Cosmology and fundamental physics with extragalactic TeV γ-rays ?

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PhD with Pierre Brun at Irfu/SPP

DDays
7-8 July 2016

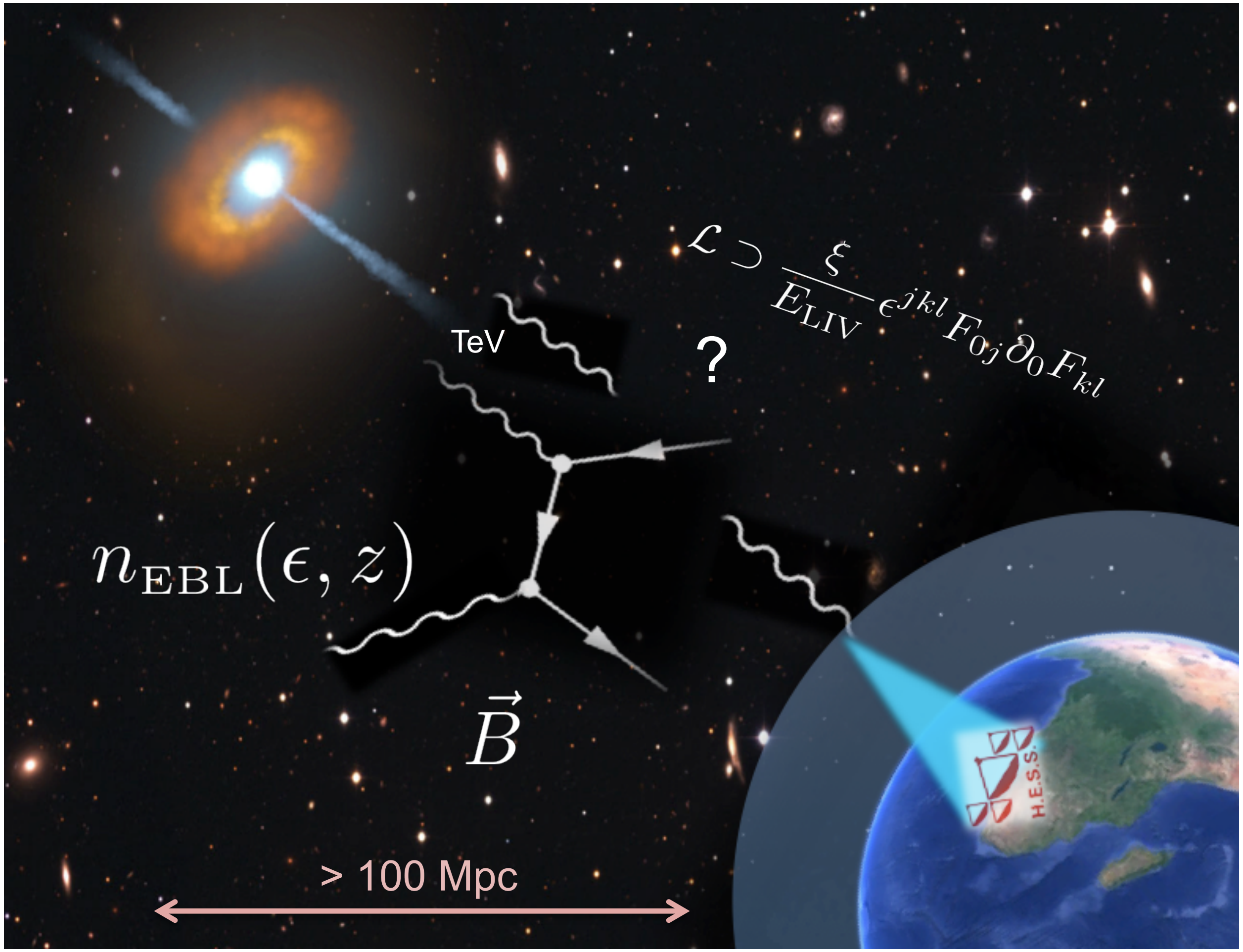
H.E.S.S.

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

Introduction : my PhD topic

What we can learn from TeV photons propagating over cosmological distances

- Extragalactic sources of TeV γs
- **Propagation effects**
  - **Background O(eV) photons (EBL)**
  - **B field in voids**
  - **Exotic…**
- H.E.S.S. data analysis



H.E.S.S. : High Energy Stereoscopic System

A leading Imaging Air Cherenkov Telescope array

- 4 telescopes with a 107 m^2 dish + 5^{th} telescope, 615 m^2 (> 10^4 m^2 effective area)
- Field of view 5° (3.5°), Point Spread Function 0.11°
- Energy range : ~50 GeV to 50 TeV (VHE), 10% energy resolution (stereoscopic)


H.E.S.S.
Khomas Highland, Namibia :
- optimal atmospheric conditions
- isolated site
➔ clear sky (almost) guaranteed
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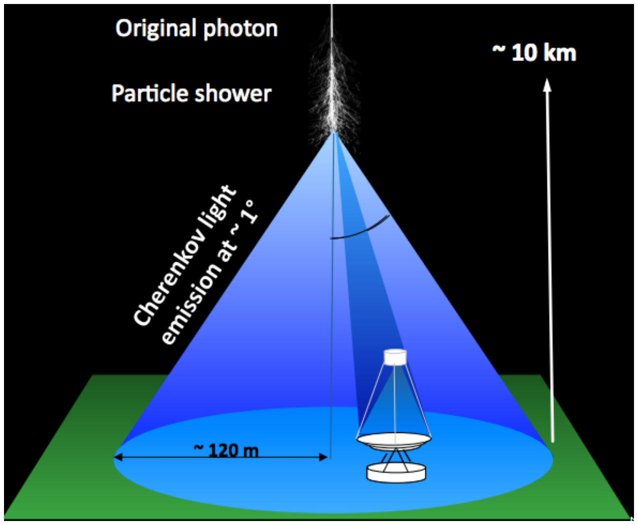
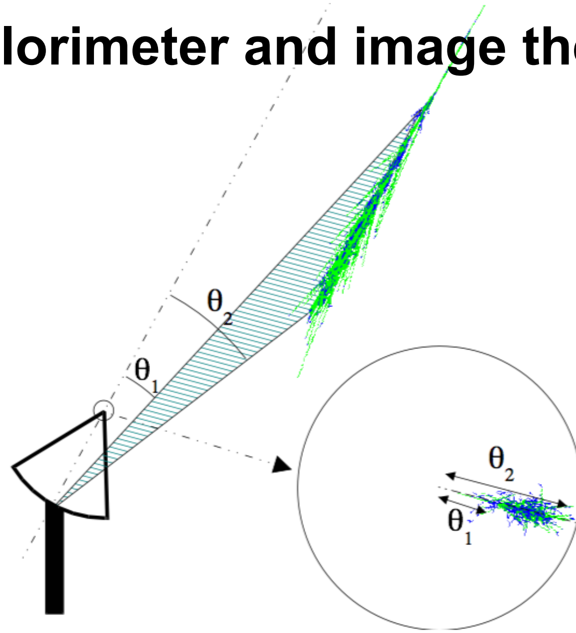
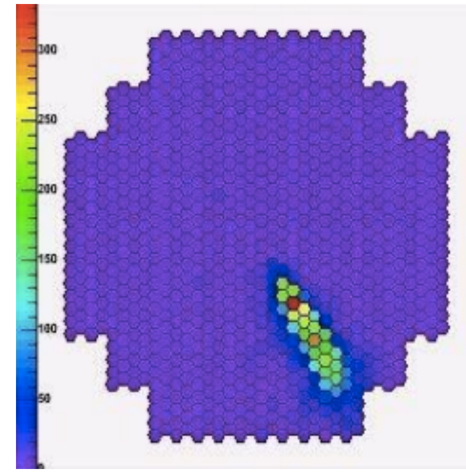
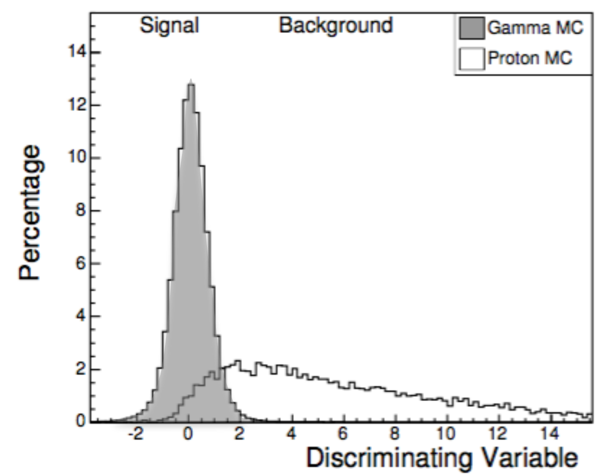
Imaging Air Cherenkov Telescope : detection technique

Use the atmosphere as a calorimeter and image the air showers







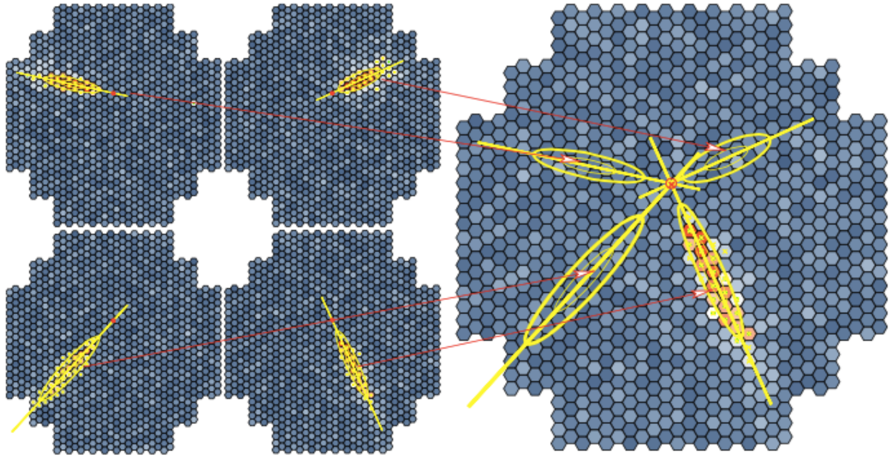


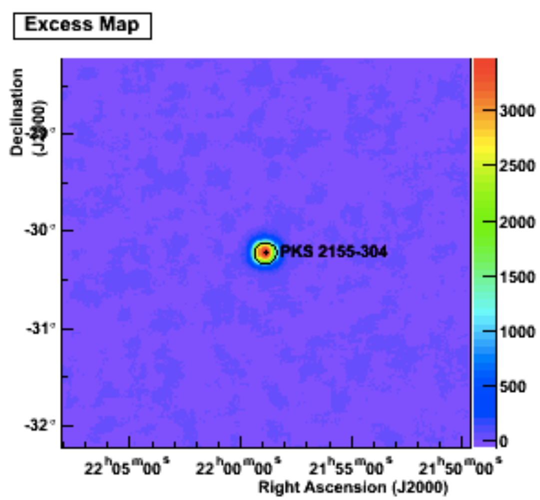
Fast electronics
Few nanoseconds signal

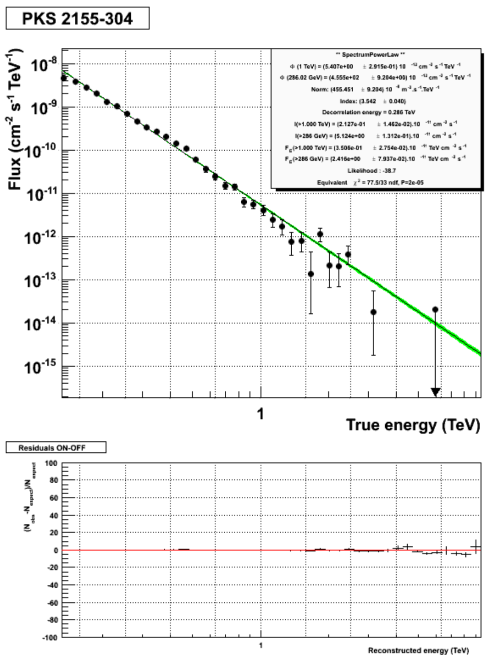
Fine pixellisation
Event tagging based on image topology

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**

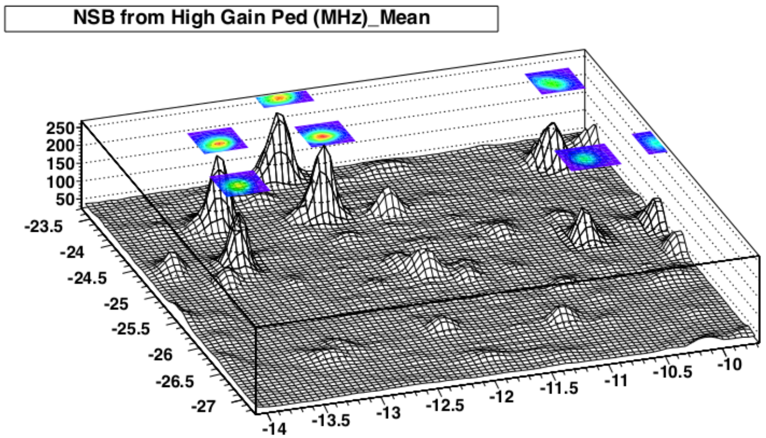






H.E.S.S. : from calibration to analysis
Personal contributions

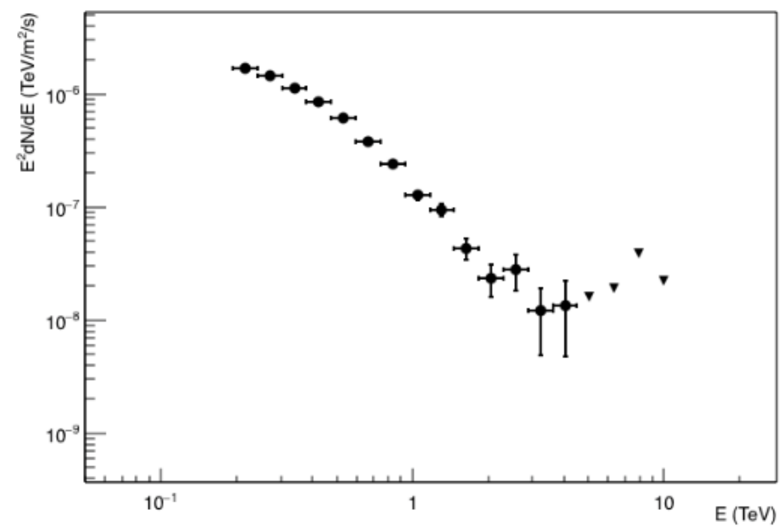
- Calibration/Reconstruction :
  method to check the pointing position with stars in the field of view



- Analysis : Implementation of an alternative spectral deconvolution method

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

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



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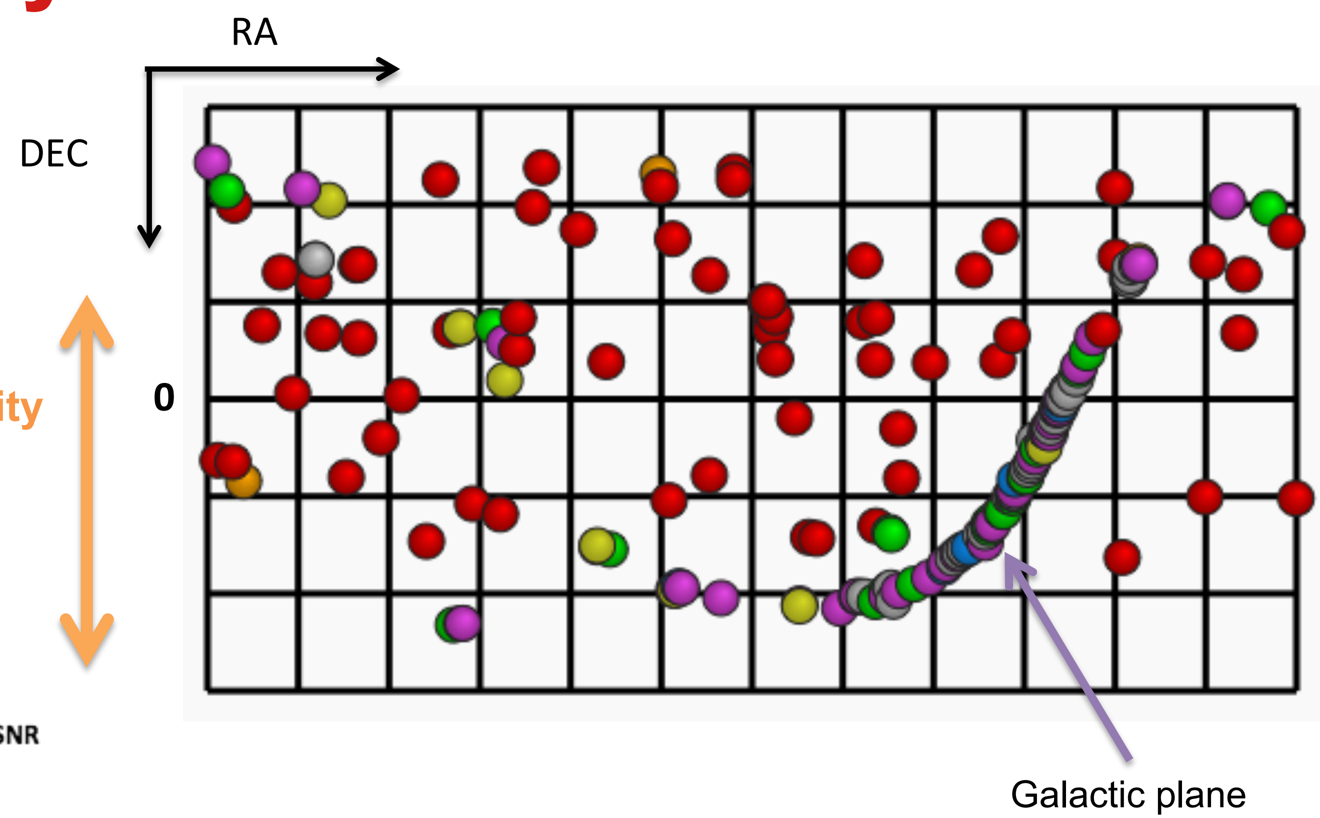
The TeV sky

tevcat2.uchicago.edu

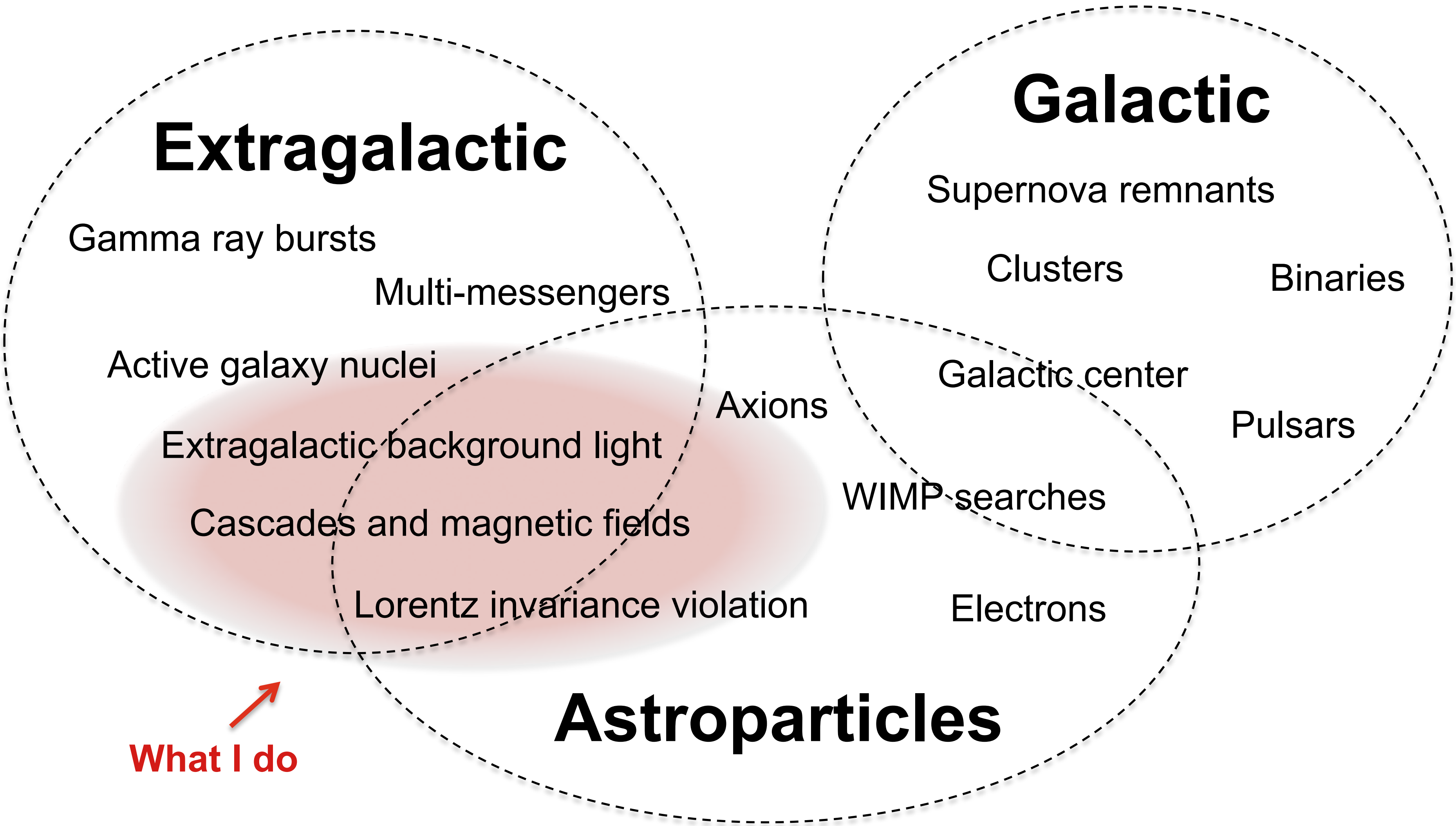
H.E.S.S. visibility (south)



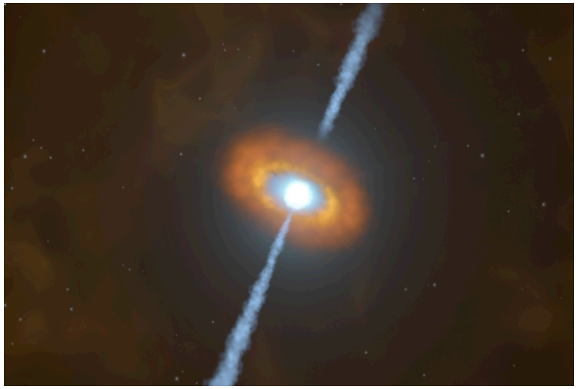
- PWN
- HBL, IBL, Blazar, FRI, FSRQ, LBL
- Shell, SNR/Molec. Cloud, Composite SNR
- Starburst, Superbubble
- UNID, DARK
- Binary, PSR
- Massive Star Cluster, Globular Cluster

176 confirmed (> 5σ) sources in total (june 2016)
62 are extragalactic (60 AGNs, 2 starburst gal.)

H.E.S.S. physics program (a selection)



Active Galaxy Nuclei, extragalactic sources of TeV γ-rays



Few % of all galaxies

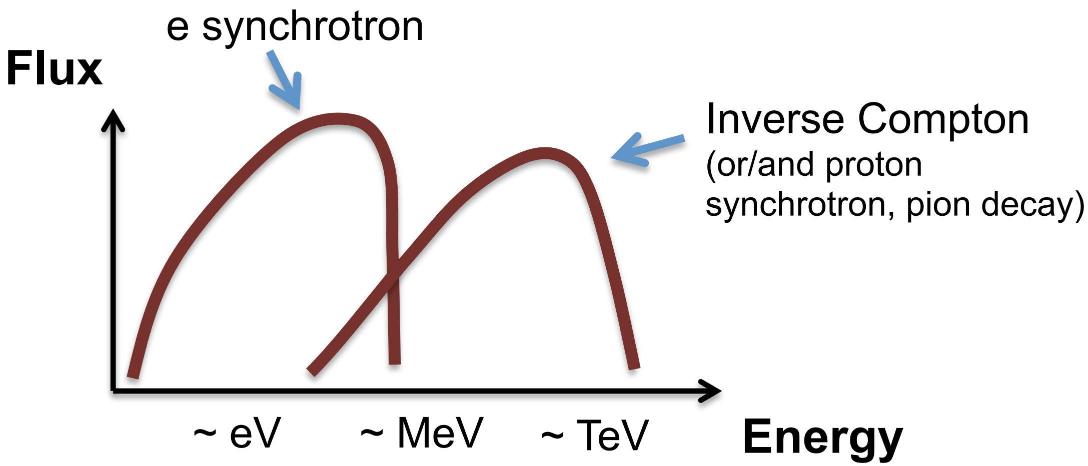
SMBH, accretion disk and highly relativistic jets

➔ Non-thermal emission across the whole EM spectrum

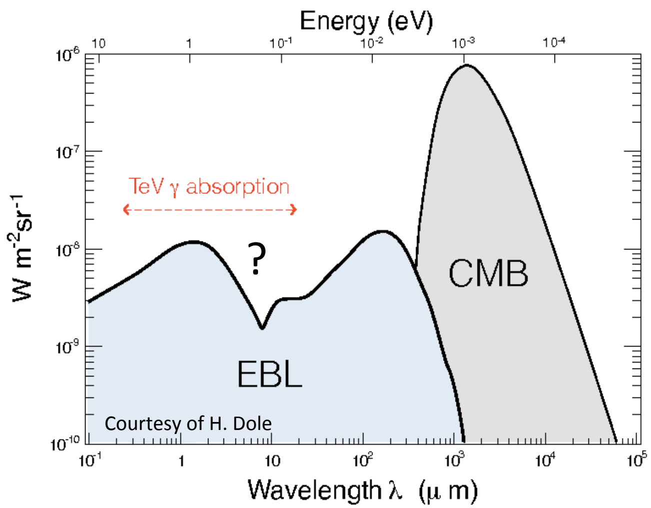
Blazars : subclass of AGN with jet closely aligned to the line of sight

Not standard candles… multi-wavelenght modeling

TeV emission spectra following ~ power laws



Extragalactic background light and γ-ray absorption

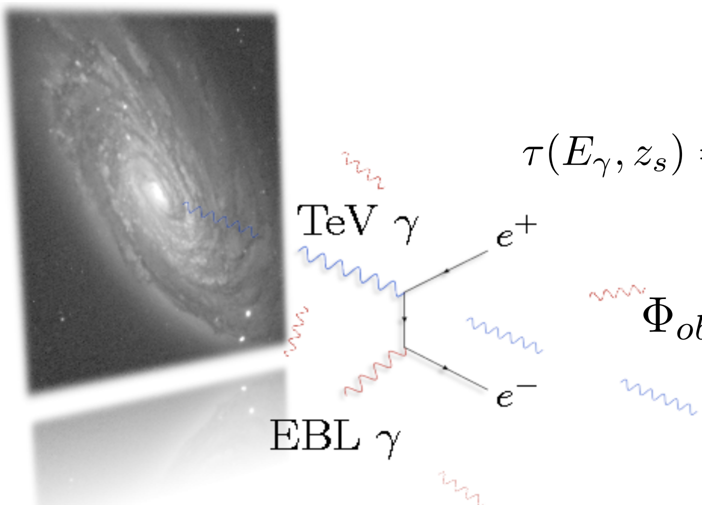


- **What is the EBL ?**
  Background photon field (IR to UV) originating from starlight and dust re-emission.
  Direct measurements are difficult

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

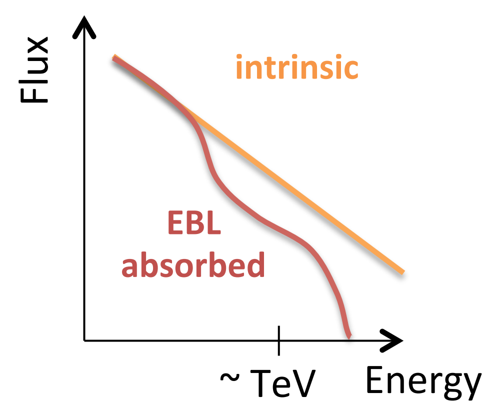
  Attenuation pattern in VHE spectra of distant sources

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



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

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



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EBL with H.E.S.S.

H.E.S.S. collaboration (2013), A&A, 550, A4

- **Model dependent approach**: model of Franceschini et al. 2008

- **Fixed shape**, normalization only
  - $\alpha = 0$: no EBL
  - $\alpha = 1$: EBL normalized to FR08

- Result with H.E.S.S. bright blazars :

  $\alpha = 1.27^{+0.18}_{-0.15}$ (stat) +/- 0.25 (syst)

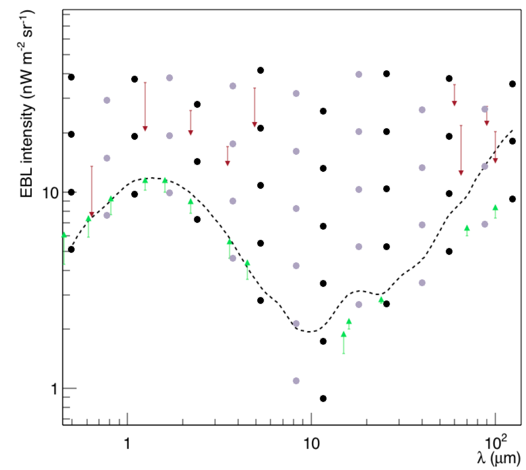
- **Now, different approach :**

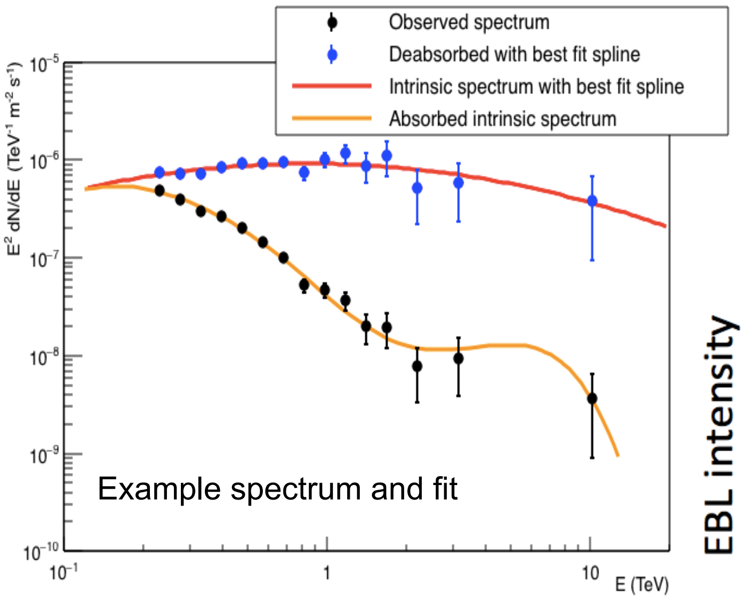
  Can we also determine the shape of the EBL with H.E.S.S. in a **model independent** way ?

Access the EBL shape ?

H.E.S.S. spectrum

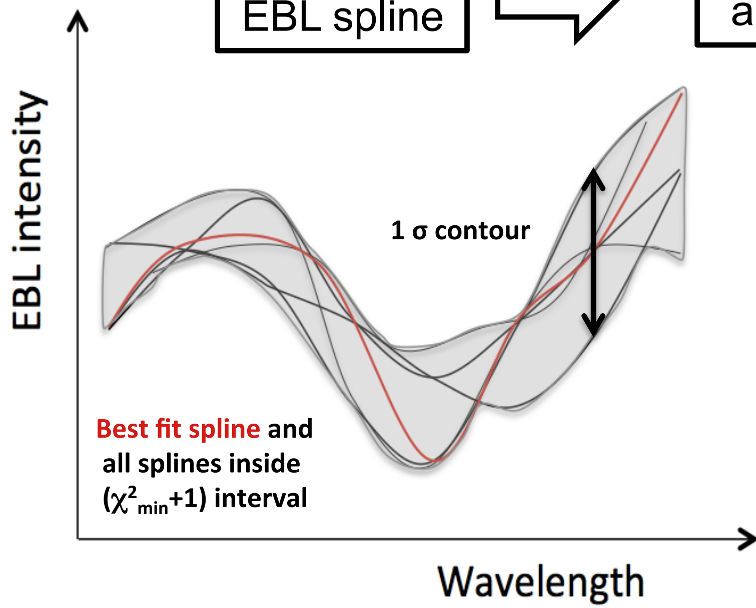
Grid scan :
Fit intrinsic + EBL absorption with every shape on the grid





Best Fit EBL spline

Envelope (χ^2_{min}+1) around best fit spline



Combine all data sets

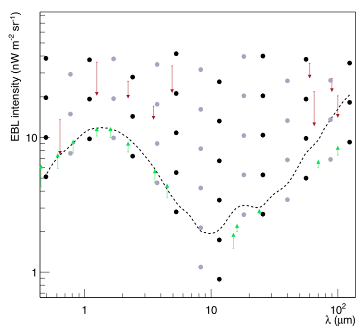
A model-independent EBL measurement !

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

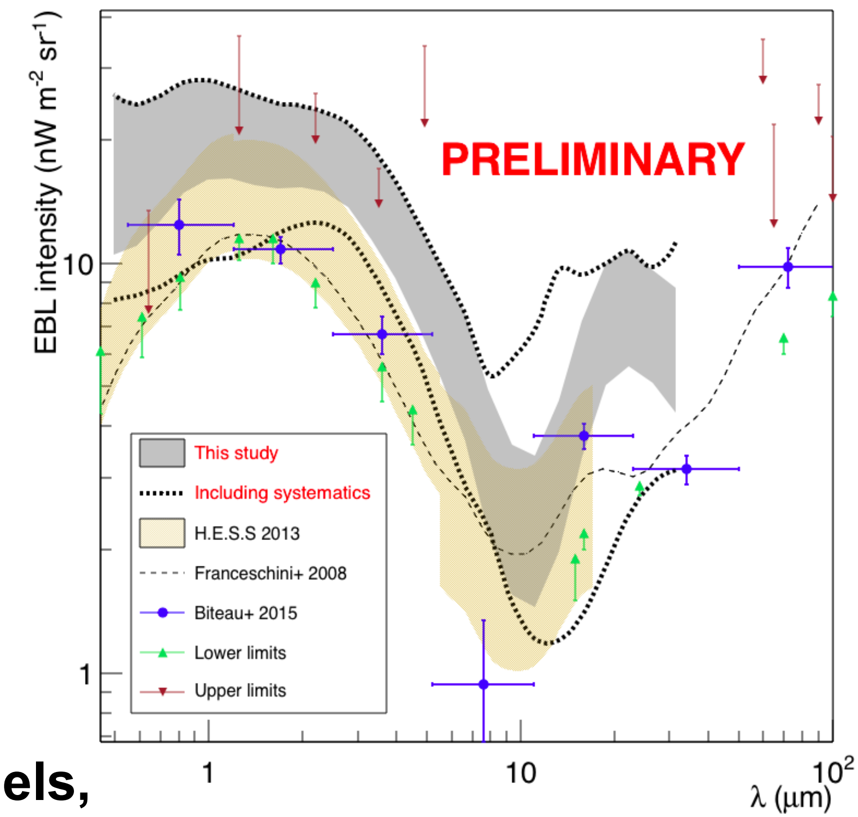
$$\frac{dN}{dE} \propto E^{-\alpha-\beta\log(E)}$$

- Scan of EBL splines constructed upon a grid

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



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



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

Cascades and extragalactic magnetic fields

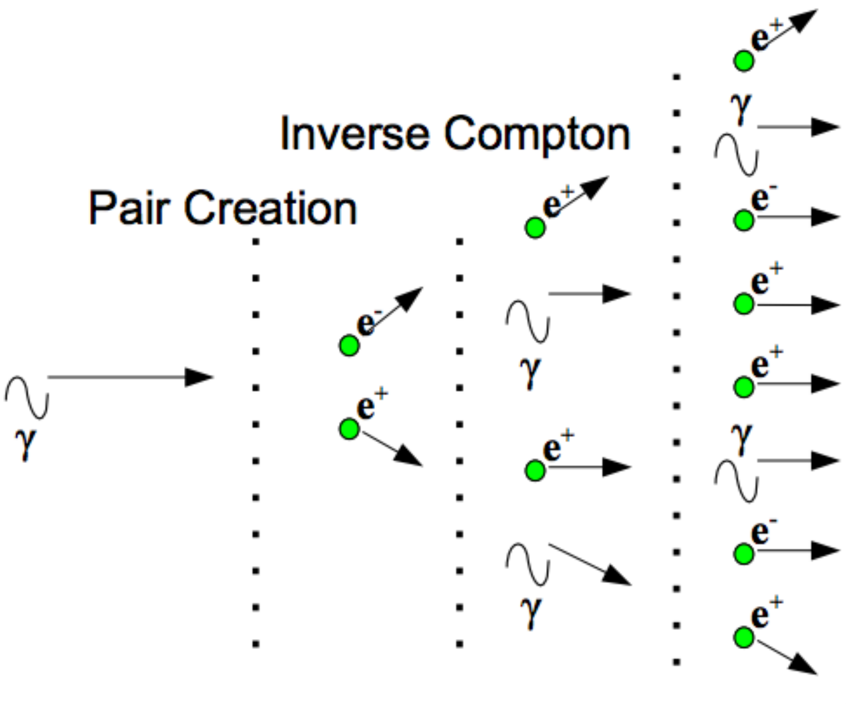
EM cascades initiated by pair creation on the EBL …

- Inverse Compton on the CMB with progressive energy losses

Typical cascade extension 0.1 to 1 Mpc 10 TeV photon reprocessed ~100 GeV

- Cascade development function of magnetic fields in the line of sight

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



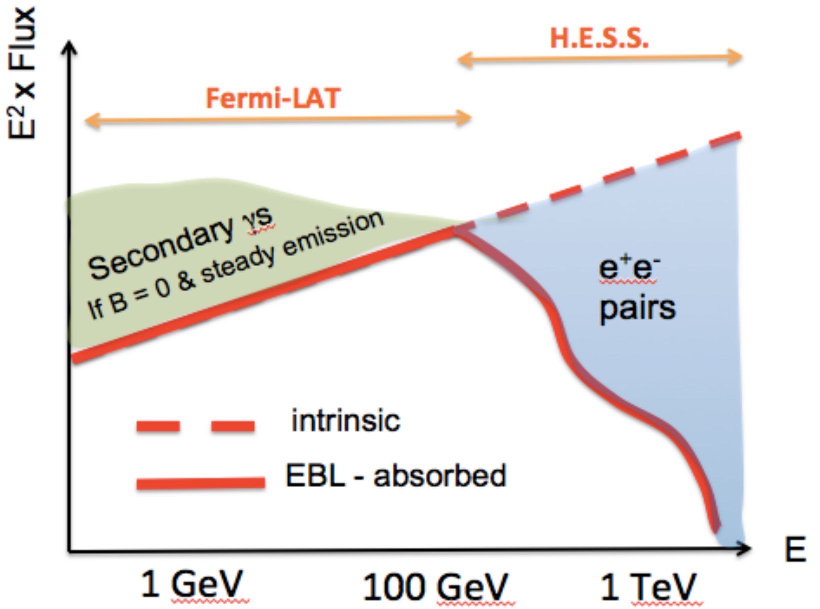
Cascades and ExtraGalactic Magnetic Fields

Power transfered from primary γ-ray beam to secondary emission

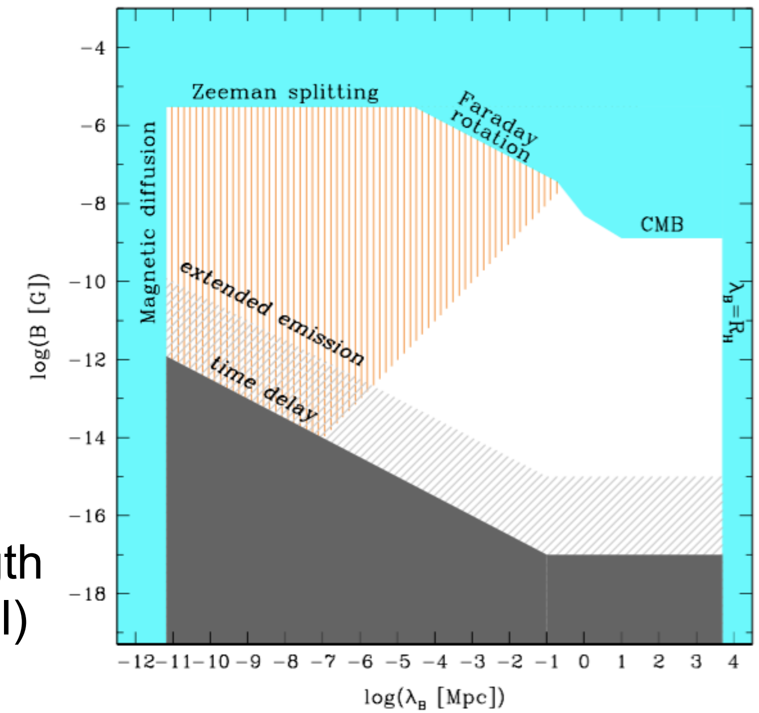
➔ Spatial (extension) and temporal (delays) features in HE / VHE

Both aspects reflected in energy spectrum

Fermi data publicly available



Taylor, Vovk & Neronov arXiv:1101.0932



Limits on the EGMF strength and coherence length

➔constrain its origin (Primordial vs. Astrophysical)

ML et al. in preparation

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

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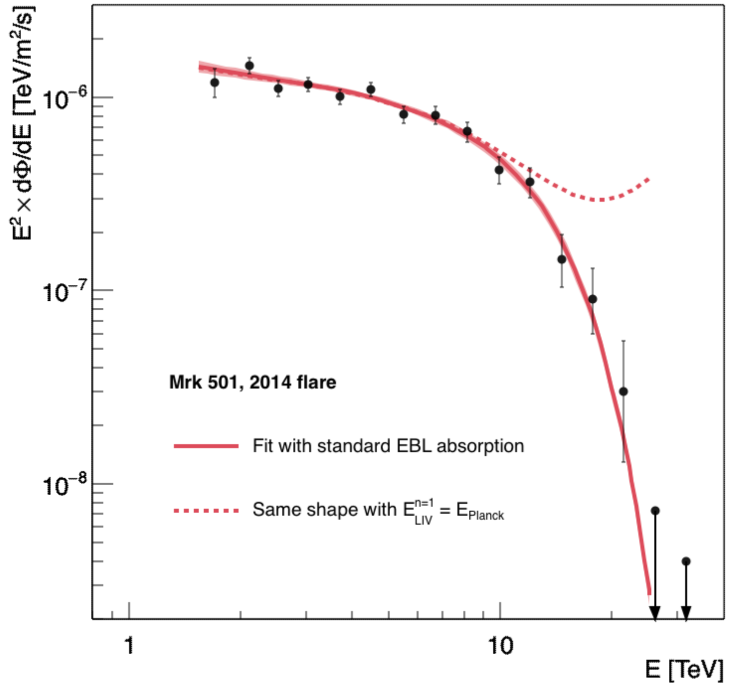
LIV limits at E_{Planck} with H.E.S.S. data

- Deviation from standard case show up at highest energies (>10 TeV)



- Mrk 501 blazar 2014 flaring state
  ➔ strong LIV limits in the photon sector
  - Planck scale exclusion for the linear case
  - Currently the best LIV limits in the quadratic case

ML & Pierre Brun, RICAP 2016
arXiv:1606.08600
H.E.S.S. paper in prep.

	$2\,\sigma$	$3\,\sigma$	$5\,\sigma$
n=1	2.8×10^{28} eV ($2.29 \times E_{Planck}$)	1.9×10^{28} eV ($1.6 \times E_{Planck}$)	1.04×10^{28} eV ($0.86 \times E_{Planck}$)
n=2	7.5×10^{20} eV	6.4×10^{20} eV	4.7×10^{20} eV

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Summary

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

- Control of telescope pointing accuracy
- Spectral deconvolution

TeV γ-ray astronomy to do 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

Future key science topics for CTA

Thanks for you attention

Extra slides

Axions

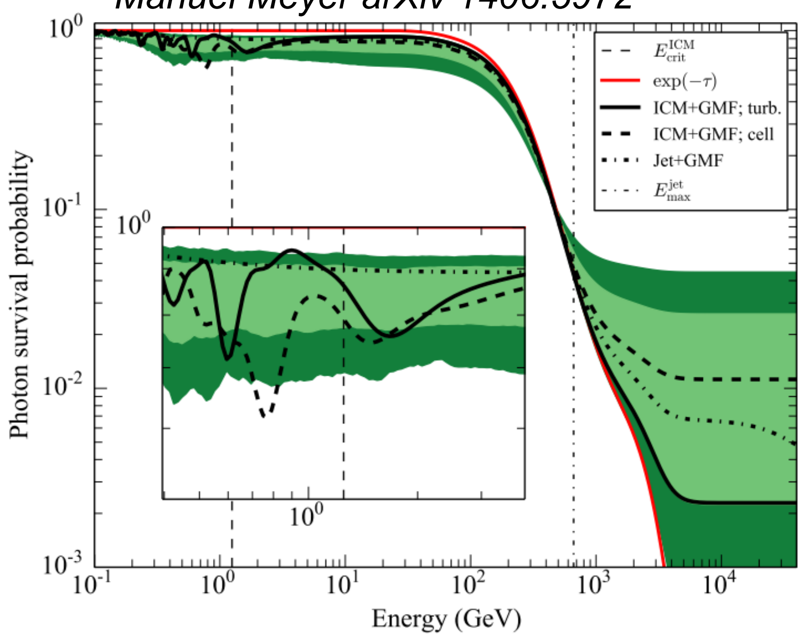
$$\mathcal{L}_{a\gamma} = \frac{1}{4} g_{a\gamma} \tilde{F}_{\mu\nu} F^{\mu\nu} a = g_{a\gamma} \, \mathbf{E} \cdot \mathbf{B} \, a.$$

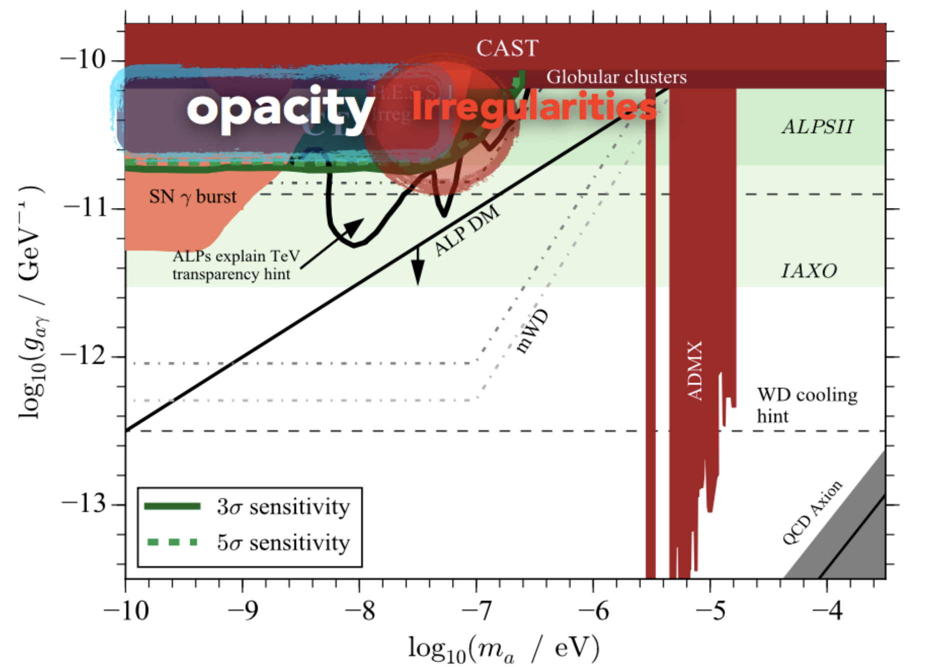
Axion-photon conversion in magnetic fields => opacity modifications

- Spectral irregularities at lower energies
- Transparency excess at higher energies

Very dependent on magnetic field configuration along line of sight
Large variance of the expected signal

Manuel Meyer arXiv 1406.5972



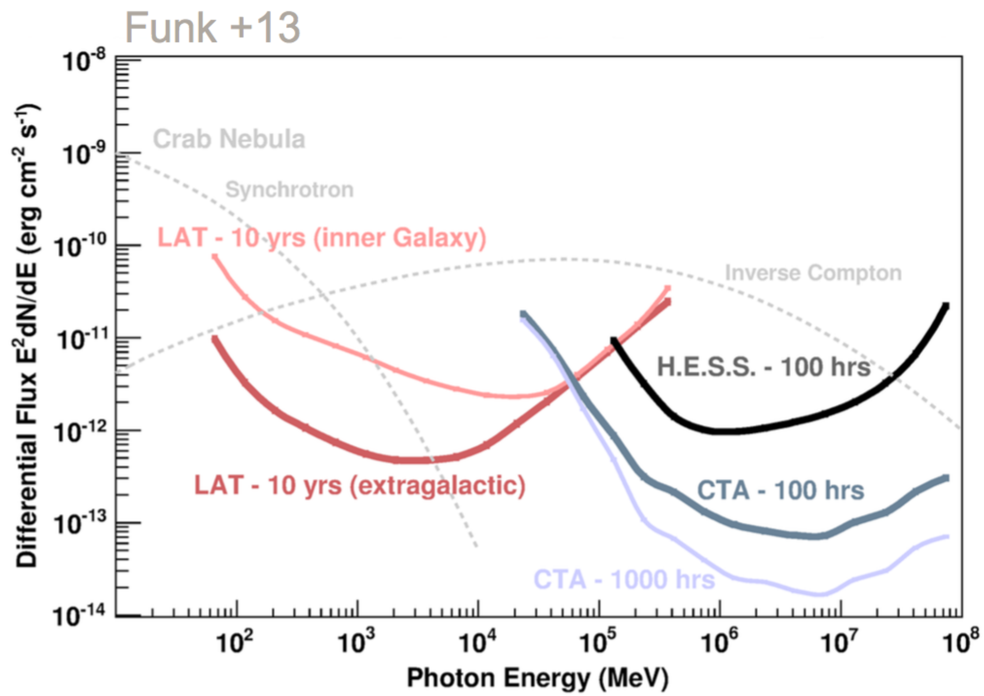


x10 sensitivity w.r.t current IACTs

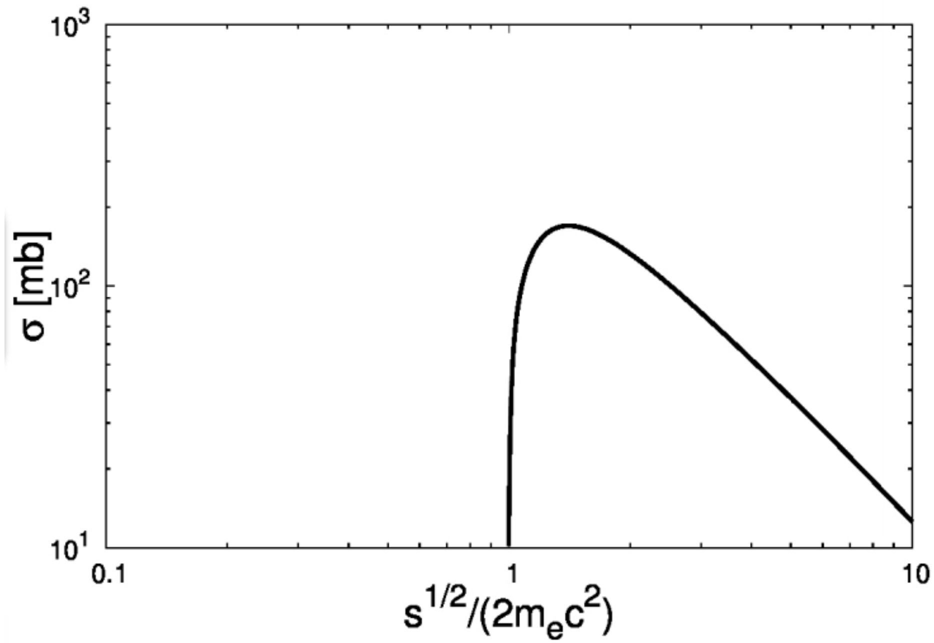
Energy range extensions
< 10s of GeV and > 10s of TeVs

Finer spectroscopy of the EBL
UV & Far IR EBL
EBL evolution
Increased sensitivity to LIV,
EGMF, axions …

Early physics analyses ~ 2020



Probed range in EBL energy



Threshold :

$$E_{EBL}\ (\mathrm{eV}) \simeq \frac{0.26}{(1+z)^2 E_\gamma(\mathrm{TeV})}$$

(~4.77 microns)

Peak :

$$E_{EBL}\ (\mathrm{eV}) \simeq \frac{1.04}{(1+z)^2 E_\gamma(\mathrm{TeV})}$$

(~1.187 microns)

Monitoring pointing accuracy using the night sky background

Pointing accuracy after mechanical corrections : down to 10” (2.7 x 10^{-3} °)

We see optical wavelenght !

Night sky background (NSB) = ambiant light + stars in the field of view

NSB enlarge pedestal

Can be used to check the pointing (analysis level) by comparing with catalog position of stars