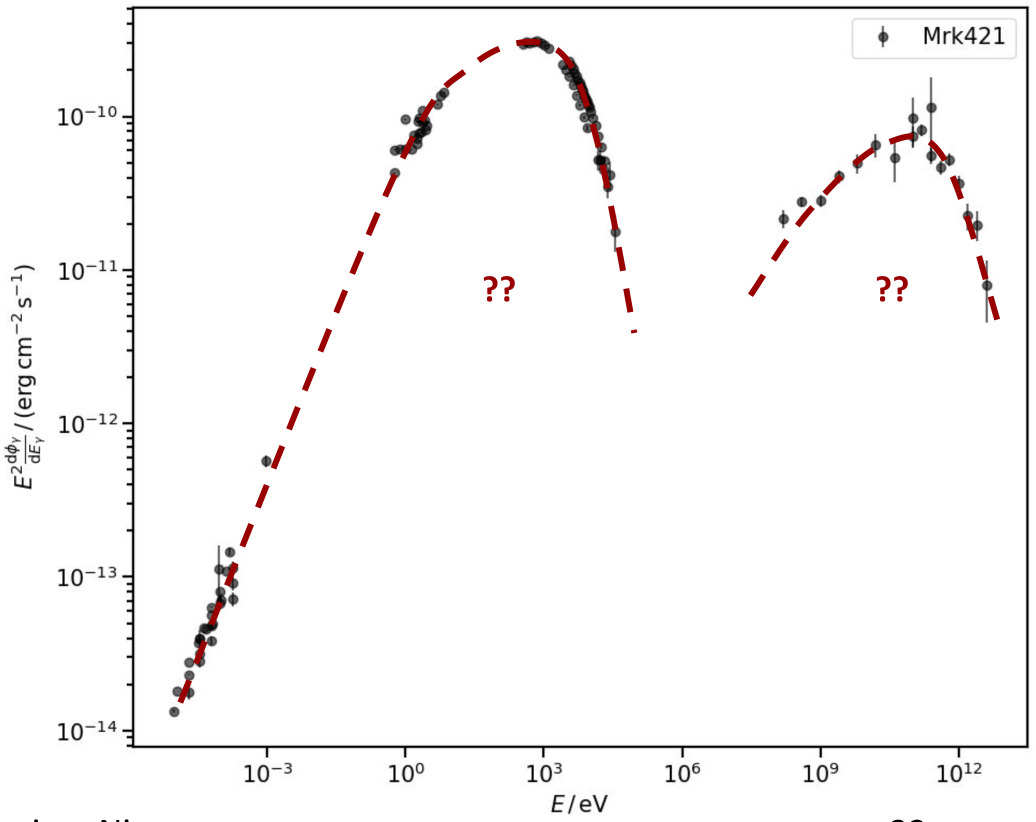


How do we measure their emission?



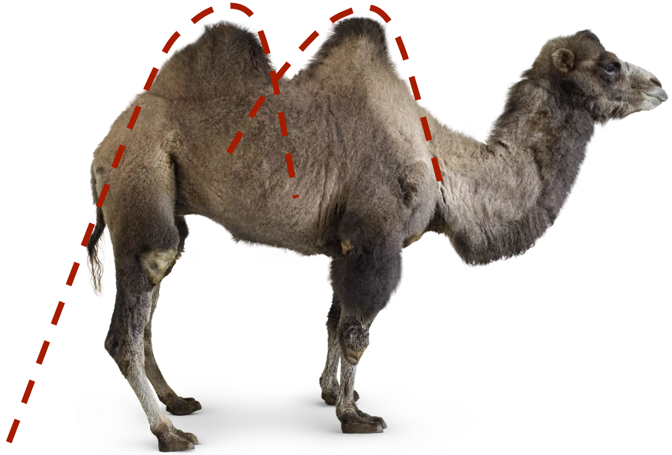
> Flux is measured by several instruments in different energy bands;

How do we interpret their emission?

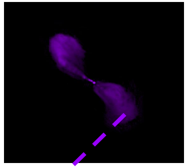


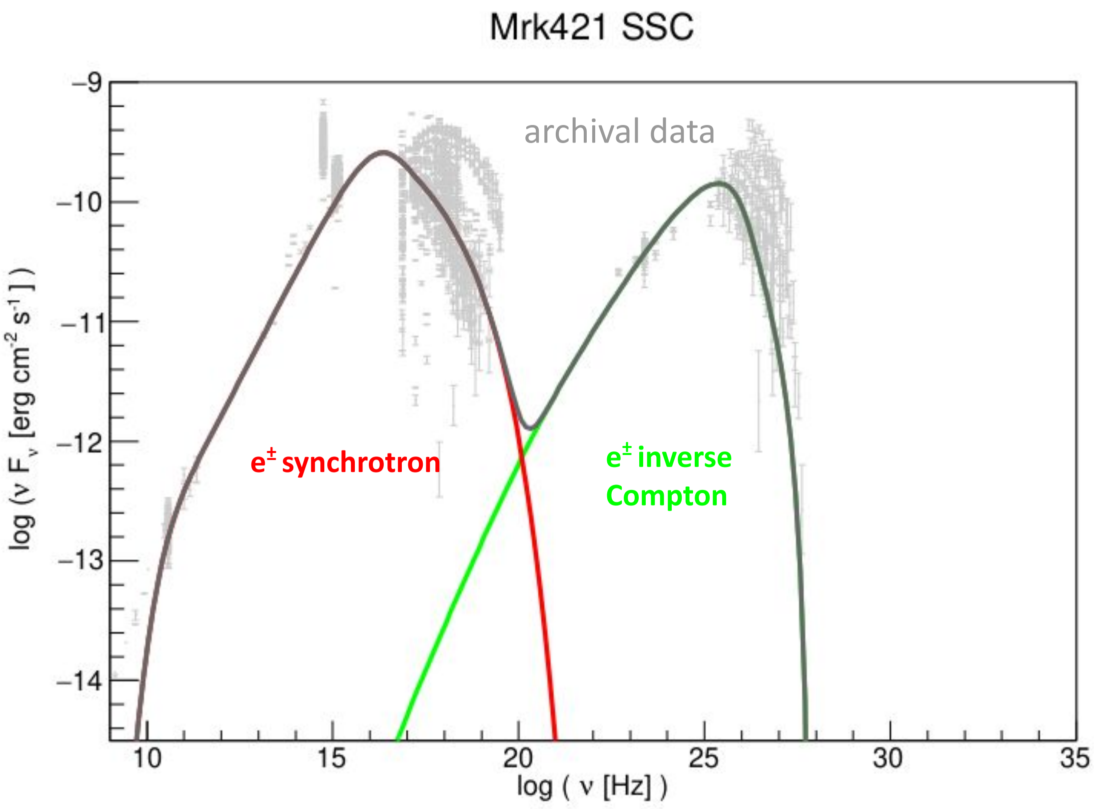
> Flux is measured by several instruments in different energy bands;

> Could you gess, from the spectra you have seen which processes are generating the two emission continua?



How do we interpret their emission? Leptonic model





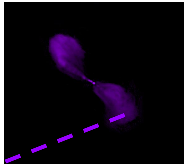
Electron-positron (electrons) plasma

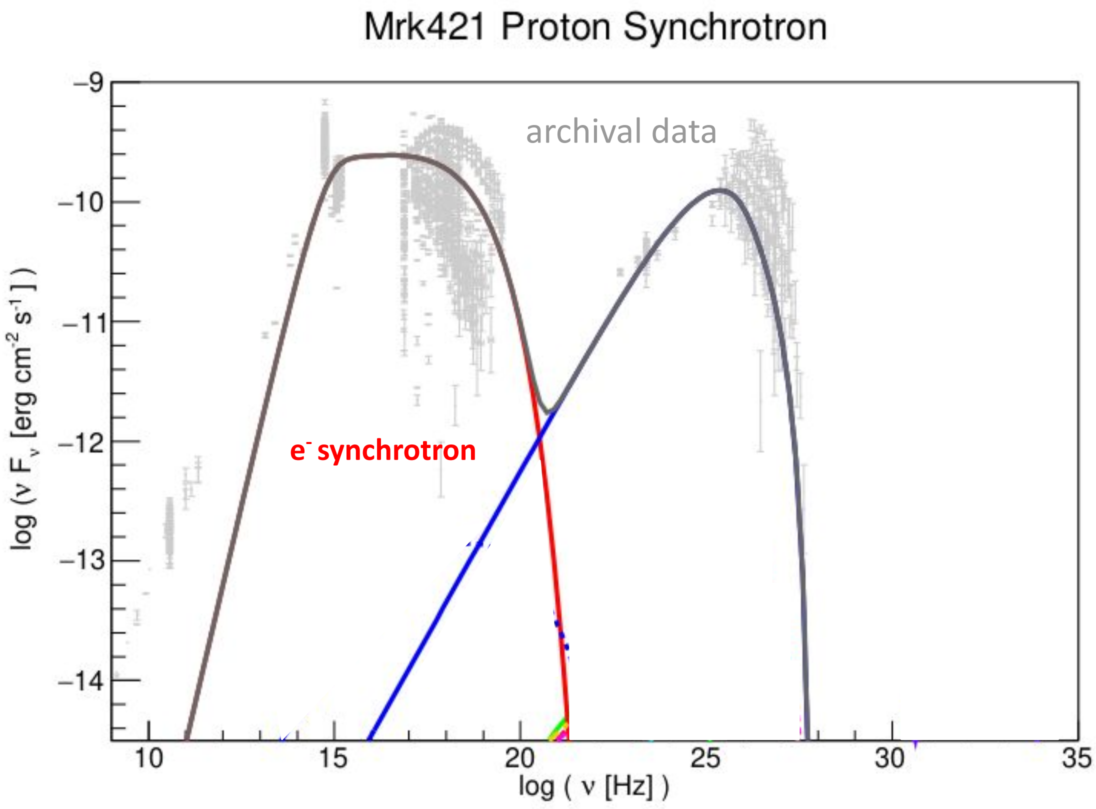
> The low-energy bump is the **synchrotron** radiation of the accelerated electrons;

> the high-energy bump is due to **inverse Compton** scattering by the electrons of their own synchrotron radiation (synchrotron self-Compton SSC);

> few observed properties (e.g. minute-scale flux variability) cannot be accommodated with this model.

How do we interpret their emission? Hadronic model

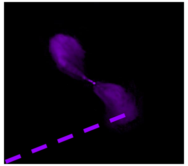


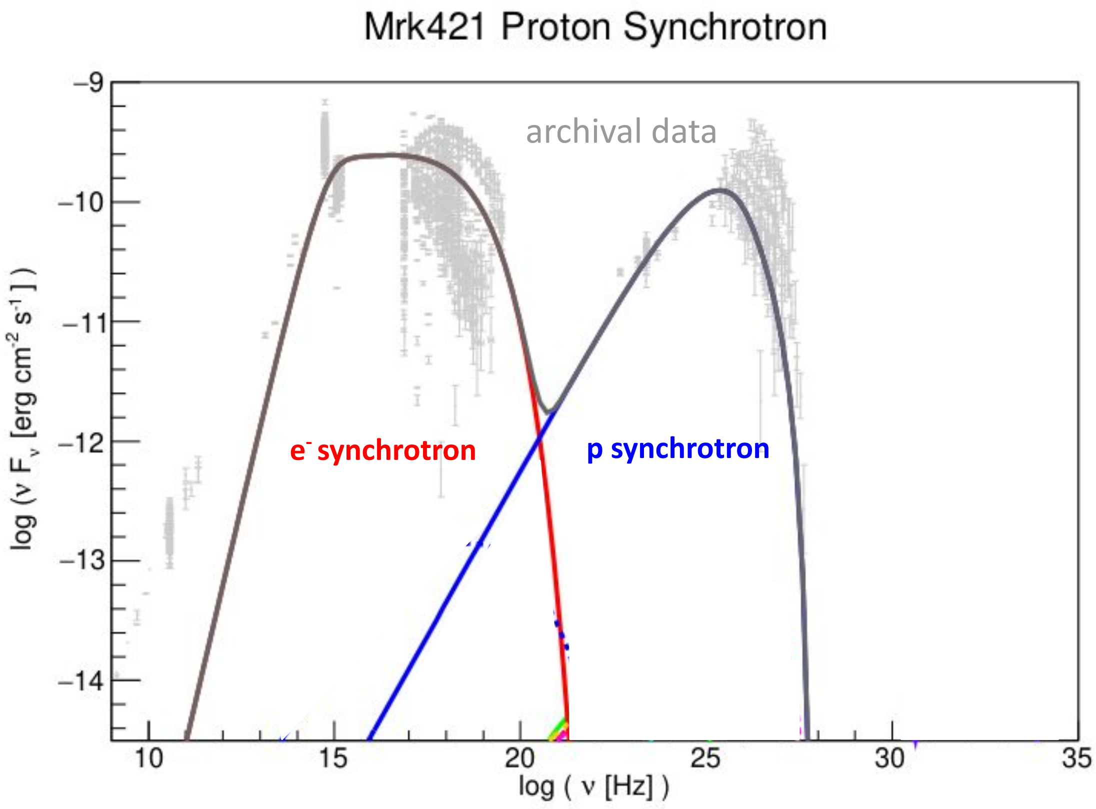


Proton-electron plasma

> The low-energy bump is still due to the **synchrotron** radiation of the accelerated **electrons**;

How do we interpret their emission? Hadronic model



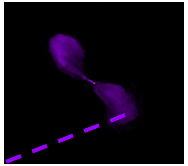


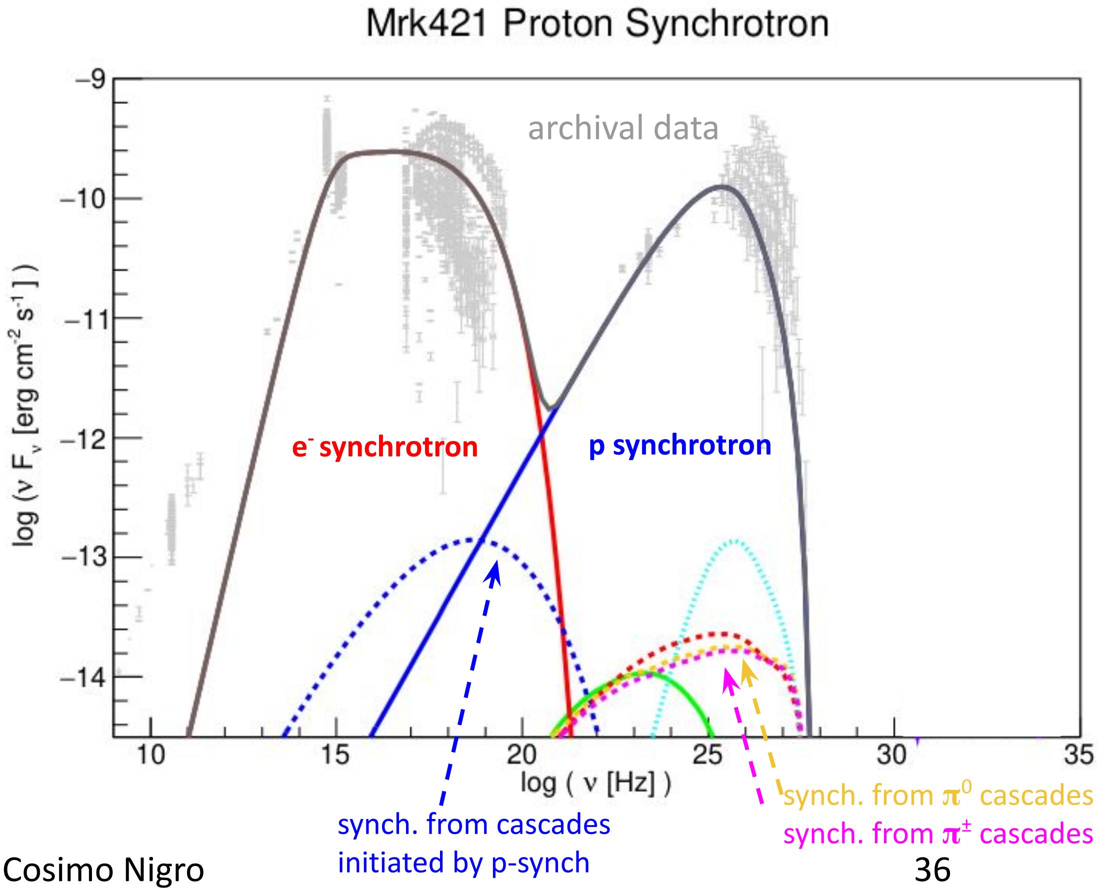
Proton-electron plasma

> The low-energy bump is still due to the **synchrotron** radiation of the accelerated **electrons**;

> the high-energy bump is due to **proton synchrotron** (but requires high values of B~10 G);

How do we interpret their emission? Hadronic model





Proton-electron plasma

> The low-energy bump is still due to the **synchrotron** radiation of the accelerated **electrons**;

> the high-energy bump is due to **proton synchrotron** (but requires high values of B~10 G);

> **proton-gamma interactions**:

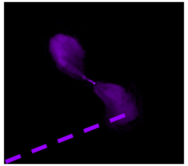
$p + \gamma \rightarrow p + \pi^0$

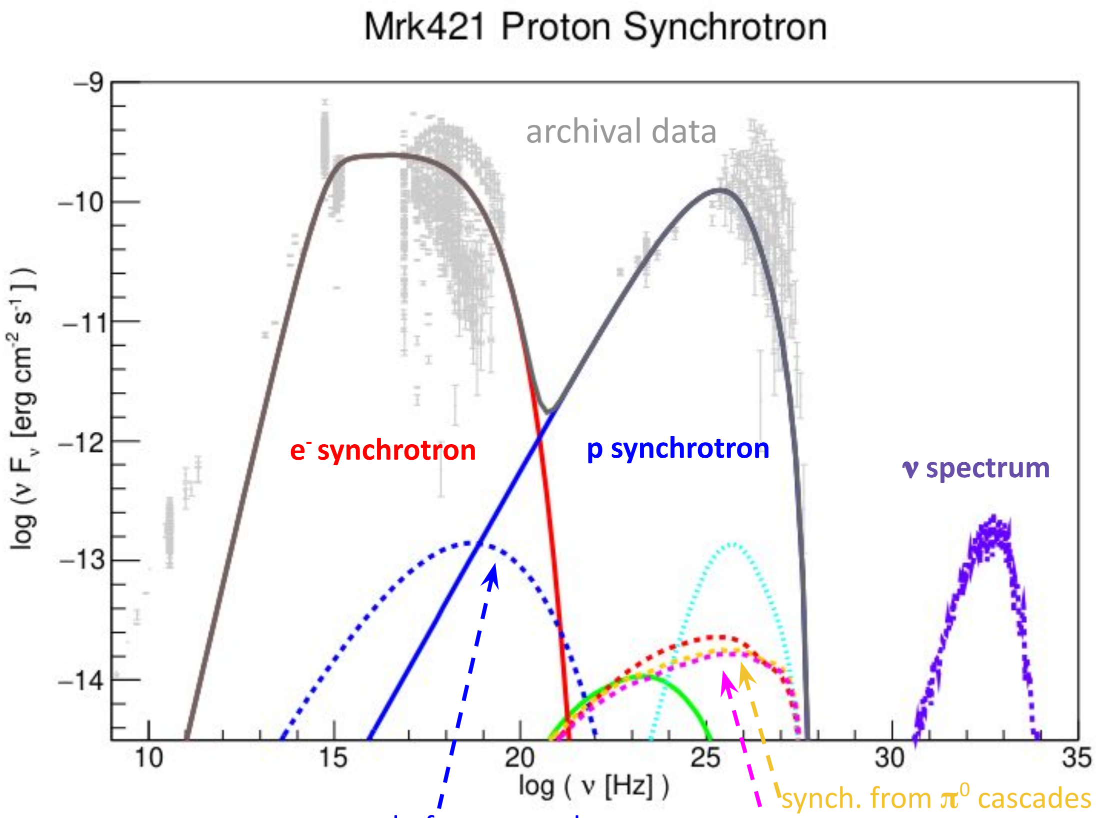
$n + \pi^+$

$p + \pi^+ + \pi^-$

produce mesons whose secondaries initiate particle cascades (that produce further radiation);

How do we interpret their emission? Hadronic model





Proton-electron plasma

> The low-energy bump is still due to the **synchrotron** radiation of the accelerated **electrons**;

> the high-energy bump is due to **proton synchrotron** (but requires high values of B~10 G);

> **proton-gamma interactions**:

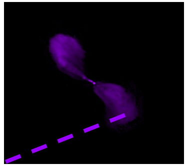
$p + \gamma \rightarrow p + \pi^0$

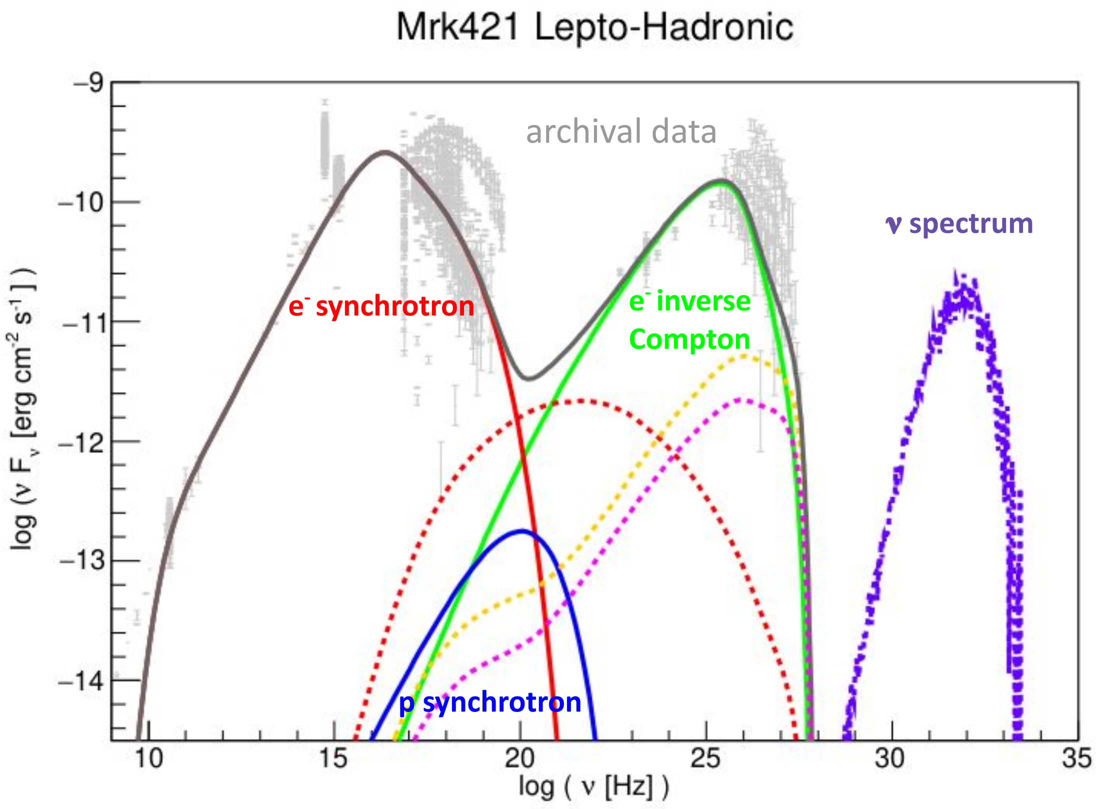
$n + \pi^+$

$p + \pi^+ + \pi^-$

produce mesons whose secondaries initiate particle cascades (that produce further radiation) and decay into **neutrinos!**

How do we interpret their emission? Leptohadronic model





Proton-electron plasma

> Same model as before but different part of the parameter space: **much lower B values** (< 1 G);

> **radiations by leptons dominant**, **radiation by pγ secondaries cascade subdominant**;

> leptonic model "loaded with hadrons".

Recap of part III:

Let us write it together in a few points:

> **AGN with jets: non-thermal emission; emit along a broader energy range;**

> **often SSC is considered, proton synchrotron feasible but with "unrealistic" B;**

> **mixed models with hadrons (subdominant components);**