PHOTON-PHOTON INTERACTIONS, BLAZAR SPECTRAL ANOMALIES, AND PHOTON-ALP MIXING

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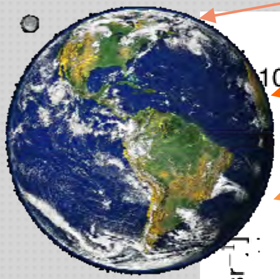
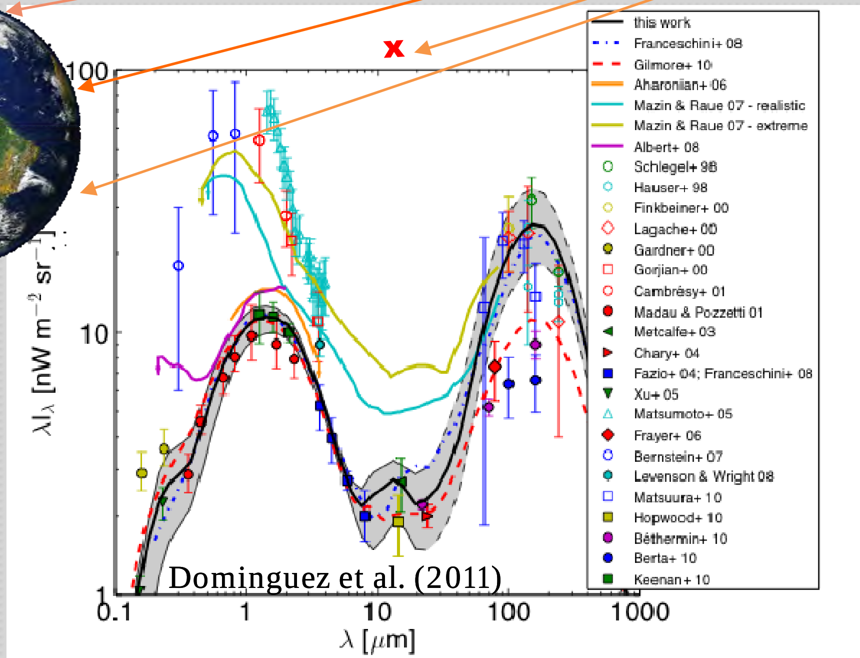
WITH F. CENEDESE AND G. GALANTI

- γ–γ interactions:
  - a bridge between high-energy and classical astrophysics
  - tests for the *Standard Model*
- Constraining the m.w. Extragalactic Background Light
- Blazar spectral anomalies? Constraints on photon-ALP mixing
- Prospects for future observations

Photon-photon interactions

1) TO CONSTRAIN THE EXTRAGALACTIC BACKGROUND LIGHT (AND TESTING MODELS OF) FROM VHE OBSERVATIONS (WITH CONSEQUENCES FOR PHYSICS AND COSMOLOGY)



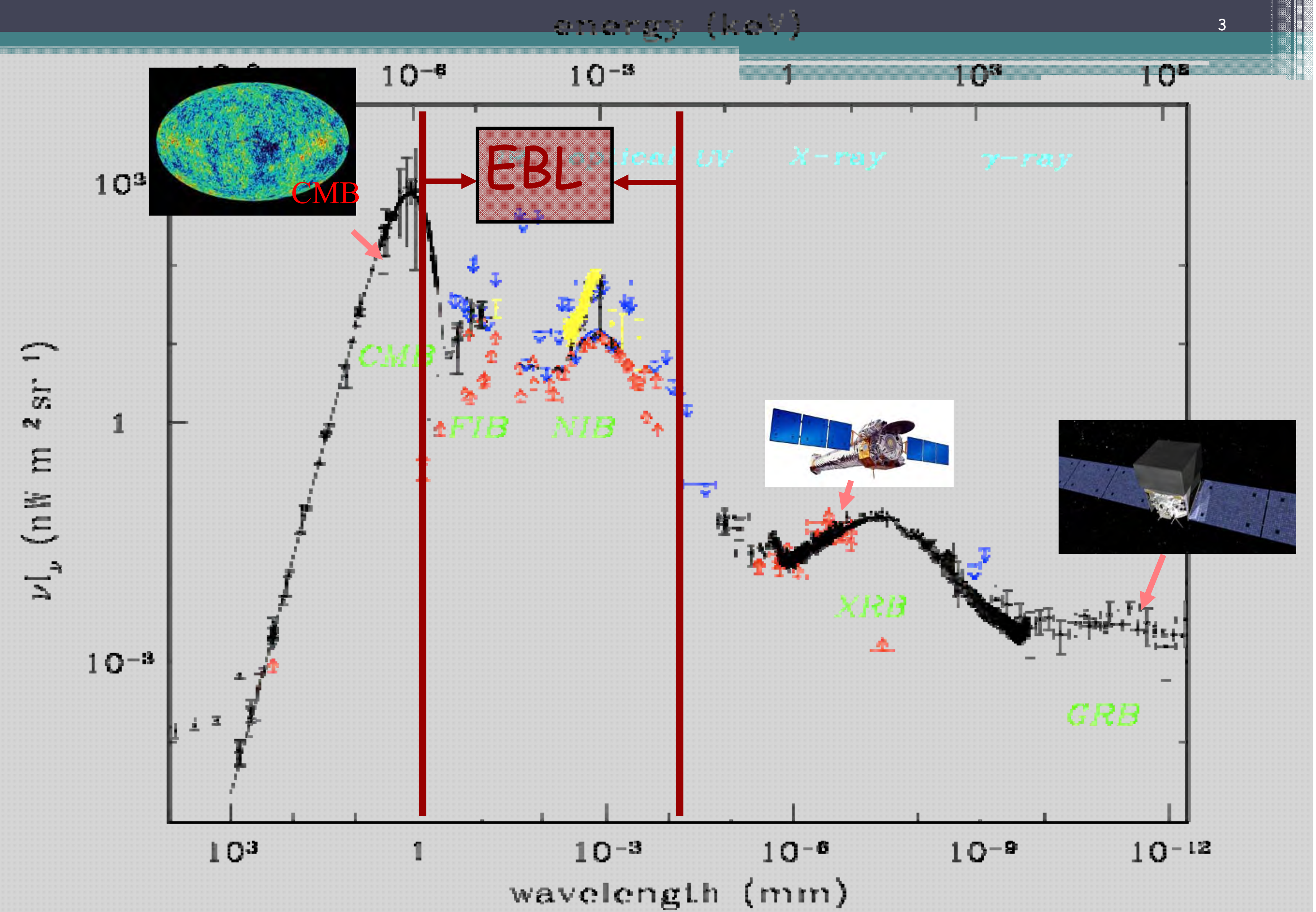


VHE photon + diffuse light → electron-positron pair production $\gamma_{VHE}\gamma_{EBL} \rightarrow e^+e^-$

$$\lambda_{\max} \simeq 1.24 \times \varepsilon_{TeV} \; [\mu m]$$

Absorption:

$dF/dE_{OBS} = (dF/dE_{EM})\, e^{-\tau}$



Background Radiations & the EBL

Radiations in the Universe

- Photons are our essential messengers to investigate how the Universe has taken shape and evolved
- The HISTORY OF COSMIC STRUCTURES, GALAXY & AGN FORMATION IS REGISTERED IN THE EBL THROUGH THEIR ENERGY PRODUCTION

- Three main physical processes for producing energy (and light):

-- Thermonuclear reactions (in stars & galaxies)

-- Gravitational accretion (in galaxy's Active Nuclei)

Point-like

-- Decaying particles (generated in the early phases of cosmic expansion - still speculative) **Diffuse, undetectable**

ENERGY SOURCES (MOSTLY STARS IN GALAXIES)

- Young (& old) stars in galaxies
- Gravitational accretion onto nuclear black-holes in active galaxies

How much energy out of this?

Energy$=\eta\rho_b c^2$

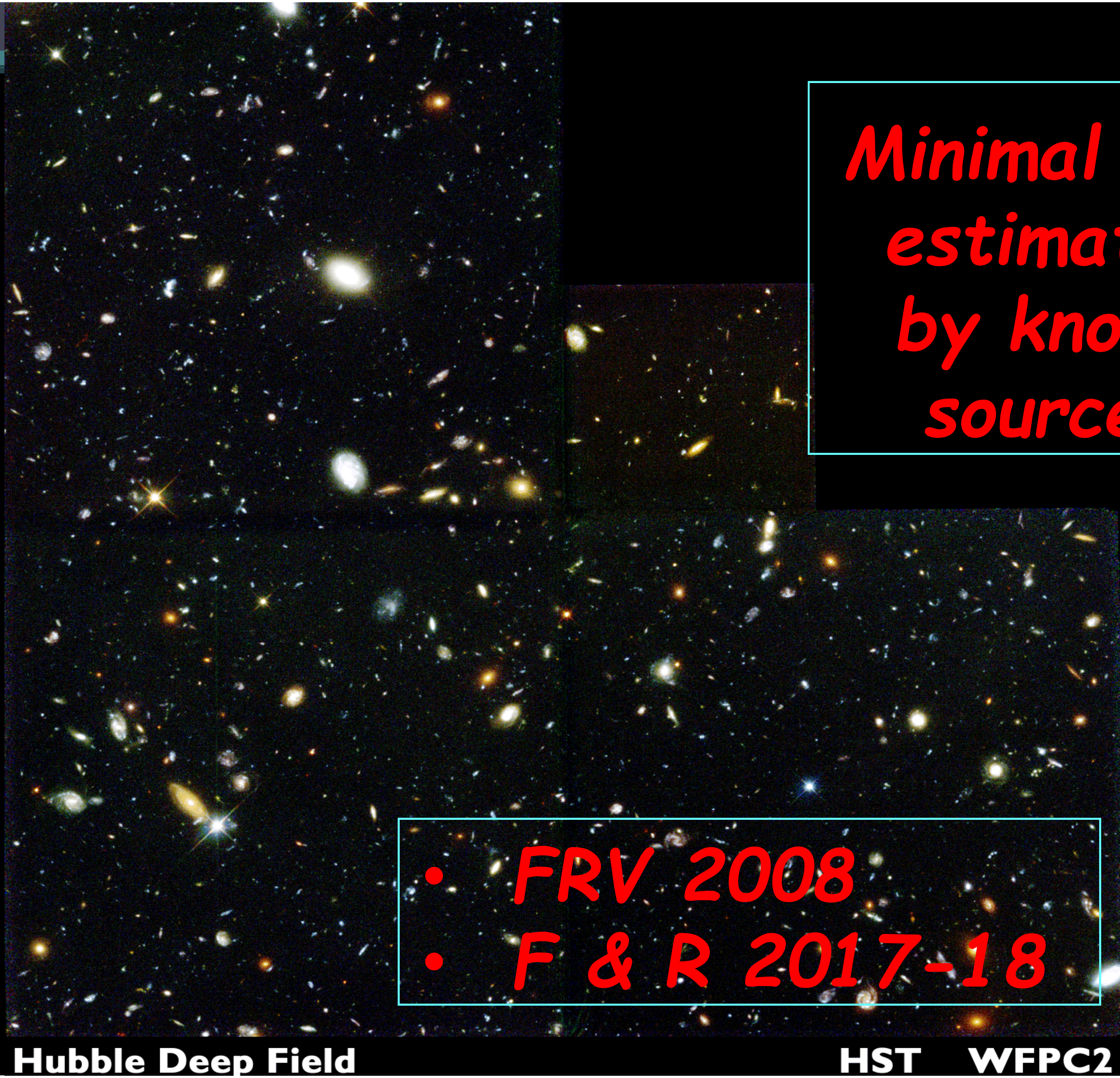
A solid constraint: mass in local Massive Dark Objects (SMBH's, the AGN remnants):
$M_{MDO} \sim 2\ 10^{-3}\ M_*$ (M_* : mass in spheroids Kormendy & Richstone)

$\eta_* \sim (1\text{-}5)\times 10^{-3}$, $\eta_{AGN} \sim 0.06\text{-}0.4$ (Kerr limit)

$$L_{AGN} \sim 2\ 10^{-3}\ \eta_{AGN}/\eta_*\ L_{star} \sim 0.1\ L_{star}$$

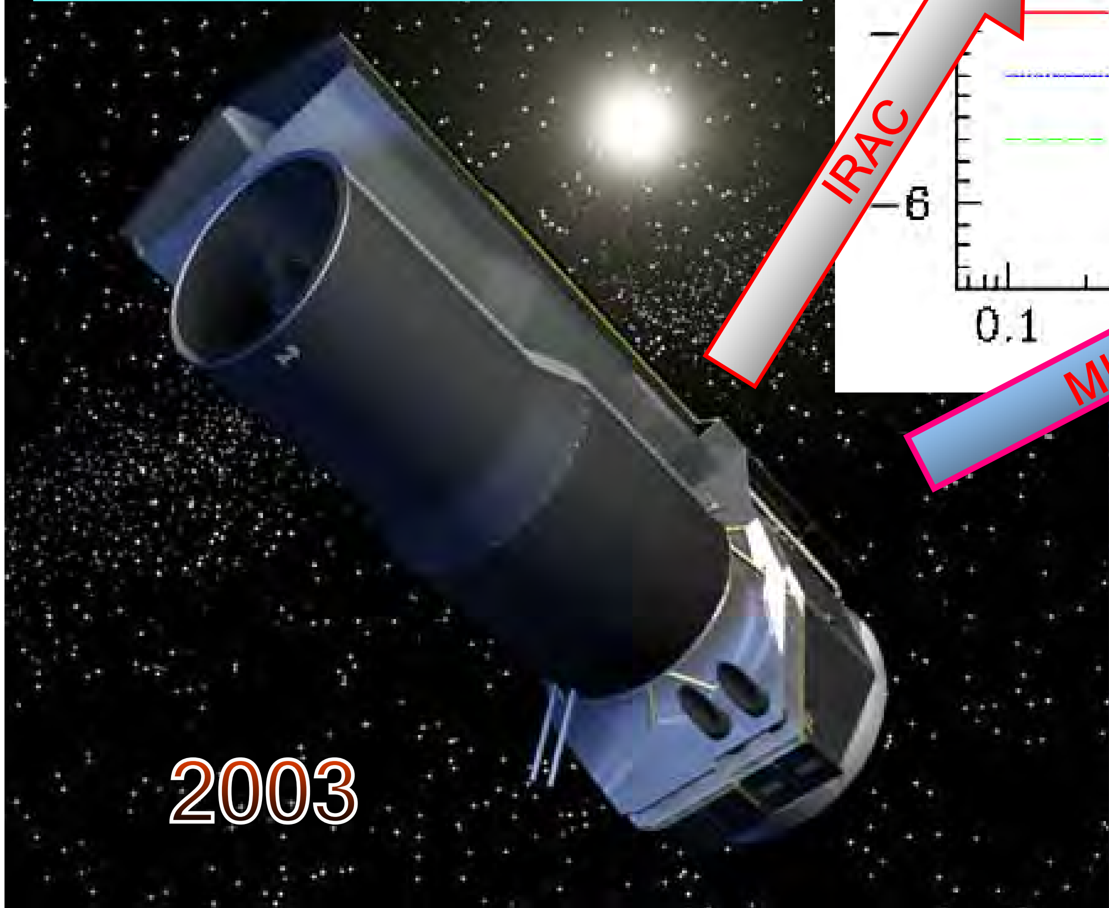
Accurate Modelling of the Extragalactic Background Light from known sources is then essential for many purposes.

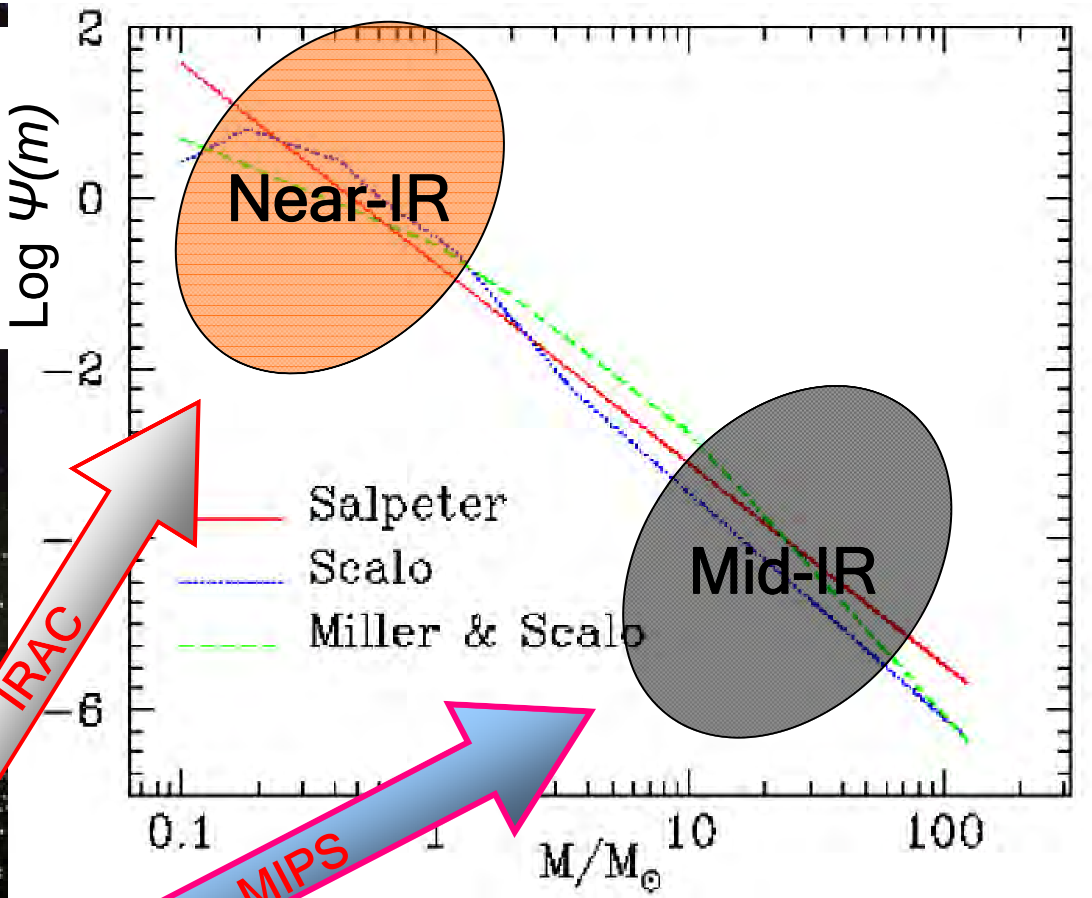
Minimal EBL estimates by known sources



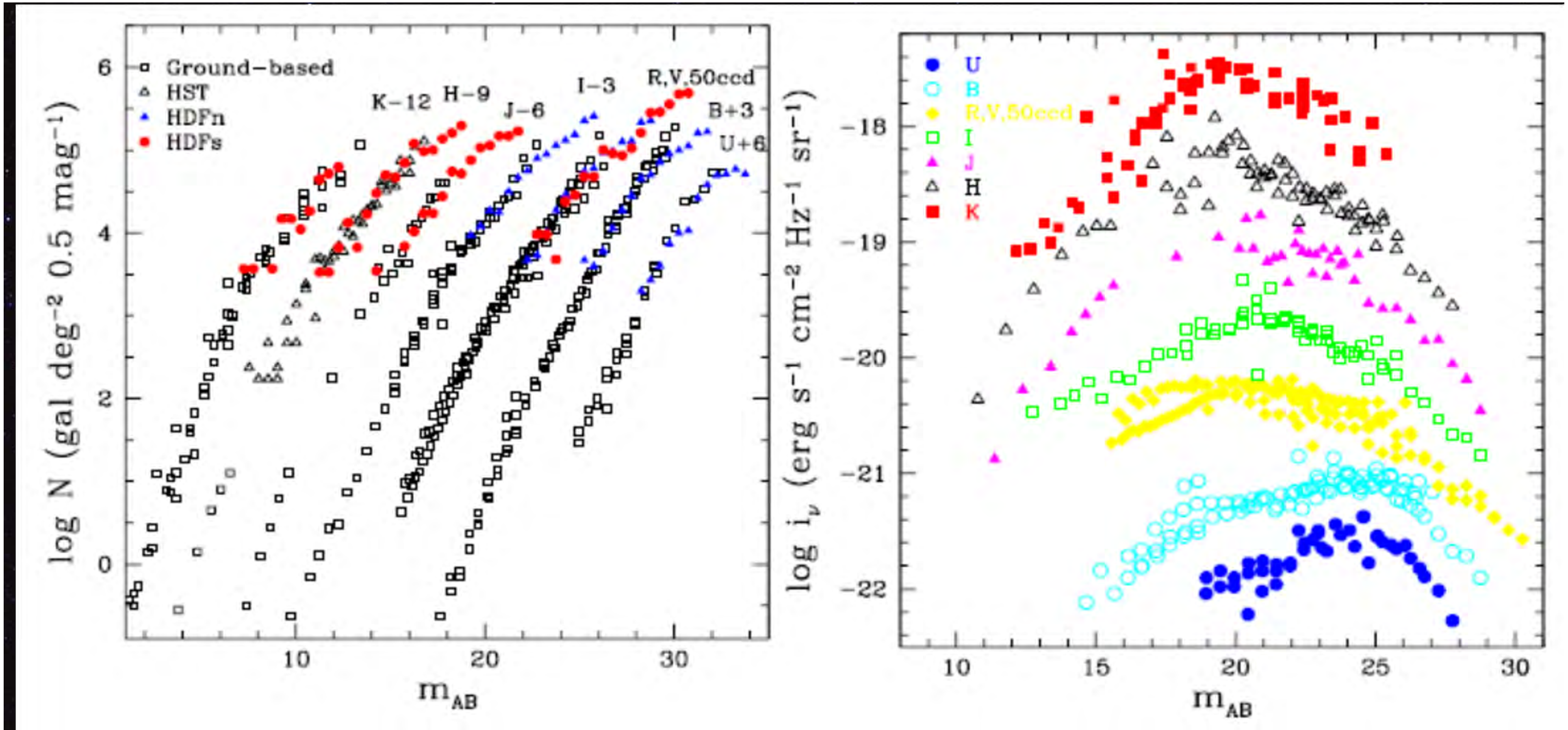
- FRV 2008
- F & R 2017-18

Major facilities for the observation of faint sources of EBL, like HST, Herschel, and the Spitzer Space Telescope





Spitzer's IRAC & MIPS photometric cameras

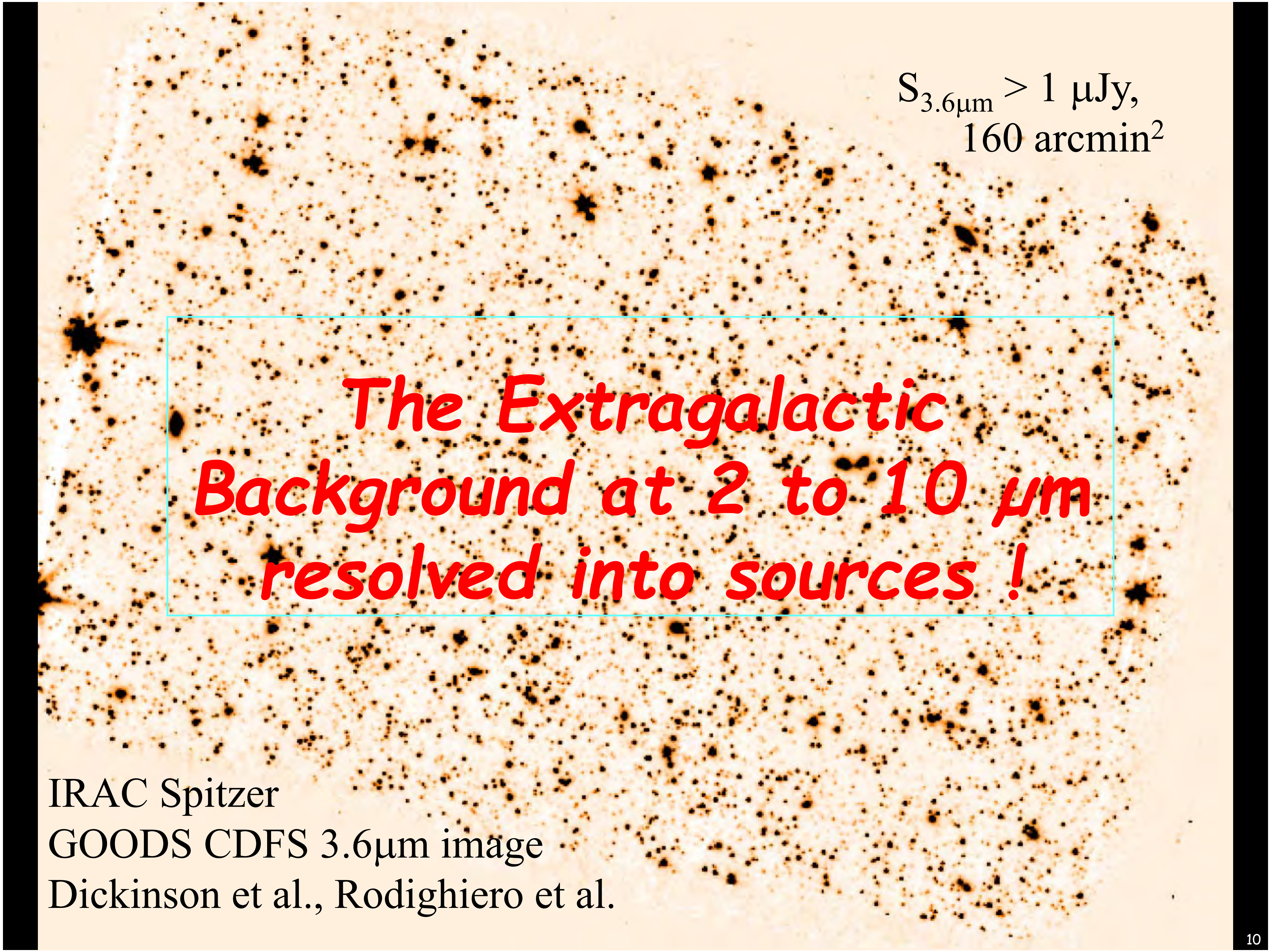


- Left: Differential UBV IJHK galaxy counts as a function of AB magnitudes. The sources of the data points are given in the text. Note the decrease of the logarithmic slope d logN/dm at faint magnitudes.

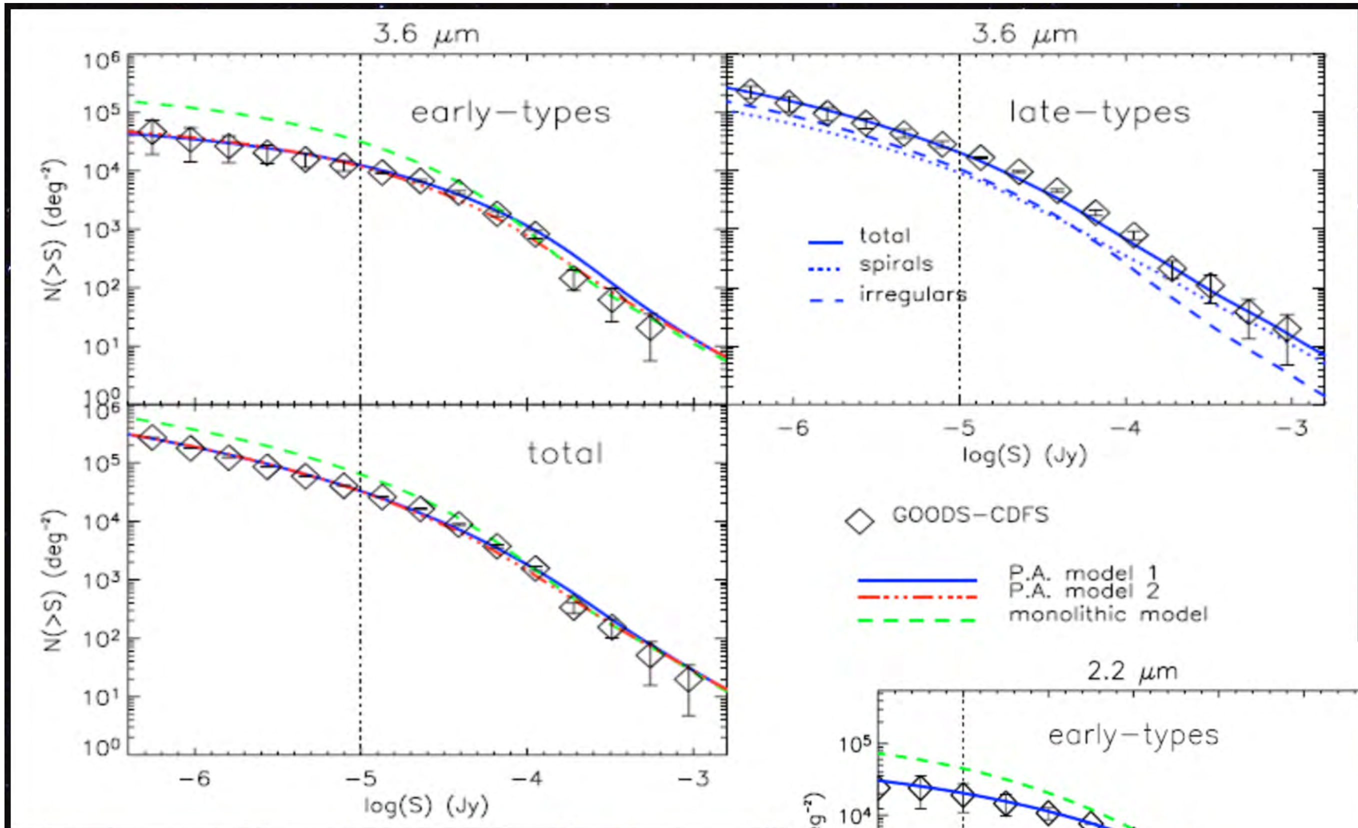
$$I_\nu = \int S_\nu \, N(S_\nu) \, dS_\nu$$

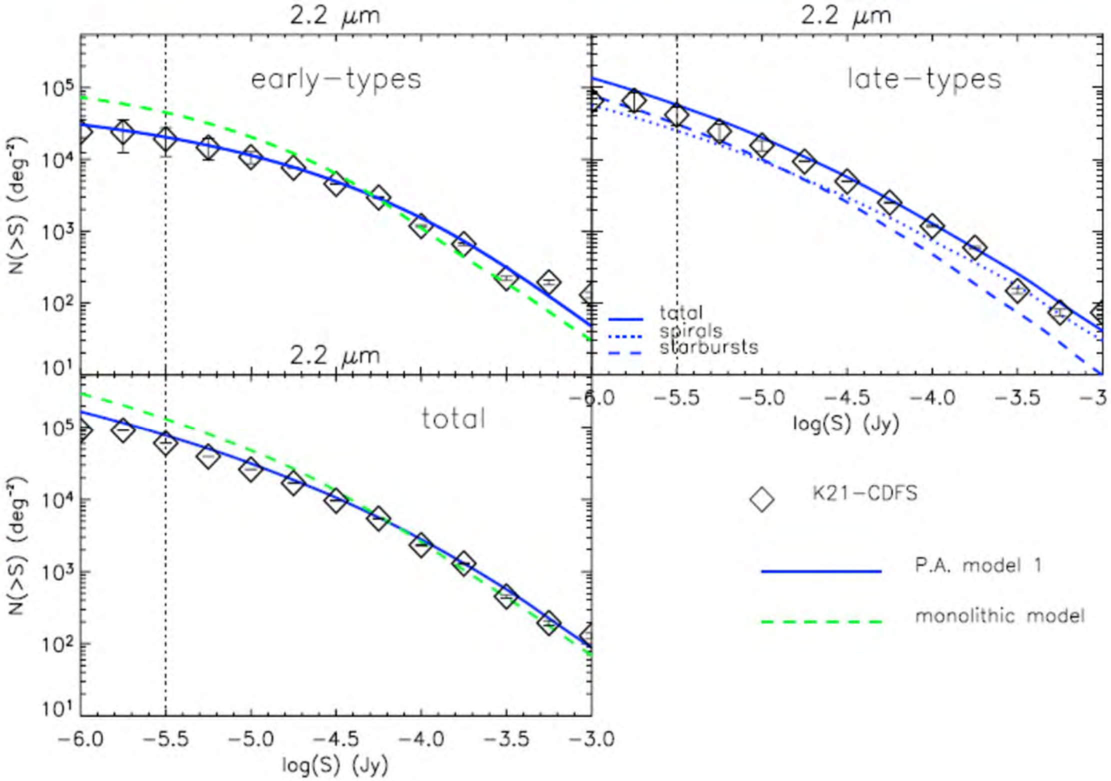
The flattening is more pronounced at the shortest wavelengths. Right: Extragalactic background light per magnitude bin, i = 10−0.4(mAB+48.6)N(m), as a function of U (filled circles), B (open circles), V (filled pentagons), I (open squares), J (filled triangles), H (open triangles), and K (filled squares) magnitudes.
For clarity, the BV IJHK measurements have been multiplied by a factor of 2, 6, 15, 50, 150, and 600, respectively.

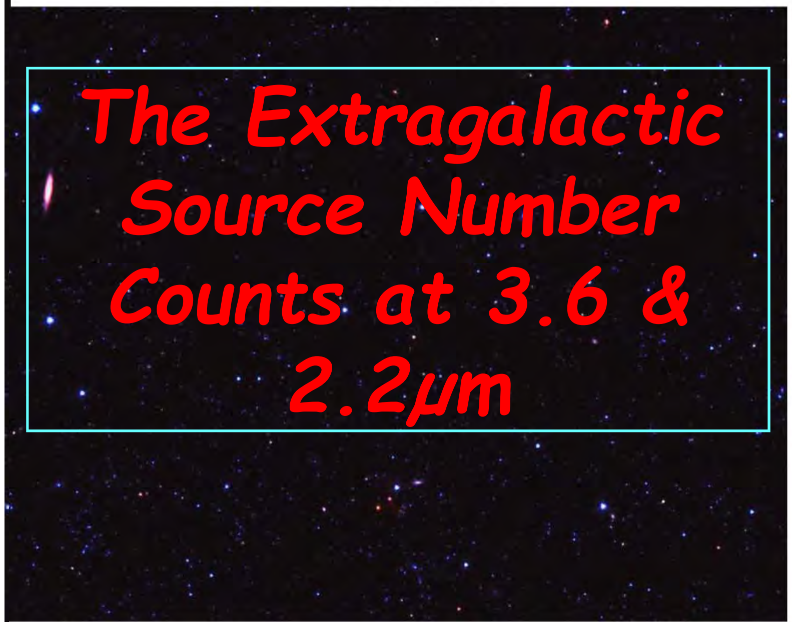
Madau & Pozzetti 2000


$S_{3.6\mu m} > 1\ \mu Jy$,
160 arcmin^2
The Extragalactic Background at 2 to 10 µm resolved into sources !
IRAC Spitzer
GOODS CDFS 3.6µm image
Dickinson et al., Rodighiero et al.

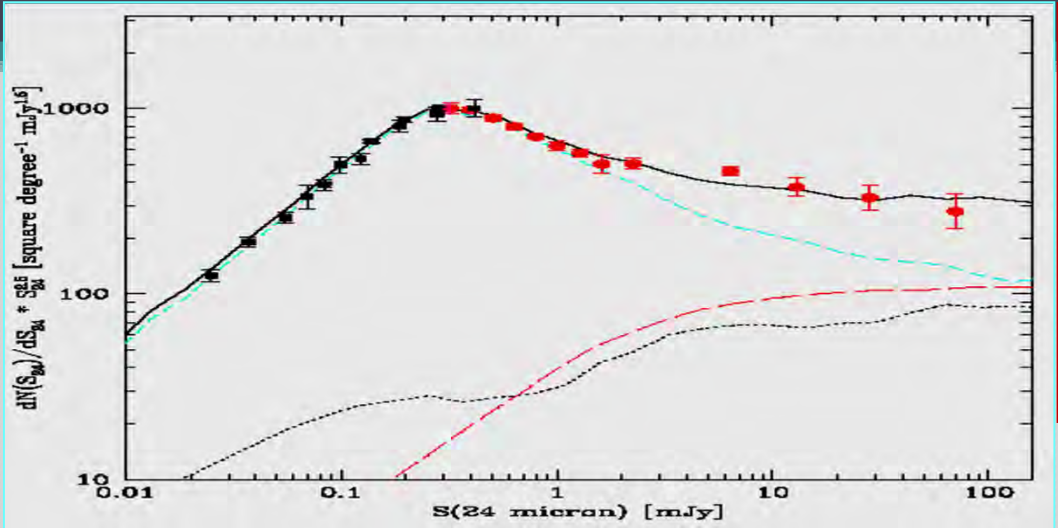
The Extragalactic Source Number Counts at 3.6 & 2.2μm

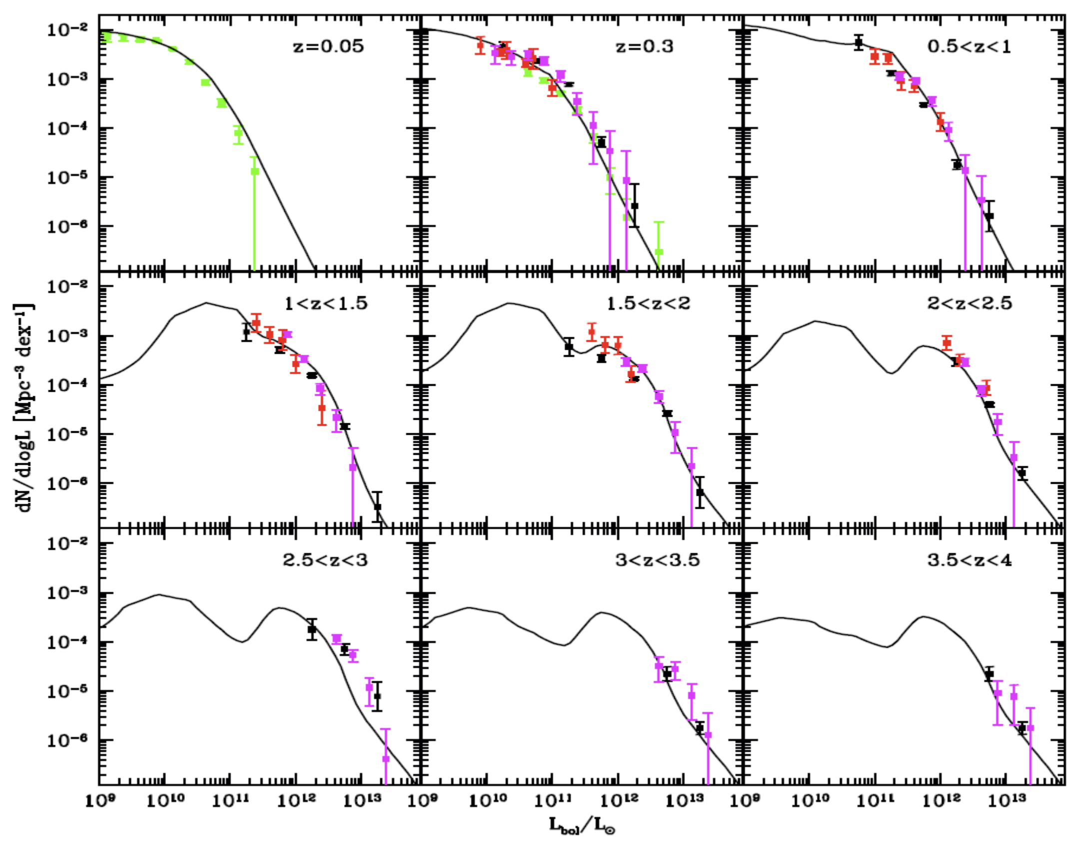


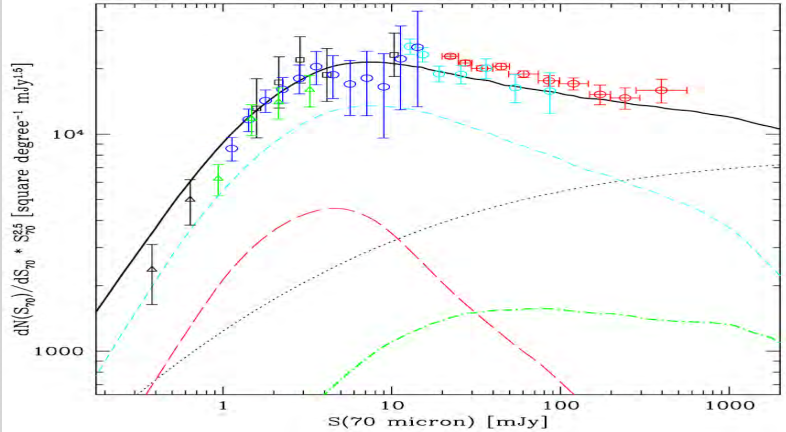


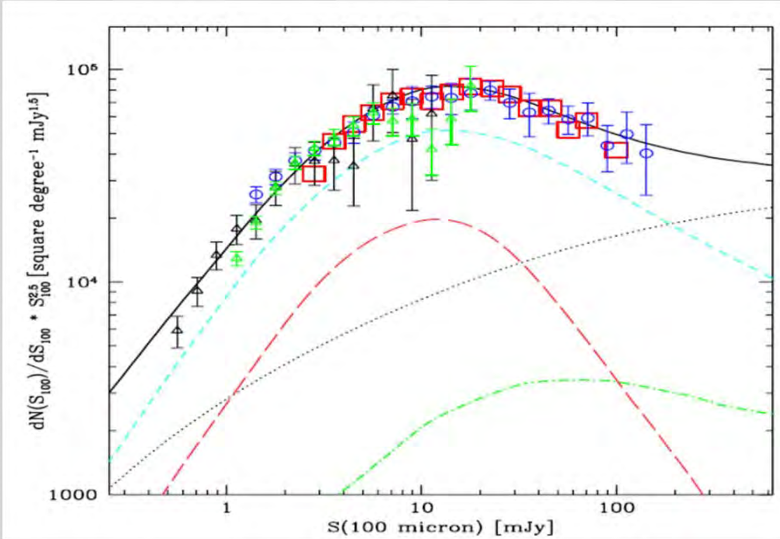


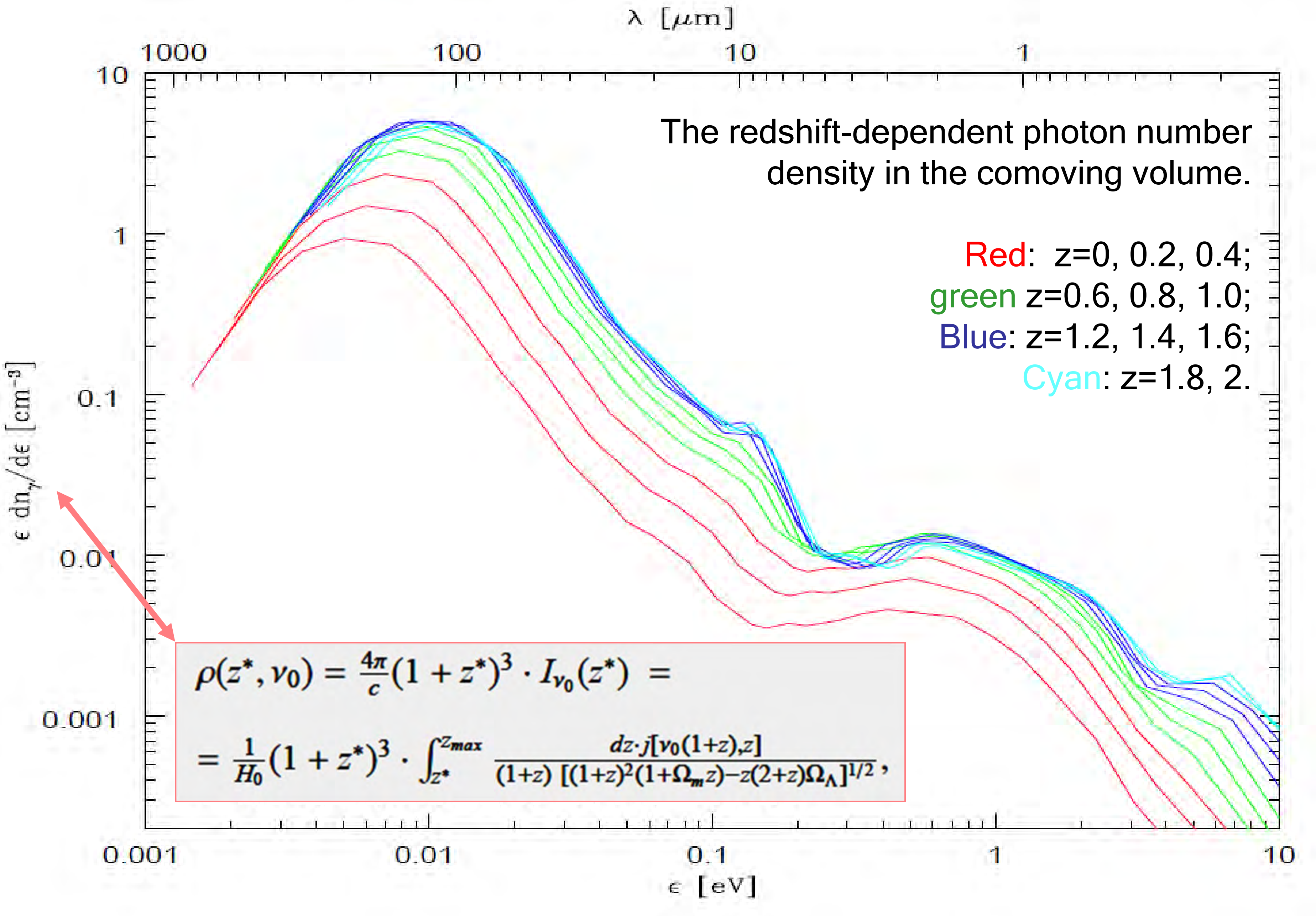
Source number counts & luminosity functions







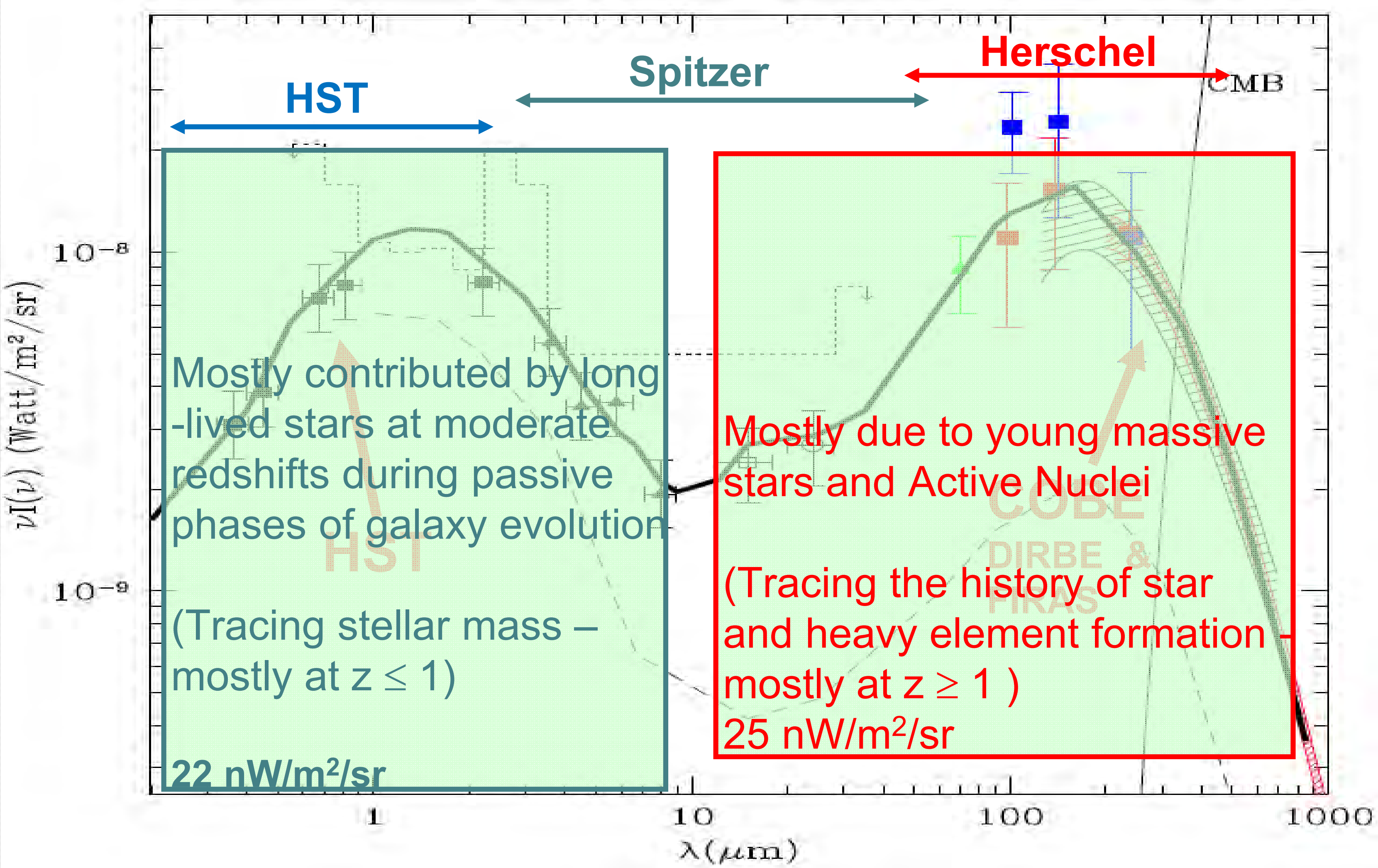




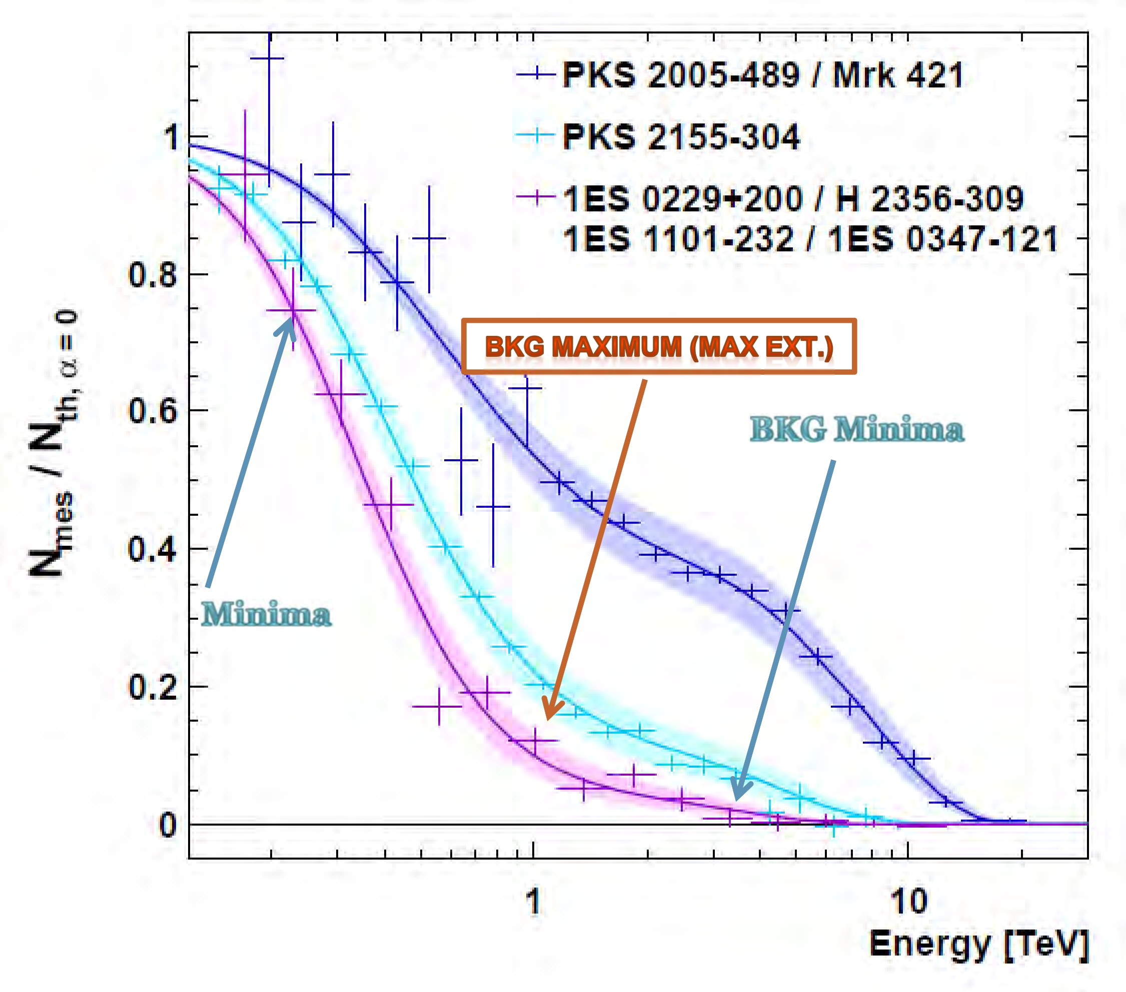
$$\rho(z^*, \nu_0) = \frac{4\pi}{c}(1+z^*)^3 \cdot I_{\nu_0}(z^*) =$$

$$= \frac{1}{H_0}(1+z^*)^3 \cdot \int_{z^*}^{z_{max}} \frac{dz \cdot j[\nu_0(1+z), z]}{(1+z)\ [(1+z)^2(1+\Omega_m z) - z(2+z)\Omega_\Lambda]^{1/2}},$$

Origin of energy and radiations

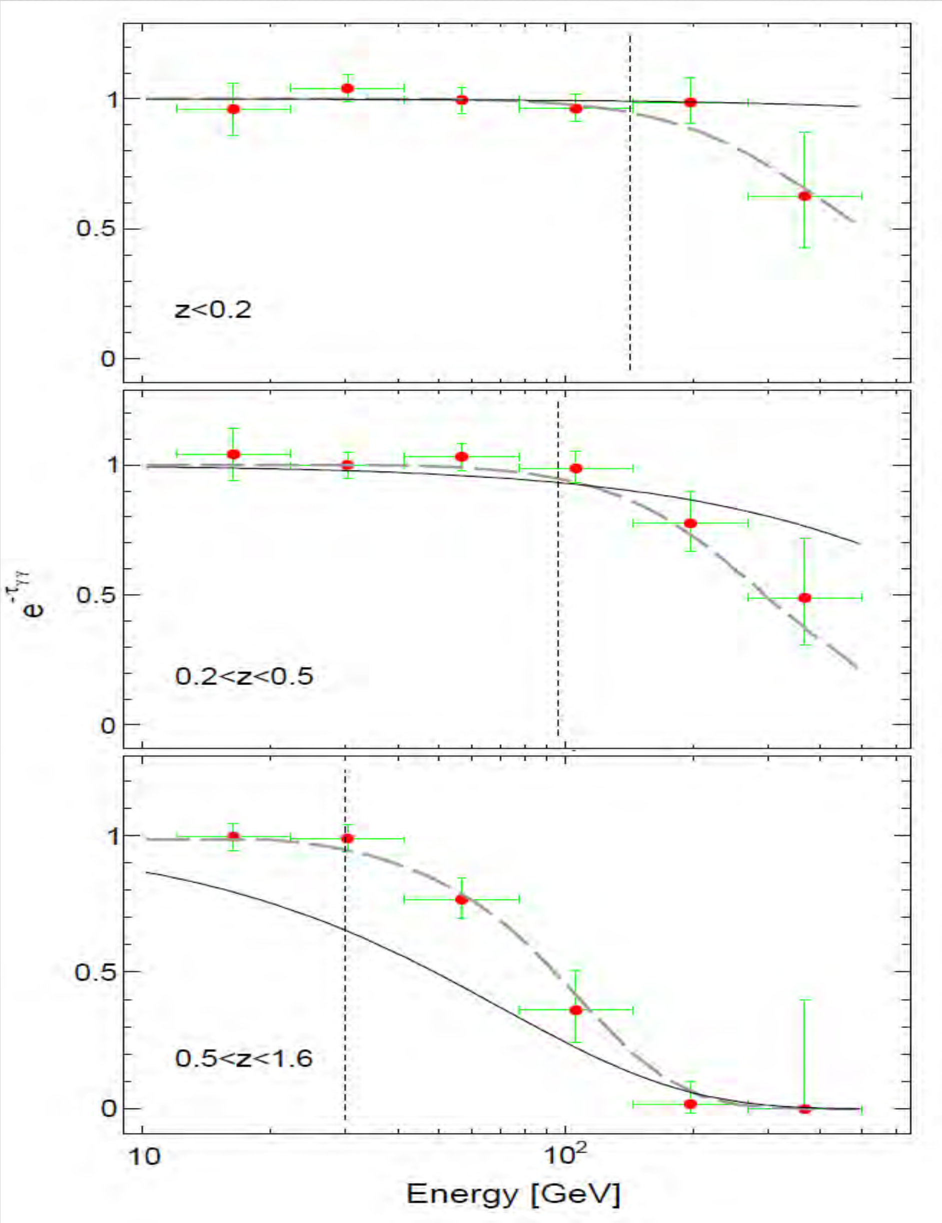


The Extragalactic Background Light intensity from 0.1 to 1000 μm vs. data



Imprints of the Extragalactic Background Light on the spectra of the brightest blazars (observed by the H.E.S.S. collaboration, Abramowski et al. 2013)

Ackermann et al. 2011

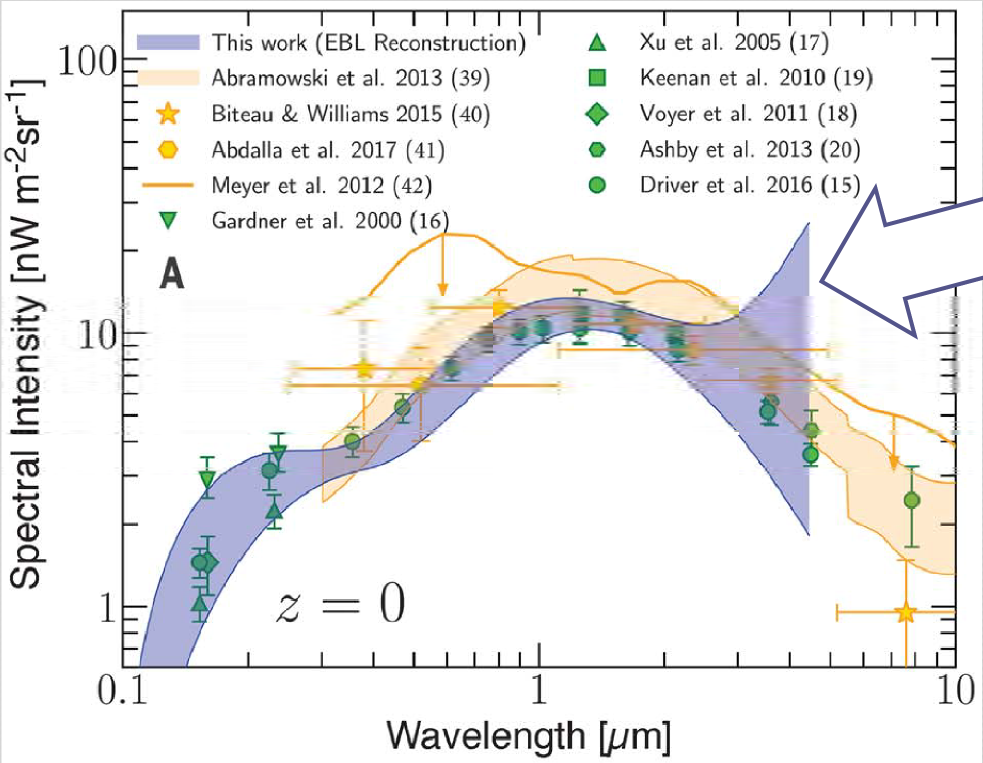


<u>Ratio of the average extrapolated vs observed Fermi LAT spectra</u> of BLAZARs in different redshift bins, showing a cut-off feature increasing with redshift. Vertical lines: energy below which <5% of the source photons are absorbed by EBL, and where the source intrinsic spectra are estimated.

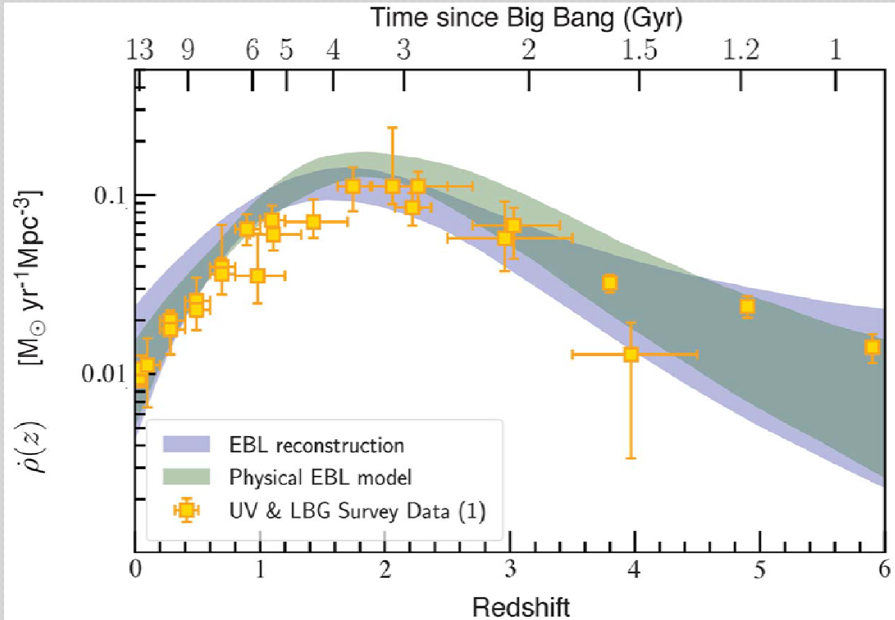
Dashed curves show the attenuation expected from the EBL (A.F. et al. 2008), obtained by averaging in each redshift and energy bin the opacities of the sample.

Thin solid curve: best-fit model assuming that all the sources have an intrinsic exponential cut-off and that blazars follow the “blazar sequence” model.

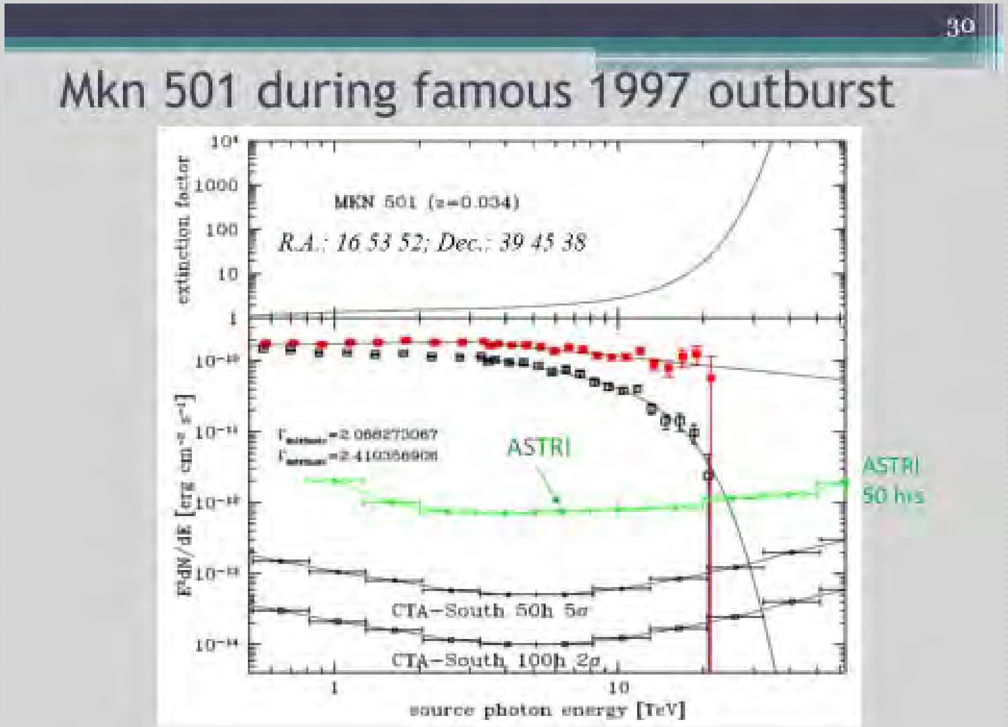
Reconstracting the redshift-dependent EBL intensity, and the history of star-formation in galaxies



Fermi-LAT collaboration
Science 2018



So, to first order, no much evidence for spectral anomalies requiring revision of standard physics



Refined tests of the Standard Model

Testing the γ-ALP oscillations Effects on cosmic optical depth

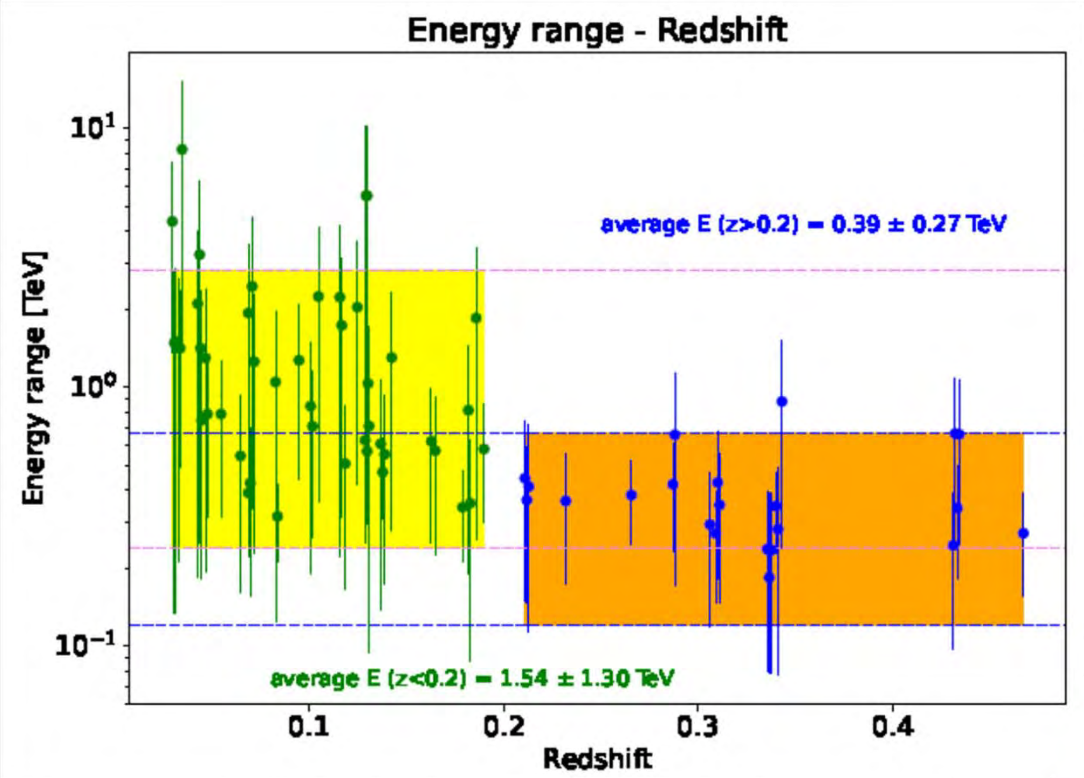
- Several extensions of the *Standard Model* (e.g. Superstring theories suggest the existence of axion-like particles [ALPs])

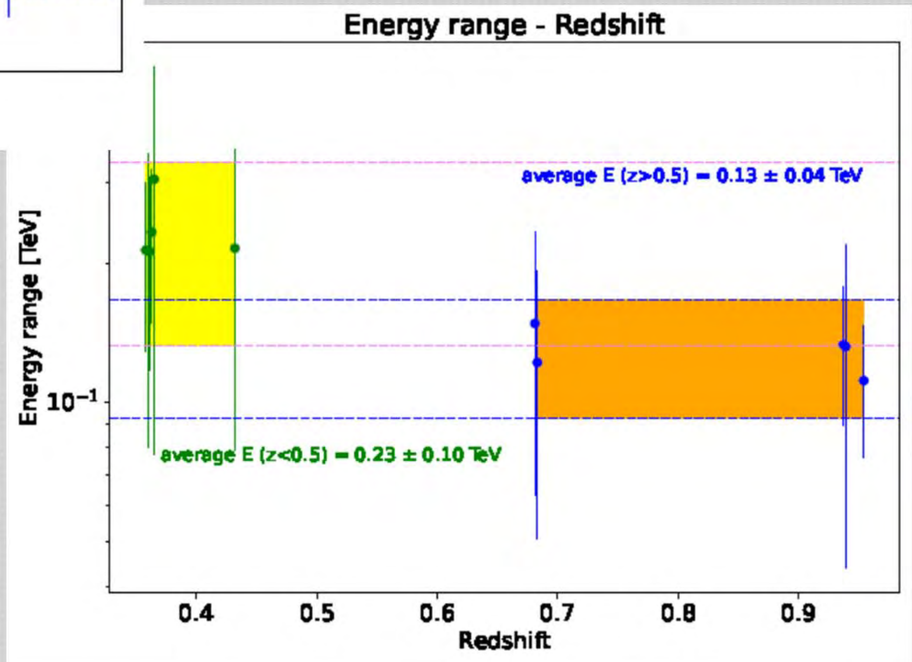
  ⇨ *See G. Galanti pres.*
- Very light spin-zero bosons with a two-photon coupling.
- As a consequence, photon-ALP oscillations may occur in the presence of an external magnetic field B.
- So VHE photons from cosmic sources may travel part of their path as ALPs (unabsorbed), further converted to γ by interaction with Galactic B
- Effect to reduce the γ-γ optical depth $\tau_{\gamma\text{-}\gamma}$

Source (spectral type)	z	Detector	$\Delta E_0(z)$ [TeV]	Γ_{obs}	K_{obs} [$cm^{-2}\, s^{-1}\, TeV^{-1}$]	References
1ES 0033+595	0.467	MAGIC	0.156-0.391	3.84±0.01	$(9.73 \pm 0.01) \times 10^{-12}$	Aleksić et al. (2015)
PG 1553+113	0.433	VERITAS	0.183-0.500	4.45±0.15	$(5.23 \pm 0.24) \times 10^{-11}$	Aliu et al. (2015)
		HESS	0.245-1.080	4.01±0.35	$(5.68 \pm 0.75) \times 10^{-11}$	Aharonian et al. (2008b)
		HESS 2005+2006	0.245-1.070	4.44±0.50	$(4.60 \pm 0.61) \times 10^{-11}$	Aharonian et al. (2008b)
		MAGIC	0.098-0.392	4.06±0.18	$(3.73 \pm 0.50) \times 10^{-11}$	Albert et al. (2007)
PKS 0447-439	0.343	HESS	0.241-1.520	3.85±0.48	$(3.48 \pm 0.93) \times 10^{-11}$	HESS Collaboration et al. (2013)
3C 66A (IBL)	0.34	VERITAS	0.228-0.466	4.08±0.28	$(4.12 \pm 0.28) \times 10^{-11}$	Acciari et al. (2009)
		MAGIC	0.078-0.488	3.44±0.16	$(2.04 \pm 0.29) \times 10^{-11}$	Klepser (2011)
TXS 0506+056 (blazar)	0.3365	VERITAS	0.142-0.226	4.85±0.97	$(2.26 \pm 1.35) \times 10^{-12}$	Abeysekara et al. (2018)
		MAGIC A	0.079-0.392	3.77±0.08	$(1.87 \pm 0.17) \times 10^{-11}$	Ansoldi et al. (2018)
		MAGIC B	0.080-0.394	3.49±0.51	$(2.62 \pm 1.45) \times 10^{-11}$	Ansoldi et al. (2018)
		MAGIC C	0.079-0.389	3.79±0.38	$(6.01 \pm 2.49) \times 10^{-12}$	Ansoldi et al. (2018)
S5 0716+714 (IBL)	0.31	MAGIC 2008	0.181-0.676	3.38±0.48	$(1.40 \pm 0.35) \times 10^{-10}$	Anderhub et al. (2009)

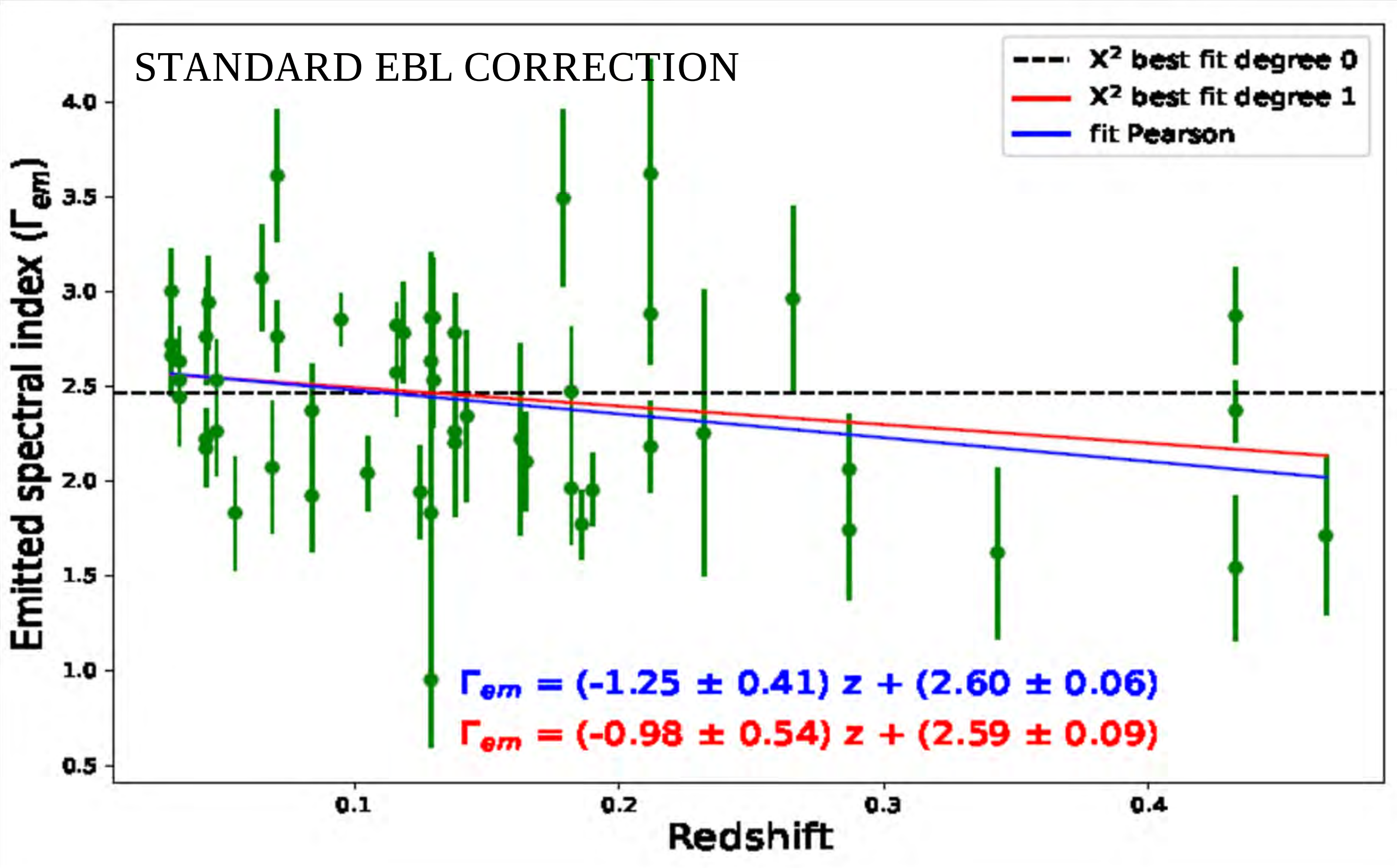
HBLs and IBLs (total of 68 spectra) and FSRQs (10 spectra)

Source (spectral type)	z	Detector	$\Delta E_0(z)$ [TeV]	Γ_{obs}	K_{obs} [$cm^{-2}\, s^{-1}\, TeV^{-1}$]	References
						…oration et al. (2018)
						…oration et al. (2018)
OJ 287 (BL Lac)	0.306	VERITAS	0.119-0.471	3.49±0.13	$(6.88 \pm 0.47) \times 10^{-12}$	O'Brien (2017)
1ES 0414+009	0.287	VERITAS	0.232-0.611	3.40±0.44	$(1.67 \pm 0.25) \times 10^{-11}$	Aliu et al. (2012)
		HESS	0.170-1.14	3.41±0.16	$(5.78 \pm 0.41) \times 10^{-12}$	HESS Collaboration et al. (2012)
PKS 0301-243	0.2657	HESS	0.247-0.519	4.42±0.65	$(9.38 \pm 1.57) \times 10^{-12}$	HESS Collaboration et al. (2013)
1RXS J023832.6-311658	0.232	HESS	0.173-0.554	3.49±0.73	$(6.03 \pm 1.62) \times 10^{-12}$	Gaté, HESS Coll., & Fitoussi (2017)
1ES 1011+496	0.212	MAGIC	0.147-0.586	4.13±0.47	$(3.66 \pm 1.04) \times 10^{-11}$	Albert et al. (2007)
		Ahnen	0.149-0.741	3.28±0.18	$(4.80 \pm 0.41) \times 10^{-11}$	Ahnen et al. (2016)
		Aleksic	0.113-0.714	3.68±0.17	$(3.00 \pm 0.32) \times 10^{-11}$	Aleksić et al. (2016)
RBS 0413	0.19	VERITAS	0.299-0.855	3.20±0.18	$(1.40 \pm 0.14) \times 10^{-11}$	Aliu et al. (2012)
1ES 1101-232	0.186	HESS	0.259-3.44	2.95±0.18	$(1.96 \pm 0.34) \times 10^{-11}$	Aharonian et al. (2007)
1ES 1218+304	0.182	VERITAS	0.189-1.44	3.14±0.22	$(3.63 \pm 0.57) \times 10^{-11}$	Acciari et al. (2009)
		MAGIC	0.087-0.626	3.03±0.21	$(4.65 \pm 0.67) \times 10^{-11}$	Albert et al. (2006)
RX J0648.7+1516	0.179	VERITAS	0.213-0.475	4.36±0.42	$(2.28 \pm 0.27) \times 10^{-11}$	Aliu et al. (2011)
H 2356-309	0.165	HESS	0.224-0.913	3.02±0.25	$(1.20 \pm 0.14) \times 10^{-11}$	Aharonian et al. (2006)
1ES 1440+122	0.163	VERITAS	0.249-0.988	3.10±0.46	$(6.98 \pm 1.73) \times 10^{-12}$	Archambault et al. (2016)

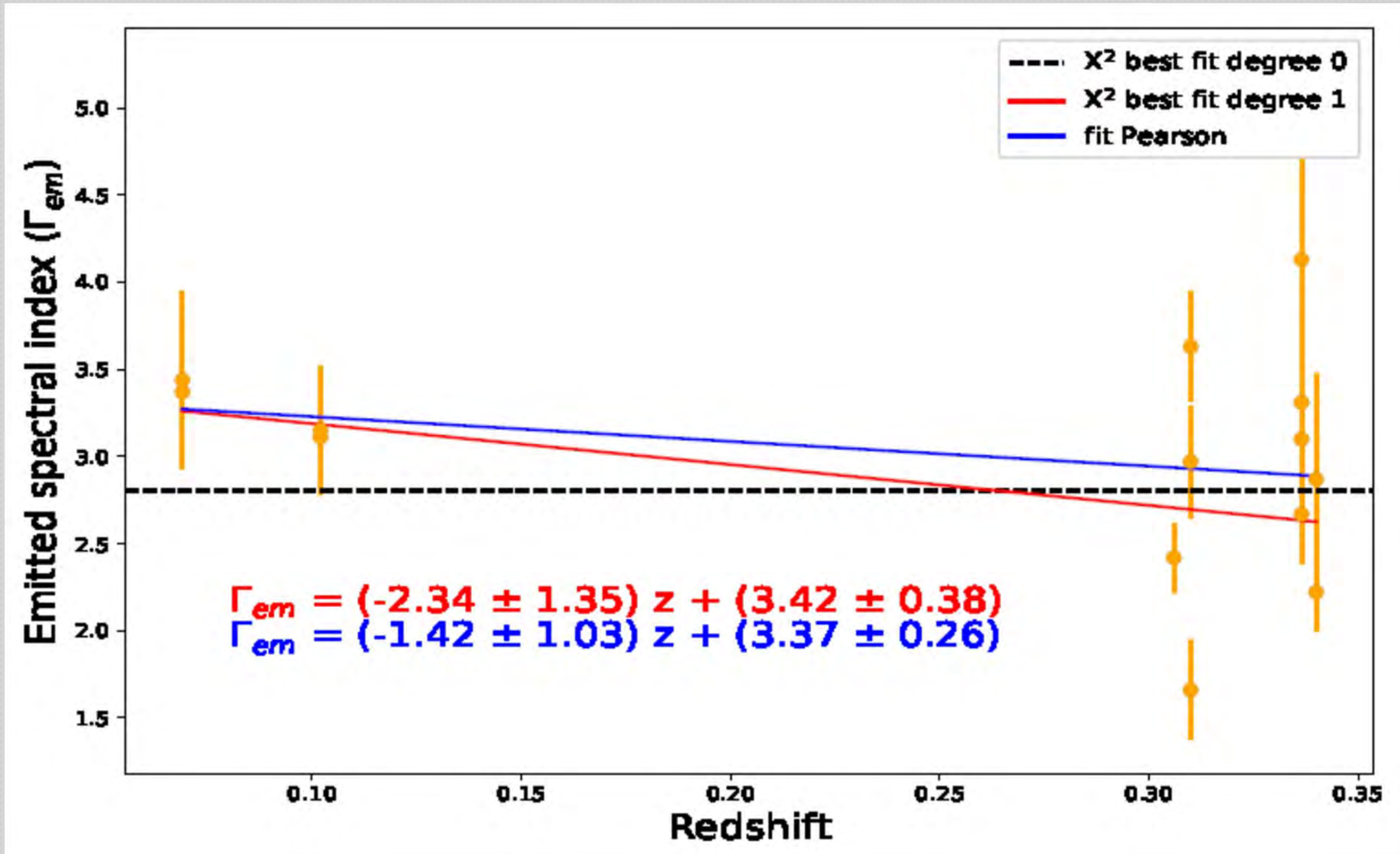

Energy range - Redshift
average E (z>0.2) = 0.39 ± 0.27 TeV
average E (z<0.2) = 1.54 ± 1.30 TeV
Energy range [TeV]
Redshift


Energy range - Redshift
average E (z>0.5) = 0.13 ± 0.04 TeV
average E (z<0.5) = 0.23 ± 0.10 TeV
Energy range [TeV]
Redshift

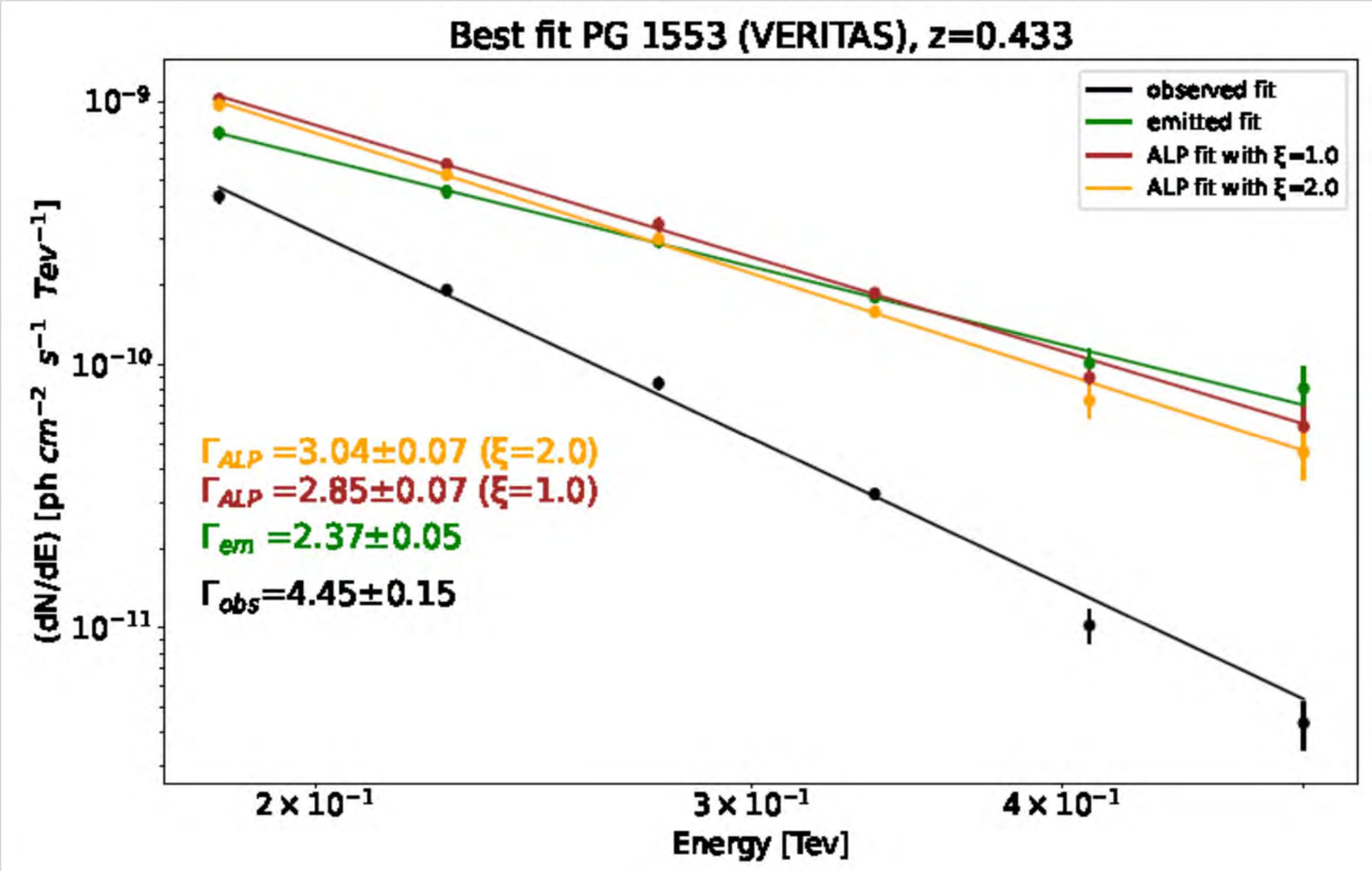
High-peak BL Lacs (HBL)



Intermediate BL Lacs (IBL)

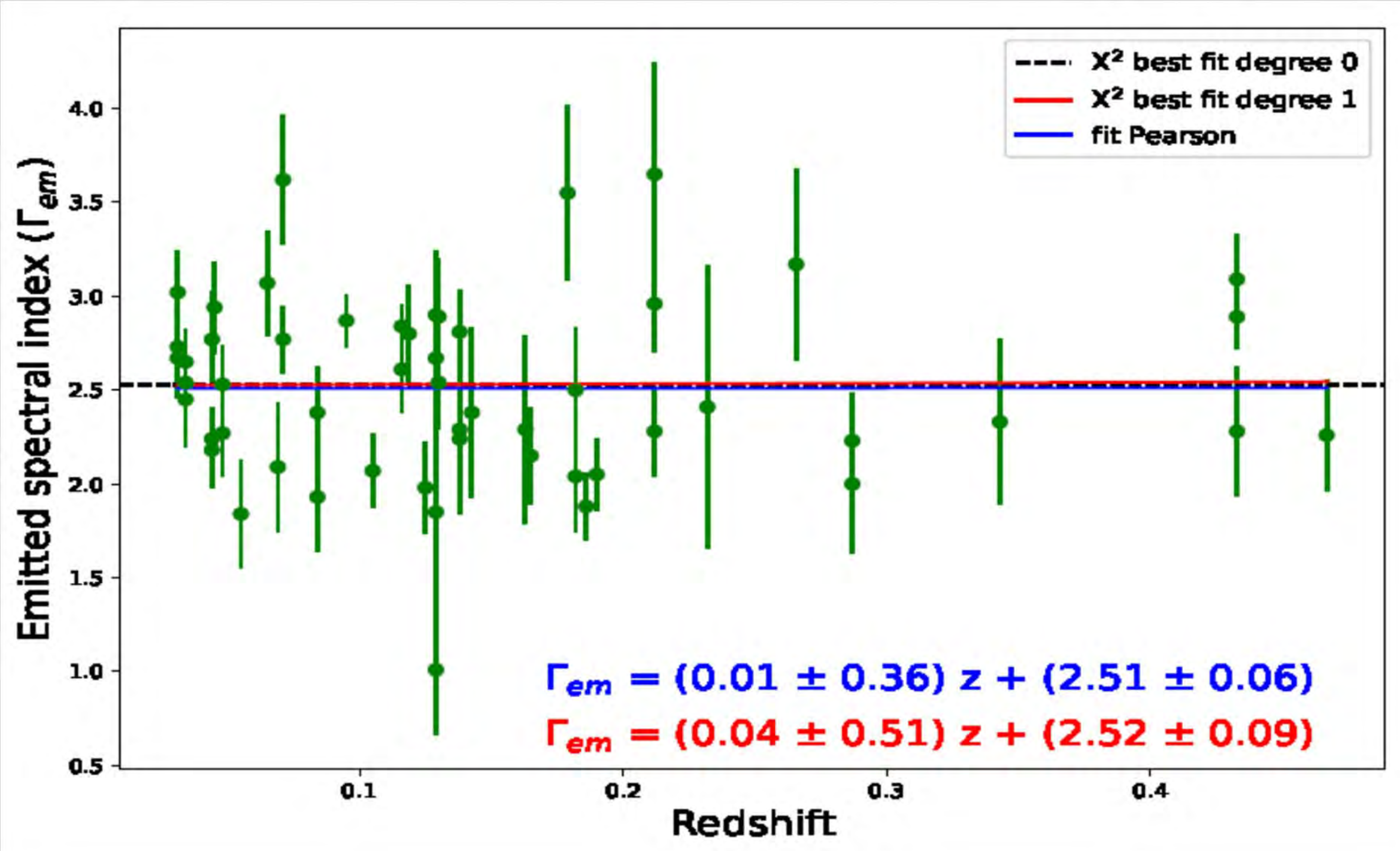


Spectral index corrections



including ALP effects

Spectral index distribution with ALPs



with $\xi \equiv \left(\frac{B}{1\,nG}\right)\left(g_{a\gamma\gamma} \cdot 10^{11} GeV\right) \approx 1$

But, estimating the significance...

Table 4. Tests of the correlations of Γ_{em} spectral indices with z for HBL BL Lacs.

Test	Pearson	Kendall	Spearman	Horizontal fit $\chi^2_{\nu,0}$ (ndof=53)	Linear fit $\chi^2_{\nu,1}$ (ndof=52)
Observed	0.57 ± 0.05	0.37 ± 0.04	0.54 ± 0.06	4.41	2.55
P-value	0.005%	0.03%	0.02%		
EBL-corrected [$\sigma(\tau_{EBL}) = 0.1\tau_{EBL}$]	-0.24 ± 0.07	-0.17 ± 0.05	-0.25 ± 0.07	3.14	3.01
P-value	12%	10%	10%		
EBL-corrected [$\sigma(\tau_{EBL}) = 0.2\tau_{EBL}$]	-0.23 ± 0.07	-0.17 ± 0.05	-0.23 ± 0.07	3.07	2.94
P-value	14%	12%	12%		
ALP-corrected ($\xi = 1.0$)	0.00 ± 0.07	-0.05 ± 0.05	-0.07 ± 0.08	2.82	2.87
P-value	70%	56%	57%		
ALP-corrected ($\xi = 2.0$)	0.09 ± 0.07	0.02 ± 0.05	0.04 ± 0.08	2.69	2.69
P-value	53%	65%	63%		

Col.1: Data sample used for the statistical tests; Col.2-3-4: Correlation coefficients and probability values obtained from different tests using Monte Carlo simulations; Col.5: Reduced chi-squared obtained by horizontal fit; Col.6: Reduced chi-squared obtained with the linear fits shown in Fig. 4, 7,10 and 11. **For the purely EBL-corrected values we report in the second and third row results assuming our two reference uncertainties $\sigma(\tau_{EBL})/\tau_{EBL} = 0.1$ and 0.2 for the EBL corrections, as indicated, while for the ALP-corrections only the values for $\sigma(\tau_{EBL}) = 0.2\tau_{EBL}$.**

Error analysis:

$$\sigma_{em} = \sqrt{(e^{\tau_{EBL}}\sigma_{stat})^2 + (S_{em}e^{\tau_{EBL}}\sigma_{EBL})^2}$$

with $$\frac{\delta\tau_{EBL}}{\tau_{EBL}} \approx \frac{\delta I_\nu}{I_\nu} = 0.1-0.2\ , \qquad \sigma_{EBL} = \frac{\delta\tau_{EBL}}{\tau_{EBL}}\tau_{EBL}$$

Conclusions

- We have collected virtually all available data on the VHE spectra of blazars, including BL Lacs and FSRQ
- We have re-analyzed all these data in terms of simple power-law spectral functions
- EBL-corrected spectral fits show indications for a residual anti-correlation of spectral indices with redshift
- but with low significance (~1.6σ)
- Forthcoming and future facilities needed (CTA, ASTRI, etc), with
  - wider VHE spectral coverage and resolution,
  - on a larger redshift interval,
  - with better statistics.