Temporal variability and SED evolution modeling of Mrk421 during its most violent year

On behalf of the MAGIC collaboration

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JetSeT
Jets SED modeler and fitting Tool

MAGIC
Major Atmospheric Gamma Imaging Cerenkov Telescopes

The archetypal Blazar: Mrk421

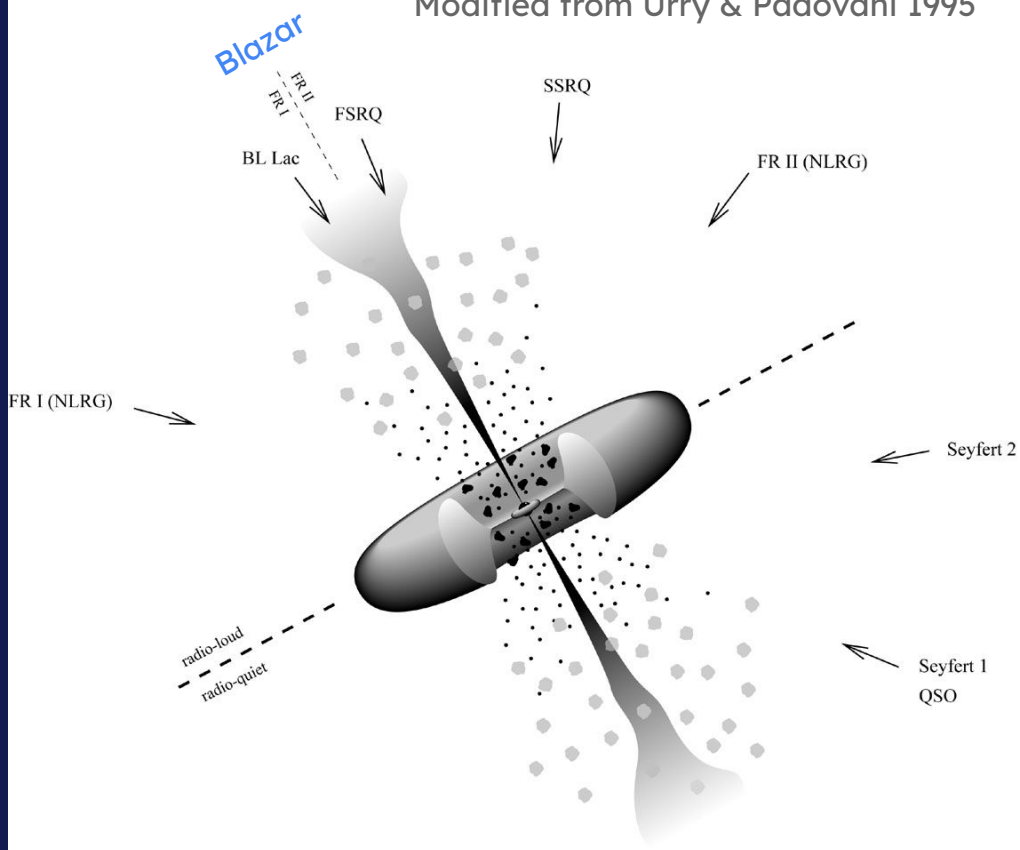
Blazars are Active Galactic Nuclei (AGN) with relativistic jets and beamed emission directed towards the observer

Markarian 421 (Mrk421) is one of the most studied AGN in Very High Energy (VHE, >100 GeV) astrophysics

The very first VHE blazar discovered by Whipple telescope in 1992

2010 saw the biggest flare ever recorded for the source with a Multi-wavelength (MWL) campaign targeted at getting a wide spectral coverage of the source

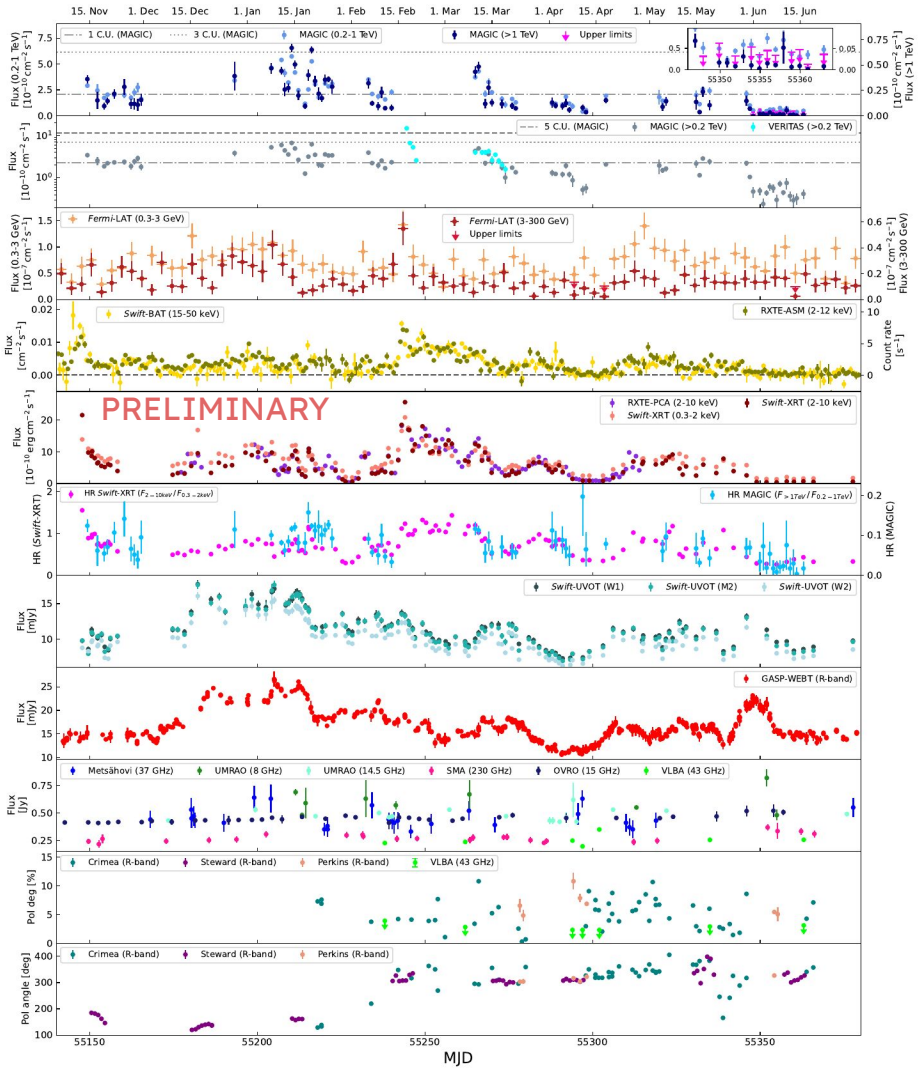
Modified from Urry & Padovani 1995



MWL Campaign

MWL observation campaign from Nov 2009 - Jul 2010 which includes the exceptional ~15 crab unit (C.U.) flare detected by VERITAS for shorter time bins. MAGIC average daily flux approaching ~3 C.U.

MAGIC et al - Characterization of Mrk 421 during its most violent year [submitted 2024]



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Variability analysis for the full period and SED modelling for January flare observed by MAGIC

MAGIC+VERITAS joint publications for this dataset

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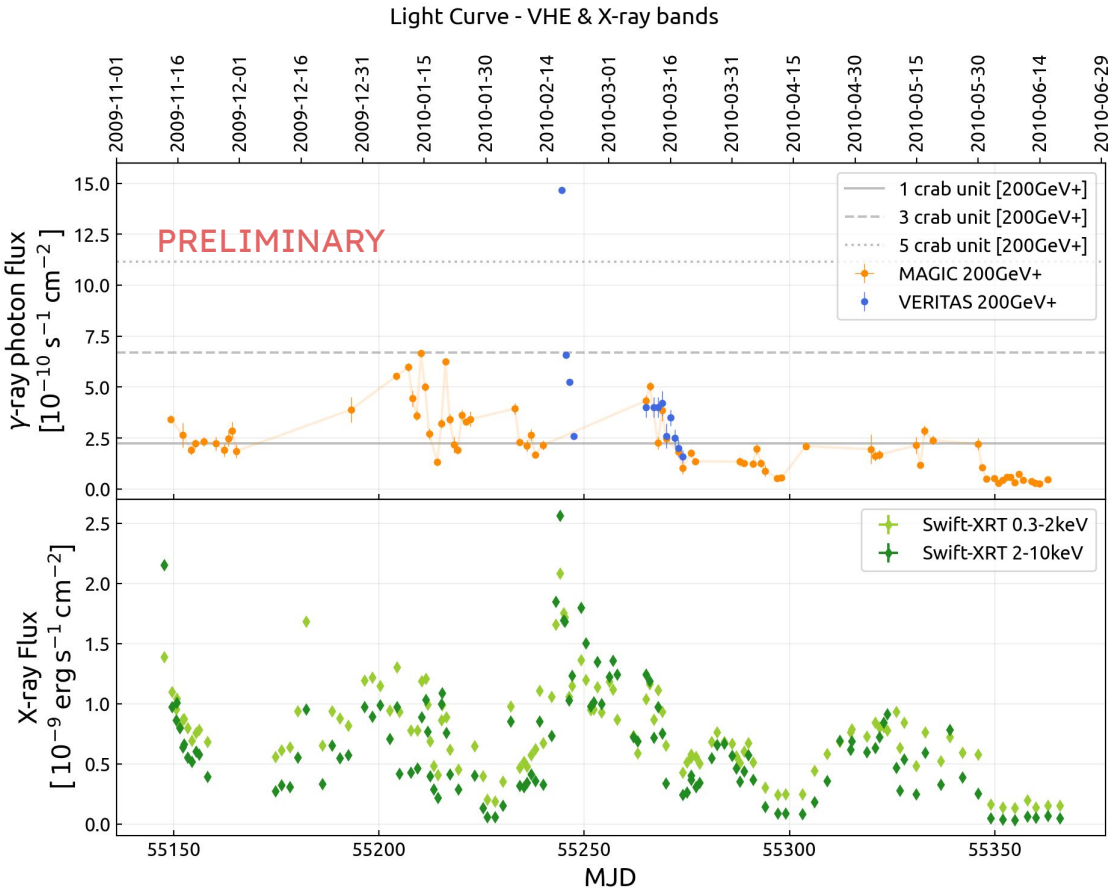
The Great Markarian 421 Flare of 2010 February: MW Variability and Correlation Studies [2020]



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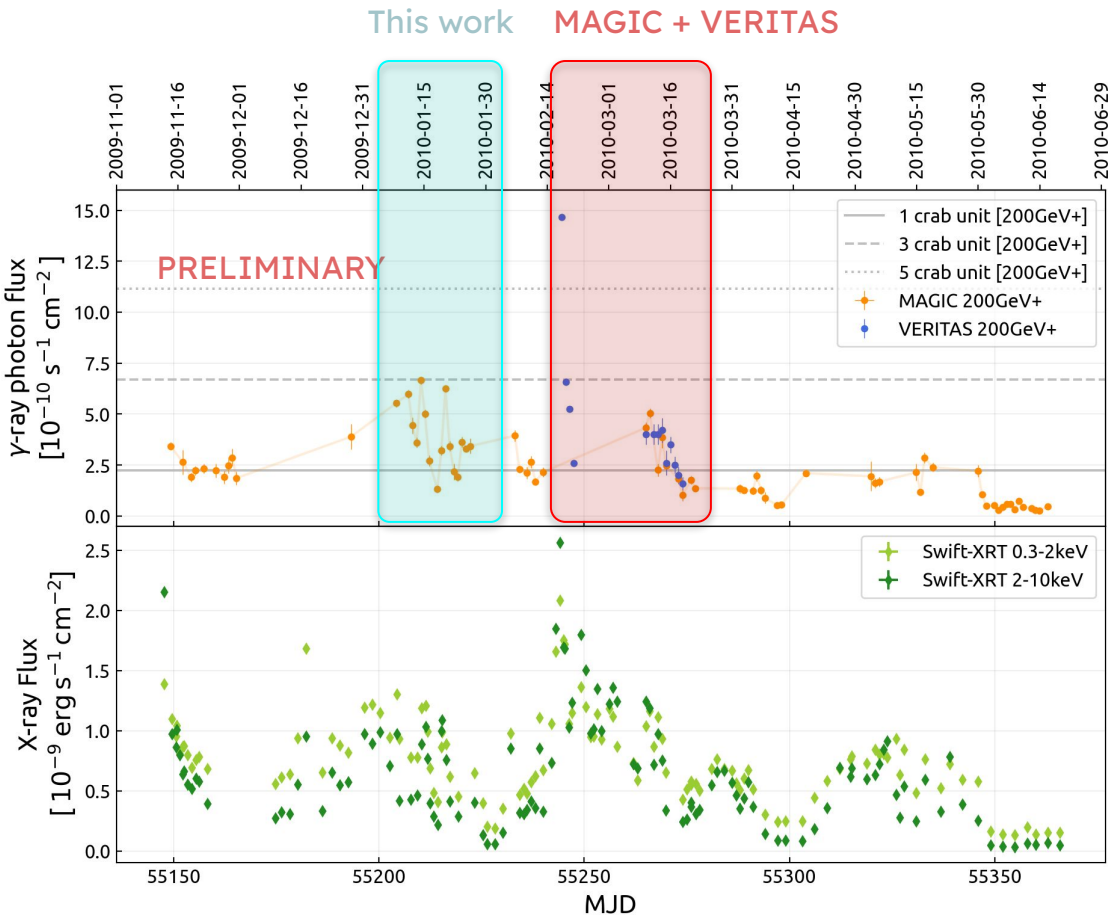
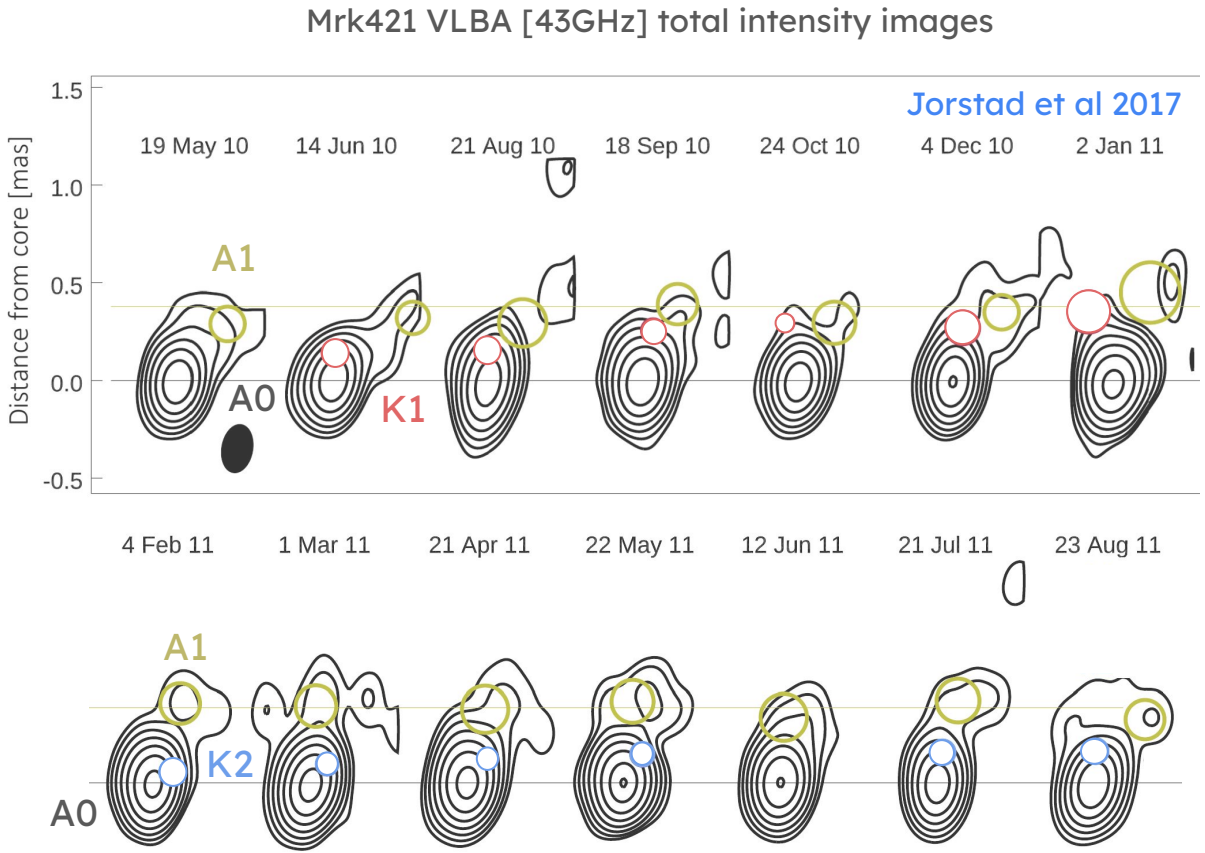


Radio Knots

The period includes the detection of radio knots K1 and K2 emitted from the core [A0] towards a static feature [A1] ~coincident with the giant flare within error bars - a first for Mrk421 [Jorstad et al 2017, MAGIC et al 2024]

Atypical behaviour for Mrk421! Moving features usually observed in FSRQs



Jorstad et al - Kinematics of Parsec-scale Jets of γ-Ray Blazars at 43 GHz within the VLBA-BU-BLAZAR Program [2017]

MAGIC et al - Characterization of Mrk 421 during its most violent year [submitted 2024]

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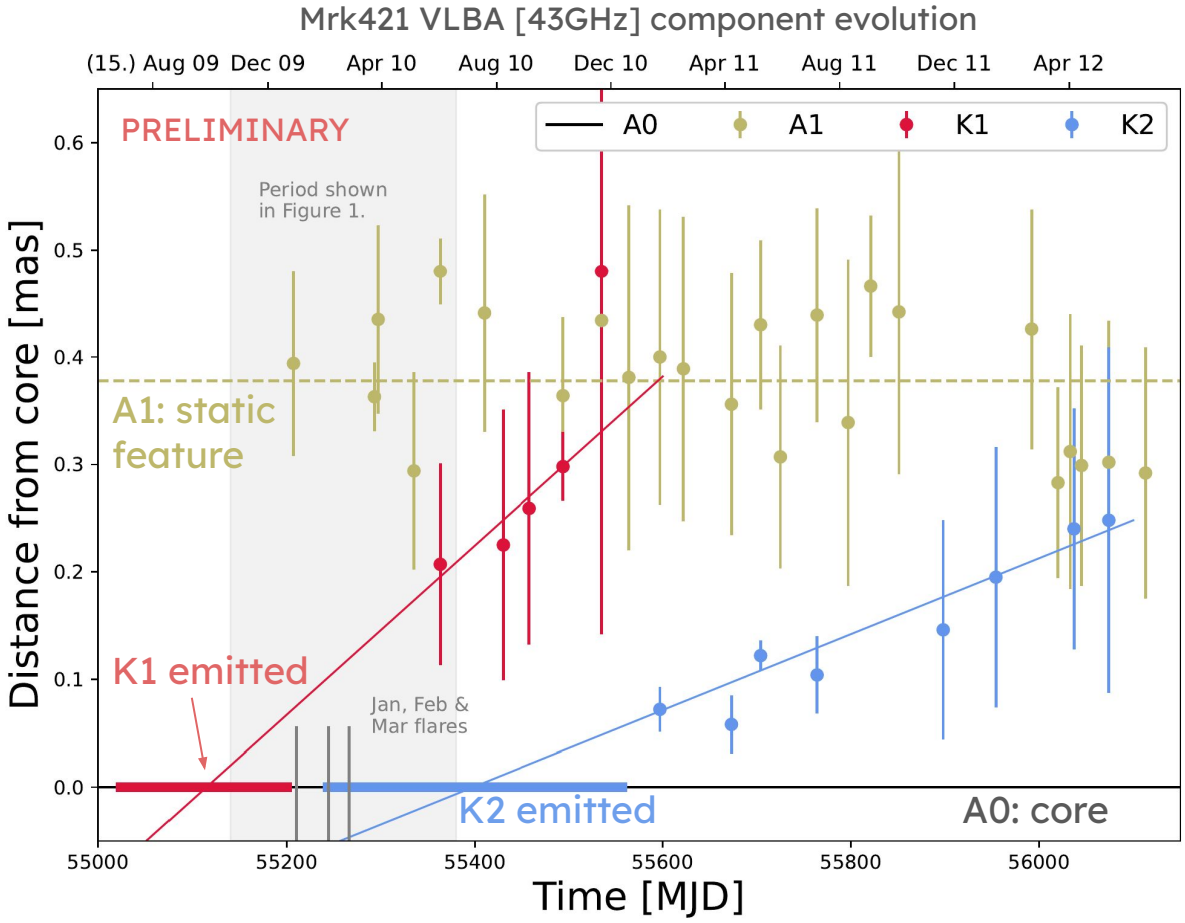
Knot expansion velocity analysis supports adiabatic expansion of emission region based on the MWL spectral evolution consistent with previous studies [Tramacere et al 2022]

Tramacere et al. - Radio-γ-ray response in blazars as a signature of adiabatic blob expansion: [2022]

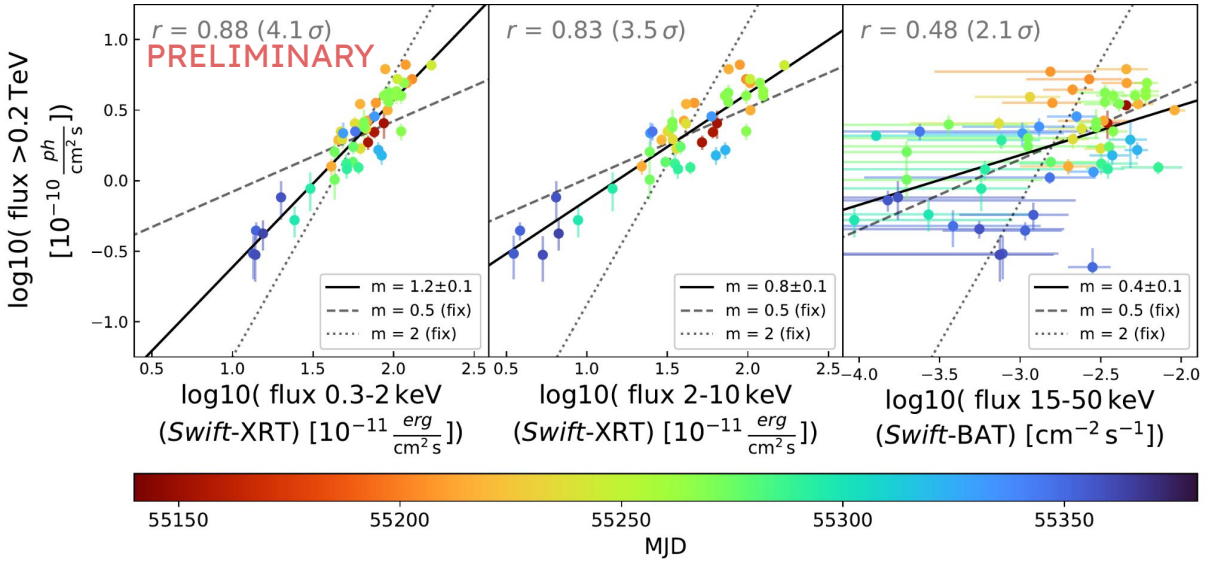


Cross-band Correlations

Detailed studies of the MWL band variability and cross correlations can be found in the associated paper [MAGIC et al 2024]

Standard energy stratified Synchrotron Self Compton (SSC) scenario is supported by the data

- X-ray and VHE γ-ray strongly correlated
- UV band and VHE γ-ray weakly correlated!



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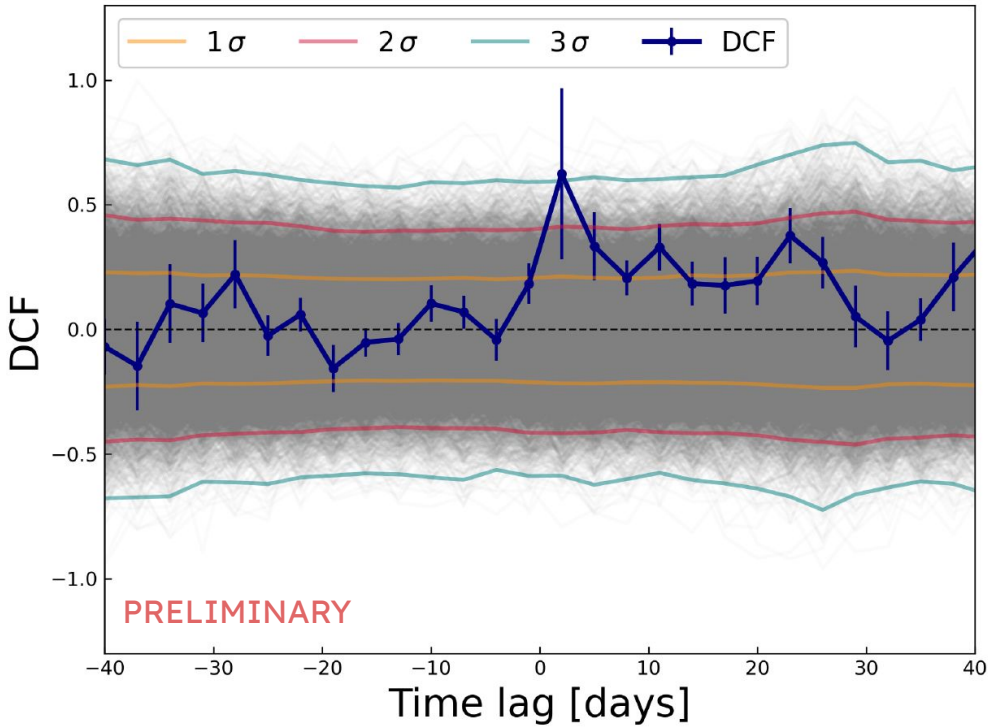

(a) >0.2 TeV (MAGIC/VERITAS) vs 3-300 GeV (*Fermi*-LAT)

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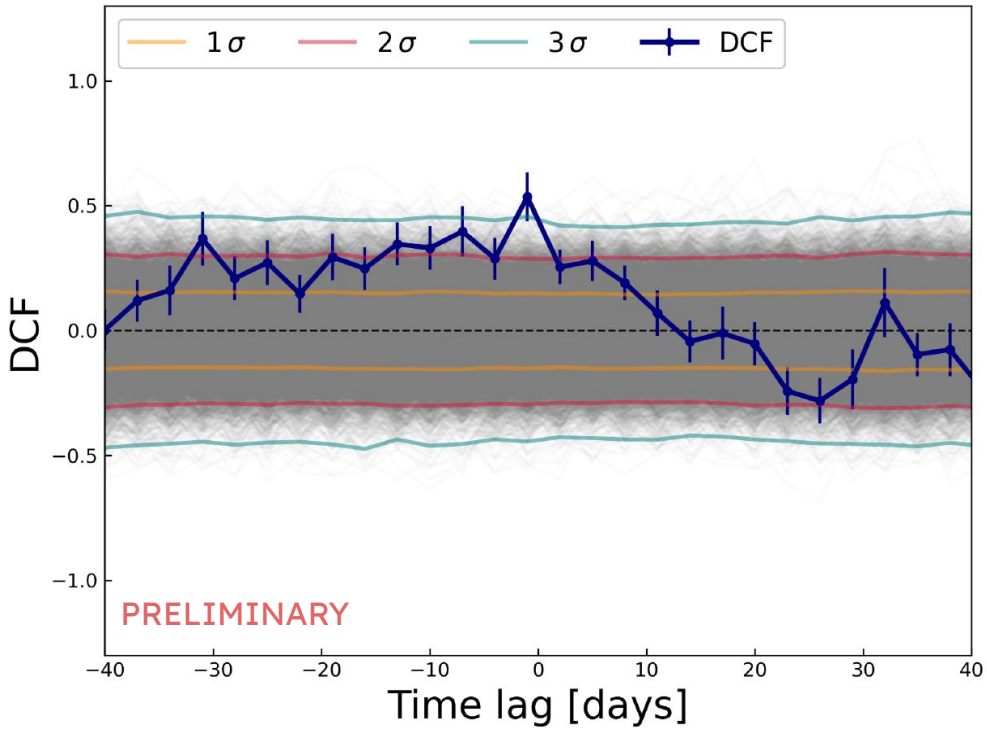


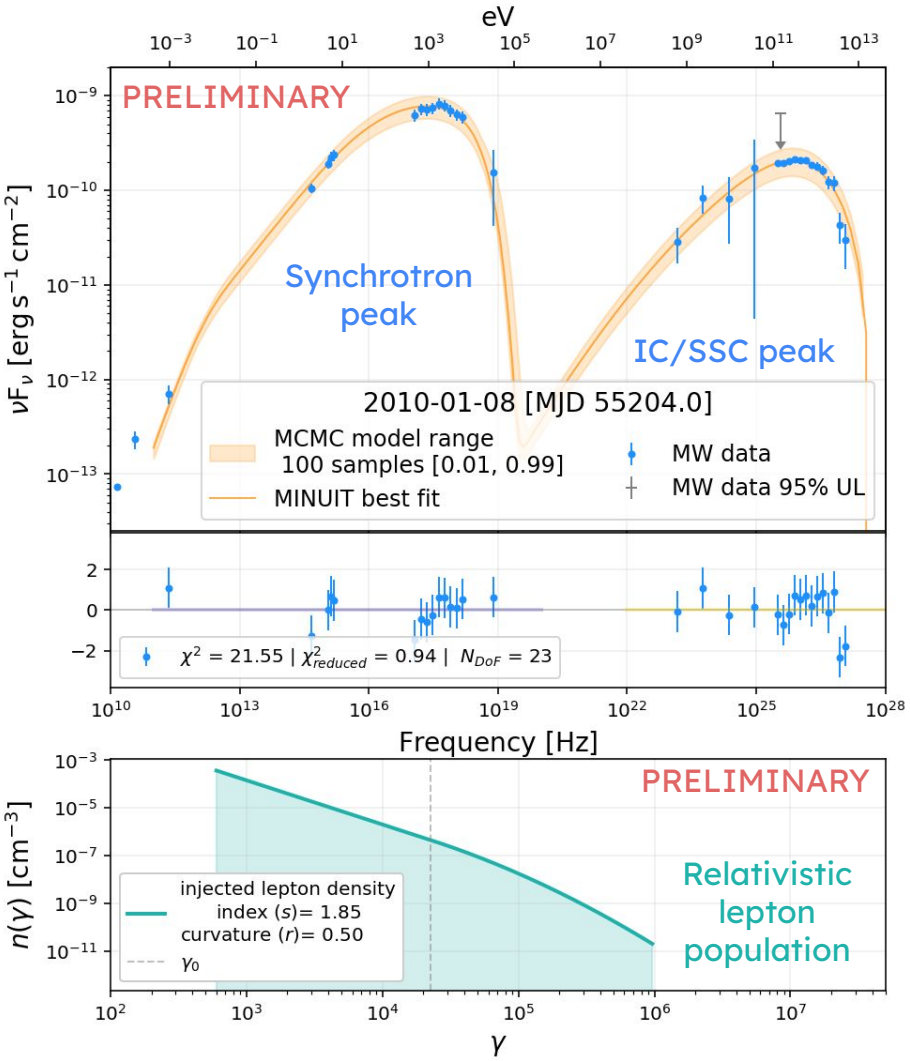
(b) 0.3-3 GeV (*Fermi*-LAT) vs W1 (*Swift*-UVOT)

SED Modelling

Starting from a distribution of high energy particles, the spectrum is obtained by temporal evolution of the particle population and subsequently compared with observations

BL Lac type blazars like Mrk421 show a double peak Spectral Energy Distribution (SED) which can be explained by radiation from a population of ultra-relativistic leptons evolving in a magnetic field and undergoing Inverse Compton (IC) scattering

IC can be with photons from lepton populations' own synchrotron field (Synchrotron self Compton, SSC)



LPPL Distribution

Single zone leptonic SED modelling was done in JetSeT with a physics motivated LPPL distribution (Log Parabolic with a low energy Power Law branch)

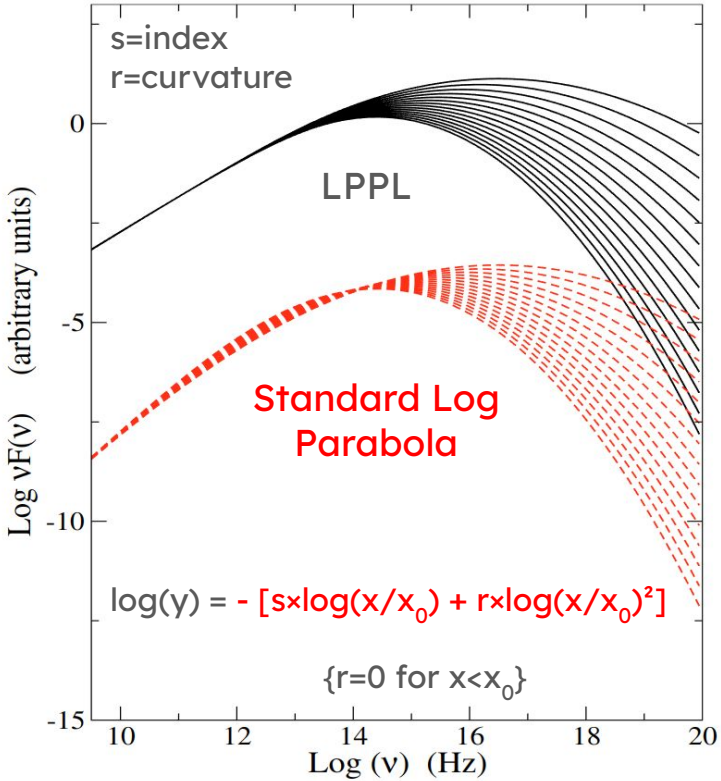
The curvature seen in the high energy part of the LPPL distribution can arise due to energy dependent probability for acceleration [Massaro et al 2004, 2006], purely stochastic acceleration or a mixture of 1st and 2nd order Fermi acceleration [Tramacere et al 2009, 2011]

Massaro et al - Log-parabolic spectra and particle acceleration in blazars: paper 2 [2004] & paper 3 [2006]

Tramacere et al - Swift observations of the very intense flaring activity of Mrk 421 during 2006 [2009]

Tramacere et al - Stochastic Acceleration and the Evolution of Spectral Distributions in Synchro-Self-Compton Sources [2011]

Comparison of the resulting general SED shape from standard LP and LPPL lepton distributions taken from Massaro et al 2006. Normalisation offset for clarity



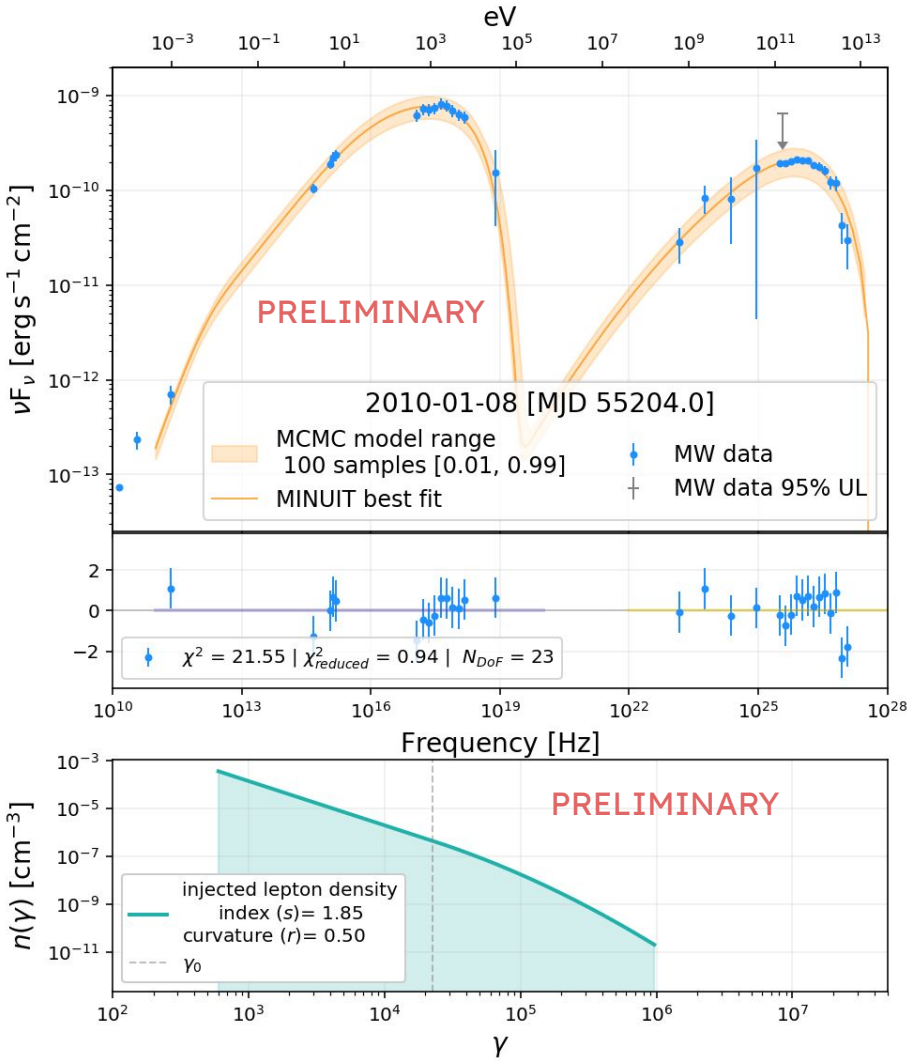
LPPL Model

Daily SEDs were prepared for Jan 2010 and MWL data was grouped together for best effort simultaneity according to the MAGIC observations

As expected, the single zone LPPL model captures the major features of the behaviour of Mrk421 quite well

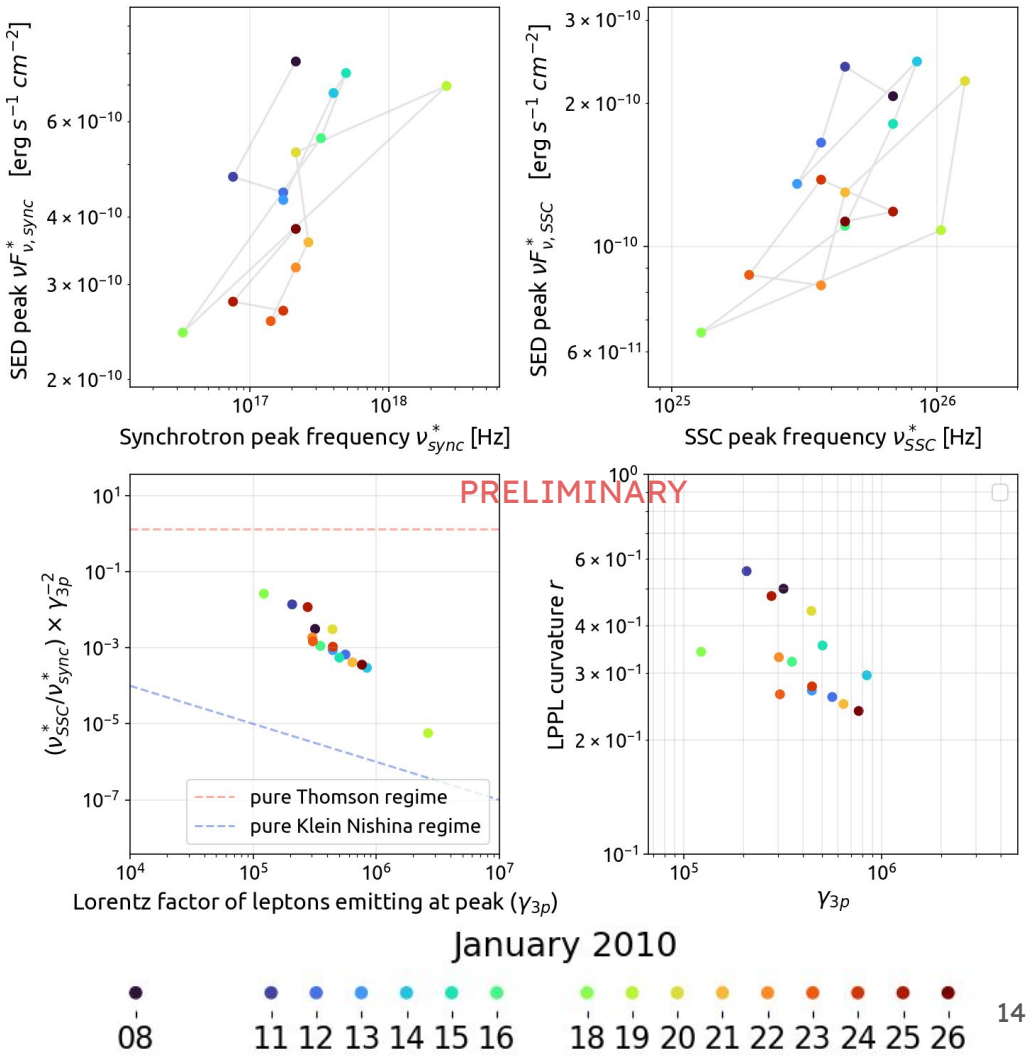
Typical values of some emission zone parameters

Doppler factor	δ	40-50	
Magnetic field	B	10-30	[mG]
Region size	R	3×10^{16}	[cm]
Lepton density	N	0.3	[1/cm³]



Phenomenology

The evolution from 18-20 Jan 2010 is the most interesting and shows up in peak flux-peak frequency correlations too



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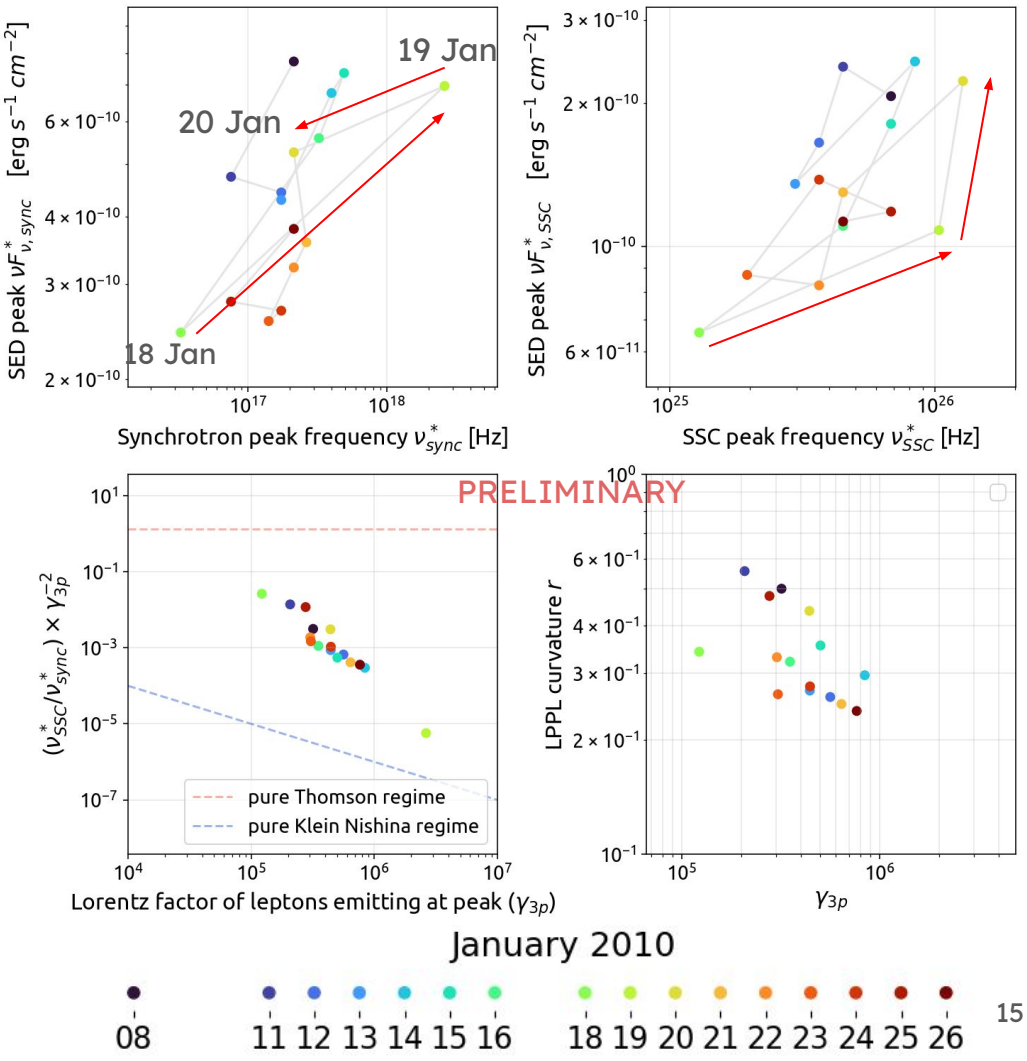

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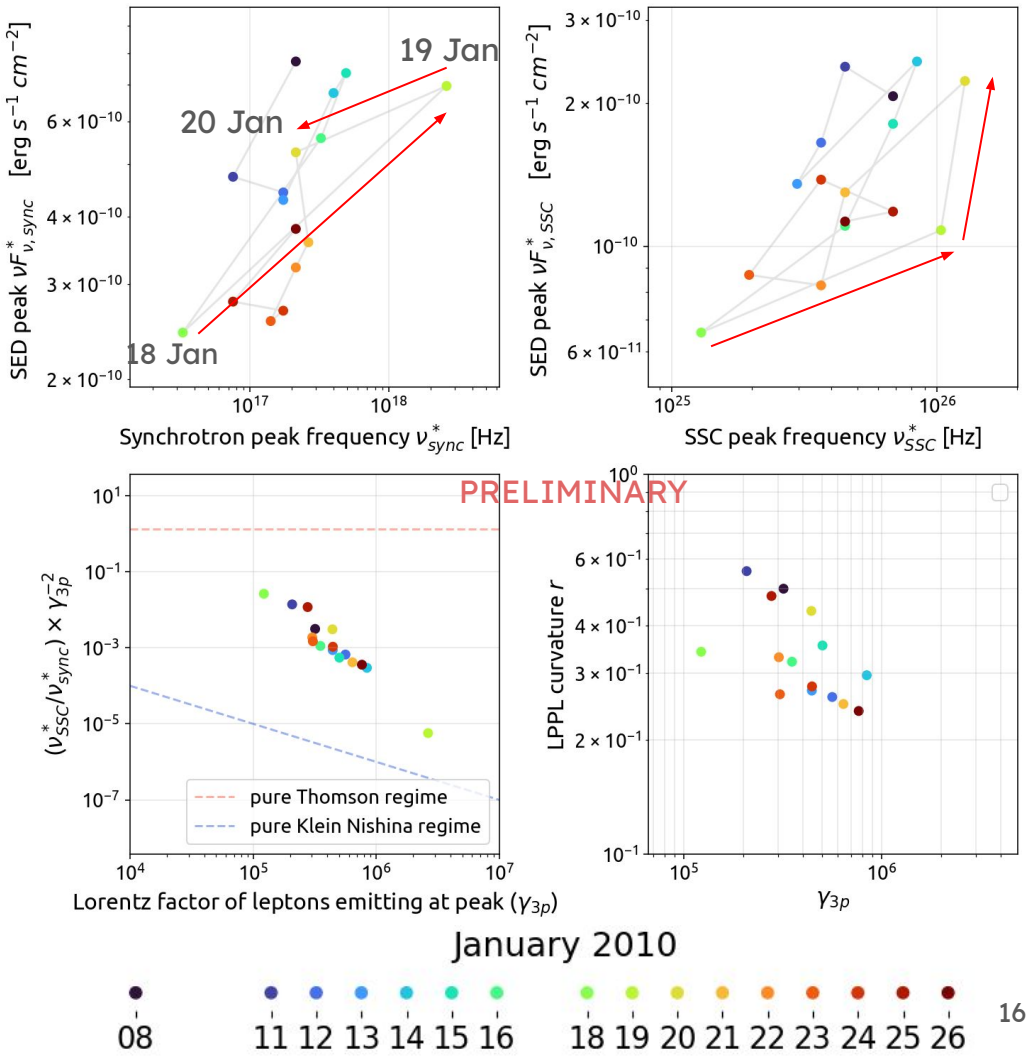
The trends for LPPL curvature (r) and γ_{3p} agree with inverse relation expected under stochastic acceleration [Tramacere et al 2009, 2011]

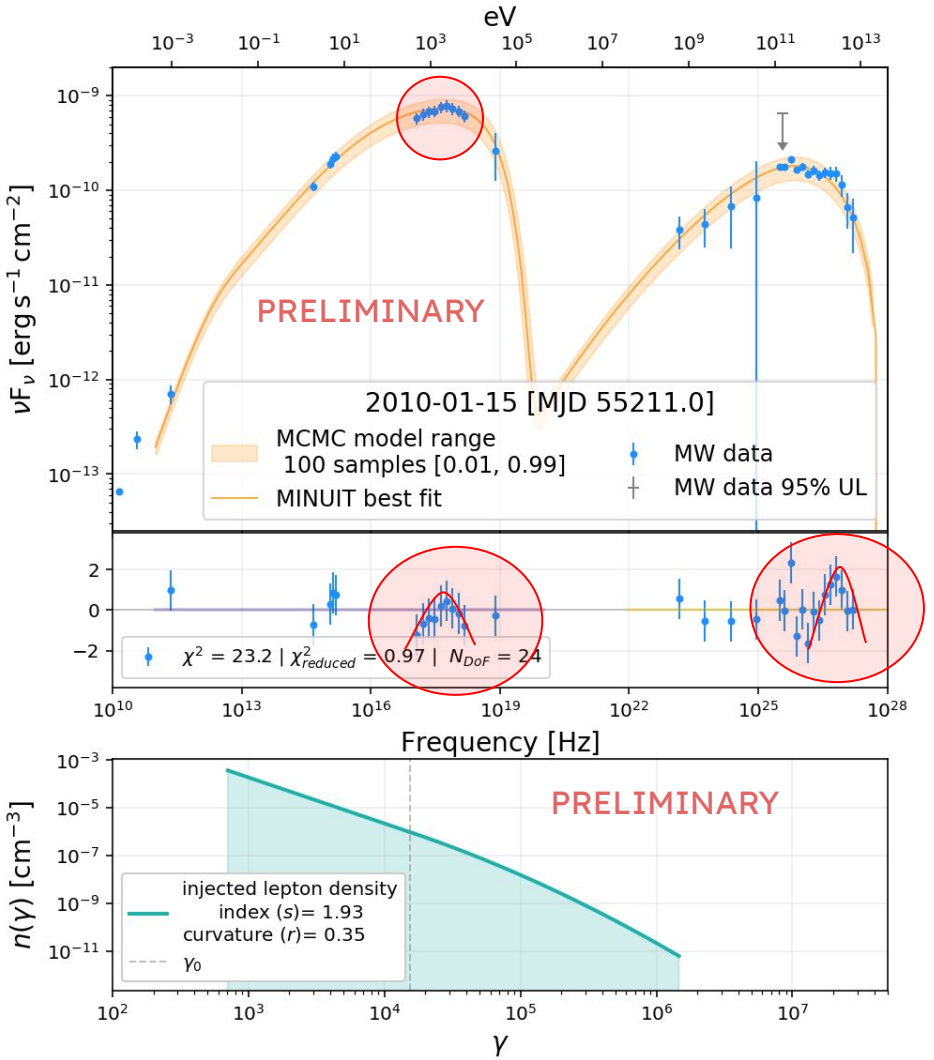
Tramacere et al - Swift observations of the very intense flaring activity of Mrk 421 during 2006 [2009]

Tramacere et al - Stochastic Acceleration and the Evolution of Spectral Distributions in Synchro-Self-Compton Sources [2011]



LPPL Model

On close inspection the residuals are not always randomly distributed and there are systematic trends in the residuals especially in the XRT range and sometimes in the MAGIC data too



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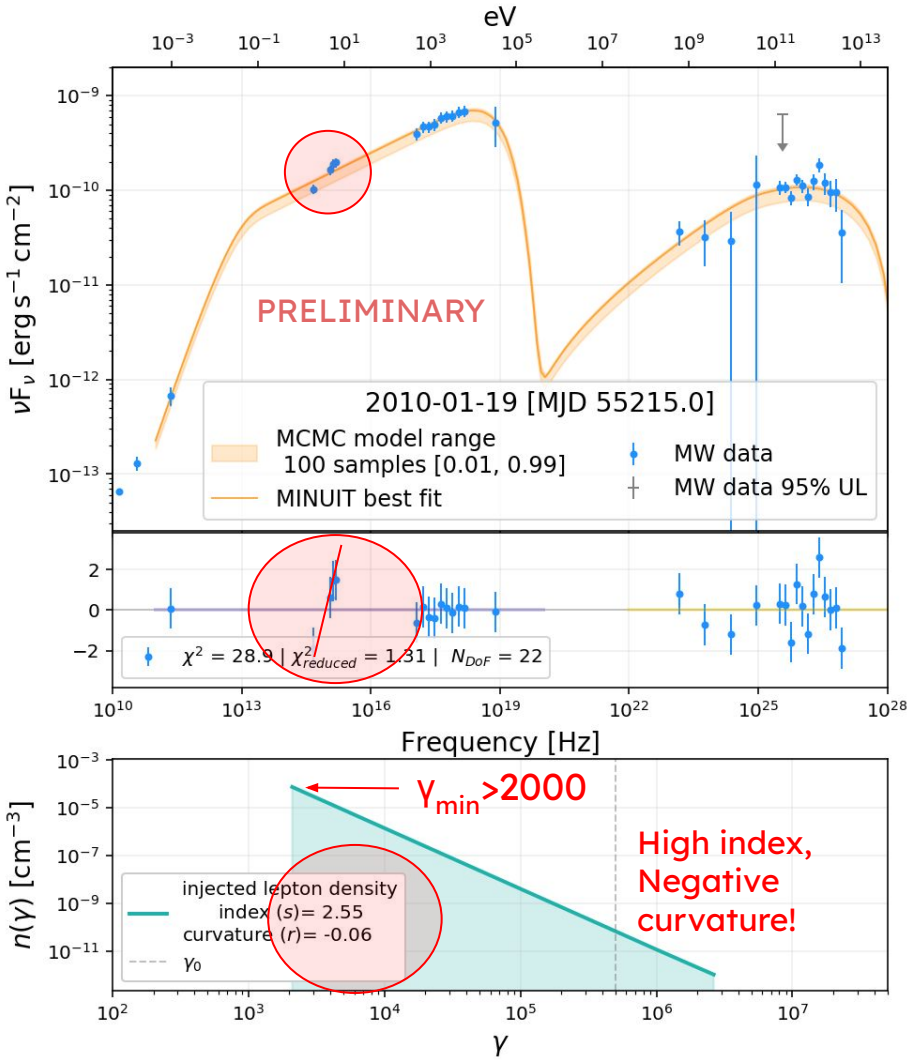

LPPL Model has Issues

Possible explanations -

- Curvature is an instrument effect
  - Estimated per-bin systematics only affect the first bin in XRT data at ~10-15% level
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Analysis and modelling of more complicated lepton distributions and multi-zone scenarios in progress

Conclusion and Outlook

The dataset shows interesting ‘firsts’ for Mrk421 - unprecedented flux levels, radio knots, VHE-HE γ-ray and UV-HE γ-ray correlations

The LPPL model provides reasonable fits to the general features in the SED with hints of more complex underlying leptonic distribution or multi-zone scenarios

Scope for trying out multi-zone models and temporal evolution of the lepton distribution evolution under particle injection, radiative losses and adiabatic expansion of the emitting zone

MAGIC-1 reflecting in MAGIC-2 | J. Abhir


Thank you for your attention!

References

The Great Markarian 421 Flare of 2010 February: Multiwavelength Variability and Correlation Studies [https://iopscience.iop.org/article/10.3847/1538-4357/ab6612]

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JetSeT - Andrea Tramacere [https://jetset.readthedocs.io/en/latest/index.html]

Log-parabolic spectra and particle acceleration in blazars: Massaro et al 2006 [https://www.aanda.org/articles/aa/abs/2006/12/aa3644-05/aa3644-05.html]

On the momentum Diffusion of Radiating Ultrarelativistic electrons in a turbulent magnetic field: Stawarz & Petrosian 2008 [https://iopscience.iop.org/article/10.1086/588813]

BACKUP

What is γ_{3p} ?