Investigating the effect of aerosol variations in high-level analyses of Cherenkov telescope data

by applying a low-cost aerosol simulation scheme to simulated CTAO-South data in `gammapy`

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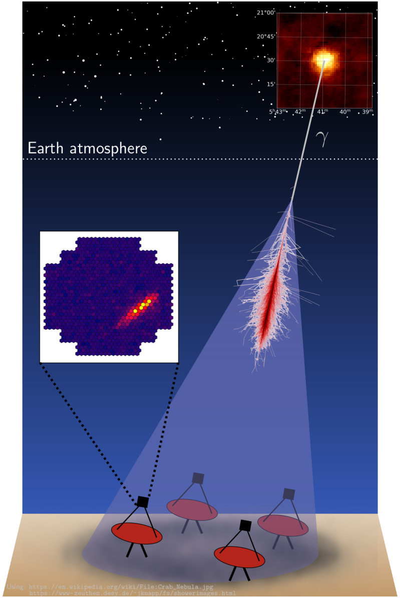
AtmoHEAD 2024, Ischia, 15.07.2024

HELMHOLTZ

DESY.

γ-ray astronomy with IACTs

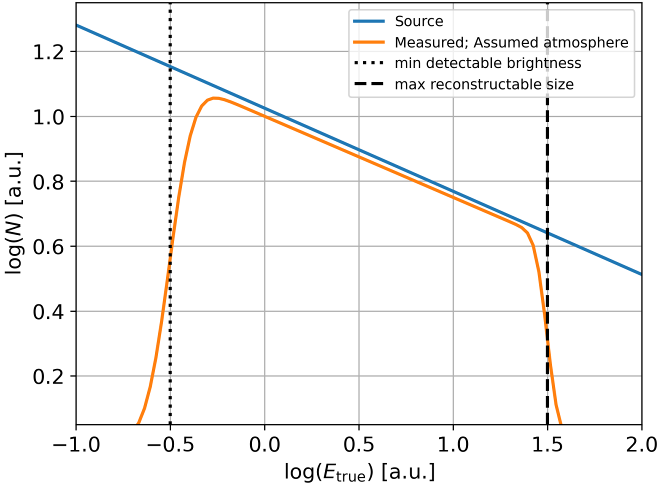
- γ rays induce extensive air-showers (EAS)
- Charged particles yield Cherenkov photons
- IACT images EAS
- Image orientation $\rightarrow$ primary particle origin
- Total brightness $\rightarrow$ primary particle energy
- Converted via instrument response functions (IRFs) generated from MCs
- Unaccounted variations in atmospheric transparency $\Rightarrow$ **Misinterpretation of EAS image!**



The effect of transparency variations

Very simply put:

- Minimum number of Cherenkov photons required for detection
- Maximum shower image size for proper reconstruction



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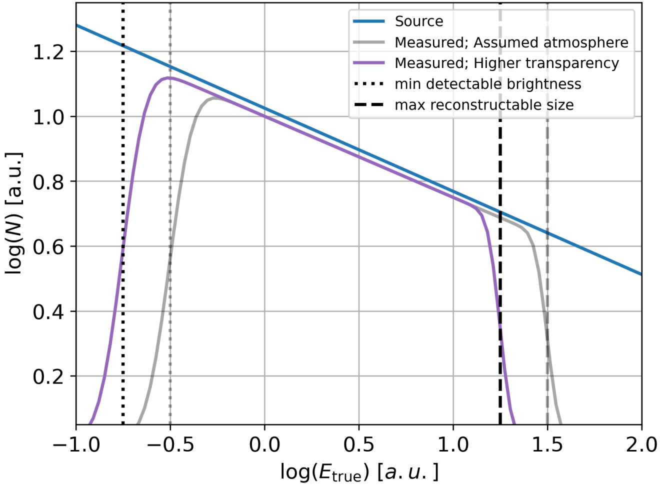
  $\rightarrow$ shift towards lower energies



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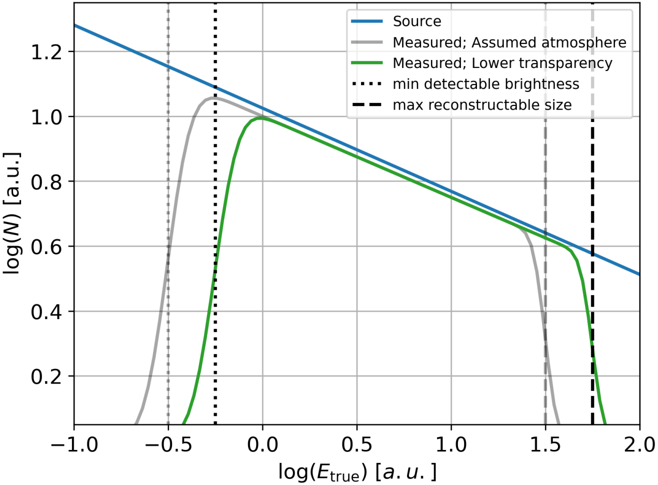

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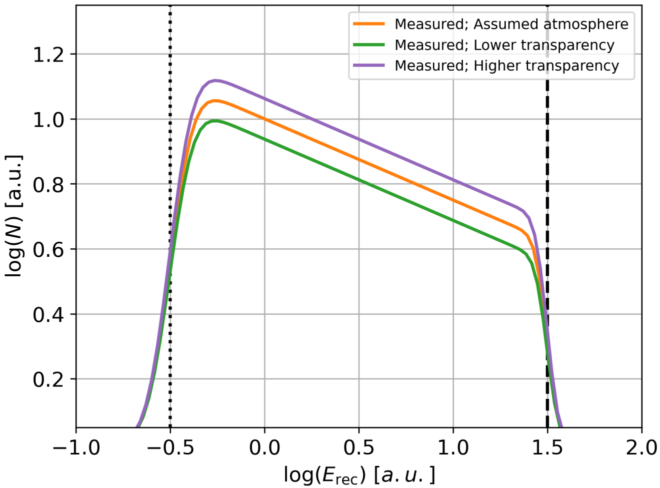

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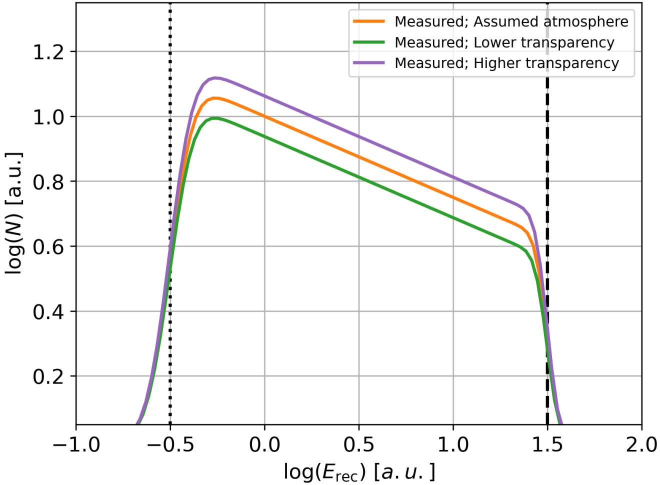
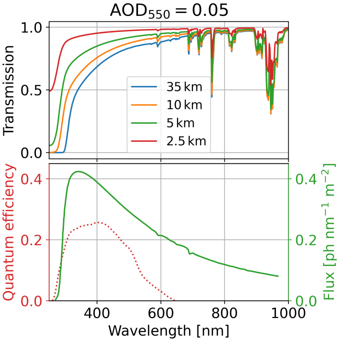
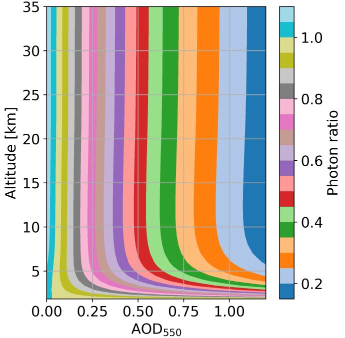
- **How does this impact the accuracy of IACT measurements?**

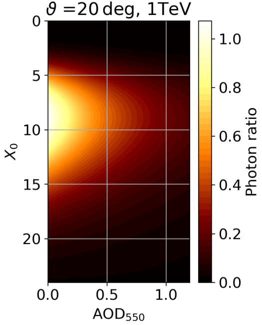


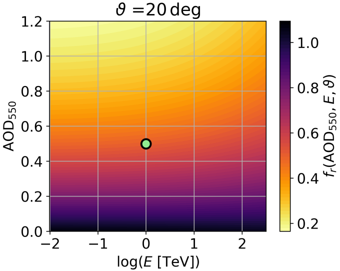
AtmoHEAD 2022: Assessing the general impact

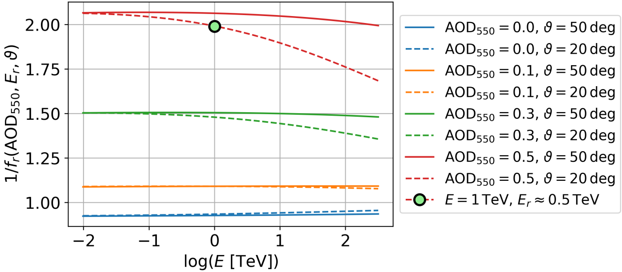
Find paper here







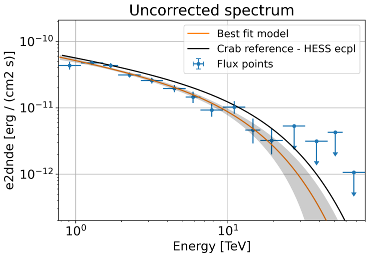


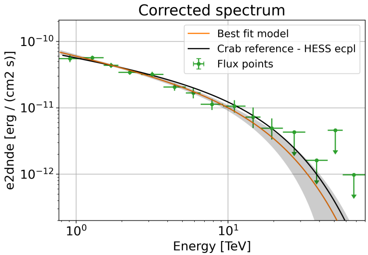


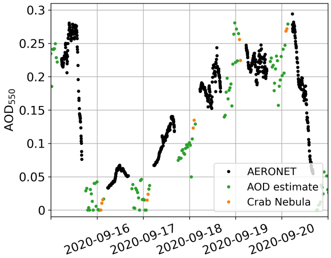
ICRC 2023: Correcting for aerosol variations

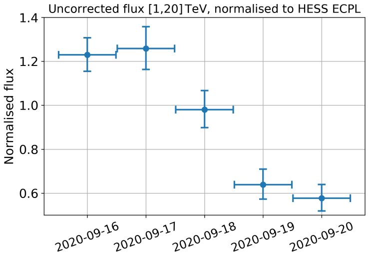
Find paper here

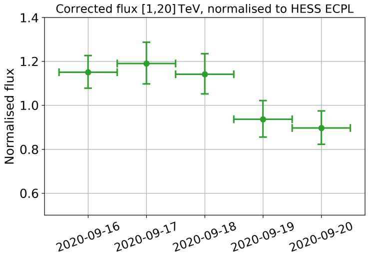
- 5 consecutive nights with Crab Nebula observations by the H.E.S.S. telescope array
- Estimated AOD levels from trigger rates and AERONET data
- Corrected event-wise E_{rec} and run-wise IRFs











AtmoHEAD 2024: Assessing high-level impact

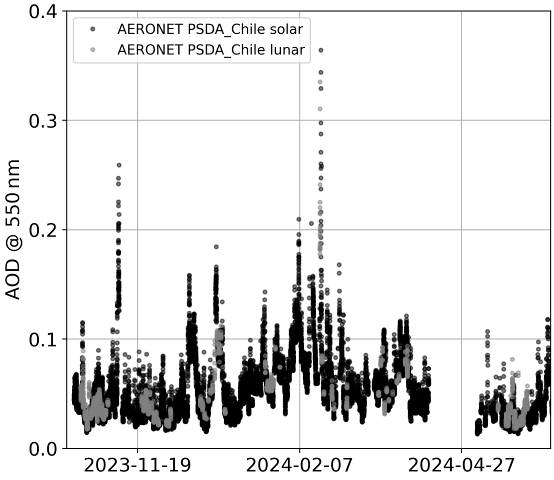
Idea: Apply the correction scheme to study high-level effects of aerosol variation on CTAO-South observations

1. Estimate aerosol conditions using AERONET stations close to observatory site
2. Generate transmission tables using Py6S and create according ratio function
3. Use published CTAO-South Prod5 IRFs to sample EAS event-lists for observations of artificial γ-ray sources in `gammapy`
4. Shift EAS energies as expected for according aerosol conditions
5. Perform `gammapy` analyses and compare results from original and aerosol-adapted event lists

Disclaimer:
Study to show *raw* effect of *unaccounted* aerosol variations,
NOT the expected CTAO performance!

Simulating observations with aerosol variations

- AERONET data suggests AOD$_{550} \sim [0.01, 0.35]$



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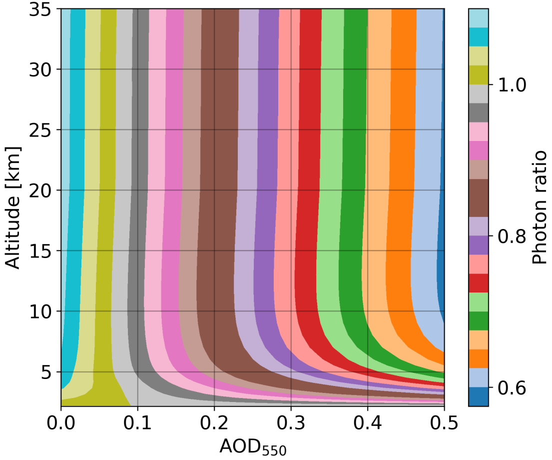

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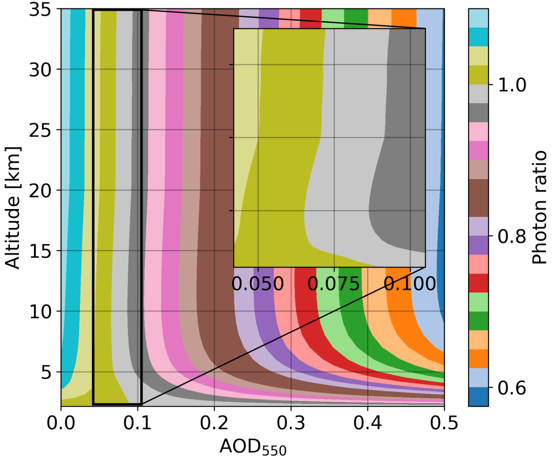

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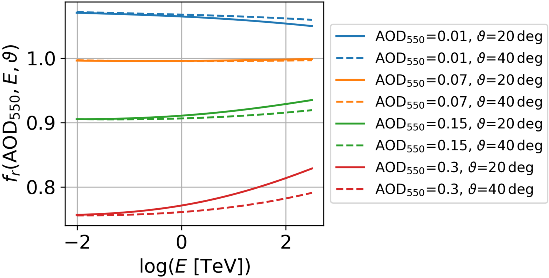

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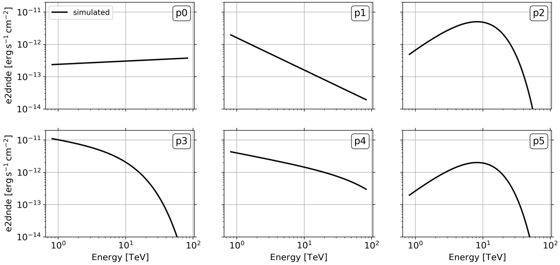
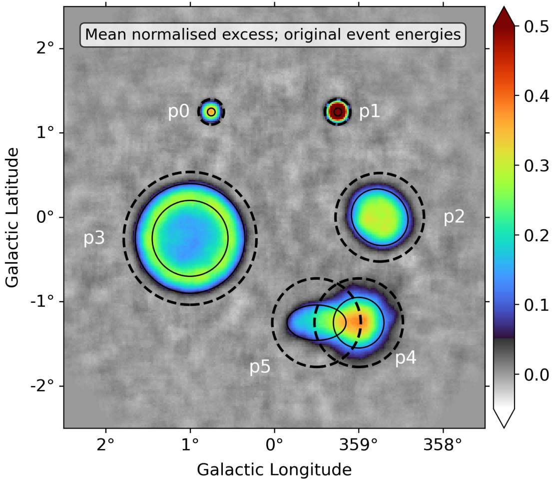


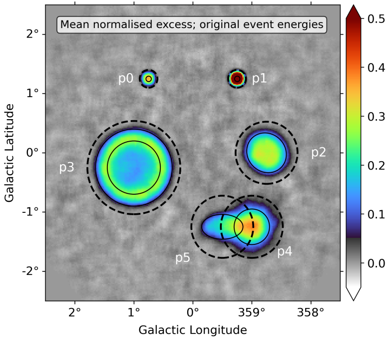


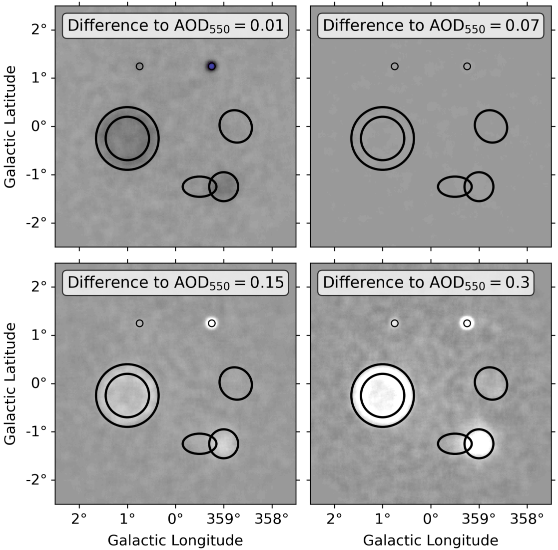
- 6 artificial γ-ray sources; different spectral, temporal and morphological properties
- Omitting any known γ-ray emission
- 25 sets of:
  8 nights with 1 h of observations alternating between 20° and 40° zenith angle and rotating 0.7° wobble offsets; all for AOD$_{550} = [0.01, 0.07, 0.15, 0.3, 0.4]$

Spectral analysis - Data reduction

- Reduction of event lists into 3D data cubes
- Background normalisation is fitted
- Original vs. aerosol-adapted excess residuals:
  - Flat in background
  - Differences in source regions

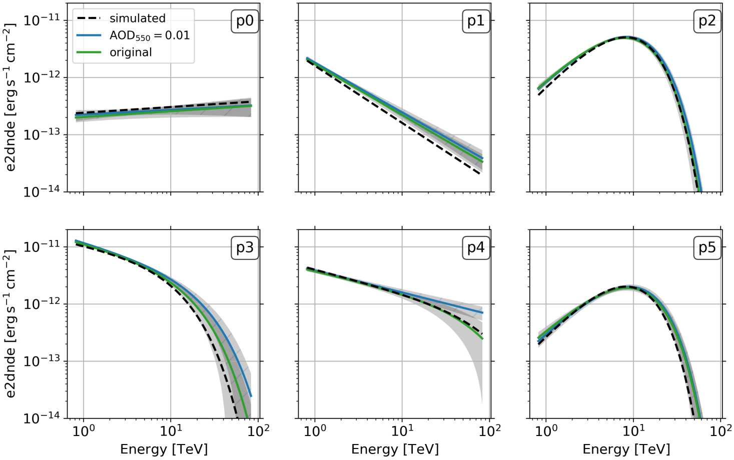
$\Rightarrow$ Influence of spectra + energy range!





Spectral analysis - 3D fit

- Fitting simulated source models to data cubes
- Unfreezing background normalisation and tilt
- Unchanged IRFs



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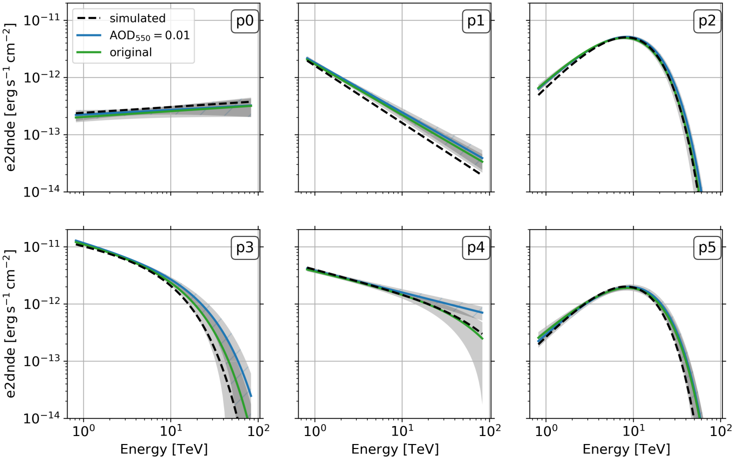

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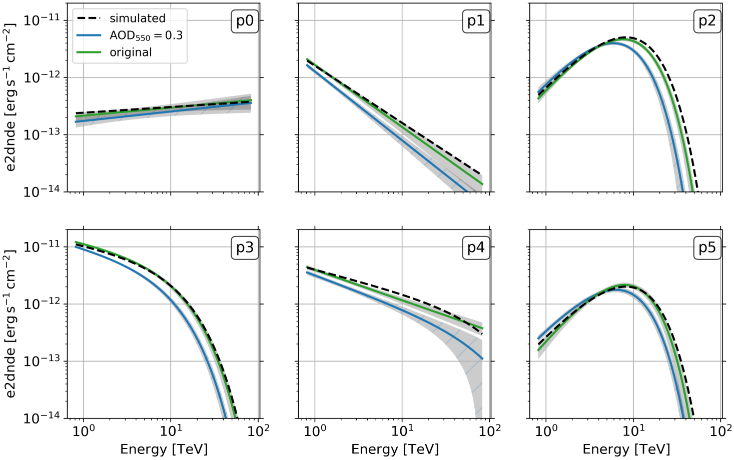

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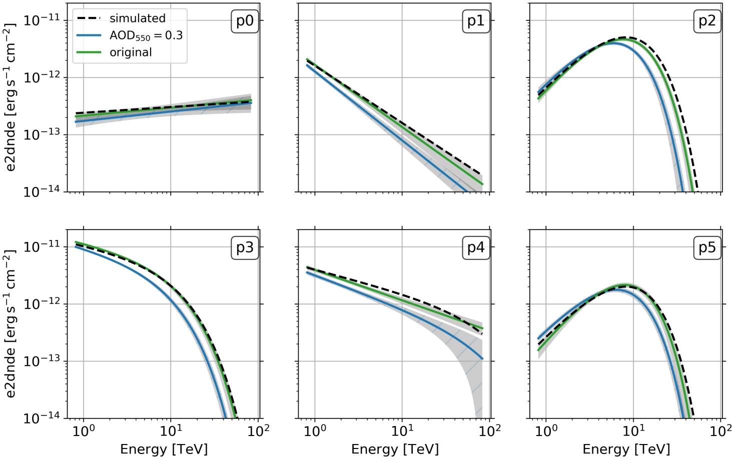
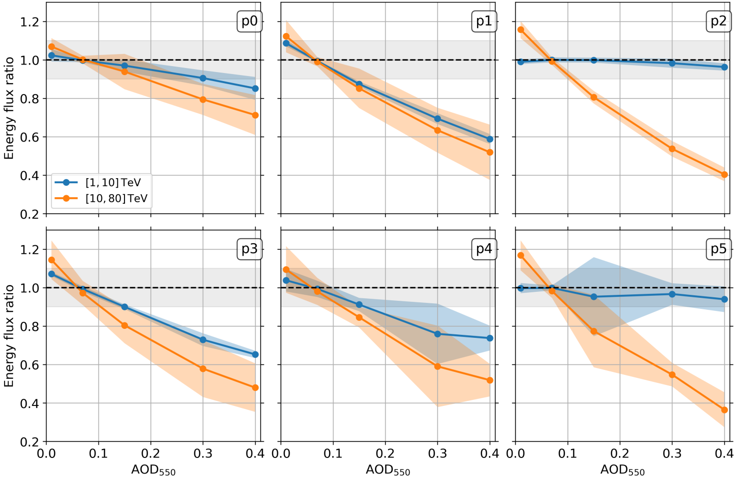
- **Different influence of aerosols on spectra over energy!**



Spectral analysis - Detailed comparison

- Mean flux ratios (original vs. aerosol-adapted) of converged best-fit models from according sets of observation sequences
- Statistical fit uncertainties not regarded
- Error bands show standard deviation from sets of converged fits



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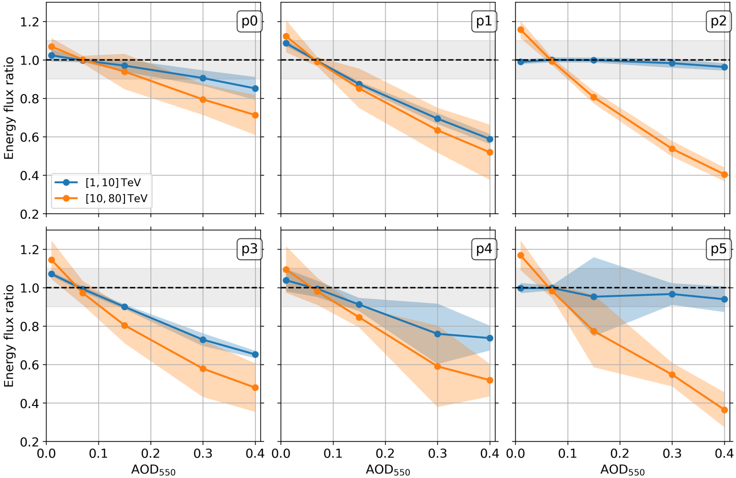

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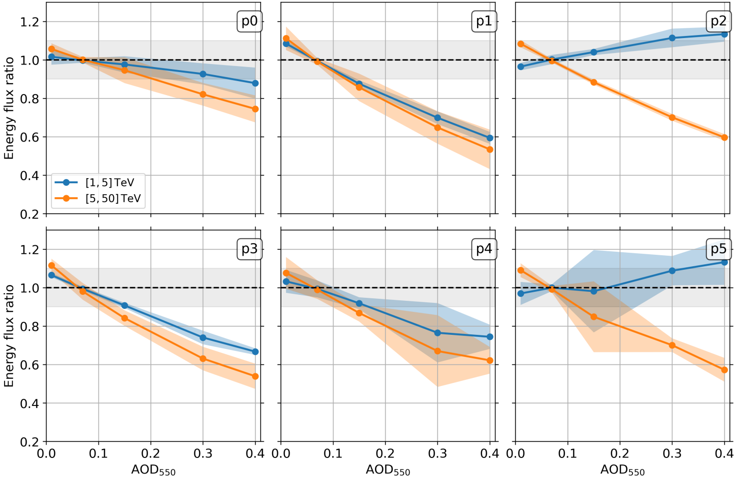

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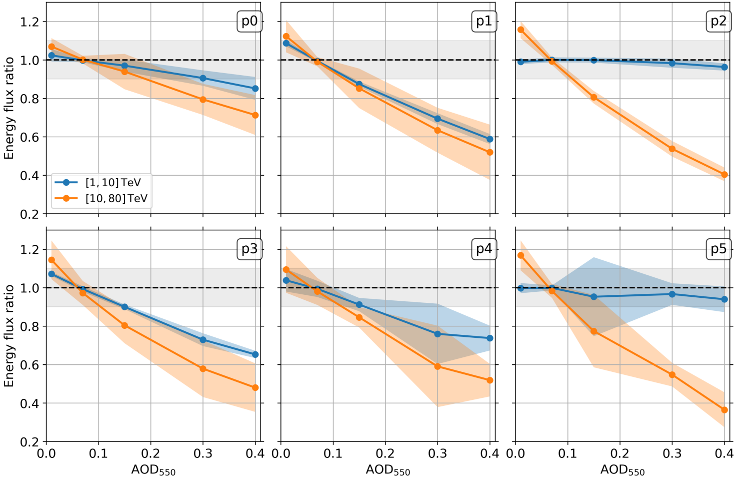


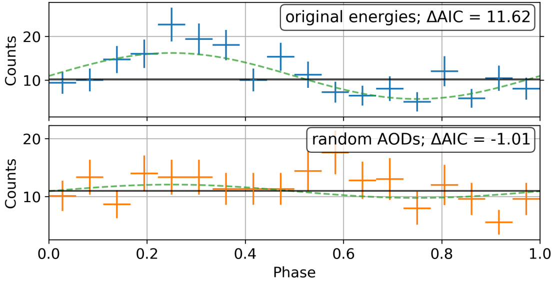
Impact of aerosol variations depends on source spectra and regarded energy range!

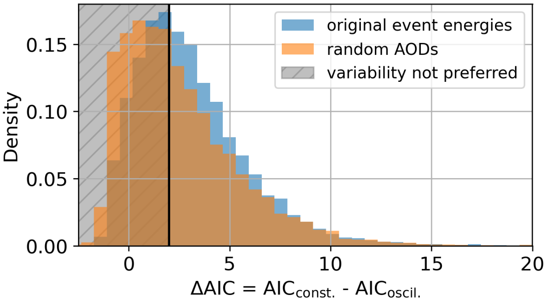
Transferring systematics of one source to another … ?

Temporal analysis

<u>Limited proof-of-concept example!</u>

- Power-law point-like source $\mathtt{p1}$ with 90 min sinusoidal flux variation
- Reference time and phase assumed to be known
- *Can we still detect variability for <u>random aerosol variations</u>?*





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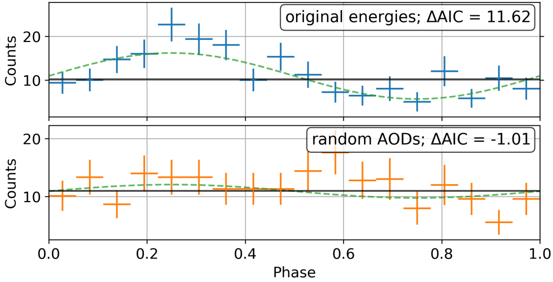
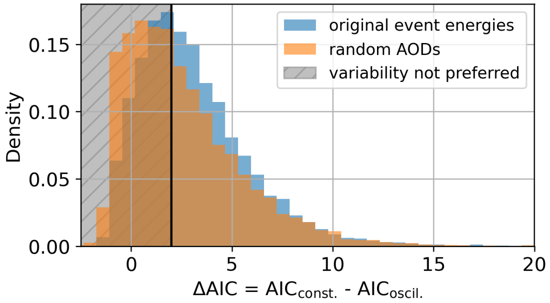


- Generate phasograms and fit constant and sine for 10k obs. sequences with random aerosol combinations
- Use $\mathtt{c\text{-}stat}$ and Akaike Information Criterion to determine preferred model
- Result: Aerosol variations introduce noise in the phasograms $\Rightarrow$ reducing probability to detect variability by $\sim 10\%$
- *NB: Strong dependency on source properties and observation details!*



Discussion

- High-level influence of aerosol variations depends on many parameters, e.g. source properties, regarded energy range and observation details
  making accurately quantifying atmosphere-induced systematics rather challenging!

- CTAO aims to produce closely matching IRFs for all observation conditions!
  $\rightarrow$ Then what could we use this correction scheme for?

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  $\rightarrow$ Then what could we use this correction scheme for?

If atmospheric conditions are known at higher time-resolution than IFRs, the presented scheme can be used to estimate / correct the effects of unaccounted variations
$\rightarrow$ E.g. *Real-time analysis*!

Thank you!

Contact

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