Transparency of the universe at very high energies: constraints on cosmology (and fundamental physics)

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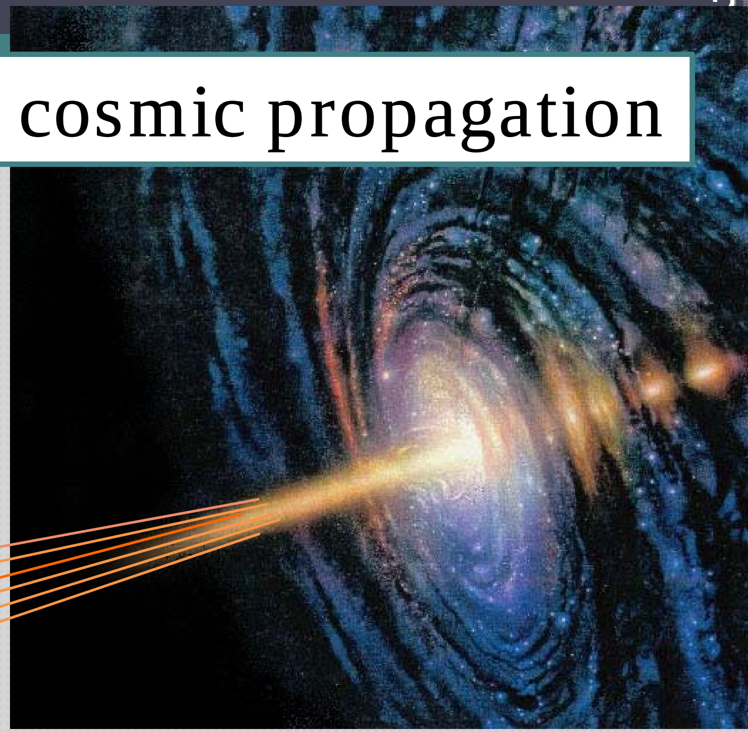
1. Direct modeling of the EBL from sources (IGL): current status (combined number counts + luminosity functions; deep and ultra-deep samples)
2. EBL inferences from VHE gamma-gamma opacity measurements. The current good convergence in optical-UV-NIR
3. Constraints on the standard model for cosmology: prospects for the CTAO surveys
4. ASTRI and CTAO SST's looking for the long-λ IR background…
5. … and for possible effects of photon-ALP mixing

Photon-photon interactions and cosmic propagation



RELEVANT IMPACT OF THE EXTRAGALACTIC BACKGROUND LIGHT FOR THE PROPAGATION OF PARTICLES AND ENERGETIC PHOTONS ACROSS THE UNIVERSE

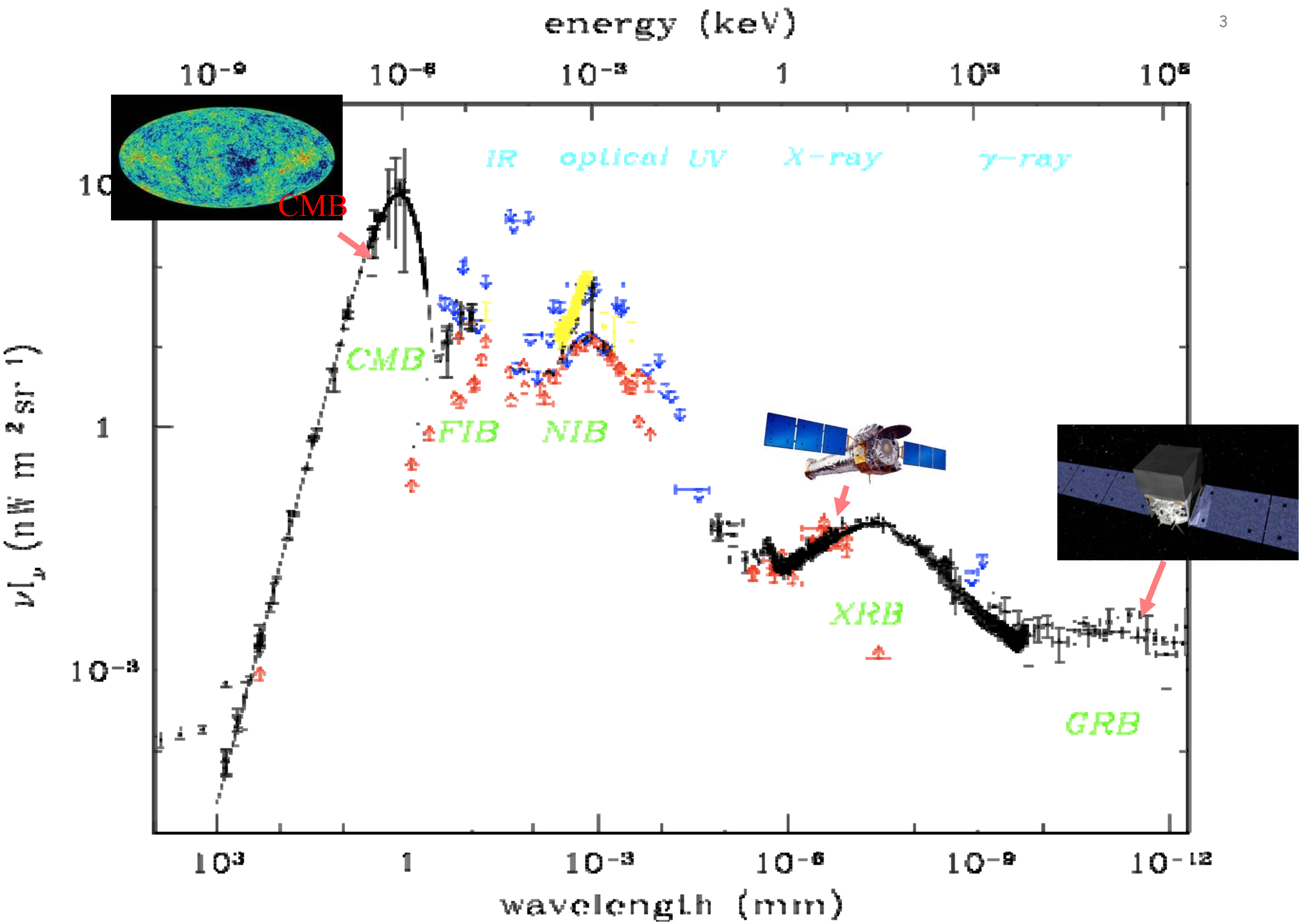
THIS PHENOMENON MAKES AN INTERESTING (AND RELEVANT) BRIDGE BETWEEN THE VHE AND LOW-ENERGY SKY (WITH CONSEQUENCES FOR PHYSICS AND COSMOLOGY)

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

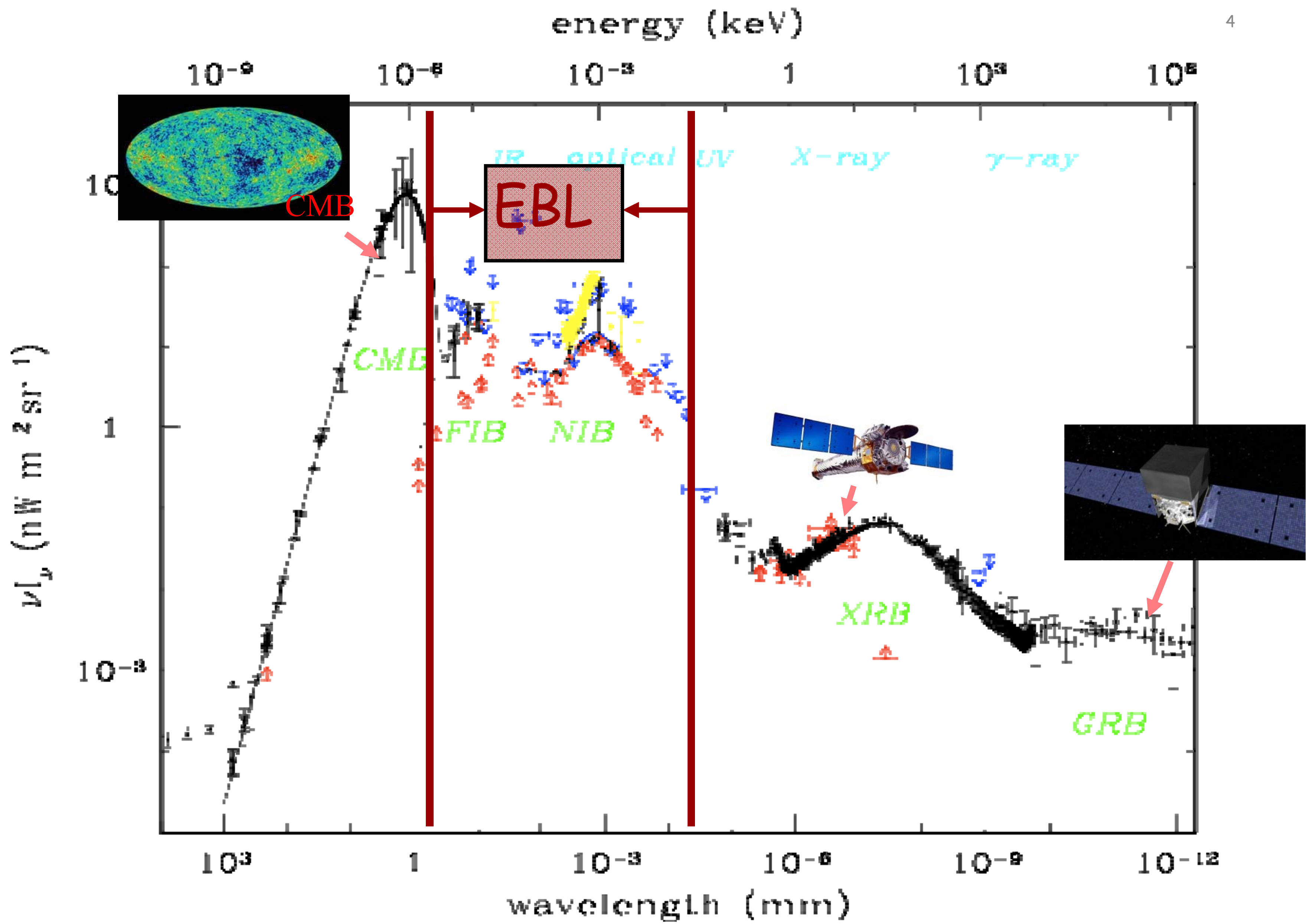
$$\lambda_{max} \simeq 1.24 \times \varepsilon_{TeV} [\mu m]$$

Absorption:

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

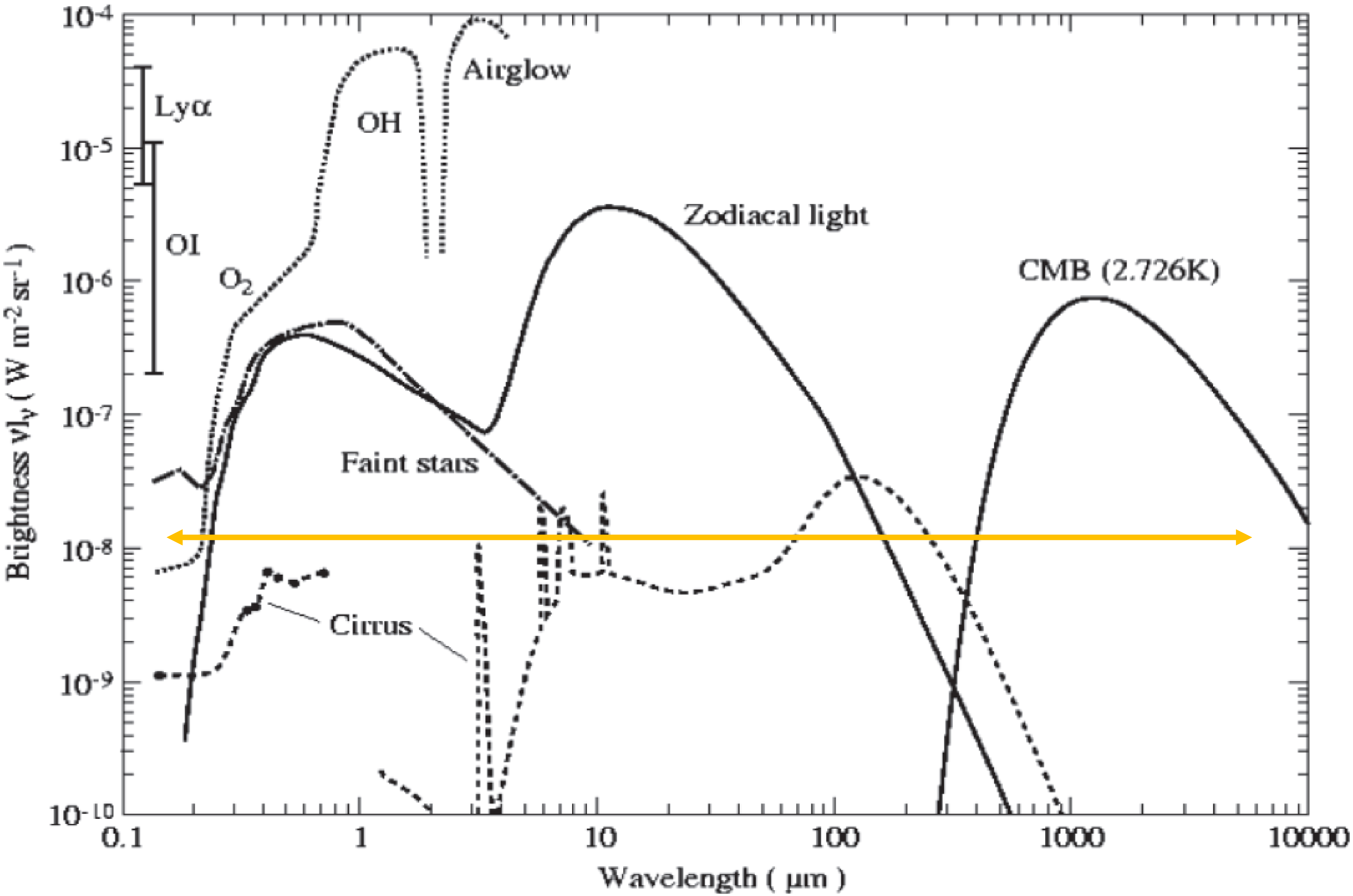


The Global Background Radiation & the EBL

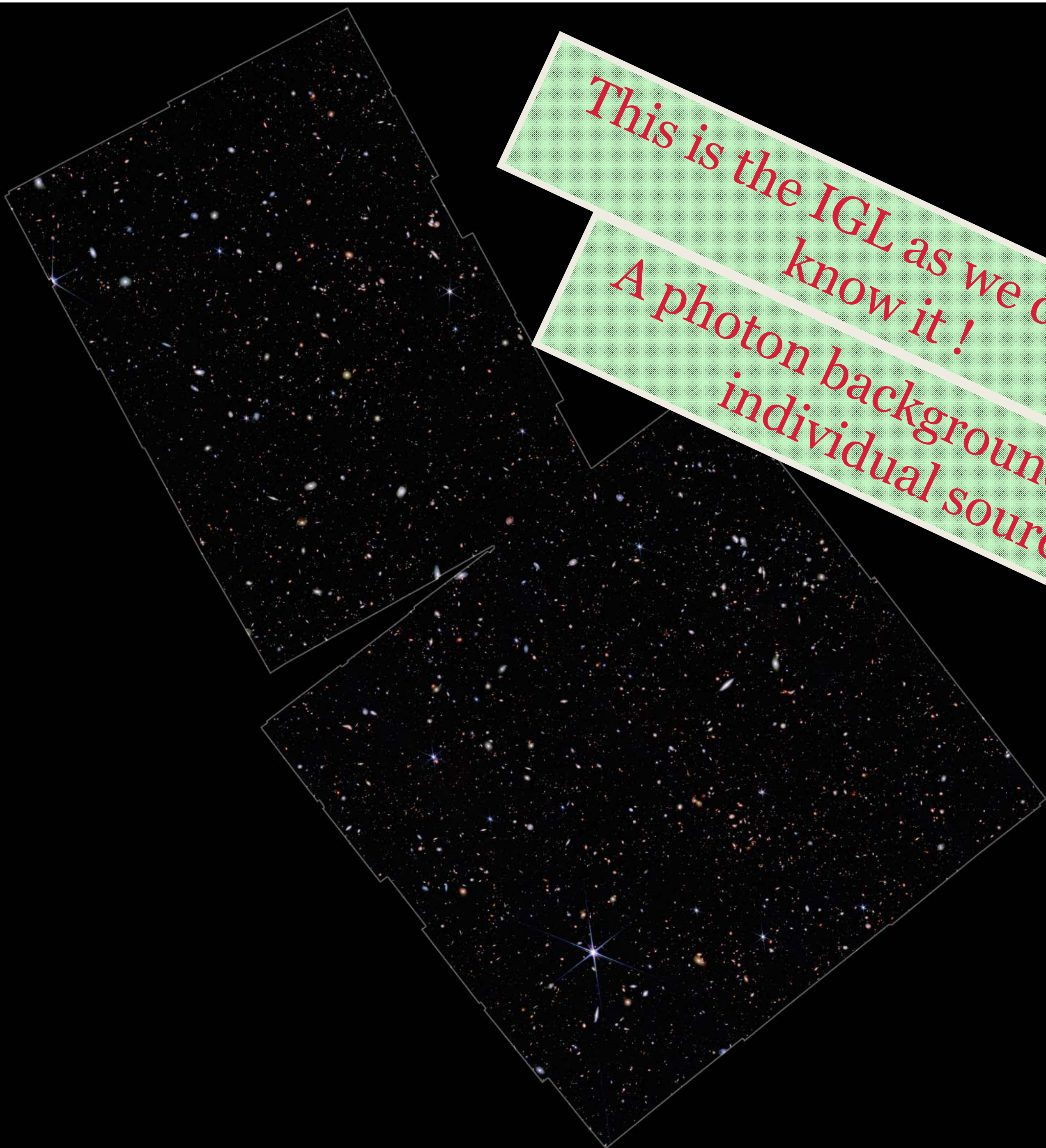


Repository of all radiant energy produced by cosmic sources since B.B.

Overview of the various components of the total night sky background at high galactic and ecliptic latitudes: large foregrounds prevent direct estimate of the EBL



1. Attempts for direct estimates of the EBL from sources: the **InterGalactic Light**, IGL)



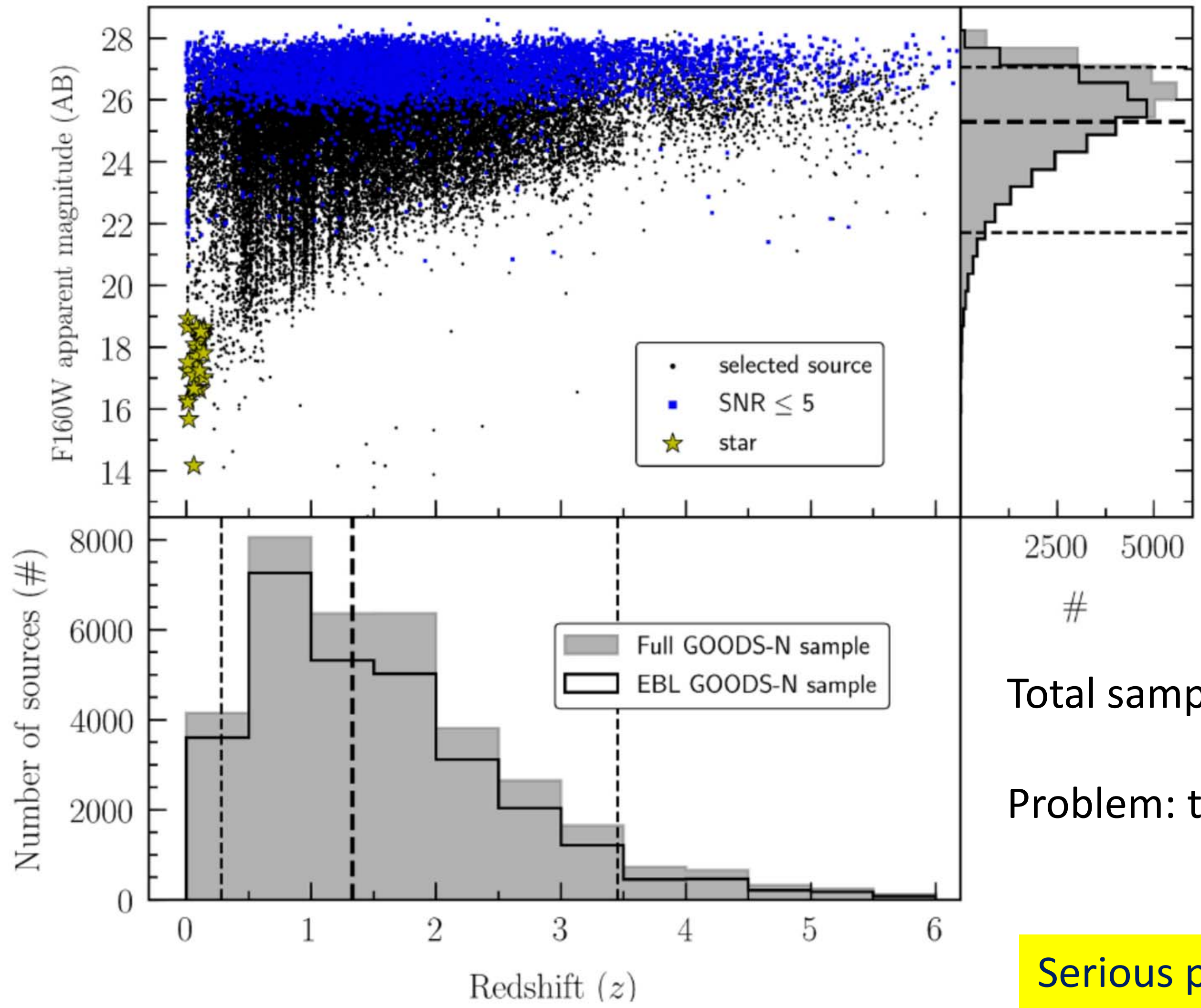
This is the IGL as we currently know it !

A photon background made by individual sources

Many published attempts to model the source's Inter-Galactic Light

- Stecker & de Jager (1993) ☒
- Stanev & Franceschini (1998) ✓
- Malkan & Stacker (1998) ☒
- Kneiske et al. (2002) ☒
- Franceschini + (FRV, 2008) ✓
- Finke, Razzaque, Dermer (2010) ☒
- Kneiske & Dole (2010) ✓☒
- Dominguez et al. (2011) ✓
- Gilmore et al. (2012) ☒
- Stecker, Scully & Malkan (2016) ✓☒
- Franceschini, Rodighiero (2017-18) ✓
- Andrews et al. (2018) ☒
- Saldana-Lopez et al. (2021) ✓
- Finke et al. (2022) ✓☒

✓ Adherent to the data
☒ Based on models
✓☒ Partially on data



5 recent ultra-deep fields selected @ λ=1.6μm

(Saldana-Lopez +21)

Total sample= 150.000 faint sources

Problem: total area *only* 900 sq.arcmin

Serious potential problem of excess cosmic variance at low redshift

… but good to estimate EBL at high-z

Cut	GOODS-S	UDS	COSMOS	EGS	GOODS-N	Total
CANDELS	34 930	35 932	38 671	41 457	35 445	186 435
F160W detection	34 848	35 752	38 216	41 353	35 440	185 609
S/N ≥ 5	32 224	28 222	33 327	32 577	29 269	155 619
After removing stars	32 170	28 742	33 297	32 518	29 242	155 969
$0 \leq z < 6$	31 736	28 496	32 906	32 362	28 947	154 447
F160W: $\mathcal{H}^{95\%}_{05\%}$	$25.64^{27.48}_{22.10}$	$25.13^{26.56}_{21.79}$	$25.13^{26.84}_{21.40}$	$25.14^{26.69}_{21.72}$	$25.29^{27.05}_{21.70}$	$25.25^{27.00}_{21.72}$

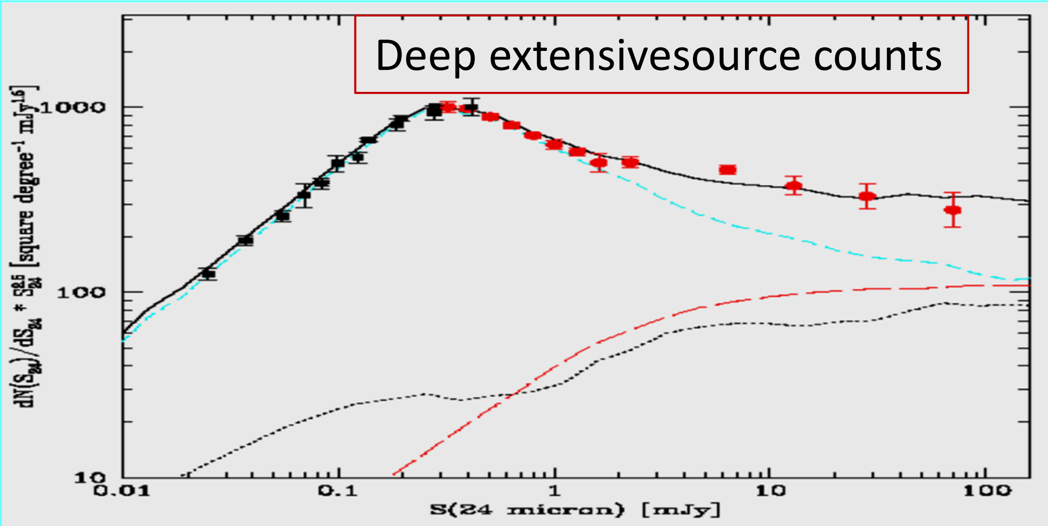
Better is a *wedding-cake* approach combining deep redshift surveys with source number counts on wide areas

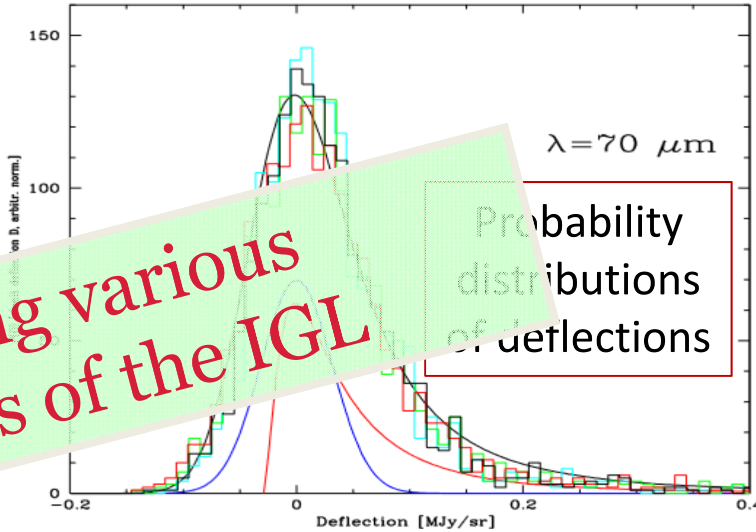
- Note that a simple integral of the deep number counts at various wavelengths

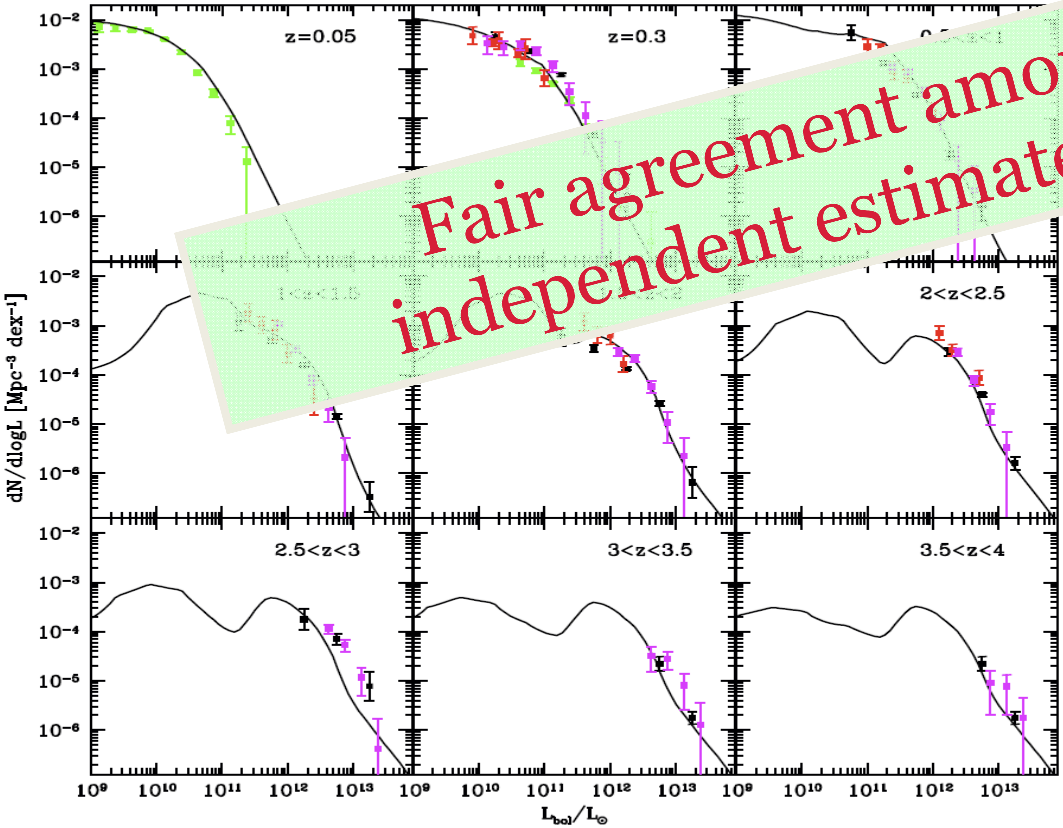
$$I_\nu = \int_0^\infty d\,S_\nu N(S_\nu) \cdot S_\nu$$

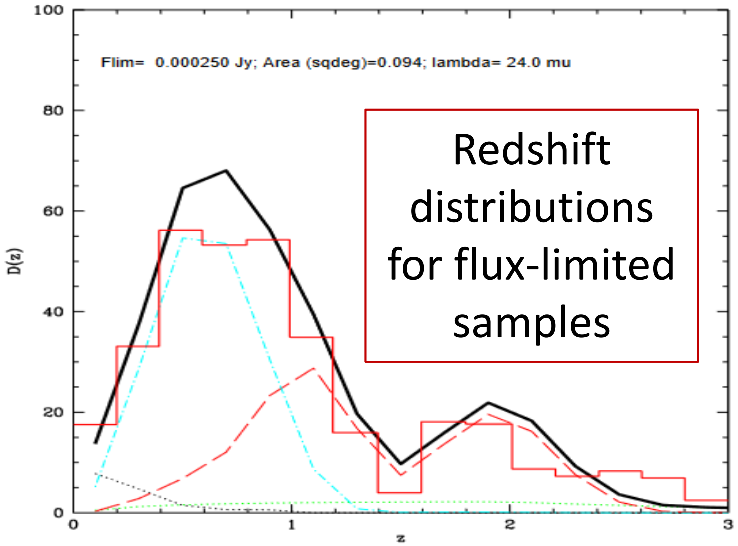
where $N(S_\nu)$ are the differential counts of sources, that is number of sources per units sky area (e.g. sr^{-1}) and unit differential flux density (e.g. Jy^{-1})

Source number counts, P(D), d(z), luminosity functions (AF+)









Fair agreement among various independent estimates of the IGL

… But in addition to the source background (IGL), we expect additional – possibly relevant - contributions by:

- Faint extended emissions in the outskirts of standard objects (like galaxy halos)
- Light from low-luminosity sources (otherwise undetectable)
- Truly diffuse processes (as emerging from the Big Bang, e.g. from decaying primordial particles)

2. A way to constrain the TOTAL Extragalactic Background Light is offered by γ-γ opacity measurements

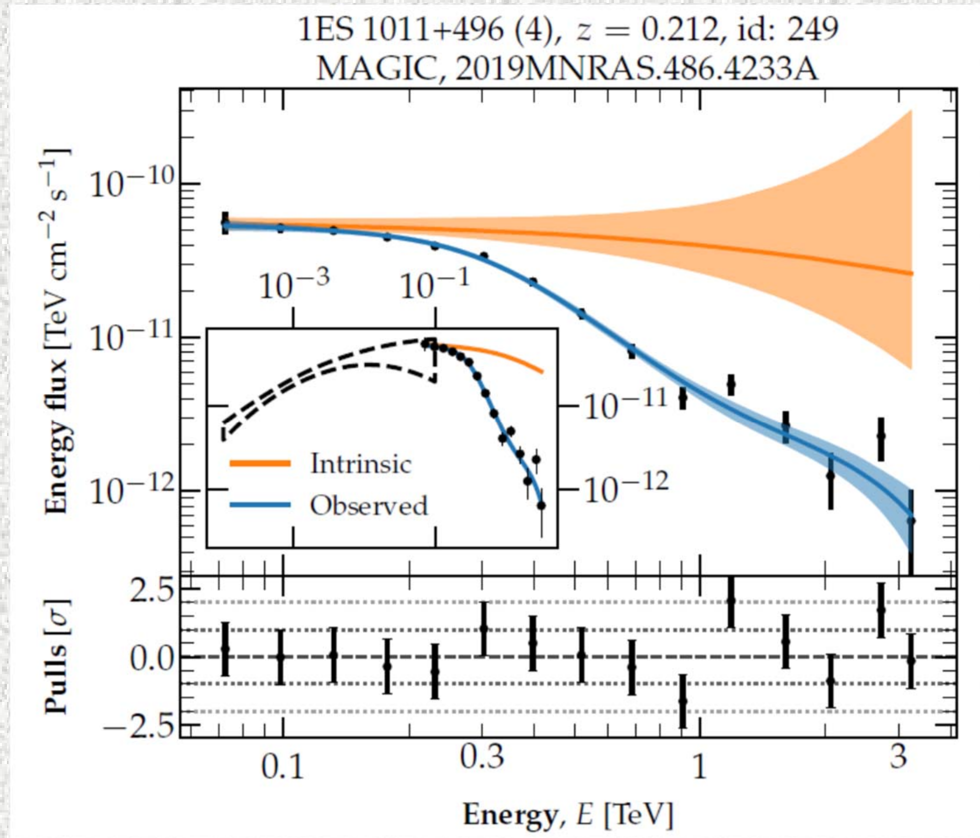
The free-form analysis (Baxter+ 2026, Greaux+2024 using a Bayesian statistics)

Based on the STeVECat catalogue (Greaux et al. 2023) including **260-286** VHE extragalactic spectra with at least **4** spectral points and spectroscopic redshifts z>0.01, the largest database of archival data from extragalactic sources to my knowledge. Including Fermi LAT data.

Intrinsic spectral fit of each source with

$$f(E) = f_0 \left\{\frac{E}{E_0}\right\}^{-a-b\,log(E/E_0)-c\,log^2(E/E_0)-d\,E}$$

a, b, c, d are best-fit parameters



$$f_{obs}(E) = e^{-\tau_{EBL}(E,z)} f(E)$$

EBL intensity versus the γ-γ optical depth

EBL

$$\tau(E,z) \approx \int_0^{z'} dz' \frac{dl}{dz'} \int_0^{\infty} d\varepsilon \frac{4\pi}{c} \frac{\nu I(\nu,z)}{\varepsilon^2} \sigma_{\gamma\gamma}[E(1+z'),\varepsilon]$$

with the differential distance element:

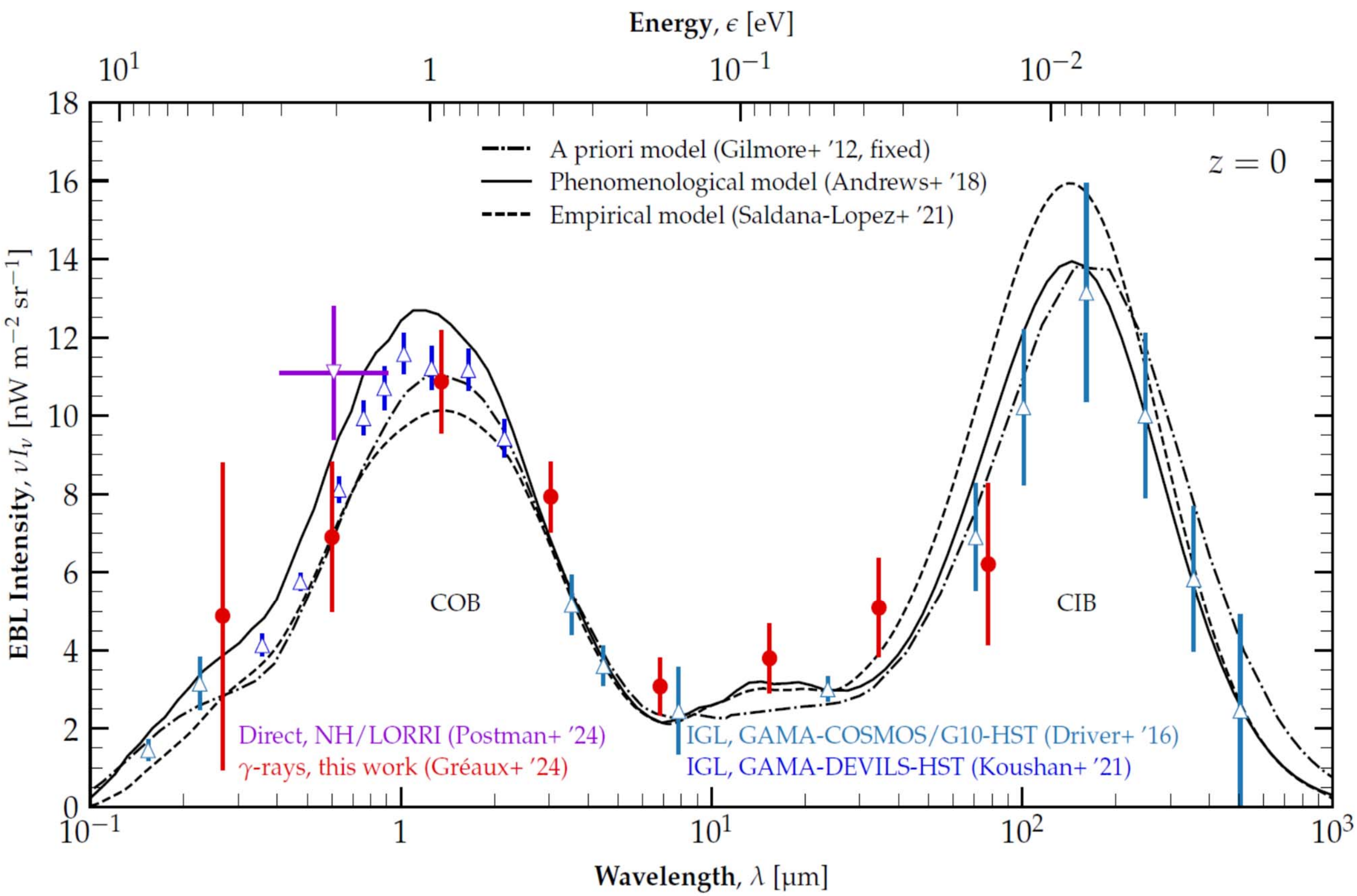
$$\frac{dl}{dz\prime} = \frac{c}{H_0} \frac{1}{1+z} \left[\Omega_\Lambda + \Omega_m (1+z)^3\right]^{-0.5} \quad \text{(eq.2)}$$

Evolution with z of the EBL parametrized as: $\nu I(\nu,z) = \nu_0 I(\nu_0,0) \times (1+z)^{f_{evol}}$

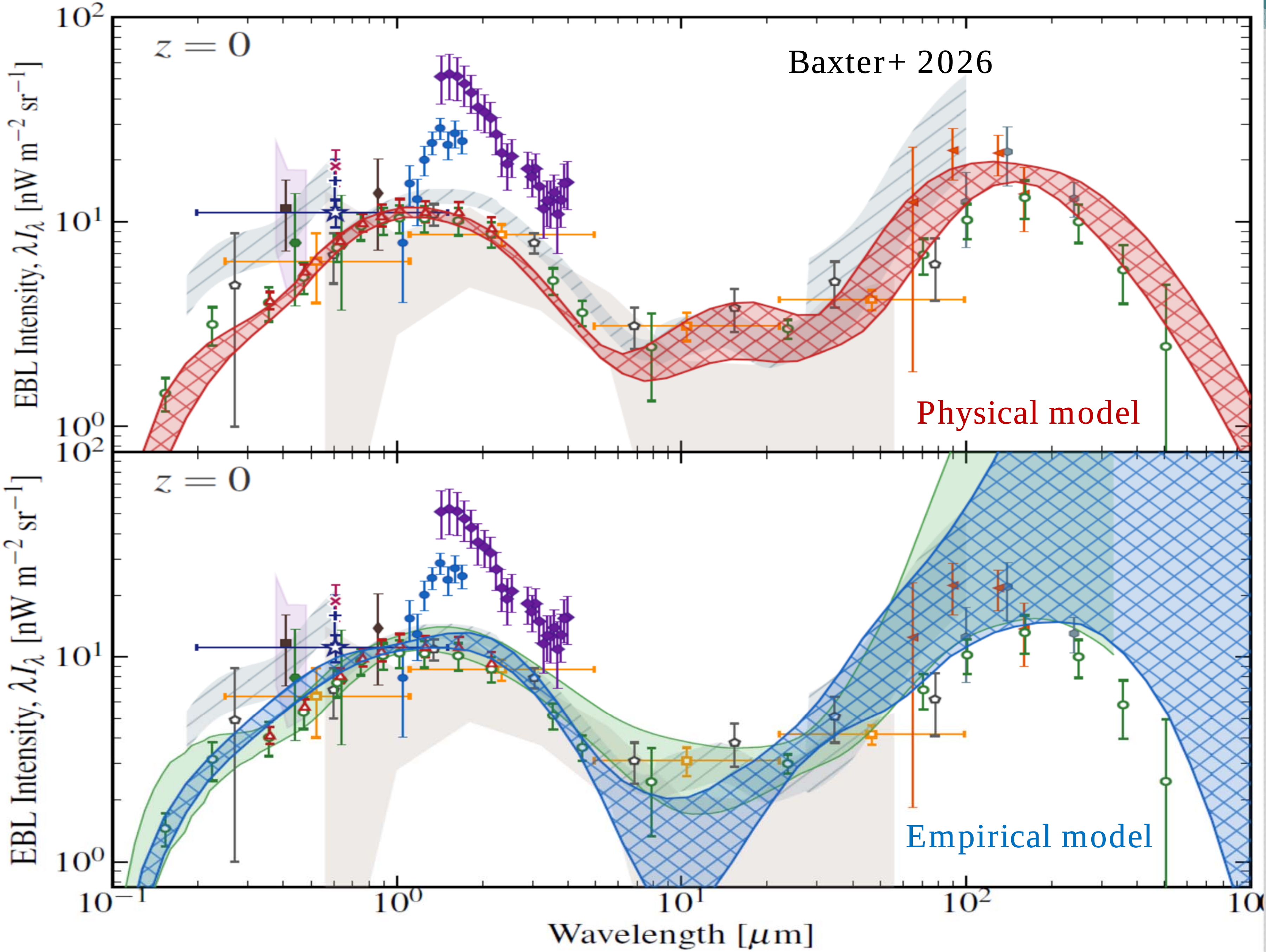
The EBL spectral intensity at z = 0 modelled as a sum of Gaussian functions of $l = \ln(\lambda/\lambda_{ref})$, with fixed means ($l_i$) and deviation σ, leaving the amplitudes (a_i) free to vary:

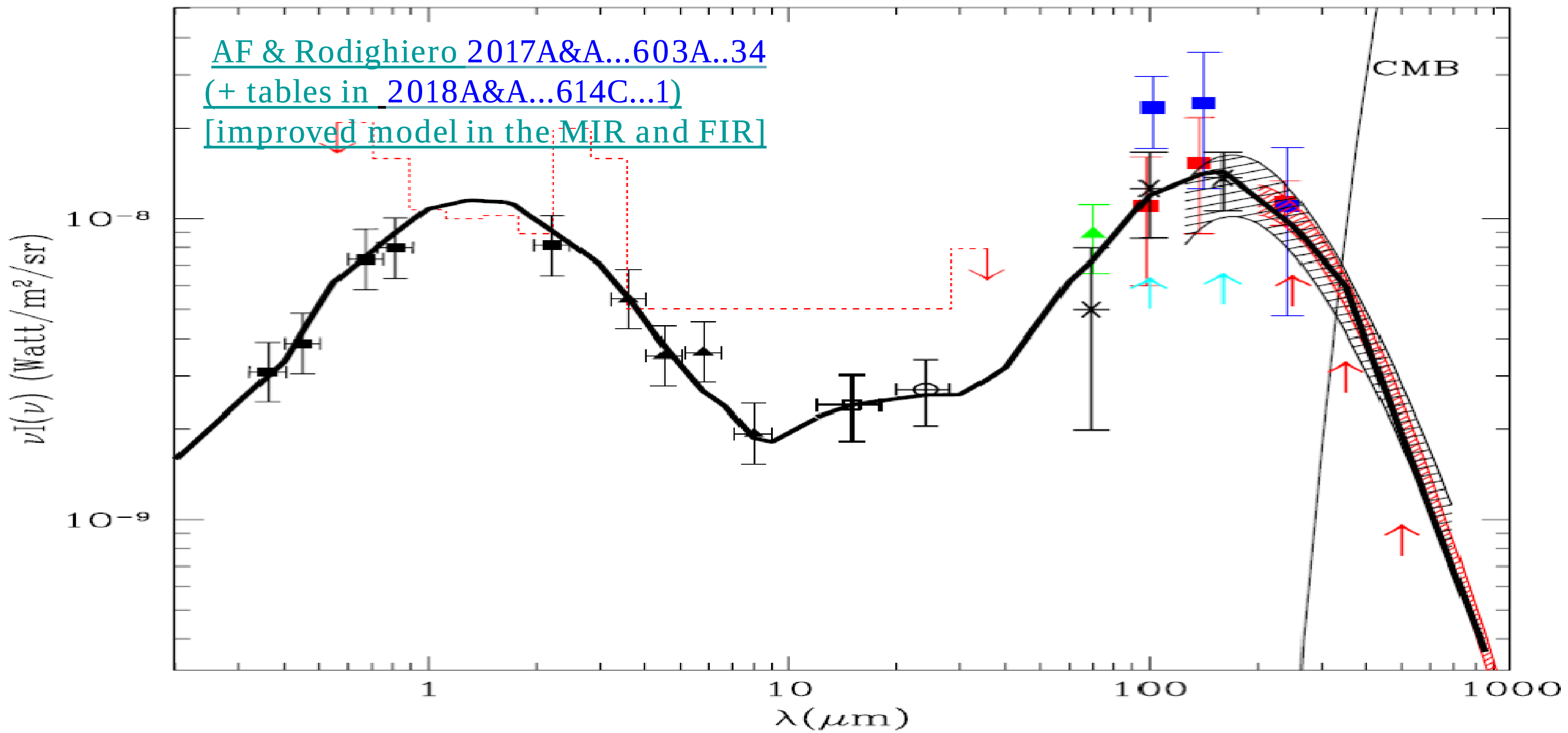
$$\nu I(l,0) = \sum_i a_i \, exp\left(-\frac{(l-l_i)^2}{\sigma^2}\right)$$

Once defined 8 values for the central wavelengths l_i, 8 Gaussians are defined by the 8 amplitudes a_i, making altogether 9 best-fit parameters, including the evolutionary parameter f_{evol}. The best fitting analysis of the 260 spectra is performed based on a Bayesian MCMC.



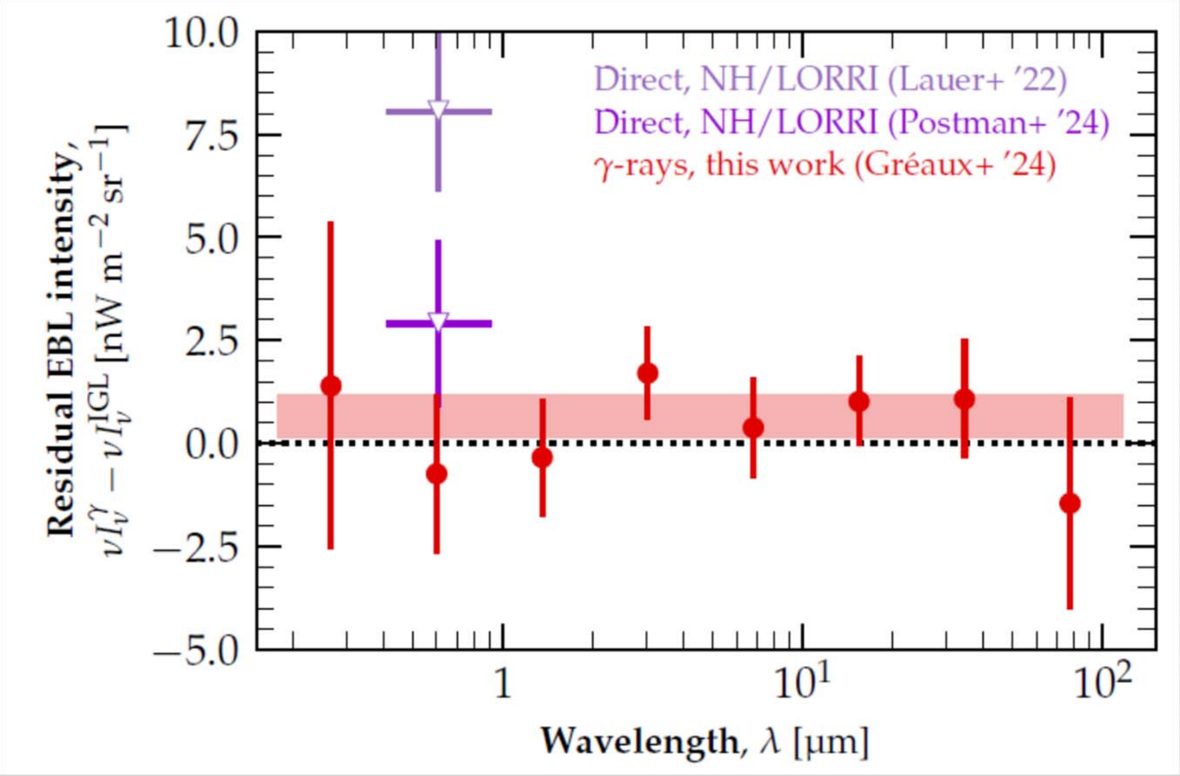
Energy, ϵ [eV]
10^1
1
10^{-1}
10^{-2}
A priori model (Gilmore+ '12, fixed)
Phenomenological model (Andrews+ '18)
Empirical model (Saldana-Lopez+ '21)
$z = 0$
EBL Intensity, νI_ν [nW m^{-2} sr^{-1}]
18
16
14
12
10
8
6
4
2
0
COB
CIB
Direct, NH/LORRI (Postman+ '24)
γ-rays, this work (Gréaux+ '24)
IGL, GAMA-COSMOS/G10-HST (Driver+ '16)
IGL, GAMA-DEVILS-HST (Koushan+ '21)
10^{-1}
1
10^1
10^2
10^3
Wavelength, λ [μm]


z = 0
Baxter+ 2026
Physical model
z = 0
Empirical model
EBL Intensity, λI_λ [nW m^-2 sr^-1]
EBL Intensity, λI_λ [nW m^-2 sr^-1]
Wavelength [μm]



Consistent with the 2017 view of the local IGL

This analysis contributes in resolving a **long standing problem with various claims of a large EBL excesses** in the optical-UV with respect to the source background, in particular that based on observations by the LORRI instrument in the New Horizon probe outside the Solar Sistem (Lauer+ 2022), but consistent with the re-analysis by Postman+ 2024.



Constraint on the excess diffuse EBL in the optical above the faint source contribution $\nu I(\nu)_{sources}$:

$$f_{diff} \equiv \frac{\nu I(\nu)_{total}}{\nu I(\nu)_{sources}} < 20\%$$

$\nu I(\nu)_{total}$ from γ-rays

Similar, or even worse, conflicts arose from IRTS and COBE-DIRBE surveys. These also currently appear to be resolved!

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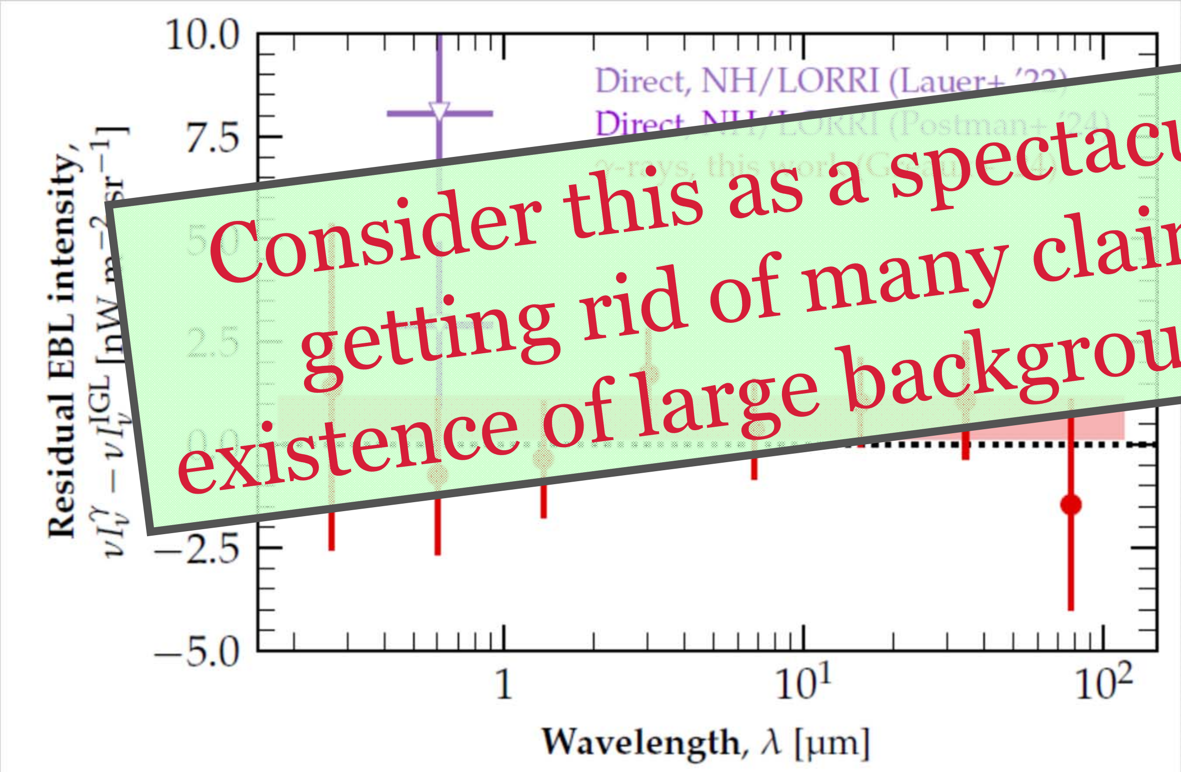

Consider this as a spectacular result, getting rid of many claims about existence of large backgrounds excesses

Constraint on the excess diffuse EBL in the optical ... the faint source contribution $\nu I(\nu)_{sources}$:

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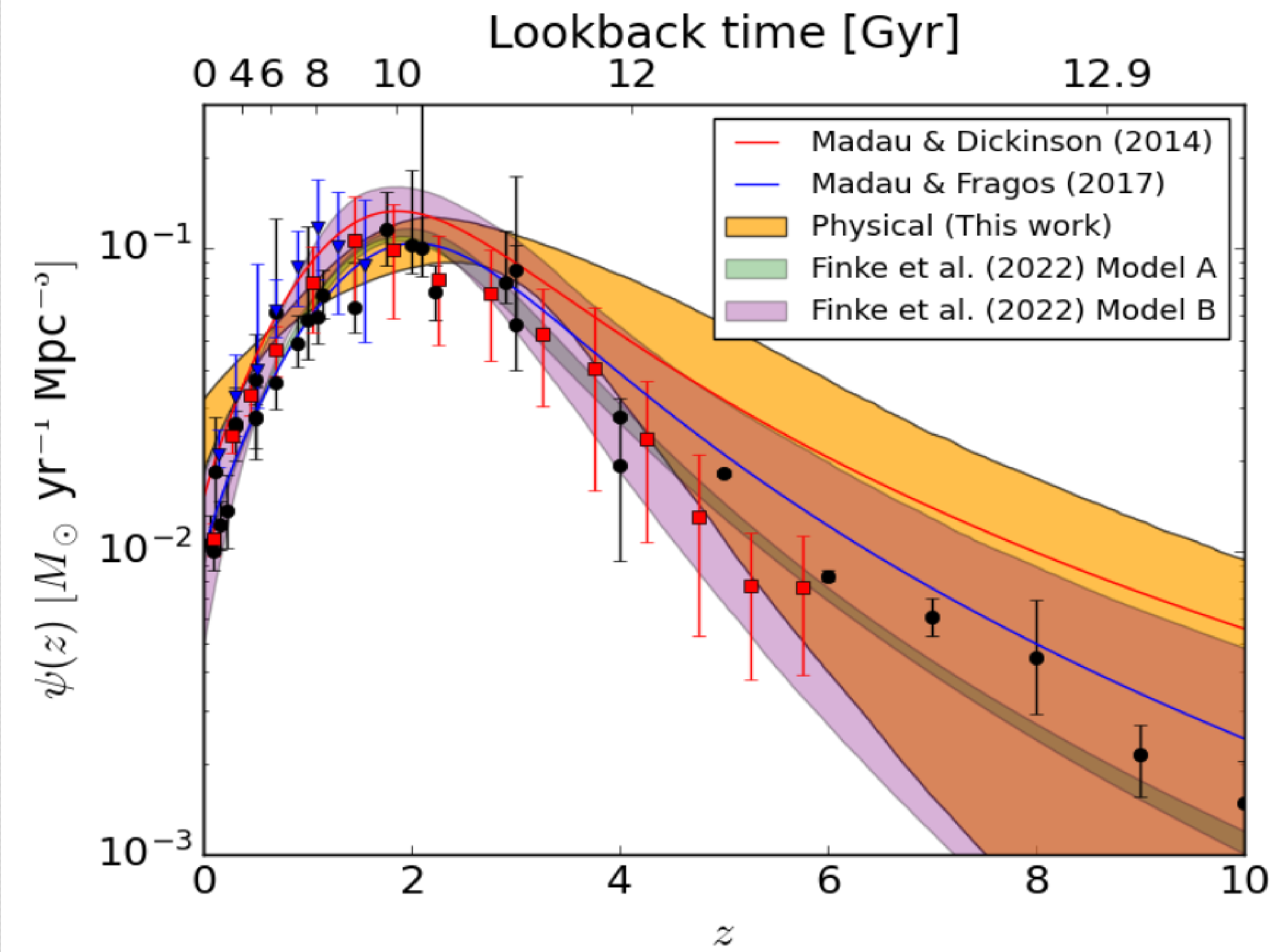
A similar approach, on a large sample of 1576 Fermi AGNs, adopted by **Banerjee** + 2026 to infer the evolution of EBL with z and the history of star formation



3. Constraints on the standard model for cosmology: prospects for the CTAO surveys

At this stage, we can claim that we know the EBL in the optical and near-IR sufficiently well to start playing with constraints of the cosmological parameters, essentially H_0 and Ω_m.

Note that (Dominguez + 2024):

$\nu I(\nu)_{sources}$ is independent on H_0 and Ω_m (because integral of counts)

$\nu I(\nu)_{total}$ (from ϒ-rays) depends on f_{diff} and $\frac{1}{H_0/(70\ \frac{Km}{s}/Mpc)}$ because of the *distance measure* (see eq.2)

$$\frac{\nu I(\nu)_{total}}{\nu I(\nu)_{sources}} = \frac{1 + f_{diff}}{H_0/(70\ \frac{Km}{s}/Mpc)}$$

$$\Rightarrow \quad H_0 \sim 67^{+7}_{-6}\,(1 + f_{diff})\ \textit{Km/sec/Mpc}$$

(Greaux+)

EBL intensity versus the γ-γ optical depth

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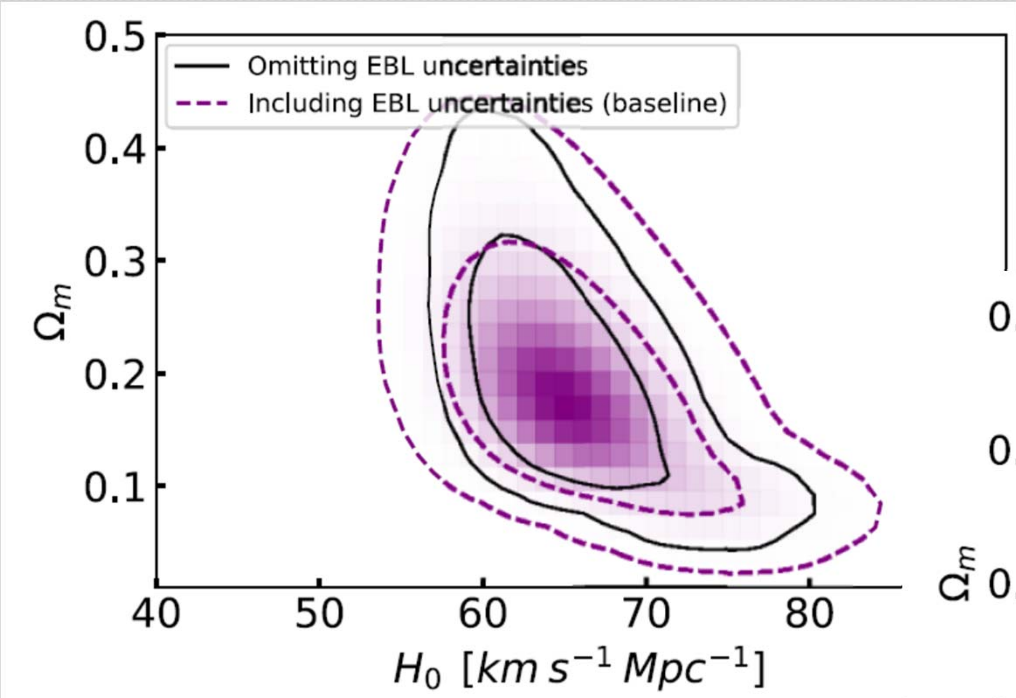
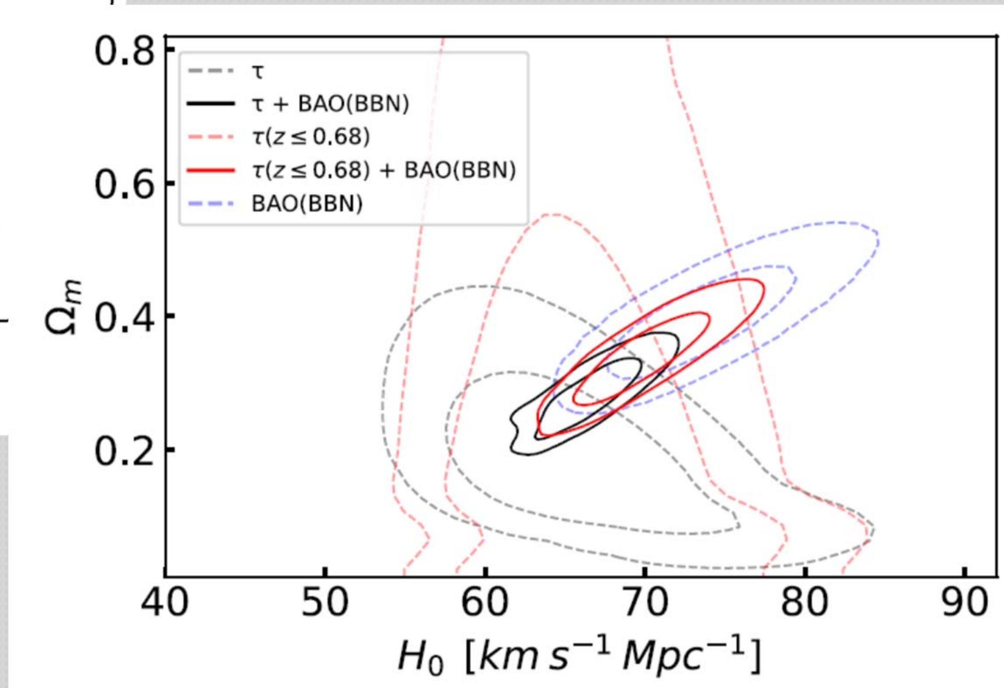
Also from eq. (2), we see there is a residual dependence on the Ω_m parameter too, assuming a flat geometry ($\Omega_m + \Omega_\Lambda = 1$).

However the Ω_m dependence emerges only at redshifts significantly higher than $z \approx 0.5$, with a scaling with the distance: $l \approx \Omega_m z^{-3/2}$. Dominguez+2024 find:





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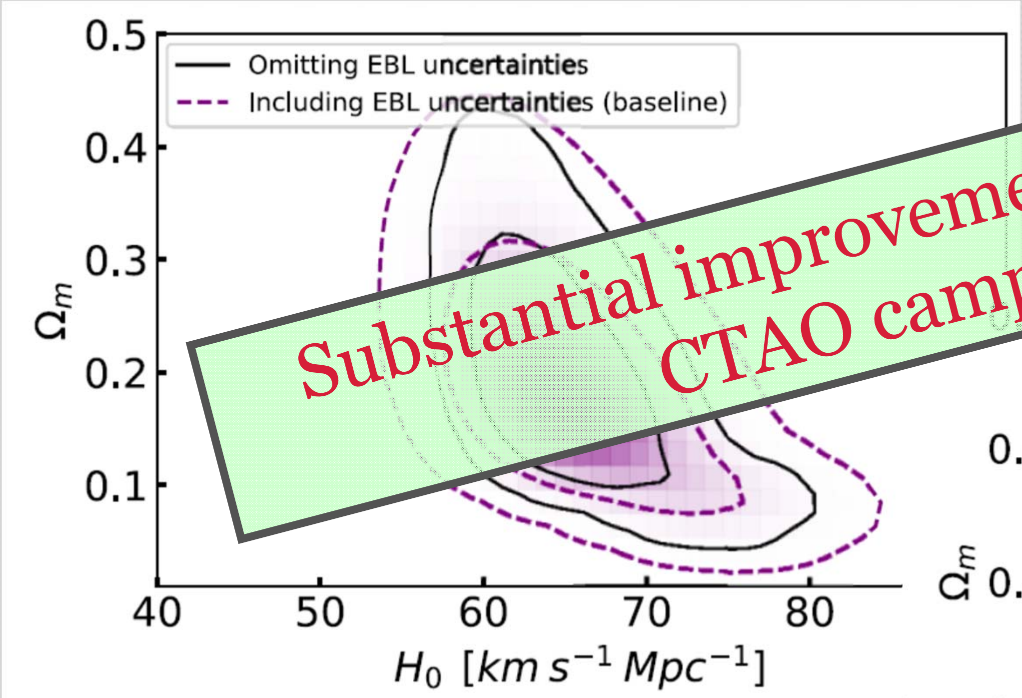
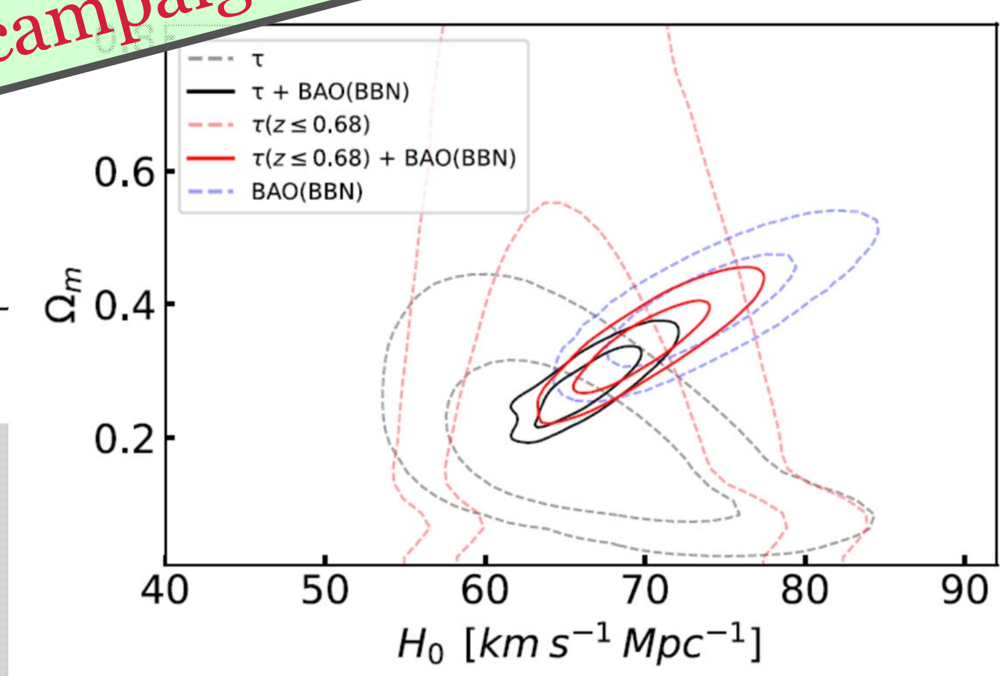
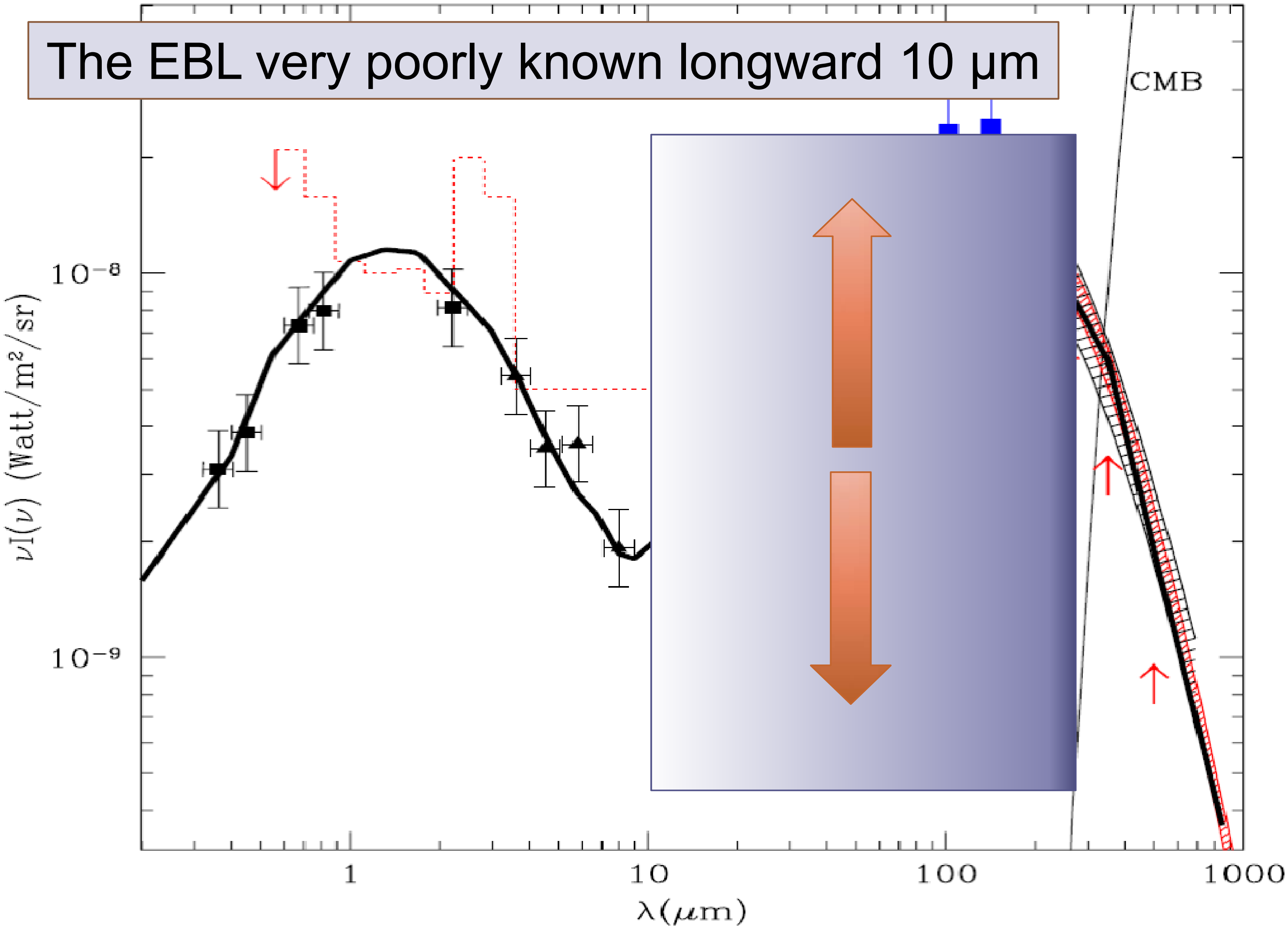


Substantial improvements expected by CTAO campaigns

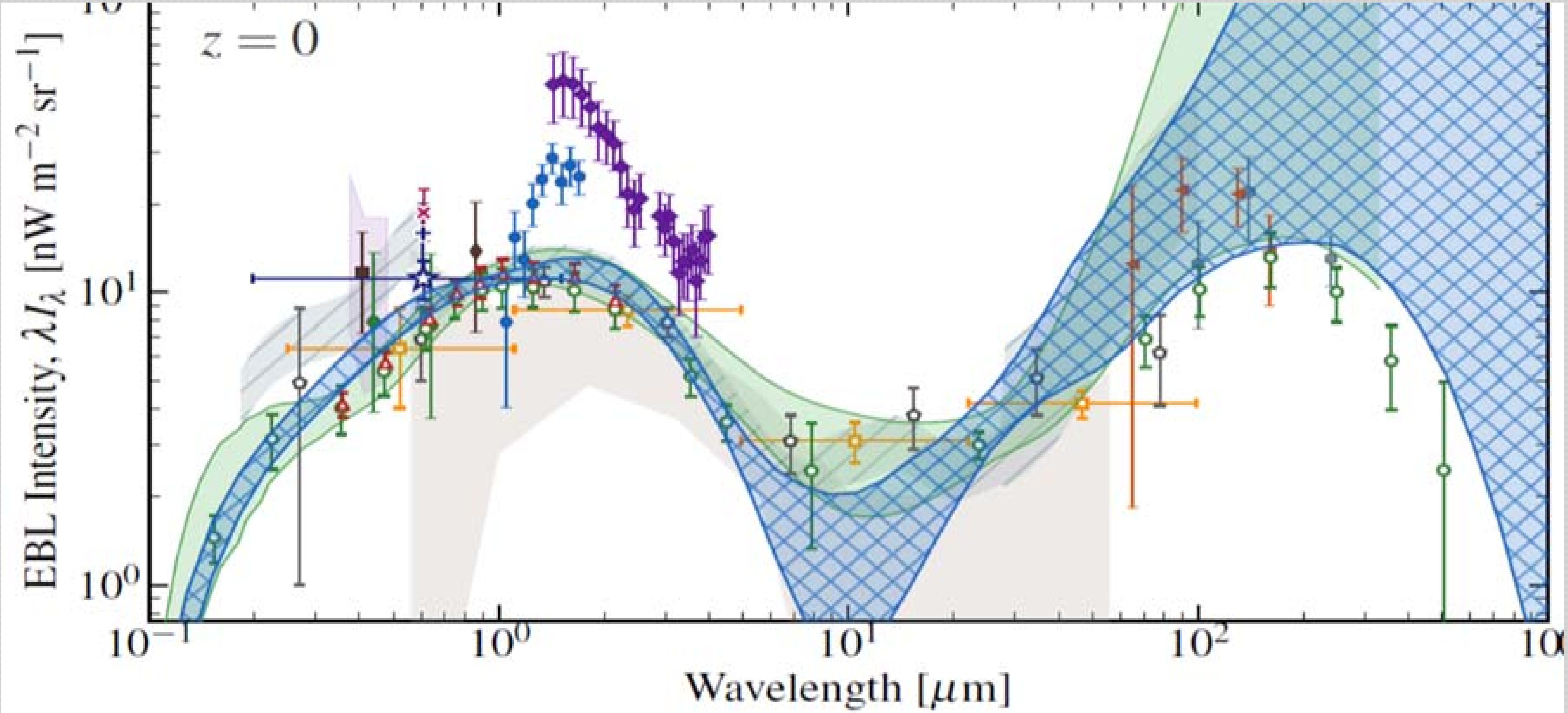


4. ASTRI and CTAO SST's for the long-λ IR EBL background

The EBL very poorly known longward 10 μm

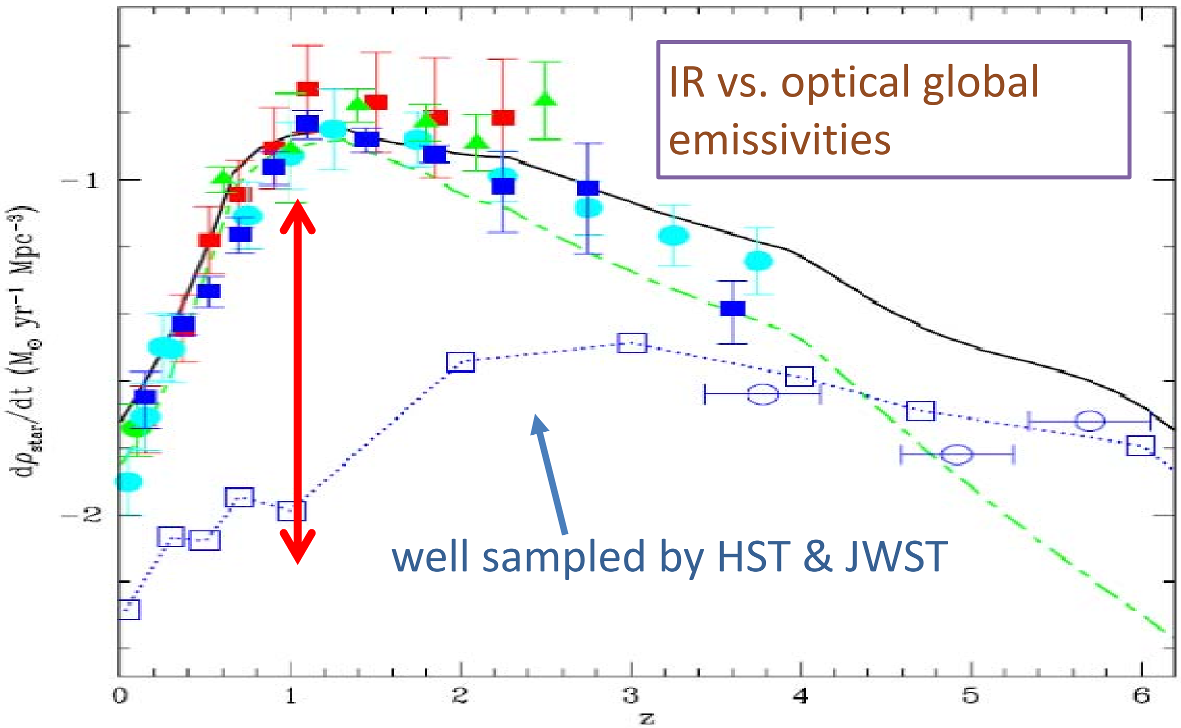


Baxter+ 2026



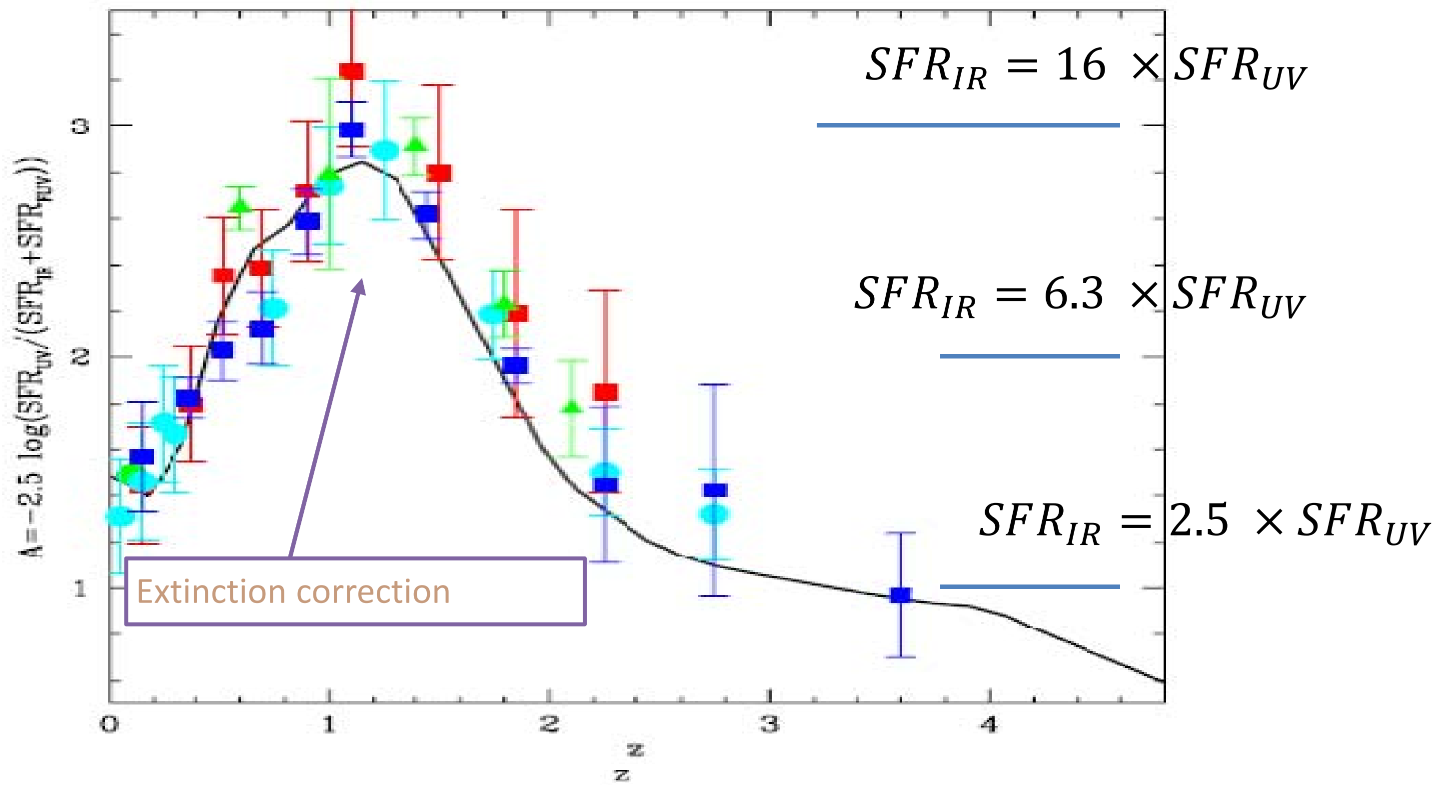
Relevance of the IR for extragalactic astrophysics & cosmology

- All inferences based on optical-UV-NIR (like those derived from HST & JWST and Fermi obs.) are highly uncertain and do not constrain the whole history at all !

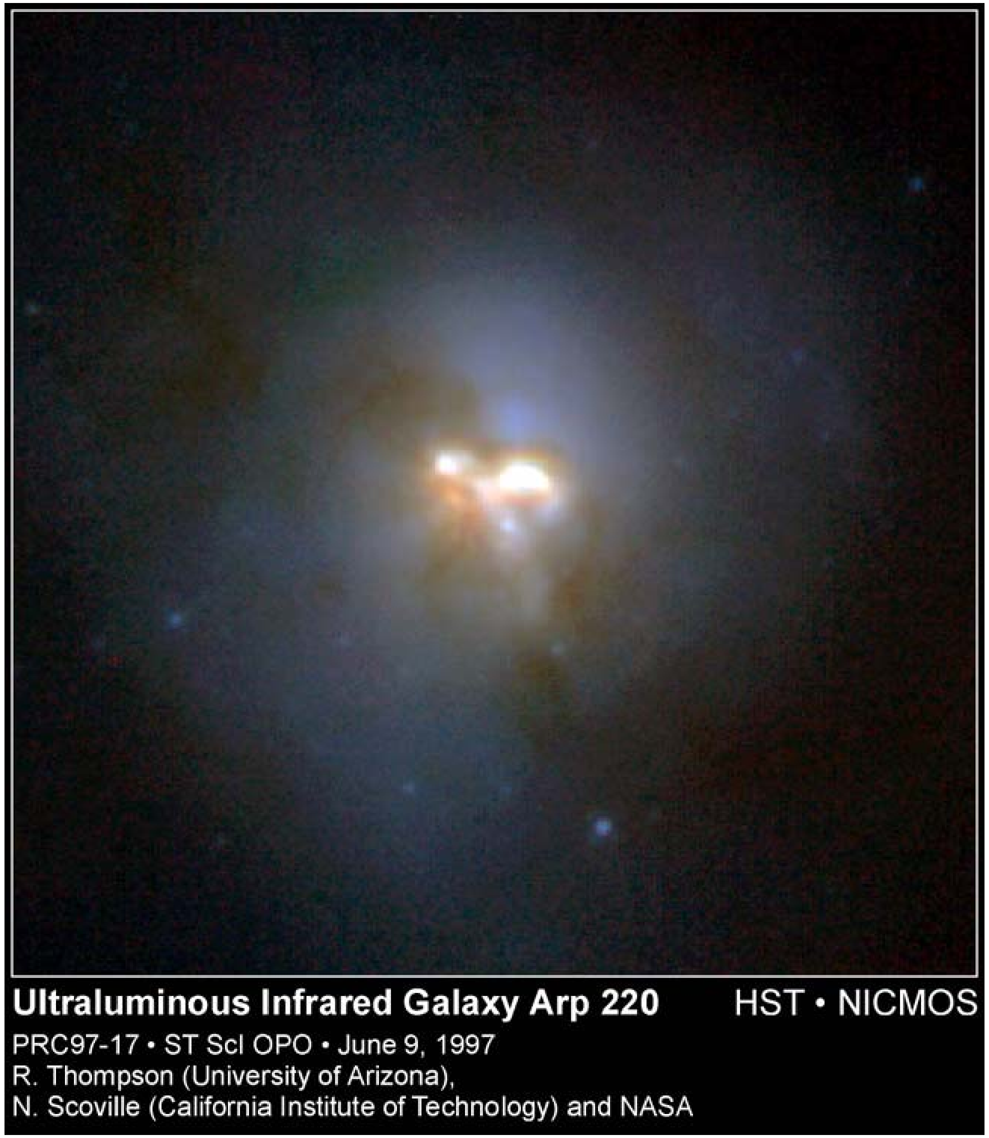


Large effects of dust extinction in cosmic structures !

- Large extinction corrections affecting the optical-UV light from cosmic sources.



All the radiation absorbed in the optical-UV-NIR is re-radiated thermally in the Infrared.

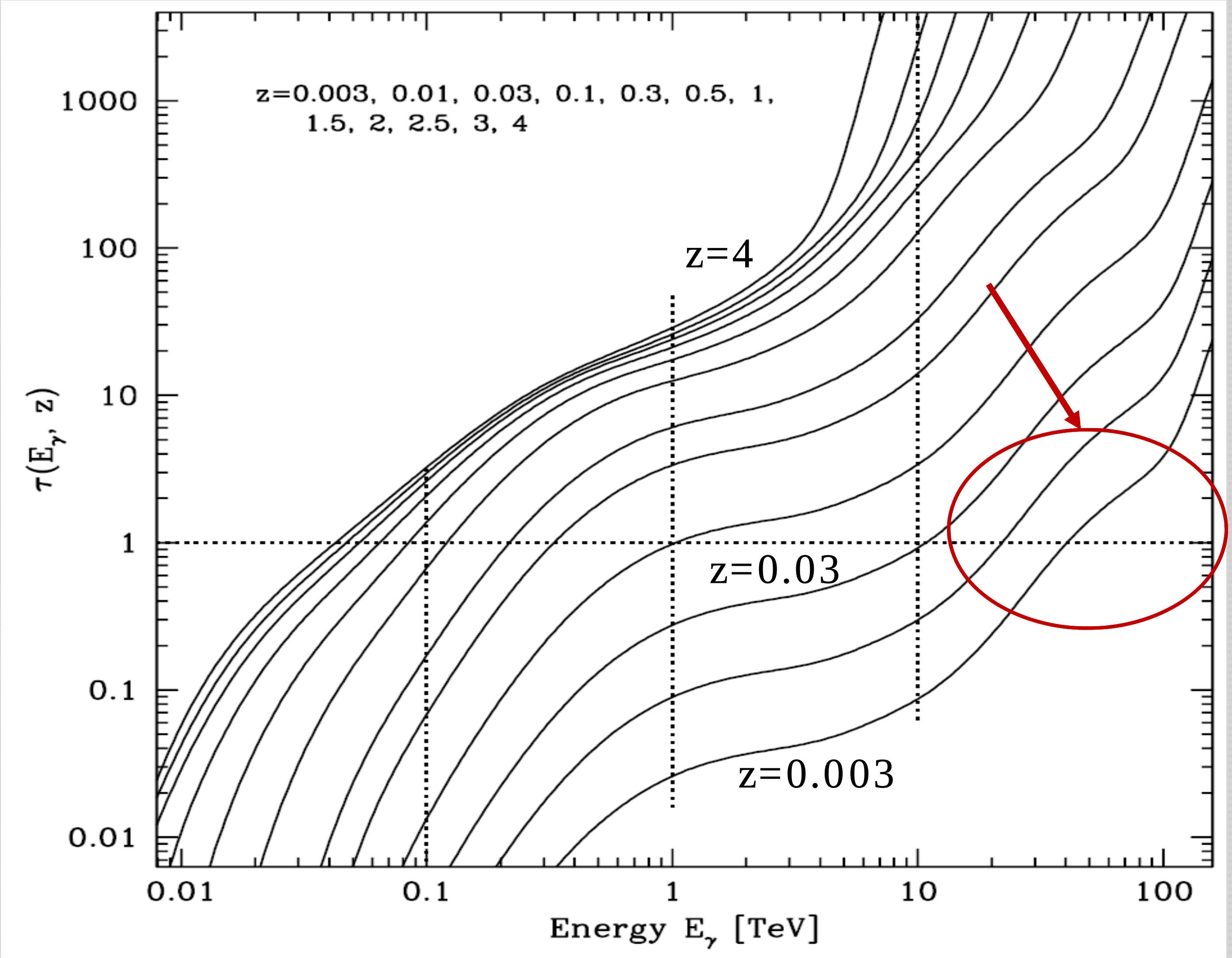


Infrared-luminous high-redshift sources (ULIRG) were very prominent in the past. They were the ancestors of local massive galaxies.

The ULIRG Arp 220 is a local analogue

Once again, γ-γ measurements needed to infer the total IR EBL

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

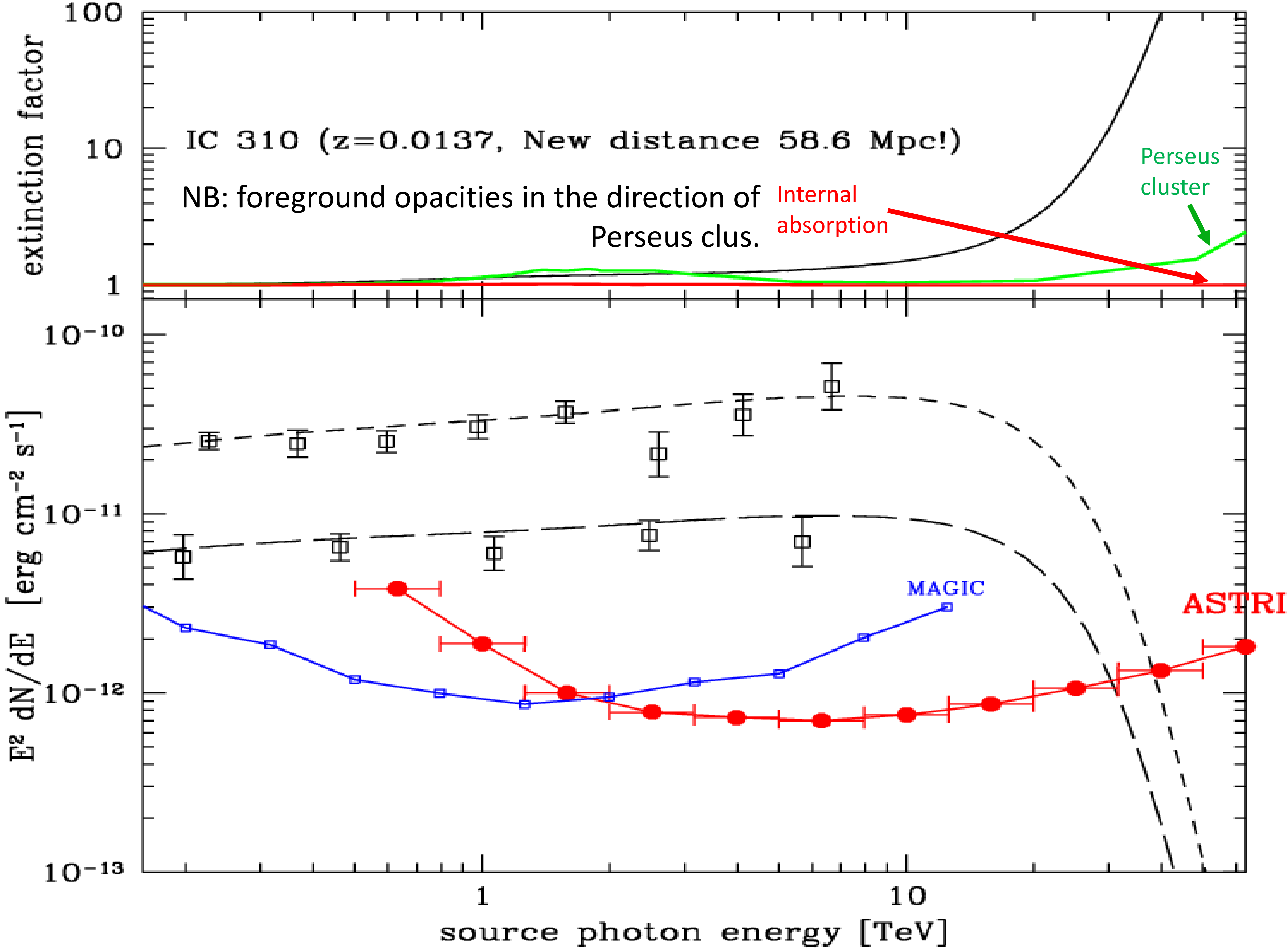


To constrain the EBL at the longest wavelengths, you need to probe sources at the highest energies, that you can do for the most local ones (z<0.03).

This is clearly matter for the SST arrays

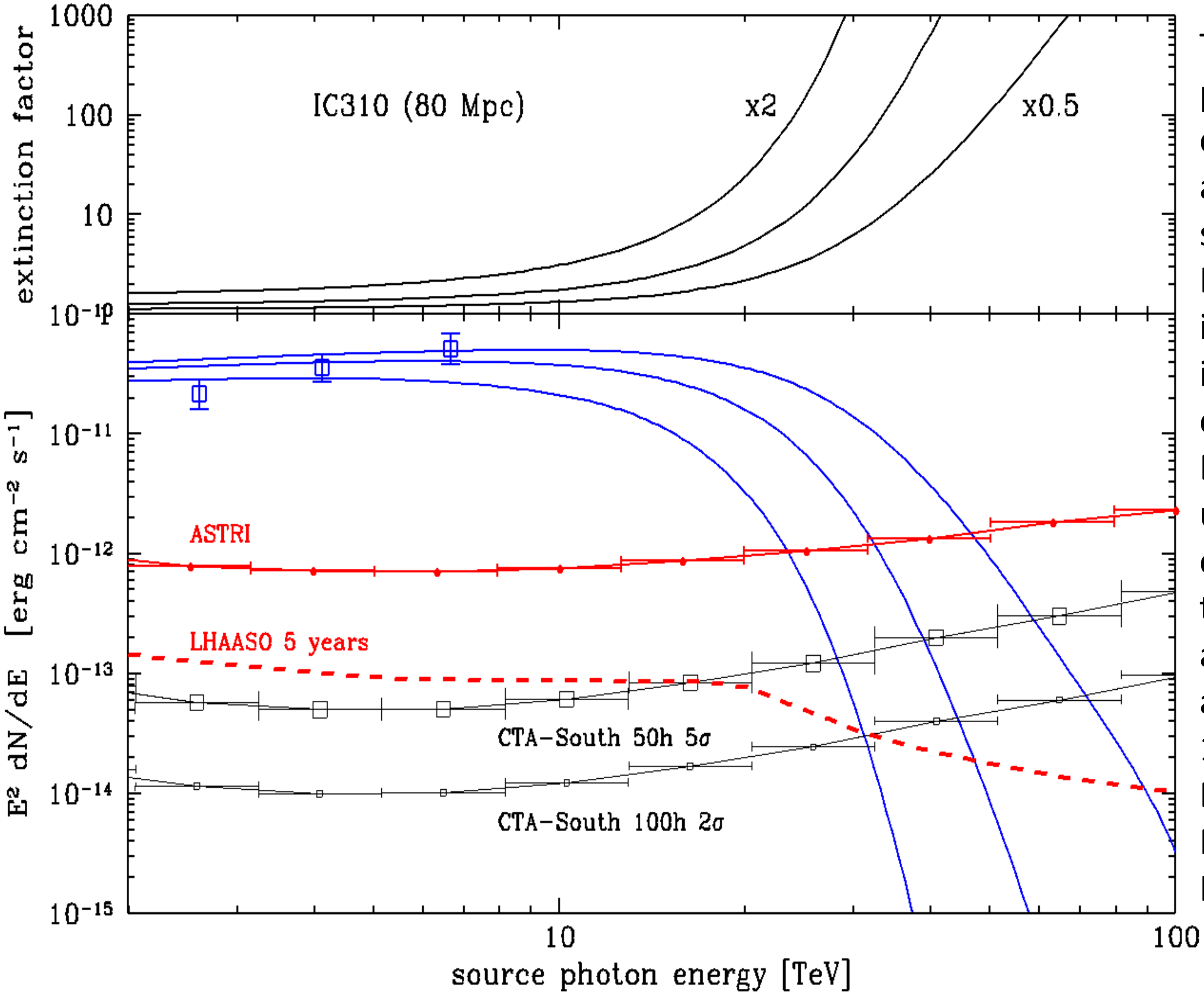
Best promising: local AGN +

- IC 310
- M 87
- Centaurus A core (too faint for CTA? but well suited for LHAASO)
- Markarian 501 (??)
- Low-z GRB’s (e.g. GRB 221009A)
- NGC 4278 (VHE detection by LHAASO)
- NGC 1275
- + low-z starbursts



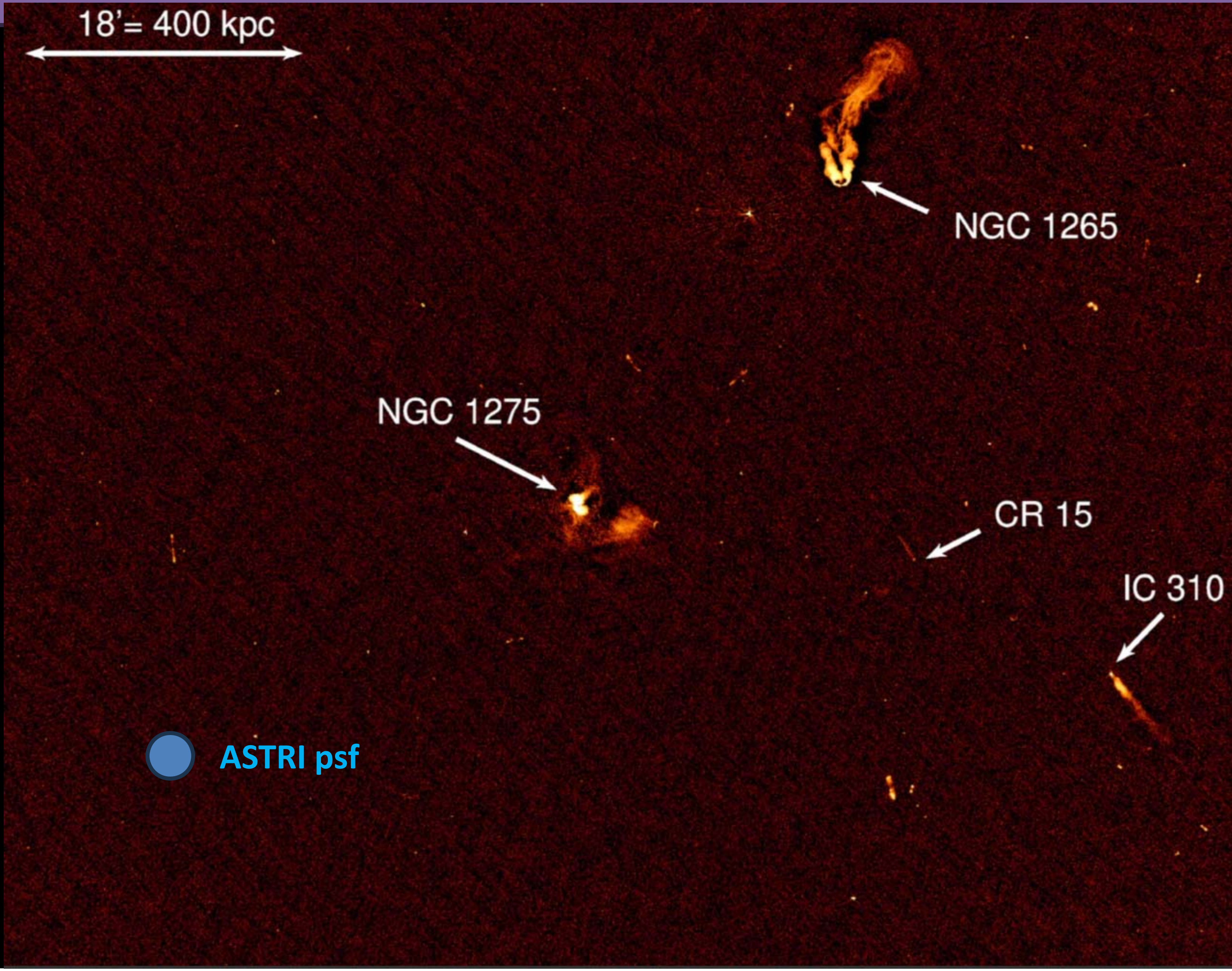
IC 310 (z=0.0137, New distance 58.6 Mpc!)
NB: foreground opacities in the direction of Perseus clus.
Internal absorption
Perseus cluster
extinction factor
100
10
1
10^{-10}
10^{-11}
10^{-12}
10^{-13}
E^2 dN/dE [erg cm^{-2} s^{-1}]
MAGIC
ASTRI
1
10
source photon energy [TeV]

Simulation for x2 variation in IR-EBL



Top panel: Photon–photon absorption correction to be applied to the IC310 spectrum for three IR EBL adopted intensities. The intermediate curve corresponds to the FR2017, and the upper and lower curves
to IR EBL intensities a factor two higher and lower between 10 and 100 μm. Bottom panel: As in Fig. 6, for the three IR EBL models.

IC310 and NGC1275 in the core of Perseus



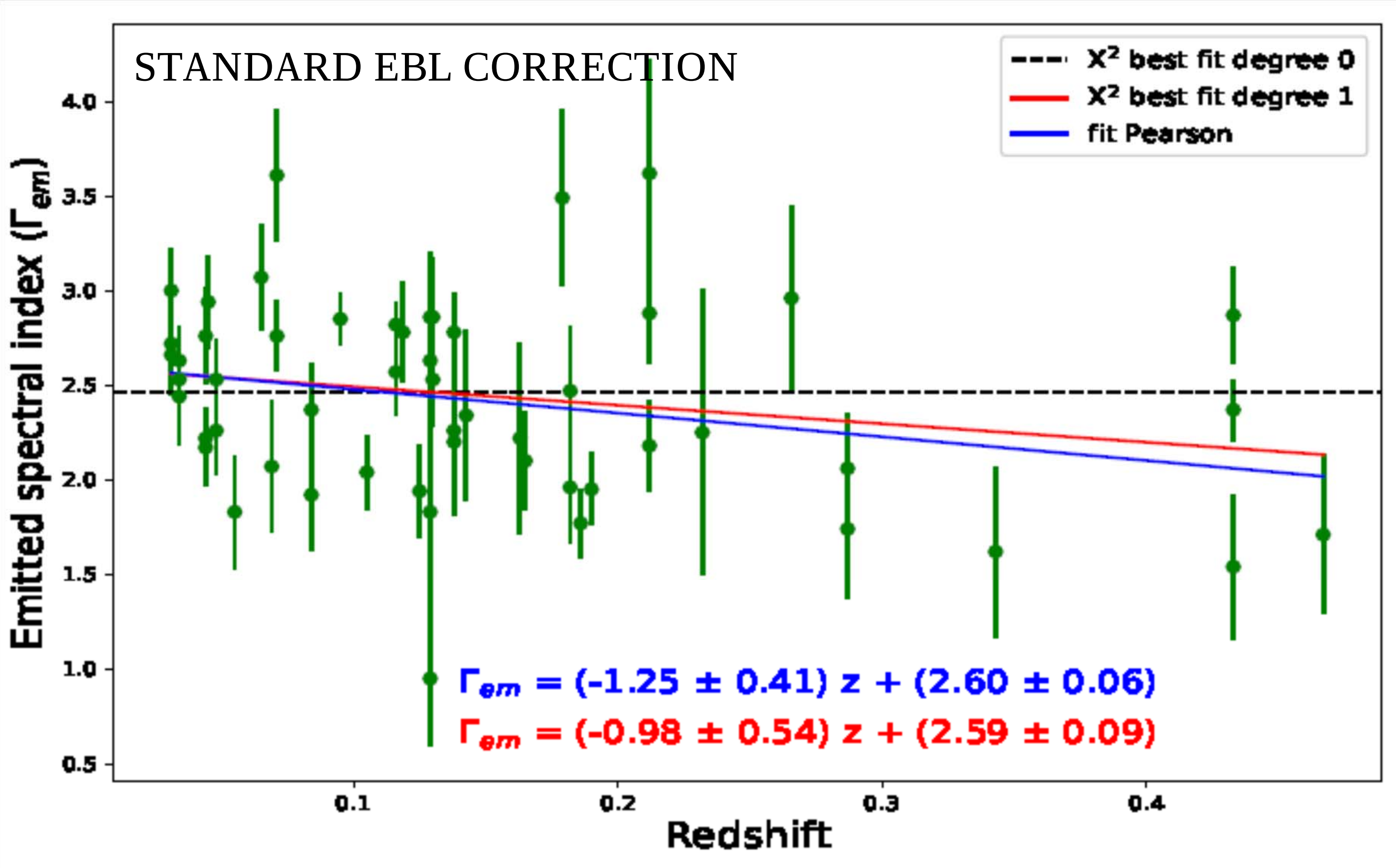
5. Refined tests of the Standard Model

Testing the γ-ALP oscillations effects in the cosmic γ-transparency

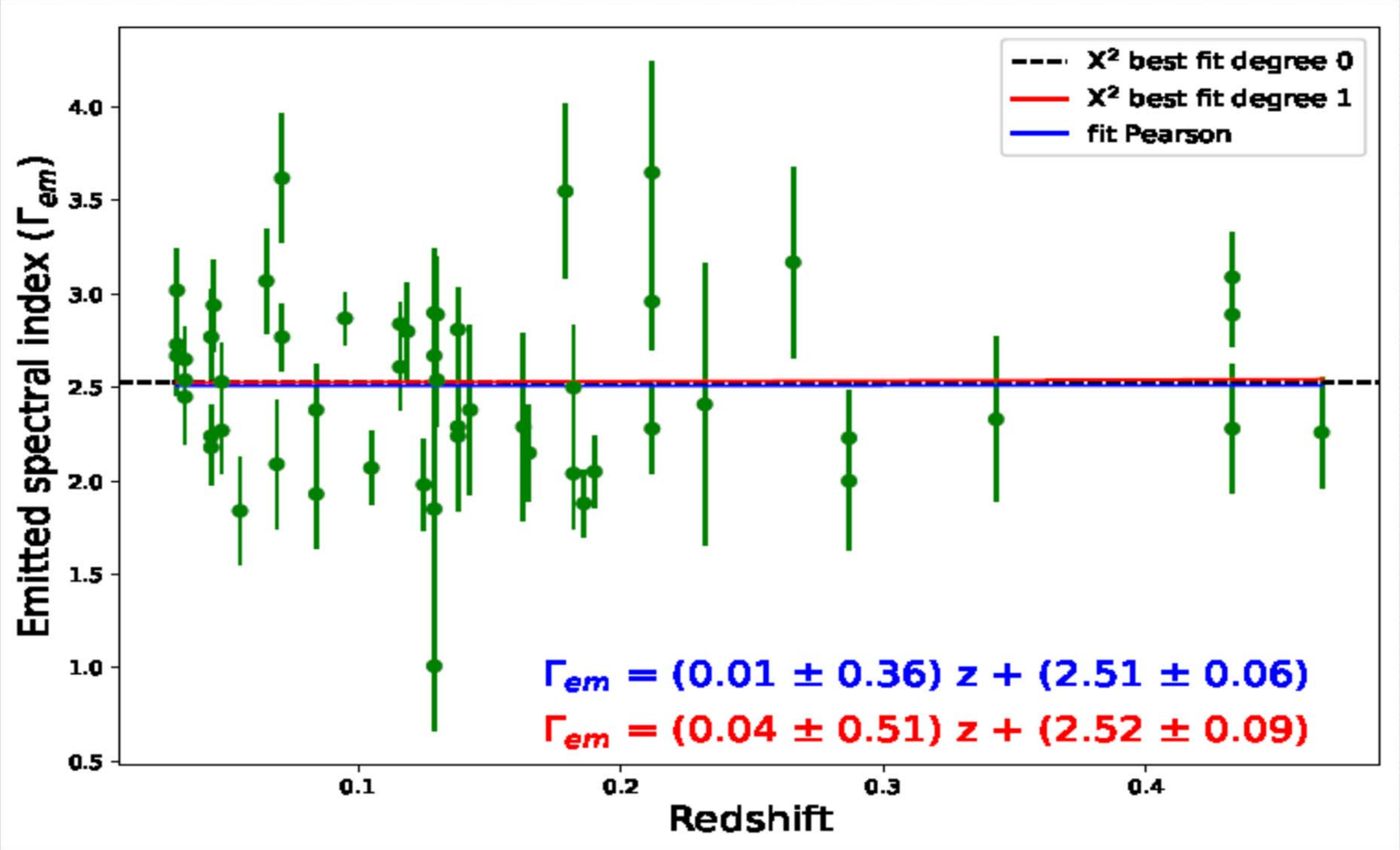
- Several extensions of the *Standard Model* (e.g. Superstring theories) suggest the existence of axion-like particles [ALPs]

  ⇒ *De Angelis, Bonnoli, Tavecchio, Galanti, Cenedese* +
- Very light spin-zero neutral pseudo-scalar bosons with a two-photon coupling ($g_{a\gamma\gamma}$).
- 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 fields.
- Effect possibly reducing $\tau_{\gamma\text{-}\gamma}$ and testable at the highest TeV energies.

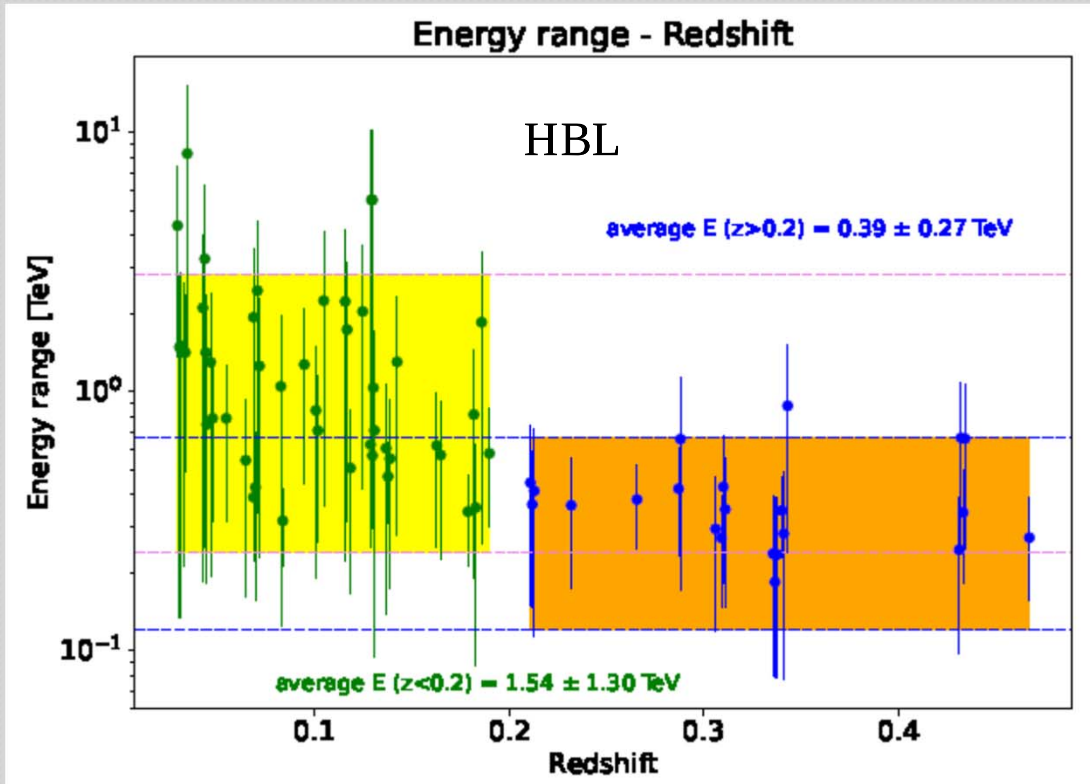
High-peak BL Lacs (HBL)



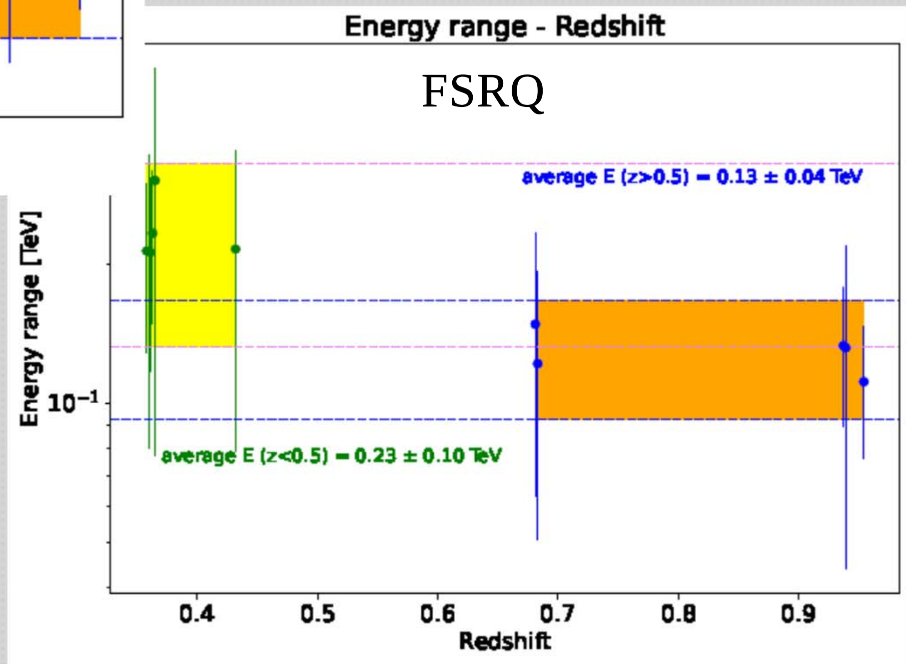
Spectral index distribution with ALPs



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



But! :
spectral coverage
as a function of z



But, estimating the significance…

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

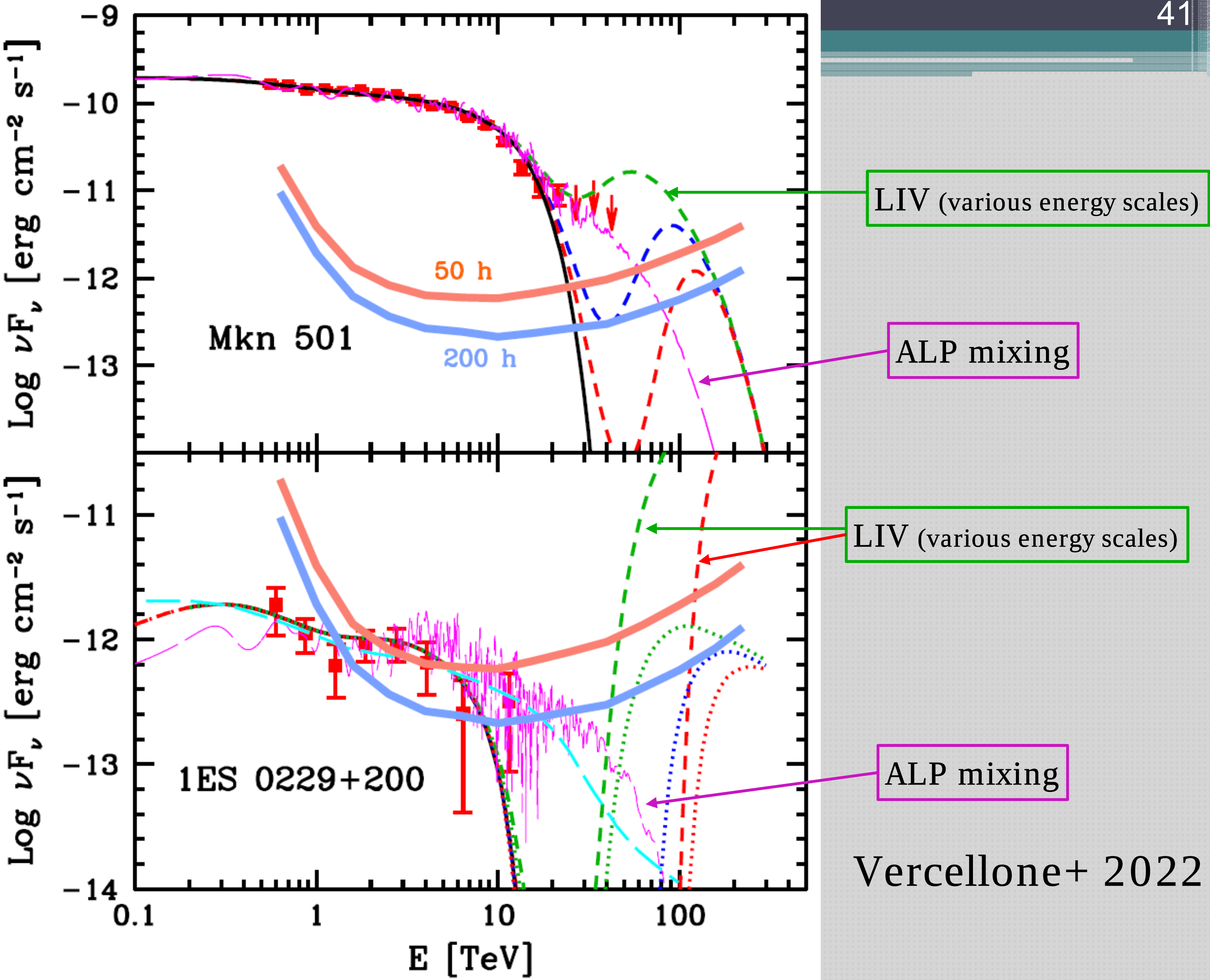
Test	Pearson	Kendall	Spearman	Horizontal fit $\chi^2_{\nu,0}$ (ndof=53)	Linear fit $\chi^2_{\nu,1}$ (ndof=52)
Observed	0.57 ± 0.05	0.37 ± 0.04	0.54 ± 0.06	4.41	2.55
P-value	0.005%	0.03%	0.02%		
EBL-corrected [$\sigma(\tau_{EBL}) = 0.1\tau_{EBL}$]	−0.24 ± 0.07	−0.17 ± 0.05	−0.25 ± 0.07	3.14	3.01
P-value	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 $\frac{\delta\tau_{EBL}}{\tau_{EBL}} \approx \frac{\delta I_\nu}{I_\nu} = 0.1 - 0.2$, $\sigma_{EBL} = \frac{\delta\tau_{EBL}}{\tau_{EBL}}\tau_{EBL}$



Vercellone+ 2022

Summary

1. The γ–γ interaction process offers great opportunities for physics, astrophysics, & cosmology.
2. Direct modeling of the IGL (EBL from sources, with combined number counts + luminosity functions; deep and ultra-deep samples): fair overall agreement
3. Total EBL measurements based on gamma-gamma opacity data have converged for the first time in showing that there is no much room in excess of the source (IGL) background, hence resolving some old issues.
4. Constraints on the standard model for cosmology: currently not effective, but good prospects for the CTAO surveys
5. ASTRI and CTAO SST's very promising for constraining, for the first time, the long-λ IR EBL and possible photon-ALP mixing.