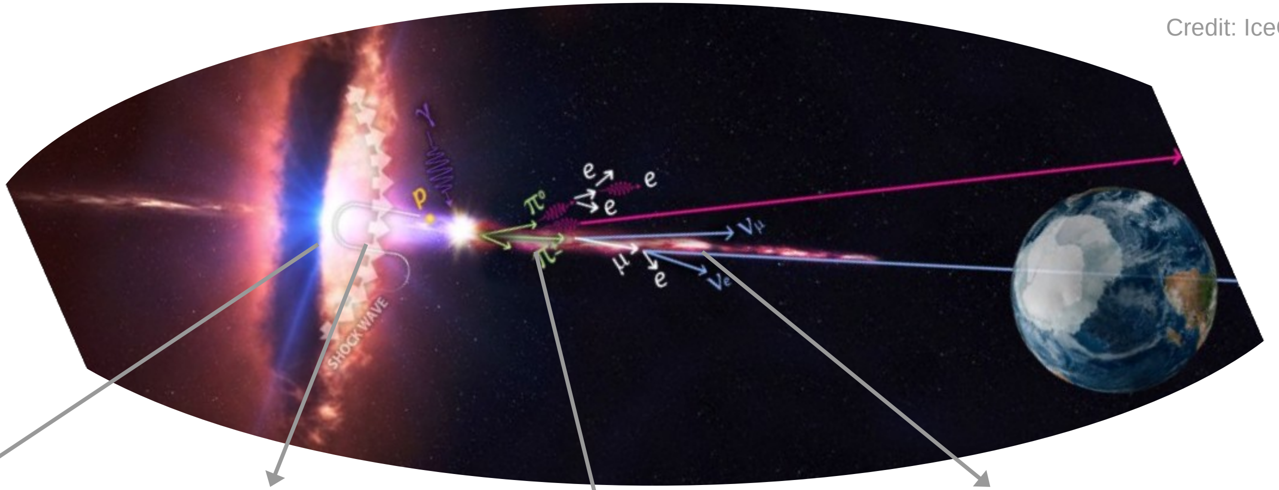
Multiwavelength modelling

Lea Heckmann

Modelling astrophysical sources

Credit: IceCube/NASA



Initial conditions:
Particle plasma,
(GR)-MHD,
PIC simulations
...

Particle acceleration & cooling

Radiation mechanisms

Propagation: absorption, boosting,..

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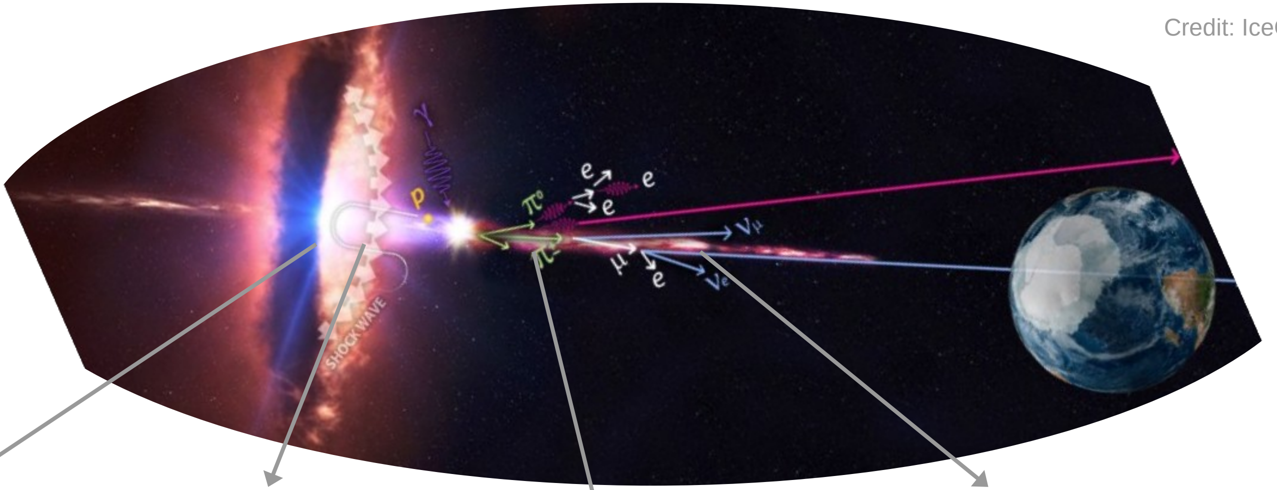

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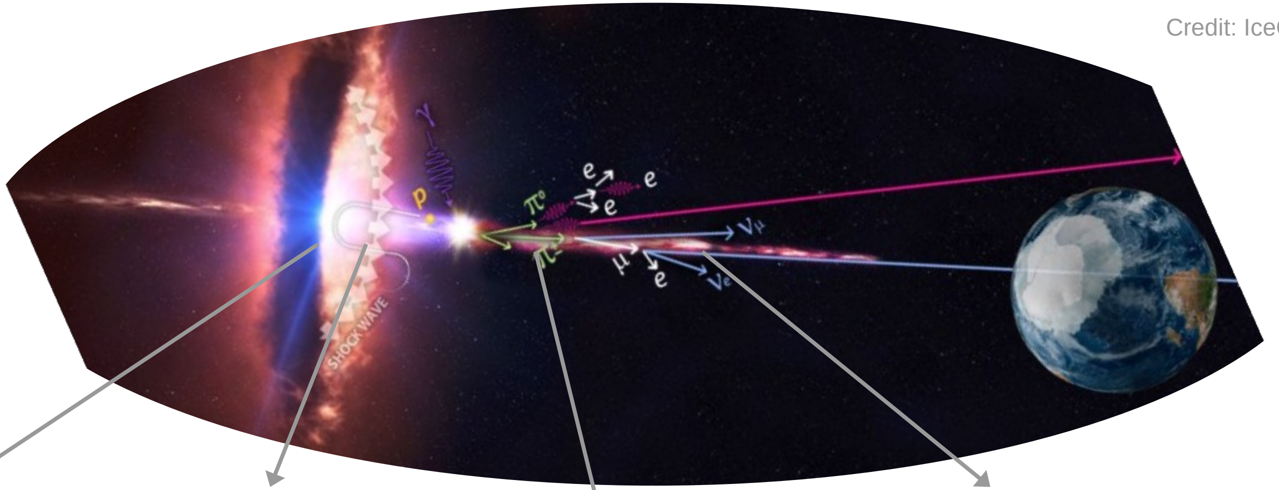

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→ Injected particle spectrum (typically a power law)

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→ Steady state (typically a broken power law) or time evolving particle distribution

Modelling astrophysical sources

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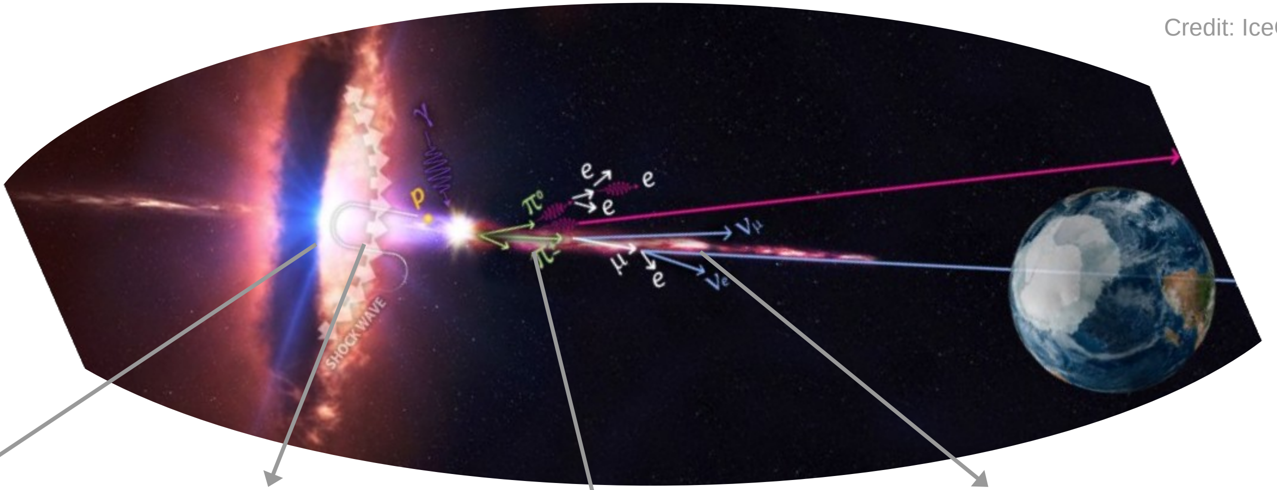

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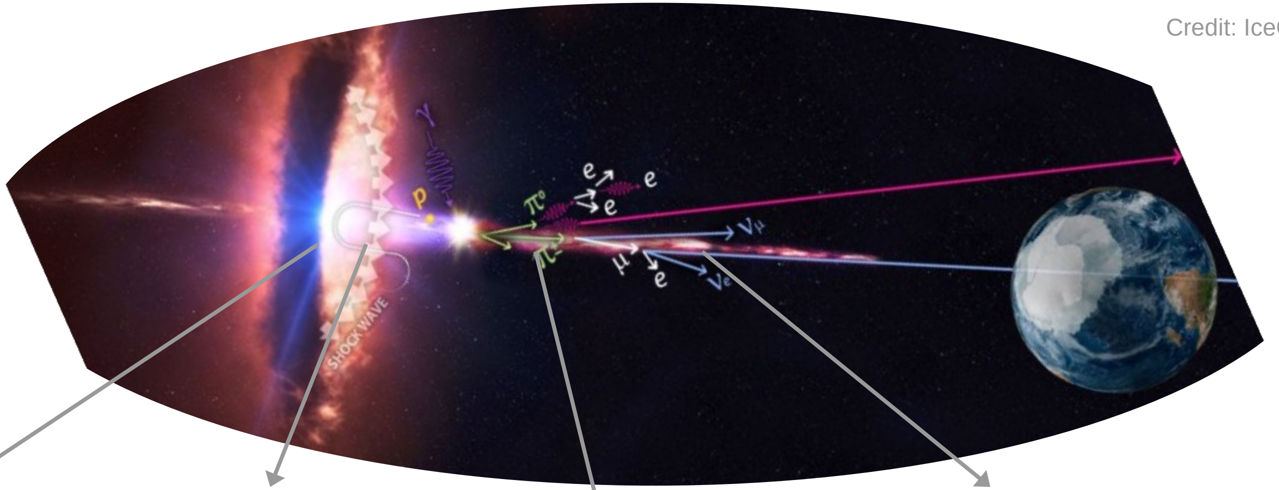

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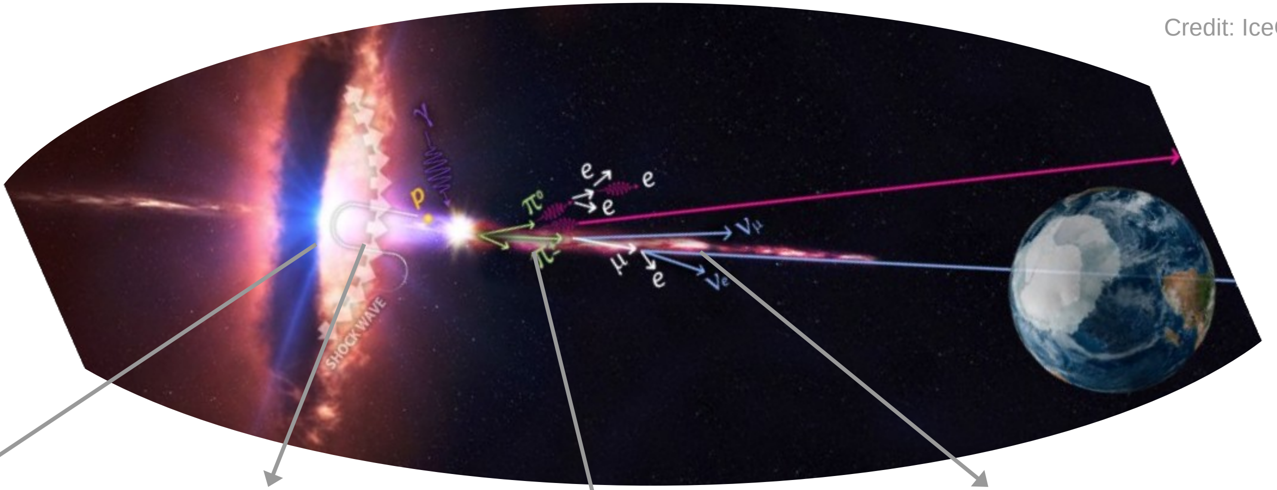

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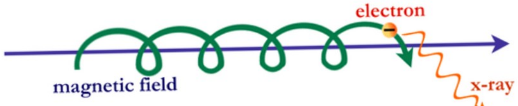
Synchrotron emission

- Charged relativistic particles spiraling around mag field lines → lower-energy photons (radio to X-rays)



Credit: http://chandra.harvard.edu/resources/illustrations/x-raysLight.html

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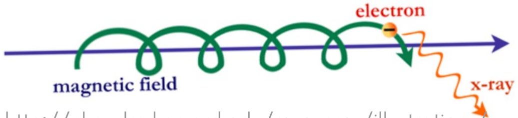

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- Typical frequency: $\nu_s \sim \gamma^2 B$
- Synchrotron power: $P_{syn} = \frac{4}{3} c\, \sigma_T \left(\frac{m_e}{m}\right)^2 \beta^2 \gamma^2 U_B$ $\quad U_B = \frac{B^2}{8\pi}$
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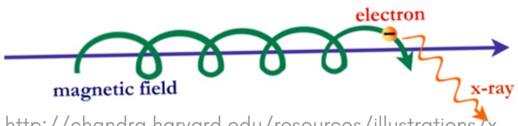

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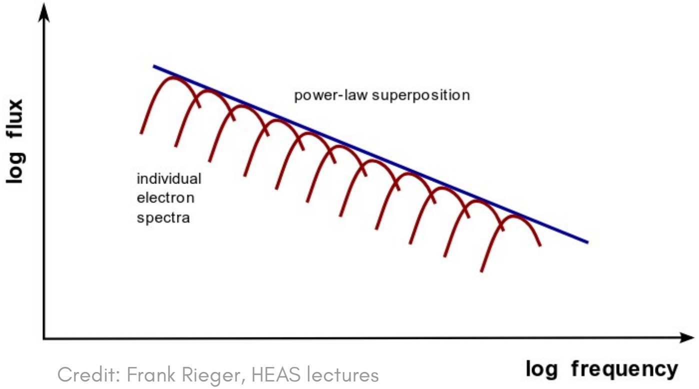
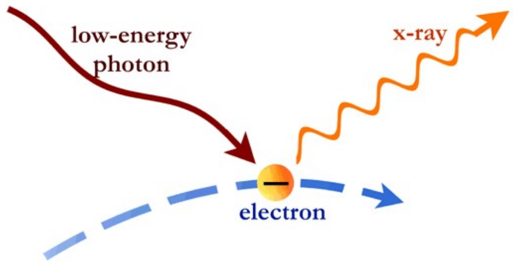
- Power law of e (index p) → power law of photons (Γ)

$$\Gamma = \frac{p-1}{2}$$



Credit: Frank Rieger, HEAS lectures

Radiation mechanisms



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Inverse Compton emission

- Upscattering of low-energy photons
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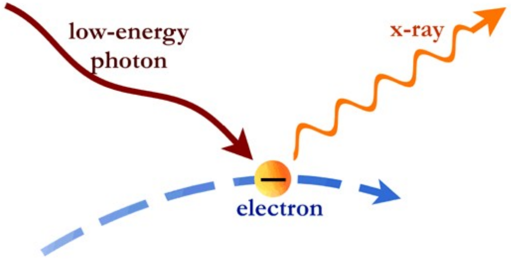

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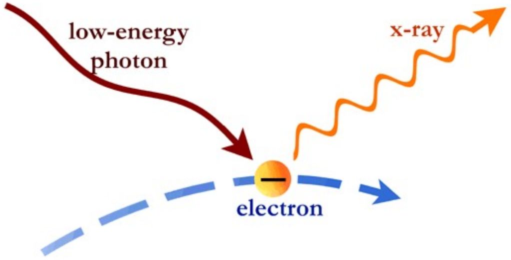

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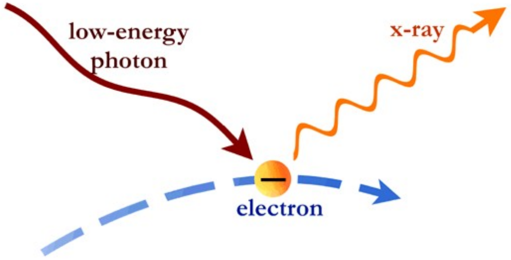

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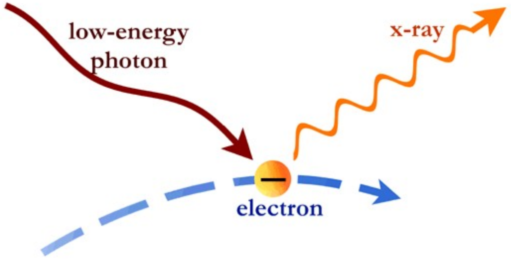

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$\Delta\nu \sim \gamma$ Klein Nishina

- Cooling time scale:

$$t_{cool} \sim \frac{1}{\gamma U_{rad} F_{KN}}$$

$F_{KN} \approx 1$ Thomson

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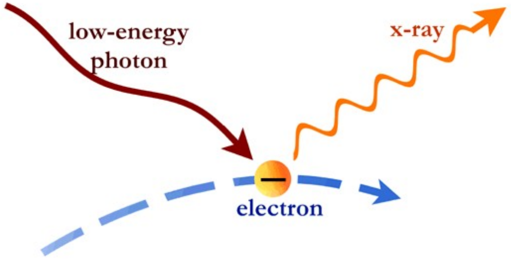

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- Spectral index:
  $$\Gamma_{IC} \sim \Gamma_{syn}$$

Radiation mechanisms

Bremsstrahlung

- Acceleration of electrons in the Coloumbfield of nuclei
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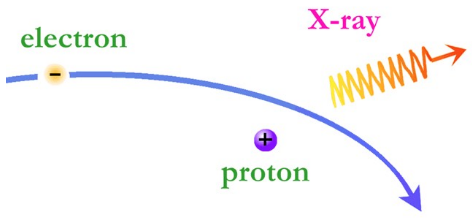

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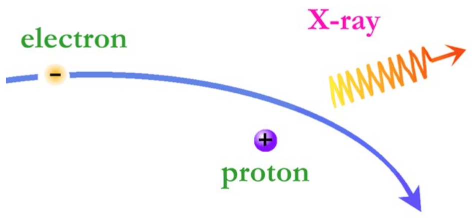

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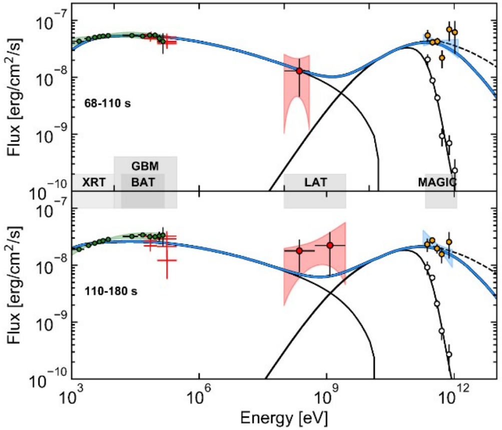
- Power: $P \sim Z^2 N v$ (non-relativistic)
  different for relativistic or thermal cases but always proportional to Z

- Cooling time:

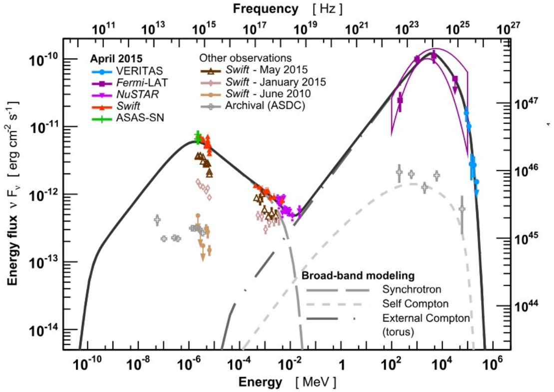
$$t_{cool} \sim 10^{10} \frac{\sqrt{(T)}}{N} \, years$$

Leptonic models

AGNs & GRBs:

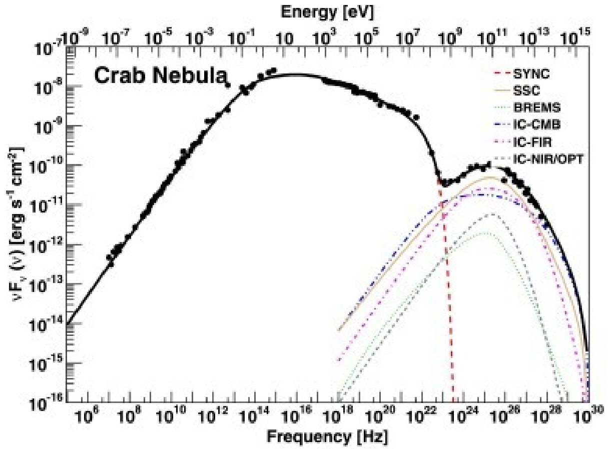


Credit: Nature volume 575, pages 459-463 (2019)

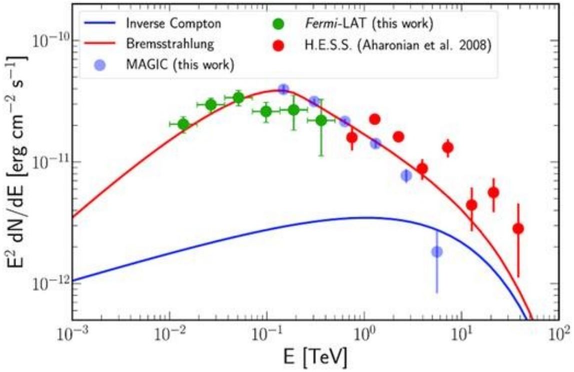


Credit: ApJL 815 L22 (2015)

Crab & other galactic sources:



Credit: JHEAP, Volume 1, p. 31-62 (2014)



Credit: MNRAS, 497, 3, P. 3734-3745 (2020)

Radiation mechanisms

Proton-proton

- Accelerated protons interact with ambient medium

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\begin{aligned}
p + p &\rightarrow p + p + \pi^0 \\
p + p &\rightarrow p + n + \pi^+ \\
p + p &\rightarrow p + p + \pi^+ + \pi^- \ldots
\end{aligned}
$$

$$
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\pi^0 &\rightarrow \gamma + \gamma \\
\pi^+ &\rightarrow \mu^+ + \nu_\mu \quad \text{and} \quad \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \\
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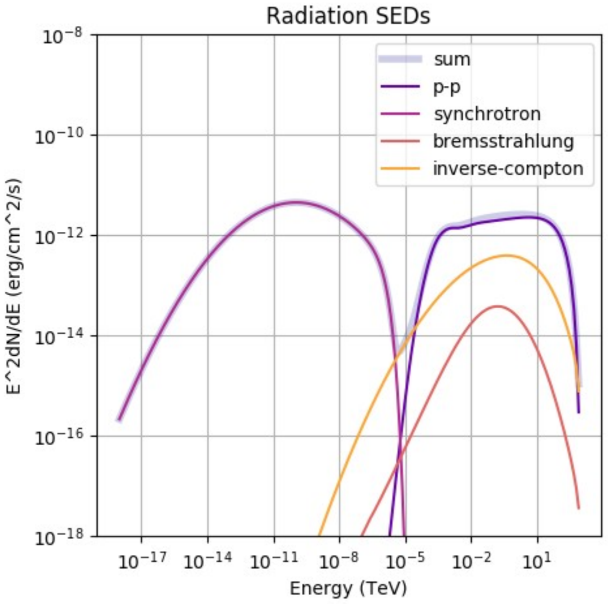
- π^0 decay shows up in gamma-rays



Credit: https://libgamera.github.io/GAMERA/docs/radiation_modeling.html

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<u>Proton-photon</u>

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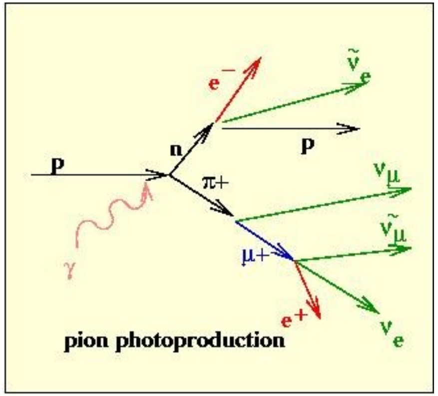

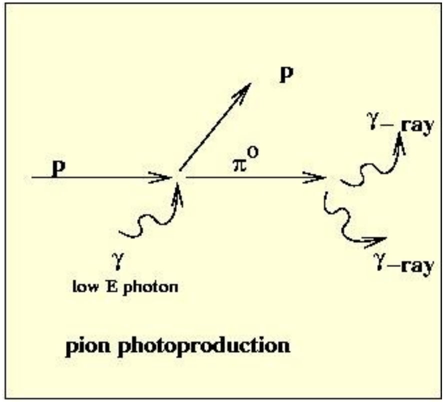

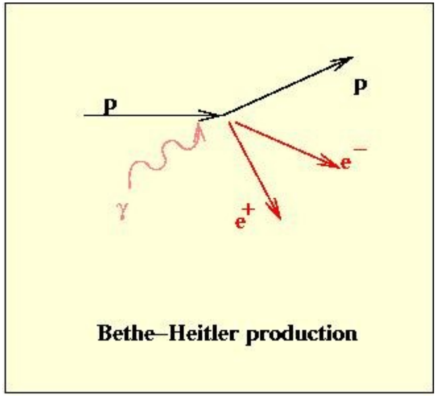

Credit: http://www.physics.adelaide.edu.au/astrophysics/theory/interactions.html

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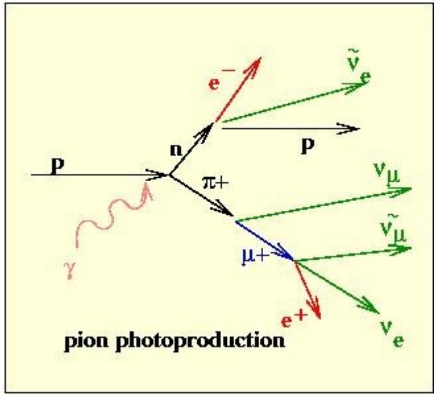

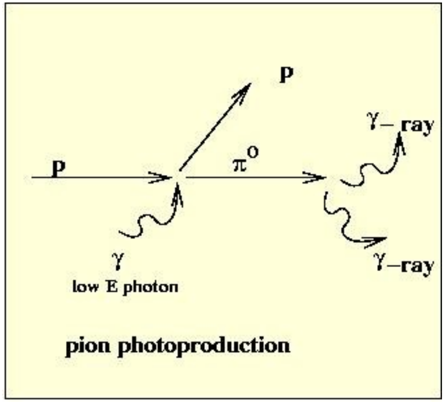

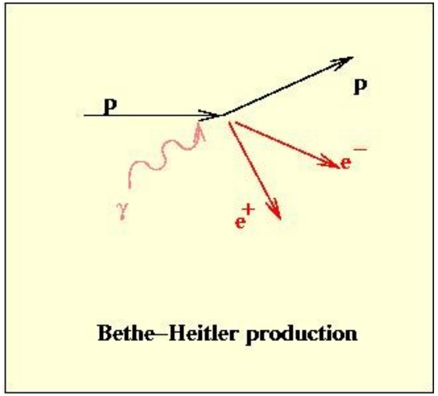

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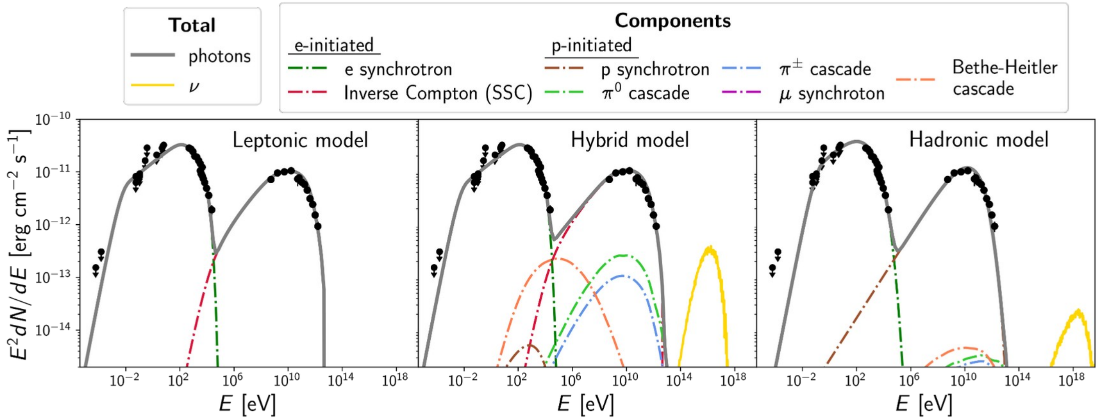
- Produced electrons and photons subsequently develop cascades

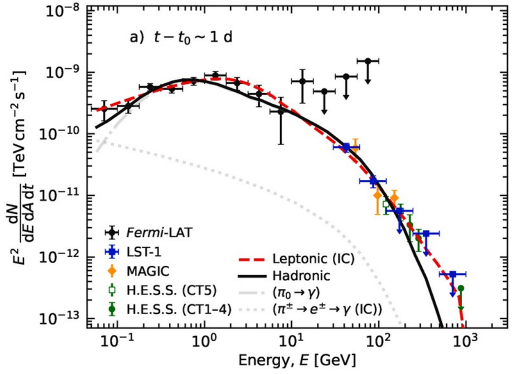
(Lepto)-hadronic models

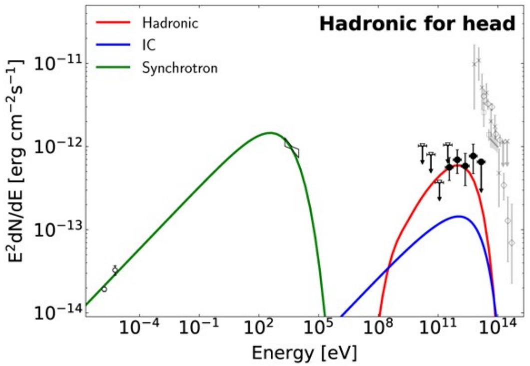
AGNs

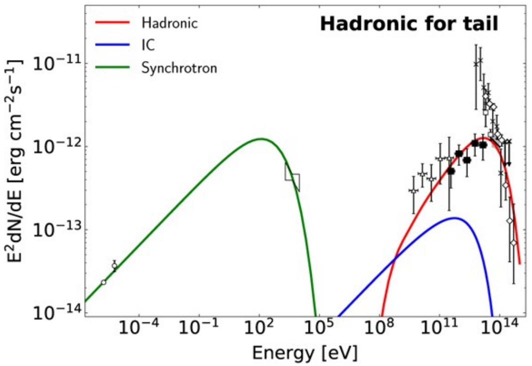


Galactic sources

Credit: A&A, 695, A152 (2025)







Credit: A&A 671, A12 (2023)

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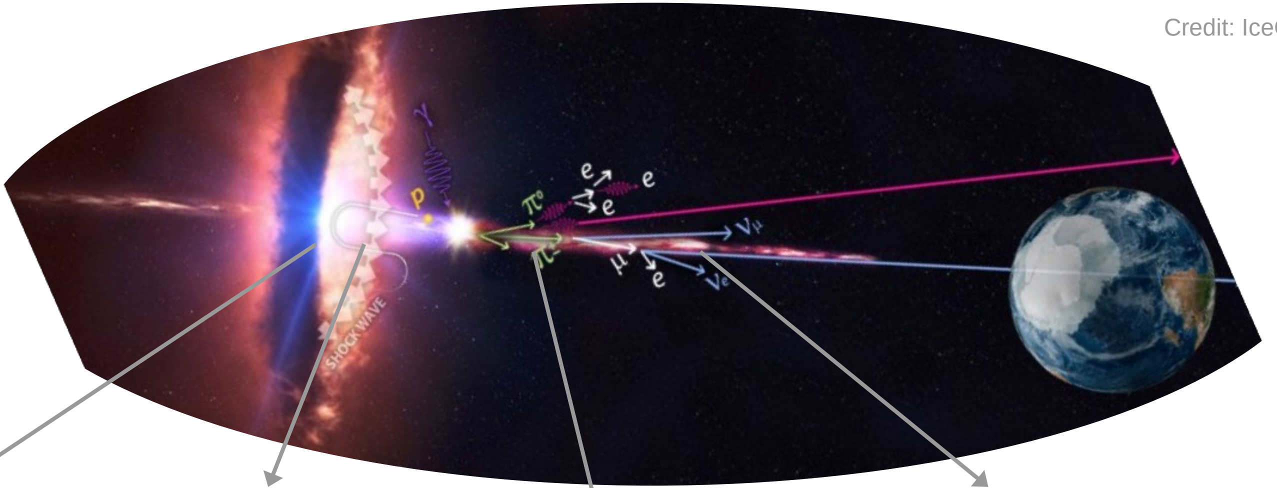

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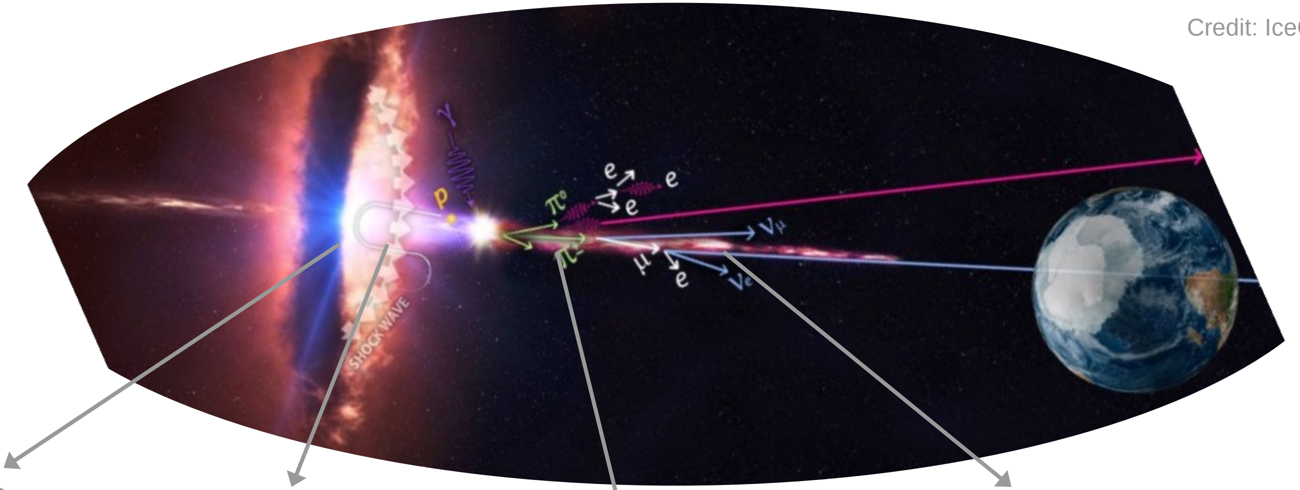

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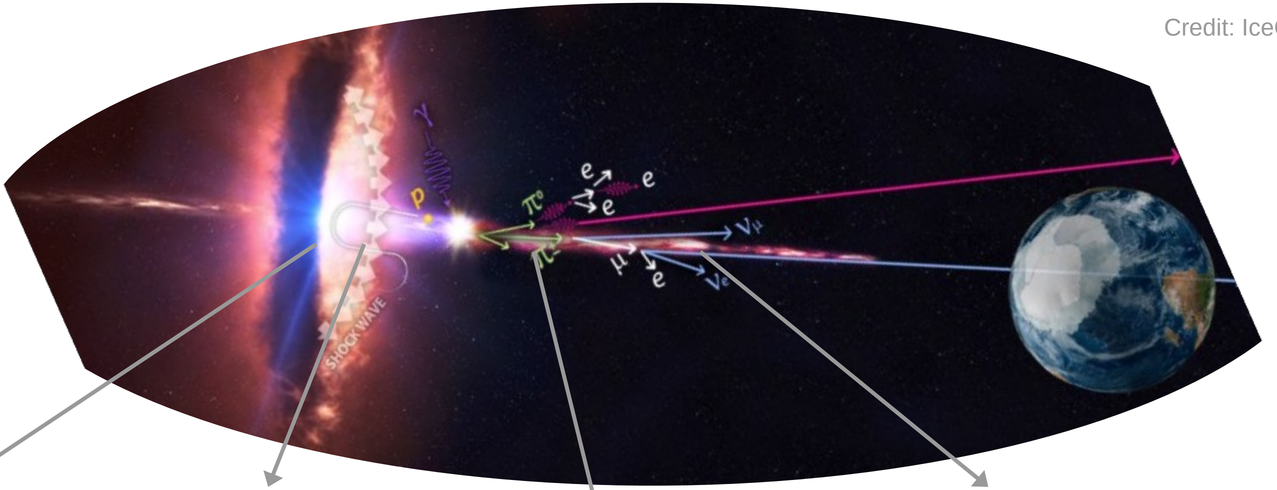

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Doppler boosting

- Enhances the flux when structures move relativistically towards us at an angle θ (e.g. AGN jets):

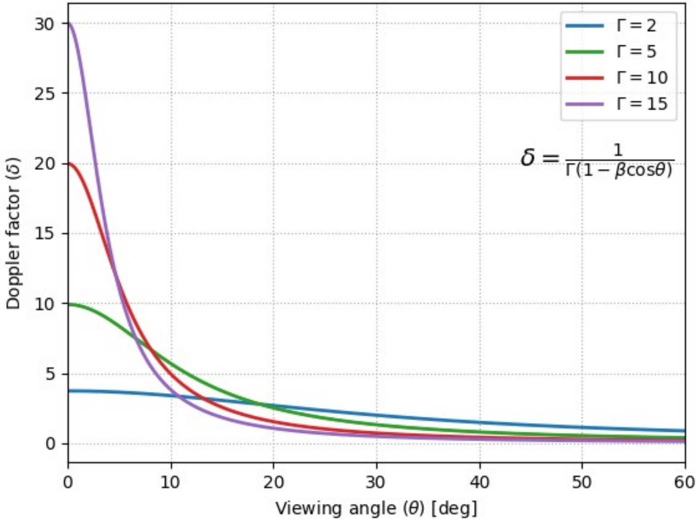
source frame vs. observer frame

$$\nu = \delta \nu'$$

$$dt = \delta^{-1} dt'$$

$$F_\nu(\nu) = \delta^{(3+\Gamma)} F'_\nu(\nu)$$

$$\delta = \frac{1}{\gamma(1-\beta\cos(\theta))}$$



Credit: https://www.mpi-hd.mpg.de/HESS/pages/home/som/2018/04/

Propagation: boosting, absorption,...

Absorption and extinction:

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- Interstellar extinction (IR – UV)

- Interstellar medium grain absorption (X-rays)

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- Synchrotron self-absorption (radio)
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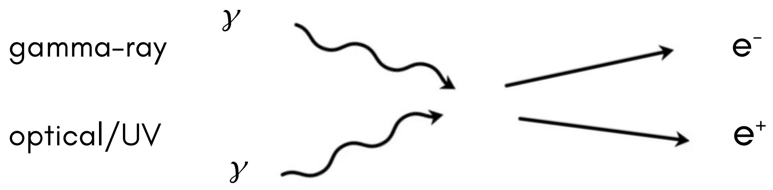
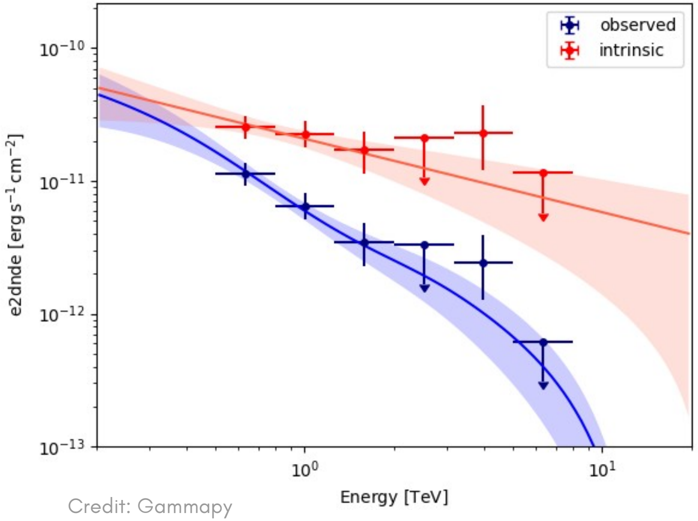
- Interstellar medium grain absorption (X-rays)
- Gamma-gamma absorption (gamma rays)
  - Extragalactic background light
  - Internal photon fields, e.g. accretion disk photons





Credit: Gammapy

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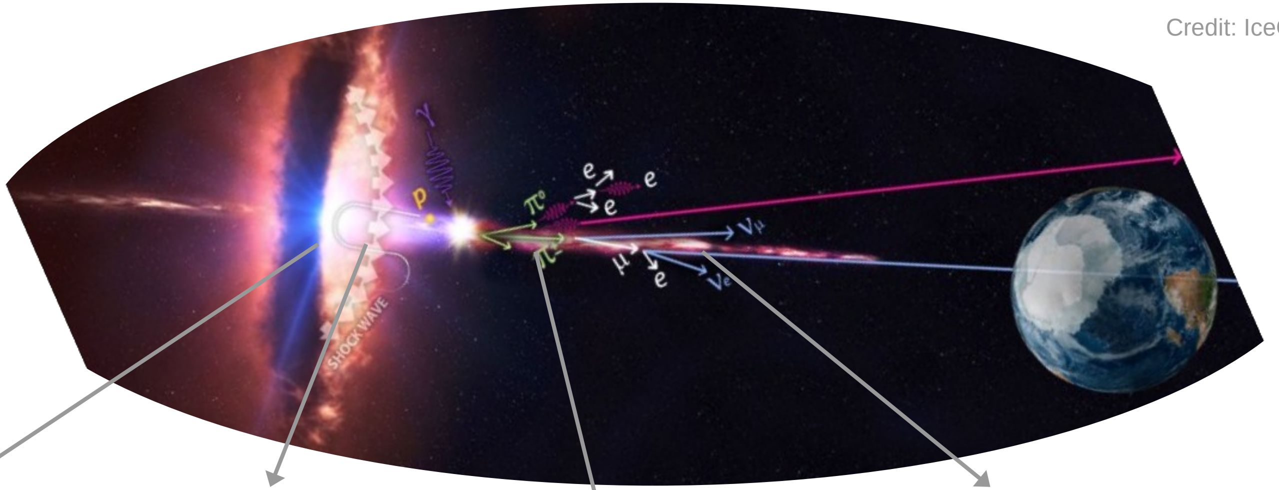

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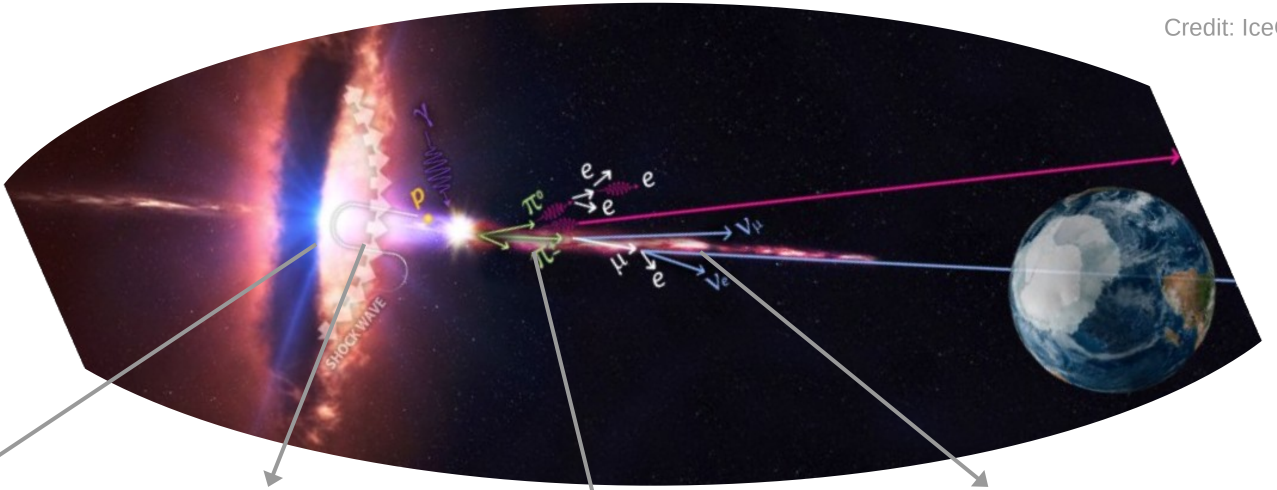

Initial conditions:
Particle plasma,
(GR)-MHD,
PIC simulations
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Particle acceleration & cooling

→ (relativistic) particle distributions

Radiation mechanisms

→ γ distributions

Propagation: absorption, boosting,..

→ altered γ distributions

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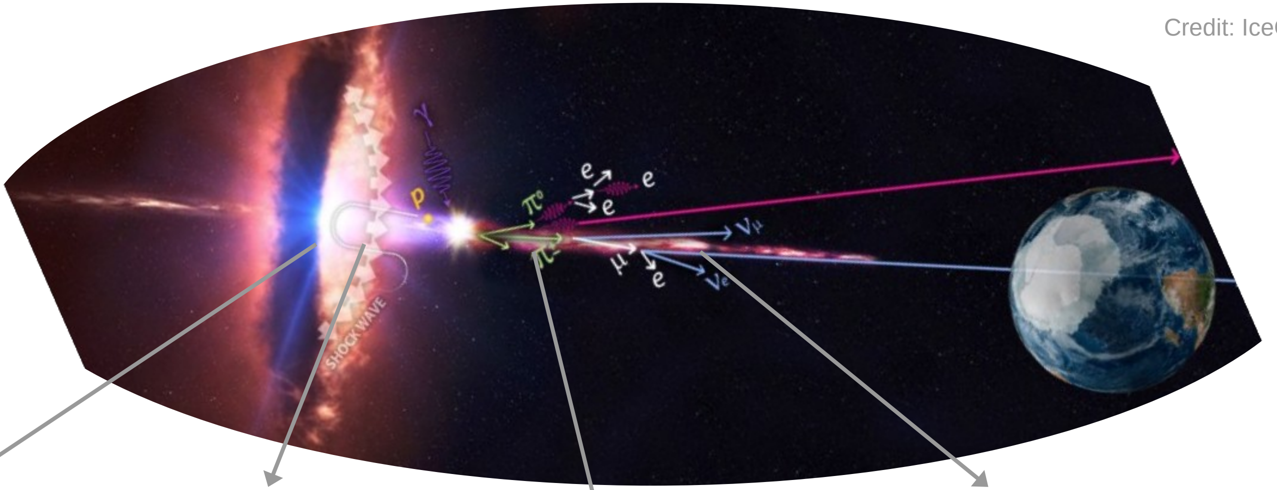

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Modelled SEDs, LCs,...

Fitting

Data

Public tools

Python based/interface:

- Naima
- Jetset
- Agnpy
- AM3
- FLAREMODEL
- ....

C/C++

- GAMERA
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Overview paper of some public codes:

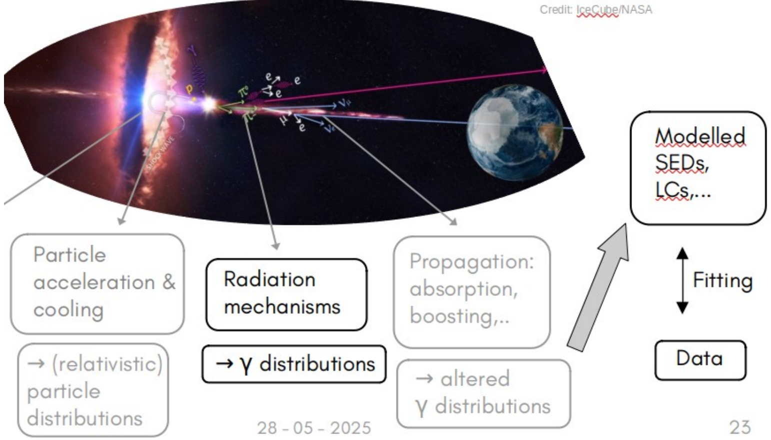
- Galaxies 2022, 10(4), 85; https://doi.org/10.3390/galaxies10040085

Hadronic code comparison paper:

- arXiv:2411.14218

Naima https://naima.readthedocs.io/en/latest/

- One-zone models
- Input: steady-state particle distributions



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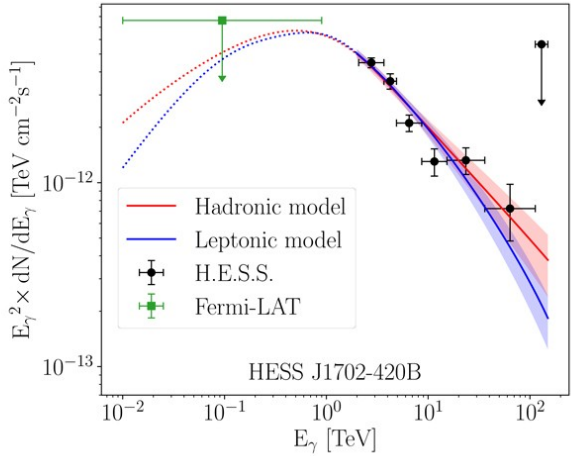
Often used for galactic sources, but can be adapted for jetted sources

Credit: A&A 653, A152 (2021)



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  - But only independent zones (no interaction)
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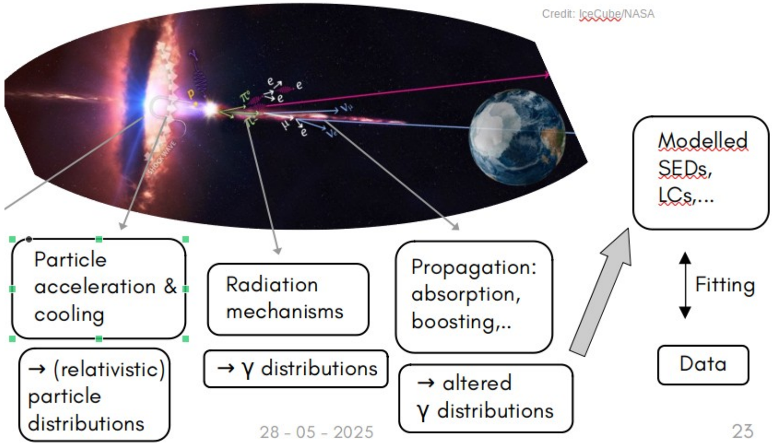

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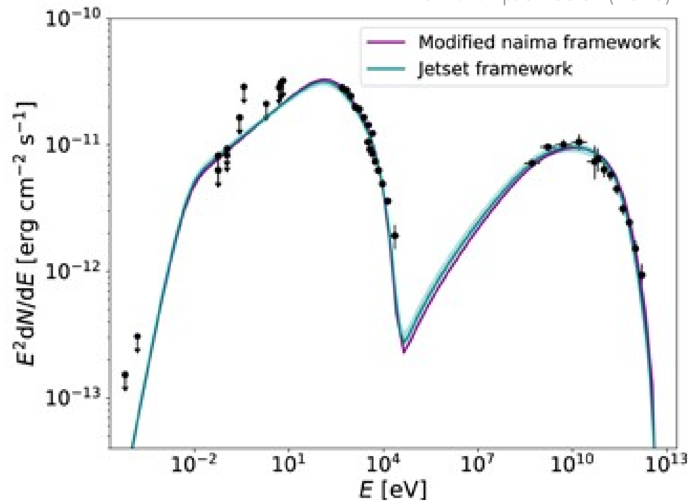
Often used for AGN

Credit: ApJS 266 37 (2023)



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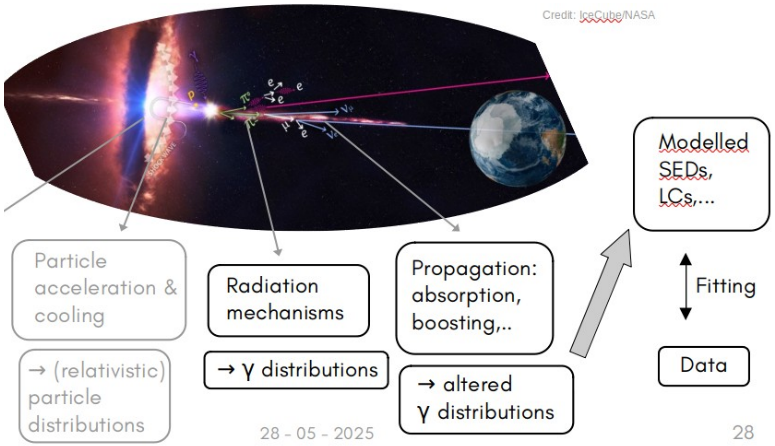

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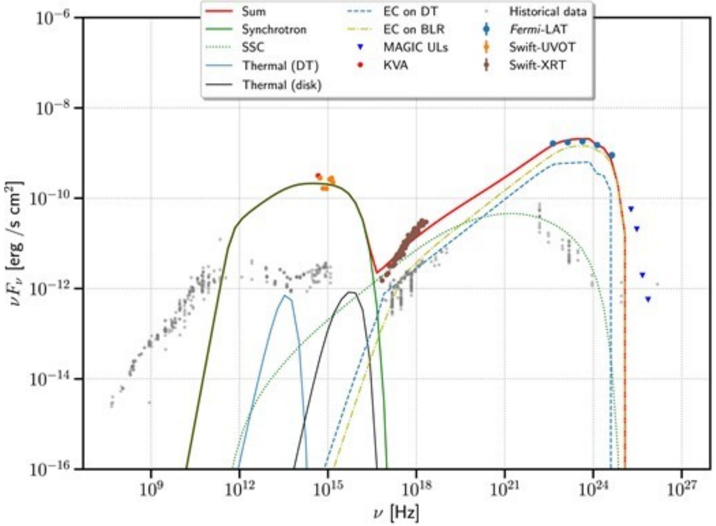
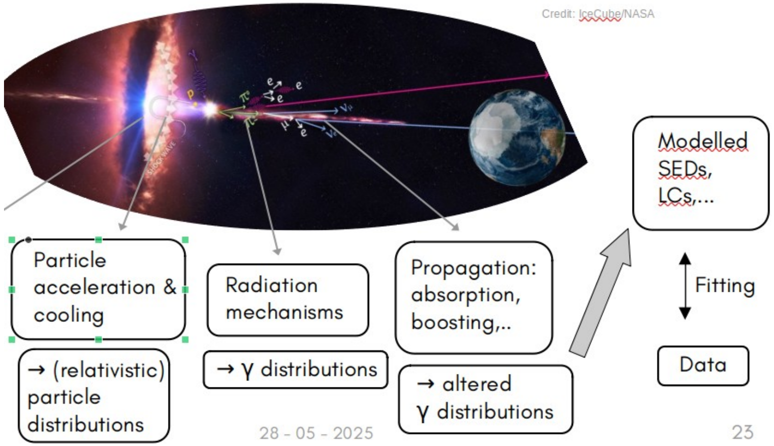
Often used for AGN, especially FSRQs.

Credit: MNRAS, 535, 2, p. 1484-1506 (2024)



(b) CTA 102

AM3 https://am3.readthedocs.io/en/latest/index.html



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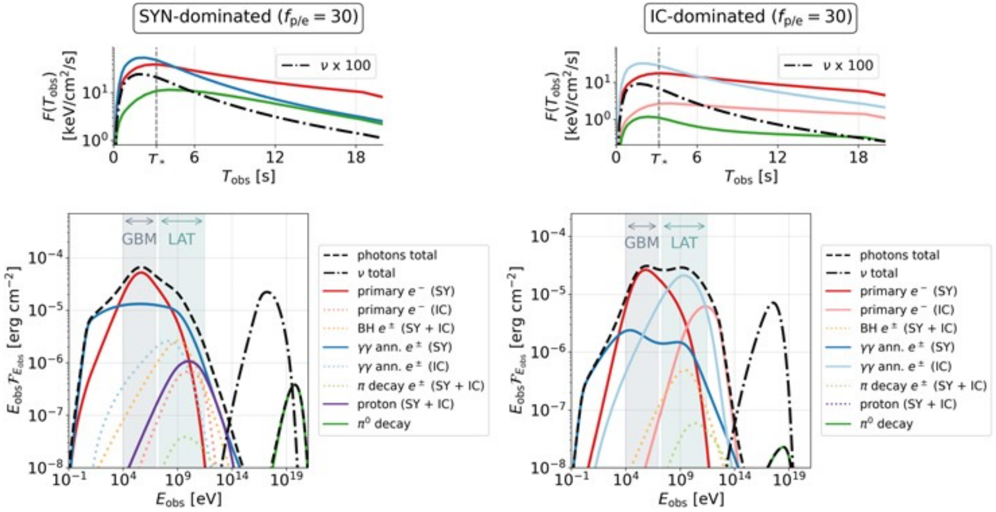
Credit: ApJ 950 28 (2023)



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  3. Fit to data → allows to constrain parameter space of the environments/particle distribution
     - Currently mostly done on flux points (SEDs)
     - Better to do it on count data (dl3) itself → Gammapy
       https://github.com/mireianievas/gammapy_mwl_workflow

Thank you
for
your attention!