Sailing with the bazar PG 1553+113

20 years of VHE data and science from MAGIC to CTAO prototypes

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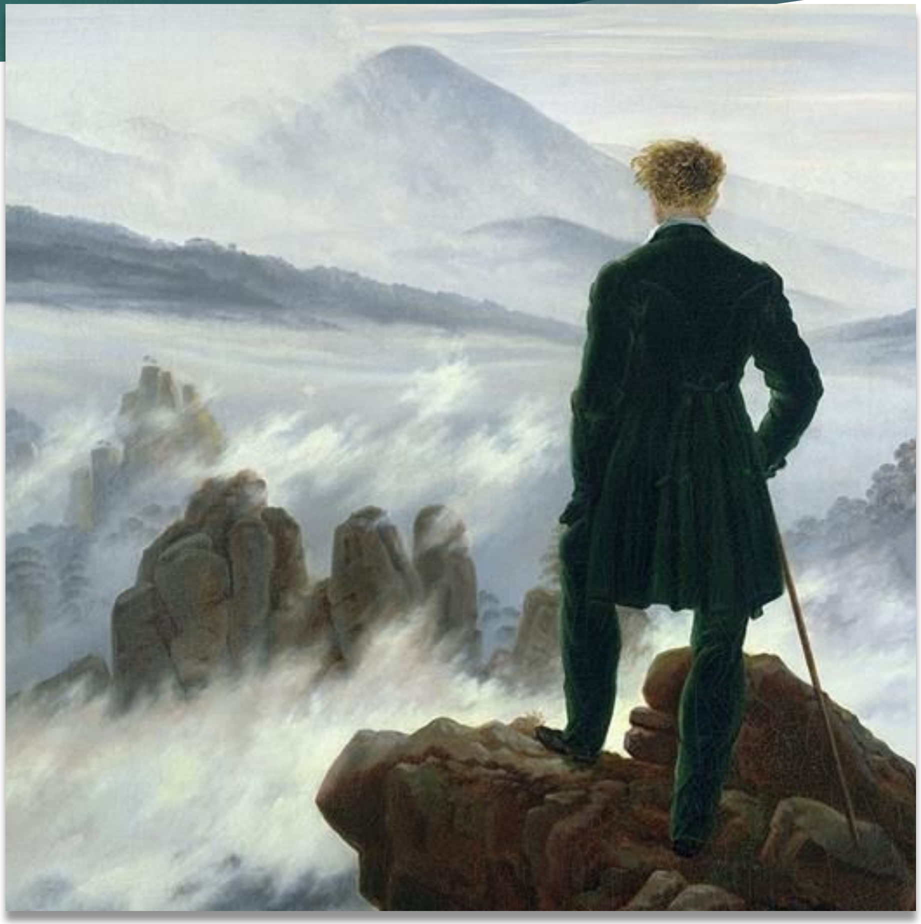
VHEGAM MEETING 16.02.2024

Outline

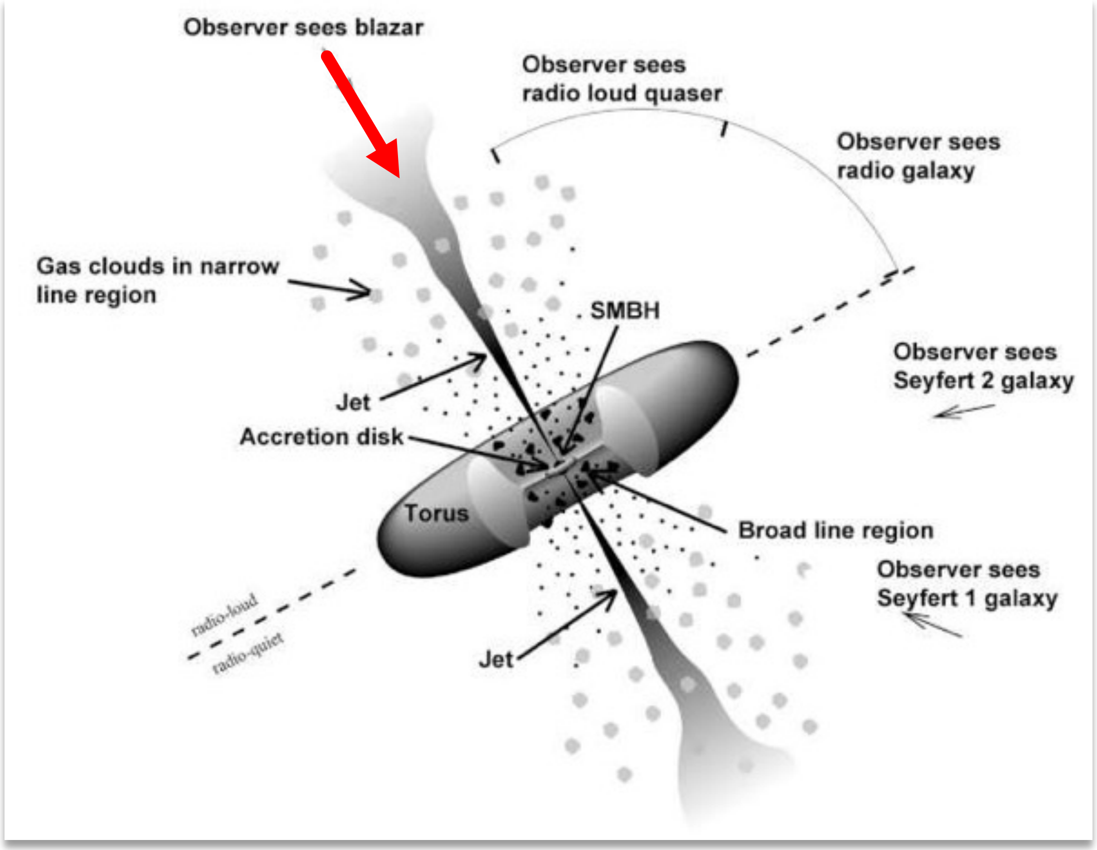
- **Introducing** one of the most interesting sources of the VHE sky
- **Brief history** of TeV observations
- ***Fermi*-LAT** detects a periodic signal!
- Recent observations: the long-term, multi-wavelength lightcurve and the **beginning of detailed studies** era
- The **LST-1** joined the effort



A few words about myself

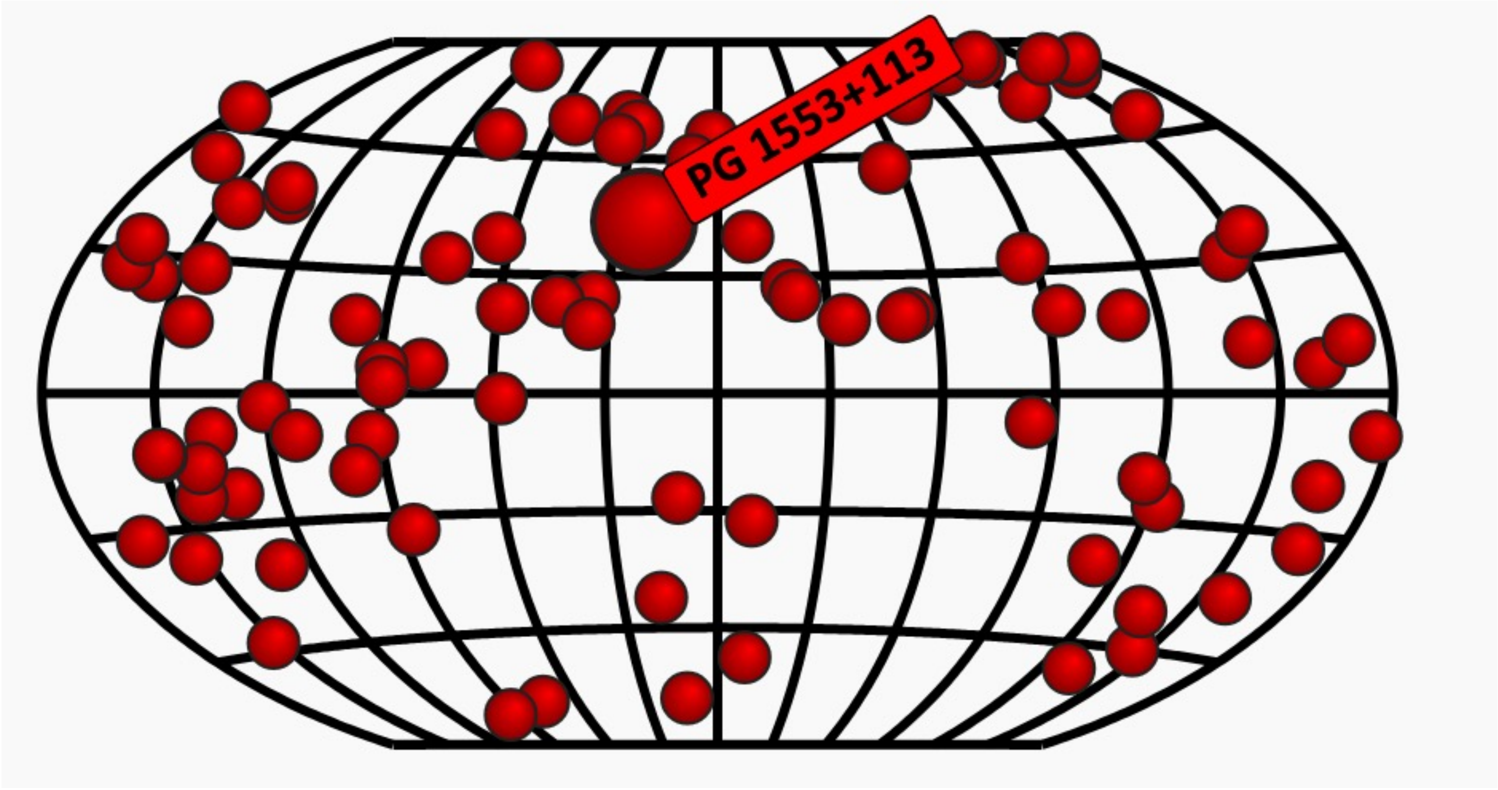
- **MAGIC member** since 2005, **CTAC** member since 2009
- **Research:** VHE gamma-ray emission in blazars in a MWL context, gamma-ray cosmology
- Past **EGAL coordinator** in MAGIC
- Past **MWL coordinator** in MAGIC
- **TAC** (time allocation commitee) member in MAGIC
- **EGAL WG** coordinator in CTAC

PG 1553+113

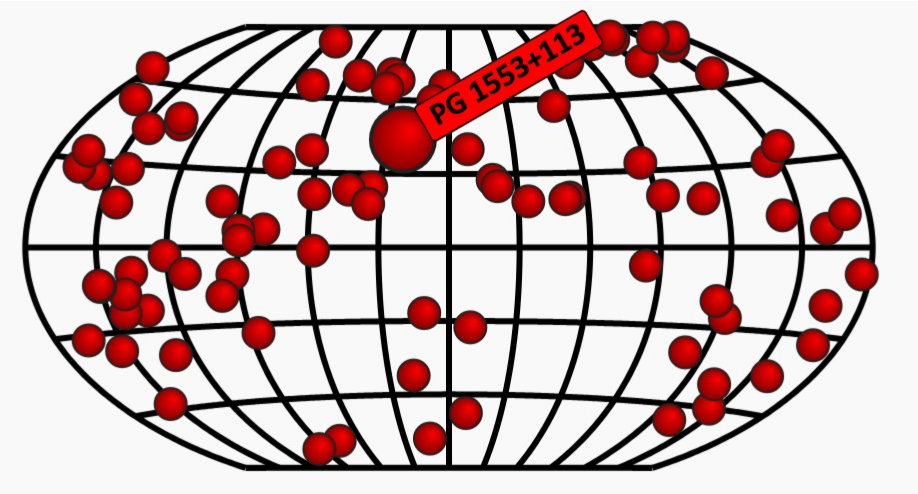


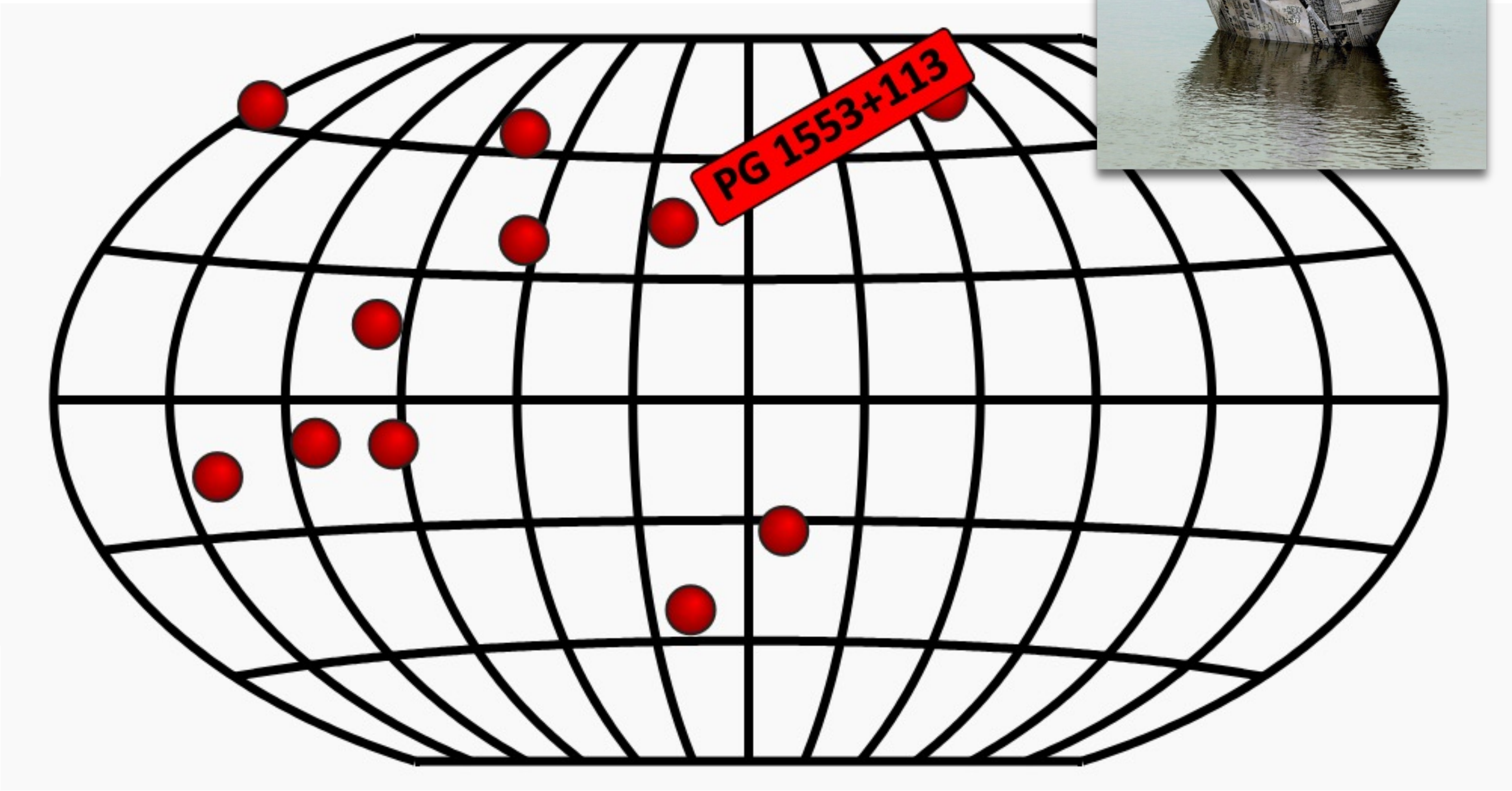
- One of the **88 jetted Active Galactic Nuclei** (AGNs) observed at TeV energies according to **TeVCat**
  - Supermassive black hole
  - Accretion of material → thermal emission
  - Jet of ultra-relativistic particles → non-thermal emission
- It is a **blazar**: the jet is closely aligned to the line of sight
- Its **redshift** was measured only recently: z = 0.433

PG 1553+113 in 2024



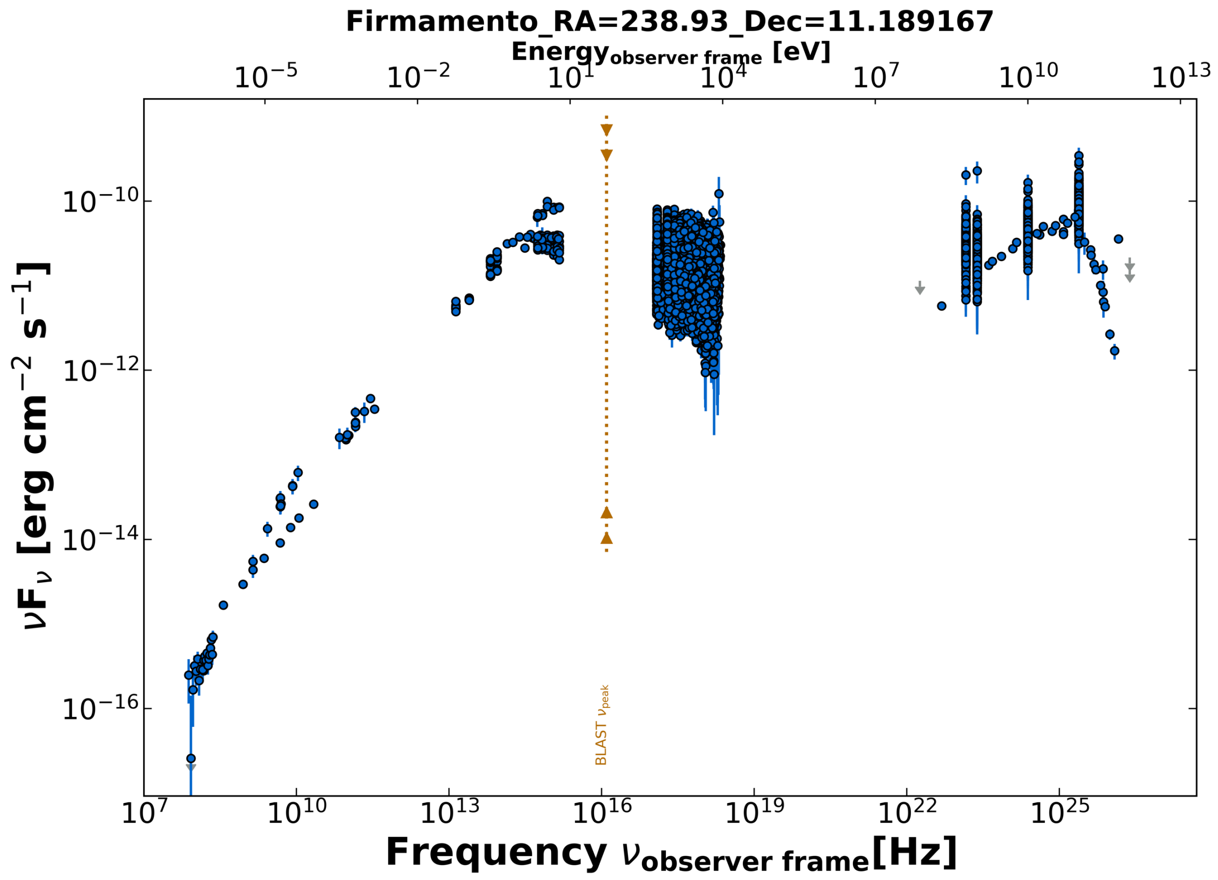
PG 1553+113 in 2005 (discovery)





Only 11 sources were known!

PG 1553+113: Spectral Energy Distribution



The Spectral Energy Distribution (SED) is dominated by the **jet emission**

→ provides insight into particle acceleration mechanisms inside the jet/jet geometry and dynamics

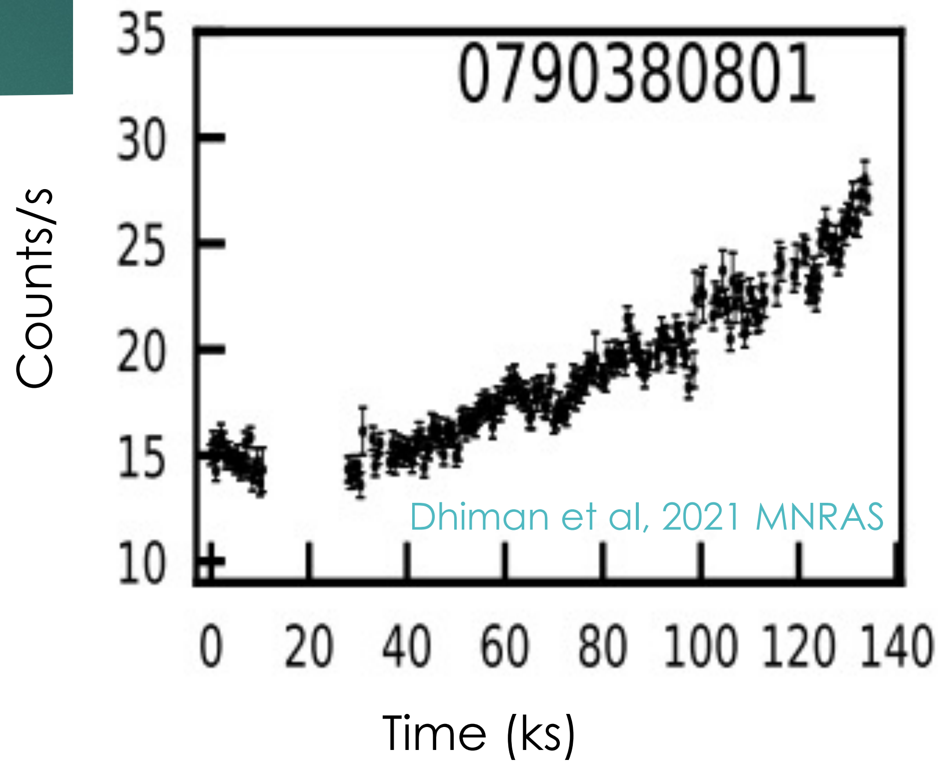
Key feature: **Variability**

https://firmamento.hosting.nyu.edu/data_access

Shortest variability timescale in PG 1553+113

- **Study based on XMM observations**
- Characterization of variability at different scales
- Short (intra-night) variability: very useful to constrain the emissing region for causality reasons

$$R \leqslant \frac{c\, t_{var}\, \delta}{1+z},$$

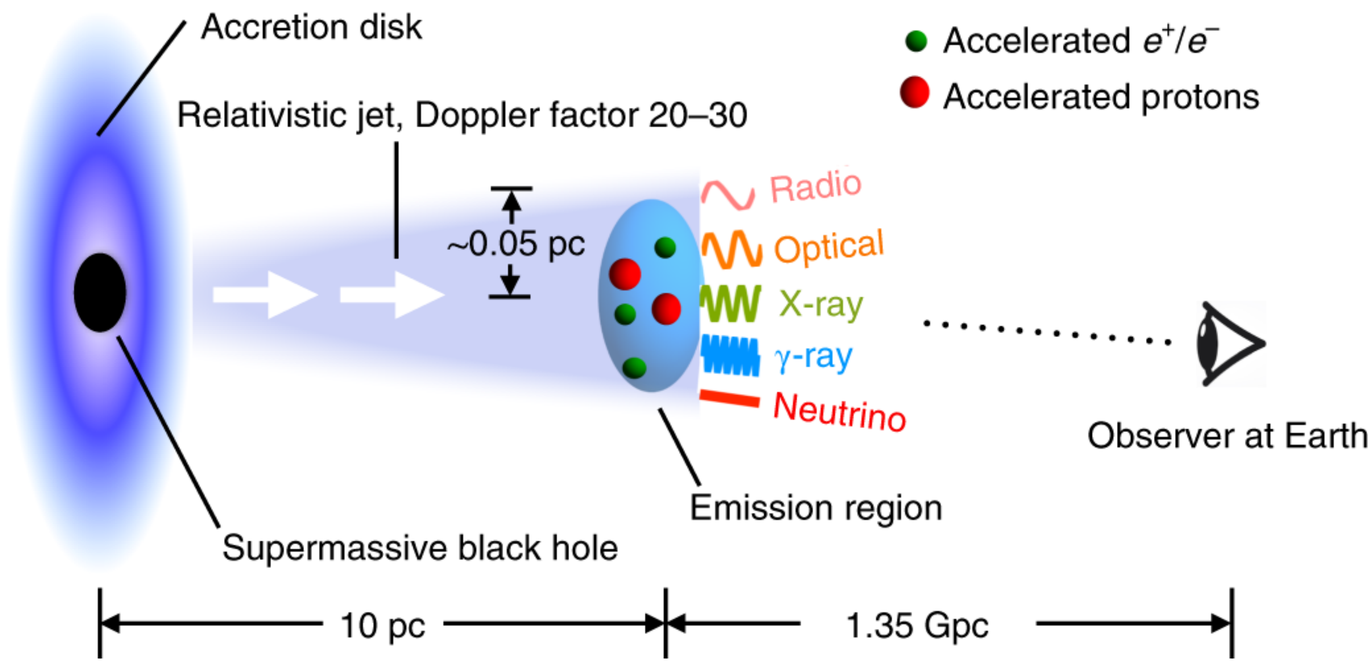


T_var assumed as the **doubling flux time → 2.4 ks**

Key questions on blazars

- **Acceleration mechanism** (magnetic reconnection, propagating shock, …)
  - largely unconstrained
- **Emission: location and mechanisms**
  - How many regions?
  - Which particles (leptons or hadrons?)
- **Blazar geometry**
  - Jet precession?
- **Propagation**
  - Effect of EBL
  - Effect of intergalactic magnetic field

Gao et al., Nature Astronomy, 2018



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  - Effect of intergalactic magnetic field

Observables & Methods:

- Imaging

→ Only in the radio band

- Time-resolved spectroscopy

→ Spectrum

→ Lightcurves

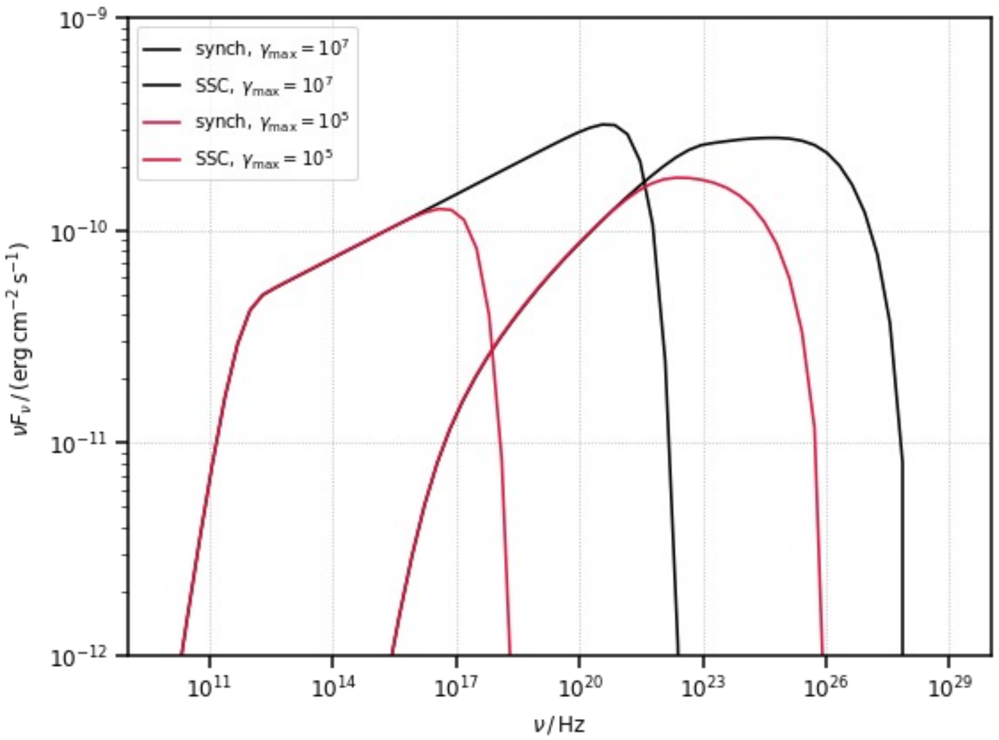
- Multi-wavelength view

(+ polarimetry)

→ Correlations

→ Overall SED modeling

PG 1553+113: Spectral Energy Distribution



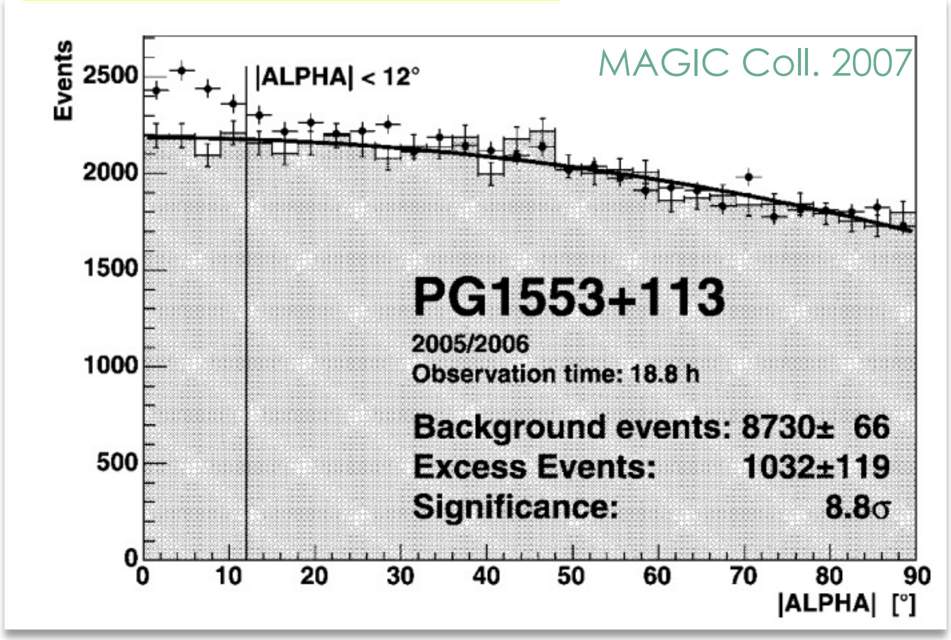
Example: testing the synchrotron self-Compton model

- single emitting zone somewhere in the jet, moving at quasi relativistic speed in a magnetic field B.
  - **Synchrotron emission**
  - **Inverse Compton emission**
- Many physical parameters can be inferred from the SED model

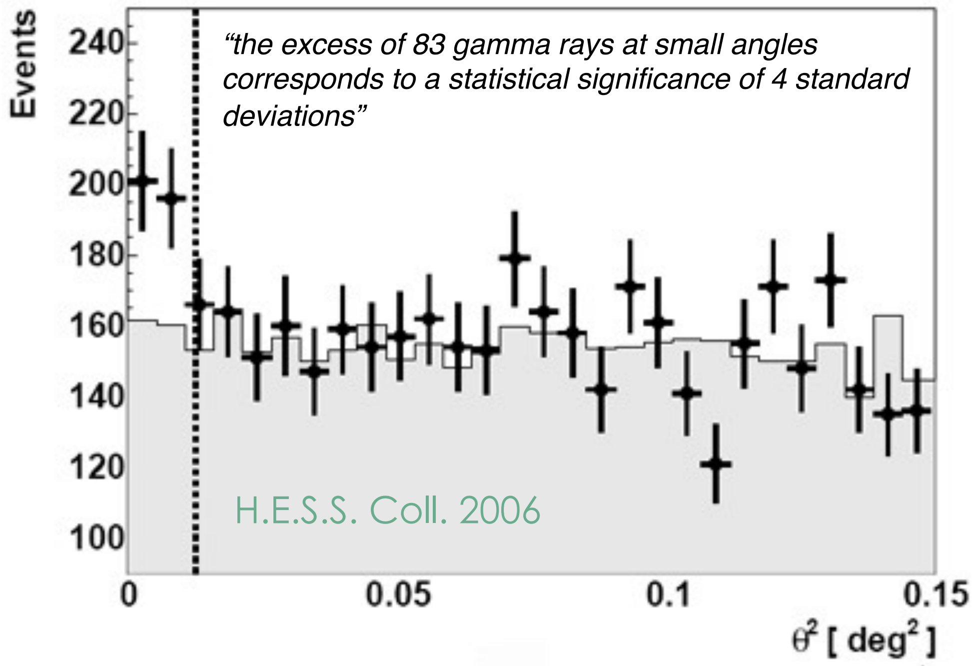
From data → to models (example: agnpy code)

PG 1553+113 detection at VHE

MAGIC detection 2005

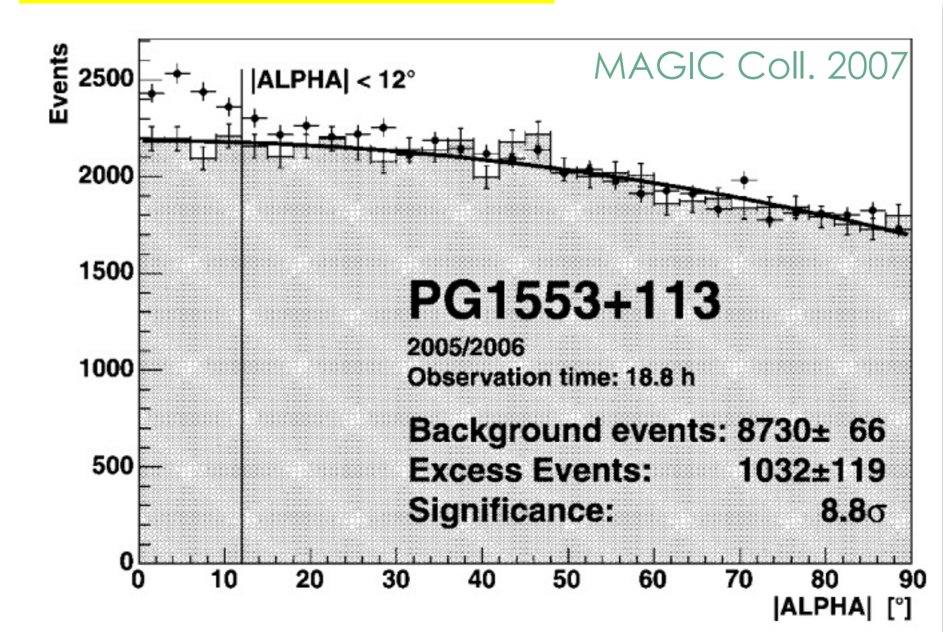


H.E.S.S. detection 2005



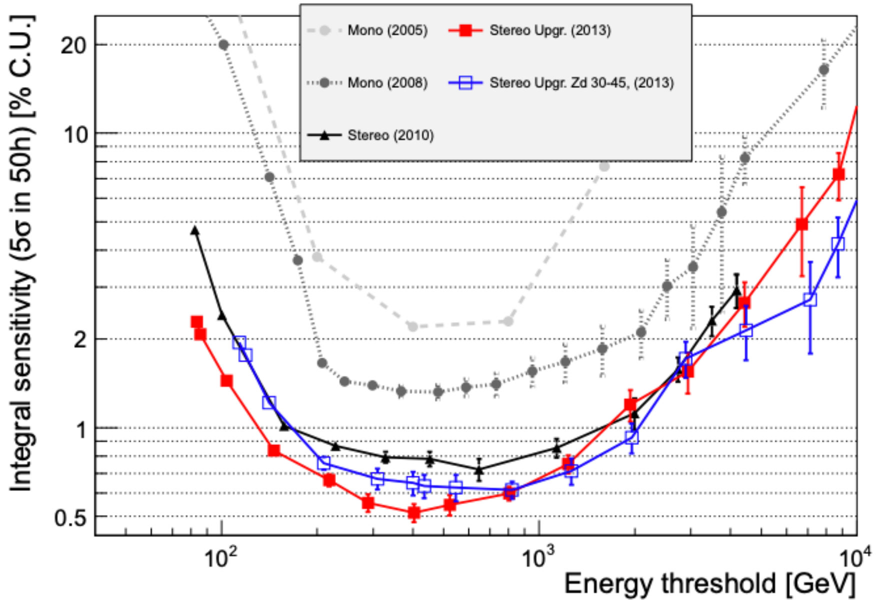
PG 1553+113 detection at VHE

MAGIC detection 2005

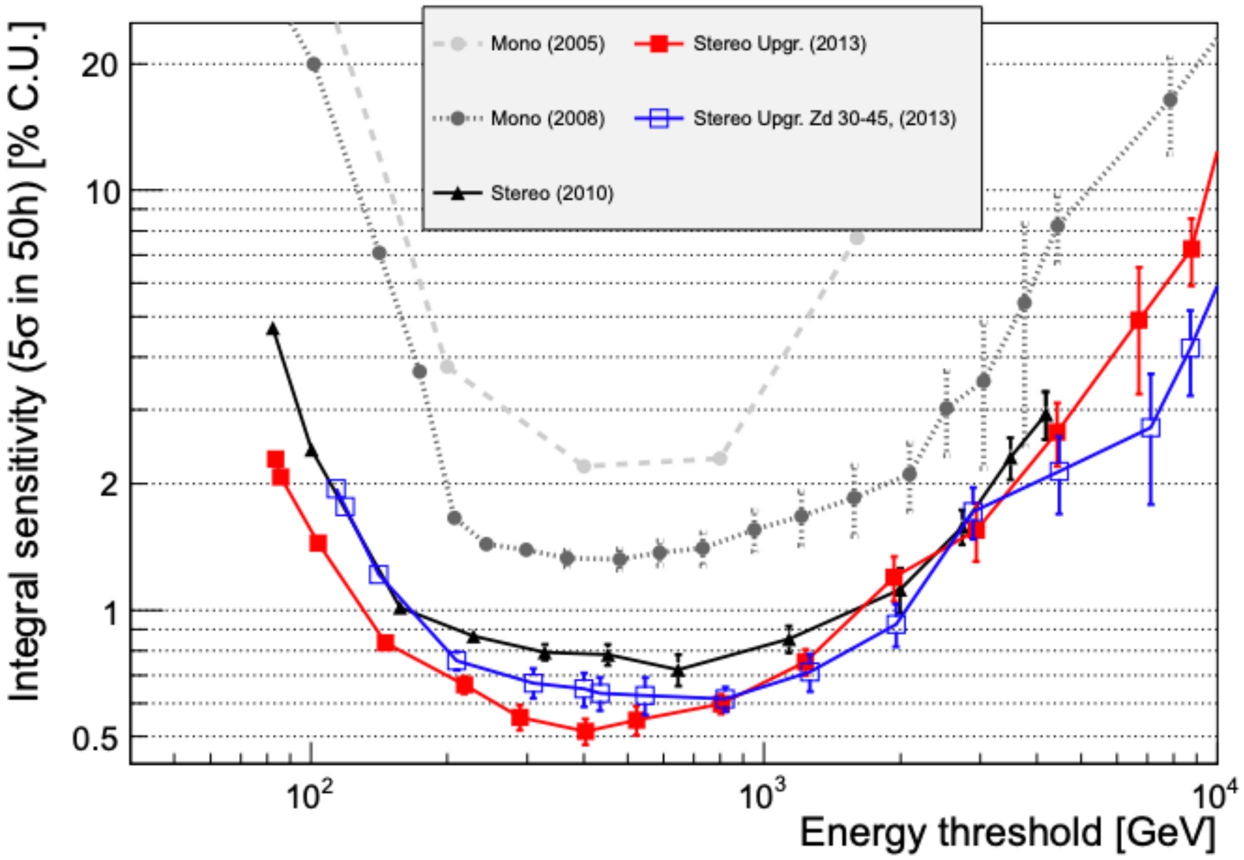


→ MAGIC needed 18.8 hours to see a signal of 8.8 sigma significance

→ **Significance scales with square root of time!**



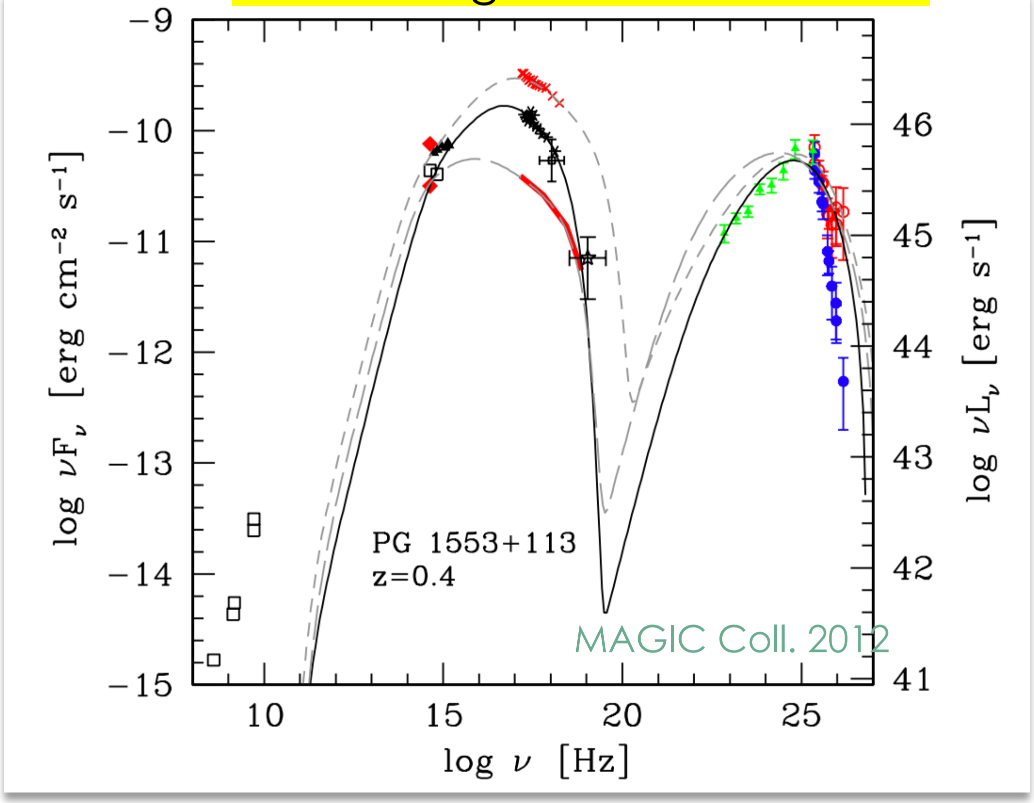
Estimating the significance of your signal



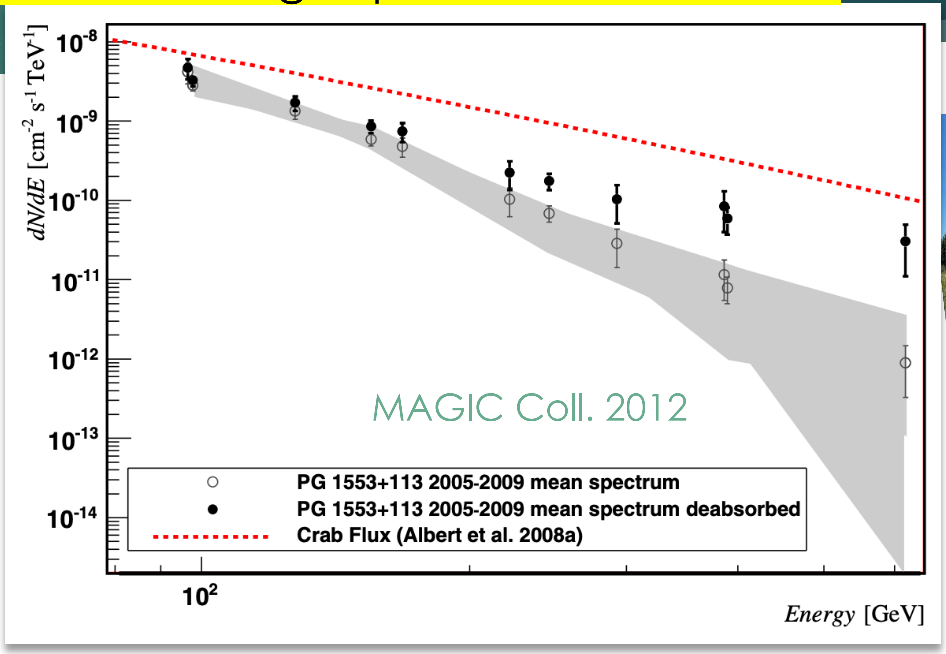
- **Sensitivity** is essential for the technical evaluation (feasibility) of an observation
- Even a small **improvement in sensitivity** might translate into a significant reduction of **observation time**!

PG 1553+113 multi-year and multi-wavelength

SED average state 2005 - 2009



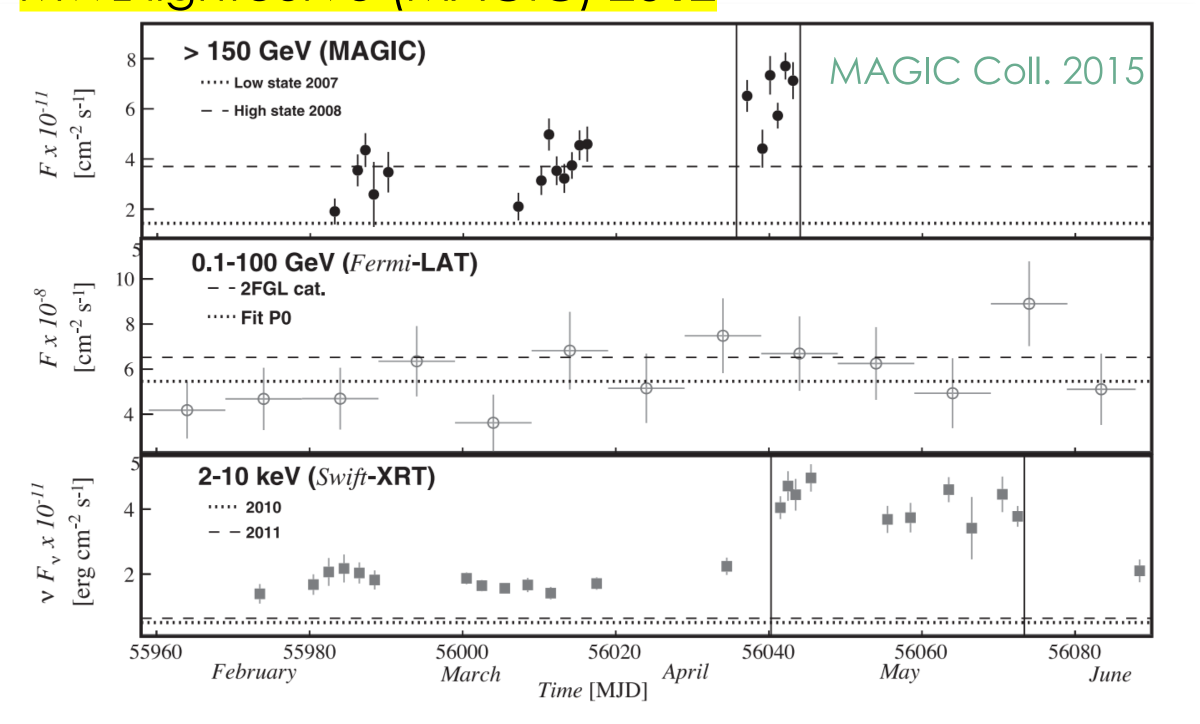
MAGIC average spectrum 2005 - 2009



- MWL data → broadband modelling
- Variable in the syncrotron peak
- **Not clearly variable** at **high energies**

Detection of variability also at very high energies

MWL lightcurve (MAGIC) **2012**

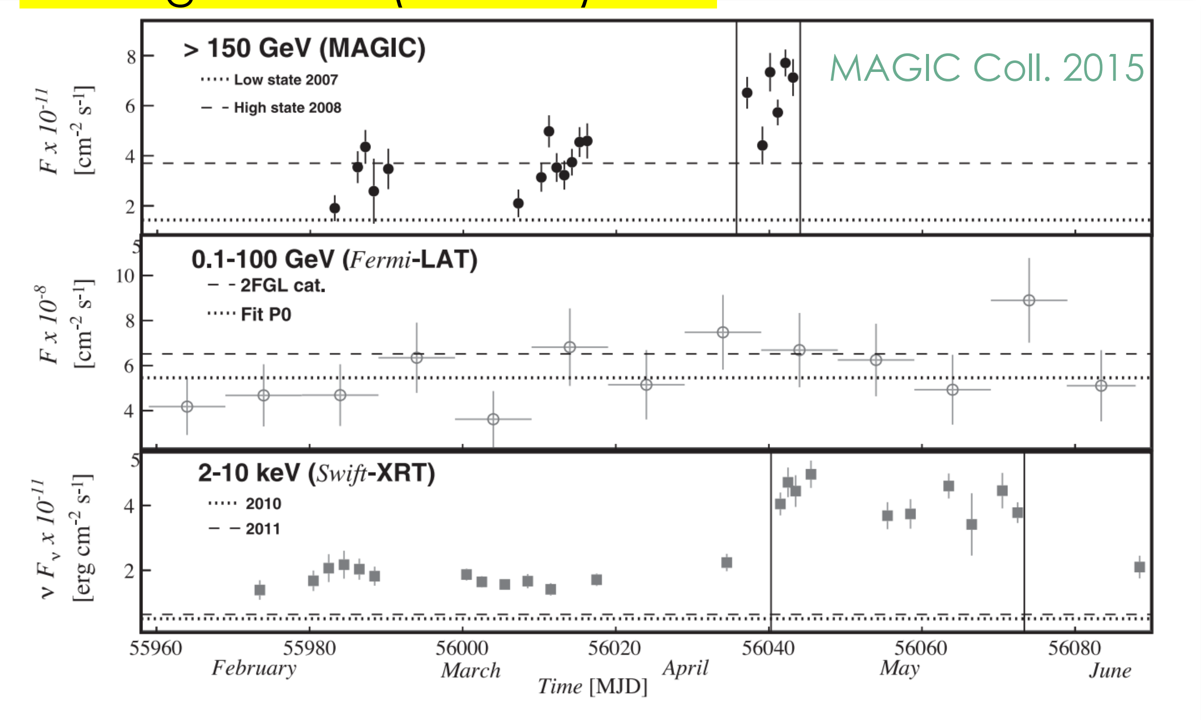


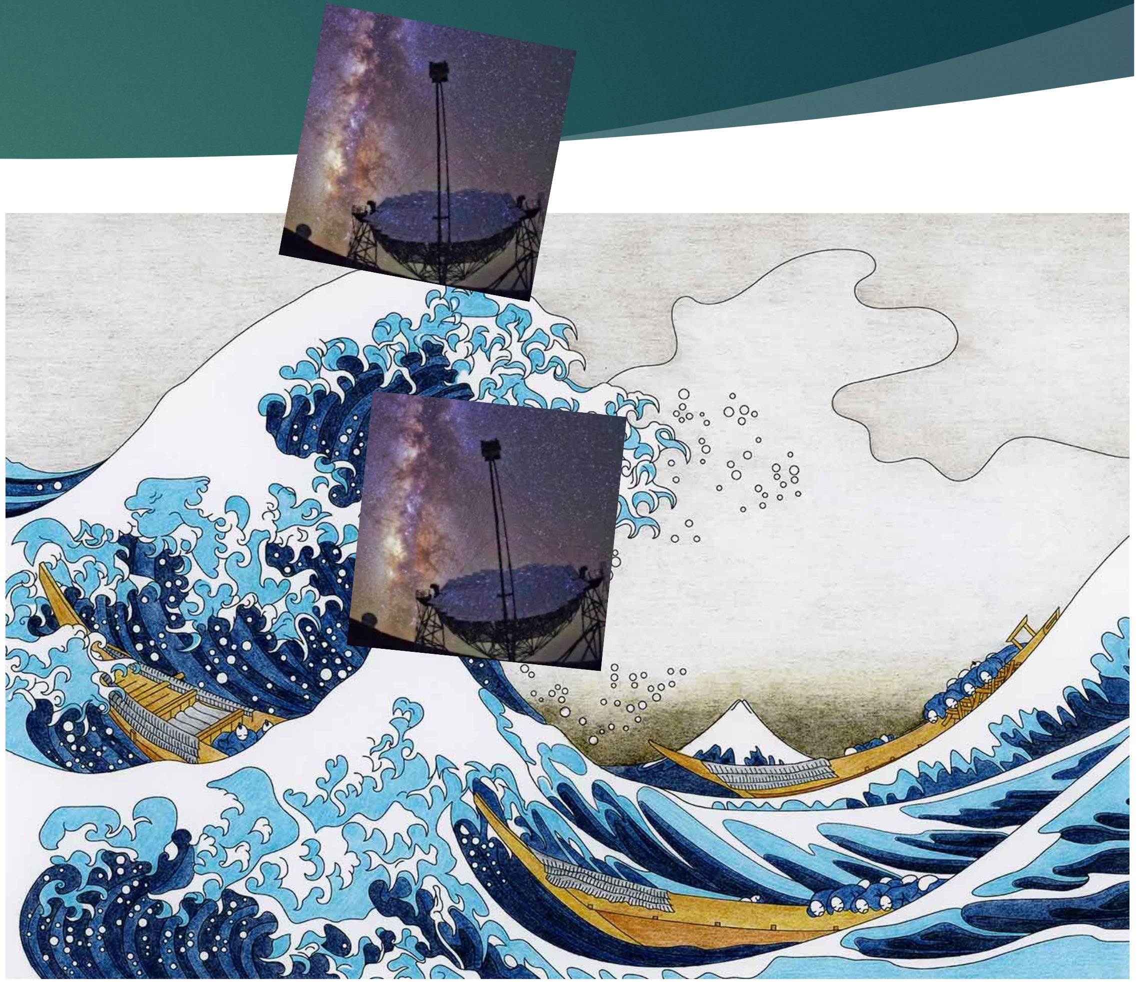
MAGIC Coll. 2015

Opened the possibility of intra-band correlation studies!

Detection of variability also at very high energies

MWL lightcurve (MAGIC) **2012**





Made possible thanks to: **MAGIC stereo upgrade!**

Key features of PG 1553+113 in flaring state

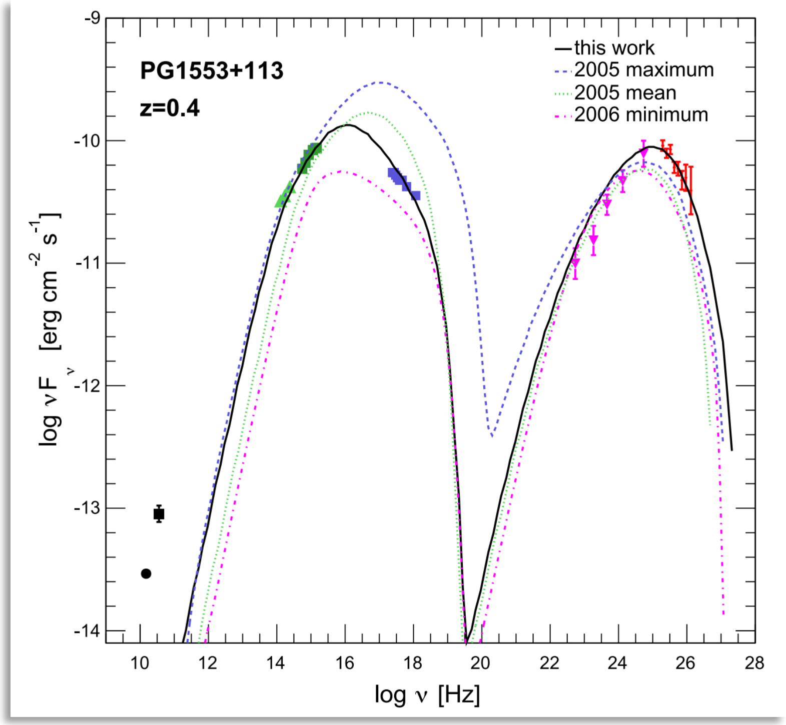
1. Very bright source in gamma rays
   → allows for a **time-resolved studies** both with *Fermi* and MAGIC (IACTs)

2. Redshift quite large (even if uncertain)
   → EBL absorption pretty strong

3. **SED modelling with simultaneous data**
   → fitting the second peak is challenging

4. Variability (not constraining): daily scale

SED 2012 high state

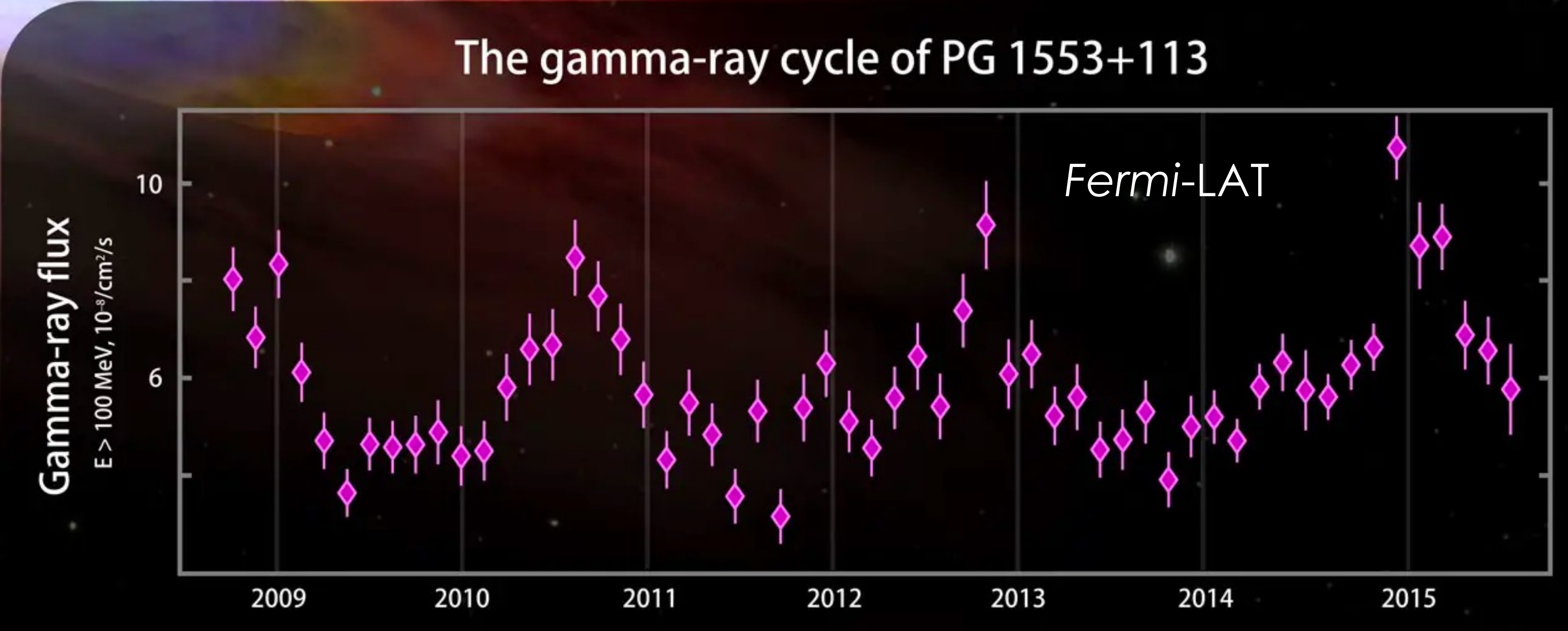


MAGIC Coll. 2015

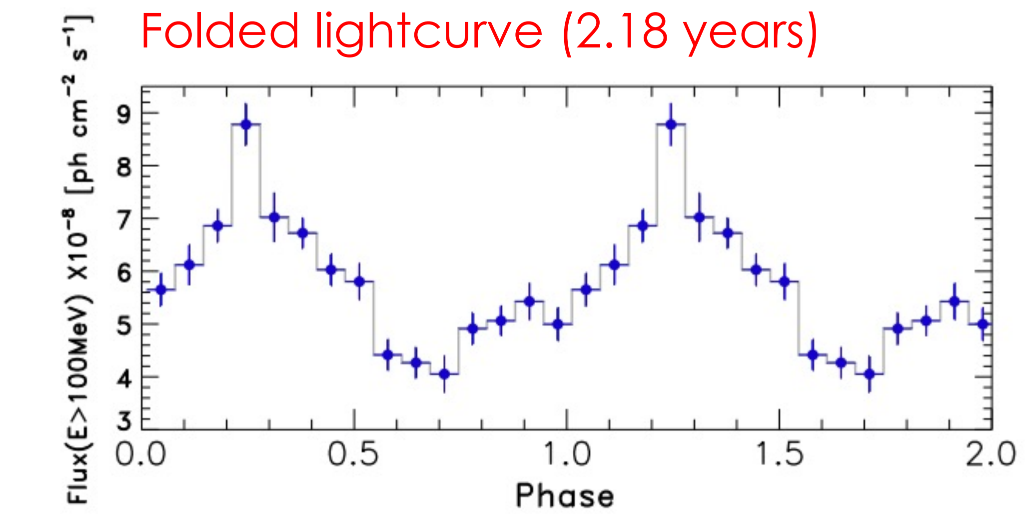
Shortest variability timescale at VHE can confirm the connection with X-ray data and provides an estimate on the emitting region!

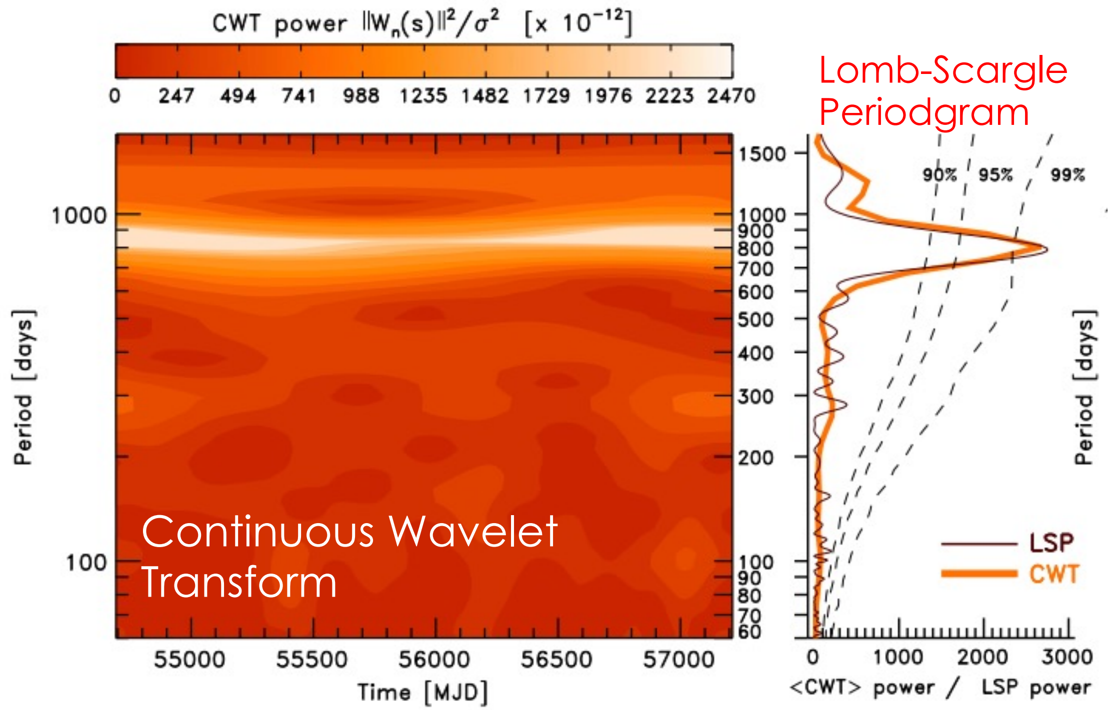
PG 1553+113: discovery of periodicity

- Is the periodicity statistically significant?
- Is it present also in other bands?
- What is the cause of the periodicity?



Probes



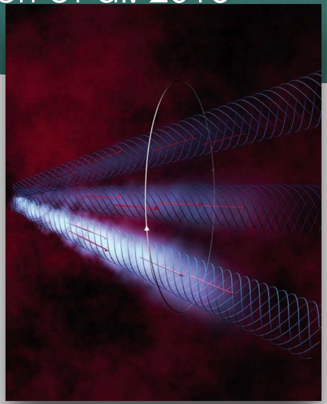


- Probing periodicity requires **proper statistical tools**
- *Fermi*-LAT period: 2.2 years
- Confirmation in other bands?
  - Hints in both optical and radio (delayed)
  - However, probing periodicity in a non-continuous lightcurve might be tricky!

Modeling the periodicity

GEOMETRICAL MODELS

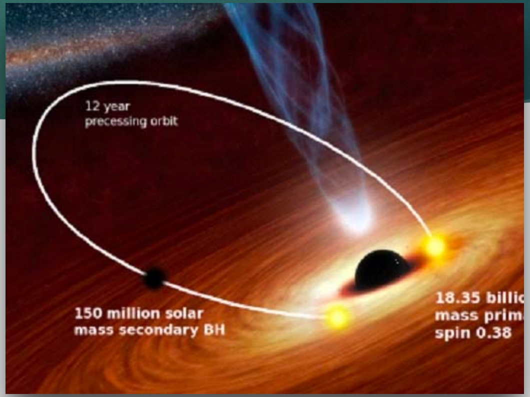
e.g. Danai et al. 2018;
Sobacchi 2017
Raiteri et al. 2015



jet precession or helical jet

change in Doppler factor: simplest models foresee an achromatic variability

ACCRETION MODULATION



accretion is modulated

e.g. Gracia et al. 2003

Double/multiple **peak sub-structure** expected in the light curve

DYNAMICAL MODELS

Instabilities in the jet due to stresses induced by a secondary (jetted?) black hole orbiting around the jetted black hole

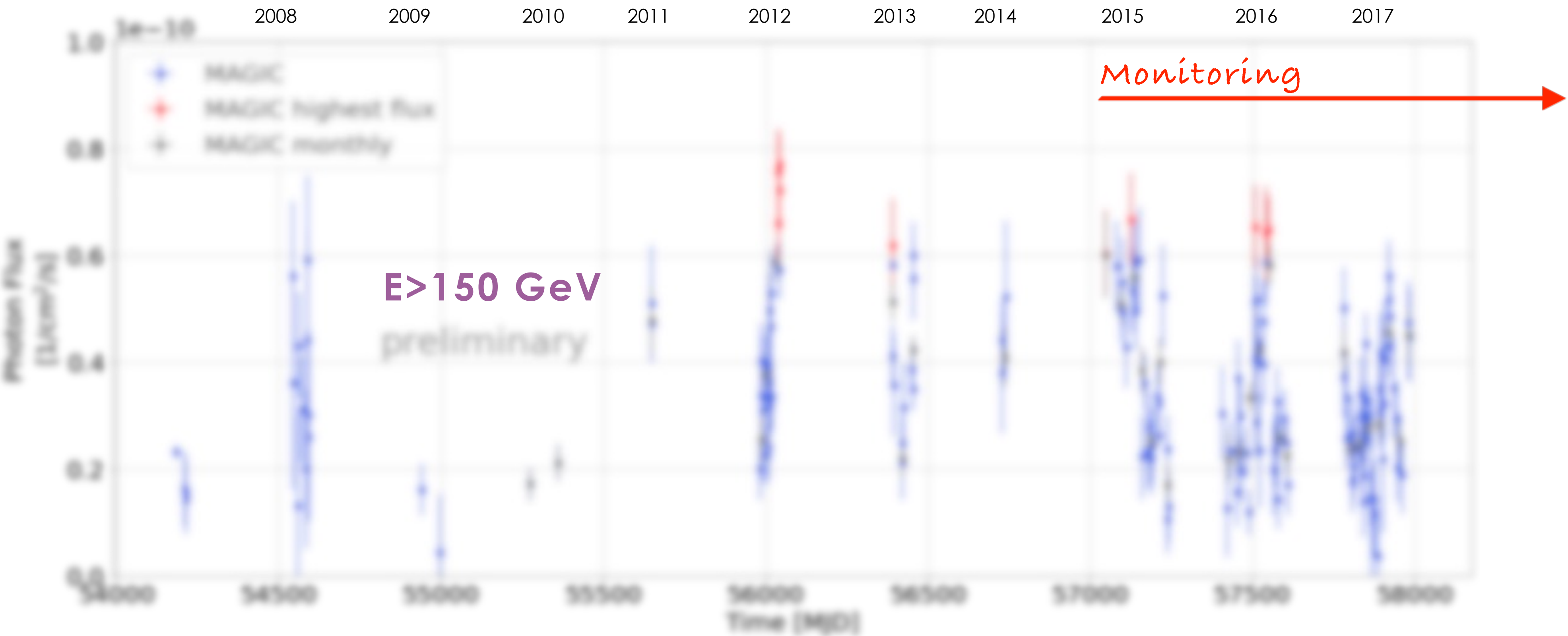
Double/multiple **peak sub-structure** expected in the light curve

e.g. Tavani et al. 2018

MAGIC observations and the monitoring campaign

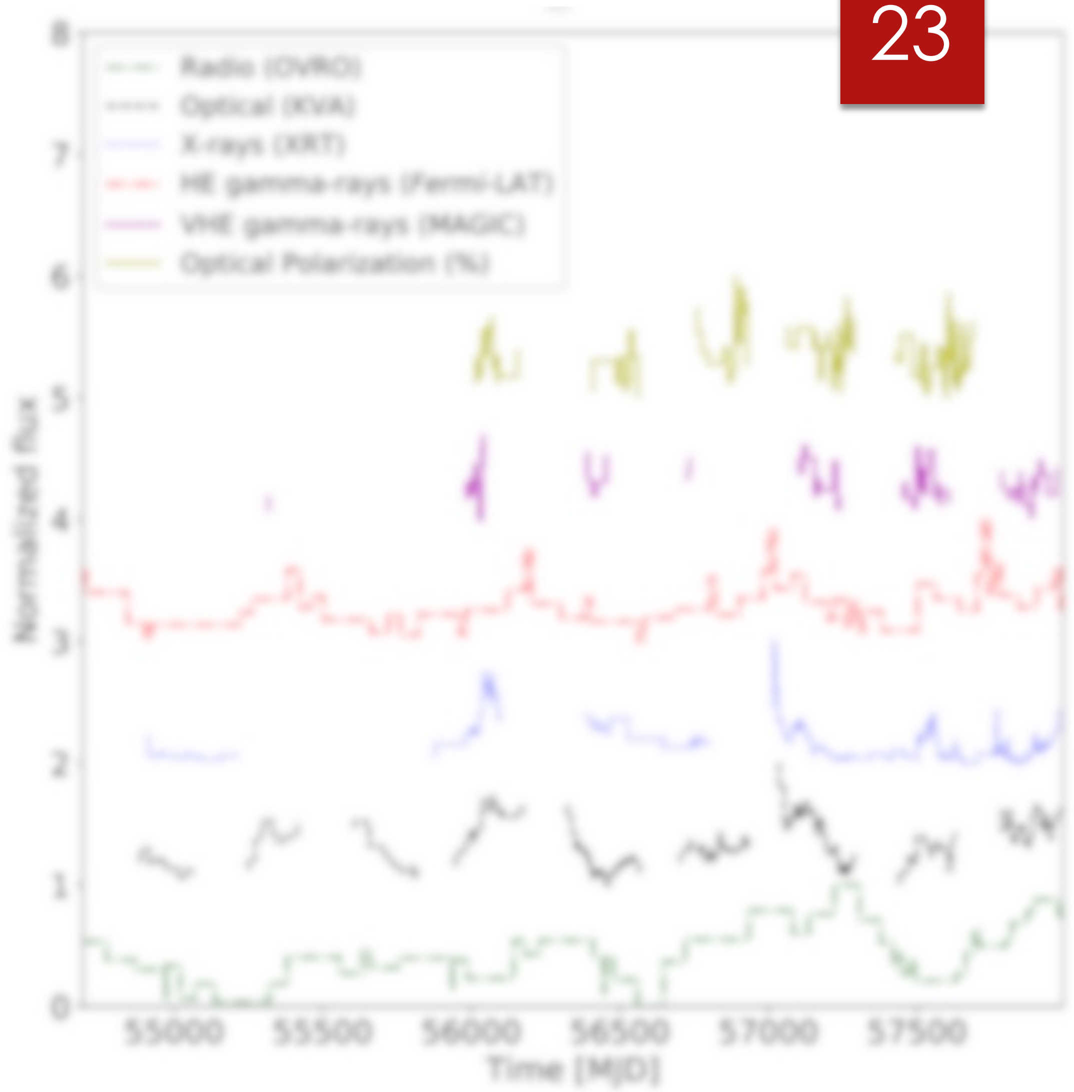
- **183 hours of data** (out of which 109 from 2015 on)
- **102 pointings** from 2015 to 2017
- **highest flux**: used for intra-night variability search
- This is the dataset used in MAGIC publication about to be published in the **MNRAS journal**

MAGIC lightcurve 2007 - 2017

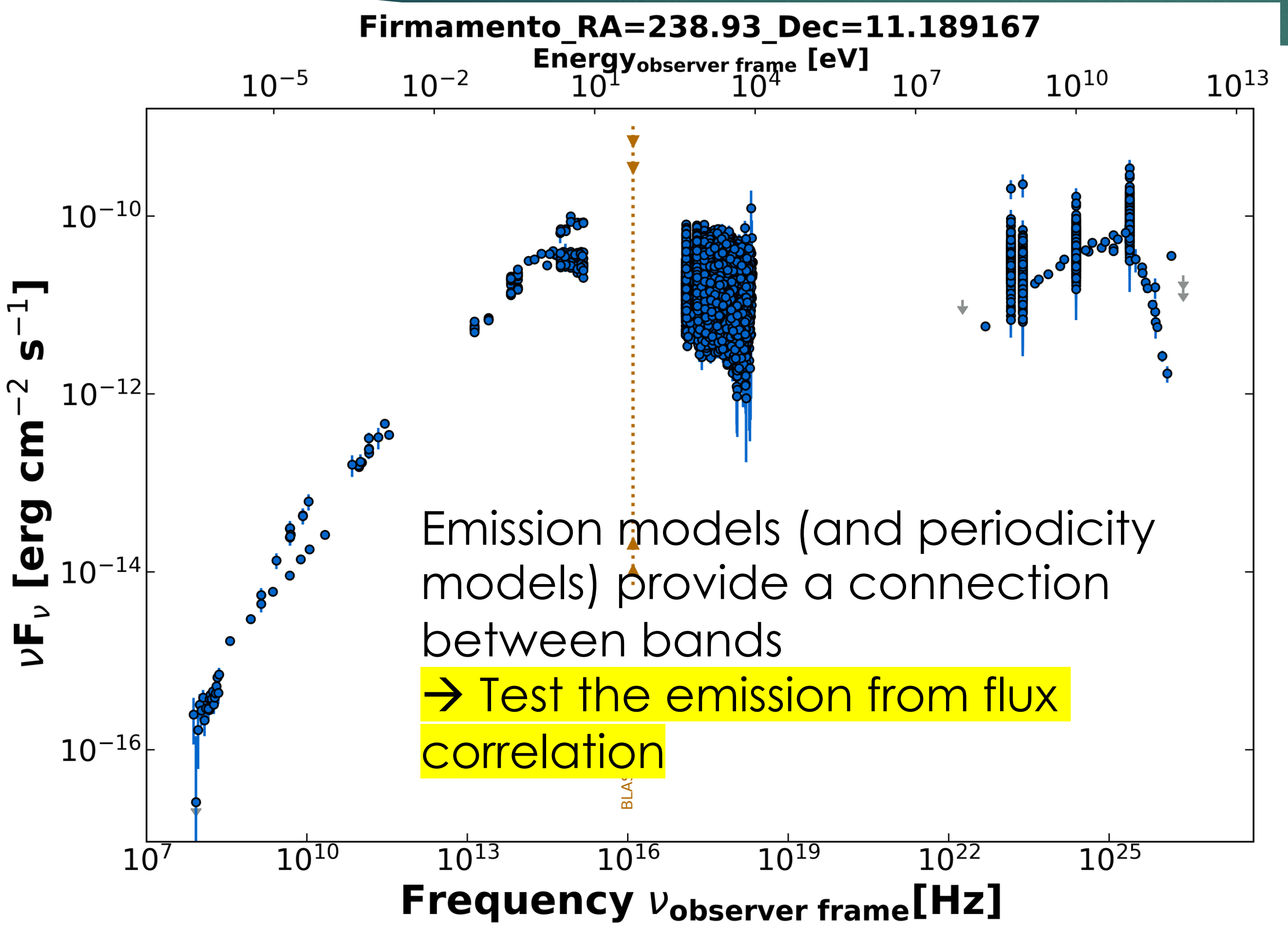


MAGIC regular monitoring started in 2015

MWL lightcurve (Bayesian bloks) 2007 - 2017

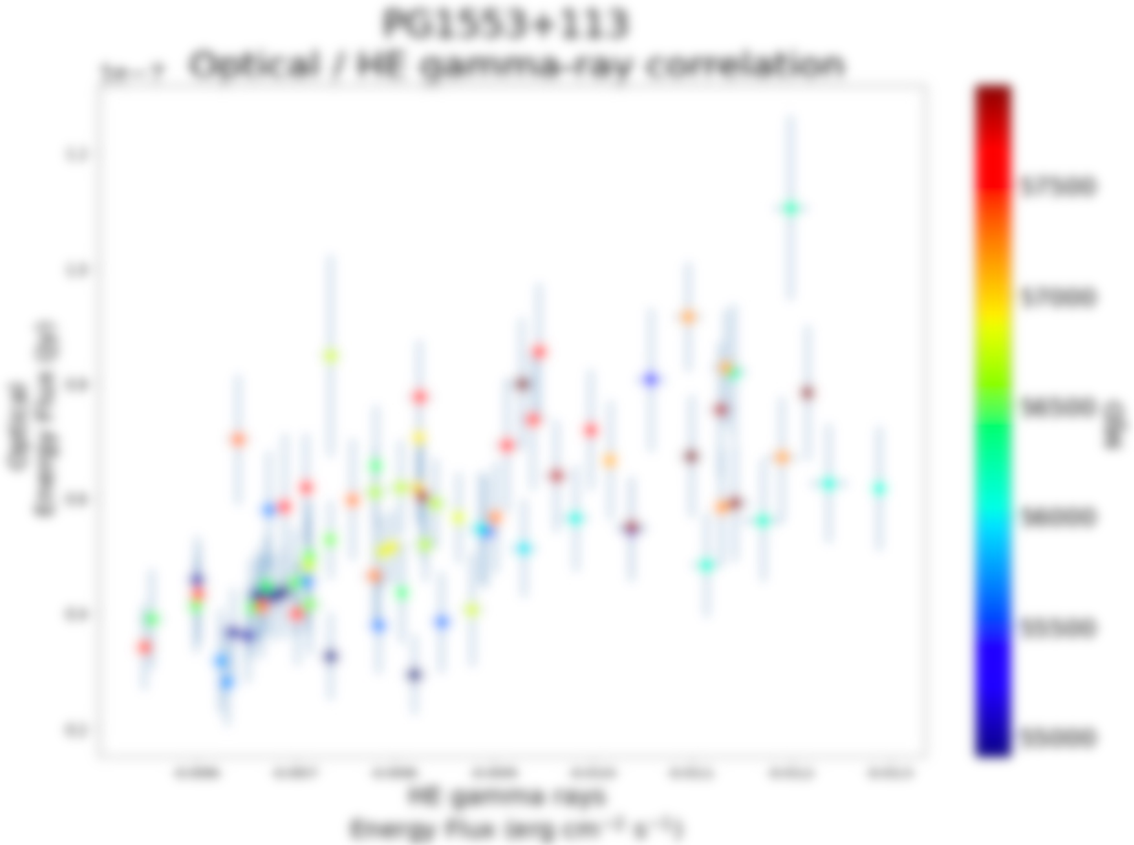


Search for intra-band correlations



Emission models (and periodicity models) provide a connection between bands

→ Test the emission from flux correlation



Systematic search for intra-band correlations

Band-1	Band-2	Spearman Coeff.
Optical	UV	0.94
Optical	IR	0.90
UV	HE γ-ray	0.66
Optical	HE γ-ray	0.63
UV	VHE γ-ray	0.62
IR	HE γ-ray	0.61
X-ray	VHE γ-ray	0.60
IR	UV	0.60
UV	X-ray	0.55
Optical	X-ray	0.37
HE γ-ray	VHE γ-ray	0.39
Optical	VHE γ-ray	0.35
X-ray	HE γ-ray	0.32
IR	VHE γ-ray	0.26
IR	X-ray	0.29

- From our analysis a **complex** intra-band connection emerge
  - Not a single synchrotron peak
- **Crisis** of the simple geometrical model for flux variations
- More data needed! (large uncertainties)

Folded MWL lightcurve 2007 - 2017

Phase-folded lightcurves

- Continuous monitoring only in the HE gamma-ray band.
- Dense monitoring in the other bands (4-6 pointings per month)
- Clear **modulation** in *Fermi*-LAT (20 days binning) and optical bands (T ~ **2.2 years**)
- No periodic modulation in *Swift*-XRT and MAGIC bands
- Complex correlation between bands

VHE gamma-rays from PG1553+113: in summary

- 2006 - early studies: detection of a stable VHE gamma-ray emission
- 2012: detection of a flare → opens the possibility of modelling the SED in different states (time-resolved modelling)
- 2005-2017: long-term monitoring allows for a detailed multi-band correlation study (and in principle also time-resolved spectral modelling)
- 2024?
  - Monitoring ongoing
  - Open point: short-term (intra-night) variability….

LST proposal: Cycle 1

- **Goal**: search for intra-night variability
- **Method**: deep observation(s), meaning long exposure, during high/flaring state of the source
- **LST evaluation**: accepted!

Observations/Preliminary results?

There is a complementary proposal in MAGIC aimed at the (long-term) monitoring of the source

Constraining short-term variability of PG 1553+113 in high emission state

Group: EGAL

PI of Proposal: Elisa Prandini, **Institute:** Padova University, **Email:** elisa.prandini@unipd.it

COI of Proposal: Michele Doro, **Institute:** Padova University, **Email:** michele.doro@unipd.it

COI of Proposal: Estelle Pons, **Institute:** LAPP, **Email:** pons@lapp.in2p3.fr

COI of Proposal: Chiara Righi, **Institute:** INAF, **Email:** chiara.righi@inaf.it

Source Name: PG 1553+113

RA [deg] = 15 55 44.7, **DEC** [deg] = +11 11 41

Min Zenith [deg] = 0, **Max Zenith** [deg] = 52

Night Sky Background [Moon/Dark/Both] = Dark

Wobbles [Standard/Custom] = Standard Wobble

Observation Time [hrs] = 20 hr

Priority = Cat1/Cat4

LST proposal: Cycle 1

- Goal: discover **intra-night variability**
- **ToO** base on strong flux (otherwise this is not feasible)
- **Strategy**: long exposures (4 hours). We set a threshold such that we do have 3 sigma in 20 min (estimated according to previous observations)
- **MWL coverage**: *Swift*-XRT data

There is a complementary proposal in MAGIC aimed at the (long-term) monitoring of the source


3. TECHNICAL JUSTIFICATION

LST proposal: Plans for Cycle 2

- We will resubmit the proposal
- Team: is well established (Padova-Trieste)

  PI: Elisa
  Co-Is: Helena, Arshia, Giuseppe

How to write a successful proposal

1. **Clear goal** (that should be well explained in a wide scientific context)
2. **Strong team** with different expertises. **Young members** usually well perceived! PIs are usually at least PhD students with some past experience
3. Strategy/**Feasibility** should be justified carefully (number of hours to reach the proposed goal(s), kind of data requested (moon/dark), Zenith angle)
4. **Impact**: provide a plan for publication also in case of no-detection
5. In our **multiwavelength/multimessenger** epoch, complementary data should be carefully considered (MWL, MM) both with major and minor facilities. It is never too early to learn submitting a Swift ToO!


Thank you!