EBL Models and Cosmology with Gamma rays

Justin Finke
US Naval Research Laboratory

14 April 2021

Marco Ajello (Clemson U), Alberto Dominguez (U Madrid), Dieter Hartmann (Clemson U), Abhishek Desai (U of Wisconsin), Lea Marcotulli (Clemson U), Vadehi Paliya (DESY), Alberto Saldana-Lopez (Observatoire de Genève)

Extragalactic Background Light

EBL photons extinguish extragalactic gamma rays.

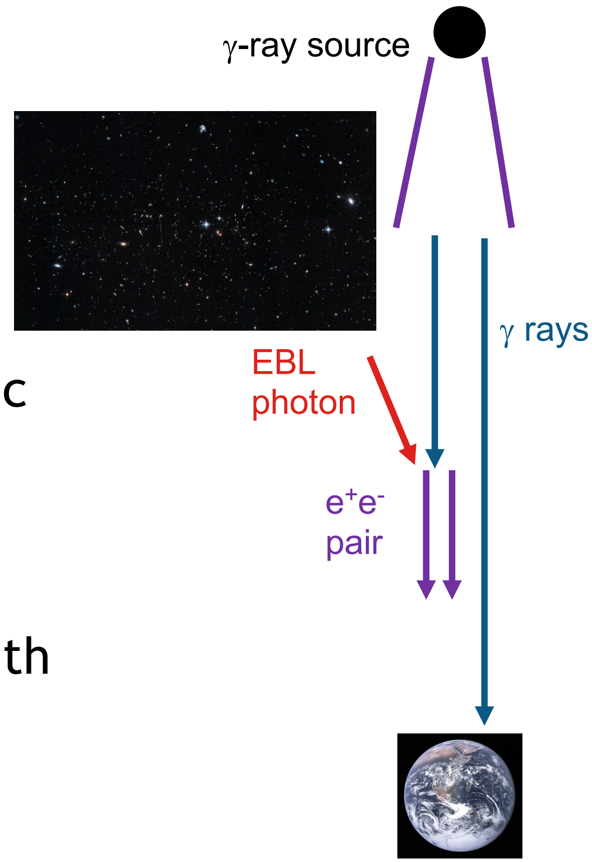
$$\gamma_{EBL} + \gamma_{\gamma\text{-ray}} \rightarrow e^- + e^+$$

Knowledge of the absorption effects due to EBL is necessary to infer the intrinsic spectra of extragalactic gamma-ray sources.

- Gamma rays we see are attenuated by:
  - $F_{obs} = F_{int} \exp[- \tau_{\gamma\gamma}(E, z)]$.

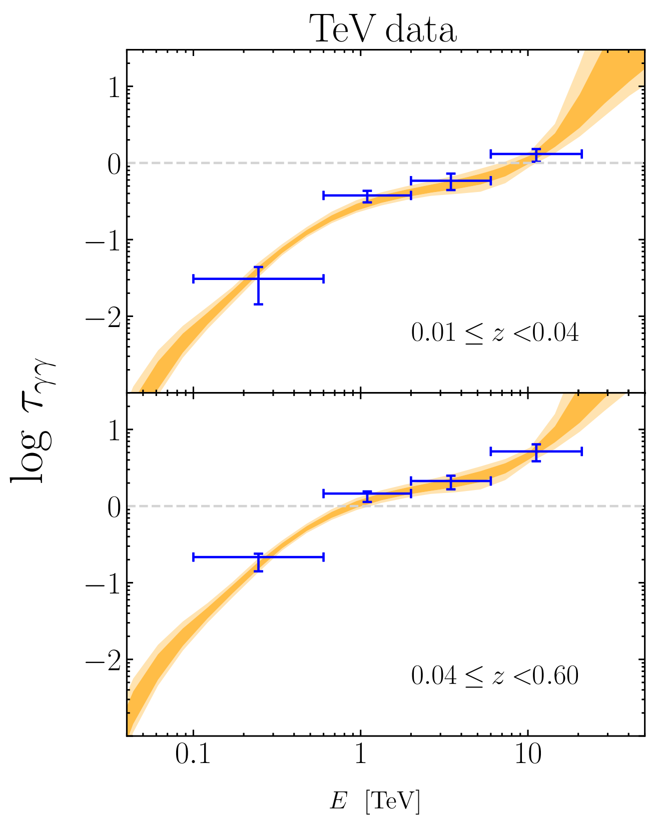
We measure/constrain the EBL absorption, $\tau_{\gamma\gamma}(E,z)$ with blazars!

Process important above 10 GeV

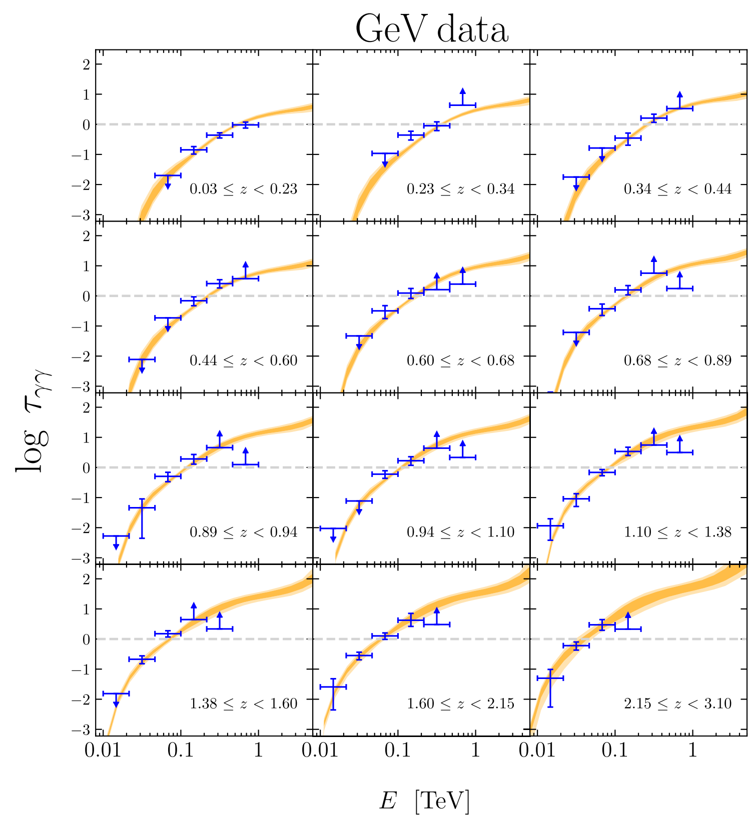


U.S. NAVAL RESEARCH LABORATORY

γ-ray absorption measurements



Desai et al. (2019) 106 VHE spectra, 38 blazars
IACTs



Abdollahi et al. (2018) 739 blazars
Fermi LAT

EBL Model

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

Initial Mass Function

dust extinction

expansion of universe

star formation rate

Stellar evolution

JF, Razzaque, Dermer (2010)
Razzaque, Dermer, JF (2009)

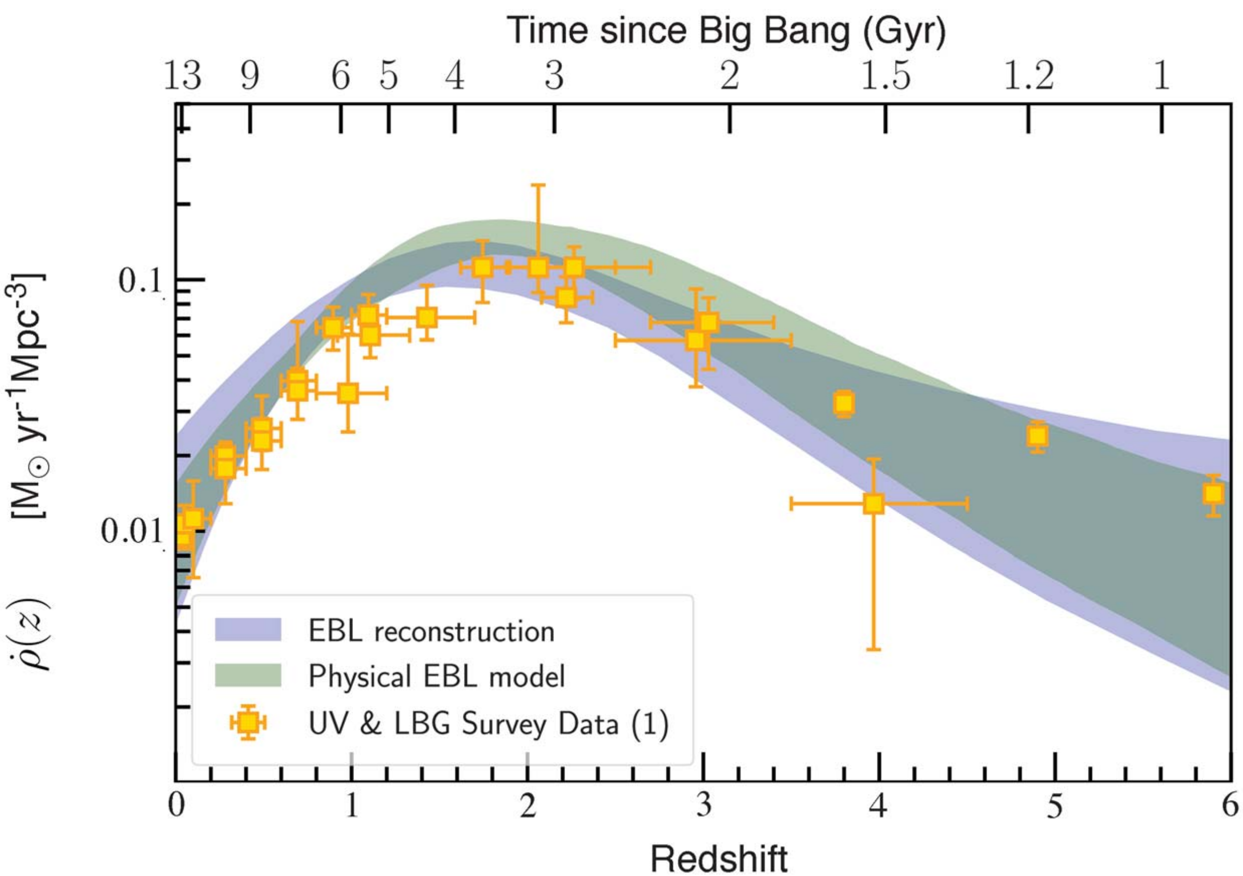
Assume absorbed LD re-radiated in the IR as three dust components, gives dust contribution to LD.

$$\epsilon_p\ u_{EBL,p}(\epsilon_p; z) = (1+z)^4 \int_z^{z_{max}} dz_1 \frac{\epsilon' j(\epsilon'; z_1)}{(1+z_1)} \left|\frac{dt_*}{dz_1}\right|$$

Compute absorption optical depth

$$\tau_{\gamma\gamma}(\epsilon_1, z_s) = \frac{c\pi r_e^2}{\epsilon_1^2 m_e c^2} \int_0^{z_s} \frac{dz'}{(1+z')^2} \left|\frac{dt_*}{dz'}\right|$$
$$\times \int_{\frac{1}{\epsilon_1(1+z')}}^{\infty} d\epsilon_p \frac{\epsilon_p u_{EBL,p}(\epsilon_p; z')}{\epsilon_p^4}\ \bar{\phi}(\epsilon_p \epsilon_1 (1+z'))$$

Star Formation Rate Measurement



Abdollahi et al. (2018)

Updates

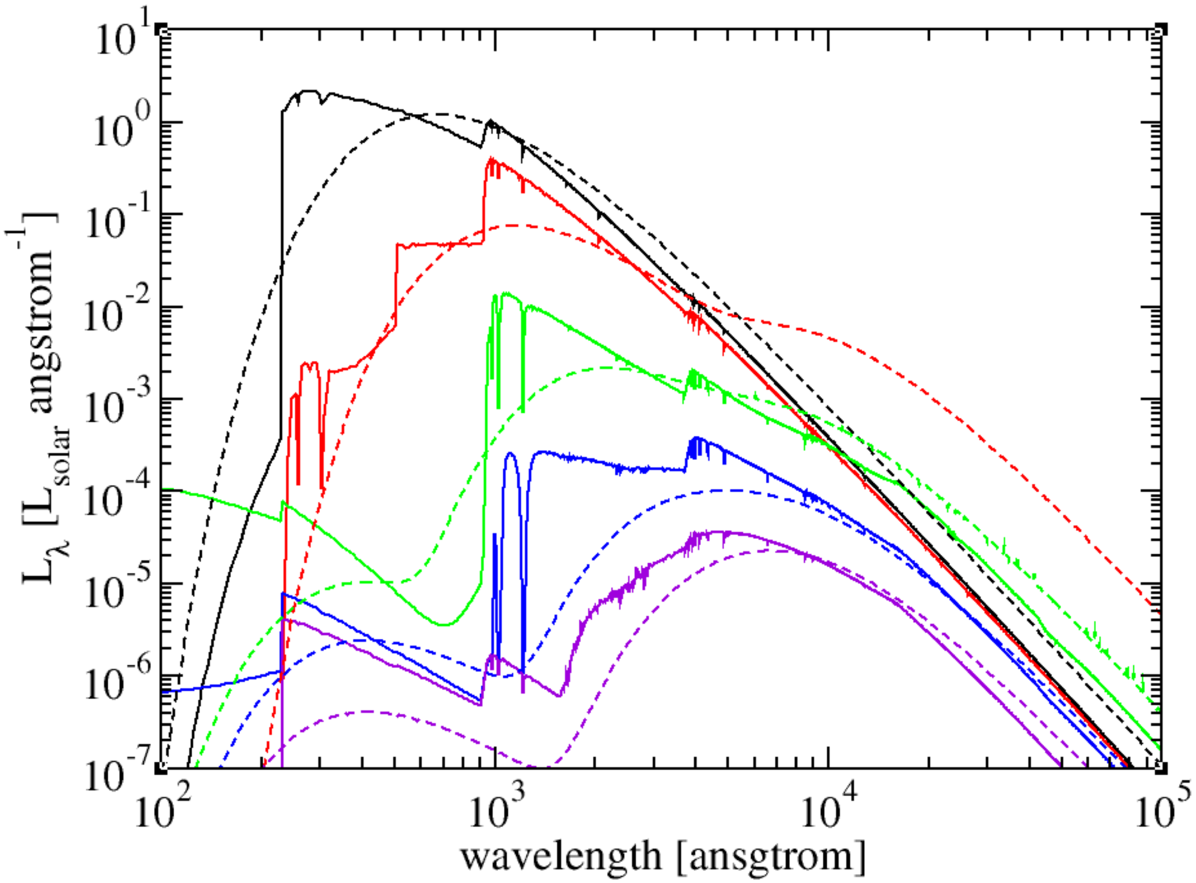
Updates from previous model (JF, Razzaque, Dermer 2010; Razzaque, Dermer, JF 2009):

- Use PEGASE simple stellar population models
- Emission dependent on age of stellar population and metallicity
- Tracks evolution of metallicity and mass density in the universe

$$\frac{d\bar{Z}}{dz} = \frac{y_{tot}(\bar{Z})[1 - R(\bar{Z})]}{\rho_b - \rho(z)} \psi(z) \left| \frac{dt}{dz} \right|$$
$$\frac{d\rho}{dz} = (1 - R(\bar{Z}))\psi(z) \left| \frac{dt}{dz} \right| \ ,$$

- Evolution of dust extinction with redshift
- Fits to gamma-ray opacity data and other data

Stellar Models

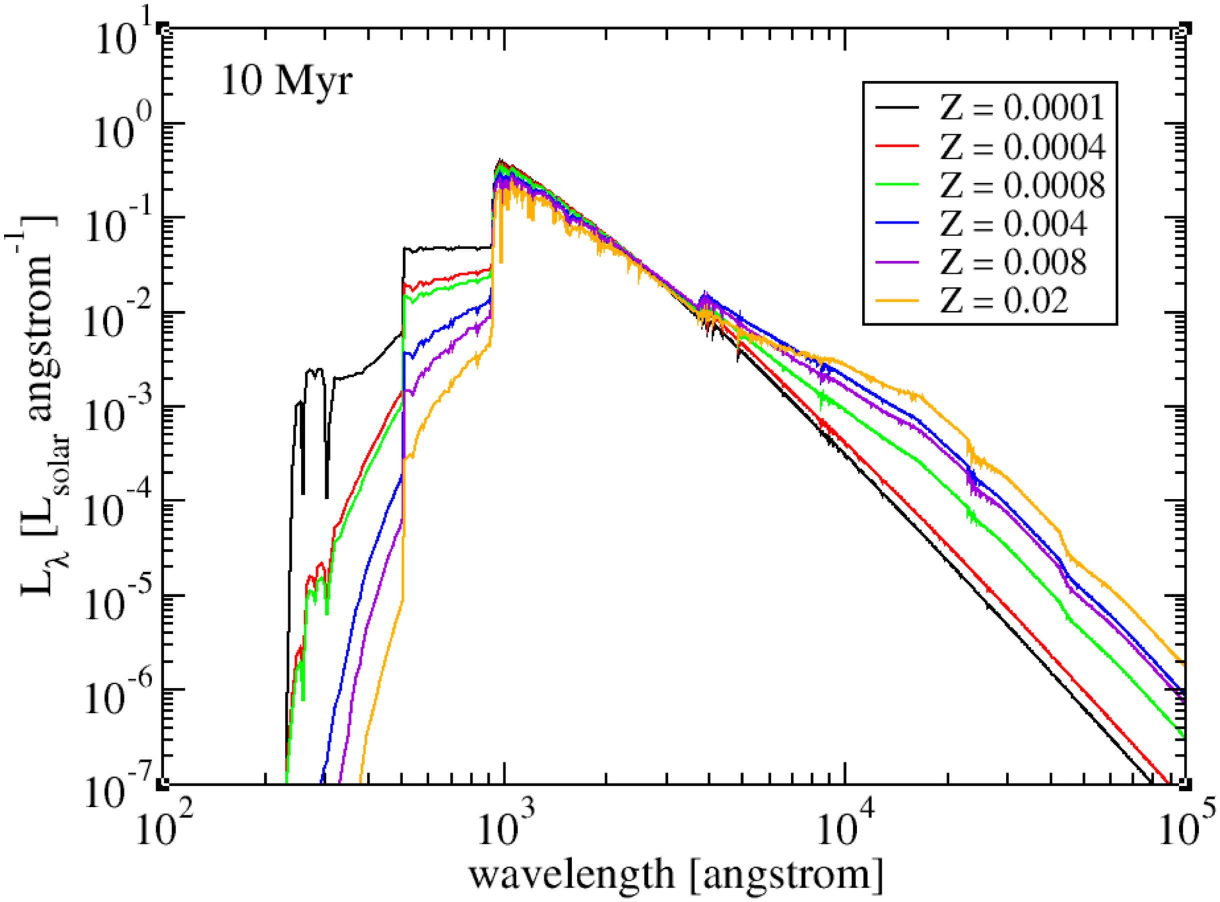


Solid: PEGASE model

Dashed: previous, blackbody stars

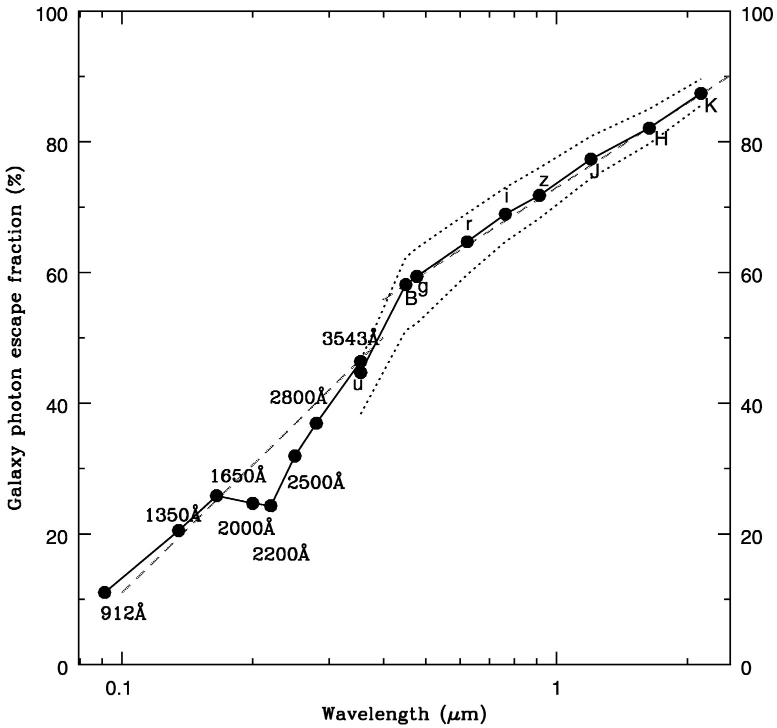
Uses Baldry-Glazebrook IMF (exploration of other IMFs saved for later)

Stellar Models

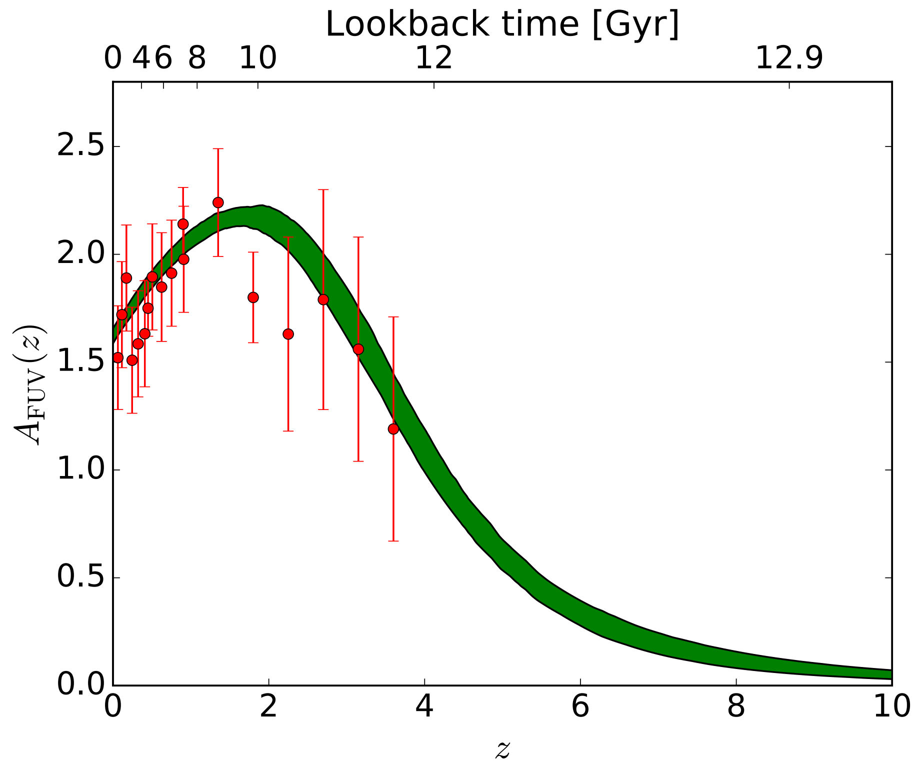


Different metallicities

Dust Extinction



Driver et al. (2008) curve used in JF+ 2010 model.



Normalization (0.15 μm) varies with z:

$$A(z) = a_d \frac{(1+z)^{b_d}}{1+[(1+z)/c_d]^{d_d}}$$

Model Free Parameters

SFR parameterization from Madau & Dickinson (2014):

$$\psi_{\rm MD}(z) = a_s \frac{(1+z)^{b_s}}{1+[(1+z)/c_s]^{d_s}}$$

Dust extinction normalization:

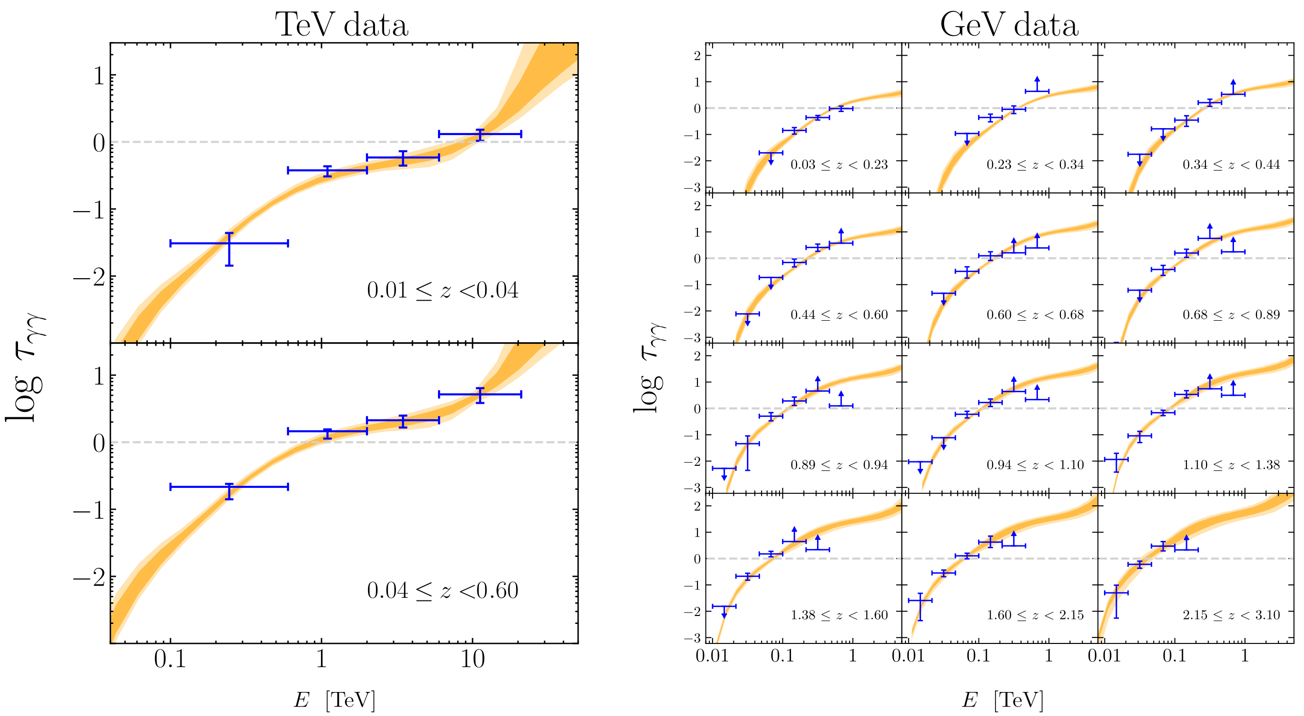
$$A(z) = a_d \frac{(1+z)^{b_d}}{1+[(1+z)/c_d]^{d_d}}$$

Free parameters: a_s, b_s, c_s, d_s,
also: f_1, f_2 (associated with dust; $f_3 = 1 - f_1 - f_2$), $T_{d,1}$, a_d, b_d, c_d, d_d

Fit Data

Do MCMC fit to data:

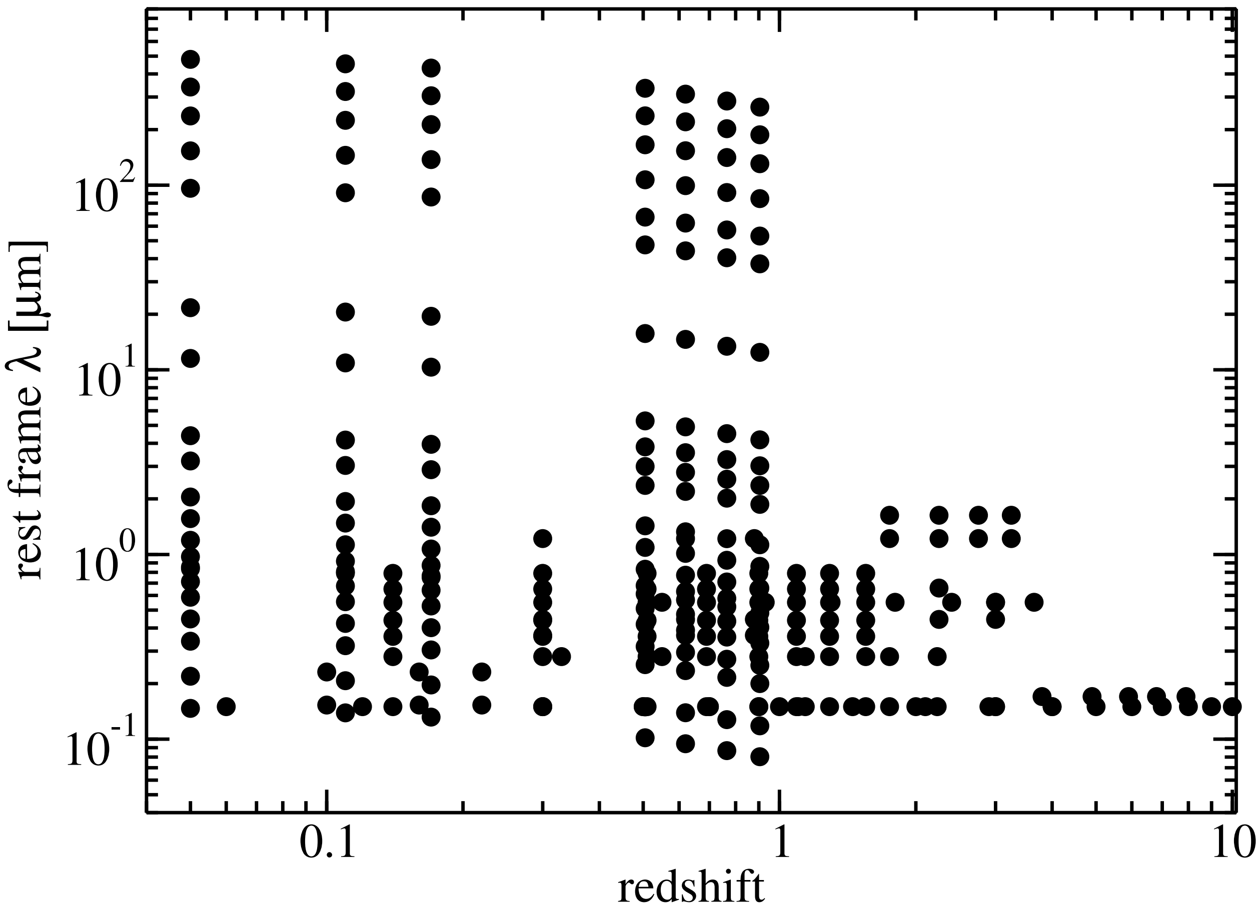
- γ-ray absorption optical depth data
  - 12 redshift bins from LAT (Abdollahi et al. 2018)
  - 1 GRB upper limit (080916C)
  - 2 redshift bins from IACTs (Desai et al. 2019)



Fit Data

Do MCMC fit to data:

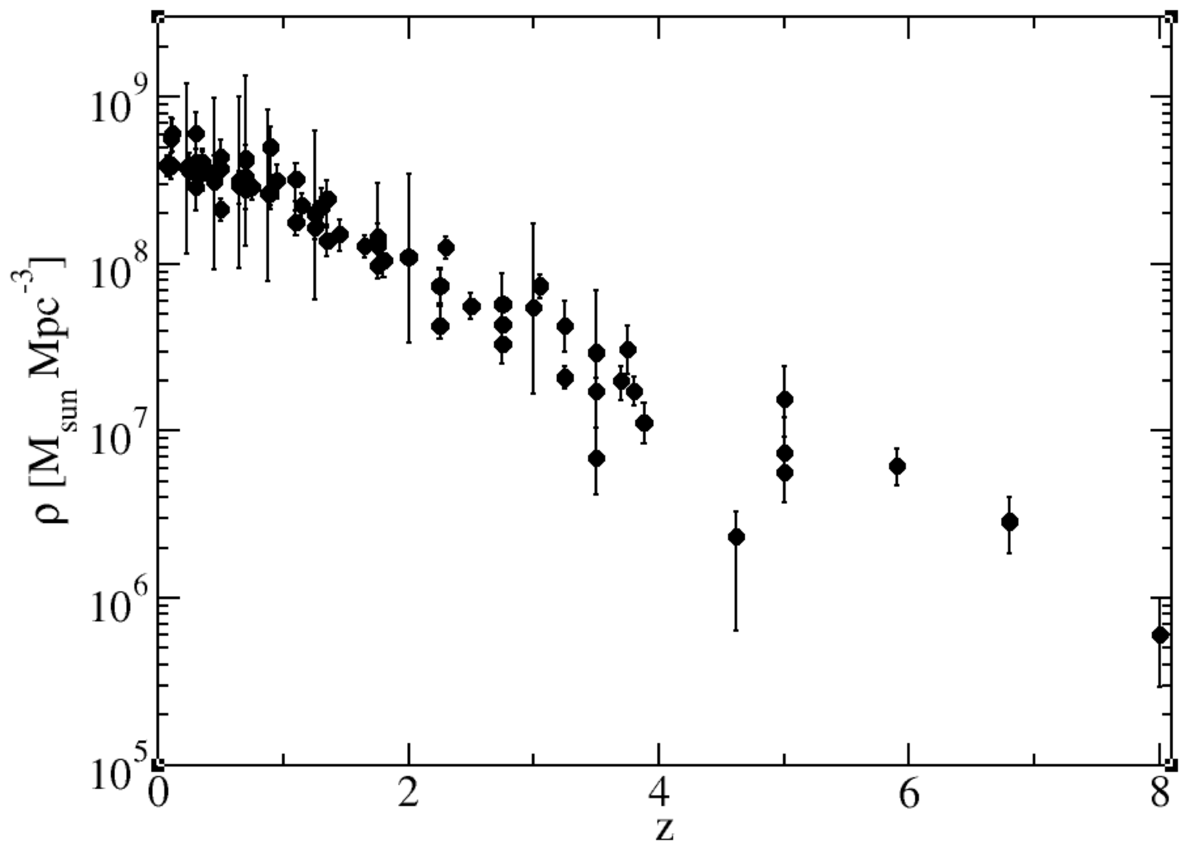
- γ-ray absorption optical depth data
  - 12 redshift bins from LAT (Abdollahi et al. 2018)
  - 1 GRB upper limit (080916C)
  - 2 redshift bins from IACTs (Desai et al. 2019)
  - luminosity density data from galaxy surveys (compilation by Scully, Stecker, Helgason, others)



Fit Data

Do MCMC fit to data:

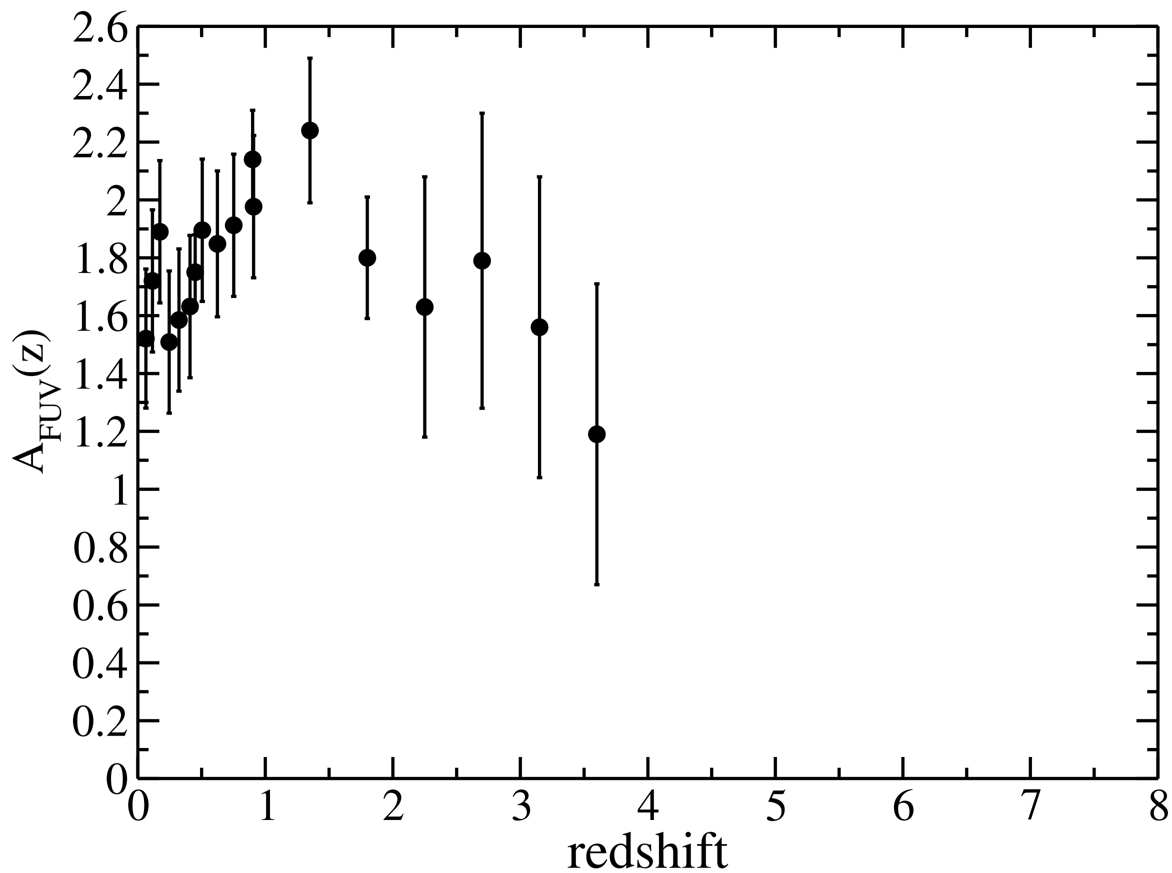
- γ-ray absorption optical depth data
  - 12 redshift bins from LAT (Abdollahi et al. 2018)
  - 1 GRB upper limit (080916C)
  - 2 redshift bins from IACTs (Desai et al. 2019)
  - luminosity density data from galaxy surveys (compilation by Scully, Stecker, Helgason, others)
  - mass density data from galaxy surveys (compilation Madau & Dickinson (2014)



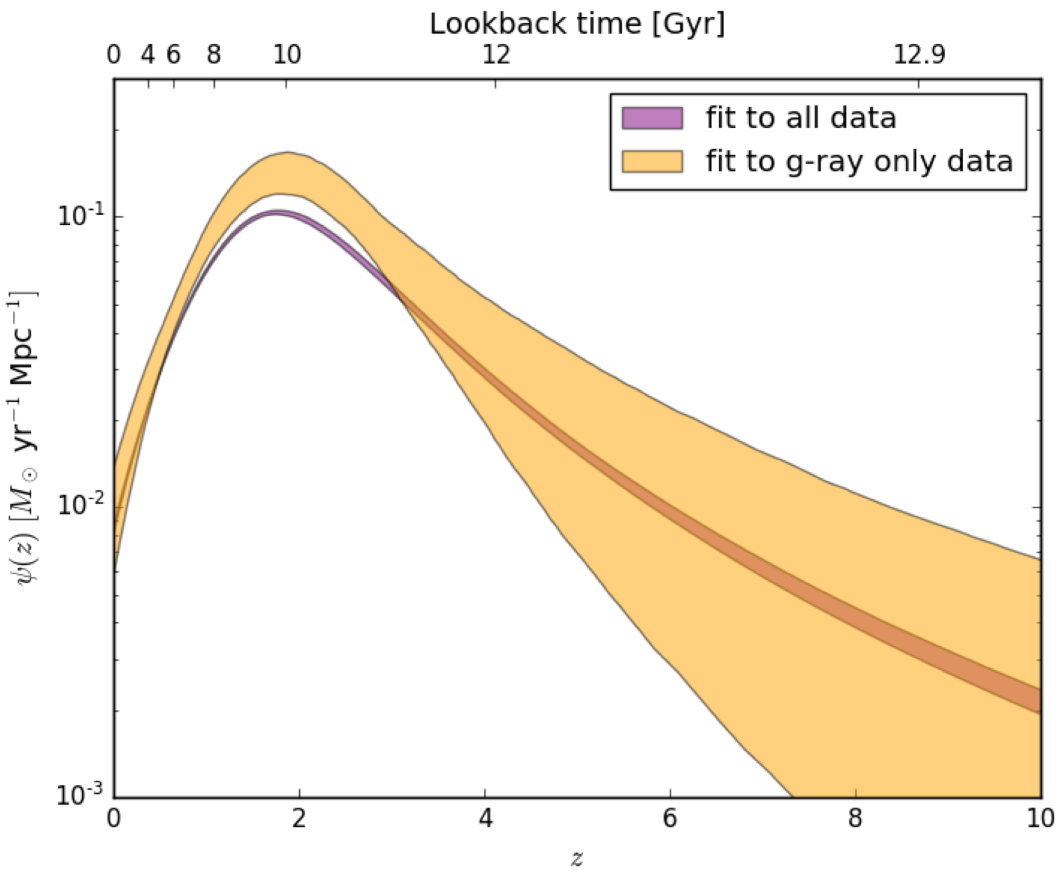
Fit Data

Do MCMC fit to data:

- γ-ray absorption optical depth data
  - 12 redshift bins from LAT (Abdollahi et al. 2018)
  - 1 GRB upper limit (080916C)
  - 2 redshift bins from IACTs (Desai et al. 2019)
  - luminosity density data from galaxy surveys (compilation by Scully, Stecker, Helgason, others)
  - FUV Dust extinction data (Cucciati et al. 2012, Burgarella et al. 2013)



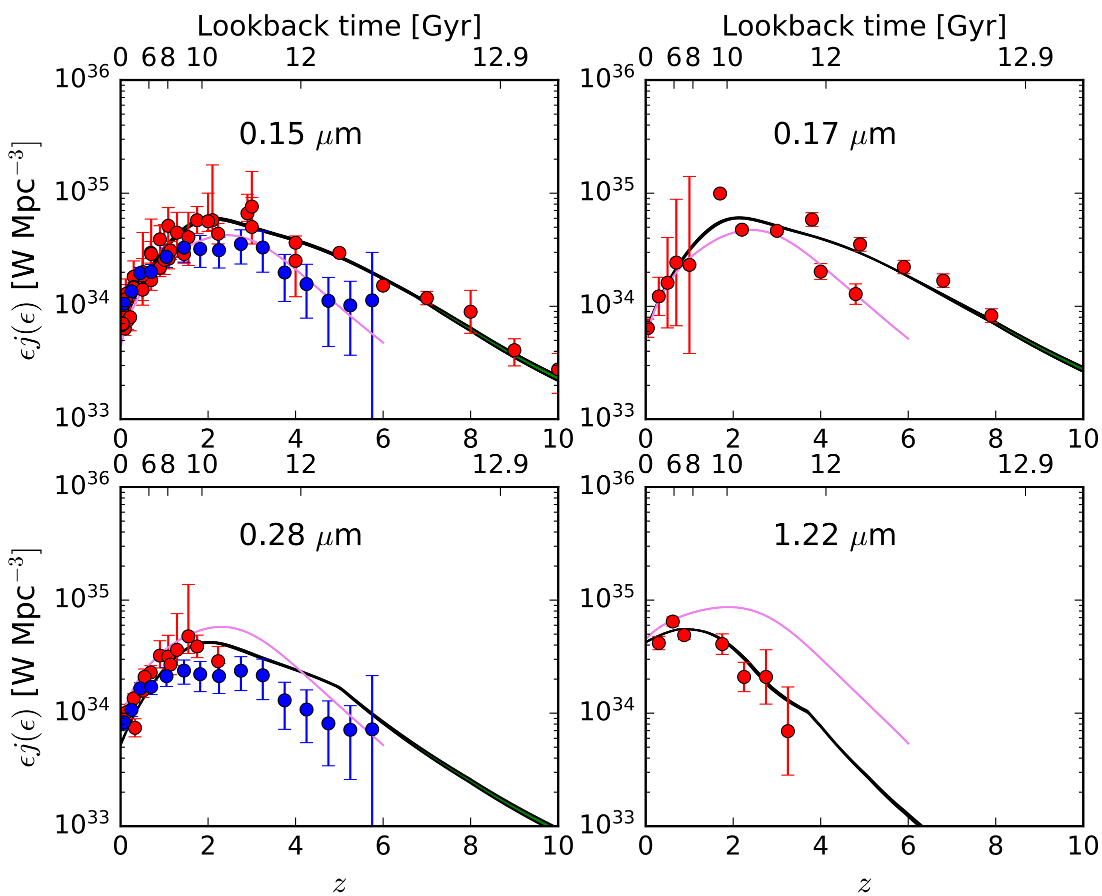
Model Results



MCMC fit to:

- Gamma-ray absorption data (similar to previously published)
- Luminosity density data
- Mass density data
- Dust Extinction data

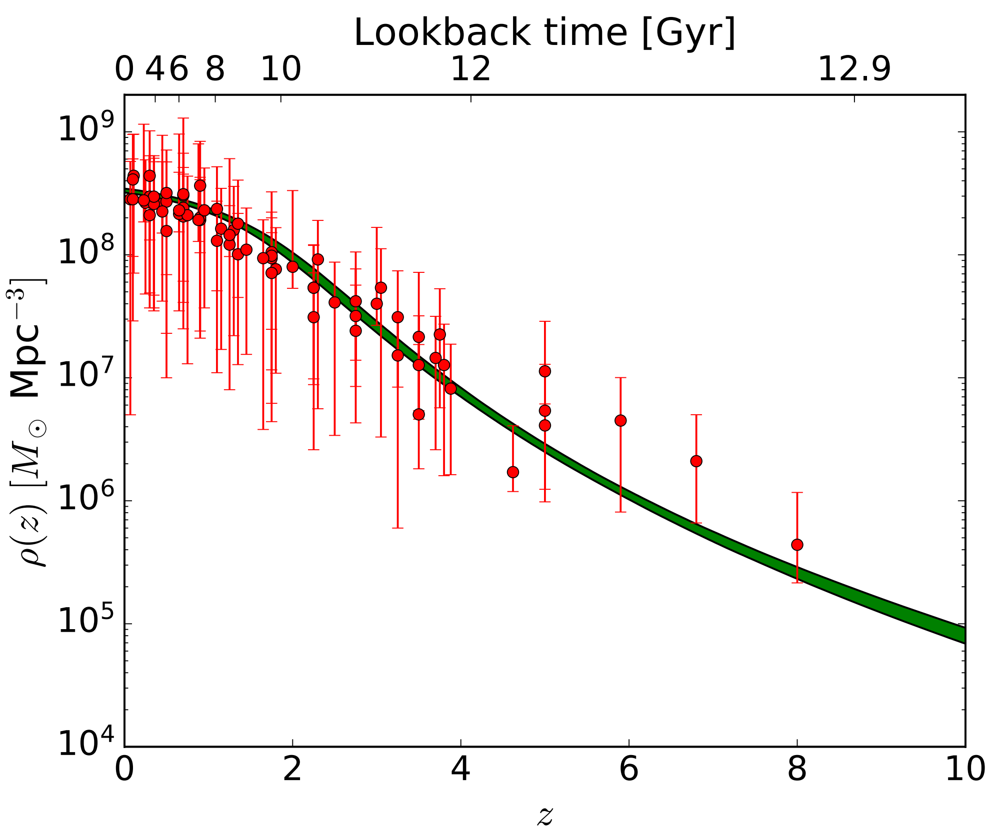
UV Luminosity Density Results



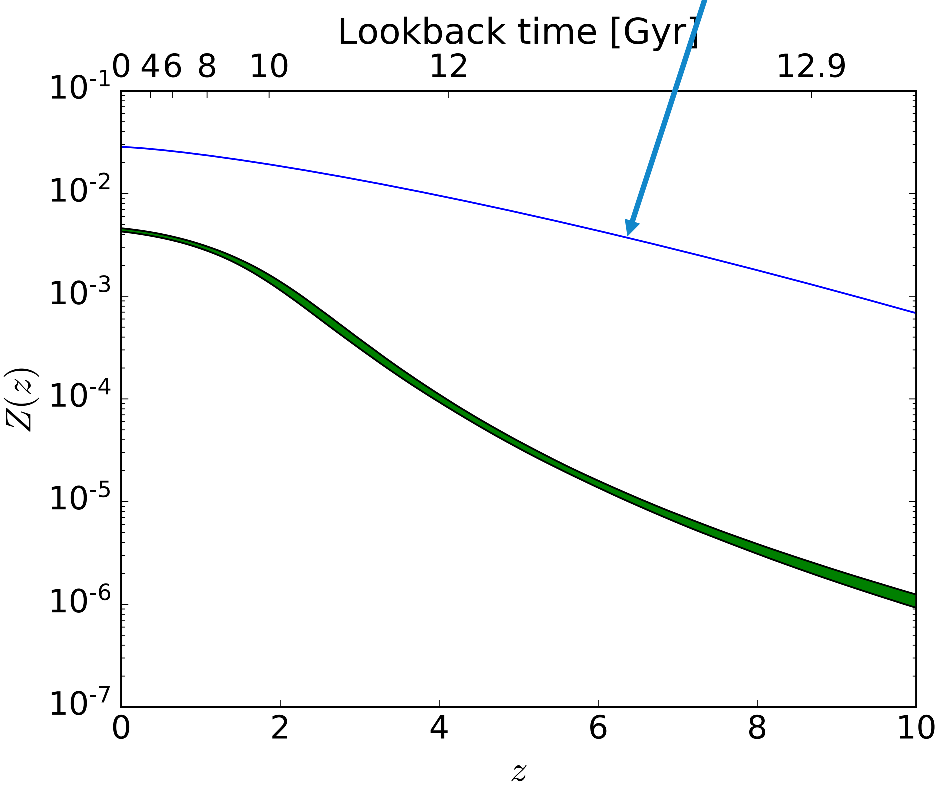
Violet curves: old (2010) model
Dark curves: new model

red points: most used in fit
blue points: Saldana-Lopez et al. (2021)

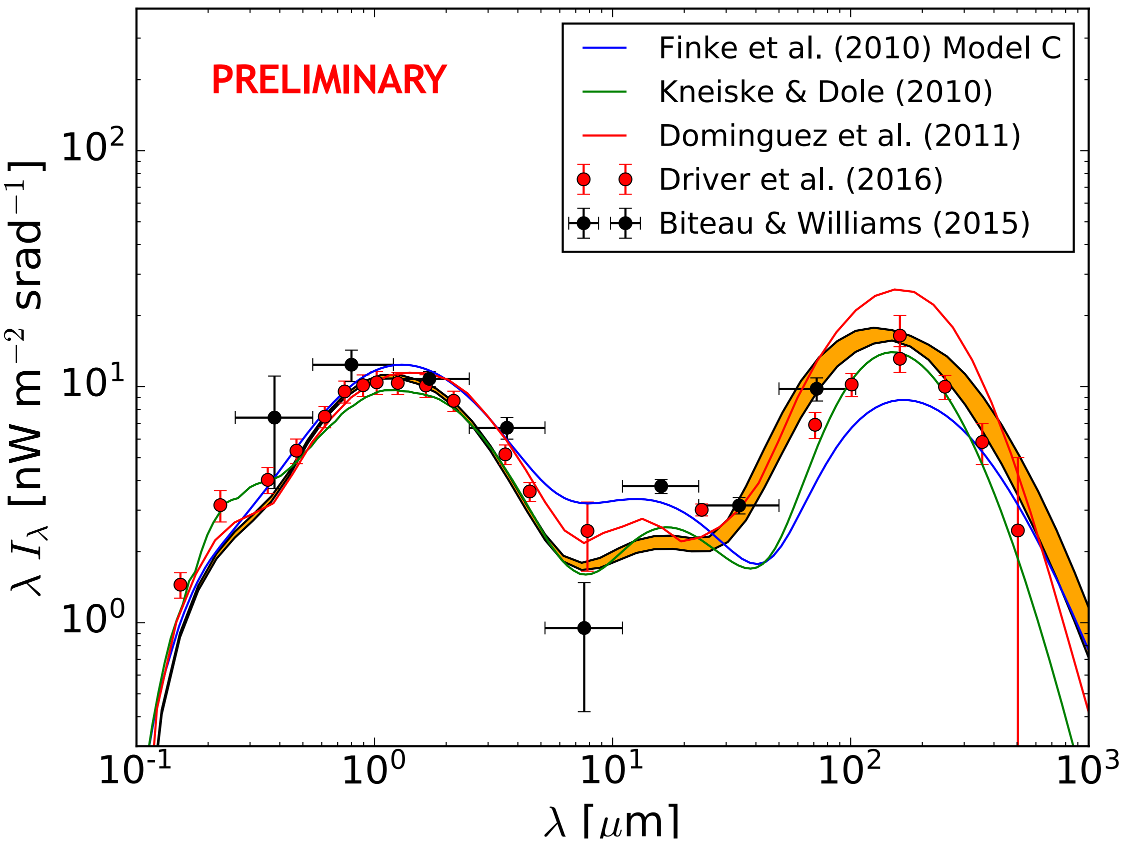
Mass Density and Metallicity



Madau & Fragos (2017)

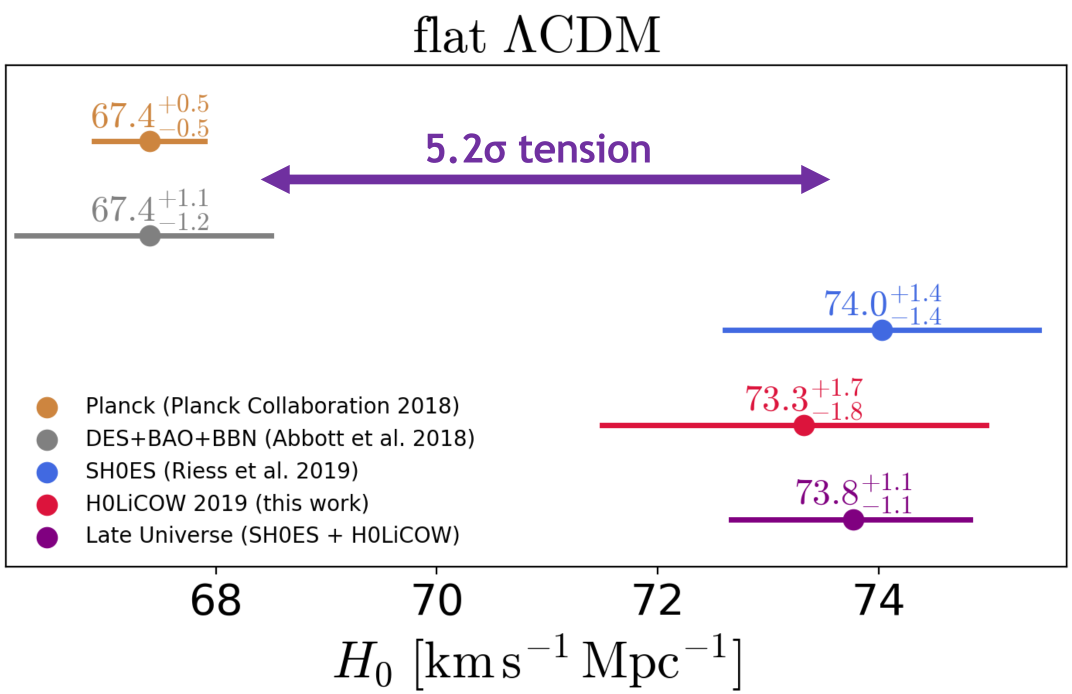


EBL intensity



Latest model is a bit below lower limits

Cosmological parameters



Wong et al. (2020)

Statistically significant tension between “early” and “late” universe measures of H_0.

Cosmological parameters

Two ways of measuring related quantities. One depends on cosmological parameters, one does not!

luminosity density measurements
Galaxy surveys
Depend on cosmological parameters

↔

Gamma ray absorption of EBL
Fermi Telescope
Does ***NOT*** depend on cosmological parameters

Allows measurements of cosmological parameters!

U.S. NAVAL RESEARCH LABORATORY

Cosmological parameters

Fit luminosity density with simple empirical model:

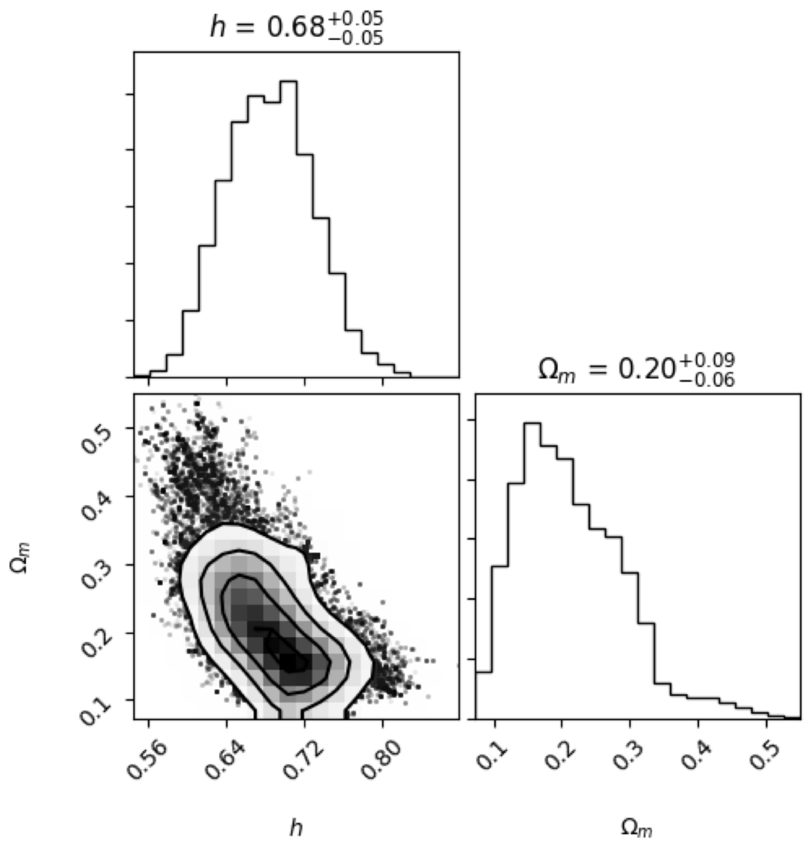
$$j(\lambda_i, z) = \sum_i a_i \cdot \exp\left[-\frac{(\log\lambda - \log\lambda_i)^2}{2\sigma^2}\right] \times \frac{(1+z)^{b_i}}{1+\left(\frac{1+z}{c_i}\right)^{d_i}}.$$

From this, compute EBL, γ-ray absorption opacity

Do MCMC fit to luminosity density and γ-ray absorption data

Free parameters: H_0, Ω_m, [a_i, b_i, c_i, d_i, i =1..4]

Cosmological parameters

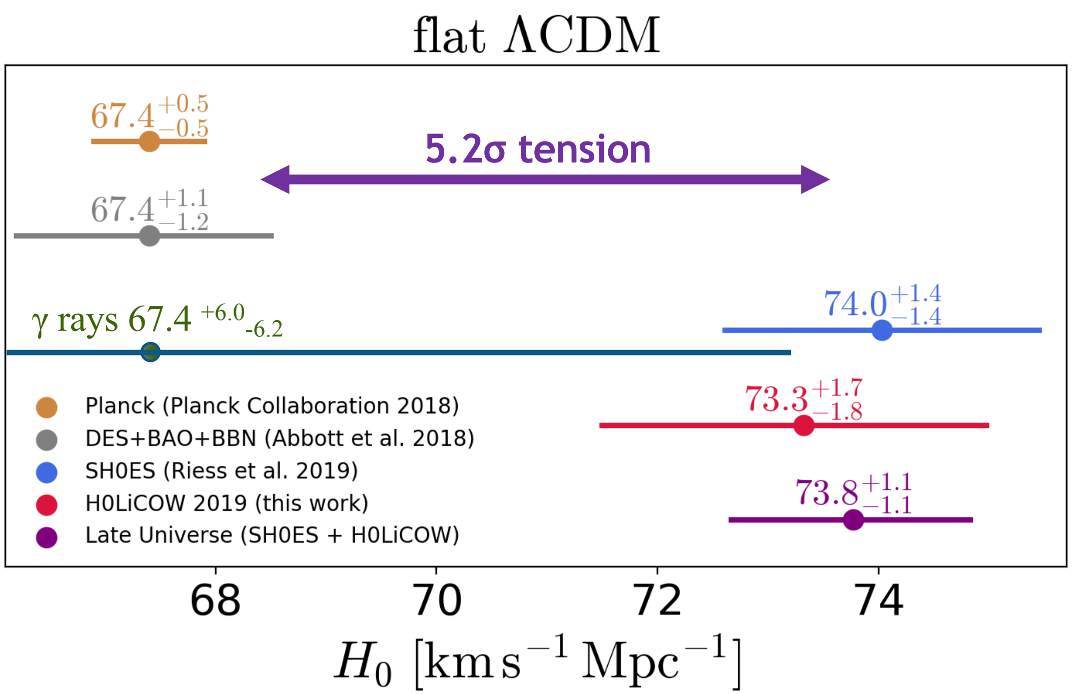


Methodology	H_0 [km s^{-1} Mpc^{-1}]	Ω_m
Gamma-ray Attenuation	$65.8^{+3.1}_{-3.0}$	0.32 (fixed)
Gamma-ray Attenuation	68 (fixed)	$0.17^{+0.07}_{-0.08}$
Gamma-ray Attenuation	$67.4^{+6.0}_{-6.2}$	$0.14^{+0.06}_{-0.07}$
Joint Likelihood Analysis	66.6 ± 1.6	0.29 ± 0.02

Dominguez et al. (2019)

Completely independent of other methods for measuring cosmological parameters!

Hubble "tension"



Wong et al. (2020)

EBL γ-ray absorption is a "late universe" measure.

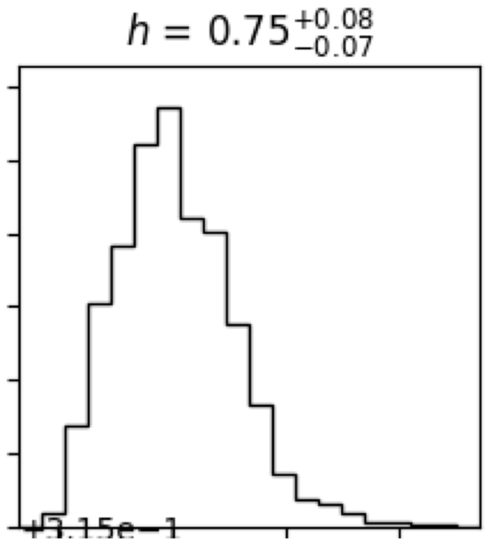
But H_0 result is closer to "early" universe measure (although errors are large and consistent with both)

Also interesting…our measure extends to higher *z* (earlier in time) than any other "late" universe measure

Cosmological parameters

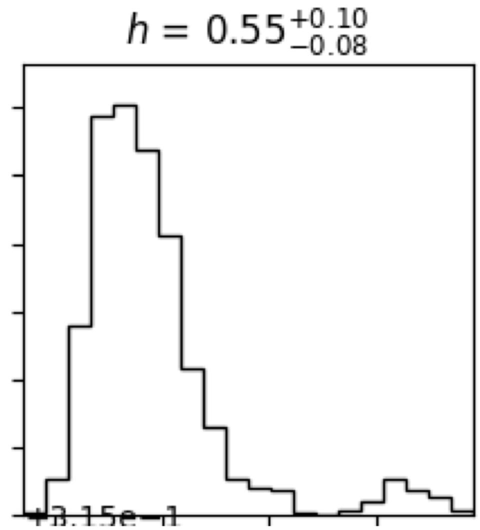
$\Omega_m = 0.315$
(Planck Collab. 2018)

z<1.4



PRELIMINARY

z>1.4



EBL result depends on redshift cut!
Errors are large though; 1.6σ tension

U.S. NAVAL RESEARCH LABORATORY

Summary

- Updated previous 2010 model to include more realistic stellar spectra, metallicity and mass density evolution.
- Did fit with model with SFR and dust parameters free to vary.
- SFR, mass density, metallicity, and dust extinction as function of redshift constrained
- Possible to use gamma-ray absorption to constrain cosmological parameters (Dominguez et al. 2019)

Acknowledgements

JDF is supported by NASA under contract S-15633Y and the Fermi GI program.

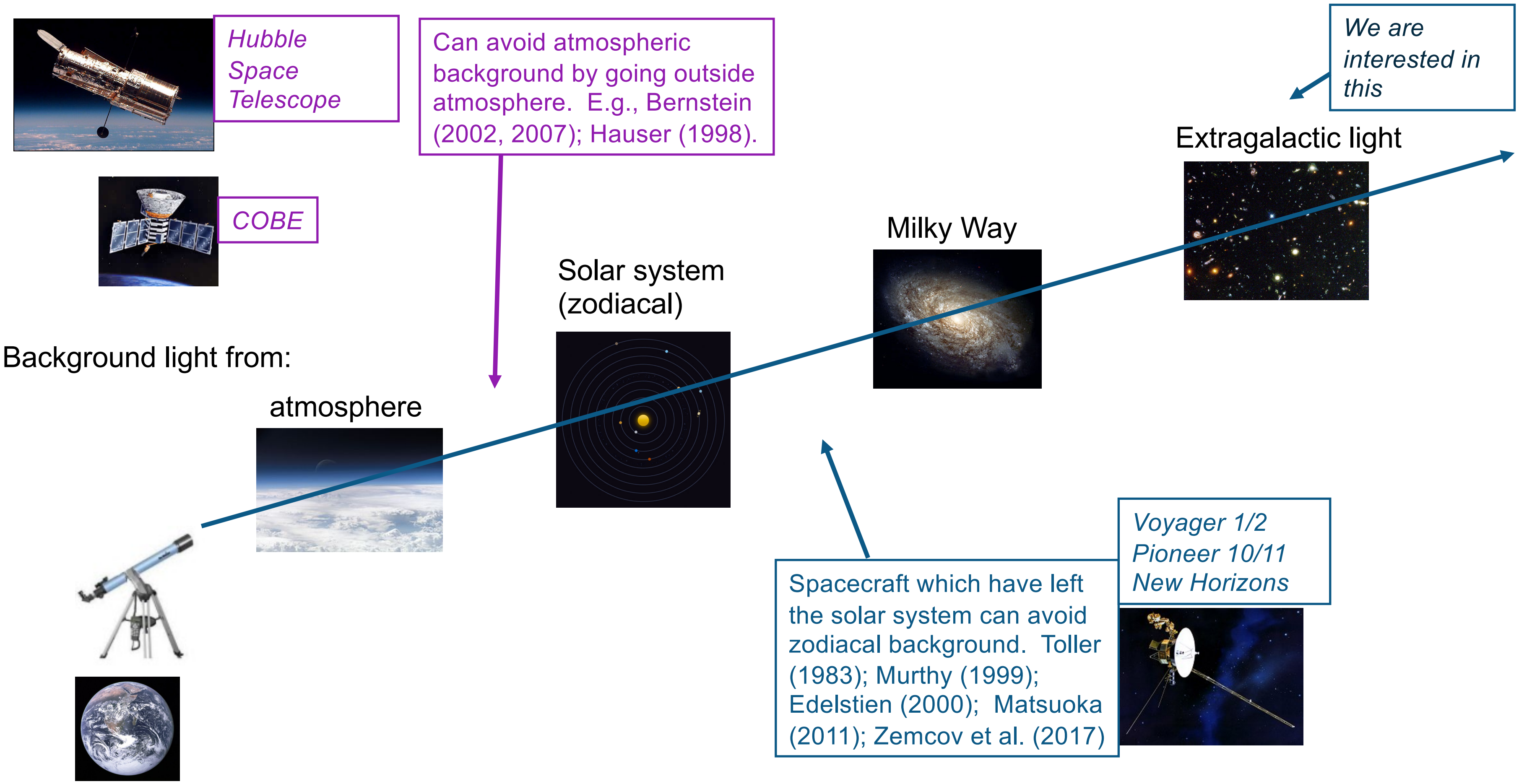
Extras

U.S. NAVAL RESEARCH LABORATORY

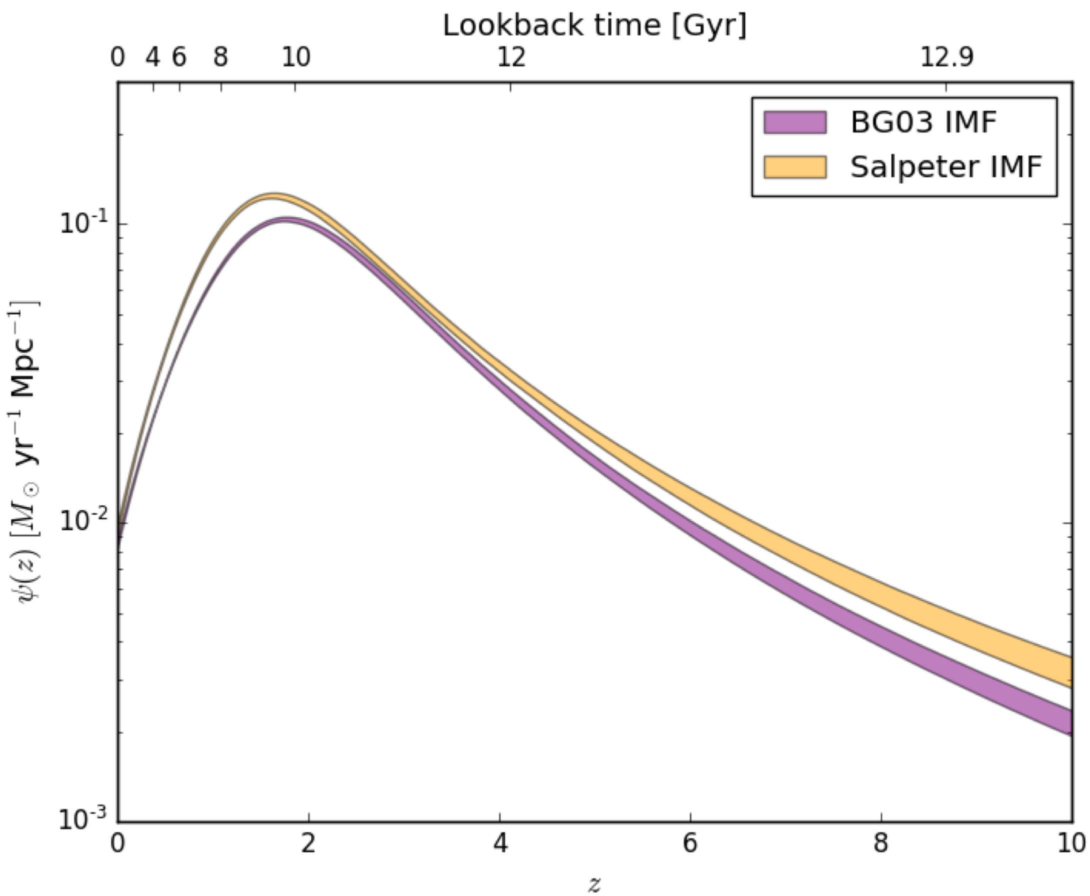
Population III stars

- Uses Schaerer (2002) model for $m > 5$
- PEGASE model for $m < 5$

U.S. NAVAL RESEARCH LABORATORY



Model Results



Results are dependent on IMF