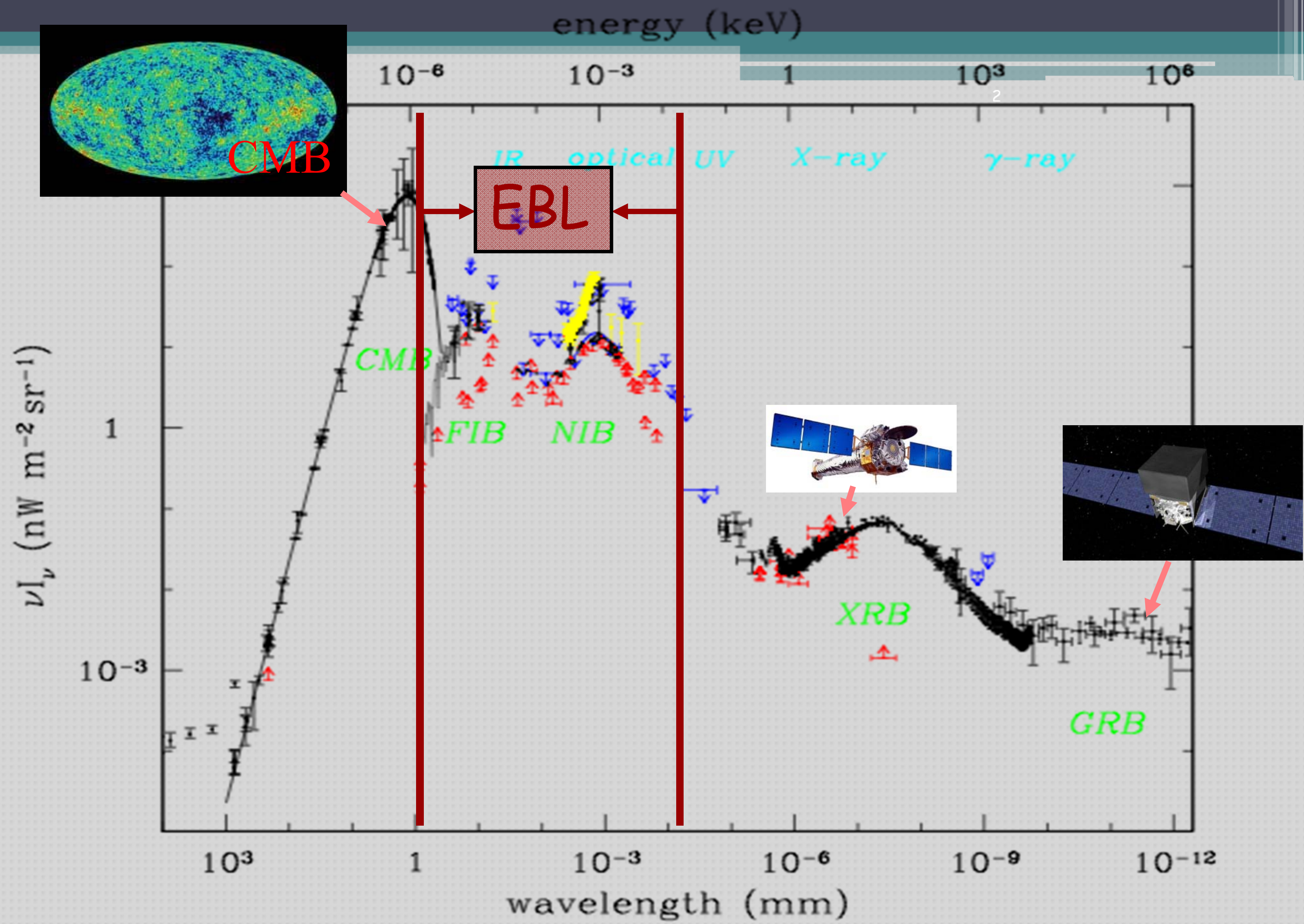
THE EXTRAGALACTIC BACKGROUND LIGHT AND THE TRANSPARENCY OF THE UNIVERSE TO GAMMA-RAYS

ALBERTO FRANCESCHINI - UNIPD

- The EBL in the IR and in the optical-UV and the cosmic γ-γ opacity
- Current status of the field
- Contributions from the MAGIC observatory

ASTROPHYSICS AND MAGIC CONFERENCE – LA PALMA 2018



The Global Background Radiation & the EBL

The Extragalactic Background Light

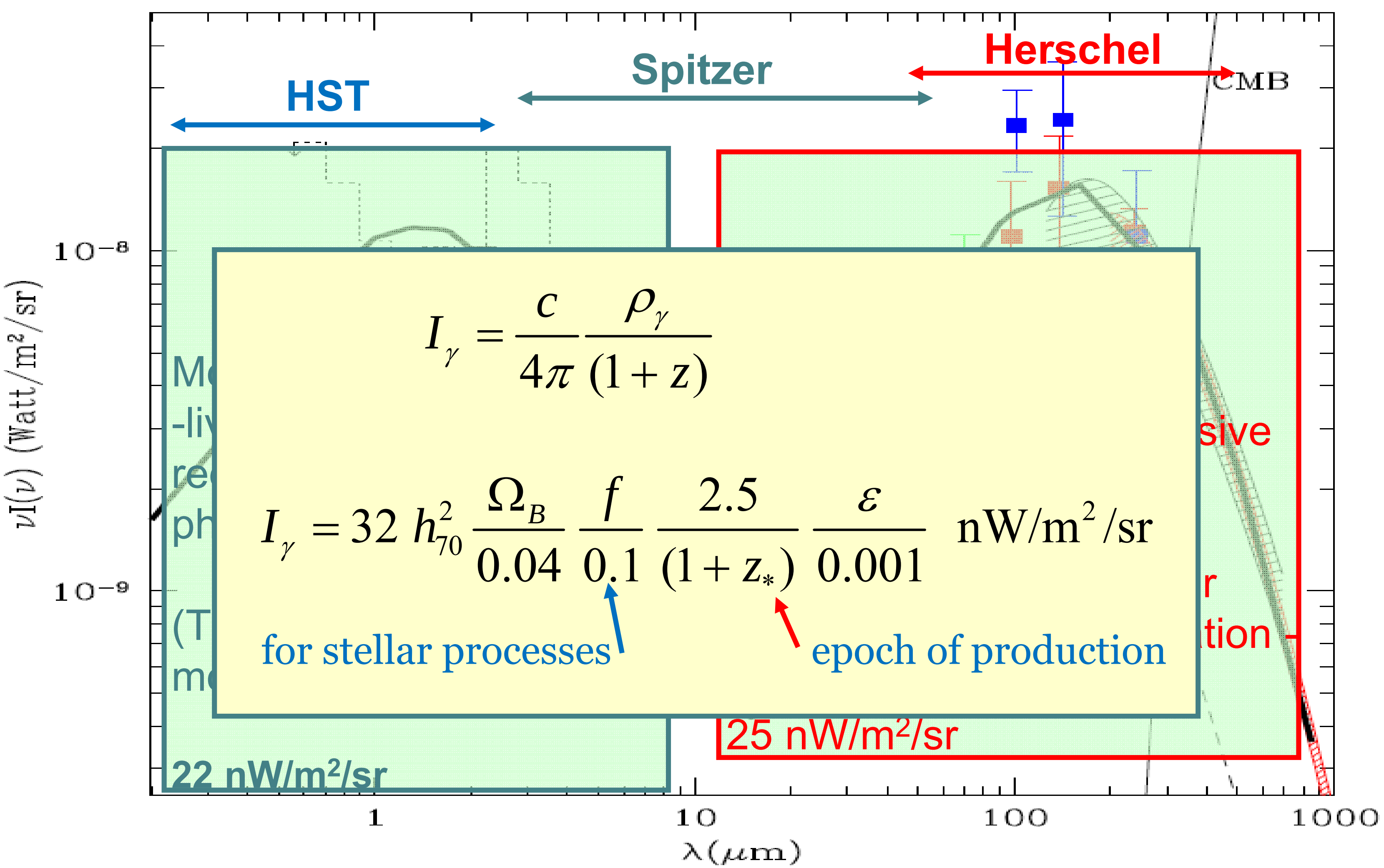
- Background radiations concern the whole history of astrophysical sources,
- They are the repository of all radiant energy produced by cosmic <u>sources</u> and cosmic <u>structures</u> since the Big Bang
- -- Point sources
- -- Diffuse structures and components
- Essential data to understand how the 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



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

$$I_\gamma = 32\ h_{70}^2\ \frac{\Omega_B}{0.04}\ \frac{f}{0.1}\ \frac{2.5}{(1+z_*)}\ \frac{\varepsilon}{0.001}\ \ \mathrm{nW/m^2/sr}$$

for stellar processes

epoch of production

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

WELL KNOWN ENERGY SOURCES

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

How much energy out of this? $\text{Energy} = \eta \rho_b c^2$

A solid constraint: mass in local Massive Dark Objects (MDO's):

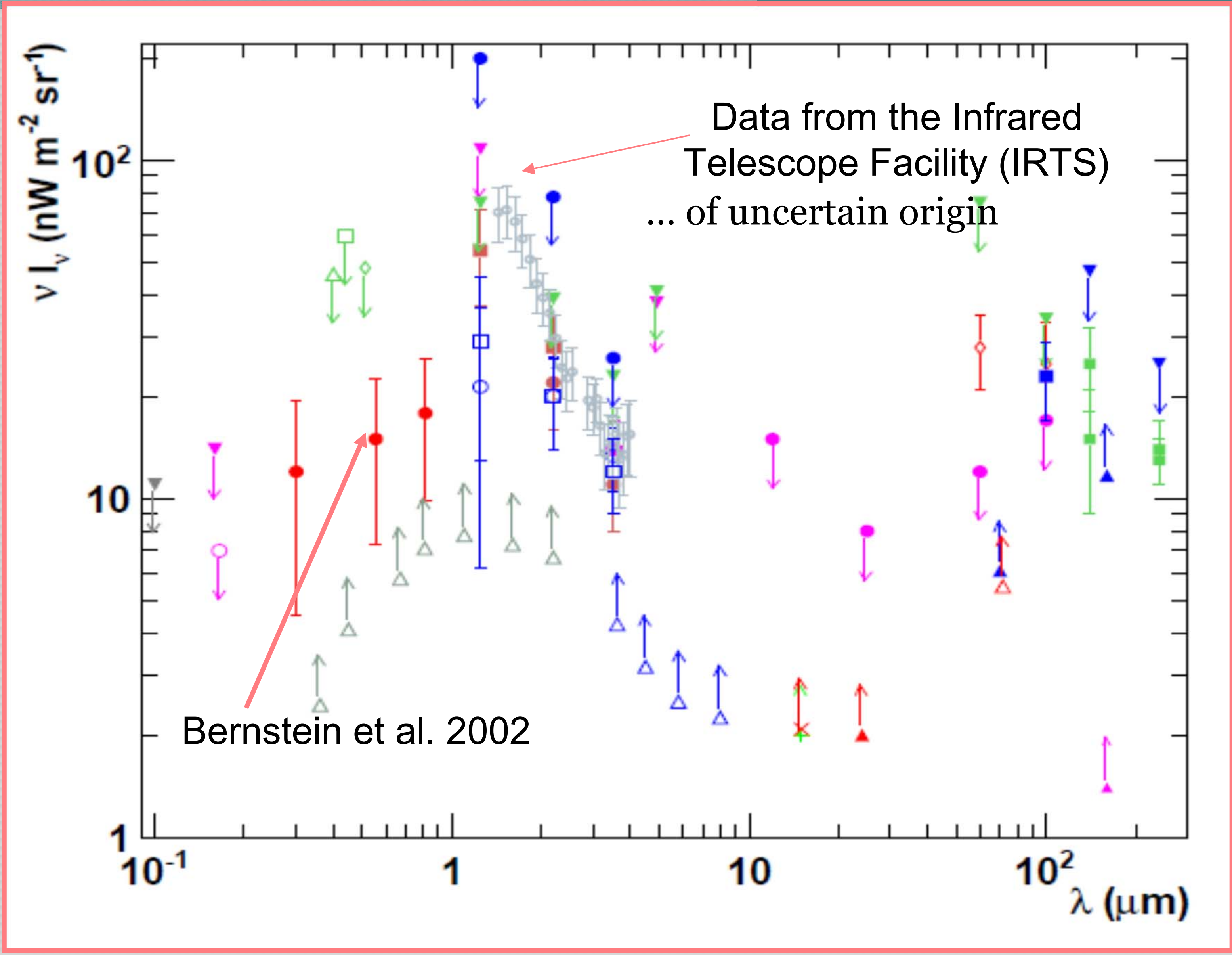
$M_{MDO} \sim 2\ 10^{-3}\ M_*$ (M_* : mass in spheroids Kormendy & Richstone)

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

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

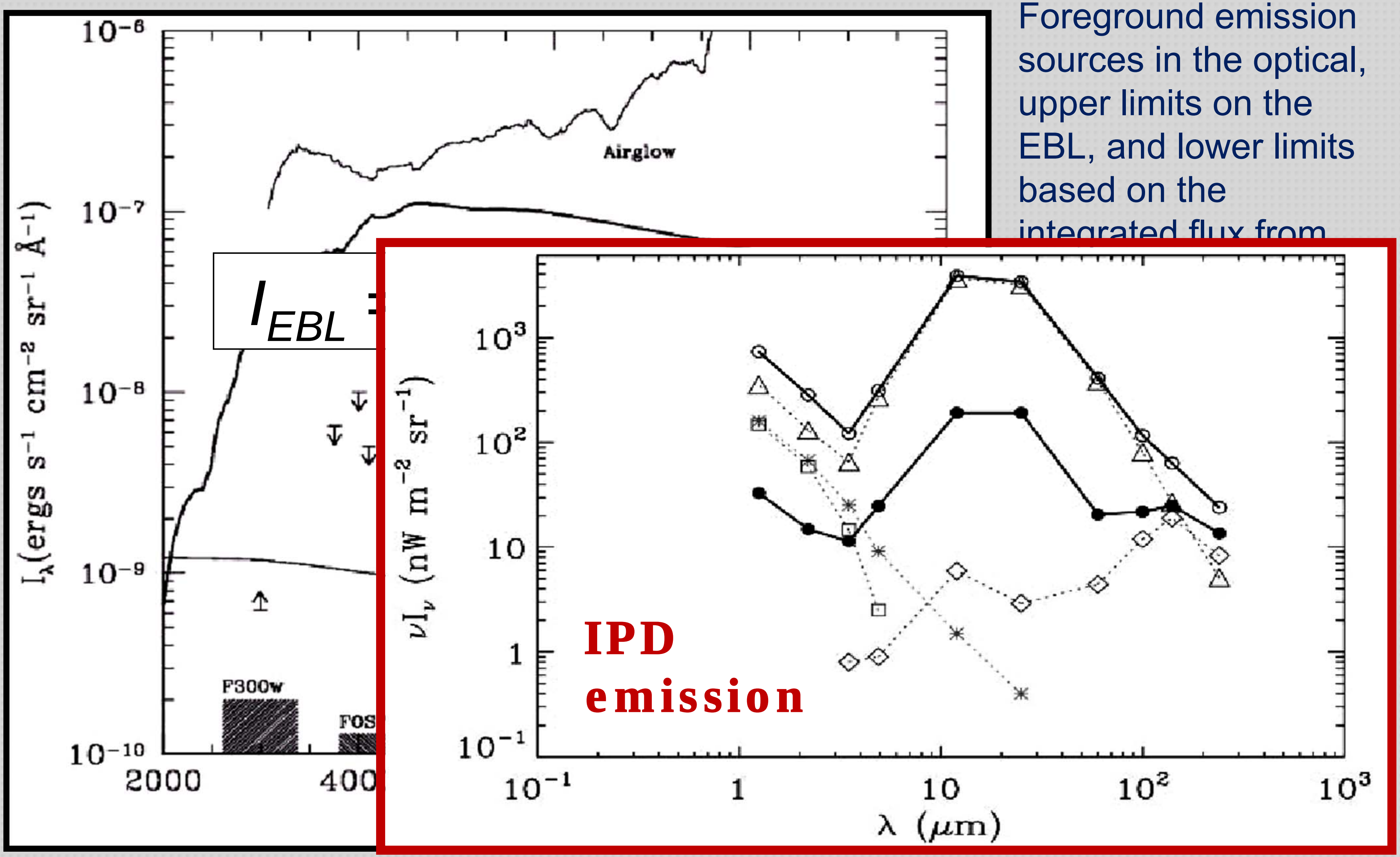
The Extragalactic Background Light

- Measurements and theoretical evaluations of the local EBL and its evolution with cosmic time are highly controversial



Mazin & Raue (2007)

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

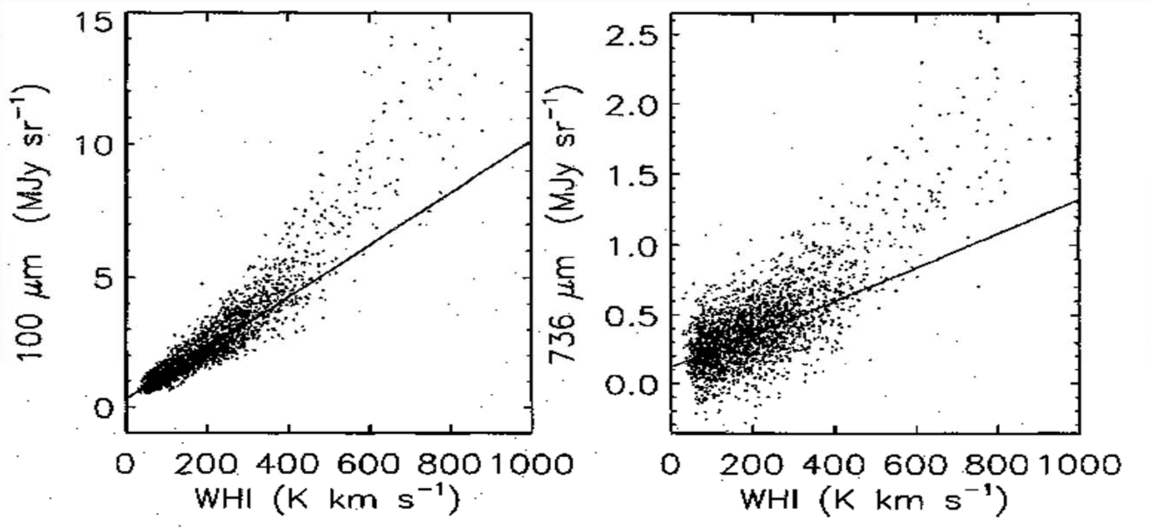
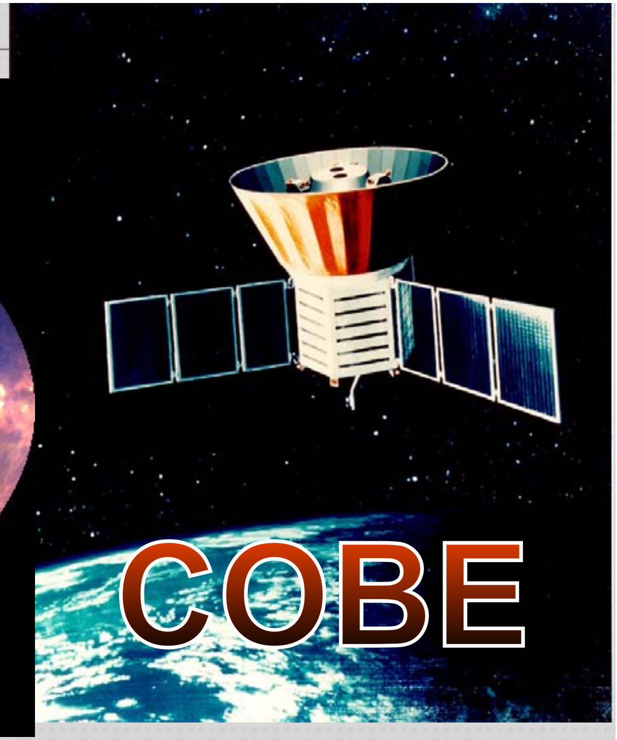
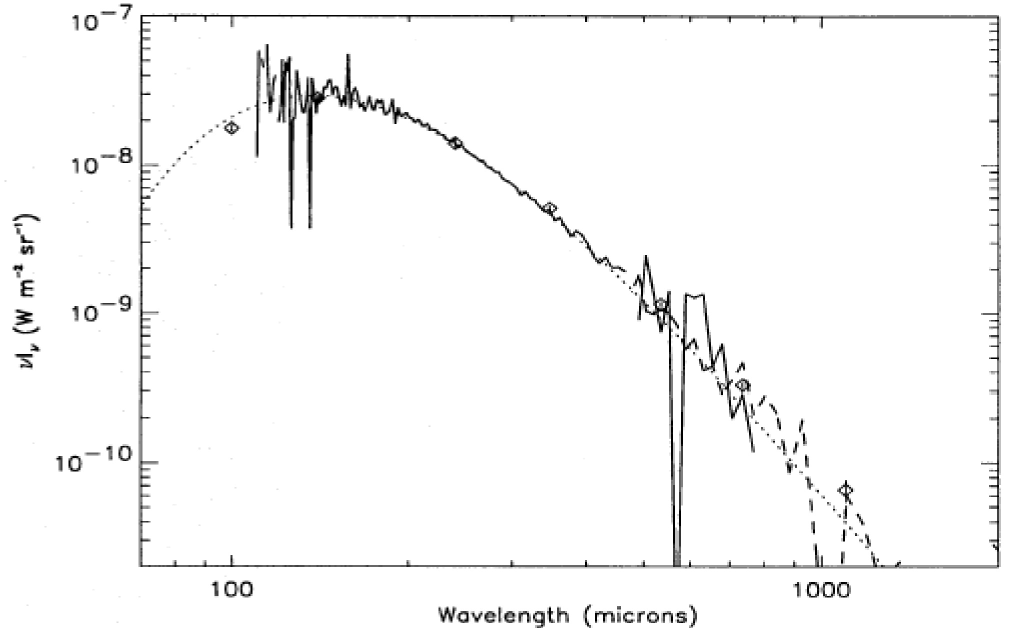


Fig. 1. Correlation between IR and HI emission at 100 μm (DIRBE data, smoothed to 7° resolution) and at 736 μm (FIRAS LLSS data, averaged between 600 and 900 μm). The lines represent fits to data at $W_{\rm HI} < 250$ K km s^{-1}.



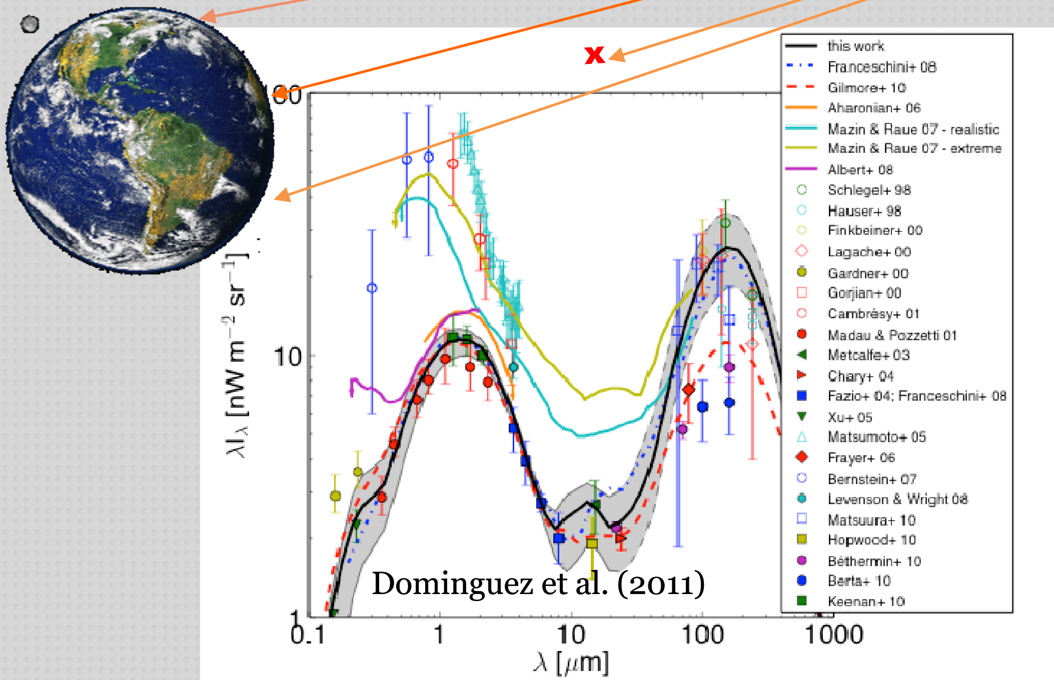
The sub-millimeter: the only spectral region where the total EBL has been reliably measured



- In all other bands, attempts for direct measurements essentially unsuccessful

- IN CONCLUSION, EBL direct measurements particularly difficult (virtually impossible) where they would be most interesting! (UV – optical – IR)

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



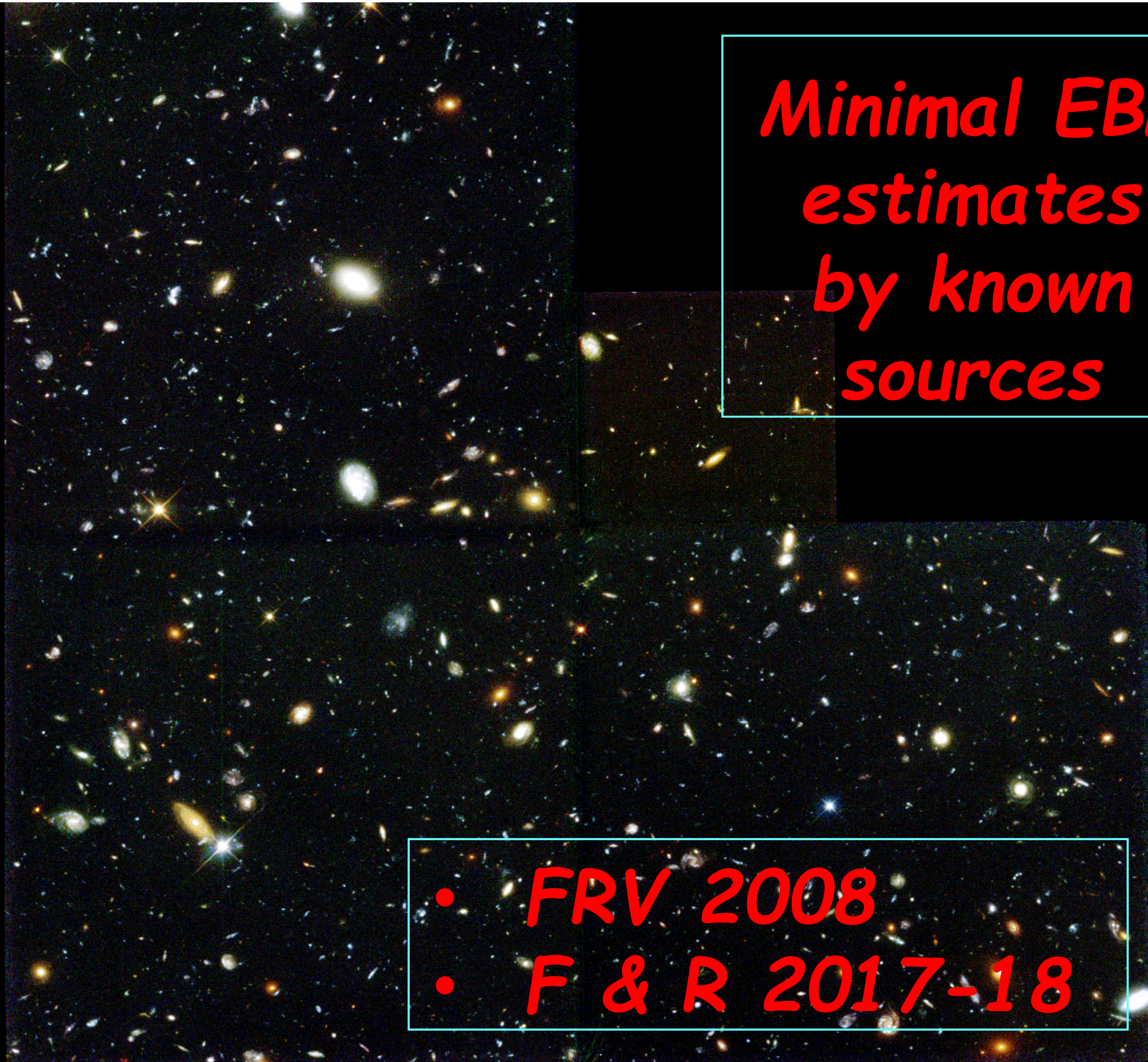
VHE photon + diffuse light
→ electron-positron pair production

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

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

Many published attempts to describe the EBL

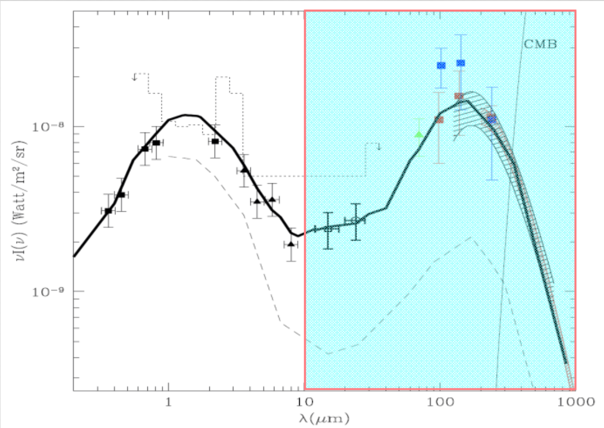
- Stecker & de Jager (1993)
- Stanev & AF (1998)
- Malkan & Stacker (1998)
- Kneiske et al. (2002)
- FRV (2008)
- Finke, Razzaque, Dermer (2010)
- Kneiske & Dole (2010)
- Dominguez et al. (2011)
- Gilmore et al. (2012)
- Stecker, Scully & Malkan (2016)



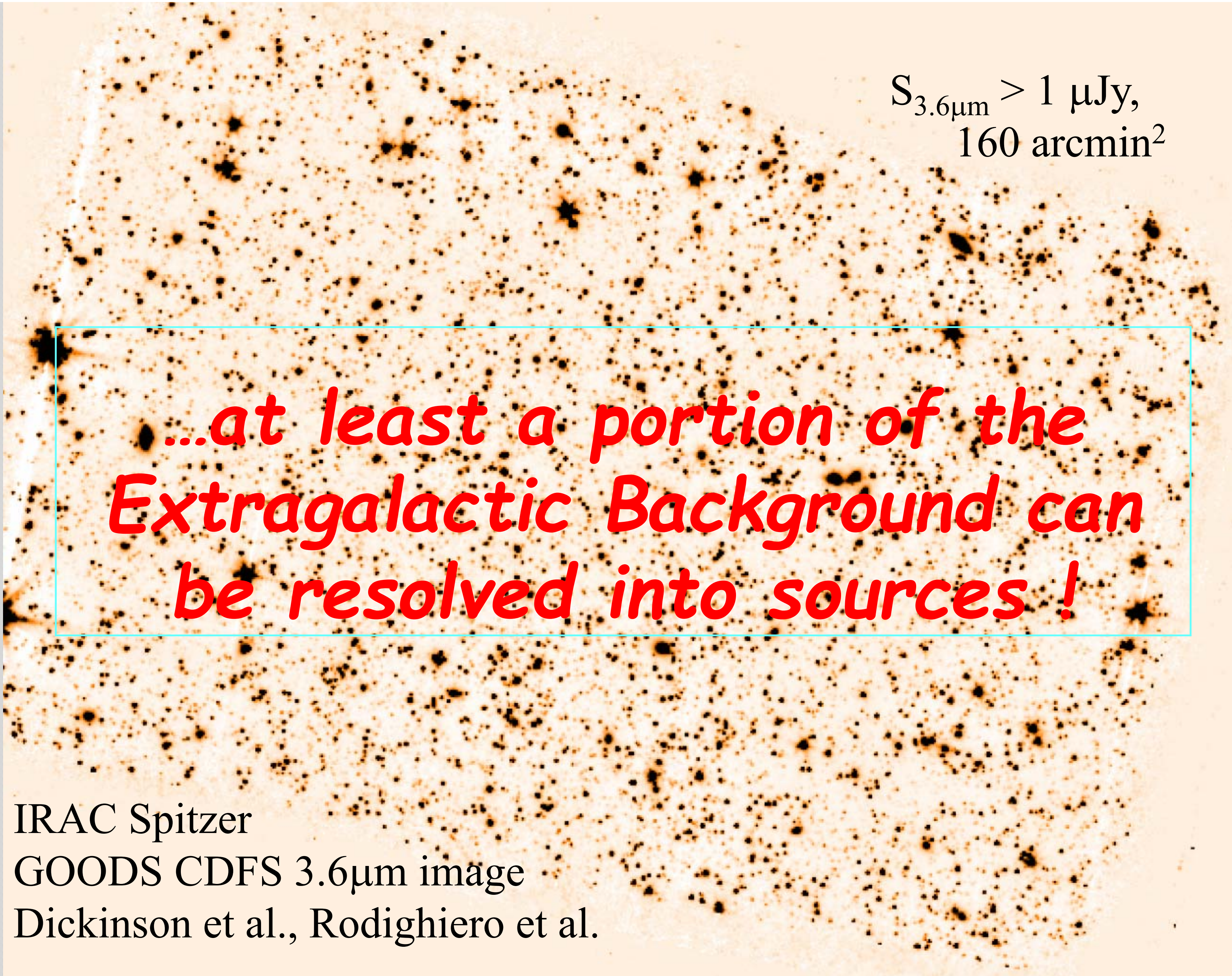
Minimal EBL estimates by known sources

- FRV 2008
- F & R 2017-18

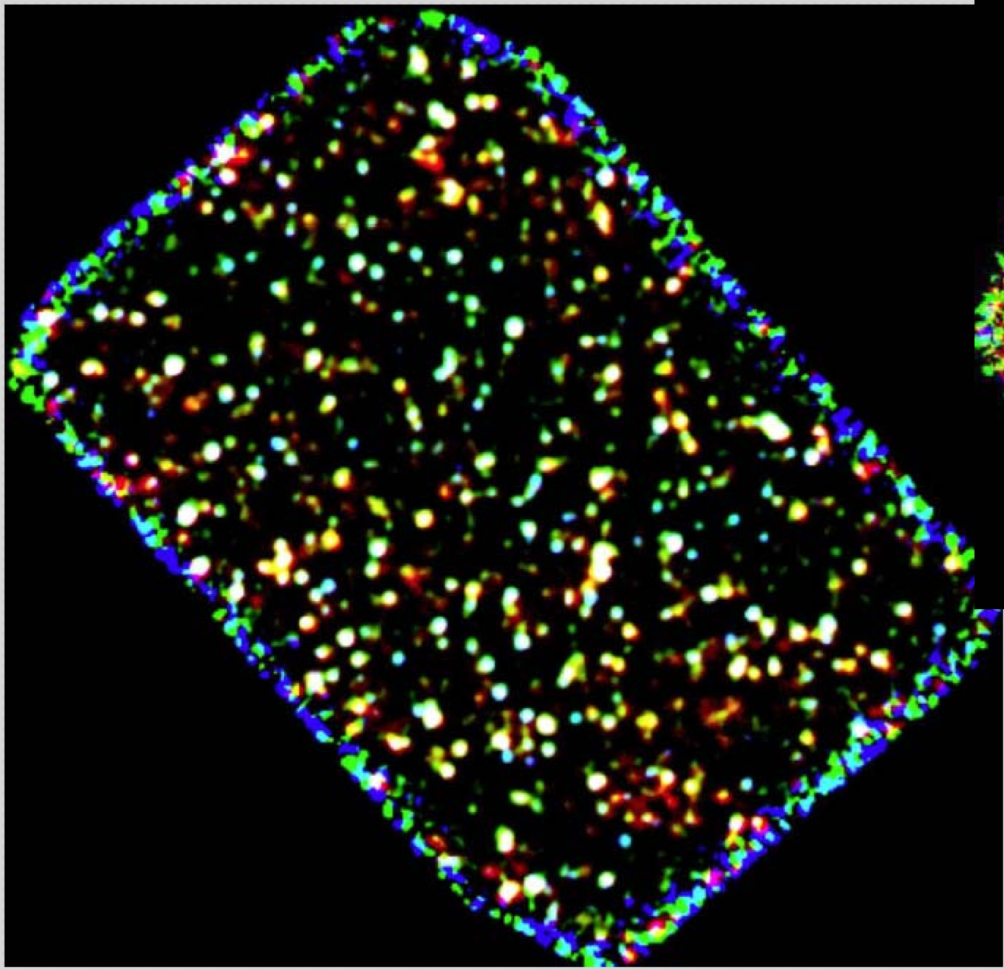
Hubble Deep Field HST WFPC2

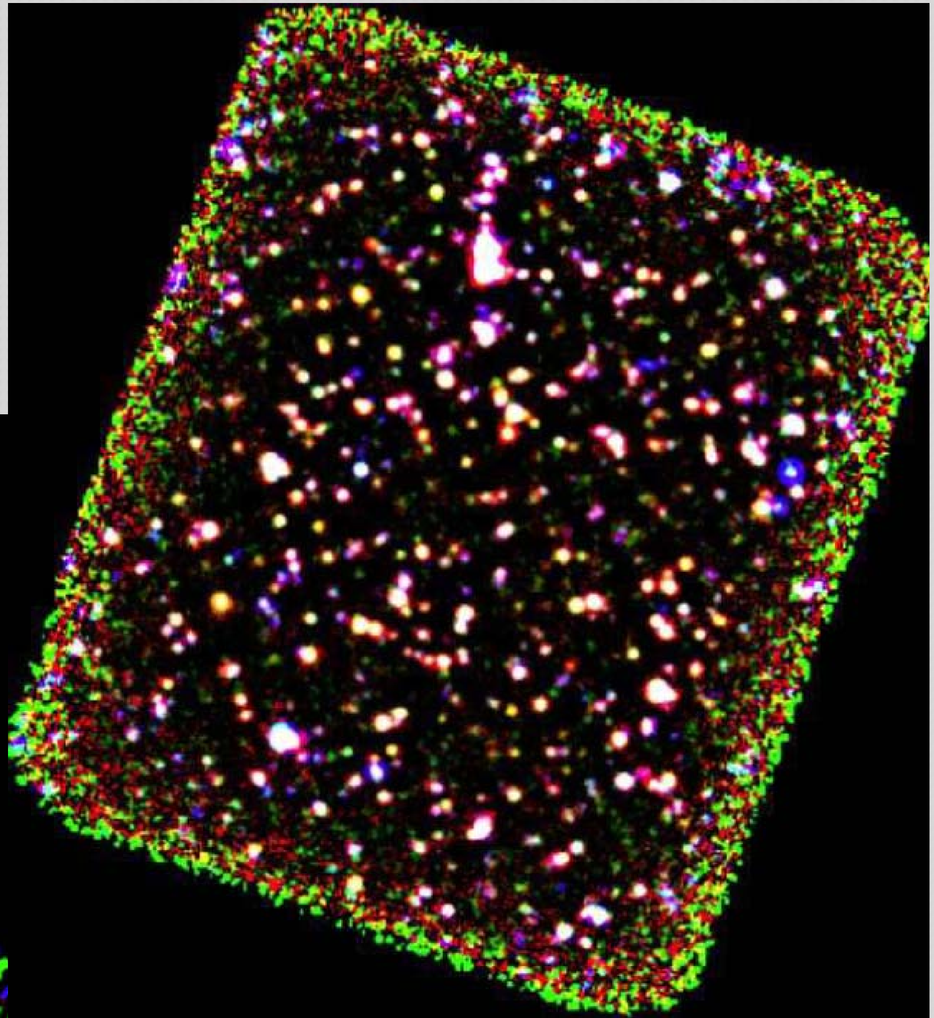


Spitzer & HERSCHEL observatories have sampled the elusive sources of the IR EBL


$S_{3.6\mu m} > 1\ \mu Jy$,
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)

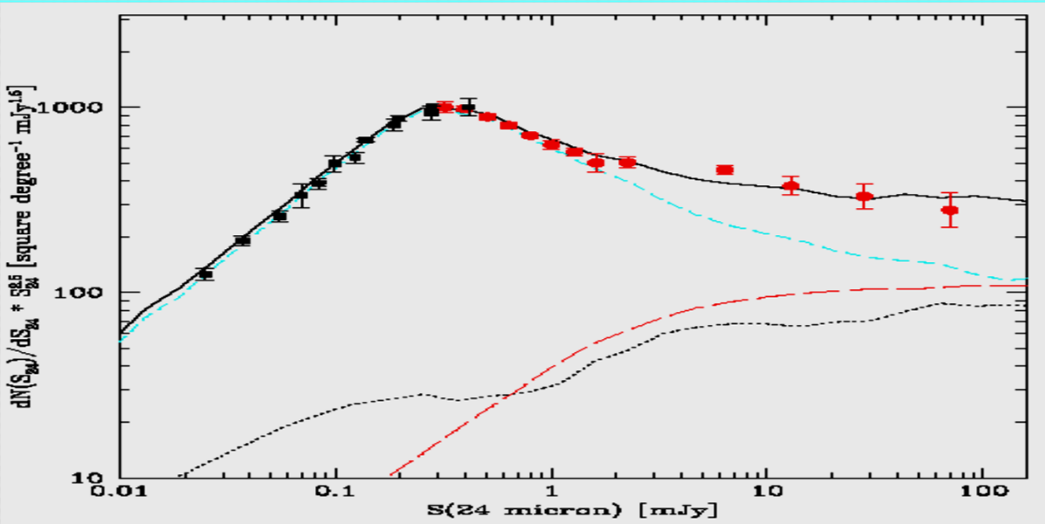


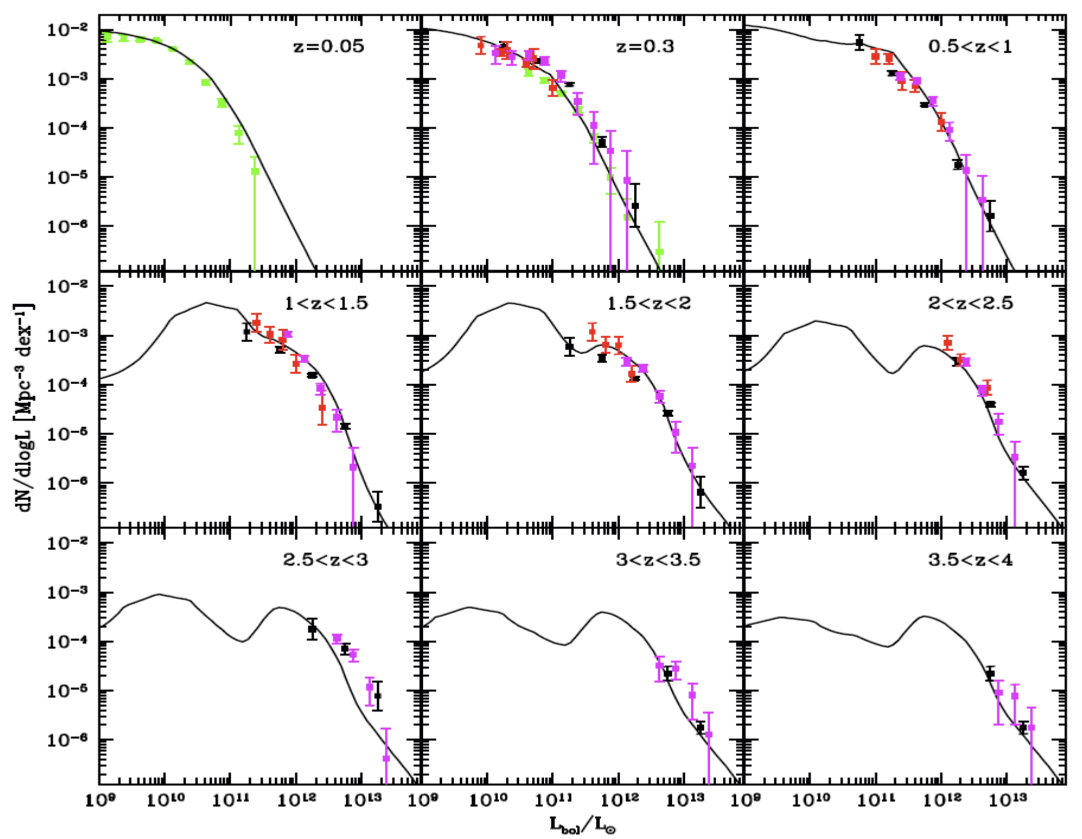


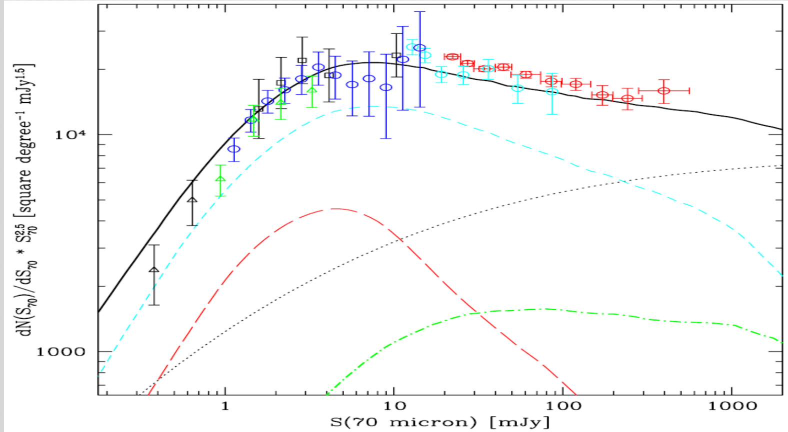
GOODS–south (10′×10′) at 24 μm (blue), 100 μm (green) and 160 μm (red)

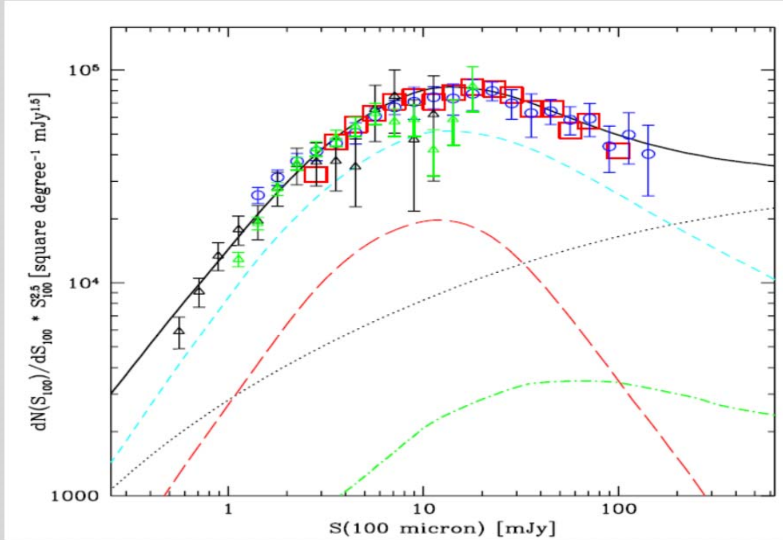
Elbaz et al. 2011

Source number counts & luminosity functions









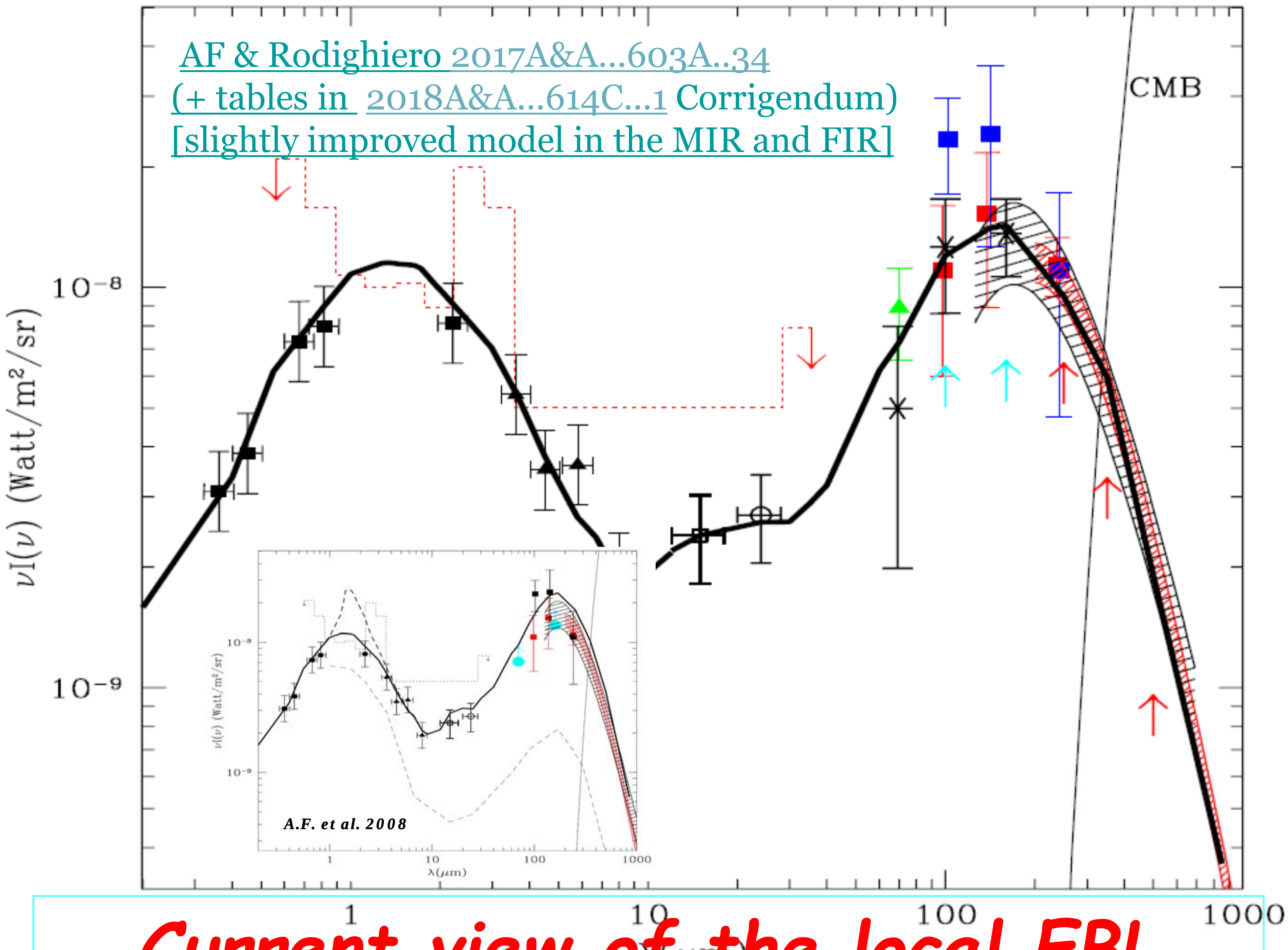
Galaxy number counts and the source contribution to the cosmic background emissivity

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

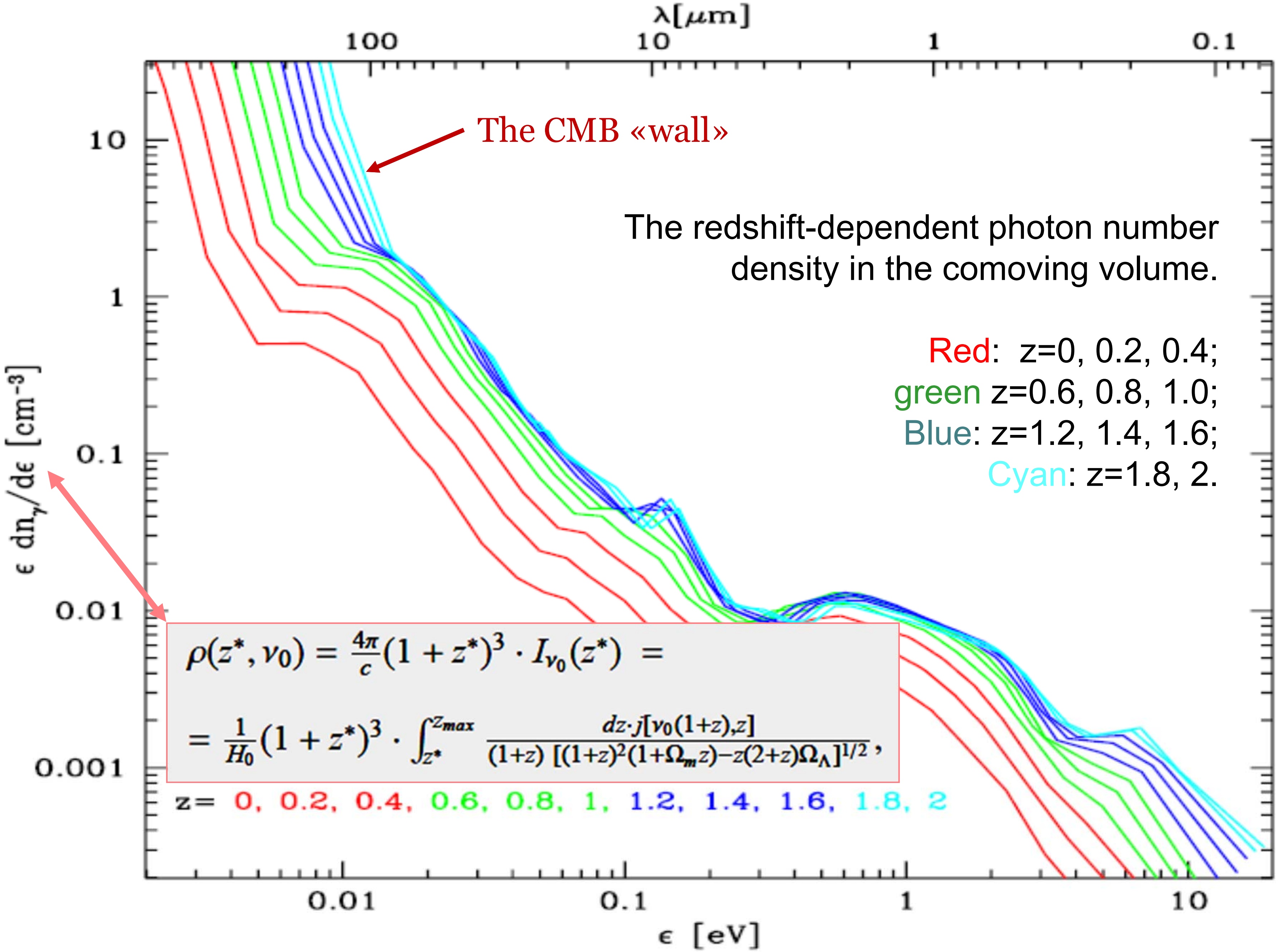
$$j_{eff}(z) = \int_{L_{min}}^{\min[L_{max}, L(S_d, z)]} d\log L\ L\ n_c(L, z) K(L, z)$$

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

AF & Rodighiero 2017A&A...603A..34
(+ tables in 2018A&A...614C...1 Corrigendum)
[slightly improved model in the MIR and FIR]



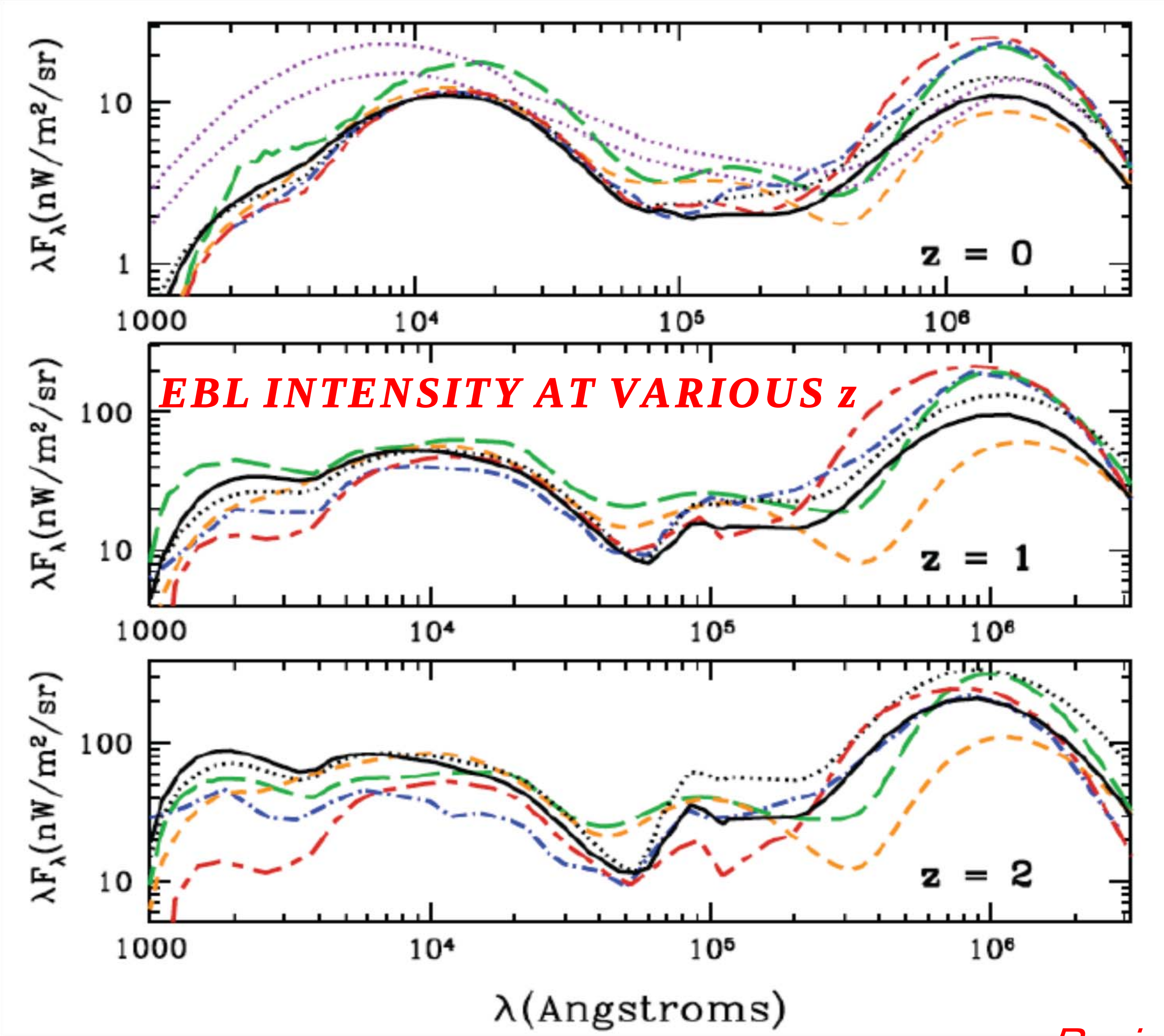
Current view of the local EBL



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

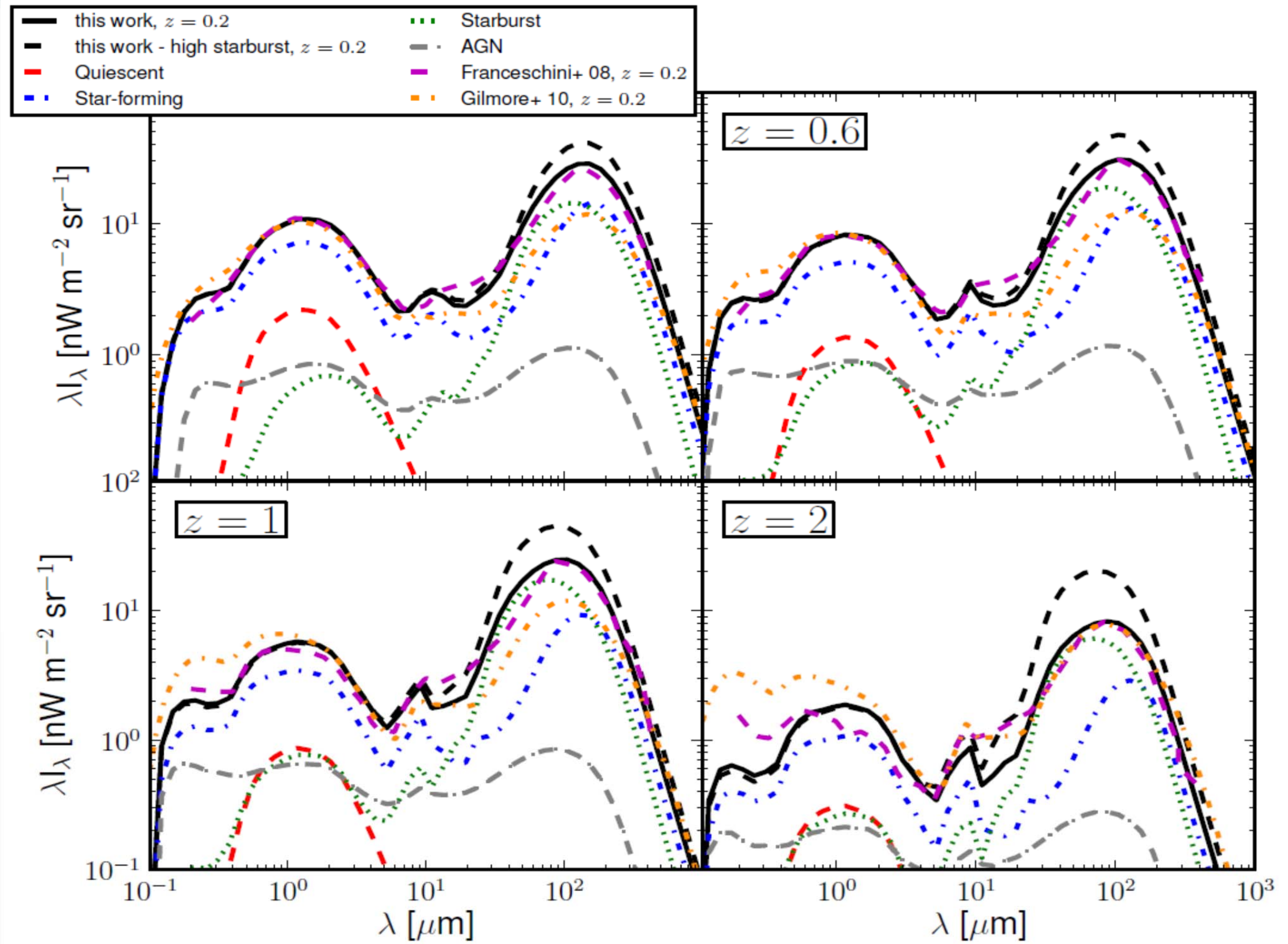
$$= \frac{1}{H_0}(1+z^*)^3 \cdot \int_{z^*}^{z_{max}} \frac{dz \cdot j[\nu_0(1+z), z]}{(1+z)\ [(1+z)^2(1+\Omega_m z) - z(2+z)\Omega_\Lambda]^{1/2}},$$

Controversial modelling 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



A. Dominguez et al. 2011

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:

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

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

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

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

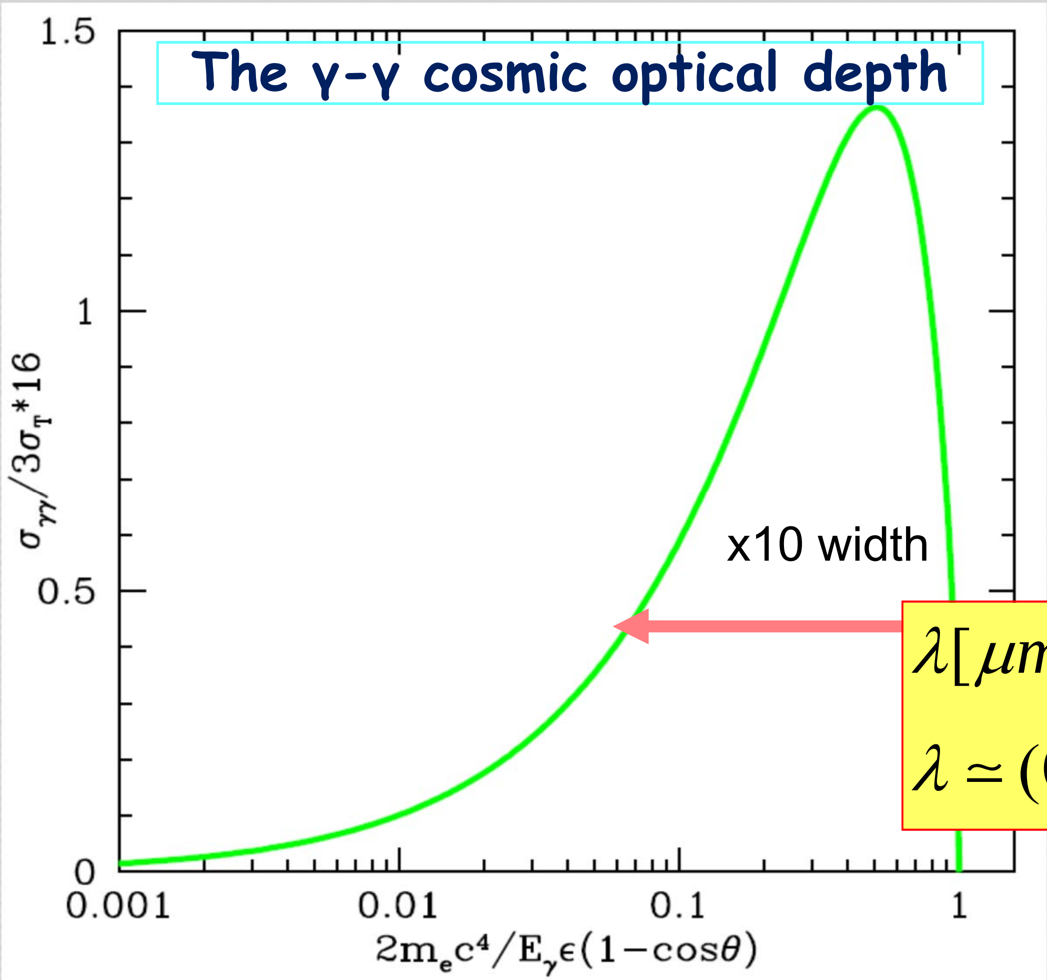
$$dt/dz = \frac{1}{H_0(1+z)} \left[(1+z)^2(1+\Omega_m z) - z(z+2)\Omega_\Lambda\right]^{-1/2}.$$

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...

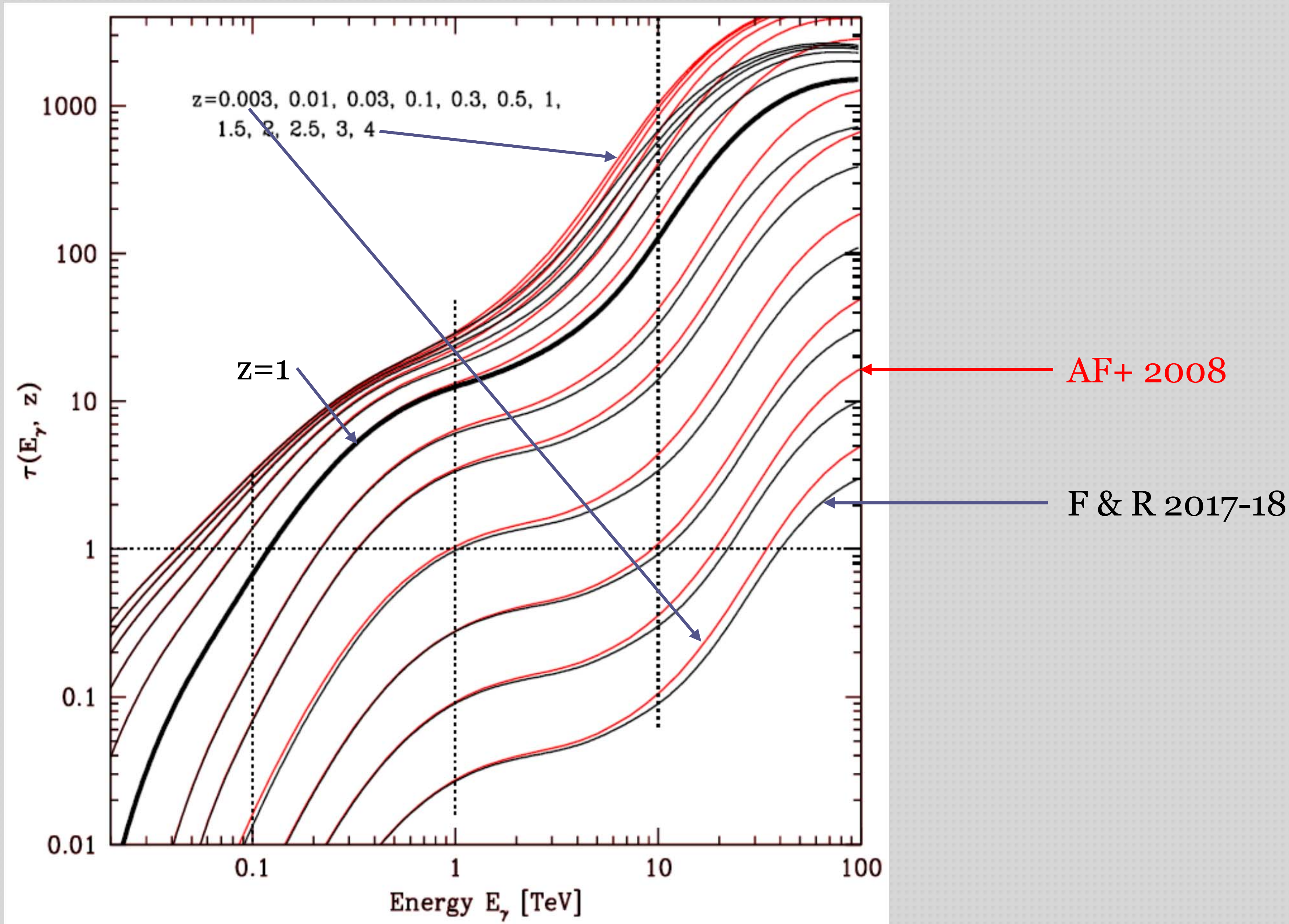


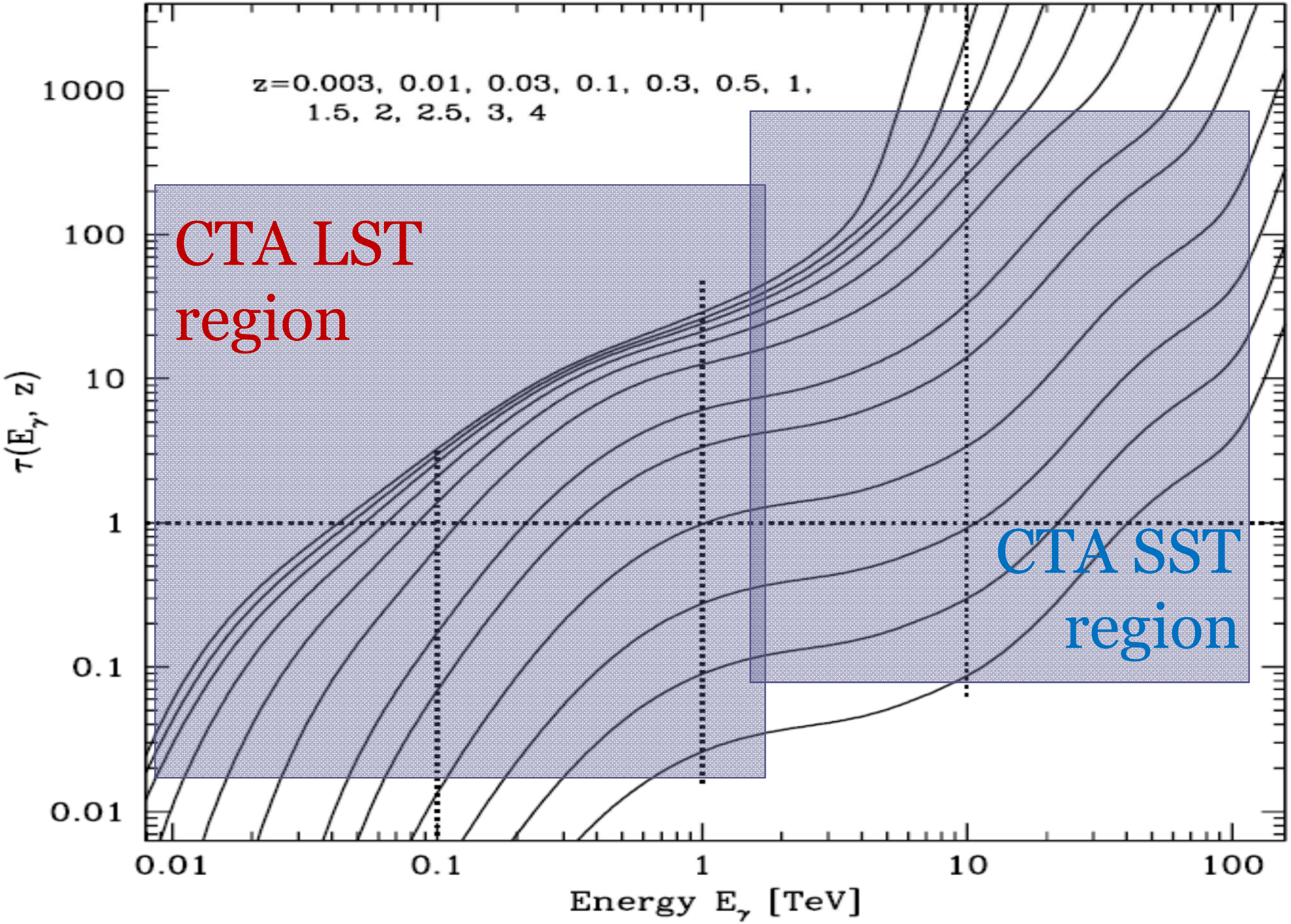
The γ-γ cross-section is quite broad...

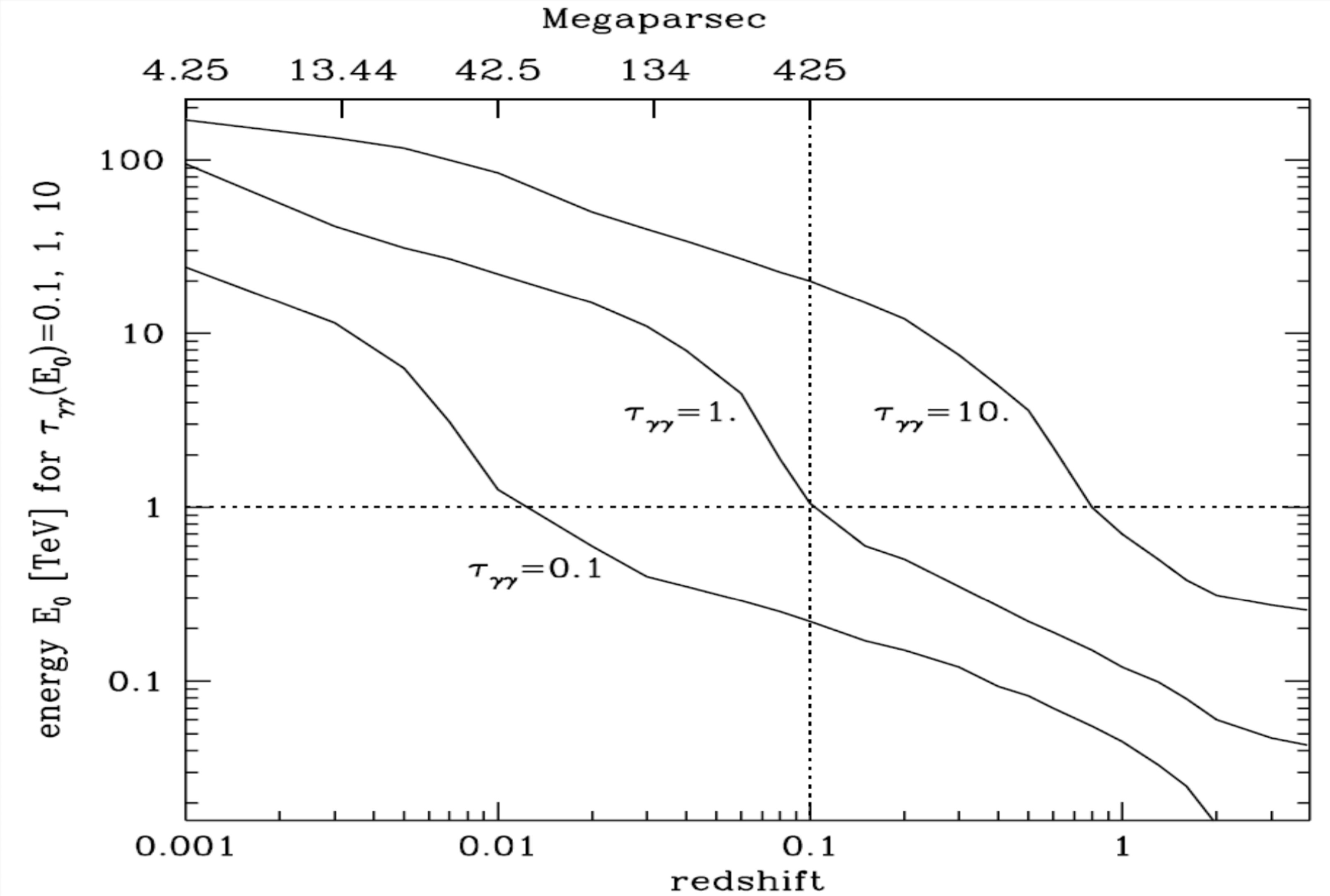
$$\lambda[\mu m] \simeq 1.2 E_\gamma [TeV] \times (1+z')^2$$

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

z' is where the γ-γ interaction happens

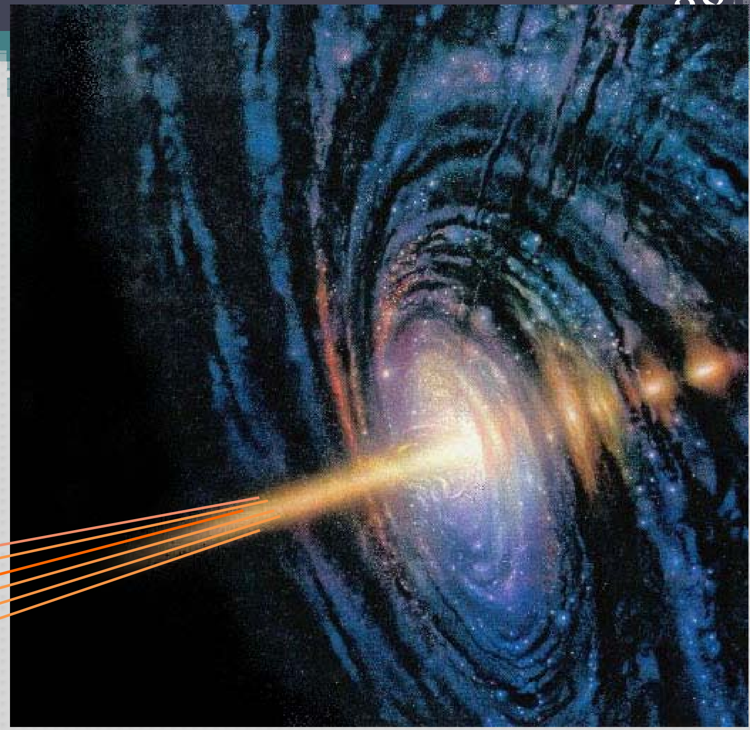

z=0.003, 0.01, 0.03, 0.1, 0.3, 0.5, 1,
1.5, 2, 2.5, 3, 4
z=1
1000
100
10
1
0.1
0.01
τ(Eγ, z)
0.1
1
10
100
Energy Eγ [TeV]
AF+ 2008
F & R 2017-18

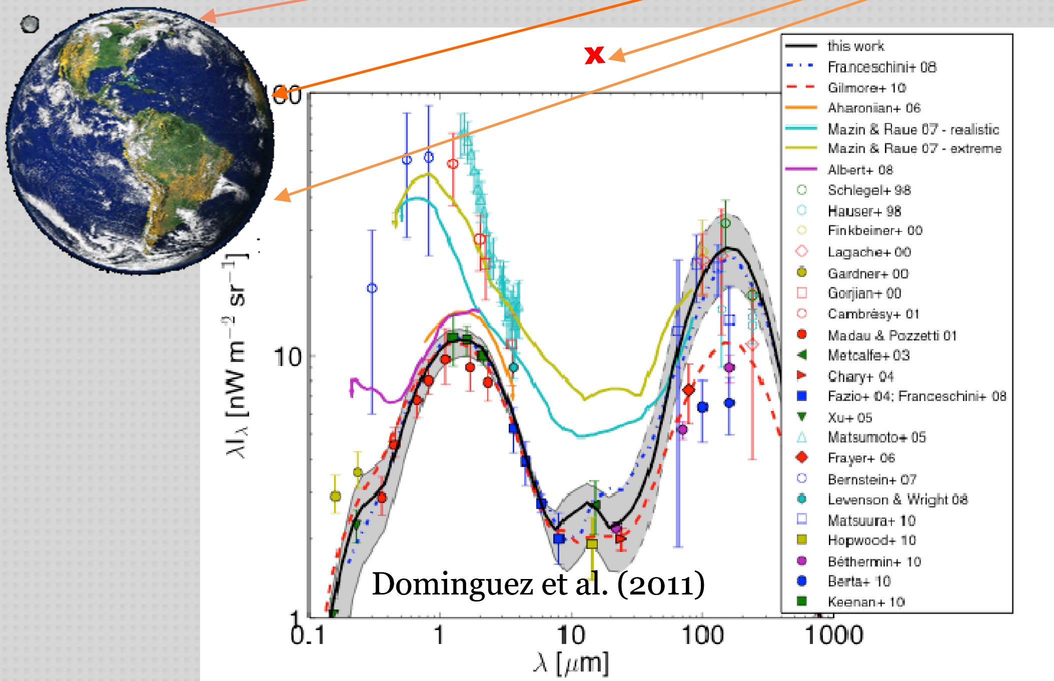

z=0.003, 0.01, 0.03, 0.1, 0.3, 0.5, 1,
1.5, 2, 2.5, 3, 4
CTA LST
region
CTA SST
region
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
Energy E_γ [TeV]
$\tau(E_\gamma, z)$



The cosmological γ-γ horizon

Applications from VHE observations of blazars



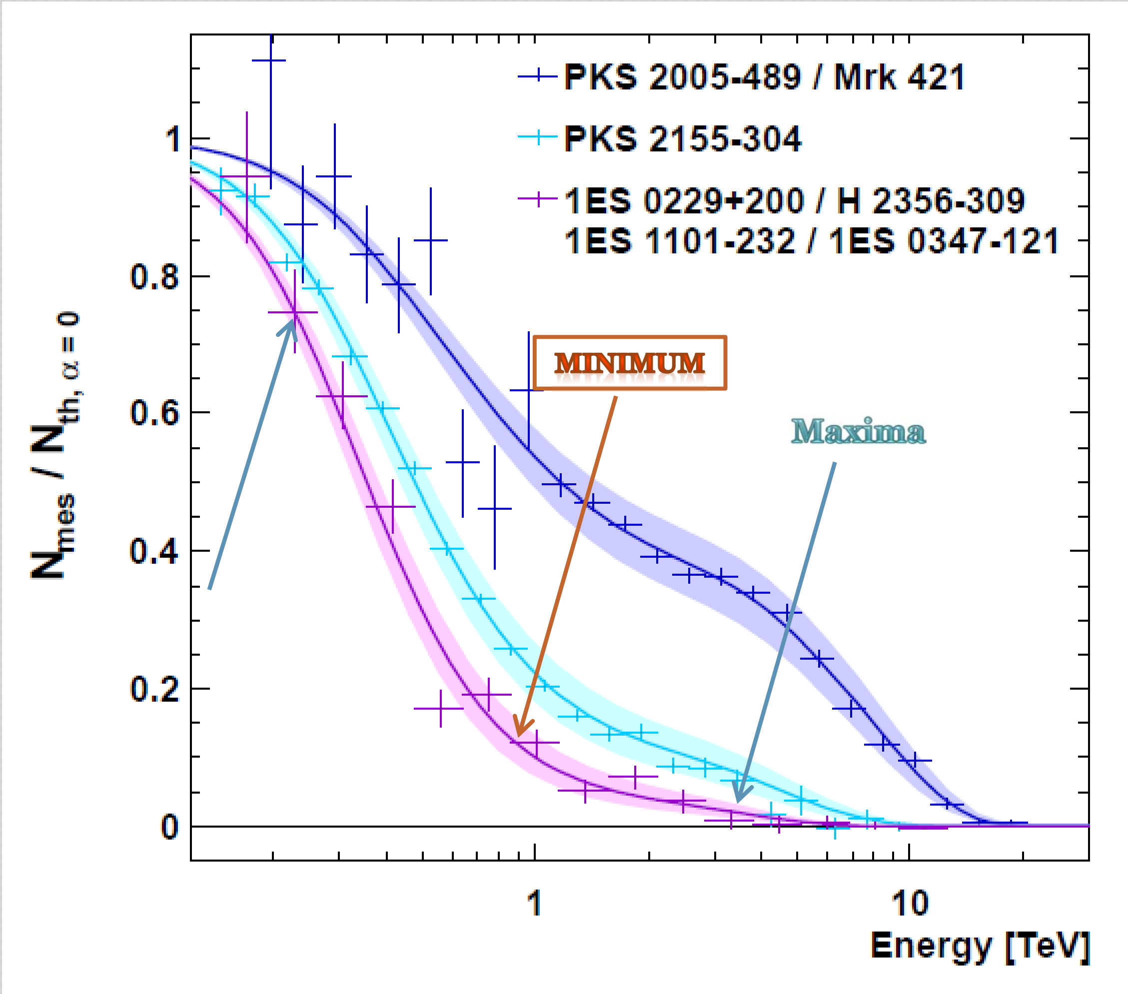


VHE photon + diffuse light → electron-positron pair production

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

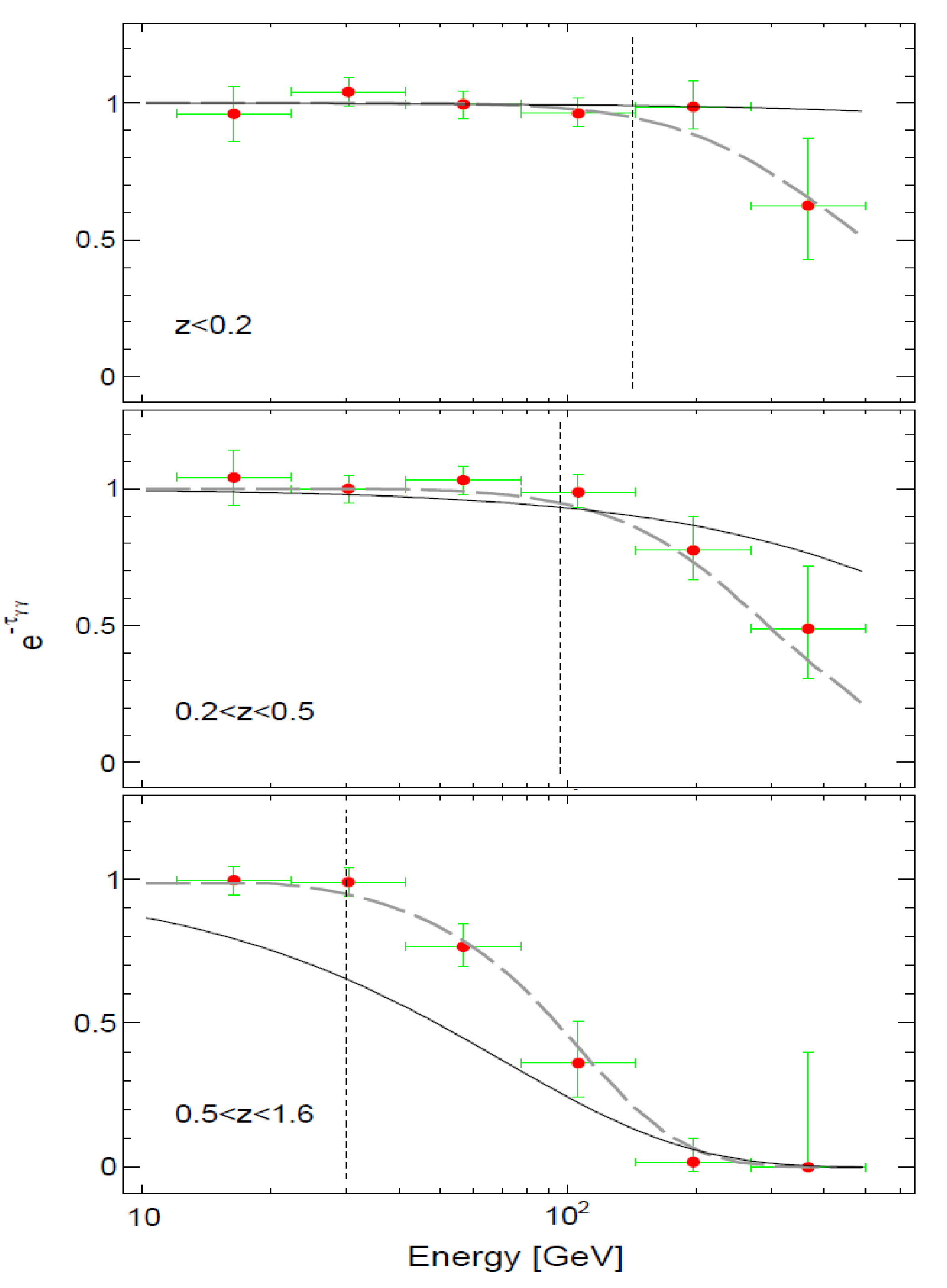
Absorption:

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



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)

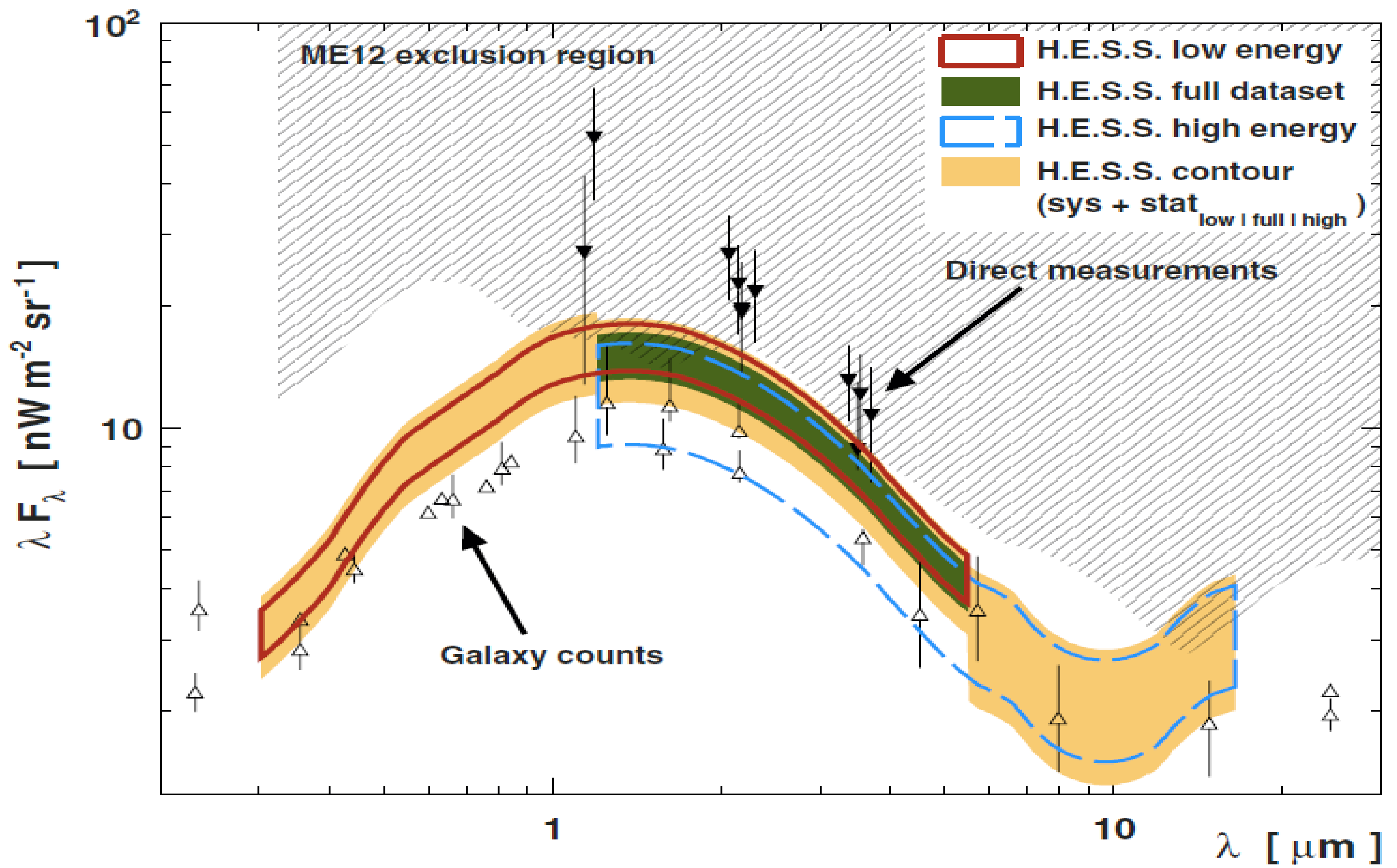
Ackermann et al. 2012



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.



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

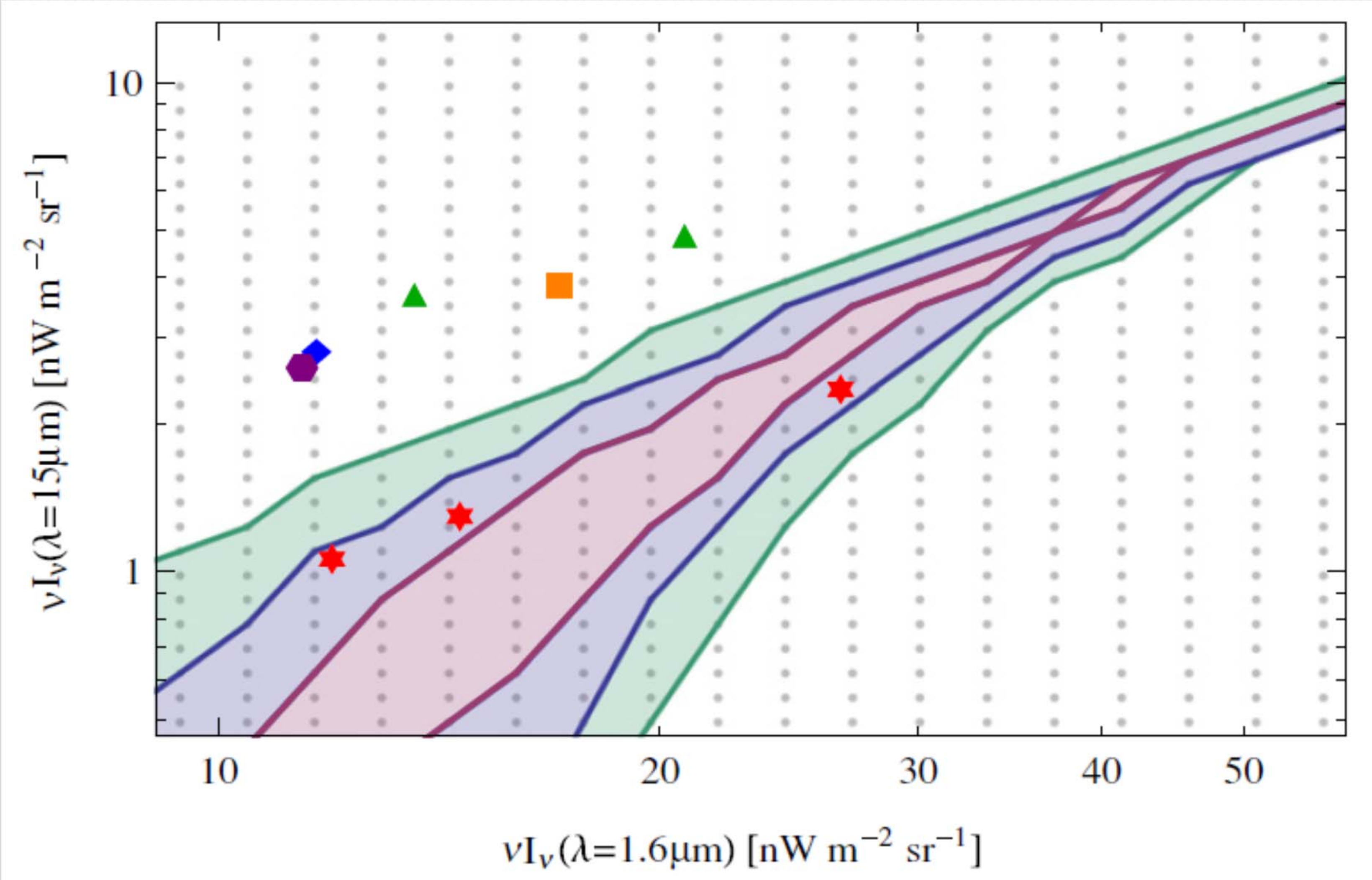
i.e. 30% higher than FRV2008 @ 1.4 μm

s.

o derive the

ctively 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.

Orr, Krennrich, Dwek (2011)



Models by Aharonian et al. (2006, red stars), Stecker et al. (2006, green triangles), Franceschini et al. (2008, blue diamond), Kneiske et al. (2004, orange square), and Dominguez et al. (2011, purple hexagon)

Mazin, Dominguez + 2017

TABLE 1. The data set used in this analysis.

Source Name	AGN Type	Redshift z	Data Taken Period	Effective Time (h)
Mrk 421	HBL	0.031	2013 Apr 10-19, 2014 Apr 26	40.4
1ES 1959+650	HBL	0.048	2015 Nov 6-18	4.8
OT 546 (1ES 1727+502)	HBL	0.055	2015 Oct 11 - Nov 2	6.4
BL Lacertae	HBL	0.069	2015 June 15	1.0
1ES 0229+200	HBL	0.140	2012 - 2015	105.2
1ES 1011+496	HBL	0.212	2014 Feb - Mar 7	11.8
PKS 1510-089	FSRQ	0.361	2015 May 18 - 19	2.4
PKS 1222+216	FSRQ	0.432	2010 Jun 18	0.5
PG 1553+113	HBL	0.43-0.58	2012 - 2016	66.3
PKS 1424+240	HBL	0.601	2014 Mar 24 - Jun 18	28.2
PKS 1441+25	FSRQ	0.939	2015 Apr 18 - 23	20.1
B 0218+35	FSRQ	0.944	2014 Jul 25 - 26	2.1
Total				**289.2**

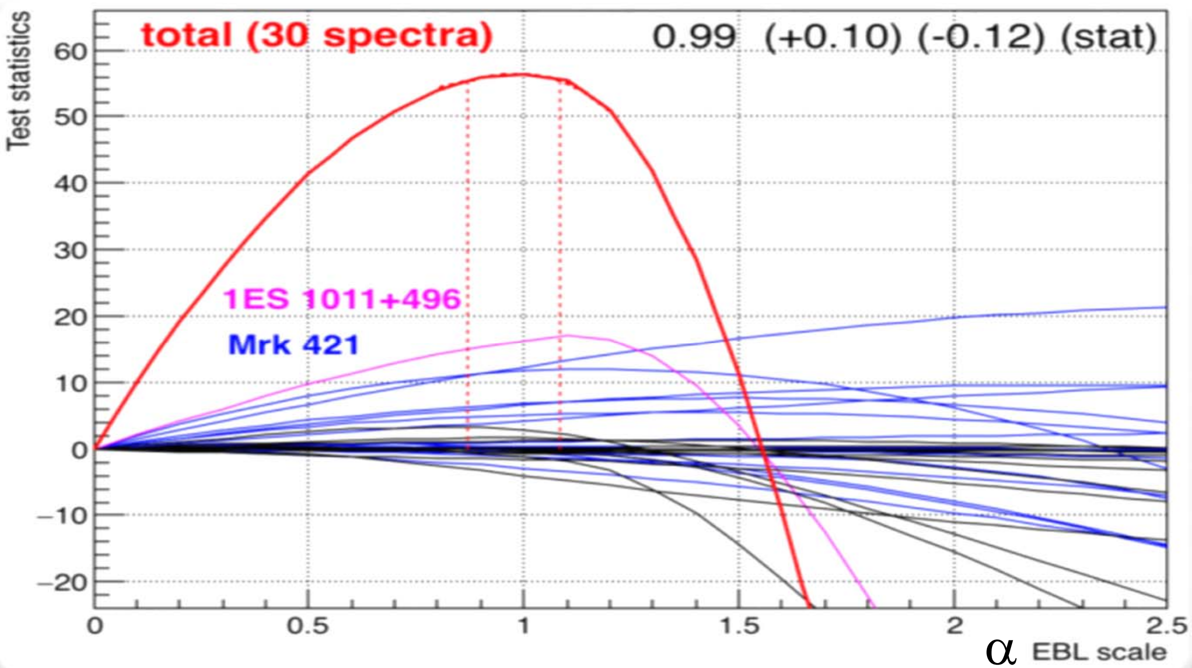
MAGIC observations of 12 blazars

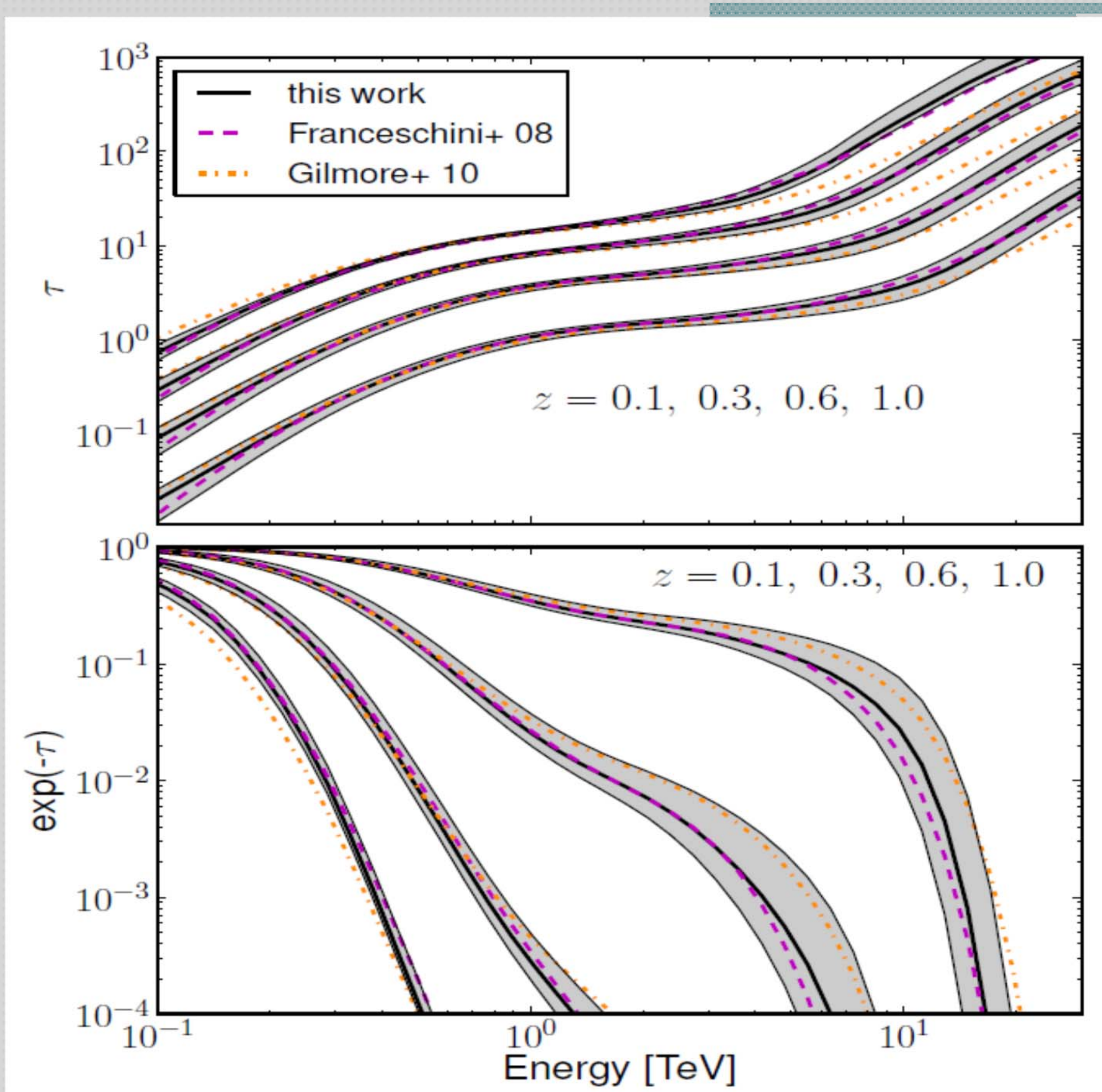
$\alpha = 0.99(+0.15)(-0.56)$

(including systematics)

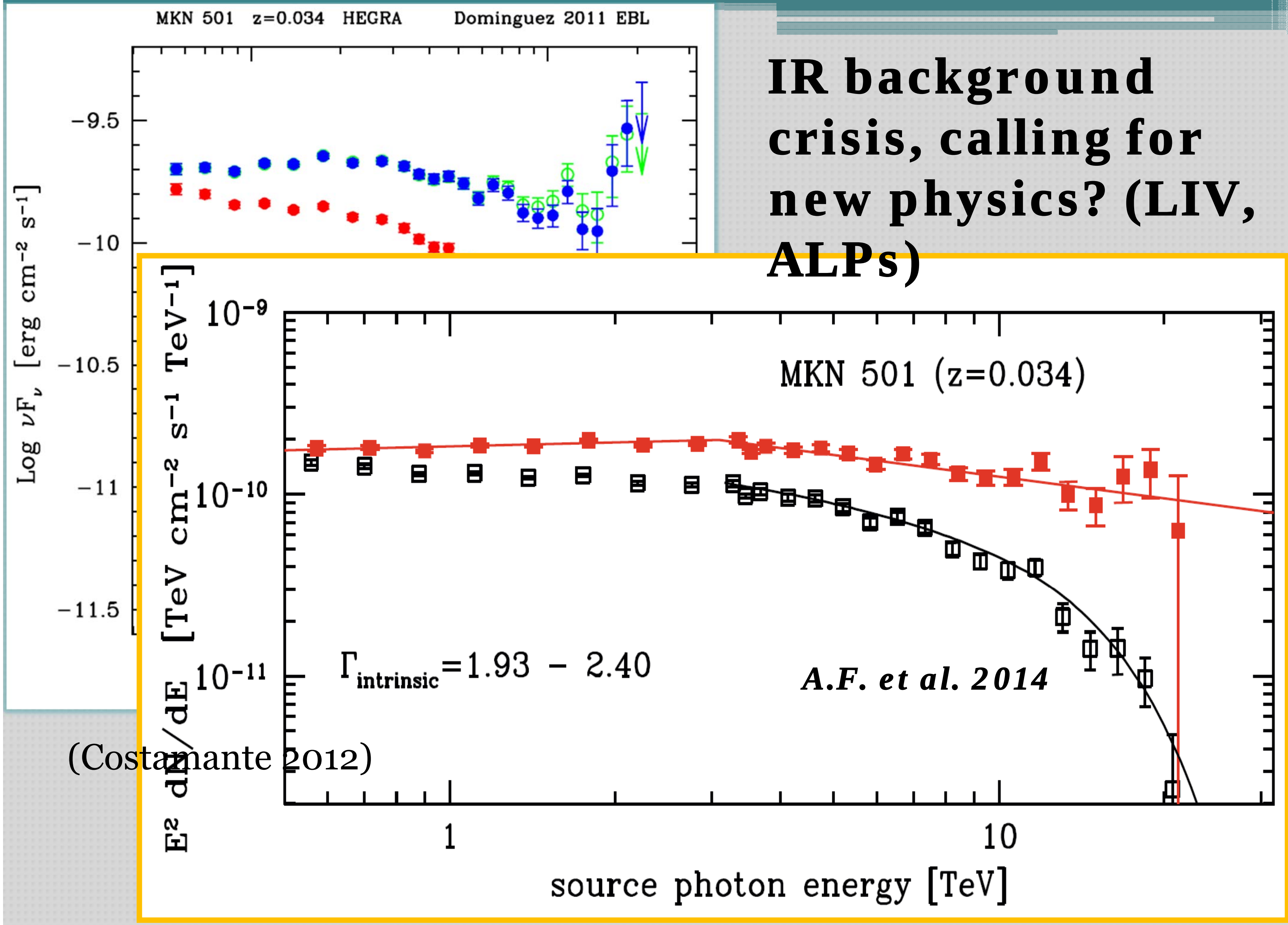
- Reference model by Dominguez + 2011
- (similar to FRV08)

$$\left(\frac{dF}{dE}\right)_{obs} = \left(\frac{dF}{dE}\right)_{int} \times \exp(-\alpha \times \tau(E,z))$$





A. Dominguez et al. 2011



IR background crisis, calling for new physics? (LIV, ALPs)

(Costamante 2012)

So, with current instrumentation, no much more than confirmation of our best guessed EBL spectral intensity and time-evolution up to z≈1...

→ **New facilities needed for substantial progress**

What is the Reionization Era?

A Schematic Outline of the Cosmic History

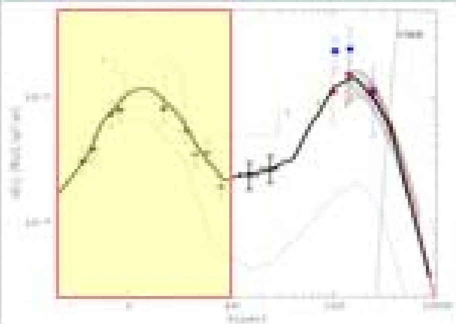
Time since the Big Bang (years)

←The Big Bang

~ 300

~ 5

~ 13 billion



Detecting the integrated background from the first-light sources with CTA LST

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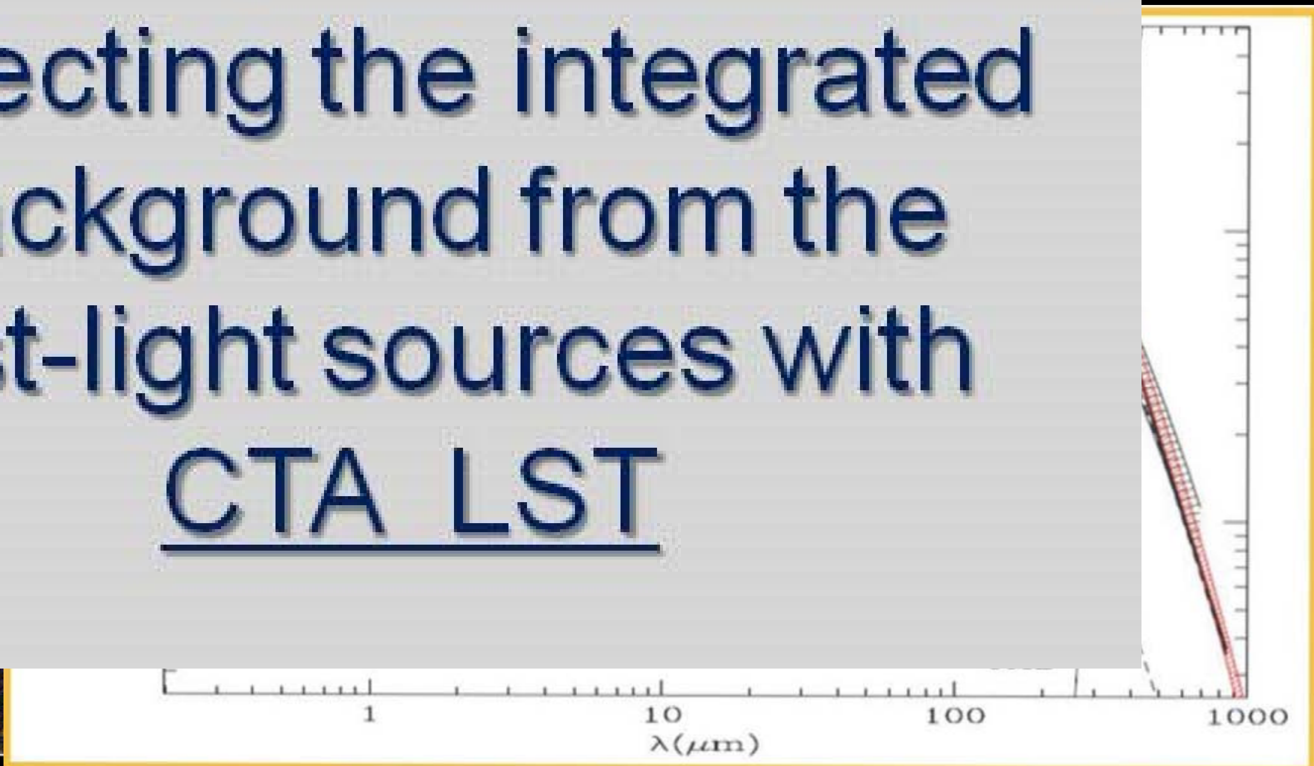
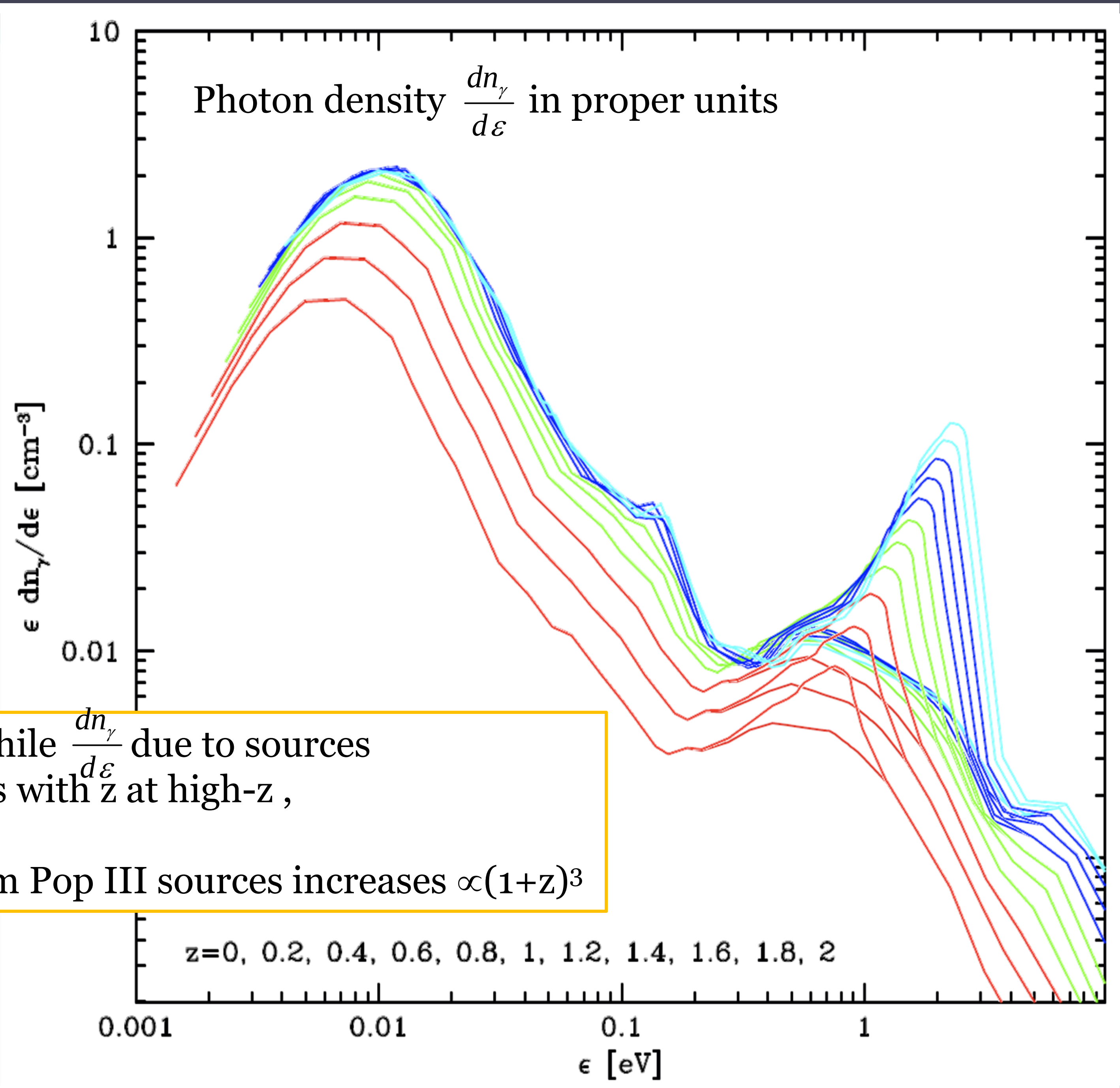
logical
ndrum



S.G. Djorgovski et al. & Digital Media Center, Caltech

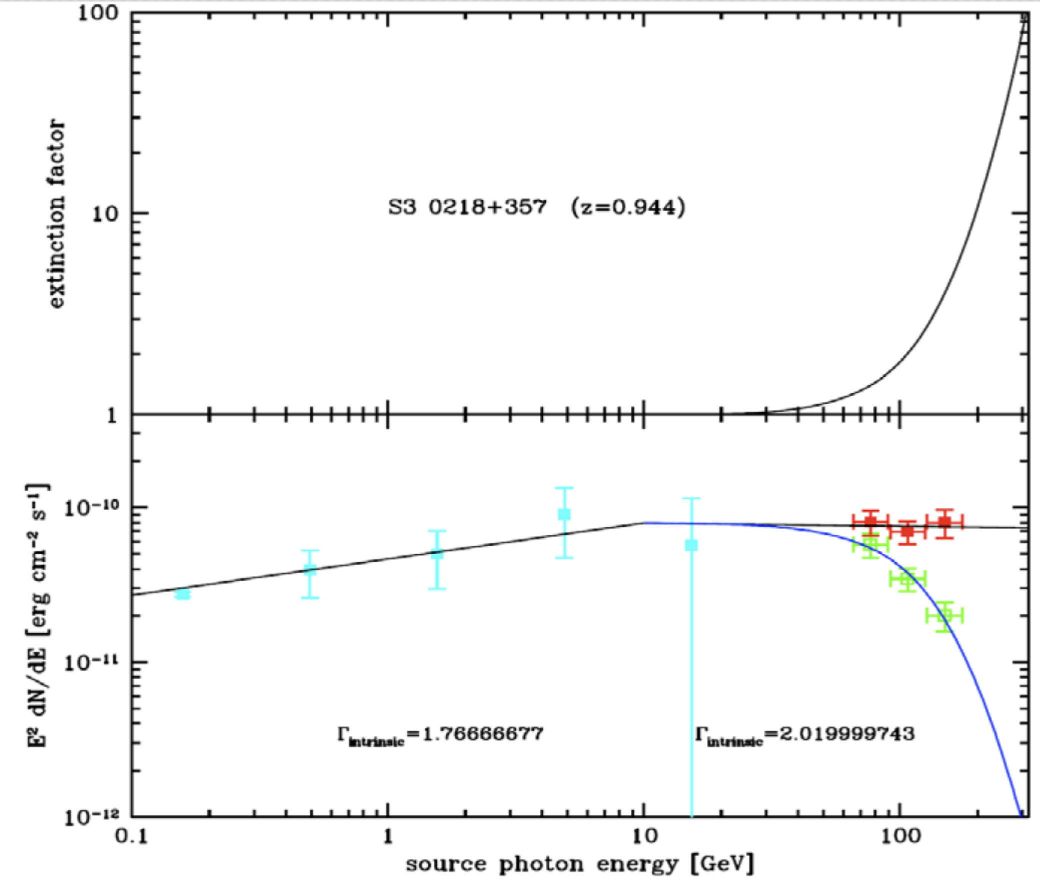
Photon density $\frac{dn_\gamma}{d\varepsilon}$ in proper units



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 $\propto(1+z)^3$

Recent discovery of TeV photons from z~1 sources

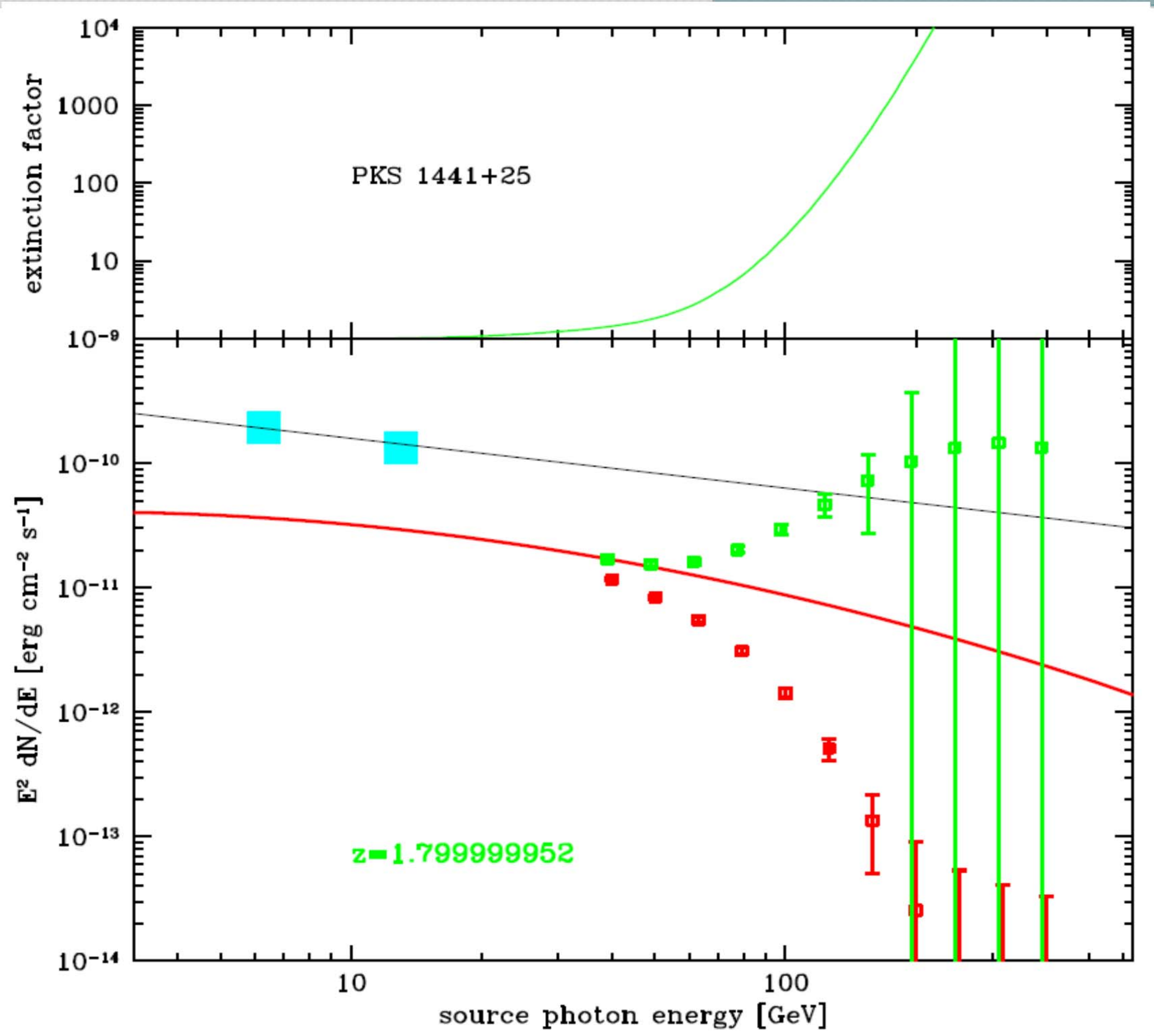


Detection of a Hard Spectrum Flare from the Gravitationally Lens Blazar B0218+357

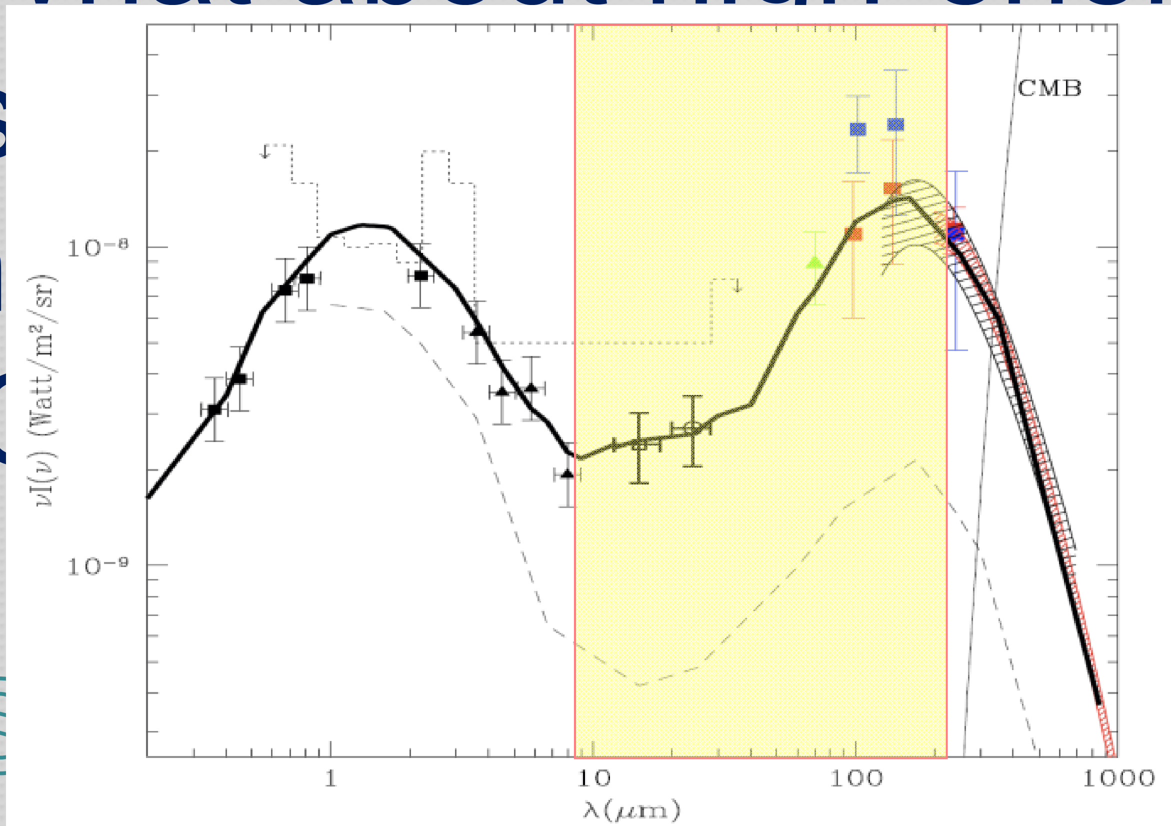
Mirzoyan et al. 2014
Buson & Cheung 2014

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).

Simulation of a CTA 50 h obs of PKS1441 at redshift z=1.8

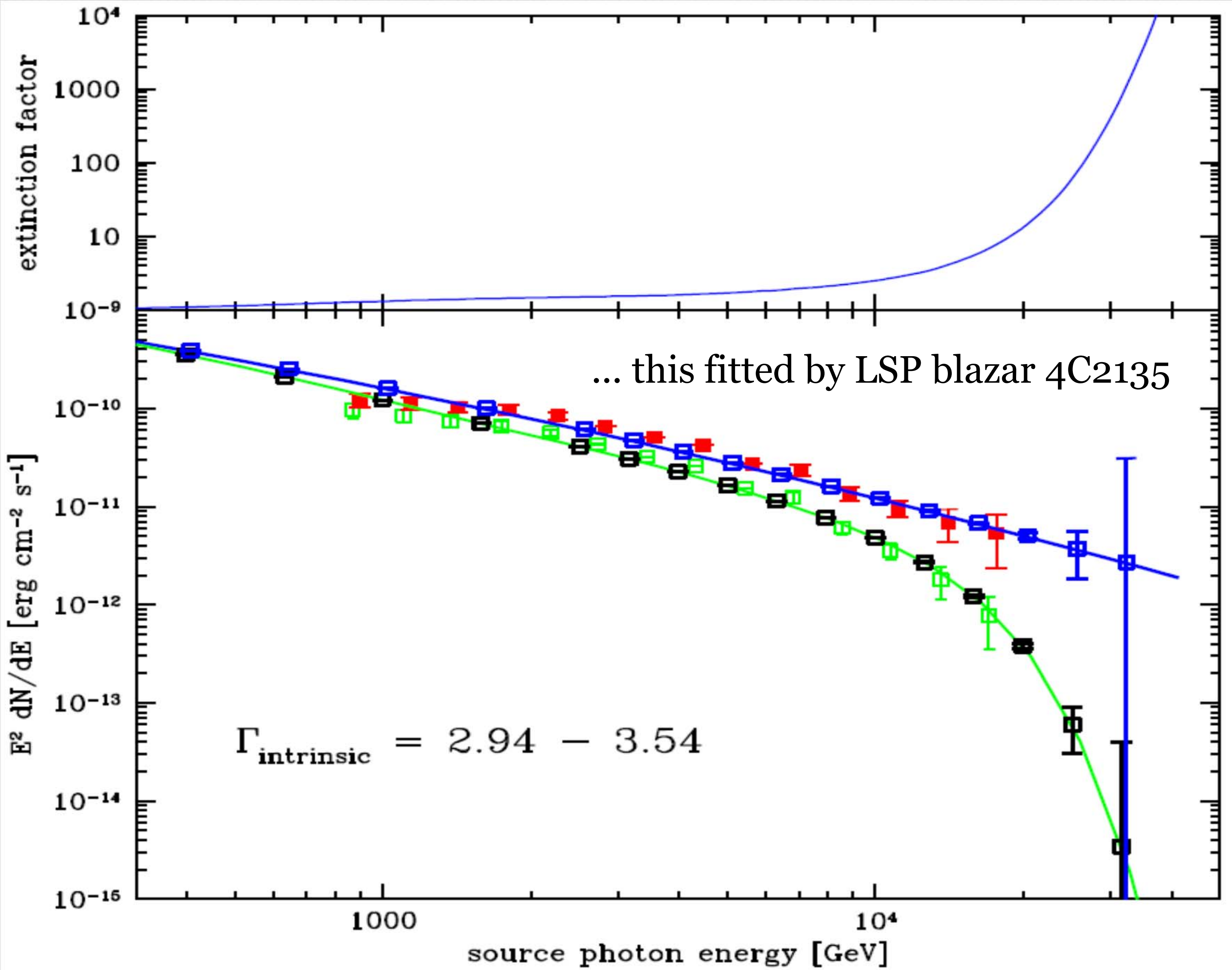


What about high-energy obs local bon strain the C ngths?



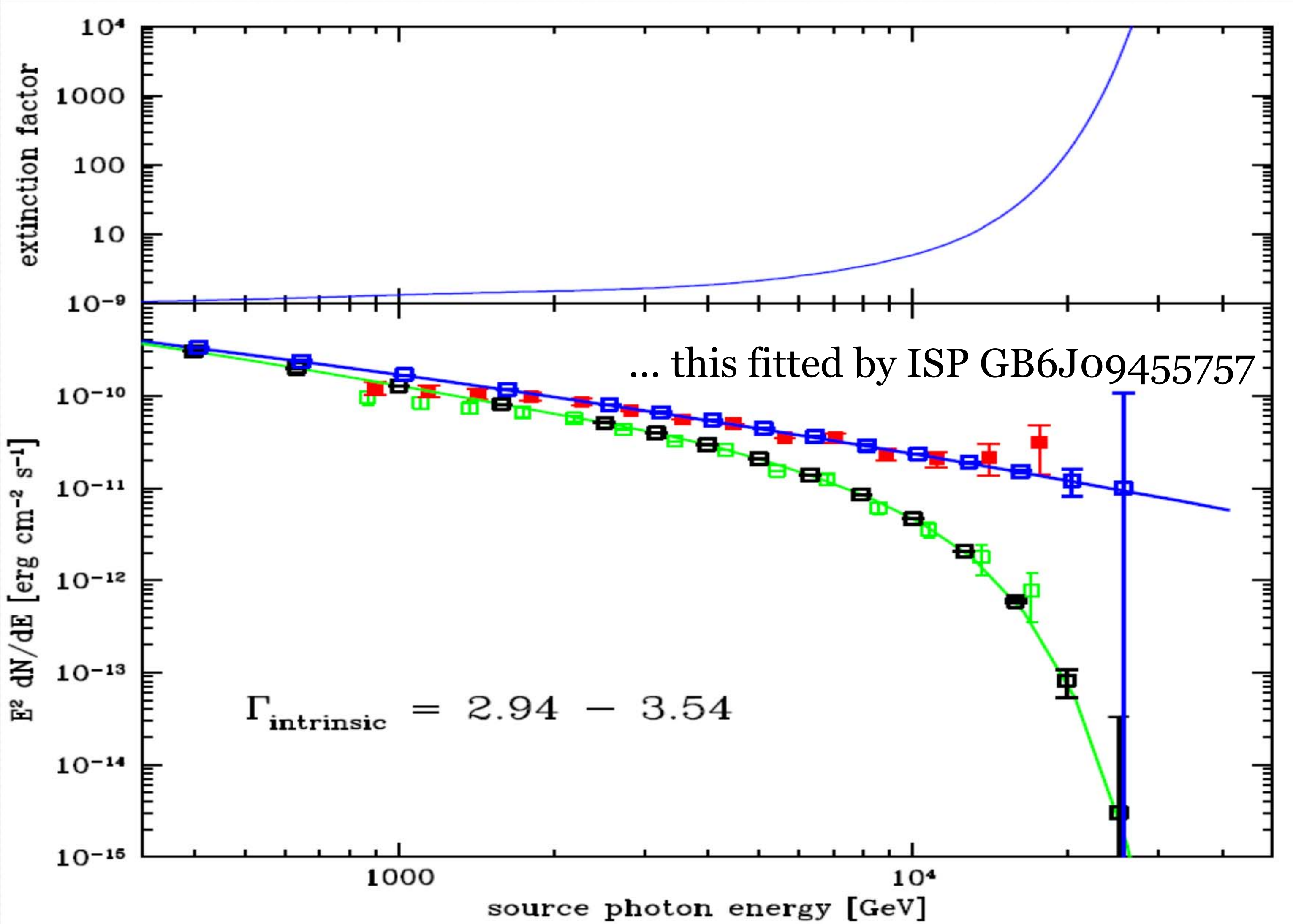
S CTA's expected performances (50 hrs)

Simulation of a CTA obs of MKN421 assuming a nominal FIR background



Simulation of a CTA obs of MKN421 assuming a high FIR background

This assumes CIRB (λ>10μm) intensity x2 higher than nominal



Summary

- Constraints on local EBL local flux and its time evolution already achieved from MAGIC and other blazar data, however limited by sensitivity and systematics

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

- The CTA Large Area Telescopes will substantially expand the Γ-ray horizon at low and intermediate energies for the high-z blazar and will offer constraints on EBL evolution with time => e.g. tests of integrated PopIII emission at $z \sim 10$.

- Simulations performed of CTA very high energy (>10 TeV) observations of local extragalactic sources (blazars) indicate that finer constraints on their spectra will be achieved, however limited by huge EBL opacity @ these ε .