The extragalactic TeV sky: past, present, and future

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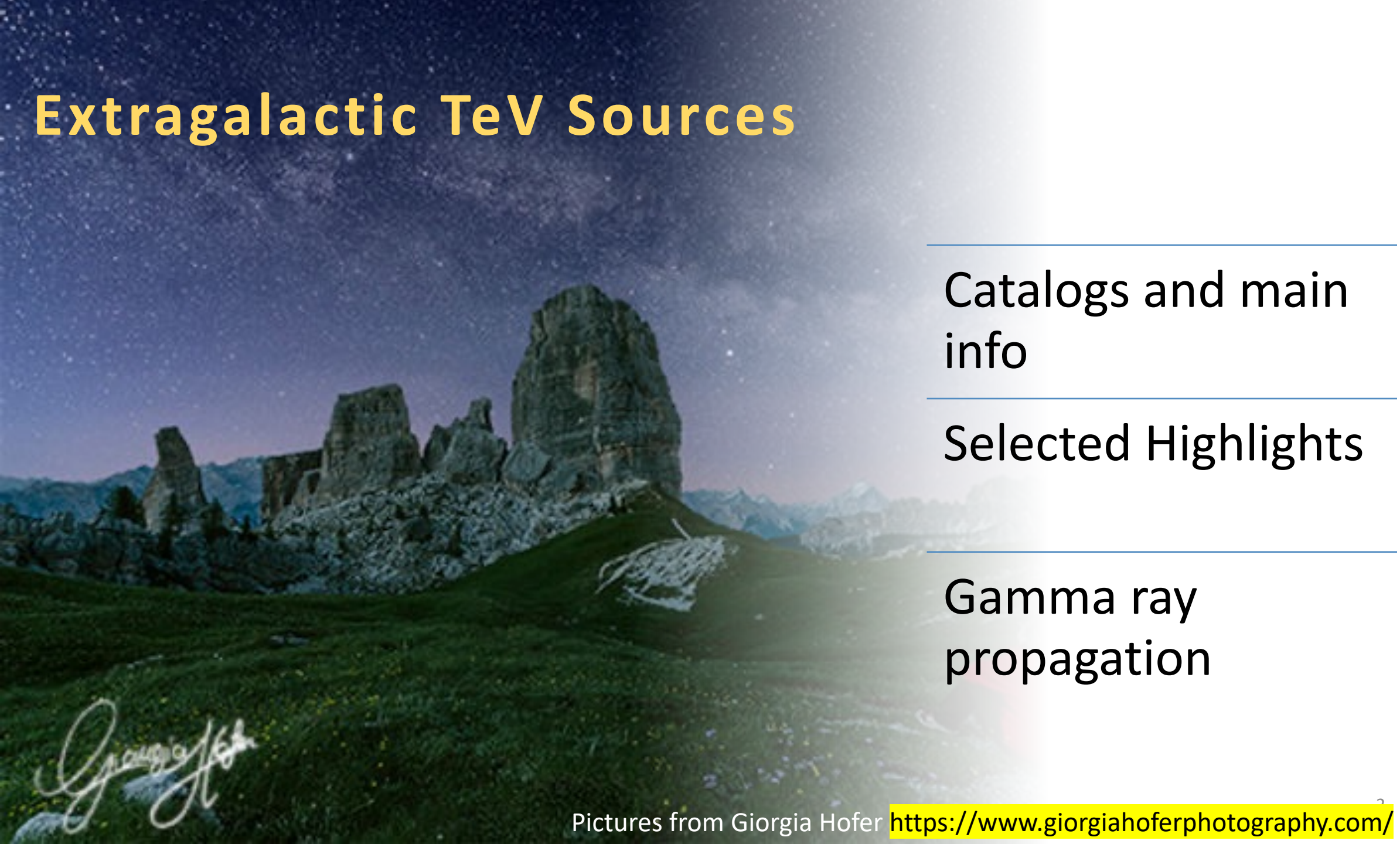
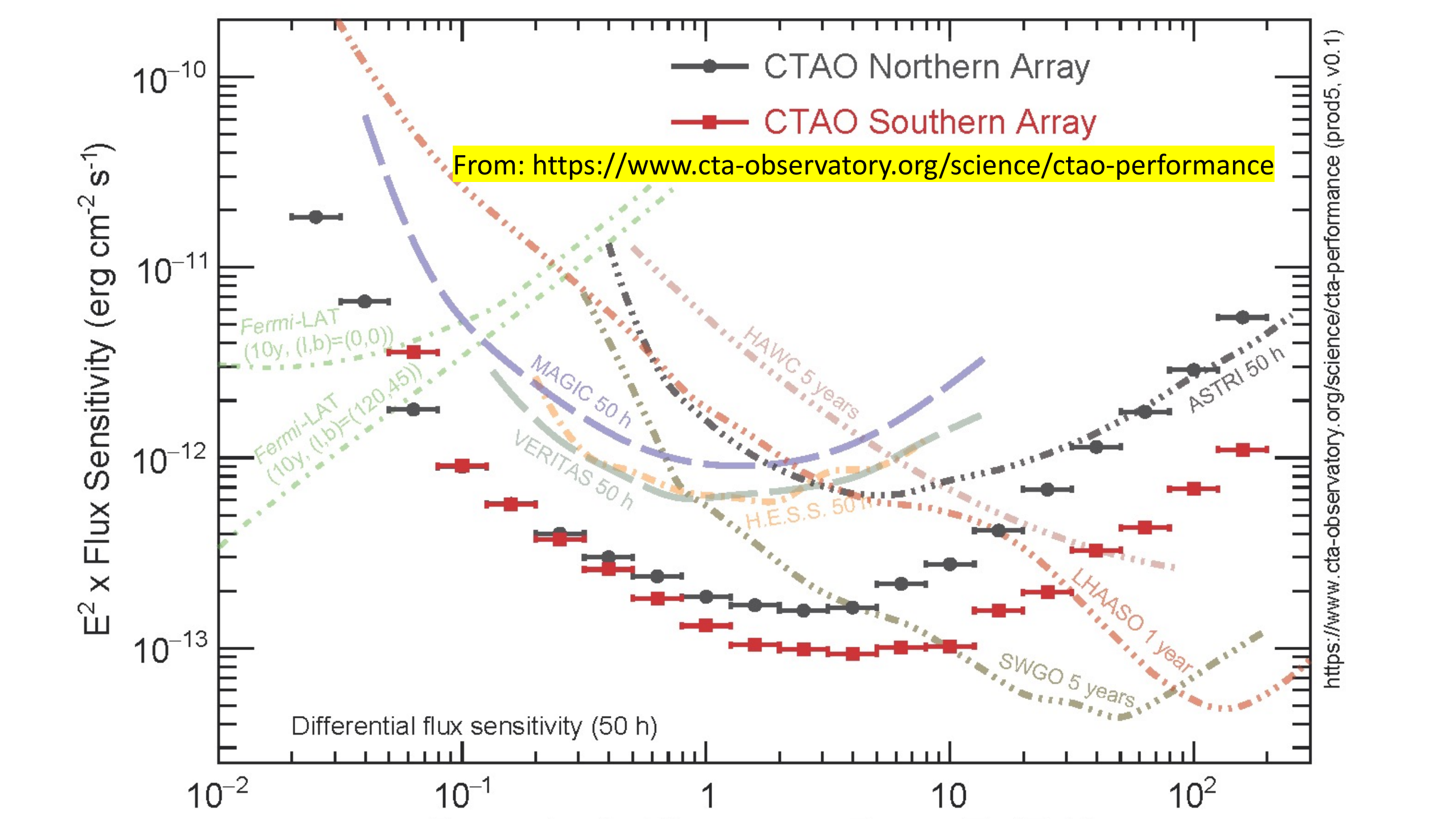
Padova University & INFN

Extragalactic TeV Sources

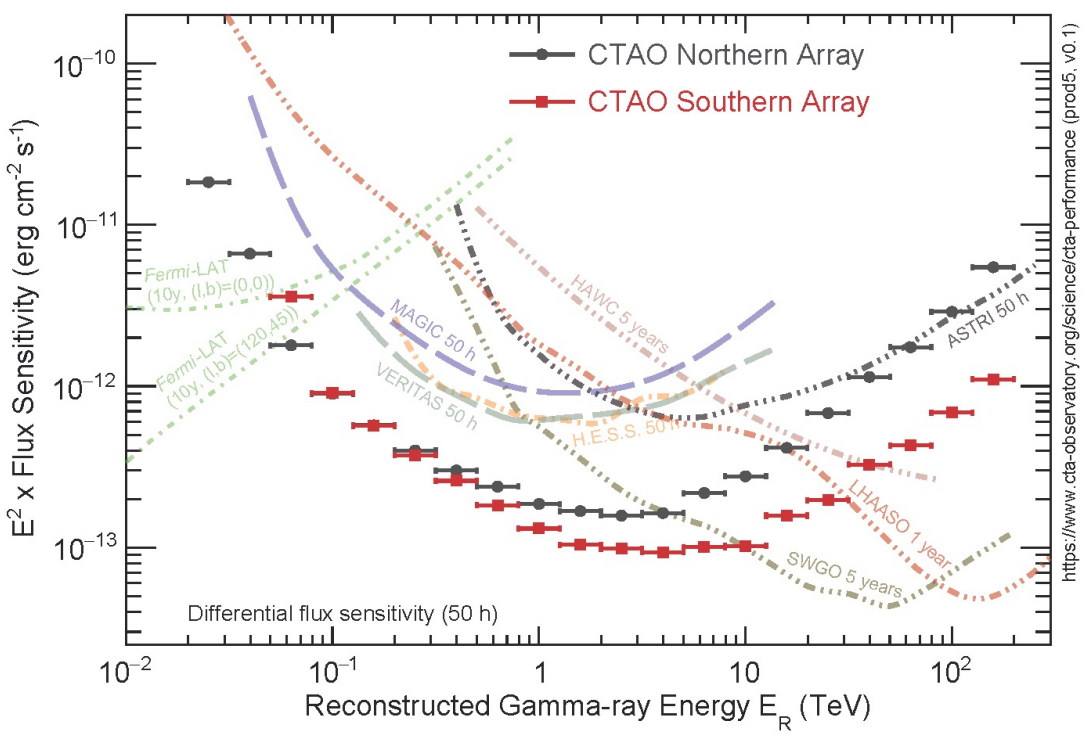


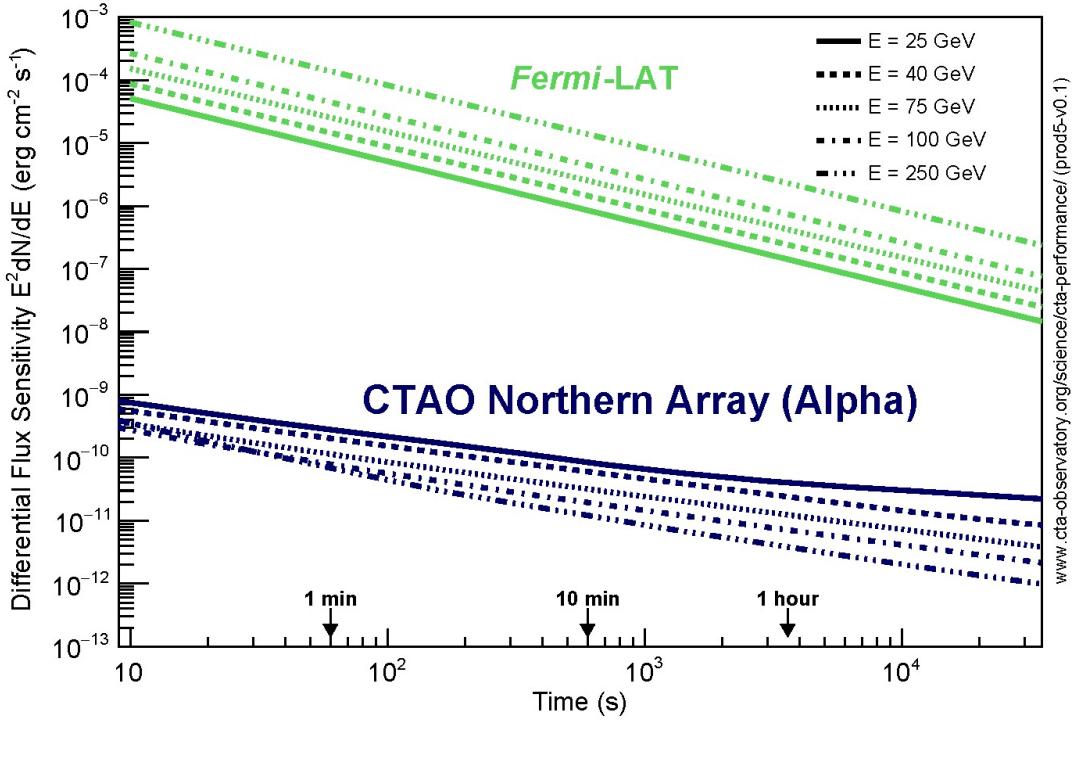
- Catalogs and main info
- Selected Highlights
- Gamma ray propagation

Pictures from Giorgia Hofer https://www.giorgiahoferphotography.com/


CTAO Northern Array
CTAO Southern Array
From: https://www.cta-observatory.org/science/ctao-performance
E² x Flux Sensitivity (erg cm⁻² s⁻¹)
Differential flux sensitivity (50 h)
Fermi-LAT (10y, (l,b)=(0,0))
Fermi-LAT (10y, (l,b)=(120,45))
MAGIC 50 h
VERITAS 50 h
HAWC 5 years
H.E.S.S. 50 h
ASTRI 50 h
LHAASO 1 year
SWGO 5 years
https://www.cta-observatory.org/science/cta-performance (prod5, v0.1)

sensitivity curves





From: https://www.cta-observatory.org/science/ctao-performance

The official TeV catalog: TeVCat

http://tevcat2.uchicago.edu/

Hands-on the extragalactic sources

TeVCat

- How many extragalactic sources are detected at TeV?
- Which kind of sources?
- Which was the first extragalactic source detected?
- What is the distance of the extragalactic TeV emitters?

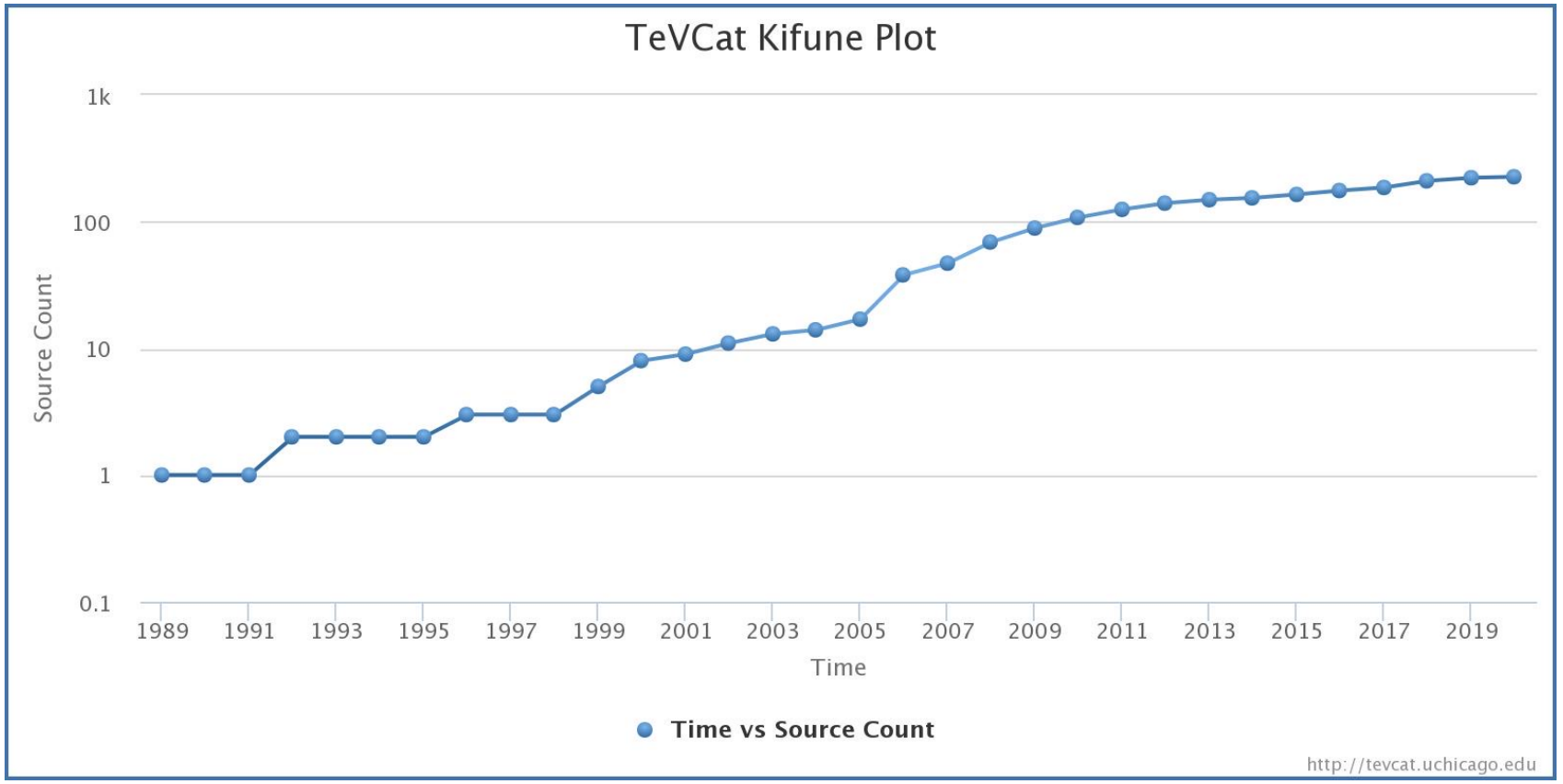
SSDC

- How can I retrieve a spectral energy distribution from a specific source

Hands-on: How many extragalactic sources?

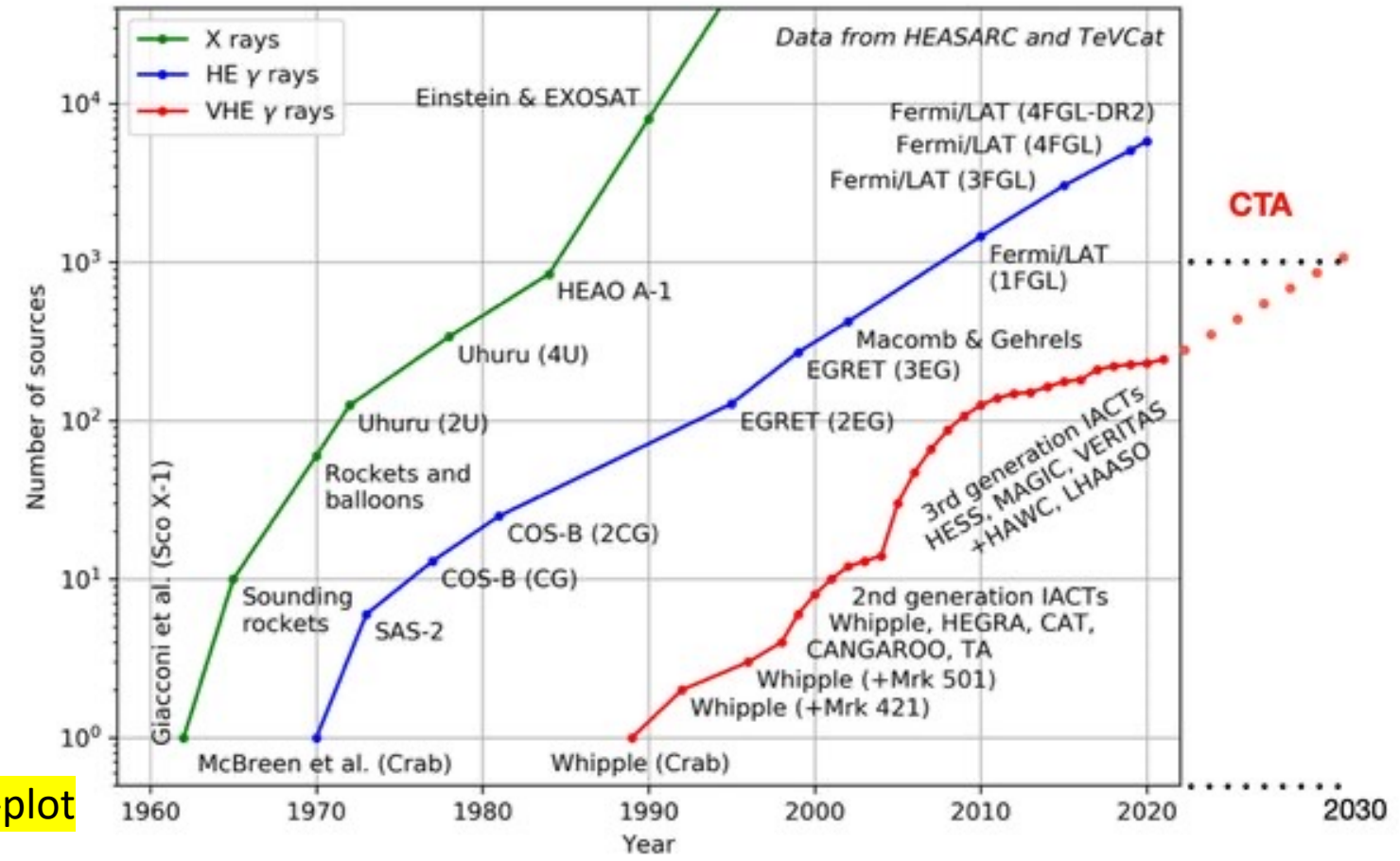
http://tevcat2.uchicago.edu/

Evolution over time: the kifune plot



Evolution over time: the kifune plot

- Large difference in the number of sources in the different energetic regimes!
- CTA is expected to exceed 1000 sources (many extragalactic)



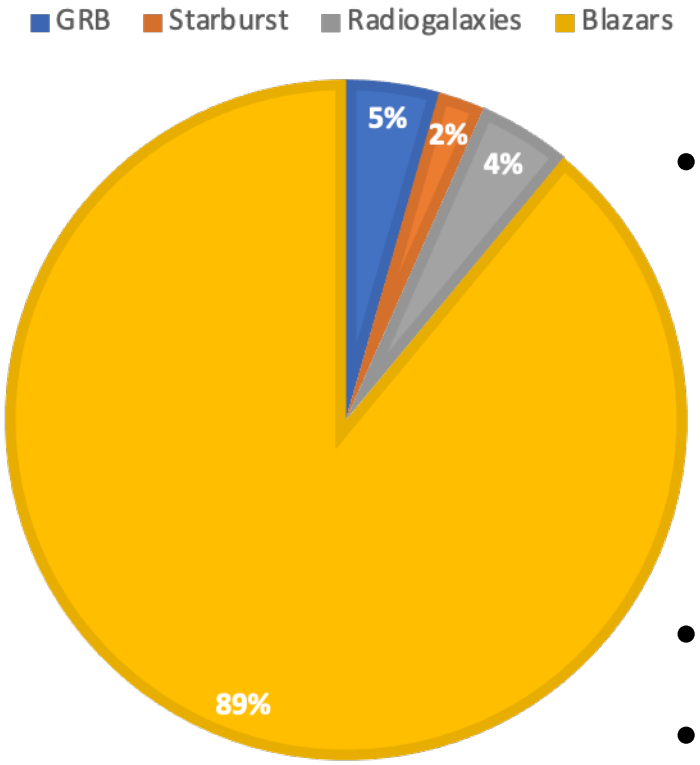
D. Bose et al. 2022

Adapted from https://github.com/sfegan/kifune-plot

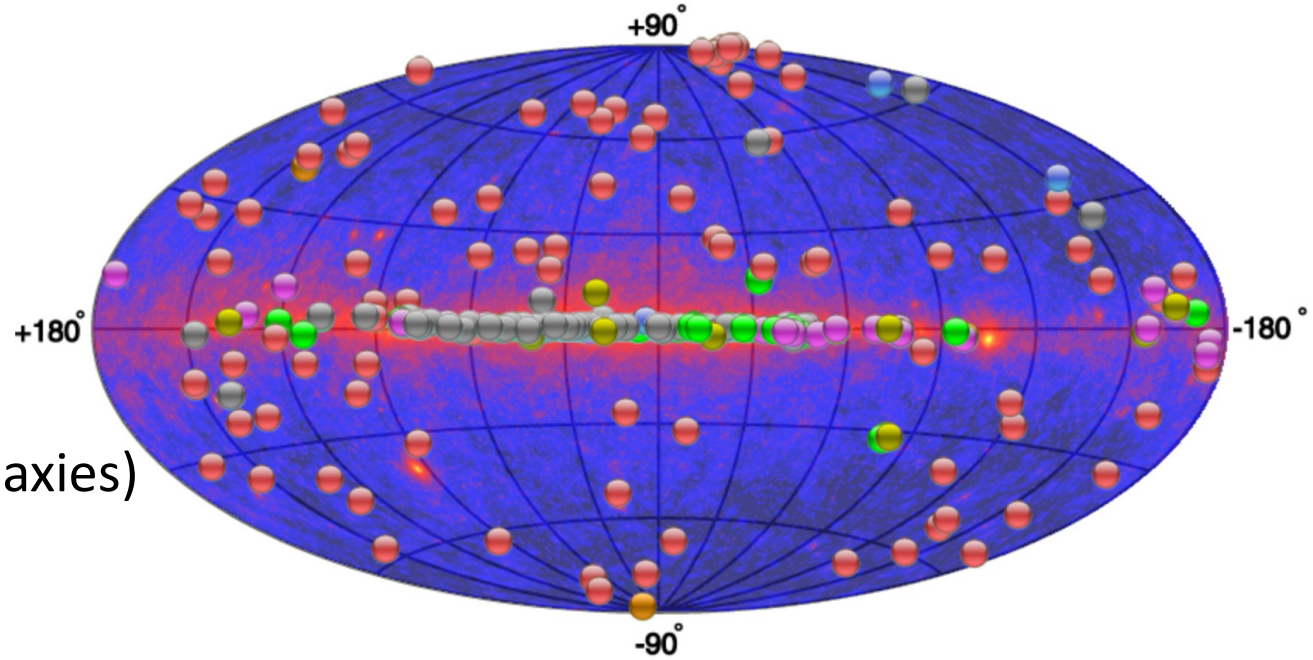
Hands-on: Which kind of extragalactic sources?

http://tevcat2.uchicago.edu/

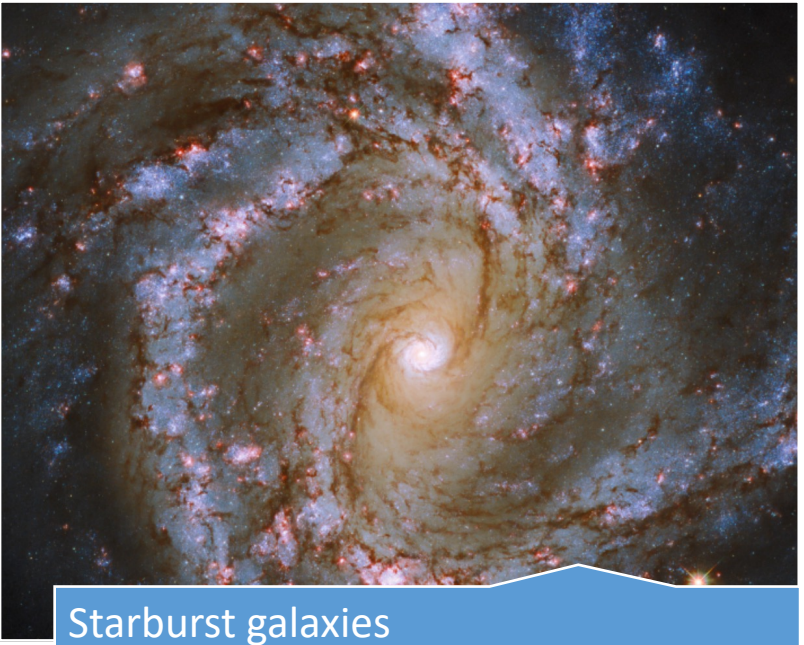
Type of sources



- AGN
  - Blazars
    - FSRQ
    - BL Lac
  - FRI (Radiogalaxies)
- GRB
- Starburst galaxies



TeV extragalactic sources in a nutshell

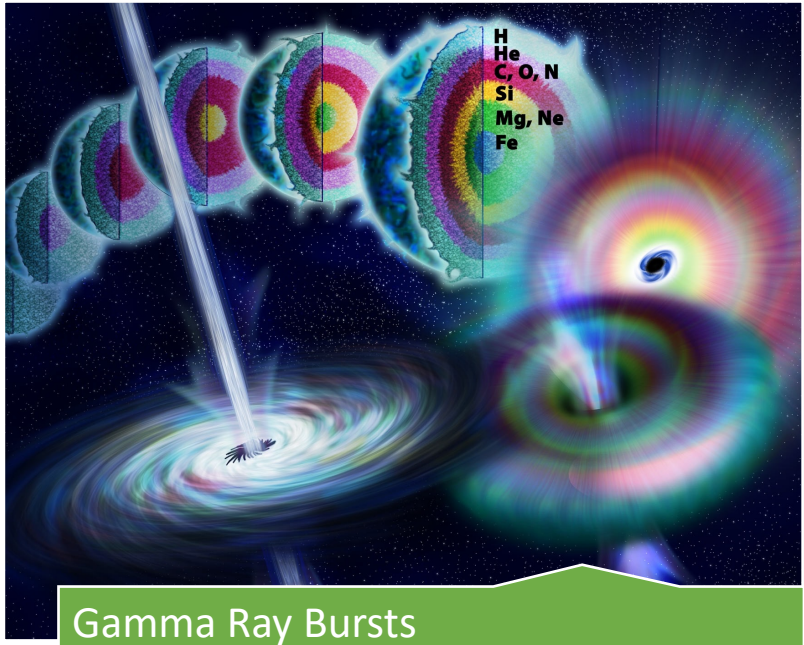


Starburst galaxies

- nearby galaxies with intense star formation
- TeV-detected: 2

Jetted Active Galactic Nuclei

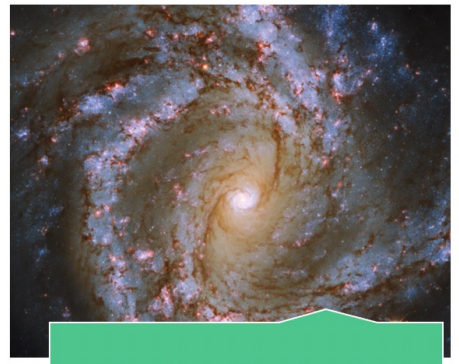
- Galaxies with an intense non-thermal emission
- TeV-detected: 85



Gamma Ray Bursts

- Most energetic bursting events in the Universe
- TeV detected: 4

Starburst galaxies key features



Starburst galaxies

TeV-detected: 2
GeV detected: 11

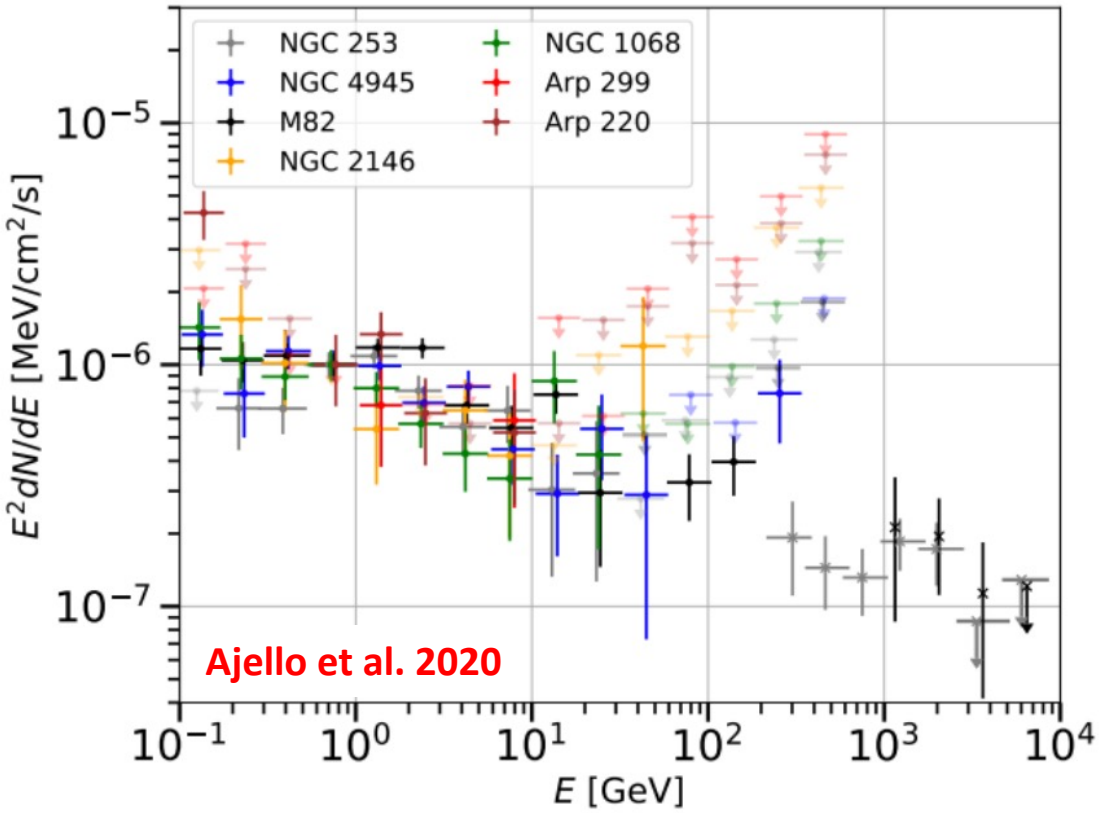
Starbursts are galaxies with ehnanced star-forming activity

Observables

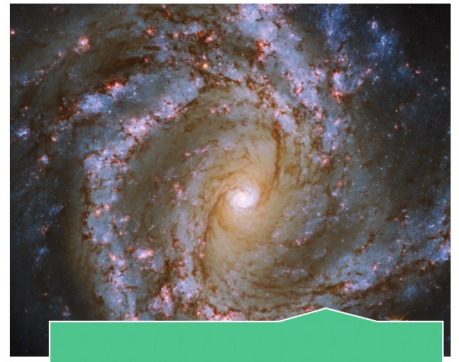
- Non variable sources
- Nearby
- Spectral peak in the Fermi energy range

Astrophysics

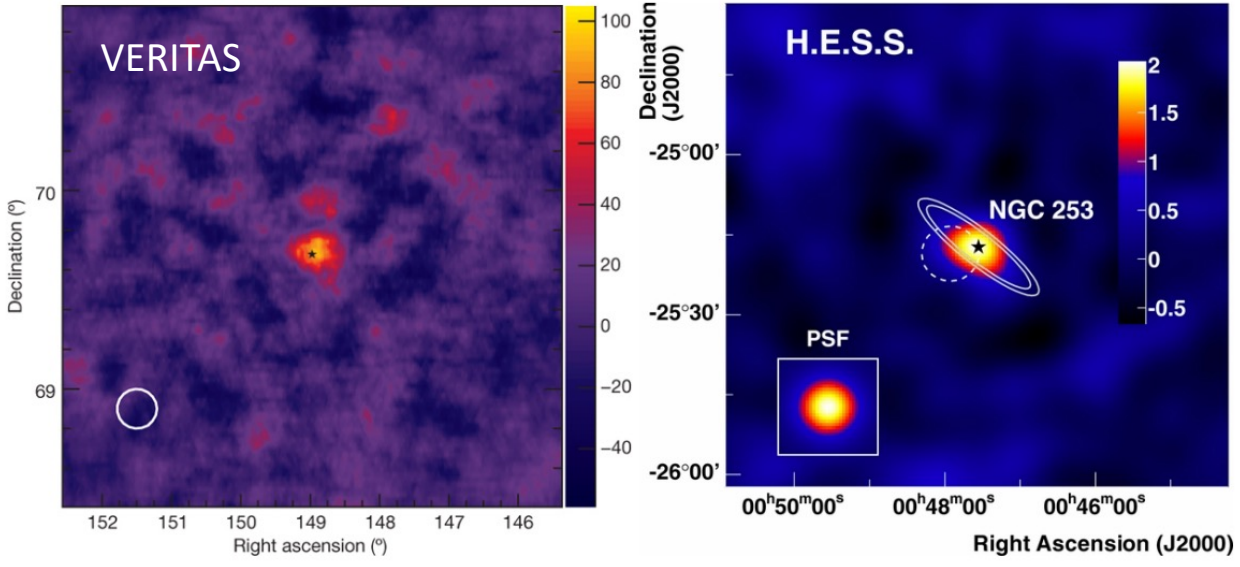
- Physical emission scenario
- Relationship between star forming process and gamma-ray emission to extragalactic environment
  - **multimessenger potential** (CR, neutrinos)
- Gamma ray background



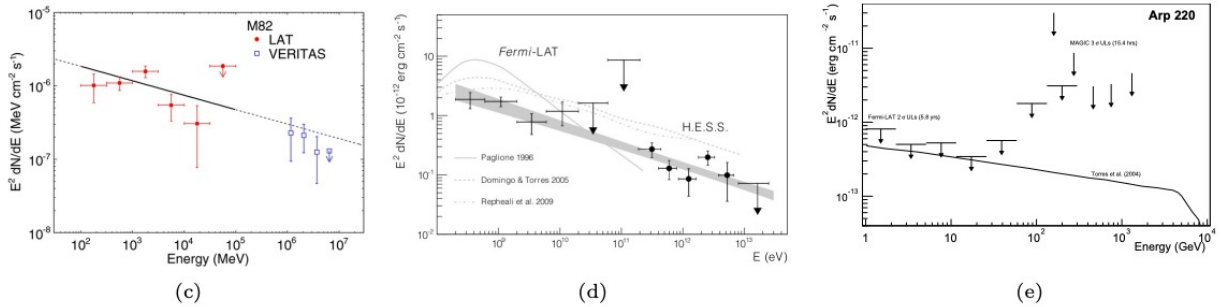
Starburst galaxies at TeV results



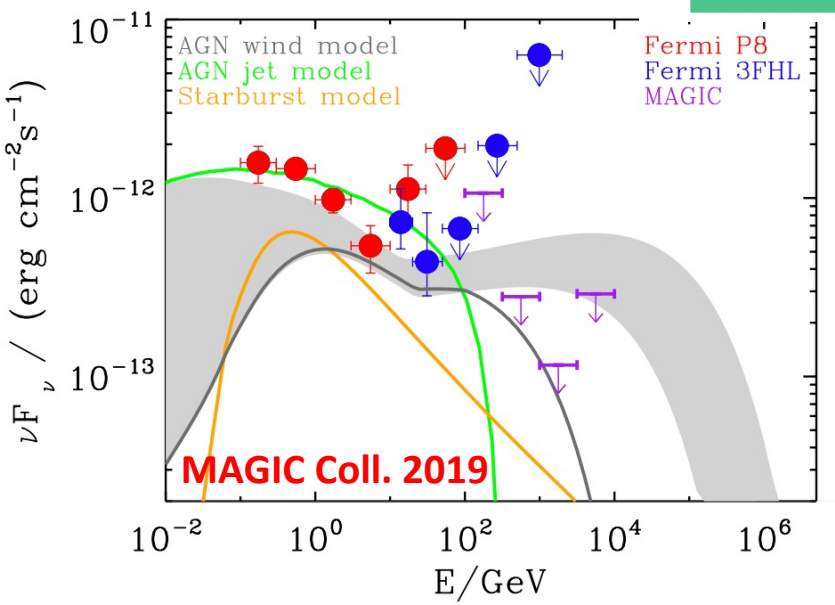
Starburst galaxies



S. Ohm, 2016



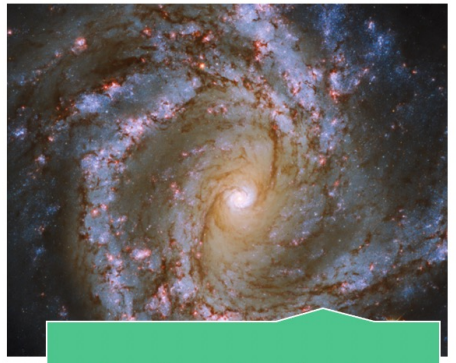
MAGIC



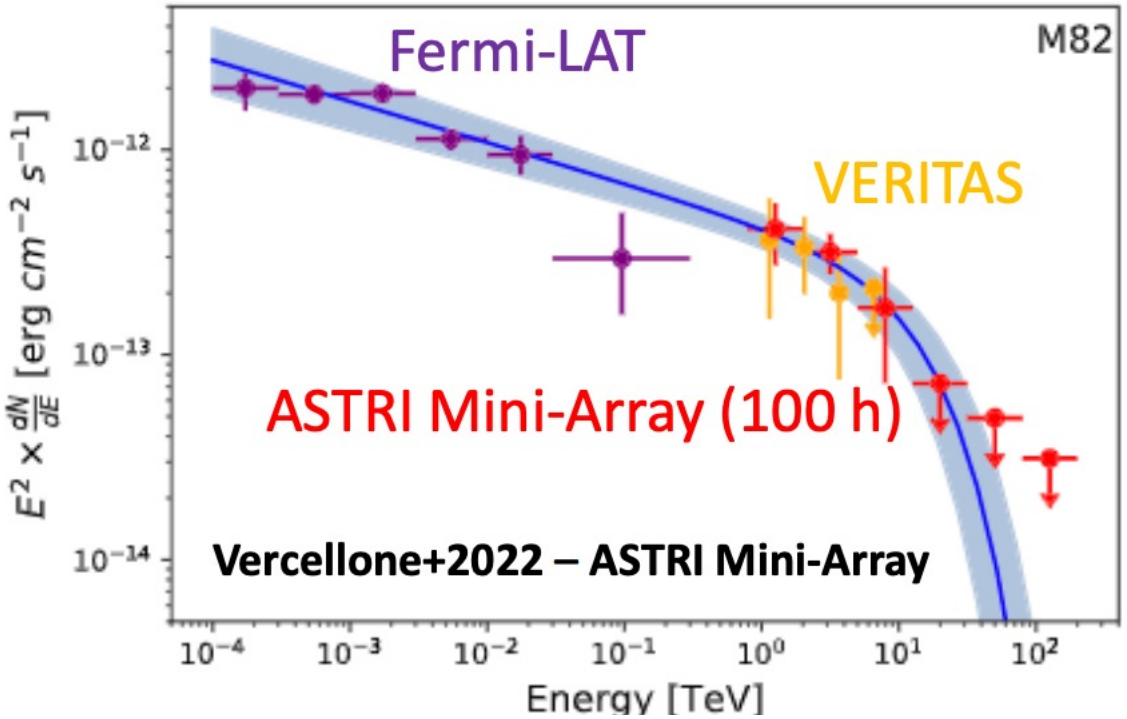
Deep exposures (not variable)

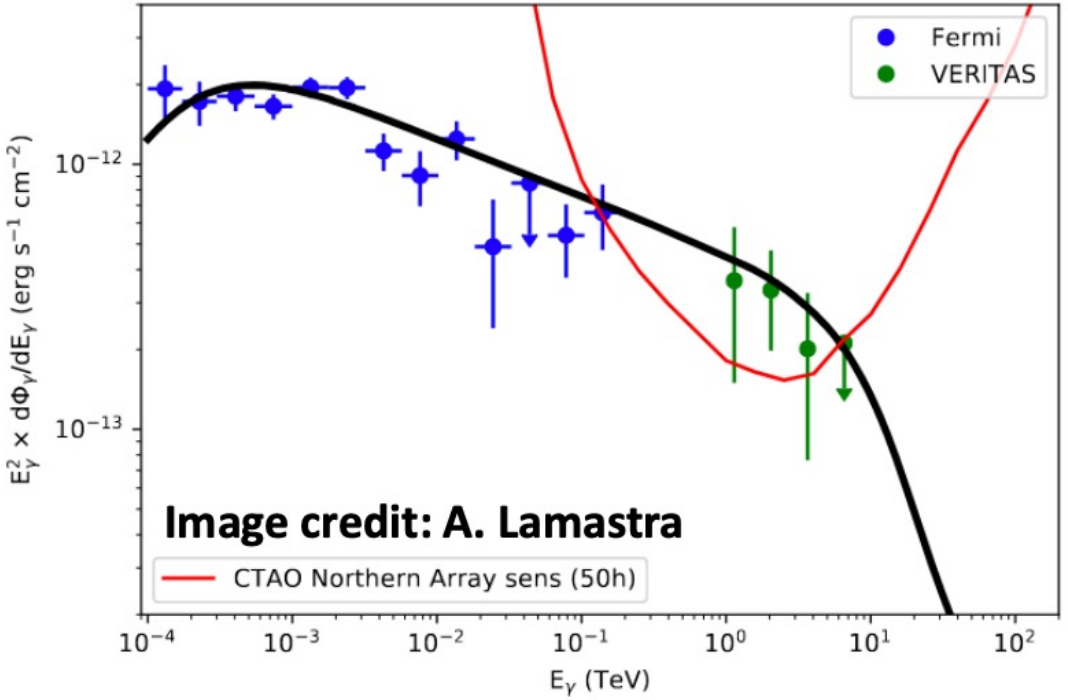
Combined HE and VHE spectra are used to constrain gamma-ray emission models

Starburst galaxies at TeV: future prospects



Starburst galaxies

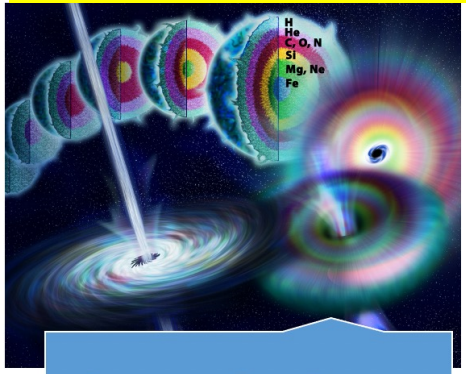




From Peretti Gamma2022

See Alessio's presentation

GRBs at TeV



Gamma Ray Bursts

TeV-detected: 4
GeV detected: >6000

D. Khangulyan, Gamma 2022

? GRB160821B: 3σ detection of a nearby short GRB ($z = 0.162$) above $0.5\,\mathrm{TeV}$ 4h after the trigger (MAGIC Col, 2021)

✔ GRB180720B: 5σ detection of a long GRB from $z = 0.65$ above $0.1\,\mathrm{TeV}$ **10h** after the trigger (HESS Col, 2019)

✔ GRB190114C: $\sim 50\sigma$ detection of a long GRB from $z = 0.42$ above $0.2\,\mathrm{TeV}$ ~min after the trigger (MAGIC Col, 2019)

✔ GRB190829A: 20σ detection of a long GRB from $z = 0.08$ at energies $0.18 - 3.3\,\mathrm{TeV}$ **4-50h** after the trigger (HESS Col, 2021)

? GRB201015A: $> 3\sigma$ detection of a long GRB at $z = 0.43$ (MAGIC Col, Atel)

✔ GRB201216C: $> 5\sigma$ detection of a long GRB at $z = 1.1$ (MAGIC Col, Atel)

GRBs at TeV

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Gamma Ray Bursts

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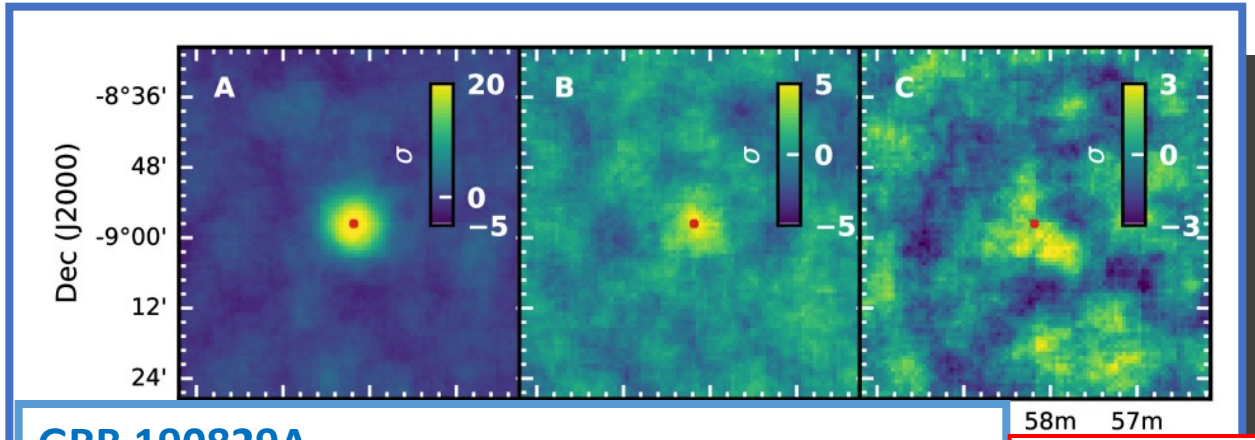
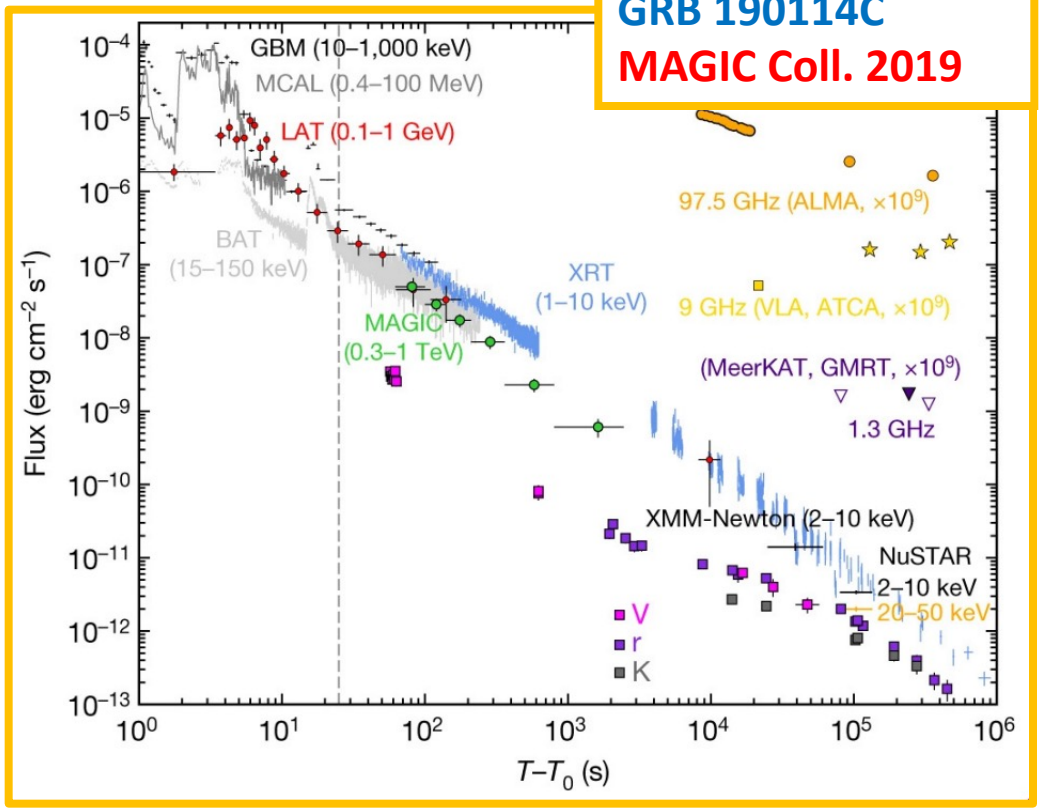


GRB 190829A
H.E.S.S. Coll. 2021 (detected for 3 nights)

GRB 190114C
MAGIC Coll. 2019



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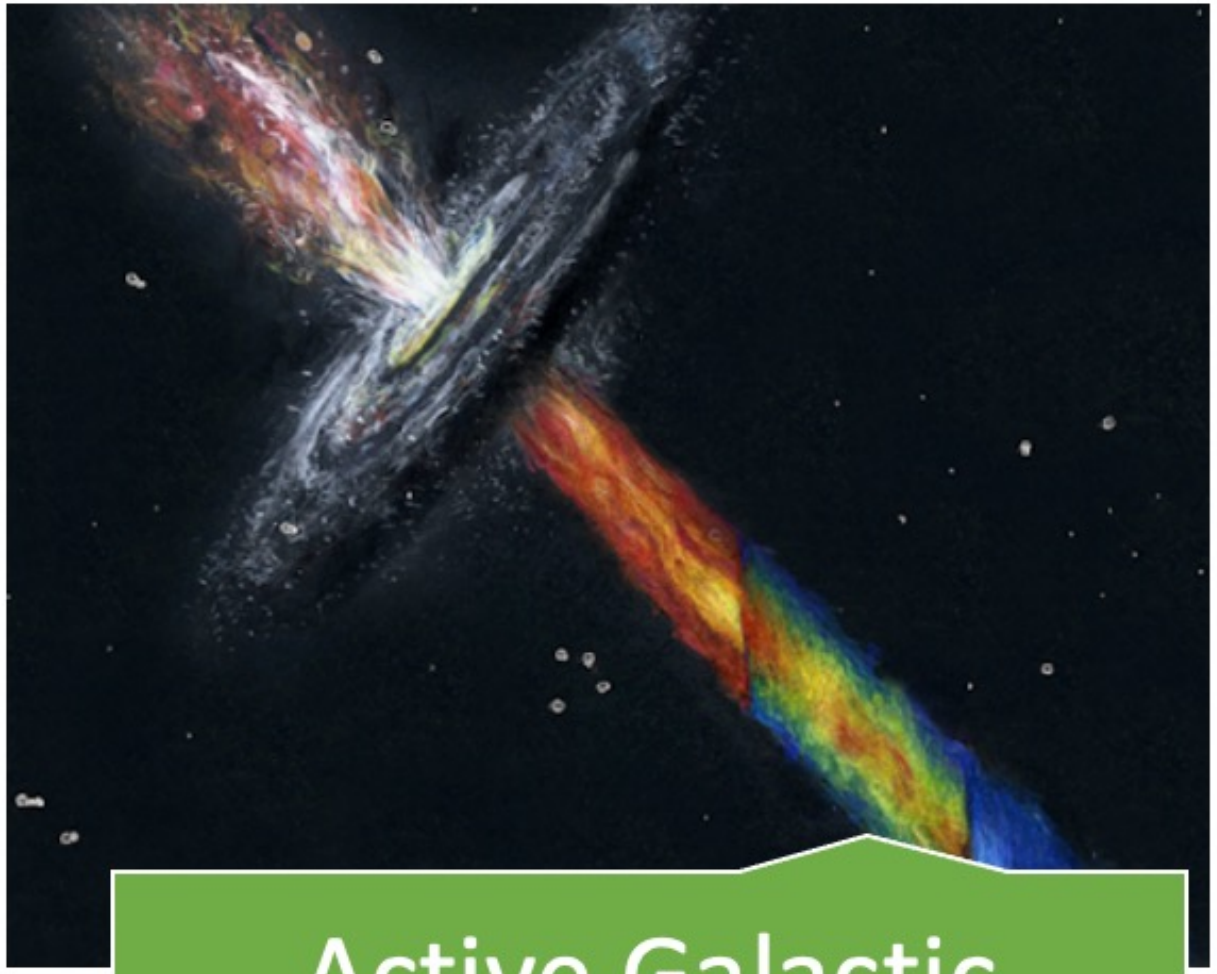


Active Galactic Nuclei

AGNs: key features

- Extremely **variable** sources
- Broadband emission from radio to TeV
  - *Challenge*: simultaneous MWL/MM observations needed to constrain models
- Strong **multimessenger** connection (neutrinos, cosmic rays)

- **Radiogalaxies**
  - Side view of the jet
  - Possibility of resolving extended emission
  - Only nearby objects possible (no boost)
    - few sources detected

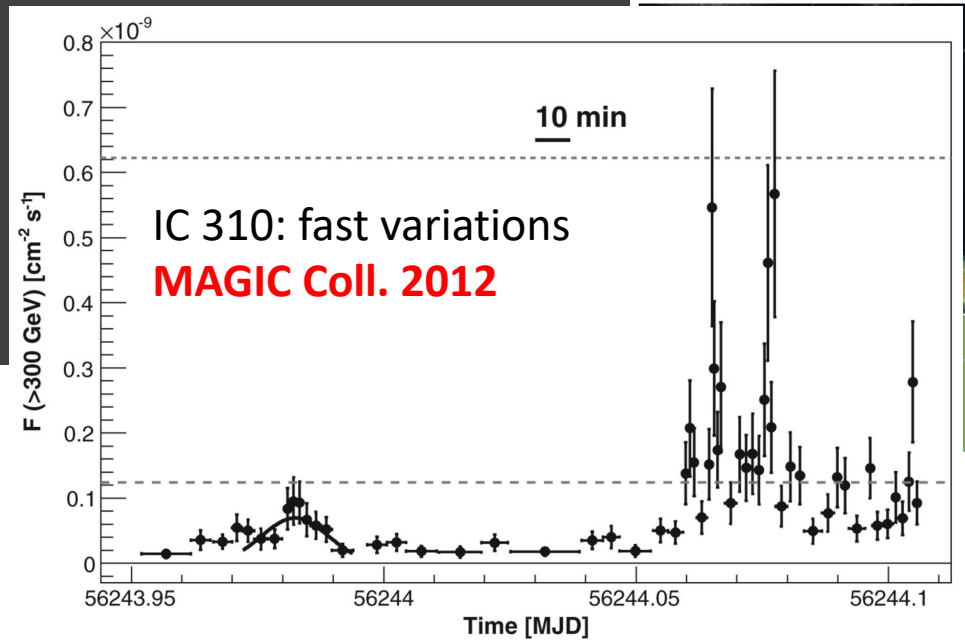
- **Blazars**
  - Direct view in the jet
  - Boosted emission, variability
  - Affected by EBL absorption

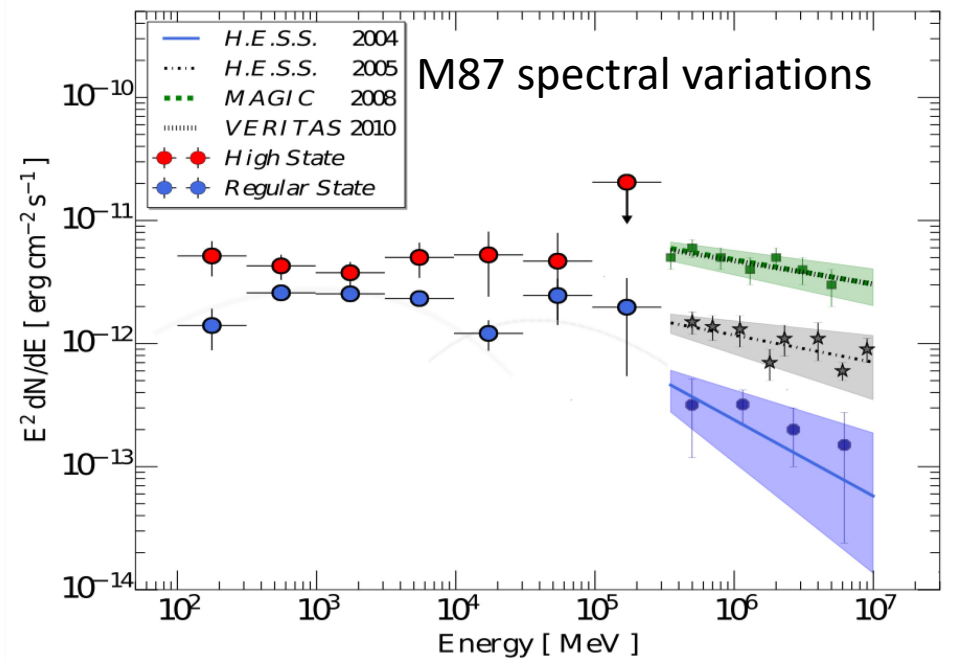
More at this school: F. Tavecchio; P. Cristarella Orestano; A. Costa; A. Sciaccaliuga; A. Franceschini

AGNs at TeV: radiogalaxies

TeV-detected: 4-6
GeV detected: 41 (4LAC)

Name	Cross-ID	Type	Distance	BH mass [10^8 M_{sun}]
Cen A	NGC 5128,	FR I	3.7 Mpc	(0.5-1)
M87	NGC 4486, Virgo A	FR I	16 Mpc	(20-60)
NGC 1275	3C84, Perseus A	FR I	70 Mpc	3-4
IC 310	B0313+411	FR I/BL Lac	80 Mpc	3 [0.3?]
3C 264	NGC 3862	FR I	95 Mpc	4-5
PKS 0625-35	OH 342	FR I/BL Lac	220 Mpc	~10





Rieger & Levinson, 2019 (special issue)

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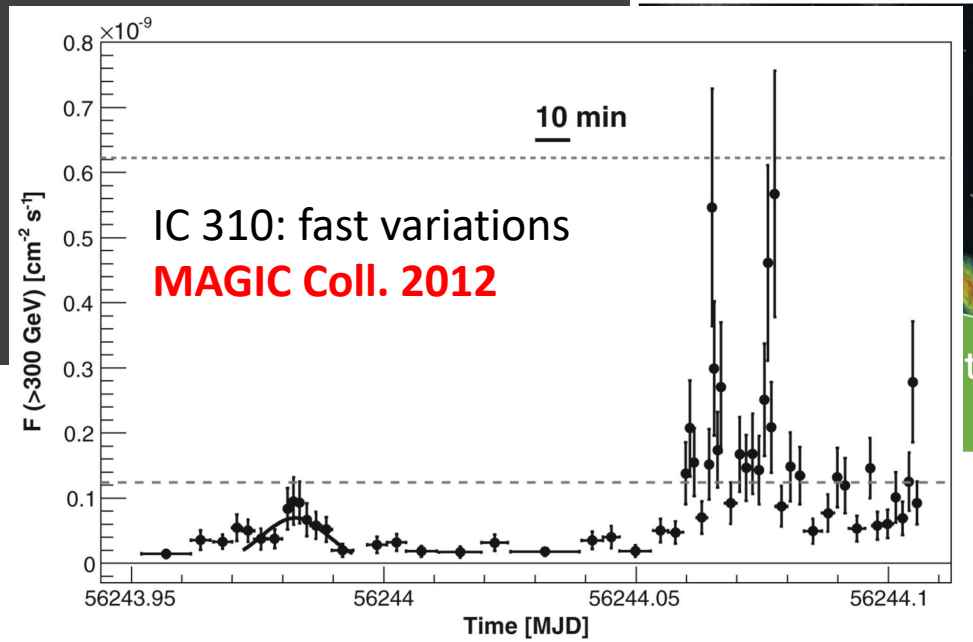
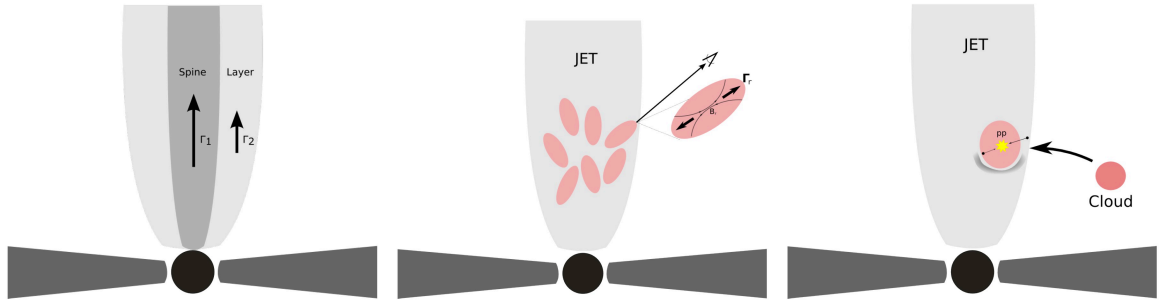
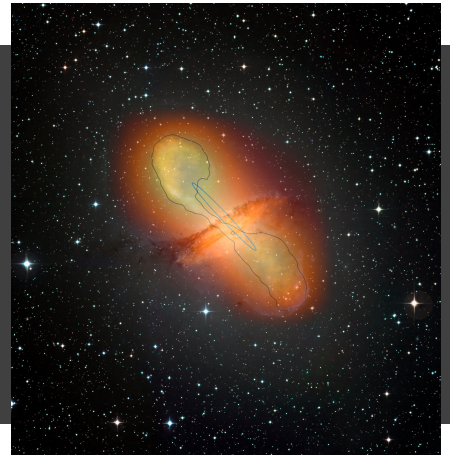


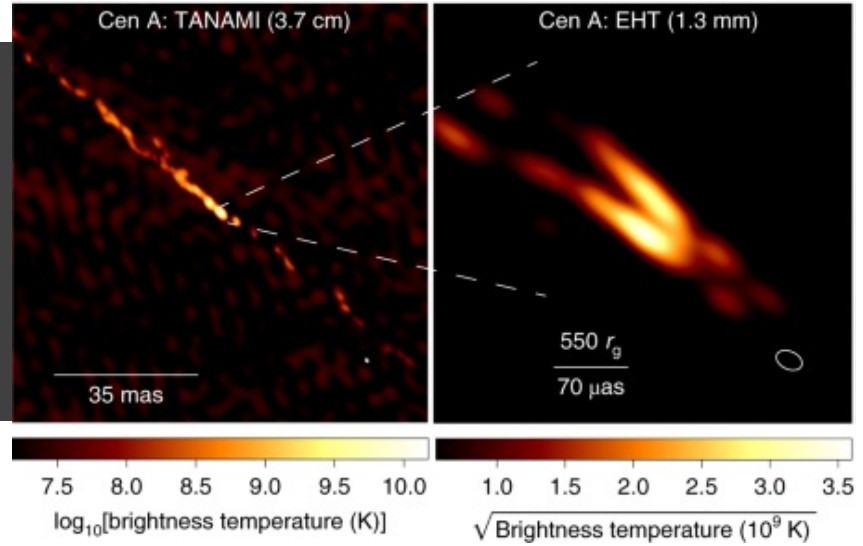


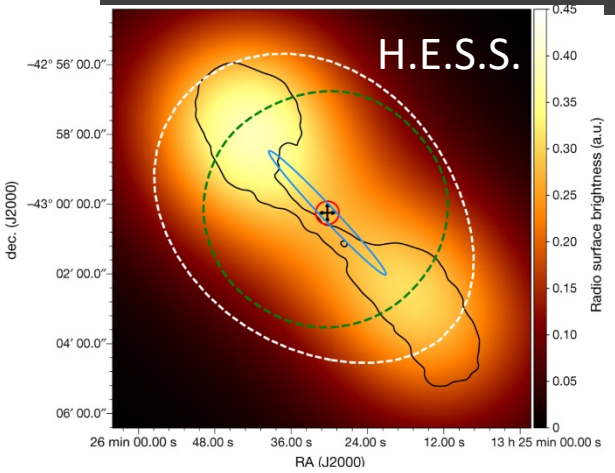
Possible scenarios for the origin of rapidly variable VHE
- stratified jet (left)
- jets-in-jet model (center)
- hadronic model (right)

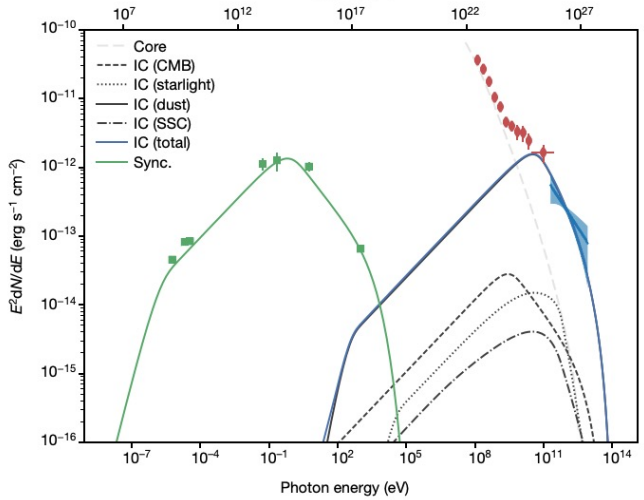
AGNs at TeV: Cen A radiogalaxy

HESS Coll. Nature, 2020

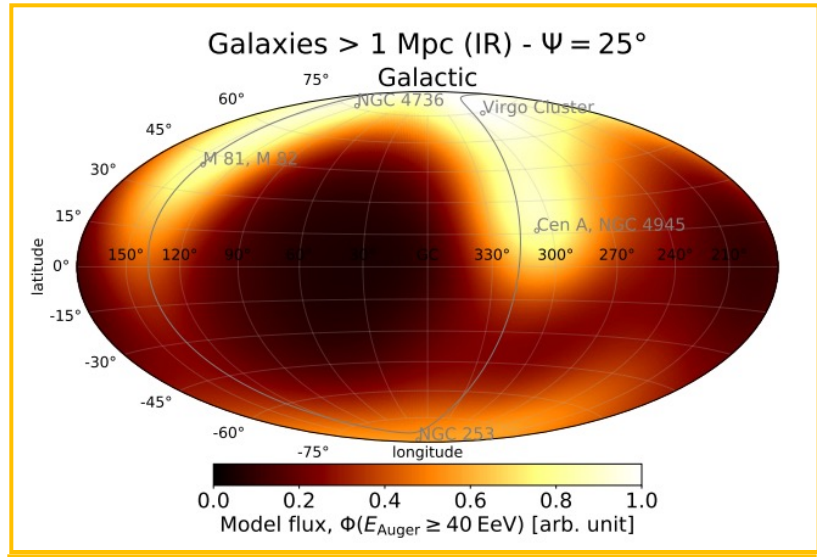






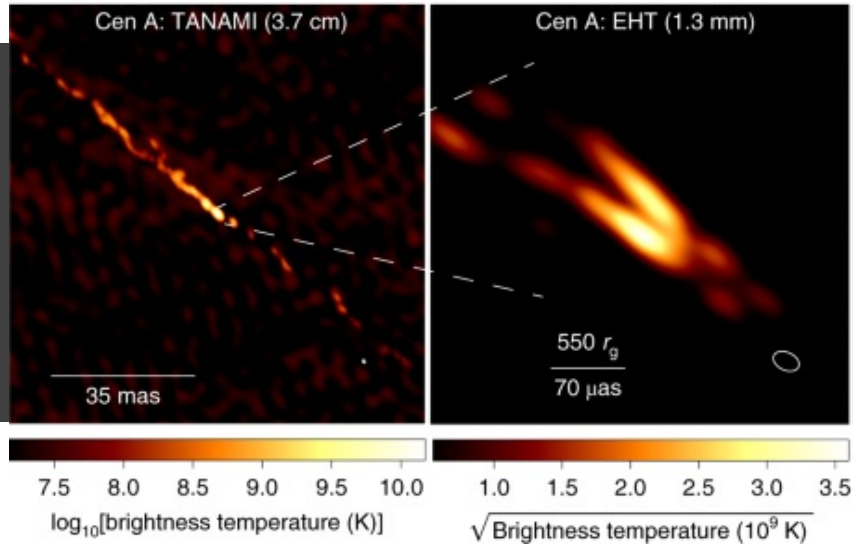


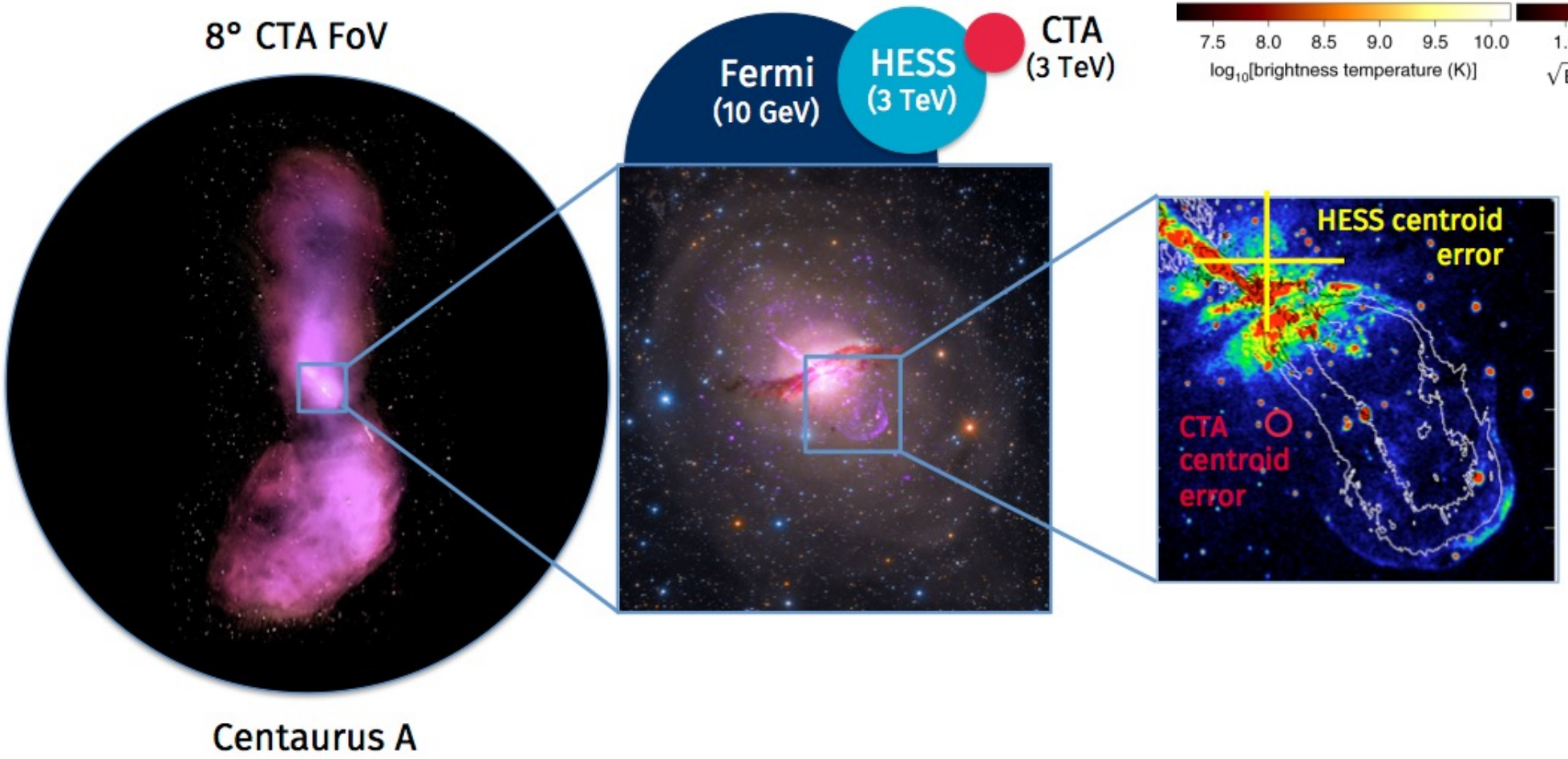
- CenA: Closest TeV-detected AGN (EHT target)
- **Extended emission** detected by HESS: morphological studies (this **is the only extragalactic source** known to date with an extension at VHE)
- TeV unusual **spectral hardening**
- Multimessenger connections (cosmic rays)
  - CenA is a bright spot in P. Auger maps at the highest energies



Best-fit UHECR source models above 40 EeV, **Pierre Auger Coll. 2022**

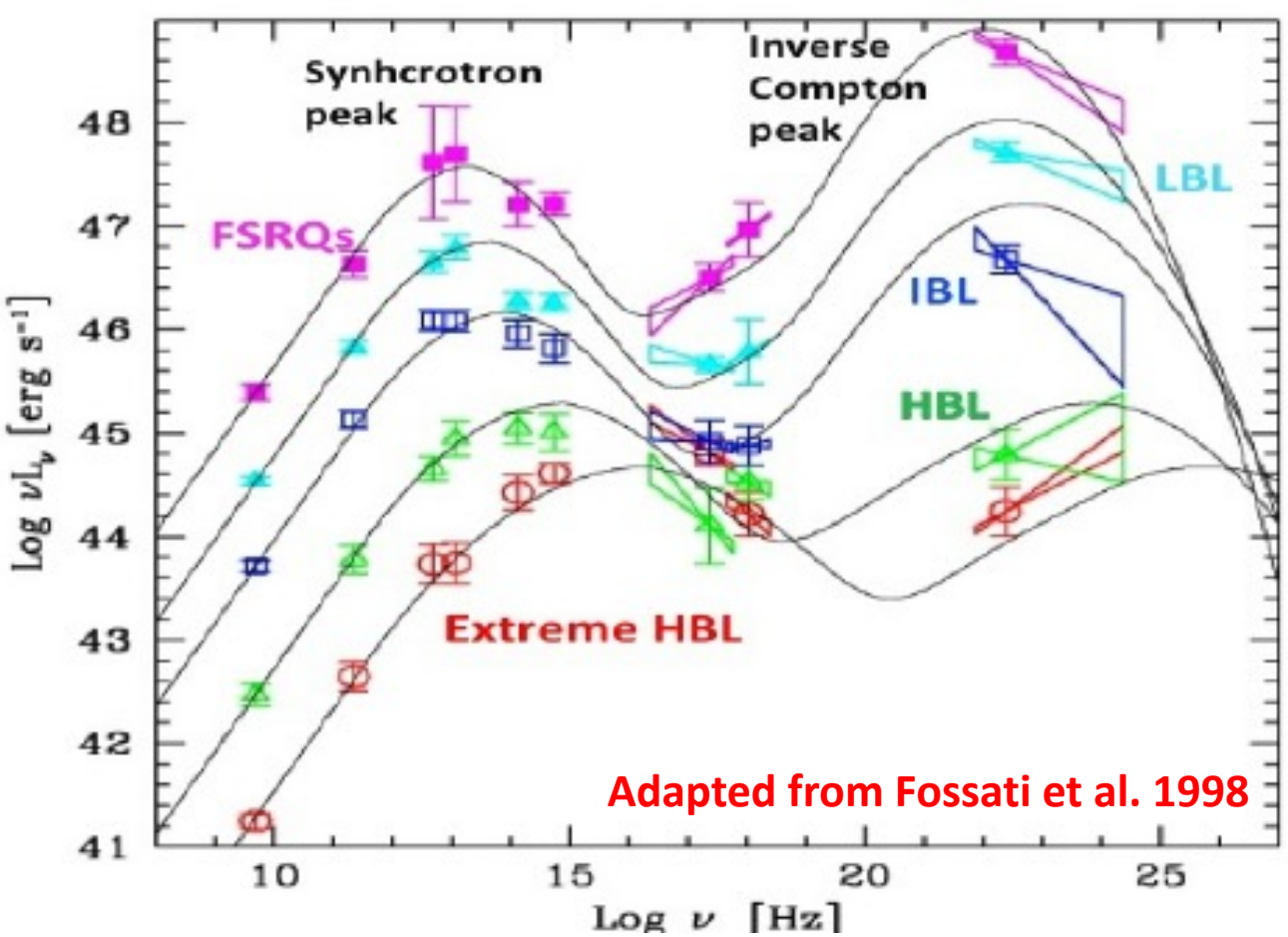
Radiogalaxies - future perspective with CTA





Which blazars at TeV?
The blazar sequence

Active Galactic Nuclei



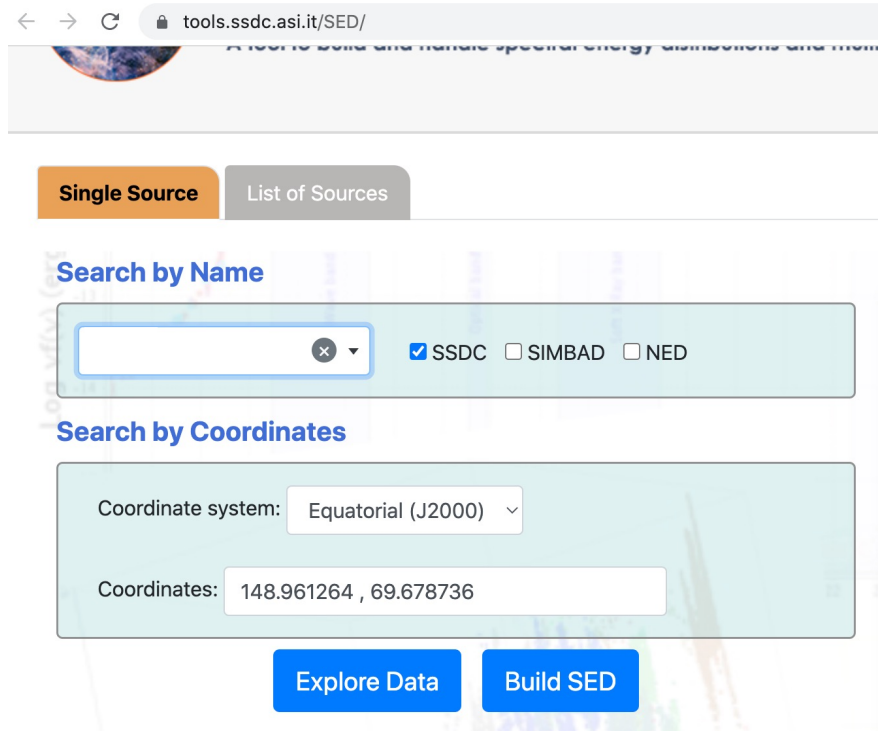
TeV-detected: 81
GeV detected: thousands

- SED brightness anti-correlates with the peak position
- TeV detections are in line with the blazar sequence
  - Low energy peaked objects → flares (ToO)
  - HBLs are the large majority
  - Extreme HBLs: long exposures

SSDC: an overview of the spectral properties

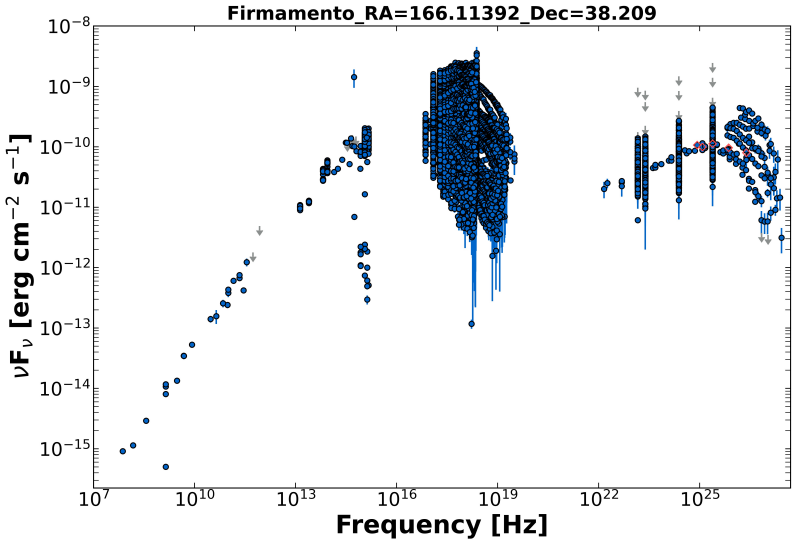
You can build the *spectral energy distribution* of the **first detected blazar: Markarian 421**

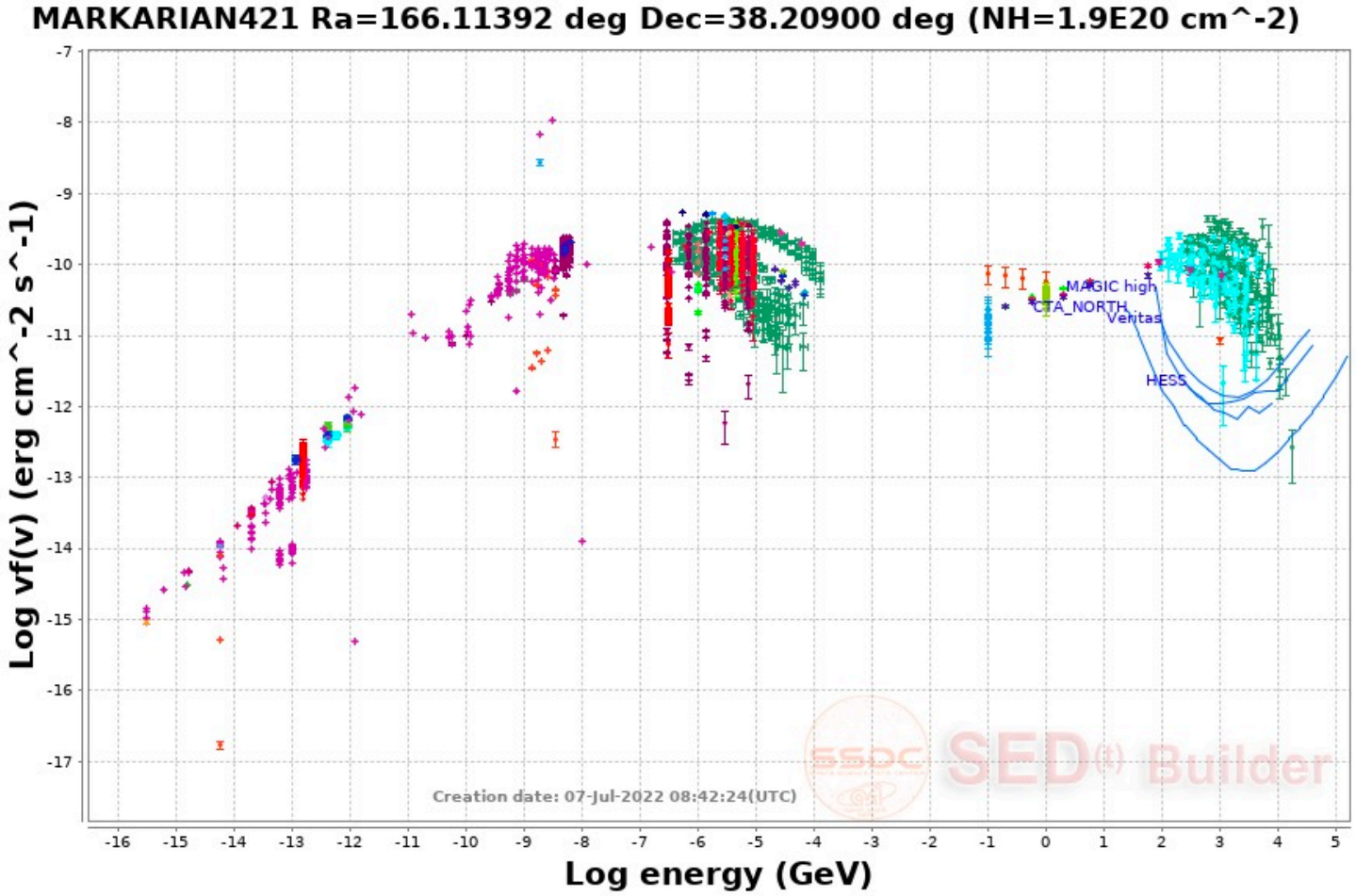
https://www.ssdc.asi.it/



If you are already expert of SSDC, you might try a new tool under development: https://firmamentoo.web.app/

The spectral energy distribution of the HBL Markarian 421





Main **observables**:

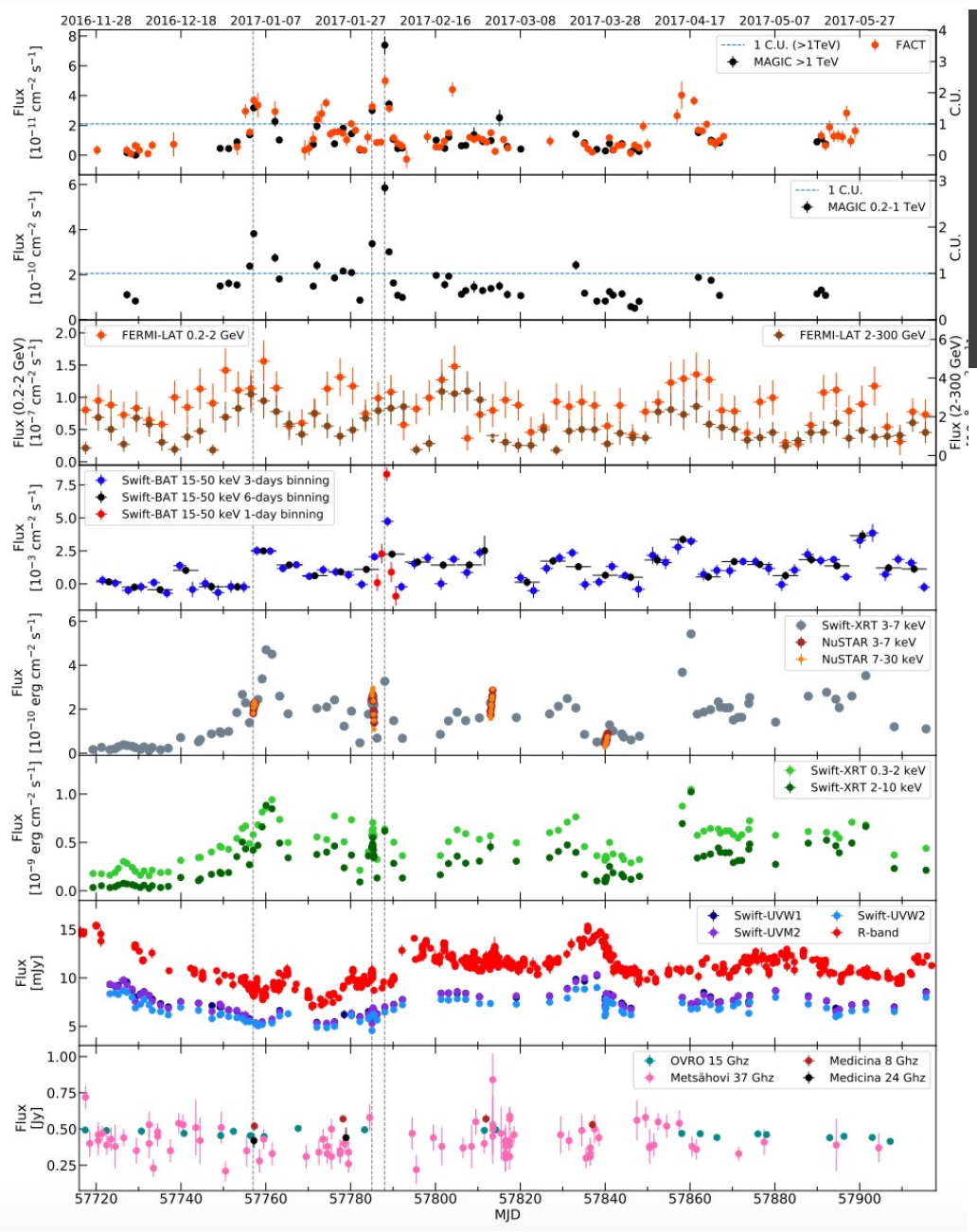
- **Bright** source
- **Variable** at all bands
- HBL: Peak location ~100 GeV

Main **astrophysical investigations**:

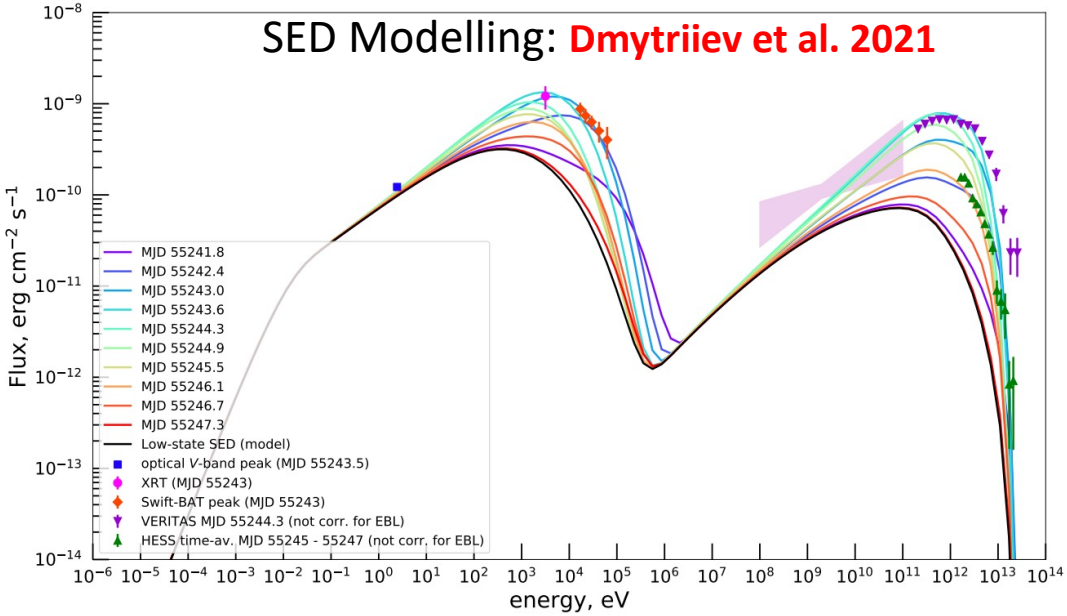
1. Spectral energy distribution
2. Temporal variations in flux and spectrum
3. Correlations (including delayed correlations) with the other bands

Where is the TeV emission originated?
What is the role of hadrons?

MAGIC and FACT Coll. 2021

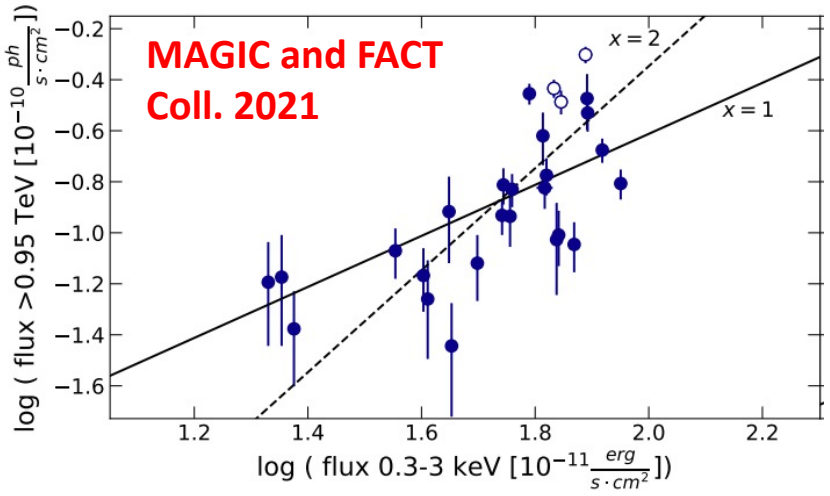


Recent result on Mkn 421

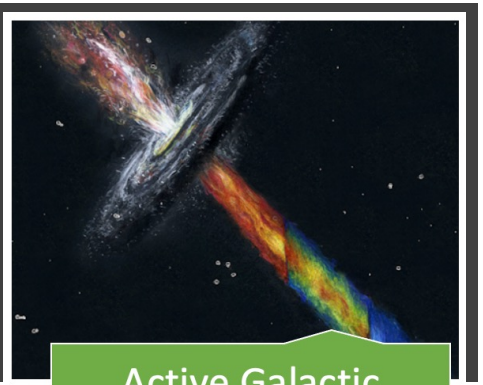


Main **astrophysical investigations**:

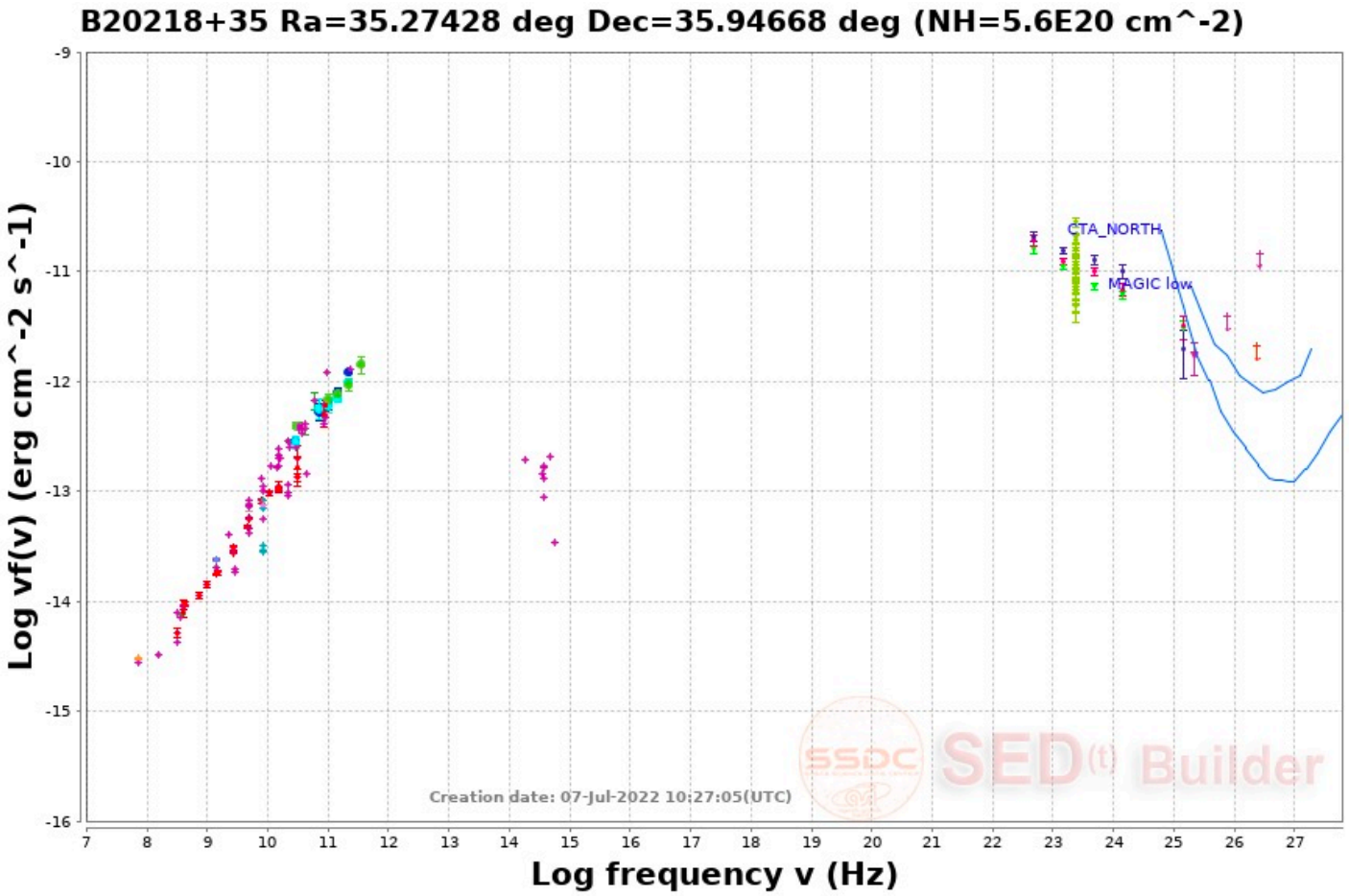
1. Temporal variations in flux and spectrum
2. Correlations (including delayed correlations) with the other bands
3. Spectral energy distribution and modeling



FSRQs from radio to VHE



Active Galactic Nuclei



Main **observational properties**:

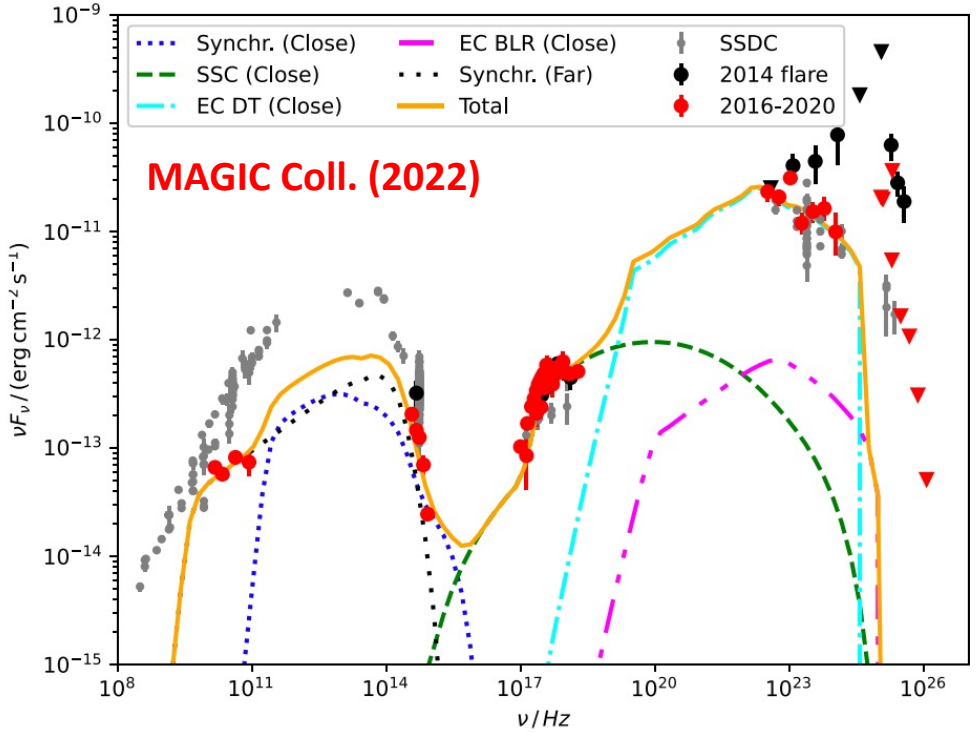
- Bright at GeV, faint at TeV
- Observable when in **flare** at TeV
- Extremely **distant objects**

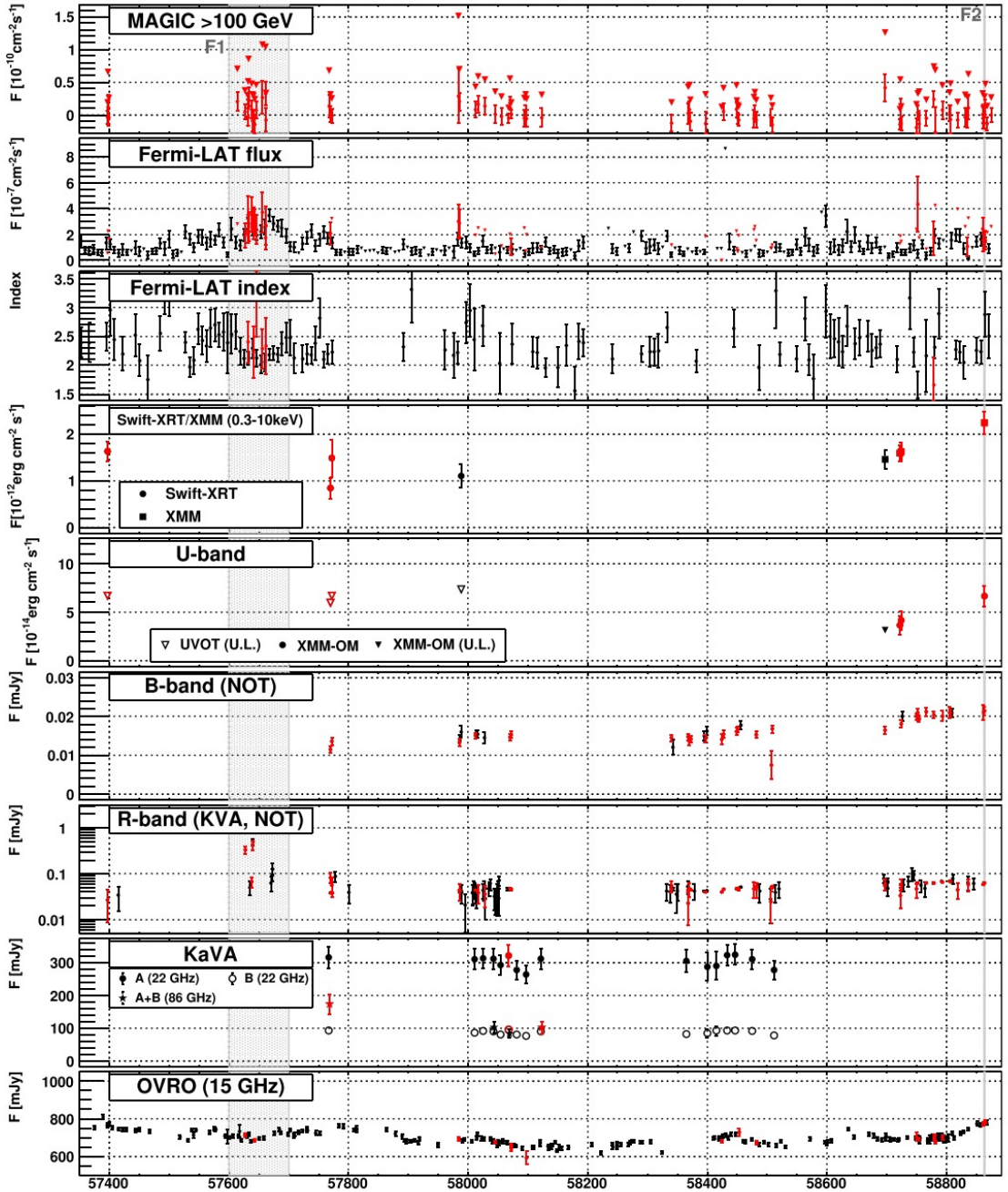
Main **astrophysical investigations**:

- The broadband emission. It is quite complex, **with multiple zones** participating in the overall SED
  - Jet
  - Disk
  - Corona
  - BLR and NLR
  - Infrared torus

The FSRQ QSO B0218+357

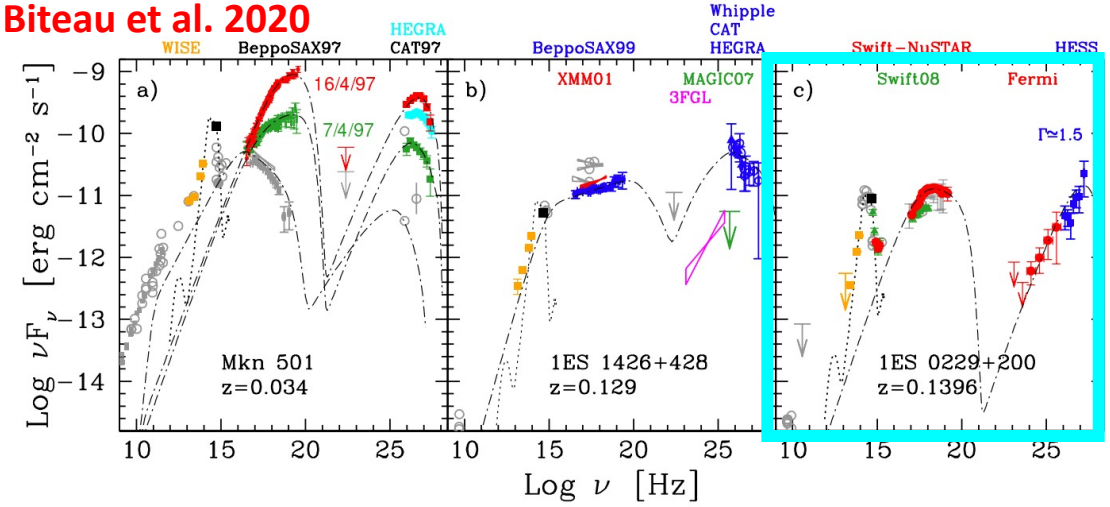
- Gravitationally lensed FSRQ
- One of the most distant TeV sources (z = 0.94)
- MWL monitoring: lensed, delayed emission after 11 days
- Broadband SED needs multiple components





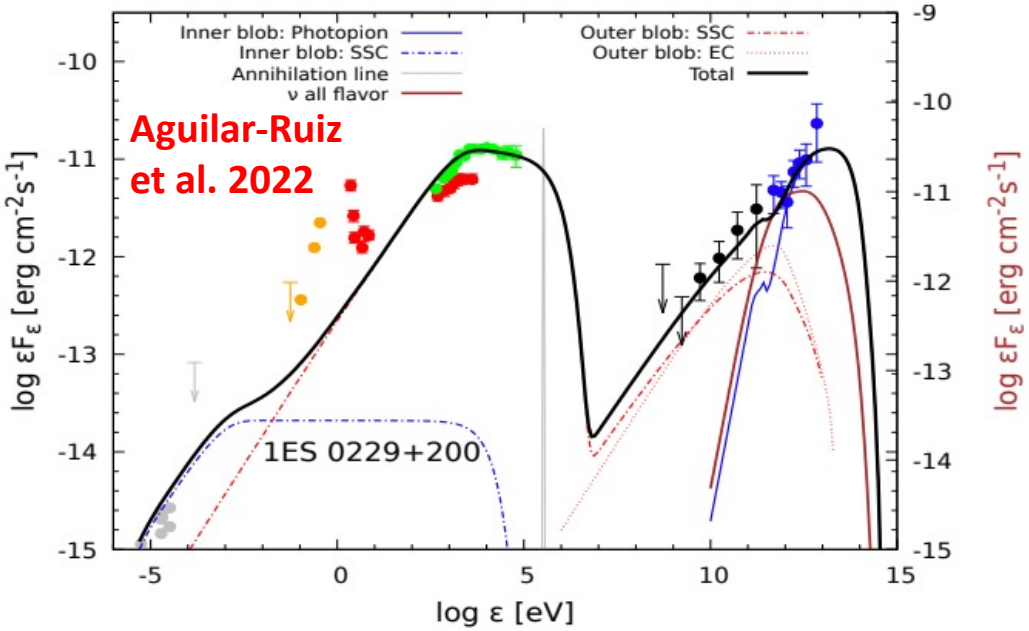
The high-energy frontier extreme blazars

Biteau et al. 2020



Observational properties

- Synchro peak at high energy
- Low overall luminosity
- Deep exposures of current generation of IACT or search for flares (only few sources variable)



Hard TeV sources: an astrophysical challenge

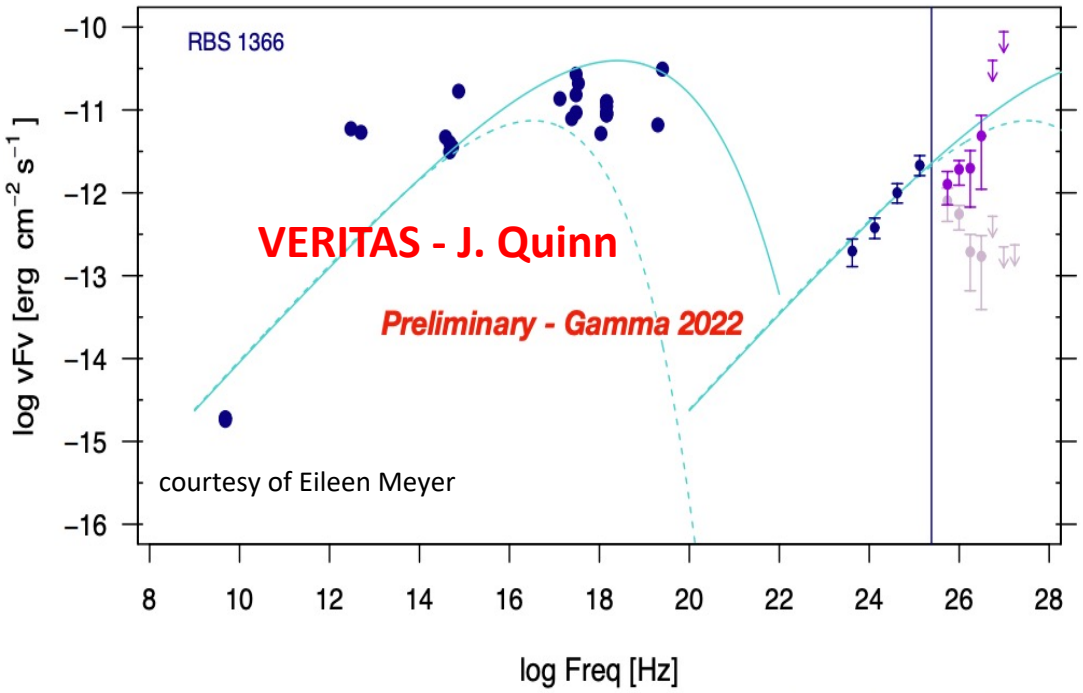
- Extreme particle acceleration
- Standard SSC: too low B
- Hadronic models: very high B

An opportunity

- Cosmology (EBL; IGMF)
- Fundamental physics (axions)

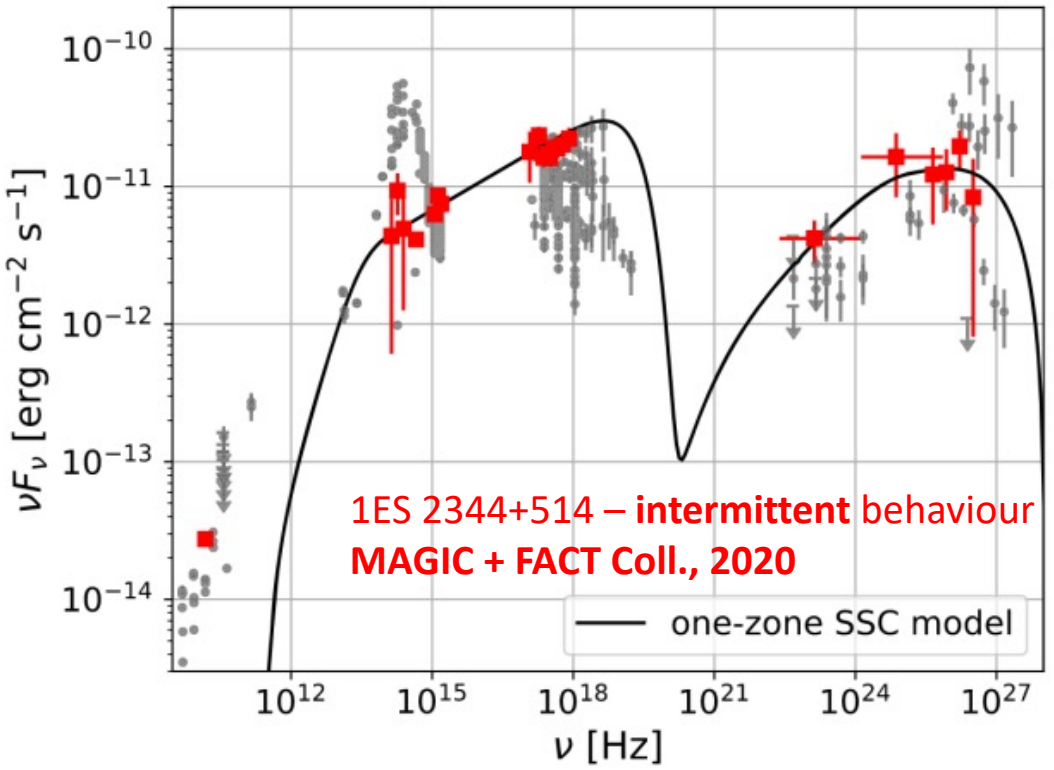
The high-energy frontier: extreme blazars ongoing observations

Search for new, hard-TeV sources



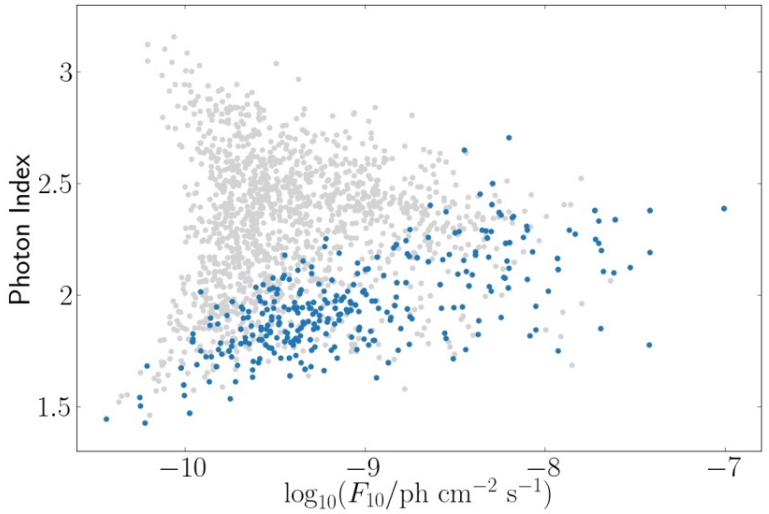
Gamma 2022 - VERITAS Highlights - Quinn

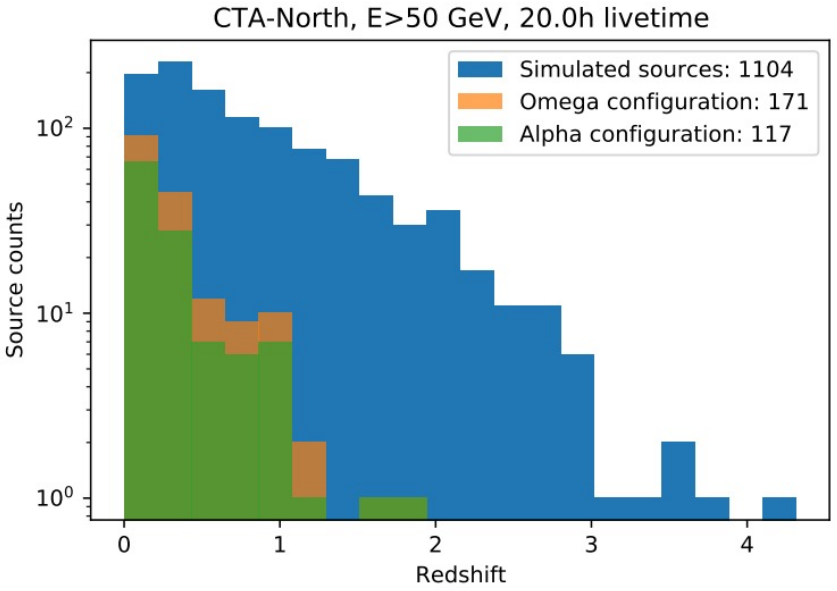
Monitoring hard-TeV sources

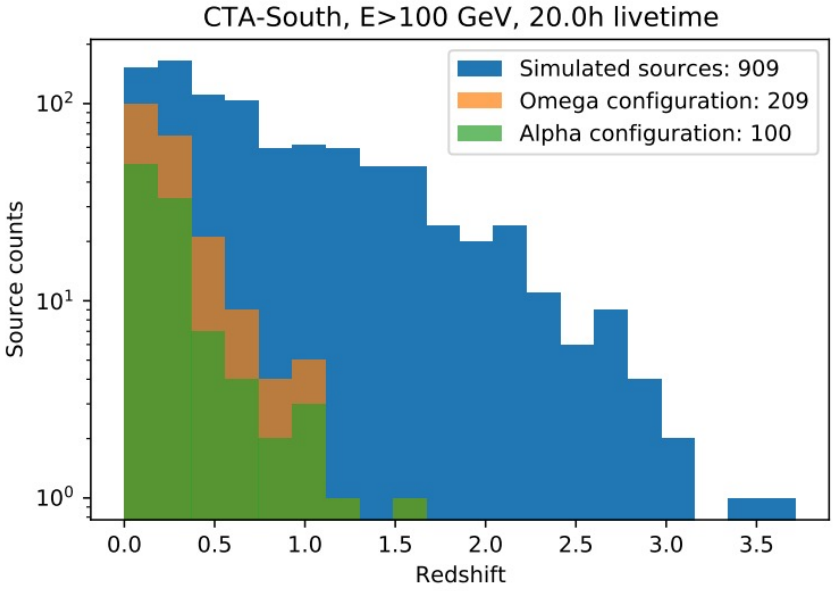


Future perspective with CTA: the extragalactic survey

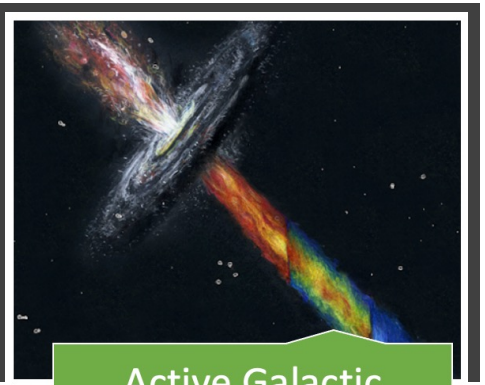
- **CTA key science project: Extragalactic survey of ¼ of the extragalactic sky**
- New detections
- Unbiased sample of sources
  - Luminosity function
  - Population study





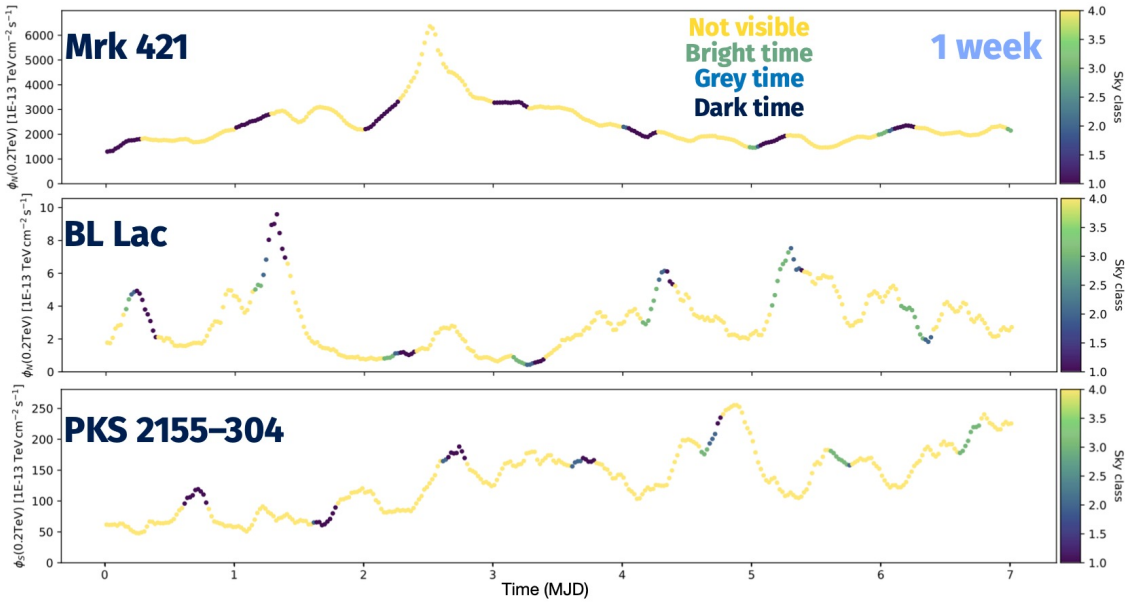


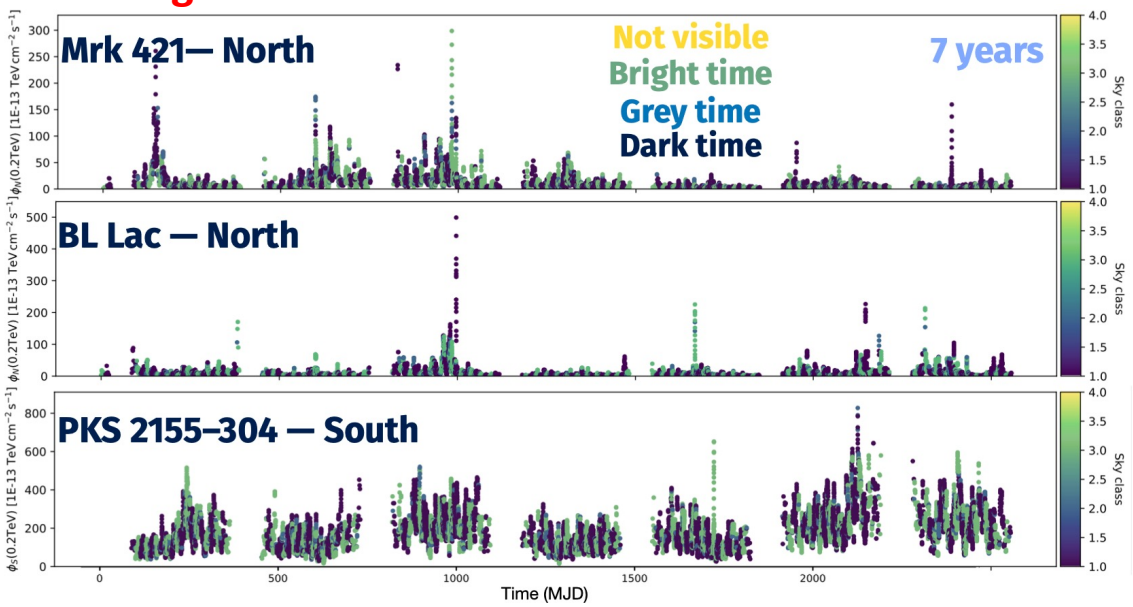
Future perspective with CTA: AGN monitoring

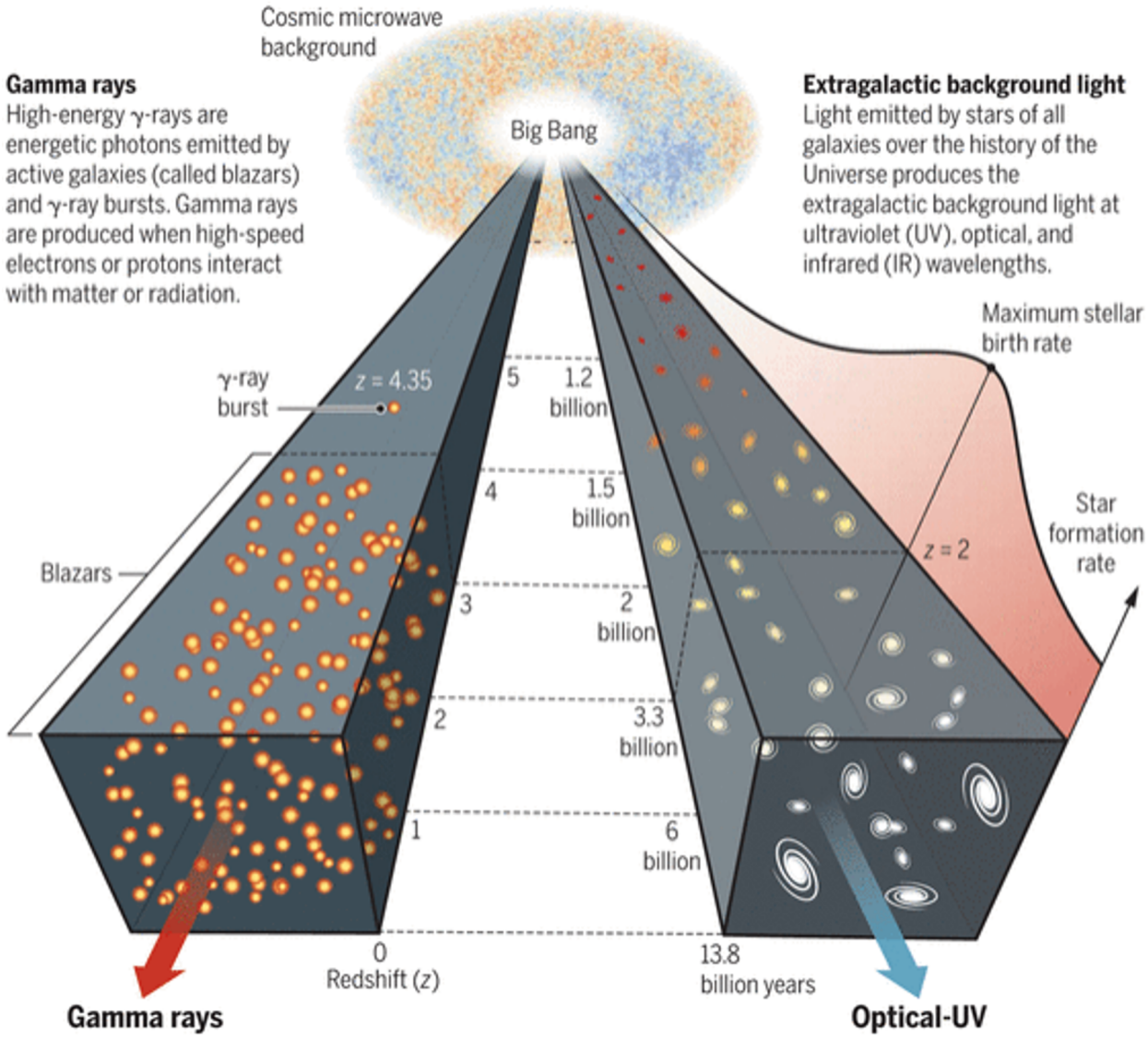


- **CTA key science project: long term monitoring of 14 sources**
- Simulations and code development ongoing to optimize observation strategy and assess CTA capabilities
- CTA consortium paper in preparation on AGN variability studies

Gamma 2022 – F. Cangemi





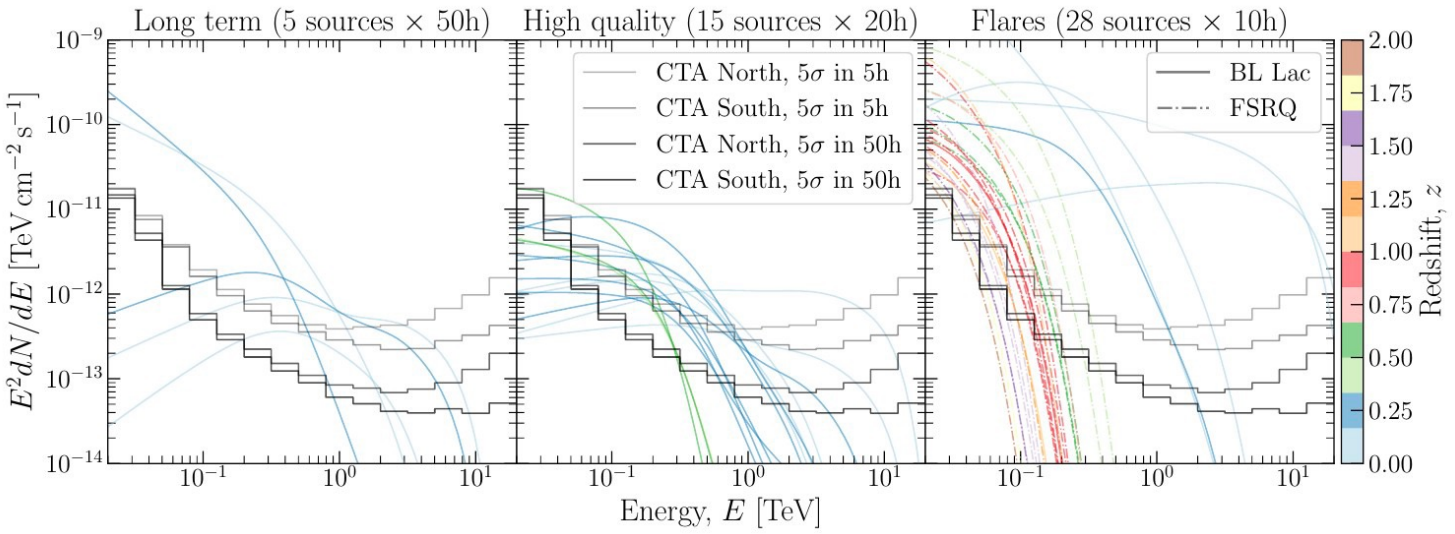


EP 2020

Cosmology with gamma rays

- TeV interaction with of the extragalactic background light photons
  - Increases with the distance
  - Increases with the energy
- Extragalactic sources have an EBL **imprint**

Future perspective with CTA: EBL



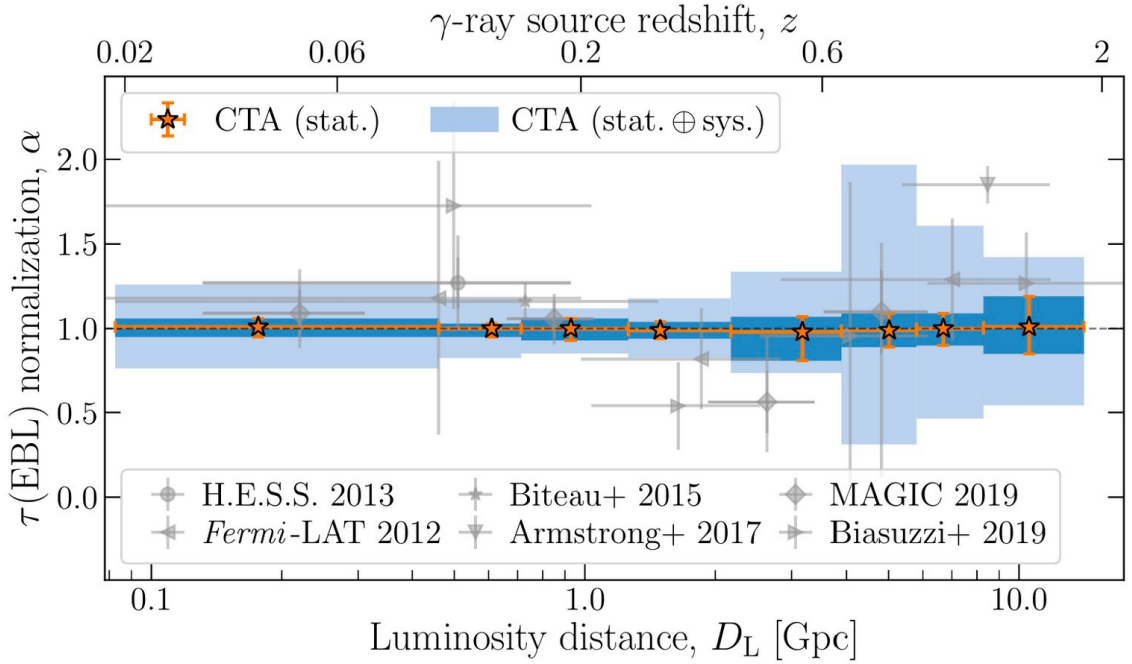
CTA AGN programs:

ICRC 2021 - Ie. Vovk

- **long-term monitoring** of selected AGNs: that will be observed regularly with short snapshots
- **high-quality spectra program**: with deep observations of AGNs of different classes and at different distances
- **blazar flares follow-up program**: target VHE flares from AGNs, triggered either by external facilities or internally by the monitoring program performed with CTA. Crucial to probe highest redshifts.

Select AGNs with **known redshift**:
- detected with >5 sigma above E(τ=1);
- present in 3FHL;
- detected on daily scales with Fermi/LAT

→ 48 sources in total in redshift range [0.05; 2]



Conclusions

- Last 20 years of VHE gamma-ray observations revolutionized our view of the extragalactic sky
- MWL, in many cases simultaneous observations are mandatory
- Detailed spectral and temporal studies needed to investigate the astrophysical environment, processes and propagation
- Next decades, with CTA, will be very exiting in terms of detailed measurements and possibly new discoveries

Extra material

RESOURCES

How can I know more about a source?

TeVCat as a starting point

NED (Nasa Extragalactic Database) from an astronomical point of view

CDS (Centre de données astronomiques de Strasbourg) access to databases

SSDC access into archival data, including having an overview of the spectral properties