



Extended Blazar Observations by VERITAS and Implications for the Extragalactic Background Light

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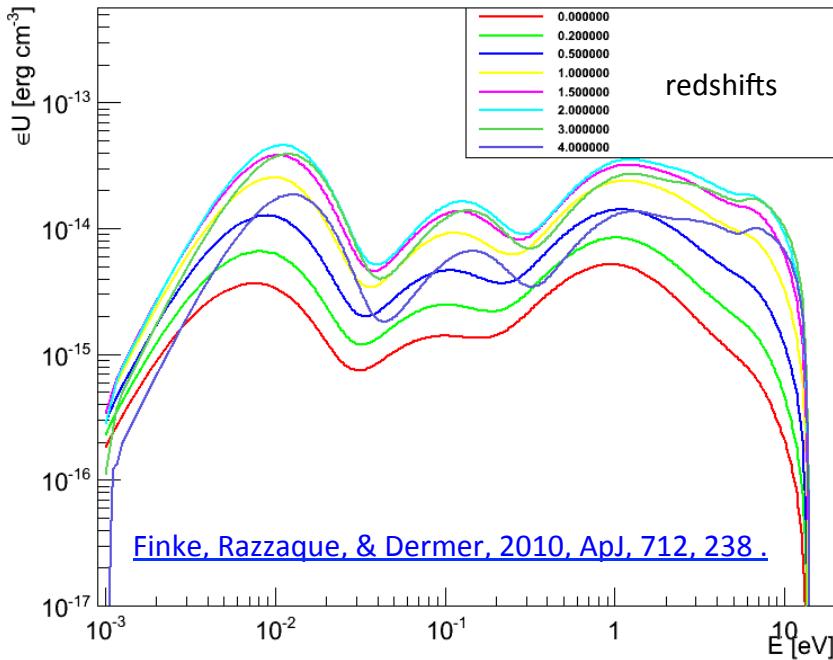
BLAZAR LONG-TERM PLAN

- Deep exposure on 15 blazars
- Good weather, 5-25 hrs/yr
- Simultaneous MWL observations on some sources
- Suitable for studies of EBL/IGMF
- Flares, variability, ToOs
- Studies of IBL/LBLs
- High redshift blazars
- Discovery and ToO on other blazars

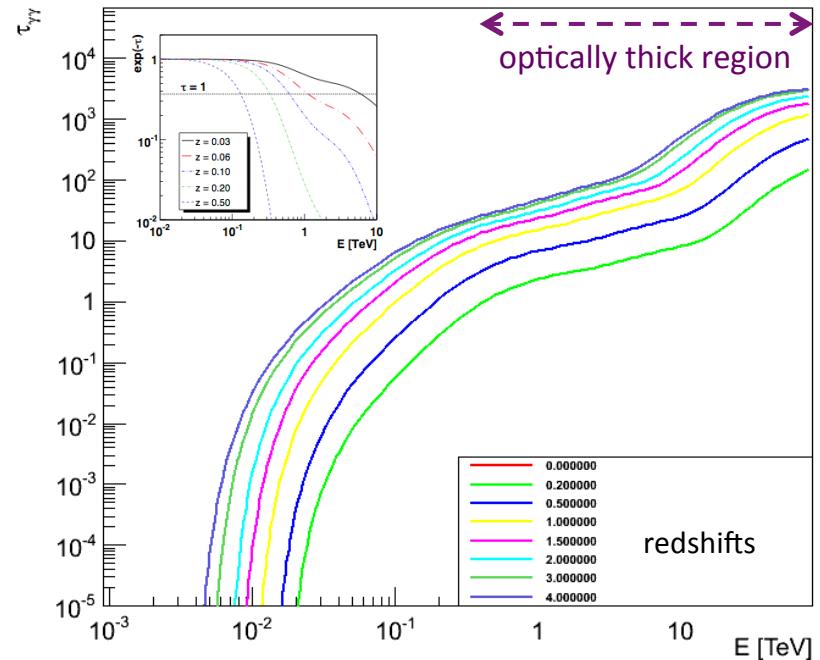
| Blazars | Total exposure [hrs] Good weather (before life-time correction) | |
|---|---|----------------|
| | As of May 2014 | Projected 2017 |
| 1ES 0229+200 | 91 | 171 |
| 1ES 0414+009 | 85 | 127 |
| RGB J0710+591 | 85 | 191 |
| 1ES 1218+304 | 110 | 221 |
| PKS 1424+240 | 138 | 238 |
| H 1426+428 | 50 | 136 |
| PG 1553+113 | 119 | 144 |
| Mrk 421 | 163* | 229 |
| Mrk 501 | 65* | 111 |
| 1ES 1959+650 | 18 | 44 |
| 1ES 2344+514 | 41 | 67 |
| 3C 66A | 68* | 98 |
| W Comae | 102* | 148 |
| S5 0716+714 | 35* | 75 |
| BL Lac | 45* | 75 |
| results are presented for highlighted sources | | |
| * as of January 2014 | | |

EXTRAGALACTIC BACKGROUND LIGHT

Energy density vs Energy



Optical Depth vs Energy



Optical depth depends γ -ray energy, redshift of the source

$$\tau_{\gamma\gamma}(E_\gamma, z) = \int_0^z dz' \frac{d\ell}{dz'} \int_{-1}^1 d\mu \frac{1-\mu}{2} \int_{\epsilon'_{th}}^{\infty} d\epsilon n_\epsilon(\epsilon, z') (1+z')^3 \sigma_{\gamma\gamma}(\beta', z')$$

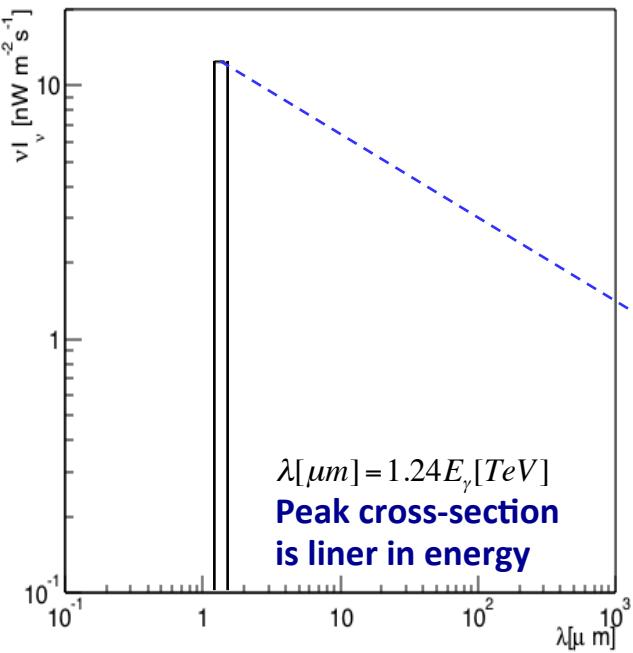
Cosmological distances Angle of interaction EBL density Cross-section

$\mu = \cos \theta$

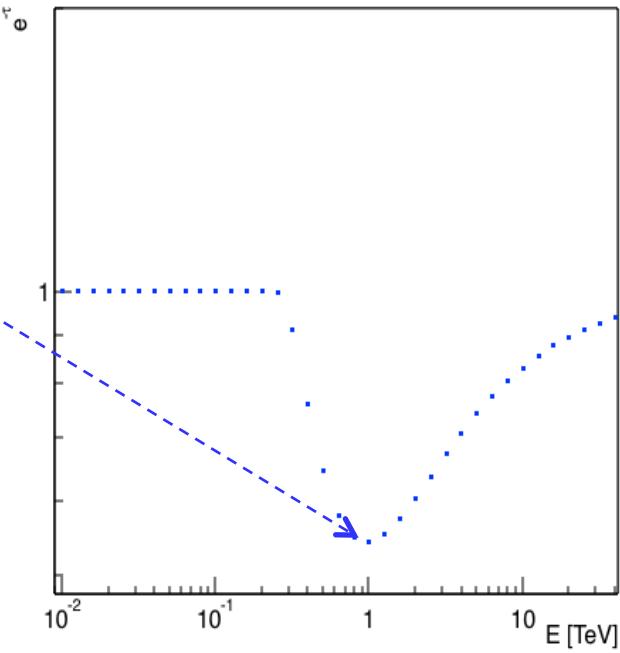
Cosmological model is important, normally used Λ CMD

EBL IMPLICATIONS

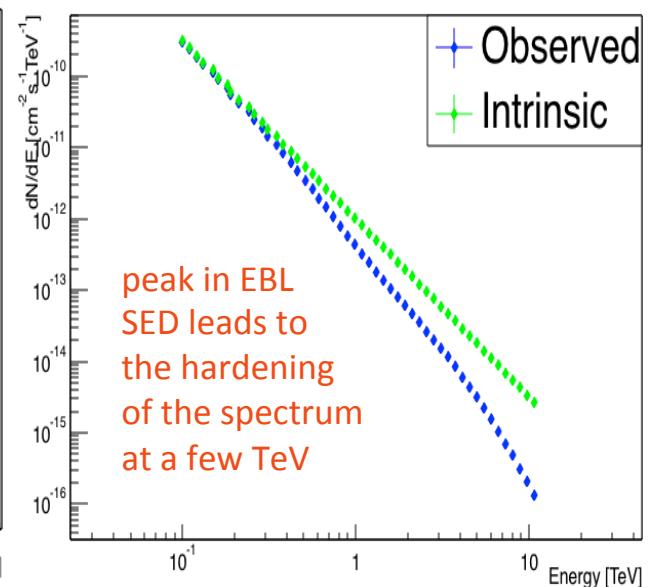
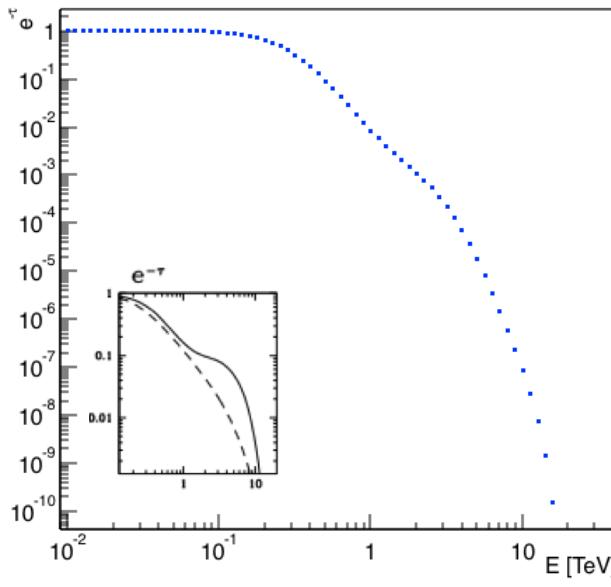
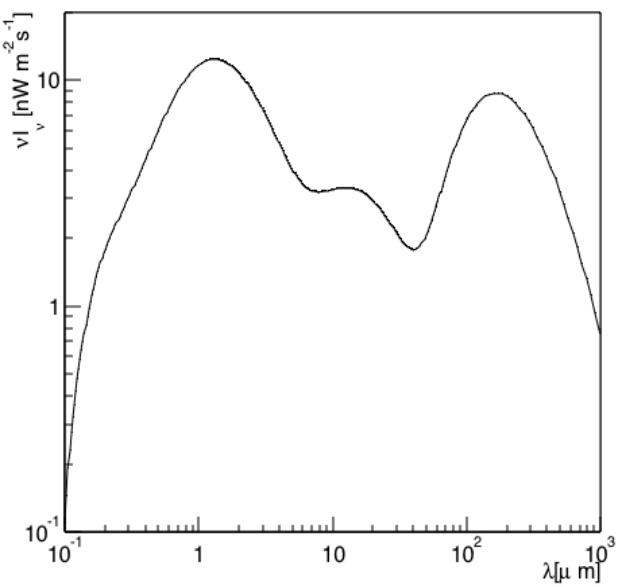
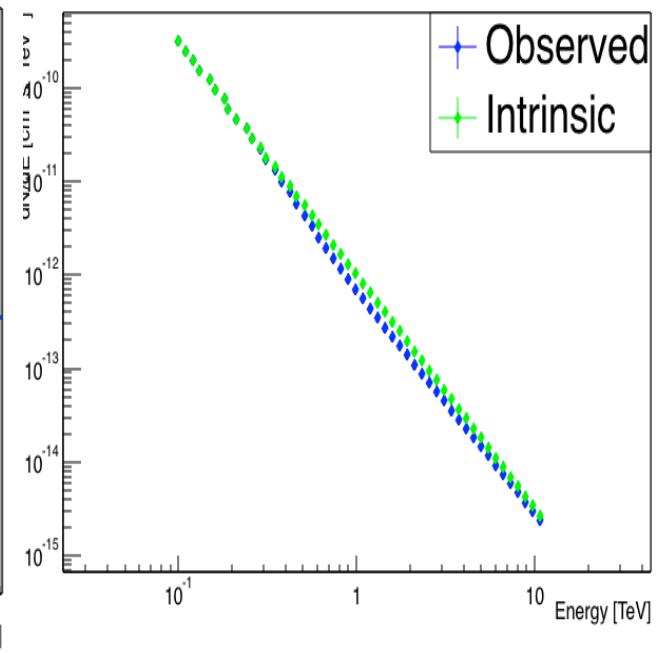
EBL intensity vs λ



Absorption vs Energy

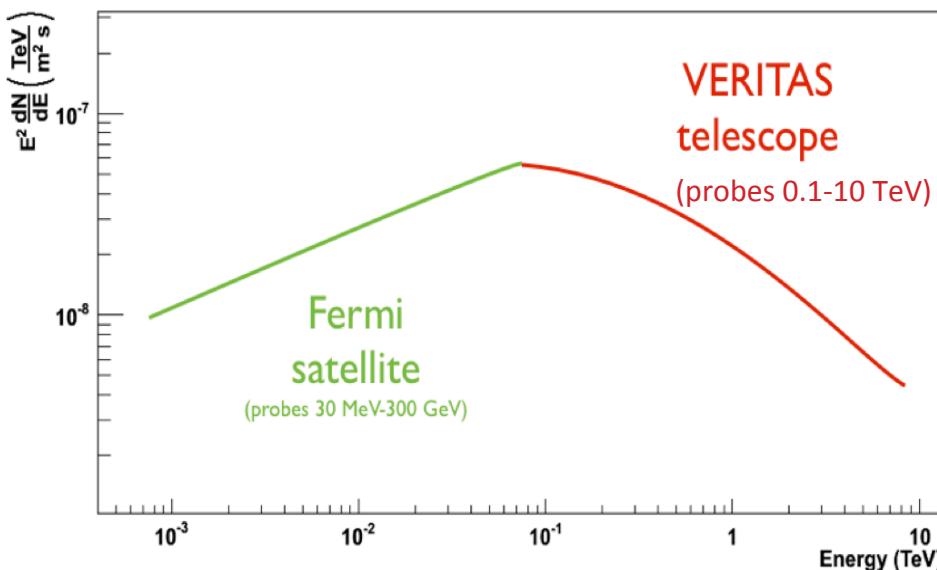
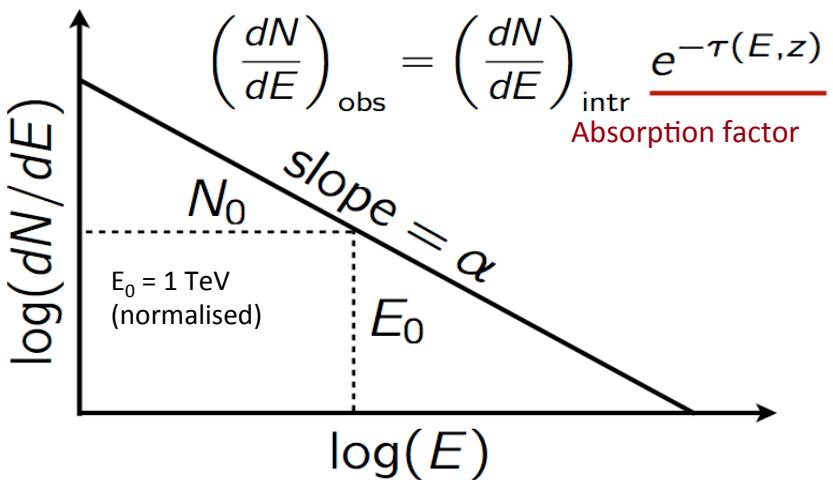


Spectrum



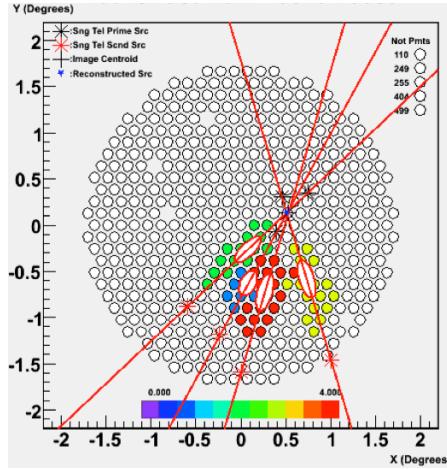
METHODS

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\alpha} \frac{\text{photons}}{\text{area} \times \text{time} \times \text{energy}}$$

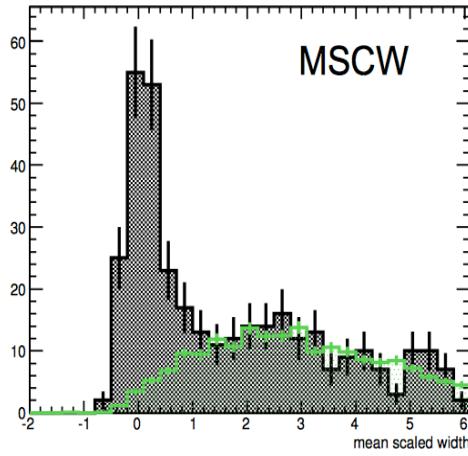


- Assume the same emission for the HE & VHE radiation
- Extrapolate Fermi-LAT into VHE
- “local” sources work best
- More stringent constraints than the steepness limit of $\Gamma = 1.5$
- Constrain EBL using 2FGL & EBL model
- Fermi spectrum of every source will be obtained
- Straightforward GeV-TeV extrapolations are in general not reliable and should be considered with caution

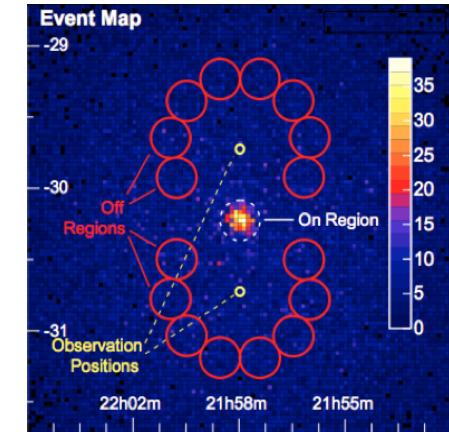
DATA ANALYSIS



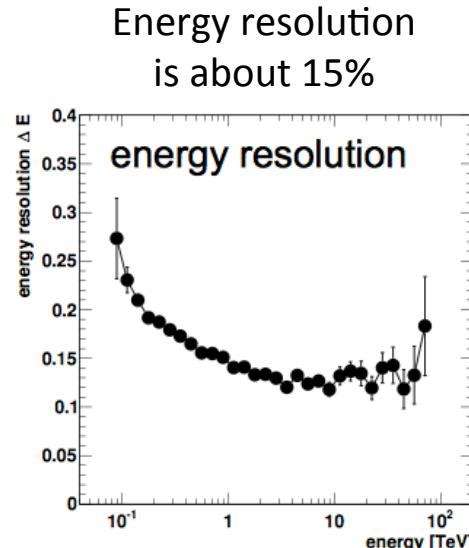
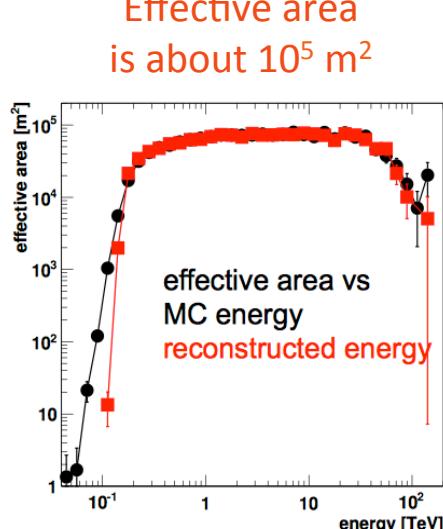
Clean noise from Cherenkov signal



Separate VHE photons from cosmic rays

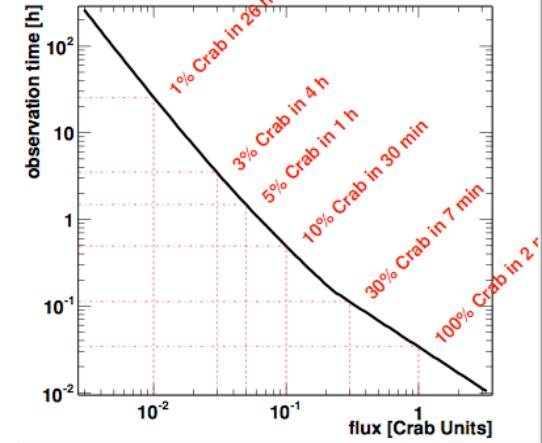


Estimate background on the source position



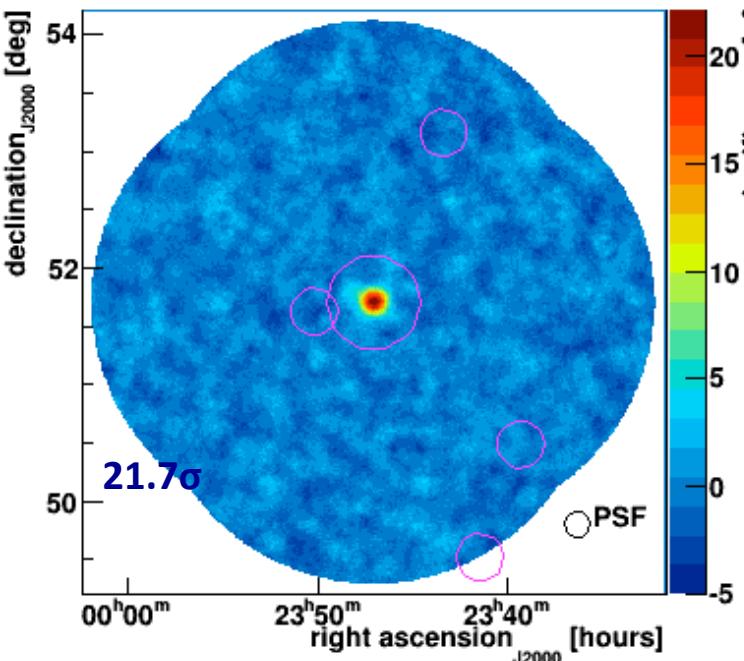
Energy resolution is about 15%

Improved sensitivity with new PMTs in 2012



$z=0.044$

example: 1ES 2344+514

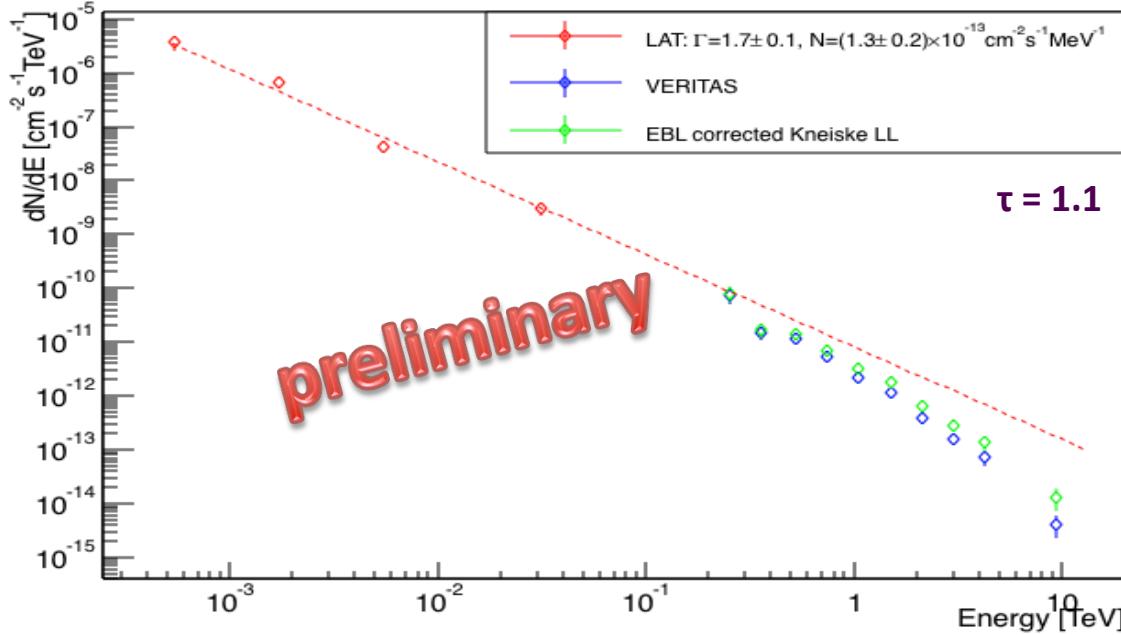
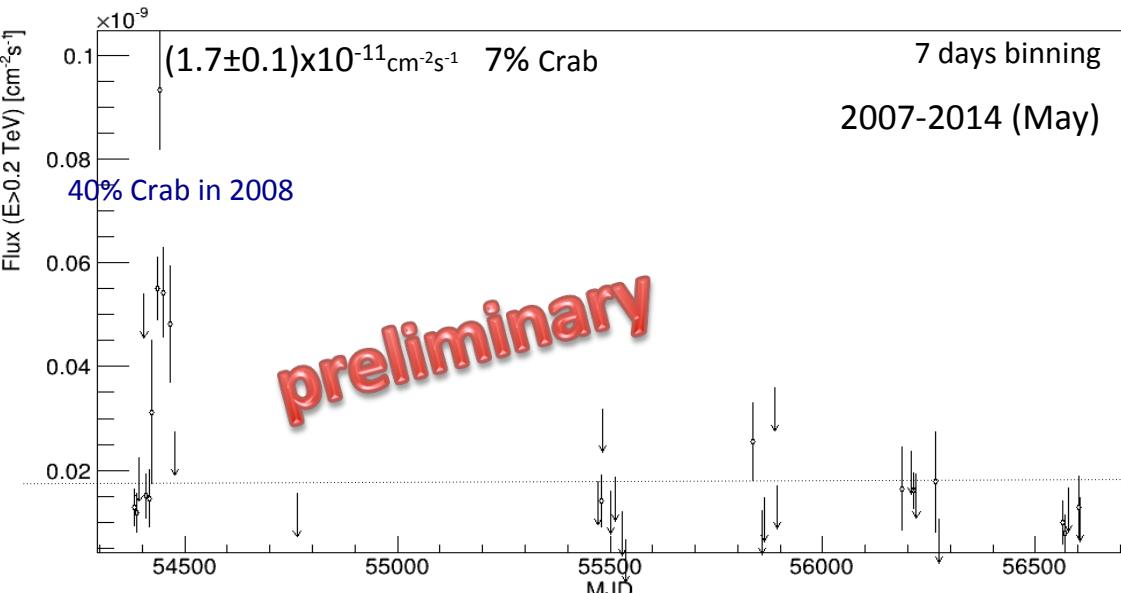


Exposure: 41 hrs

Observed VHE spectral fit: [$\text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$]

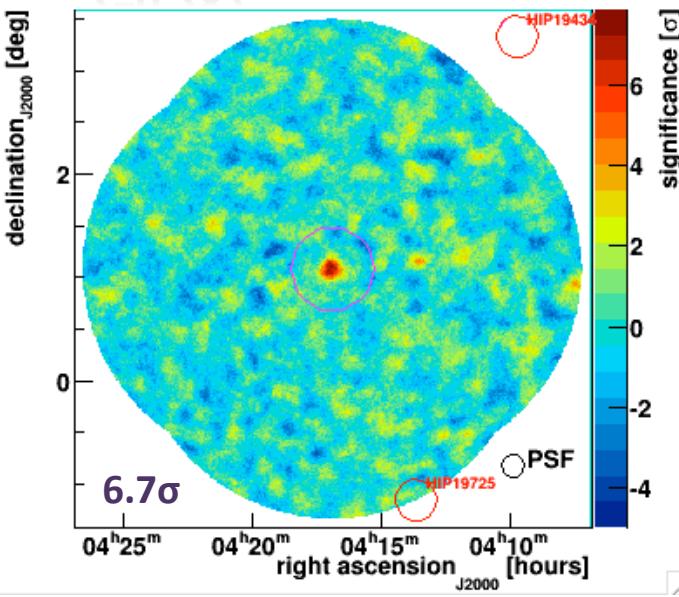
$$\frac{dN}{dE} = (3.4 \pm 0.4) \times 10^{-12} \left(\frac{E}{1\text{TeV}} \right)^{-2.0 \pm 0.2} e^{-\frac{E}{3.9 \pm 1.3}}$$

χ^2/dof : 8.2/7 (1.2)



$z=0.287$

example: 1ES 0414+079

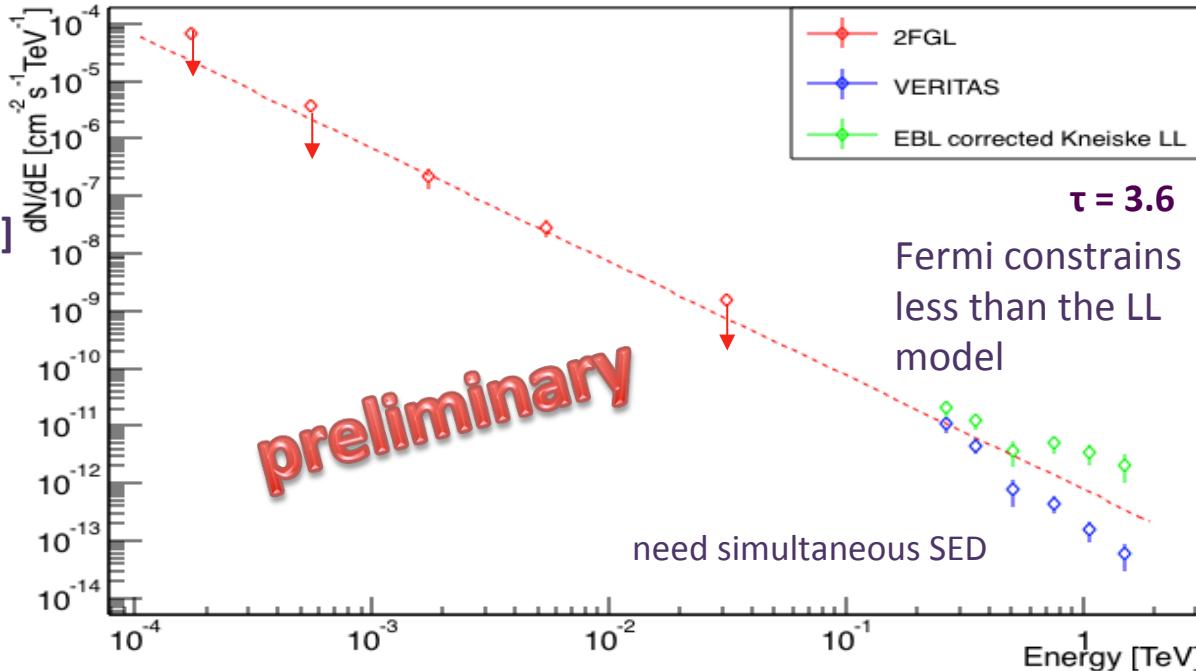
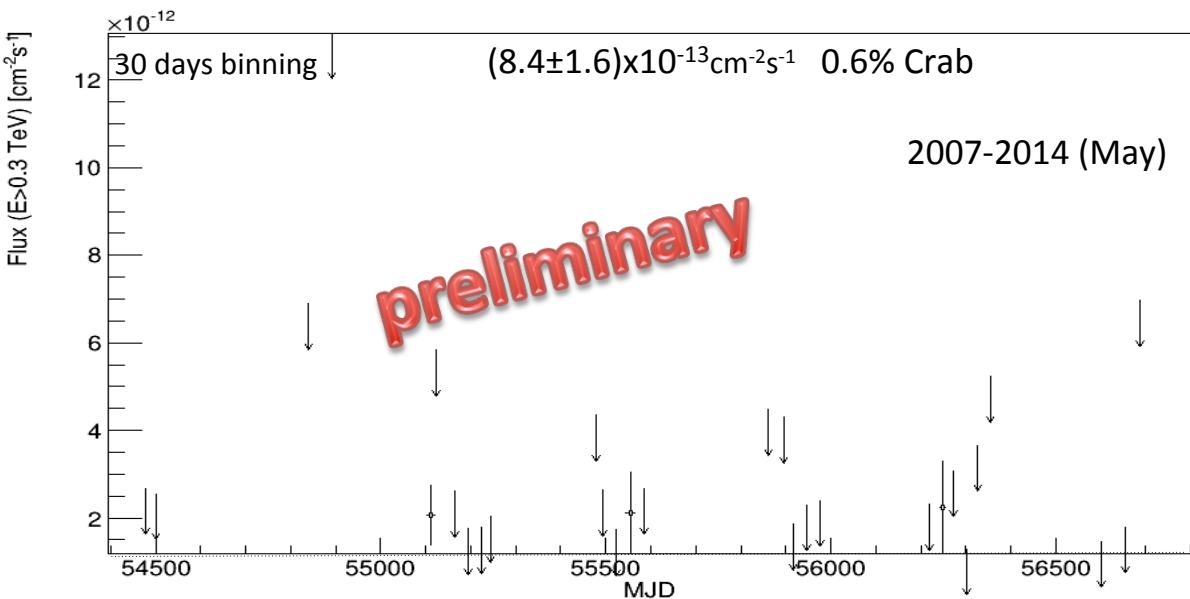


Exposure: 85.4 hrs

Observed VHE spectral fit: [$\text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$]

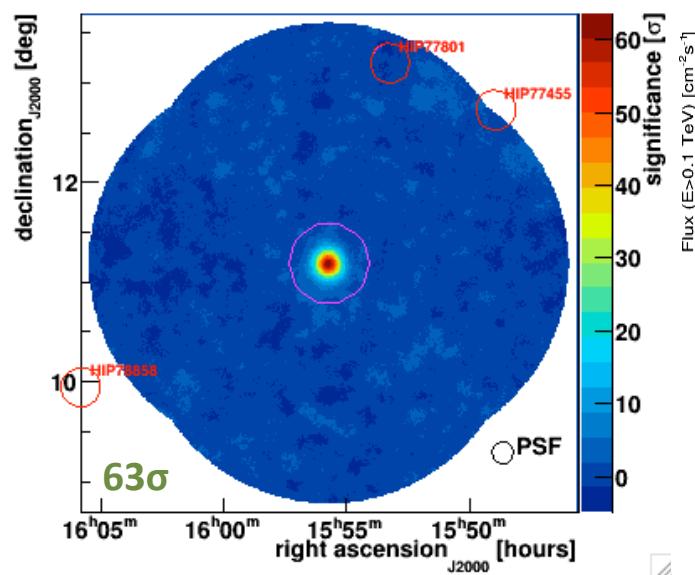
$$\frac{dN}{dE} = (1.6 \pm 0.4) \times 10^{-13} \left(\frac{E}{1\text{TeV}} \right)^{-3.0 \pm 0.3}$$

$\chi^2/\text{dof}: 3.32/4 (0.83)$



$z=0.395-0.62$

example: PG 1553+113

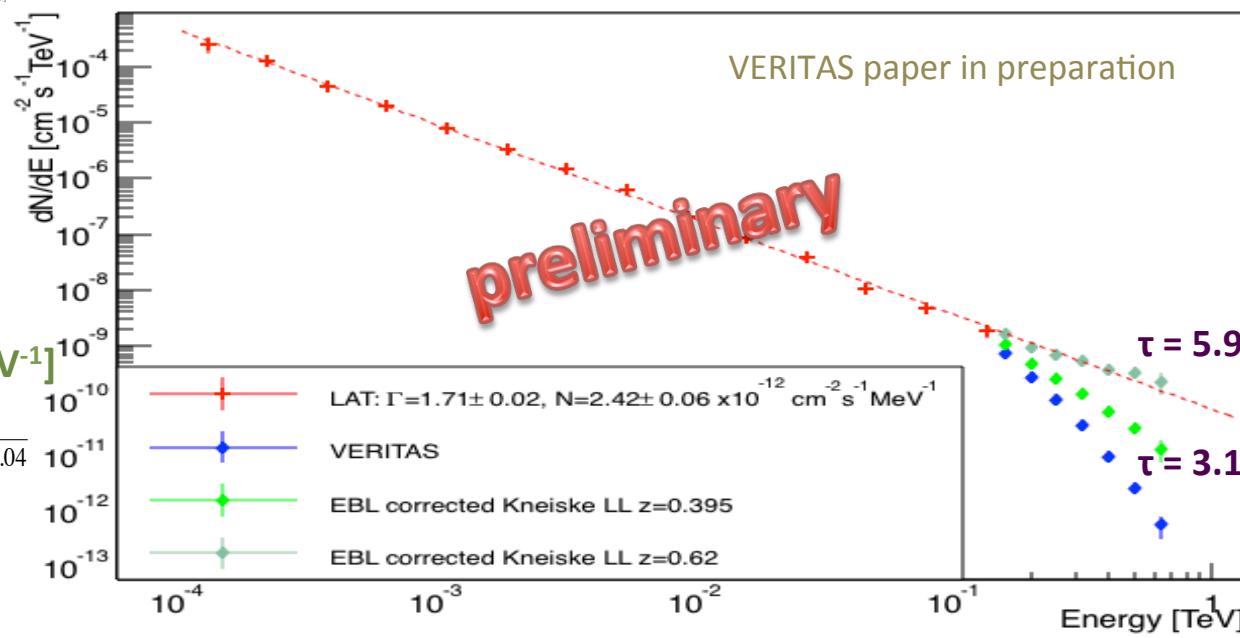
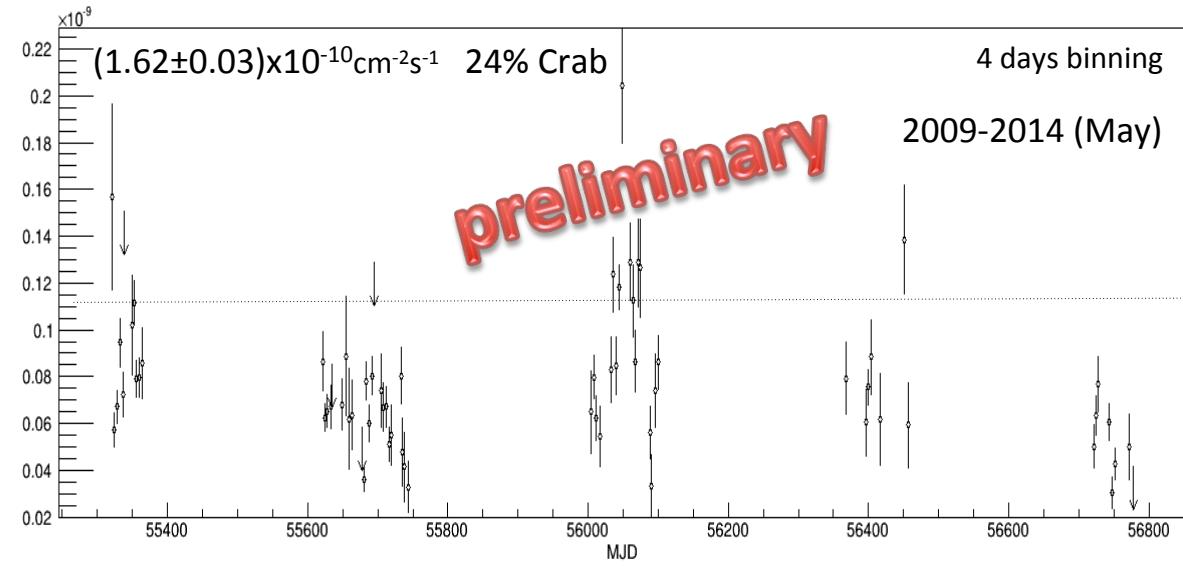


Exposure: 119 hrs

Observed VHE spectral fit: $[\text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}]$

$$\frac{dN}{dE} = (6.6 \pm 6.1) \times 10^{-12} \left(\frac{E}{1\text{TeV}} \right)^{-3.0 \pm 0.4} e^{-\frac{E}{0.17 \pm 0.04}}$$

$\chi^2/\text{dof}: 3.62/4 (0.9)$



SUMMARY OF SOURCES

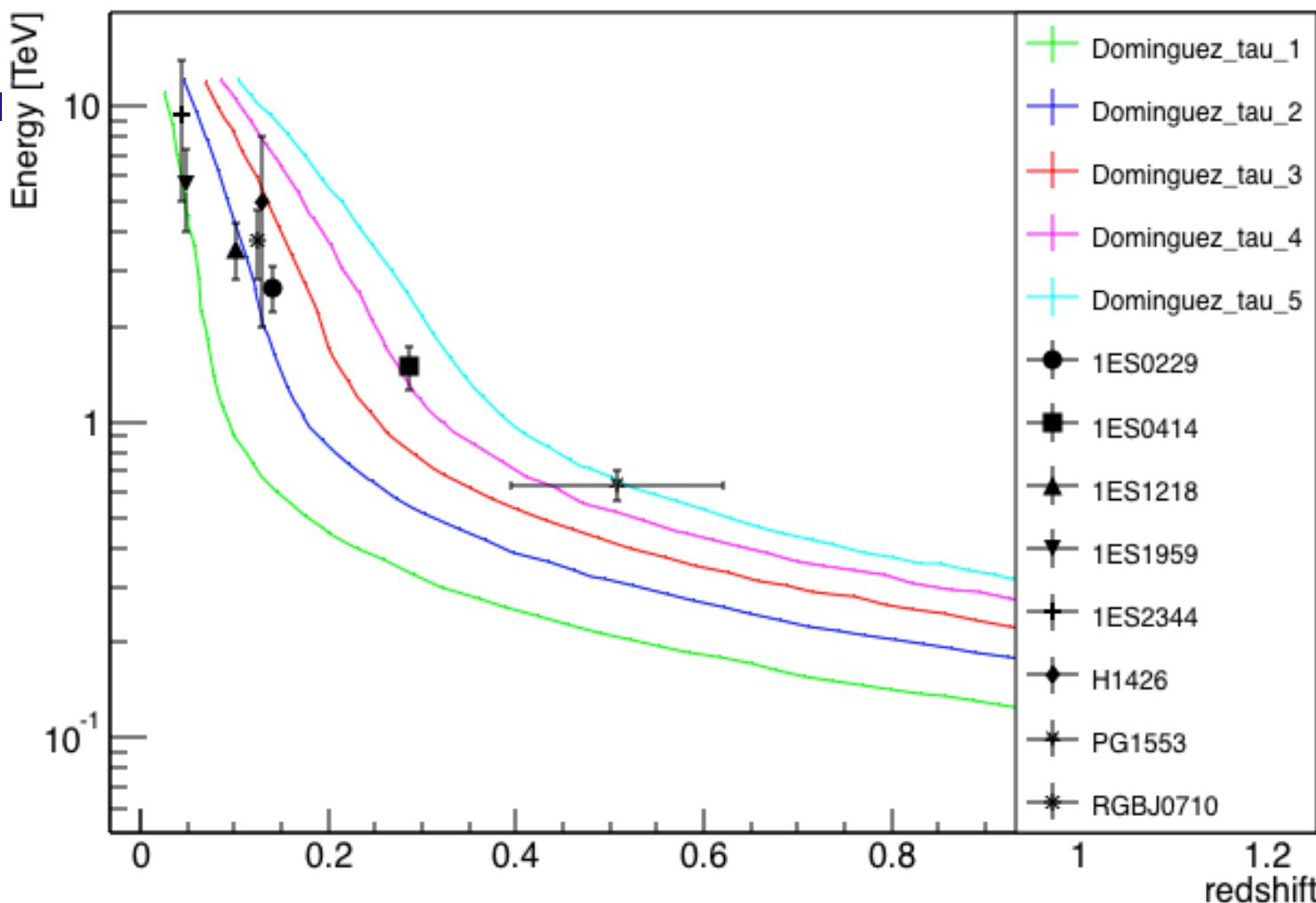
| SOURCE | REDSHIFT | EXPOSURE | DETECTION | CRAB FLUX | MAX τ PROBED |
|---------------|------------|----------|---------------|---------------|-------------------|
| 1ES 2344+514 | 0.044 | 41 hr | 21.7 σ | 7% >0.2 TEV | 1.1 |
| 1ES 1959+650 | 0.048 | 19 hr | 25.7 σ | 17% >0.3 TEV | 0.9 |
| 1ES 1218+304 | 0.102 | 110 hr | 44.4 σ | 9% >0.1 TEV | 1.5 |
| RGB J0710+591 | 0.125 | 85 hr | 9.3 σ | 2% >0.3 TEV | 1.9 |
| H 1426+428 | 0.129 | 50 hr | 11.5 σ | 2% >0.2 TEV | 2.3 |
| 1ES 0229+200 | 0.14 | 91 hr | 11.8 σ | 1.7% >0.2 TEV | 2 |
| 1ES 0414+009 | 0.287 | 85 hr | 6.7 σ | 0.6% >0.3 TEV | 3.6 |
| PG 1553+113 | 0.395-0.62 | 119 hr | 63 σ | 24% >0.1 TEV | 3.1-5.9 |

GAMMA-RAY HORIZON

The gamma-ray horizon calculated from the EBL model described in Dominguez et al. (2011) are given as curves with corresponding opacity.

Sources are given with a black points.

PG 1553+113 has a range of possible redshifts represented with a black line.

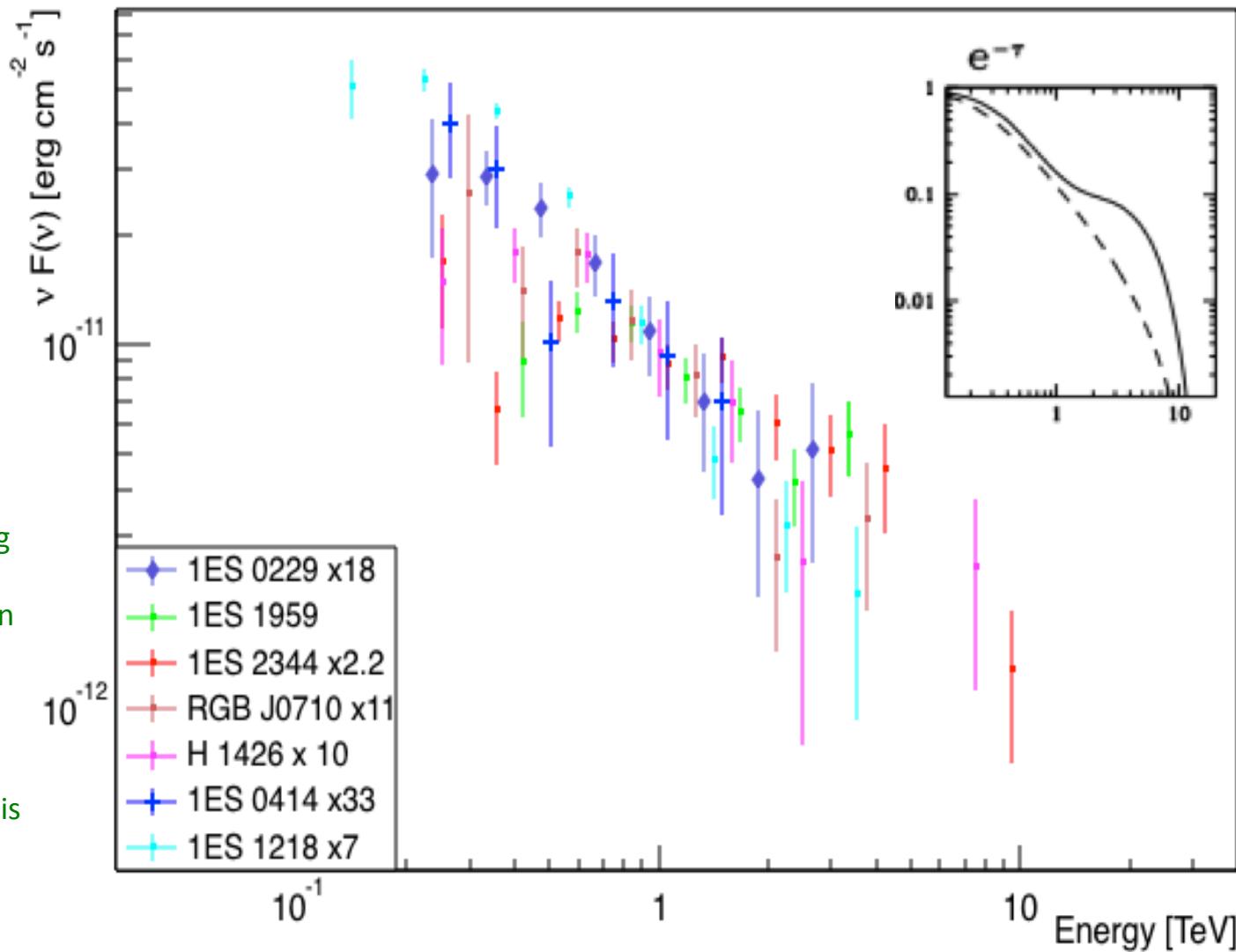


COMBINED SPECTRA

With a sufficient number of blazars and photon statistics, it becomes feasible to try to measure the collective imprint of the EBL on the VHE spectra.

Fluxes are rescaled to match 1ES1959+650 around 1 TeV. The data points above 1 TeV lie above the extrapolation from lower energies, showing the flattening feature expected from $\gamma\text{-}\gamma$ absorption with an EBL spectrum.

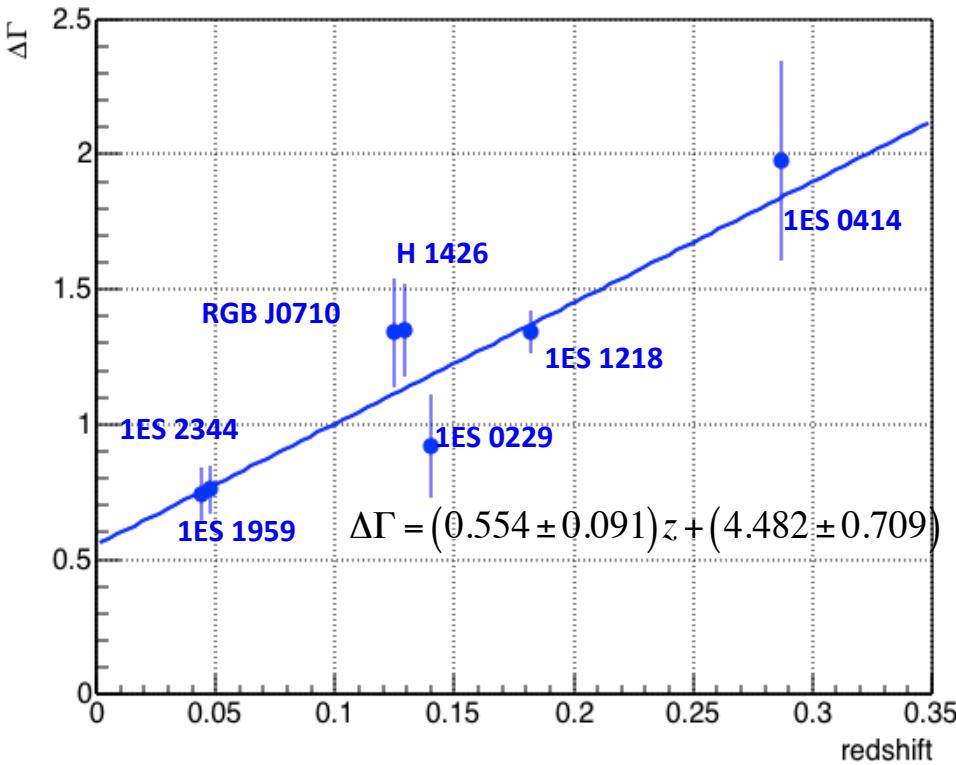
PG 1553+113 spectrum does not reach 1 TeV, therefore it is excluded



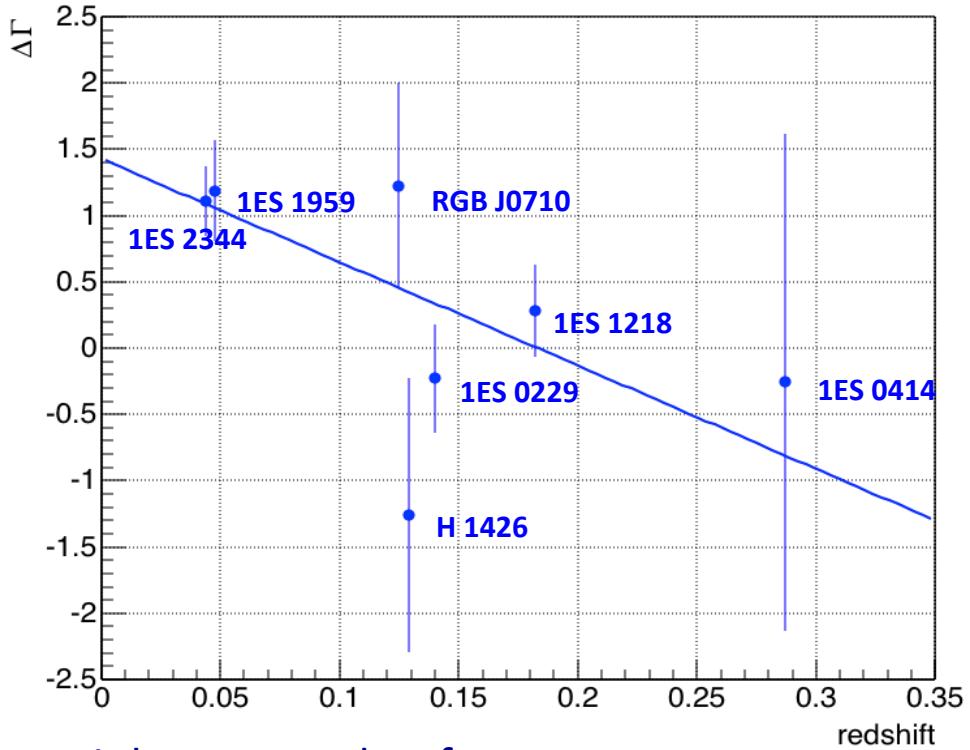
SPECTRAL BREAK

- Empirical relation between Fermi-LAT and VERITAS spectra of the blazars
- Fit by a power law

GeV-TeV break



TeV break



Fit by a power law for $E_1 > 1 \text{ TeV} > E_2$ ranges

Measures the ratio of the $1.6\mu\text{m}$ peak to the $15\mu\text{m}$ trough

N.B. Cannot apply PG 1553+113, because its spectrum does not reach 1 TeV

PERSPECTIVES

- Obtain Fermi spectra of remaining sources
- Use constraints from Fermi-LAT and the steepness limit of -1.5
- Use empirical constraints from spectral breaks
- Obtain allowed ranges of EBL and divide into a grid
- Try a number of EBL shapes and numerically calculate the opacities
- Compare with data and exclude the shapes
- Leave the EBL intensities which survive and place the limits

CONCLUSIONS

- VERITAS' EBL effort is well on track (most up-to-date results on 8 blazars)
- Higher opacities have already been probed [$\tau \approx 5$]
- Indication of spectral hardening feature above a few TeV
- Empirical relation between Fermi-LAT & VERITAS and spectral break $> 1\text{TeV}$

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