image credit M. Rebisz

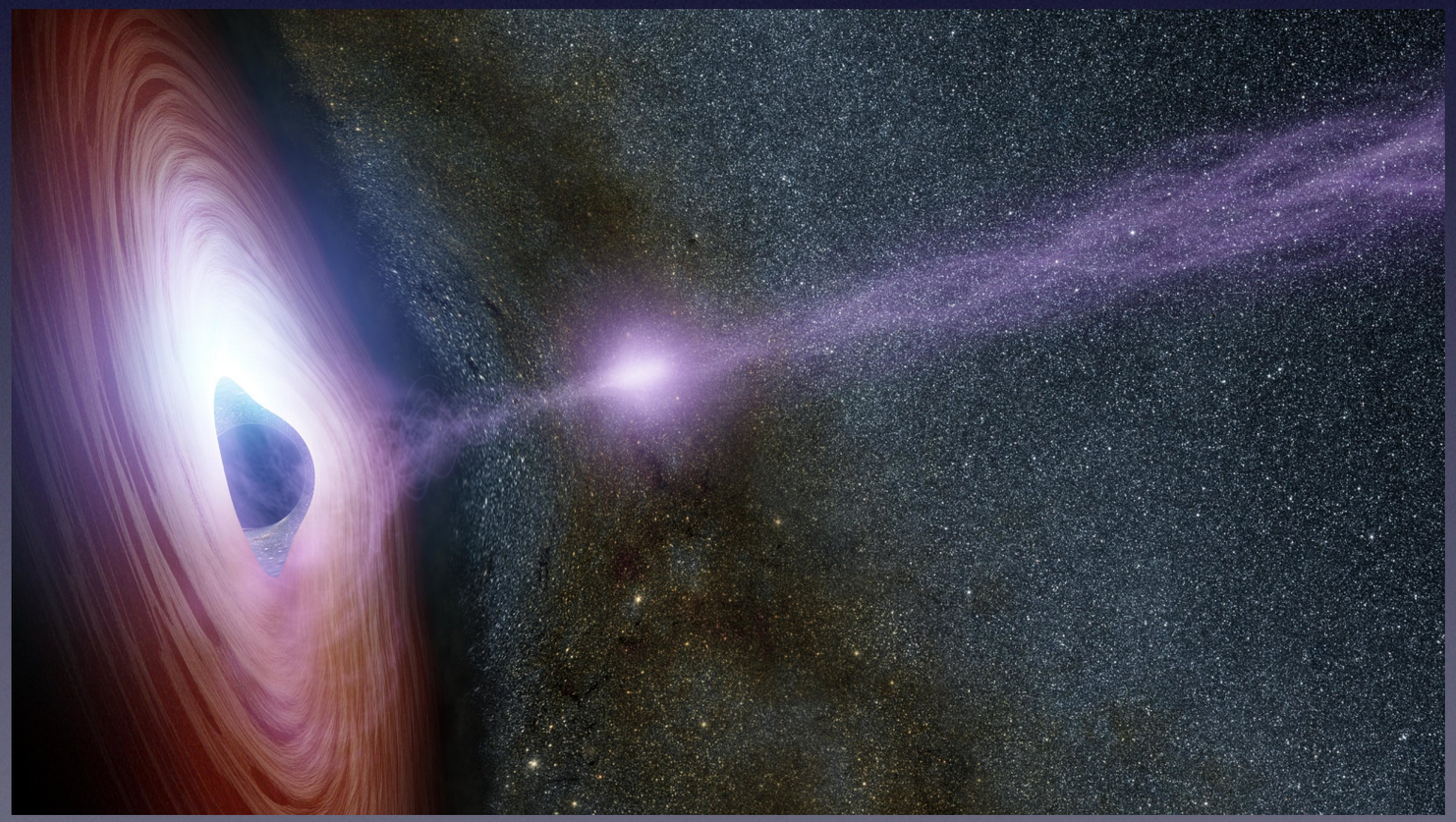
A Multimessenger Study of Blazars

Narek Sahakyan
ICRANet Armenia

XVIII International Conference on Topics in Astroparticle and Underground Physics 2023

Blazars: AGN with Jet Aligned to Our Line of Sight

Blazars are a special subclass of quasars. The common model for blazar emission is that these sources are quasars in which a relativistic jet is pointing at the observer, or very close to the observer's line of sight (Beckmann & Shrader, 2012)

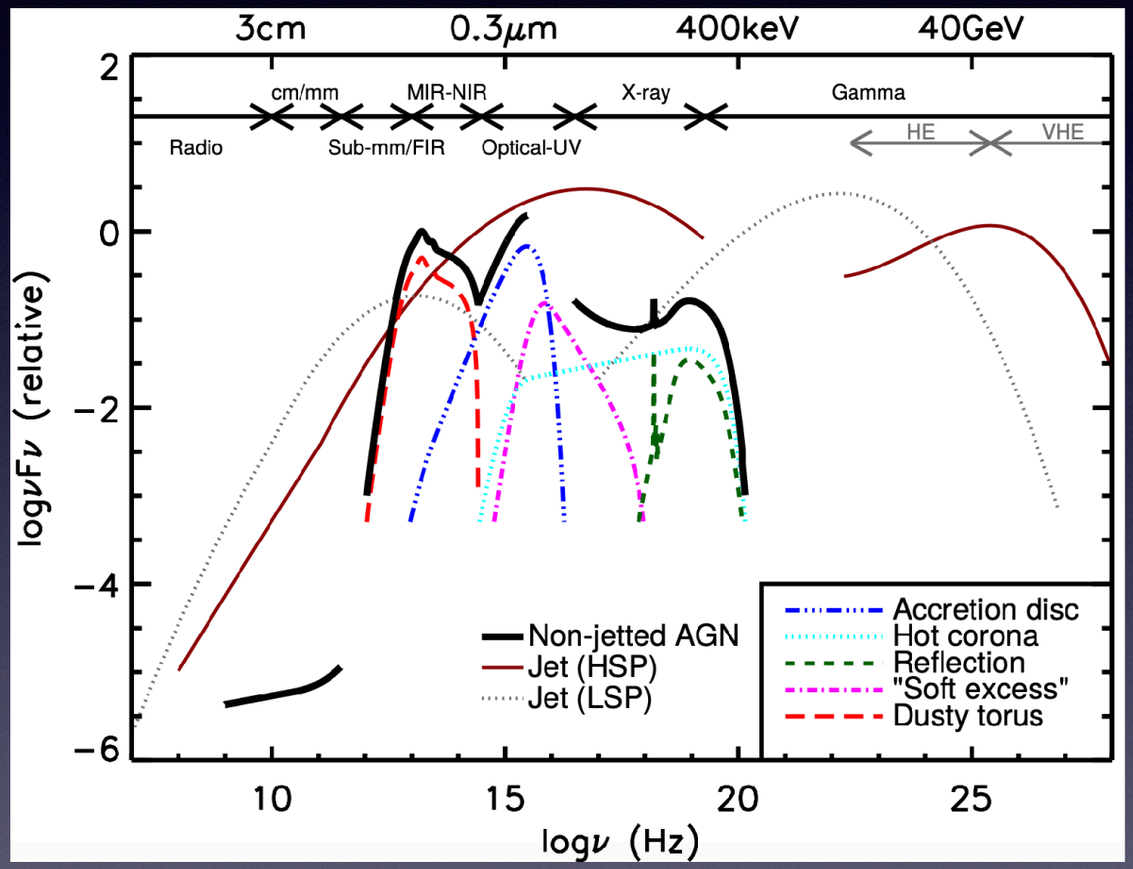


Doppler Amplification: The radiation from the jet is amplified due to the relativistic motion.

Strong Gamma-Ray Sources: Blazars are dominant extragalactic sources in the gamma-ray sky.

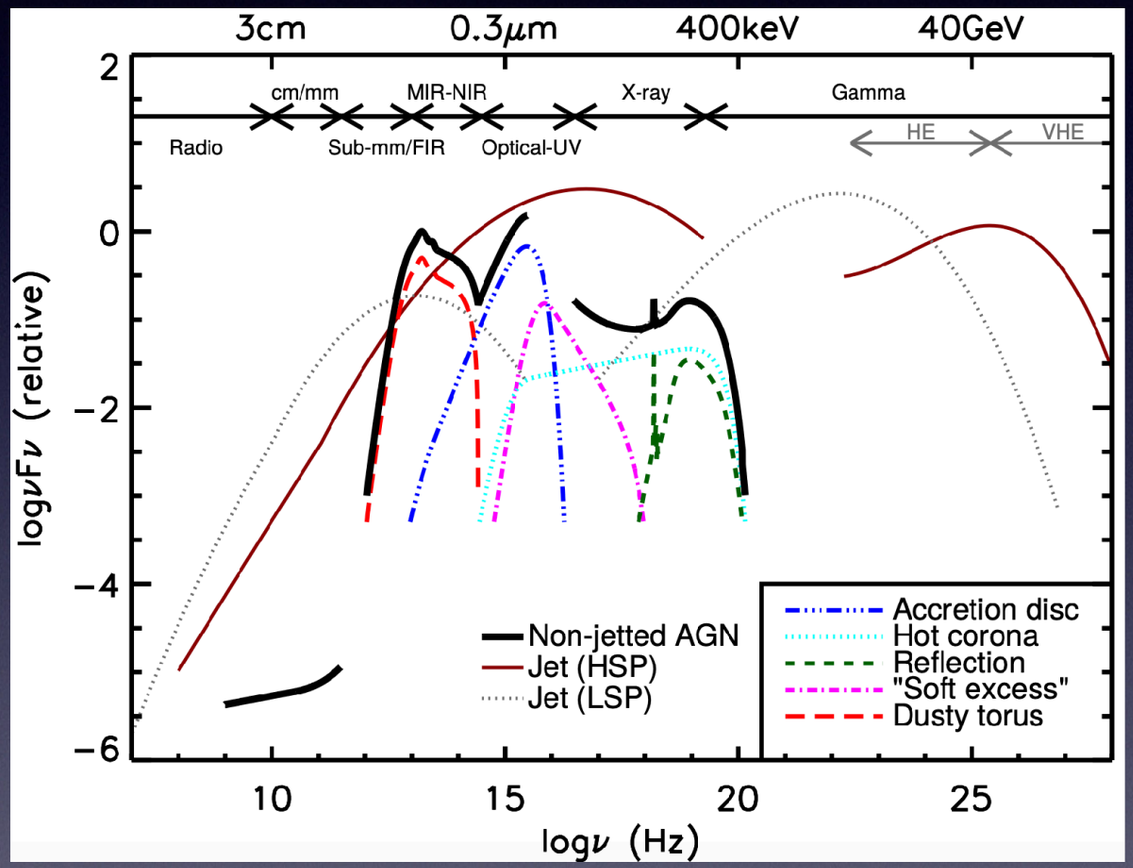
Polarization: The radiation from blazars is often polarized, especially in the radio and optical bands.

Multiwavelength Emission from Blazars



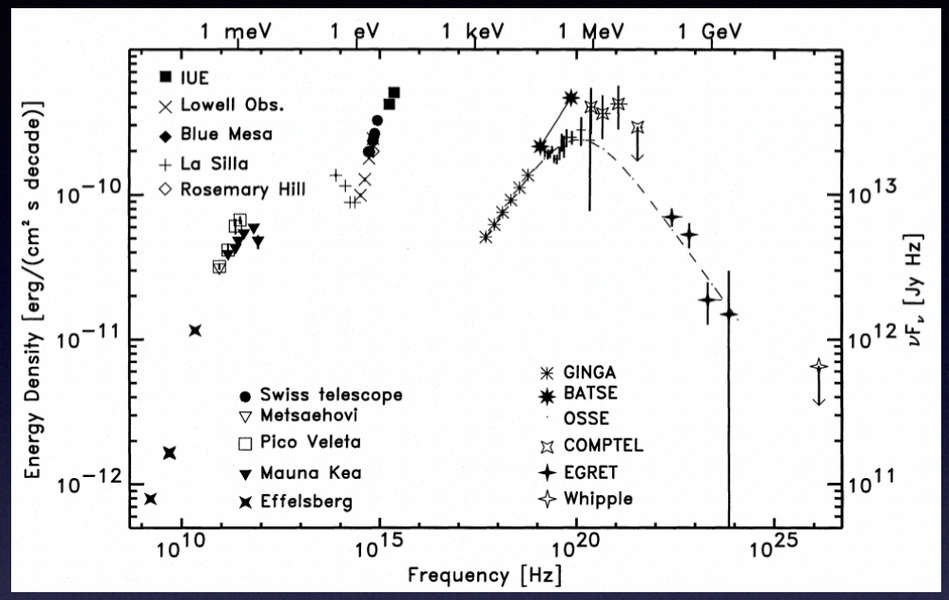
Padovani et al. A&A Review, 2017

Multiwavelength Emission from Blazars



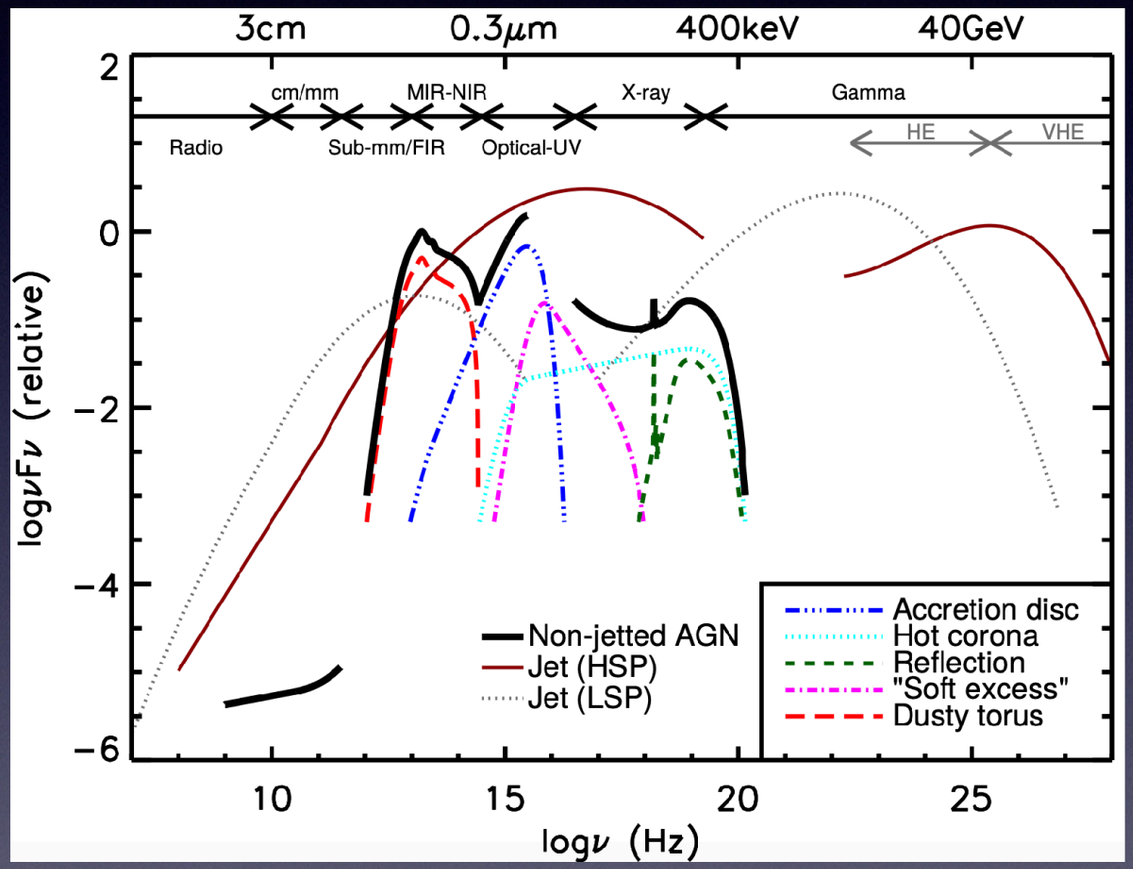
Padovani et al. A&A Review, 2017

1995



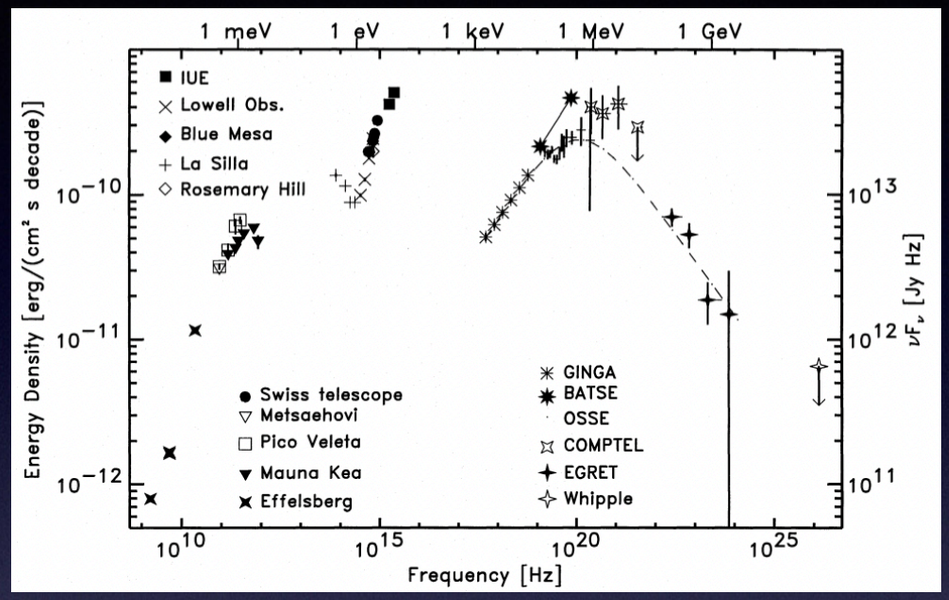
Lichti, et al, A&A, 1995

Multiwavelength Emission from Blazars



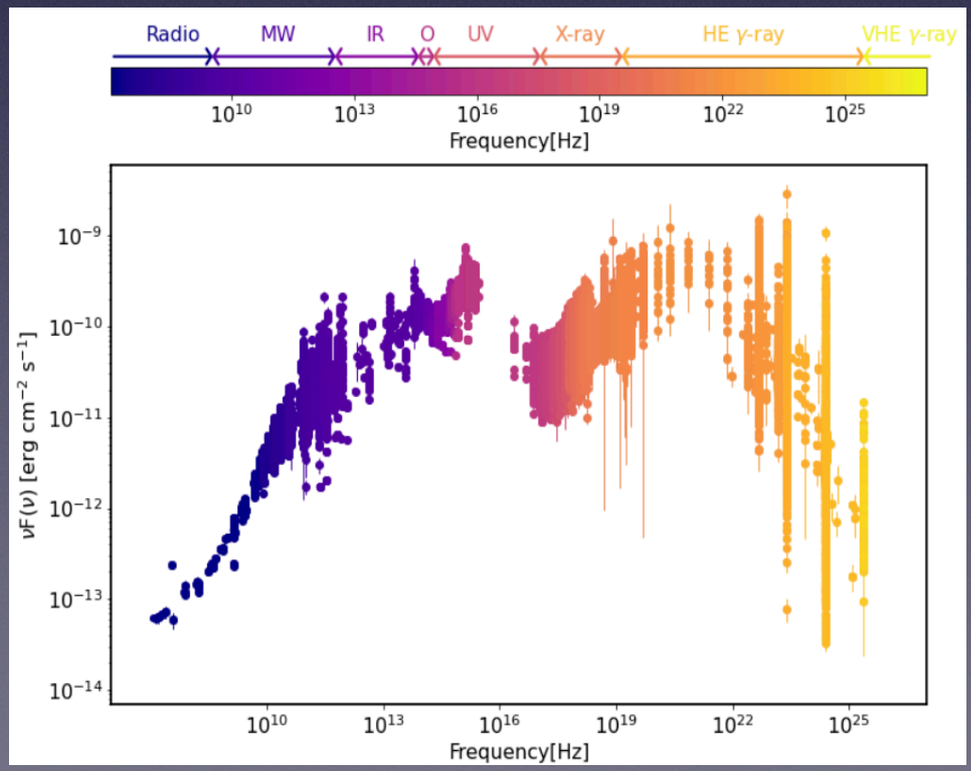
Padovani et al. A&A Review, 2017

1995

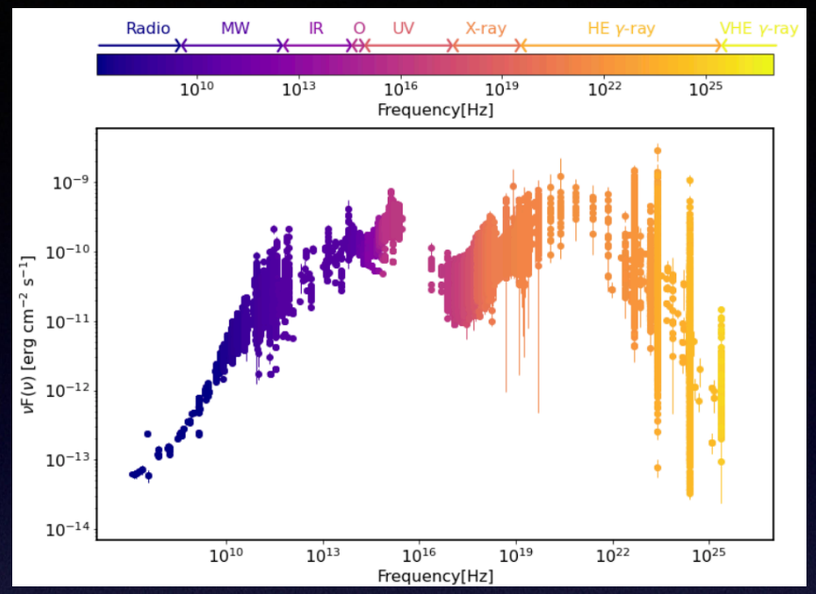


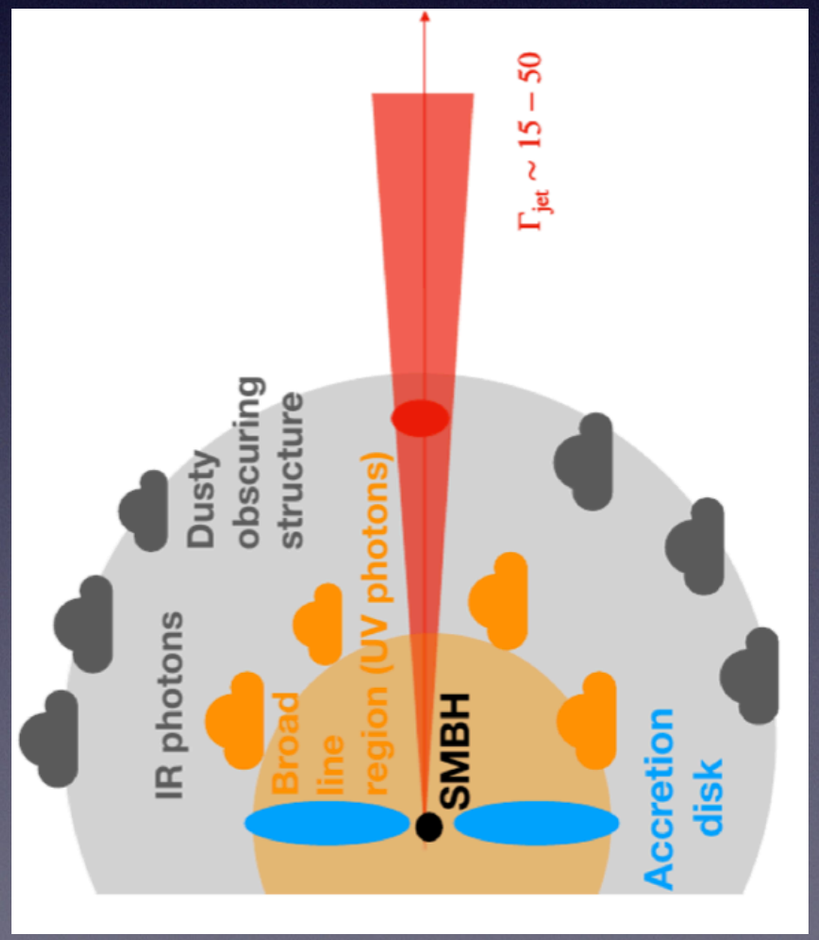
Lichti, et al, A&A, 1995

now....



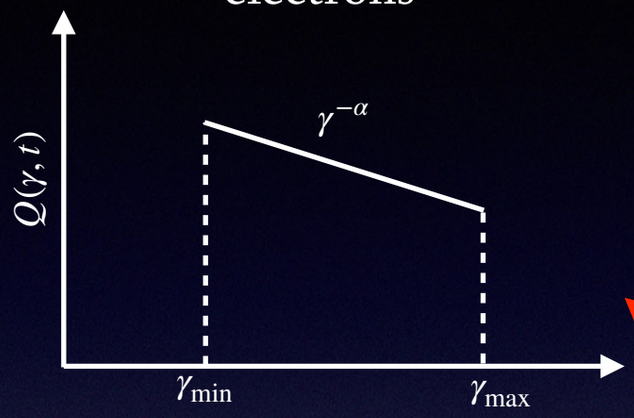
The origin of emission



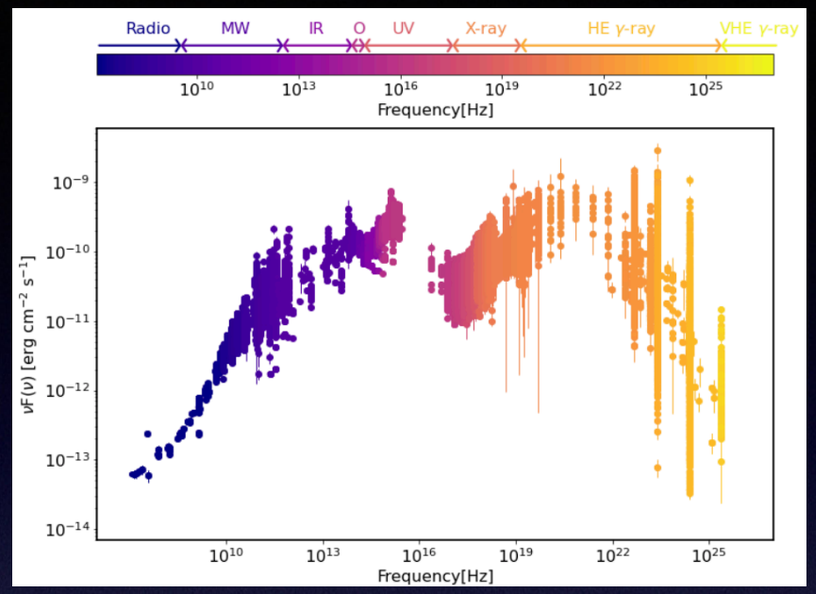


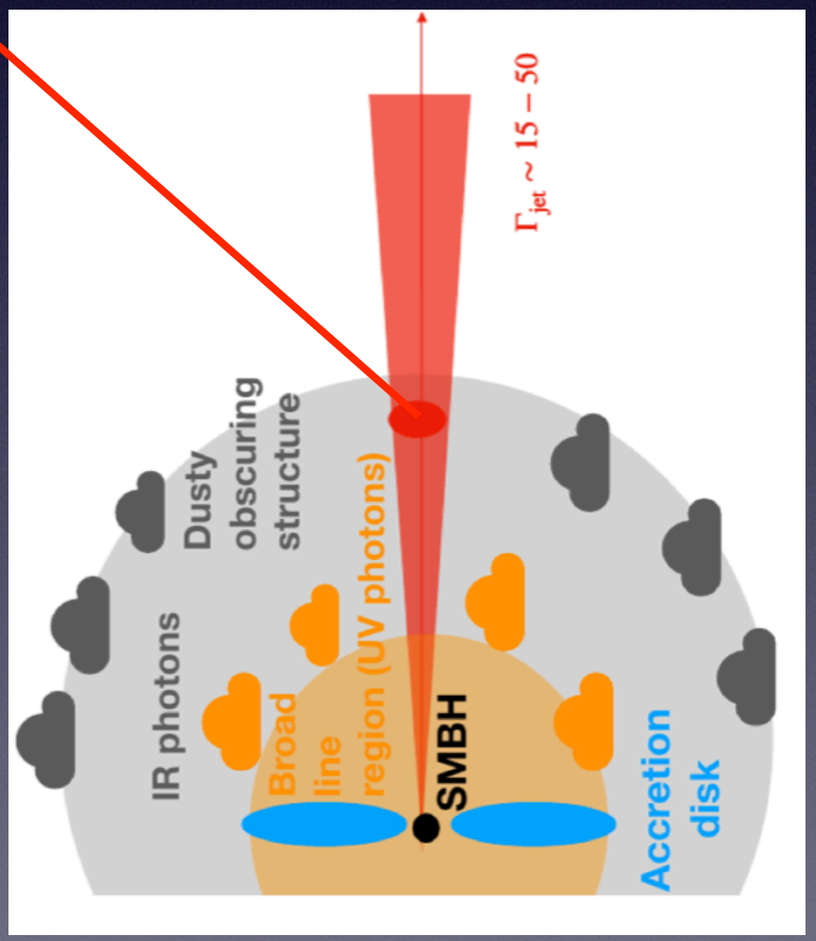
The origin of emission

Injection or acceleration of electrons



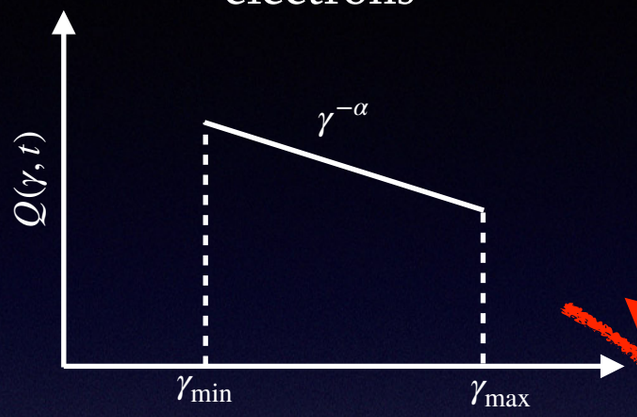
synchrotron radiation



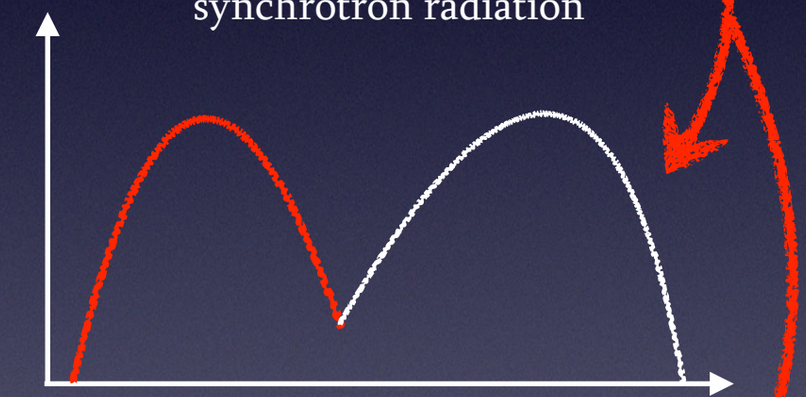


The origin of emission

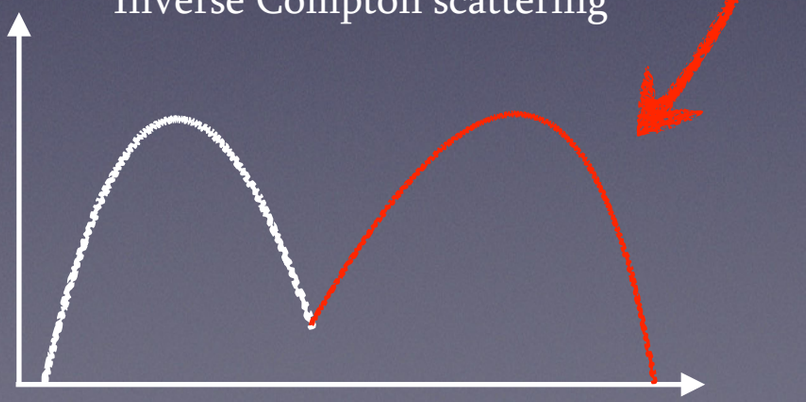
Injection or acceleration of electrons

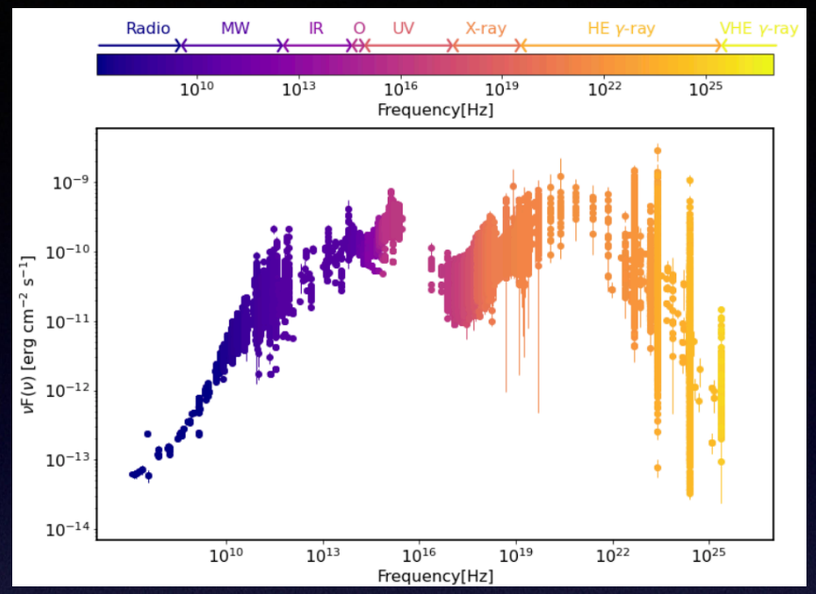


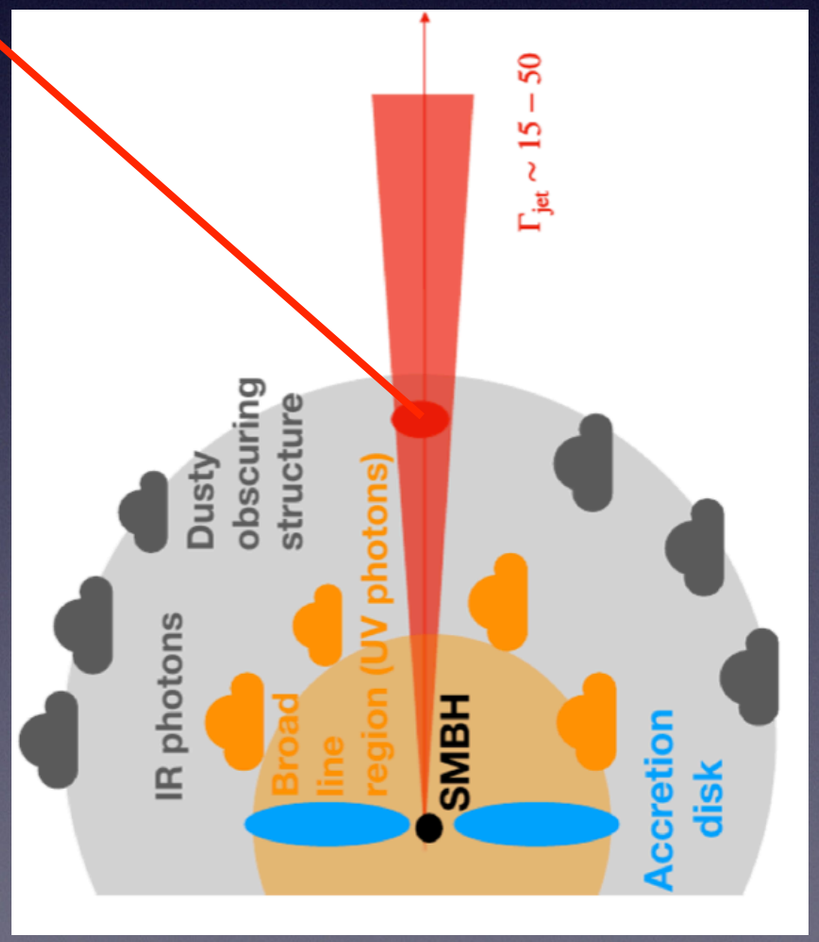
synchrotron radiation



Inverse Compton scattering

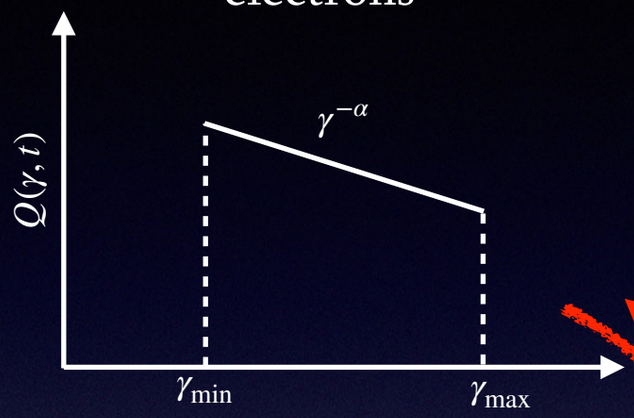




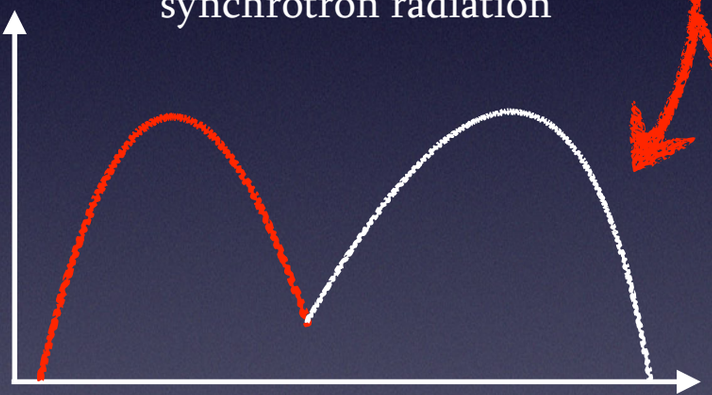


The origin of emission

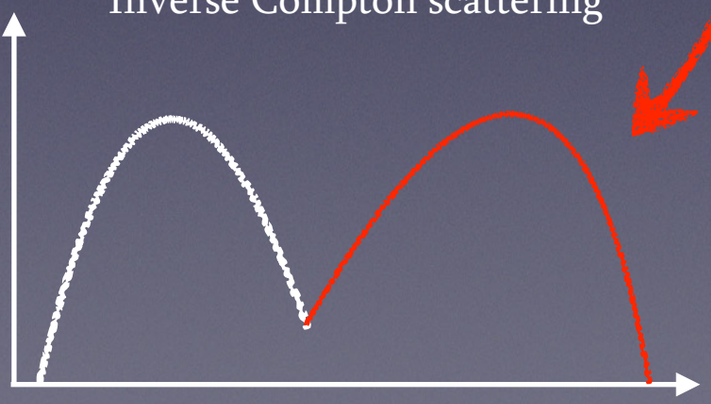
Injection or acceleration of electrons

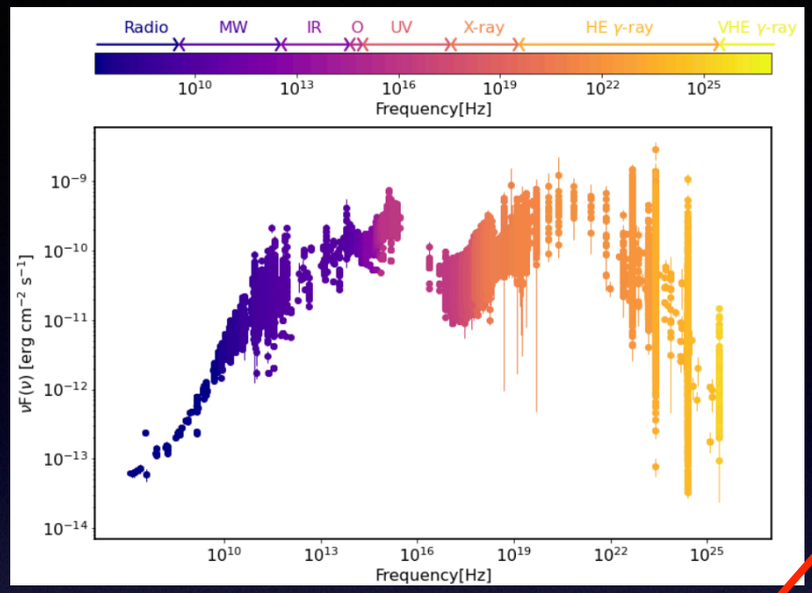


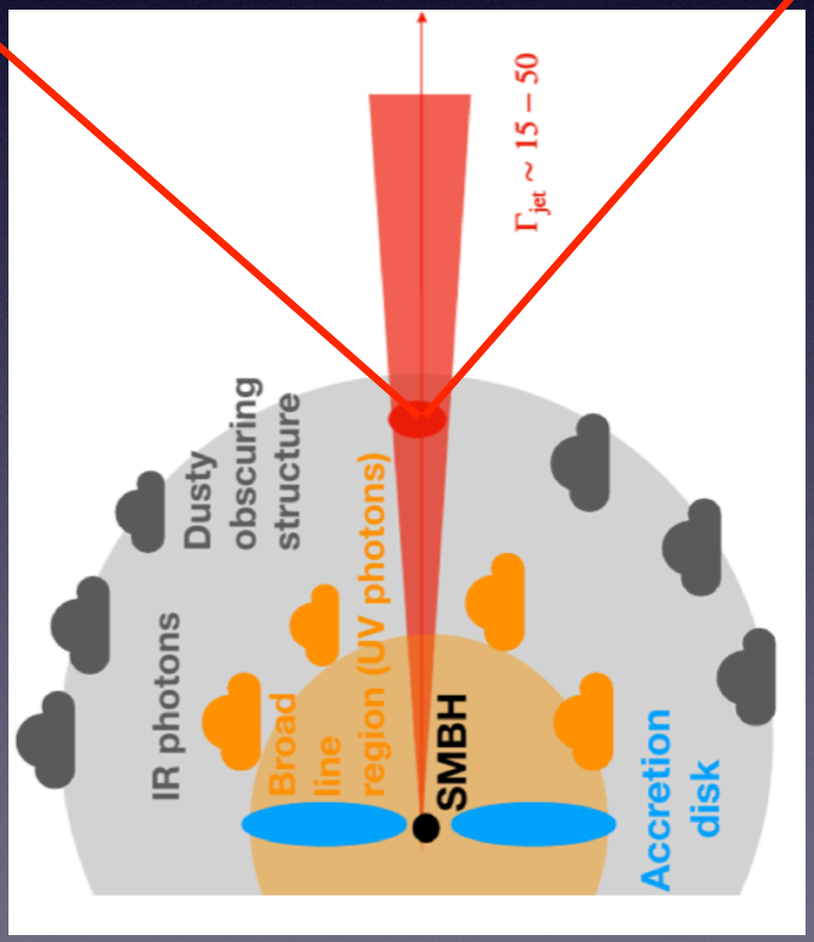
synchrotron radiation



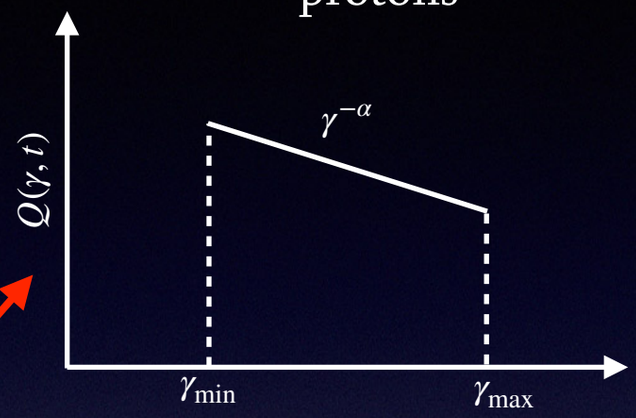
Inverse Compton scattering





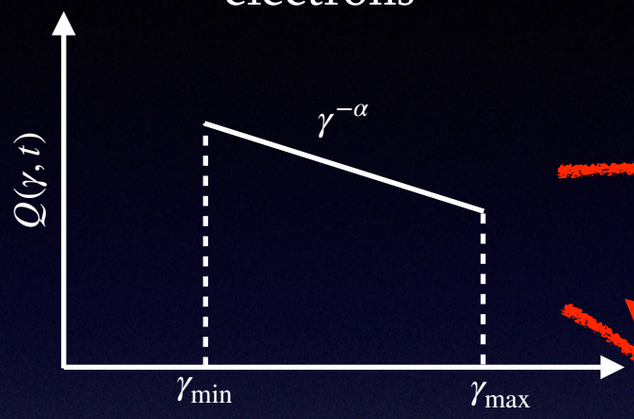


Injection or acceleration of protons

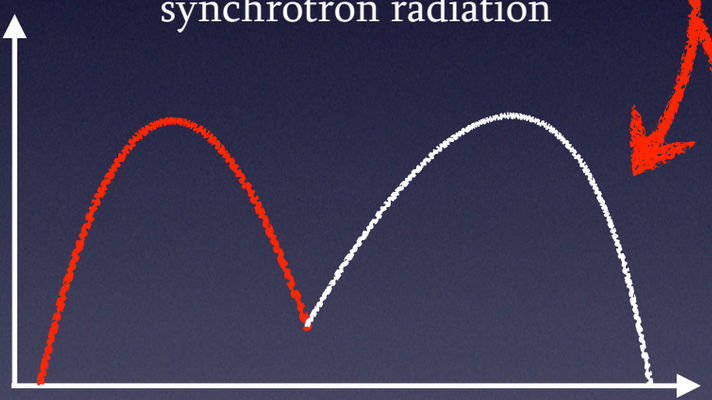


The origin of emission

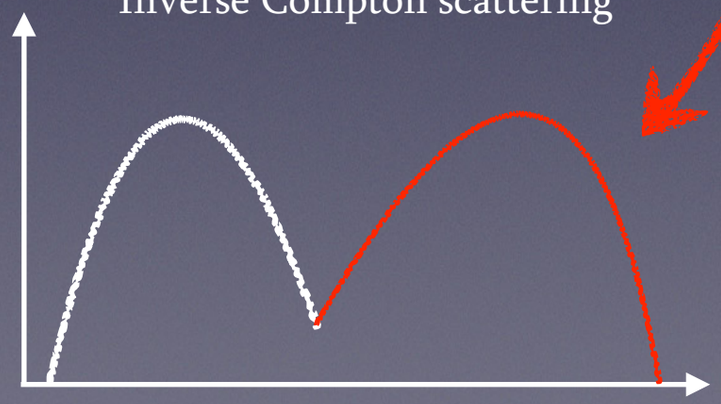
Injection or acceleration of electrons

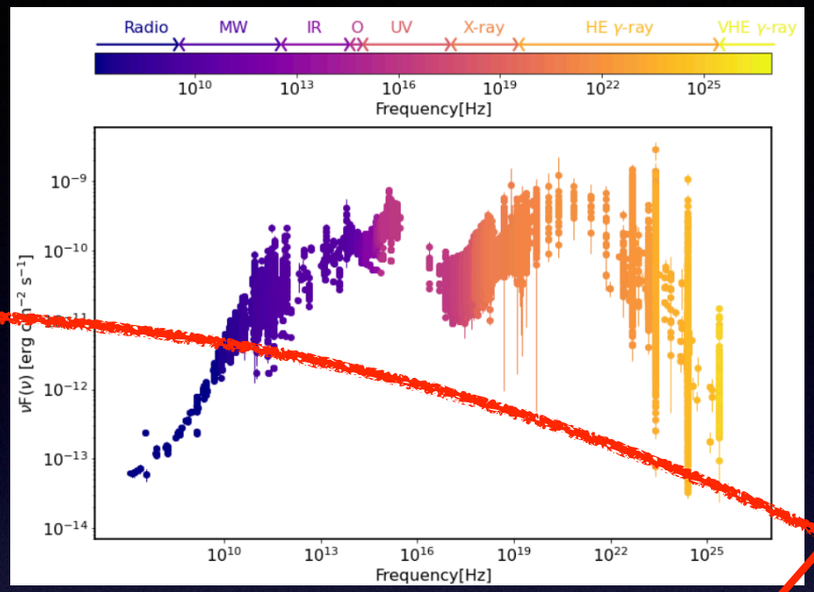


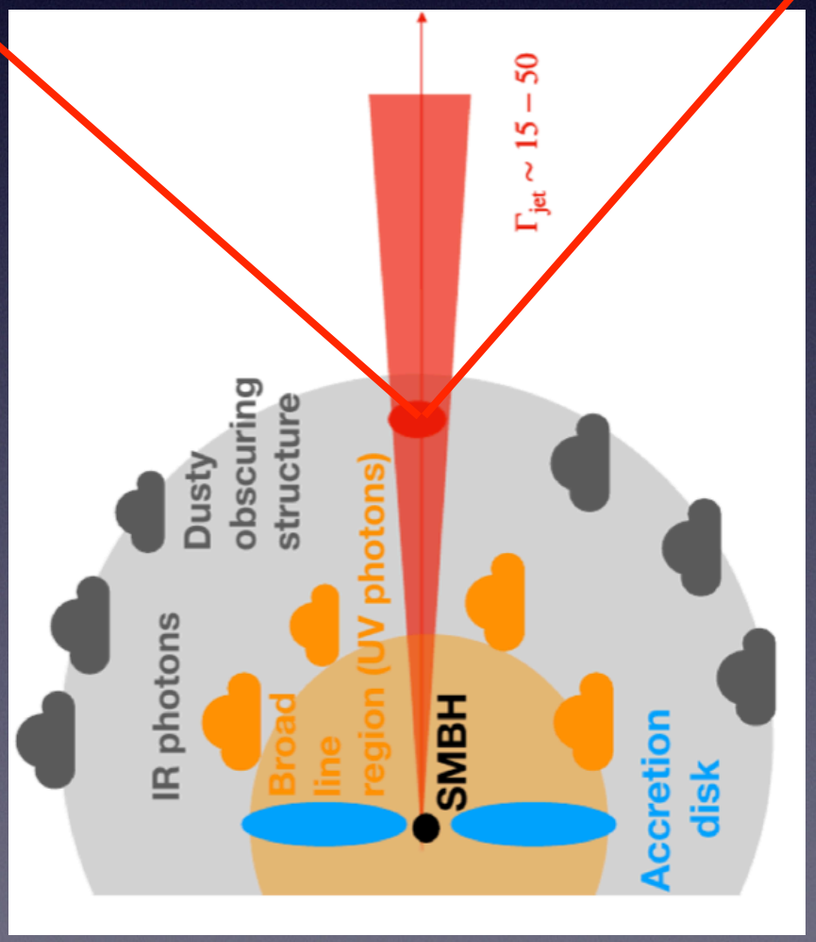
synchrotron radiation



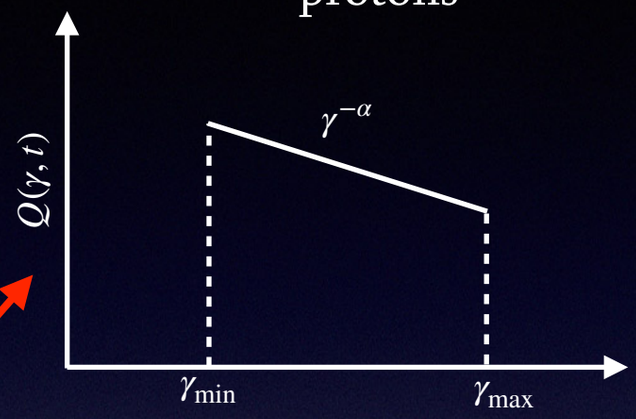
Inverse Compton scattering



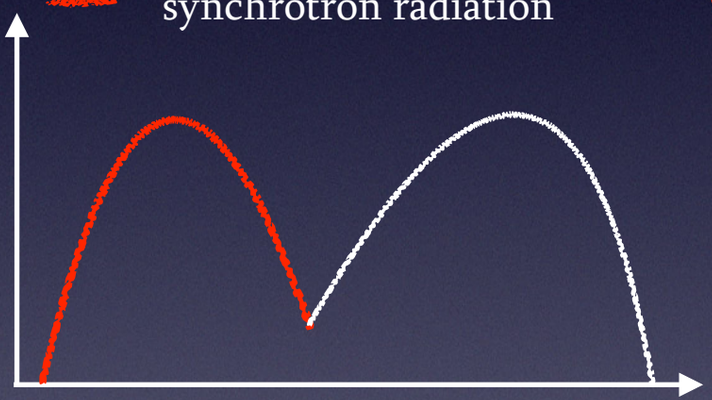




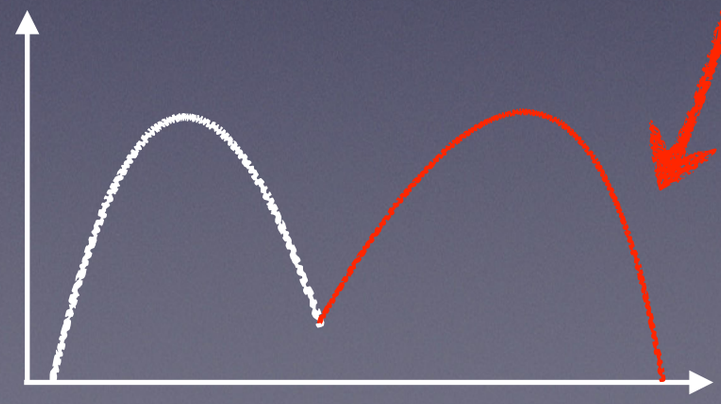
Injection or acceleration of protons



synchrotron radiation

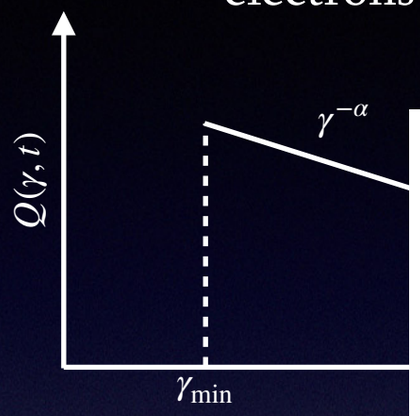


Proton emission

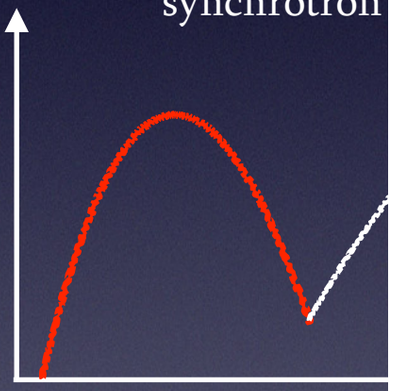


The origin of emission

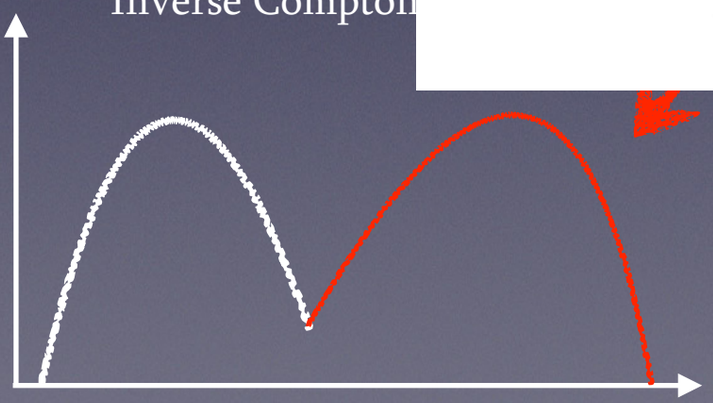
Injection or acceleration of electrons



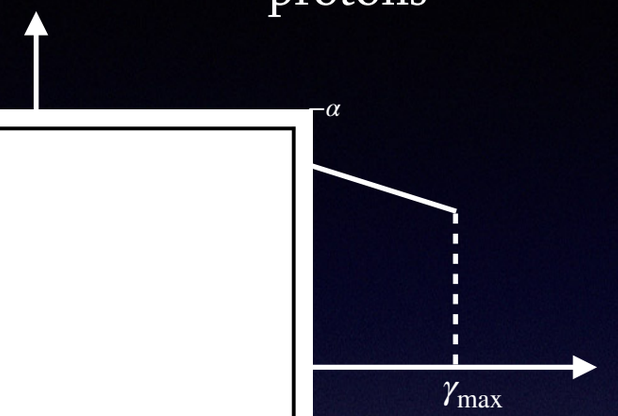
synchrotron



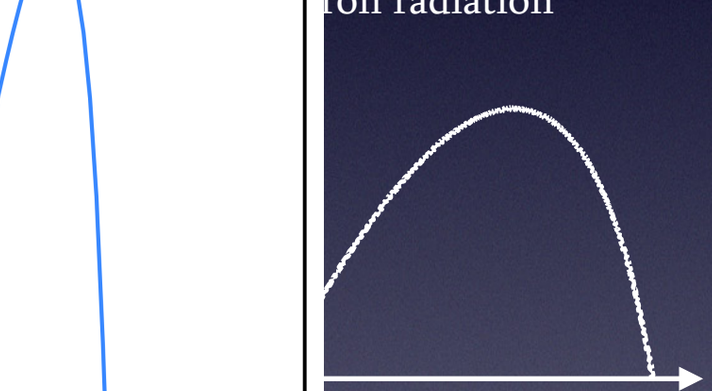
Inverse Compton



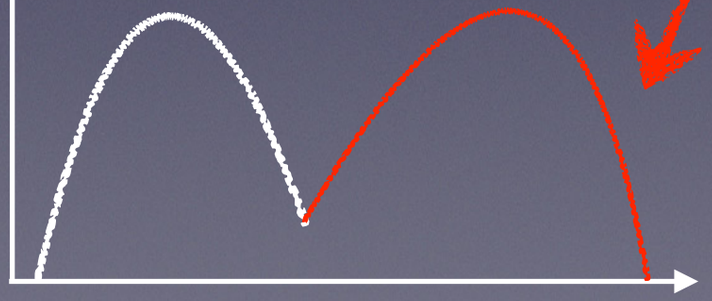
Injection or acceleration of protons

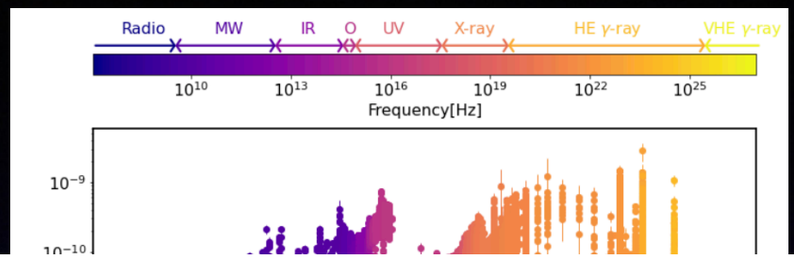


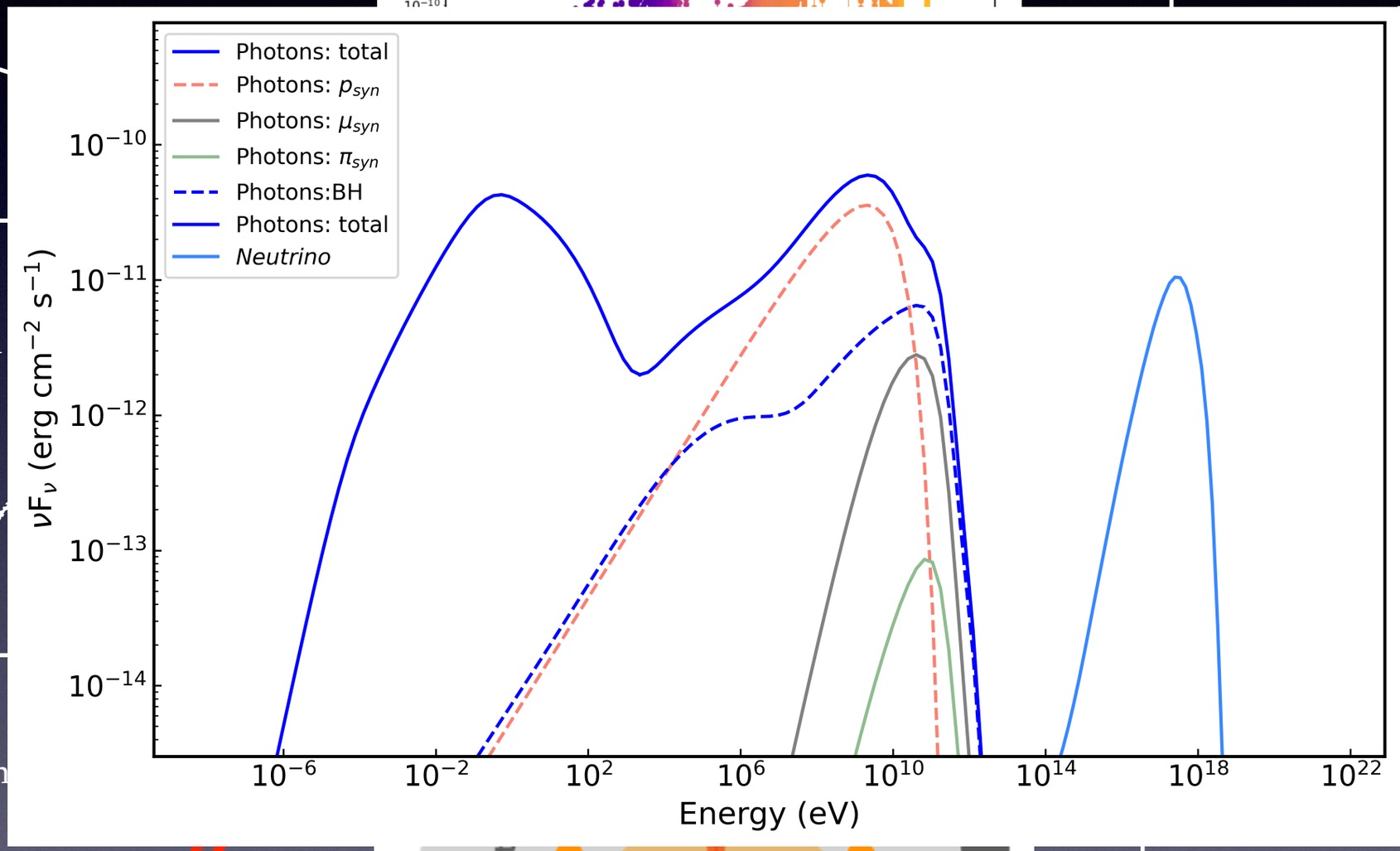
ron radiation

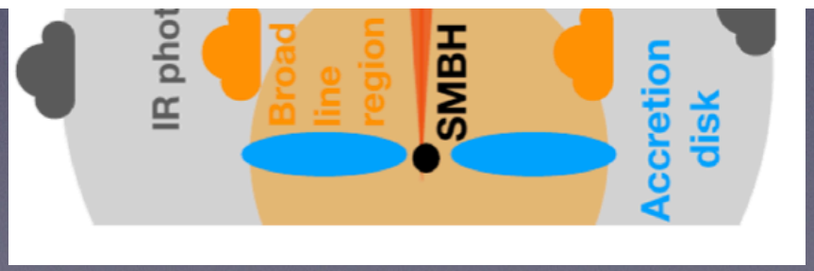


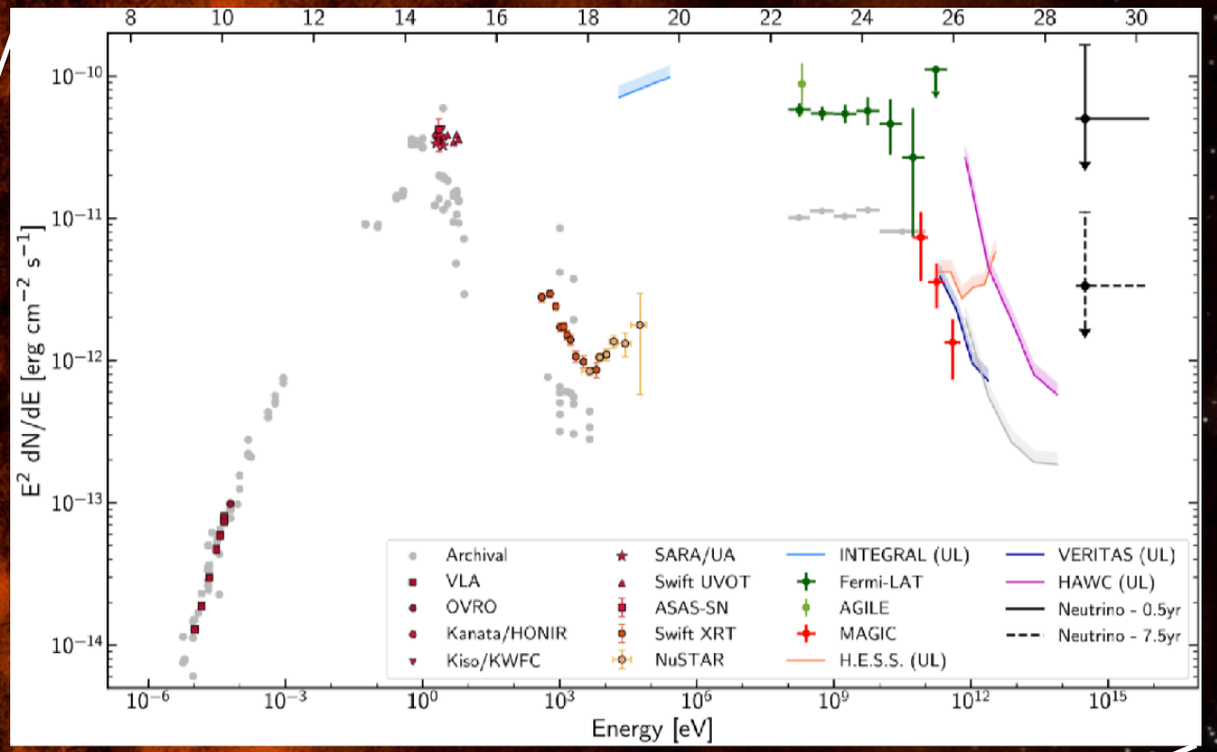
on emission



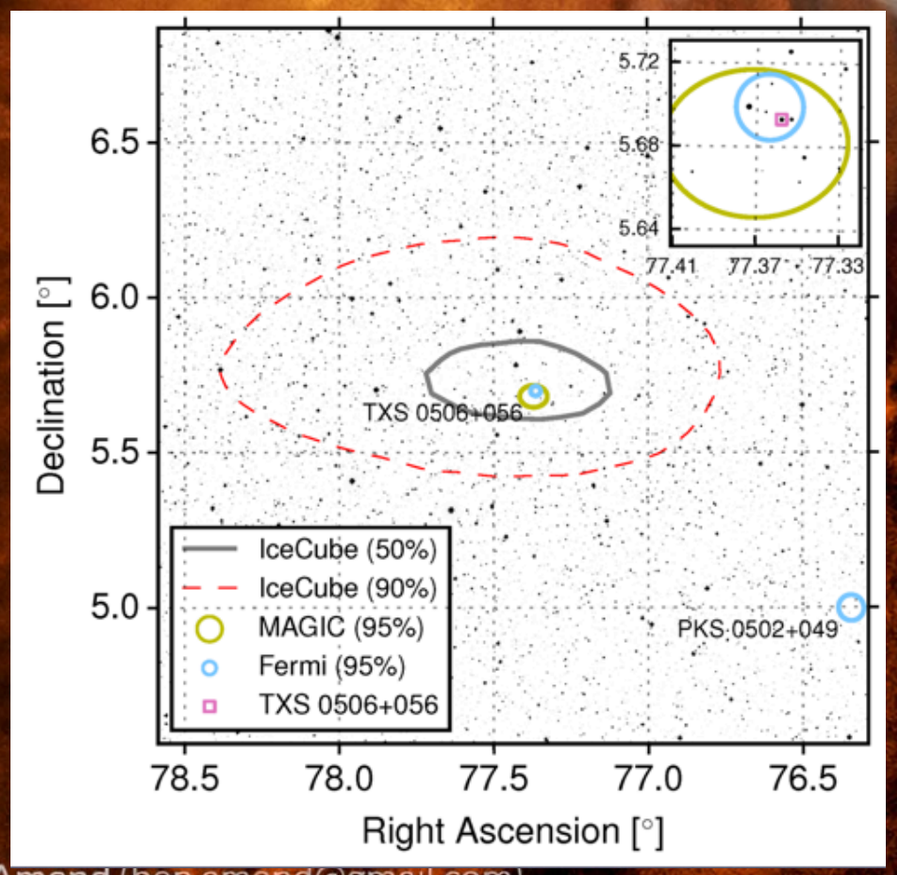






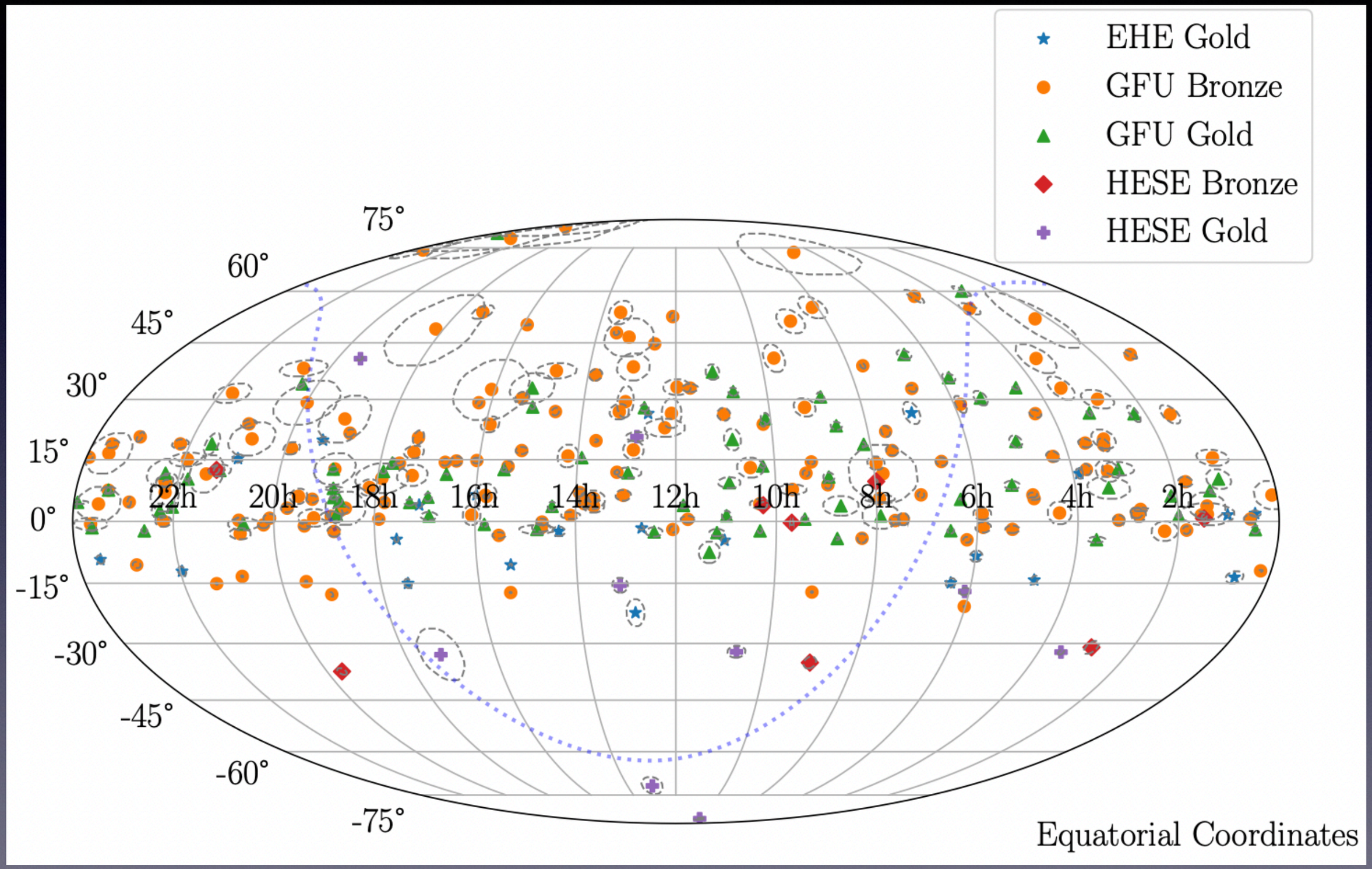


IceCube Collaboration 2018



Amend (ben.amend@gmail.com)

All-sky distribution of the alerts



IceCube collaboration 2023

Next major neutrino source candidate ?

TITLE: GCN CIRCULAR
NUMBER: 31191
SUBJECT: IceCube-211208A - IceCube observation of a high-energy neutrino candidate track-like event
DATE: 21/12/08 21:28:14 GMT
FROM: Marcos Santander at U. Alabama/IceCube <jmsantander@ua.edu>

The IceCube Collaboration (http://icecube.wisc.edu/) reports:

On 2021-12-08 at 20:02:51.1 UT IceCube detected a track-like event with a moderate probability of being of astrophysical origin. The event was selected by the ICECUBE_Astrotrack_Bronze alert stream. The average astrophysical neutrino purity for Bronze alerts is 30%. This alert has an estimated false alarm rate of 1.197 events per year due to atmospheric backgrounds. The IceCube detector was in a normal operating state at the time of detection.

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon_g_b/136015_21306805.amon, more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 2021-12-08
Time: 20:02:51.1 UT
RA: 114.52 (+2.82 -2.50 deg 90% PSF containment) J2000
Dec: 15.56 (+1.81 -1.39 deg 90% PSF containment) J2000

Next major neutrino source candidate ?

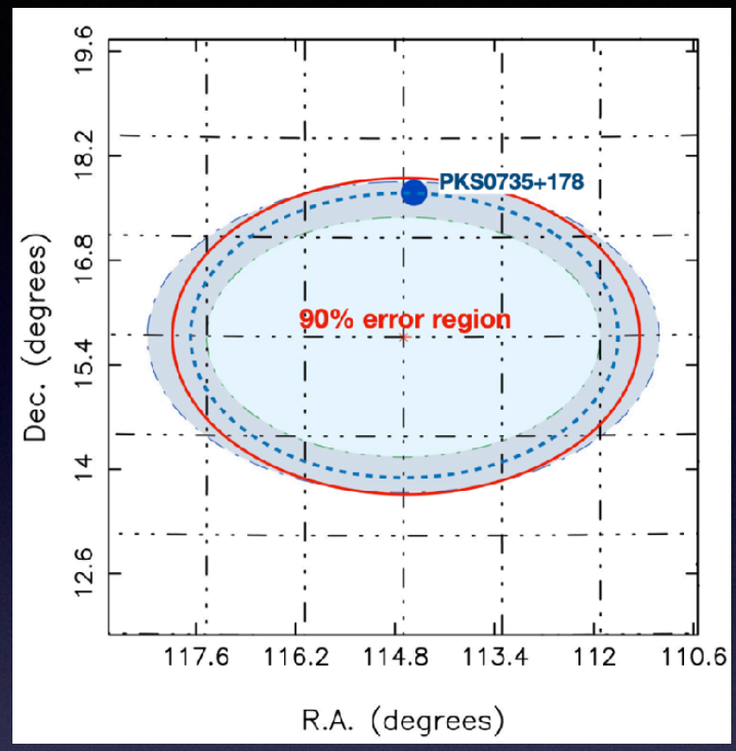
```
TITLE:   GCN CIRCULAR
NUMBER:  31191
SUBJECT: IceCube-211208A - IceCube observation of a high-energy neutrino candidate track-like
event
DATE:    21/12/08 21:28:14 GMT
FROM:    Marcos Santander at U. Alabama/IceCube  <jmsantander@ua.edu>

The IceCube Collaboration (http://icecube.wisc.edu/) reports:

On 2021-12-08 at 20:02:51.1 UT IceCube detected a track-like event with a moderate
probability of being of astrophysical origin. The event was selected by the
ICECUBE_Astrotrack_Bronze alert stream.  The average astrophysical neutrino purity for Bronze
alerts is 30%. This alert has an estimated false alarm rate of 1.197 events per year due to
atmospheric backgrounds. The IceCube detector was in a normal operating state at the time of
detection.

After the initial automated alert
(https://gcn.gsfc.nasa.gov/notices_amon_g_b/136015_21306805.amon, more sophisticated
reconstruction algorithms have been applied offline, with the direction refined to:

Date: 2021-12-08
Time: 20:02:51.1 UT
RA: 114.52 (+2.82 -2.50 deg  90% PSF containment) J2000
Dec: 15.56 (+1.81 -1.39 deg 90% PSF containment) J2000
```



Next major neutrino source candidate ?

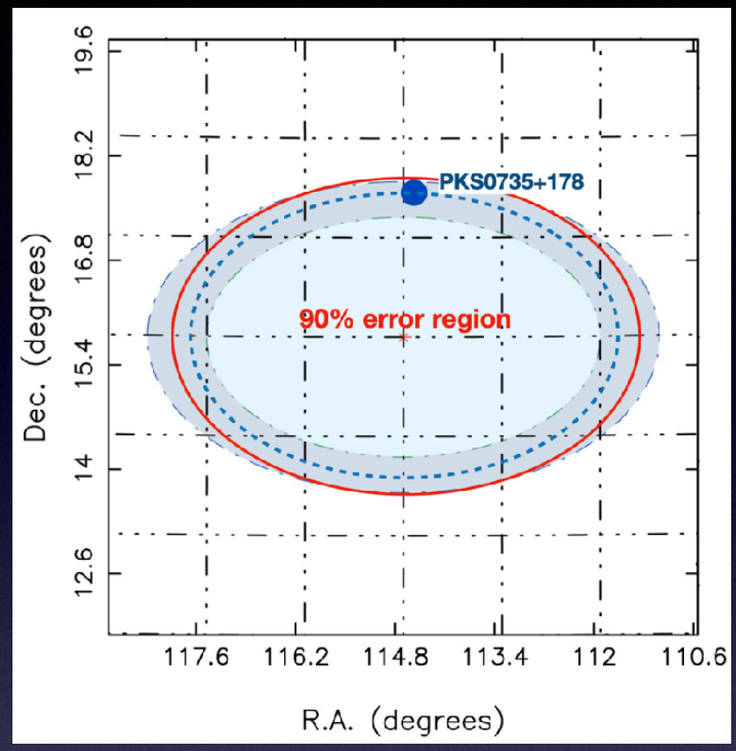
TITLE: GCN CIRCULAR
NUMBER: 31191
SUBJECT: IceCube-211208A - IceCube observation of a high-energy neutrino candidate track-like event
DATE: 21/12/08 21:28:14 GMT
FROM: Marcos Santander at U. Alabama/IceCube <jmsantander@ua.edu>

The IceCube Collaboration (http://icecube.wisc.edu/) reports:

On 2021-12-08 at 20:02:51.1 UT IceCube detected a track-like event with a moderate probability of being of astrophysical origin. The event was selected by the ICECUBE_Astrotrack_Bronze alert stream. The average astrophysical neutrino purity for Bronze alerts is 30%. This alert has an estimated false alarm rate of 1.197 events per year due to atmospheric backgrounds. The IceCube detector was in a normal operating state at the time of detection.

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon_g_b/136015_21306805.amon, more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 2021-12-08
Time: 20:02:51.1 UT
RA: 114.52 (+2.82 -2.50 deg 90% PSF containment) J2000
Dec: 15.56 (+1.81 -1.39 deg 90% PSF containment) J2000



Baksan Underground Scintillation Telescope observation of a GeV neutrino candidate event at the time of a gamma-ray flare of the blazar PKS 0735+17, a possible source of coinciding IceCube and Baikal high-energy neutrinos

ATel #15143; *V. B. Petkov, Yu. F. Novoseltsev and R. V. Novoseltseva (INR RAS) for the Baksan Underground Scintillation Telescope group*
*on **25 Dec 2021; 17:21 UT***

Baikal-GVD observation of a high-energy neutrino candidate event from the blazar PKS 0735+17 at the day of the IceCube-211208A neutrino alert from the same direction

ATel #15112; *Zh.-A. Dzhilkibaev and O. Suvorova (INR RAS, Moscow) for the Baikal-GVD collaboration*

Next major neutrino source candidate ?

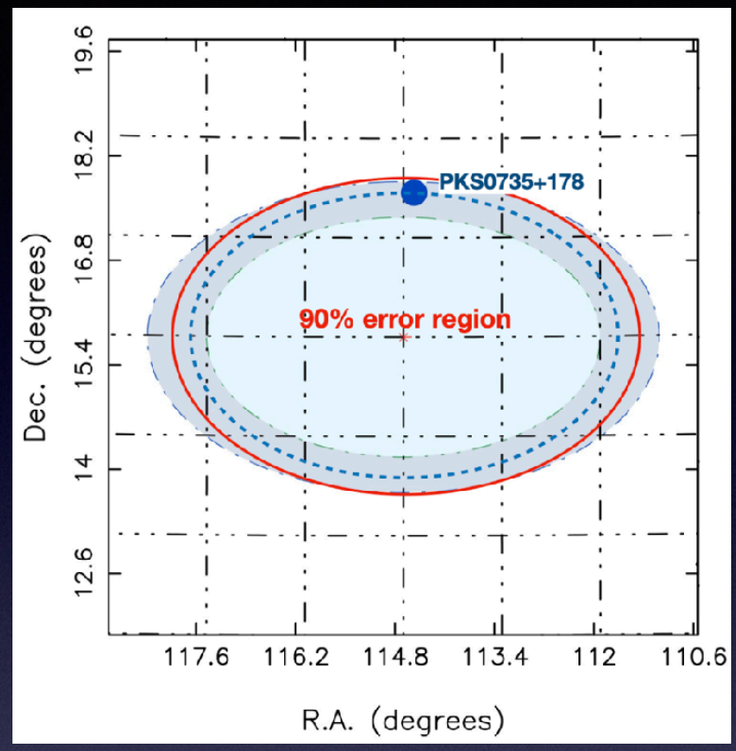
TITLE: GCN CIRCULAR
NUMBER: 31191
SUBJECT: IceCube-211208A - IceCube observation of a high-energy neutrino candidate track-like event
DATE: 21/12/08 21:28:14 GMT
FROM: Marcos Santander at U. Alabama/IceCube <jmsantander@ua.edu>

The IceCube Collaboration (http://icecube.wisc.edu/) reports:

On 2021-12-08 at 20:02:51.1 UT IceCube detected a track-like event with a moderate probability of being of astrophysical origin. The event was selected by the ICECUBE_Astrotrack_Bronze alert stream. The average astrophysical neutrino purity for Bronze alerts is 30%. This alert has an estimated false alarm rate of 1.197 events per year due to atmospheric backgrounds. The IceCube detector was in a normal operating state at the time of detection.

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon_g_b/136015_21306805.amon, more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 2021-12-08
Time: 20:02:51.1 UT
RA: 114.52 (+2.82 -2.50 deg 90% PSF containment) J2000
Dec: 15.56 (+1.81 -1.39 deg 90% PSF containment) J2000



Baksan Underground Scintillation Telescope observation of a GeV neutrino candidate event at the time of a gamma-ray flare of the blazar PKS 0735+17, a possible source of coinciding IceCube and Baikal high-energy neutrinos

ATel #15143; *V. B. Petkov, Yu. F. Novoseltsev and R. V. Novoseltseva (INR RAS) for the Baksan Underground Scintillation Telescope group*
*on **25 Dec 2021; 17:21 UT***

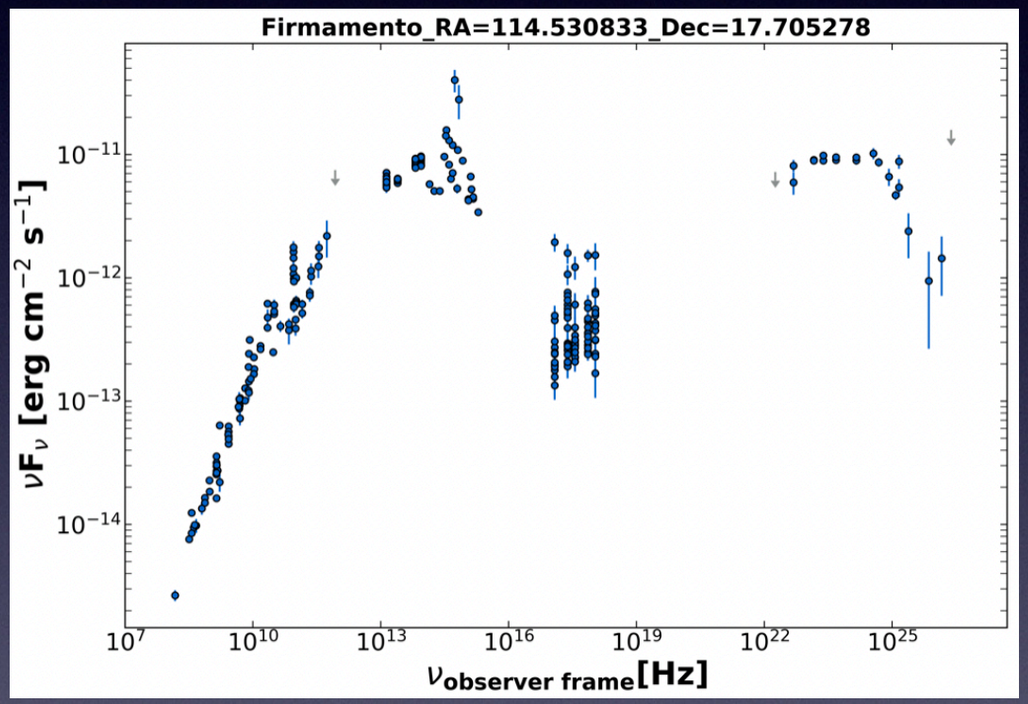
Baikal-GVD observation of a high-energy neutrino candidate event from the blazar PKS 0735+17 at the day of the IceCube-211208A neutrino alert from the same direction

ATel #15112; *Zh.-A. Dzhilkibaev and O. Suvorova (INR RAS, Moscow) for the Baikal-GVD collaboration*

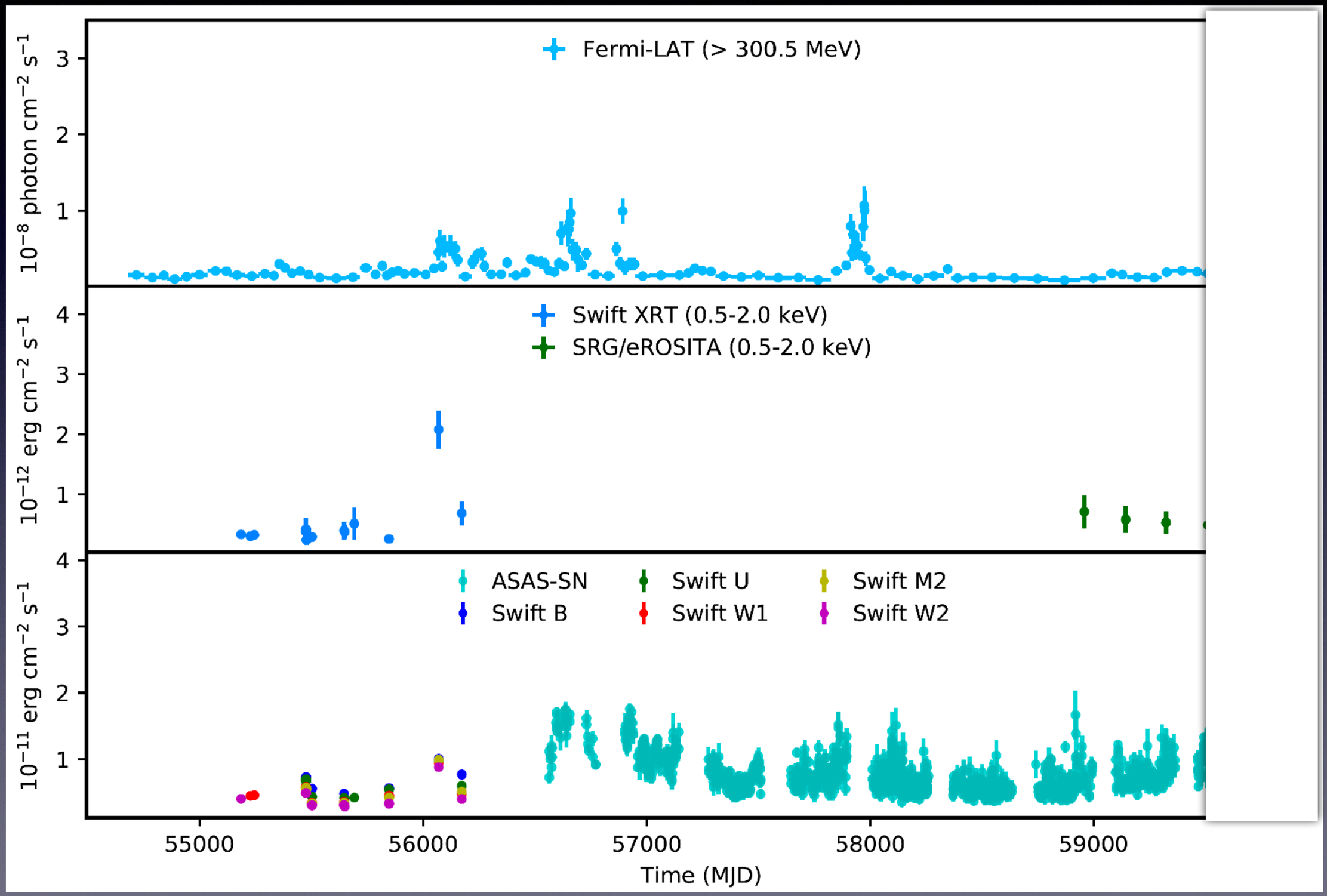
Search for neutrino counterpart to the blazar PKS0735+178 potentially associated with IceCube-211208A and Baikal-GVD-211208A with the KM3NeT neutrino detectors.

PKS 0735+178 ?

- ☑ is one of the brightest BL Lac objects, in the sky.
- ☑ is the fifth radio brightest BL Lac in the Roma-BZCat catalogue (5th), with a flux density of 2.3 Jy at 1.4 GHz.
- ☑ is a prominent source in the high-energy gamma-ray band, ranking 19th among nearly 1,500 IHBL blazars in the Fermi 4LAC-DR2.
- ☑ its optical spectrum is featureless. A lower limit of the redshift $z \geq 0.424$. A more recent estimation $z \sim 0.65$.

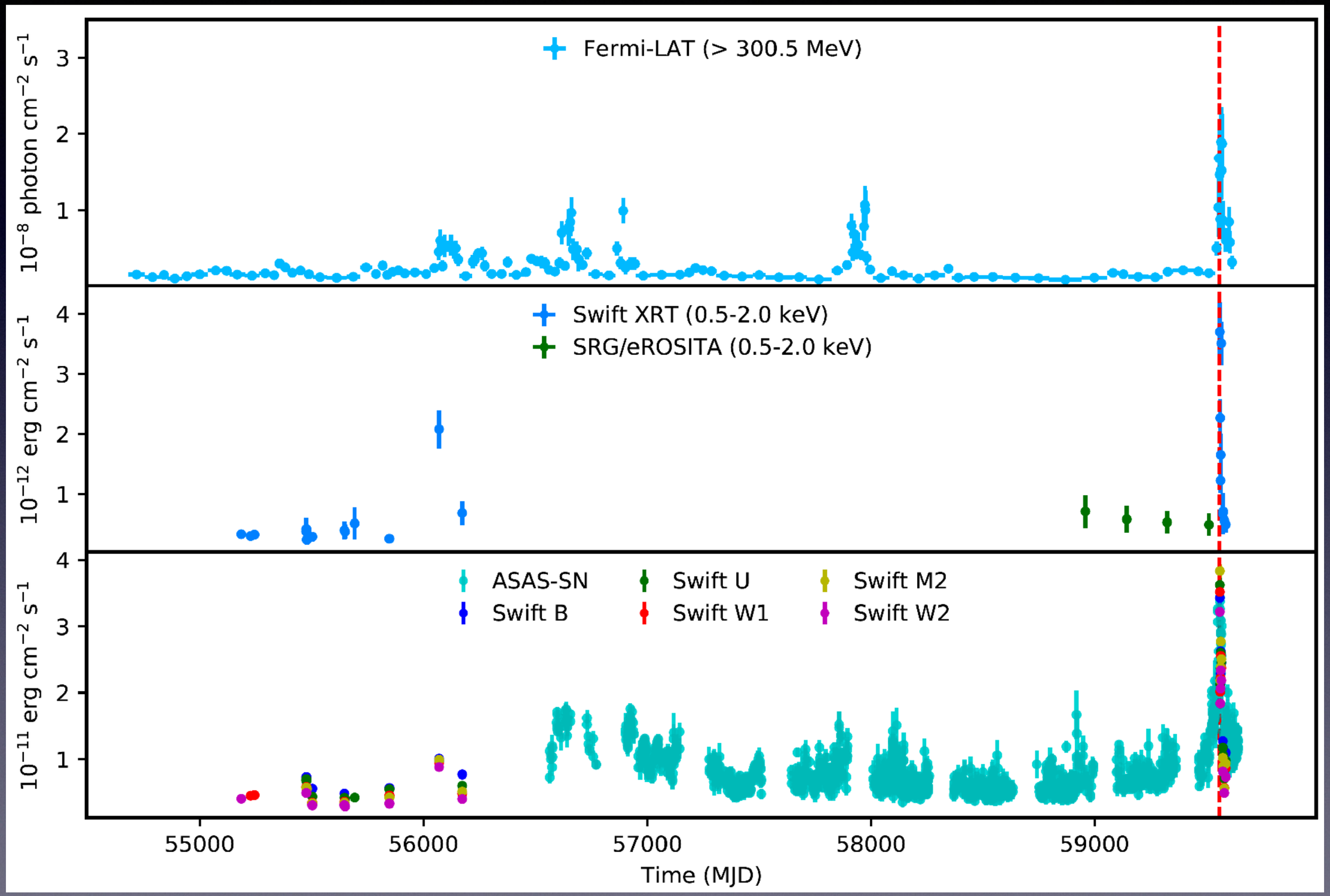


MW lightcurve of PKS 0735+178



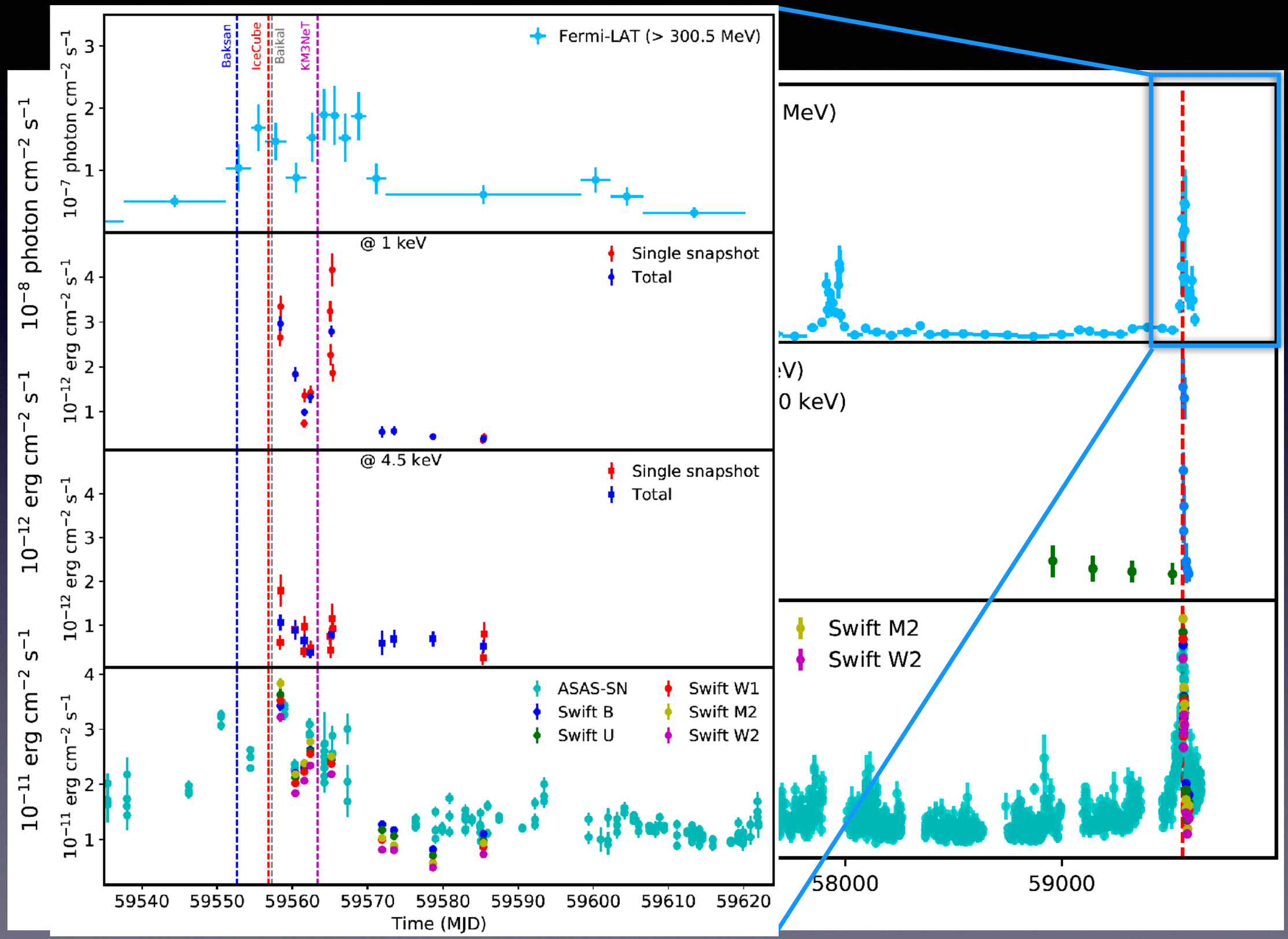
Sahakyan, Giommi, et al., MNRAS, 2023

MW lightcurve of PKS 0735+178



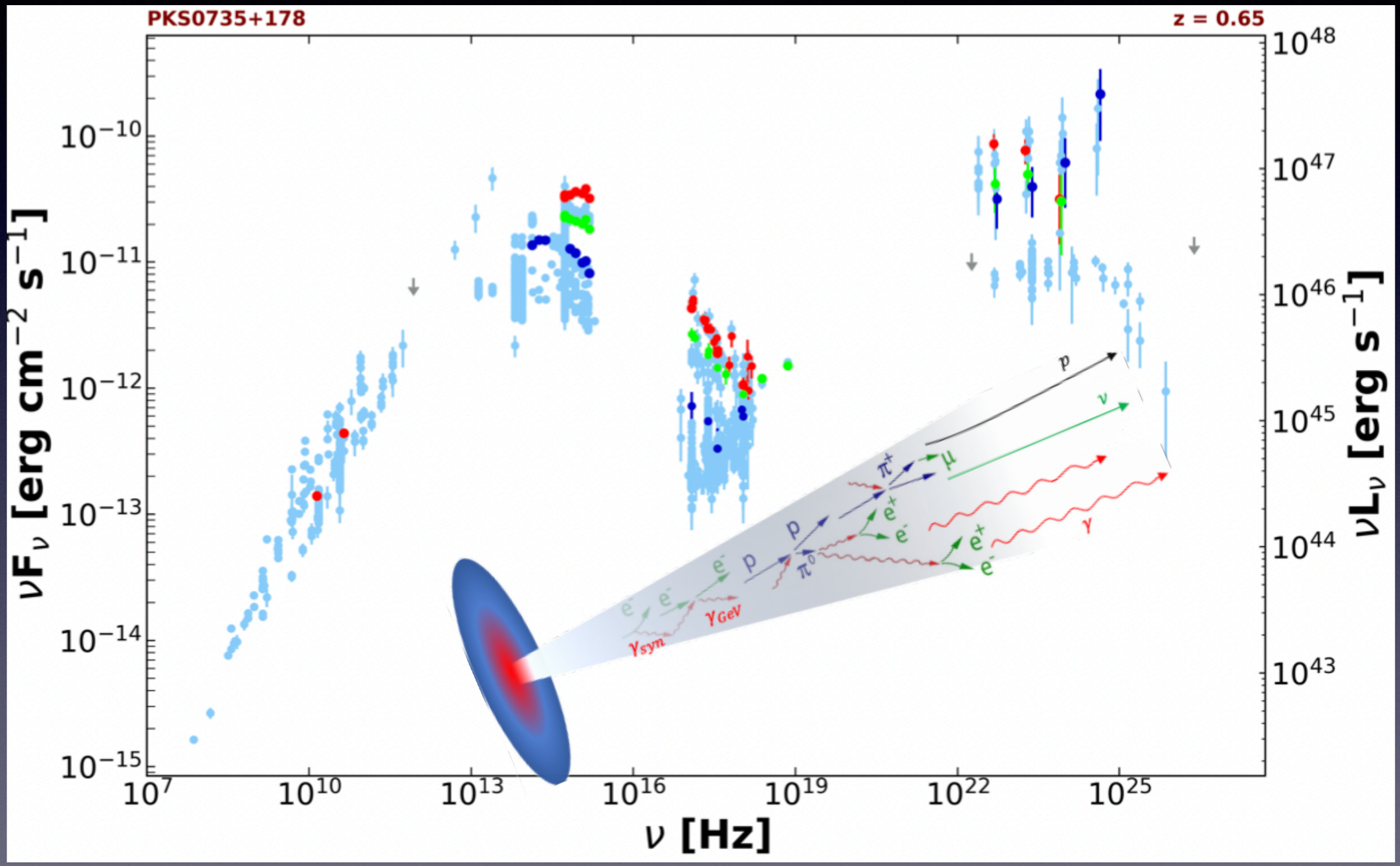
Sahakyan, Giommi, et al., MNRAS, 2023

MW lightcurve of PKS 0735+178



Sahakyan, Giommi, et al., MNRAS, 2023

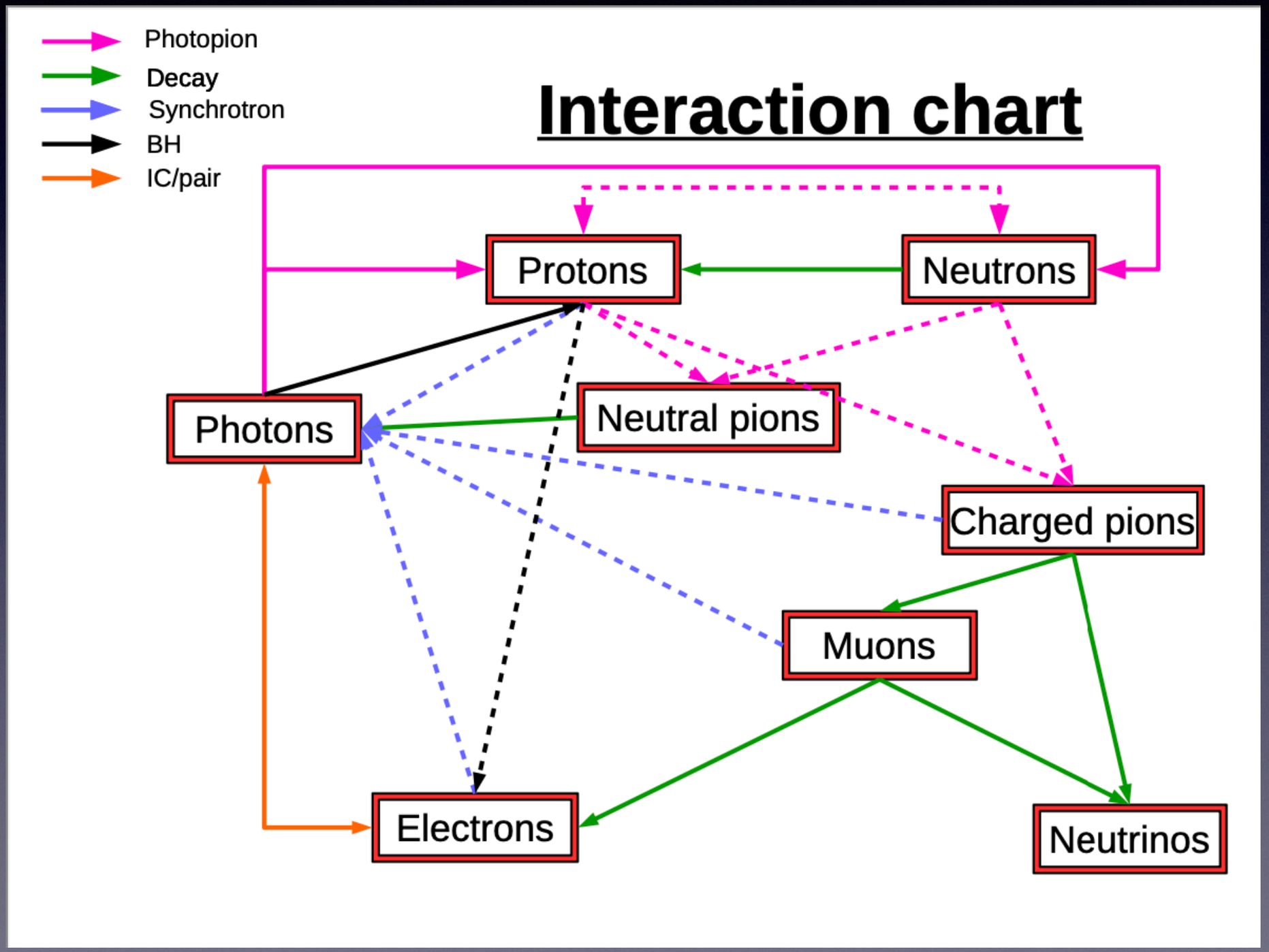
Broadband SED



Sahakyan, Giommi, et al., MNRAS, 2023

Simulator Of Processes in Relativistic AstroNomical Objects (SOPRANO)

A new python/C based fully time-dependent numerical self-consistent code



Gasparyan, Begue & Sahakyan, MNRAS, 2022

Evolution of the particle distribution

$$\frac{\partial N_p}{\partial t} = C_{p\gamma\to p\pi} + C_{p\gamma\to e^+e^-} + C_{\rm synch} - S_{\gamma p\to n\pi} + Q_{\gamma n\to p\pi}$$

$$\frac{\partial N_n}{\partial t} = - S_{n\gamma\to p\pi} + Q_{p\gamma\to n\pi} + C_{n\gamma\to n\pi}$$

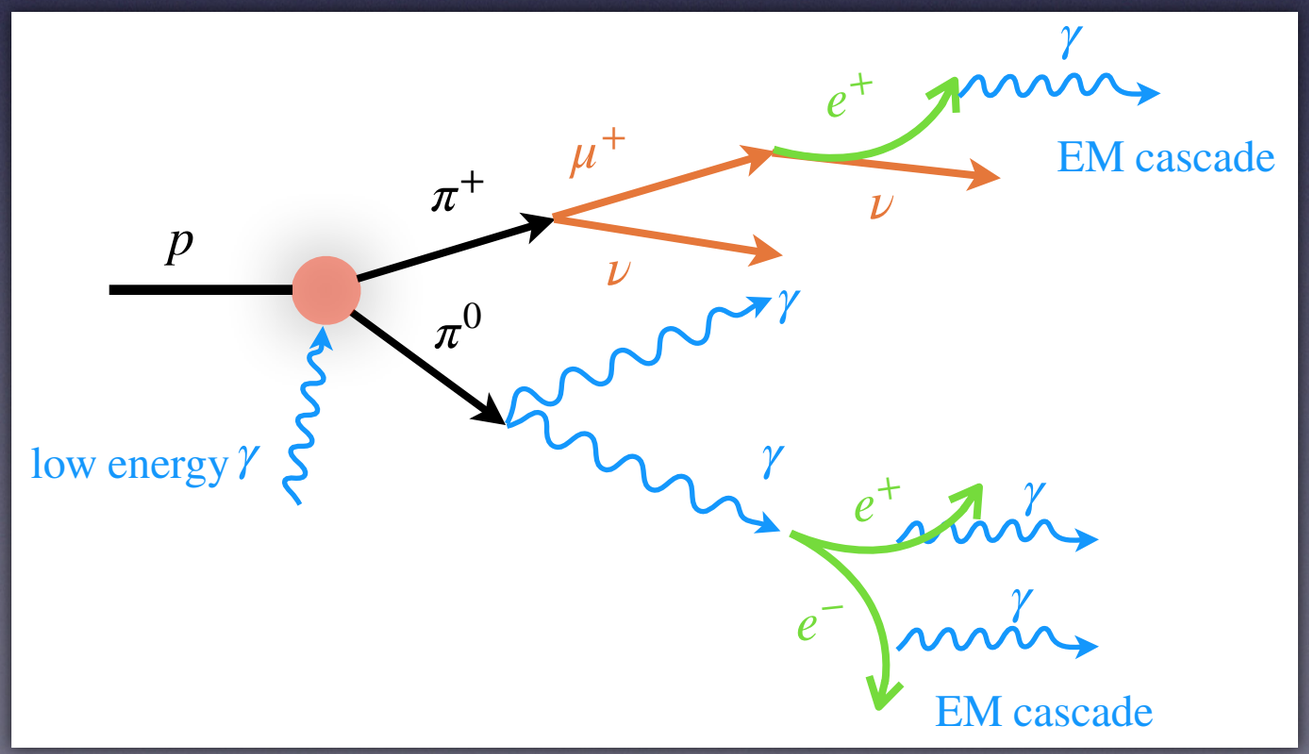
$$\frac{\partial N_{\pi_\pm}}{\partial t} = Q_{p\gamma\to\pi} + Q_{n\gamma\to\pi} - S_\pi + C_{\rm synch}$$

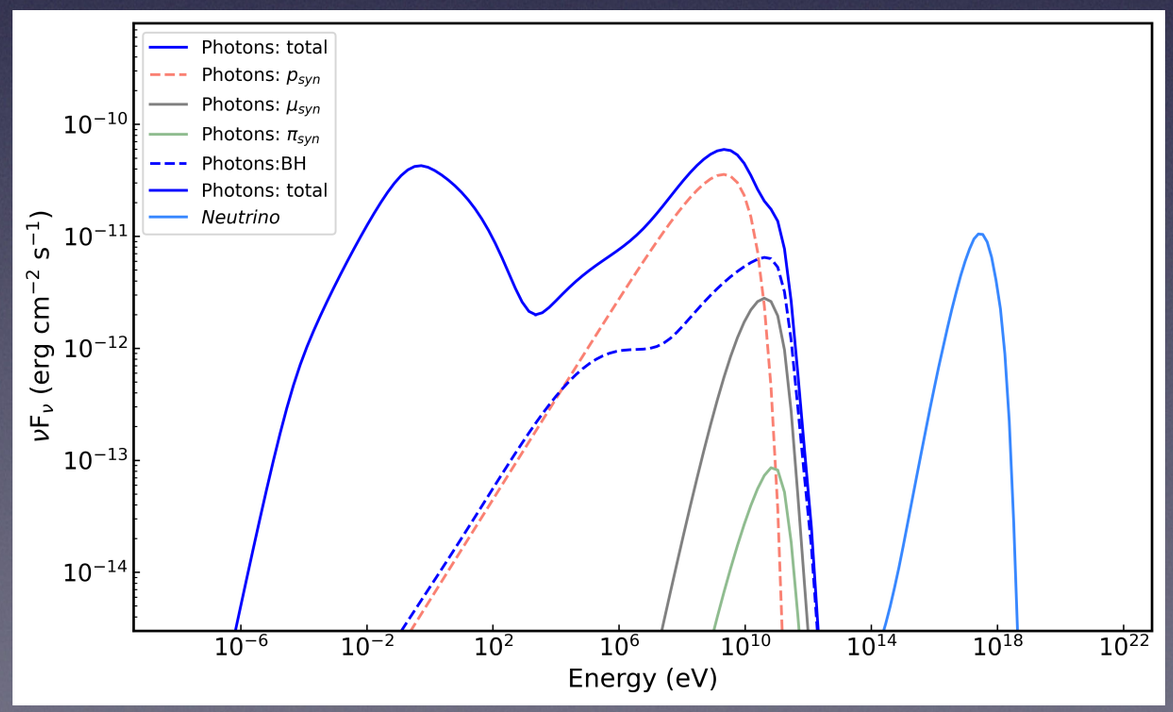
Q: sink term
S: source term
C: cooling term

$$\frac{\partial N_\mu}{\partial t} = Q_{\pi_\pm} - S_\mu + C_{\rm synch}$$

$$\frac{\partial N_{\nu,\zeta}}{\partial t} = Q_{\pi_\pm} + Q_\mu$$

$$\frac{\partial N_{e^\pm}}{\partial t} = Q_\mu + Q_{p\gamma\to e^+e^-} + Q_{\gamma\gamma\to e^+e^-} C_{\rm IC} + C_{\rm synch}$$



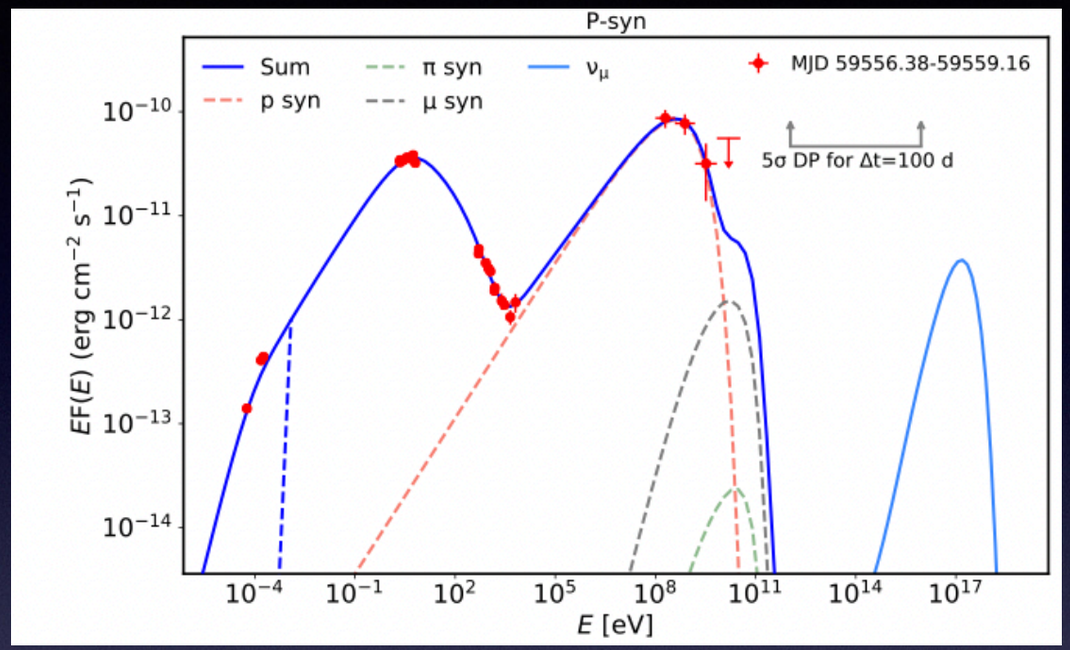


Gasparyan, Begue & Sahakyan, MNRAS, 2022

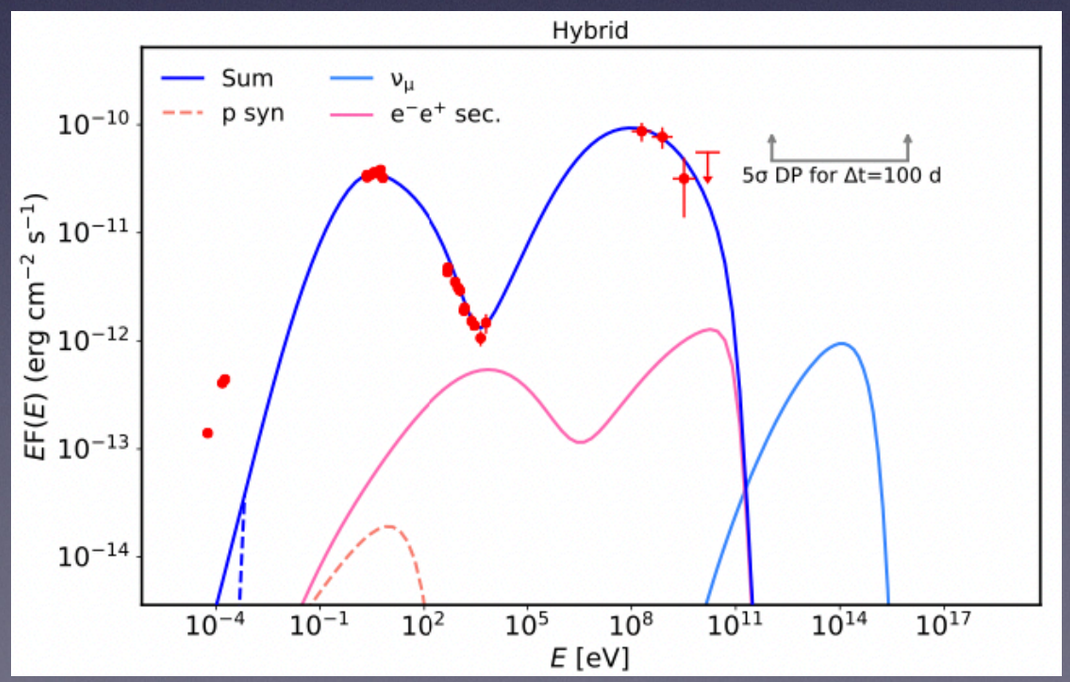
PKS 0735+178: SED modeling

Both electrons and protons are injected in the radiating region continuously with distribution function of

$$Q'_{\rm i}(\gamma_{\rm i}) = \begin{cases} Q'_{0,{\rm i}}\gamma_{\rm i}^{-\alpha_{\rm i}} \exp\left(-\dfrac{\gamma_{\rm i}}{\gamma_{\rm i,cut}}\right) & \gamma_{\rm i,min} \le \gamma_{\rm i} \le \gamma_{\rm i,max}, \\ 0 & \text{otherwise,} \end{cases}$$



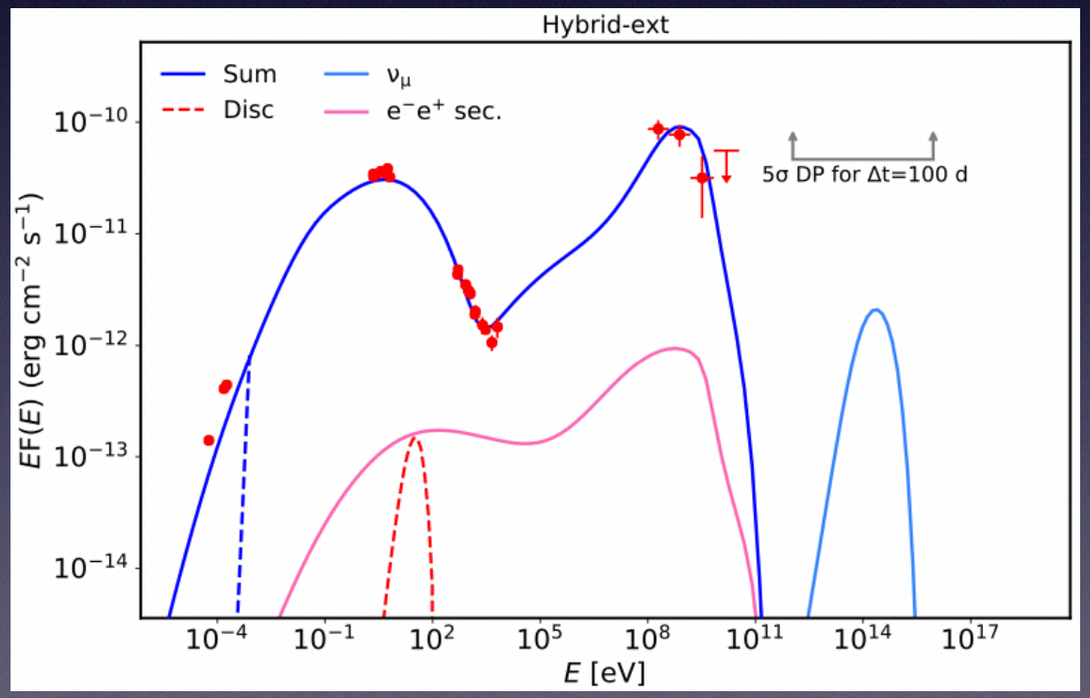
- a proton-synchrotron model in which the high energy component is mostly produced by proton synchrotron.
- a hybrid model in which the low and high energy peaks are explained by leptonic processes and the maximum proton luminosity is constrained by the radiation in the X-ray band from the secondaries produced by the Bethe-Heitler and photo-pion processes.



Sahakyan, Giommi, et al., MNRAS, 2023

PKS 0735+178: SED modeling

☑ a hybrid model where we also con- sider the presence of an external radiation field as target for proton- photon interactions and inverse Compton scattering by relativistic leptons



	P-syn	Hybrid	Hybrid-ext[(a)]
δ	30	30	30
R (10^{15} cm)	2.8	2.8	2.8
B (G)	120	1.8	5.9
$\gamma_{e,min}$	300	1.4×10^3	1.4×10^2
$\gamma_{e,cut}$	1.9×10^3	1.8×10^4	7×10^3
$\gamma_{e,max}$	2×10^6	5×10^4	2.3×10^4
α_e	2.0	2.0	1.9
$\alpha_p = \alpha_e$	2.0	2.0	1.9
$\gamma_{p,min}$	1	1	1
$\gamma_{p,max}$	3.0×10^8	3.5×10^5	3.5×10^5
$L_{e,jet}$ (erg s^{-1})	3.35×10^{44}	1.82×10^{45}	1.20×10^{45}
$L_{B,jet}$ (erg s^{-1})	3.81×10^{47}	8.57×10^{43}	9.20×10^{44}
$L_{p,jet}$ (erg s^{-1})	2.63×10^{47}	1.36×10^{50}	3.06×10^{47}

(a) The radiation from the BLR is modelled as a grey body with a peak energy at 2×10^{15} Hz and a luminosity of $L_{BLR} = 4 \times 10^{43}$ erg s^{-1}.

Sahakyan, Giommi, et al., MNRAS, 2023

- ☑ a bright BL Lac type blazar (2.2 to 5 Jy in the radio band) is located within the localization area of IceCube-211208A slightly expanded from the nominal 90 percent error region to take into account systematic uncertainties.
- ☑ the SED of PKS 0735+178 is of the IHBL type and is similar in shape and intensity to those of TXS 0506+056, the source so far considered as the most likely neutrino candidate.
- ☑ PKS 0735+178, like TXS 0506+056, PKS 1424+240 and GB6 J1542+6129, is most likely a masquerading BL Lac.
- ☑ At the time of the arrival of the IceCube-211208A neutrino, PKS 0735+178 was undergoing the largest γ-ray, X-ray and optical flare observed since 2008.
- ☑ Three independent observatories detect additional neutrinos at different level of significance with position consistent with that of PKS 0735+178 within a short time of IceCube-211208A and during the γ-ray flare.

PKS 0735+178 can be considered one of the best VHE neutrino source candidates detected so far.

Summary

The concomitance of the opening era of multimessenger astrophysics and the on-going data revolution, triggered by the recent, but rapidly growing adoption of open scientific data policies, is causing a shift from the paradigm of physical interpretation relying on data from a single observatory to a more complete approach based on the use of multi-frequency, multi-temporary and multimessenger data, a new research frontier holding the potential for a large expansion of the discovery space.