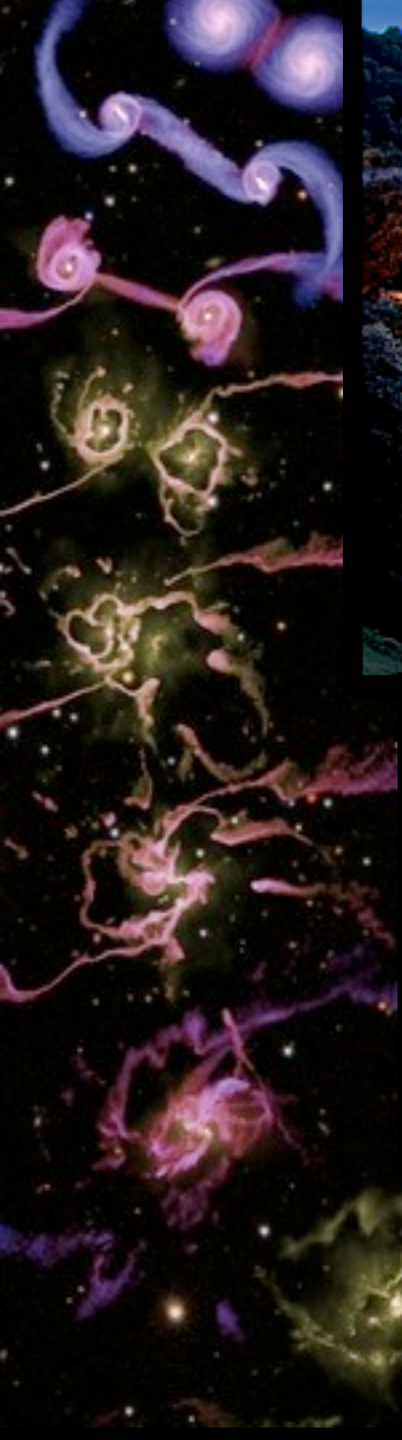
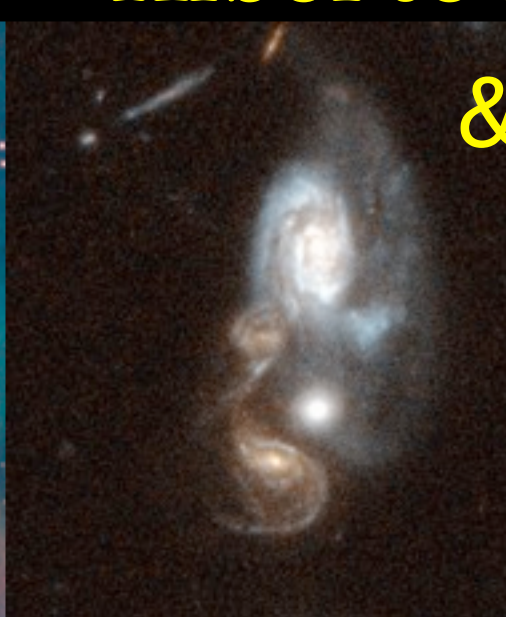



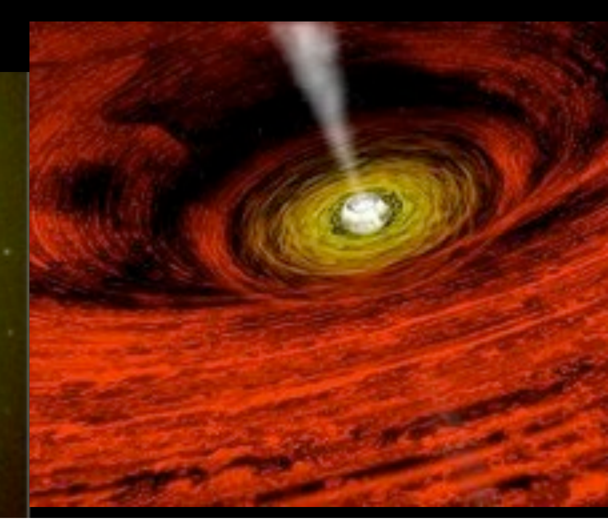
# Diffuse Extragalactic Background Light and Gamma-Ray Attenuation

**Joel Primack**,

Alberto Dominguez, Rudy Gilmore,

& Rachel Somerville





# Preview

Data from (non-)attenuation of gamma rays from AGN and GRBs gives upper limits on the EBL from UV to mid-IR that are ~2x lower limits from observed galaxies. These upper limits now rule out some EBL models and purported observations, with improved data likely to provide even stronger constraints.

EBL calculations based on careful extrapolation from observations and on semi-analytic models are consistent with these lower limits and with the gamma-ray upper limit constraints.

Such comparisons "close the loop" on cosmological galaxy formation models, since they account for all the light, including that from galaxies too faint to see.

Catching a few GRBs with ground-based ACT arrays or HAWC could provide important new constraints on star formation history.

The EBL is very difficult to observe directly because of foregrounds, especially the zodiacal light. Reliable lower limits are obtained by integrating the light from observed galaxies. The best upper limits come from (non-) attenuation of gamma rays from distant blazars, but these are uncertain because of the unknown emitted spectrum of these blazars.

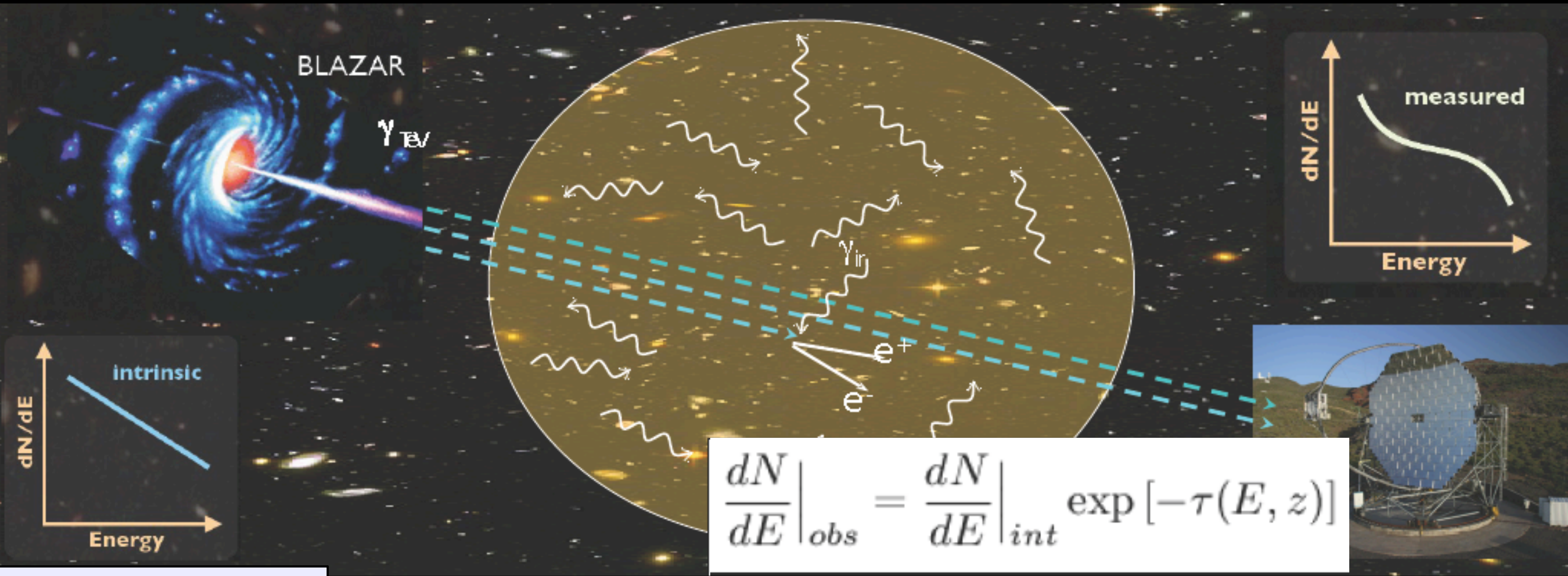
This talk concerns both (1) the optical-IR EBL relevant to attenuation of TeV gamma rays, and also (2) the UV EBL relevant to attenuation of gamma rays from very distant GRBs & blazars observed by *Fermi* and low-threshold ground-based ACTs, including future arrays (AGIS, CTA, ACTA).

Just as IR light penetrates dust better than shorter wave-lengths, so lower energy gamma rays penetrate the EBL better than higher energy. Low threshold is essential to see high-$z$ gamma rays.


PILLAR OF STAR BIRTH
Carina Nebula in UV Visible Light
WFC3/UVIS


PILLAR OF STAR BIRTH
Carina Nebula in IR Light
Longer wavelength light penetrates the dust better
Longer wavelength gamma rays also penetrate the EBL better
WFC3/IR

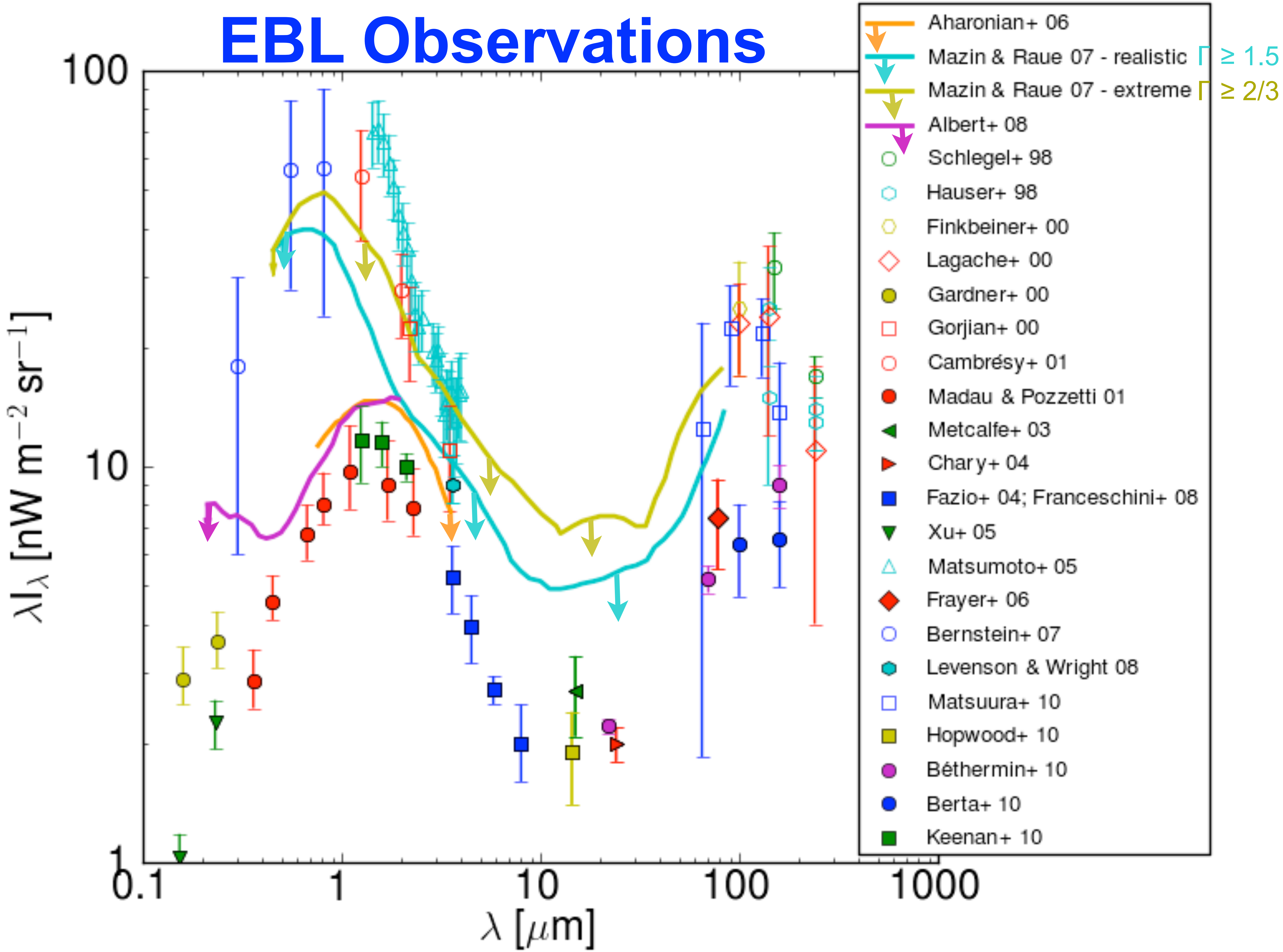
# Gamma Ray Attenuation due to γγ → e+e-




Ilustration: D. Mazin & M. Raue

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 $\Gamma \geq 2$.

# EBL Observations



Four approaches to calculate the EBL:

Backward Evolution, which starts with the existing galaxy population and evolves it backward in time -- e.g., Stecker, Malkan, & Scully 2006. Dangerous!

Backward Evolution Inferred from Observations -- e.g., Kneiske et al. 2002, 04; Franceschini et al. 2008.

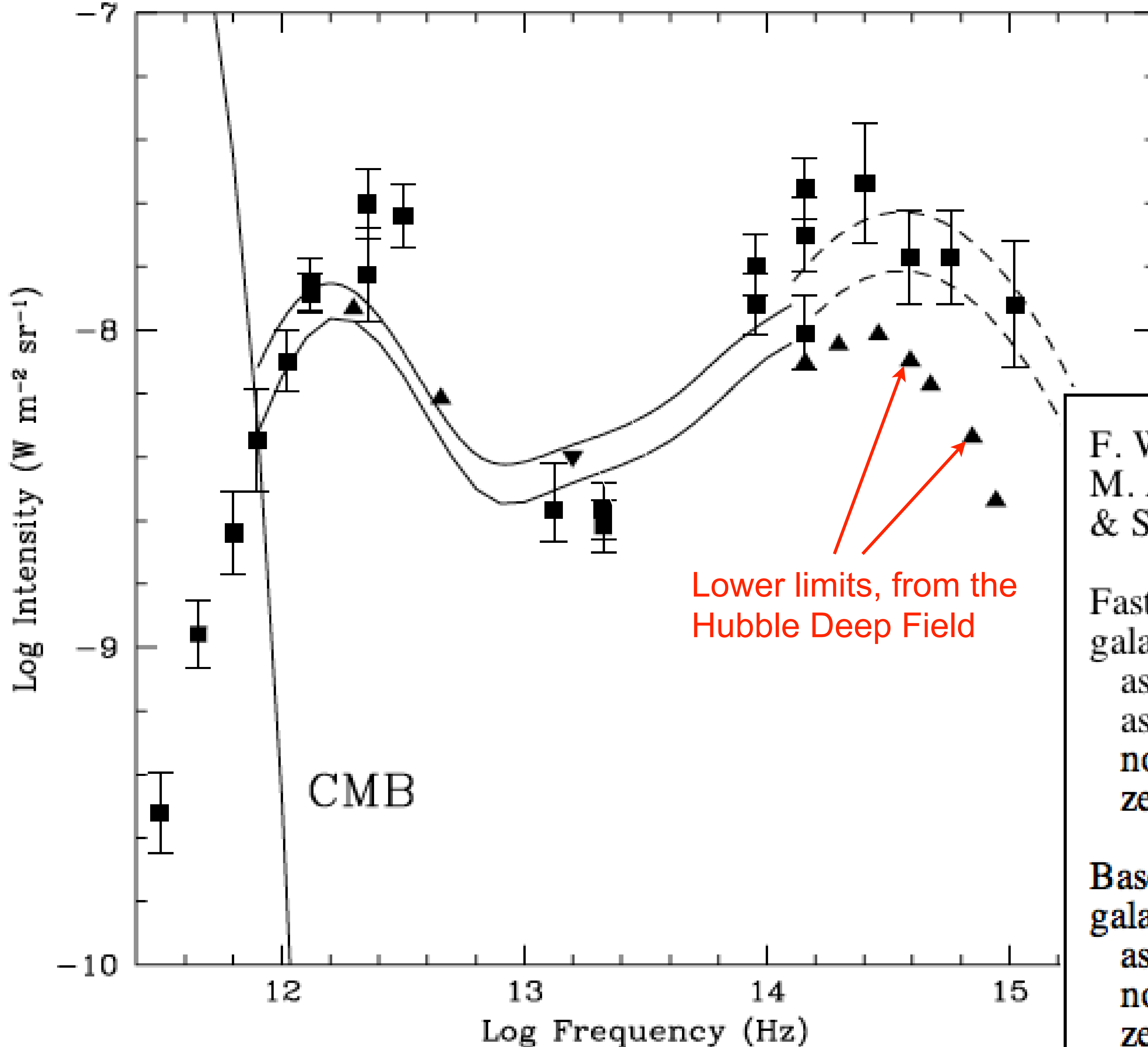
Evolution Directly Observed -- Dominguez, Primack, et al. 2010 using AEGIS data.

Forward Evolution, which begins with cosmological initial conditions and models gas cooling, formation of galaxies including stars and AGN, feedback from these phenomena, and light absorption and re-emission by dust -- Gilmore+10.

All methods currently require modeling galactic SEDs. Forward Evolution requires semi-analytic models (SAMs) based on cosmological simulations.

# Backward Evolution

A problem with this approach is that high-z galaxies are very different from low-z galaxies.



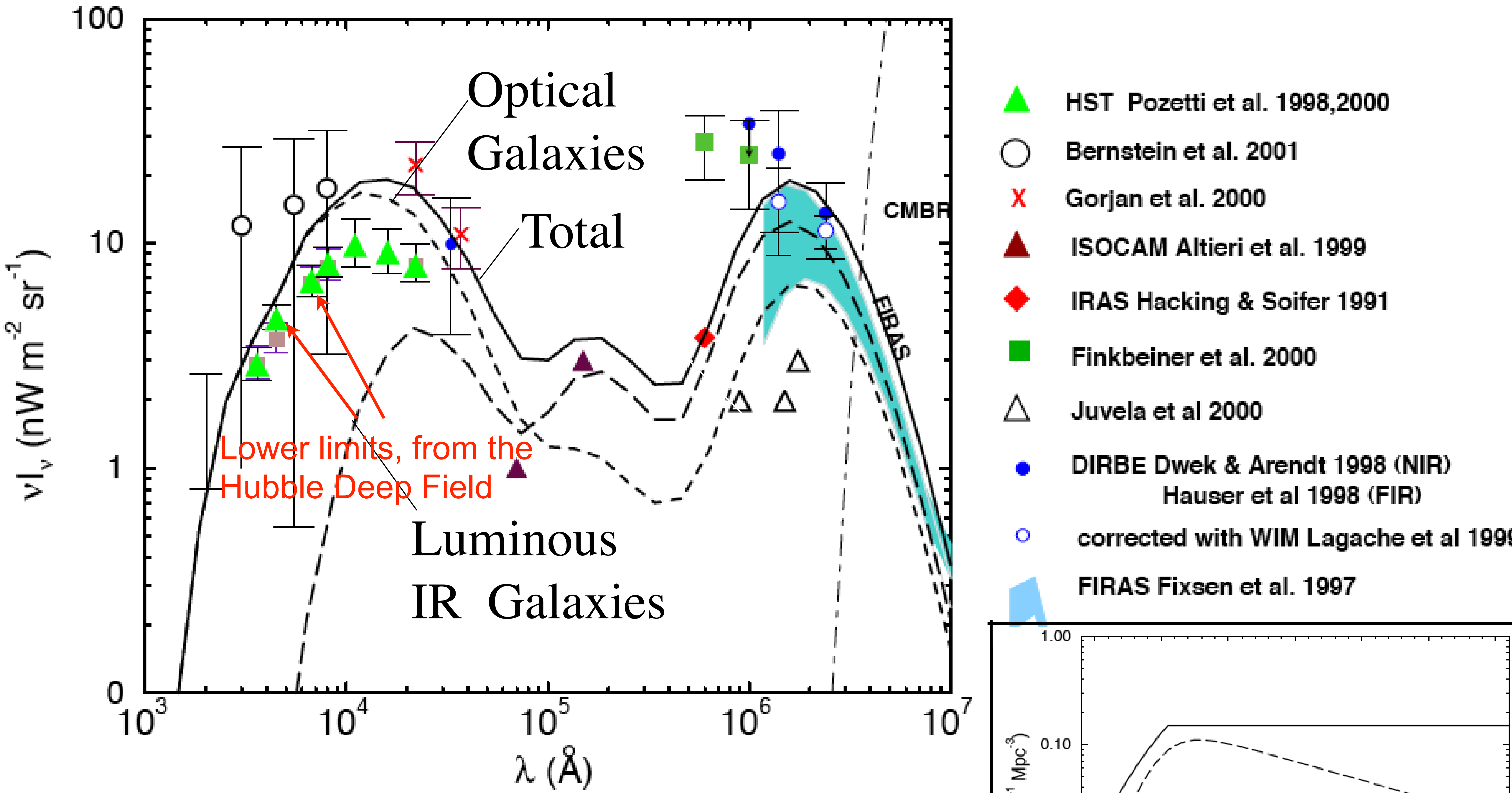

F. W. Stecker, M. A. Malkan, & S. T. Scully 2006

Fast Evolution:
galaxy luminosities evolve
as $(1+z)^4$ for $0 < z < 0.8$,
as $(1+z)^2$ for $0.8 < z < 1.5$,
no evolution $1.5 < z < 6$,
zero luminosityfor $z > 6$.

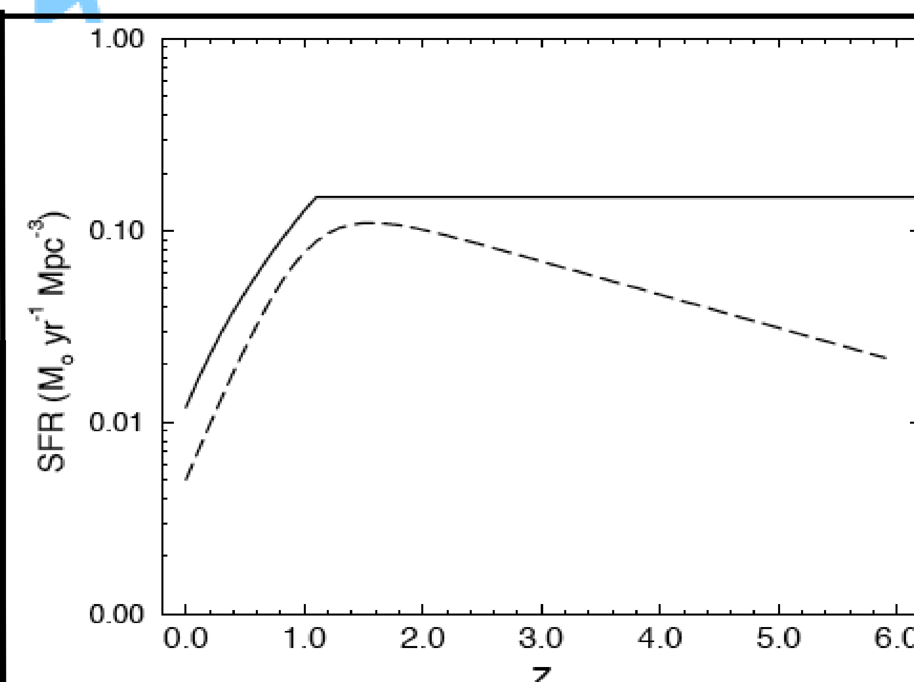
Baseline Model:
galaxy luminosities evolve
as $(1+z)^{3.1}$ for $0 < z < 1.4$,
no evolution $1.4 < z < 6$,
zero luminosityfor $z > 6$.

# Backward Evolution Inferred from Observations

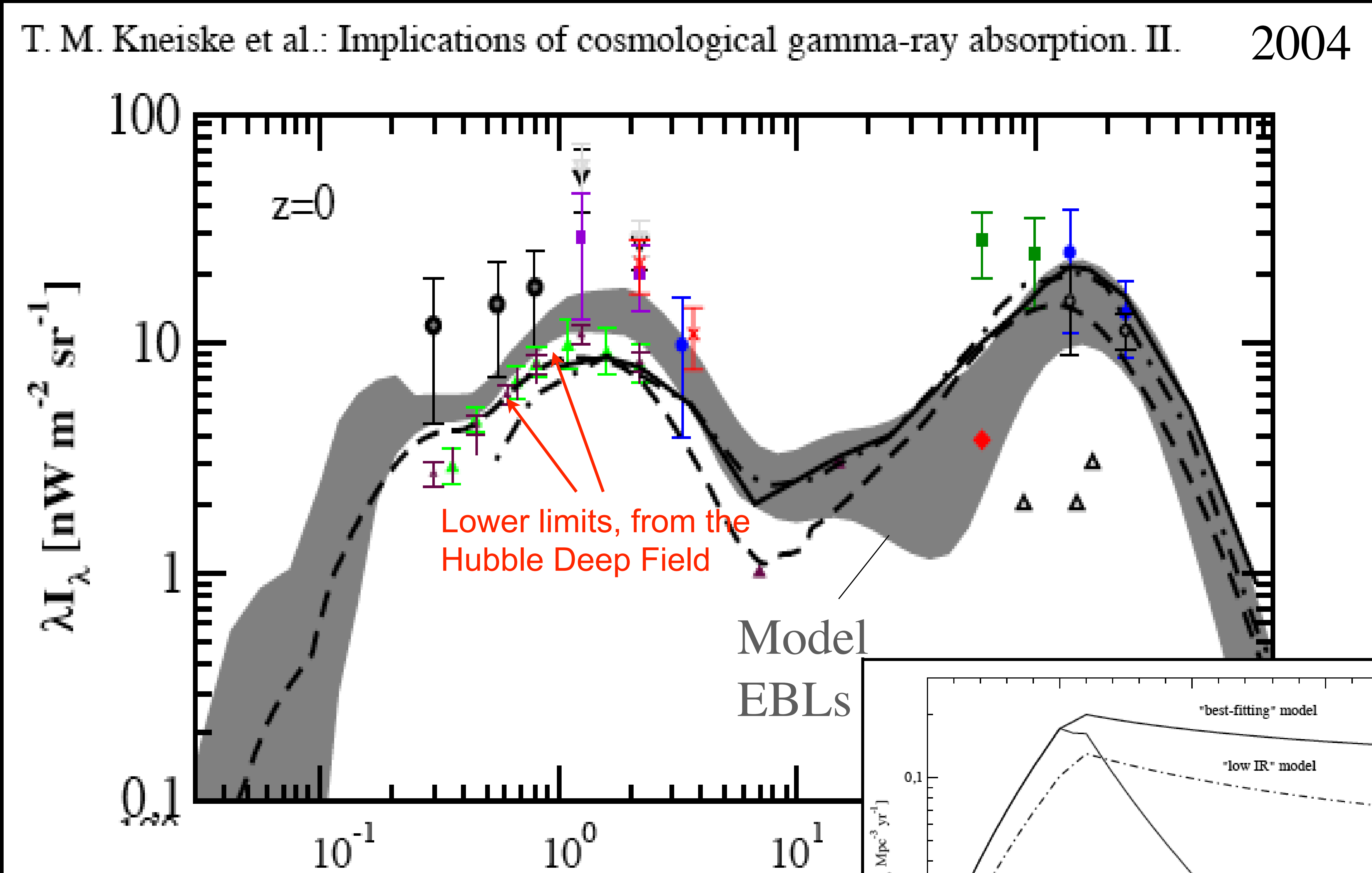
T. M. Kneiske et al.: Implications of cosmological gamma-ray absorption. I. 2002



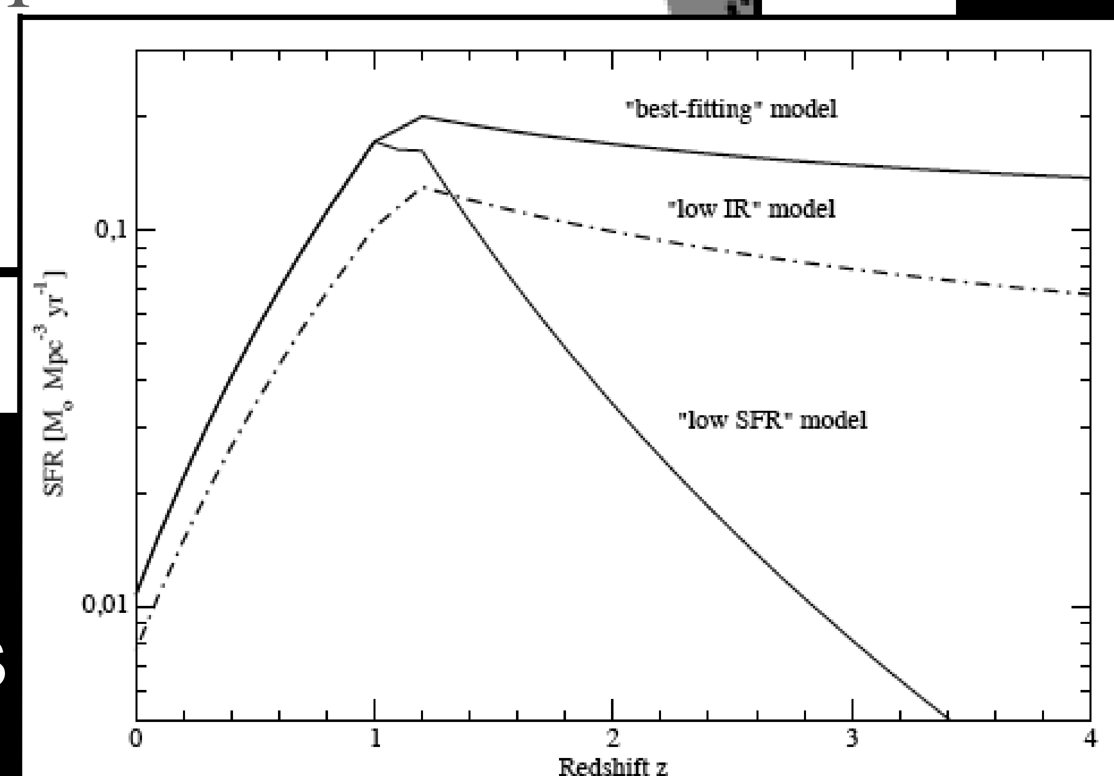

Assumed Star Formation Rate
(solid curve)



# Backward Evolution Inferred from Observations



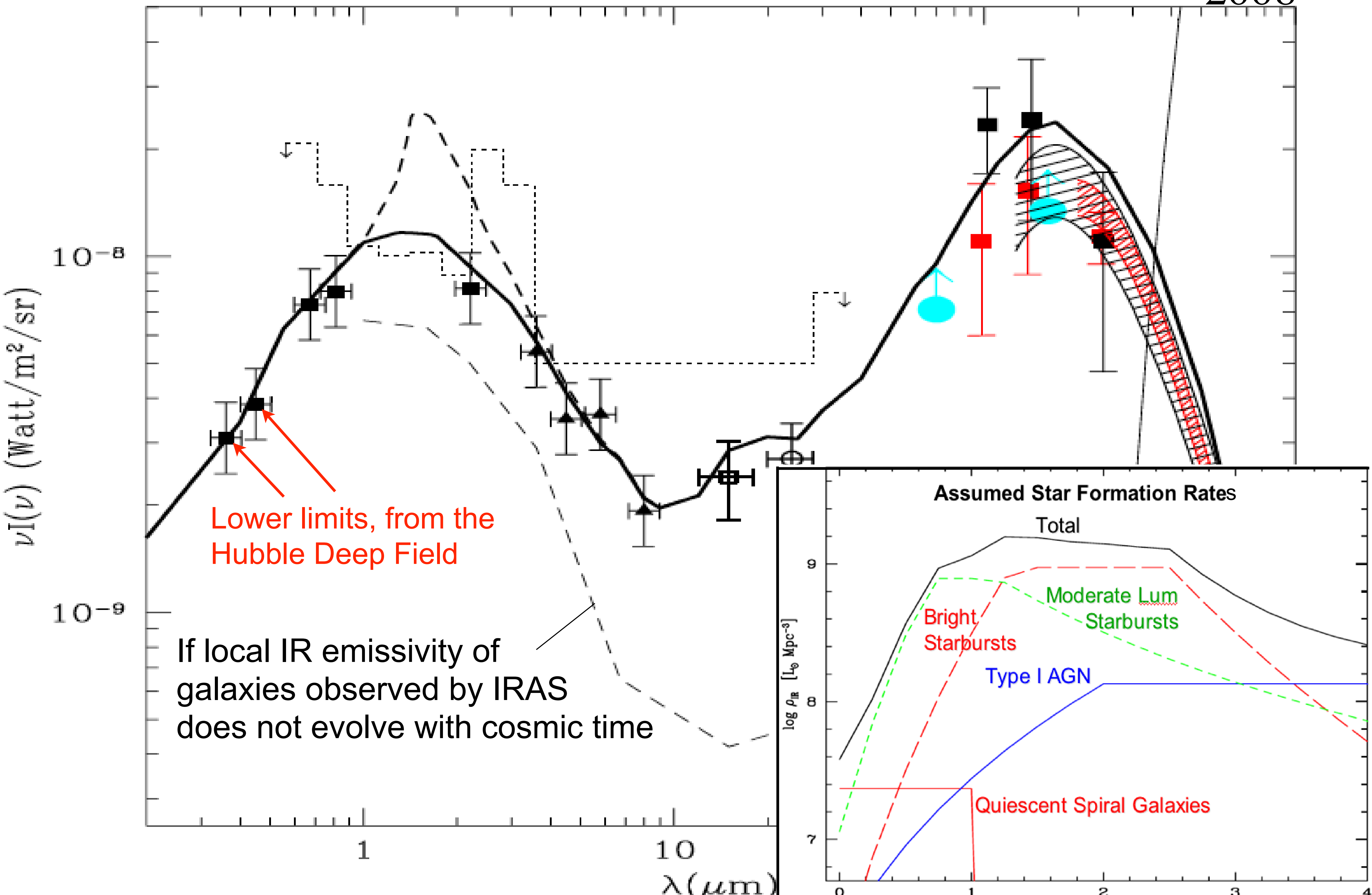

Assumed Star Formation Rates



# Backward Evolution Inferred from Observations

A. Franceschini, G. Rodighiero, M. Vaccari: Background radiations and the cosmic photon-photon opacity

2008



# Evolution Calculated from Observations Using AEGIS Multiwavelength Data

Alberto Dominguez et al. (2010)

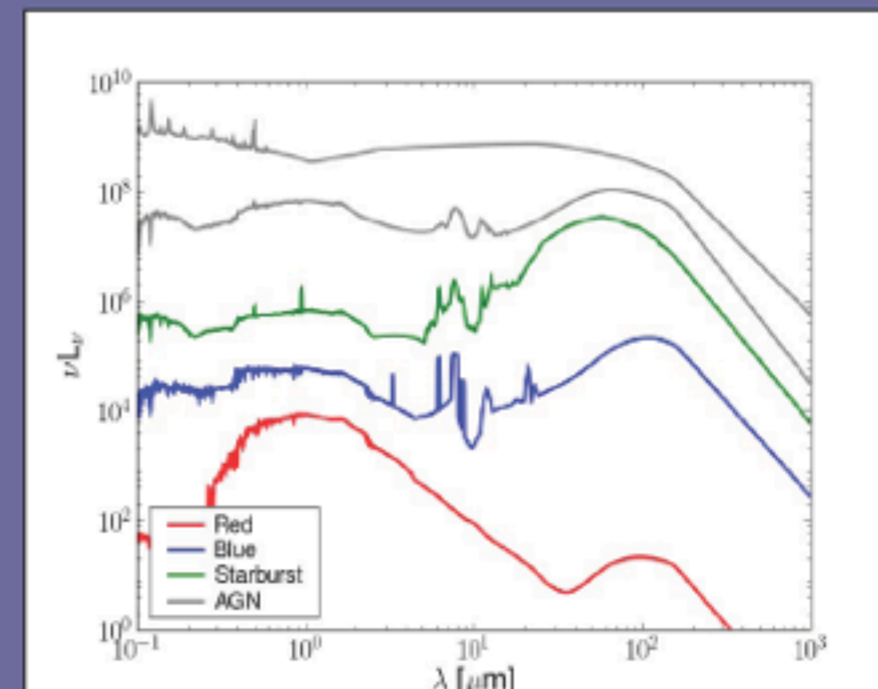
$$j_i(\lambda, z) = j_i^{faint} + j_i^{mid} + j_i^{bright} =$$

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

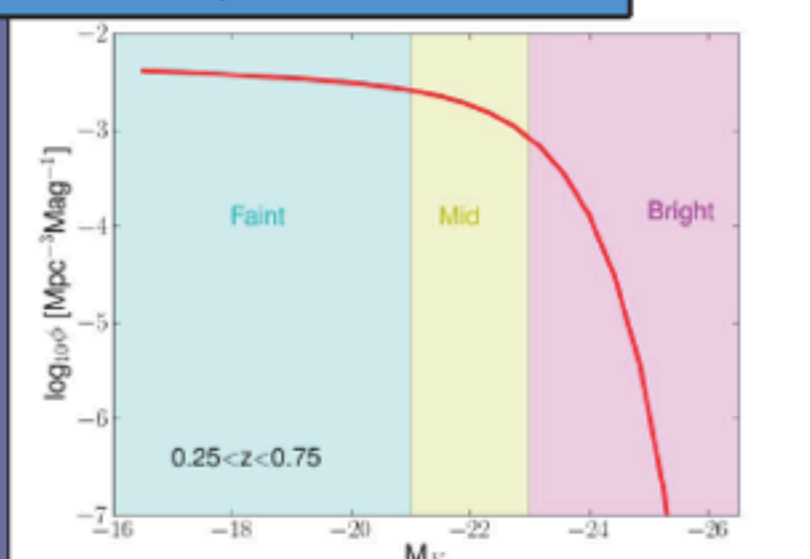
$$+ \int_{M_2}^{M_3} \Phi(M_K, z) m_i T_i(M_K, \lambda) dM_K +$$

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

Spectral energy distributions
SWIRE template library, Polletta+ 07




Luminosity function
observed K-band, Cirasuolo+ 09



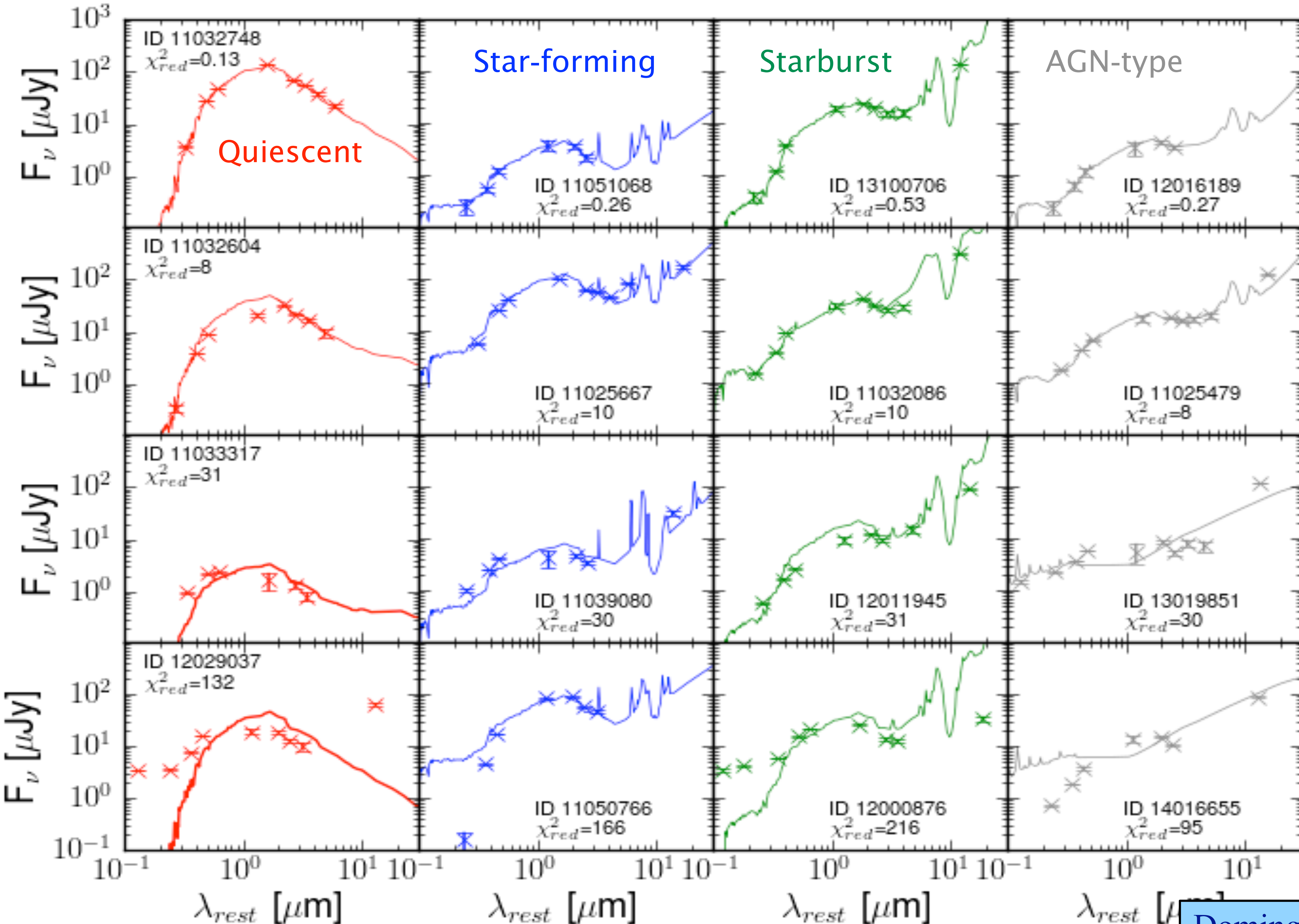

Spectral-type fractions

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


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




Dominguez+ 10

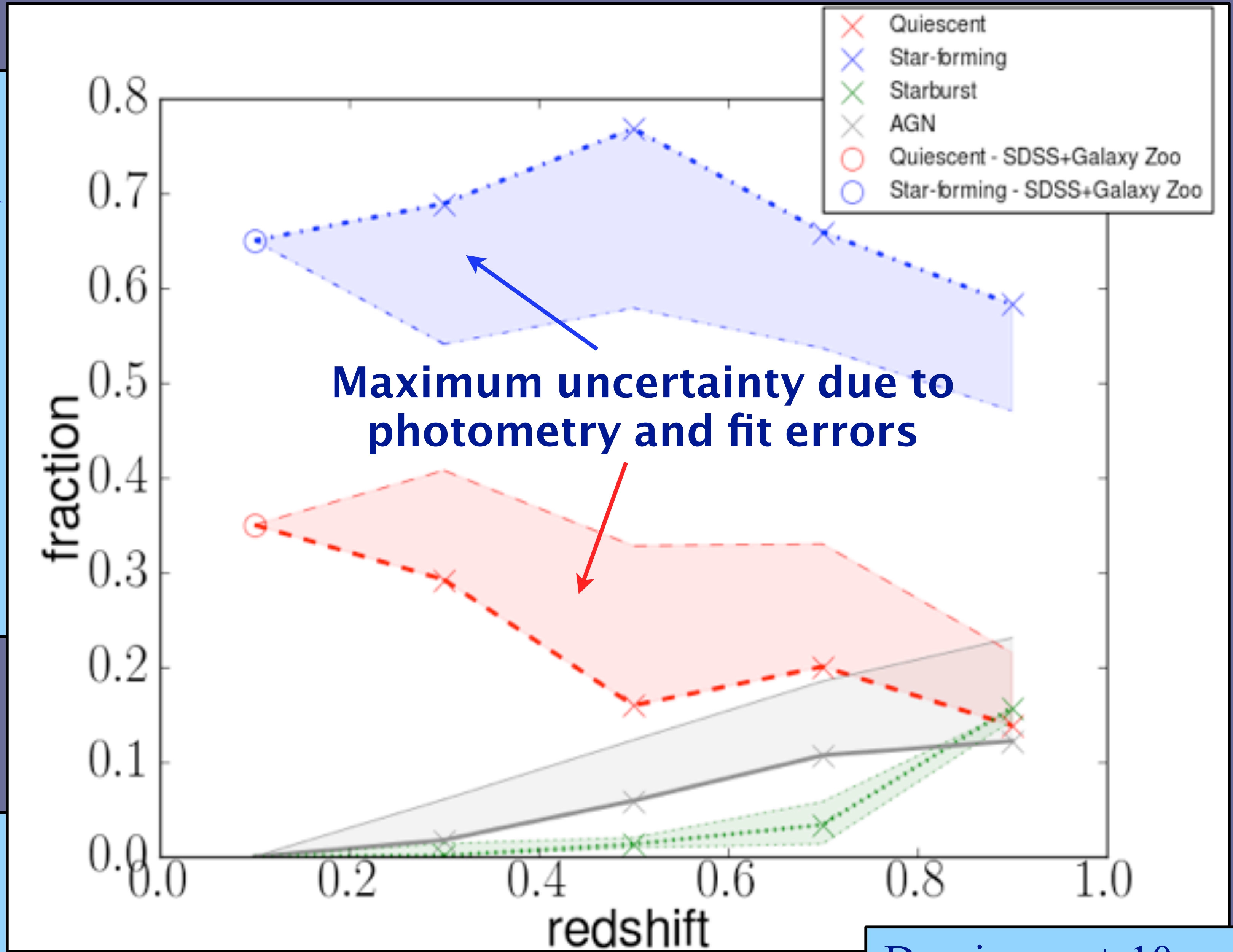
# SED-Type Evolution

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



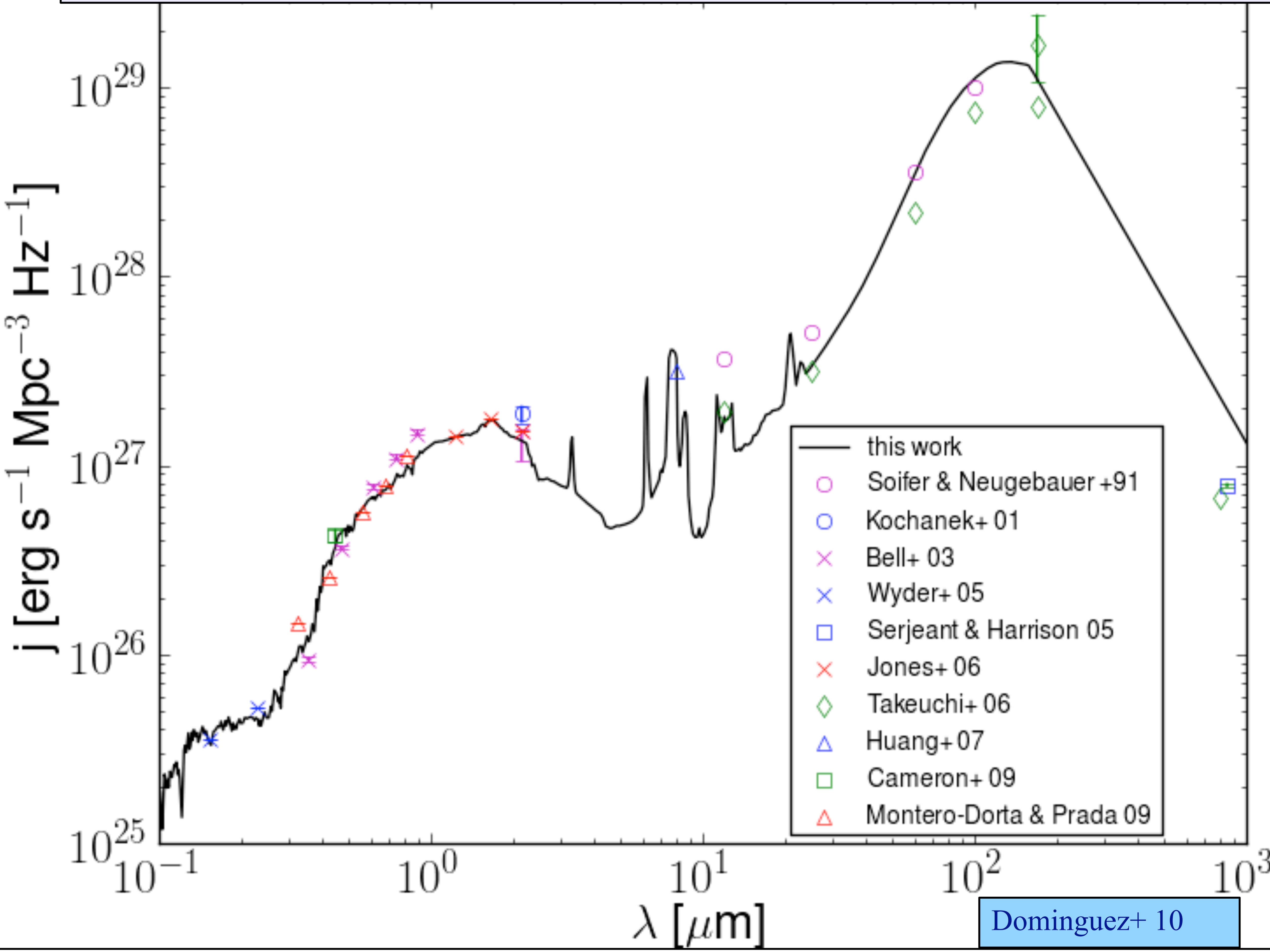

Dominguez+ 10

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

Two approaches:
1. Keep constant the fractions of our last redshift bin
2. Quickly increase starburst population from 16% at z=0.9 to 60% at z=

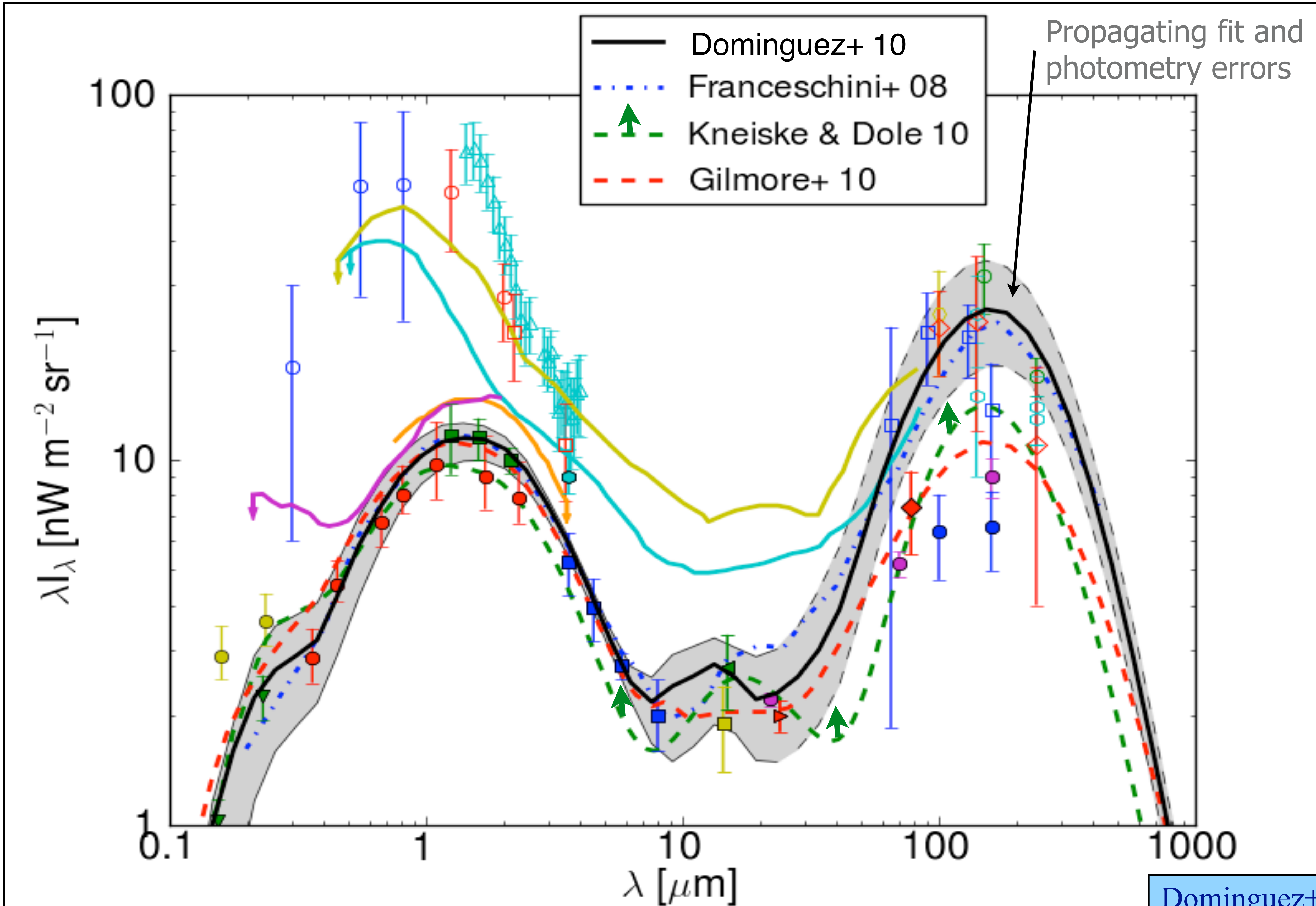
**Details**: Aberto Dominguez's talk at the P8 parallel session, this afternoon

# Local Luminosity Density



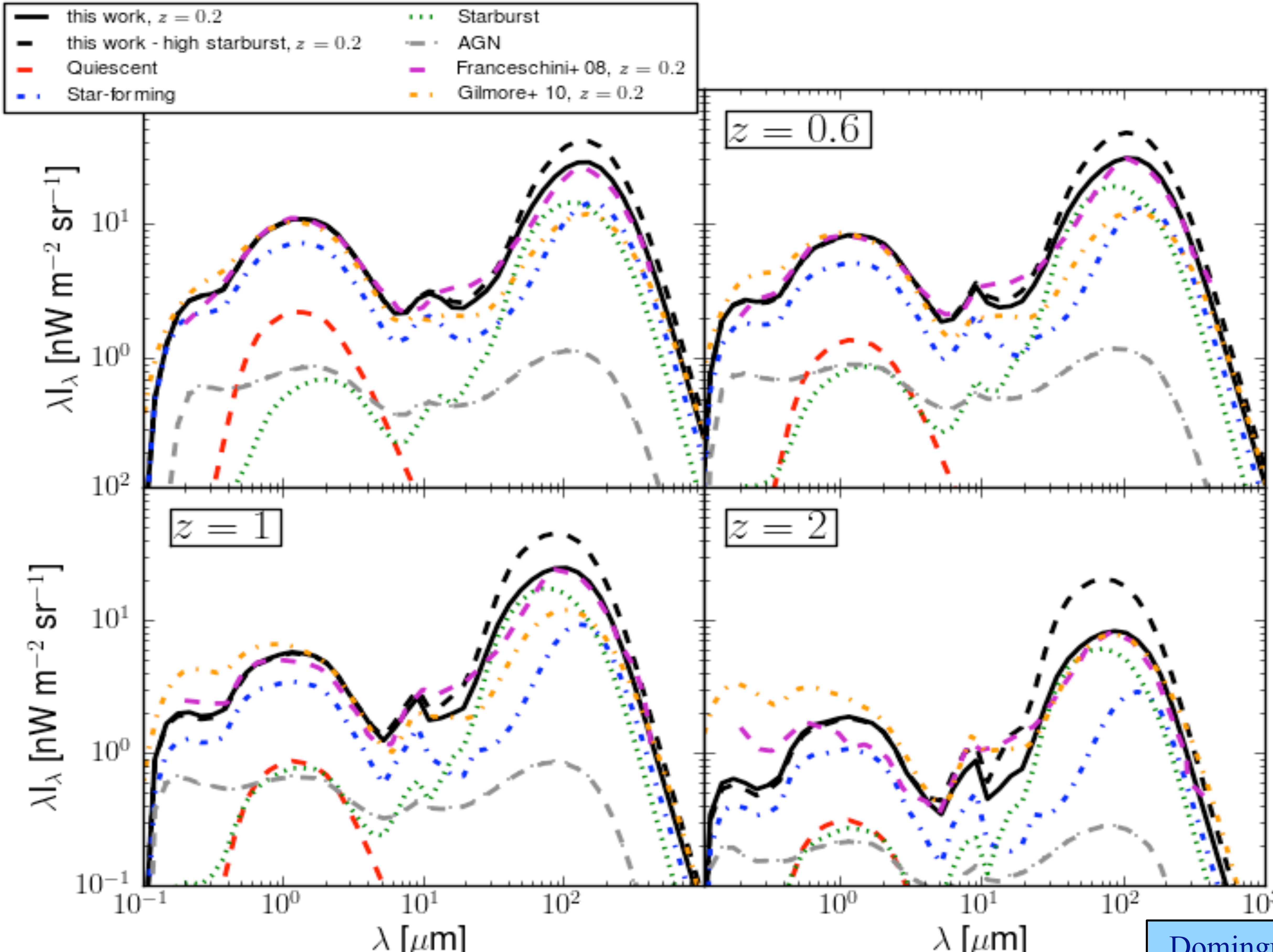

Dominguez+ 10

# Extragalactic Background Light




Dominguez+ 10

# EBL Evolution




Dominguez+ 10

# Conclusions - Part 1

Dominguez+10 is a new calculation of the EBL that for the first time uses galaxy data (LFs and SEDs) over a wide redshift range (from the AEGIS multi-wavelength catalog of ~6000 galaxies between z=0.2-1), with EBL normalized by Cirosuolo+10 K-band luminosity function to z~4. The methodology is transparent and reproducible.

We find intensities matching the lower limits from galaxy counts from UV up to mid IR, but higher at far IR in agreement with direct measurements. Our model is consistent with upper limits from gamma-ray astronomy.

The predicted transparency of the universe to gamma-rays agrees within uncertainties with the observationally-based backward evolution results by Franceschini+08 and forward evolution predictions by Gilmore+10.

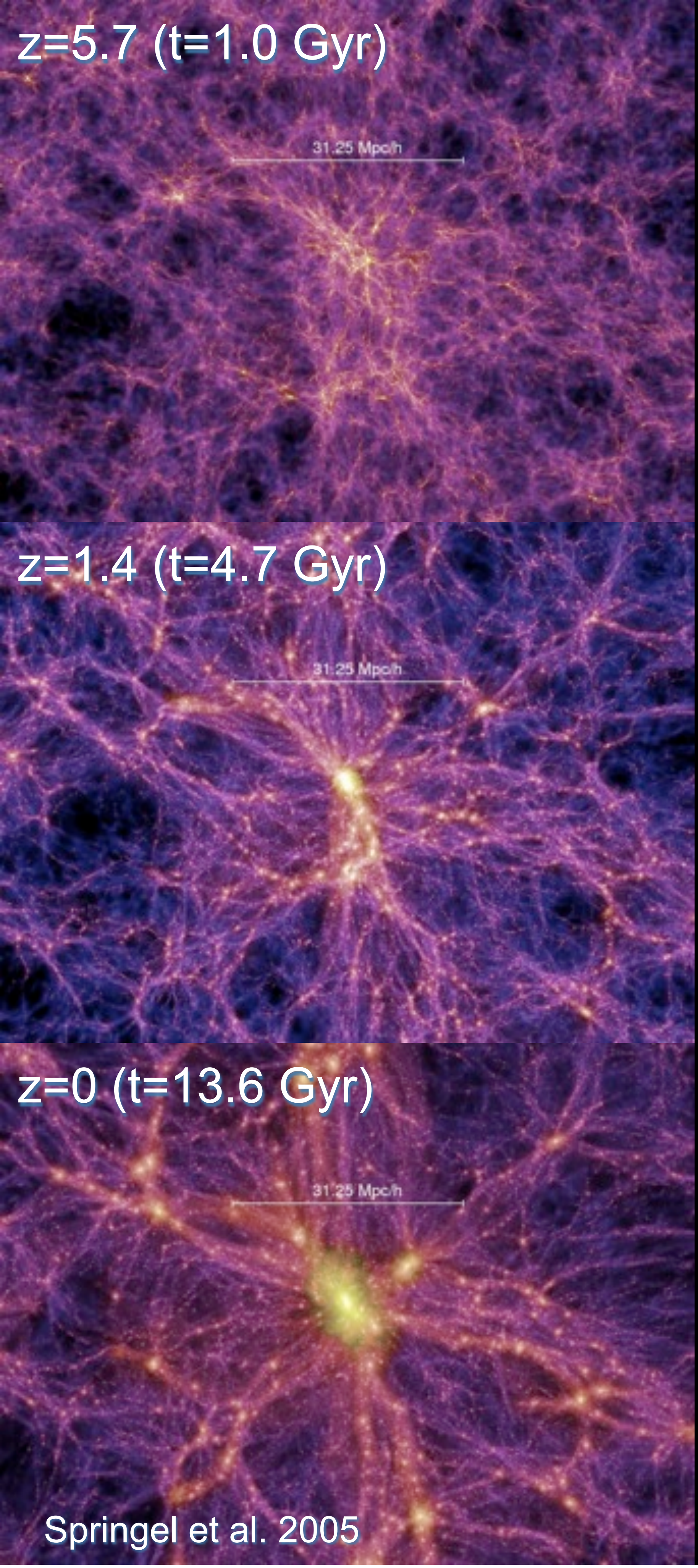
The main uncertainties are in the far IR. They need to be reduced by better understanding of galaxy far-IR emission at z>0.3, galaxy SED-type fractions for z>1, and gamma-ray observations of local sources at E>10 TeV.

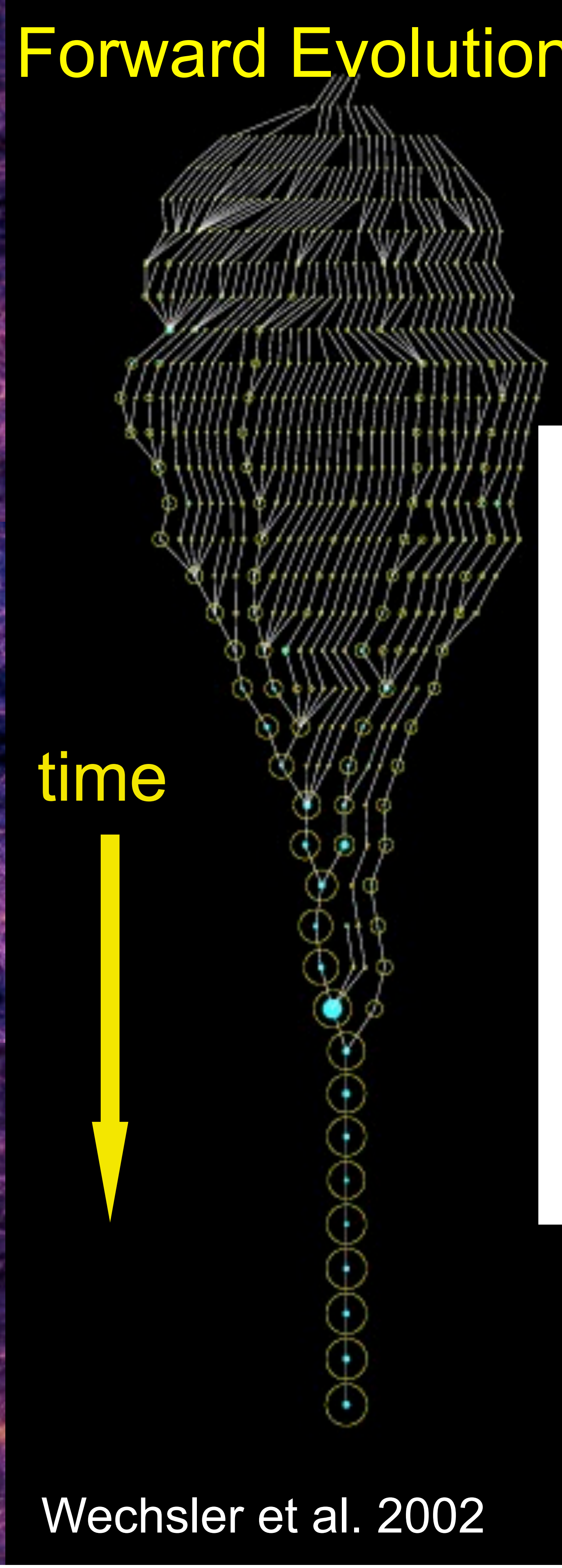
EBL intensities and optical depths are available on-line at: **side.iaa.es/EBL**

# Forward Evolution

When we first tried doing this (Primack & MacMinn 1996), 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 my report here is based on a semi-analytic model (SAM) using 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.

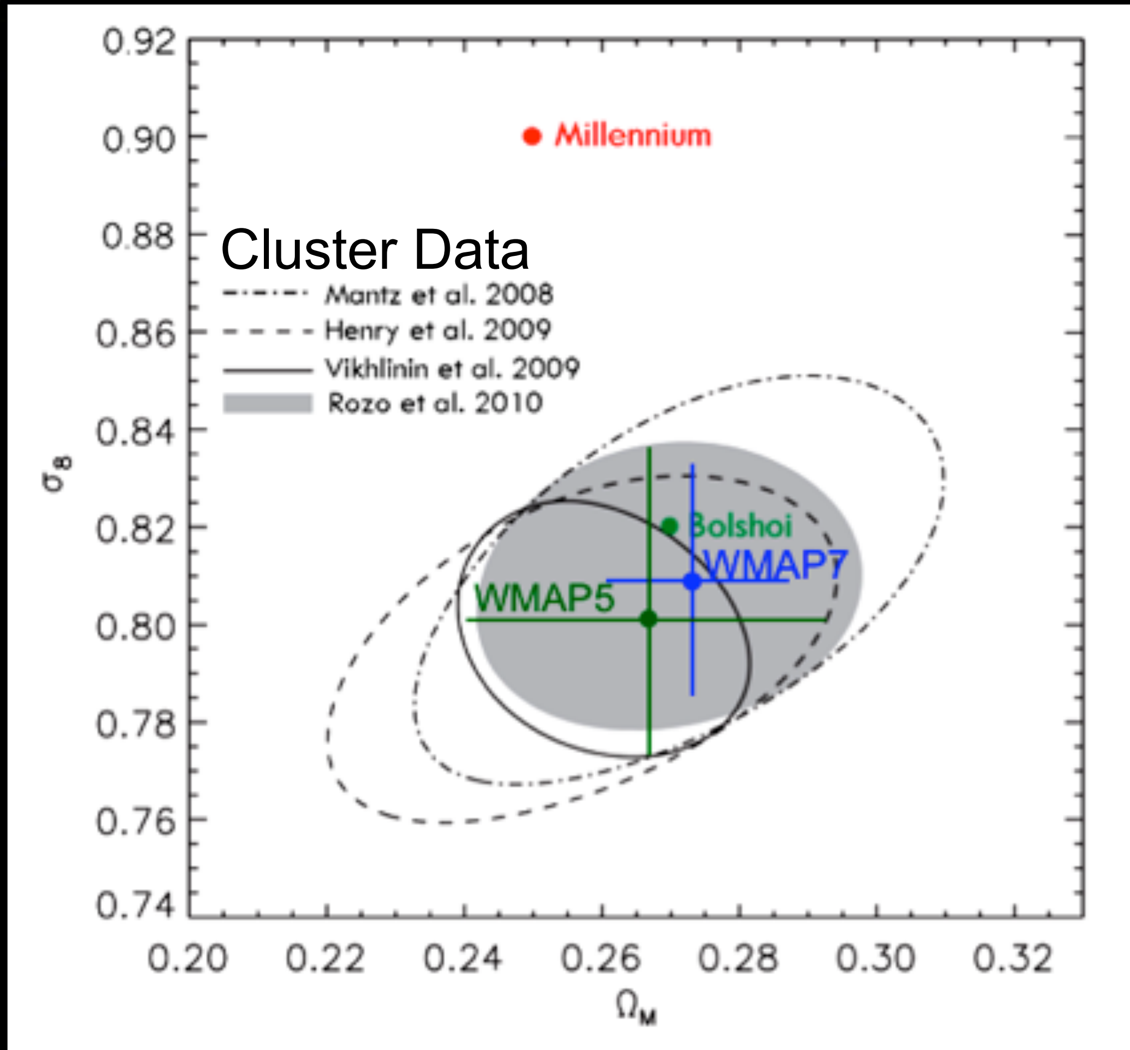
There is still uncertainty whether the IMF evolves, possibly becoming "top-heavy" at higher redshifts (e.g., Fardal et al. 2007, Dave 2008), and uncertainty concerning the nature of sub-mm galaxies and the feedback from AGN.



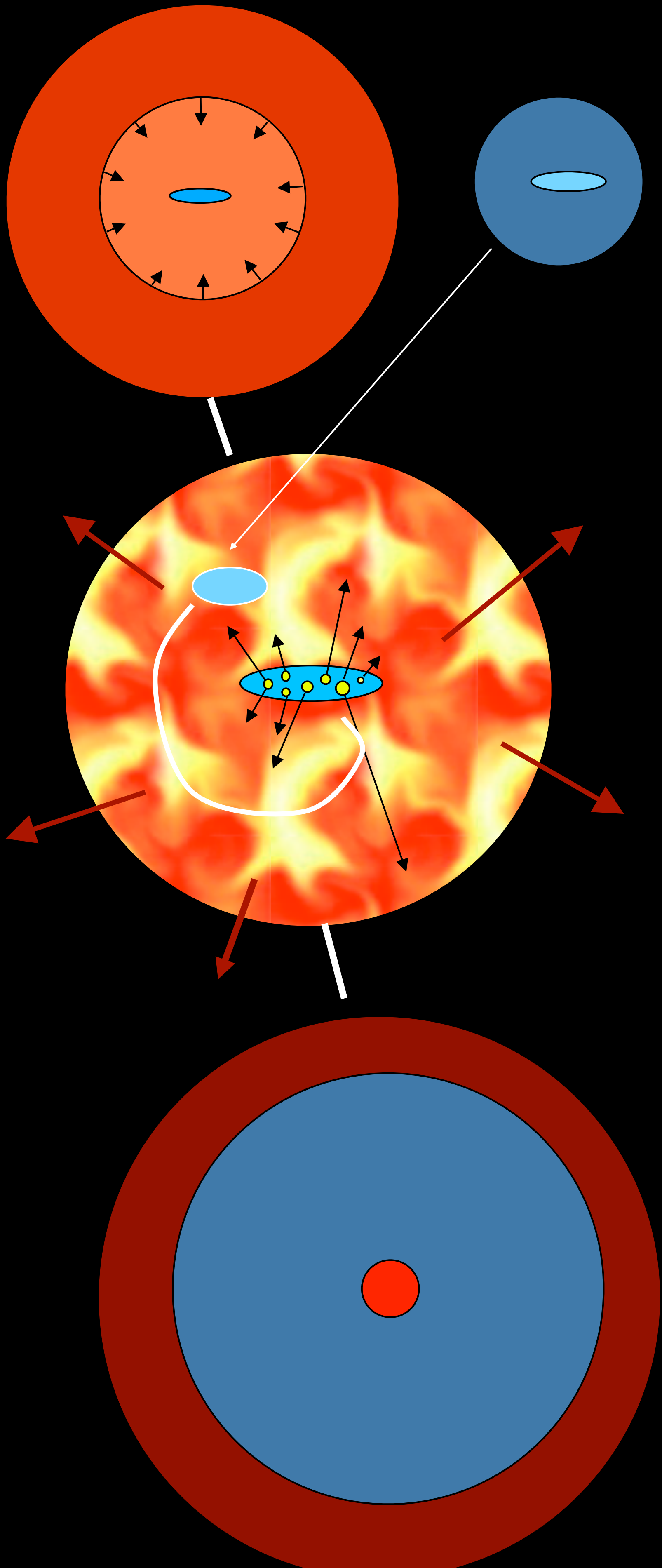

# Present status of ΛCDM "Double Dark" theory:

- 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

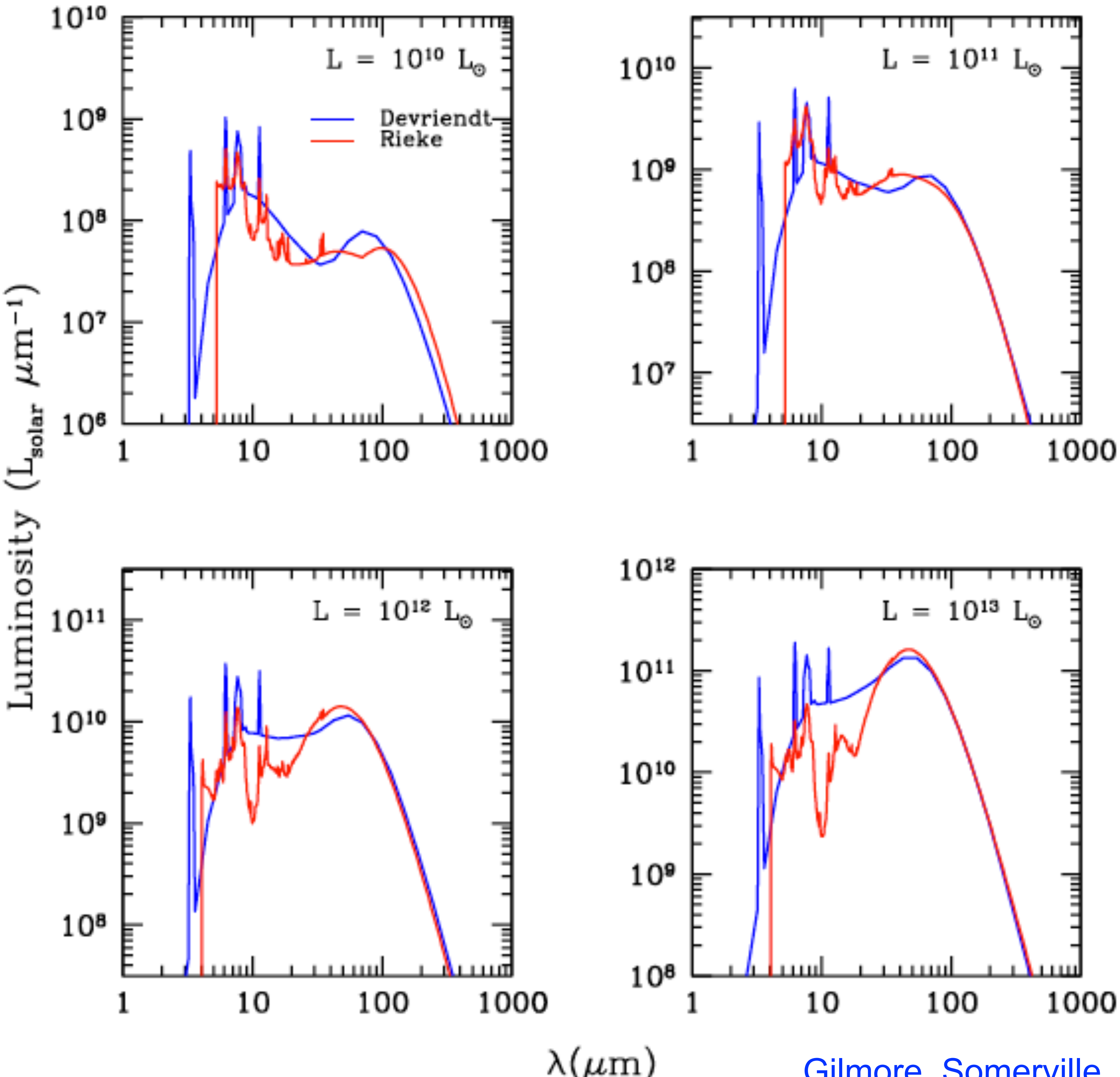
# Galaxy Formation in ΛCDM



- 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; Somerville, Gilmore, Primack, & Dominguez 11 (reported here)

# Improved Dust Emission Templates



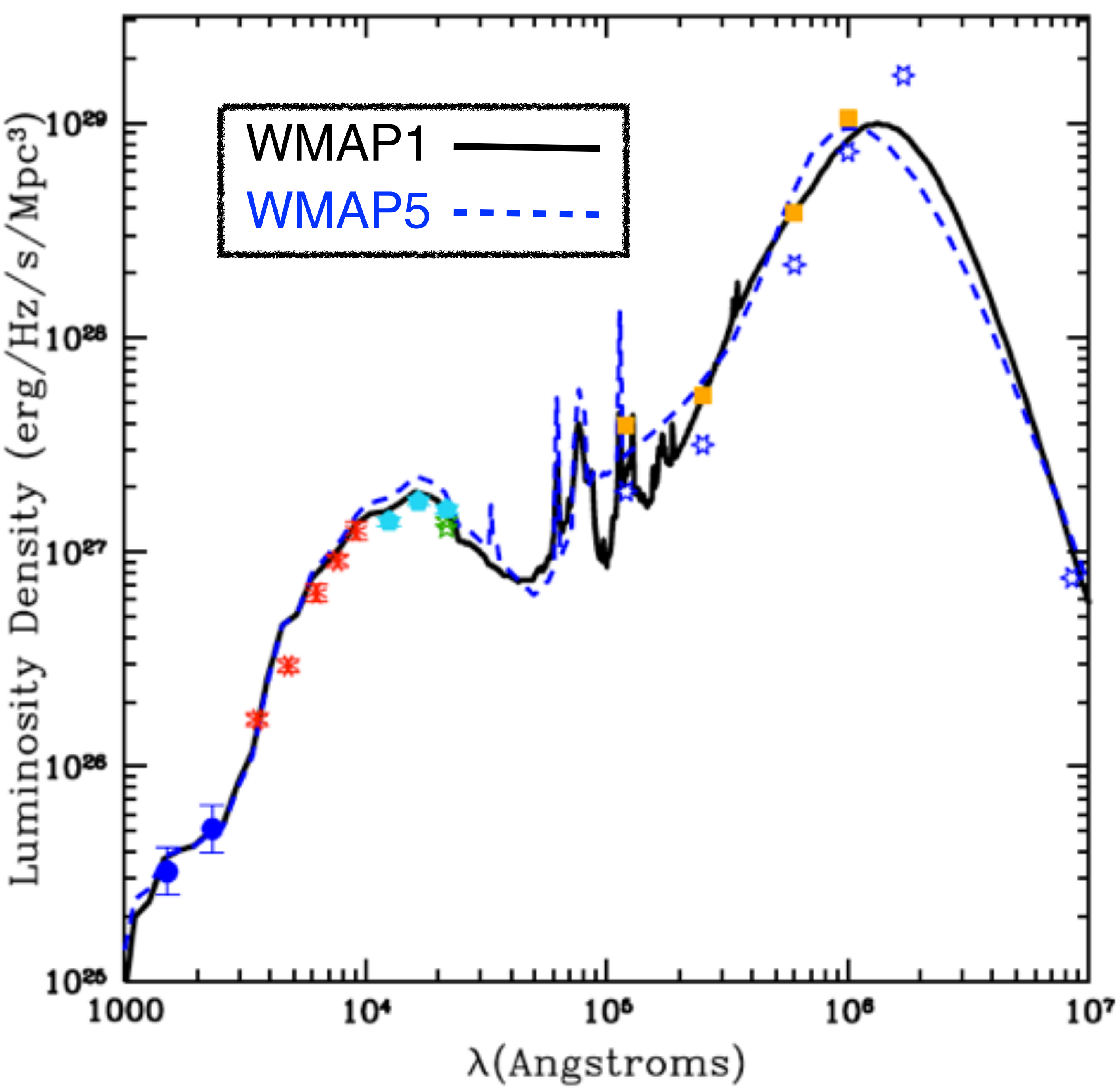

In previous work we used Devriendt & Guiderdoni 2000 dust emission templates, based on IRAS data.

In our new models we use the new Rieke+09 dust emission templates based on Spitzer data.

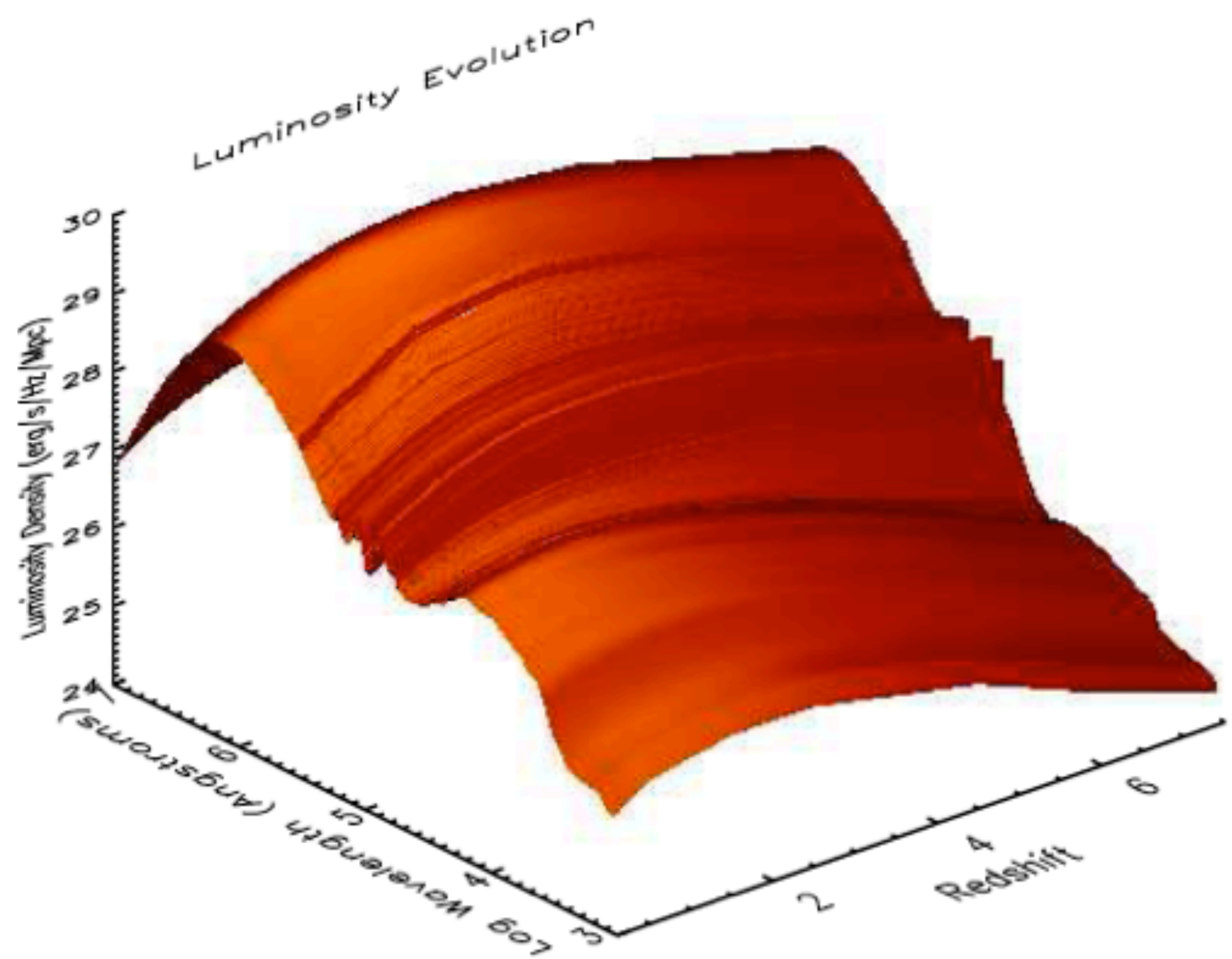
Gilmore, Somerville, Primack, & Dominguez (2010)

# Some Results from our Semi-Analytic Models

## z=0 Luminosity Density



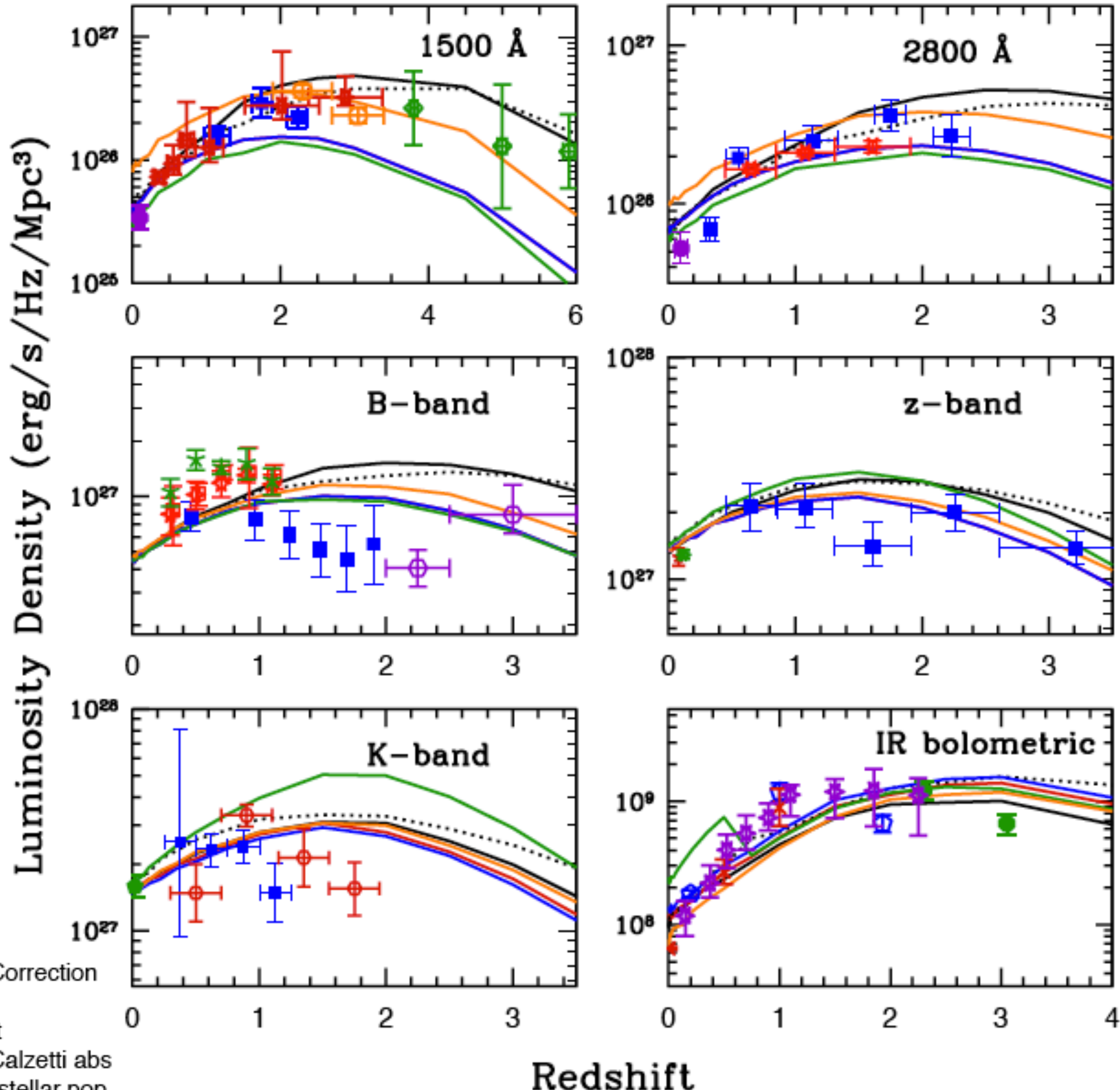

## Evolving Luminosity Density




Gilmore, Somerville, Primack, & Dominguez (2010)

# Results from our Semi-Analytic Models

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

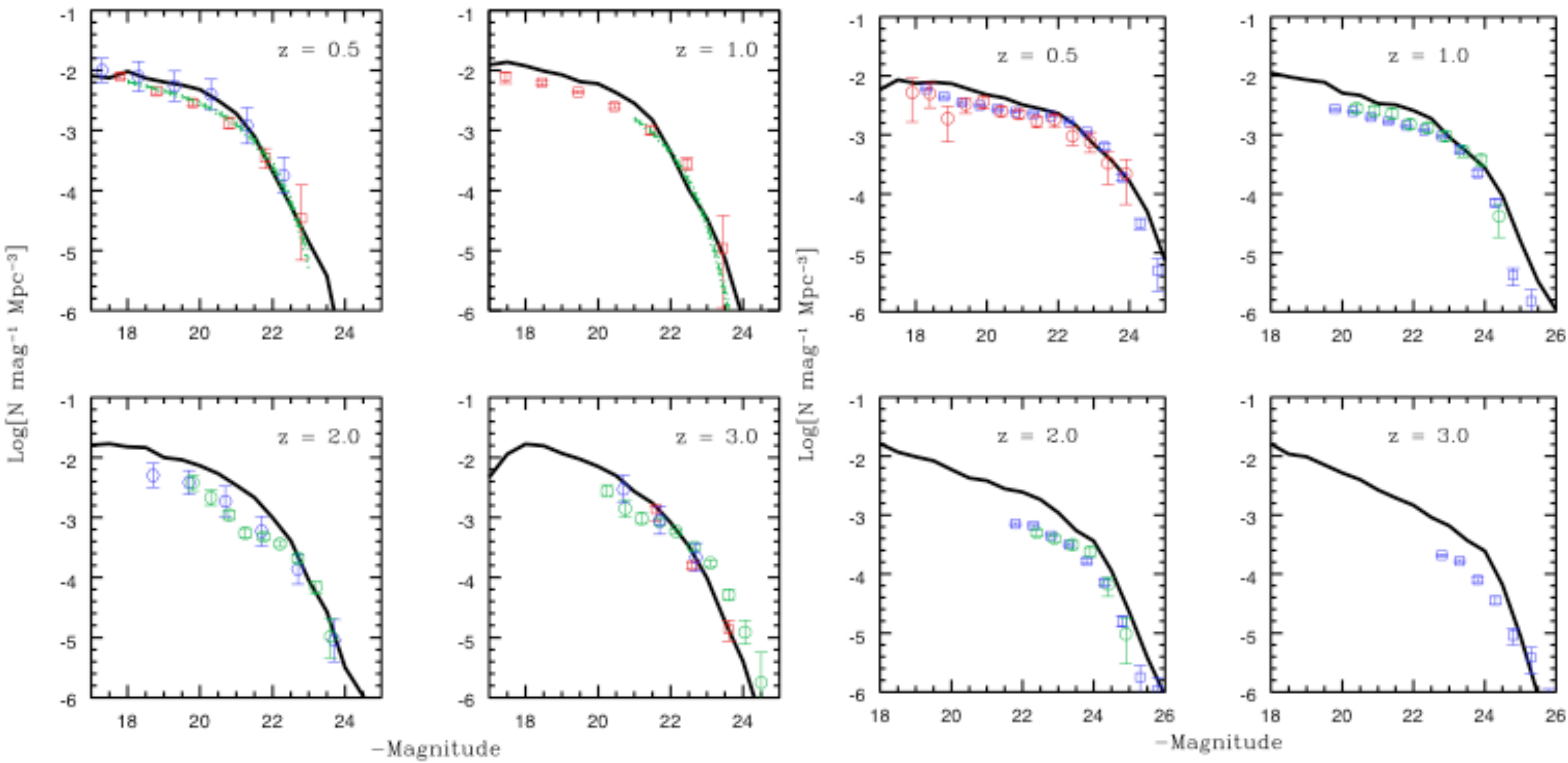



Somerville, Gilmore, Primack, & Dominguez (2010)

# Some Results from our Semi-Analytic Models

## Evolving Luminosity Functions

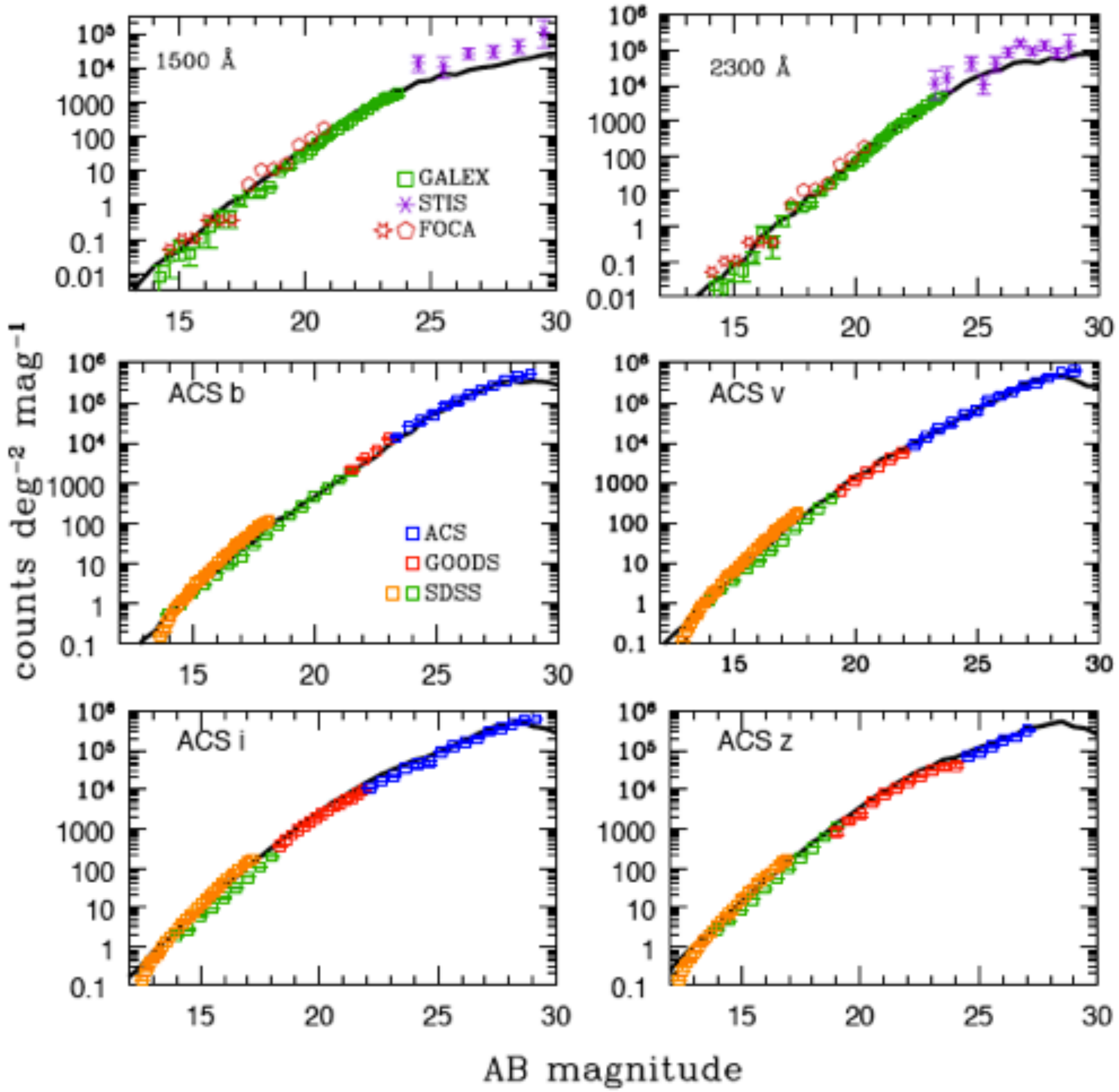
B-band K-band



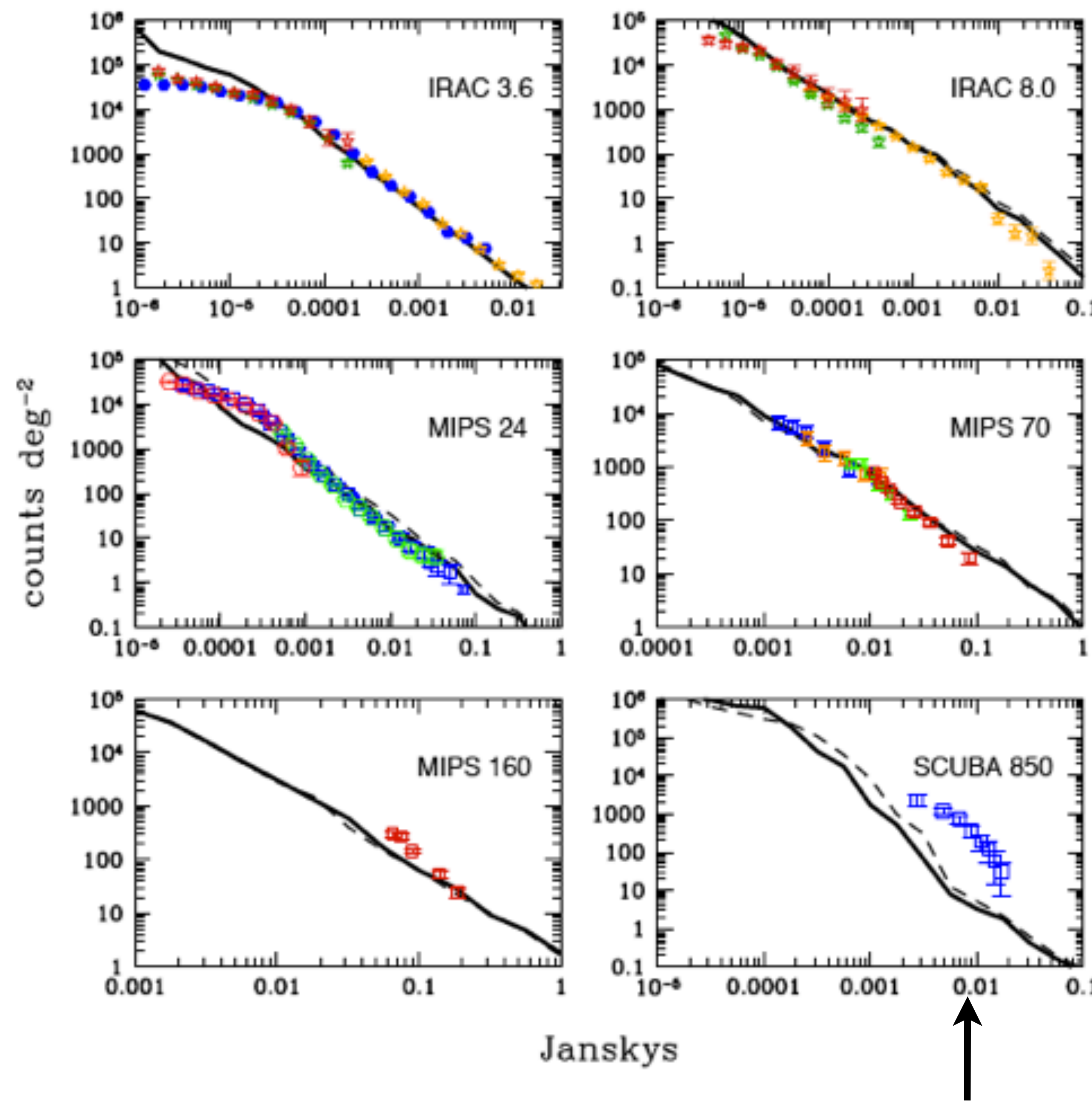

Somerville, Gilmore, Primack, & Dominguez (2010)

# Some Results from our Semi-Analytic Models

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



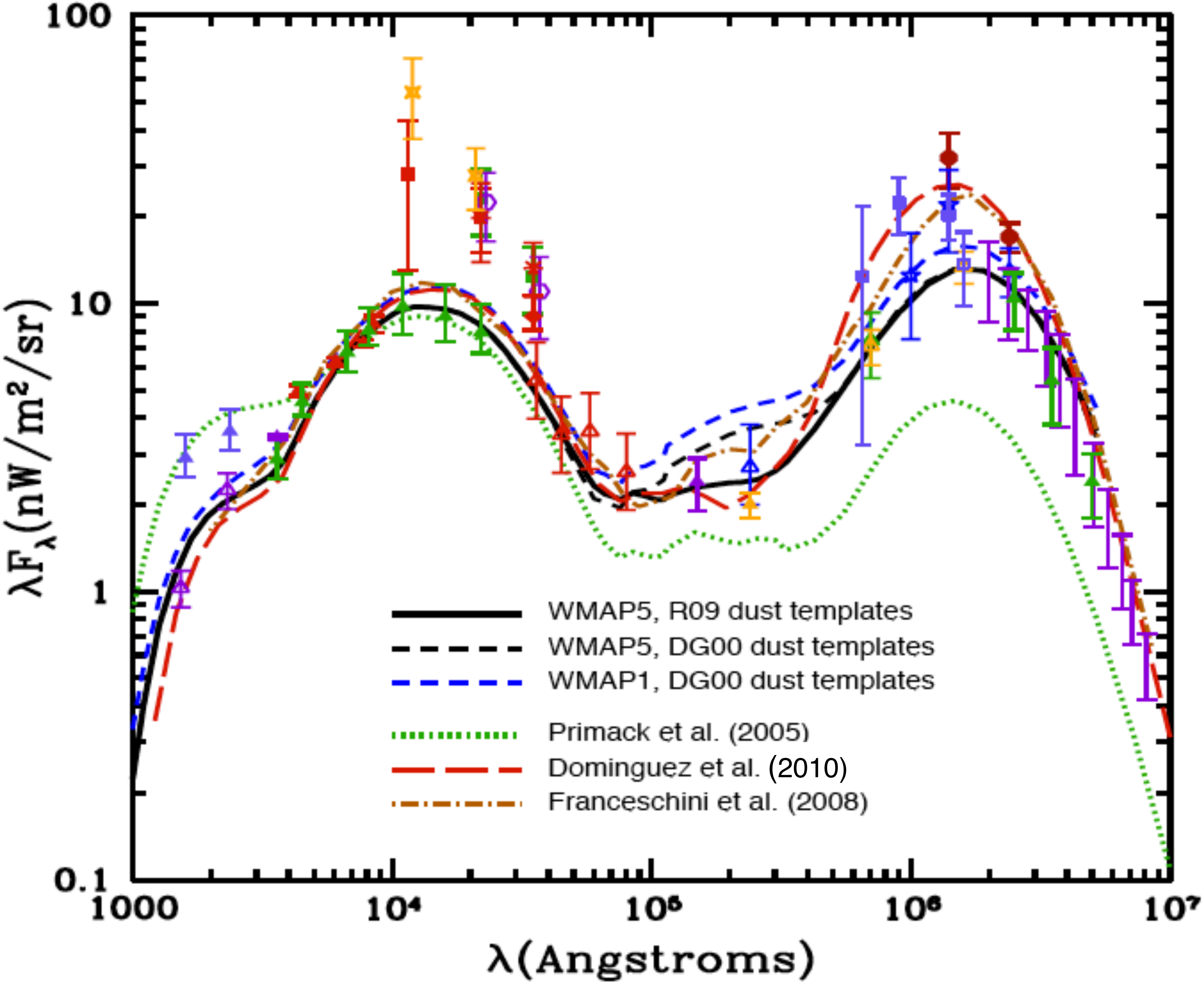

## 3.6, 8, 24 and 24, 70, 160, & 850 μm Bands




Gilmore, Somerville, Primack, & Dominguez (2010)

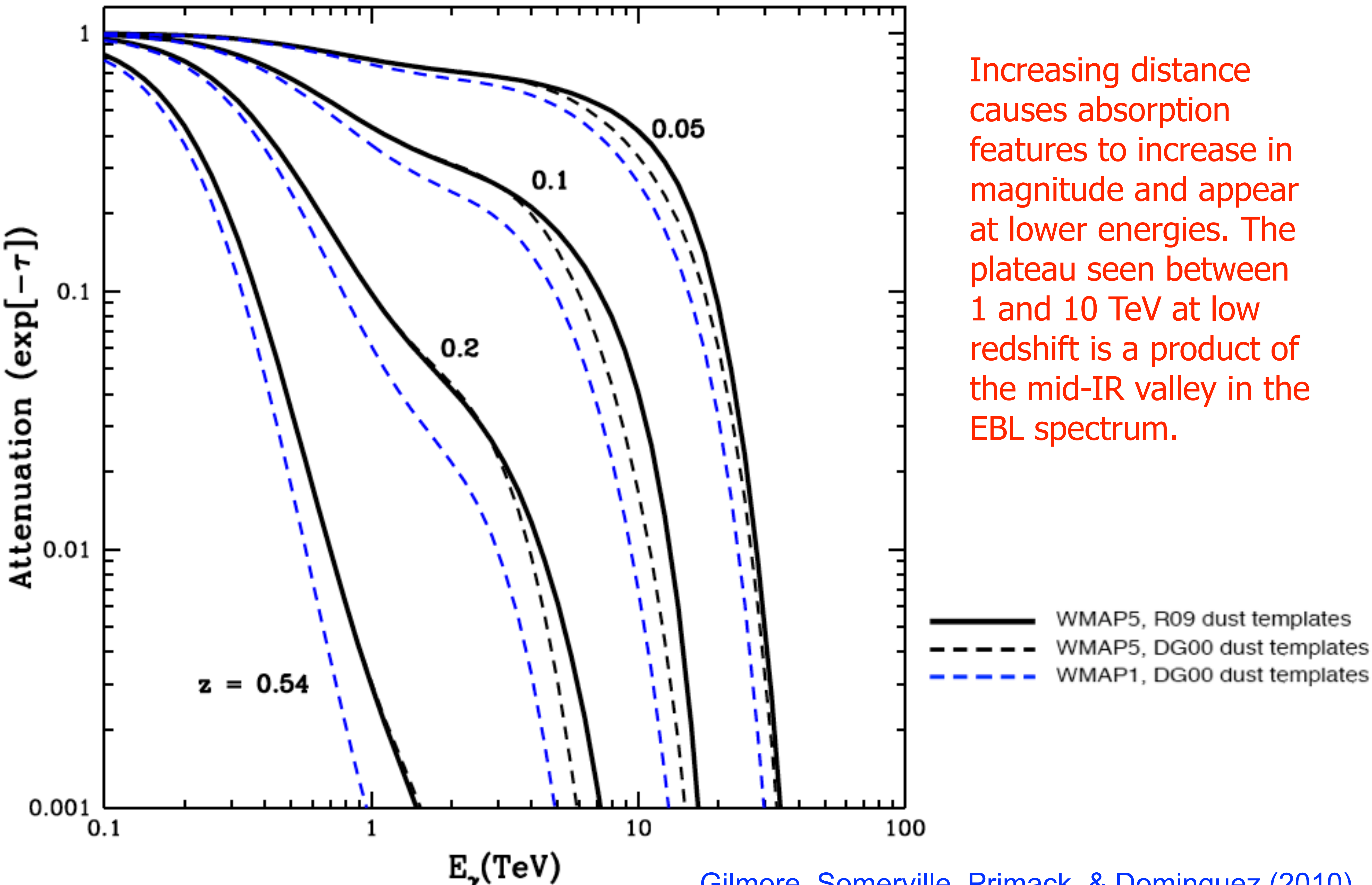
The one failure is at 850 μm

# EBL from our Semi-Analytic Models




Gilmore, Somerville, Primack, & Dominguez (2010)

# Predicted Gamma Ray Attenuation



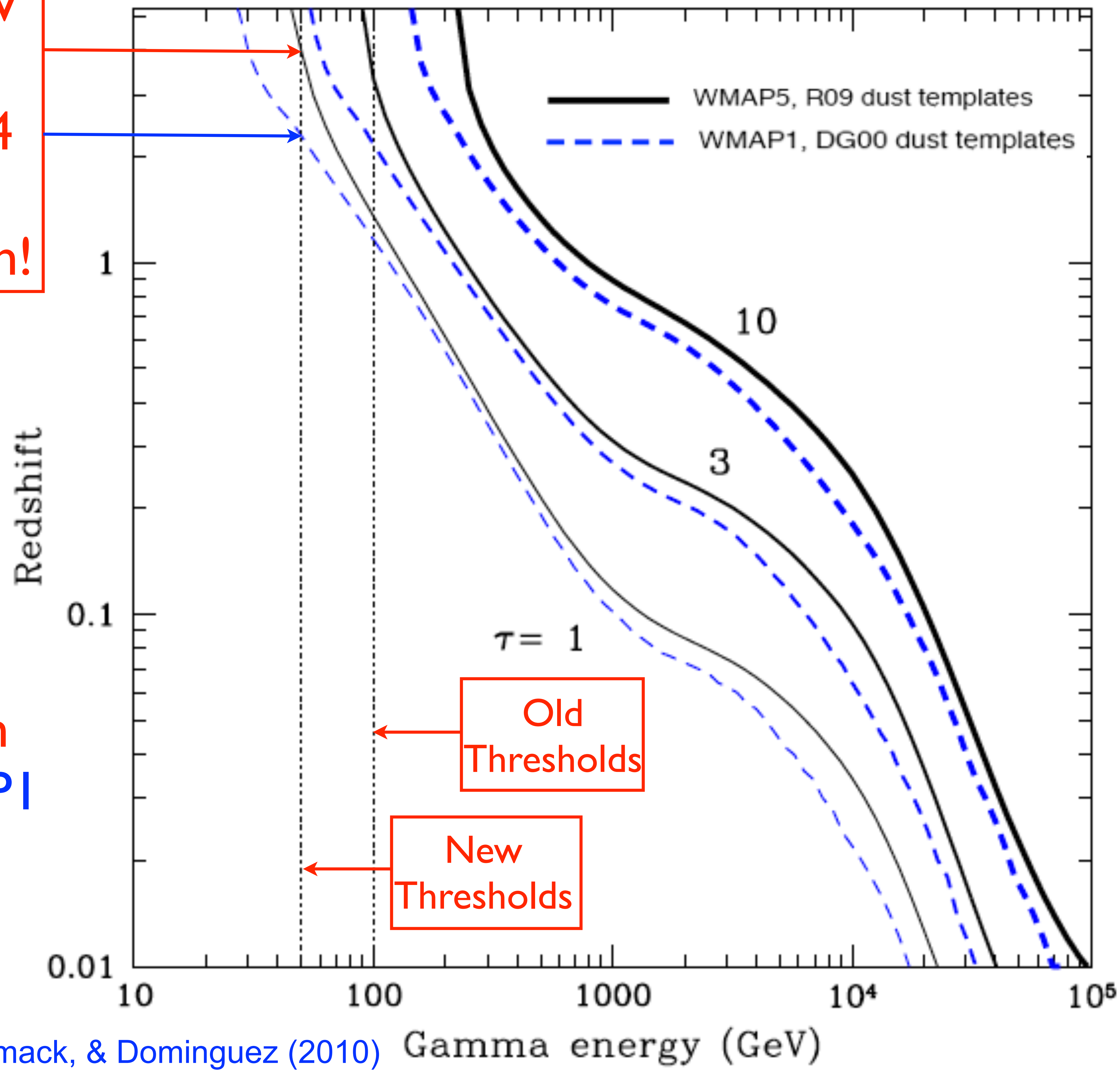

Increasing distance causes absorption features to increase in magnitude and appear at lower energies. The plateau seen between 1 and 10 TeV at low redshift is a product of the mid-IR valley in the EBL spectrum.

Gilmore, Somerville, Primack, & Dominguez (2010)

# Gamma-Ray Absorption Edge

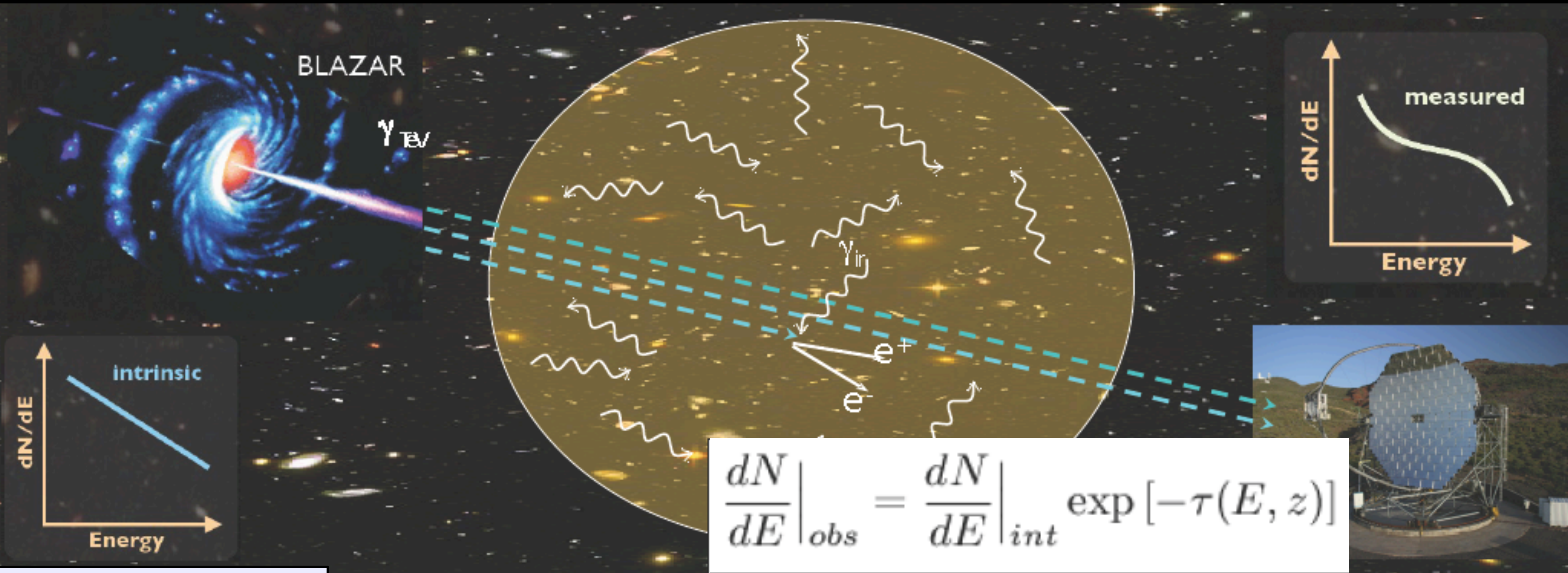
With a 50 GeV threshold, we see to z≈2.5-4 with less than 1/e attenuation!

for WMAP5 compared with our old WMAP1 models




Gilmore, Somerville, Primack, & Dominguez (2010)

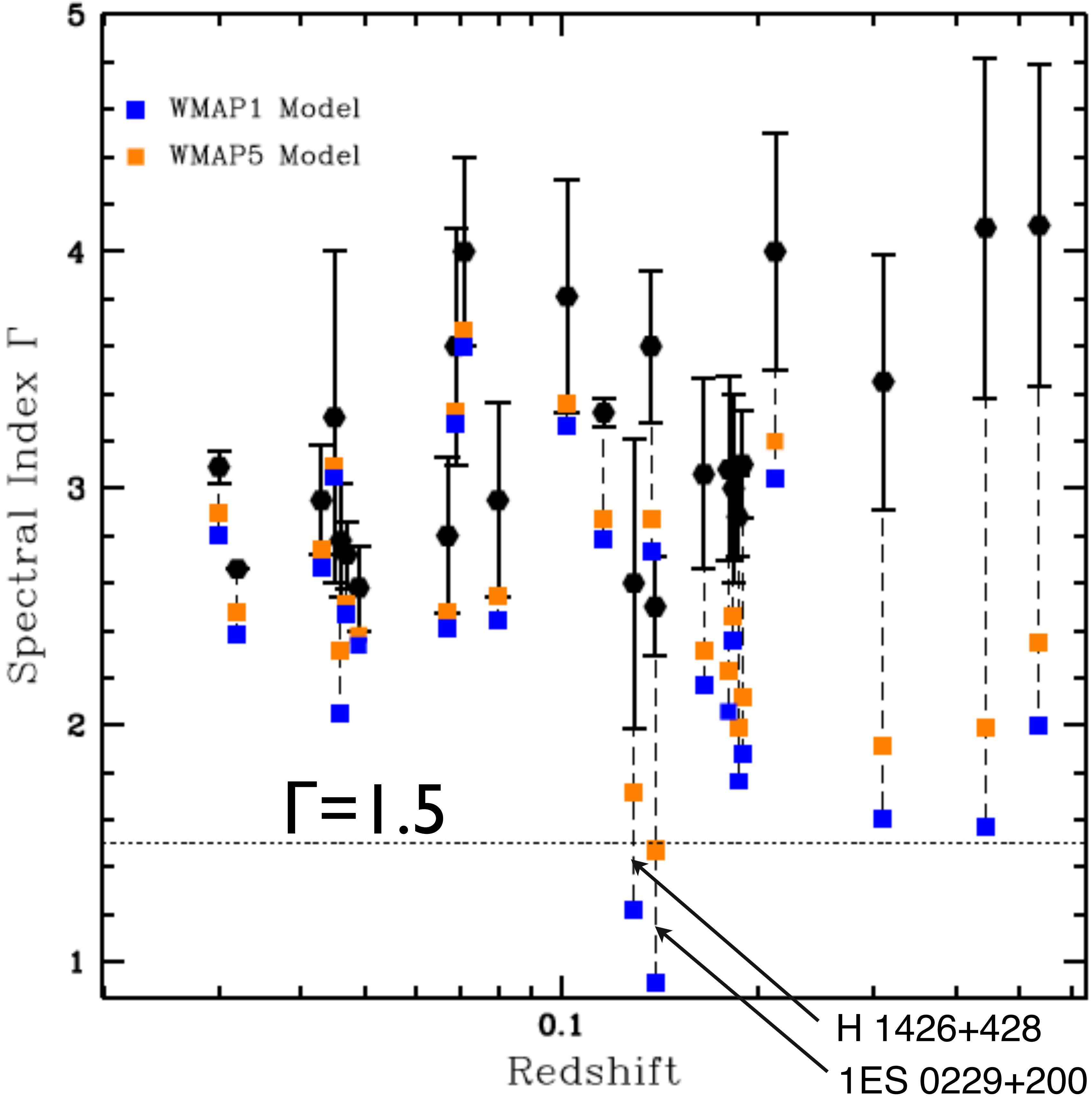
# Gamma Ray Attenuation due to $\gamma\gamma \rightarrow e^+e^-$




Ilustration: D. Mazin & M. Raue

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 $\Gamma \geq 2$.

# Reconstructed Blazar Spectral Indexes




With our SAM based on current WMAP5 cosmological parameters and Rieke+09 dust emission templates, all high redshift blazars have spectral indexes ≤1.5, as expected from nearby sources.

# Conclusions - Part 2

The latest semi-analytic models (SAMs) by our group are in very good agreement with observed galaxies both nearby and at higher redshifts. Our predicted EBL intensities and optical depths will be available on-line soon.

The predicted transparency of the universe to gamma rays is consistent with upper limits from high-energy gamma-ray observations assuming unattenuated spectral index $\Gamma \geq 1.5$, and agrees within uncertainties with the observationally-based backward evolution results by Franceschini+08 and the observational calculation by Dominguez+10.

The more optimistic predicted transparency to gamma rays implies that new ACT thresholds of ~ 50 GeV will allow detection of blazars or GRBs to z ~ 4 with little attenuation.

Local observation of the EBL is difficult, and direct observation at higher redshifts is impossible, so theoretical calculations are essential. These calculations are increasingly sensitive to the star formation rates and dust reprocessing by galaxies at high redshifts, which will be informed by new observations with new instruments and by self-consistent dust modeling.

# Catching GRBs with IACTs

This work is based on Rudy Gilmore's 2009 PhD dissertation research with me and our continuing collaborations, including the following papers:

- Gilmore, Madau, Primack, Somerville, Haardt 2009 MNRAS, GeV Gamma Ray Attenuation and the High-Redshift UV Background
- Gilmore, Prada, Primack 2010 MNRAS, Modeling GRB Observations by *Fermi* and MAGIC Including Attenuation by Extragalactic Background Light

  Gilmore and Ramirez-Ruiz 2010 ApJ, Local Absorption of High-Energy Emission from Gamma-Ray Bursts
- Abdo et al. 2010 ApJ, Fermi LAT Constraints on the Gamma-Ray Opacity of the Universe

  Somerville, Gilmore, Primack, Dominguez 2010, Galaxy Properties from the UV to the Far-IR: ΛCDM Models Confront Observations

  Gilmore, Somerville, Primack, Dominguez 2010, Extragalactic Background Light and Gamma Ray Attenuation
- Gilmore, Bouvier, Otte, Primack, Williams 2011, Modeling GRB Observations by *Fermi* and Atmospheric Cherenkov Telescope Arrays, in preparation

# Gamma Rays from High-z GRBs

While AGN have typically been the focus of extragalactic background light (EBL) studies, GRBs are also potentially useful:

- BATSE on CGRO detected thousands of GRBs at 20 keV - 2 MeV
- EGRET saw 5 bursts above 30 MeV (45 photons, 4 above 1 GeV) in 4 years of operations
- Swift has allowed us to systematically determine redshifts for many GRBs (467 events, ~140 with redshift) from launch in 2004 to 2009
- Fermi GBM detects many GRBs, and Fermi LAT has thus far detected 4 bright GRBs from $z > 1$ with $E_{obs} > 1$ GeV ($E_{rest}$ up to 93 GeV)
- A definite detection of GRB gammas from the ground has yet to occur, although campaigns are underway especially at MAGIC and VERITAS

Goals here:

- make a simple model for high energy GRB emission, including z-dependence
- make predictions for current experiments (Fermi and MAGIC) after factoring in EBL attenuation
- make predictions for proposed new ACT arrays (CTA, AGIS, ACTA)

# The High Redshift UV Background

• Affects gamma-rays from distant sources, observed in 10-100 GeV energy range.

• Fermi LAT is studying the little-understood energy decade of 10-100 GeV.

• Next generation of ground based experiments (MAGIC-II, H.E.S.S.-II, VERITAS upgrade) will observe gamma-rays down to ~ 50 GeV.

We attempted to compute this background with various models to bound the uncertainty:

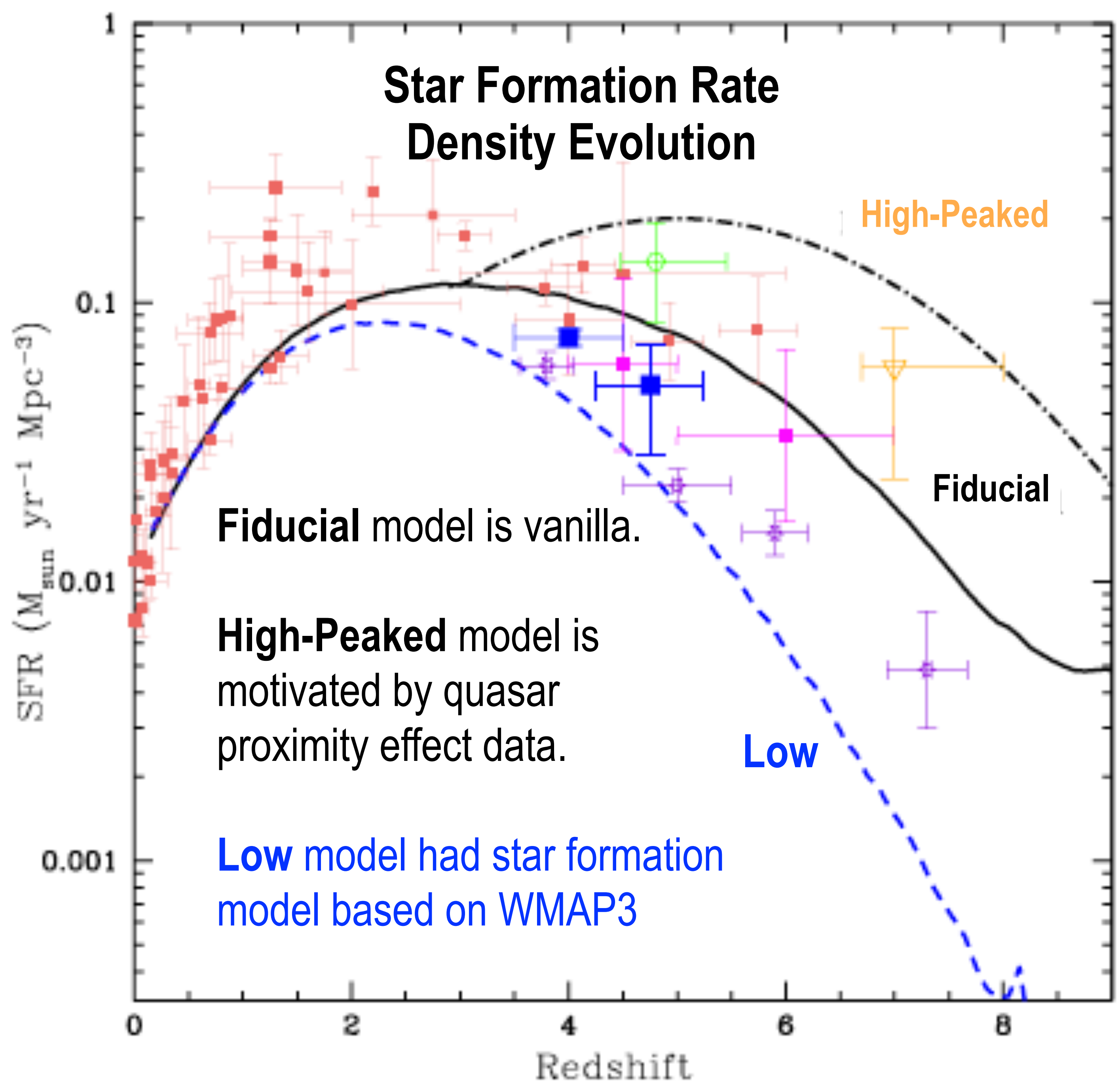
- Quasar contribution based on observational estimates (Hopkins et al. 2007)
- Transfer of ionizing radiation through IGM calculated with CUBA code (Haardt & Madau 2001, now being updated)
- Reasonable estimates of ionizing escape fraction from star-forming galaxies

Gilmore, Madau, Primack, Somerville, Haardt 2009, GeV Gamma-Ray Attenuation and the High-Redshift UV Background

**Fiducial**, **Low**, and **High-Peaked** UV EBL evolution models -- consistent with CMB, z~6 H reionization, z~3 He reionization, realistic star formation evolution, and GALEX data.

**Fiducial**, **Low**, and **High-Peaked** UV EBL evolution models -- roughly consistent with CMB, z~6 H reionization, z~3 He reionization, realistic star formation evolution, and GALEX data.

Gilmore, Madau, Primack, Somerville, Haardt 2009 MNRAS, GeV Gamma Ray Attenuation and the High-Redshift UV Background

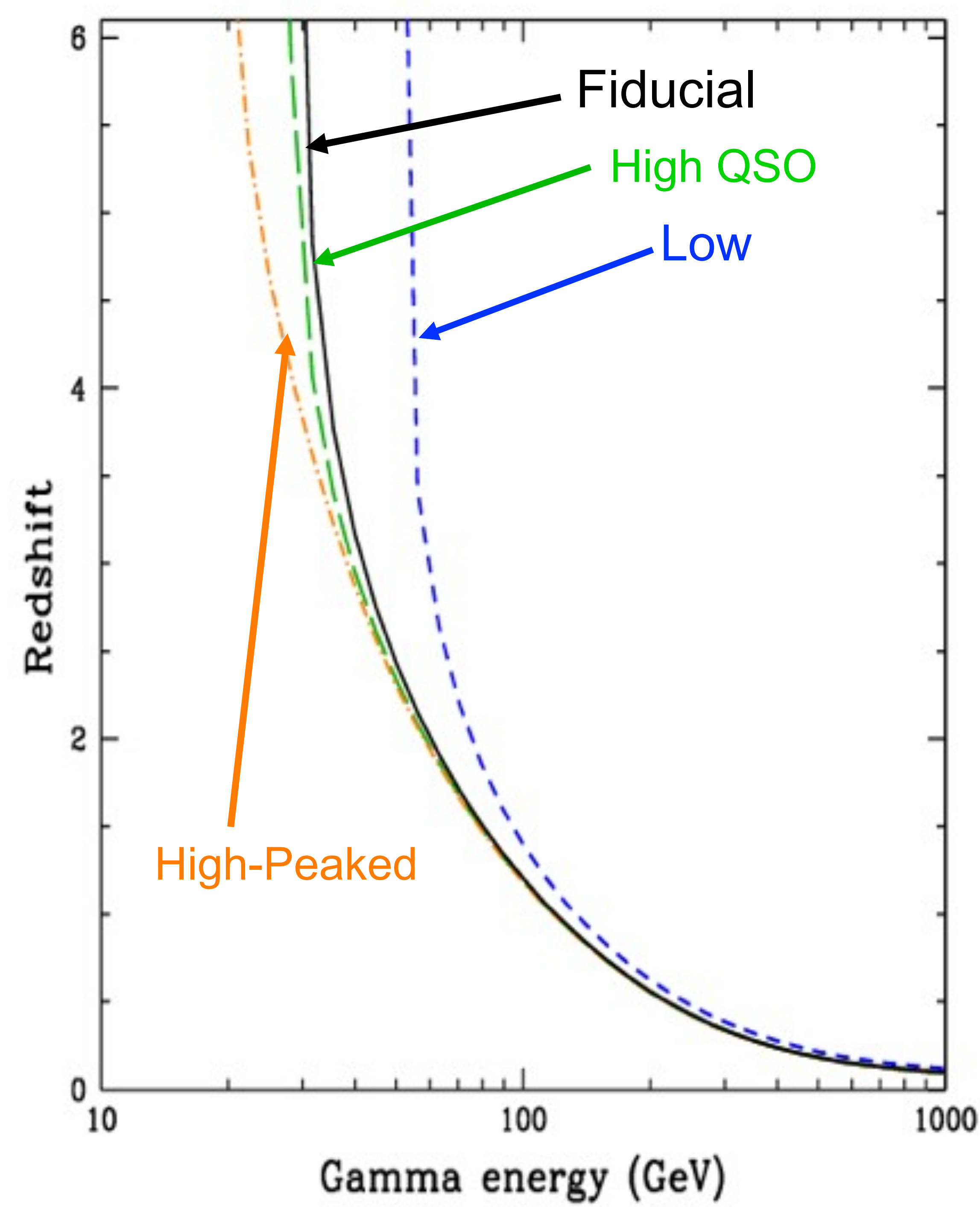



**Fiducial** model is vanilla.

**High-Peaked** model is motivated by quasar proximity effect data.

**Low** model had star formation model based on WMAP3

Gamma-ray Absorption Edge ($\tau$ = 1)

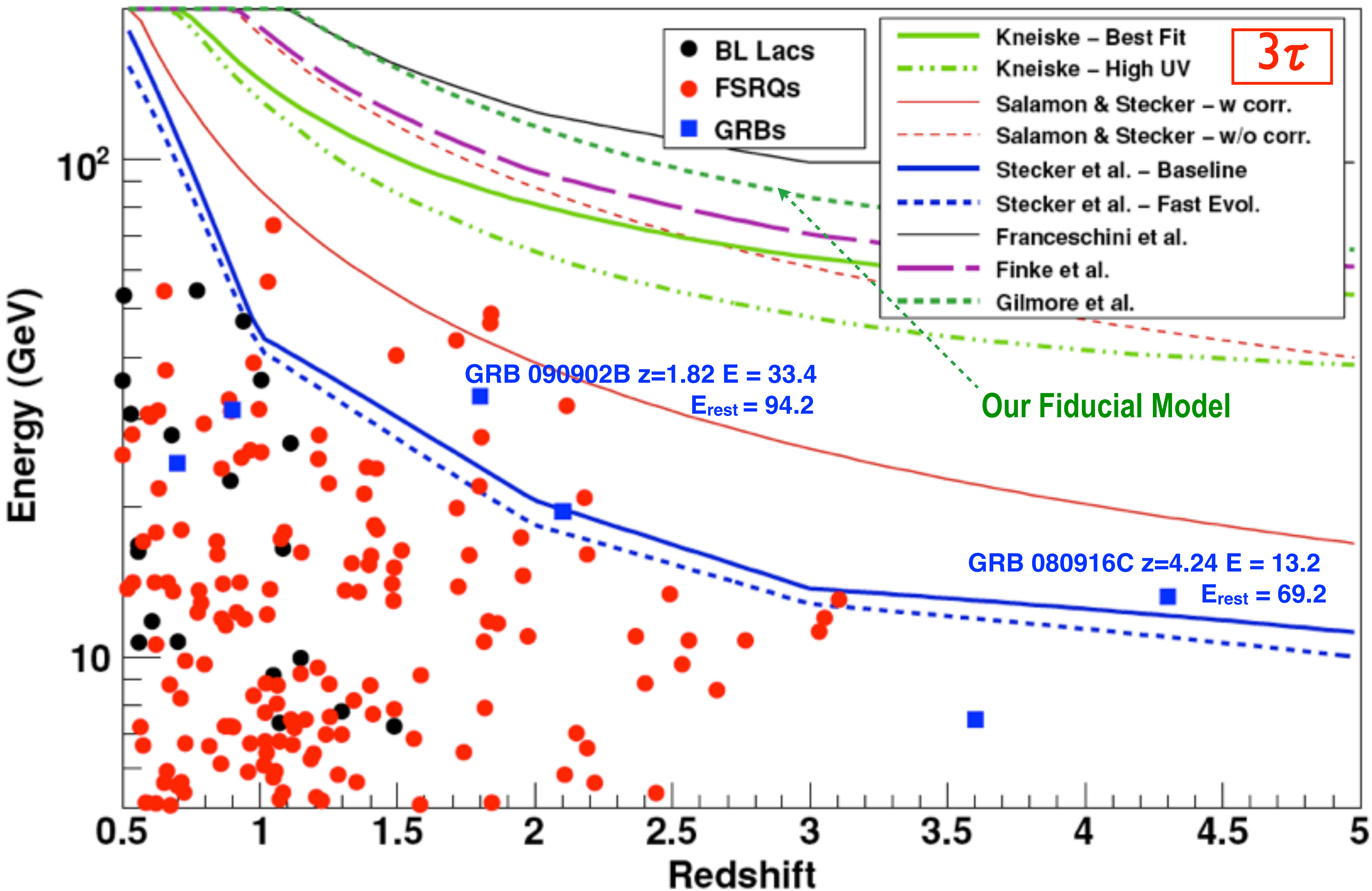


# *FERMI* LARGE AREA TELESCOPE CONSTRAINTS ON THE GAMMA-RAY OPACITY OF THE UNIVERSE

Abdo et al.

THE ASTROPHYSICAL JOURNAL, 723:1082–1096, 2010 November 10

**Using Fermi LAT photons of E >10 GeV from blazars up to z ~ 3 and GRBs up to z ~ 4.3, we constrain EBL models. The models of Stecker et al. can be ruled out with high confidence.**



# Modeling Instrument Properties

<u>Fermi</u>

- 20500 sr · $cm^2$ integrated field of view
- assume telescope in survey mode full time
- we do not account for triggered rotations to burst events

<u>MAGIC</u>

results are sensitive to effective area at low energies, and slew time (for prompt phase)

- effective area vs. energy from published data
- assume threshold energy vs. zenith angle θ

$$E_{th}(\theta) = E_{th}(0) \cdot \cos(\theta)^{-2.5}$$

$$\Rightarrow E_{th}(40°) \approx 2 \times E_{th}(0°)$$

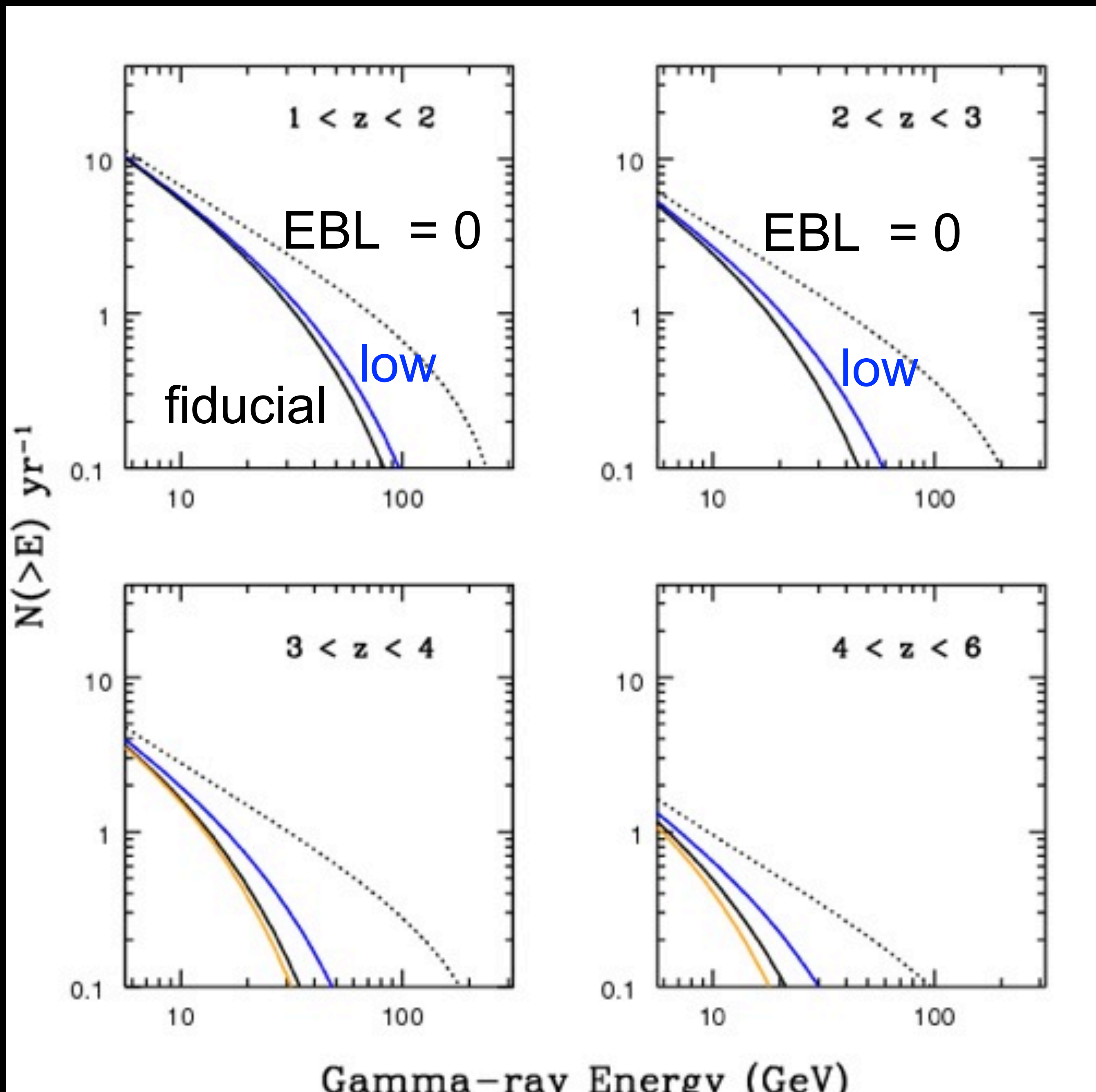
with $E_{th}(0) = 50$ and 100 GeV

Gilmore, Prada, Primack 2010 MNRAS Modeling GRB Observations by *Fermi* and MAGIC Including Attenuation by Extragalactic Background Light

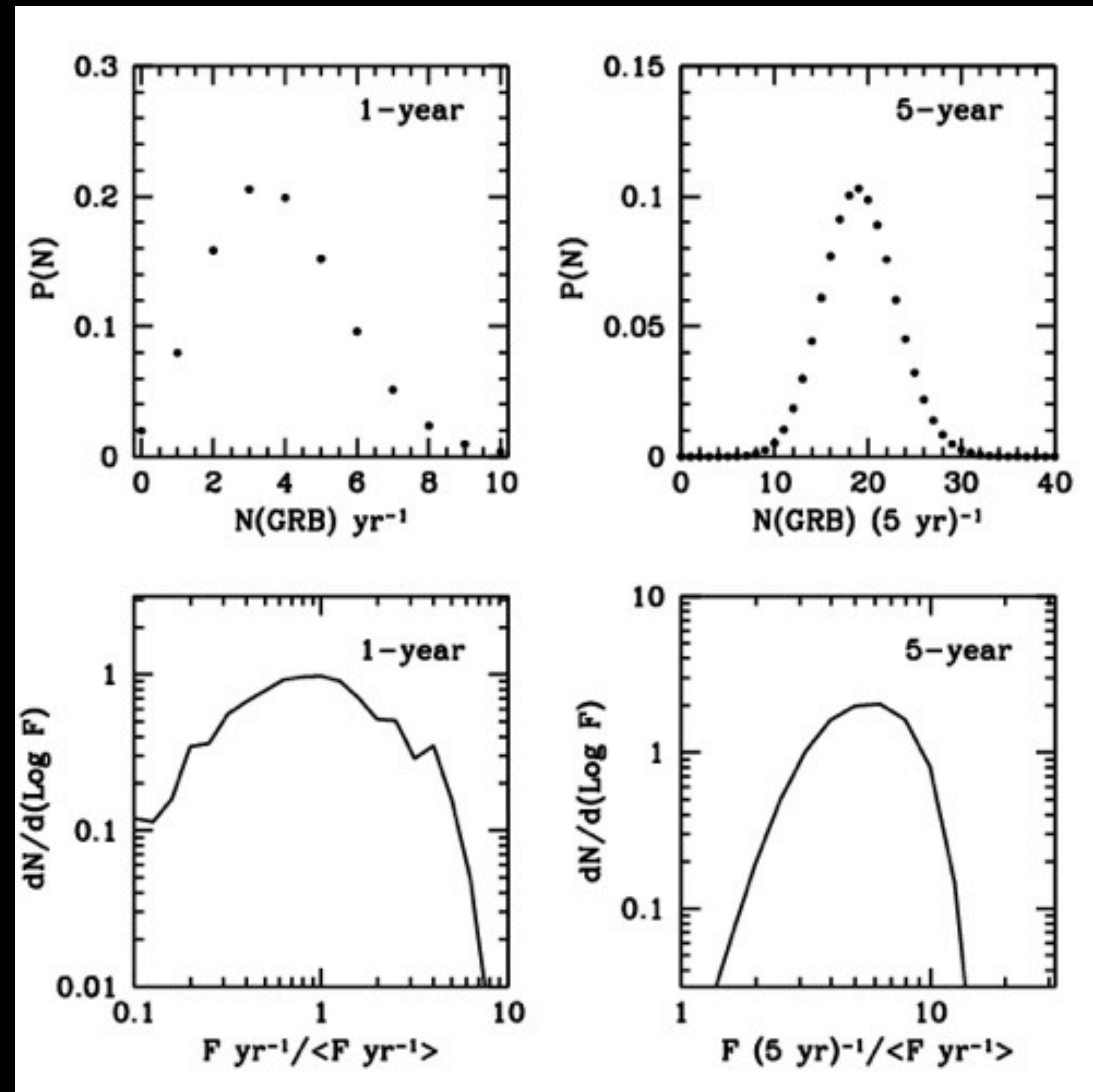
# Results for Fermi

Gilmore, Prada, Primack 2010 MNRAS
Modeling GRB Observations by *Fermi* and MAGIC Including Attenuation by Extragalactic Background Light

Annual # of integrated GRB photons for 4 redshift bins, with attenuation from low, fiducial, and high-peaked models



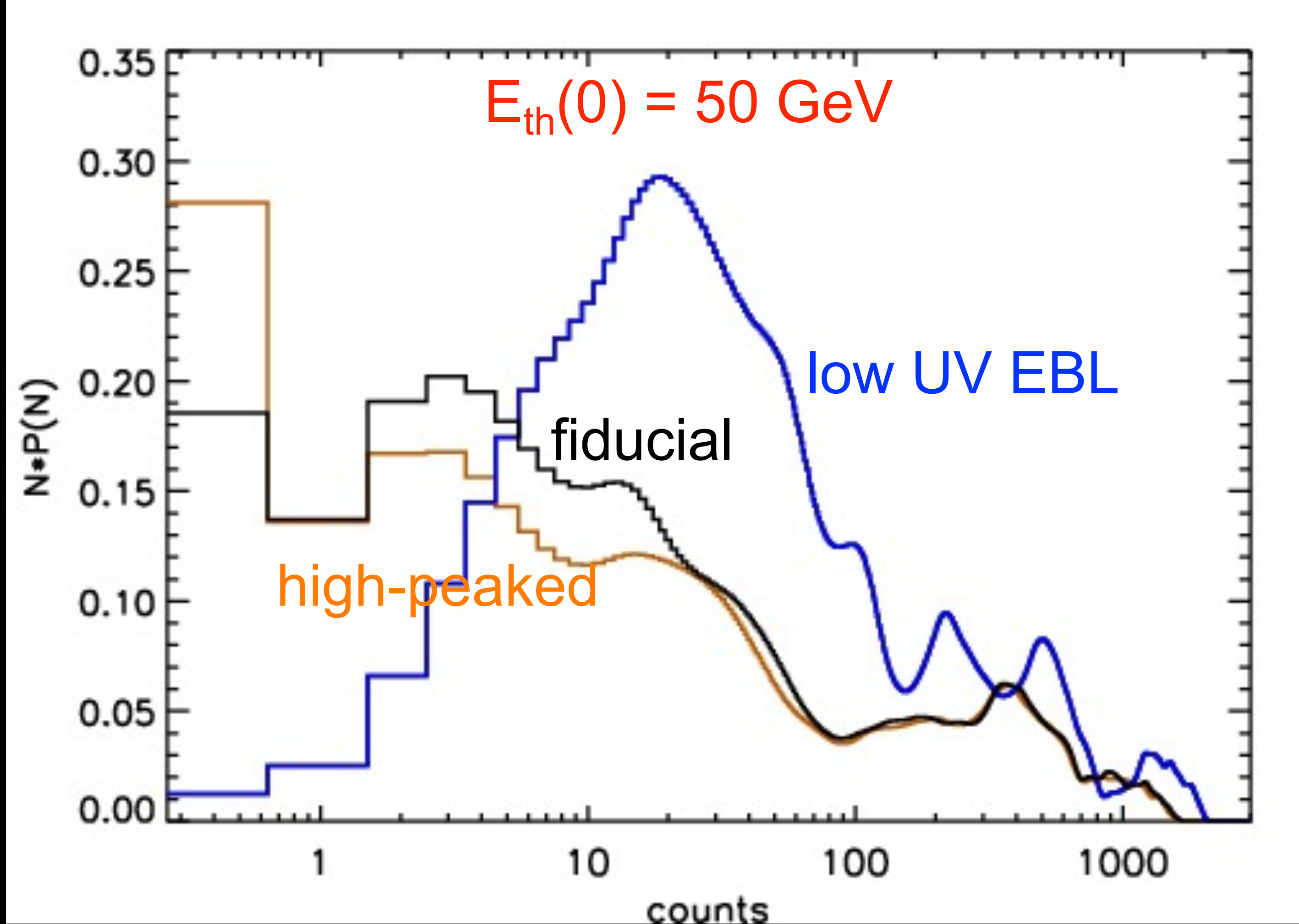

Annual number of LAT GRBs w/ redshifts



# Results for MAGIC

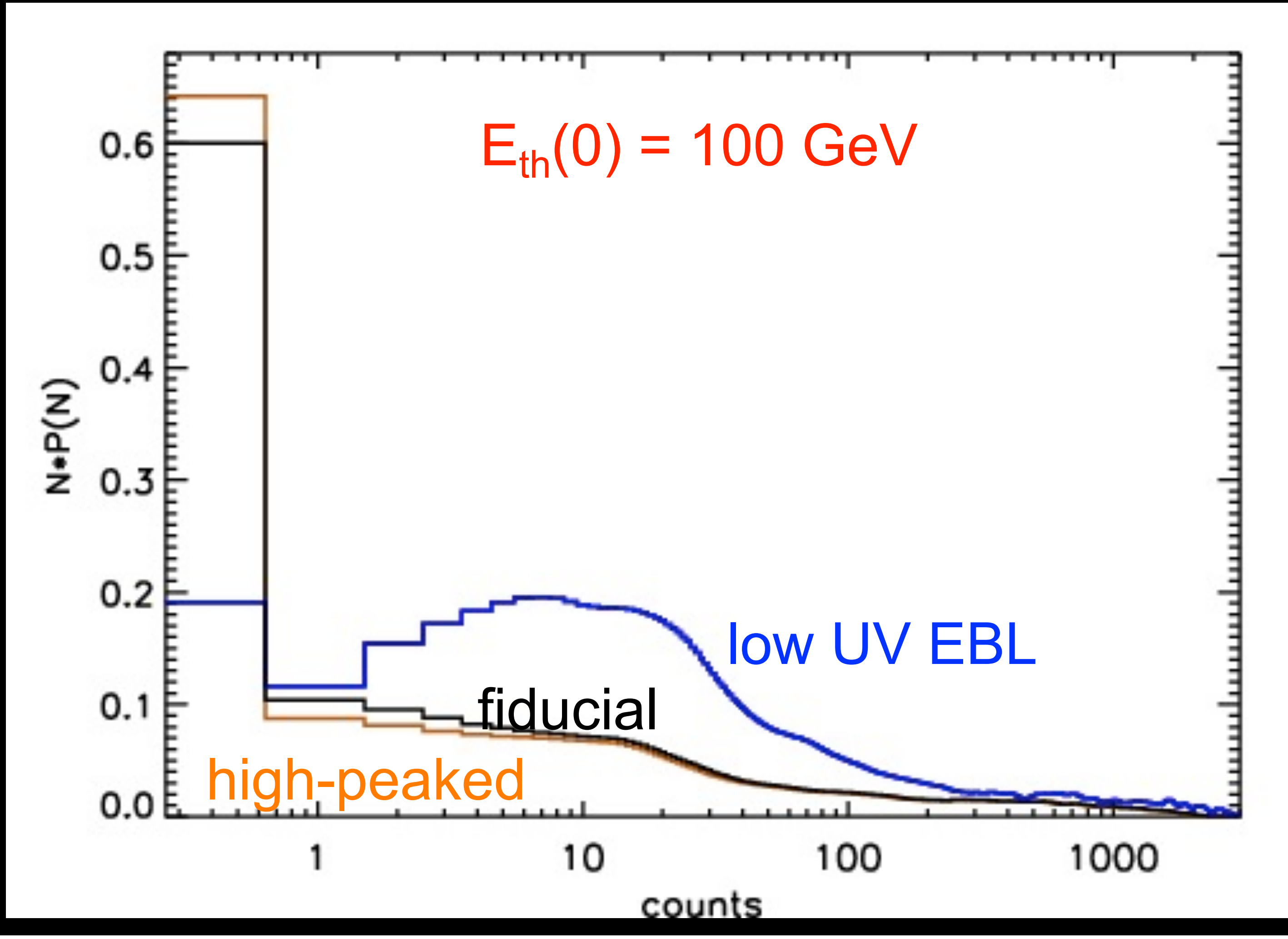
- For IACT like MAGIC:
  - duty cycle ≈ 10%
  - sky coverage (θ<40) ≈ 11%

(duty cycle)·(sky coverage) ≈ 1%

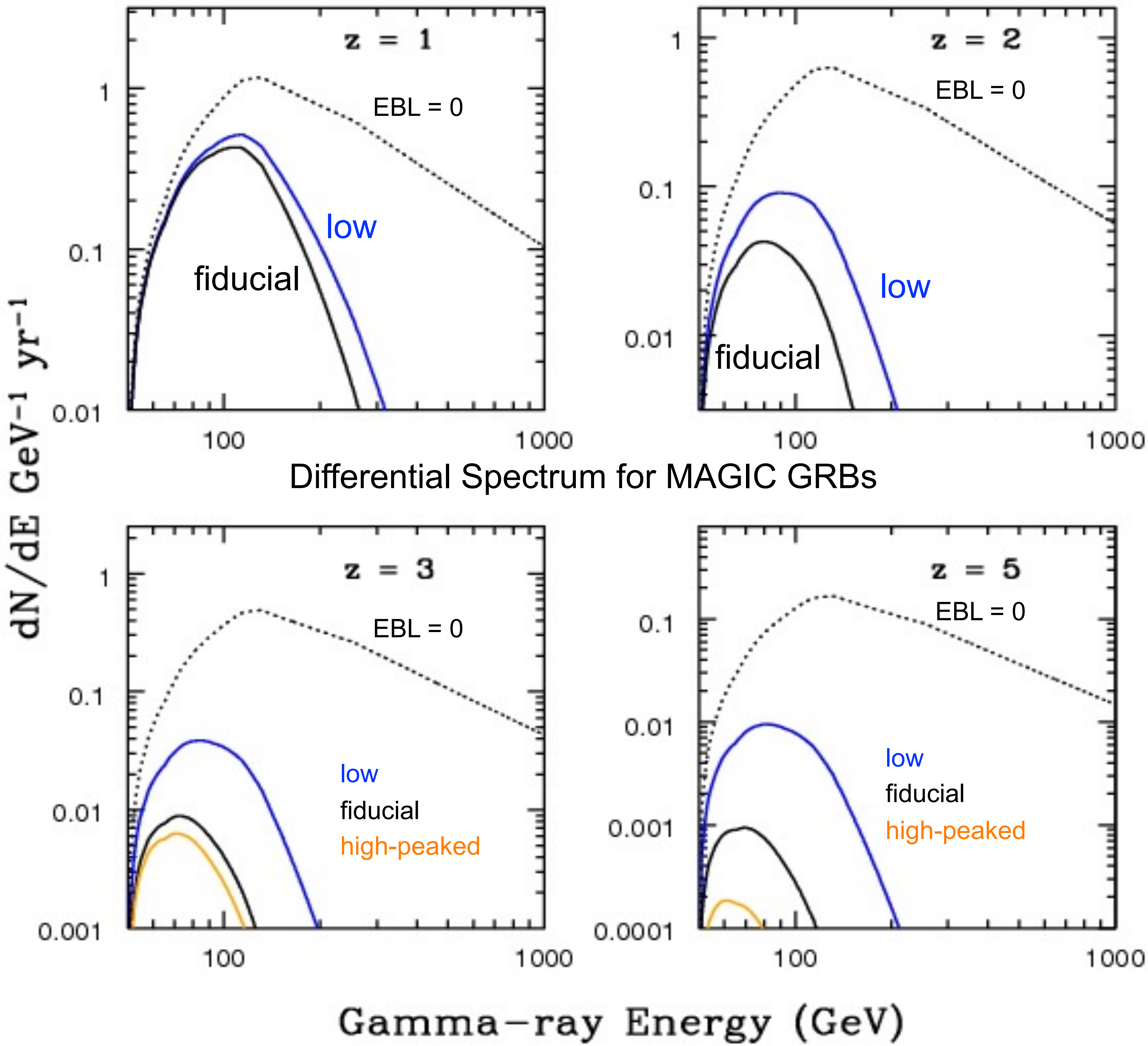


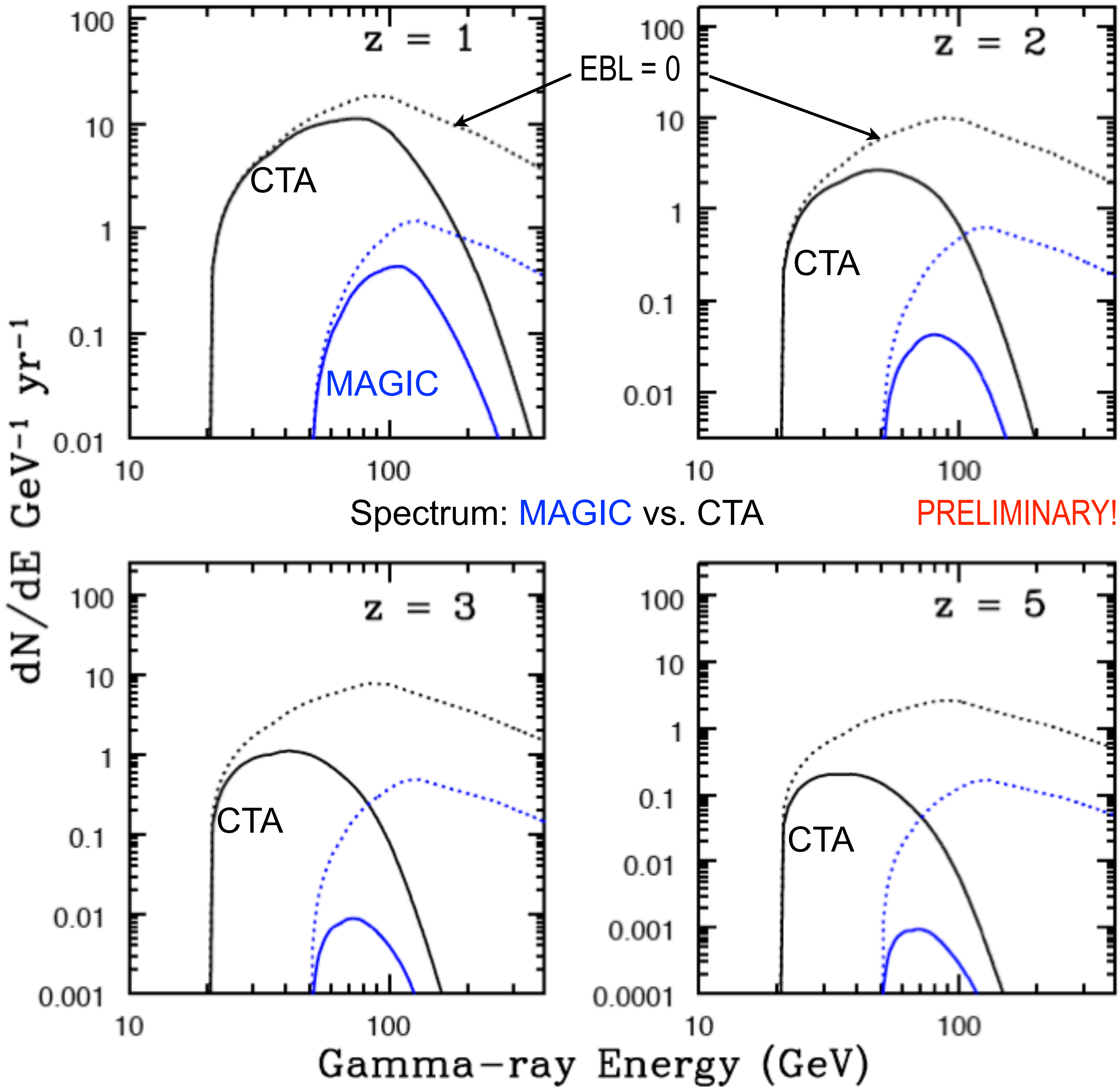

**Predicted number of MAGIC gamma-ray counts for a single GRB within sky coverage, with $E_{th}$ = 50 GeV at θ=0°.**

100 Gev threshold seriously decreases the expected number of gamma rays compared to 50 GeV threshold!

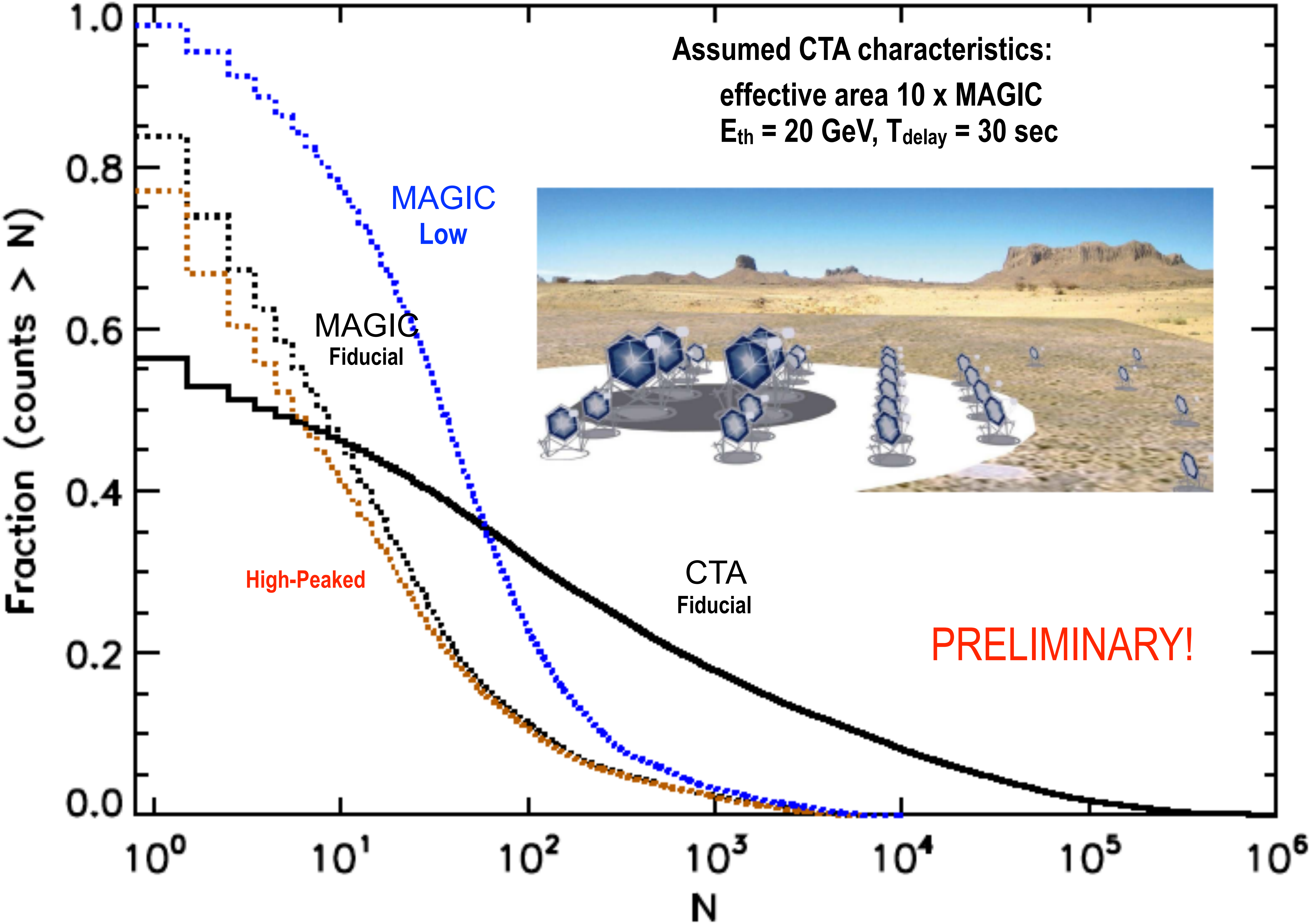



Gilmore, Prada, Primack 2010 MNRAS

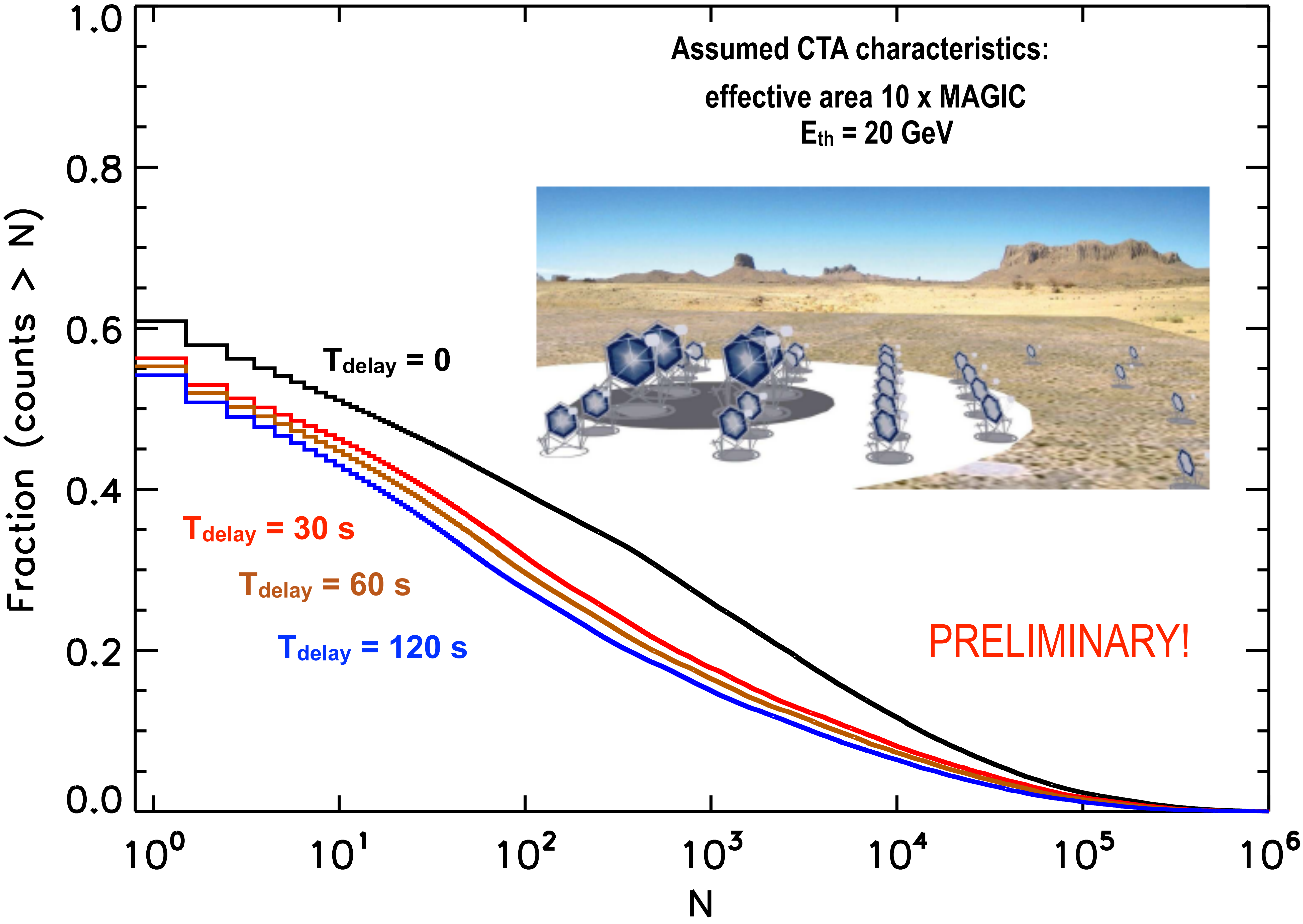

z = 1
EBL = 0
low
fiducial
z = 2
EBL = 0
low
fiducial
Differential Spectrum for MAGIC GRBs
z = 3
EBL = 0
low
fiducial
high-peaked
z = 5
EBL = 0
low
fiducial
high-peaked
dN/dE GeV⁻¹ yr⁻¹
Gamma−ray Energy (GeV)
100
1000
1
0.1
0.01
0.001
0.0001


z = 1
z = 2
z = 3
z = 5
EBL = 0
CTA
MAGIC
Spectrum: MAGIC vs. CTA
PRELIMINARY!
dN/dE GeV⁻¹ yr⁻¹
Gamma−ray Energy (GeV)
10
100
0.01
0.1
1
0.001
0.0001

# GRB PHOTON NUMBER DISTRIBUTION: MAGIC vs. CTA



# CTA GRB PHOTON COUNT DISTRIBUTION



# Conclusions - Part 3

- GRBs are a potential source of high-energy gamma rays, but little is known about emission above a few10s of GeV
  - Intrinsic cutoff or internal absorption could be a problem

- Fermi may be able to constrain EBL with several years' stacked data for redshifts 1 ➔ 4 or above
  - More bright GRBs with redshifts over next few years?

- IACTs like MAGIC could detect a large number of gammas within a narrow energy band from single GRB, but annual probability of detection is low
  - Spectral hardening with time may help with slew time
  - Several multi-photon GRBs could constrain UV EBL

- Next-generation IACT arrays will have much larger effective areas and better low energy coverage with $E_{th}(0) \approx 20$ GeV, but will still have sky coverage and duty cycle limitations, unlike HAWC
  - Now is the time to study implications of various designs for GRB multi-GeV photon observations
  - Preliminary indications favor low threshold (~20 GeV)

Details: Rudy Gilmore's talk in P6, Thursday afternoon

# Review

Data from (non-)attenuation of gamma rays from AGN and GRBs gives upper limits on the EBL from UV to mid-IR that are ~2x lower limits from observed galaxies. These upper limits now rule out some EBL models and purported observations, with improved data likely to provide even stronger constraints.

EBL calculations based on careful extrapolation from observations and on semi-analytic models are consistent with these lower limits and with the gamma-ray upper limit constraints.

Such comparisons "close the loop" on cosmological galaxy formation models, since they account for all the light, including that from galaxies too faint to see.

Catching a few GRBs with ground-based ACT arrays could provide important new data on reionization and star formation history.