Spying on the next-door blazar Markarian 501 during multiple years

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and GASP-WEBT, F-GAMMA

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RAPP Ruhr Astroparticle-Plasma Physics Center

RUHR UNIVERSITÄT BOCHUM

Why study the Markarians?

Studying blazars poses two big observational challenges:

1) Emission over very broad energy range (radio to VHE gamma-rays)
2) Variability on very different time-scales

→ Excellent broad-band coverage and temporal coverage is needed

→ Need campaigns which run over many years

→ Limited resources -> need to focus on few targets

Markarians:

- Bright → Sample the SED with every "shot"
- Near-by → Imaging with VLBA possible down to <0.1pc
  → Minimal effect from EBL absorption
- No strong BLR → Less additional uncertainties (than in FSRQs)

→ **Excellent laboratories to study the nature and behavior of blazars**

The campaigns

2009

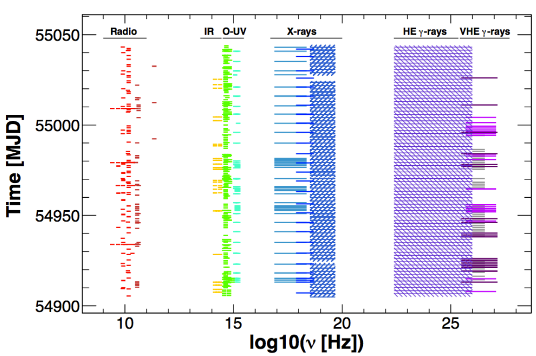
1st campaign with Fermi-LAT

4.5 months, every ~5 days

>30 instruments, radio to VHE

optical polarisation (Steward O.)

VLBA coverage

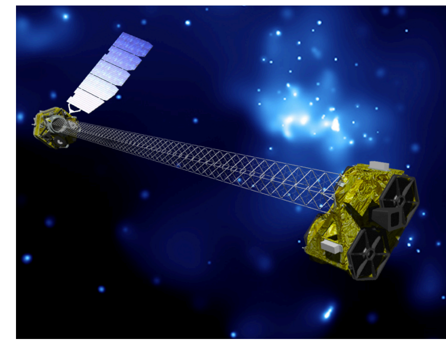


2012

1st campaign with FACT as monitoring instrument

including also GASP-WEBT and F-GAMMA

2013



1st campaign with NuSTAR

also 1st time use of LIDAR corrected VHE data

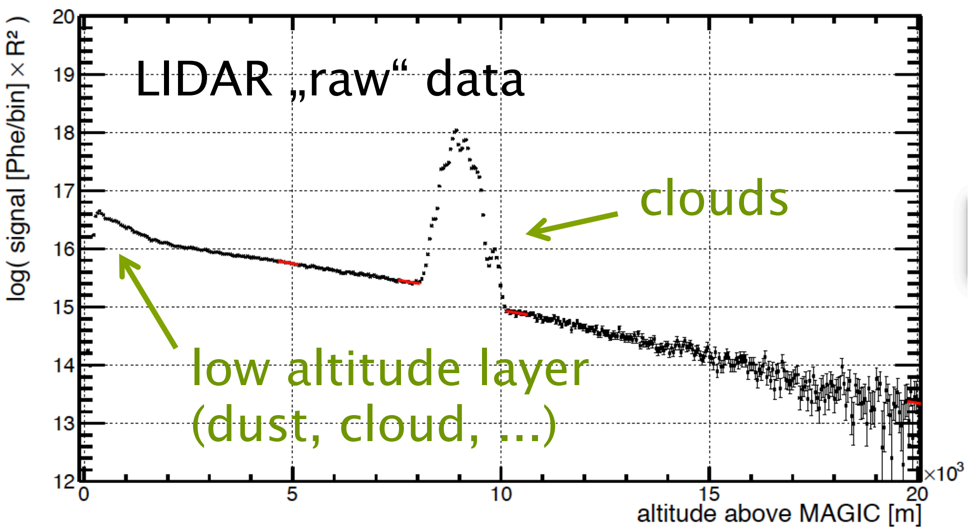
(MAGIC telescope data)

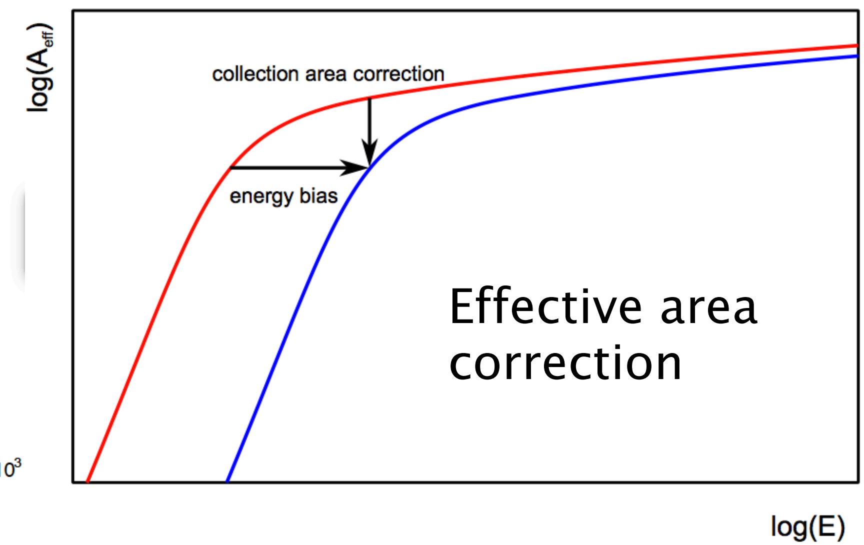
MAGIC LIDAR to improve data quality

1) Correction of data taken under non-perfect atmospheric conditions
2) Recovery of data taken under adverse conditions

- Strategy presented in ICRC 2013 (Fruck et al., #1054)
- Transmission $\tau(h)$ vs. altitude h
  1st-order correction estimates E: $E_{corr} = E_{est} / \overline{\tau}$
- Effective area and energy corrected event-wise

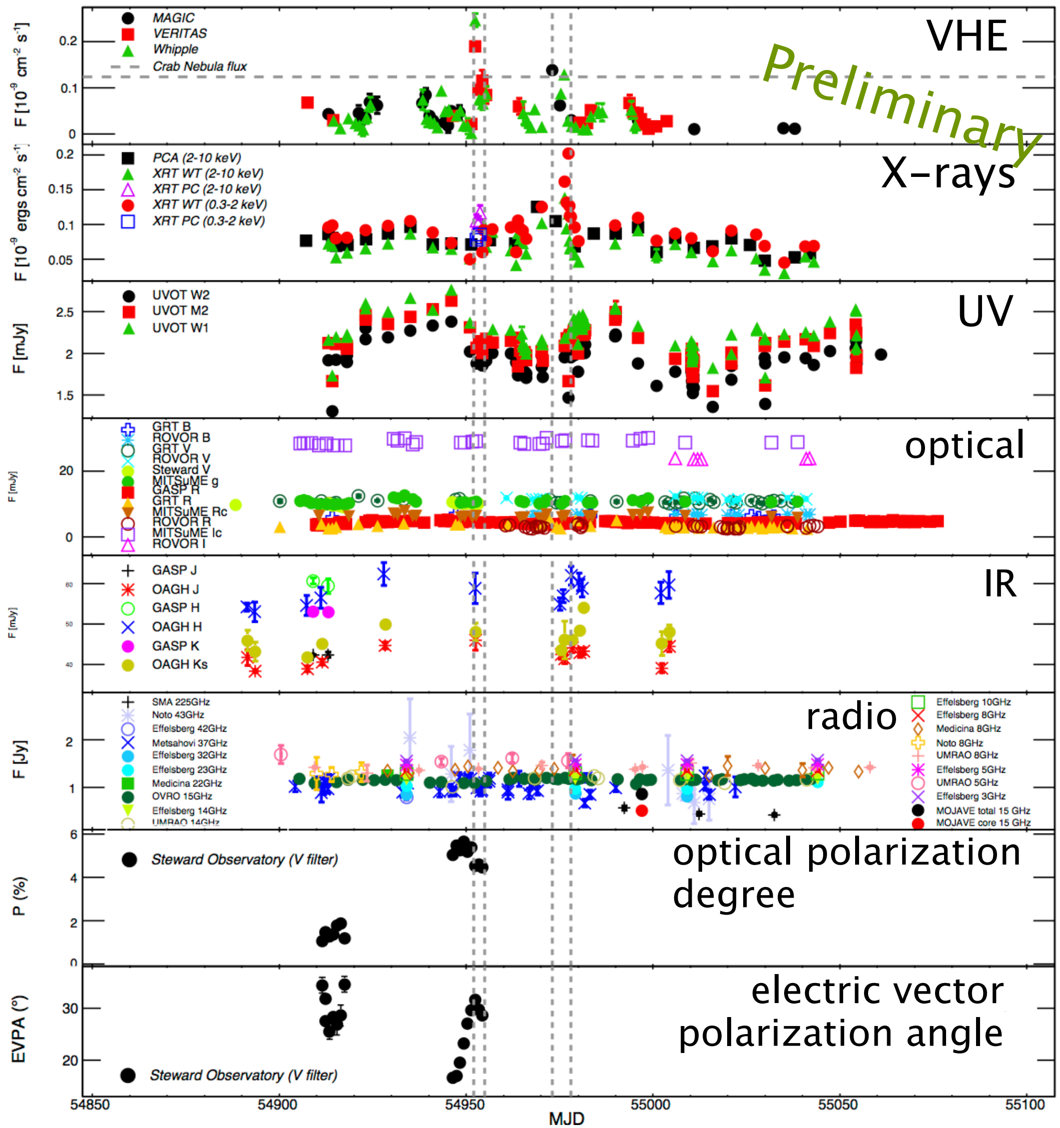
LIDAR at the MAGIC site





Recovered ~10 hrs of crucial data during flaring activity
1st time LIDAR used in a physics paper with IACT observations
Noda et al. (arXiv:1508.05026), Furniss et al. (arXiv:1509.04936)

Results: Flaring activity



Flares seen in all campaigns

2009:

Two very different VHE flares:

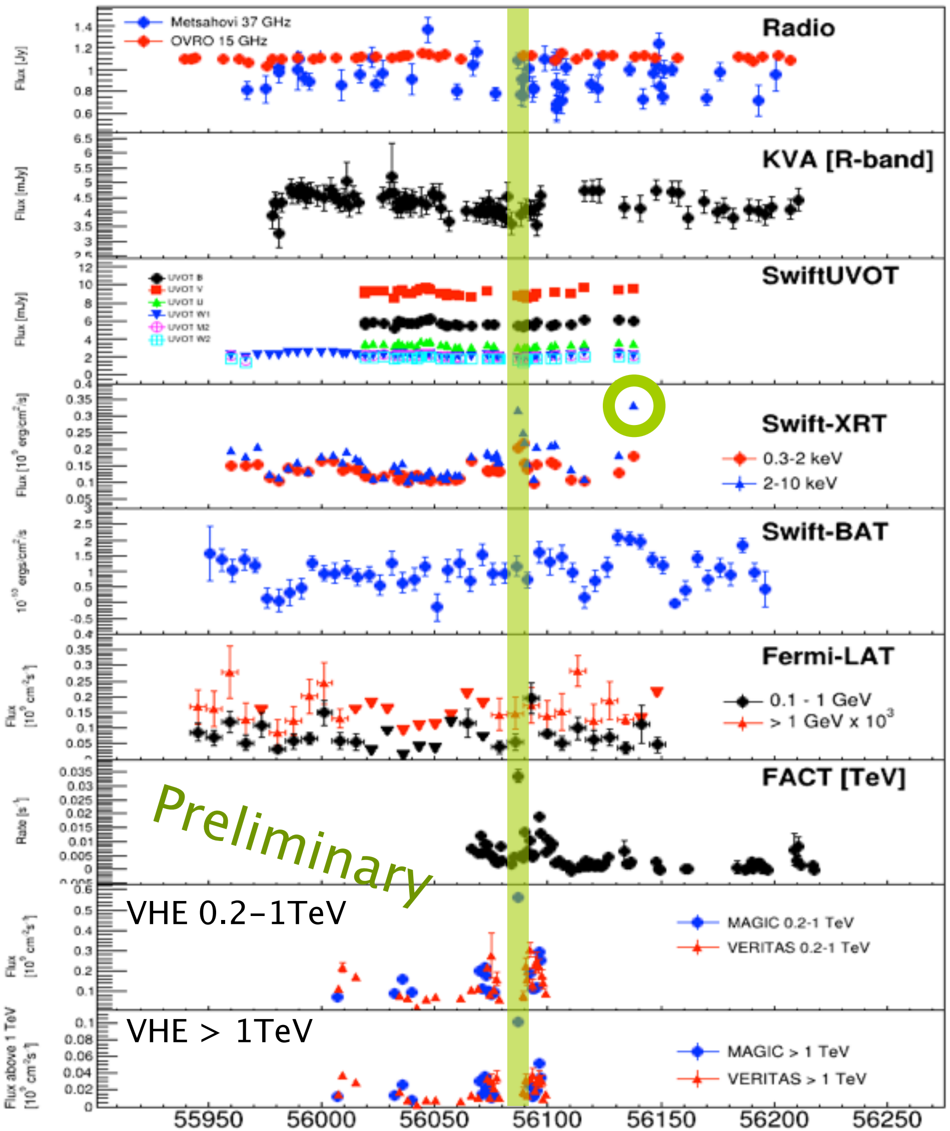
1^{st} flare:

- t_{var}<1hr (Pichel et al. 2011)
- No flaring in X-rays, but strong spectral hardening
- Coinciding with polarization changes

2^{nd} flare:

- t_{var} ~ 1 day
- Contemporaneous X-ray flare

Results: Flaring activity

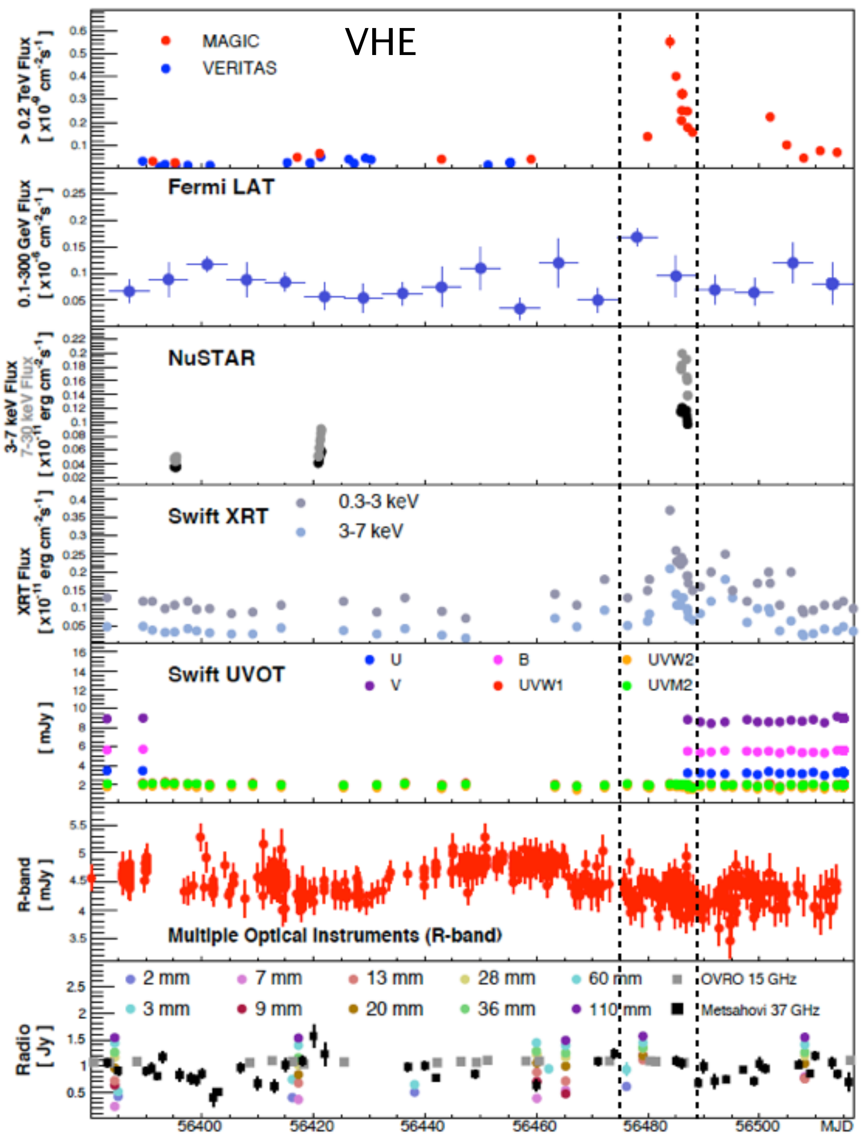


2012:

Extreme flare:

- Seen with MAGIC, FACT and XRT
- Flux > 10 C.U. (above 1 TeV)
- t_{var}~ several hrs
- Followed by a larger X-ray flare seen by Swift-XRT, but no simultaneous VHE observation
- Excellent agreement between MAGIC and FACT above 1 TeV
- Very hard VHE and X-ray spectra over entire campaign! -> “extreme blazar” behavior

Results: Flaring activity



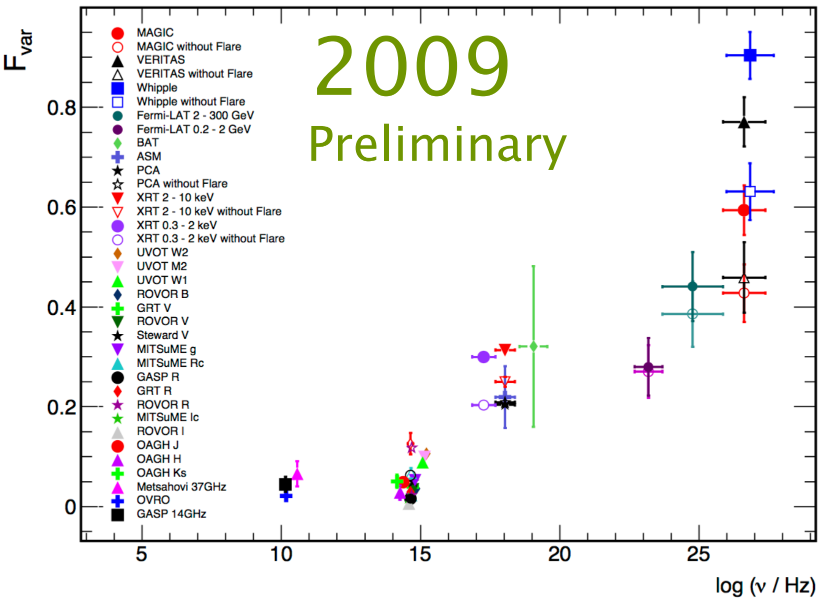
2013:

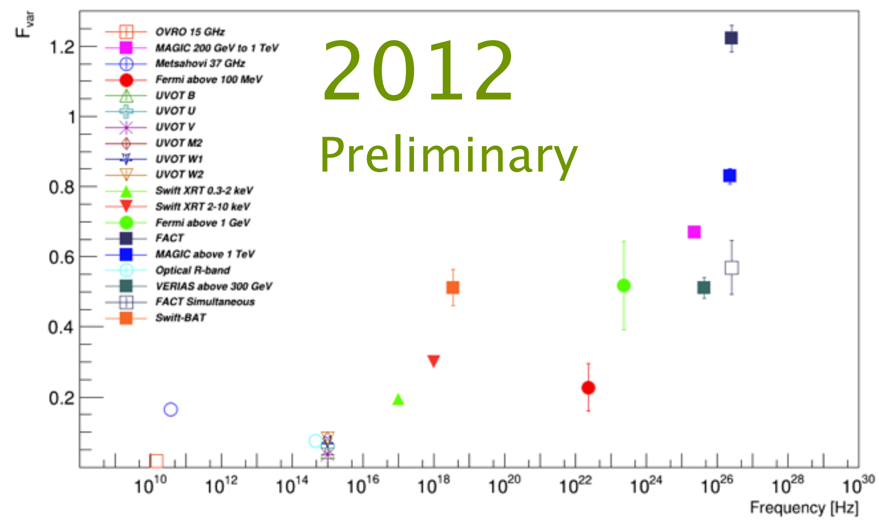
Flaring state over ~4 days:

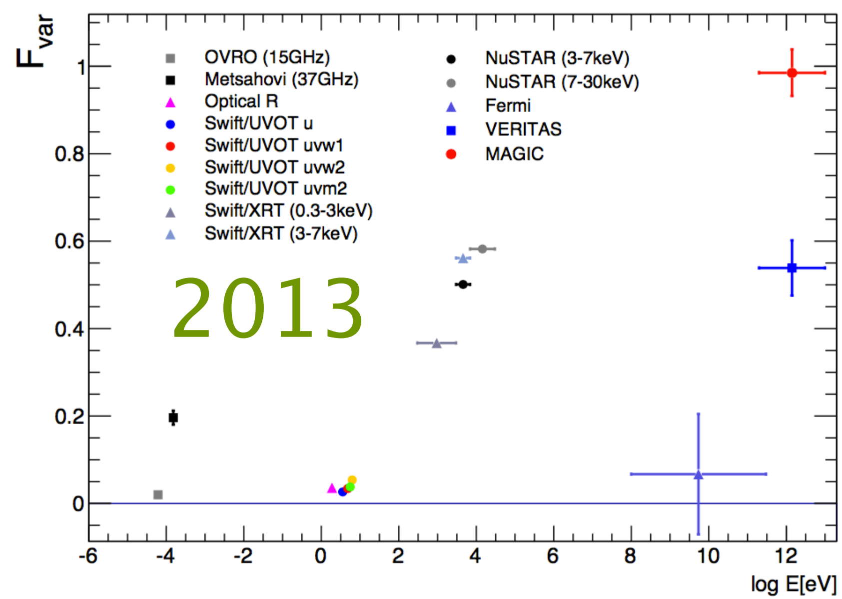
- ToO triggered by high rate in Swift/XRT
- Observed over 4 consecutive nights with MAGIC (& Swift/XRT). Flux up to ~2.5 Crab, t_{var} ~ few hours
- MAGIC data were LIDAR corrected
- Correlation found between VHE (MAGIC) and X-ray (NuSTAR & Swift/XRT)

ApJ **812** (1) 65, 22 pp. (2015)
arXiv:1509.04936

Results: Variability







ApJ 812 (1) 65, 22 pp. (2015)

Fractional variability:

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

- Roughly increasing with energy in 2009 and 2012
- 2013: double bump structure more similar to Mrk 421.

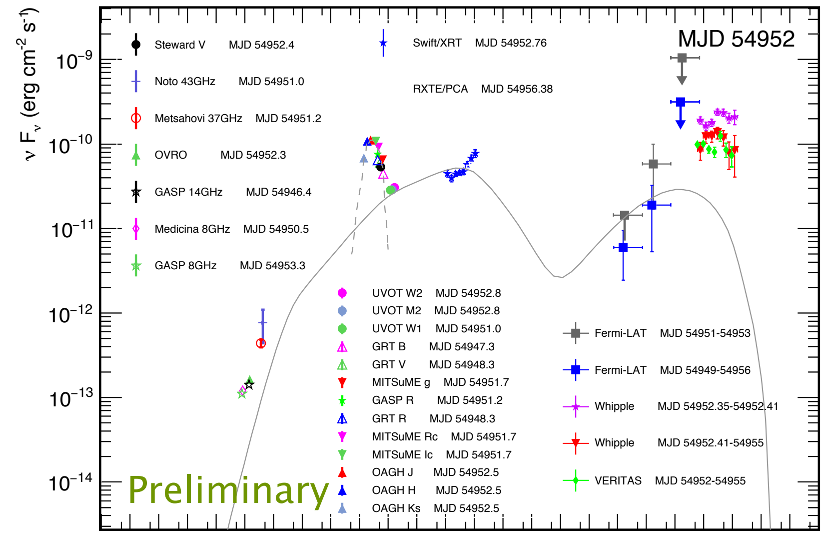
Results: Spectral Energy Distribution

2009

Two flaring SEDs

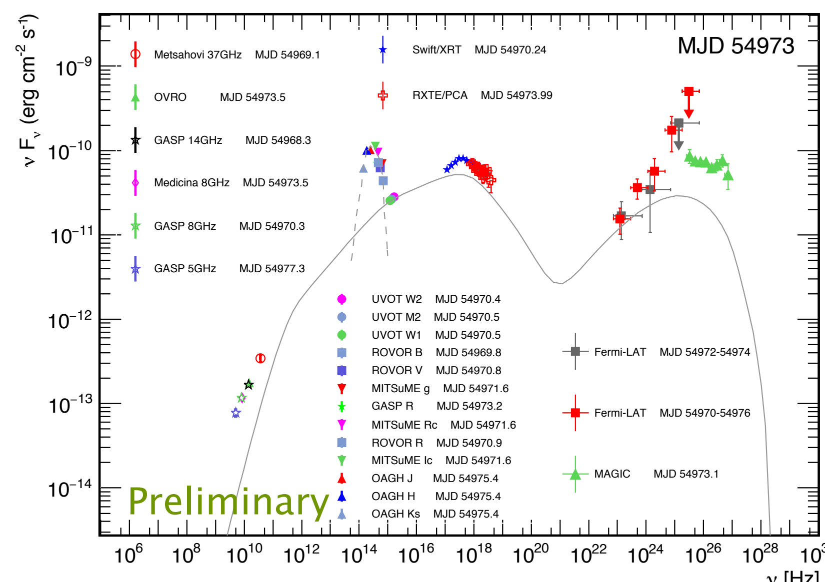
1st flare: large increase in IC peak, Swift/XRT spectrum shows hint for upward curvature!

2nd flare: shows more „regular“ flaring behaviour for Mrk 501, increase in X-rays and in VHE.



Modeling:

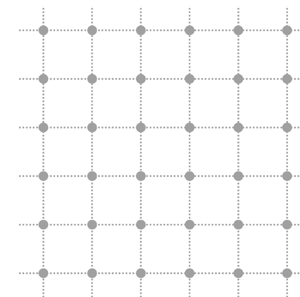
- UV, X-rays, HE and VHE gamma-rays taken into account
- radio points serve as upper limits, optical and IR not taken into account (dominated by host galaxy)



Results: Spectral Energy Distribution

2009

Modeling performed using a **novel grid scan method** with SSC models (used model by Takami 2011, one and two independent zones)



Grid Scan Method:

- Define generous parameter ranges
- Define step size
- Produce model curve for each point on parameter grid
- Evaluate agreement with data for each model based on the X^2
- Apply additional constraints:

  $u_e/u_B < 10^3$,

  $T_{var,min} = (1+z)\ R\ /(c \bullet \delta)$

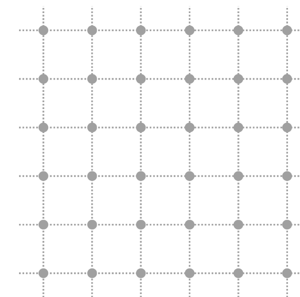
Aims:

- **Less bias** on chosen parameter regions!
- Find **several SSC models** which best match the data set
- Find interesting regions in the model parameter space
- Study **degeneracy of model parameters**

Results: Spectral Energy Distribution

2009

Modeling performed using a **novel grid scan method** with SSC models (used model by Takami 2011, one and two independent zones)



Producing the models

- One-zone SSC:
  EED with 2 spectral breaks
  → **11 free parameters!**

coarse grid two-zone	γ_{min}	γ_{max}	γ_{break}	α_1
min	1×10^2	1×10^5	1×10^4	1.7
max	1×10^6	7×10^8	1×10^7	2.3
# steps	5	4	7	7
spacing	log	log	log	lin

α_2	n_e	B/mG	$\log(\frac{R}{cm})$	δ
2.0	100	5	14.0	1
4.8	1×10^6	250	18.0	60
8	9	9	9	7
lin	log	log	lin	log

- Two-zone SSC:
  First zone fixed to quiescent emission model (Abdo et al 2011),
  define second zone from grid scan with 1 spectral break in EED
  → **9 free parameters!**

→ Tens of millions of SSC model calculations

→ Cluster computing necessary!

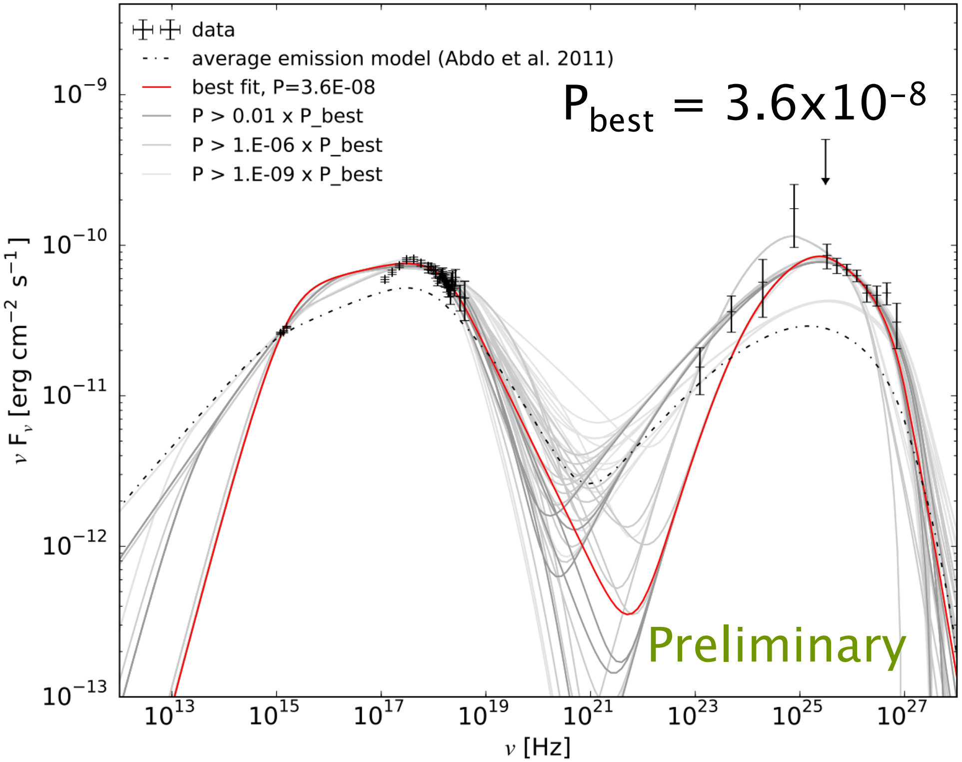
Results: Spectral Energy Distribution

2009

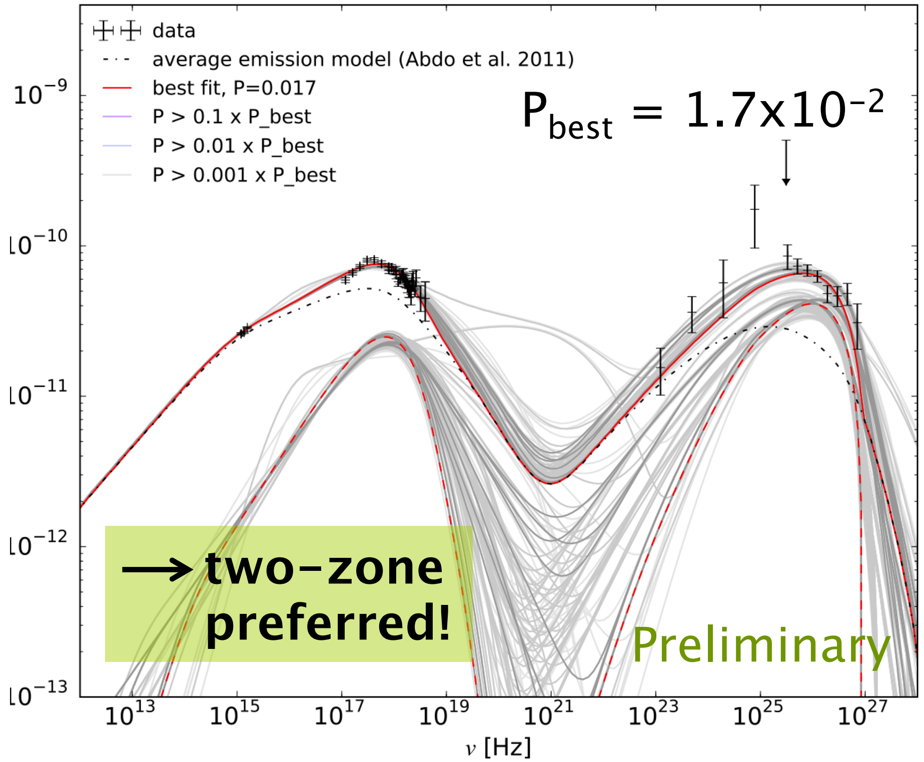
1st flare: very bad fit probability (derived from χ^2): $P < 10^{-10}$
no further investigation because of fast variability and no strict data simultaneity

2nd flare:

one-zone models:



two-zone models:



Results: Spectral Energy Distribution

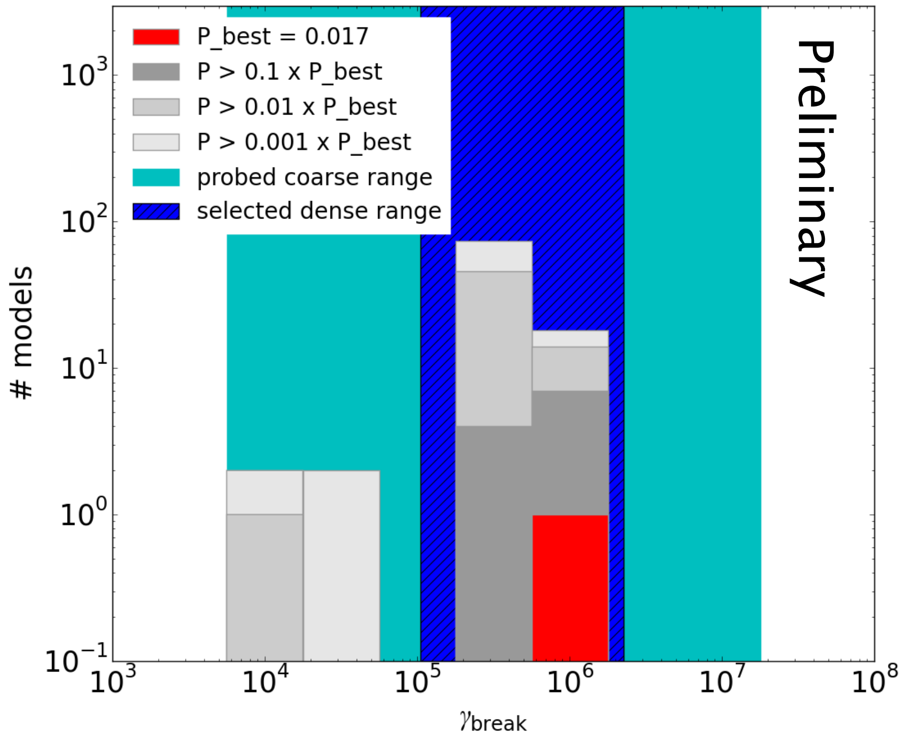
2009 2nd flare:

Results from two-zone scenario are promising:

→ Choose interesting parameter regions for a second iteration of the scan, with more narrow ranges and a finer step size

Go to:
histograms of best models in each model parameter, e.g. in γ_{break}:

→ Second iteration of the grid scan



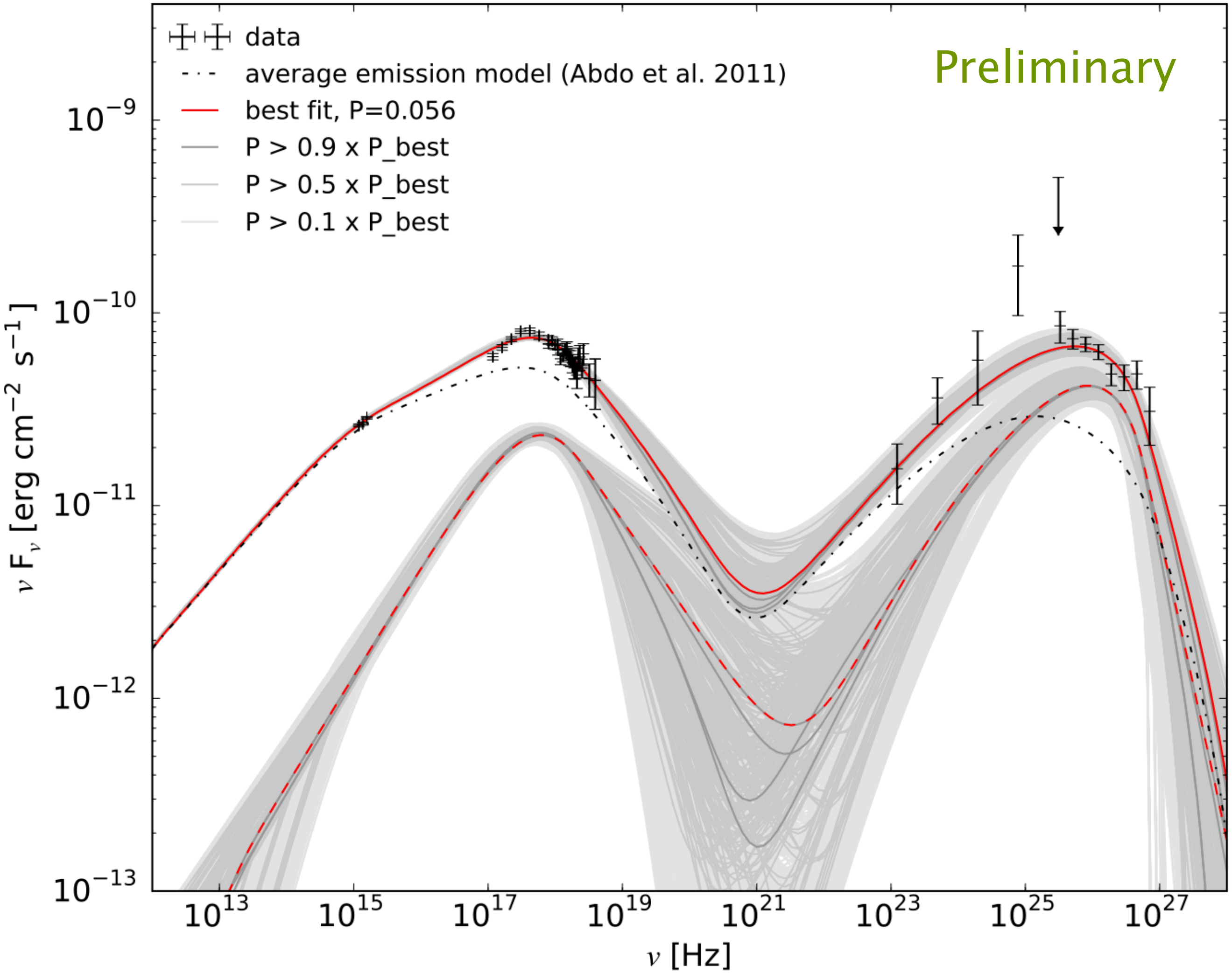
Results: Spectral Energy Distribution

2009 2nd flare:

two-zone models
dense grid

- Best model:
  $P_{best} = 5.6 \times 10^{-2}$

→ **slightly better than two-zone coarse scan**

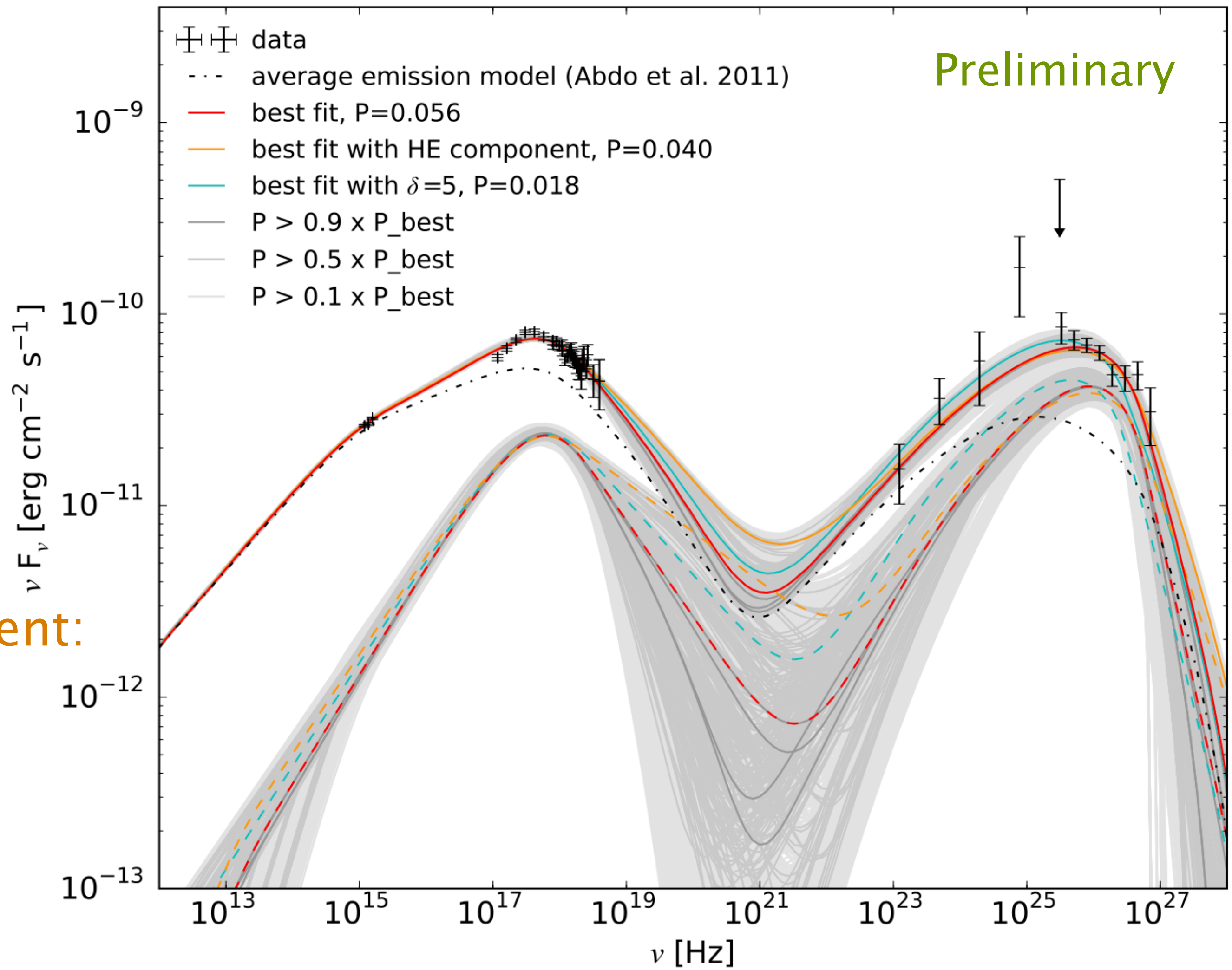


Results: Spectral Energy Distribution

2009 2nd flare:

two-zone models
dense grid

- Best model:
  $P_{best} = 5.6 \times 10^{-2}$
- Best model with strong HE component:
  $P_{best} = 4.0 \times 10^{-2}$
- Best model with low Doppler (δ=5):
  $P_{best} = 1.8 \times 10^{-2}$

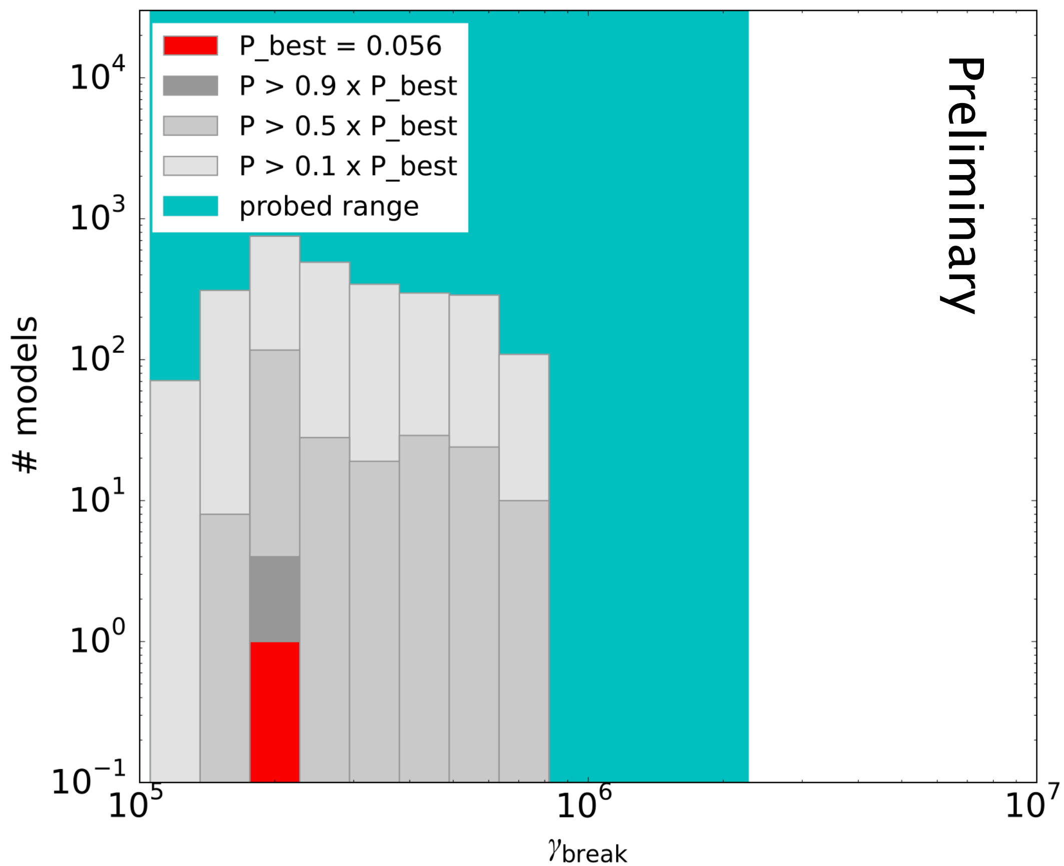


Results: Spectral Energy Distribution

2009 2nd flare:

Degeneracy of model parameters

Again: study histograms of best models in the space of model parameters



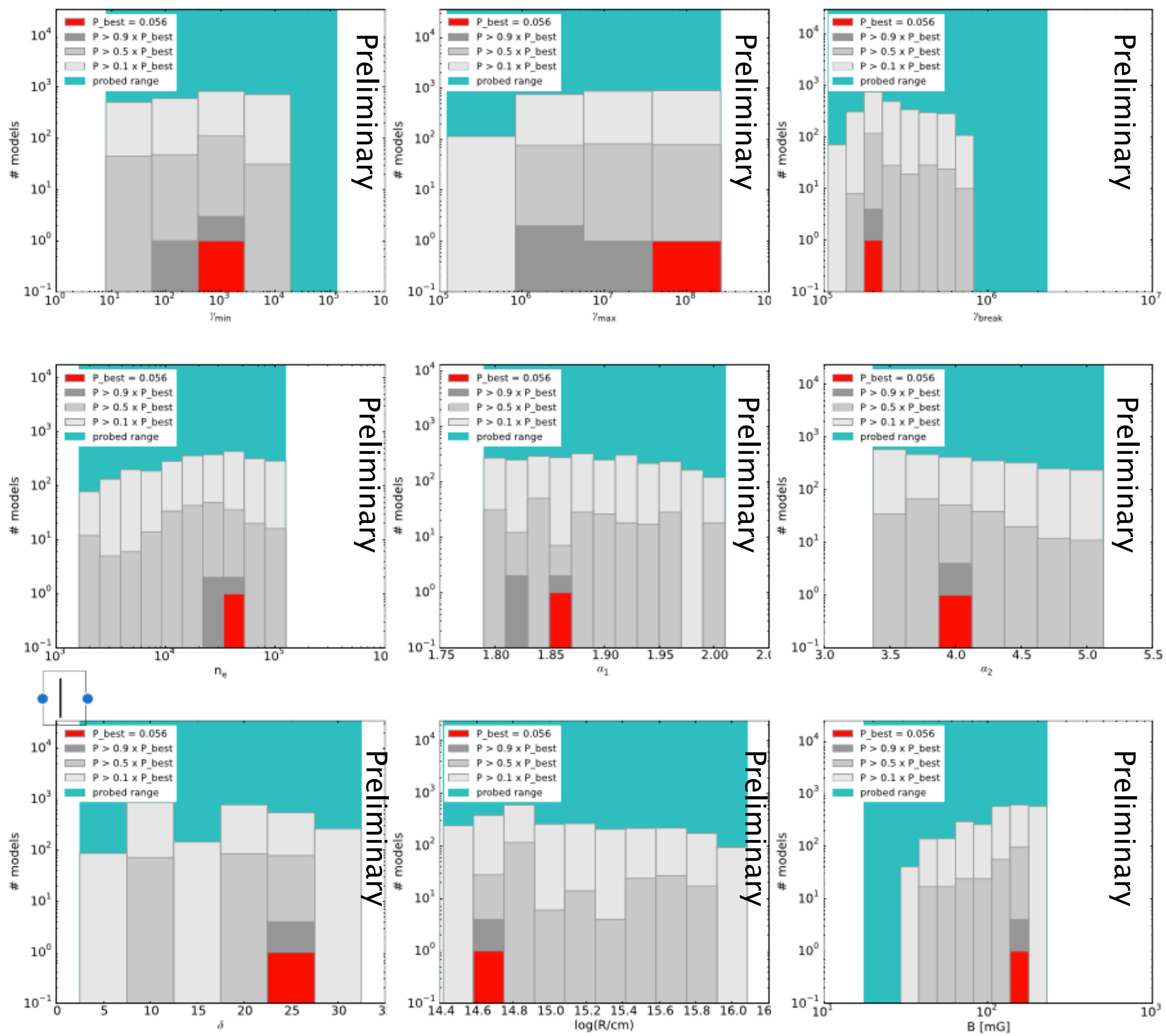
Results: Spectral Energy Distribution

2009 2nd flare:

Degeneracy of model parameters

Some model parameters are rather constrained, e.g. γ_{break},

some still show a broad distribution,
e.g. γ_{max} or n_e



Conclusions

- Markarians: excellent lab to study blazars.
  MWL campaigns: excellent method to learn more.
  ⟶ **We get an unbiased picture and we often get surprises**.

- Gain in new technologies/instruments achieves much better campaigns from year to year (FACT, NuSTAR, LIDAR correction)

- Lesson learned: Mrk's are far from being completely understood.
  They show different faces and new features each time.

- We saw an extreme shift of the SED of Mrk 501 in 2012.
  ⟶ **Maybe "extreme blazar" is rather a state than a class.**

- Surprising similarities to other blazar classes (polarization correlation, LBLs and FSRQs) ⟶ **Intrinsic similarities of all blazars!**

- We can model the SED of Mrk 501 with Doppler factor of 5
  and with a strong high energy component
  ⟶ **Surprises if we search with less bias**.

- Synchrotron Self Compton models work well, but we require well-sampled SEDs to really constrain the parameter space!