Cosmology with *Fermi*-LAT

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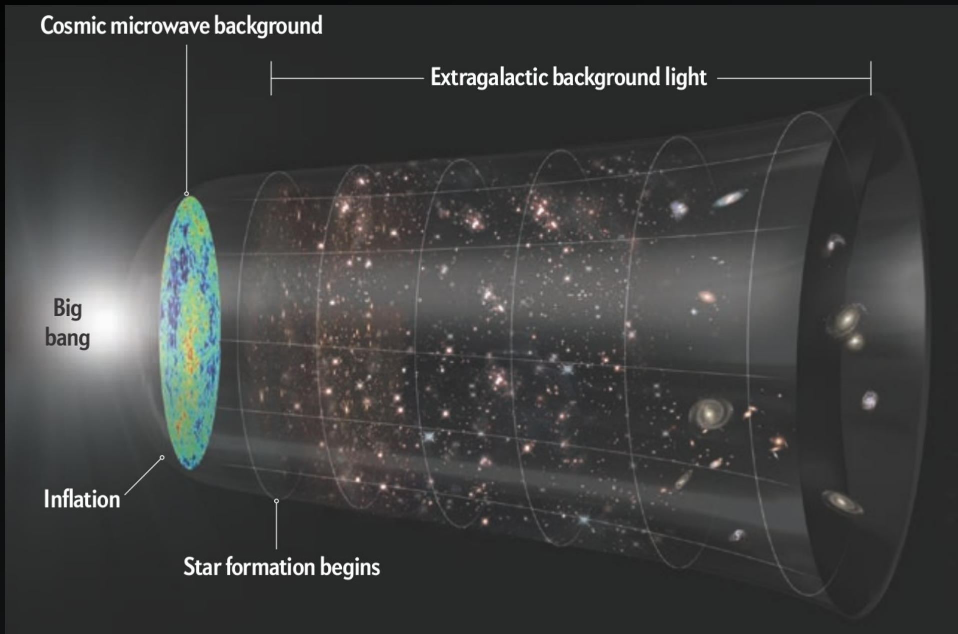
Preliminary!

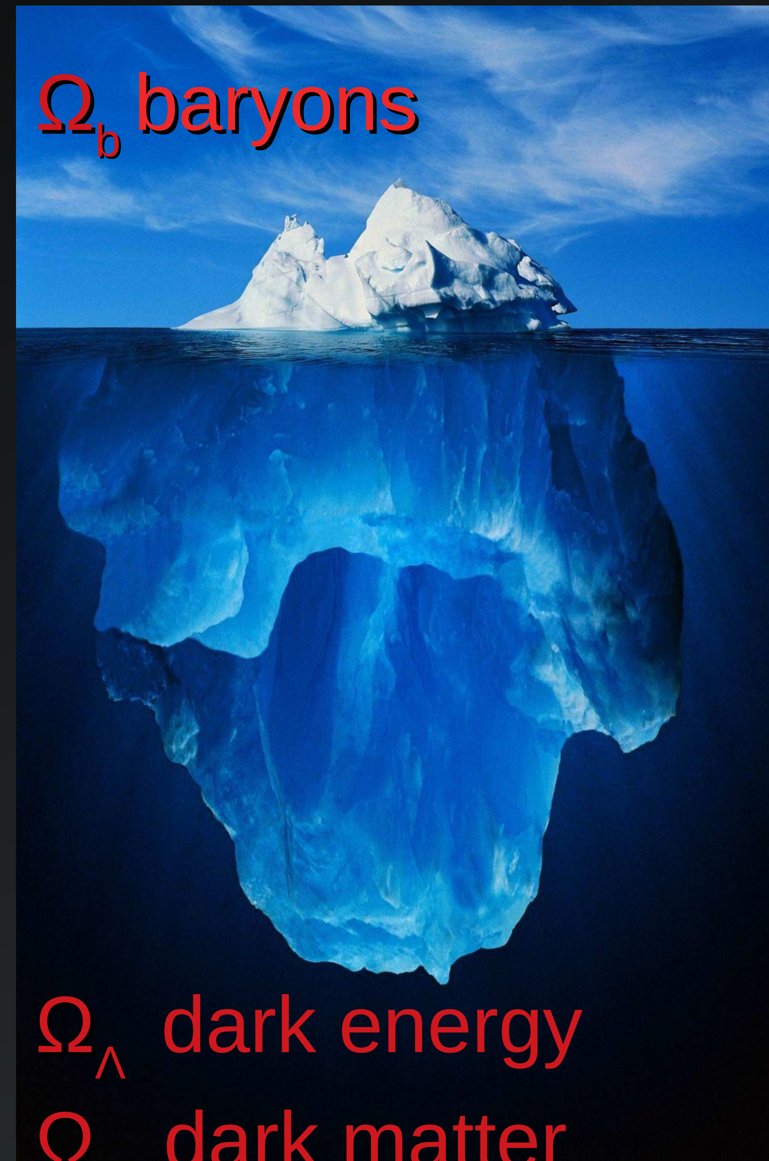
Domínguez, Primack, Bell

Scientific American, August 2015

Fermi Symposium 10th Anniversary, Baltimore 14 – 19 October 2018

Galaxy Evolution and Cosmology





Ω_b baryons

Ω_Λ dark energy

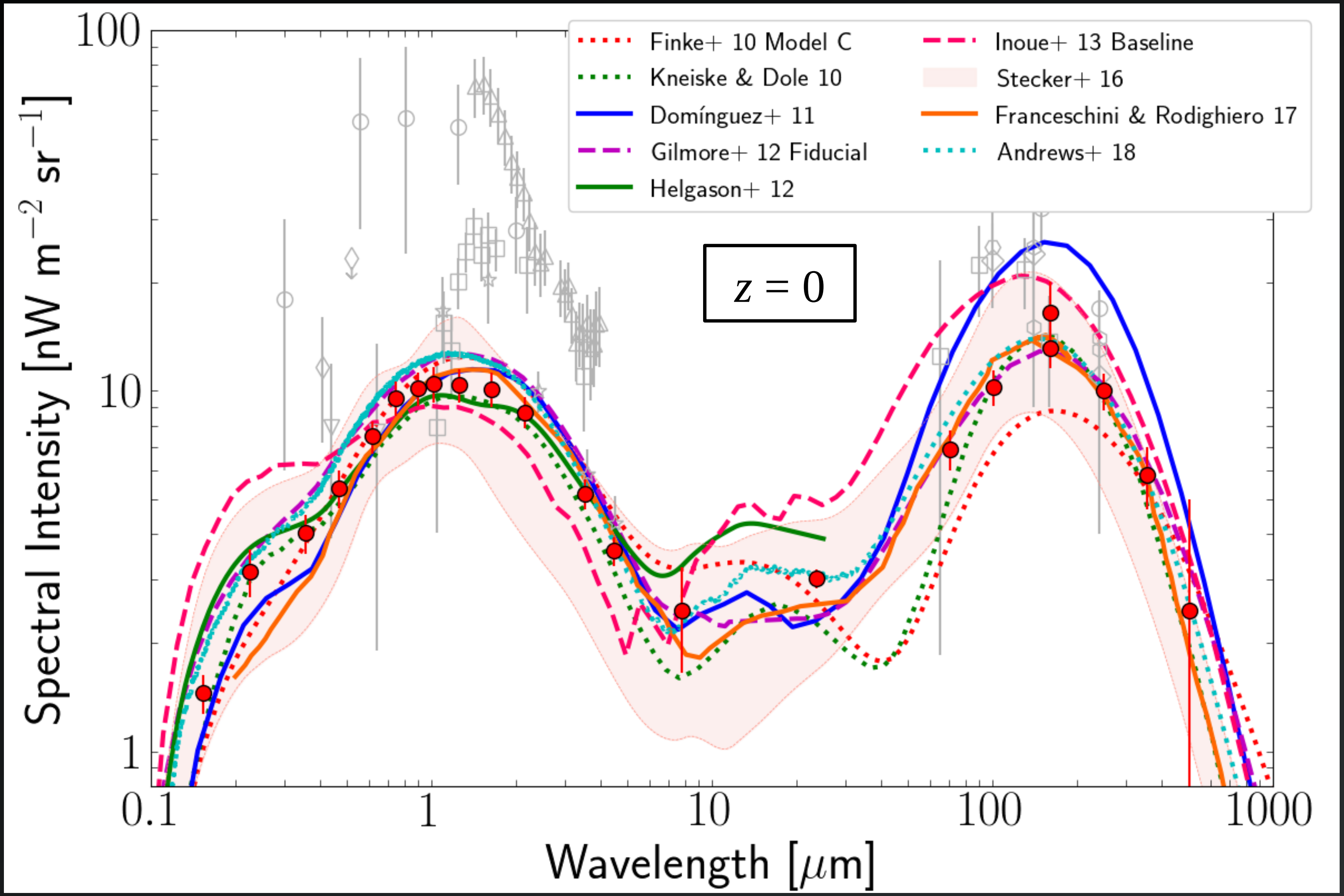
Ω_D dark matter

Λ Cold Dark Matter

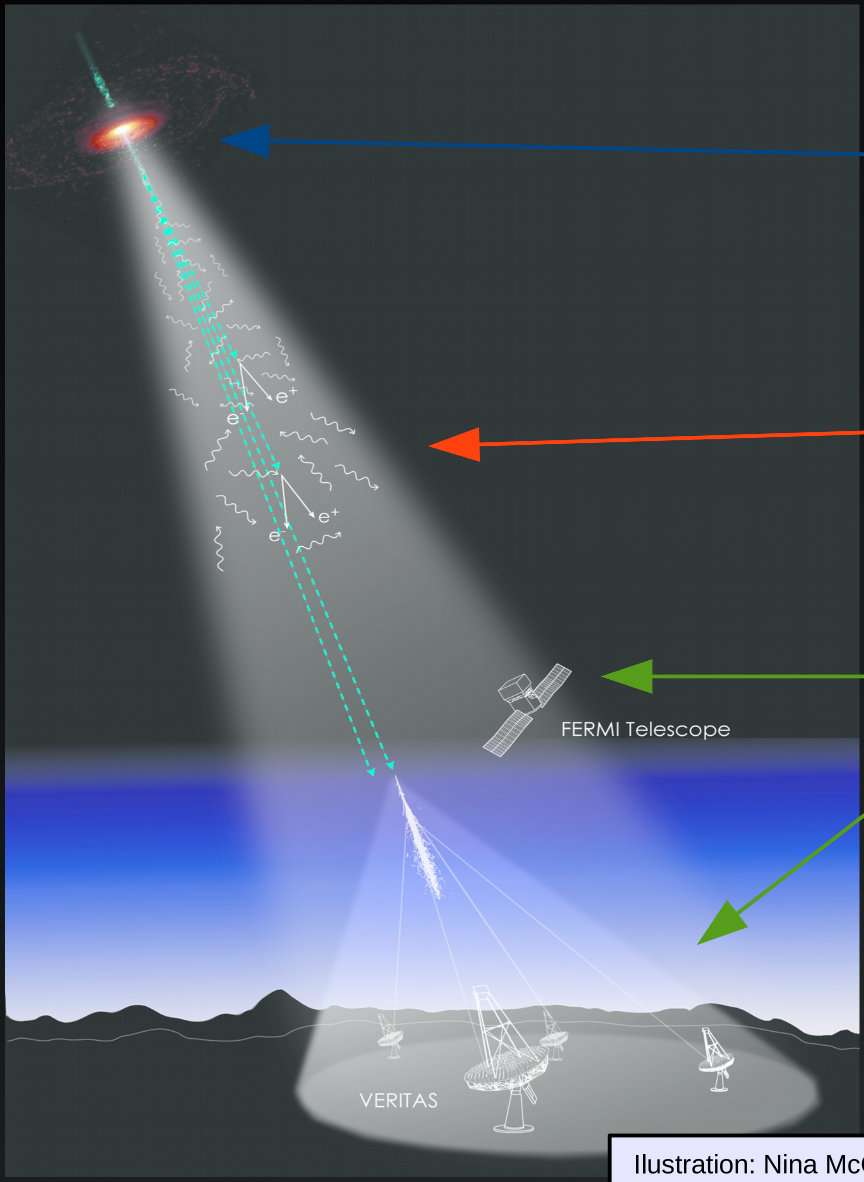
$$\Omega_m = \Omega_b + \Omega_D$$

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

Extragalactic Background Light



Gamma-ray Attenuation



Extragalactic source:
e.g. Blazar

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

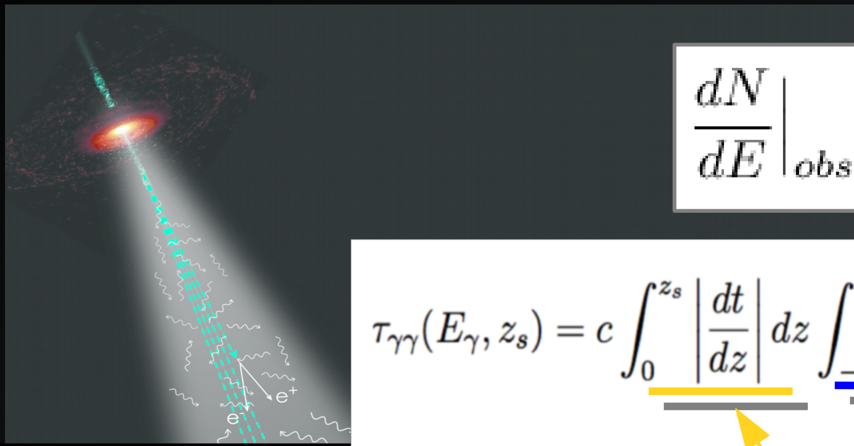
Pair-production interaction

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



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

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

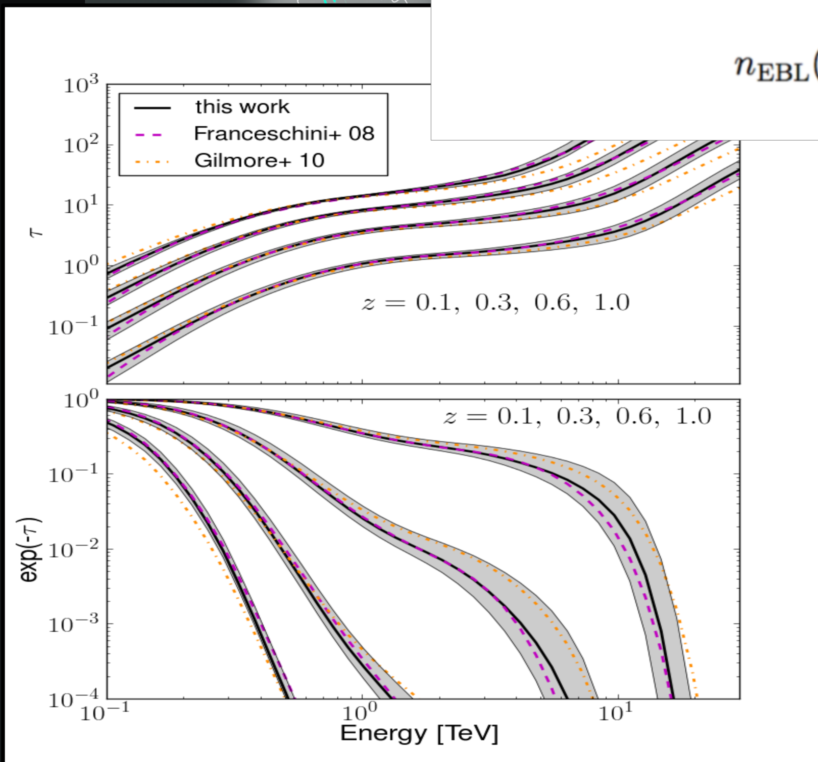
$$n_{\rm EBL}(\epsilon,z) = (1+z)^3\int_z^{\infty}\frac{j(\epsilon,z)}{\epsilon}\left|\frac{dt}{dz'}\right|dz'$$

distance

cross section

EBL photon density evolution

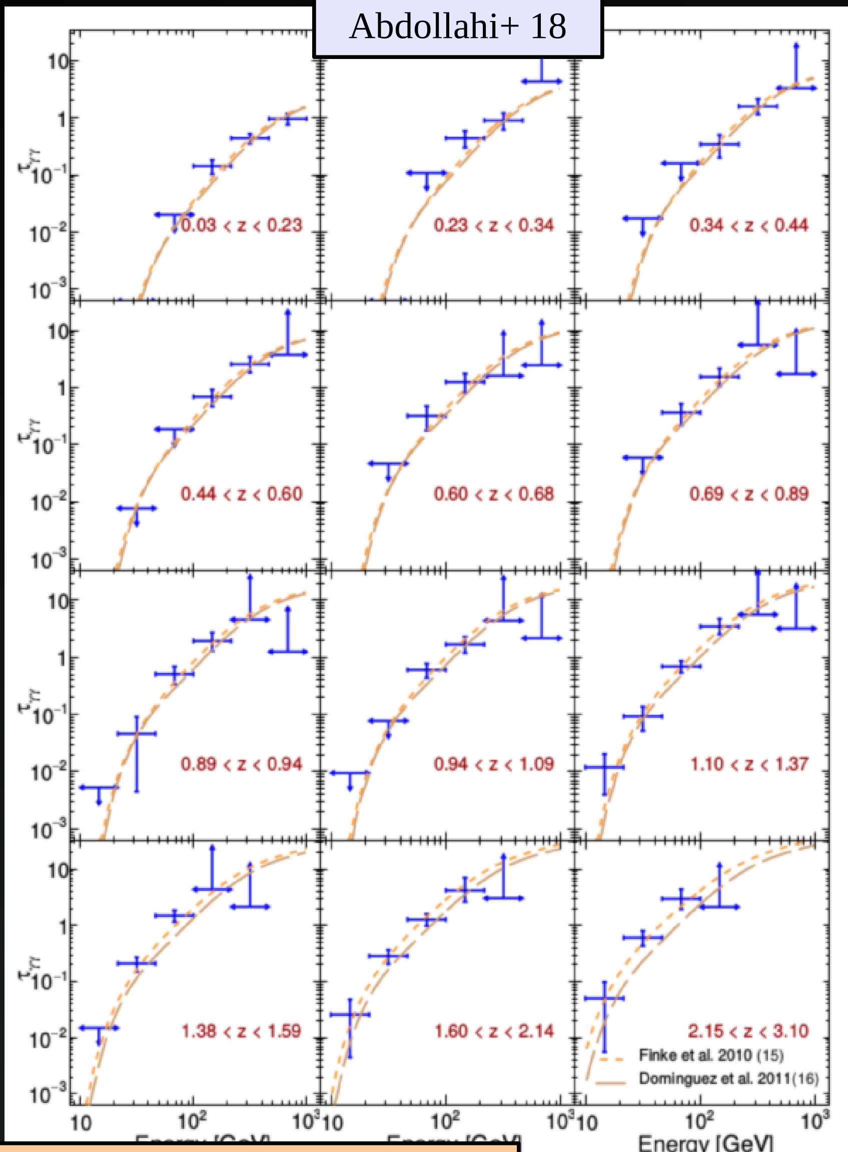
See Domínguez & Prada 13, Biteau & Williams 15



: Nina McCurdy & Joel Primack

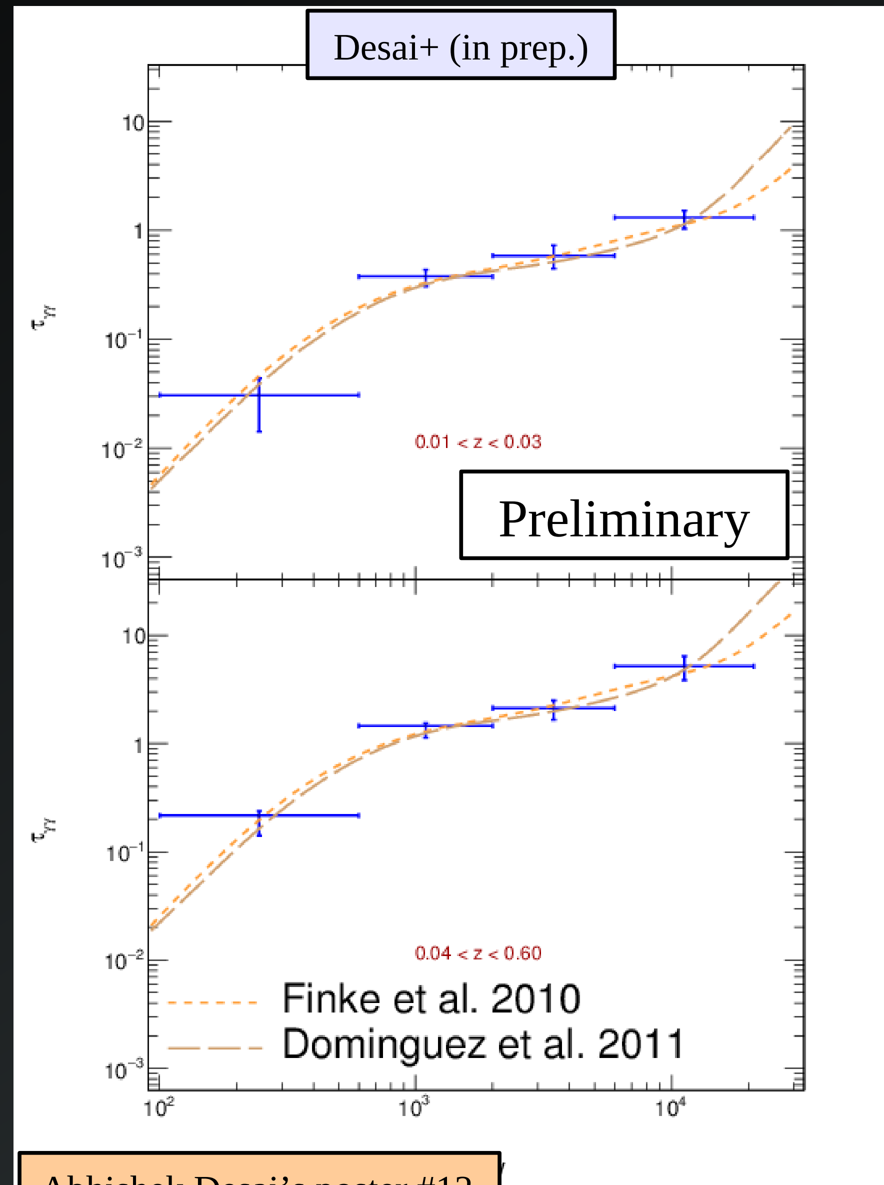
Optical Depths from Gamma-ray data

Abdollahi+ 18



Marco Ajello's talk on Wednesday

Desai+ (in prep.)



Abhishek Desai's poster #12

EBL model compatibility with Gamma-ray data

Model	Ref.	Significance of b=0 Rejection[a]	b[b]	Significance of b=1 Rejection[c]
Scully et al. (2014) – high	(49)	16.0	0.42±0.03	17.4
Kneiske et al. (2004) – best -fit	(50)	16.9	0.68±0.05	6.0
Gilmore et al. (2012) – fixed	(51)	16.7	1.30±0.10	3.0
Gilmore et al. (2012) – fiducial	(51)	16.6	0.81±0.06	2.9
Dominguez et al. (2011)	(16)	16.6	1.31±0.10	2.9
Franceschini et al. (2017)	(52)	16.4	1.25±0.10	2.5
Gilmore et al. (2009)	(53)	16.7	1.03±0.08	2.4
Inoue et al. (2013)	(54)	16.2	0.87±0.06	2.1
Kneiske & Dole (2010)	(55)	16.8	0.94±0.08	1.7
Helgason et al. (2012)	(17)	16.5	1.10±0.08	1.3
Finke et al. (2010) – model C	(15)	17.1	1.03±0.08	0.4
Scully et al. (2014) – low	(49)	16.0	1.00±0.07	0.1

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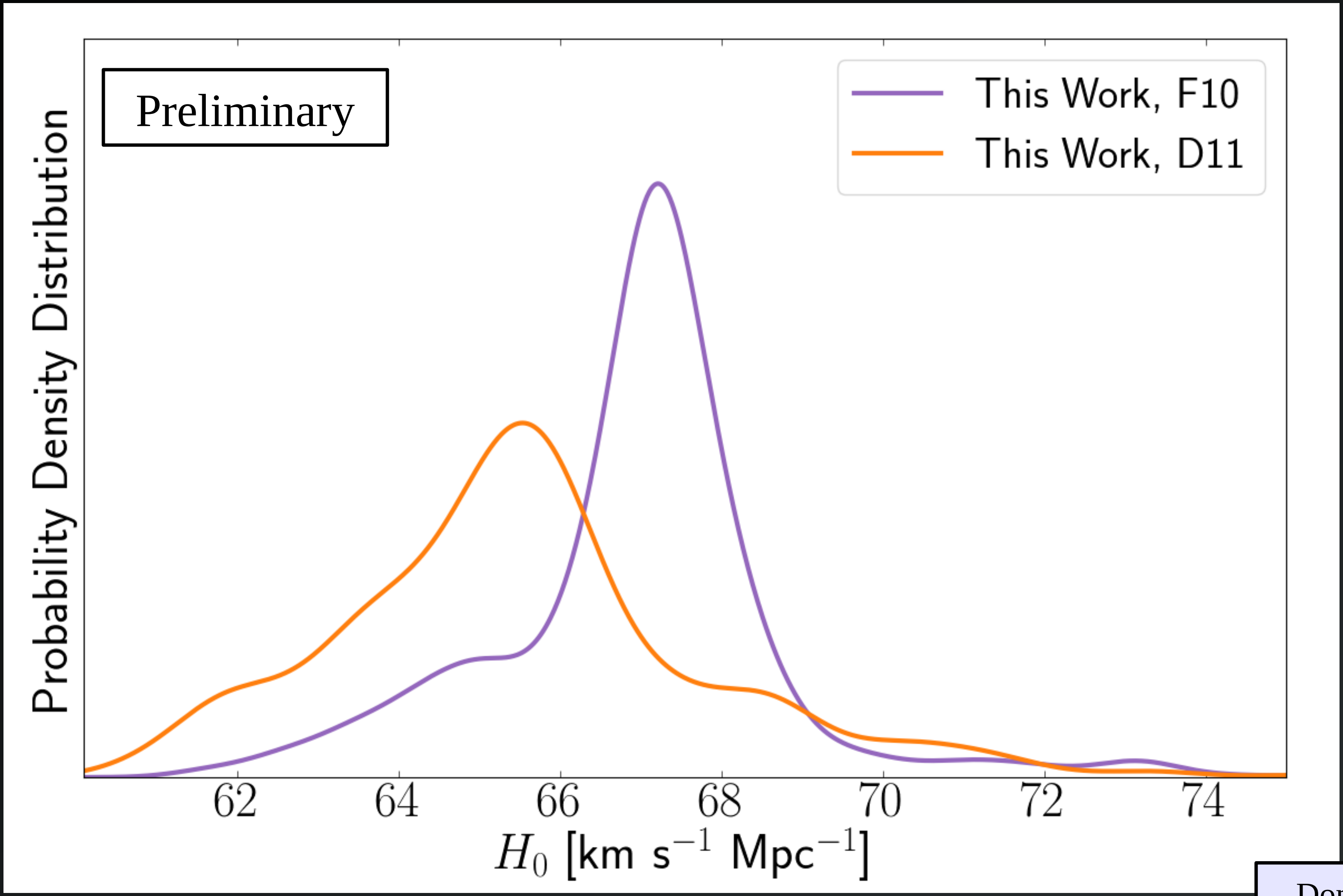
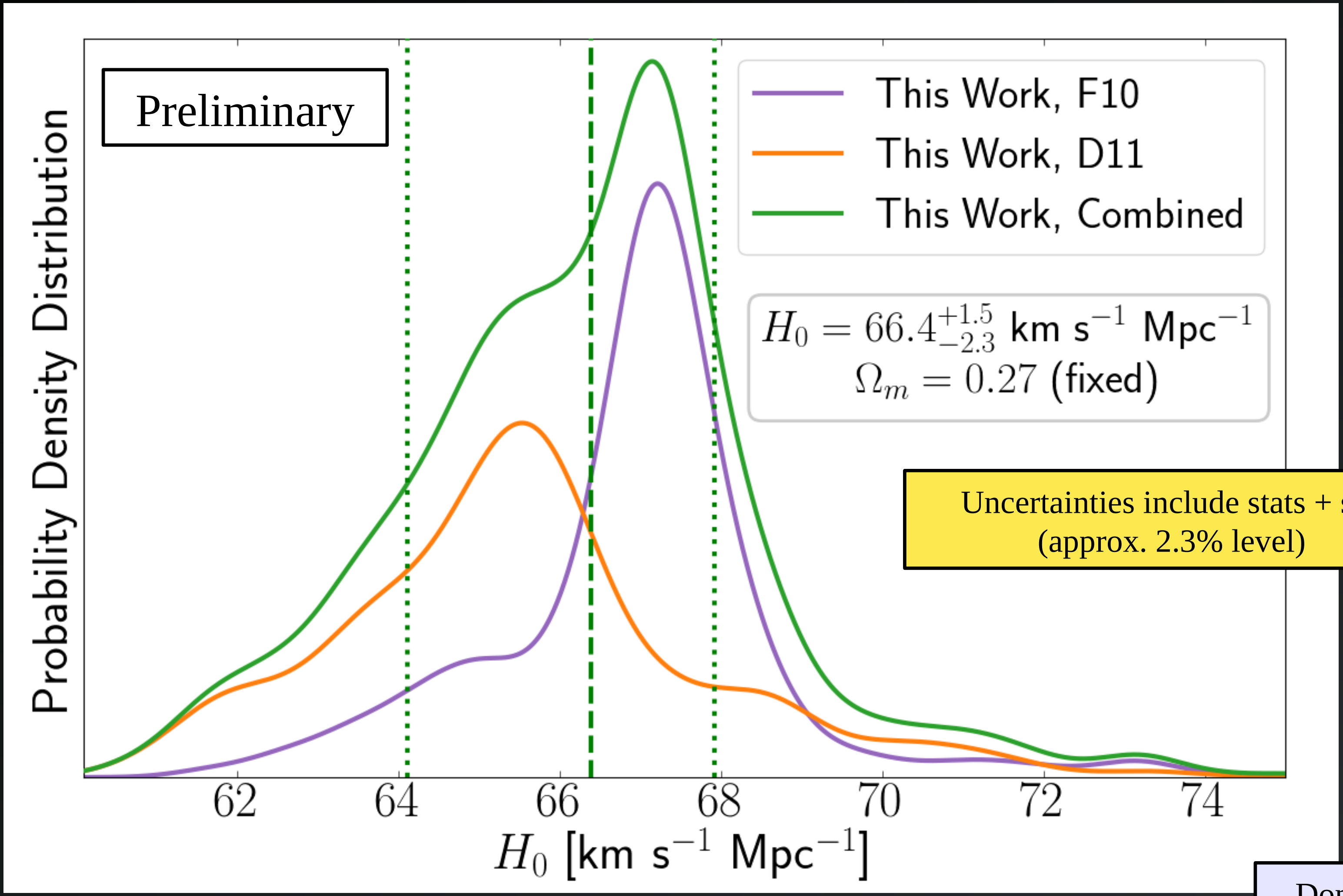
Somehow these two models bracket the EBL uncertainties that are compatible with gamma-ray attenuation

Measuring H_0 with Gamma-ray attenuation



Domínguez+
(in prep.)

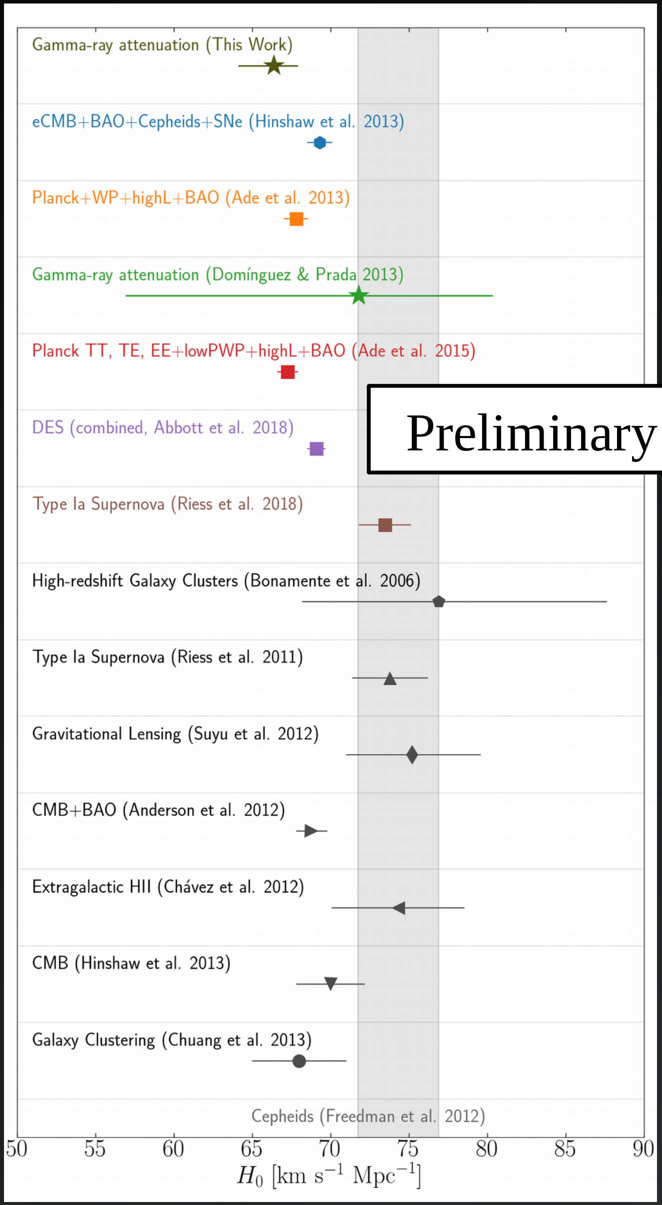
Measuring H_0 with Gamma-ray attenuation



Uncertainties include stats + sys (approx. 2.3% level)

Domínguez+ (in prep.)

Comparison with other Methodologies

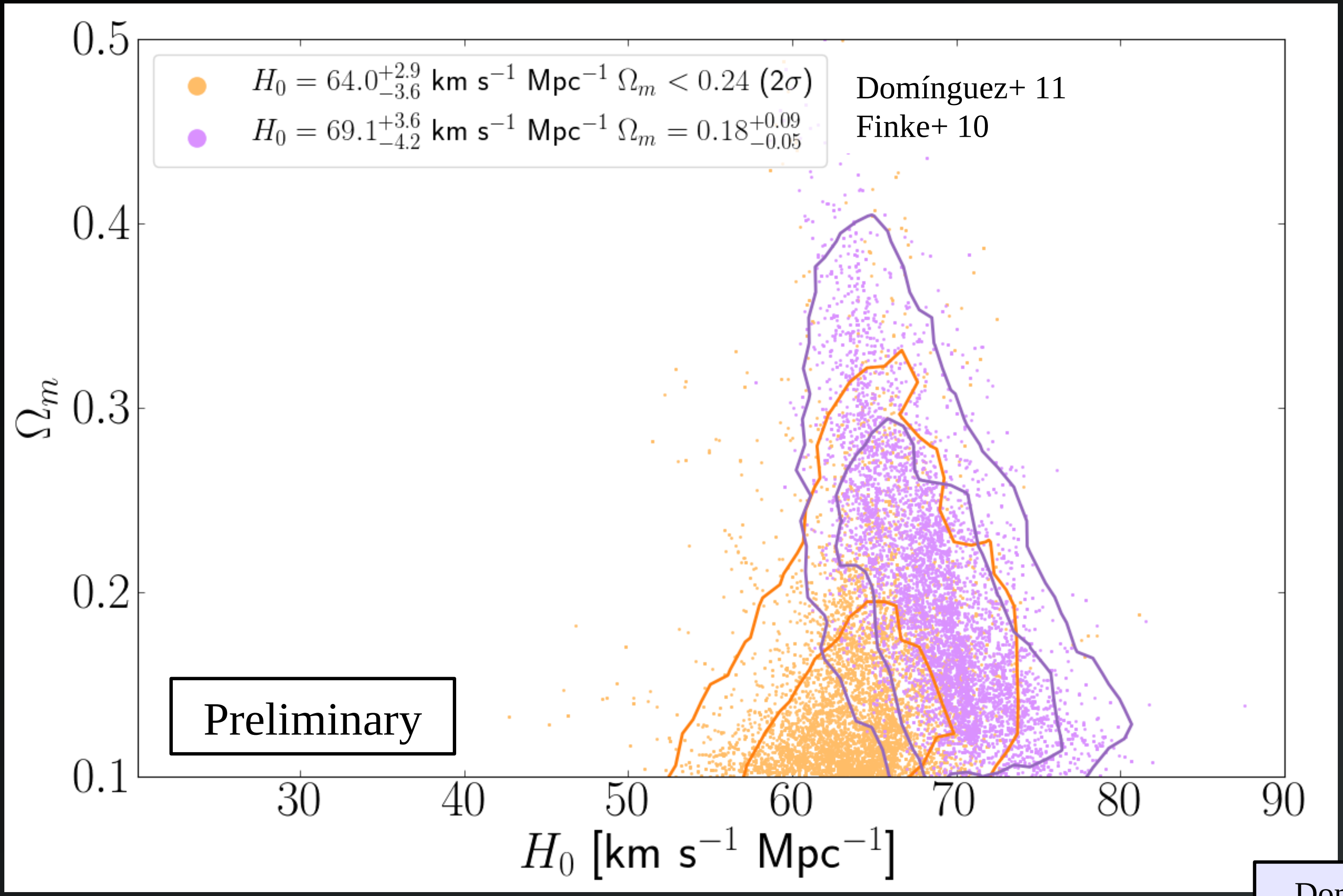


Preliminary

Combination of techniques is important to control systematics

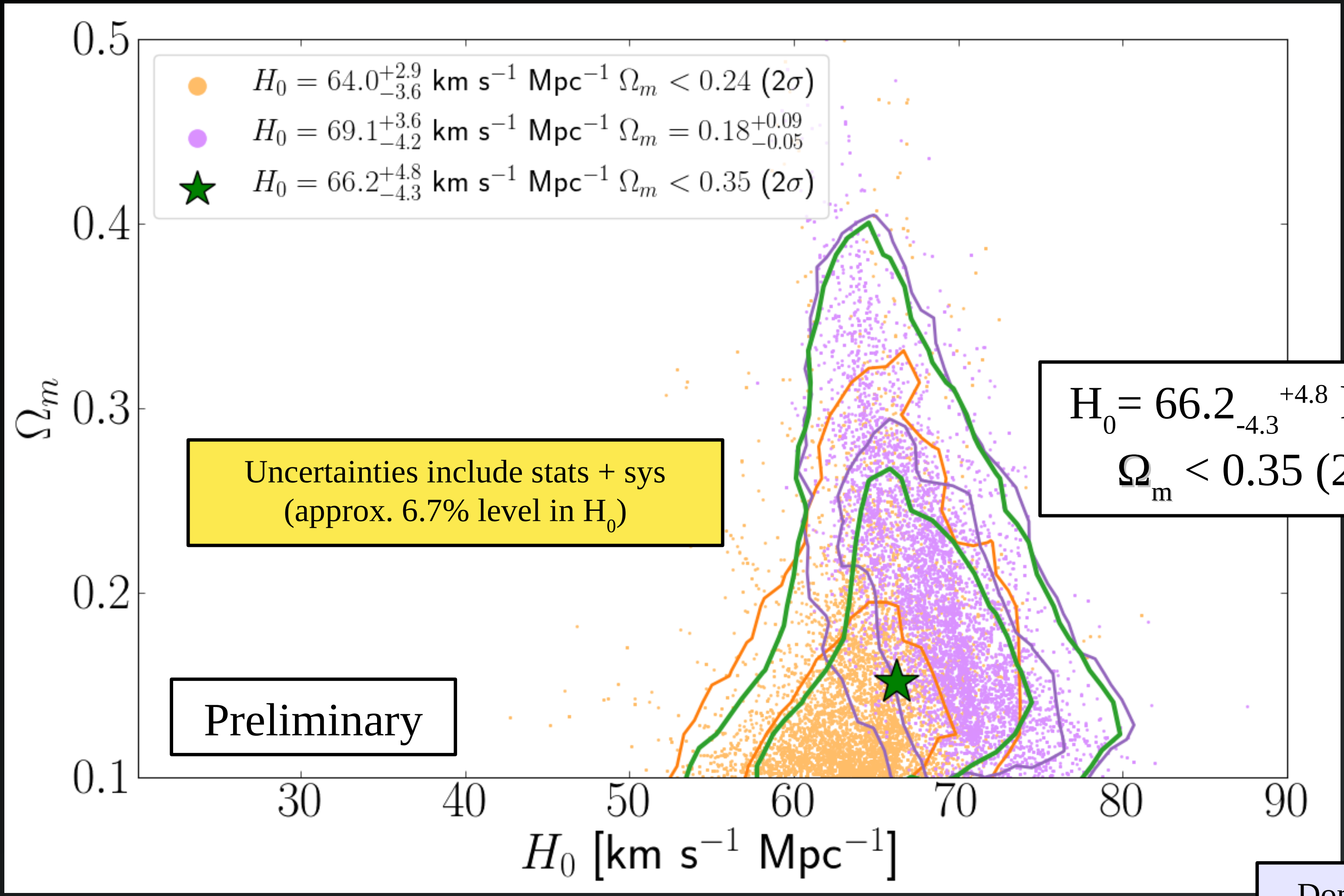
Domínguez+ (in prep.)

Results: Only Gamma Rays



Domínguez+
(in prep.)

Results: Only Gamma Rays

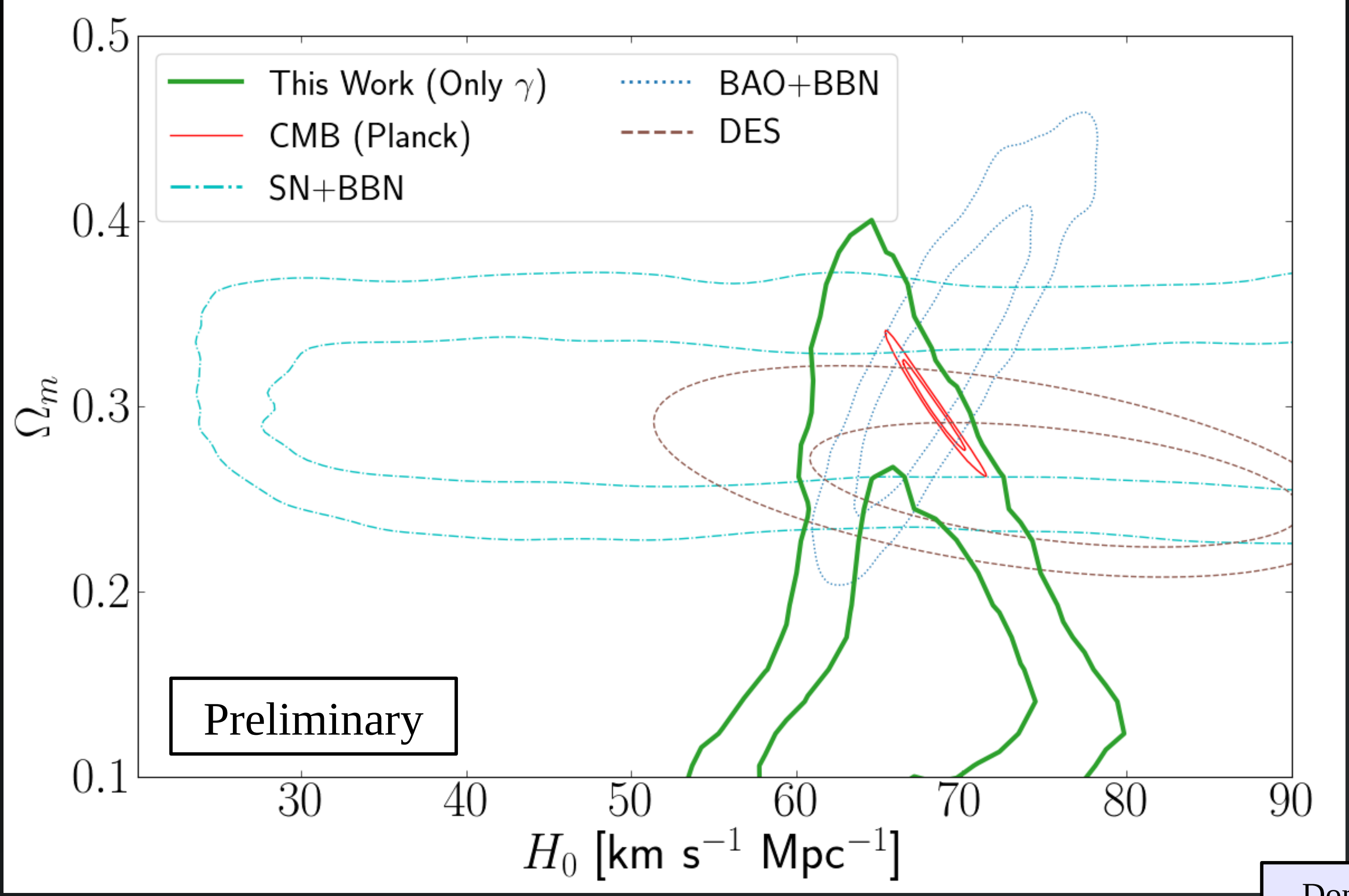


$H_0 = 66.2_{-4.3}^{+4.8}$ km/s/Mpc

$\Omega_m < 0.35$ (2sigma)

Domínguez+
(in prep.)

Results: Combined with other Methodologies



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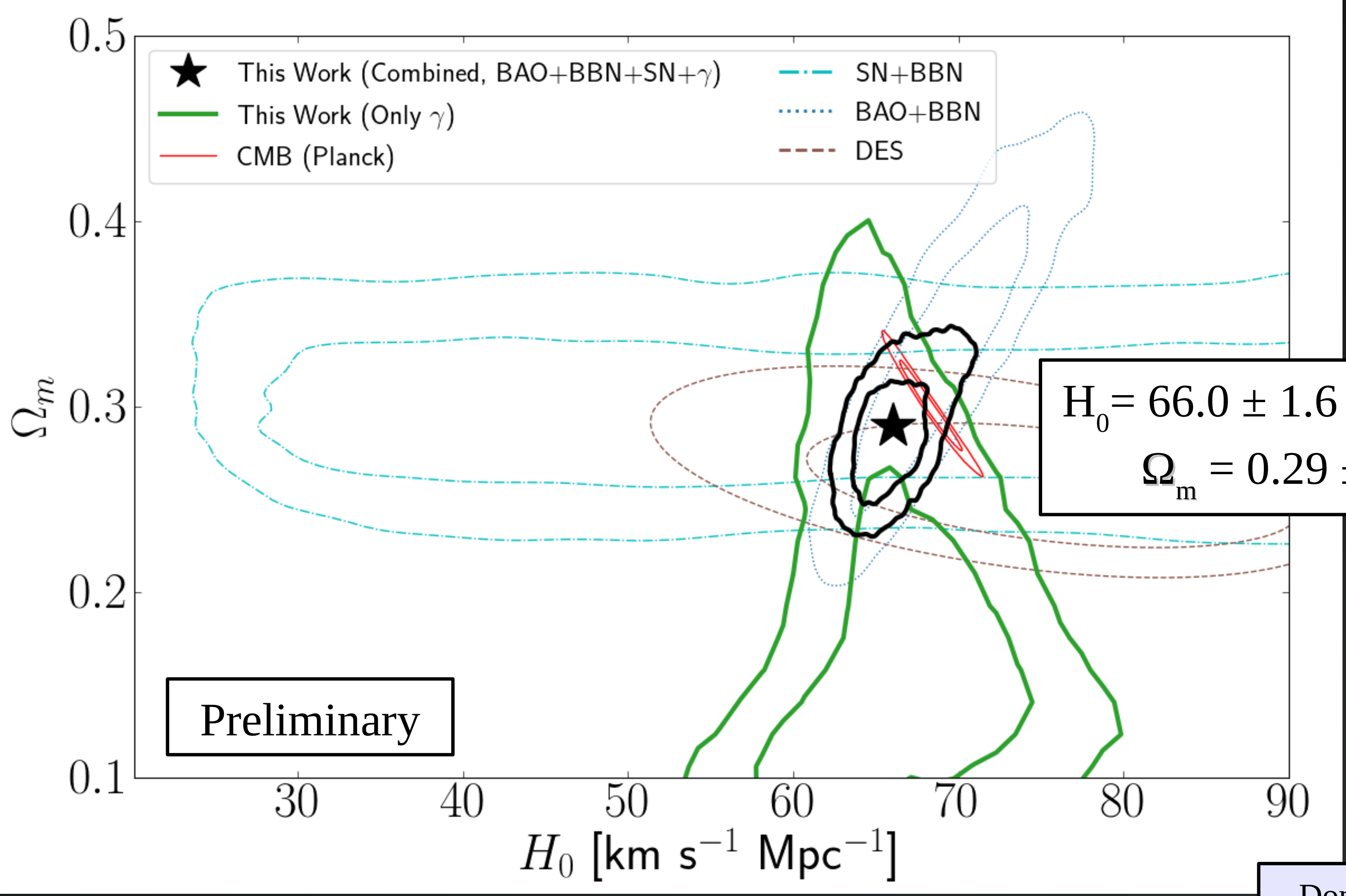
(in prep.)

Results: Combined with other Methodologies



H_0 = 66.0 ± 1.6 km/s/Mpc

Ω_m = 0.29 ± 0.02

Domínguez+
(in prep.)

Summary

- Measurements of gamma-ray attenuation can be used to extract cosmological information: novel and independent technique

- These latest optical-depth measurements, both from *Fermi*-LAT and Cherenkov telescopes, have been used to search for the H_0 and Ω_m values

- We obtain $H_0 = 66.4_{-2.3}^{+1.5}$ km/Mpc/s (fixing WM=0.27) compatible with the lower end of Hubble constant measurement from other methodologies

- First attempt of measuring simultaneously H_0 and Ω_m with gamma rays leading to $\Omega_m < 0.35$ (2sigma)

Backup

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:

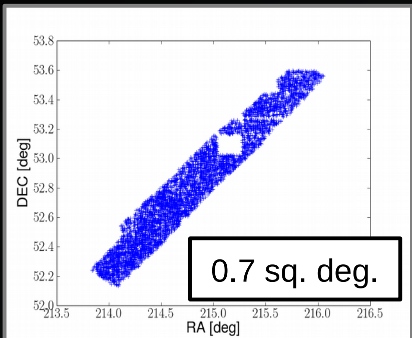
Component	n	f_n	T_n [K]	Θ_n [10^{-9}]
Warm Large Grains	1	0.60	40	7
Hot Small Grains	2	0.05	70	12
PAHs	3	0.35	450	76

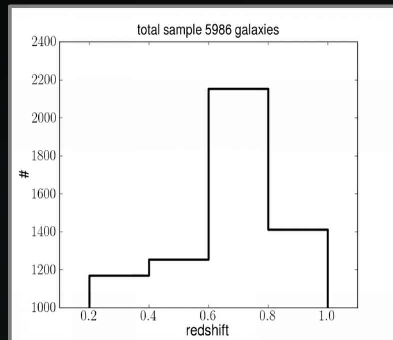
EBL energy density:

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

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

EBL models: Domínguez+ 11

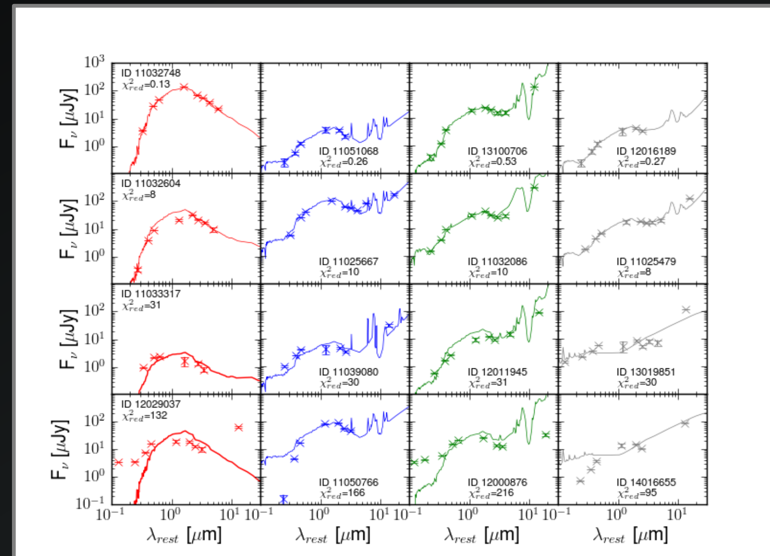


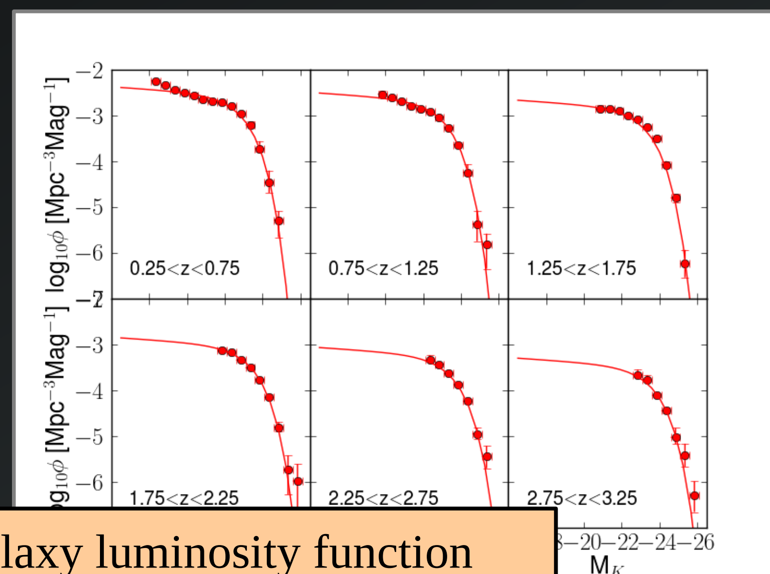


EGS field

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

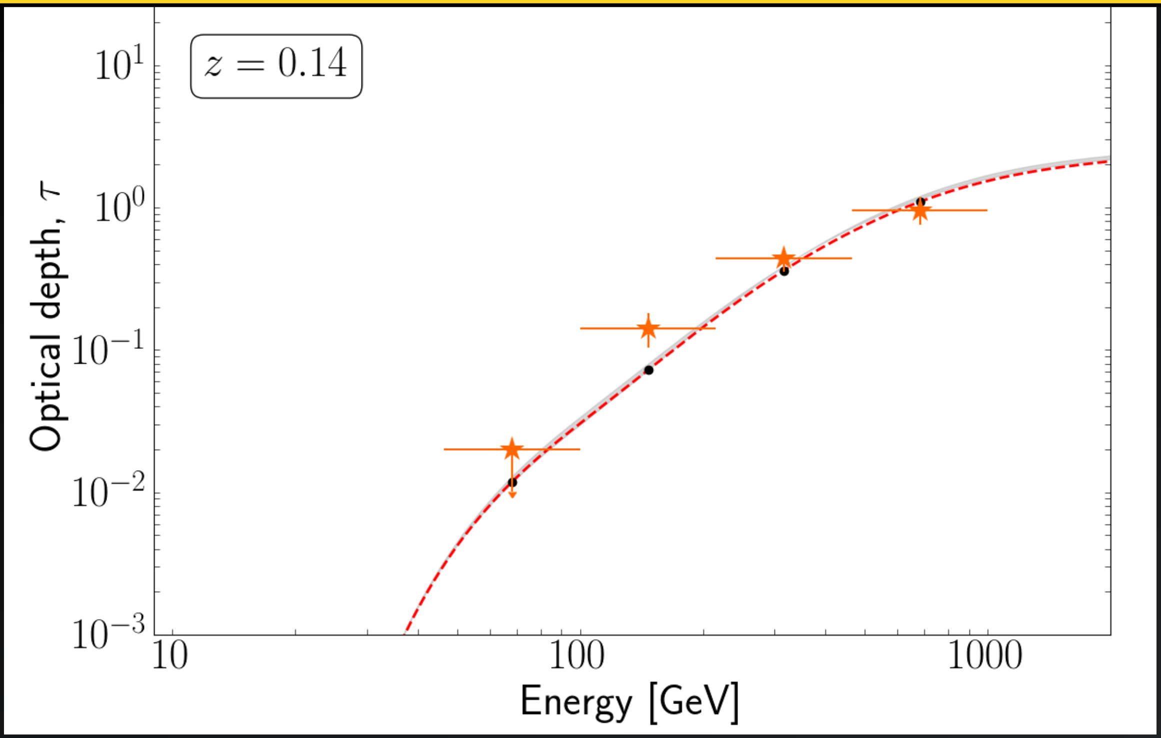




Galaxy luminosity function
rest-frame K-band, Cirasuolo+ 10

Optical depth dependence with Ω_m

For a fixed h (h=0.7), the figure shows the maximum variation of tau with Ω_m



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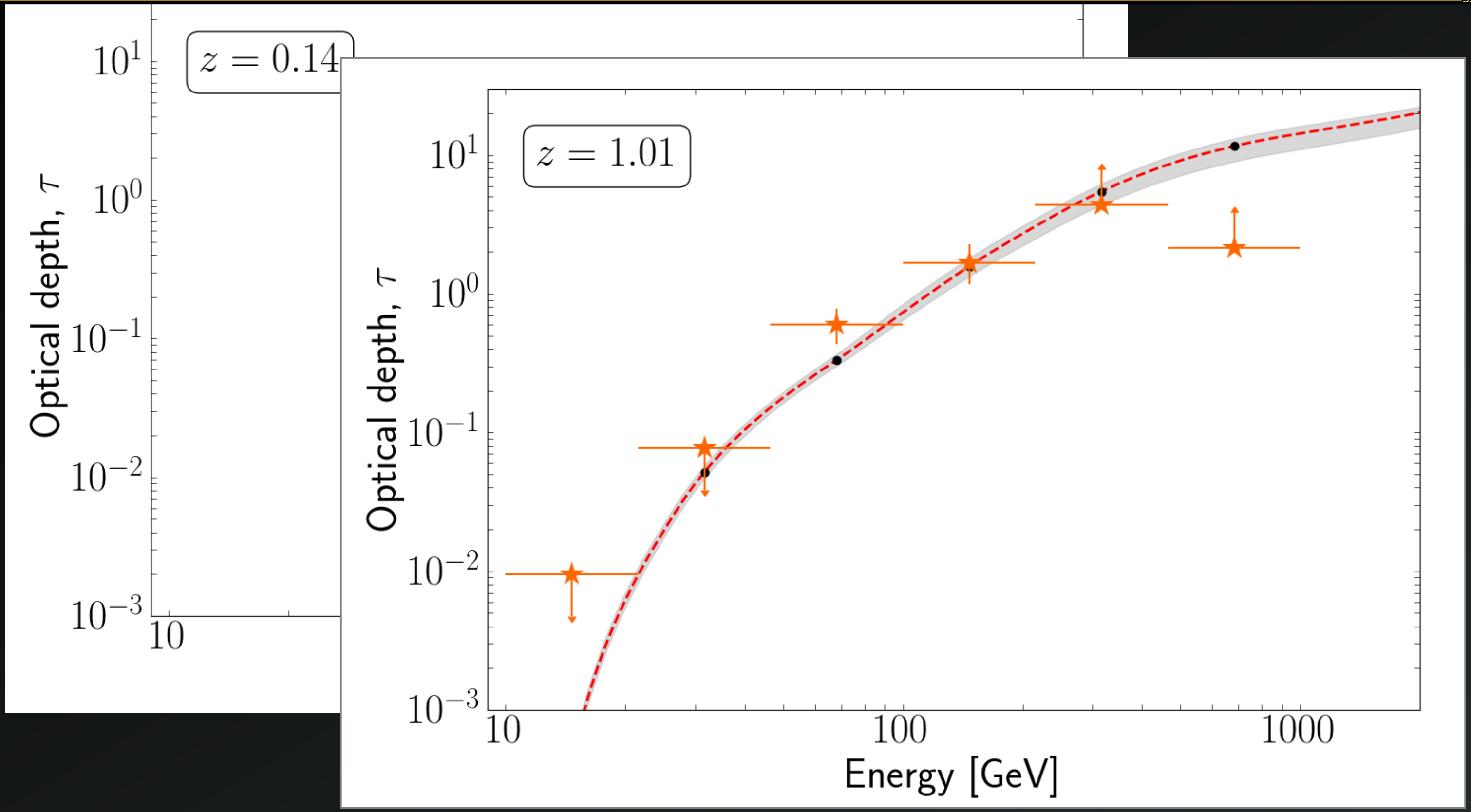

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