GeV/TeV γ-ray Spectrum of Blazars

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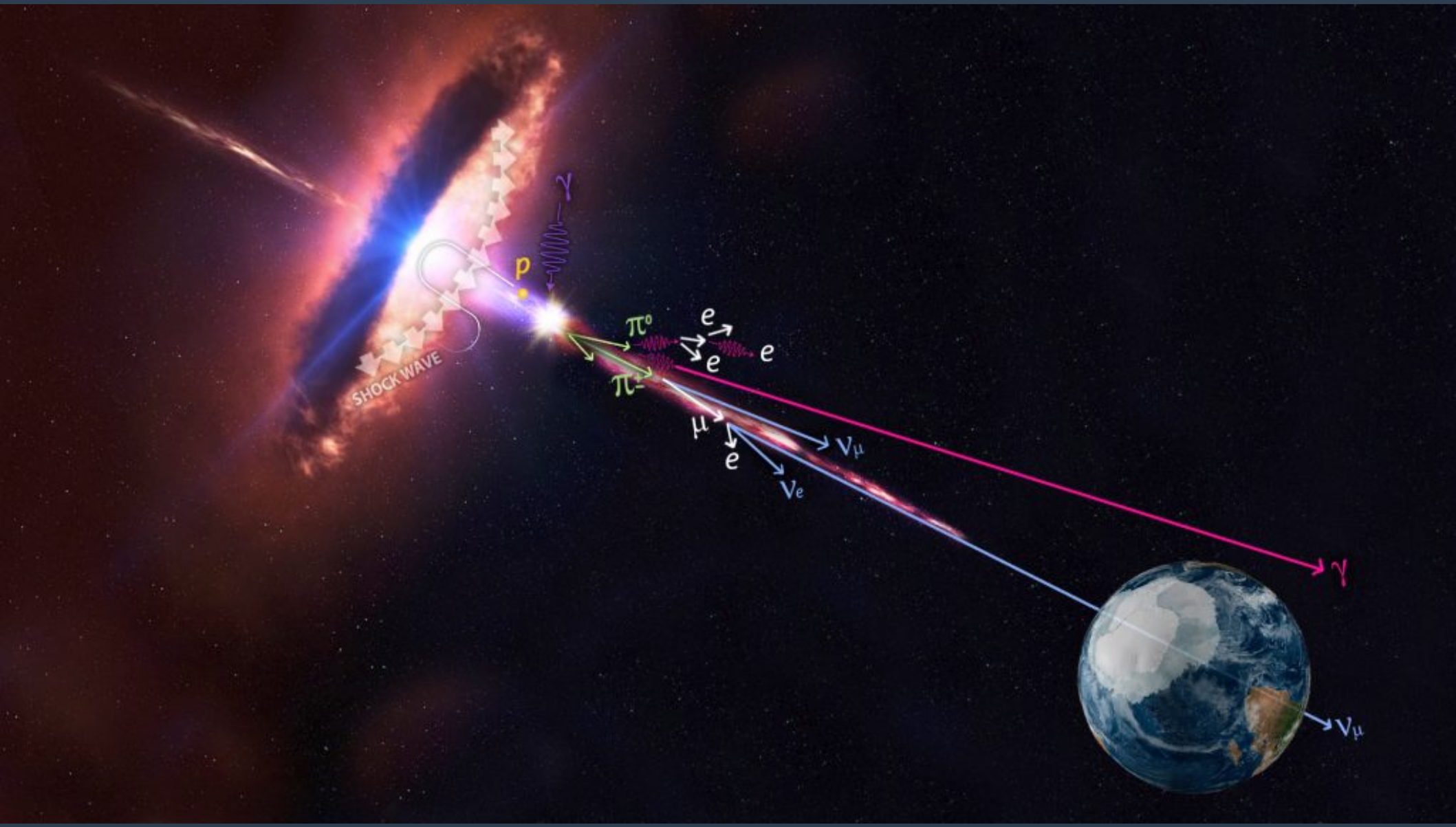
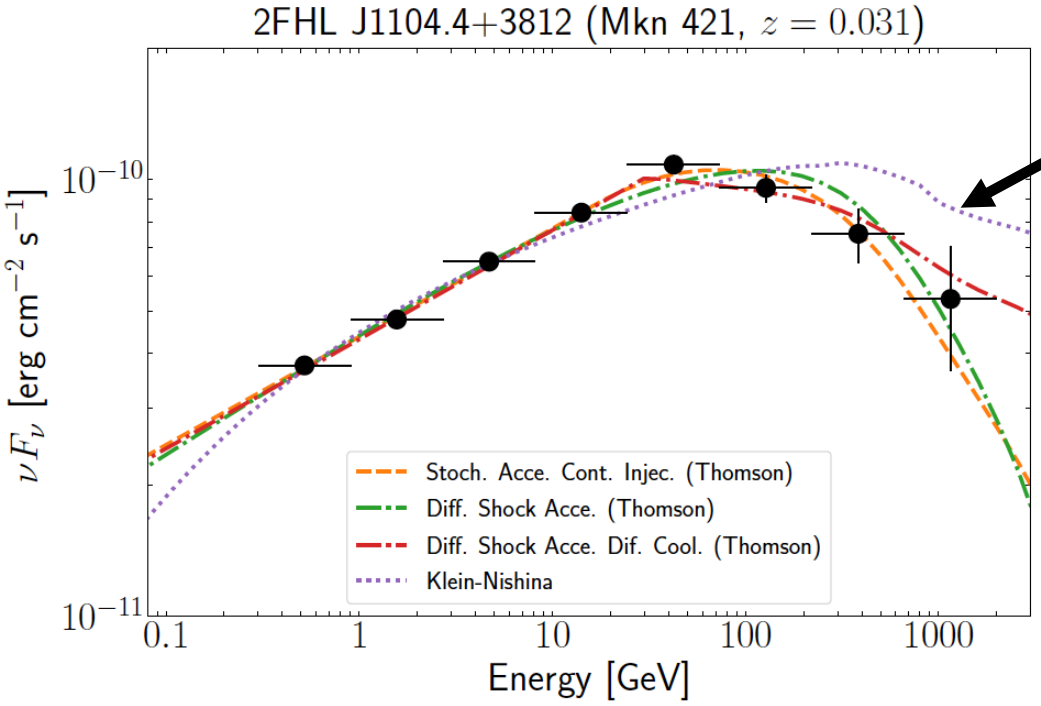
γ-ray Blazars: Extreme Particle Accelerations



Why Spectral Curvature?
– Particle Acceleration and Cooling

- Probe **underlying electron population** and **acceleration/cooling**
- GeV-TeV spectra alone are useful! Do not require full multiwavelength spectrum
- Spectral shape differs for different flavors of Compton scattering
  - Thomson or Klein-Nishina regime?
  - What acceleration and cooling mechanisms?



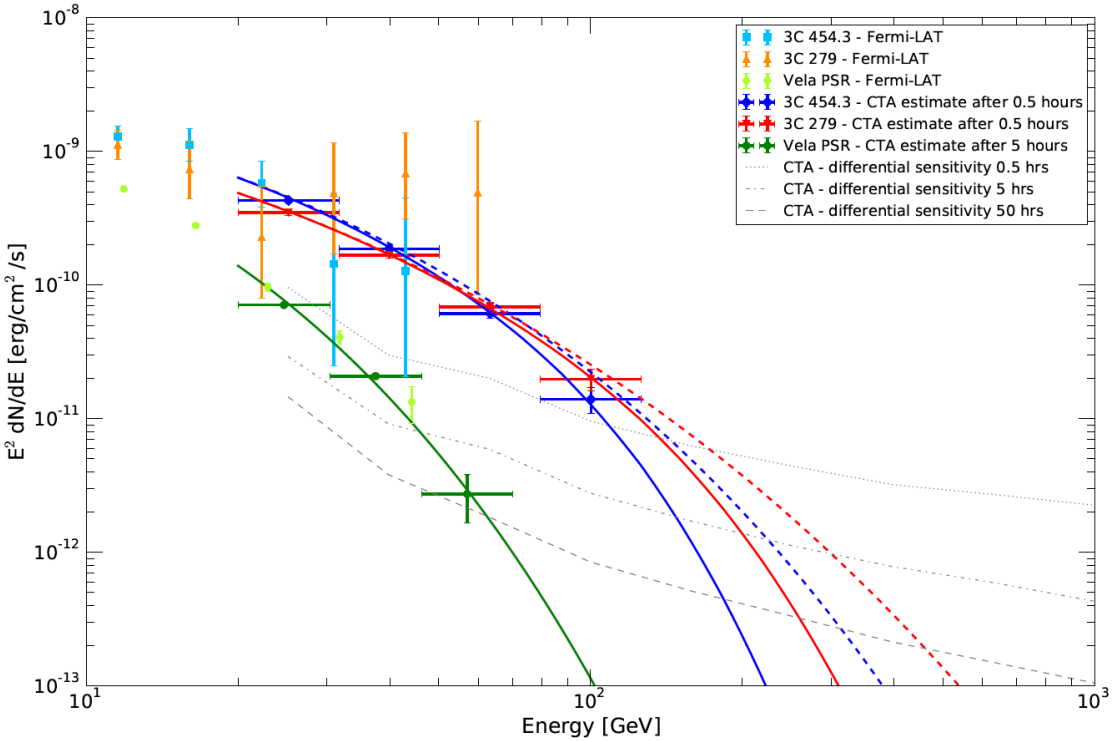
Predictions differ significantly at high energy

Van den Berg+ 2019
arXiv:1901.03494v1

Why Spectral Curvature?
– Particle Acceleration and Cooling

- Interplay of acceleration and cooling
  → parent particle spectrum with modified/stretched exponential cutoff
- For Synchrotron Self-Compton model, easily related to gamma-ray spectrum

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left[-\left(\frac{E}{E_c}\right)^{\beta_\gamma}\right] \qquad \text{for SSC} \quad \beta_\gamma = \frac{\beta_e}{\beta_e + 4}$$

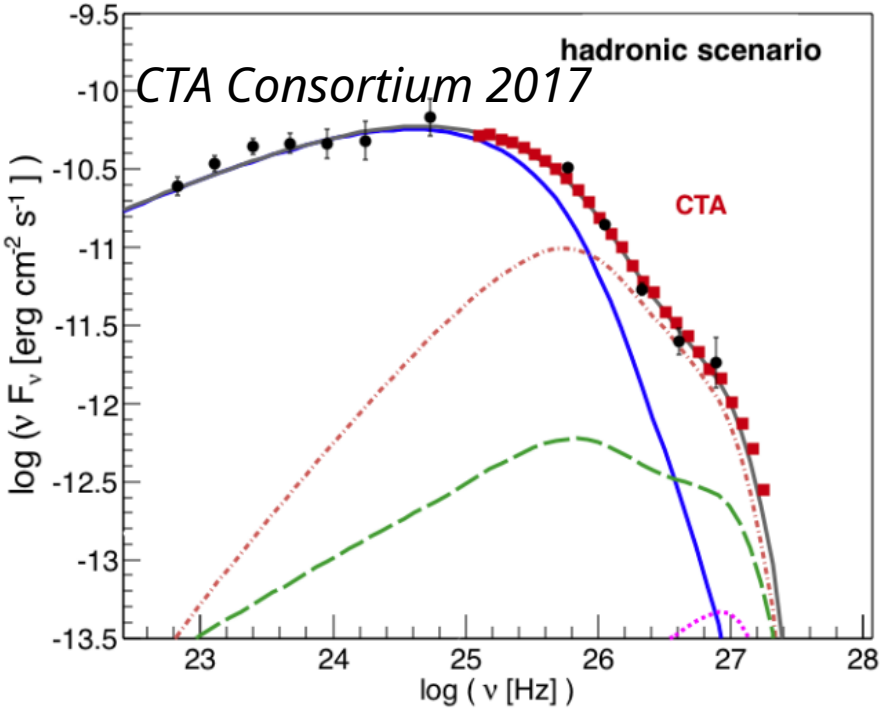


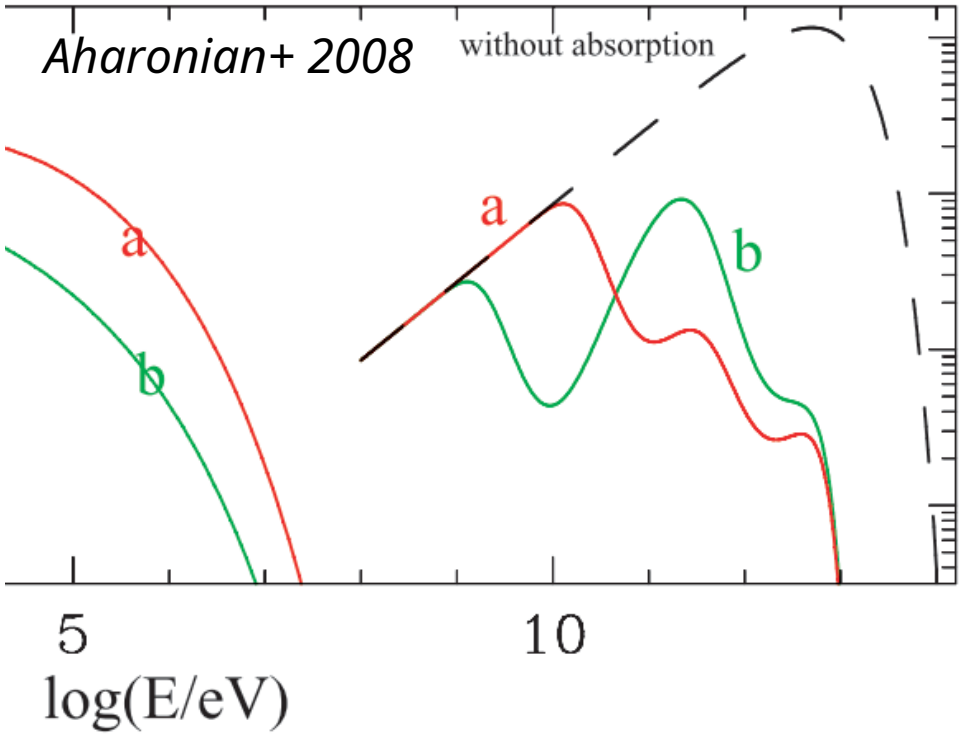
CTA will decrease uncertainties on β with short observation times

Romoli+ 2016
arXiv:1608.01501

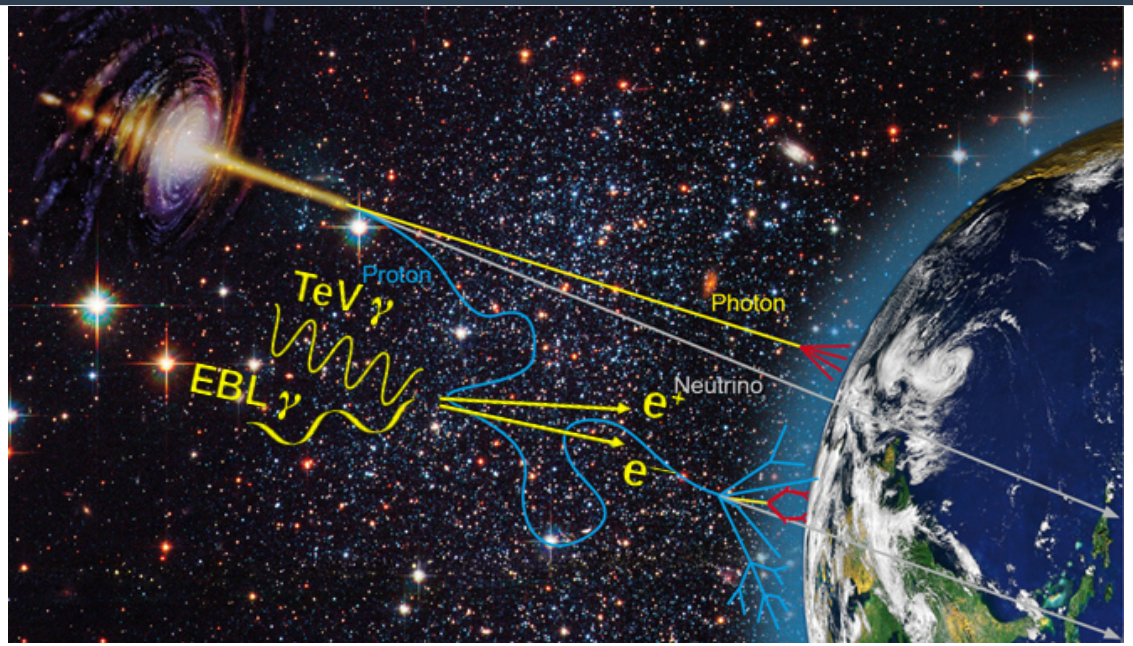
Why Spectral Curvature?
– for Spectral Hardening/Upturns

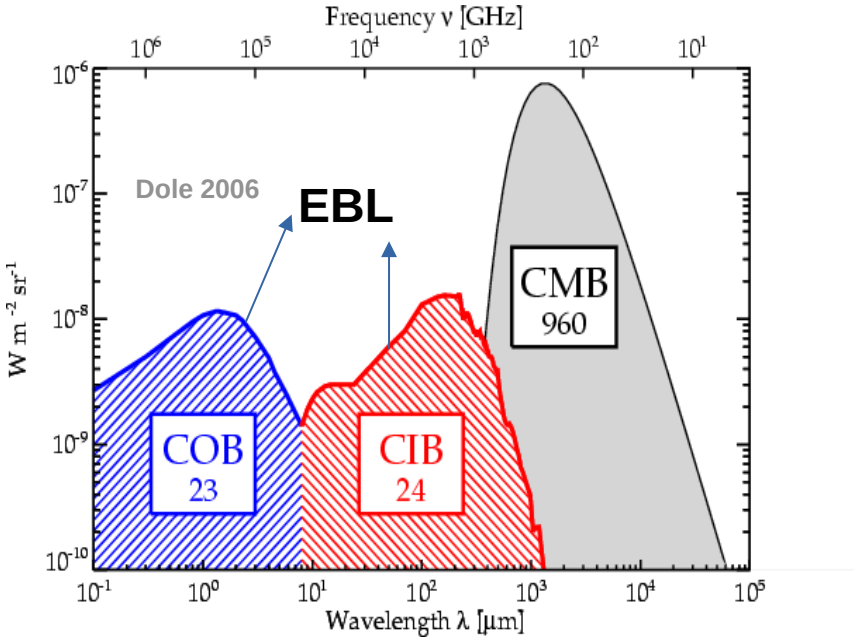
- Single vs multiple spectral components? Hadronic? *e.g. CTA Consortium 2017*
- Internal absorption in the emission region? *e.g., Aharonian+ 2008*
- Exotic physics (Lorentz invariance violation; LIV)





Effects from Propagation
– Interactions with Extragalactic Background Light (EBL)



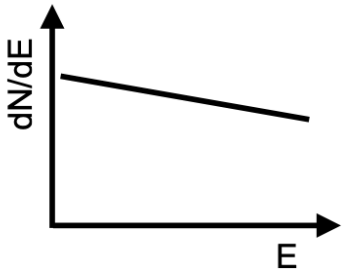


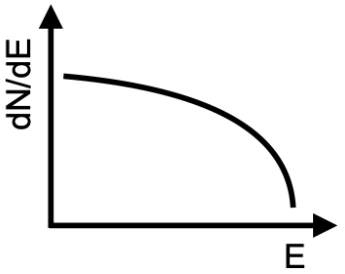
Intrinsic spectrum:

$$\frac{dN}{dE} \propto E^{-\Gamma}, \frac{dN}{dE} \propto E^{-\Gamma} \exp\left(-\frac{E}{E_C}\right), ...?$$

Observed spectrum:

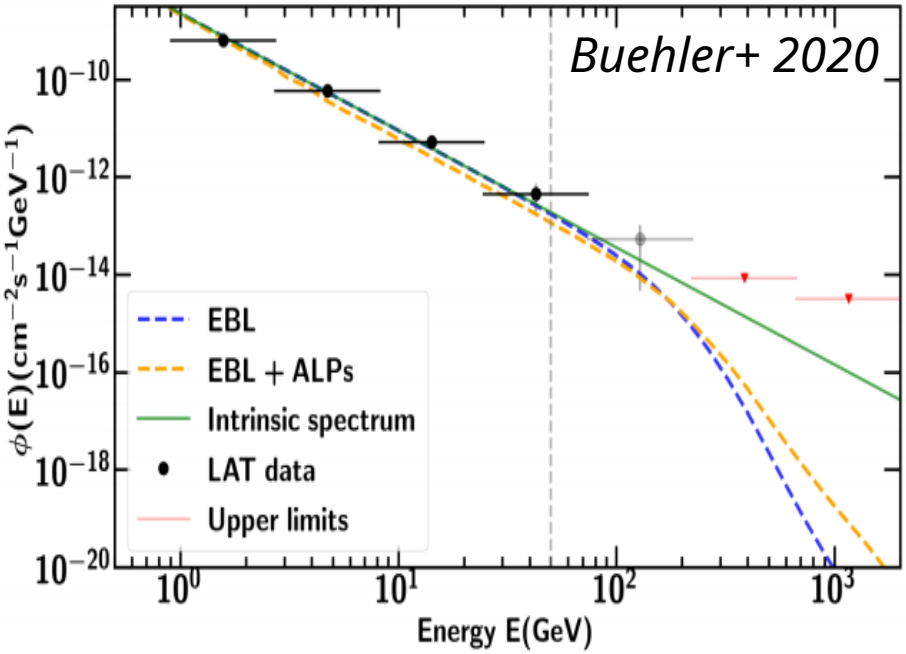
$$\frac{dN}{dE} \propto \left(\frac{dN}{dE}_{int}\right) \exp(-\tau_{\gamma\gamma})$$

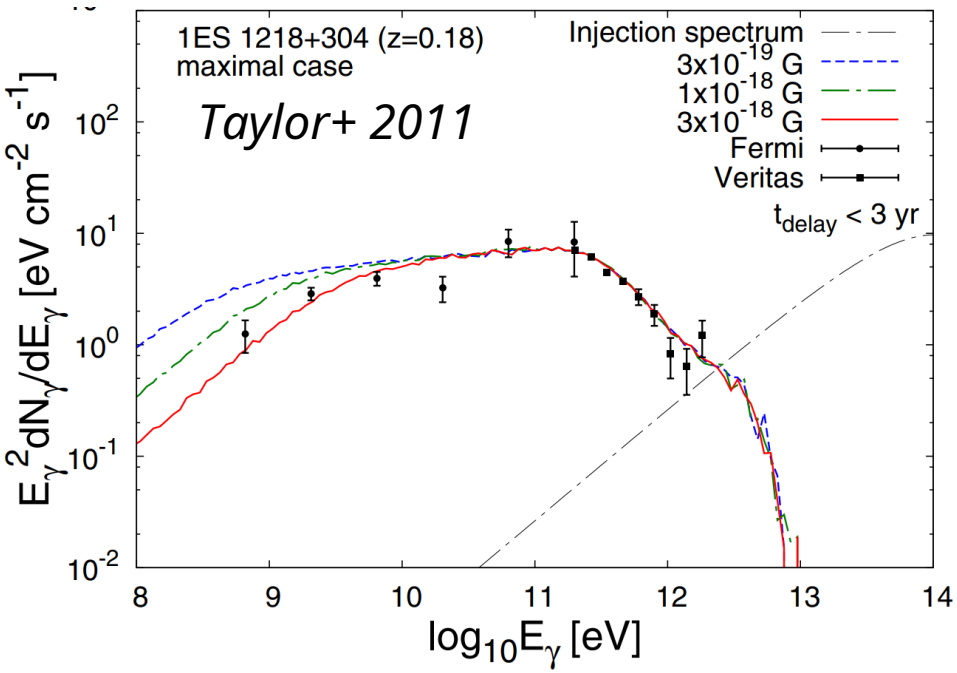




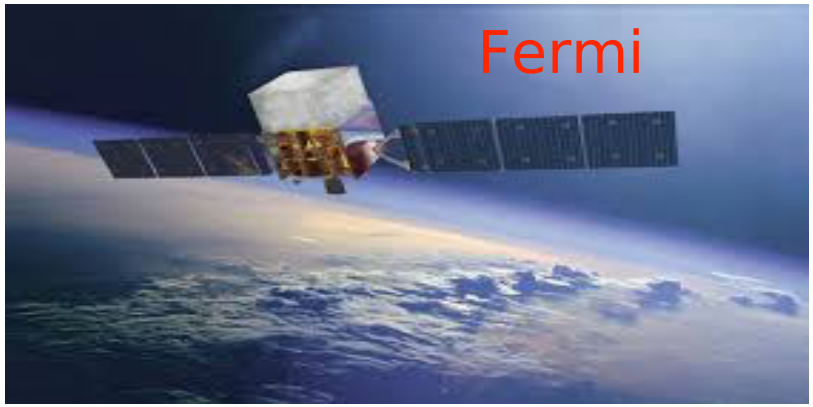
Effects from Propagation
– Exotic physics and effects of intergalactic magnetic field

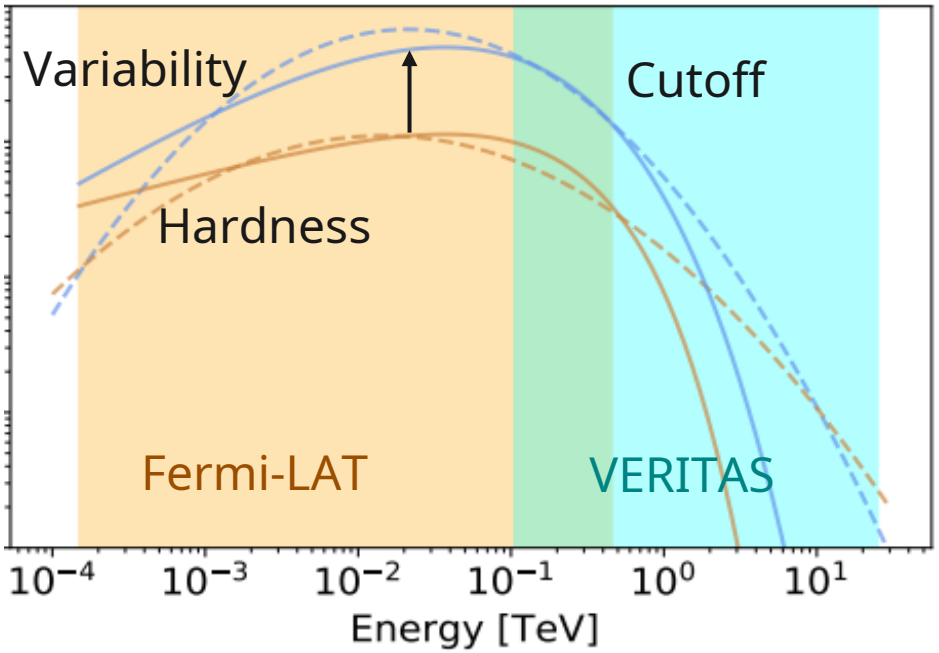
- Is there exotic physics at work? (Lorentz invariance violation, axion-like particles)
  e.g., Buehler+ 2020
- How does the intergalactic magnetic field alter the gamma-ray spectrum?
  e.g., Taylor+ 2011





The Instruments





The Sources

- 17 high-frequency-peaked blazars strongly detected by VERITAS
- Selected 4 brightest sources with known redshift for this work

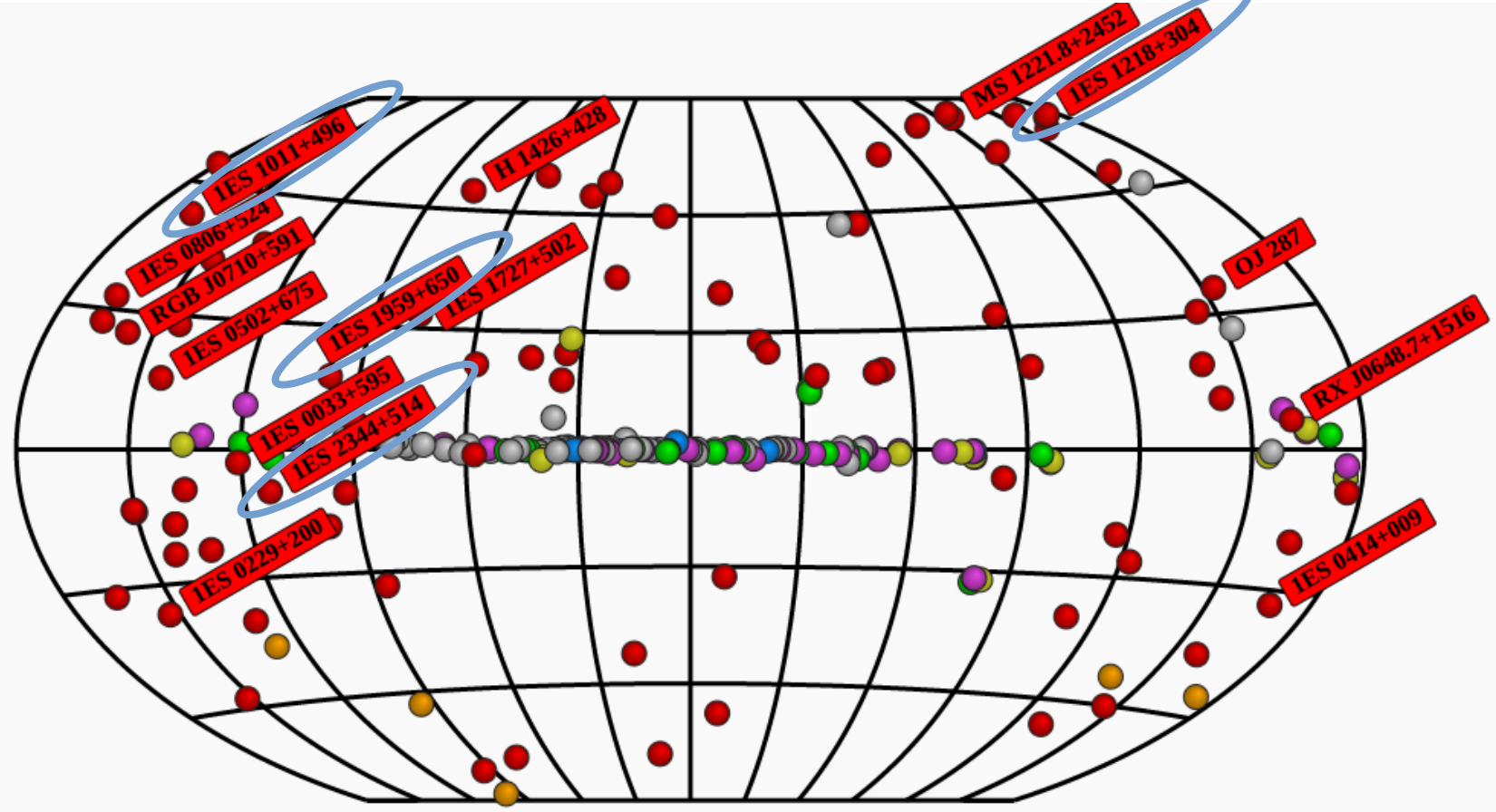


Image from TeVCat: http://tevcat2.uchicago.edu

The Analysis

Time-averaged joint spectra

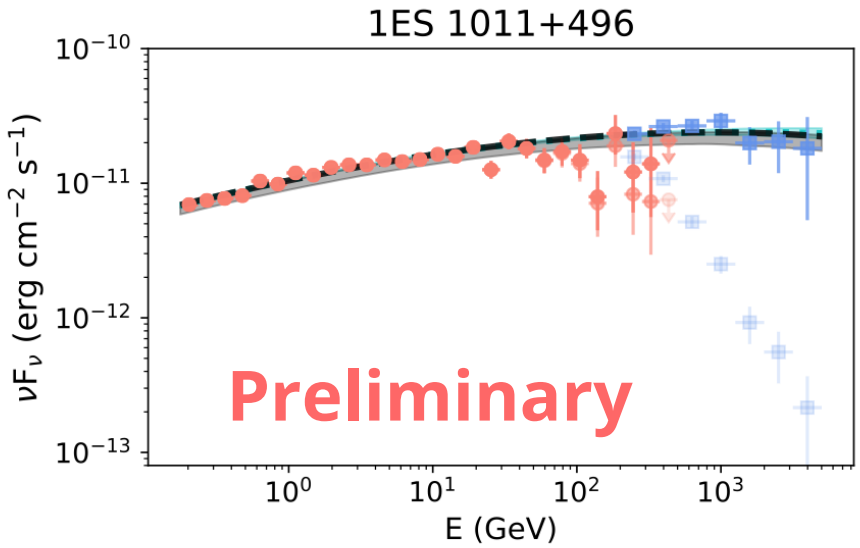
- Pro: statistical power
- Con: averaging together flux states
- EBL correction (*Dominguez+ 2011*)
- Fit joint spectra
  - Stretched exponential cutoff
  - Log parabola

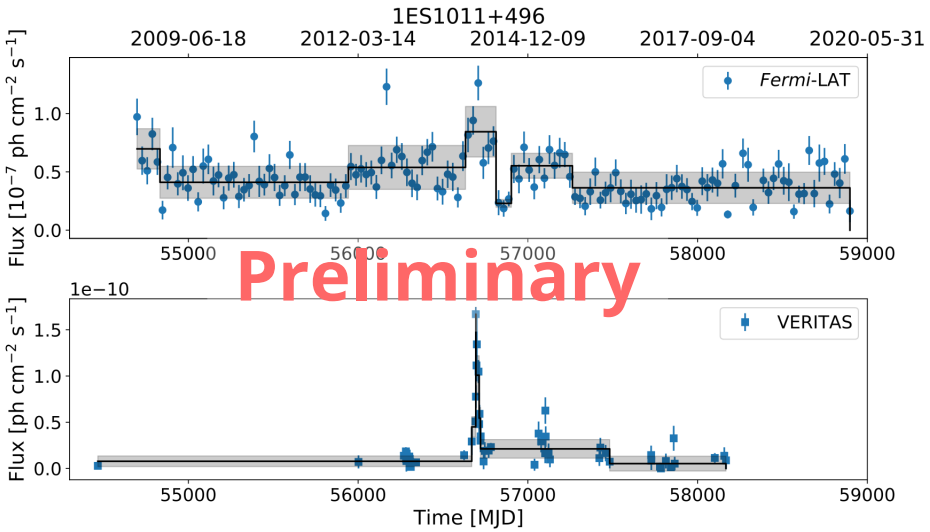
Light curves

- Nightly VERITAS, monthly Fermi-LAT
- Bayesian block analysis with 3σ change points
- Identify intervals without significant variability in either band → joint blocks

Time-resolved joint spectra

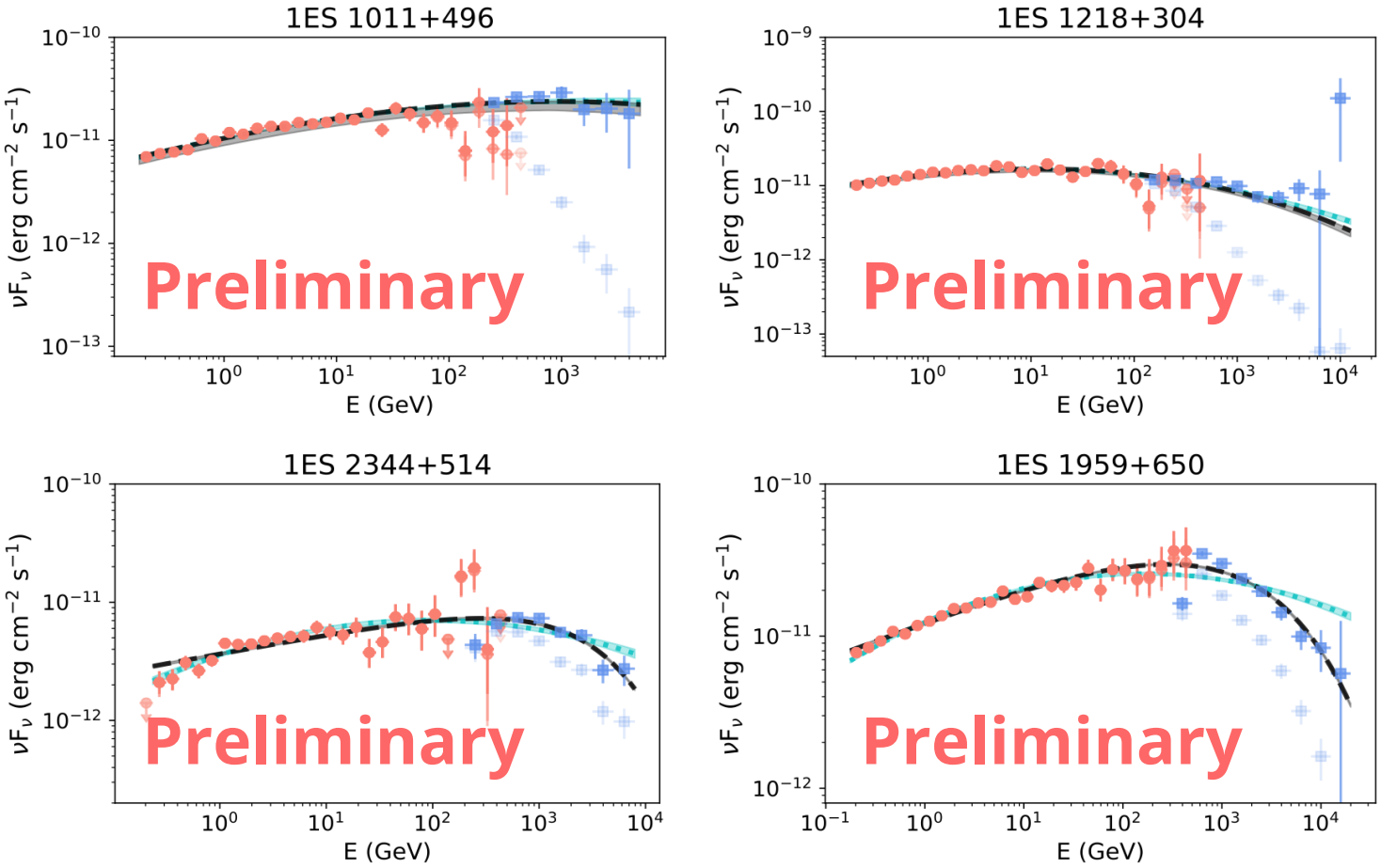
- In each joint block





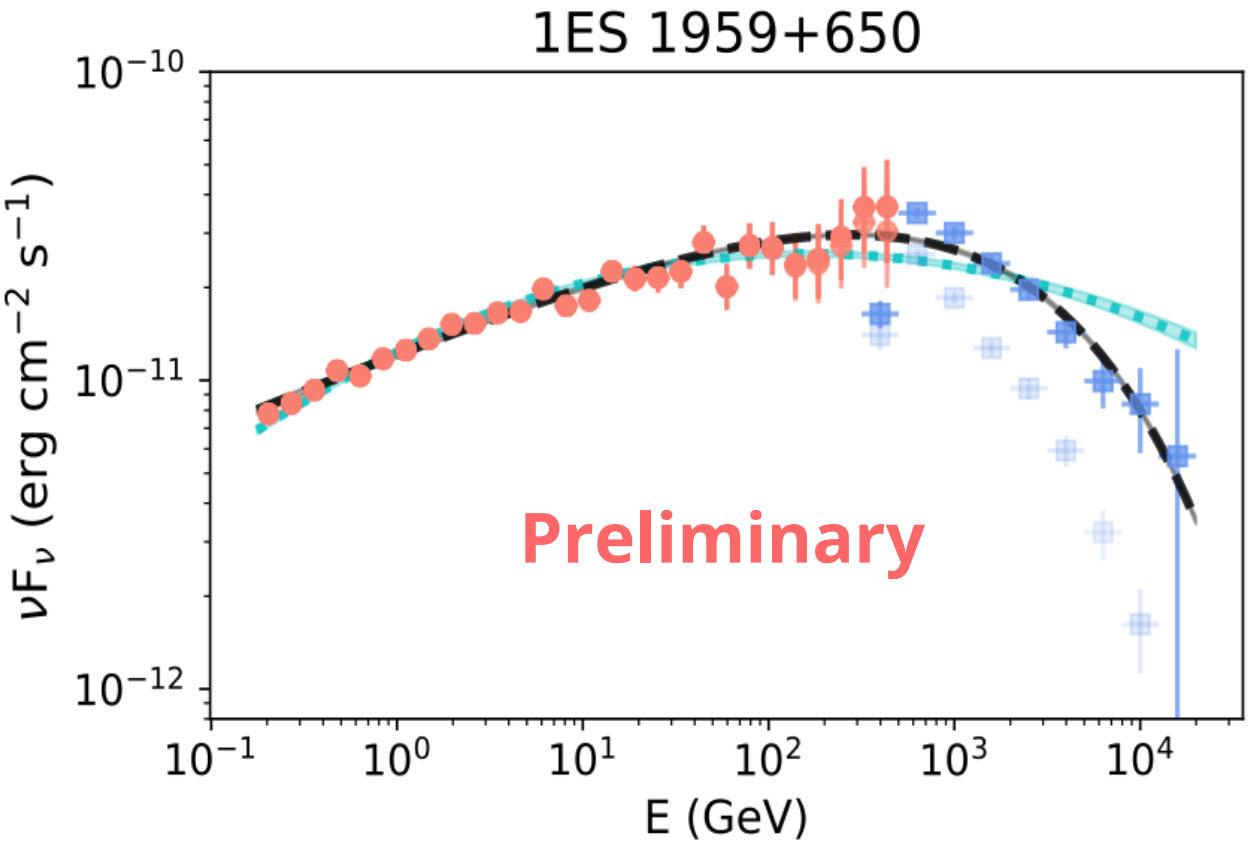
Preliminary Time-Averaged Spectra

- Sub-exponential cutoffs visible for all sources
- No significant preference for log parabola versus stretched exponential for 1ES 1011+496, 1ES 1218+304, 1ES 2344+514

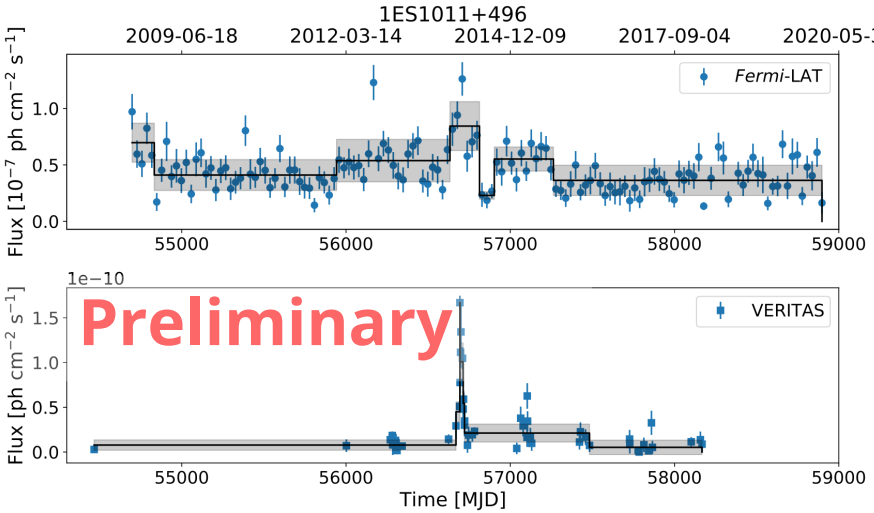


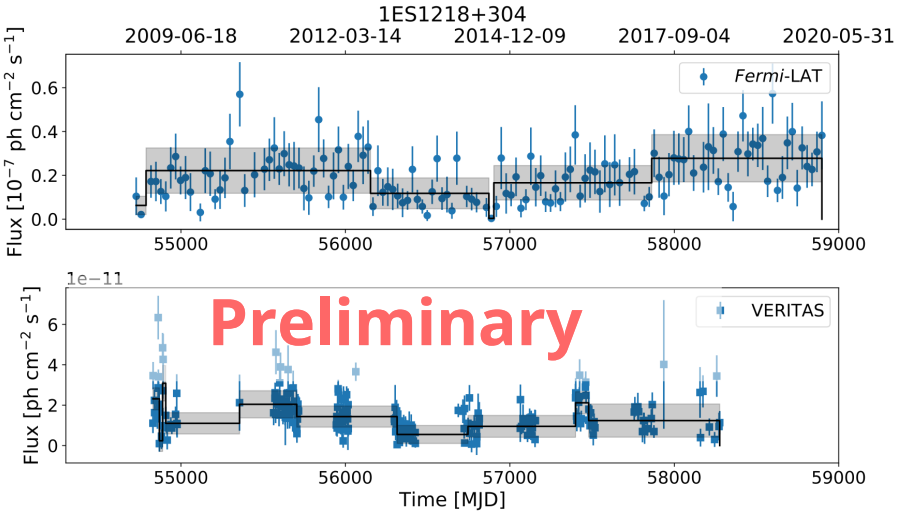
Preliminary Time-Averaged Spectrum

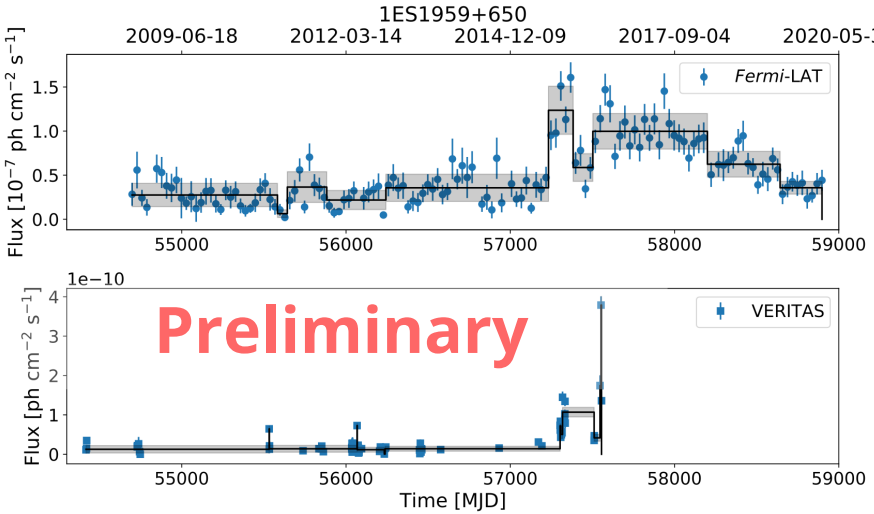
- Sharpest cutoff in 1ES 1959+650
- Stretched exponential cutoff model favored
- $\beta\gamma \sim 0.44 \rightarrow \beta e \sim 3.1$ for Synchrotron Self-Compton

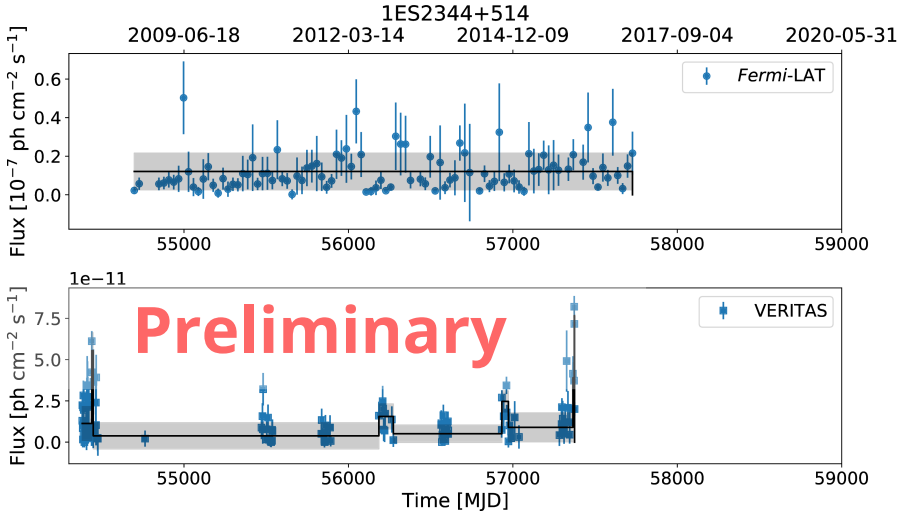


Light Curves and Bayesian Blocks

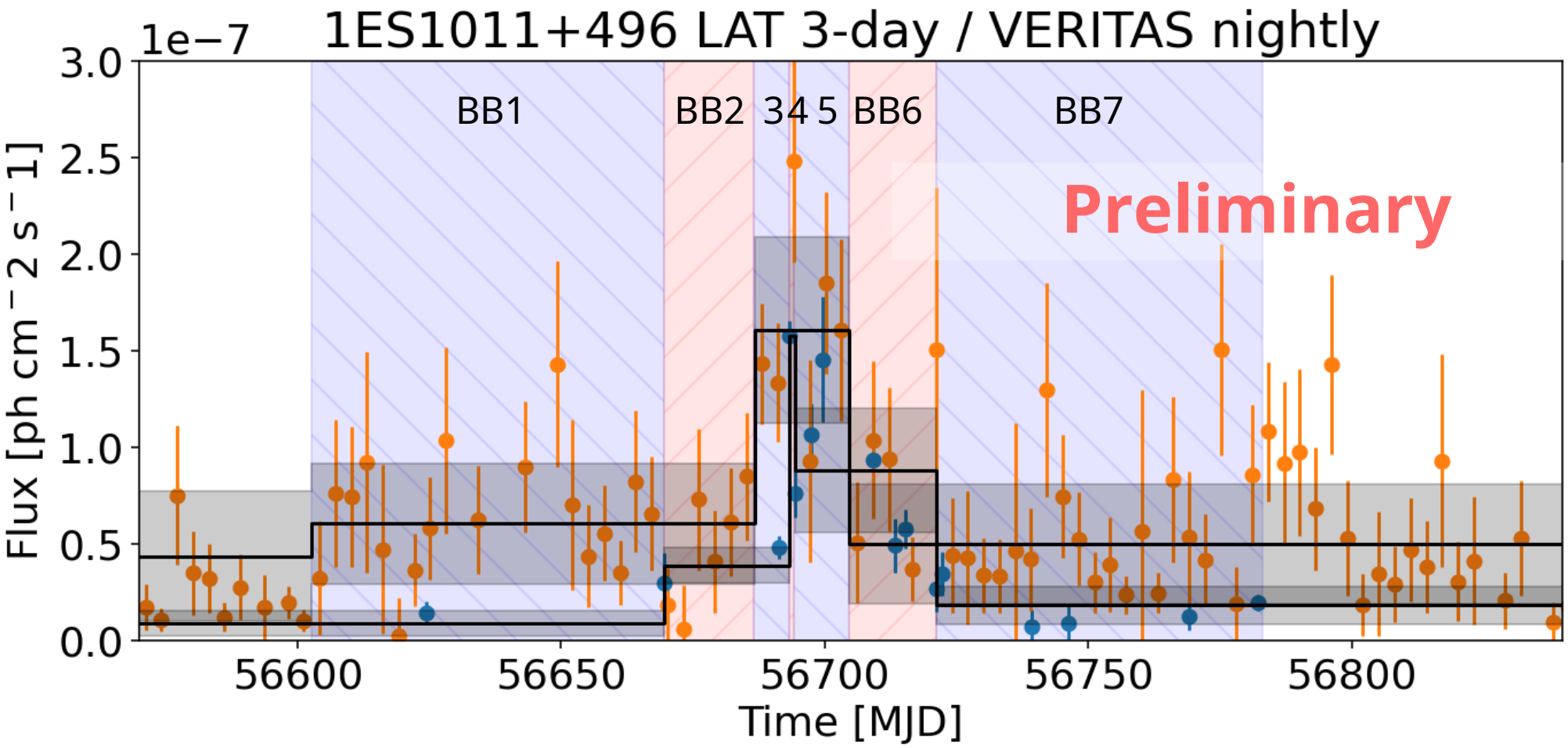






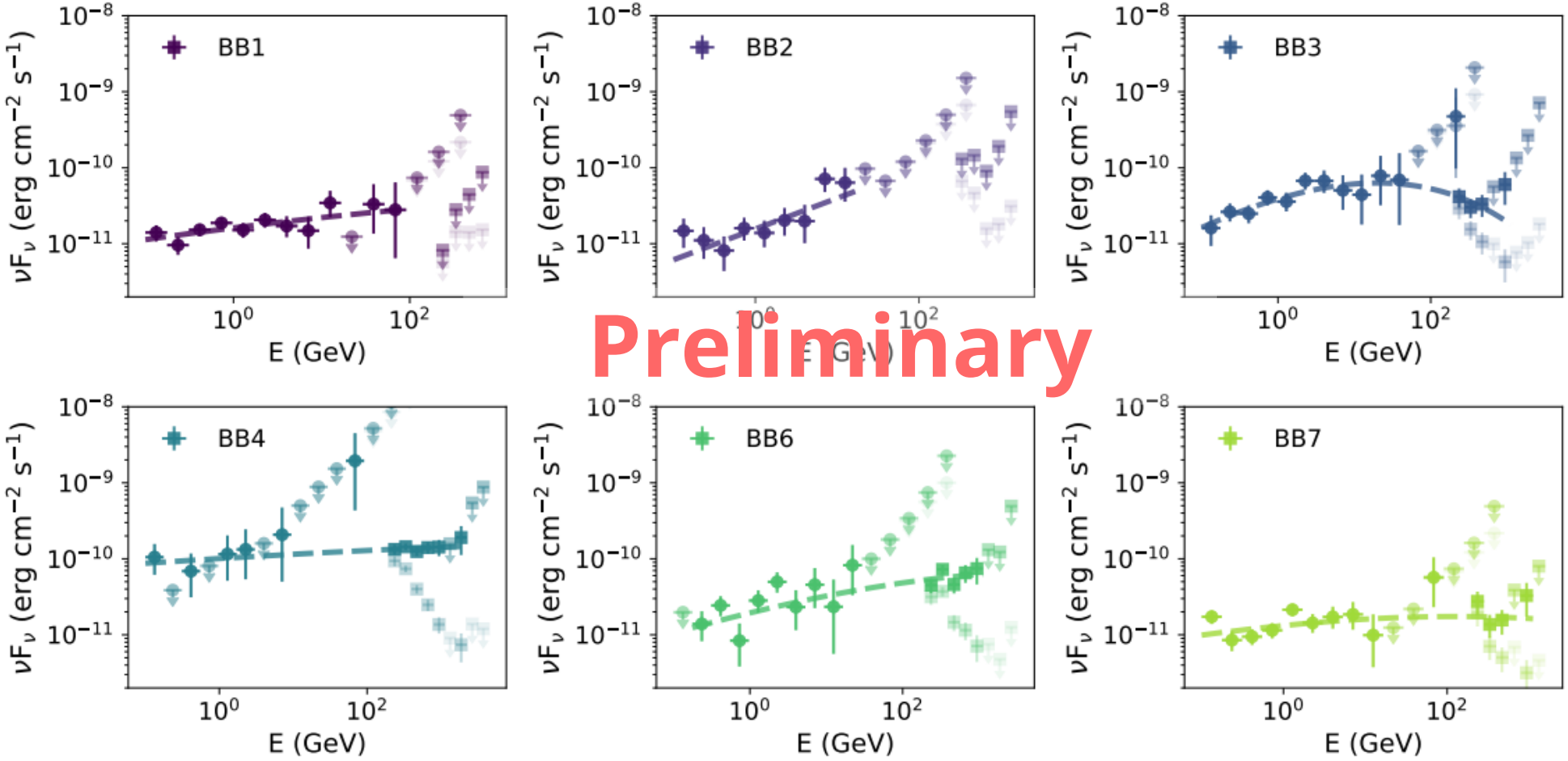


Defining Time Intervals of Constant Flux



Time-Binned Spectral Fits – 1ES1011+496

- Statistically limited for 1ES 1011+496
- Unable to constrain cutoff
- Many sources and blocks still to look at



Summary & Outlook

- Gamma-ray spectral curvature →
  – Particle population, emitting environment, γ-ray propagation
- To constrain spectral curvature:
  - Joint GeV/TeV data sets
  - Addressing variability → joint Bayesian Blocks
- More data being analyzed: 17 TeV blazars
- Spectral variability for the population
  - “Harder-when-brighter” trends
  - Exceptionally hard spectral indices
- CTA will provide better characterization of TeV spectra of blazars