Cosmology and fundamental physics with extragalactic TeV $\gamma$-rays

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PHENIICS days
9-11 May 2016
... basically with one diagram
Plan

- The H.E.S.S. experiment
- Measuring the Extragalactic Background Light (EBL)
- Probing magnetic fields in cosmic voids
- Testing Lorentz invariance up to the Planck scale
H.E.S.S. : High Energy Stereoscopic System
A leading Imaging Air Cherenkov Telescope array

- 4 telescopes with a 107 m² dish + 5th telescope, 600 m²
- Field of view 5° (3.5°), PSF 0.1°
- Energy range : ~50 GeV to 50 TeV (VHE regime)
Khomas Highland, Namibia:
- optimal atmospheric conditions
- isolated site
→ clear sky (almost) guaranteed
H.E.S.S. : from calibration to analysis

- Calibration
  - From electronic signal to Cherenkov photons

- Reconstruction
  - $\gamma$/hadron separation
  - $\gamma$ properties

- Analysis
  - Maps
  - Lightcurves
  - Energy spectrum
H.E.S.S. : from calibration to analysis

Personal contributions

- Calibration/Reconstruction: method to check the pointing position with stars in the field of view

- Analysis: Implementation of an alternative spectral deconvolution method

\[ N_T^{(n+1)} = \sum_j^{n_R} \frac{P(E_R|E_T)_{ij} N_T^{(n)}_{T,i}}{N_R^{(n)}_{R,j}} N_{R,j} \]

*bayesian unfolding* to get spectral points in the true energy basis
H.E.S.S. science cases (a selection)

Extragalactic
- Gamma ray bursts
- Active galaxy nuclei
- Extragalactic background light
- Cascades and magnetic fields
- Lorentz invariance violation

Galactic
- Supernova remnants
- Clusters
- Galactic center
- Binaries
- Pulsars
- WIMP searches
- Electrons

Astroparticles
- Multi-messengers
- Axions

What I do

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Extragalactic background light and $\gamma$-ray absorption

- **What is the EBL?**
  - Background photon field (IR to UV) originating from starlight and dust re-emission.
  - Direct measurements are difficult

- **EBL absorbs $\gamma$ rays by pair creation**
  - Universe not transparent to $\gamma$ rays over extragalactic distances: **optical depth** $\tau$
  - Attenuation pattern in VHE spectra of distant sources

\[
\tau(E_\gamma, z_s) = c \int_0^{z_s} \frac{dz}{dz} \int_0^2 d\mu \frac{\mu}{2} \int_{\epsilon_{thr}}^{\infty} d\epsilon \frac{dn_{EBL}(\epsilon, z_s)}{d\epsilon} \sigma_{\gamma\gamma}(E_\gamma(1 + z), \epsilon, \mu)
\]

\[
\Phi_{obs}(E_\gamma) = \Phi_{int}(E_\gamma) e^{-\tau(E_\gamma, z_s)}
\]

\[\gamma_{VHE} + \gamma_{EBL} \rightarrow e^+ + e^-\]
A model-independent EBL measurement

- Simple assumptions on the intrinsic spectra, using 6 bright blazars
  \[ \frac{dN}{dE} \propto E^{-\alpha-\beta \log(E)} \]

- Scan of EBL splines constructed upon a grid

General agreement with current models, in between upper and lower limits

H.E.S.S. paper (as corresponding author) in preparation
Cascades and extragalactic magnetic fields

EM cascades initiated by pair creation on the EBL …

- Inverse Compton on the CMB with progressive energy losses
- Cascade development function of magnetic fields in the line of sight

⇒ $\gamma$-rays features as possible constraints on the extragalactic magnetic fields (EGMF)

Typical cascade extension $\sim 1$ Mpc
10 TeV photon reprocessed $\sim 100$ GeV

$$E_\gamma = \left(\frac{4}{3}\right)\epsilon_{CMB}(E_e/m_e c^2)^2 \sim 88 \left[E_{\gamma_0}/10 \text{ TeV}\right]^2 \text{ GeV}$$
Cascades and extragalactic magnetic fields

Power transferred from primary $\gamma$-ray beam to secondary emission

$\Rightarrow$ Spatial (extension) and temporal (delays) features in HE / VHE

Both aspects reflected in energy spectrum

Example with blazar $z \sim 0.5$

Taylor, Vovk & Neronov arXiv:1101.0932

Limits on the EGMF strength and coherence length

$\Rightarrow$ constrain its origin (Primordial vs. astrophysical)

M. Lorentz et al. in preparation
Lorentz invariance violation and $\gamma$-ray absorption?

- Effective parameterization of LI breaking with modified dispersion relation

$$E_\gamma^2 = p_\gamma^2 \pm E_\gamma^2 \left(\frac{E_\gamma}{E_{LIV}}\right)^n$$

Symmetry breaking around Planck energy in some quantum gravity models

$$E_{LIV}^n/\xi_n = E_{Planck} = \sqrt{\hbar c^5/G} \approx 1.22 \times 10^{28} \text{eV}$$

- Affects center of mass energy and pair creation threshold

**Propagates into EBL optical depth:**

$$\tau(E_\gamma, z_e) = c \int_0^{z_e} \frac{dz}{dz} \int_0^\pi d\theta \sin \theta \frac{(1 - \cos \theta)}{2} \int_{\epsilon_{thr}}^{\infty} d\epsilon' \frac{dn(\epsilon', z)}{d\epsilon' dV_p} \sigma_{\gamma\gamma}(E'_\gamma, \epsilon', \theta)$$

Planck scale limits with H.E.S.S. data

- Deviation from standard case show up at highest energies (>10 TeV)
  - Need for a bright and not too EBL-absorbed source

- Analysis of the Mrk 501 blazar flaring state: strong LIV limits in the photon sector
  - Planck scale exclusion for the linear case
  - Currently the best limits in the quadratic case

To appear in proceedings of RICAP 2016 (21-24 June 2016)
Summary

Involvement in H.E.S.S. calibration and analysis:

- Control of telescope pointing accuracy
- Spectral deconvolution

TeV $\gamma$-ray astronomy to study particle-physics and cosmology!

- Independent measurement of the O(eV) cosmic background
- Constraints on the strength of large scale magnetic fields
- Competitive tests on Lorentz invariance