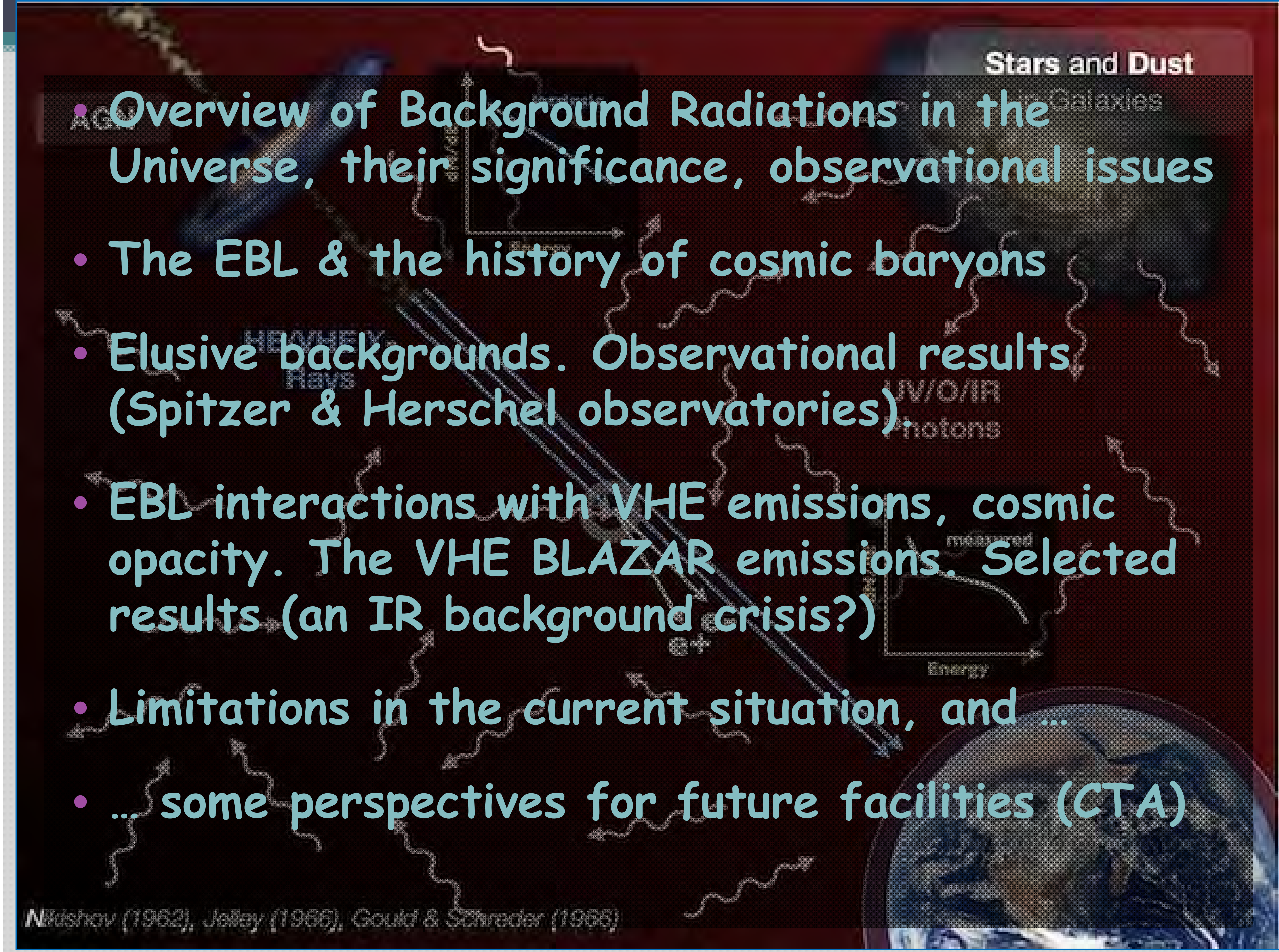
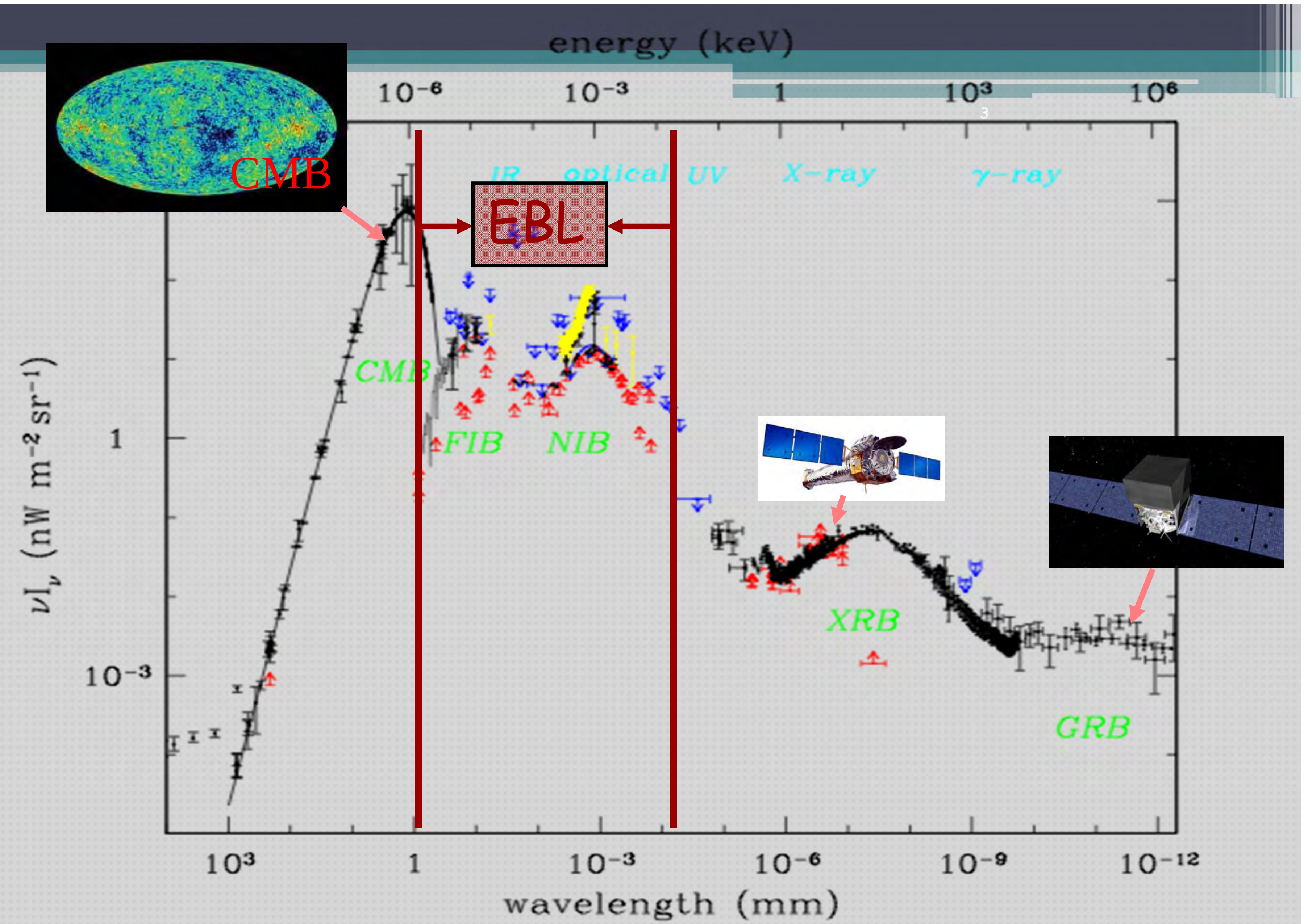
THE EXTRAGALACTIC BACKGROUND LIGHT AND THE COSMIC PHOTON OPACITY

A. FRANCESCHINI - UNIPD

- The EBL in the IR and in the optical-UV: open problems
  - EBL and the cosmic γ-γ opacity
- New perspectives in EBL studies offered by Cherenkov observations

- Overview of Background Radiations in the Universe, their significance, observational issues
- The EBL & the history of cosmic baryons
- Elusive backgrounds. Observational results (Spitzer & Herschel observatories).
- EBL interactions with VHE emissions, cosmic opacity. The VHE BLAZAR emissions. Selected results (an IR background crisis?)
- Limitations in the current situation, and …
- … some perspectives for future facilities (CTA)

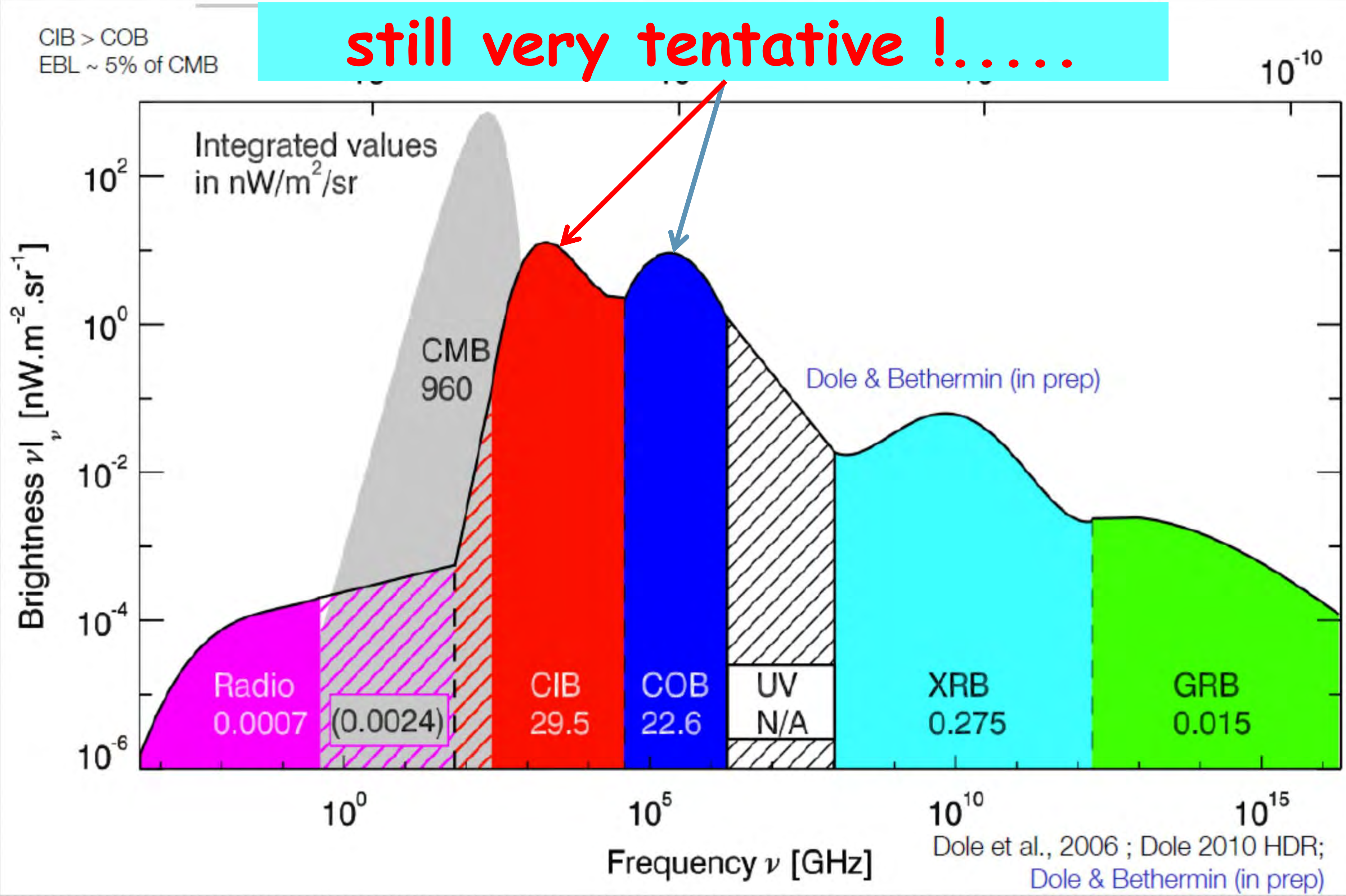




The Global Background Radiation & the EBL

The Background Radiation Energetics

still very tentative !.....



The Extragalactic Background Light

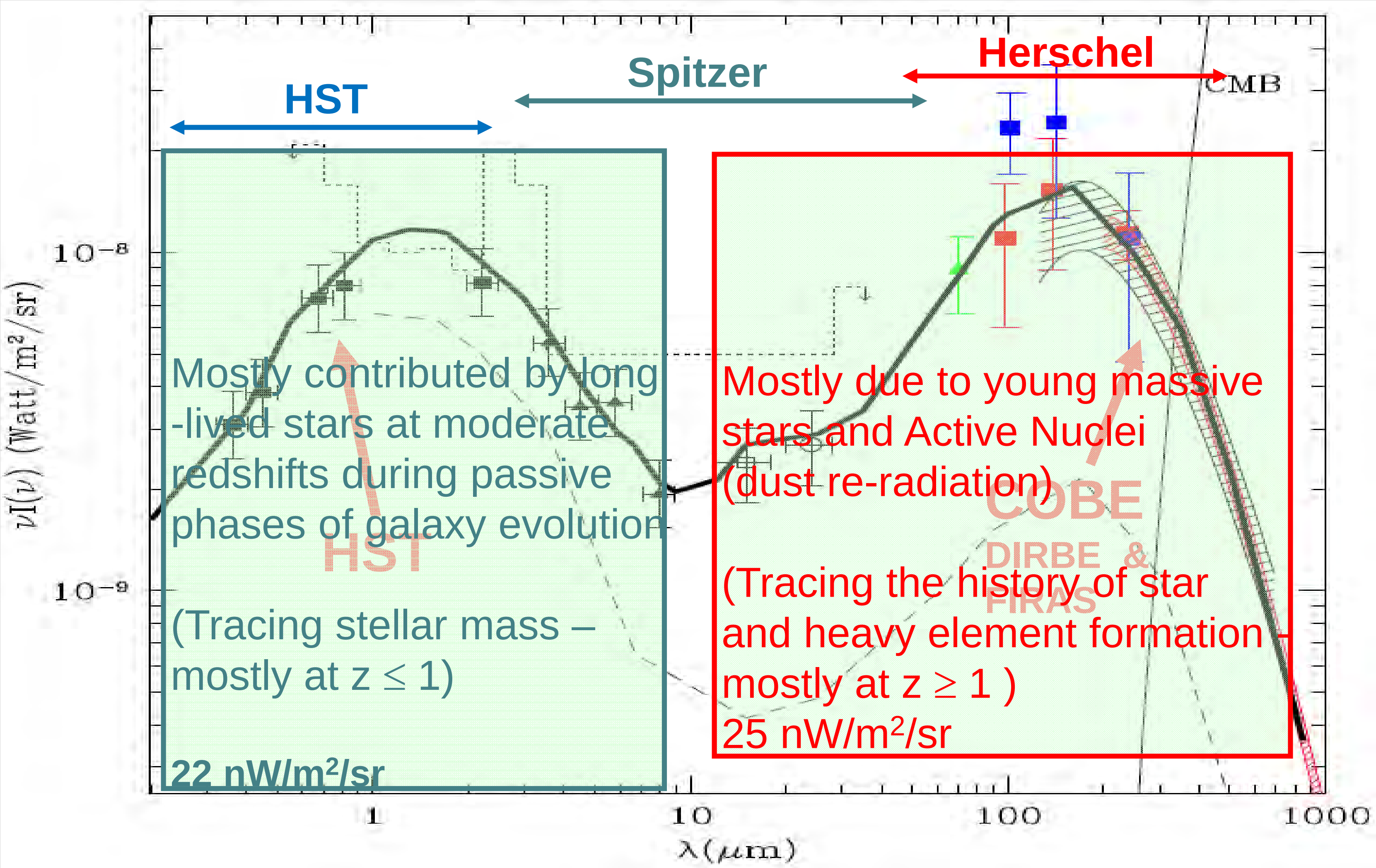
- Background radiations involve the whole history of astrophysical sources
- and are the repository of all radiant energy produced by cosmic <u>sources</u> and cosmic <u>structures</u> since the Big Bang
- -- Point sources
- -- Diffuse structures and components
- Essential data to understand how the Universe has taken shape and evolved
- Three main physical processes for generating energy and light:

  -- Thermonuclear reactions (in stars)

  -- Gravitational accretion (in galaxy nuclei – Active Galactic Nuclei)

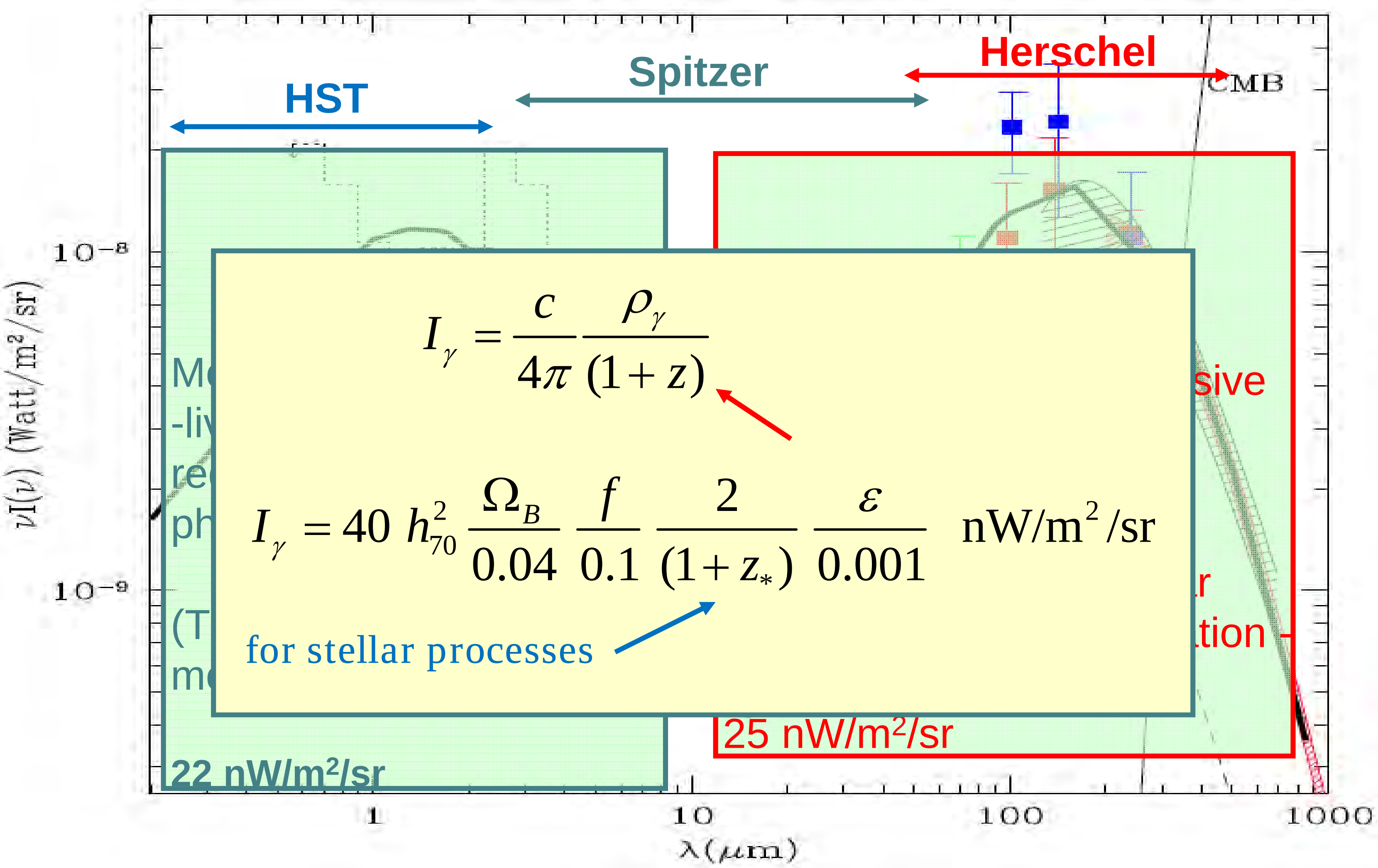
  -- Decaying particles (generated in the early phases of cosmic expansion - still speculative)

Origin of diffuse radiations



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

Origin of diffuse radiations



$$I_\gamma = \frac{c}{4\pi}\frac{\rho_\gamma}{(1+z)}$$

$$I_\gamma = 40\ h_{70}^2 \frac{\Omega_B}{0.04}\ \frac{f}{0.1}\ \frac{2}{(1+z_*)}\ \frac{\varepsilon}{0.001}\quad \mathrm{nW/m^2/sr}$$

for stellar processes

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

ULTIMATE ENERGY SOURCES (AGNs)

- **Stellar activity versus…**
- **…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 (MDO's):

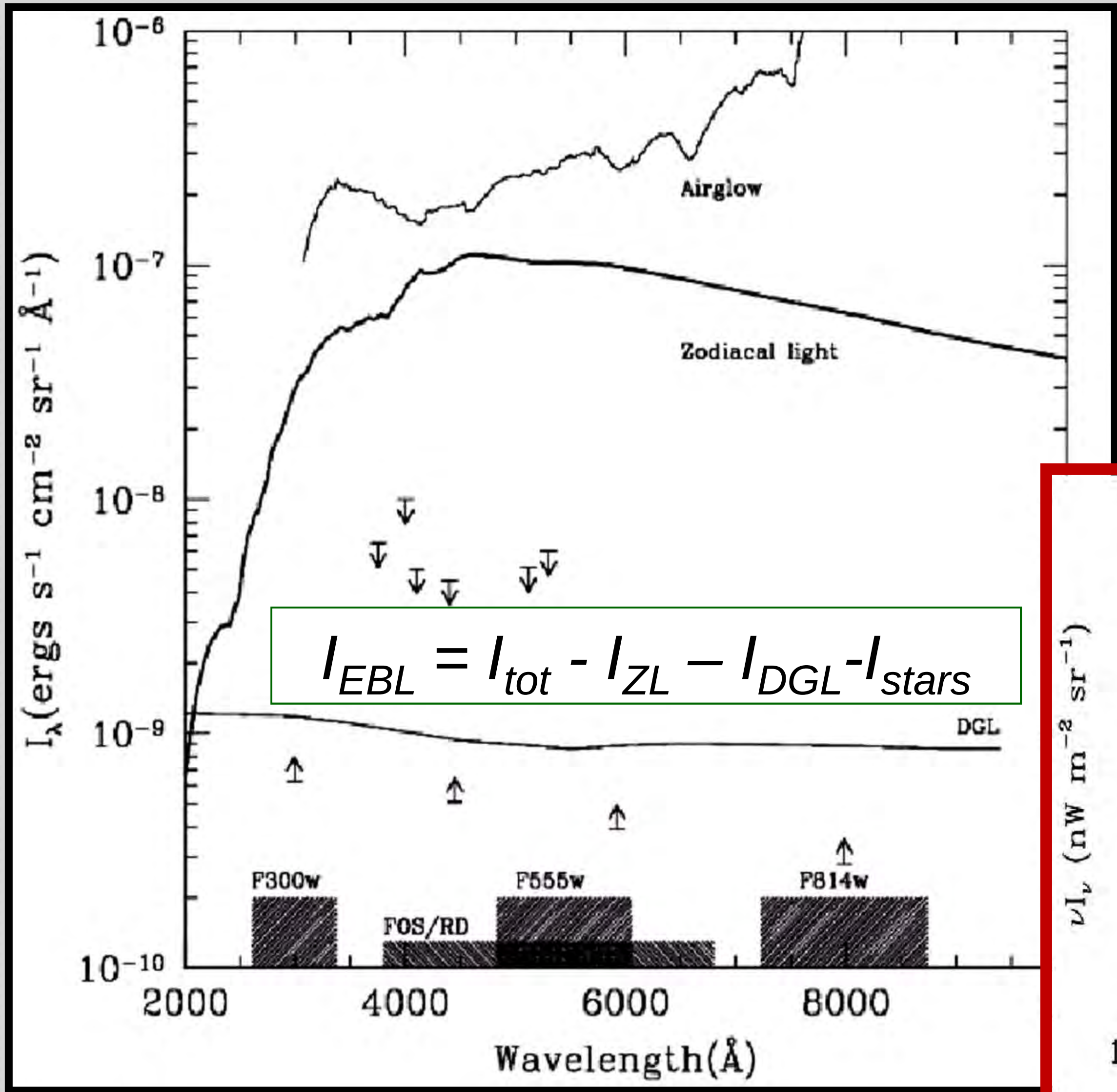
$M_{MDO} \sim 2\ 10^{-3}\ M_*$ (M_* : mass in spheroids Kormendy & Richstone)

$\eta_* \sim (1\text{-}5)\times10^{-3}$, $\eta_{AGN}\sim0.06\text{-}0.4$ (Kerr limit)

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

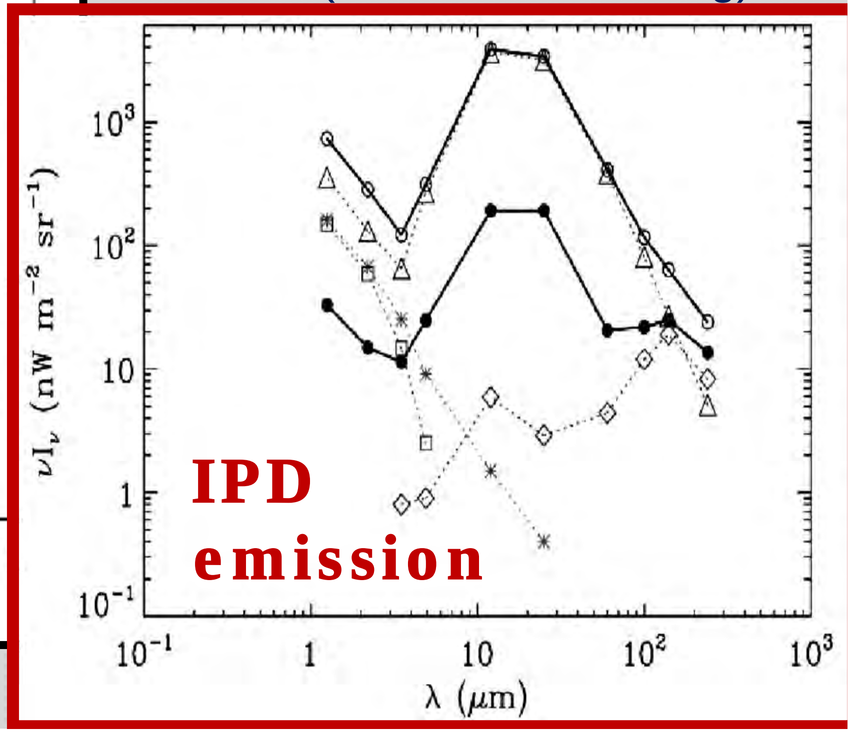
- So measuring EBL radiations essential particularly for retriving the evolutionary history of the fundamental cosmic component, the baryons.
- EBL offers key constraints to understand how they evolved from the undifferentiated plasma registered in the CMB to the currently highly structured universe (with galaxies, galaxy aggregations, stars, planets [and life])

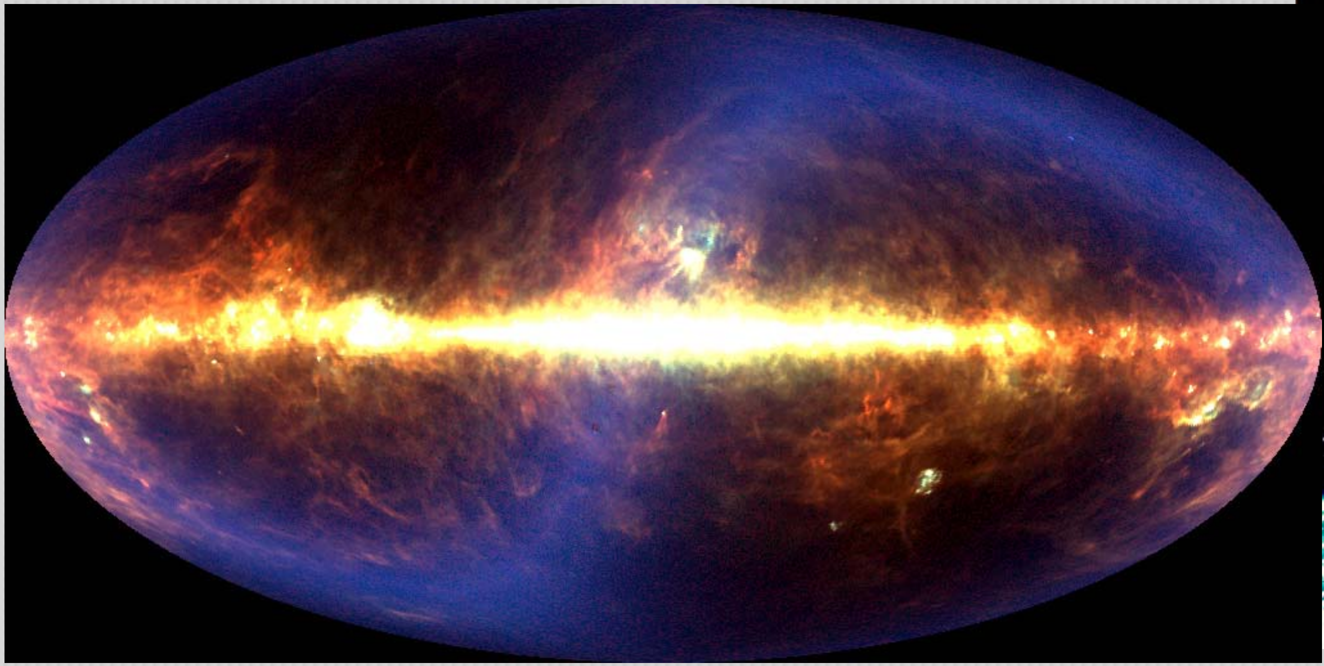
Can we directly measure the Extragalactic Background Light ?

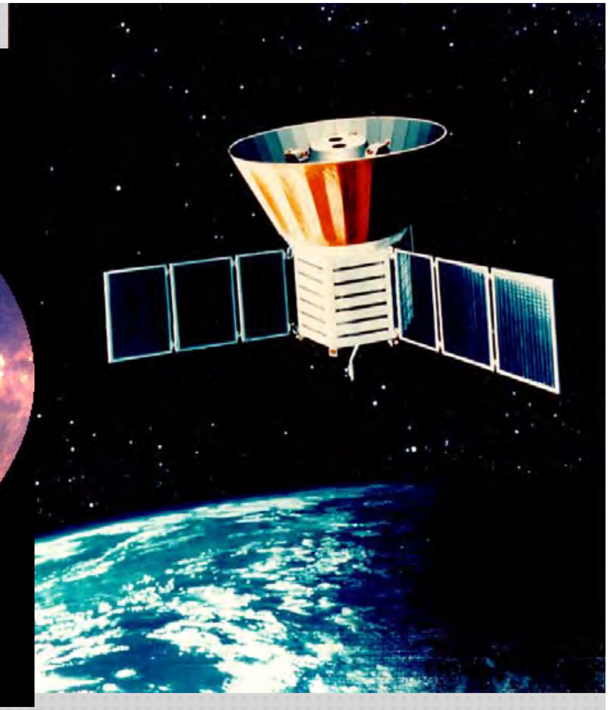


$$I_{EBL} = I_{tot} - I_{ZL} - I_{DGL} - I_{stars}$$

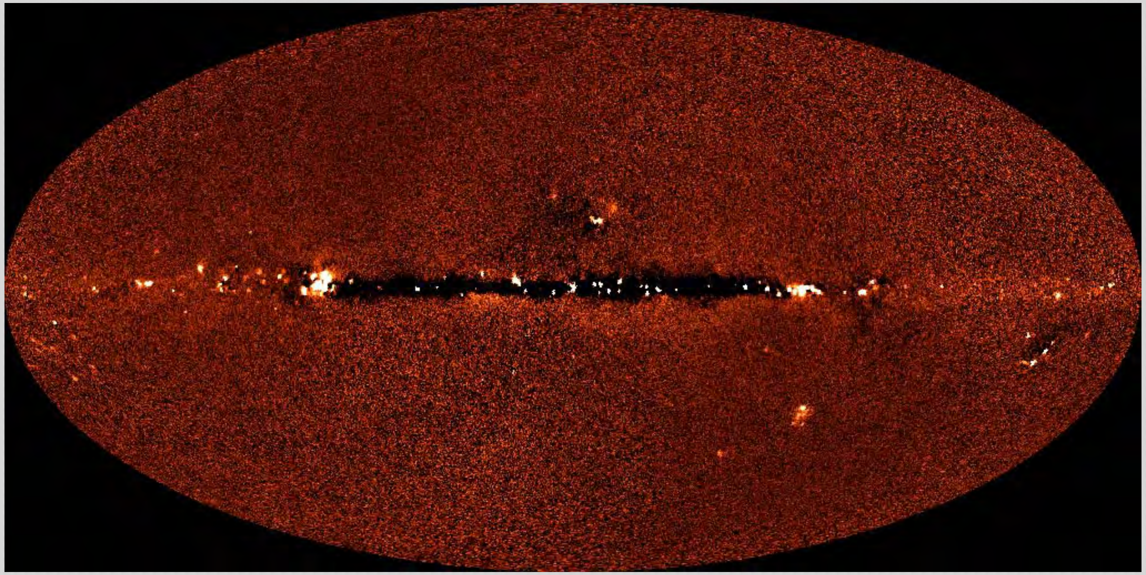
Foreground emission sources in the optical, upper limits on the EBL, and lower limits based on the integrated flux from resolved galaxies (V555 > 23 AB mag)







COBE



Discovery of the Cosmic Infrared Background (CIRB)

(Puget et al. 1996; Hauser et al. 1998)

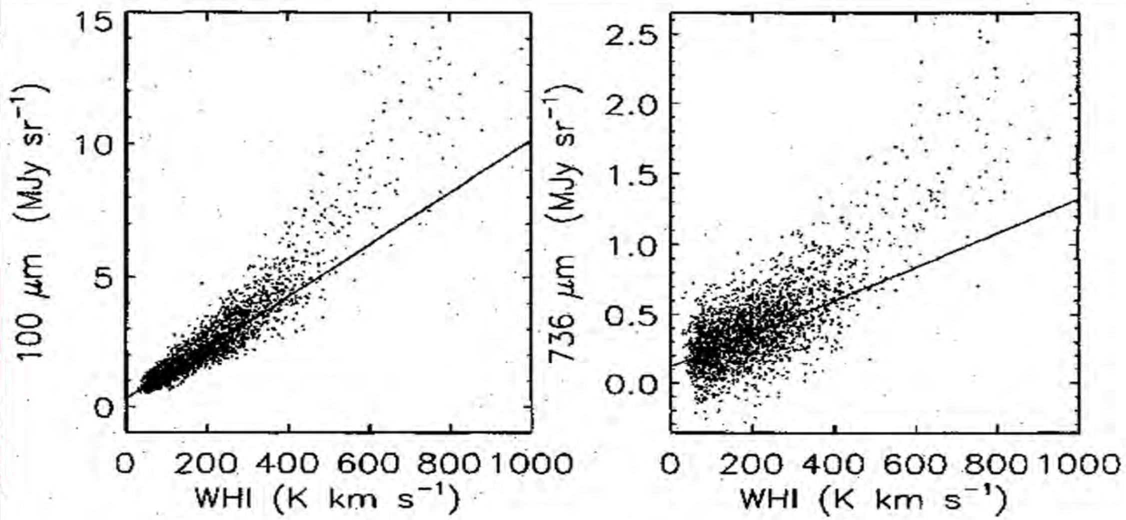
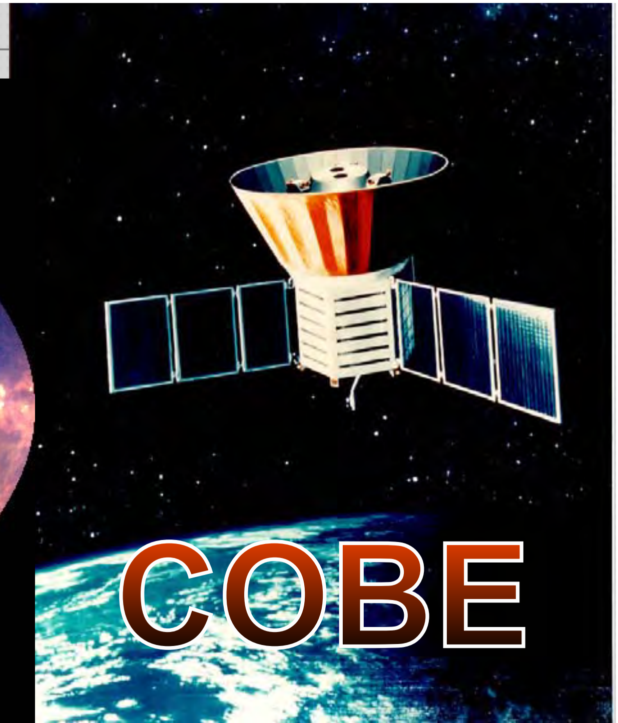
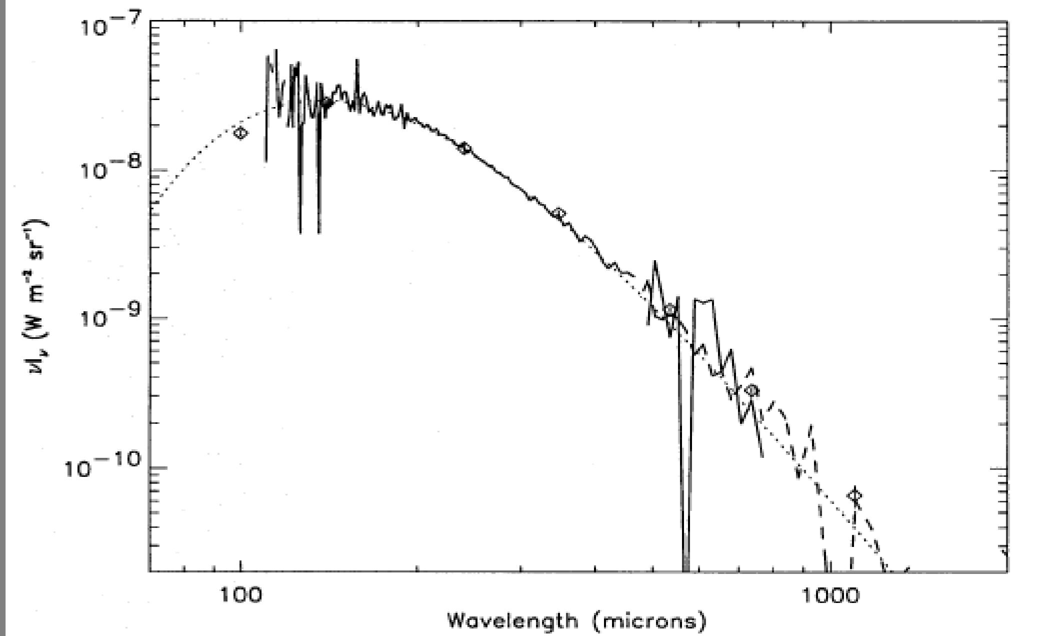


Fig. 1. Correlation between IR and HI emission at 100 μm (DIRBE data, smoothed to 7° resolution) and at 736 μm (FIRAS LLSS data, averaged between 600 and 900 μm). The lines represent fits to data at $W_{\rm HI} < 250$ K km s^{-1}.



The sub-millimeter: the only spectral region where the total EBL has been reliably measured

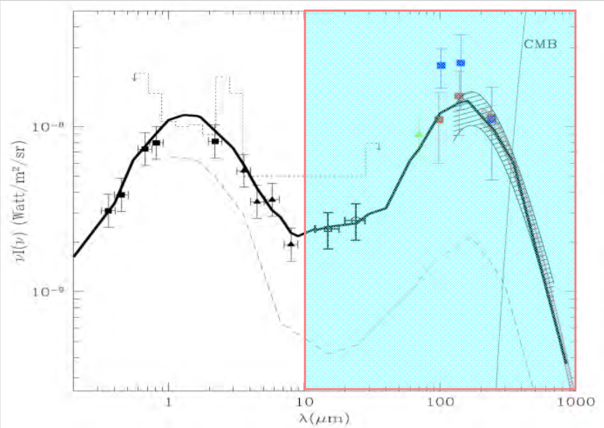


IN CONCLUSION, EBL direct measurements particularly difficult
(virtually impossible)
where they would be most interesting!

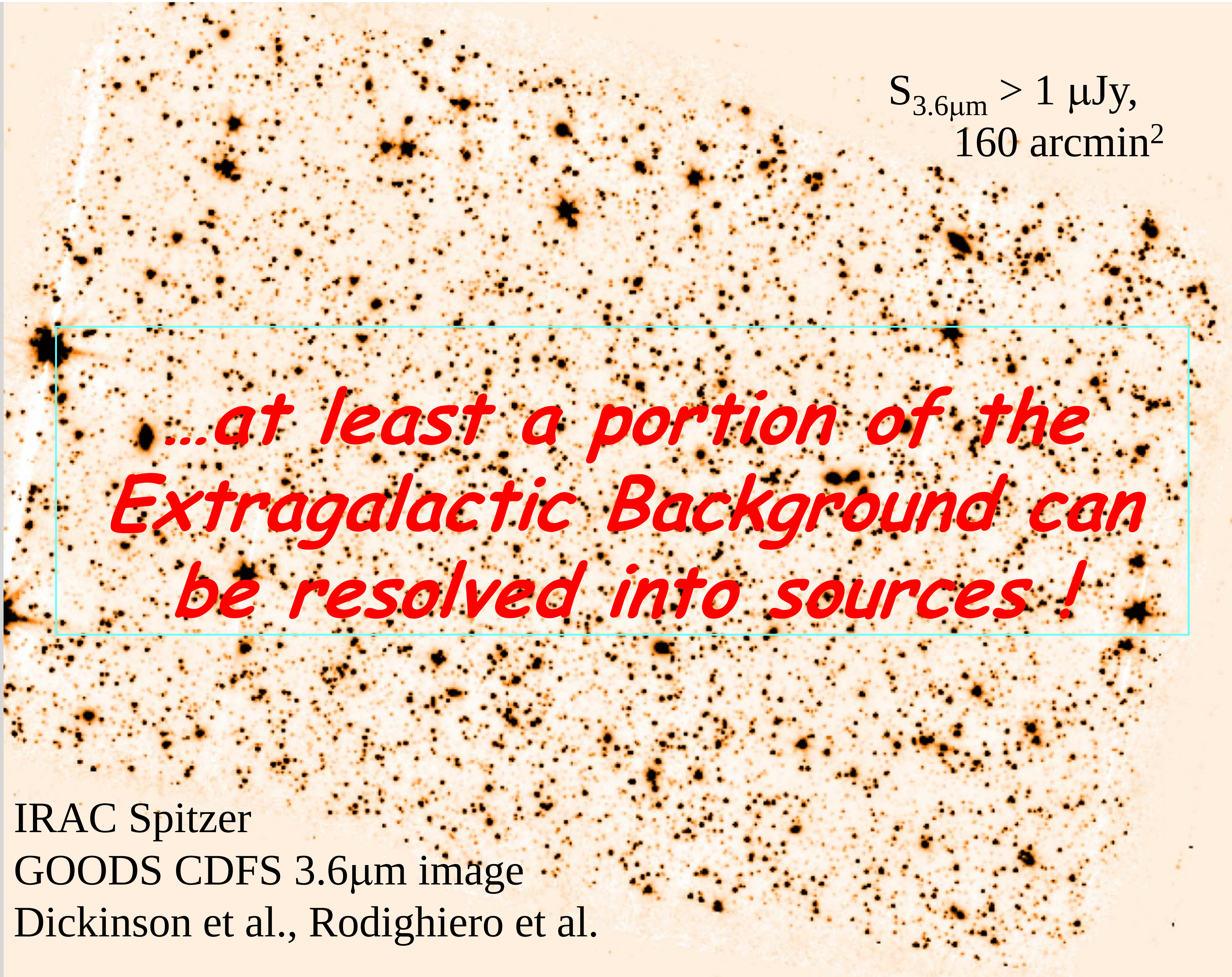
- (UV – optical – IR)

Minimal EBL estimates by known sources

Hubble Deep Field **HST WFPC2**



Spitzer & HERSCHEL observatories have sampled the elusive sources of the IR EBL

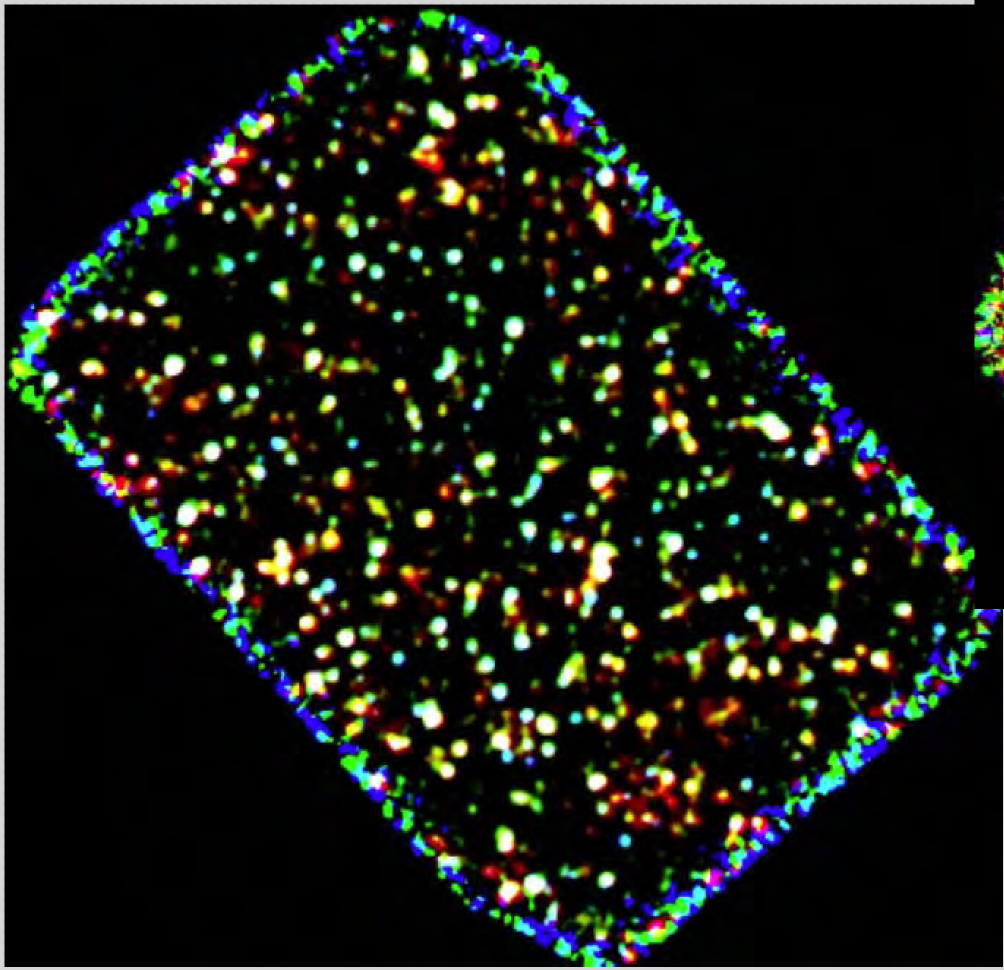


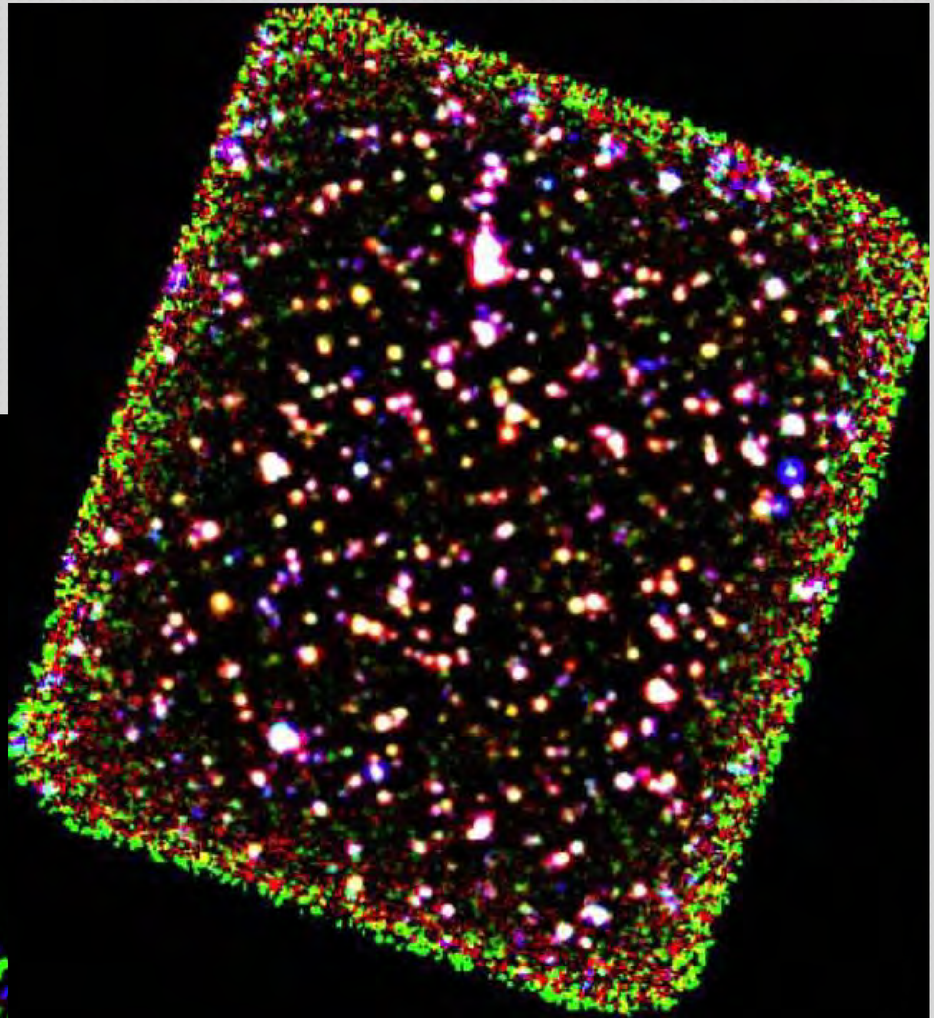
$S_{3.6\mu m} > 1\ \mu Jy$,
160 $arcmin^2$

...at least a portion of the Extragalactic Background can be resolved into sources !

IRAC Spitzer
GOODS CDFS 3.6μm image
Dickinson et al., Rodighiero et al.

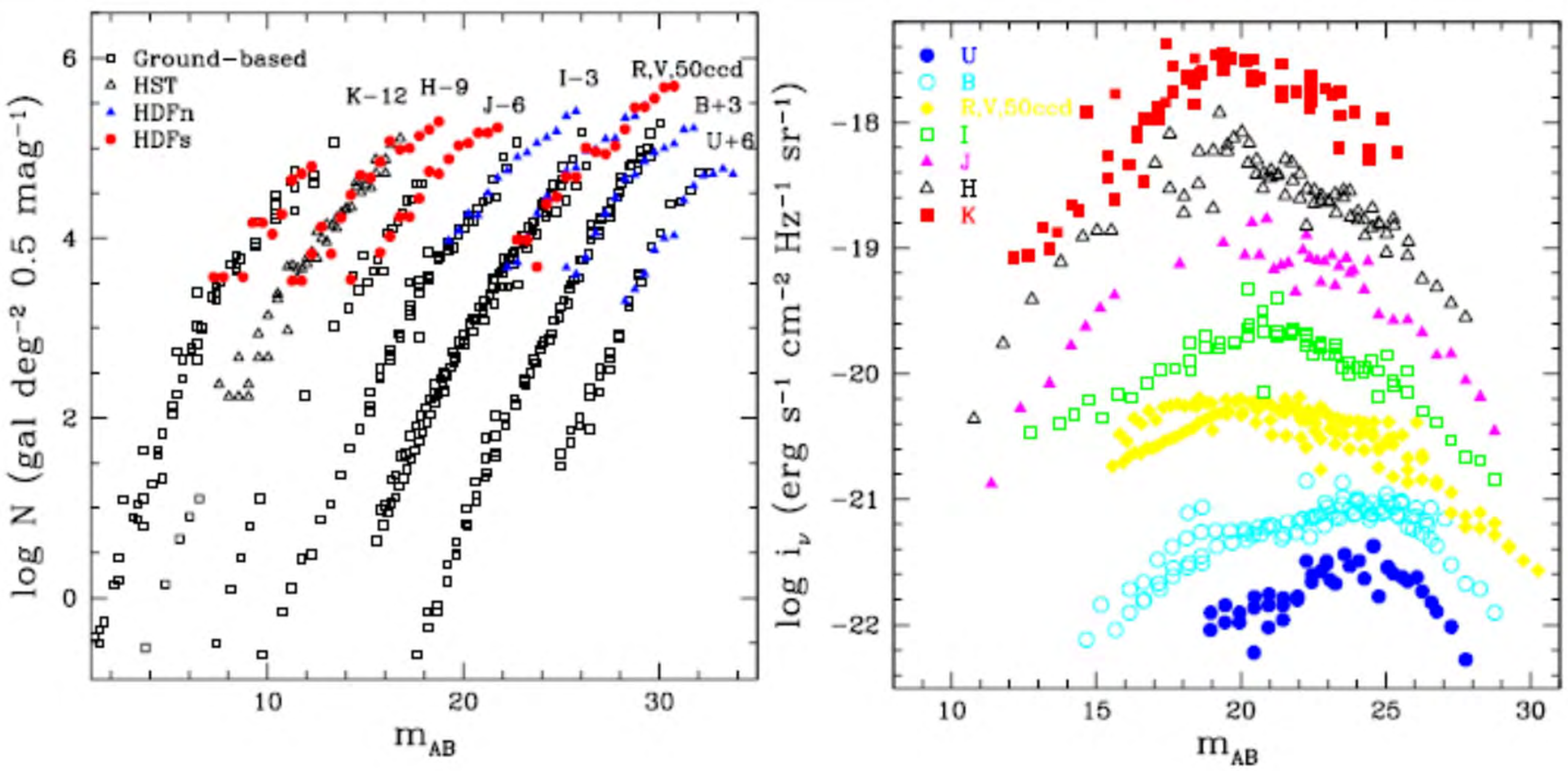
GOODS–north field (10′×15′) at 100 μm (blue), 160 μm (green) and 250 μm (red)





GOODS–south (10′×10′) at 24 μm (blue), 100 μm (green) and 160 μm (red)

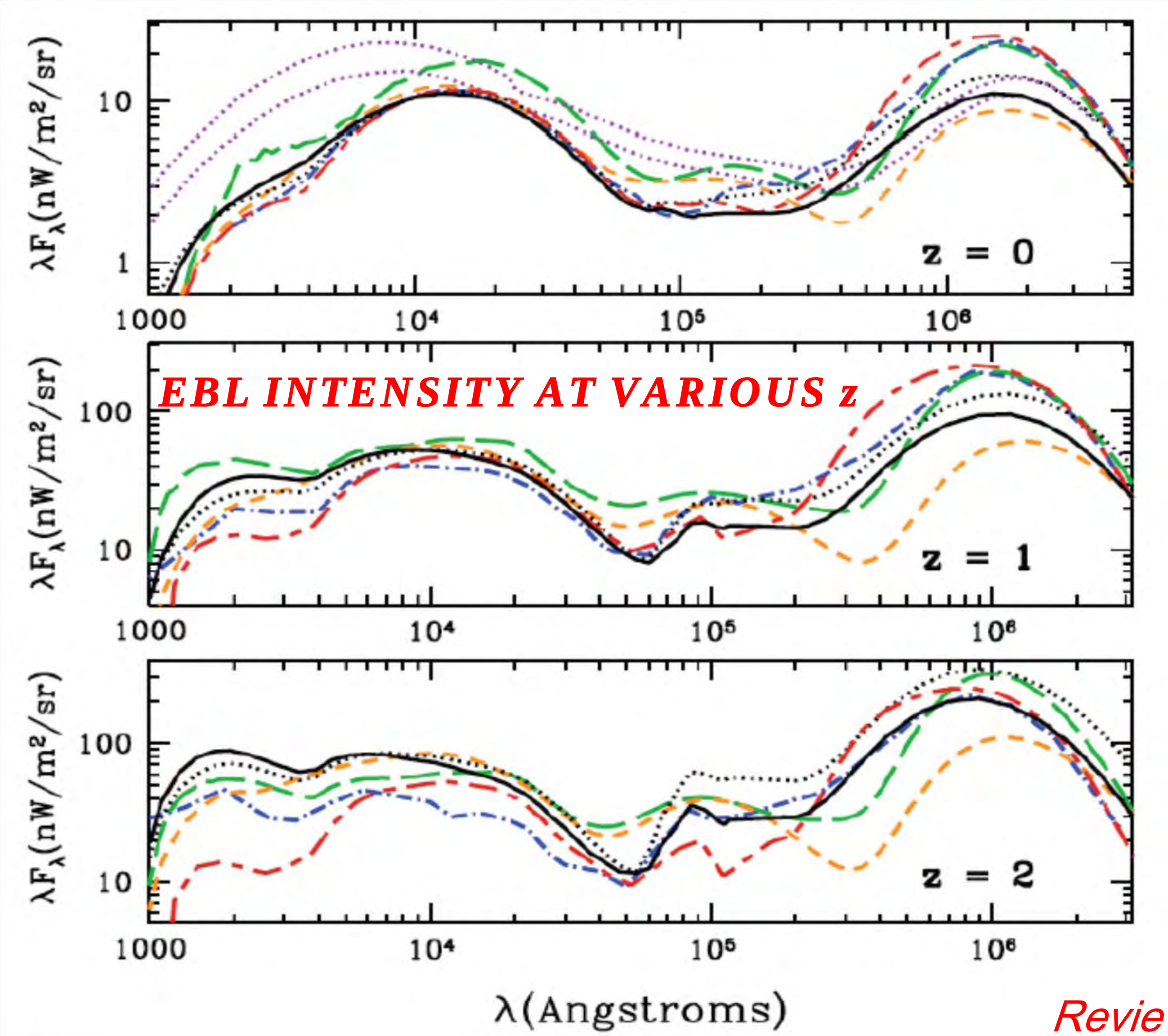
Elbaz et al. 2011



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.
The flattening is more pronounced at the shortest wavelengths. Right: Extragalactic background light per magnitude bin, $i = 10{-}0.4(m_{AB}+48.6)N(m)$, 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

Modelling the sources of EBL



Dashed-dotted blue: Franceschini et al. 2008; Long-short dashed red & solid and dotted black lines: Gilmore et al. 2012 long-dashed green: Kneiske et al. (2004); dashed orange: Finke et al. (2010); low and high dotted violet points: Stecker et al. 2006.

Reviewed by Gilmore et al. 2012

Modelling the sources of EBL

Three kinds of models:

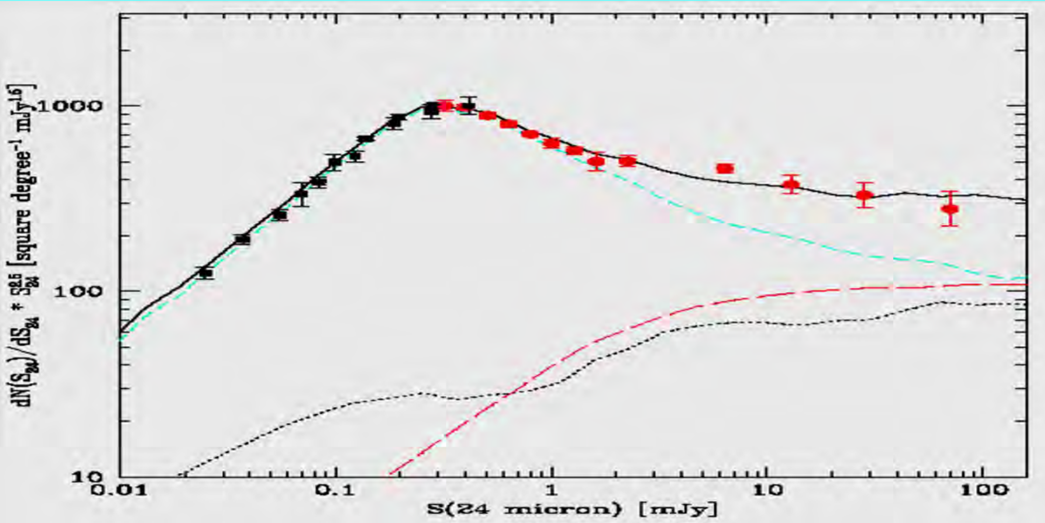
- Physically motivated (galaxy & structure formation from first principles)
- General euristic prescriptions for EBL evolution
- Adherent to the (many available) data, with educated analytical representations and fitting functions

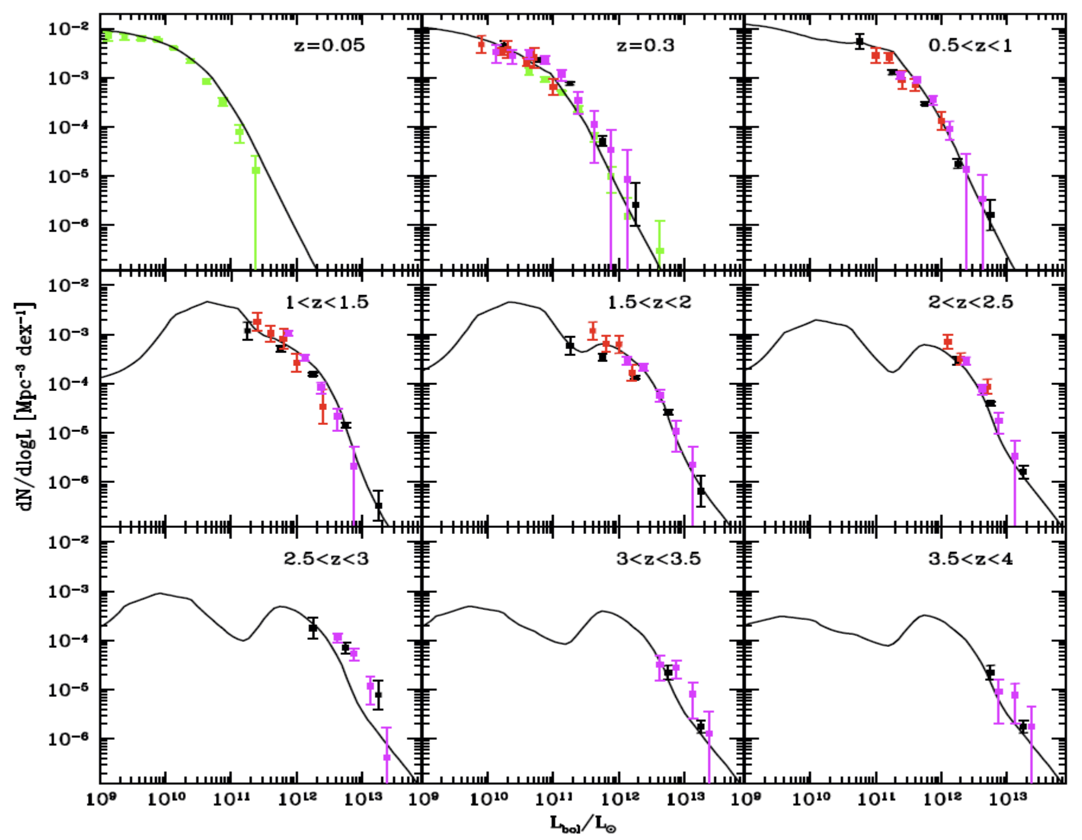
Reviewed by Gilmore et al. 2012

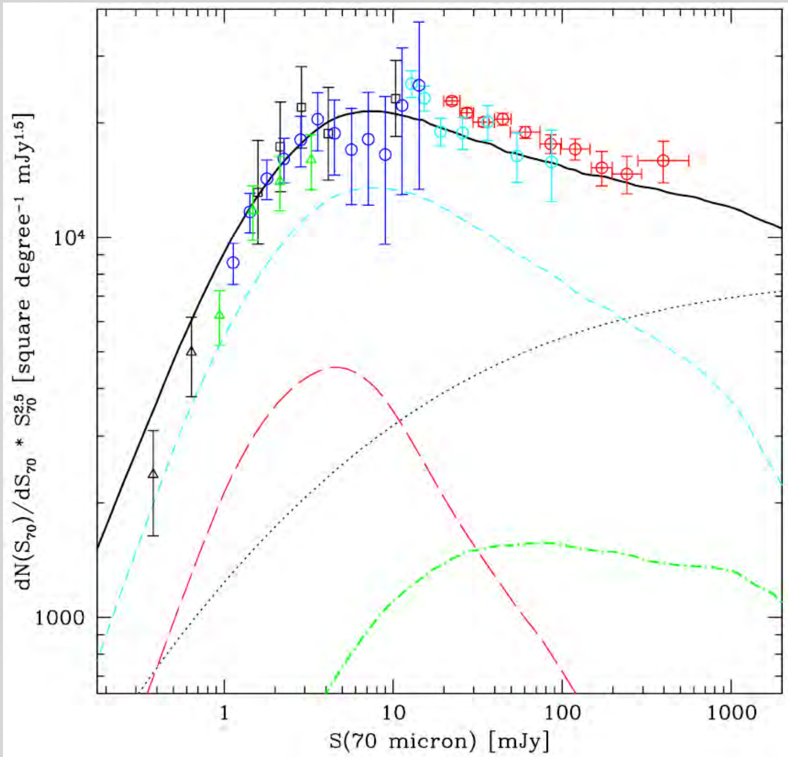
Modellistic scheme to integrate all the data

- The most adherent possible to the multi-wavelength data
- Basic split into the photospheric stellar component (0.1 – 10 μm) and the dust-reradiation (10 – 1000 μm) parts
- Each section identifies fundamental galaxy categories with reference to their different cosmic evolutionary properties: non-evolving spirals, spheroidal (elliptical) galaxies, fast-evolving starburst galaxies, Active Galactic Nuclei and quasars
- For all components both luminosity and comoving density evolution are treated with free parameters:
  - density evolution for representing the galaxy merging and hierarchical assembly
  - luminosity evolution following the aging stellar populations and the evolution of the rate of star formation (typically much larger at $z \geq 1$ than locally)

Source number counts & luminosity functions





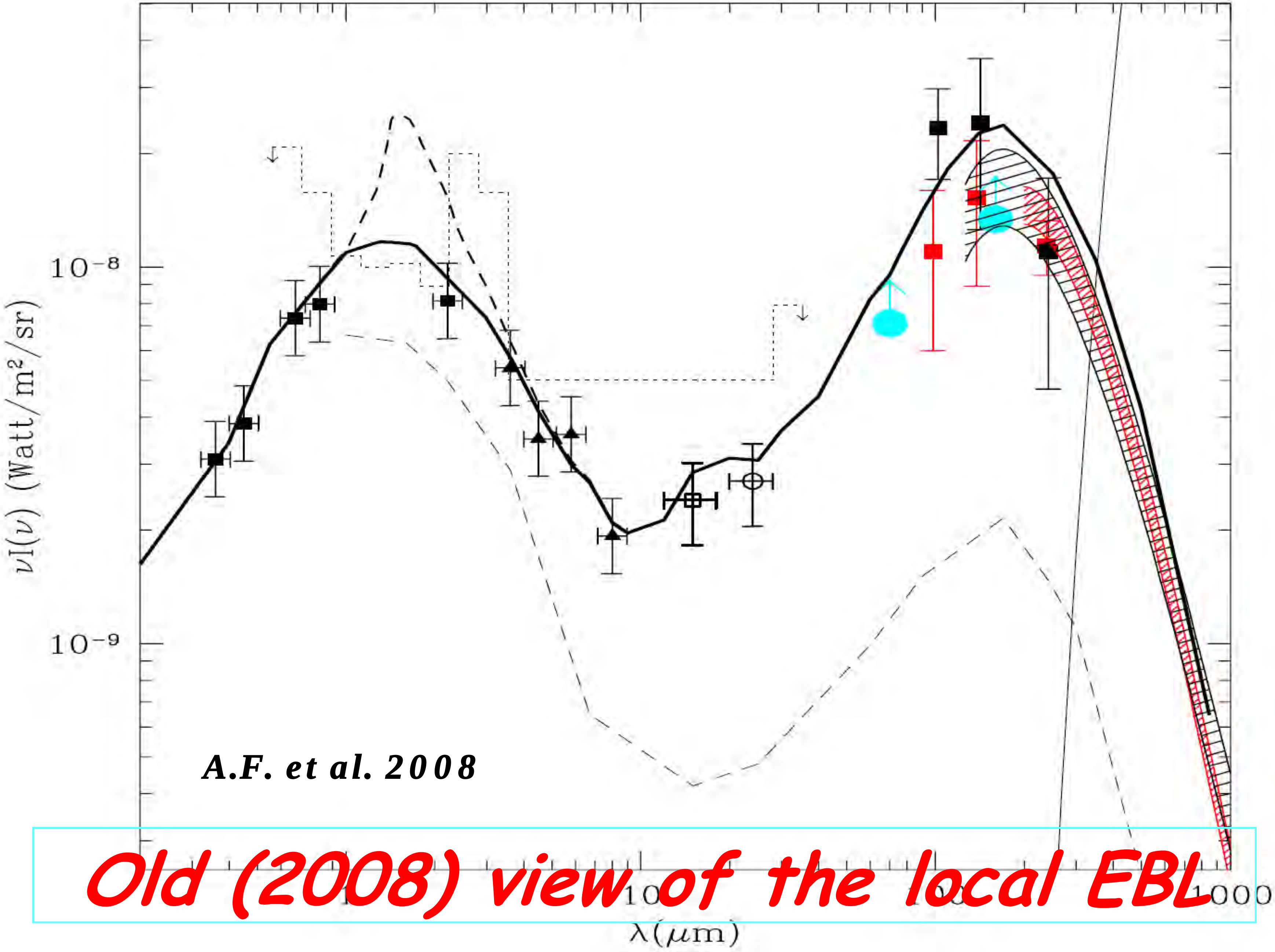


Galaxy number counts and the cosmic background emissivity

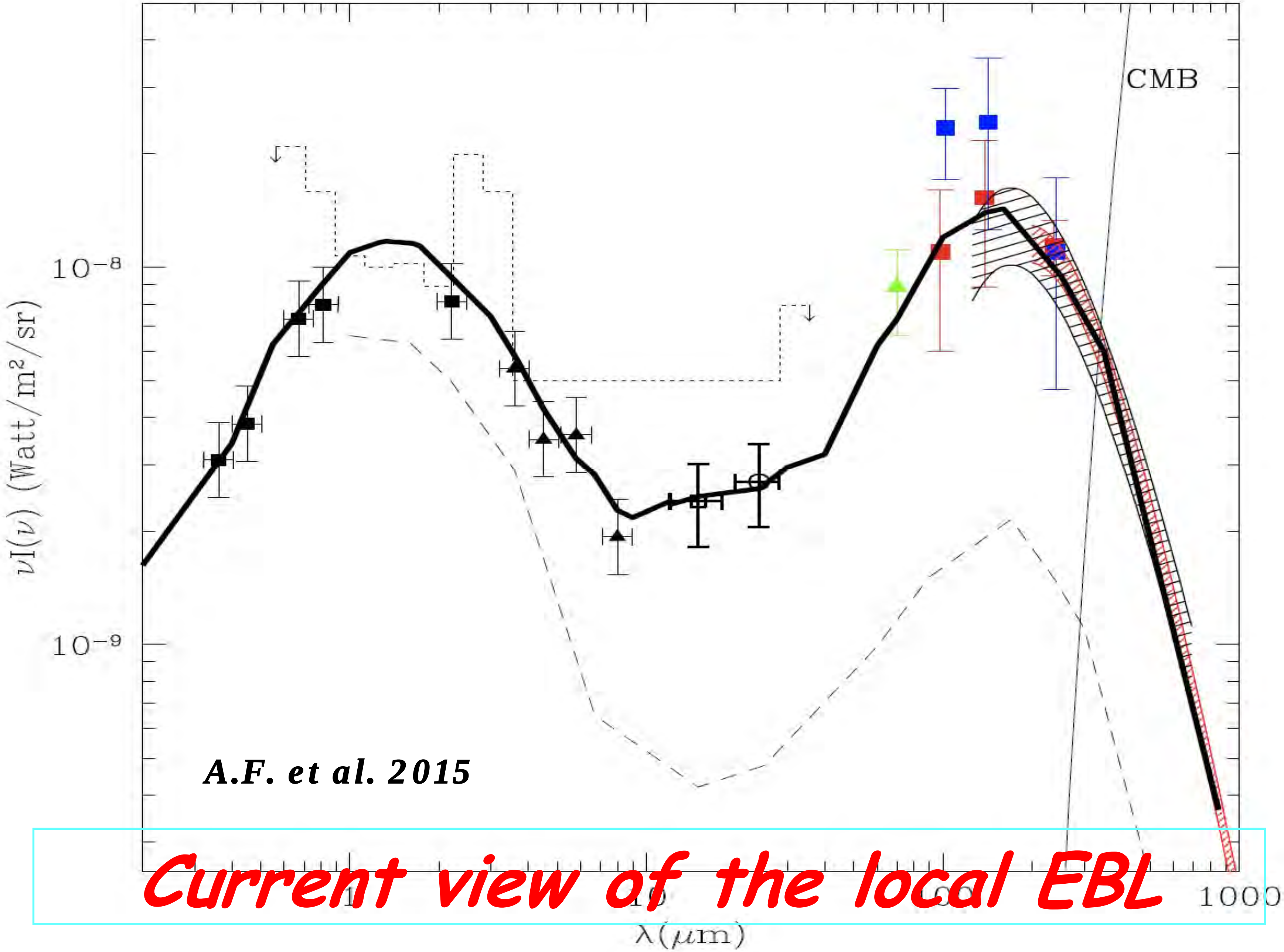
$$I = \int_0^{S_d} \frac{dN}{dS} S\, dS = \frac{1}{4\pi} \frac{c}{H_0} \int_{z(S_d, L_{\min})}^{z_{\max}} \frac{dz}{(1+z)^6 (1+\Omega z)^{1/2}} j_{\rm eff}(z)$$

$$j_{\rm eff}(z) = \int_{L_{\min}}^{\min[L_{\max}, L(S_d, z)]} d\log L\; L\; n_c(L,z) K(L,z)$$

$$S_{\Delta\nu} = \frac{L_{\Delta\nu} K(L,z)}{4\pi d_L^2}$$

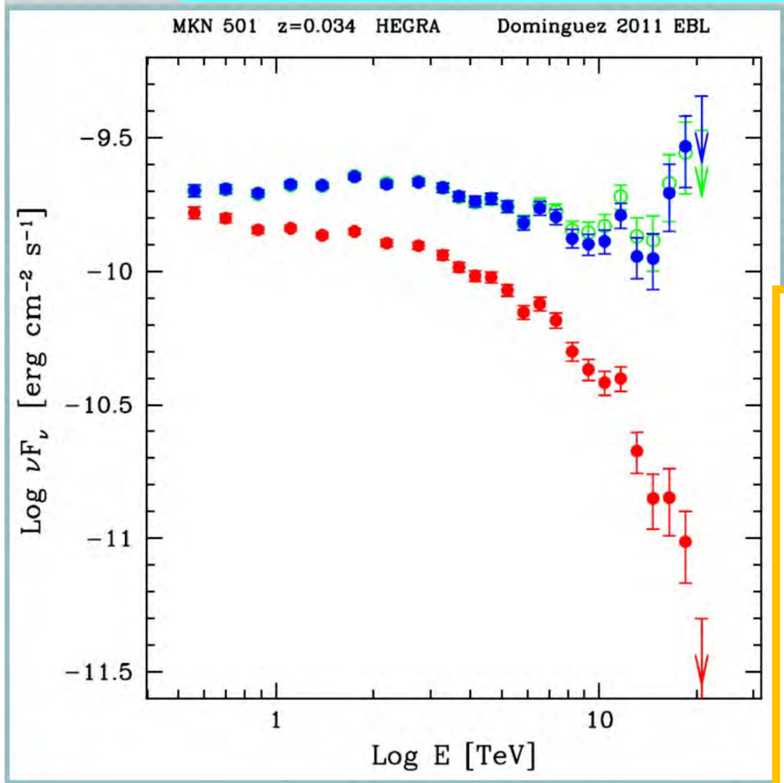


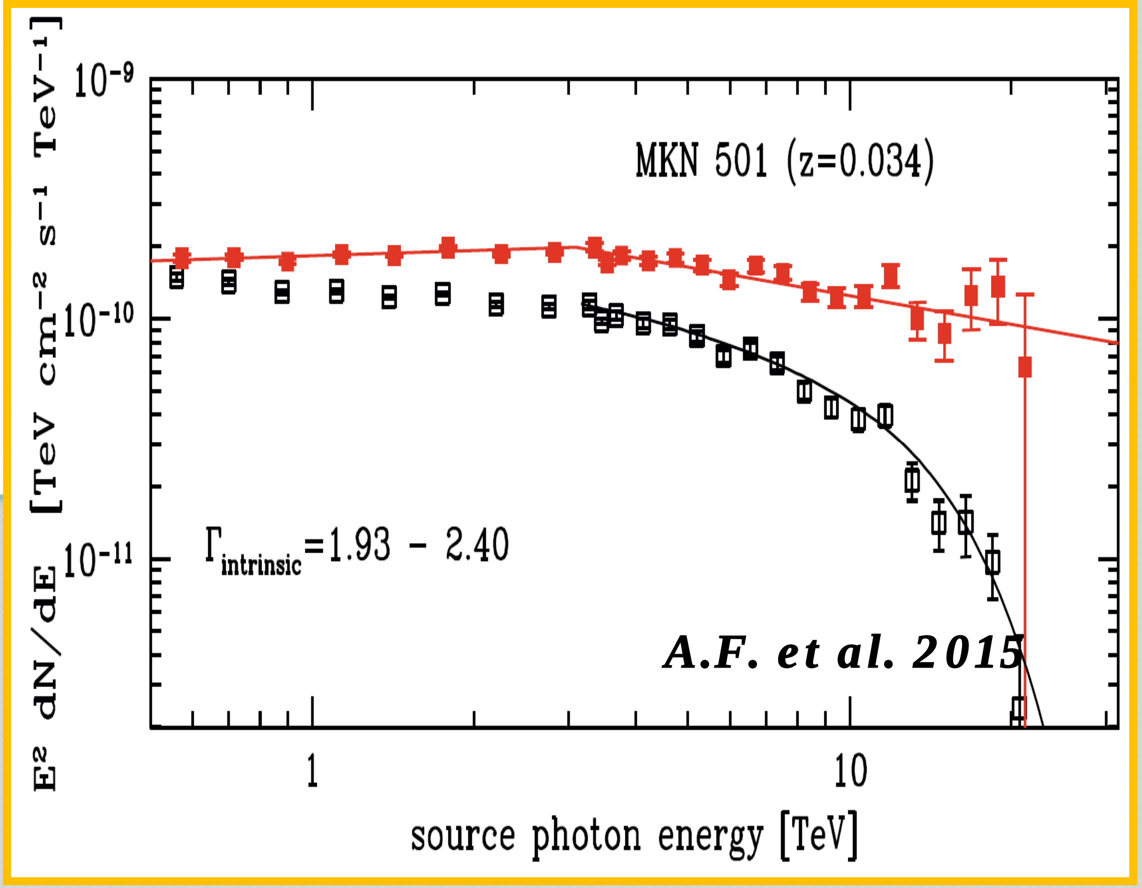
Old (2008) view of the local EBL

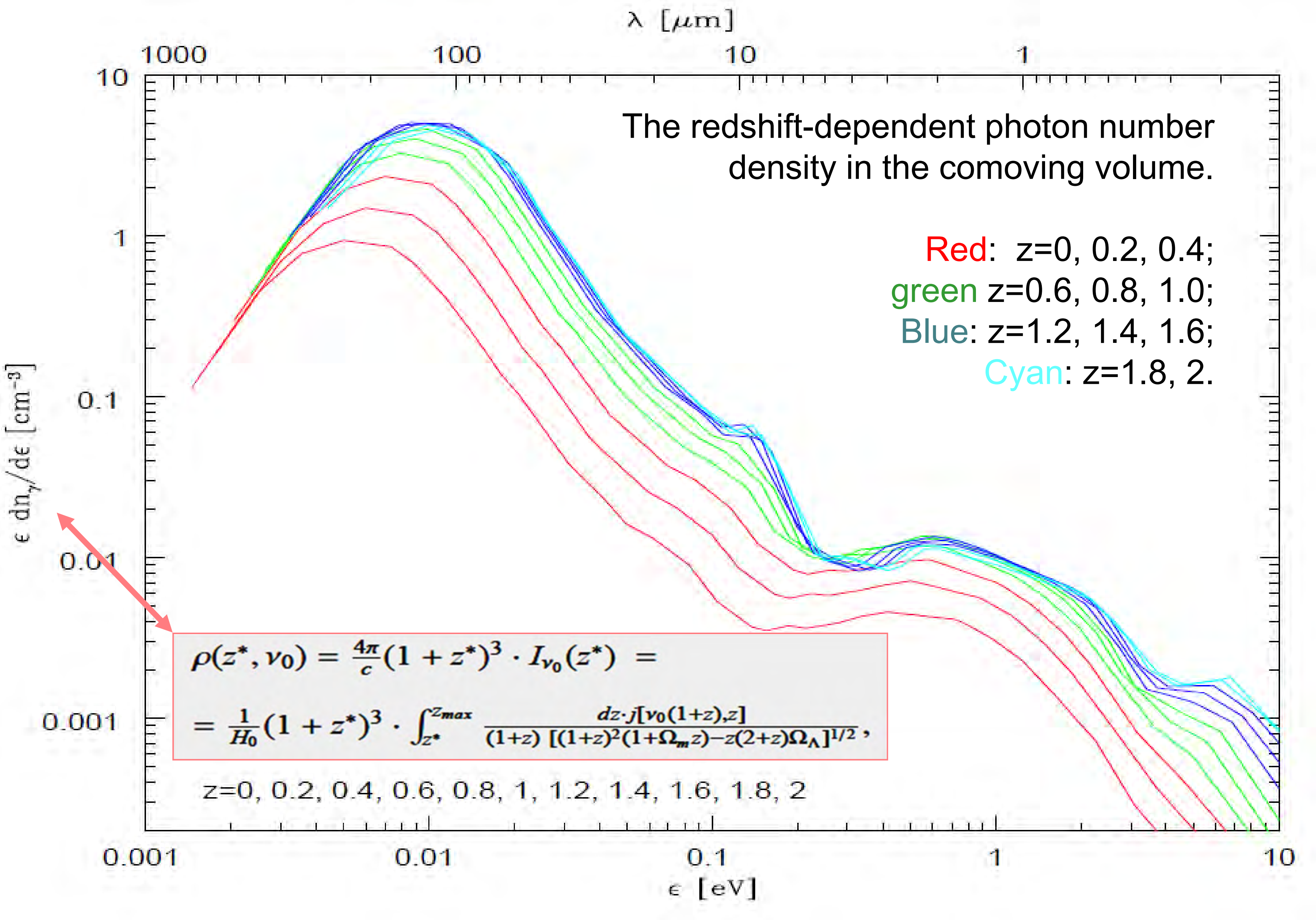


Current view of the local EBL

An IR EBL crisis ?







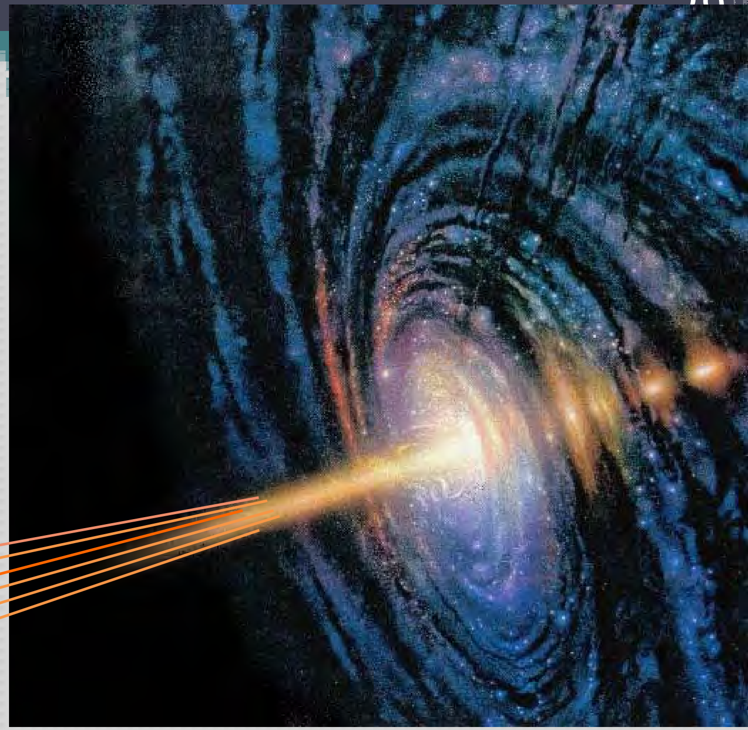
$$\rho(z^*,\nu_0) = \frac{4\pi}{c}(1+z^*)^3 \cdot I_{\nu_0}(z^*) =$$

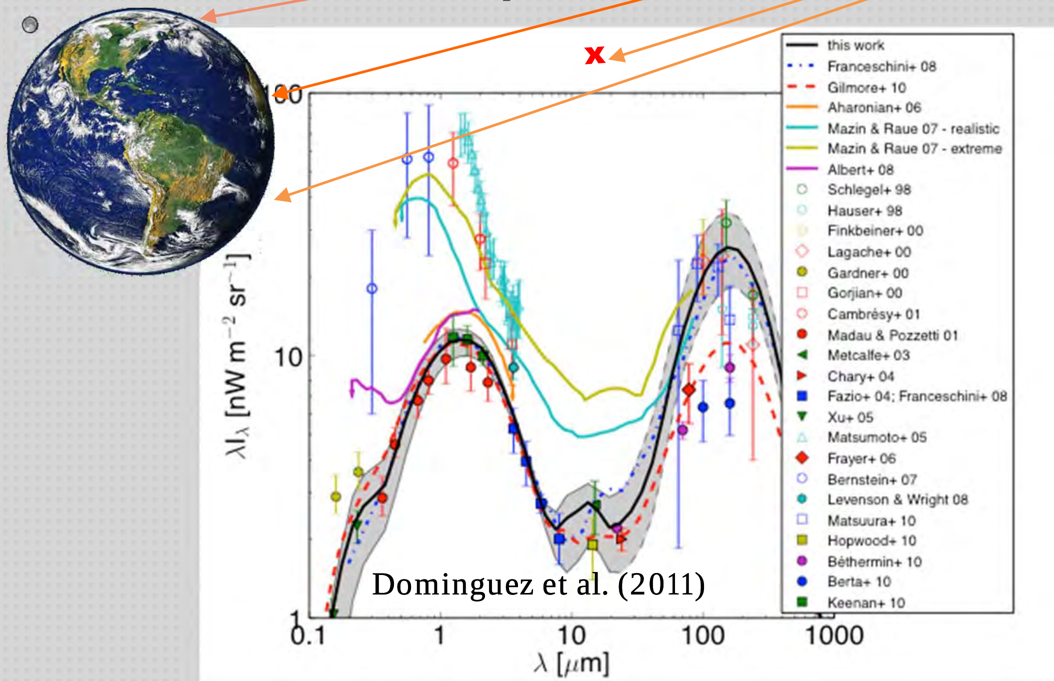
$$= \frac{1}{H_0}(1+z^*)^3 \cdot \int_{z^*}^{z_{max}} \frac{dz \cdot j[\nu_0(1+z),z]}{(1+z)\ [(1+z)^2(1+\Omega_m z)-z(2+z)\Omega_\Lambda]^{1/2}},$$

All this concerns only the contribution of discrete, identified sources.

Nothing is said at the moment about purely diffuse components or unknown (very faint) populations of sources.

COMPLEMENTARY INSIGHT ONTO THE EXTRAGALACTIC BACKGROUND LIGHT ISSUE FROM VERY-HIGH-ENERGY ASTROPHYSICS (WITH CONSEQUENCES FOR PHYSICS AND COSMOLOGY)





VHE photon + diffuse light

→ electron-positron pair production

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

Absorption:

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

The γ-γ cosmic optical depth

The optical depth for $\gamma\gamma$ collision of a high-energy photon with E_γ from a source at z_e:

$$\tau(E_\gamma, z_e) = c\int_0^{z_e} dz\frac{dt}{dz}\int_0^2 dx\frac{x}{2}\int_{\frac{2m_e^2c^4}{E_\gamma \epsilon x(1+z)}}^{\infty} d\epsilon\frac{dn_\gamma(\epsilon, z^*)}{d\epsilon}\sigma_{\gamma\gamma}(\beta)$$

$$\sigma_{\gamma\gamma}(E_\gamma, \epsilon, \theta) = \frac{3\sigma_T}{16}\cdot(1-\beta^2)\times\left[2\beta(\beta^2-2)+(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right],$$

$$\beta \equiv (1-4m_e^2c^4/s)^{1/2}; \quad s \equiv 2E_\gamma\epsilon x(1+z); \quad x \equiv (1-\cos\theta),$$

For a flat universe, the differential of time to be used in eq. 1 is:

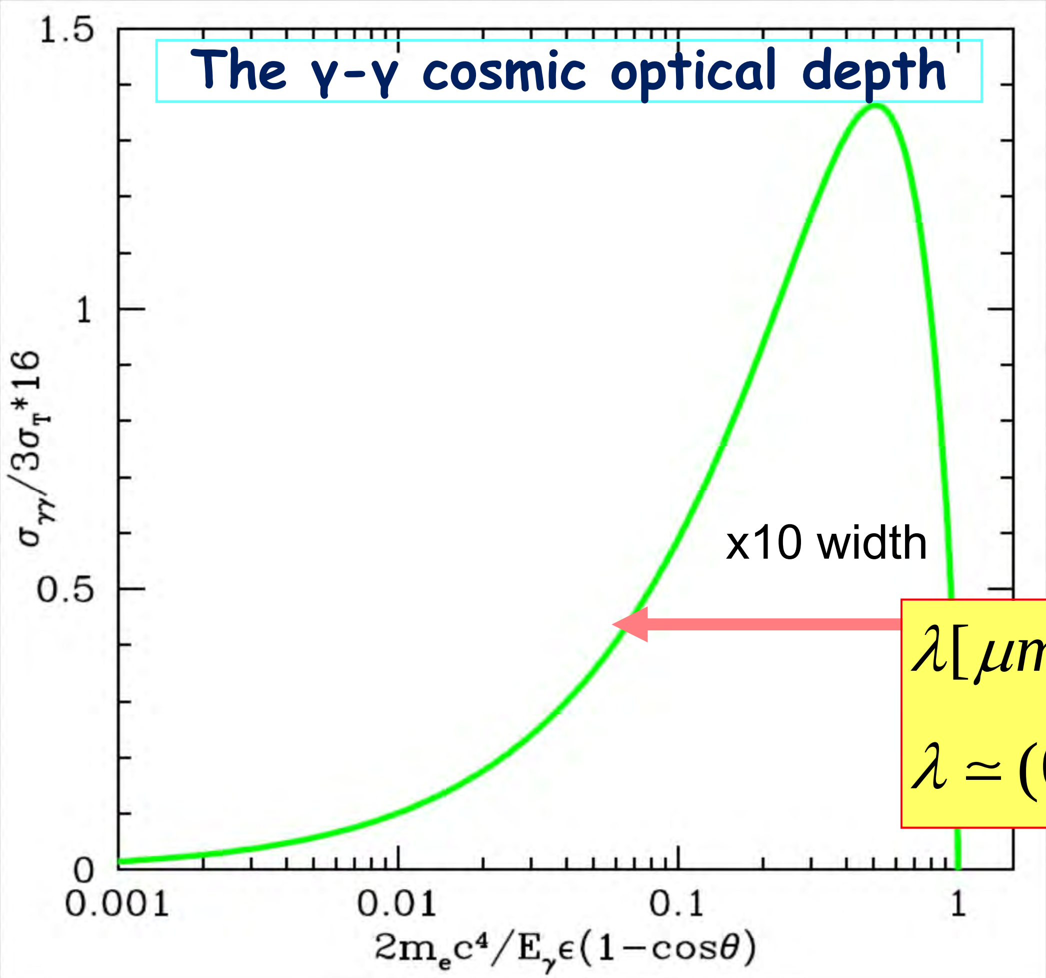
$$dt/dz = \frac{1}{H_0(1+z)}\left[(1+z)^2(1+\Omega_m z) - z(z+2)\Omega_\Lambda\right]^{-1/2}.$$

ϵ: energy of the background photon,

E_γ that of the high-energy colliding one,

θ being the angle between the colliding photons.

However, not a full mapping of EBL and γ-γ absorption...

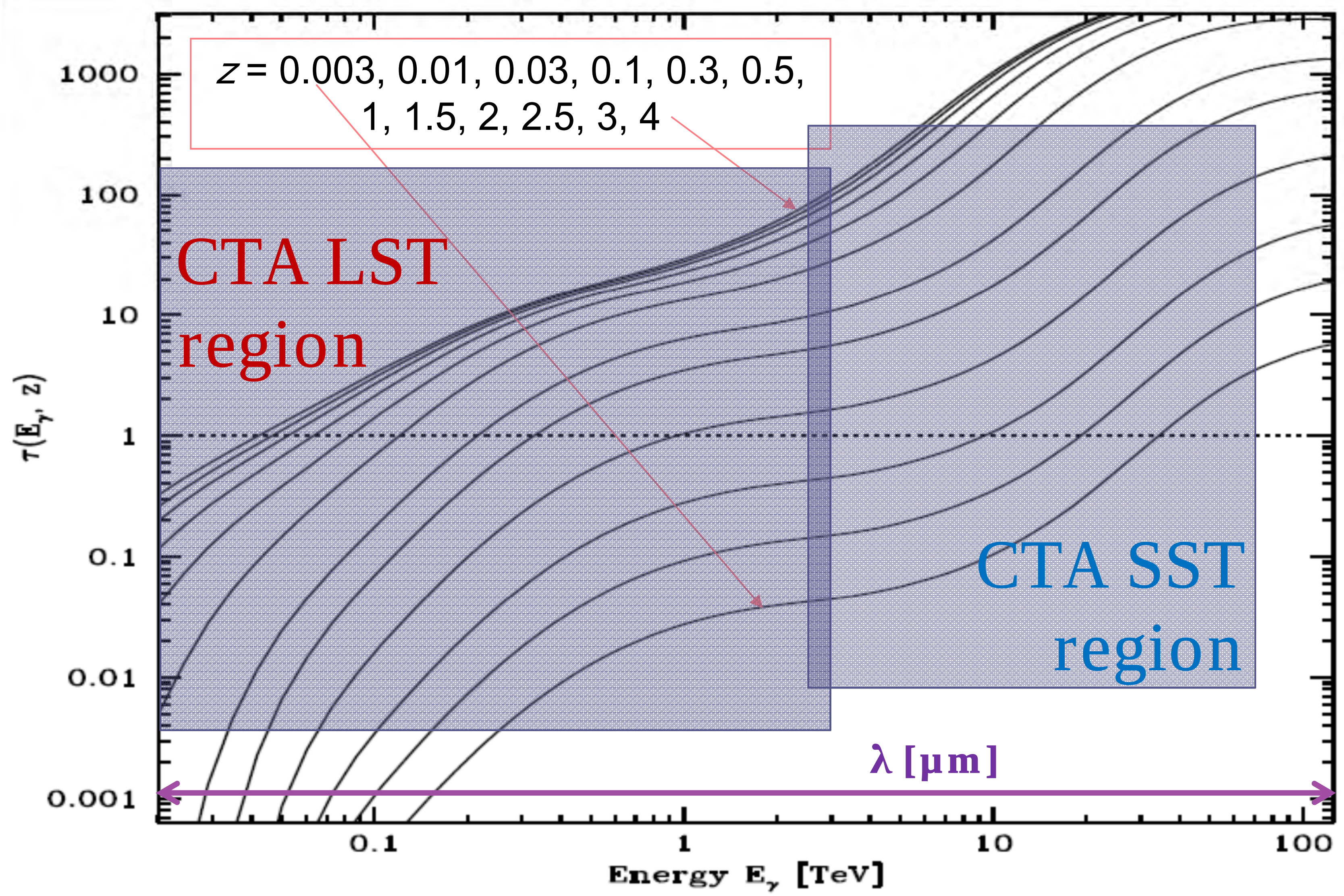


The γ-γ cross-section is quite broad...

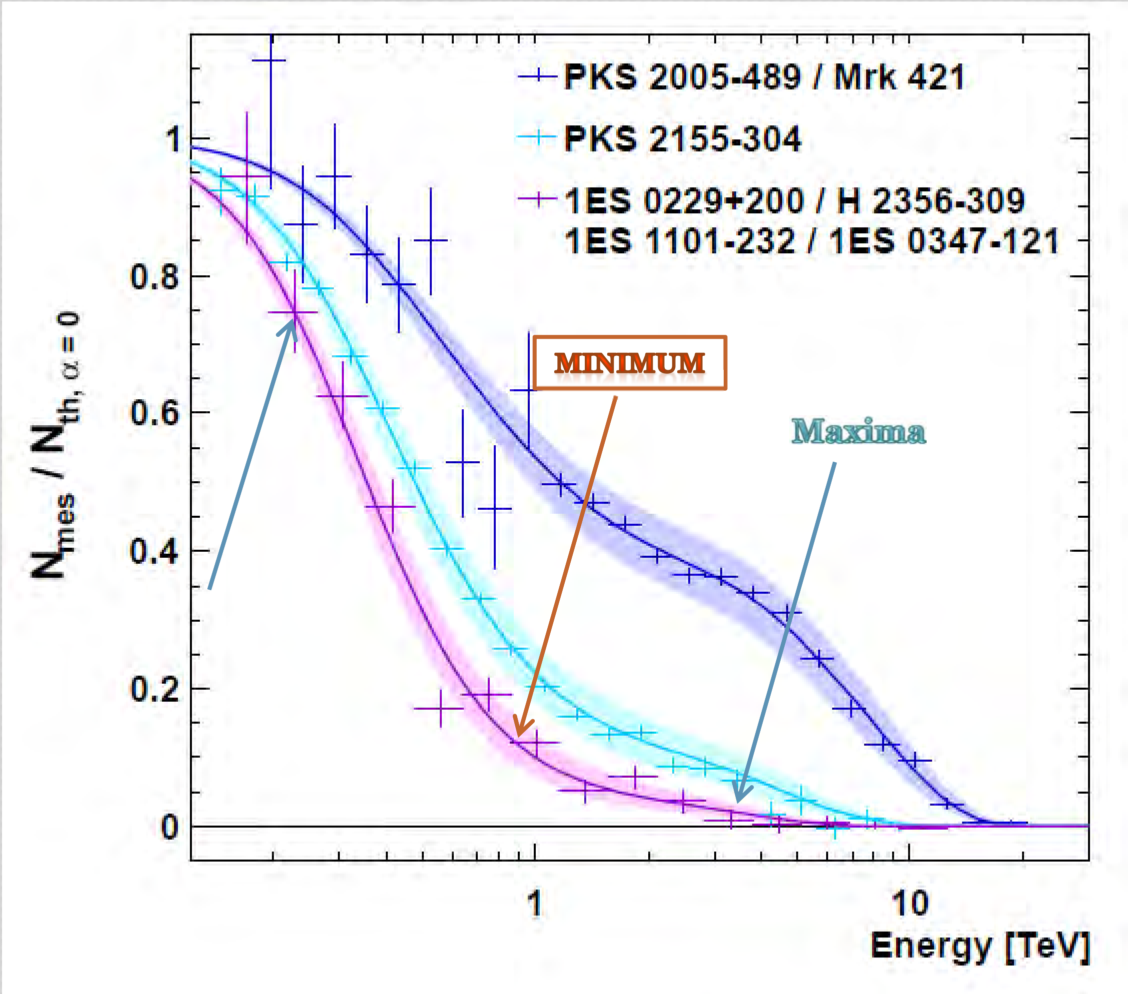
$$\lambda[\mu m] \simeq 1.2 E_\gamma [TeV] \times (1+z')^2$$

$$\lambda \simeq (0.1-2.4)\mu m\, E_\gamma [TeV] \times (1+z')^2$$

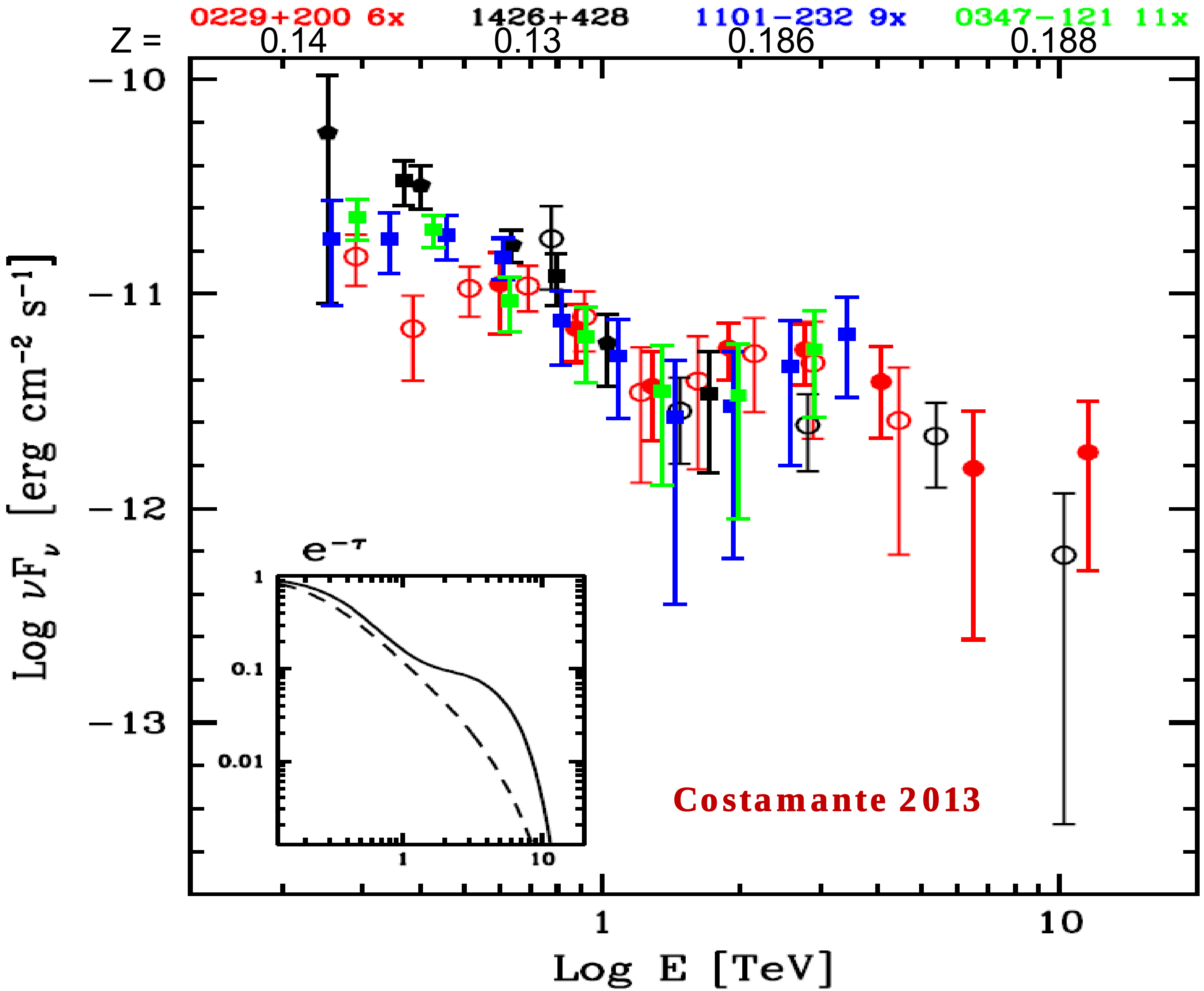
z' is where the γ-γ interaction happens



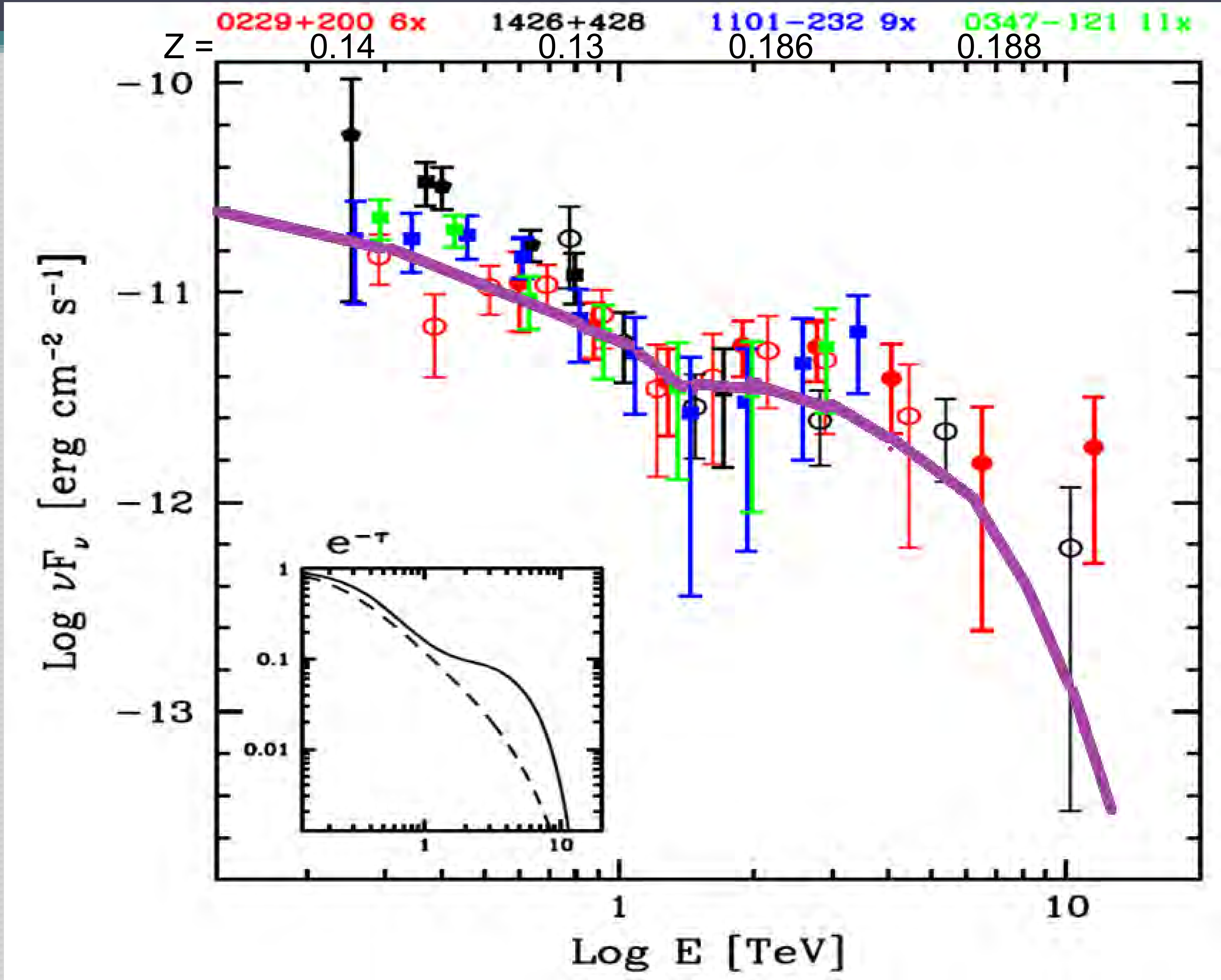
Relationship of γ-γ optical depth, energy & source redshift



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



0229+200 6x
1426+428
1101-232 9x
0347-121 11x
Z =
0.14
0.13
0.186
0.188
Log νF_ν [erg cm^-2 s^-1]
-10
-11
-12
-13
e^-τ
1
0.1
0.01
1
10
Costamante 2013
1
10
Log E [TeV]



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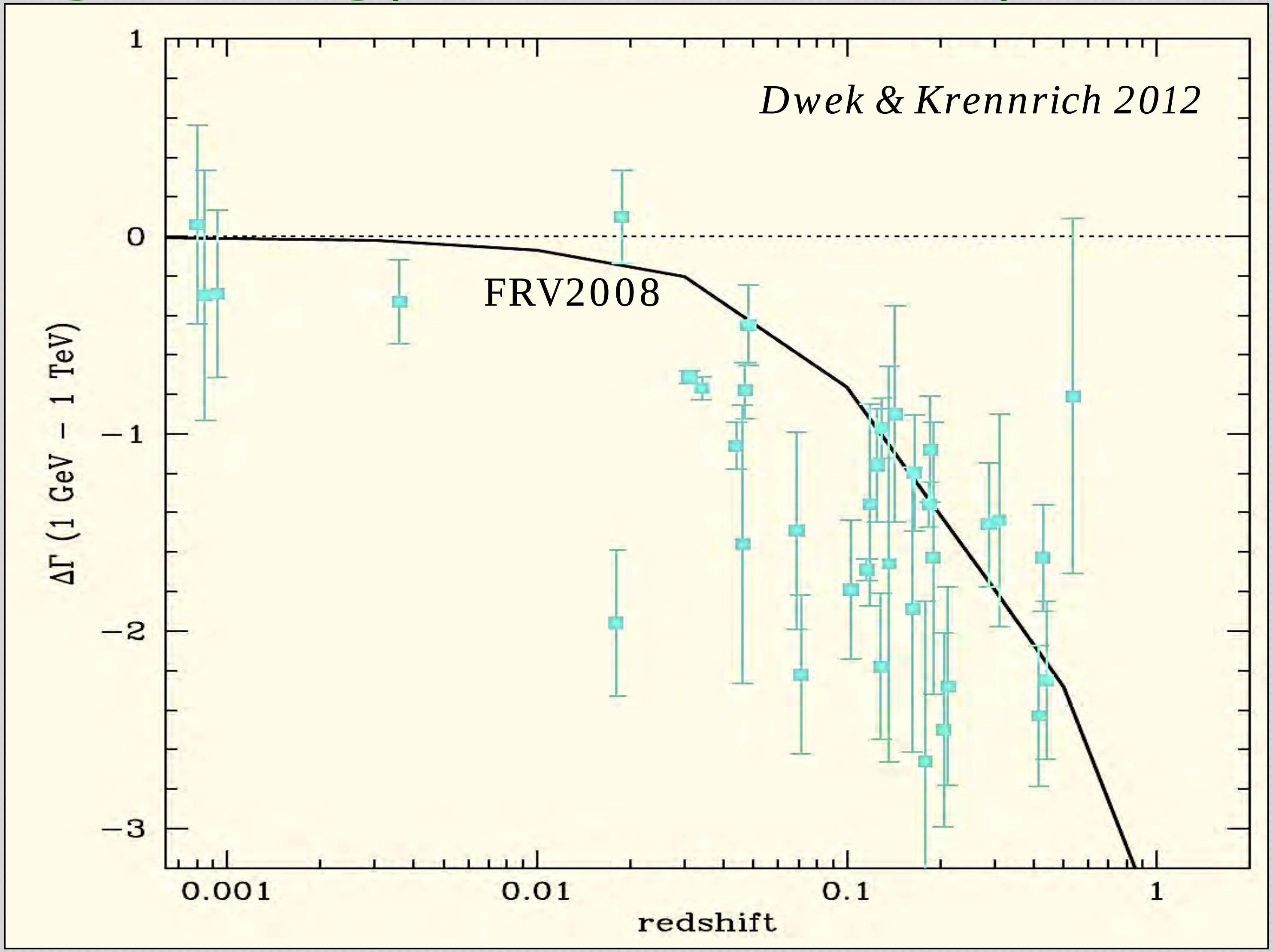
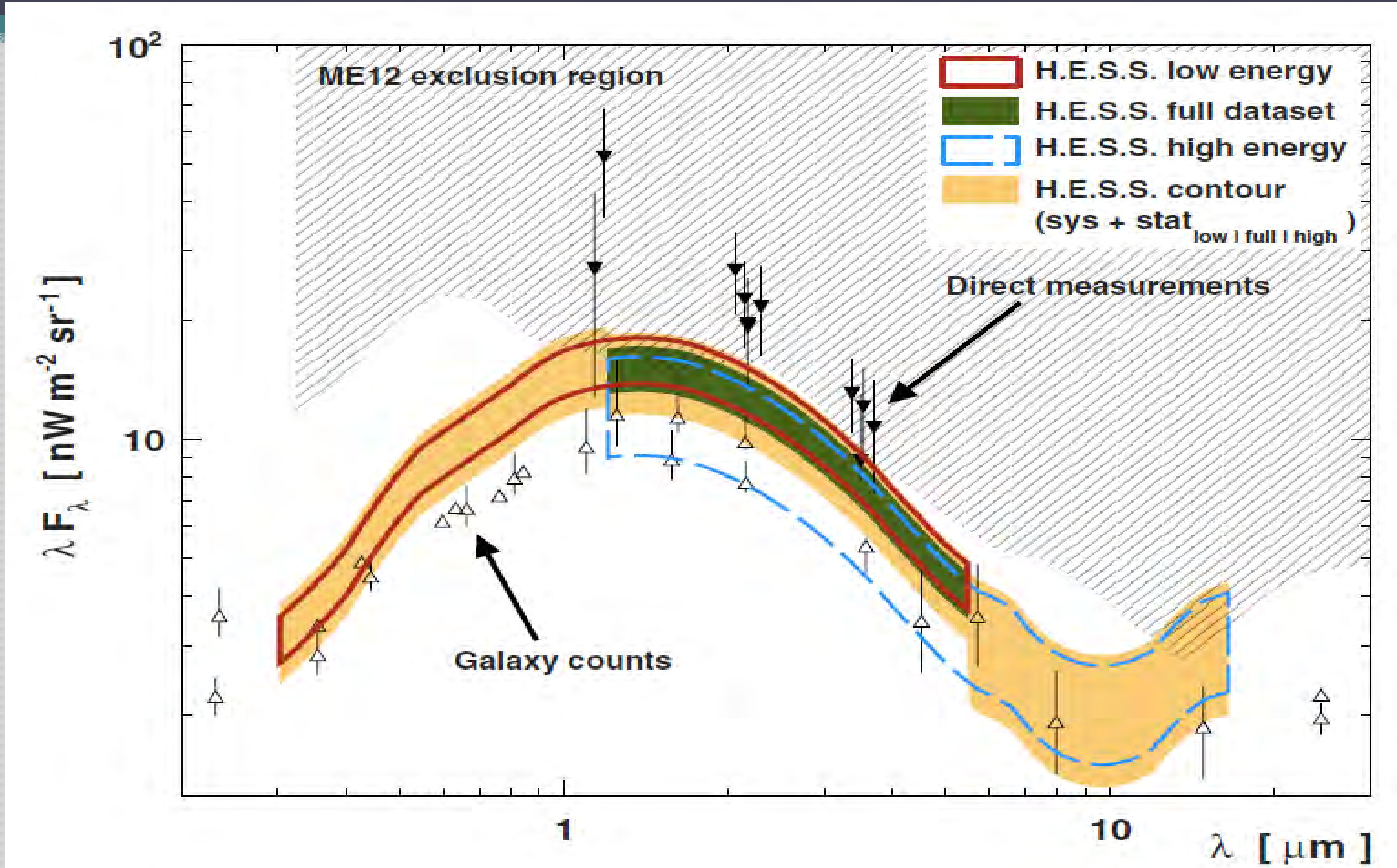
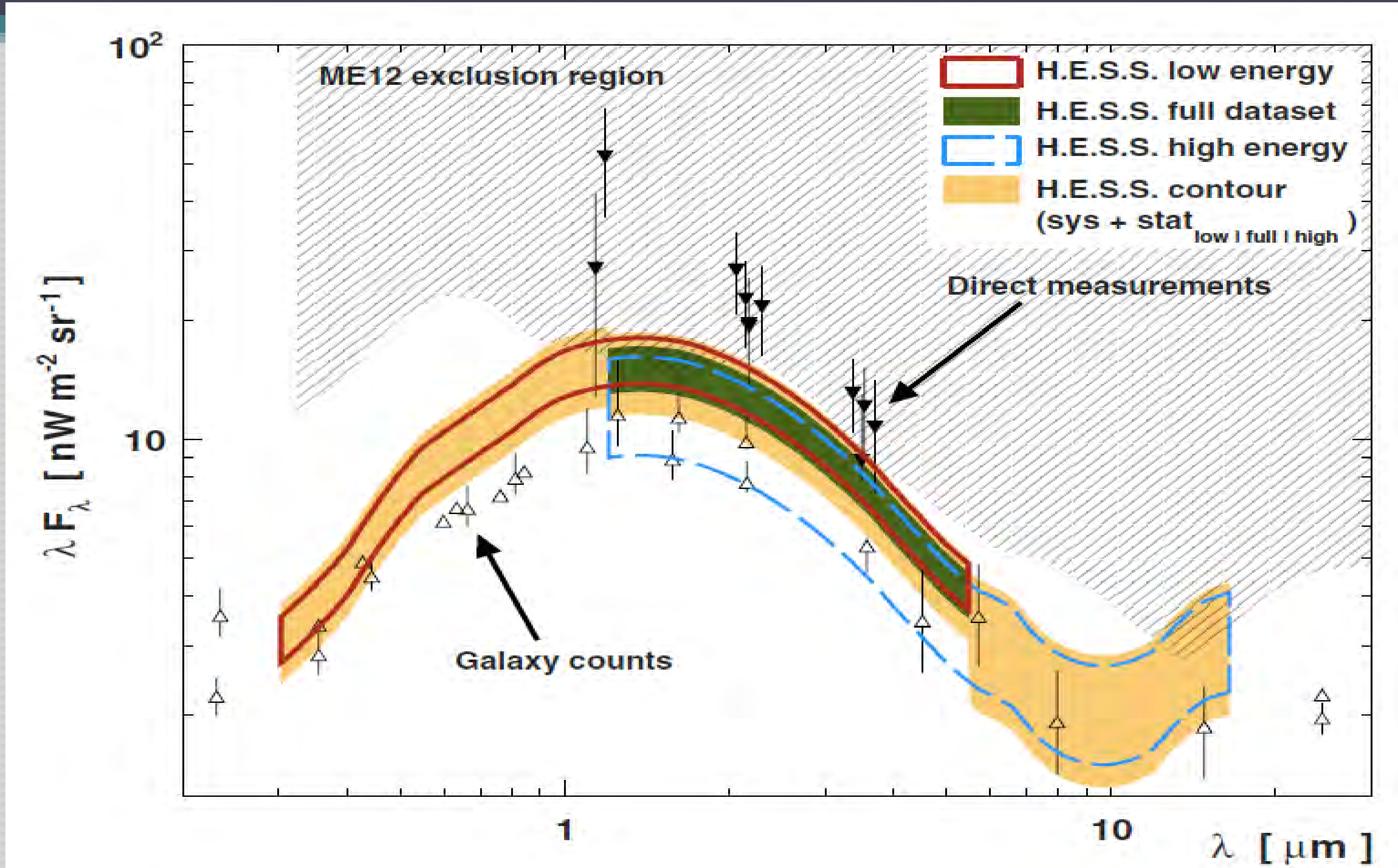
Z =
0.14
0.13
0.186
0.188
Log νF_ν [erg cm^-2 s^-1]
Log E [TeV]
e^-τ

Scaling with redshift of the BLAZAR high-energy (GeV to TeV) spectra





Constraints on EBL intensity. (Abramowski et al. 2013)
Based on the analysis of the TeV spectra from HESS of several BLAZARs.
The systematic uncertainty is added quadratically to the statistical one to derive the H.E.S.S. contour.
Lower limits based on galaxy counts and direct measurements are respectively shown with empty upward and filled downward pointing triangles . The region excluded by Meyer et al. (2012) with VHE spectra is represented by the dashed area.



$$\lambda I_\lambda = 15 \pm 2_{stat} \pm 3_{sys}\ [nW/m^2/sr]$$

i.e. 30% higher than FRV2008 @ 1.4 µm

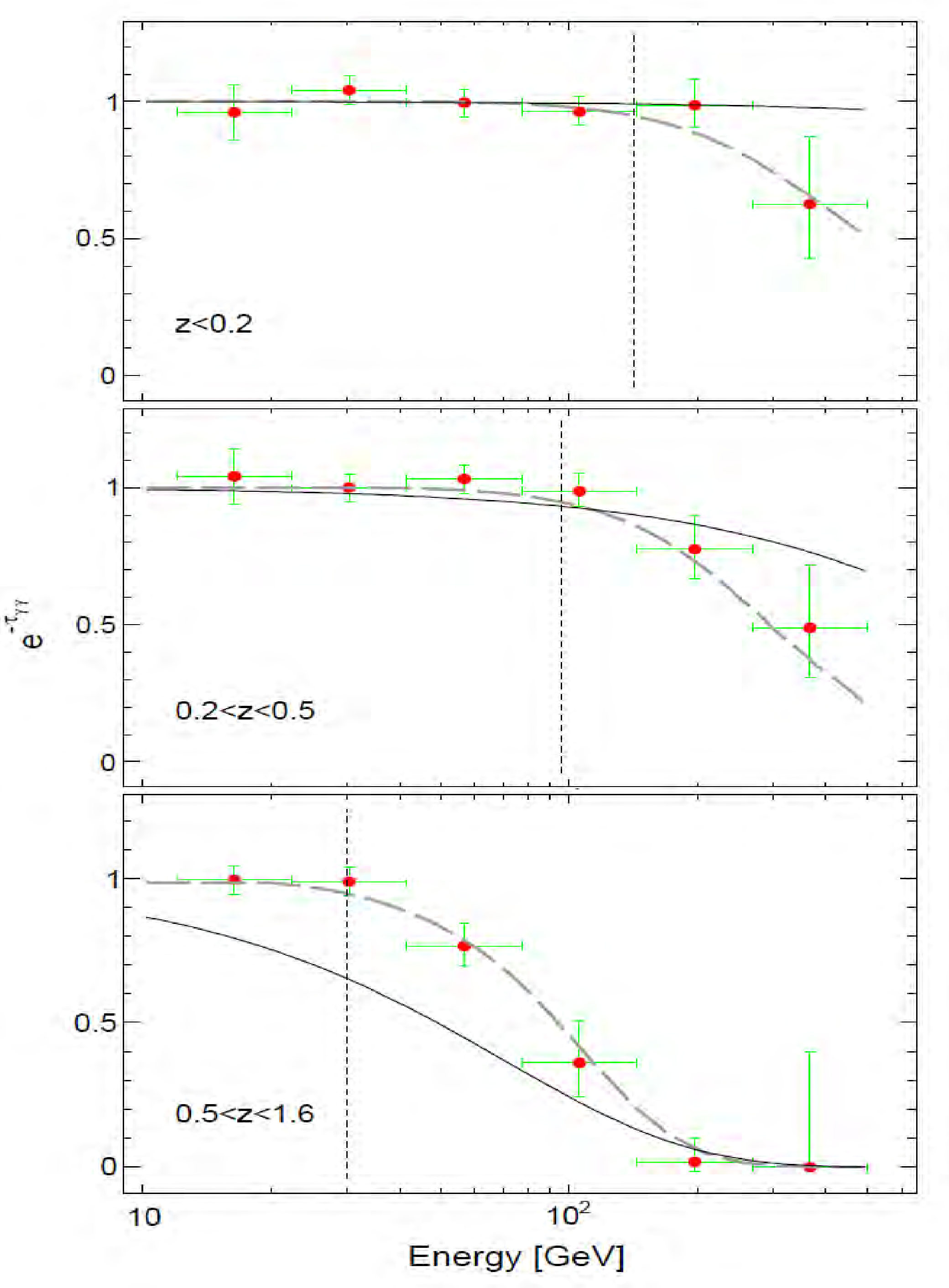
he

wi

This also consistent with Orr, Krennrich & Dwek 2012

Meyer et al. (2012) with VHE spectra is represented by the dashed area.

Ackermann et al. 2012

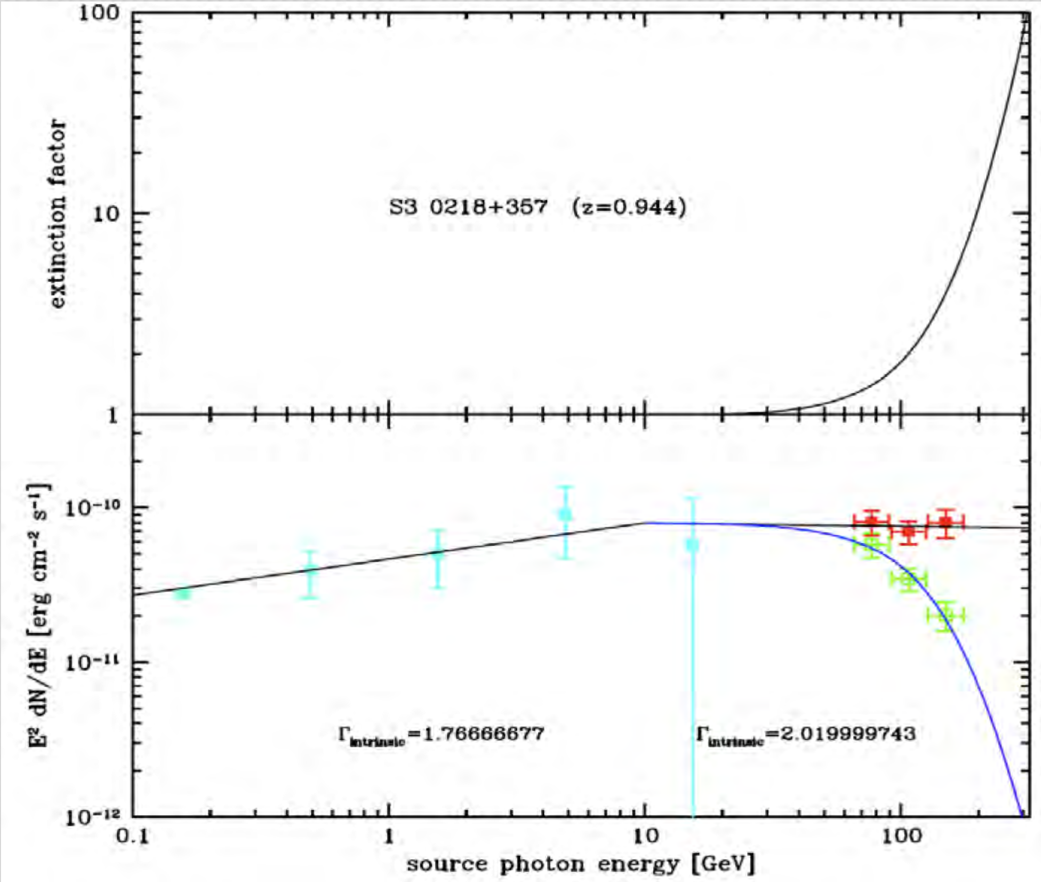


Ratio of the average extrapolated vs observed Fermi LAT spectra of BLAZARs in different redshift bins, showing a cut-off feature increasing with redshift. Vertical lines: energy below which <5% of the source photons are absorbed by EBL, and where the source intrinsic spectra are estimated.

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.

Recent discovery of TeV photons from z~1 sources

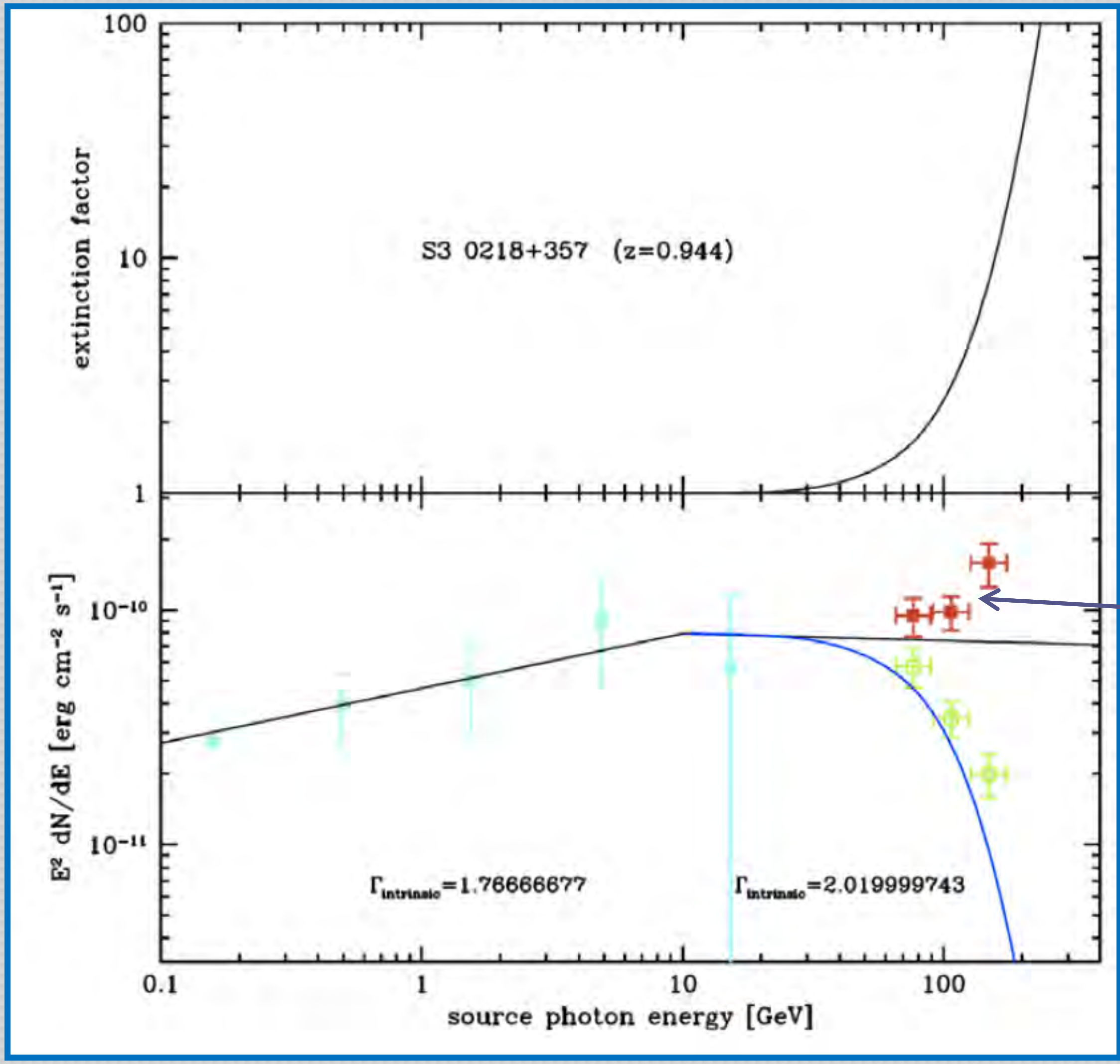


Detection of a Hard Spectrum Flare from the Gravitationally Lens Blazar B0218+357

Mirzoyan et al. 2014
Buson & Cheung 2014

MAGIC observed spectrum (green datapoints) corrected (red datapoints) for photon-photon absorption assuming EBL as in FRV2008. Top: the γ-γ extinction. Bottom panel: Fermi and MAGIC data (black lines are the model spectrum, the blue line is corrected by absorption).

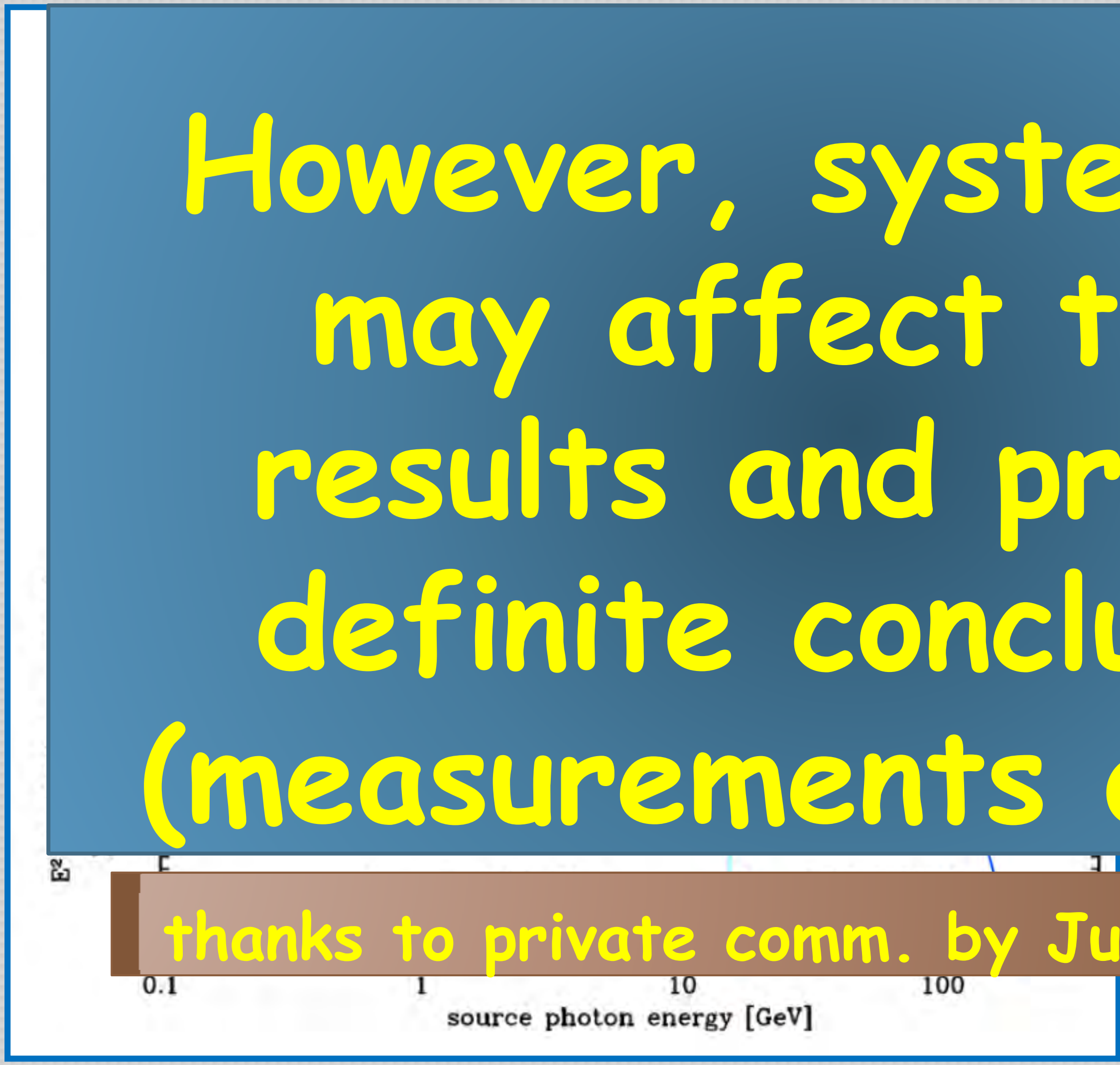
The enormous space-time path to the source allows us a significant test of EBL intensity in the optical



The MAGIC observed spectrum of S0218 (green data-points) corrected for γ-γ absorption assuming EBL intensity in the optical a factor 1.5 larger at all redshifts than estimated by FRV2008, as suggested by HESS observations by Abramowski, A. et al. 2013

The enormous space-time path to the source allows us a significant test of EBL intensity in the optical

However, systematics may affect these results and prevent definite conclusions (measurements of EBL)



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observations by
A. et al.
2013

thanks to private comm. by Julian Sitarek

The enormous space-time path to the source allows us a significant test of EBL intensity in the optical

Systematics about:

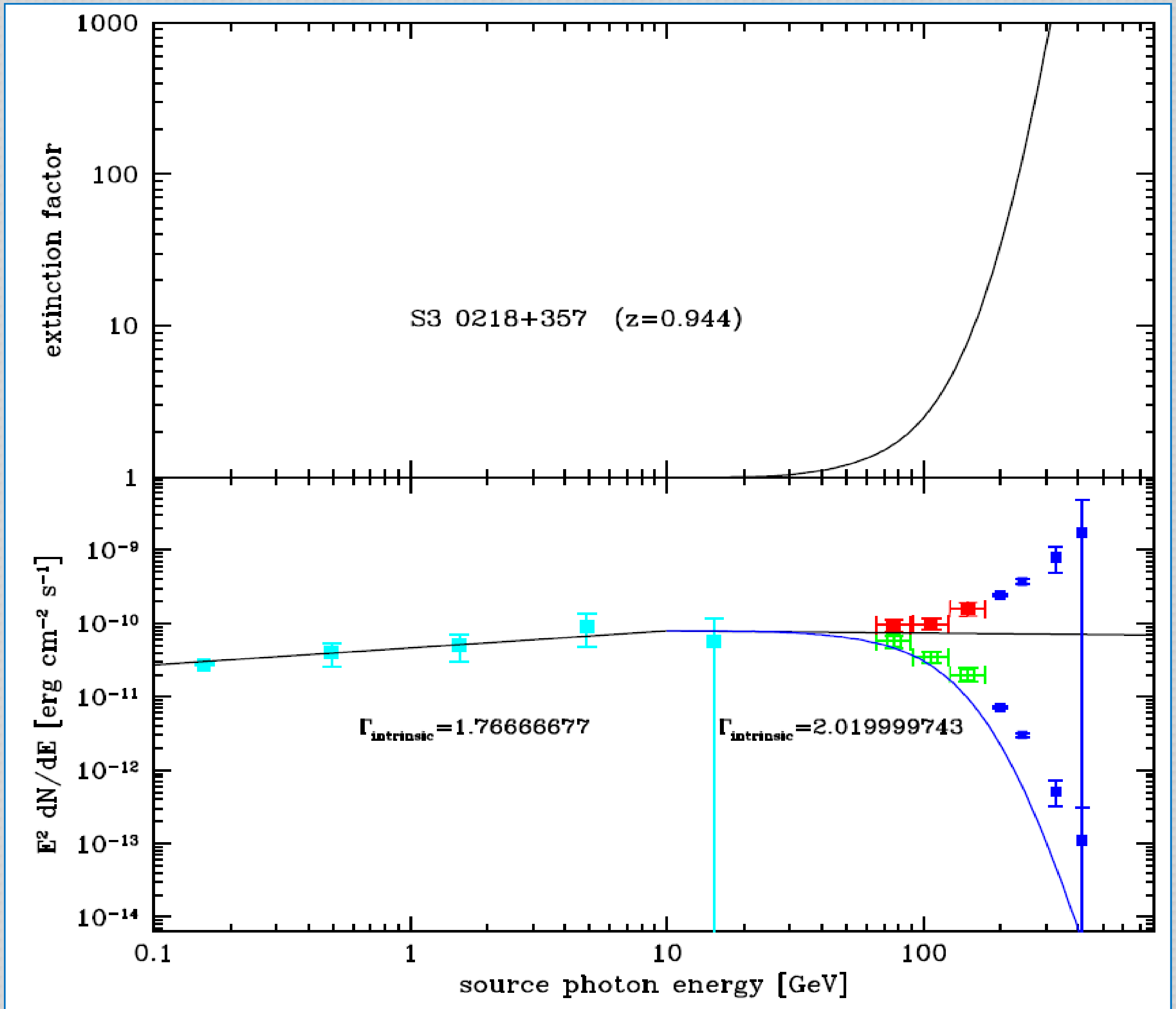
- absolute energy calibration of photons
- Statistical independence of databins
- Uncertainties in the intrinsic source spectral shapes

In conclusion, while observations are excellent, even providing unexpected and amazing results (e.g. TeV detections of z=1 BLAZARs), use of these data for EBL determinations should be done carefully.

So far, perhaps mostly confirmations of best guessed EBL spectral intensity and time-evolution models...

→ **New facilities needed**

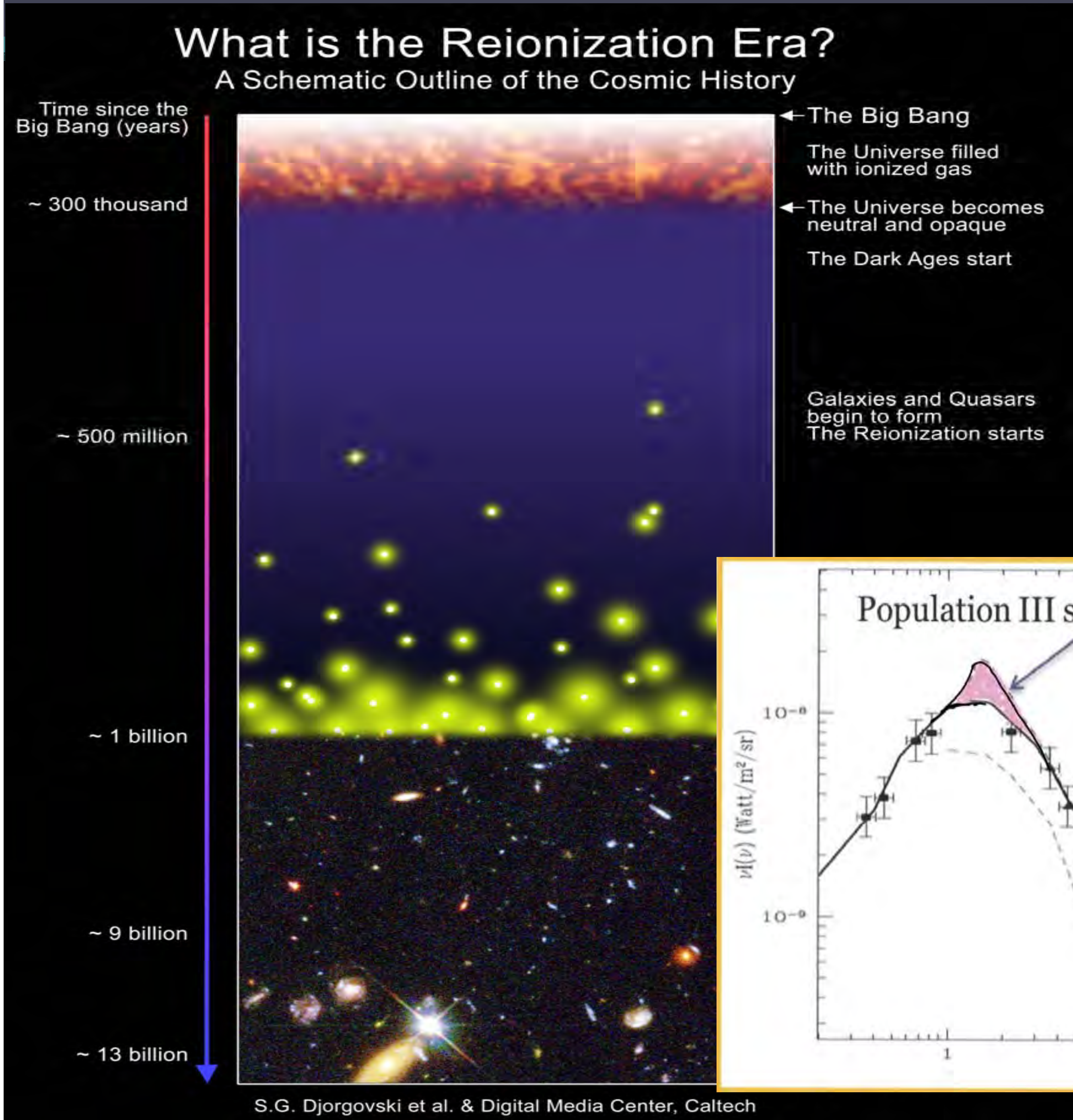
Simulated observation with CTA



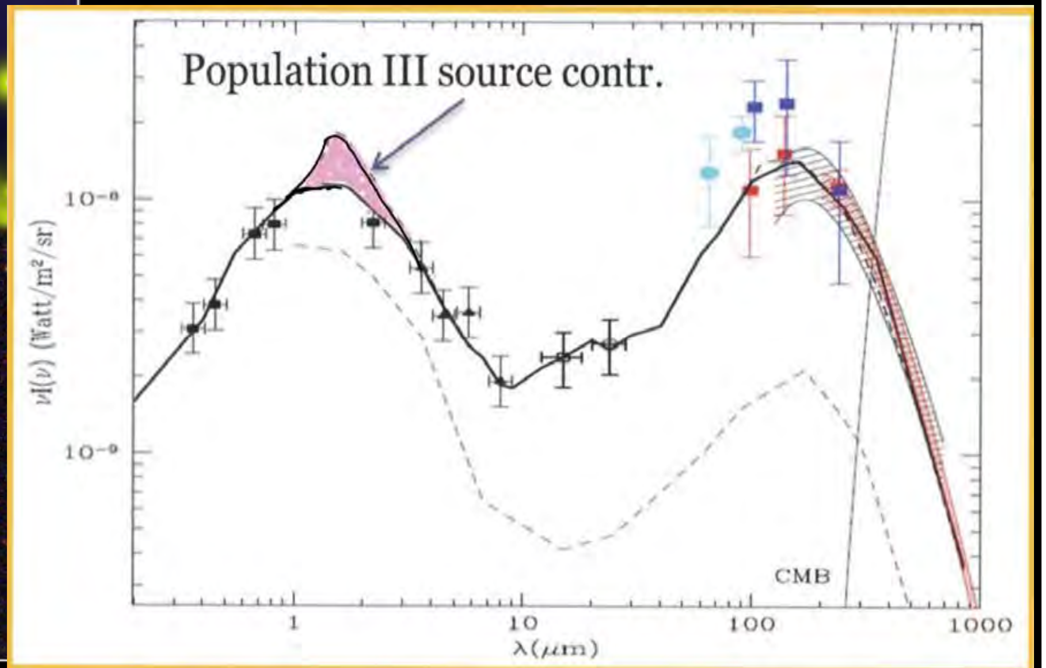
Simulation of the outcome of CTA observations of S0218 based on the "wrong" assumption of an EBL that is locally 15 nW/m^2/sr at the near-IR peak (a factor 1.5 the level of FRV2008)

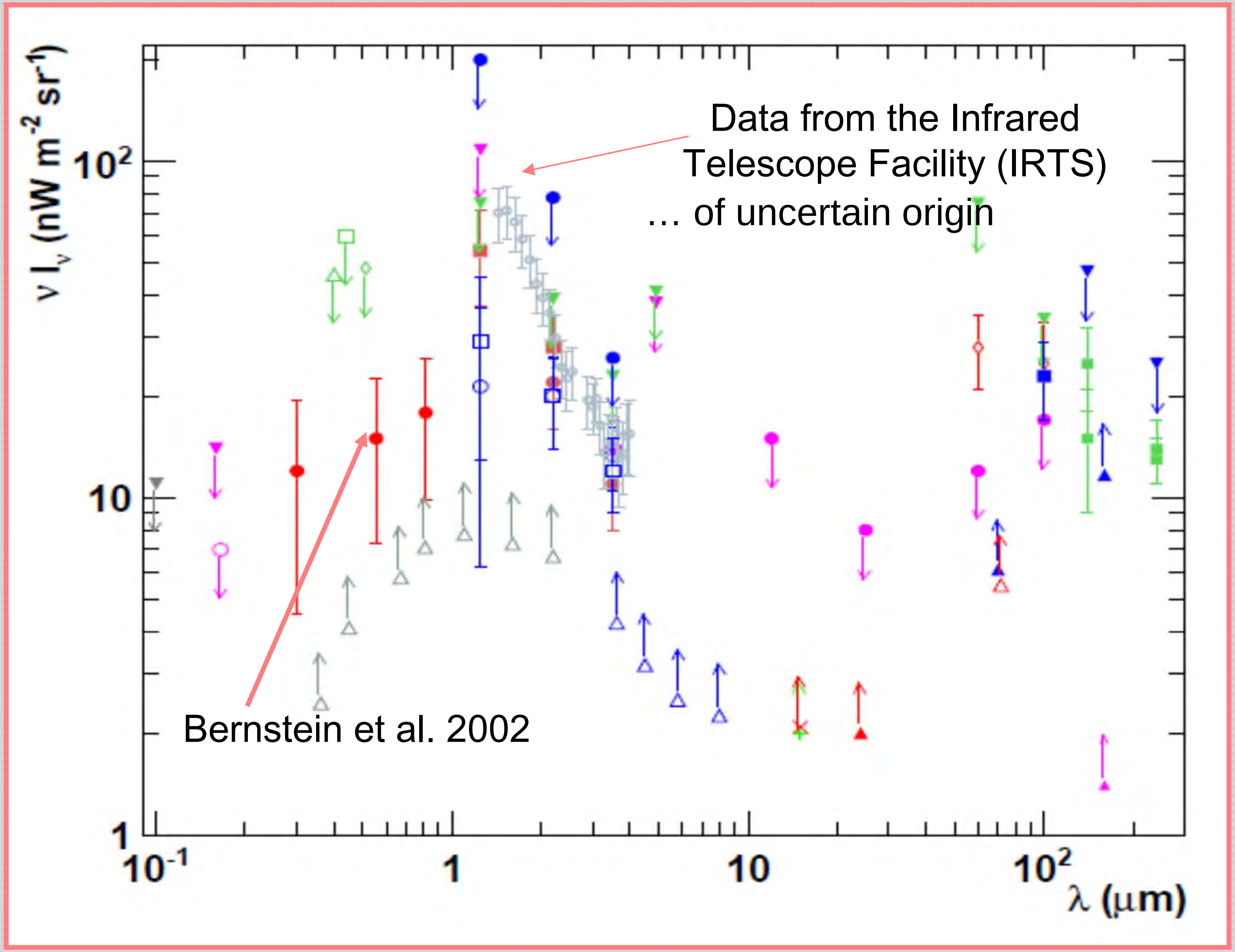
CTA will have:

- Much better sensitivity (> x10)
- Better spectral resolution
- Lower, and better controlled, systematics

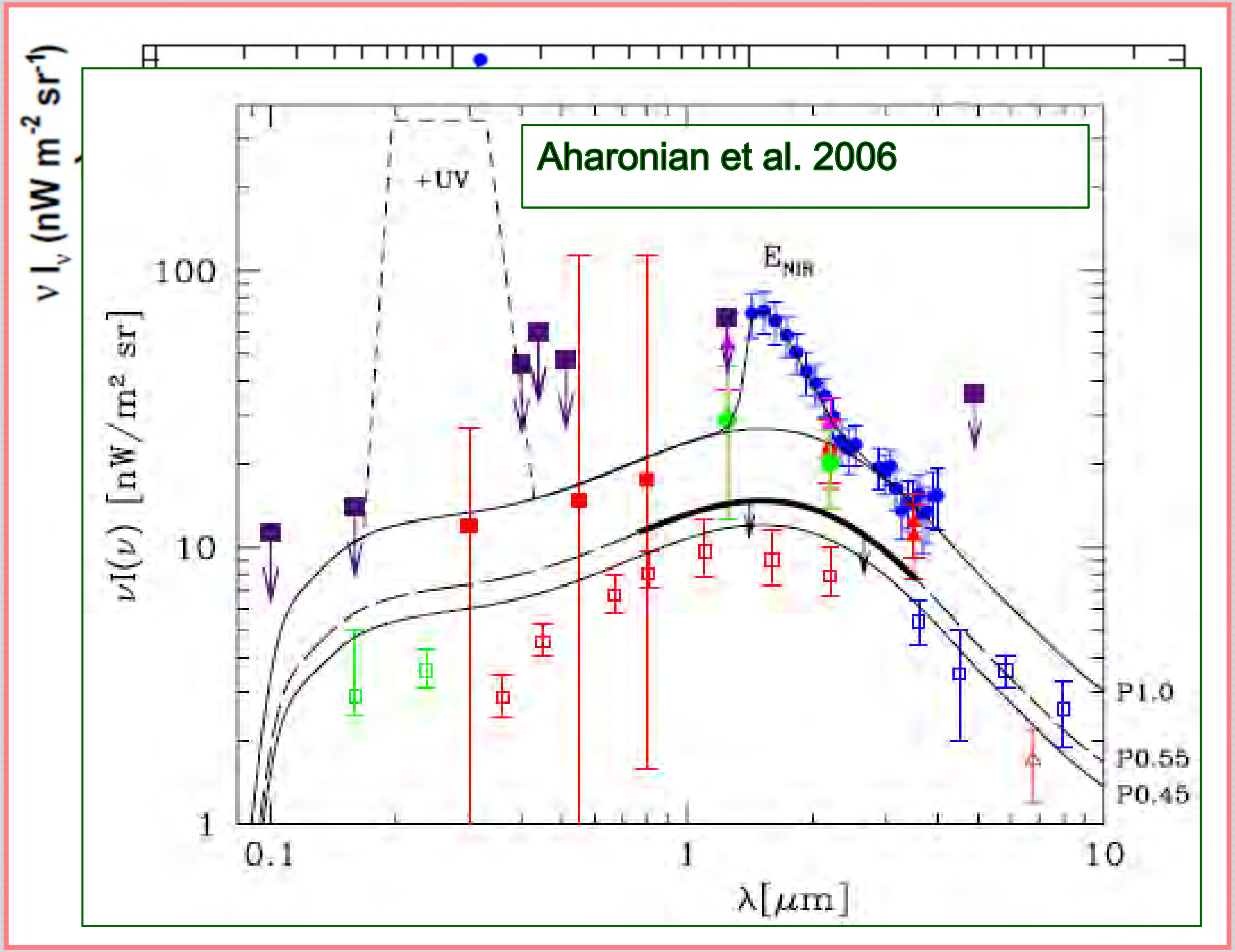


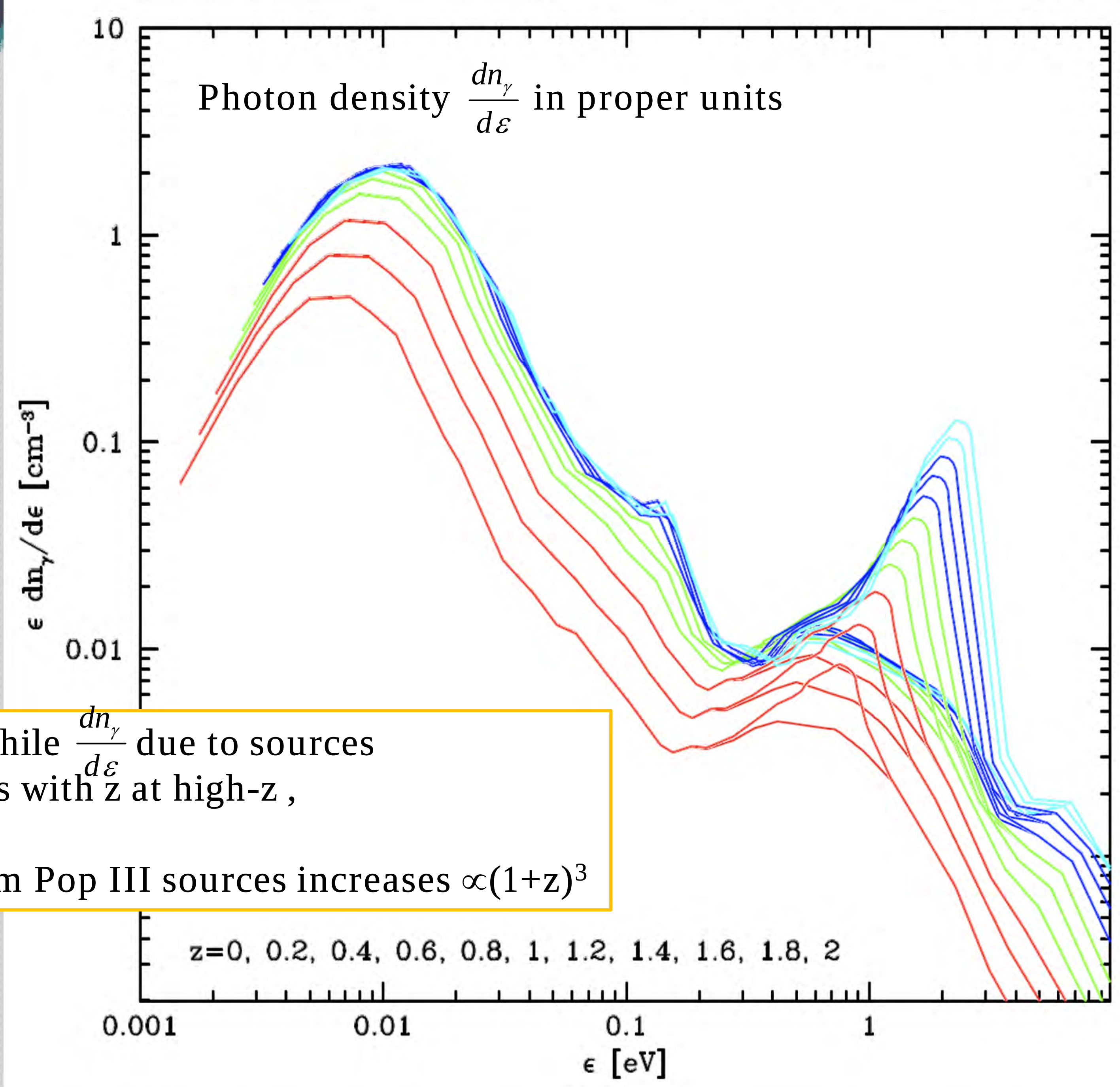
The current cosmological conundrum





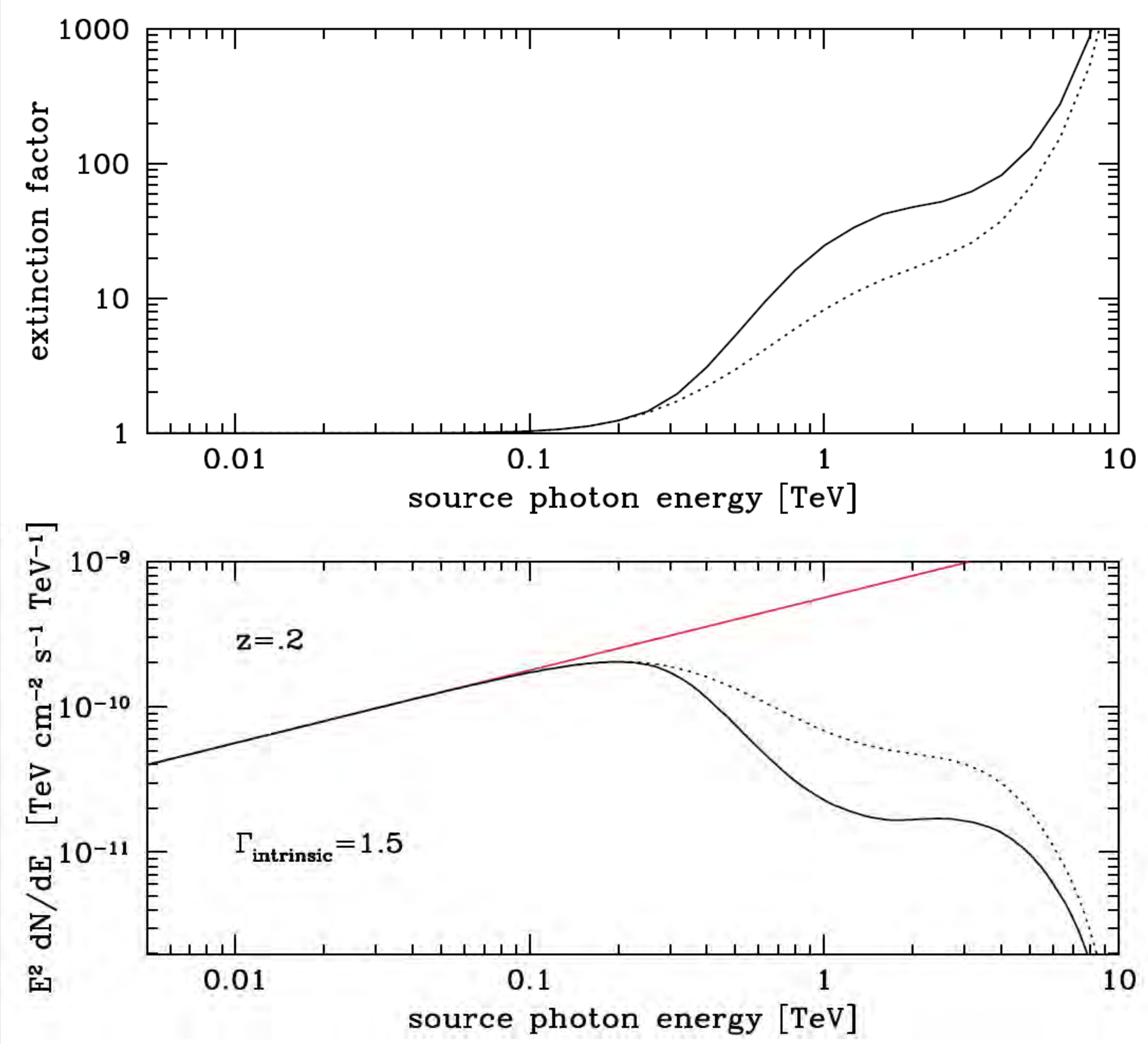
Mazin & Raue (2007)

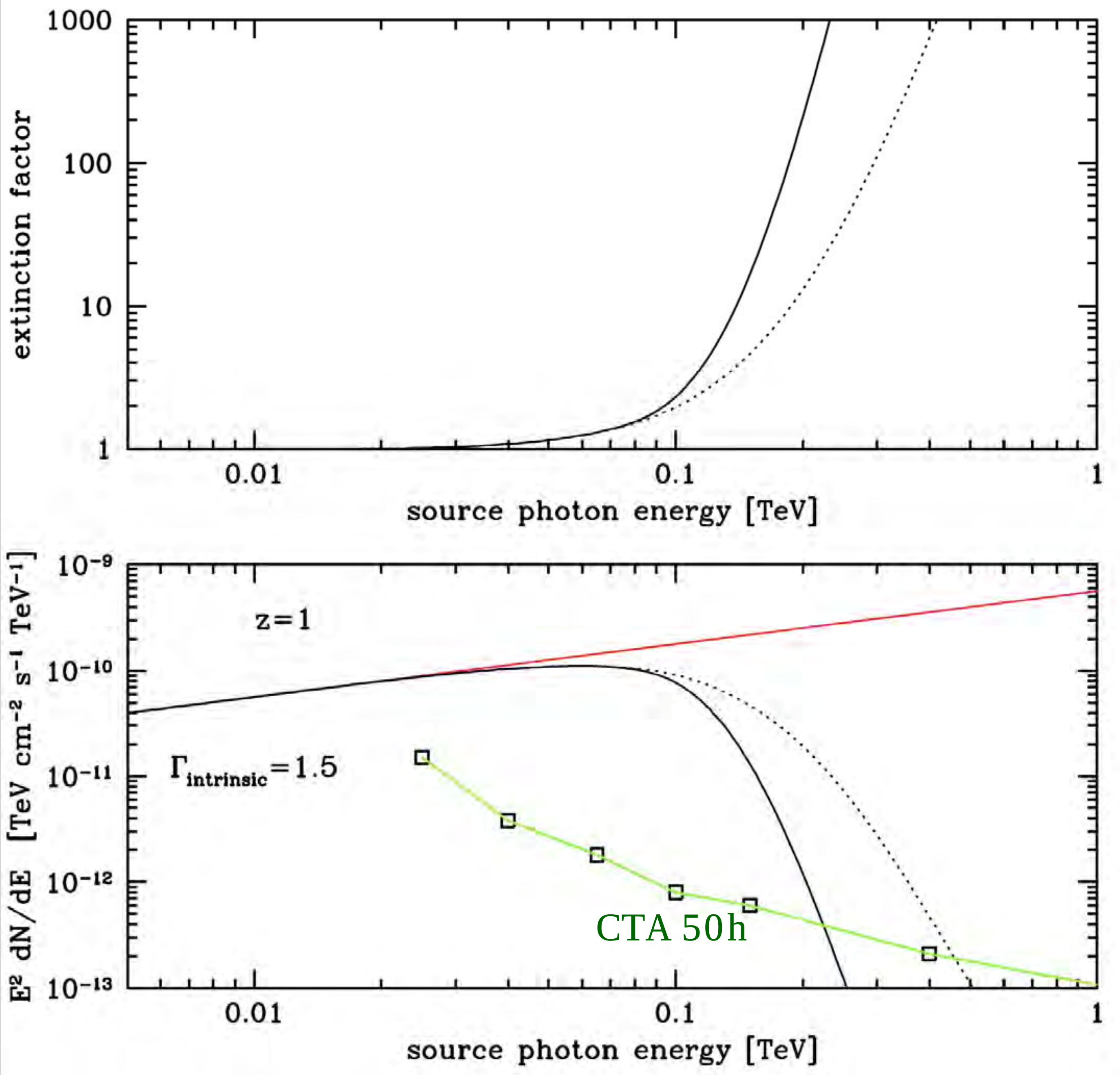

Aharonian et al. 2006
ν I_ν (nW m^-2 sr^-1)
νI(ν) [nW/m² sr]
+UV
E_NIR
100
10
1
0.1
1
10
λ[μm]
P1.0
P0.55
P0.45



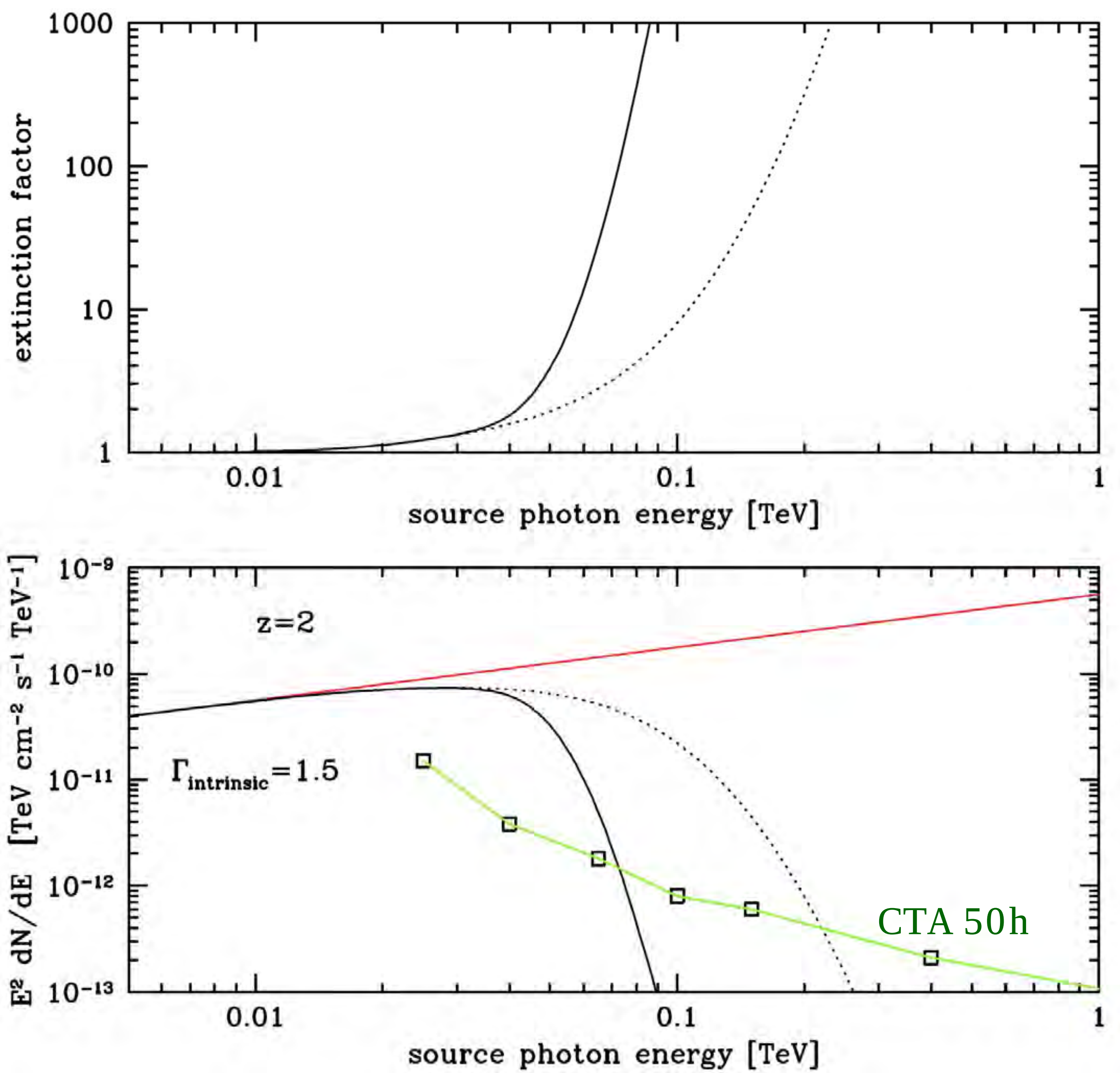
Note: while $\frac{dn_\gamma}{d\varepsilon}$ due to sources decreases with z at high-z ,

$\frac{dn_\gamma}{d\varepsilon}$ from Pop III sources increases $\propto (1+z)^3$


1000
100
10
1
extinction factor
0.01
0.1
1
10
source photon energy [TeV]
10^{-9}
10^{-10}
10^{-11}
E^2 dN/dE [TeV cm^{-2} s^{-1} TeV^{-1}]
z=.2
$\Gamma_{intrinsic}$=1.5
0.01
0.1
1
10
source photon energy [TeV]



extinction factor
1000
100
10
1
0.01
0.1
1
source photon energy [TeV]
E² dN/dE [TeV cm⁻² s⁻¹ TeV⁻¹]
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
z=1
Γintrinsic=1.5
CTA 50h
0.01
0.1
1
source photon energy [TeV]


1000
100
10
1
extinction factor
0.01
0.1
1
source photon energy [TeV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
E^2 dN/dE [TeV cm^{-2} s^{-1} TeV^{-1}]
z=2
$\Gamma_{intrinsic}$=1.5
CTA 50h
0.01
0.1
1
source photon energy [TeV]

Summary

- Some constraints on EBL local flux and evolution already achieved, however limited by sensitivity and systematics.

- The analyses of the TeV spectra of well-known Blazars indicate ***consistency*** with present state-of-art models of the EBL based on known sources

- The general two-peak shape of EBL consistent with TeV observations and $\gamma\gamma$-opacity corrections. Interesting hints of consistency from high-z Fermi LAT BLAZARs.
No much evidence for *new physics…*

- The CTA Large Area Telescopes, and the other forthcoming facilities, will enormously expand the Γ-ray horizon. E.g. tests of integrated PopIII emission at z~9 (LST), and the IR EBL (SST).