Galactic Stellar Populations, the EBL, and the Cosmic Photon Opacity

Alberto Franceschini
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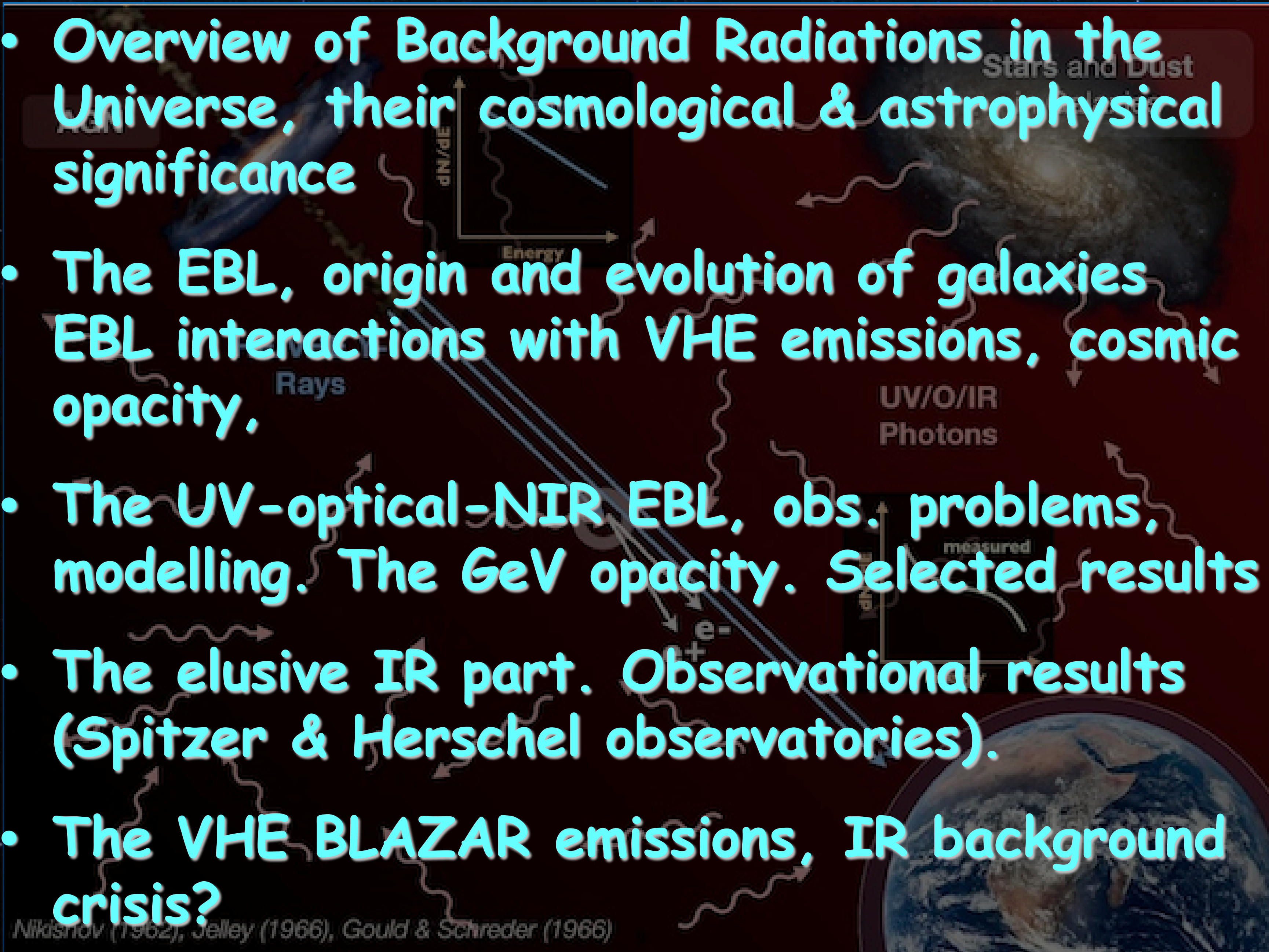
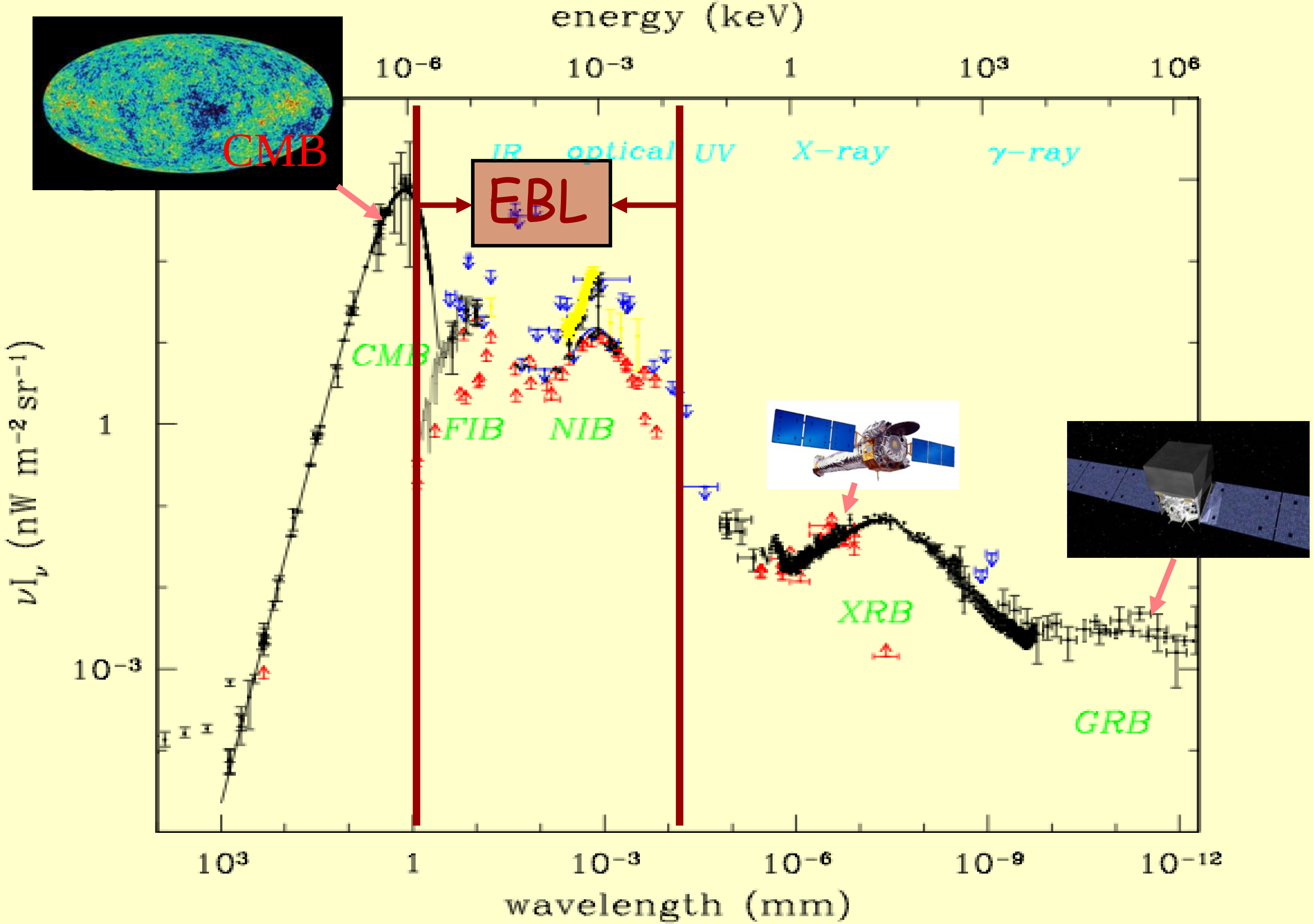
- Overview of Background Radiations in the Universe, their cosmological & astrophysical significance
- The EBL, origin and evolution of galaxies EBL interactions with VHE emissions, cosmic opacity,
- The UV-optical-NIR EBL, obs. problems, modelling. The GeV opacity. Selected results
- The elusive IR part. Observational results (Spitzer & Herschel observatories).
- The VHE BLAZAR emissions, IR background crisis?

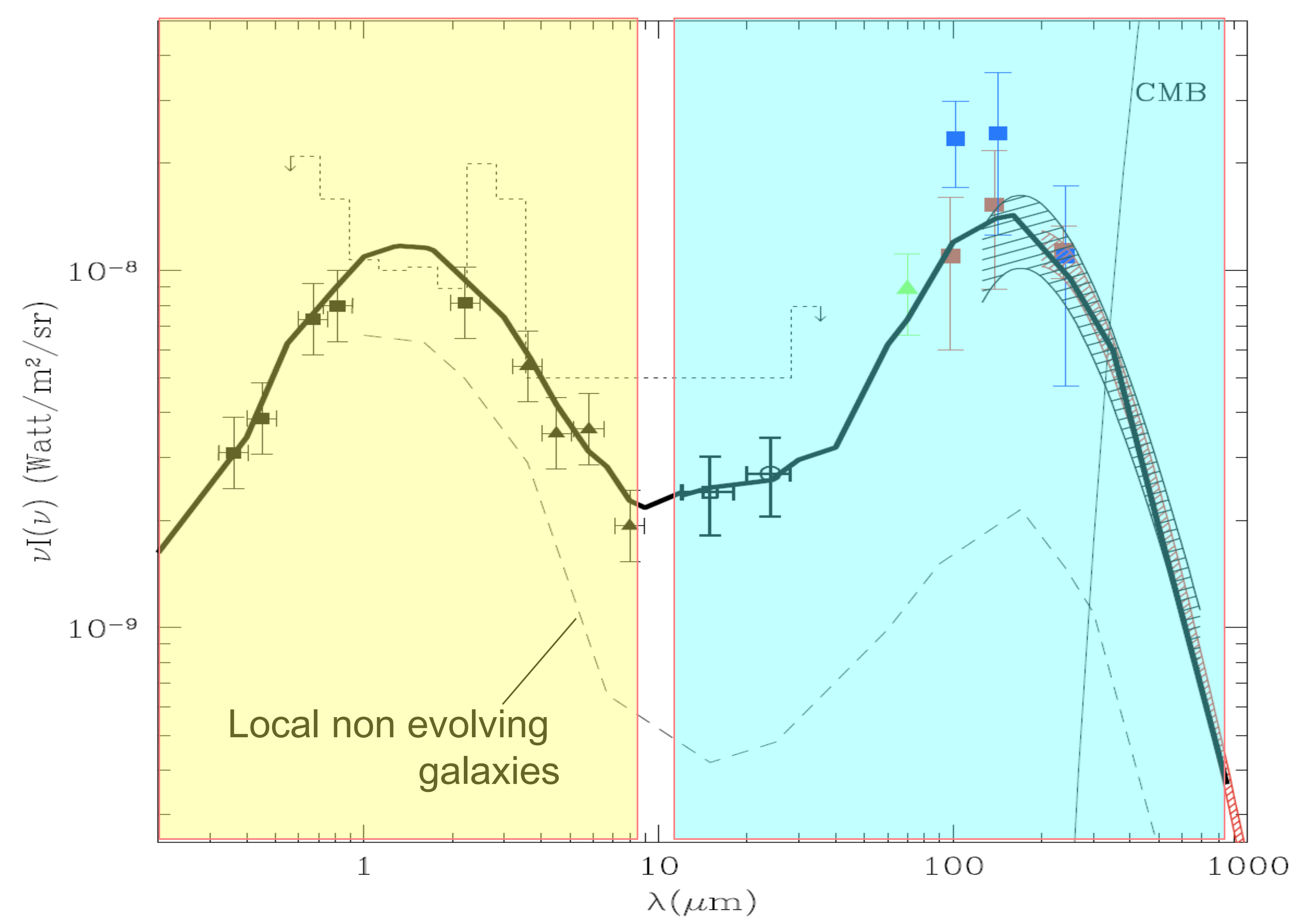




The Global Background Radiation & the EBL

The Extragalactic Background Light

- The repository of all radiant energy produced by cosmic sources and cosmic structures since the Big Bang
  - -- Point sources
  - -- Diffuse structures
- 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)



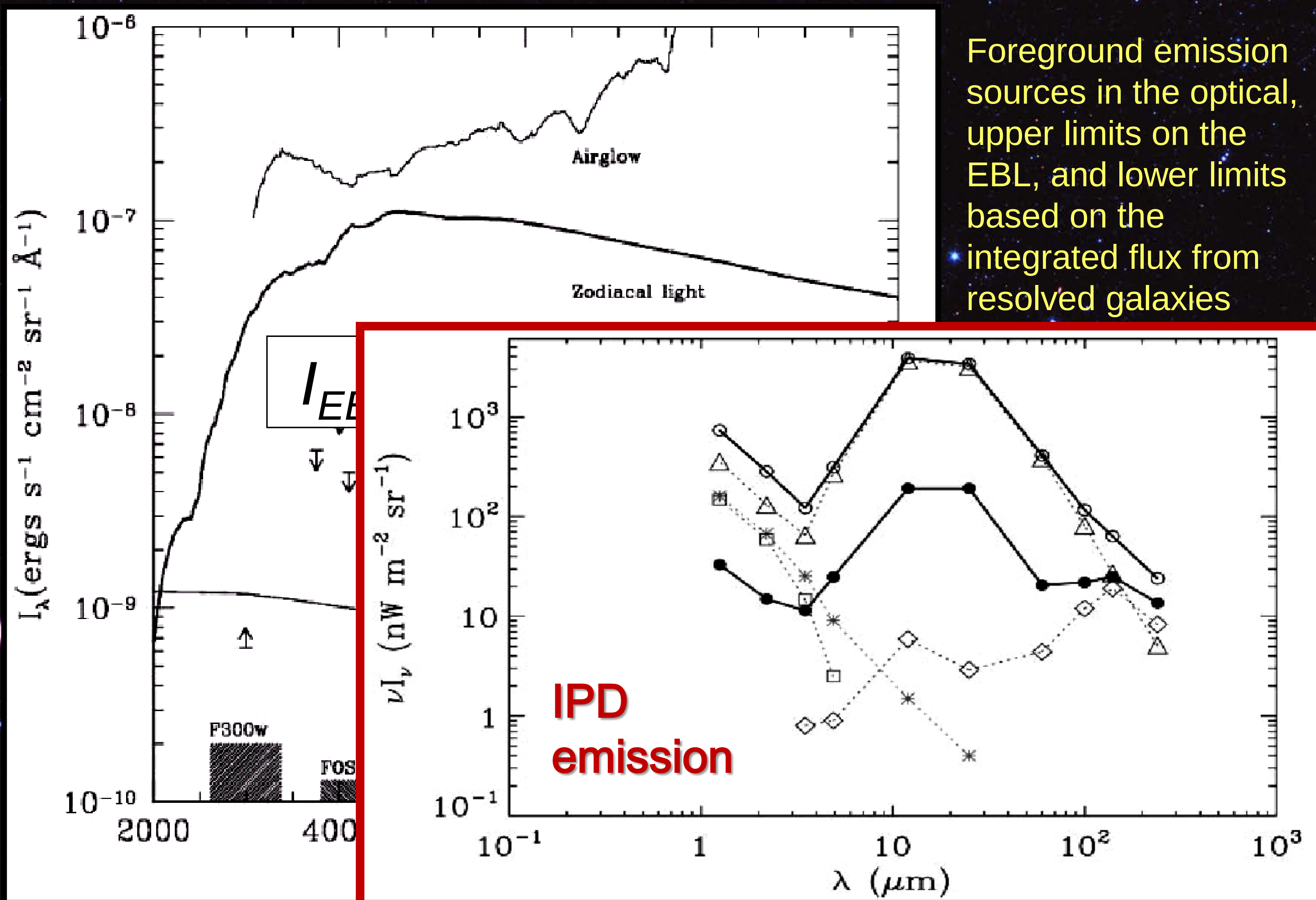
The Extragalactic Background Light (UV to mm)

A.F. et al. 2014

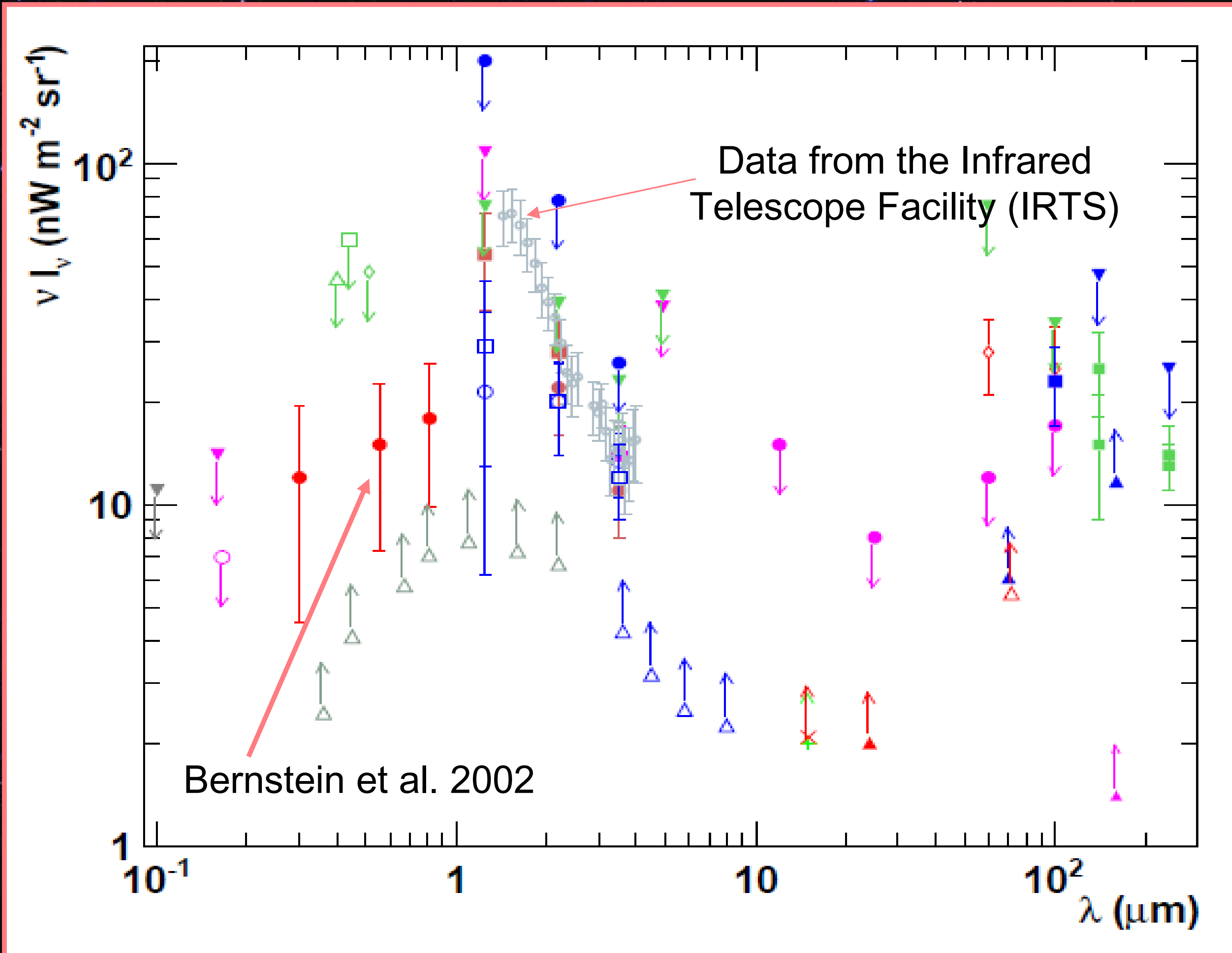
EBL measurements particularly difficult (essentiallyly impossible) where they would be most interesting!

(UV – optical – IR)

Can we directly measure the Extragalactic Background Light ?



Foreground emission sources in the optical, upper limits on the EBL, and lower limits based on the integrated flux from resolved galaxies

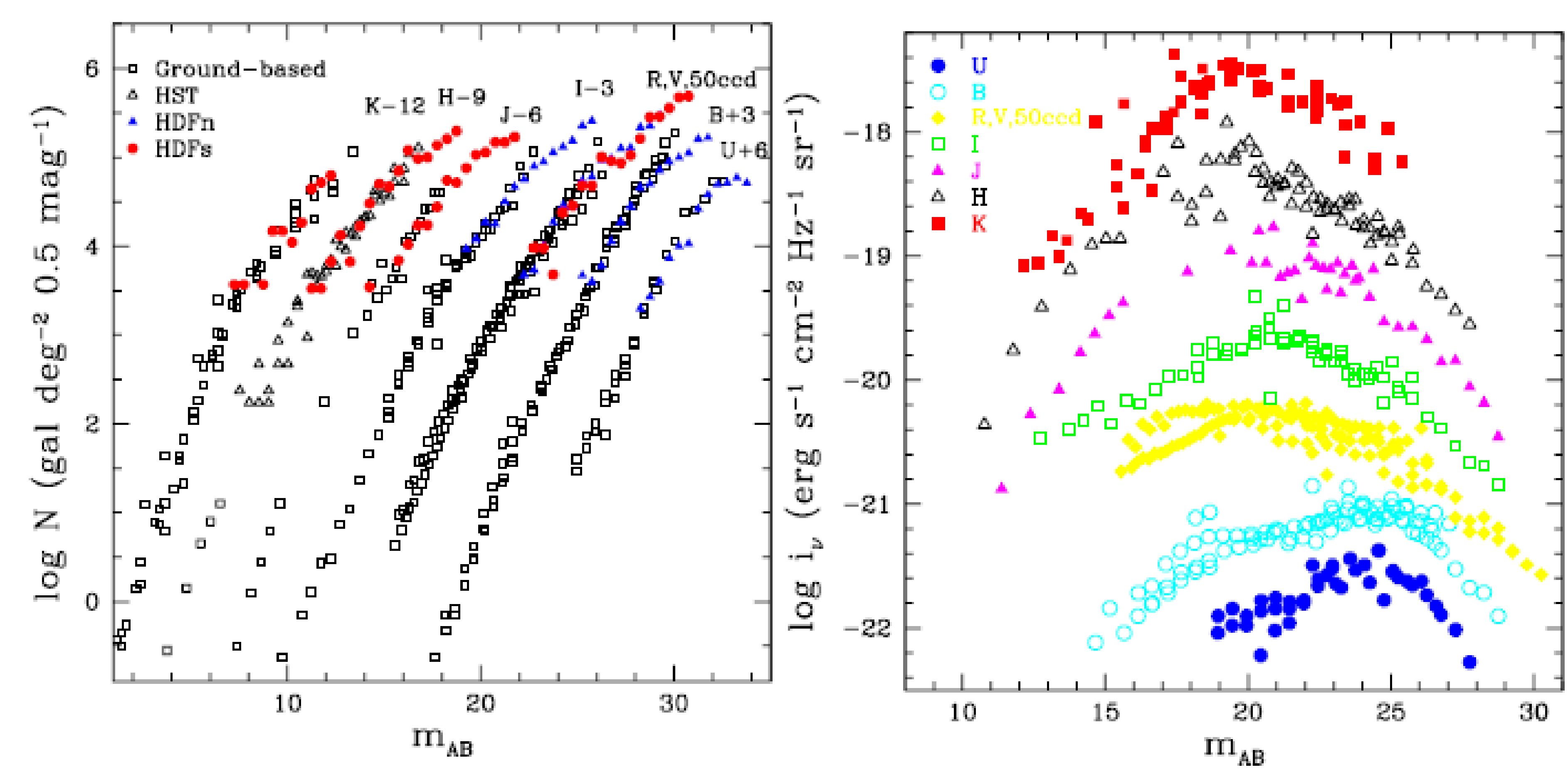


Mazin & Raue (2007)

Minimal EBL estimates by known sources

Hubble Deep Field

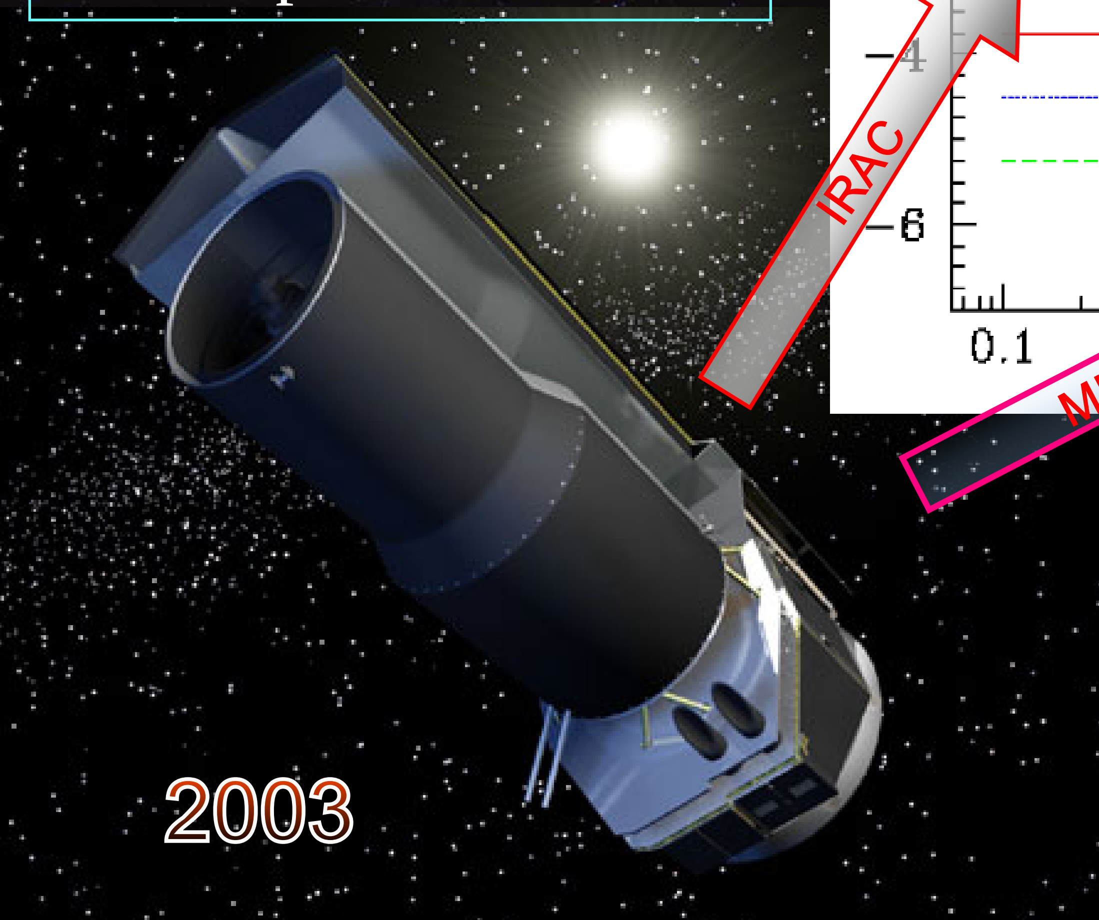
HST WFPC2

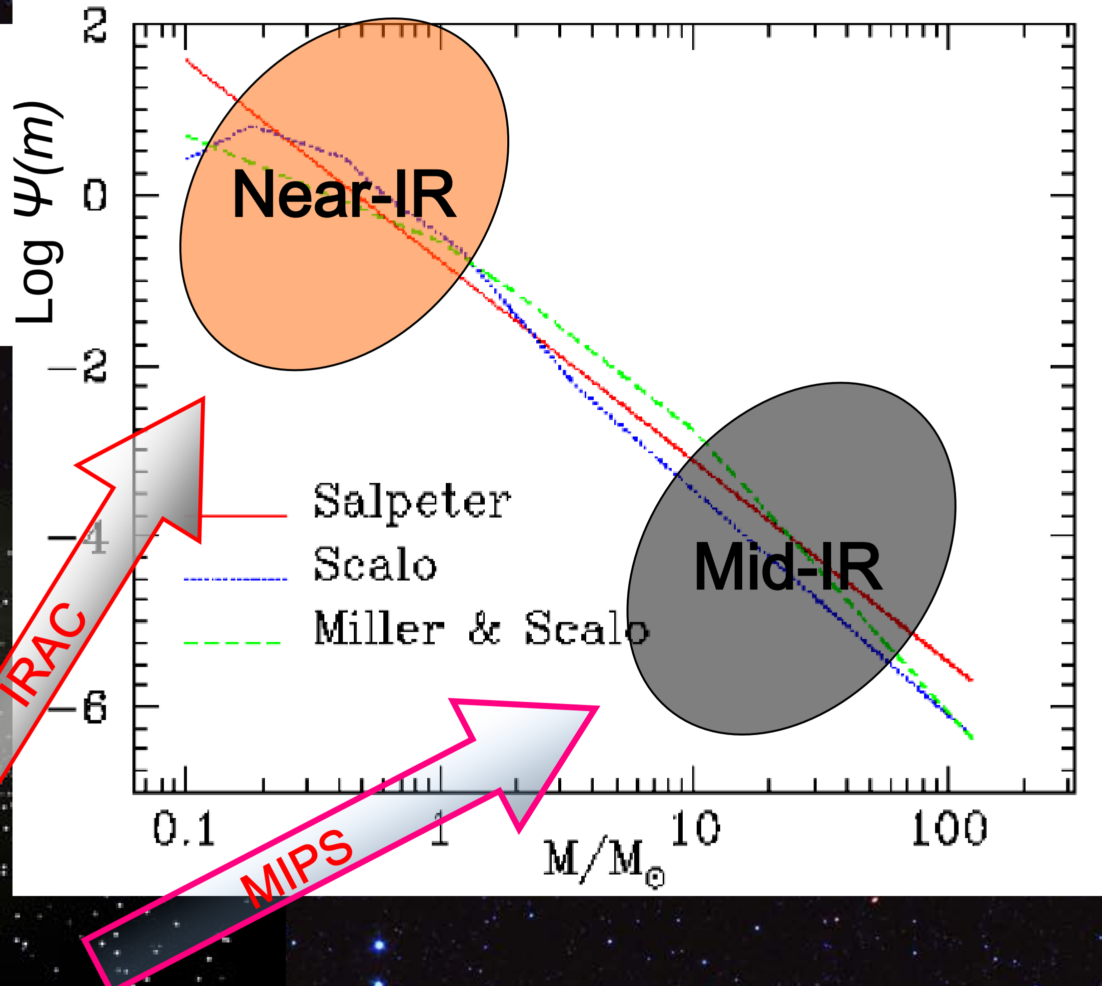


Left: Differential UBV IJHK galaxy counts as a function of AB magnitudes. The sources of the data points are given in the text. Note the decrease of the logarithmic slope d logN/dm at faint magnitudes.
The flattening is more pronounced at the shortest wavelengths. Right: Extragalactic background light per magnitude bin, $i = 10-0.4(mAB+48.6)N(m)$, 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.

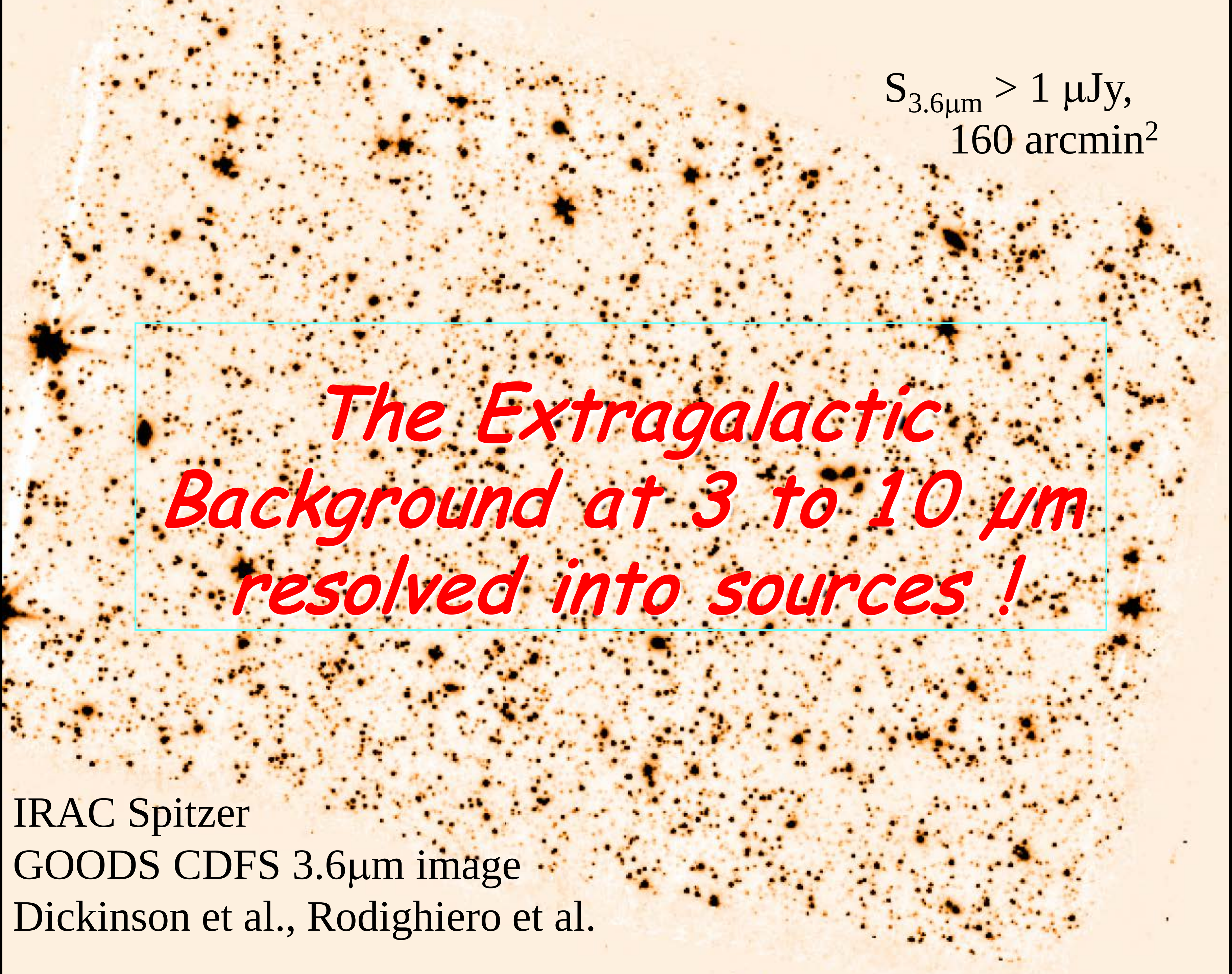
Madau & Pozzetti 2000

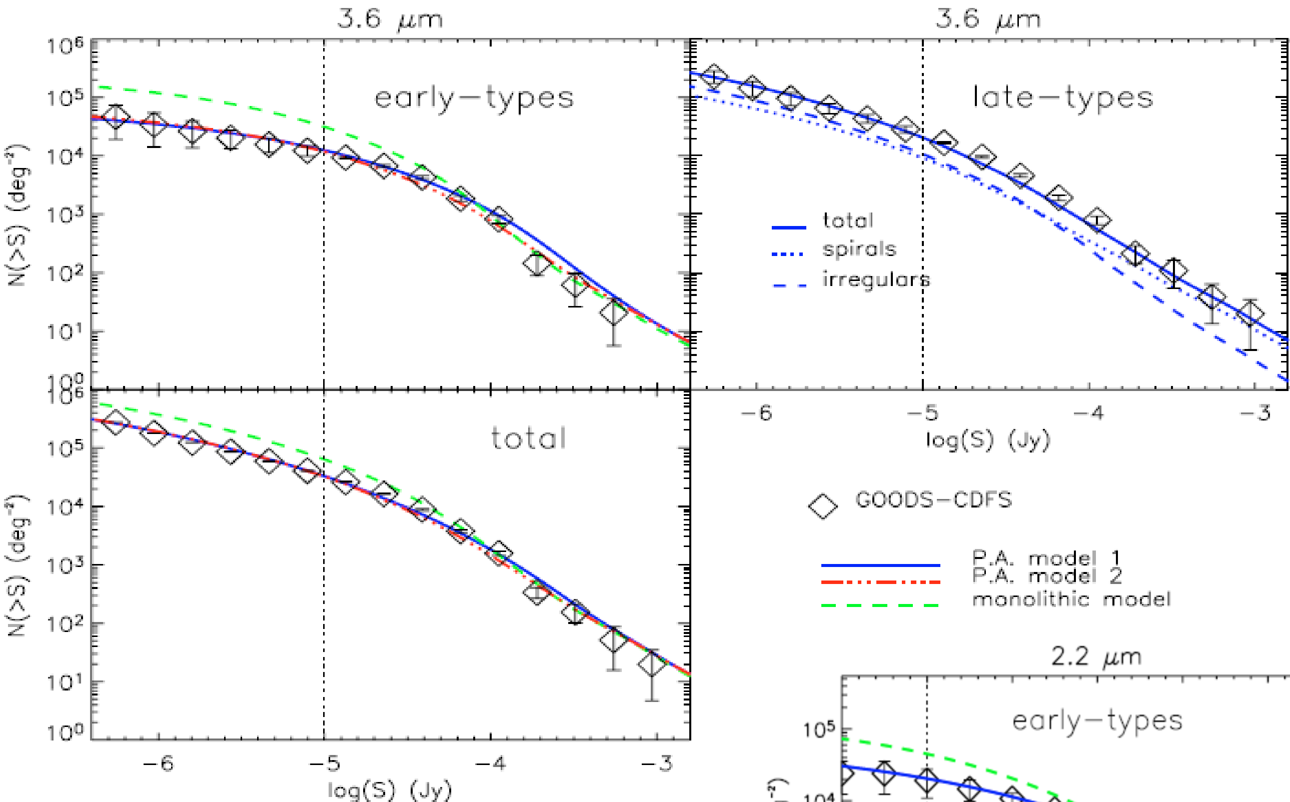
Great progress in the observation of faint sources of EBL by the Spitzer Space Telescope

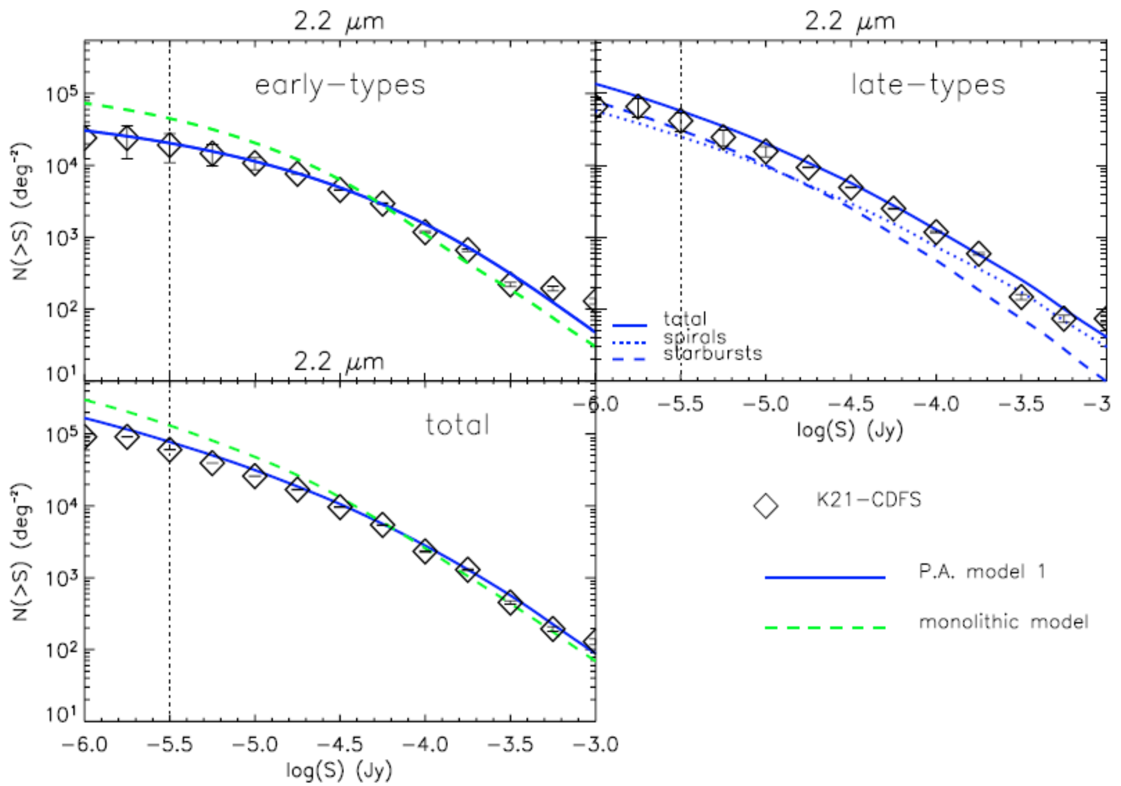




Spitzer's IRAC & MIPS photometric cameras


$S_{3.6\mu m} > 1\ \mu$Jy,
160 arcmin^2
The Extragalactic Background at 3 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 !

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:

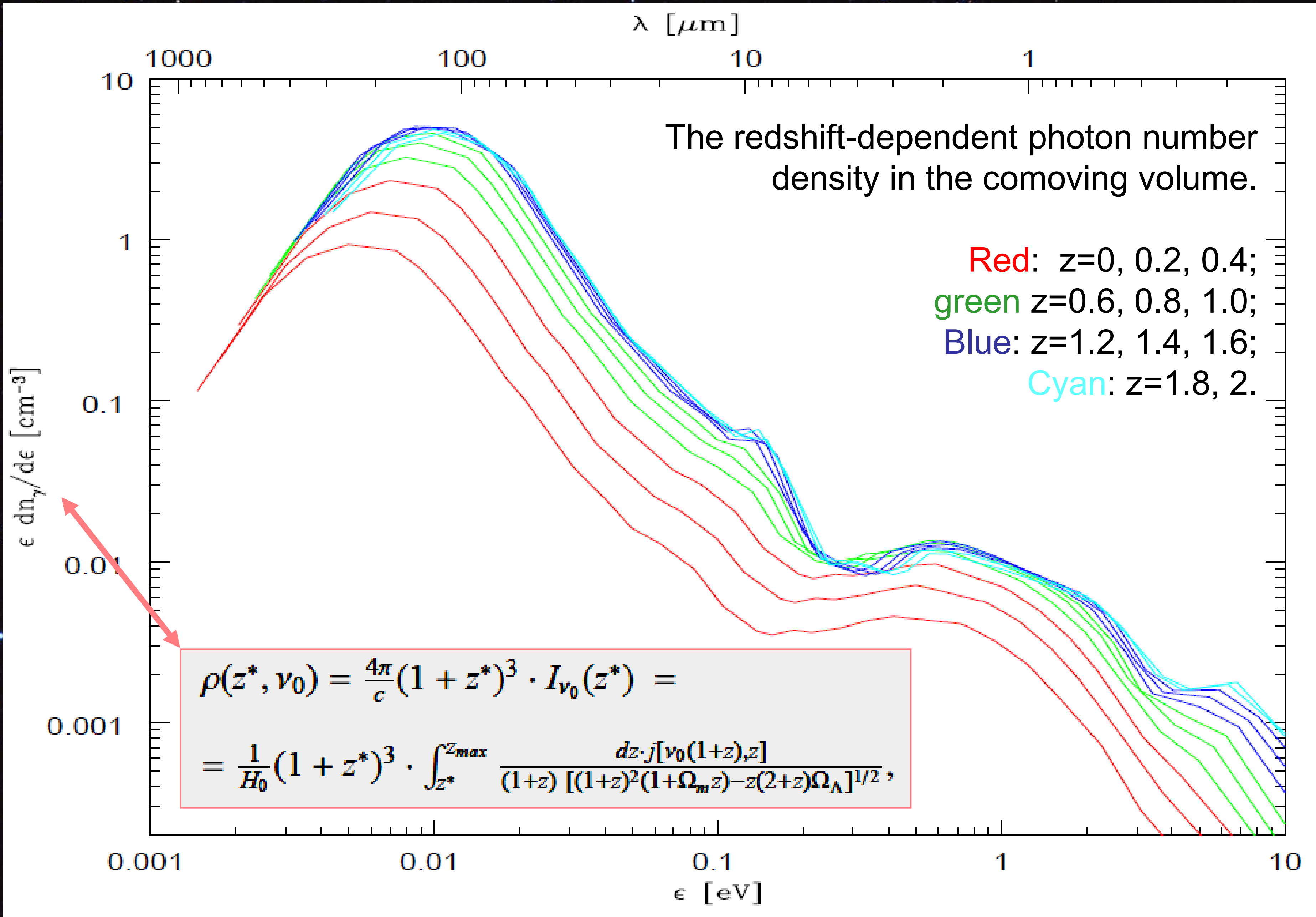
  - density evolution for representing the galaxy merging and hierarchical assembly
  - luminosity evolution following the aging stellar populations and the evolution of the rate of star formation (typically much larger at $z \geq 1$ than locally)

Galaxy number counts and the cosmic background emissivity

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

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

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



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

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

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:

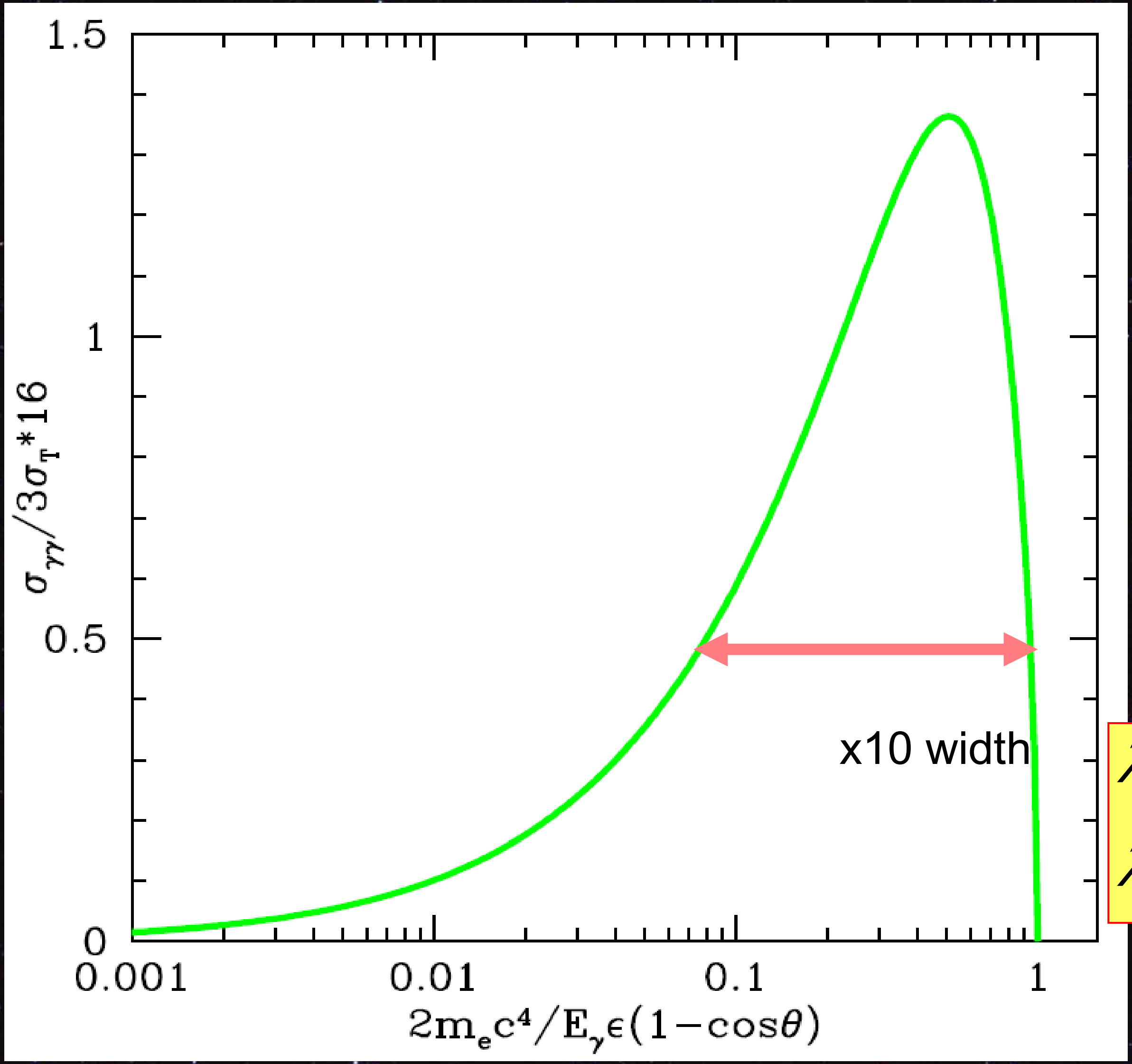
$$dt/dz = \frac{1}{H_0(1+z)} \left[(1+z)^2(1+\Omega_m z) - z(z+2)\Omega_\Lambda\right]^{-1/2}.$$

ϵ: energy of the background photon,

E_γ that of the high-energy colliding one,

θ being the angle between the colliding photons.

The γ-γ cosmic optical depth

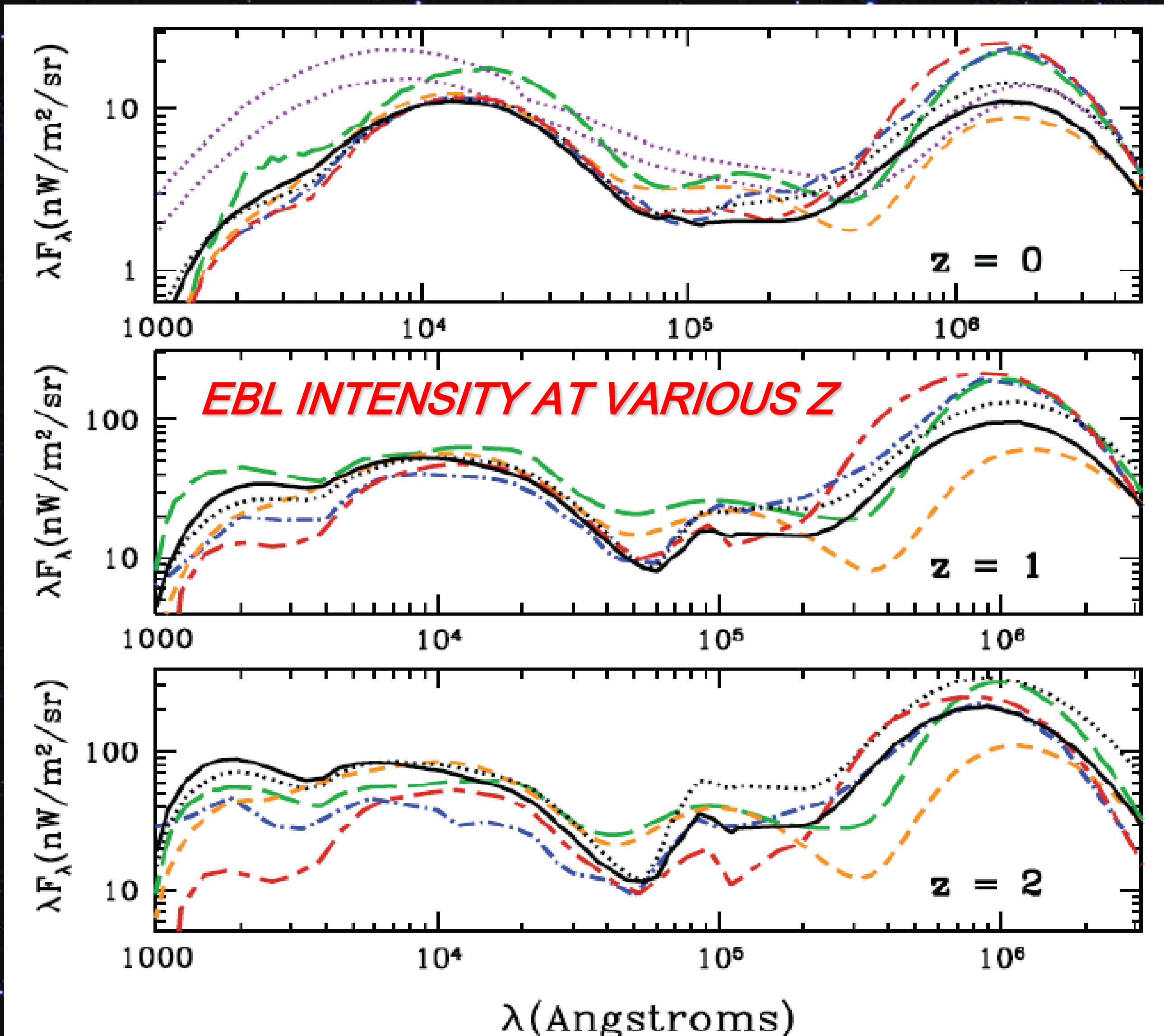


The γ-γ cross-section is quite broad...

$$\lambda[\mu m] \simeq 1.2 E_\gamma [TeV]$$

$$\lambda \simeq (0.1-2.4)\mu m\, E_\gamma [TeV]$$

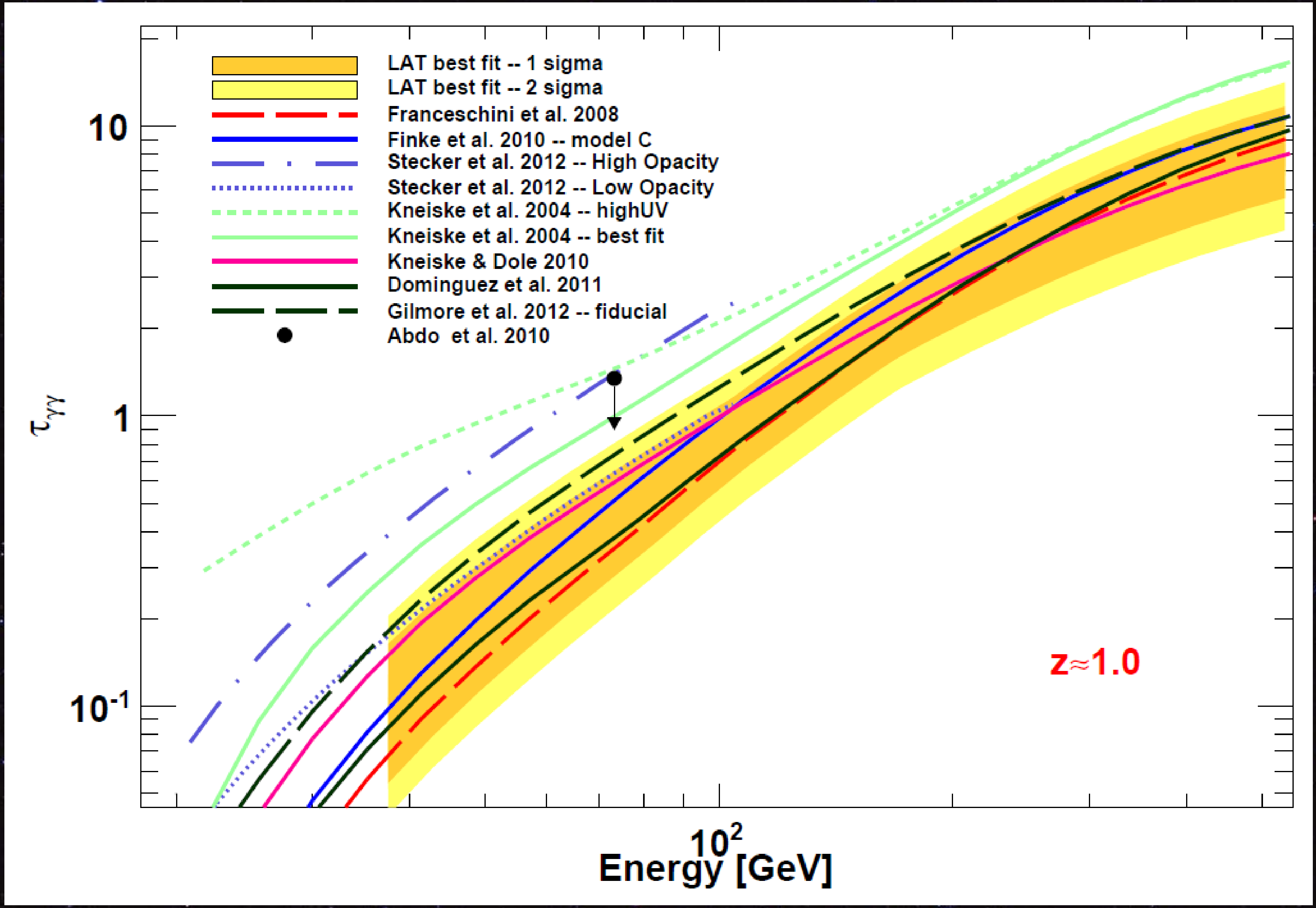
Modelling the sources of EBL



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

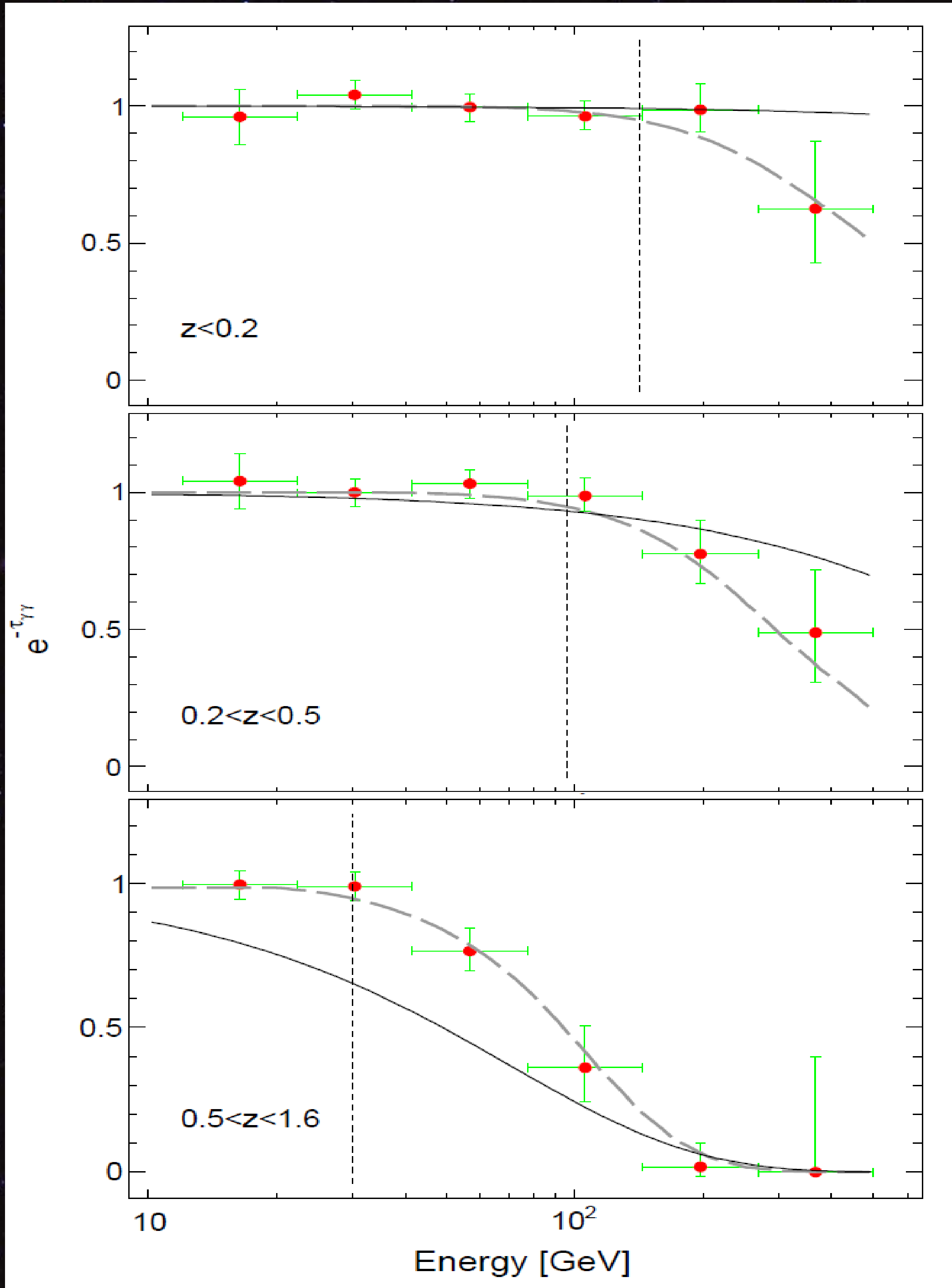
Gilmore et al. 2012

Ackermann et al. 2012



Confidence regions including systematic uncertainties on the opacity − from the best fits to the Fermi-LAT data compared to predictions of various EBL models. The plot shows the measurement at $z \approx 1$, which is the average redshift of the most constraining bin (i.e. $0.5 < z < 1.6$).

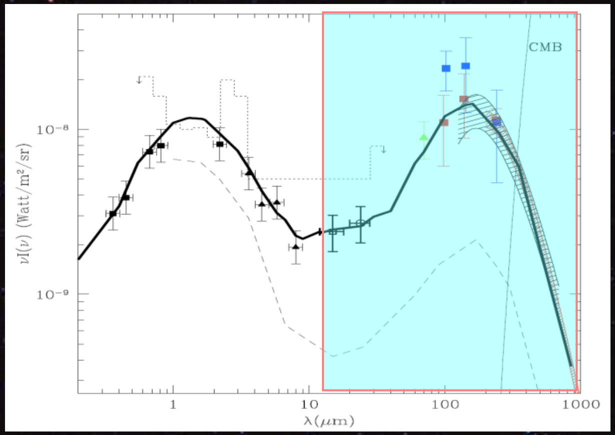
Ackermann et al. 2012



Ratio of the <u>average extrapolated vs observed 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.



The elusive IR EBL

The sub-millimeter (λ>100 μm) background: the only safe detection !

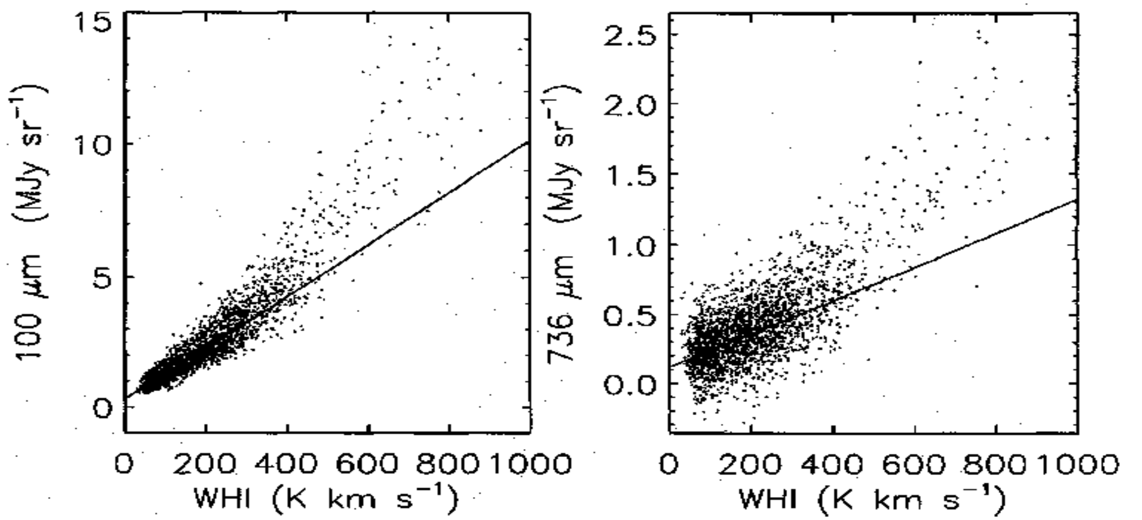
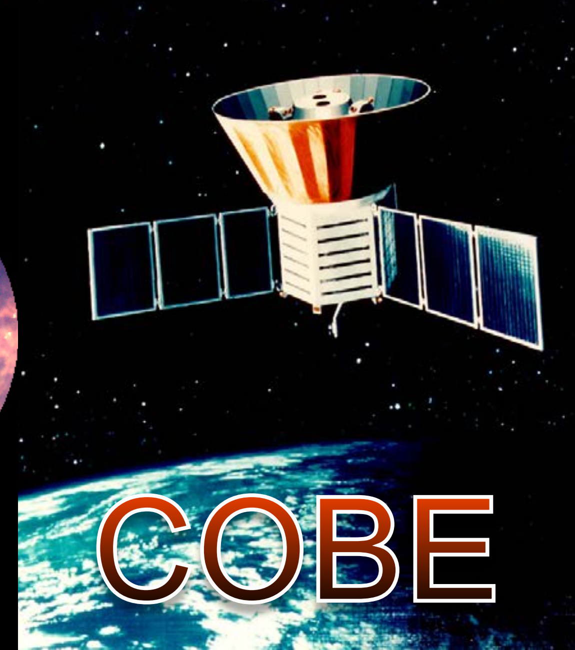
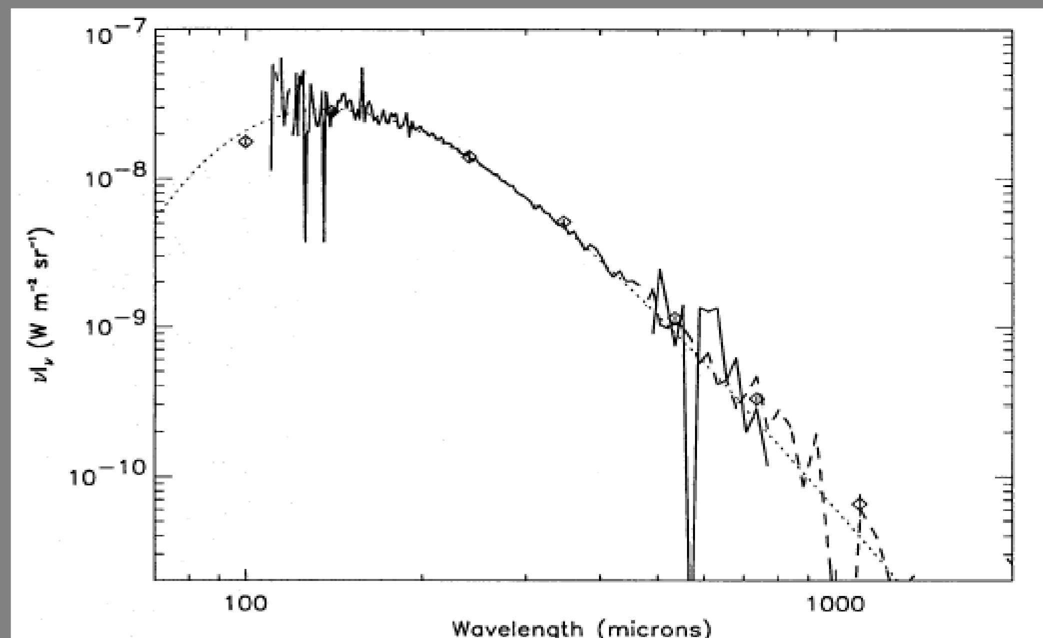


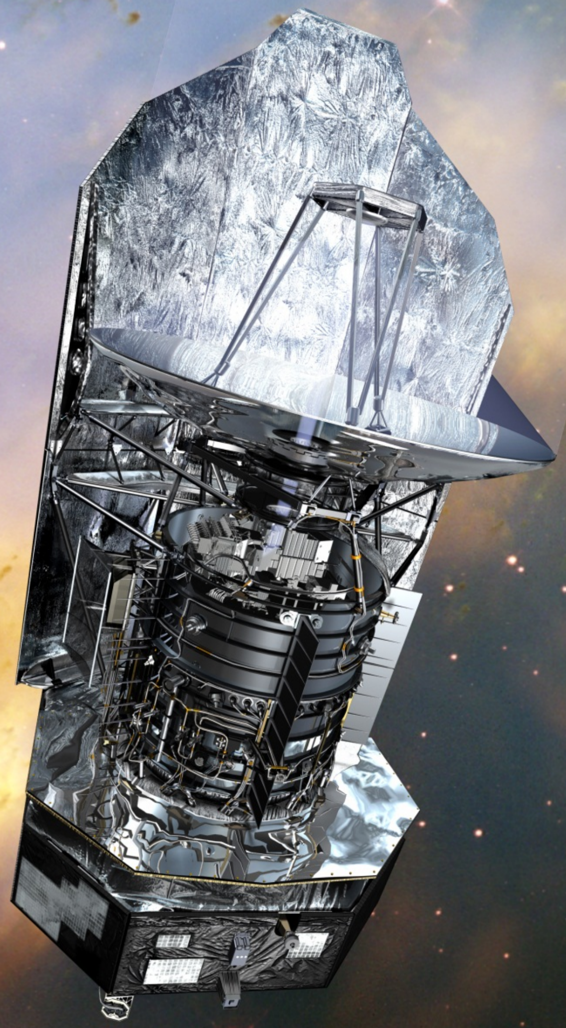
Fig. 1. Correlation between IR and HI emission at 100 μm (DIRBE data, smoothed to 7° resolution) and at 736 μm (FIRAS LLSS data, averaged between 600 and 900 μm). The lines represent fits to data at $W_{\rm HI} < 250$ K km s^{-1}.





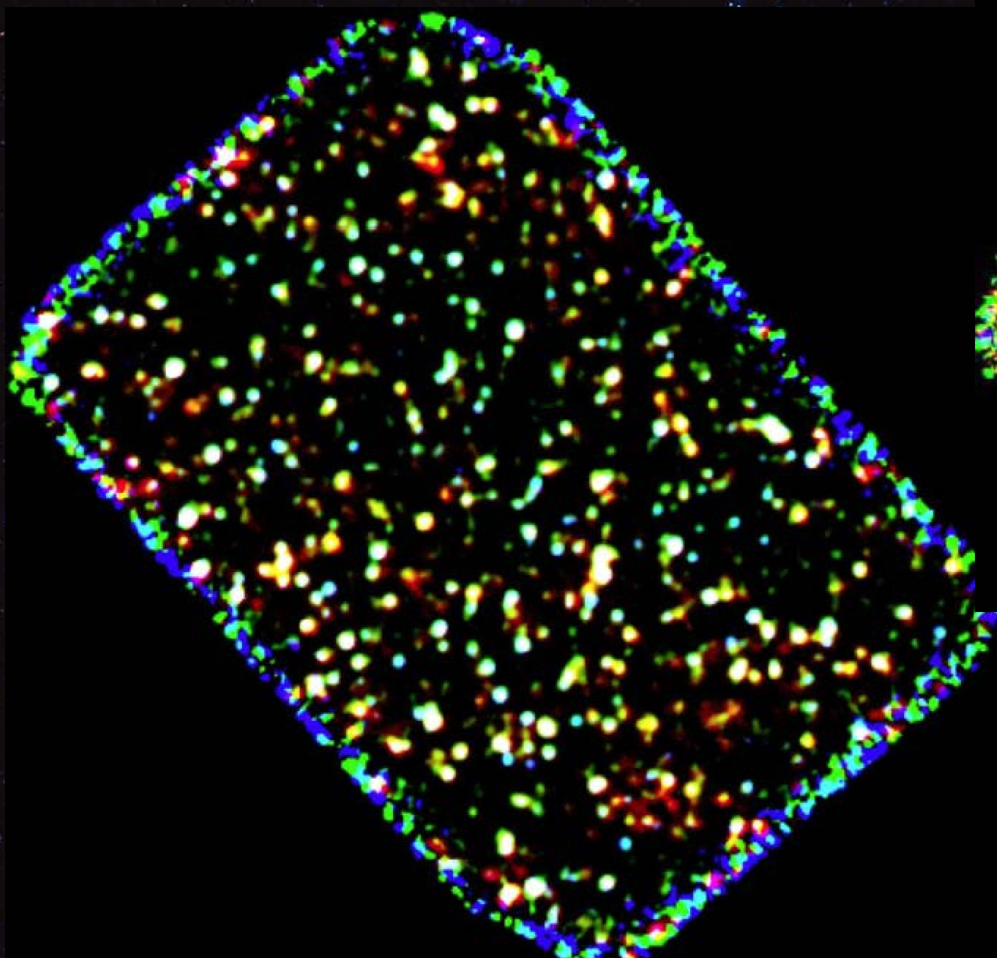
The sub-millimeter: the only spectral region where the total EBL has been reliably measured

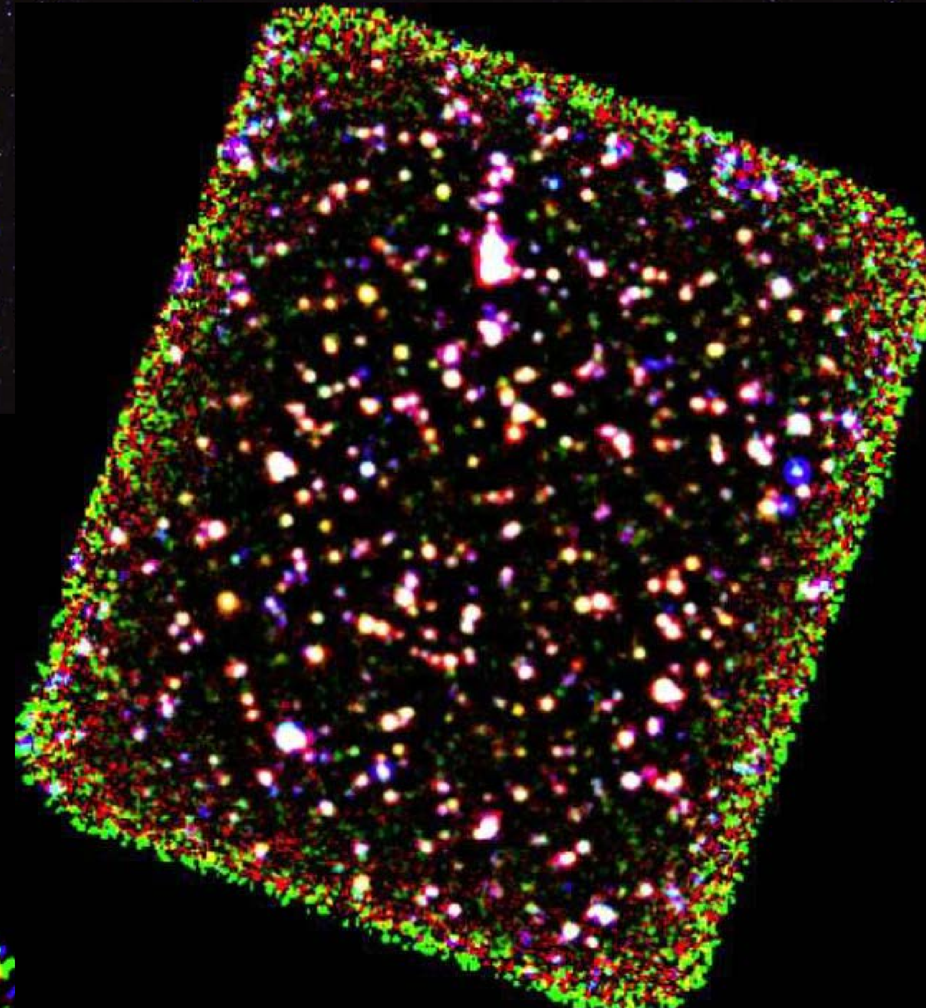
The Herschel Infrared Space Observatory



2009-
2013

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

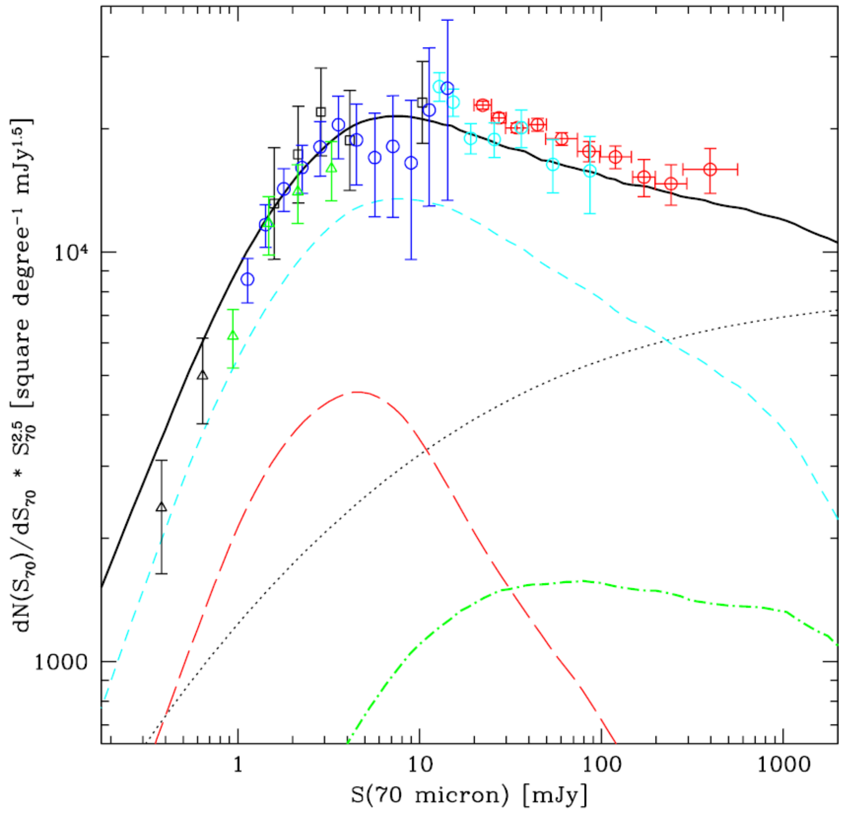


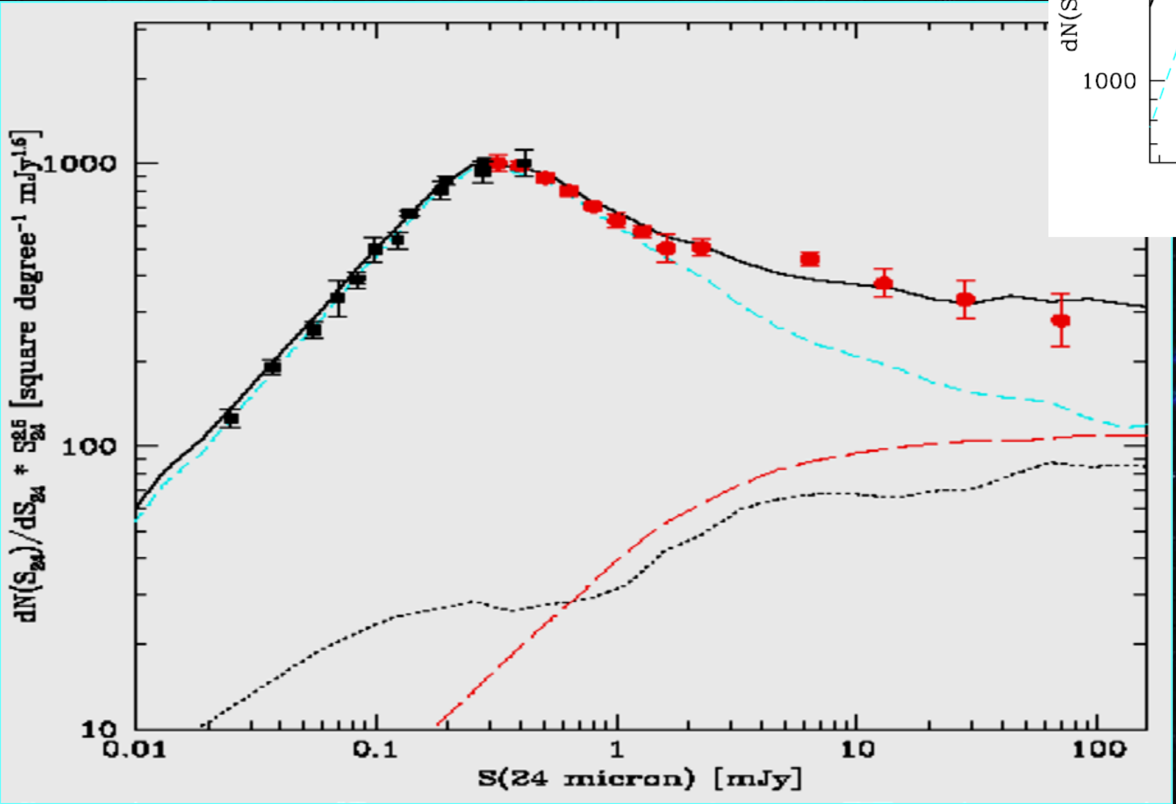


GOODS–south (10′×10′) at 24 μm (blue), 100 μm (green) and 160 μm (red)

Elbaz et al. 2011

Spitzer & Herschel have provided accurate assessment of the 24 μm statistics

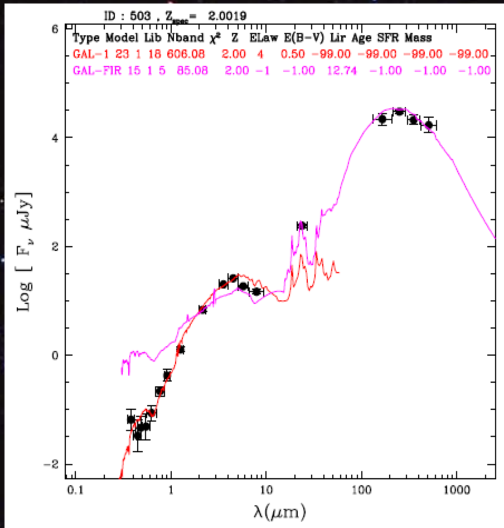


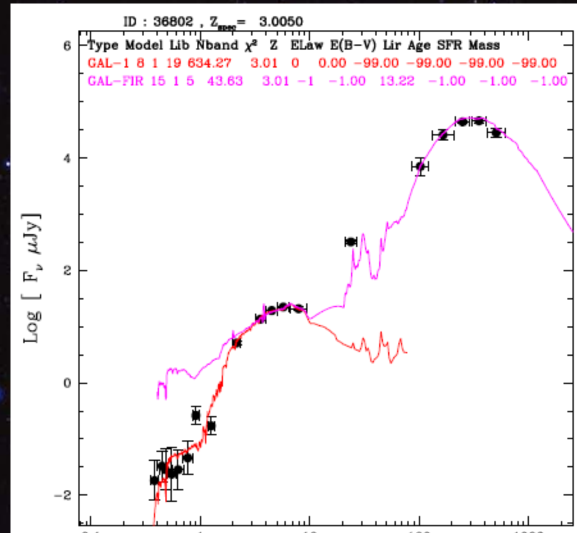


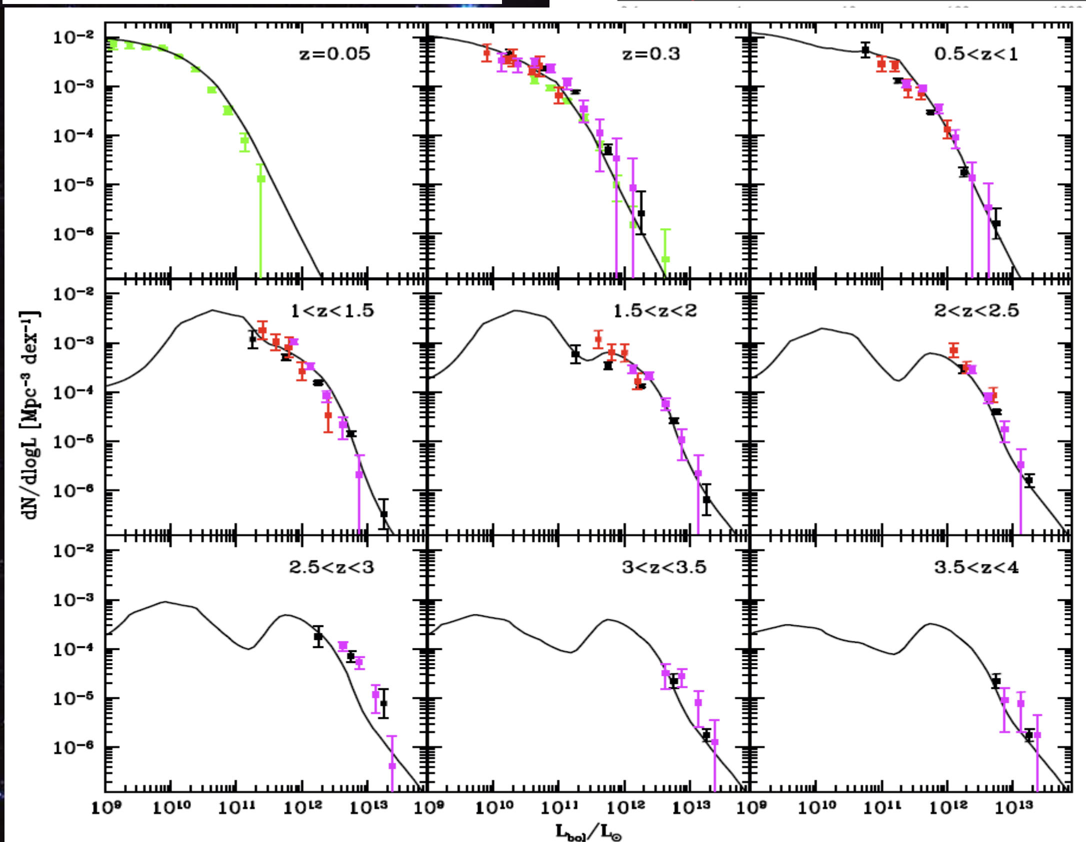
Red: SWIRE data (Shupe et al. 2008)

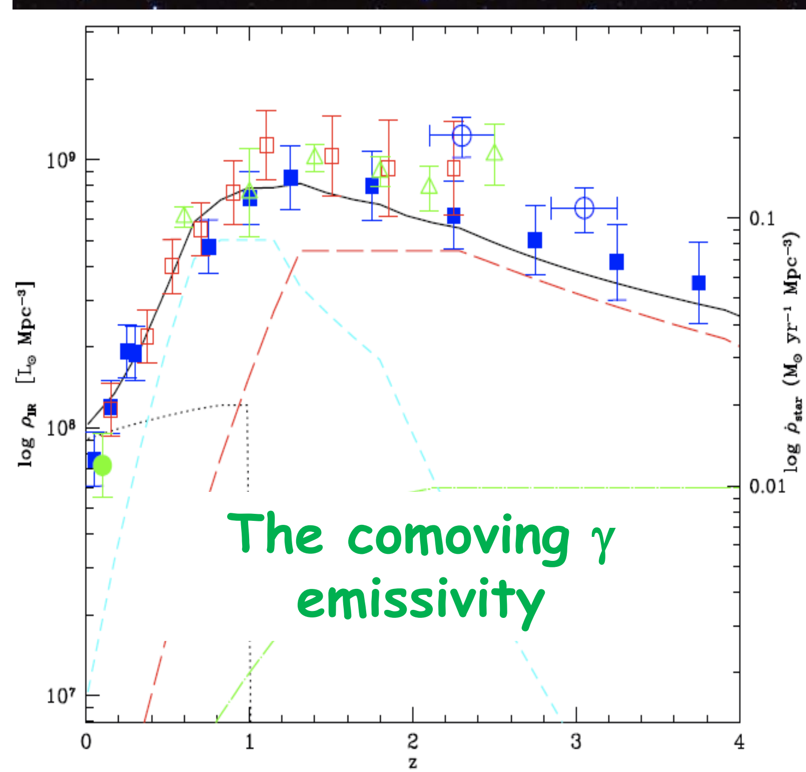
Black: Papovich et al (2004), Chary et al (2004) Magnelli et al. (2013)

Spectral modelling of source populations & luminosity functions





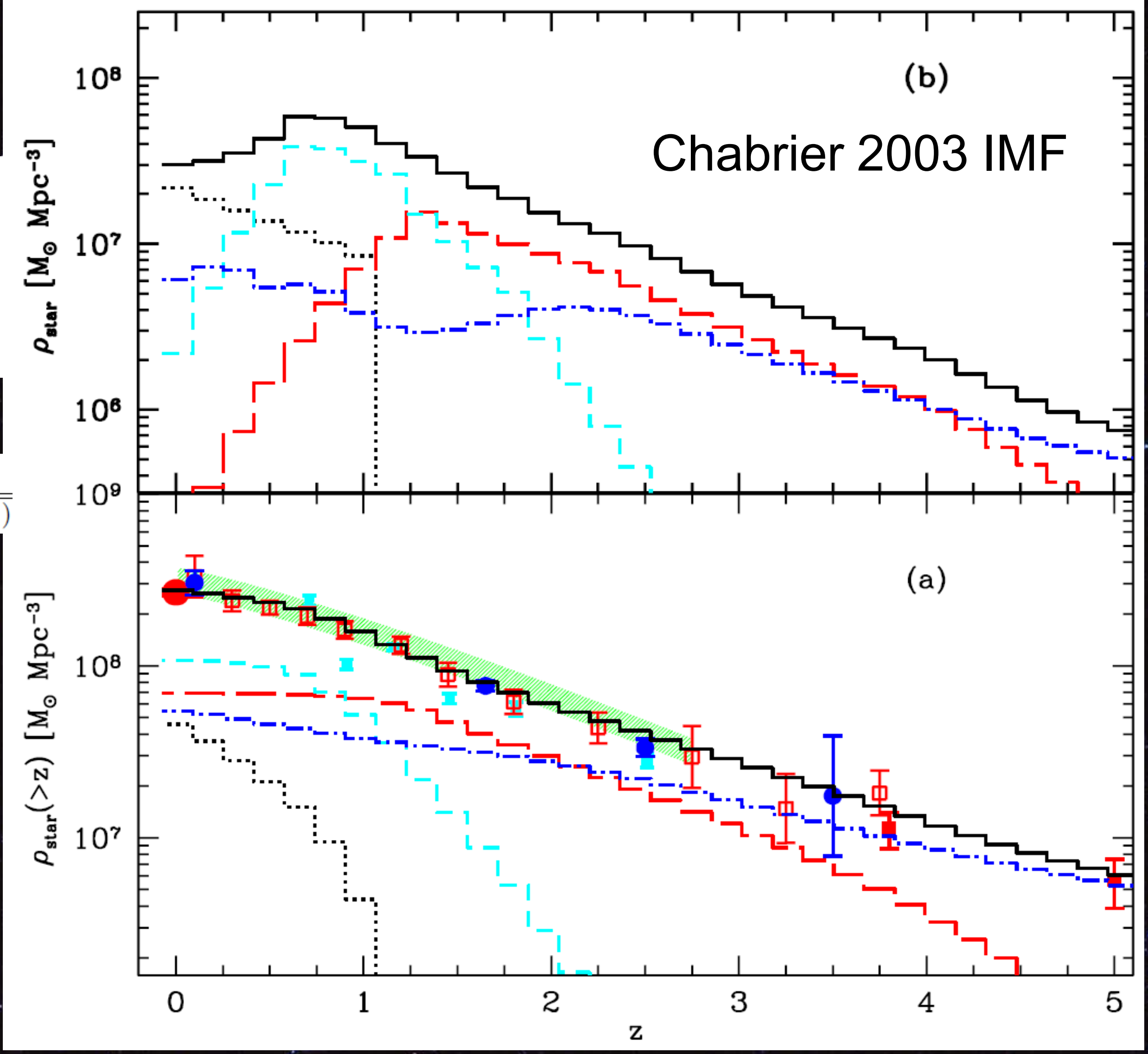




Interesting check of the redshift-dependent galaxy emissivity

$$\rho_{star}(>z) = K \int_{z}^{z_{max}} dz' \rho_{IR+UV}(z') \cdot \left(\frac{dt}{dz'}\right) \cdot f_*[t(z) - t(z')],$$

$$\frac{dt}{dz} = \frac{1}{H_0 \cdot (1+z) \cdot \sqrt{(1+z)^2(1+\Omega_m z) - z(2+z)\Omega_\Lambda}}$$



Data from:

Perez-Gonzalez et al 2008

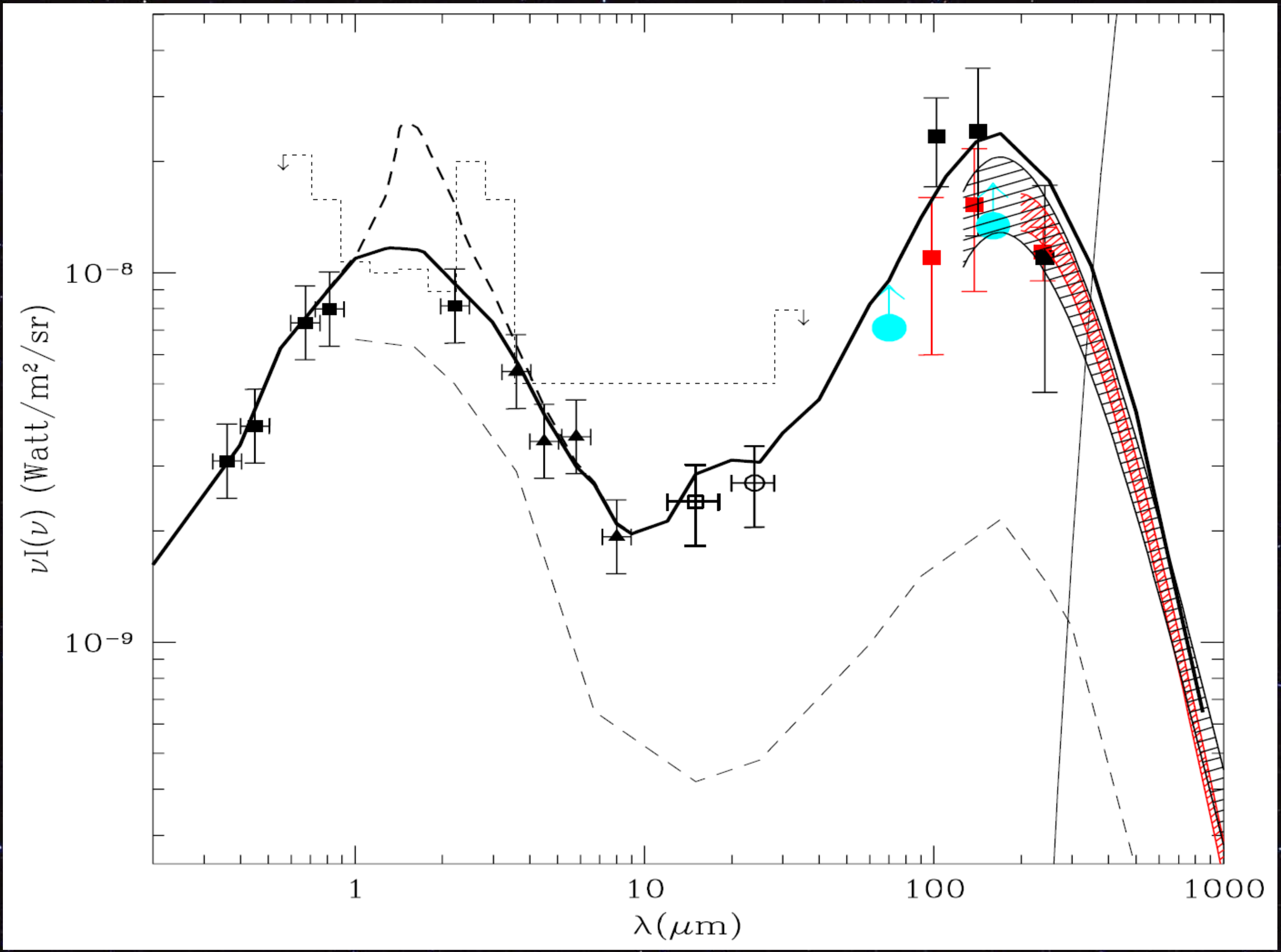
Marchesini et al 2009

Gonzalez et al 2011

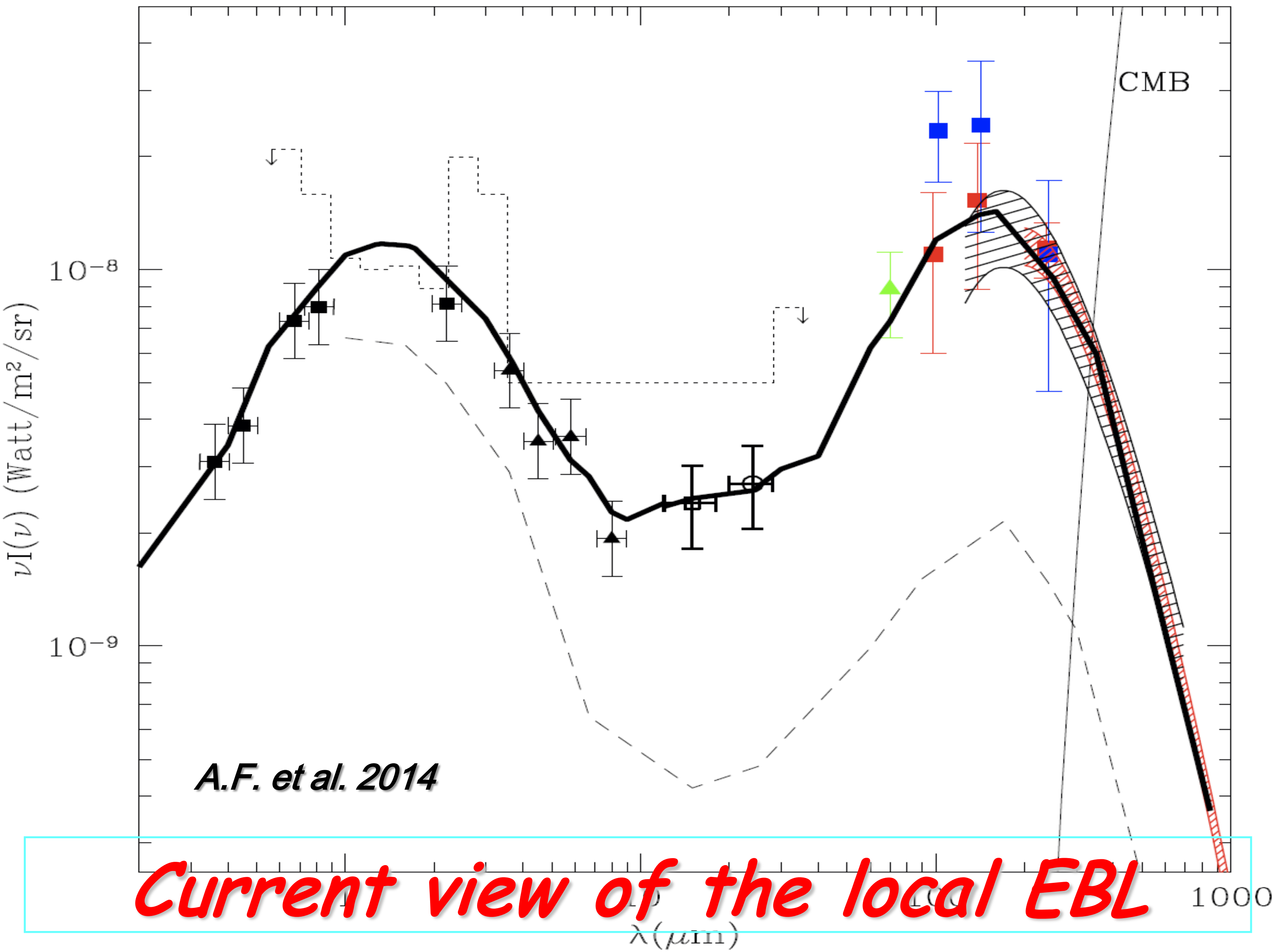
Wilkins et al 2008

Eke et al 2005

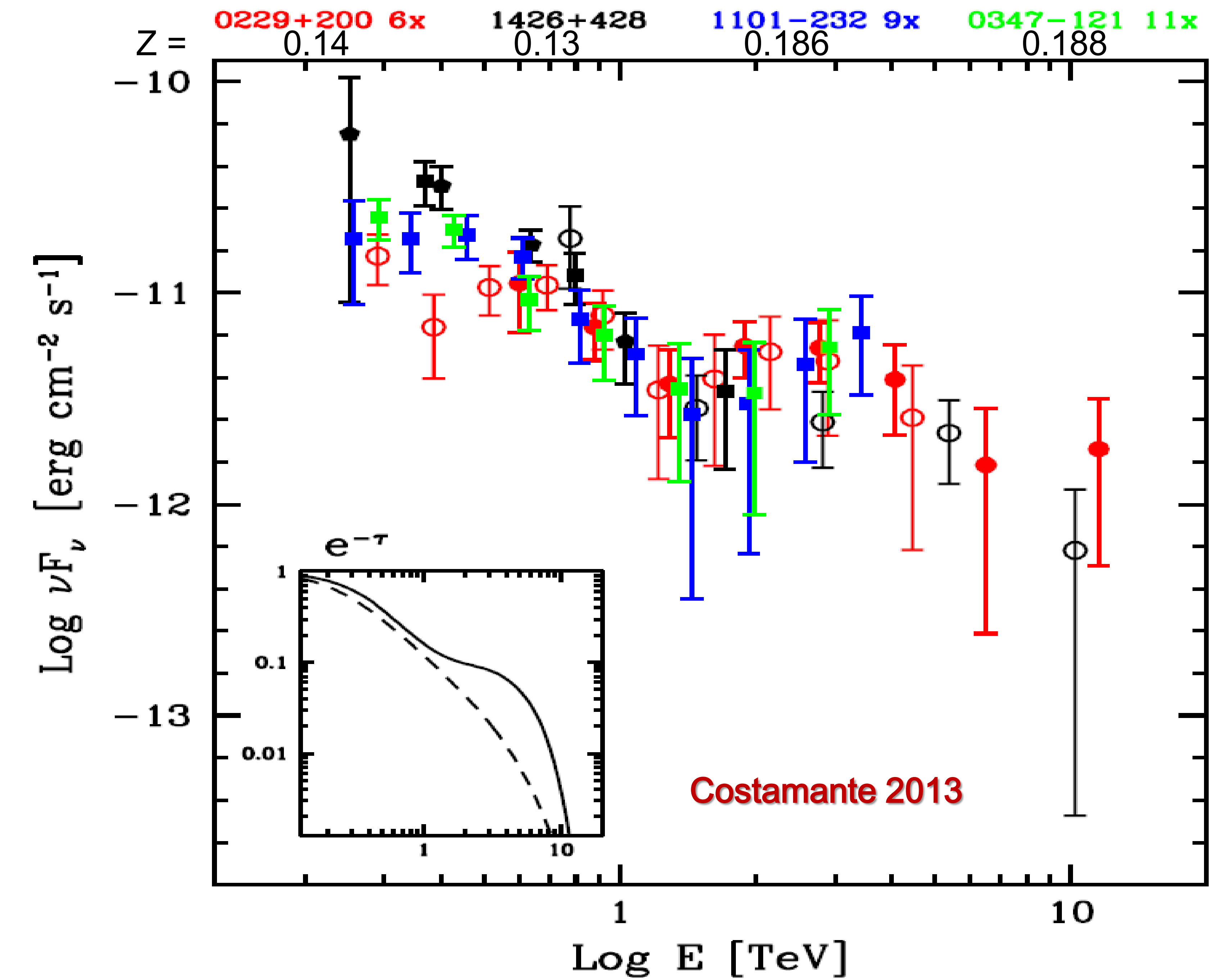
Panter et al. 2004

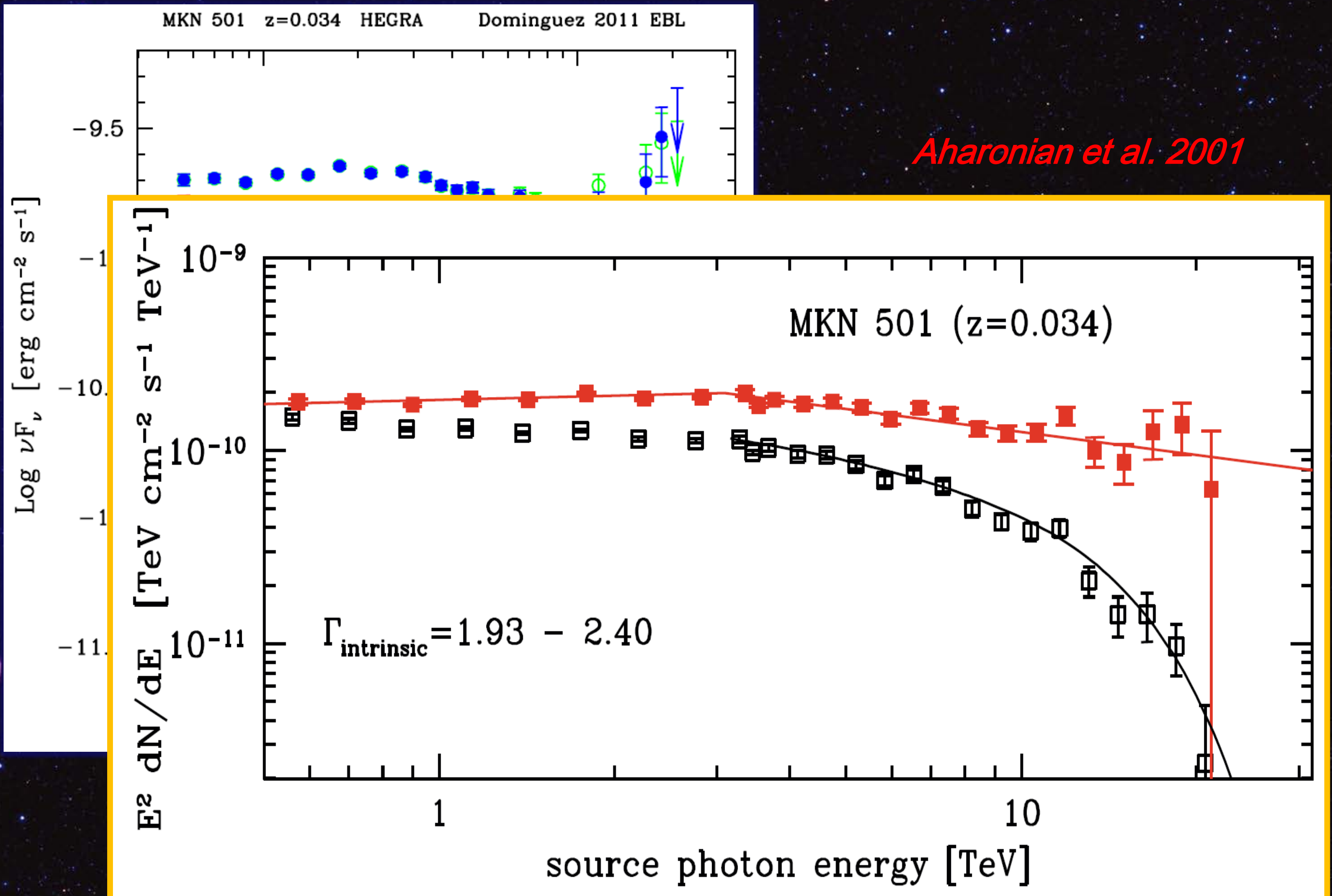


10^{-8}
10^{-9}
$\nu I(\nu)$ (Watt/m^2/sr)
1
10
100
1000
$\lambda(\mu m)$

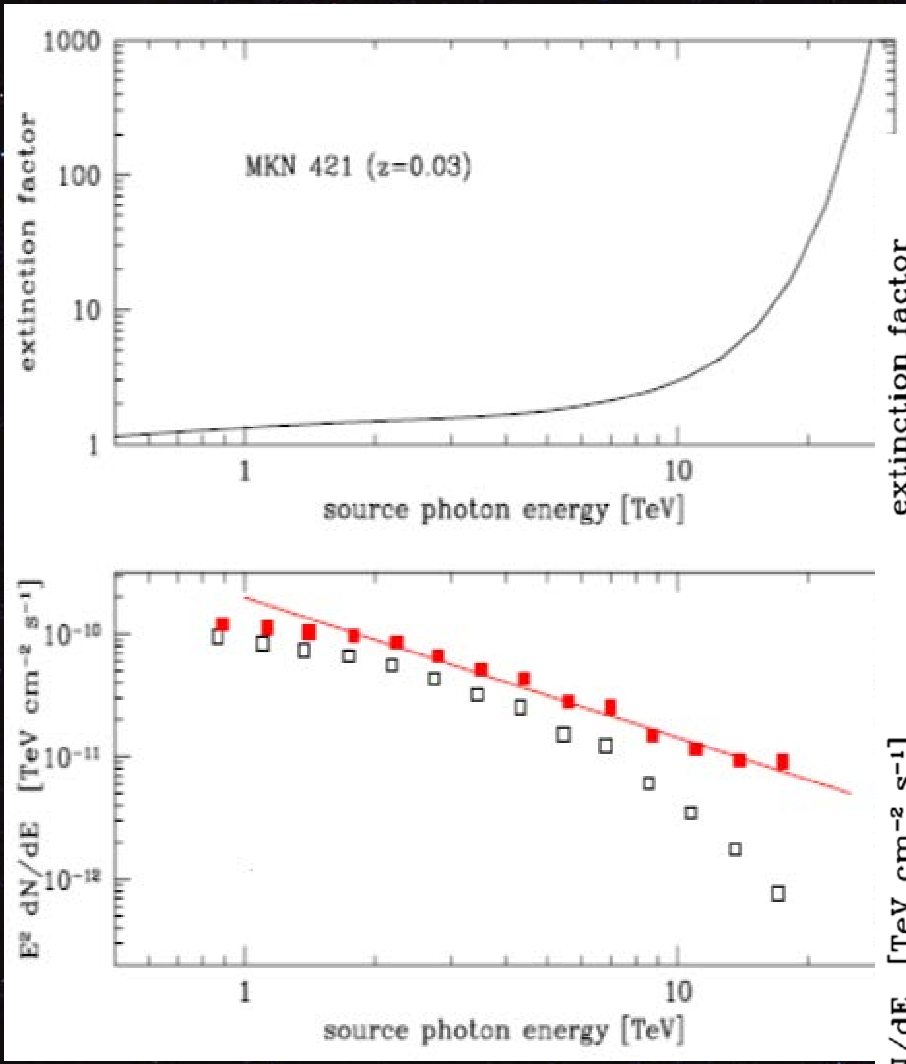


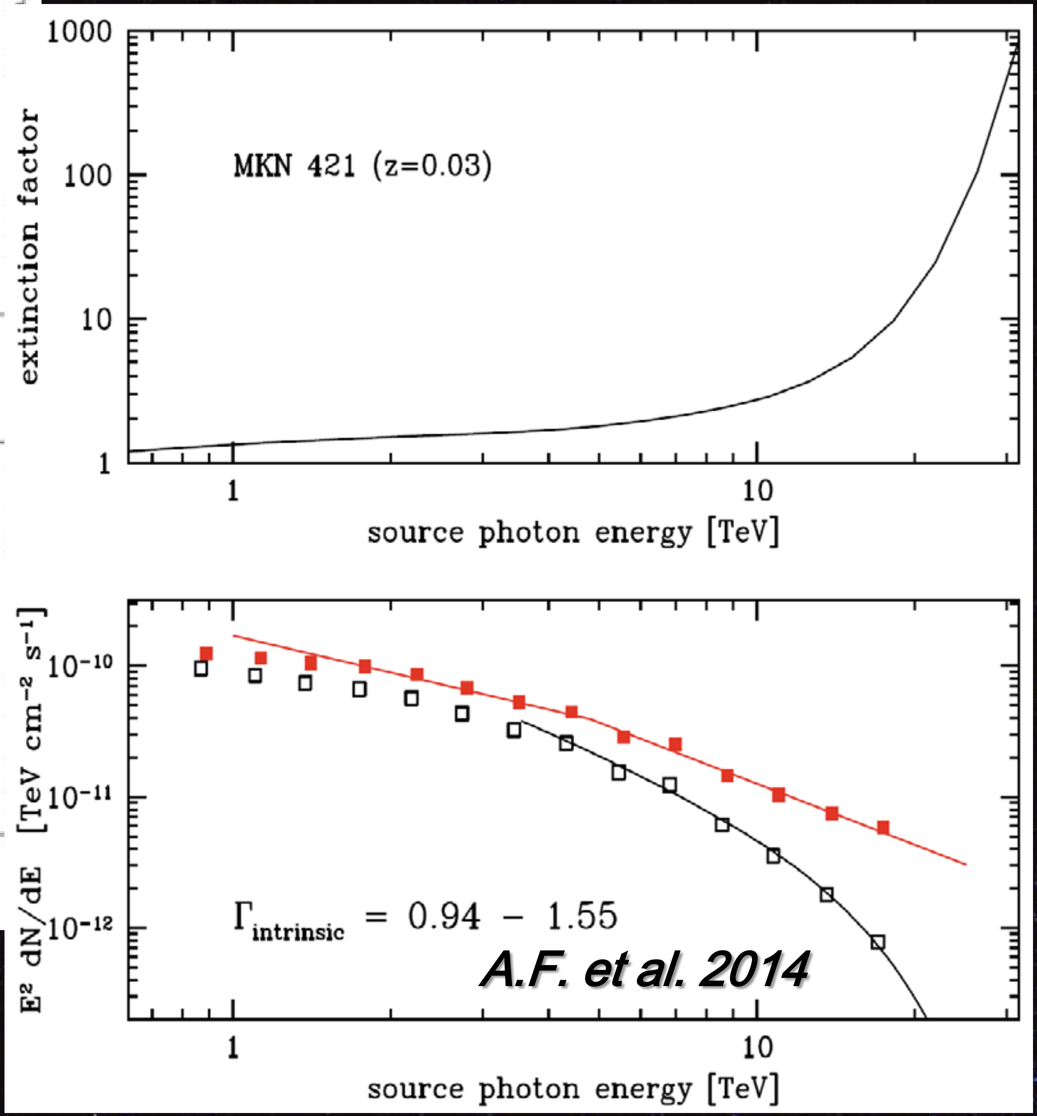
Current view of the local EBL


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
Log E [TeV]
1
10
e^{−τ}
1
0.1
0.01
1
10
Costamante 2013



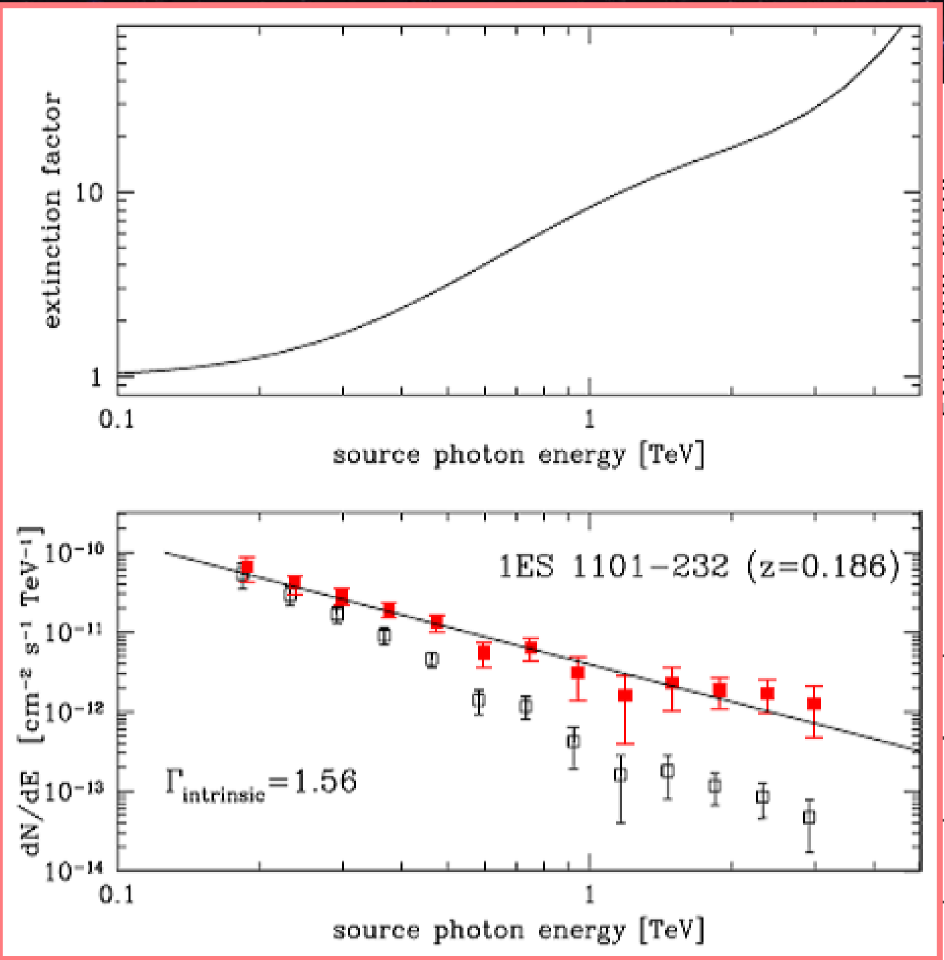
MKN 501 z=0.034 HEGRA Dominguez 2011 EBL
−9.5
−10.
−11.
Log νF_ν [erg cm^{-2} s^{-1}]
Aharonian et al. 2001
MKN 501 (z=0.034)
$\Gamma_{intrinsic}$=1.93 − 2.40
10^{-9}
10^{-10}
10^{-11}
E^2 dN/dE [TeV cm^{-2} s^{-1} TeV^{-1}]
1
10
source photon energy [TeV]


MKN 421 (z=0.03)
extinction factor
source photon energy [TeV]
E² dN/dE [TeV cm⁻² s⁻¹]

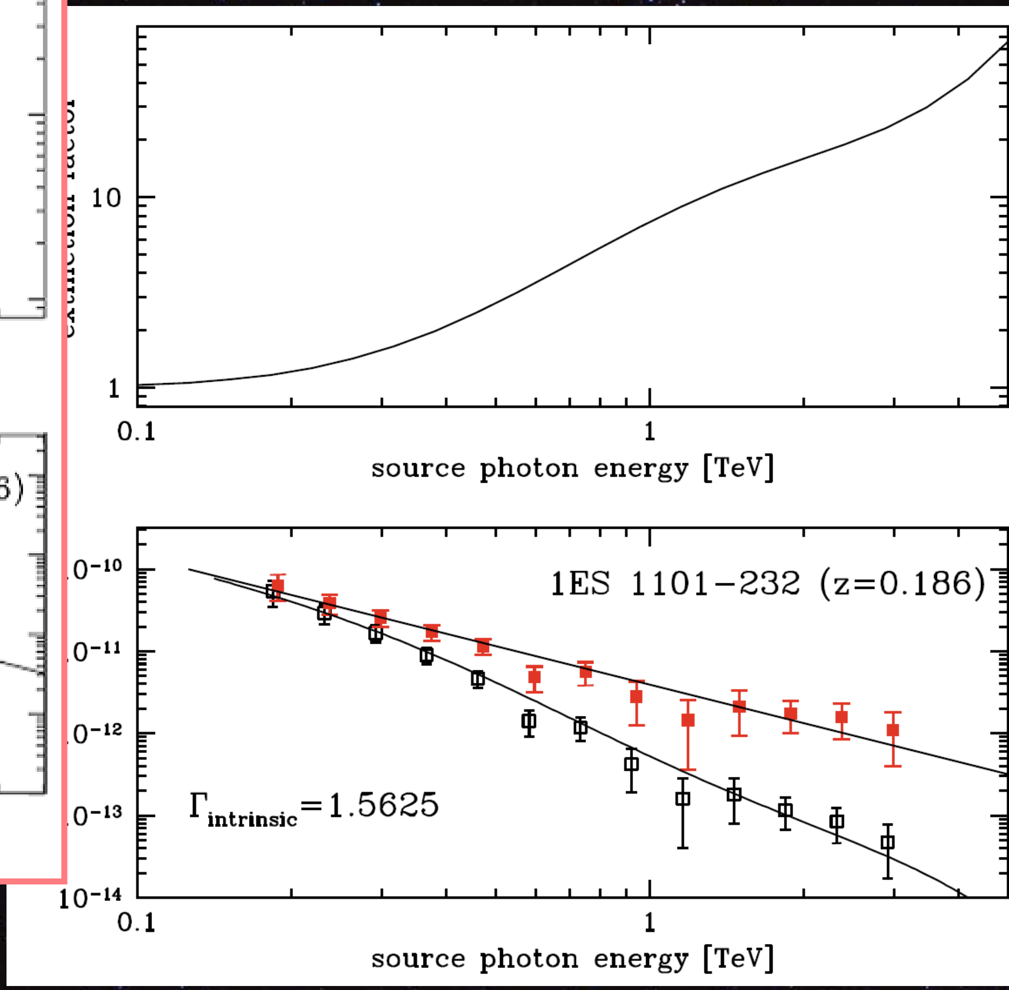

MKN 421 (z=0.03)
extinction factor
source photon energy [TeV]
E² dN/dE [TeV cm⁻² s⁻¹]
Γ intrinsic = 0.94 – 1.55
A.F. et al. 2014

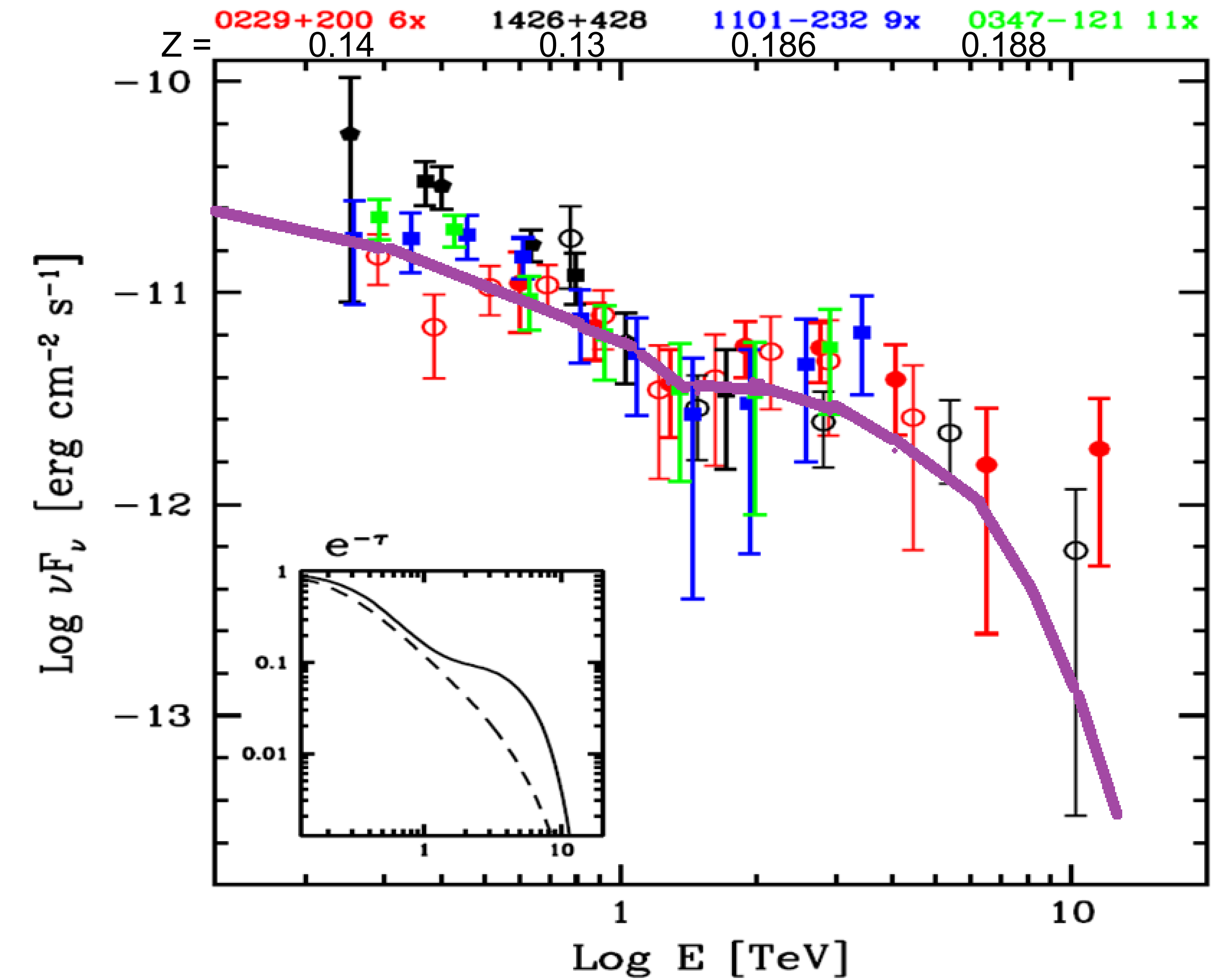
The source used to rule out the claimed IRTS EBL excess by Matsumoto et al. (2005)

1ES 1101-232

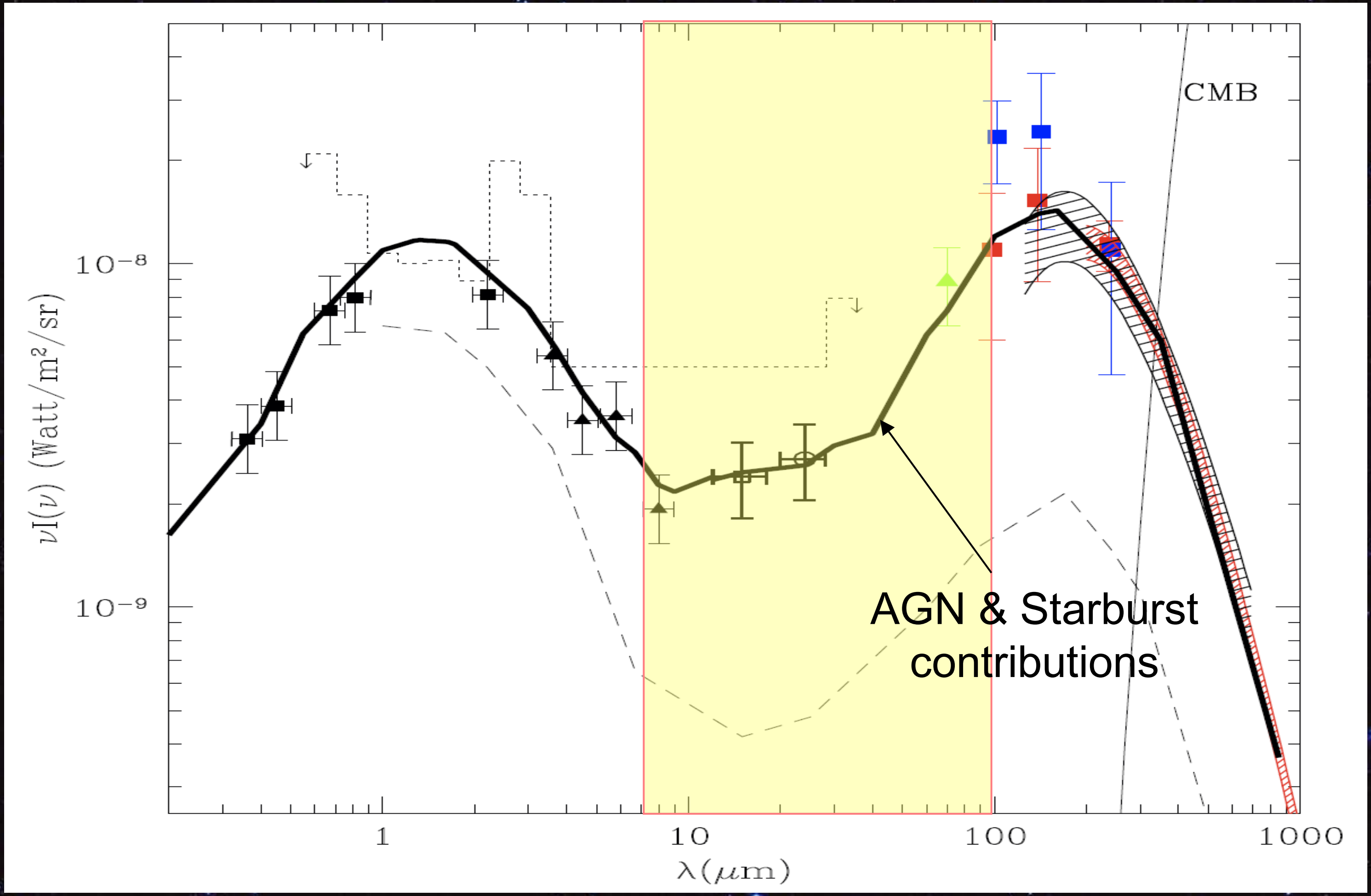


(Aharonian et al. 2006)




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

The CTA Small Telescope array → very high TeV energy observations: the far-IR EBL



The CTA Small Telescope array → very high TeV energy observations: the far-IR EBL (cnt.)

1. The increasing local EBL flux at λ>10 μm untestable directly (due to huge IPD foregrounds)
2. NASA JWST (2019) will observe IR sources only to λ<28 μm, and no diffuse flux measurement
3. Past obs. of MKN421 and MKN501 limited by sensitivity and spectral resolution
4. CTA measurements at 10<ε<50-100 TeV will allow us measurements of the IR EBL where it will always be untestable
5. Dust extinction and re-emission; integrated emissions by gravitational accretion in AGNs

Summary

- Already significant constraints on the EBL local flux
- The analysis of the TeV spectra of well-known Blazars indicates that the present model of the EBL produces *intrinsic* spectra *rather consistent* with natural power-laws and realistic (Γ>1.5) spectral slopes
- The general two-peak shape of EBL consistent with TeV observations and $\gamma\gamma$-opacity corrections
- The very high energy spectra sometimes claimed in conflict with $\gamma\gamma$ opacities (perhaps requiring *new physics*), but **NO** overwhelming evidence so far => ***clean universe***
- A new era in the field of the EBL-TeV relation is expect after the *dramatic improvement* that will be allowed by CTA