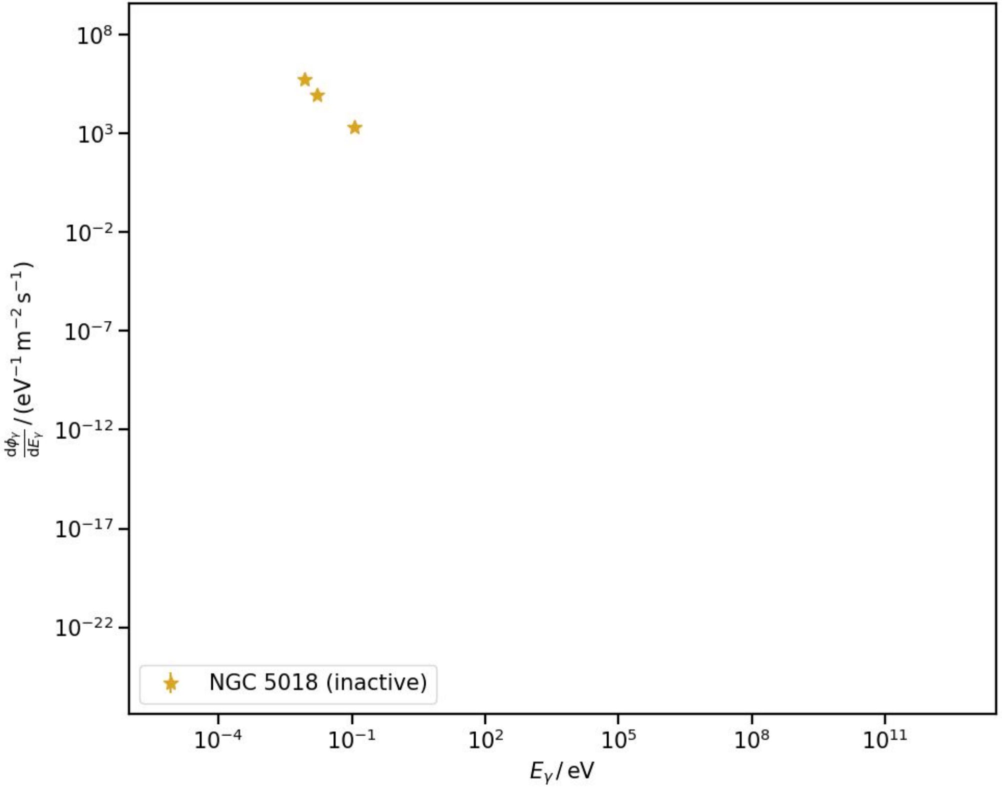
CAN OPEN-SOURCE SOFTWARE ADDRESS CRUCIAL ASTROPHYSICAL QUESTIONS?

The case of high-energy emission from jetted active galaxies

Cosimo Nigro
IFAE Pizza Seminar 9/11/2022

Broad-band emission of galaxies

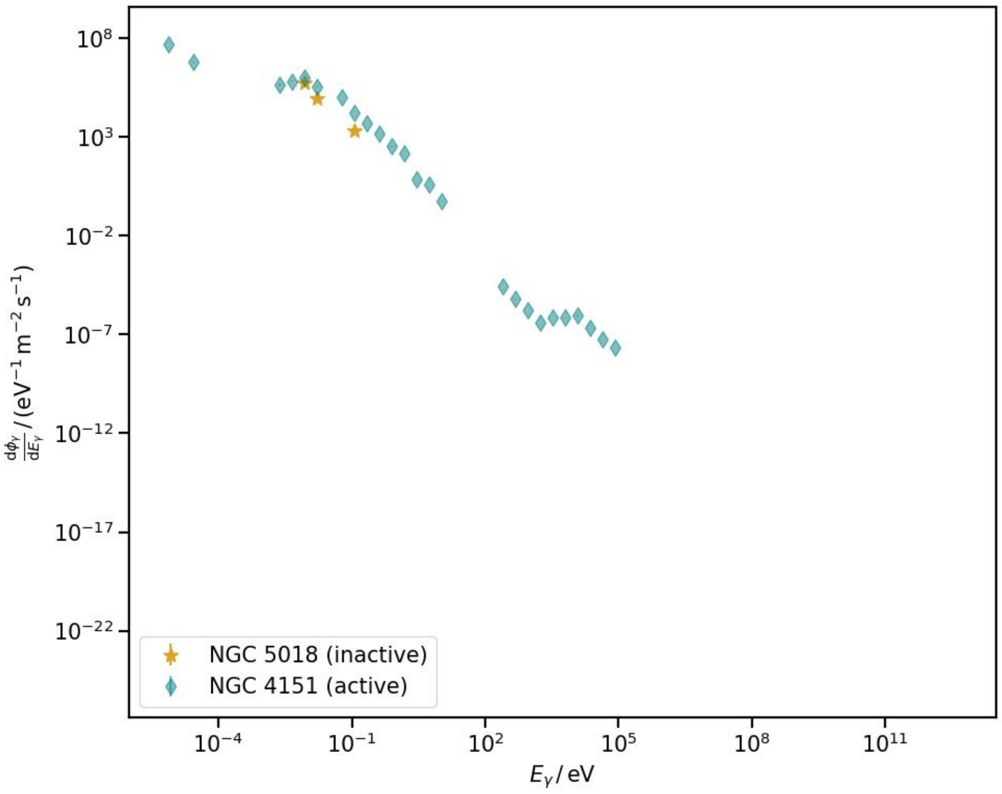


Normal galaxy:

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

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

Broad-band emission of active galaxies



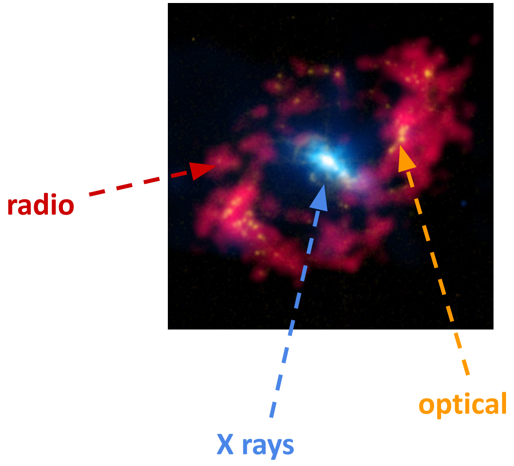
Active galactic nucleus (AGN):

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

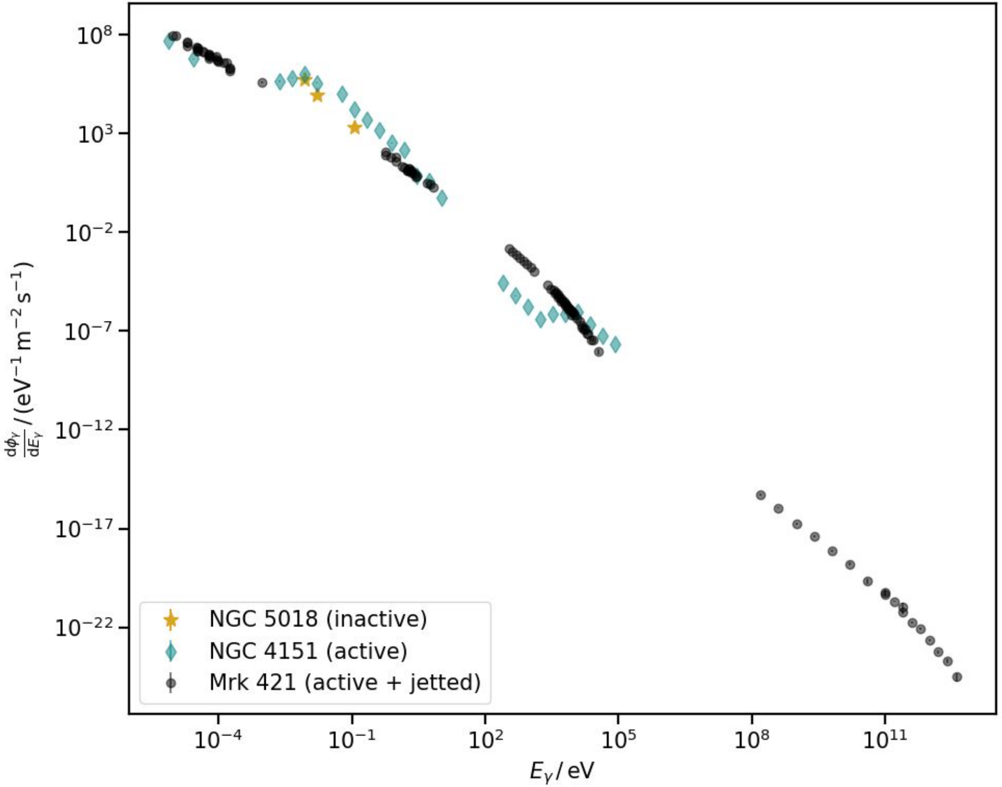
> **thermal emission** from black hole's (BH) accretion disk;

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

> broadband emission from radio to X rays.



Broad-band emission of jetted active galaxies



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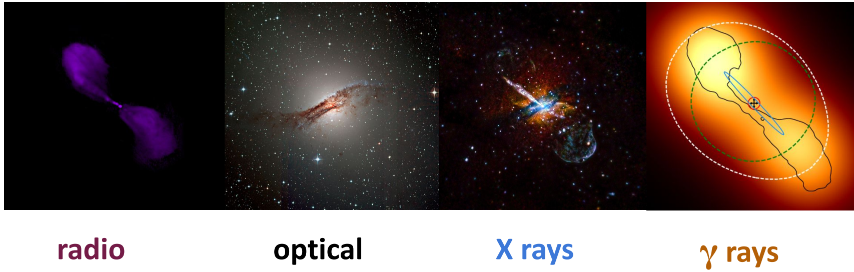
> power-law emission $d\phi/dE \sim E^{-\Gamma}$;



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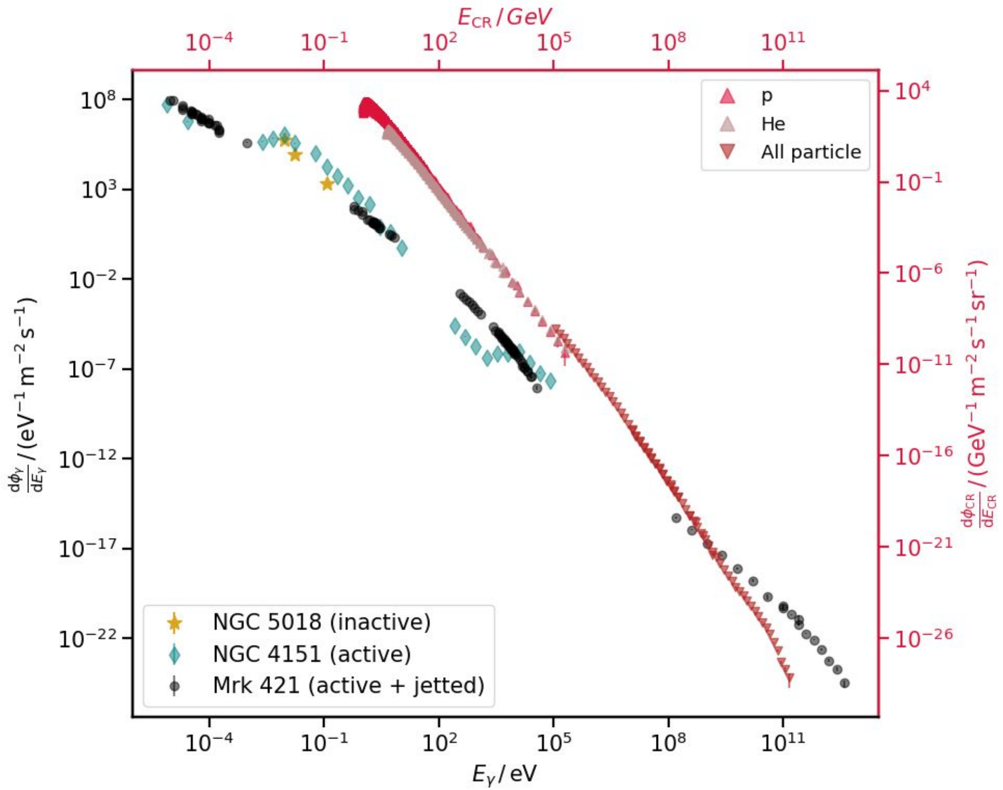

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radio | optical | X rays | γ rays

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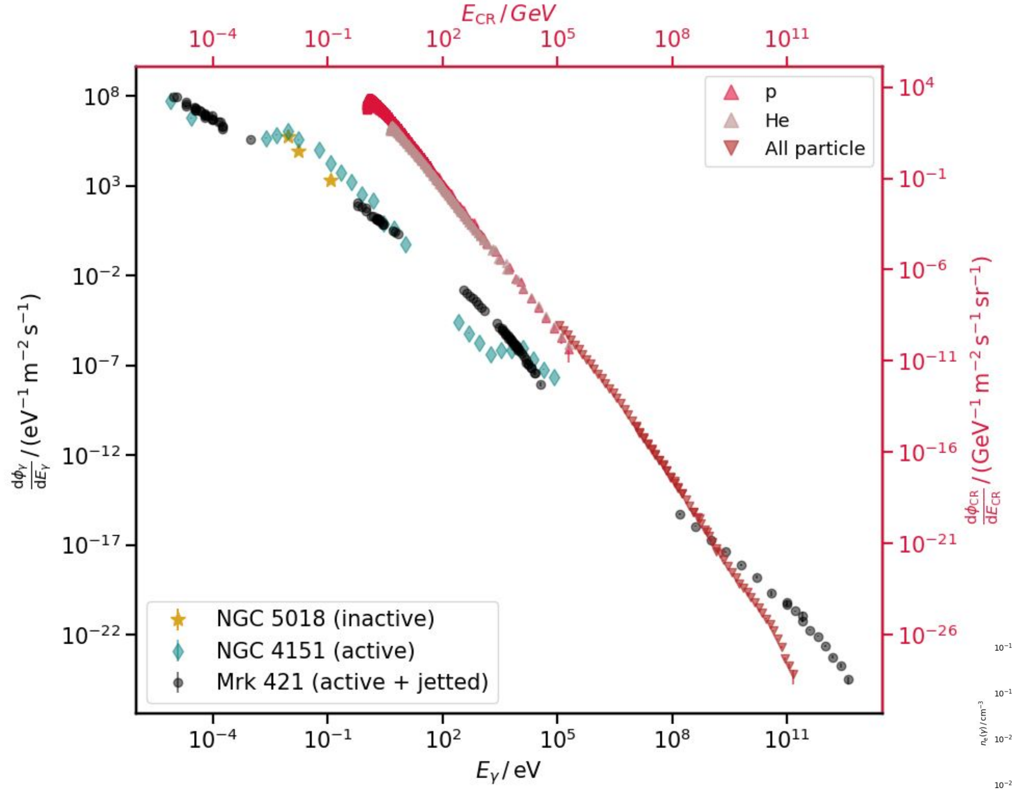

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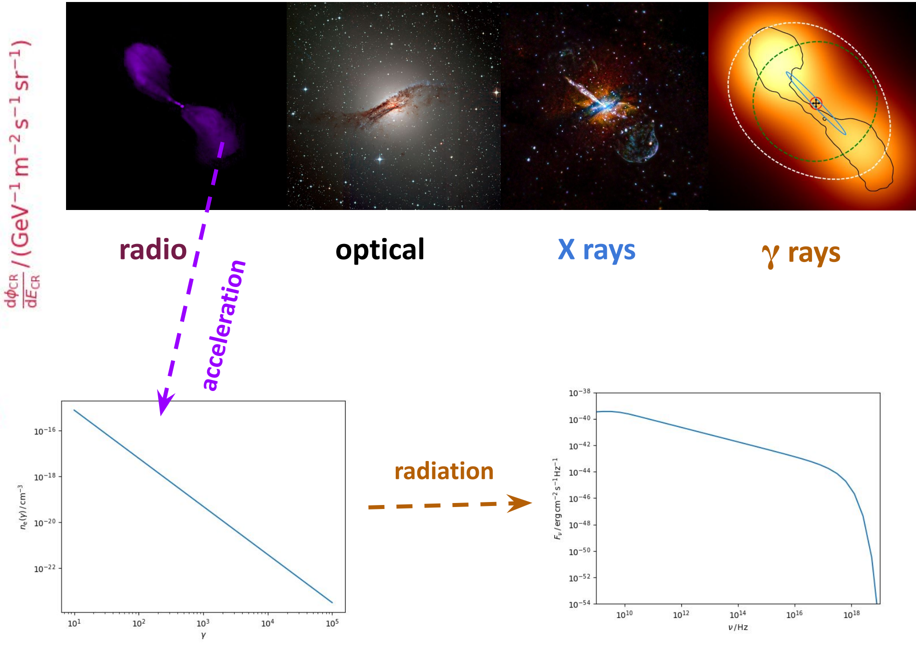
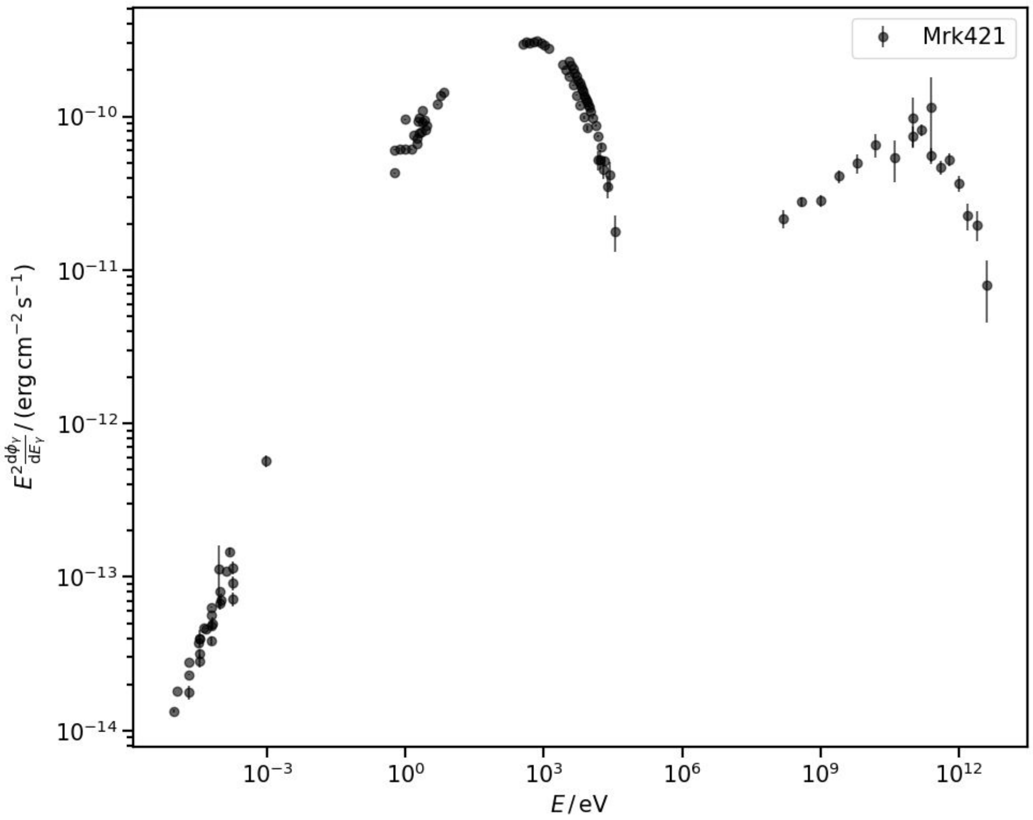


How do we measure their emission?



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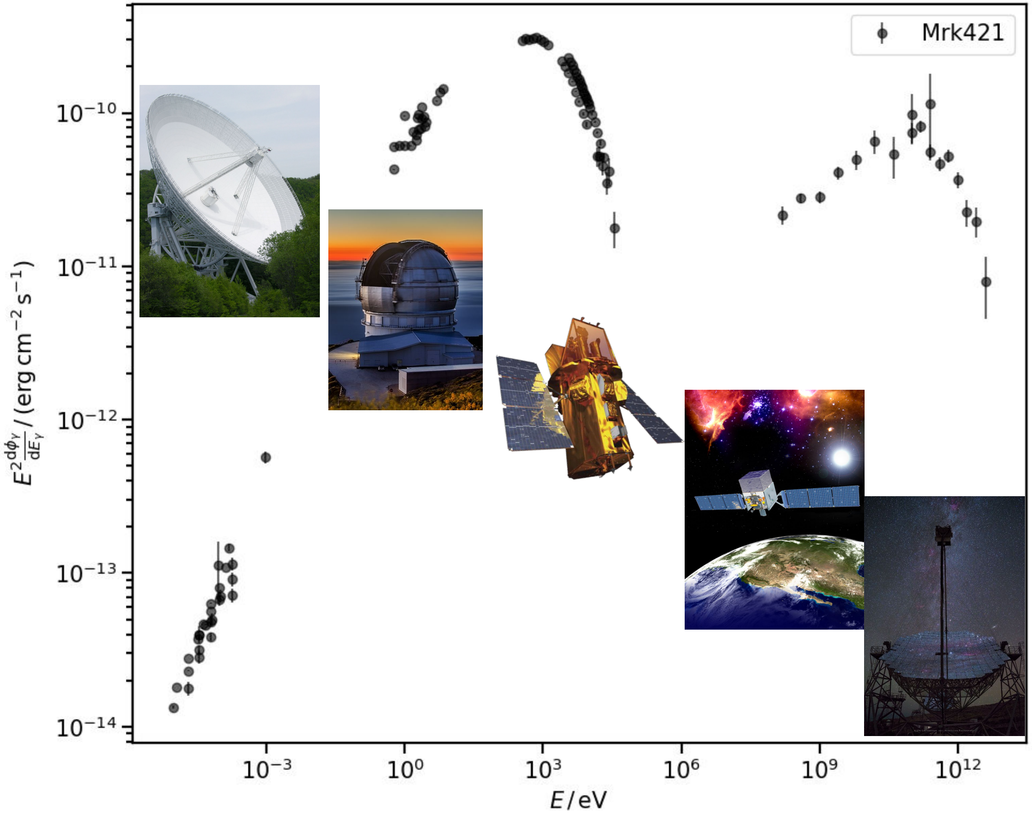
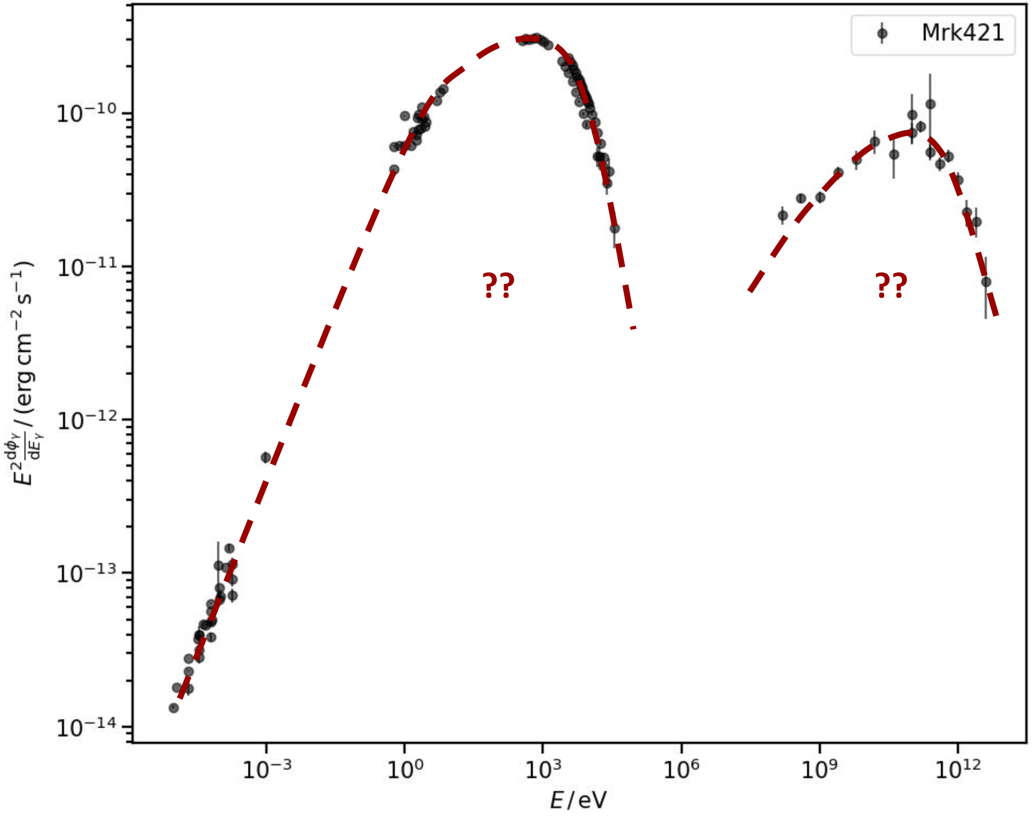
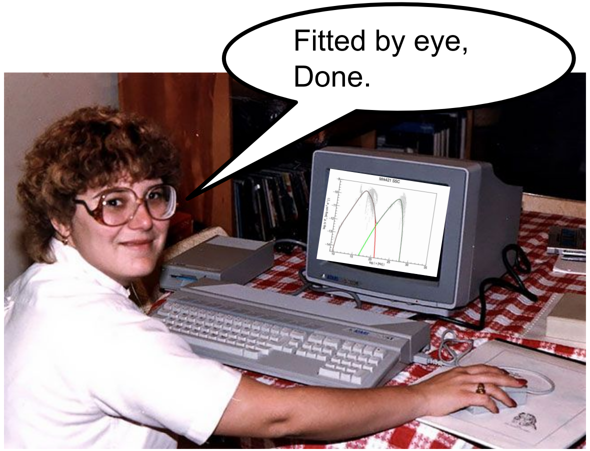


> Flux is measured by several instruments in different energy bands;

> each **collaboration** implements some **review or cross-check system for their analyses**.

How do we interpret their emission? Who does it?





> Even in the collaborations reducing and analysing the data, **modelling and interpretation** is performed by **few persons with closed-source software**;

> more often, these small groups publish their own papers modelling published data;

> often a fit by-eye is performed (parameters manually adjusted).

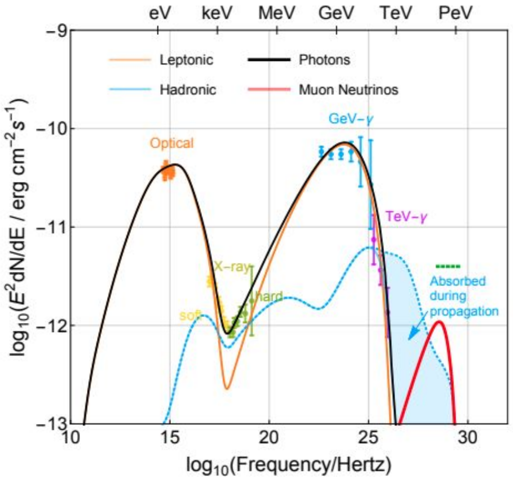
What are the problems with this modelling approach? (I)

> No doubt these few scientists have shaped the understanding of the field with their tools;

> but their **results are not reproducible** (you cannot re-perform the calculations in a paper in autonomy and verify its conclusions);

> interpretation is **accessible** only to a **restricted group of people**;

> despite implementing the same physical processes these tools were **never validated against each other**, only recently a systematic comparison of their results has been publicly presented.



One of the authors of this model and this plot complained in a seminar that experimentalists should release the "raw data" because he did not trust "what they were doing".

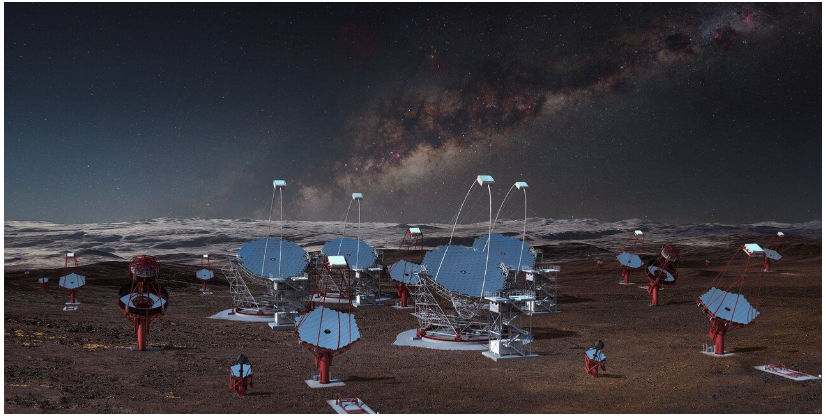
We are instead supposed to trust a modelling code he wrote a decade ago and that only him and few of his collaborators can use.

What are the problems with this modelling approach? (II)

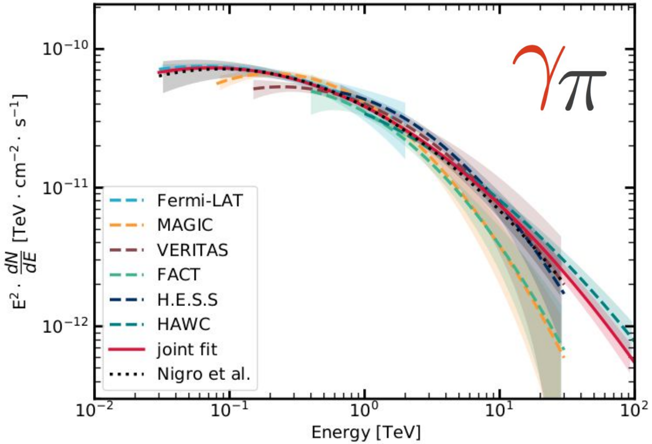
> The next generation of high-energy astrophysics instruments will provide **open access to their data**;

> the amount of MWL data we already have and will accumulate makes the **interpretation by few groups unsustainable**;

> preparing for the forthcoming generation astrophysicist have already started to develop **open-source analysis tools**. Can we do the same with the modelling software?



CTA will provide open access to its data.



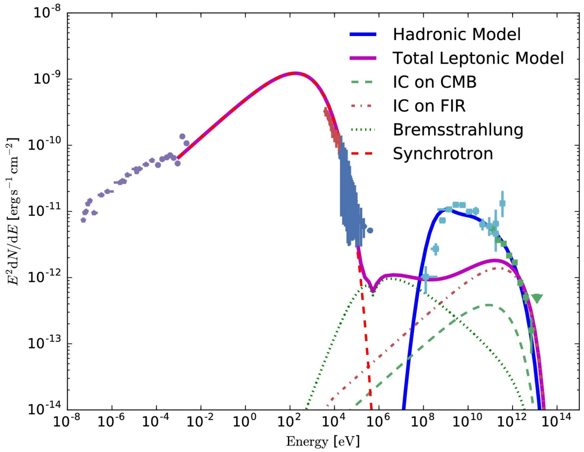
Crab Nebula spectrum obtained from all operating gamma-ray instrument using open-source software [Albert, A. et al. (2022)](#).

Open-source tools for modelling

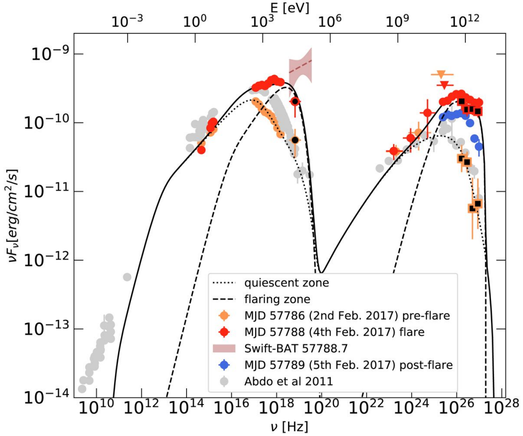
> Several **open-source software** developed to interpreting the non-thermal emission of astrophysical sources have been recently developed (naima, gamera, jetset, agnpy, BHJet, FLAREMODEL);

> designed for different sources (galactic or extragalactic) but easily expanded to science cases where same radiative processes occur;

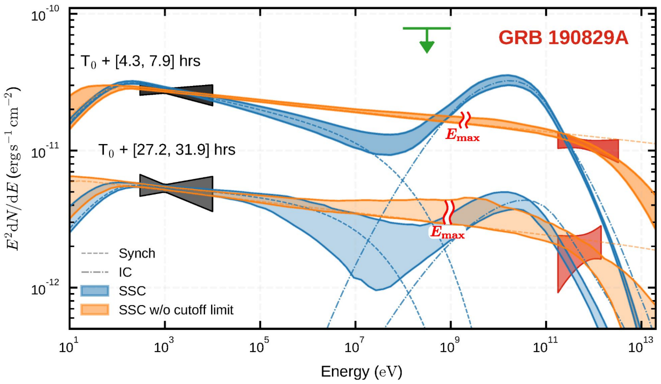
> interpretation open to analysers.



Naima applied to model a SNR Ahnen, M. L. et al. (2017)



Naima applied to model a AGN Acciari, V. A. et al. (2021)



Naima applied to model a GRB H.E.S.S. Coll. (2021)

Open-source tools for modelling

JetSeT

Jets SED modeler and fitting Tool

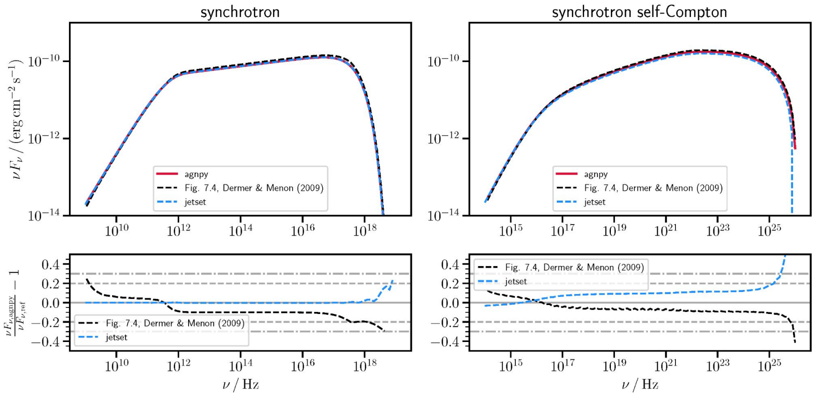
Author: Andrea Tramacere

AGNpy

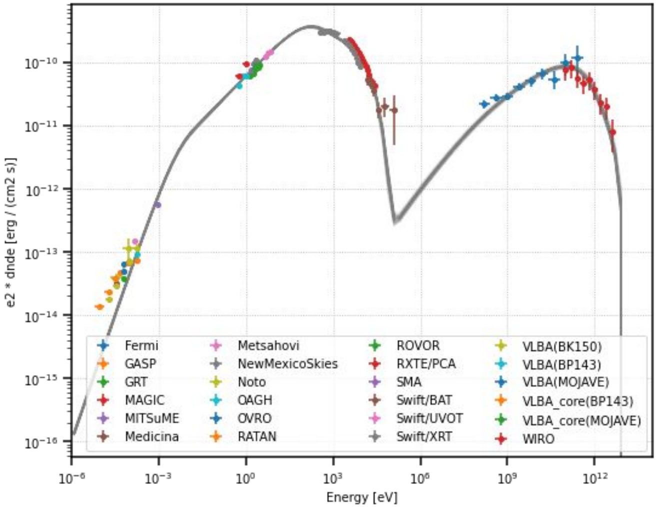
> all these tools are **documented**, **tested** and **released with package managers**;

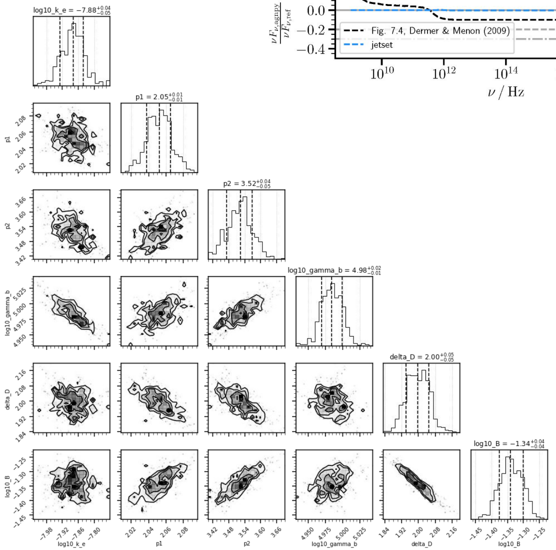
> they show a **commitment to validation** (against the literature and against other software);

> they are **directly interfaceable to open-source data-analysis tools**. Sophisticated statistical analysis can be easily performed.



Nigro, C. et al. (2022)

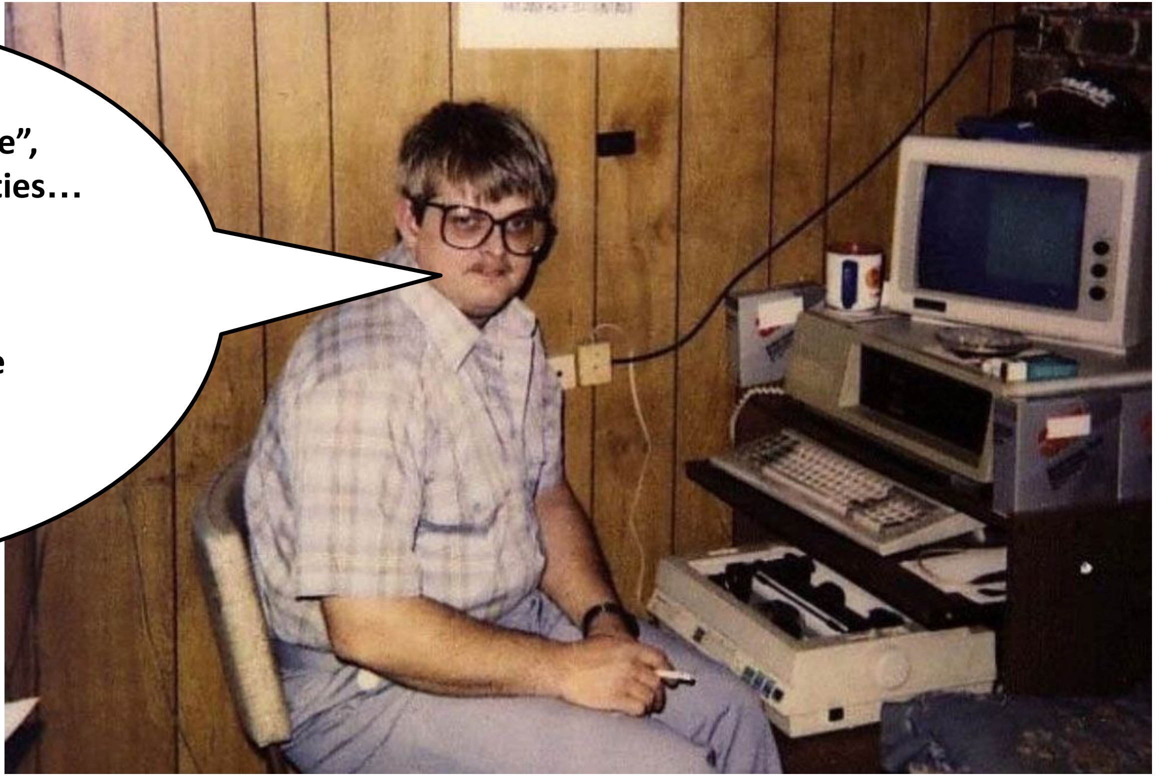




Ok, these new tools are "nice",
but these are just technicalities…

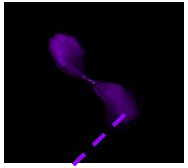
What about physics?

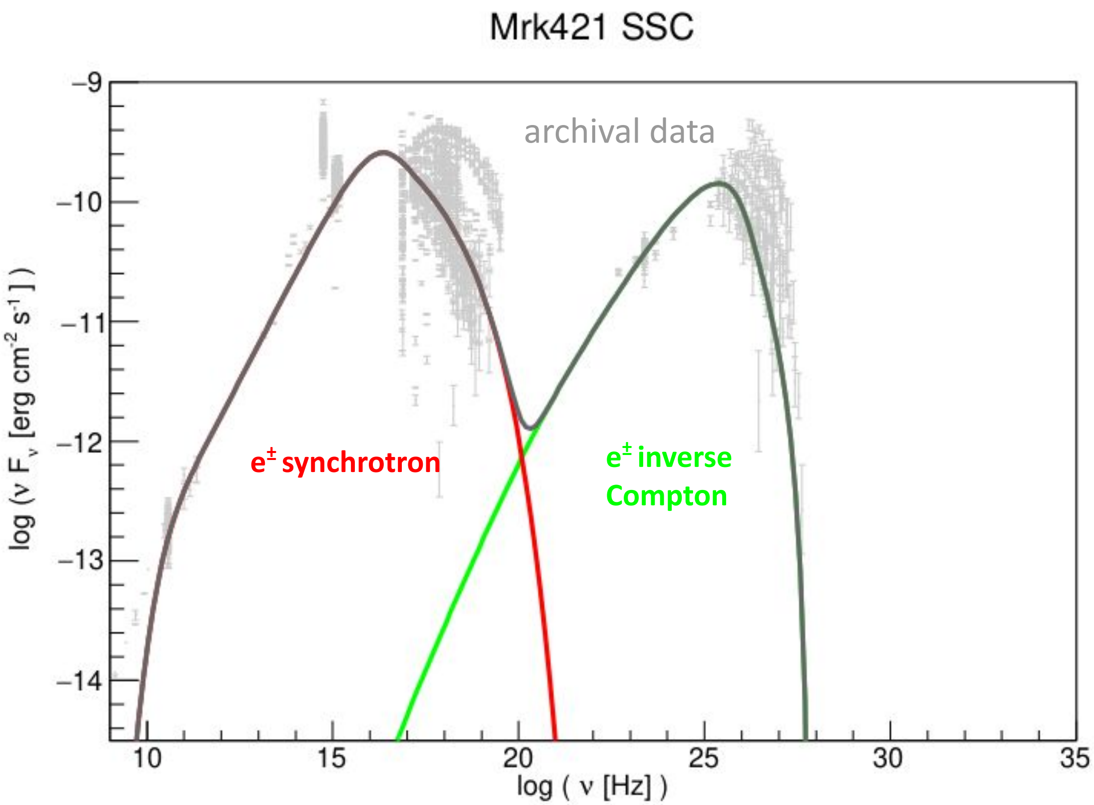
Don't they address the same physical questions as the proprietary software?



DISCLAIMER: all results shown were obtained with the old generation of software.

How do we interpret their emission? Leptonic model





[Cerruti, M. (2020)](#)

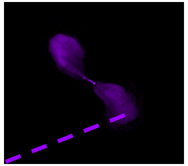
Electron-positron (electrons) plasma

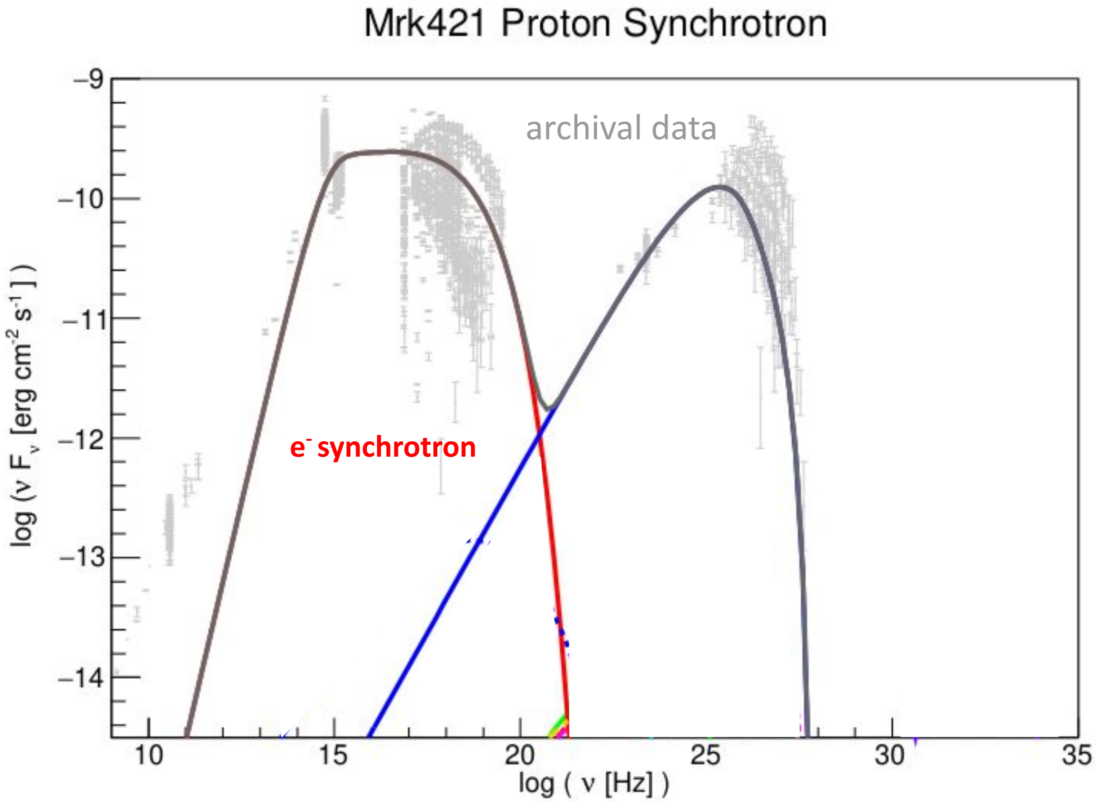
> The low-energy bump is the **synchrotron** radiation of the accelerated electrons;

> 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**;

Cerruti, M. (2020)

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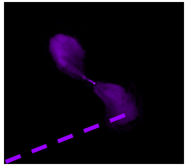

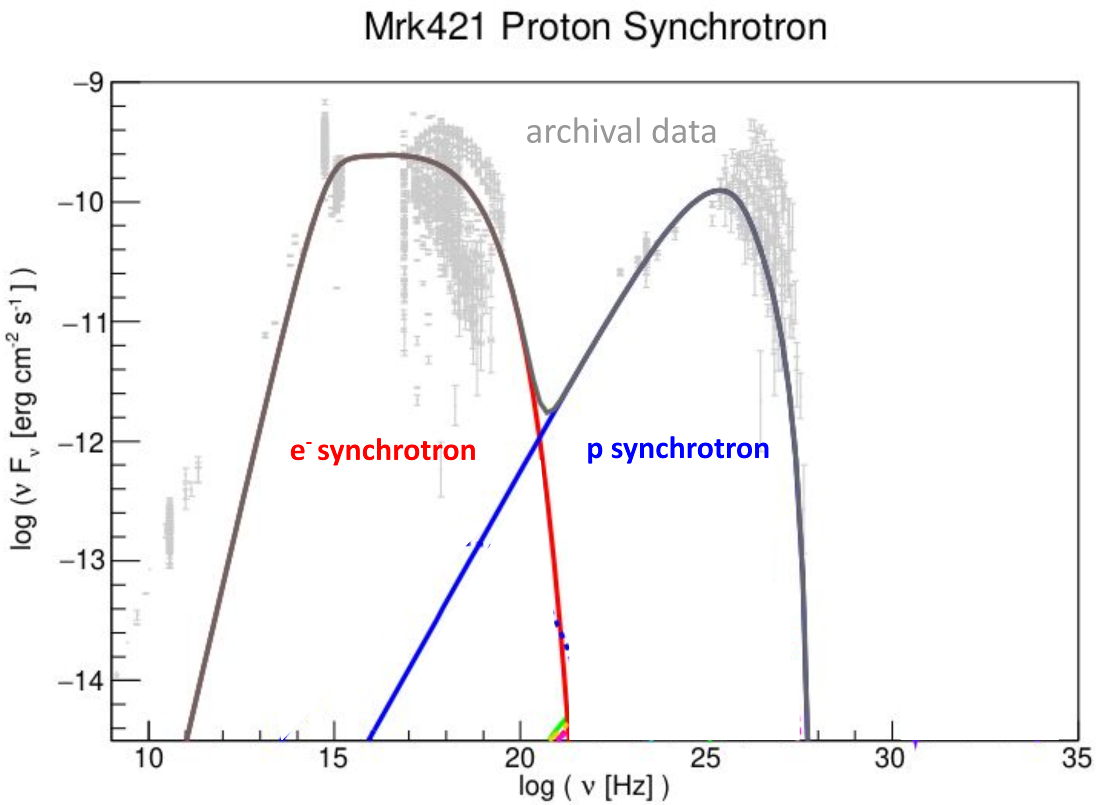

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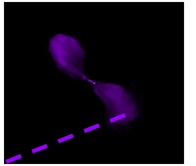

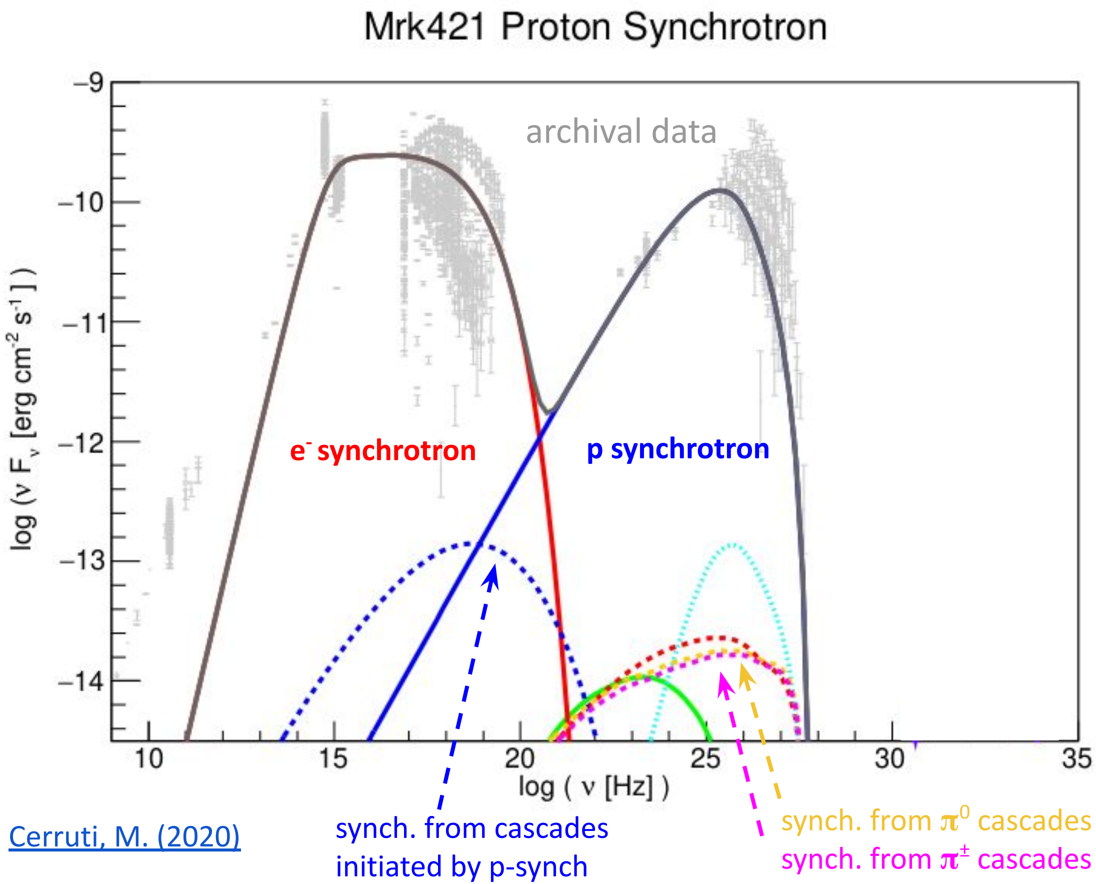

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> **proton-gamma interactions**:

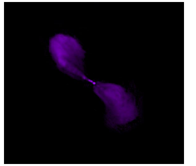
$p + \gamma \rightarrow p + \pi^0$

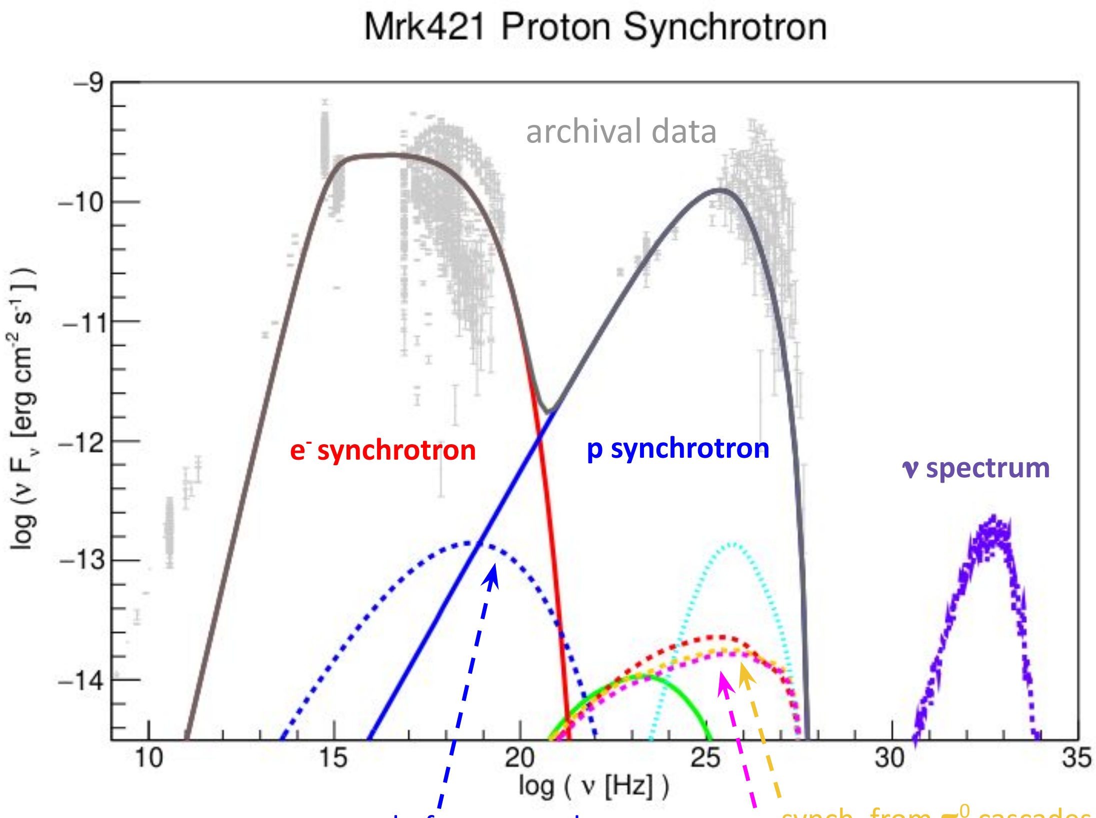
$n + \pi^+$

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

produce mesons whose secondaries initiate particle cascades and further radiation;

How do we interpret their emission? Hadronic model





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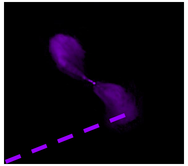
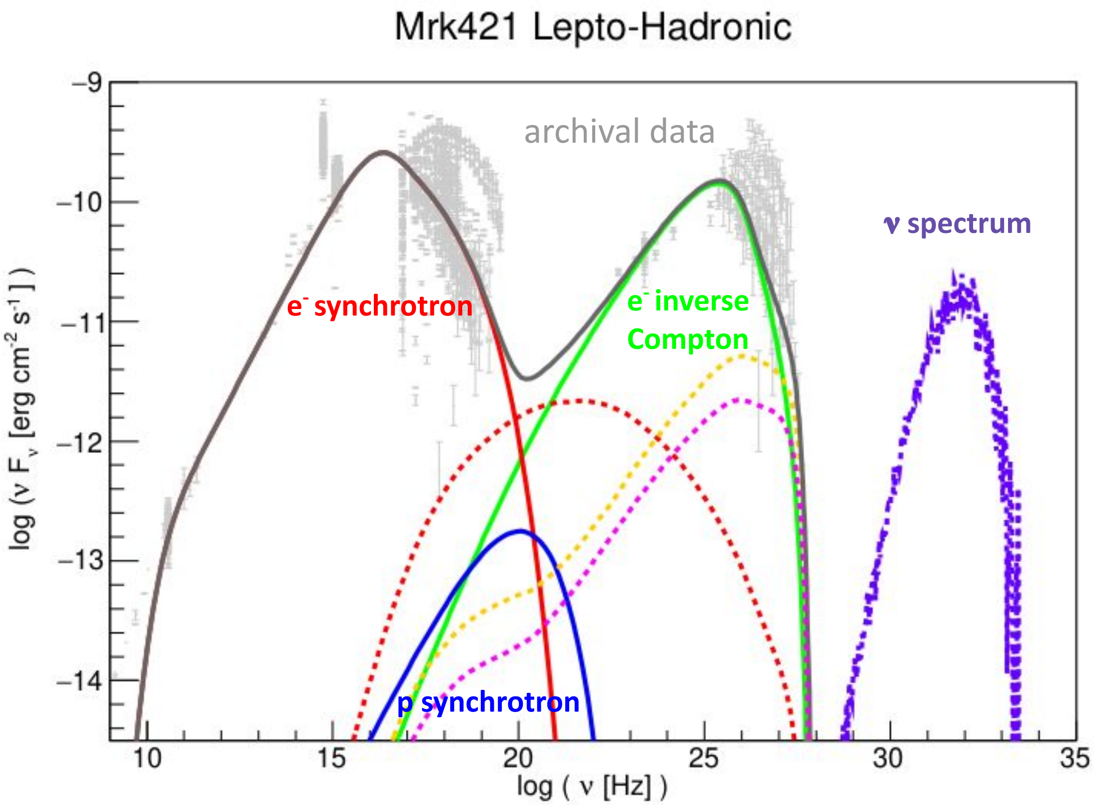
> **neutrino production!**

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".

Cerruti, M. (2020)

Hadronic or leptonic high-energy emission?

The origin of high-energy emission in blazars jets (i.e., leptonic versus hadronic) has been a longstanding matter of debate. Here, we focus on one variant of hadronic models where proton synchrotron radiation accounts for the

two broad bumps. While the lower-energy one likely arises from synchrotron radiation of primary electrons, the origin of the higher-energy one is still a matter of debate. In leptonic models it is described by in-

of relativistic electrons in the jet magnetic field. The origin of the HE component is still under debate, mostly between two main scenarios. In leptonic scenarios, the HE component is due to inverse

The processes operating in blazar jets are still an open question.

Distinguishing between hadronic and leptonic gamma-ray emission is challenging, but, at least in principle, gamma-rays

Despite all this exciting progress, questions remain plentiful: Are jets leptonic, or lepto-hadronic? How important is entrain-

providing a potentially greater observed flux of accelerated particles (Urry & Padovani 1995). Current observations of blazars are unable to distinguish between leptonic, hadronic, and mixed emission scenarios (Cerruti et al. 2019; Böttcher et al. 2013). When a hadronic component is included, a neutrino counterpart is expected alongside photon

multi-messenger observations, especially towards addressing the following questions, where the author believes that major breakthroughs are possible through dedicated blazar observations within the next decade:

- What is the matter composition of blazar jets, and what is the dominant particle population responsible for the high-energy emission? Answering this question will allow major progress

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"Matter of debate" group

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"Open question" group

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"We need more data" group

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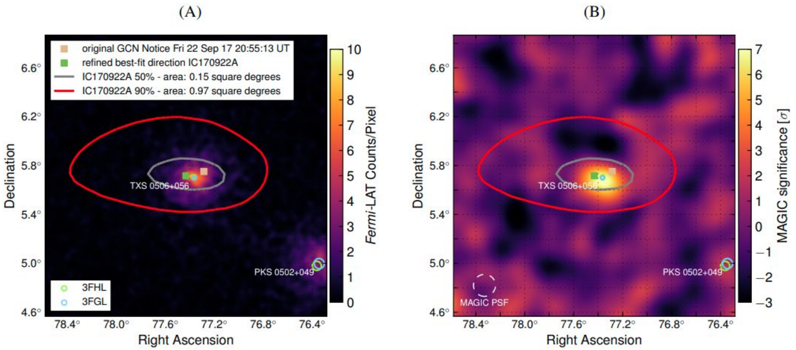
Is it an open question? (a single source)



> **IceCube-170922A direction consistent with the flaring blazar TXS0506+056**;

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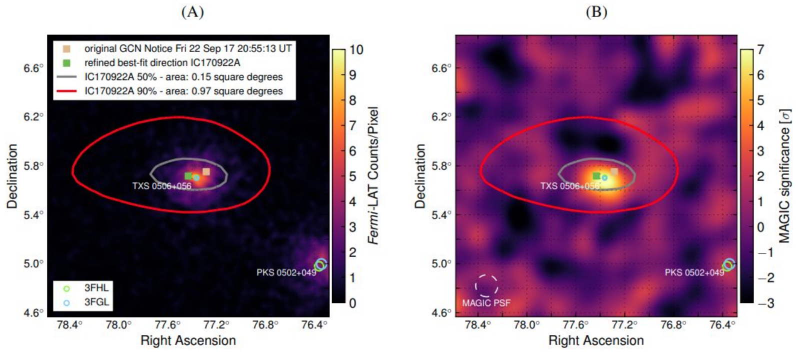

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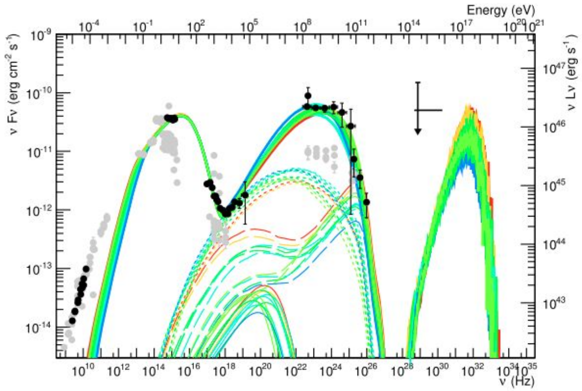
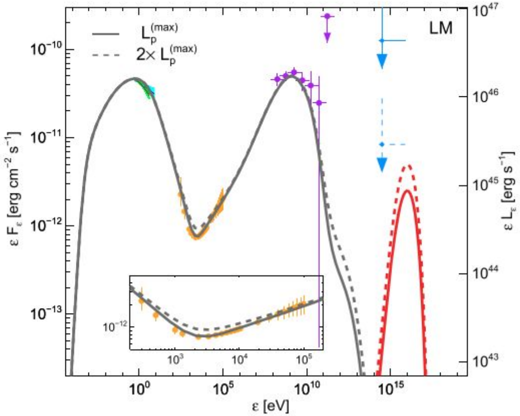
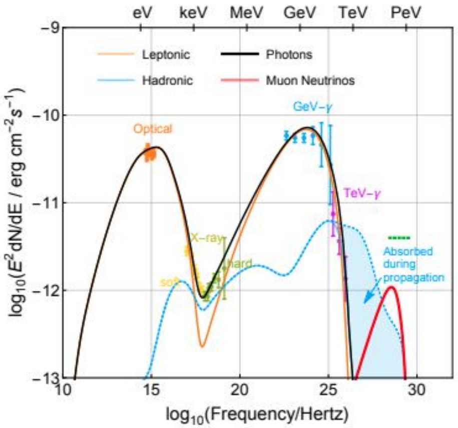


Cerruti, M. et al. (2018)

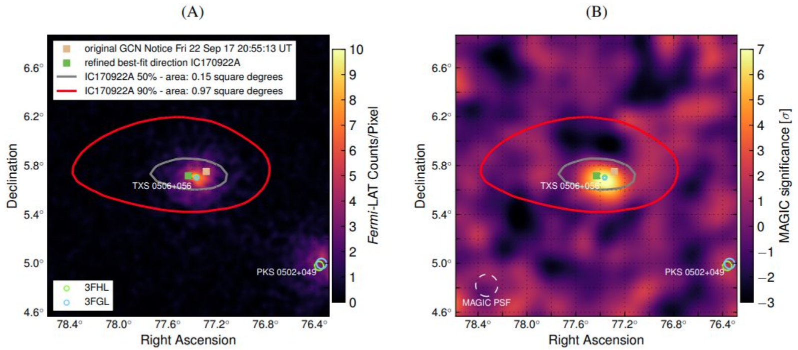


Keivani, A. et al. (2018)



Gao, S. et al. (2018)

Is it an open question? (a single source)



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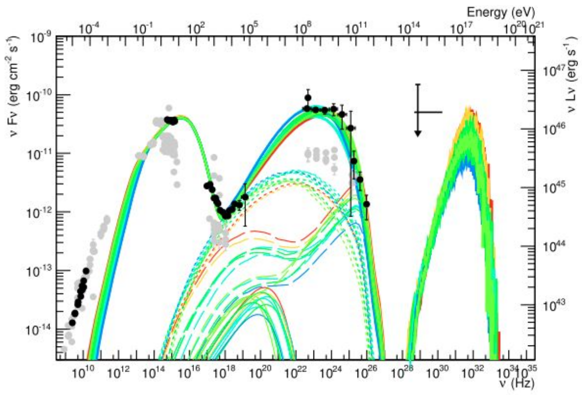

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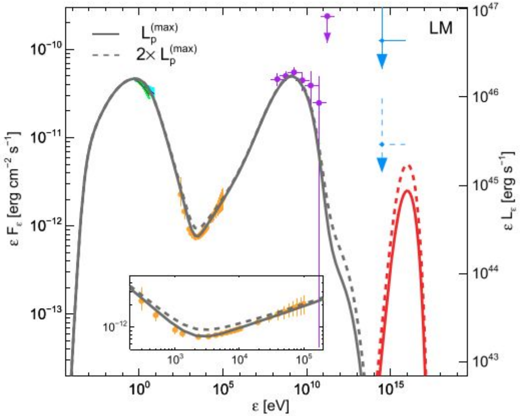

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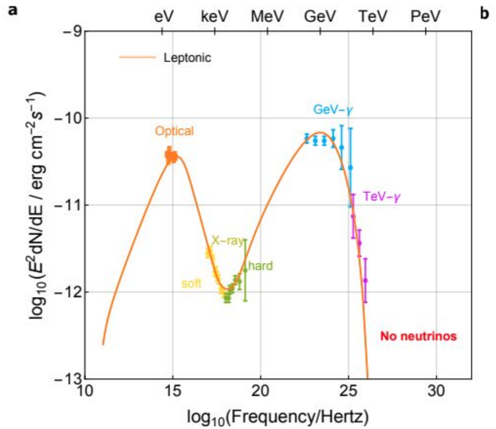

The energy spectrum is well reproduced by a purely leptonic model

Is it an open question? (a large sample of sources)

> Hadronic models applied to a few selected sources (possibly associated with neutrinos).
Systematic statistical studies should give more general answers;

> Liodakis et al. (2020) fitted 145 sources high-energy emission assuming a proton synchrotron model.
Largest and only systematic statistical analysis of blazars with hadronic models;

Proton Synchrotron Gamma-Rays and the Energy Crisis in Blazars

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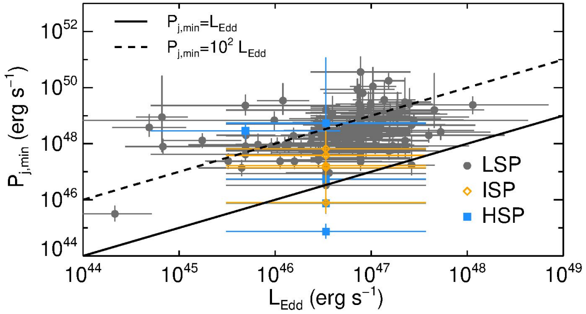
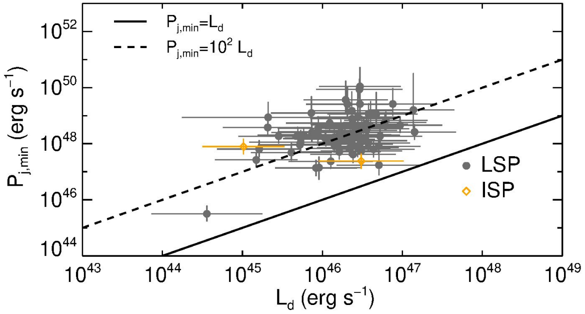
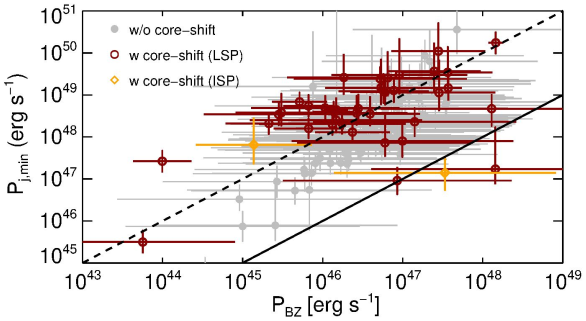
> **estimated jet power orders of magnitude above typical "energy estimators" of blazars**;



Maximum luminosity not to get disrupted by radiation pressure.



Luminosity of the accretion disk.



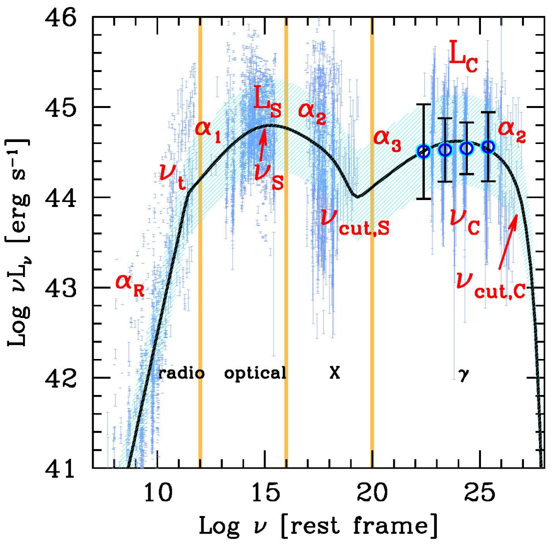
Power of the EM process launching the jet.

> **if there is hadronic emission it can only be subdominant**;

> analytical approximation used to estimate high-energy emission (hadronic models computationally expensive).

Systematic studies with leptonic models

> Are full radiative models used <u>at least</u> for systematic studies with leptonic models?
Leptonic models are computationally simpler and have less parameters (8) than hadronic ones (>12).



> Ghisellini et al. (2017) fitted the spectrum of 747 blazars assuming a leptonic model. **Again, an analytical approximation was used to model the broad-band emission**.

Systematic studies with leptonic models

> **Are full radiative models used <u>at least</u> for systematic studies with leptonic models?**

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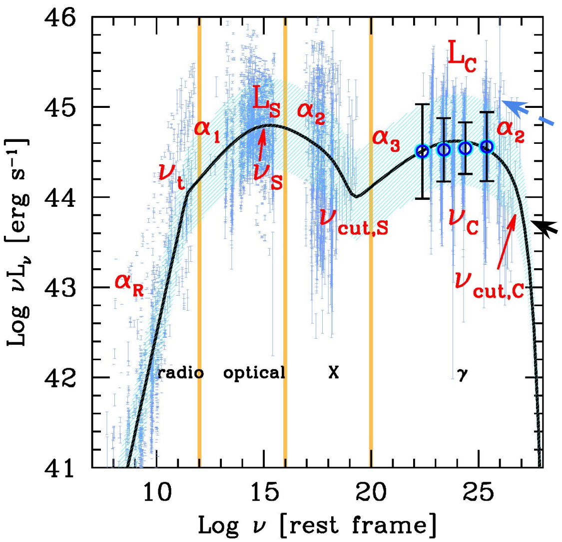


> Ghisellini et al. (2017) fitted the spectrum of 747 blazars assuming a leptonic model. **Again, an analytical approximation was used to model the broad-band emission**.

more than two decades of data

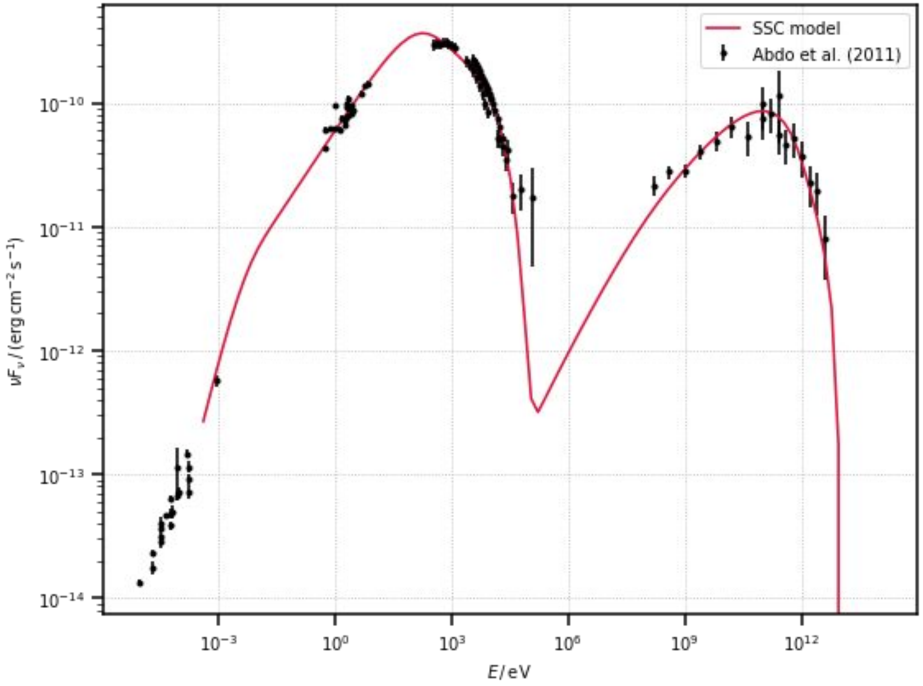
a model established since three decades (synchrotron + inverse Compton)

> and yet a systematic statistical analysis of a large sample of blazars using a physical radiative model seems not possible… **is it a problem of the old generation of closed-source software?**

A large sample of sources analysed with leptonic models

> Are full radiative models used at least for systematic studies with leptonic models?

Leptonic models are computationally simpler and have less parameters (8) than hadronic ones (>12).




```
Fit succesful =  True
Method                  = levmar
Statistic               = chi2
Initial fit statistic = 3533.13
Final fit statistic    = 270.786 at function evaluation 71
Data points             = 86
Degrees of freedom      = 80
Probability [Q-value] = 1.47258e-22
Reduced statistic       = 3.38482
Change in statistic    = 3262.35
   ssc.log10_k_e    -7.88461     +/- 0.0702959
   ssc.p1          2.05281      +/- 0.0231709
   ssc.p2          3.53711      +/- 0.0517896
   ssc.log10_gamma_b    4.99003      +/- 0.0228676
   ssc.delta_D     19.809       +/- 0.612714
   ssc.log10_B     -1.33284     +/- 0.0389128
CPU times: user 18.6 s, sys: 6.84 s, total: 25.4 s
Wall time: 25.7 s
```

Data from 24 instruments fitted in 25 s with the new generation of software, using a real physical model.

Potential problems of the closed-source modelling software

> Probably written in outdated programming language, not interfaceable with modern data-analysis tools;

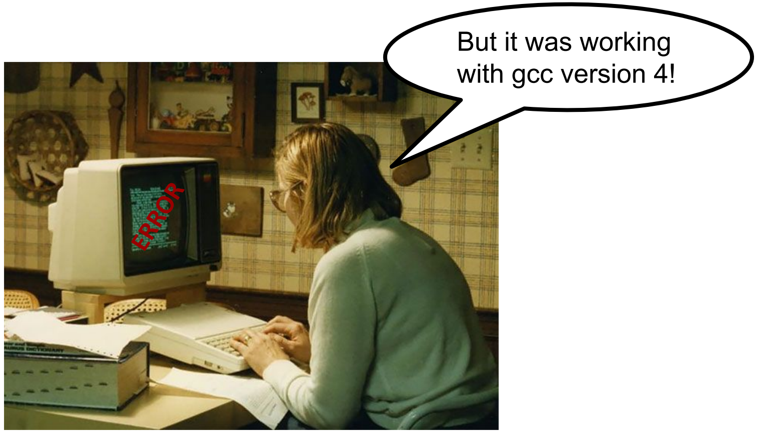
> difficult to distribute the statistical analysis of hundreds of sources on a computer cluster without a modelling software provided via package managers and tested on different environments;

> **closed-source modelling software might be lagging a decade behind data and analysis software;**

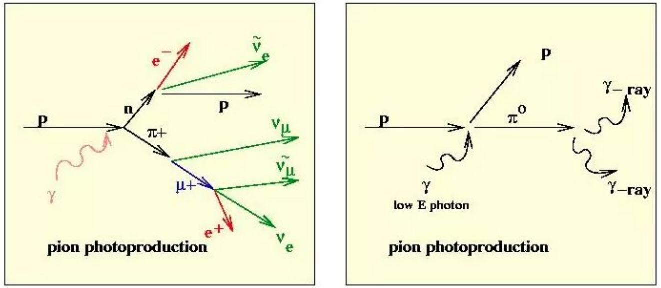
> the new generation of open-source tools is validated, tested, easily installable and interfaceable with the latest data-analysis tools;

> but no open-source tool implements yet hadronic models!

> a Monte Carlo for $p\gamma$ interactions was written in 2000 in FORTRAN and is available only on request to the author.



The SOPHIA Monte Carlo Code



Monte Carlo simulations of photohadronic processes in astrophysics

What question should we ask and how should we address it?

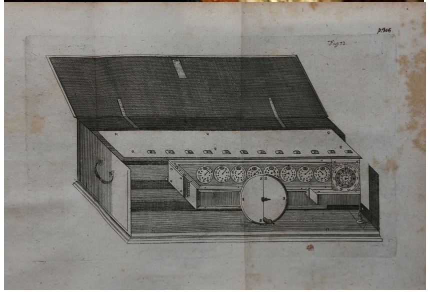
> **New generation of open-source software** modelling the non-thermal emission of astrophysical sources being developed:
- **opens up the modelling effort to the community**;
- **compensate the technical obsolescence of the previous generation closed-source software**;

> can be used to perform systematic studies to address a **crucial question** related to **blazars high-energy emission**:
- ~~**is it hadronic or leptonic in origin**~~?
- **with how much statistical significance can we still accommodate a subdominant hadronic emission**?

> current generation of tools not fit to address this question. Systematic statistical studies with a full radiative model simply cannot be performed;

> none of the new generation of tools includes hadronic radiative processes! The development effort should be concentrated on adding them, in order to finally make an informed statement on the blazar emission.

Modelling software is a scientific instrument



"Indignum enim est excellentium virorum horas servili calculandi labore perire, qui Machina adhibita vilissimo transcribi potest."

> *"It is unworthy of excellent men to suffer in the long hours of the servile labour of calculation, which can be delegated very cheaply to a machine."*

> every time you write a good piece of software and you make it available, <u>you are freeing another excellent human being from the slavish labour of calculation</u>;

> but the *machina* we develop performs complex computations:

- that cannot be verified with pen and paper;
- that are not trivial at all to reproduce (months of coding);

> the **software** that we write **for physical interpretation** is part of our apparatus;

> we should hold it to the **same validation and reproducibility standards that we require for hardware and analysis software**.