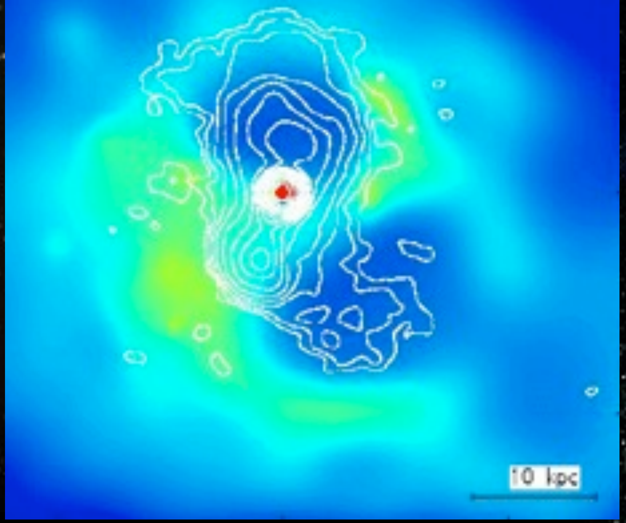




Exploring the Non-thermal Universe with Gamma Rays
On the occasion of the 60th birthday of Felix Aharonian
Barcelona, November 6 - 9, 2012

# EBL Extragalactic Background Light

**Joel Primack & Alberto Domínguez**

University of California Santa Cruz — FIAT SLUG

Fermi Gamma-ray Space Telescope

UC Riverside — University of California

MultiDark — Multimessenger Approach for Dark Matter Detection



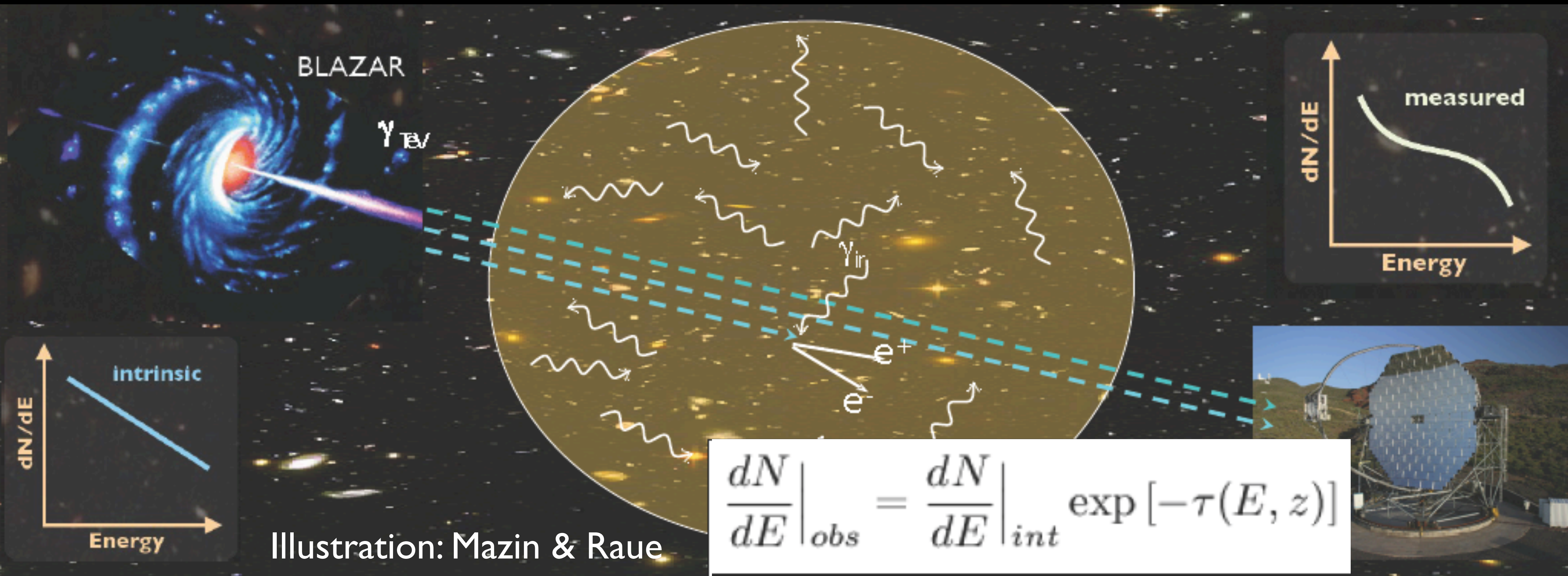



# Extragalactic Background Light (EBL)

**Joel Primack & Alberto Domínguez**

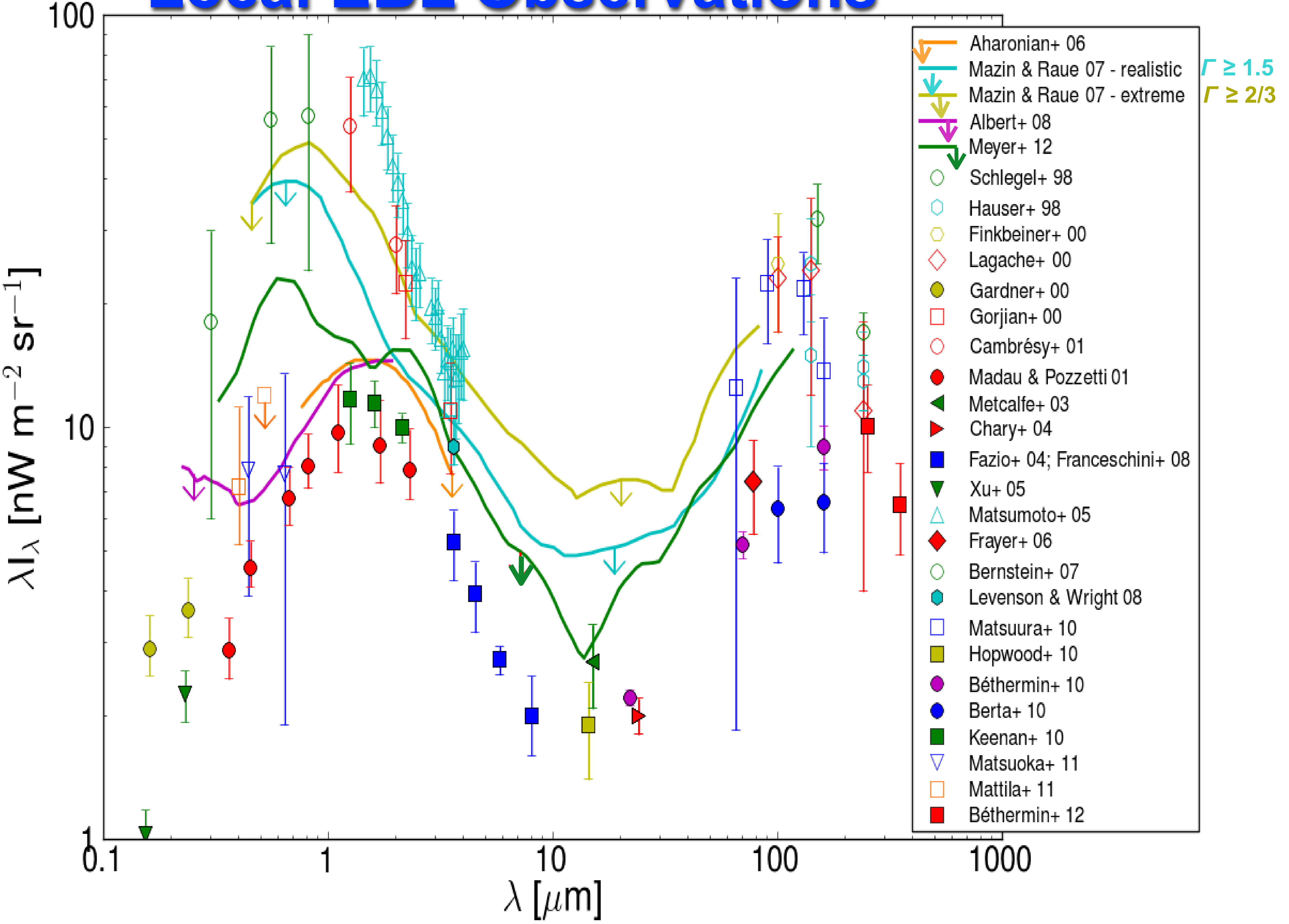
**Data from (non-) attenuation of gamma rays from blazars and gamma ray bursts (GRBs) give upper limits on the EBL from the UV to the mid-IR that are only a little above the lower limits from observed galaxies. New data on attenuation of gamma rays from blazers now lead to statistically significant measurements of the cosmic gamma ray horizon (CGRH) as a function of source redshift and gamma ray energy that are independent of EBL models. These new measurements are consistent with recent EBL calculations based both on multiwavelength observations of thousands of galaxies and also on semi-analytic models of the evolving galaxy population. Such comparisons account for all the light, including that from galaxies too faint to see. Catching a few high-redshift GRBs with Fermi or low-threshold atmospheric Cherenkov telescope (ACT) arrays could provide important new constraints on the high-redshift star formation history of the universe.**

# Gamma Ray Attenuation due to $\gamma\gamma \rightarrow e^+e^-$




**If we know the intrinsic spectrum, we can infer the optical depth $\tau(E,z)$ from the observed spectrum. In practice, we typically *assume* that $dN/dE|_{int}$ is not harder than $E^{-\Gamma}$ with $\Gamma = 1.5$, since local sources have $\Gamma \geq 2$. More conservatively, we can assume that $\Gamma \geq 2/3$.**

# Local EBL Observations



# Evolution Calculated from Observations Using AEGIS Multiwavelength Data

Alberto DomÍnguez, Joel Primack, et al. (MNRAS, 2011)

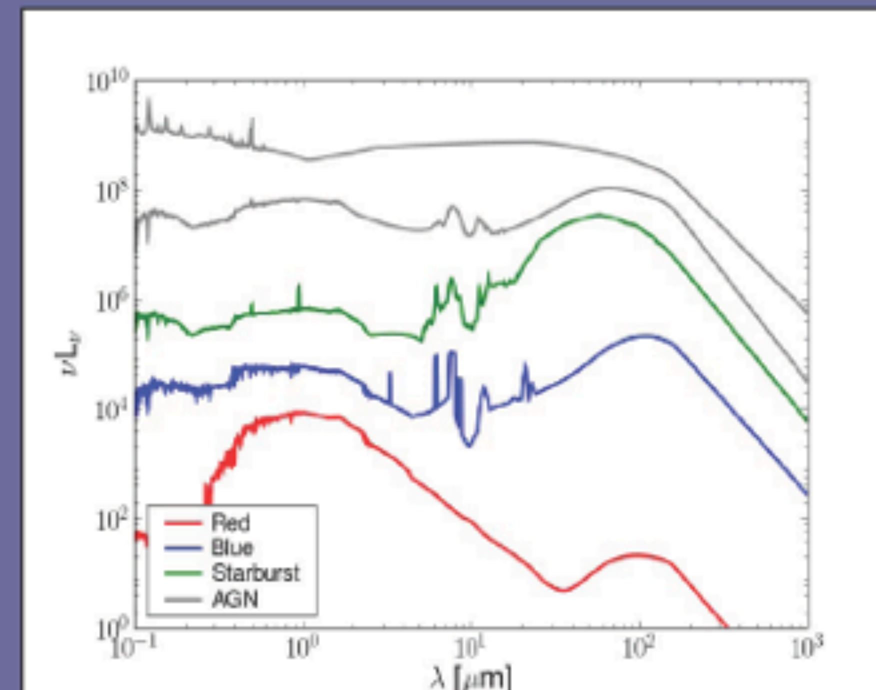
$$j_i(\lambda,z) = j_i^{faint} + j_i^{mid} + j_i^{bright} =$$

$$= \int_{M_1}^{M_2} \Phi(M_K,z) f_i T_i(M_K,\lambda) dM_K +$$

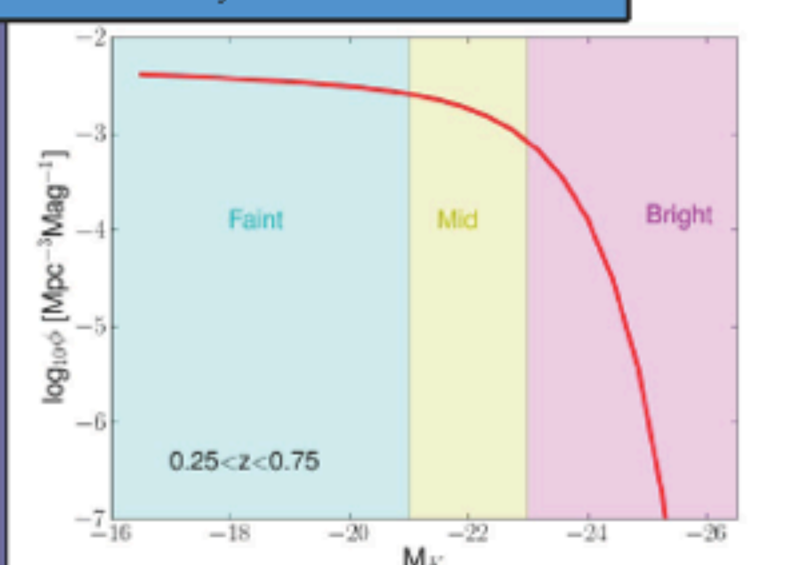
$$+ \int_{M_2}^{M_3} \Phi(M_K,z) m_i T_i(M_K,\lambda) dM_K +$$

$$+ \int_{M_3}^{M_4} \Phi(M_K,z) b_i T_i(M_K,\lambda) dM_K$$

Spectral energy distributions
SWIRE template library, Polletta+ 07




Luminosity function
observed K-band, Cirasuolo+ 09



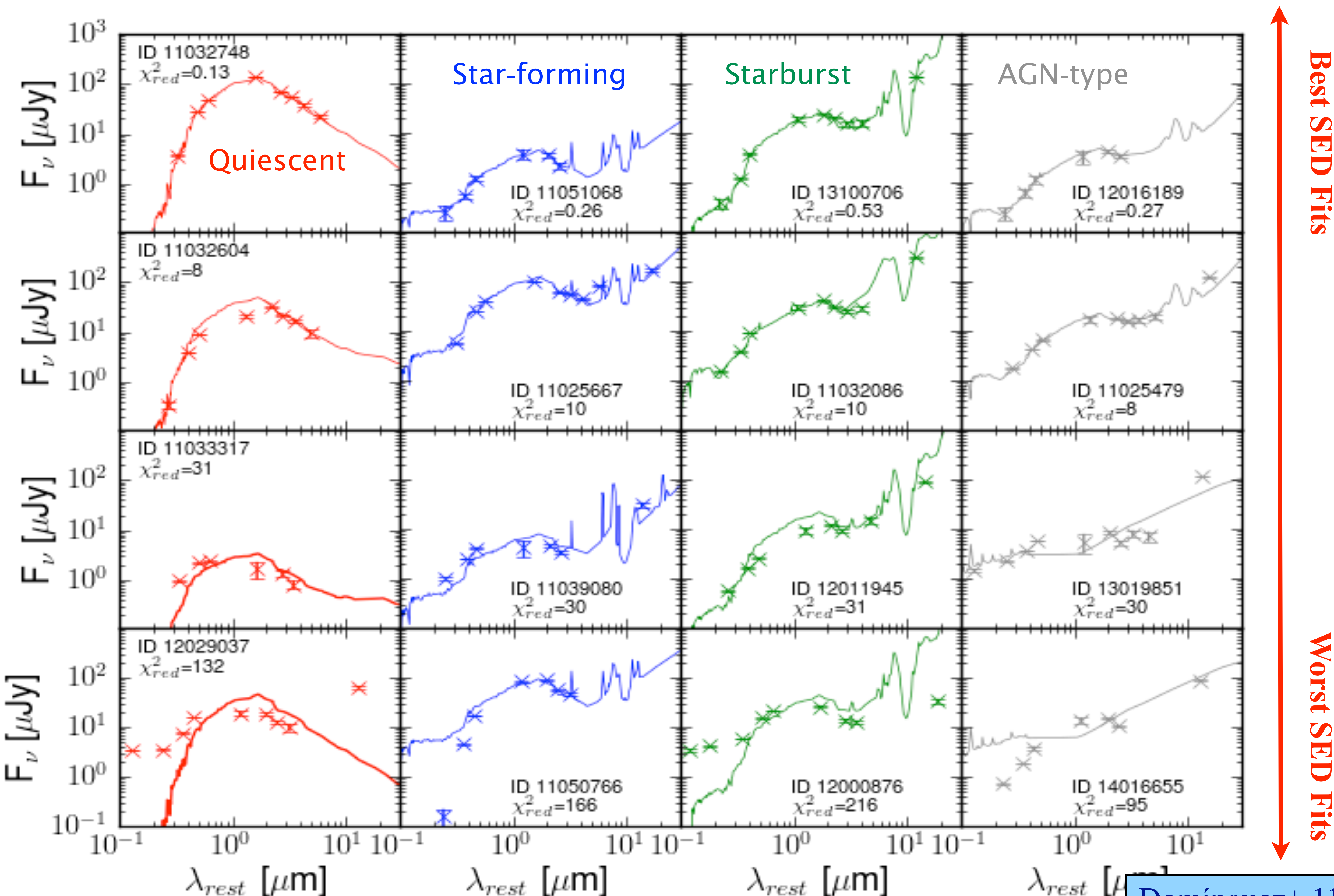

Spectral-type fractions

$$\lambda I_\lambda(z) = \frac{c}{4\pi} \int_z^{z_{max}} j_{total}[\lambda(1+z)/(1+z'), z'] \left|\frac{dt}{dz'}\right| dz'$$


http://aegis.ucolick.org/

# $\chi^2$ SED Fitting

Le PHARE code for fitting the SWIRE templates in FUV, NUV, B, R, I, Ks, IRAC1, 2, 3, 4 and MIPS24




Domínguez+ 11

# SED-Type Evolution

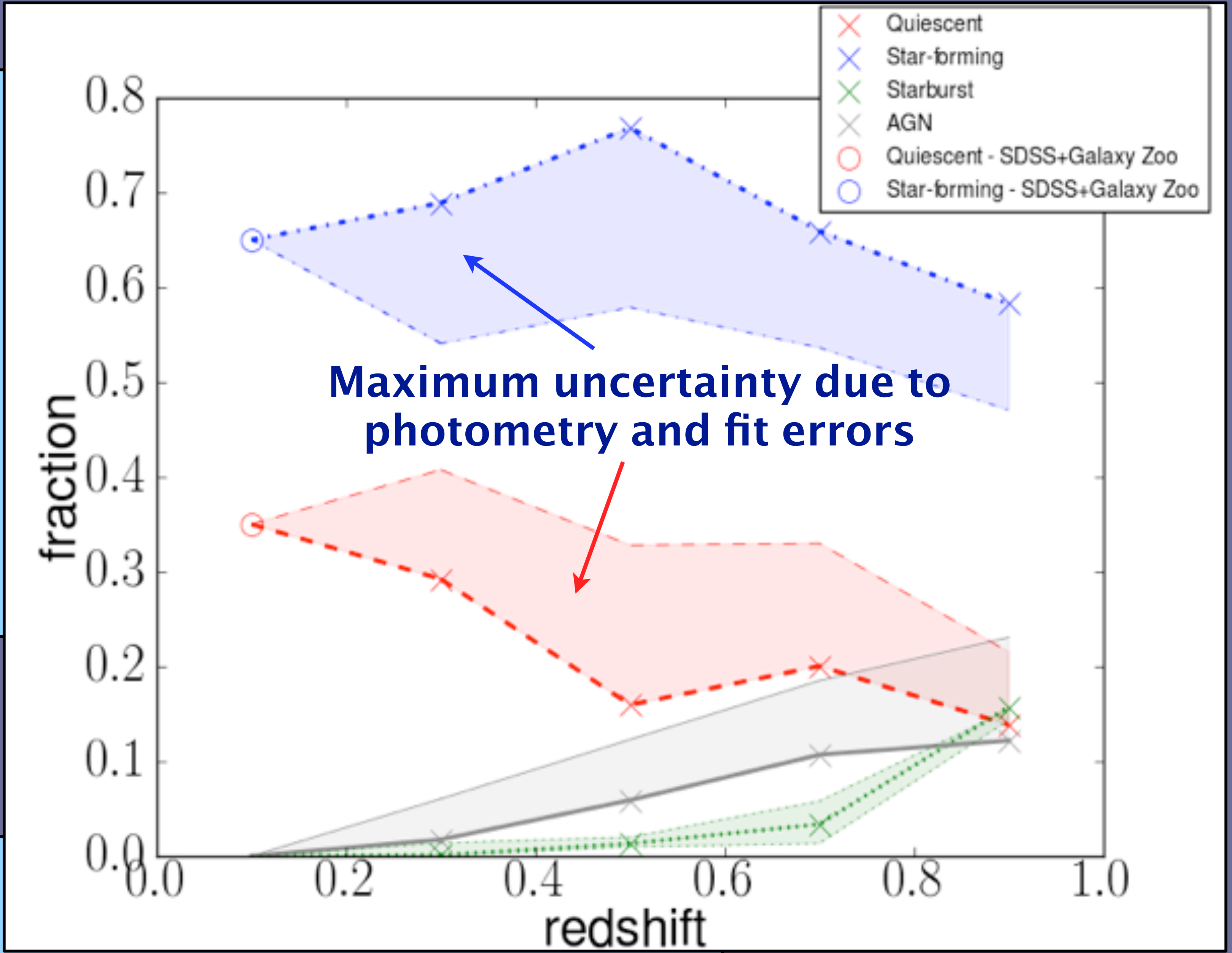
Local fractions, z<0.2:

Goto+ 03, morphologically classified from Sloan converted to spectral classification using results from Galaxy Zoo

Skibba+ 09 ~6% blue ellipticals
Schawinski+ 09 ~25% red spirals

Results:

35% red-type galaxies
65% blue-type galaxies




**High-redshift universe, z>1:**

Two approaches:
1. Keep constant the fractions of our last redshift bin (Fiducial Model), or
2. Quickly increase starburst population from 16% at $z = 0.9$ to 60% at $z \geq 2$

We find that the differences in the predicted EBL are small except at long wavelengths, affecting attenuation only for $E \geq 5$ TeV.

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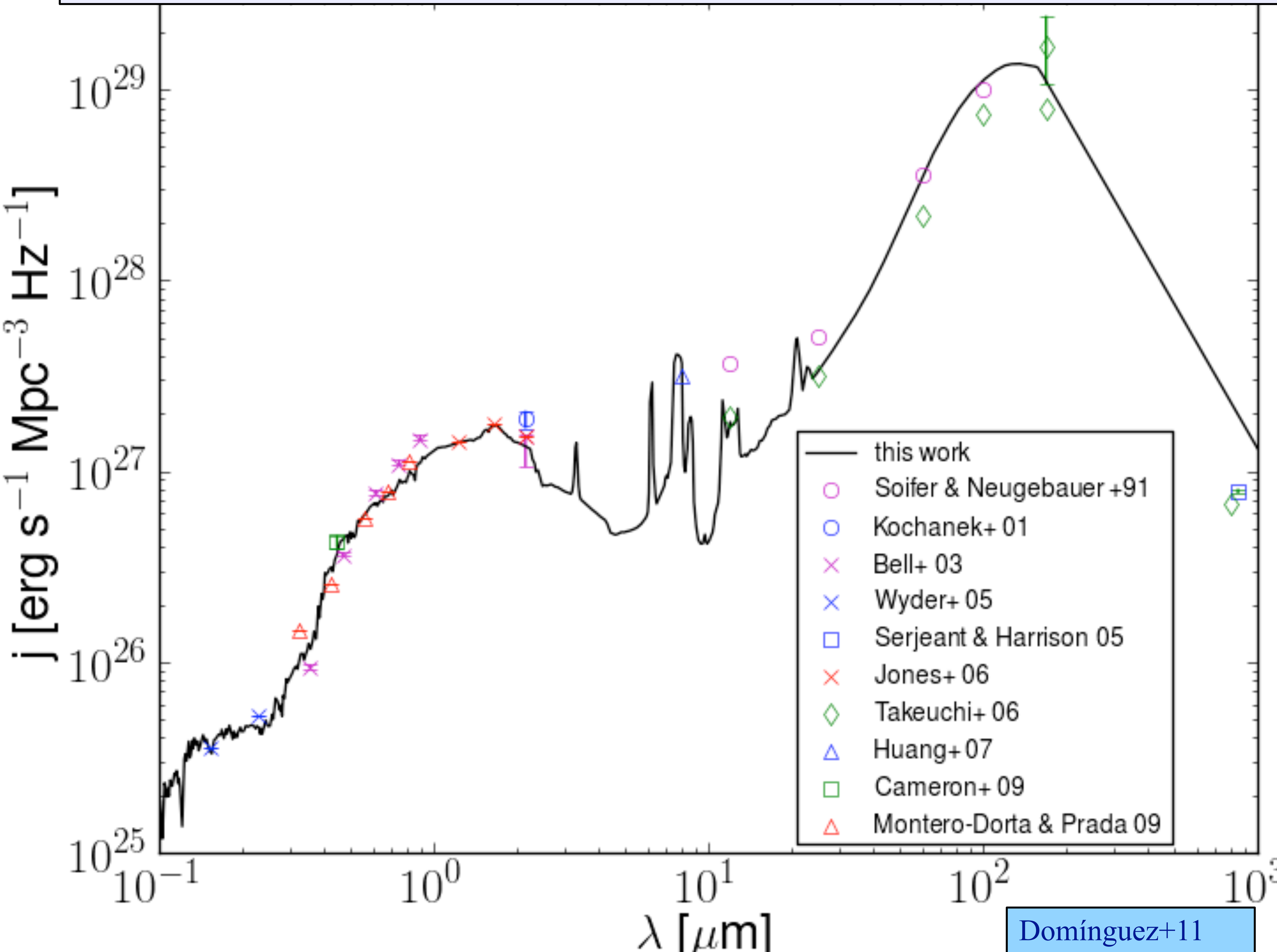
# Local Luminosity Density

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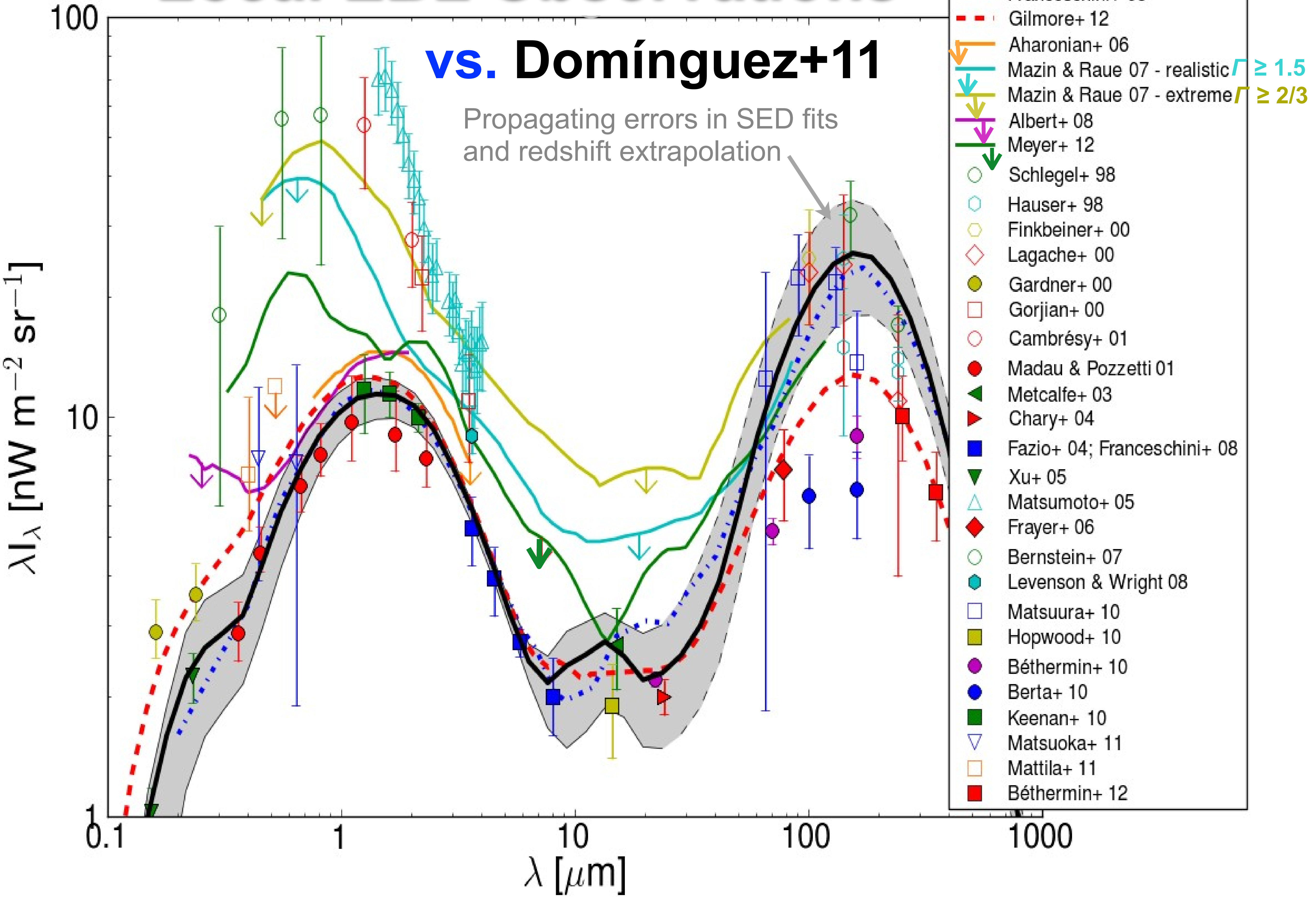
# Local EBL Observations

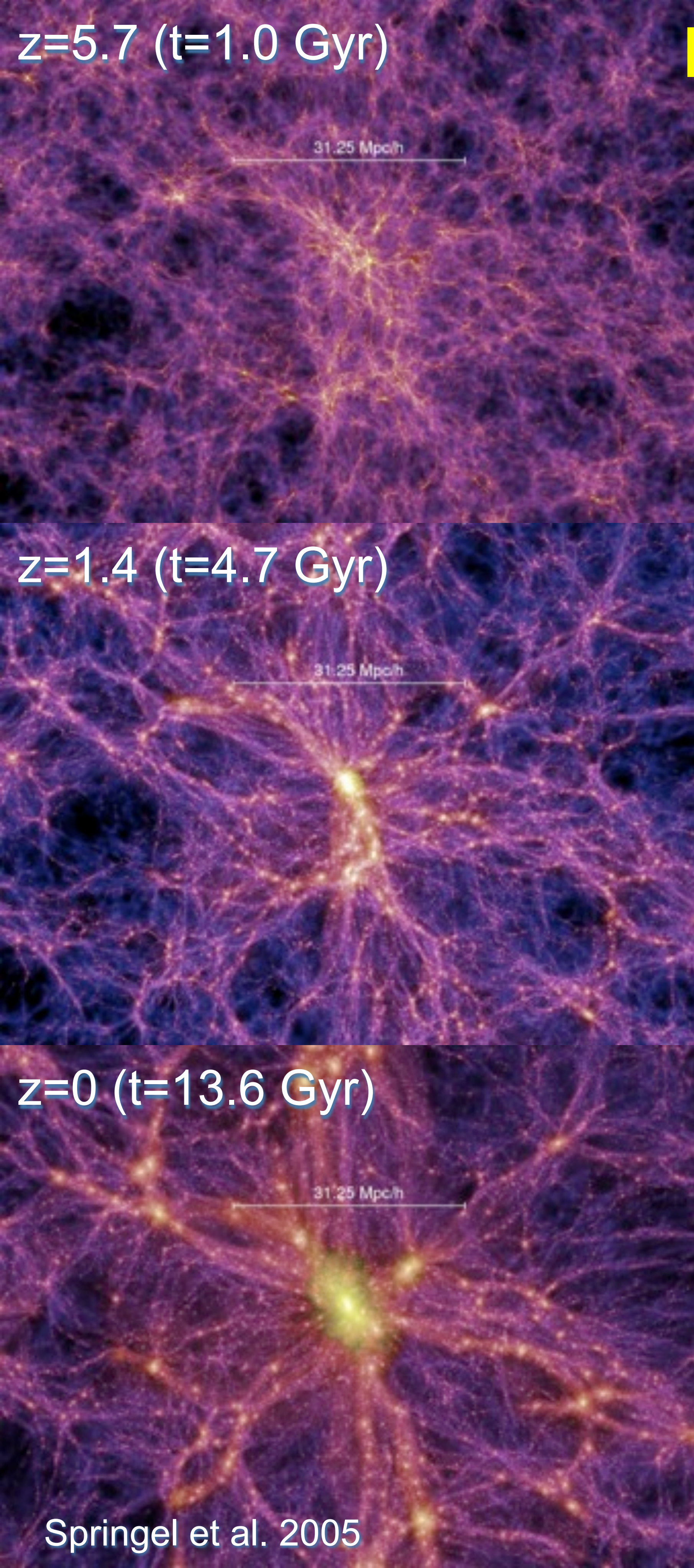
## vs. Domínguez+11



# EBL Calculated by Forward Evolution using SAMs

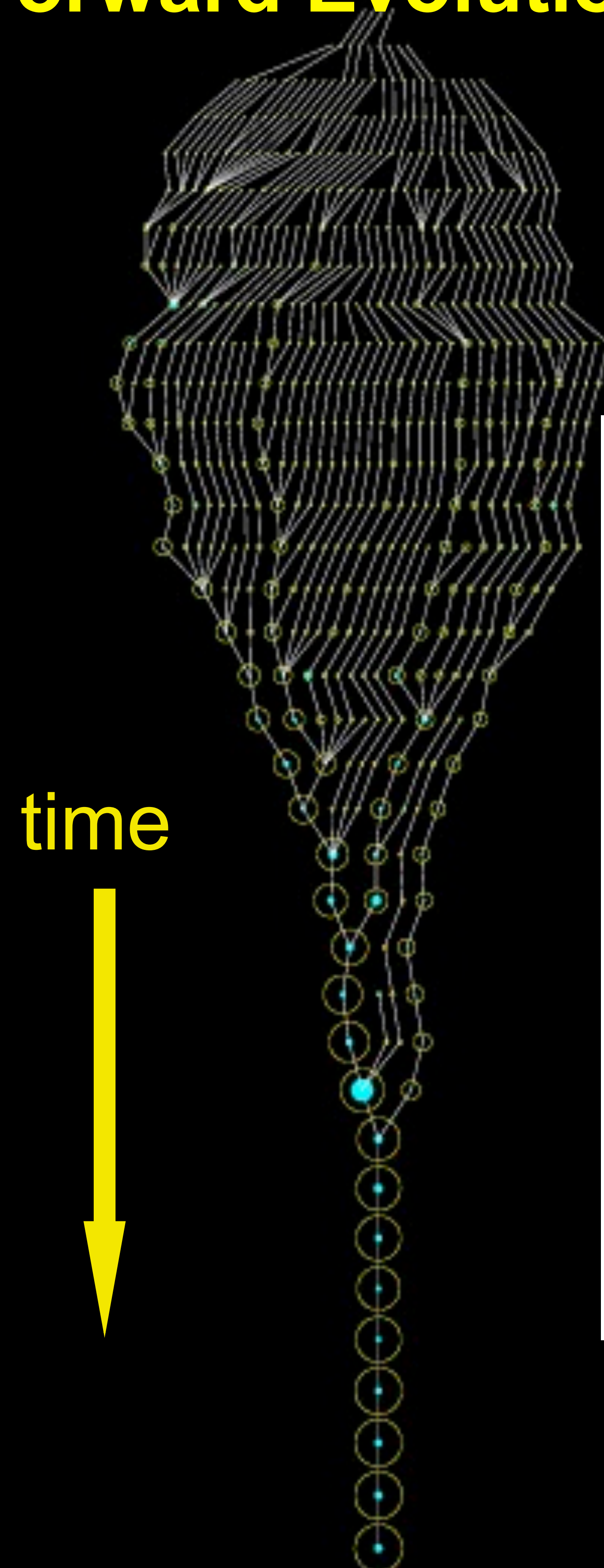
When we first tried doing this (Primack & MacMinn 1996, presented at Felix Aharonian's first Heidelberg conference), both the stellar initial mass function (IMF) and the values of the cosmological parameters were quite uncertain. After 1998, the cosmological model was known to be ΛCDM although it was still necessary to consider various cosmological parameters in models. Now the parameters are known rather precisely, and our latest semi-analytic model (SAM) uses the current (WMAP5) cosmological parameters. With improved simulations and better galaxy data, we can now normalize SAMs better and determine the key astrophysical processes to include in them.

Remaining uncertainties include whether the IMF is different in different galaxies (possibly "bottom-heavy" in massive galaxies), feedback from AGN, the nature of sub-mm galaxies, and the star formation rate at high redshifts.




Springel et al. 2005

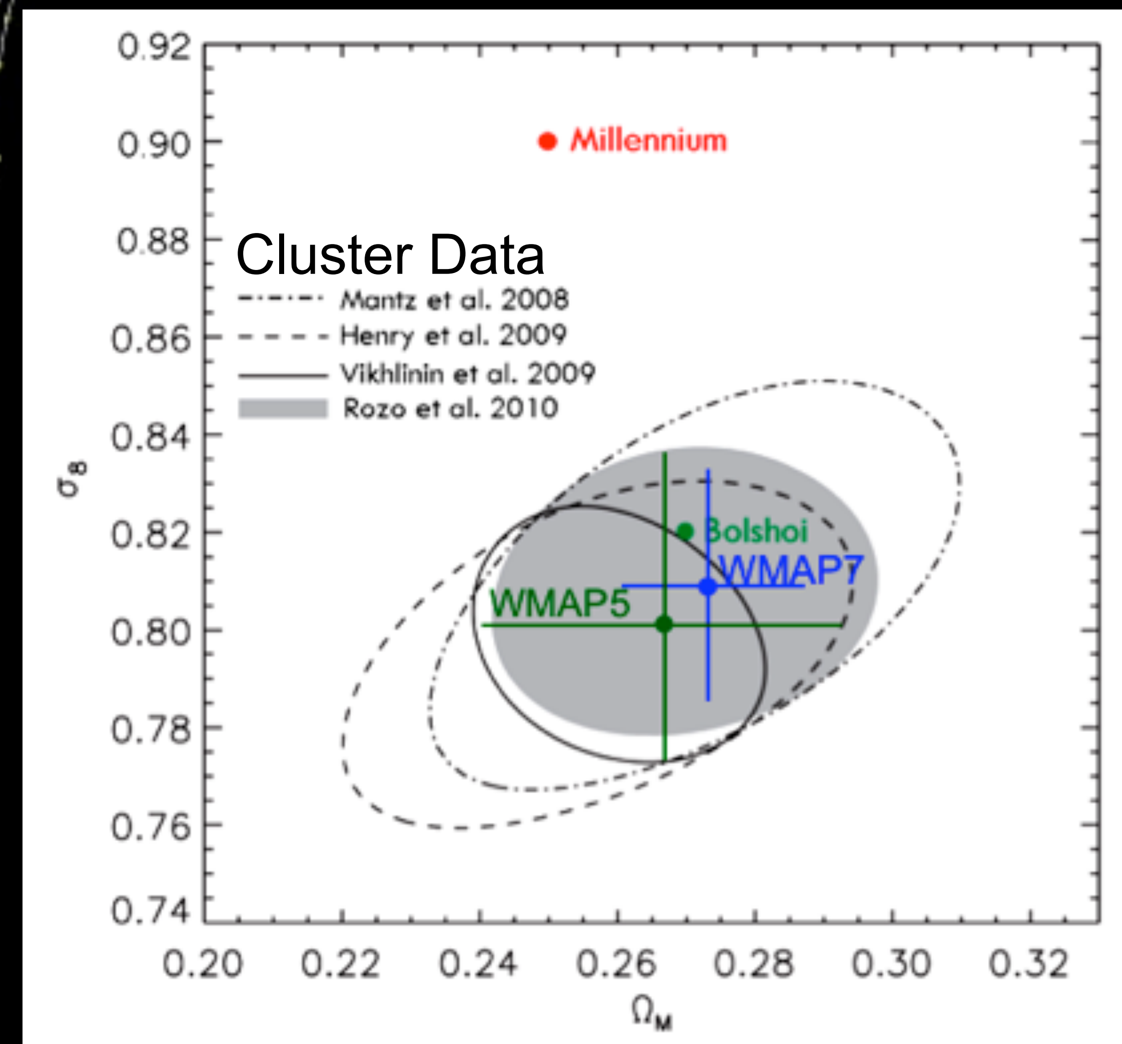
# Forward Evolution




Wechsler et al. 2002

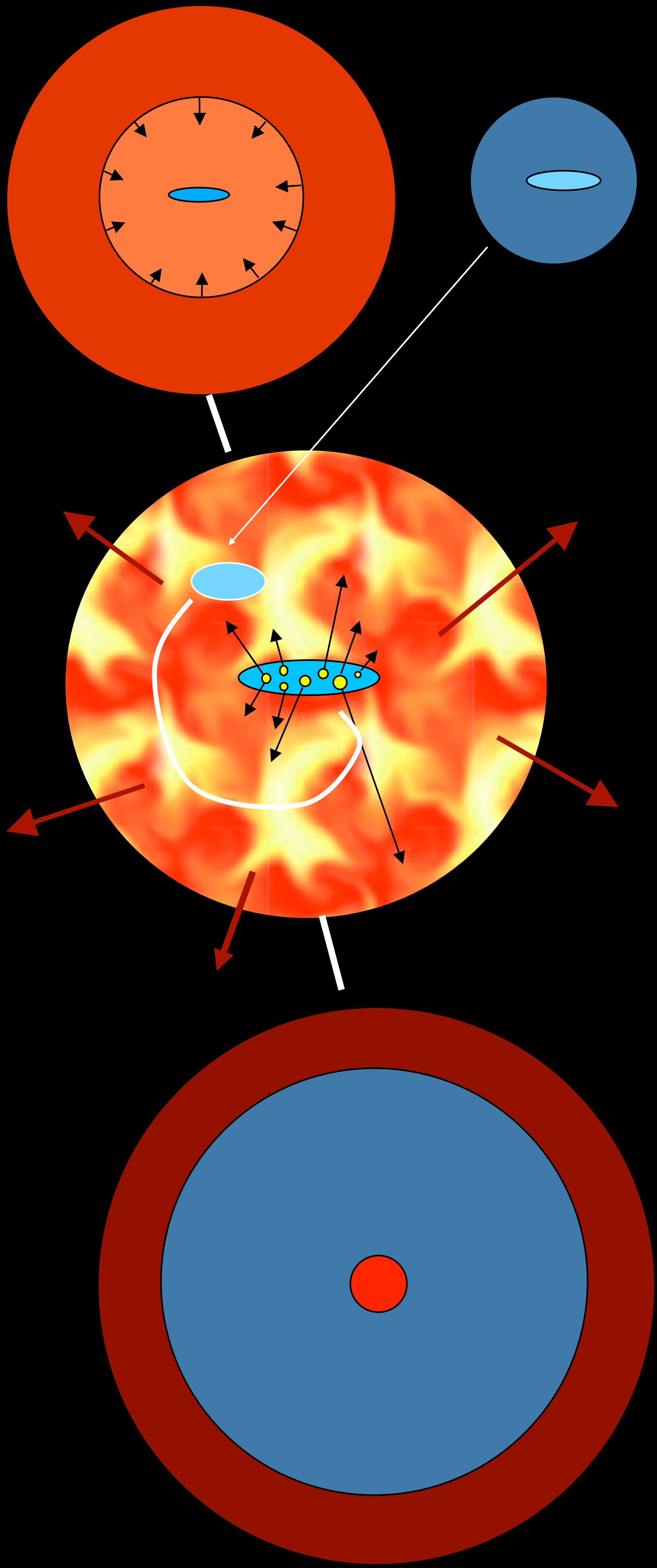
# Present status of ΛCDM "Double Dark" theory:

- cosmological parameters are now well constrained by observations




- mass accretion history of dark matter halos is represented by 'merger trees' like the one at left

# Galaxy Formation in ΛCDM

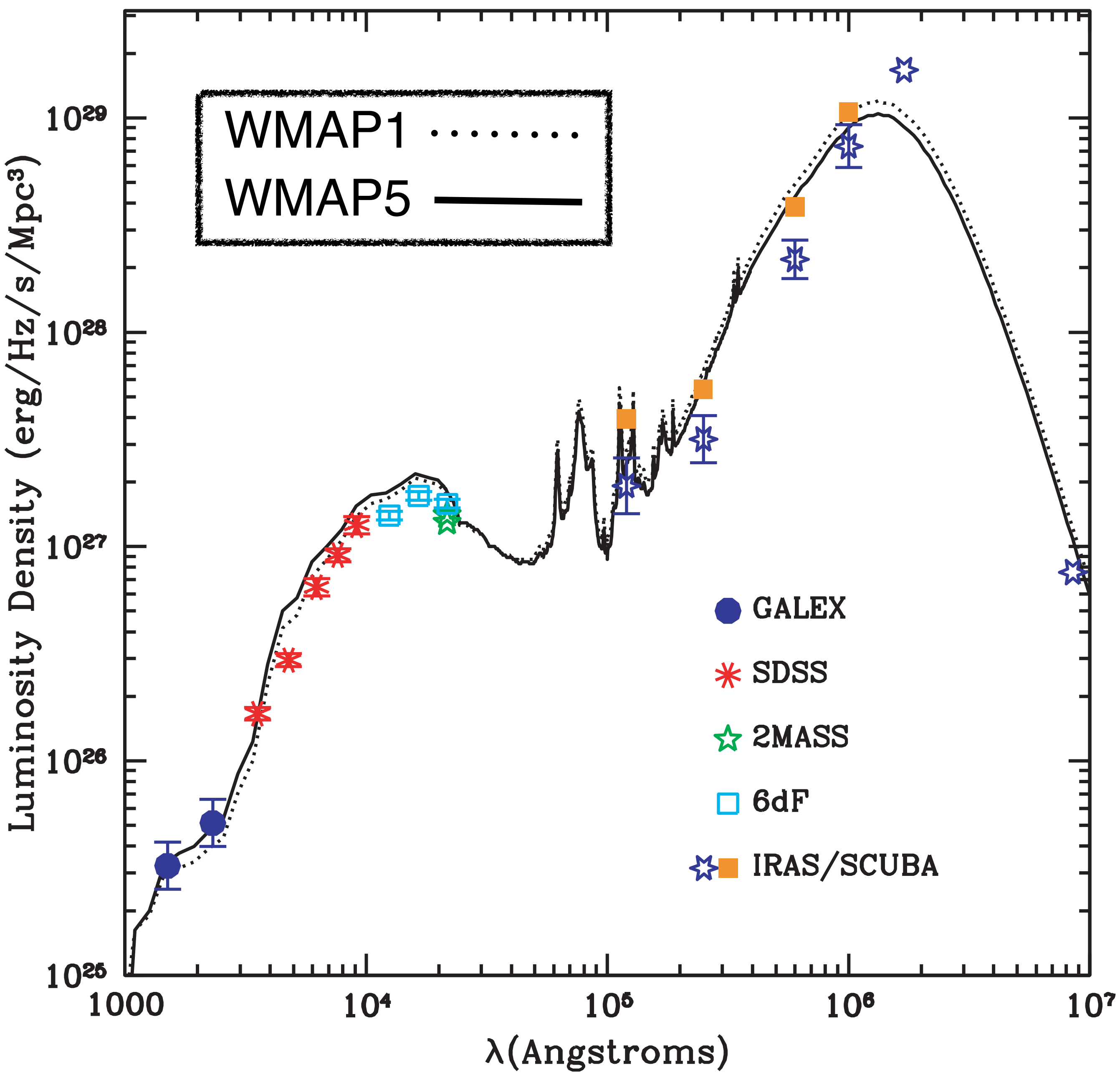


- gas is collisionally heated when perturbations 'turn around' and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law)
- massive stars and SNae reheat (and in small halos expel) cold gas and some metals
- galaxy mergers trigger bursts of star formation; 'major' mergers transform disks into spheroids and fuel AGN
- AGN feedback cuts off star formation

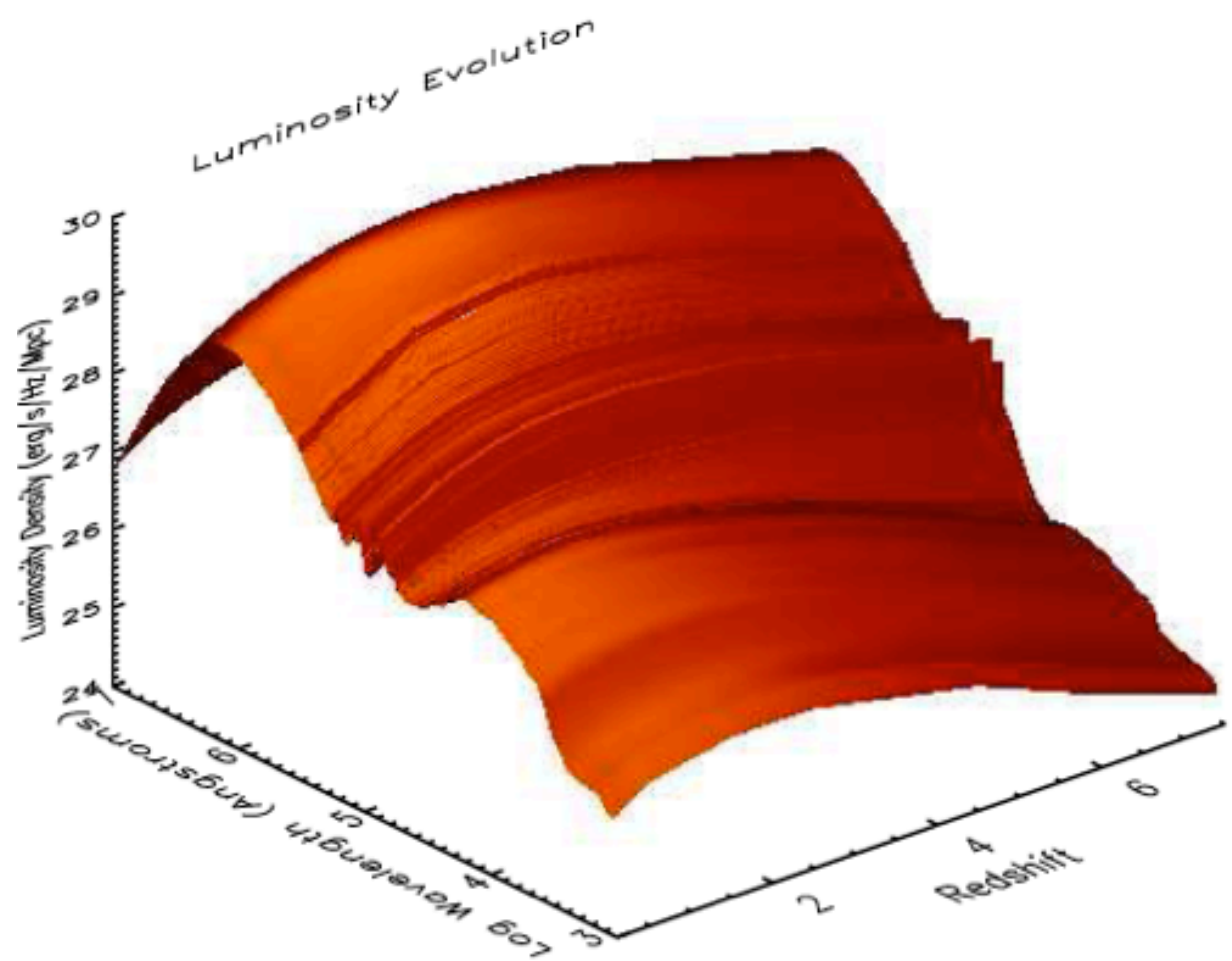
White & Frenk 91; Kauffmann+93; Cole+94; Somerville & Primack 99; Cole+00; Somerville, Primack, & Faber 01; Croton et al. 2006; Somerville +08; Fanidakis+09; Guo+2011; Somerville, Gilmore, Primack, & Domínguez 12 (discussed here)

# Some Results from our Semi-Analytic Models

## z=0 Luminosity Density




## Evolving Luminosity Density

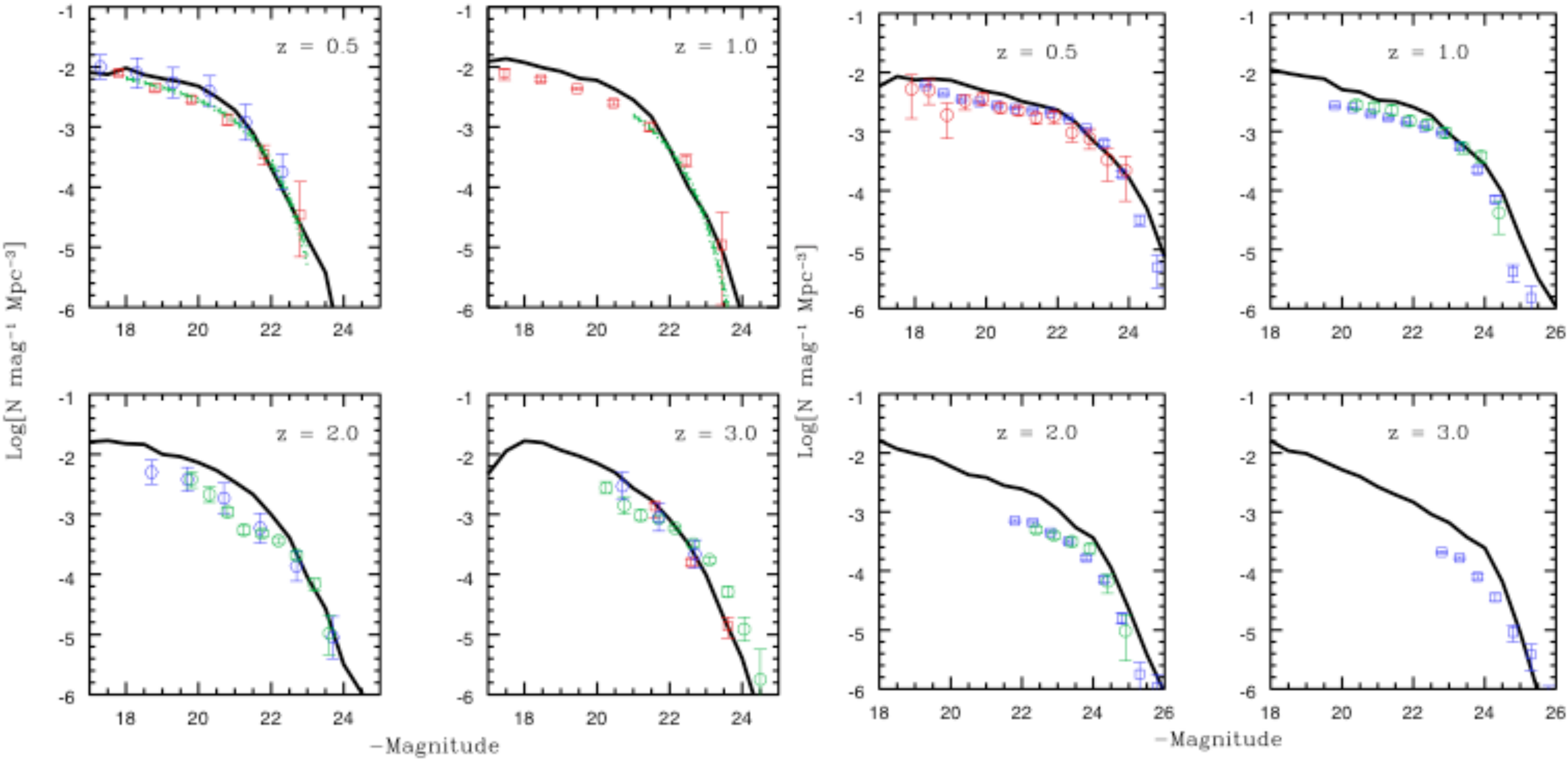



Gilmore, Somerville, Primack, & Domínguez (2012)

# Some Results from our Semi-Analytic Models

## Evolving Luminosity Functions

### B-band K-band



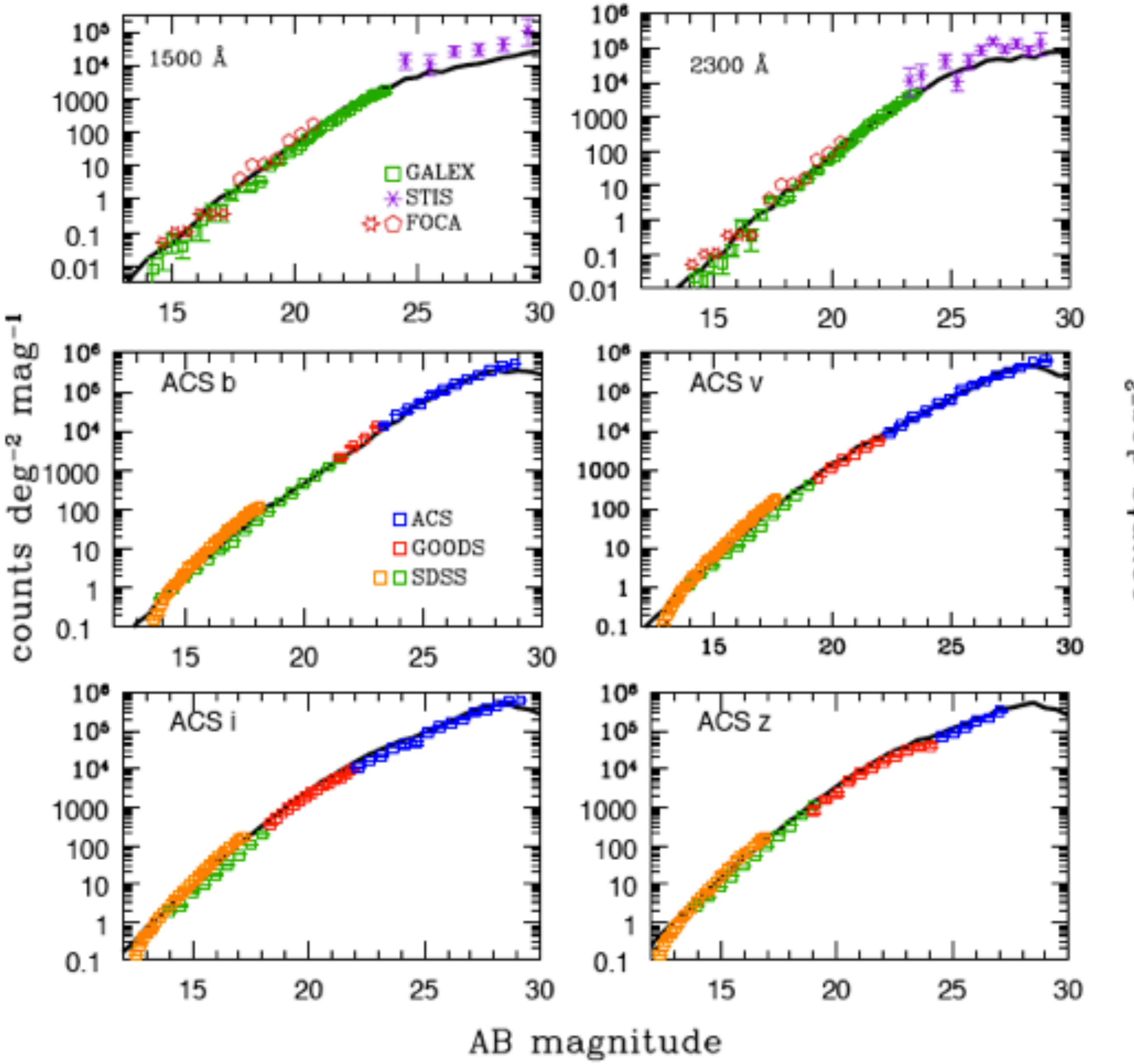

An advantage of the SAM approach is that it is possible to compare predictions and observations at all redshifts and in all spectral bands.

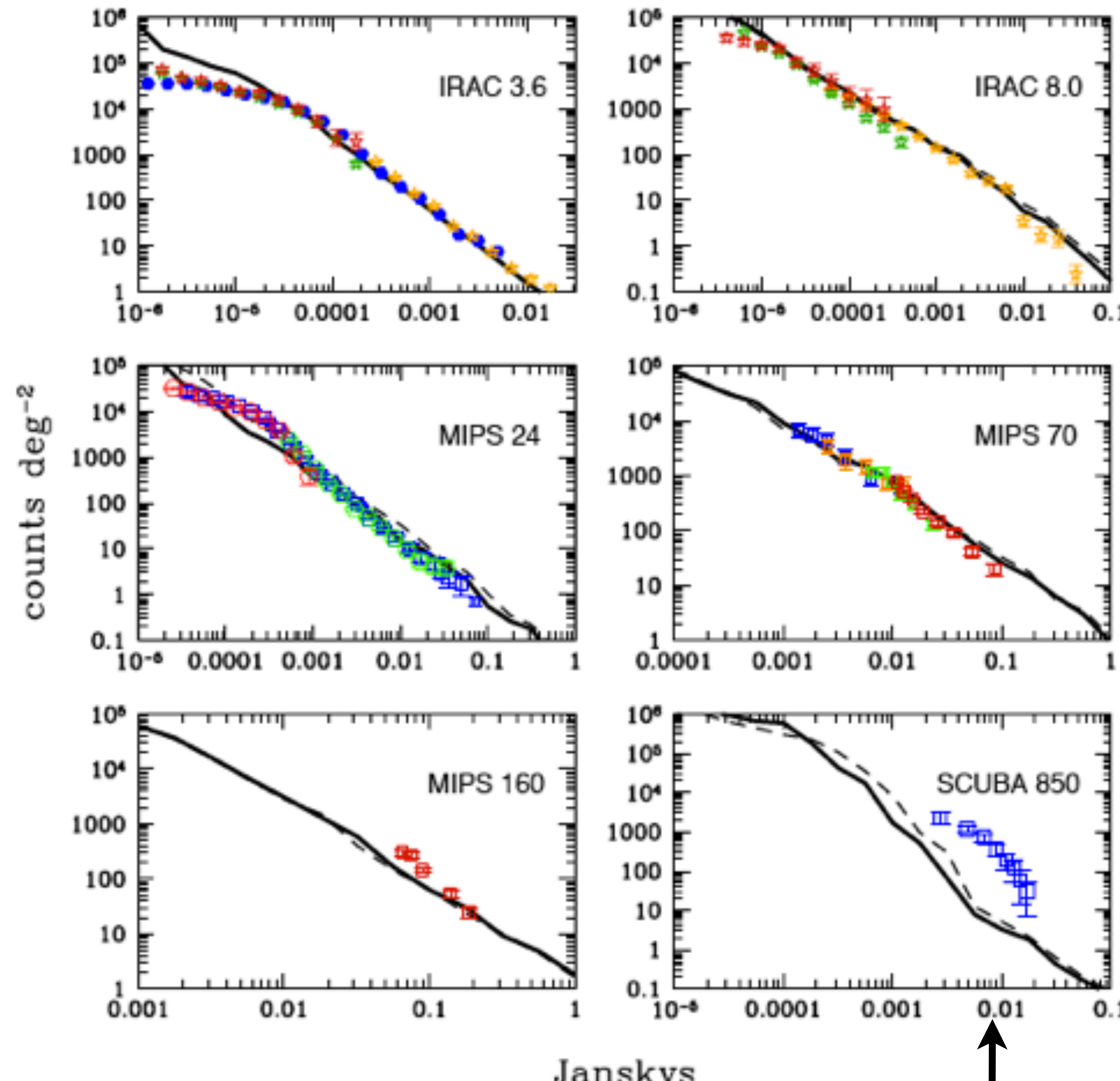
Gilmore, Somerville, Primack, & Domínguez (2012)

# Some Results from our Semi-Analytic Models

## Number Counts in UV, b, v, i, and z Bands

## 3.6, 8, 24 and 24, 70, 160, & 850 μm Bands

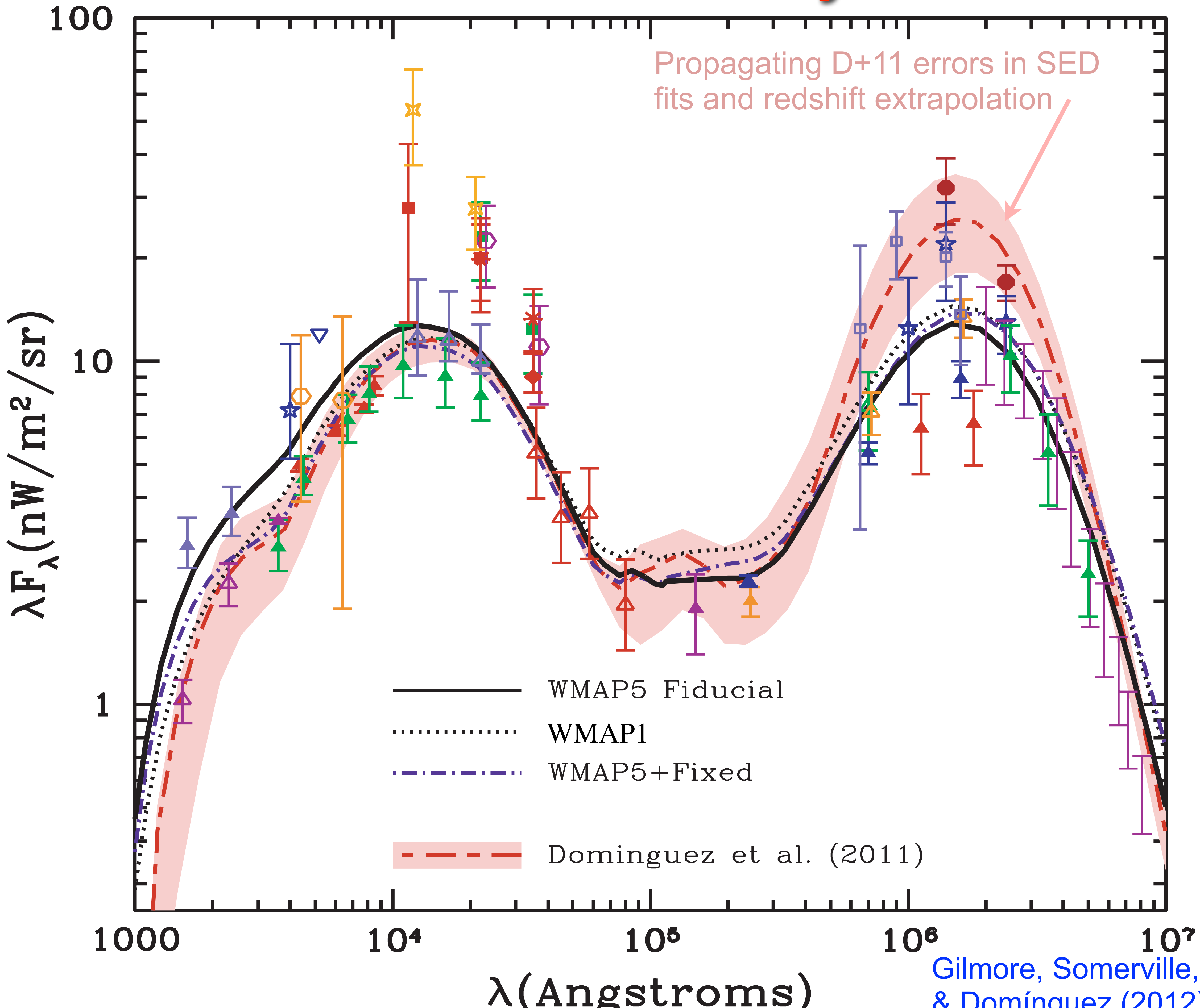



Somerville, Gilmore, Primack, & Domínguez (2012)

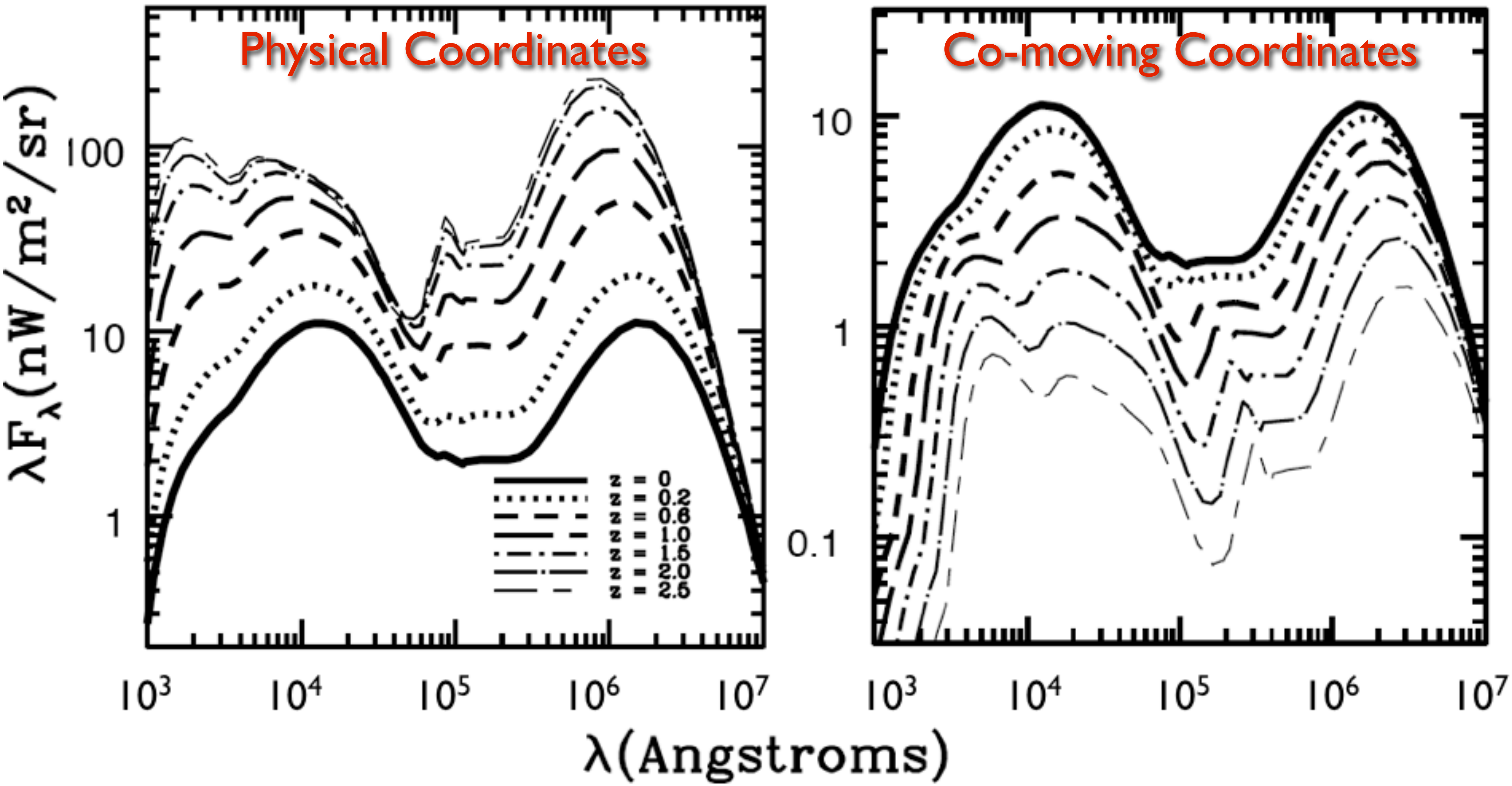
Worst failure is at 850 μm

# EBL from our Semi-Analytic Models




Gilmore, Somerville, Primack, & Domínguez (2012)

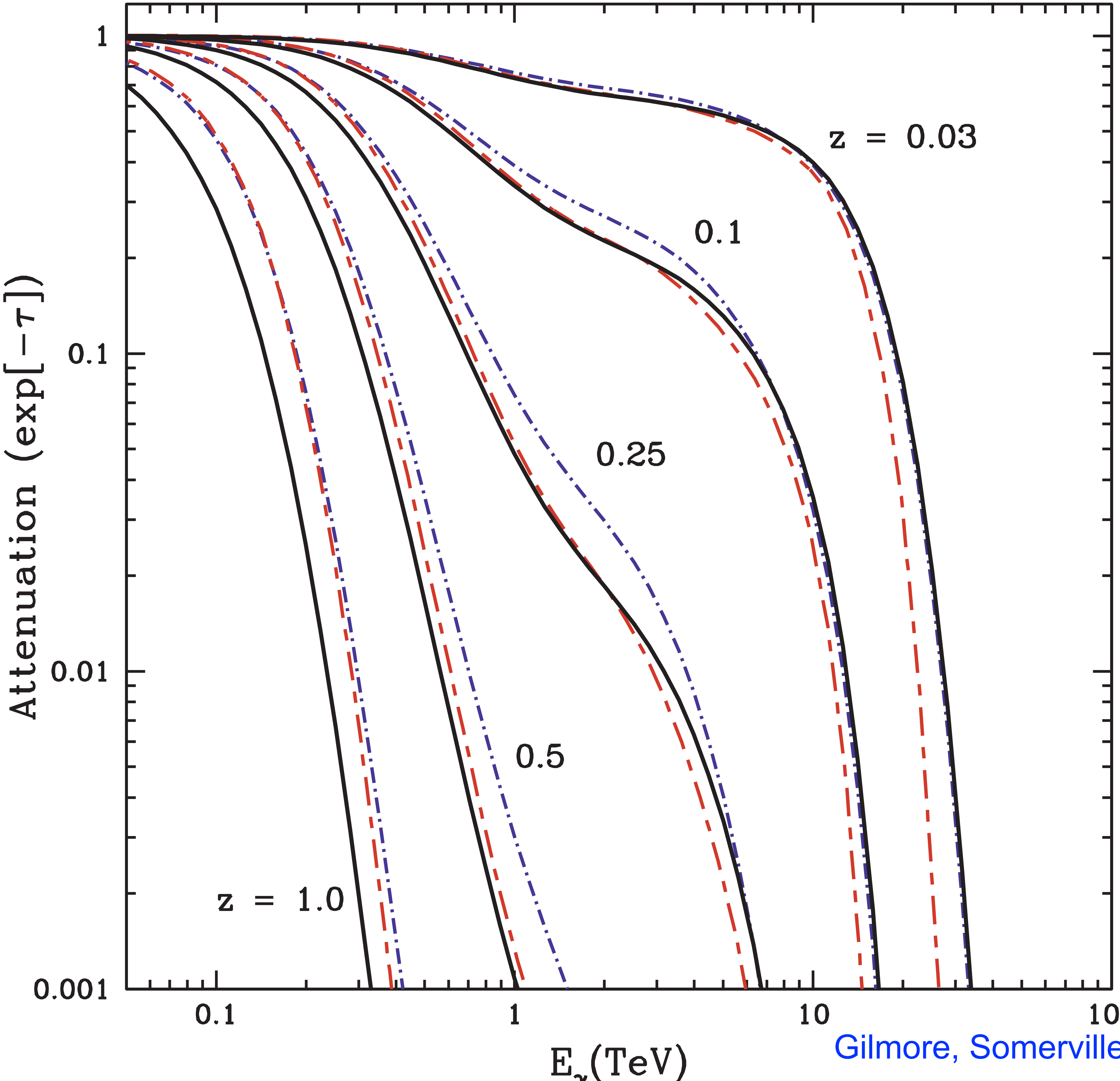
# Evolution of the EBL



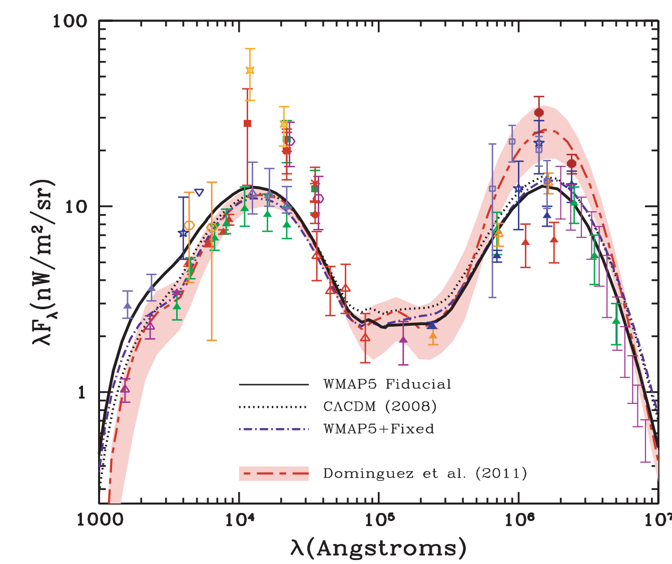

The evolution of the EBL in our WMAP5 Fiducial model. This is plotted on the left panel in standard units. The right panel shows the build-up of the present-day EBL by plotting the same quantities in comoving units. The redshifts from 0 to 2.5 are shown by the different line types in the key in the left panel.

Gilmore, Somerville, Primack, & Domínguez (2012)

# Predicted Gamma Ray Attenuation



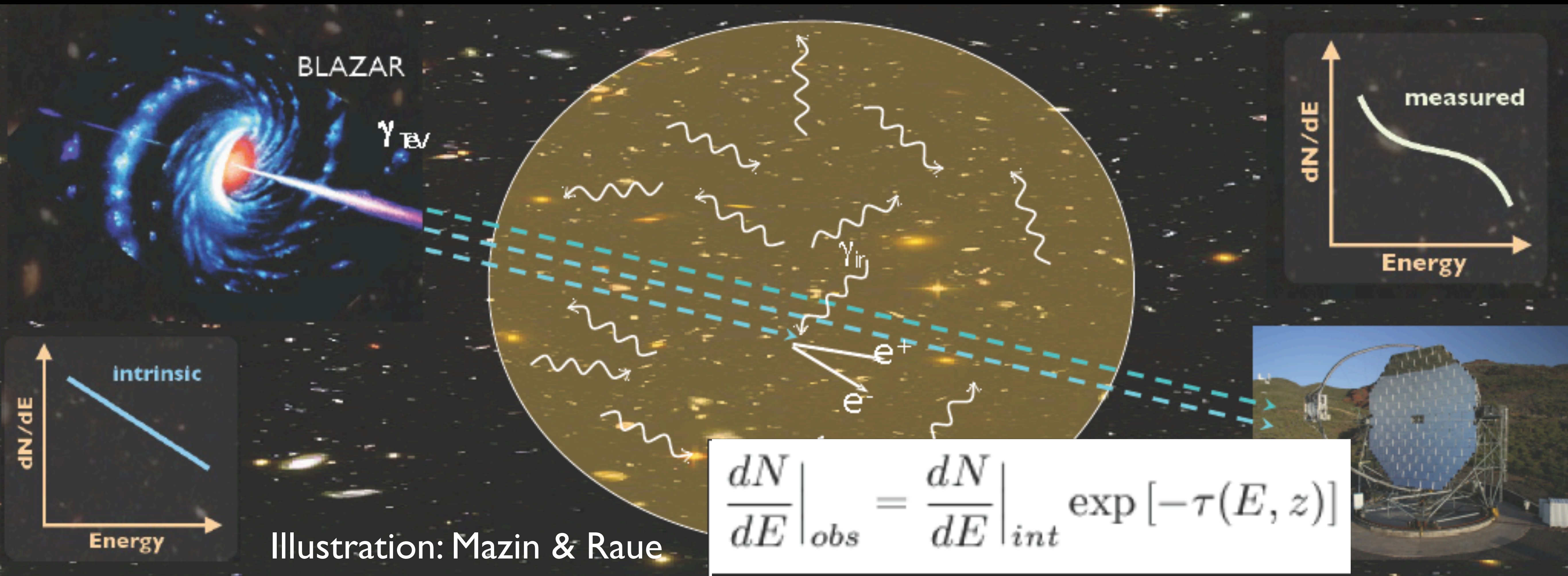

Increasing distance causes absorption features to increase in magnitude and appear at lower energies. The plateau seen between 1 and 10 TeV at low z is a product of the mid-IR valley in the EBL spectrum.




WMAP5 Fiducial
WMAP5 Fixed
Domiínguez+11

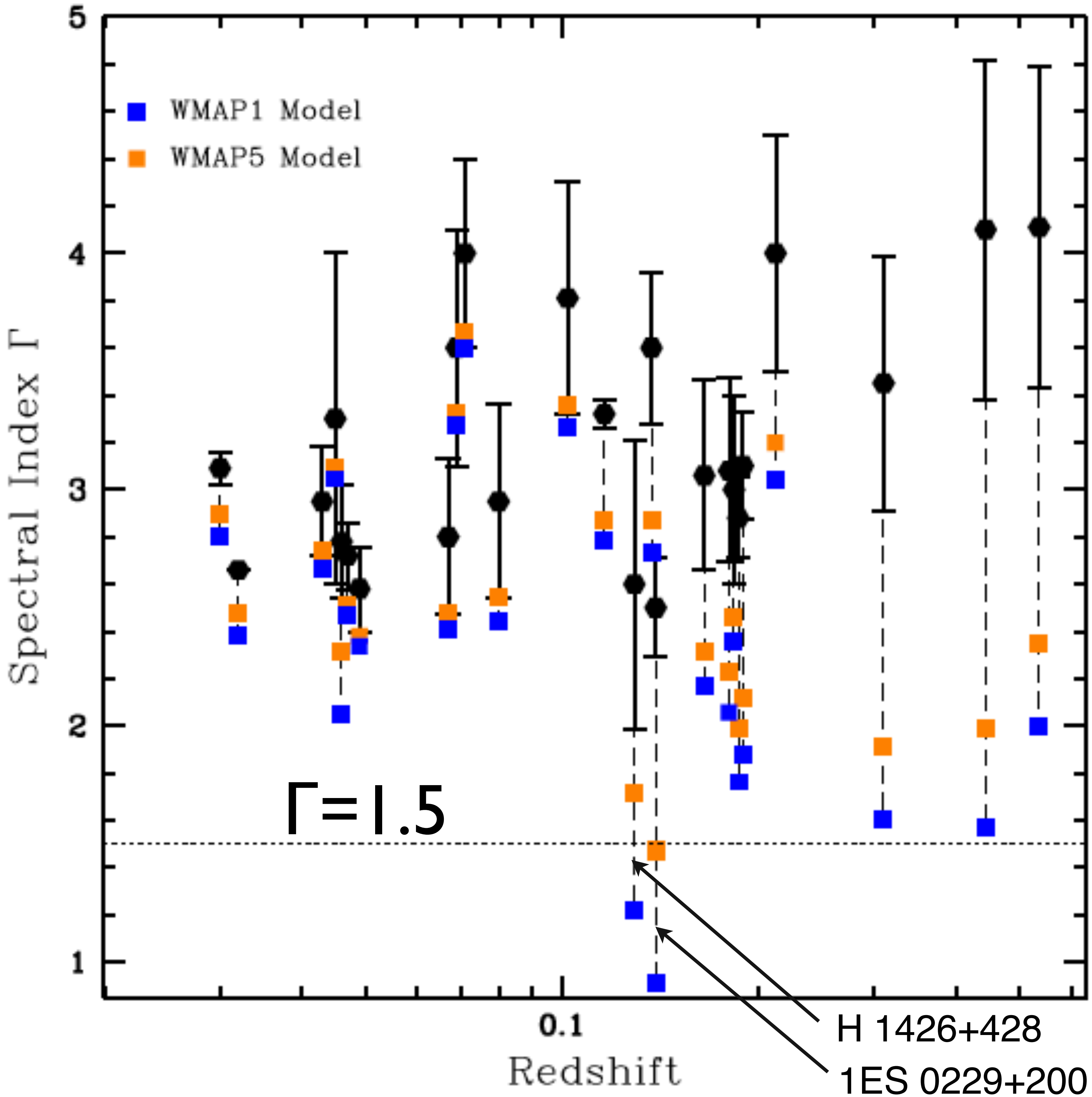
Gilmore, Somerville, Primack, & Domínguez (2012)

# Gamma Ray Attenuation due to γγ → e+e-




**If we know the intrinsic spectrum, we can infer the optical depth τ(*E*,*z*) from the observed spectrum. In practice, we typically *assume* that $dN/dE|_{int}$ is not harder than $E^{-\Gamma}$ with $\Gamma$ = 1.5, since local sources have $\Gamma \geq 2$. More conservatively, we can assume that $\Gamma \geq 2/3$.**

# Reconstructed Blazar Spectral Indexes



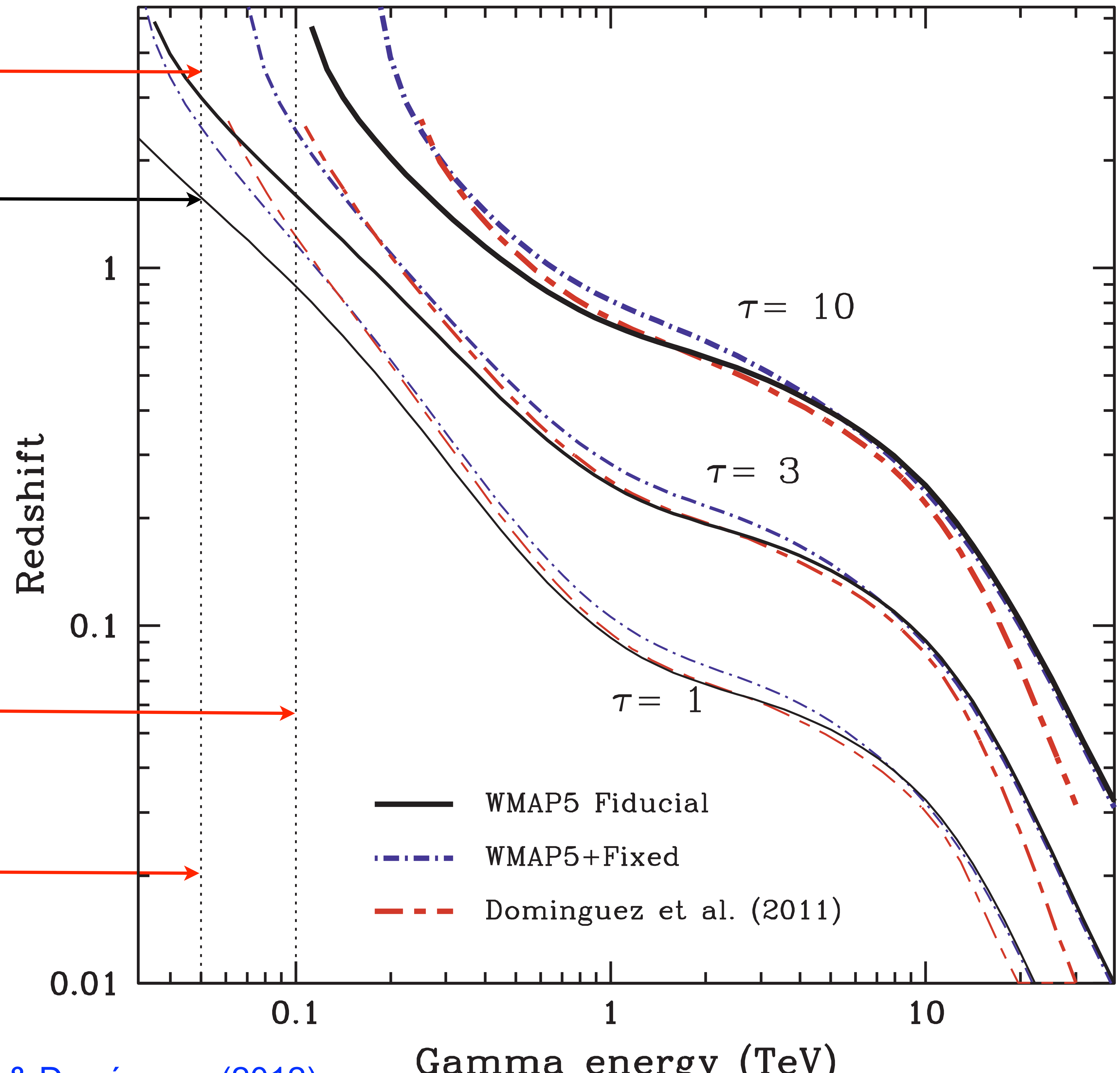

With our SAM based on current WMAP5 cosmological parameters and Spitzer (Rieke+09) dust emission templates, all high redshift blazars have spectral indexes $\Gamma \geq 1.5$, as expected from nearby sources.

(Of course, Felix can make them much harder!)

Gilmore, Somerville, Primack, & Domínguez (2012)

# Cosmic Gamma-Ray Horizon

With a 50 GeV threshold, we see to z≈1.5-3 with less than 1/e attenuation!




100 GeV Threshold

50 GeV Threshold

Gilmore, Somerville, Primack, & Domínguez (2012)

# Approved by the Fermi Publication Board 31 Oct 2012

## Detection of the cosmic $\gamma$-ray horizon from multiwavelength observations of blazars

Submitted but not on arXiv


A. Domínguez[1⋆], J. D. Finke[2], F. Prada[3,4,5], J. R. Primack[6], F. S. Kitaura[7], B. Siana[1], S. Ciprini[8,9], J. Knödlseder[10,11] and D. Paneque[12,13]

[1] *Dept. Physics & Astronomy, University of California, Riverside, CA 92521, USA*
[2] *U.S. Naval Research Laboratory, Space Science Division, Code 7653, 4555 Overlook Ave. SW, Washington, DC, 20375 USA*
[3] *Campus of International Excellence UAM+CSIC, Cantoblanco, E-28049 Madrid, Spain*
[4] *Instituto de Física Teórica, (UAM/CSIC), Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[5] *Instituto de Astrofísica de Andalucía (CSIC), Glorieta de la Astronomía, E-18080 Granada, Spain*
[6] *Department of Physics, University of California, Santa Cruz, CA 95064, USA*
[7] *Leibniz-Institut für Astrophysik (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany*
[8] *INAF, Observatory of Rome, Monte Porzio Catone, Roma, Italy*
[9] *Agenzia Spaziale Italiana (ASI) Science Data Center, I-00044 Frascati (Roma), Italy*
[10] *Institut de Recherche en Astrophysique et Planétologie (CESR), F-31028 Toulouse Cedex 4, France*
[11] *GAHEC, Université de Toulouse, UPS-OMP, IRAP, Toulouse, France*
[12] *Kavli Institute for Particle Astrophysics and Cosmology, SLAC, Stanford University, Stanford, CA 94305, USA*
[13] *Max-Planck-Institut für Physik, D-80805 München, Germany*


# Presented at the 4th Fermi Symposium in Monterey, CA

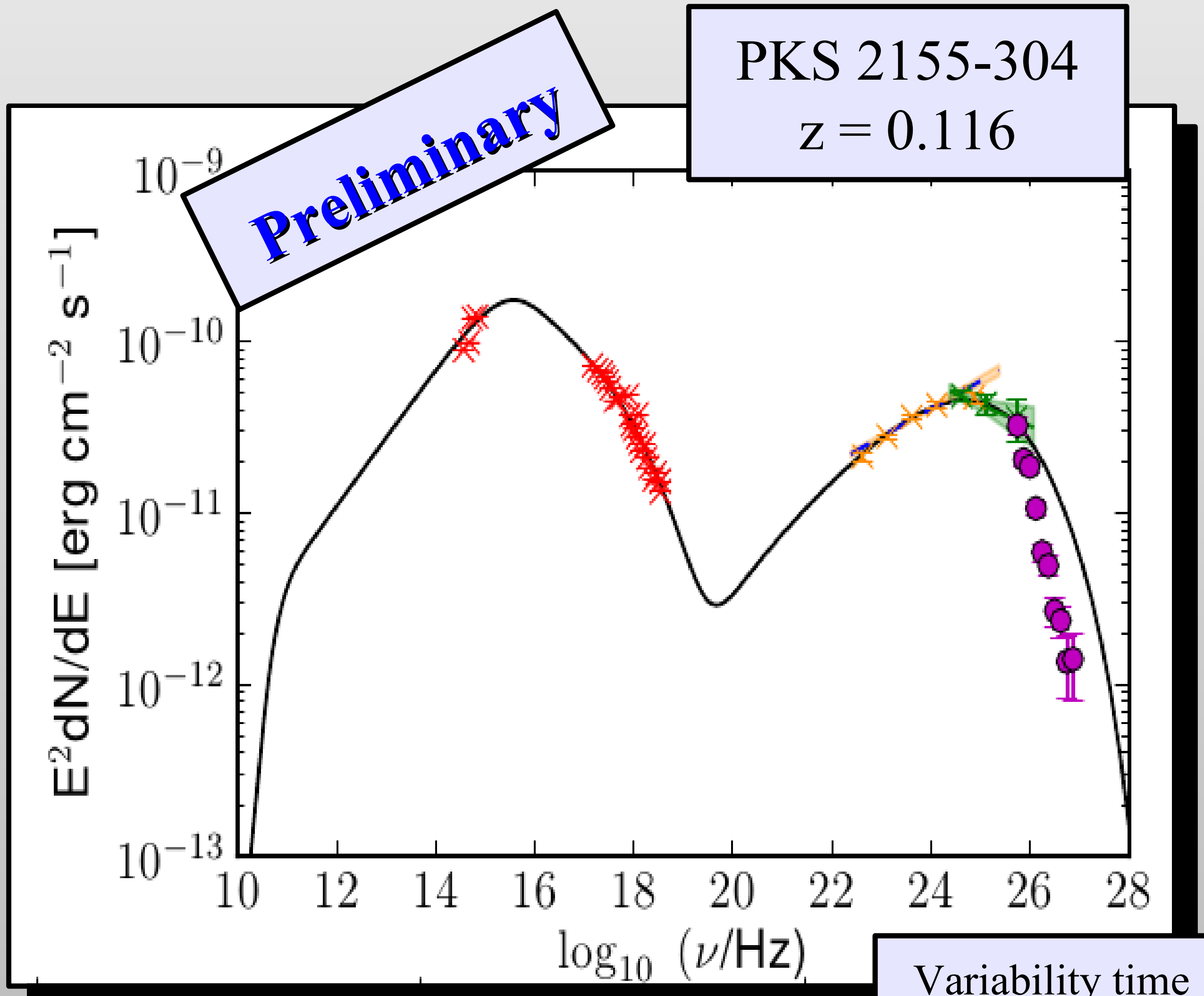
## The Detection of the Cosmic $\gamma$-ray Horizon

**Alberto Domínguez**

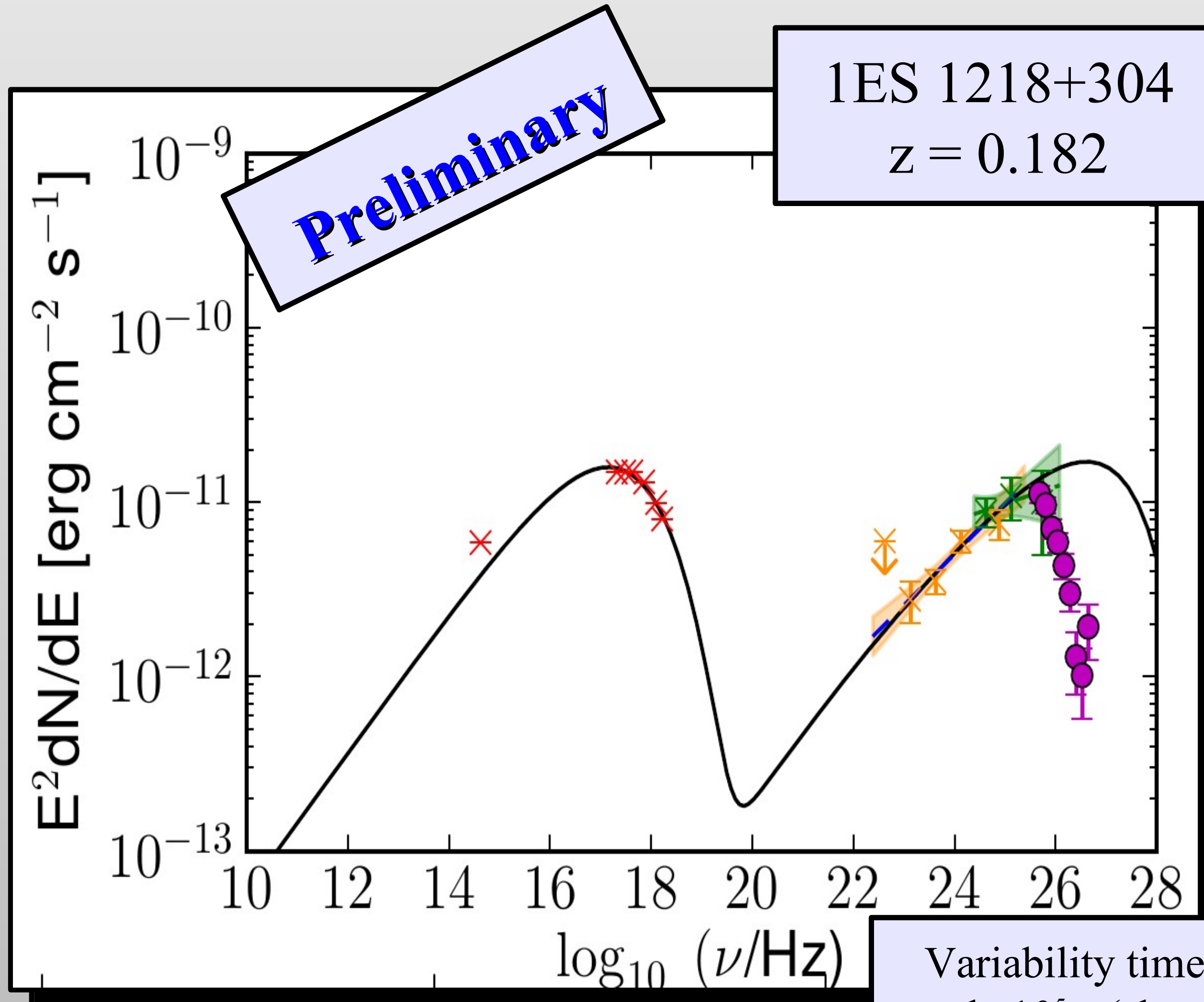
**(University of California, Riverside)**

# SED multiwavelength fits

A one-zone synchrotron/SSC model is fit to the multiwavelength data excluding the Cherenkov data, which are EBL attenuated. Then, this fit is extrapolated to the VHE regime representing the intrinsic VHE spectrum. Technique similar to Mankuzhiyil et al. 2010.



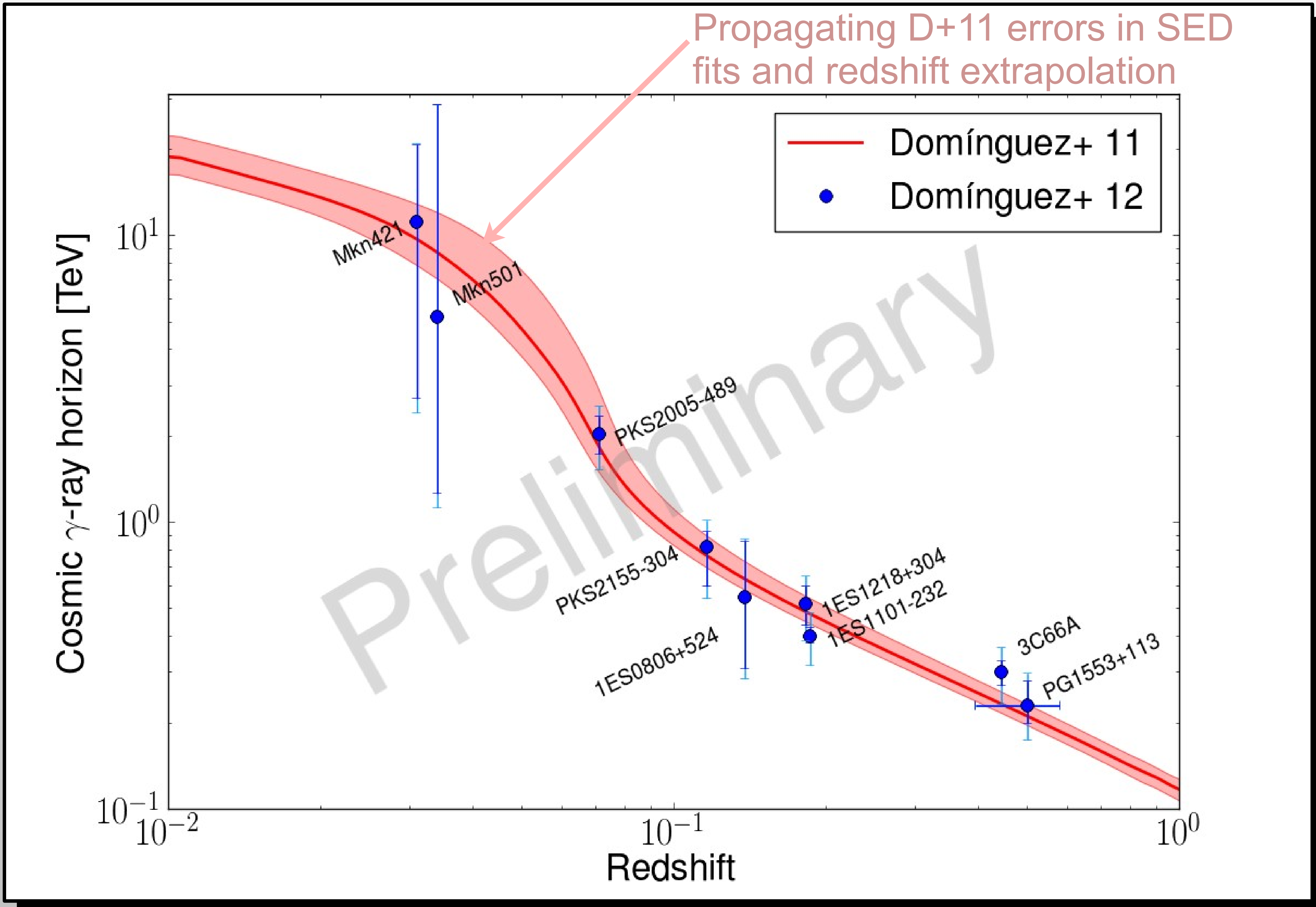

Variability time scale $10^4$ s (fast)




Variability time scale $10^5$ s (slow)

Domínguez+12

# Cosmic γ-ray Horizon: results




There are 4 out of 15 cases where our maximum likelihood methodology could not be applied since the prediction from the synchrotron/SSC model was lower than the detected flux by the Cherenkov telescopes.

Two other cases where the statistical uncertainties were too high to set any constraint on E0.

Domínguez+12

# Published Online in Science 4 Nov 2012

Sciencexpress

The Imprint of the Extragalactic Background Light in the Gamma-Ray Spectra of Blazars

M. Ackermann,[1] M. Ajello,[2,3]* A. Allafort,[2] P. Schady,[4] L. Baldini,[5] J. Ballet,[6] G.

**ABSTRACT** The light emitted by stars and accreting compact objects through the history of the universe is encoded in the intensity of the extragalactic background light (EBL). Knowledge of the EBL is important to understand the nature of star formation and galaxy evolution, but direct measurements of the EBL are limited by galactic and other foreground emissions. Here, we report an absorption feature seen in the combined spectra of a sample of gamma-ray blazars out to a redshift of $z \sim 1.6$. This feature is caused by attenuation of gamma rays by the EBL at optical to ultraviolet frequencies and allowed us to measure the EBL flux density in this frequency band.

# Presented at the 4th Fermi Symposium in Monterey, CA

## The Imprint of the EBL in the Spectra of Blazars

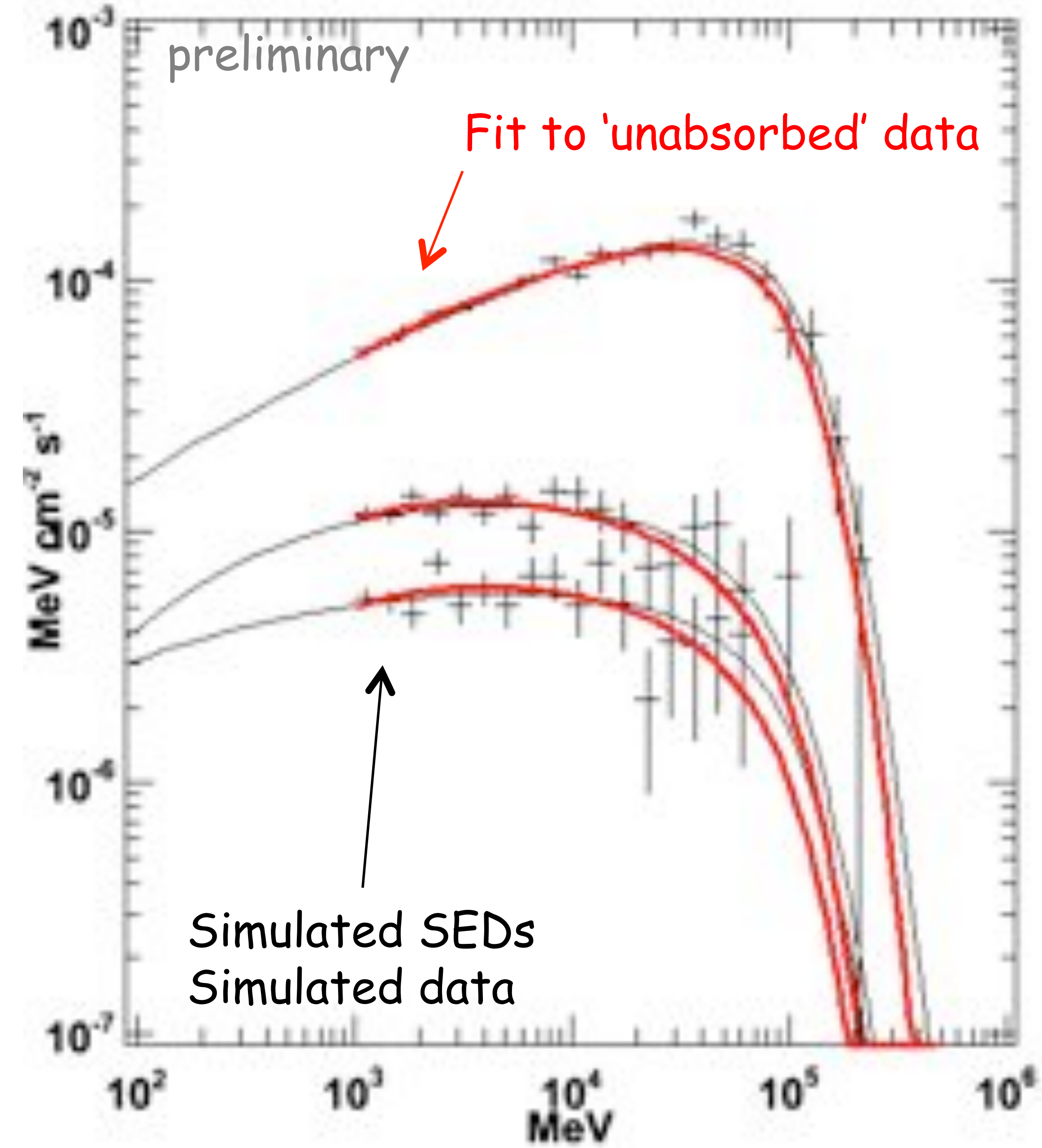
Marco Ajello[1,2], Anita Reimer[3], Rolf Buehler[1]

*on behalf of the Fermi-LAT collaboration*

# Analysis Procedure

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

- We use 46months of P7V6 1-500 GeV data
- We define 3 redshift bins with 50 sources each:
  - z= 0-0.2, 0.2-0.5, 0.5 -1.6
- All BL Lacs are modeled with a *LogParabola* spectrum
- We perform a combined fit where:
  - The spectra of all sources are fit independently
  - The spectra of all sources are modified by a common $e^{-b\,\tau(E,z)}$ term
- We evaluate 2 cases:
  1. Null hypothesis b=0 : there is no EBL
  2. Null hypothesis b=1 : the model predictions are correct



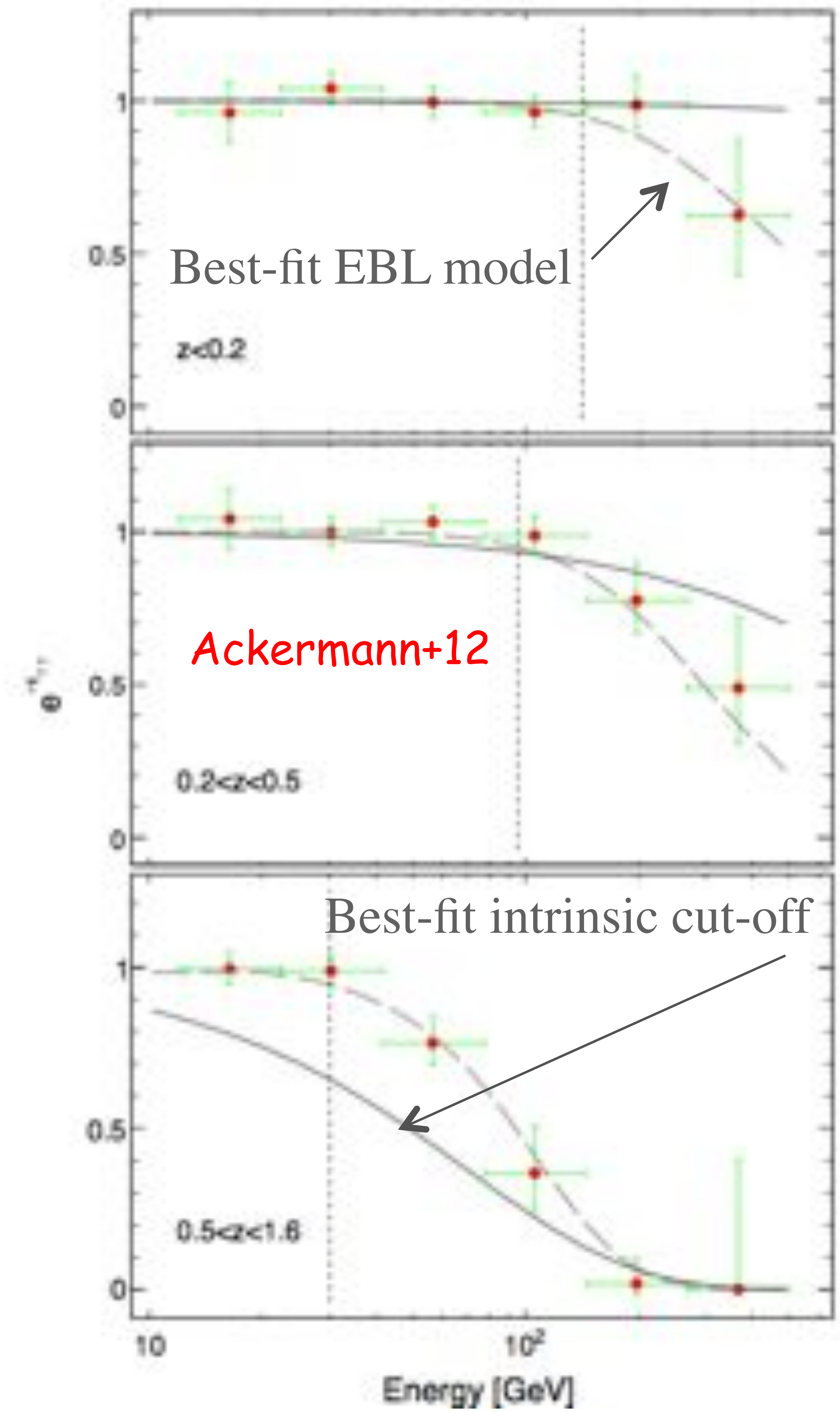

$$F(E)_{absorbed} = F(E)_{\mathrm{int}\,rinsic} \cdot e^{-b \cdot \tau_{\mathrm{mod}\,el}}$$

# Measurement of Tau with Energy and Redshift

- We use the composite likelihood in small energy bins to measure the collective deviation of the observed spectra from the intrinsic ones

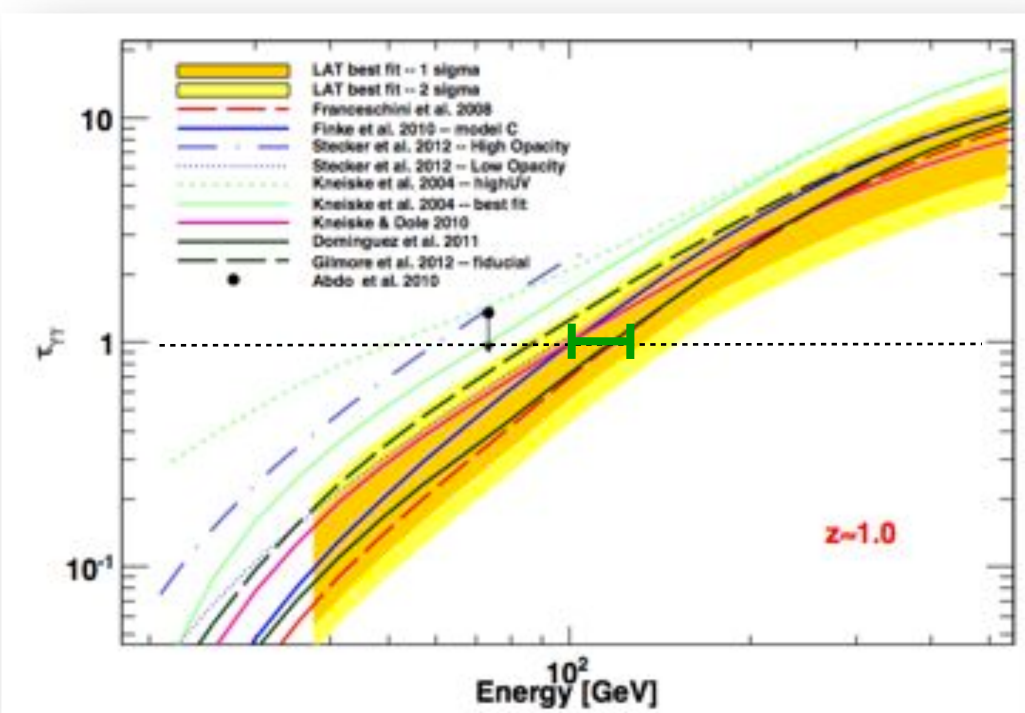
- The cut-off moves in z and energy as expected for EBL absorption (for low opacity models)

- It is difficult to explain this attenuation with an intrinsic property of BL Lacs
  1. BL Lacs required to evolve across the z=0.2 barrier
  2. Attenuation change with energy and redshift cannot be explained by an intrinsic cut-off that changes from source to source because of redshift and blazar sequence effects



# Composite Likelihood Results: 2

- A significant steepening in the blazars' spectra is detected
- This is consistent with that expected by a 'minimal' EBL:
  - i.e. EBL at the level of galaxy counts
  - 4 models rejected above 3sigma
- All the non-rejected models yield a significance of detection of 5.6-5.9 σ
- The level of EBL is 3-4 times lower than our previous UL (Abdo+10, ApJ 723, 1082)




Ackermann+12

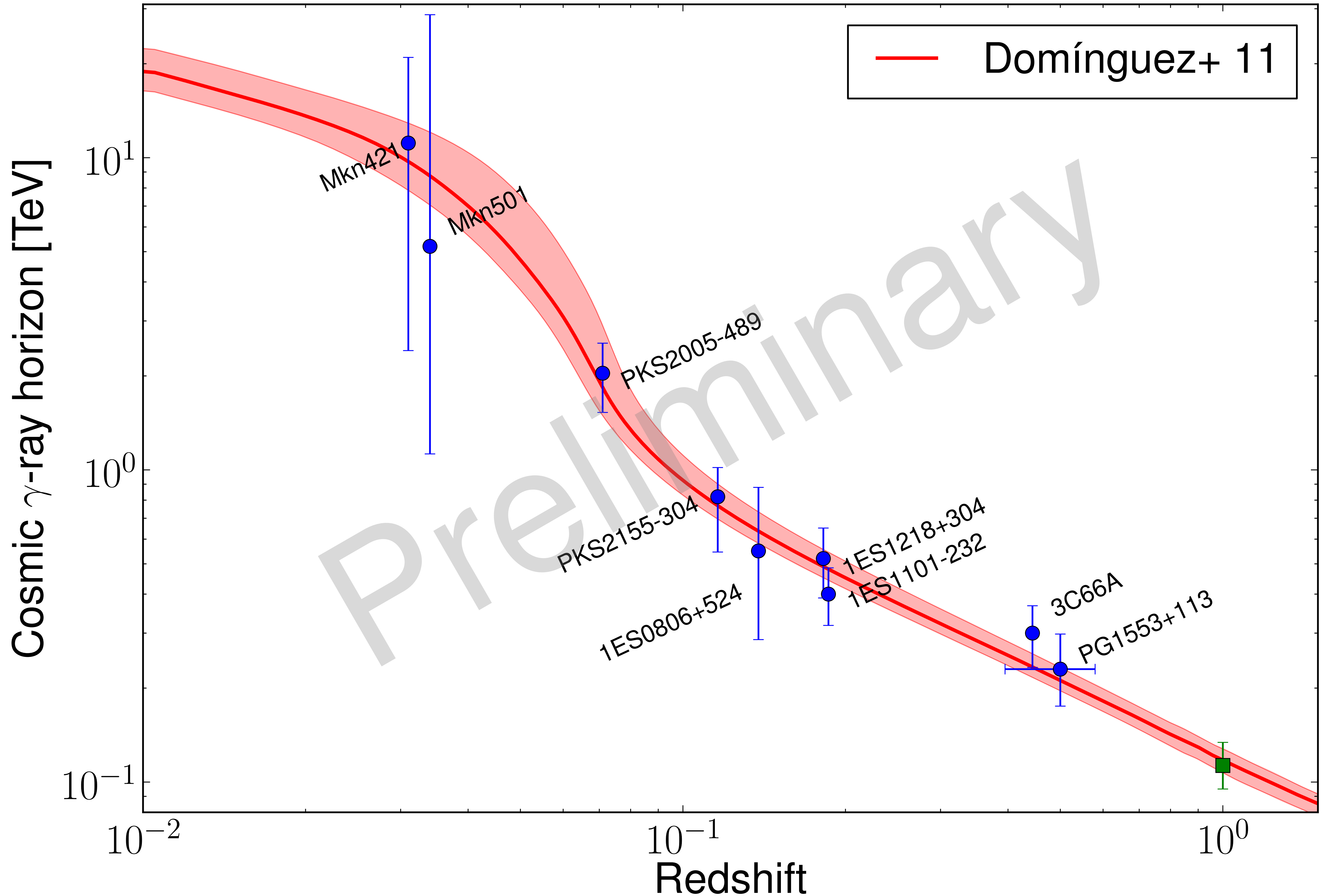
EBL Detection Significance

Model Rejection Significance

| Model[a] | Ref.[b] | Significance of $b$=0 Rejection[c] | $b$[d] | Significance of $b$=1 Rejection[e] |
|---|---|---|---|---|
| *Stecker et al. (2006) – fast evolution* | (23) | 4.6 | 0.10±0.02 | 17.1 |
| *Stecker et al. (2006) – baseline* | (23) | 4.6 | 0.12±0.03 | 15.1 |
| *Kneiske et al. (2004) – high UV* | (22) | 5.1 | 0.37±0.08 | 5.9 |
| *Kneiske et al. (2004) – best fit* | (22) | 5.8 | 0.53±0.12 | 3.2 |
| *Gilmore et al. (2012) – fiducial* | (27) | 5.6 | 0.67±0.14 | 1.9 |
| *Primack et al. (2005)* | (56) | 5.5 | 0.77±0.15 | 1.2 |
| *Dominguez et al. (2011)* | (25) | 5.9 | 1.02±0.23 | 1.1 |
| *Finke et al. (2010) – model C* | (24) | 5.8 | 0.86±0.23 | 1.0 |
| *Franceschini et al. (2008)* | (7) | 5.9 | 1.02±0.23 | 0.9 |
| *Gilmore et al. (2012) – fixed* | (27) | 5.8 | 1.02±0.22 | 0.7 |
| *Kneiske & Dole (2010)* | (26) | 5.7 | 0.90±0.19 | 0.6 |
| *Gilmore et al. (2009) – fiducial* | (2) | 5.8 | 0.99±0.22 | 0.6 |

# Cosmic Gamma-Ray Horizon

## Dominguez+12 + Ackermann+12

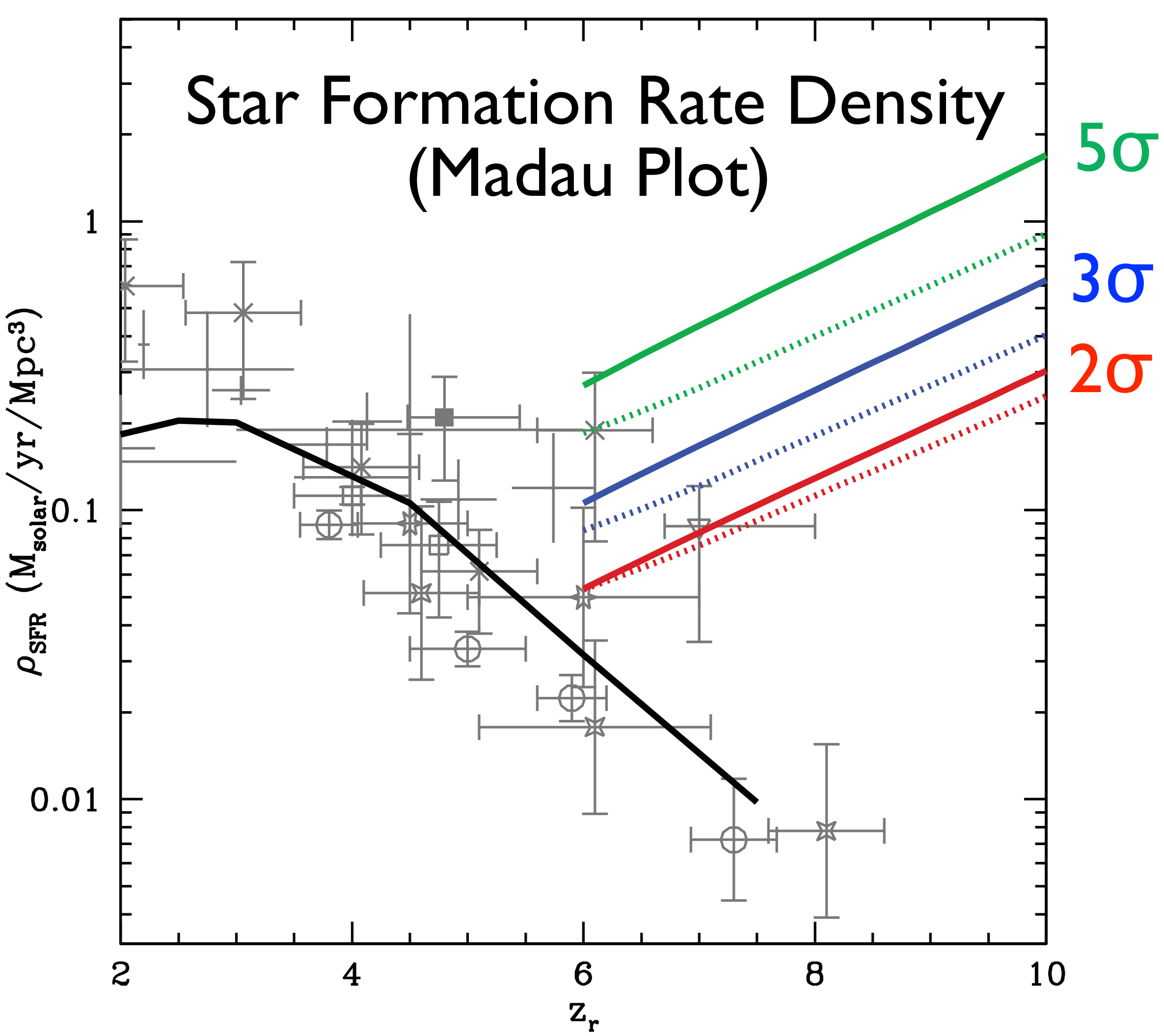


Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY 420, 800–809 (2012)

# Constraining the near-infrared background light from Population III stars using high-redshift gamma-ray sources

Rudy C. Gilmore

**ABSTRACT** The *Fermi* satellite has detected GeV emission from a number of gamma-ray bursts and active galactic nuclei at high redshift, $z \gtrsim 1.5$. We examine the constraints that the detections of gamma-rays from several of these sources place on the contribution of Population III stars to the extragalactic background light. Emission from these primordial stars, particularly redshifted Lyman α emission, can interact with gamma-rays to produce electron–positron pairs and create an optical depth to the propagation of gamma-ray emission, and the detection of emission at >10 GeV can therefore constrain the production of this background. We consider two initial mass functions for the early stars and use derived spectral energy distributions for each to put upper limits on the star formation rate density of massive early stars from redshifts 6 to 10. Our limits are complementary to those set on a high near-infrared background flux by ground-based TeV-scale observations and show that current data can limit star formation in the late stages of re-ionization to less than 0.5 $M_\odot$ $yr^{-1}$ $Mpc^{-3}$ . Our results also show that the total background flux from Population III stars must be considerably less than that from resolved galaxies at wavelengths below 1.5 μm.




Upper bounds on the redshift $z$ = 6 - 9 Pop-III SFRD in two possible scenarios with future *Fermi* GRBs, in the Larson IMF case. The solid lines show the limits from a GRB with the same redshift and spectral characteristics of GRB 080916C ($z$ = 4.35), but with a highest energy observed photon of 30 GeV (160 GeV as emitted) instead of 13.2 GeV, in combination with the 5 most constraining $z \gtrsim 2$ sources (Abdo+2010). The dotted lines show a case with a GRB at $z$ = 7 and a highest energy observed photon at 15 GeV (120 GeV emitted).

# Conclusions

**New data on attenuation of gamma rays from blazers**

- **X-ray + Fermi + ACT SSC fits to 9 blazars (Dominguez+12)**
- **Fermi data on 150 blazars at $z = 0$ - 1.6 (Ackermann+12)**

**now lead to statistically significant measurements of the cosmic gamma ray horizon and EBL as a function of source redshift and gamma ray energy**

**These new measurements are consistent with recent EBL calculations based both on multiwavelength observations of thousands of galaxies and also on semi-analytic models of the evolving galaxy population. Such comparisons account for all the light, including that from galaxies too faint to see.**

**Catching a few high-redshift GRBs with Fermi or low-threshold atmospheric Cherenkov telescope arrays could provide important new constraints on the high-redshift star formation history of the universe.**

**Happy Birthday Felix!**