Cosmology and fundamental physics with extragalactic TeV γ-rays

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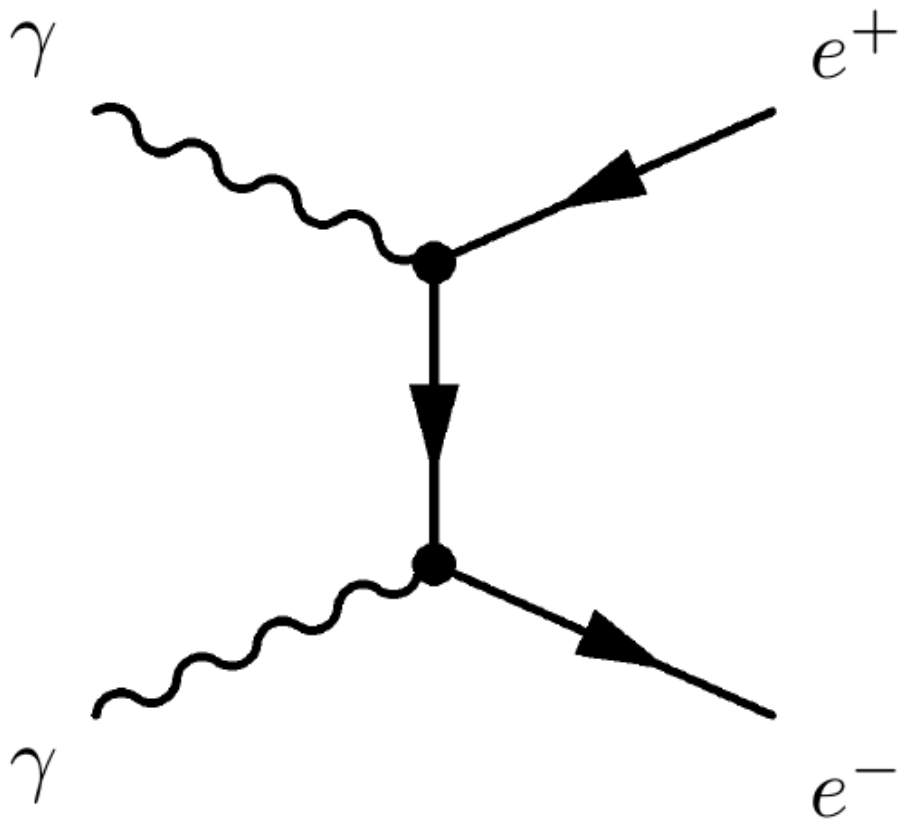
PHENIICS days

9-11 May 2016

H.E.S.S.

Irfu - CEA Saclay
Institut de recherche sur les lois fondamentales de l'Univers

… basically with one diagram

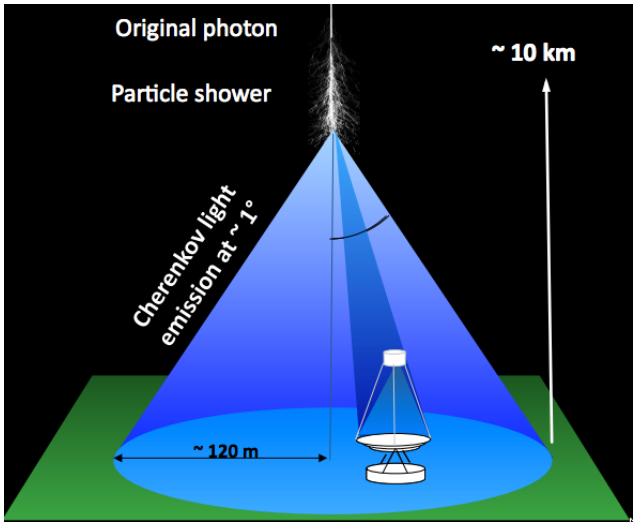


Plan

- 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



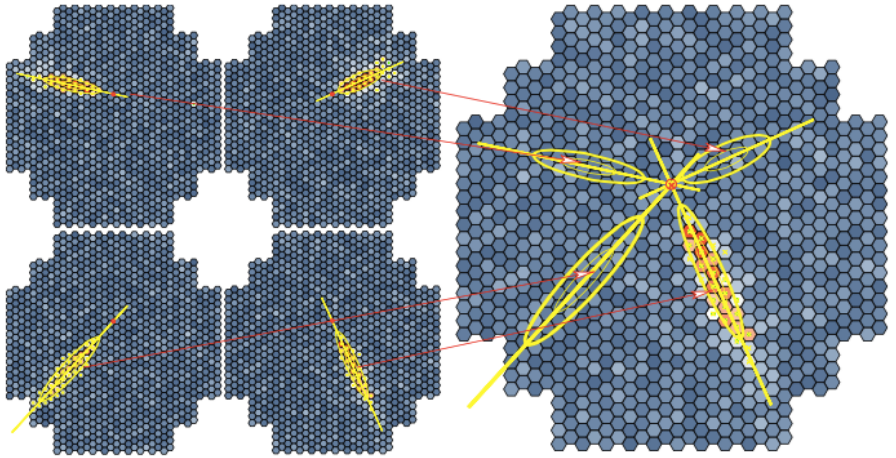
- 4 telescopes with a 107 m^2 dish + 5th telescope, 600 m^2
- Field of view 5° (3.5°), PSF 0.1°
- Energy range : ~50 GeV to 50 TeV (VHE regime)

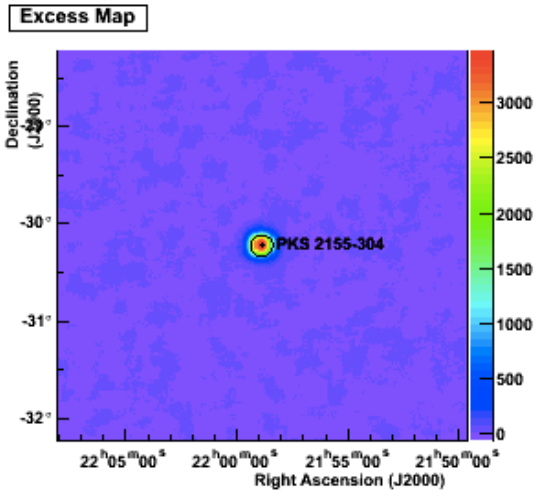
H.E.S.S.

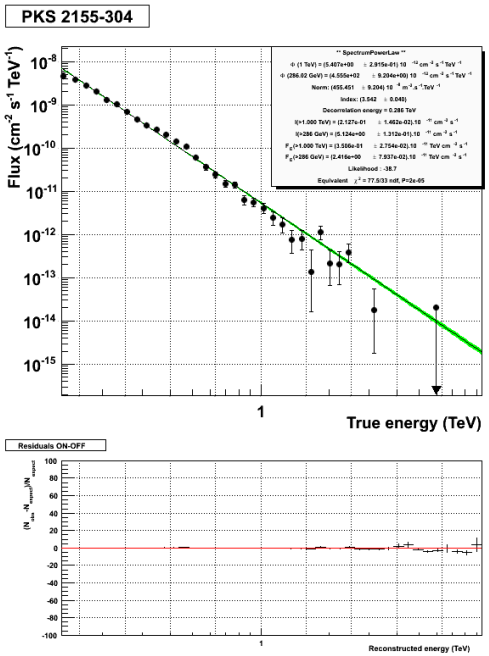

H.E.S.S.
Khomas Highland, Namibia :
- optimal atmospheric conditions
- isolated site
➔ clear sky (almost) guaranteed
©Matthias Lorentz

H.E.S.S. : from calibration to analysis

- Calibration
  - From electronic signal to Cherenkov photons
- Reconstruction
  - γ/hadron separation
  - γ properties
- Analysis
  - Maps
  - Lightcurves
  - **Energy spectrum**

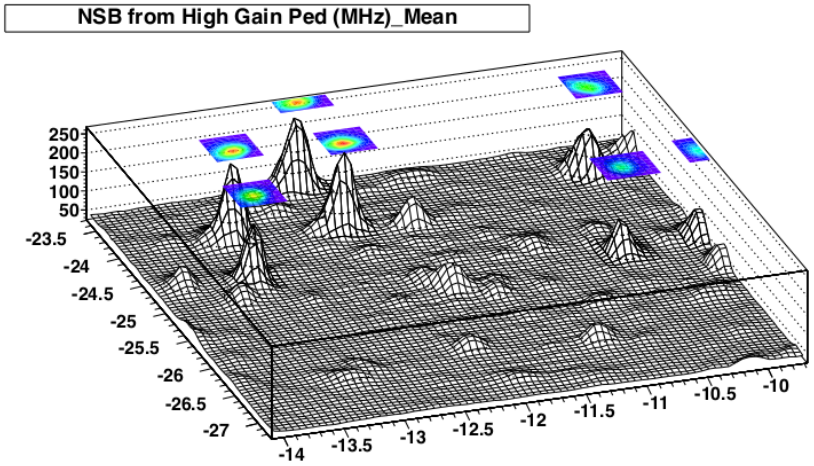






H.E.S.S. : from calibration to analysis
Personal contributions

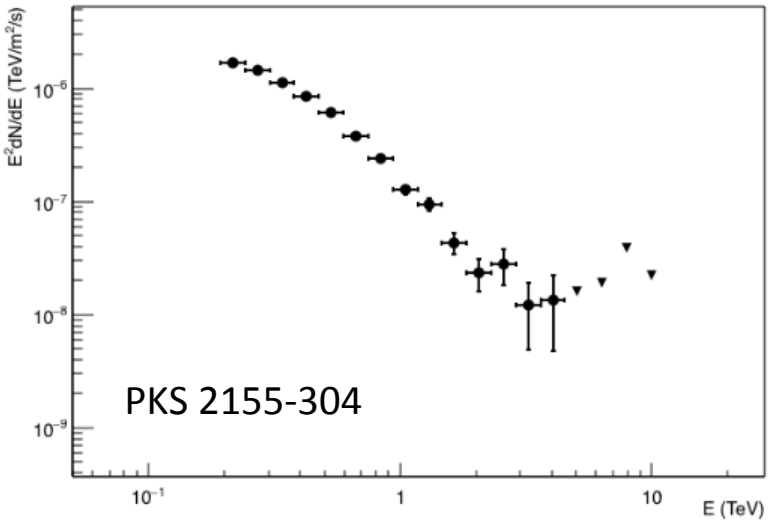
- Calibration/Reconstruction :
  method to check the pointing position with stars in the field of view



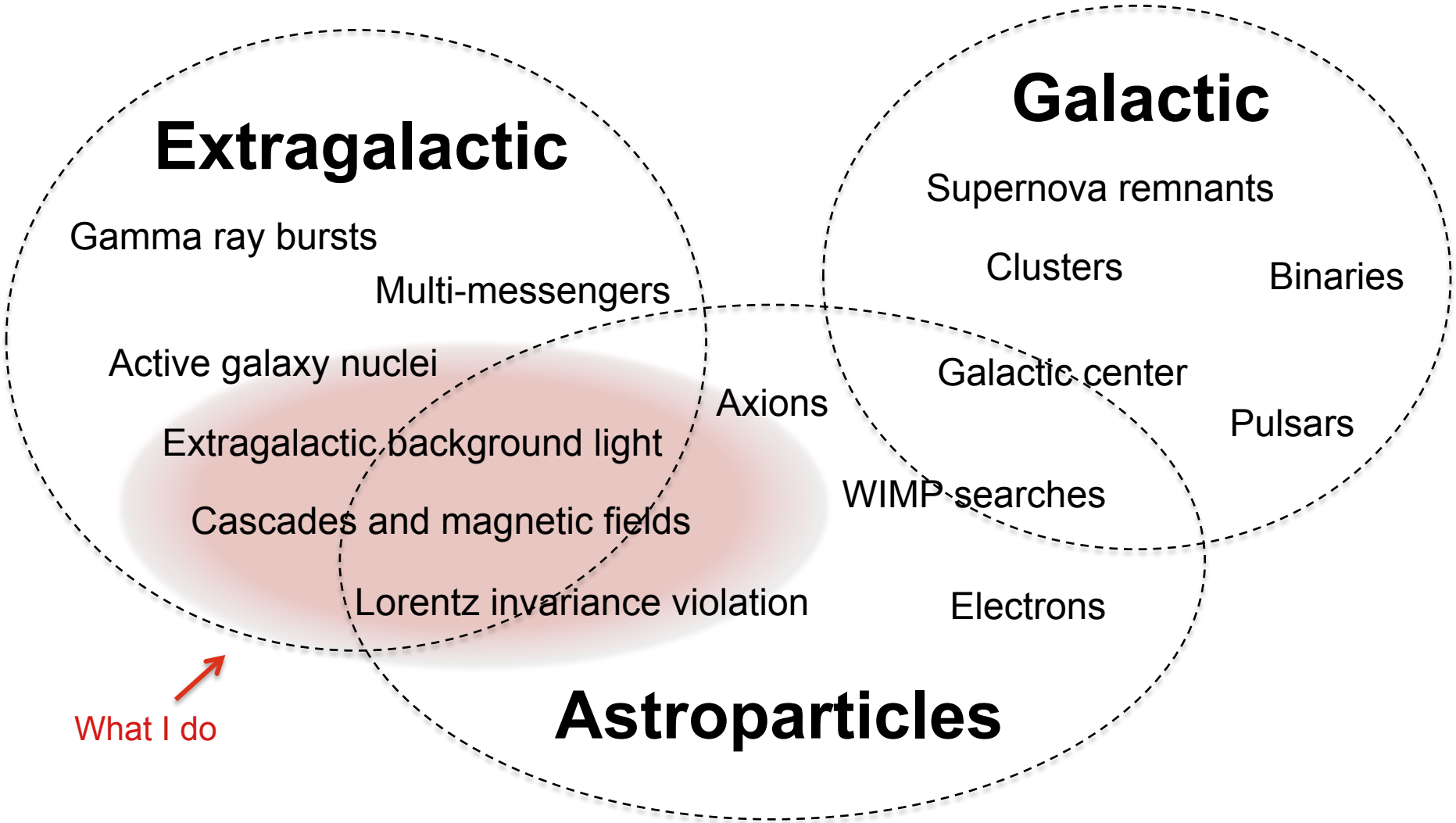
- Analysis : Implementation of an alternative spectral deconvolution method

bayesian unfolding *to get spectral points in the true energy basis*

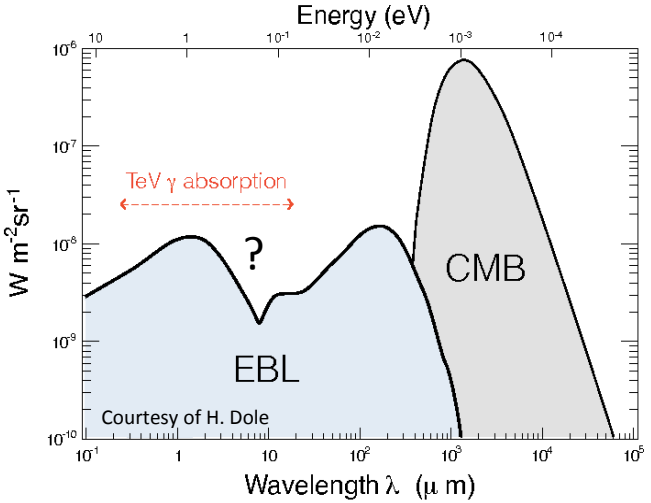
$$N_T^{(n+1)} = \sum_j^{n_R} \frac{P(E_R|E_T)_{ij} N_{T,i}^{(n)}}{N_{R,j}^{(n)}} N_{R,j}$$



H.E.S.S. science cases (a selection)



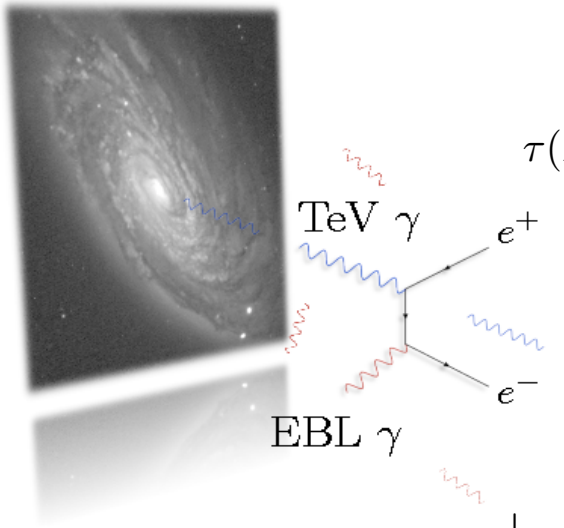
Extragalactic background light and γ-ray absorption



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

- **EBL absorbs γ rays by pair creation**
  Universe not transparent to γ rays over extragalactic distances : **optical depth τ**

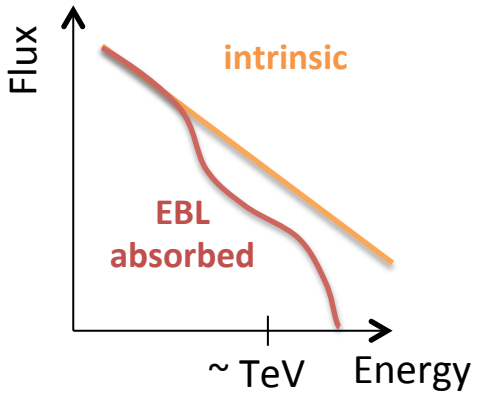
  Attenuation pattern in VHE spectra of distant sources



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

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

$$\gamma_{\mathrm{VHE}} + \gamma_{\mathrm{EBL}} \rightarrow e^+ + e^-$$



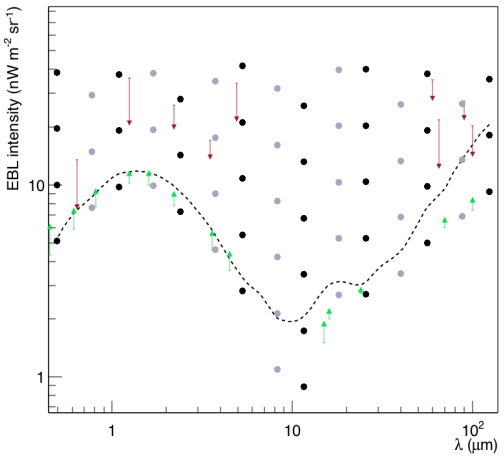
A model-independent EBL measurement

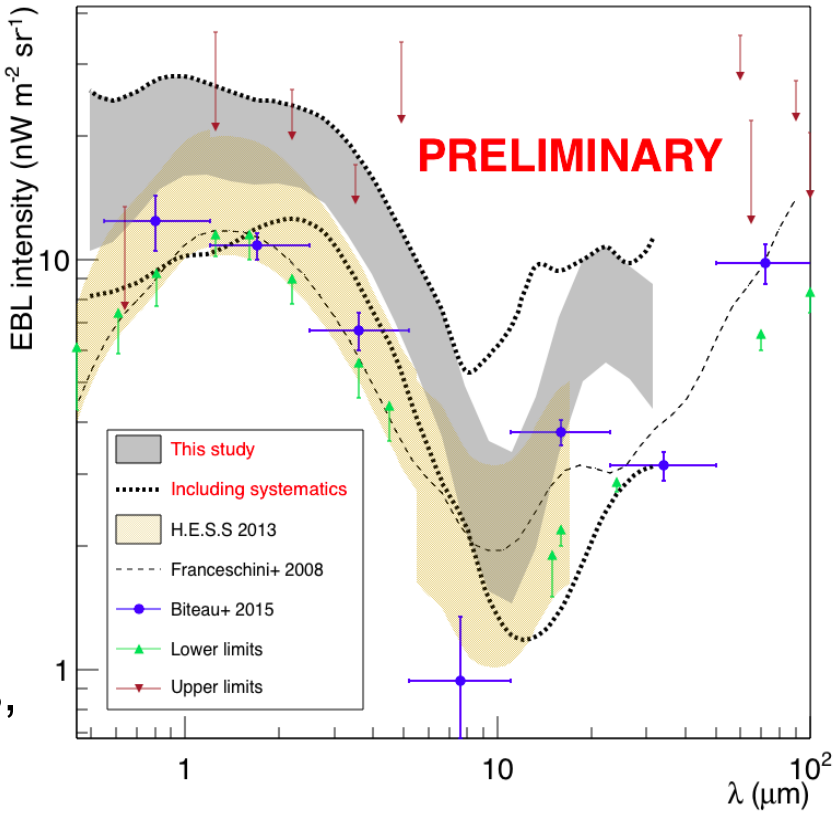
- Simple assumptions on the intrinsic spectra, using 6 bright blazars

$$\frac{dN}{dE} \propto E^{-\alpha-\beta\log(E)}$$

M. Lorentz et al. ICRC 2015 Proc. arXiv:1509.03477
H.E.S.S. paper (as corresponding author) in preparation

- Scan of EBL splines constructed upon a grid





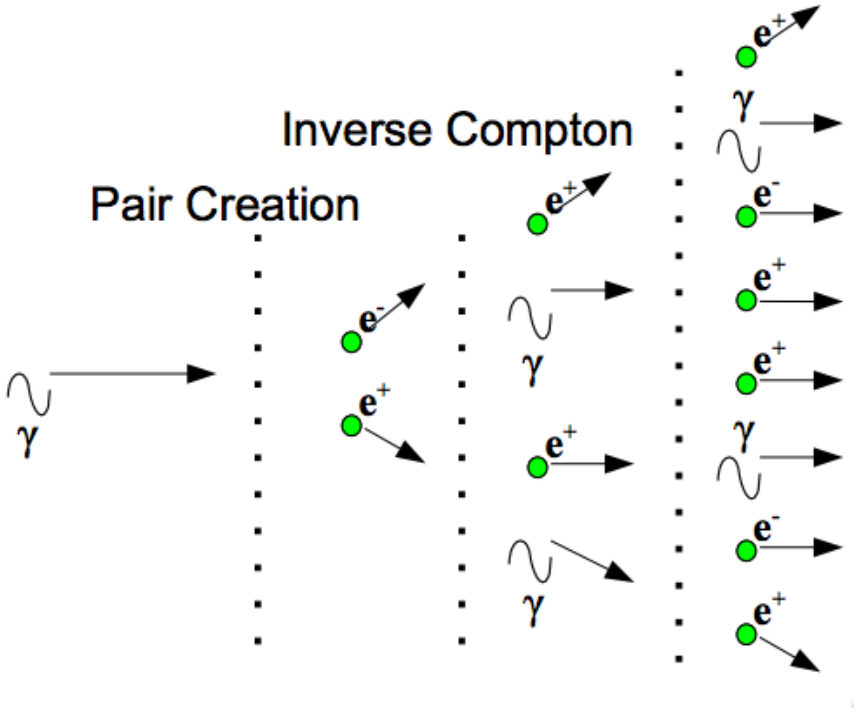
General agreement with current models, in between upper and lower limits

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

⇒ γ-rays features as possible constraints on the extragalactic magnetic fields (EGMF)



Typical cascade extension ~1 Mpc
10 TeV photon reprocessed ~100 GeV

$$E_\gamma = (4/3)\epsilon_{CMB}(E_e/m_e c^2)^2 \simeq 88\,[E_{\gamma_0}/10\ \mathrm{TeV}]^2\ \mathrm{GeV}$$

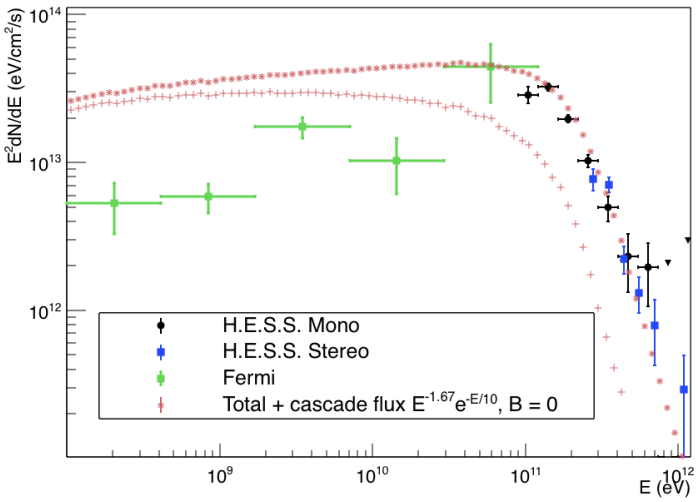
Cascades and extragalactic magnetic fields

Power transfered from primary γ-ray beam to secondary emission

➔ Spatial (extension) and temporal (delays) features in HE / VHE

Both aspects reflected in energy spectrum

Example with blazar z ~ 0.5

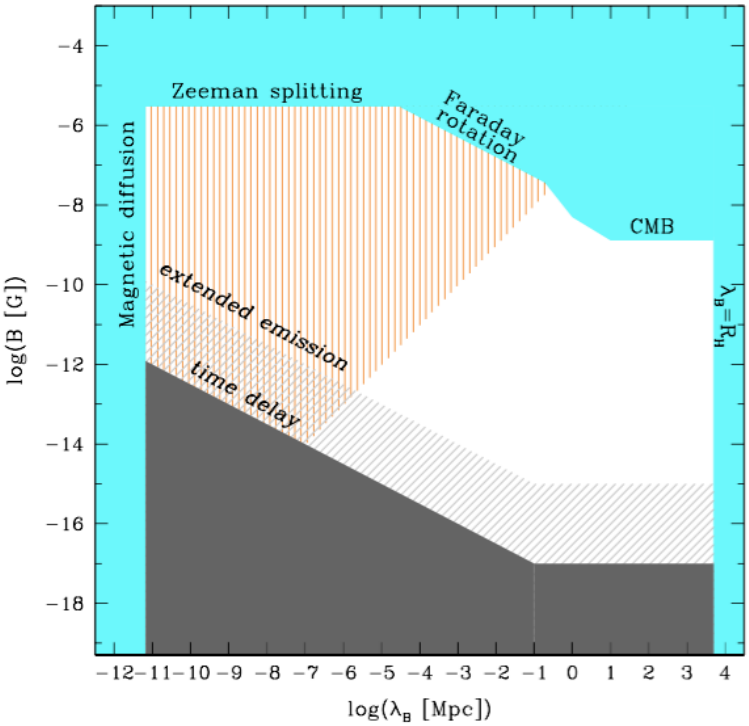


Limits on the EGMF strength and coherence length

➔constrain its origin (Primordial vs. astrophysical)

M. Lorentz et al. in preparation

Taylor, Vovk & Neronov arXiv:1101.0932



Lorentz invariance violation and γ-ray absorption ?

- Effective parameterization of LI breaking with modified dispersion relation

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

Symmetry breaking around Planck energy in some quantum gravity models

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

- Affects center of mass energy and pair creation threshold

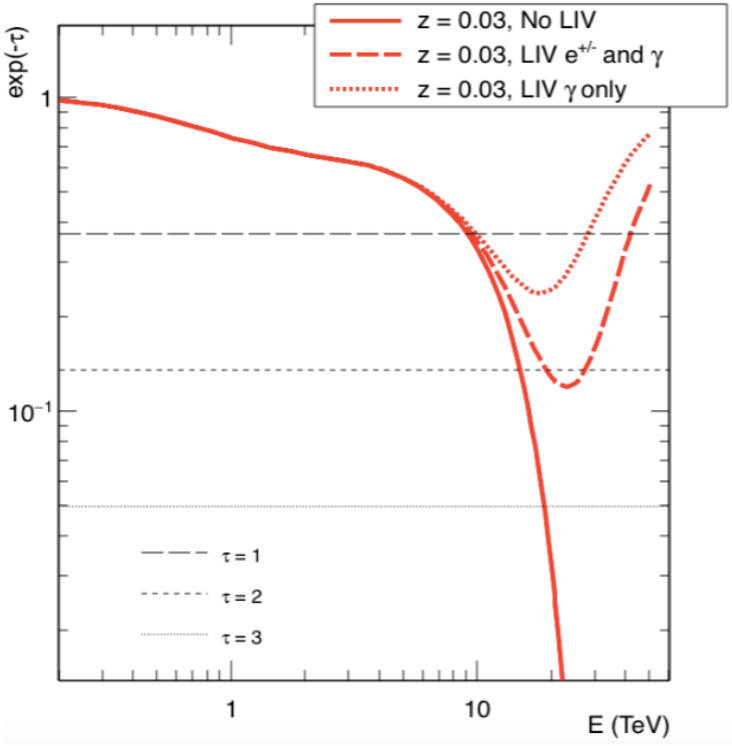
Propagates into EBL optical depth :

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

Jacob, U., & Piran, T. (2008). Phys. Rev D, arxiv 0810.1318
Fairbairn, M., Nilsson, A., Ellis, J., Hinton, J., & White, R. (2014) JCAP

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 γ-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

H.E.S.S.