Study of the variability of active galactic nuclei at very high energy with H.E.S.S.

Thesis defense by **Gabriel Emery**

Supervised by Jean-Philippe Lenain

16/09/2020

Content

I – Active Galaxy Nuclei
Content

I) Active galactic nuclei

II) Observation technique

III) Improvements for variability studies

- **III-A)** Adaptive lightcurve
- **III-B)** Bad interval filtering

IV) Flare analyses

- **IV-A)** 3C 279 : A bright FSRQ
- **IV-B)** PKS 2022-077 : A distant blazar

V) TXS 0506+056 / neutrino

I – Active Galaxy Nuclei

1 – Intense extra-galactic sources

Extra-galactic

Bright at multiple wavelengths

Usual source of light in galaxies :
Stars, dust and gas

Active galaxy nuclei :
Strong additional source at the center of some galaxies

Hubble Space Telescope
Messier 7

Credit: NASA, ESA
& A. van der Hoeven

Hubble Space Telescope
Markarian 817

Credit: NASA, ESA and
the Hubble SM4 ERO Team

I – Active Galaxy Nuclei

2 – Complex objects

Super Massive Black Hole
- The “engine”

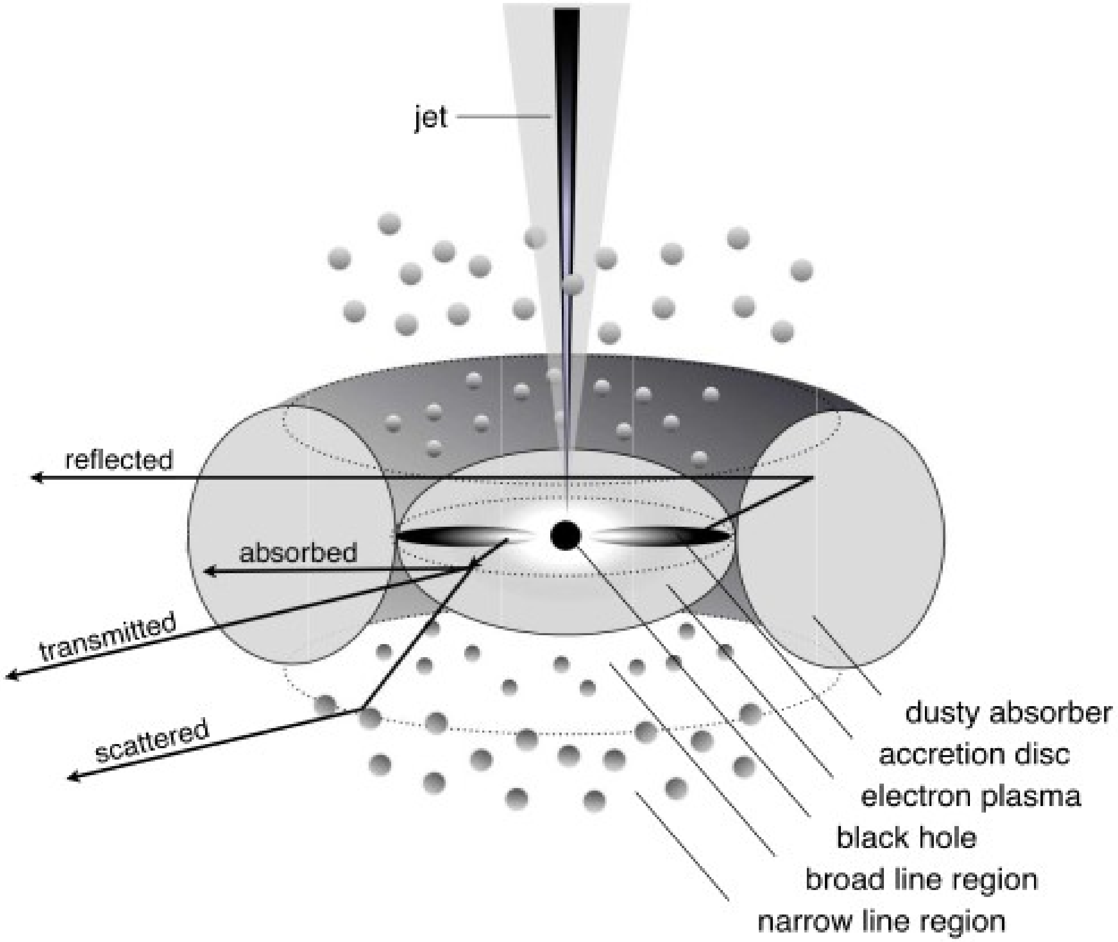
Accretion disk
- Thermal spectrum Optical → UV + lines

Gas corona
- Reprocess disk emission
- IC creates X-rays

Narrow and Broad line regions
- Gas emission lines

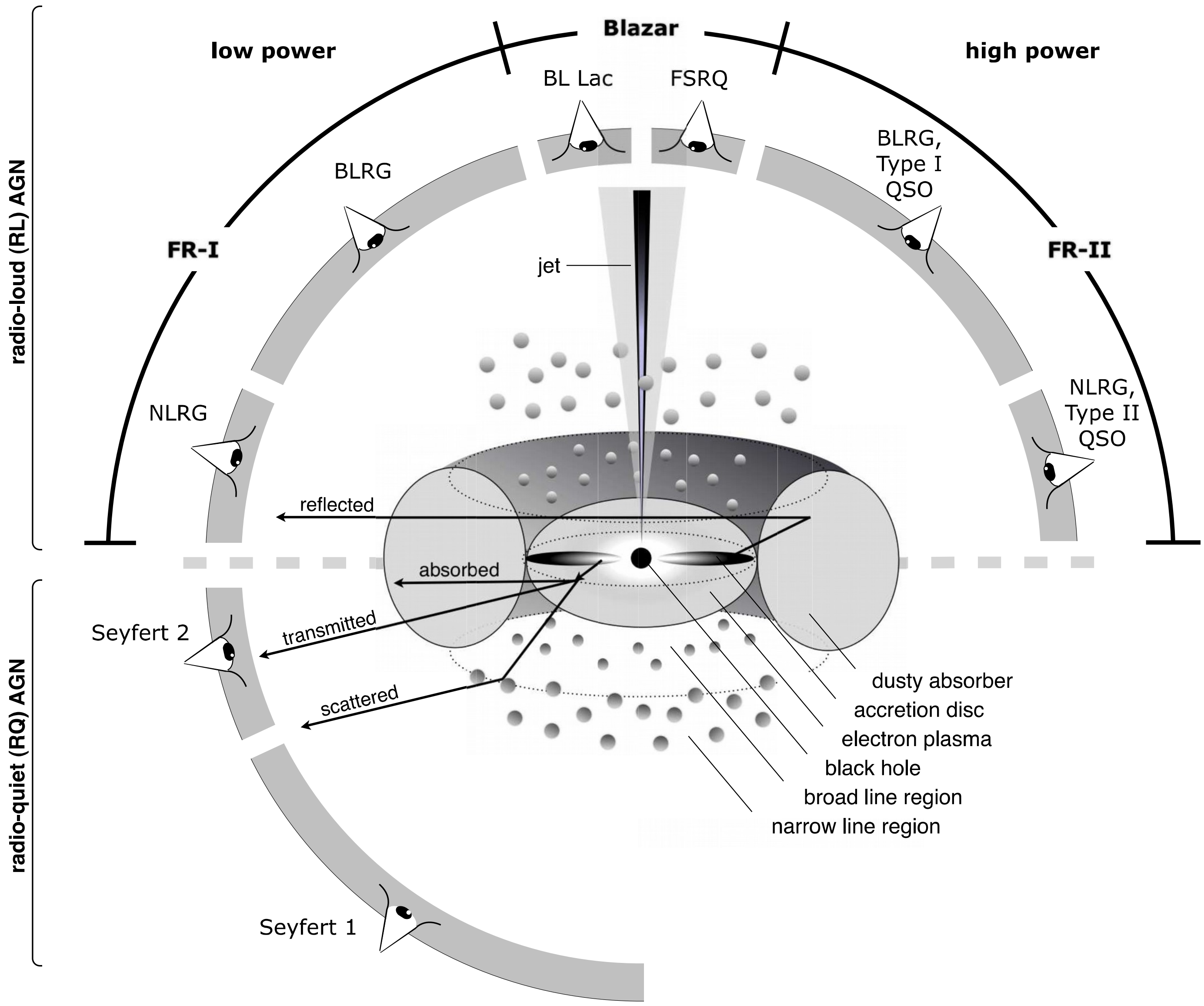
Dust torus
- Absorption and refraction
- Infra-red

Relativistic jet
- Beamed
- Full observed EM spectrum



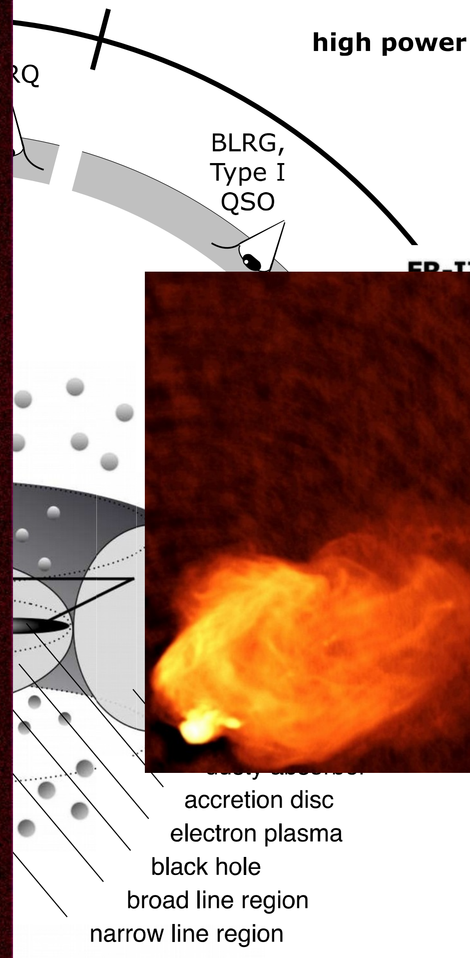
Commonly used AGN classification and associated properties. From Beckmann and Shrader, Active Galactic Nuclei. 2012.

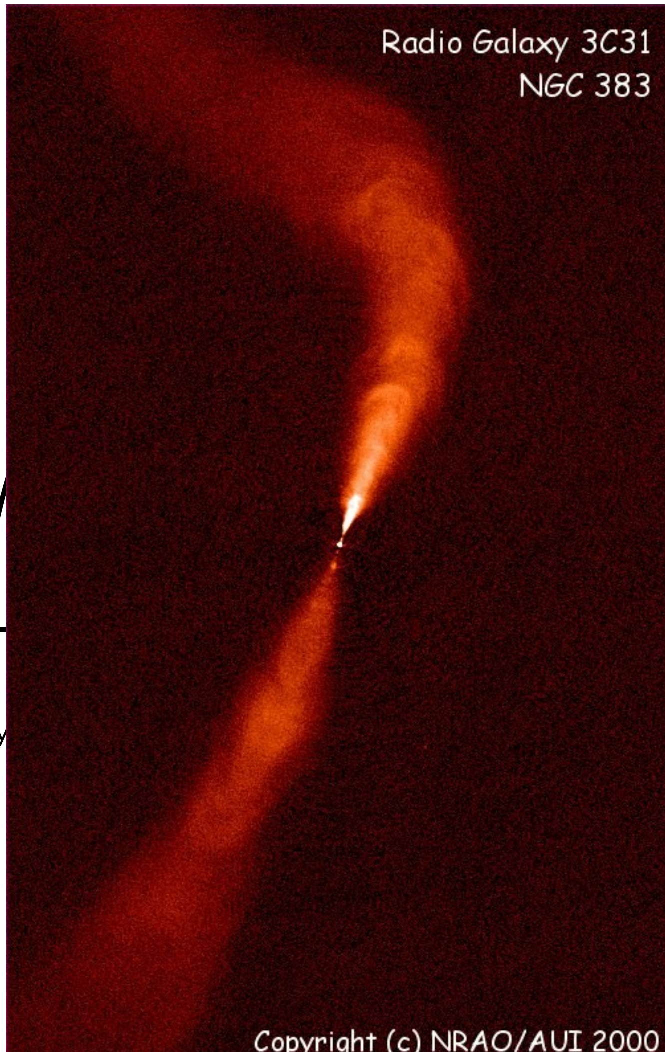
I – Active Galaxy Nuclei
3 – Classification

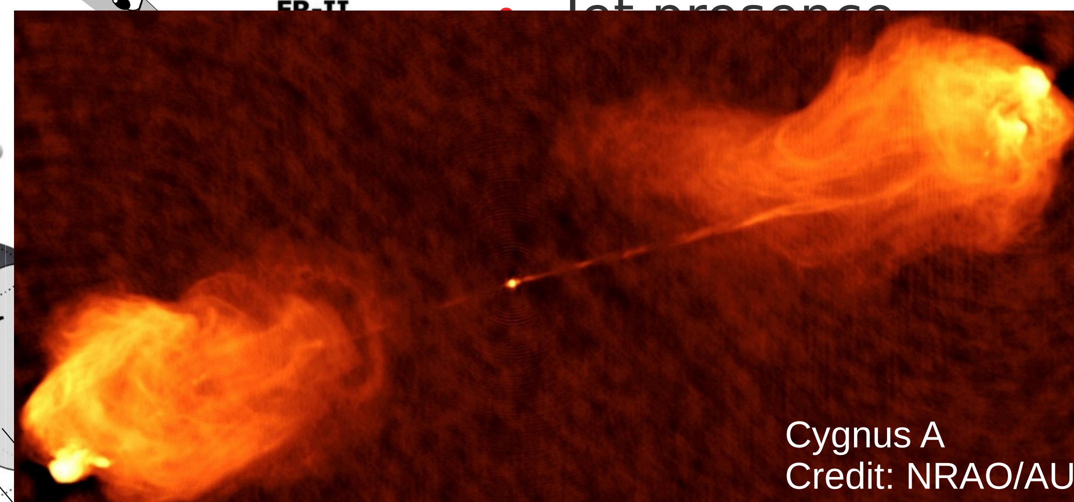


- Jet presence
- Bolometric luminosity
- Orientation

I – Active Galaxy Nuclei
3 – Classification



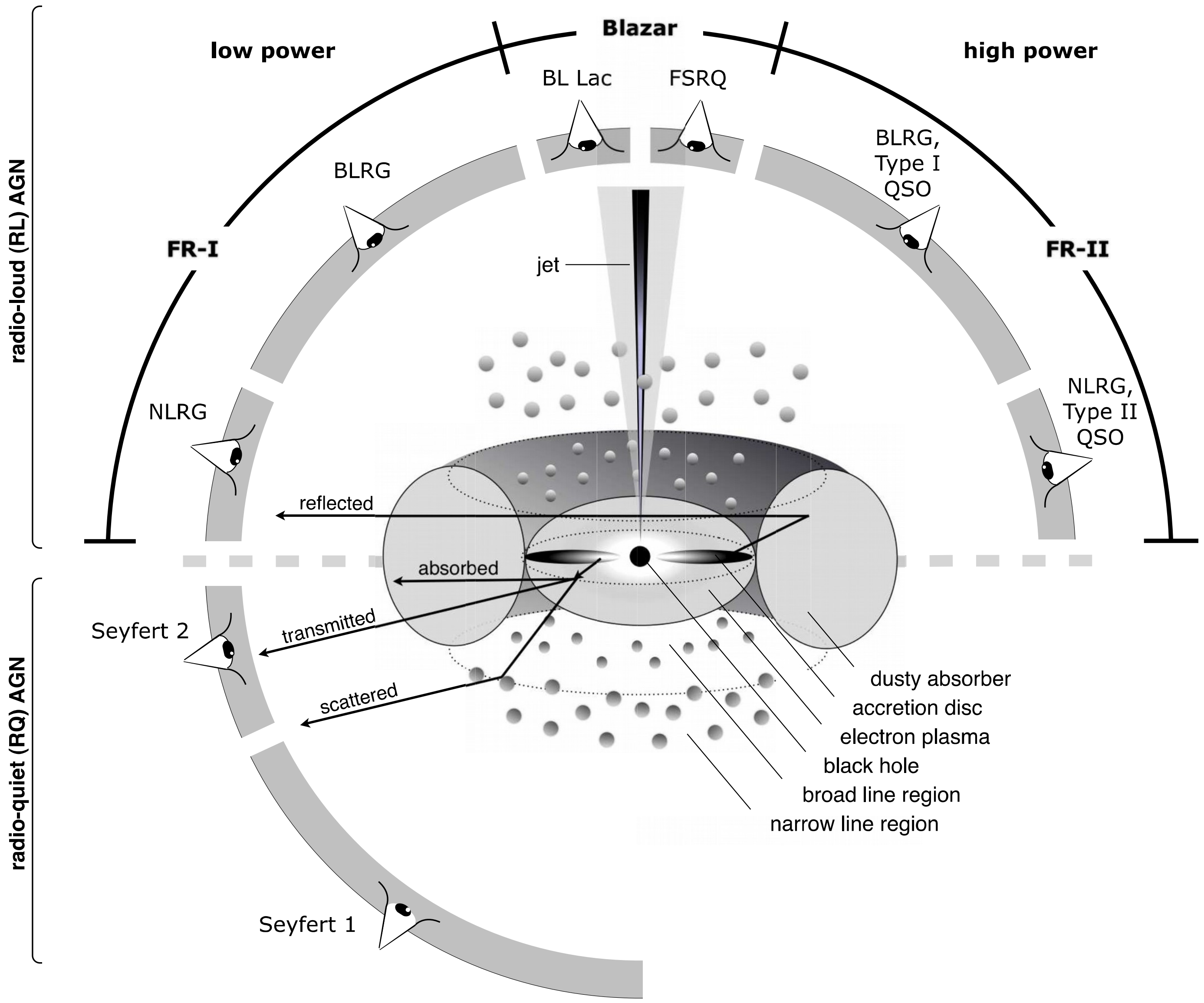




- Jet presence
- ...ty
- Orientation

I – Active Galaxy Nuclei

3 – Classification



- Jet presence
- Bolometric luminosity
- Orientation

I – Active Galaxy Nuclei

4 - Blazars

SED : two bumps

Observed at all frequencies

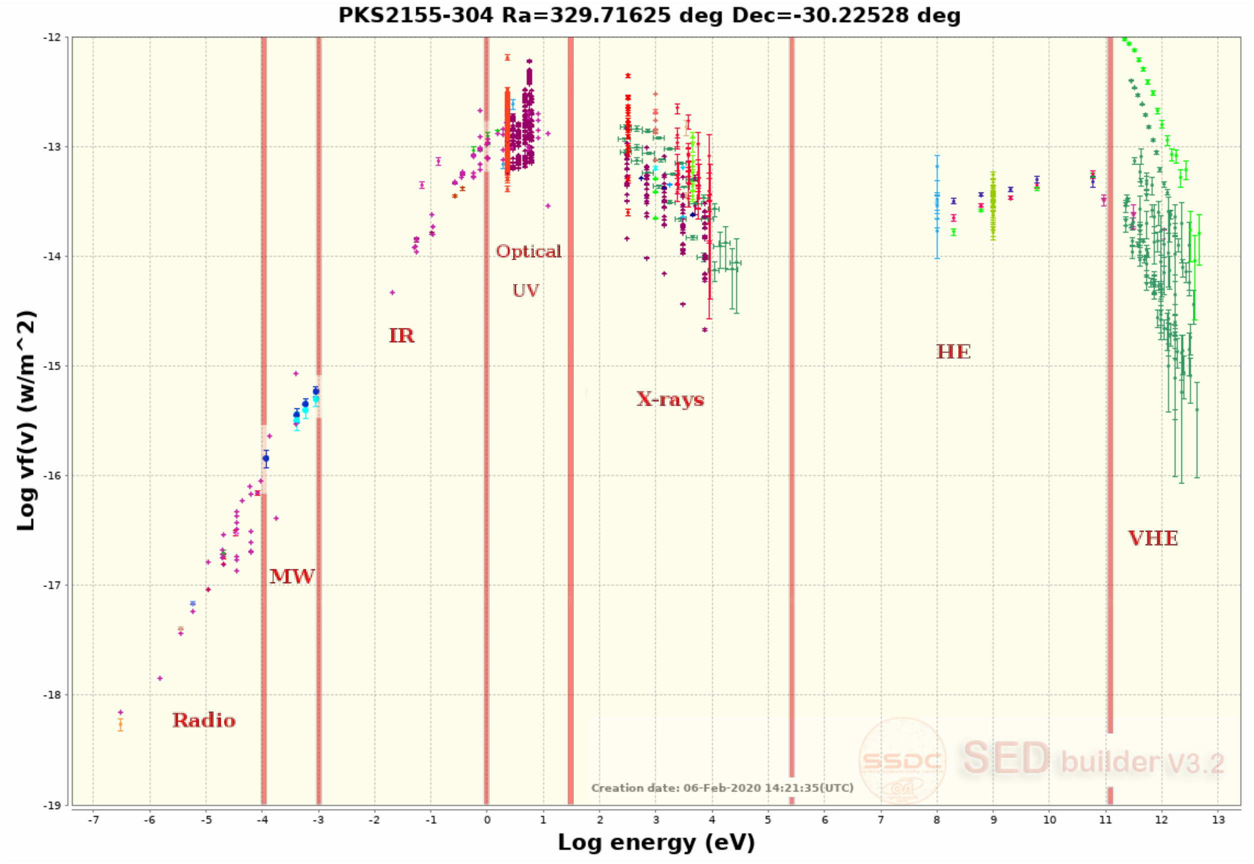
Variable

Peaks : source dependent

WISE blazar-like radio-loud sources (2014, IR) : 7855

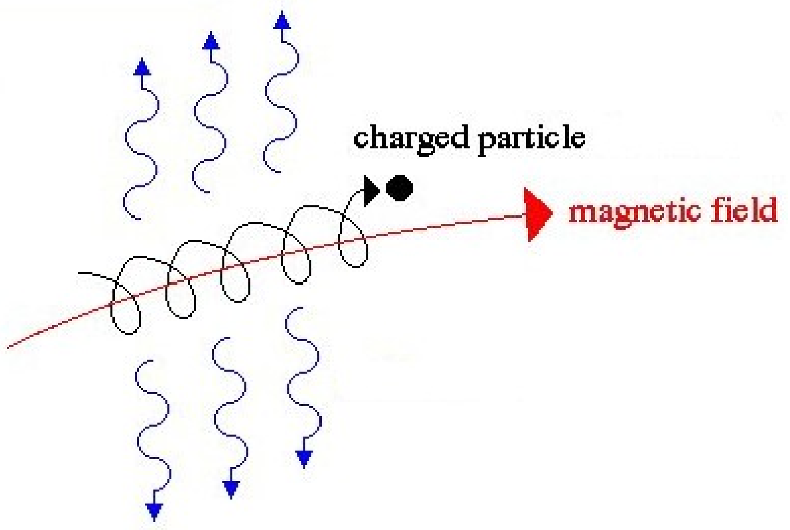
5th edition of the Roma-BZCAT Multi frequency Catalogue of Blazar : 3561

4FGL-DR2 (2020, HE): 3437
TeVCat (2020, VHE) : 74

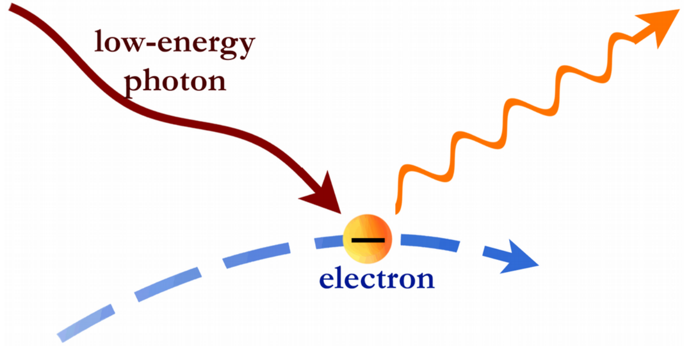


I – Active Galaxy Nuclei
5 – Leptonic emission processes

Synchrotron
- Accelerated charged particles radiate



- Inverse Compton (IC)
  - Relativistic electrons transmit energy to low energy photons



I – Active Galaxy Nuclei

6 – Hadronic emission processes

- Meson production

$$p + \gamma \rightarrow p + n_0\pi^0 + n_{\pm}(\pi^+ + \pi^-)$$

$$p + \gamma \rightarrow n + n_0\pi^0 + n_{\pm}(\pi^+ + \pi^-) + \pi^+$$

$$\pi^0 \rightarrow \gamma + \gamma \rightarrow EM\,showers$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu_\mu} + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu_\mu} \rightarrow e^- + \bar{\nu_e} + \nu_\mu + \bar{\nu_\mu}$$

- Bethe-Heitler

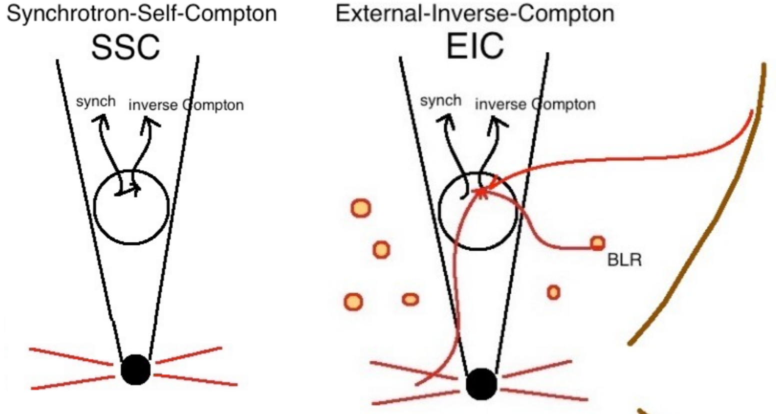
$$p + \gamma \rightarrow p + e^+ + e^-$$

- Synchrotron

I – Active Galaxy Nuclei

7 – Macrophysics effects

- Doppler boosting
  - Full jet power boosted as the power 4 of the relativistic Doppler factor
- Geometry
  - One zone? Multi-zone? Shape? Directions?
- Environment
  - External fields? Surrounding medium?

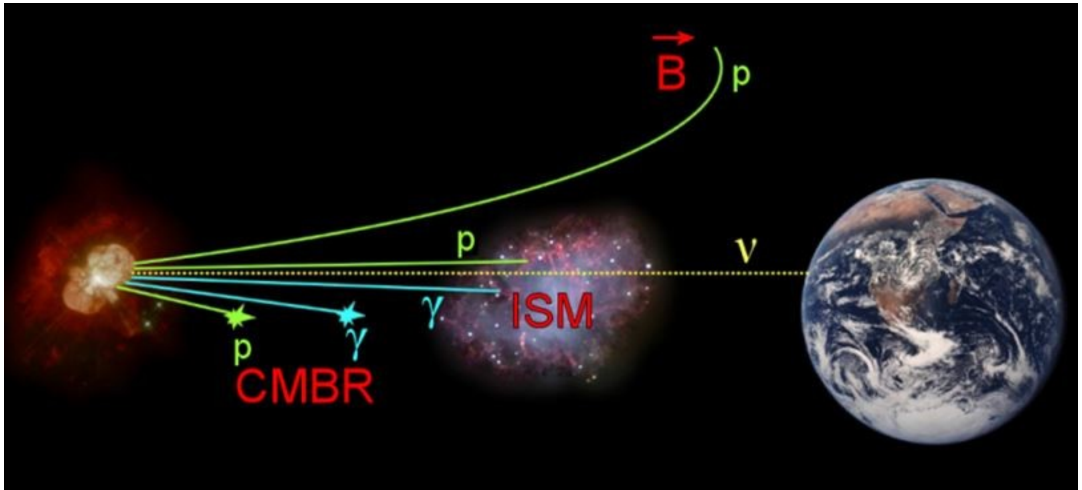


II – Observation technique
Content

II – Observation technique

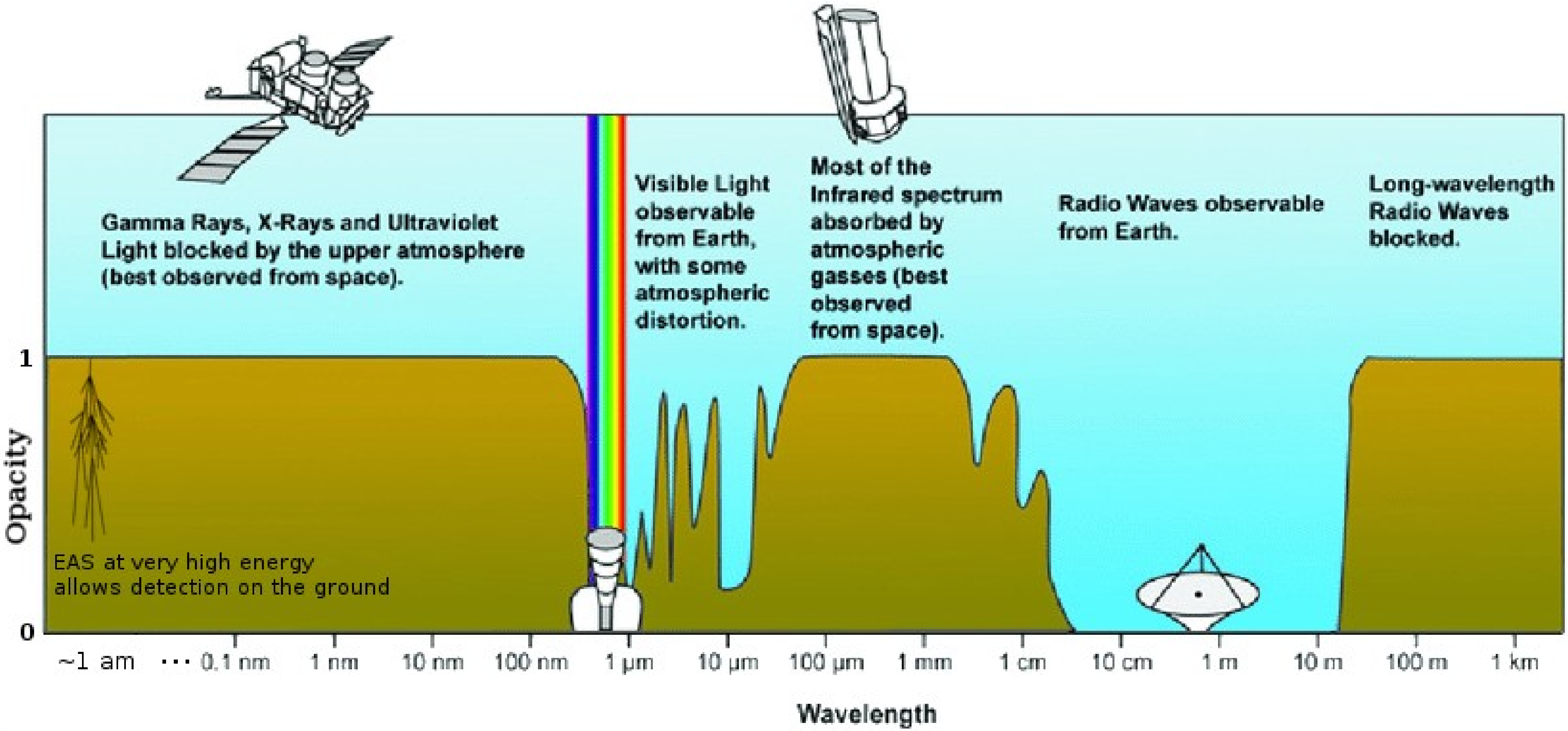
1 – A variety of messengers

- Photons
  - Geodesic – interact
- Charged cosmic rays
  - Deflected – varied
- Neutrinos
  - Geodesic – interact weakly – oscillate



II – Observation technique

2 – Energy dependence



II – Observation technique

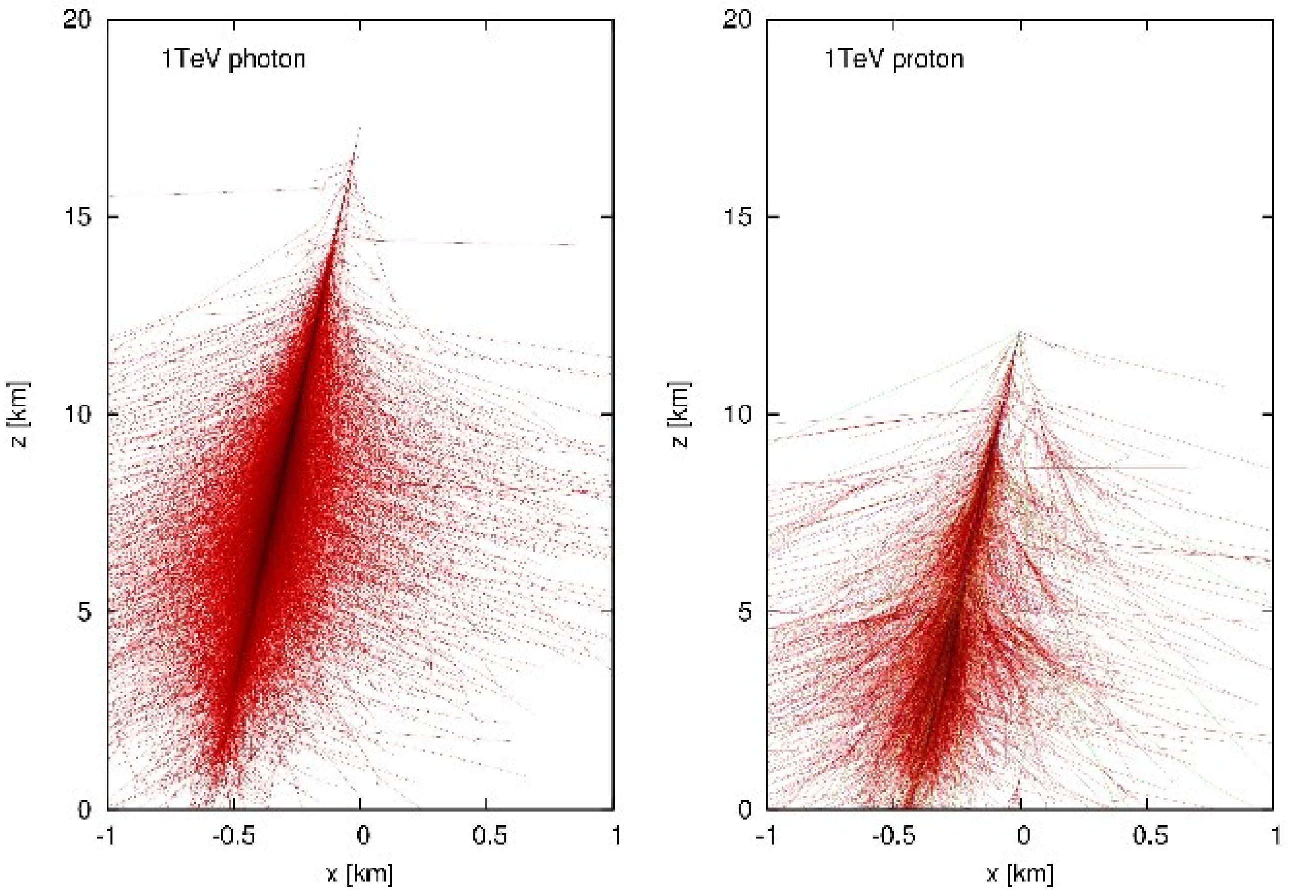
3 – Extensive air showers

Electromagnetic :

- Bremsstrahlung
- Pair creation

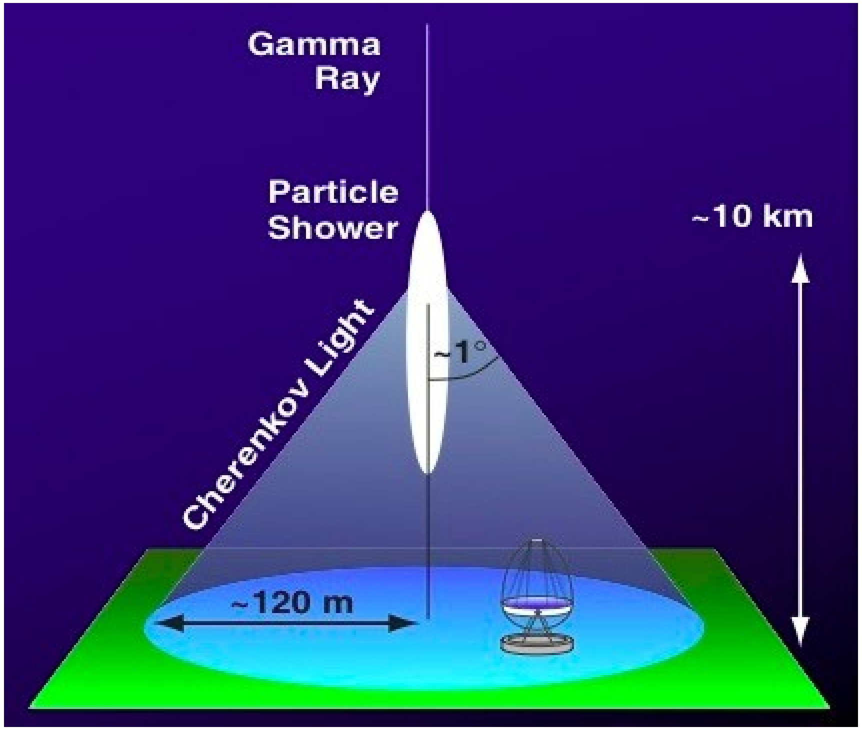
Hadronic :

- Pion production
- Other processes



II – Observation technique

4 – Cherenkov light



Supraluminic particles $v = \frac{c}{n}$

Blue light observed

Large area

II – Observation technique

5 – High Energy Stereoscopic System

Hybrid IACT array

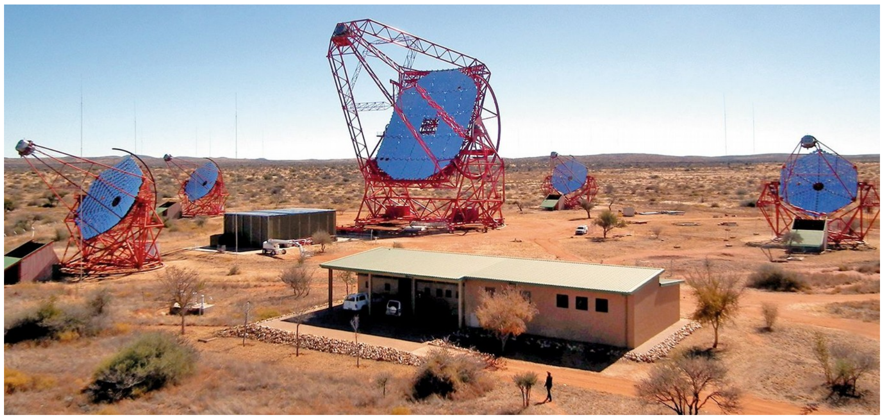
- 12m diameter mirror CT1-4
- 28m diameter mirror CT5

	H.E.S.S. experiment		
duty cycle	10 %		
coordinates	Khomas Highland,Namibia 23.3S 16.5E		
altitude	1800 m		
	HESS1	**HESS1U**	**HESS2**
pixels	960		2048
field of view	5°		3.2°
dead time	450 μs	7.2 μs	< 25 μs
energy threshold	$\sim$100 GeV	$\sim$100 GeV	$\sim$30 GeV

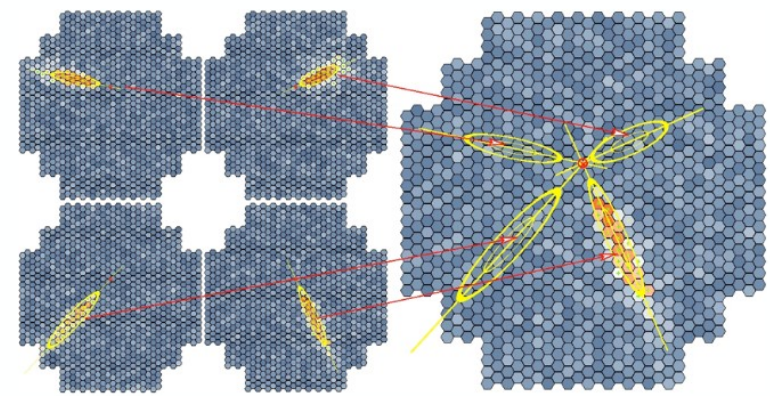
II – Observation technique

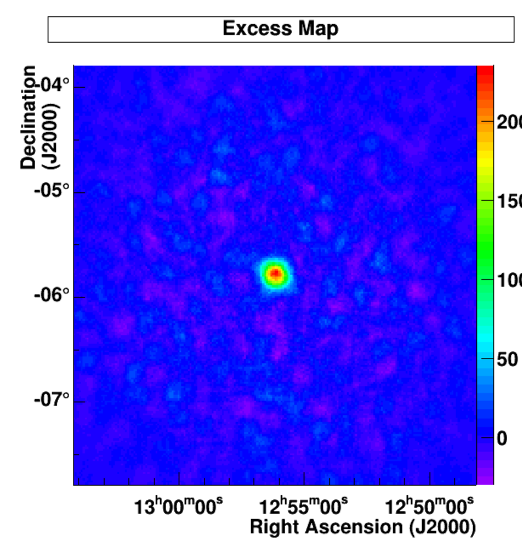
6 – Observation and analysis

Telescopes collect Cherenkov light

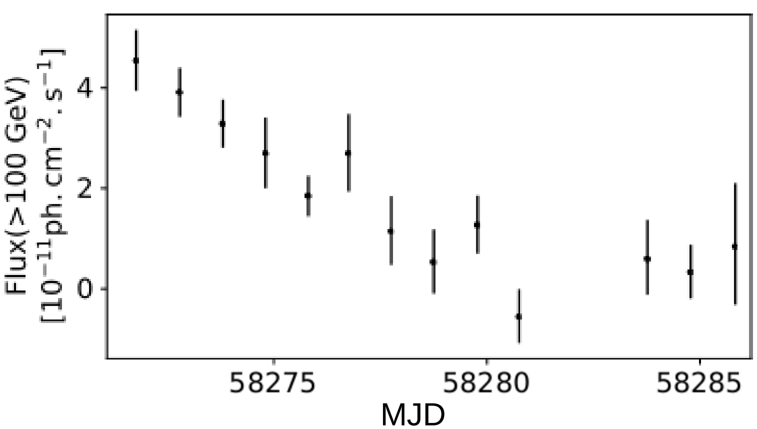


Elliptic images used to reconstruct original photon





Photons are stacked



Source properties are studied

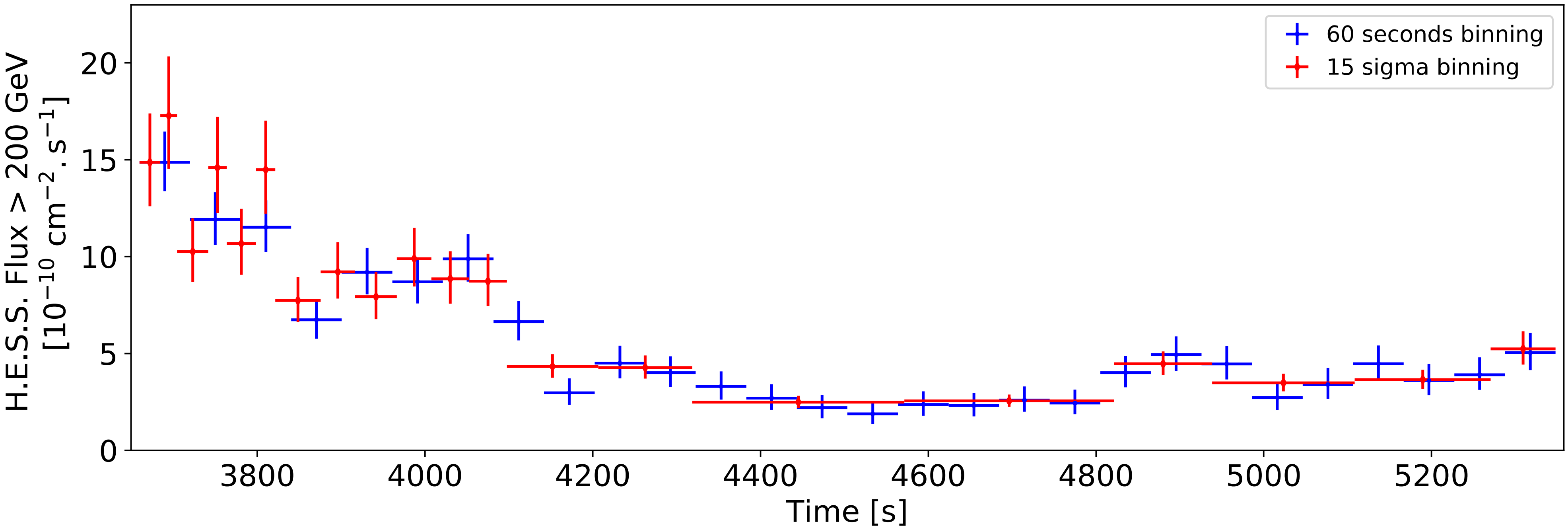
Content

III – Improvements for variability studies
A1 – Adaptive lightcurve creation

Goal : See as much short time structures as possible

How : Dynamically change binning based on signal significance

Properties : works run by run; non-uniform



PKS 2155-304, 28th July 2006

III – Improvements for variability studies

A2 – Variability estimators

Normalised excess variance :

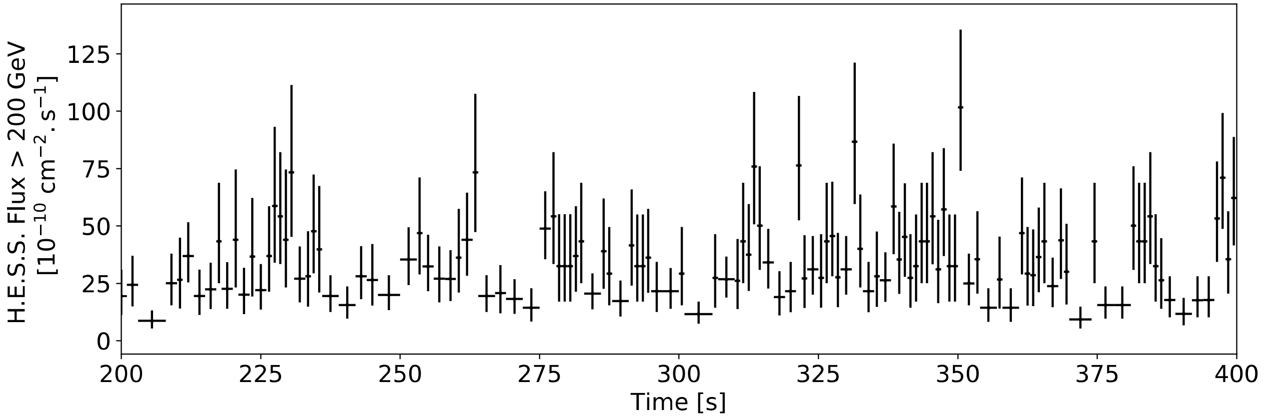
$$\sigma^2_{NXV} = \frac{1}{N\mu^2}\sum_{i=1}^{N}(x_i-\mu)^2-\sigma_i^2$$

$$\sigma^2_{NXV} = \frac{1}{T\mu^2}\sum_{i=1}^{N}t_i\{(x_i-\mu)^2-\sigma_i^2\}$$

Uniform binning → Non-uniform binning

PKS 2155-304, 28th July 2006

60s binning : 0.31 ± 0.03
5σ binning : 0.35 ± 0.02

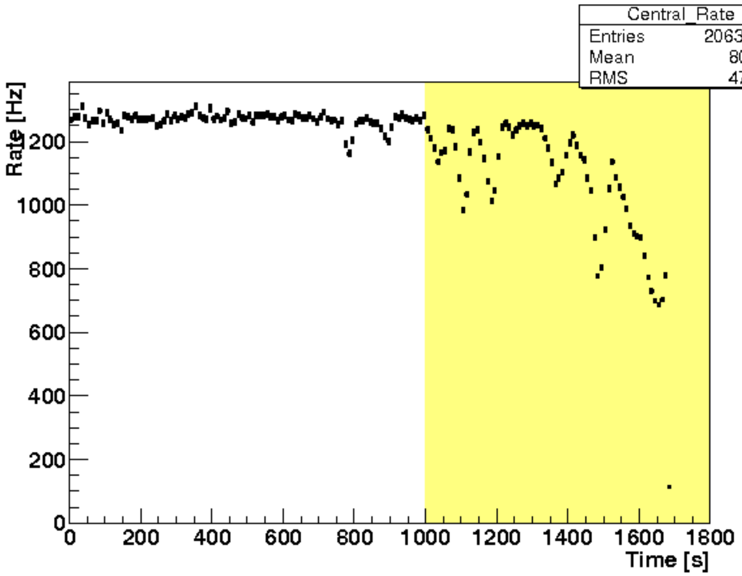


Doubling time :

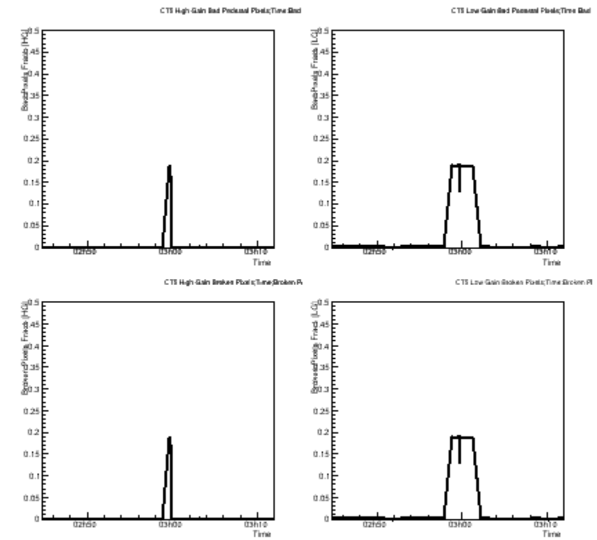
$$T_{2,ij} = \left|\Delta T_{ij}\frac{F_{ij}}{\Delta F_{ij}}\right|$$

- No uniform binning
- Individual point errors

III – Improvements for variability studies
B1 – Interval filtering tool



Bad weather



Electronic issue

Goal : Remove bad quality data but not full runs

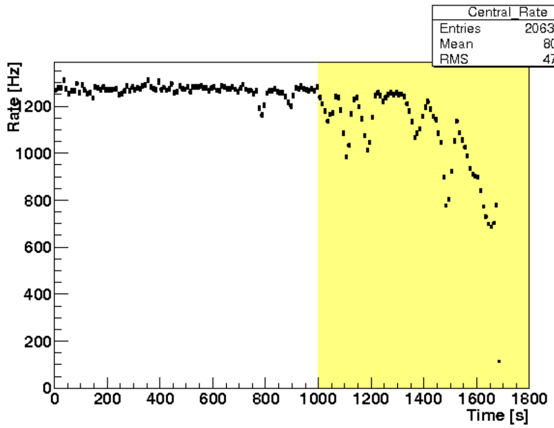
How : Flag events in specified interval; correct livetimes

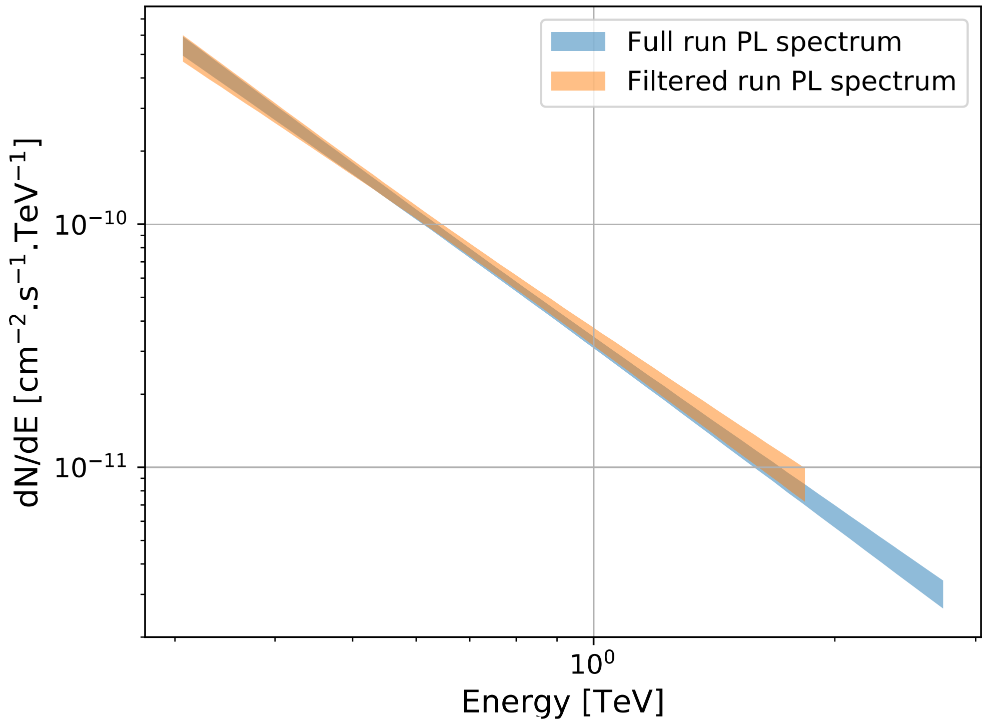
Properties : No recalibration; manual time interval selection

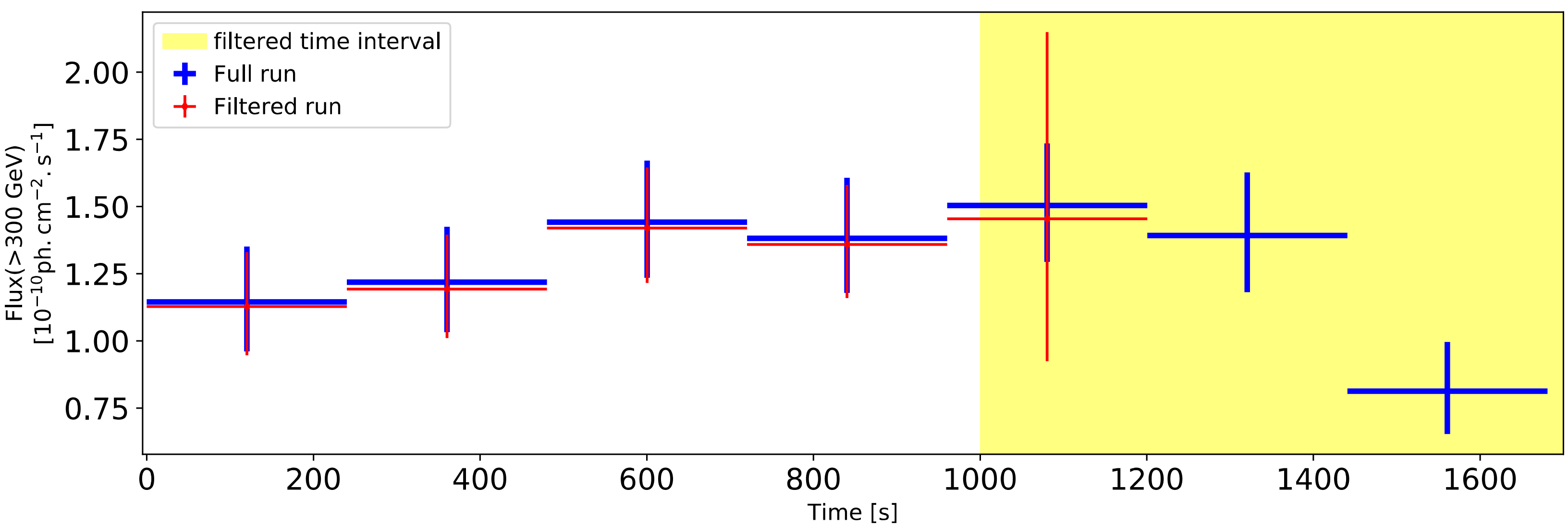
III – Improvements for variability studies

B2 – Interval filtering example

Crab Nebula – 1 run







ToO program

Overview

H.E.S.S. : Limited duty cycle and FOV

Sources : Variable → easier detection & extreme behaviours

ToO program :

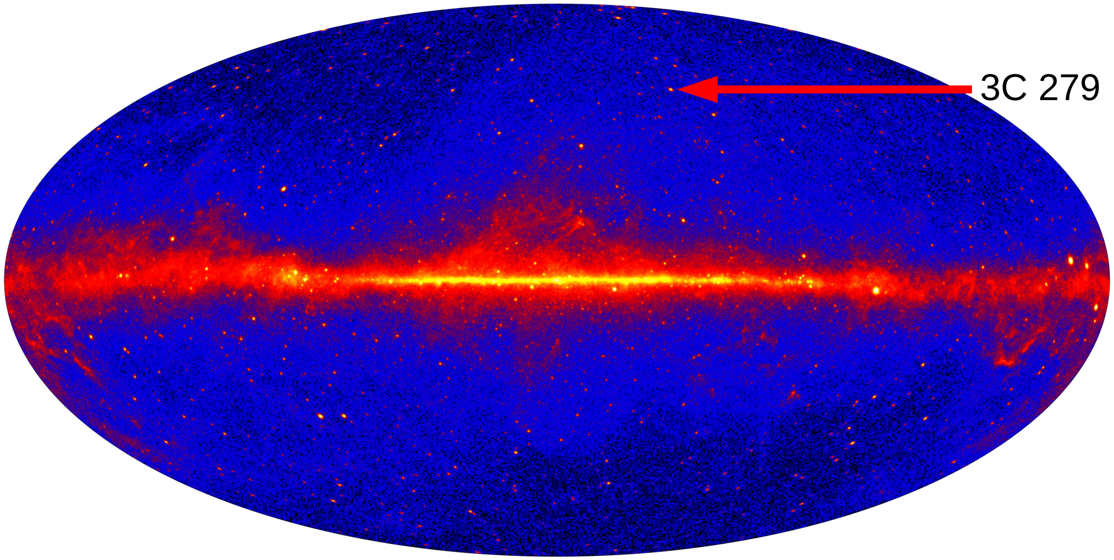
- Daily MWL monitoring
- Interest assessment
- Priority observations (110h divided into 12 triggers)
- MWL ToO

Analysis : Outside of ToO task force

IV – Flare analysis
Content

IV-A – 3C 279
Content

IV-A – 3C 279
1 - Properties



9 year Fermi-LAT sky map.
Credit: NASA/DOE/Fermi LAT Collaboration

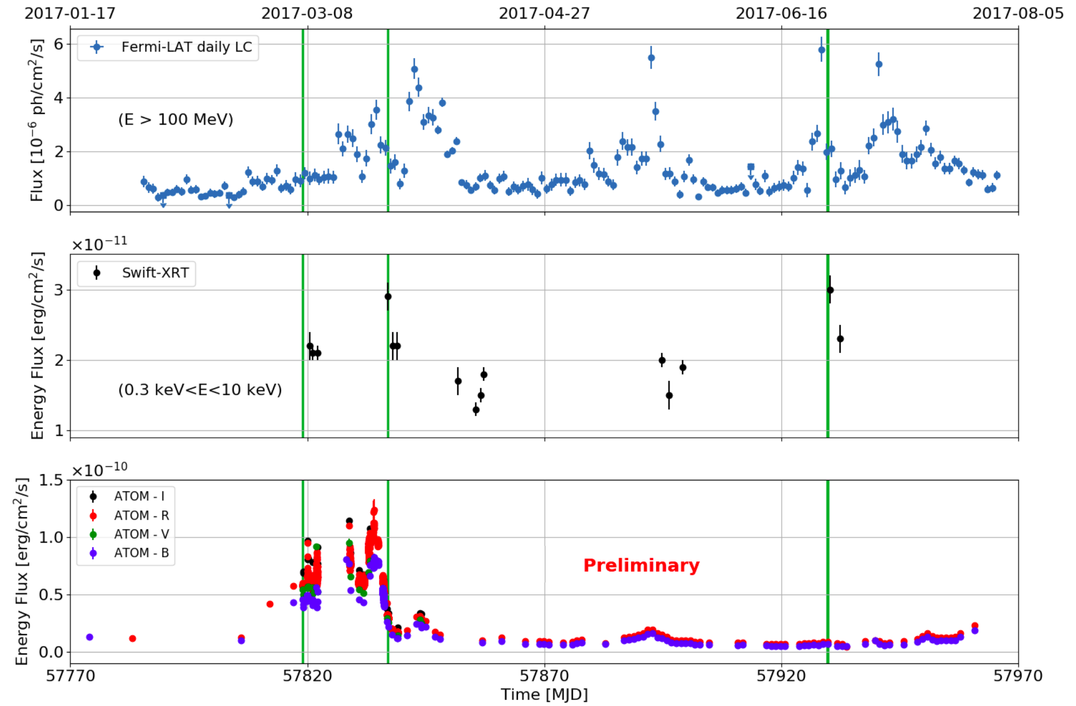
- FSRQ at redshift z = 0.536
- One of the brightest FSRQs seen with the Fermi-LAT
- Intense variability since years
- 6 H.E.S.S. observations campaigns in 2017/ 2018
  - 2 optical triggers
  - 4 HE triggers

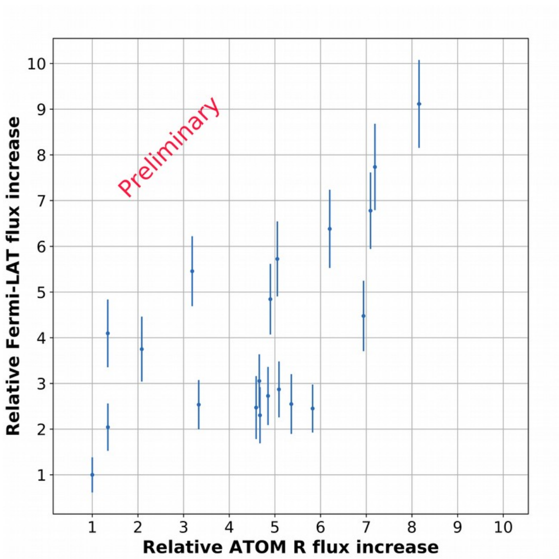
- Detected one night with H.E.S.S. in 2015 (A&A, 627 (2019) A159)

IV-A – 3C 279
2 – 2017 Activity

- Intense optical activity in march
- HE activity later with no optical counterpart
- No H.E.S.S. detection
- Mild correlation between optical and HE during the optical flare
  - Pearson correlation coefficient :

$$\rho_{Opt/HE} = 0.61 \pm 0.05$$

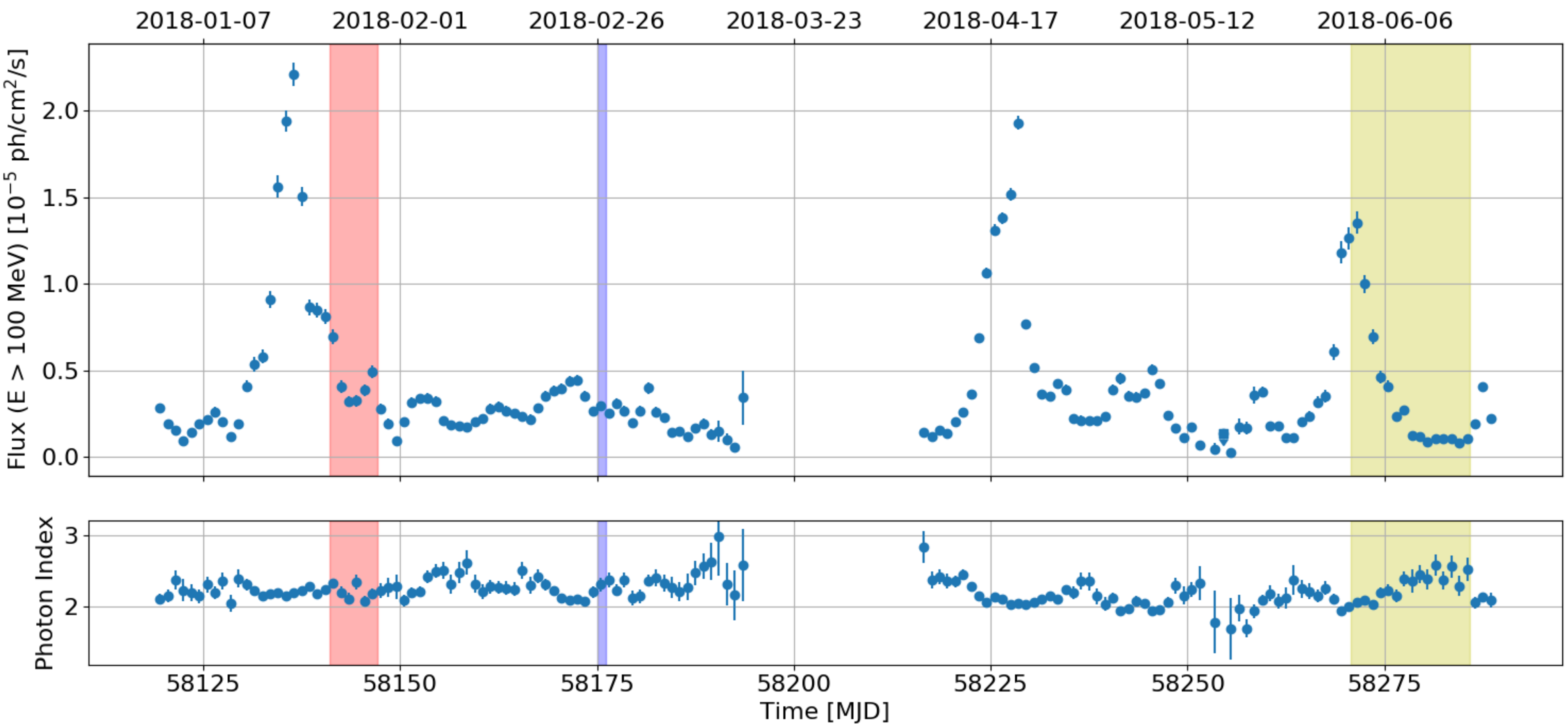




Emery, G et al. – PoS ICRC2019 668

IV-A – 3C 279

3 – 2018 overview



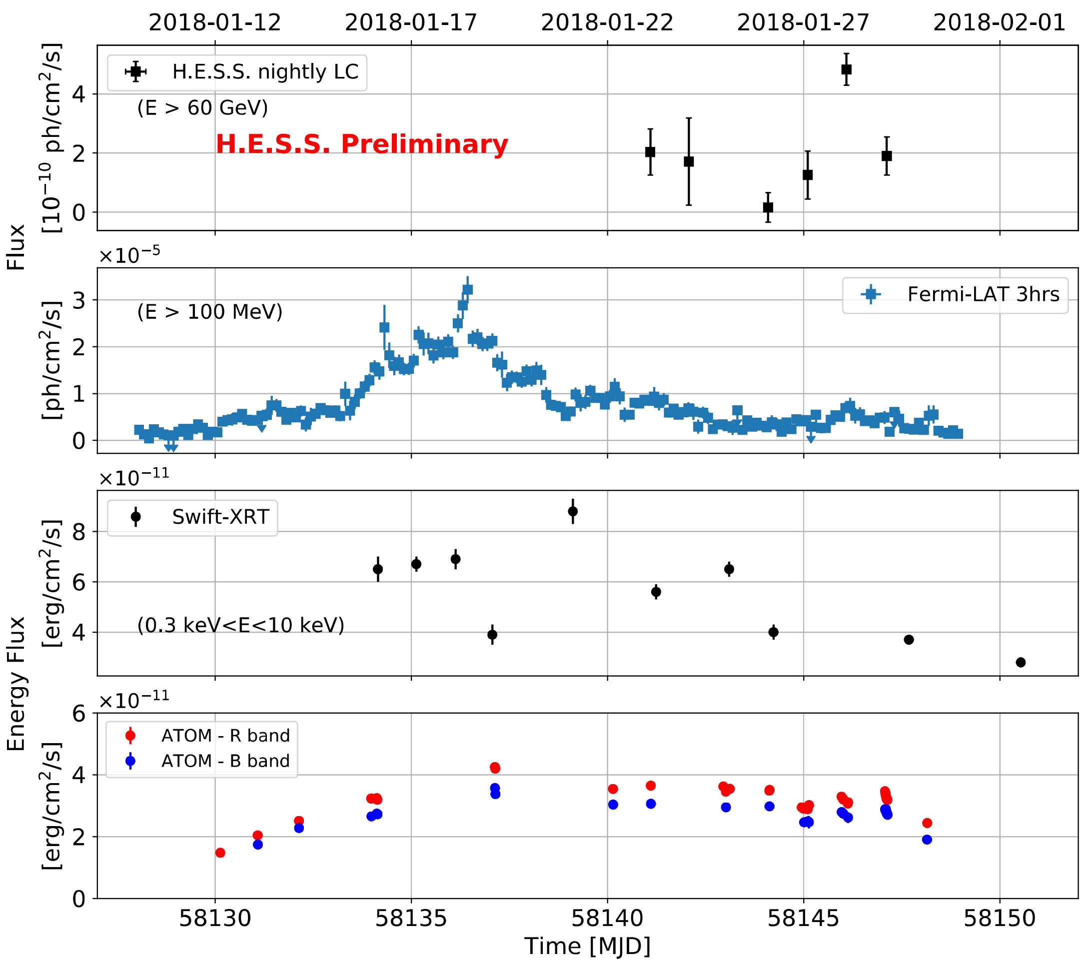
Originally Mono analysis

Spectral analysis issue : cross-check still ongoing

Delay the physical exploitation

IV-A – 3C 279

4 – January 2018



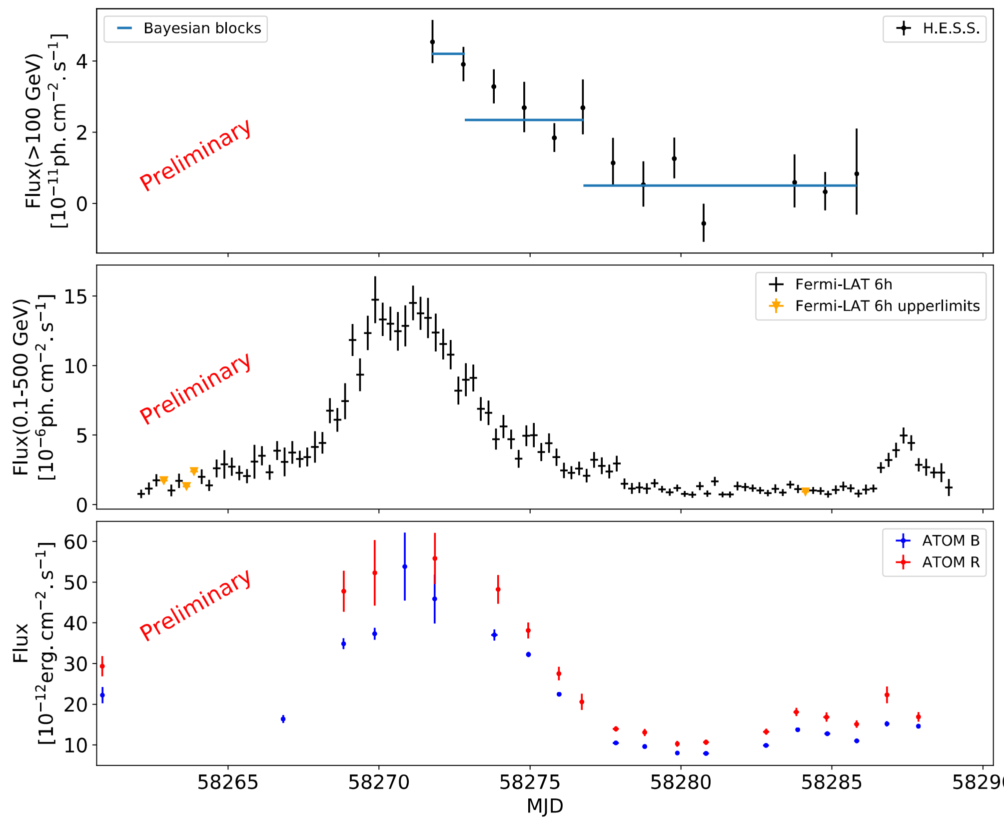
- Late VHE follow-up due to weather
  - Still caught the end of the HE flare and optical still high
- Detection of a short VHE flare → 10.7σ (Mono)
- HE and optical correlation is weak (Pearson correlation):

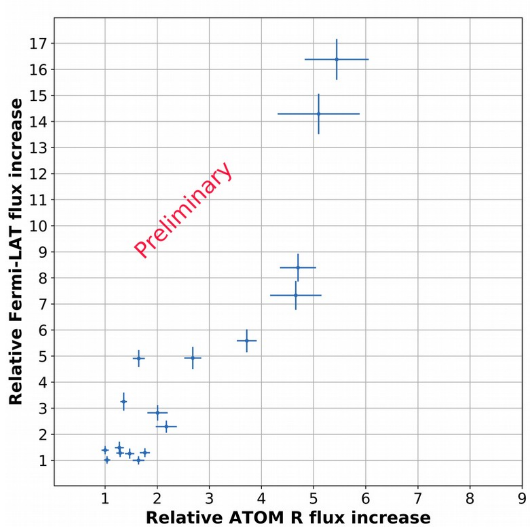
$$\rho_{Opt/HE} = 0.41 \pm 0.02$$

Emery, G et al. – PoS ICRC2019 668

IV-A – 3C 279
5 – June 2018

- Start observations at the HE maximum
- Monitored the full decreasing trend and the following days
- High state found to be up to MJD 58277
- Latest analysis :
  - 21.9σ in Stereo
  - Better cross-check
- Consistent evolution of Fermi-LAT and H.E.S.S. fluxes





Strong HE/optical correlation :

$$\rho_{Opt/HE} = 0.91 \pm 0.03$$

HE variations > 2x optical variations

Emery, G et al. – PoS ICRC2019 668

IV-B – PKS 2022-077
Content

- **I)** Active galactic nuclei
- **II)** Observation technique
- **III)** Improvements for variability studies
  - **III-A)** Adaptive lightcurve
  - **III-B)** Bad interval filtering
- **IV)** Flare analyses
  - **IV-A)** 3C 279 : A bright FSRQ
  - **IV-B)** PKS 2022-077 : A distant blazar
- **V)** TXS 0506+056 / neutrino

IV-B – PKS 2022-077

1 - Properties

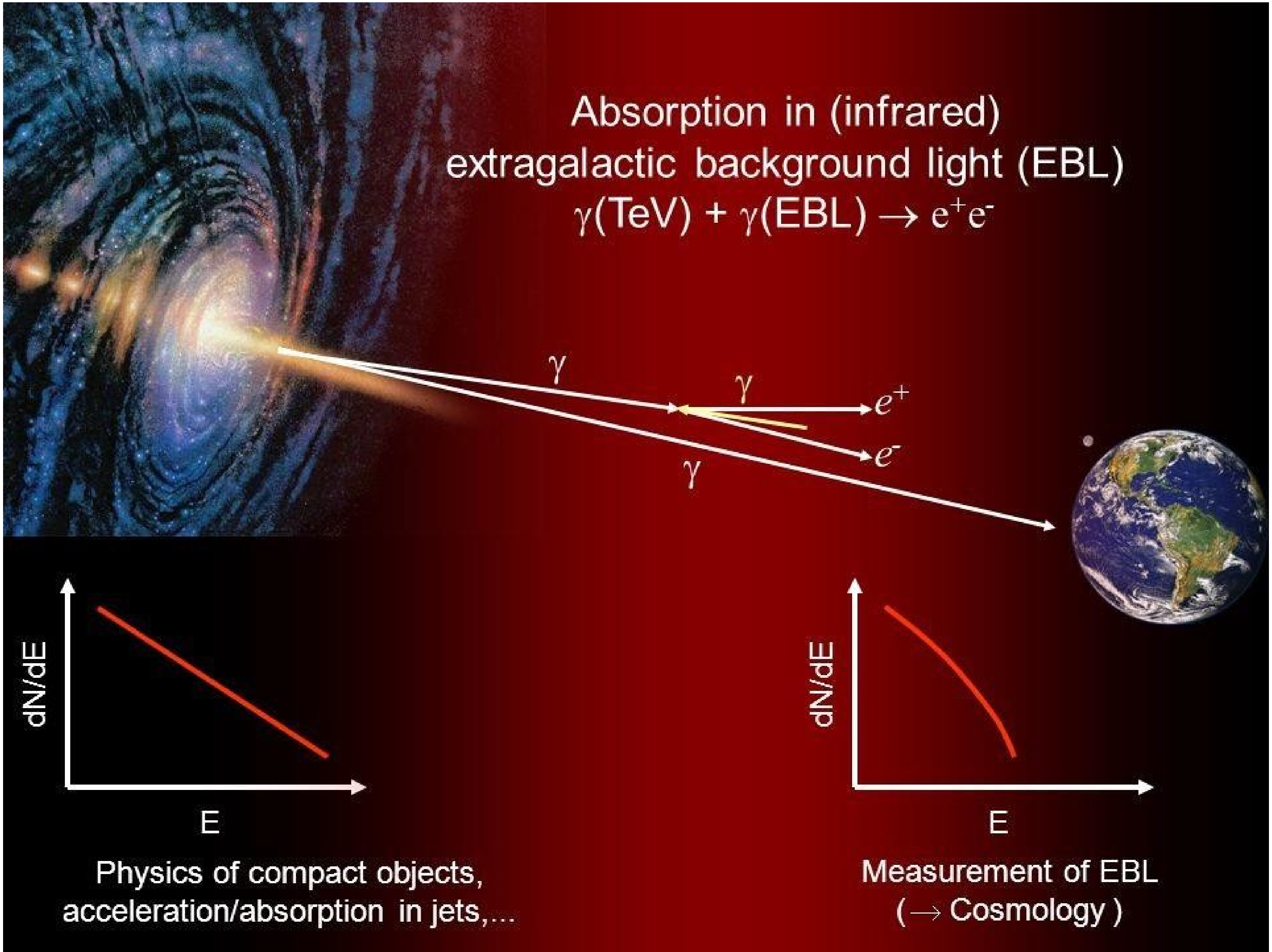
- Strong activity seen at HE with Fermi-LAT in :
  - April 2016
  - September 2017
  - October 2017

- Blazar located at a redshift of 1.388
  → very difficult to detect at VHE

- Absorption of VHE by the extragalactic background light

  → Detection would constrain the EBL

IV-B – PKS 2022-077
1bis - EBL



IV-B – PKS 2022-077

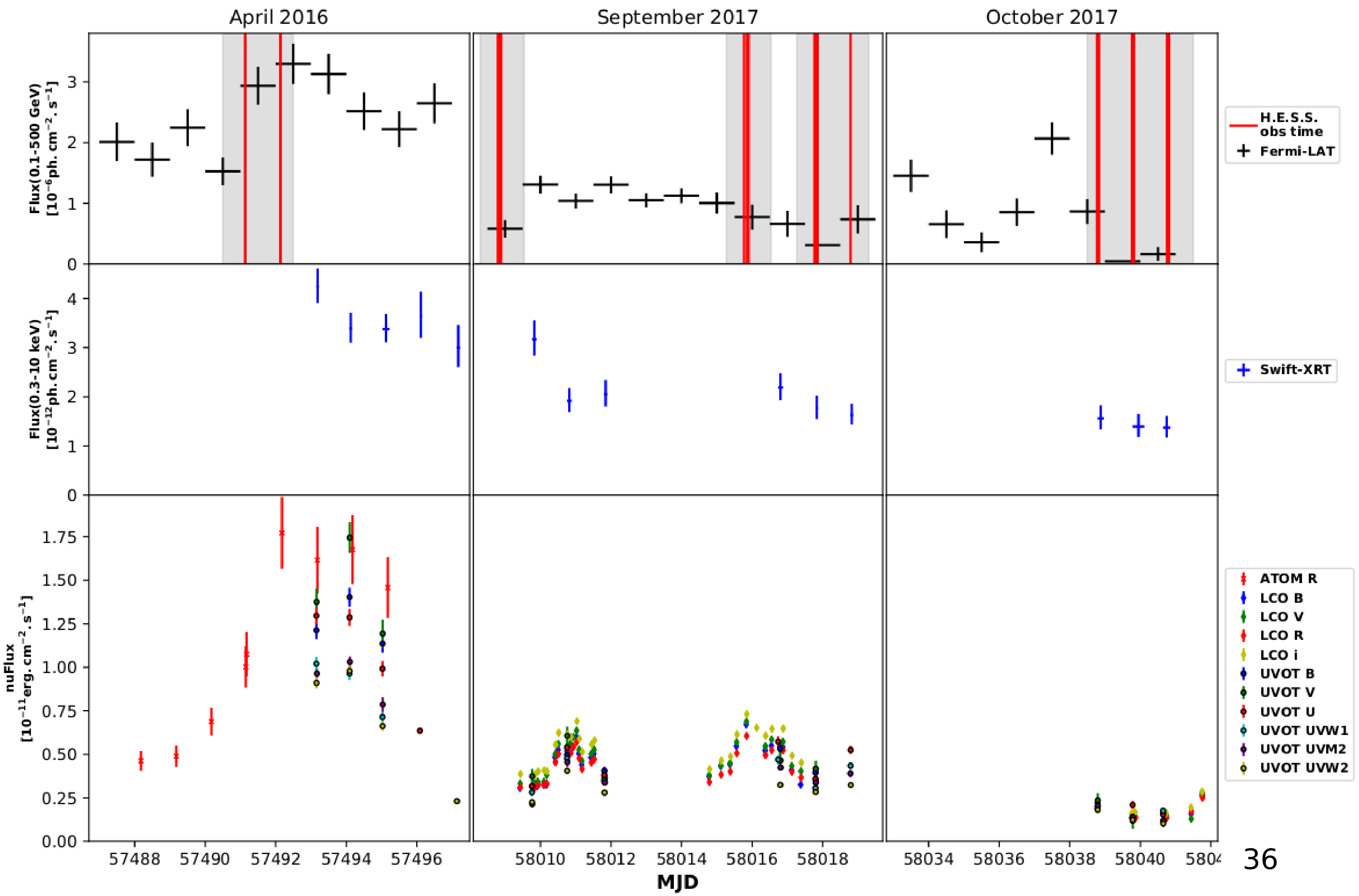
2 – MWL overview

H.E.S.S.
no detection

HE
Fermi-LAT

X-rays
Swift-XRT

Optical



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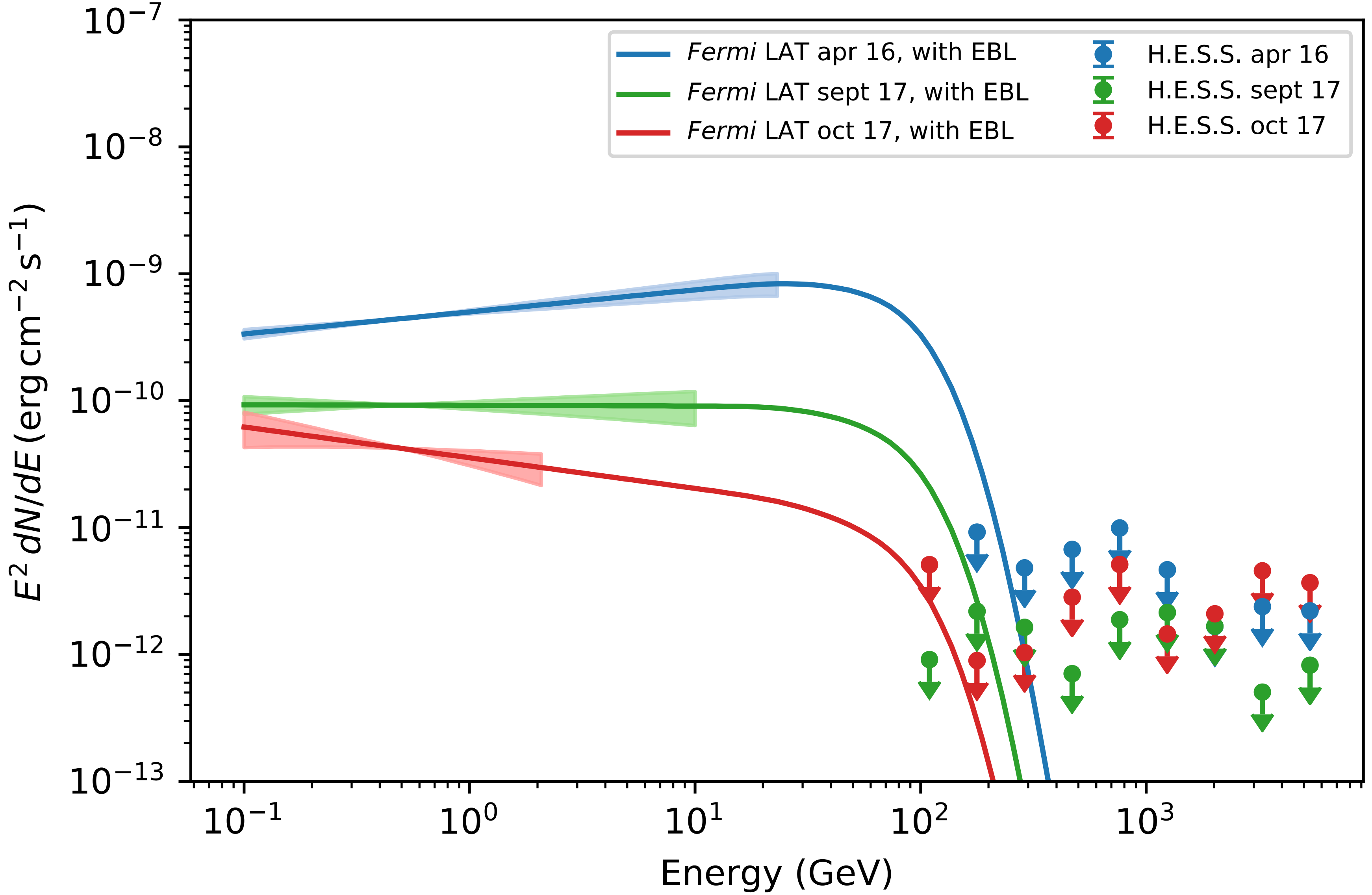
IV-B – PKS 2022-077

3 – High and very high energy spectra



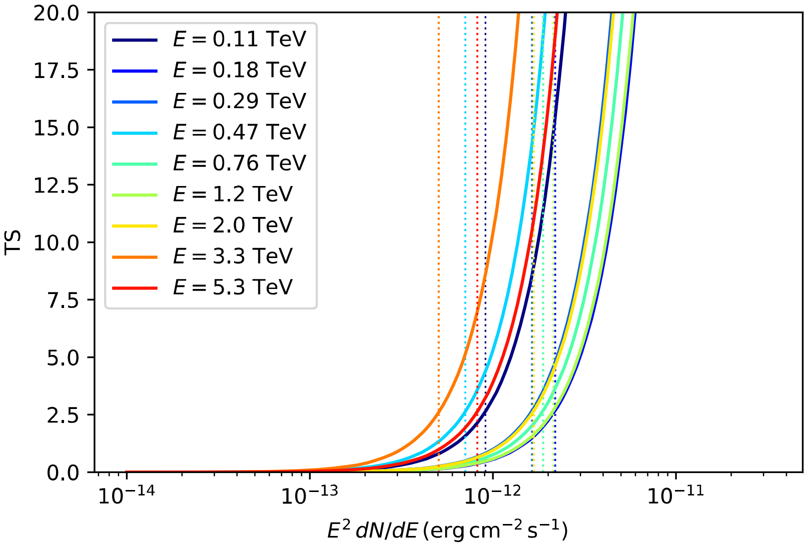
Emery, G et al. – PoS ICRC2019 669

IV-B – PKS 2022-077

4 – Physical properties extraction

- 3 hypotheses tested :
  - Different EBL density
  - Specific absorption in the source
  - Cut-off in emitting particles energy
- Perform a profile likelihood ratio test for each hypothesis modifying the HE extrapolation for each hypothesis separately and iteration over the control parameter value

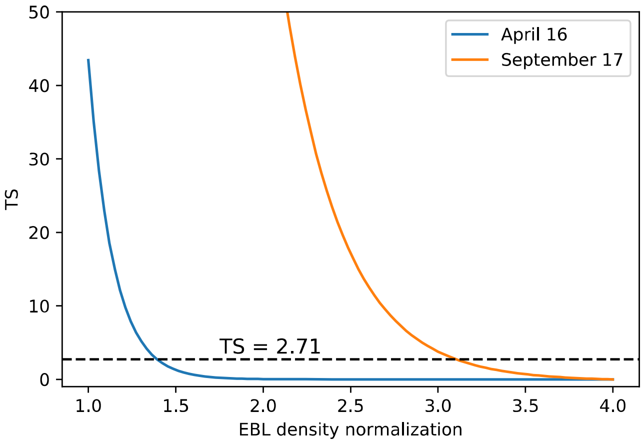
H.E.S.S. upper limits as Gaussian likelihood profiles

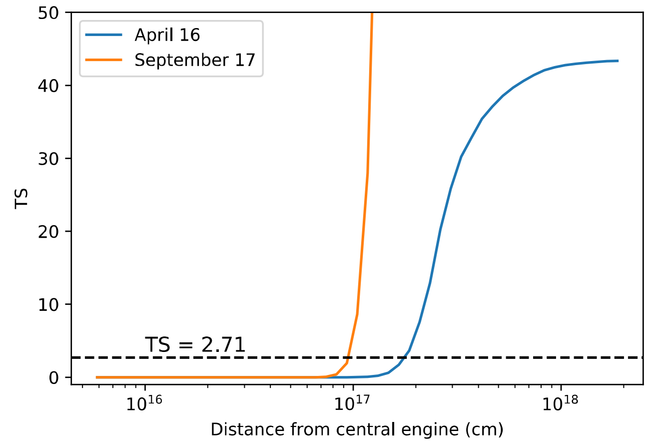


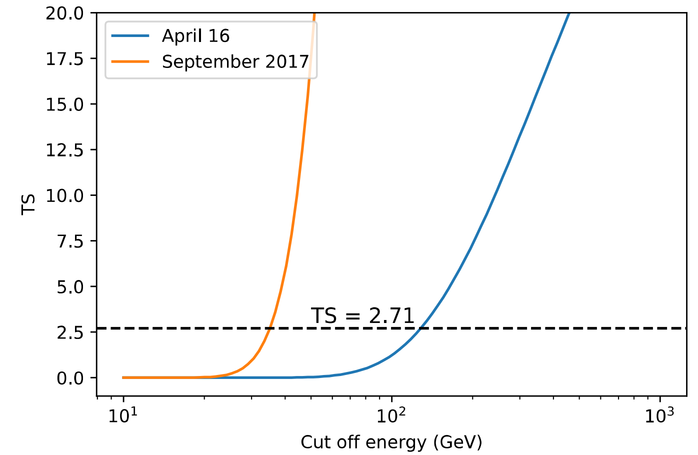
Emery, G et al. – PoS ICRC2019 669

IV-B – PKS 2022-077

4 – Physical properties extraction







- A correction to the EBL density compared to the model by Dominguez et al. is ruled out
- Both an internal cut-off and absorption possible. Limits on the control parameter derived :

	Absorption : distance to BH	Cut-off : Ecut
April 2016	≤ 1.8 X 10^{17} cm	≤ 128 GeV
September 2017	≤ 9.5 X 10^{16} cm	≤ 35 GeV

Emery, G et al. – PoS ICRC2019 669

V – TXS 0506+056 / neutrino
Content

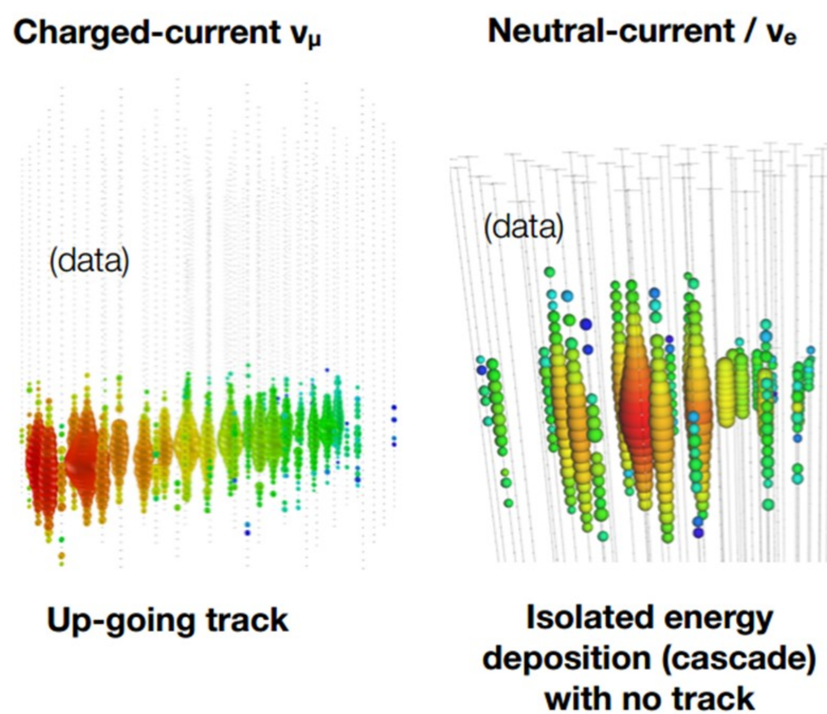
V – TXS 0506+056 / neutrino
1 - Context

September 2017 : IceCube-170922A
- muon track event

Spatial coincidence : 0.1°

TXS 0506+056 :
- z=0.337
- Complex classification
- MWL flare

Temporal coincidence :
- 6 month high state HE
- VHE detection few days later along with X-ray increase



→ **3 sigma association**

V – TXS 0506+056 / neutrino

1 - Context

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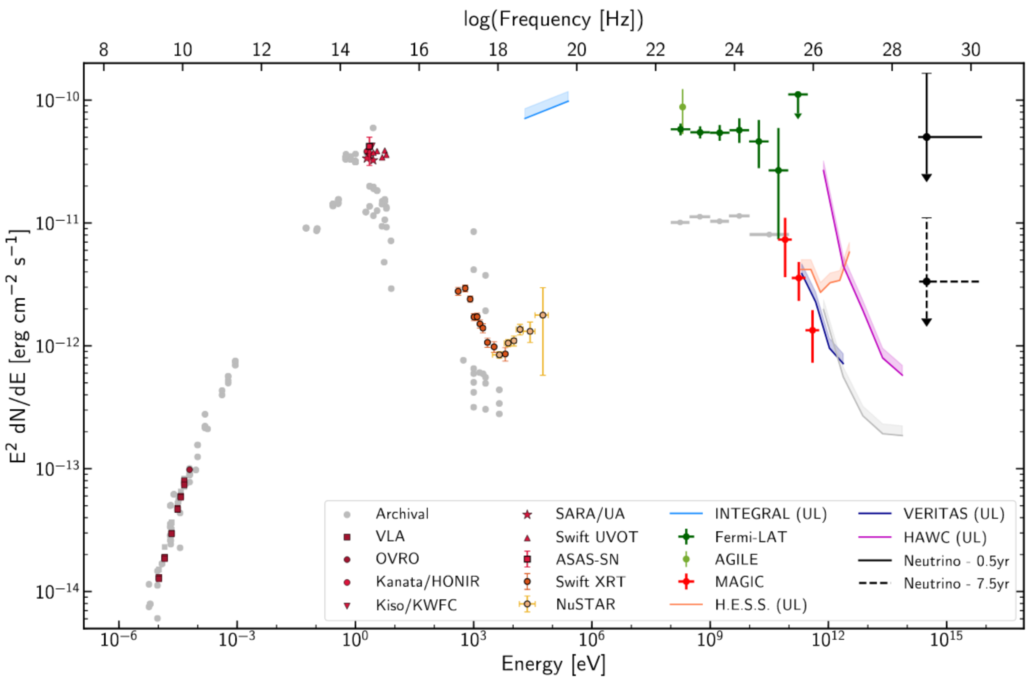


TXS 0506+056 contemporaneous to the neutrino detection

IceCube Collaboration et al. Science 361,eaat1378(2018)

V – TXS 0506+056 / neutrino
2 – Model

- LeHa code* : stationary, one zone, lepto-hadronic model
  - electrons/positrons and protons
  - broken power-laws with an exponential cut-off
  - 15 parameters

- Neutrino flux convoluted with 2 IceCube sensitivities :
  - EHE : Extremely high energy
  - PS : Point Source

- Simplifications :
  - common acceleration
  - synchrotron cooling $e^{\pm}$
  - Fixed E_{min}
  - E_{max} proton fixed by cooling
  - R_{max} by causality

→ 8 parameters

* Cerruti, M et al. MNRAS448 (2015) Mar. 910–927

V – TXS 0506+056 / neutrino

3 – The study

- Low energy bump → e^{+-} synchrotron

- High energy bump → 2 solutions
  - p synchrotron
  - pions + SSC

- Step 1 : General fit by hand

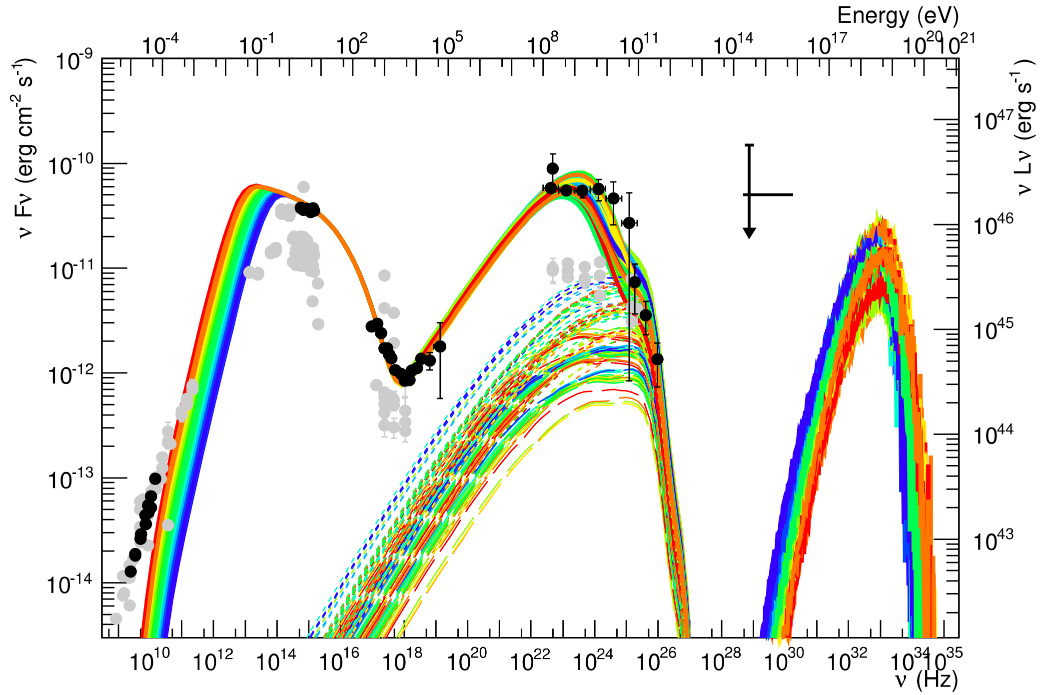
- Step 2 : Scan of reduced parameter space

Cerruti, M; Zech, A; Boisson, C; Emery,G; Inoue, S; Lenain. J-P; – MNRAS 483 (2019) Feb L12-16

V – TXS 0506+056 / neutrino

4 – Proton synchrotron solutions

- X-rays → HE constraints protons
- 17500 models
- jet power : 8×10^{45} – 1.7×10^{48} erg.s^{-1}
  L_{edd} = 3.8×10^{46} erg.s^{-1}
- Neutrinos (EHE) :
  - tot : 5.7×10^{-3} – 0.16 yr^{-1}
  - IC : 2.4×10^{-5} – 1.7×10^{-3} yr^{-1}

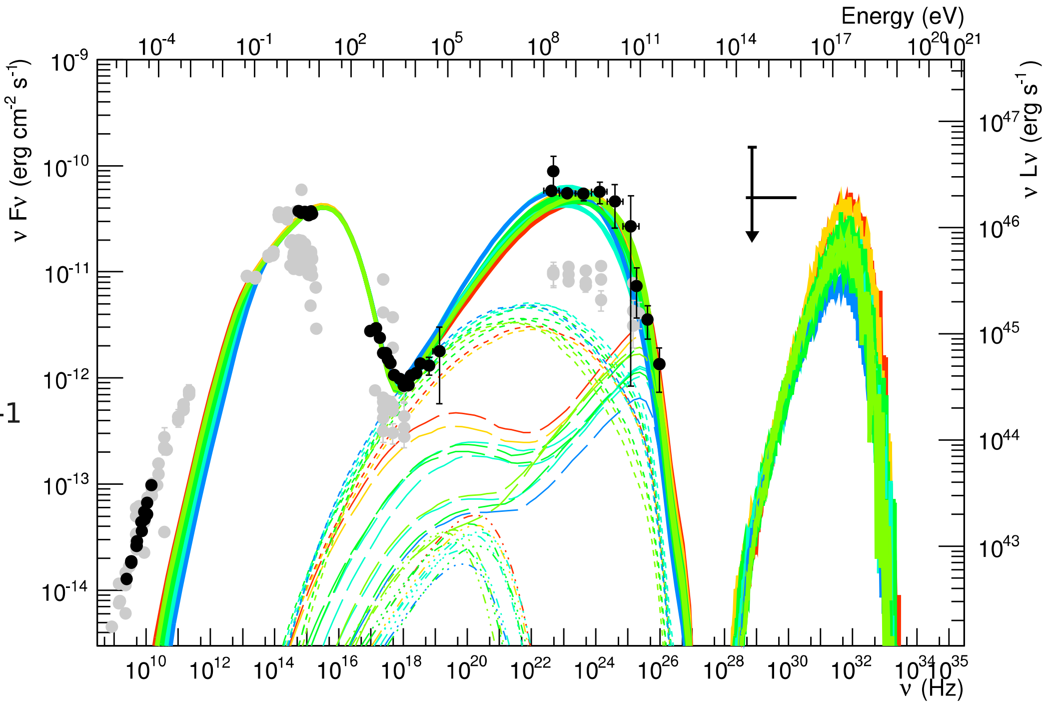


Cerruti, M; Zech, A; Boisson, C; Emery,G; Inoue, S; Lenain. J-P; – MNRAS 483 (2019) Feb L12-16

V – TXS 0506+056 / neutrino

5 – Mixed lepto-hadronic solutions

- X-rays constraints cascades
- few fixed parameters
- 3500 models
- jet power : $3.5\times10^{47} - 3.5\times10^{48}$ erg.s^{-1}
  $L_{edd} = 3.8\times10^{46}$ erg.s^{-1}
- Neutrinos (EHE) :
  - tot : 0.1 – 3.0 yr^{-1}
  - IC : 0.008 – 0.11 yr^{-1}
- Neutrinos (PS) :
  - tot : 0.3 – 6.9 yr^{-1}
  - HE : 0.2 – 6.4 yr^{-1}



Cerruti, M; Zech, A; Boisson, C; Emery,G; Inoue, S; Lenain. J-P; – MNRAS 483 (2019) Feb L12-16

Conclusions

- **A varied work including monitoring, software development , analysis and interpretation. Common aim : Variability studies and AGN physics**
- **Analysis : 9 flares from 2 AGNs**
  - **Constraining limits on distant PKS 2022-077 in a MWL context. 2 hypotheses :**
    - **Intrinsic cut-off of the emitted spectra**
    - **Absorption by the BLR photons**

  → **Publication**
  - **2 very different detections of 3C 279**
    - **Diverse MWL behaviour : correlated Optical/HE/VHE, VHE only flare, HE flare with no optical,...**

  → **Publication**

Conclusions

- **New technique : Adaptive lightcurve allowed to see seconds scale variability during a flare of PKS 2155-304**

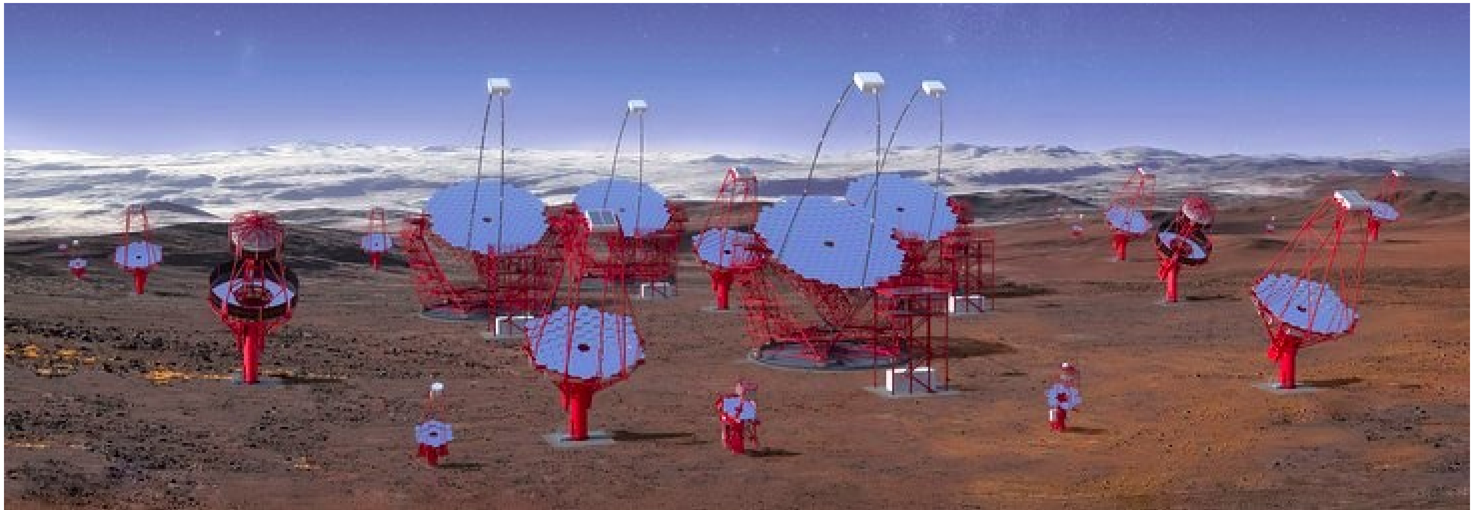
- **Modeling : Study of TXS 0506+056 with a lepto-hadronic model in the context of an association with a neutrino**
  - **p synchrotron solutions unlikely to emit the neutrino**
  - **mixed solutions constrained by single neutrino detection**

→ **Publication**

Perspectives

- **Future interpretation of 3C 279 properties promising thanks to the MWL data available and different flare properties**

- **CTA : IACT observatory**
  - **Ongoing construction, 2 sites, improved sensitivity,…**
  - **Possibility to resolve shorter time intervals and more AGN**
  - **Adaptive LC in gammapy**
- **Active research field**

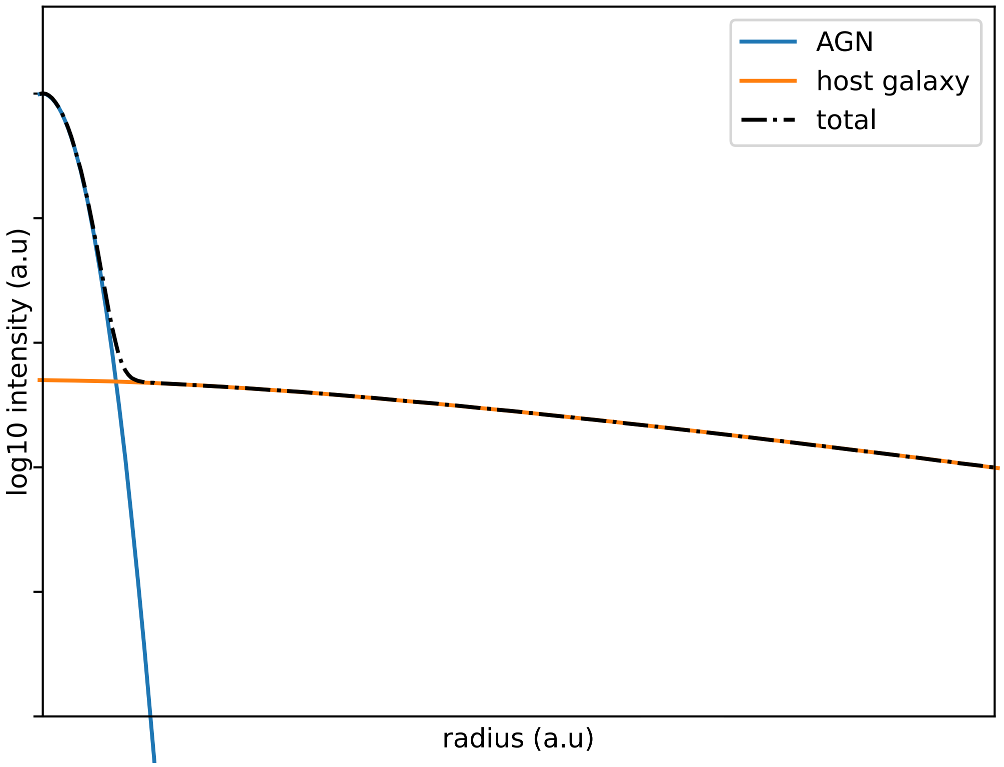


End

Questions?

Back Up

Luminosity profile



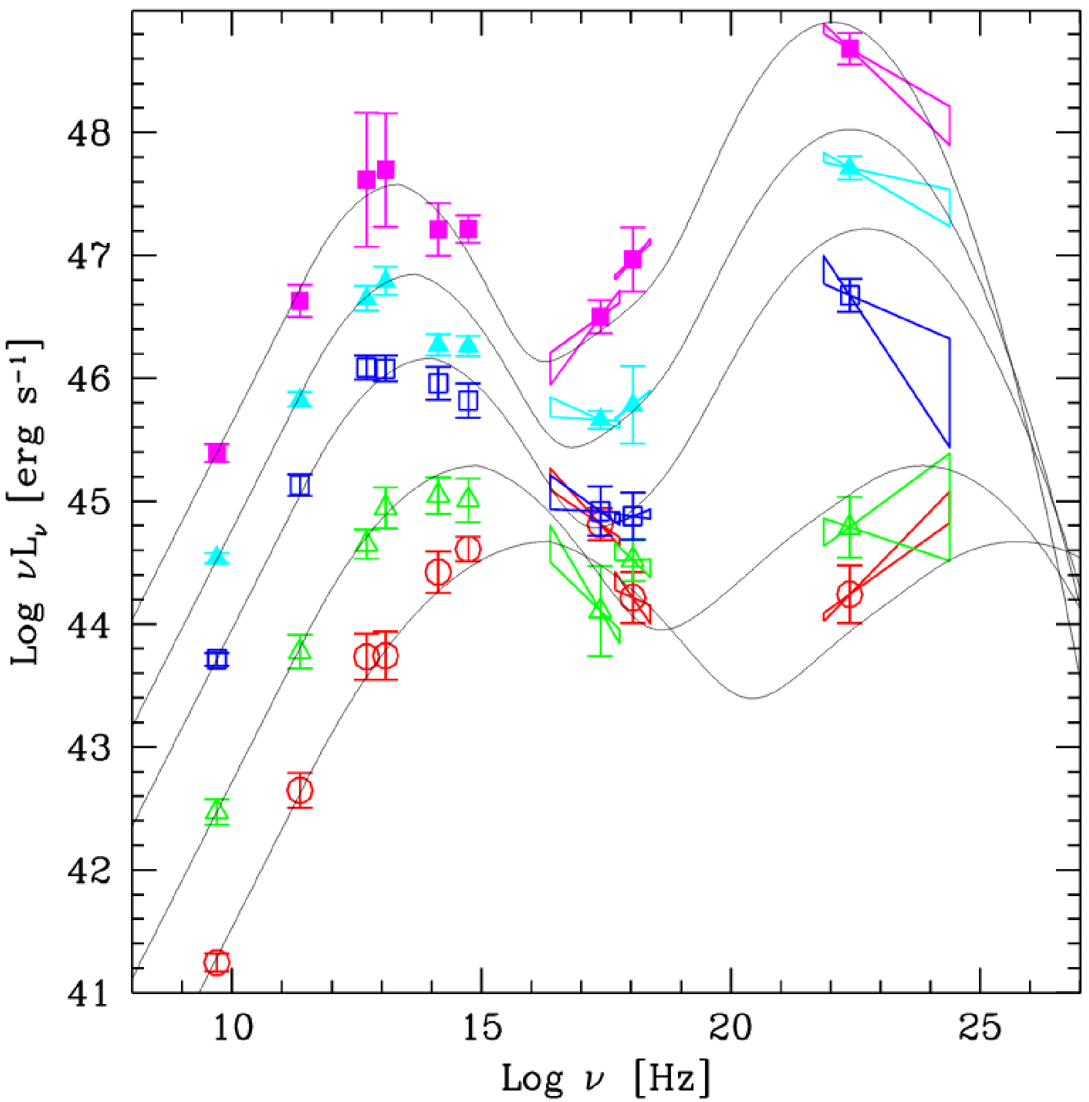
Schematic optical luminosity profile of an AGN and its host galaxy.

Back Up
Blazar sequence

Peaks source dependent

low E peak
FSRQ : 10^{12}-10^{14}Hz

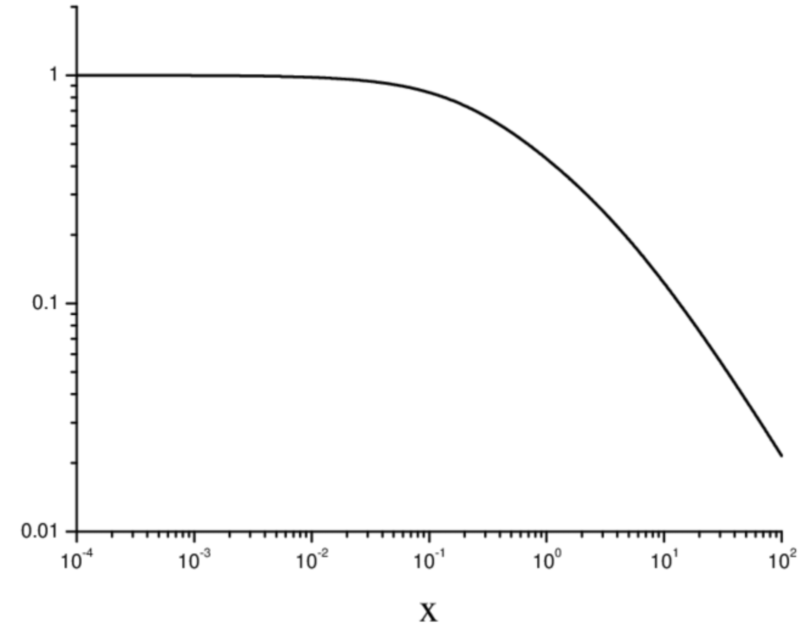
LBL : 10^{12}-10^{14}Hz
IBL : 10^{15}-10^{16}Hz
HBL : 10^{17}-10^{18}Hz



Donato et al. (2003) adapted from Fossati et al. 1998

Back Up

Inverse Compton



Two regimes in the electron rest frame :

- Thomson :
  Scattering without energy modification

$$E_{\gamma f} = \gamma_e^2 E_{\gamma i}(1 + \beta cos\theta_f^*)(1 - \beta cos\theta_i)$$

- Klein-Nishina :
  Scattering with energy $m_e c^2$

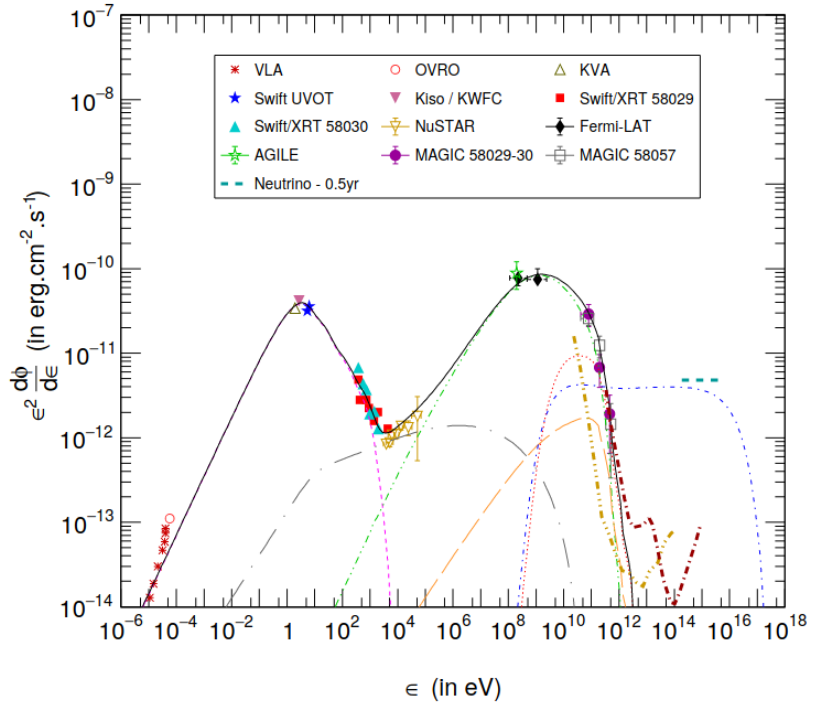
$$E_{\gamma f} = m_e c^2 \gamma_e (1 + \beta cos\theta_f^*)$$

→ Additional energy from Lorentz transform

Back Up
pp interaction

- pp → pions
- requires high proton densities ($> 10^6 cm^{-3}$)
- Multiple scenarios :
  - Clouds in jet = target proton injection
  - Large quantity of cold protons in jet
- Charge neutrality either $e^{\pm}$ or $e^- p^+$
- Associated with high luminosity jets
- Applied to TXS 0506+056 and another neutrino detection

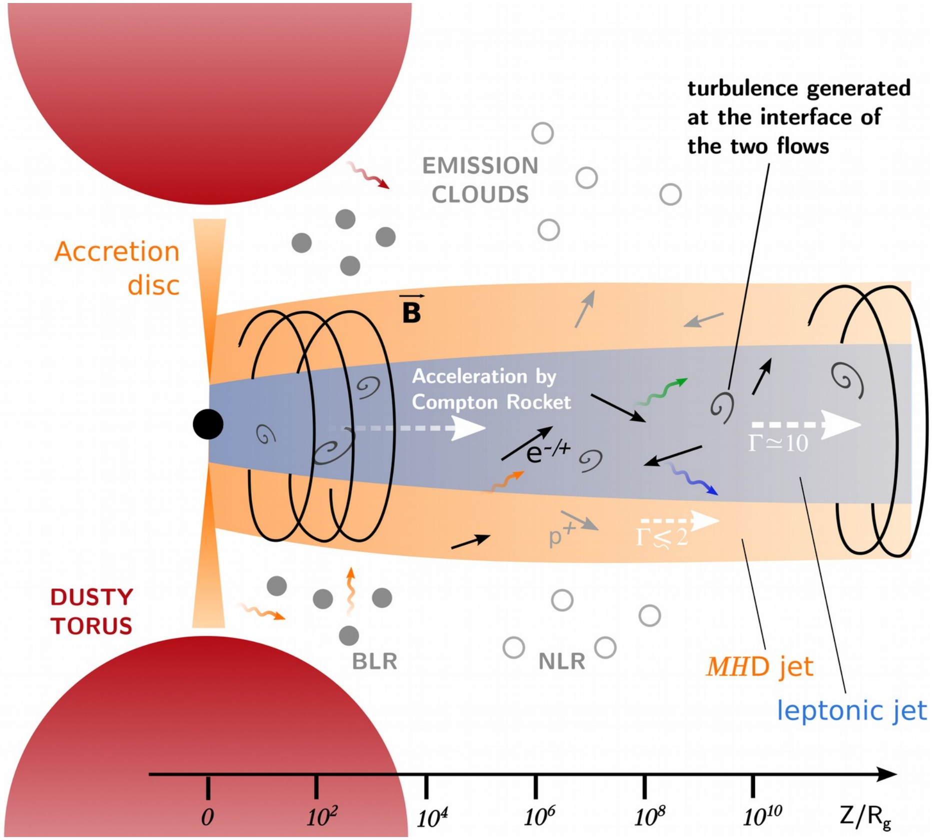
Banik, P. et al, Physical Review D, Volume 101, Issue 6, article id.063024, March 2020



Banik, P. et al, Physical Review D, March 2020

Back Up
Multi-zone jet

- Inner and outer jet



Back Up

EBL VHE constraints

- Opacity to VHE vs redshift → EBL density vs redshift
- Complementary with local direct measurement

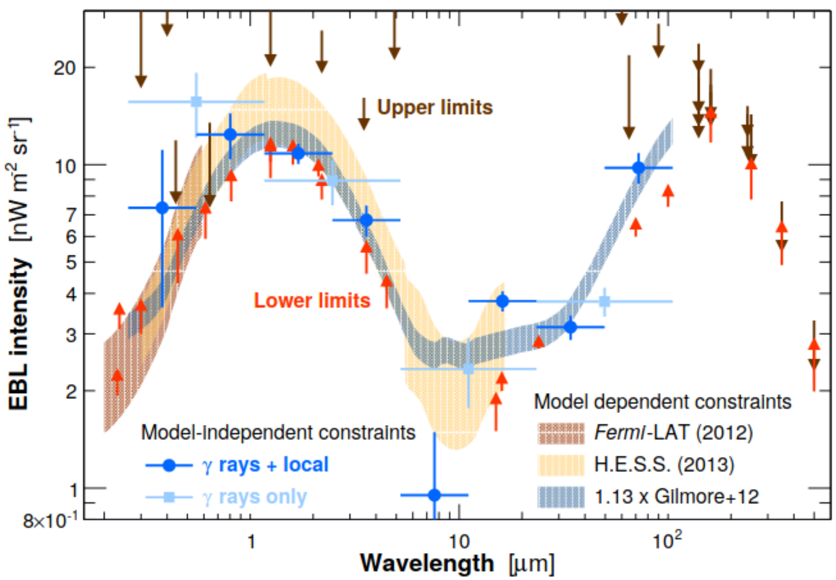


FIG. 3.— EBL intensity at $z = 0$ as a function of wavelength.

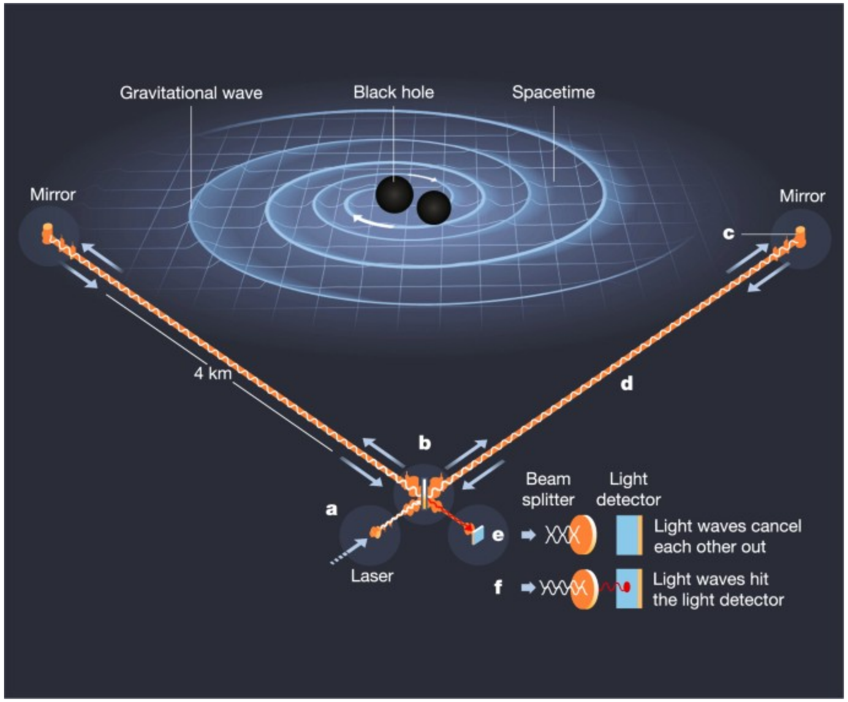
Biteau, J. and Williams, D. A.; The Astrophysical Journal; 2015

Back Up

Gravitational waves

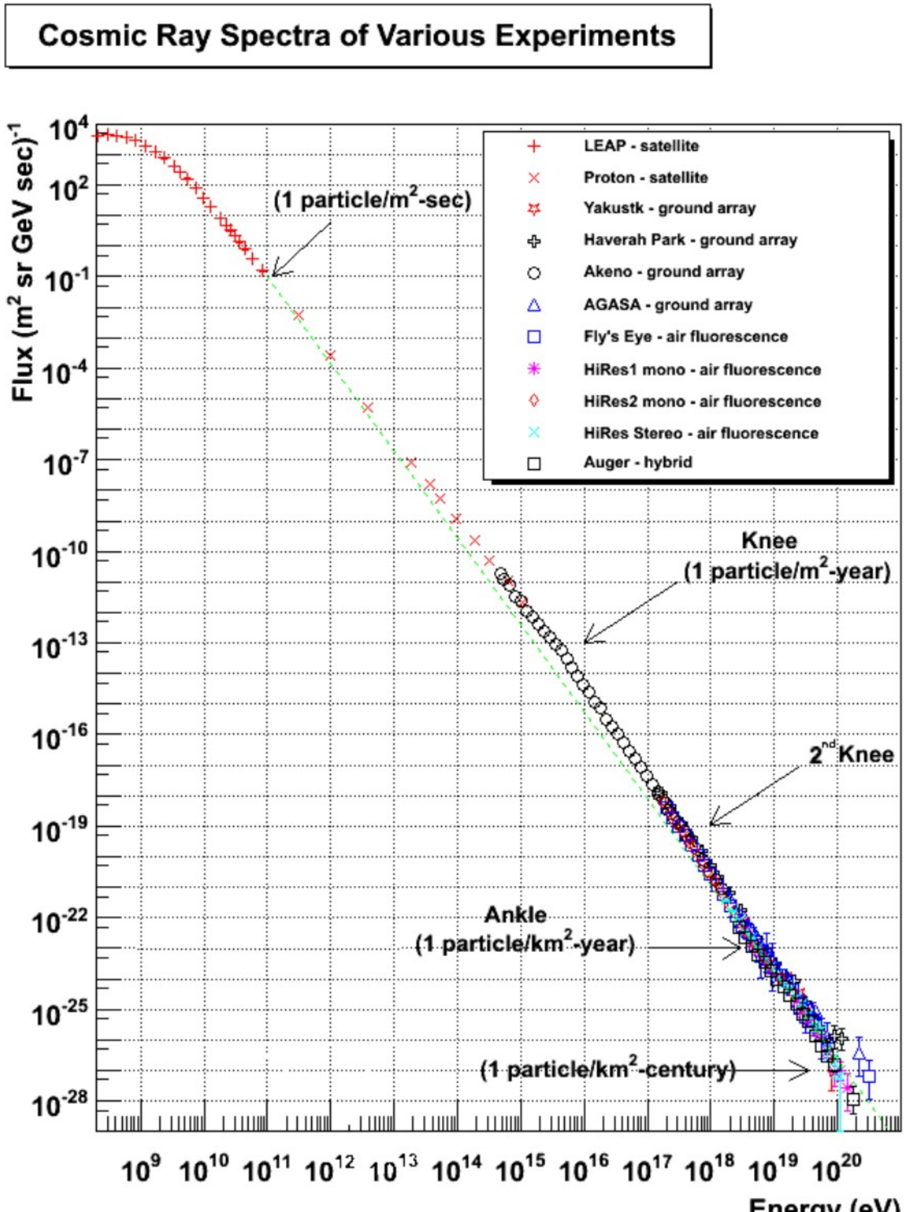
- Deformation of space
- Merging of compact object observed

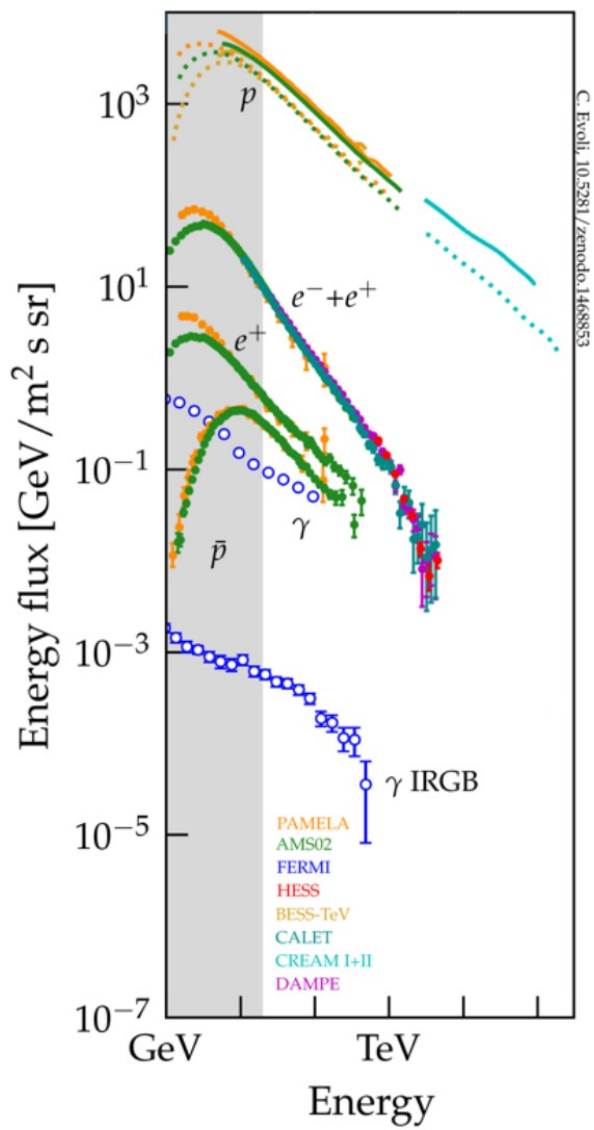
- LISA should be able to see SMBH merging months in advance



Back Up

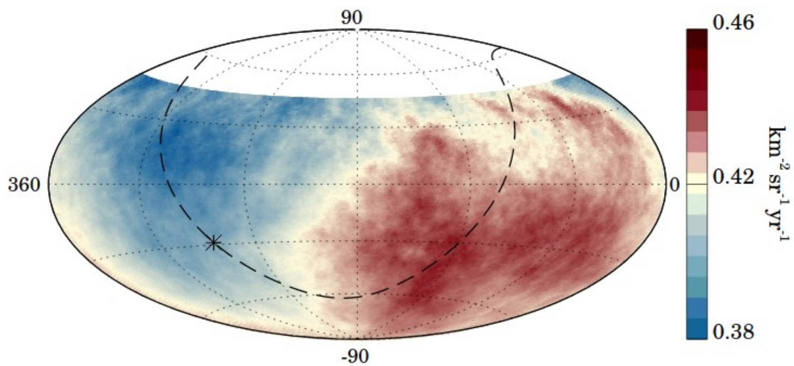
Cosmic ray spectrum





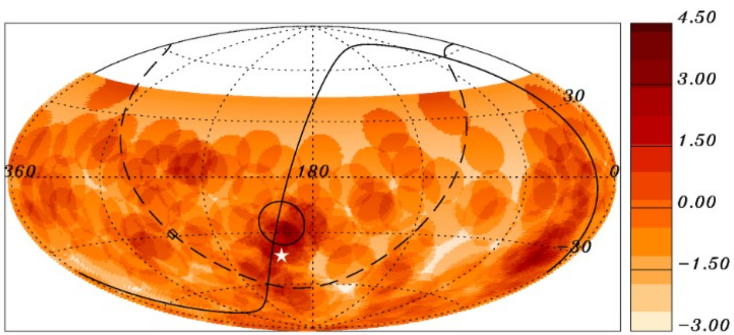
Back Up
UHECR

- Dipole
- Hint of hotspots
- Composition changes

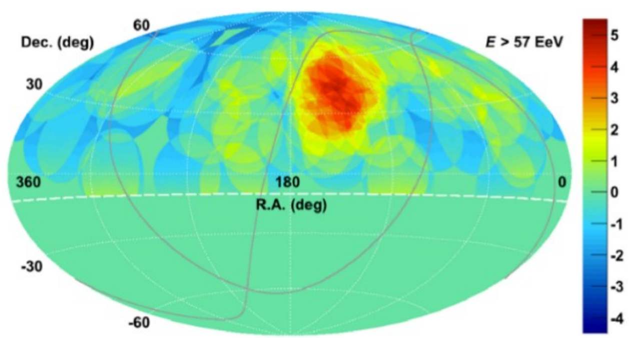


Smoothed cosmic-ray flux for $E_{\text{Auger}} > 8\,\text{EeV}$ in Equatorial coordinates.

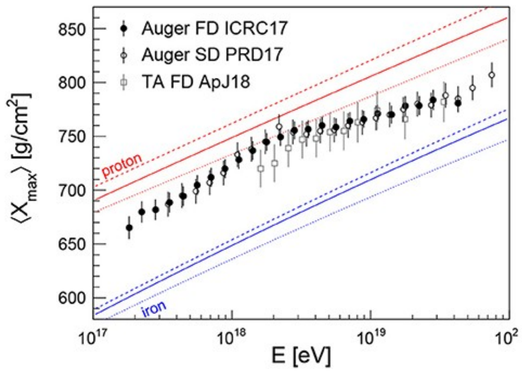
Blind →

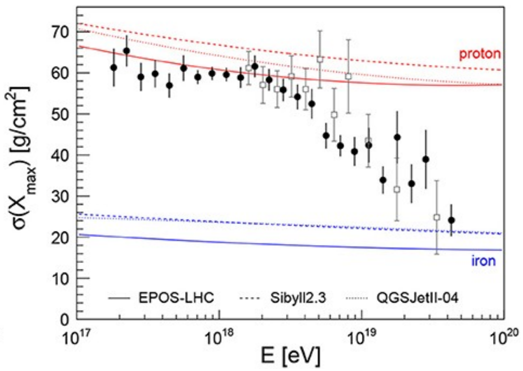


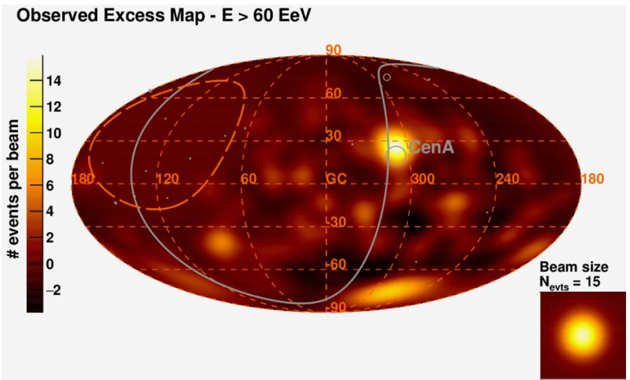
Auger>54 EeV



TA>57EeV







← AGN catalog

Back Up

Trigger H.E.S.S.

Multi-level :

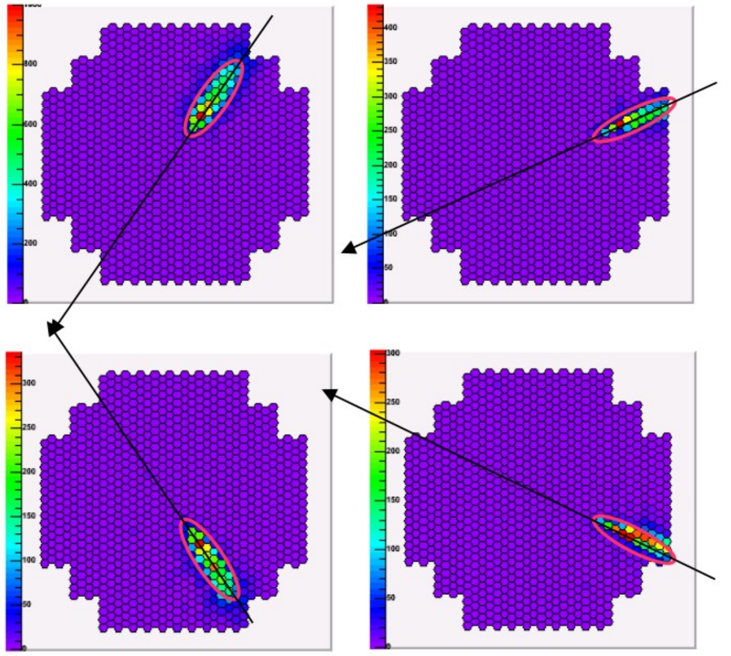
- Camera : 3 pixels > X photoelectrons
  Coincidence ~1.5 ns
- Central :
  - 2+ telescopes → stereo recording
  - CT5 only → mono recording
  - 1 HESS1 telescope → rejected

  Coincidence 80 ns

Back Up

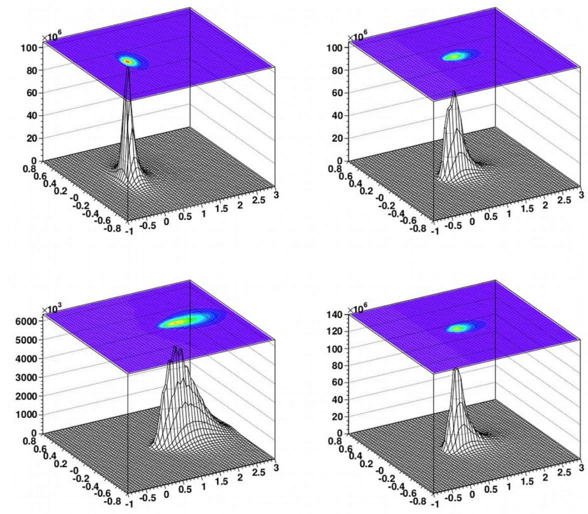
Event reconstruction

- Photon shower → Elliptic images
  - shape → direction
  - distance from camera center → distance of impact
  - deposited charge → energy
- Multiple reconstructions
  - Hillas
    Hillas, ICRC 1985
  - Model
    de Naurois and Rolland, Astroparticle physics 2009
  - ImPACT
    Parson and Hinton, Astroparticle physics 2014
- Mono or stereo



Back Up

Model

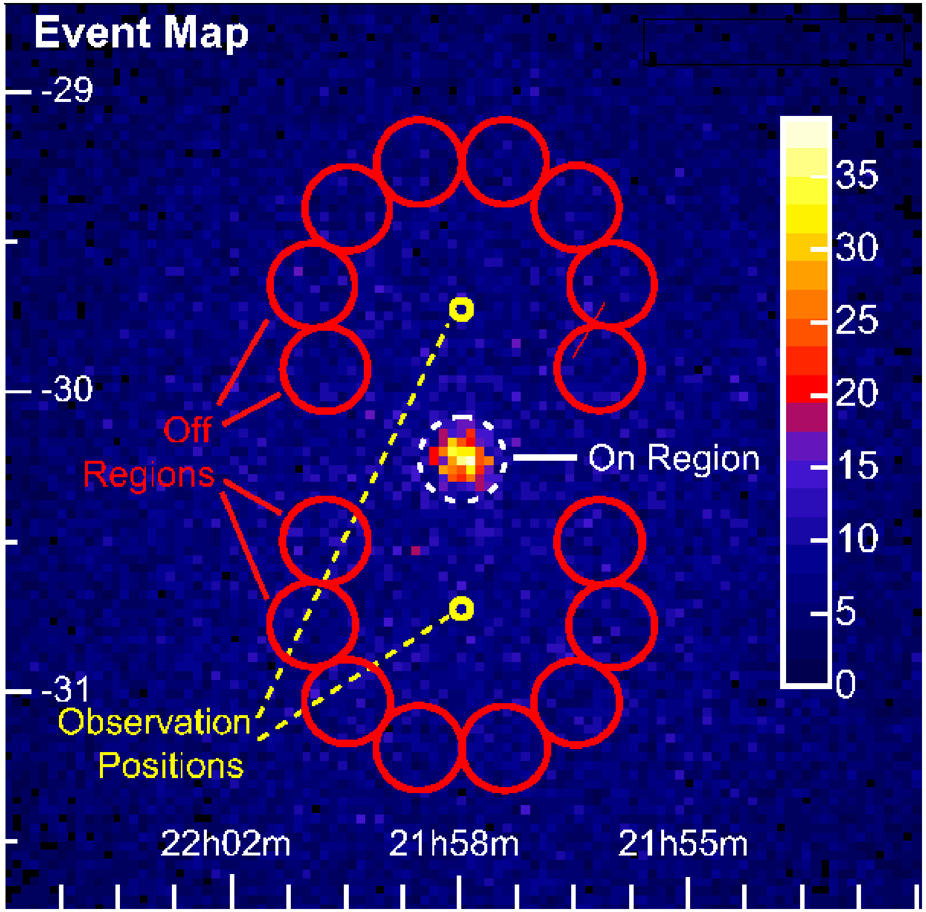


- Simulate shower images
- Fit NSB and shower in data using lookup tables of the simulated shower
- Deduce photon properties
- Goodness of fit used to estimate the quality of the fit and discriminate photons and hadrons

$$G = \frac{\sum_{\text{pixel } i} \left[\ln L(s_i|\mu_i) - \langle \ln L \rangle |_{\mu_i} \right]}{\sqrt{2 \times \text{NDoF}}}$$

Back Up
ON-OFF background estimation

- Reflected background



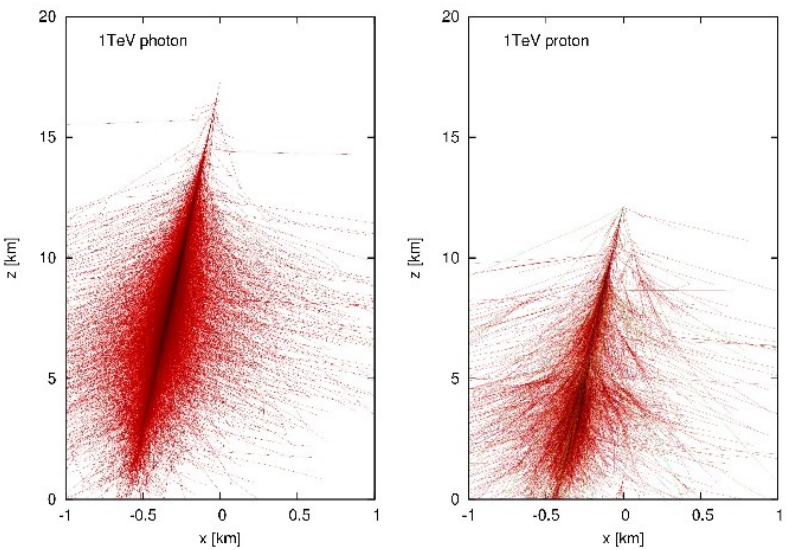
Berge et al. A&A 2007

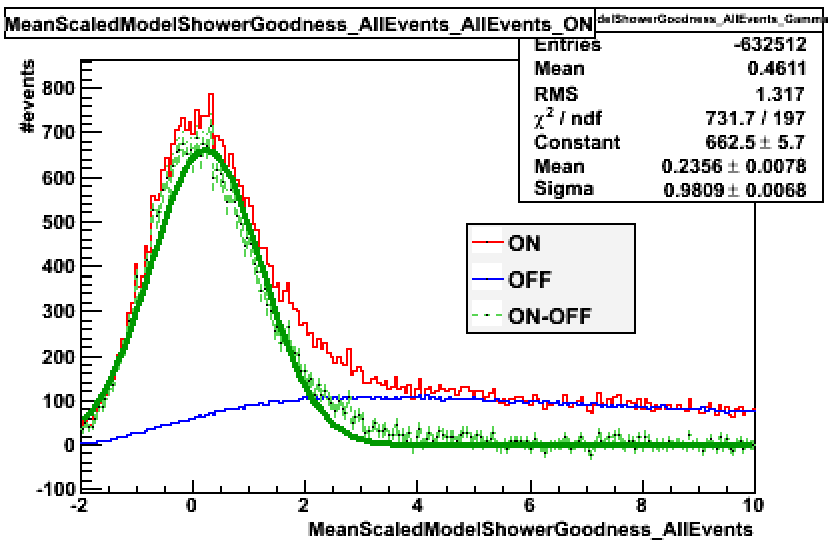
$$Excess = N_{ON} - \alpha N_{OFF}$$

Back Up

Gamma hadron discrimination

- Different image morphology
- Discriminating variable
- Cuts : purity vs efficiency

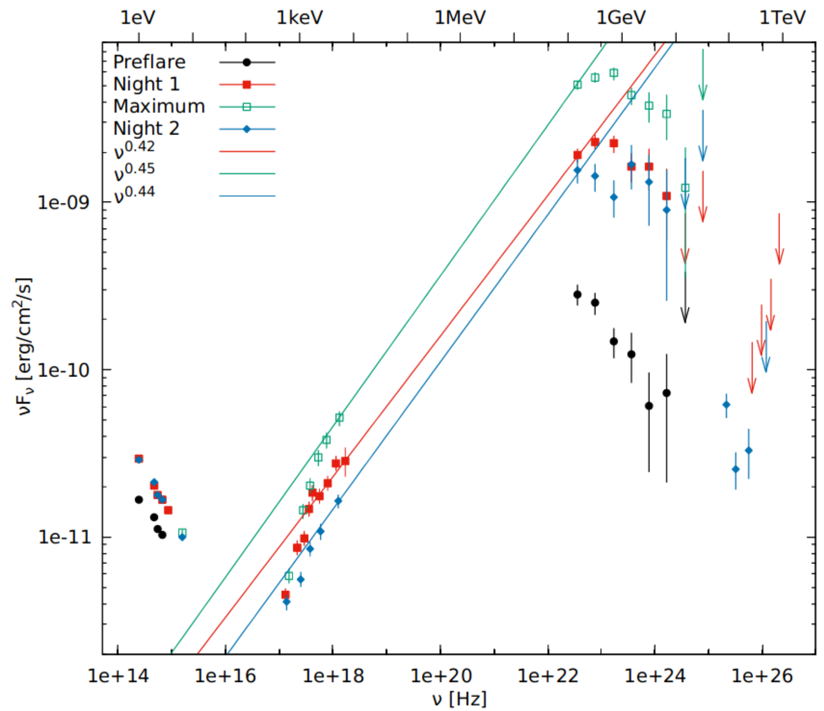




Back Up

3C 279 2014/2015 main results

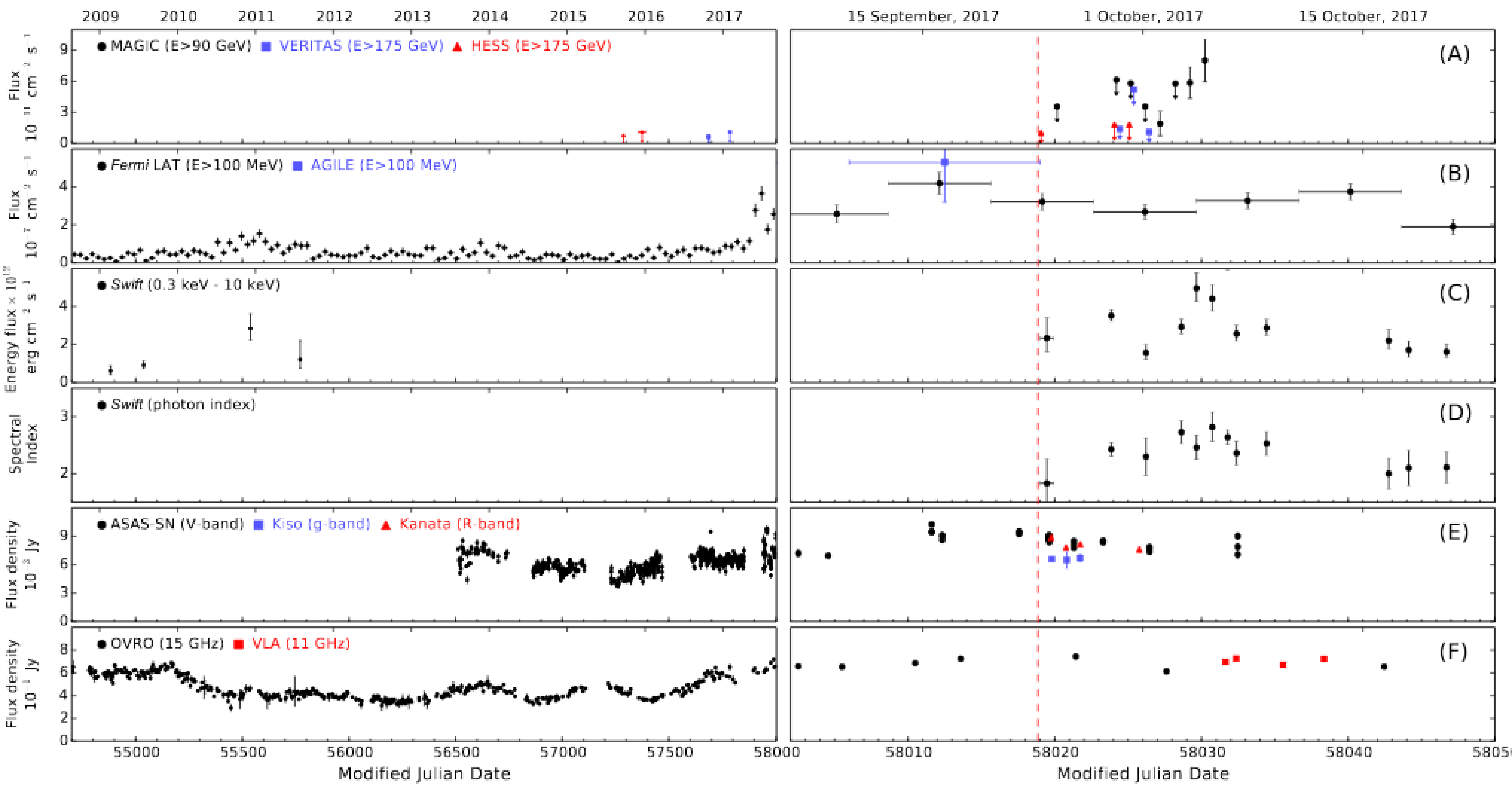
- Using the *Fermi*-LAT + H.E.S.S. detection of ‘‘night 2‘‘
- Minimum distance of the emission region from the black hole
  - lack of absorption feature by the BLR photons
  - $r > 1.7 \times 10^{17} cm$
- One-zone models cannot reproduce the observed characteristics of the 2015 flare



2015 SED taken from the 2014/2015 paper published :
A&A, 627 (2019) A159

Back Up

TXS 0506+056 MWL lightcurve



IceCube Collaboration et al. Science 361,eaat1378(2018)

Back Up

TXS 0506+056/neutrino Full results

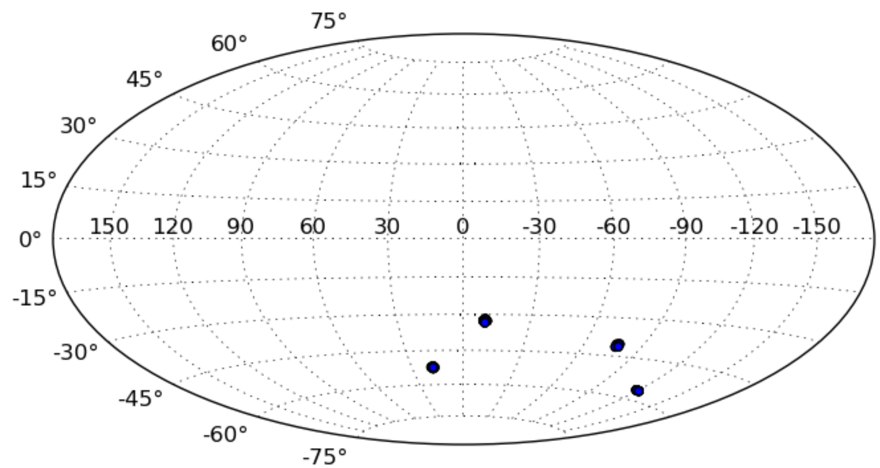
	Proton-synchrotron	Lepto-hadronic
δ	$35 - 50$	$30 - 50$
R [10^{16} cm]	$0.1 - 9.7$	$0.2 - 1.5$
$^\star\tau_{\rm obs}$ [days]	$0.01 - 1.0$	$0.02 - 0.3$
B	$0.8 - 32$	$0.13 - 0.65$
$^\star u_B$ [erg.cm^{-3}]	$0.02 - 0.16$	$6.5 \times 10^{-4} - 0.017$
$\gamma_{e,\rm min}$	500	500
$\gamma_{e,\rm break}$	$= \gamma_{e,\rm min}$	$= \gamma_{e,\rm max}$
$\gamma_{e,\rm max}$ [10^4]	$0.6 - 1.0$	$0.8 - 1.7$
$\alpha_{e,1} = \alpha_{p,1}$	2.0	2.0
$\alpha_{e,2} = \alpha_{p,2}$	3.0	3.0
K_e [cm^{-3}]	$6.3 - 9.1 \times 10^3$	$9.5 \times 10^3 - 2.6 \times 10^5$
$^\star u_e$ [10^{-5} erg.cm^{-3}]	$0.4 - 15.1$	$2.2 \times 10^3 - 43 \times 10^3$
$\gamma_{p,\rm min}$	1	1
$\gamma_{p,\rm break}$[10^9]	$= \gamma_{p,\rm max}$	$= \gamma_{p,\rm max}$
$\gamma_{p,\rm max}$[10^9]	$0.4 - 2.5$	$0.06 - 0.2$
η	$20 - 50$	10
K_p [cm^{-3}]	$10.4 - 2.0 \times 10^4$	$3.5 \times 10^3 - 6.6 \times 10^4$
$^\star u_p$ [erg.cm^{-3}]	$0.7 - 45$	$100 - 1400$
$^\star u_p/u_B$	$1.0 - 89$	$3.9 \times 10^4 - 79 \times 10^4$
$^\star L$ [10^{46} erg.s^{-1}]	$0.8 - 170$	$35 - 350$
$^\star\nu_{\rm EHE}$ [yr^{-1}]	$5.7 \times 10^{-3} - 0.16$	$0.11 - 3.0$
$^\star\nu_{\rm EHE,(0.183-4.3)\,PeV}$ [yr^{-1}]	$2.4 \times 10^{-5} - 1.7 \times 10^{-3}$	$0.008 - 0.11$
$^\star\nu_{\rm PS}$ [yr^{-1}]	$0.011 - 0.32$	$0.3 - 6.9$

Back Up

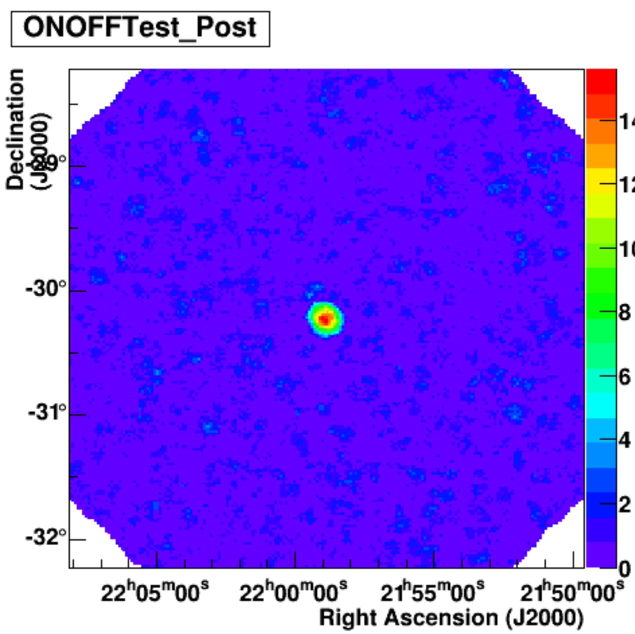
Round Up

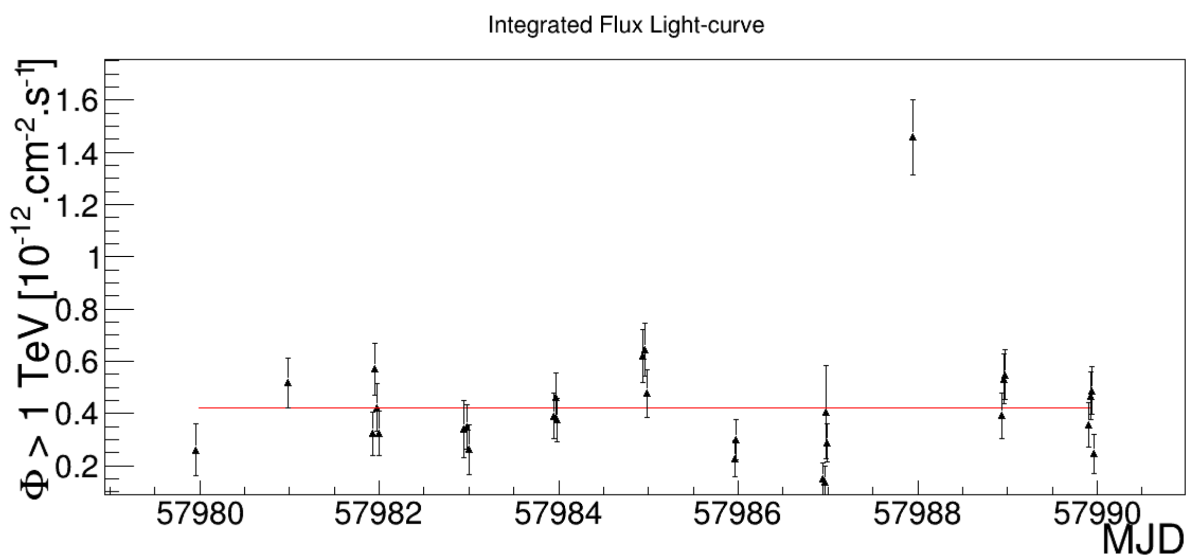
- Service task
- Monthly analysis and presentation
- Semi-automatic
- Search for variability (source and FOV)
- ~1500 runs analysed over 28 lunar periods

Back Up
Round Up



Example run distribution for one period



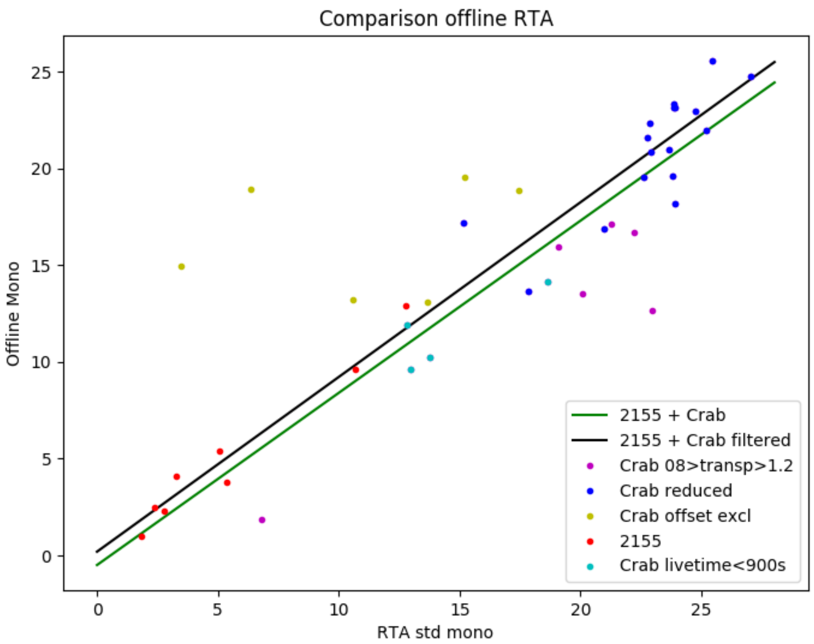


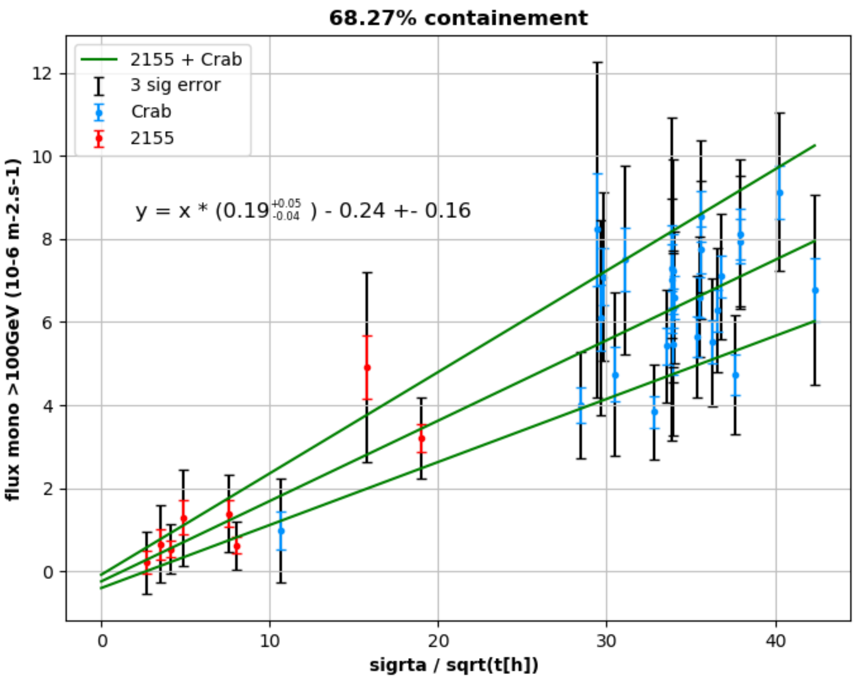
Variability found on source position

Back Up

Real time analysis

- Fast analysis during observations
- Study of online vs offline significance
- Study of qualitative flux estimation





Back Up
Adaptive lightcurve full algorithm