Observations of Very-High-Energy Blazars as Extragalactic Probes

David A. Williams
for the
VERITAS Collaboration

daw@ucsc.edu

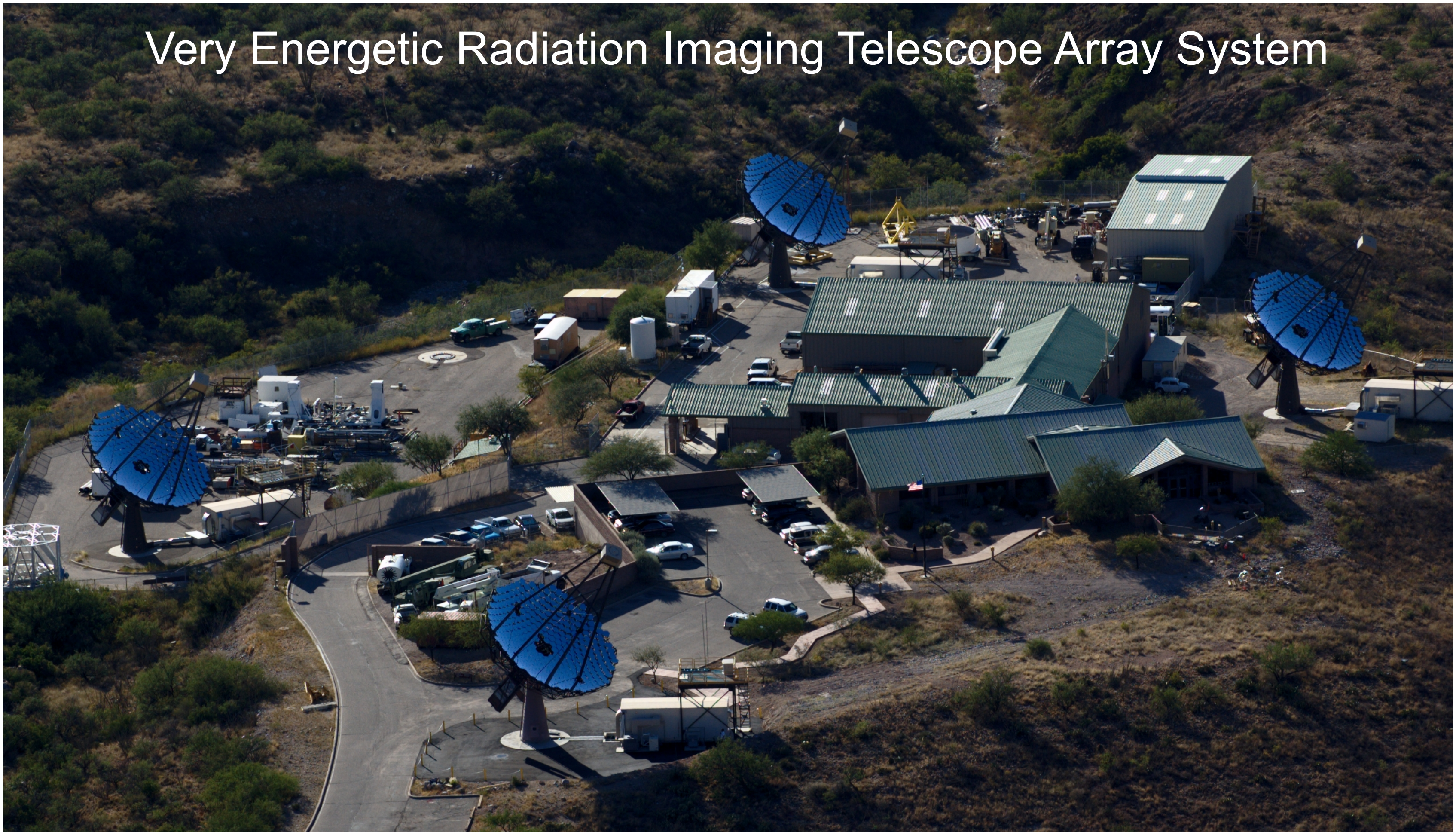
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz

September 16, 2014

Outline

- VERITAS and the imaging atmospheric Cherenkov technique
- Active galactic nuclei (AGN), especially blazars
- Absorption of γ-rays by the extragalactic background light (EBL)
- γ-rays from AGN as probes of the EBL
- Possible complications: secondaries from cascades or conversions between photons and axion-like particles (ALPs)
- Effects of intergalactic magnetic fields (IGMF)
- Tests of Lorentz invariance

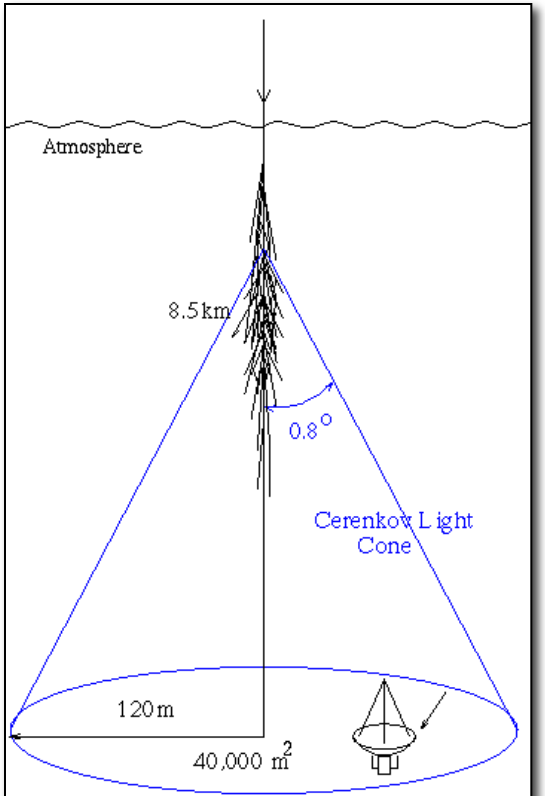
VERITAS: Imaging Atmospheric Cherenkov Telescope



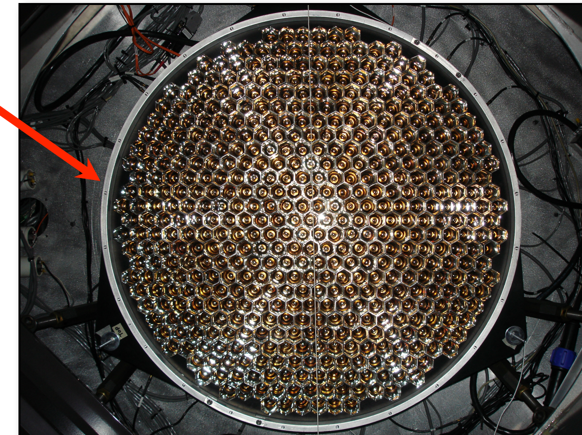
Whipple Observatory Basecamp (el. 1275 m) at foot of Mt. Hopkins

Atmospheric Imaging Technique

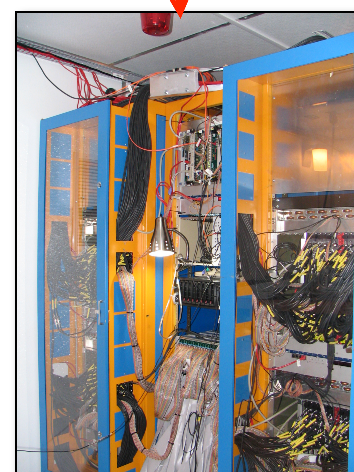
γ−ray



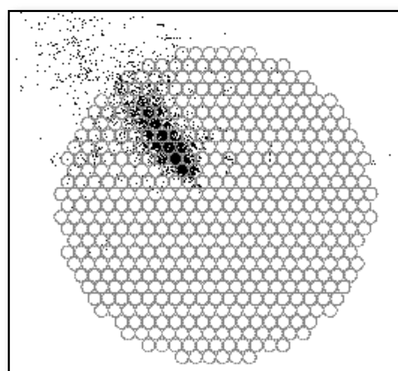
12 m Mirror



499-PMT camera



500-MHz FADC electronics



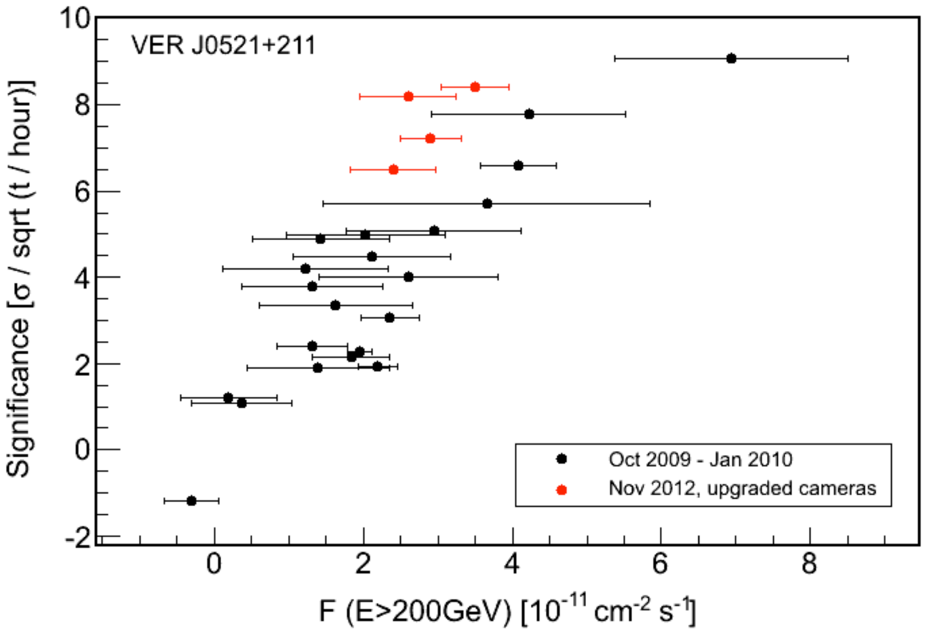
Cherenkov image

Area = $10^4 - 10^5$ m^2
~60 optical photons/m^2/TeV

γ-rays above ~100 GeV

VERITAS Performance

Upgrades 2009–2012:
We detect sources >2x faster



Significance normalized to observing time as a function of source flux

Similar fluxes give 30-50% higher significance since the upgrades

- 15% energy resolution >300 GeV
- 0.1° angular resolution, r_{68}
- Threshold
  - ✓ Trigger ~65 GeV
  - ✓ Spectral reconstruction ~100 GeV
- Systematic errors
  - ✓ Flux ~20%
  - ✓ Spectral index ~0.1
- Detect 1% Crab Nebula in <25 h

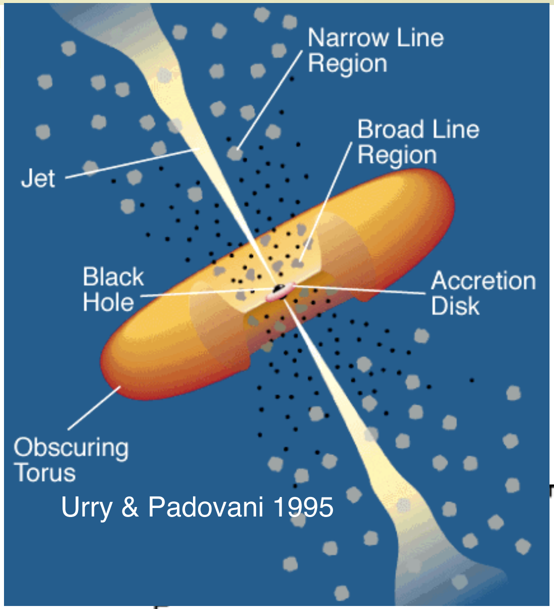
Active Galactic Nuclei

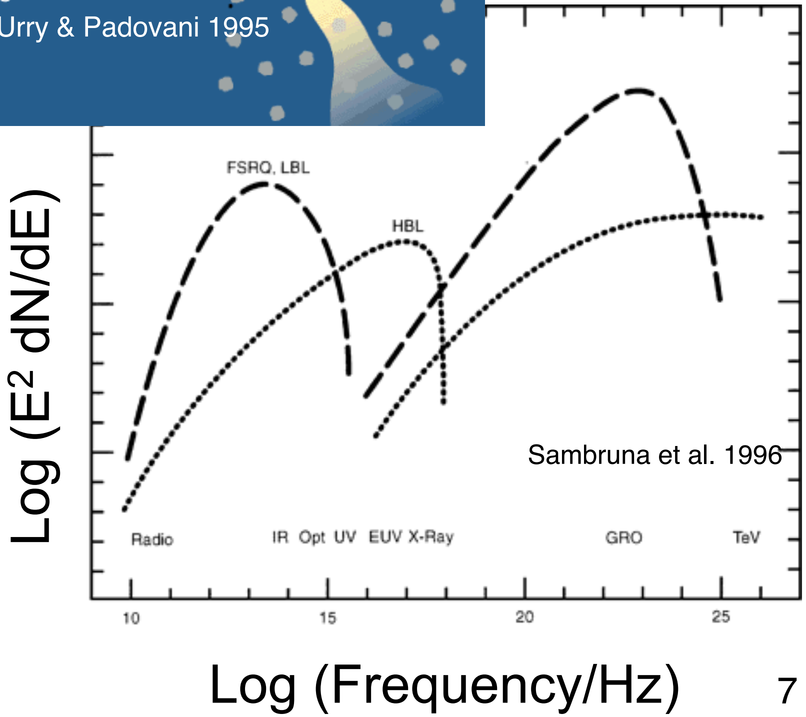
~55 VHE blazars; 3 radio galaxies
- ~80% HBL
- Other blazars "only" seen during flares

VHE spectra soft
- $dN/dE \sim E^{-\Gamma}$ where Γ >~ 3

Mostly z<0.25 (EBL horizon)
- Distant blazars harder than expected => low EBL
- 3C 279: z = 0.536
- PKS 1424+240: z > 0.60
- S3 0218+357: z = 0.944

Variability
- Time scales as short as ~2 minutes



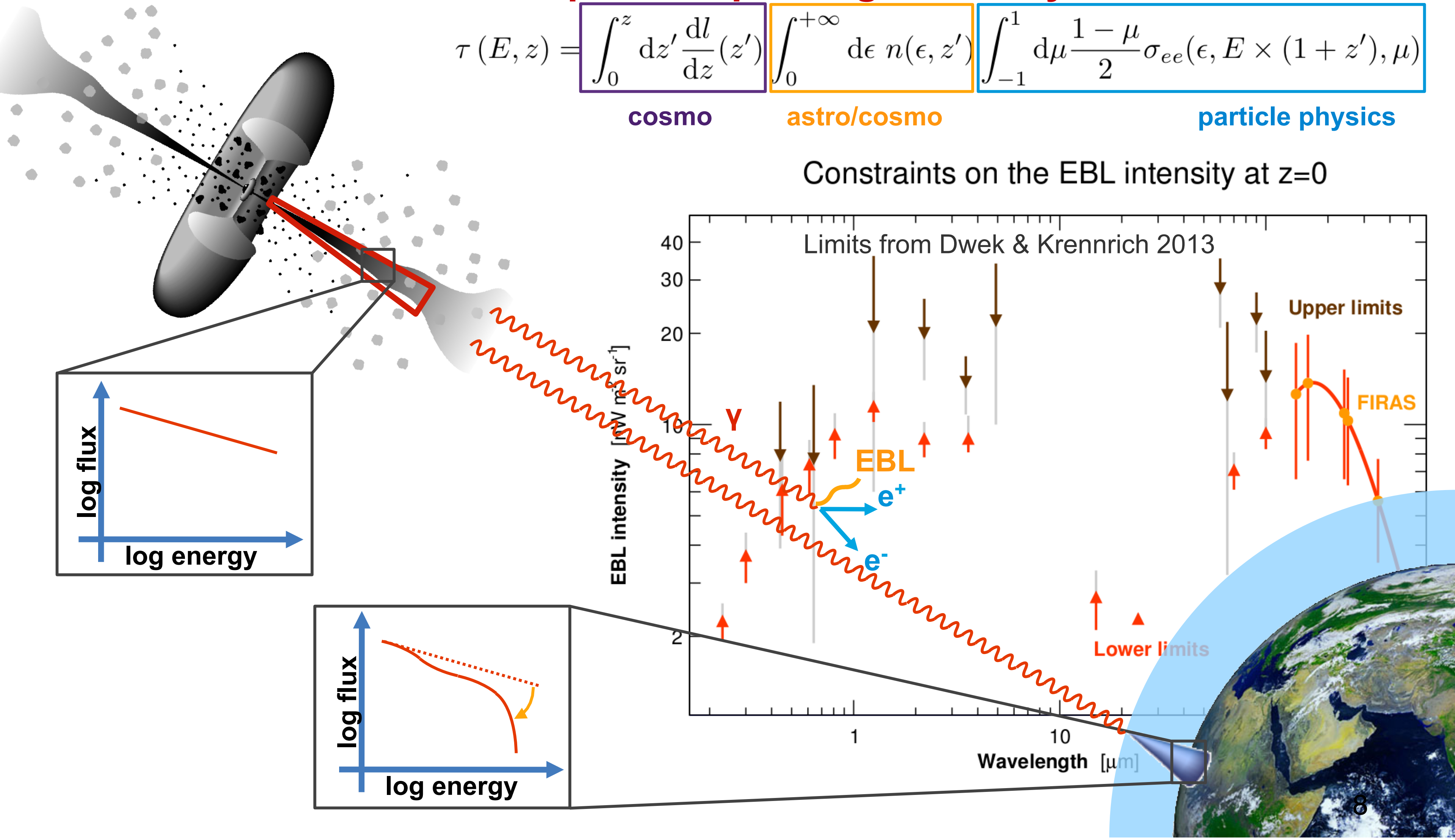


Probing the Extragalactic Background Light

EBL optical depth to gamma rays:

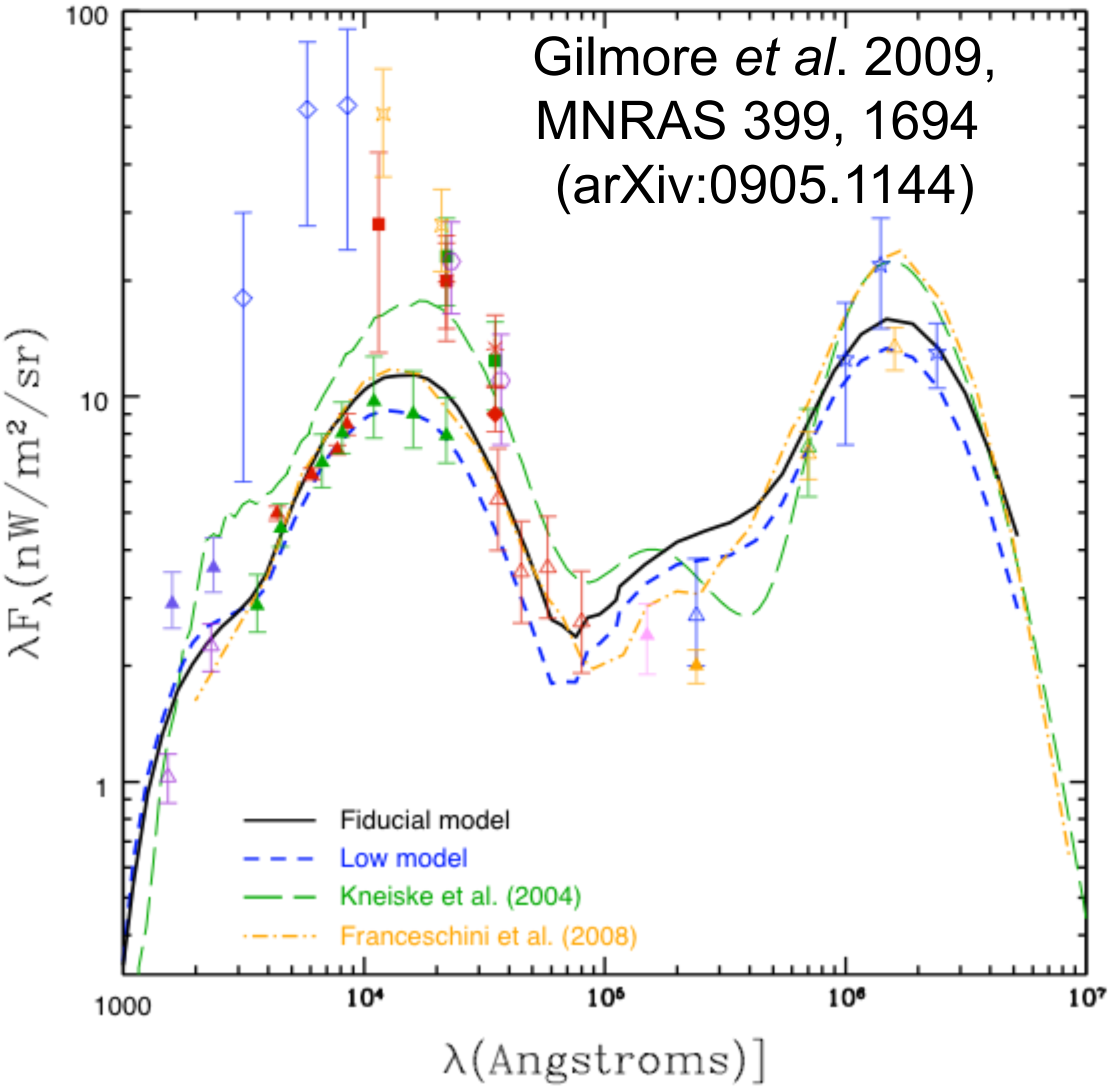
$$\tau(E,z) = \int_0^z dz' \frac{dl}{dz}(z') \int_0^{+\infty} d\epsilon \; n(\epsilon, z') \int_{-1}^{1} d\mu \frac{1-\mu}{2} \sigma_{ee}(\epsilon, E\times(1+z'), \mu)$$

cosmo | astro/cosmo | particle physics



Credit: Jonathan Biteau

Extragalactic Background Light



$\gamma_{\text{High Energy}} + \gamma_{\text{EBL}} \text{ –> } e^+ e^-$

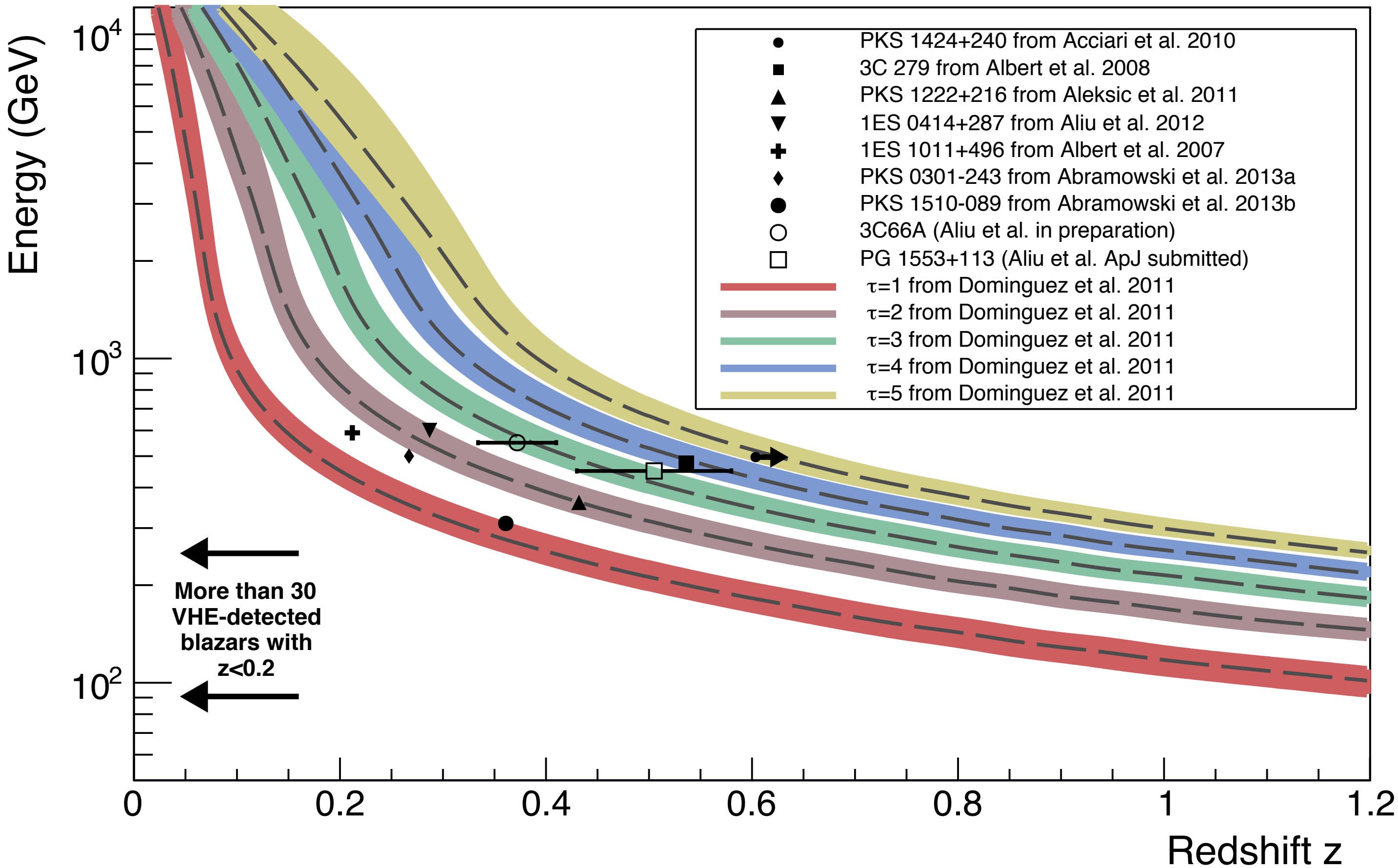
Difficult to measure EBL because of foreground sources

Test of cosmology

Attenuation by 1/e (*i.e.* $e^{-\tau}$ with $\tau = 1$) for
z ~ 1.2 at 100 GeV
z ~ 0.1 at 1 TeV

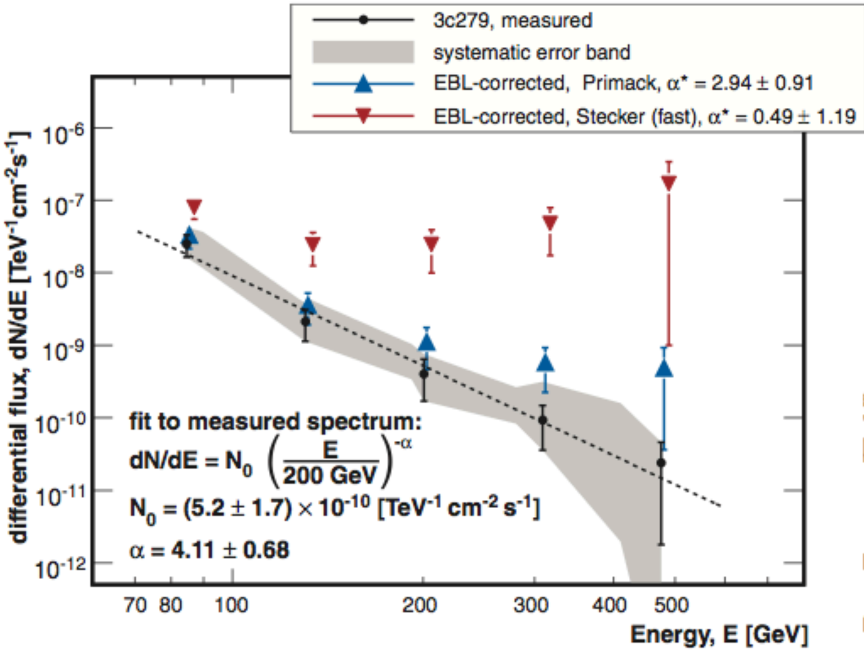
Recent modeling consistent with the published experimental results

The Gamma-Ray Horizon



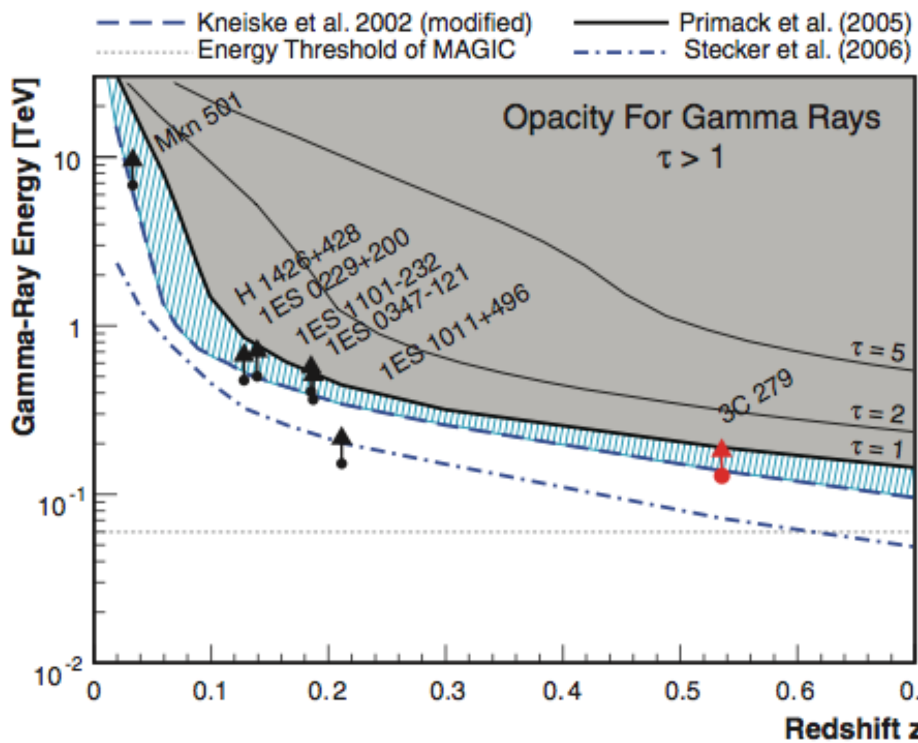
Attenuation from model of Dominguez et al. 2011

3C 279



Flat spectrum radio quasar (FSRQ) at redshift 0.536

Detected by MAGIC in a 2-day outburst in 2006

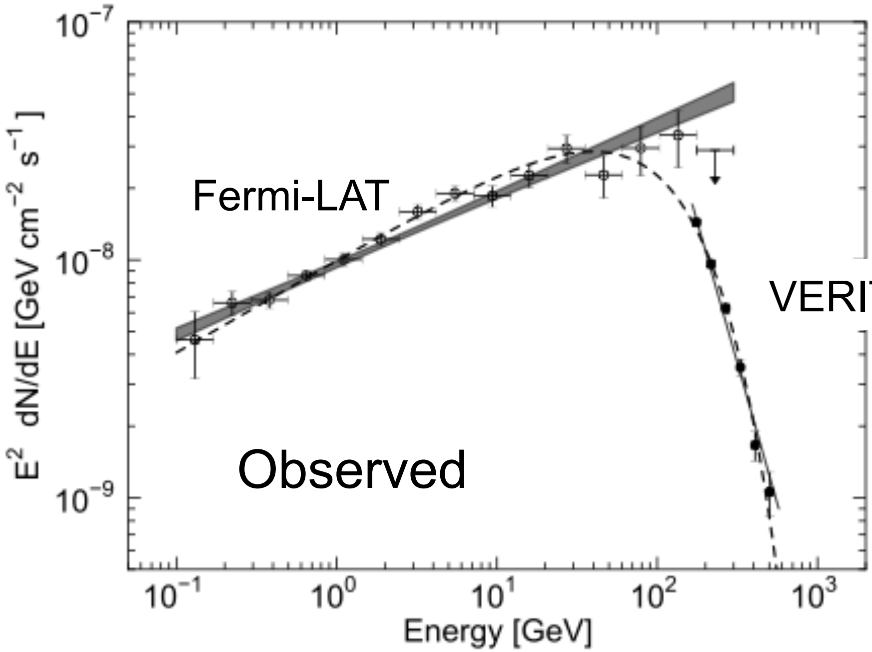


Place limits on EBL assuming intrinsic (i.e. deabsorbed) spectrum cannot be harder than

$dN/dE \sim E^{-1.5}$

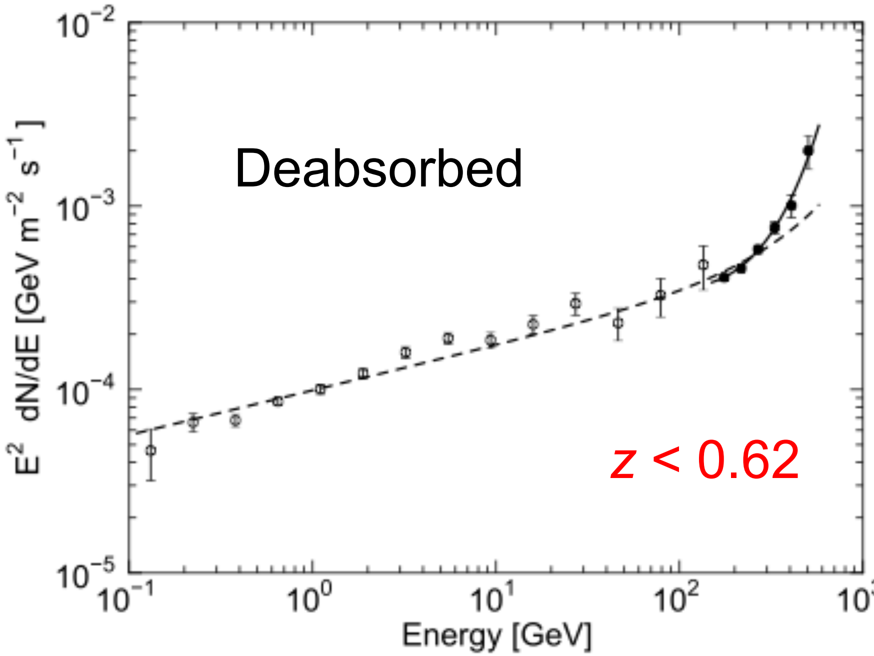
J. Albert et al. 2008 (MAGIC Collaboration), Science 320, 1752

PG 1553+113



High-frequency-peaked BL Lac (HBL) at $0.395 \leq z < \sim 0.58$

Data from May 2010 to June 2012



Place limits on EBL or z assuming intrinsic (i.e. deabsorbed) spectrum cannot have an exponential rise

E. Aliu et al. (VERITAS Collaboration) submitted to ApJ.

PKS 1424+240

High-frequency-peaked BL Lac (HBL) with $0.6035 \leq z$

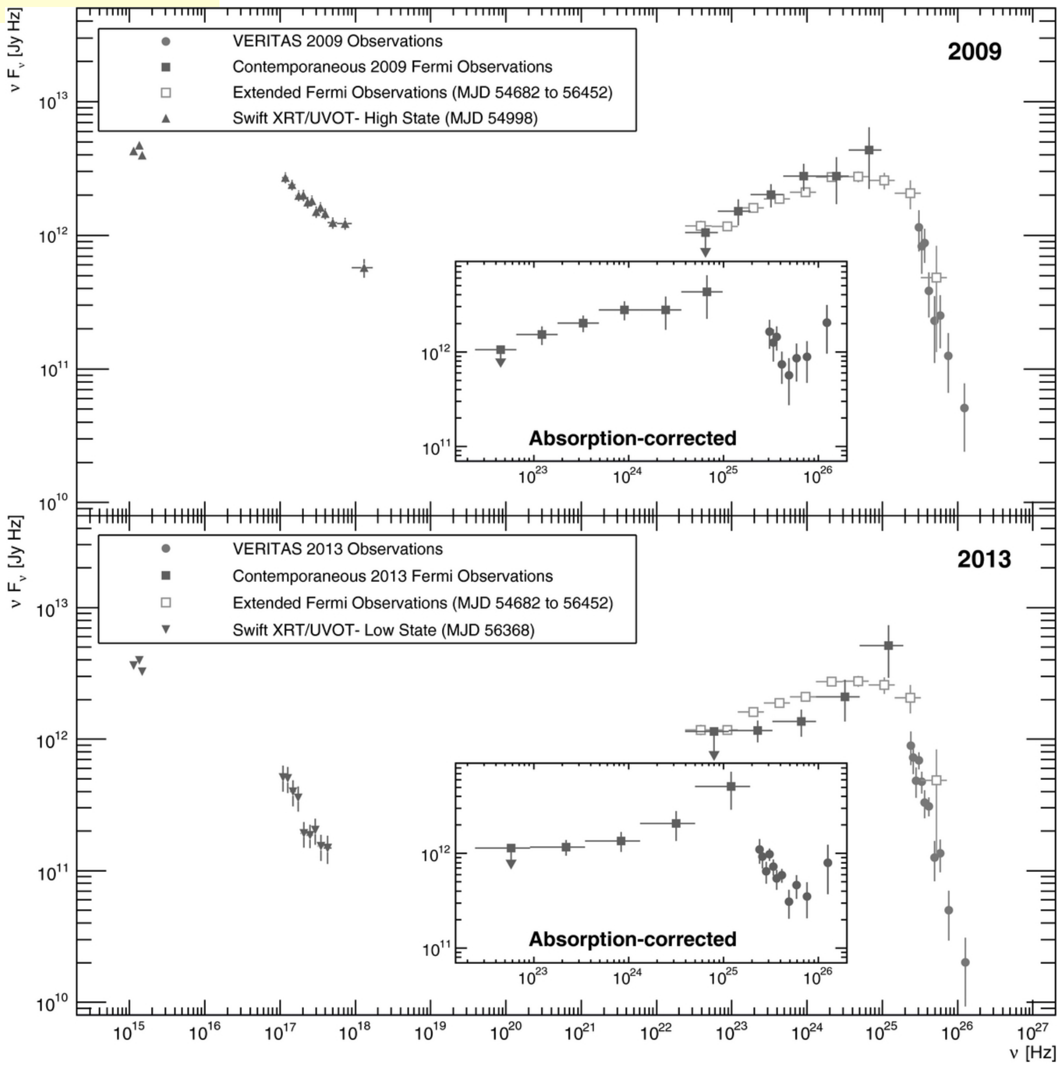
Data from spring 2009 and spring 2013

Flux is lower in 2013 by about a factor of 2

Both absorption corrected spectra show low-significance indication of hardening at high energy

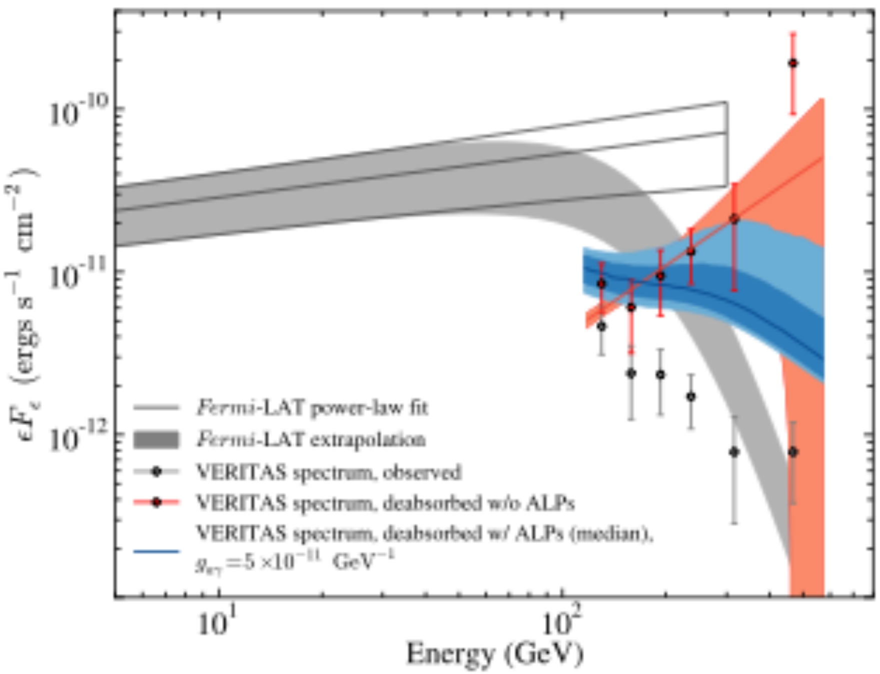
Inconclusive whether the high energy (>310 GeV flux) is variable, (5.6±3.6) vs. (3.6±1.8) x 10^{-9} m^{-2} s^{-1}

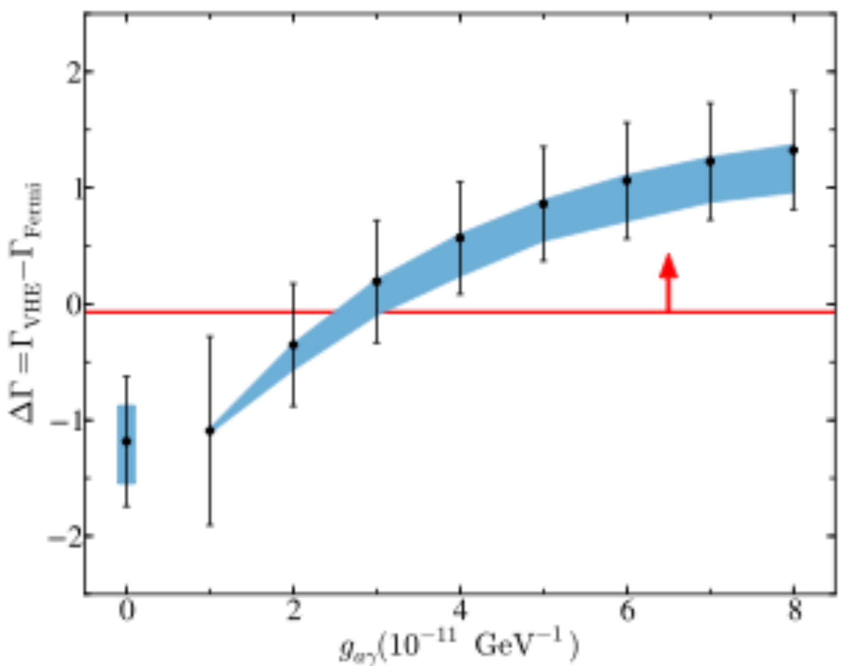
Lower state still in 2014



Figures from S. Archambault et al. 2014 (VERITAS Collaboration), ApJL 785, L16.

PKS 1424+240 — ALPs?





γ converting to axion-like-particles in B-field propagate freely through EBL, but must convert back for detection.

Assume AGN is embedded in B-field of a galaxy cluster.

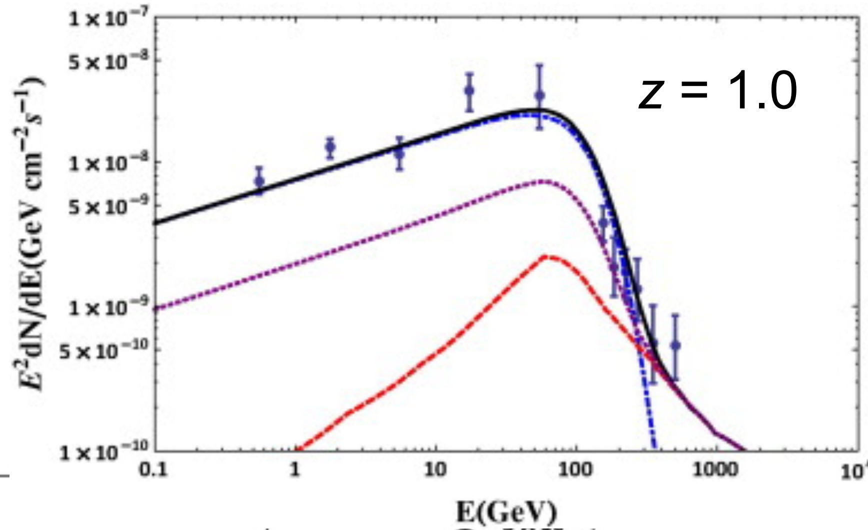
Find axion coupling that makes emitted spectrum in VERITAS band softer than Fermi-LAT spectrum.

Meyer & Horns 2013, Proc. EPS-HEP2013, arXiv:1310.2058

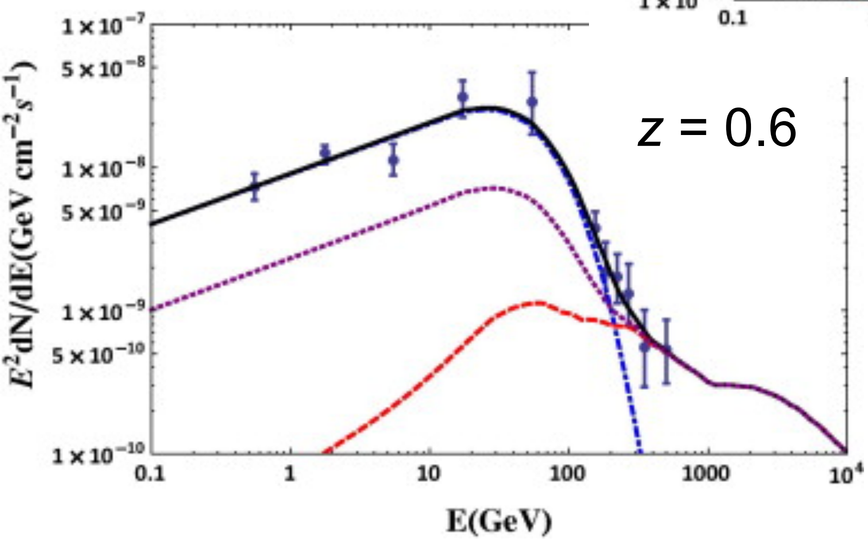
PKS 1424+240 — UHECR?

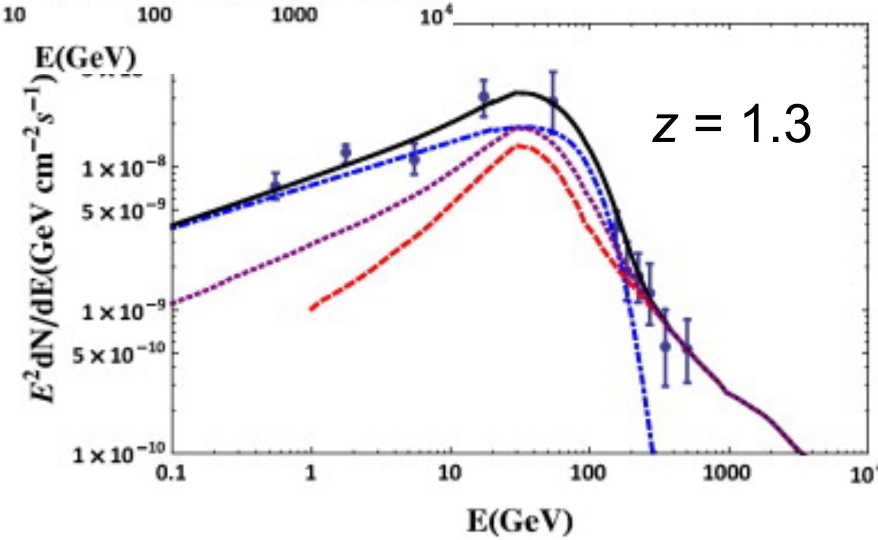
Secondary γ's produced closer to Earth in cascades of UHECR

Assume B = 10^{-15} G



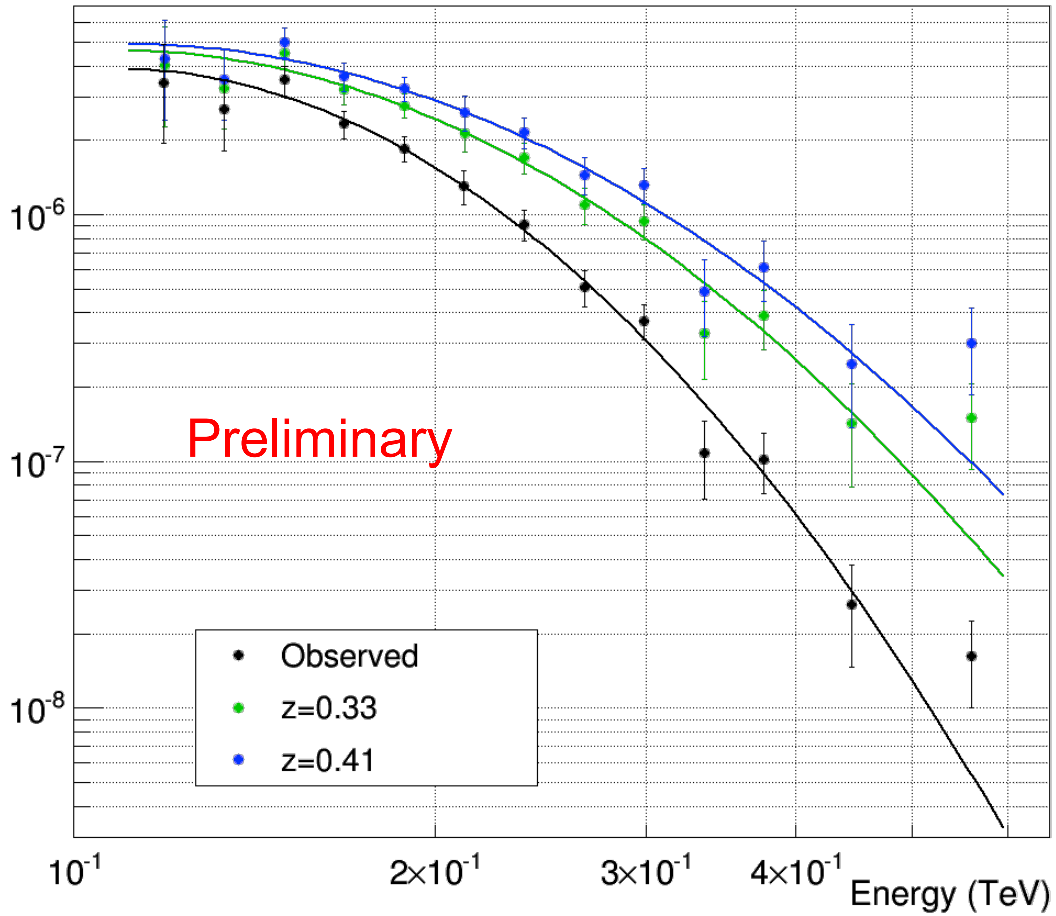
Hard secondary component should not show rapid variability





W. Essey & A. Kusenko 2014, ApP 57-58, 32.

3C 66A



Intermediate-frequency-peaked BL Lac (IBL) with $0.33 < z < 0.41$

VERITAS data from 2007–2013

Spectra deabsorbed according to Gilmore et al., 2009 EBL model

Continuing observations

Credit: Caitlin Johnson

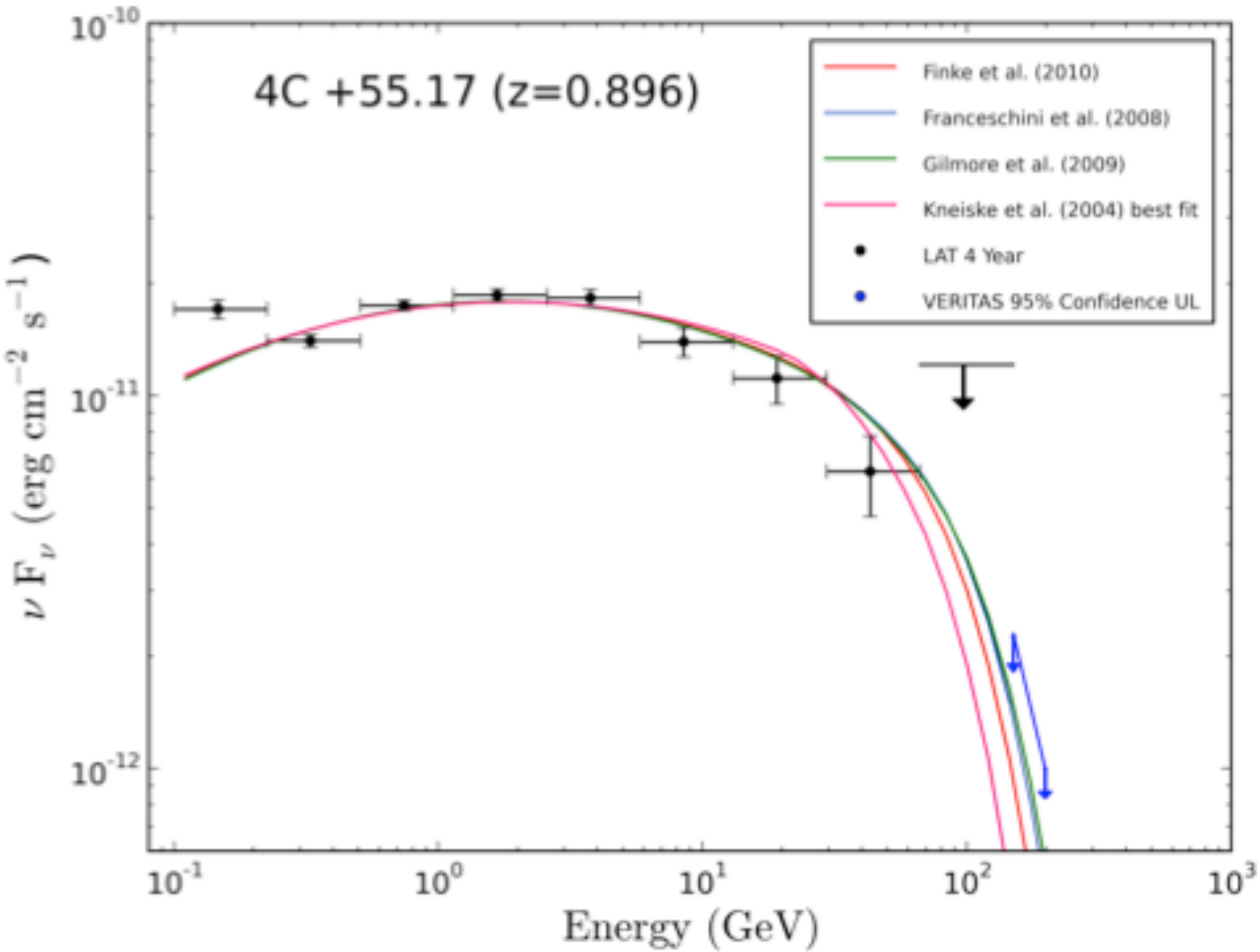
4C +55.17

FSRQ at z = 0.89

High, hard, steady flux in Fermi-LAT

45 hours of VERITAS observations

Upper limit turns out not to be constraining, given the curvature eventually seen in the Fermi-LAT data



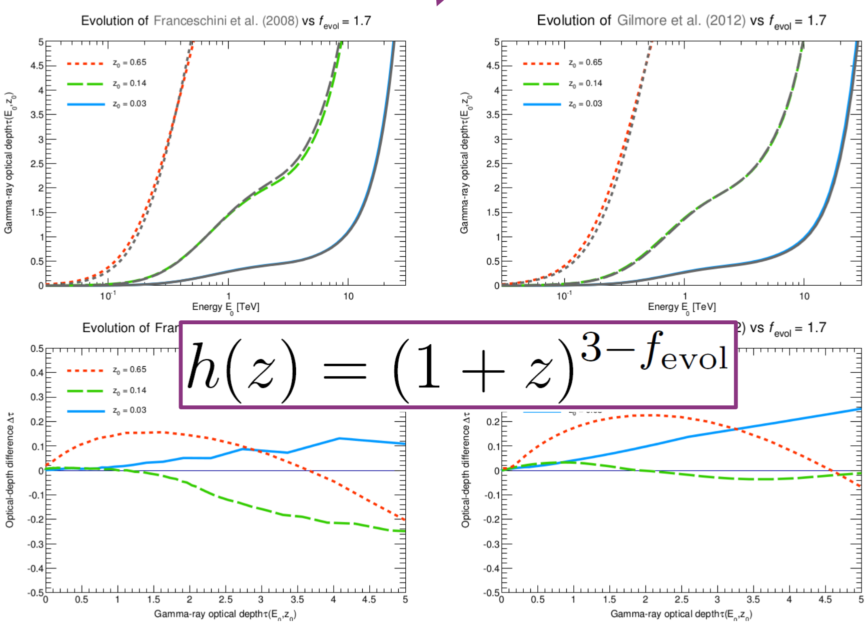
A. Furniss & W. McConville 2013, arXiv:1303.1103

EBL spectrum: hypotheses and model

$$\mathrm{d}\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) = h(z) \times \mathrm{d}\epsilon_0 \frac{\partial n}{\partial \epsilon_0}(\epsilon_0, 0)$$

As in Madau & Phinney 1996, Raue & Mazin 2008

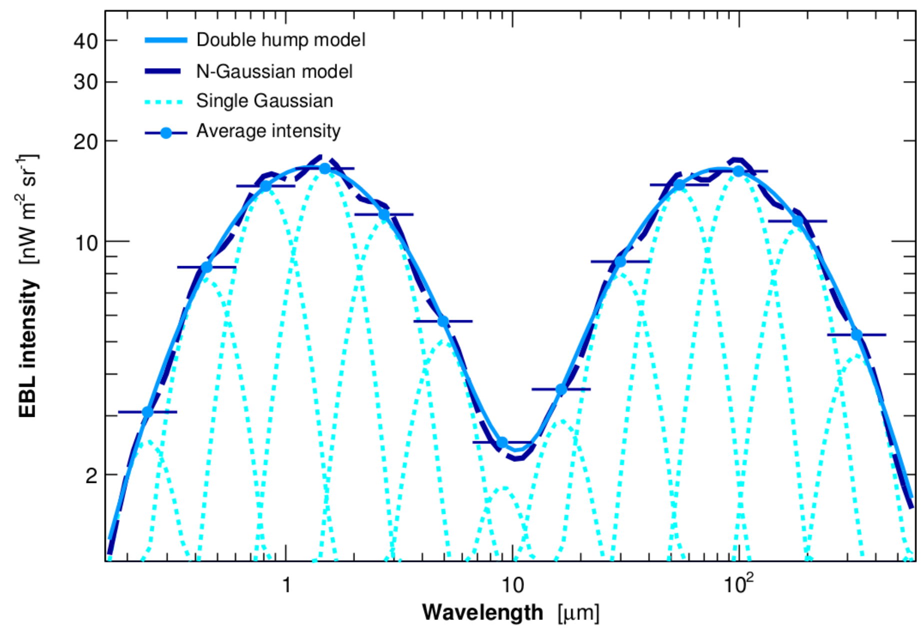
Intensity at z=0 described as a sum of Gaussians of ln λ, with fixed width and position



$$h(z) = (1+z)^{3-f_{\mathrm{evol}}}$$

$f_{\mathrm{evol}} = 1.7$

Constraints on the EBL intensity at z=0



Spectral model from a suggestion of Steve Fegan

Credit: Jonathan Biteau

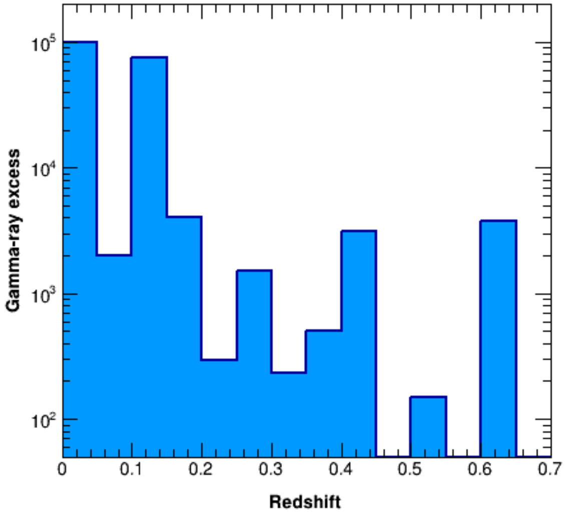
Preliminary data set: 184,000 gamma rays!

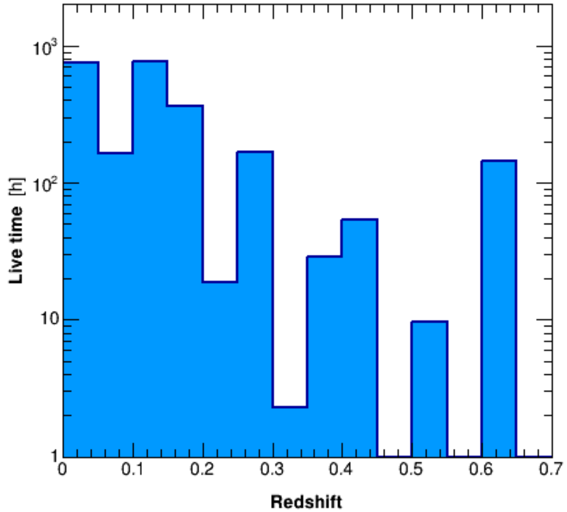
Ongoing collection: ~80% completed

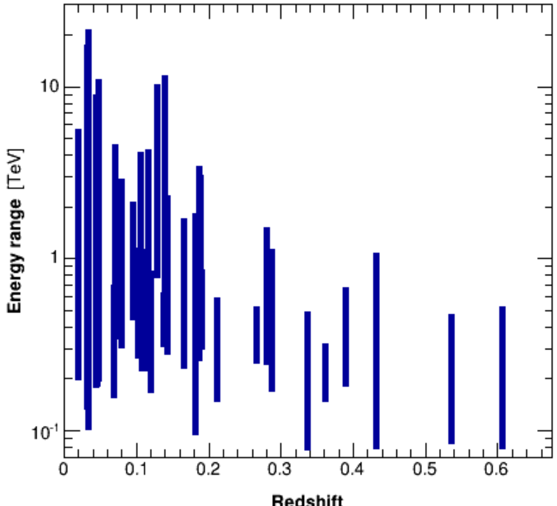
- Data from corresponding authors: HESS, MAGIC, VERITAS, CAT, HEGRA, Whipple, TACTIC, TIBET, ARGO-YBG...

Preliminary dataset:

- 75 spectra from 30 blazars with known redshift
- 184,000 gamma rays
- 2150 h of IACT observations & 2310 days of TIBET/ARGO-YBG observations







Credit: Jonathan Biteau

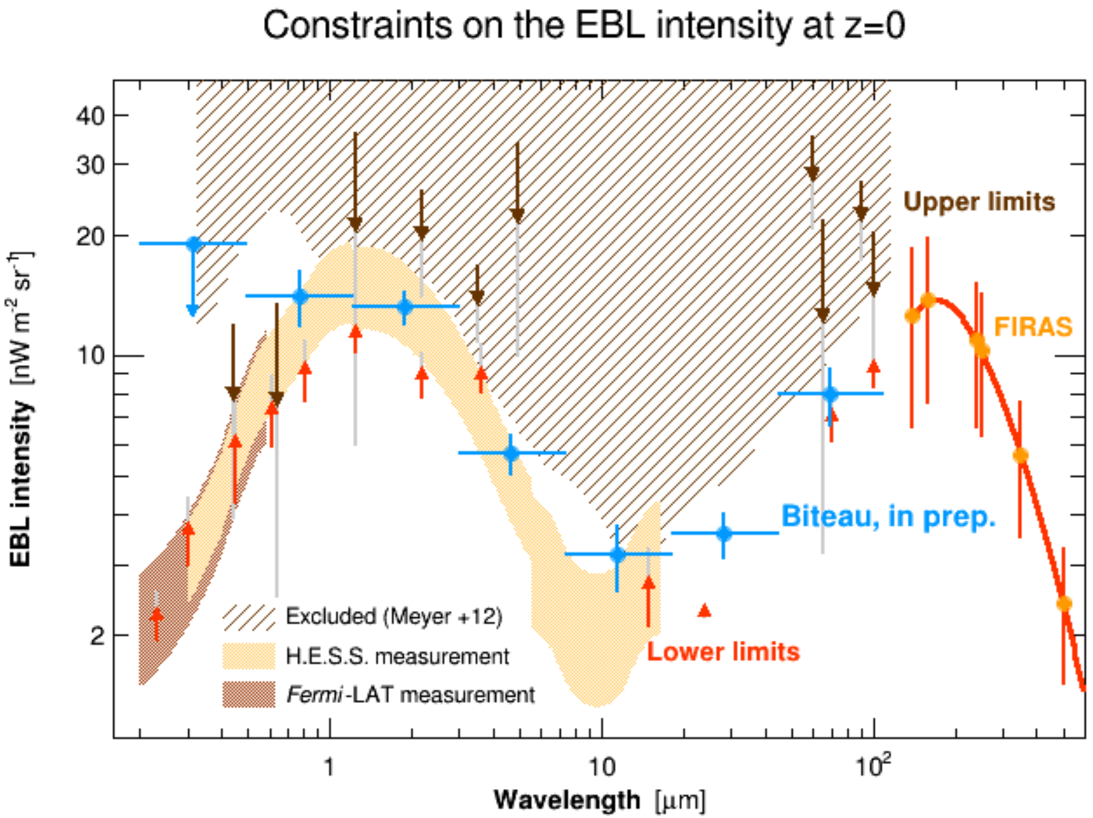
Gamma-ray Spectroscopy of the EBL

Constraints from λ = 0.2 μm to λ = 110 μm!

- Binning d(ln λ) = 0.9
- Upper limit at the 95% c.l.
- Points with 1σ uncertainties
- 12 spectra contribute to last bin
- Ongoing investigation to study any "pair production" anomaly

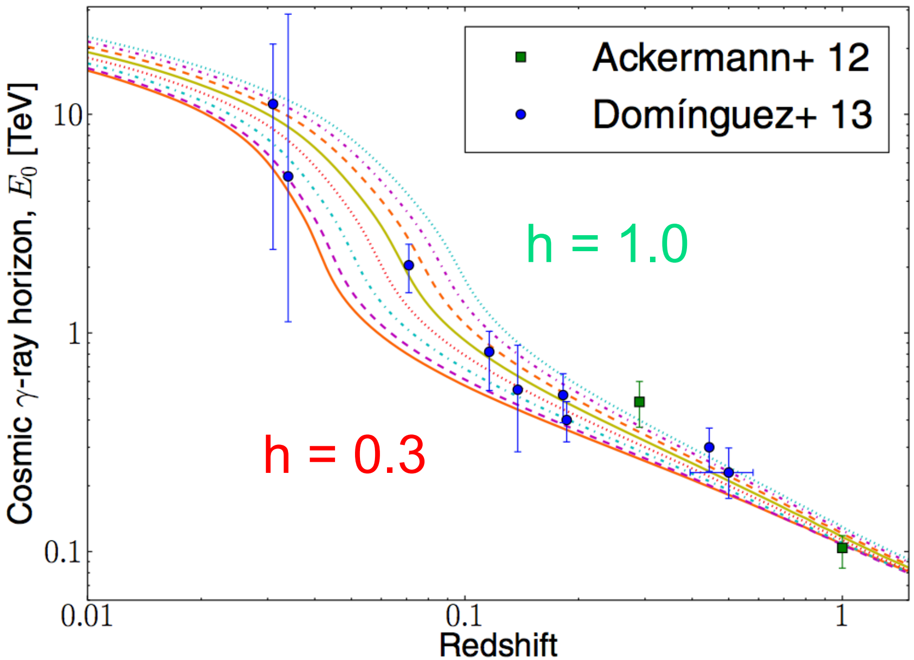
Statistics

- χ^2 / ndf = 293.9 / 329
- 7-parameter model preferred at **7.9σ** to no EBL



Credit: Jonathan Biteau

H_0 from EBL Horizon

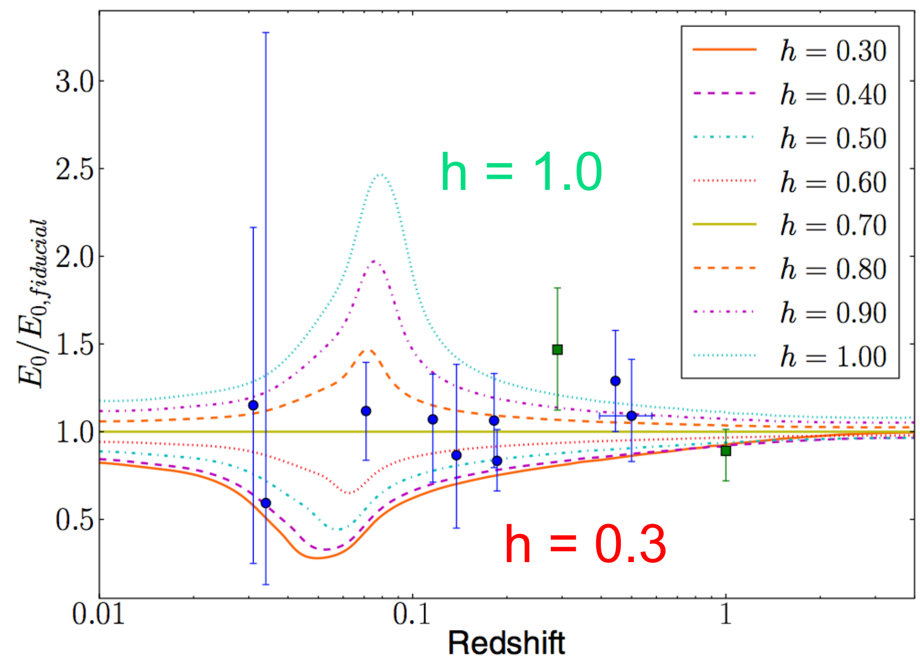


$H_0 = 71.8^{+4.6}_{-5.6}$ (stat) $^{+7.2}_{-13.8}$ (sys)

Improve by:
More measurements $0.04 < z < 1.0$
Better knowledge of the EBL

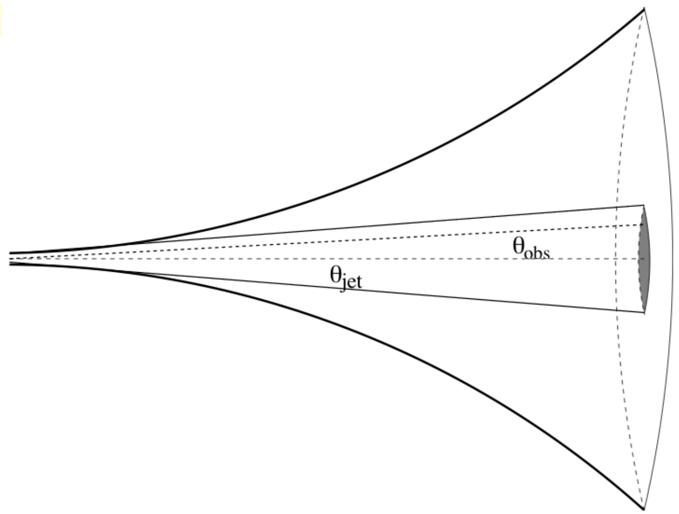
Evolution of the γ-ray horizon with redshift depends on H_0

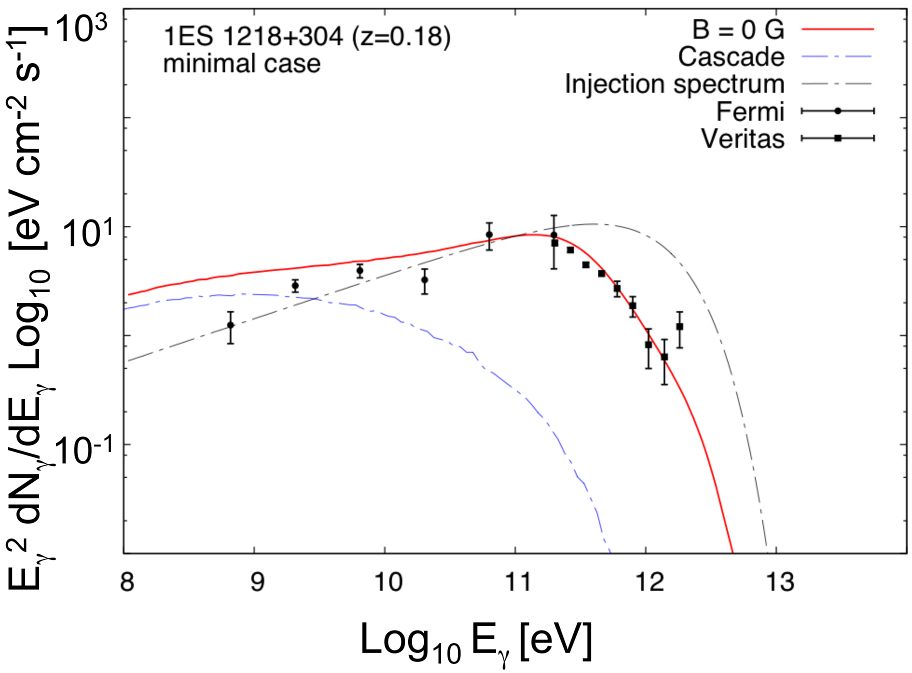
Data on the horizon from about a dozen VHE blazars and from Fermi-LAT



A. Dominguez & F. Prada 2013, ApJL 771, L34

The EBL and Intergalactic B Fields





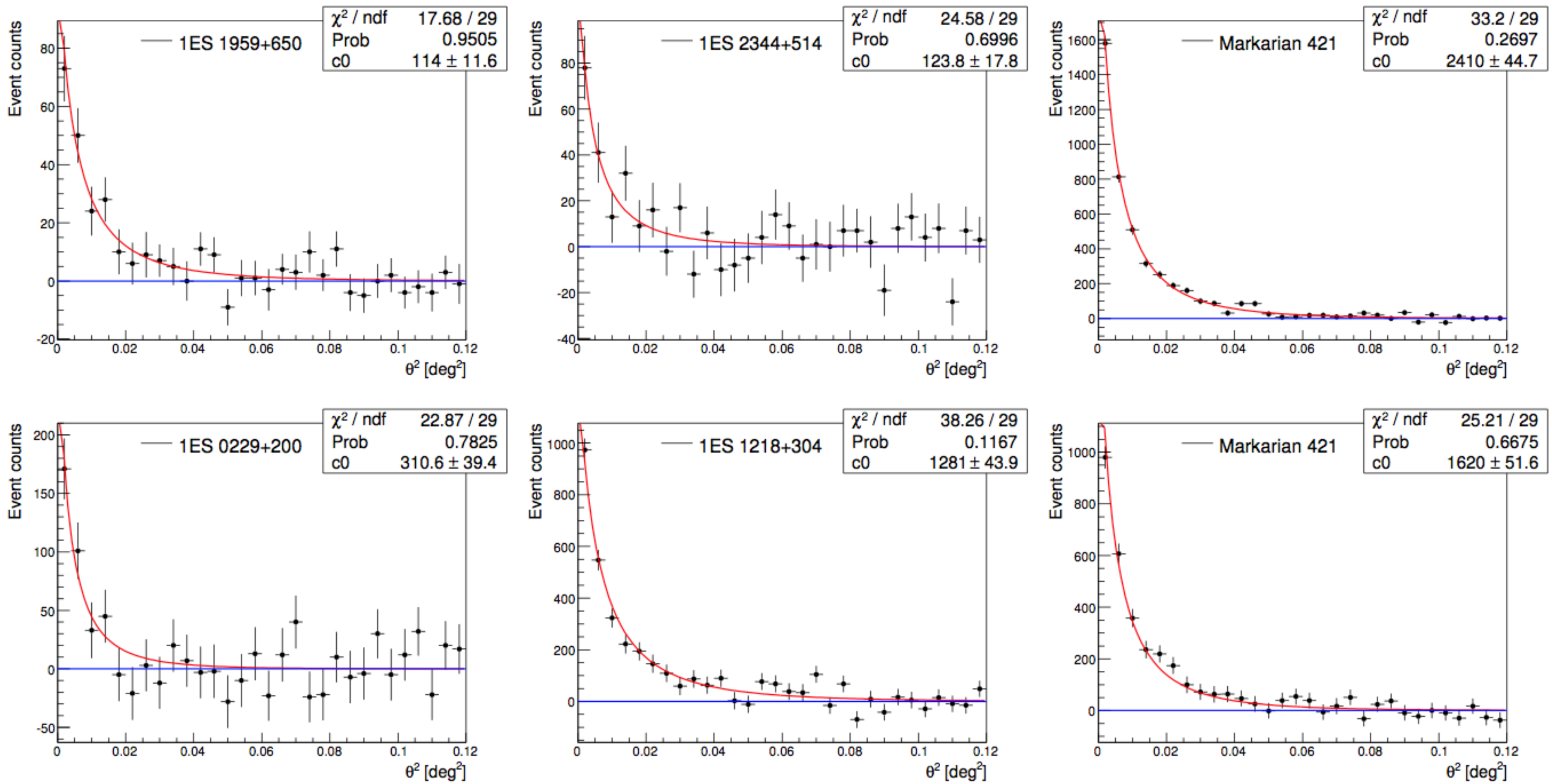
- Electrons produced by

  $\gamma_{\text{High Energy}} + \gamma_{\text{EBL}} \rightarrow e^+ e^-$

  Compton scatter off EBL to produce more photons
- Amount that the cascade fans out depends on intergalactic magnetic field (IGMF) strength
- Observable effects:
  - Pair halo
  - Spectral distortion
  - Time delays between prompt and reprocessed photons

Figures from Taylor *et al*. 2011, arXiv: 1101.0932

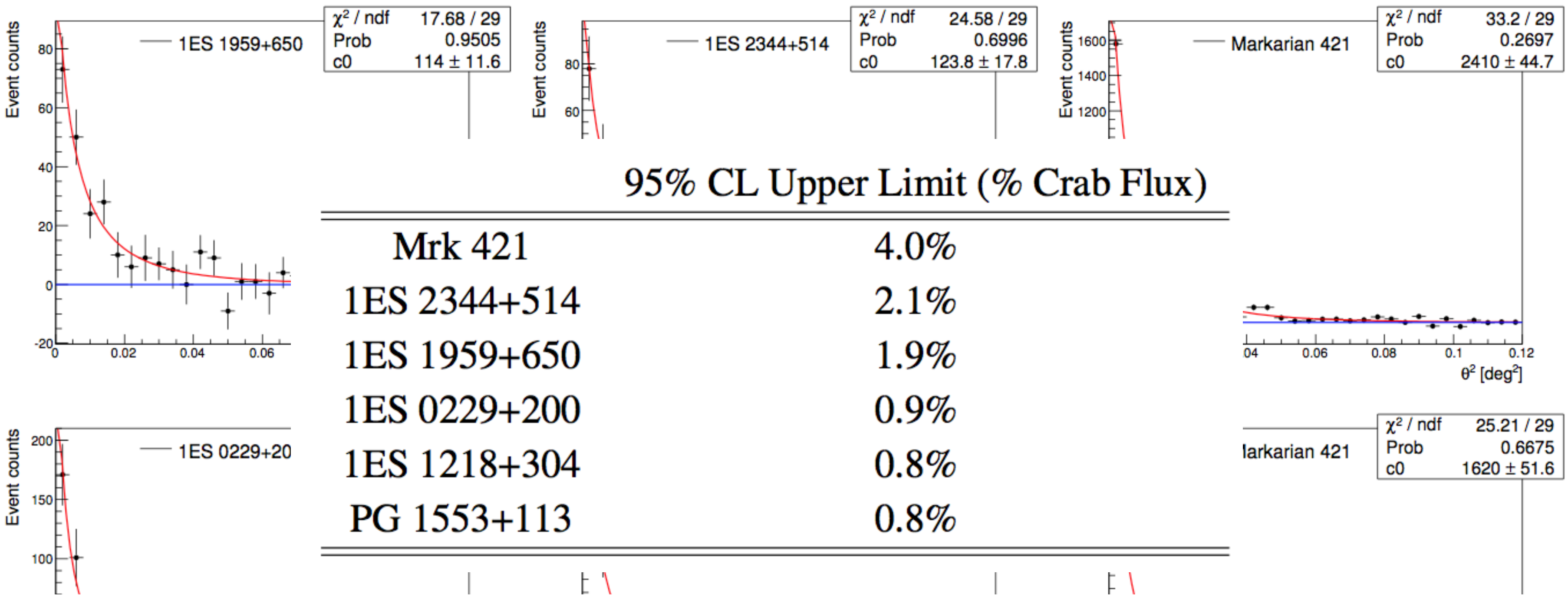
VERITAS Search for Pair Halos



Preliminary

Credit: Elisa Pueschel

VERITAS Search for Pair Halos



	95% CL Upper Limit (% Crab Flux)
Mrk 421	4.0%
1ES 2344+514	2.1%
1ES 1959+650	1.9%
1ES 0229+200	0.9%
1ES 1218+304	0.8%
PG 1553+113	0.8%

Interpretation still under study

More straightforward to constrain fields 10^{-15}–10^{-14} G

Constraining stronger fields depends on past emission history

Preliminary

Credit: Elisa Pueschel

Test of Lorentz Invariance

Test for time delay as a function of energy

$v = c(1 - (E/M_{qg}))$

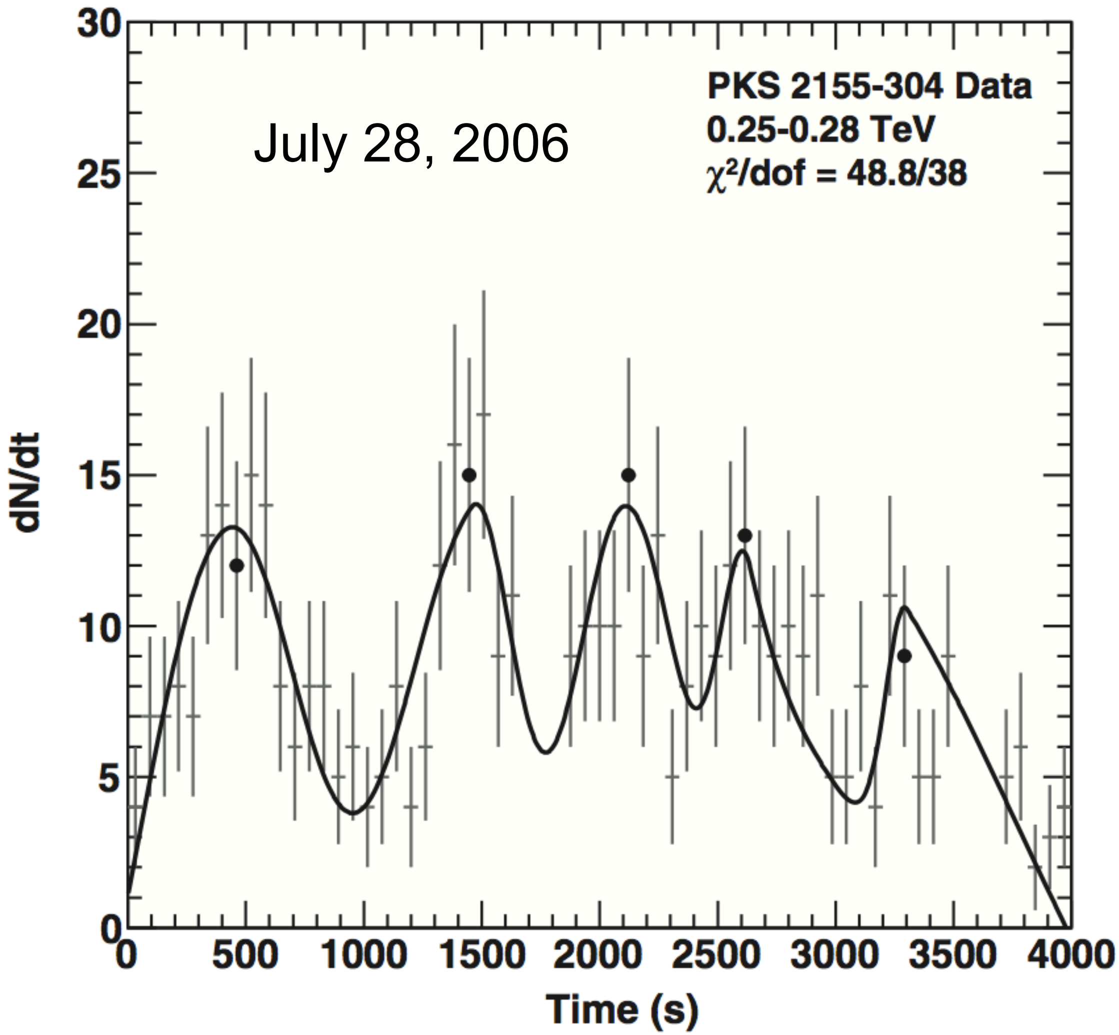
$M_{qg} > 2.1 \times 10^{18}$ GeV

~10x better limit from Fermi-LAT & GRB 090510

$v = c(1 - (E/M_{qg})^2)$

$M_{qg} > 6.4 \times 10^{10}$ GeV

~Best limit



A. Abramowski et al. 2011 (HESS Collaboration), ApP 34, 738

Summary

- The very-high-energy γ-ray emission from extragalactic sources is affected by a number of processes of cosmological, astrophysical and particle physics interest
  - ✓ Absorption by the extragalactic background light — details depend on H_0 and star-formation history
  - ✓ Secondary γ-ray production in γ- or p-initiated cascades — detection sensitive to intergalactic magnetic field
  - ✓ Possible γ-ray interactions with axion-like particles
  - ✓ Lorentz invariance violation
- Many similar or related efforts to those presented here
- Details challenging to separate from intrinsic source properties, but making progress with a growing number of sources, improved instrument sensitivity, and deep observations