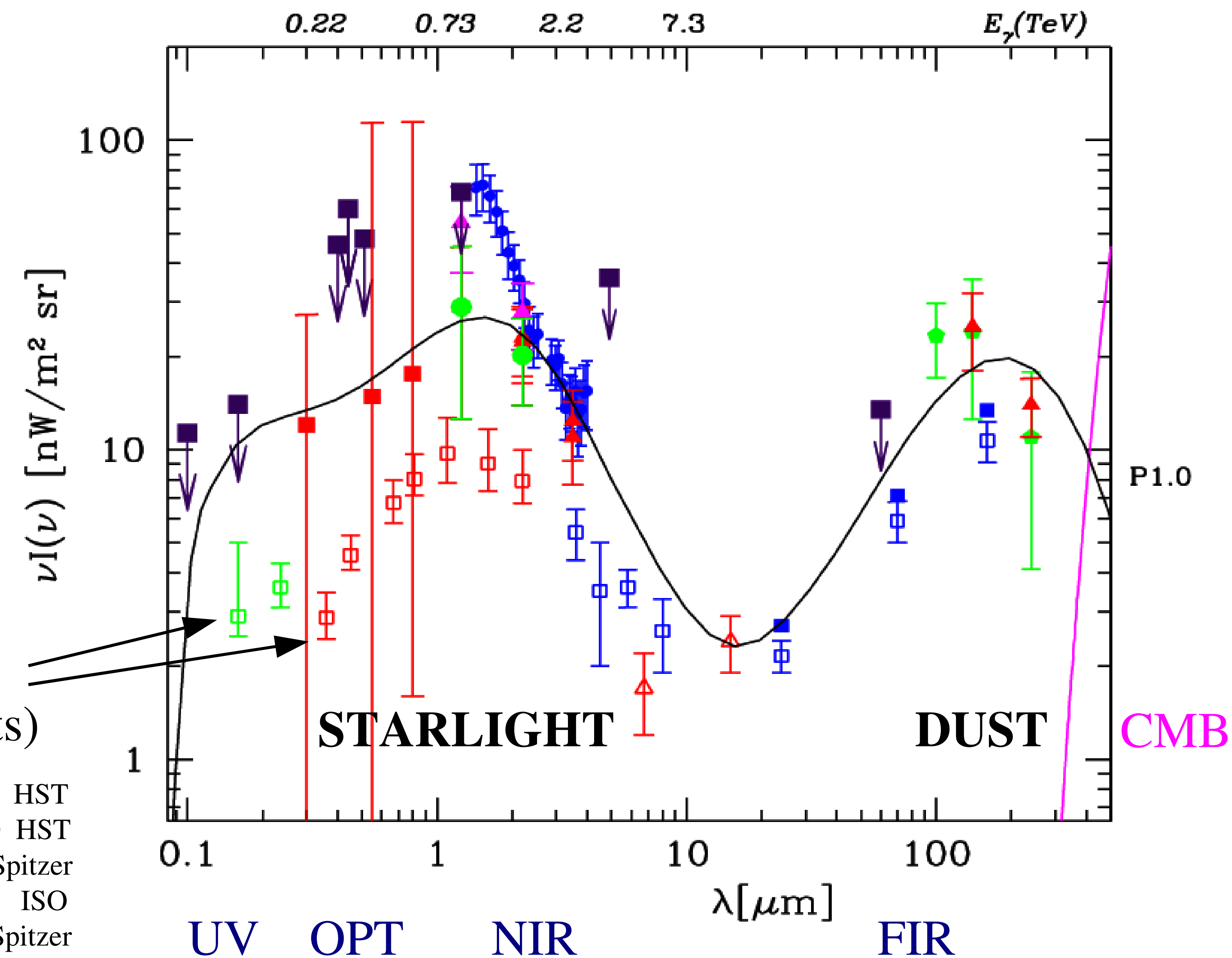
Probing the diffuse Extragalactic Background Light (EBL) with blazars' TeV spectra

Luigi Costamante (MPI-K Heidelberg)

- EBL diagnostics: interplay between TeV and EBL spectra
- Breakthrough from H.E.S.S. data: derivation of the upper limit + possible alternatives
- Further observational tests & implications +possible new discoveries with GLAST

Extragalactic Background Light: the SED

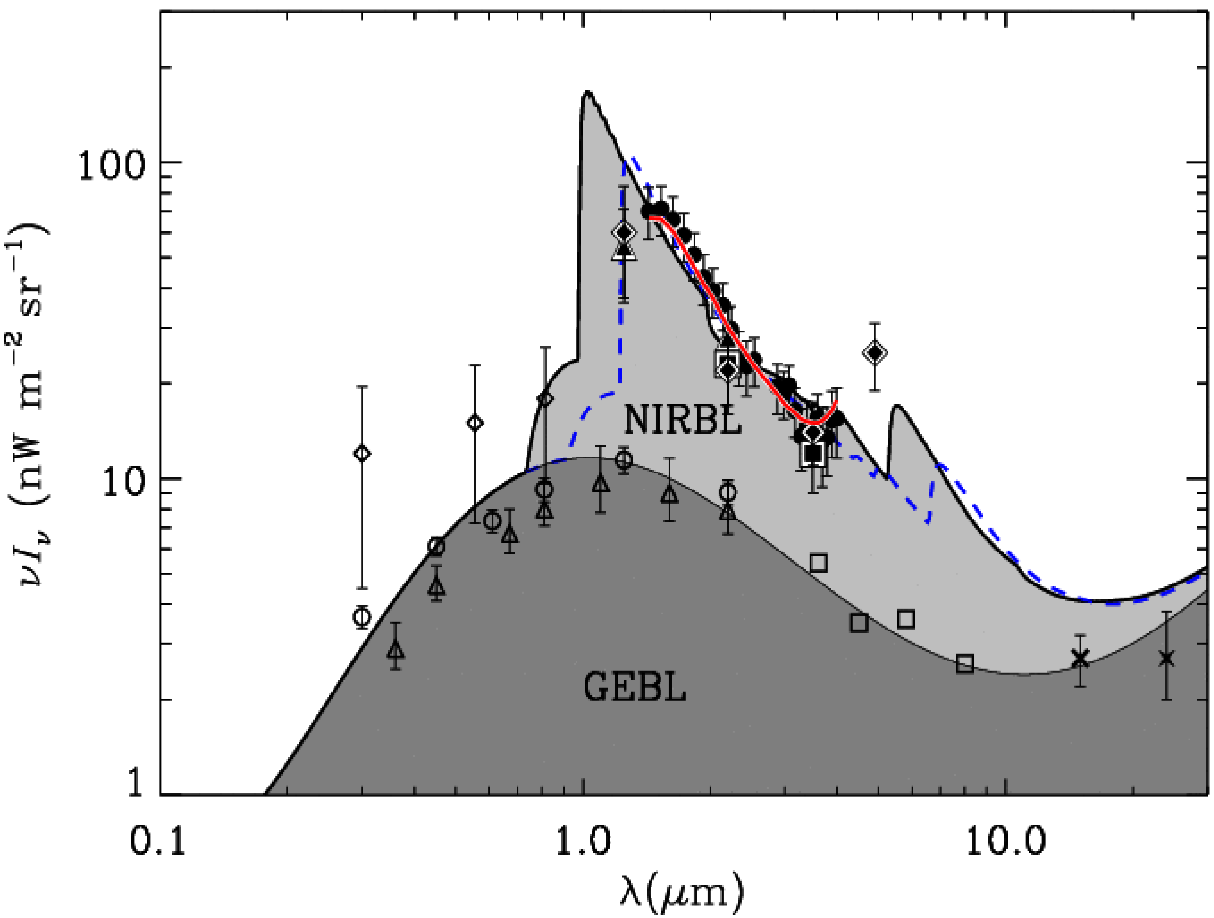


Lower limits
(source counts)

Gardner et al. 2001	HST
Madau & Pozzetti 2000	HST
Fazio et al. 2004	Spitzer
Elbaz et al. 2002	ISO
Dole et al. 2006	Spitzer

Pop III stars ?

Santos et al. 02
Salvaterra & Ferrara 03,
Kashlinsky et al. 03-05



z = 7 - 15

z = 9 - 30

spectrum of zodiacal light (interplanetary dust emission)

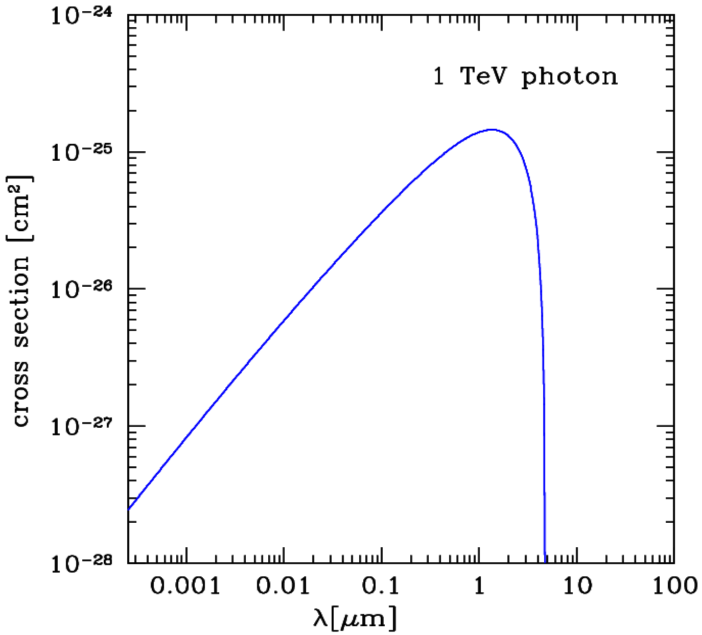
Dwek et al. 2006

BUT huge budget problem: where to hide so many baryons in order to avoid conflict with data of the Universe at present time ??

(metallicity, soft X bkg, BH mass density; see Madau & Silk 2005)

TeV gamma-rays can probe the EBL in the intergalactic space:

$\gamma\gamma \longrightarrow e^+ e^-$



$$F_{obs}(E) = F_{intr}(E) \times e^{-\tau(E)}$$

Nikishov 62
Gould & Schreder 66
Jelley 66

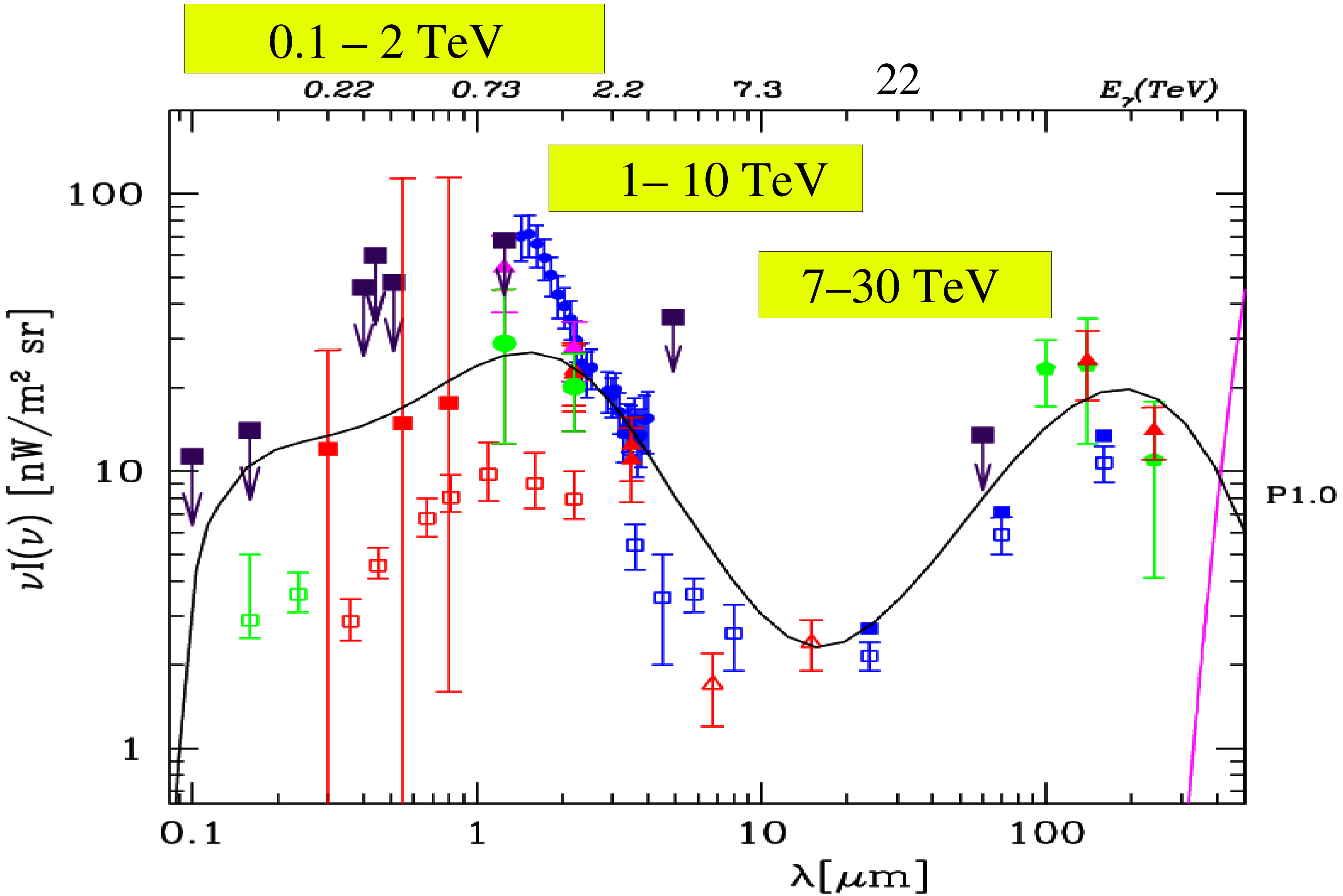
Need sources of TeV beams: Blazars !

Pluses: large apparent luminosities --> can be detected at large distances

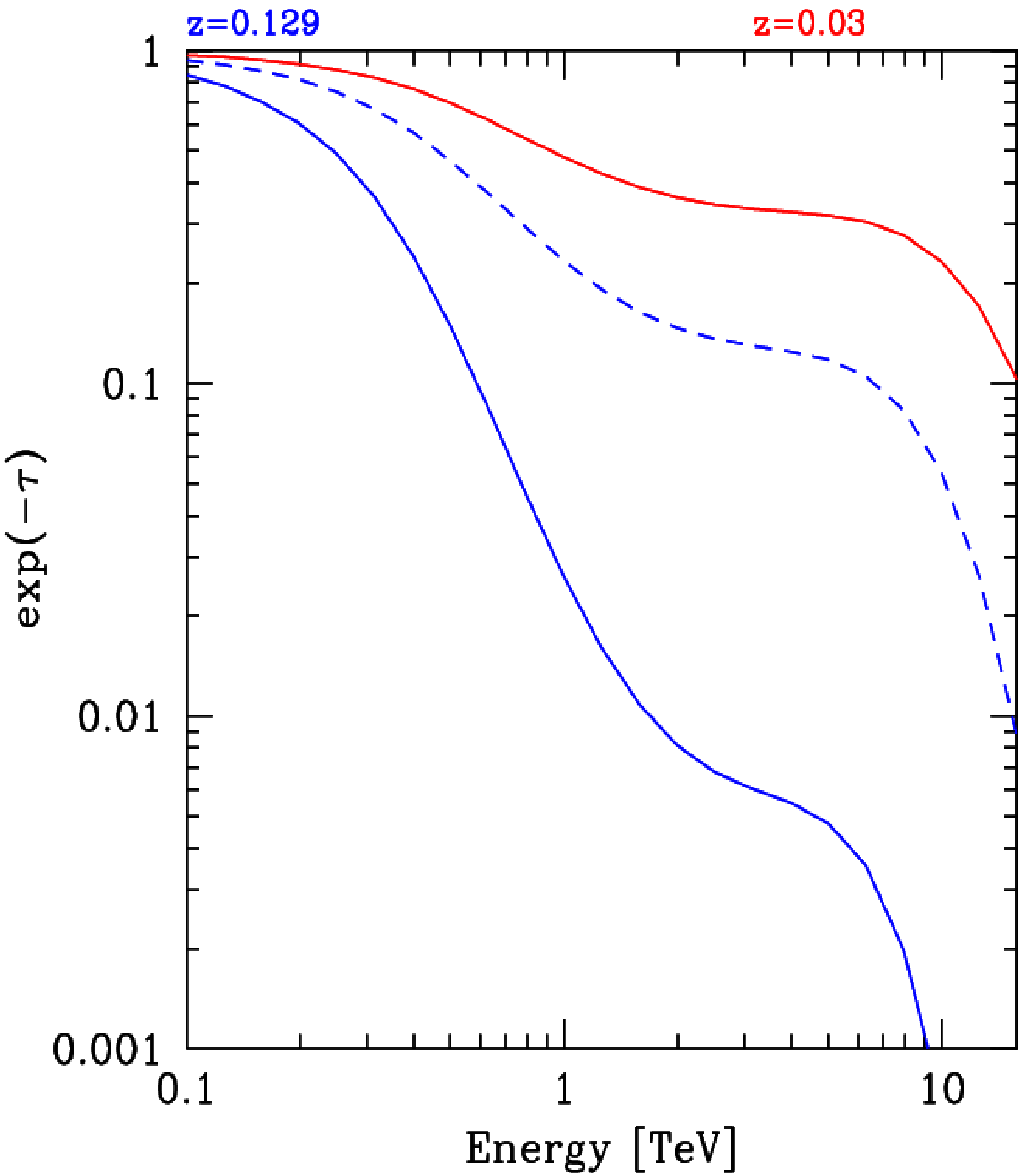
--> provide good photon statistics

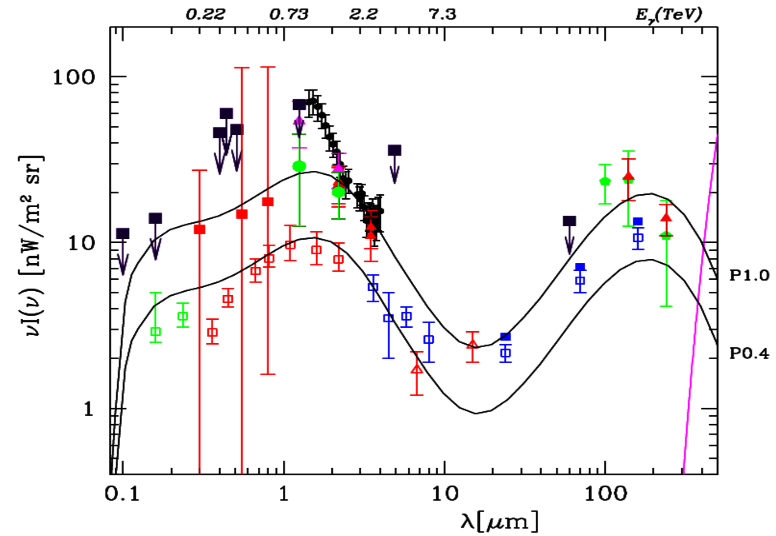
Problem: they are NOT standard candles (variable, wide range of spectra)

Different objects to probe different EBL energy ranges (combinations TeV energy - redshift)



How absorption deforms original TeV spectra ?

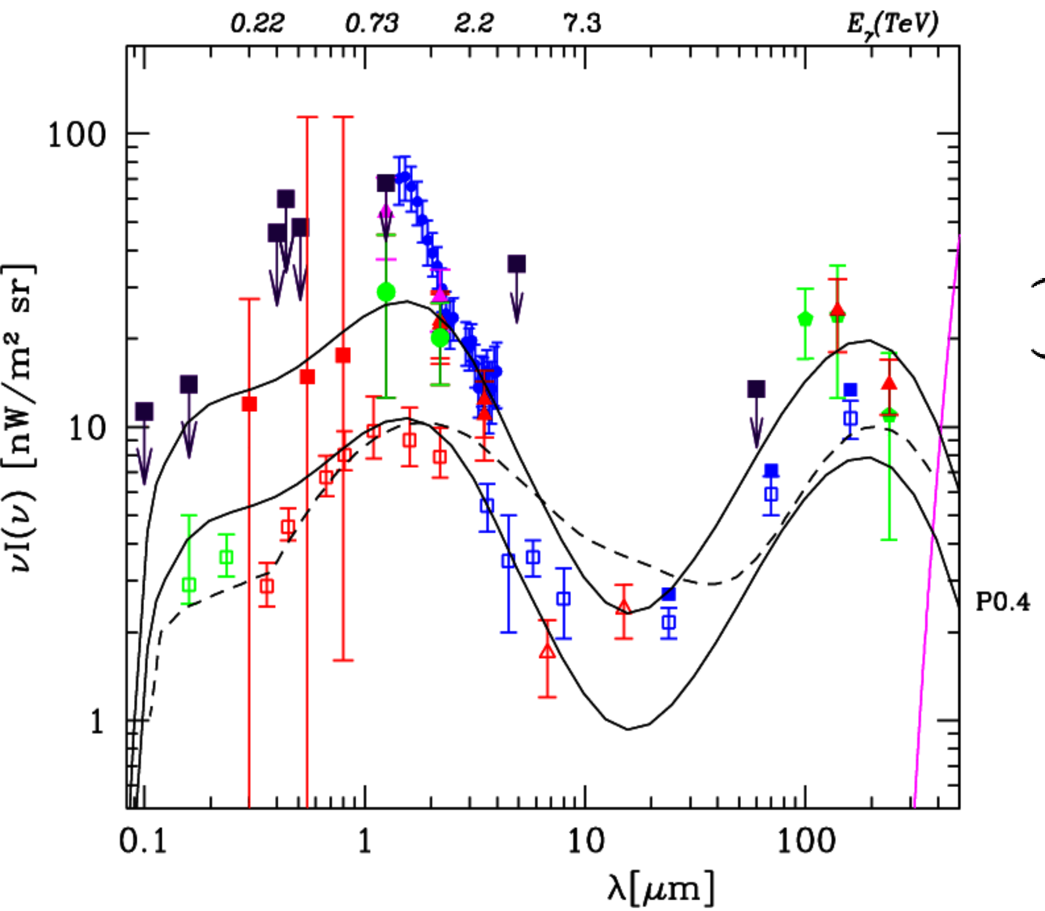


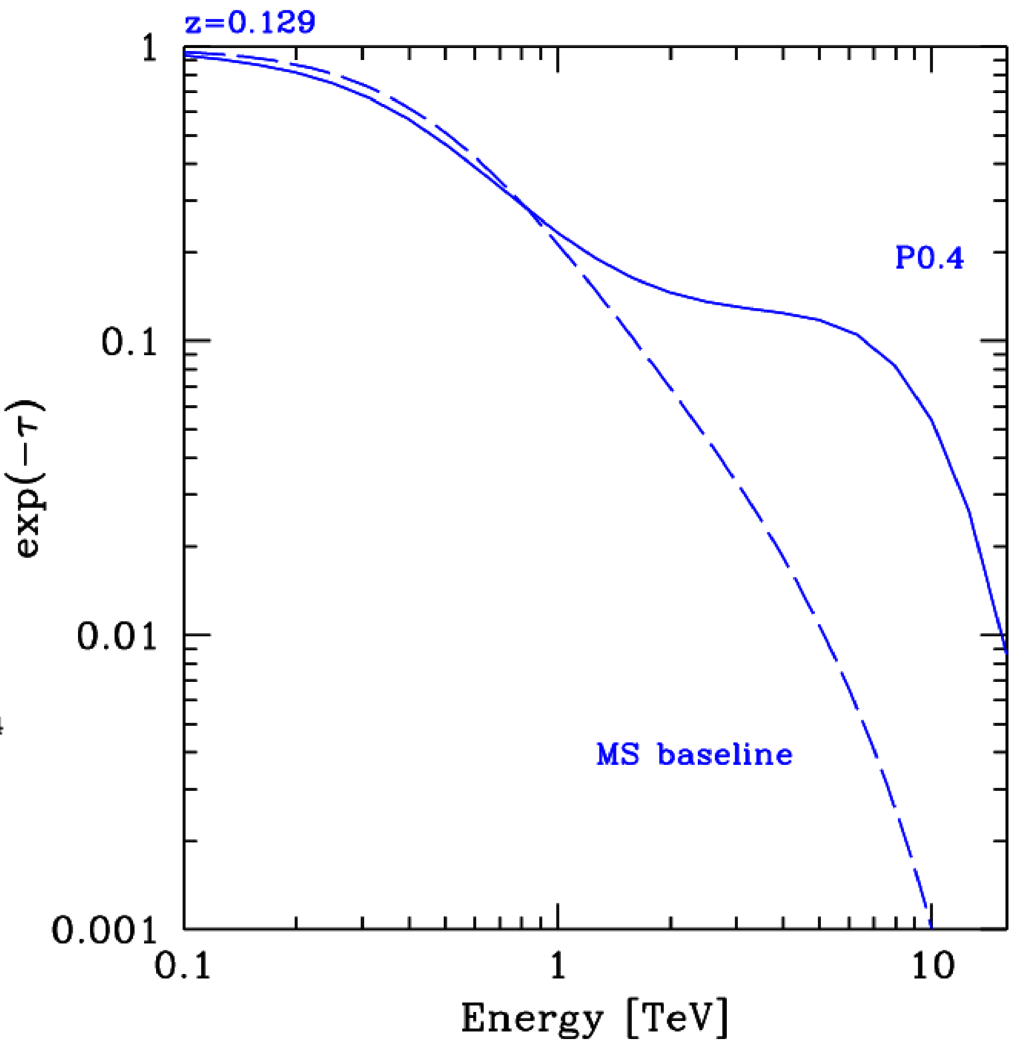


- 0.2 – 2 TeV: steepening
- 2 – 6 TeV : flattening

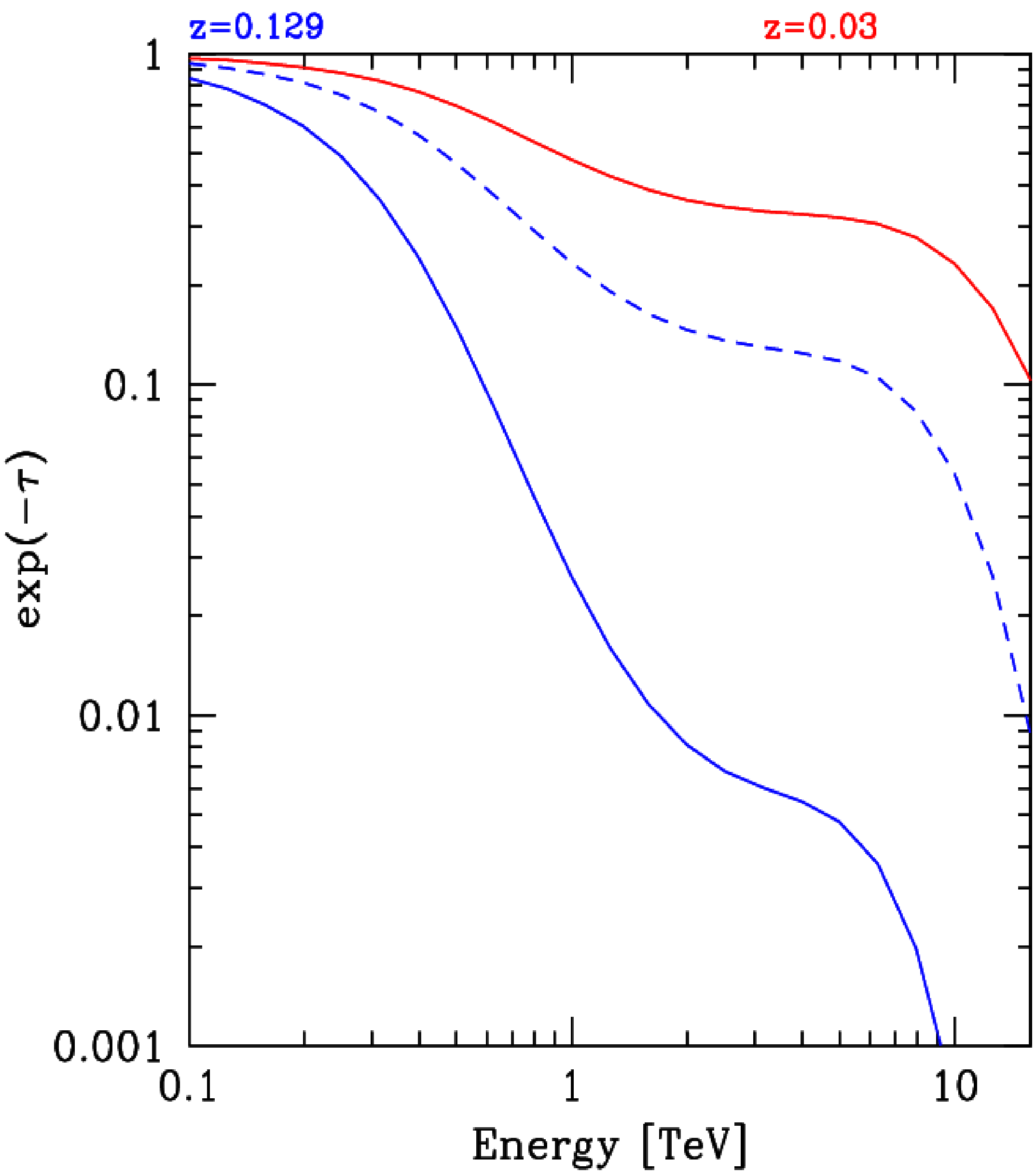
  (partial recover of original spectrum: $n(\epsilon) \sim \epsilon^{-1} \rightarrow \tau(E) \sim E^{0}$ ~constant)
- > 6 TeV: cut-off

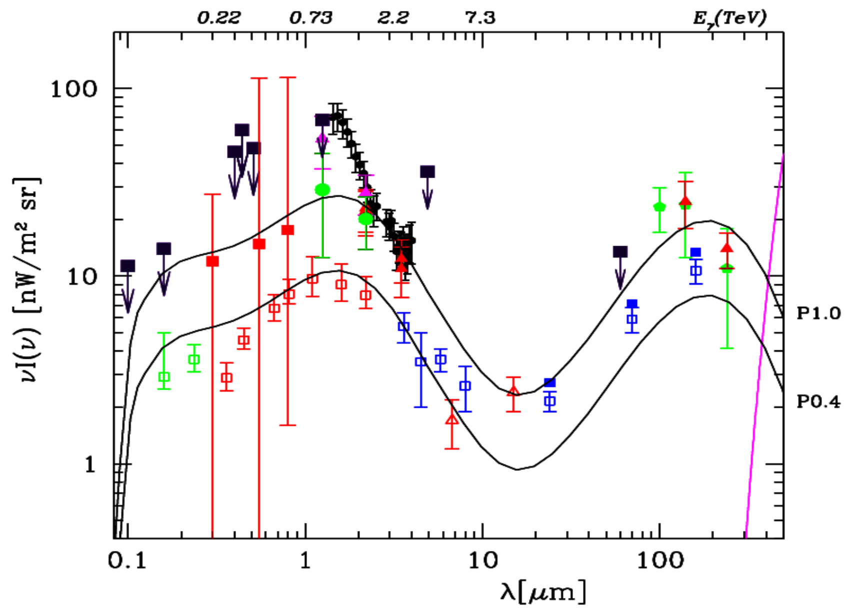
Differences Primack-like vs Stecker shapes





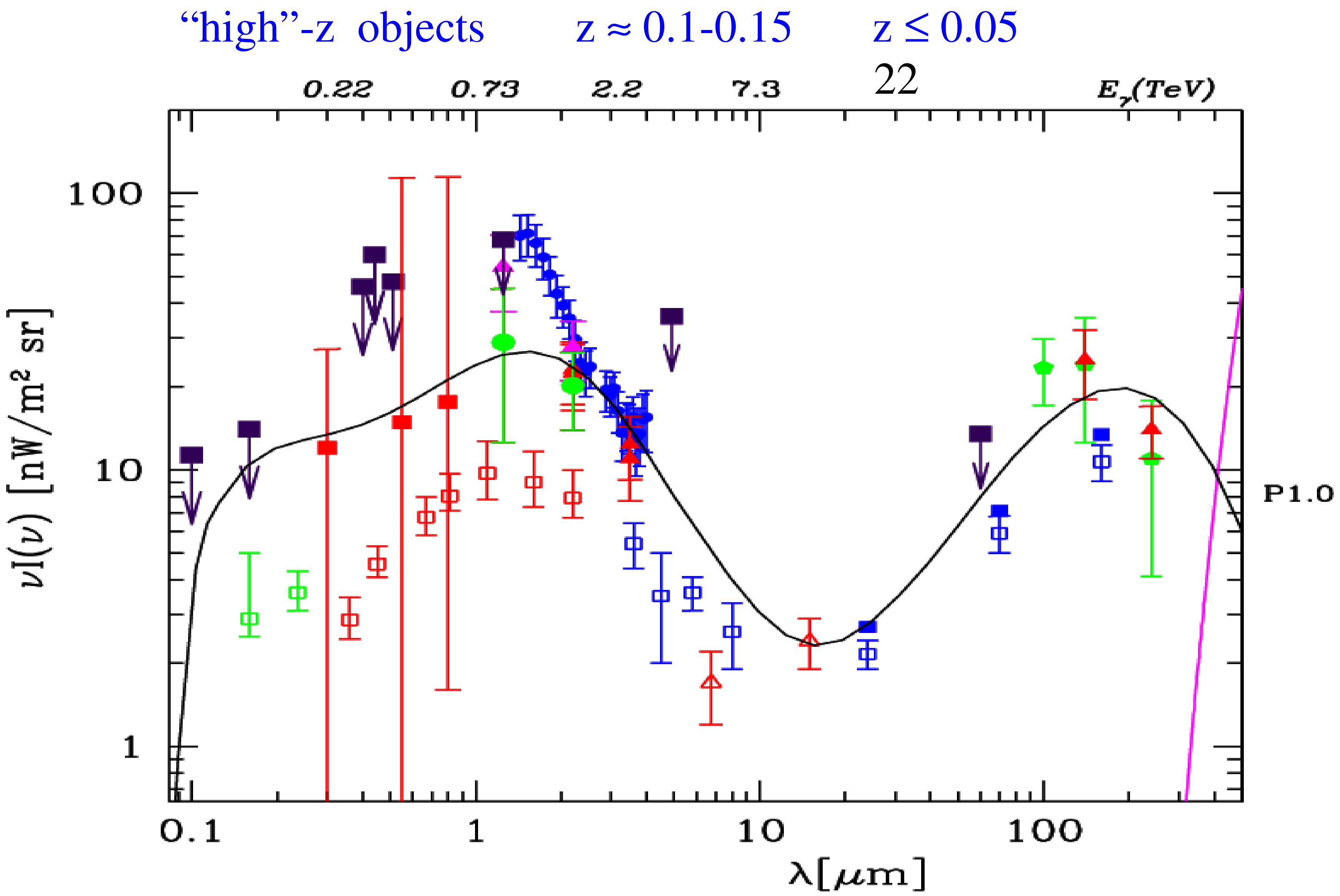
How absorption deforms original TeV spectra ?





- Features & attenuation increase with z and EBL level
- Optimal redshift as compromise between strength of the feature and enough statistics (=less atten.)

Specific combinations (TeV energy band – redshift) are needed to probe different EBL energy ranges



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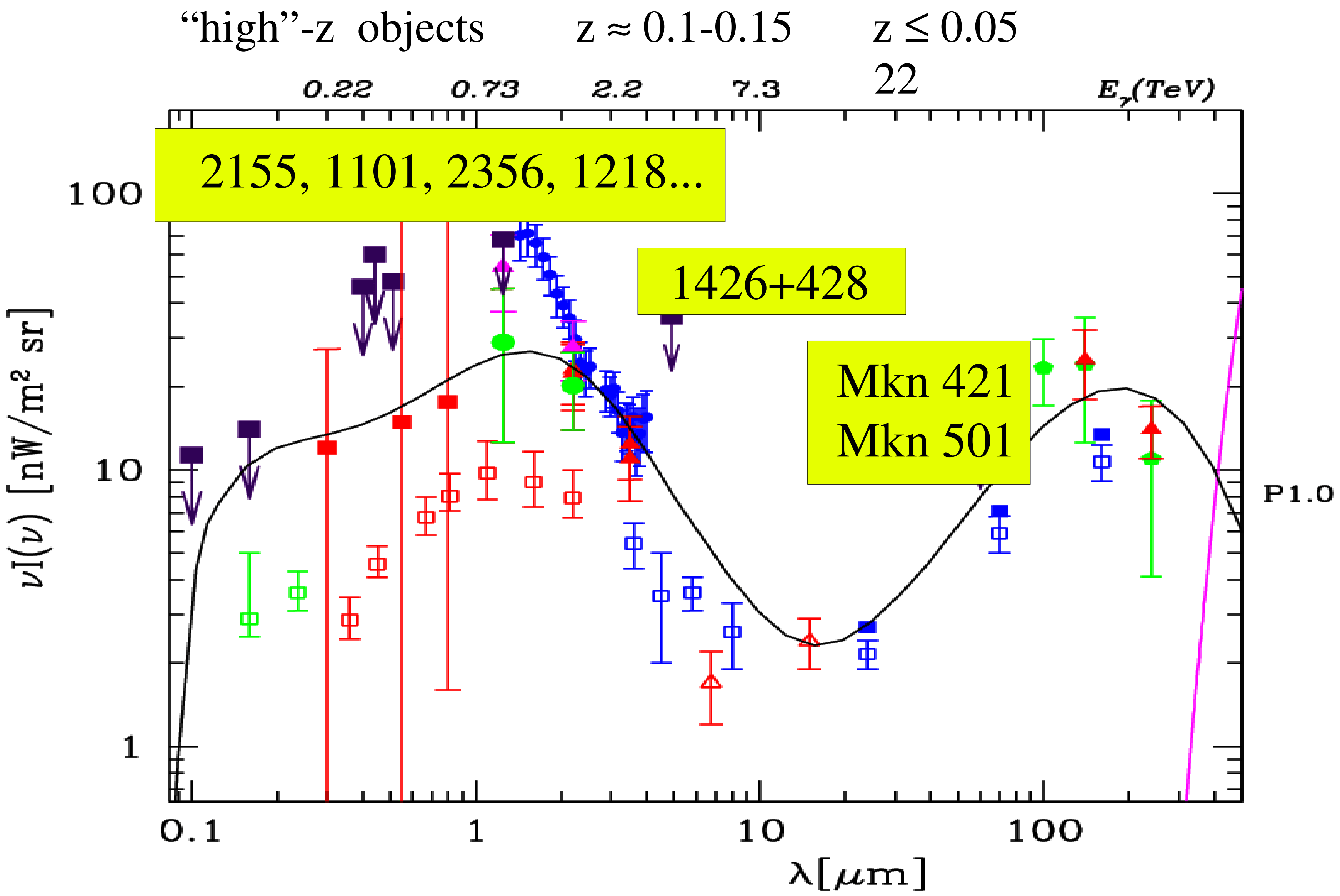
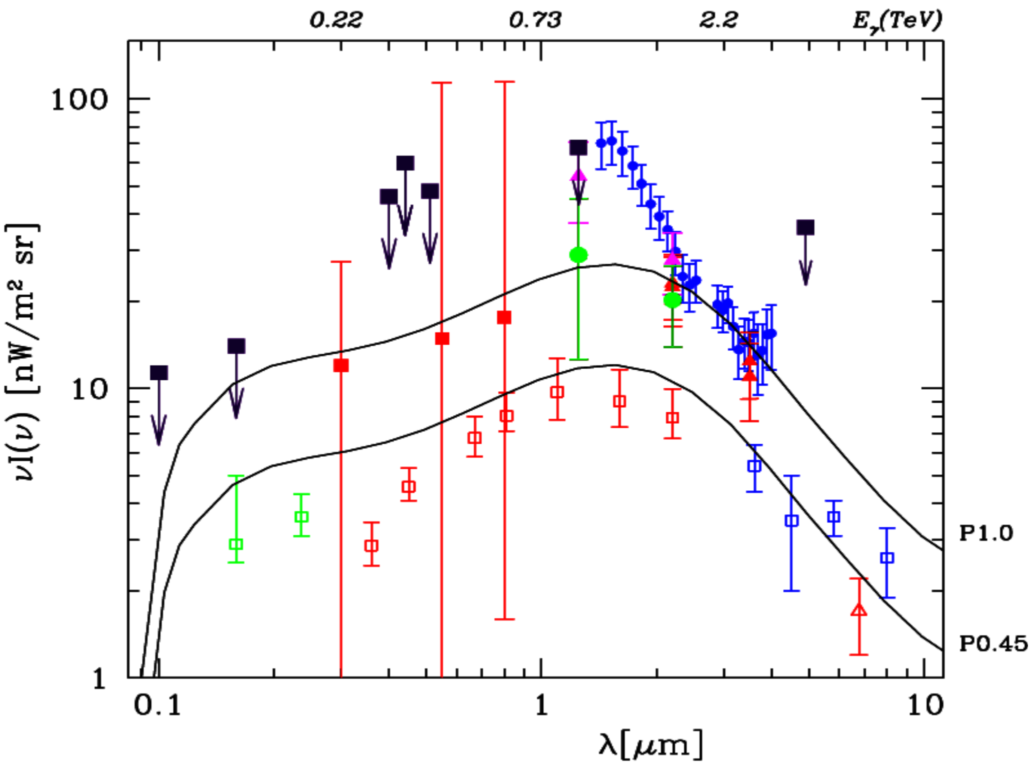
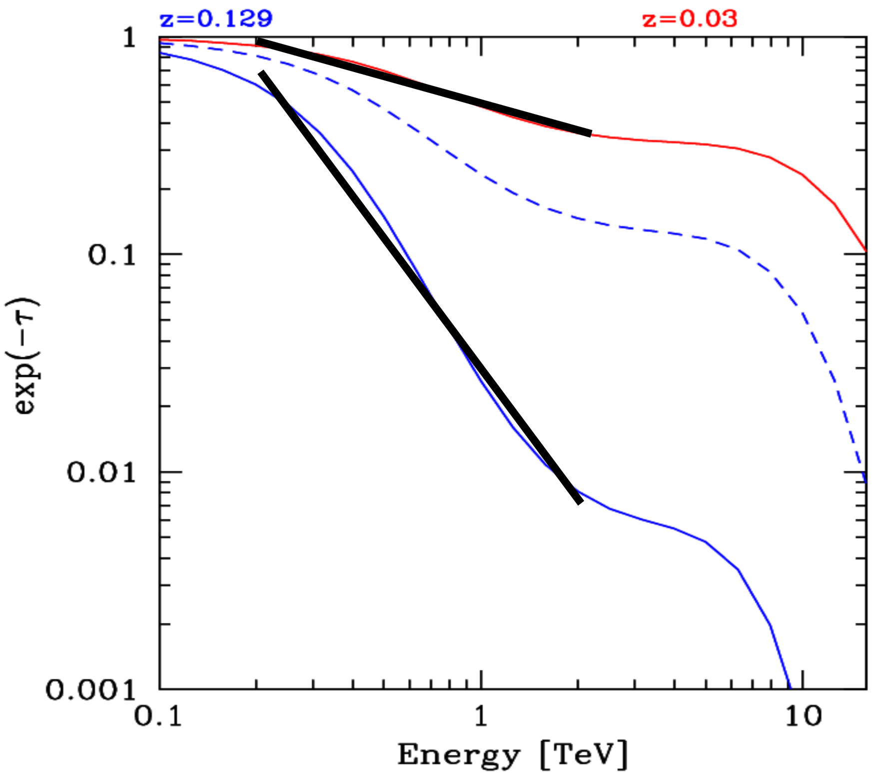


Zoom in the Opt-NIR band





EBL diagnostics: dependencies as a function of

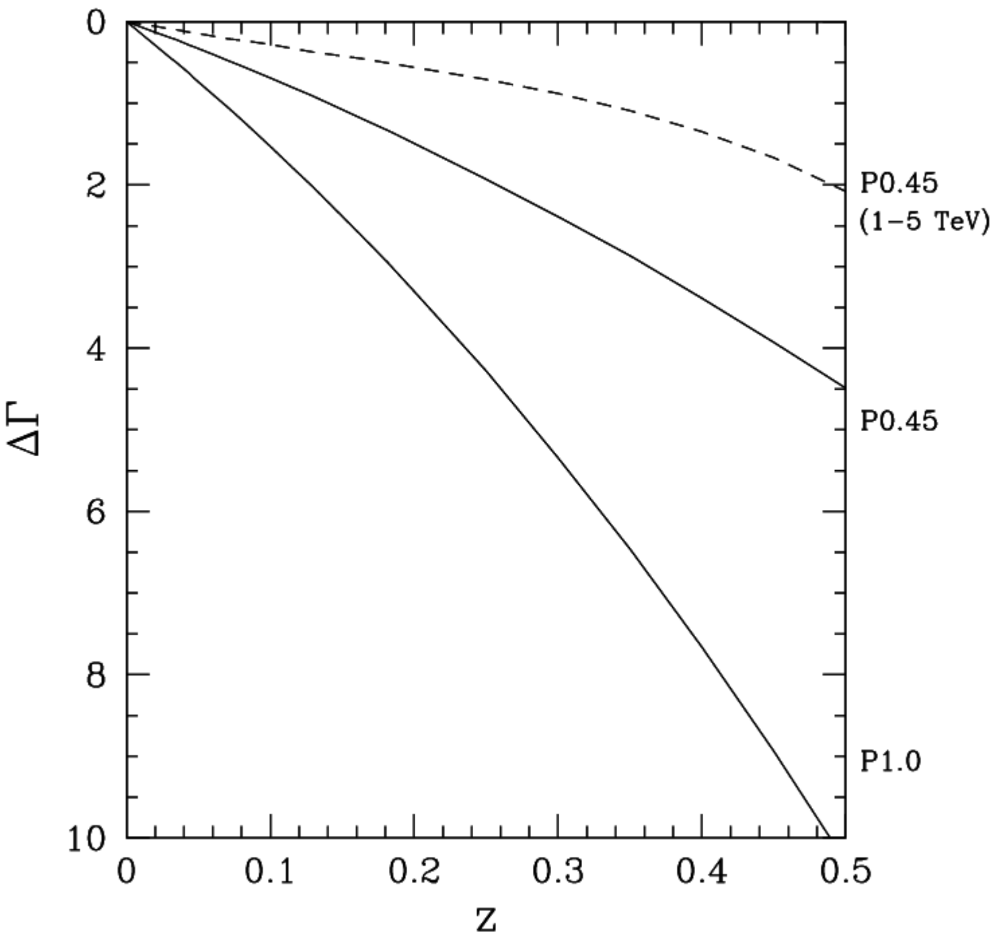
- redshift,
- normalization,
- NIR flux
- UV flux

Dependencies: for a fixed EBL spectral shape

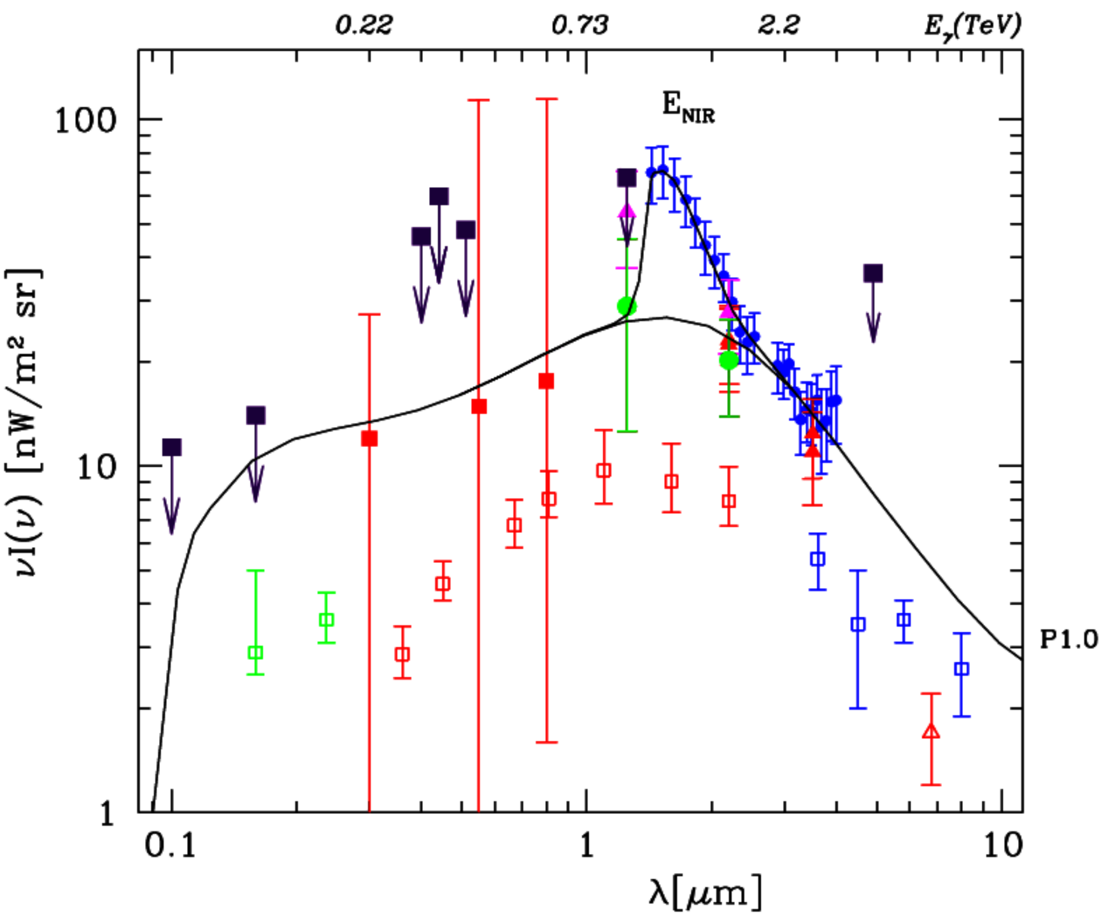
0.2-2 TeV fits, power-law

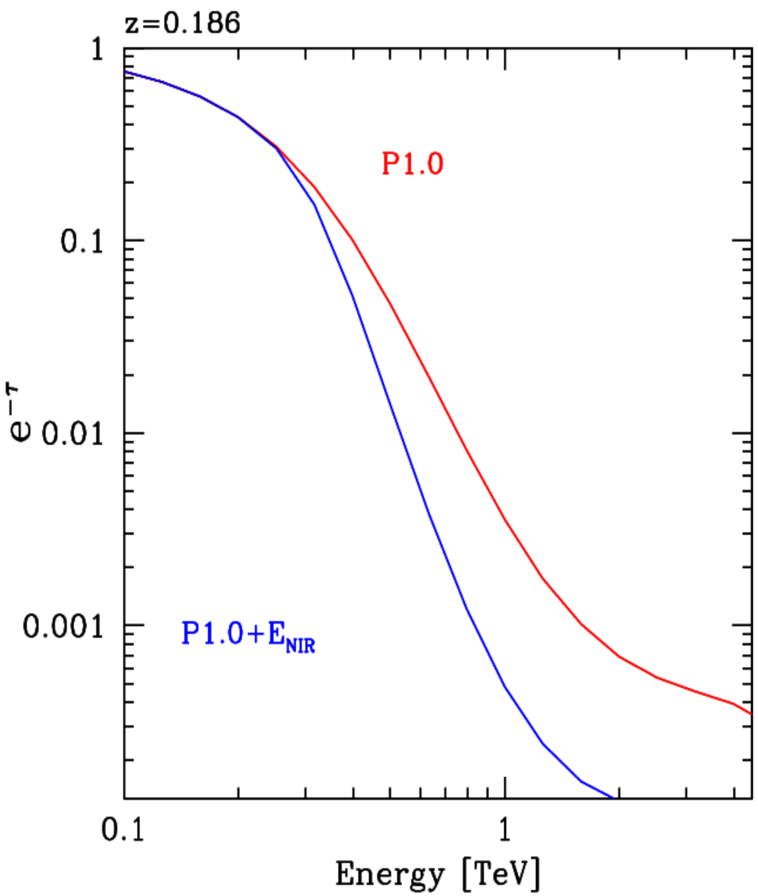
For the same intrinsic spectrum:

- Steepening increases with redshift
- Steepening increases with EBL normalization
- The two combines:
  redshift gives leverage !
  (same EBL change --> gives larger spectral changes at larger z)

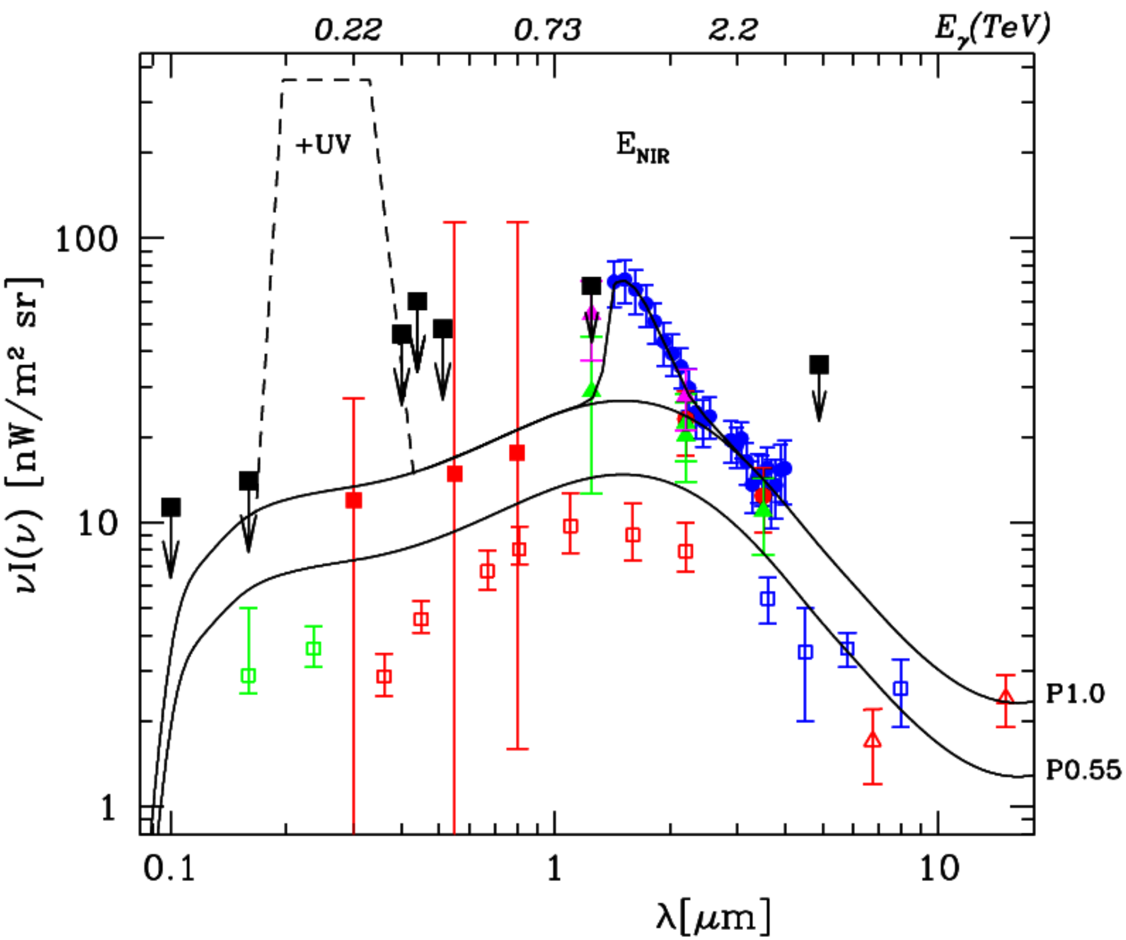


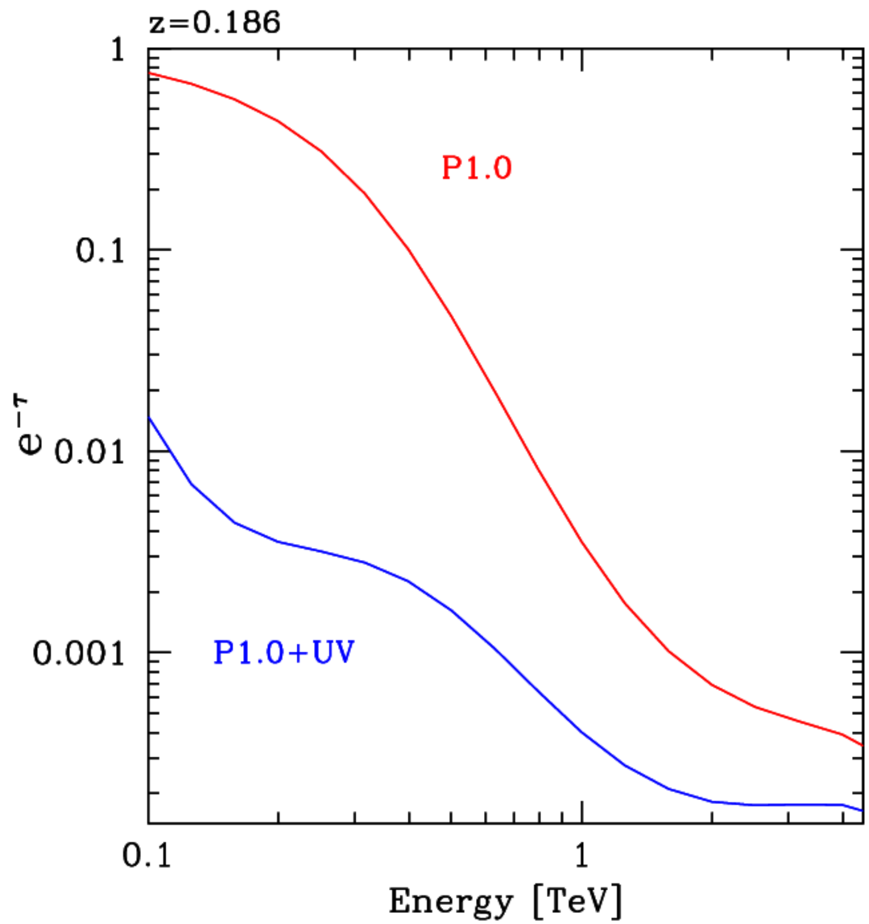
Dependencies, EBL SED changes: NIR flux



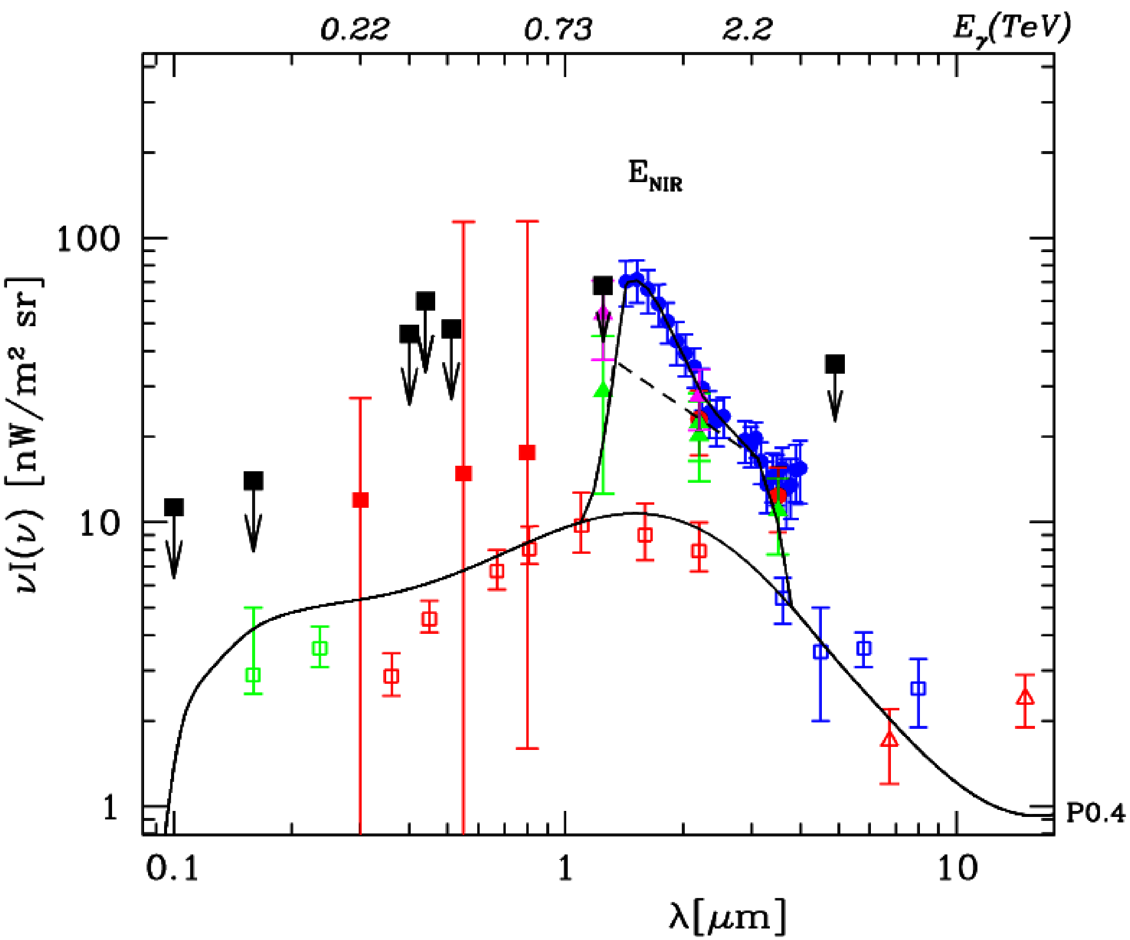


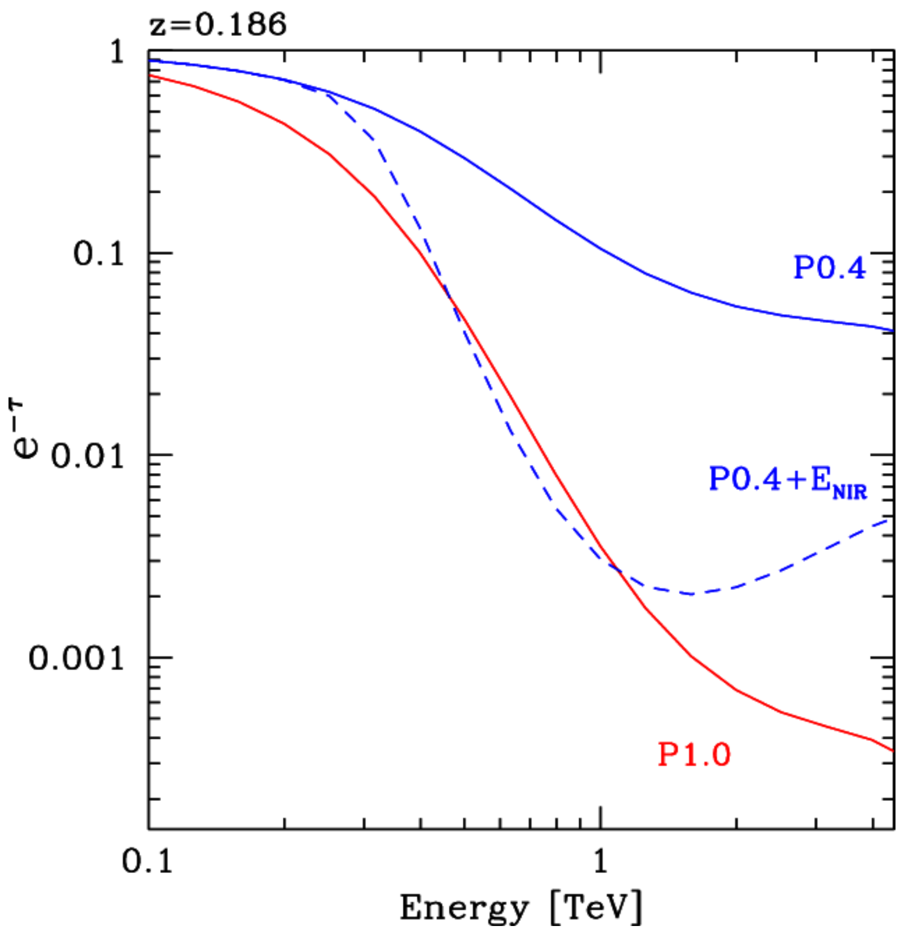
Dependencies, EBL SED changes: UV flux



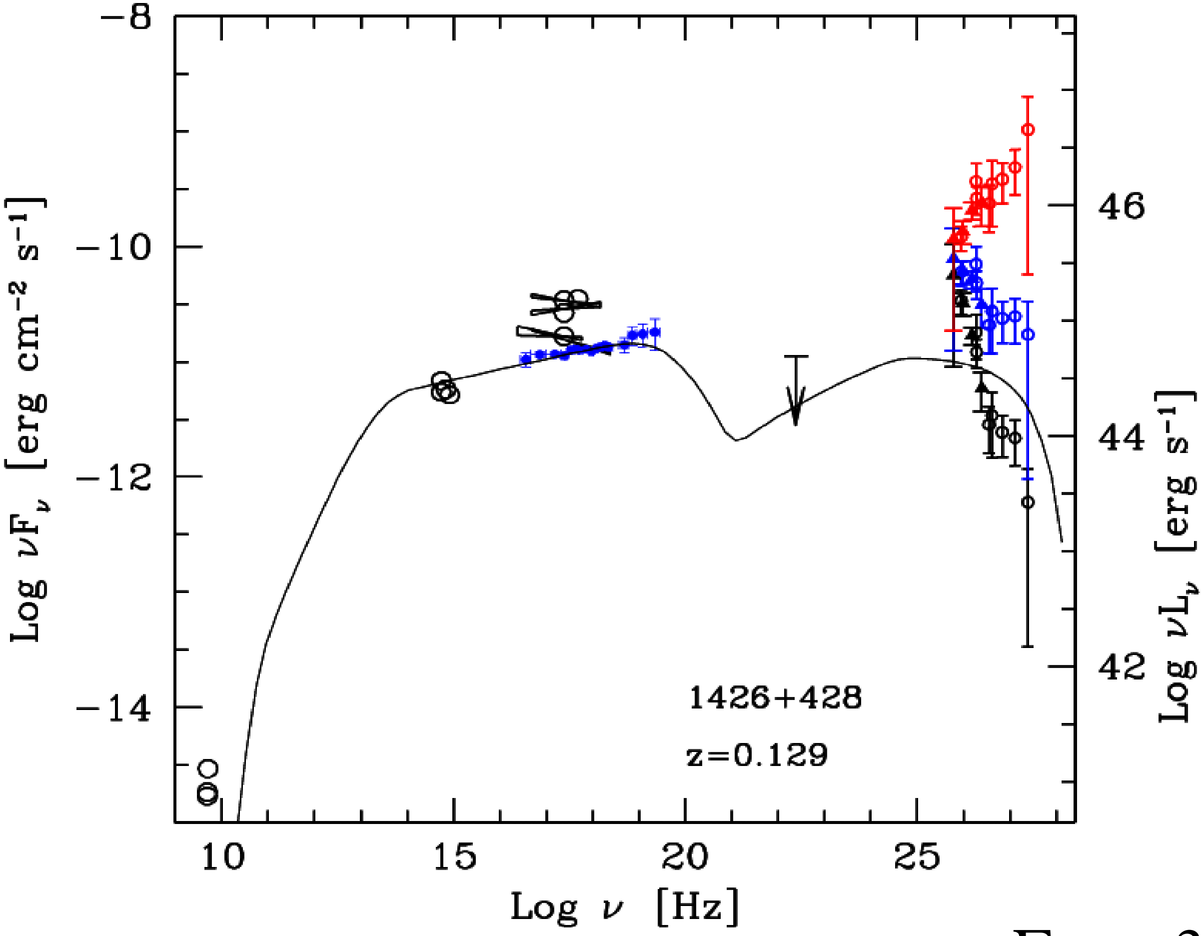


Dependencies, EBL SED changes: less UV flux





Problem: interpretation of TeV blazars spectra



With a high EBL:

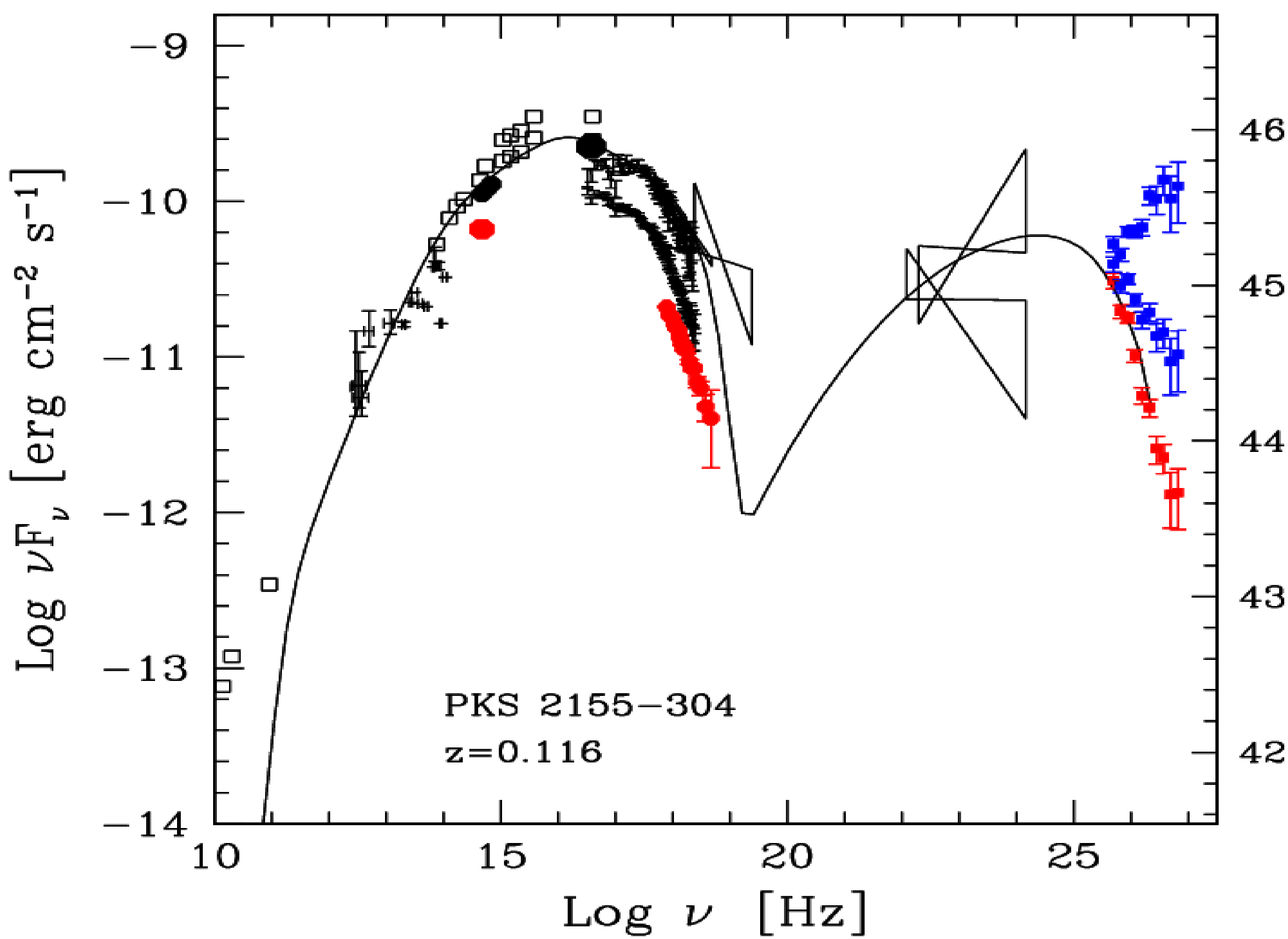
- IC peak > 10 TeV
  Lc >> Ls

- Bolometric luminosity is strongly under-estimated

- 1ES 1426+428 one of the most problematic

$\Gamma_{obs} = 3.5 \pm 0.3$

PKS 2155-304 did not solve the issue



$\Gamma_{int} \simeq 1.5$

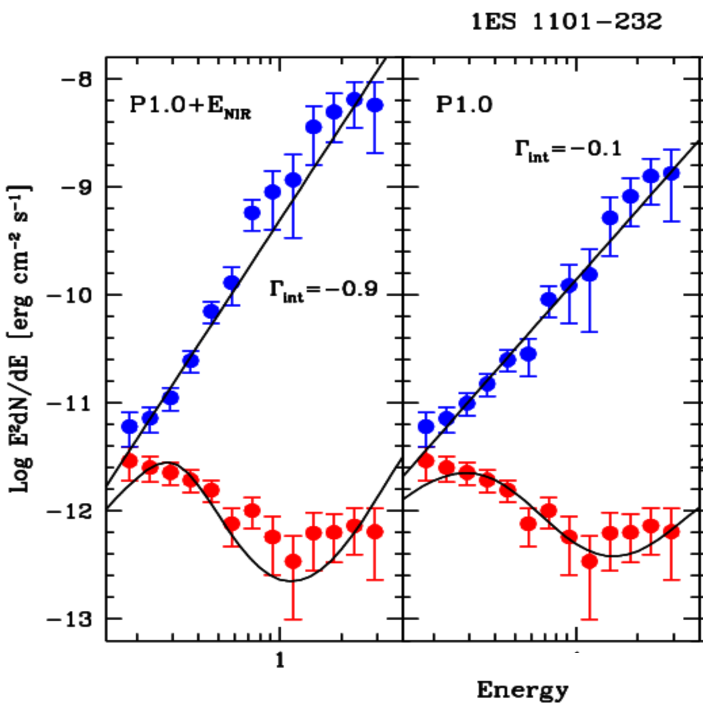
$\Gamma_{int} \simeq 2.5$

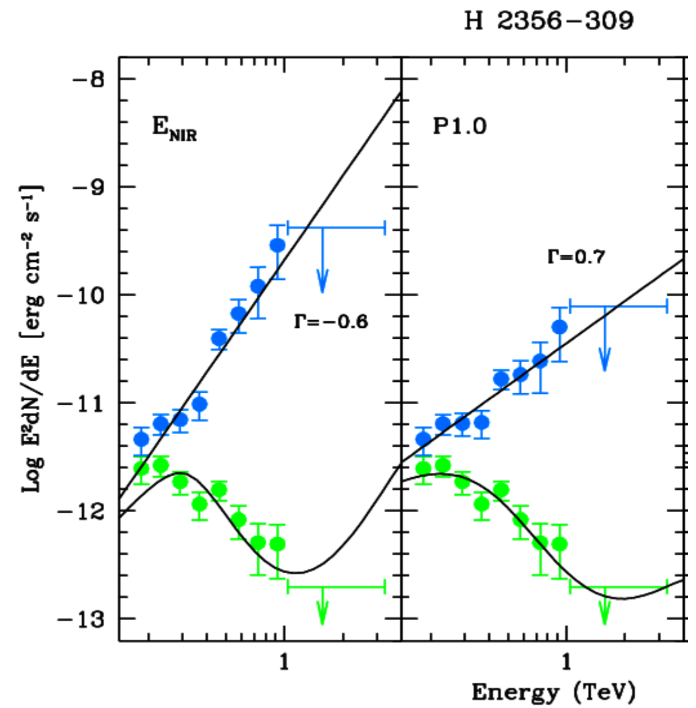
$\Gamma_{obs} = 3.37 \pm 0.07$

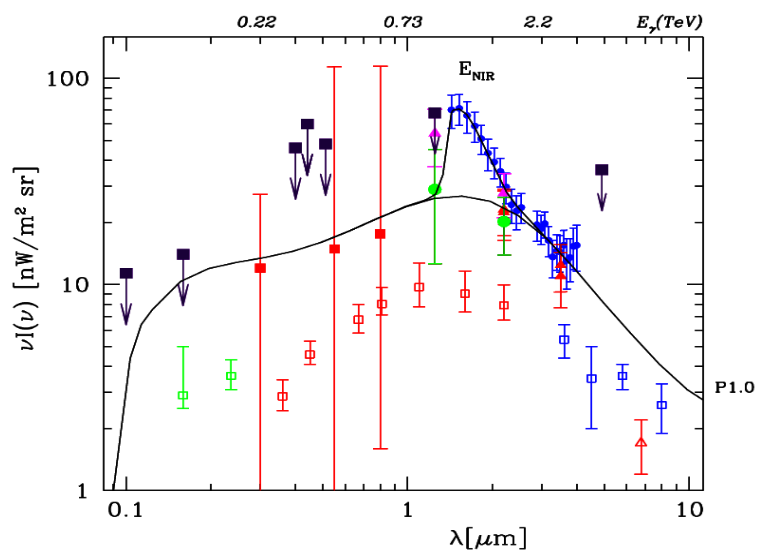
Aharonian et al. 2005

Only reasonable hints: arguments in Dwek et al. 2005 counterfuted by observations (Mkn 421 & 501) and/or slightly higher EBL UV fluxes

Breaktrough: H.E.S.S. spectra of 1ES 1101-232 & H 2356-309





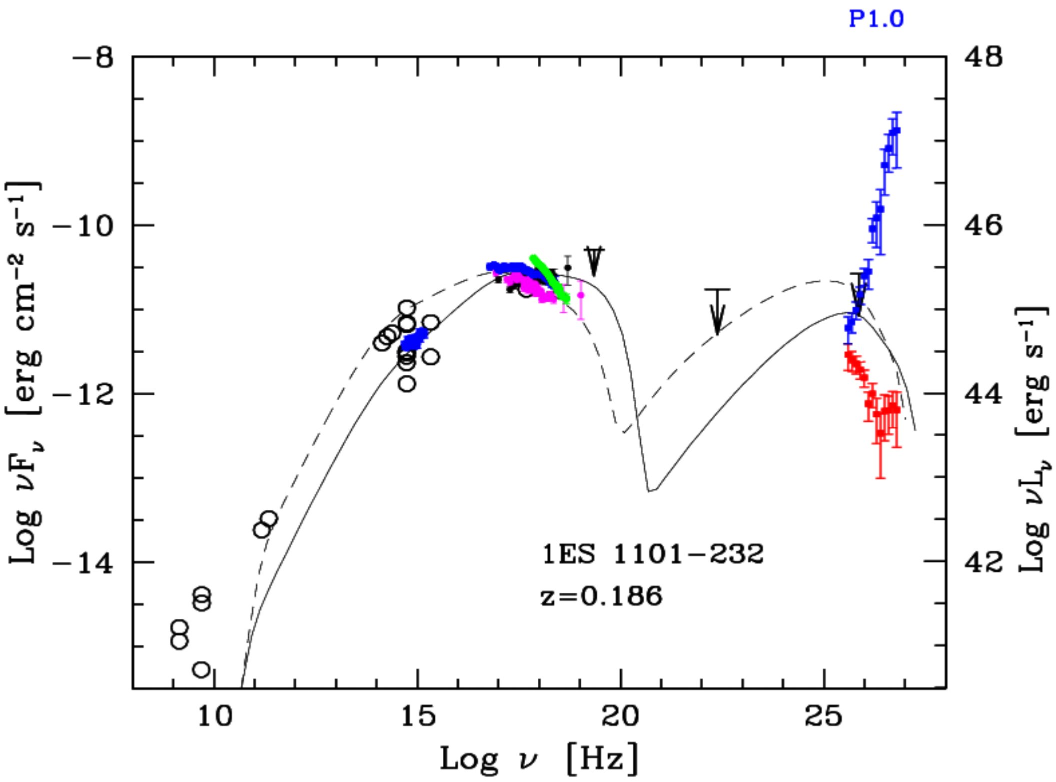


Γ=2.88 ±0.17
z = 0.186

Γ=3.06 ±0.21
z = 0.165

Aharonian et al. 2006, Nature 440, 1018

1ES 1101-232 same-epoch SED



Wolter et al. 2000, Aharonian et al. 2007, in prep.

Such hard spectra ($\Gamma \leq 0$) are difficult to explain (harder than even monochromatic particle distr.)

$\Rightarrow$ EBL level is lower

How much ?

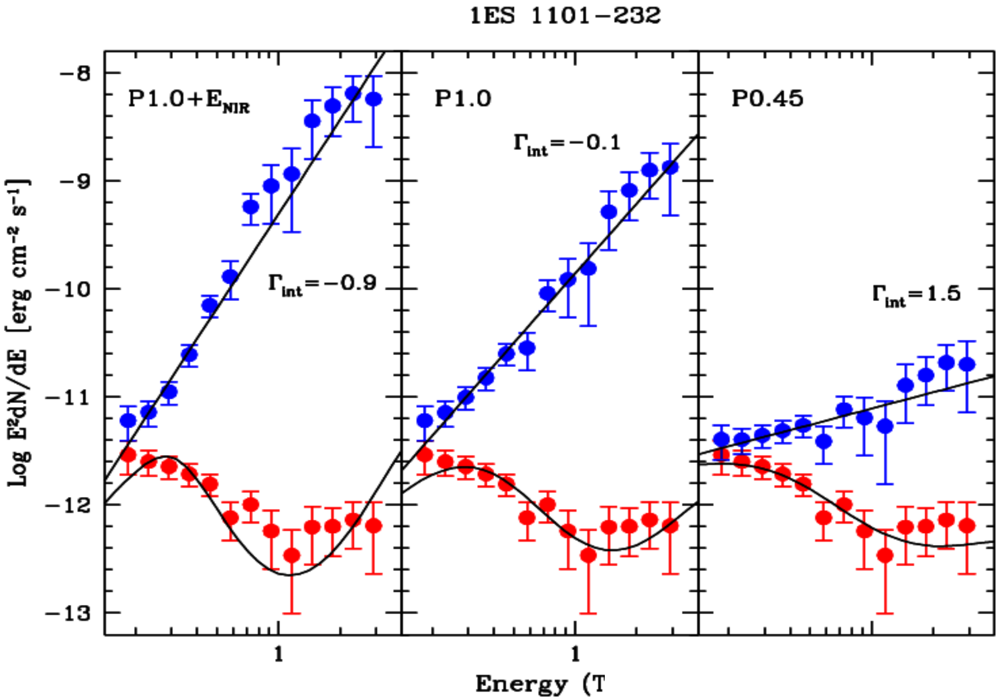
If we believe the standard picture for blazar emission (broad band SED due to broad band electron distribution, particle acceleration in shocks), then:

since particle acceleration $s \geq 1.5$ (non-linear theory; Malkov & Drury 2001)
$\Gamma \geq 1.5$ under most circumstances.

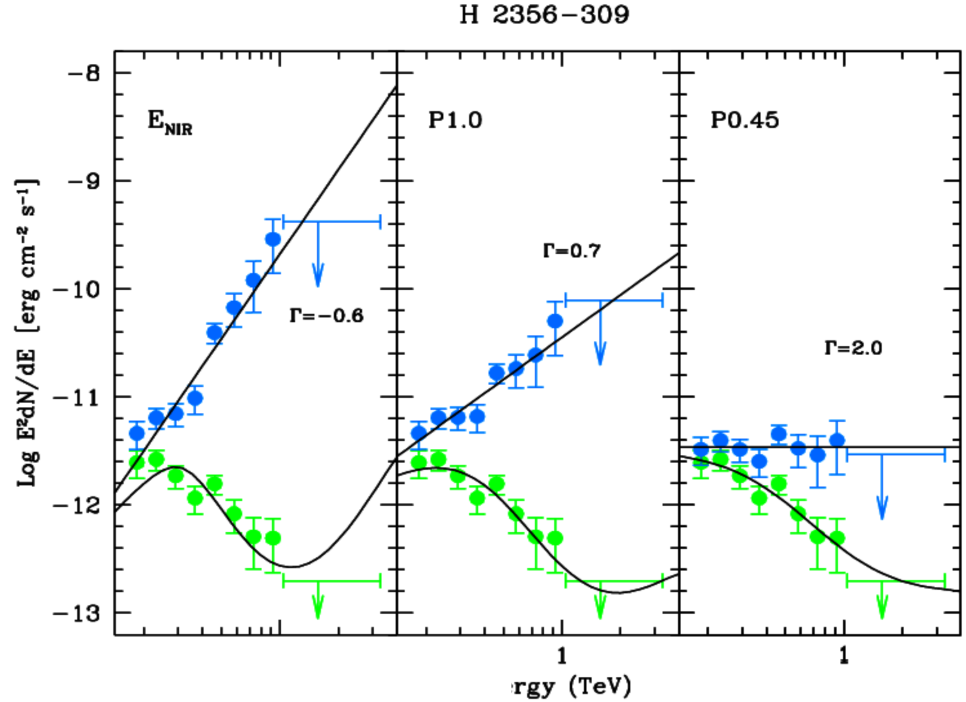
Assumption: true average TeV blazar spectrum was not harder than 1.5

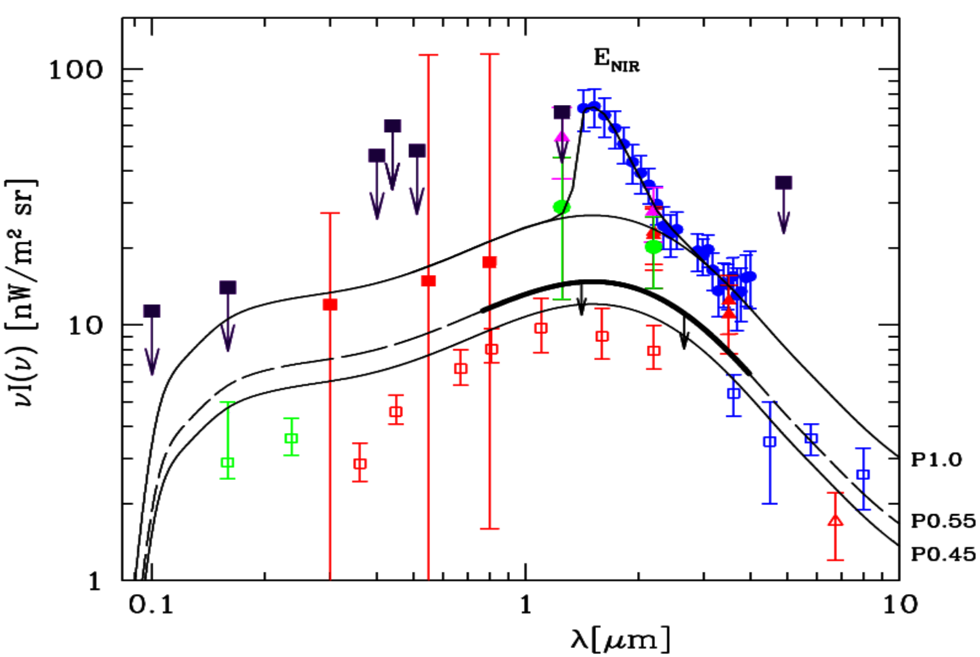
$\Gamma \geq 1.5$ does not require the price to change significantly the known blazar phyics scenarios to agree with observations (also slightly lower Γ, ~1.2-1, do not change relevantly the conclusions)

1ES 1101-232



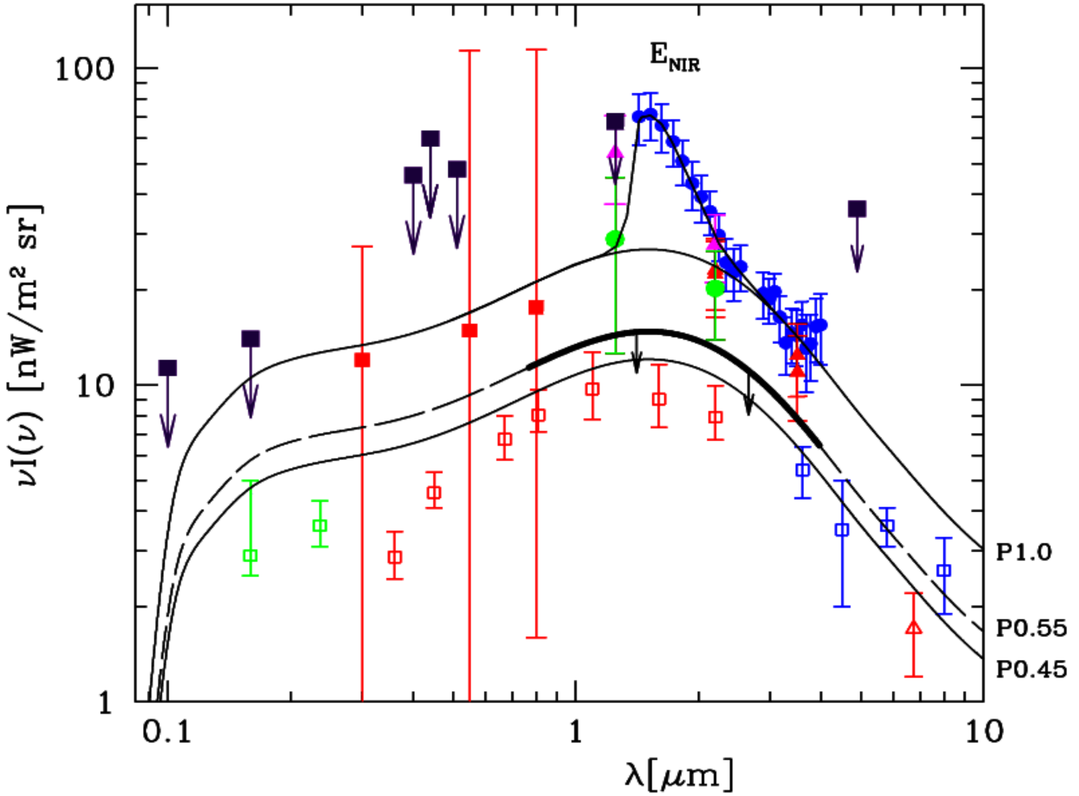
H 2356-309





Upper limit: robustness

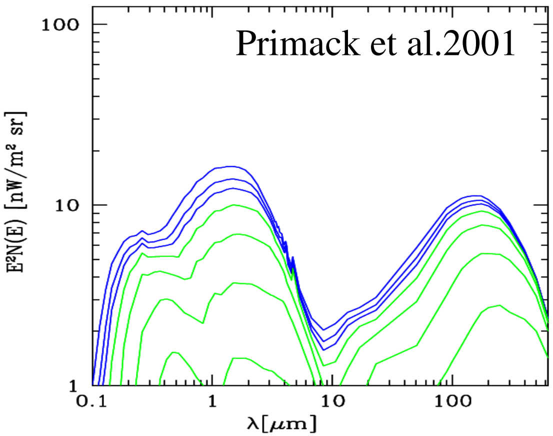
$\Delta P \approx 0.34\ \Delta\Gamma$ (for 1101-232)



Statistical & system uncertainties:

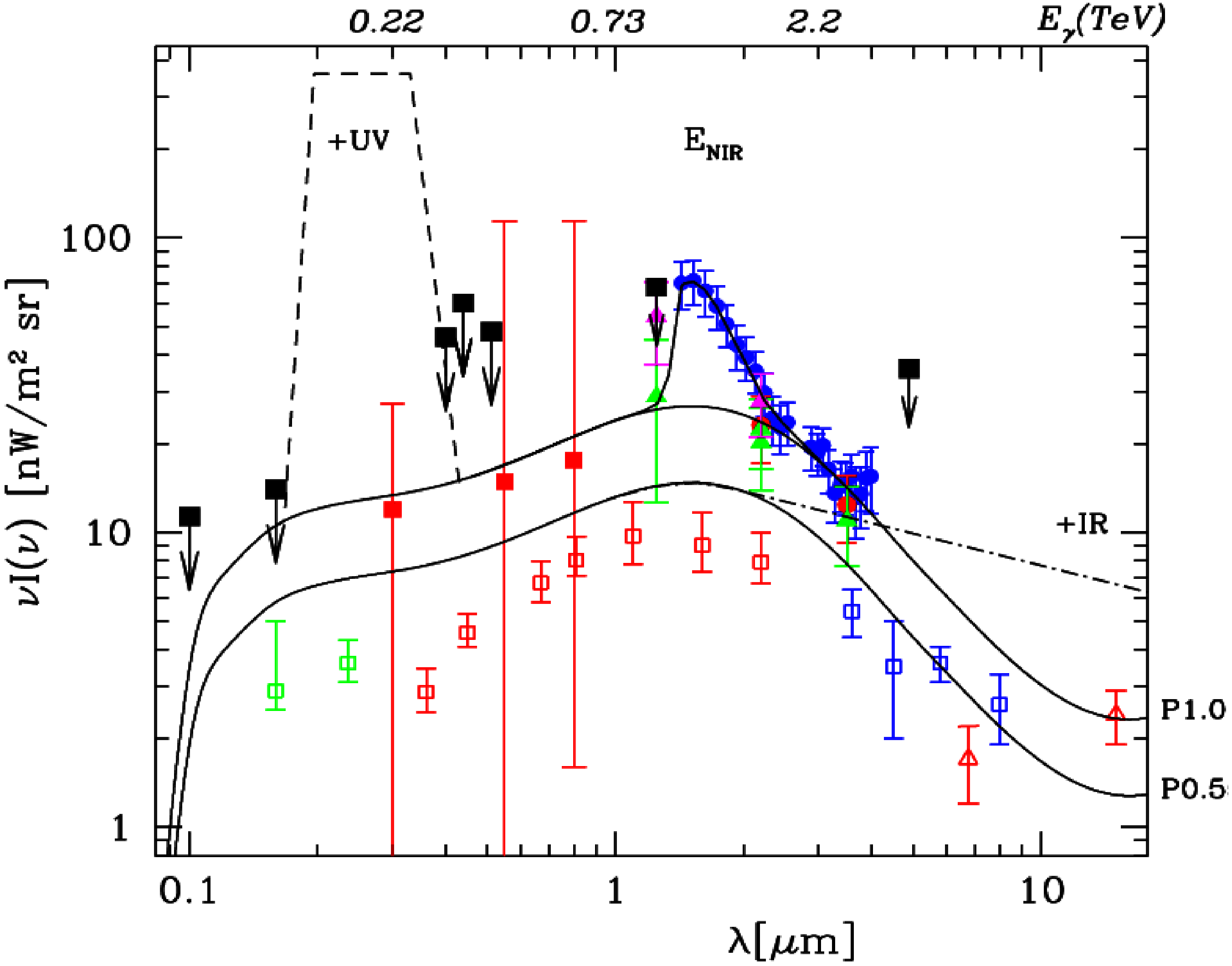
$\Delta\Gamma_{stat} + \Delta\Gamma_{sys}$ --> $\Delta P<0.1$

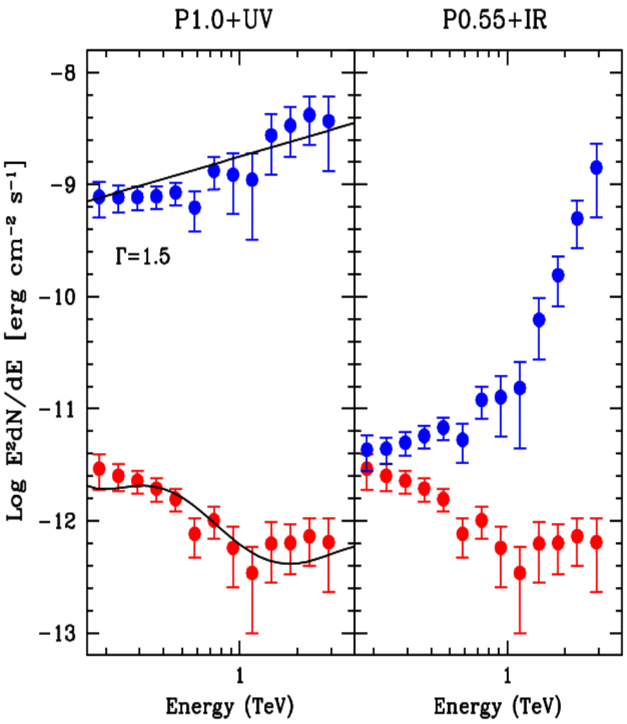
Energy scale (-15%) --> $\Delta P<0.05$



EBL Evolution: $\Delta\Gamma < 0.2 \rightarrow \Delta P < 0.1$

Upper limit: robustness on EBL SED changes





Alternative scenarios ?

- High UV background --> too high
- Origin of redshift is not cosmological
- Breaking of Lorentz Invariance (different $\gamma\gamma$ interaction)

$\Rightarrow$ More viable: possible intrinsic blazar feature

Possible mechanisms to produce very hard spectra

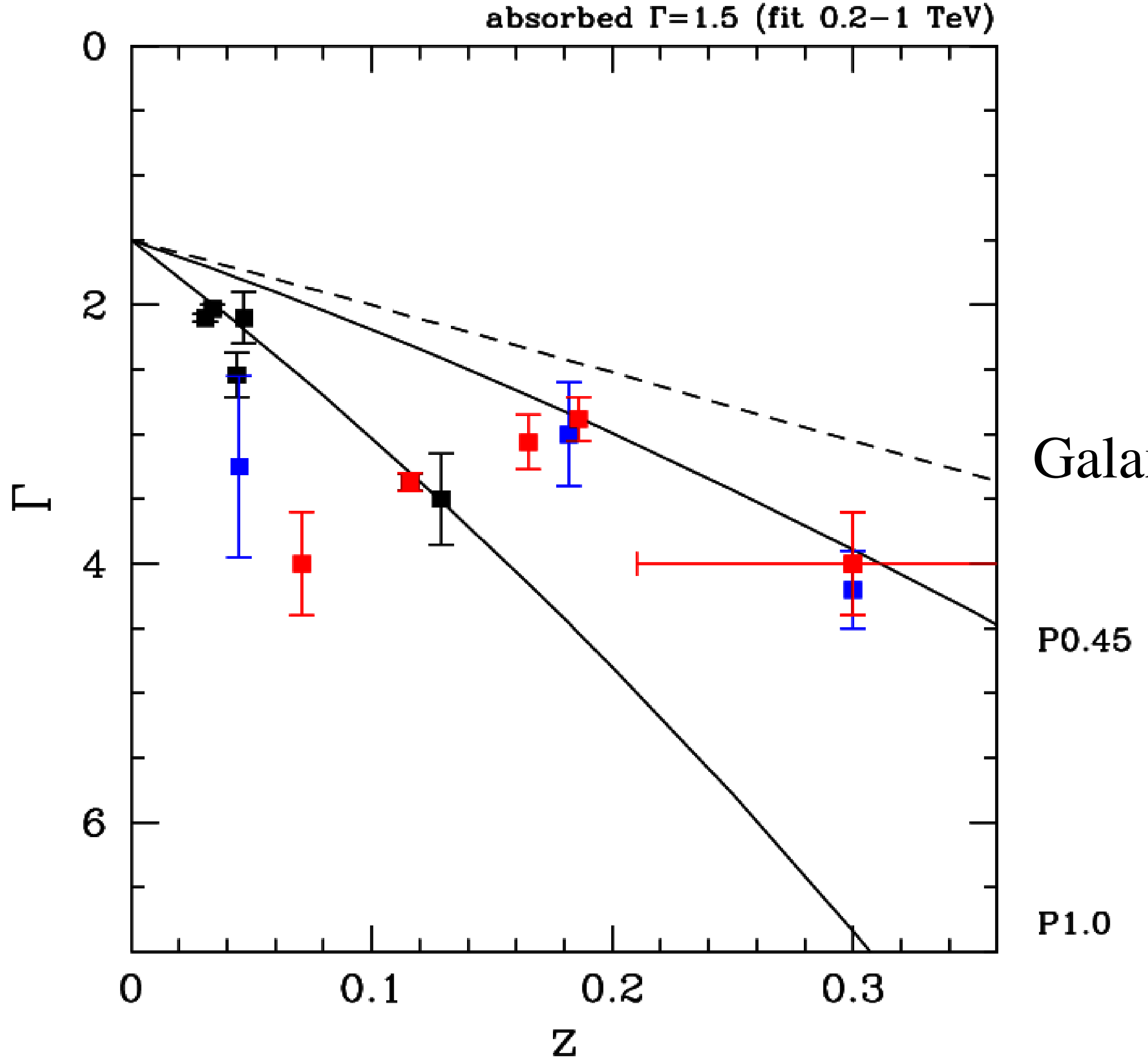
- Bulk motion Comptonization in deep KN regime of a narrow-band photon distribution (e.g. BB) ---> sharp pile-ups (Aharonian 2001)

- Pile-up /maxwellian e^- distributions seem natural outcome for turbulent acceleration
  (Henri & Sauge` 2004, Schlickeiser 98, Henri & Pellettier 91, Petrosian et al 94-04)

- Sharp "low" energy cut-off ($\gamma_{min} > 10^5$):
  ~ monoenergetic electrons, $\nu^{1/3}$ ---> Γ=0.66 (Katarzynski et al. 2005)

But such mechanisms should not "know" the level of the EBL... --->

BLLacs hardest observed TeV spectra:



HESS
MAGIC
past CTs

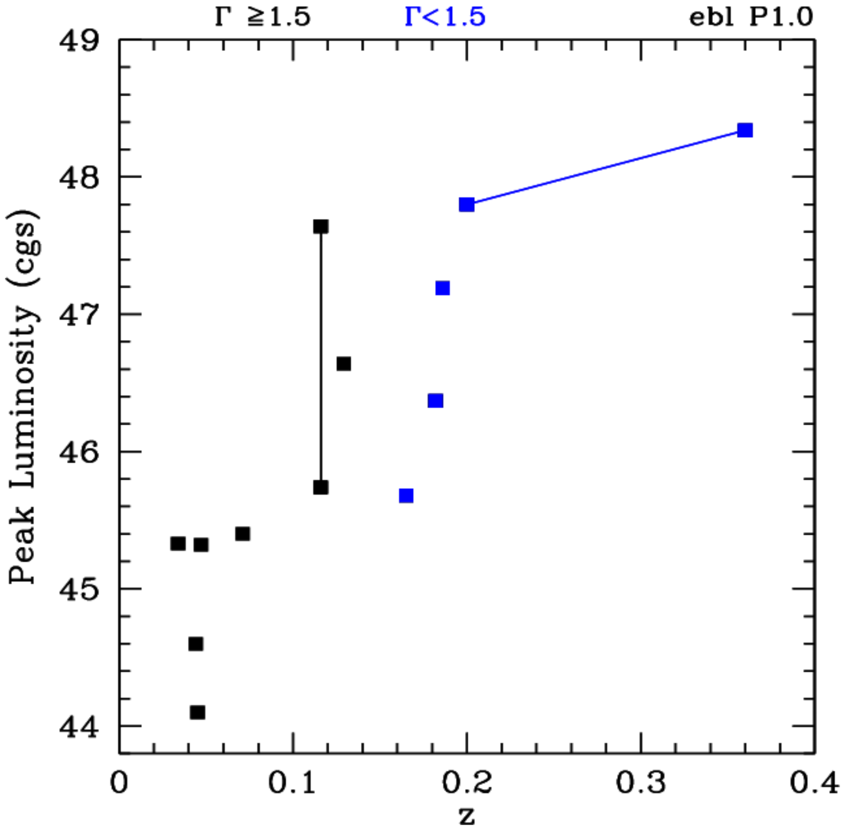
Galaxy counts, +evol

A high EBL would require strong evolution of properties between z=0.2 and 0.1

Other explanations ?

1) Blazar evolution → but redshift range too narrow

2) We are moving along the luminosity function:
switch of properties with luminosity ?



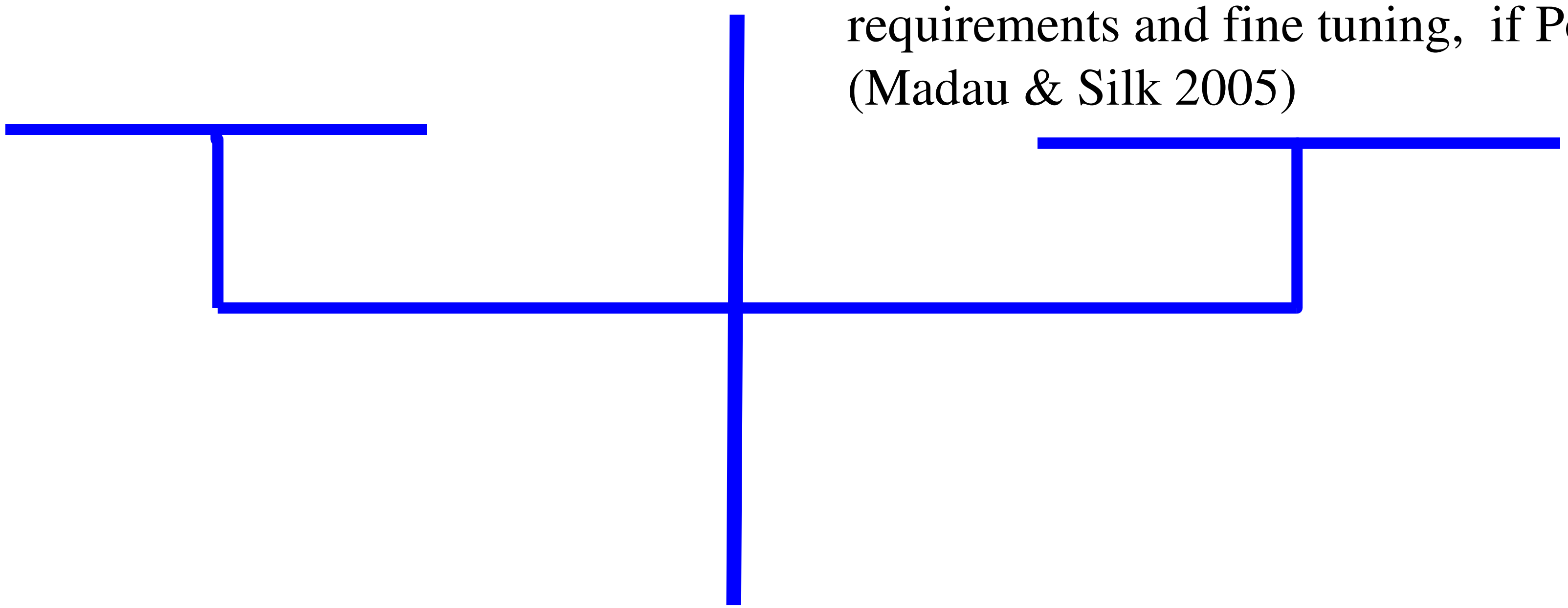
- Invent new scenario for blazars (line-like spectra, monochromatic particle distributions, but still lower EBL required)

- Always hide such features with absorption (never seen directly: EBL conspiracy ?) & below synchr. peak

- Explain redshift correlation (why features are absent in closer objects ? evolution or luminosity?)

- Too many baryons, extreme energetic requirements and fine tuning, if Pop III (Madau & Silk 2005)

Low EBL



Bottom line:

Though not (yet) the smoking gun, the H.E.S.S. spectra provide strong circumstantial evidence that the EBL density is very low, near the galaxy counts limits.

$\Rightarrow$ The EBL is mainly determined by the starlight from known galaxies (no strong Pop III contribution $\rightarrow$ solve the energy budget problem).

$\Rightarrow$ The intergalactic space is more transparent to TeV gamma-rays $\rightarrow$ we can look further

$\Rightarrow$ Reduced uncertainty on blazar spectra reconstruction

Inaccurate rumors from the Nature paper

1) Assumption of Γ=1.5 as the hardest theoretically possible spectrum

2) Only a fixed, predefined EBL shape has been used

3) Claim that contribution from Pop III stars is excluded

Inaccurate rumors from the Nature paper

1) Assumption of Γ=1.5 as the hardest theoretically possible spectrum

Hardest spectra ARE possible, and examples are provided in the paper. Γ≈1.5 is the hardest spectrum that does not require dramatic changes in blazars scenario (only to gain half-way)

2) Only a fixed, predefined EBL shape has been used

It is the starting point, tested all changes with respect to the template shape

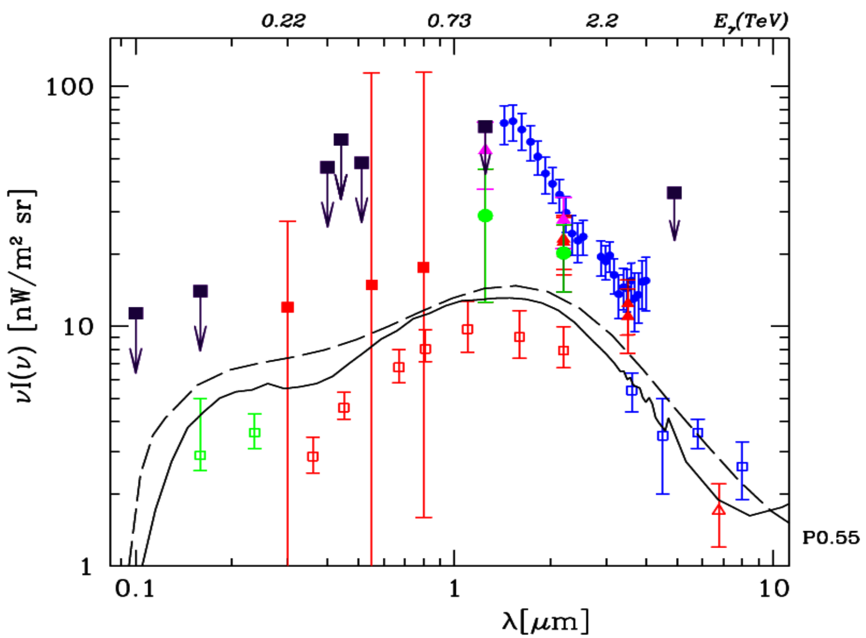
3) Claim that the contribution from Pop III stars is excluded

We exclude not the presence, but the dominance of the contribution

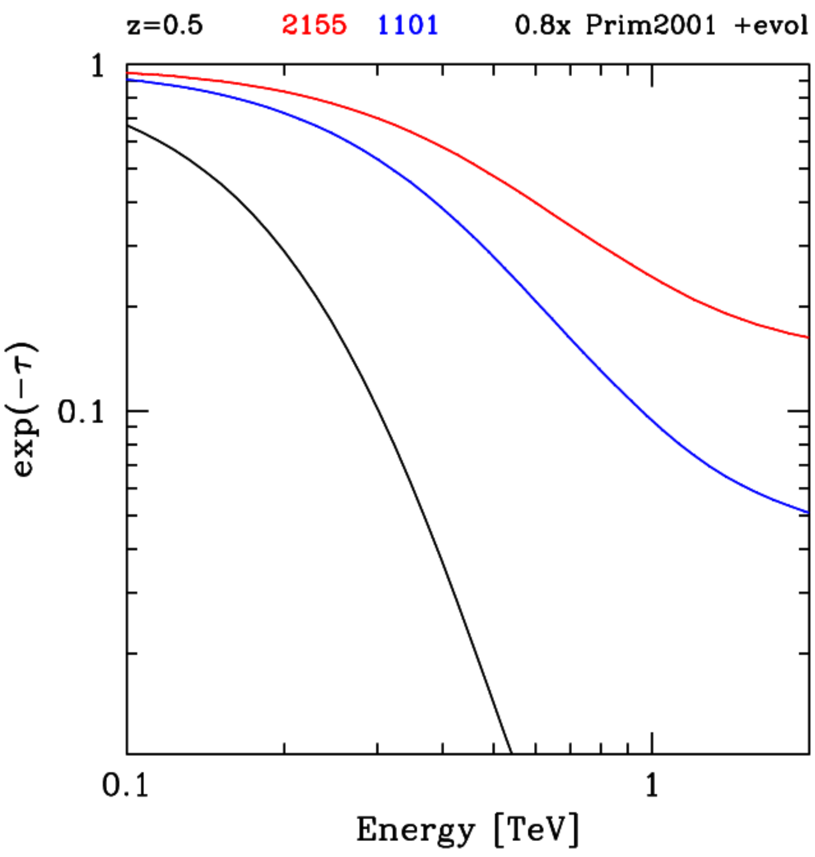
How can we test/falsify this conclusion ?

- Detecting and monitoring low-z (=low attenuation) TeV blazars (look for $\Gamma < 1$)

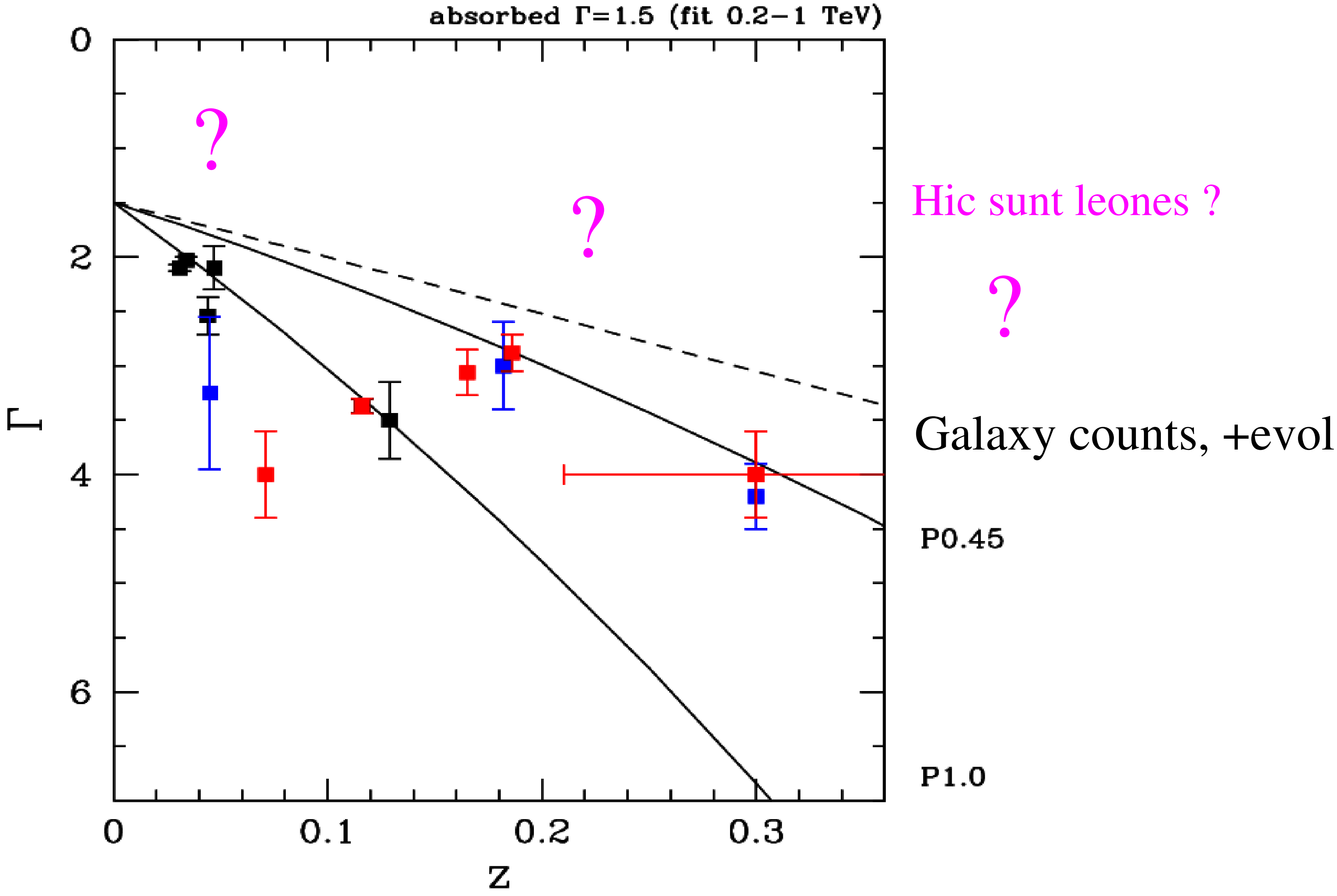
- Observing high redshift objects (z=0.4-0.5): Γ=1.5 $\Rightarrow$ below gal. counts ?
  --> test blazar physics + Lorentz invariance



Primack et al. 2001, 0.8x

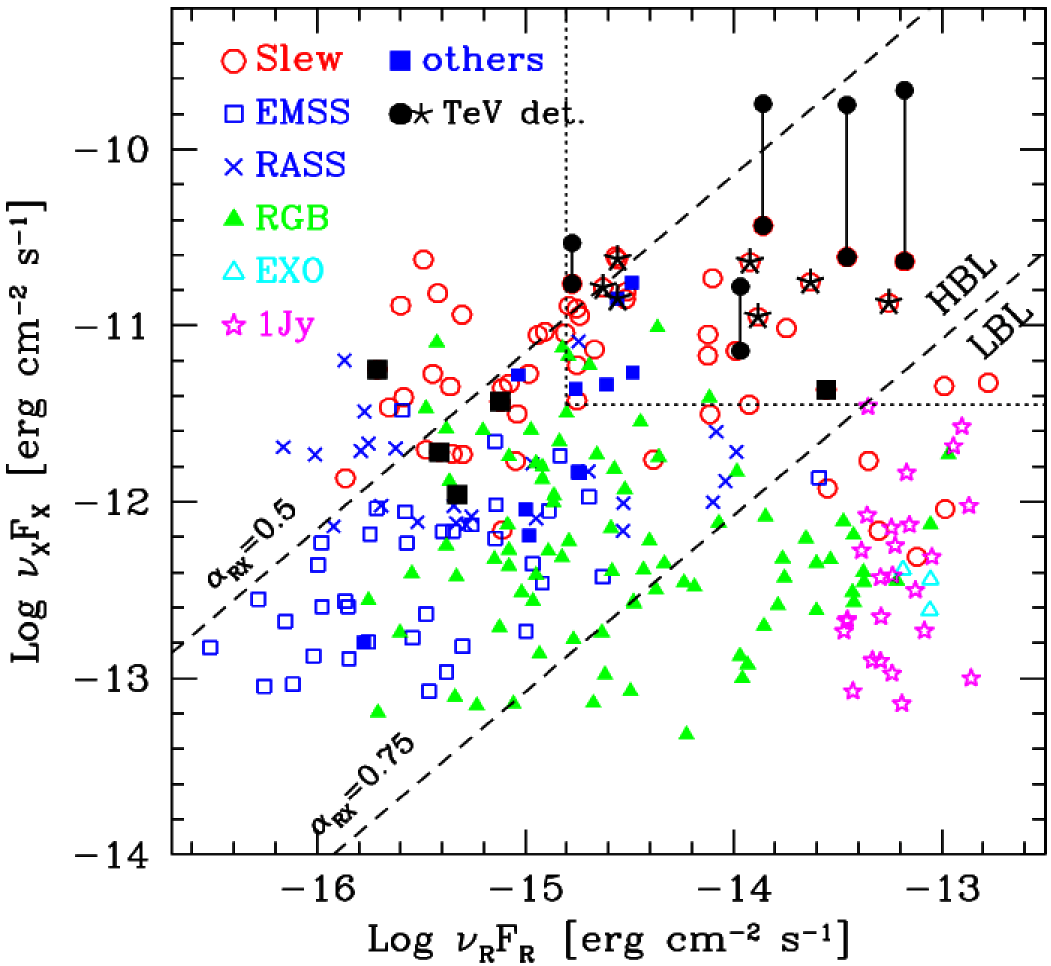


Hunt for sources in the unexpected zone



Proposed high-z targets for HESS (south) and MAGIC+VERITAS (north):

Needs: culmination near telescope's zenith (lowest possible threshold)
+ high X-ray flux objects (large number of TeV electrons)

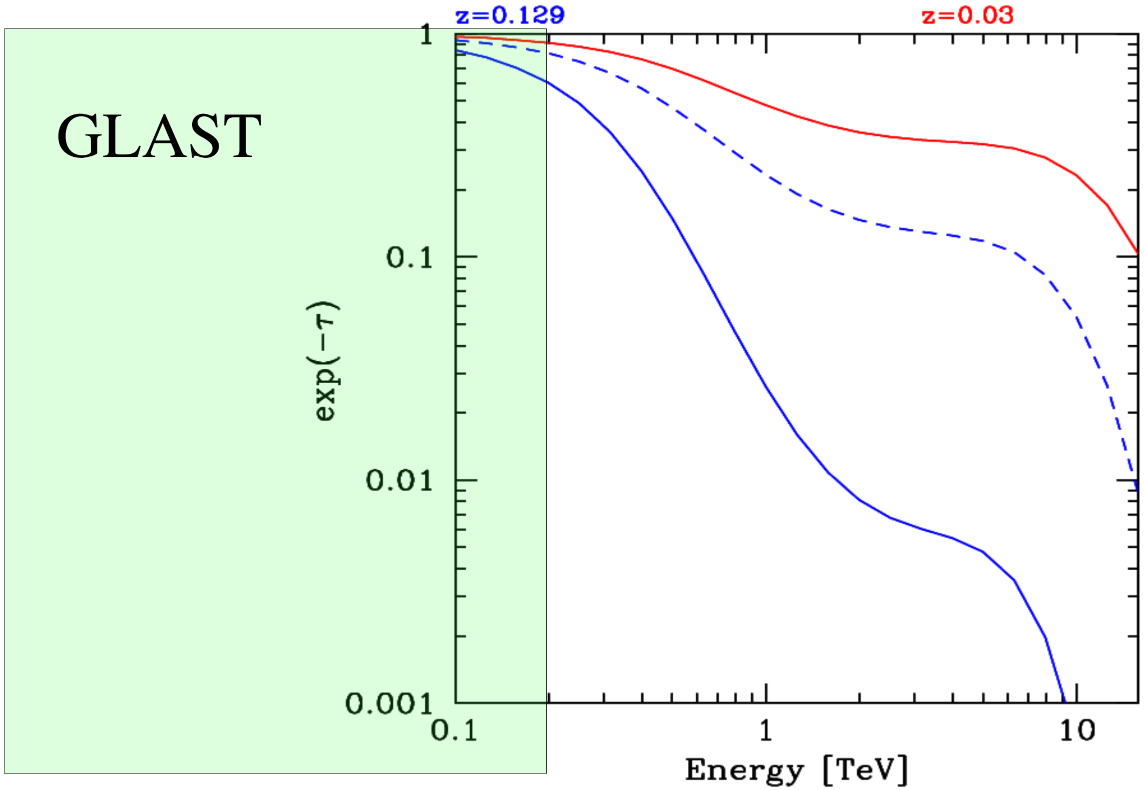


Costamante & Ghisellini 2002

1ES 1248–296	z=0.487
1ES 1332–295	z=0.513
1ES 1106+244	z=0.460
RXJ 1326.2+2933	z=0.431
1ES 0219+428	z=0.444

Next steps:

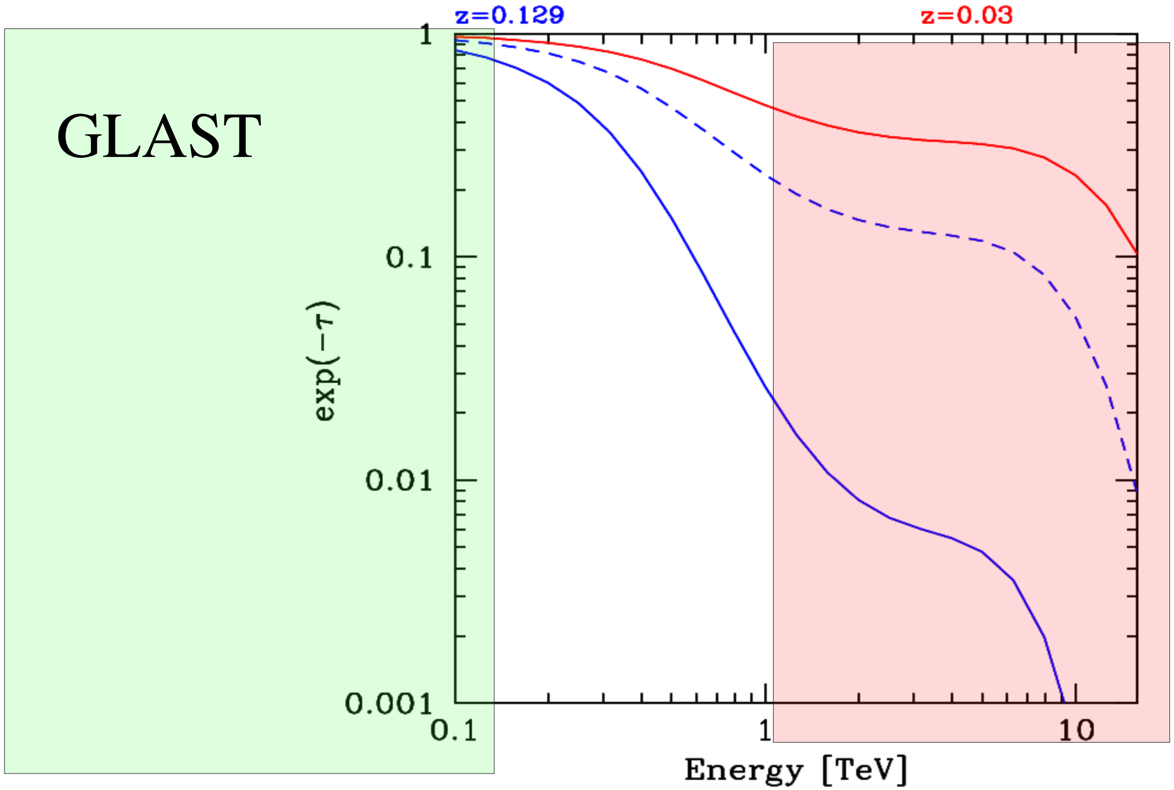
1)



But warning: zone of
internal absorption for FSRQ !

Next steps:

1)



Cherenkov Telescopes

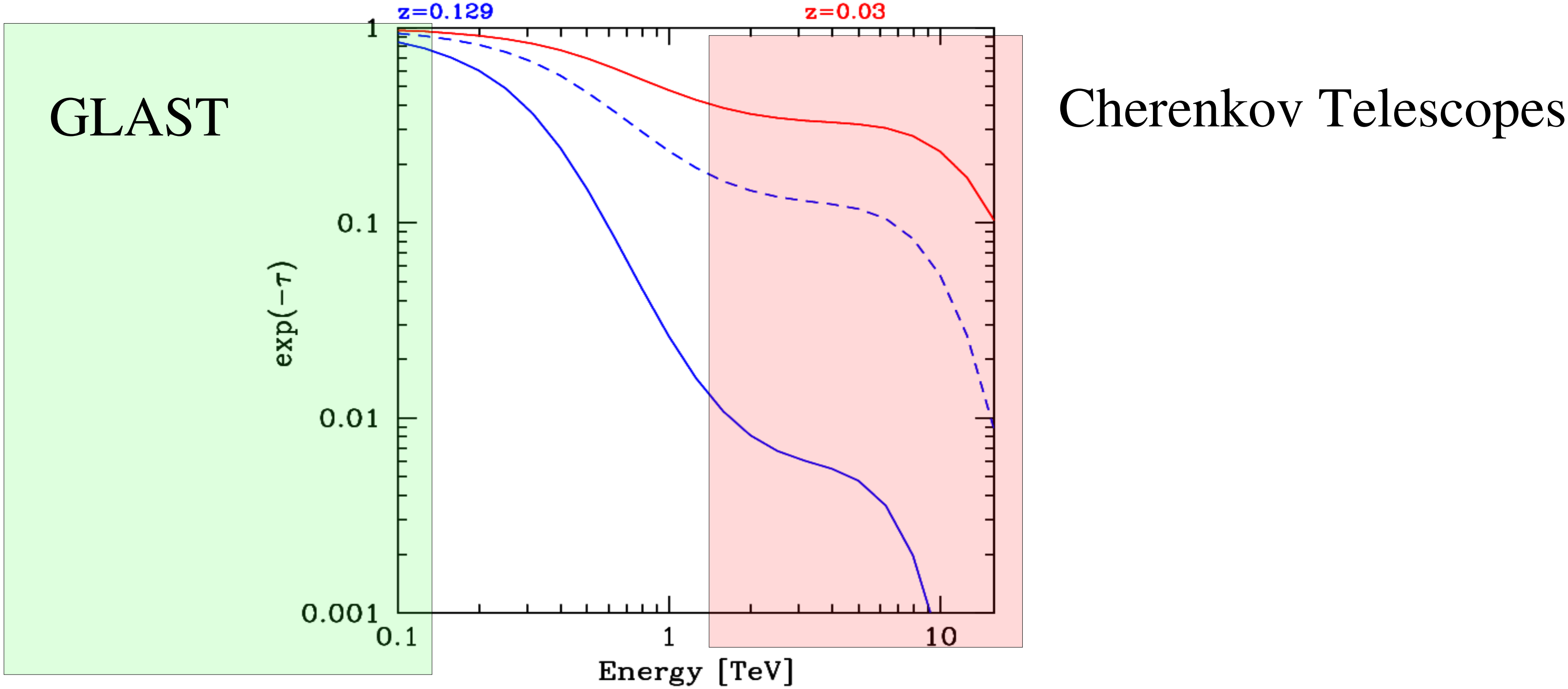
multi-TeV spectra:

a) 1426+428 + ...

b) Mkns, M87

Next steps:

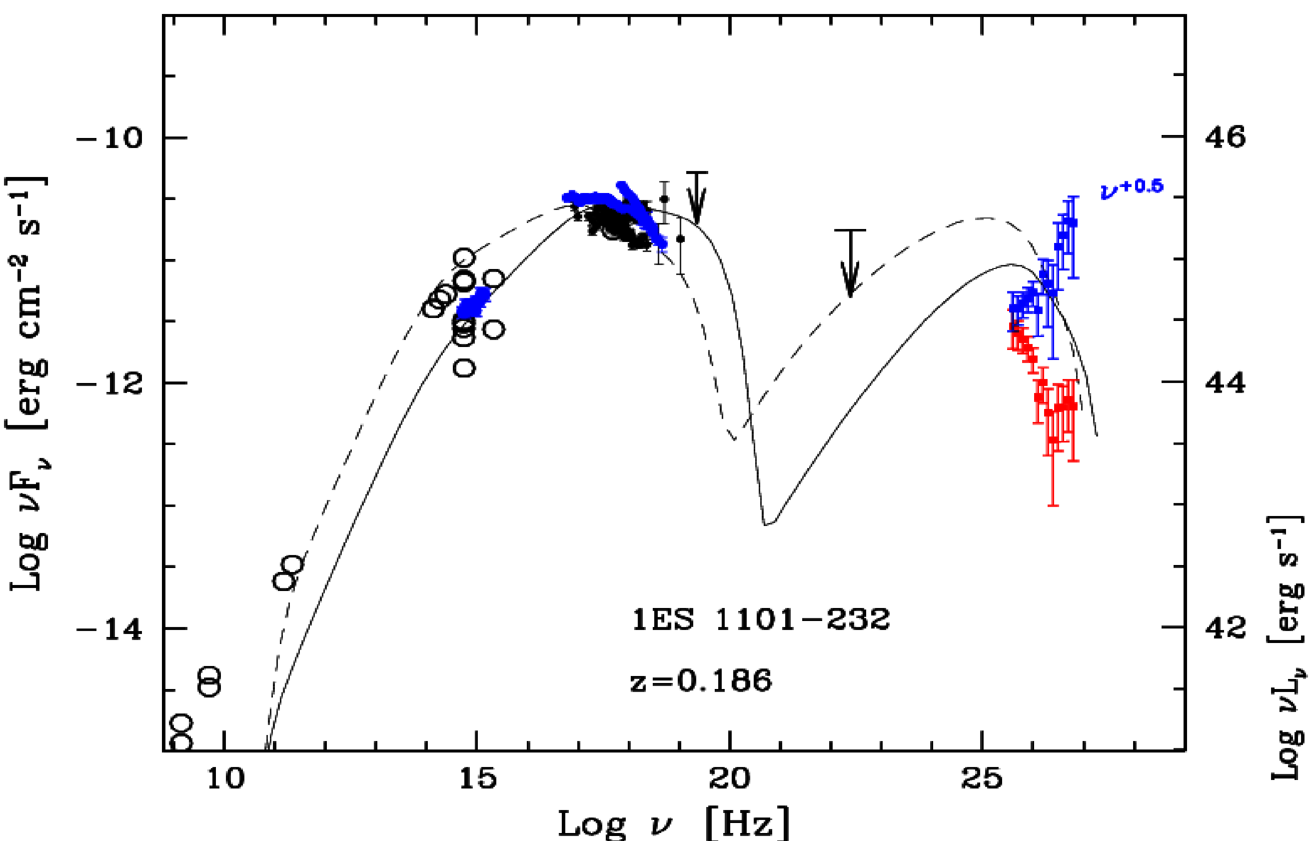
1)



2) HBL physics: the puzzling SEDs of 1ES 1101-232 & PKS 2155-304

Puzzling issue: TeV spectra harder than (even soft) X-ray ones

XMM, RXTE, HESS (Aharonian et al, HESS coll, 2007)



1ES 1101-232: intrinsic TeV spectrum always hard ! (EBL-independent):

Γ=1.5 (--> 1.9-2.0)

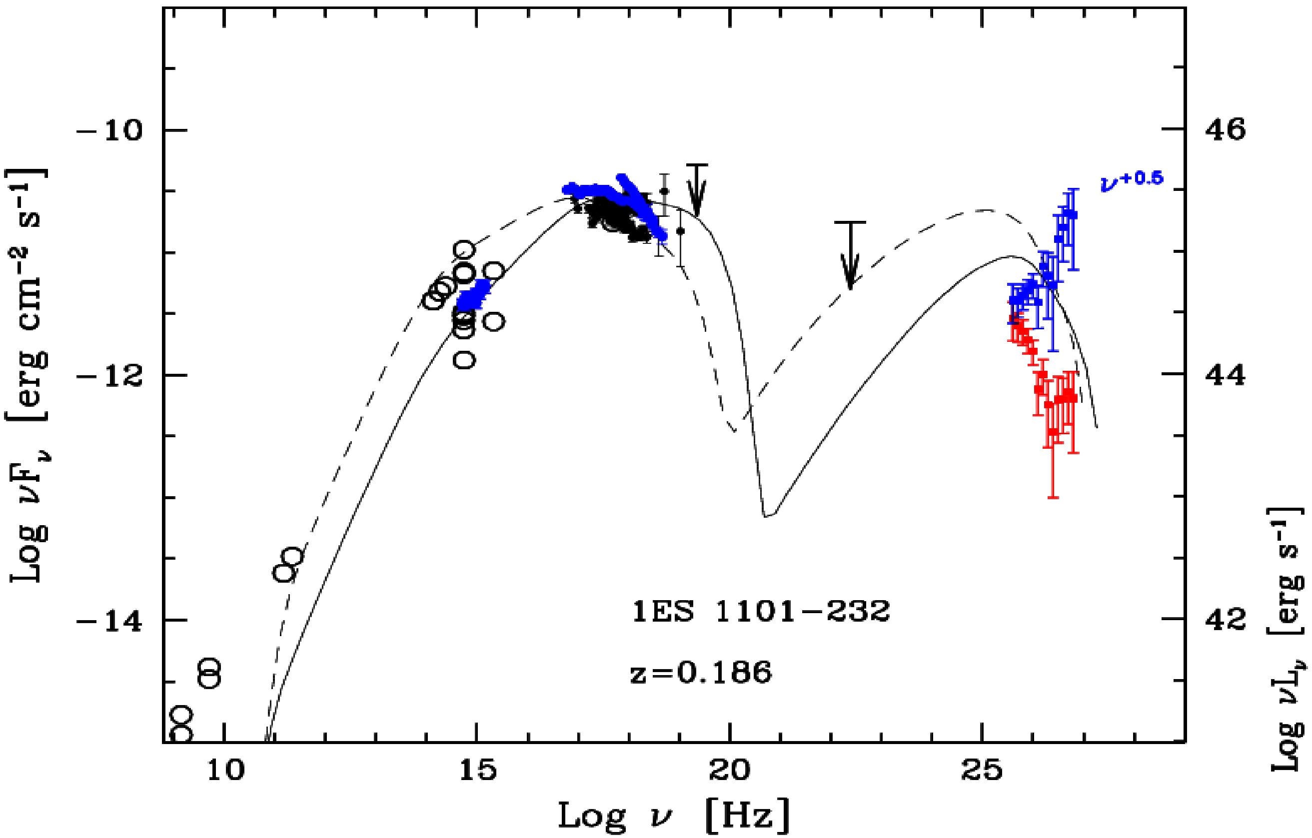
To produce 1 TeV photons...

Energy conservation: --> $$\gamma_e \geq \frac{2\times10^6}{\delta}$$

Their synchrotron emission: --> $$E_{sync} \geq 20 \frac{B}{\delta} keV$$

Puzzling issue: TeV spectra harder than (even soft) X-ray ones

XMM, RXTE, HESS (Aharonian et al, HESS coll, 2007)



$$E_{sync} \geq 20 \frac{B}{\delta} keV$$

Where is the synchrotron emission of these TeV electrons ??

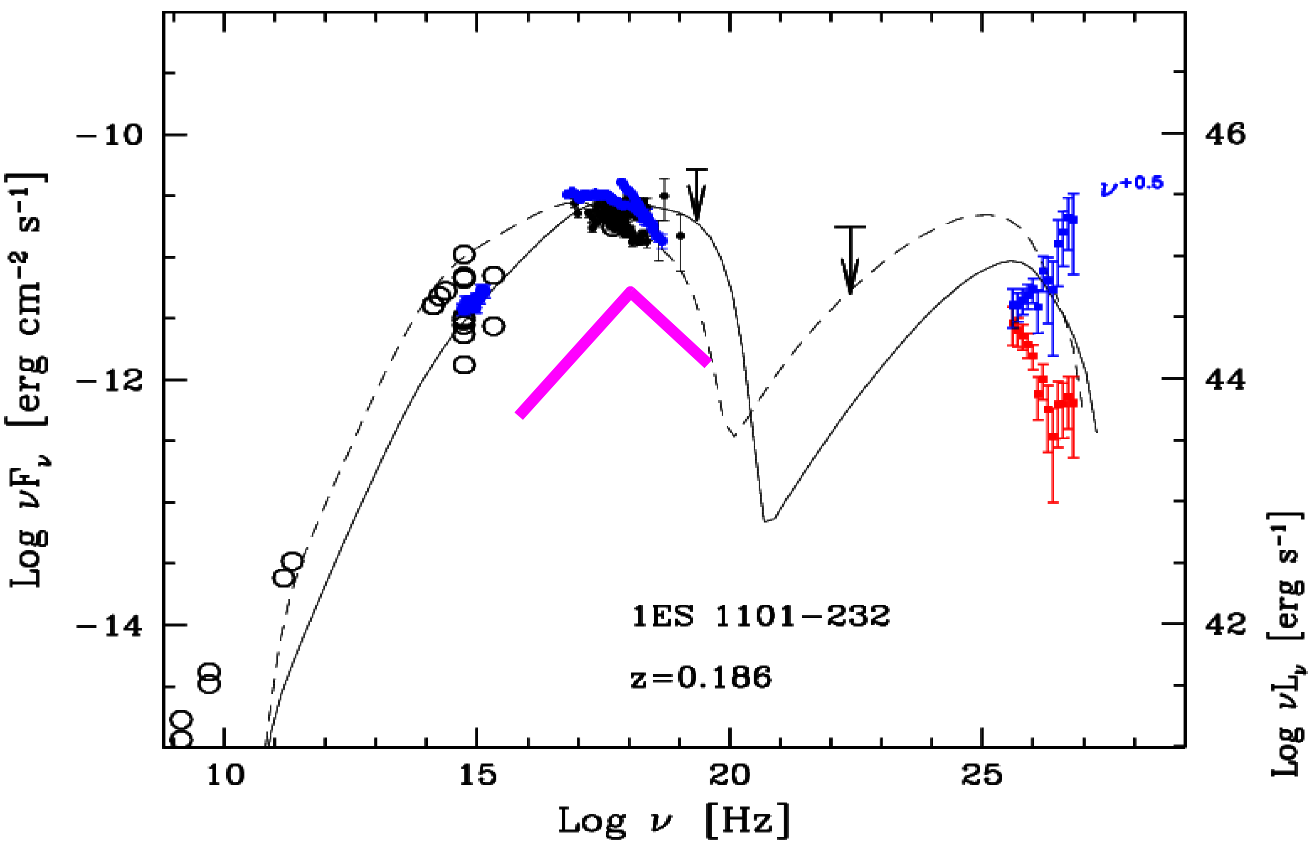
B ~ 0.1 Gauss

δ ~ 10

$\Rightarrow$ ~0.2 keV

Puzzling issue: TeV spectra harder than (even soft) X-ray ones

XMM, RXTE, HESS (Aharonian et al, HESS coll, 2007)



$$E_{sync} \geq 20 \frac{B}{\delta} keV$$

Where is the synchrotron emission of these TeV electrons ??

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Different possibilities (in SSC scenario):

- 2 components (particle populations) → X-ray emiss. below main one

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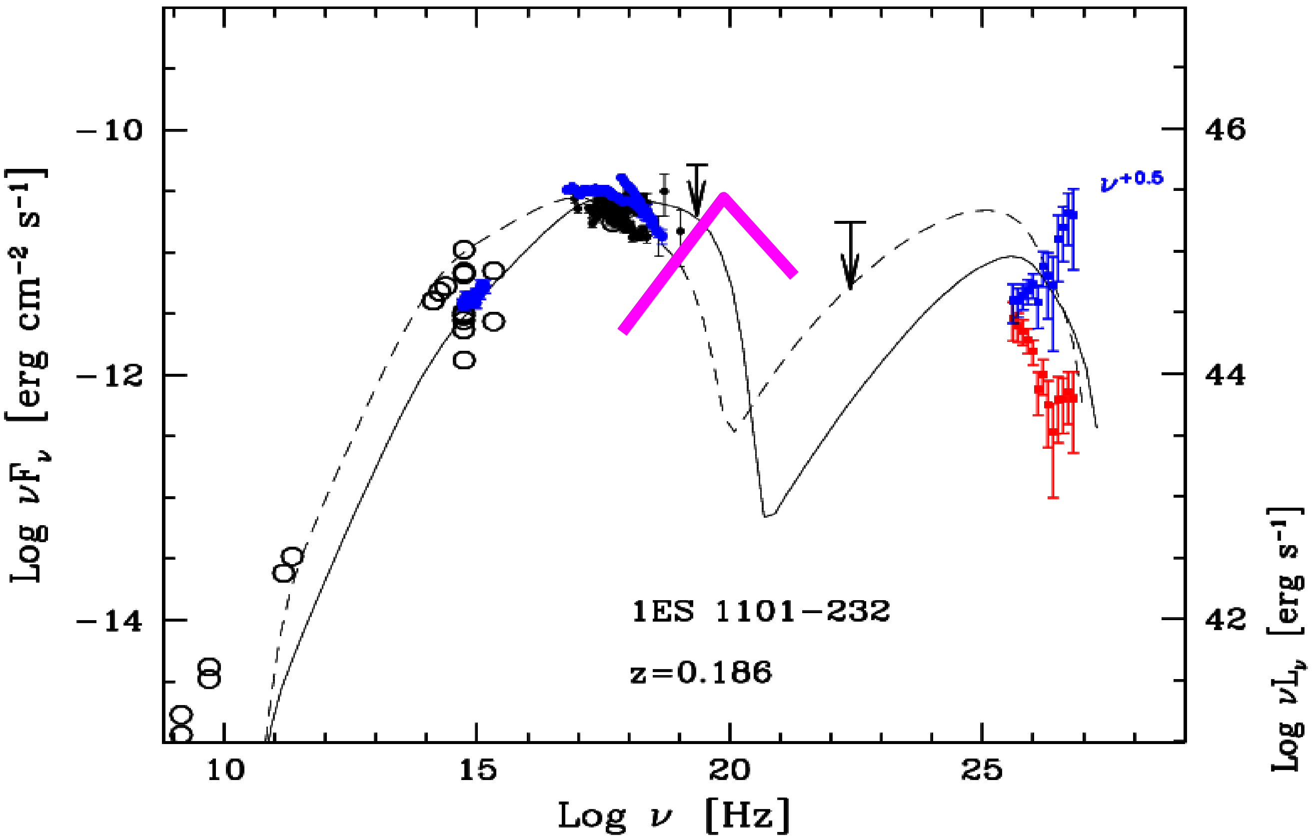

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Different possibilities (in SSC scenario):

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  ➔ emerging above 10-20 KeV

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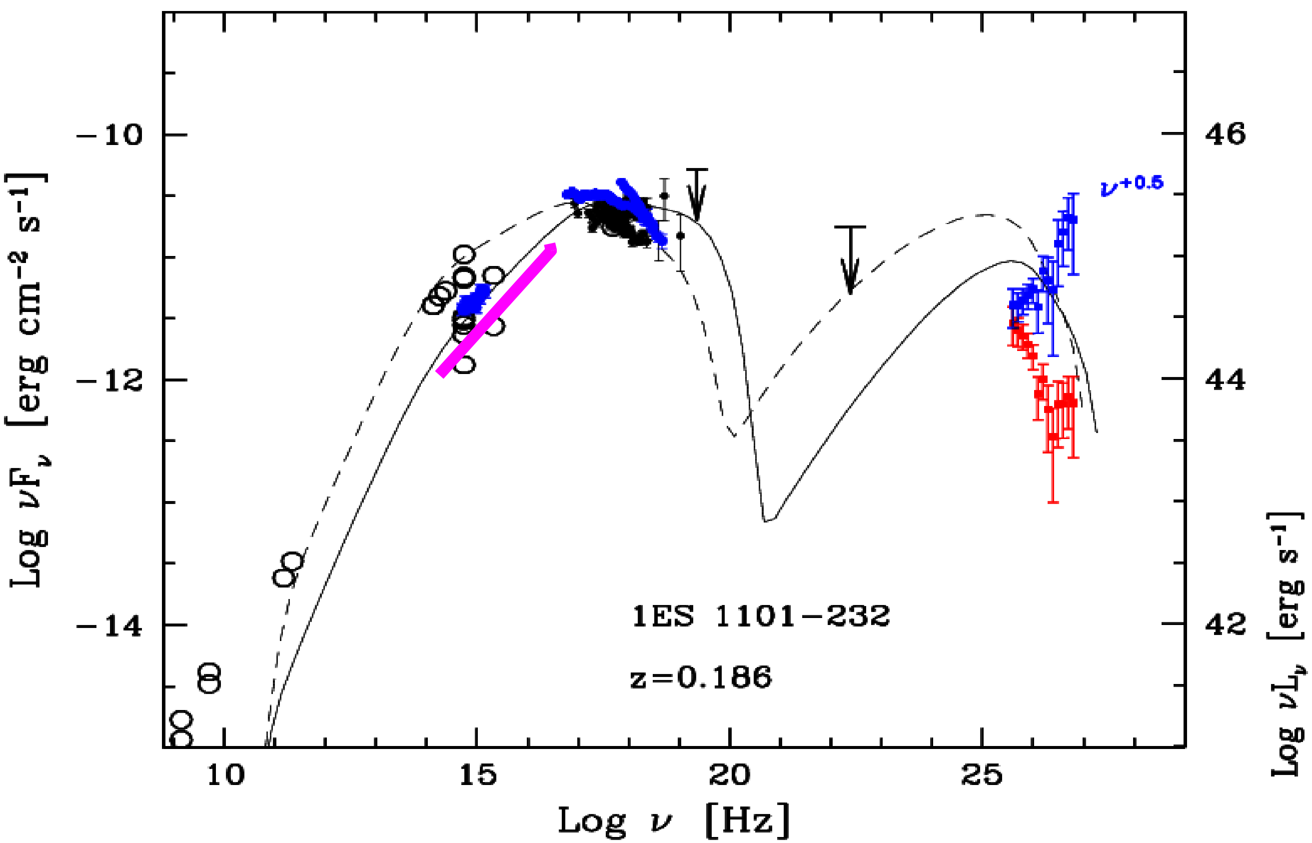
XMM, RXTE, HESS (Aharonian et al, HESS coll, 2007)



$$E_{sync} \geq 20 \frac{B}{\delta} keV$$

Where is the synchrotron emission of these TeV electrons ??

B ~ 0.1 0.01 Gauss

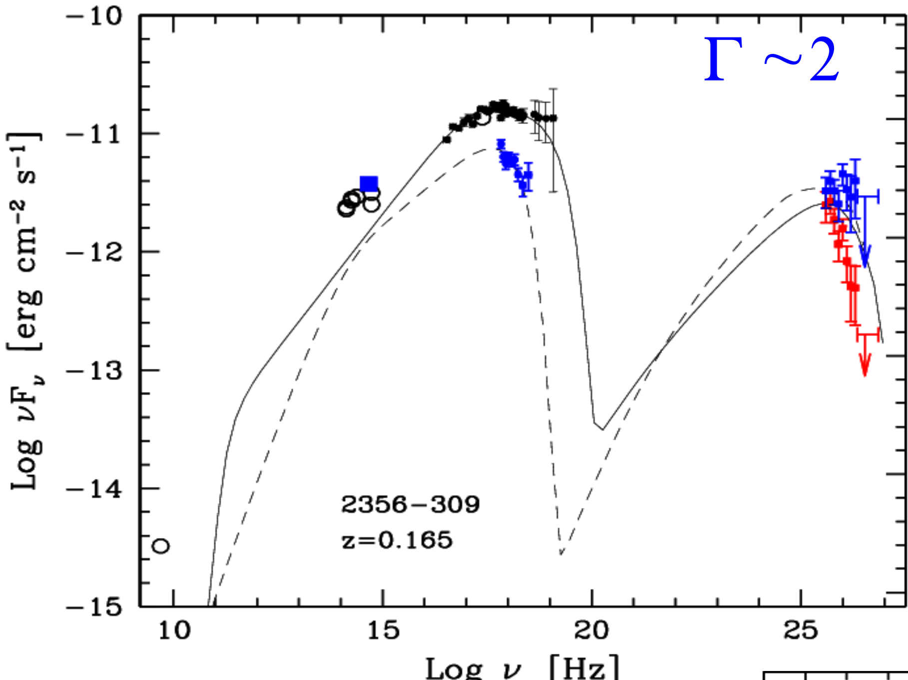
δ ~ 10 100

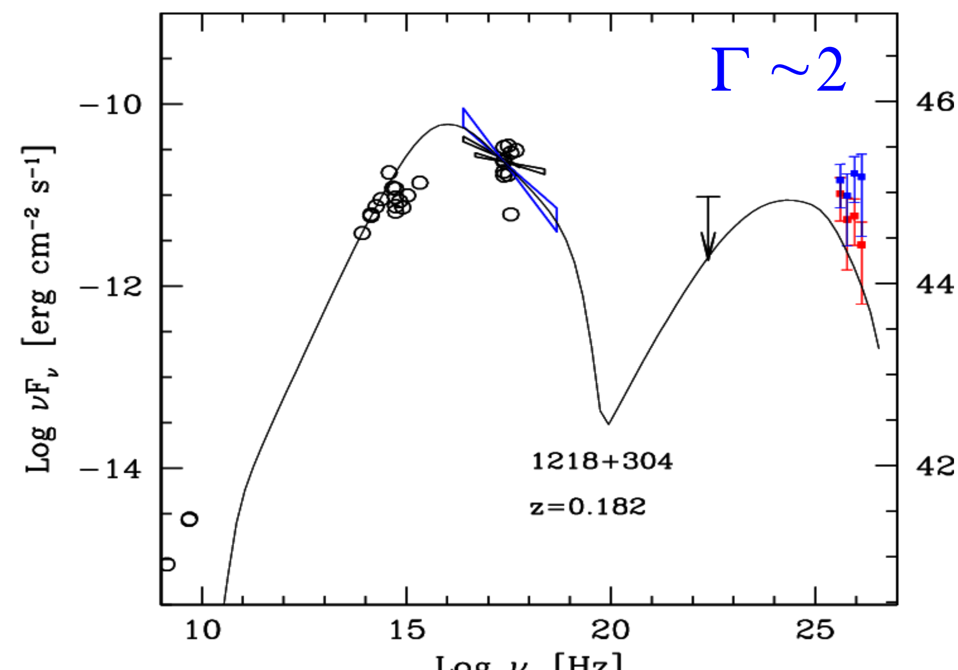
Different possibilities (in SSC scenario):

- 2 components (particle populations) ➔ X-ray emiss. below main one
  ➔ emerging above 10-20 KeV

- Synch. Emission Opt-UV ⇒ high bulk Lorentz factors

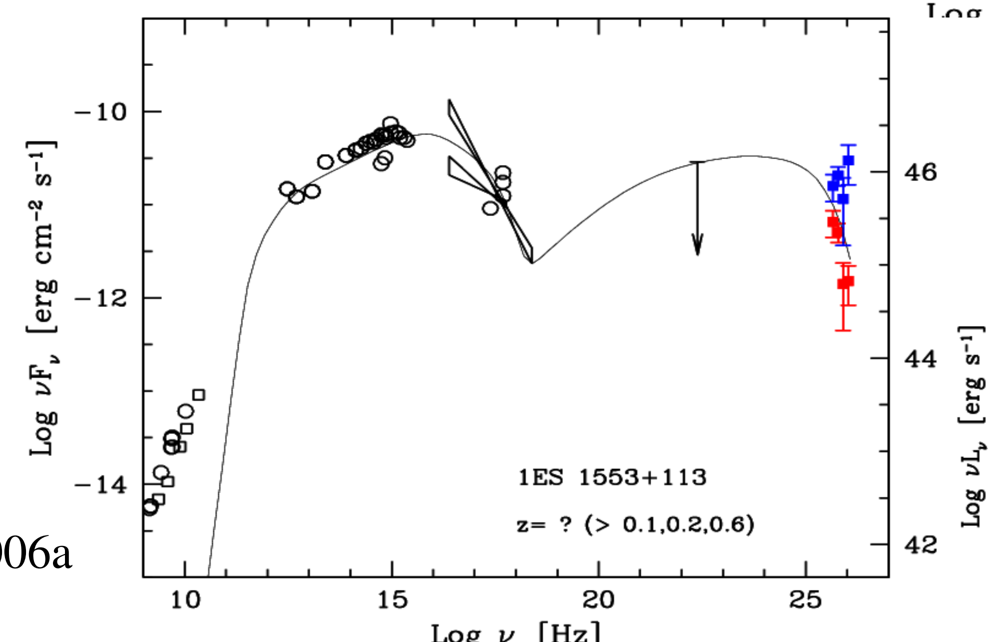
Common issue for "high-z" HBL ? (EBL >≈gal. counts)





Aharonian et al. (HESS coll) 2006b

Albert et al. (MAGIC coll) 2006



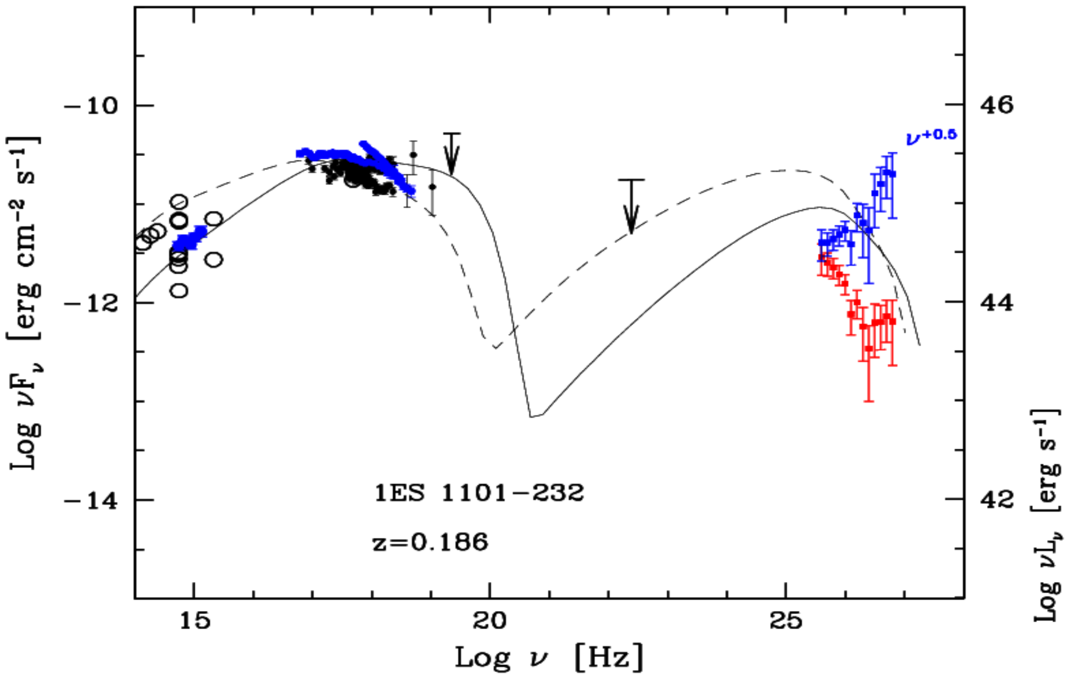
Γ < 2
for z > 0.3

Aharonian et al. (HESS coll) 2006a

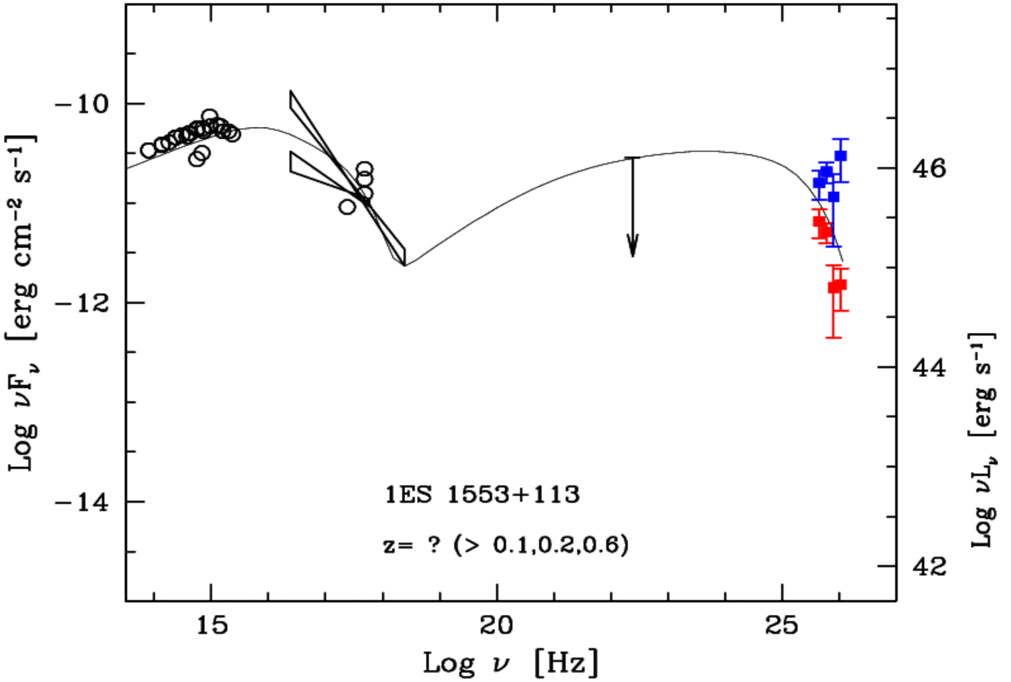
Test with Suzaku !

(below 1 keV + above 10 KeV)

1101-232



1553+113

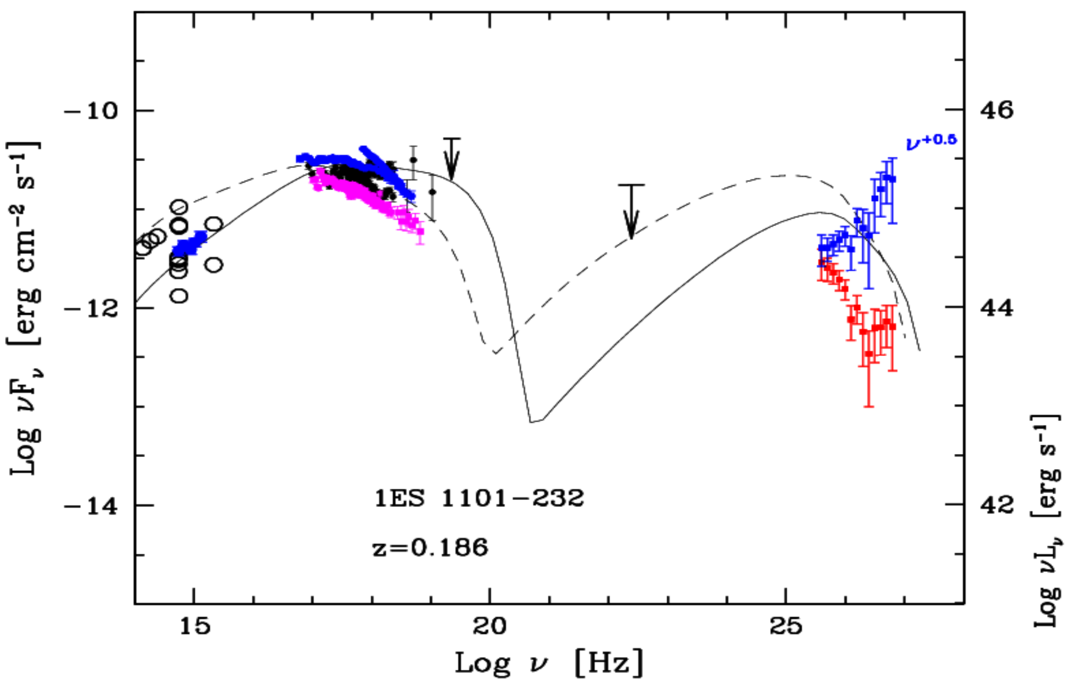


2 observation campaigns HESS-Suzaku in 2006 (May & July)

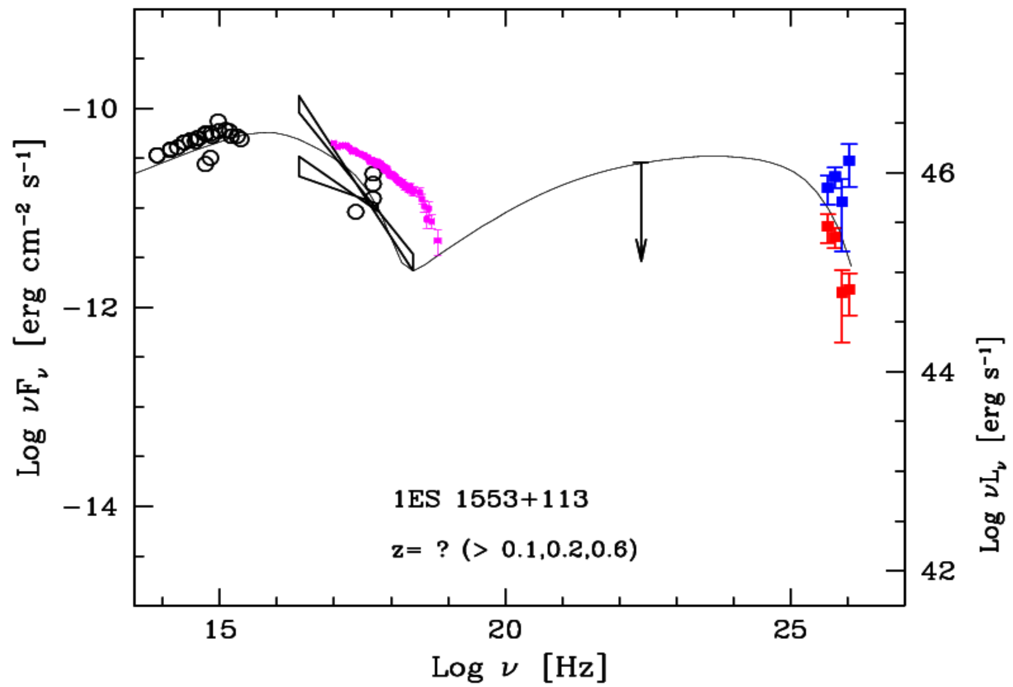
Test with Suzaku !

(below 1 keV + above 10 KeV)

1101-232



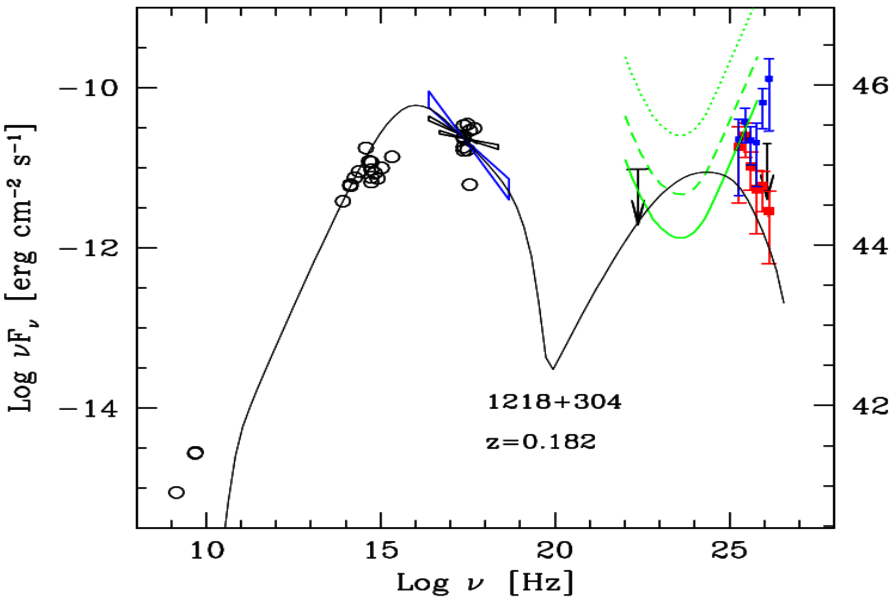
1553+113

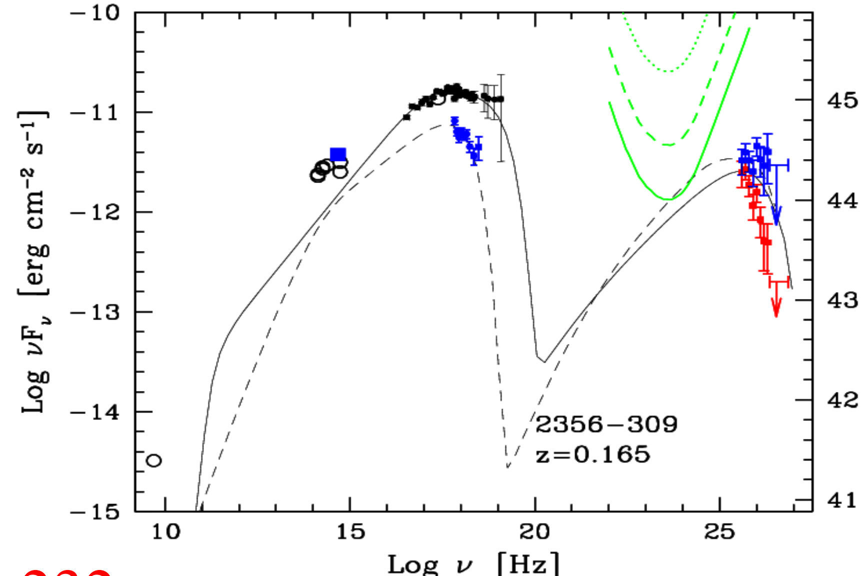


Detection up to ~30 keV; soft spectra; details in poster by A. Reimer

(work in cooperation with "the Reimers" and G. Madejski)

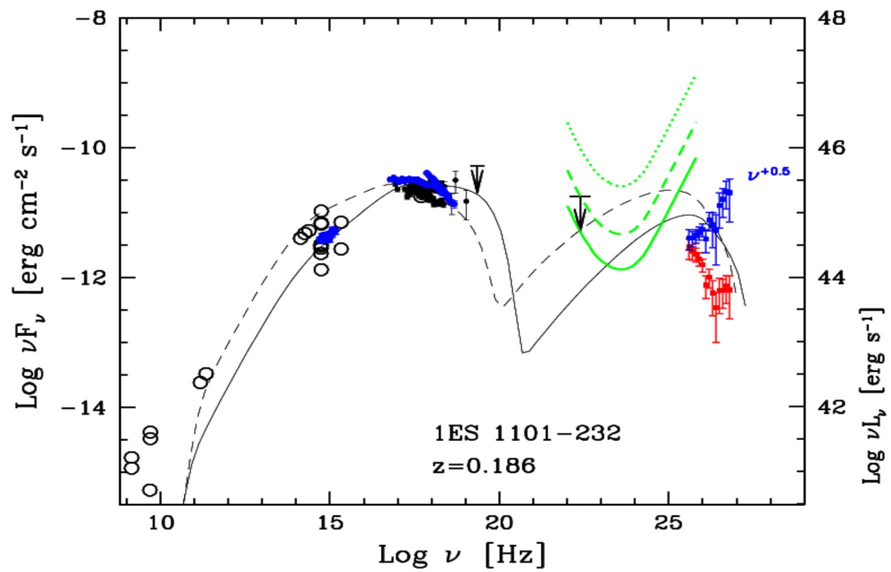
GLAST answers for HBLS





1ES 1101-232

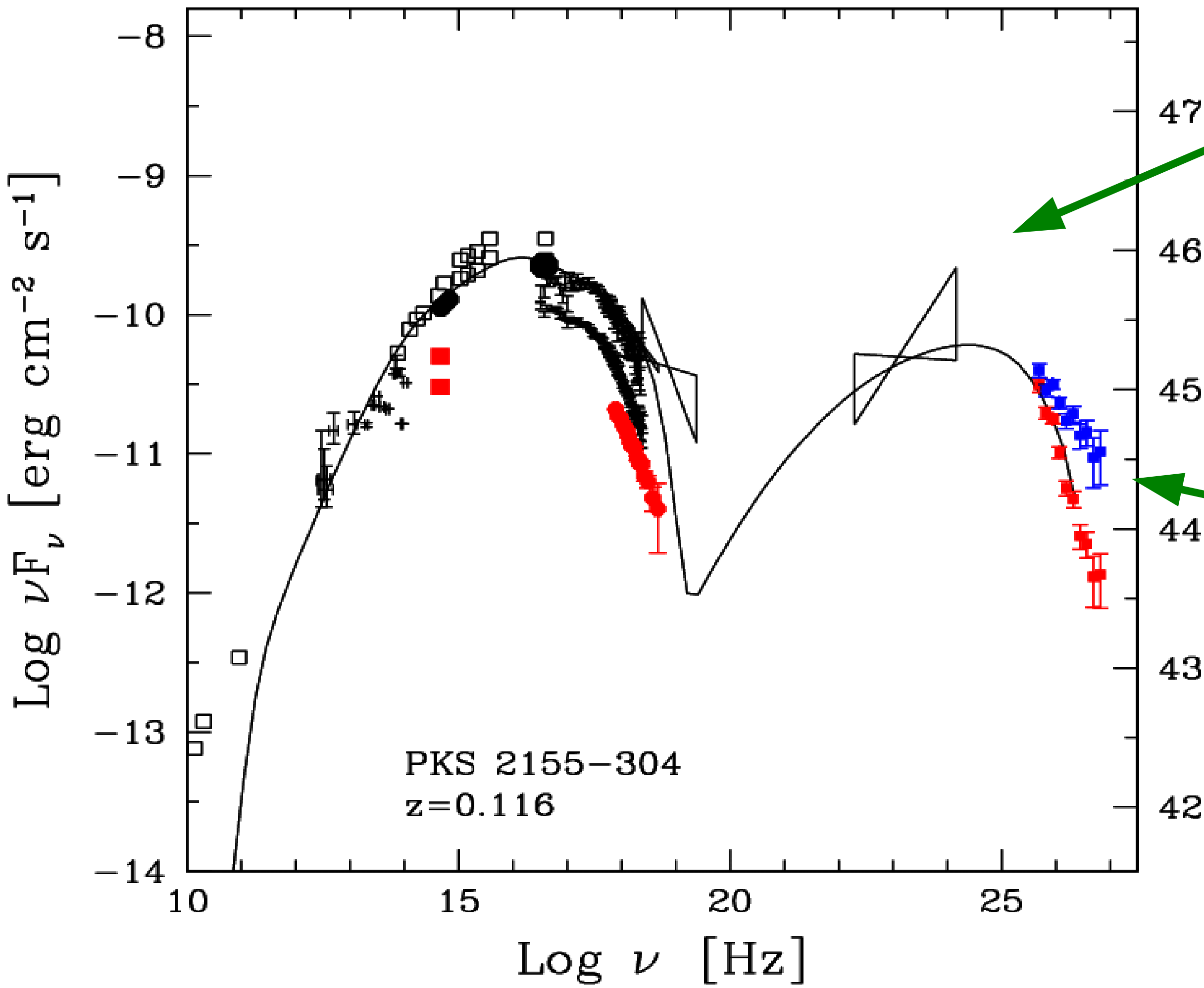
1ES 1218+304



H 2356-309

Expected spectra: always hard ($\Gamma < 2$)

It seems so, but... is it true ??



EGRET
VP 404.0

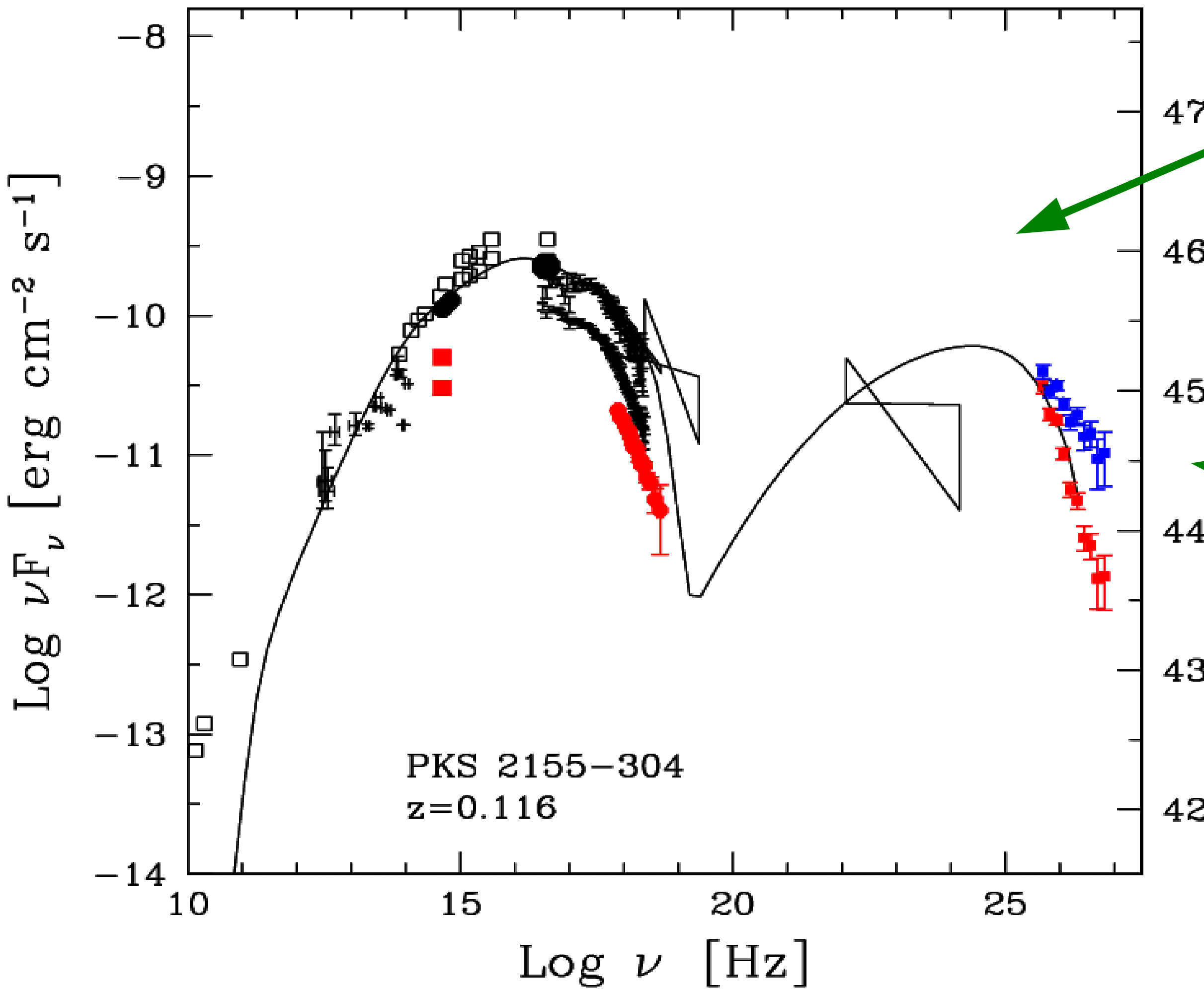
Vestrand et al. 1995

HESS spectrum:
EBL-corrected
observed

Aharonian et al.
2004, 2005

Expected spectra: always hard (Γ < 2)

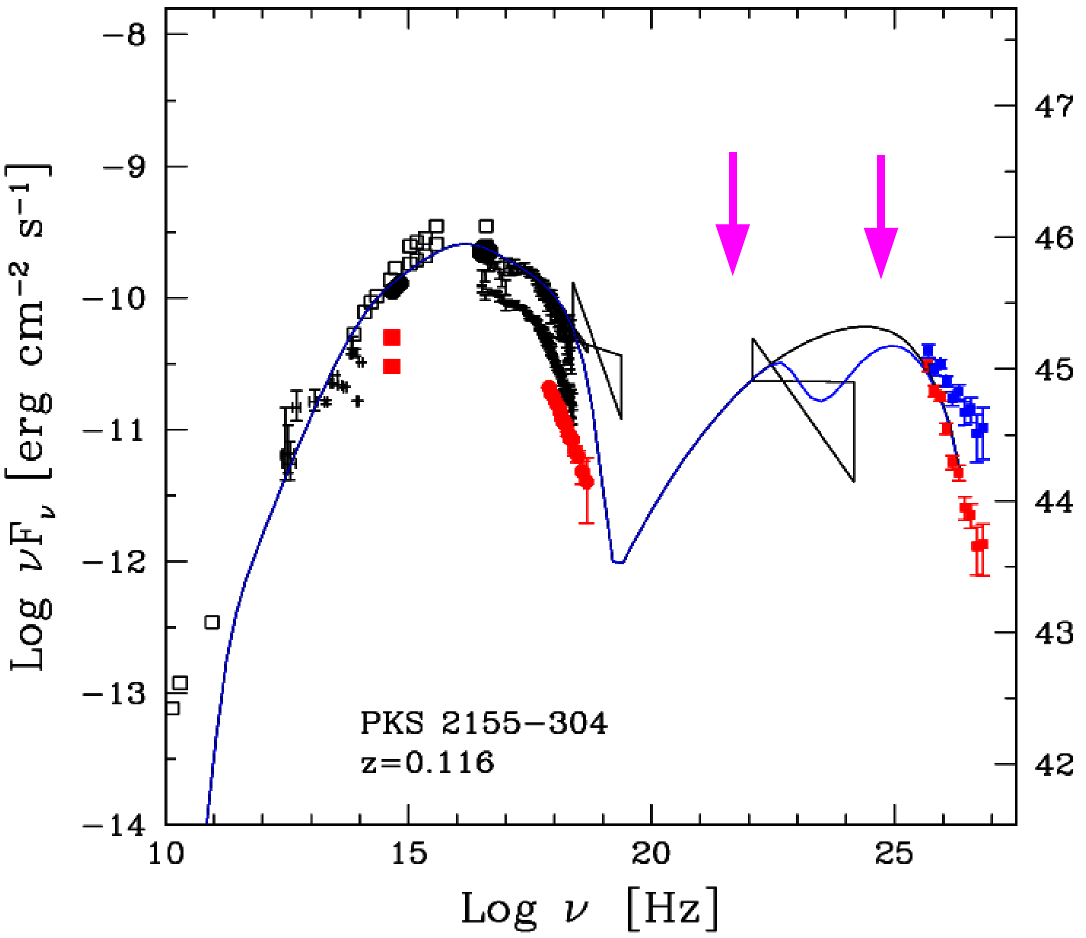
It seems so, but... is it true ??



EGRET
3rd catalogue
(4 years obs.)
Γ=2.35±0.26
STEEP !

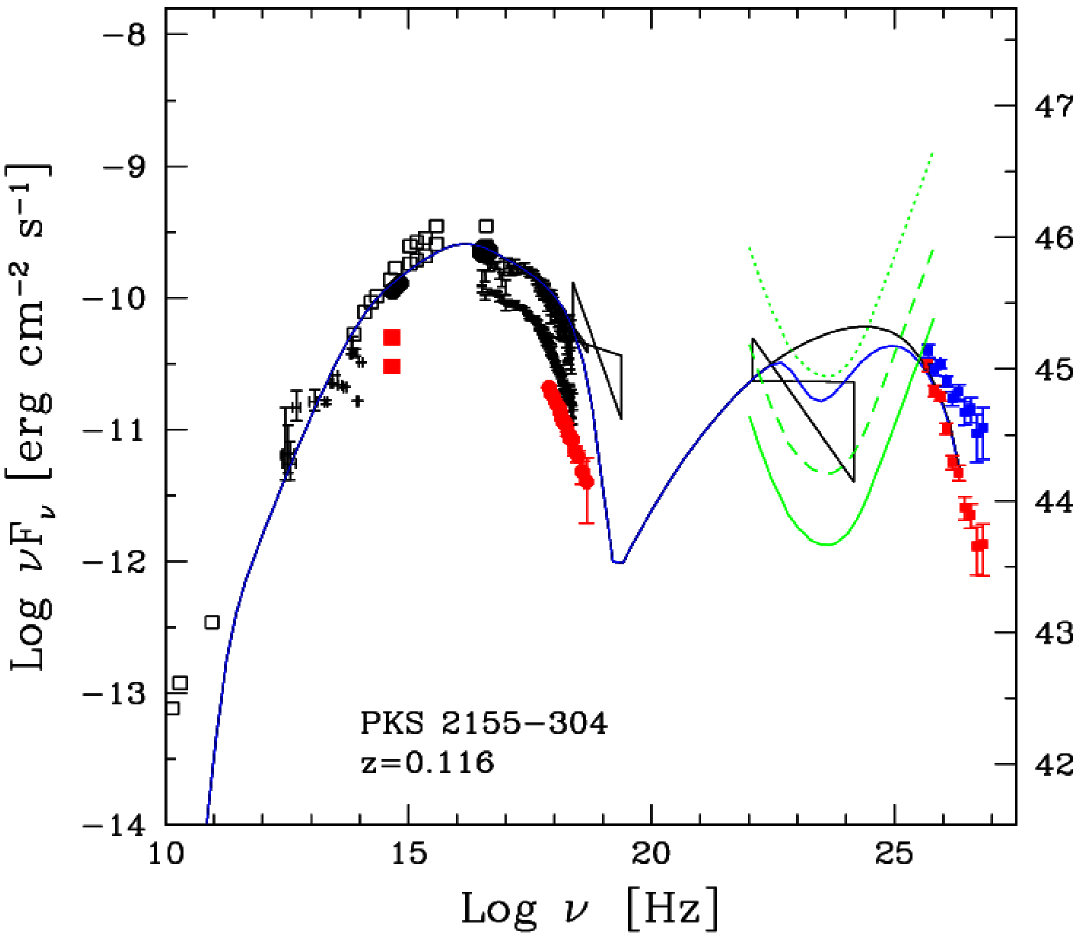
Both EGRET & HESS: typical spectra over several years

Double humped IC peak ??



- 2 particle populations ?
- Bulk motion Comptonization ?
  - Var. few min. ⇒ compact region, & Γ~100
  - Cold e$^-$ + 1 keV phot. ⇒ 10 MeV
- Internal absorption due to narrow-band circumnuclear radiation field ?

GLAST answer in few months / one year



- 2 particle populations ?
- Bulk motion Comptonization ?
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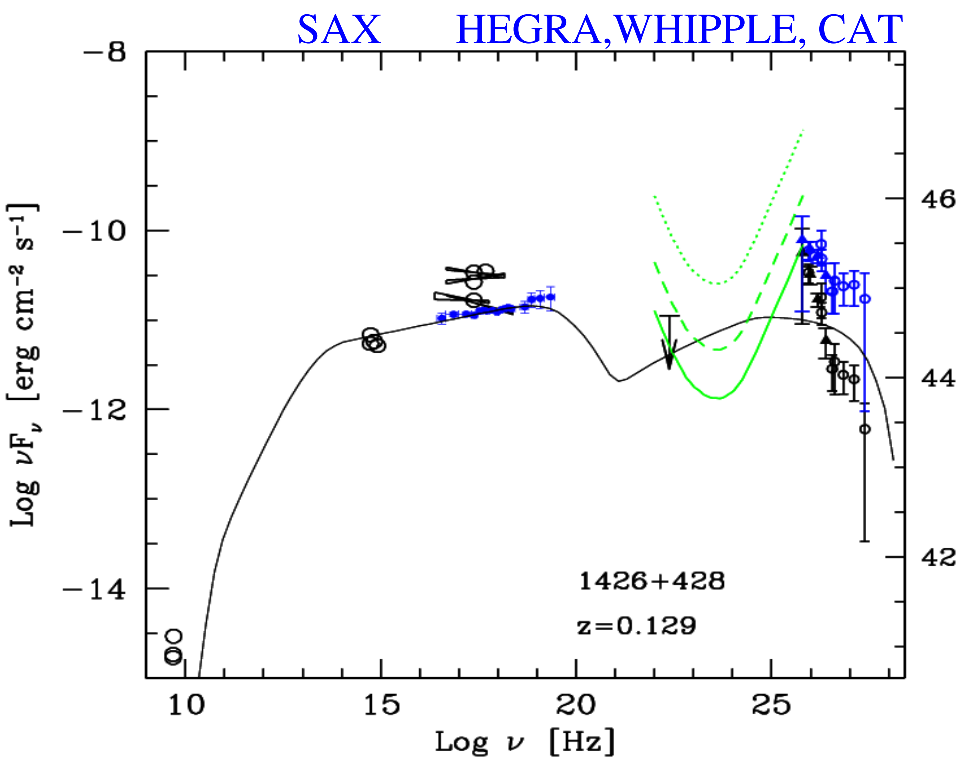
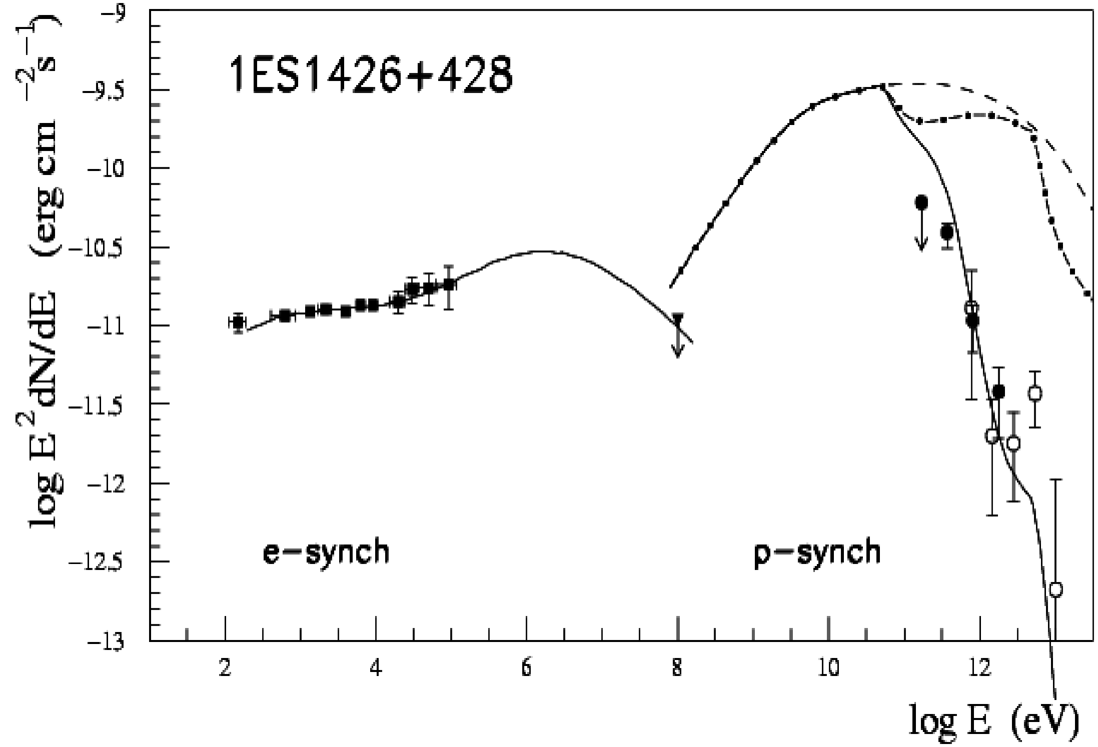
    - Cold e$^-$ + 1 keV phot. ⇒ 10 MeV
- Internal absorption due to narrow-band circumnuclear radiation field ?

Test electron/proton synchrotron scenario





Electrons,SSC: very low B ~0.1-0.01G

Protons: B=100G , R= 3x10^{15} cm

δ=20 , particle index= 2

X-rays from secondary electrons

γ–γ on external fields: 100, 1 eV

Costamante et al. 2001, 2003

Ghisellini et al. 2002

Aharonian et al. 2004

HBL $\rightarrow$ extreme BL $\rightarrow$ higher ??

Synch peak: 10 –1000 eV $\rightarrow$ 1–100 KeV $\rightarrow$ max energy ??

Maximum (theoretically possible) acceleration rate:

= minimum acceleration time $t_{min} = \eta \, R_L/c$

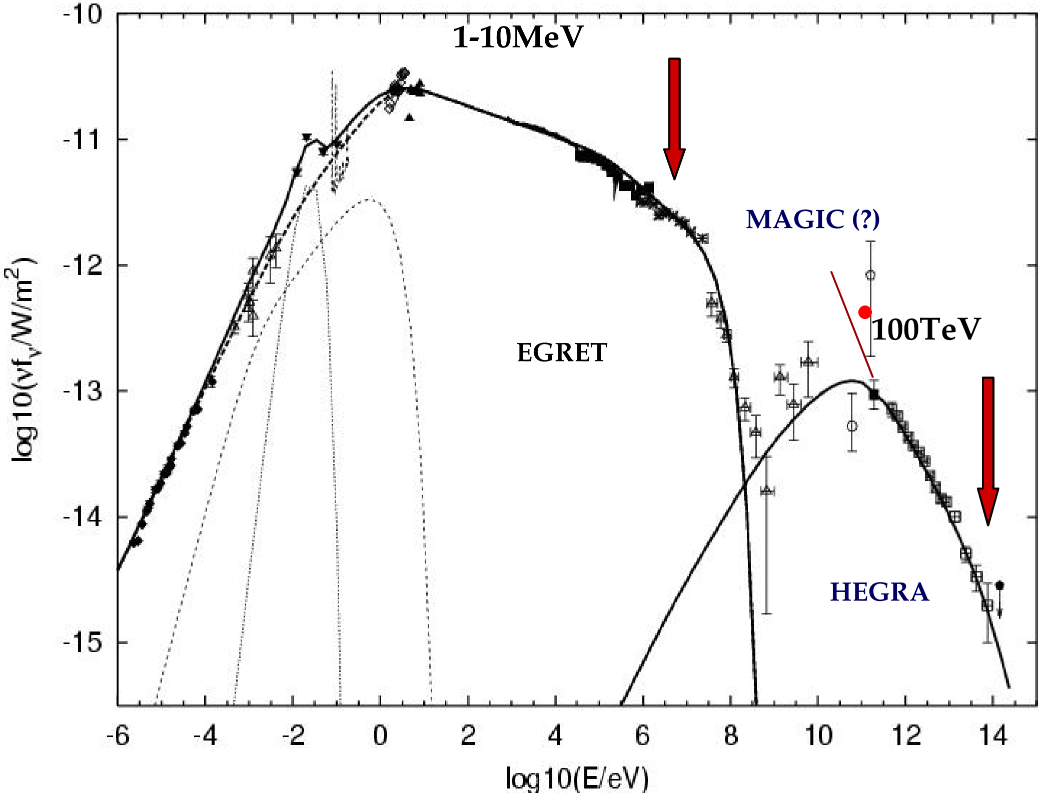
$\eta \geq 1$; low η (1-10) $\Rightarrow$ extreme accelerators

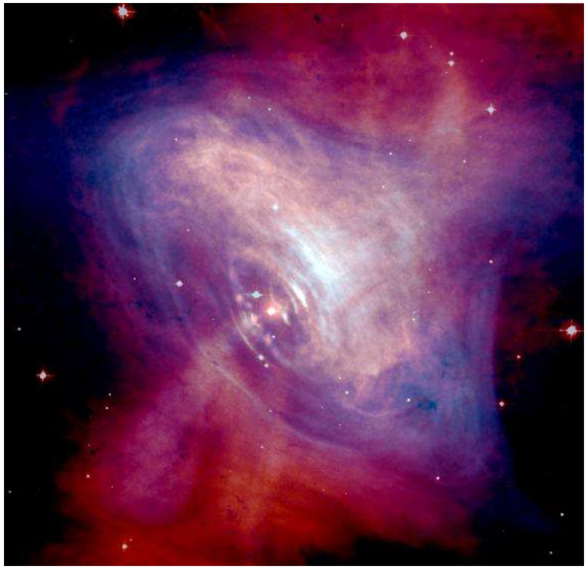
From $t_{acc} = t_{cool}$ $\Rightarrow$ max synchrotron frequency for electrons indep. of B

$$h\nu_{cutoff} = (9/4)\, \alpha_f^{-1}\, mc^2 \approx 150\, \eta^{-1} \text{ MeV}$$

(see e.g. Aharonian 2004 and refs therein)

Example of extreme accelerator: Crab !





Standard MHD theory
(Kennel & Coroniti 84)

Synchrotron cut-off $h\nu_{cutoff}$ = 10-20 MeV $\Rightarrow$ $\eta \approx 10$

acceleration at 10% of max rate

Are blazars extreme accelerators ??

Maximum (theoretically possible) acceleration rate:

= minimum acceleration time $t_{min} = \eta\, R_L/c$

$\eta \geq 1$; low η (1-10) $\Rightarrow$ extreme accelerators

From $t_{acc} = t_{cool}$ $\Rightarrow$ max synchrotron frequency for electrons indep. of B

$h\nu_{cutoff} = (9/4)\, \alpha_f^{-1}\, mc^2 \approx 150\, \eta^{-1}$ MeV

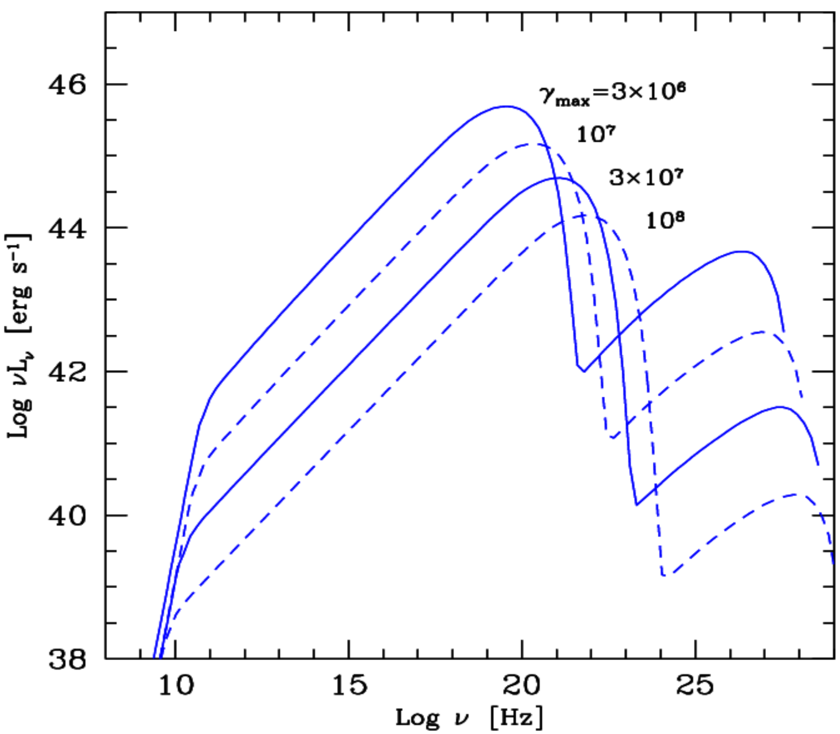
Blazars (even extreme BLLacs): $h\nu = 100 / \delta$ keV

1-10 keV $\leftrightarrow$ 150 η^{-1} MeV $\Rightarrow$ $\eta > 10^4$ NOT extreme accelerators !

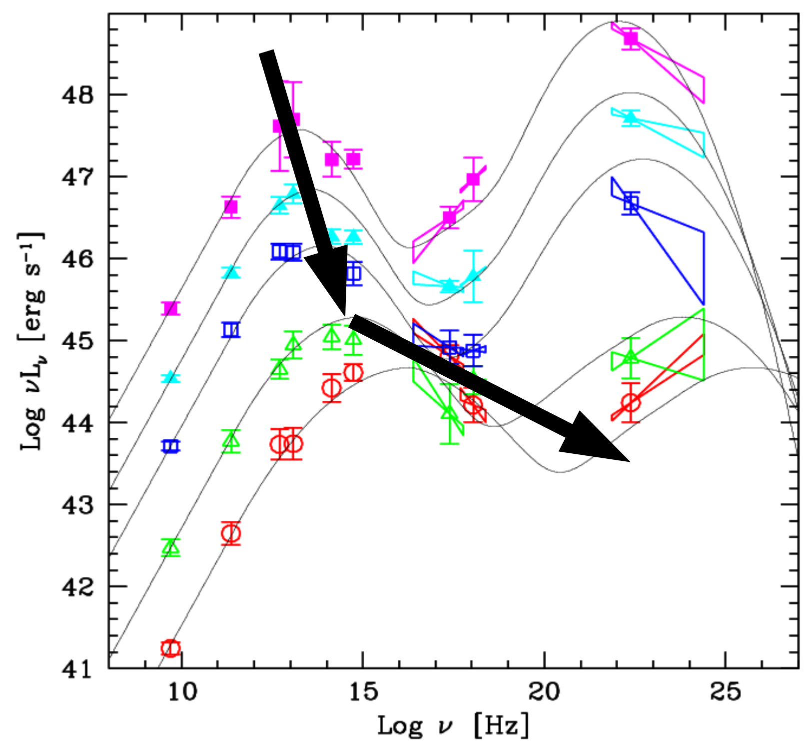
Can BLLacs accelerate at $\eta \approx$ 1-10 ??

η=10, δ=20 $\Rightarrow$ synchrotron peak can be at ~200 MeV !

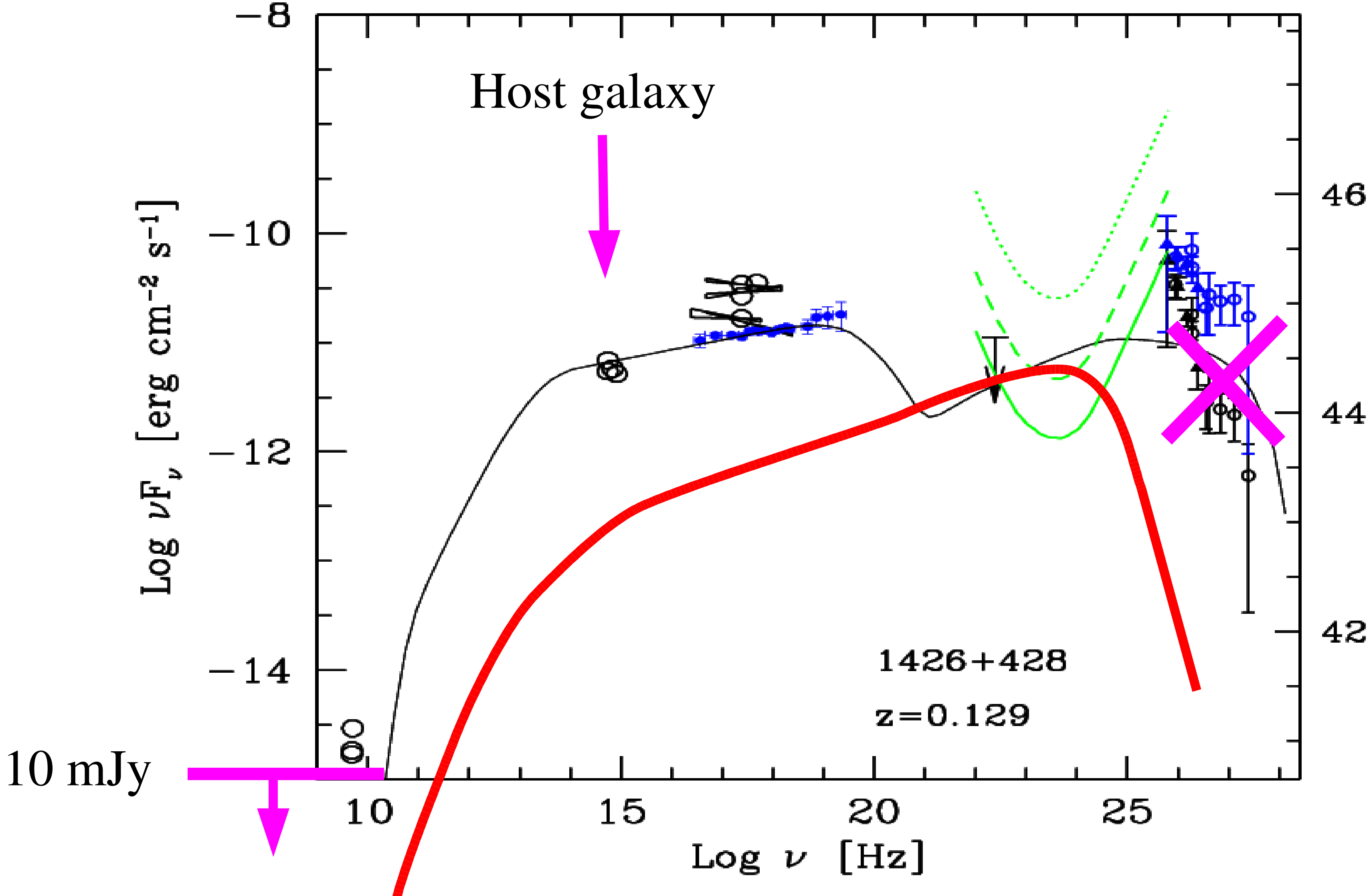
Do MeV-synchrotron BLLacs exist ? (Ghisellini 98)



Ghisellini 1998



Donato et al 2001


Host galaxy
10 mJy
1426+428
z=0.129
Log νF_ν [erg cm^-2 s^-1]
Log ν [Hz]
−8
−10
−12
−14
10
15
20
25
46
44
42

MeV-synchrotron blazars

- could have escaped detection so far ! Bright only in MeV band.
  - Too faint in radio for large area surveys
  - dominated by thermal emission from host galaxy in optical
  - very faint (but hard) in X-rays

- Only GLAST can unveil the (extreme) BLLac nucleus inside !

  Signature: - variable γ-rays from normal (radio-weak) elliptical galaxy
  - X-ray follow-up: faint but hard non-thermal continuum