All the Light There Ever Was

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Domínguez, Primack, Bell

Scientific American, June 2015

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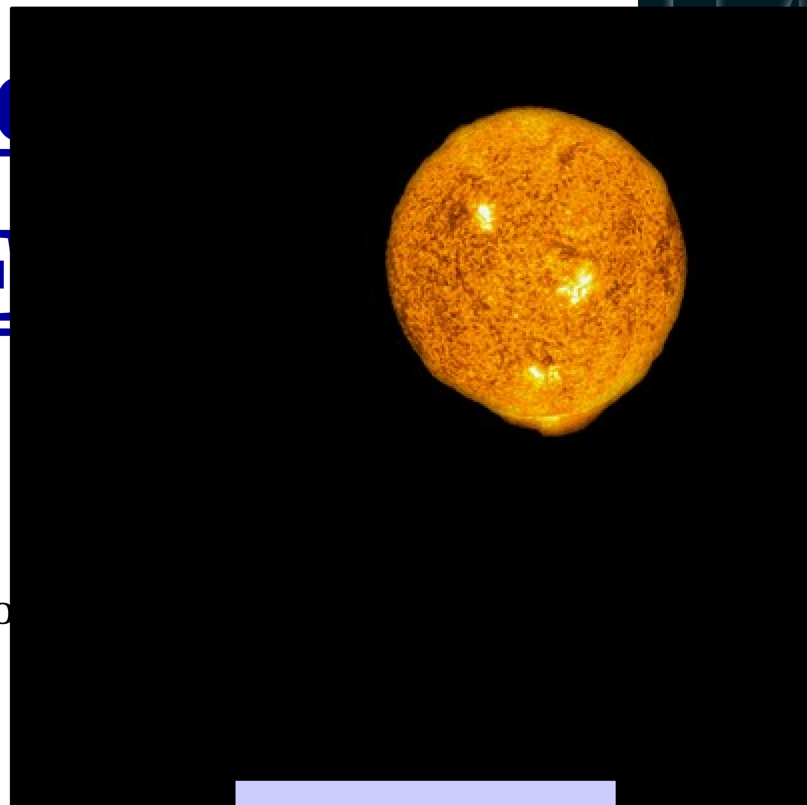
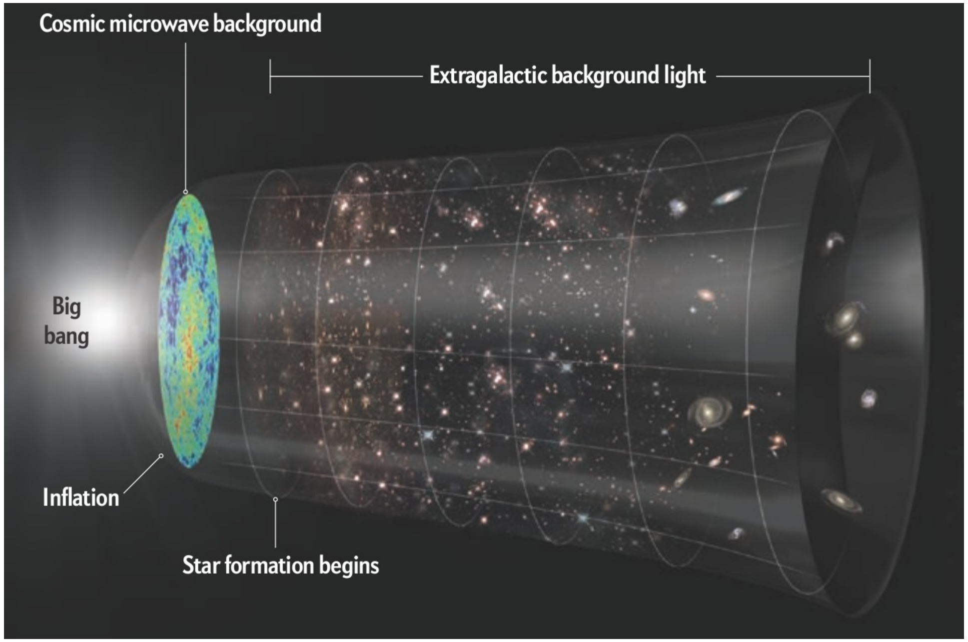


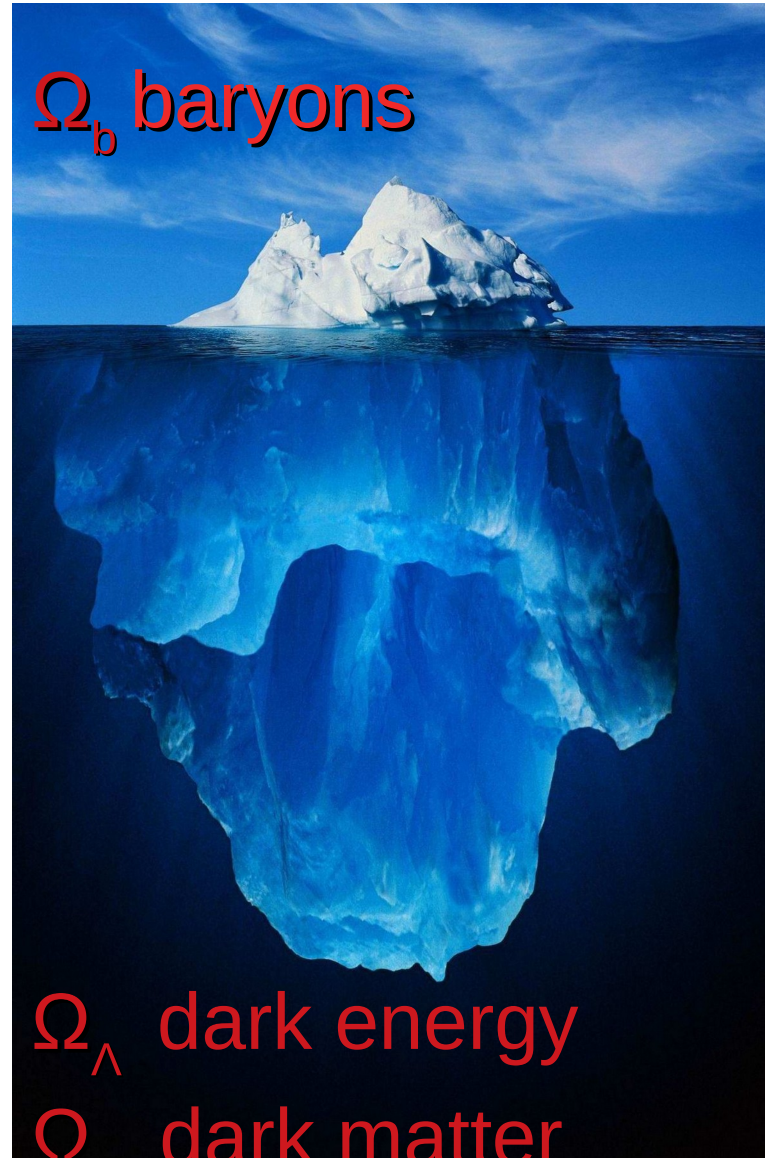
Domínguez, Primack, Bell

Scientific American, June 2015

Galaxy Evolution and Cosmology



Scientific American, June 2015

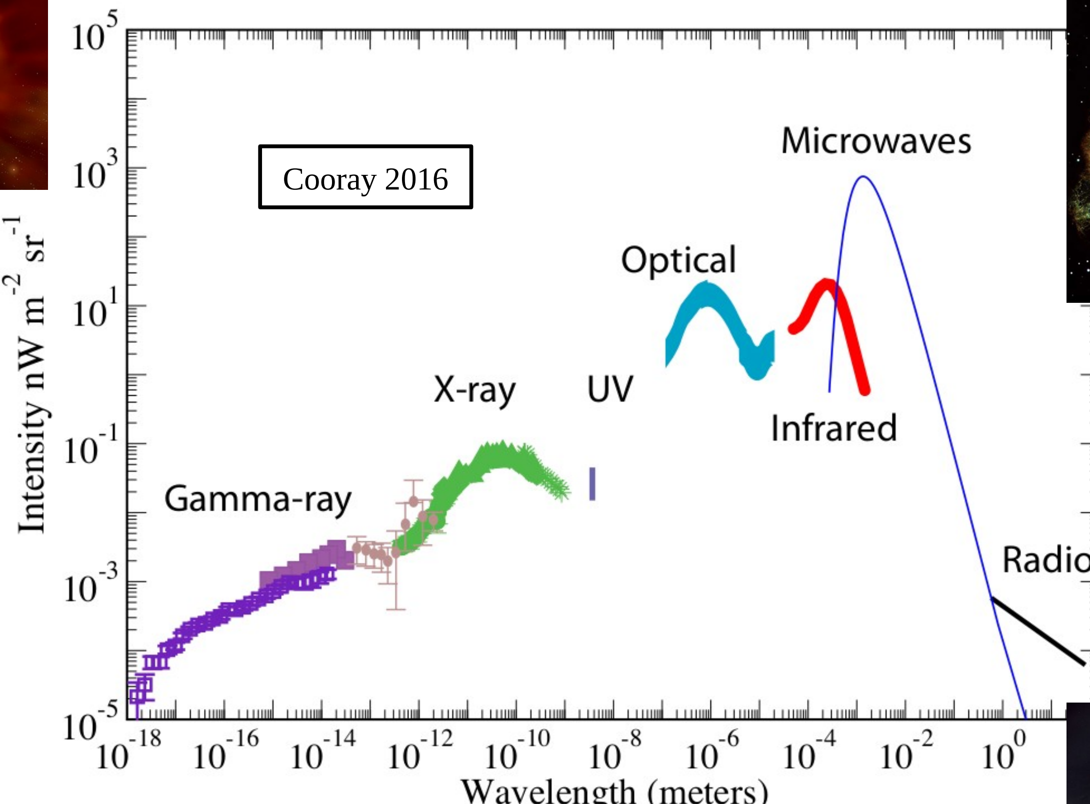


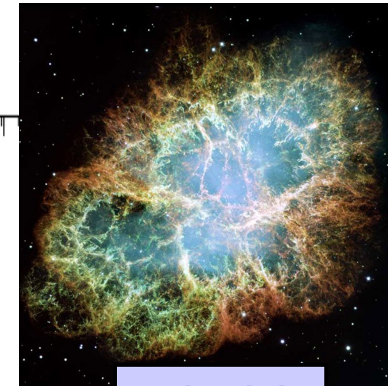
$$\Omega_m = \Omega_b + \Omega_D$$

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

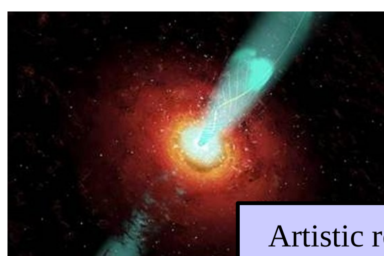
Cosmic Diffuse Extragalactic Backgrounds

Artistic representation of a binary system





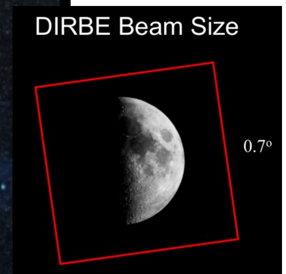
Crab Nebula

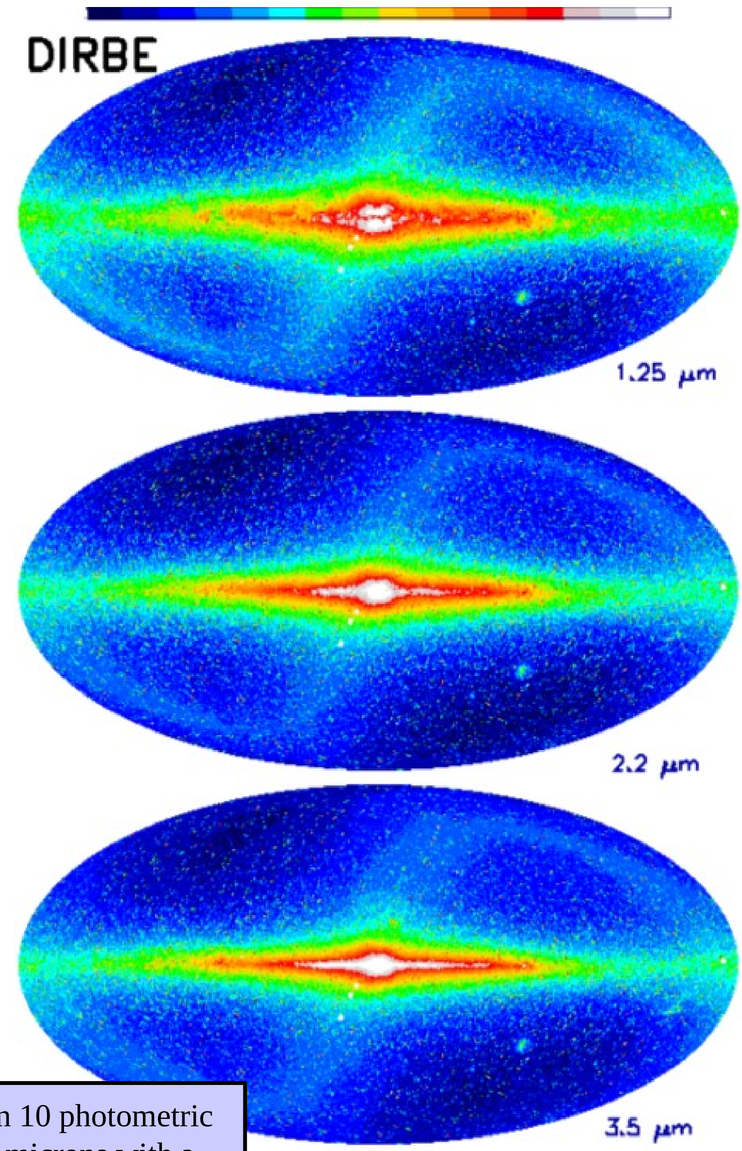


Artistic representation of a blazar

Orion Nebula (birth place of stars)

Measuring the Extragalactic Background Light





DIRBE imaged the sky in 10 photometric bands from 1.25 to 240 microns with a beam size of 0.7x0.7 sq. degrees

Measuring the Extragalactic Background Light

Zodiacal light, visible under the right conditions: typically after the sunset in Spring and right before sunrise in Autumn

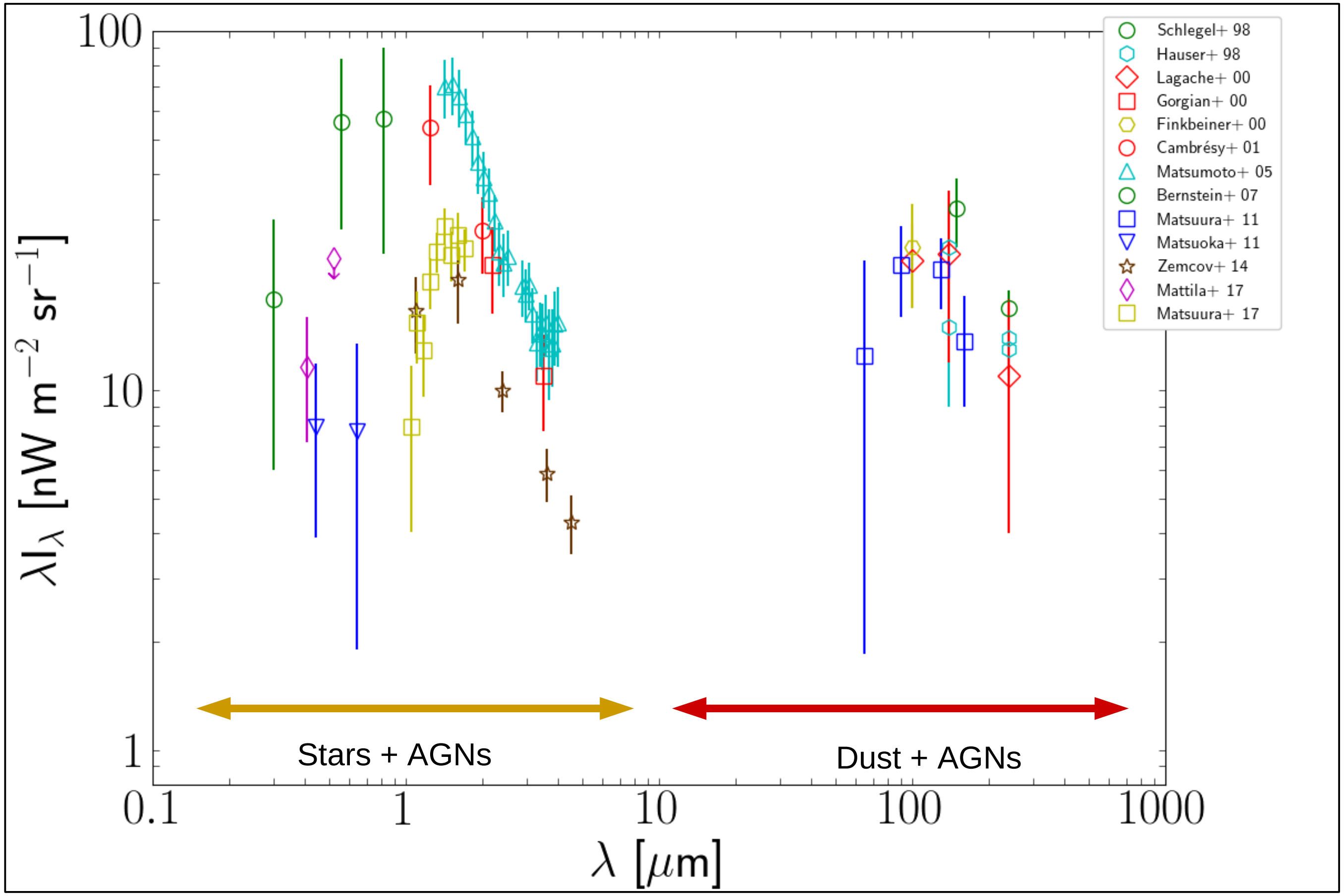
TABLE 2

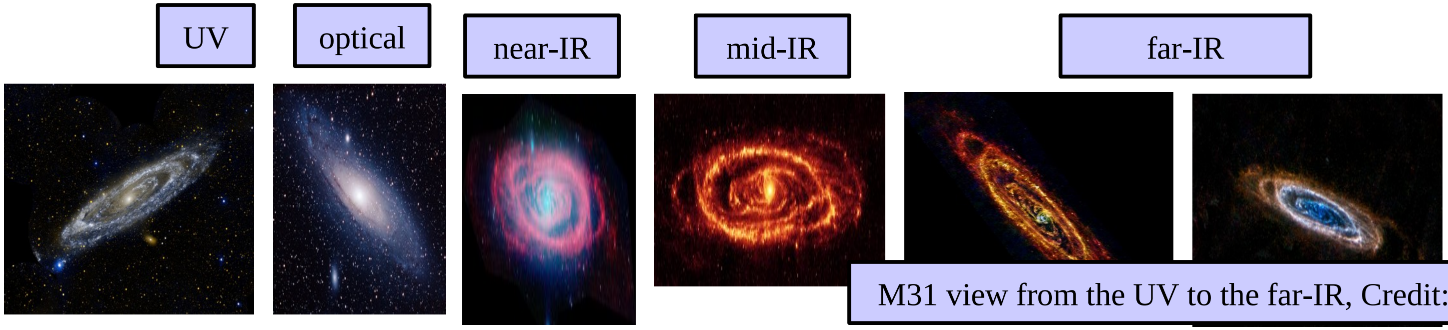
DECOMPOSITION OF THE DIRBE INTENSITY

Component	2.2 μm (kJy sr^{-1})	3.5 μm (kJy sr^{-1})
Total	137.5 ± 0.3	105.3 ± 0.3
Zodi	101.8 ± 3.8	80.4 ± 3.3
ISM	...	1.1 ± 0.2
Stars, $m < 9$ mag	7.4 ± 2.2	5.3 ± 1.8
Stars, $m > 9$ mag	11.9 ± 0.6	5.7 ± 0.3
EBL	16.4 ± 4.4	12.8 ± 3.8

EBL is an order of magnitude lower than foregrounds and subject to large systematic uncertainties, e.g. Gorjian+ 00

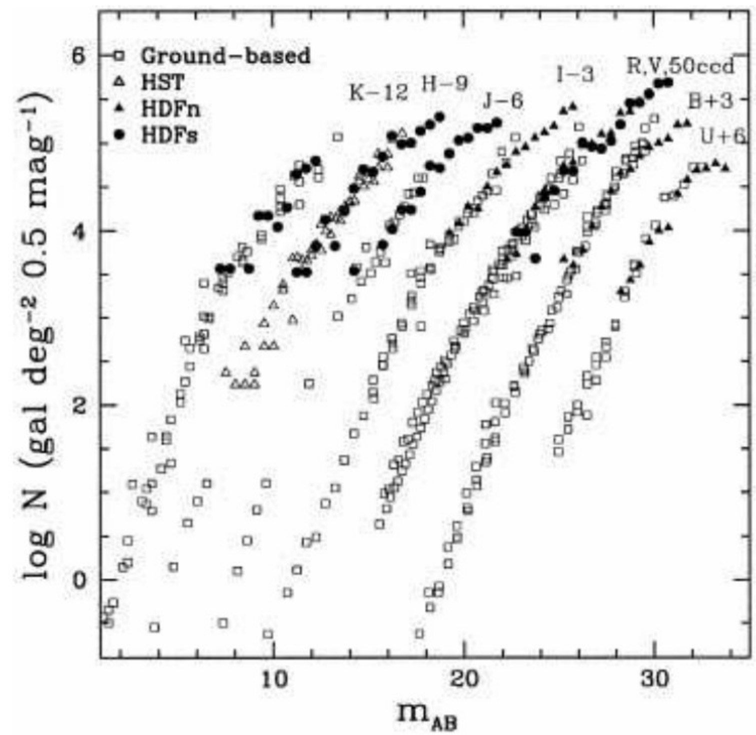
Measuring the Extragalactic Background Light





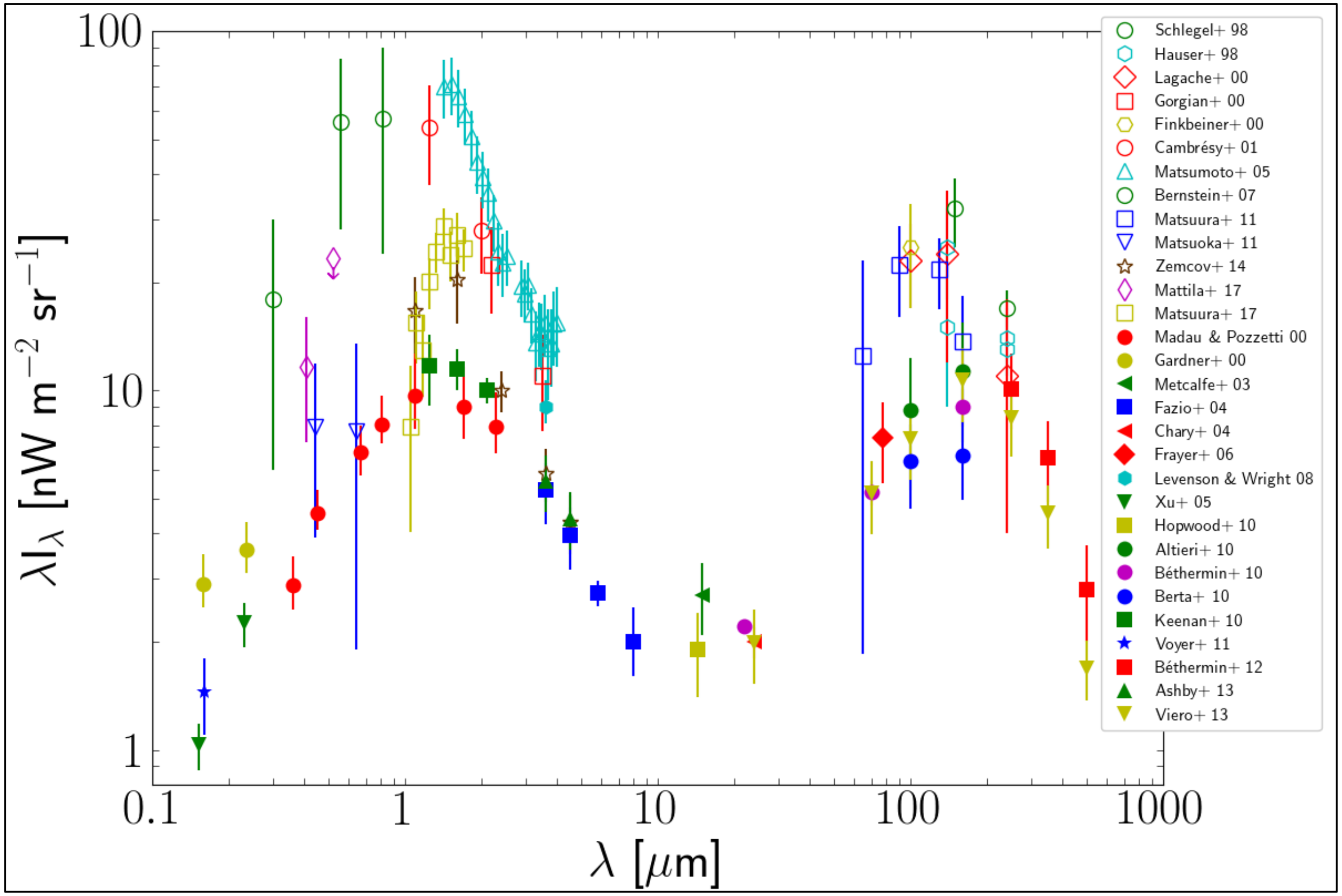
M31 view from the UV to the far-IR, Credit: NASA & ESA

Measuring the Extragalactic Background Light

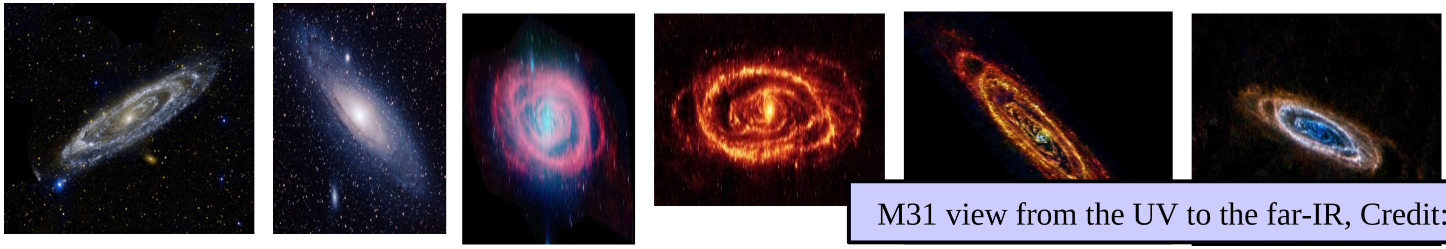


Galaxy number counts in the Hubble Deep Field,
e.g. Madau & Pozzetti, 2000

Measuring the Extragalactic Background Light



UV | optical | near-IR | mid-IR | far-IR



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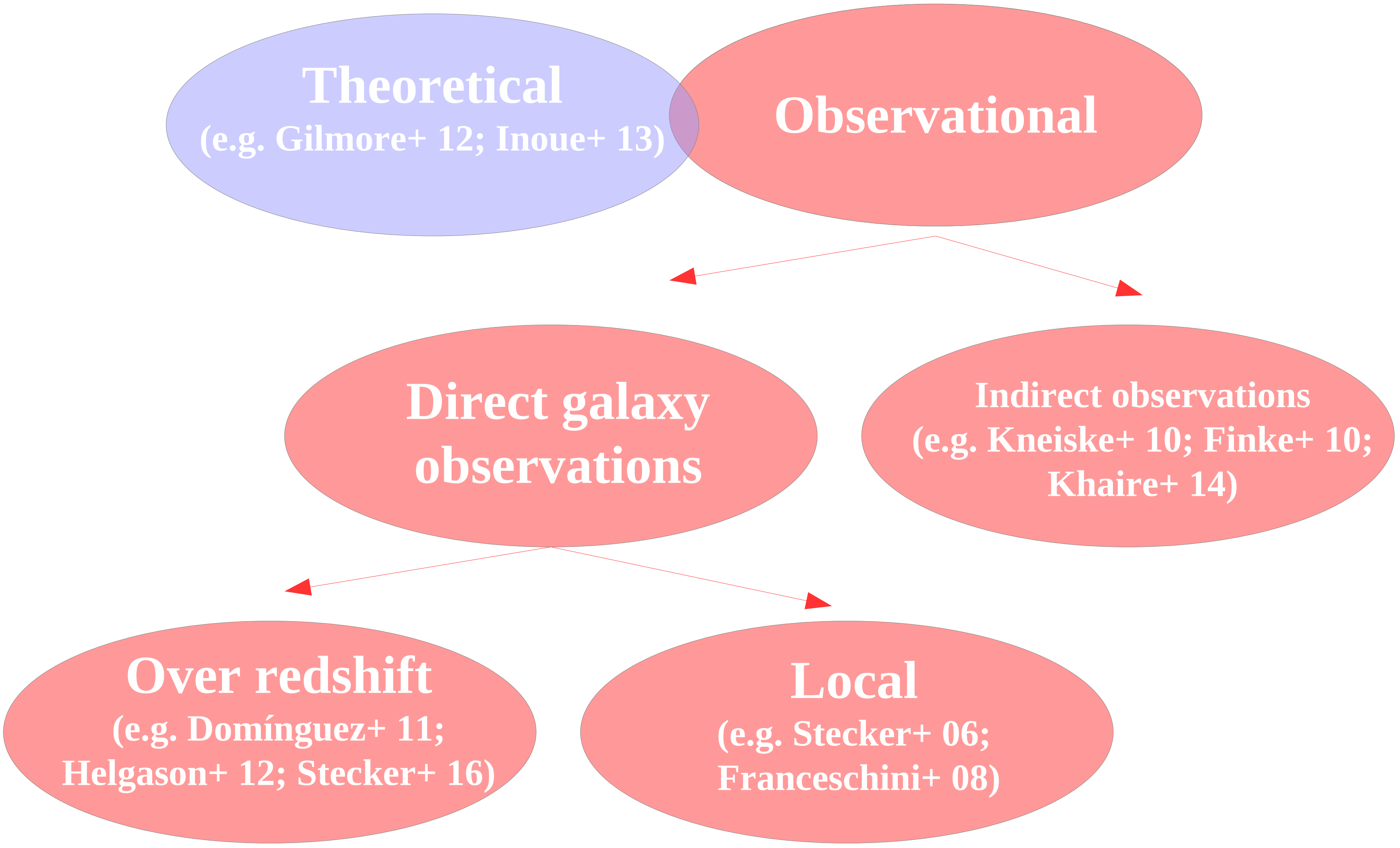
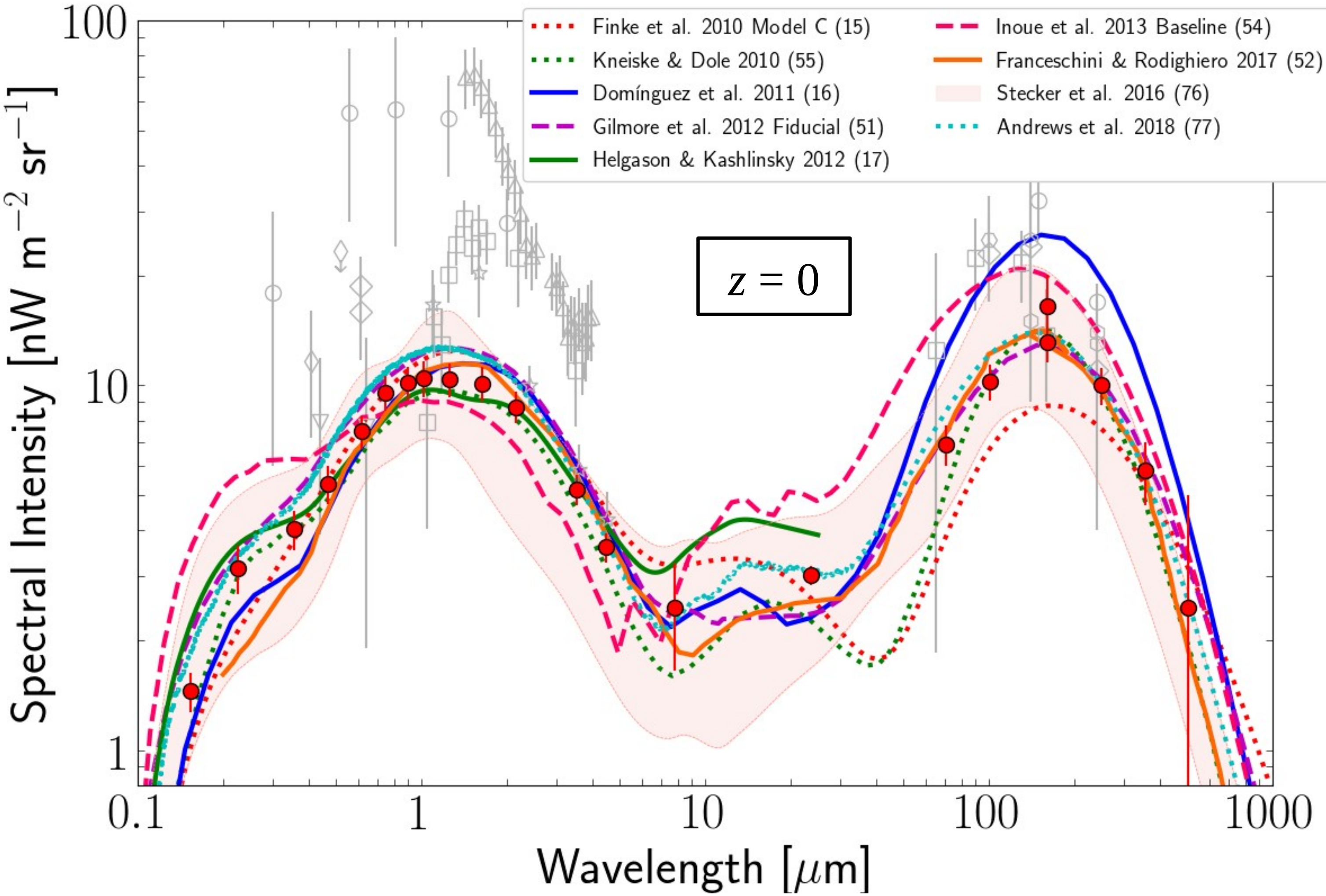
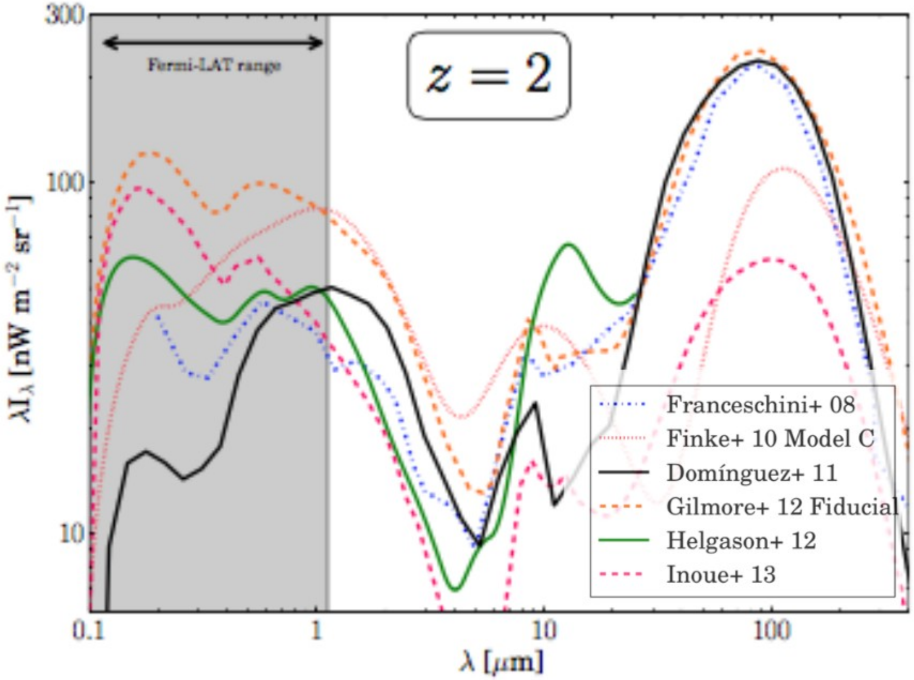
Measuring the Extragalactic Background Light

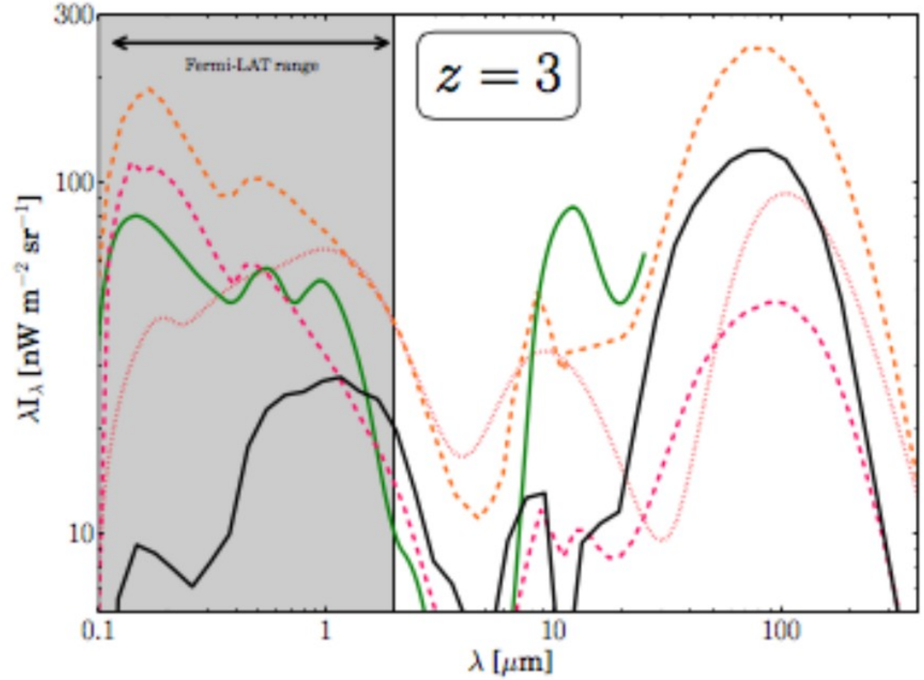


Extragalactic Background Light (Local)



Extragalactic Background Light (Evolution)

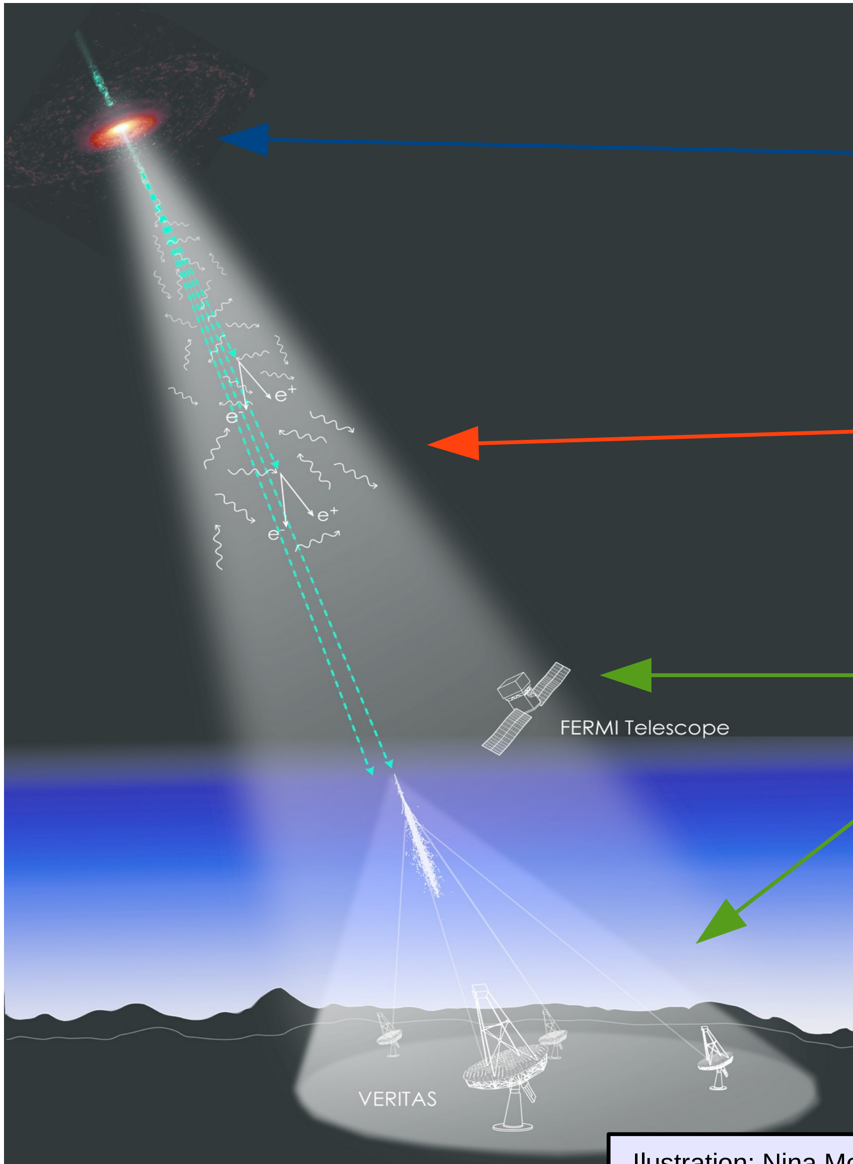




See Saldana-Lopez+ 21

Strong divergence

Gamma-ray Attenuation



Extragalactic source:
e.g. Blazar

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

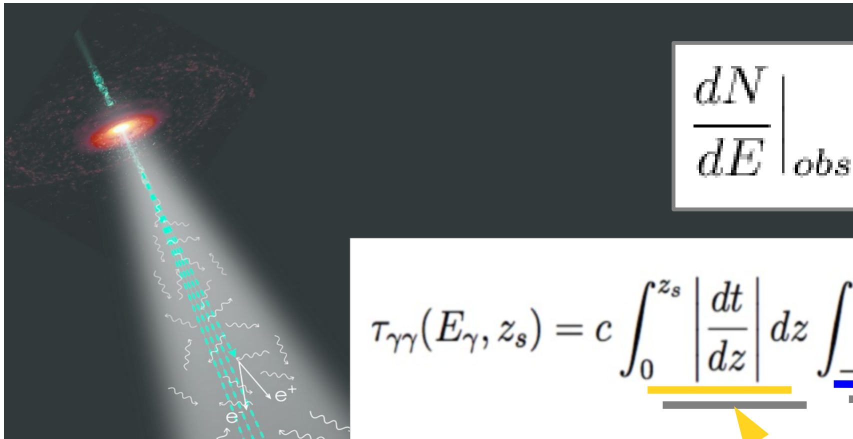
Pair-production interaction

Reverse of most known electron-positron annhilation process

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

Ilustration: Nina McCurdy & Joel Primack

Gamma-ray Attenuation



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

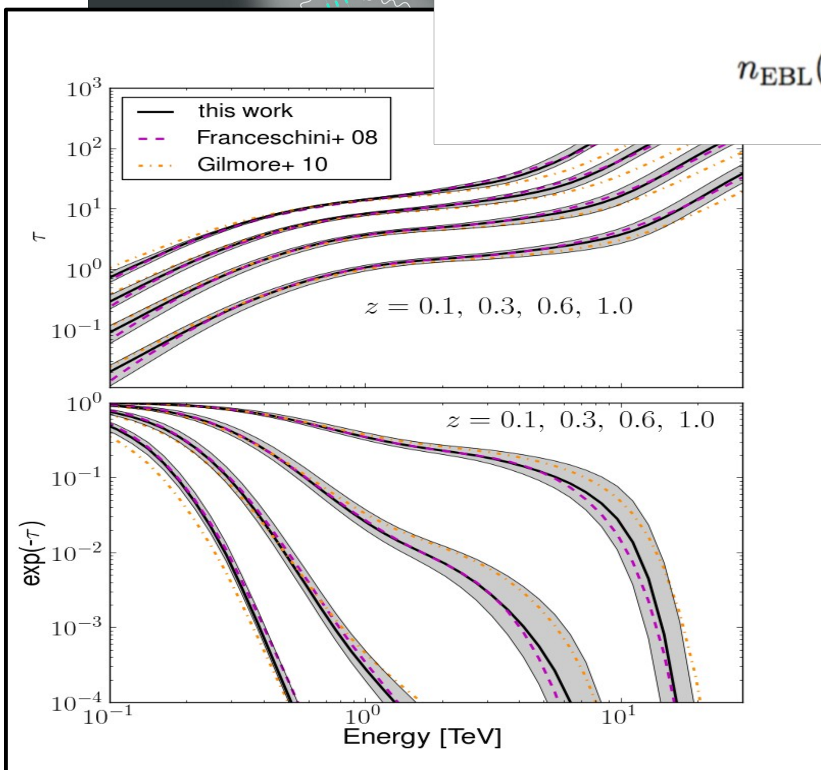
$$\tau_{\gamma\gamma}(E_\gamma, z_s) = c \int_0^{z_s} \left|\frac{dt}{dz}\right| dz \int_{-1}^{1} (1-\mu) \frac{d\mu}{2} \int_{2m_e^2c^4/\epsilon_\gamma(1-\mu)}^{\infty} \sigma(\epsilon_{\rm EBL}, \epsilon_\gamma, \mu) n_{\rm EBL}(\epsilon, z) d\epsilon_{\rm EBL}$$

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

distance

cross section

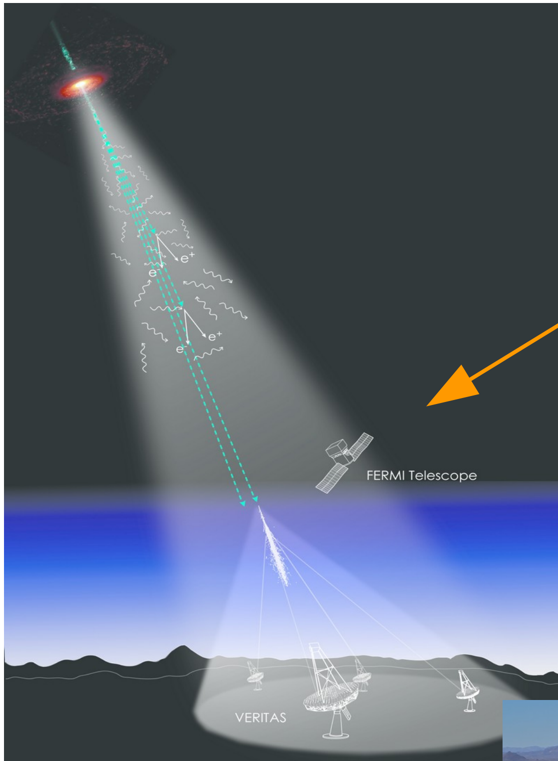
EBL photon density evolution

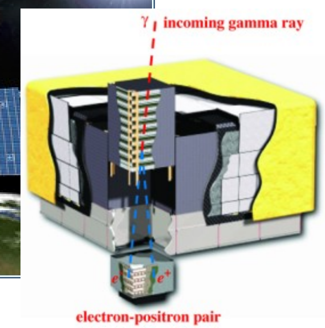


...: Nina McCurdy & Joel Primack

Gamma-ray Telescopes

Fermi-LAT





All-sky, Energy range
100 MeV – 100s GeV

VERITAS, Arizona (USA)

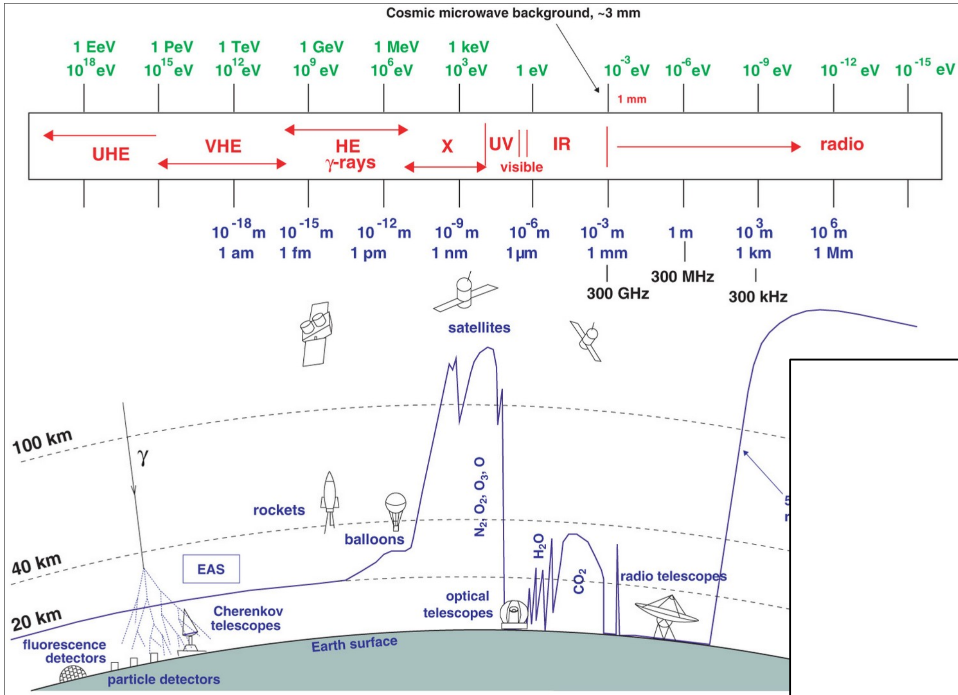
CTA North, La Palma (Spain)

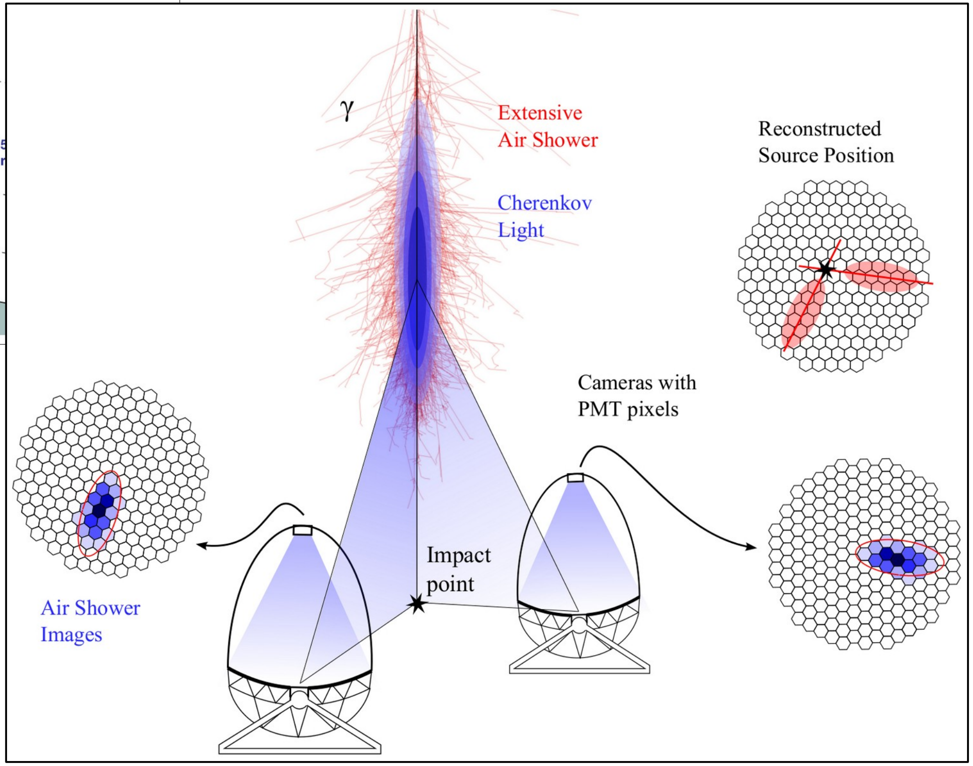
IACTs
Small field of view,
High sensitivity, Energy range
100 GeV – 10s TeV

H.E.S.S., Namibia

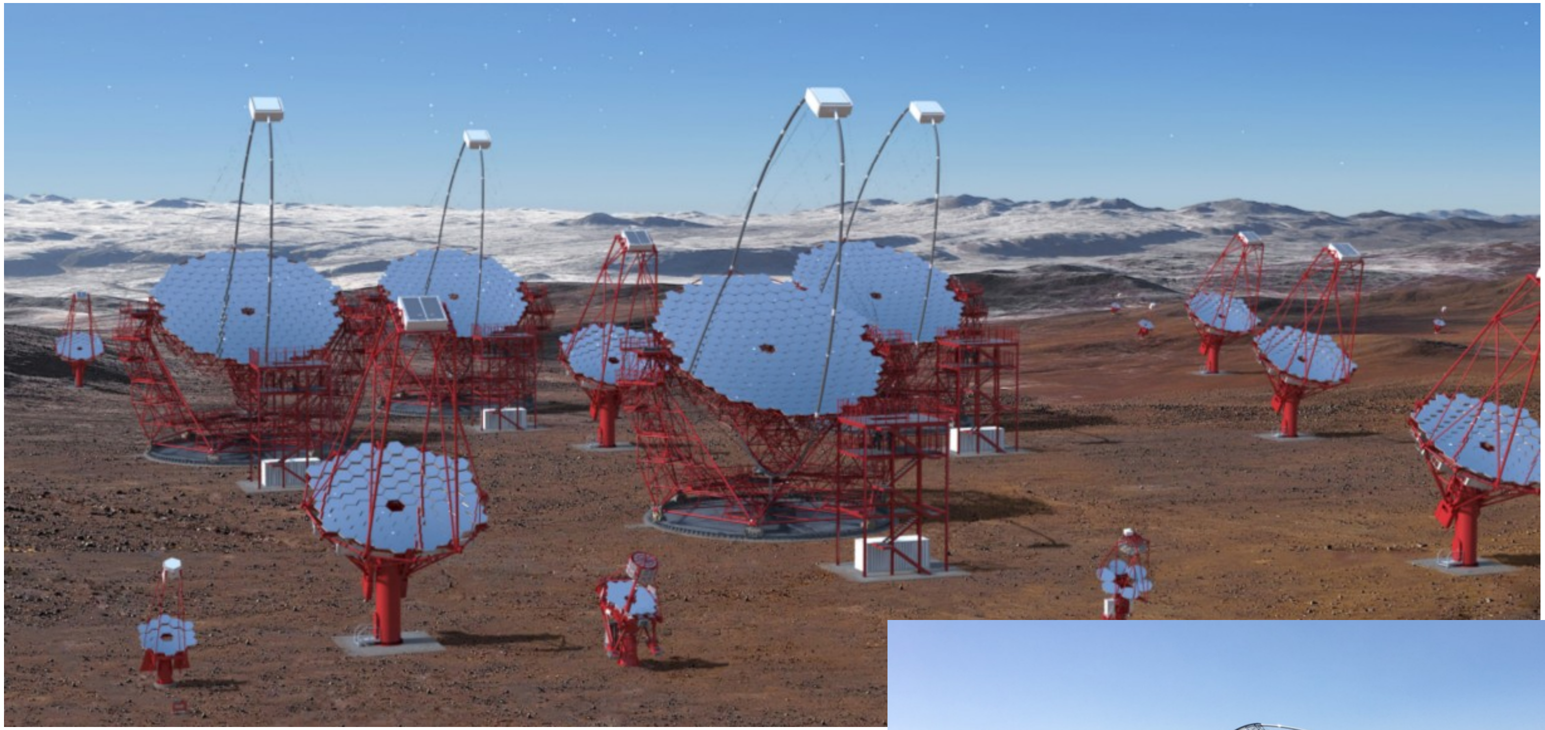
MAGIC, La Palma (Spain)

Gamma-ray Cherenkov Telescopes (IACTs)

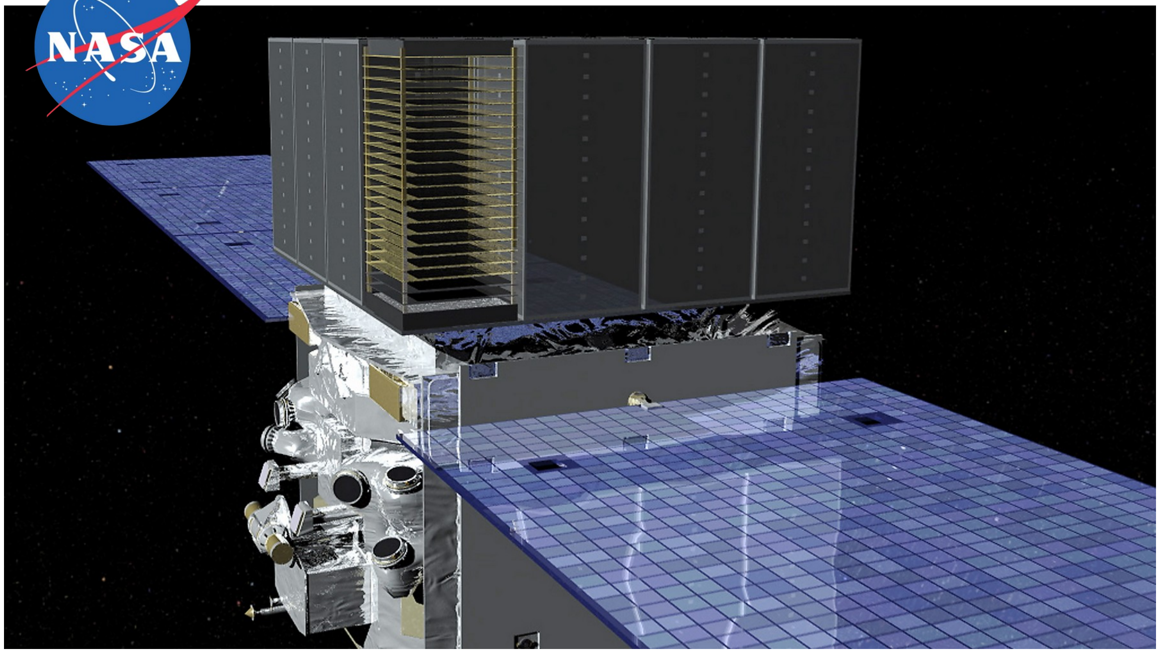




Gamma-ray Cherenkov Telescopes (IACTs)



NASA's Fermi Gamma-Ray Space Telescope



Launch June 11, 2008

1. Tracking system:

- converts an incident gamma ray to an electron-positron pair
- reconstructs the gamma-ray direction from the tracks of the pair

2. Calorimeter:

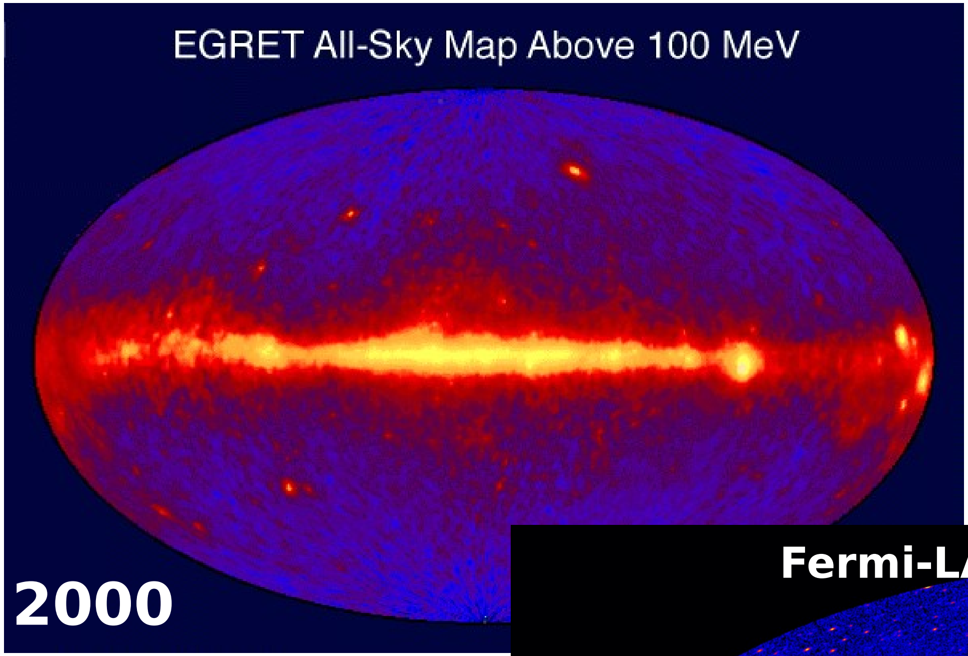
- measures the photon energy

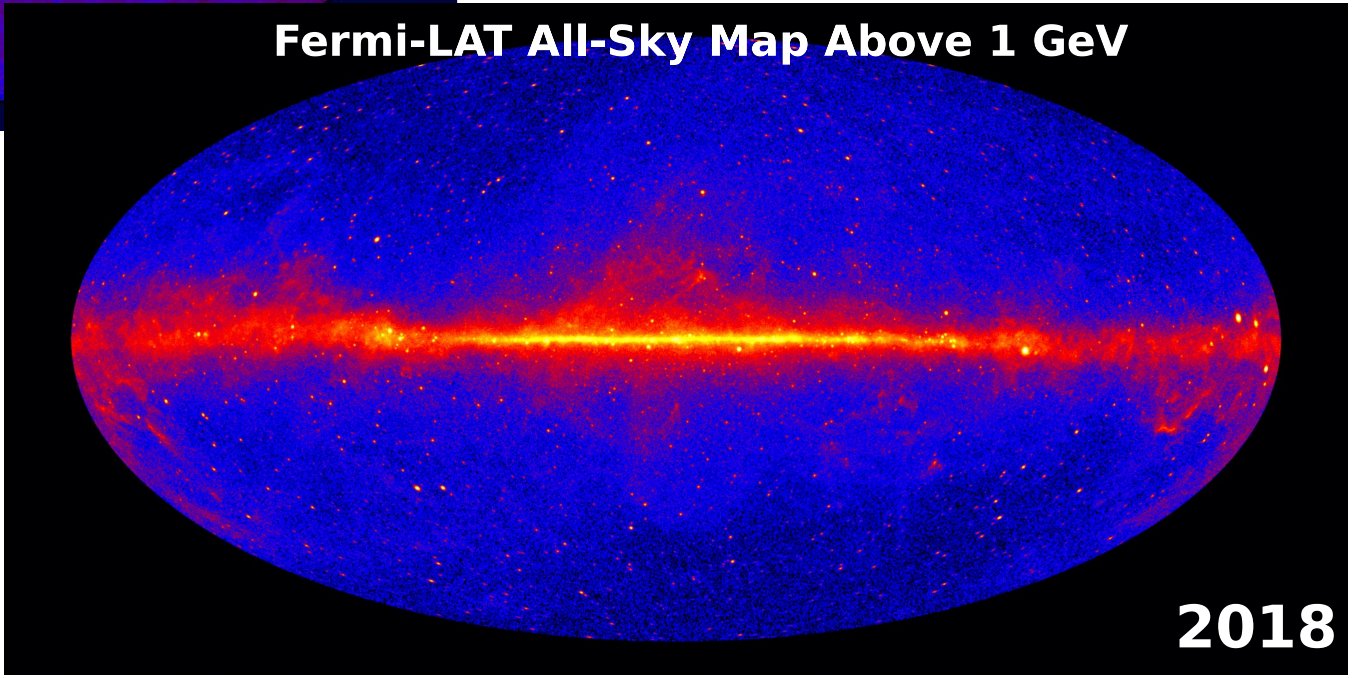
3. Anti-coincidence detector:

- limits the cosmic-ray background

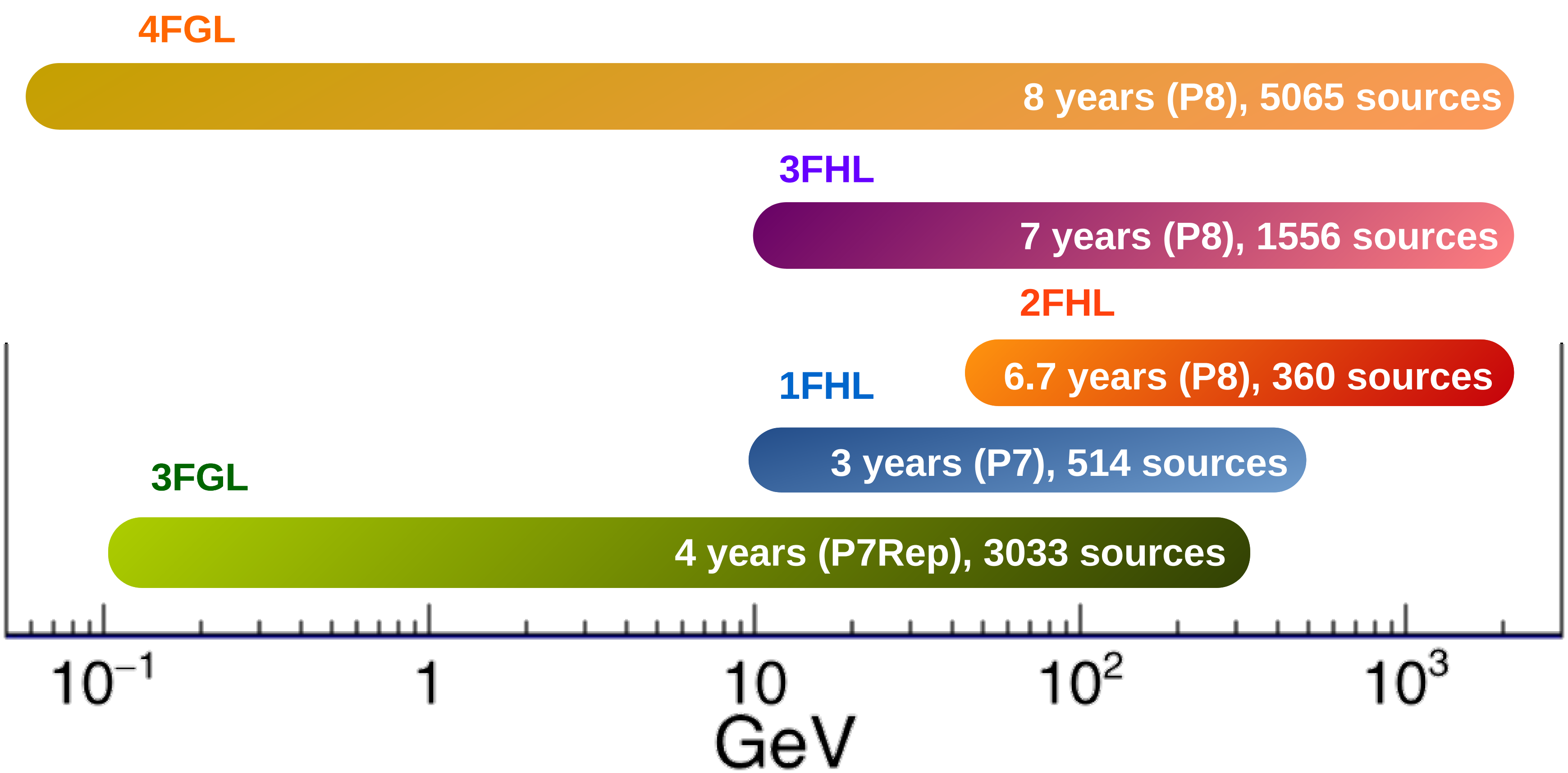
- Wide field of view (2.4 sr, 20% of the sky)
- Large effective area (~0.9 m^2 above 1 GeV)
- Low dead time (~27 μs)

The Gamma-Ray Sky

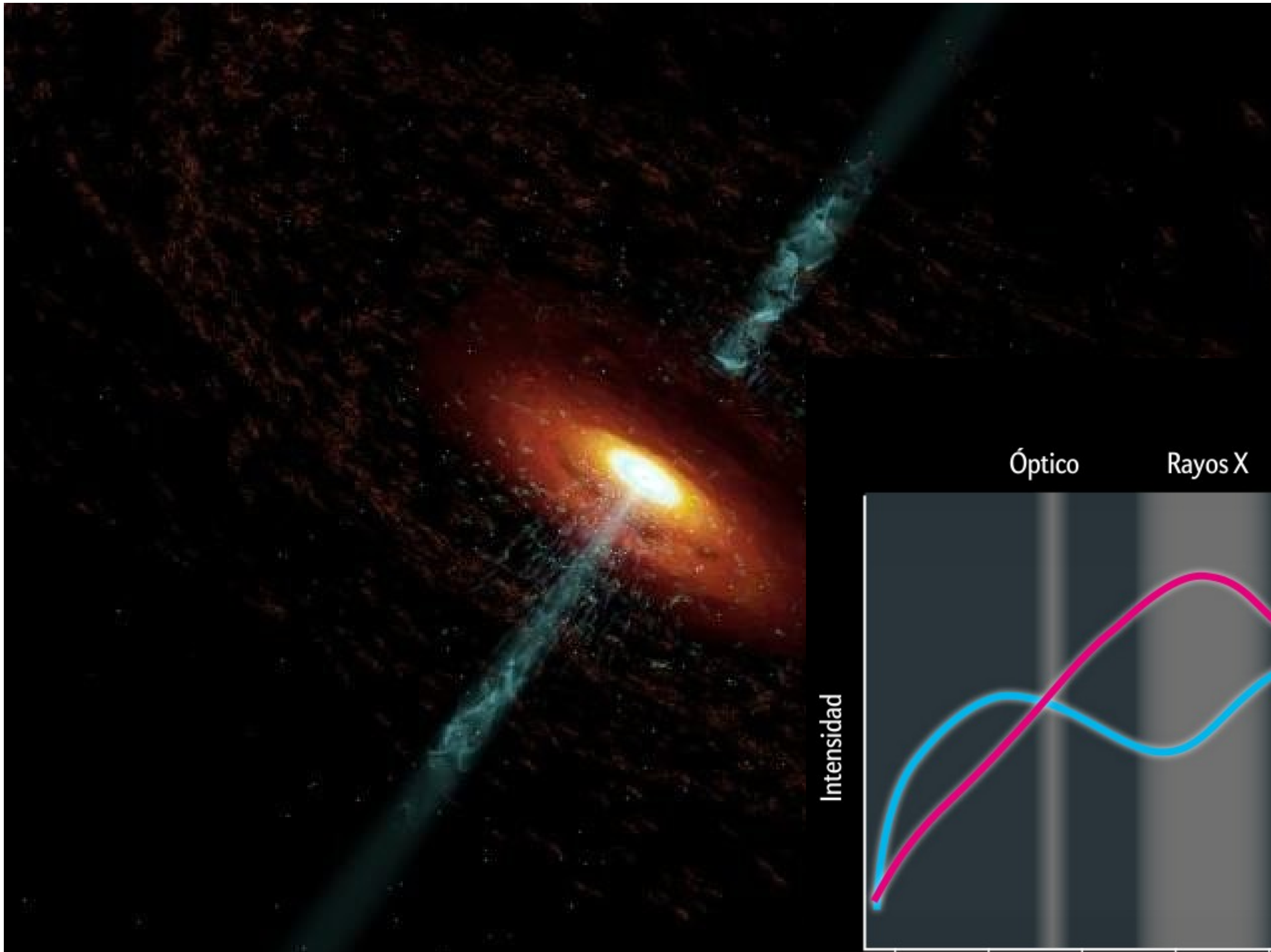


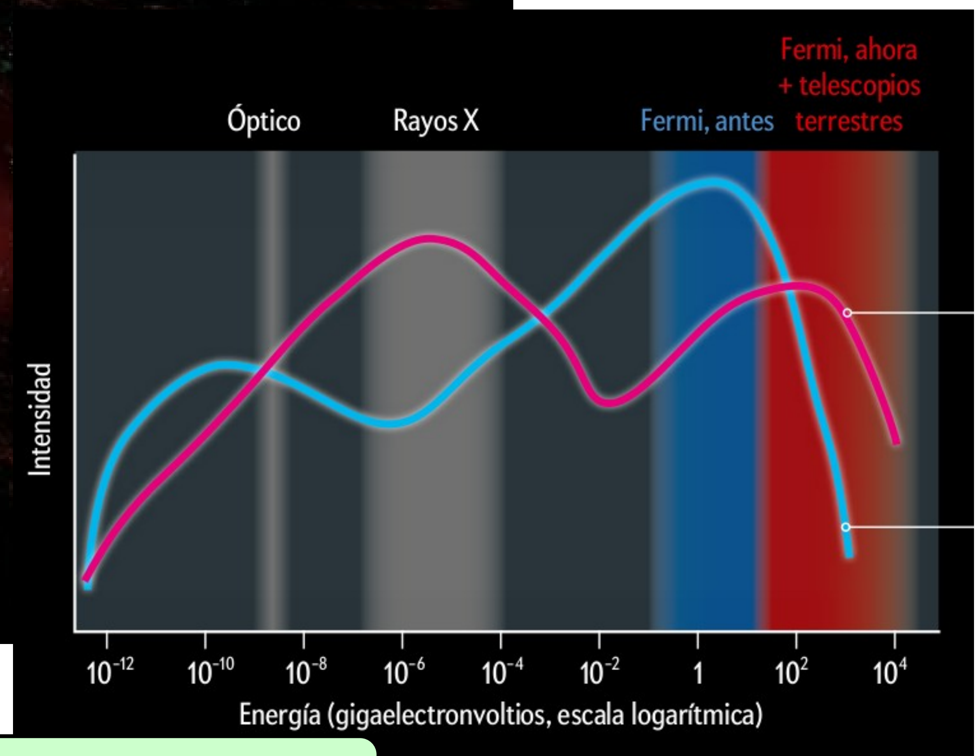


Gamma-ray Fermi-LAT Catalogs



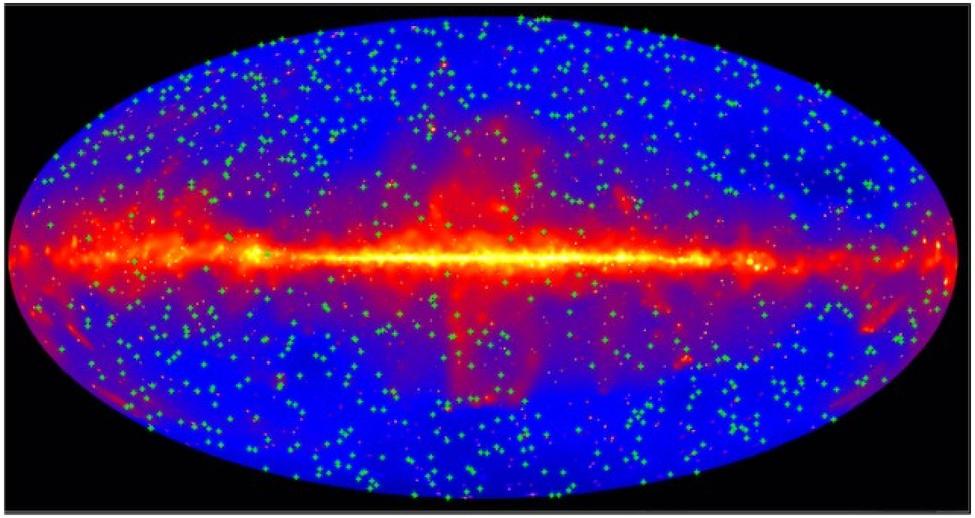
Blazars

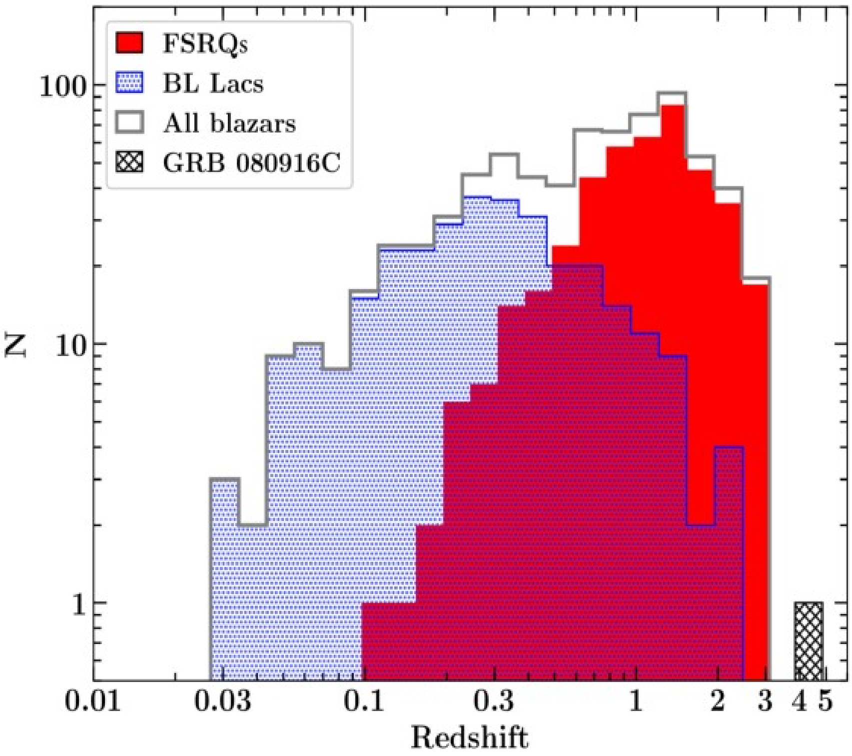




Emission described by homogeneous synchrotron/synchrotron-self Compton model.

Optical Depths from Gamma-ray Data

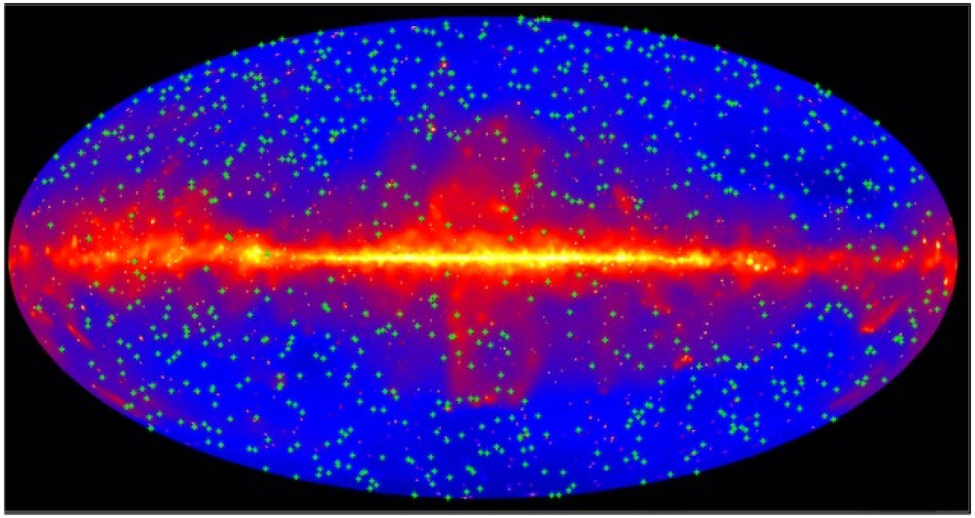


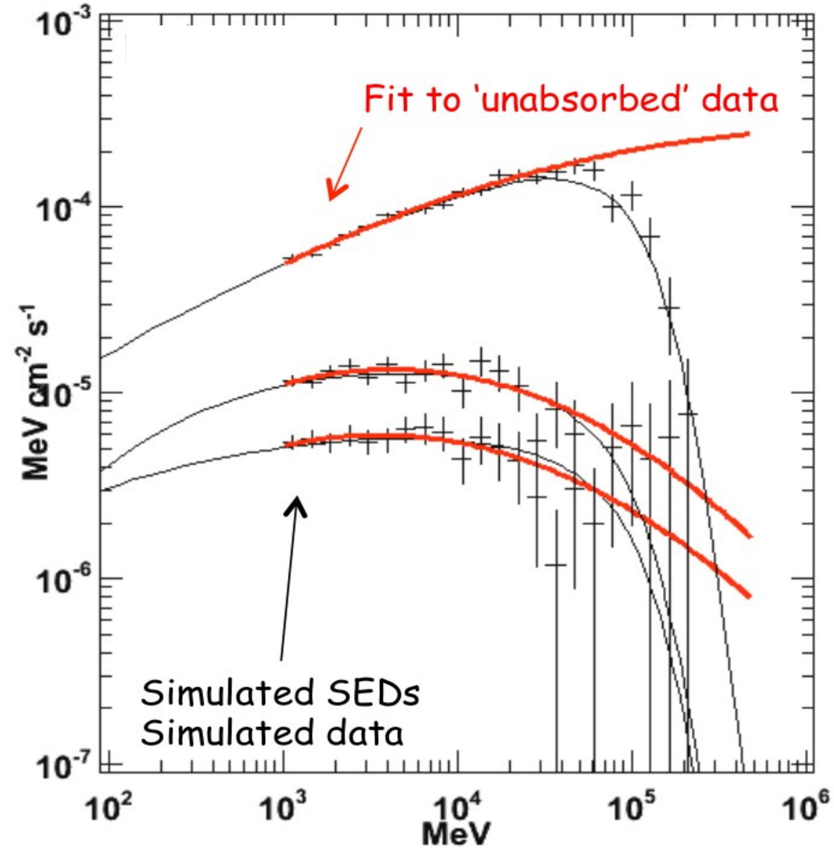


- Use 9 years of P8 LAT data
- 739 blazars + 1 GRB
- Perform a time-resolved analysis,
- Analysis optimized on simulations

Analysis improved over the Ackermann+12 results

Optical Depths from Gamma-ray Data





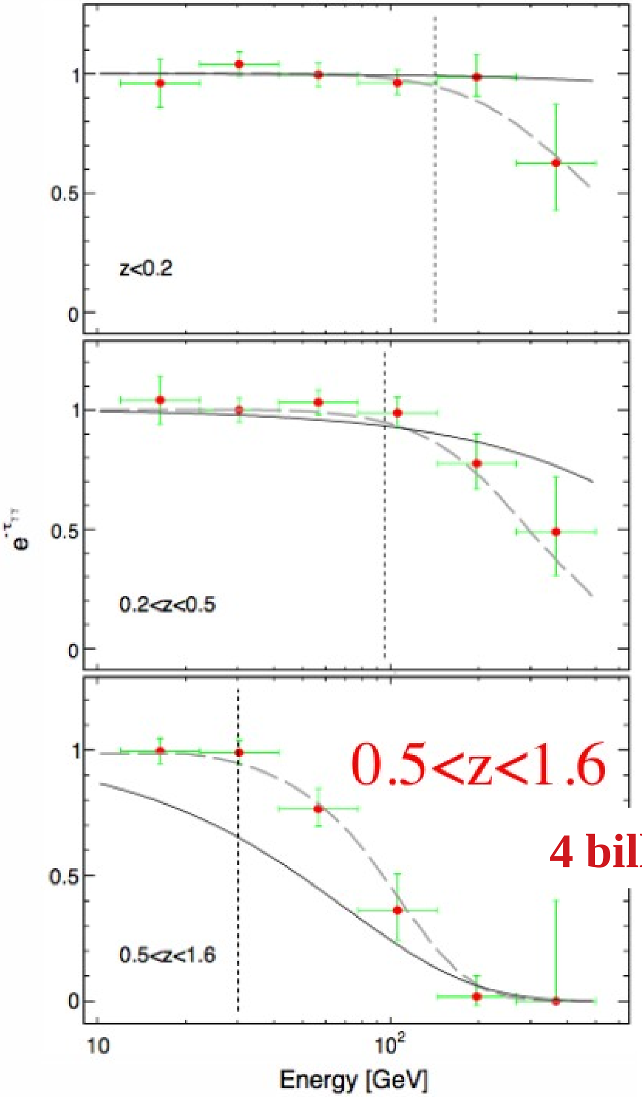
- Use 9 years of P8 LAT data
- 739 blazars + 1 GRB
- Perform a time-resolved analysis,
- Analysis optimized on simulations

$$F(E)_{absorbed} = F(E)_{\mathrm{int}\,rinsic} \cdot e^{-b\cdot\tau_{\mathrm{mod}\,el}}$$

Analysis improved over the Ackermann+12 results

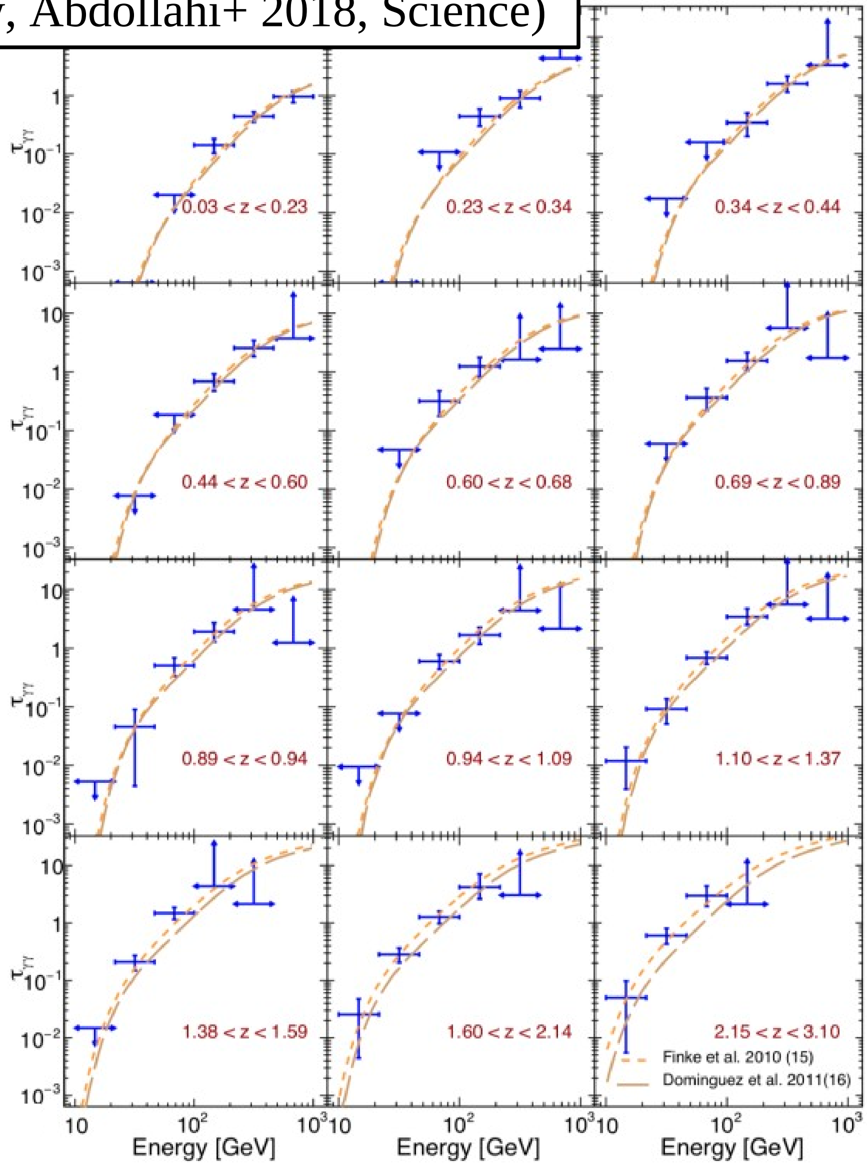
Optical Depths from Gamma-ray Data

From detection (2012) to characterization (Now, Abdollahi+ 2018, Science)

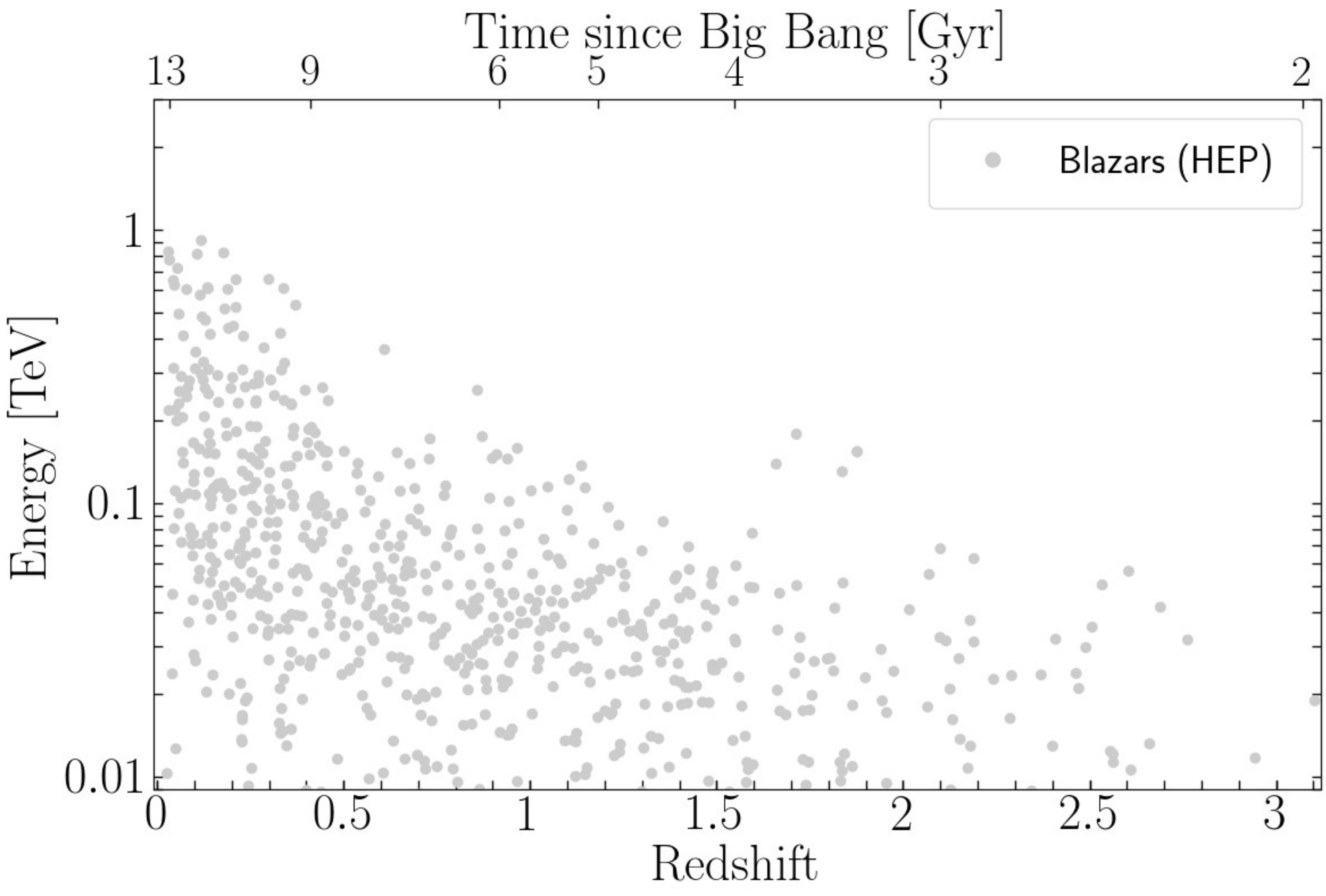


0.5<z<1.6

4 billion years



Cosmic Gamma-Ray Horizon



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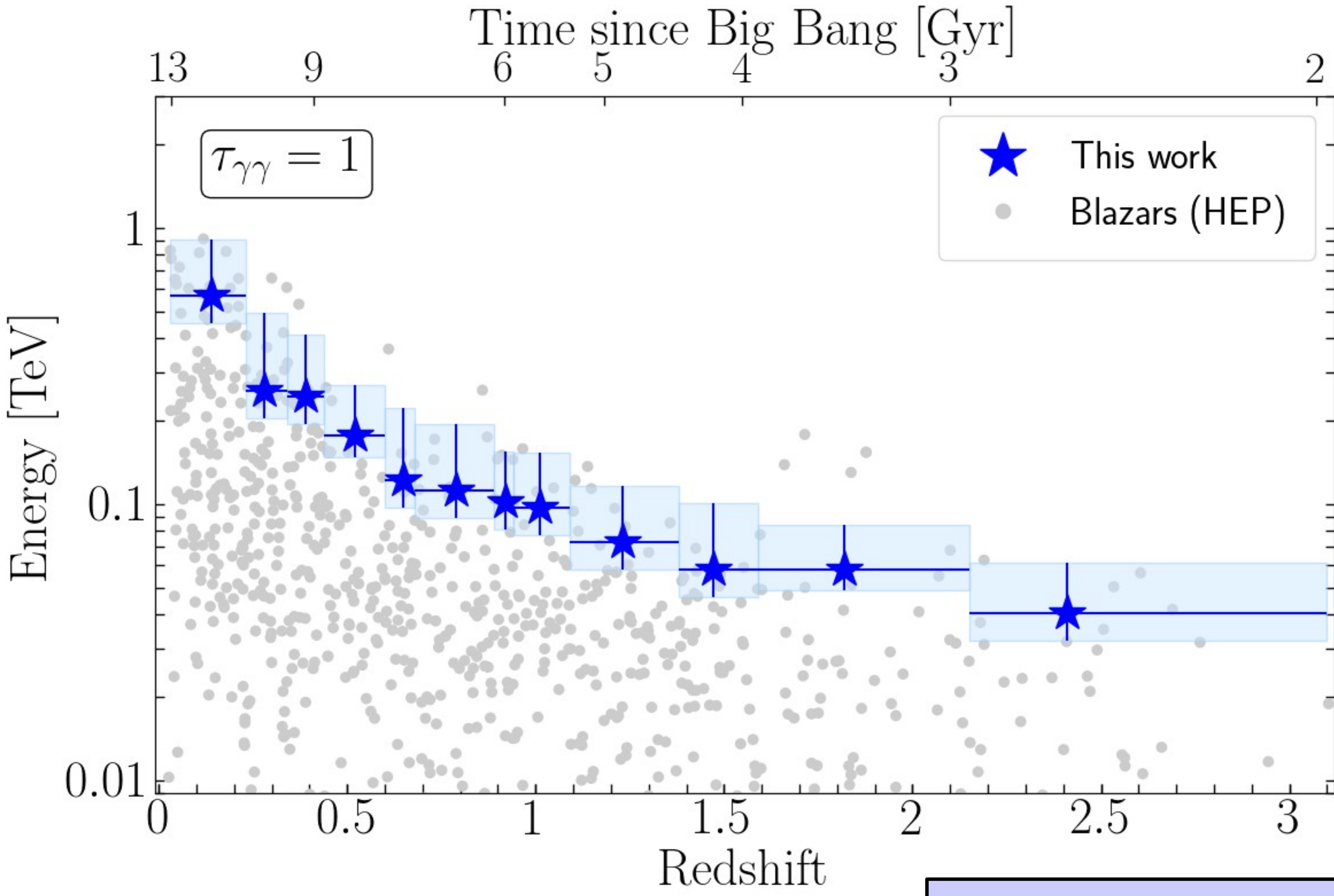
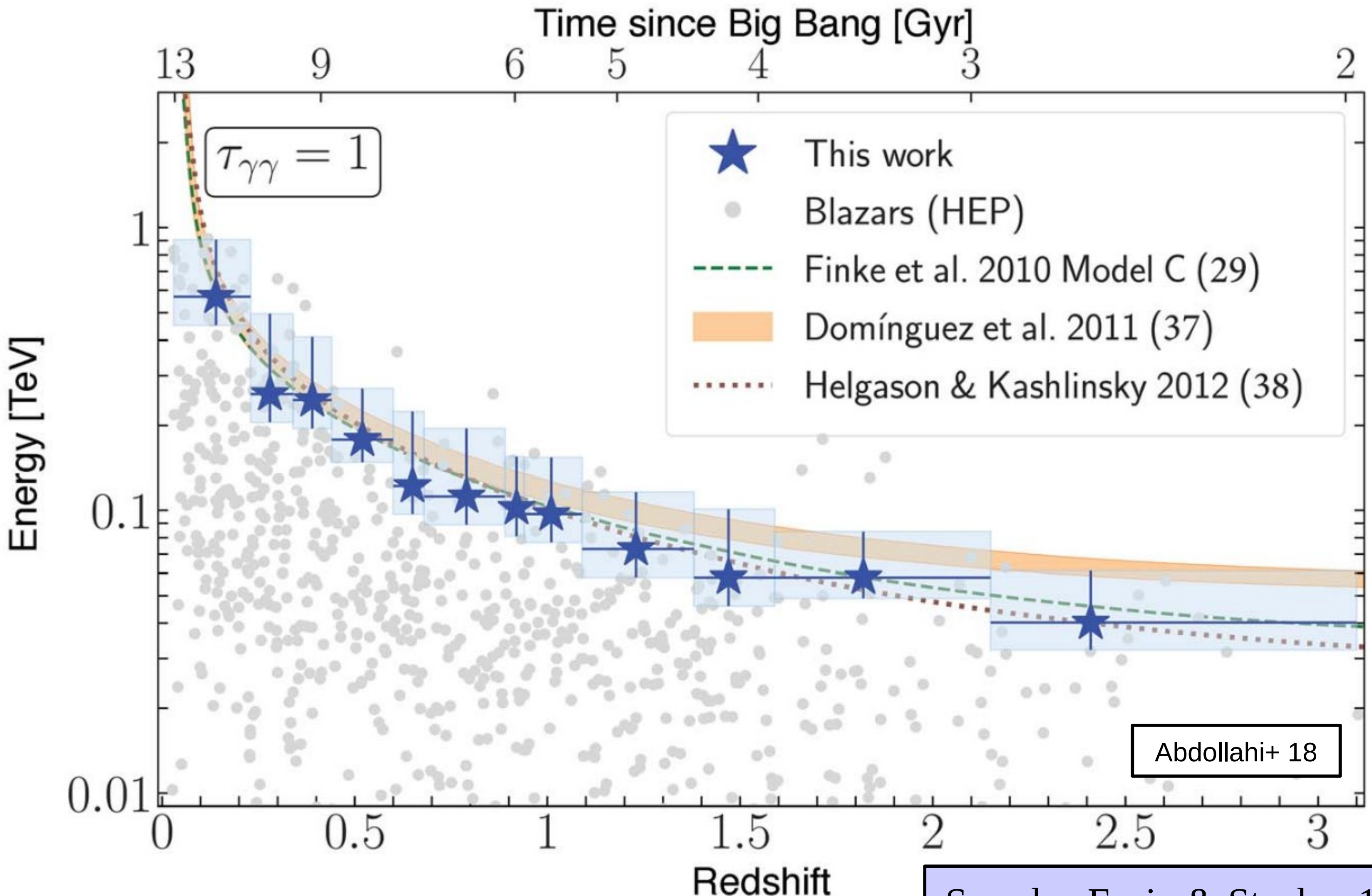


See also Fazio & Stecker 1970,
Domínguez et al. 2013

Cosmic Gamma-Ray Horizon



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

Galaxy Luminosity Densities and EBL

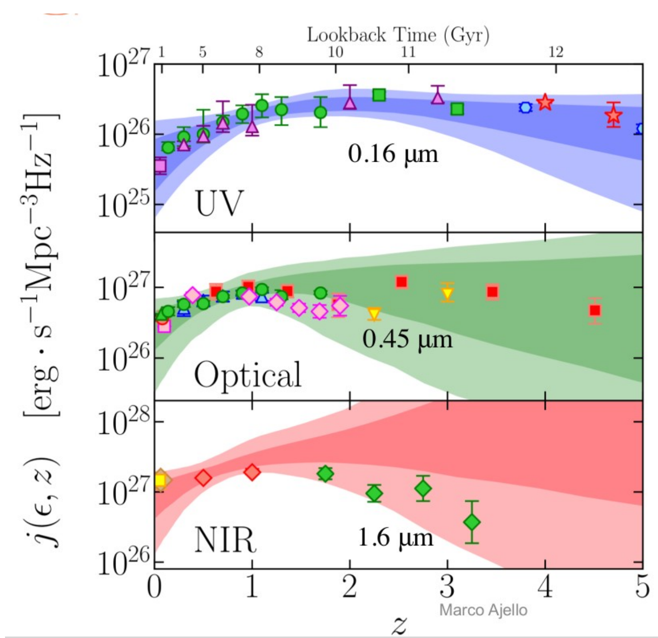
$$\tau_{\gamma\gamma}(E_\gamma, z_s) = c\int_0^{z_s}\left|\frac{dt}{dz}\right|dz\int_{-1}^{1}(1-\mu)\frac{d\mu}{2}\int_{2m_e^2c^4/\epsilon_\gamma(1-\mu)}^{\infty}\sigma(\epsilon_{\rm EBL},\epsilon_\gamma,\mu)n_{\rm EBL}(\epsilon,z)d\epsilon_{\rm EBL}$$

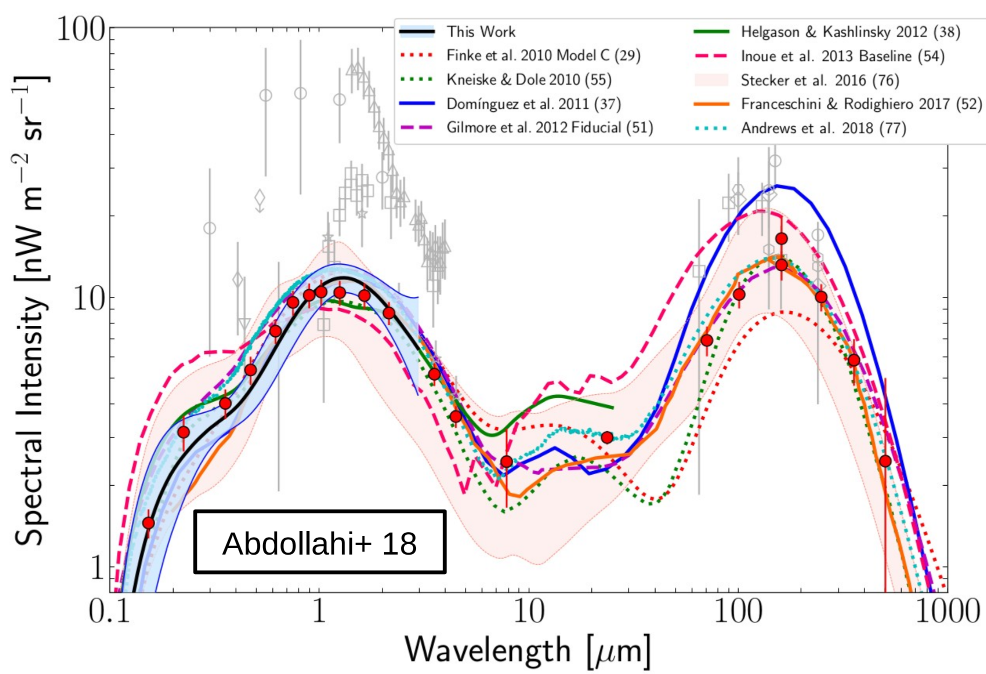
$$n_{\rm EBL}(\epsilon, z) = (1+z)^3\int_z^\infty \frac{j(\epsilon,z)}{\epsilon}\left|\frac{dt}{dz'}\right|dz'$$

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

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

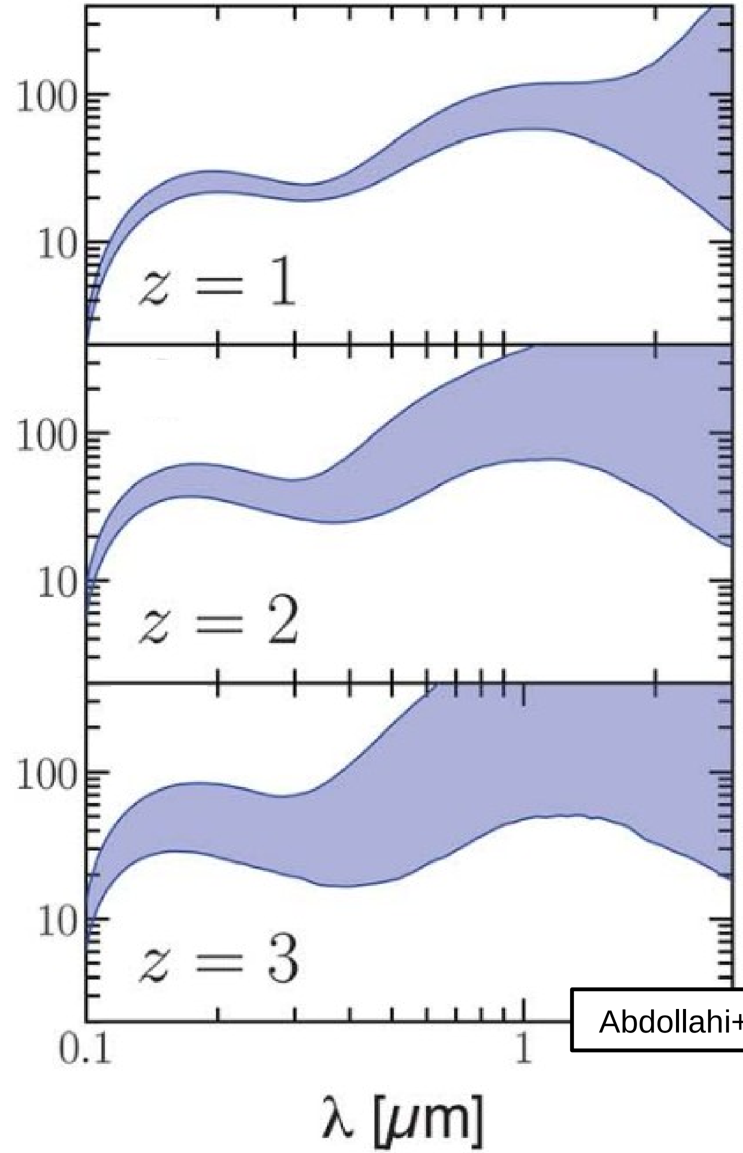
$$j(\lambda_i, z) = \sum_i a_i \cdot \exp\left[-\frac{(\log\lambda - \log\lambda_i)^2}{2\sigma^2}\right] \times \frac{(1+z)^{b_i}}{1+\left(\frac{1+z}{c_i}\right)^{d_i}},$$





Galaxy Luminosity Densities and EBL

First EBL determination at $z>0$



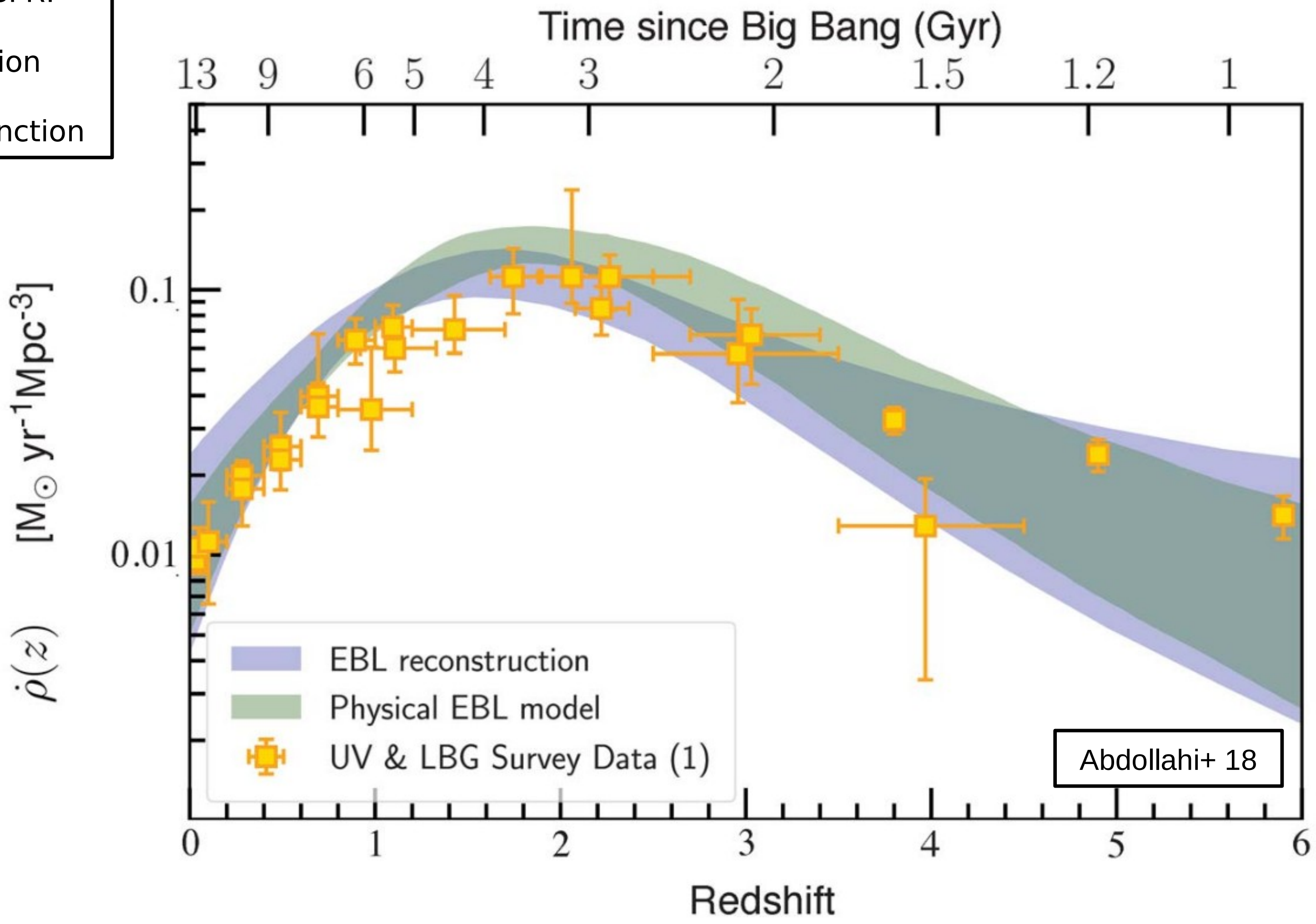
Abdollahi+ 18

Cosmic Star Formation Rate

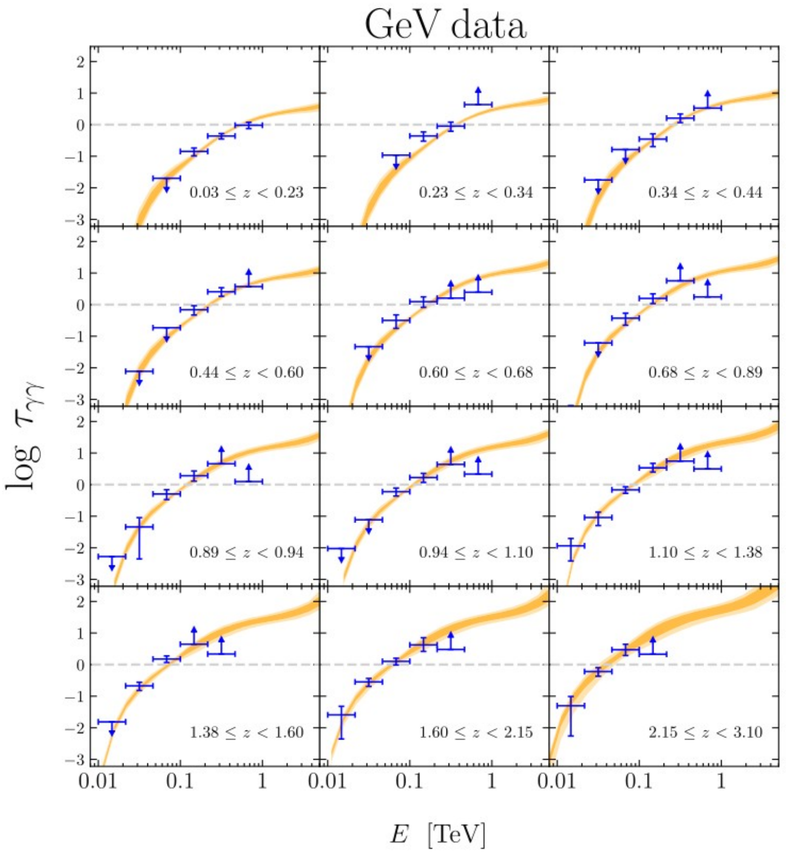
UV (0.16 microns) to SFR:

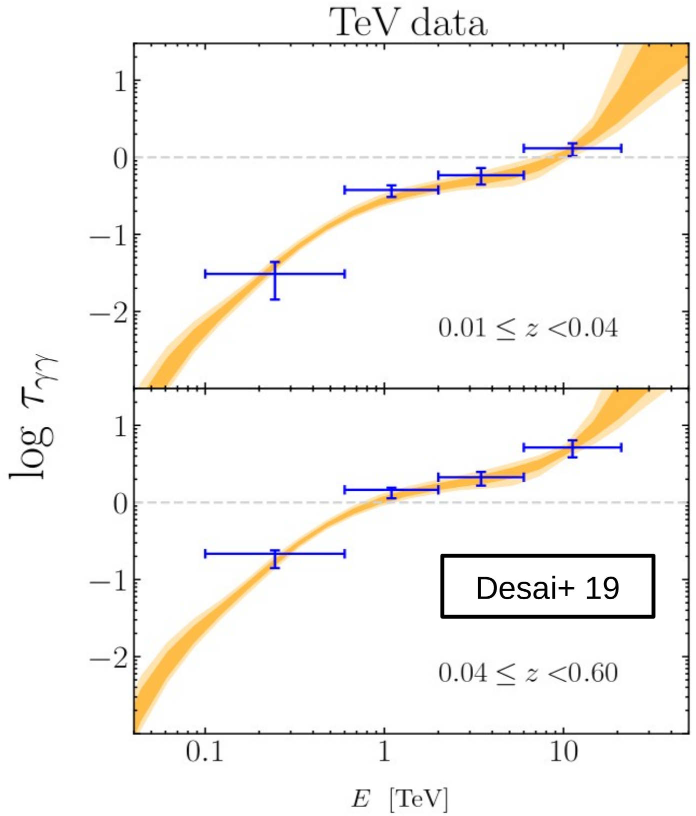
(1) Initial Mass Function

(2) Average Galaxy Extinction

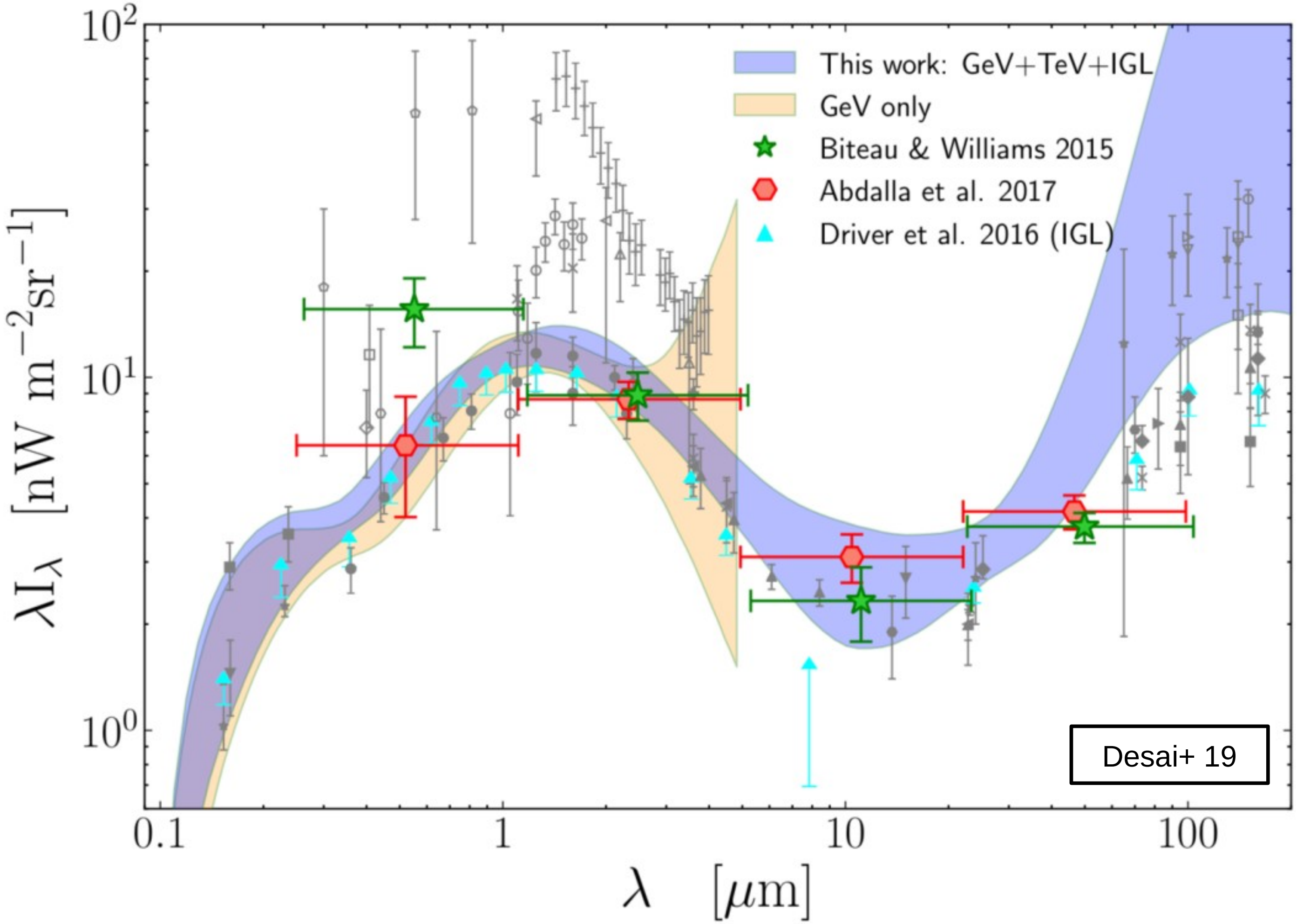


Optical Depths from Gamma-ray Data



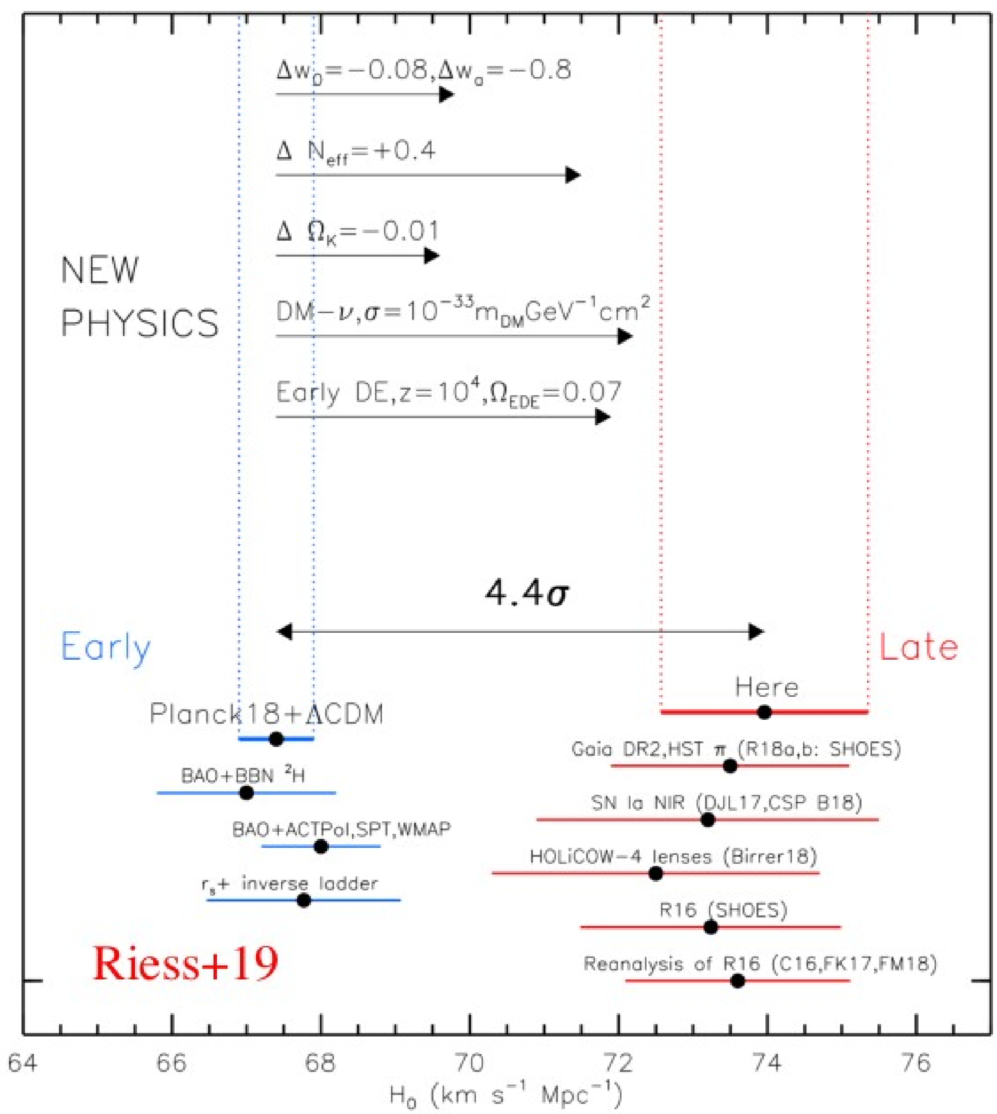


Extragalactic Background Light from Gamma Rays

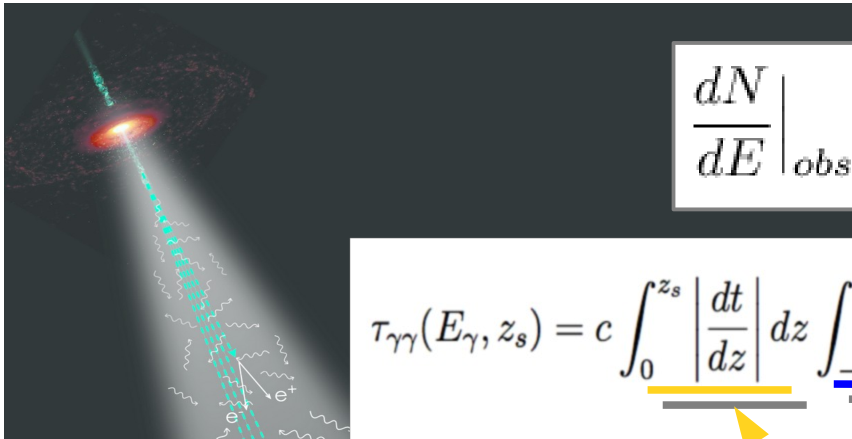


Local Extragalactic Background Light
(also see works by the MAGIC, VERITAS, and H.E.S.S. Collaborations)

Tension on H_0 Measurements



Gamma-ray Attenuation



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

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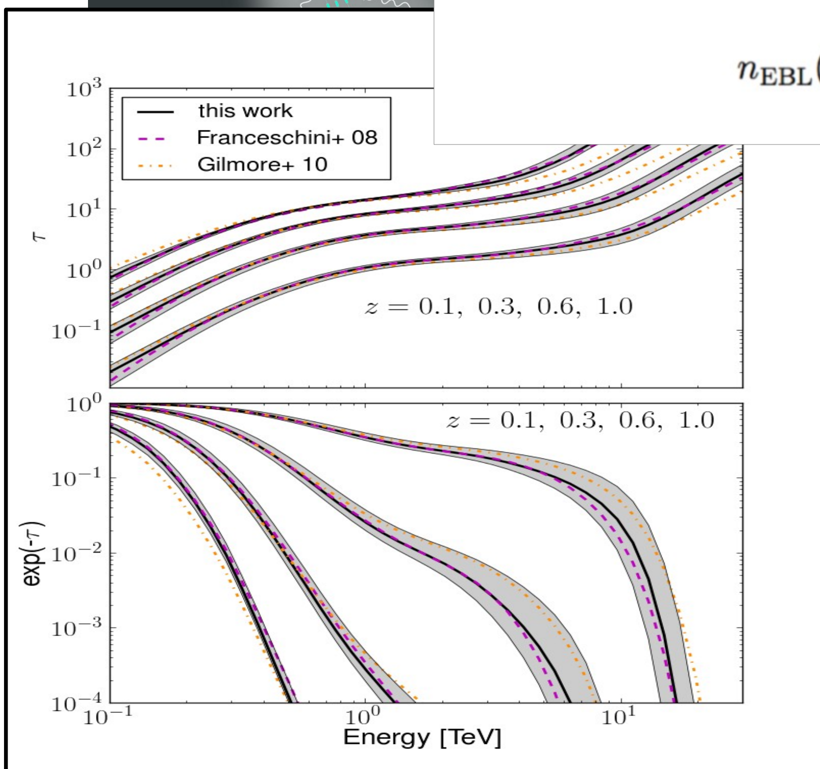
$$n_{\rm EBL}(\epsilon, z) = (1+z)^3 \int_z^{\infty} \frac{j(\epsilon, z)}{\epsilon} \left|\frac{dt}{dz'}\right| dz'$$

distance

cross section

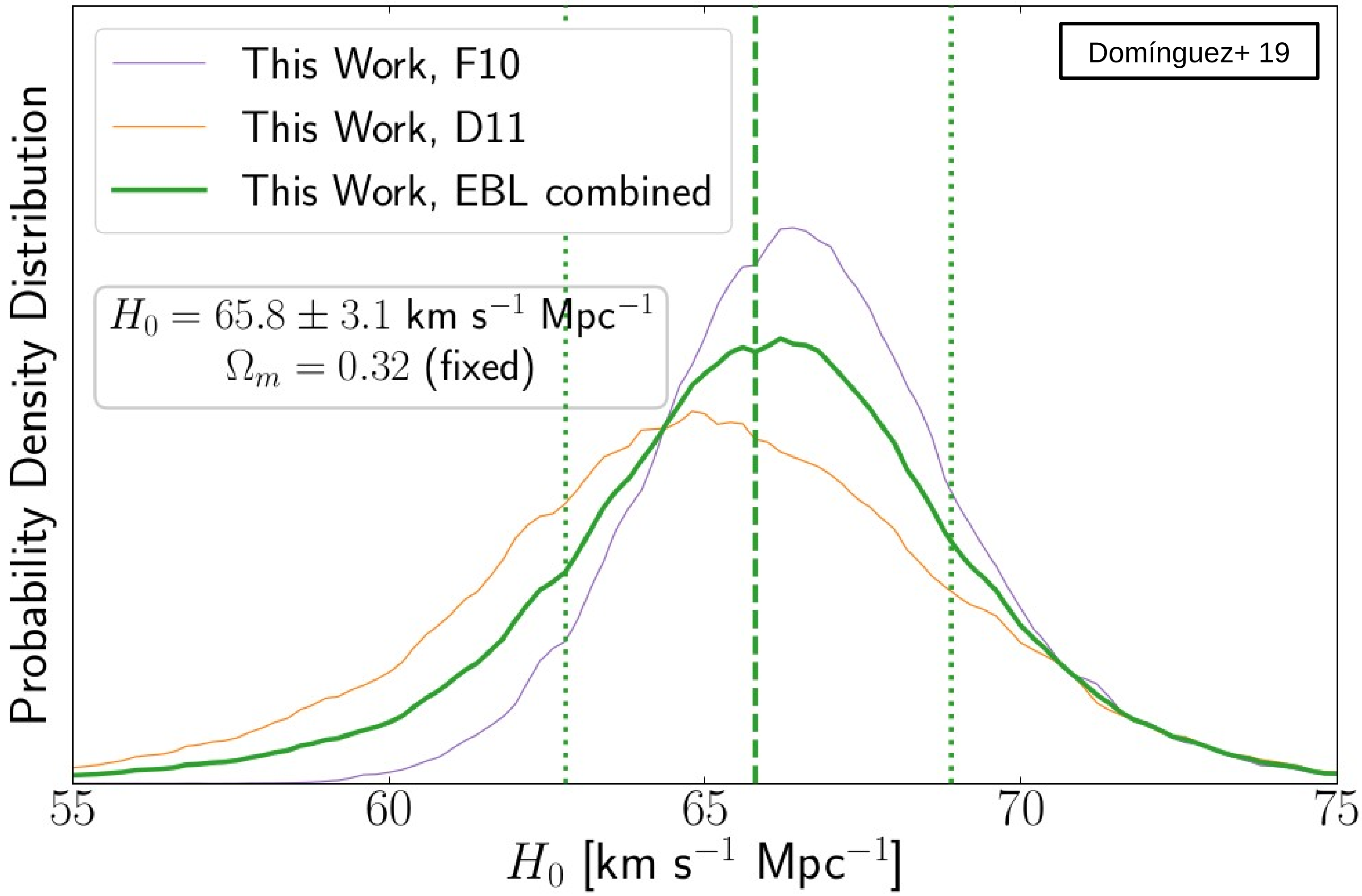
EBL photon density evolution

See Domínguez & Prada 13, Biteau & Williams 15



: Nina McCurdy & Joel Primack

Measuring H_0 with Gamma-ray Attenuation



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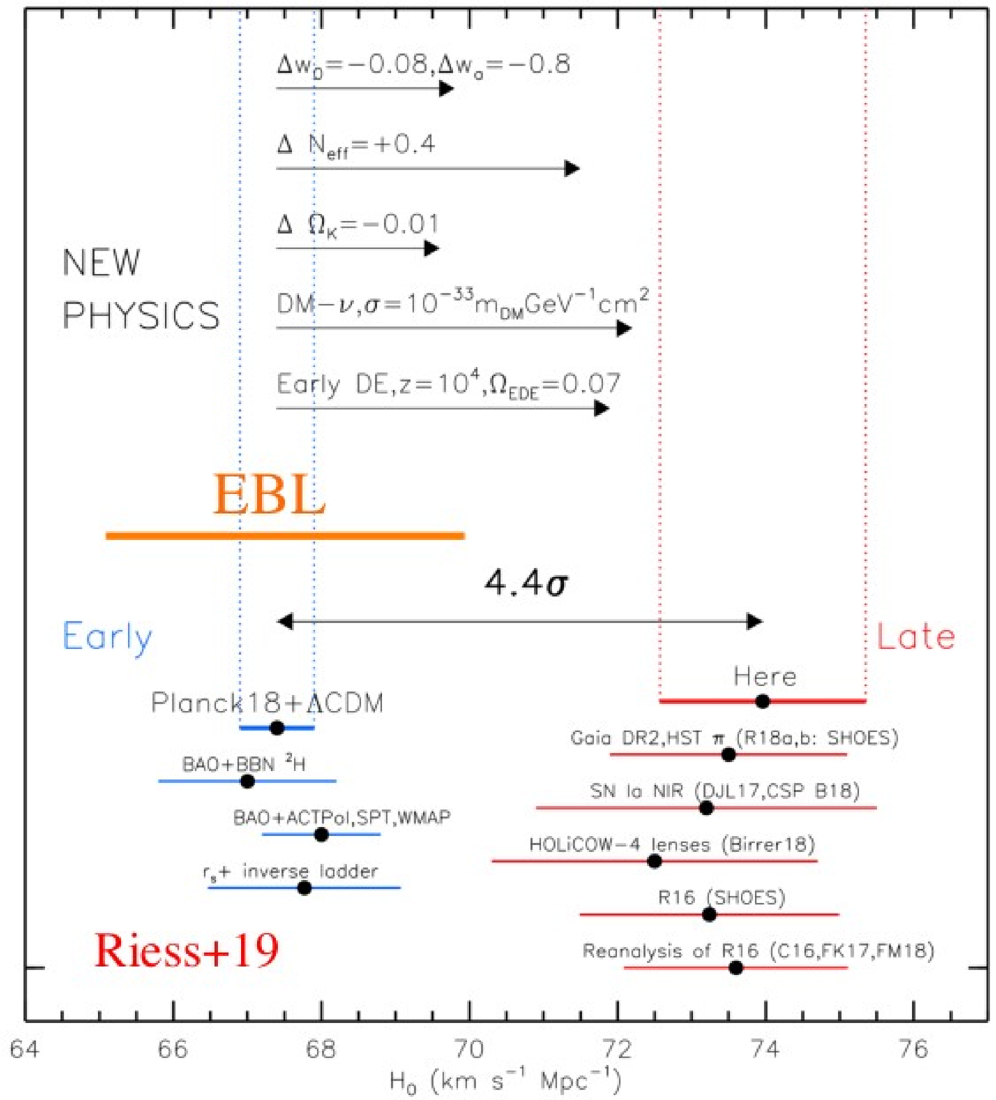

Take Home Messages

There is fundamental information about cosmology and galaxy evolution encoded in the extragalactic background light (EBL), and gamma-ray observations can be helpful for extracting this information.

The EBL makes the Universe not completely transparent to the propagation of gamma-ray photons, i.e. gamma-ray observations are in general affected by EBL attenuation.