The challenge of studying blazars: the crucial role of gamma-ray astronomy

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Outline

1- Introduction: the challenge of studying blazars

2- Population studies

→ Blazars detected at very high energy gamma-rays

3- Long-term studies on selected blazars

→ Extensive MW campaigns on Mrk421 and Mrk501

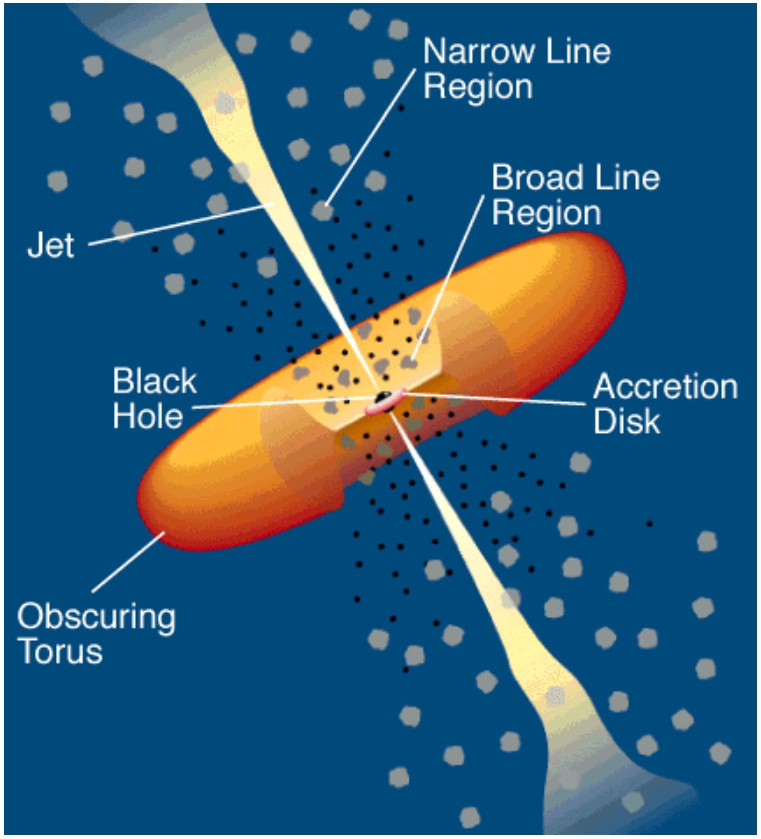
4 - Conclusions

1- Introduction: the challenge of studying blazars

Active Galactic Nuclei (AGNs)

Pictorial description of an AGN

Image Credit: C.M.Urry & P. Padovani



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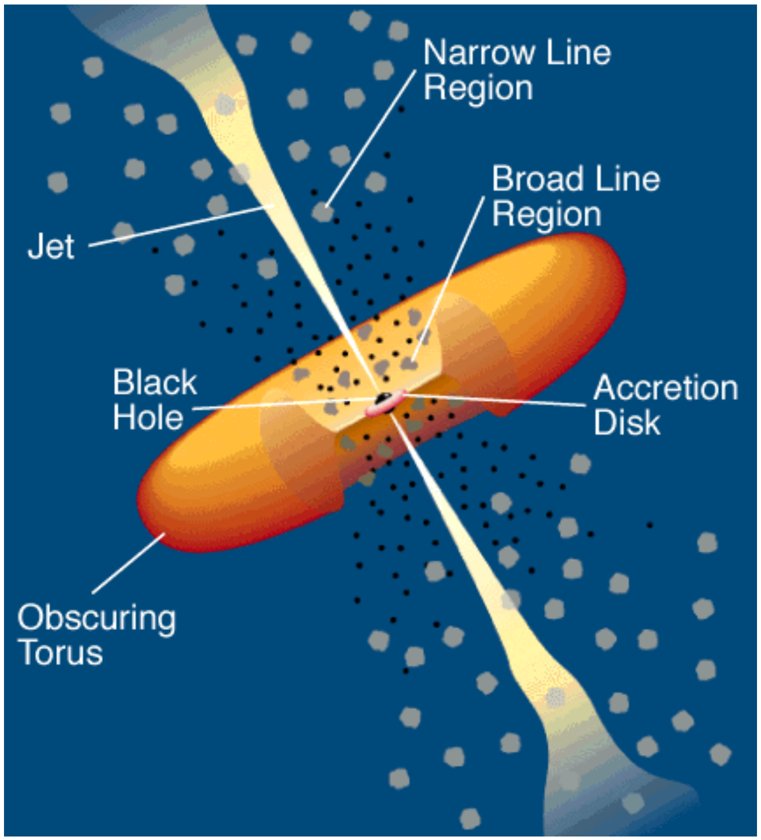
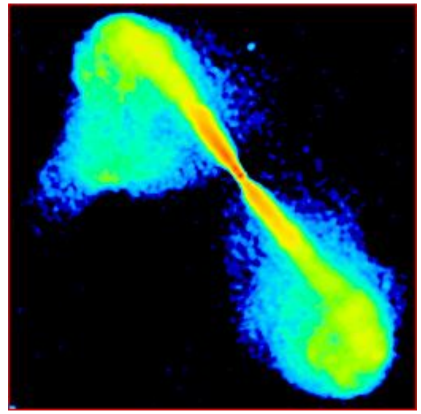




Jets are extremely well collimated streams of plasma emanating from the centers of active galactic nuclei (AGNs), and propagating with relativistic bulk velocities up to kpc/Mpc distances.

Extragalactic jets are **the largest structures in the Universe**, reaching even Mpc scales. They are everywhere **up to the highest redshifts**.

Jets are produced by rapidly rotating supermassive (~ 10^6-10^9 $M_\odot$) black holes surrounded by magnetized accretion disks. Thus, jets **are direct probes of black hole physics.**

Jets are **extremely efficient accelerators of particles** to ultrarelativistic energies. They are known to produce electrons with 10^{14} eV energies, and are claimed to accelerate protons up to the highest observed energies $\geq 10^{20}$ eV .

Active Galactic Nuclei (AGNs)

Why do we need to study AGNs (→ Jets) ??

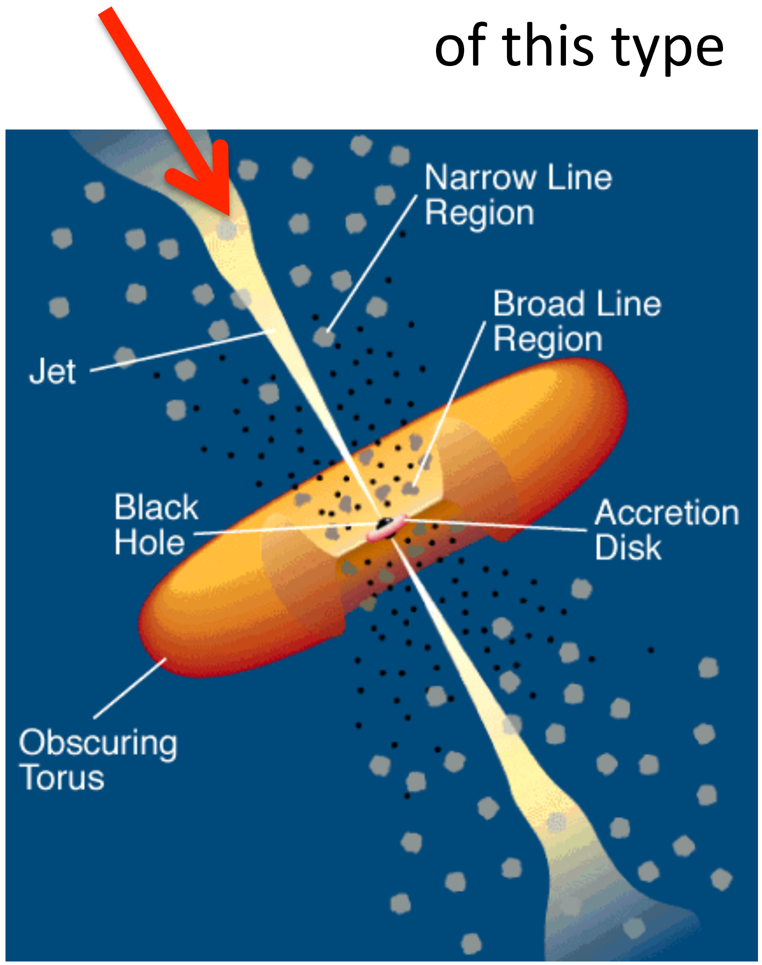
Although widely studied during the last half century at different frequencies (from low-frequency radio up to very high γ-ray photon energies) they are still superficially understood objects.

Many key questions regarding extragalactic jets remain open:

- Jet composition *(B and ultrarelativistic e-e+; something else?)*
- Jet magnetic field *(how strong? what is its structure?)*
- Jet launching *(rotating SMBHs vs accretion disks)*
- Jet evolution and energetics *(kinetic power, lifetimes, „feedback")*
- Particle acceleration *(shocks? turbulence? reconnection?)*
- What produces variability on various timescales (years down to minutes)

Blazars are those radio loud AGNs with the jet pointing towards the Earth

Emission is doppler boosted. Most gamma-ray AGNs are of this type



It is relatively easy to learn about physical processes you can reproduce in the lab

Things get more complicated when "our lab" is outside the Earth

- Disadvantage: We cannot play with knobs, we can only observe
- **Advantage: we can study processes that are extreme and we would never be able to study in our lab**

In the past, astronomical studies of extreme environments led to outstanding achievements

Examples of outstanding scientific achievements from astronomical observations

Tycho Brahe: observations of planetary motion

→ **Johannes Kepler**: laws of planetary motion

→ **Isaac Newton**: **Gravitation (1665)**

Balmer series of hydrogen involved spectroscopic observations of violet and ultraviolet lines of hydrogen in *white dwarf stars*

→ **Niels Bohr**: **atomic structure (1913)**

Nobel Prize (1923)

Hulse and **Taylor** discovered a *binary pulsar system (1974)*

→ **Gravitational radiation loss predicted by General Theory of Relativity**

Nobel Prize (1993)

Examples of outstanding scientific achievements from astronomical observations

Things in common from all these discoveries

1) Extreme "experiments" that could not be performed on Earth laboratories (at that time)

2) New instrumentation was used (at that time)

3) These phenomena were reproducible

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AGNs fulfill condition 1) , and gamma-ray instrumentation fulfills condition 2) but we have problems with 3) due to variability,

→ specially for Blazars, which that show extreme variability

→ and in addition we need to deal with the somewhat unknown distortions in the gamma-ray spectra due to their travel (from long distances) to us

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Another complication for understanding AGNs: these extreme particle accelerators emit over a wide energy range

It is challenging to study blazars

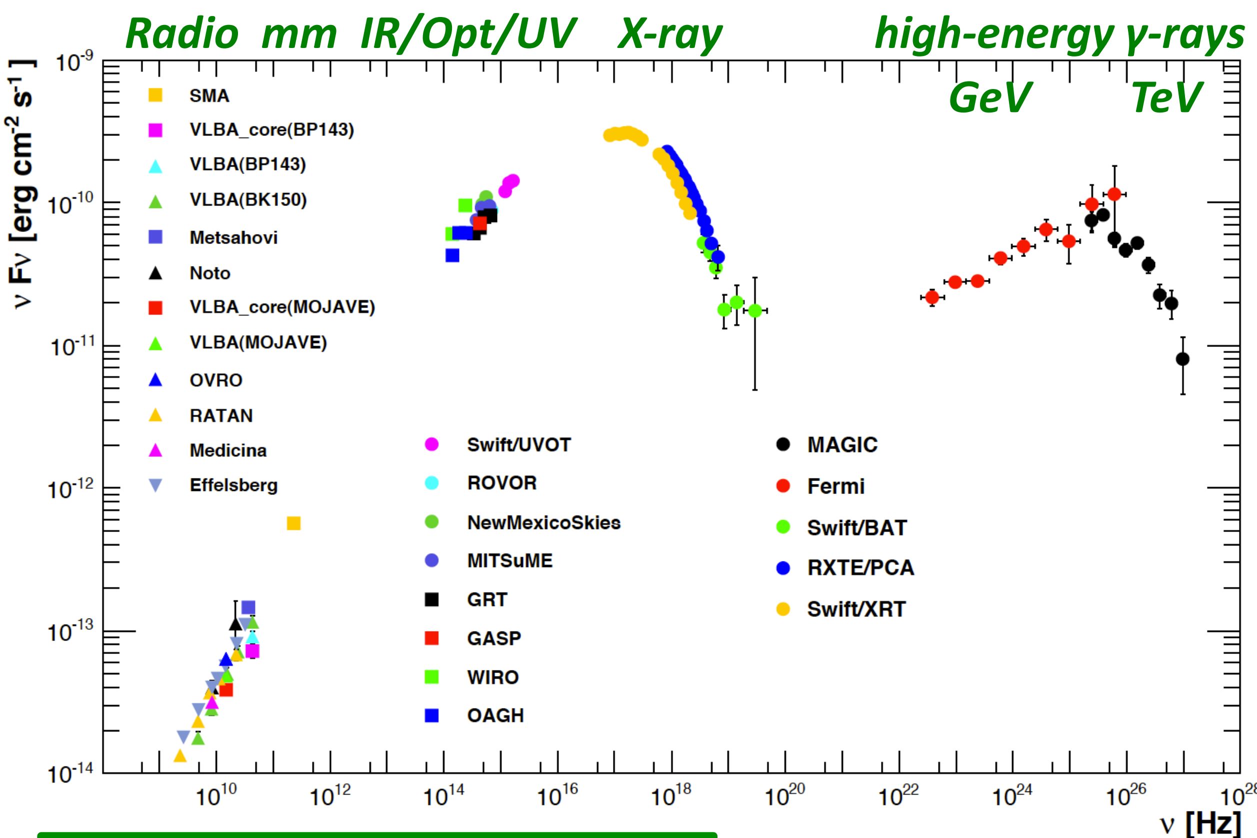
It is VERY CHALLENGING to study blazars

From <u>Observational perspective</u>, there are two major practical challenges

a) Blazars emit over a very wide energy range (from radio to very high energy gamma-rays)

Emission in different energy bands could be produced by same population of particles

→ *Need many instruments (covering many bands) to fully study these objects*



Spectral energy distribution (SED) of the Blazar Markarian 421

Abdo et al 2011, ApJ 736, 131

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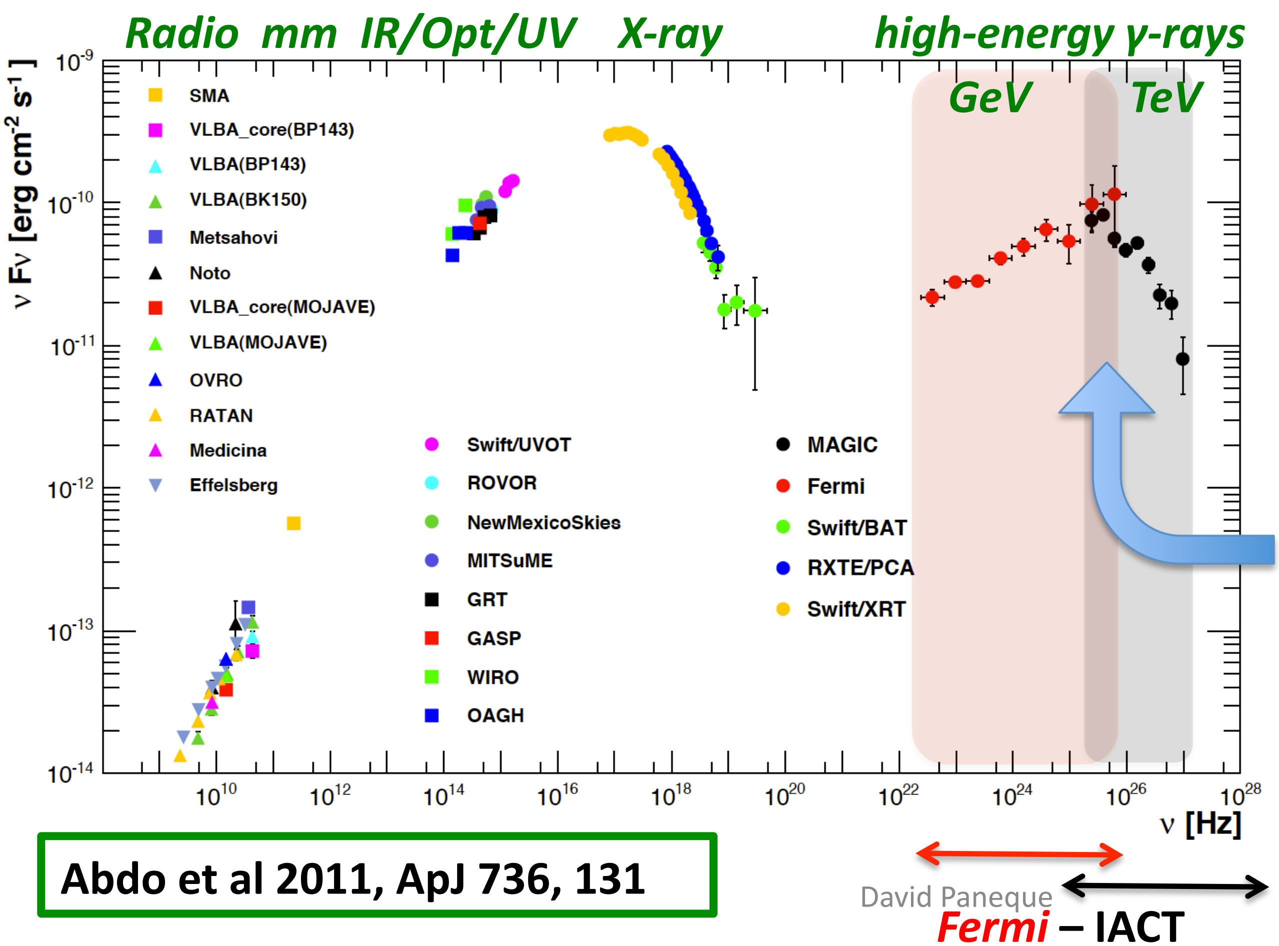


Abdo et al 2011, ApJ 736, 131

Spectral energy distribution (SED) of the Blazar Markarian 421

Gamma-ray bump could only be measured recently, with *Fermi*-LAT + modern IACTs like HESS/MAGIC/VERITAS

***Fermi* – IACT** spectra cover, for the first time, the complete high energy component over 5 orders of magnitude without gaps

→ *Crucial for the theoretical modeling of the broad emission*

Non-thermal Emission Processes in AGN Jets: Leptons

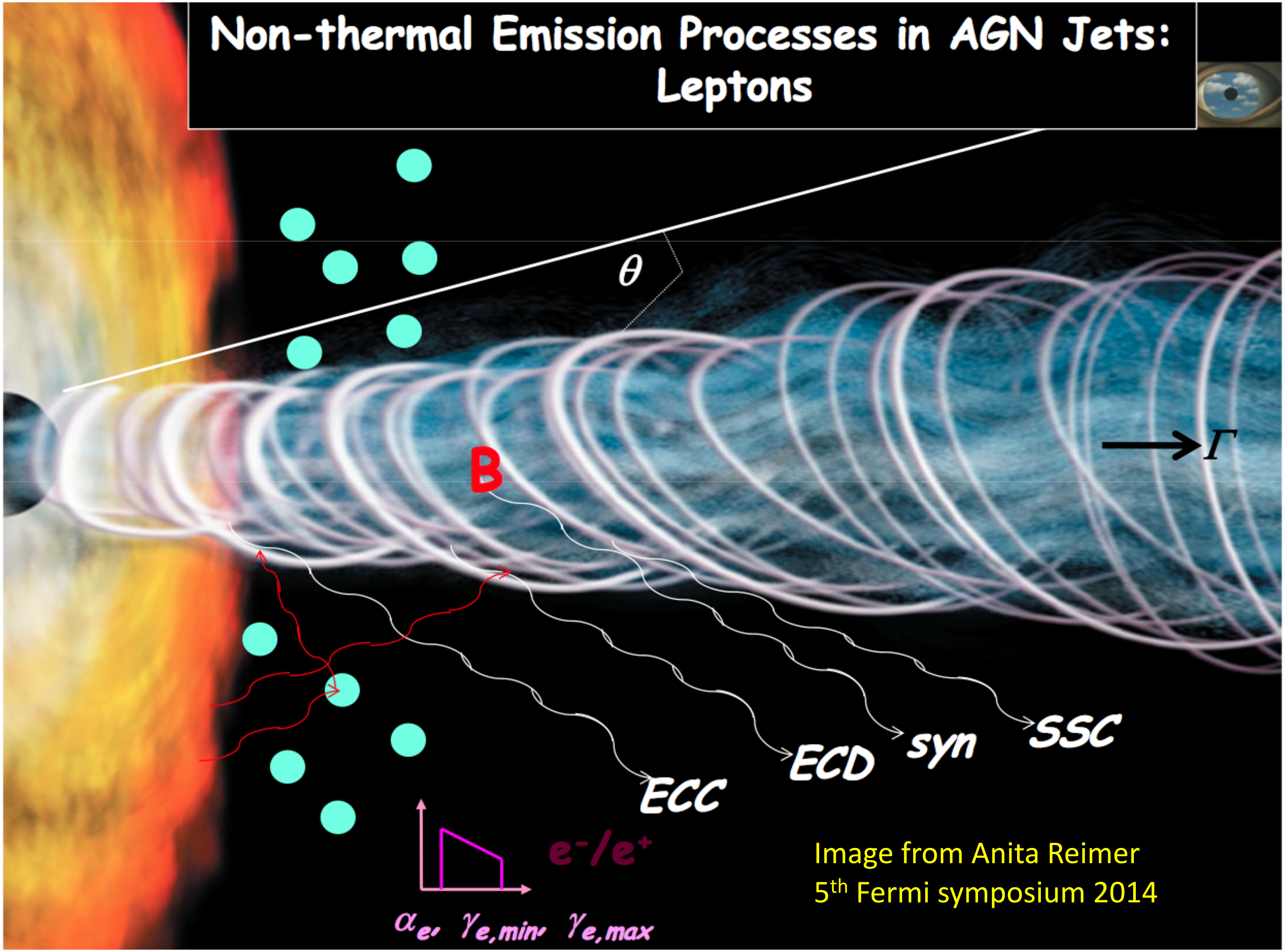
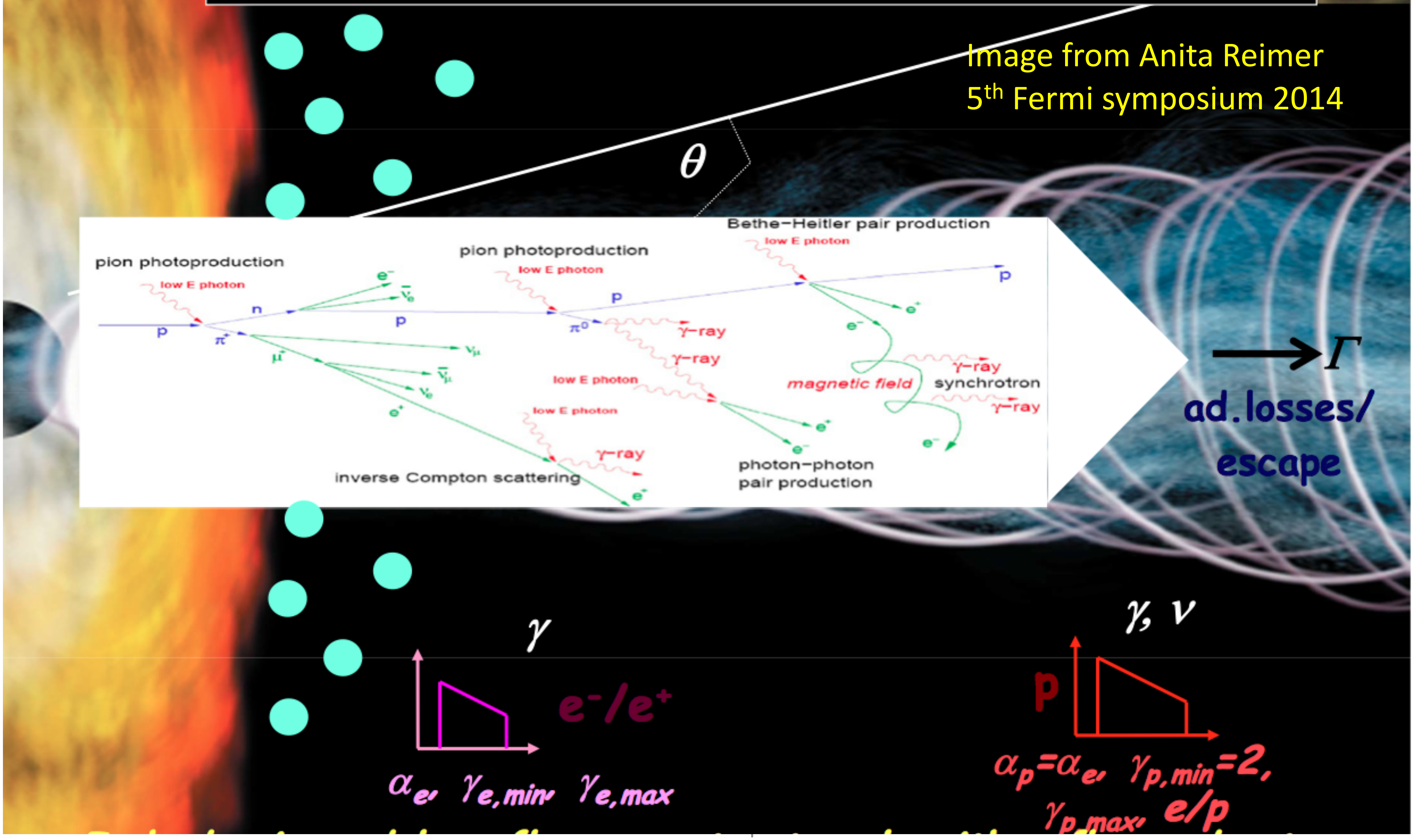


Image from Anita Reimer
5th Fermi symposium 2014

Non-thermal Emission Processes in AGN Jets: Leptons & Hadrons



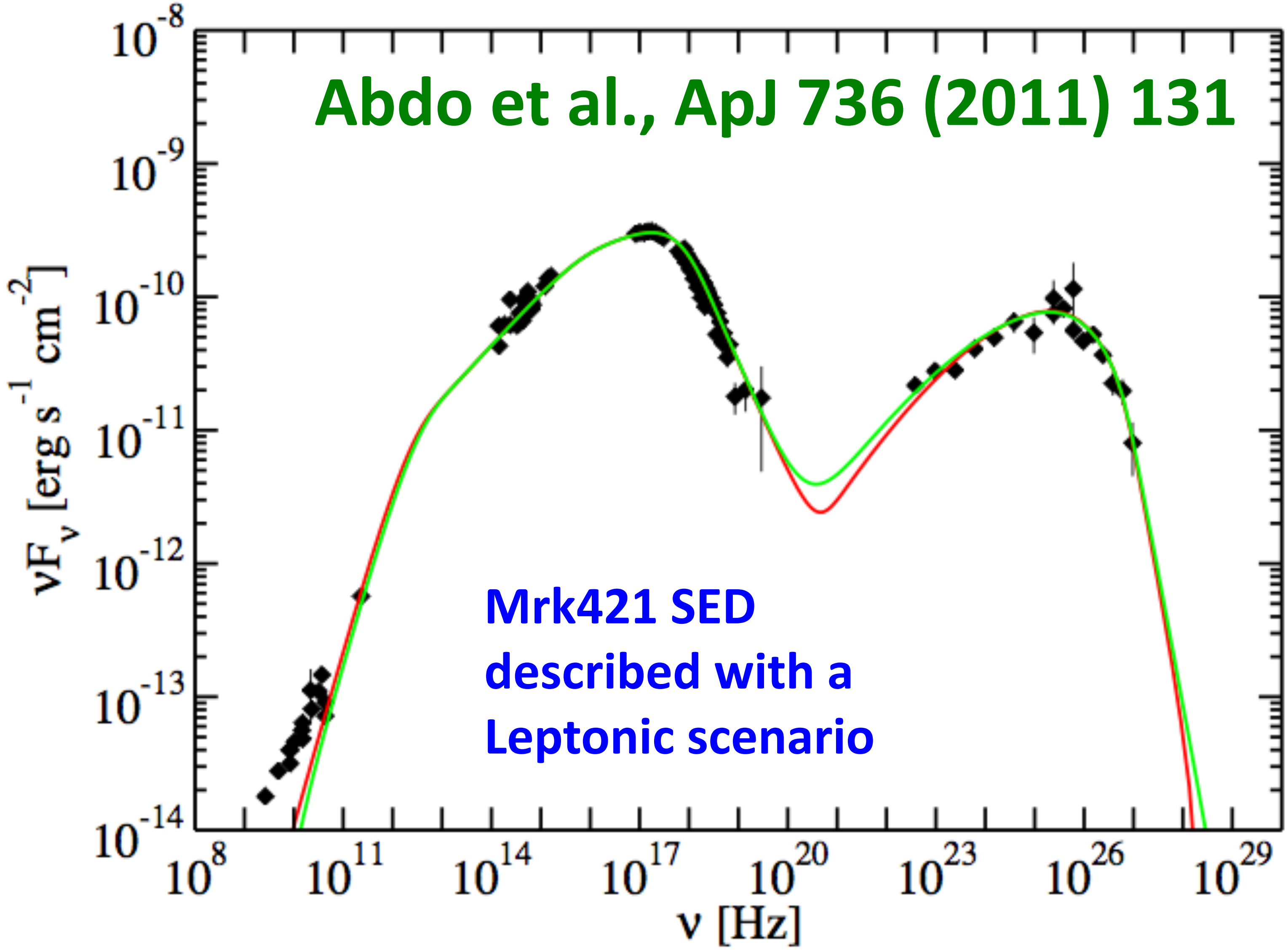


Figure 11. SED of Mrk 421 with two one-zone SSC model fits obtained with different minimum variability timescales: $t_{\rm var} = 1$ day (red curve) and $t_{\rm var} = 1$ hr (green curve). The parameter values are reported in Table 4. See the text for further details.

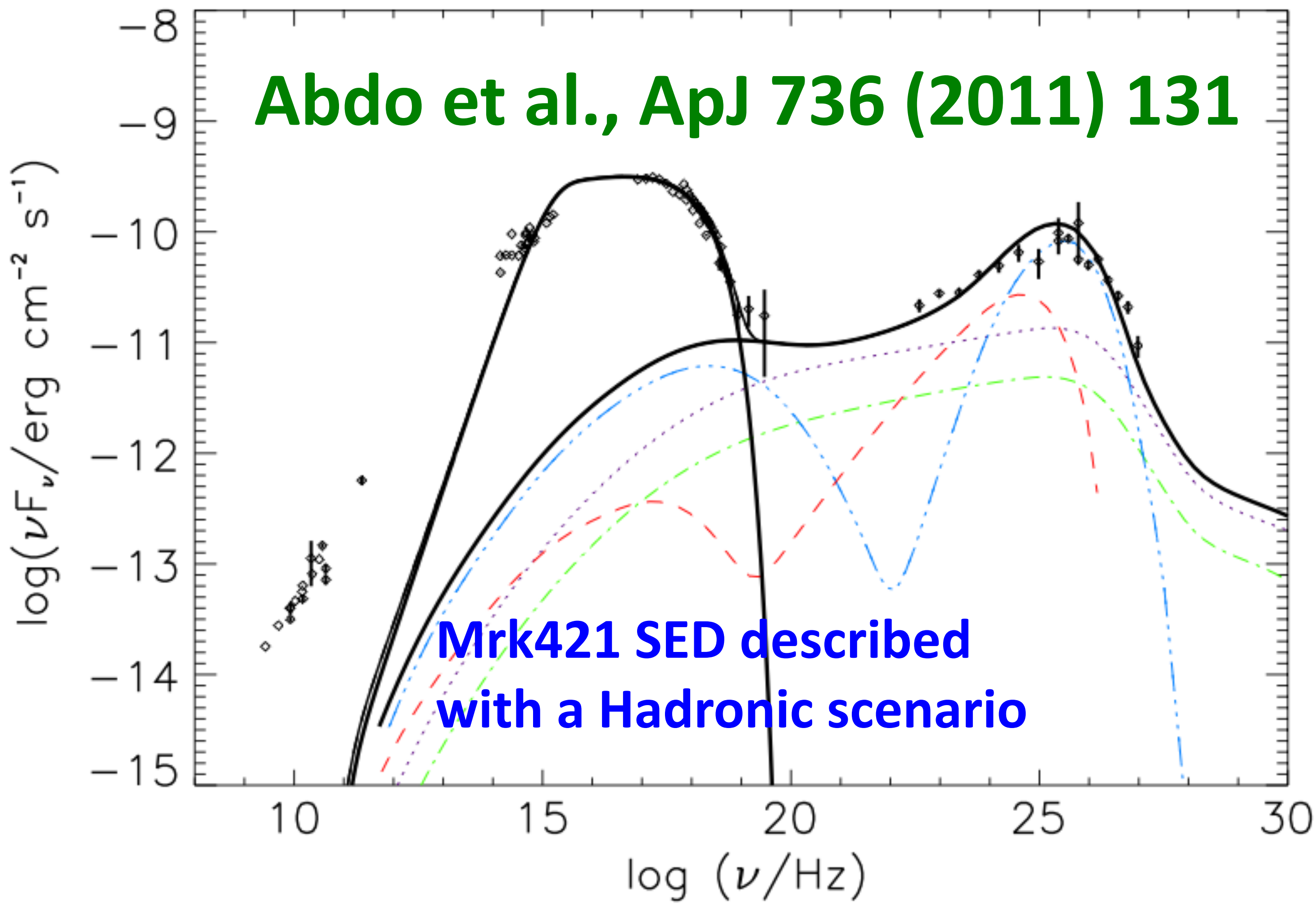
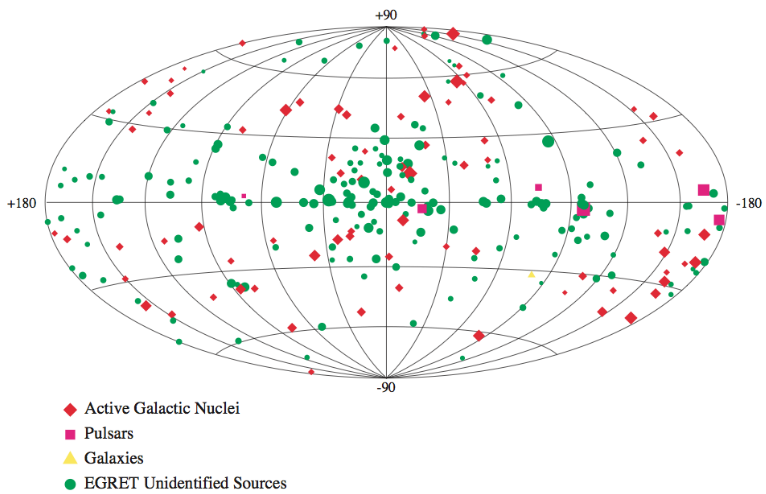


Figure 9. Hadronic model fit components: π^0-cascade (black dotted line), $\pi^{\pm}$ cascade (green dash-dotted line), μ-synchrotron and cascade (blue triple-dot-dashed line), and proton synchrotron and cascade (red dashed line). The black thick solid line is the sum of all emission components (which also includes the synchrotron emission of the primary electrons at optical/X-ray frequencies). The resulting model parameters are reported in Table 3.

Gamma-rays are crucial to understand AGNs (blazars)

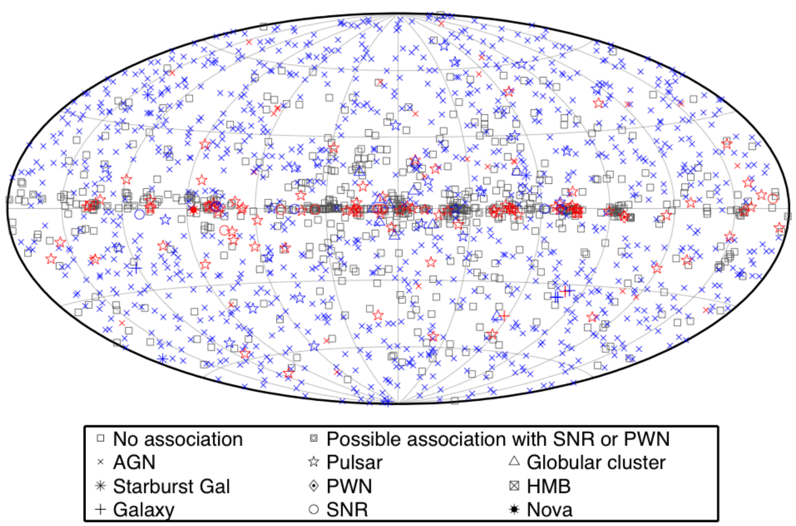
Our understanding of the Gamma-ray sky has improved “dramatically” during the last 2 decades (due to the improvement in the gamma-ray instrumentation)

The "GeV" gamma-ray sky : Gamma-rays above 100 MeV



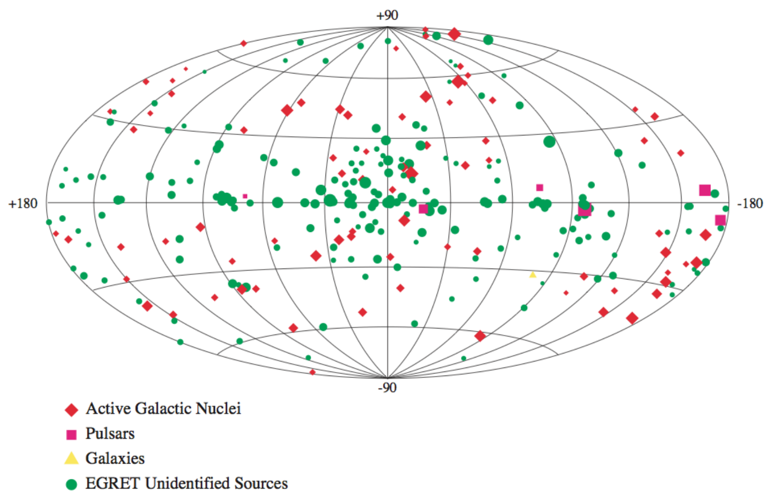
3rd EGRET Catalog
Hartman et al., 1999, ApJS, 123, 79
271 sources
- **170 unidentified**
- **101 identified/associated**
  - → **66 blazars**

Large improvement in the knowledge of the gamma-ray sky in only ~10 years



2nd Fermi-LAT Catalog (2 years of operation)
Nolan et al., 2012, ApJS, 199, 31
1873 sources
- **576 unidentified**
- **1297 identified/associated**
  - → **886 AGNs (862 blazars)**

The “GeV” gamma-ray sky : Gamma-rays above 100 MeV



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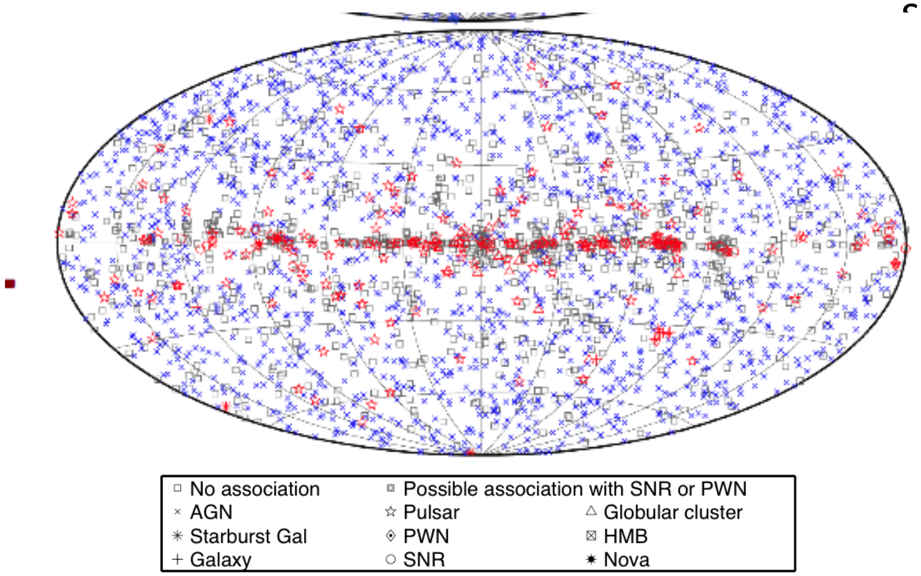
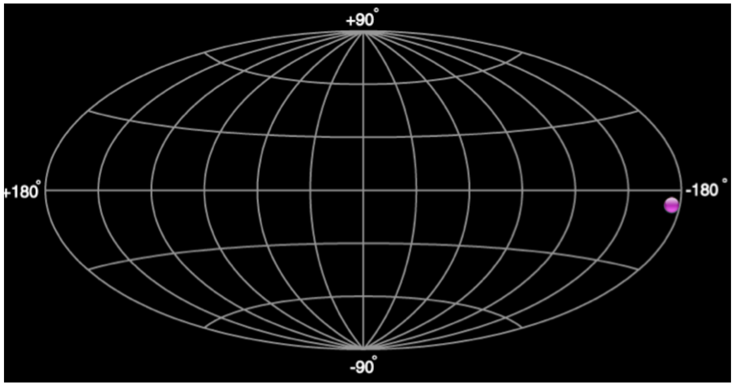


3 FGL (4 years of operation)
Cavazutti et al ., 5th Fermi symposium 2014
3033 sources
992 unidentified
2041 identified/associated
→ 1444 AGNs (1420 blazars)

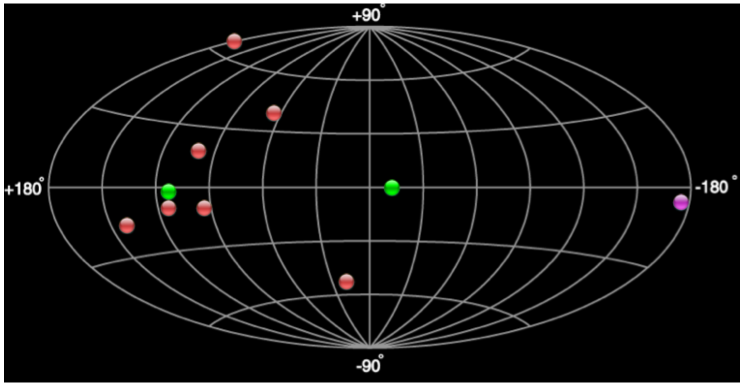
The "TeV" gamma-ray sky : Gamma-rays above 100 GeV

Plots obtained from the TeVCat
http://tevcat.uchicago.edu/



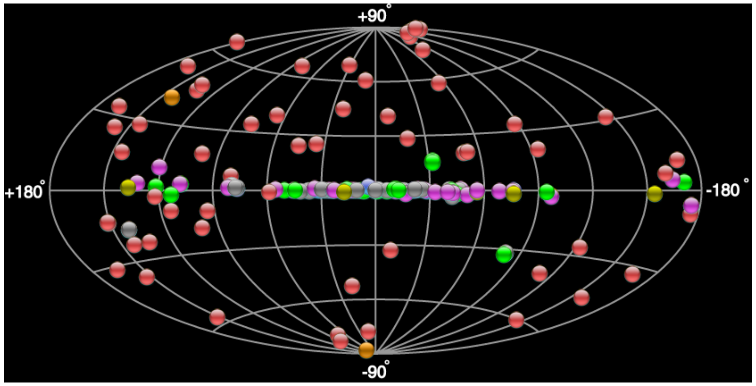
Similar improvements in the GeV and TeV energy domains

September 1991 (~20 years ago) : 1 source



Large improvement in the knowledge of the TeV gamma-ray sky in only ~10 years

September 2001 (~10 years ago) : 10 sources



Large improvement in the knowledge of the TeV gamma-ray sky in only ~10 years

November 2014 : 154 sources

(30 unidentified, 58 AGNs, 53 blazars)

Instrumentation for gamma-ray astronomy (the big picture)

	Exploration phase	Established field	"Ultimate" (?) generation (*population + precision studies)*
	~ 10 sources	~ 100 sources	~ 1000-10000 sources
Pair conversion experiments (MeV-GeV) **Space**	*70s (SAS-2, COS-B)*	*90s (EGRET)*	Now **Fermi**
Ground ***Cherenkov Telescopes (GeV-TeV)***	*80-90s (WHIPPLE, HEGRA,CAT)*	*00s* ***(Cangaroo, HESS, MAGIC, VERITAS)***	future **CTA**

Now **MAGIC II HESS II VERITAS upgraded**

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Novel discipline

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lots of room for improvement and potential discovery

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Novel discipline

The Max-Planck-Institute in Munich and the Institute for Cosmic Ray Research (Prof. Teshima) is strongly involved in MAGIC and CTA (since beginning), ***and participates in Fermi since 2011***

→ ***Forefront of experimental gamma-ray astronomy***

lots of room for improvement and potential discovery

It is VERY CHALLENGING to study blazars

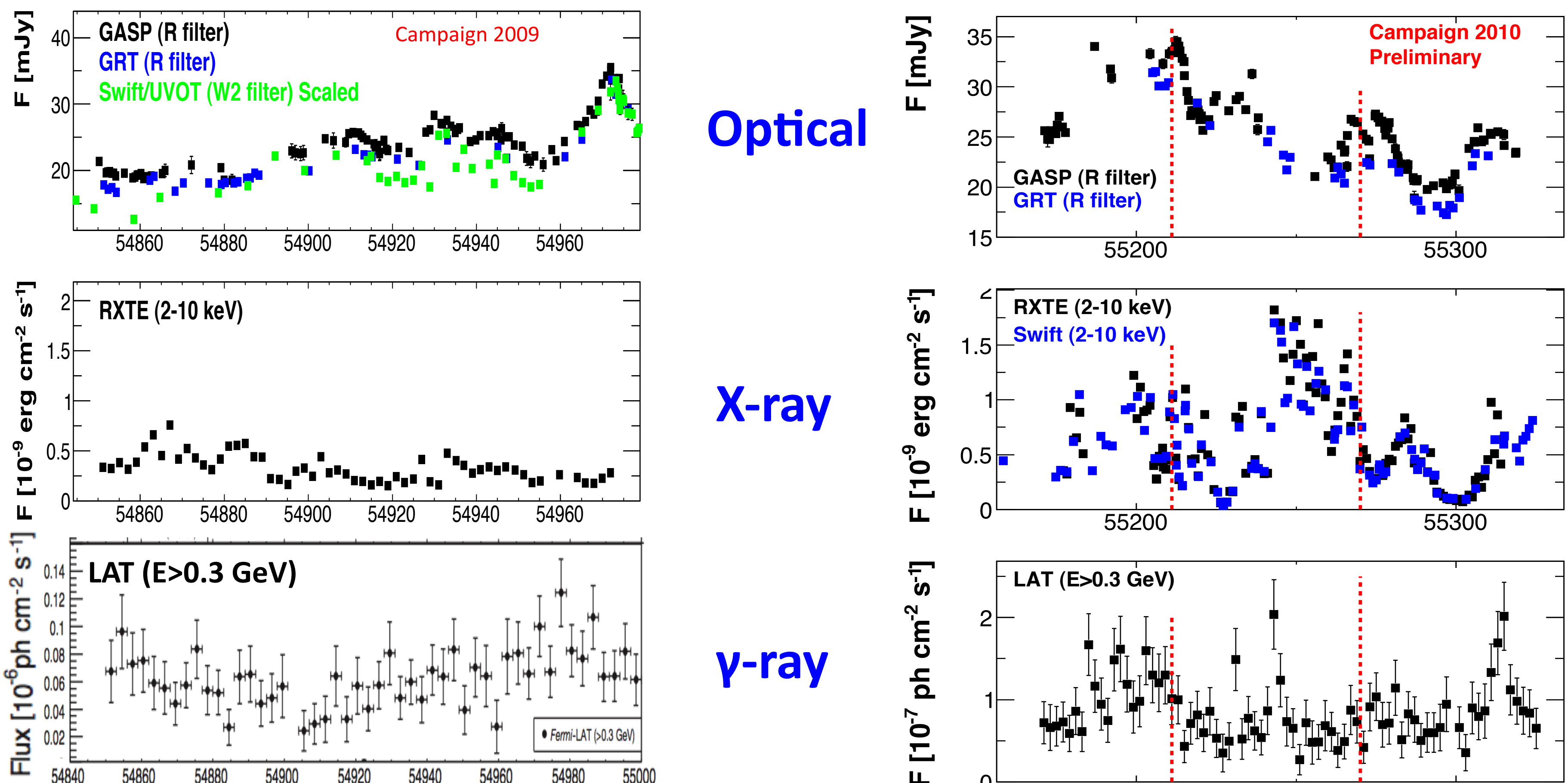
From Observational perspective, there are two major practical challenges

b) Blazar emission is variable on very different timescales (from years down to minutes)

Variability connected to acceleration/radiation processes

→ *The instruments need to observe simultaneously OFTEN and during LONG BASELINES*

Mrk421 showed very distinct behavior in the 2009 and 2010 campaigns



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(from radio to very high energy gamma-rays)

b) Blazar emission is variable on very different timescales

(from years down to minutes)

Studying blazars accurately requires excellent broadband (radio to gamma-rays) AND temporal (minutes to years) coverage

… like making Mochi …

Need persistency and coordination among different parties

a+b

→Requirement for MW campaigns lasting many years

→ Not possible for many objects

What we need to study blazars (AGNs in general):

1 – Good Broadband coverage

→ Several AGNs emit from radio up to VHE,
and there are relations among several energies

2 – Good Temporal coverage

→ AGNs are variable on timescales from years to minutes

→ *<u>Difficult to get reproducibility of observations</u>*

3 – A large number of objects that allow us to generalize behaviors

→ **Population studies**

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Roadmap → **We need population studies**
We need deep studies on individual sources

It will not be easy, it will not be fast…

but the new gamma-ray instrumentation and the large world-wide connectivity provides us with opportunities that did not exist before

2 - Population studies

→Need to start with the increase the number of VHE AGNs (MW coverage)

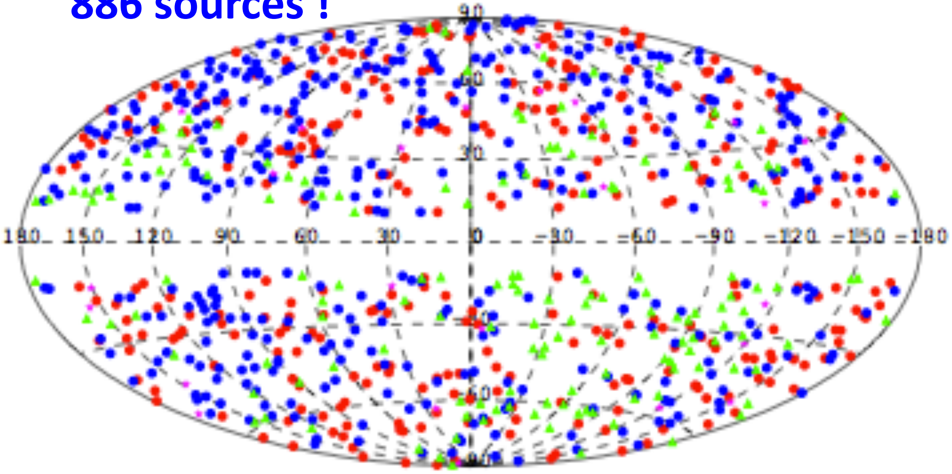
Number of VHE AGNs is low

2nd LAT AGN Catalog (2LAC)

Ackerman et al (Fermi collab.),
2011, ApJ, 743, 171

E> 0.1 GeV

886 sources !

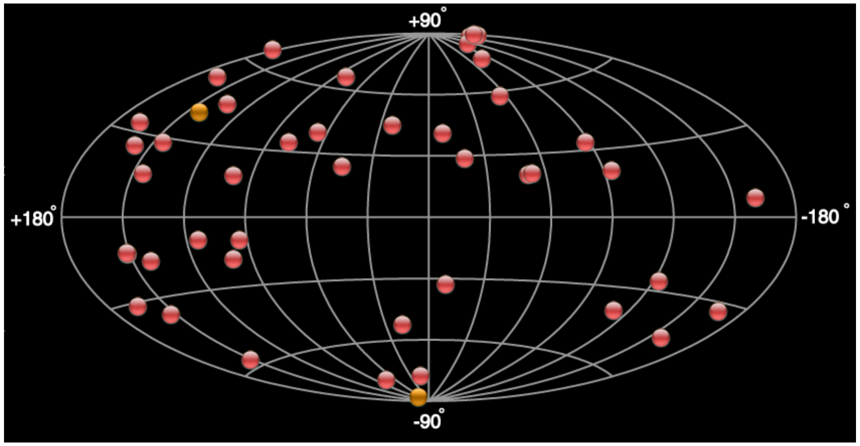


395 BL Lac
310 FSRQ
156 blazars of Unknown type
24 Non-blazar AGNs

Few TeV sources

VHE (>100 GeV) extragalactic sky
58 sources = 56 AGNs
+ 2 Starburst galaxies

http://tevcat.uchicago.edu/



47 BL Lac
3 FSRQ
3 Unknown type
5 Non-blazar AGNs

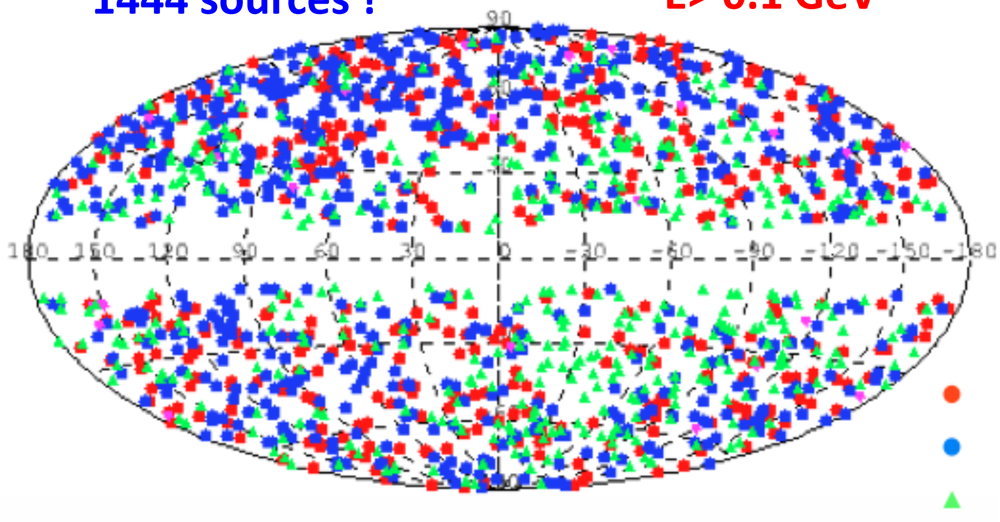
Need to increase the number of extragalactic VHE sources to perform population studies.

Number of VHE AGNs is low

3rd LAT AGN Catalog (3LAC)

Lott et al, 5th Fermi symposium 2014

1444 sources ! **E> 0.1 GeV**



604 BL Lac
414 FSRQ
402 blazars of Unknown type
24 Non-blazar AGNs

Few TeV sources

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58 sources = 56 AGNs
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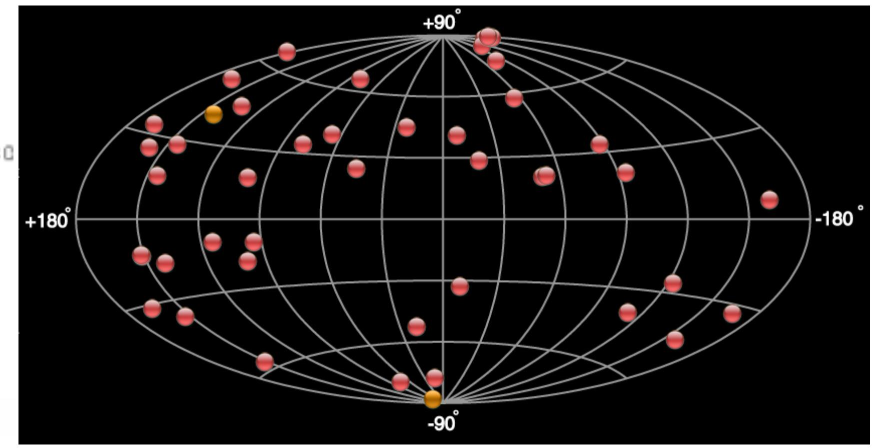

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Need to increase the number of extragalactic VHE sources to perform population studies.

~1000 AGNs @ > 0.1 GeV (Fermi low-energy, 2FGL & 2LAC)

+3FGL & 3LAC

~20 times less sources above 100 GeV. Why ???

1) intrinsic turnovers or cutoffs
2) Extrinsic turnovers or cutoffs (EBL)
3) **Region not sufficiently explored with IACTs**

IACTs have low duty cycles and small FoV

→ Difficult to make surveys over large areas

(*HESS Galactic plane scan is special because of high source density)*

~50 AGNs @ >100 GeV (Cherenkov Telescopes)

Since 2009, we have a close collaboration between Fermi-LAT and Cherenkov Telescopes to increase the number of VHE AGNs

1) We identify VHE AGN candidates using Fermi-LAT data

2) Cherenkov telescopes observe some of these objects
   - Detection of the source or upper limits (both are useful)

Often IACT observations are triggered by an enhanced activity in LAT, or by enhanced activity in optical/X-ray in a VHE candidate source

In the last 5 years (since 2009):

IACTs discovered 34 new VHE AGNs, most of them following information from Fermi-LAT (TeV candidates and/or flaring LAT sources)
The total number of reported VHE AGNs is now 58 (after ~25 years of operation with IACTs, see TeVCat for details)

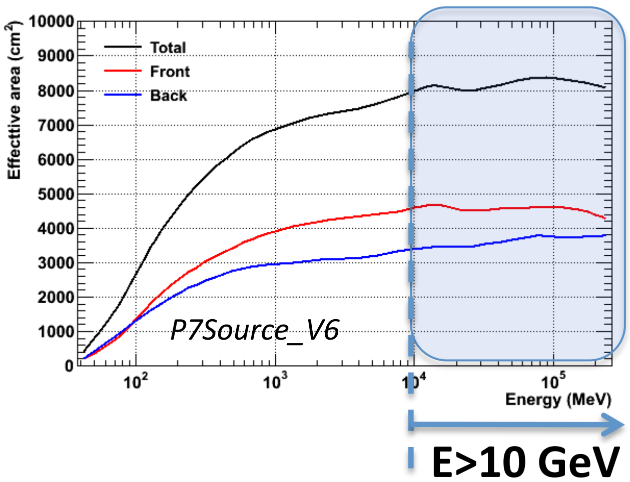
→ **In last 5 years we have increased the known VHE extragalactic sky by 142%(=34/(58-34)), and Fermi-LAT played a crucial role**

→ *Important to increase the census of VHE AGNs and improve population studies*

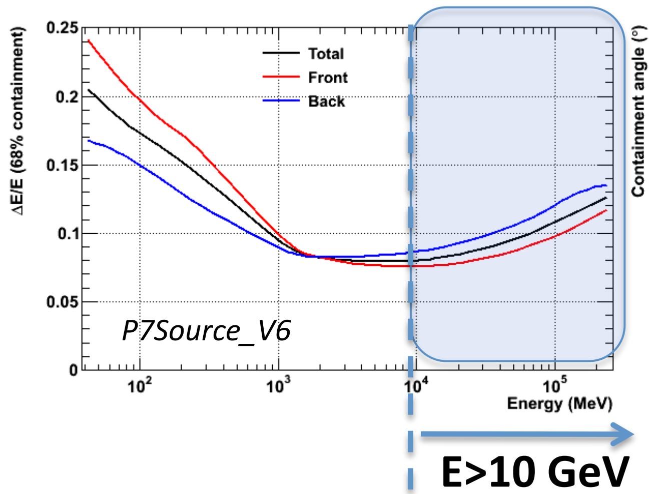
Performance of LAT for astronomy above 10 GeV

Performance of LAT for E> 10 GeV is excellent (compared to that for E>100 MeV)

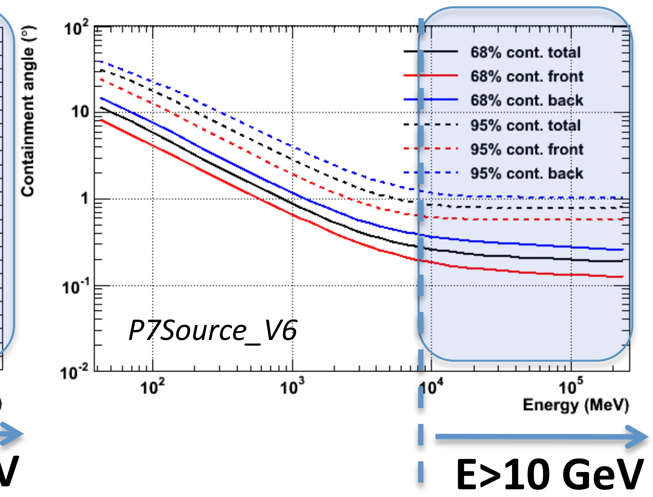
Effective Area



Energy resolution



Point Spread Function



http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Best possible effective area and PSF occur at the highest energies
Slightly worse energy resolution due to worse shower containment

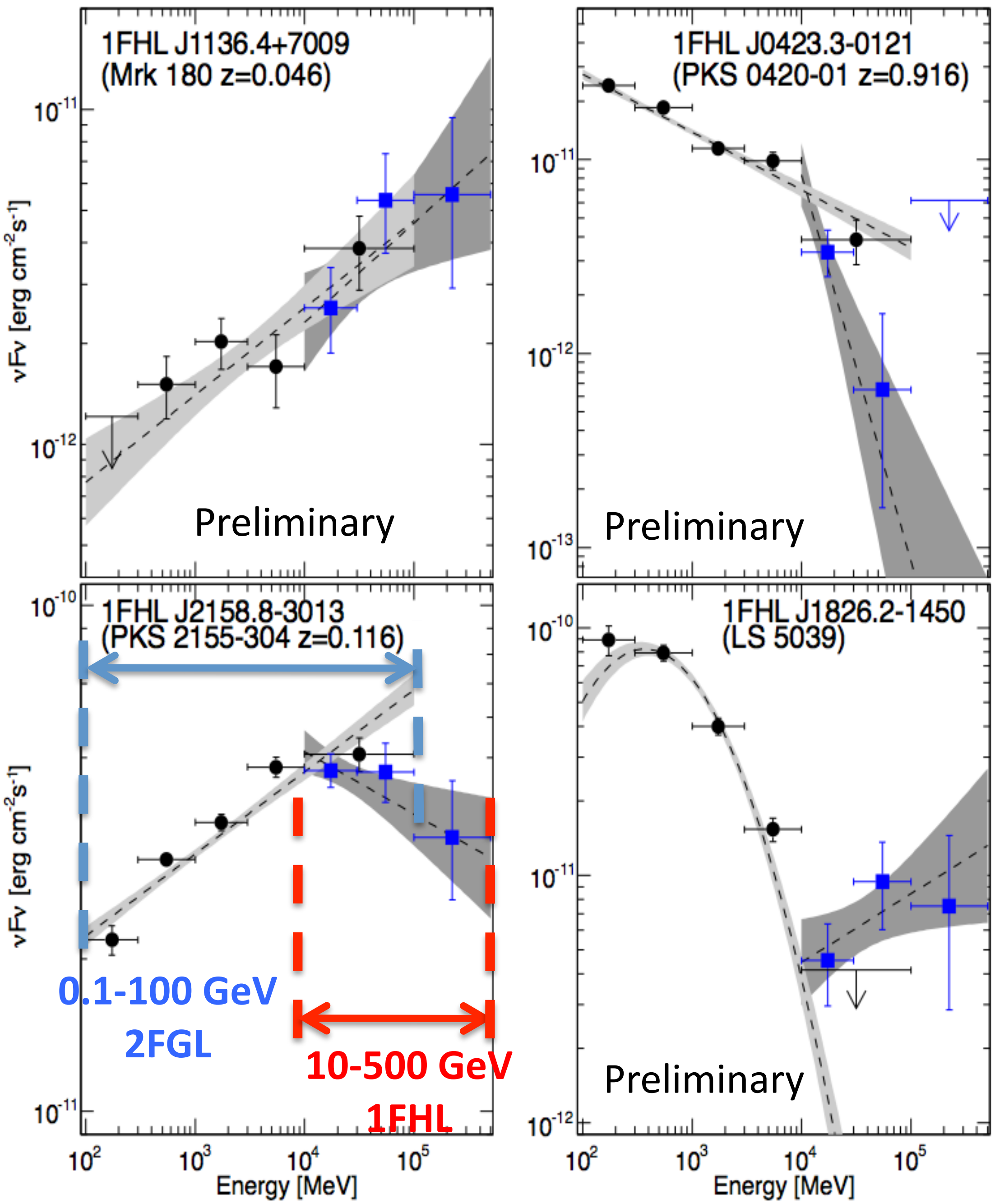
The Challenge: Nature of the sources we want to detect…

→ fluxes fall (typically) with power-law index of about 2.5

→ **Many detections are limited by a small amount of photons**

Photon statistics is the big limitation for src. characterization above 10 GeV

Low- and high-energy spectra for few exemplary Srcs



Large diversity in the spectra obtained above 10 GeV (in comparison to above 100 MeV)

Some sources show a >10 GeV spectrum that is roughly a continuation of that at > 100 MeV

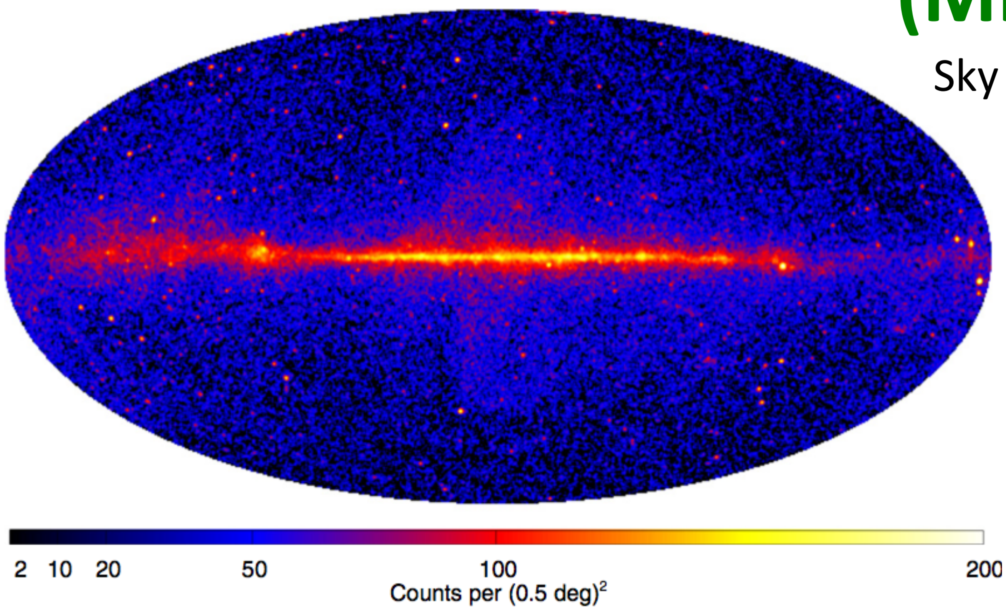
Others show internal breaks
(→ **important physics inside**)

Others show attenuations, likely due to the absorption in the EBL
(→ important for cosmology studies)

Others show new hard components
(→ new physical processes in source)

Need dedicated >10 GeV catalog to characterize Fermi sources at the highest energies (right before IACTs start operating)
Spectral Characterization is limited by photon statistics

The First Fermi-LAT Catalog of Sources above 10 GeV (1FHL) Ackermann et al, 2013, ApJS 209, 34 (MPP-2013-174)



Sky map with > 10 GeV events

LAT saw more than 1.5×10^5 gamma-rays in only 3 years

Big improvement with respect to EGRET !!! 1.5×10^3 evts in 9 years (Thompson et al. 2005)

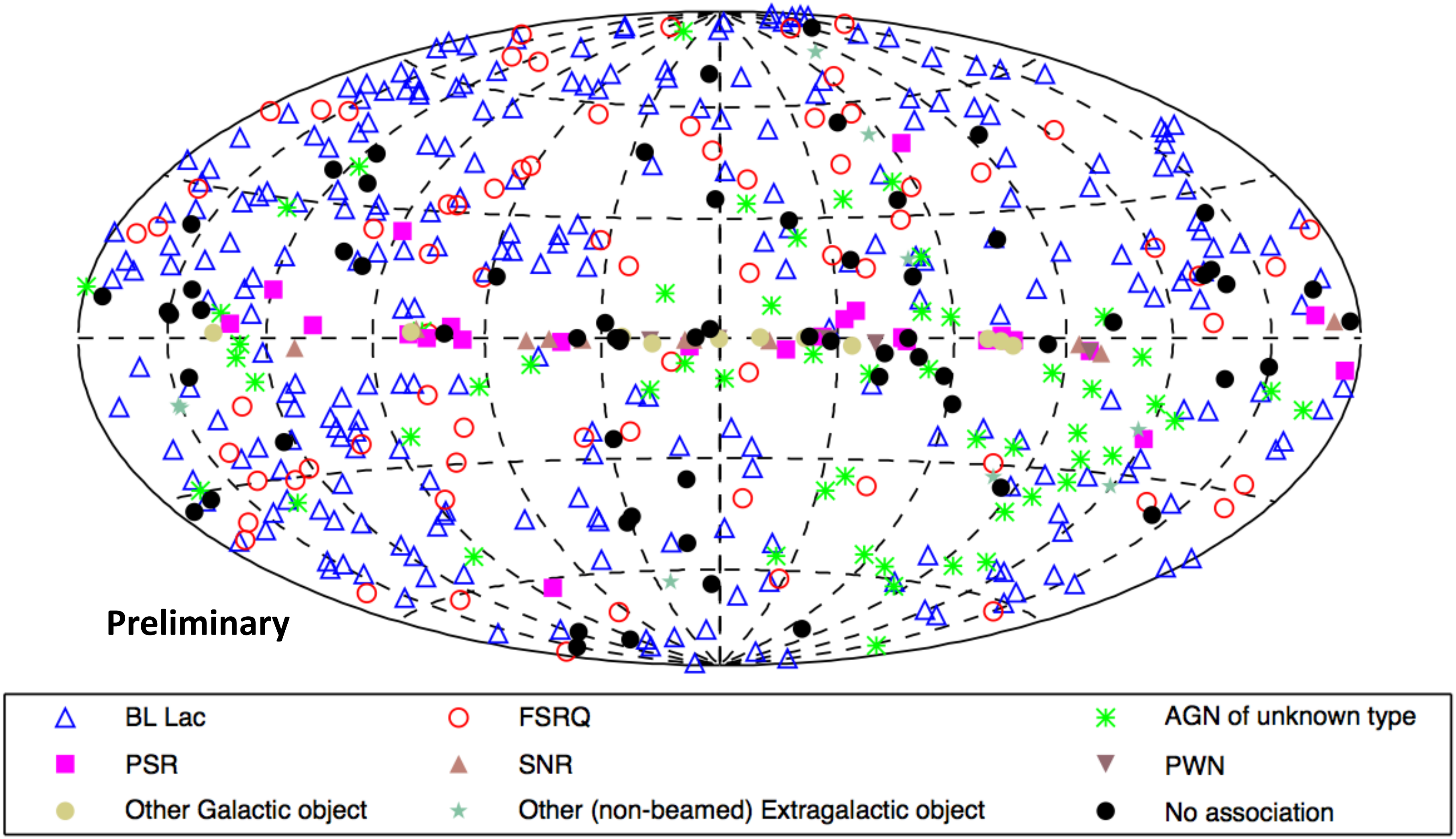
The analysis pipeline used is the same as that for the 2FGL catalog:
candidate sources ("seeds") are identified and localized, and then a maximum likelihood analysis extracts results on statistical significance, flux, and energy spectrum.
Galactic and isotropic diffuse background models similar to those used for the 2FGL catalog (available through the Fermi Science Support Center)
Only sources with a Test Statistic (TS) larger than 25 are reported

514 sources ***(63 not contained in 2FGL)***
9 of the 63 sources are extended, while in **2FGL exist as point-like sources**
All sources could be fitted with a simple power law

Skymap with all the 1FHL sources

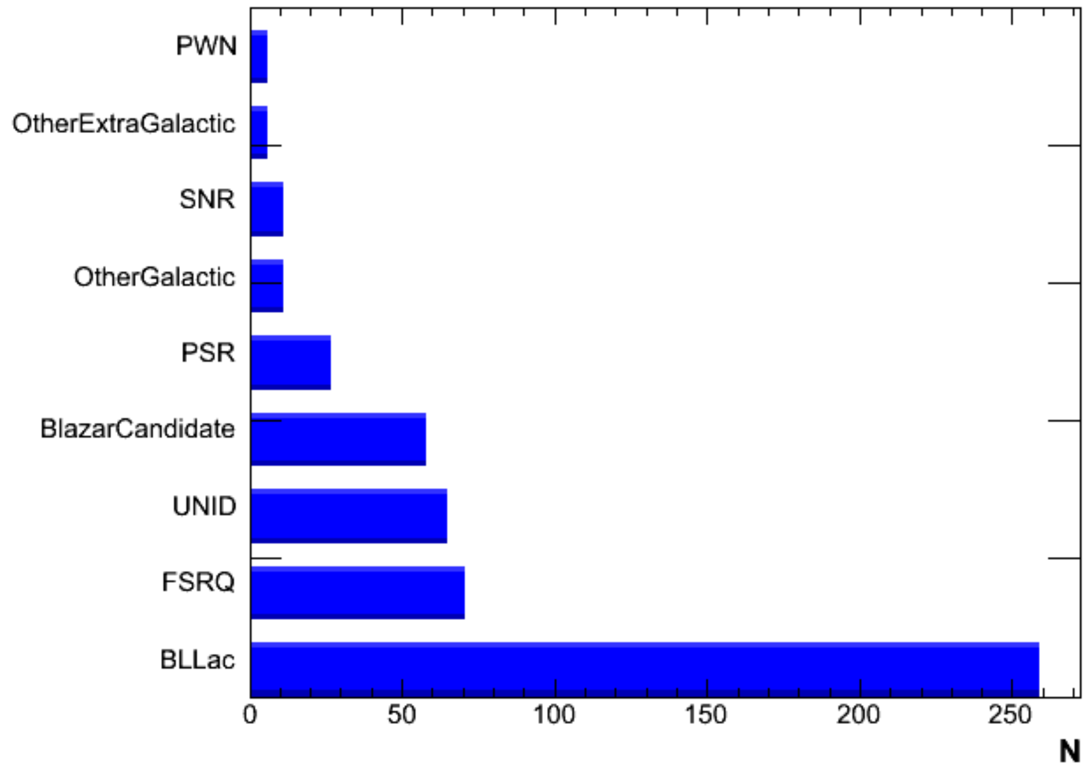
514 sources in the 1FHL catalog

→ The sky is full of high-energy gamma-ray sources



Associated sources (All)

514 sources in the 1FHL catalog



6 (**1%**)
6 (**1%**)
11 (**2%**)
11 (**2%**)
27 (**5%**)
58 (**12%**)
65 (**13%**)
71 (**14%**)
259 (**50%**)

AGN (mostly BL Lacs) dominate the Fermi-LAT sky above 10 GeV (394 objects→ 76%)

12.6% of the sources remain unassociated

Many of the UNID are expected to be AGNs

~1000 AGNs @ > 0.1 GeV (Fermi low-energy, 2FGL & 2LAC)

~2 times less sources

~400 AGNs @ >10 GeV (Fermi high-energy, 1FHL)

~10 times less sources above 100 GeV. Why ???

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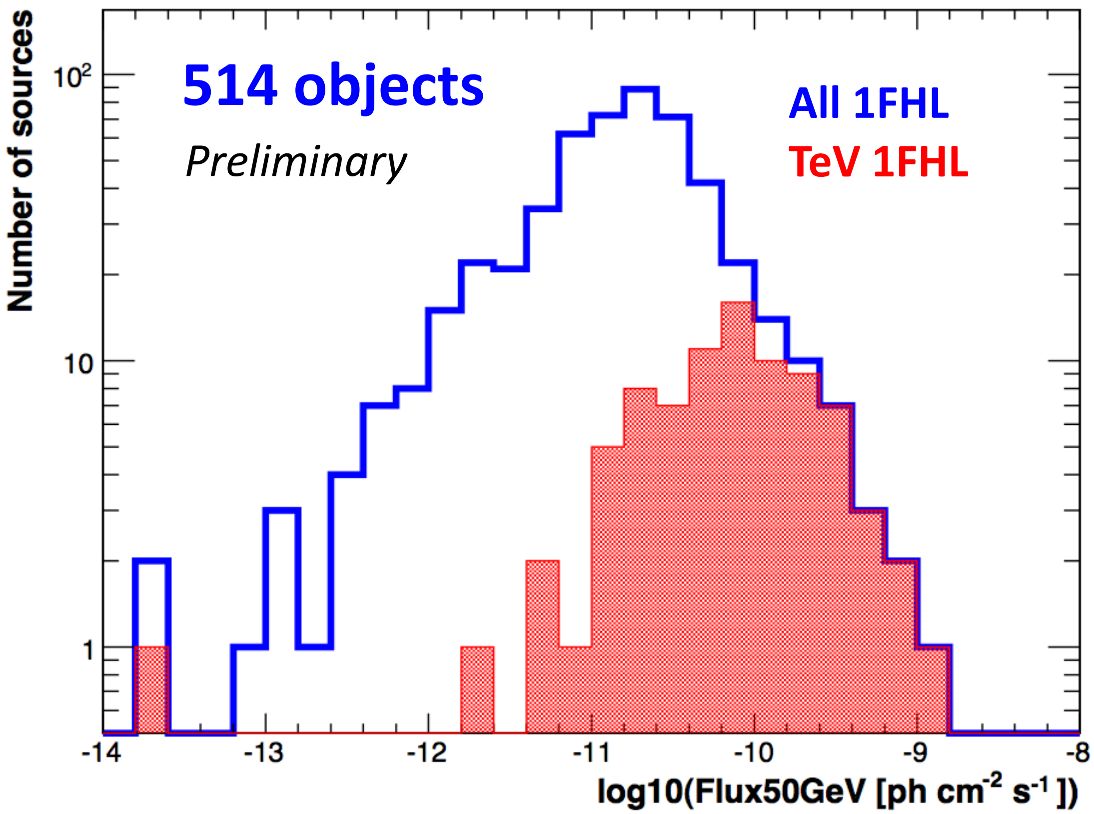
~50 AGNs @ >100 GeV (Cherenkov Telescopes)

Source candidates for detection at VHE (E>100 GeV)

Distribution of LAT flux above 50 GeV for all the 1FHL objects



Flux above 50 GeV determined using the power law fit derived with events above 10 GeV

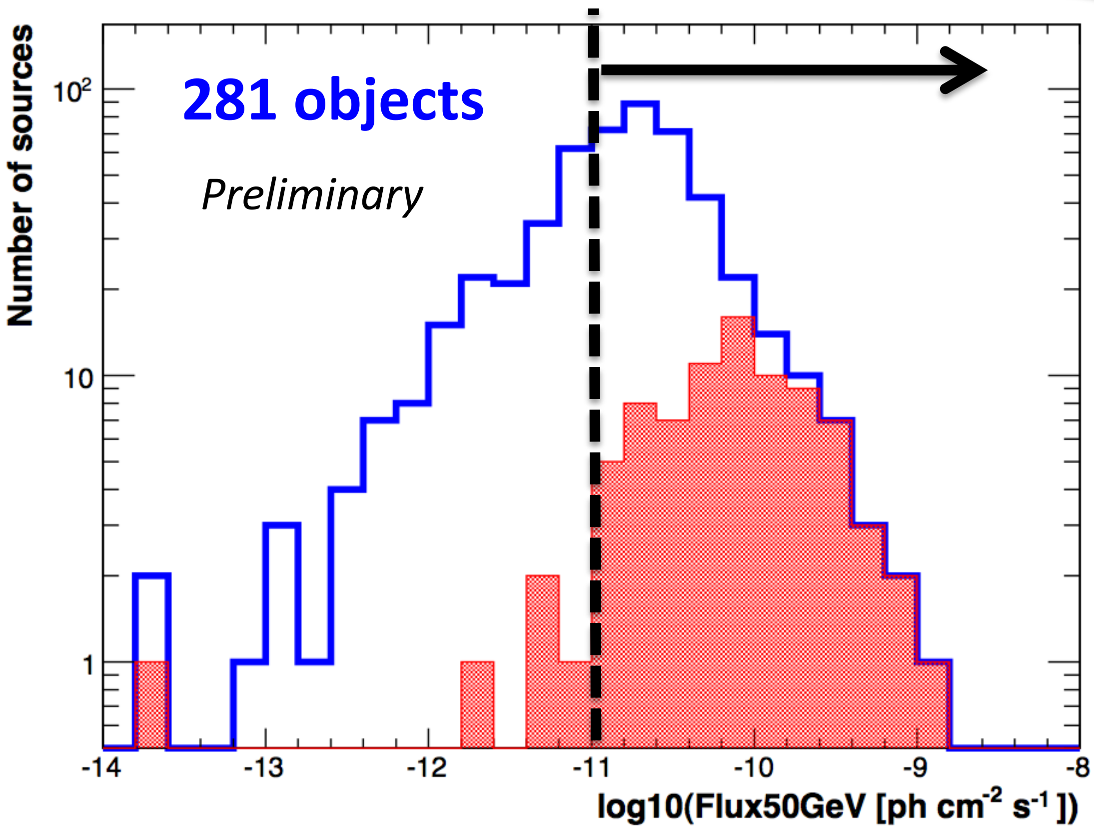
84 objects from the 1FHL list have been already detected with IACTs at VHE (→ TeV Src) http://tevcat.uchicago.edu/

430 objects from the 1FHL list have not been detected with IACTs

Sources detected at VHE with IACTs have high extrapolated fluxes above 50 GeV

Source candidates for detection at VHE (E>100 GeV)

Distribution of LAT flux above 50 GeV for the 1FHL objects that survive the <u>selection of *good TeV candidates*</u>



Log10(F50GeV] > -11
(Flux >~ 1% Crab Nebula)
Power-law index < 3
Significance (>30GeV) > 3σ

From the 84 TeV src in 1FHL, 69 objects survive the *TeV candidate selection cuts*

212 objects are flagged as good TeV candidates for being detected with IACTs

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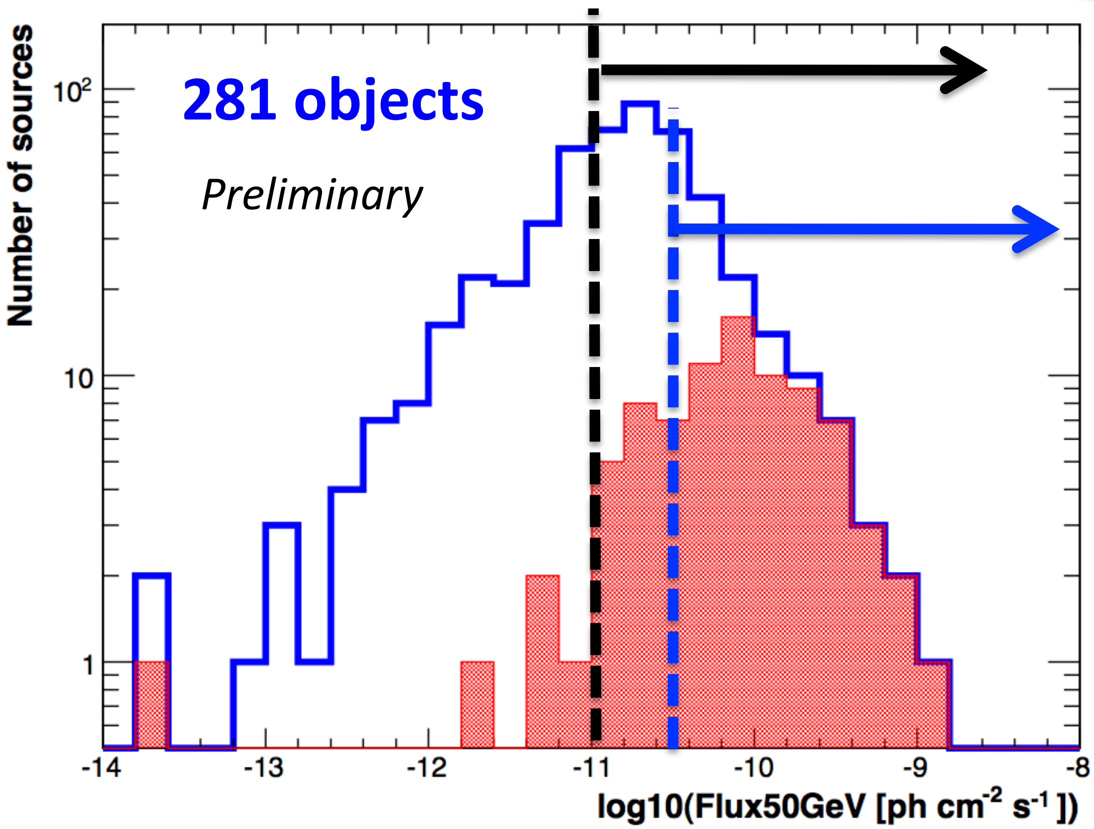

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From the 84 TeV src in 1FHL, 69 objects survive the *TeV candidate selection cuts*

212 objects are flagged as good TeV candidates for being detected with IACTs

In September 2012 we informed HESS/MAGIC/VERITAS about the best 72 candidates

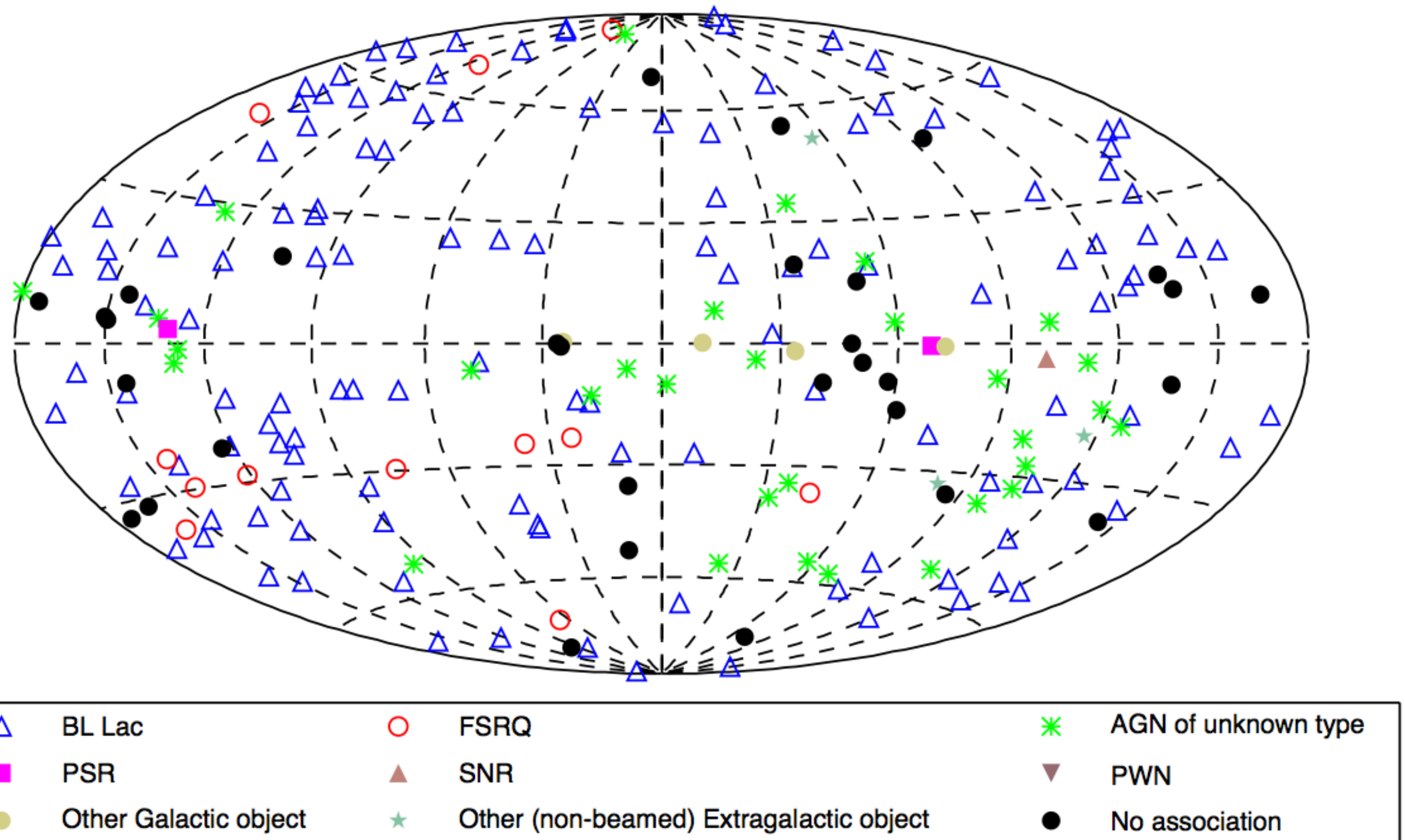
→ **log10[F50GeV] > -10.5**

Sources detected at VHE with IACTs have high extrapolated fluxes above 50 GeV

Source candidates for detection at VHE (E>100 GeV)

Sky map showing the 1FHL sources that we identify as good candidates for VHE detection.

→ The sky is full of (very probable) VHE sources



Source candidates for detection at VHE (E>100 GeV)

Among best 72 VHE candidates, we have 18 blazars with high redshift (z>0.2)

1FHL Name	RA	DEC	Association	z	$F50Crab$
J0538.8-4405	84.714	-44.088	PKS 0537-441	0.89	13.4
J0957.6+5522	149.421	55.377	4C +55.17	0.90	7.8
J0428.7-3756	67.178	-37.937	PKS 0426-380	1.11	6.6
J1936.8-4721	294.214	-47.356	PMN J1936-4719	0.26	5.7
J0250.6+1712	42.657	17.206	NVSS J025037+171209	1.10	5.2
J1248.1+5821	192.041	58.361	PG 1246+586	0.85	4.9
J1224.5+2437	186.146	24.628	MS 1221.8+2452	0.22	4.7
J0847.0+1132	131.773	11.544	RX J0847.1+1133	0.20	4.6
J0913.1-2104	138.289	-21.078	MRC 0910-208	0.20	4.5
J1501.0+2238	225.275	22.639	MS 1458.8+2249	0.23	4.4
J2001.1-1752	300.278	-17.868	PKS 1958-179	0.65	4.3
J1243.2+3628	190.807	36.468	Ton 116	1.06	3.9
J1309.3+4304	197.345	43.069	B3 1307+433	0.69	3.7
J0909.3+2312	137.339	23.205	RX J0908.9+2311	0.22	3.6
J1748.5+7006	267.127	70.101	S4 1749+70	0.77	3.5
J0325.7-1647	51.437	-16.792	RBS 0421	0.29	3.5
J1058.5+0133	164.628	1.564	4C +01.28	0.89	3.5
J2345.0-1556	356.261	-15.937	PMN J2345-1555	0.62	3.4

F50Crab is the extrapolated flux above 50 GeV normalized to the flux of the Crab nebula (in percentage)

Detecting the high-redshift blazars with IACTs has a large scientific return (blazar physics, cosmology and particle physics)

Should they be detected at VHE, these sources could be used as tools to study a large variety of things related to the environment traversed by the gammas-rays:

1 - Extragalactic Background Light
2 - Intergalactic Magnetic Fields
3 - Tests of Lorentz Invariance Violation
4 - Search for Axion Like Particles

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Detected at VHE (with MAGIC) Atel #5038 (May 2nd, 2013)

Detected at VHE (with MAGIC) Atel #5768 (Jan 15, 2014)

Should they be detected at VHE, these sources could be used as tools to study a large variety of things related to the environment traversed by the gammas-rays:

1 - Extragalactic Background Light

2 - Intergalactic Magnetic Fields

3 - Tests of Lorentz Invariance Violation

4 - Search for Axion Like Particles

Candidate TeV sources from FHL are being detected

Discovery of Very High Energy Gamma-Ray Emission from MS1221.8+2452 with the MAGIC telescopes

ATel #5038; *Juan Cortina (IFAE Barcelona) on behalf of the MAGIC collaboration*
on 2 May 2013; 19:25 UT
Credential Certification: Juan Cortina (cortina@ifae.es)

z=0.20

DISCOVERY OF VERY HIGH ENERGY GAMMA-RAY EMISSION FROM RBS 0723 WITH THE MAGIC TELESCOPES

z=0.20

ATel #5768; *Razmik Mirzoyan (Max-Planck-Institute for Physics, Munich, Germany)*
on 15 Jan 2014; 17:53 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Discovery of Very High Energy Gamma-Ray Emission from BL Lac object H1722+119 by the MAGIC Telescopes

z>0.17

ATel #5080; *Juan Cortina (IFAE Barcelona) on behalf of the MAGIC collaboration*
on 22 May 2013; 19:03 UT
Credential Certification: Juan Cortina (cortina@ifae.es)

Discovery of Very High Energy Gamma-Ray Emission from BL Lac object RX J1136.5+6737 by the MAGIC Telescopes

z=0.13

ATel #6062; *Razmik Mirzoyan (Max-Planck-Institute for Physics) on behalf of the MAGIC Collaboration*
on 11 Apr 2014; 11:11 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

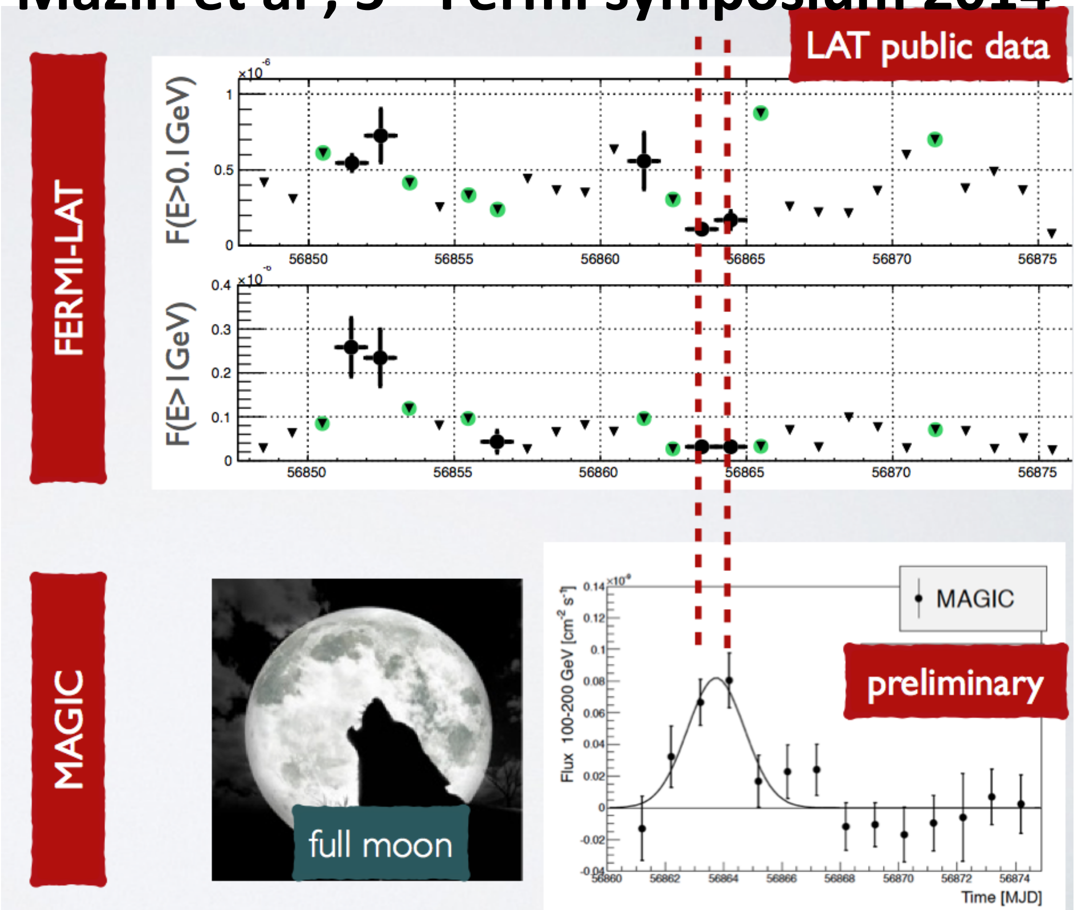
Discovery of 4+1 new VHE AGNs (with MAGIC) from the list of good TeV candidates from FHL

Discovery of Very High Energy Gamma-Ray Emission From Gravitationally Lensed Blazar S3 0218+357 With the MAGIC Telescopes

ATel #6349; *Razmik Mirzoyan (Max-Planck-Institute for Physics) On Behalf of the MAGIC Collaboration*
on 28 Jul 2014; 14:20 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

This one was ALSO in the list of good TeV candidates from FHL

Mazin et al , 5th Fermi symposium 2014



In many occasions, the trigger using Fermi-LAT data will come from flux enhancements

The recent detection (by MAGIC) of the lensed emission from the distant (**z=0.94**) blazar is the most spectacular of those

Candidate TeV sources from FHL are being detected

Surely there will be more VHE detections in the next years

Many detections will be possible due to a flaring state of the source (determined with Fermi-LAT or optical/X-ray)

→ **Search for new VHE candidates done in 3D (RA,Dec, Time)**

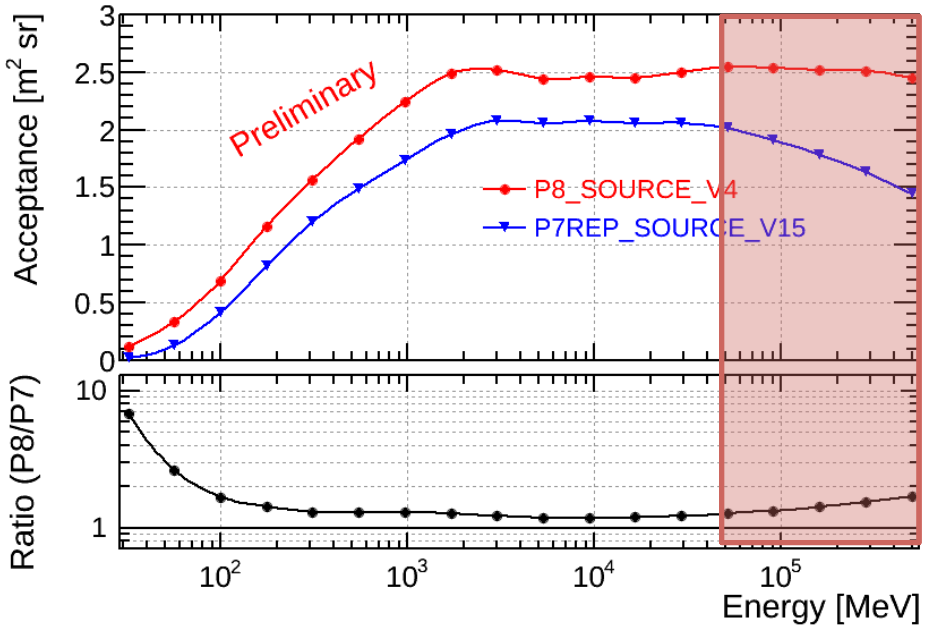
However, many observations with current IACTs will also lead to non-detections (upper limits) due to limited sensitivity and not-low-enough energy threshold. This will also be useful to understand better these sources

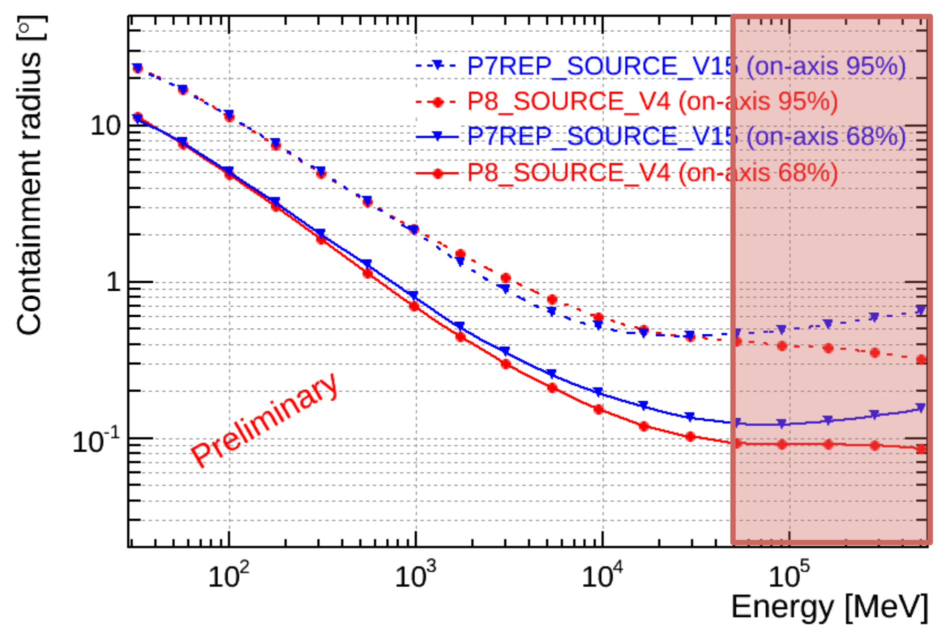
Large increase in number of sources expected with LST

→ Energy threshold going down to 20 GeV

2FHL : Pass 8 + 6 years

Ajello et al. 5th Fermi symposium 2014





- ***Large Progress Expected at >50 GeV:***
  1. **Improve PSF and Acceptance (factor of 0.5-2 in P8)**
  2. **Low background and good (constant) PSF (0.1 deg at 68%)**
  3. **All-sky exposure**

- ***Catalog of sources detected at >50 GeV***
  - **Allows study of the EBL, EGB, Galactic plane etc.**
  - **Continues our effort to characterize sources at high energies**
  - **Connects well to ACTs, HAWC and the upcoming CTA**

Count Map

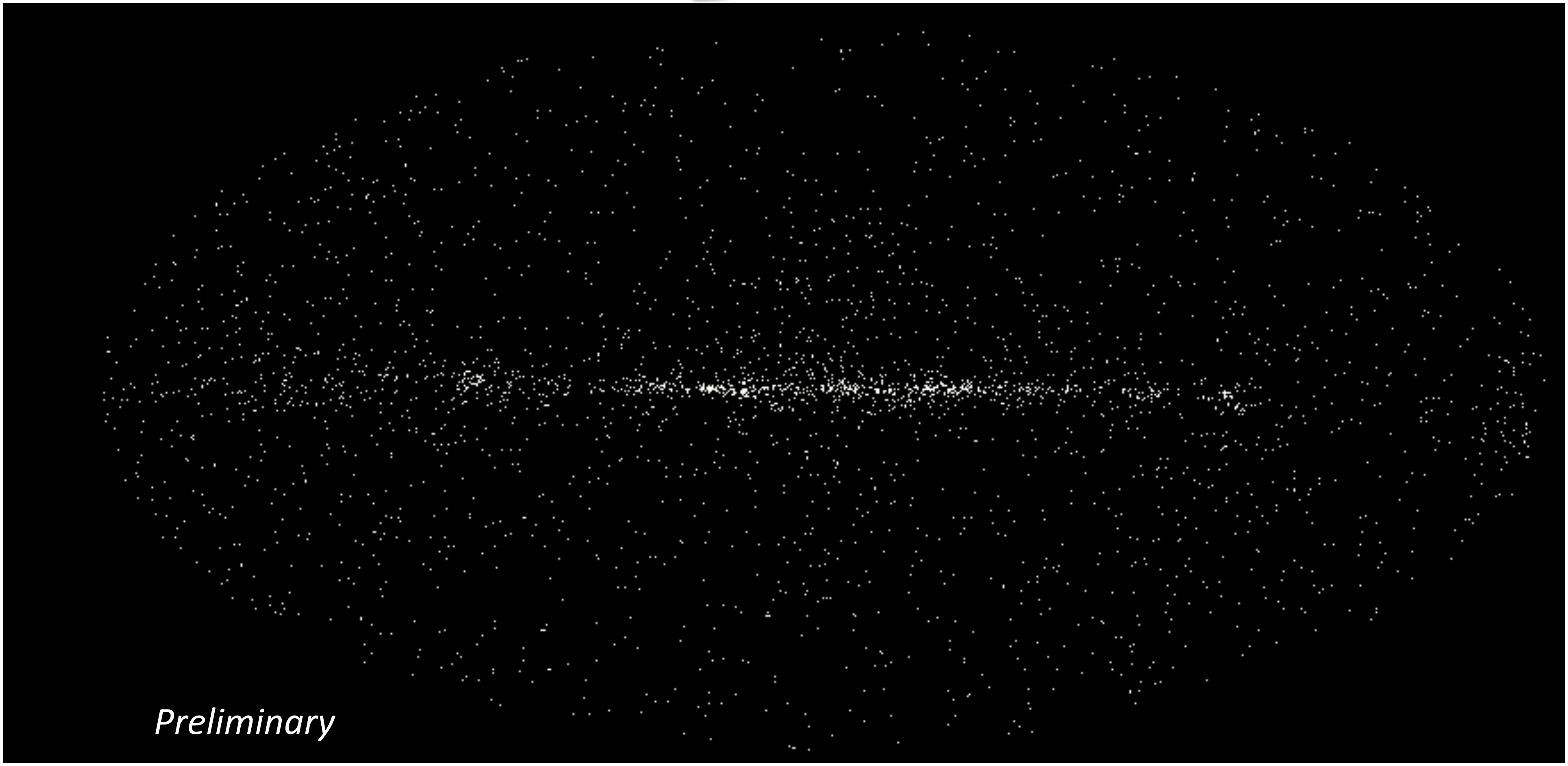
Ajello et al. 5th Fermi symposium 2014

~6 years of P8 data (50 GeV – 2 TeV)

51,000 photons E > 50 GeV
18,000 photons E > 100 GeV
2,000 photons E > 500 GeV

~1 photon every deg^2

Number of photons at >500 GeV are preliminary



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Ajello et al. 5th Fermi symposium 2014

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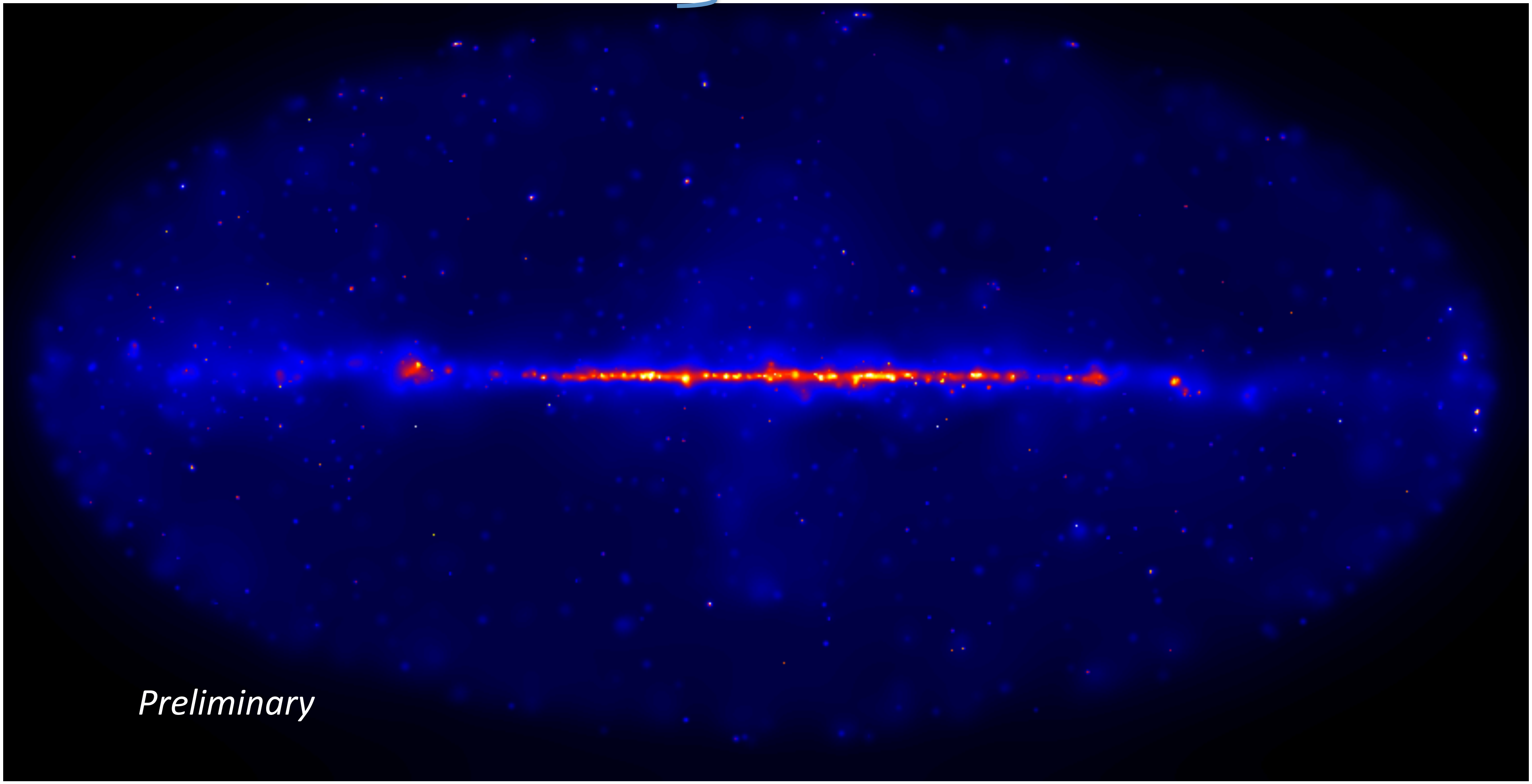


Ajello et al. 5th Fermi symposium 2014

2FHL Some Numbers

Numbers are not definitive since depend on IRFs and diffuse emission model which are subject to change

- Analysis
  - 50 GeV – 2 TeV
  - ~6 years of data
  - Pass 8 (source)
- Detections (preliminary numbers, will change somewhat)
  - **~320 sources**
  - 71 detected by ACTs (TeVCat)
  - **206 detected in 1FHL**
  - 234 detected in 3FGL (4 years, up to 300 GeV)
  - **~60 brand new sources**

Bottom line:* *~100 sources not in 1FHL and ~250 not in TeVCat

2FHL vs 1FHL

Ajello et al. 5th Fermi symposium 2014

	2FHL	1FHL
# Sources	320	514
Energy Range	50 GeV – 2 TeV	10 GeV – 500 GeV
Exposure	6 years	3 years
Av. Sp. index	2.9+/-0.9	2.5+/-0.9
Av. Error Rad (95%)	0.068 deg (4 arcmin!)	0.088 deg
% BL Lacs	~51%	~51%
% FSRQs	~ 1%	~14%

These numbers are preliminary

- ***Median sensitivity of ~10^{-11} erg/cm^2/s***
- ***Half of the sources are in the plane of the Galaxy***

Further performance increase at the highest Fermi-LAT energies

Takahashi et al. 5th Fermi Symposium 2014

Calorimeter-only analysis of the Fermi Large Area Telescope

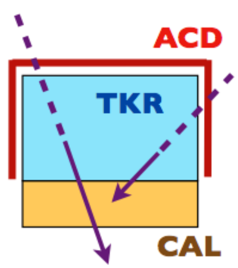
M. Takahashi[1], R. Caputo[2], D. Paneque[3,1], and C. Sgró[4]

The University of Tokyo [1], University of California Santa Cruz [2], Max Planck Institute for Physics [3], and INFN Sezione di Pisa [4]

Calorimeter-only analysis provides a new class of events without usable tracker information, which potentially can increase the instrument acceptance above few tens of GeV. Here we explain the concept and report some preliminary characteristics of this novel analysis.

Regular Fermi-LAT analysis

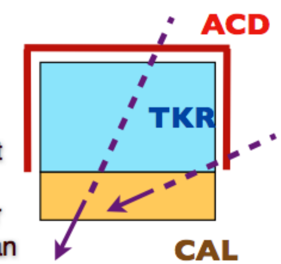
The LAT has three detectors, namely, the Anti-Coincidence Detector (ACD), the Tracker (TKR) and the Calorimeter (CAL). The regular event classes require usable information from the TKR, otherwise, the events are rejected.



Calorimeter-only (CalOnly) Fermi-LAT analysis

The CalOnly adds a new class of events, where events with no usable TKR information can be utilized if sufficient information from the CAL is available. This may occur for events going through the onboard high-pass filter, which have energies larger than 20-30 GeV.

Through the CalOnly analysis one can recover valuable gamma-ray events that are not converted in the TKR. CalOnly events are expected to have a worse signal/background separation and angular resolution with respect to the regular event classes. However, the gamma-rays recovered by the CalOnly analysis can be very valuable above few tens of GeV, where the performance of Fermi-LAT for doing astronomy is photon-statistics limited.



Potentially could increase acceptance by ~1/3 (larger bkg)

→ Important also the increase in temporal coverage of the source !!!

Such event class could potentially be used in a later improvement of 2FHL (or in 3FHL)

3 - Long-term studies of selected blazars

There are several interesting objects

I am involved in the study of the "classical TeV objects" Mrk421 and Mrk501

Extensive MW Campaigns on Mrk421 and Mrk501

Why studying Mrk421 and Mrk501 ?

- **Nearby blazars (z~0.03; ~140 Mpc)**
  → Imaging with VLBA possible down to scales of 0.01-0.1 pc (>~ blob size)
  → Minimal effect from EBL (among VHE blazars), which is not well known
  → systematics for VHE blazar science

- **Bright blazars (in part also due to the fact that they are nearby)**
  → Easy to detect with IACTs, *Fermi*, and X-rays, Optical, radio instruments in short times
  → "Relatively Easy" to characterize the entire SED in every "shot"
  → Can study the evolution of the entire SED

- **No strong BLR (another unknown… composition, shape…)**
  → More simple to understand than FSRQs

In summary:

→ **Mrk421 and Mrk501 are among the "easiest" blazars to study**

It is more difficult to study other blazars that are farther away, dimmer, or have more complicated structures

Mrk421 and Mrk501 can be used as high-energy physics laboratories to study blazars

Extensive MW Campaigns on Mrk421 and Mrk501

A multi-instrument and multi-year project

Since 2009, we have substantially **improved Temporal and Energy coverage** of the sources in order to obtain SEDs as simultaneous as possible, as well as to be able to perform multi-frequency variability/correlation studies over a long baseline and correlate with high resolution radio images and polarizations (to learn about the jet structure)

•More than 25 instruments participate, covering frequencies from radio to VHE

Radio: VLBA, OVRO, Effelsberg, Metsahovi…
mm: SMA, IRAM-PV
Infrared: WIRO, OAGH
Optical: GASP-WEBT, GRT, Liverpool, Kanata…
UV: Swift-UVOT
X-ray: (RXTE), Swift-XRT, NuSTAR
Gamma-ray: *Fermi*-LAT
VHE: MAGIC, VERITAS, FACT

Monitored regardless of activity (*increase coverage during flares*)
→ observed every few days for about half year (*every year* !)

Extensive MW Campaigns organized on Mrk421/Mrk501

Mrk421 (Jan19th, 2009-Jun1st ,2009: 4.5 months)- Planned observations: every 2 days

Mrk501 (Mar15th, 2009-Aug1st,2009: 4.5 months) -Planned observations: every 5 days

Mrk421 (Dec8, 2009-Jun20 ,2010: 6 months)- Planned observations: every 1-2 days

Mrk421 (Dec1, 2010-Jun15 ,2011: 6 months)- Planned observations: every 2 days

Mrk501 (March1, 2011-Sep1,2011: 6 months) -Planned observations: every 3 days

Mrk421 (Dec23, 2011-May31 ,2012: 5.5 months)- Planned observations: every 2 days

Mrk501 (Feb15, 2012-June31,2012: 4.5 months) -Planned observations: every 4 days

Mrk421 (Dec, 2012-May ,2013: 6 months)- Planned observations: every 2 days

Mrk501 (April, 2013-Sep,2013: 5 months) -Planned observations: every 4 days

Mrk421 (Dec, 2013-May ,2014: 6 months)- Planned observations: every 2 days

Mrk501 (March, 2014-Aug,2014: 5 months) -Planned observations: every 3 days

Long term goals

The <u>practical goal</u> is build a very complete pool of MW data that allows us to make detailed studies on the observables we have:

- Quantify the overall (entire SED) flux variability and correlations during long baseline

- Correlate with VLBA images and polarization measurements
  - → VLBA can spatially resolve ~1.e16 cm for Mrk421/Mrk501
    - → because these blazars are nearby !!
- Put strong experimental constrains to the currently used emission models
  - → *Time dependent SED modeling !!*

The <u>ultimate goal</u> is to address fundamental questions on how Mrk421 and Mrk501 (and perhaps HBLs in general) work:

- Nature of the radiating particles
- Location of the blazar emission
- Acceleration and radiation processes
- How flux variations are being produced; what changes in the source
- NEED to connect with people working on simulations of *jet formation and collimation*

These multifrequency (multi-instrument) efforts will deliver several publications while we collect these exquisite MW data

Highlight results from first MW campaigns

In this talk I will report results on several topics

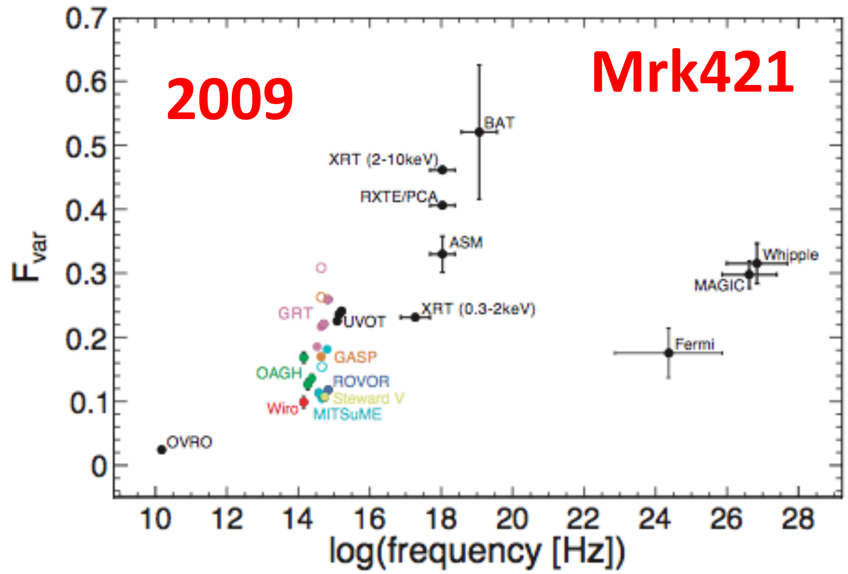
3.1 – Variability
3.2 – Correlations
3.3 – SED modeling
3.4 - Flaring activity with a EVPA rotation
3.5 – Flaring activity with ejection of a VLBA blob

Most results extracted from the following scientific publications

- Abdo et al., 2011 (ApJ 727, 129) + Abdo et al., 2011 (ApJ 736, 131)
- Aleksic et al 2014a (accepted in A&A, **arXiv:1410.6391**)
- Lico et al., 2014 (accepted in A&A, **arXiv:1410.0884**)
- Aleksic et al 2014b (Submitted to A&A)
- Aleksic et al., 2014c (Submitted to A&A)
- Campaign to observe Mrk421 in 2013 (paper in internal review)
- Campaign to observe Mrk501 in 2014 (paper in internal review)

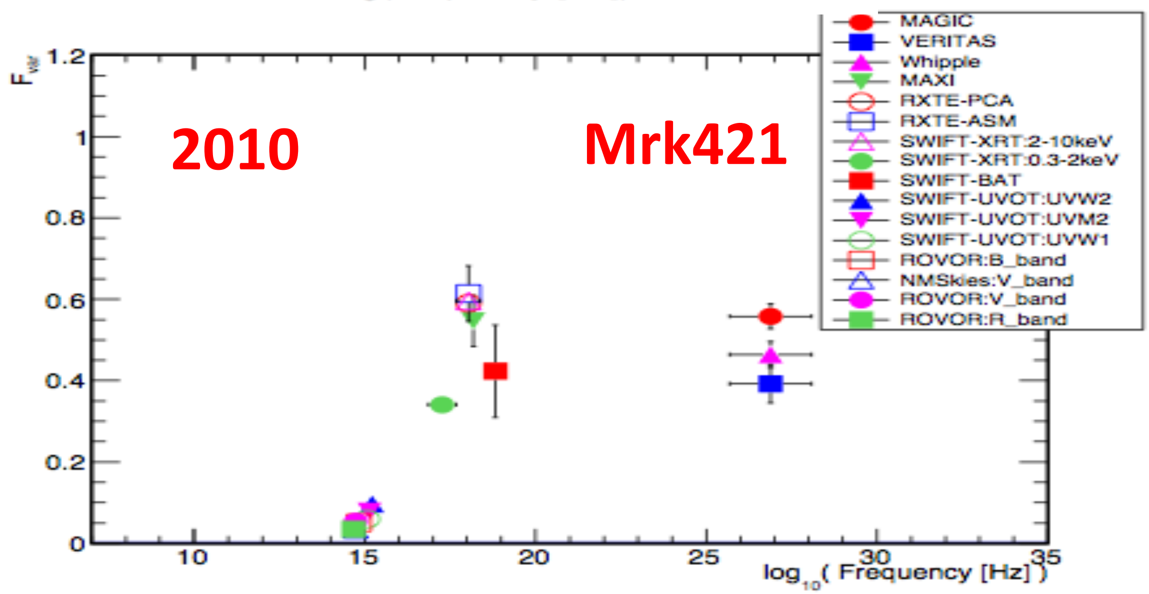
3.1 – Variability

Variability quantified following prescription from Vaughan et al. 2003



$$F_{\text{var}} = \sqrt{\frac{S - \langle \sigma_{err} \rangle^2}{\langle Flux \rangle^2}}$$

Highest variability occurs at X-ray and VHE



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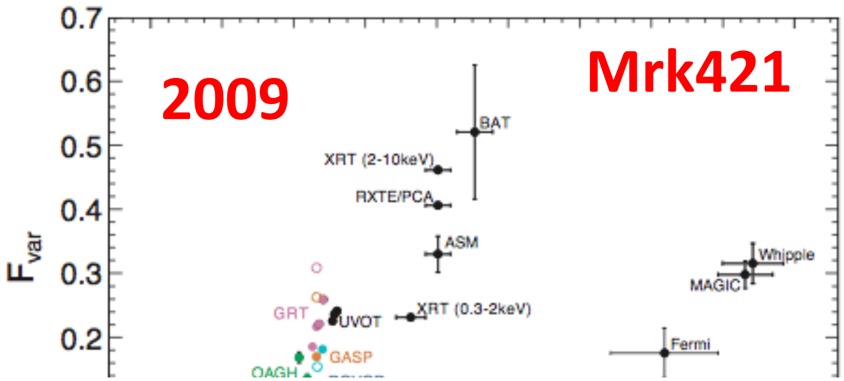
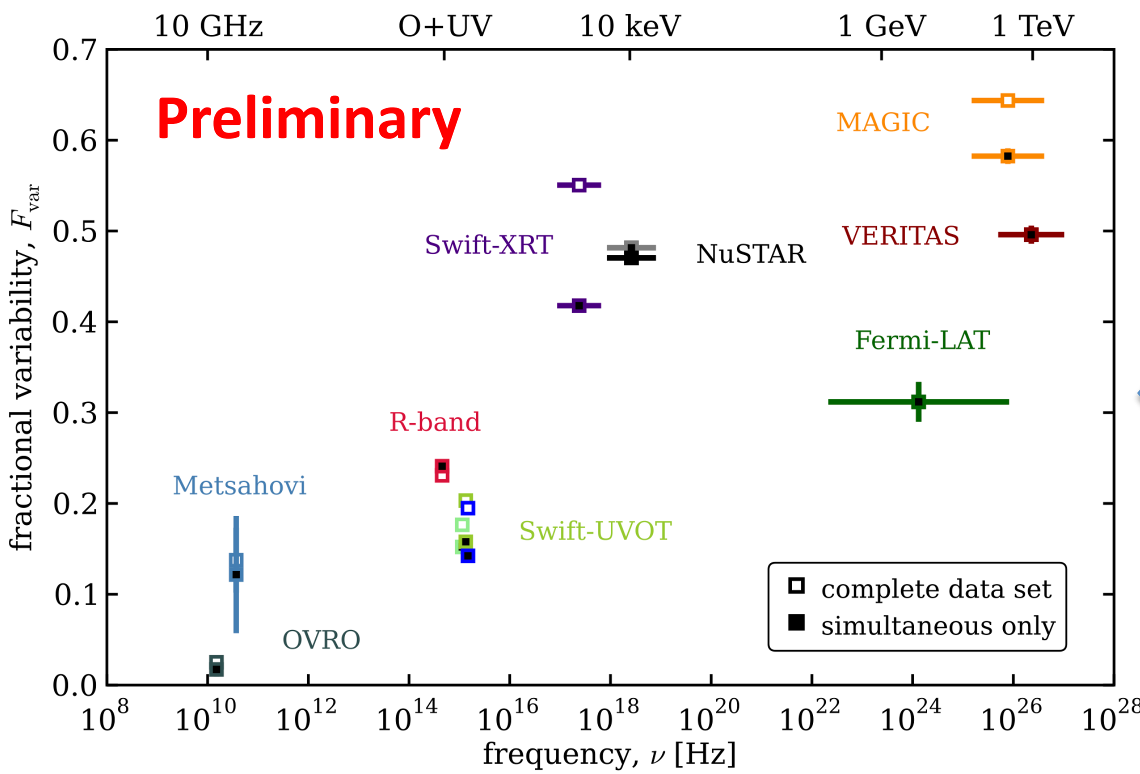


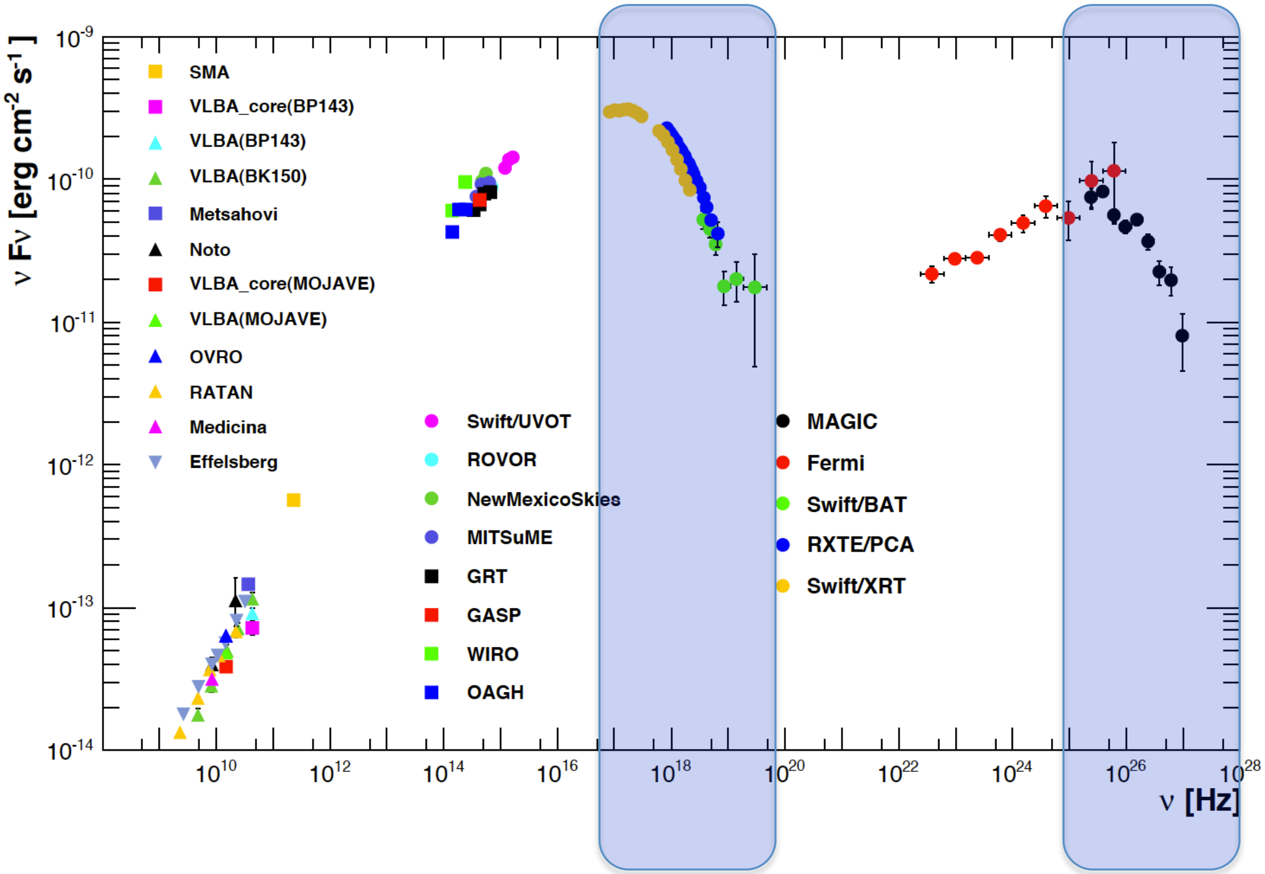
$$F_{var} = \sqrt{\frac{S - \langle \sigma_{err} \rangle^2}{\langle Flux \rangle^2}}$$

Highest variability occurs at X-ray and VHE



Mrk421 2013

3.1 – Variability

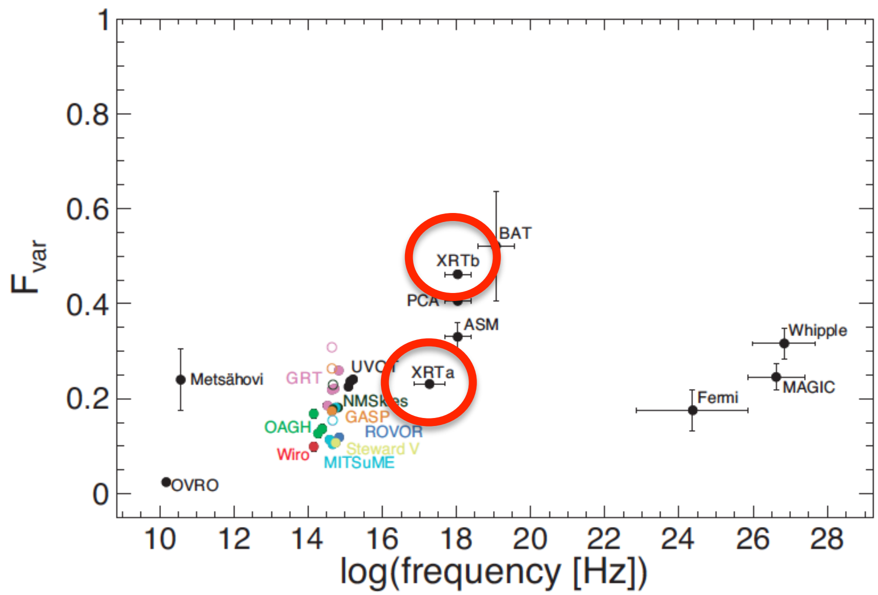


"Falling segments" of the low- and high-energy bumps are more variable than the "rising segments"

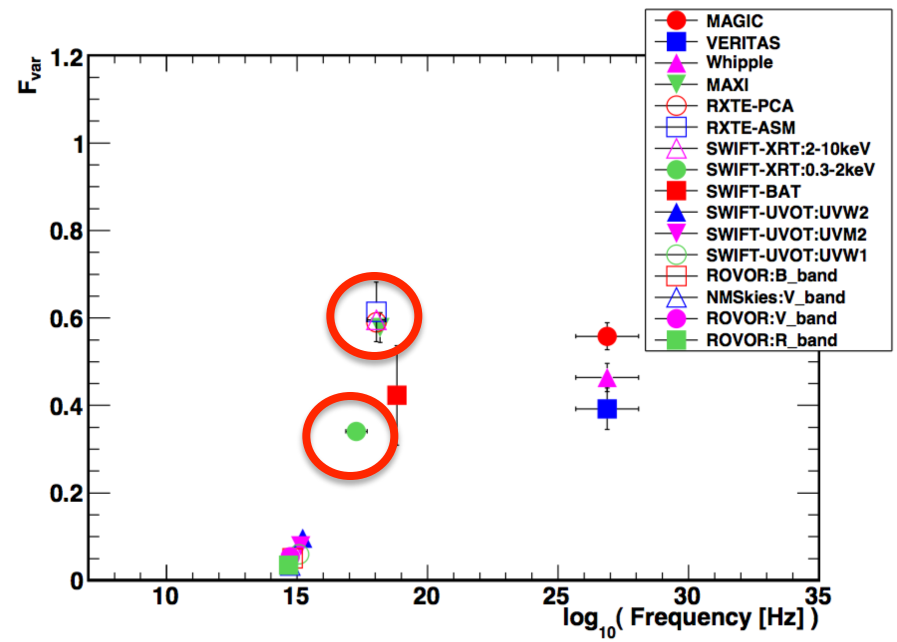
→ *Within the synchrotron self-Compton scenario, the X-ray and VHE emission is produced by the highest-energy electrons*

Fractional variability larger in the 2-10 keV than in the 0.3-2 keV

Mrk421 MW 2009



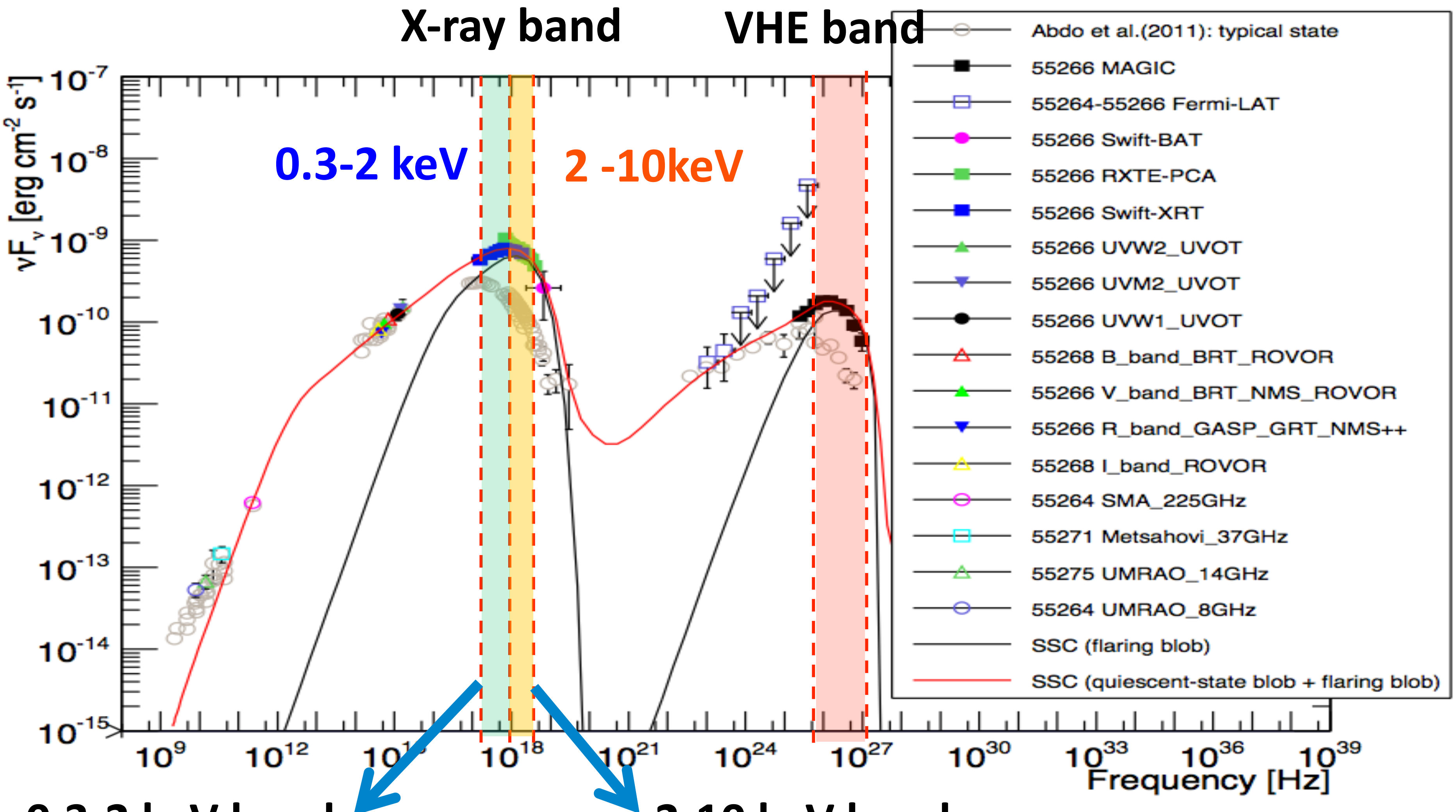
Mrk421 MW 2010 (March)



Similar behaviour observed during the non-flaring and the flaring activity of Mrk421 in the campaigns from 2009 and 2010

→ Some features get repeated over time, in high and low state (intrinsic characteristic of the source)

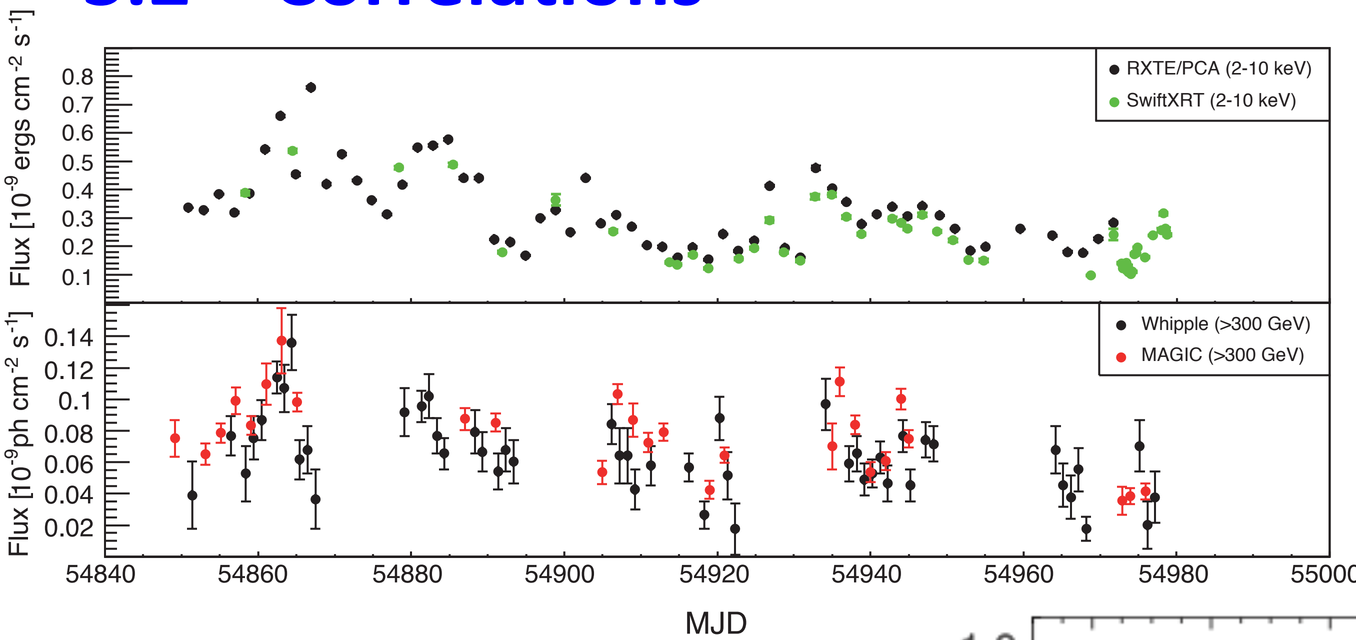
3.1 – Variability



0.3-2 keV band
samples the emission
At or BEFORE the Sync. peak

2-10 keV band
samples the emission
At or AFTER the Sync. peak

3.2 – Correlations

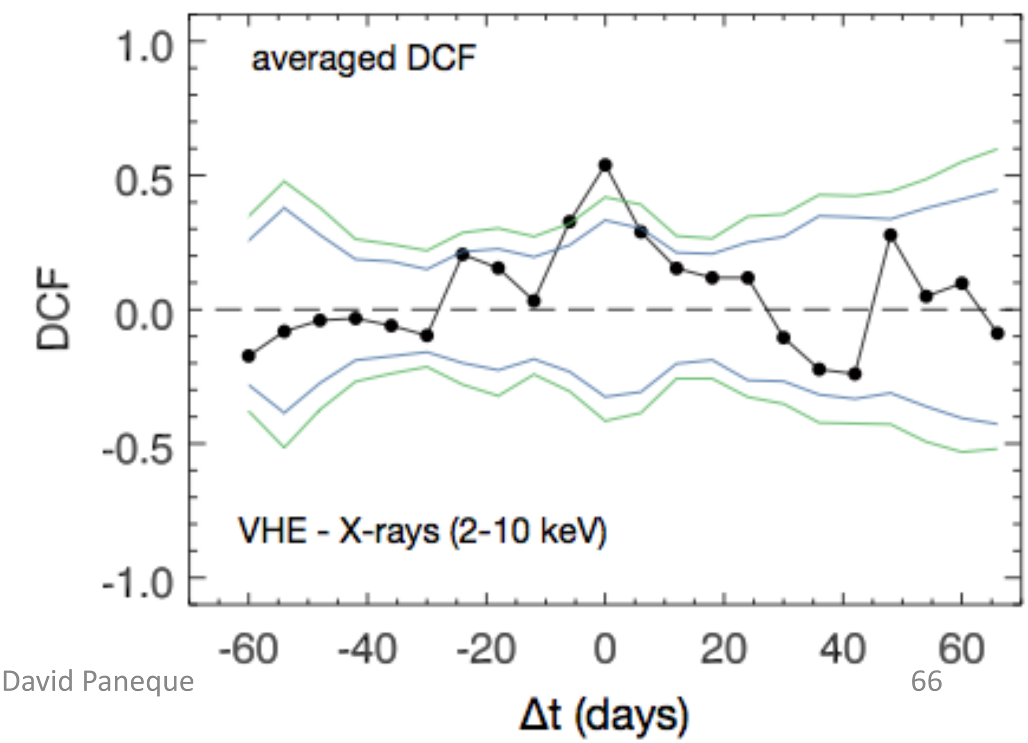


Mrk421
MW 2009

Low state and little variability in X-ray/VHE (no flares !!)

X-ray and VHE are correlated ALSO on long-term timescales and during the low activity (no flaring activity)

→ Similar processes during flaring and non-flaring activity



3.2 – Correlations

Correlation between radio (VLBA 43 GHz) and gamma (>0.1 GeV) also detected for Mrk421 during non-flaring (but variable !!) activity

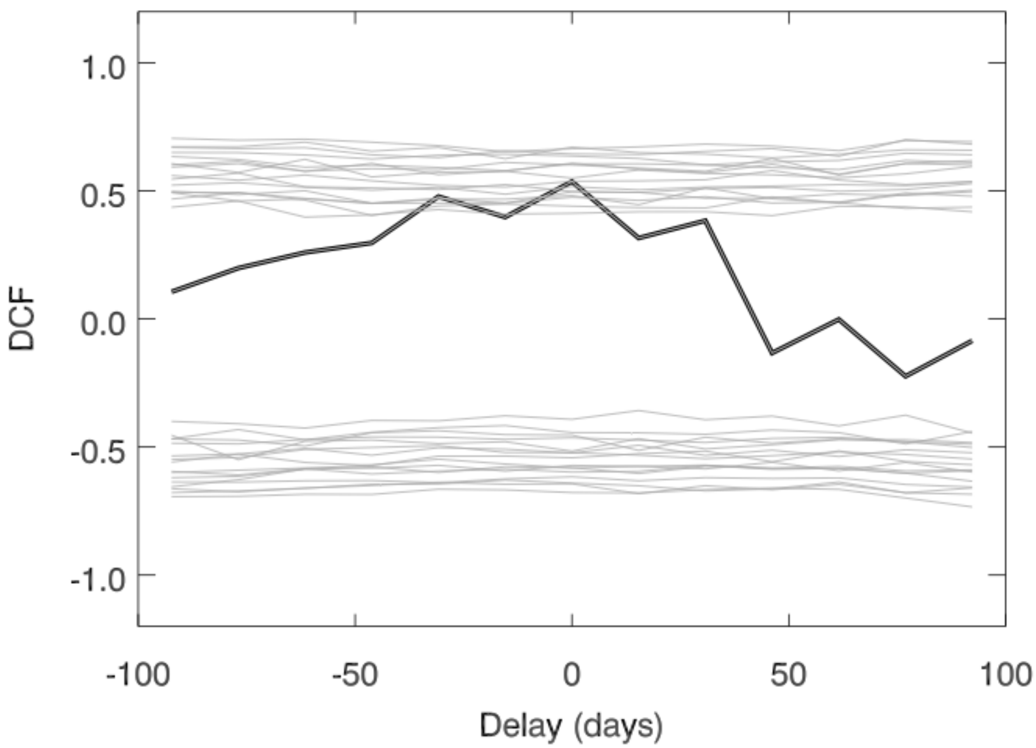


Fig. 7. Discrete cross-correlation function between the γ-ray and the 43 GHz radio light curves (black curve). The gray curves represent the 99.7% confidence limits relative to stochastic variability, obtained from the combination of different power spectral density slopes. See section 3.5 for more details.

3.2 – Correlations

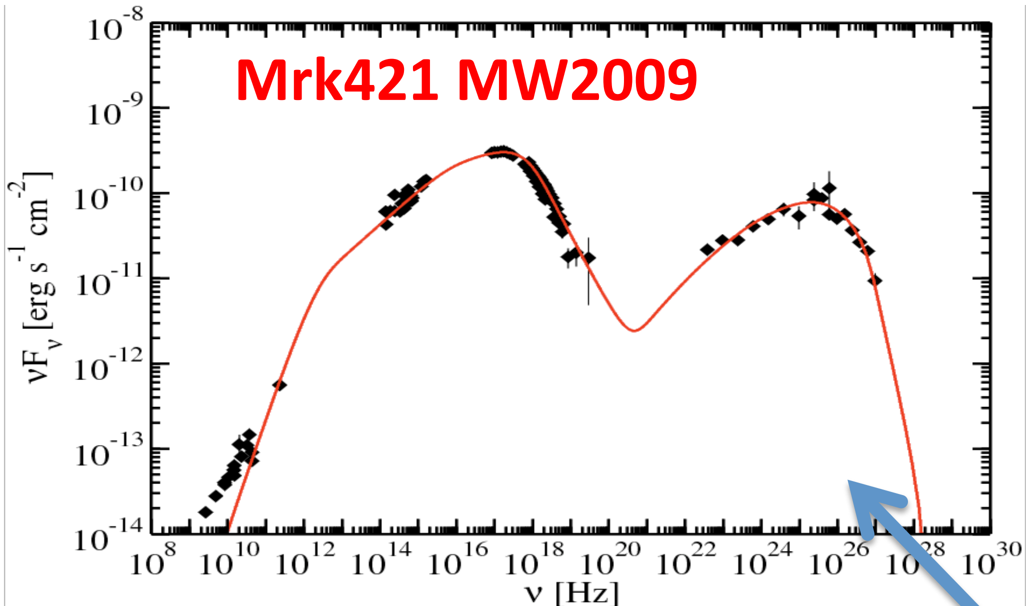
Correlations
Radio/Gamma
X-ray/TeV
observed on months timescales, non-flaring activity

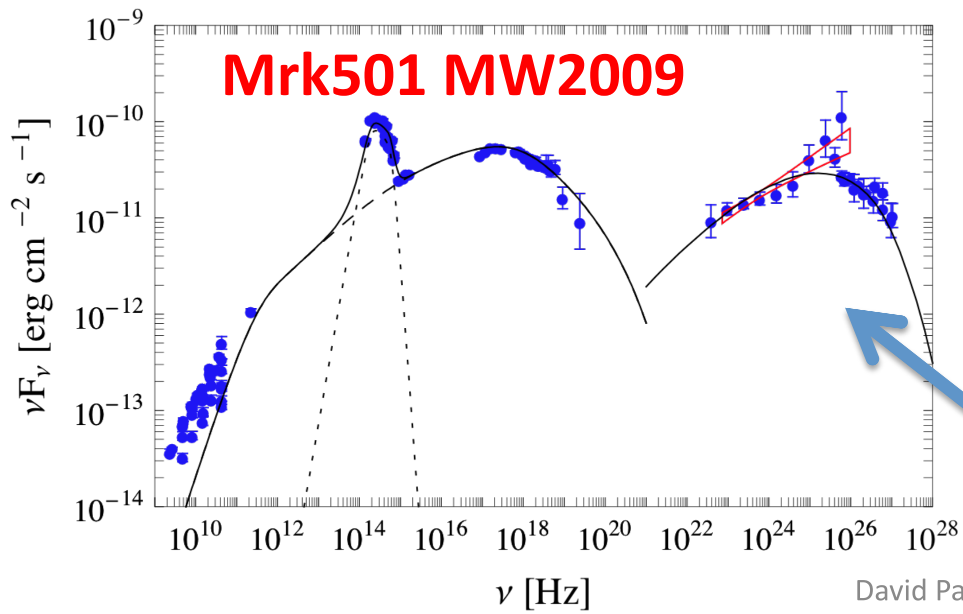
→ Favor leptonic scenarios

Hadronic scenarios cannot explain this persistent correlation (radio/gamma and X-ray/VHE) during non-flaring activity and long timescales

An hadronic component is not excluded, but it cannot dominate the overall broadband variability

3.3 – SED modeling





One-zone SSC describes well the broadband (radio to VHE) data collected for Mrk421 and Mrk501 during non-flaring activity

→Done many times in the past, but with less temporal and energy coverage.
First time with Fermi-LAT !!

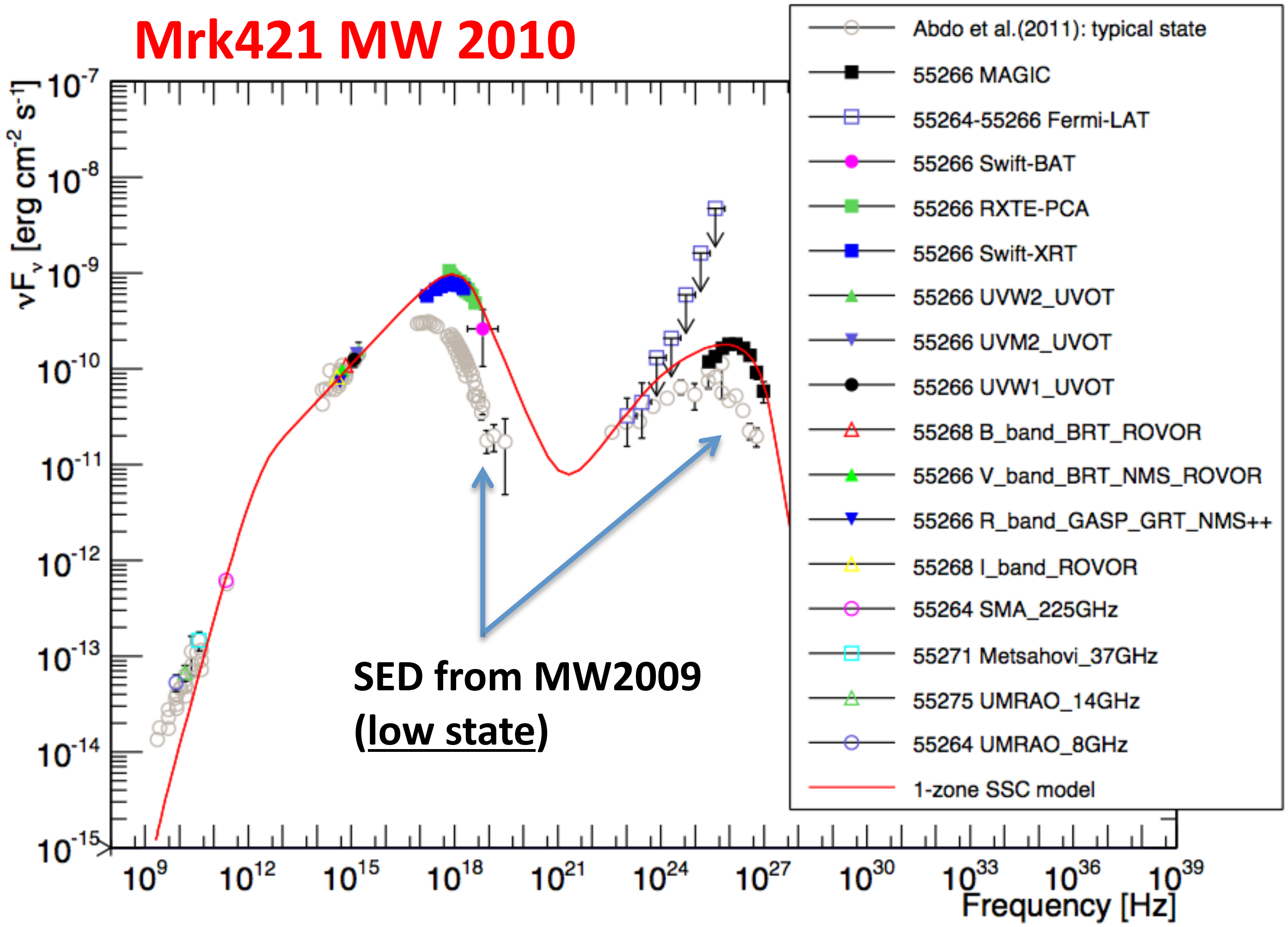
Abdo et al., ApJ 736 (2011) 131

Abdo et al., ApJ 727 (2011) 129

3.3 – SED modeling

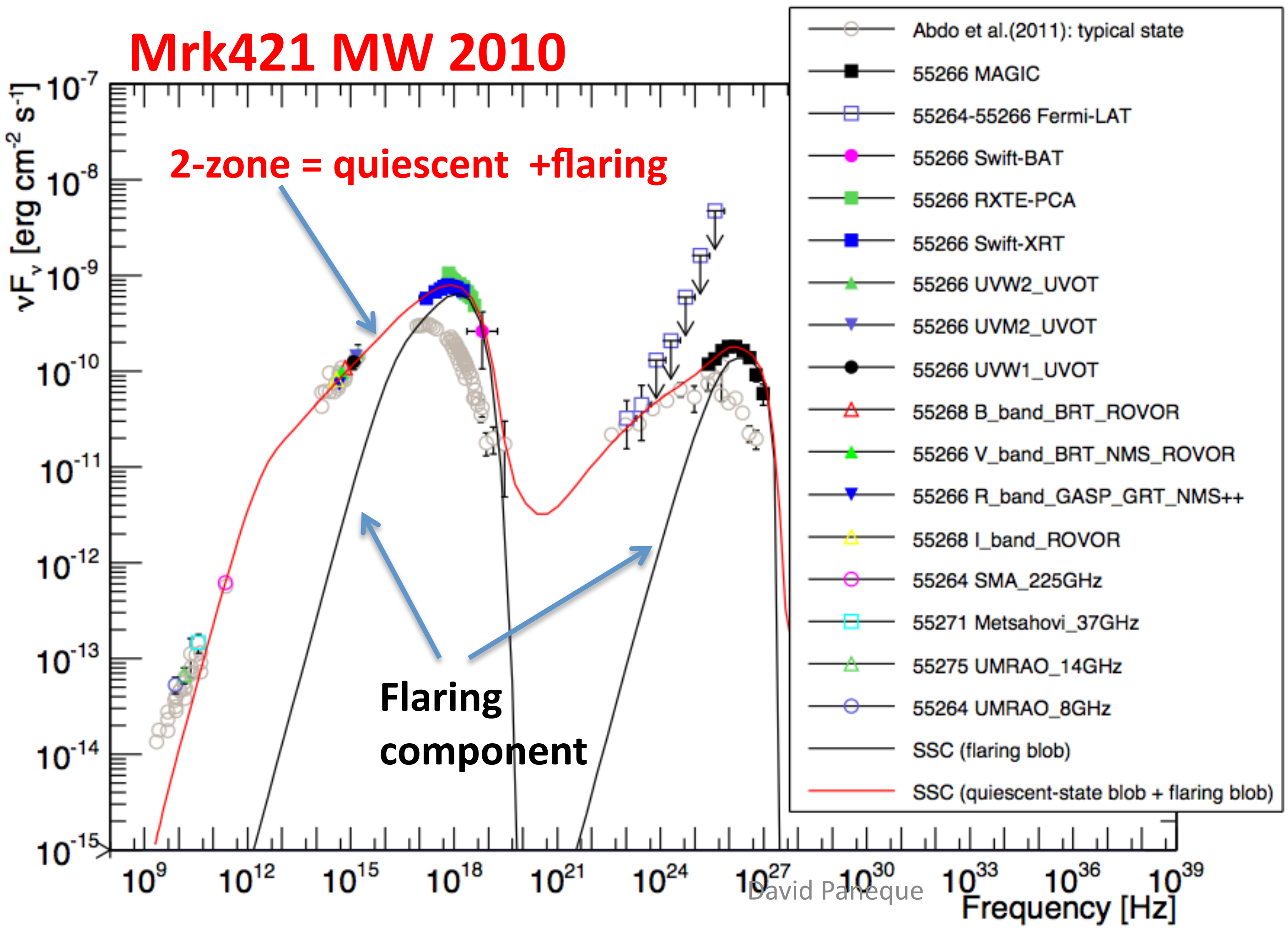
One-zone SSC also describes well the broadband (radio to VHE) data collected for Mrk421 when it flares

→ Done many times in the past, but with less temporal and energy coverage



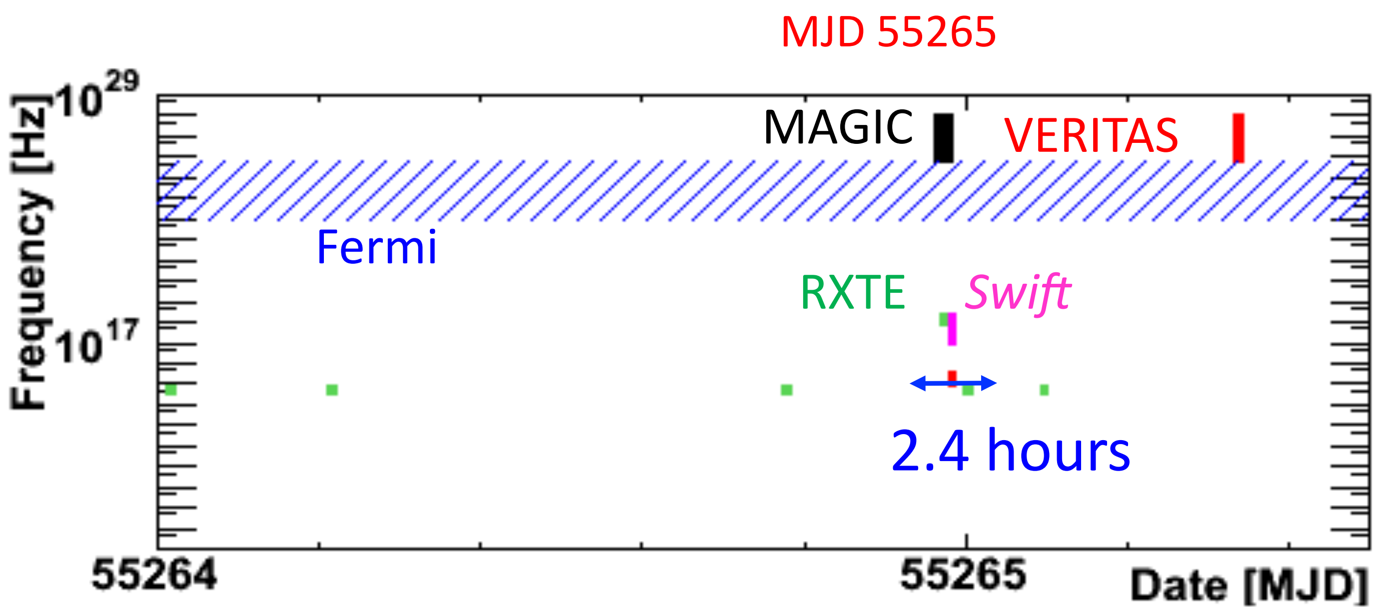
3.3 – SED modeling

We also successfully modeled the SED with a <u>two-zone SSC</u>
→ quiescent + flaring (essentially only in X-ray and VHE)



SED modeling (Mrk421, 2010 March flare)

Very good simultaneity in MW observations

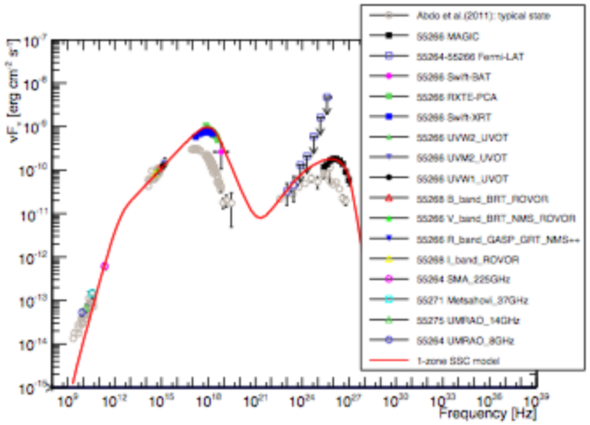


Observations are truly simultaneous

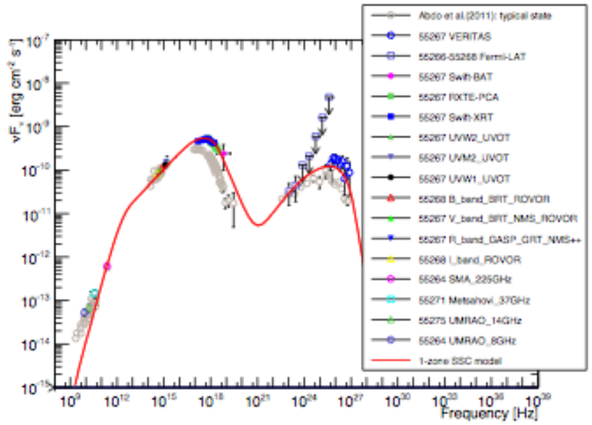
→ Very important during flaring activity

→ reliability in the results derived with these data

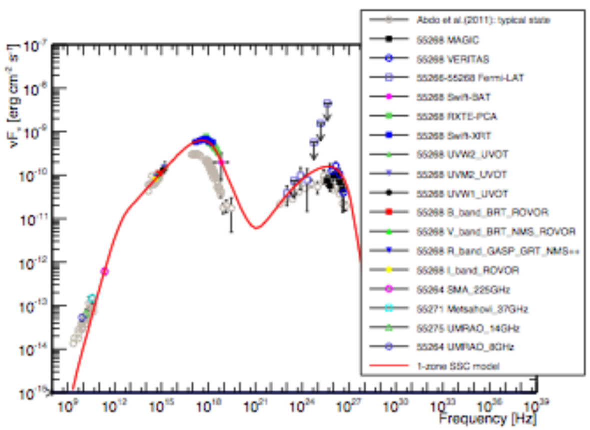
We can study the evolution of the SED during 13 consecutive days



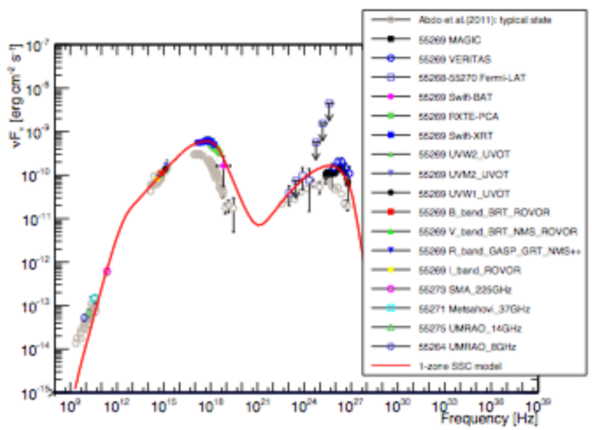
(a) MJD 55266.



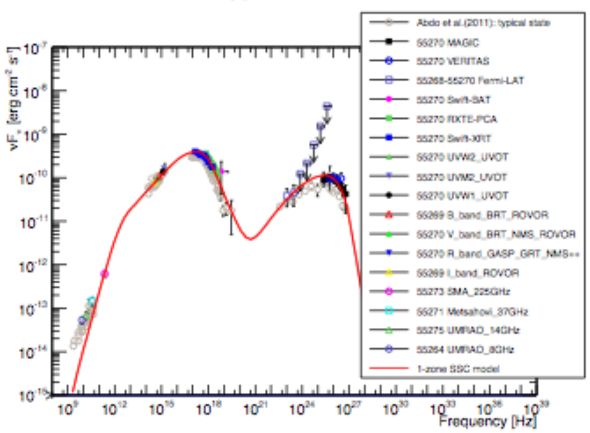
(b) MJD 55267.



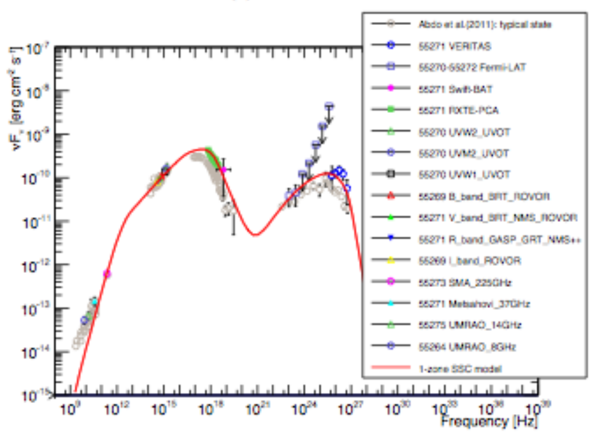
(c) MJD 55268.



(d) MJD 55269.



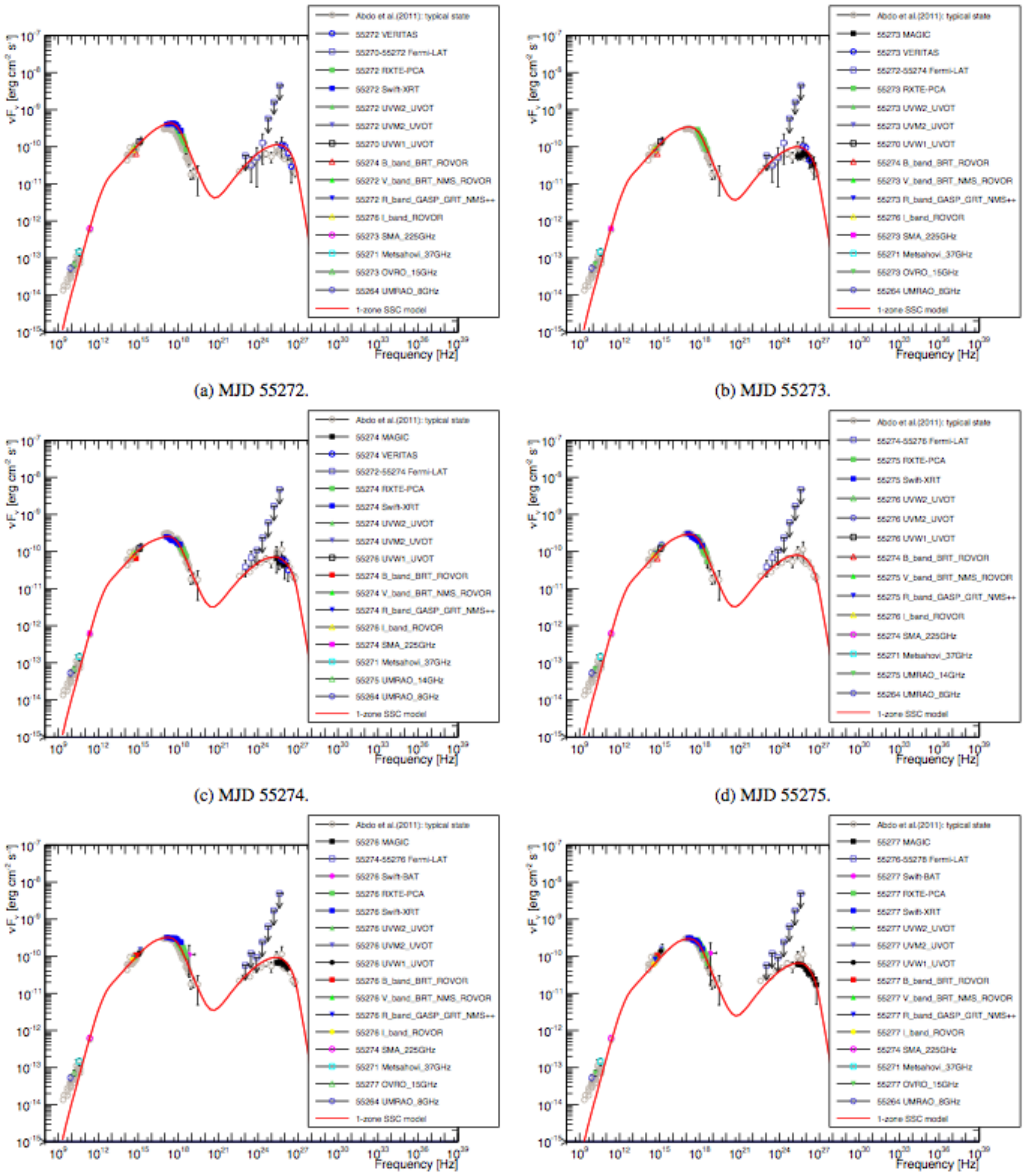
(e) MJD 55270.



(f) MJD 55271.

Mrk421 13-day long flaring activity during March 2010

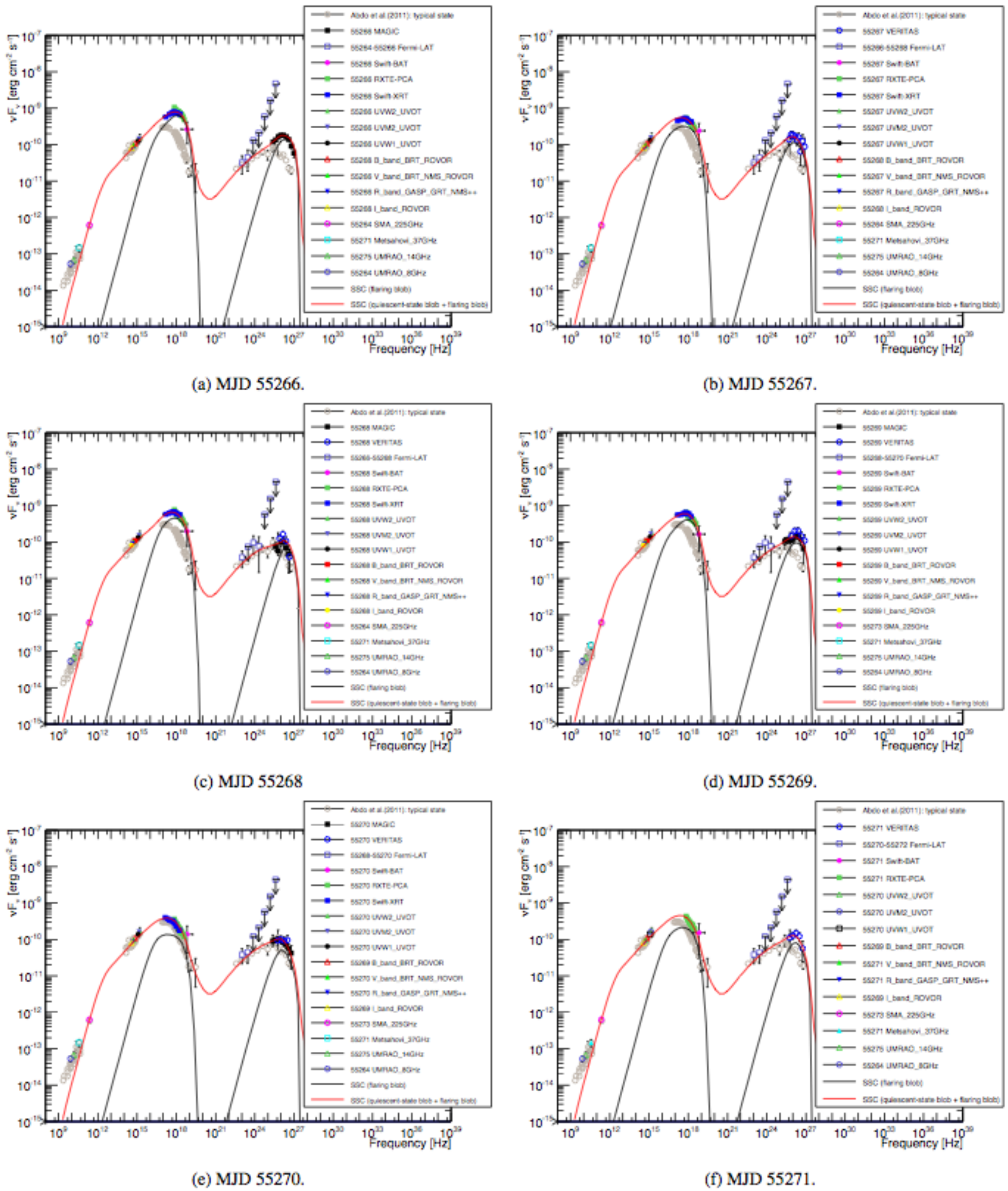
Broadband SEDs measured on single days can be described with 1-zone SSC model (Part 1)



(a) MJD 55272. (b) MJD 55273. (c) MJD 55274. (d) MJD 55275. (e) MJD 55276. (f) MJD 55277.

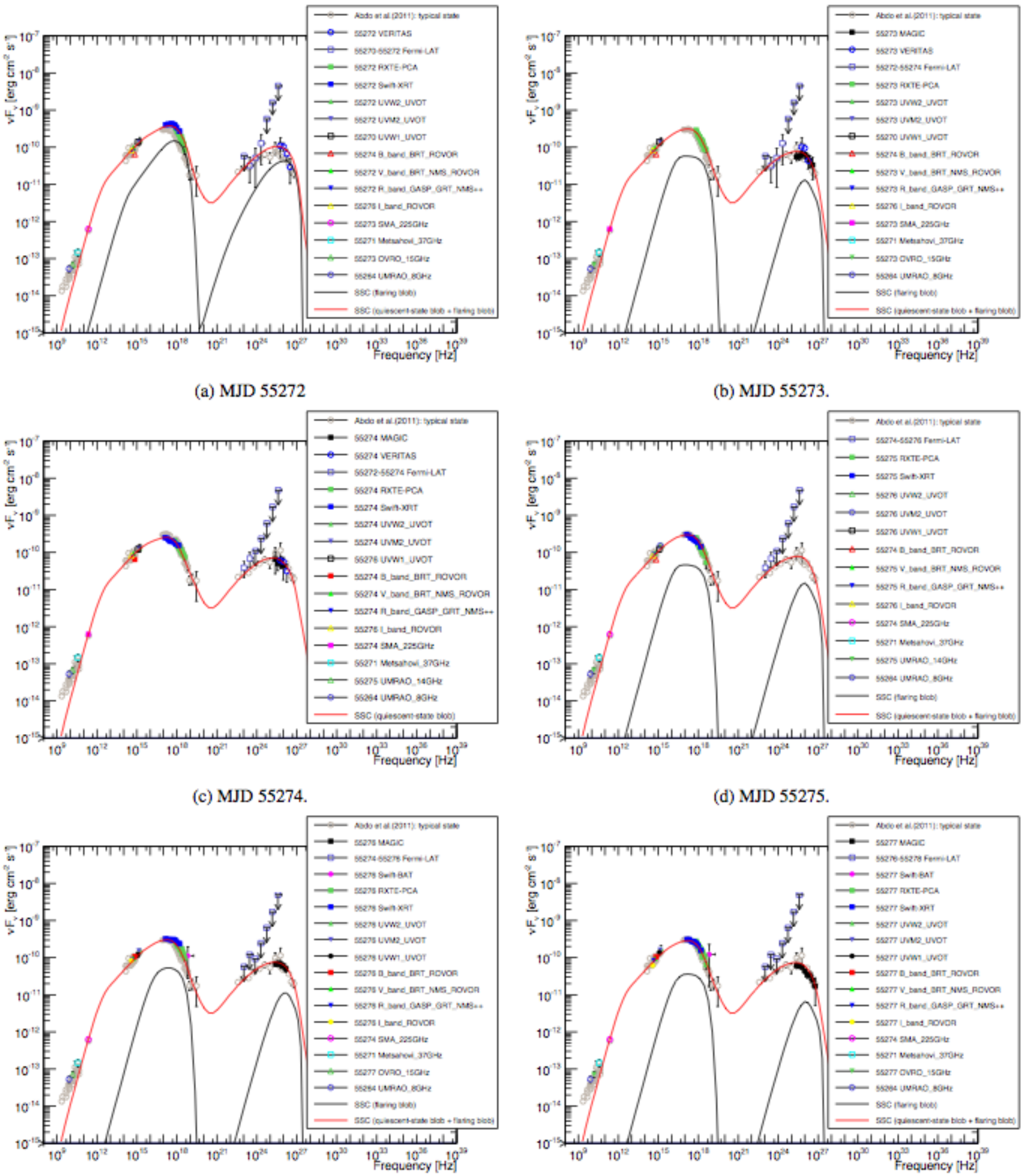
Mrk421 13-day long flaring activity during March 2010

Broadband SEDs measured on single days can be described with 1-zone SSC model (Part 2)



Mrk421 13-day long flaring activity during March 2010

Broadband SEDs measured on single days can be described with 2-zone SSC model (Part 1)



(a) MJD 55272

(b) MJD 55273.

(c) MJD 55274.

(d) MJD 55275.

(e) MJD 55276.

(f) MJD 55277.

Mrk421 13-day long flaring activity during March 2010

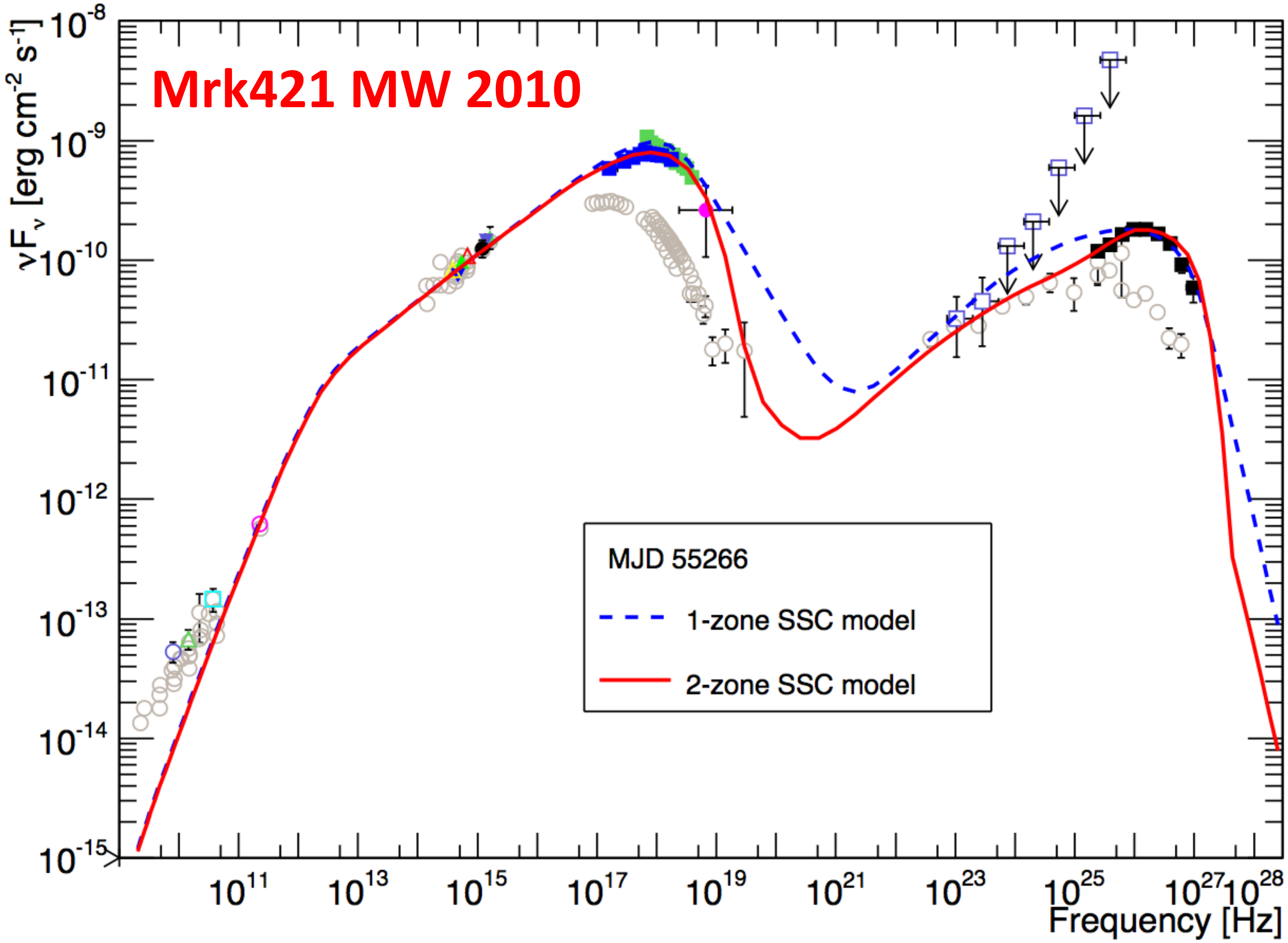
Broadband SEDs measured on single days can be described with 2-zone SSC model (Part 1)

3.3 – SED modeling

One-zone vs two-zone SSC model

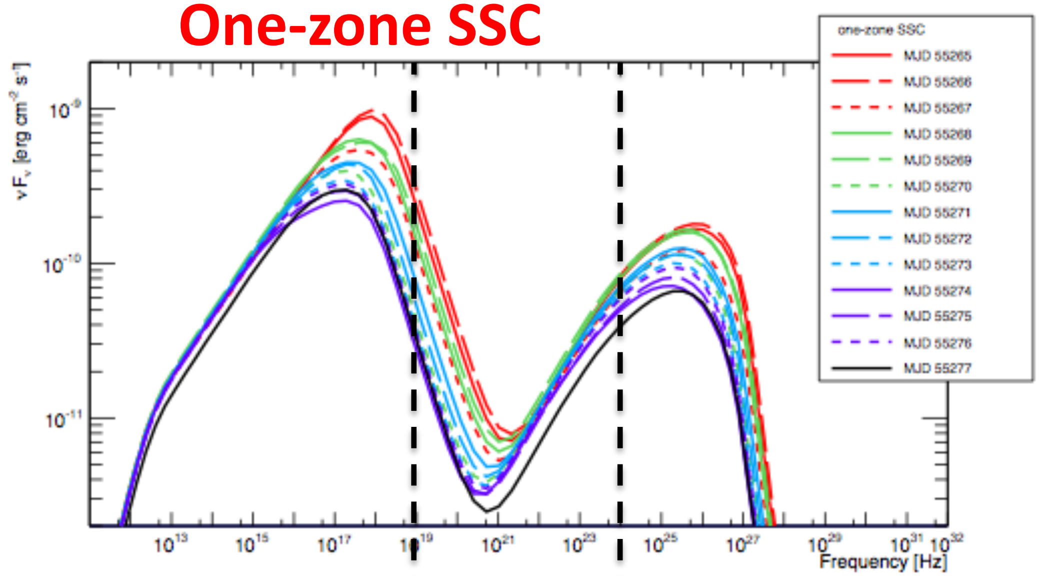
→ Both of them provide reasonably good agreement

→ Two-zone SSC describes slightly better the narrow peaks

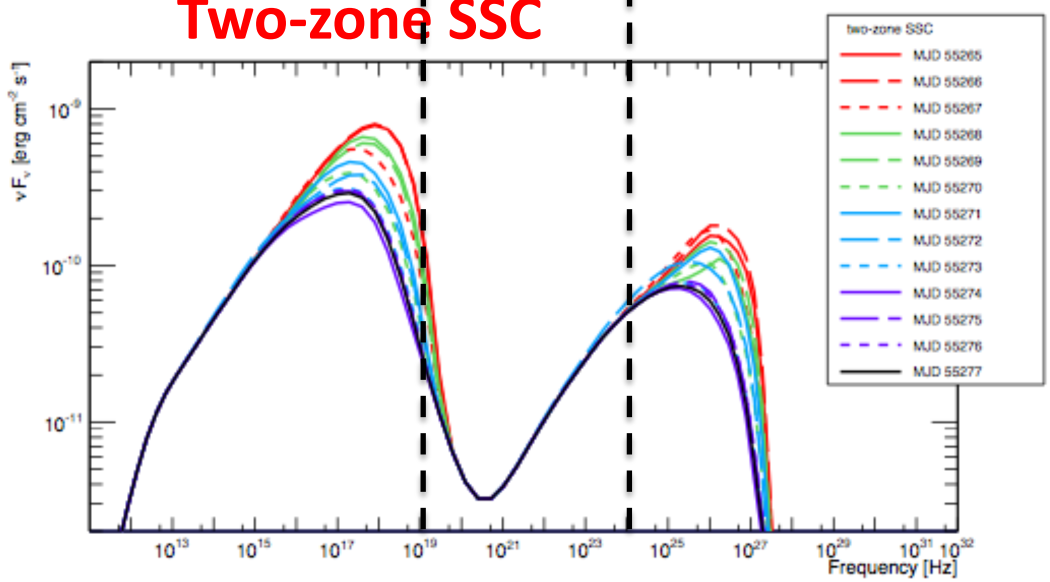


3.3 – SED modeling

One-zone SSC



Two-zone SSC



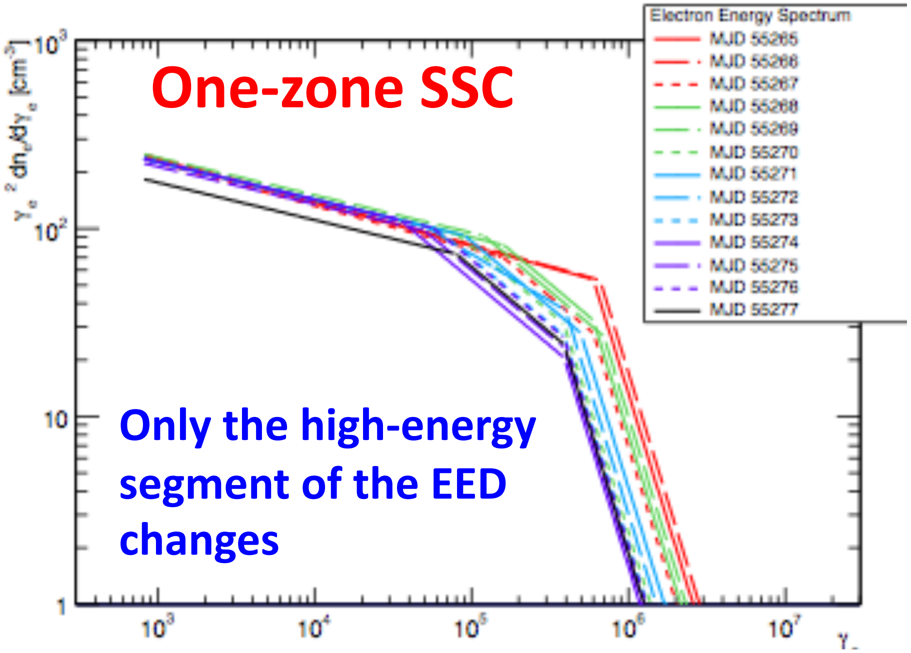
Mrk421 MW 2010

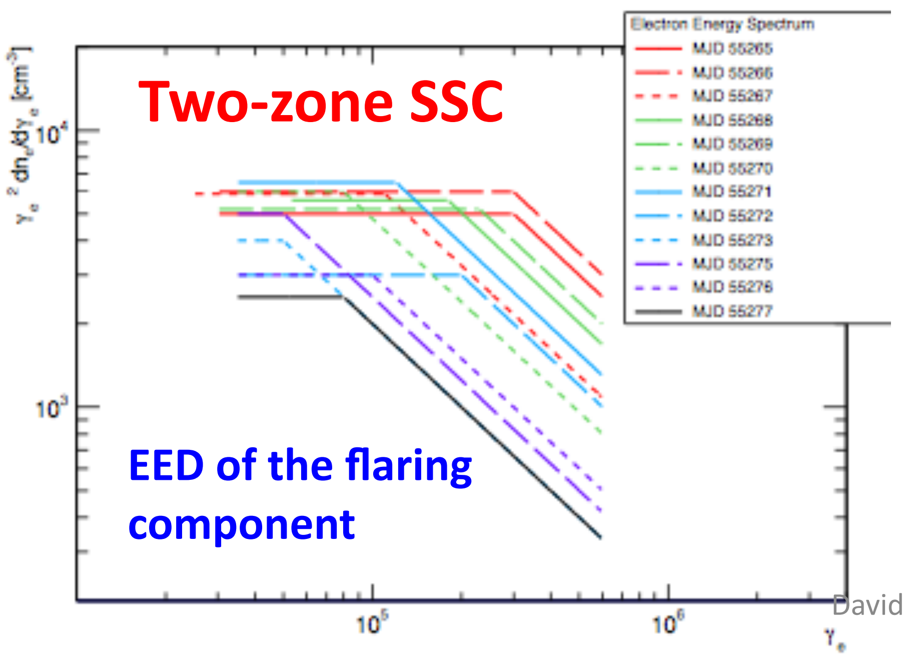
13 SEDs from models

Variability patterns for the one-zone and two-zone SSC broadband emission is somewhat different, specially in the range between 50 keV and 50 GeV

The multi-band variability measured during the 13-day long flare in March 2010 could not distinguish between these two scenarios. *More prominent and longer flaring activities might make this distinction possible*

3.3 – SED modeling





Mrk421 MW 2010

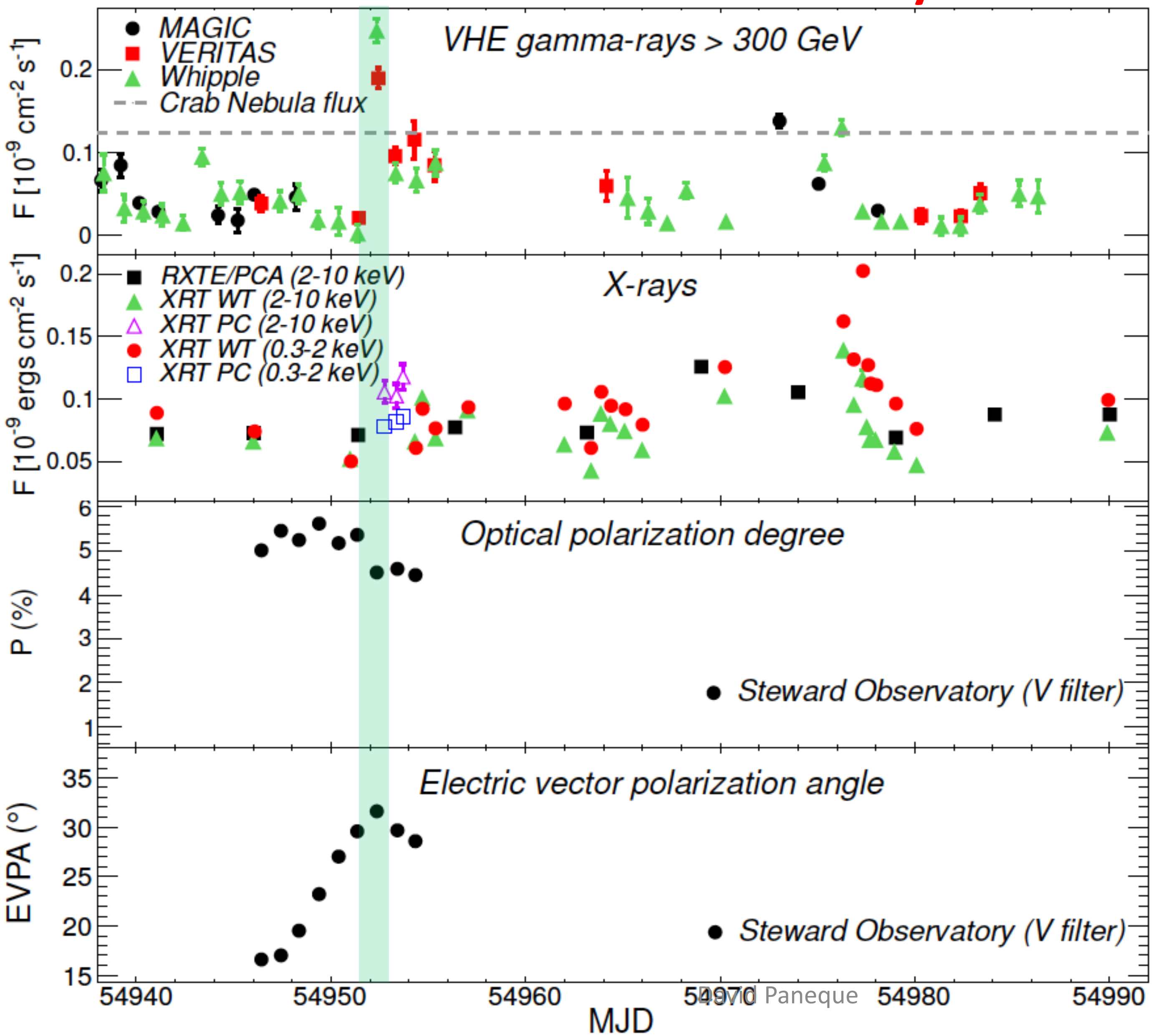
One-zone vs two-zone SSC model

In both cases we could describe the 13-day long flaring activity with changes in the electron energy distribution (EED)

Variations in the broadband SED during the flaring episodes in blazars may be dominated by particle acceleration-and-cooling

3.4 - Flaring activity with EVPA rotation

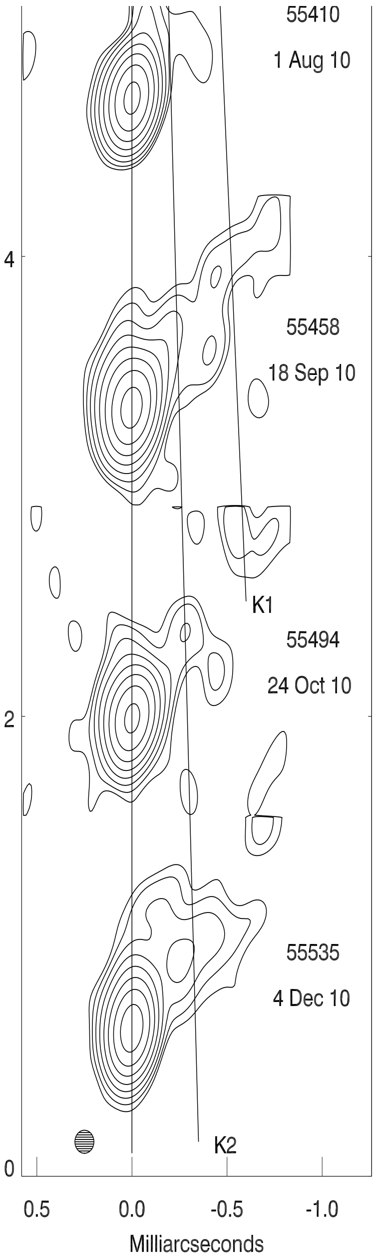
Mrk501 MW 2009 Preliminary



Rotation of EVPA that stops right at the day of the big TeV flare

NEVER observed before for Mrk501

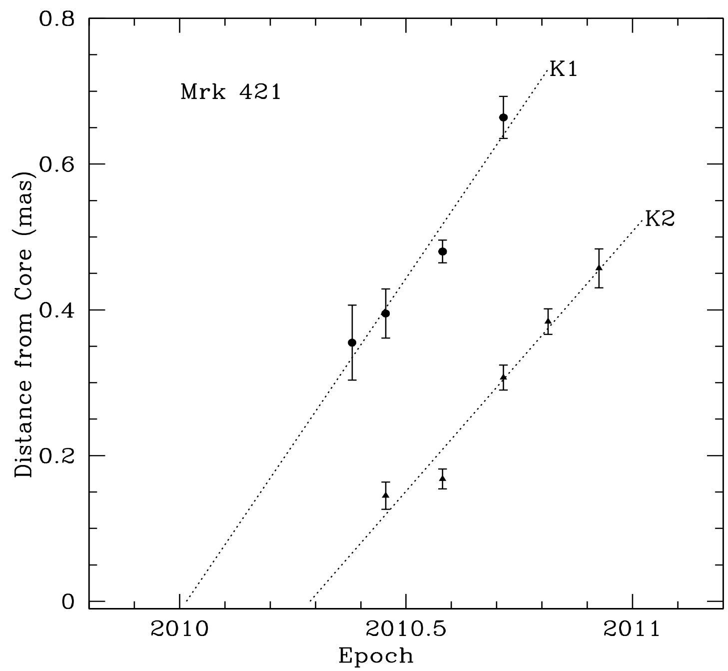
3.5 – Flaring activity with ejection of VLBA blobs

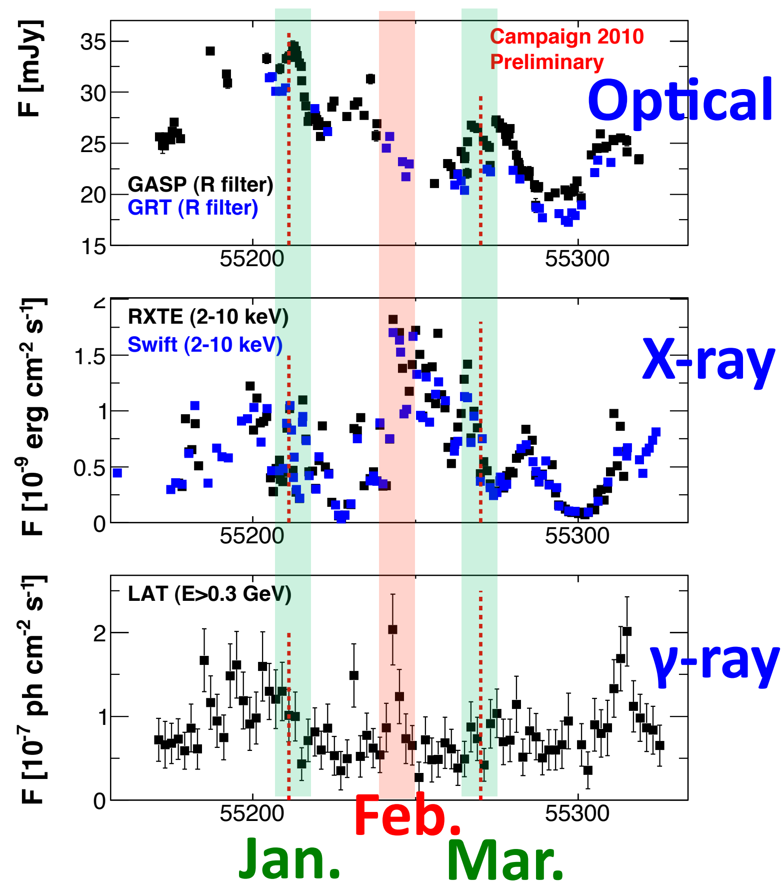


Mrk421 is also monitored with VLBA by the Boston Univ. Blazar group

VLBA components K1 and K2 traced back to the VLBA core in January and March 2010, coinciding with the flaring activities in 2010 January and March (but NOT with the BIG Flare in February)

Correlation between flaring activity and "ejection" of VLBA blobs NEVER seen before for Mrk421





Flaring activity with EVPA rotation
+
Flaring activity with ejection of VLBA blobs

Similar (but not identical !!) behaviour observed for various other sources (LBLs and FSRQs) in the last years:

BL Lacertae : Marscher et al, Nature 452 (966), 2008
PKS 1510-089 : Marscher et al, ApJL, 710 (126), 2010
3C 279 : Abdo et al, Nature 463 (919), 2010
3C 454.3 : Jorstad et al, ApJ 715 (362), 2010
OJ 287 : Agudo et al, ApJ 726 (13), 2011
AO 0235+164 : Agudo et al, ApJ 735 (10), 2011

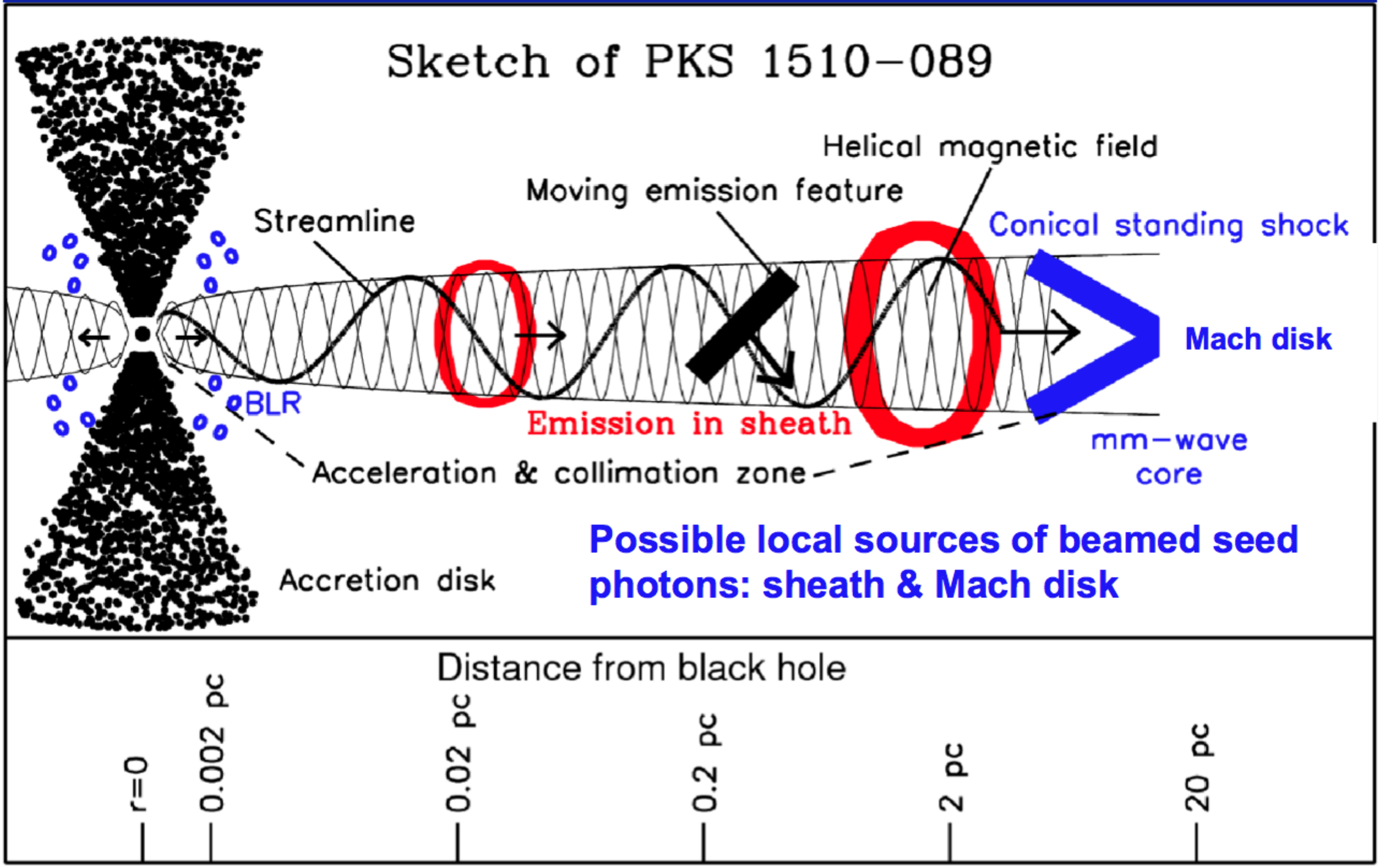
NEVER observed before for Mrk421, Mrk501 or any other HBL

→ similar physical processes occur in jets of different blazar subclasses (which have different apparent jet speeds and overall power outputs).

Some flares may occur in the "acceleration and collimation region"
(highly ordered B field)

Other flares may occur in the "quasi-stationary VLBA core"
(turbulent B field, 1-100 pc downstream the supermassive black hole)

Sites of γ-ray Flares in PKS 1510-089 (Marscher et al. 2010 ApJL)



4 - Conclusions

Instrumentation for gamma-ray astronomy (Fermi and modern IACTs like MAGIC) provide **high quality data with a large discovery potential**

→ *Large number of scientific results in relatively short time*

New instruments + good usage of the ones at low frequencies provides a breakthrough in the study of blazars (and AGNs in general). From the observational point of view we need

- **Population studies**
- **Long-term studies on selected sources**

Fermi-LAT >10 GeV (and the coming 50 GeV) catalog shows that the sky is full of high-energy sources

→ *Preview of the CTA VHE sky*

Many potential VHE blazars

→ Some of them already detected with IACTs, many more to come

4 - Conclusions

The MW campaigns on Mrk421 and Mrk501 are a multi-year AND multi-instrument program that is running since 2009.

Deepest Temporal and Energy coverage on any TeV object

→ *Many interesting (novel) results, and many more to come*

We can use Mrk421 and Mrk501 as our blazar physics laboratory

Lessons learnt might be applied to other blazars (farther away or weaker)

Large complexity in the temporal evolution of the broadband (radio to VHE γ-rays) SED.

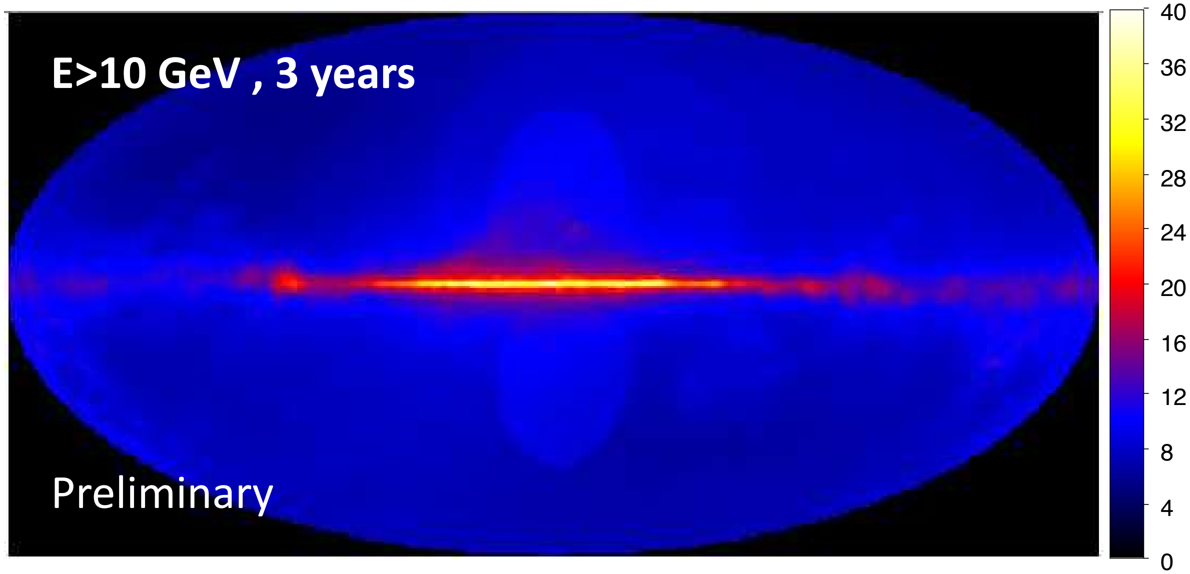
→Lots of things to learn….

Backup

Performance of LAT for astronomy above 10 GeV

Calculated point source flux limit using photons above 10 GeV after 3 years of operation

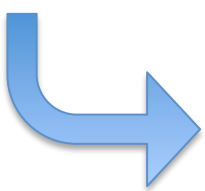
Minimum detectable flux in units of **10^{-11} ph/cm^2/s**



Apart from some structures (Galactic diffuse and Fermi bubbles) **the flux limit at >10 GeV after 3 years is about 10^{-10}ph/cm^2/s** and rather uniform (within factor of 2)

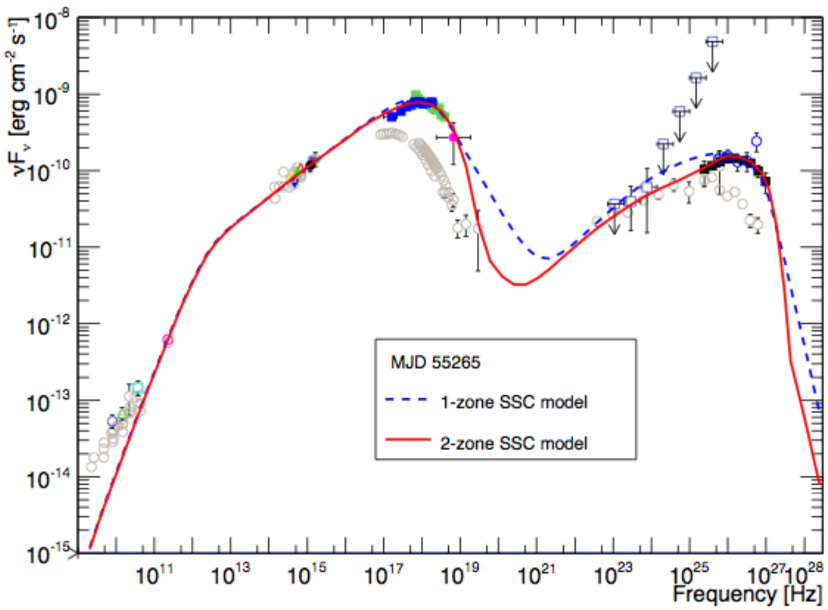
This sensitivity is good enough to be able to detect hundreds of sources

At E>100 GeV (3 years) the flux limit is about 3x10^{-11} ph/cm^2/s which corresponds to the sensitivity of achieved by current IACTs for an observation of 6 hours (effective time)

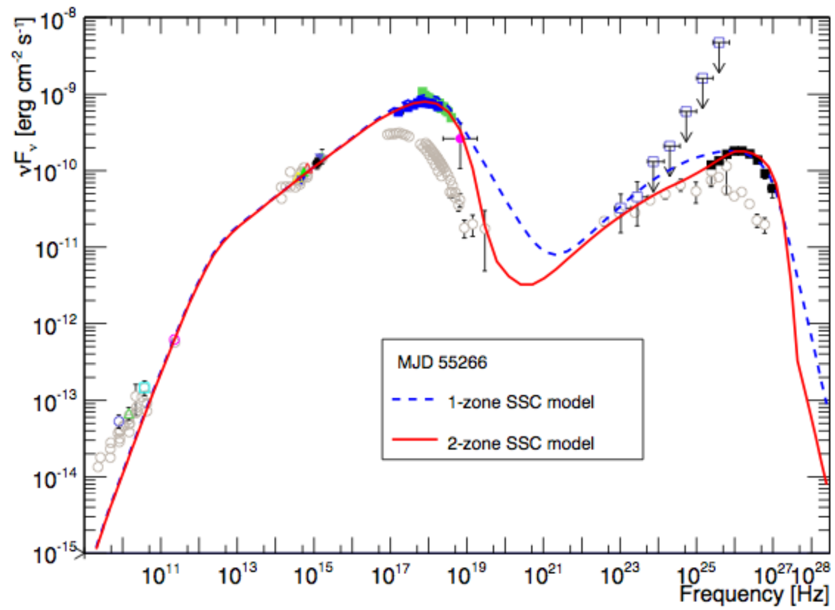


Fermi-LAT provides a true >100 GeV scan of the sky with a sensitivity that could be comparable to 6 hours of (*good or effective time*) observation with a current IACT in every direction

Mrk421, flaring activity from March 2010



(a) MJD 55265.



(b) MJD 55266.

Fig. 15: Broadband SEDs from MJD 55265 and 55266 (the two days with the highest activity) with the one-zone and two-zone model curves described in sections 4.2 and 4.3. Refer to Figures 7 and 8a for details of the data points.

Table 2: Integral flux above 200 GeV and parameters of the one-zone SSC model. Bold-faced text is used to depict the model parameters that were varied to describe the SED during the 13-day period.

Date [MJD]	MAGIC flux [10^{-10}cm^{-2}s^{-1}]	VERITAS flux [10^{-10}cm^{-2}s^{-1}]	Whipple flux [10^{-10}cm^{-2}s^{-1}]	γ_{min} [10^2]	γ_{max} [10^8]	γ_{br1} [10^4]	γ_{br2} [10^5]	s_1	s_2	s_3	n_e [10^3cm^{-3}]	B [mG]	log(R) [cm]	δ
55265	3.8 ± 0.2	4.0 ± 0.5		8	1	**60.**	**6.0**	**2.23**	**2.23**	4.70	**1.14**	38	16.72	21
55266	4.7 ± 0.2			8	1	**66.**	**6.6**	**2.23**	**2.23**	4.70	**1.16**	38	16.72	21
55267		4.0 ± 0.5	5.3 ± 0.3	8	1	**16.**	**6.0**	**2.23**	**2.70**	4.70	**1.10**	38	16.72	21
55268	2.1 ± 0.3	4.0 ± 0.6	4.8 ± 0.3	8	1	**16.**	**6.0**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55269	3.3 ± 0.3	4.2 ± 0.6	4.2 ± 0.3	8	1	**12.**	**7.0**	**2.20**	**2.70**	4.70	**0.95**	38	16.72	21
55270	2.3 ± 0.2	2.6 ± 0.4	3.0 ± 0.2	8	1	**8.0**	**3.9**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55271		3.5 ± 0.4	4.1 ± 0.5	8	1	**9.0**	**5.0**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55272		2.5 ± 0.4		8	1	**5.0**	**4.0**	**2.20**	**2.50**	4.70	**0.90**	38	16.72	21
55273	1.5 ± 0.2	2.0 ± 0.4	2.5 ± 0.3	8	1	**6.0**	**3.9**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55274	1.0 ± 0.3	1.6 ± 0.3	1.9 ± 0.2	8	1	**3.5**	**3.9**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55275			1.8 ± 0.3	8	1	**5.0**	**3.9**	**2.20**	**2.70**	4.70	**0.85**	38	16.72	21
55276	1.6 ± 0.2		1.5 ± 0.3	8	1	**5.7**	**3.9**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55277	1.2 ± 0.1		1.4 ± 0.4	8	1	**8.0**	**3.9**	**2.20**	**2.70**	4.70	**0.70**	38	16.72	21

Notes. VERITAS and Whipple fluxes were measured around seven hours after the MAGIC observations.

Table 3: Integral flux above 200 GeV and parameters of the two-zone SSC model. Bold-faced text is used to depict the model parameters that were varied to describe the SED during the 13-day period.

Date [MJD]	MAGIC flux [10^{-10}cm^{-2}s^{-1}]	VERITAS flux [10^{-10}cm^{-2}s^{-1}]	Whipple flux [10^{-10}cm^{-2}s^{-1}]	γ_{min} [10^4]	γ_{max} [10^5]	γ_{br1} [10^5]	γ_{br2} [10^5]	s_1	s_2	s_3	n_e [10^3cm^{-3}]	B [mG]	log(R) [cm]	δ
the quiescent blob														
Parameters fixed for all dates to those from MJD 55274 one-zone SSC				0.08	1000	0.35	3.9	2.2	2.7	4.7	0.9	38	16.72	21
the flaring blob														
55265	3.8 ± 0.2	4.0 ± 0.5		**3.0**	6	**3.0**	- -	2.0	3.0	- -	**5.0**	**105**	15.51	35
55266	4.7 ± 0.2			**3.0**	6	**3.0**	- -	2.0	3.0	- -	**6.0**	**100**	15.51	35
55267		4.0 ± 0.5	5.3 ± 0.3	**2.5**	6	**1.1**	- -	2.0	3.0	- -	**5.9**	**100**	15.51	35
55268	2.1 ± 0.3	4.0 ± 0.6	4.8 ± 0.3	**5.3**	6	**1.8**	- -	2.0	3.0	- -	**5.6**	**100**	15.51	35
55269	3.3 ± 0.3	4.2 ± 0.6	4.2 ± 0.3	**3.0**	6	**2.3**	- -	2.0	3.0	- -	**5.2**	**90**	15.51	35
55270	2.3 ± 0.2	2.6 ± 0.4	3.0 ± 0.2	**3.5**	6	**0.8**	- -	2.0	3.0	- -	**6.0**	**75**	15.51	35
55271		3.5 ± 0.4	4.1 ± 0.5	**3.5**	6	**1.2**	- -	2.0	3.0	- -	**6.5**	**75**	15.51	35
55272		2.5 ± 0.4		**3.5**	6	**2.0**	- -	2.0	3.0	- -	**3.0**	**75**	15.51	35
55273	1.5 ± 0.2	2.0 ± 0.4	2.5 ± 0.3	**3.5**	6	**0.5**	- -	2.0	3.0	- -	**4.0**	**75**	15.51	35
55274	1.0 ± 0.3	1.6 ± 0.3	1.9 ± 0.2	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
55275			1.8 ± 0.3	**3.5**	6	**0.5**	- -	2.0	3.0	- -	**5.0**	**60**	15.51	35
55276	1.6 ± 0.2		1.5 ± 0.3	**3.5**	6	**1.0**	- -	2.0	3.0	- -	**3.0**	**60**	15.51	35
55277	1.2 ± 0.1		1.4 ± 0.4	**3.5**	6	**0.8**	- -	2.0	3.0	- -	**2.5**	**60**	15.51	35

Notes. On MJD 55274, Mrk 421 had the lowest broadband activity among all the 13 dates. The quiescent blob emission was fixed to the SED of this date, and consequently the emission of the flaring blob on this date is null.

Table 4: Peak positions and widths of the synchrotron and inverse-Compton bumps derived from the two-zone SSC model parameters reported in Table 3.

Date	ν^{syn}_{peak}	$(\nu F_\nu)^{syn}_{peak}$	ν^{syn}_1	ν^{syn}_2	$\log(\nu^{syn}_2/\nu^{syn}_1)$	ν^{ic}_{peak}	$(\nu F_\nu)^{ic}_{peak}$	ν^{ic}_1	ν^{ic}_2	$\log(\nu^{ic}_2/\nu^{ic}_1)$
- -	$[10^{17}]$	$[10^{-10}]$	$[10^{15}]$	$[10^{18}]$	- -	$[10^{25}]$	$[10^{-11}]$	$[10^{23}]$	$[10^{26}]$	- -
[MJD]	[Hz]	[erg cm^{-2}s^{-1}]	[Hz]	[Hz]	- -	[Hz]	[erg cm^{-2}s^{-1}]	[Hz]	[Hz]	- -
55265	8.1	7.9	34.	6.1	2.3	10.	15.	60.	9.5	2.2
55266	8.1	8.0	34.	5.9	2.2	10.	18.	94.	9.9	2.0
55267	4.0	5.5	11.	3.3	2.5	10.	17.	56.	5.1	2.0
55268	4.0	6.6	30.	4.5	2.2	17.	11.	16.	7.3	2.7
55269	4.0	6.1	1.9	4.5	2.4	10.	14.	42.	7.8	2.3
55270	2.0	3.9	5.7	2.3	2.6	6.0	10.	11.	4.3	2.6
55271	2.0	4.6	9.0	2.6	2.5	1.0	13.	30.	5.4	2.3
55272	4.0	3.8	4.9	2.8	2.8	3.4	11.	7.4	4.5	2.8
55273	2.0	3.1	3.1	1.9	2.8	1.9	7.7	3.9	3.0	2.9
55274	2.0	2.5	1.8	1.6	2.9	1.9	7.1	3.0	2.4	2.9
55275	2.0	3.0	2.8	1.8	2.8	3.4	7.9	4.2	3.0	2.9
55276	2.0	3.1	3.1	1.8	2.8	1.9	7.5	3.6	3.2	2.9
55277	2.0	2.9	2.7	1.7	2.8	1.9	7.4	3.4	2.8	2.9

Notes. ν^{syn}_{peak}: the peak frequency of the synchrotron bump; $(\nu F_\nu)^{syn}_{peak}$: the peak energy flux of the synchrotron bump; ν^{ic}_{peak}: the peak frequency of the inverse-Compton bump; $(\nu F_\nu)^{ic}_{peak}$: the peak energy flux of the inverse-Compton bump. For each bump in the SED, the value of $(\nu F_\nu)_{peak}/2$ determines the two frequencies (ν_1 and ν_2) that are used to quantify the width of the bump in the logarithmic scale $\log(\nu_2/\nu_1)$.

Table 5: Jet powers and luminosities derived with the parameters from the one-zone SSC model reported in Table 2.

Date - - - [MJD]	N_e $[10^{-1}]$ $[\mathrm{cm}^{-3}]$	$\langle\gamma_e\rangle$ $[10^3]$ - - -	L_e $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	L_p $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	L_B $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$	U'_e/U'_B $[10^1]$ - - -	L_{jet} $[10^{44}]$ $[\mathrm{erg\ s^{-1}}]$	L_{syn} $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$	L_{IC} $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	L_{ph} $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$
55265	2.5	3.4	7.8	4.2	6.5	1.2	1.3	6.6	14.	8.1
55266	2.5	3.4	8.0	4.3	6.5	1.2	1.3	7.2	16.	8.8
55267	2.4	3.3	7.3	4.0	6.5	1.1	1.2	4.6	11.	5.7
55268	2.5	3.5	7.9	4.2	6.5	1.2	1.3	5.4	14.	6.7
55269	2.6	3.4	8.2	4.4	6.5	1.3	1.3	5.5	14.	6.9
55270	2.5	3.3	7.5	4.1	6.5	1.2	1.2	3.5	9.8	4.5
55271	2.5	3.4	7.6	4.1	6.5	1.2	1.2	4.0	11.	5.1
55272	2.5	3.3	7.5	4.1	6.5	1.1	1.2	3.7	10.	4.7
55273	2.5	3.2	7.3	4.1	6.5	1.1	1.2	3.1	8.7	4.0
55274	2.5	3.1	7.0	4.1	6.5	1.1	1.2	2.5	6.5	3.1
55275	2.3	3.2	6.8	3.9	6.5	1.1	1.1	2.8	7.2	3.5
55276	2.5	3.2	7.3	4.1	6.5	1.1	1.2	3.0	8.2	3.8
55277	1.9	3.3	5.8	3.2	6.5	.90	.97	2.6	5.7	3.2

Notes. N_e: total electron number density; $\langle\gamma_e\rangle$: mean electron Lorentz factor; L_e: jet power carried by electrons; L_p:the jet power carried by protons; L_B: jet power carried by the magnetic field; U'_e/U'_B: the ratio of comoving electron and magnetic-field energy densities; L_{jet}: total jet power; L_{syn}: the synchrotron luminosity; L_{IC}: inverse-Compton luminosity; L_{ph}: total photon luminosity from the SSC model. See the calculation explanation in Section 5.

Table 6: Jet powers and luminosities derived with the parameters from the two-zone SSC model reported in Table 3.

Date - - - [MJD]	N_e $[10^{-1}]$ $[\mathrm{cm}^{-3}]$	$\langle\gamma_e\rangle$ $[10^4]$ - - -	L_e $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	L_p $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	L_B $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	U'_e/U'_B $[10^1]$ - - -	L_{jet} $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	L_{syn} $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	L_{IC} $[10^{40}]$ $[\mathrm{erg\ s^{-1}}]$	L_{ph} $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_e$ $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_p$ $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_B$ $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_{jet}$ $[10^{44}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_{syn}$ $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_{IC}$ $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_{ph}$ $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$
the quiescent blob																	
- -	2.5	.31	7.0	410	65.	1.1	12.	25.	65.	31.							
the flaring blob											the quiescent blob + the flaring blob						
55265	1.6	9.0	1.4	2.8	5.3	2.6	1.5	13.	18.	15.	8.4	4.1	7.0	1.3	3.8	8.3	4.6
55266	1.9	9.0	1.7	3.4	4.8	3.4	1.7	13.	23.	15.	8.7	4.1	7.0	1.4	3.8	8.8	4.6
55267	2.1	6.5	1.3	3.8	4.8	2.8	1.4	7.9	18.	9.7	8.3	4.1	7.0	1.3	3.3	8.3	4.1
55268	.89	12.	1.1	1.6	4.8	2.2	1.1	9.5	8.8	10.	8.1	4.1	7.0	1.3	3.4	7.4	4.1
55269	1.6	8.6	1.4	2.9	3.9	3.5	1.4	8.7	15.	10.	8.4	4.1	6.9	1.3	3.4	8.0	4.1
55270	1.3	7.6	1.0	2.4	2.7	3.7	1.1	3.4	7.3	4.2	8.0	4.1	6.8	1.3	2.8	7.2	3.5
55271	1.6	8.4	1.3	2.9	2.7	4.8	1.4	5.0	12.	6.2	8.3	4.1	6.8	1.3	3.0	7.7	3.7
55272	.77	9.3	.71	1.4	2.7	2.6	.76	3.5	9.9	4.5	7.7	4.1	6.8	1.3	2.8	7.5	3.5
55273	.74	6.9	.50	1.3	2.7	1.9	.54	1.5	1.9	1.7	7.5	4.1	6.8	1.3	2.7	6.7	3.3
55274	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	7.0	4.1	6.5	1.2	2.5	6.5	3.1
55275	.93	6.9	.63	1.7	1.7	3.6	.66	1.2	2.2	1.5	7.6	4.1	6.7	1.3	2.6	6.7	3.2
55276	.70	8.0	.56	1.3	1.7	3.2	.59	1.3	1.7	1.5	7.6	4.1	6.7	1.3	2.6	6.7	3.2
55277	.56	7.6	.42	1.0	1.7	2.4	.45	.92	.95	1.0	7.4	4.1	6.7	1.2	2.6	6.6	3.2

Notes. N_e: total electron number density; $\langle\gamma_e\rangle$: mean electron Lorentz factor; L_e: jet power carried by electrons; L_p: jet power carried by protons; L_B: jet power carried by the magnetic field; U'_e/U'_B: ratio of comoving electron and magnetic-field energy densities; L_{jet}: total jet power; L_{syn}: synchrotron luminosity; L_{IC}: inverse-Compton luminosity; L_{ph}: total photon luminosity from the SSC model. See the calculation explanation in Section 5. The quantities with the ^{sum} superscript report the sums of the quantities from the quiescent and the flaring blob.

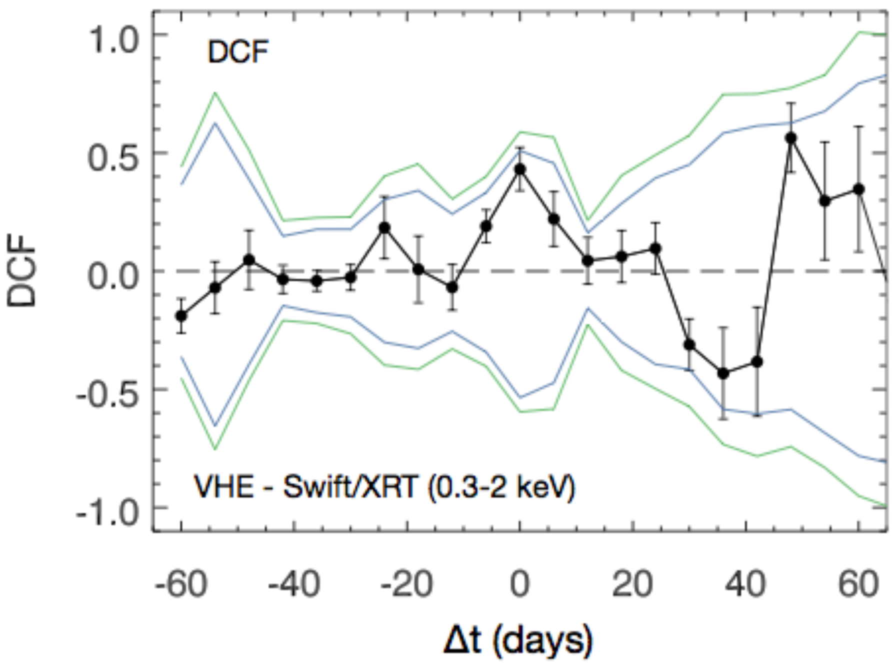


Fig. 6. DCF of the combined Whipple and MAGIC ("VHE") light curve, correlated with the *Swift*/XRT (0.3-2 keV) light curve. The black error bars represent the uncertainties as derived from Edelson & Krolik (1988). The green lines represent the 1% and 99% extremes of the DCF distribution of simulated *Swift*/XRT light curves when correlated with the measured VHE light curve. The blue lines represent the 5% and 95% extremes.

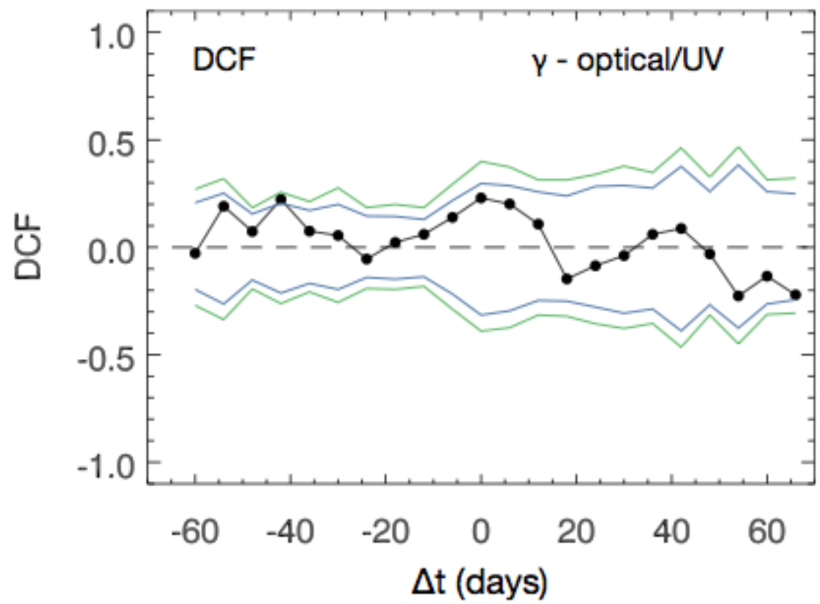
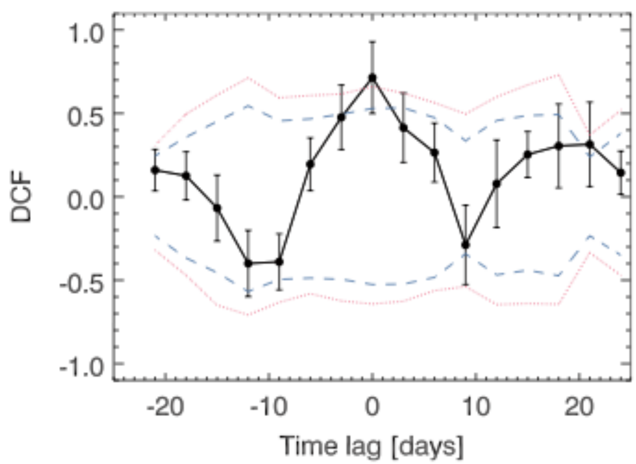


Fig. 7. The average DCF of the *Fermi*-LAT HE γ-ray light curve, correlated with the optical and UV light curves (GASP *R*-band, GRT *BVRI*, MITSuME g, MITSuME Ic and UVOT W1), is shown in black. The green lines represent the 1% and 99% extremes of the likewise averaged DCF distribution of simulated optical/UV light curves when correlated with the real *Fermi*-LAT light curve. The blue lines represent the 5% and 95% extremes.

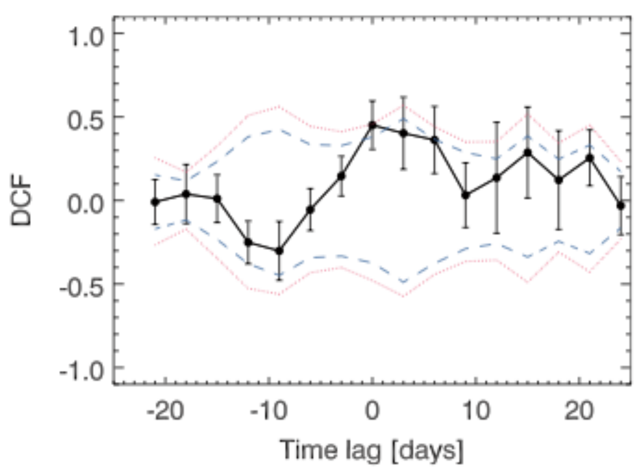
3.2 – Correlations

Mrk501



(a) *RXTE*/PCA vs. *Swift*/XRT

Little variability in 2008 (see marginal correlation RXTE with SwiftXRT)



(b) *RXTE*/PCA vs. MAGIC & VERITAS

Marginal correlation for X-ray and VHE

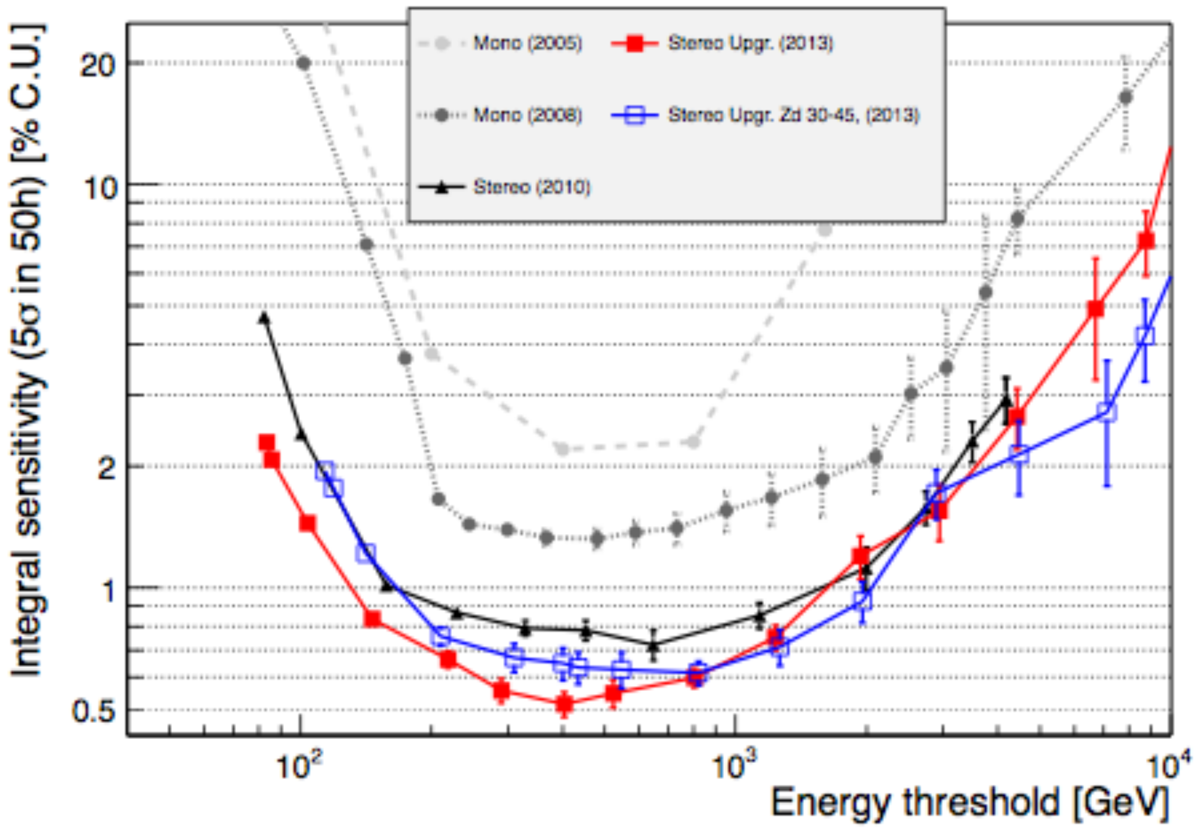


Figure 16: Evolution of integral sensitivity of the MAGIC telescopes, i.e. the integrated flux of a source above a given energy for which $N_{excess}/\sqrt{N_{bkg}} = 5$ after 50 h of effective observation time, requiring $N_{excess} > 10$ and $N_{excess} > 0.05 N_{bkg}$. Gray circles: sensitivity of the MAGIC-I single telescope with the Siegen (light gray, long dashed, Albert et al. (2008b)) and MUX readouts (dark gray, short dashed, Aleksić et al. (2012a)). Black triangles: stereo before the upgrade (Aleksić et al., 2012a). Squares: stereo after the upgrade: zenith angle below 30° (red, filled), 30 – 45° (blue, empty)

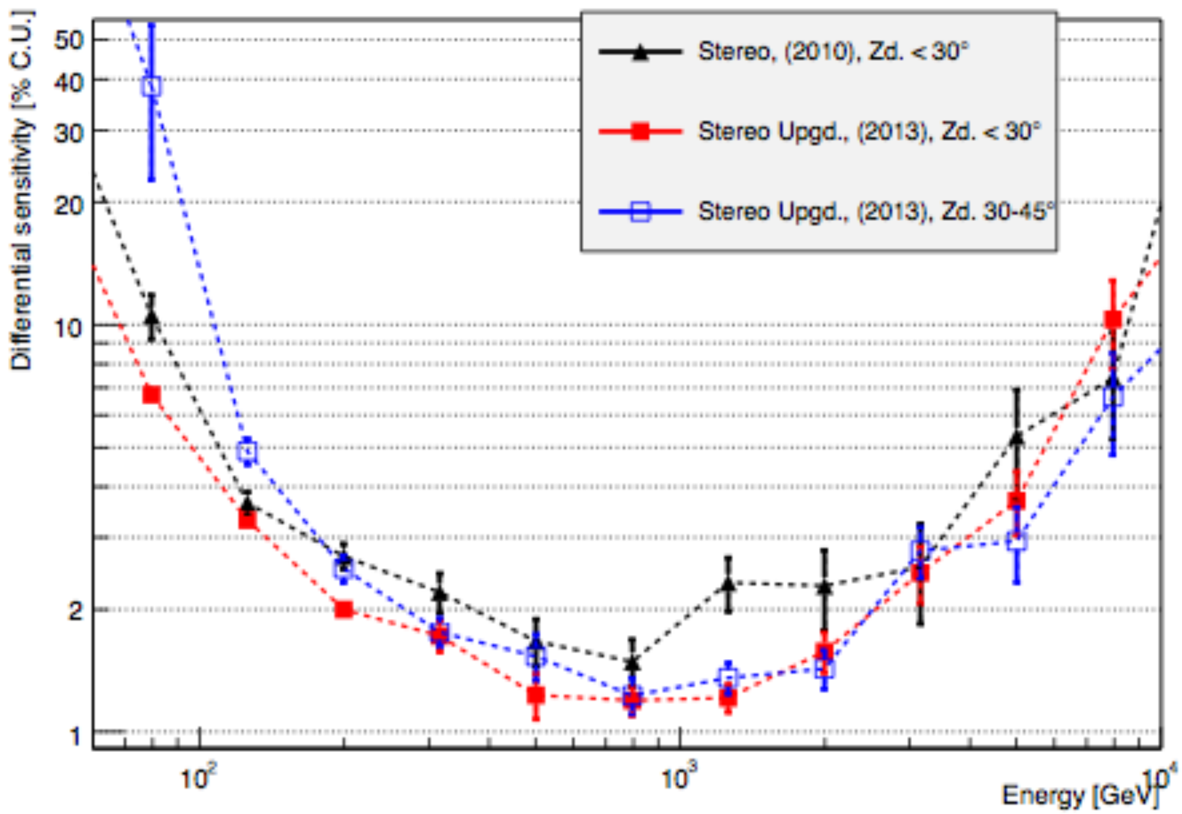


Figure 17: Differential (5 bins per decade in energy) sensitivity of the MAGIC Stereo system. We compute the flux of the source in a given energy range for which $N_{\mathrm{excess}}/\sqrt{N_{\mathrm{bkg}}} = 5$ with $N_{\mathrm{excess}} > 10$, $N_{\mathrm{excess}} > 0.05 N_{\mathrm{bkg}}$ after 50 h of effective time.

Differential sensitivity plots with the performance of CTA
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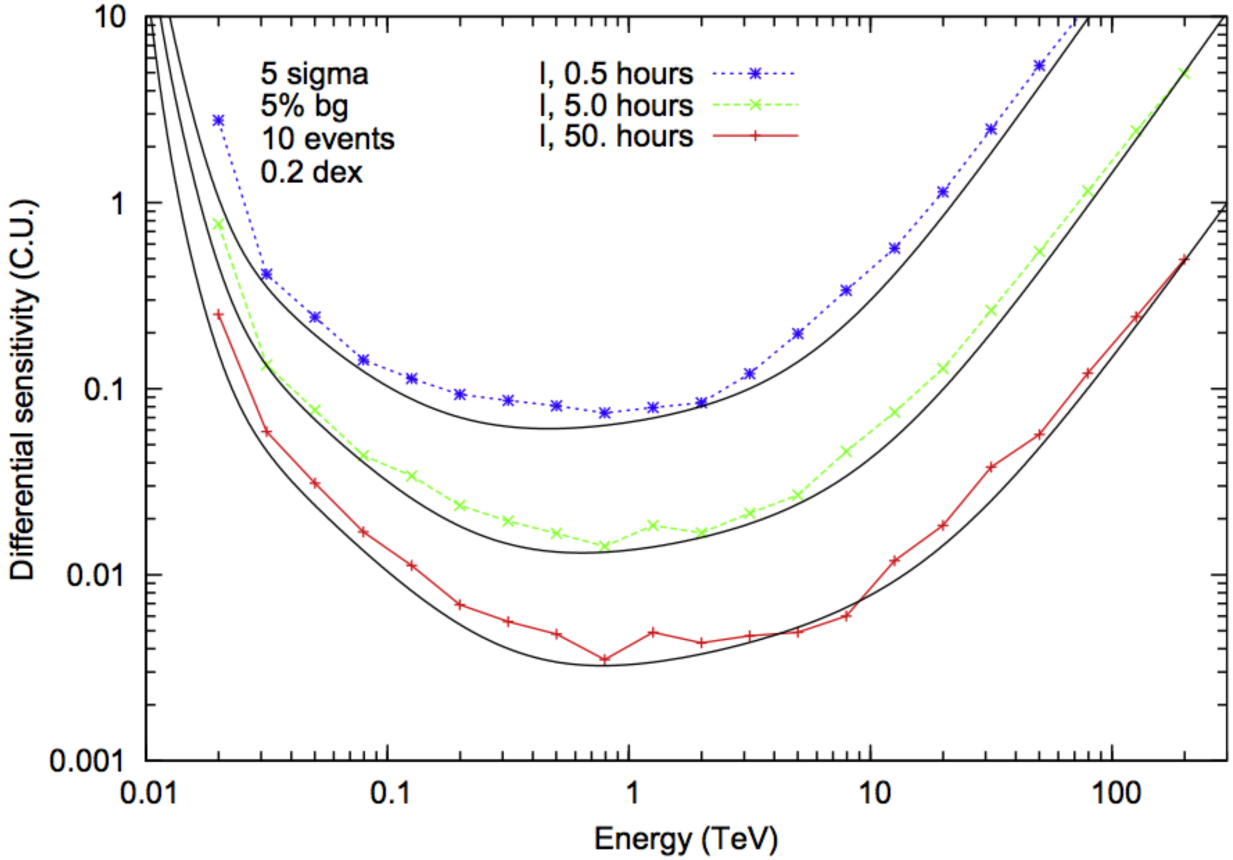

Fig. 8. Point source sensitivity of array I (in units of 1 C.U. $= 2.79 \times 10^{-7} (E/\mathrm{TeV})^{-2.57}$ $\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$) for observation times of 0.5 h, 5 h, and 50 h, respectively. Also shown as black solid lines are approximations to the best performance of any of the 11 CTA South arrays at any energy (as in Fig. 6), for the given observation times. Array I, being close to this optimum at all energies, is indeed a well-balanced array.

Differential sensitivity plots with the performance of CTA
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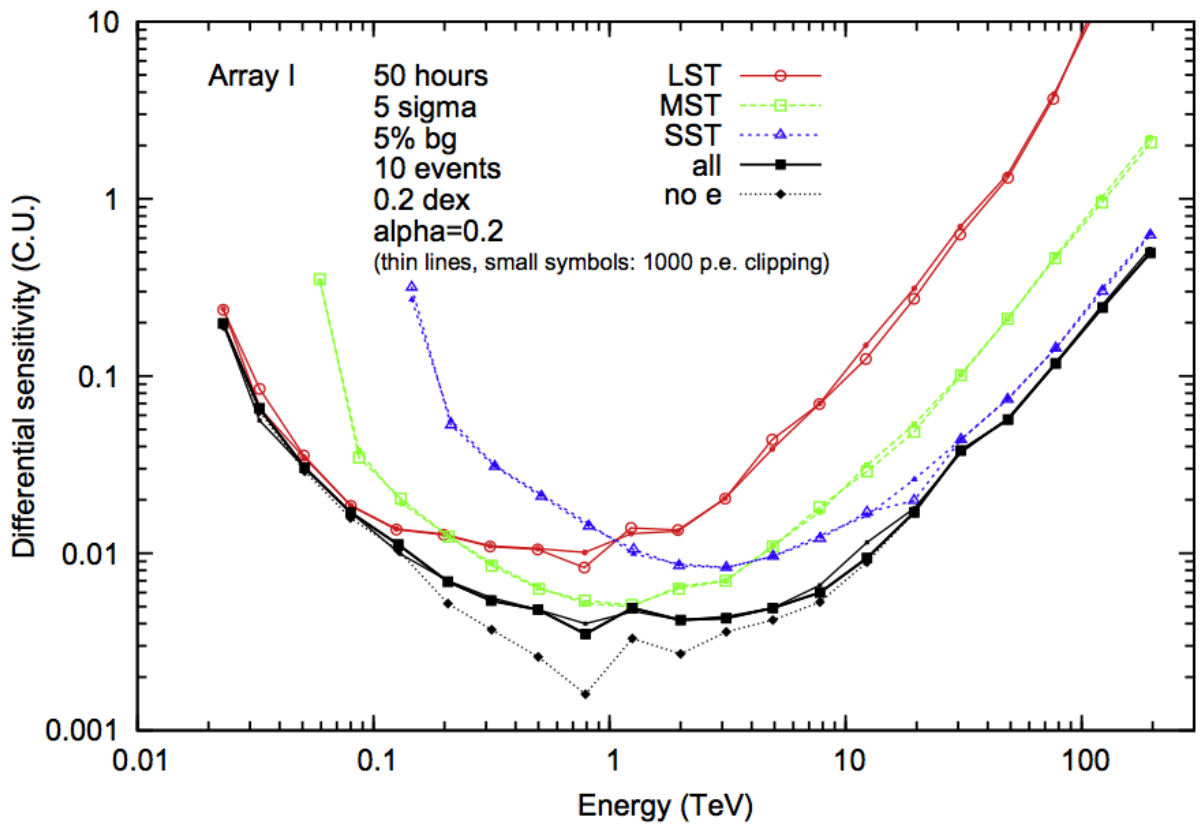

Fig. 9. Point source sensitivity of array I (solid black line, filled squares) and its components, 3 LSTs (red, open circles), 18 MSTs (green, open squares), 56 SSTs (blue, open triangles). Thin lines with small symbols illustrate the limited impact of a reduced dynamic range of PMT readout electronics. For the relevance of the electron background on the combined sensitivity see also the dashed black line with diamonds, where this background is ignored. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)