Time-dependent modelling and spectral analysis of the extraordinary outburst of Mrk 421 during April 2013

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On behalf of the MAGIC Collaboration

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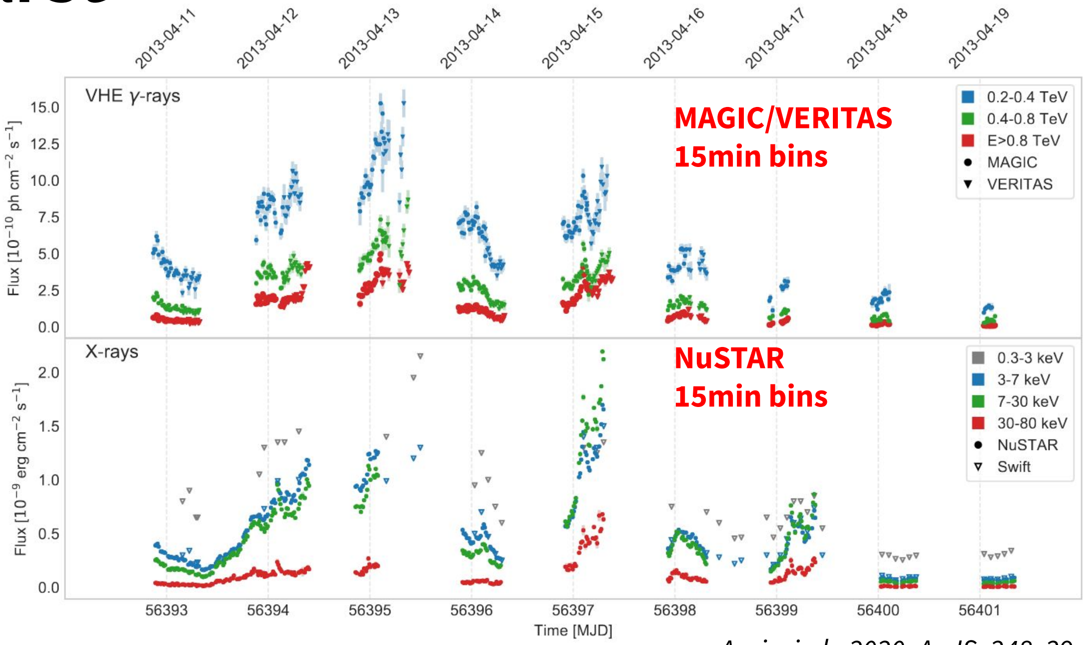
The Mrk 421 2013 outburst

- Mrk 421: bright & nearby (z~0.03)
  BL Lac object

- Flare in April 2013
  - ~15x Crab Nebula flux at very-high-energy
  - ~40 hrs of simultaneous X-ray/VHE coverage (Swift-XRT/NuSTAR/MAGIC/VERITAS)



Acciari al., 2020, ApJS, 248, 29

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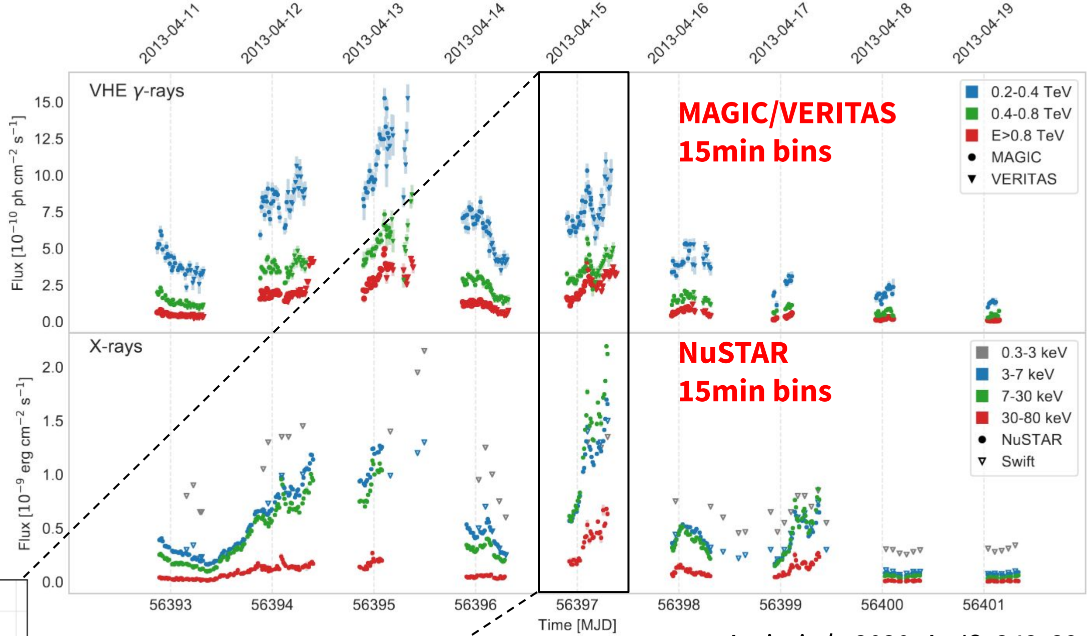

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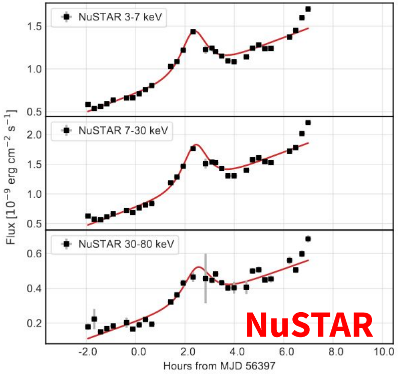
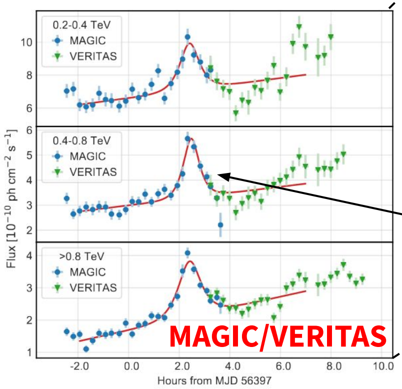
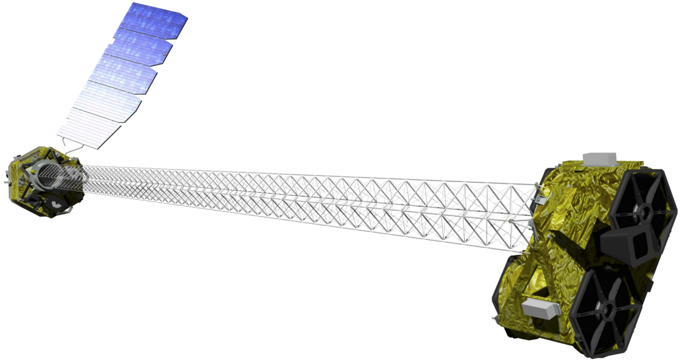




Fast variability features in light curves (15min flux doubling/halving time)

X-ray & VHE spectral evolution on sub-hour timescale

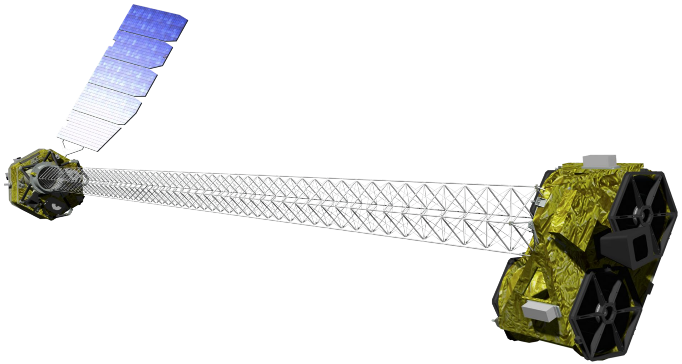
- *Re-analyzed* **NuSTAR & MAGIC data**



X-ray & VHE spectral evolution on sub-hour timescale

- *Re-analyzed* **NuSTAR & MAGIC data**

- **NuSTAR spectral parameters** resolved down to **15 min** timescale



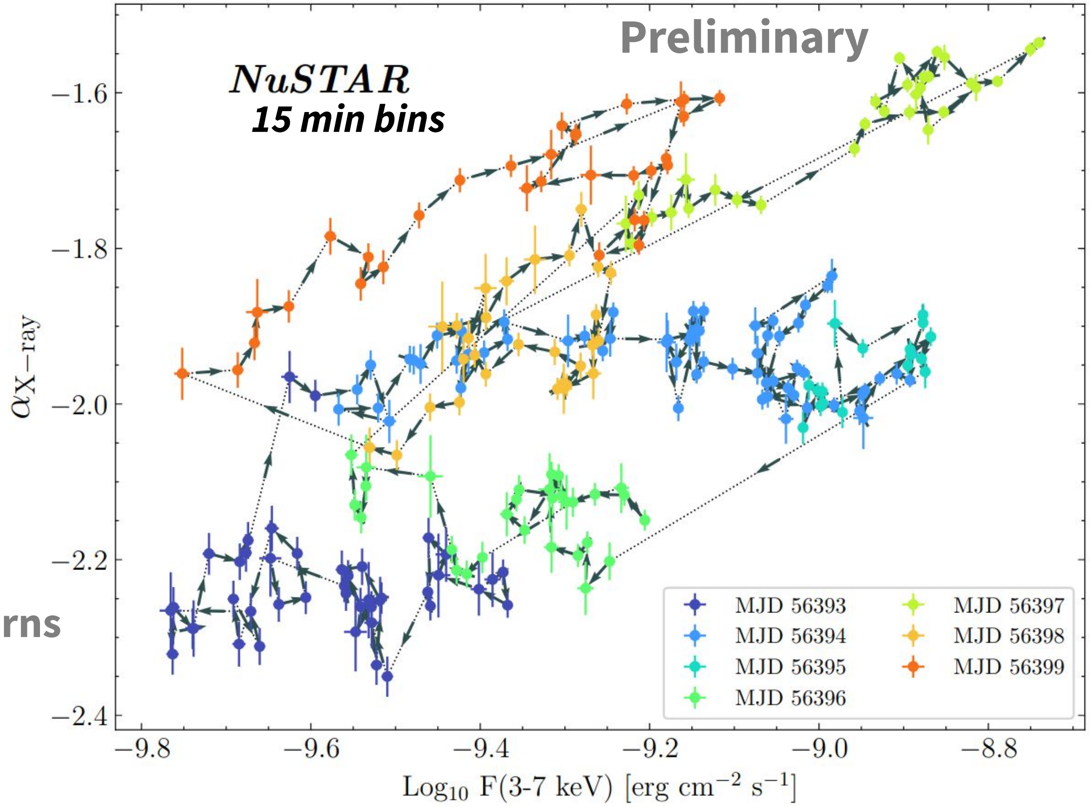
X-ray & VHE spectral evolution on sub-hour timescale

- *Re-analyzed* **NuSTAR & MAGIC data**

- **NuSTAR spectral parameters** resolved down to **15 min** timescale
- Fitted with a **log-parabola** with fixed curvature (β = 0.38, E_0=1 keV)

$$\frac{dN}{dE} = f_0 \left(\frac{E}{E_0}\right)^{\alpha-\beta\log_{10}\left(\frac{E}{E_0}\right)}$$

- **Strong variability, with complex patterns**
  - **Indication of hysteresis loops in clockwise directions**



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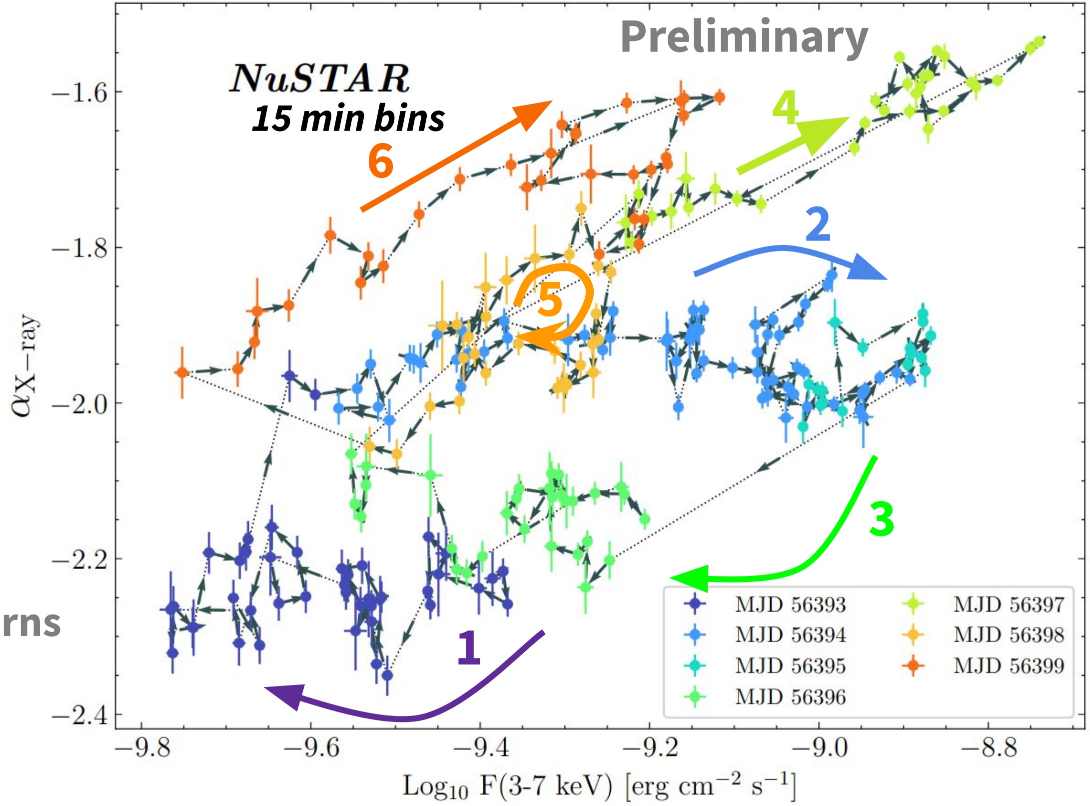
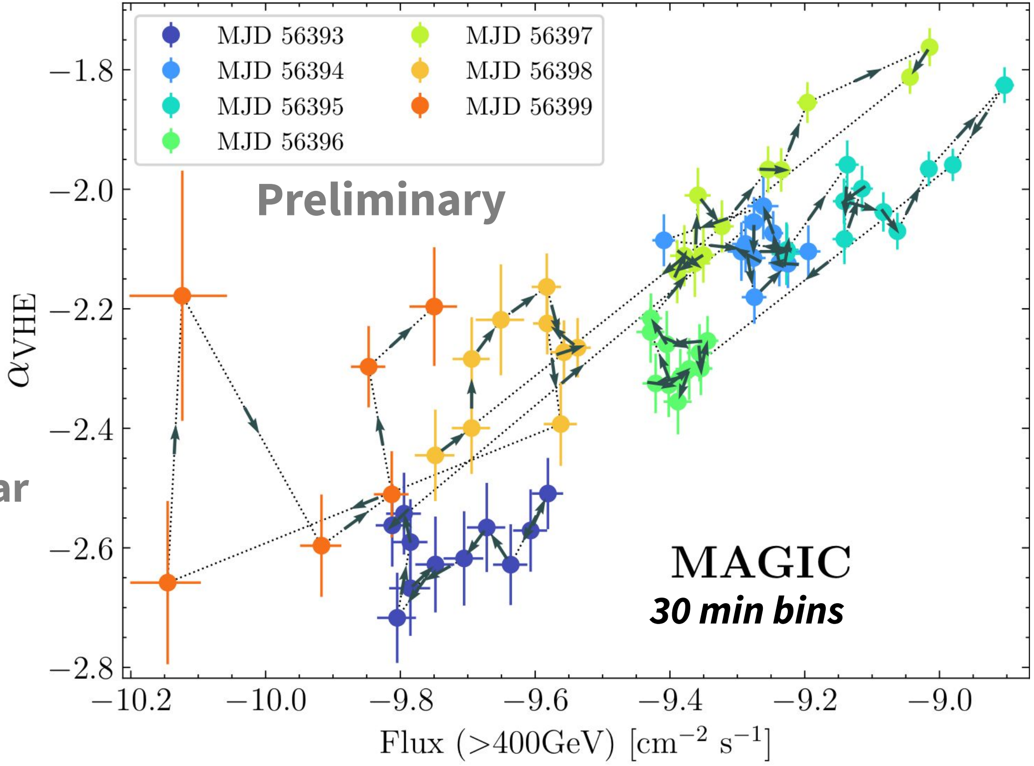
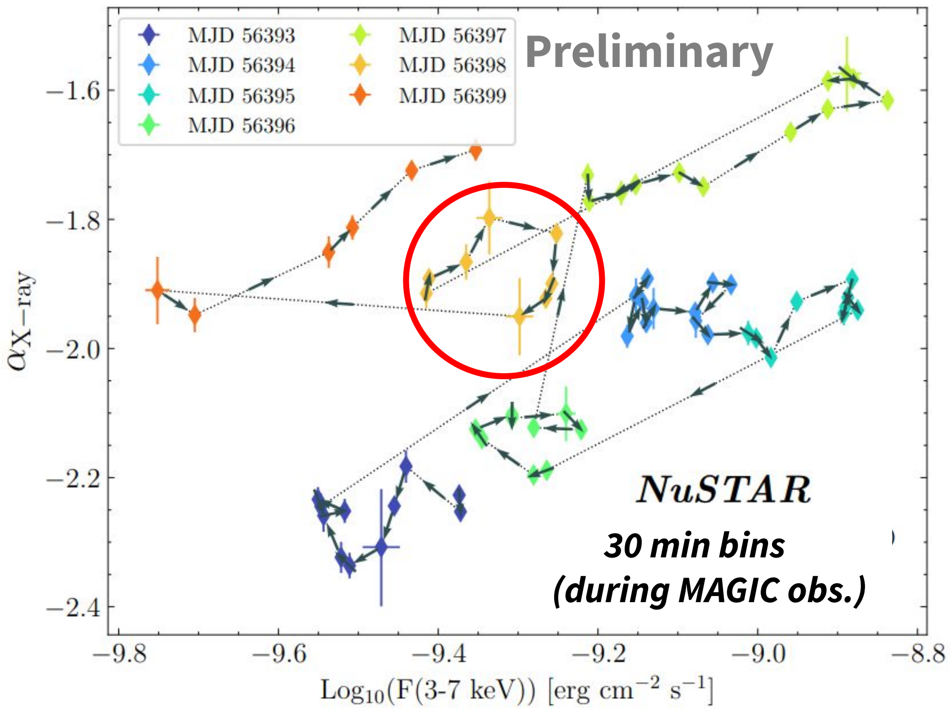


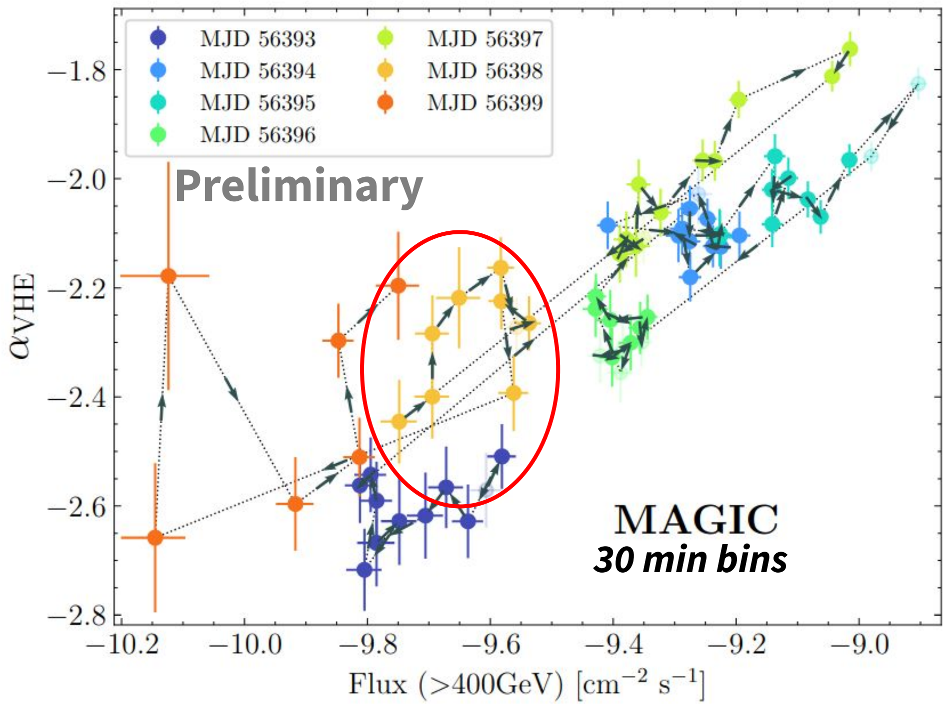
X-ray & VHE spectral evolution on sub-hour timescale

- **MAGIC spectral evolution** resolved in **30 min** bins
- MAGIC spectra fitted with a **log-parabola** with fixed curvature (β = 0.4, E_0=0.5 TeV)
- **Variability goes beyond the "simple" *harder-when-brighter trend* reported so far at VHE**



X-ray & VHE spectral evolution on sub-hour timescale





MAGIC & NuSTAR spectra follow very similar patterns
→ Evidence of simultaneous VHE / X-ray hysteresis pattern (e.g. MJD 56398)
→ Strong prediction of leptonic models

Time-dependent modelling

AIM: **Model the broadband variation in a time-dependent approach throughout the entire flare**

→ Keep track of the particle distribution history
(improvement with respect to most of the literature that uses stationary models to fit observations)

→ We will focus on describing the complex VHE/X-ray spectral variations

→ Modelling is performed over the 9 days of the flare, on 15min timescale

Time-dependent modelling

Leptonic model
2-zones
(spatially separated)

“Slow” zone

UV/optical & MeV/GeV

Parameters vary on daily timescale
(motivated by ~daily variability from optical & Fermi-LAT observations)

“Fast” zone

X-ray & VHE

Parameters vary down to 15 min timescale
(motivated by ~15min variability from NuSTAR & MAGIC/VERITAS observations)

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<u>"Slow" zone</u>

UV/optical & MeV/GeV

Parameters vary on daily timescale
(motivated by ~daily variability from optical & Fermi-LAT observations)

- Doppler factor = 50
- $R = 10^{16}$ cm
- B = 0.07 G
- Parameters of electron distribution left free & evolve on daily timescale

Not a unique solution (Doppler factor, R, B)

Time-dependent modelling

Leptonic model
2-zones
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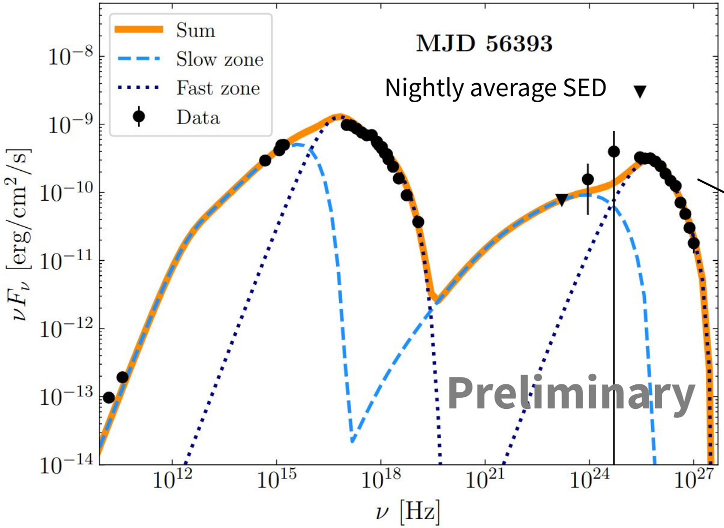
A) Find a baseline model for each day before modeling the variations on shorter timescales. We **determine B and Doppler factor** by fitting **nightly averaged SEDs** (R fixed to 10^{15} cm)



Doppler factor fixed to 100 required to fit VHE data!

B varies moderately, factor ~2 between the days

<u>“Fast” zone</u>

X-ray & VHE

Parameters vary down to 15 min timescale

(motivated by ~15min variability from NuSTAR & MAGIC/VERITAS observations)

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B) Then, we evolve **luminosity & slope (*p*)** of **injected** electrons on 15 min to **reproduce X-ray & VHE variability**

$$\frac{dN}{d\gamma} \propto \begin{cases} \gamma^{-p}, & \gamma_{\min} < \gamma < \gamma_{\max} \\ \gamma^{-p} \exp\left(-(\gamma/\gamma_{\max})^{a}\right), & \gamma > \gamma_{\max} \end{cases}$$

with a = 2, provides the best description of measured spectra & fluxes

<u>"Fast" zone</u>

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B) Then, we evolve **luminosity & slope (*p*)** of **injected** electrons on 15 min to **reproduce X-ray & VHE variability**

- ***p*** constrained directly using NuSTAR fit on 15 min scale
- **Luminosity (l_e)** varied assuming linear dependence on 3-7 keV flux

$$l_e(t) = l_{e,0} \times \left(\frac{F_{3-7\mathrm{keV}}(t)}{F_{3-7\mathrm{keV},0}} \right)$$

"Fast" zone

X-ray & VHE

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Solve kinetic equations assuming radiation cooling and escape, $t_{esc} = R/c$

Using the leptonic module of ATHEvA *(Dimitrakoudis+ 2012* and *Polkas+ 2021*

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Loss terms

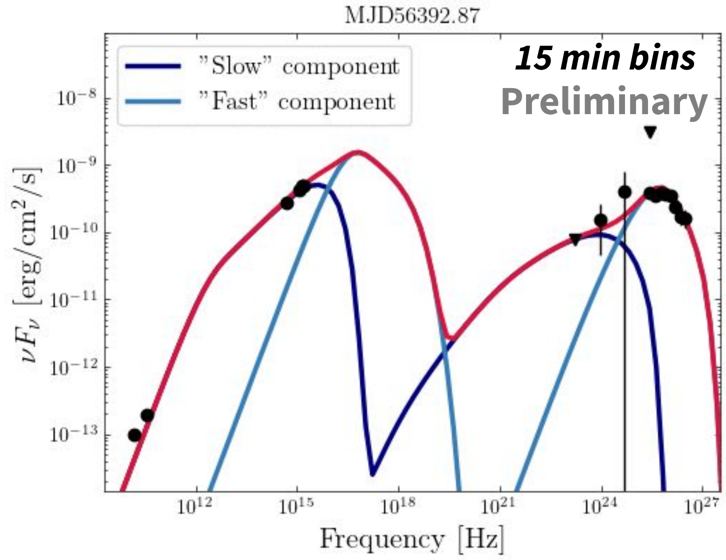
$$\frac{\partial n_e}{\partial t} + \frac{n_e}{t_{\mathrm{e,esc}}} + L_e^{\mathrm{IC}} + L_e^{\mathrm{syn}} = Q_e^{\mathrm{inj}} + Q_e^{\gamma\gamma}$$

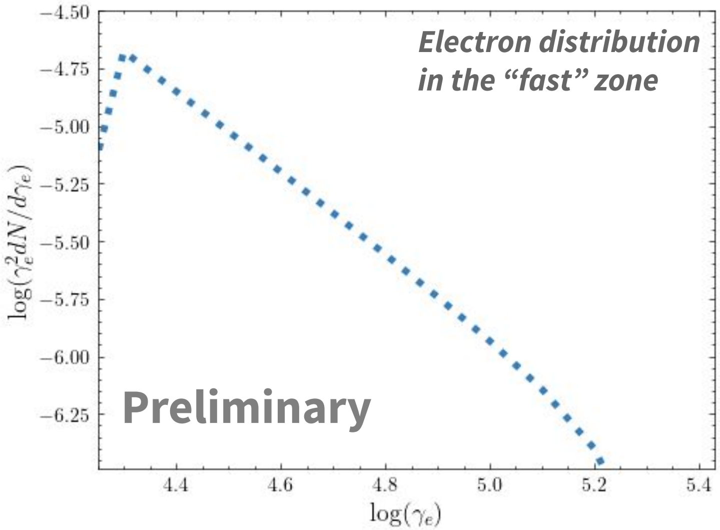
$$\frac{\partial n_\gamma}{\partial t} + \frac{n_\gamma}{t_{\gamma,\mathrm{esc}}} + L_\gamma^{\mathrm{ssa}} + L_\gamma^{\gamma\gamma} = Q_\gamma^{\mathrm{syn}} + Q_\gamma^{\mathrm{IC}}$$

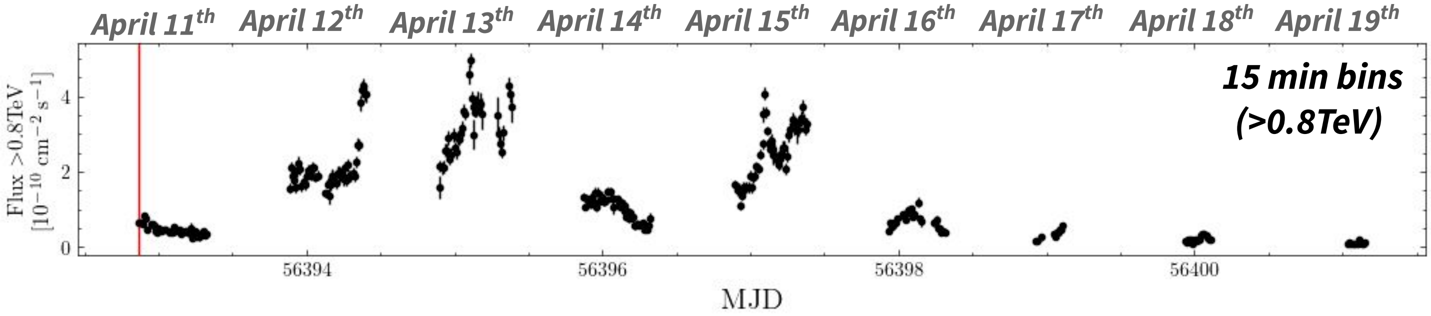
Injection terms

$$t_{\mathrm{e,esc}} = t_{\gamma,\mathrm{esc}} = R/c$$

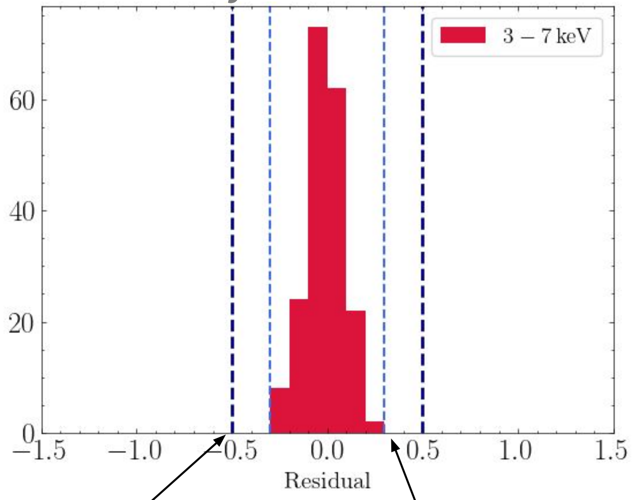
Time-dependent modelling - results

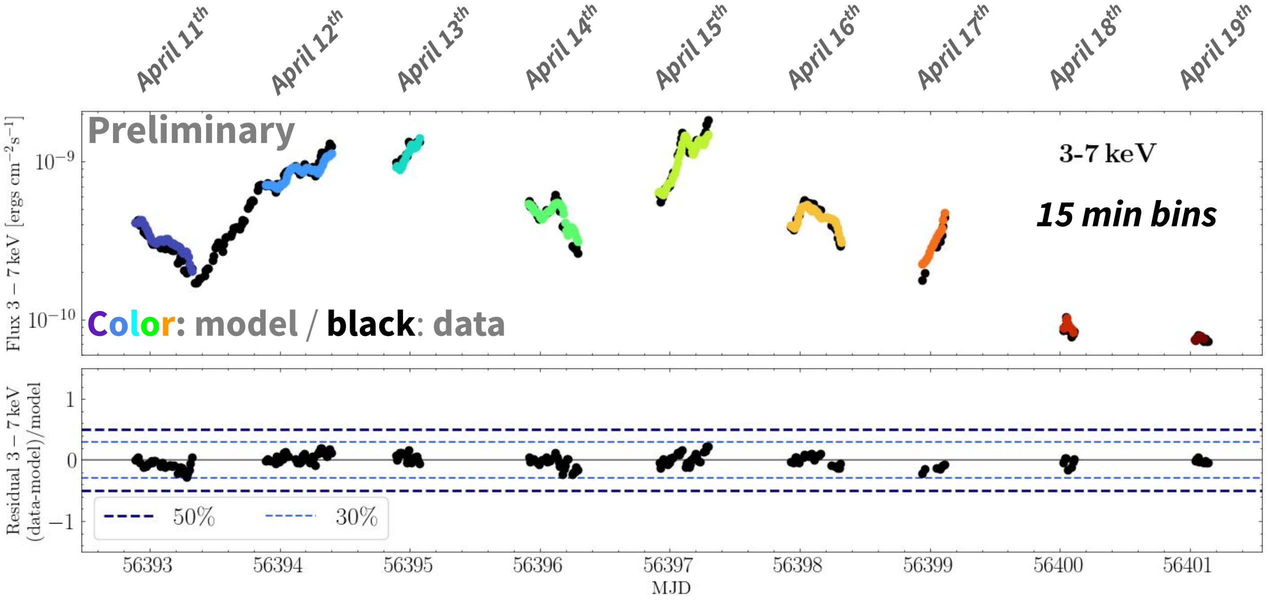






Time-dependent modelling - results : X-ray fluxes



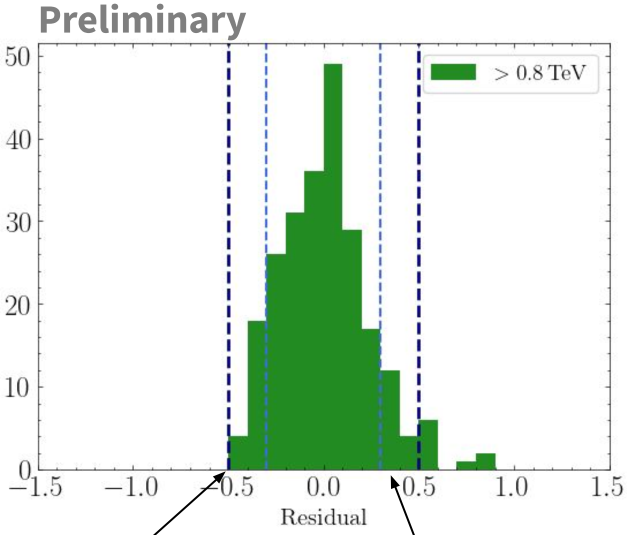


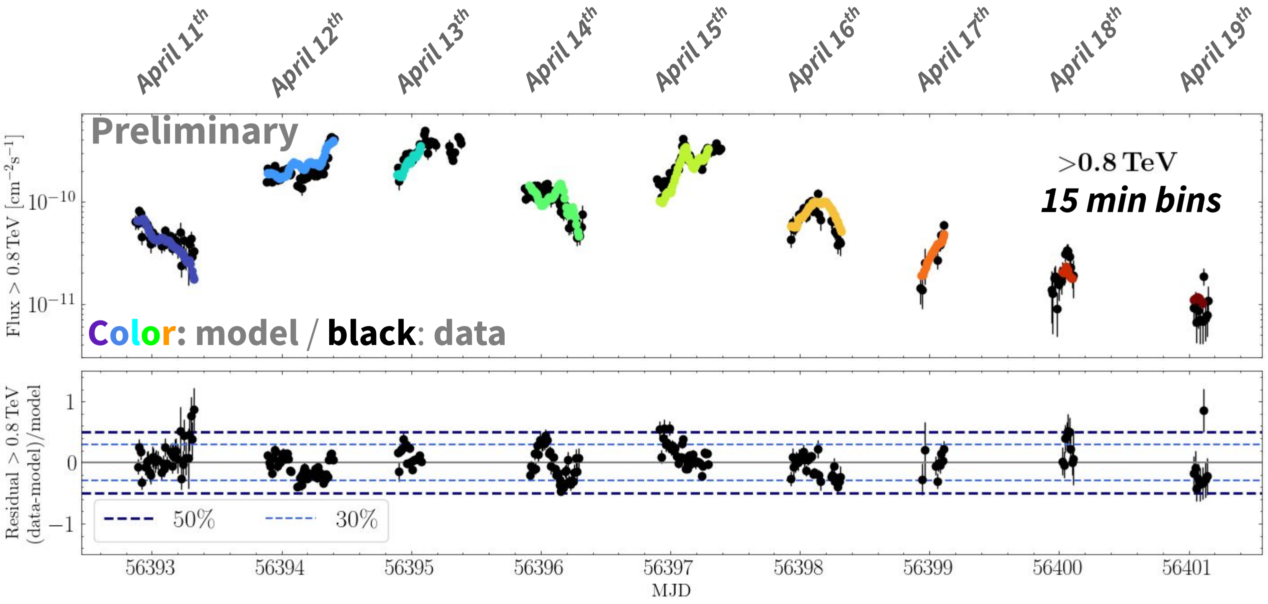
50 % residual (in linear scale)

30 % residual (in linear scale)

At 3-7 keV, all bins described within 30%

Time-dependent modelling - results: VHE fluxes





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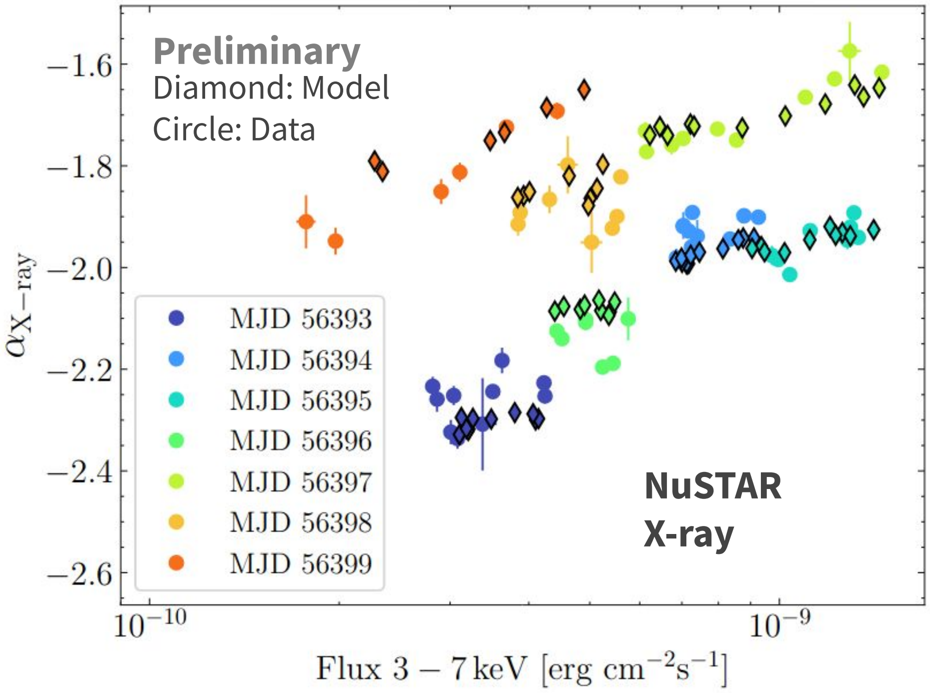

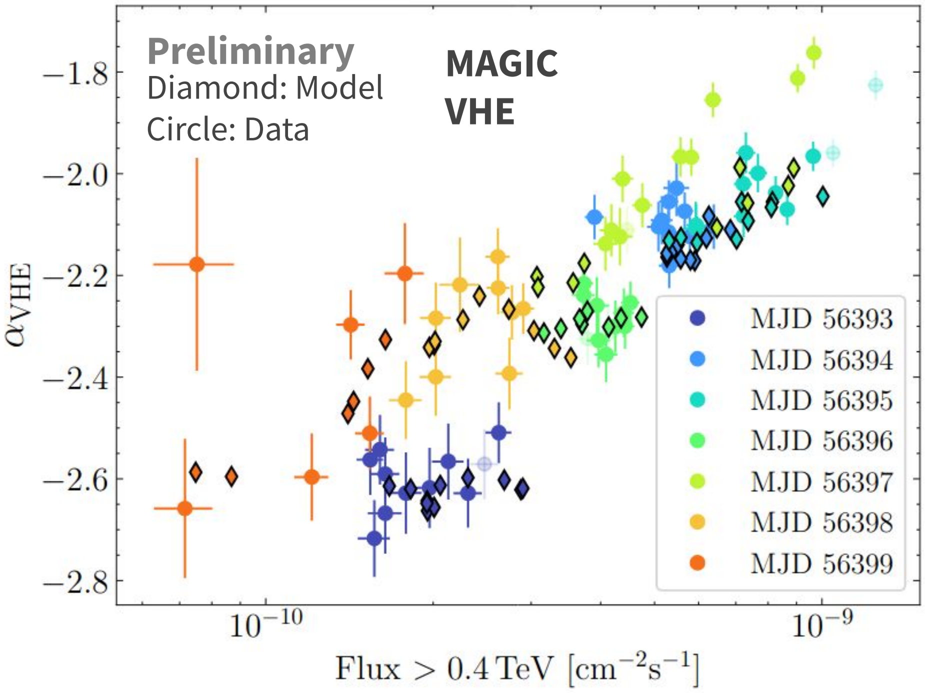

Spectral index reproduced within ~10% in most of the cases

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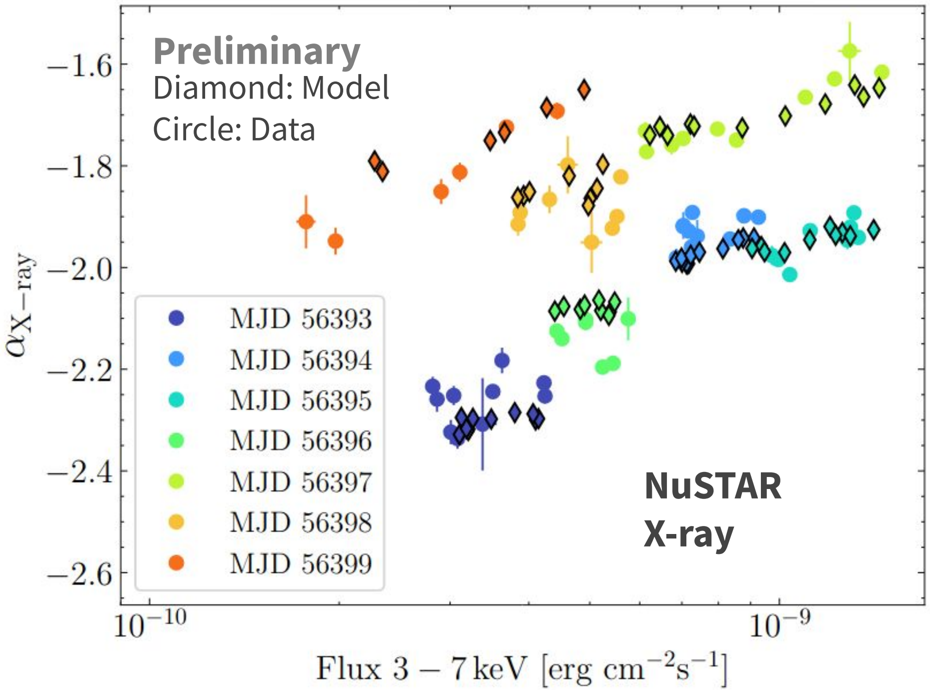

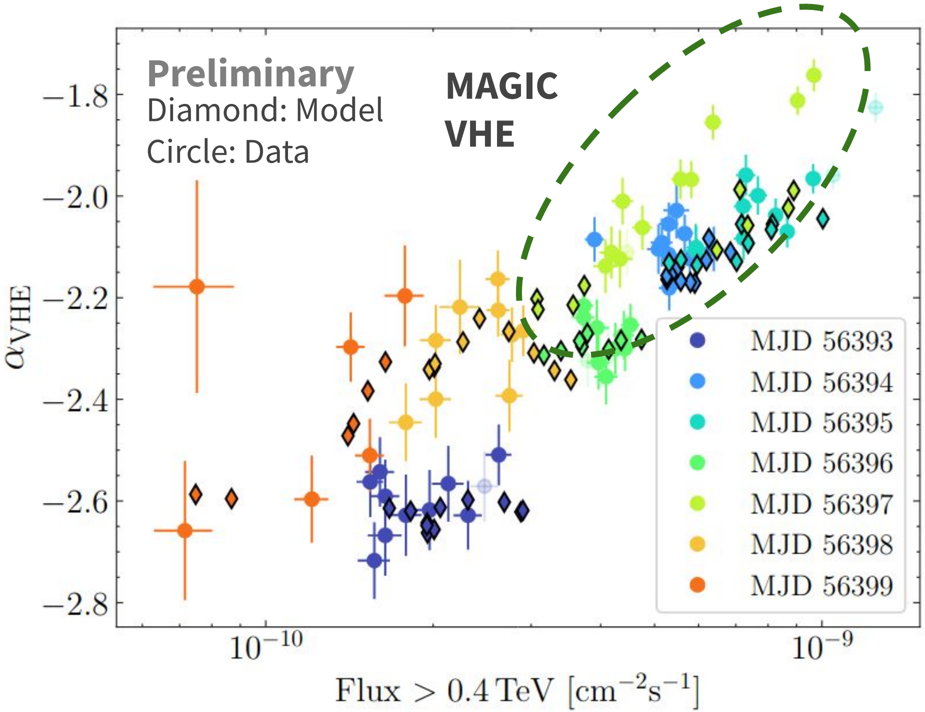

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A systematic difference at VHE on MJD 56397 for the highest fluxes
→ Appearance of emitting zones with Doppler >100 (or extra component)?

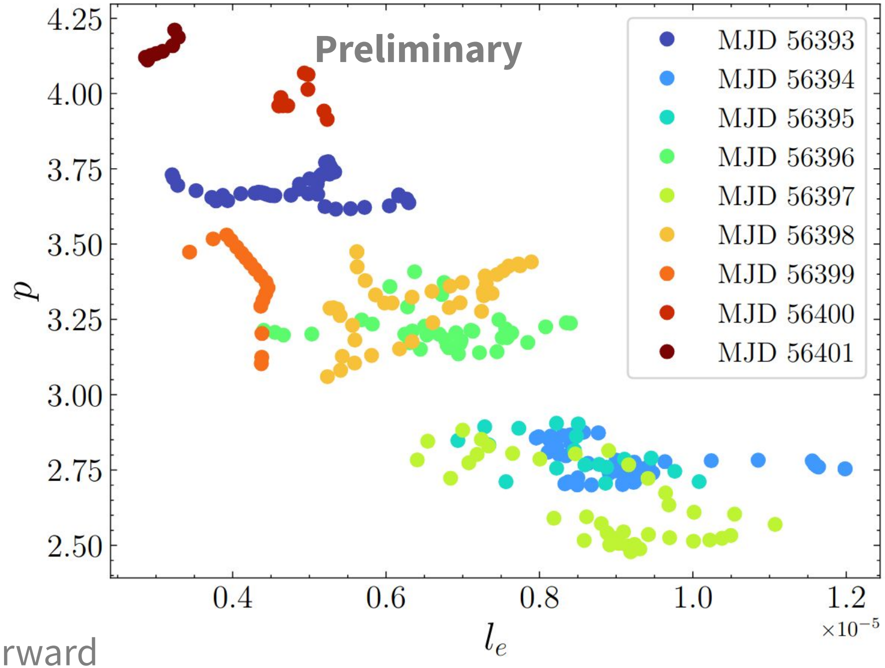
Time-dependent modelling - results

- Injected index (***p***) vs. luminosity (l_e)
  - harder at higher luminosity

- If accelerated via **magnetic reconnection** , **change in magnetization** may explain ***Δp ~ 1.5***
  (see e.g. PIC simulations from L. Sironi and A. Spitkovsky 2014)
  p>2.5 imply magnetization <= 3 w/o guide field
  (Werner+2016)
  Steeper slopes possible with stronger guide field
  (Werner+Uzdensky 2017)

- If accelerated via **shock** (DSA), **change in compression ratio** may explain changes in ***p***
  (Kirk et al. 2000, Virtanen et al. 2005)

- In both scenarios, ***p*** and l_e correlation is not straightforward

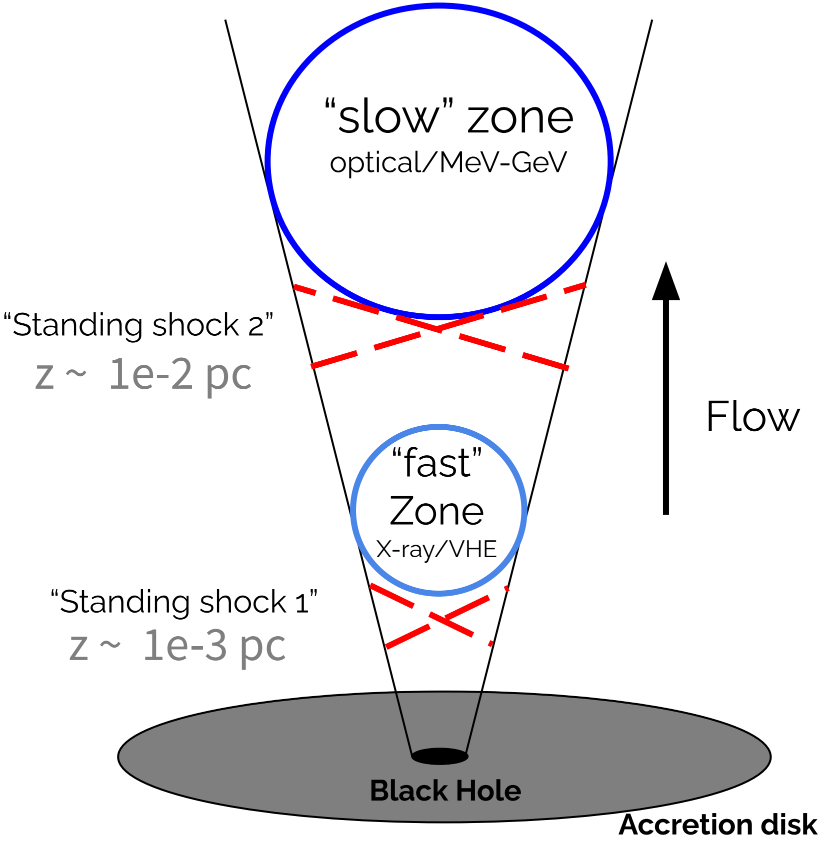


Time-dependent modelling - note on Doppler=100

- We found Doppler = 100 in “fast” zone

  → displacement ~ $\delta^2 * c * \Delta t_{obs}$ ~ 10 pc / day,
  if emitting region moving downstream with δ
  → contradicts stability of R (constant)
  and B (varies by factor ~2) in our model

- Suggest that emitting region is fixed in jet’s frame (e.g. recollimation shock)
  (Hervet et al. 2019, Daly & Marscher 1988)



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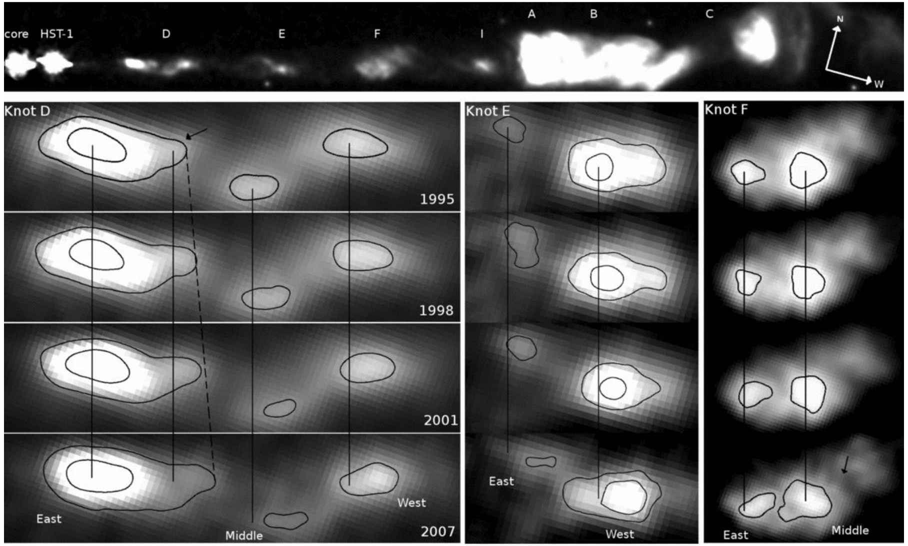
M87 optical jet (Meyer et al. 2013)



Conclusions

- **Major outburst in April 2013** of Mrk 421
  - observed over 9 days with **~40 hrs of VHE / X-ray simultaneous data**
  - Spectral & flux variability on sub-hour scale

- Spectral analysis of MAGIC and NuSTAR data during April 2013 flare
  - **High degree of complexity in the spectral evolution**
  - **Evidence of simultaneous VHE/X-ray spectral hysteresis**

- Time-dependent modelling of the flare, on 15min timescale
  - **Evolution of electron luminosity & hardness** describes most of VHE/X-ray sub-hour variations
  - **Doppler factor ~ 100**, required to capture VHE hardness
  - $\Delta p \sim 1.5$ implies change in plasma magnetization or guide field strength (magnetic reconnection)
    or change in shock compression ratio (DSA)

Thank you!

Back up

The Mrk 421 2013 outburst

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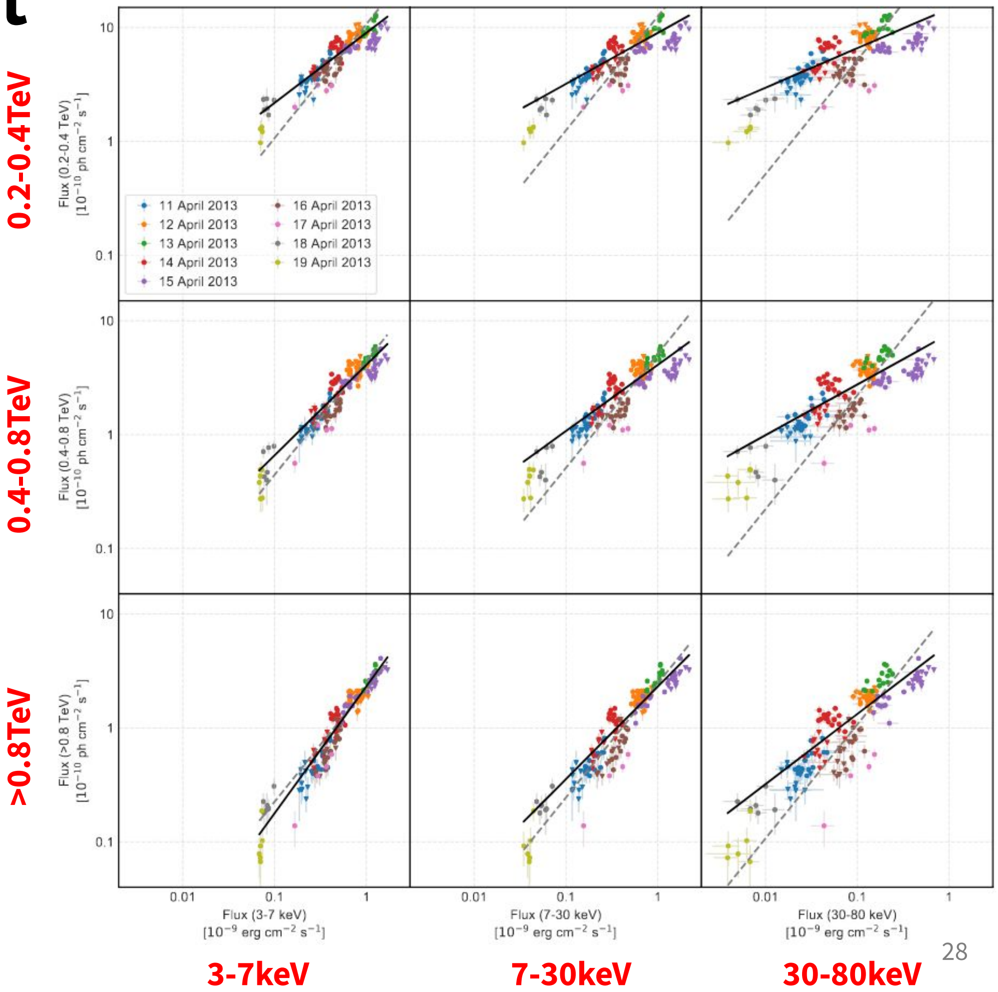
- Flare in April 2013
  - ~15x Crab Nebula flux at very-high-energy
  - ~40 hrs of simultaneous X-ray/VHE coverage (Swift-XRT/NuSTAR/MAGIC/VERITAS)

- Tight X-ray vs. VHE correlation
  - Correlation slope is energy dependent

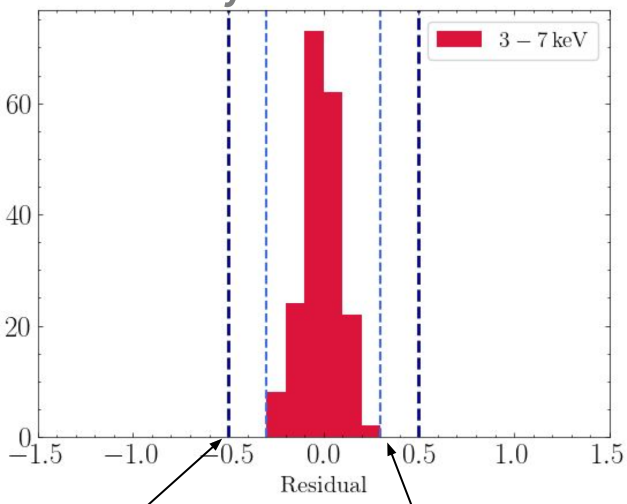
Acciari al., 2020, ApJS, 248, 29



Time-dependent modelling - “stationary states” parameters

Day	$\log_{10}(l_e)+5$	p	$\log_{10}(\gamma_{\rm min})$	$\log_{10}(\gamma_{\rm max})$	B [G]	R [10^{16}cm]
“Slow” zone				$\delta = 50$		
56393	0.15	2.0	2.5	4.5	0.07	1
56394	0.15	2.0	2.5	4.5	0.07	1
56395	0.10	2.0	2.5	4.7	0.07	1
56396	0.05	2.0	2.5	4.7	0.07	1
56397	0.60	2.0	2.5	4.6	0.07	0.5
56398	−0.05	2.0	2.5	4.7	0.07	1
56399	0.05	2.0	2.5	4.6	0.07	1
56400	0.05	2.0	2.5	4.6	0.07	1
56401	−0.05	2.0	2.5	4.6	0.07	1
“Fast” zone				$\delta = 100$		
56393	−0.3	3.63	4.2	5.2	0.160	0.122
56394	−0.1	2.94	4.3	5.3	0.100	0.122
56395	−0.05	2.82	4.3	5.3	0.110	0.122
56396	−0.1	3.20	4.3	5.3	0.100	0.122
56397	−0.1	2.61	4.2	5.4	0.100	0.122
56398	−0.3	3.11	4.2	5.4	0.120	0.122
56399	−0.45	3.35	4.2	5.5	0.130	0.122
56400	−0.3	3.96	4.3	5.4	0.086	0.122
56401	−0.55	3.96	4.3	5.3	0.110	0.122

Time-dependent modelling - results : X-ray fluxes



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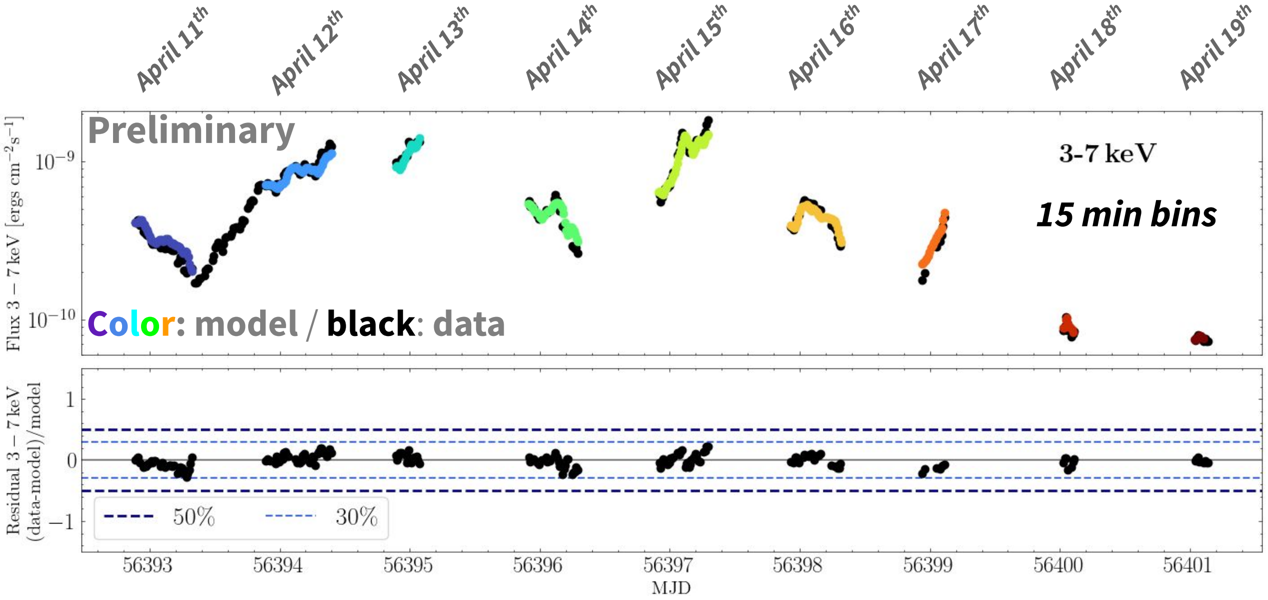

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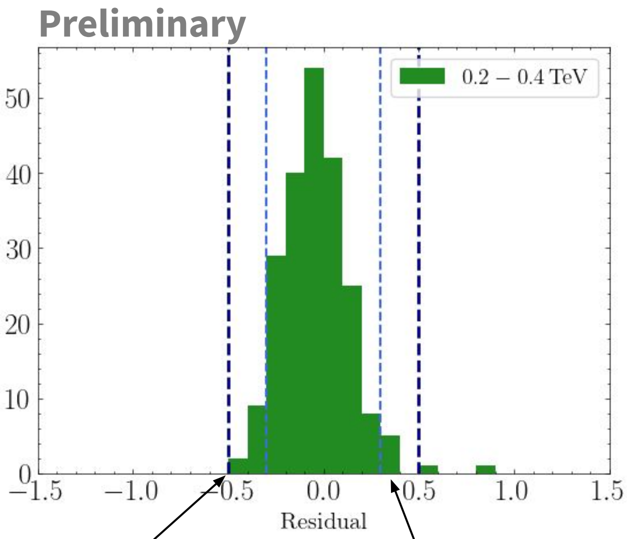
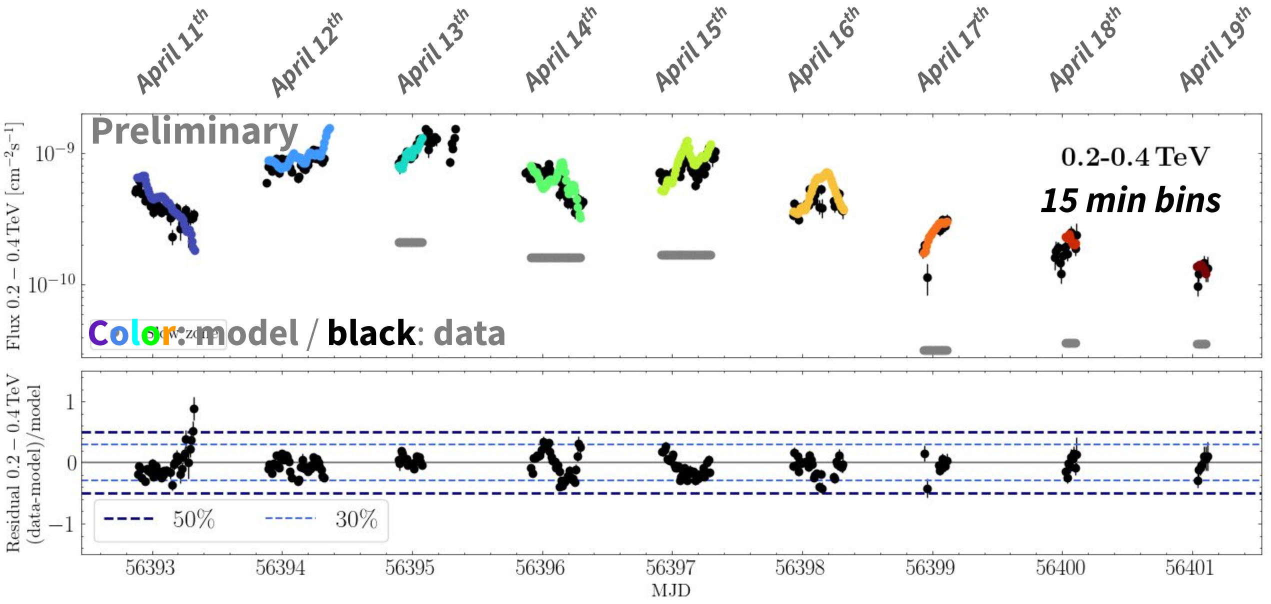
Time-dependent modelling - results: VHE fluxes





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At VHE majority of the bins described within 30%

Time-dependent modelling - results

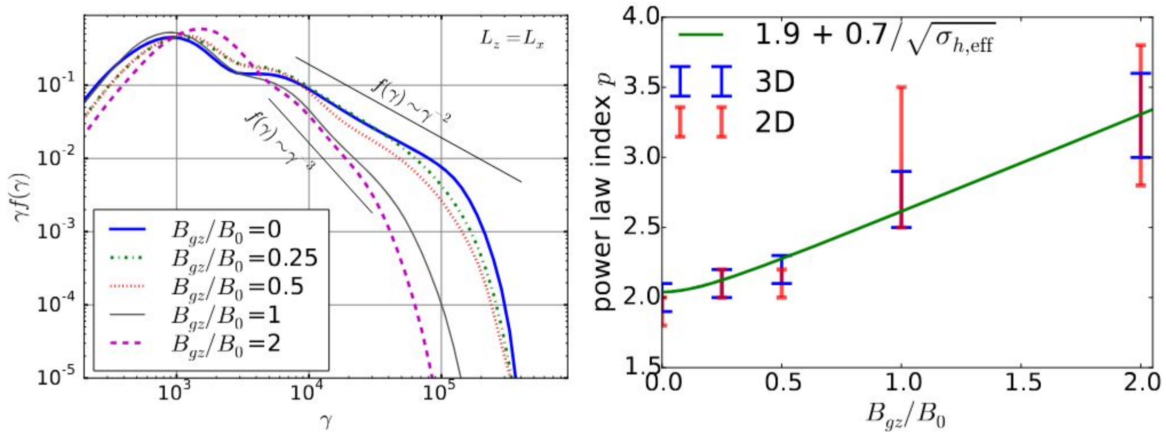

Figure 4. (Left) Strong B_{gz} hinders particle acceleration, as shown by the particle spectra from simulations with $L_z = L_x$ and varying B_{gz}. (Right) The spectral slopes are similar in 2D and 3D, but steepen significantly with strong guide field [Eq. (2)]. The range of p indicates variation within a single simulation.

Werner+Uzdensky 2017