
# GeV-TeV Observations of the most energetic blazars

## What can we learn about the jet emission and the extragalactic background light

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# Curiculum Vitae

**PhD at Laboratoire Leprince-Ringuet (LLR) 2007-2010**

- Preparation, analysis and publication of the first GeV-TeV simultaneous ground/space observations
- *Fermi* data analysis
- Modelling (Model synchrotron self-Compton, SSC)
- *Fermi* experiment: Parametrization and determination of the trigger threshold of the calorimeter

**Position Post-Doctoral (Max-Planck-Institut fur Kernphysik)**

- H.E.S.S. data analysis, *Fermi* local expert
- Development/Maintenance of HAP module
- Responsible of analysis wp, Ph-D supervision
- Different publications in preparation or submitted

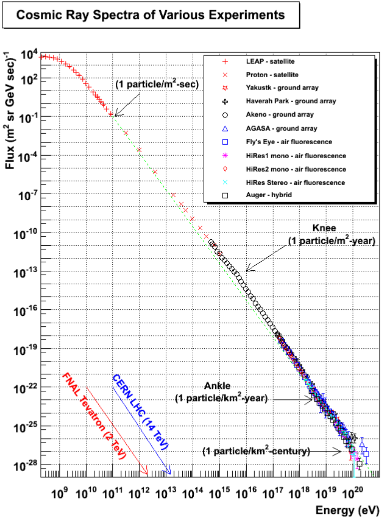
H.E.S.S. collaboration member and affiliated *Fermi*

# Outline

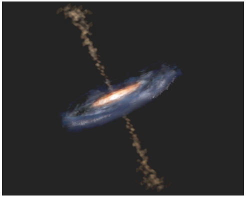
# Outline

# Cosmic rays origins

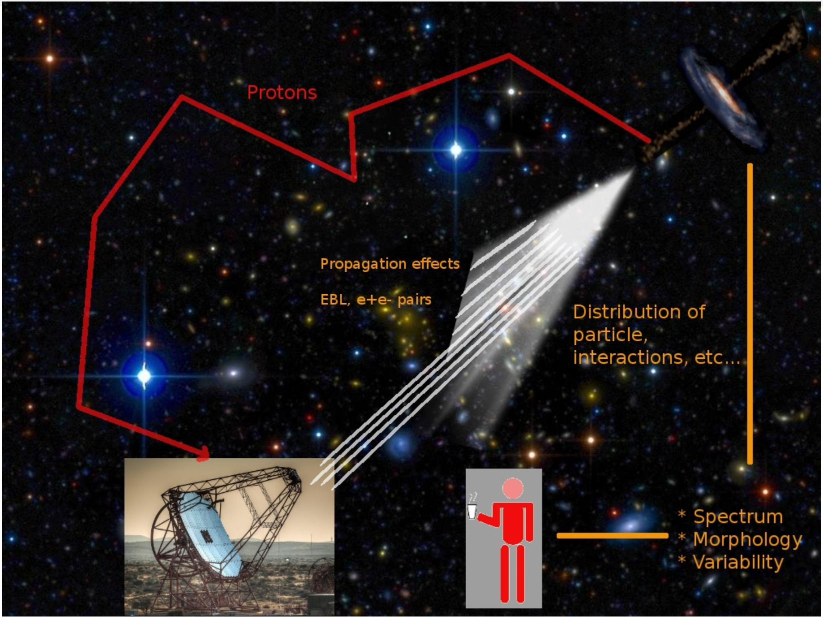
Flux $\propto E^{-\alpha}$, Site of acceleration: E$>10^{17}eV$ ?



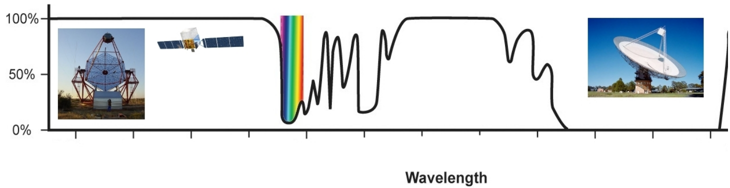

- Shock: Pulsars winds, SNR
- Compact objects: GRB, Active Galaxy Nuclei



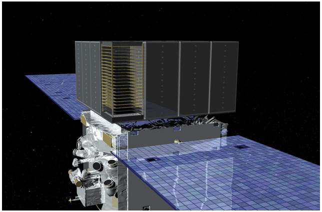
# Methodology



# Instrumentation




**Fermi LAT**

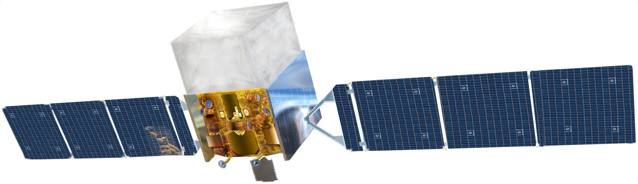


Space born
100 MeV - 300 GeV

**H.E.S.S.**

Ground based
$\simeq$ 50 GeV - 10 TeV

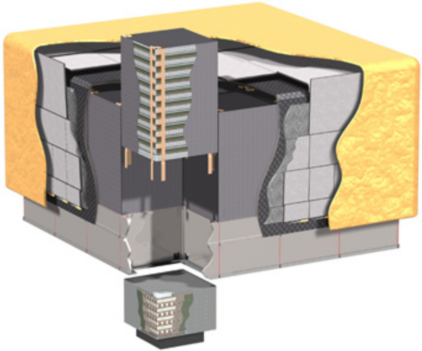
# *Fermi* satellite



**Characteristics**

- Launched 11 June 2008
- All sky monitor
- 100 MeV- 300 GeV
- Data and software publicly available

# Large Area Telescope



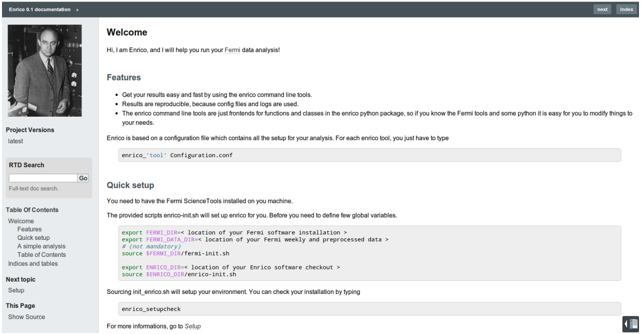
**LAT:**

- $4 \times 4$ array of identical towers
- Each one including a Tracker, a Calorimeter and an Electronics Module
- Surrounded by an Anti-Coincidence shield to reject charged particles

Analysis software (ScienceTools) and Data provided by the NASA

# LAT data analysis: Enrico python package

https://github.com/gammapy/enrico



Enrico 0.1 documentation » next index

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## Welcome

Hi, I am Enrico, and I will help you run your Fermi data analysis!

### Features

- Get your results easy and fast by using the enrico command line tools.
- Results are reproducible, because config files and logs are used.
- The enrico command line tools are just frontends for functions and classes in the enrico python package, so if you know the Fermi tools and some python it is easy for you to modify things to your needs.

Enrico is based on a configuration file which contains all the setup for your analysis. For each enrico tool, you just have to type

```
enrico_'tool' Configuration.conf
```

### Quick setup

You need to have the Fermi ScienceTools installed on you machine.

The provided scripts enrico-init.sh will set up enrico for you. Before you need to define few global variables.

```
export FERMI_DIR=< location of your Fermi software installation >
export FERMI_DATA_DIR=< location of your Fermi weekly and preprocessed data >
# (not mandatory)
source $FERMI_DIR/fermi-init.sh

export ENRICO_DIR=< location of your Enrico software checkout >
source $ENRICO_DIR/enrico-init.sh
```

Sourcing init_enrico.sh will setup your environment. You can check your installation by typing

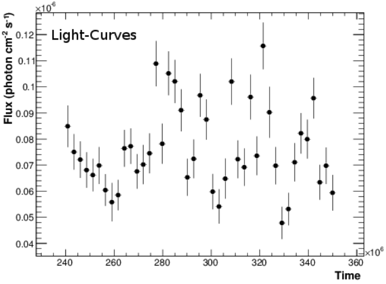
```
enrico_setupcheck
```

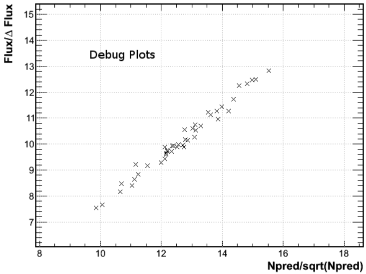
For more informations, go to *Setup*

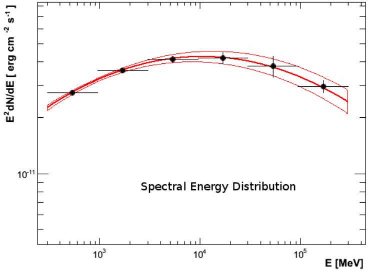
## Features:

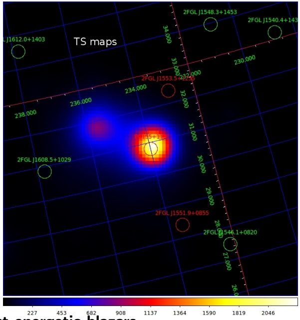
- Front-end pakage for the ST tools
- One configuration file for `Spectrum`, `LC`, `TS map`
- Debug plots

# Enrico python package

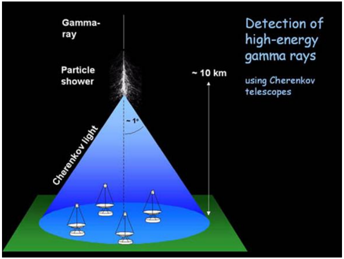


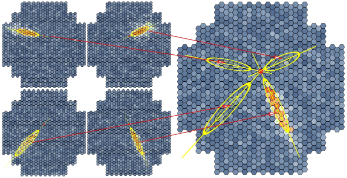



# H.E.S.S.

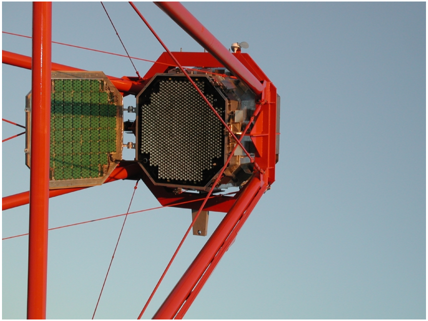



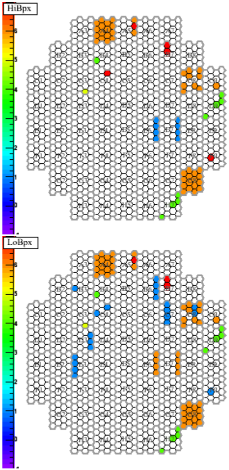
**Stereoscopy:**

- Better Gamma-Hadron separation
- Better Point Spread Function (PSF), energy resolution, etc...

# H.E.S.S camera

H.E.S.S I camera consist of 960 PMTs, good image of the shower.

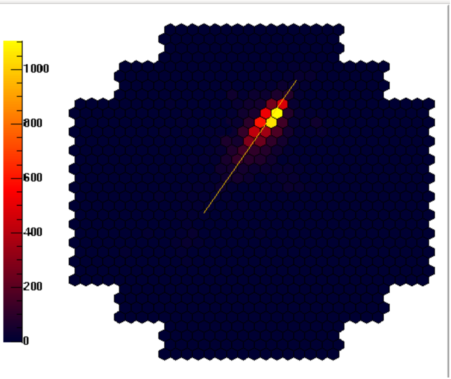


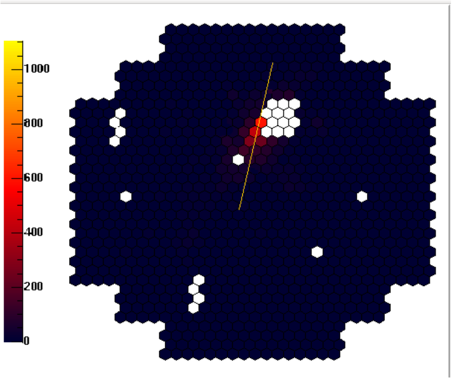



Some pixel are "broken"

- Star in the pixel
- Hardware failure

# Illustration



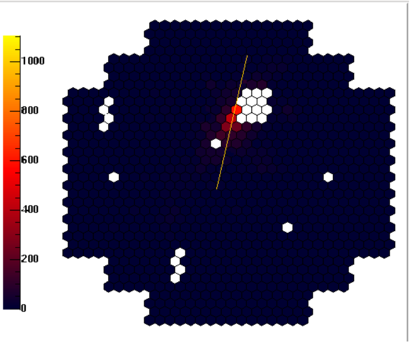




in collaboration with V. Marandon (MPIK)

# Effect of the 'broken' pixels on the PSF

**A good knowledge of PSF is important:**

- Flux determination
- Morphology studies of small source (e.g Cen A)



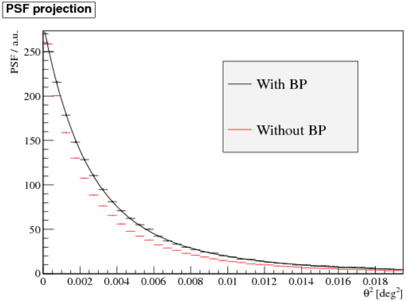

MC simulation ⇒ Data analysis ⇒ PSF, MC effective area, energy reconstruction, etc... (lookup table)

in collaboration with V. Marandon (MPIK)

# Effect of the 'broken' pixels on the PSF

MC simulation ⇒ 'broken' pixels ⇒ Data analysis ⇒ PSF, MC effective area, energy reconstruction, etc... (lookup table)

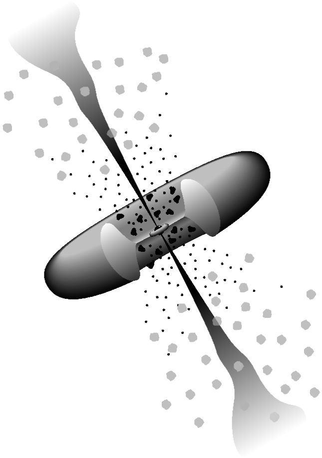
Inclusion of the 'broken' pixels:
Preliminary analyses show an increase of 8-10% of the 68% containment radius



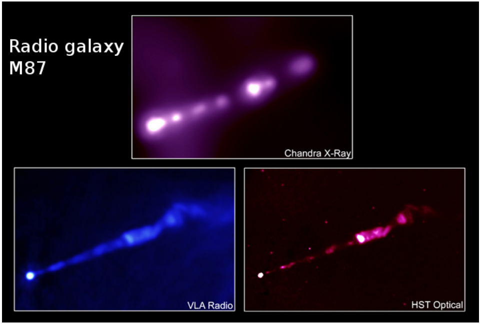

⇒ Affect also the MC effective area, energy reconstruction

in collaboration with V. Marandon (MPIK)

# The AGN's anatomy

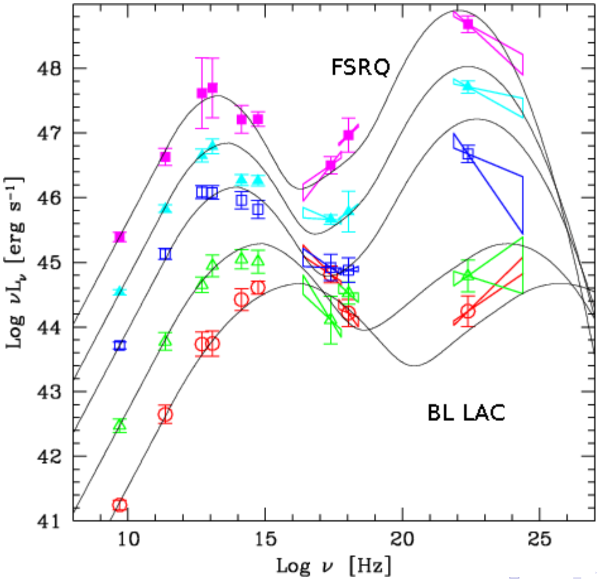


- Black Hole
- Torus, Cloud, Jet

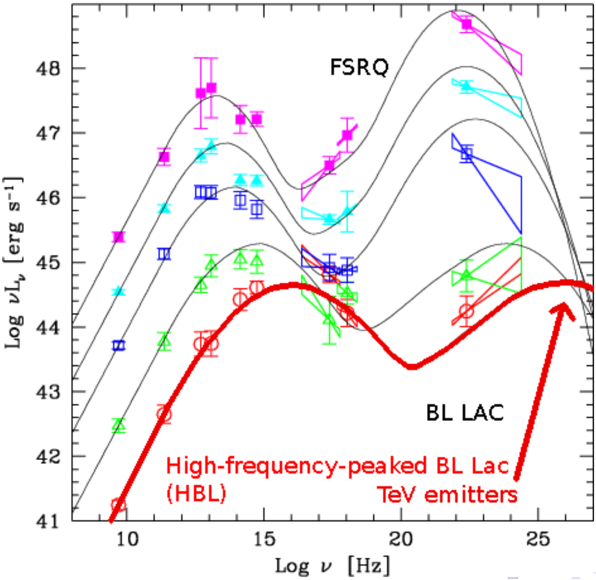


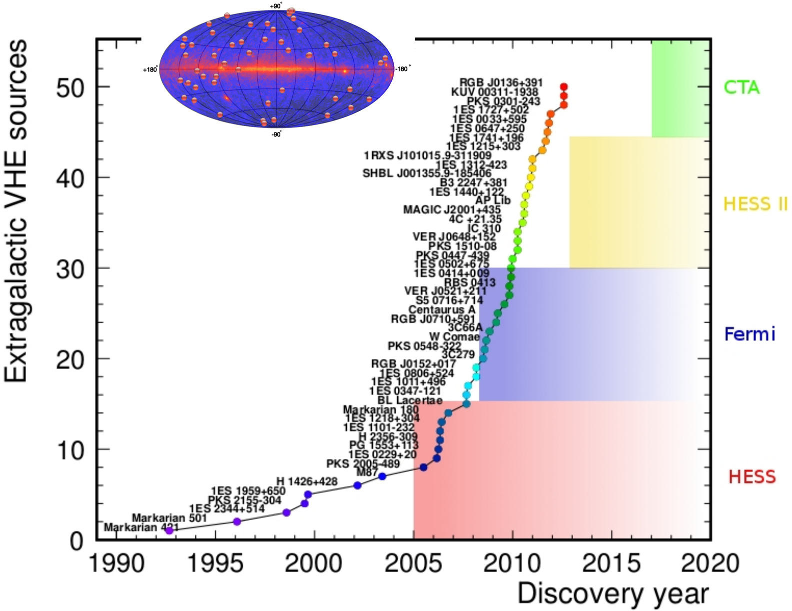

Jet Toward the observer: Blazar.

# The blazar sequence



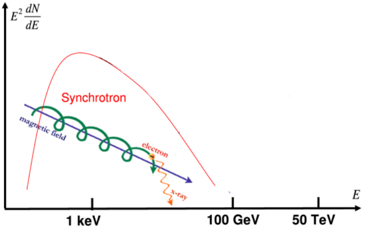
# The blazar sequence



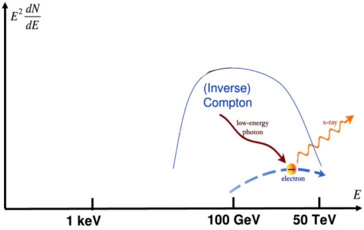

Extragalactic VHE sources
Discovery year
0
10
20
30
40
50
1990
1995
2000
2005
2010
2015
2020
CTA
HESS II
Fermi
HESS
+90°
-90°
+180°
-180°
RGB J0136+391
KUV 00311-1938
PKS 0301-243
1ES 1727+502
1ES 0033+595
1ES 0647+250
1ES 1741+196
1ES 1215+303
1RXS J101015.9-311909
1ES 1312-423
SHBL J001355.9-185406
B3 2247+381
1ES 1440+122
AP Lib
MAGIC J2001+435
4C +21.35
IC 310
VER J0648+152
PKS 1510-08
PKS 0447-439
1ES 0502+675
1ES 0414+009
RBS 0413
VER J0521+211
S5 0716+714
Centaurus A
RGB J0710+591
3C66A
W Comae
PKS 0548-322
3C279
RGB J0152+017
1ES 0806+524
1ES 1011+496
1ES 0347-121
BL Lacertae
Markarian 180
1ES 1218+304
1ES 1101-232
H 2356-309
PG 1553+113
1ES 0229+20
PKS 2005-489
M87
H 1426+428
1ES 1959+650
PKS 2155-304
1ES 2344+514
Markarian 501
Markarian 421

# Emission Models

Synchrotron process:
Radio to X-ray emission



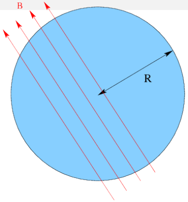

Inverse Compton process:
Soft gamma to TeV energies




Field of soft photons for IC scattering:

- External field: **External Compton (EC)**: FSRQ
- Synchrotron photons: **synchrotron self-Compton (SSC)**: HBL

# Emission Models

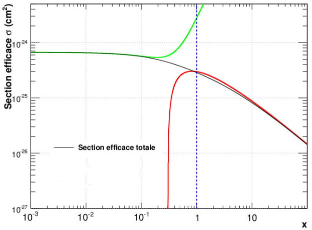



### SSC (Band & Grindlay 1985)

- Homogeneous zone of size $R$
- Constant $B$ field
- $N_e(\gamma)$ electron

### IC emission: 2 regimes

- Thomson, $E_{\rm photon} < E_{\rm electron}$
- Klein-Nishina: reduction of the cross section



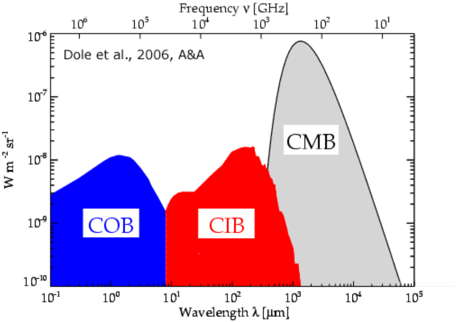

### IC bump

- Position of the peak
- Shape and size of the IC bump

Origin of the peak: break in the electron distribution or KN effects? Acceleration effect?

# Outline

# Origin of the EBL





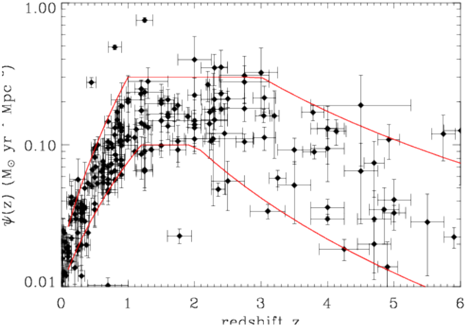
- **CMB:** Cosmic microwave background, remnant of the big bang
- **COB:** Cosmic UV & optical background, star light accumulated throughout the lifetime of the Universe
- **CIB:** Cosmic IR background, star light reprocessed by dust in the Universe

# Star Forming Rate Density

Possible to link SFRD to EBL

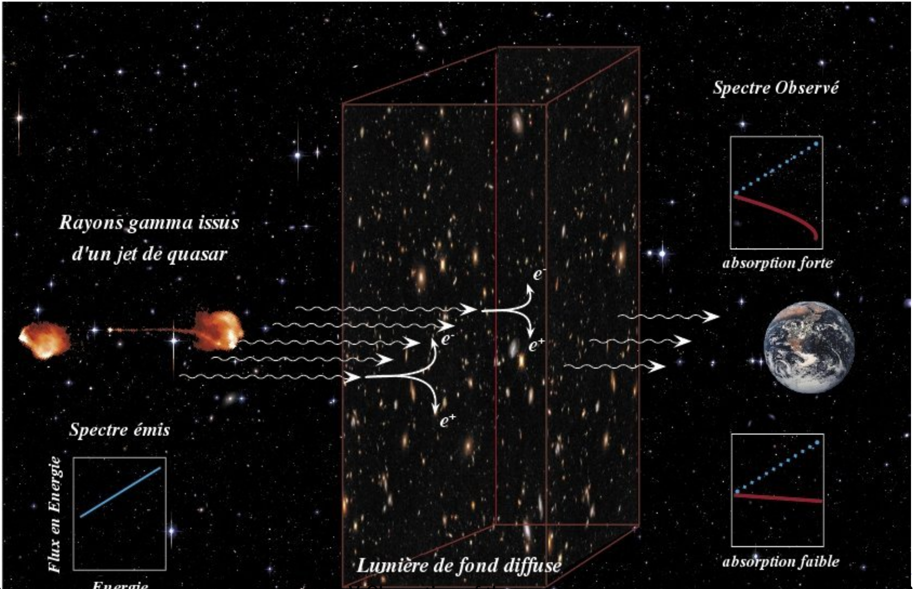
Dwek et al. 1998, Kneiske, Mannheim, Hartmann 2002

Raue & Meyer, 2012 probe the SFRD with *Fermi* and TeV data



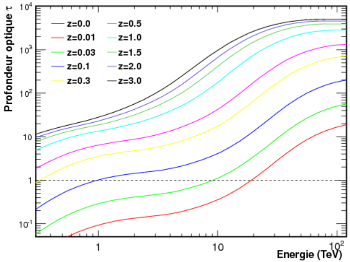

*Fermi* and Cherenkov observations can be used for cosmology.

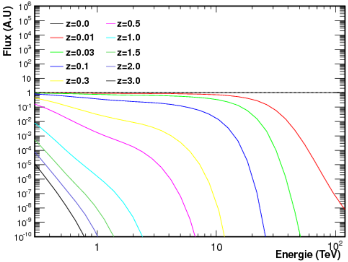
# EBL: foreground or research topic



# Effect of the EBL on TeV data

$$\phi(E)_{\mathrm{Obs}} = \phi(E)_{\mathrm{Int}} \cdot \exp(-\tau(E,z))$$



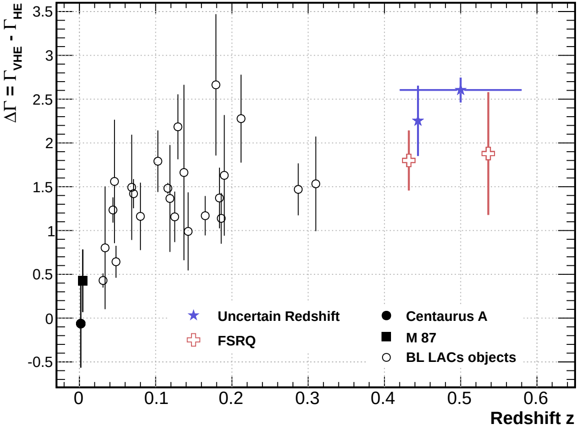

- TeV spectrum absorbed, $\Gamma_{\mathrm{TeV}} > 2$
- GeV spectrum (**unaffected**) was unknown before *Fermi*

First answer: Abdo, et al. 2009, ApJ, 707, 1310

$$\Delta\Gamma = \Gamma_{\mathrm{TeV}} - \Gamma_{\mathrm{GeV}} \geq \Gamma_{\mathrm{TeV}} - \Gamma_{\mathrm{Int}} \approx \frac{\mathrm{d}\tau(E,z)}{\mathrm{d}\log E}$$

# Dependence of $\Delta\Gamma$ with $z$

D. A. Sanchez, S. Fegan, B. Giebels, submitted




- Well represented by EBL prediction
- Linear fit cannot work: intrinsic break

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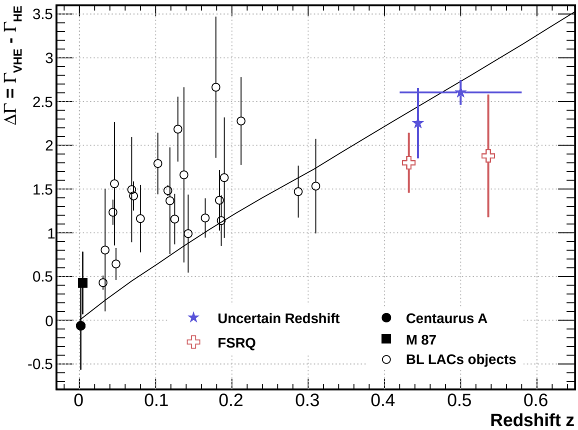


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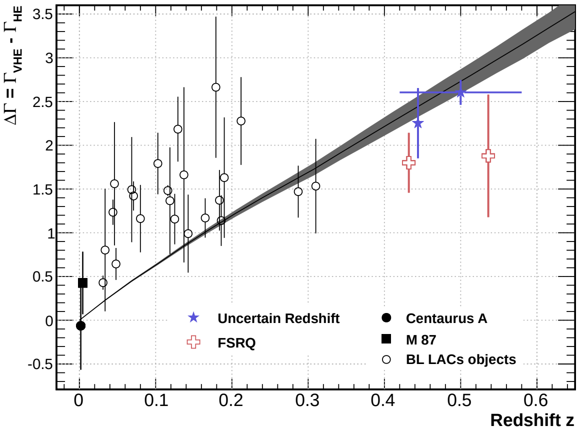


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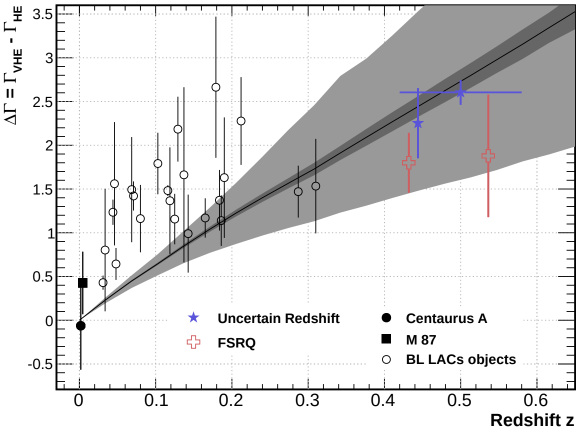
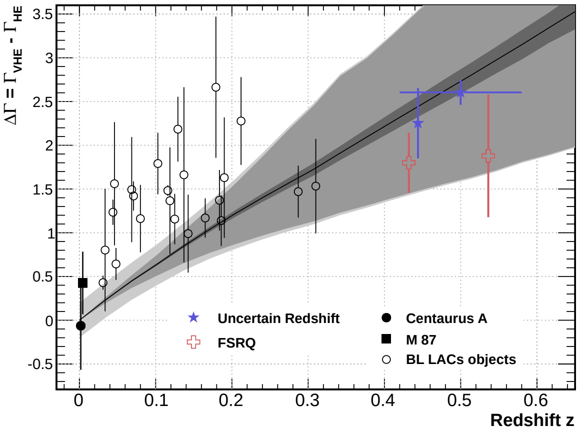



- Well represented by EBL prediction
- Linear fit cannot work: intrinsic break

# Dependence of ΔΓ with *z*

D. A. Sanchez, S. Fegan, B. Giebels, submitted




- Well represented by EBL prediction
- Linear fit cannot work: intrinsic break

# Bayesian approach: Model

- Data $Y = \{\Gamma^M_{\mathrm{G}i}, \Gamma^M_{\mathrm{T}i}\}$
- Model parameters $\Theta = \{\Gamma^I_{\mathrm{G}i}, \Gamma^I_{\mathrm{T}i}, \Gamma^A_{\mathrm{G}i}, \Gamma^A_{\mathrm{T}i}, G\}$.

$$P(\theta|Y) = P(\theta)P(Y|\theta)$$

## Likelihood $P(Y|\theta)$

- Independent measurements of $\Gamma^A_{\mathrm{G}i}, \Gamma^A_{\mathrm{T}i}$.

## Prior $P(\theta)$

- No absorption at HE
- In VHE, assume some EBL model for $\Delta\Gamma_{\mathrm{EBL}} = \Gamma^A_{\mathrm{T}i} - \Gamma^I_{\mathrm{T}i}$
- Relation $\Gamma^I_{\mathrm{G}i}$, $\Gamma^I_{\mathrm{T}i}$ is some function F

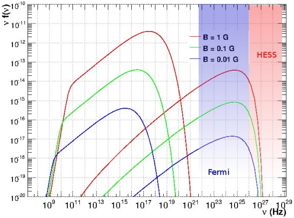
$\Rightarrow$ **F is given by SSC simulations.**

D. A. Sanchez, S. Fegan, B. Giebels, submitted

# Bayesian approach: SSC simulations

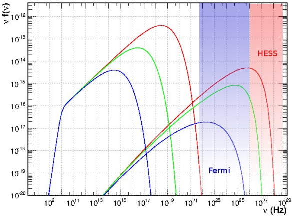
Jet Parameters are $B$, $R$, $\delta$
Distribution of electrons

$$N_e = N_0 \gamma^p \exp(-\gamma/\gamma_{\rm cut})$$




**Interesting parameters for the simulations**

- Magnetic field B: energy of the soft photons
- $\gamma_{\rm cut}$: high-energy electrons




$10^5$ simulations have been performed

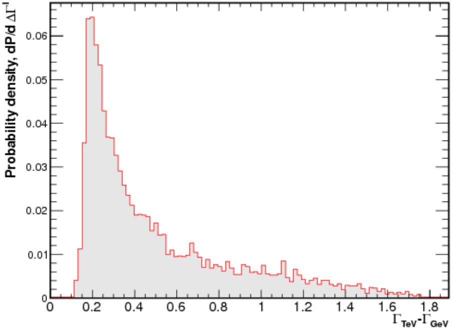
D. A. Sanchez, S. Fegan, B. Giebels, submitted

# Bayesian approach: SSC simulations

Only HBL type sources have been selected, based on the peaks positions

Distribution of simulated $\Delta\Gamma$

- Peaked around $\Delta\Gamma = 0.2$
- Long tail

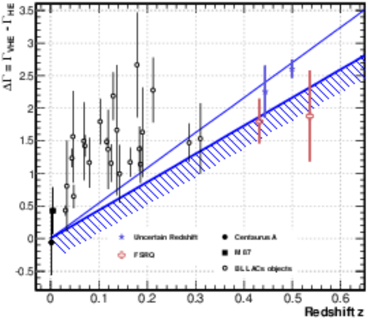


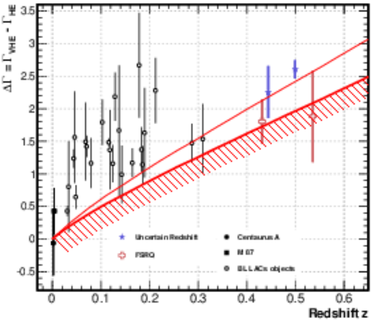

This approach allows the intrinsic break to be taken into account

D. A. Sanchez, S. Fegan, B. Giebels, submitted

# Bayesian approach: results

- $\Delta\Gamma_{\mathrm{EBL}} = az$ as in Stecker & Scully, 2006
- $\Delta\Gamma_{\mathrm{EBL}} = \alpha\Delta\Gamma_{\mathrm{Fra08}}$




D. A. Sanchez, S. Fegan, B. Giebels, submitted

# Bayesian approach: results

| Parameter | Linear model | Parameter | Scaled Fra08 model |
|---|---|---|---|
| Mean value: $\langle a \rangle$ | 5.37 | Mean value: $\langle \alpha \rangle$ | 0.85 |
| RMS: $\sqrt{\langle a^2 \rangle - \langle a \rangle^2}$ | 0.65 | RMS: $\sqrt{\langle \alpha^2 \rangle - \langle \alpha \rangle^2}$ | 0.10 |
| Upper limit: $a_{P<95\%}$ | 6.44 | Upper limit: $\alpha_{P<95\%}$ | 1.02 |
| Lower limit: $a_{P>5\%}$ | 4.32 | Lower limit: $\alpha_{P>5\%}$ | 0.69 |

- (Stecker & Scully, 2006) *baseline model*, $a \approx 8$: Our results cannot be reconciled
- Good agreement with the model of Franceschini et al., 2008

D. A. Sanchez, S. Fegan, B. Giebels, submitted

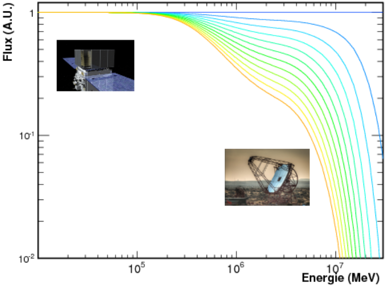
# Disentangle EBL and intrinsic spectra using H.E.S.S. data

J. Biteau, B. Giebels, D. A. Sanchez, HESS collaboration, submitted

- The EBL effect is more complex than a power law
- 'wiggle' which is redshift dependent

$$\phi(E)_{\mathrm{Obs}} = \phi(E)_{\mathrm{Int}} \cdot \exp(-\alpha \cdot \tau(E, z))$$

- $\alpha$ is a parameter
- $\alpha$ and $\phi(E)_{\mathrm{Int}}$ are fitted together

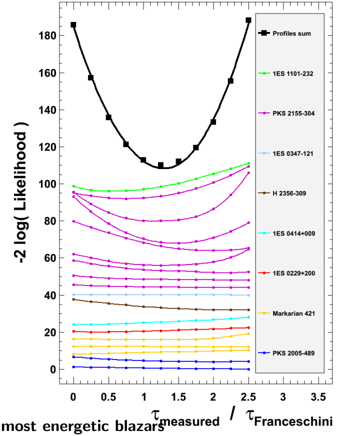


# Data set and Results

| | | Used Model |
|---|---|---|
| Mrk 421 | | |
| | 1 | LogParabola |
| | 2 | PowerLaw |
| | 3 | PowerLaw |
| PKS 2005-489 | | |
| | 1 | PowerLaw |
| | 2 | SuperExpCutoffPL |
| | 3 | PowerLaw |
| PKS 2155-304 | | |
| | 1 | SuperExpCutoffPL |
| | 2 | PowerLaw |
| | 3 | SuperExpCutoffPL |
| | 4 | SuperExpCutoffPL |
| | 5 | SuperExpCutoffPL |
| | 6 | LogParabola |
| | 7 | ExpCutoffLogParabola |
| | 2008 | SuperExpCutoffPL |
| 1ES 0229+200 | | PowerLaw |
| H 2356-309 | | SuperExpCutoffPL |
| 1ES 1101-232 | | LogParabola |
| 1ES 0347-121 | | PowerLaw |
| 1ES 0414+009 | | LogParabola |

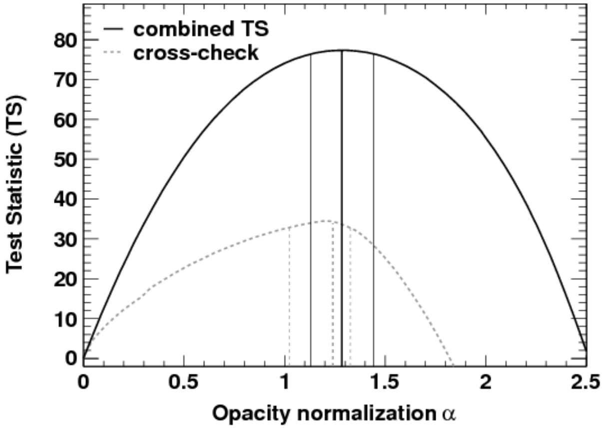
TABLE 1
MODELS DESCRIBING THE INTRINSIC SPECTRA

- 7 bright or distant AGN
- Index-flux dependence taken into account



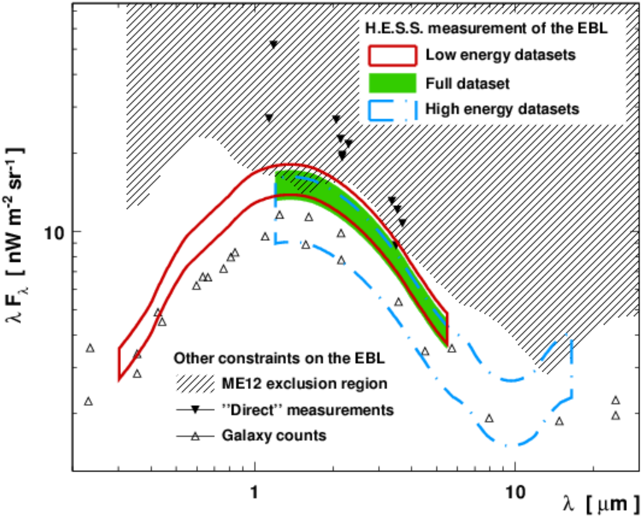
# Results

Discovery at $8\sigma$ with the `Model` analysis: $\alpha_0 = 1.27^{+0.18}_{-0.15}$
Cross-check with HD Hillas analysis



# Constraint on the SED of the EBL

Measurement of $\alpha \Rightarrow$ Measurement of the EBL density



# Conclusion on the EBL

- EBL density has some uncertainties
- Cosmological probe

**Comparison GeV-TeV spectrum**

- GeV is the intrinsic spectrum
- Can rule out models *if* the intrinsic break is taken into account
- Close to minimal EBL models

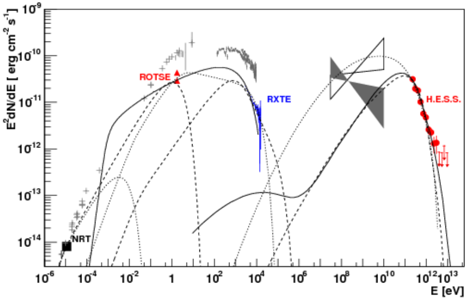
**Direct H.E.S.S measurement**

- Detection of the "wiggle": first time
- H.E.S.S. and *Fermi* agrees
- More to come with HESS II and CTA

# Outline

# Before *Fermi*

- PKS 2155-304 (2003)
- Shape of the GeV emission?
- only 8 sources in 3EG



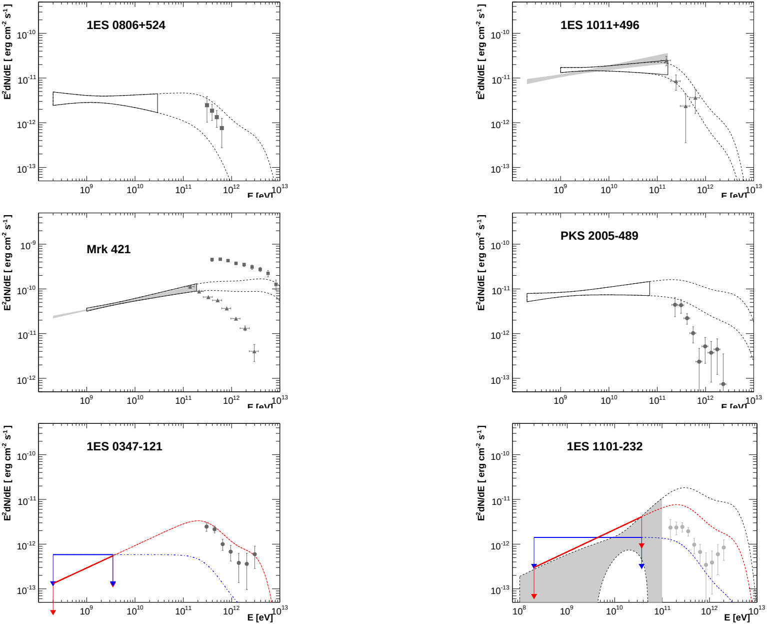

HESS collaboration, A&A, 2005

*Fermi* study of all the TeV emitters (first answer)

- 28 TeV sources, 22 seen by Fermi in 5.5 months (spectra, LCs)
- $\Gamma_{\mathrm{GeV}} < 2$, spectra agree

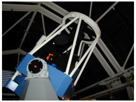
$\Rightarrow$ only 1 component

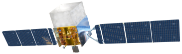
Abdo et al. ApJ, 707:1310-1333, December 2009.

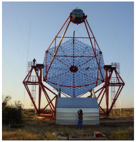



Abdo, A. A. et al. 2009, ApJ, 707, 1310

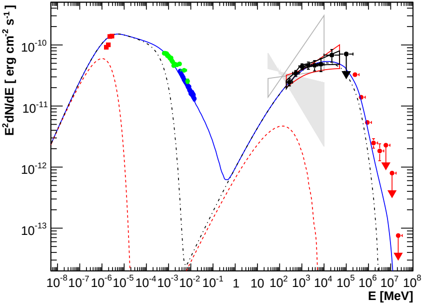
# PKS 2155-304: Observation campaign in 2008



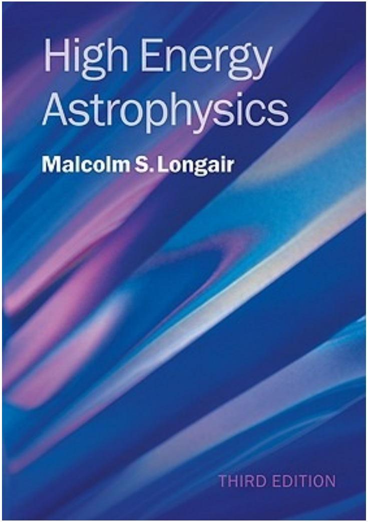




- Brightest, well-known southern source
- $z = 0.116$
- Klein-Nishina effect?




Aharonian et al., Abdo et al. ApJL, 696:L150-L155, May 2009.



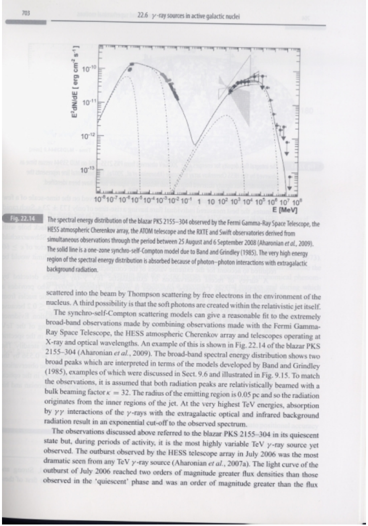






Fig. 22.14 The spectral energy distribution of the blazar PKS 2155–304 observed by the Fermi Gamma-Ray Space Telescope, the HESS atmospheric Cherenkov array, the ATOM telescope and the RXTE and Swift observatories derived from simultaneous observations through the period between 25 August and 6 September 2008 (Aharonian *et al.*, 2009). The solid line is a one-zone synchro-self-Compton model due to Band and Grindley (1985). The very high energy region of the spectral energy distribution is absorbed because of photon–photon interactions with extragalactic background radiation.

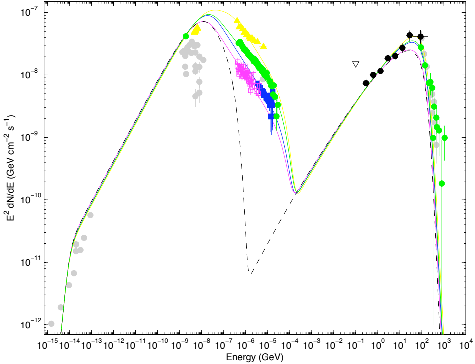
scattered into the beam by Thompson scattering by free electrons in the environment of the nucleus. A third possibility is that the soft photons are created within the relativistic jet itself.

The synchro-self-Compton scattering models can give a reasonable fit to the extremely broad-band observations made by combining observations made with the Fermi Gamma-Ray Space Telescope, the HESS atmospheric Cherenkov array and telescopes operating at X-ray and optical wavelengths. An example of this is shown in Fig. 22.14 of the blazar PKS 2155–304 (Aharonian *et al.*, 2009). The broad-band spectral energy distribution shows two broad peaks which are interpreted in terms of the models developed by Band and Grindley (1985), examples of which were discussed in Sect. 9.6 and illustrated in Fig. 9.15. To match the observations, it is assumed that both radiation peaks are relativistically beamed with a bulk beaming factor $\kappa = 32$. The radius of the emitting region is 0.05 pc and so the radiation originates from the inner regions of the jet. At the very highest TeV energies, absorption by $\gamma\gamma$ interactions of the $\gamma$-rays with the extragalactic optical and infrared background radiation result in an exponential cut-off to the observed spectrum.

The observations discussed above referred to the blazar PKS 2155–304 in its quiescent state but, during periods of activity, it is the most highly variable TeV $\gamma$-ray source yet observed. The outburst observed by the HESS telescope array in July 2006 was the most dramatic seen from any TeV $\gamma$-ray source (Aharonian *et al.*, 2007a). The light curve of the outburst of July 2006 reached two orders of magnitude greater flux densities than those observed in the 'quiescent' phase and was an order of magnitude greater than the flux

# *Fermi* observations of PG 1553+113

- Steady source in HE-VHE
- Hard spectrum
  $\Gamma = 1.68 \pm 0.03$
- Unknown redshift, Fermi extrapolation
  $z = 0.75^{+0.04}_{-0.05}$
- Last measurement
  $z \approx 0.5$

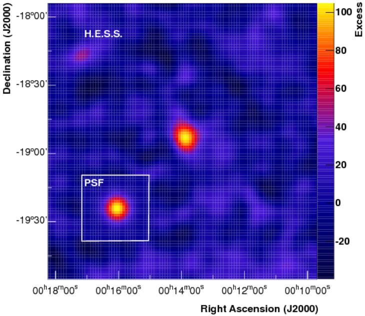


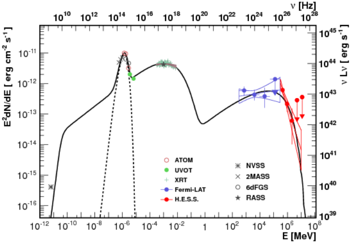

$\Rightarrow$ Variability in X-ray can be blurred by KN effect

Abdo, et al. 2010, ApJ, 708, 1310

# H.E.S.S. and *Fermi* detection of SHBL J001355.9-185406

- High-energy-peaked BL Lac
- Redshift $z = 0.095$
- H.E.S.S. and *Fermi* detection




- Synchrotron peak in X-ray
- Thomson regime: unrealistic $\delta$

Abramowski, et al. in Prep.

# Determination of the Spectra

EBL absorption distort the spectrum

$$\phi(E)_{\mathrm{Obs}} = \phi(E)_{\mathrm{Int}} \cdot \exp(-\alpha \cdot \tau(E, z))$$

$\rightarrow$ Access to the intrinsic parameters of VHE spectrum

**Methodology:**

- *Fermi* : 3.5 years of data
- H.E.S.S.: VHE spectrum, corrected for EBL

**Fit Fermi and H.E.S.S data points**

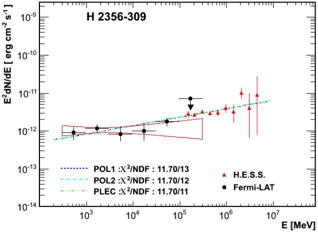
- PowerLaw: peak constrained?
- LogParabola, PL exponential cutoff: shape?

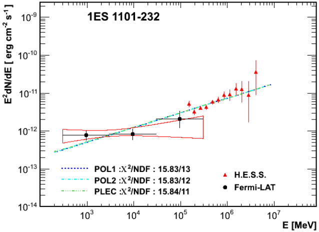
$\rightarrow$ Agreement between *Fermi* and H.E.S.S.
$\rightarrow$ Acceleration or emission process effects?

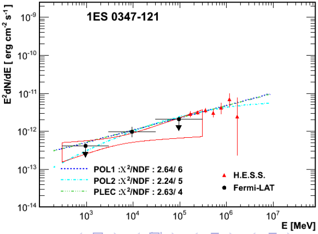
# Other objects

3 Sources do not have the position of the peak constrained

- H 2356-309, 1ES 1101-232, 1ES 0347-121
- Use a bayesian approach to derive a LL
- Challenge for SSC models

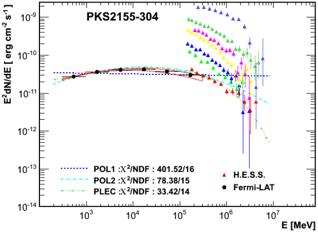


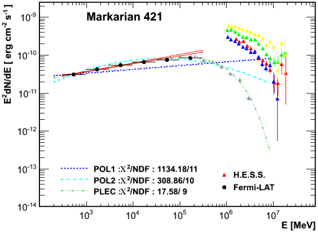



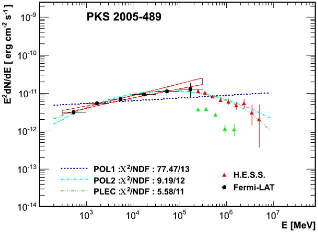



# Sources with peak constrained

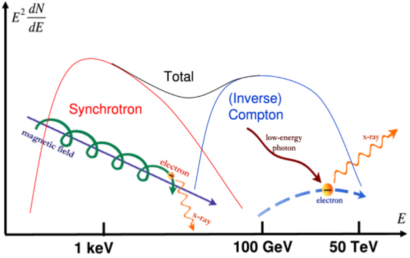
- Position of the peak constrained
- PKS 2155-304, Mrk 421, PKS 2005-489
- Described by a PLEC



# SSC modelling: VERY PRELIMINARY




$$N_e(\gamma) \propto E^{-a} \exp\left(-(E/E_c)^{\beta}\right)$$

- IC in Thomson regime $\beta_c = \beta/(\beta+4)$
- IC in KN regime $\beta_c = \beta$

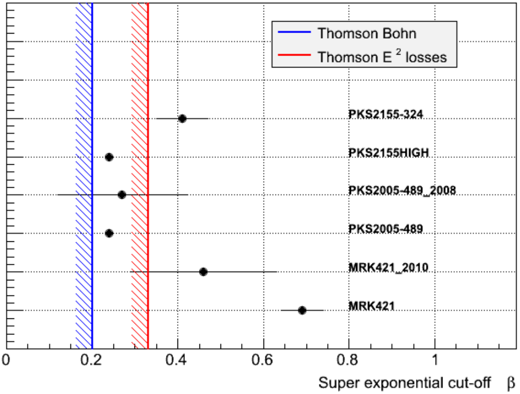
$N_e(\gamma)$ shape can be seen in the photon spectrum
*Lefa et Al., 2012*

Acceleration

- Bohm diffusion: $\beta = 3/2$
- $E^2$ losses: $\beta = 2$

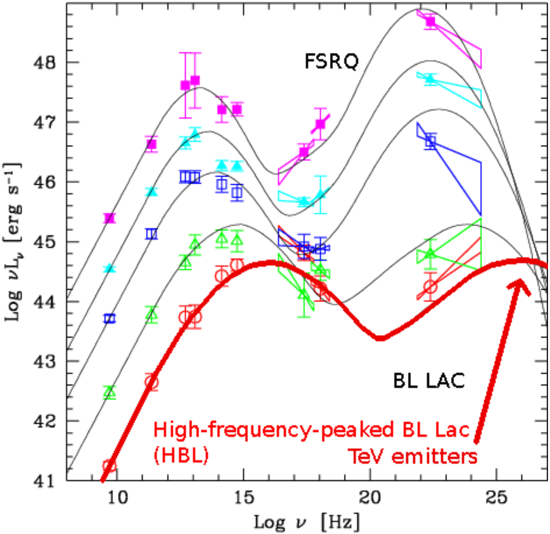
$\beta_c$ can goes from 0.27 to 0.33 in Thomson

# Super exponential cut-off exponent

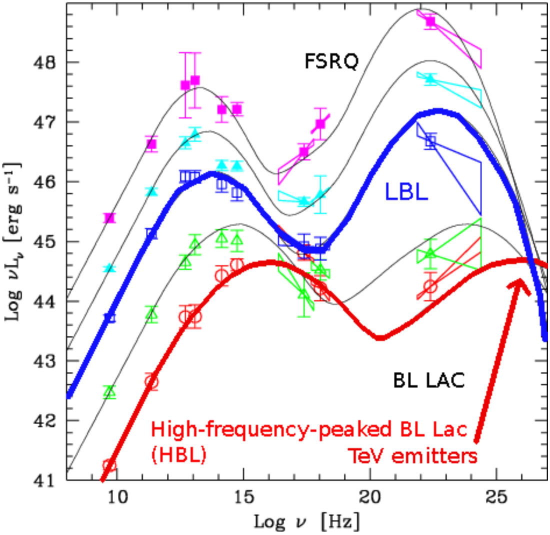



**VERY PRELIMINARY conclusions** KN effects visible?

# The blazar sequence



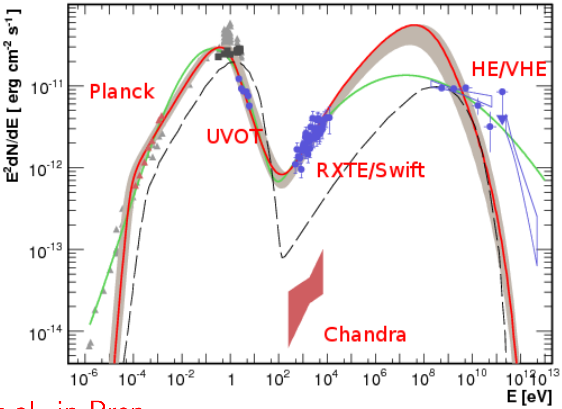
# The blazar sequence



# The challenging SED of Ap Librae

- One of the 4 LBL detected, but best characterization of an LBL
- Broad inverse Compton component

SSC model cannot work!




Aharonian et al. in Prep.

# Outline

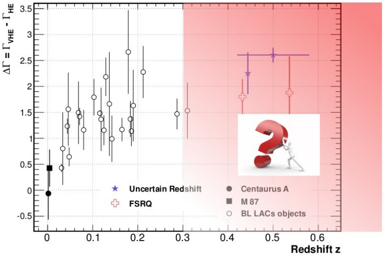
# EBL

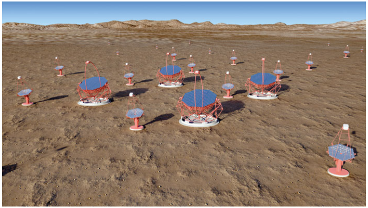
## New instruments

- More distant sources
- Wider energy range

## Future

- Wider EBL wavelength probed
- Attenuated and non-attenuated spectrum

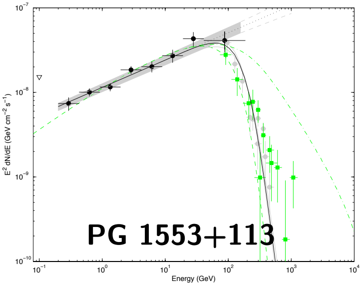


# Possible observation of H.E.S.S. II

**PKS 2155-304: Variability**

- Characterization of the Variability (Flux, TF)
- Correlation with Fermi

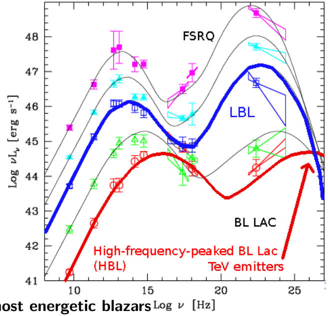



**PG 1553+113**

- Biggest GeV-TeV break
- Peak measurement: Constraints

**Observation of LBLs**

2 appealing sources for HESS and HESS II



# Summary

### *Fermi*

LAT Calorimeter monitoring
Python package for simple data analysis

### H.E.S.S.

Development of a position/morphological fitting module (HAP)
coordinator of wp analysis @ MPIK

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### EBL studies

$\Delta\Gamma$ vs $z$
D.A. Sanchez, B. Giebels and S. Fegan, submited
detection of EBL by H.E.S.S.
submited
+ follow up paper, in Prep.

### GeV-TeV Connection

Study of GeV counterpart of TeV emitters
Abdo et al. ApJ, 707 :1310-1333, December 2009.

### Single sources

PKS 2155-304: Aharonian et al., Abdo et al. ApJL, 696:L150-L155, May 2009.
PG 1553+113: Abdo et al. ApJ, 708:1310-1320, January 2010

### Single sources

AP Librae in Prep
SHBL J001355.9-185406 in Prep
1ES 1312-423 in Prep