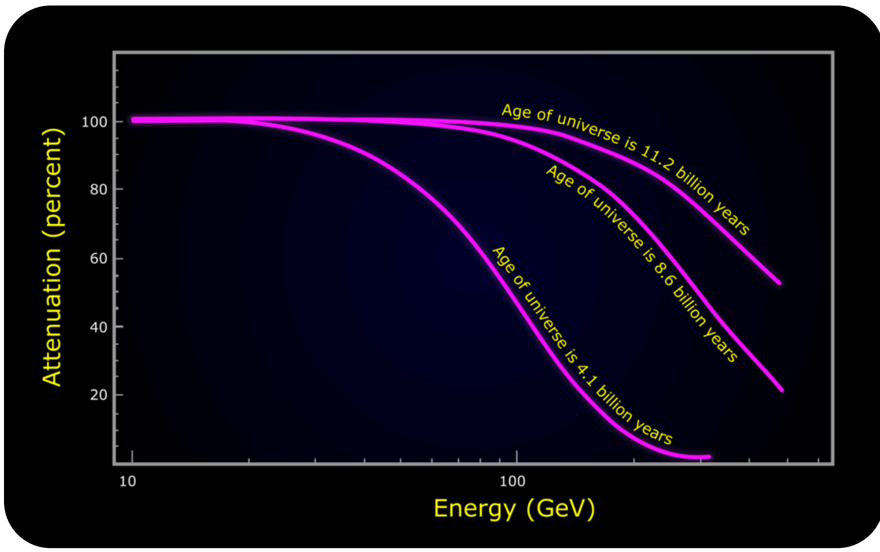
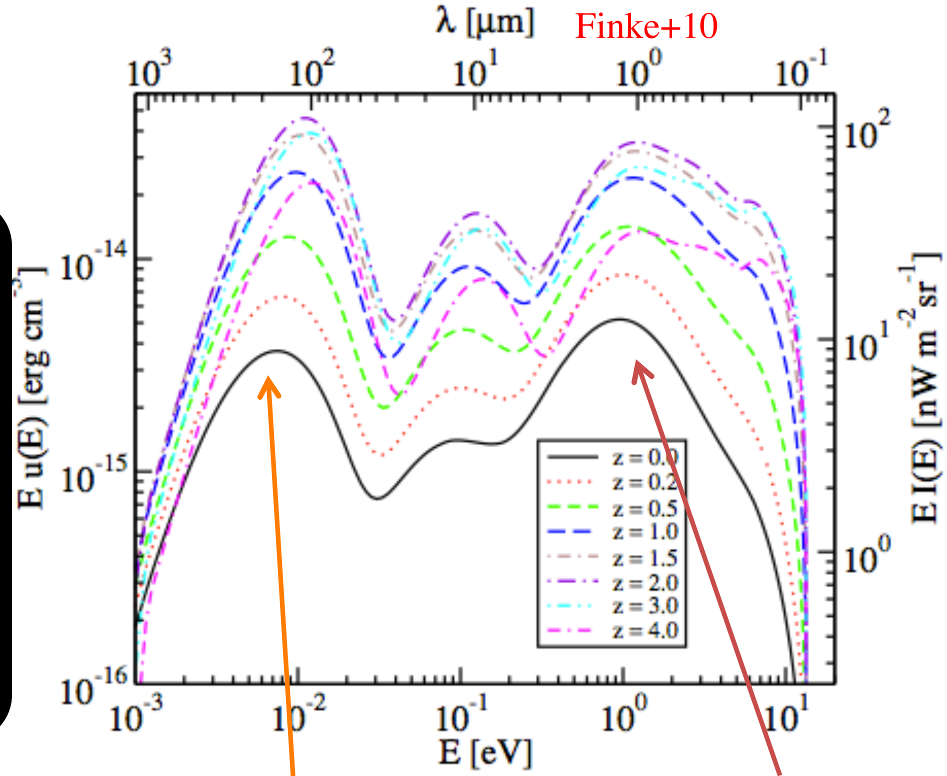
EBL Review and New Results





star light
reprocessed by dust

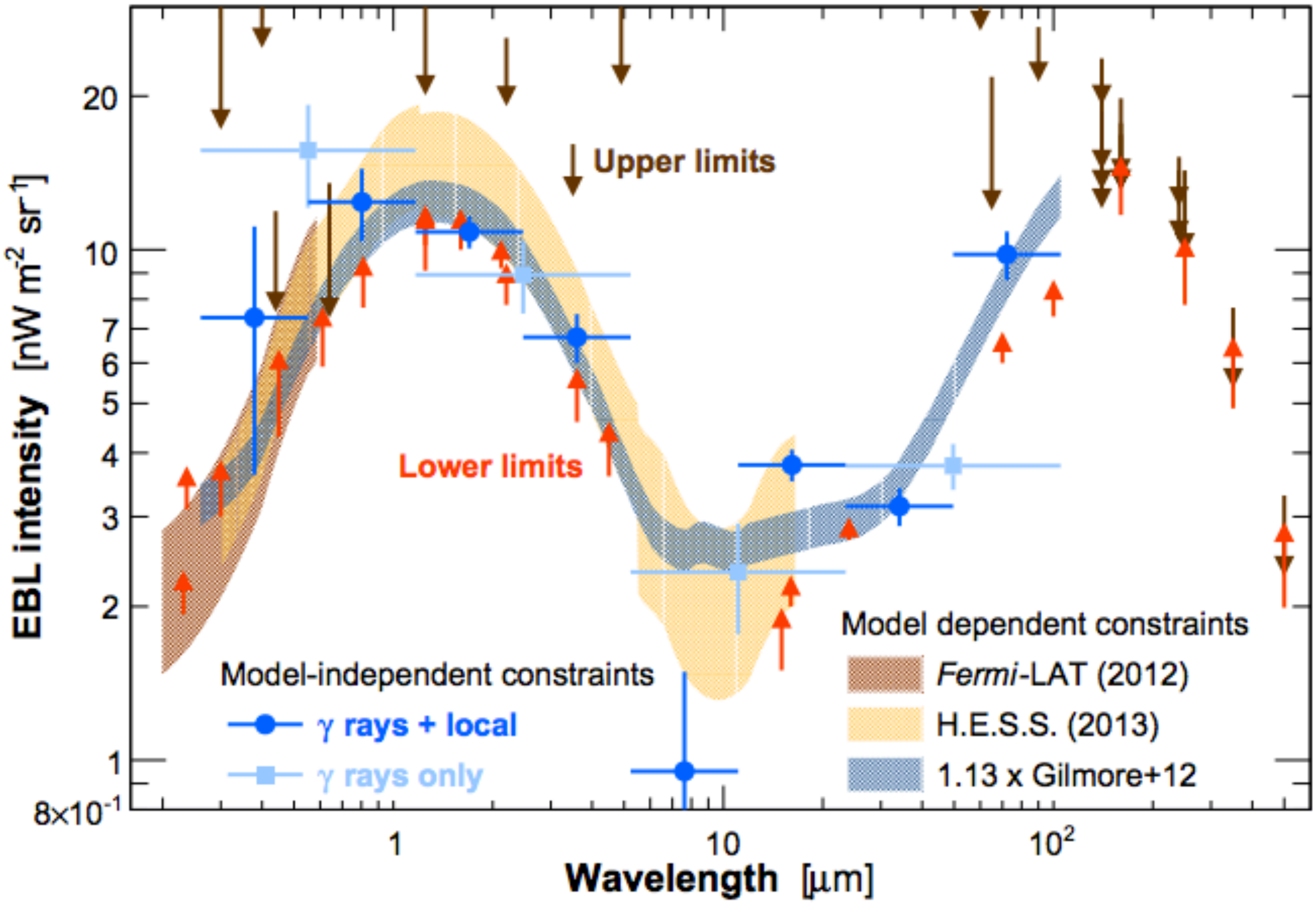
Light emitted by stars

Marco Ajello[1], Vaidehi Paliya[1], Kari Helgason, Abishek Desai[1], Justin Finke, Alberto Domínguez

[1]Clemson University

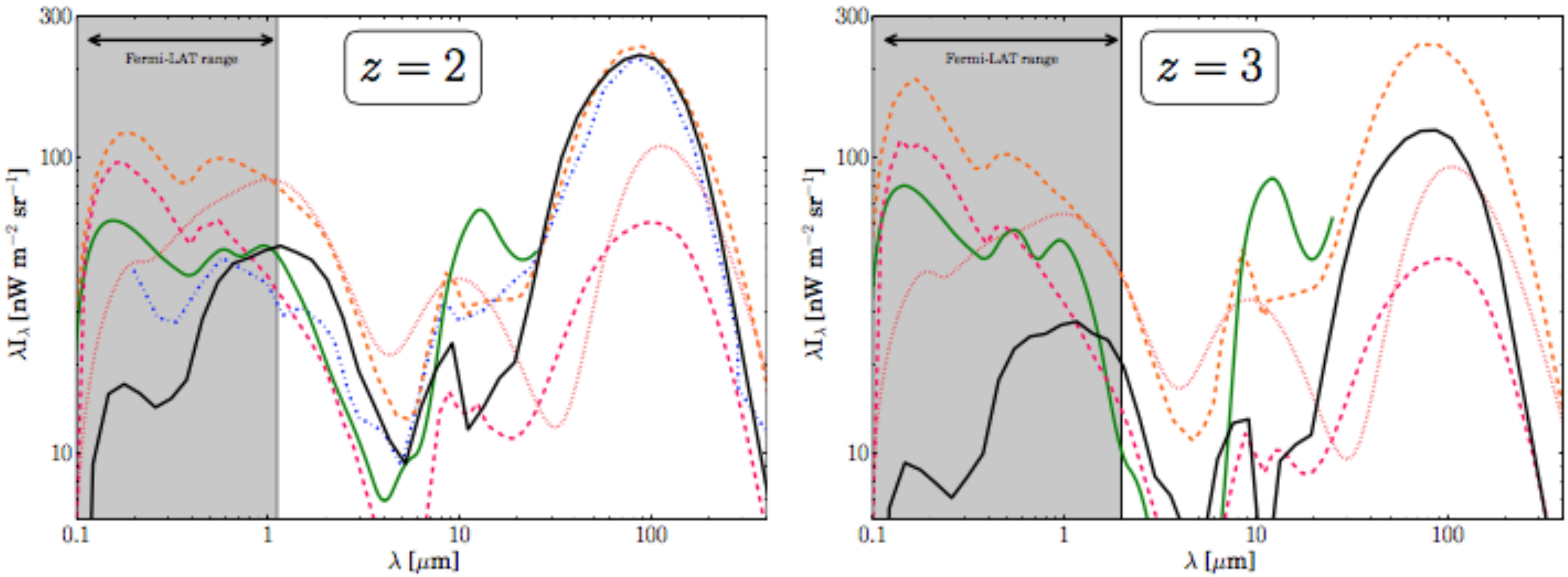
on behalf of the LAT Collaboration

Up-to-date Status



Biteau & Williams 2015

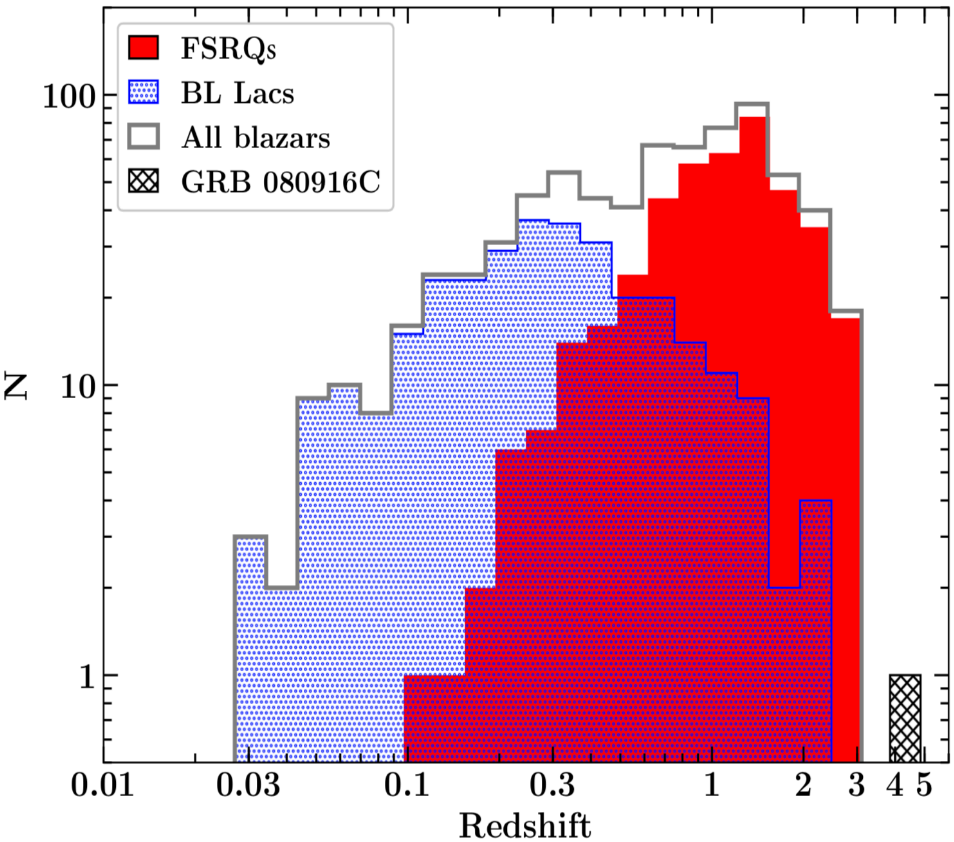
Reality Check



Build up of the EBL largely undetermined

This work

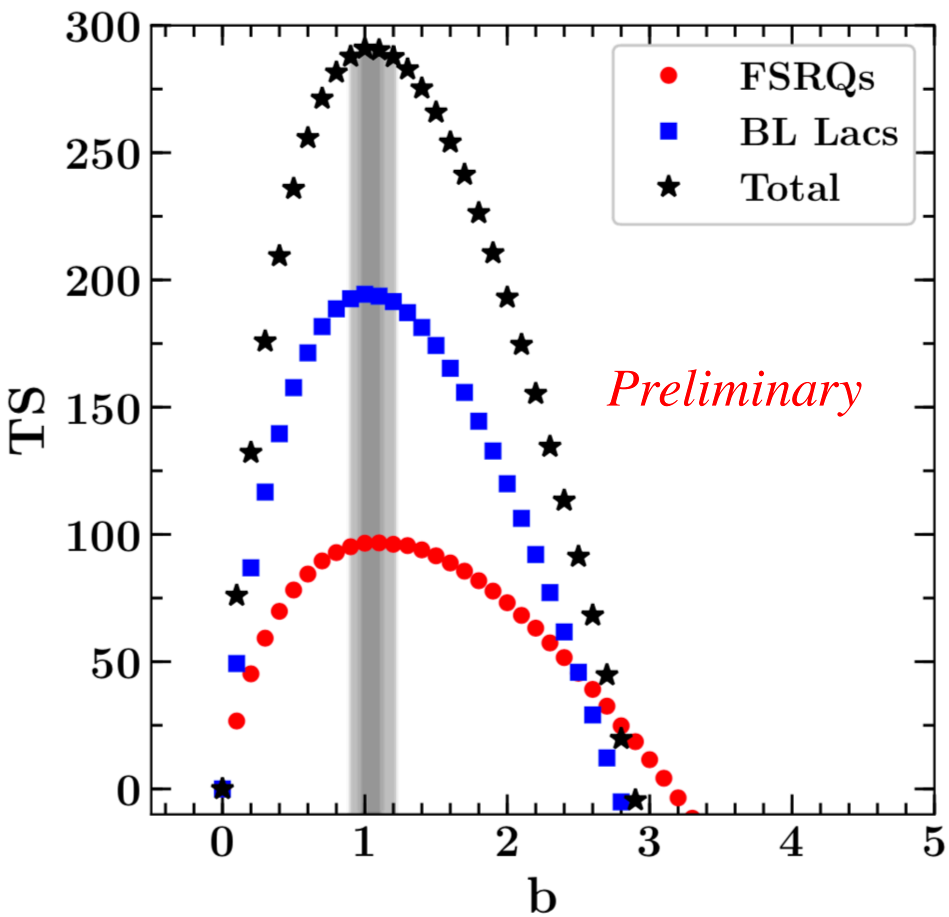
- Use 9 years of P8 LAT data
- 759 blazars + 1 GRB
- Measure intrinsic spectrum (τ<0.1) and extrapolate
- Perform a time-resolved analysis
- Analysis optimized on simulations



EBL Detection

- TS~300
- TS from BLLs ~200
- TS from FSRQs ~100

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

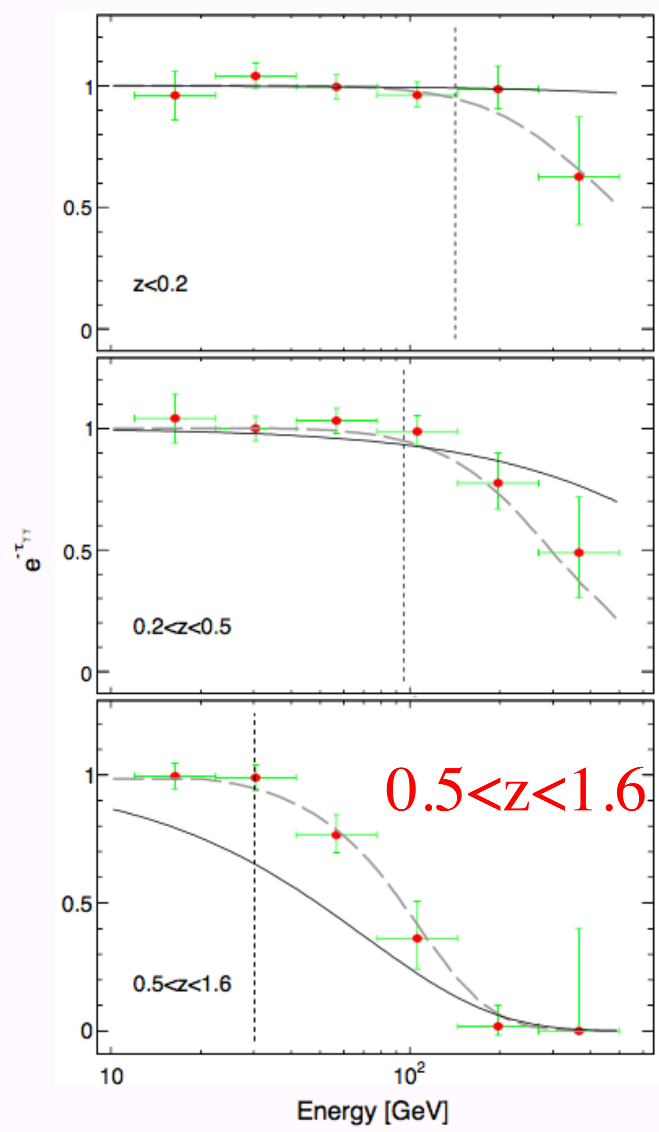


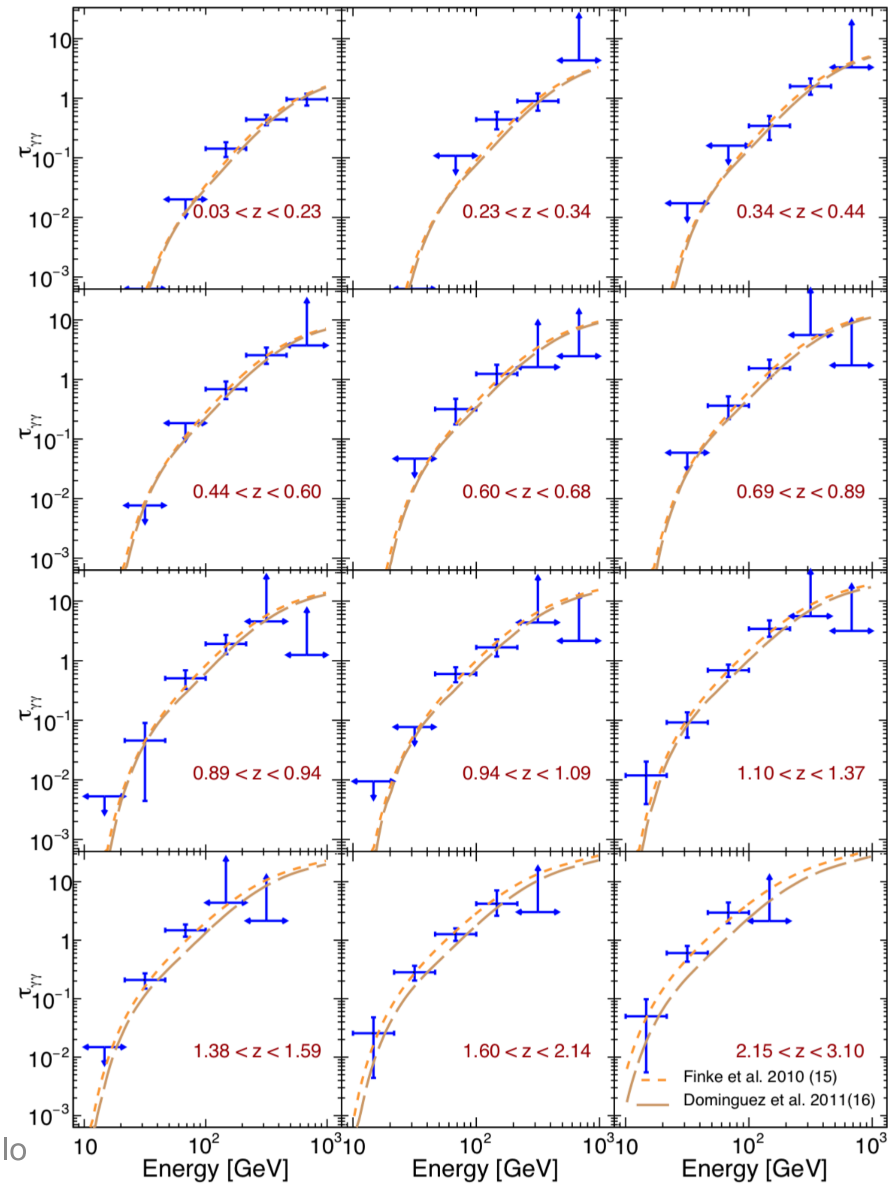
- In 2012:
  - Uncertainty was ~25%

Notice the consistency between BL Lacs and FSRQs, see also S. Cutini, M. Meyer talks

Before Now

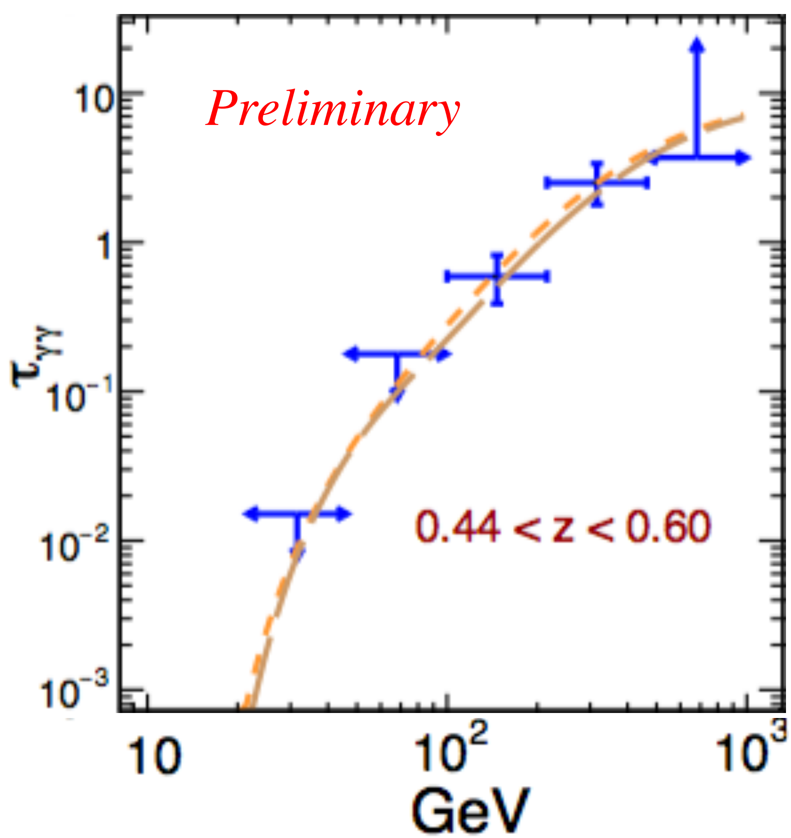
Ackermann et al. 2012

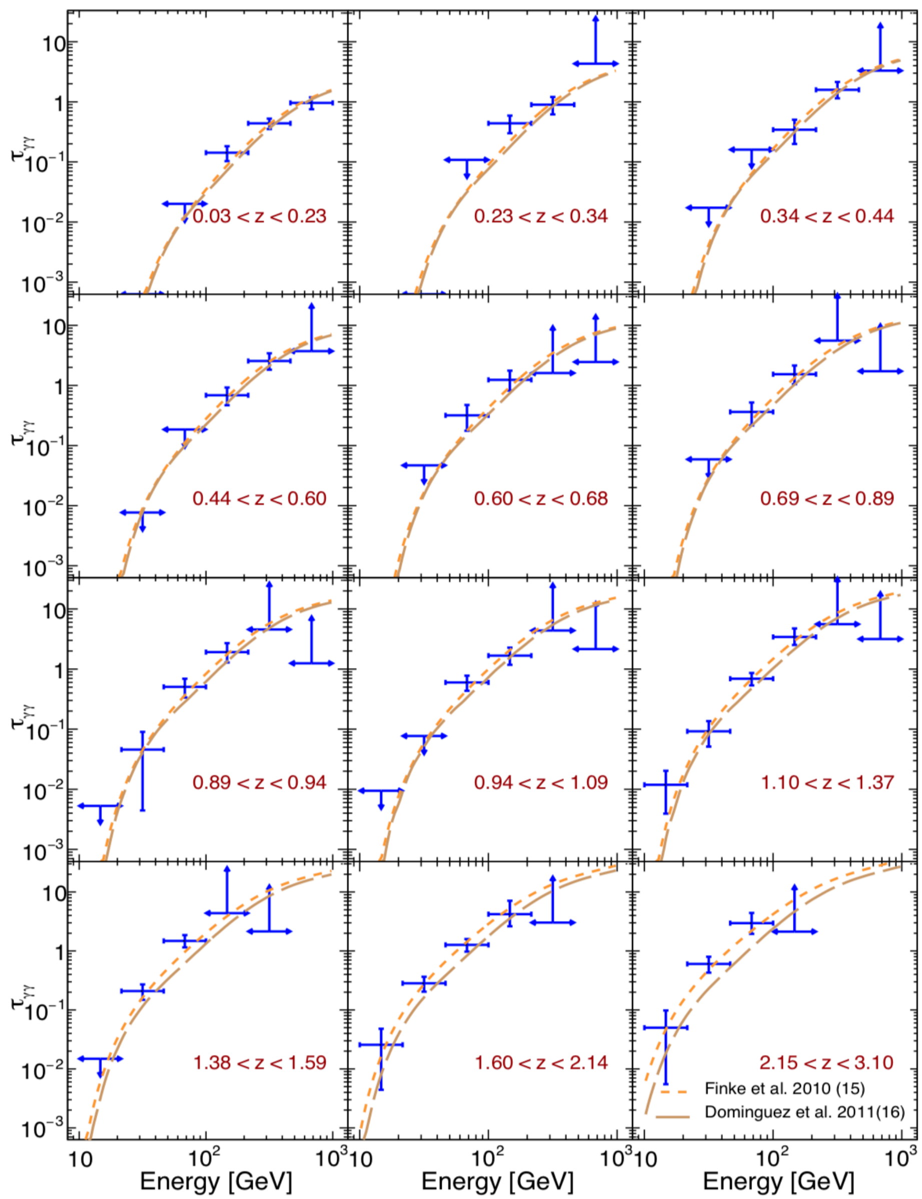




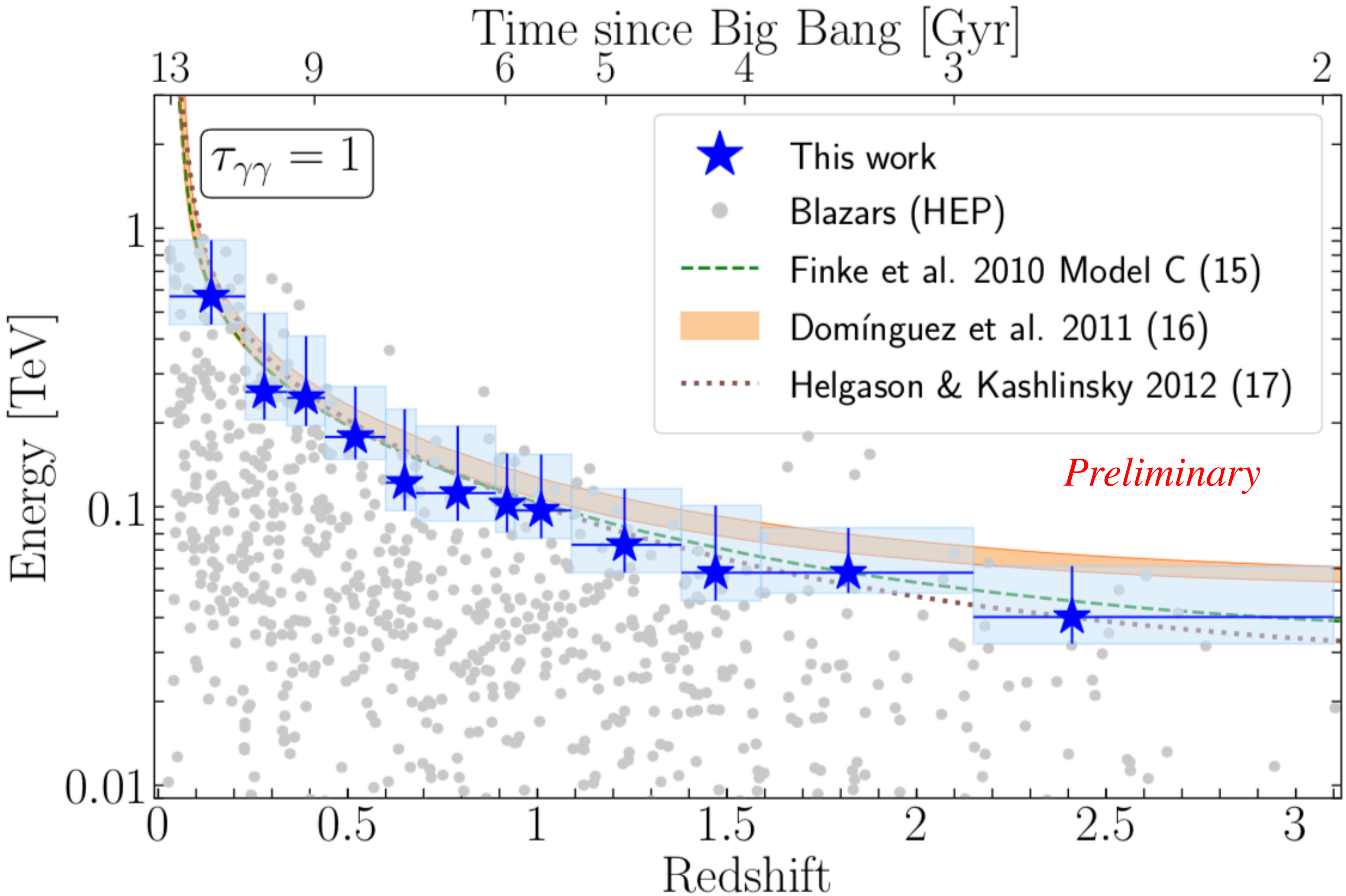
Marco Ajello

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





The Cosmic Gamma-ray Horizon



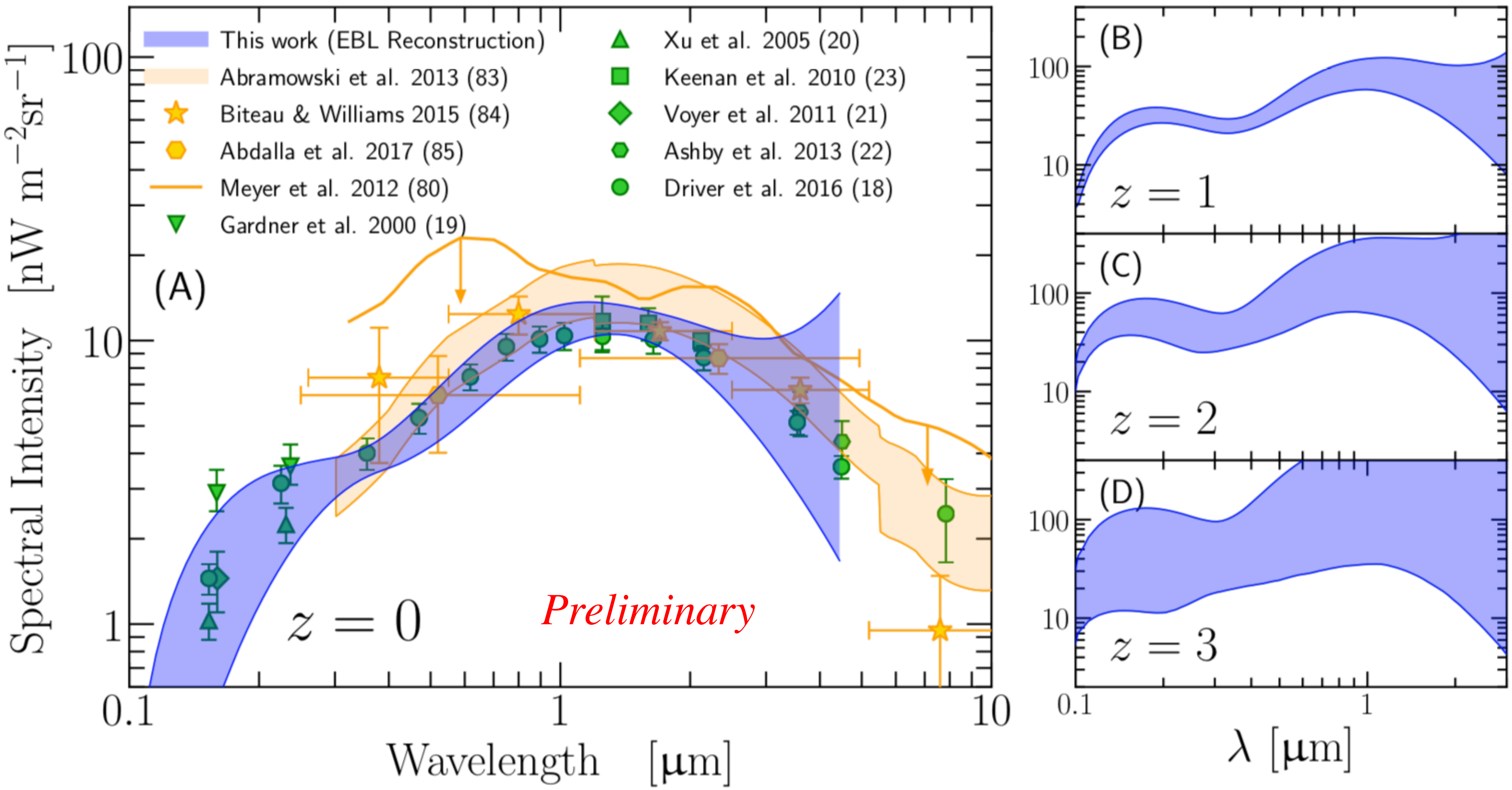
More Fun

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

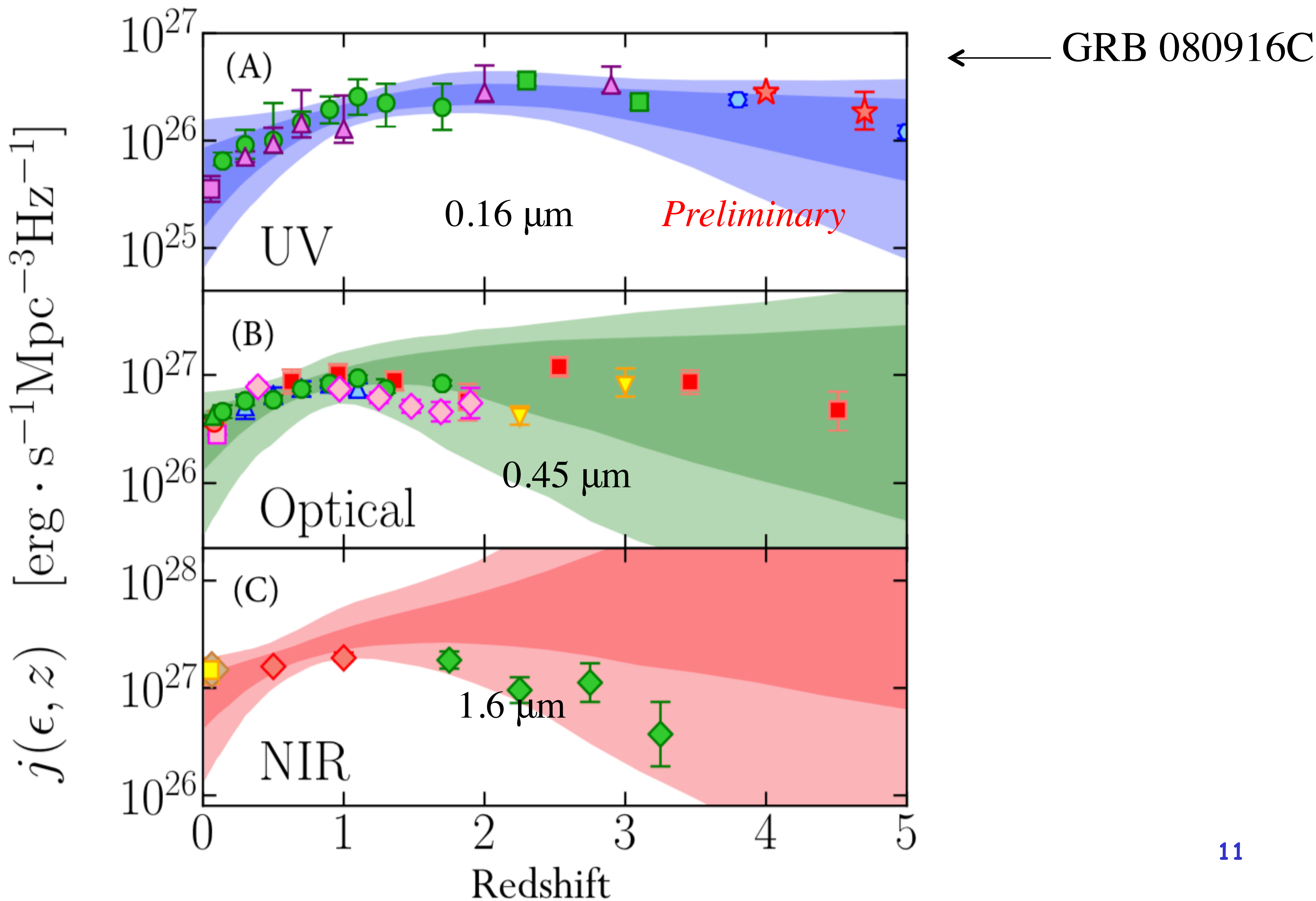
$$n_{\rm EBL}(\epsilon, z) = (1+z)^3 \int_z^{\infty} \frac{j(\epsilon, z)}{\epsilon} \left|\frac{dt}{dz'}\right| dz'$$

- 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 and optimize the parameters of the Cosmic Star Formation History

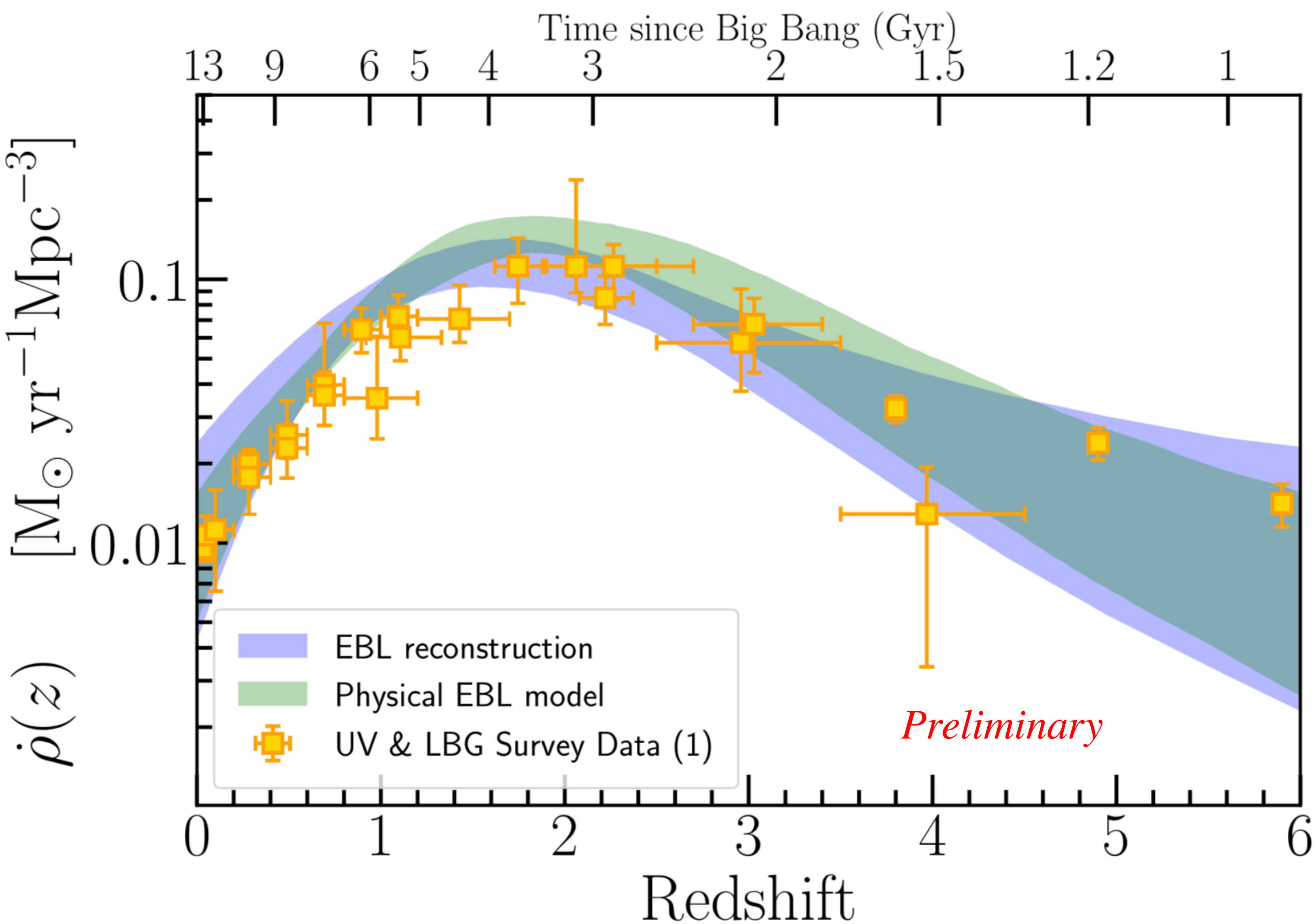
The EBL with Redshift



Cosmic Luminosity Density

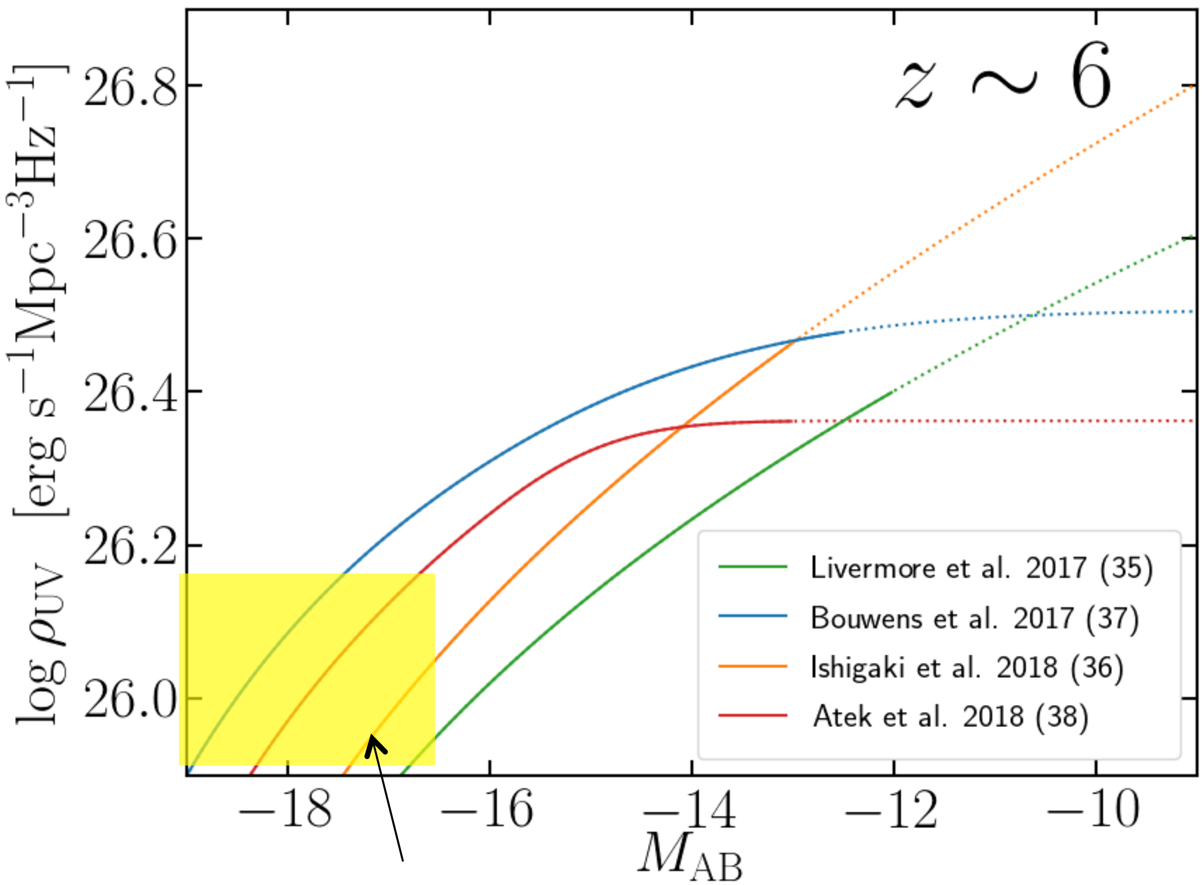


Star Formation History



Re-ionization

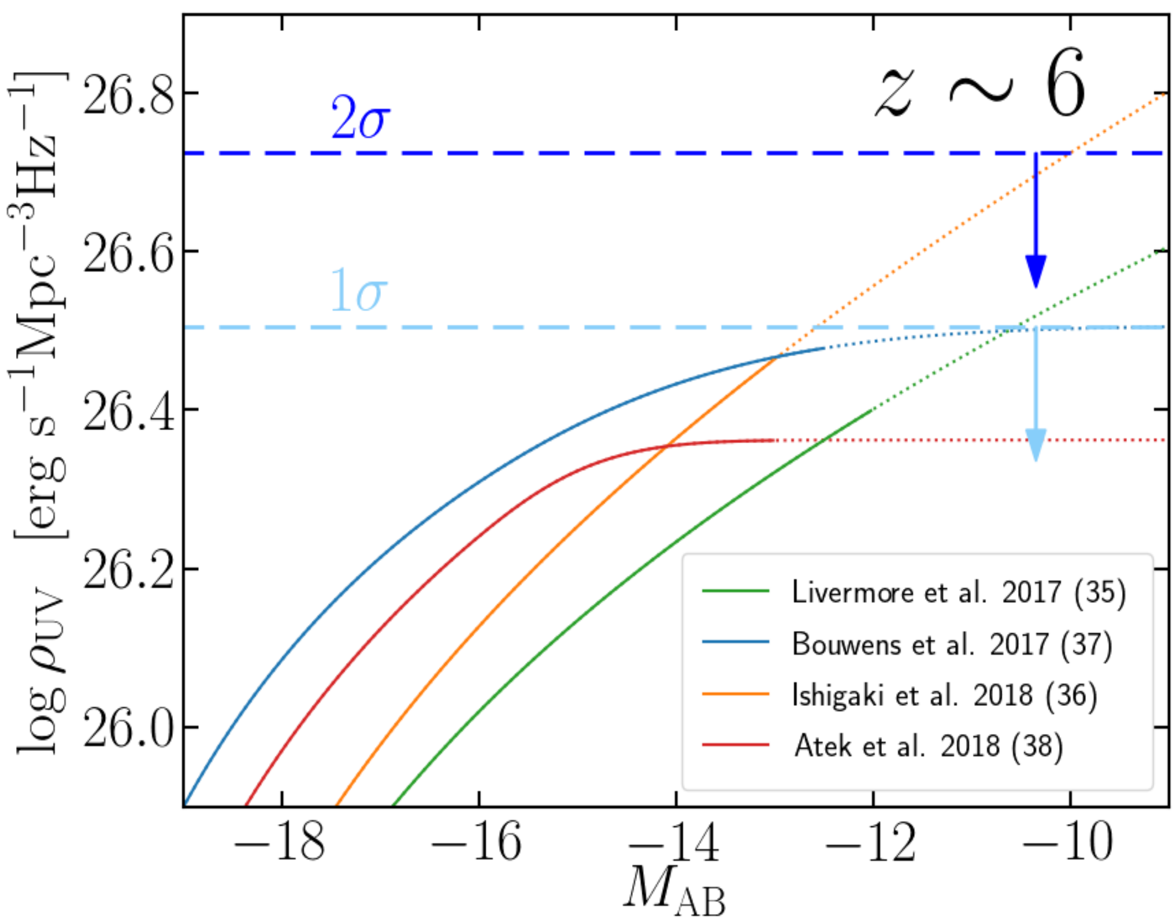
Hubble Frontier Fields



Hubble Deep Fields

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 coming up, stay tuned !

Faculty Position @ Clemson U.

- Position in MM/TD Astrophysics
- Deadline Oct 1st
- Link: https://jobregister.aas.org/ad/f8545be3

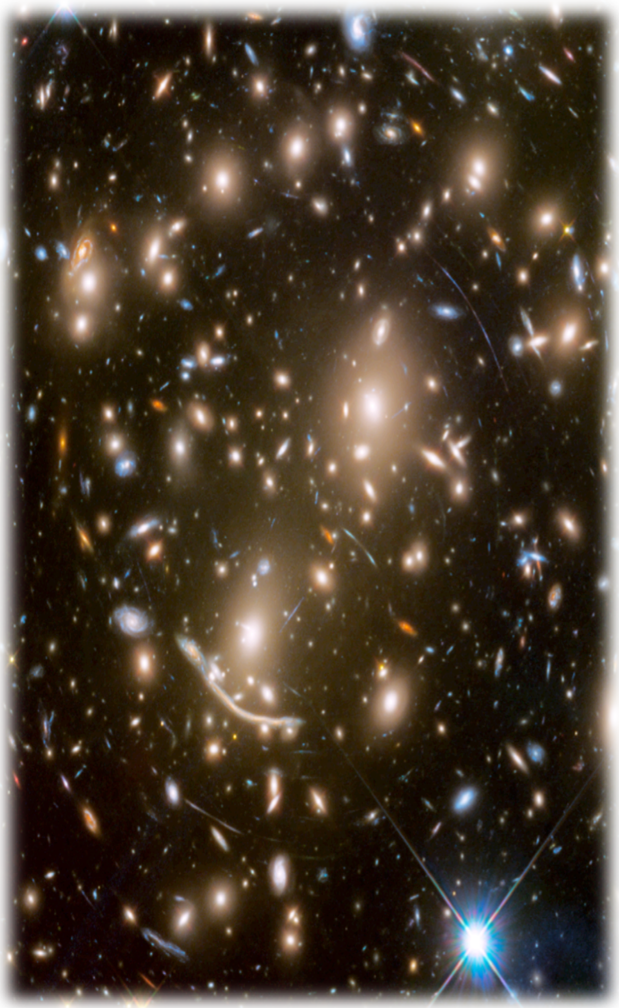
Testing models

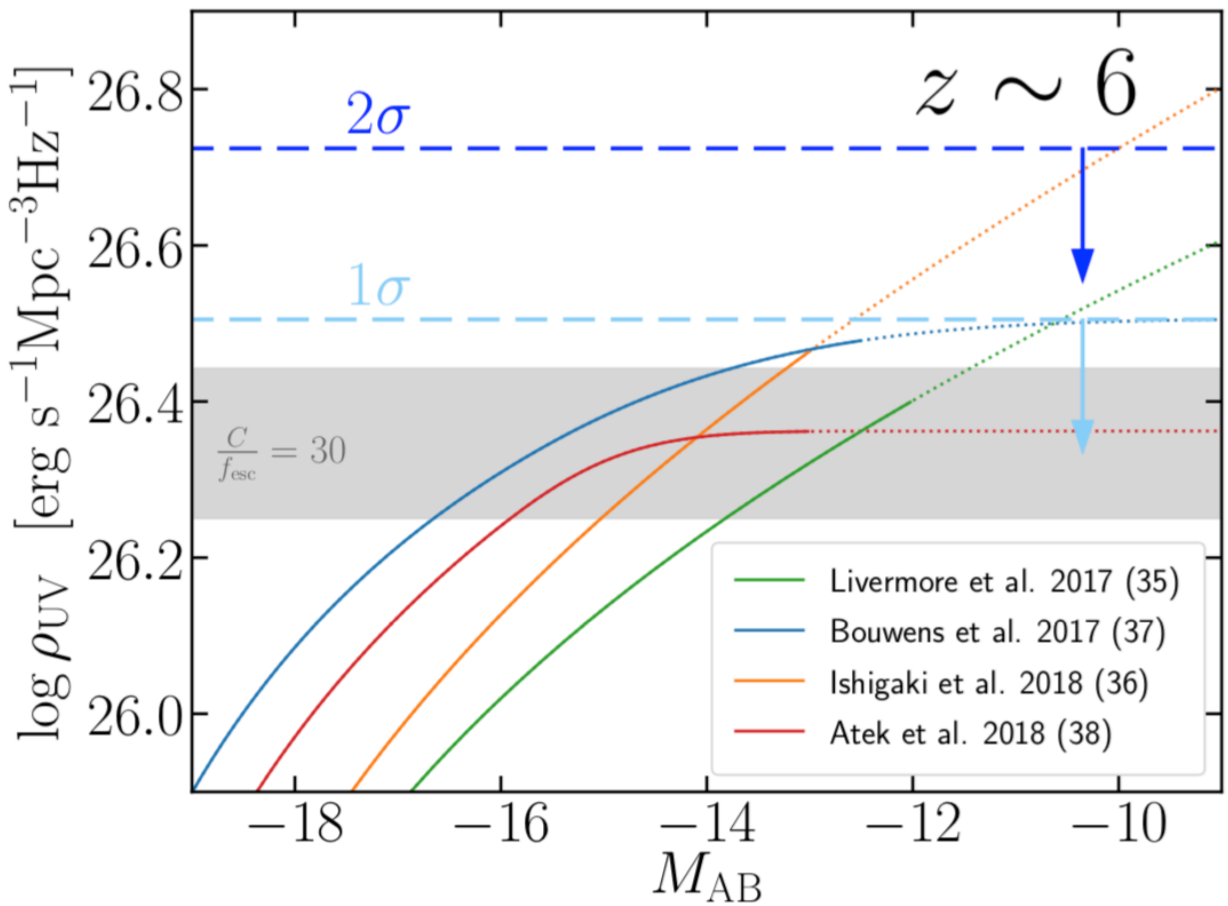
- Large power to discriminate between models
- Note: not all models reach 1TeV / z~3

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

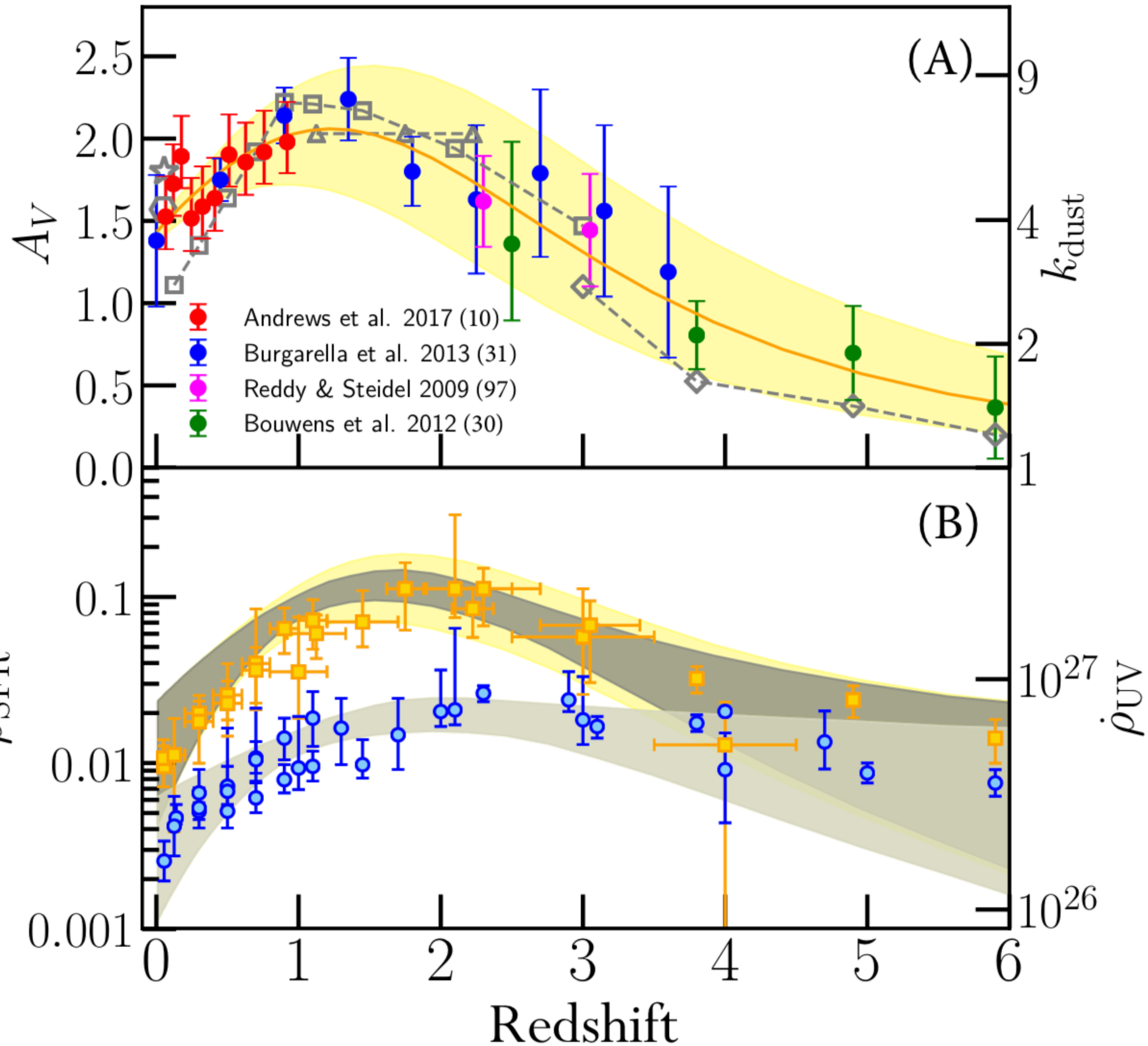
Re-ionization





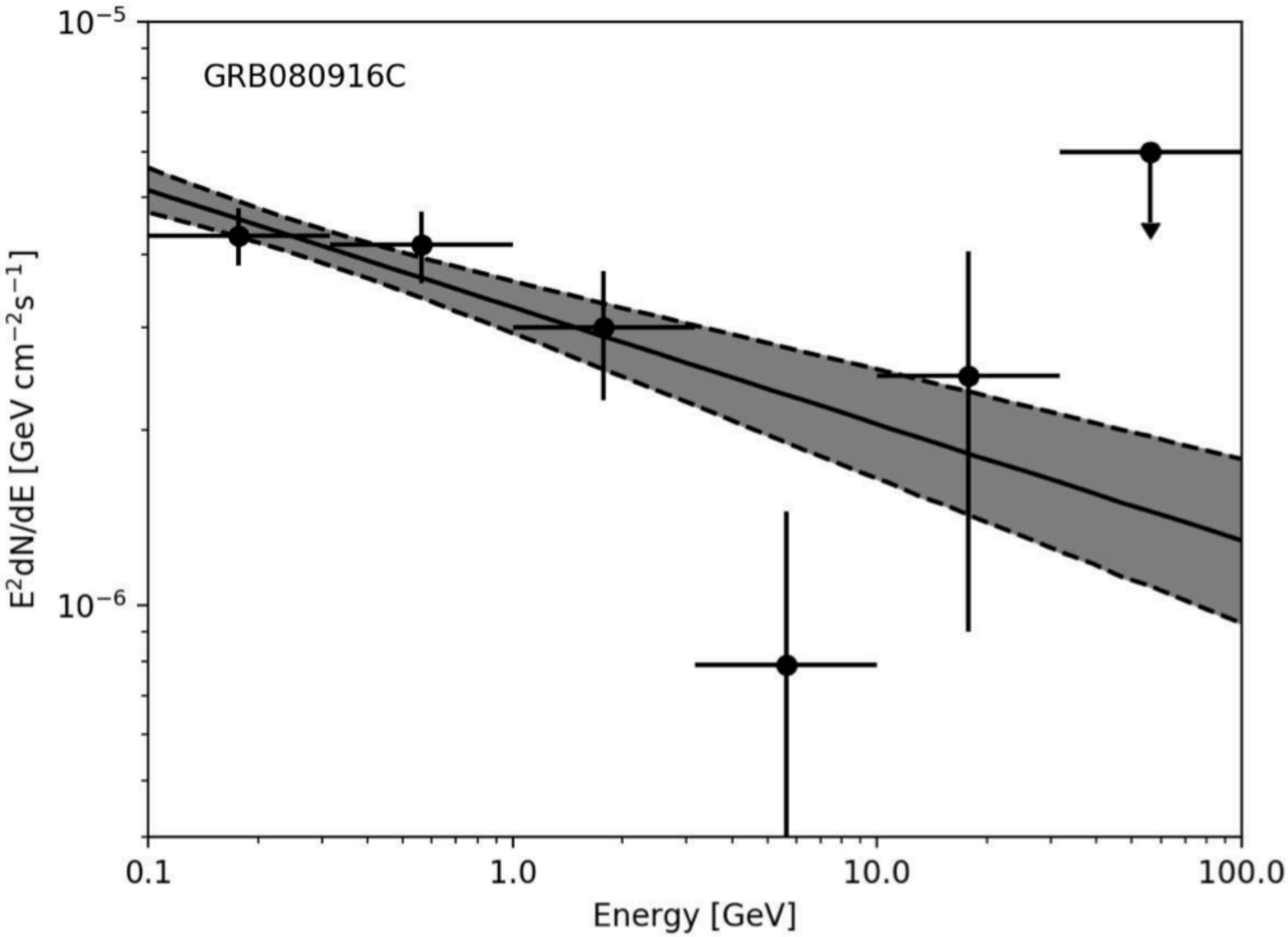
Hubble Frontier Fields

Dust

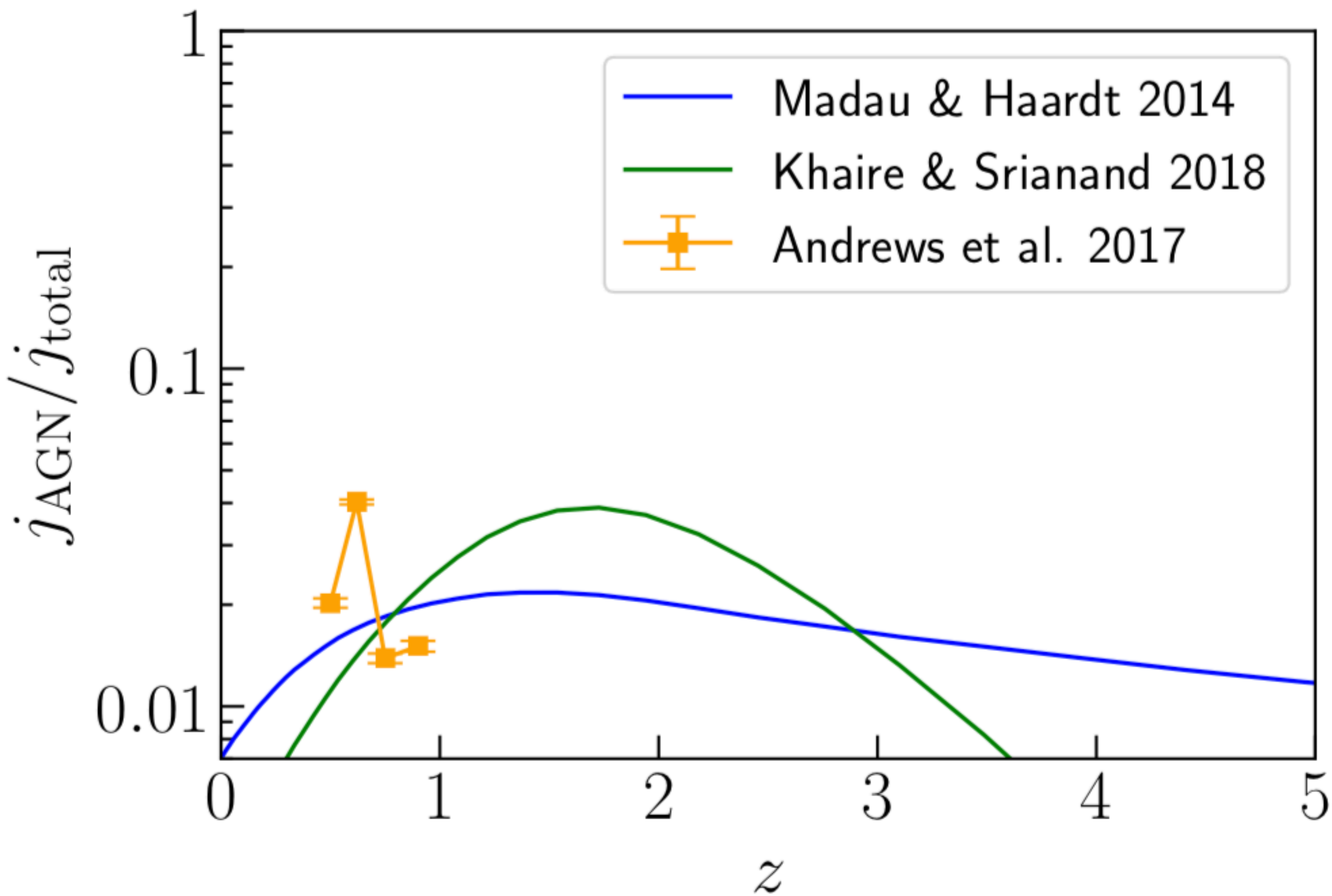


(A)
(B)
A_V
$k_{\rm dust}$
$\dot\rho_{\rm SFR}$
$\dot\rho_{\rm UV}$
Andrews et al. 2017 (10)
Burgarella et al. 2013 (31)
Reddy & Steidel 2009 (97)
Bouwens et al. 2012 (30)
Redshift
0
1
2
3
4
5
6
2.5
2.0
1.5
1.0
0.5
0.0
9
4
2
1
0.1
0.01
0.001
10^{27}
10^{26}

GRB 080916C

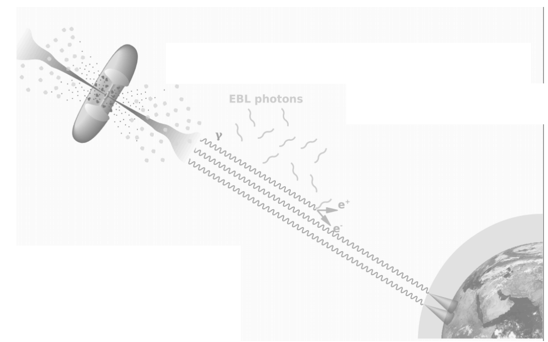

GRB080916C
10^{-5}
10^{-6}
E^2dN/dE [GeV cm^{-2}s^{-1}]
0.1
1.0
10.0
100.0
Energy [GeV]

AGN

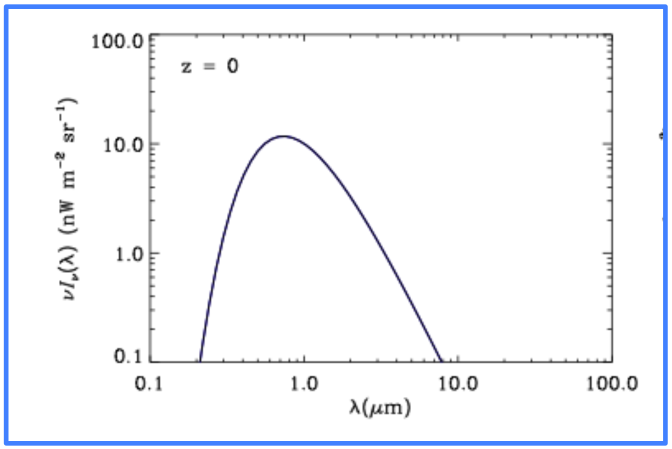

Madau & Haardt 2014
Khaire & Srianand 2018
Andrews et al. 2017
$j_{\mathrm{AGN}}/j_{\mathrm{total}}$
1
0.1
0.01
0
1
2
3
4
5
z

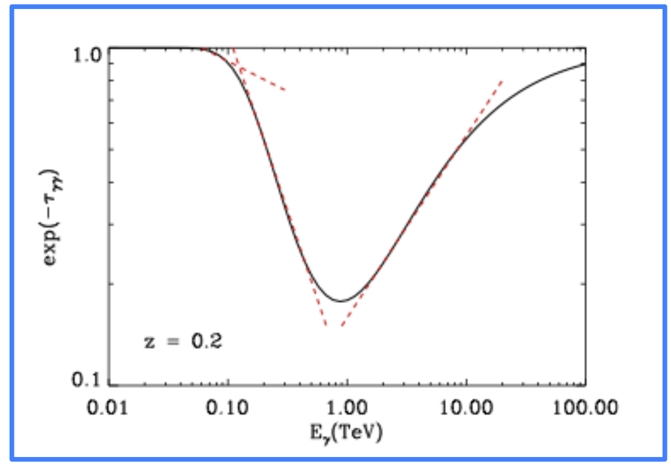
Background gamma-ray sources

- 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

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

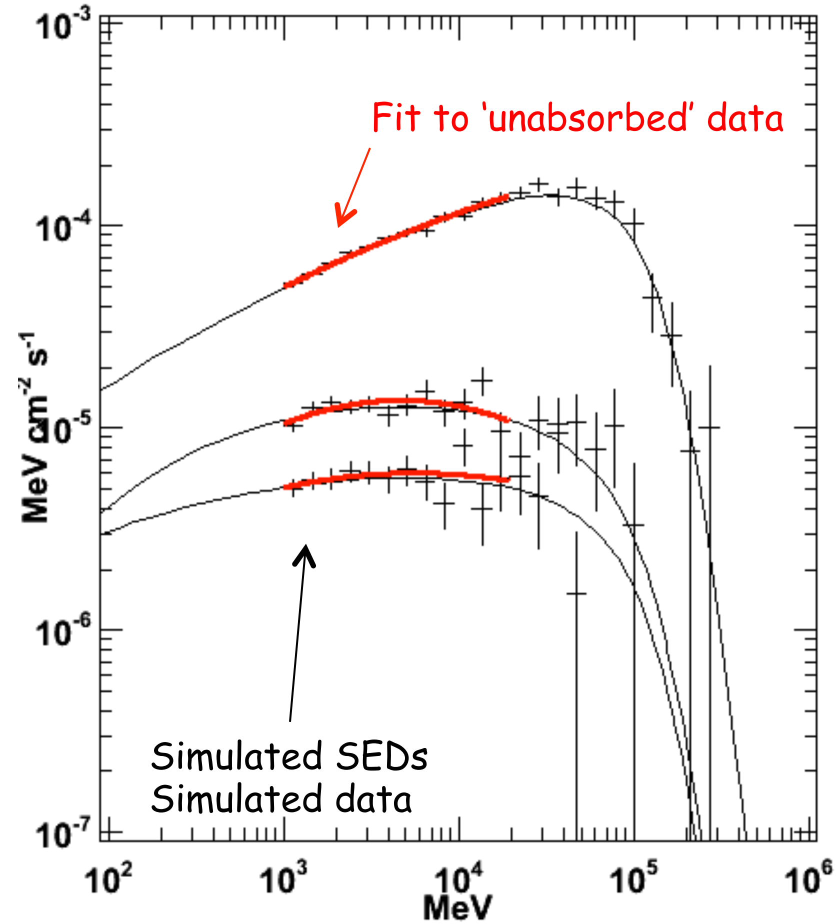
Optical Depth

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

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



$$F(E)_{absorbed} = F(E)_{intrinsic} \cdot e^{-b \cdot \tau_{model}}$$

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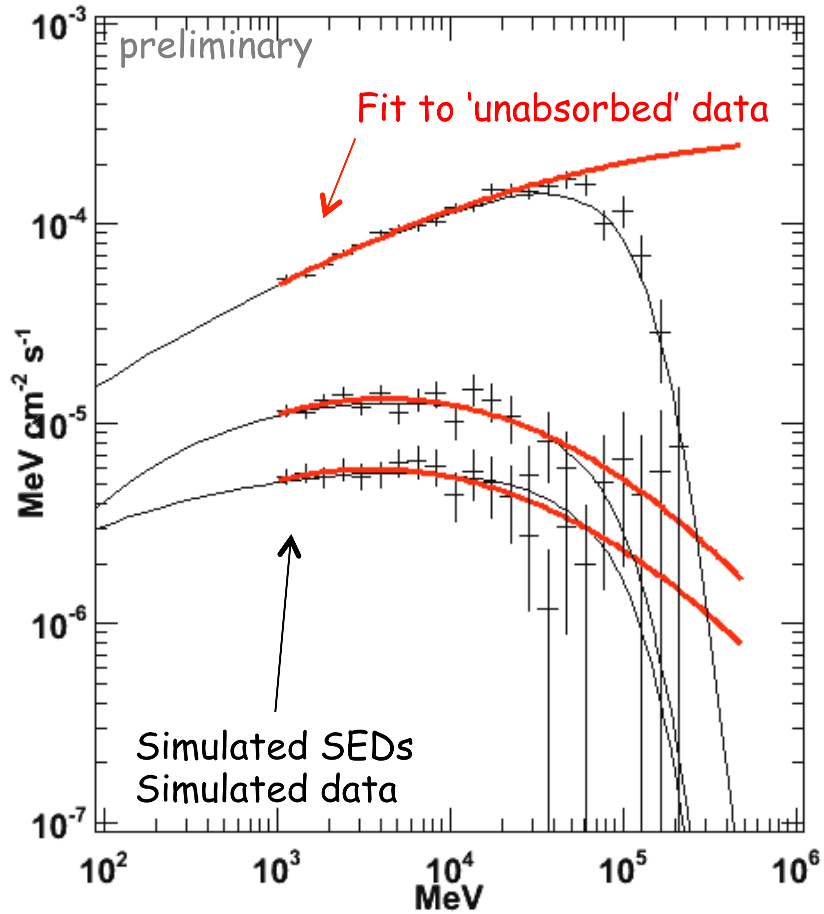
2. Extrapolate it to higher energies
3. Plug an attenuation model (τ(E,z)) and fit all sources at once for `b’
   1. b=0: there is no EBL
   2. b=1: EBL absorption is as predicted



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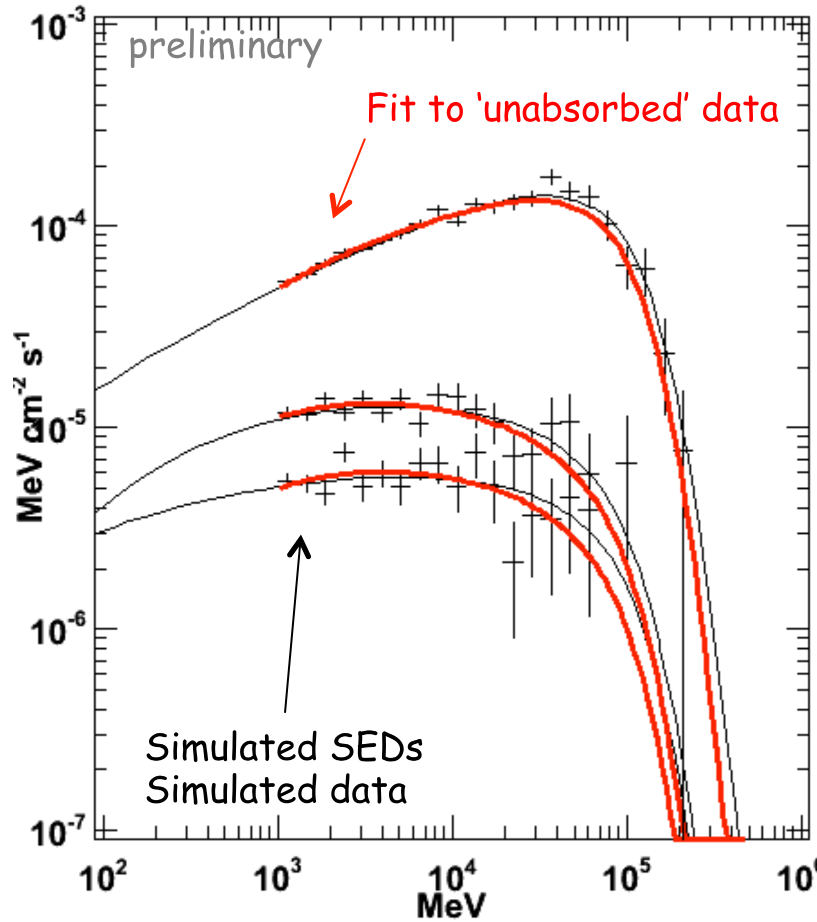
2. Extrapolate it to higher energies
3. Plug an attenuation model (τ(E,z)) and fit all sources at once for `b'
   1. b=0: there is no EBL
   2. b=1: EBL absorption is as predicted
   3. b≠1: EBL absorption is there but not as predicted



$$F(E)_{absorbed} = F(E)_{intrinsic} \cdot e^{-b \cdot \tau_{model}}$$

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