Dublin Summer School on
High Energy Astrophysics
4th - 15th July 2011

Radiation Fields in the Universe:
Extragalactic Background Light and Gamma-ray Attenuation

Joel Primack

University of California, Santa Cruz

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.

See the written version of my invited talk at the Texas 2010 meeting for a brief summary with refs: http://arxiv.org/abs/1107.2566

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 multi- GeV gamma rays from very distant GRBs & blazars observed by *Fermi* and low-threshold ground-based ACTs, including future arrays (e.g., CTA).

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

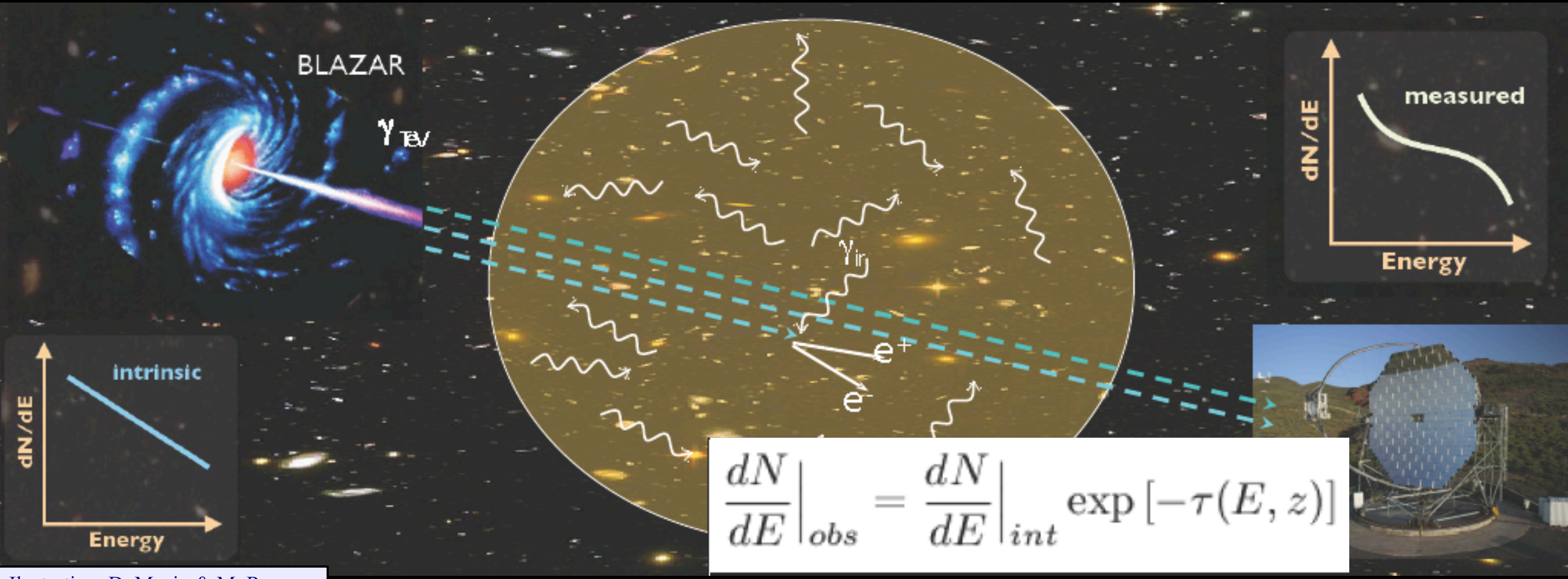
PILLAR OF STAR BIRTH
Carina Nebula in UV Visible Light

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

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

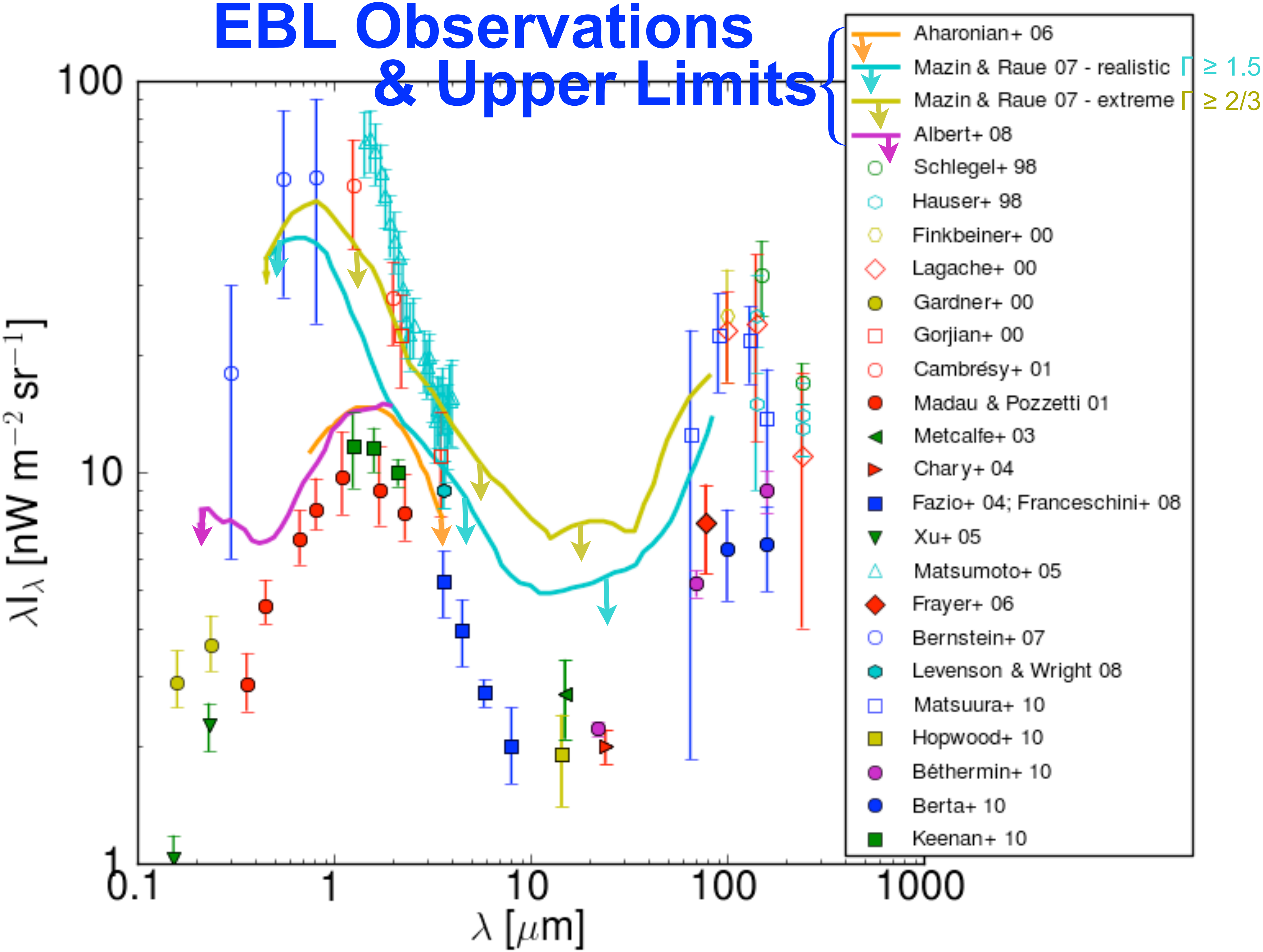


$$\left.\frac{dN}{dE}\right|_{obs} = \left.\frac{dN}{dE}\right|_{int} \exp\left[-\tau(E,z)\right]$$

Ilustration: D. Mazin & M. Raue

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 Γ = 1.5, since local sources have Γ ≥ 2.

EBL Observations & Upper Limits



Four approaches to calculate the EBL:

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

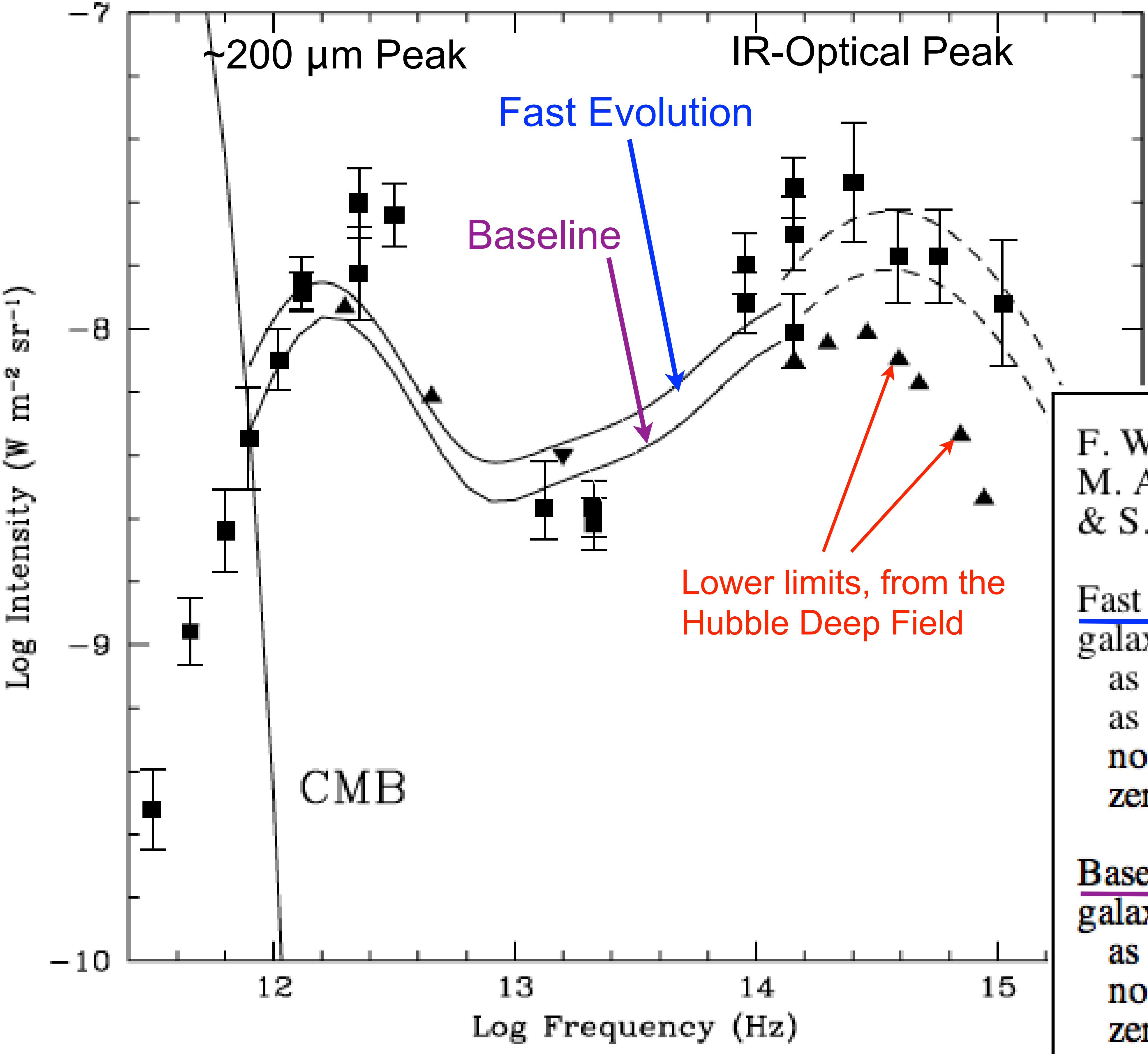
Backward Evolution Inferred from Observations -- e.g., Kneiske et al. 2002, 04; Franceschini et al. 2008.

Evolution Directly Observed -- Dominguez, Primack, et al. 2011 using multiwavelength AEGIS data and K-band LF.

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+11.

All methods currently require modeling galactic SEDs. Forward Evolution requires semi-analytic models (SAMs) based on cosmological simulations, e.g. Somerville+11.

Backward Evolution



Lower limits, from the Hubble Deep Field

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

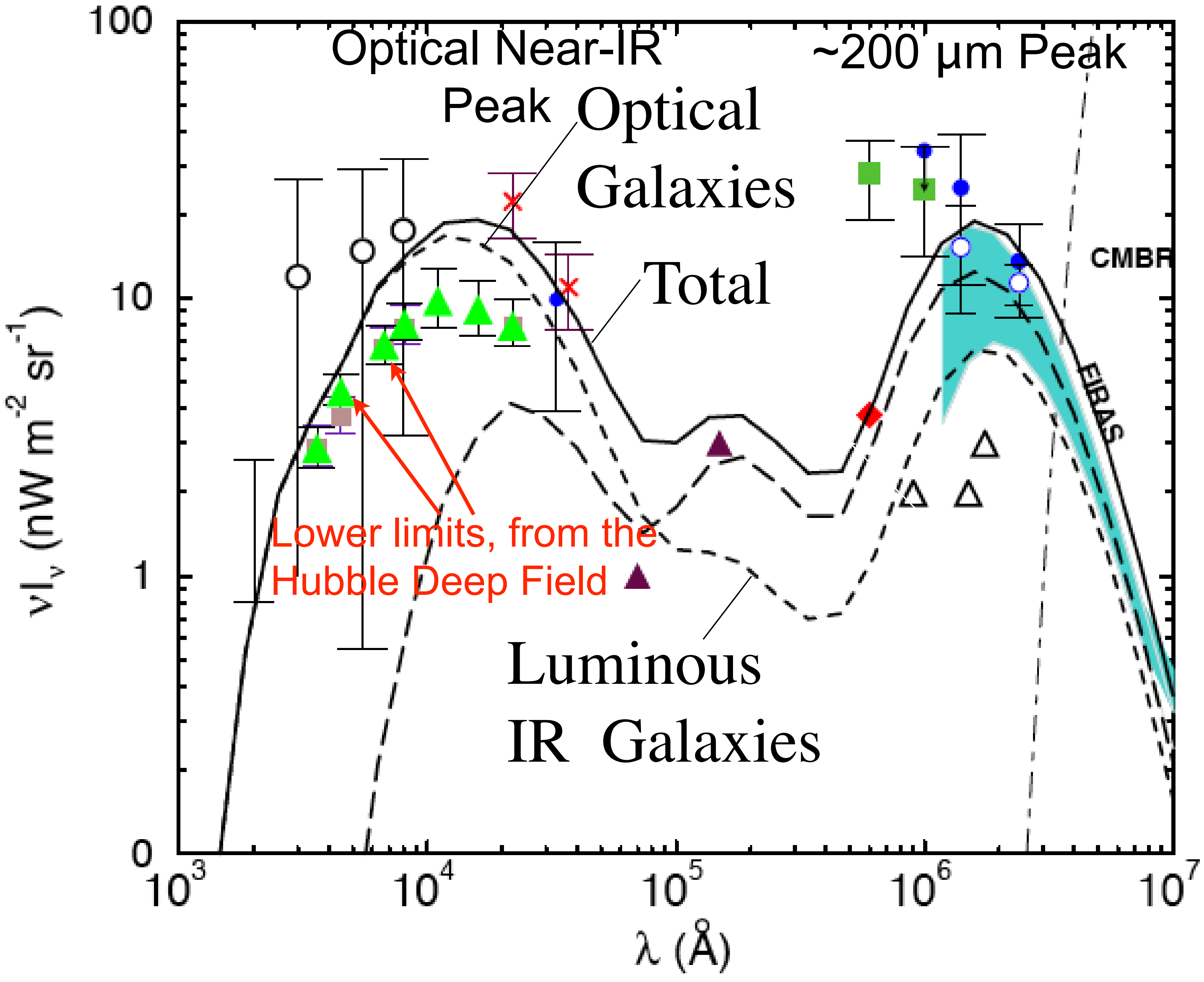
F. W. Stecker,
M. A. Malkan,
& S. T. Scully 2006

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 $z > 6$.

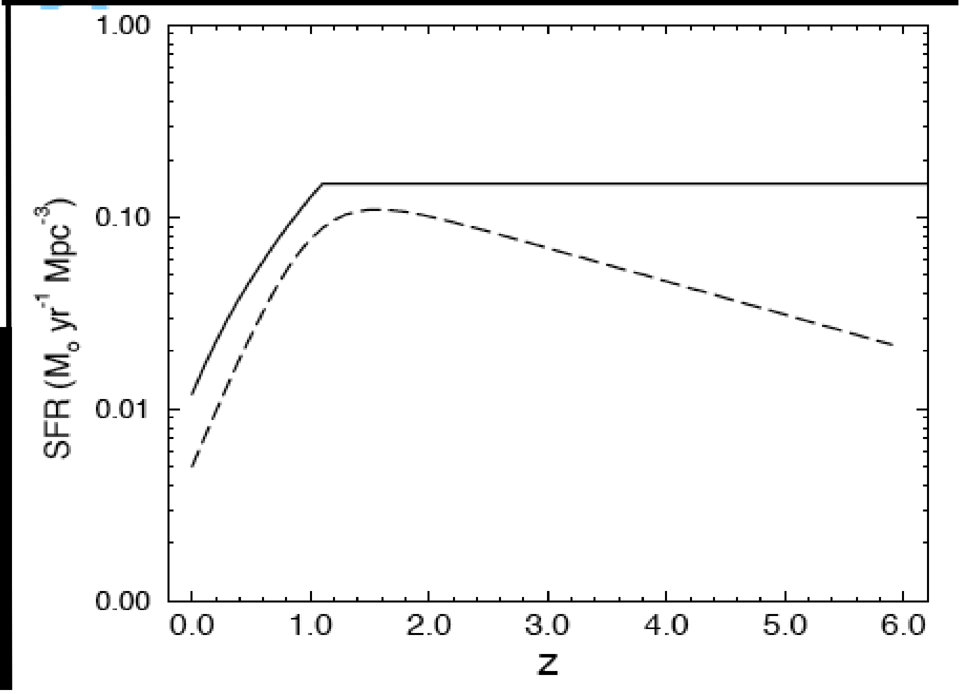
Backward Evolution Inferred from Observations

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

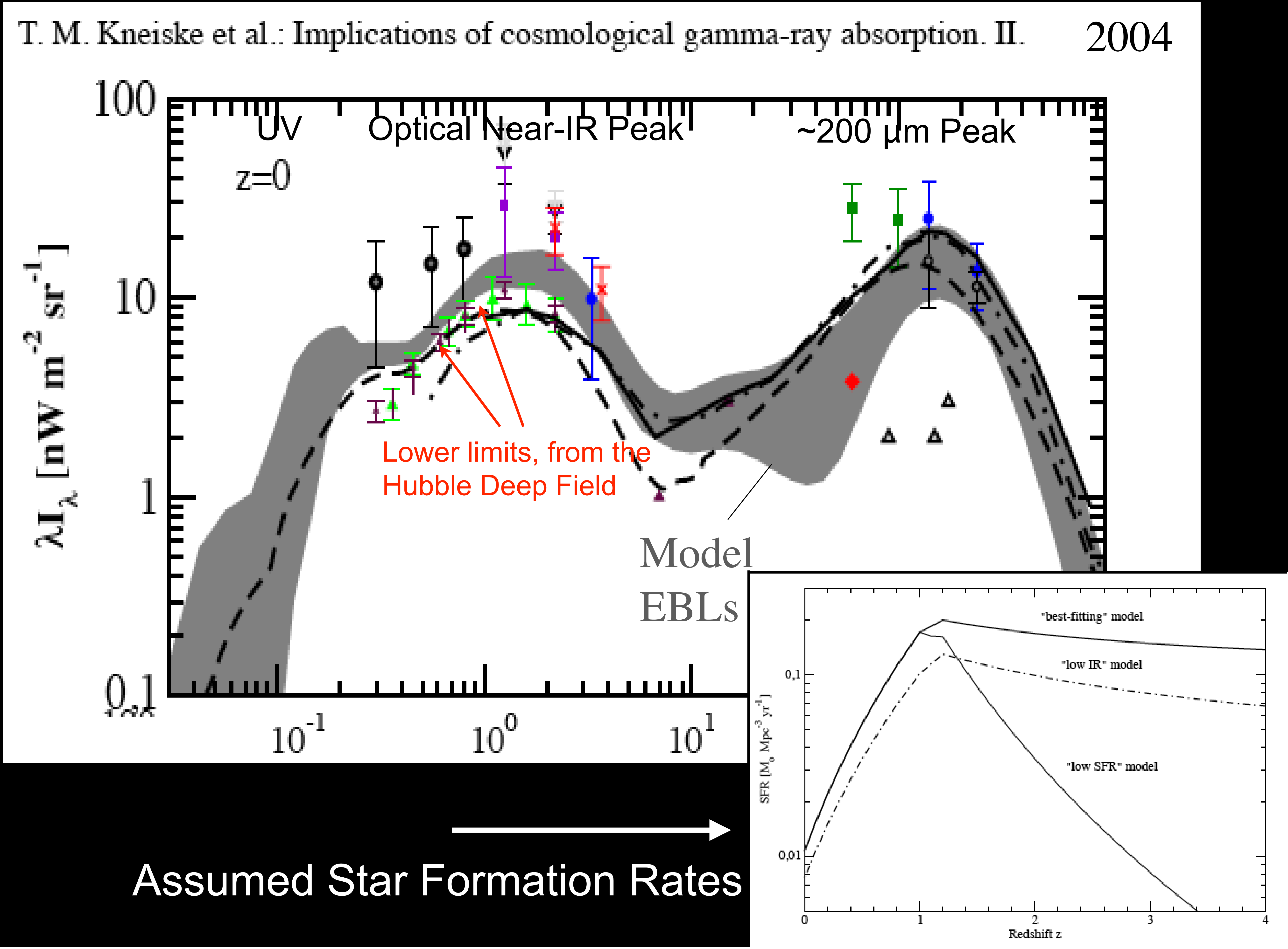


→

Assumed Star Formation Rate
(solid curve)



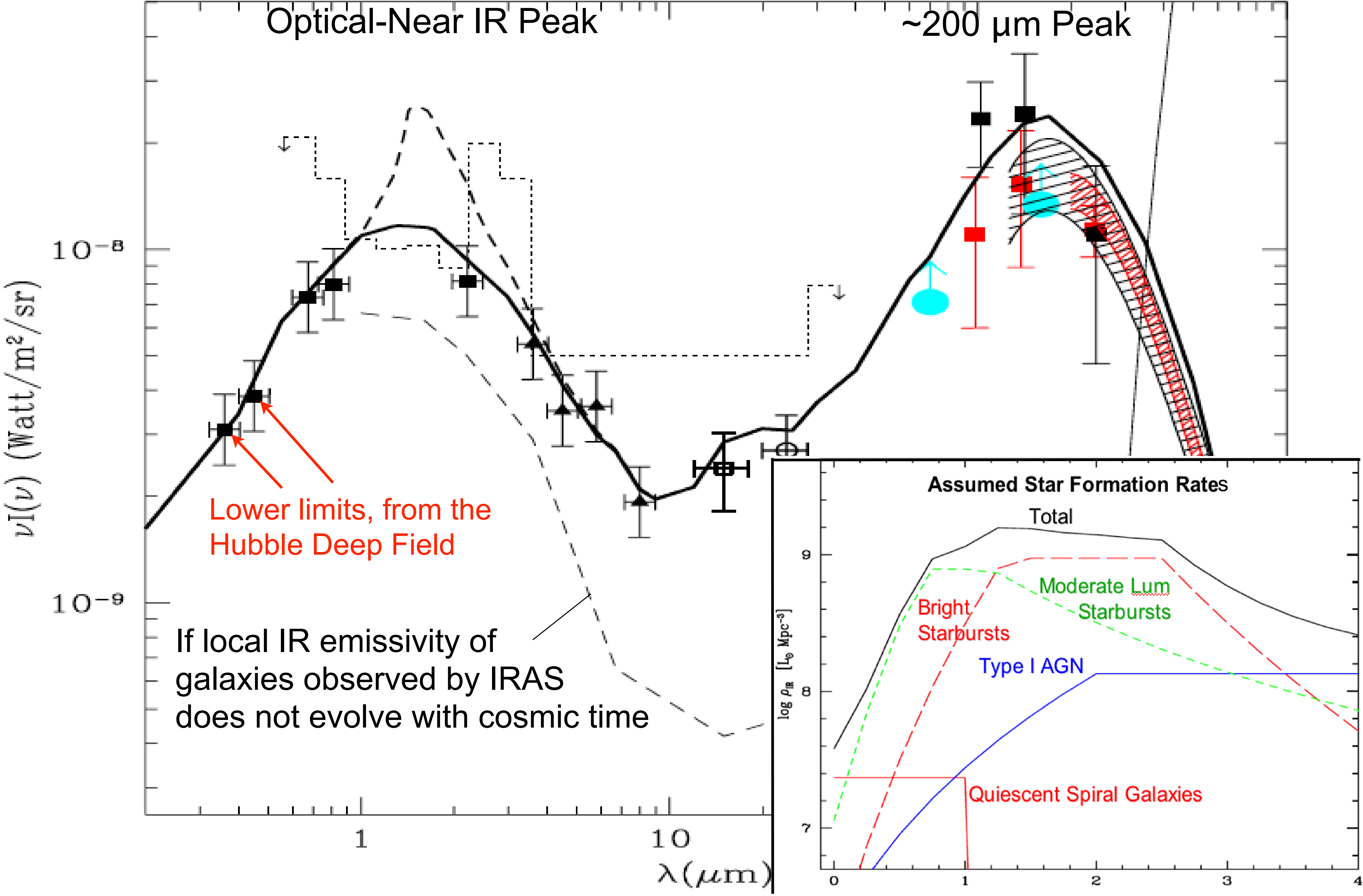
Backward Evolution Inferred from Observations



Assumed Star Formation Rates

Backward Evolution Inferred from Observations

A. Franceschini, G. Rodighiero, M. Vaccari: Background radiations and the cosmic photon-photon opacity 2008



Optical-Near IR Peak

~200 µm Peak

Lower limits, from the Hubble Deep Field

If local IR emissivity of galaxies observed by IRAS does not evolve with cosmic time

Evolution Calculated from Observations: AEGIS Multiwavelength Data & K-band LF

Alberto Dominguez et al. (2011)

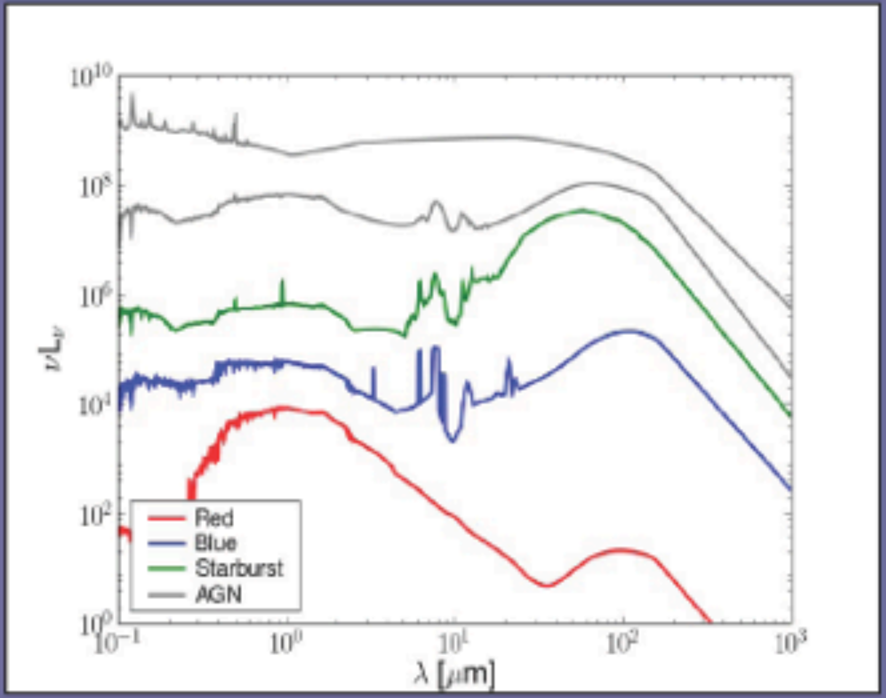
$$j_i(\lambda,z) = j_i^{faint} + j_i^{mid} + j_i^{bright} =$$

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

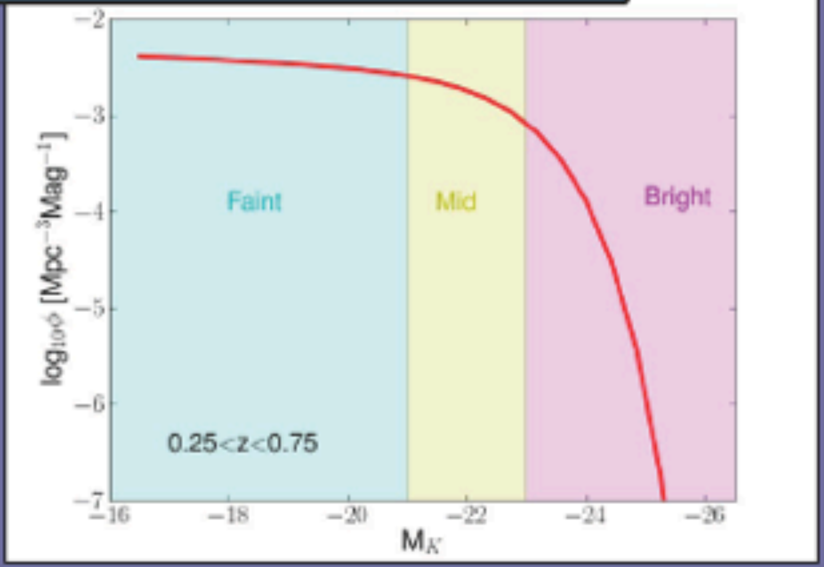
$$+ \int_{M_2}^{M_3} \underline{\Phi(M_K,z)}\,\underline{m_i}\,\underline{T_i(M_K,\lambda)}\,dM_K +$$

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

Spectral energy distributions
SWIRE template library, Polletta+ 07



Luminosity function
observed K-band, Cirasuolo+ 09



Spectral-type fractions

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

AEGIS

All-wavelength Extended Groth strip International Survey

0.7 □°

The AEGIS Survey...

...is unlocking the secrets of galaxy and large-scale structure formation over the last 9 billion years.

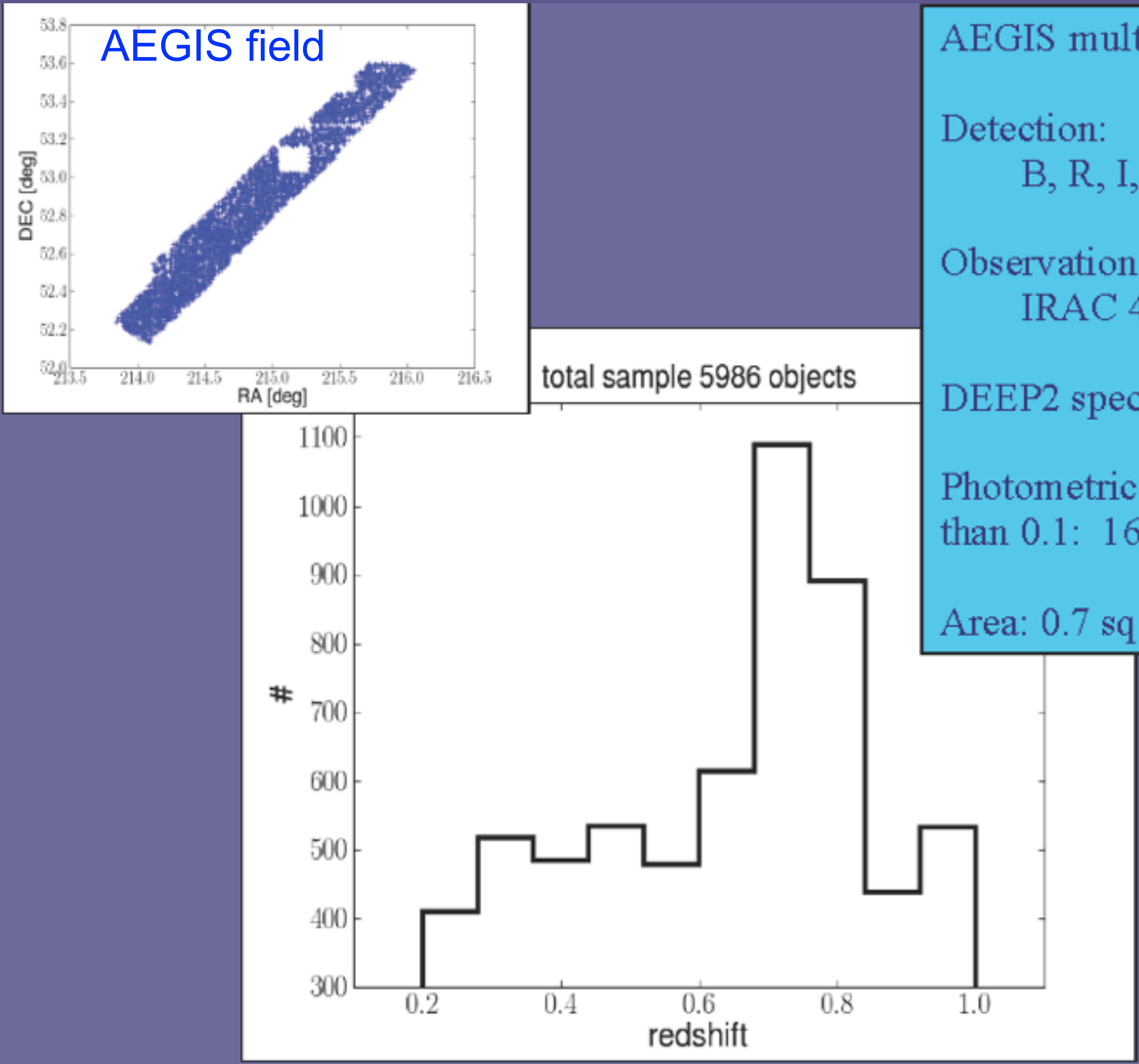
AEGIS is targeted on a special area of the sky, called the Extended Groth Strip (EGS), that has been observed with the world's most powerful telescopes on the ground and in space, from X-rays to radio waves.

Each telescope contributes its own key information to create a complete portrait of every galaxy. By looking out far into space and back in time, AEGIS literally shows us galaxies in all their glory that are emerging from infancy into adulthood. More...

http://aegis.ucolick.org/

Evolution Calculated from Observations Using AEGIS Multiwavelength Data

Dominguez, Primack, et al. (2011)



AEGIS multi-wavelength sample

Detection:
B, R, I, Ks, IRAC 3.6

Observation:
IRAC 4.5, IRAC 5.8, IRAC 8, MIPS 24

DEEP2 spectroscopic redshift: 4376 galaxies

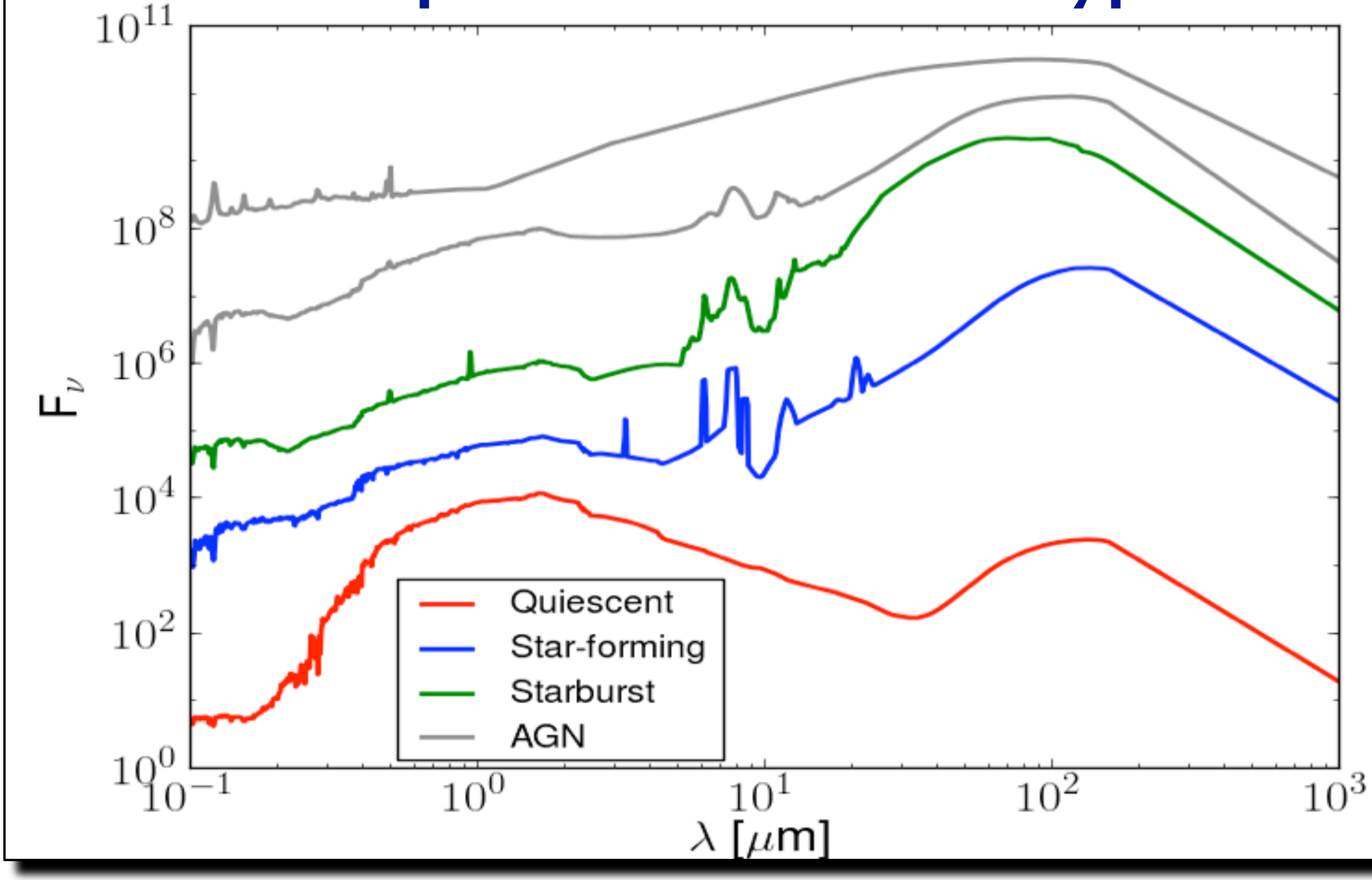
Photometric redshift with mean error less than 0.1: 1610 galaxies

Area: 0.7 sq deg

High redshift $z > 1$

Either assume SED types are constant, or else make extreme assumptions to bound the uncertainty.

Examples of SWIRE SED Types



25 different local galaxy SEDs: quiescent, star-forming, starburst and AGN.

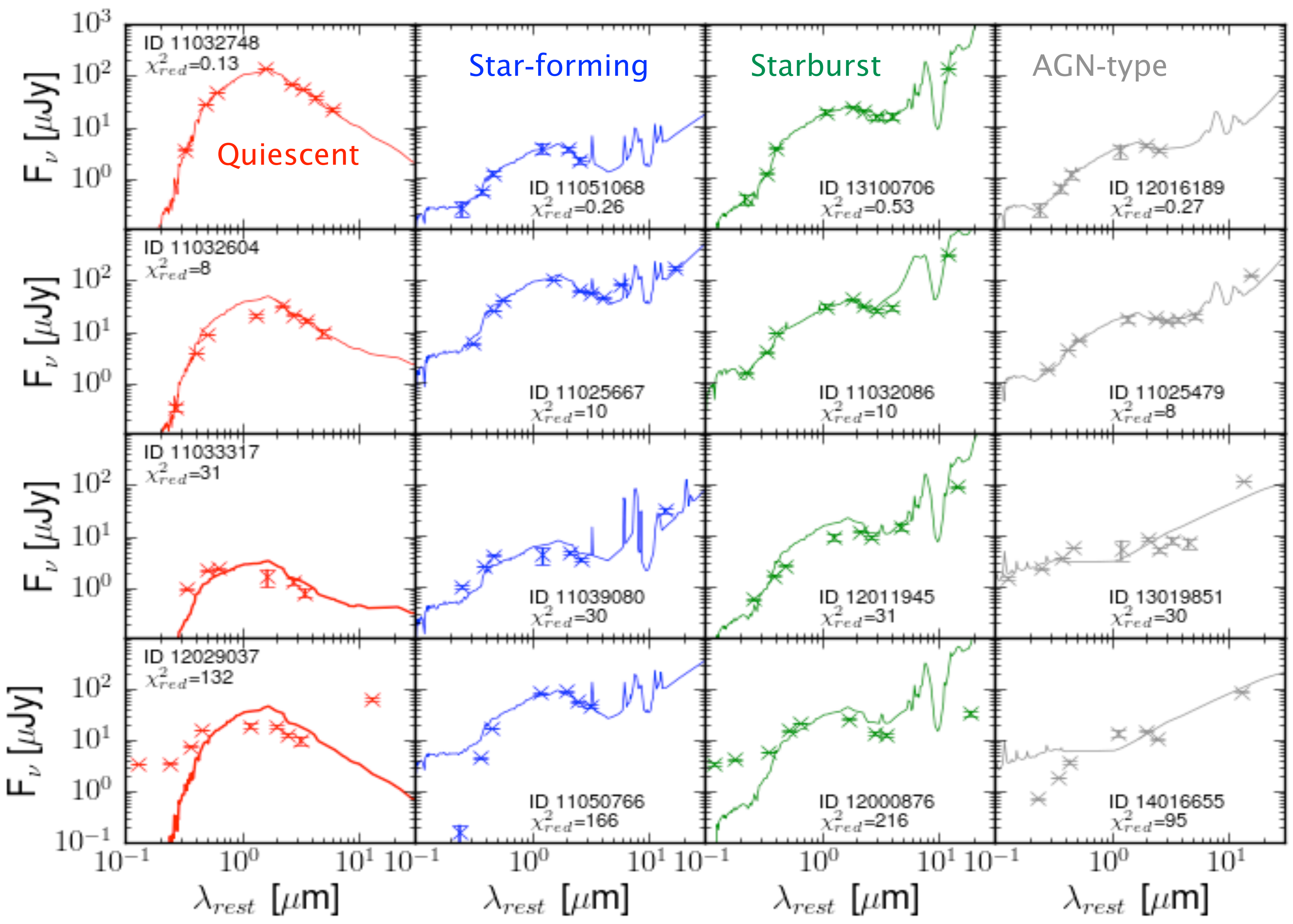
Fit to AEGIS ~6000 galaxies based on observations from the UV to the far-IR.

Dominguez+ 2011

χ^2 SED Fitting

Dominguez+ 2011

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



Best SED Fits

Worst SED Fits

SED-Type Evolution

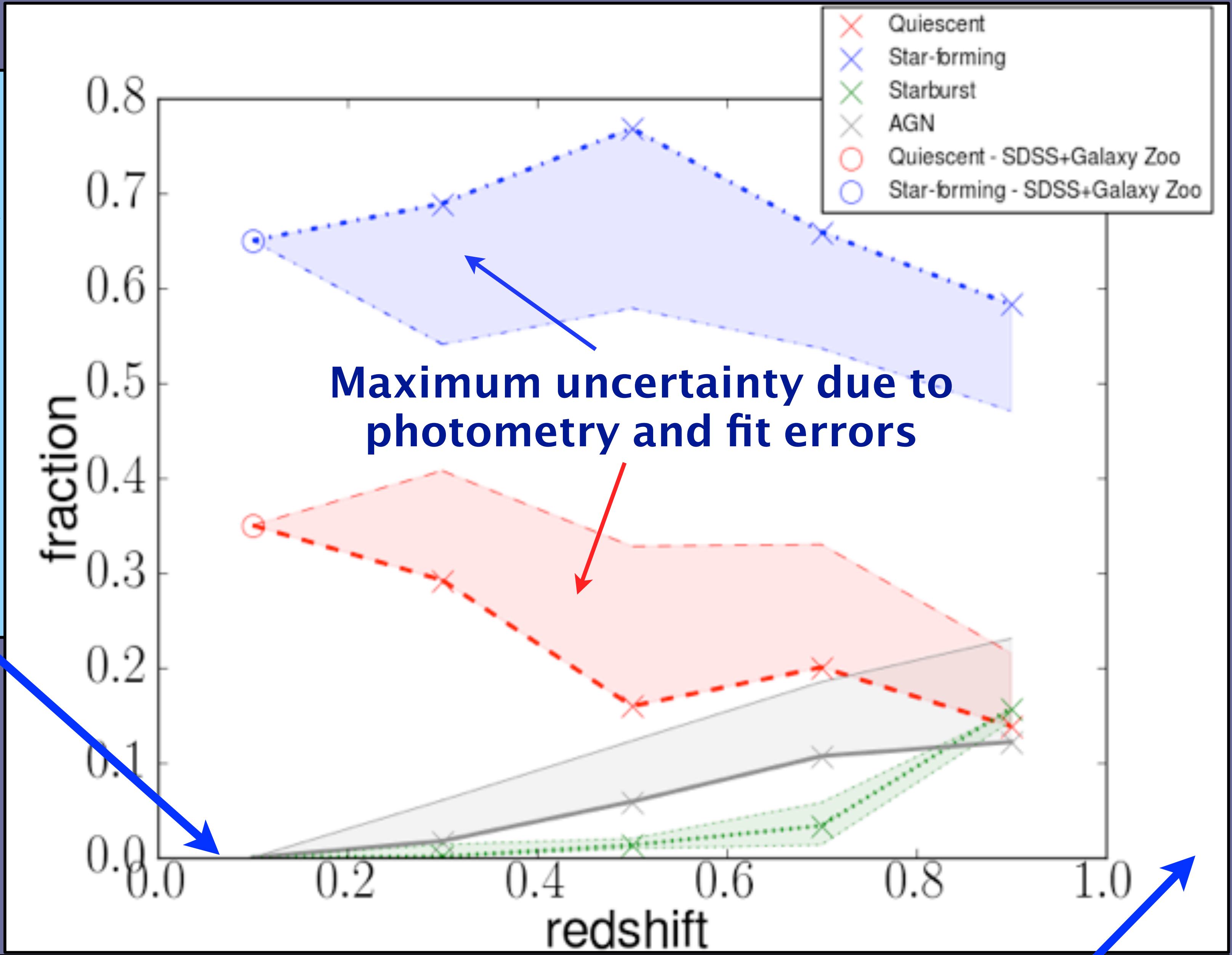
Local fractions, z<0.2:

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



Maximum uncertainty due to photometry and fit errors

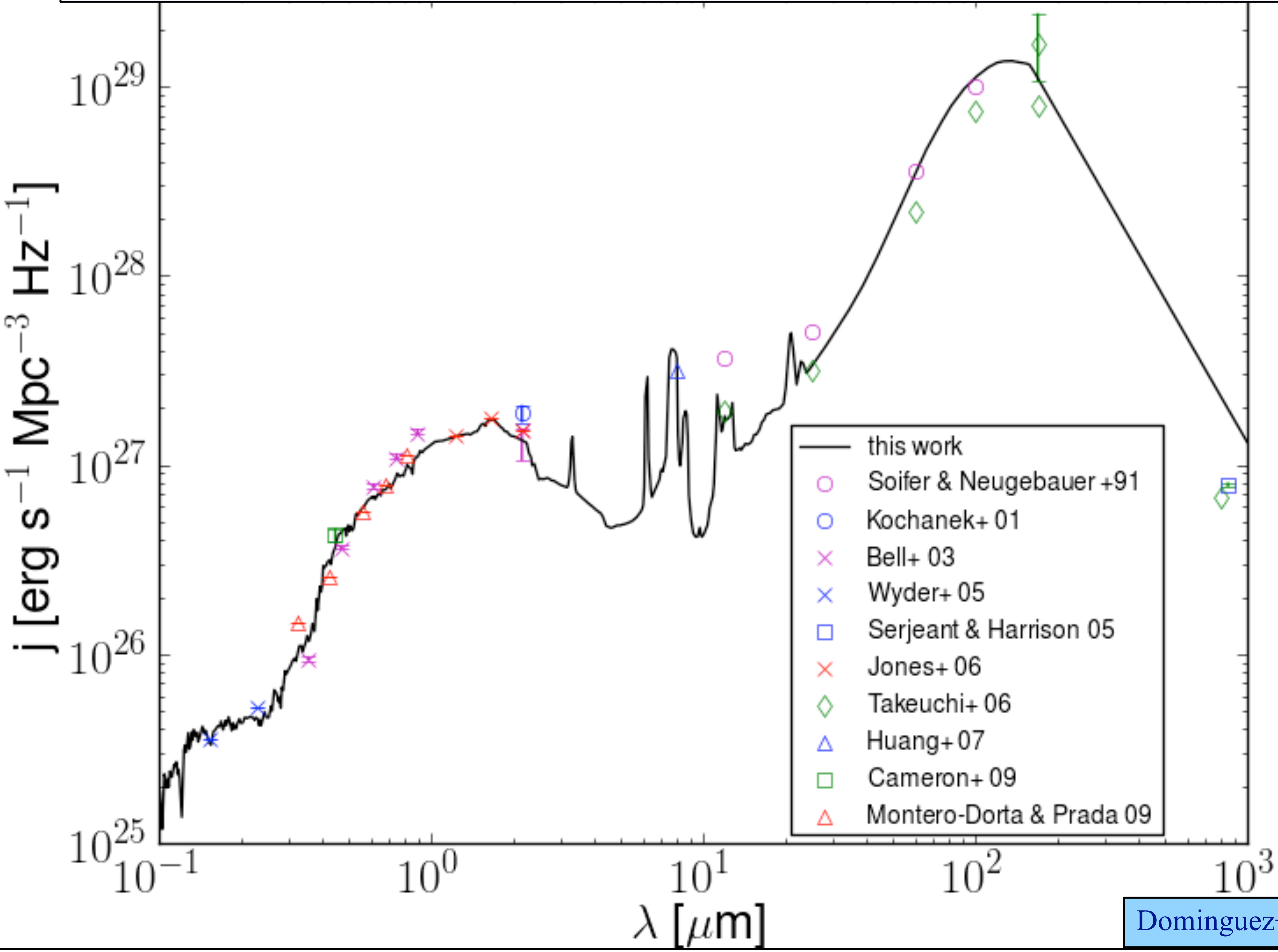
High-redshift universe, z>1:

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=2

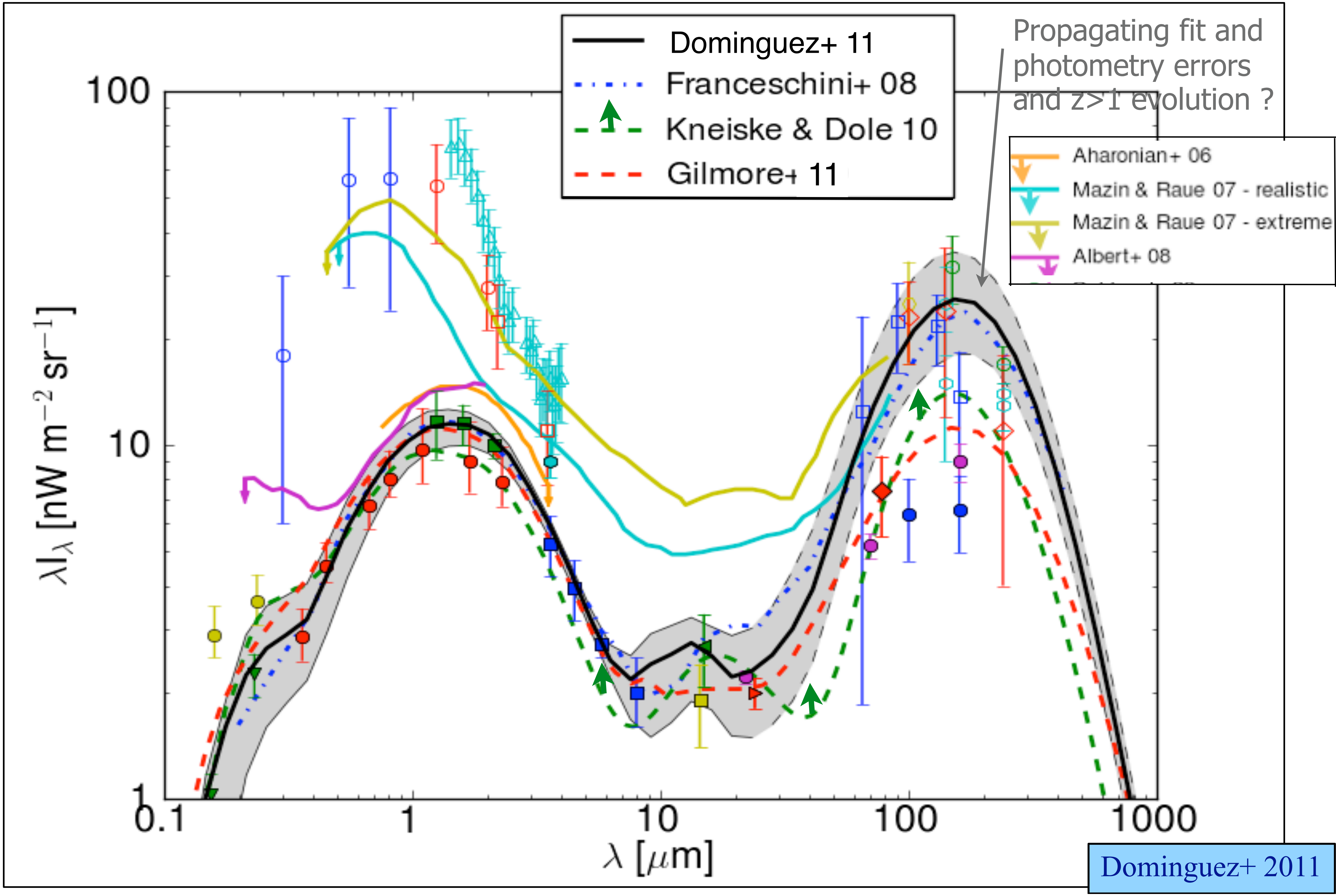
Dominguez+ 2011

Local Luminosity Density



Dominguez+ 2011

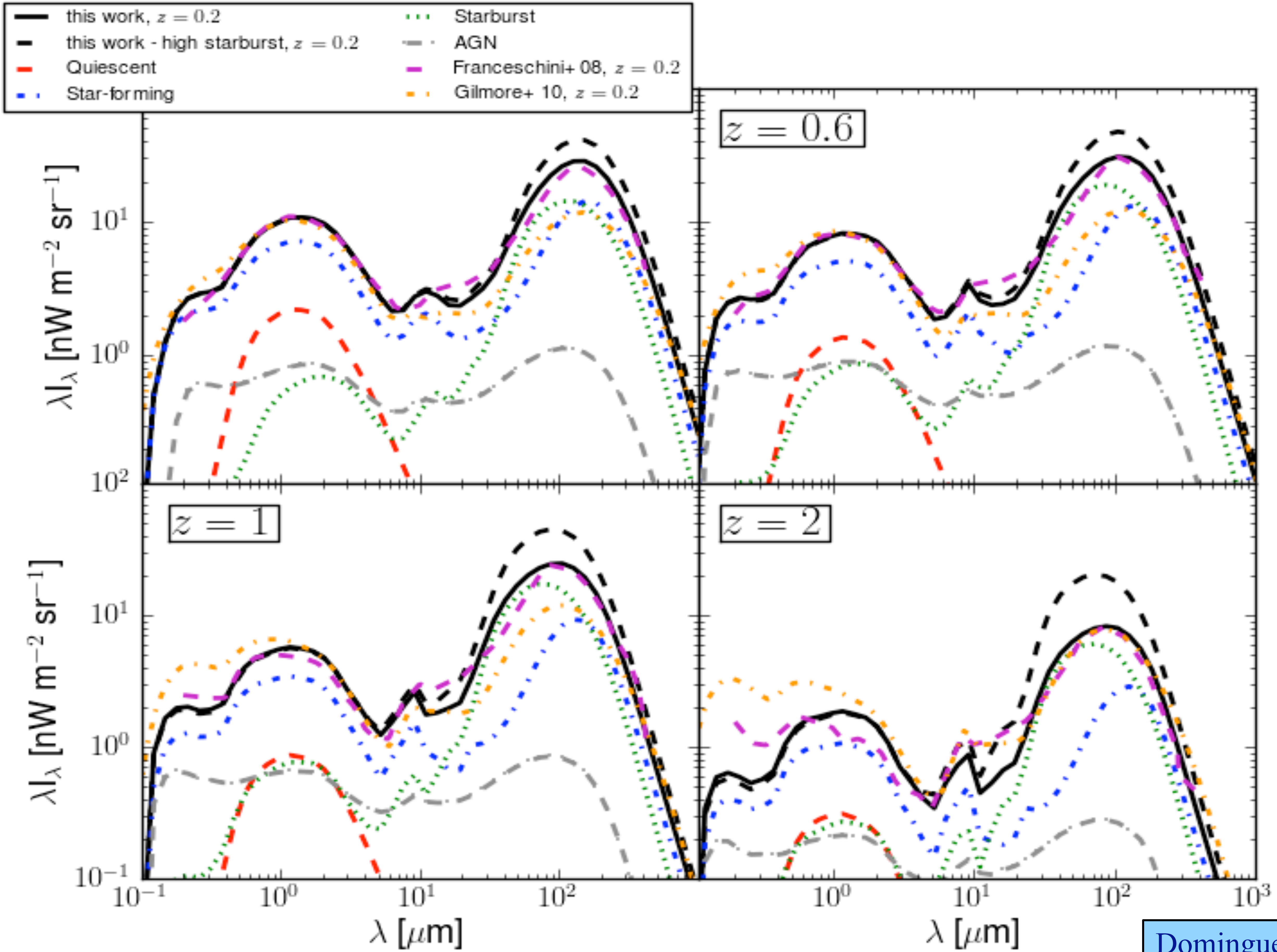
Extragalactic Background Light



Propagating fit and photometry errors and z>1 evolution ?

Dominguez+ 2011

EBL Evolution



Dominguez+ 2011

Conclusions - Part 1

Dominguez+11 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.

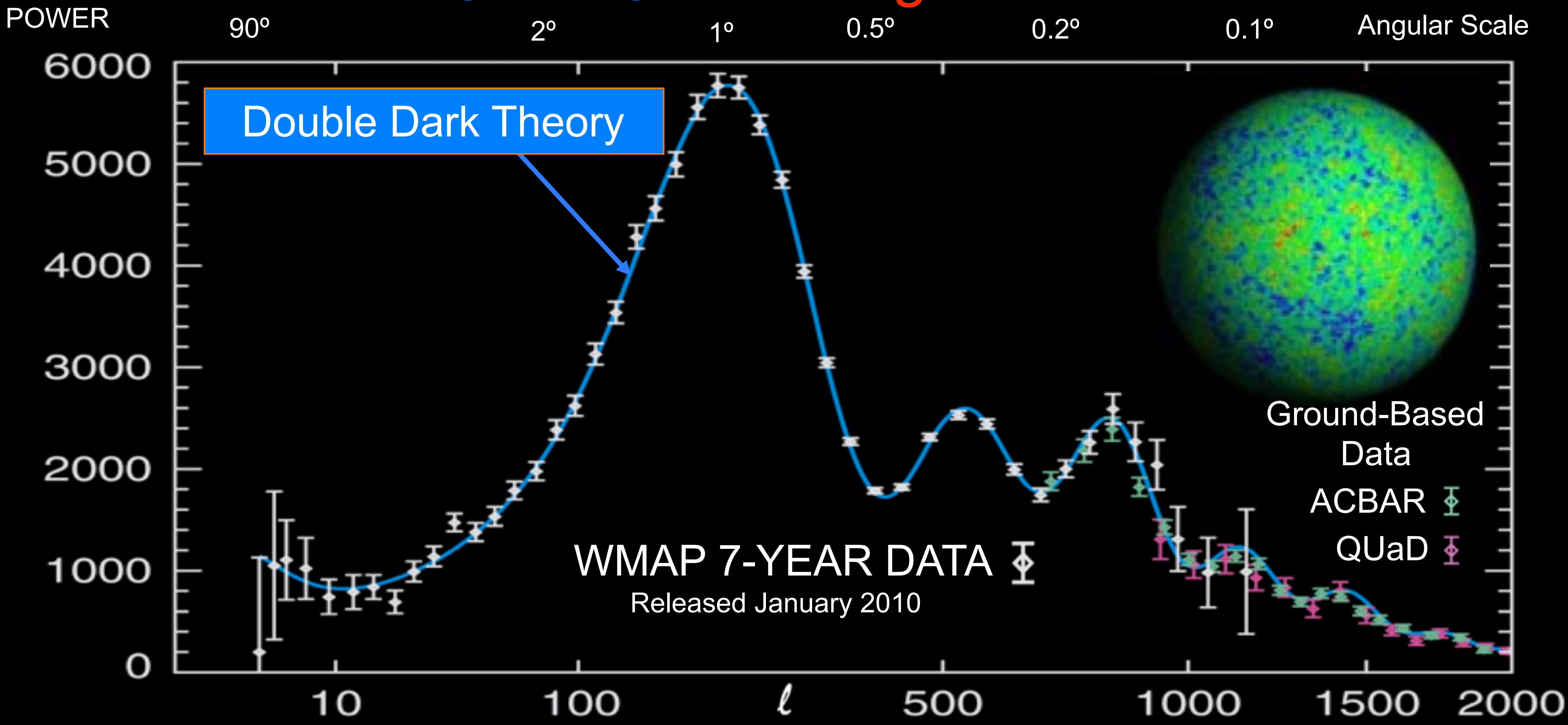
EBL intensities and optical depths are available on-line at: side.iaa.es/EBL

Forward Evolution

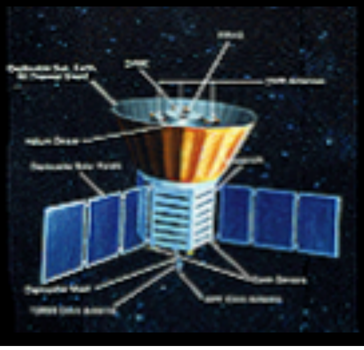
When we first tried doing this (Primack & MacMinn 1996), both the stellar initial mass function (IMF) and the values of the cosmological parameters were quite uncertain. After 1998, the cosmological model was known to be ΛCDM, although it was still necessary to consider various cosmological parameters in models. Now the parameters are known rather precisely, and my report here is based on a semi-analytic model (SAM) using the current (WMAP5/7) 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.

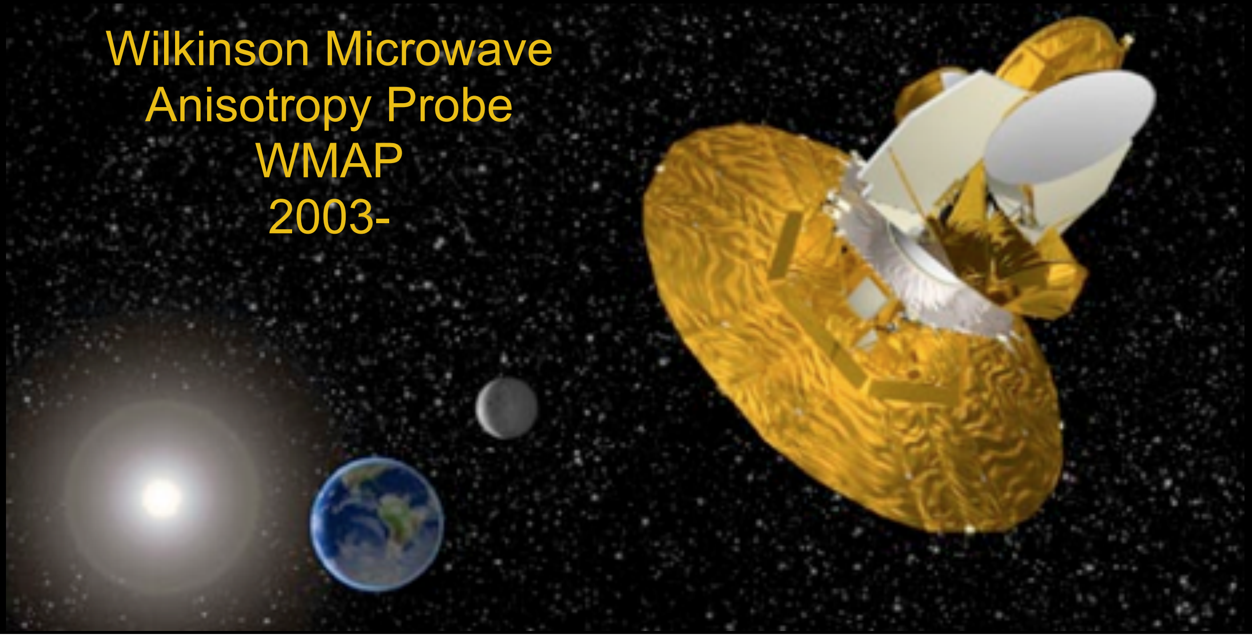
There is still uncertainty whether the IMF evolves, possibly becoming “top-heavy” in starbursts (e.g., Baugh et al. 2005) or at higher redshifts (e.g., Fardal et al. 2007, Dave 2008), and also uncertainty concerning the nature of sub-mm galaxies and the feedback from AGN.

Big Bang Data Agrees with ΛCDM



Cosmic Background Explorer
COBE
1992



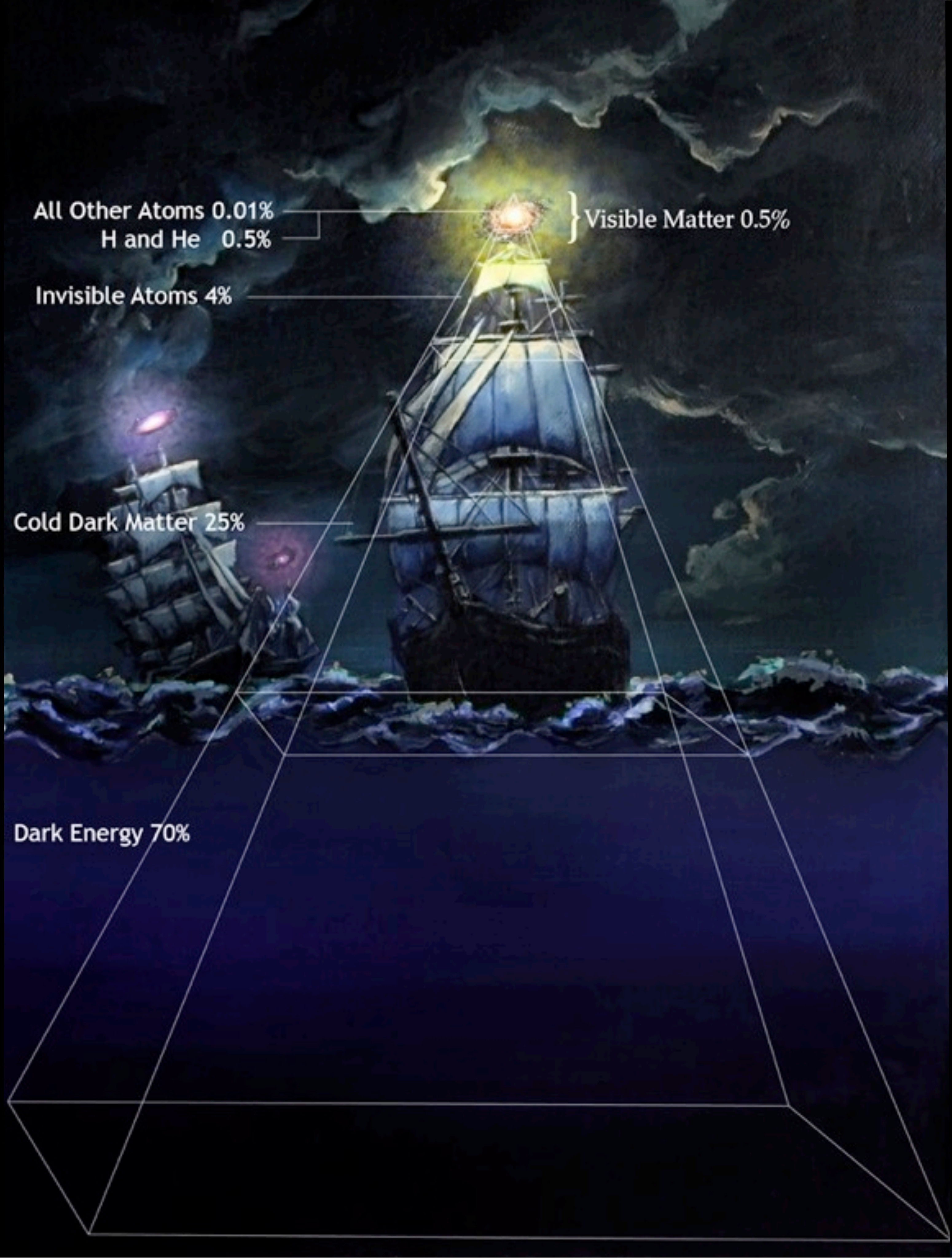


Wilkinson Microwave Anisotropy Probe
WMAP
2003-

ACBAR

QUaD

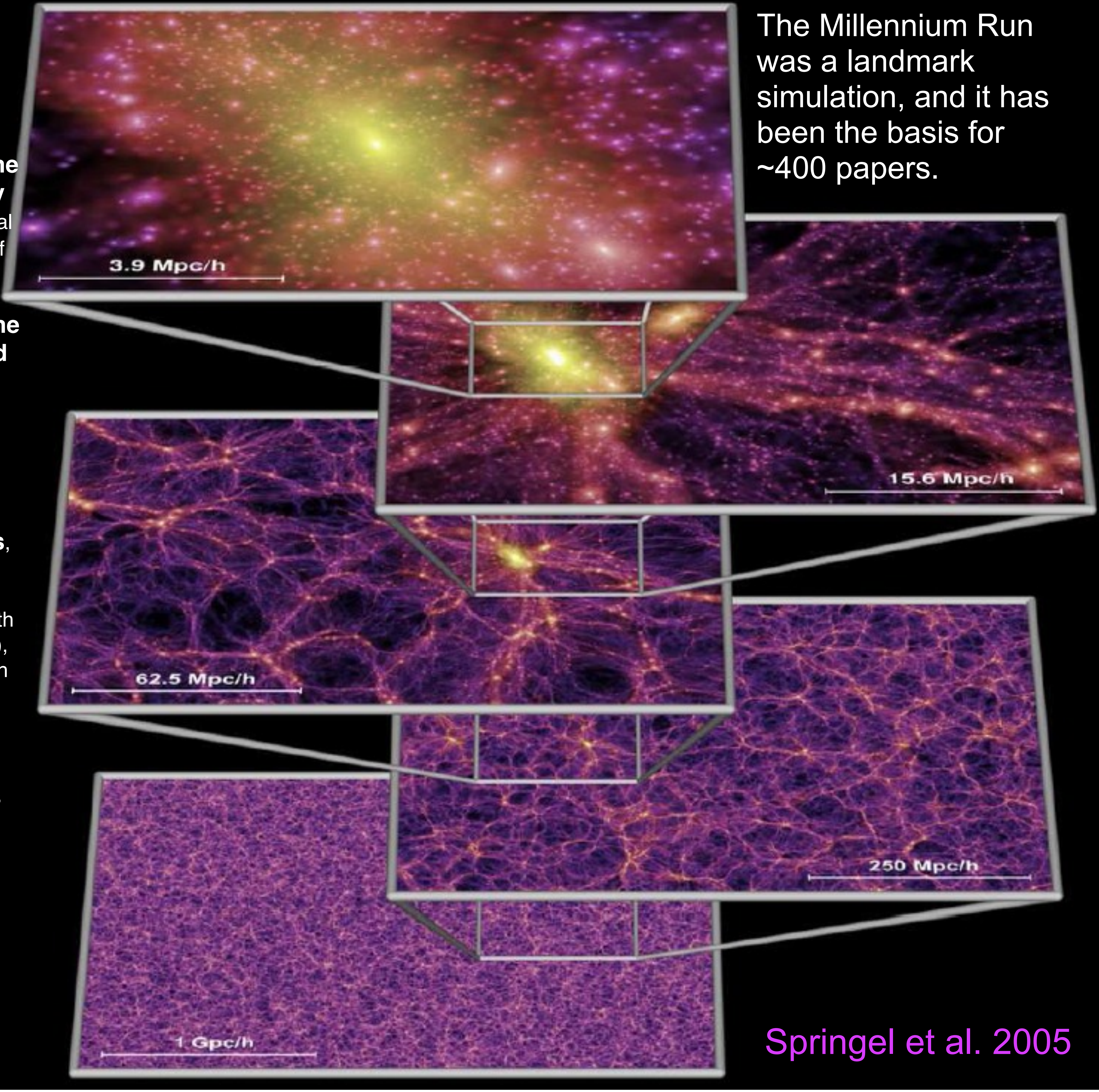
Friday, July 15, 2011



Imagine that the entire universe is an ocean of dark energy, On that ocean sail billions of ghostly ships made of dark matter. We don't see the ocean or the ships, just the lights at the tops of the tallest masts of the largest ships -- the galaxies.

The Millennium Run

- **properties of halos** (radial profile, concentration, shapes)
- **evolution of the number density of halos**, essential for normalization of Press-Schechter-type models
- **evolution of the distribution and clustering of halos** in real and redshift space, for comparison with observations
- **accretion history of halos**, assembly bias (variation of large-scale clustering with as- sembly history), and correlation with halo properties including angular momenta and shapes
- **halo statistics** including the mass and velocity functions, angular momentum and shapes, subhalo numbers and distribution, and correlation with environment

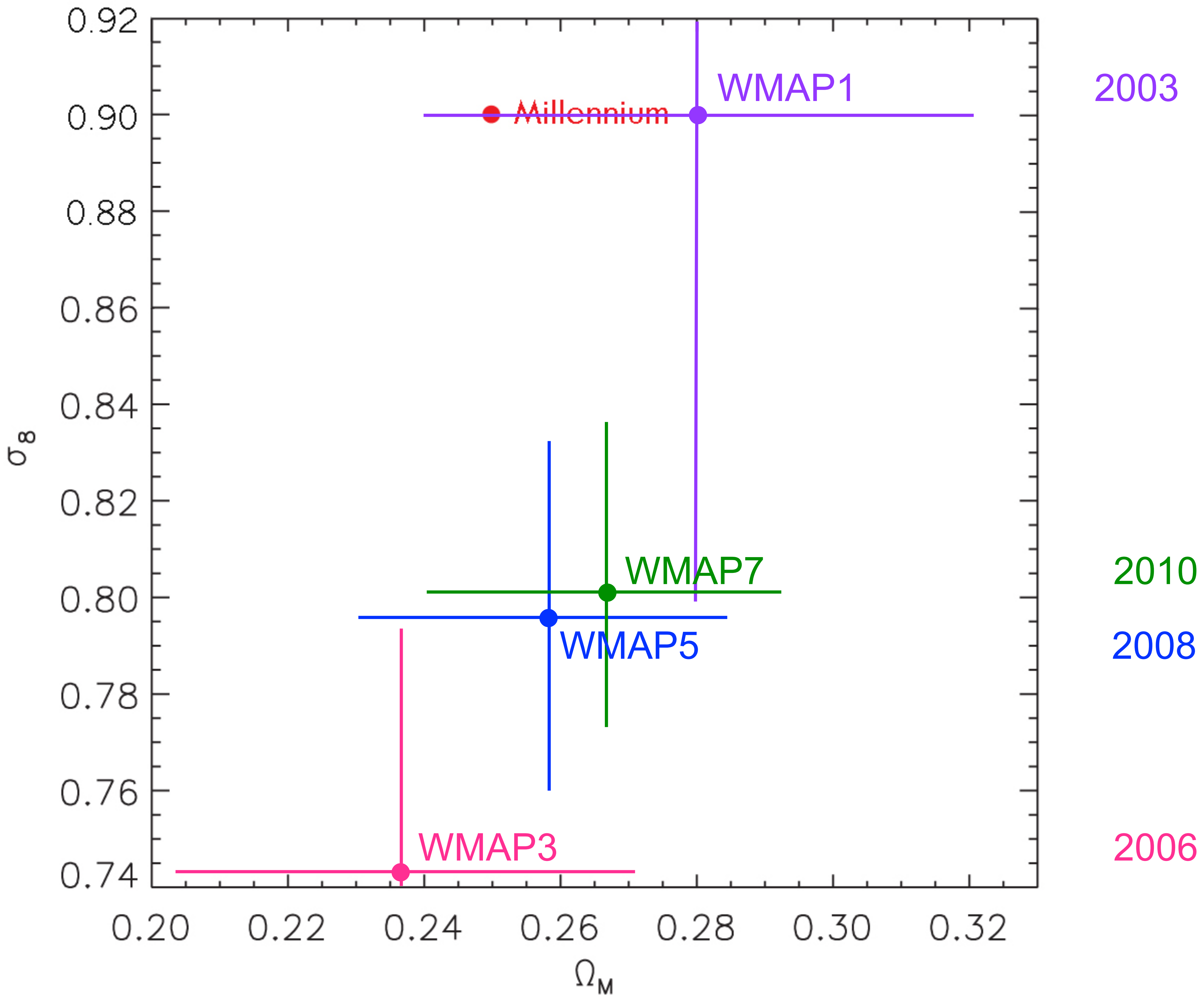


The Millennium Run was a landmark simulation, and it has been the basis for ~400 papers.

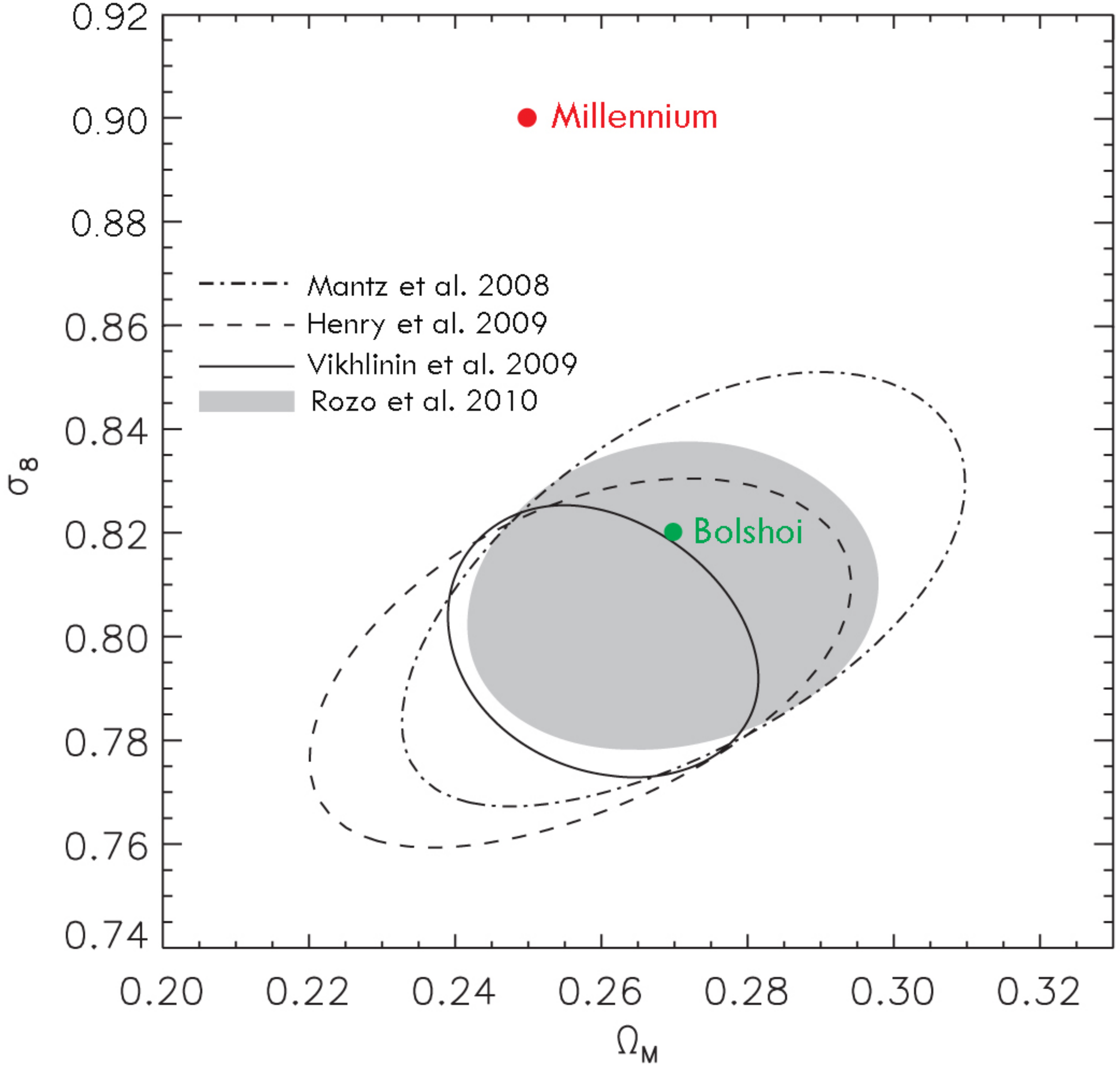
Springel et al. 2005

- **void statistics**, including sizes and shapes and their evolution, and the orientation of halo spins around voids
- quantitative descriptions of the evolving **cosmic web**, including applications to weak gravitational lensing
- preparation of **mock catalogs**, essential for analyzing SDSS and other survey data, and for preparing for new large surveys for dark energy etc.
- **merger trees**, essential for **semi-analytic modeling** of the evolving galaxy population, including models for the galaxy merger rate, the history of star formation and galaxy colors and morphology, the evolving AGN luminosity function, stellar and AGN feedback, recycling of gas and metals, etc.

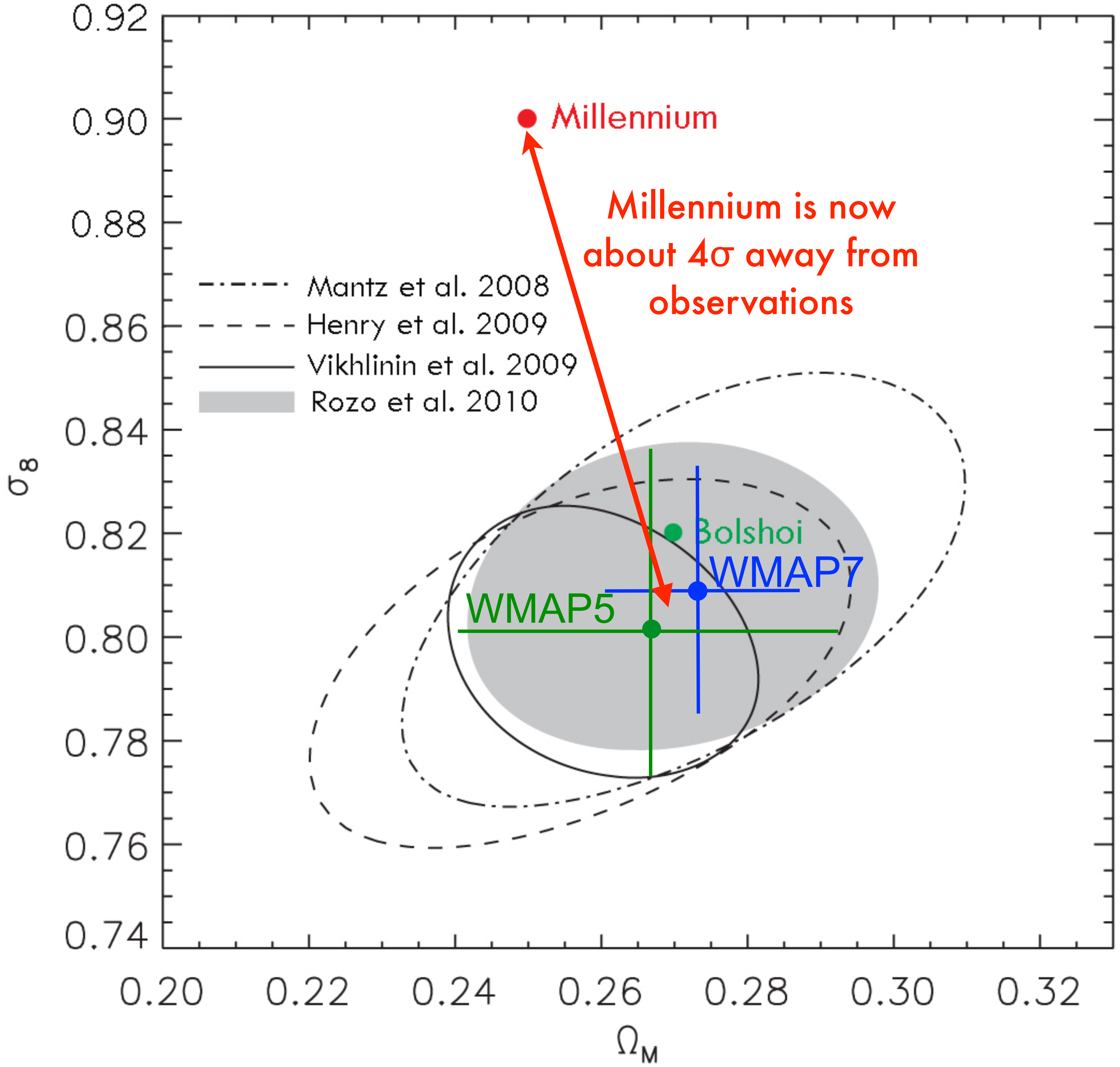
WMAP-only Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



Millennium is now about 4σ away from observations

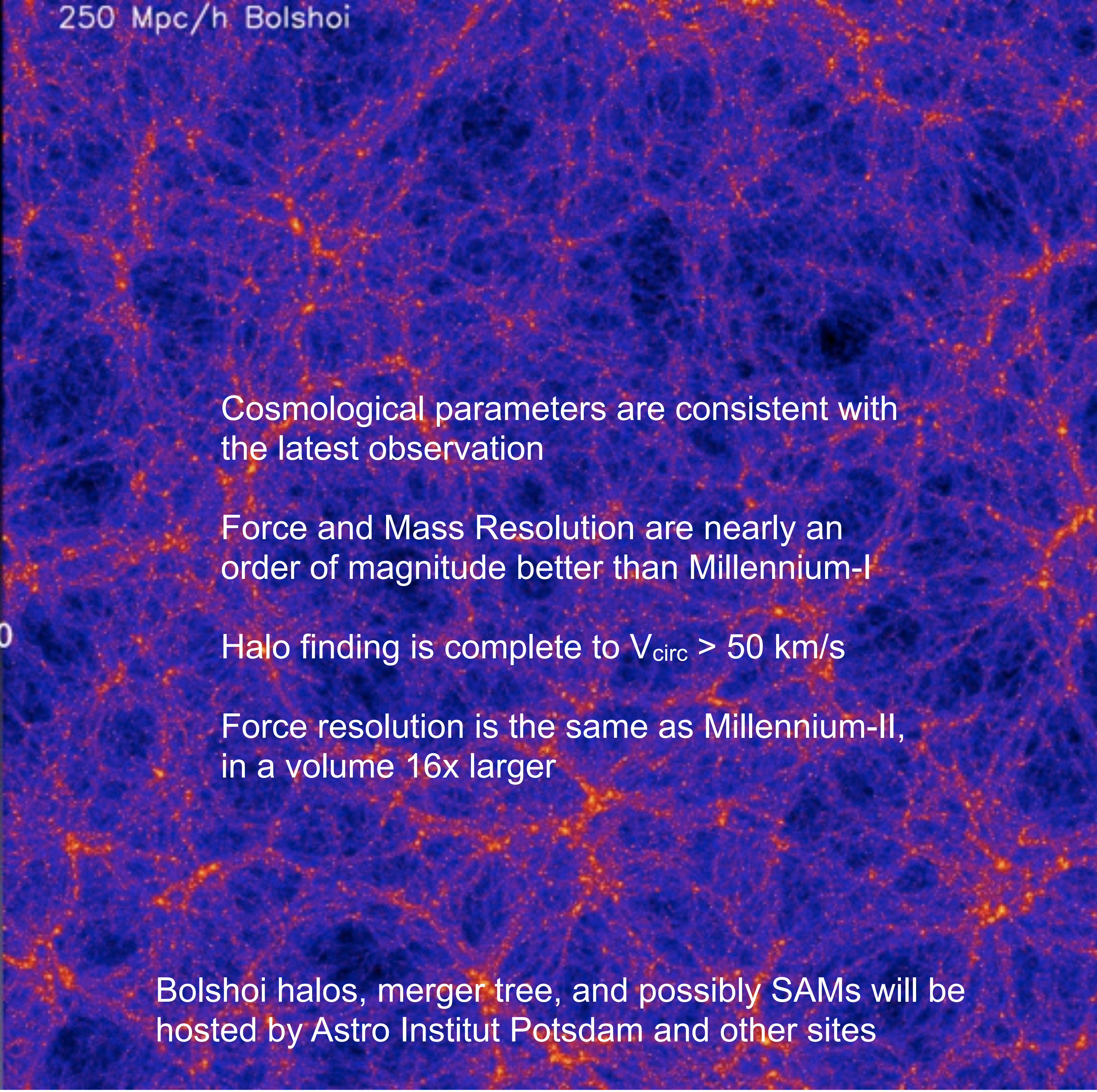
The Bolshoi simulation

ART code

250Mpc/h Box
LCDM
$\sigma_8 = 0.82$
h = 0.73
8G particles
1kpc/h force resolution
1e8 Msun/h mass res

dynamical range 262,000
time-steps = 400,000

NASA AMES
supercomputing center
Pleiades computer
13824 cores
12TB RAM
75TB disk storage
6M cpu hrs
18 days wall-clock time



Cosmological parameters are consistent with the latest observation

Force and Mass Resolution are nearly an order of magnitude better than Millennium-I

Halo finding is complete to V_{circ} > 50 km/s

Force resolution is the same as Millennium-II, in a volume 16x larger

Bolshoi halos, merger tree, and possibly SAMs will be hosted by Astro Institut Potsdam and other sites

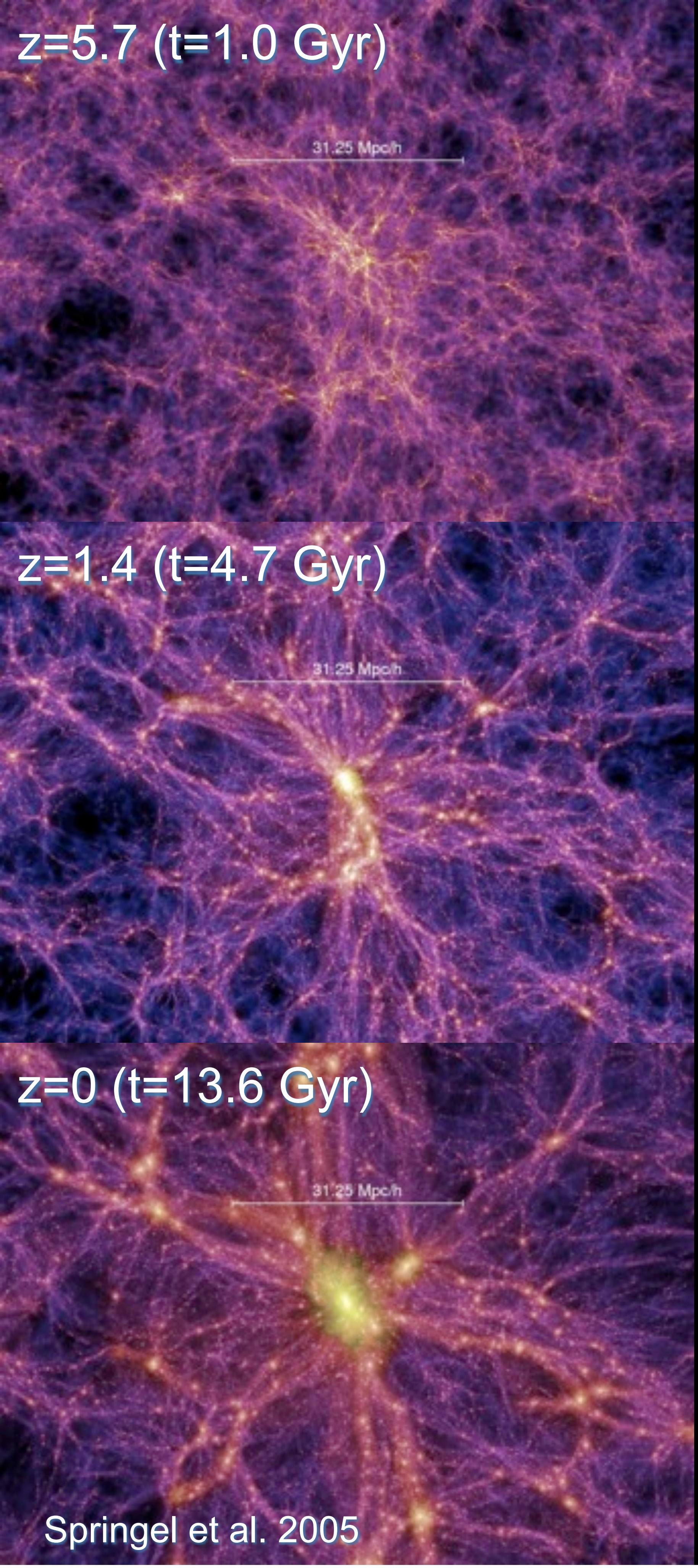
BOLSHOI SIMULATION FLY-THROUGH

less than
1/1000
of the
Bolshoi
Simulation
Volume

↔

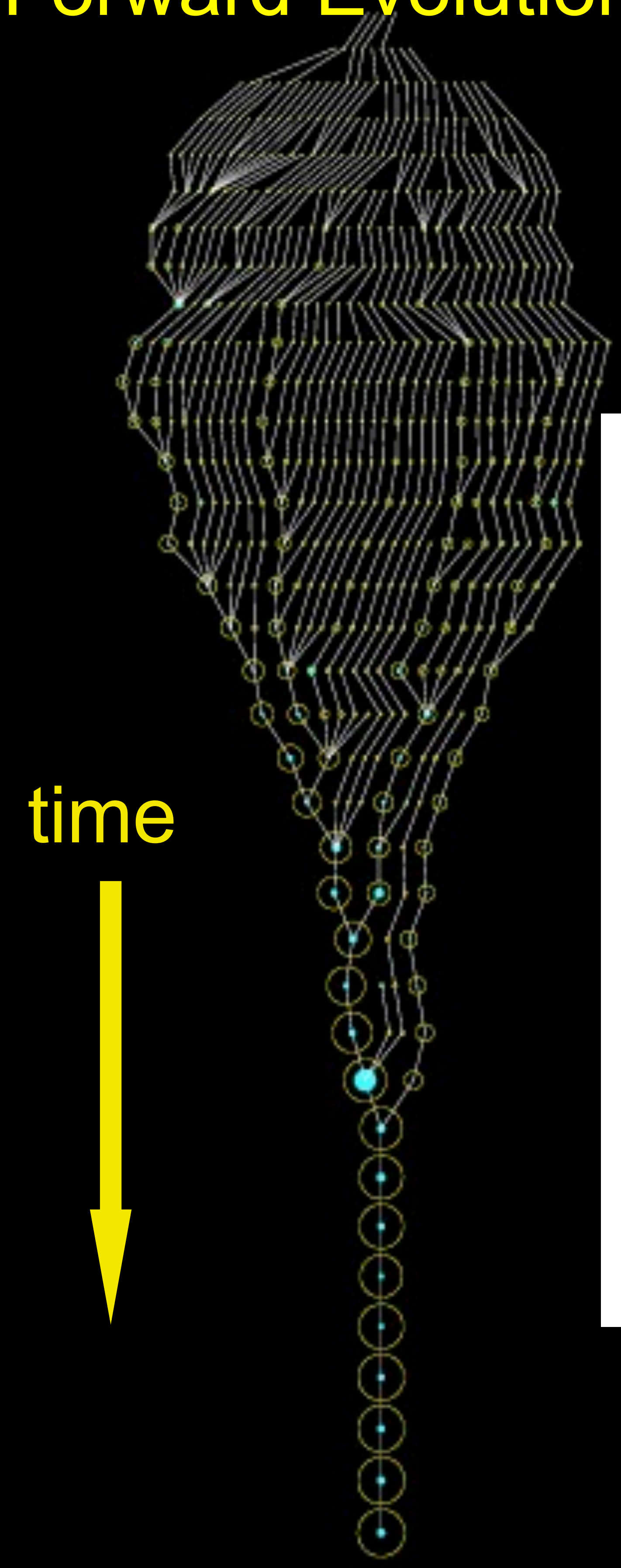
100 million light years

Present status of ΛCDM “Double Dark” theory:



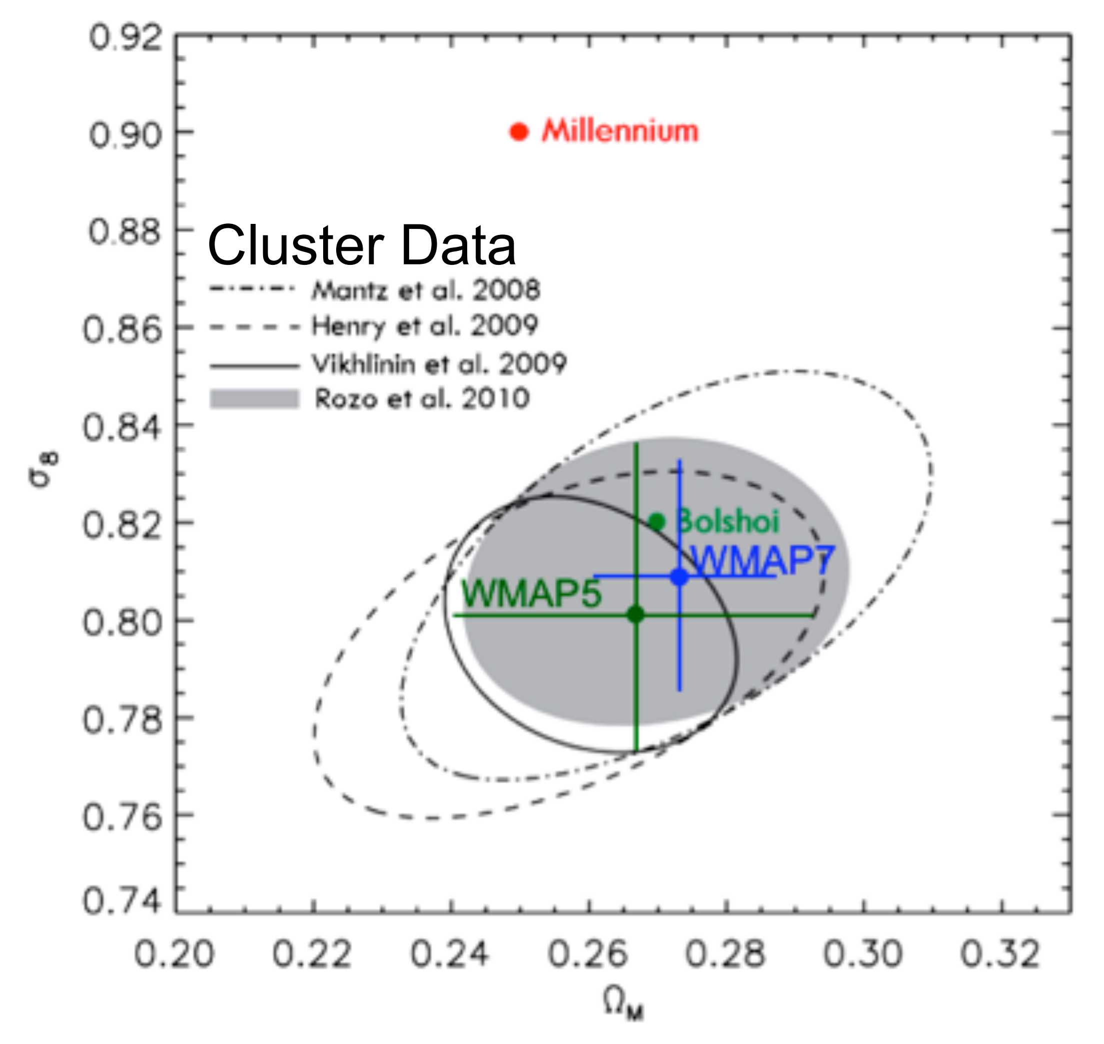
Springel et al. 2005

Forward Evolution



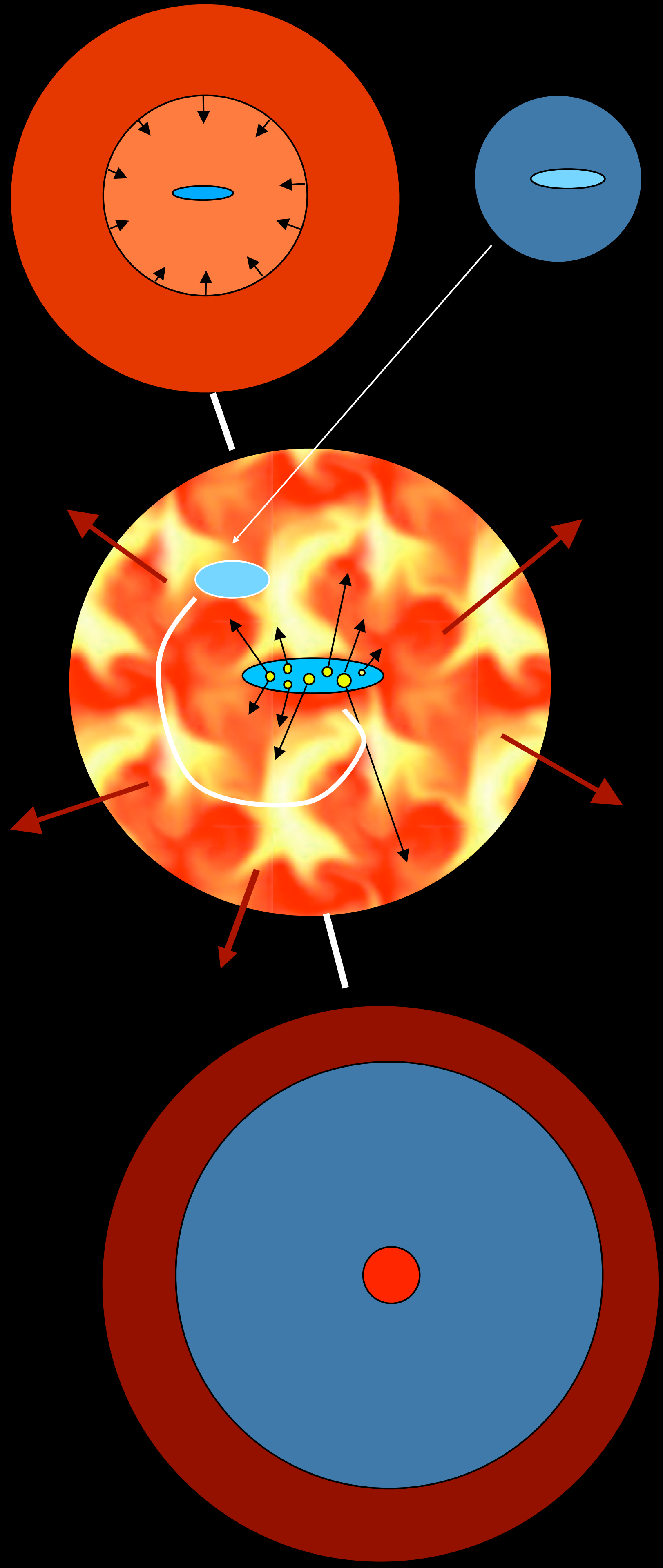
Wechsler et al. 2002

- 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

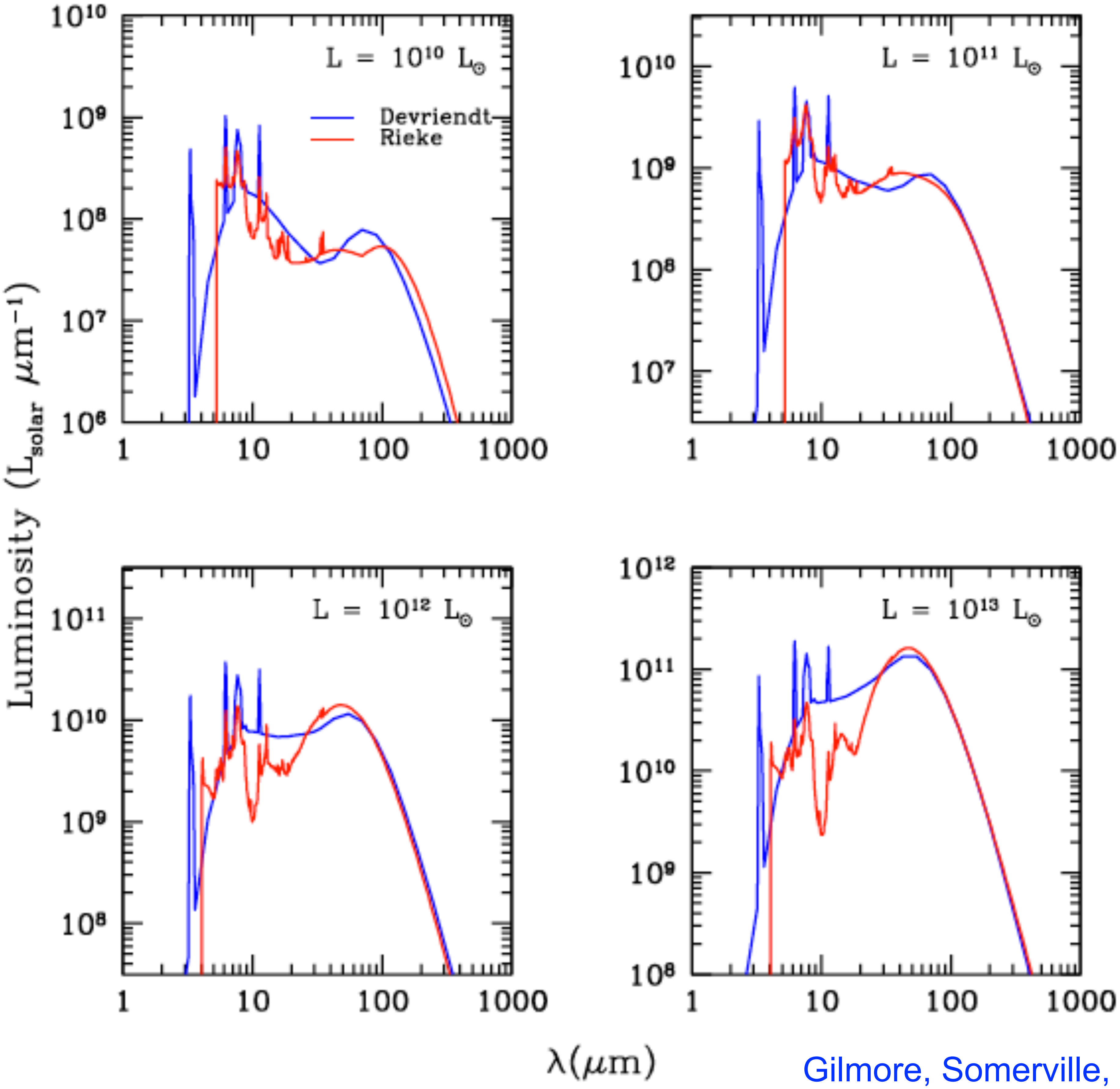
Galaxy Formation in ΛCDM



- 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 and cold flows trigger bursts of star formation; ‘major’ mergers transform disks into spheroids and fuel bright AGN
- “bright mode” AGN feedback cuts off star formation
- “radio mode” AGN feedback prevents later SF

White & Frenk 1991; Kauffmann+93; Cole+94; Somerville & & Primack 99; Cole+00; Somerville, Primack, & Faber 01; Croton et al. 06; Somerville +08; Fanidakis+09; Somerville, Gilmore, Primack, & Dominguez 2011 (reported here)

Improved Dust Emission Templates



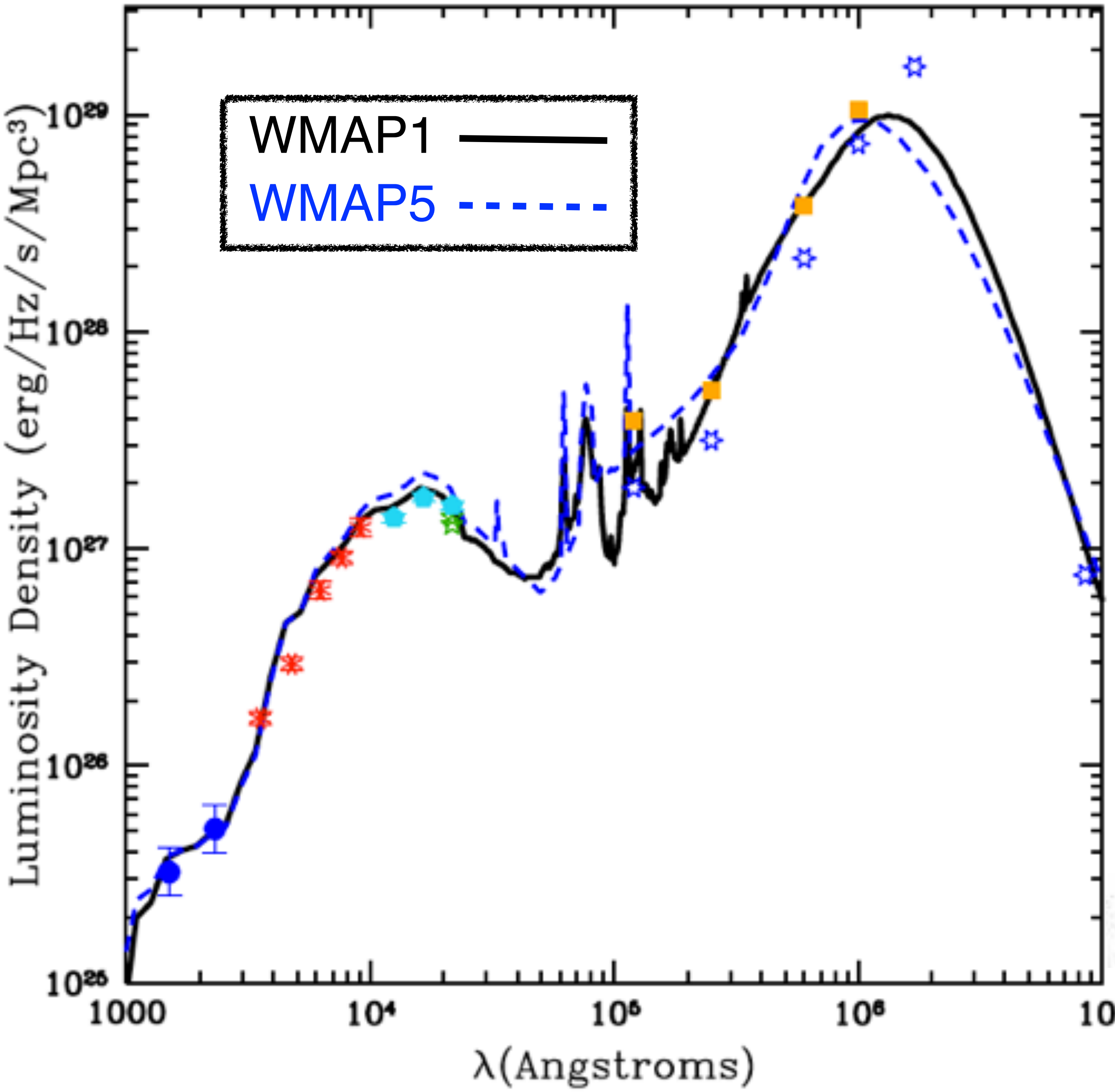
In previous work we used Devriendt & Guiderdoni 2000 dust emission templates, based on IRAS data.

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

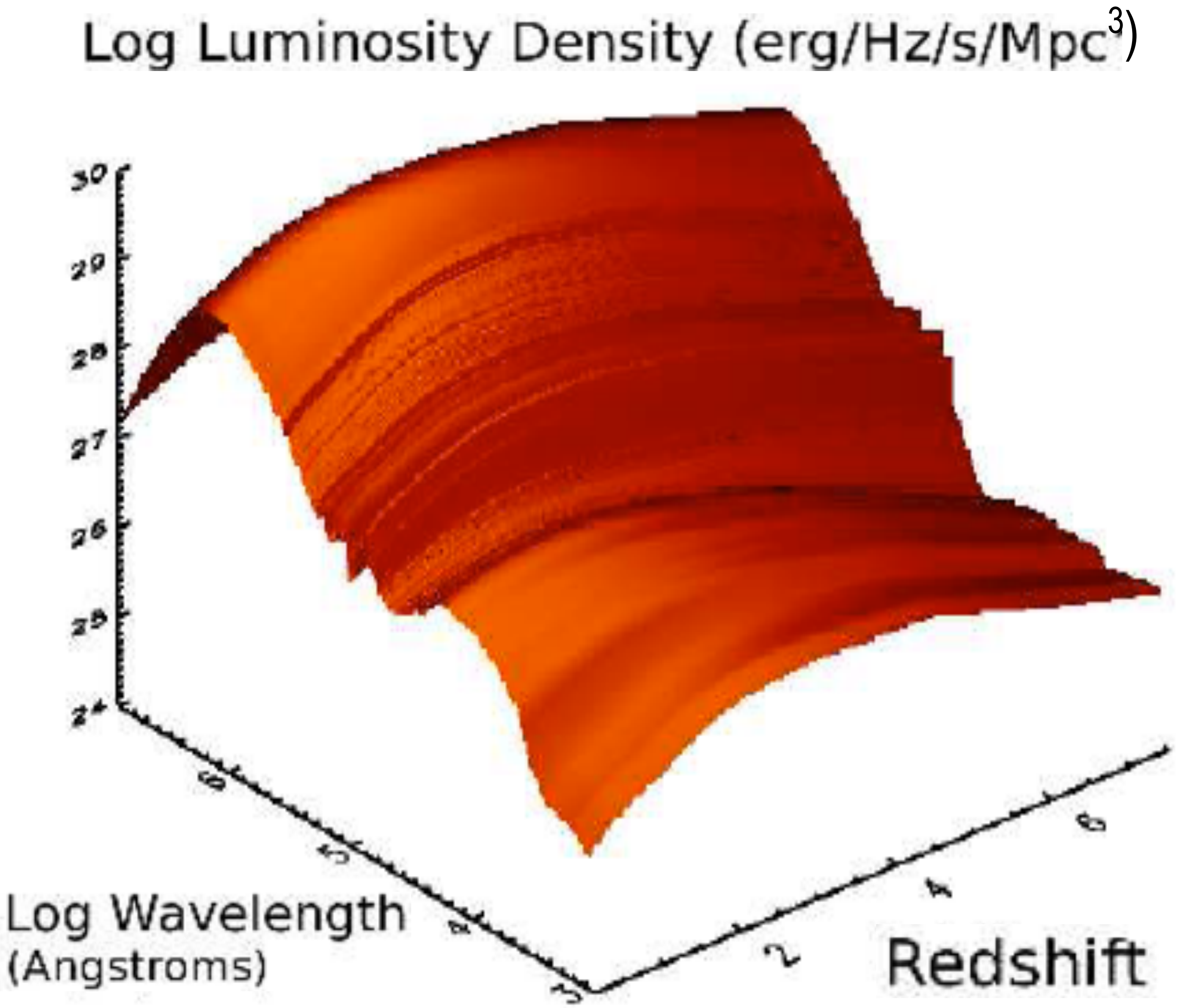
Gilmore, Somerville, Primack, & Dominguez (2011)

Some Results from our Semi-Analytic Models

z=0 Luminosity Density

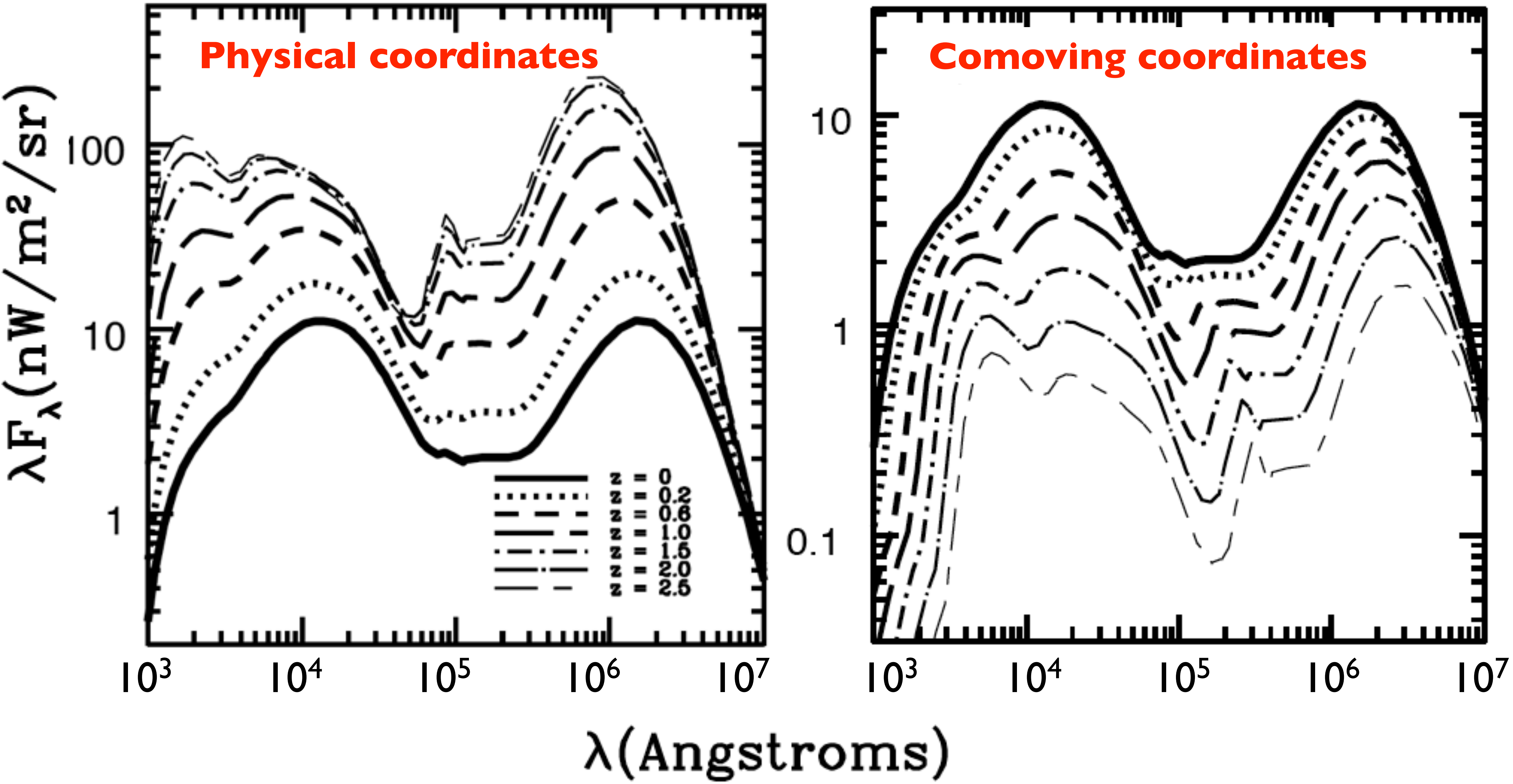


Evolving Luminosity Density



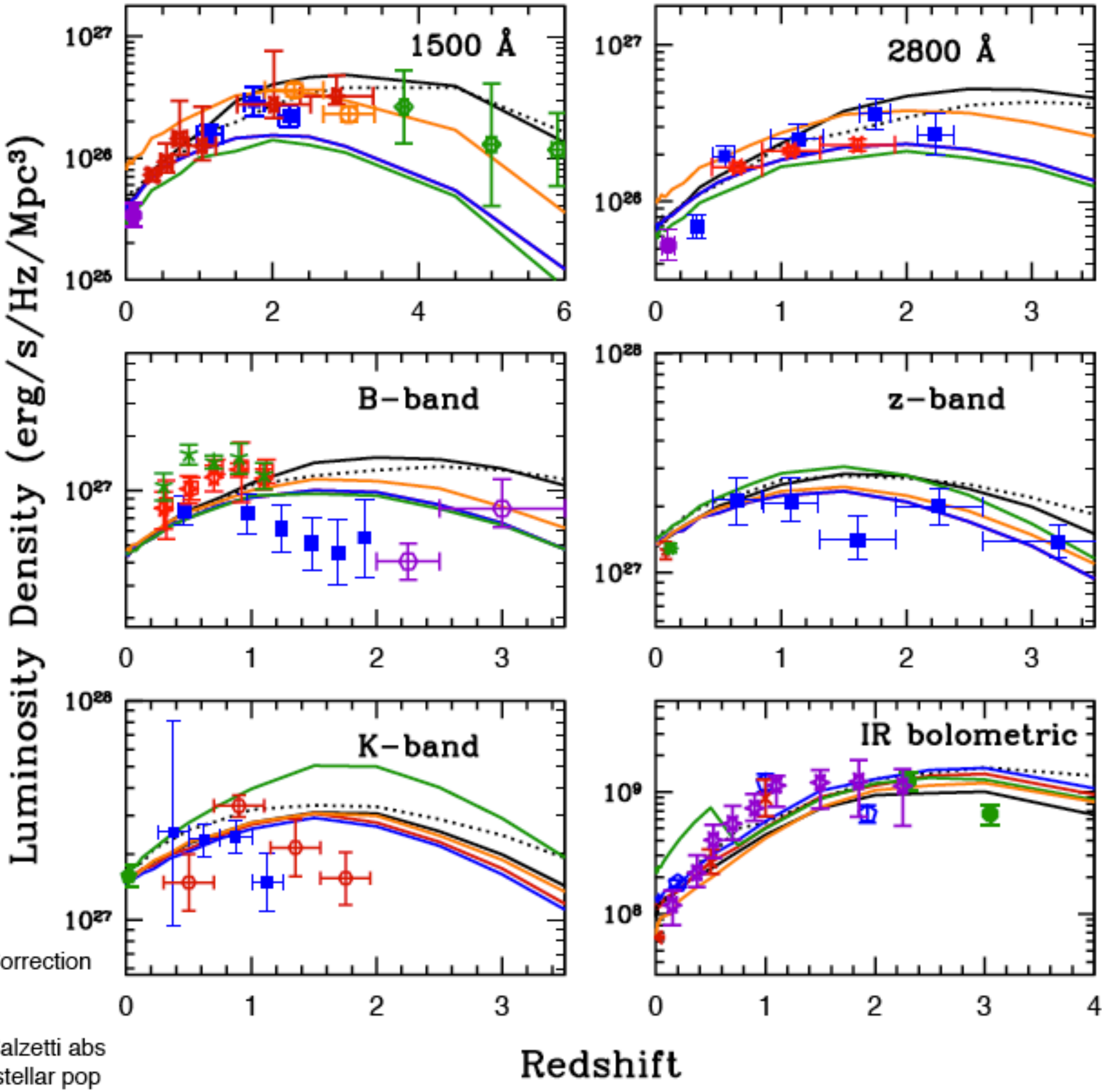
Gilmore, Somerville, Primack, & Dominguez (2011)

Evolution z=2.5→0 of the EBL in Fiducial WMAP5 Model



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.

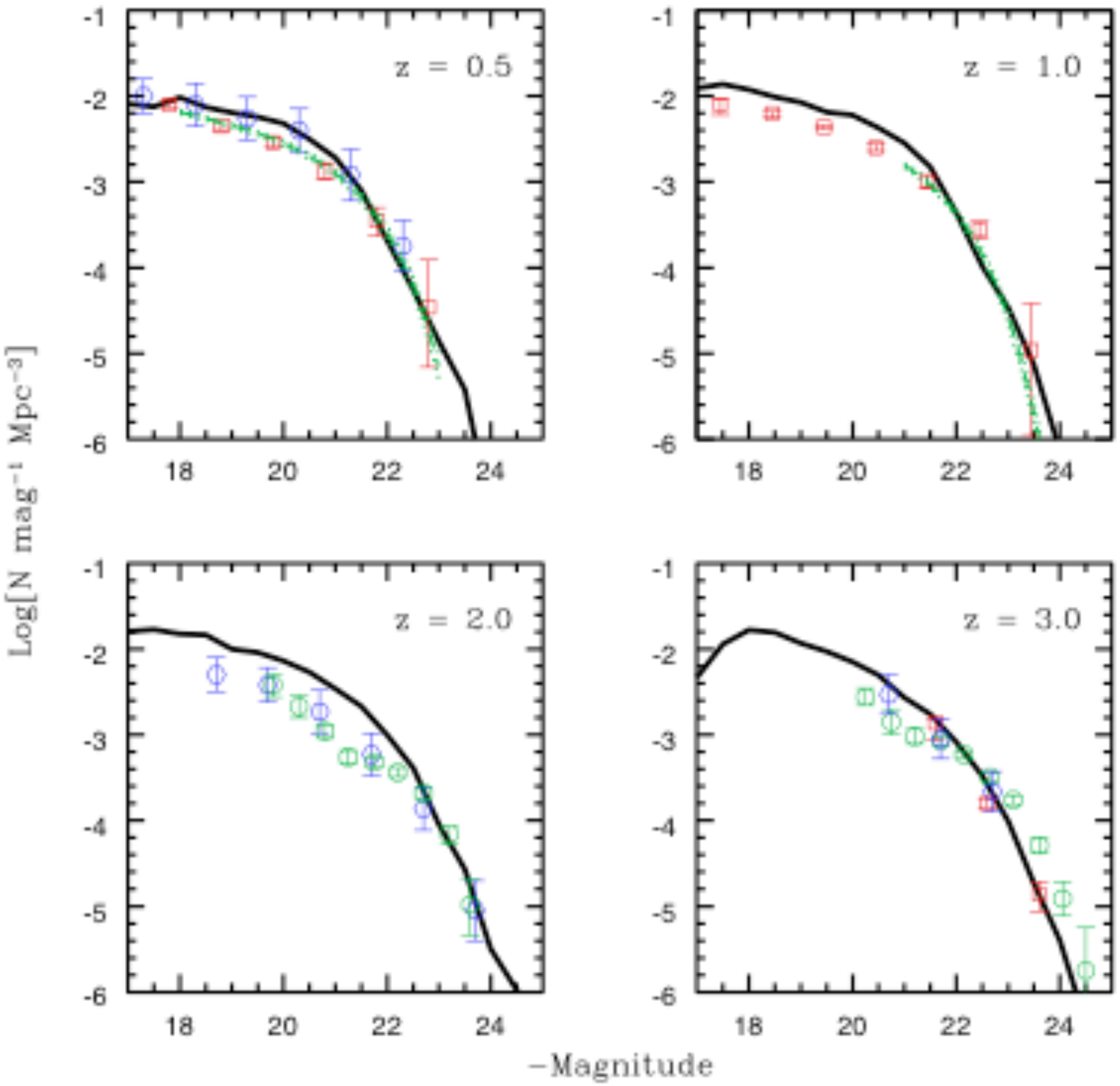


Somerville, Gilmore, Primack, & Dominguez (2011)

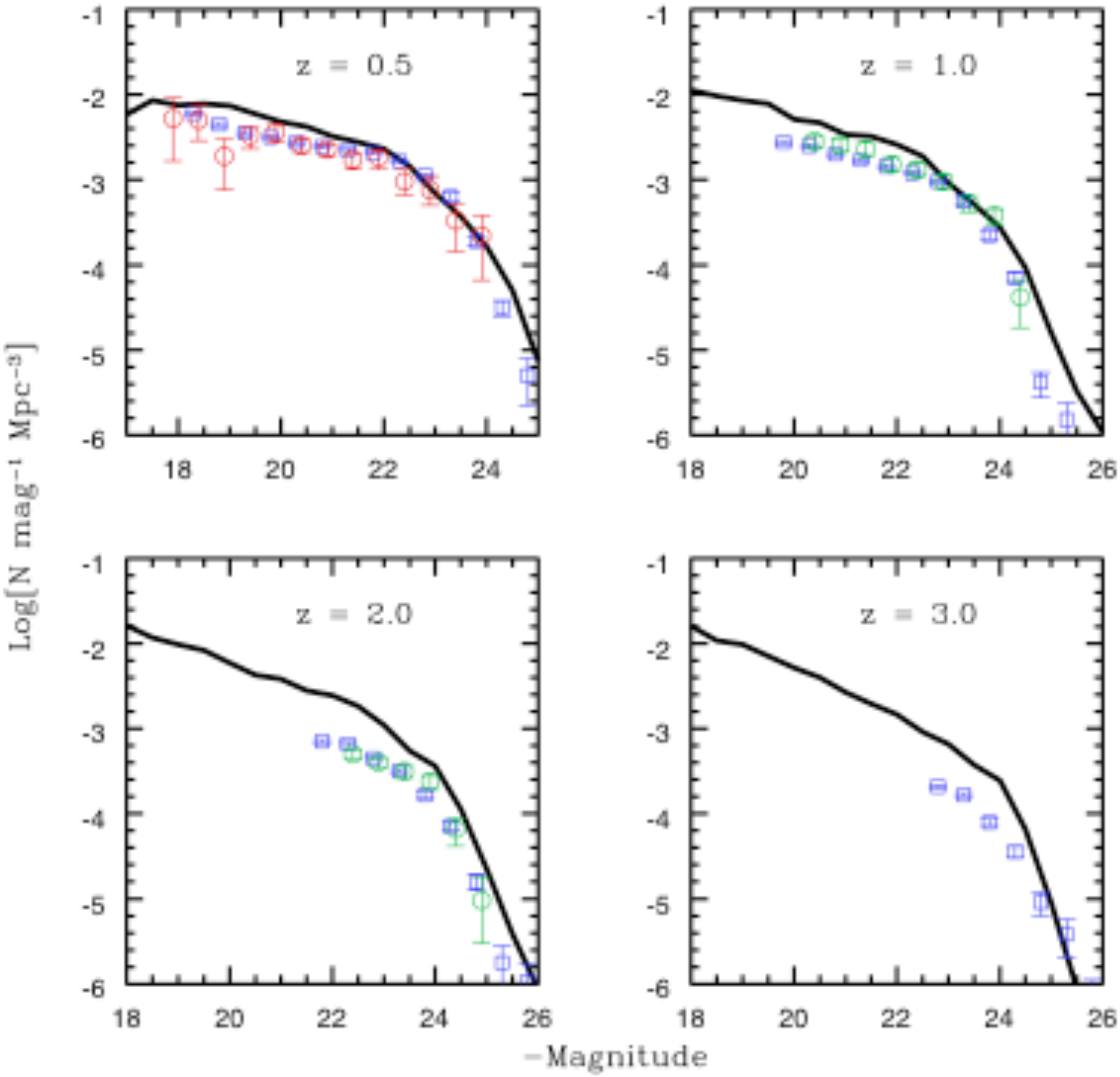
More Results from Our Semi-Analytic Models

Evolving Luminosity Functions

B-band



K-band

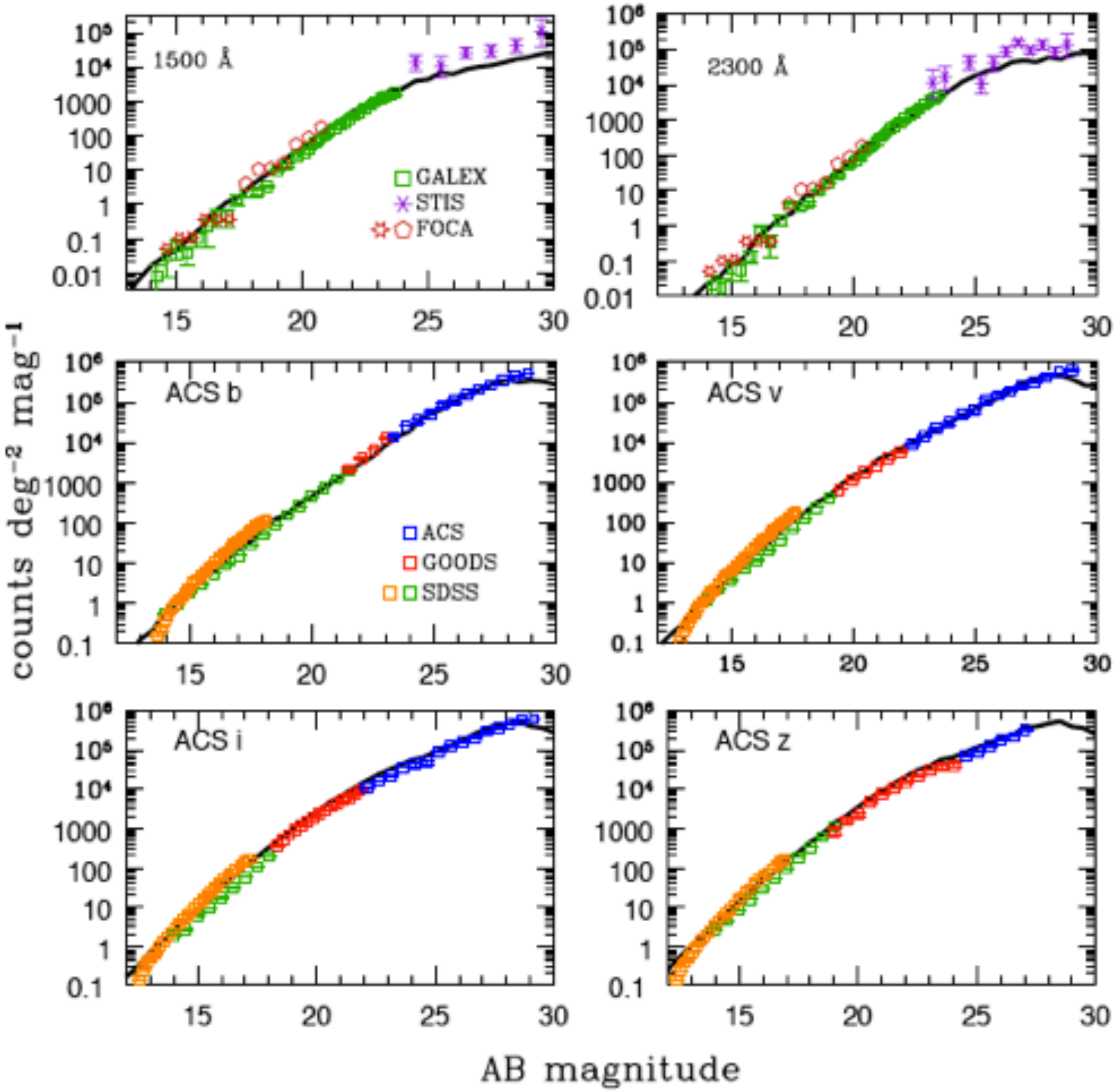


Somerville, Gilmore, Primack, & Dominguez (2011)

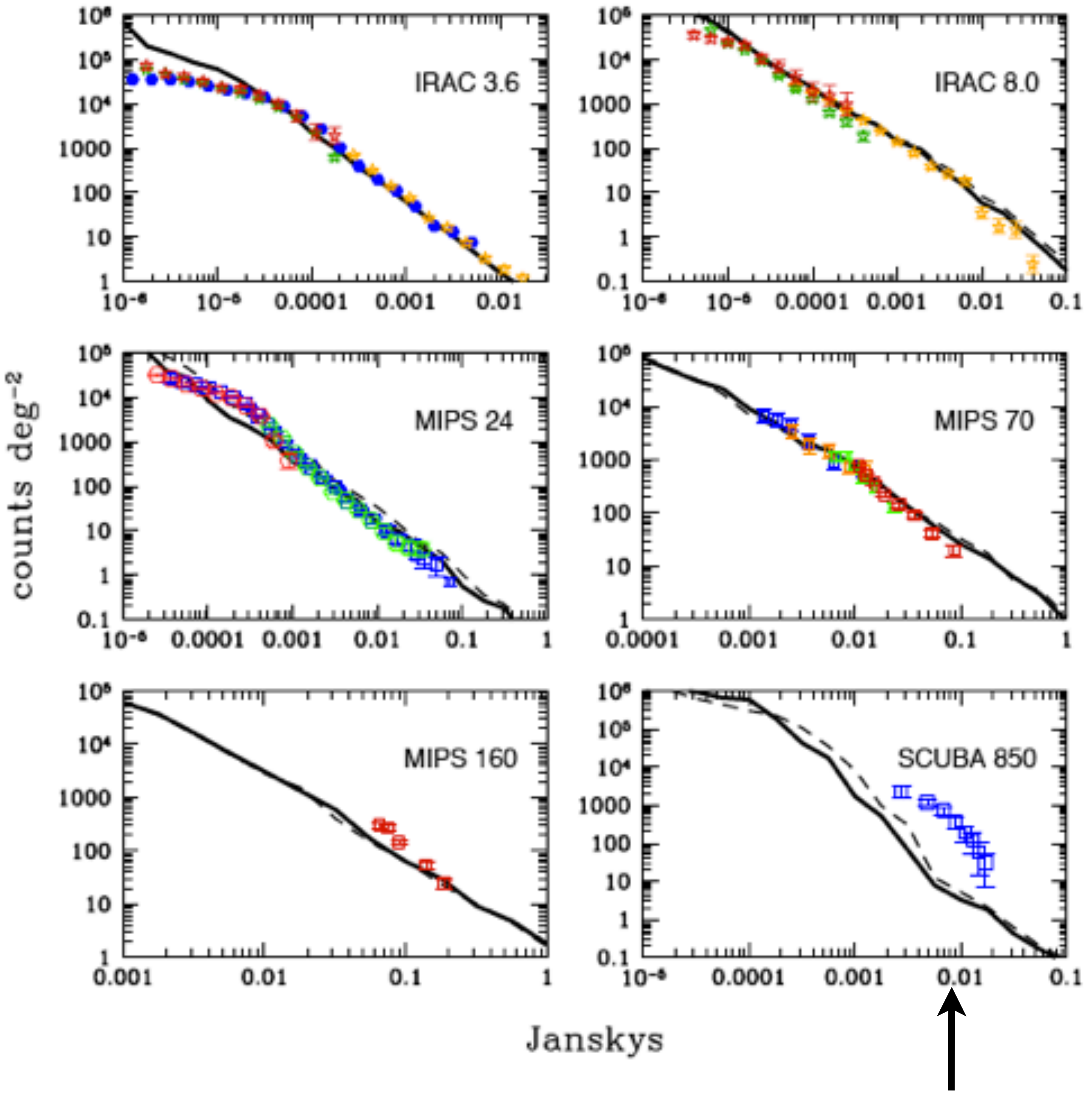
More Results from Our Semi-Analytic Models

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

Number Counts in 3.6, 8, 24, 70, 160, & 850 μm Bands

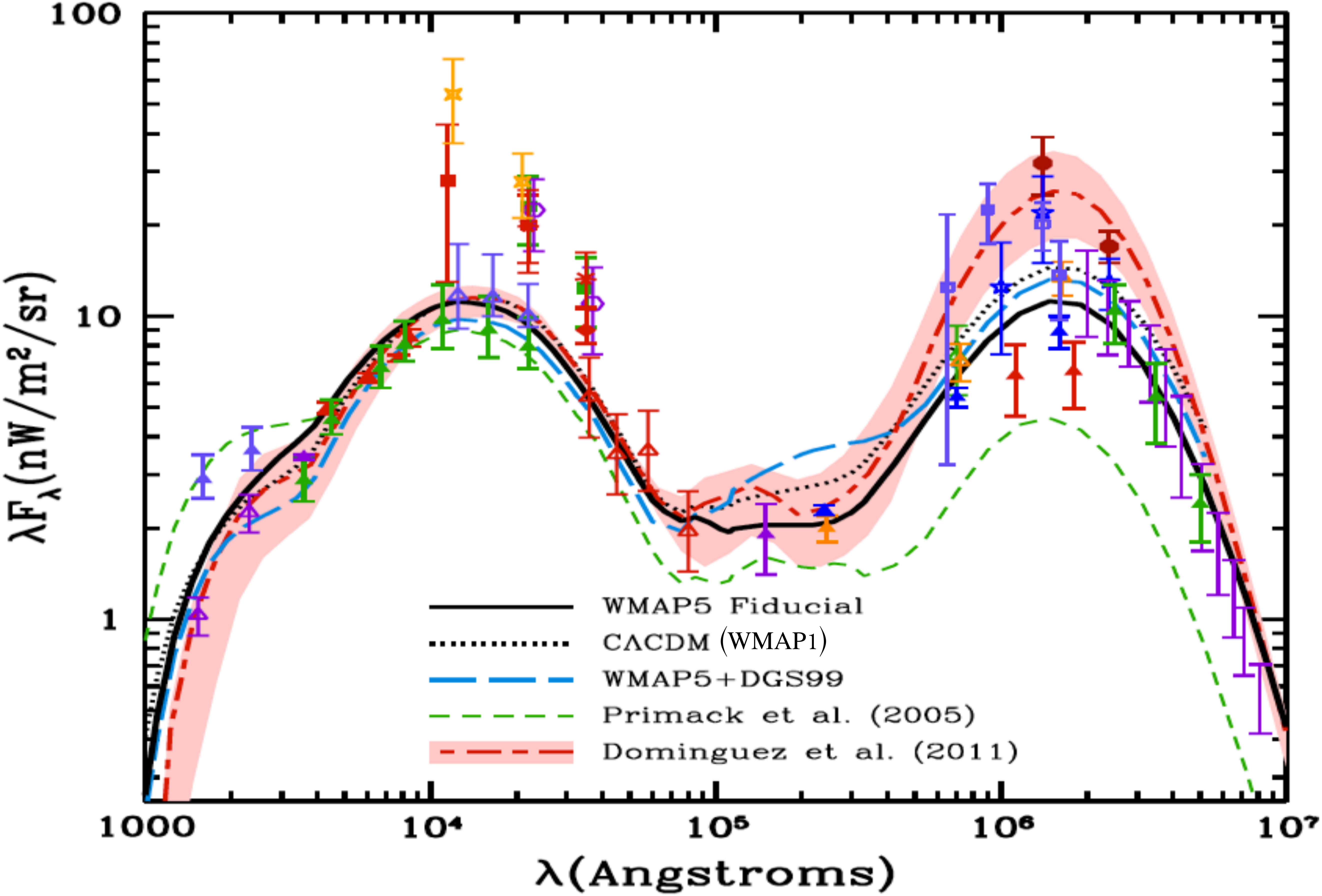


Gilmore, Somerville, Primack, & Dominguez (2011)



The one clear failure is at 850 μm

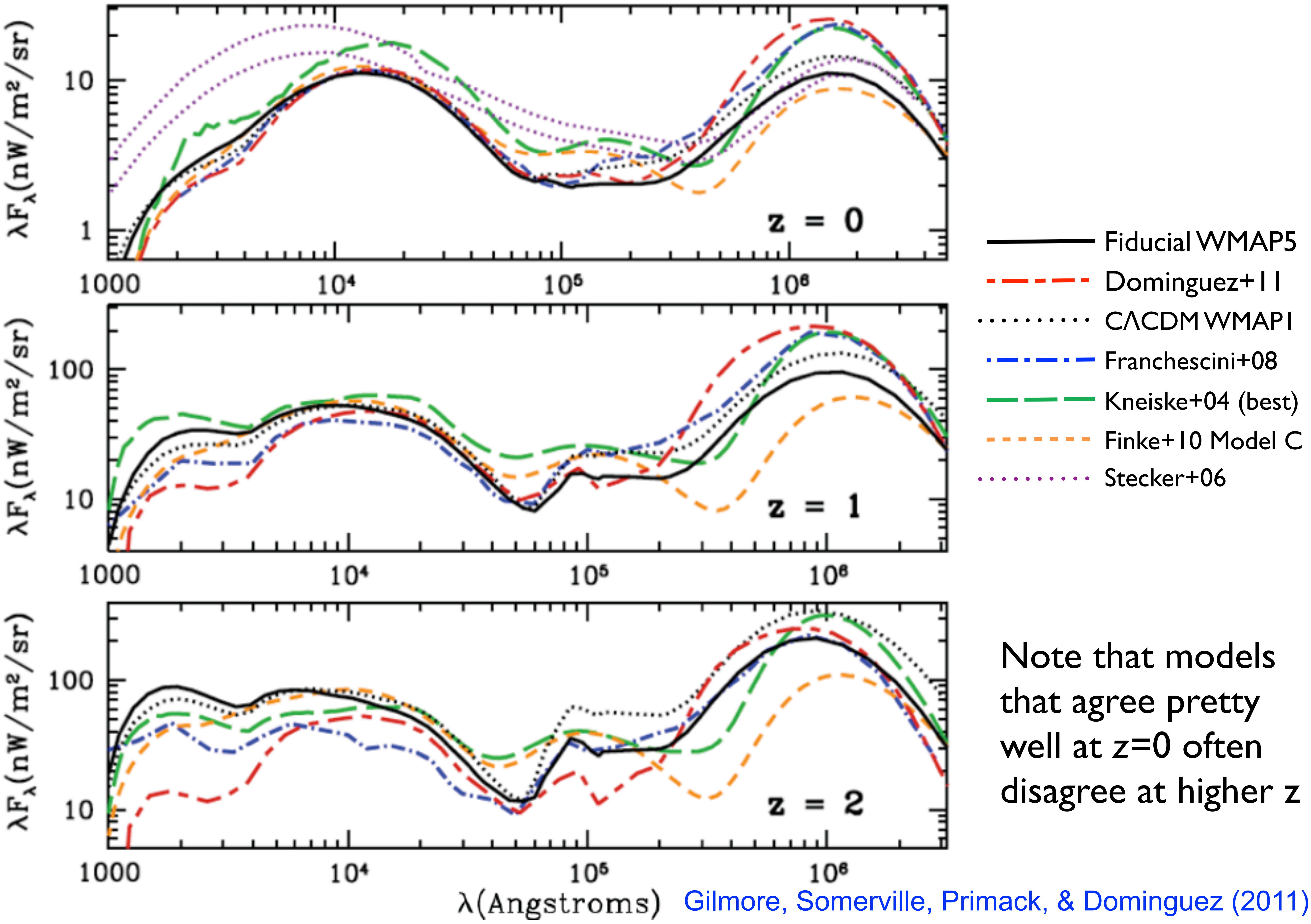
Our SAM and Observational Local EBL



Gilmore, Somerville, Primack, & Dominguez (2011)

Friday, July 15, 2011

Comparison with Other Works



Note that models that agree pretty well at z=0 often disagree at higher z

Gilmore, Somerville, Primack, & Dominguez (2011)

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

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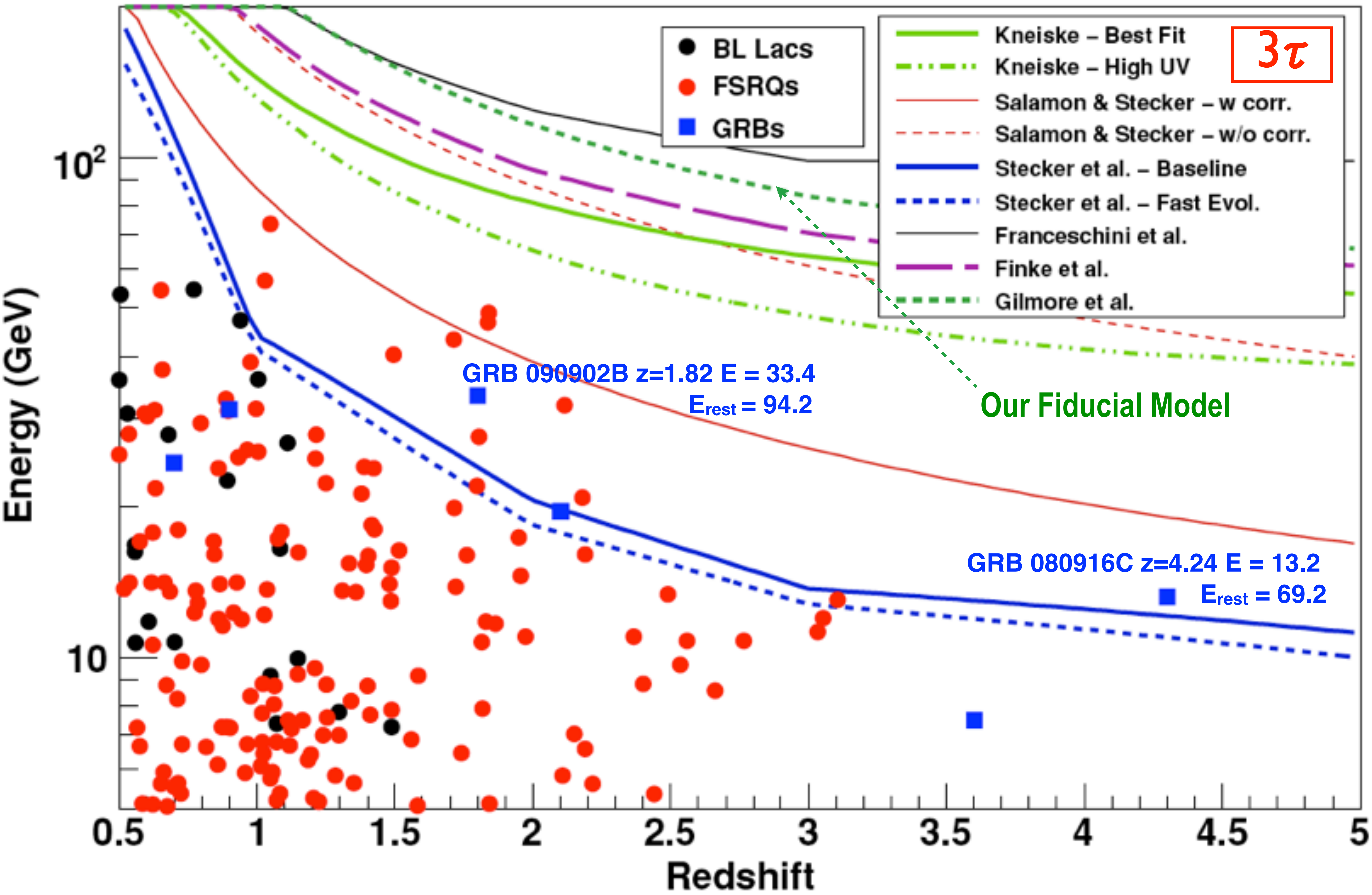
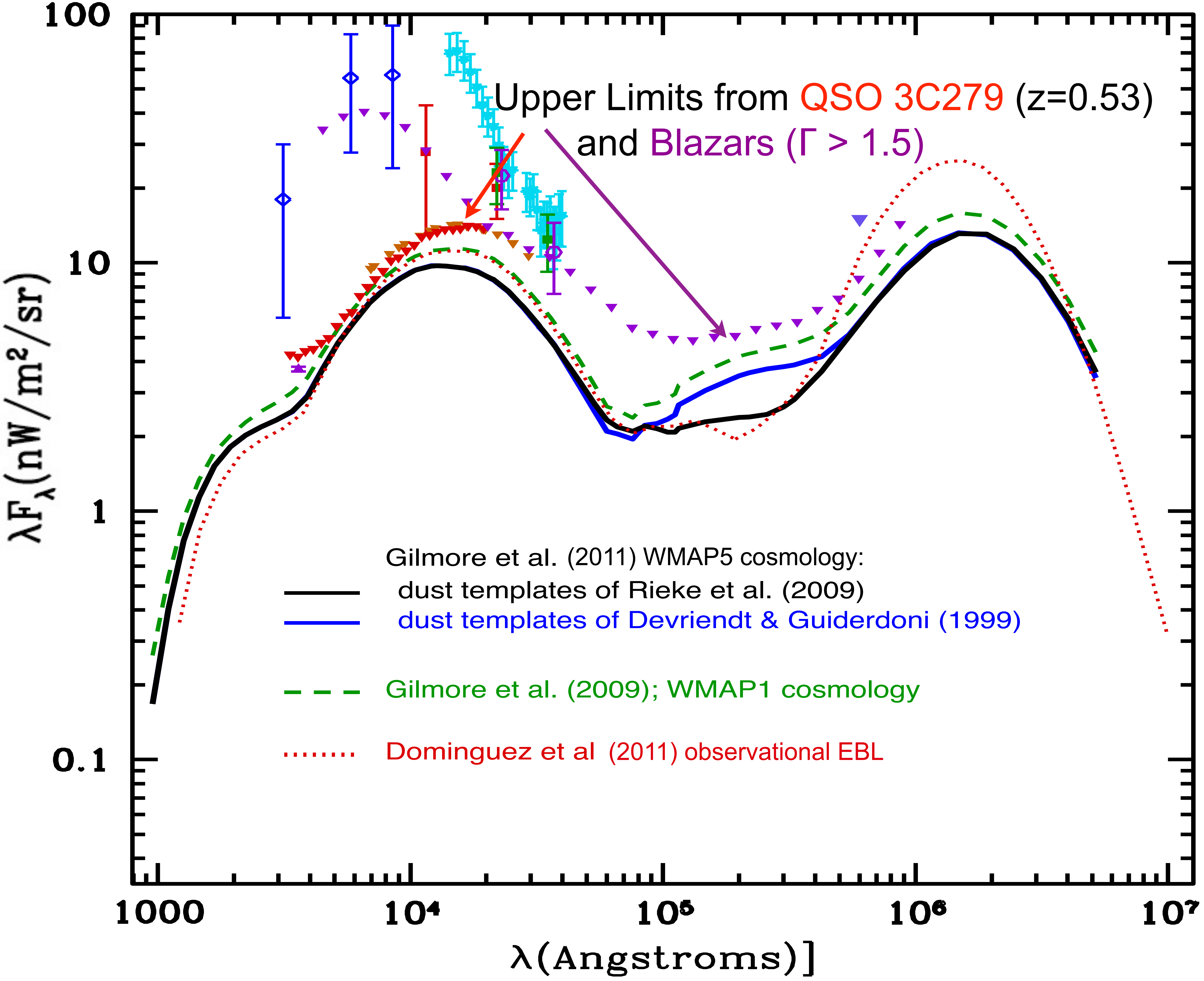
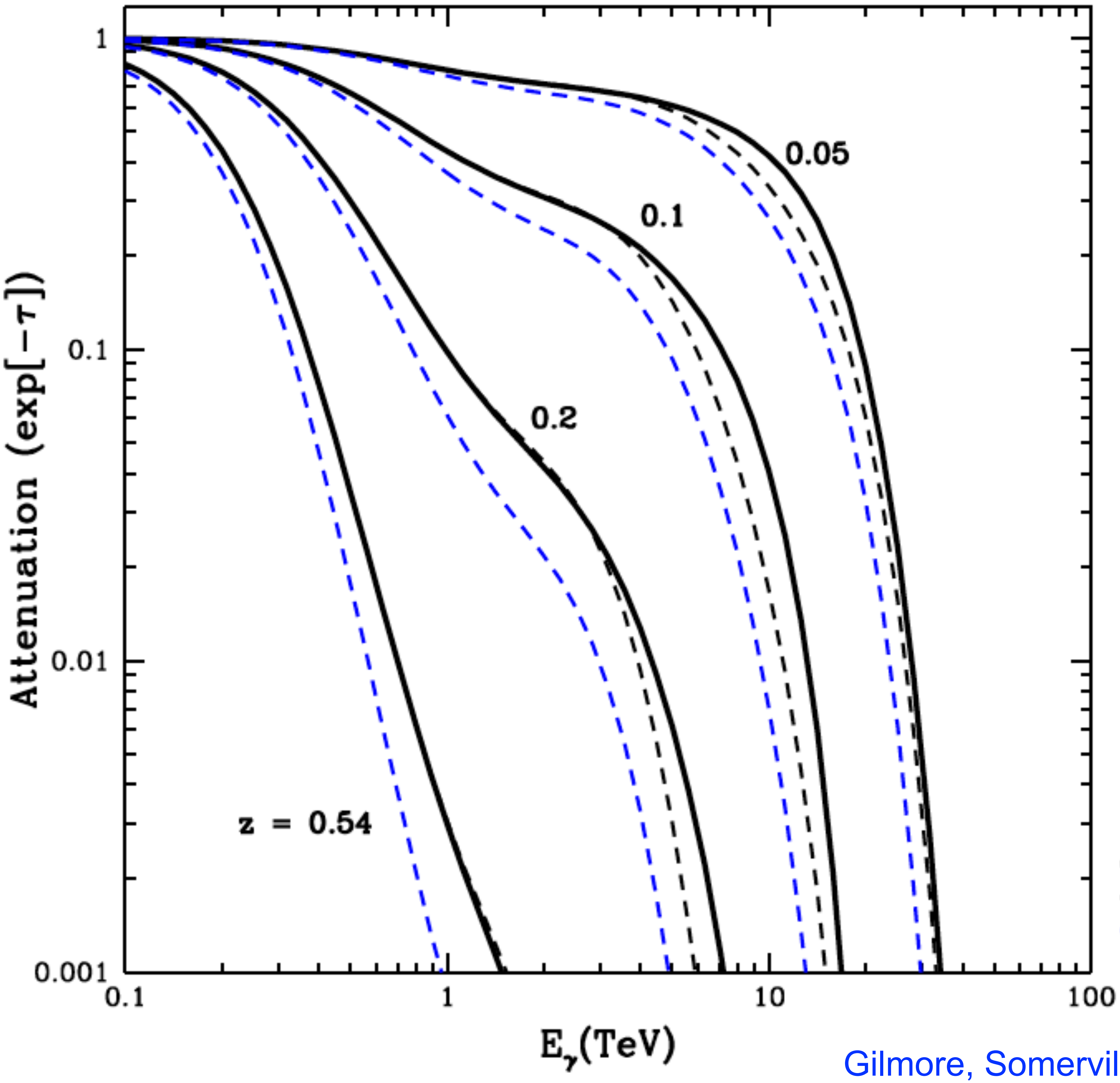


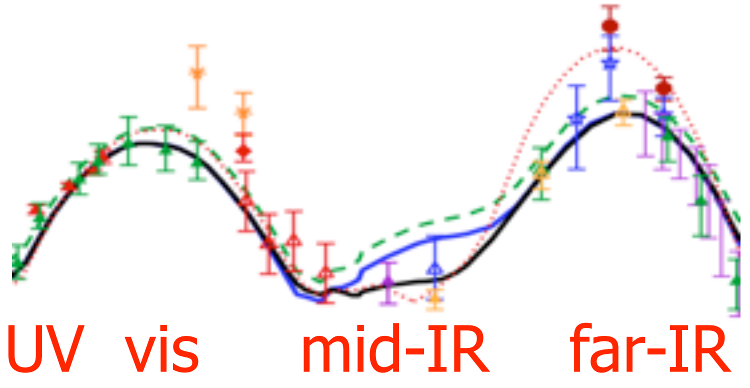


Upper Limits from QSO 3C279 (z=0.53) and Blazars (Γ > 1.5)

Predicted Gamma Ray Attenuation



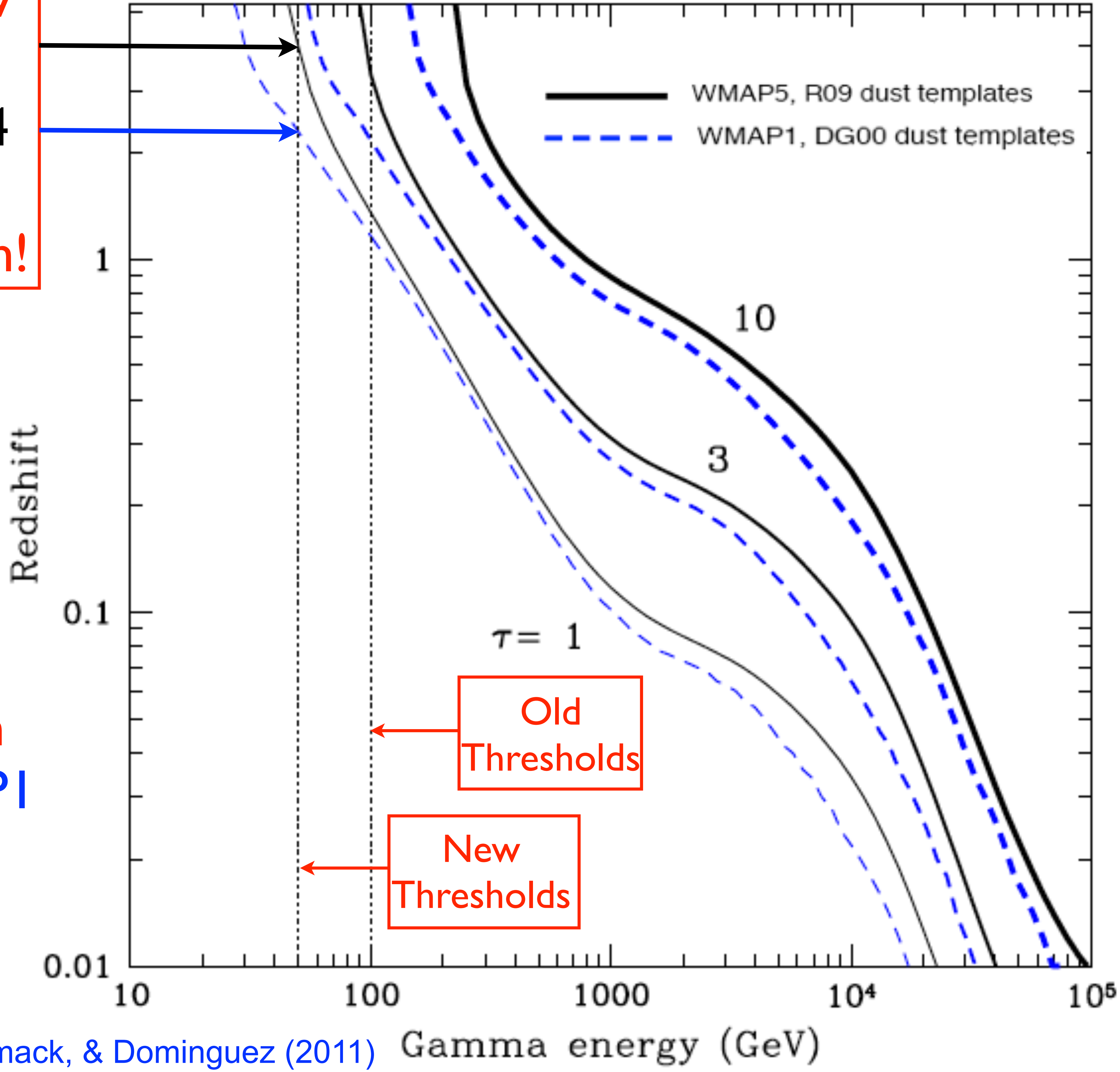
Increasing distance causes absorption features to increase in magnitude and appear at lower energies. The plateau seen between 1 and 10 TeV at low redshift is a product of the mid-IR valley in the EBL spectrum.



Gilmore, Somerville, Primack, & Dominguez (2011)

Gamma-Ray Absorption Edge

With a 50 GeV threshold, we see to z≈2.2-4 with less than 1/e attenuation!



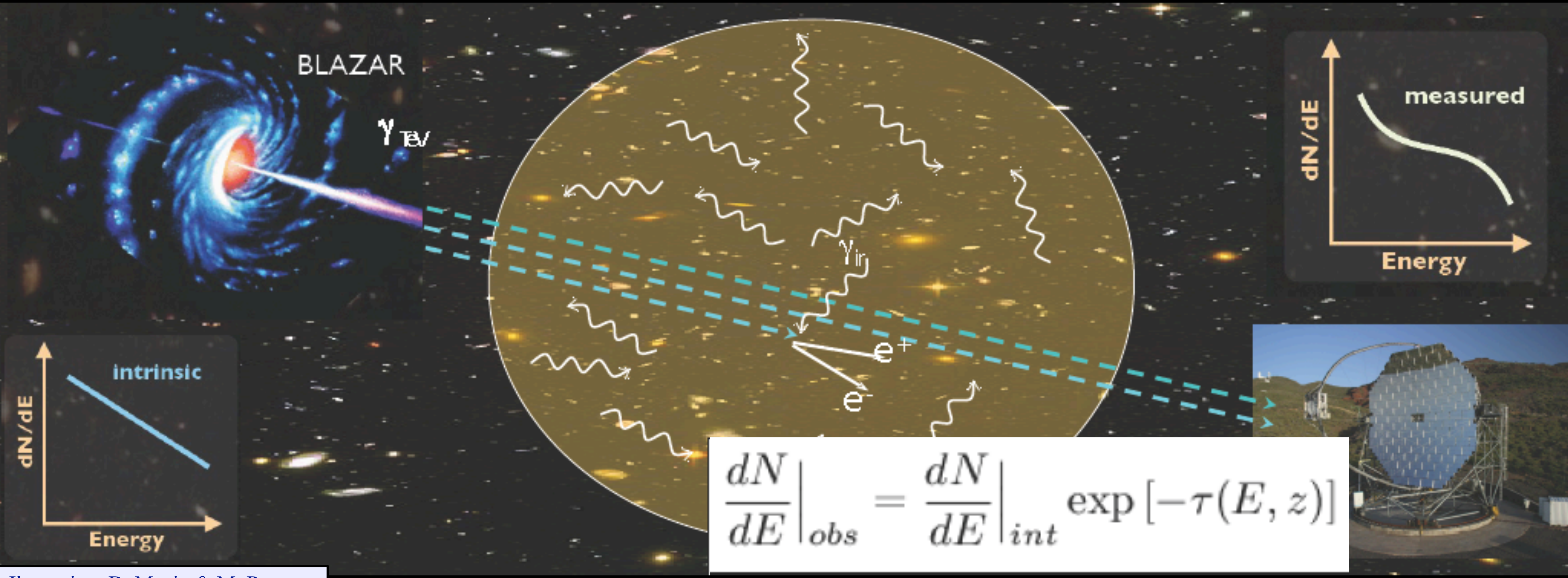
Old Thresholds

New Thresholds

for WMAP5 compared with our old WMAP1 models

Gilmore, Somerville, Primack, & Dominguez (2011)

Gamma Ray Attenuation due to γγ → e+e-

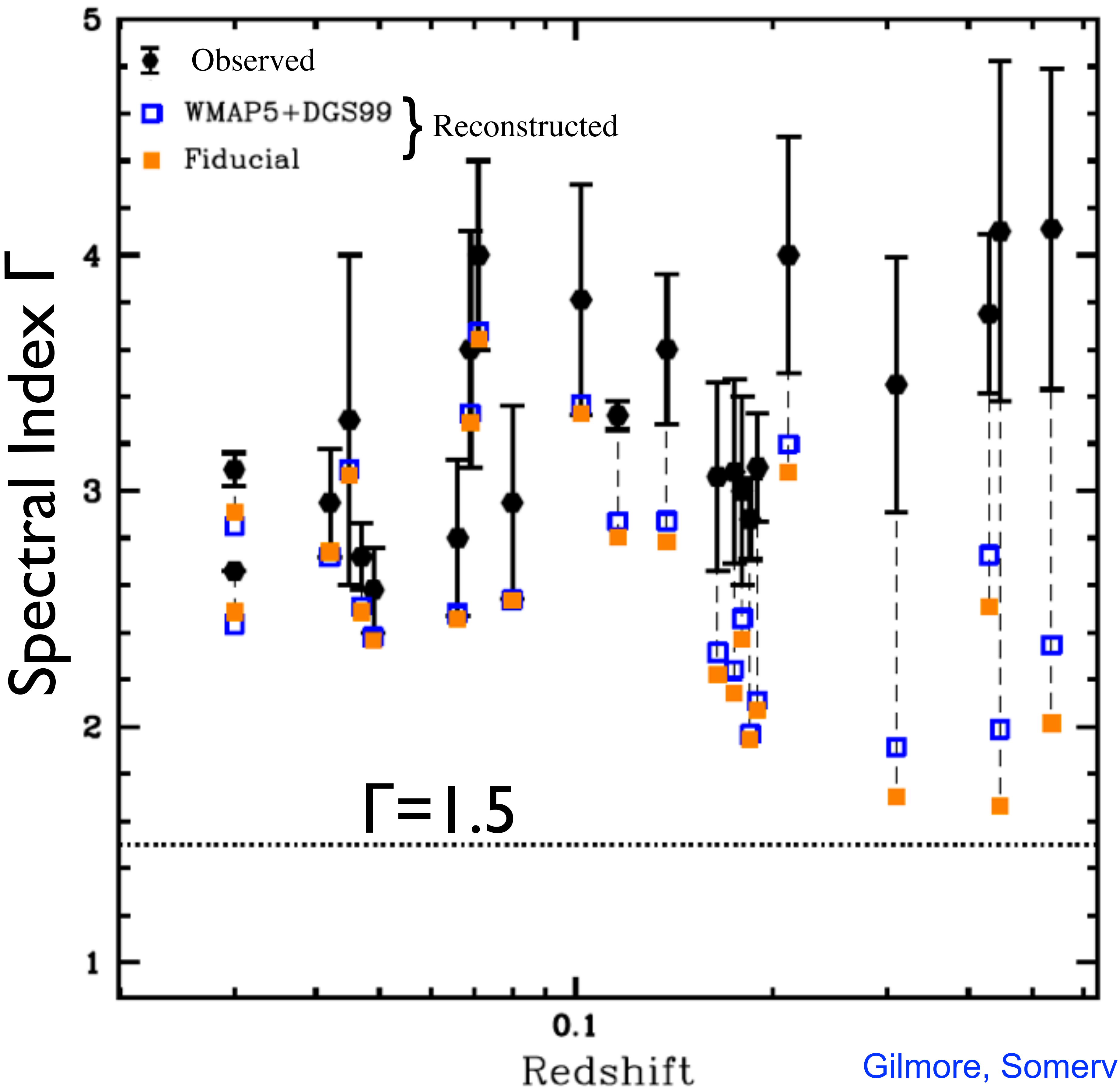


$$\left.\frac{dN}{dE}\right|_{obs} = \left.\frac{dN}{dE}\right|_{int} \exp\left[-\tau(E,z)\right]$$

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: SAM EBL

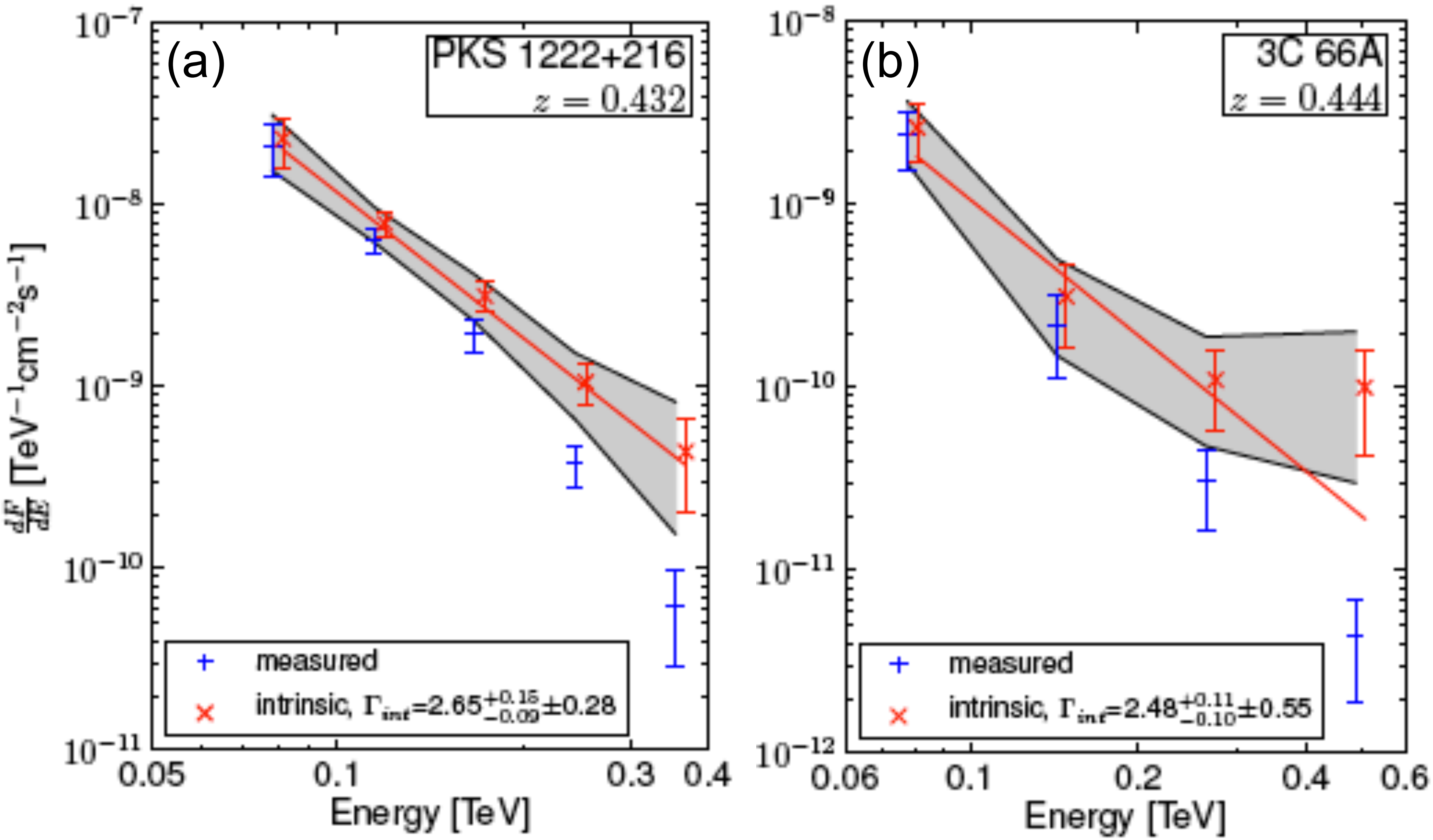


With our SAM based on current WMAP5 cosmological parameters and Rieke+09 dust emission templates, **all high redshift blazars have spectral indexes ≤1.5**, as expected from theory and observations of nearby sources.

Gilmore, Somerville, Primack, & Dominguez (2011)

Friday, July 15, 2011

Reconstructed Blazar Spectral Indexes:
Observational EBL (Dominguez+2011)



Panels (a) and (b) show that Γint > 1.5, consistent with expectations, for the two highest-redshift MAGIC blazars

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+11 except for the far-IR.

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.

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.

See the written version of my invited talk at the Texas 2010 meeting for a brief summary with refs: http://arxiv.org/abs/1107.2566

Catching GRBs with Fermi & 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
- Abdo et al. 2010 ApJ, Fermi LAT Constraints on the Gamma-Ray Opacity of the Universe

  Somerville, Gilmore, Primack, Dominguez 2011, Galaxy Properties from the UV to the Far-IR: ΛCDM Models Confront Observations

  Gilmore, Somerville, Primack, Dominguez 2011, Extragalactic Background Light and Gamma Ray Attenuation
- Gilmore, Bouvier, Otte, Primack 2011, Modeling GeV Observations of GRBs
- Gilmore, Bouvier, Connaughton, Otte, Primack, Williams 2011, Modeling GRB Observations by *Fermi* and Atmospheric Cherenkov Telescope Arrays, in prep.

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 array CTA

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:

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

- ➢ Quasar contribution based on observational estimates (Hopkins et al. 2007)

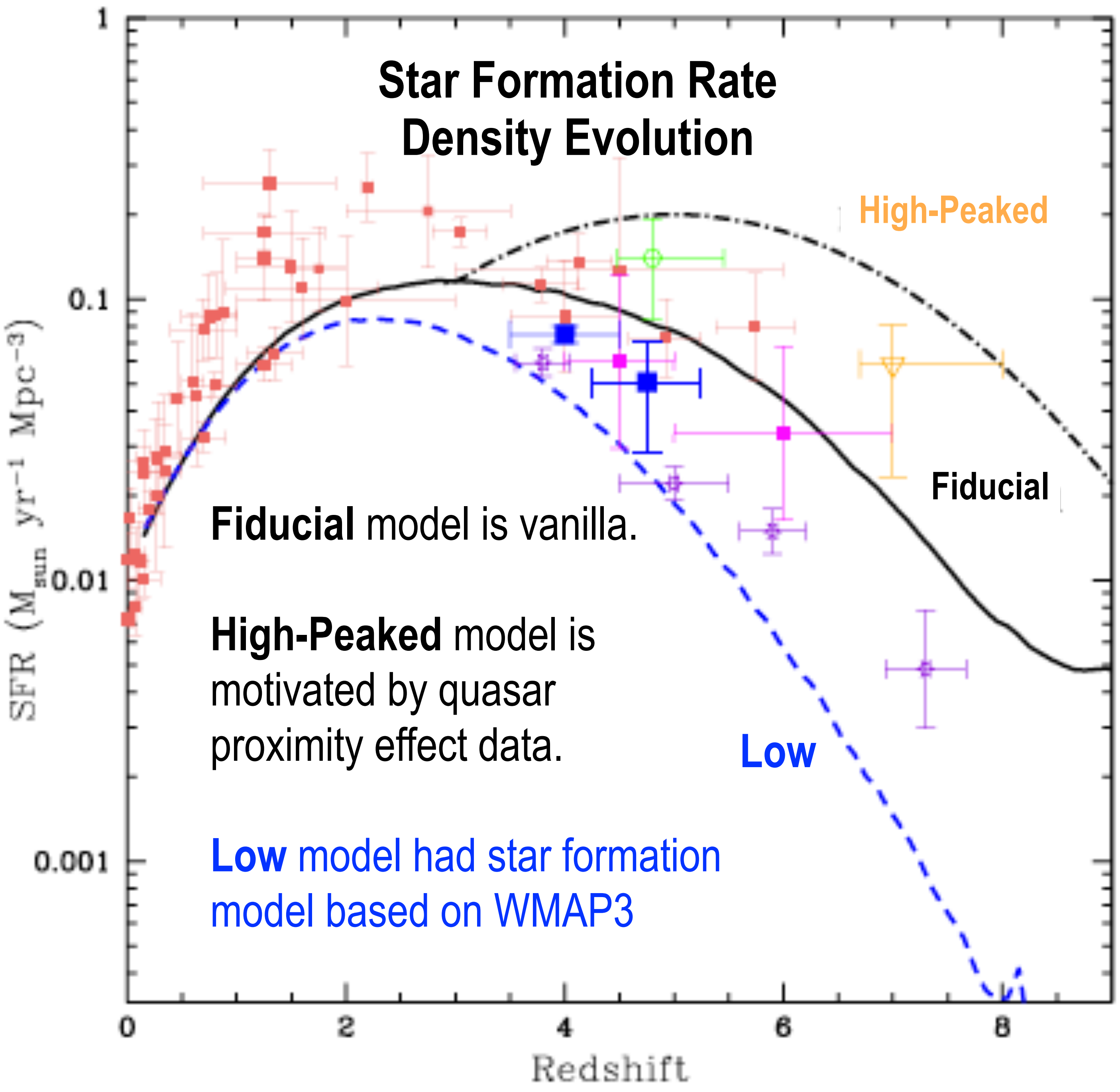
- ➢ Transfer of ionizing radiation through IGM calculated with CUBA code (Haardt & Madau 2001, now being updated)

- ➢ Reasonable estimates of ionizing escape fraction from star-forming galaxies

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



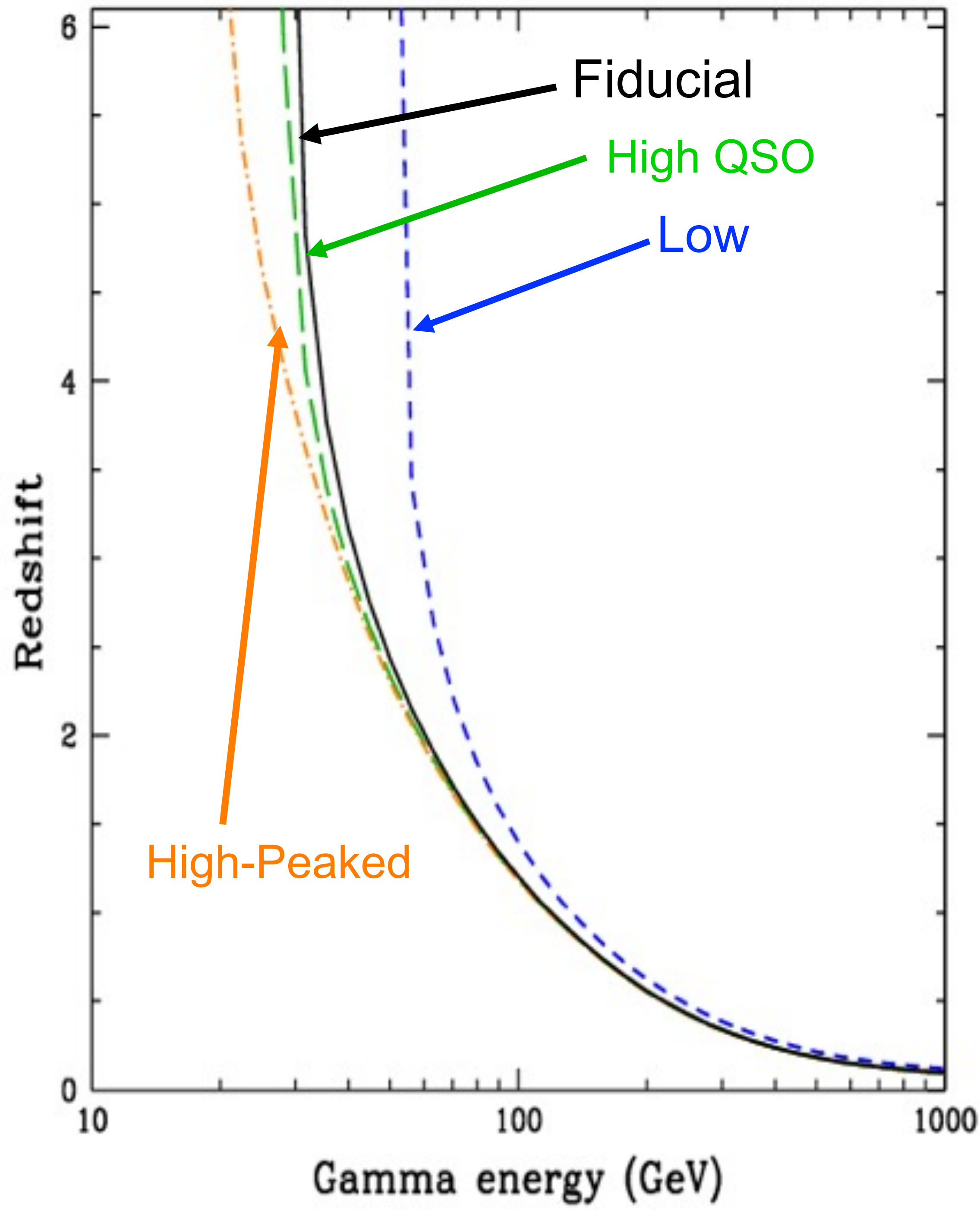
Star Formation Rate Density Evolution

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 (τ = 1)



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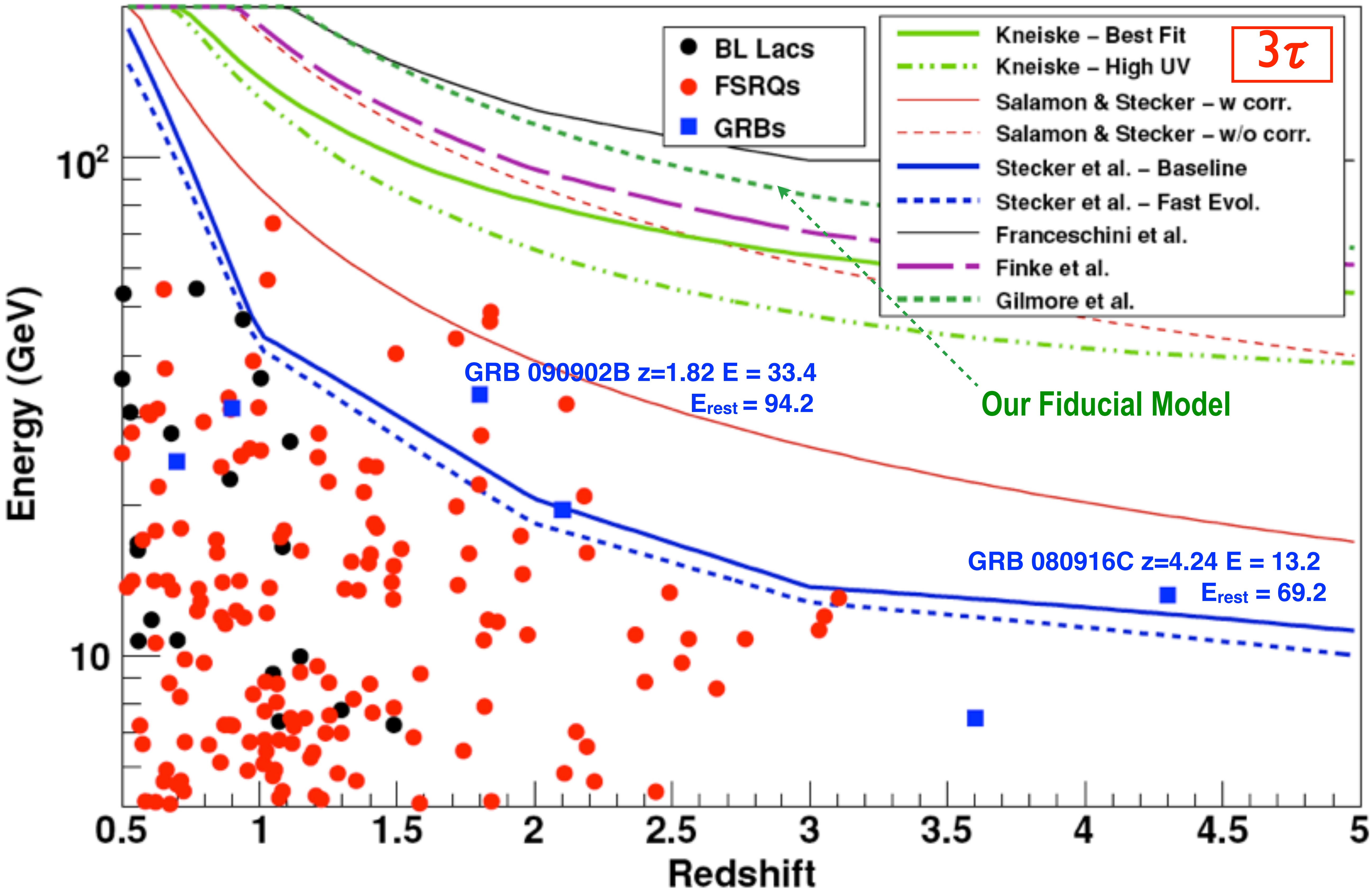


GRB 090902B z=1.82 E = 33.4
E_{rest} = 94.2

Our Fiducial Model

GRB 080916C z=4.24 E = 13.2
E_{rest} = 69.2

Modeling Instrument Properties

Fermi

- 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

MAGIC

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

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

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

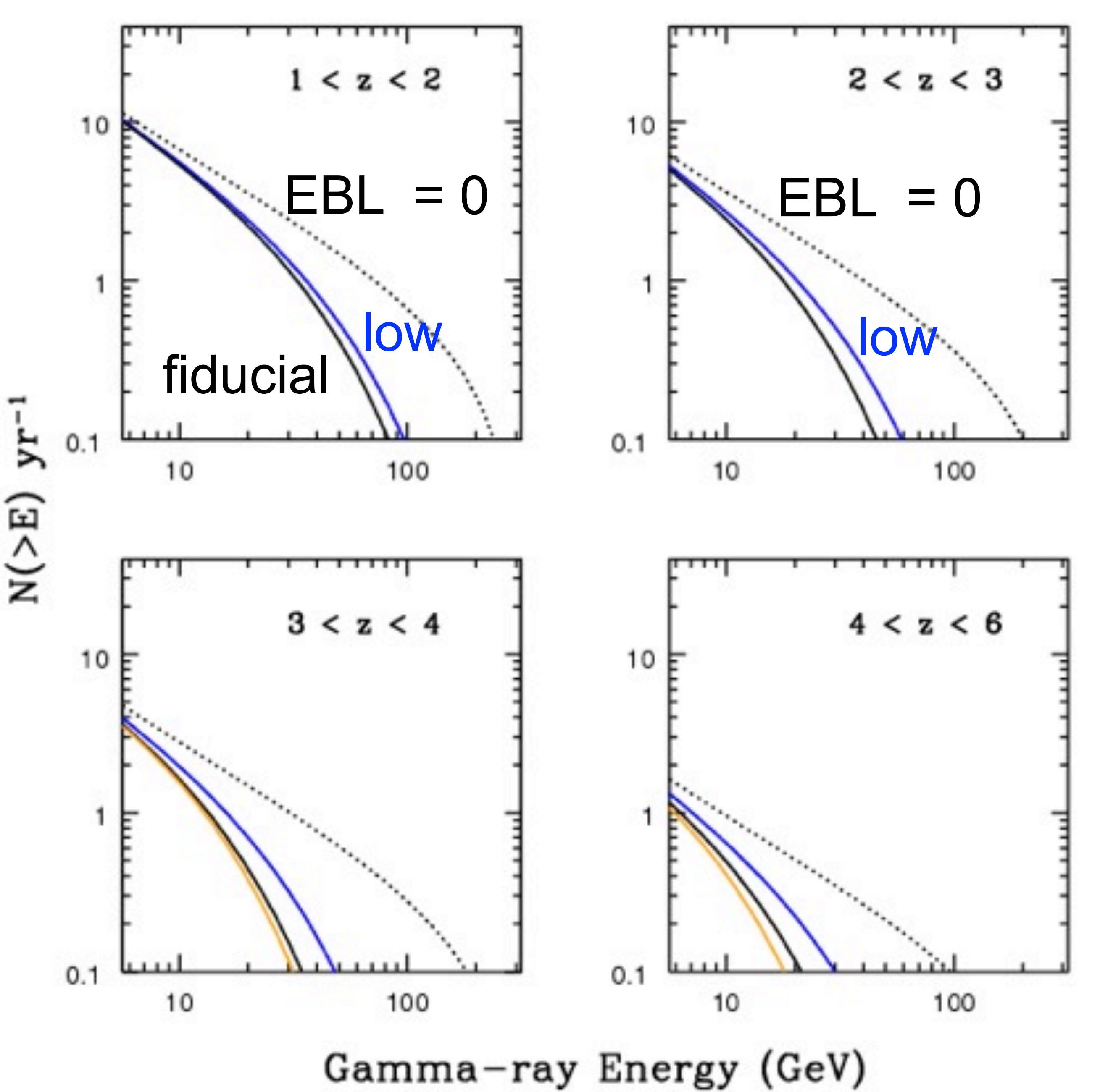
with $E_{th}(0) = 50$ and 100 GeV

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

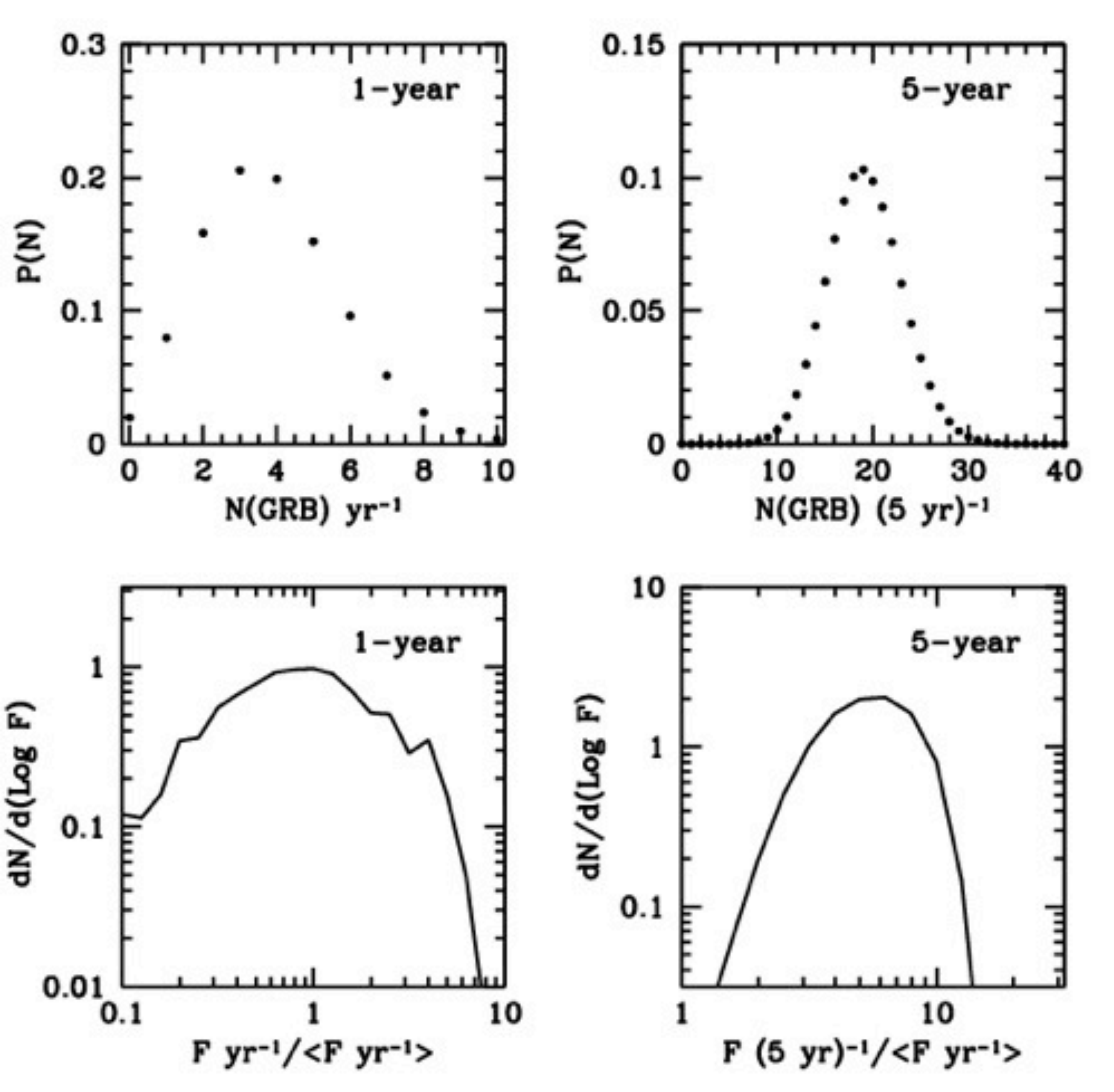
Results for Fermi

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

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

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

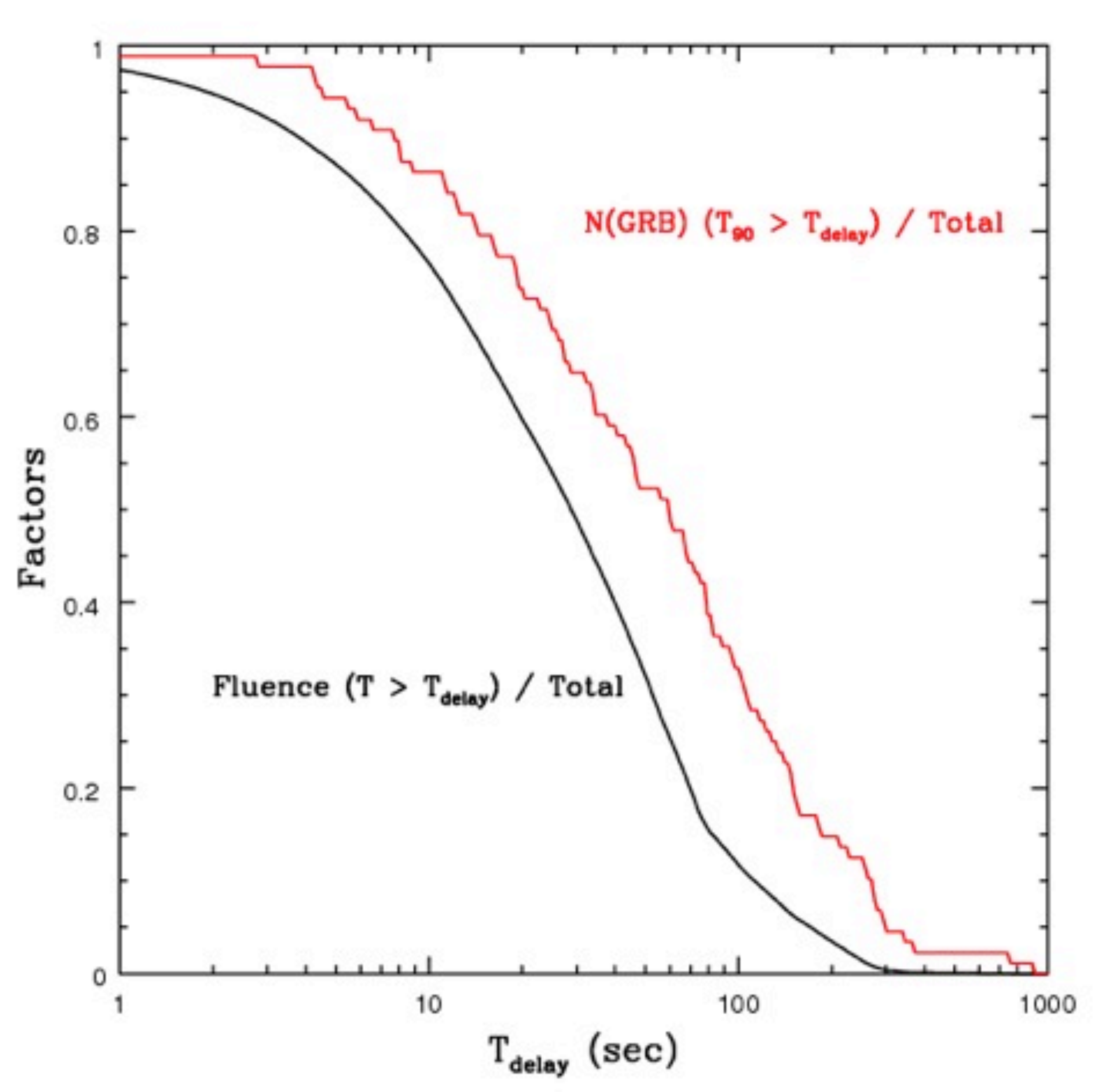
- IACT response time to GCN alert is same order as typical T_{90}
  - Fastest response to date: 43 sec; ≥100 sec more typical
  - We will be optimistic, and assume 45 sec

- assume approximately flat prompt phase: $(T_{90} - T_{slew})/T_{90}$ (flat emission)

- afterglows not affected by delay time

- For IACT like MAGIC:
  - duty cycle ~ 10%
  - sky coverage (θ<40) ≈ 11%
  - ∴ (duty cycle)·(sky coverage) ≈ 1%

FLUENCE AND N(GRB) vs. T_{delay}



Results for MAGIC

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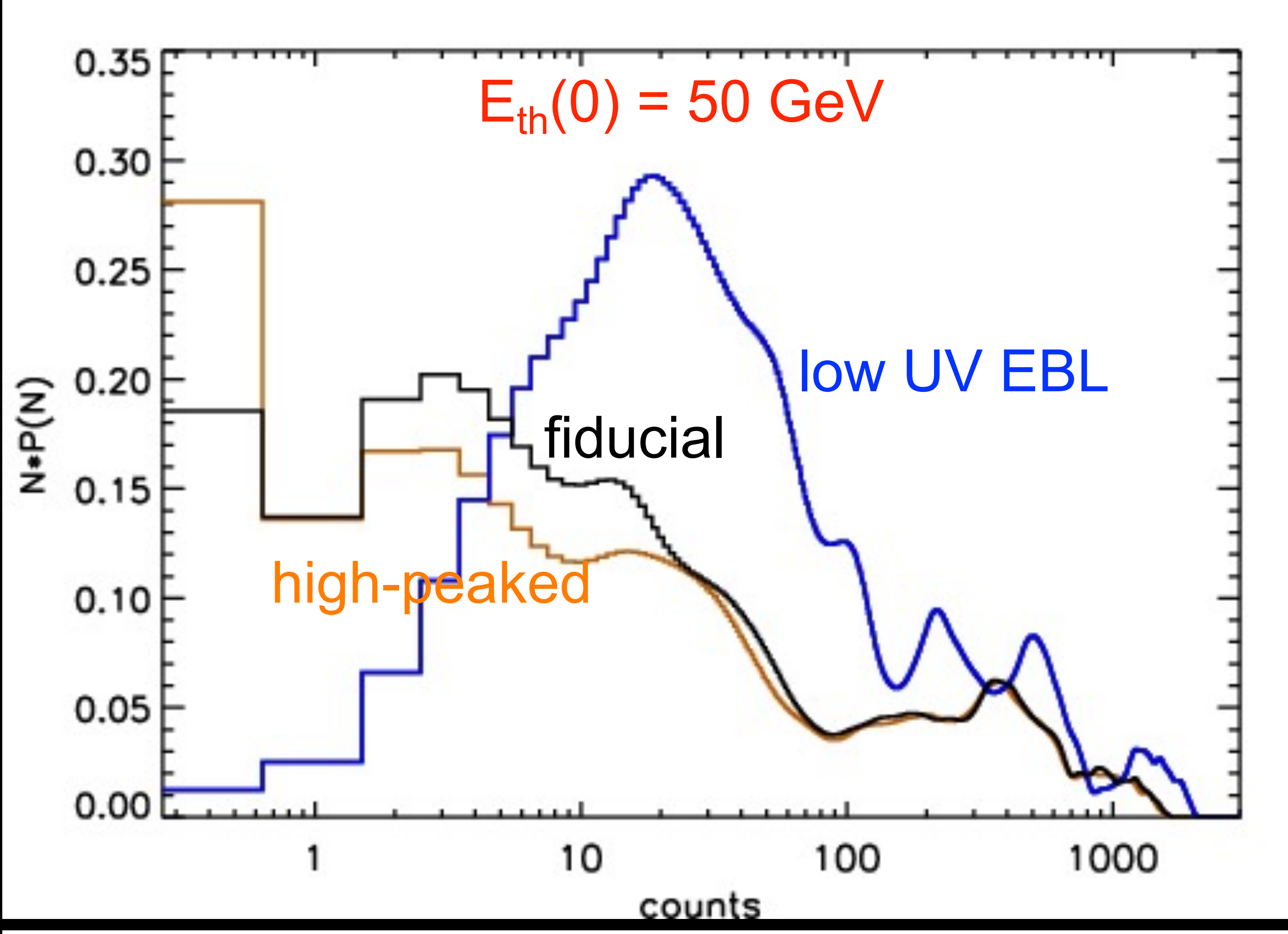
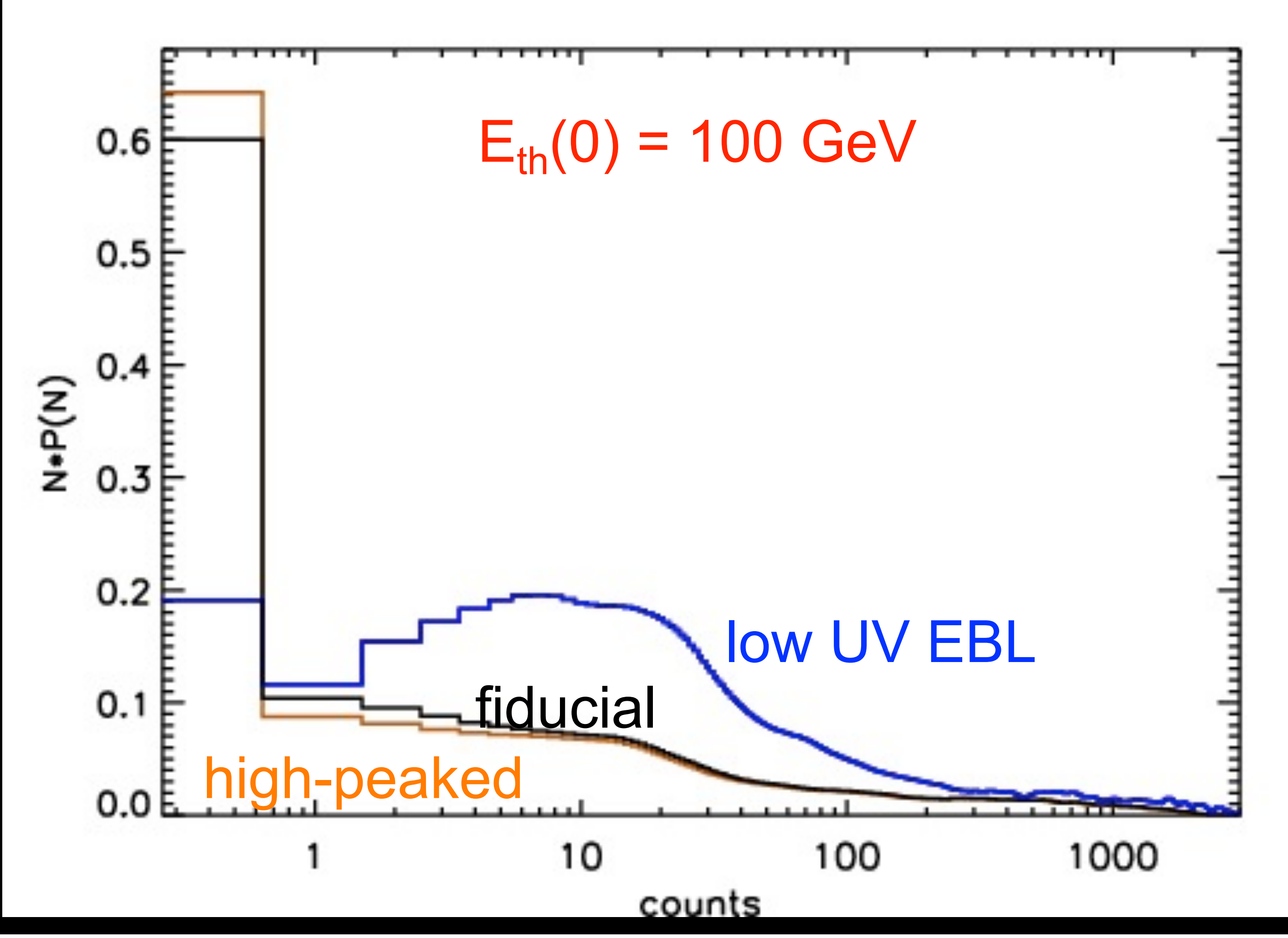


Predicted number of MAGIC gamma-ray counts for a single GRB within sky coverage, with E_{th} = 50 GeV at θ=0°.



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

Gilmore, Prada, Primack 2010 MNRAS

Simulated Results for GRB 080916C

Gilmore, Prada, Primack 2010 MNRAS

- Seen Sep. 16, 2008 by Fermi LAT and GBM

- 145 gammas above 100 MeV, 14 above 1 GeV

- highest energy gamma ray 13.2 GeV

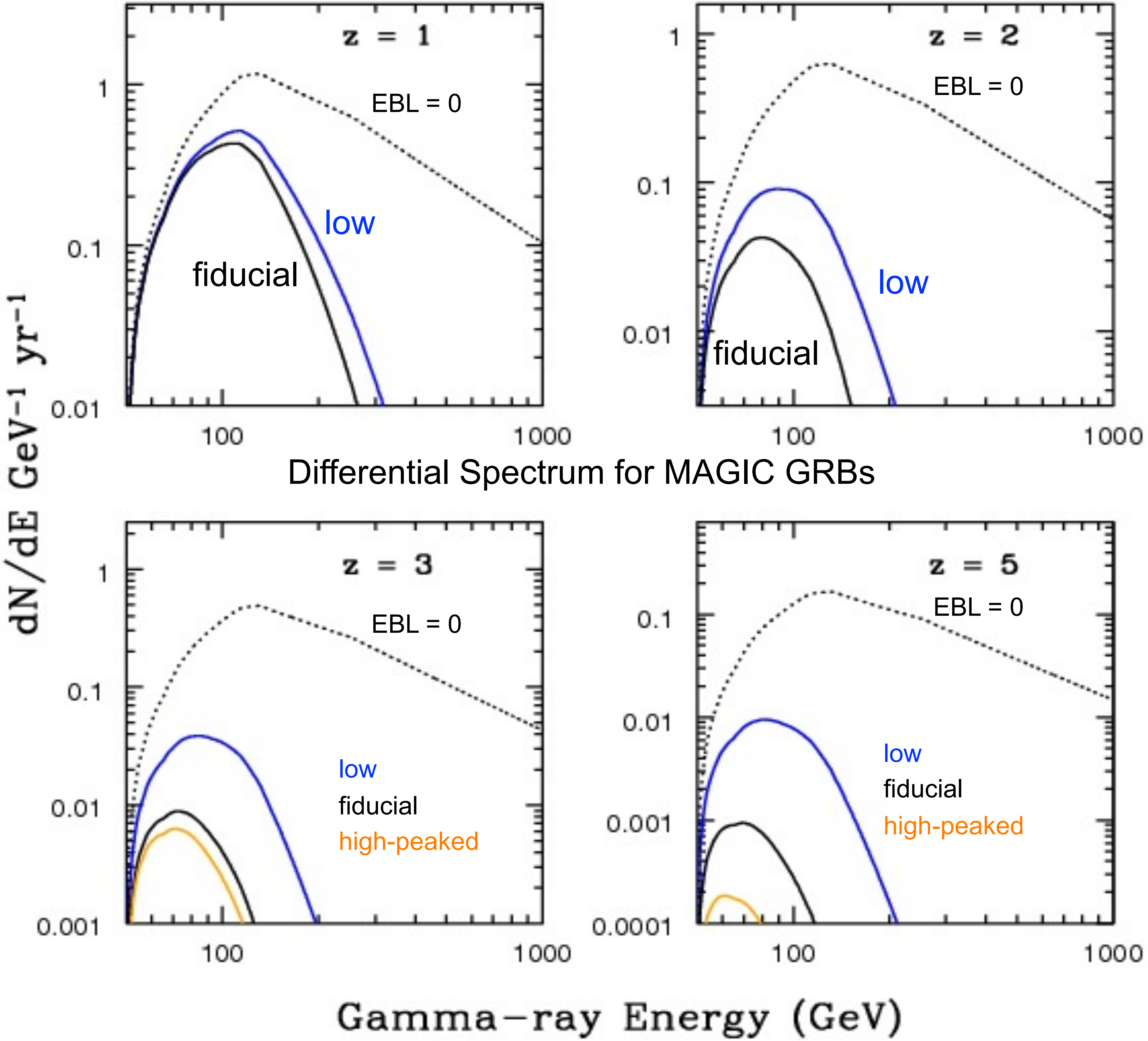
- redshift z = 4.35

- our model overpredicts number of gamma rays >1 GeV (~24 vs 14 detected) but does correctly predict the energy of the highest energy gamma ray observed: 11 to 15 GeV, depending on EBL model

- If MAGIC had observed it, the predicted number of gamma rays varies strongly with EBL model and angle from zenith (using $E_{th}(0)$ = 50 GeV):

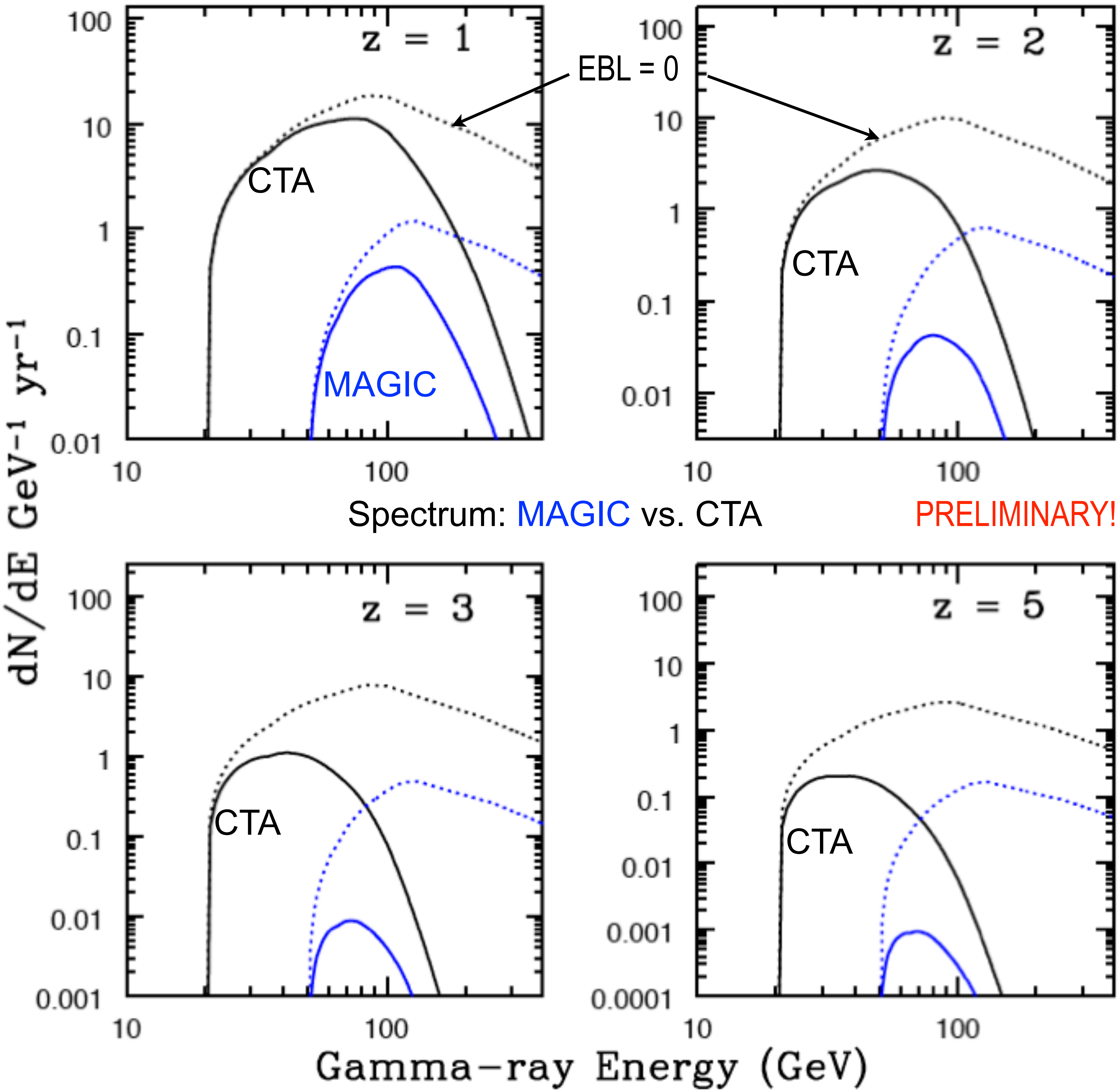
EBL model	θ_{zenith} = 0 deg	θ = 45 deg
High-Peaked	20	<1
Fiducial	60	2
Low	350	60

Differential Spectrum for MAGIC GRBs

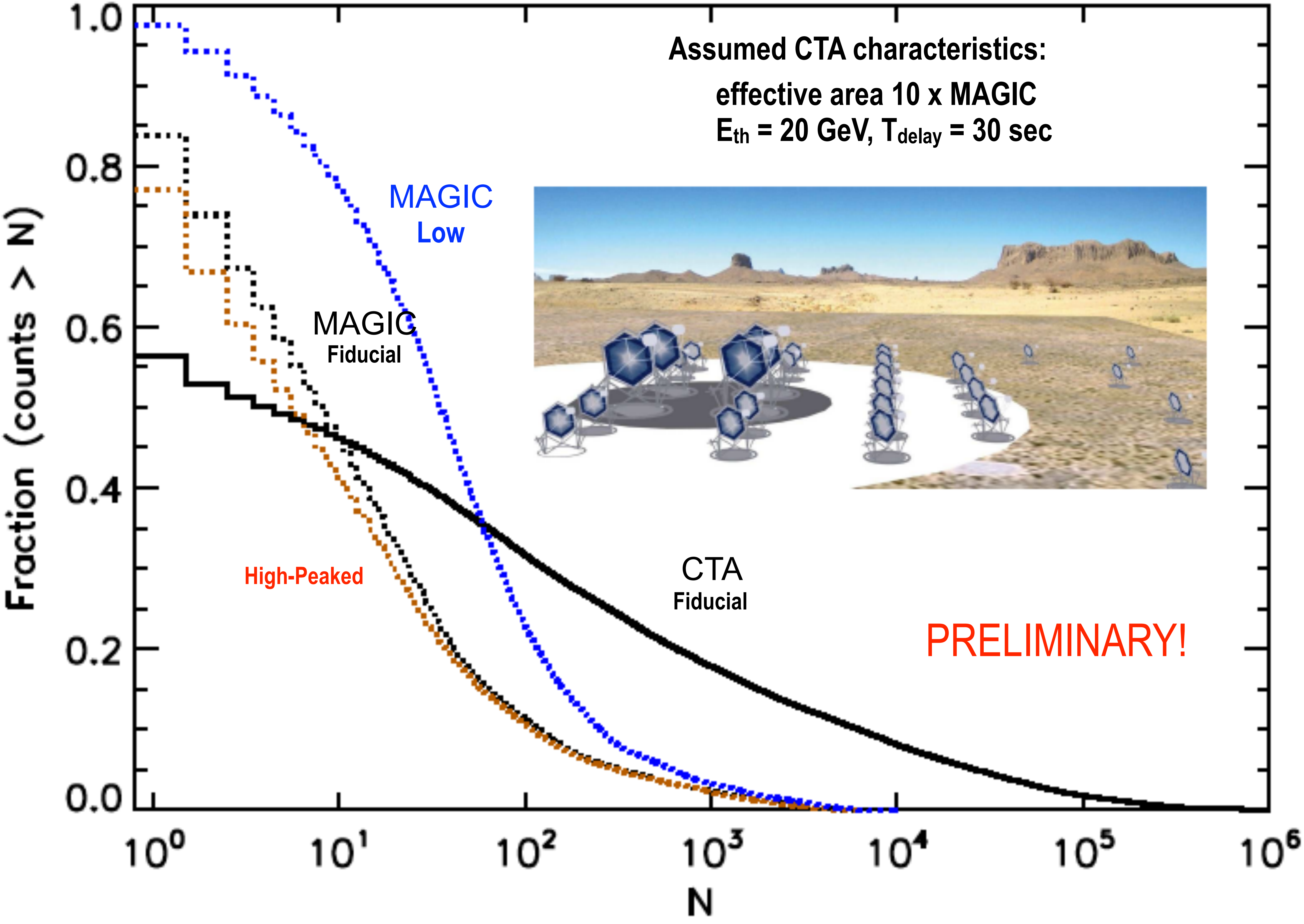


Spectrum: MAGIC vs. CTA

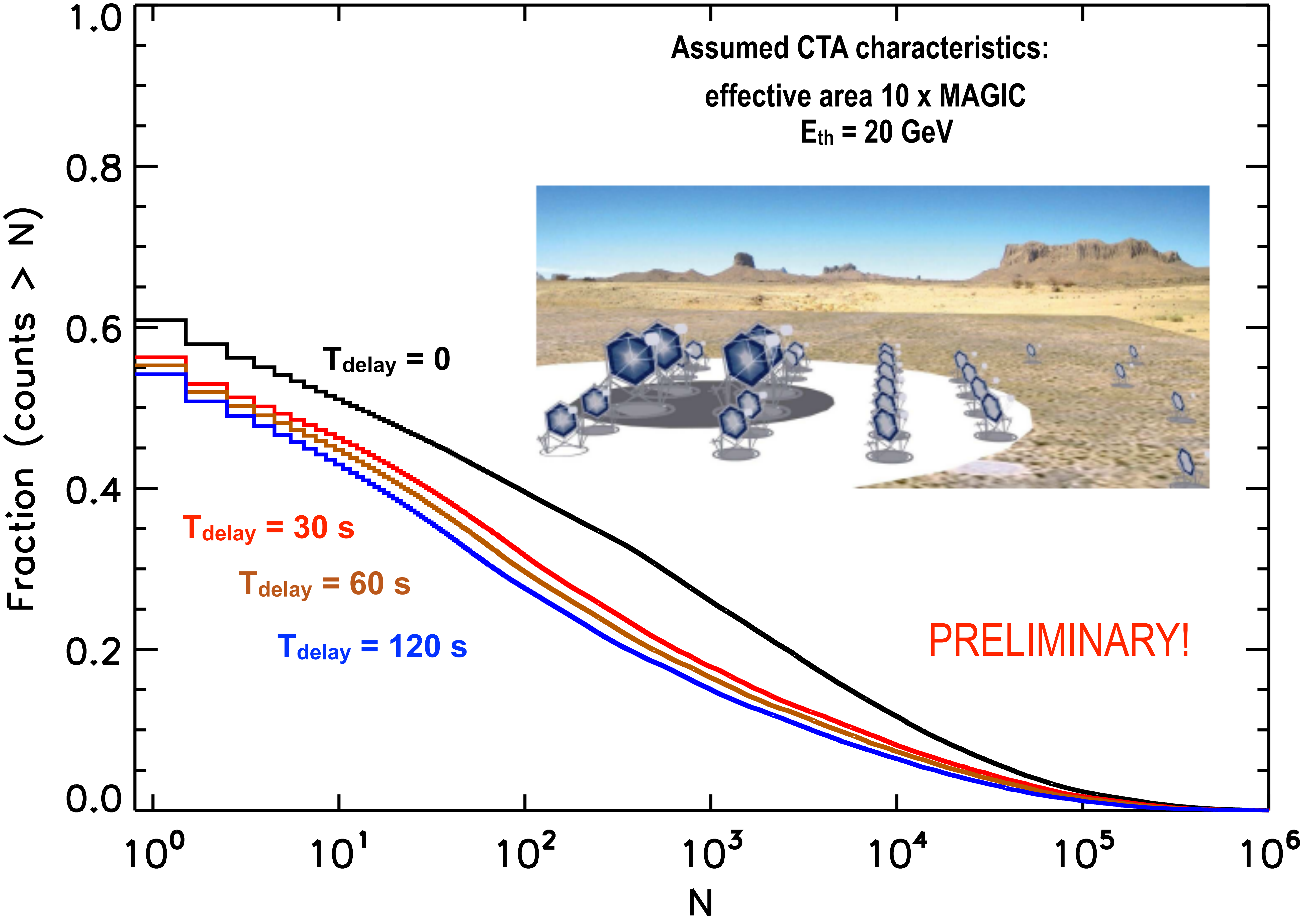
PRELIMINARY!



GRB PHOTON NUMBER DISTRIBUTION: MAGIC vs. CTA



CTA GRB PHOTON COUNT DISTRIBUTION



Assumed CTA characteristics:

effective area 10 x MAGIC
E_{th} = 20 GeV

PRELIMINARY!

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 results favor low threshold (~20 GeV)

Review

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