Cosmology with *Fermi*-LAT

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and also R. Wojtak, F. Prada, L. Marcotulli, D. Hartmann

***Fermi*-LAT Collaboration, 2018, Science, 362, 1031**

Desai et al., 2019, ApJL, 874, 7

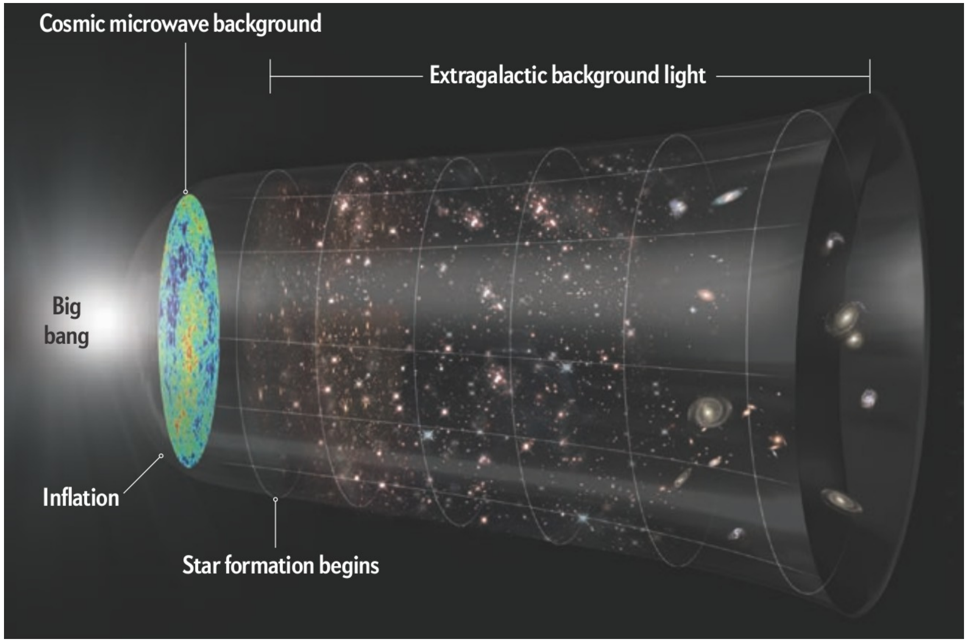
Domínguez et al., 2019, arXiv:1903.12097

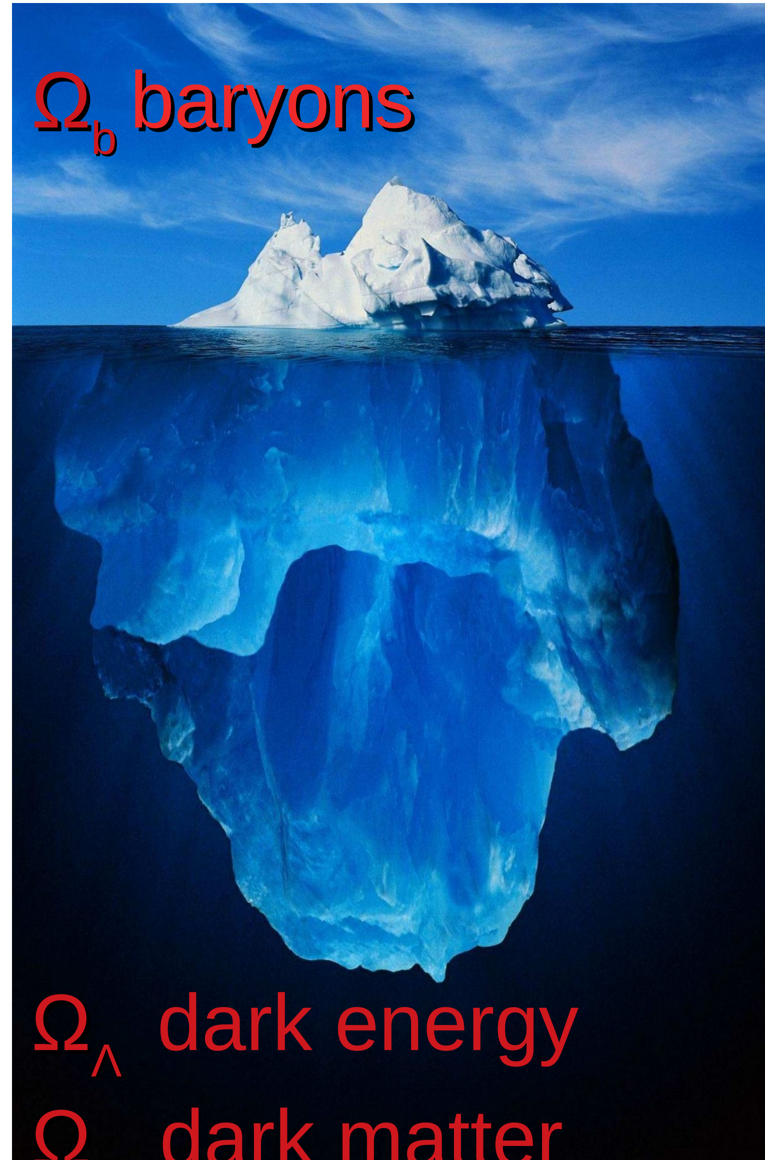
Domínguez, Primack, Bell

Scientific American, August 2015

31st Rencontres de Blois / June 2 – 7, 2019

Galaxy Evolution and Cosmology





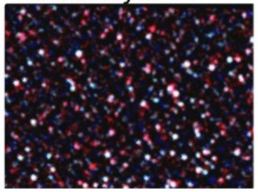
$$\Omega_m = \Omega_b + \Omega_D$$

$$\Omega_m + \Omega_\Lambda = 1$$

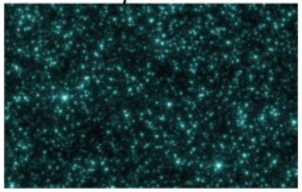
Cosmic Diffuse Extragalactic Backgrounds

Artistic representation of a binary system

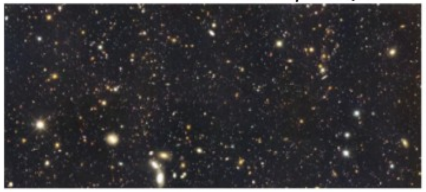
Herschel far-IR

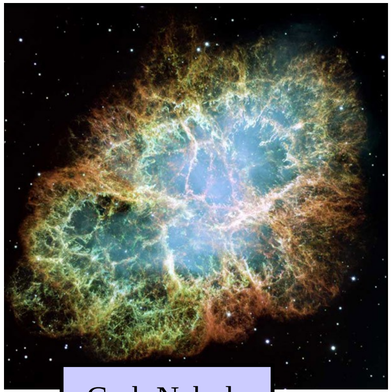


Spitzer mid-IR



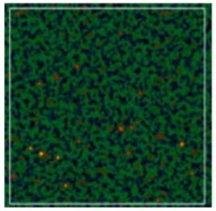
HST-optical/UV



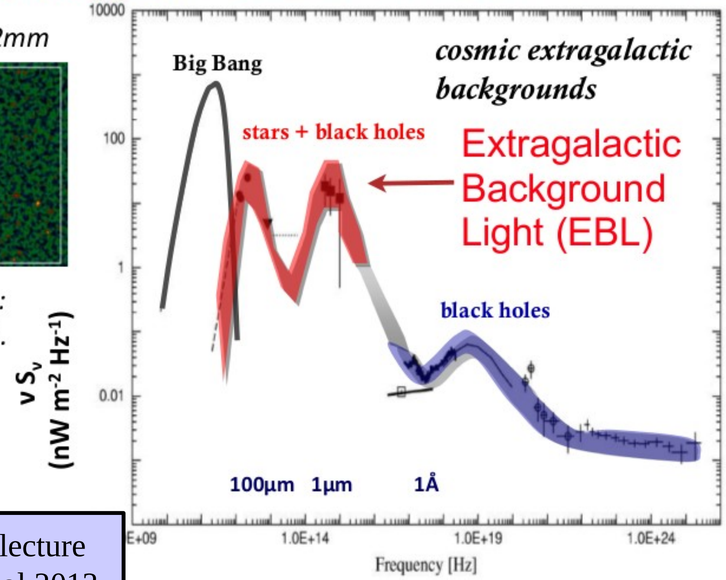


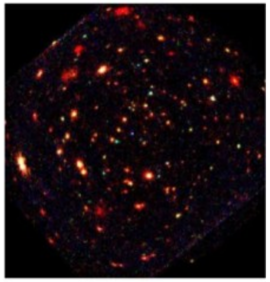
Crab Nebula

0.850-1.2mm



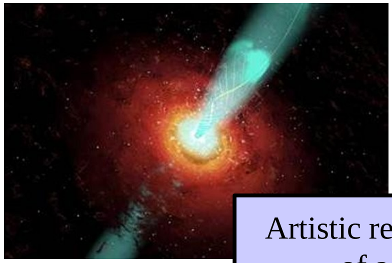
in the future:
ALMA, CCAT..





Chandra/XMM –X-ray

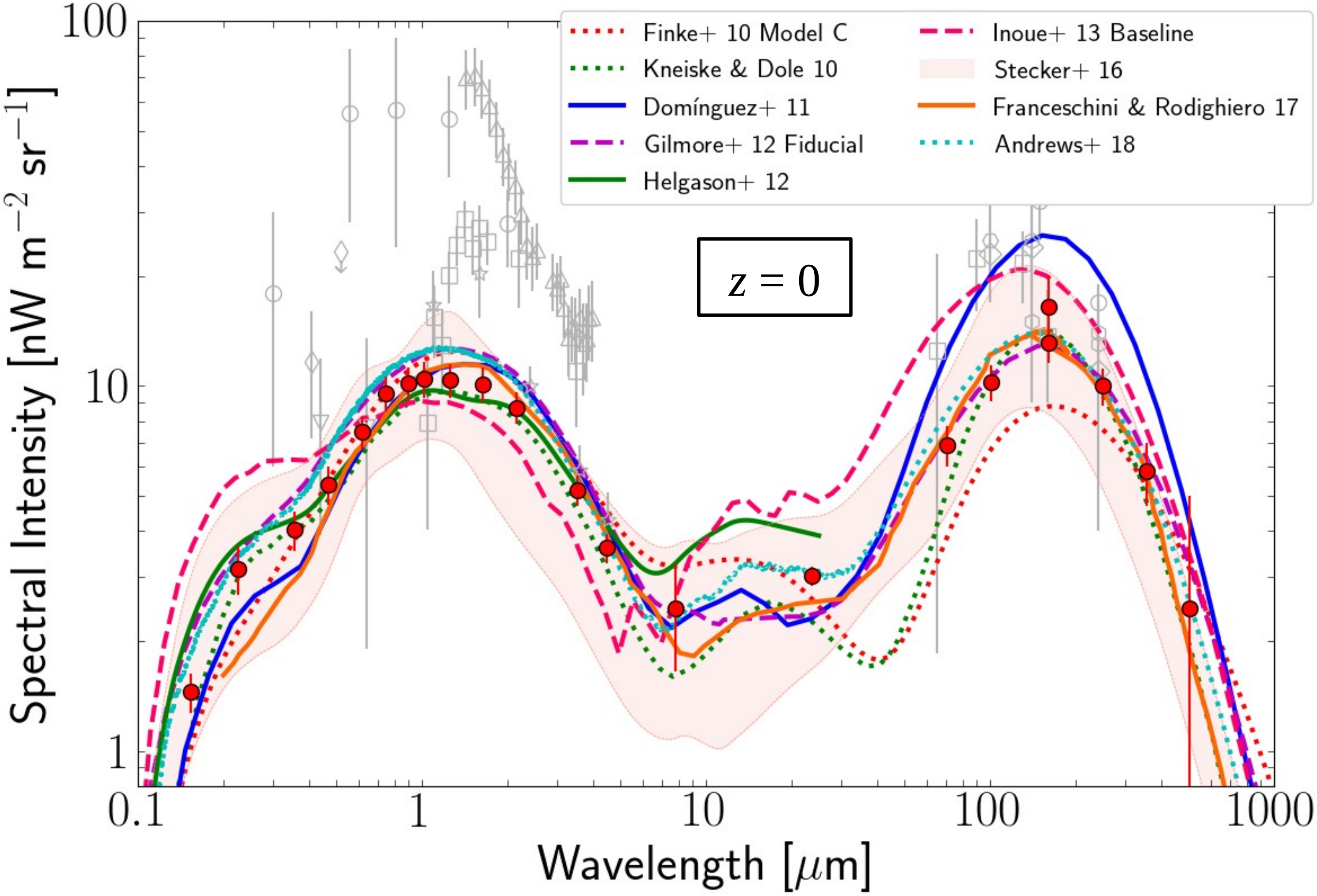
From Reinhard Genzel's lecture @ Jerusalem Winter School 2013



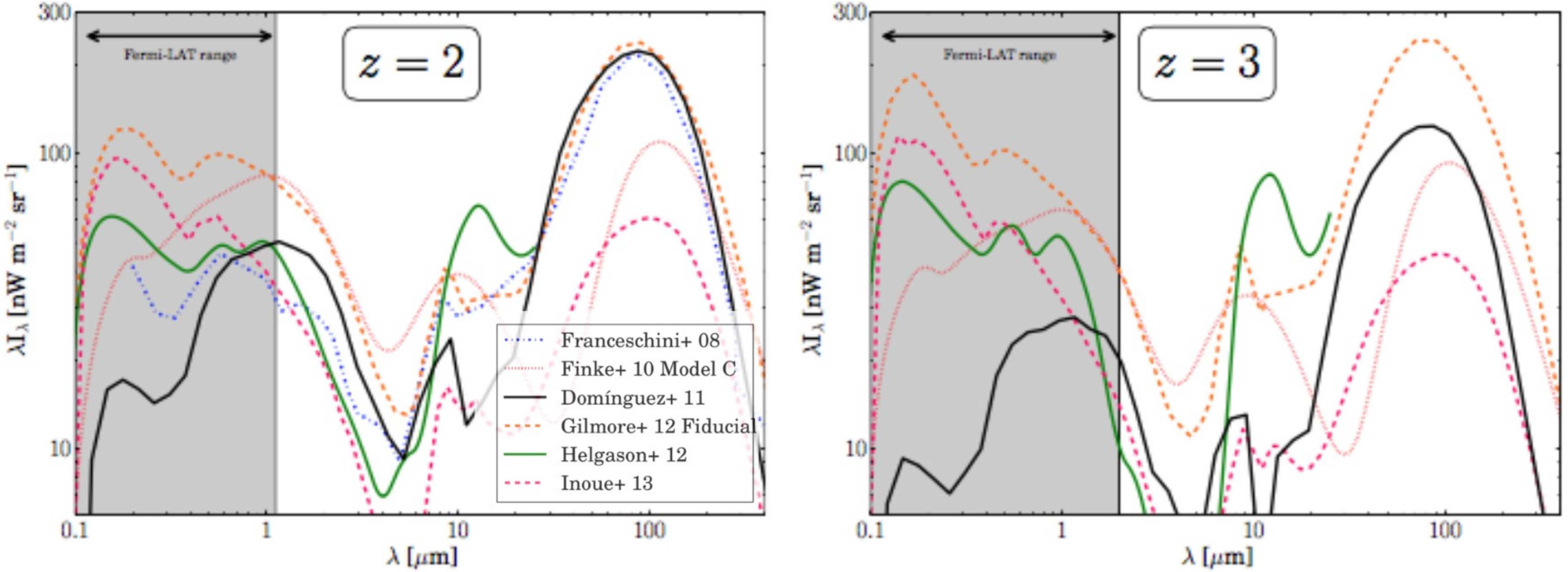
Artistic representation of a blazar

Orion Nebula (birth place of stars)

Extragalactic Background Light

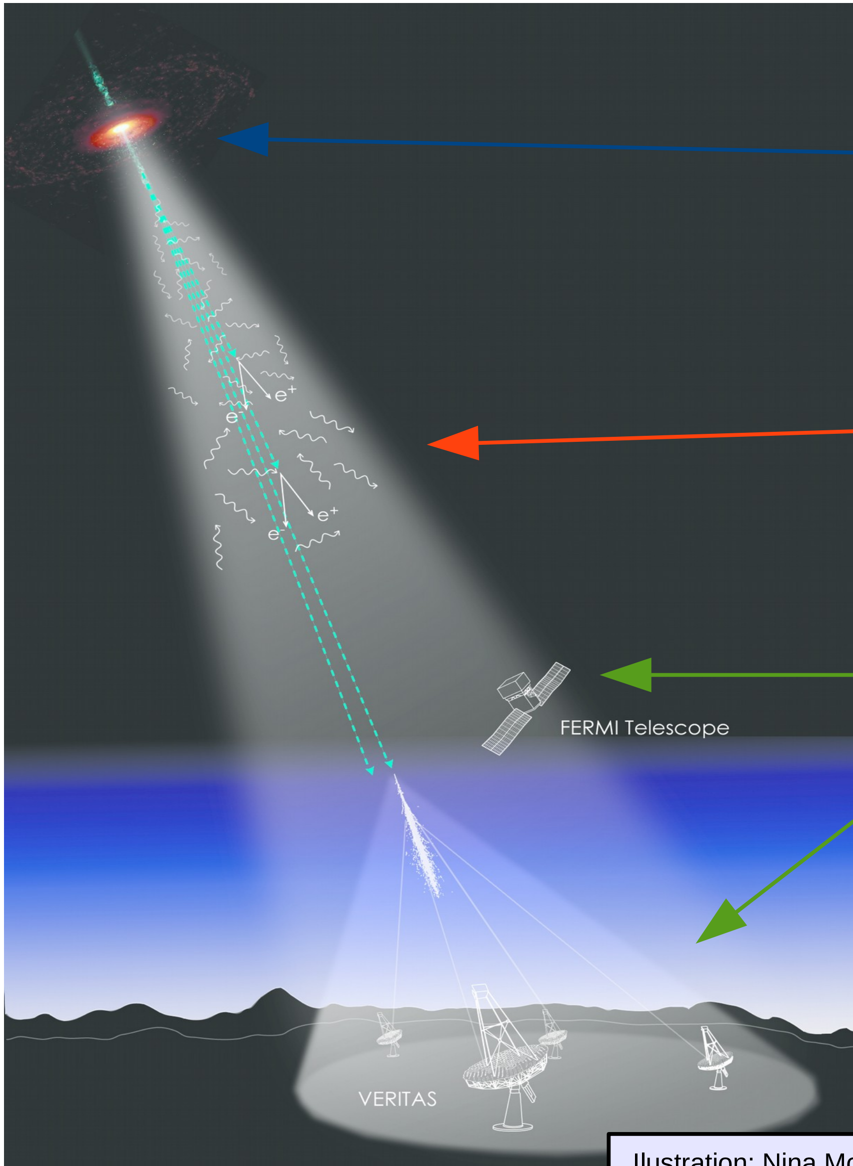


Extragalactic Background Light (Evolution)



Strong divergence

Gamma-ray Attenuation



Ilustration: Nina McCurdy & Joel Primack

Extragalactic source:
e.g. Blazar

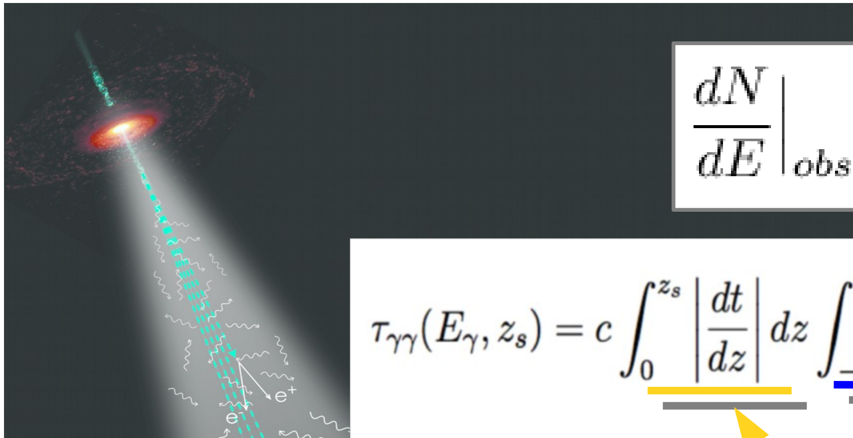
Blazars: AGNs emitting at all wavelength with energetic jets pointing towards us.

Pair-production interaction

Reverse of most known electron-positron annhilation process

Telescopes: Fermi-LAT and Imaging Atmospheric Cherenkov Telescopes (IACTs)

Gamma-ray Attenuation



$$\left.\frac{dN}{dE}\right|_{obs} = \left.\frac{dN}{dE}\right|_{int} \exp\left[-\tau(E,z)\right]$$

$$\tau_{\gamma\gamma}(E_\gamma, z_s) = c\int_0^{z_s}\left|\frac{dt}{dz}\right|dz\int_{-1}^{1}(1-\mu)\frac{d\mu}{2}\int_{2m_e^2c^4/\epsilon_\gamma(1-\mu)}^{\infty}\sigma(\epsilon_{\rm EBL},\epsilon_\gamma,\mu)\,n_{\rm EBL}(\epsilon,z)\,d\epsilon_{\rm EBL}$$

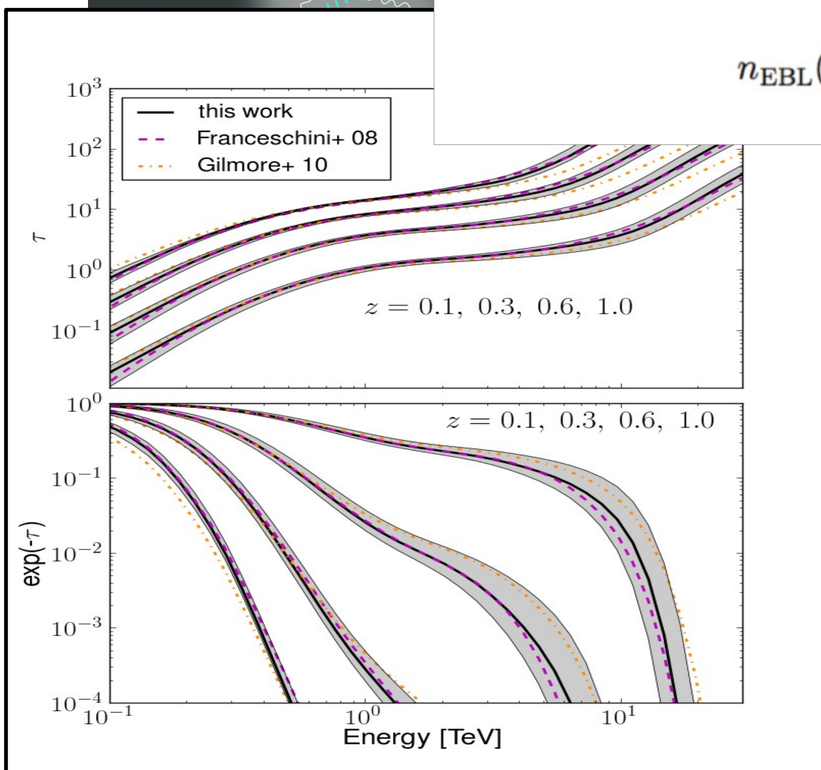
$$n_{\rm EBL}(\epsilon, z) = (1+z)^3\int_z^{\infty}\frac{j(\epsilon,z)}{\epsilon}\left|\frac{dt}{dz'}\right|dz'$$

distance

cross section

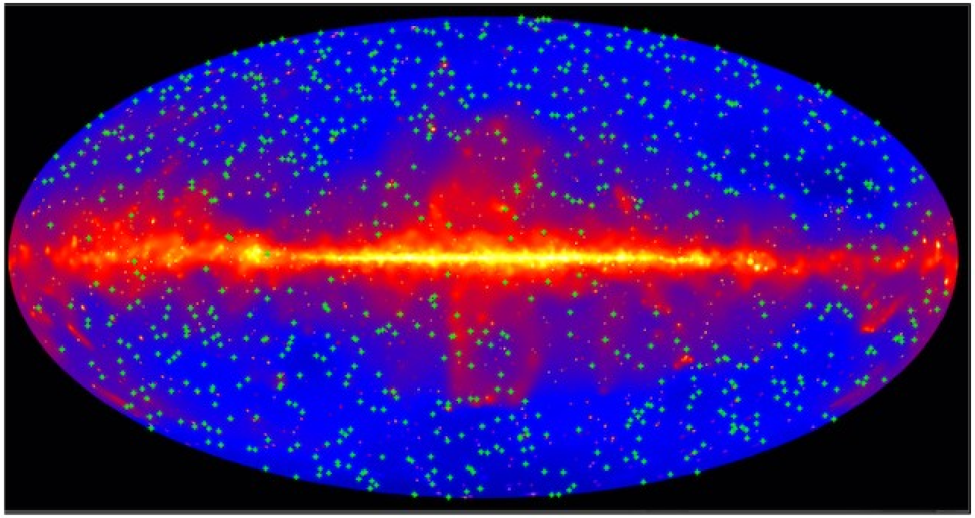
EBL photon density evolution

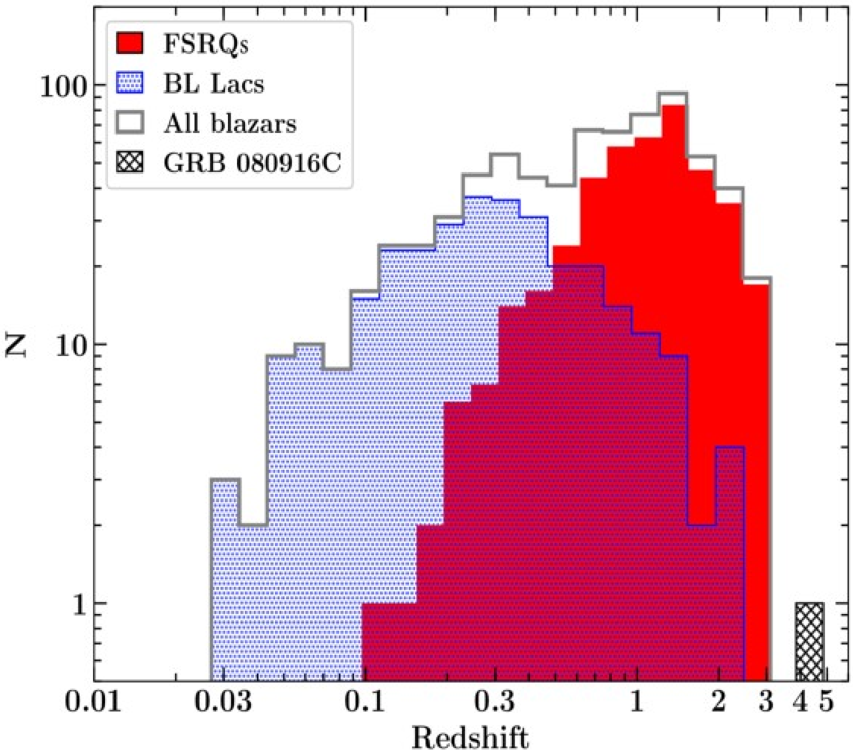
See Domínguez & Prada 13,
Biteau & Williams 15



: Nina McCurdy & Joel Primack

Optical Depths from Gamma-ray Data



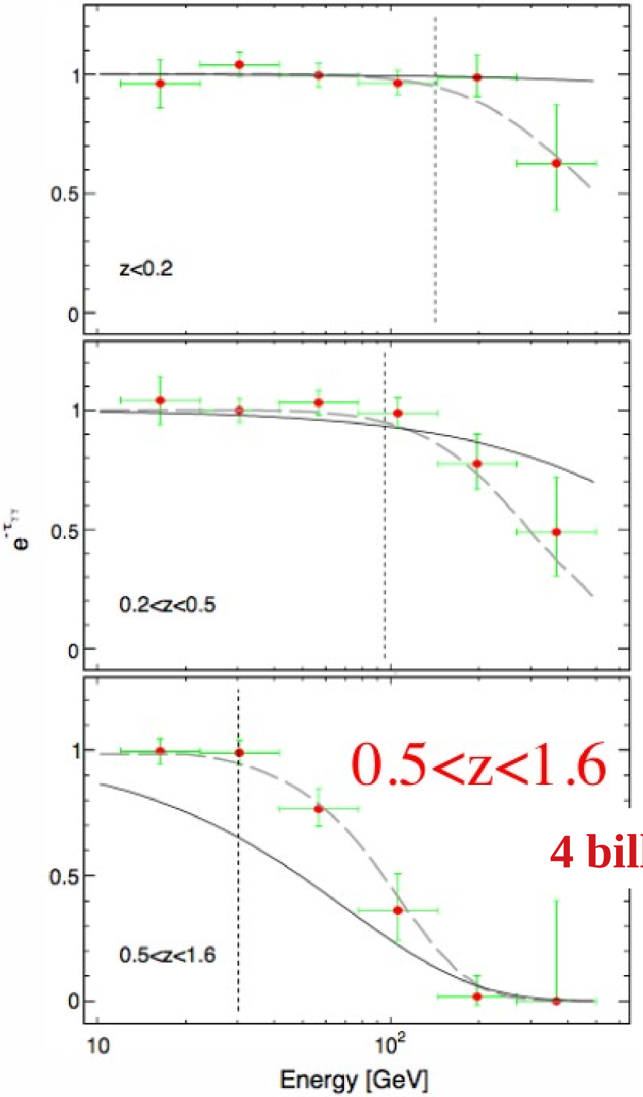


- Use 9 years of P8 LAT data
- 739 blazars + 1 GRB
- Perform a time-resolved analysis,
- Analysis optimized on simulations

Analysis improved over the Ackermann+12 results

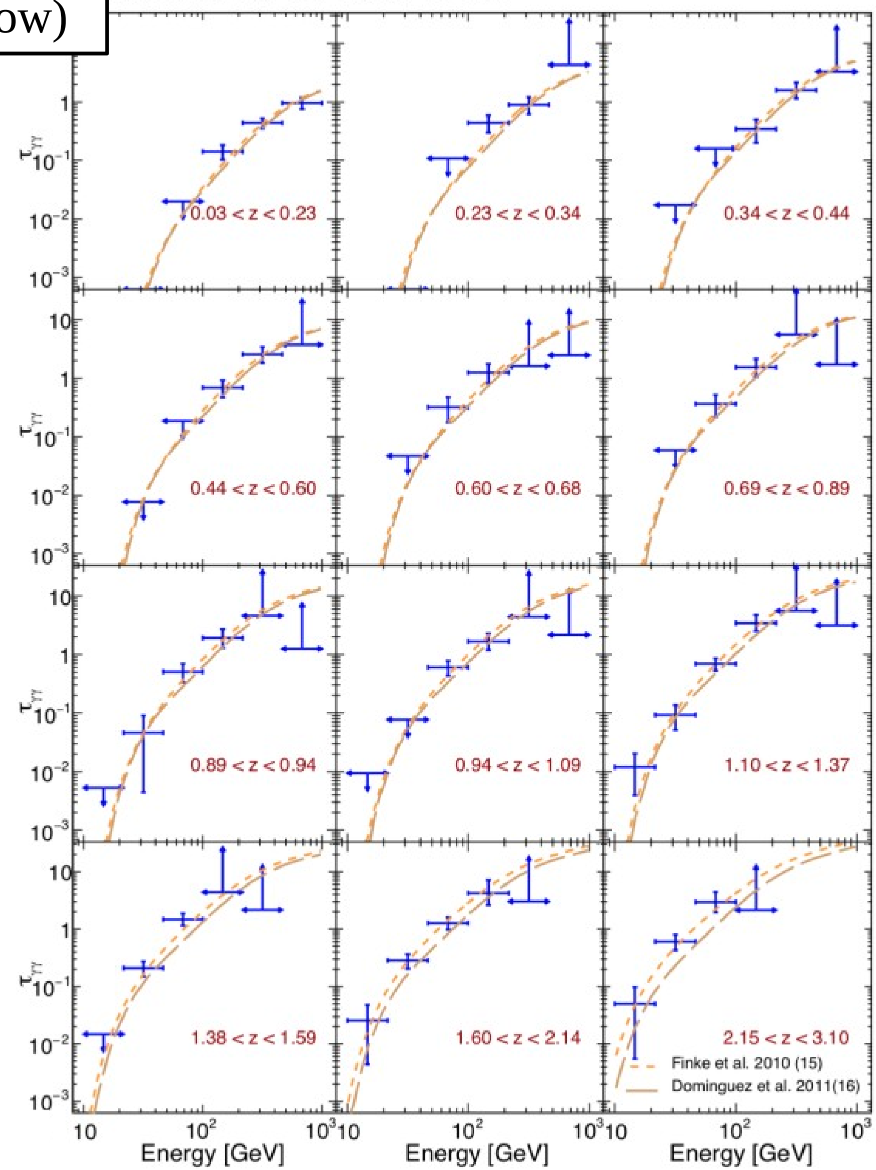
Optical Depths from Gamma-ray Data

From detection (2012) to characterization (Now)

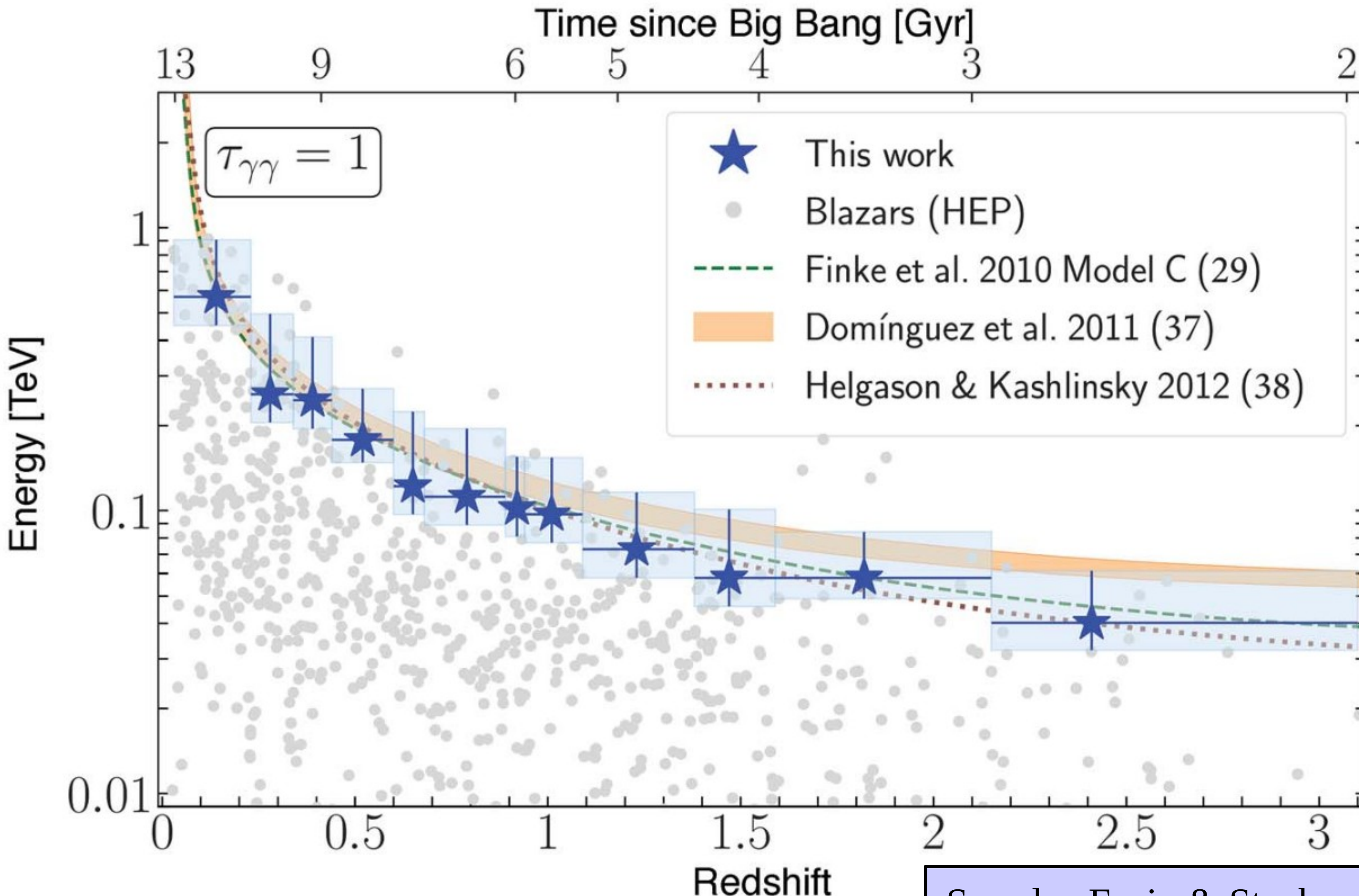


0.5<z<1.6

4 billion years



Cosmic Gamma-Ray Horizon



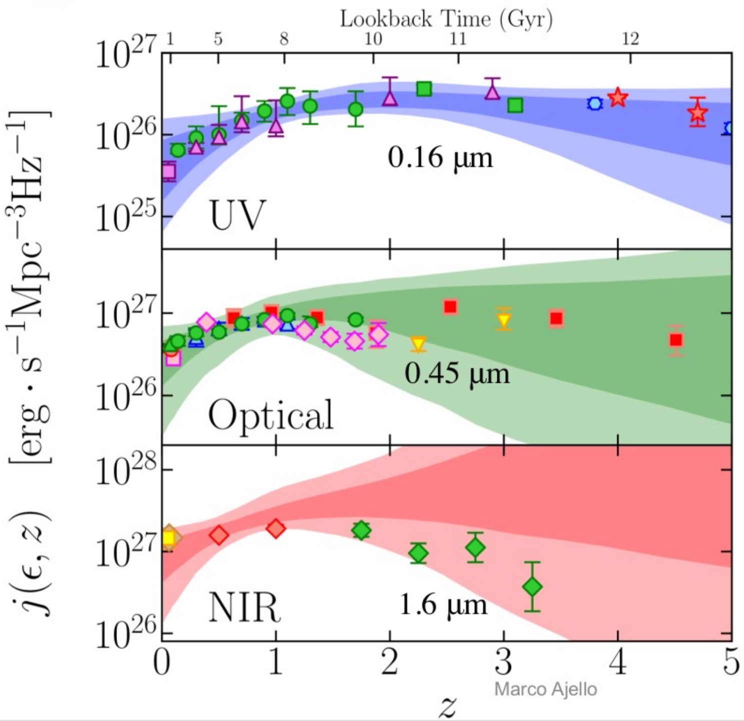
See also Fazio & Stecker 1970, Domínguez et al. 2013

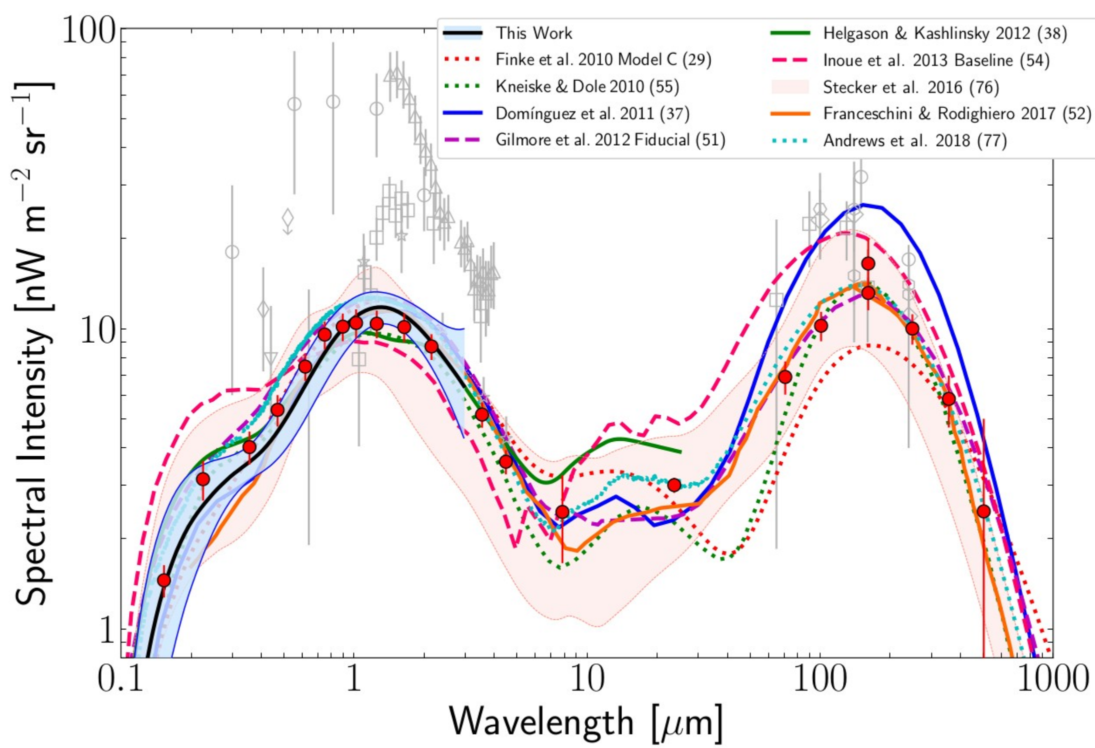
Galaxy Luminosity Densities and EBL

$$n_{\mathrm{EBL}}(\epsilon, z) = (1+z)^3 \int_z^{\infty} \frac{j(\epsilon, z)}{\epsilon} \left| \frac{dt}{dz'} \right| dz'$$

$$j(\lambda_i, z) = \sum_i a_i \cdot \exp\left[-\frac{(\log\lambda - \log\lambda_i)^2}{2\sigma^2} \right] \times \frac{(1+z)^{b_i}}{1 + \left(\frac{1+z}{c_i}\right)^{d_i}},$$

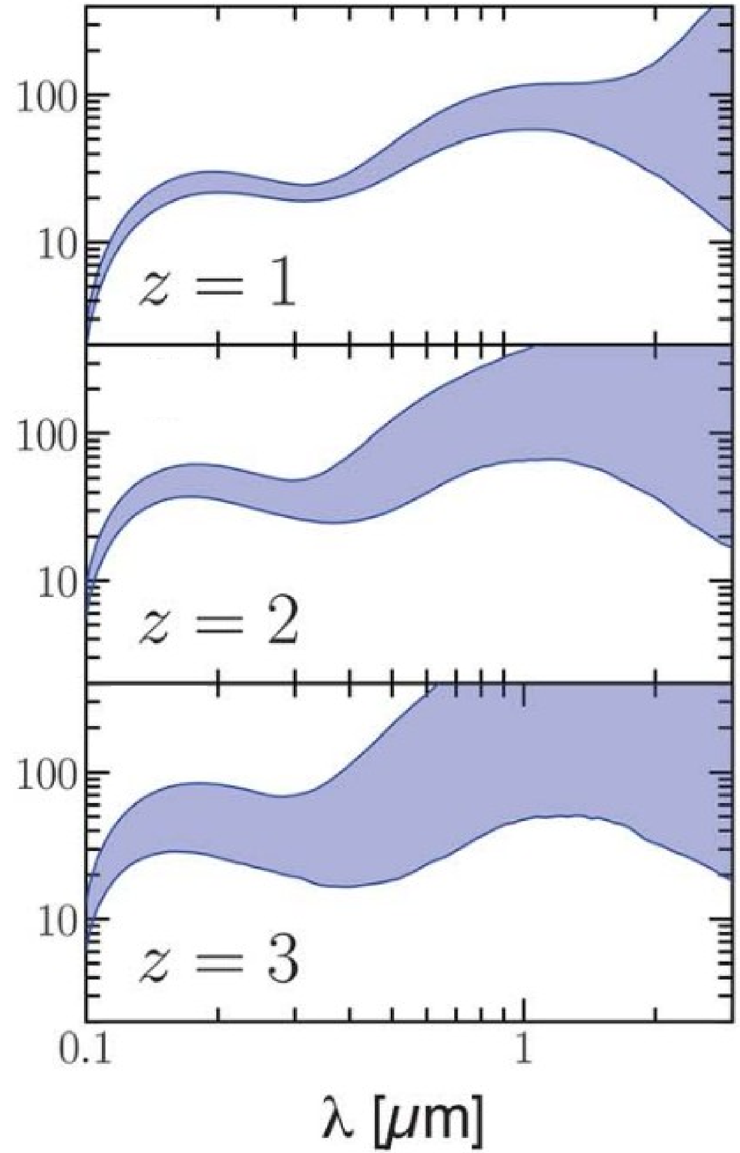
Luminosity density evolution as sum of log-normal distributions that can evolve independently





Galaxy Luminosity Densities and EBL

First EBL determination at $z>0$

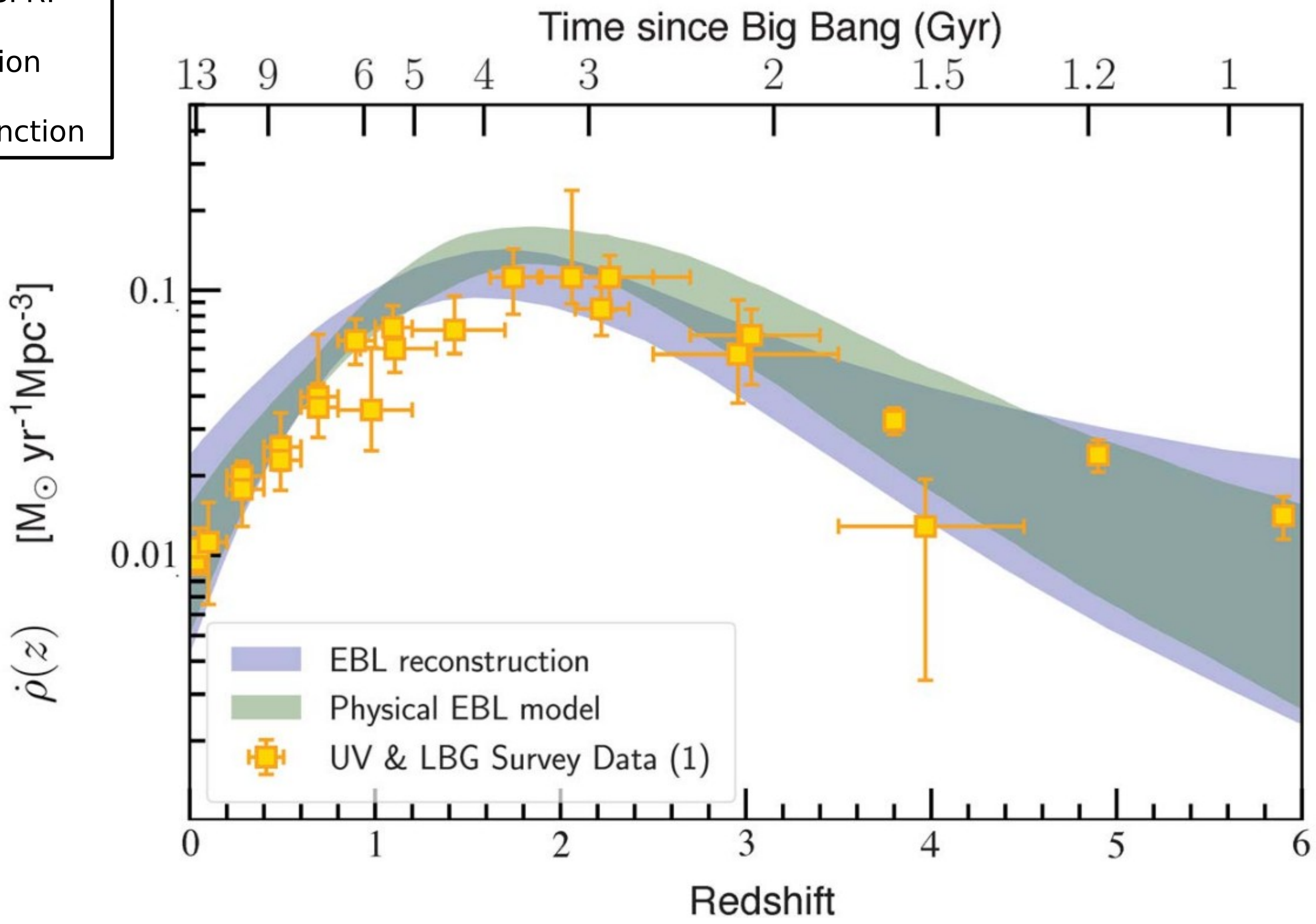


Cosmic Star Formation Rate

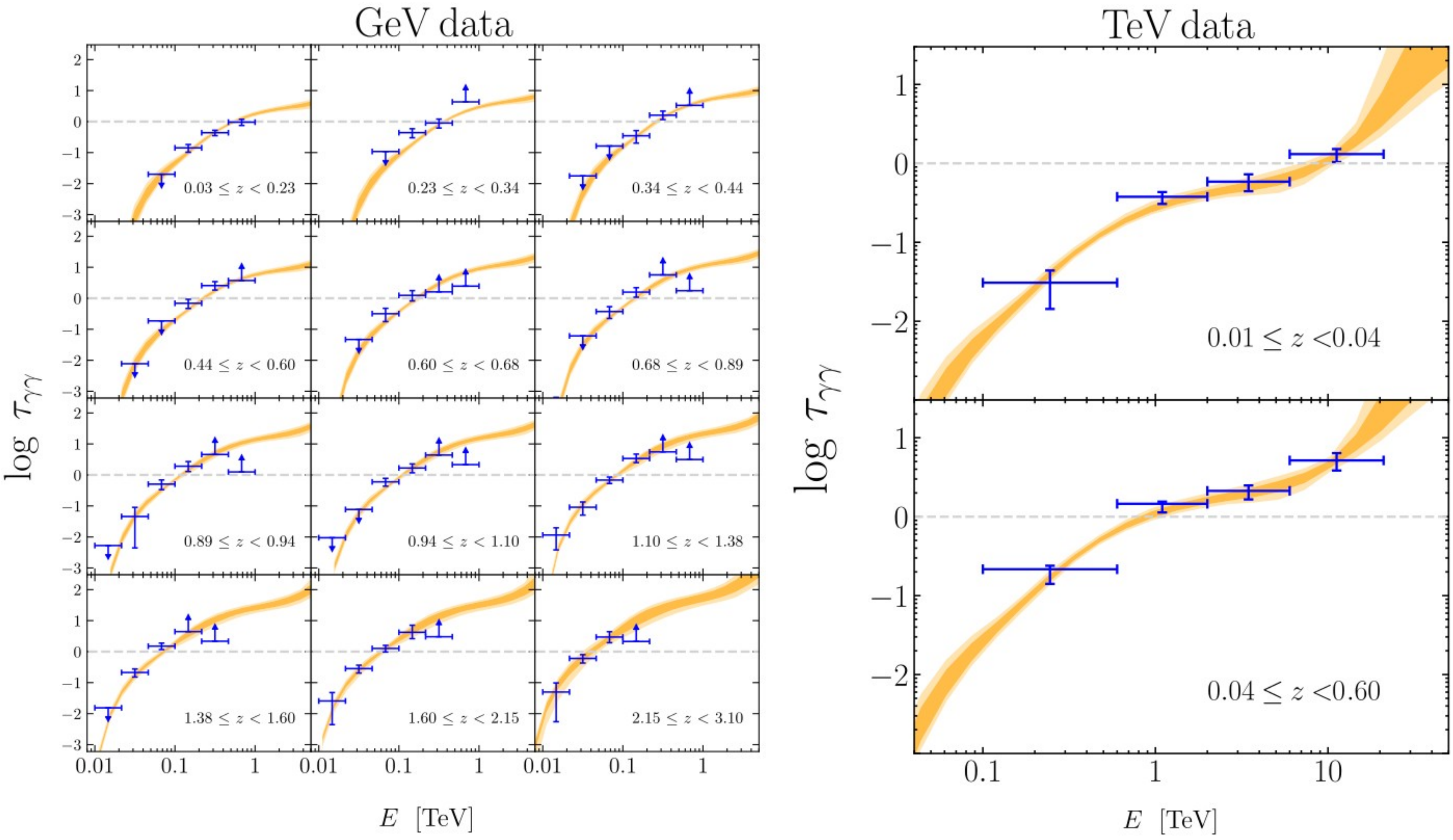
UV (0.16 microns) to SFR:

(1) Initial Mass Function

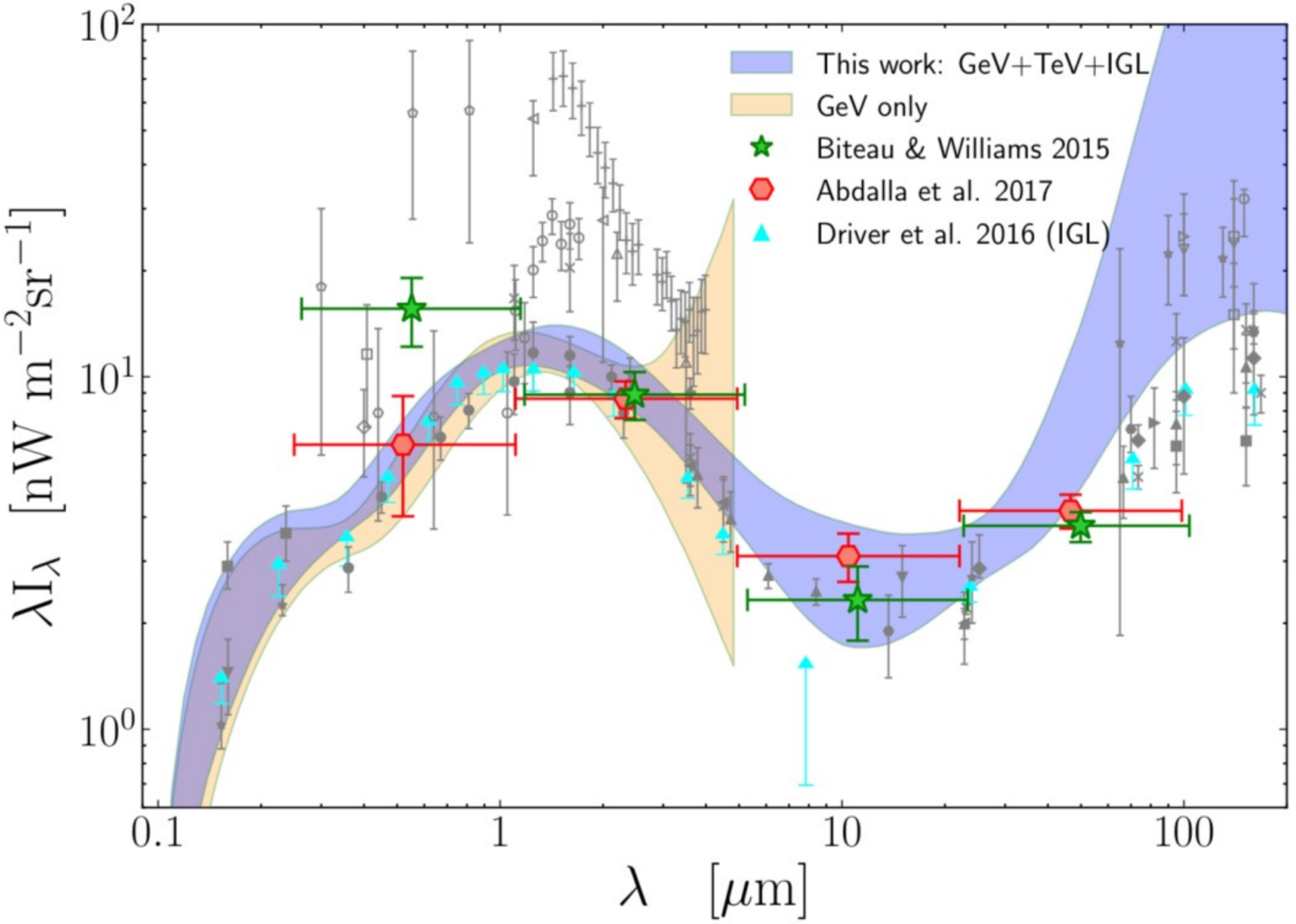
(2) Average Galaxy Extinction



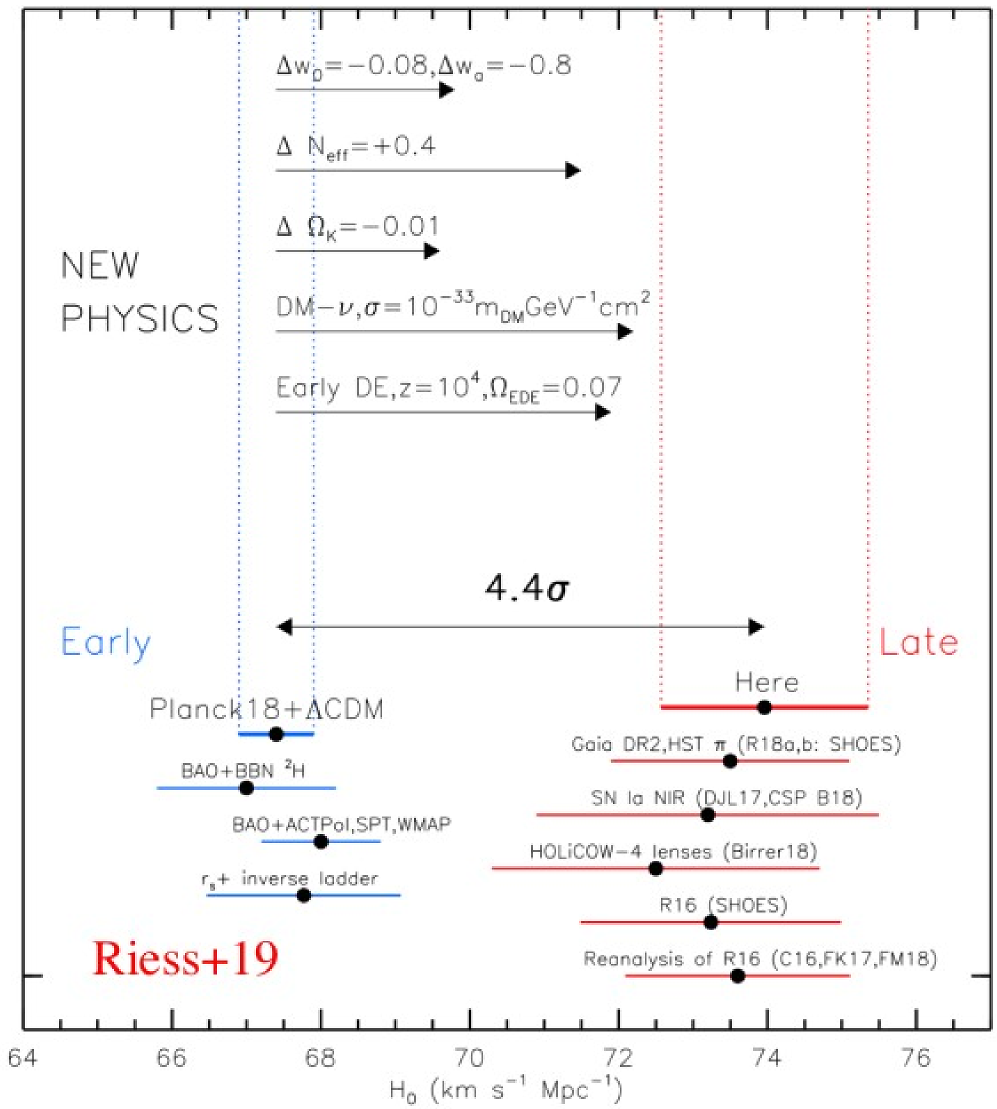
Optical Depths from Gamma-ray Data



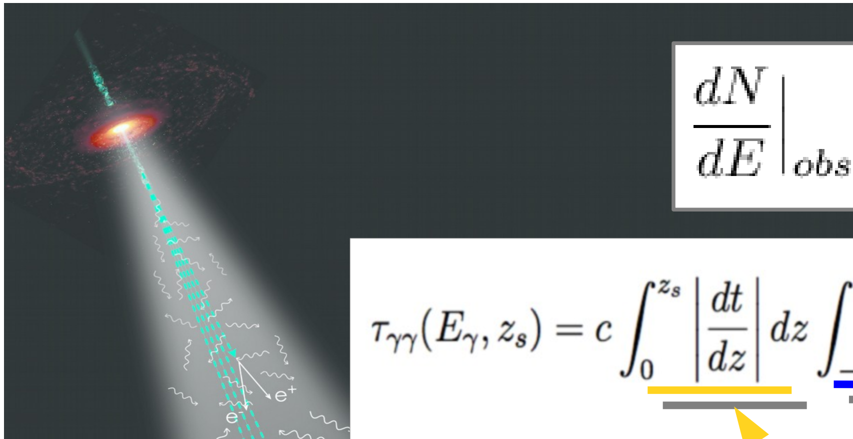
Extragalactic Background Light from Gamma Rays



Tension on H_0 Measurements



Gamma-ray Attenuation



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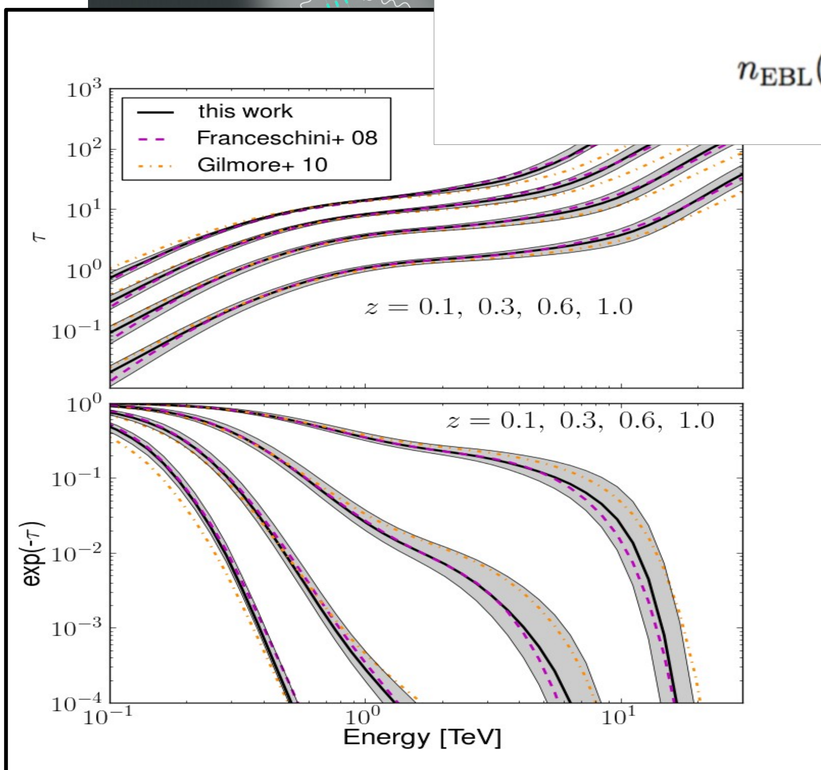
$$n_{\rm EBL}(\epsilon,z) = (1+z)^3\int_z^\infty \frac{j(\epsilon,z)}{\epsilon}\left|\frac{dt}{dz'}\right|dz'$$

distance

cross section

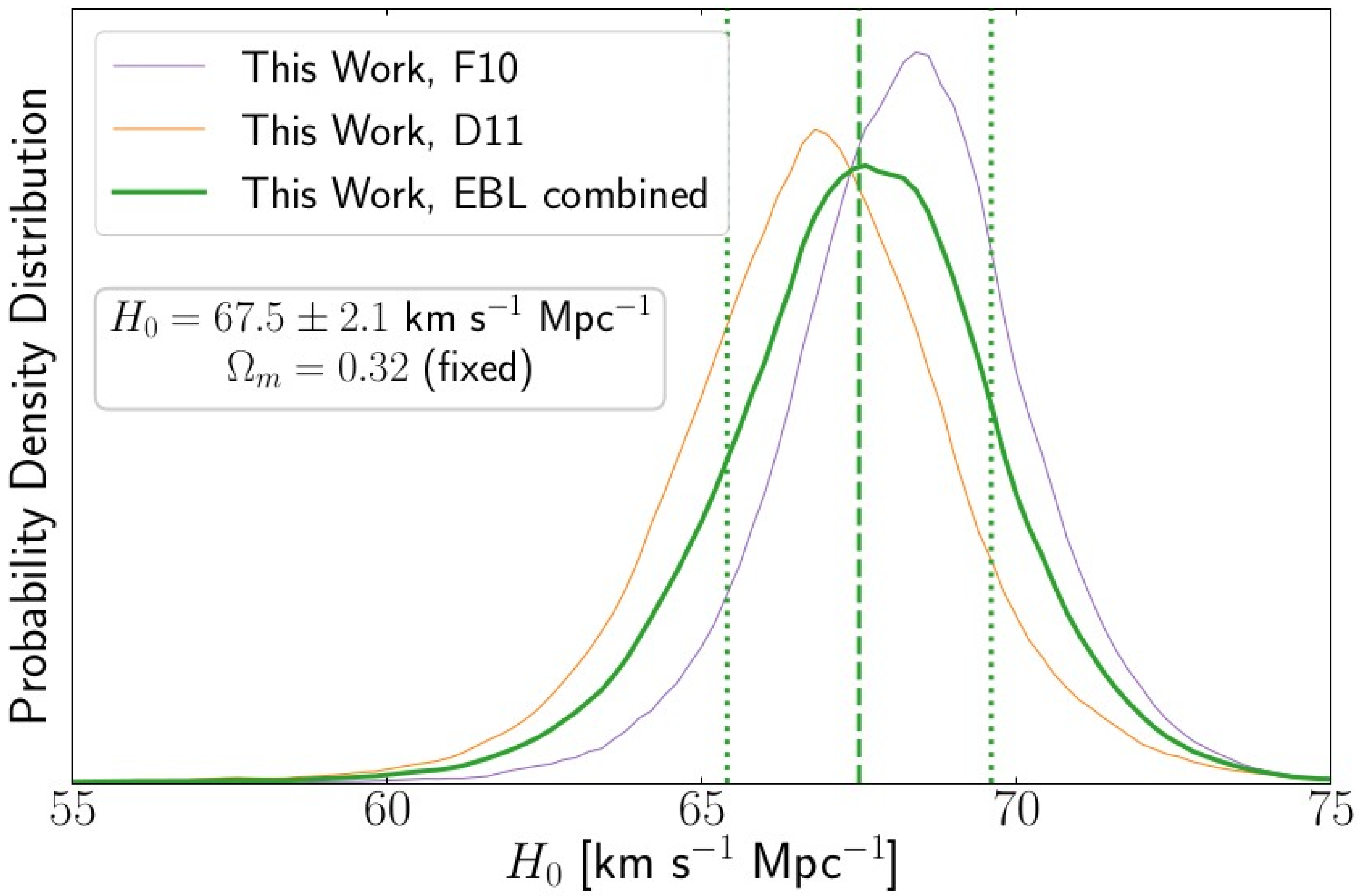
EBL photon density evolution

See Domínguez & Prada 13, Biteau & Williams 15

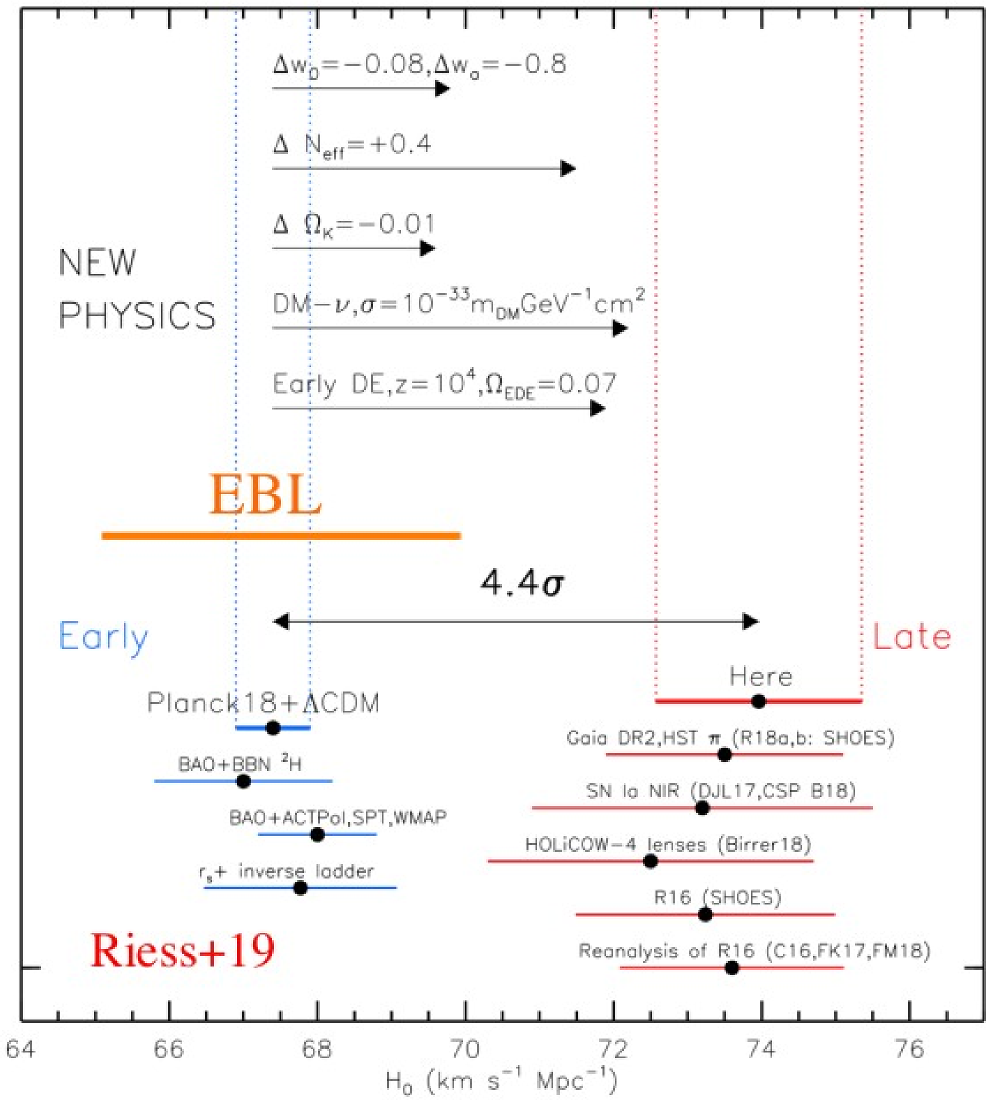


: Nina McCurdy & Joel Primack

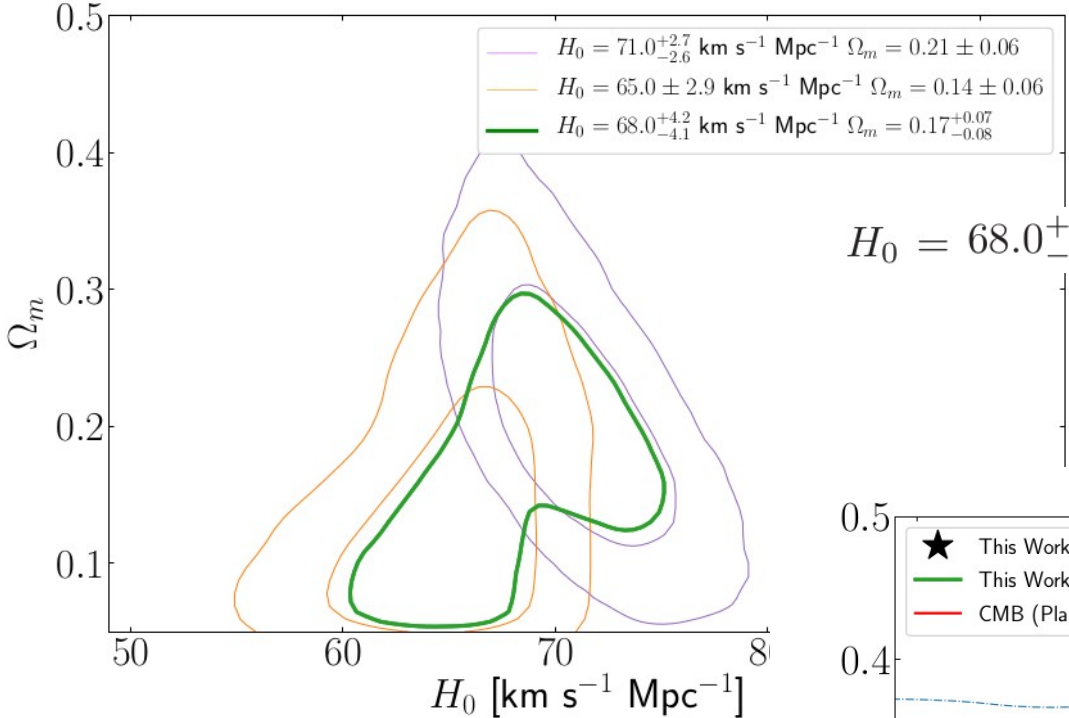
Measuring H_0 with Gamma-ray Attenuation



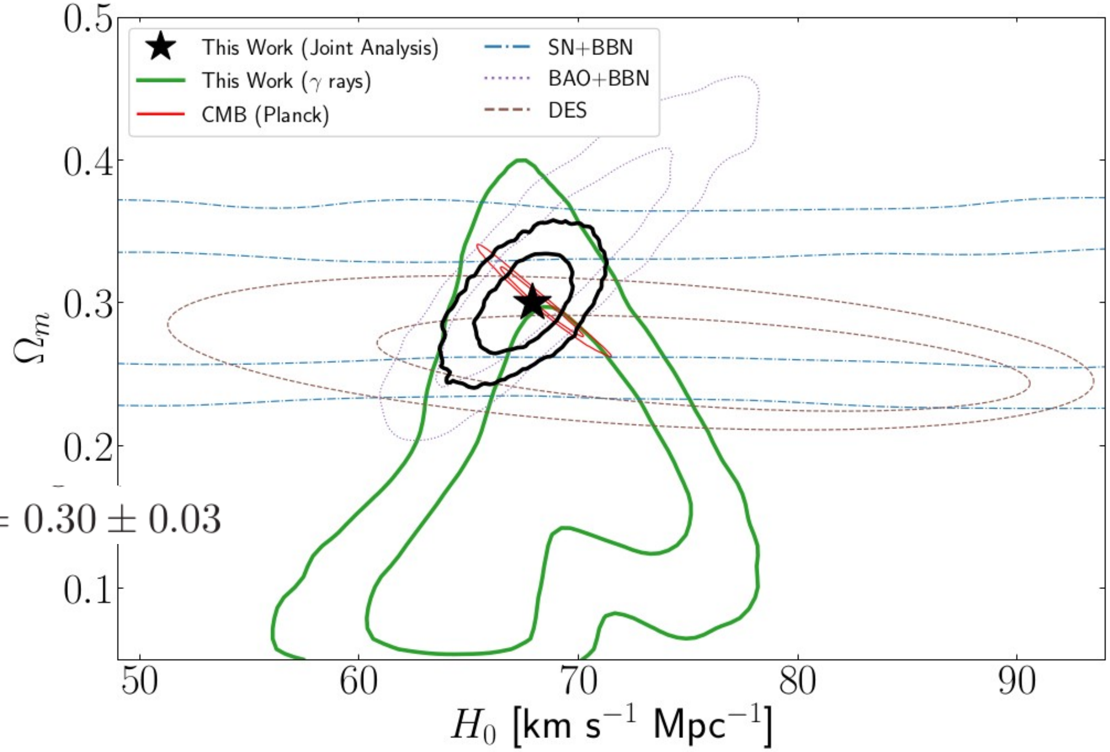
Tension on H_0 Measurements



Measuring H_0 and Ω_m with Gamma-ray Attenuation



$$H_0 = 68.0^{+4.2}_{-4.1}\ \text{km s}^{-1}\ \text{Mpc}^{-1}\ \text{and}\ \Omega_m = 0.17^{+0.07}_{-0.08}$$



$$H_0 = 67.5^{+1.4}_{-1.5}\ \text{km s}^{-1}\ \text{Mpc}^{-1}\ \text{and}\ \Omega_m = 0.30 \pm 0.03$$

Take Home Messages

1.- Very significant detection and characterization of the EBL attenuation up to z~3.

2.- Most complete derivation so far of the local EBL and its evolution over redshift from *Fermi*-LAT and Cherenkov data.

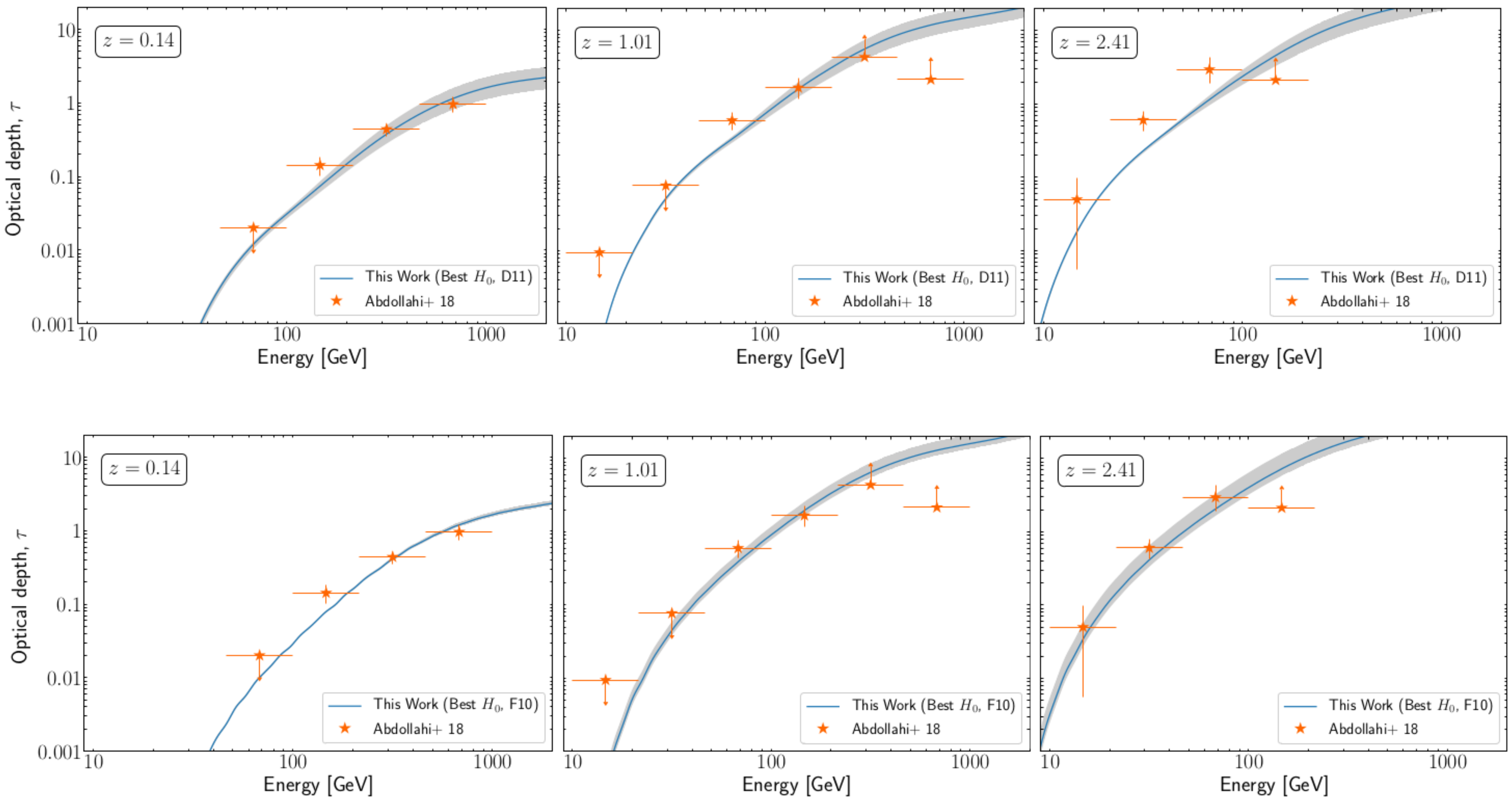
3.- Derived Cosmic Star formation Rate Density up to z~5 unbiased from different galaxy survey incompleteness.

4.- Cosmological measurement of H_0 and Ω_m from our independent technique.

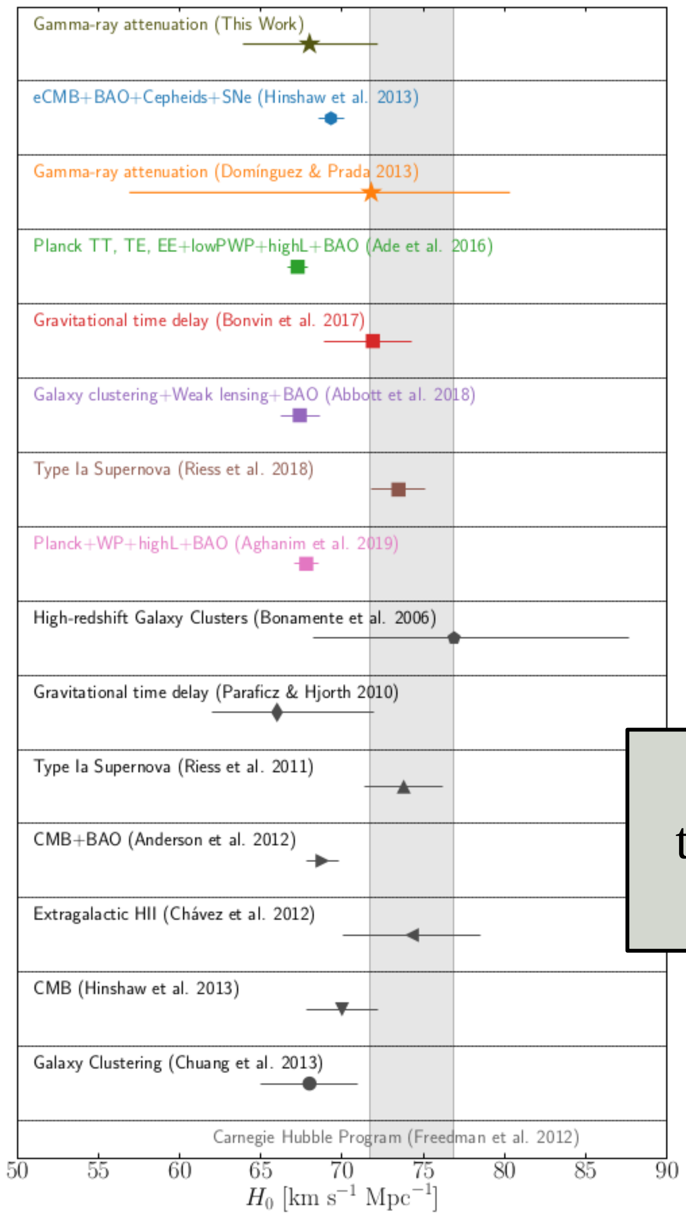
Gamma-ray astronomy has matured enough to provide useful measurements in galaxy evolution and cosmology

Backup

Cosmology Dependence on the Optical Depth



Comparison with other Methodologies



Combination of techniques is important to control systematics

EBL models: Finke+ 10

Dust absorption

IMF

Stellar photons

SFR

Expansion of universe

Stellar emissivity (luminosity density):

$$\epsilon\, j_\epsilon^{stars}(z) = m_e c^2 \epsilon^2 \frac{dN}{dt\, d\epsilon\, dV} = \epsilon^2 f_{esc}(\epsilon) \int_{m_{min}}^{m_{max}} dm\ \xi(m)\ \dot{N}_*(\epsilon; m, t_*(z)) \times \int_z^{z_{max}} dz_1 \left| \frac{dt_*}{dz_1} \right| \psi(z_1).$$

Stellar parameters from Eggleton et al. (1989), ApJ, 347, 998
Dust absorption: Driver et al. (2008), ApJ, 678, L101

Dust emission computed self-consistently:

$$f_n \int d\epsilon\, \frac{1}{f_{esc}(\epsilon)} [1 - f_{esc}(\epsilon)]\, j_\epsilon^{stars}(z) = \int d\epsilon\, j_{\epsilon,n}(\Theta_n)$$

Three component dust model:

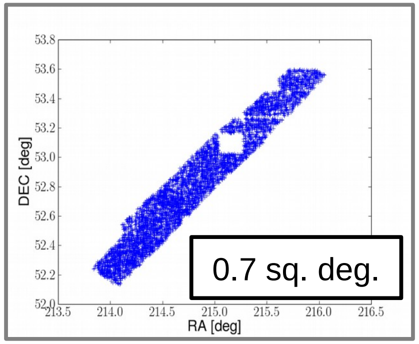
Component	n	f_n	T_n [K]	Θ_n $[10^{-9}]$
Warm Large Grains	1	0.60	40	7
Hot Small Grains	2	0.05	70	12
PAHs	3	0.35	450	76

EBL energy density:

$$\epsilon\, u_{EBL}(\epsilon; z) = \int_z^{z_{max}} dz_1\, \frac{\epsilon'' j_{\epsilon''}(z_1)}{(1+z_1)} \left| \frac{dt_*}{dz_1} \right|$$

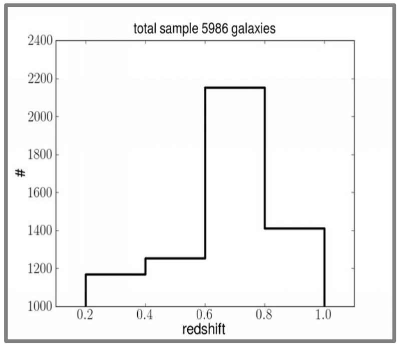
JF, Razzaque, & Dermer, (2010), ApJ, 712, 238
Razzaque, Dermer, & JF, (2009), ApJ, 697, 483

EBL models: Domínguez+ 11



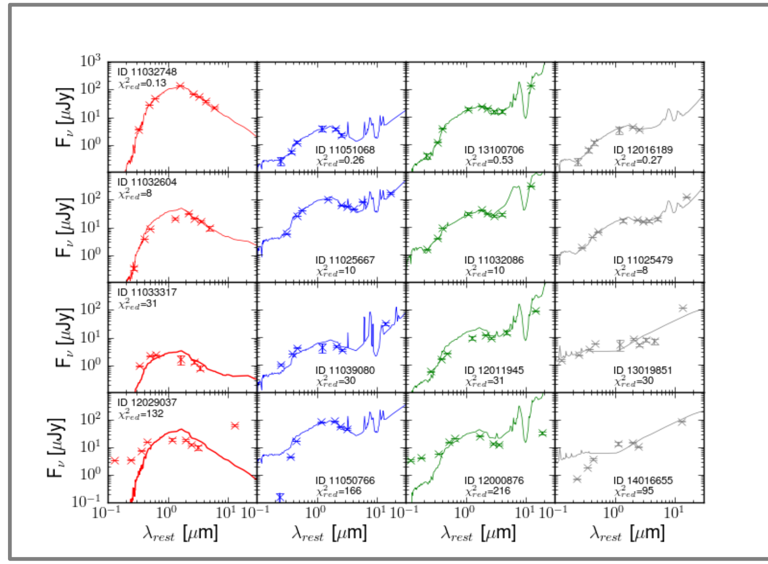
0.7 sq. deg.

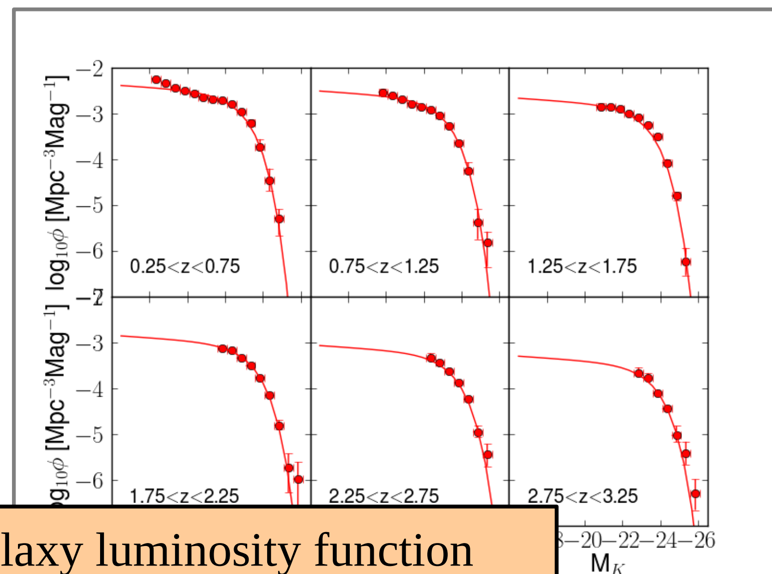
EGS field



Band	λ_{eff} [μm]	Observatory	Req.	UL [μJy]
FUV	0.1539	GALEX	ext	-
NUV	0.2316	GALEX	ext	-
B	0.4389	CFHT12K	det	-
R	0.6601	CFHT12K	det	-
I	0.8133	CFHT12K	det	-
K_S	2.14	WIRC	det	-
IRAC 1	3.6	IRAC	det	-
IRAC 2	4.5	IRAC	obs	1.2
IRAC 3	5.8	IRAC	obs	6.3
IRAC 4	8.0	IRAC	obs	6.9
MIPS 24	23.7	MIPS	obs	30

Total: 5986 galaxies





Galaxy luminosity function
rest-frame K-band, Cirasuolo+ 10