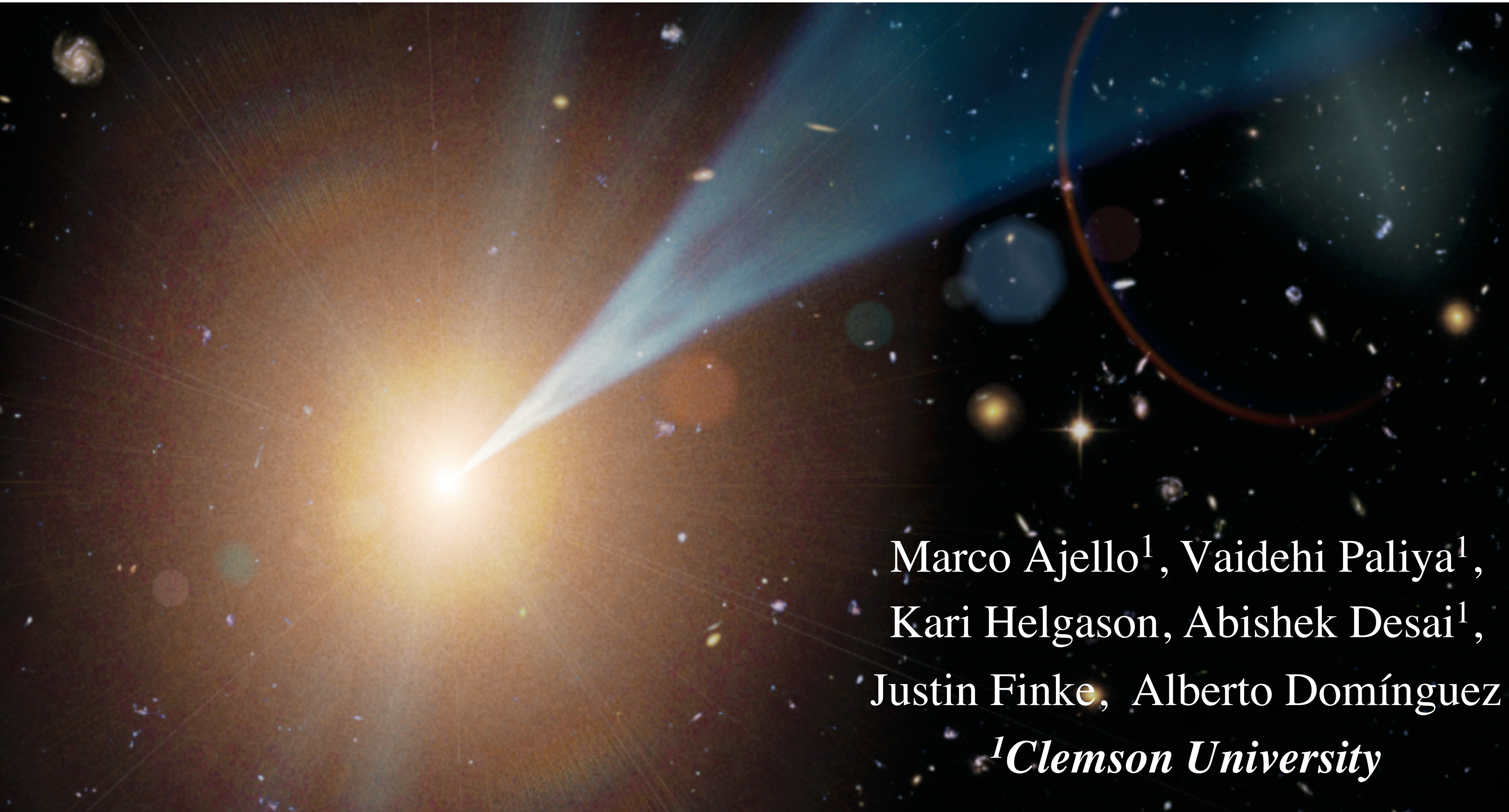
The Extragalactic Background Light in the *Fermi*-LAT Era



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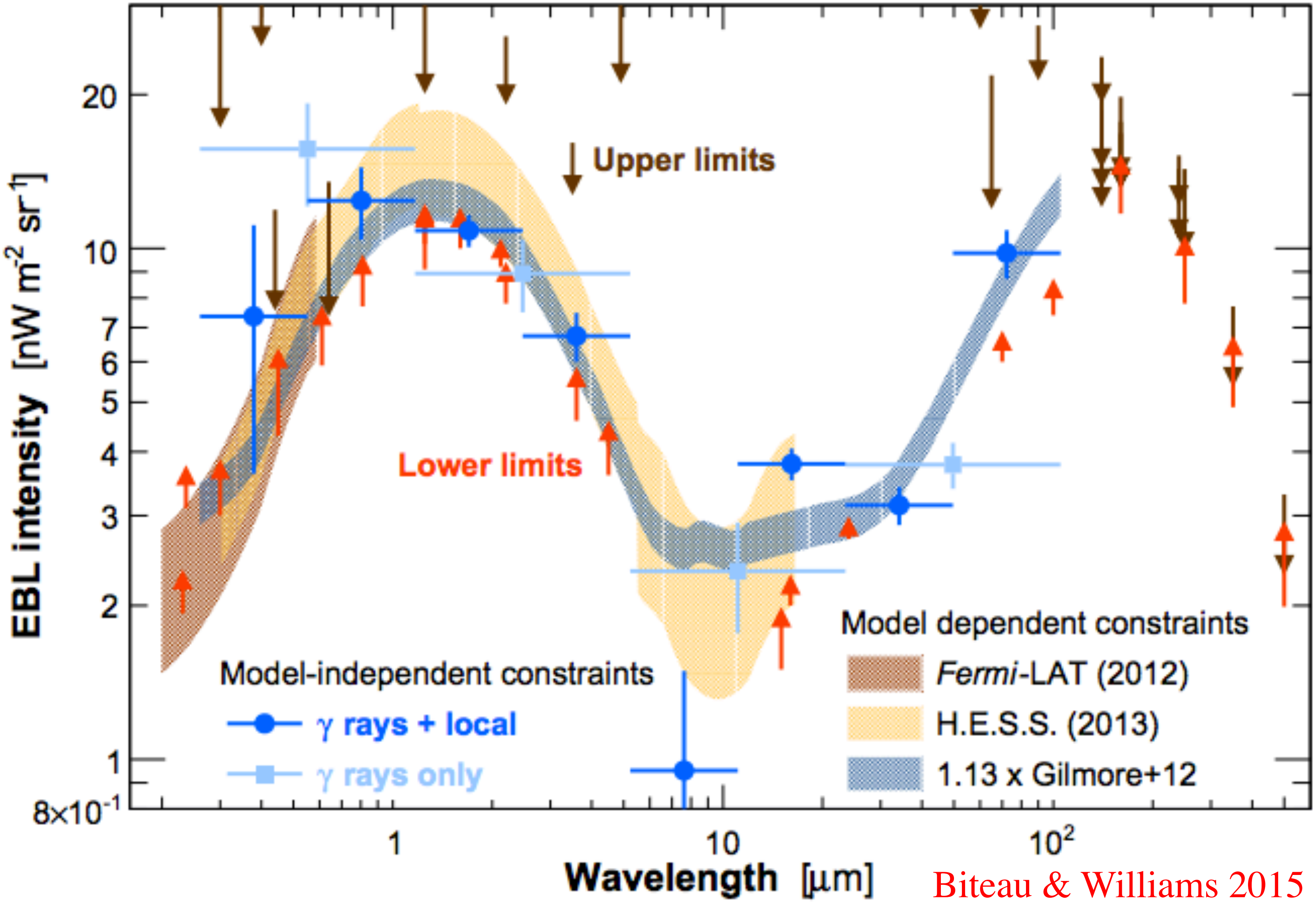
[1]Clemson University

on behalf of the LAT Collaboration

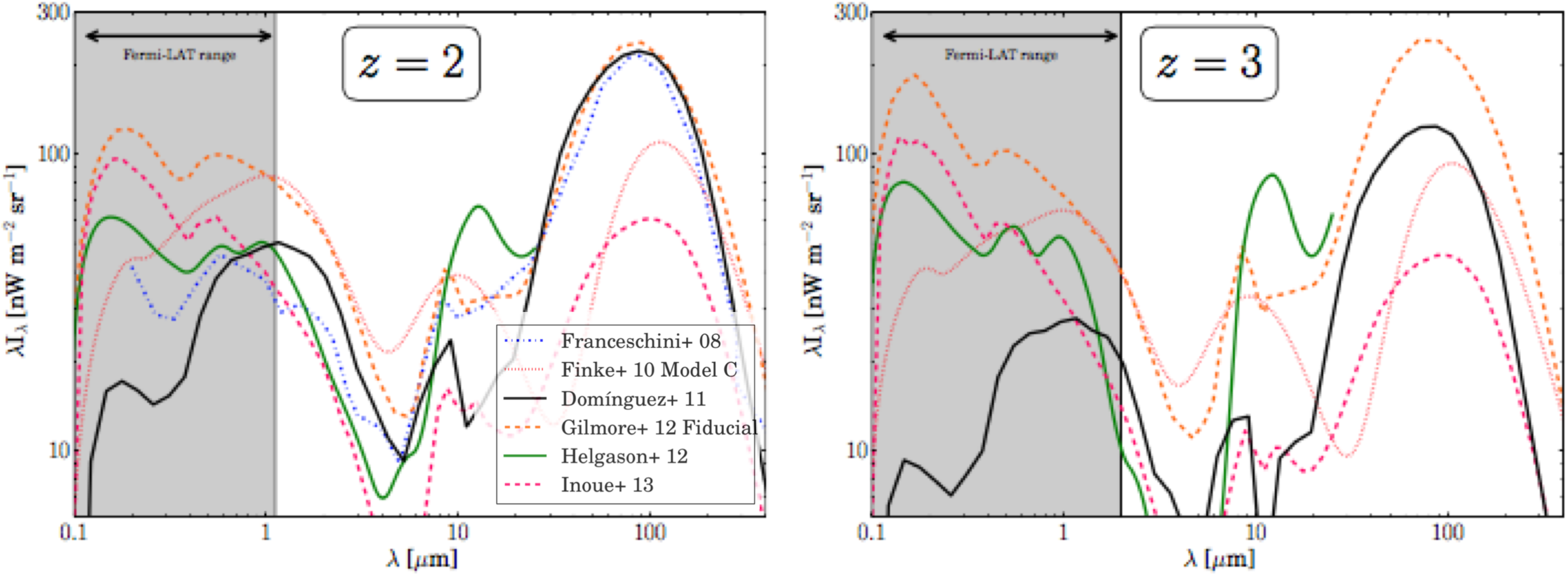
Abdollahi+18, Science, accepted

EBL Measurements



Biteau & Williams 2015

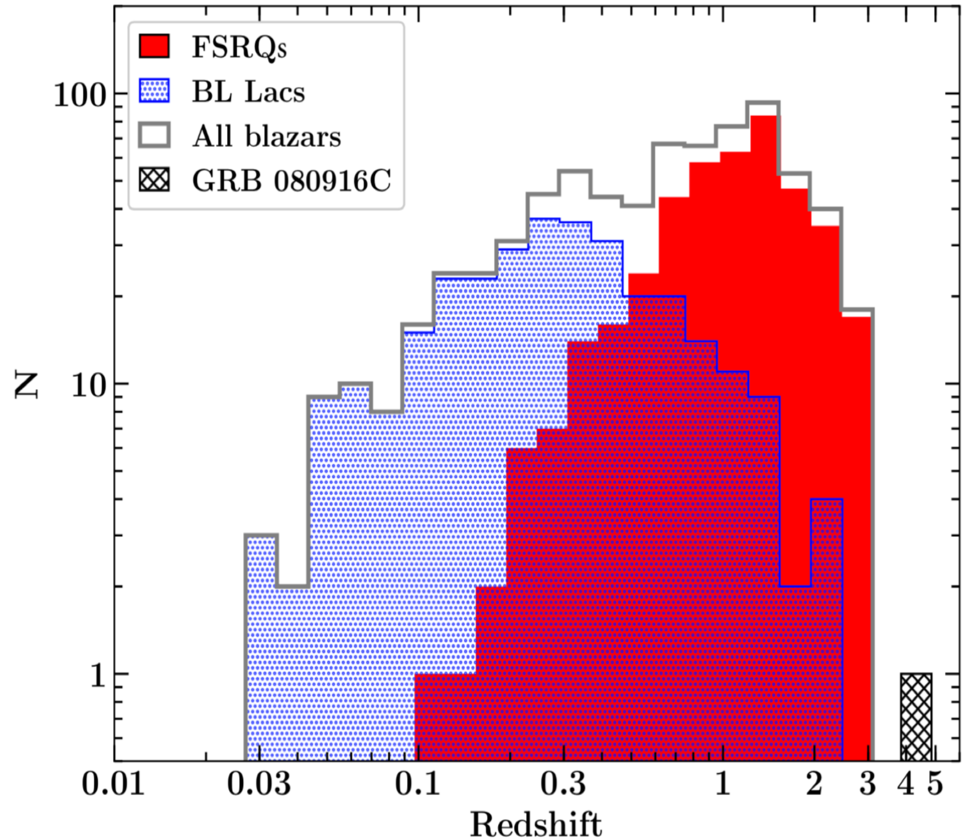
Reality Check



1. *Build up of the EBL largely undetermined*
2. *Build up fundamental to determine galaxy/stellar evolution processes*

This work

- Use 9 years of P8 LAT data
- 739 blazars + 1 GRB
- Measure intrinsic spectrum (τ<0.1)
  and extrapolate
- Perform a time-resolved analysis
- Analysis optimized on simulations

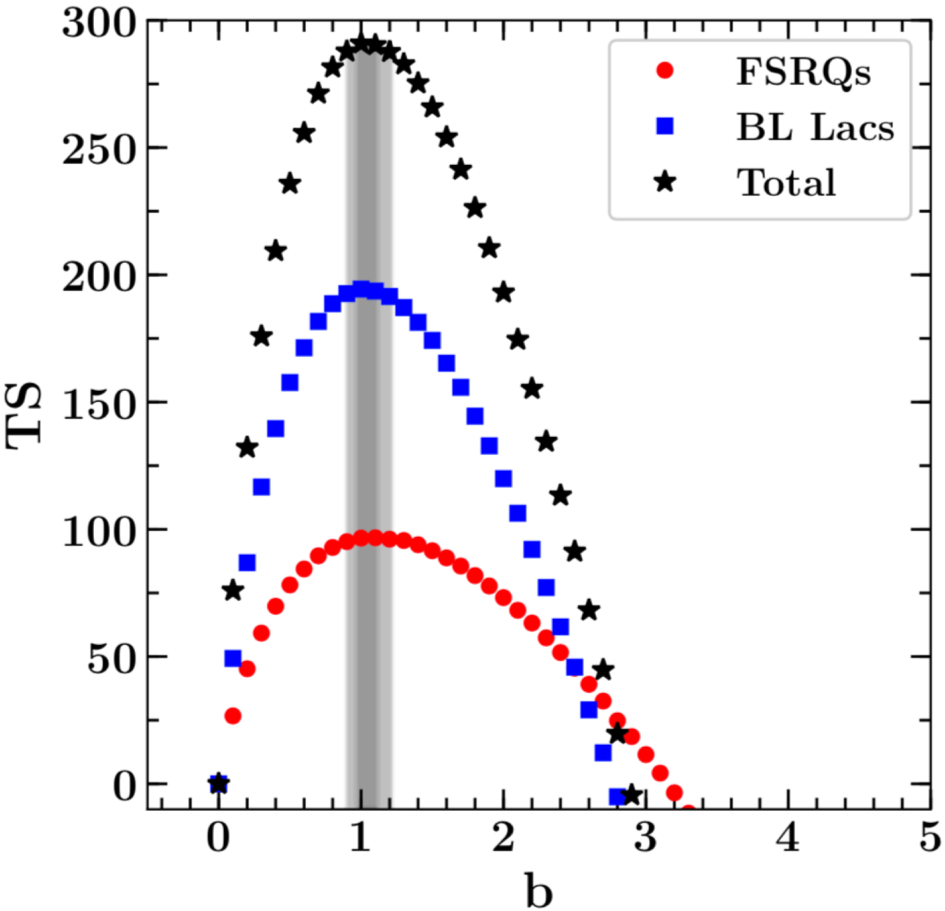


Analysis improved over the Ackermann+12 results

EBL Detection

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\mathrm{obs}} = \left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\mathrm{int}} \times \mathrm{e}^{-b\cdot\tau_{\gamma\gamma}(E,z)}$$

- **Uncertainty on the level of EBL ~7% (1σ)**

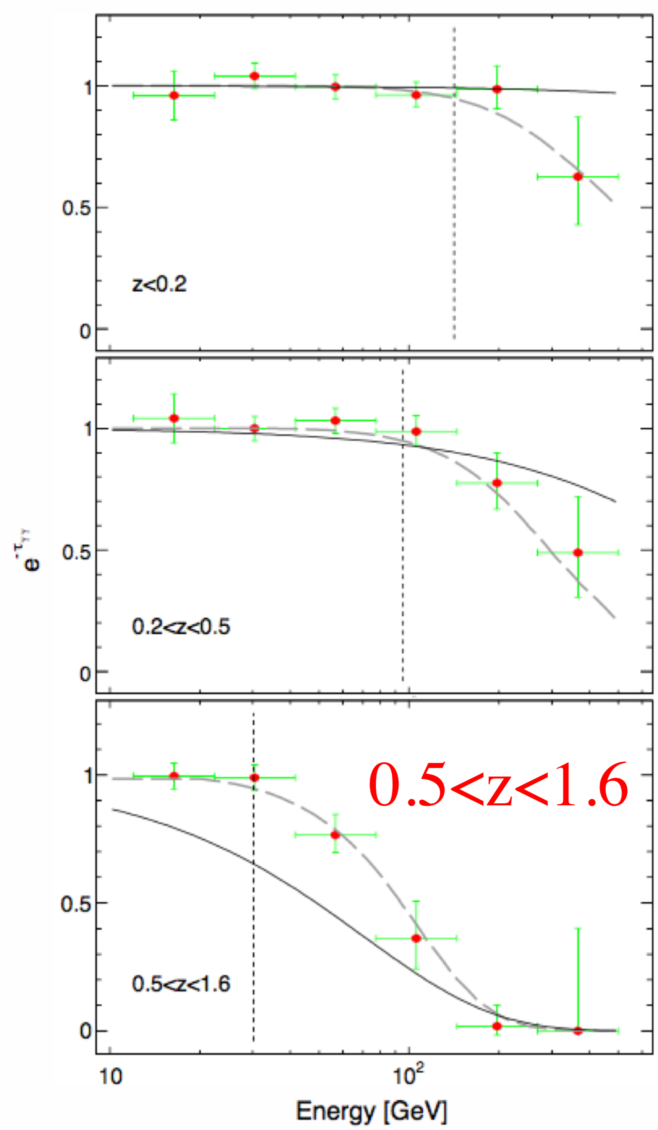


- **In 2012:**
  - **Uncertainty was ~25%**

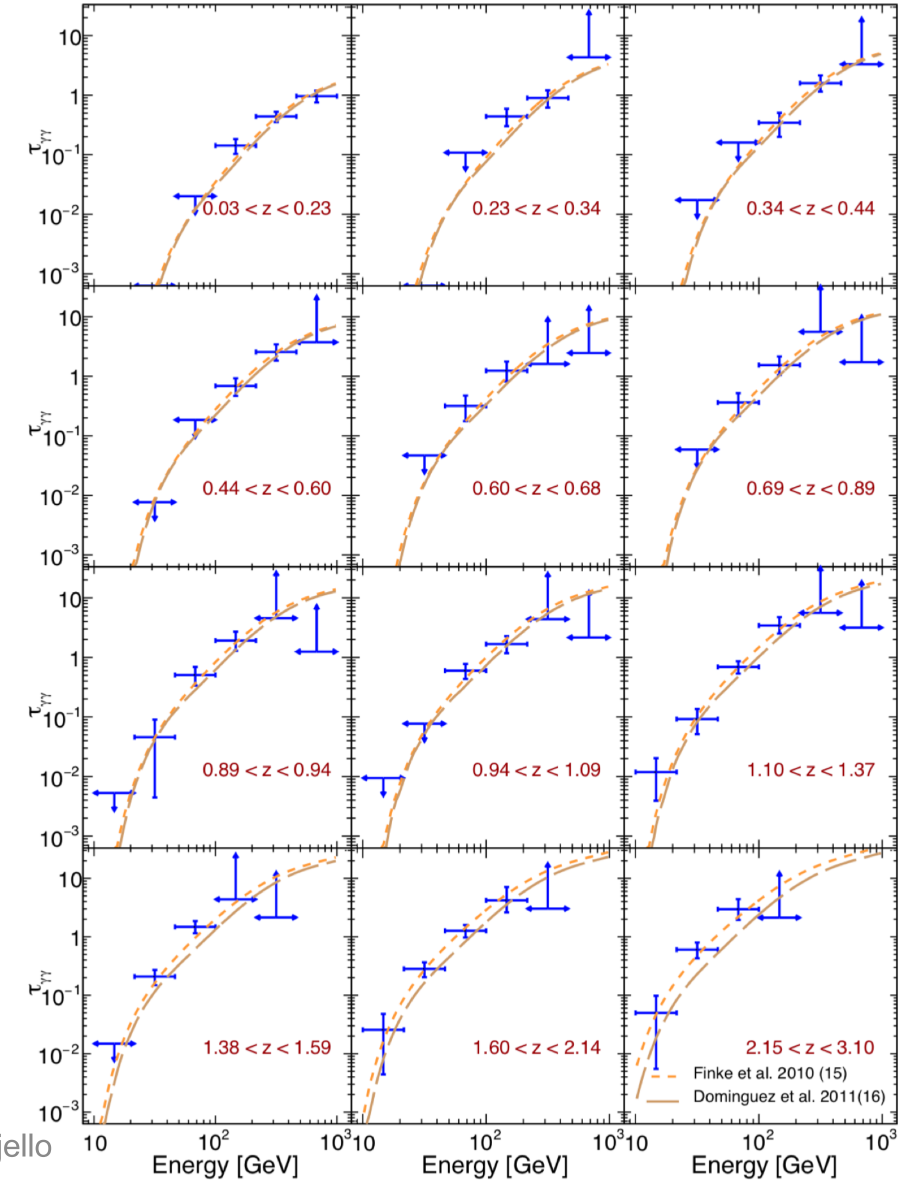
Notice the consistency between BL Lacs and FSRQs, see also Costamante+18 and M. Meyer talk

From ‘Detection’ to ‘Characterization’

Ackermann et al. 2012

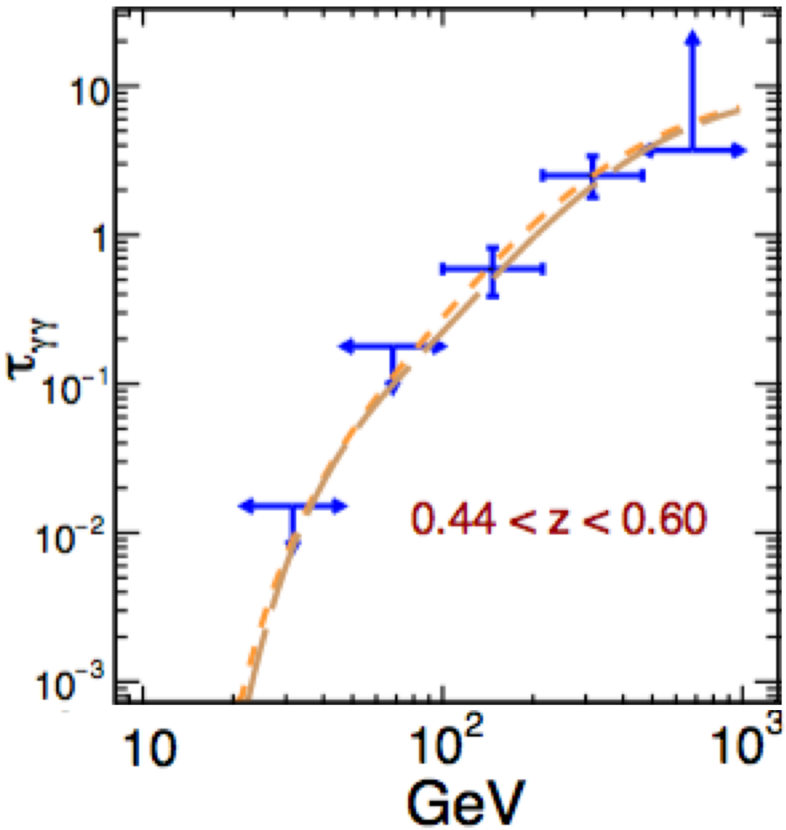


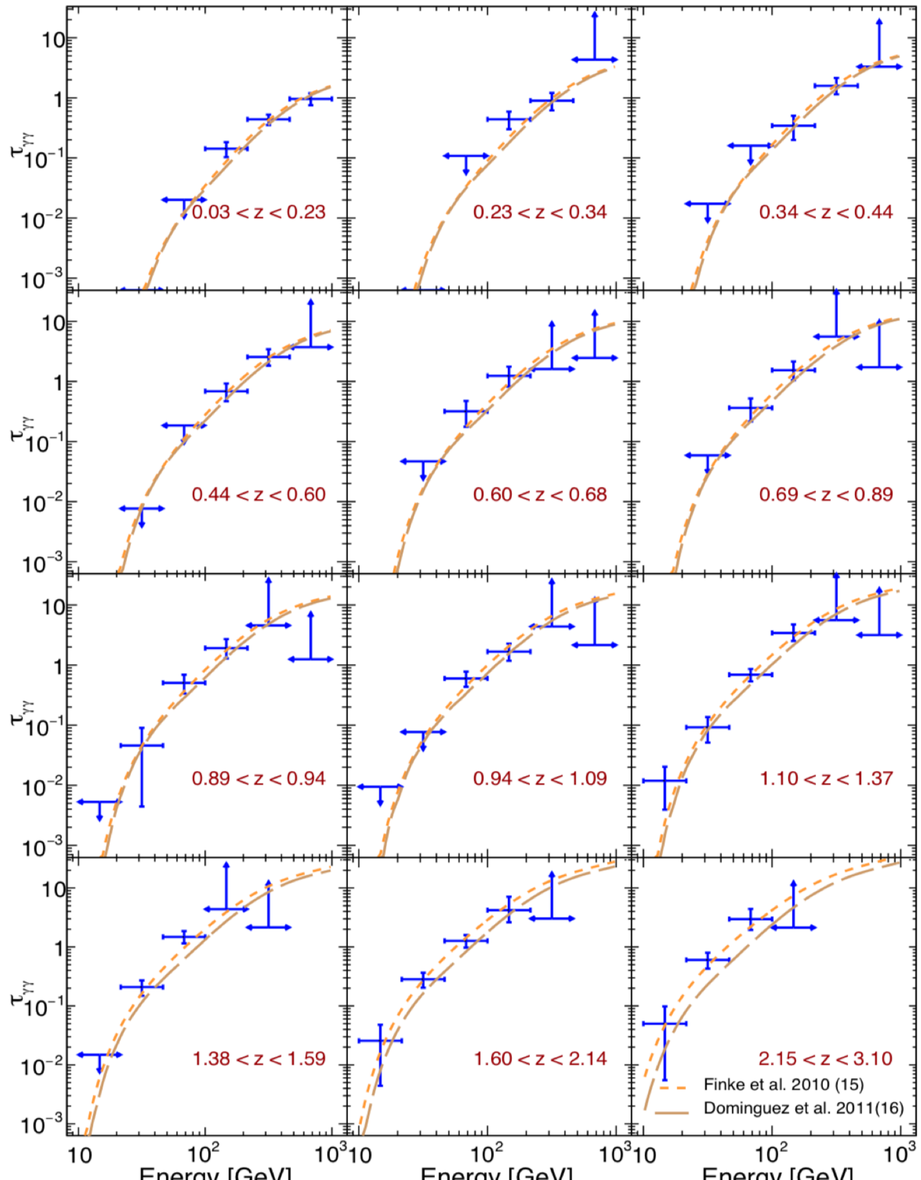
Abdollahi et al. 2018



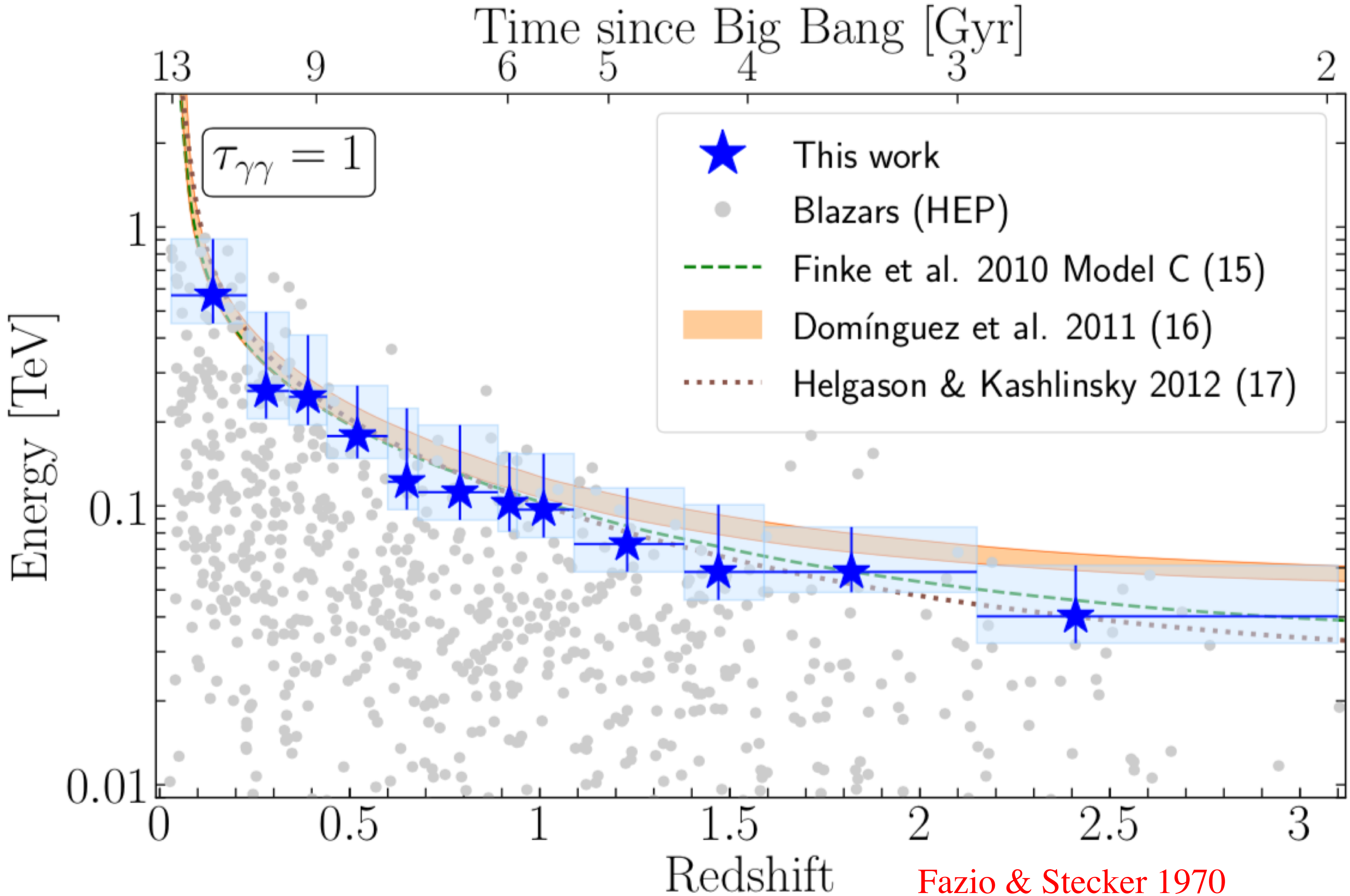
Marco Ajello

The fun part: Evolution with *z* from z=0.03 to 3.1





The Cosmic Gamma-ray Horizon



Fazio & Stecker 1970

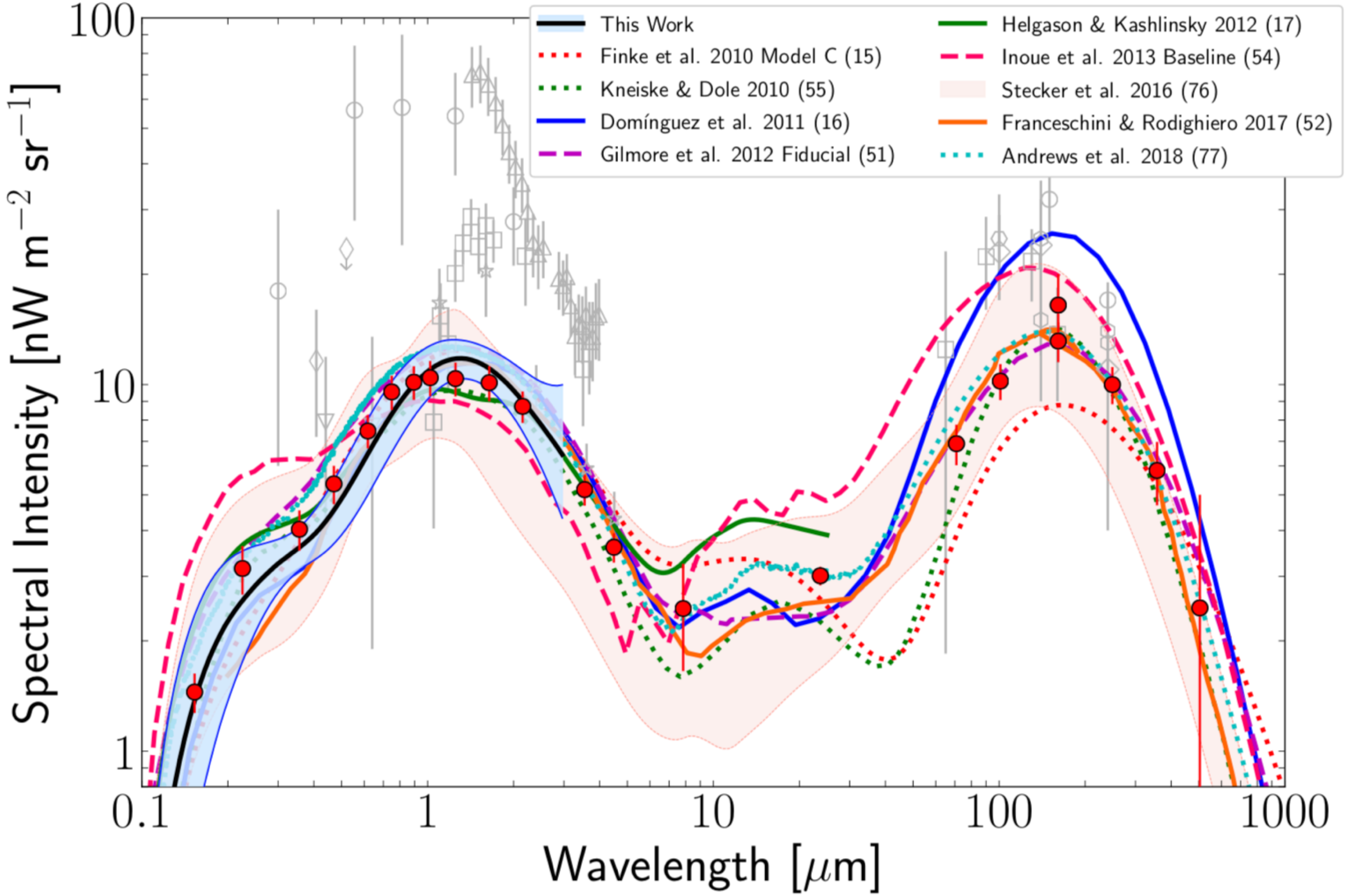
More (Astrophysical) Fun

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

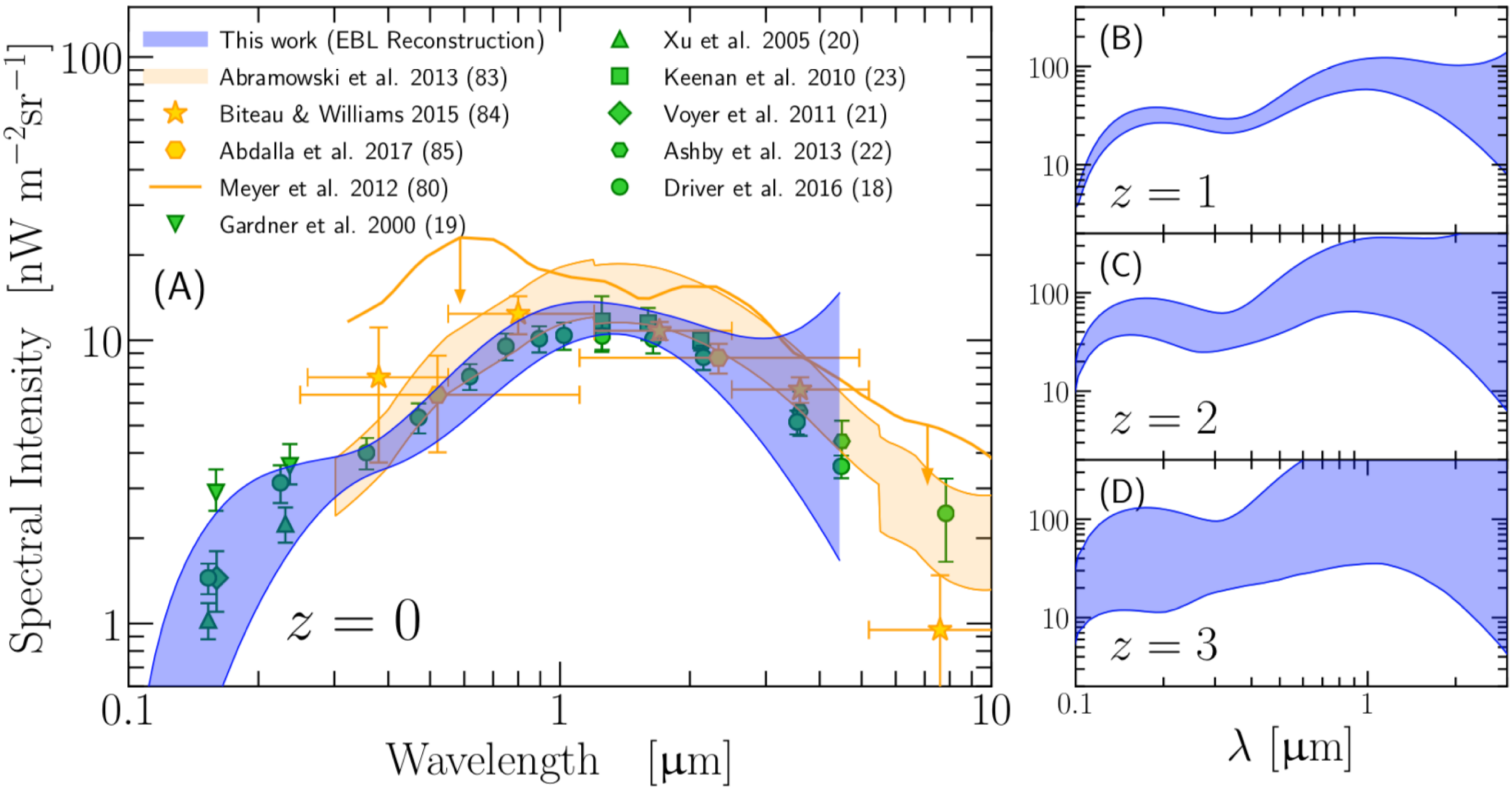
$$n_{\rm EBL}(\epsilon,z) = (1+z)^3\int_z^{\infty}\frac{j(\epsilon,z)}{\epsilon}\left|\frac{dt}{dz'}\right|dz'$$

- We can't invert 3-4 integrals, so we need to find another way
- Two methods, both fitted via MCMC to LAT τ data
- Method 1: model j(e,z) has sum of log-normal distributions that can evolve independently
- Method 2: use stellar population models (Finke et al. 2010) and optimize the parameters of the Cosmic Star Formation History

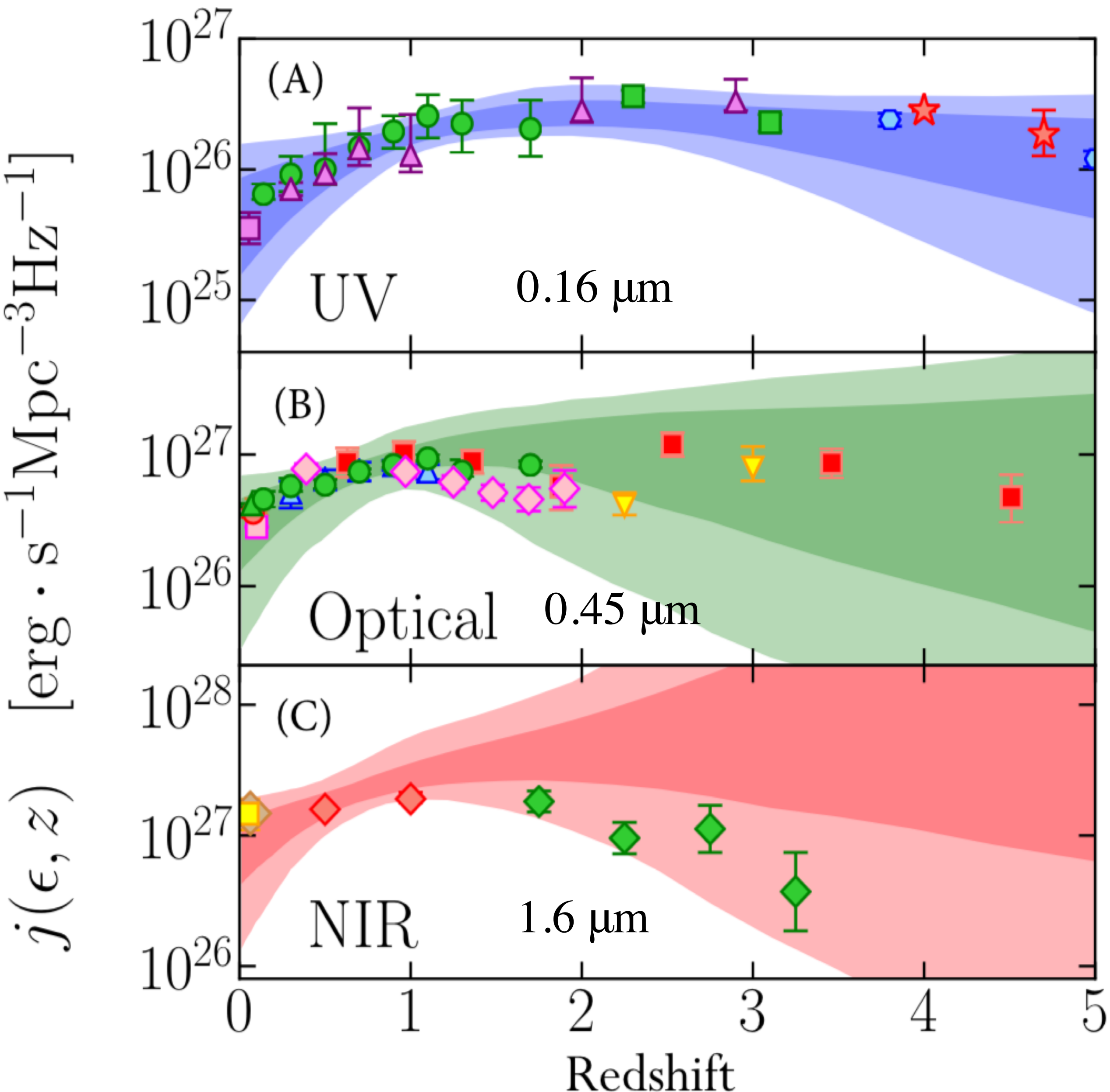
Extragalactic Background Light at z=0



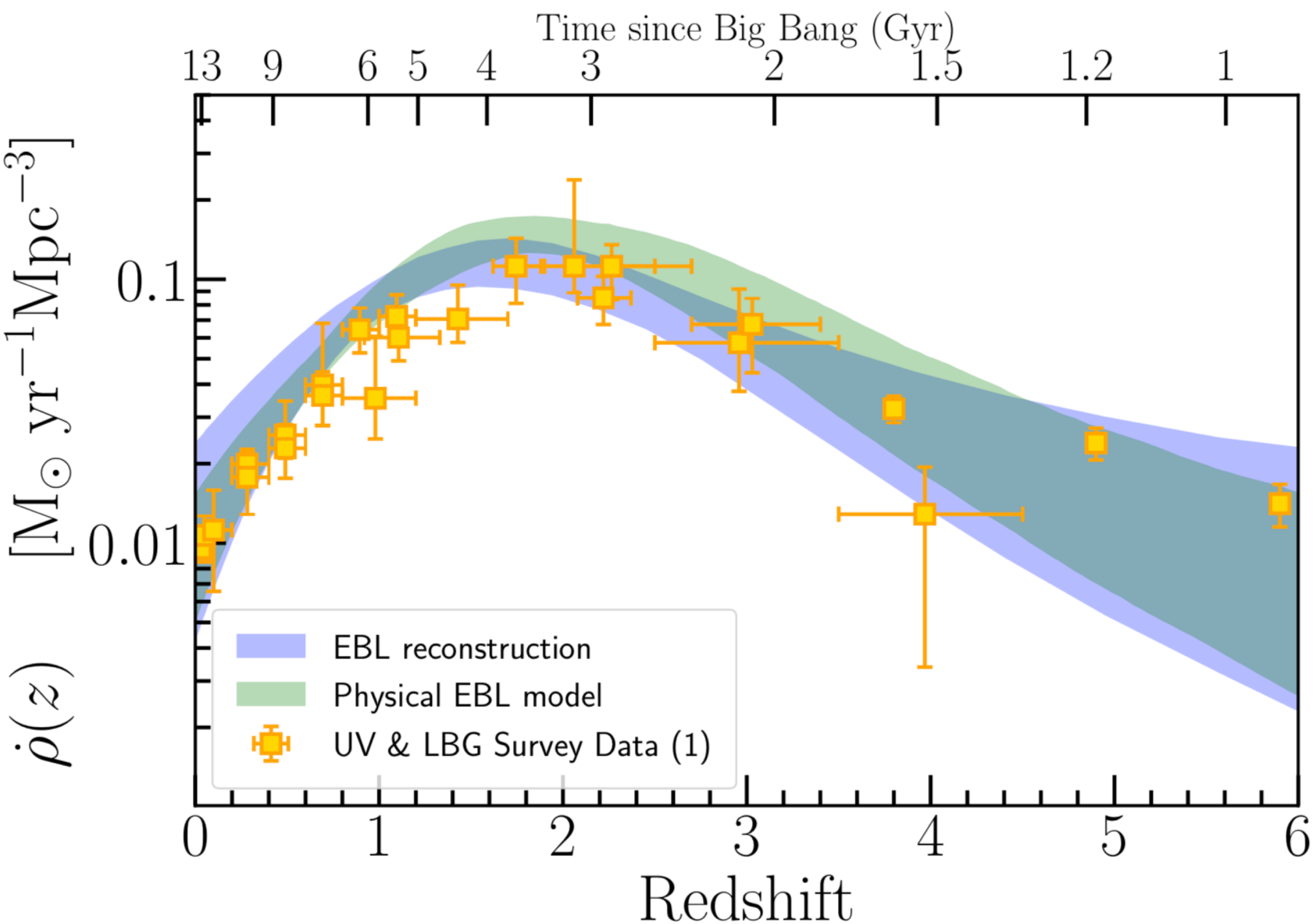
The EBL with Redshift



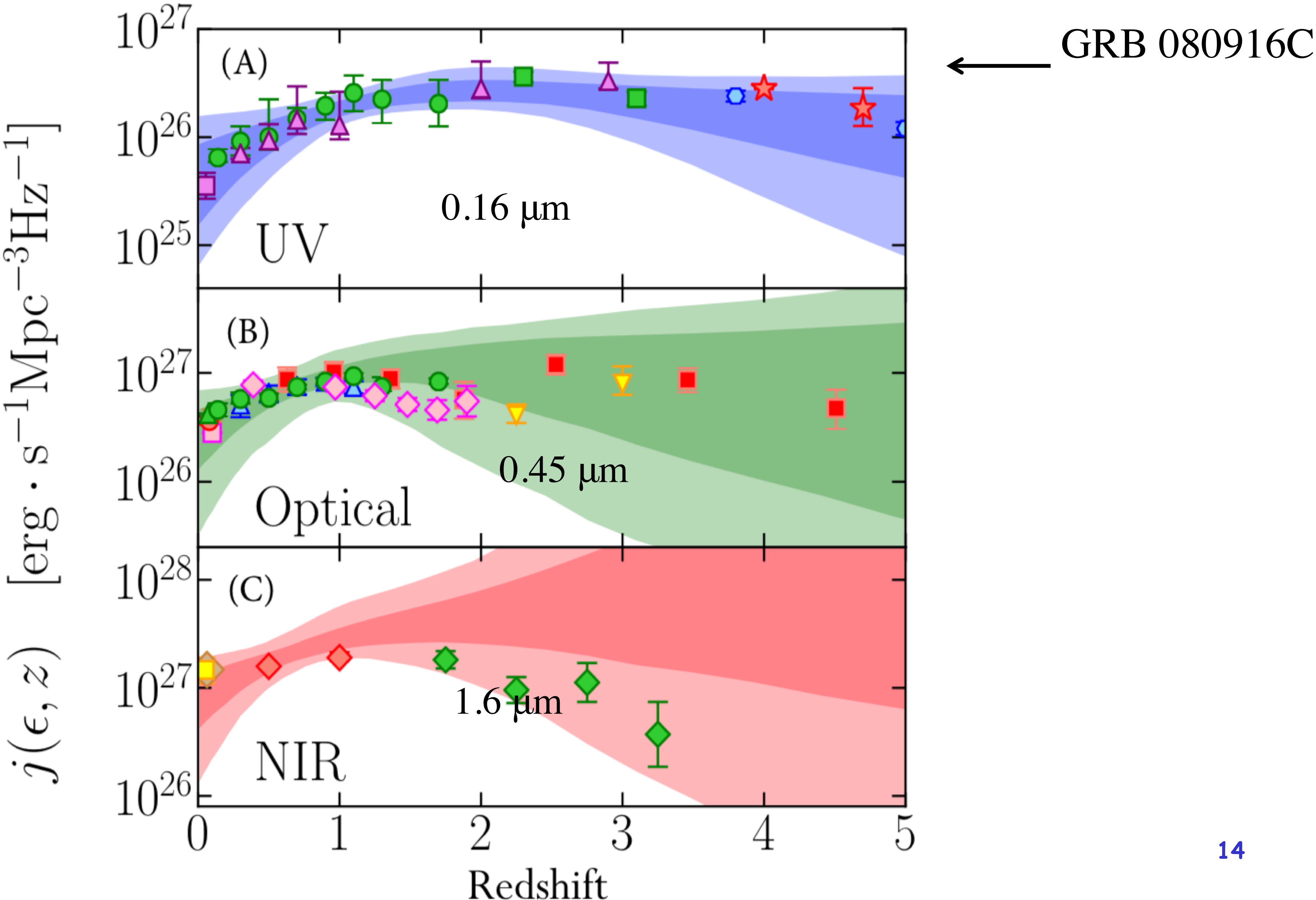
Cosmic Luminosity Density



Star Formation History



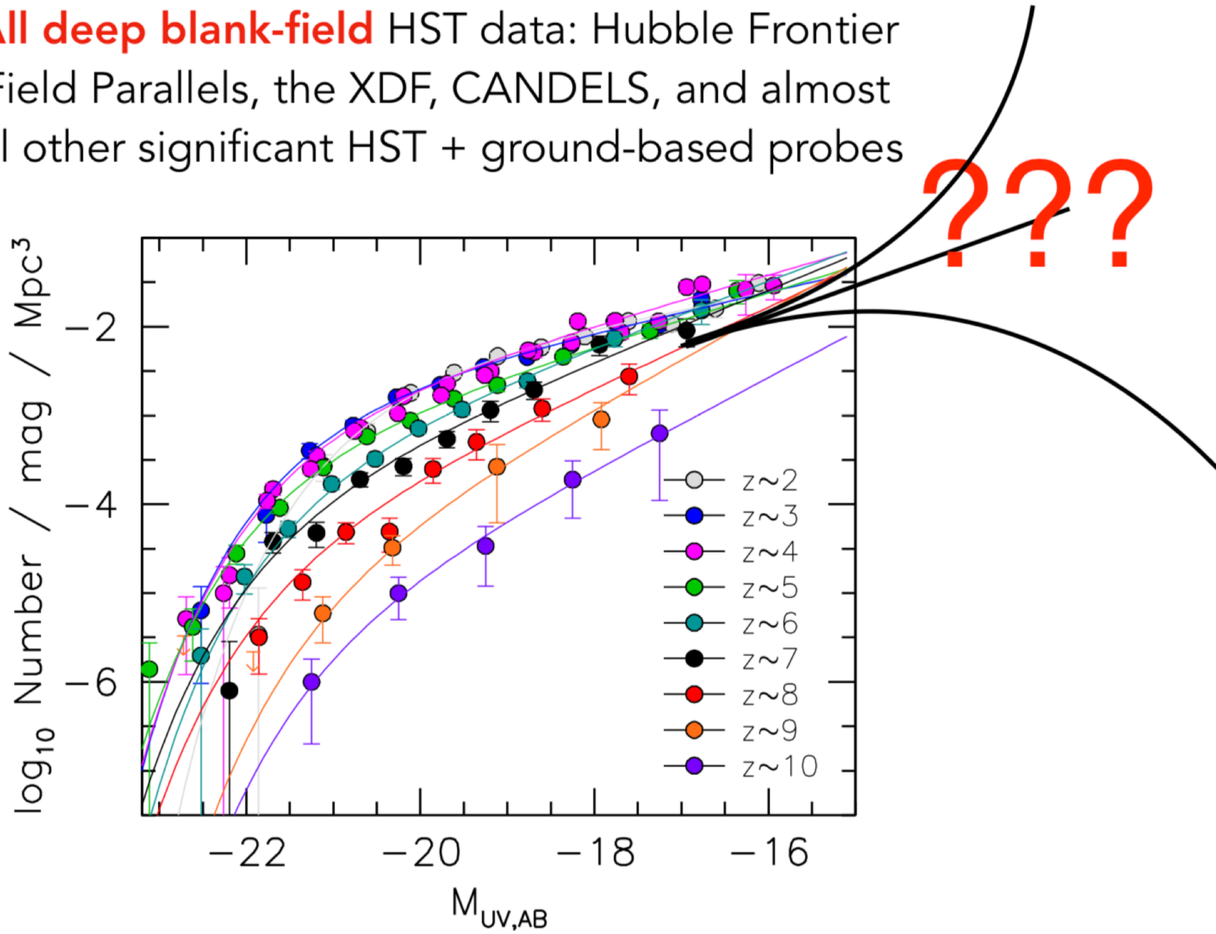
Cosmic Luminosity Density



Re-ionization

Hubble Frontier Fields

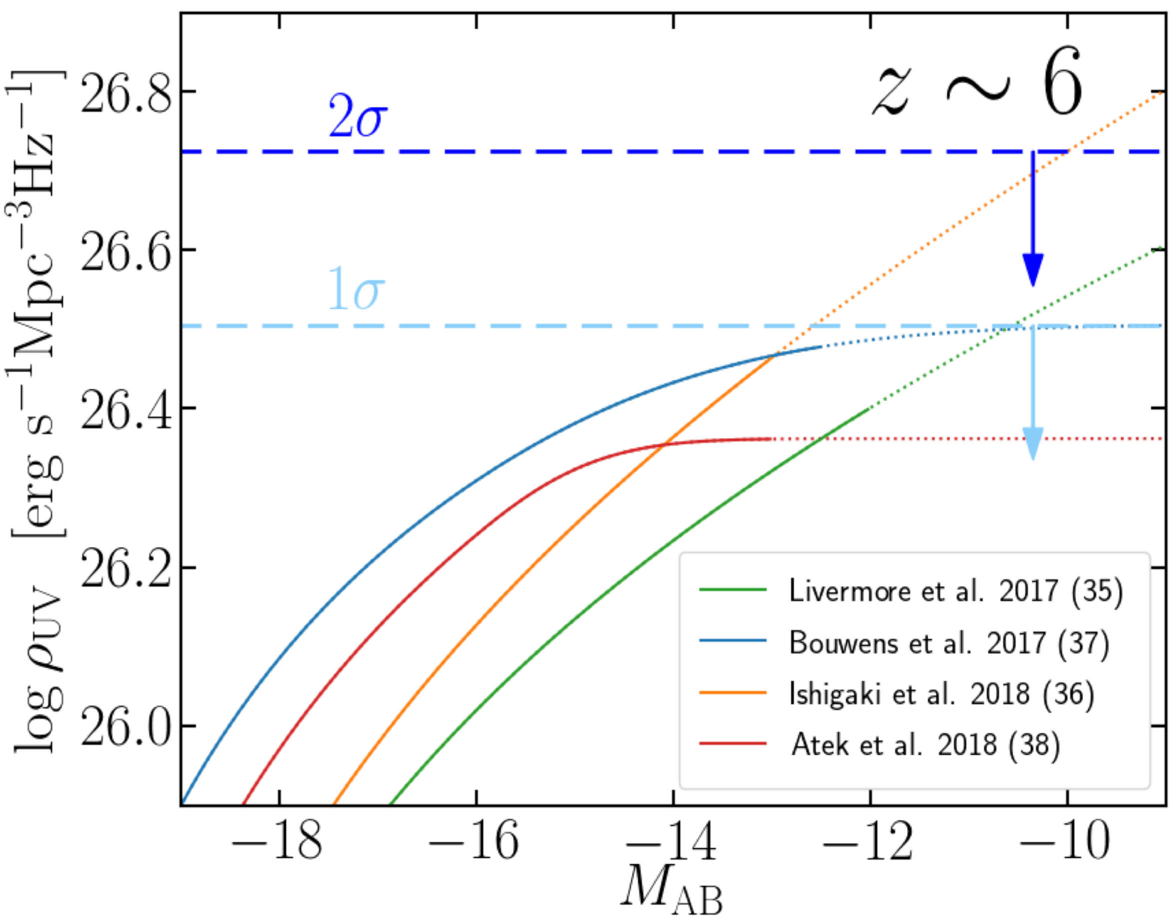
All deep blank-field HST data: Hubble Frontier Field Parallels, the XDF, CANDELS, and almost all other significant HST + ground-based probes



Bouwens+2018 (in prep); Oesch+2017

Re-ionization

Hubble Frontier Fields



The End

- LAT has produced an unprecedented measurement of the EBL optical depth at 12 different epochs

- It allowed us to:
  - measure the EBL well up to z~3
  - measure the UV/optical/NIR luminosity densities
  - measure the Universe's star-formation history
  - Provide the only upper limit to the galaxy luminosity density at the end of the re-ionization era

- More Results to come:
  - See A. Domínguez talk on Thursday: Cosmology with the EBL
  - See poster from A. Desai: GeV-TeV measurement of the EBL

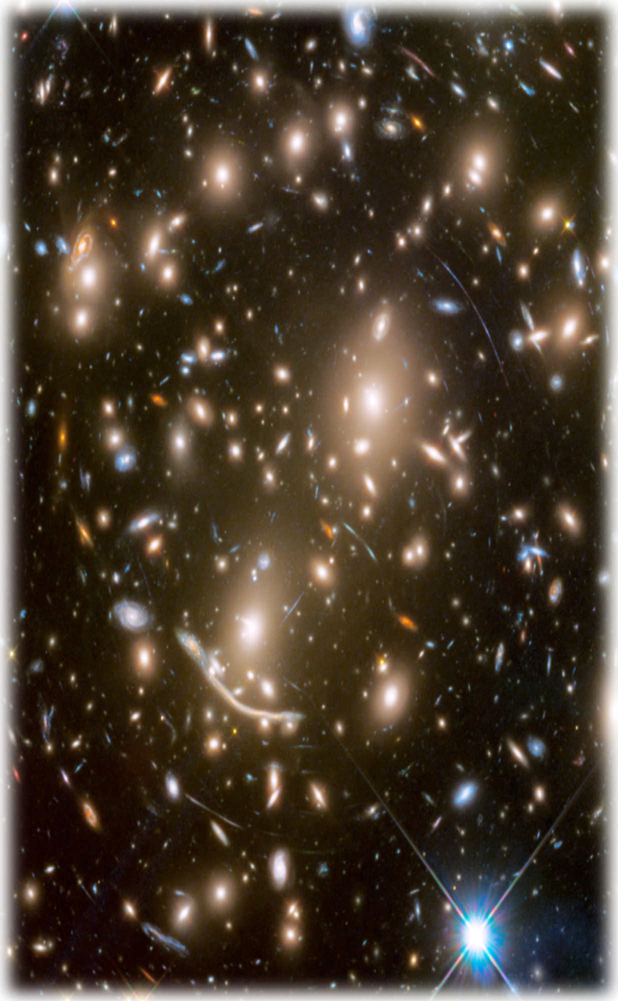
Testing models

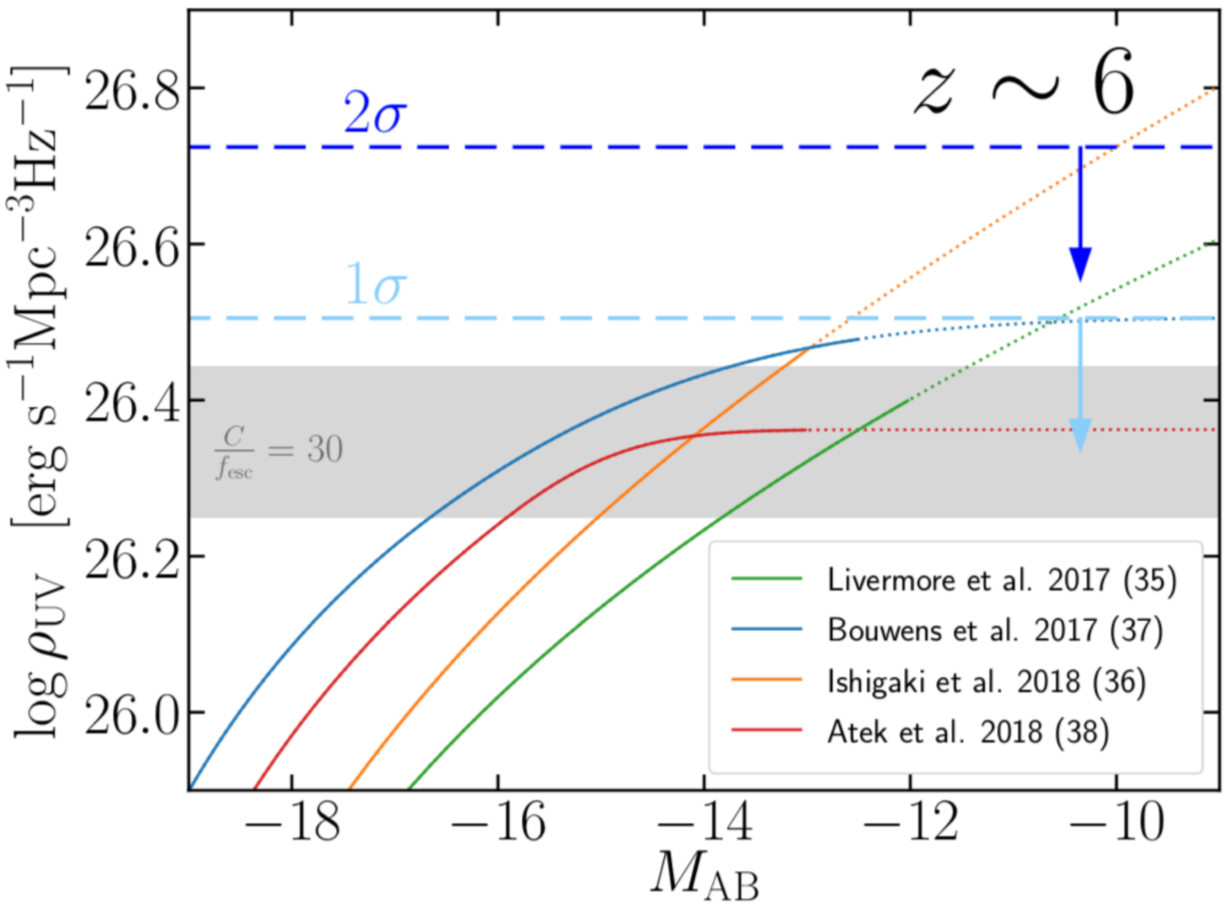
- Large power to discriminate between models
- Note: not all models reach 1TeV / z~3

Preliminary

Model	Ref.	Significance of b=0 Rejection[a]	b[b]	Significance of b=1 Rejection[c]
Scully et al. (2014) – high	(45)	16.0	0.42±0.03	17.4
Kneiske et al. (2004) – best -fit	(46)	16.9	0.68±0.05	6.0
Gilmore et al. (2012) – fixed	(47)	16.7	1.30±0.10	3.0
Gilmore et al. (2012) – fiducial	(47)	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)	(48)	16.4	1.25±0.10	2.5
Gilmore et al. (2009)	(49)	16.7	1.03±0.08	2.4
Inoue et al. (2013)	(50)	16.2	0.87±0.06	2.1
Kneiske & Dole (2010)	(51)	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	(45)	16.0	1.00±0.07	0.1

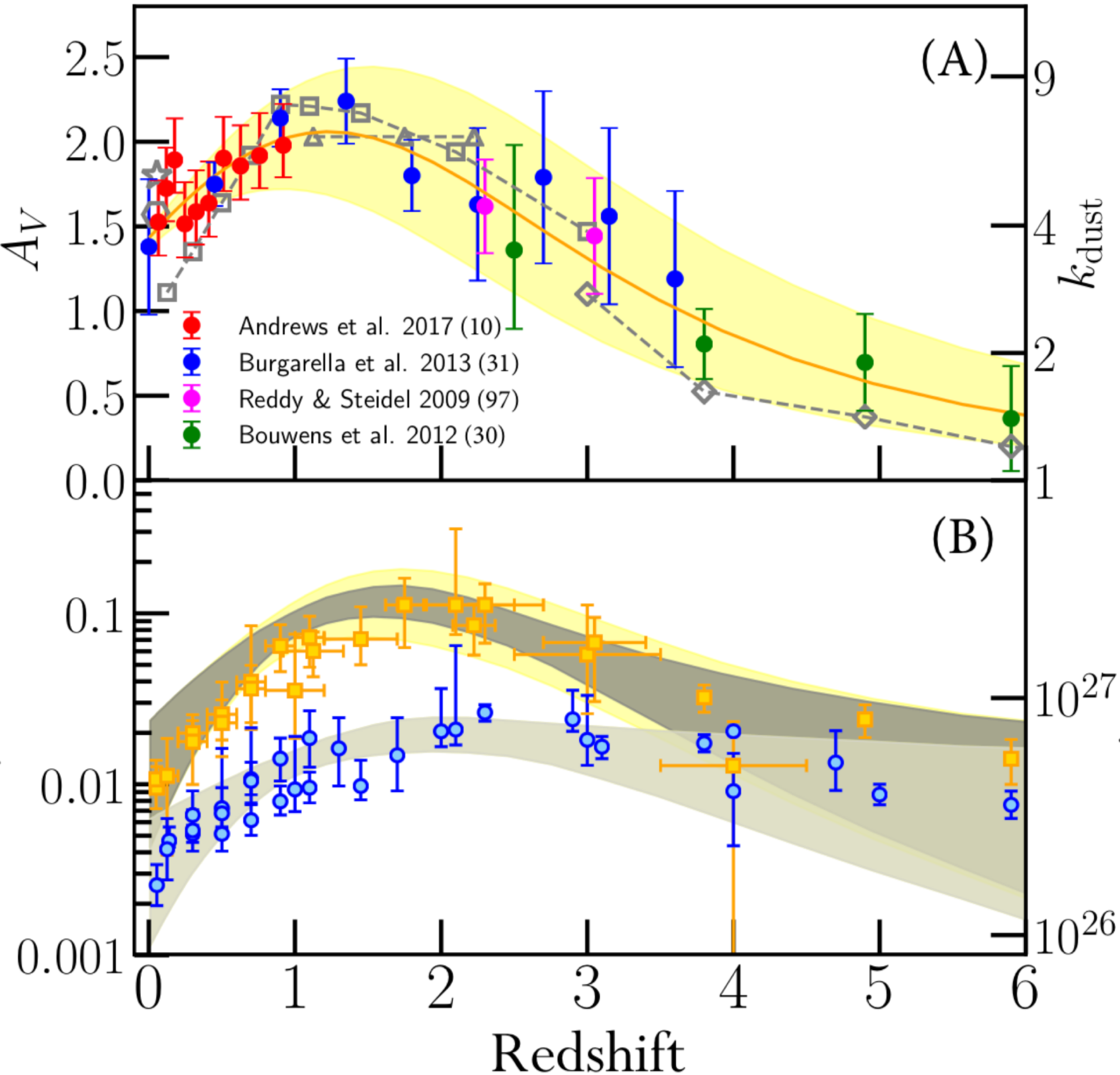
Re-ionization



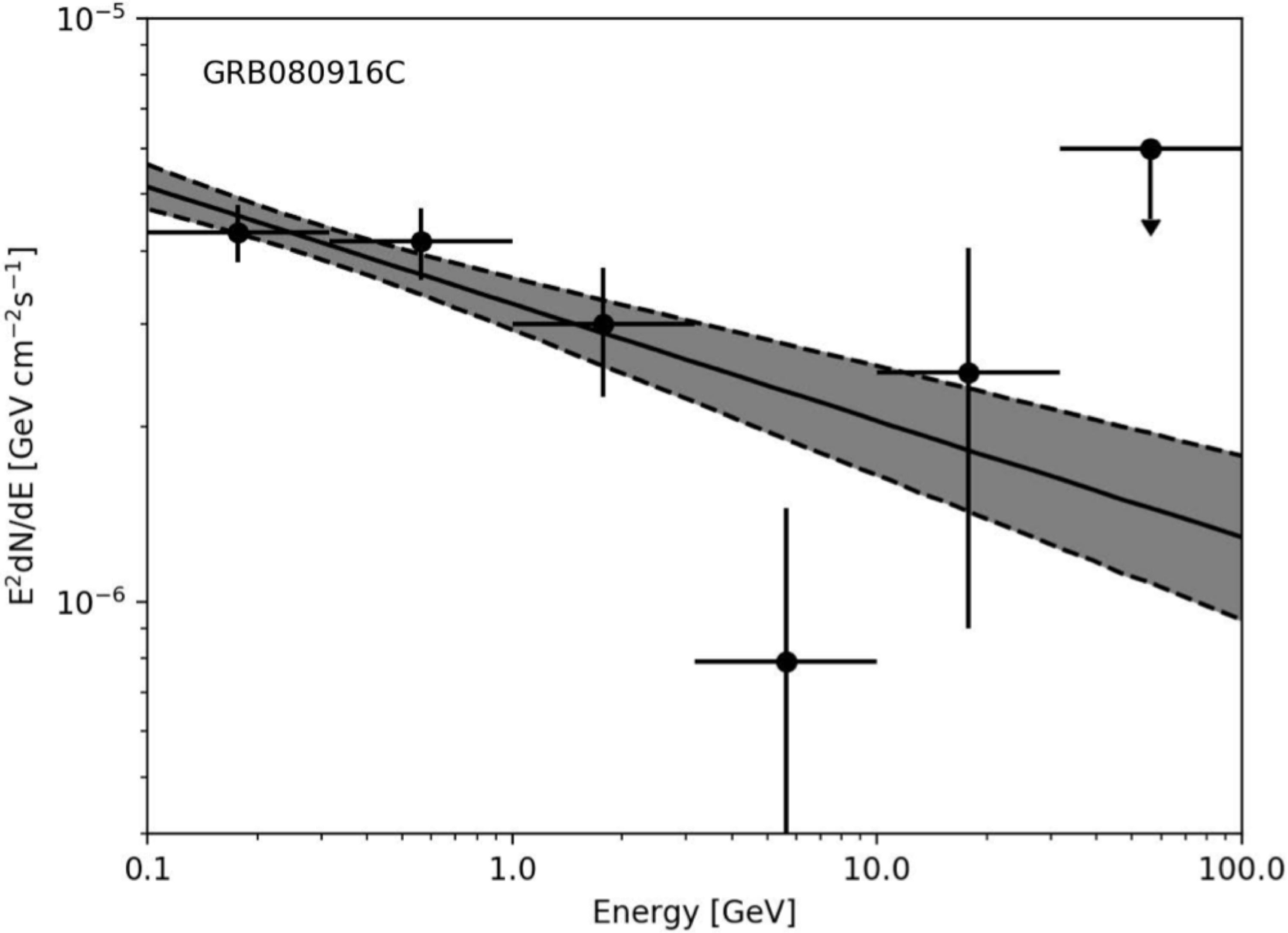


Hubble Frontier Fields

Dust

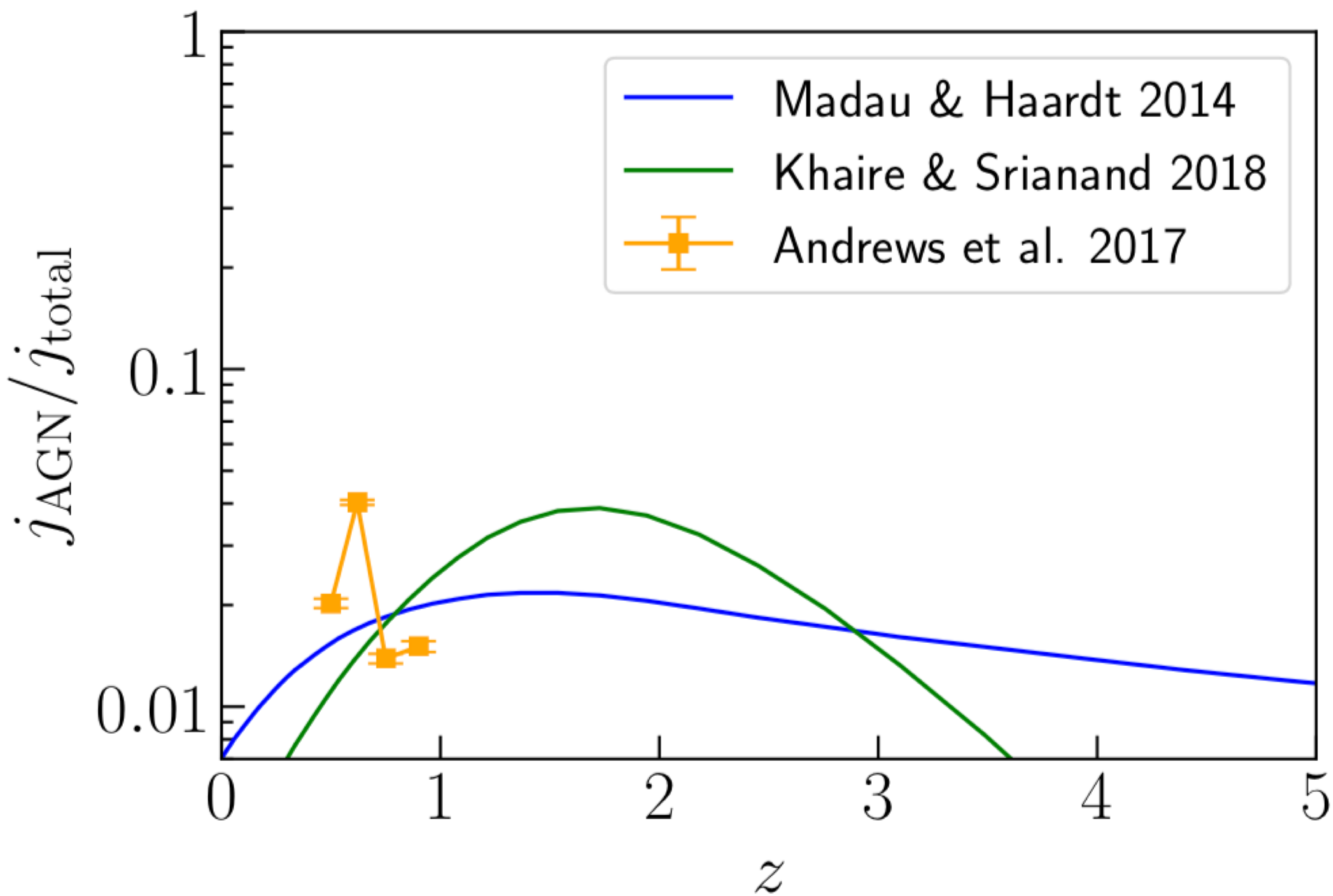

(A)
(B)
A_V
k_{dust}
$\dot{\rho}_{SFR}$
$\dot{\rho}_{UV}$
Redshift
2.5
2.0
1.5
1.0
0.5
0.0
9
4
2
1
0.1
0.01
0.001
10^{27}
10^{26}
0
1
2
3
4
5
6
Andrews et al. 2017 (10)
Burgarella et al. 2013 (31)
Reddy & Steidel 2009 (97)
Bouwens et al. 2012 (30)

GRB 080916C



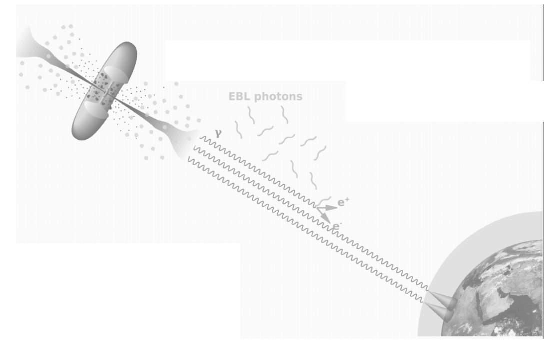
GRB080916C
10^{-5}
10^{-6}
E^2dN/dE [GeV cm^{-2}s^{-1}]
0.1
1.0
10.0
100.0
Energy [GeV]

AGN

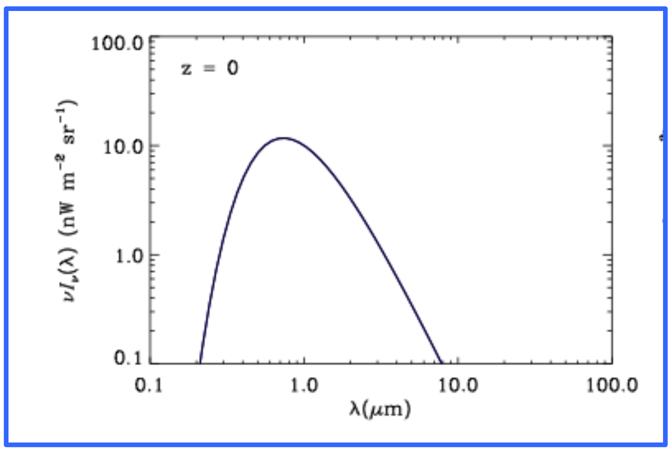

1
0.1
0.01
$j_{\rm AGN}/j_{\rm total}$
0
1
2
3
4
5
z
Madau & Haardt 2014
Khaire & Srianand 2018
Andrews et al. 2017

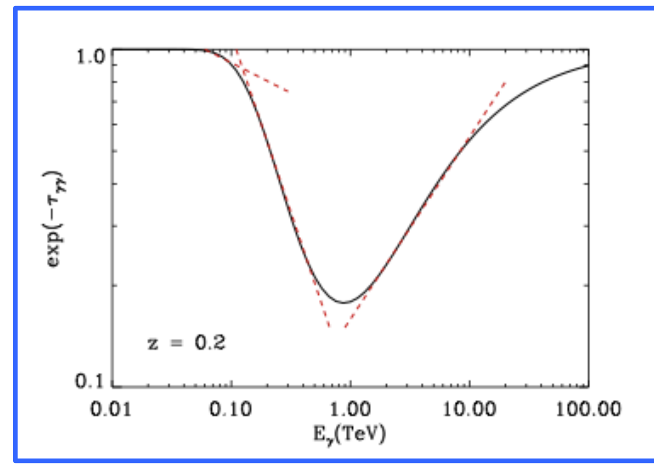
Background gamma-ray sources

- 2 Photons convert into an electron-positron pair if :
  - $E\gamma \times E_{EBL} \geq 2(m_e c^2)^2$



- Photons of 100 GeV convert with 5eV photons (UV)
- Photons of 1 TeV convert with 0.3 eV photons (IR)





Intrinsic spectrum is attenuated

$$\frac{dN_{obs}}{dE} = \frac{dN_{int}}{dE} \times e^{-\tau_\gamma(E,z)}$$

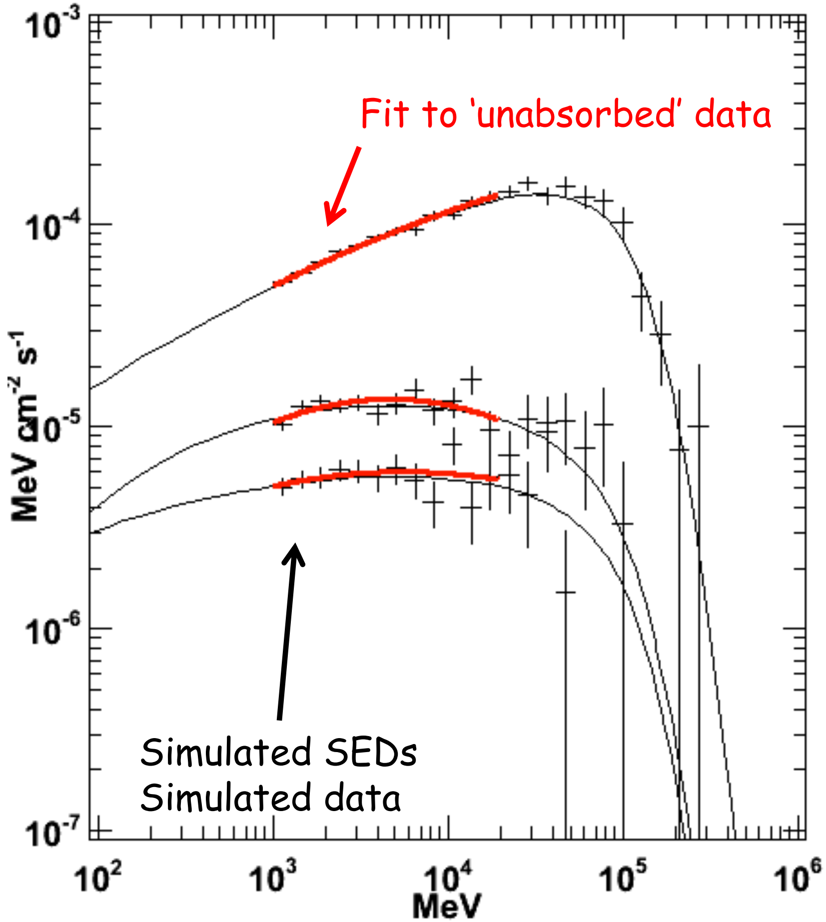
Optical Depth

$$\tau_\gamma = \int_0^z d\ell(z) \int_{-1}^{+1} d\mu \frac{1-\mu}{2} \int_{\epsilon'_{thr}}^{\infty} d\epsilon' \frac{dn_{bkg}}{d\epsilon} \sigma_{\gamma\gamma}(E', \epsilon', \mu)$$

Analysis Procedure: `the boring part'

We look for the collective deviation of the spectra of blazars from their intrinsic spectra

1. Measure the unabsorbed Blazar spectrum up to ~20 GeV
   – It measures the *intrinsic* spectrum



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

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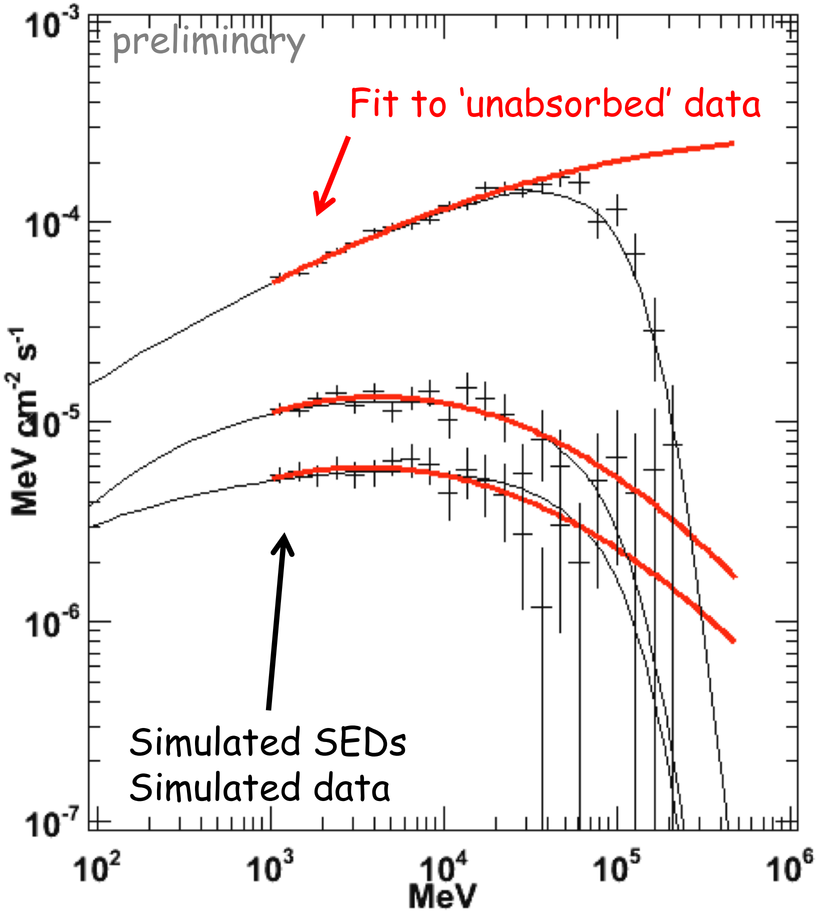
2. Extrapolate it to higher energies
3. Plug an attenuation model (τ(E,z)) and fit all sources at once for `b’
   1. b=0: there is no EBL
   2. b=1: EBL absorption is as predicted



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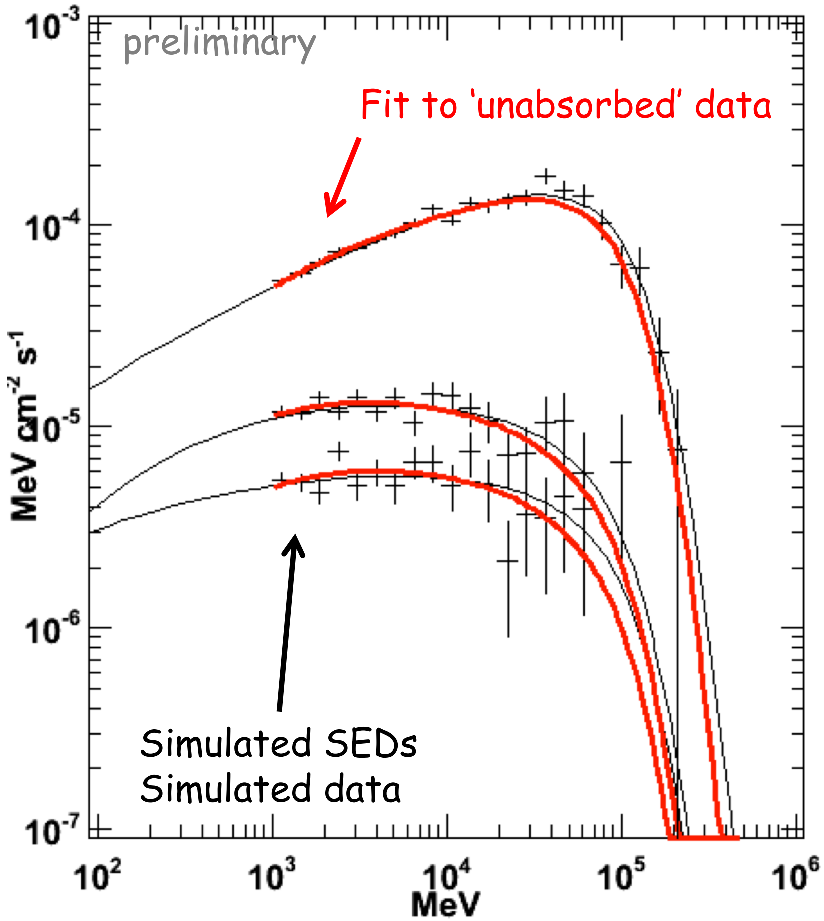
2. Extrapolate it to higher energies
3. Plug an attenuation model (τ(E,z)) and fit all sources at once for `b'
   1. b=0: there is no EBL
   2. b=1: EBL absorption is as predicted
   3. b≠1: EBL absorption is there but not as predicted



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

To determine a blazar's intrinsic shape

- Fit spectra between 1GeV and Emax
  - Emax = maximum energy at which EBL is non important: $\tau<0.1$ for Finke, Dominguez etc

- Default spectrum is a logParabola
  - Test exp-Cutoff power-law with $\gamma_2 = 0.5$ fixed ($TS_{c,1}$ w.r.t logParabola)
  - Test exp-Cutoff power-law with γ_2 free to vary ($TS_{c,2}$ w.r.t logParabola)

- Conditions for choosing a model:
  - logParabola: $TS_{c,1} < 1$ and $TS_{c,2} < 3$
  - exp-Cutoff with $\gamma_2 = 0.5$: $TS_{c,1} > 1$ and $TS_{c,2} < 3$
  - exp-Cutoff with γ_2 free : $TS_{c,2} > 3$

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_b}\right)^{-(\alpha+\beta\log(E/E_b))}$$

- FSRQs: 376 LPs, 6 γ_2 =0.5, 32 γ_2=free
- BLLs: 281 LPs, 8 γ_2 =0.5, 38 γ_2=free

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{\gamma_1} \exp\left(-\left(\frac{E}{E_c}\right)^{\gamma_2}\right)$$

- For the rest of the analysis γ_2 remains fixed at its best fit value
  - Strong degeneracy with EBL and not convergence otherwise

Simulations

- We employ physically motivated SEDs of FSRQs and BL Lacs that reproduce the characteristics of 3LAC blazars:
  - Peak position, luminosity, disk emission, curvature etc.

- *Fermi*-LAT data are simulated and analyzed with the previous prescription