INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

Sorgenti astrofisiche di alta energia

Stefano Vercellone – INAF/OAB

Introduction

The Galactic companions

The extra-galactic realm

Perspectives

Caveats

This topic is **extremely vast** → just a few examples

Mostly from an **observational point of view**, discussing models would require a book !

The link between HE/VHE/UHE sources and neutrino emission is covered by other speakers

Introduction – main catalogues

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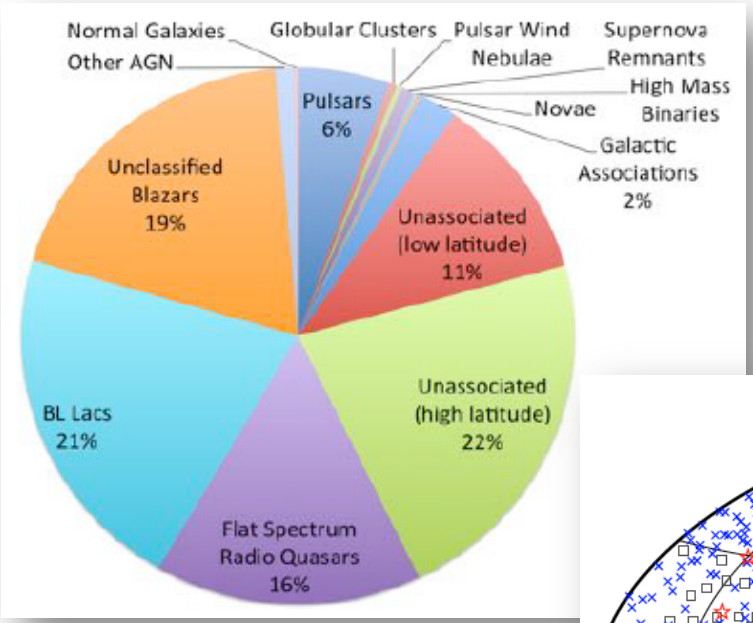
Major observing facilities

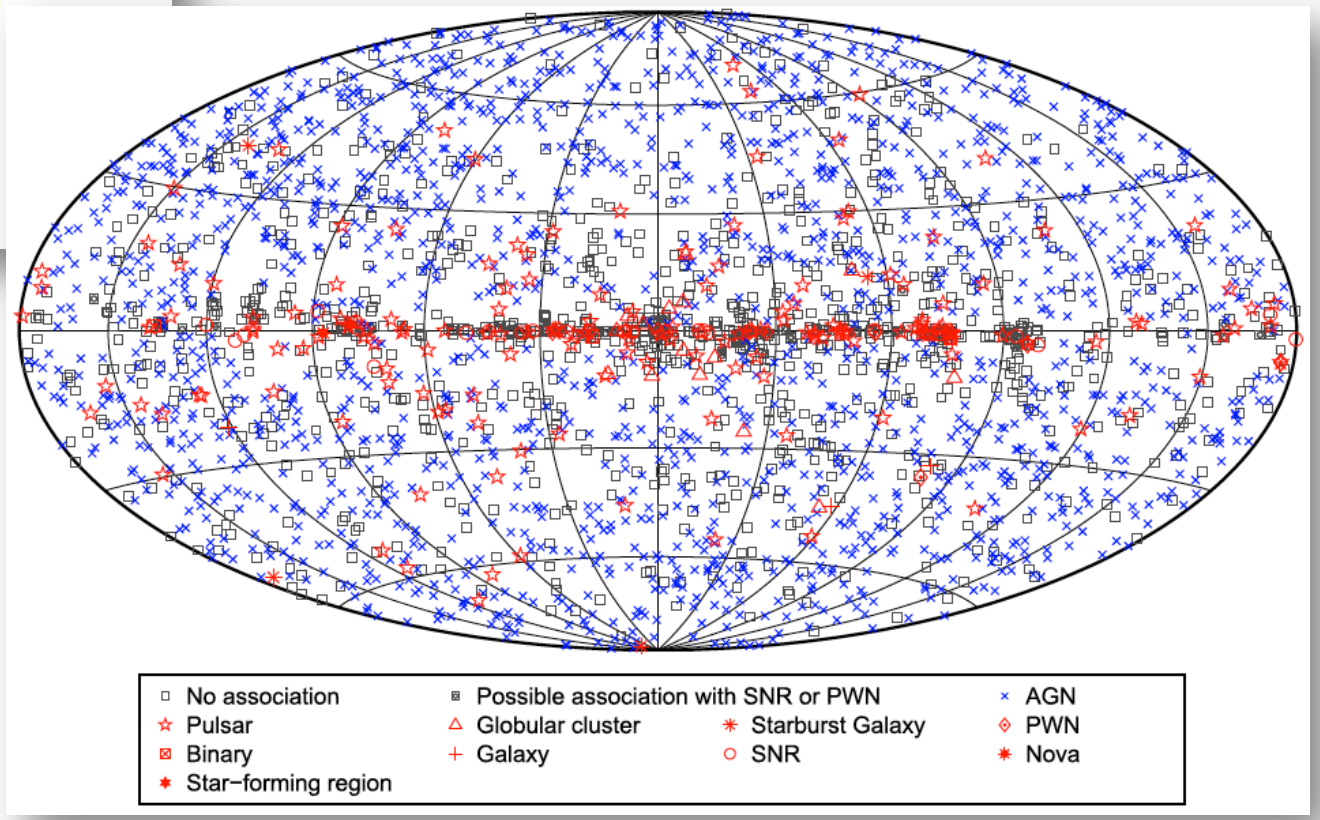
- **High-energy (~30 MeV – ~100 GeV) –** pair-conversion tracker detectors
  - **AGILE, *Fermi*/LAT**
    - Wide FoV (~1/5 of the sky), scanning mode, public data (1yr [A], full [F]), thousands of sources.
- **Very high-energy (~100 GeV – ~50 TeV)** – Imaging Atmospheric Cherenkov Telescopes (IACTs)
  - **MAGIC (N), H.E.S.S. (S), VERITAS (N)**
    - Narrow FoV (~2-3 deg), pointed mode, improved energy and angular resolution, modest duty-cycle. Almost proprietary data, hundreds of sources.
- **Ultra high-energy (~0.5 – ~100 TeV) –** Water Cherenkov detectors
  - **HAWC (N)**
    - Wide FoV (~2/3 of the sky/day), synoptic survey instrument, less extreme energy and angular resolution, high duty-cycle (95%). Proprietary data, tens of sources.

30 MeV – 100 GeV sky

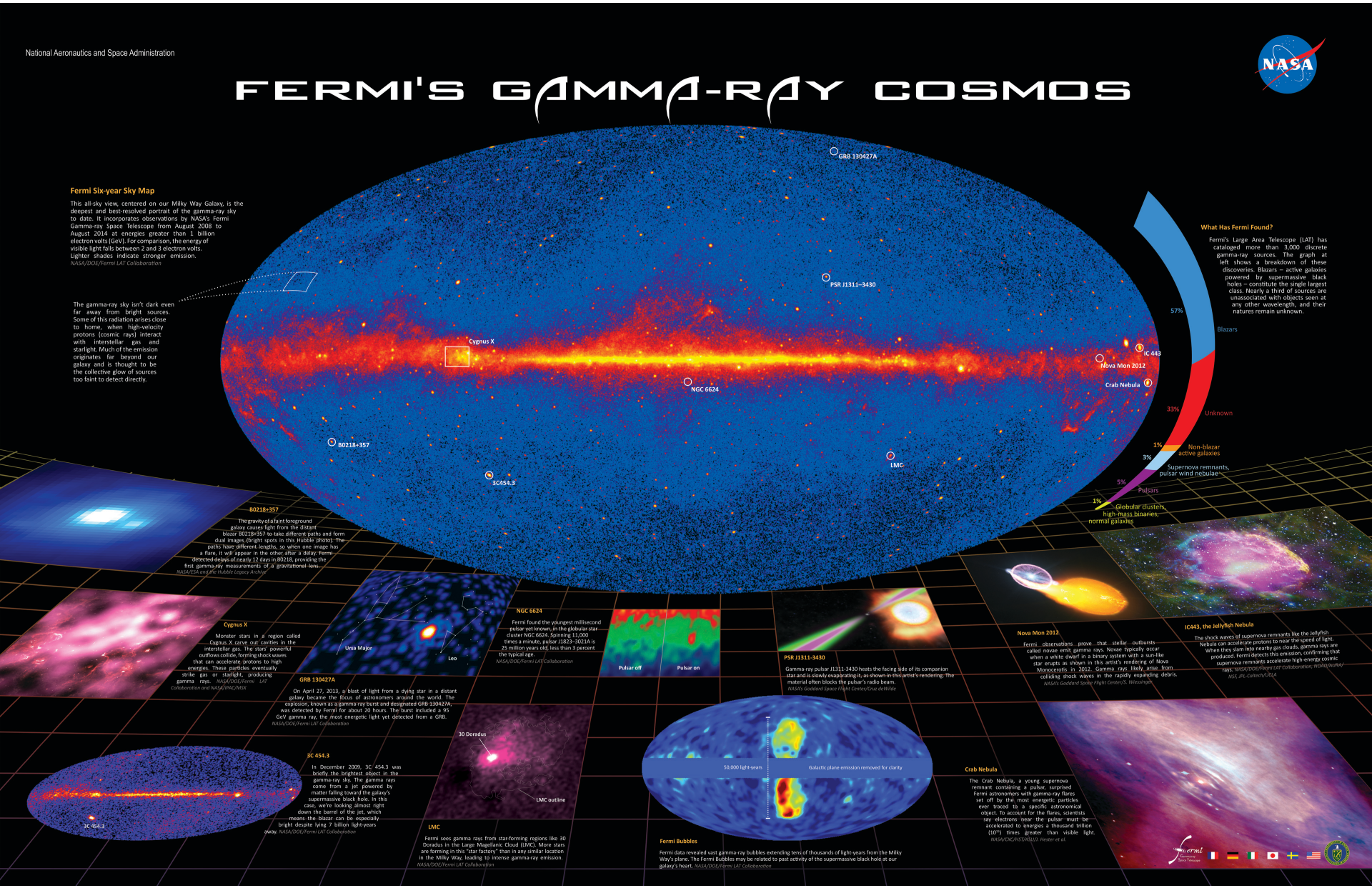


3FGL
3033 sources
48 months
E>100 MeV

Acero+15

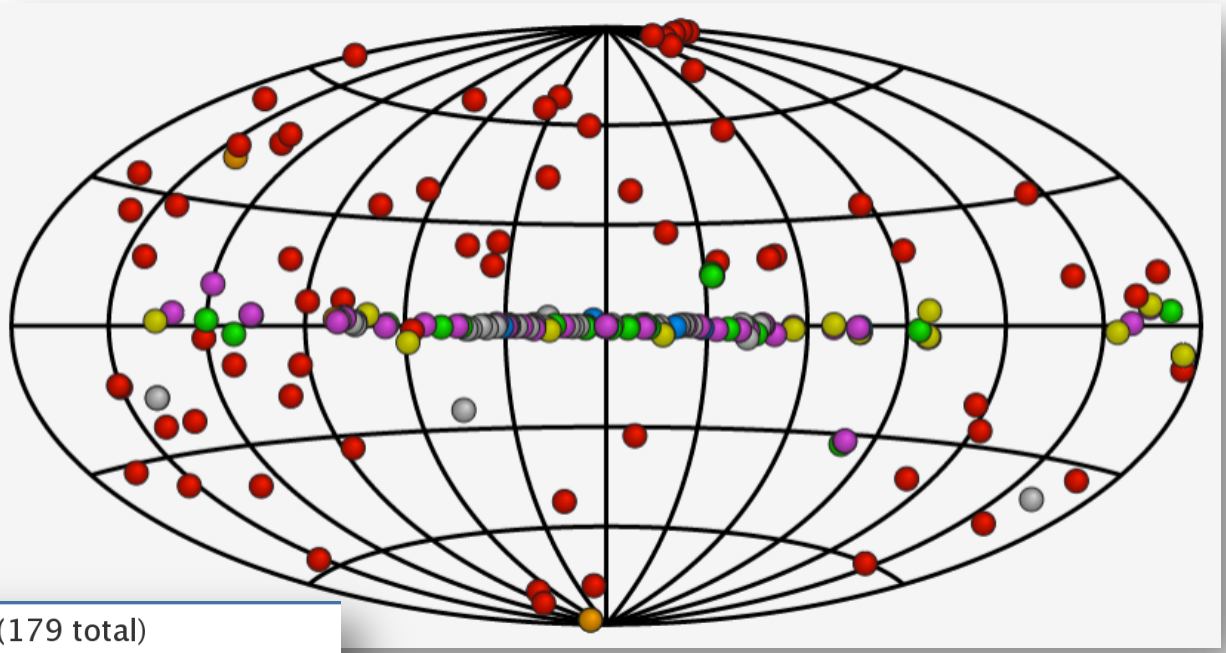


30 MeV – 100 GeV sky

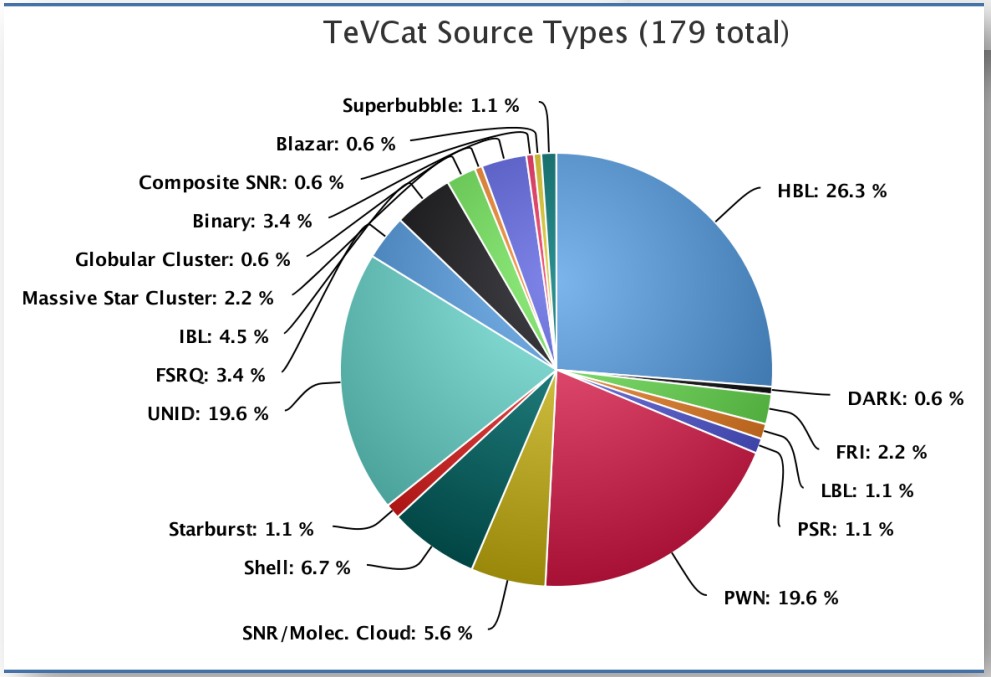


100 GeV – 50 TeV sky

TeVCat 2
H.E.S.S., MAGIC, VERITAS
~180 sources
E>100 GeV



Deidre & Horan+16



100 GeV – 50 TeV sky

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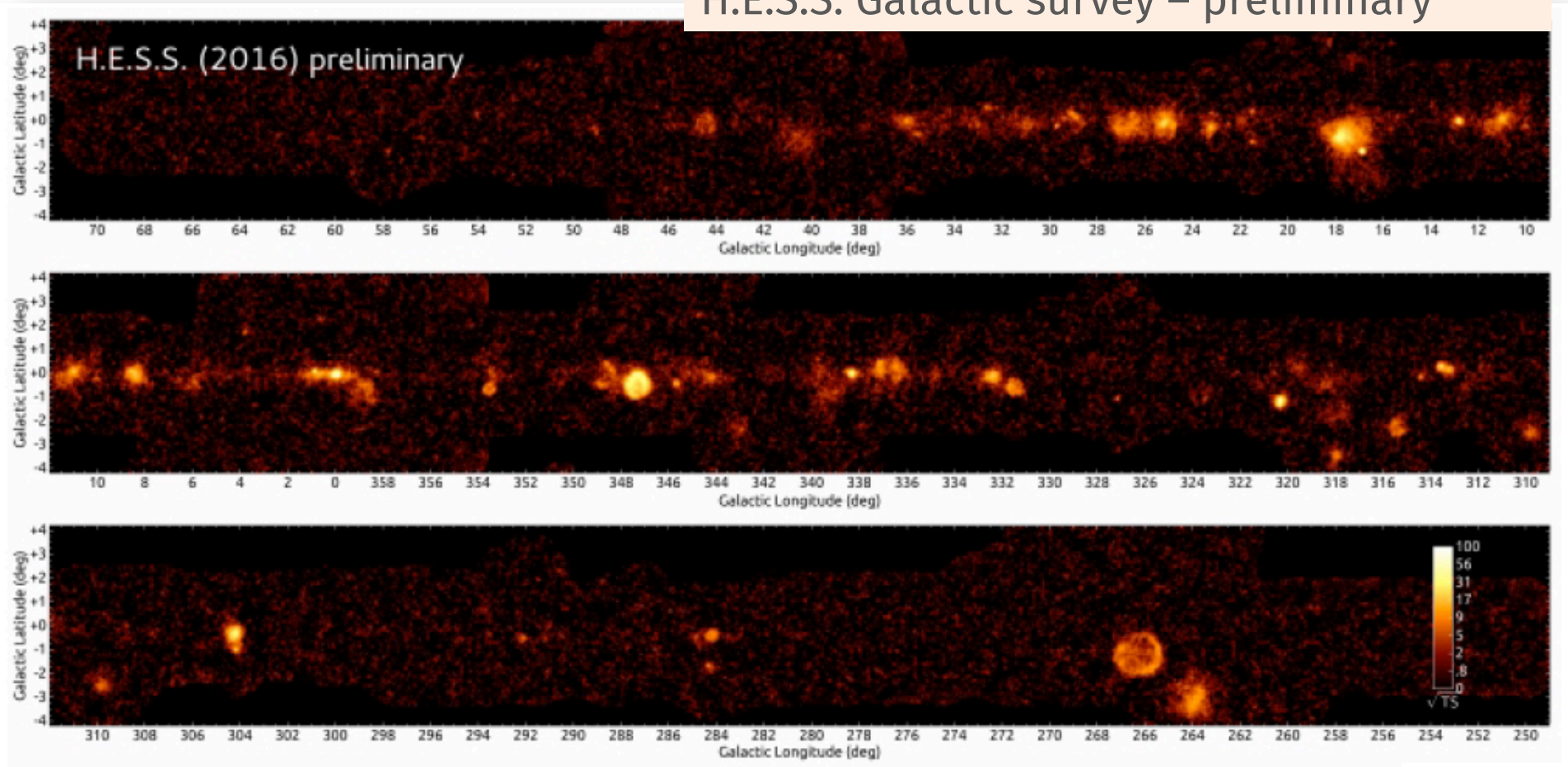
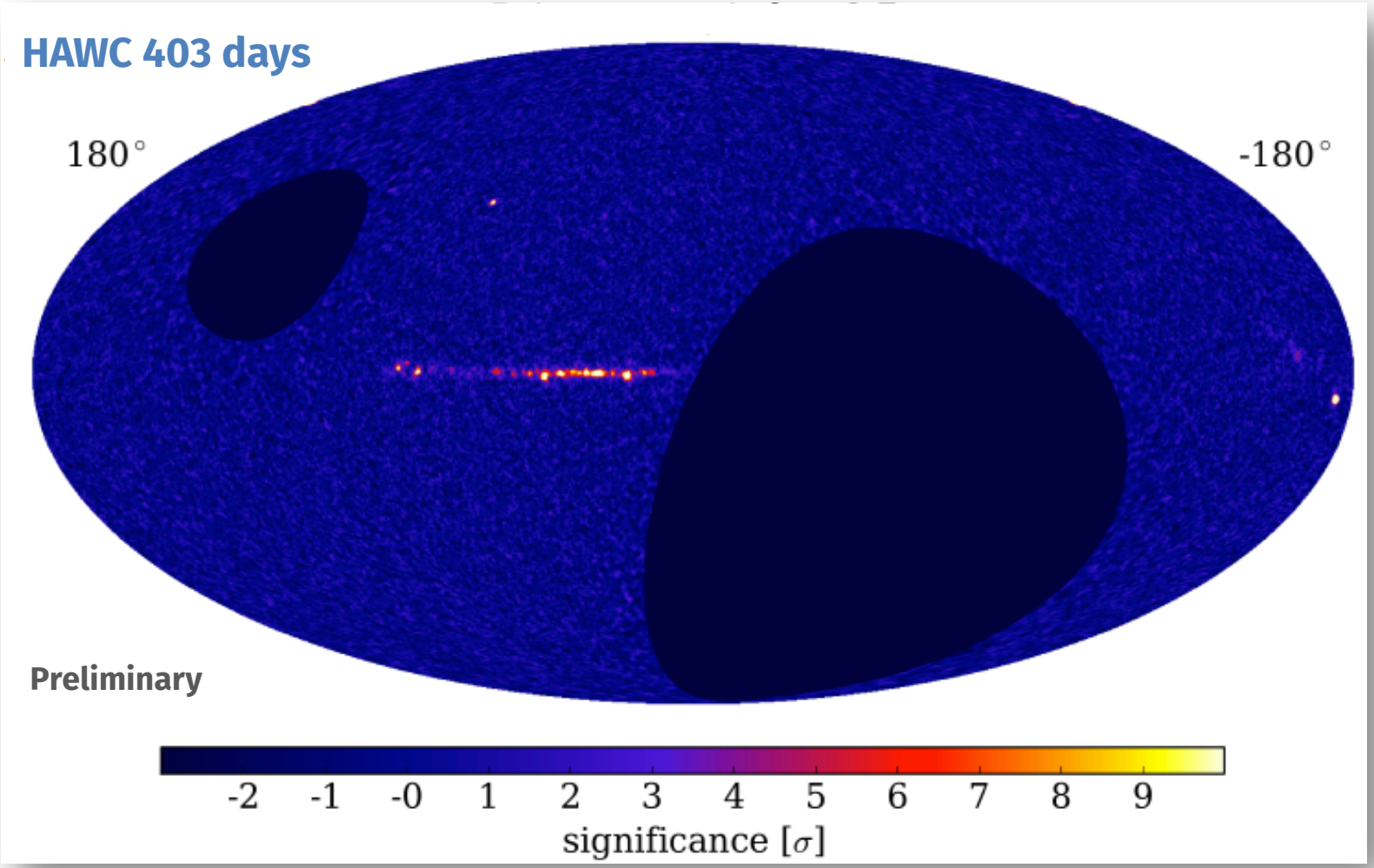
H.E.S.S. Galactic survey – preliminary



Deidre & Horan+16

0.1 – 100 TeV sky

Sandoval & HAWC Coll. 2016



2nd HAWC Catalogue in preparation. ~40 sources
Several sources are also in TeVCat, but about ¼ have no low-energy counterparts

0.1 – 100 TeV sky

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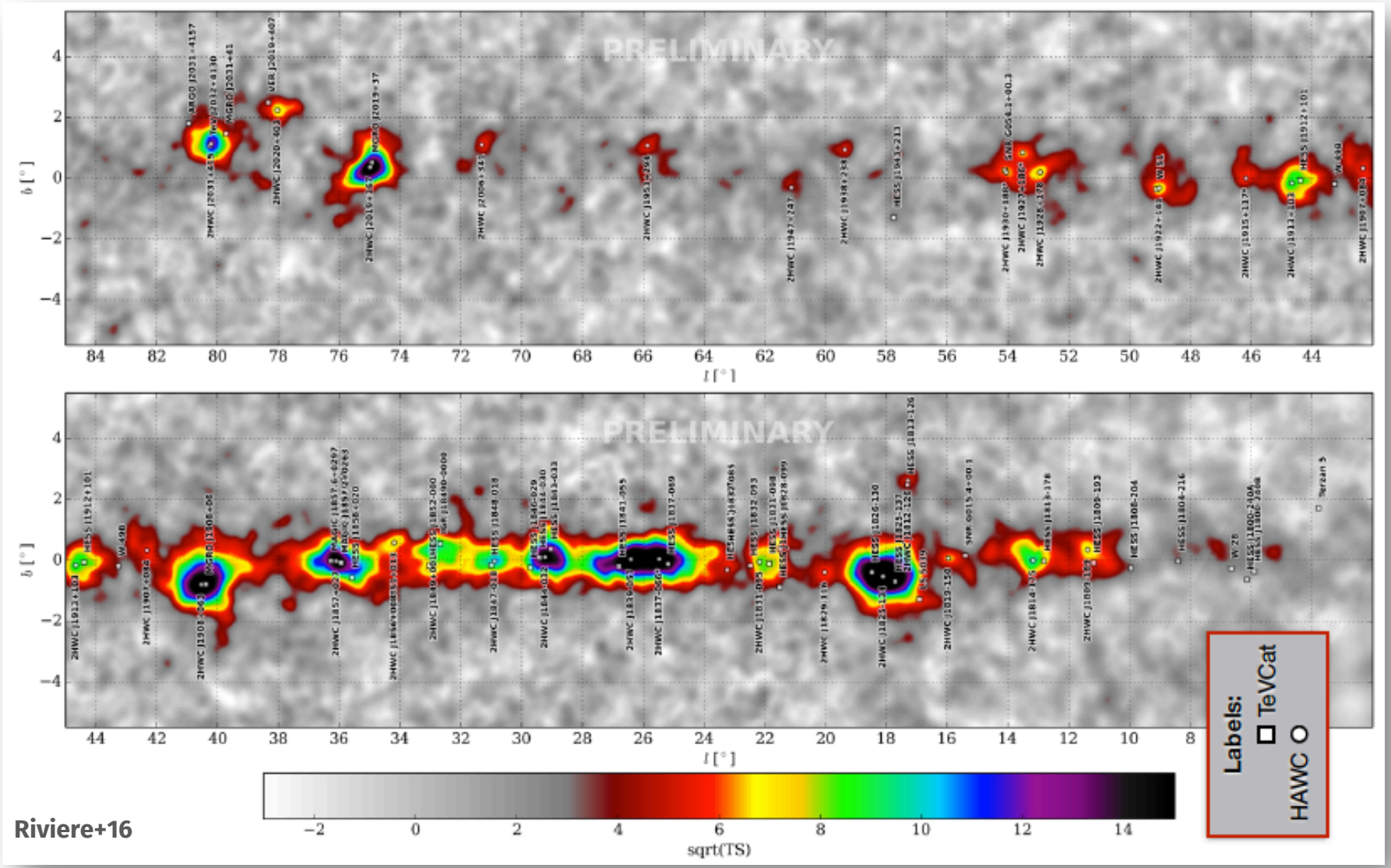
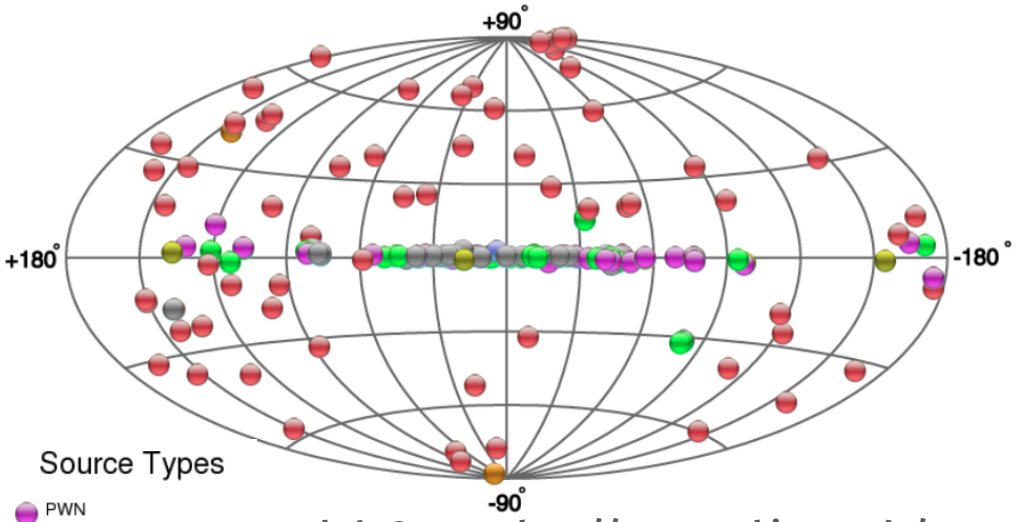
HAWC view of the Inner Galactic plane



Riviere+16

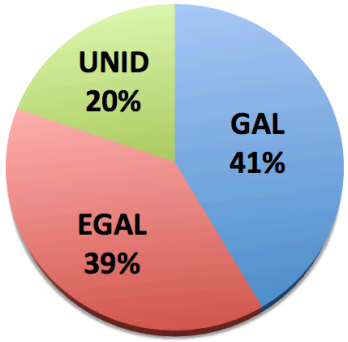
Introduction – bridging the gap

The *Fermi* sky above 50 GeV

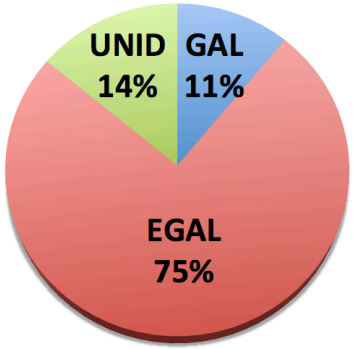


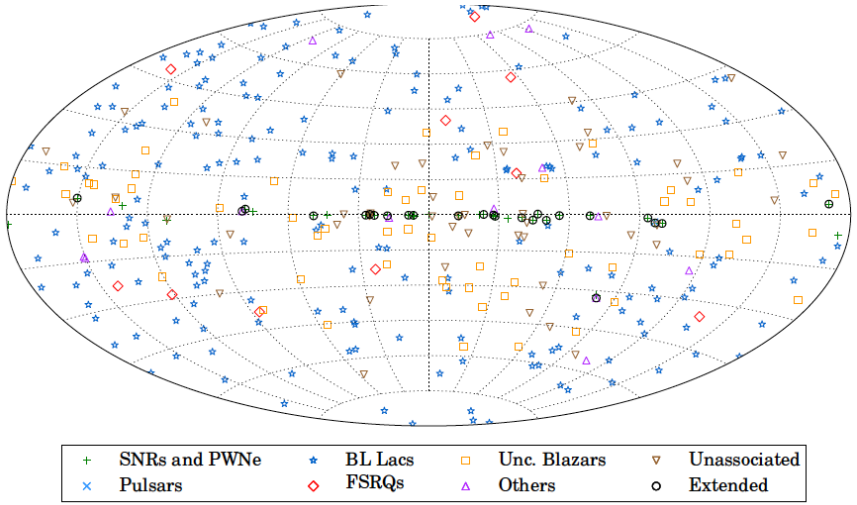
Wakely & Horan http://tevcat.uchicago.edu/

~180 TeVCat sources



360 *Fermi*-LAT sources E>50 GeV

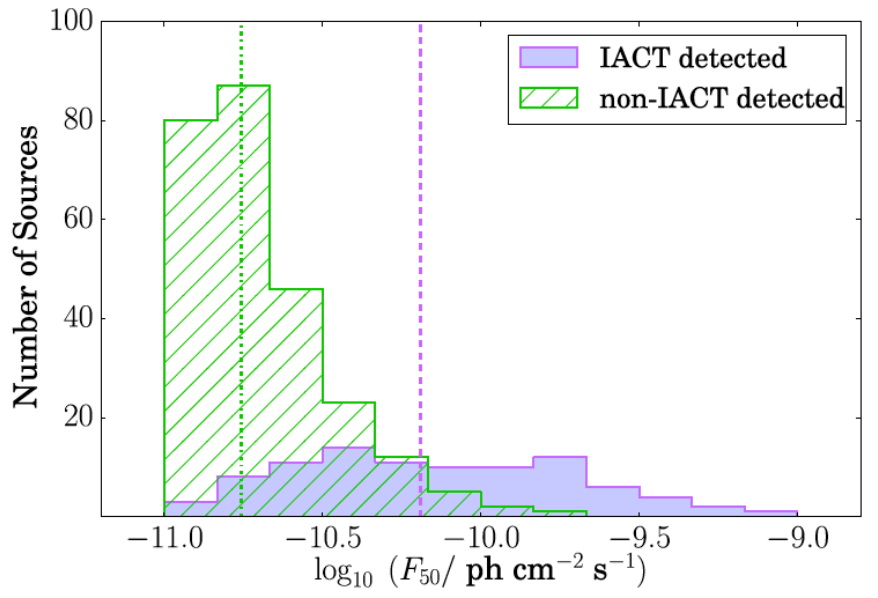


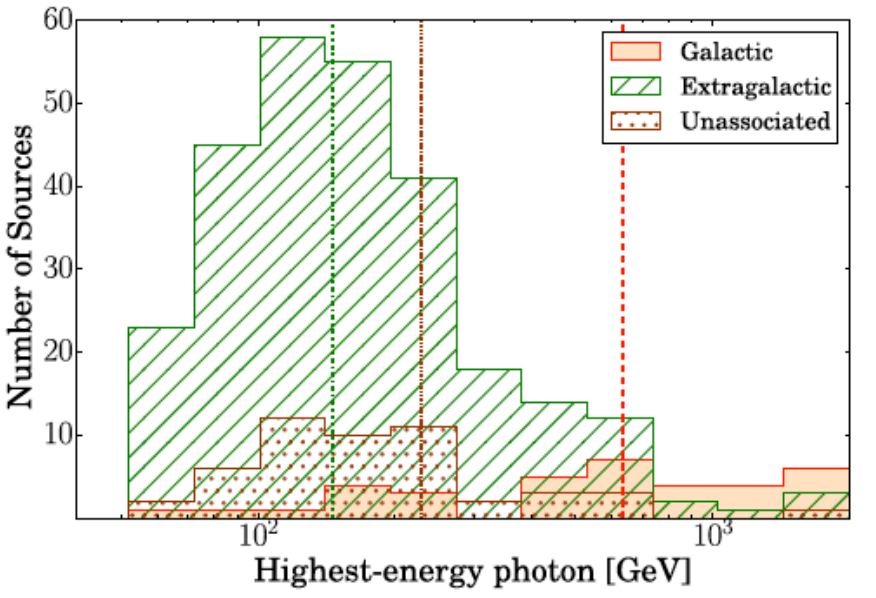


2FHL Ackermann+16

Only ~25% of the 2FHL sources have been previously detected by Cherenkov telescopes.
2FHL provides a reservoir of candidates to be followed up at very high energies.

The *Fermi* sky above 50 GeV





2FHL Ackermann+16

360 sources

282 non-IACT

216 |b|>10°

66 |b|<10°

94 IACT sources detected in 2FHL

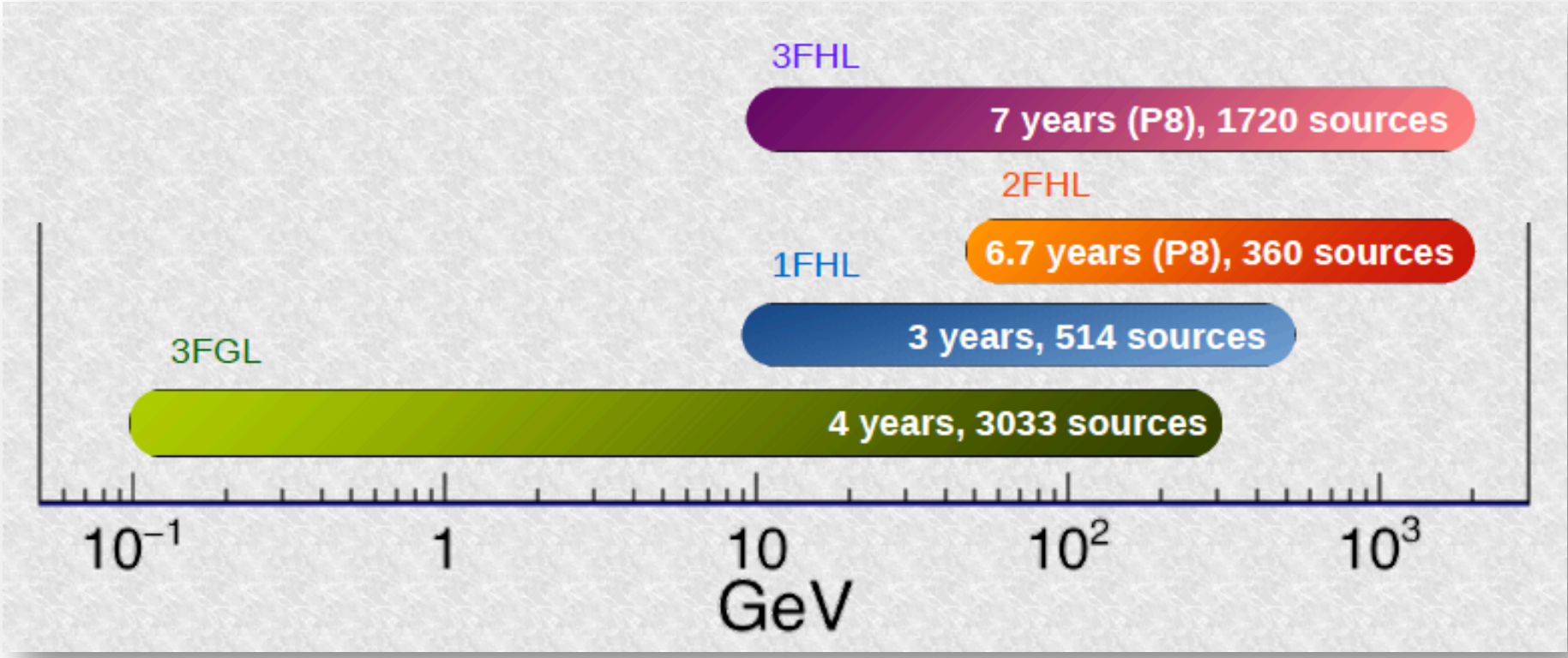
~25% of Galactic sources (20-30) has a photon index harder than 2 → high-energy SED peak in the TeV band.

Fermi-LAT detects emission from many Galactic sources well beyond 500 GeV.

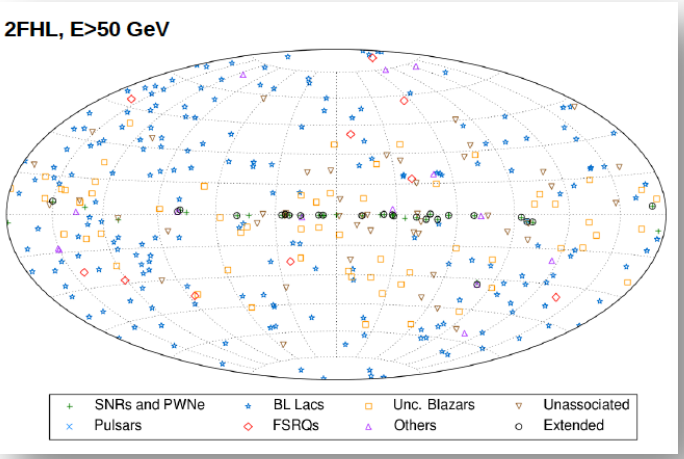
Beyond 2FHL → 3FHL

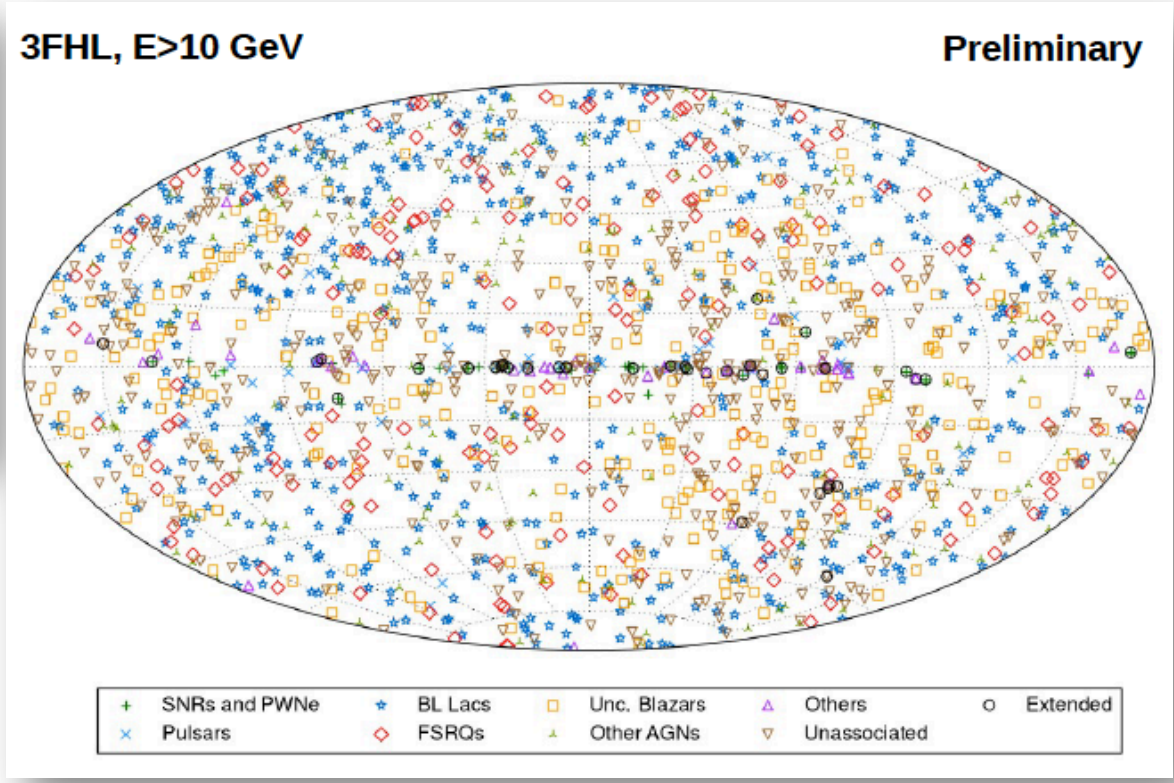
Preliminary *Fermi*/LAT results E>10 GeV

3FHL Dominguez+16

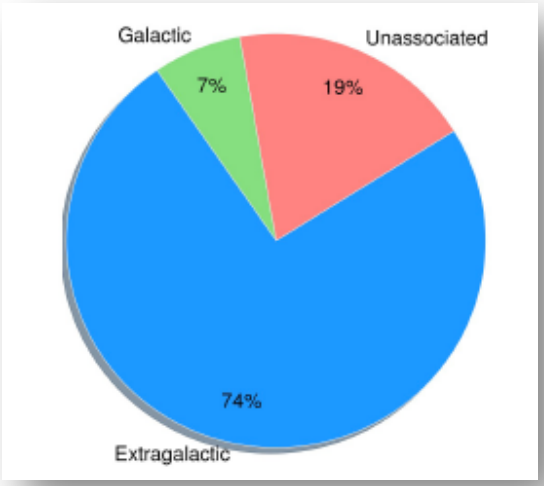


Beyond 2FHL → 3FHL





3FHL Dominguez+16



10 GeV – 2 TeV

84 months of data (until August 2015)

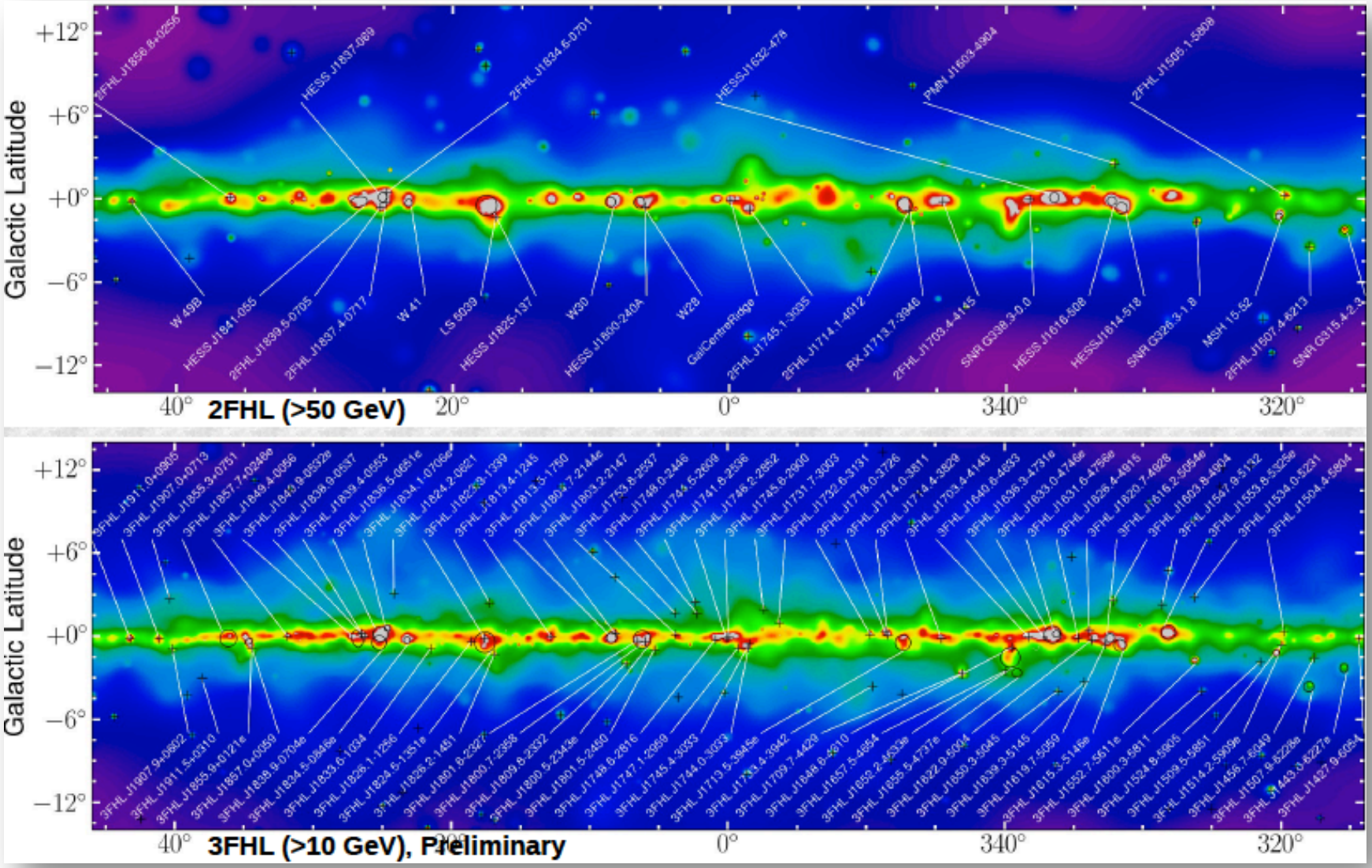
1720 (54 extended); 129 detected by IACTs (TeVCat)

358 brand new sources (not in 1FHL/2FHL/3FGL/TeVCat)

Median localization accuracy is 2.3' in radius (95%)

Beyond 2FHL → 3FHL

3FHL (E>10 GeV) vs 2FHL (E>50 GeV) – Galactic plane

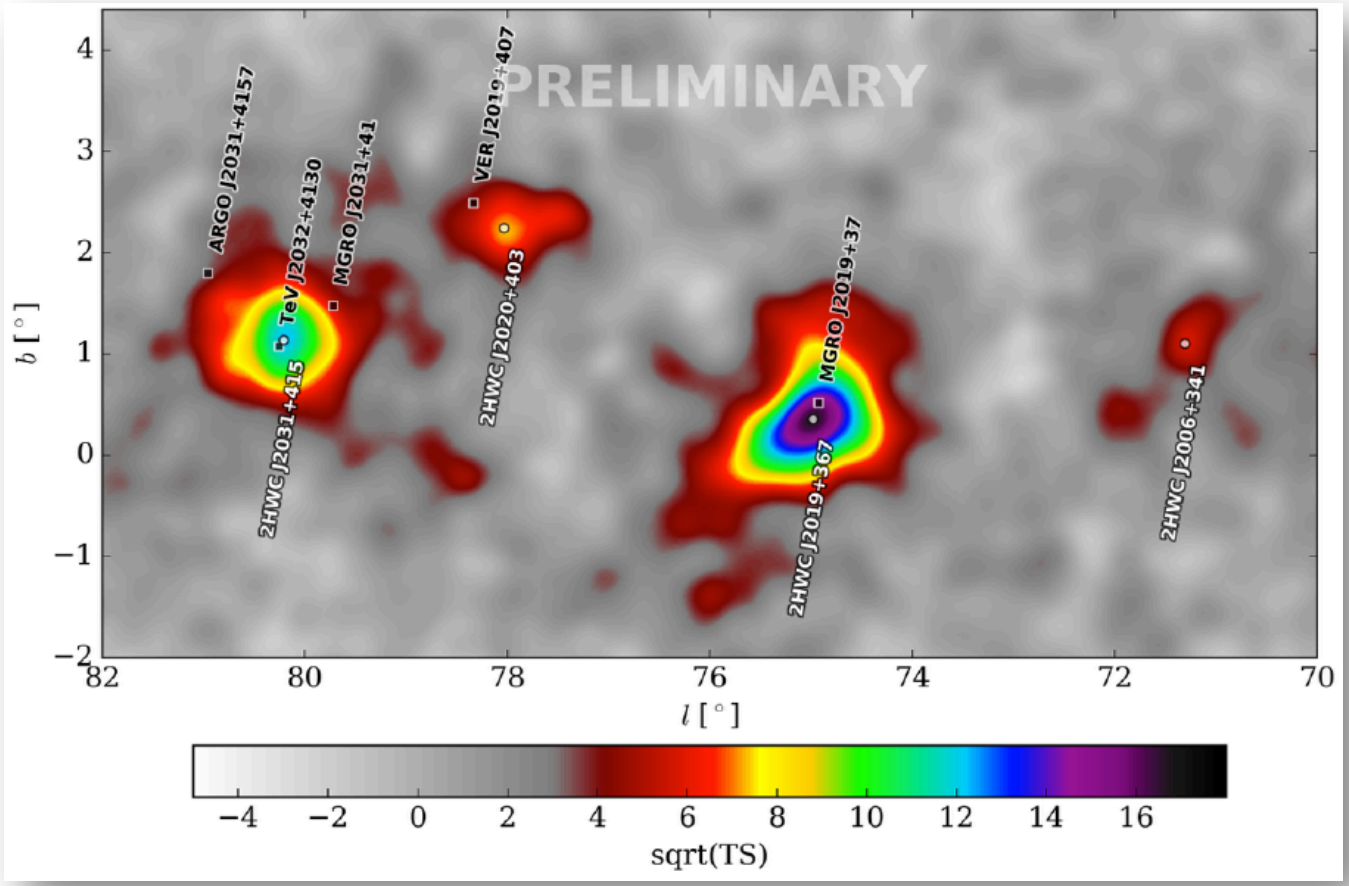


3FHL Dominguez+16

The Galactic companions

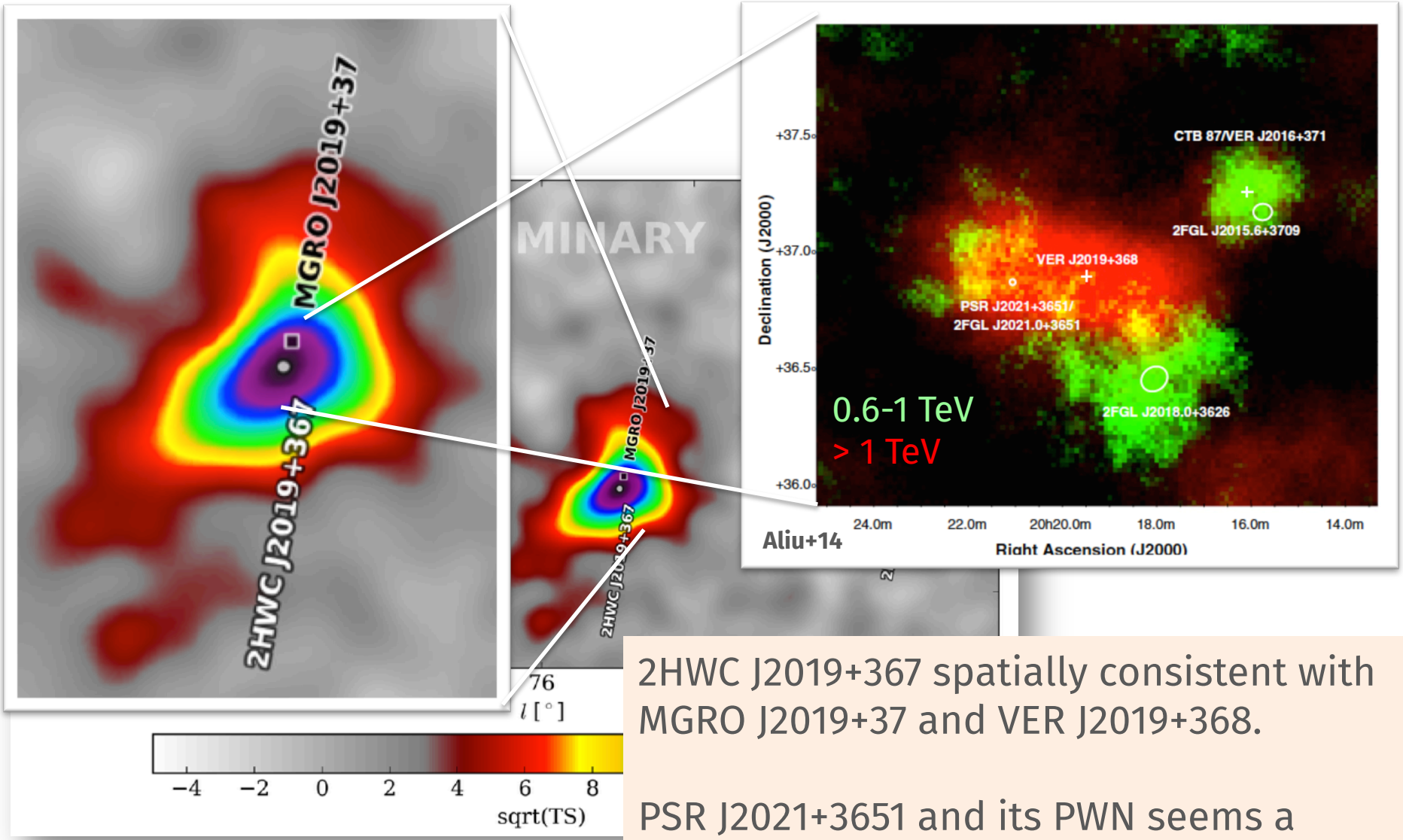
Cygnus region

HAWC data



Riviere+16

Cygnus region

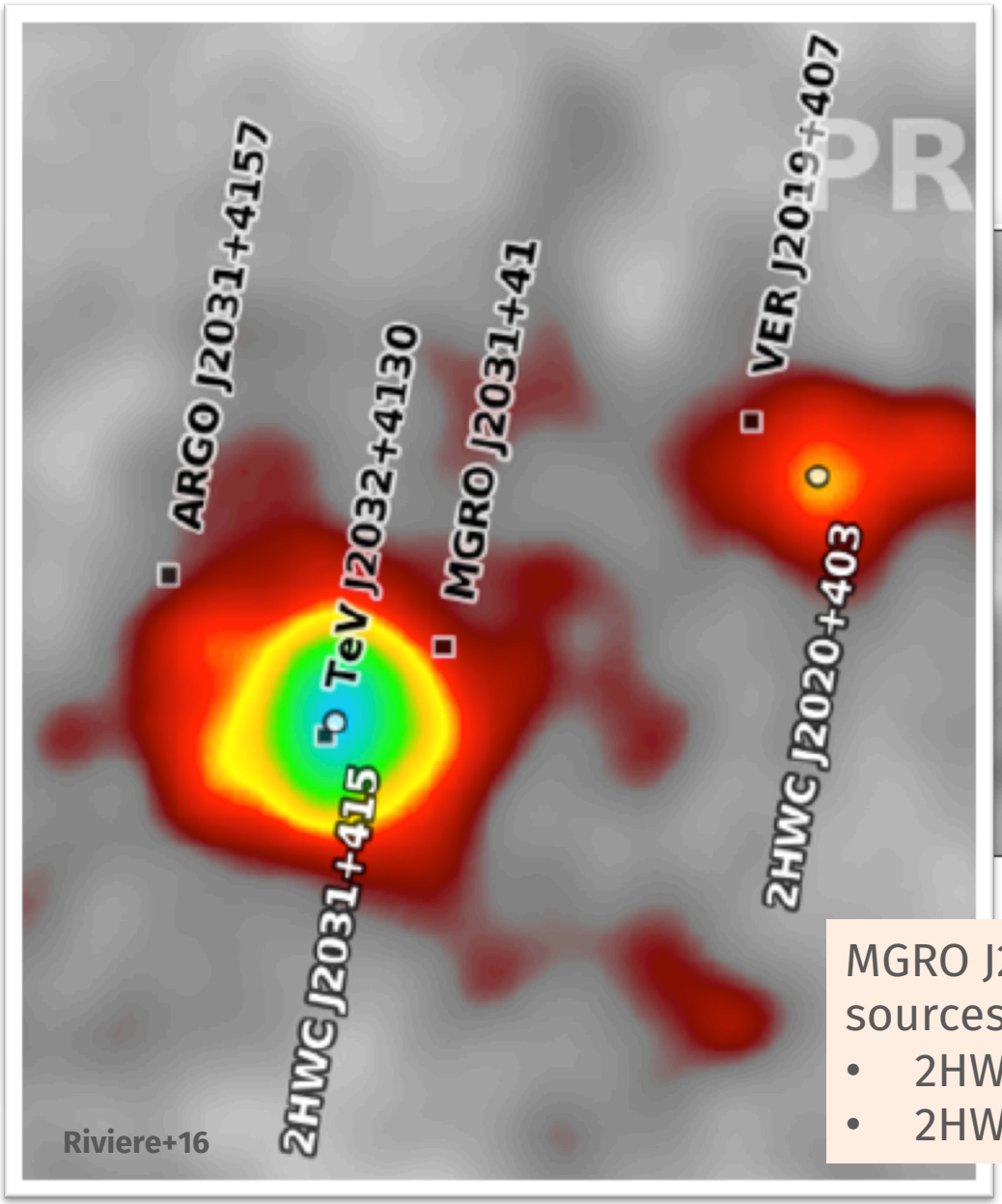


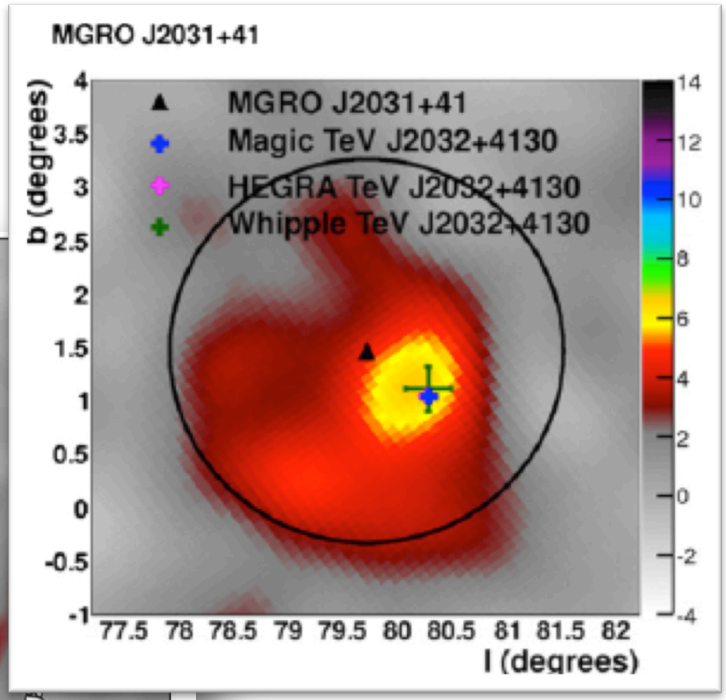
Riviere+16

2HWC J2019+367 spatially consistent with MGRO J2019+37 and VER J2019+368.

PSR J2021+3651 and its PWN seems a possible contributor to the emission of VER J 2019+368 and MGRO/HWC emission.

Cygnus region



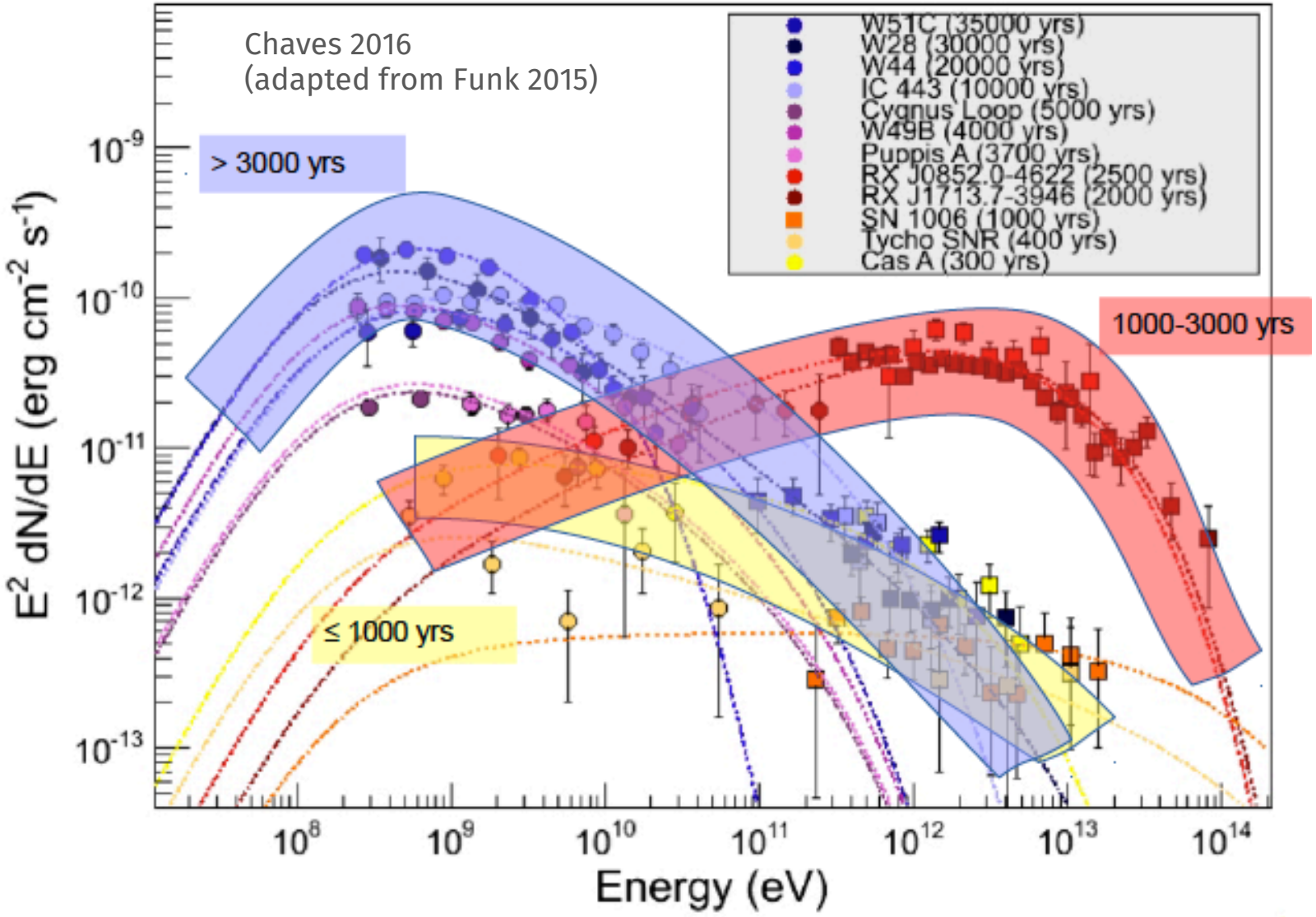


MGRO J2031+41 is resolved into 2 distinct sources

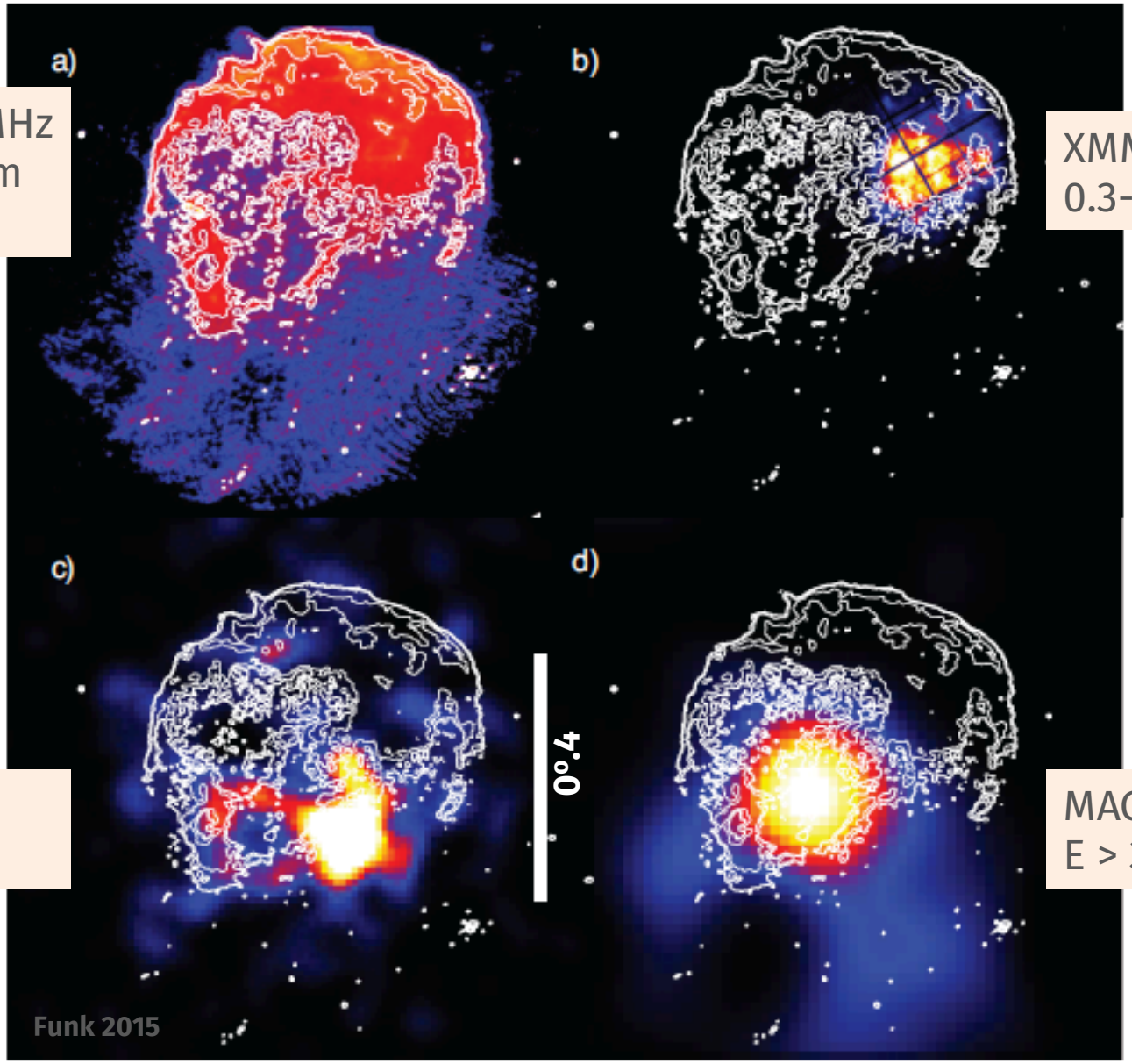
- 2HWC J2020+403/VER J2019+407 (UID)
- 2HWC J2031+415/TeV J2032+4130 (PWN)

SNRs population at a glance

Different SNRs may be preferred targets of ground- or space-based facilities



IC 443 – a multi-wavelength view



VLA 330 MHz continuum emission

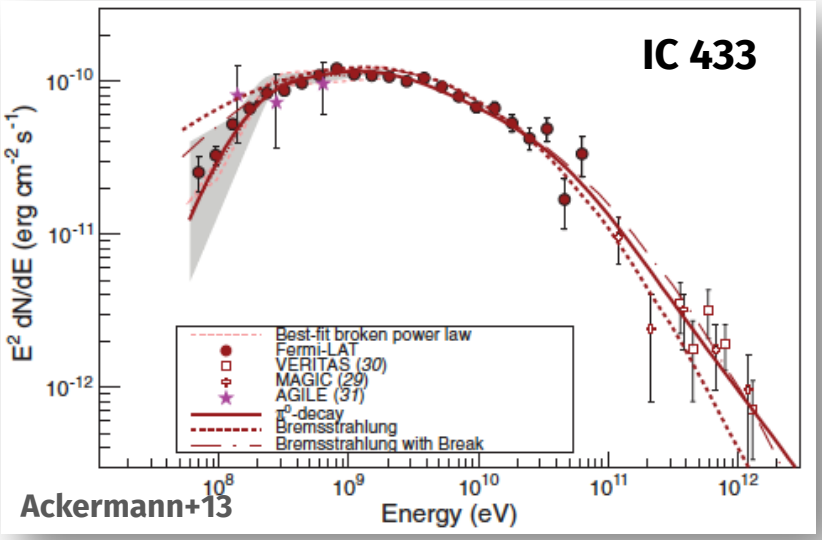
XMM-*Newton* 0.3- 8 keV

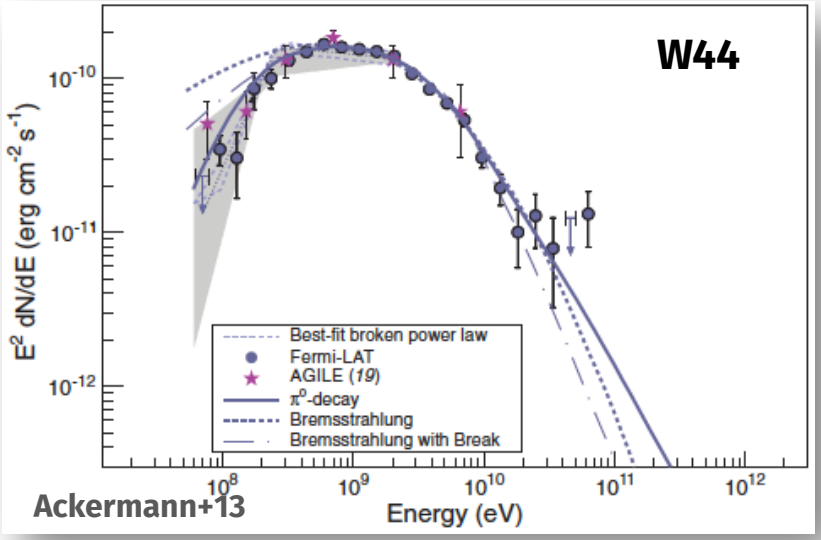
Fermi-LAT E > 10 GeV

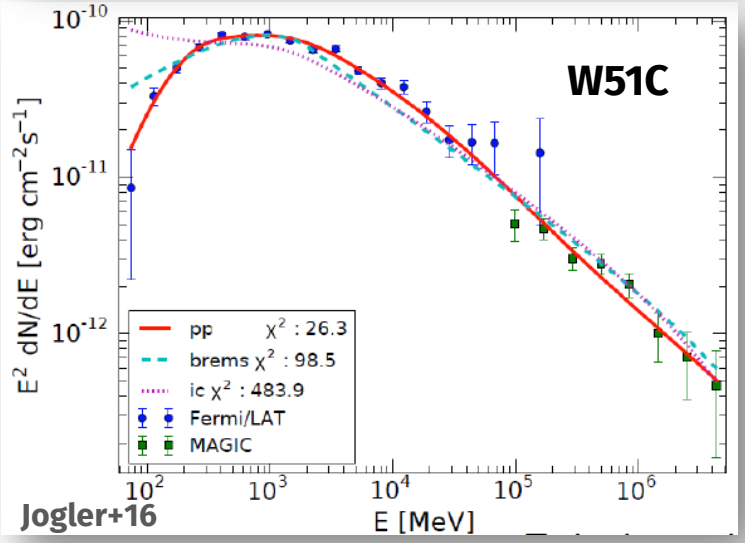
MAGIC E > 380 GeV

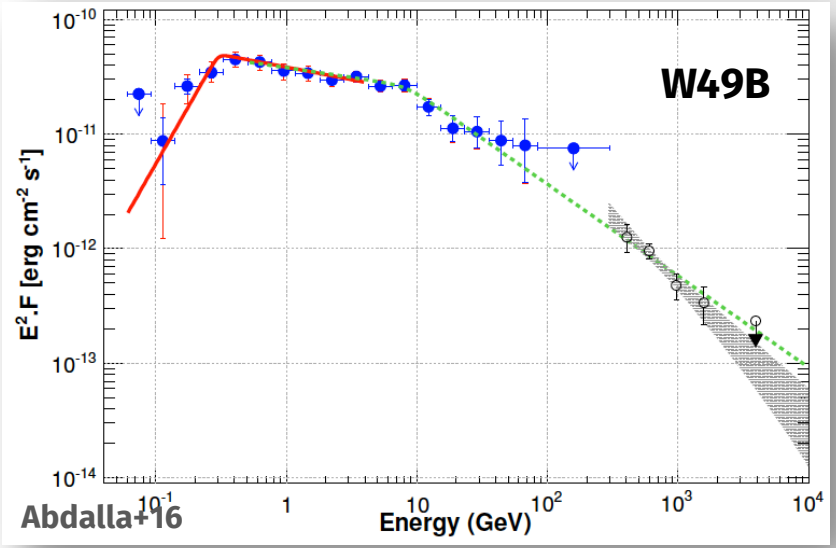
The “Fab-four” pion-bumbers

Pion-decay signature in the AGILE & *Fermi*-LAT data









RX J1713.7-3946 – a multi-wavelength view

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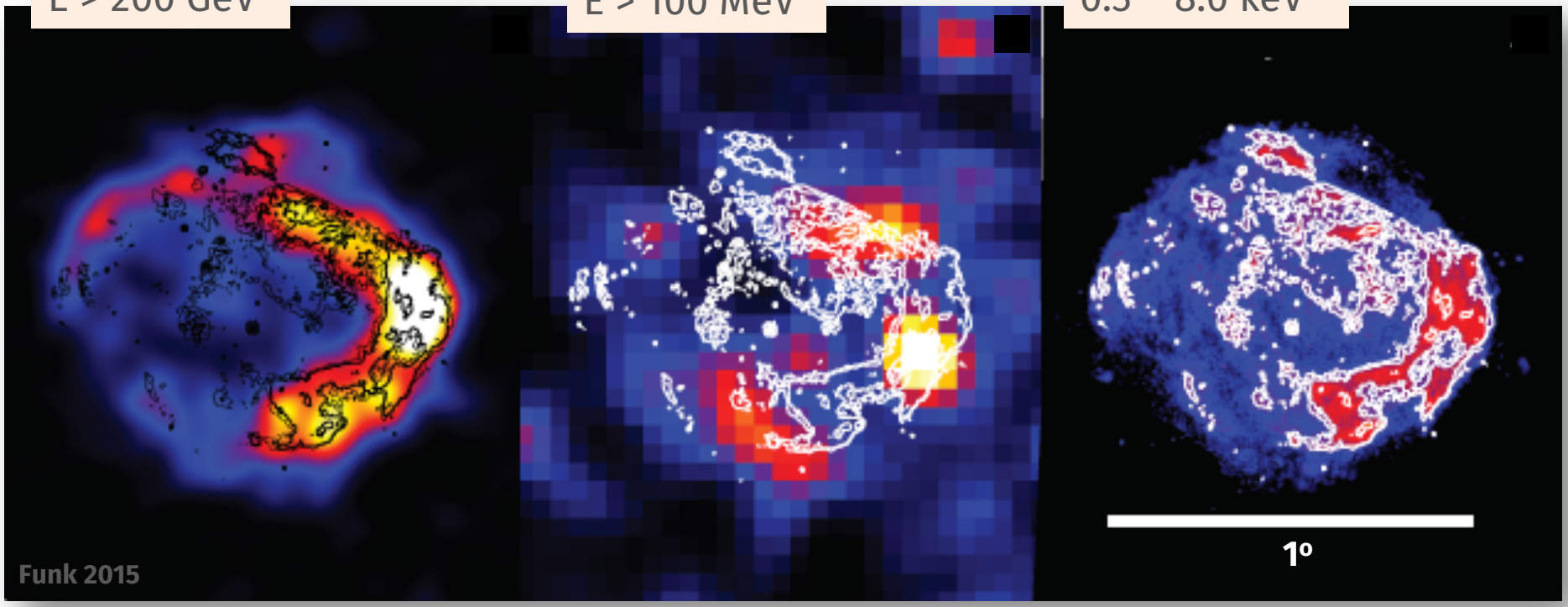
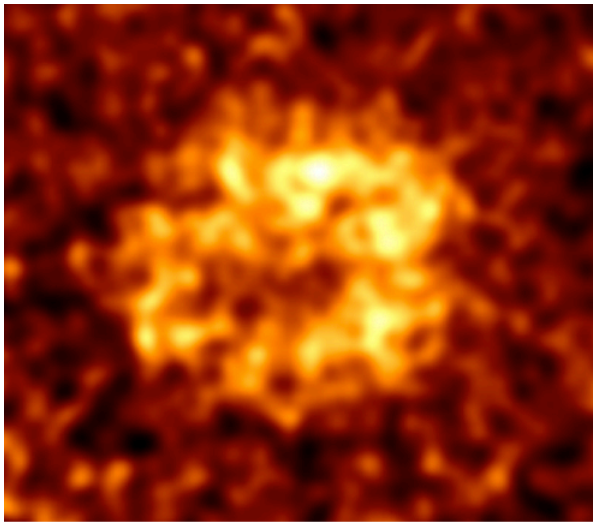
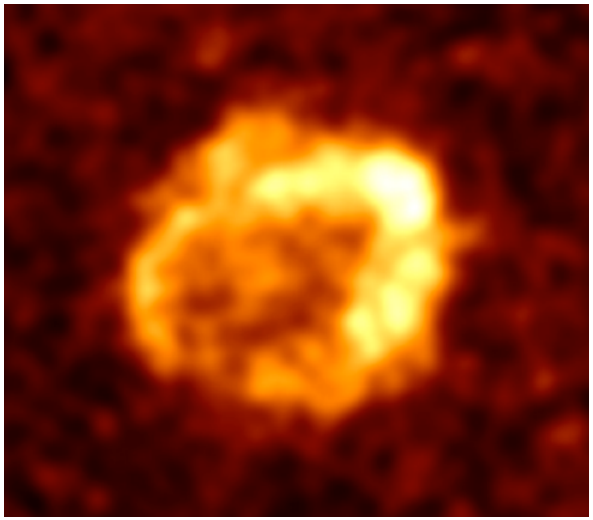
Ideal laboratory for particles propagation studies (see Abdalla+16)

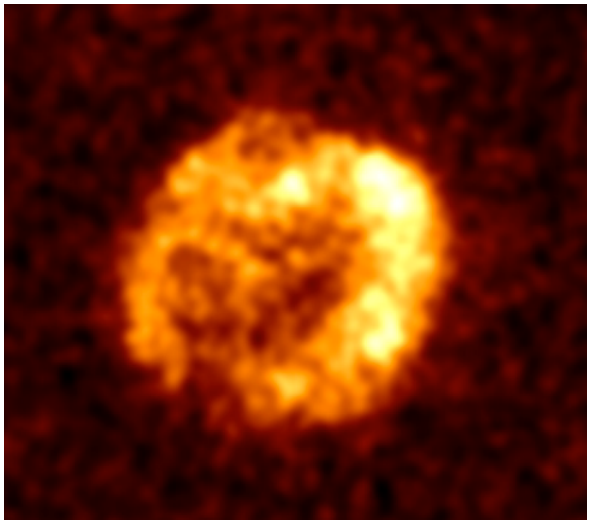


RX J1713.7-3946 over time

Chaves 2016







2004

18 h livetime

E_{min} = 1 TeV

γ-ray excess: 1430

PSF ($R_{68\%}$) = 4.8'

2006

63 h livetime

E_{min} = 0.3 TeV

γ-ray excess: 6700

PSF ($R_{68\%}$) = 3.6'

2016

164 h livetime

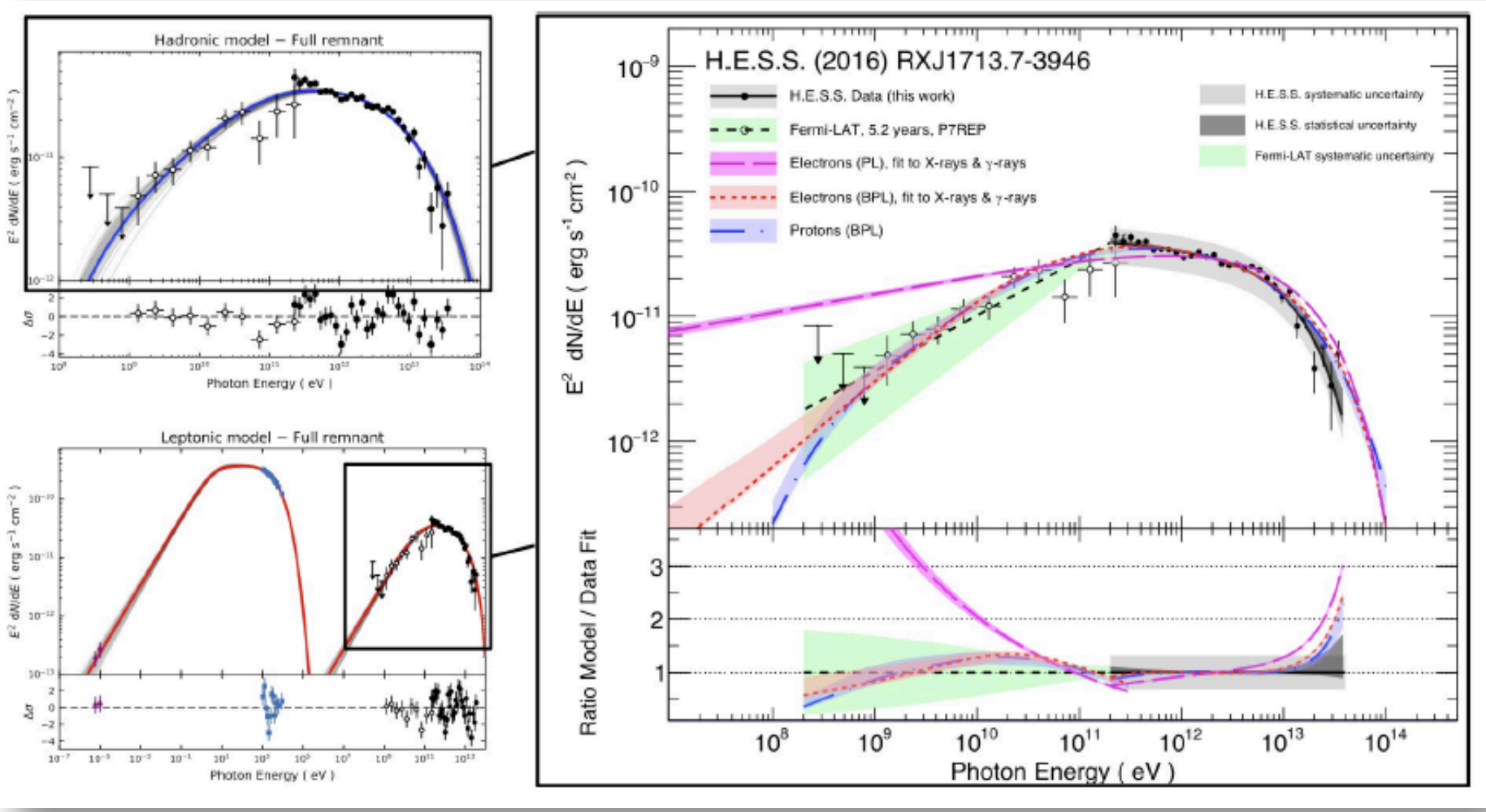
E_{min} = 0.25 TeV

γ-ray excess: 31000

PSF ($R_{68\%}$) = 2.9'

Better err_{sys} control

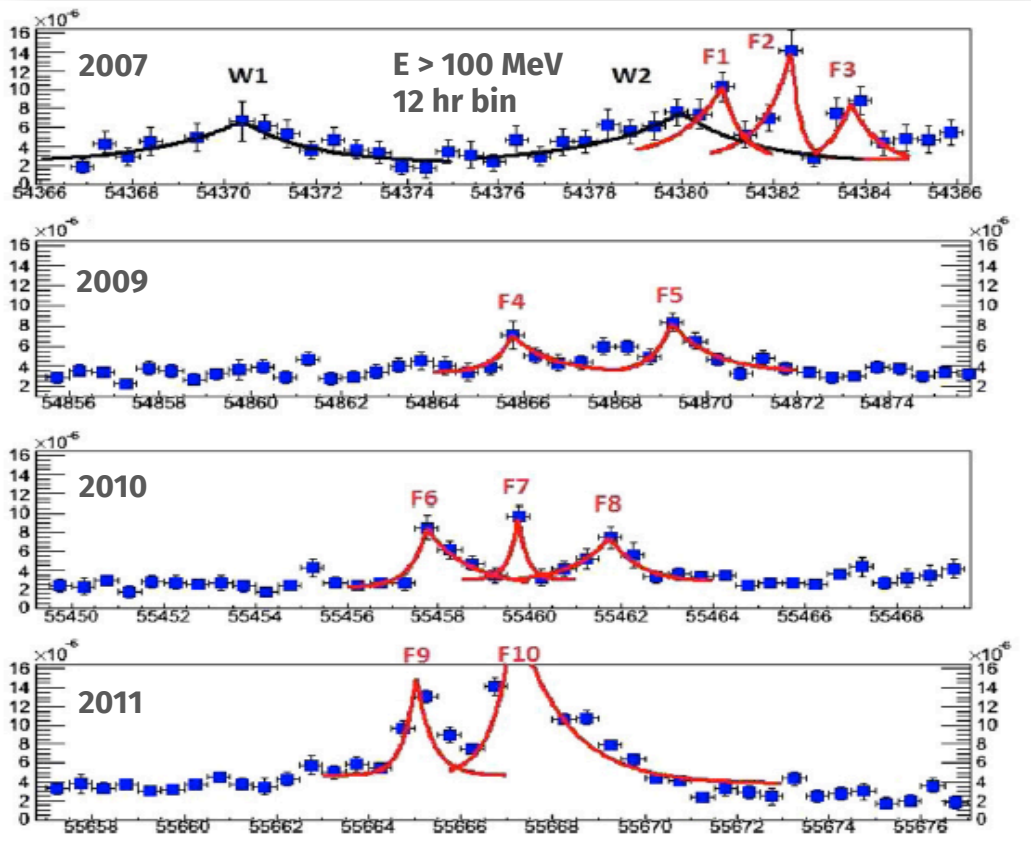
RX J1713.7-3946 SED



Abdalla+16

Neither of the two scenarios (leptonic or hadronic), or a mix of both, can currently be concluded to explain the data unambiguously.

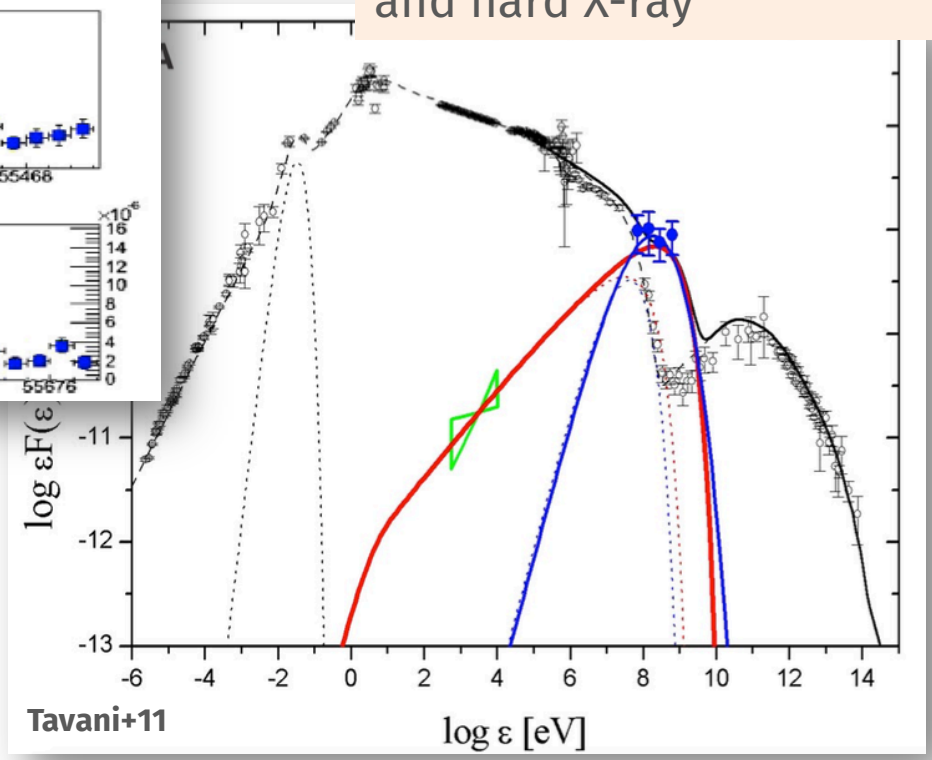
PWN – the “violently quiet” Crab



Striani+13

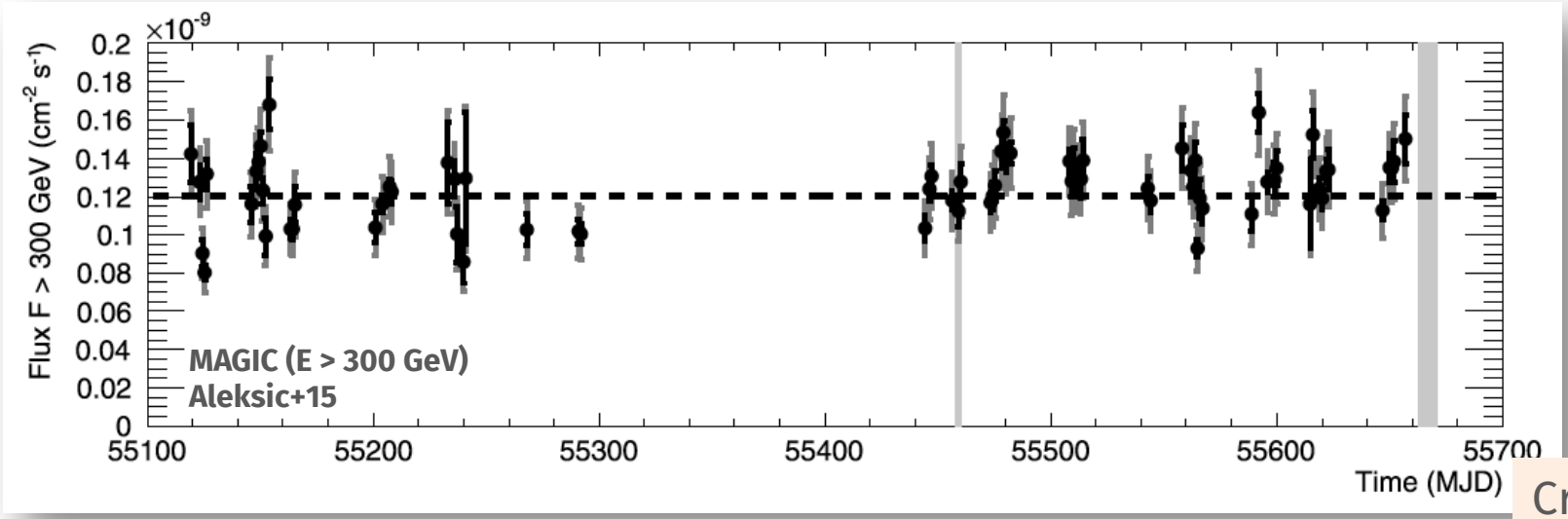
Crab is highly variable (a factor of 5-10) in the AGILE and *Fermi*-LAT energy band.

No variability in the soft and hard X-ray

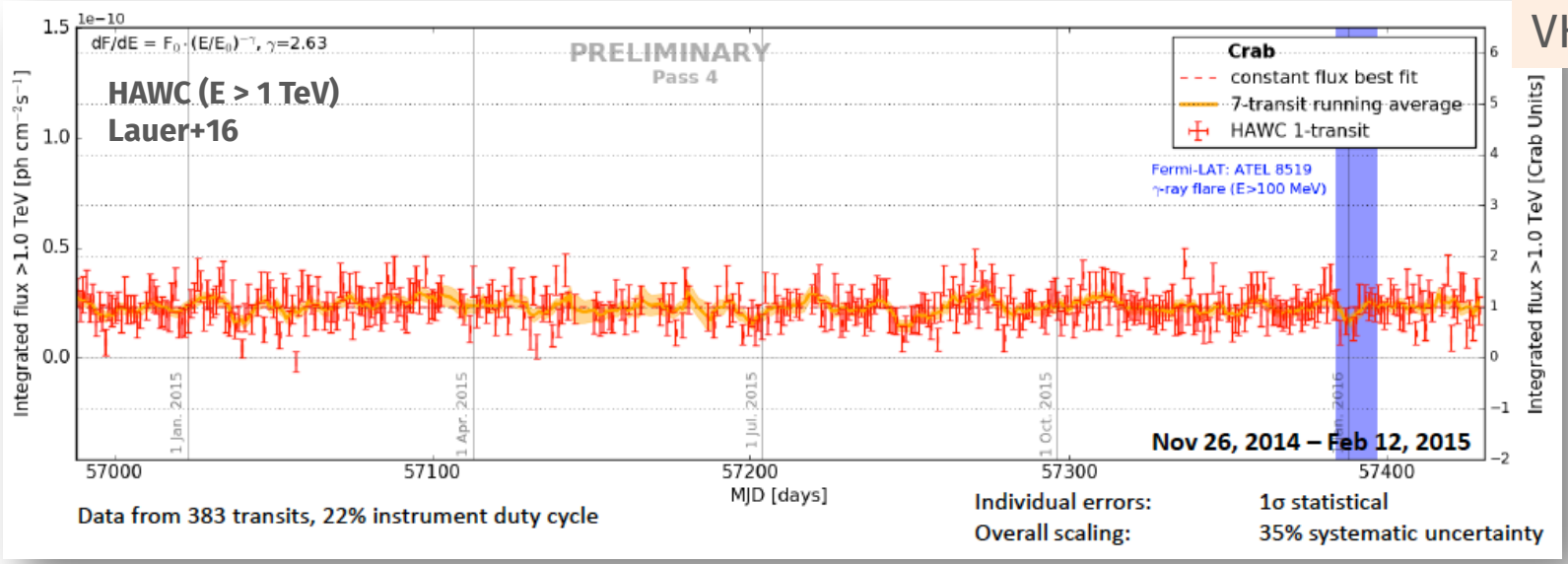


Tavani+11

PWN – the “violently quiet” Crab



Crab is stable at VHE !



The extra-galactic realm

The extra-galactic realm

Active Galactic Nuclei

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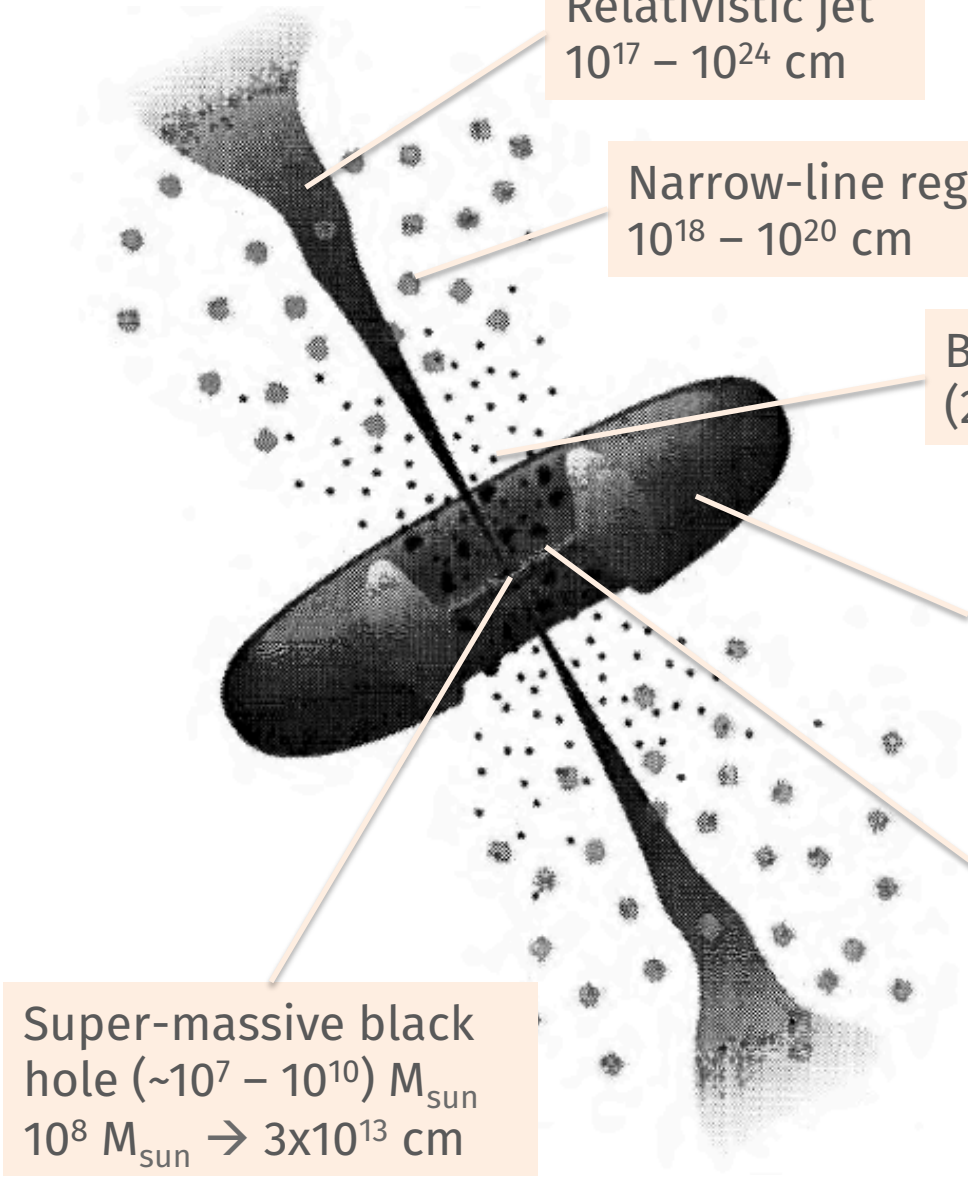
Urry & Padovani 1995



Relativistic jet
10^{17} – 10^{24} cm

Narrow-line region
10^{18} – 10^{20} cm

Broad-line region
(2-20)x10^{16} cm

Thick dusty torus
~10^{17} cm (inner radius)

Optical thick, geometrical thin accretion disk
(1-30)x10^{14} cm

Super-massive black hole (~10^{7} – 10^{10}) M_{sun}
10^{8} M_{sun} → 3x10^{13} cm

A (over)-simplified and classical view

HE/VHE AGNs

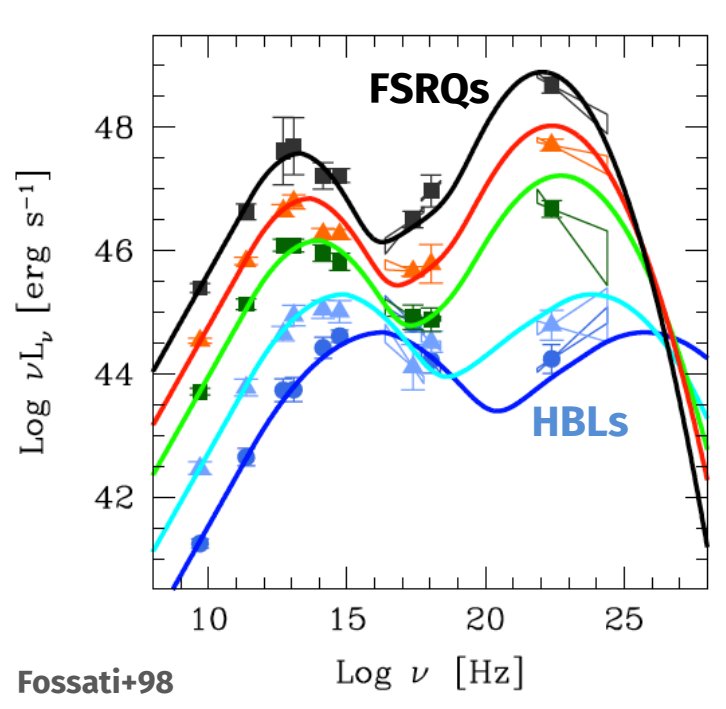
Flat-spectrum radio quasars

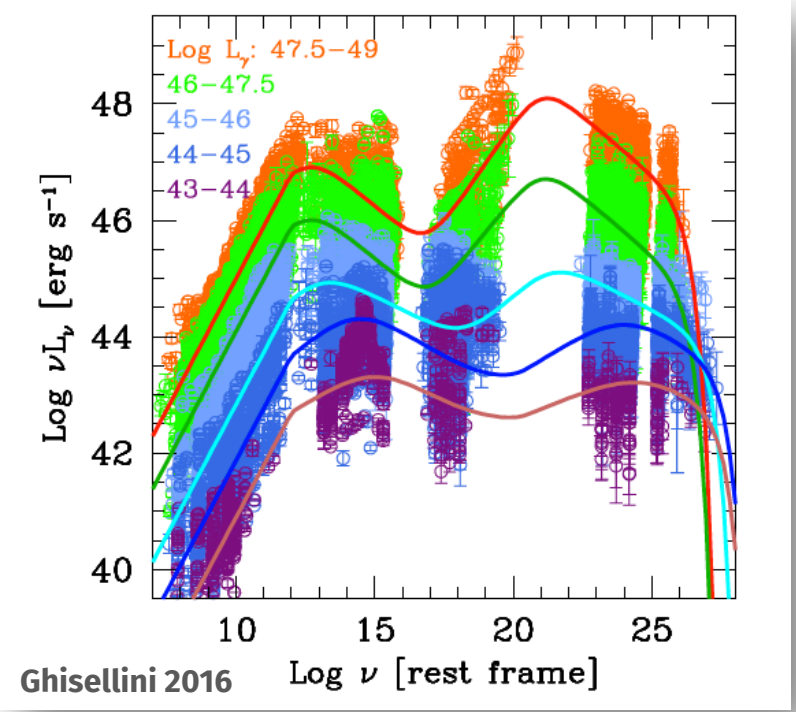
BL Lacs object

Radio Galaxies

Radio-loud narrow-line Seyfert-1 galaxies

Blazars: to sequence or not to sequence?





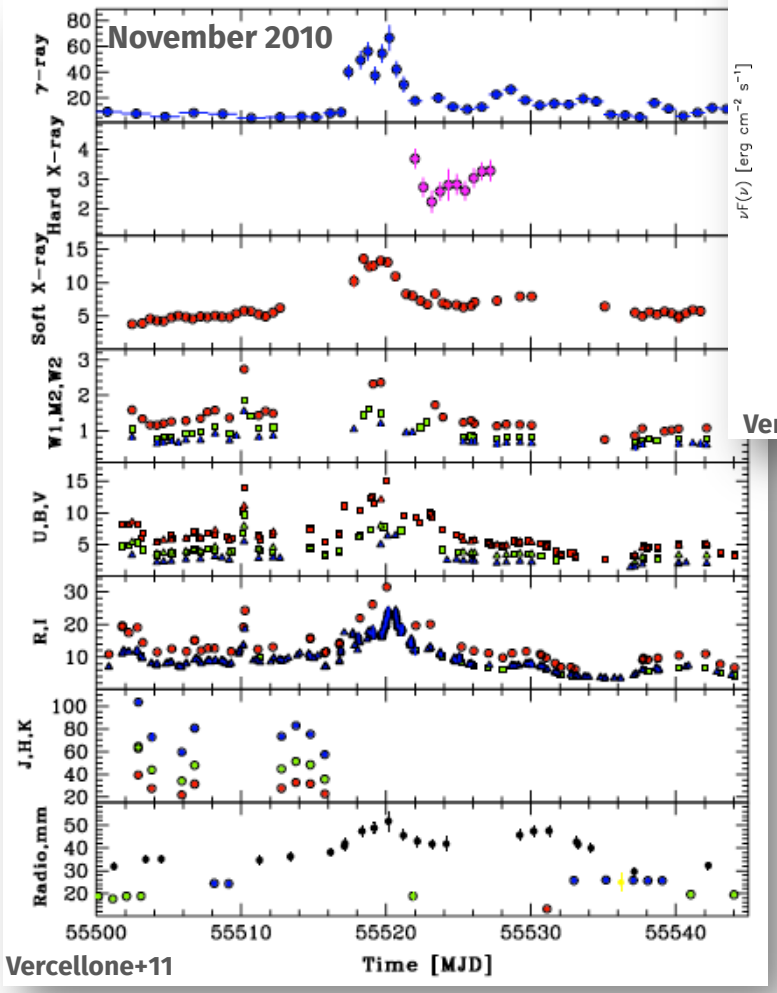
Phenomenological blazar sequence based on the observed bolometric luminosity.

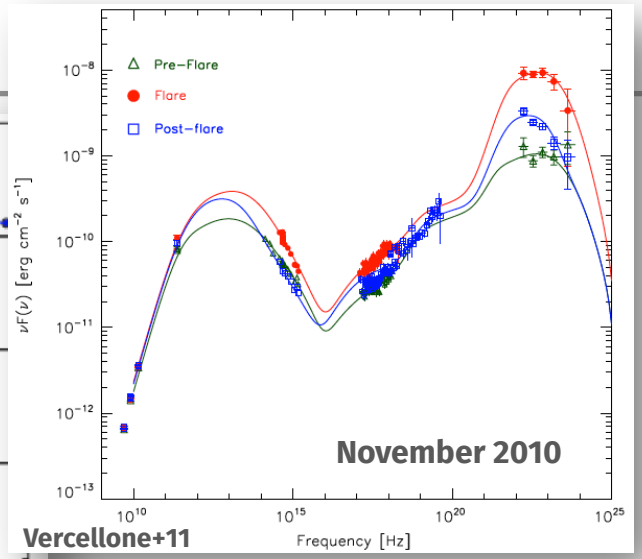
Some controversy (see Giommi +12) on selection bias.

Analytical (power-law segments) phenomenological SED for five luminosity bins.

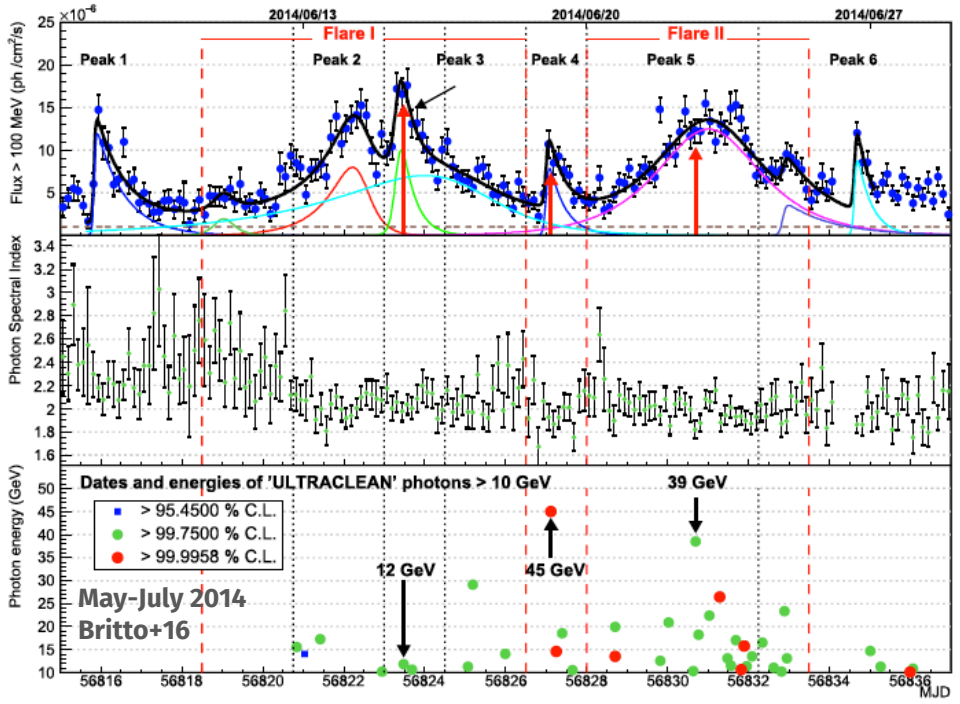
The Sequence holds: the SED becomes redder, and the Compton dominance increases as the total luminosity increases.

FRSQs – 3C454.3



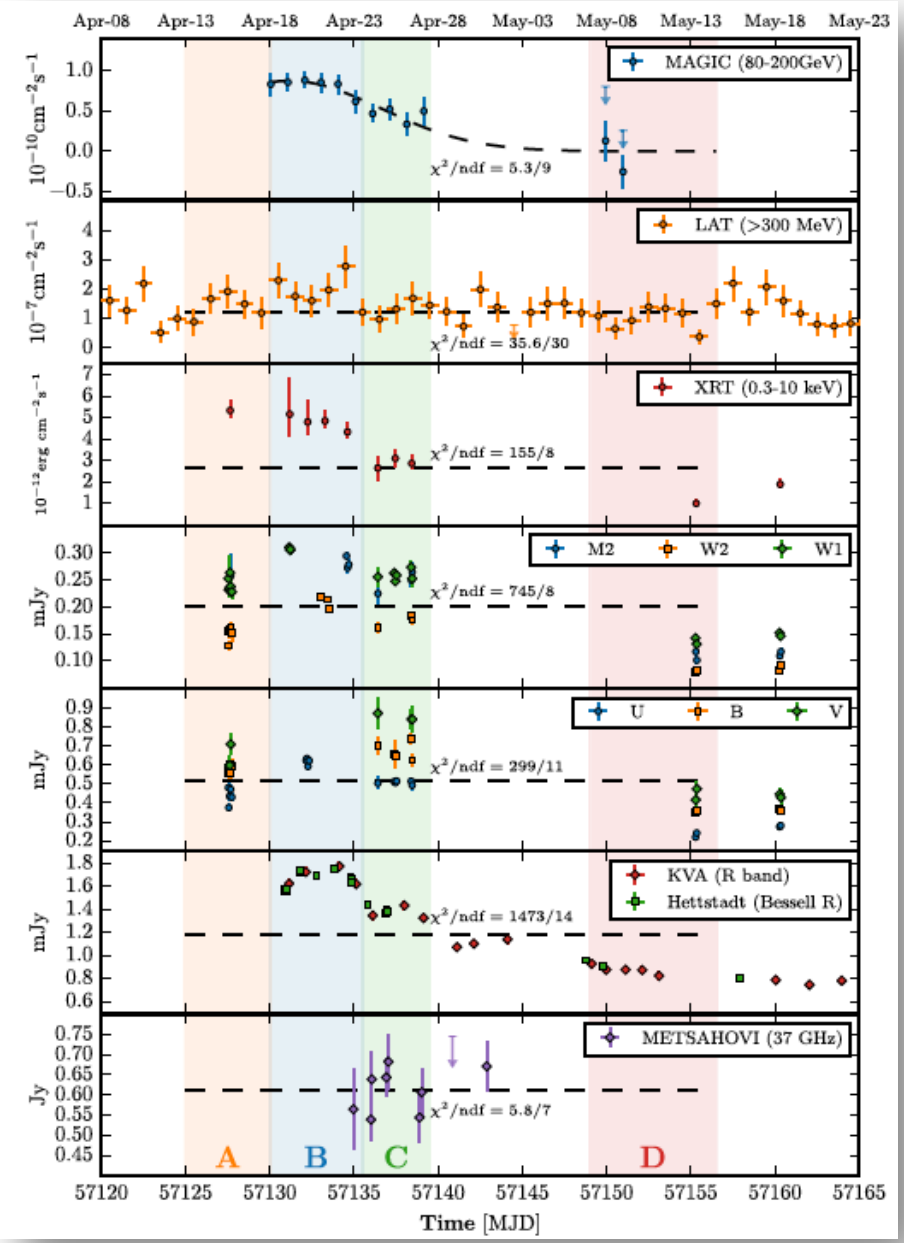


Several photons above 20 GeV (one at 45 GeV on MJD 56827), constraining the γ-ray emission region to be located close to the outer boundary of the BLR, leading to fast flux variability.



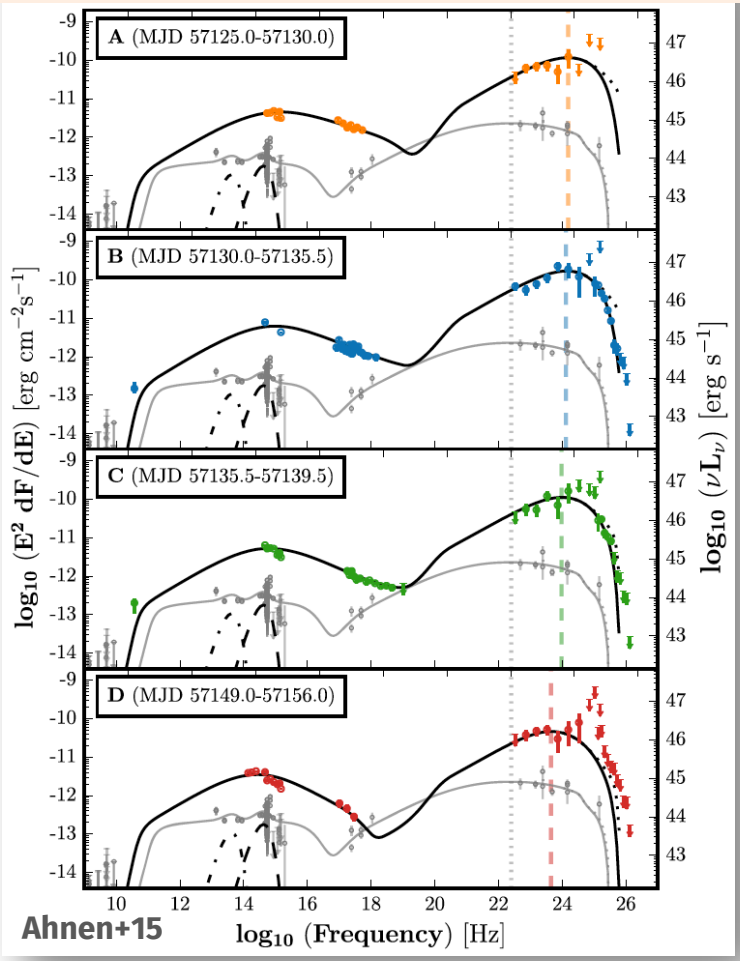
A one zone-leptonic model fit observed AGILE and MWL data (but see Diltz & Boettcher for a lepto-hadronic model of Fermi and MWL data).

FSRQs – PKS 1441+25

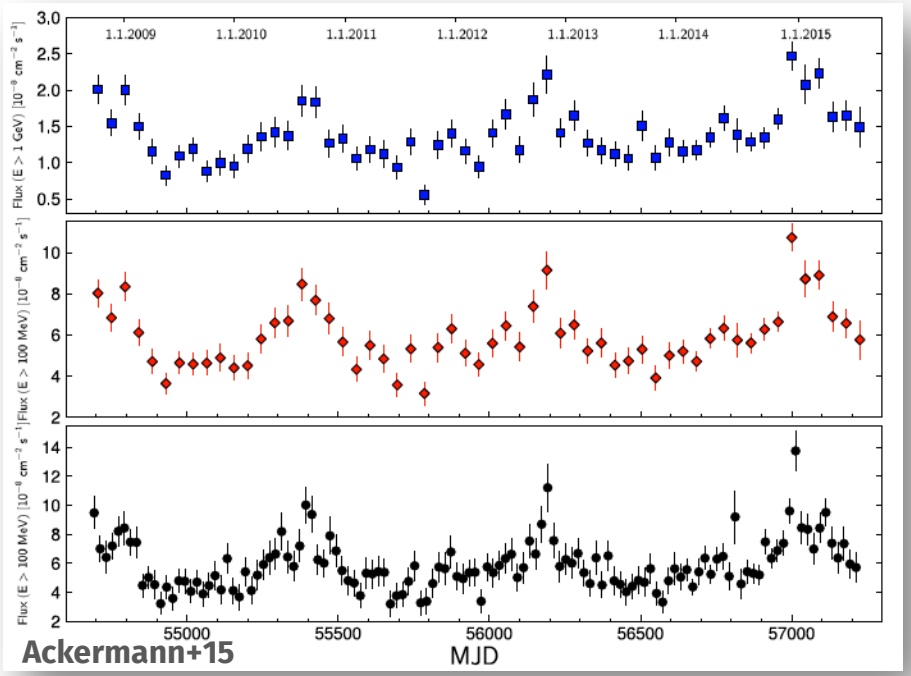


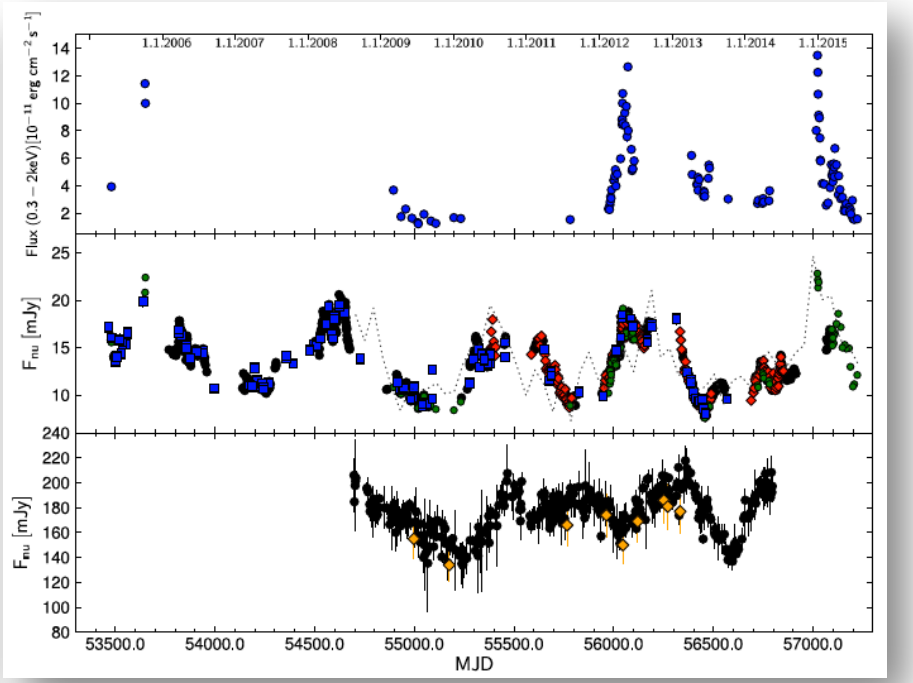
The location of the emitting region:

- in the jet outside the BLR during the period of high activity
- partially within the BLR during the period of low (typical) activity



BL Lacs – PG 1553+113: periodicities



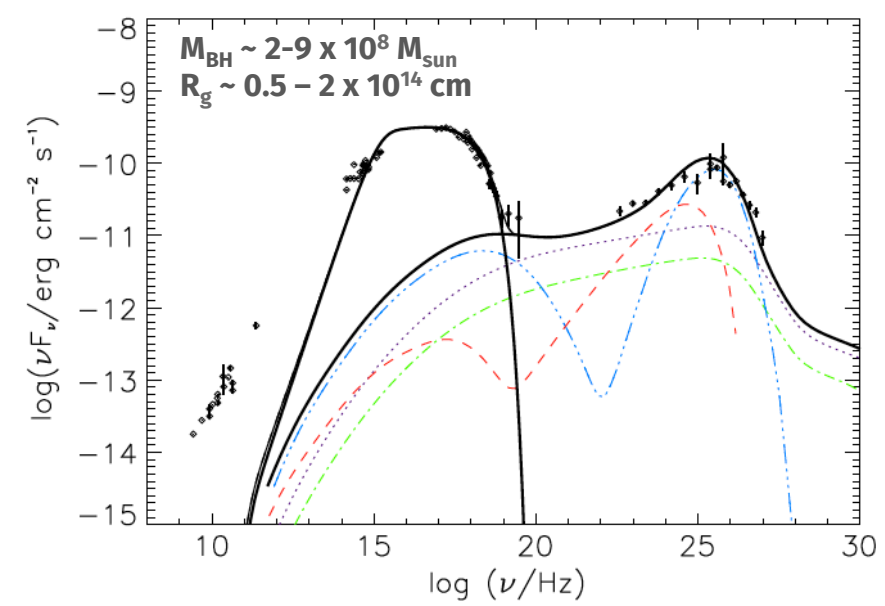


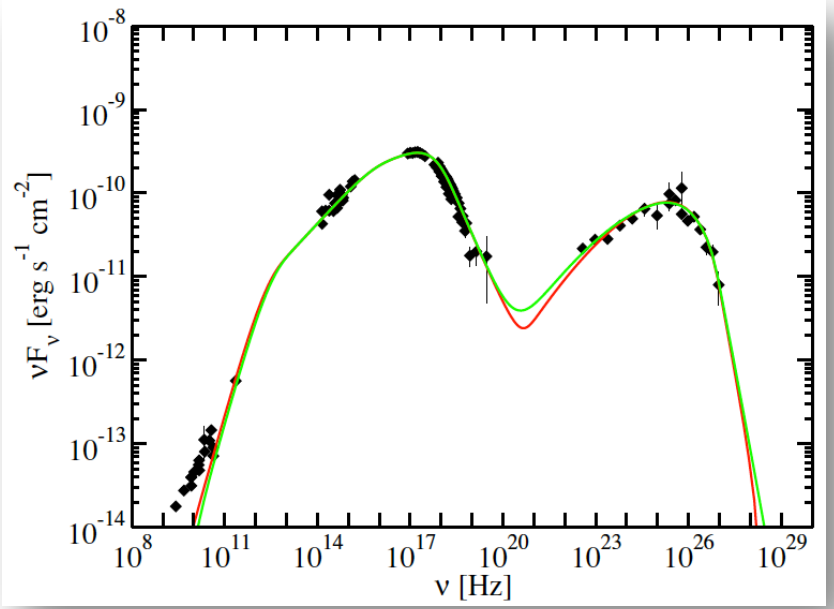
Discovery of a possible ~2 year periodic modulation in PG 1553+113. Possible explanations

- Pulsational accretion flow instabilities, approximating periodic behavior;
- geometrical models (jet precession/rotation, an helical structure);
- a mechanism analogous to low-frequency QPO from Galactic high-mass binaries/microquasars;
- the presence of a gravitationally bound binary SMBH system.

BL Lacs – Mrk 421

A look at the quiescent spectral energy distribution (SED) for this source





Abdo+11

Hadronic

- Size of the emitting region of a few R_g
- Magnetic field B~50 G
- Protons with energies up to $2x10^{18}$ eV

Leptonic

- Size of the emitting region of ~10^4 R_g
- Magnetic field B~0.05 G
- Electrons with energies up to $5x10^{13}$ eV

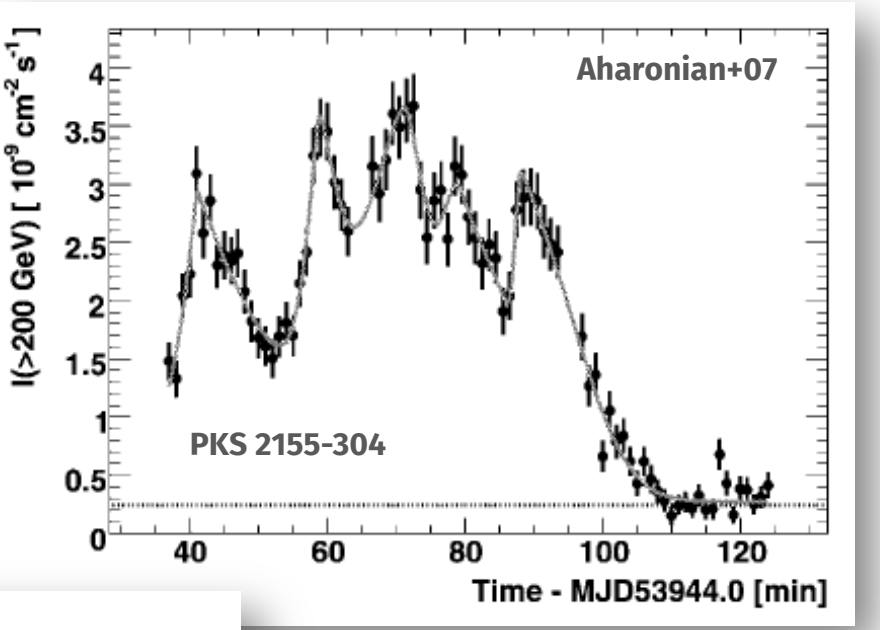
Blazar variability at short-timescales

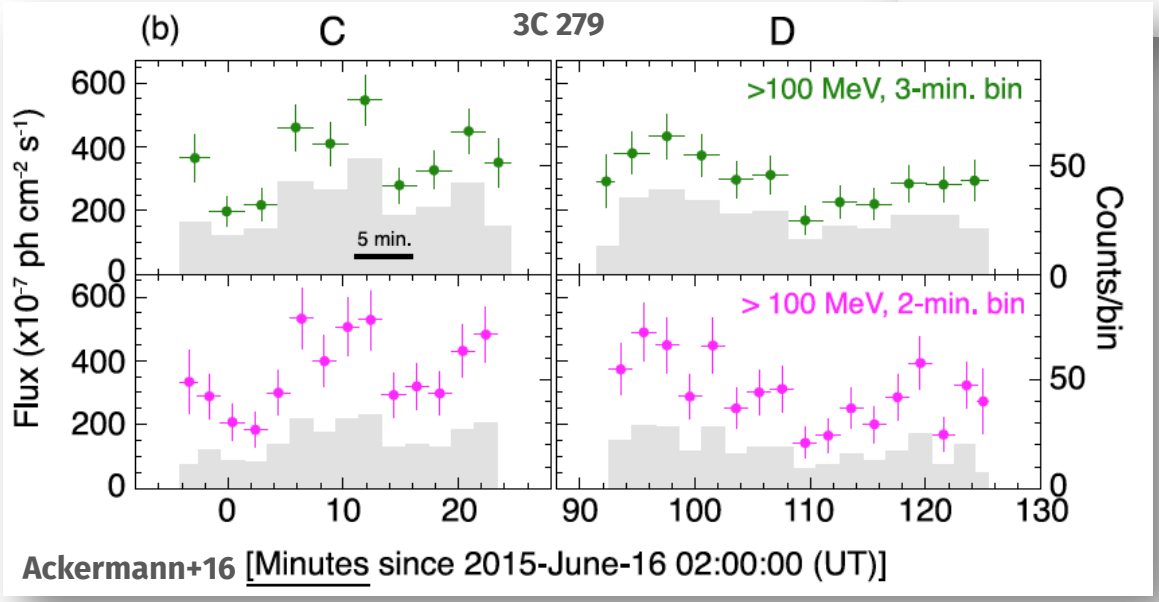
PKS 2155-304

- H.E.S.S. observation with 1 min time-bin
- Outbursts on 200s time-scale are resolved
- Doppler factor ~100 are required to explain this rapid variability

3C 279

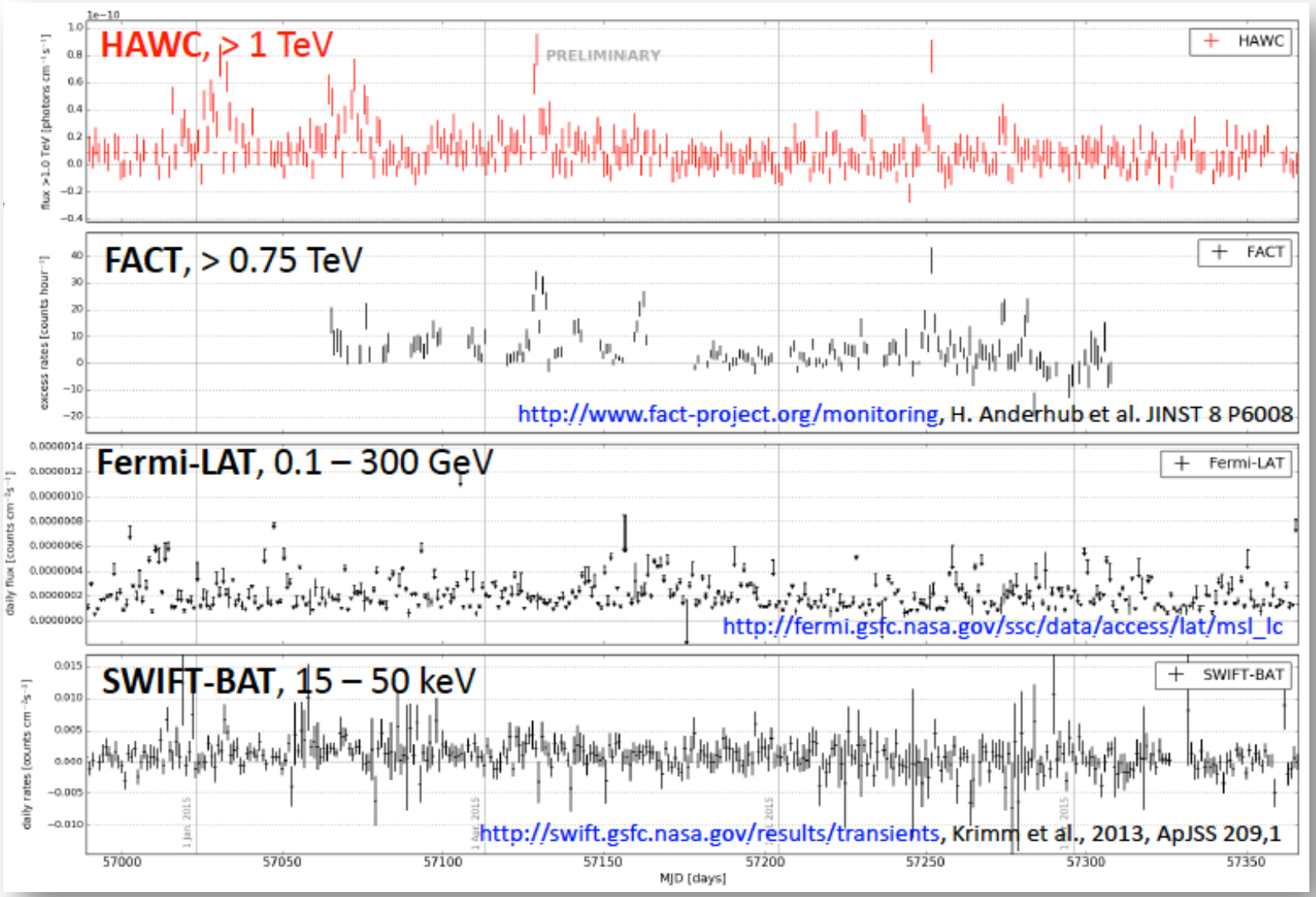
- *Fermi*-LAT observation with variability down to 2 min binned time-scale
- Challenges for current emission models





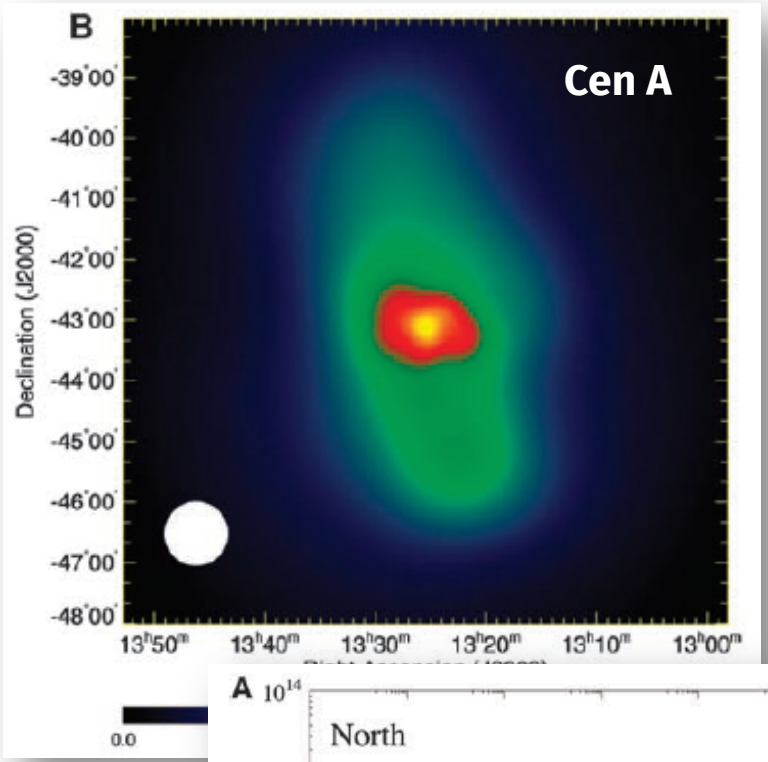
Blazar monitoring

Several facilities are currently performing blazar monitoring at HE/VHE



Lauer+16

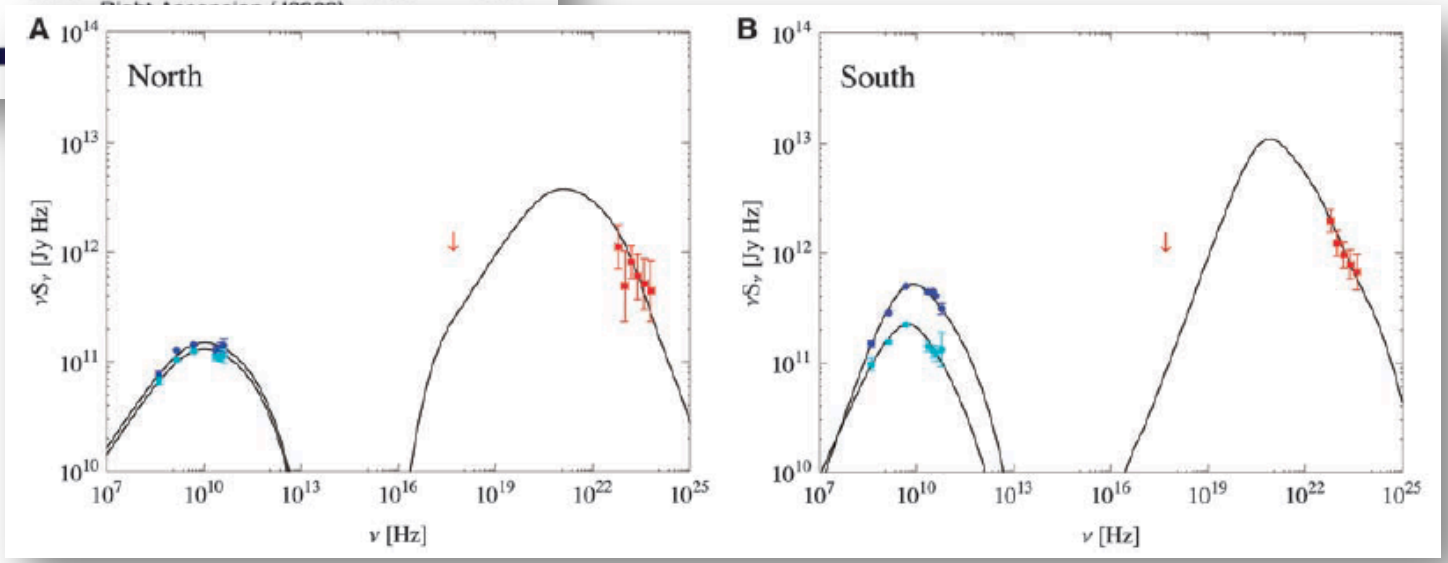
Radio Galaxies – Centaurus A



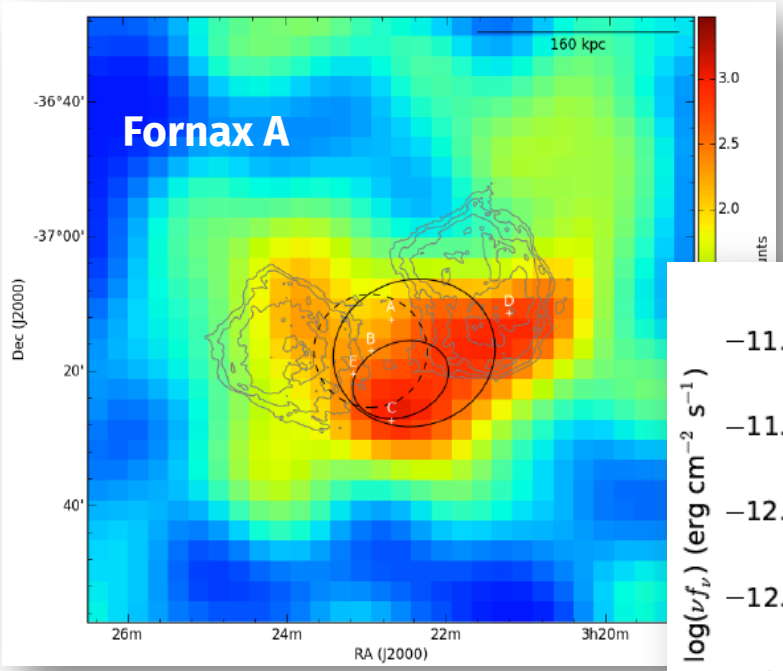
Abdo+10

The lobe flux constitutes a considerable portion (greater than one-half) of the total source emission.

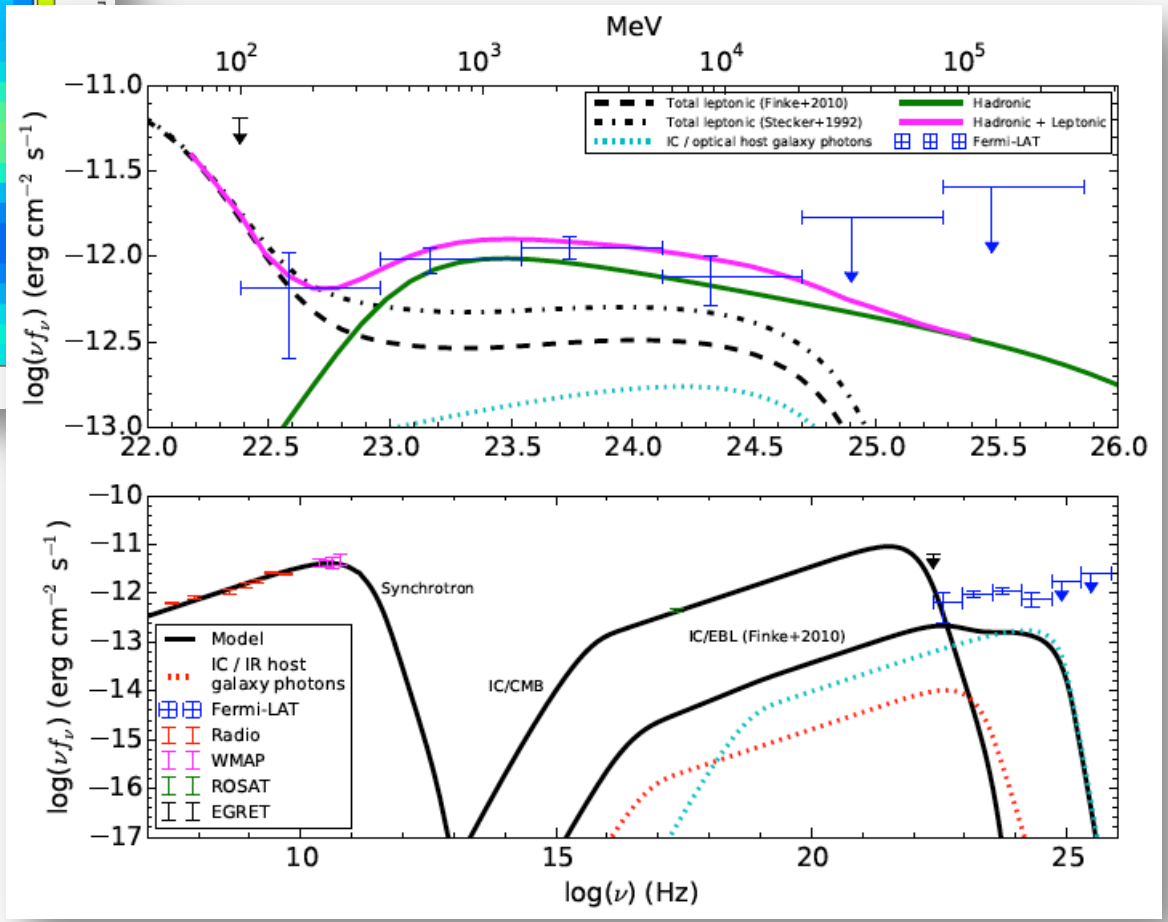
The γ-ray emission from the lobes is interpreted as inverse Compton–scattered relic radiation from the cosmic microwave background, with additional contribution at higher energies from the infrared-to-optical extragalactic background light.



Radio Galaxies – Fornax A



Ackermann+16



No variability.

Lobes origin for γ-rays.

Leptonic emission does not model data, proton-proton collisions of CR with thermal plasma in the radio lobe might be required.

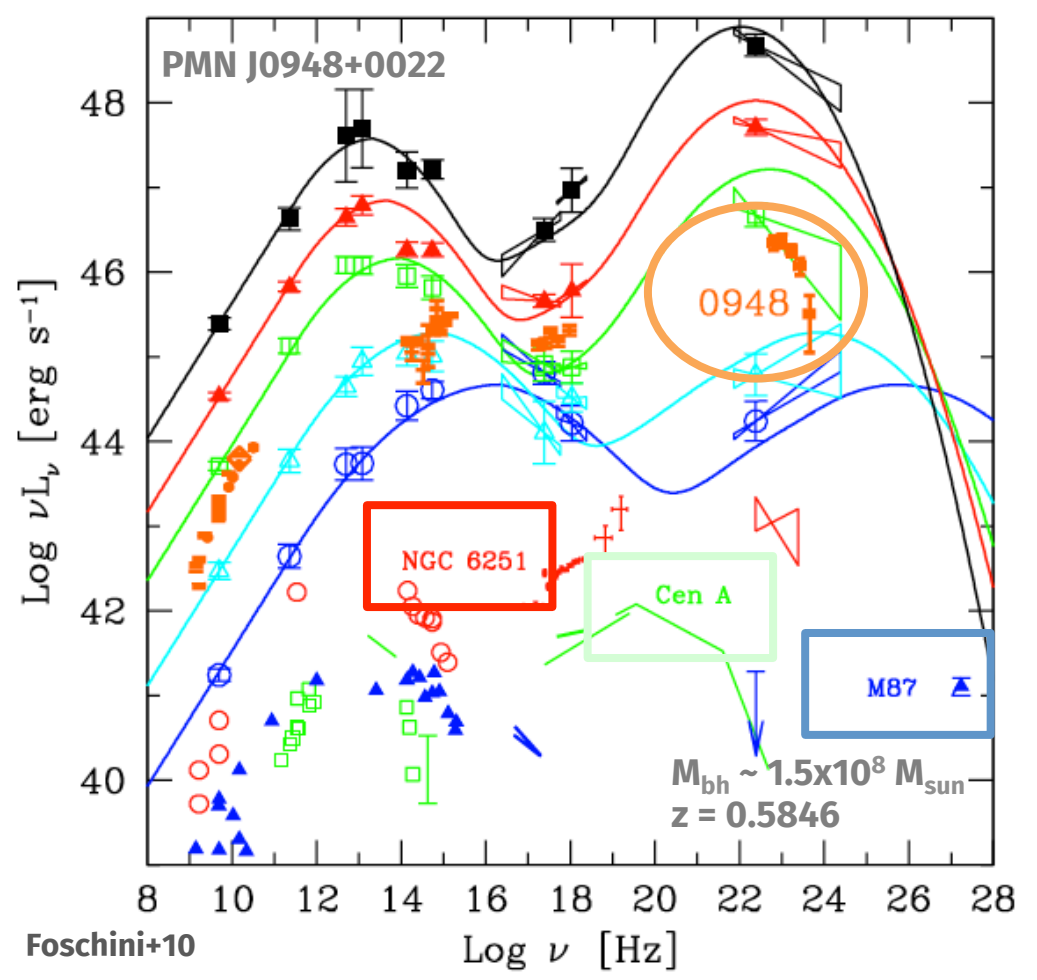
Radio-loud narrow-line Seyfert-1 galaxies

Foschini+08,09 identified a small sample of radio-loud NLS1 galaxies with FSRQ-like properties (flat-spectrum radio nuclei, variability).

The SED of PMN J0948+0022 compared with the blazar sequence (continuous lines of different colors) and a few of the most powerful radiogalaxies (Cen A, M 87, NGC 6251).

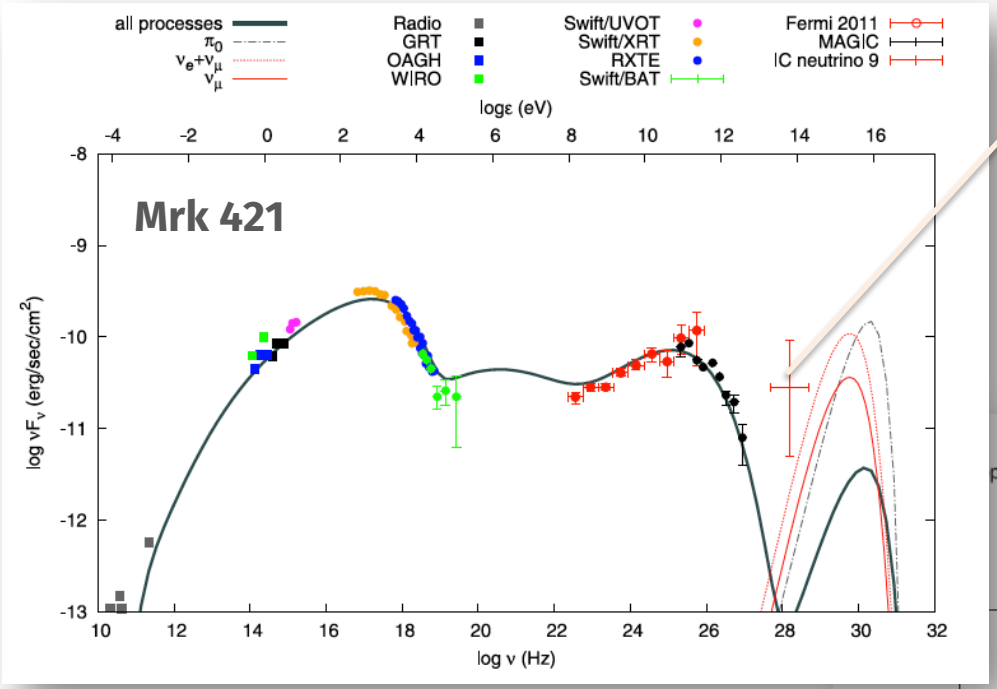
PMN J0948+0022 is in the blazars region, with the observed emitted power well above the traditional radio galaxies region.

About ten of confirmed objects → a new class of γ-ray AGNs



Perspectives

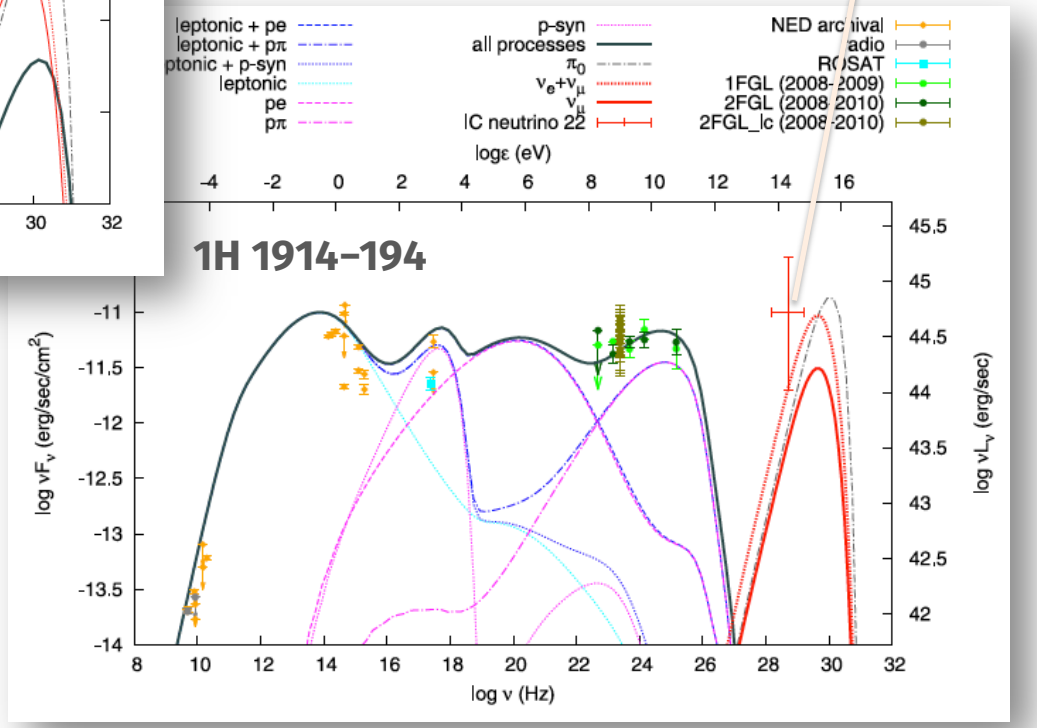
HBL and extreme HBLs



IceCube event ID 9

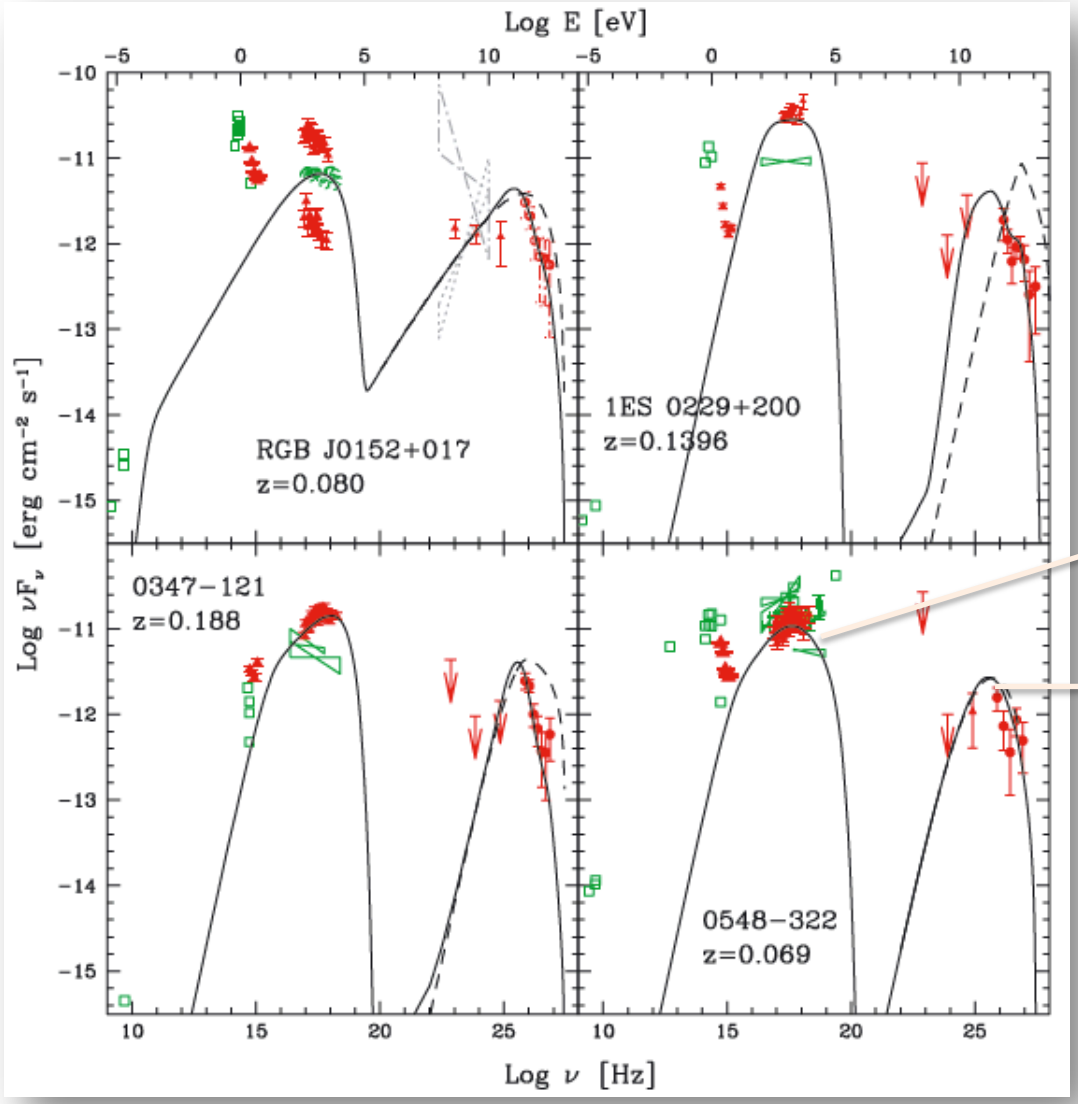
IceCube event ID 22

Petropoulou+15



BL Lacs are possible candidates (but <15-20% see e.g. Padovani+15)

HBL and extreme HBLs

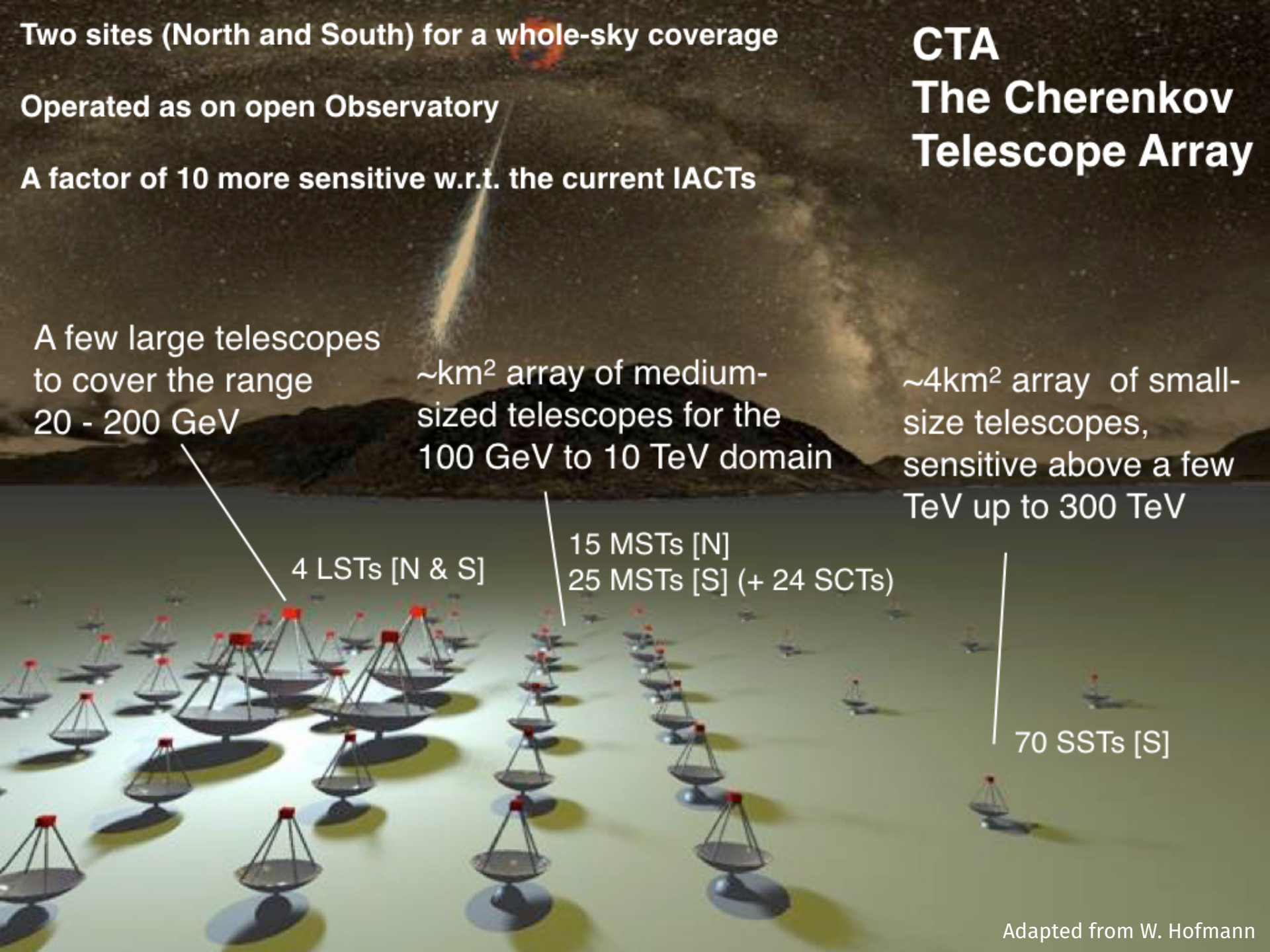


Tavecchio+11
Bonnoli+15

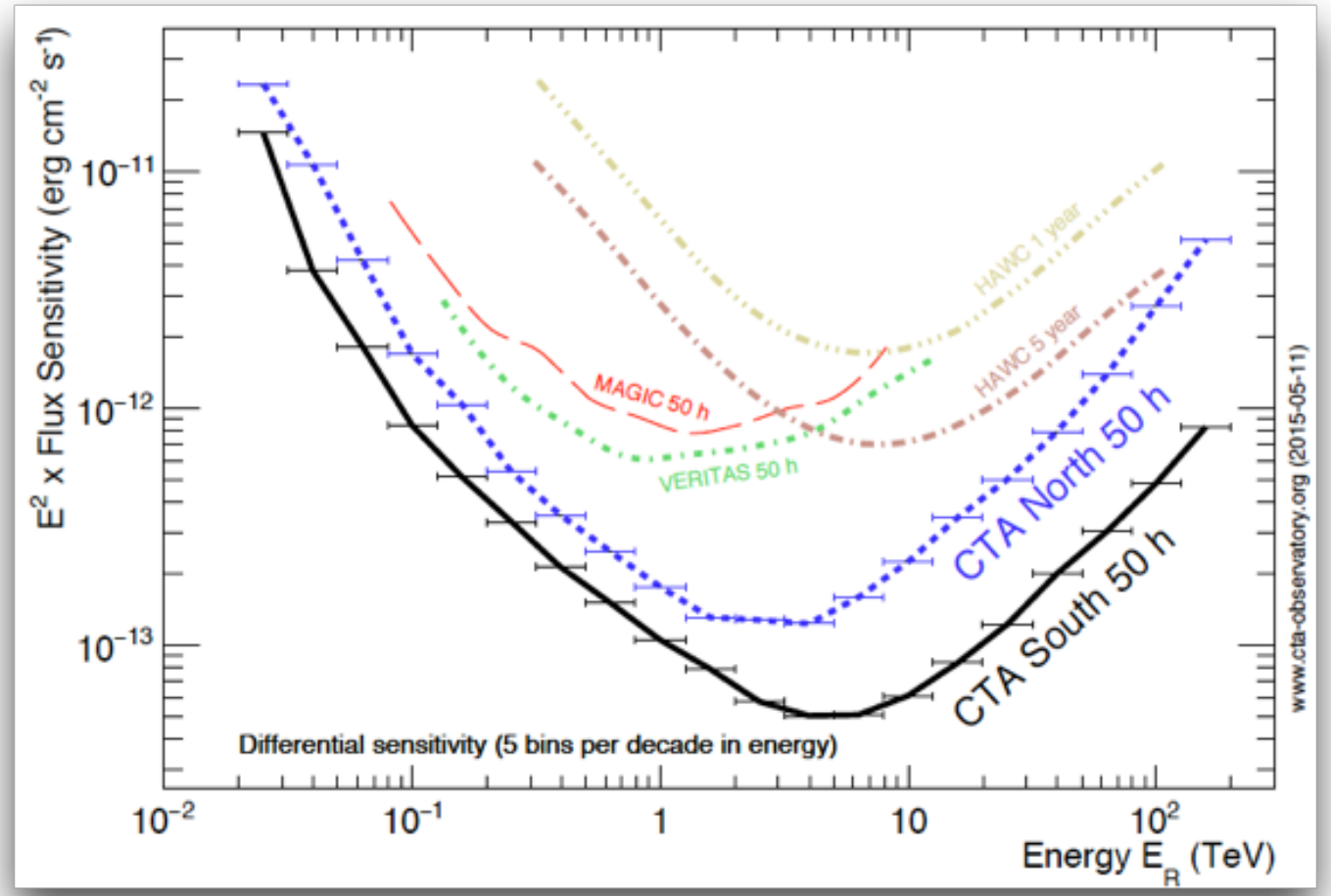
Extreme HBLs

ν_p^{syn} ~ keV

ν_p^{IC} ~ TeV


Two sites (North and South) for a whole-sky coverage
Operated as on open Observatory
A factor of 10 more sensitive w.r.t. the current IACTs
CTA
The Cherenkov
Telescope Array
A few large telescopes
to cover the range
20 - 200 GeV
~km² array of medium-
sized telescopes for the
100 GeV to 10 TeV domain
~4km² array of small-
size telescopes,
sensitive above a few
TeV up to 300 TeV
4 LSTs [N & S]
15 MSTs [N]
25 MSTs [S] (+ 24 SCTs)
70 SSTs [S]
Adapted from W. Hofmann

CTA performance



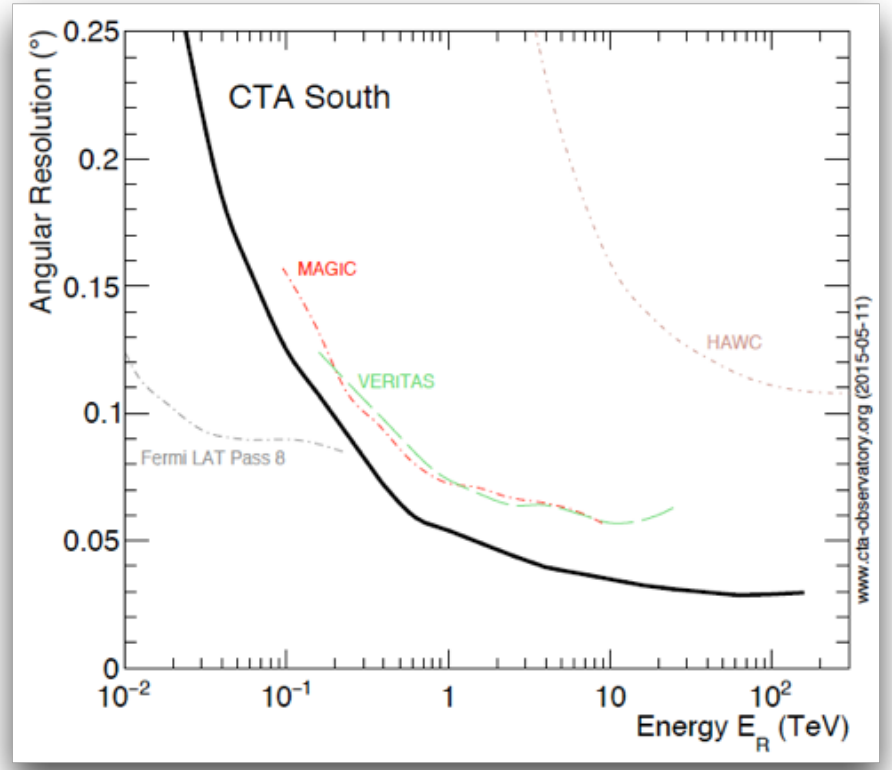
Credits: The CTA Consortium

A factor of **5-10 improvement** in sensitivity in the domain of **about 100 GeV to some 10 TeV.**

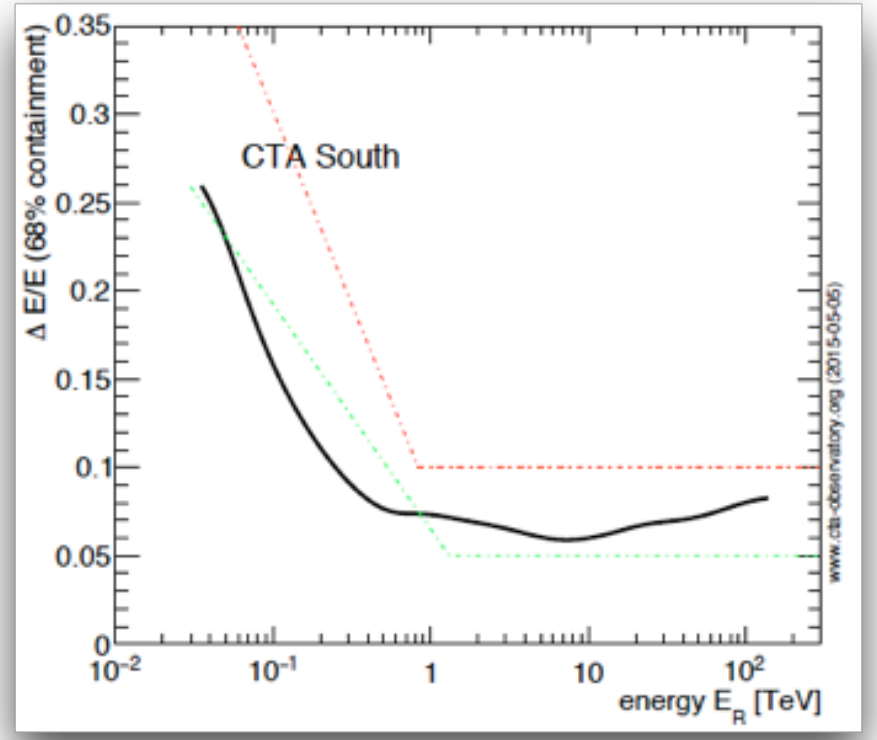
Extension of the accessible energy range from **well below 100 GeV to above 100 TeV.**

CTA performance

Angular Resolution



Energy Resolution



Credits: The CTA Consortium

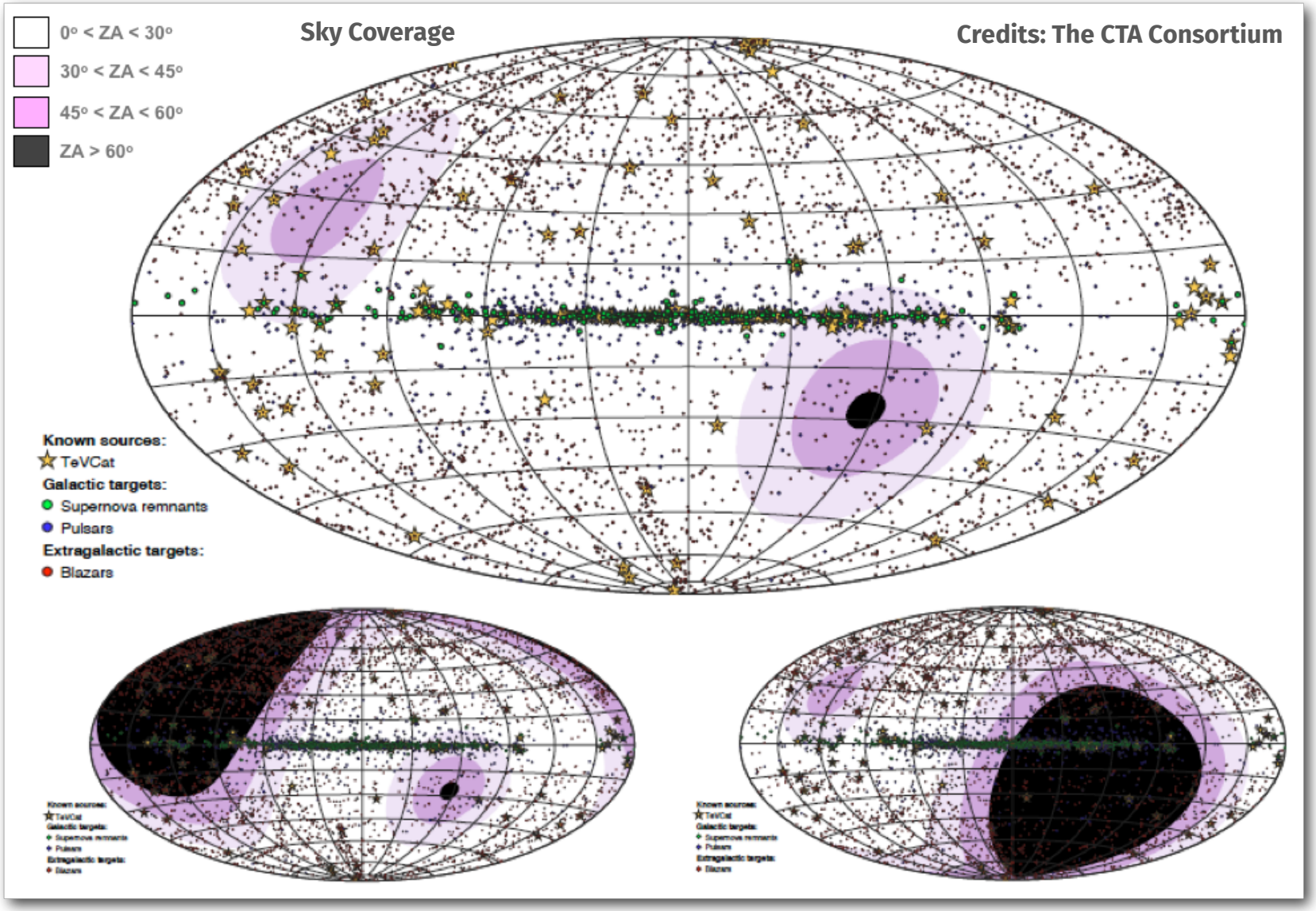
Further optimization of event selection can improve the angular resolution

You can download the Instrument response functions at the following URL:
https://portal.cta-observatory.org/Pages/CTA-Performance.aspx

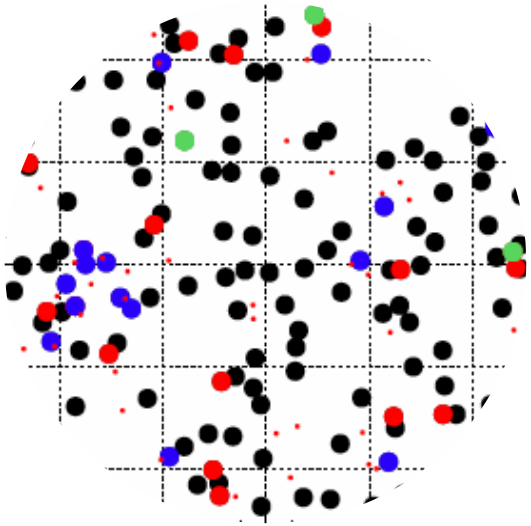
CTA Key Science Projects

1. Dark Matter Programme
2. Galactic Centre Survey
3. Galactic Plane Survey
4. Large Magellanic Cloud Survey
5. Extragalactic Survey
6. Transients
7. Cosmic-ray PeVatrons
8. Star-forming Systems
9. Active Galactic Nuclei
10. Cluster of Galaxies
11. Non-Gamma-ray Science

CTA as an *all-sky* Observatory



CTA extra-galactic survey



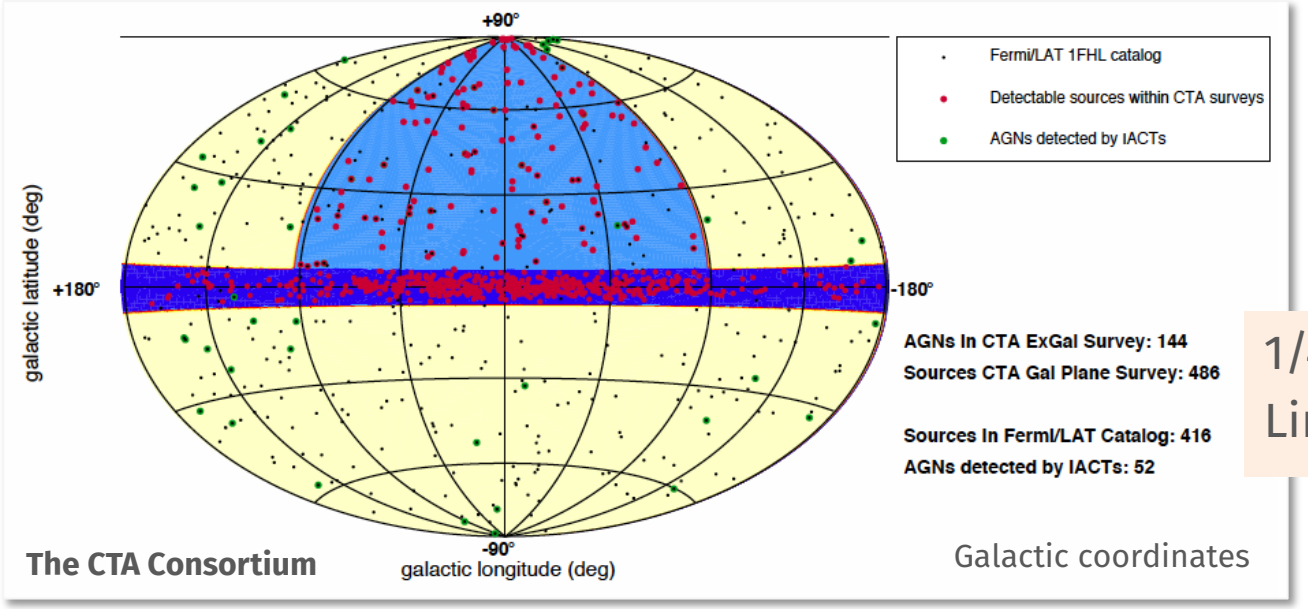
Credits: The CTA Consortium

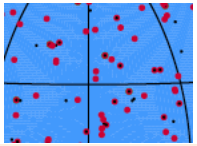
The aim is to perform a blind survey of 25% of the sky, and to construct an unbiased VHE extragalactic source catalogue with an integral sensitivity limit of ~5 mCrab.

CTA will combine the **deep MSTs sensitivity** for E > 100 GeV and the **wide SSTs field of view** (>9^{o}).

We expect the **discovery of extreme BL Lac objects peaking in the 0.1 – 1 TeV region**, thanks to the good spectral coverage provided by MSTs and SSTs in the 0.1 – 10 TeV energy range.

CTA extra-galactic survey





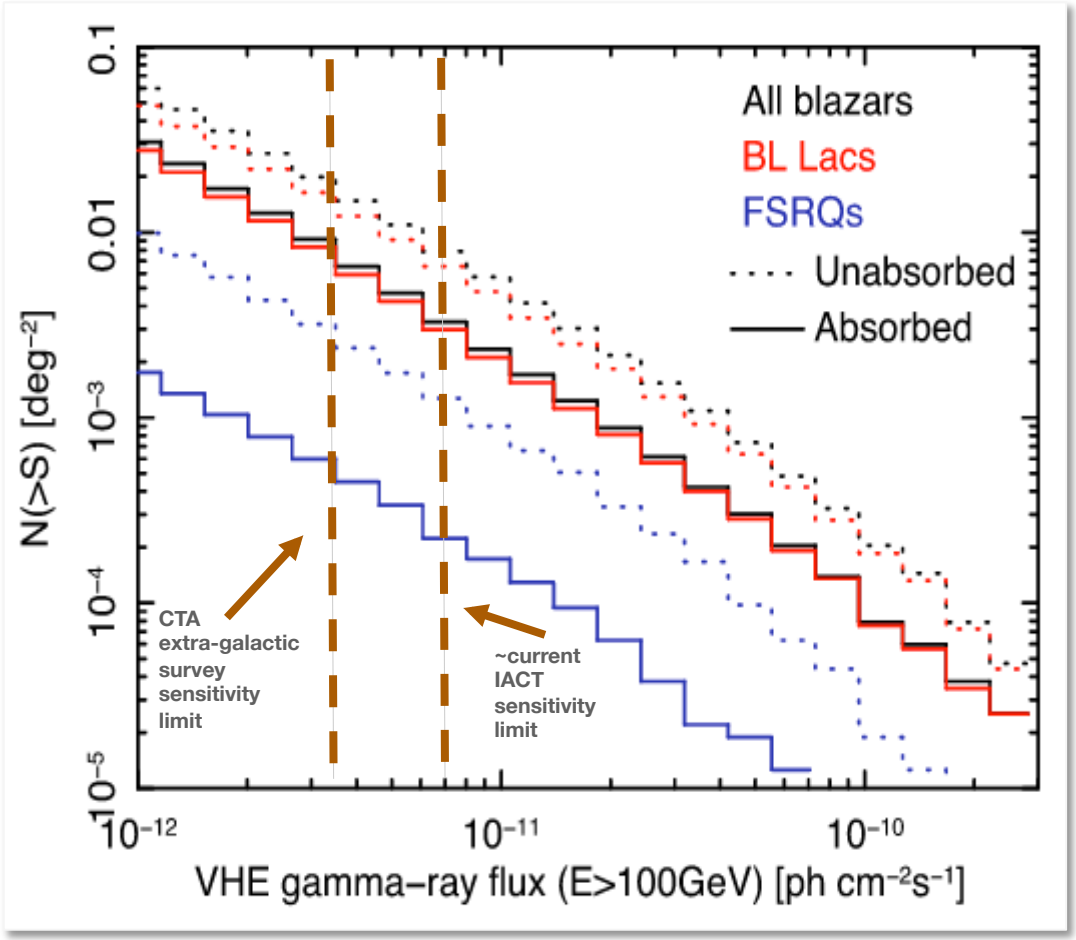
1/4 of the sky (~10^4 deg^2)
Limiting flux ~ 5 mCrab

The survey would connect with the Galactic Plane Survey ($|b| < 5^o$) over Galactic longitude $-90^o < l < 90^o$.

Several highly interesting regions such as the Virgo & Coma clusters, the Fermi Bubbles (North) and Cen A (South) will be covered by the proposed survey.
The EGAL survey will be useful to investigate dark matter sub-halos.

Current simulations suggest that a wide-field, shallow survey should detect more sources than a narrow-field, deep survey (given an equal survey time).

CTA extra-galactic survey



Padovani & Giommi 2015

Padovani & Giommi (2015) derived the expected number of blazars on the sky in the GeV–TeV domain.

With the 5 mCrab sensitivity during the proposed survey**, CTA should detect around 100 sources in 10,000 deg^2.**

Final remarks

High- and very high-energy astrophysics is a rapidly evolving field.

Number of detected HE/VHE sources is steadily increasing.

Multi-messengers astrophysics (neutrino/ gravitational waves) is the current frontier.