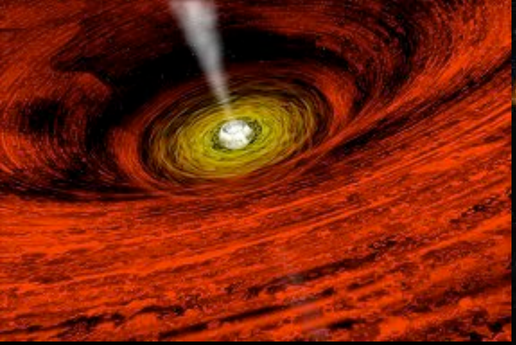
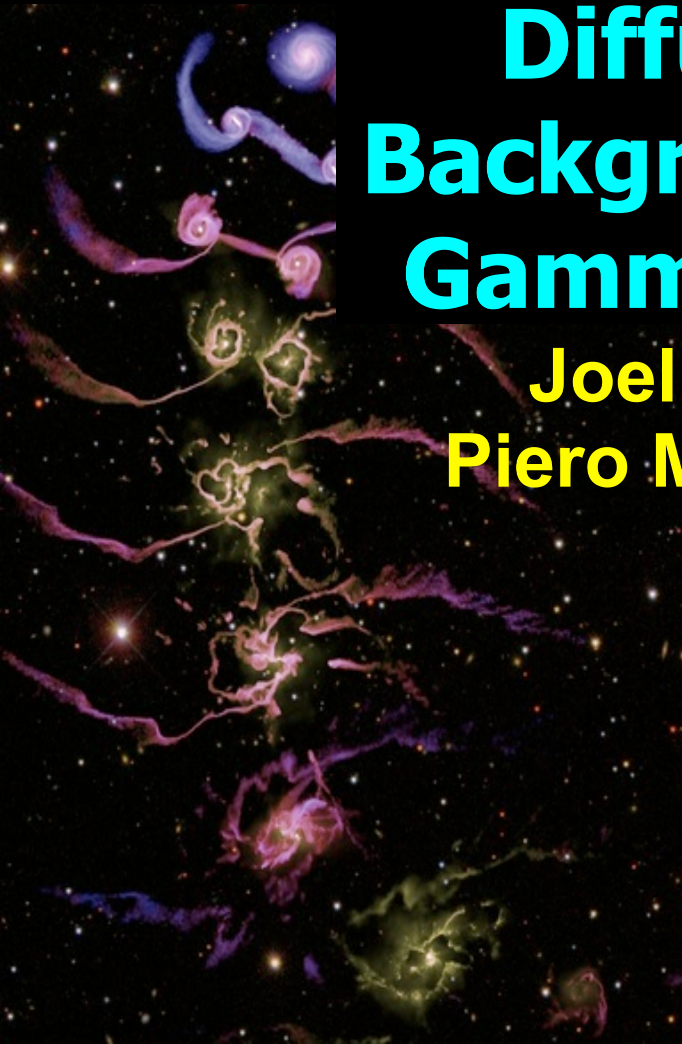
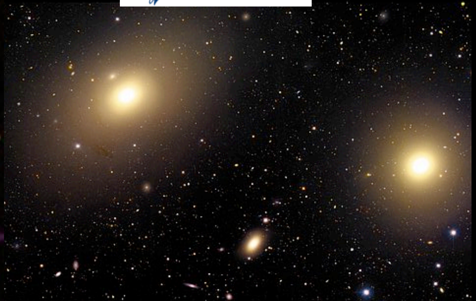


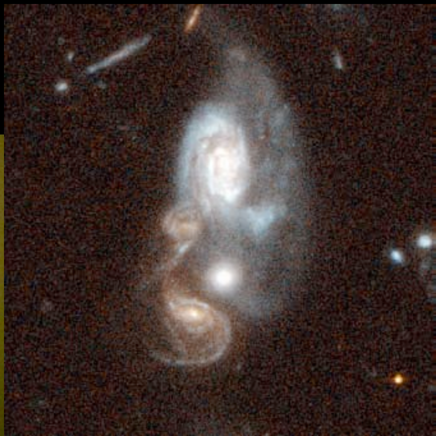
Diffuse Extragalactic Background Radiation and Gamma-Ray Attenuation

Joel Primack, Rudy Gilmore, Piero Madau & Rachel Somerville

UCSC & STScI







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 the optical-IR EBL and also the UV EBL relevant to absorption of gamma-rays from very distant sources observed by GLAST and low-threshold ground-based ACTs.

This talk will describe three approaches to calculate the EBL, and compare the results with each other and with observational constraints.

Three approaches to calculate the EBL (as described by Kneiske, Mannheim, & Hartmann 2002):

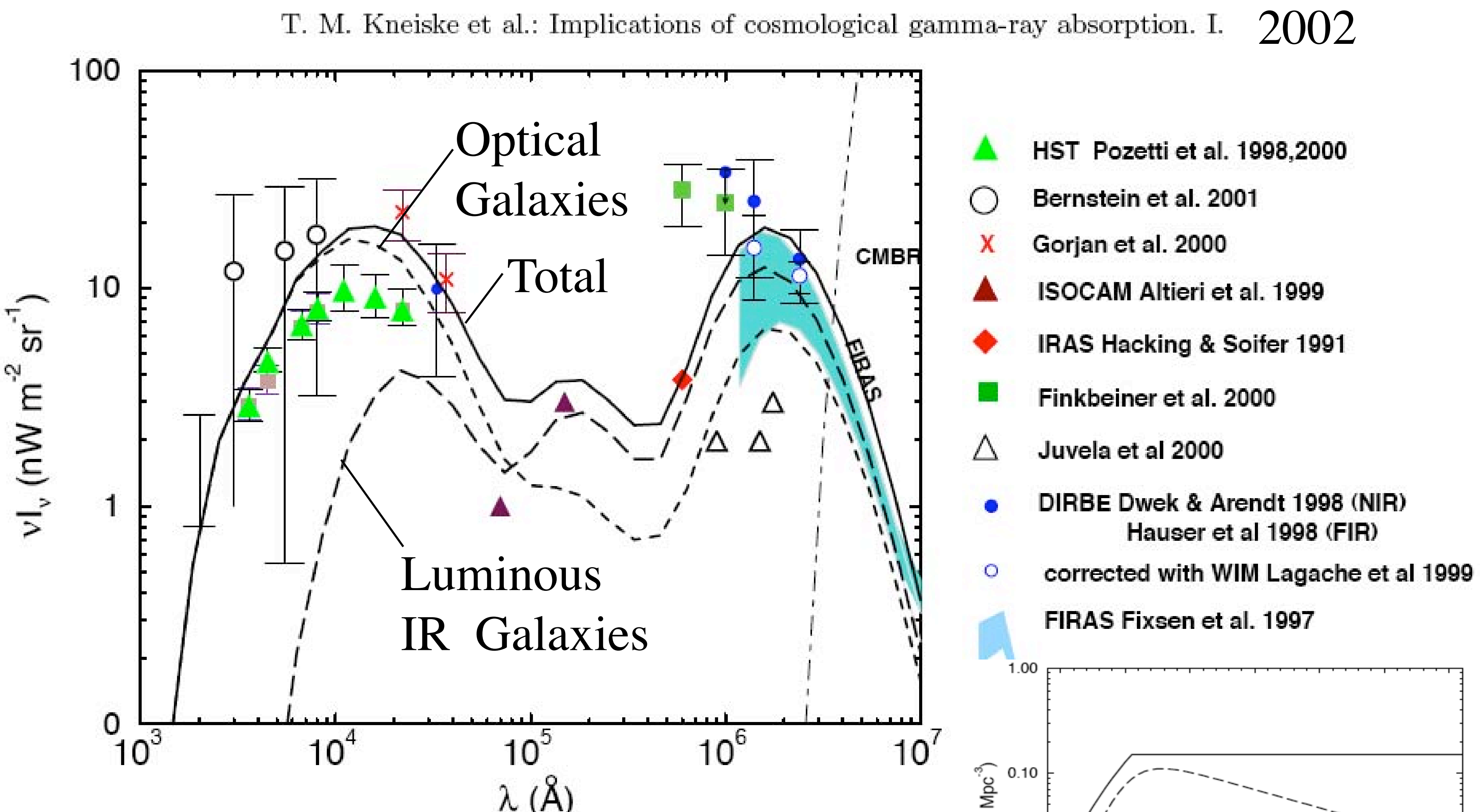
Evolution Inferred from Observations -- e.g., Kneiske et al. 2002, Franceschini et al. 2008.

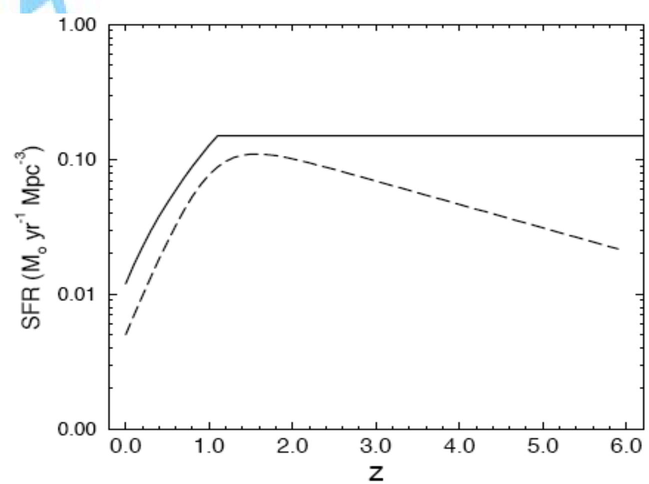
Backward Evolution, which starts with the existing galaxy population and evolves it backward in time -- e.g., Stecker, Malkan, & Scully 2006.

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 -- e.g., Primack et al. 2005, this talk, and Gilmore et al. Poster 18 and in preparation.

All methods currently require modeling galactic SEDs.

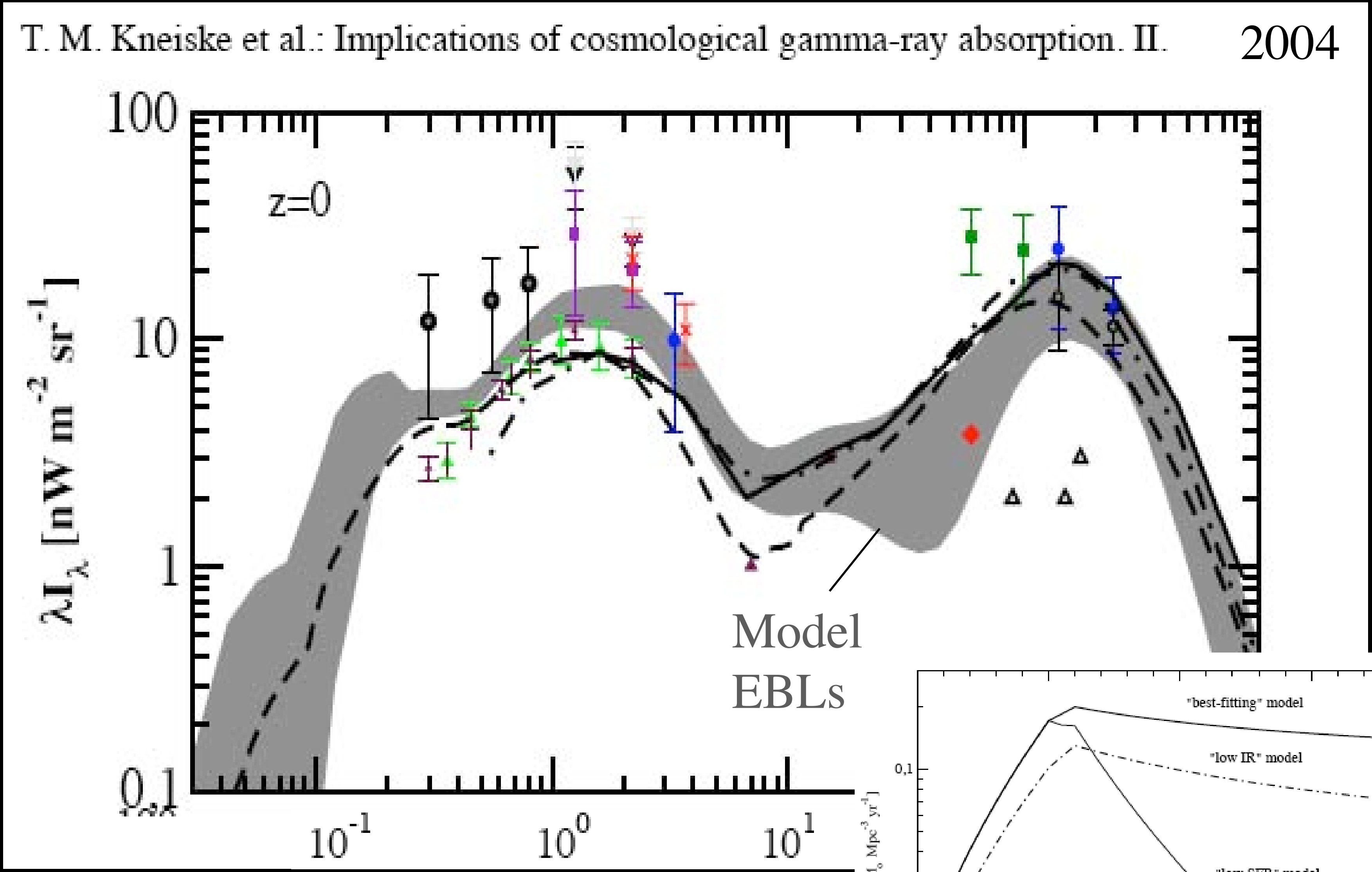
Evolution Inferred from Observations



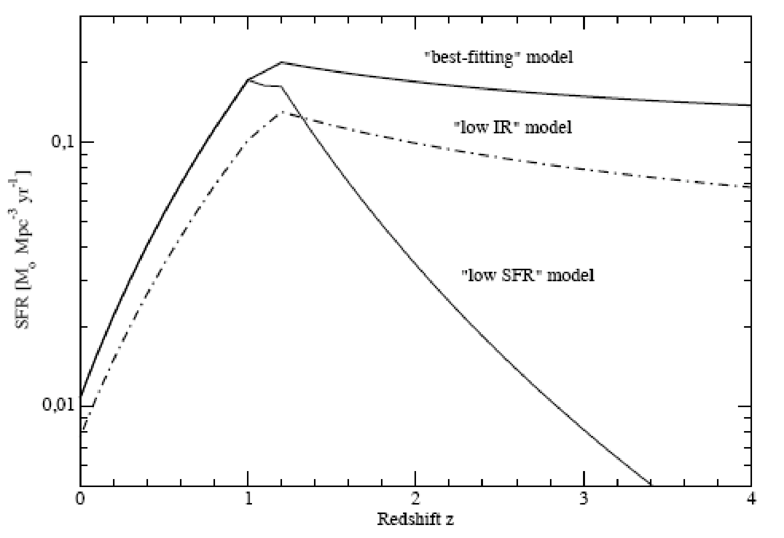


Assumed Star Formation Rate
(solid curve)

Evolution Inferred from Observations



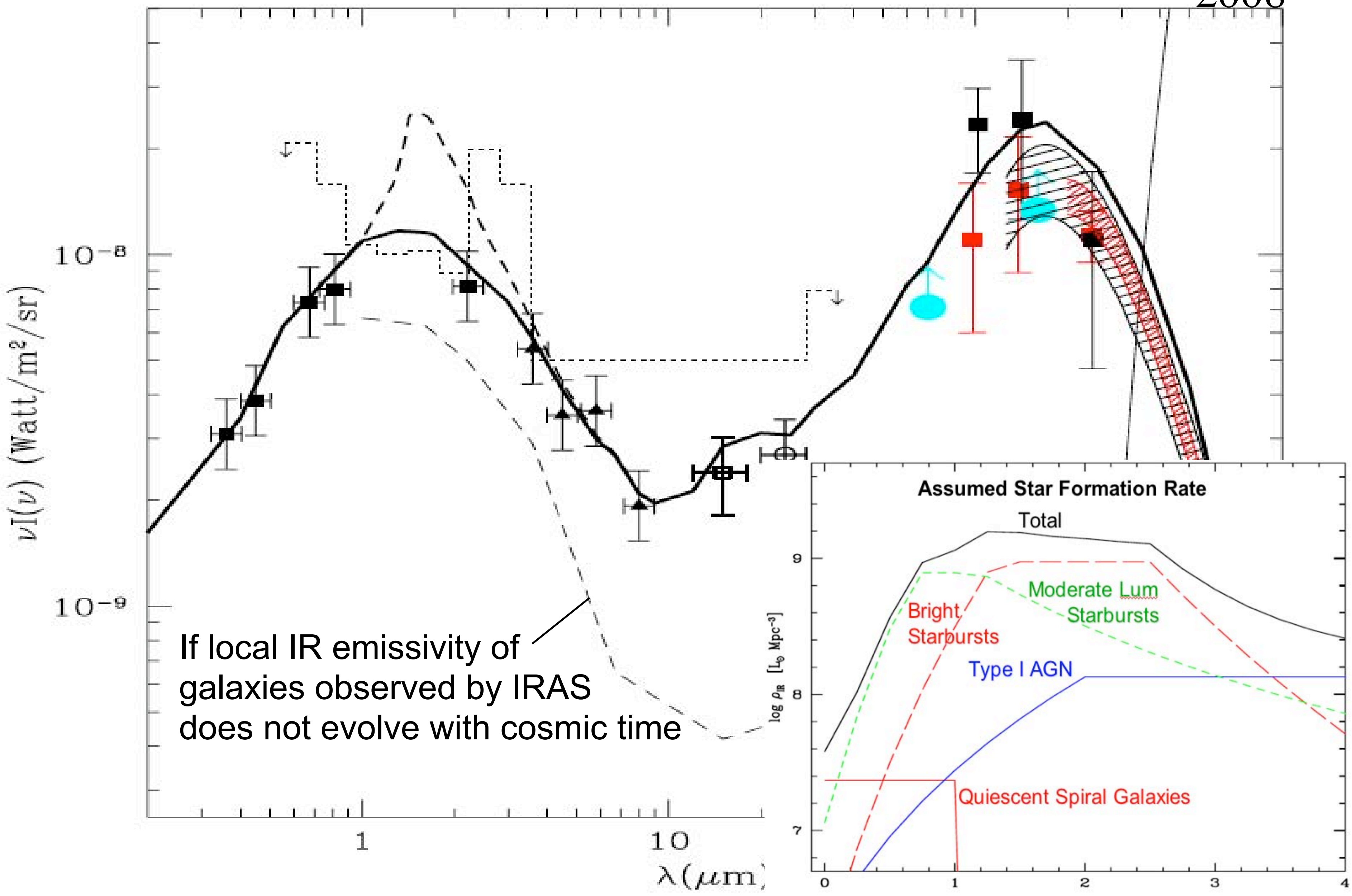
Assumed Star Formation Rate



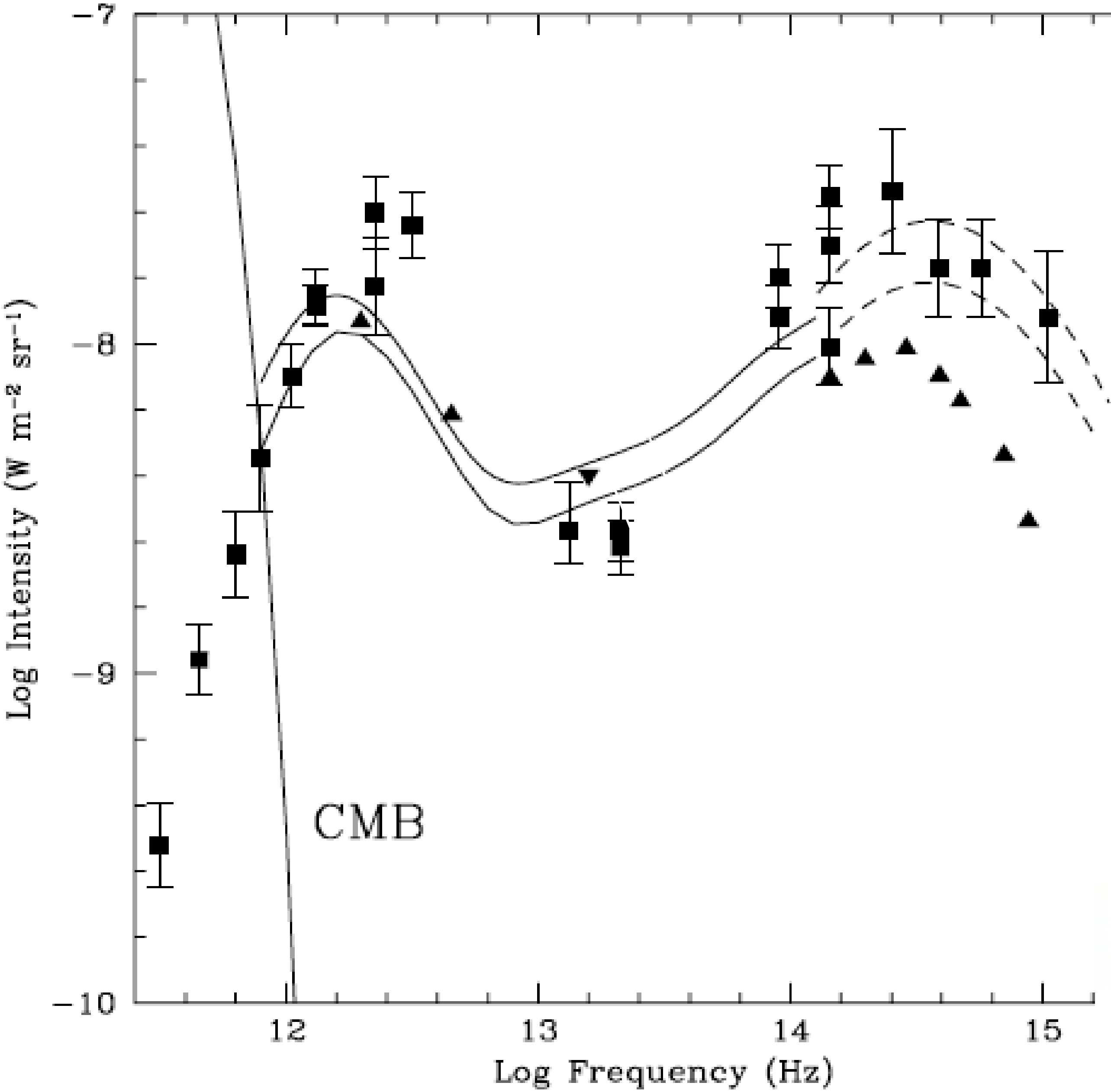
Evolution Inferred from Observations

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

2008



Backward Evolution



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 $z > 6$.

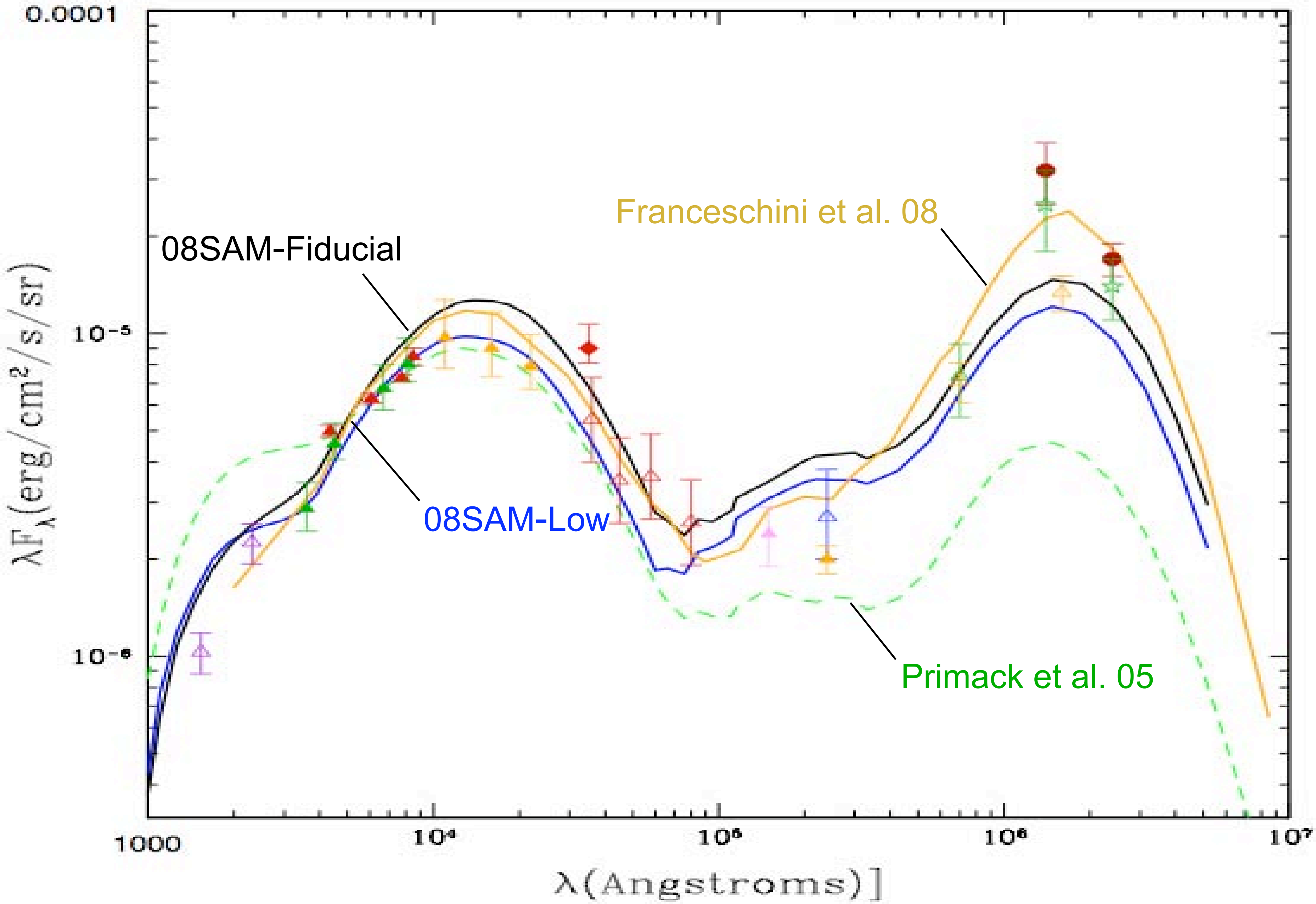
Baseline Model:
galaxy luminosities evolve
as $(1+z)^{3.1}$ for $0 < z < 1.4$,
no evolution $1.4 < z < 6$,
zero luminosityfor $z > 6$.

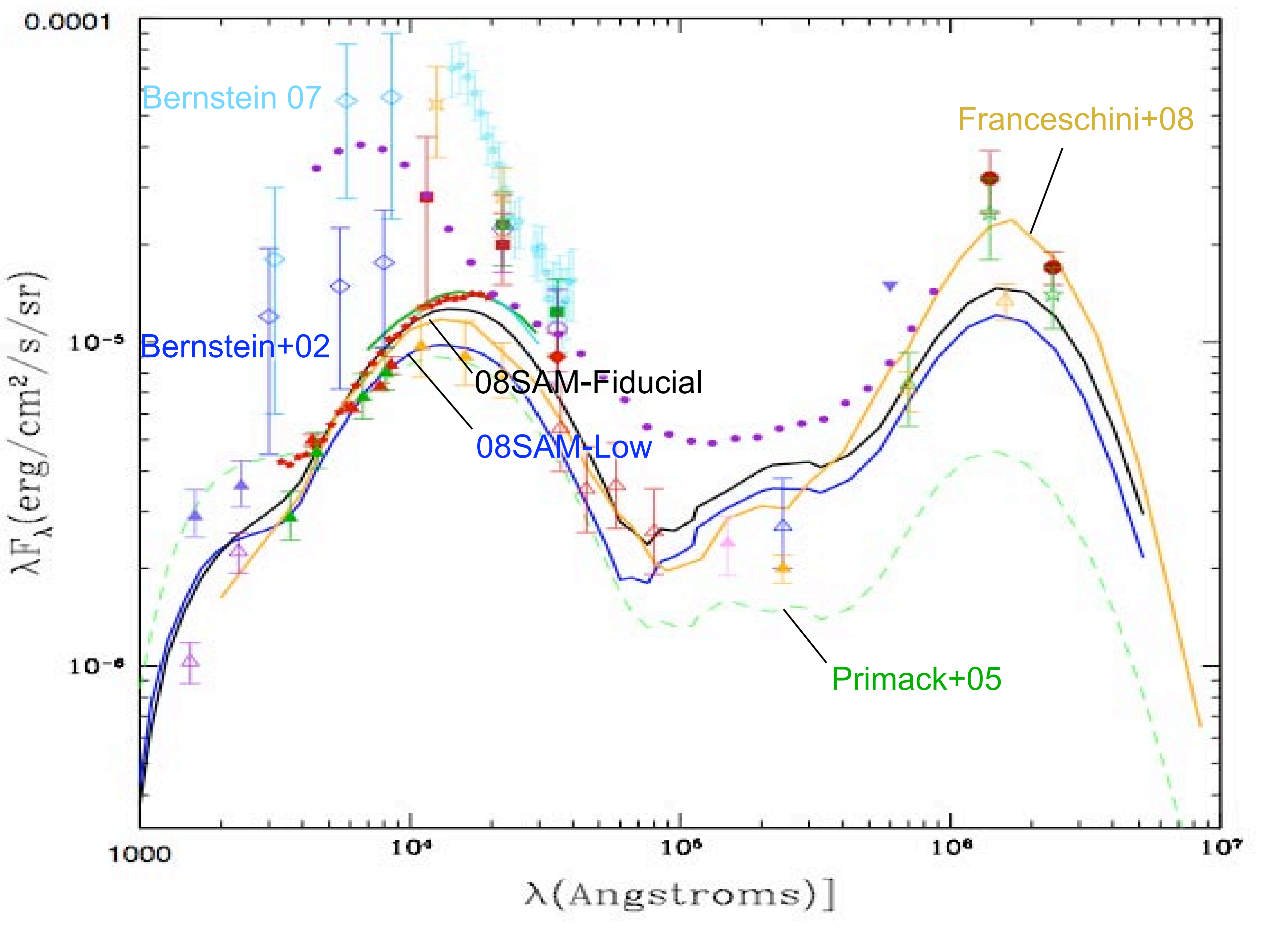
Forward Evolution

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 1997, the cosmological model was known to be **ΛCDM** although it was still necessary to consider various cosmological parameters in models (Primack et al. 1999, 2000). Now all the cosmological parameters are known rather precisely, and my report here will be based on a semi-analytic model (SAM) that is an improved version of the one I described at the 2004 Heidelberg ϒ-Ray meeting. With improved simulations and better galaxy data, we can now normalize SAMs better and determine the key astrophysical processes to include in them.

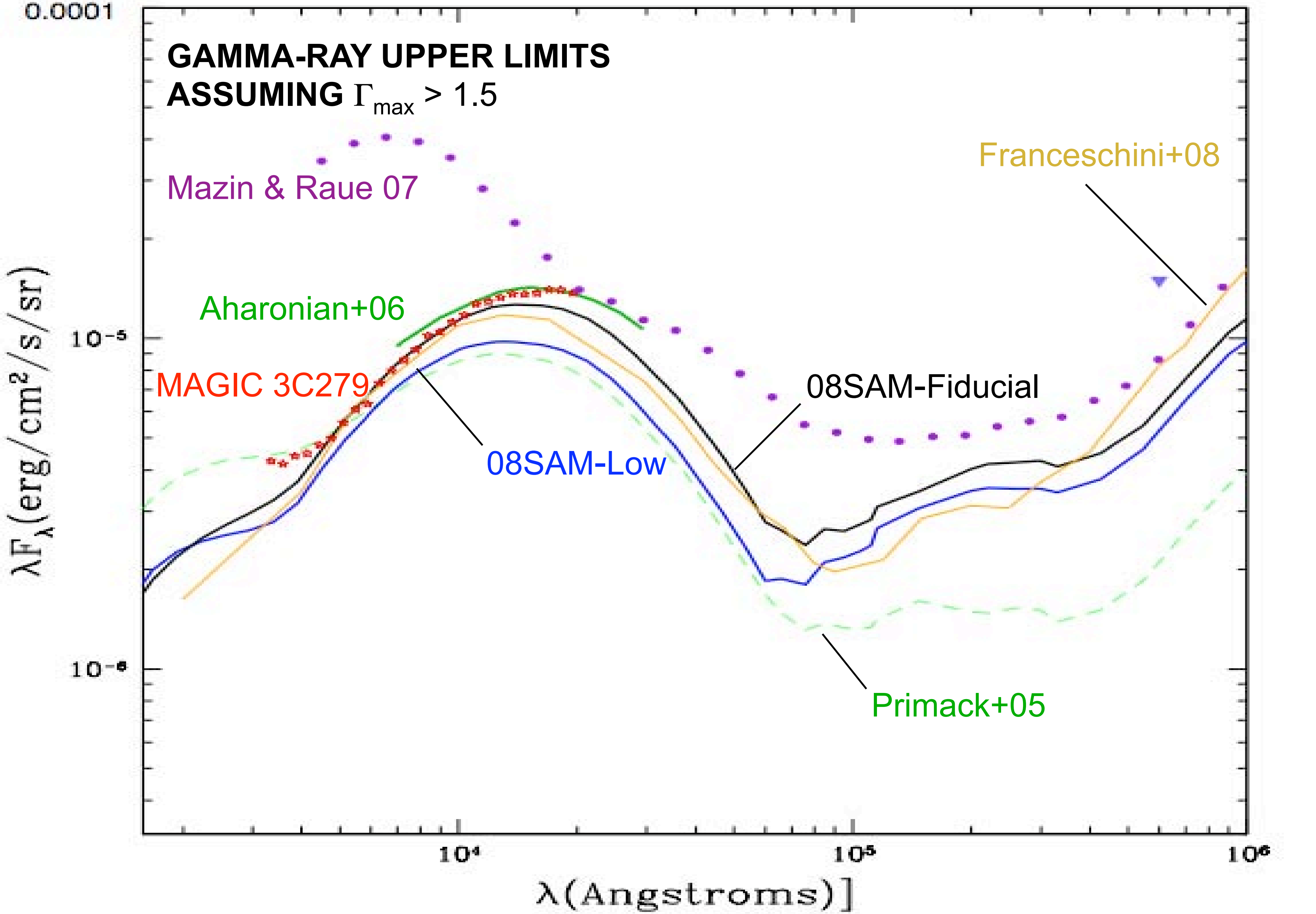
There is still uncertainty whether the IMF evolves, possibly becoming "top-heavy" at higher redshifts (Fardal et al. 2007, Dave 2008), and concerning the nature of sub-mm galaxies.

Forward Evolution





Bernstein 07
Franceschini+08
Bernstein+02
08SAM-Fiducial
08SAM-Low
Primack+05
0.0001
10^{-5}
10^{-6}
1000
10^{4}
10^{5}
10^{6}
10^{7}
$\lambda F_\lambda (erg/cm^2/s/sr)$
λ(Angstroms)]

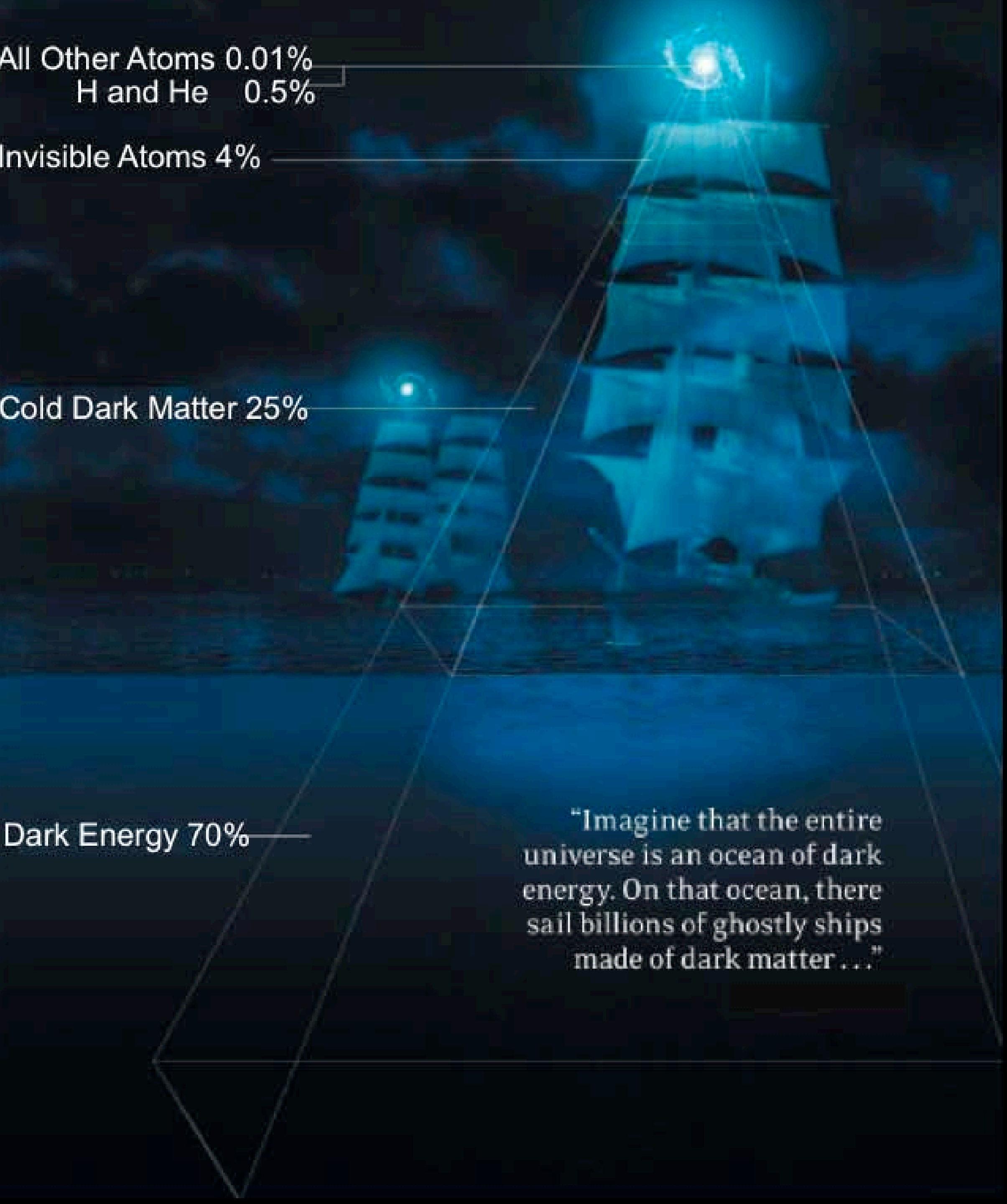


GAMMA-RAY UPPER LIMITS
ASSUMING Γ_{max} > 1.5
Mazin & Raue 07
Franceschini+08
Aharonian+06
MAGIC 3C279
08SAM-Fiducial
08SAM-Low
Primack+05
0.0001
10^{-5}
10^{-6}
10^{4}
10^{5}
10^{6}
λF_λ(erg/cm^2/s/sr)
λ(Angstroms)]

Forward Evolution

Present status of ΛCDM "Double Dark" DE + DM cosmology:

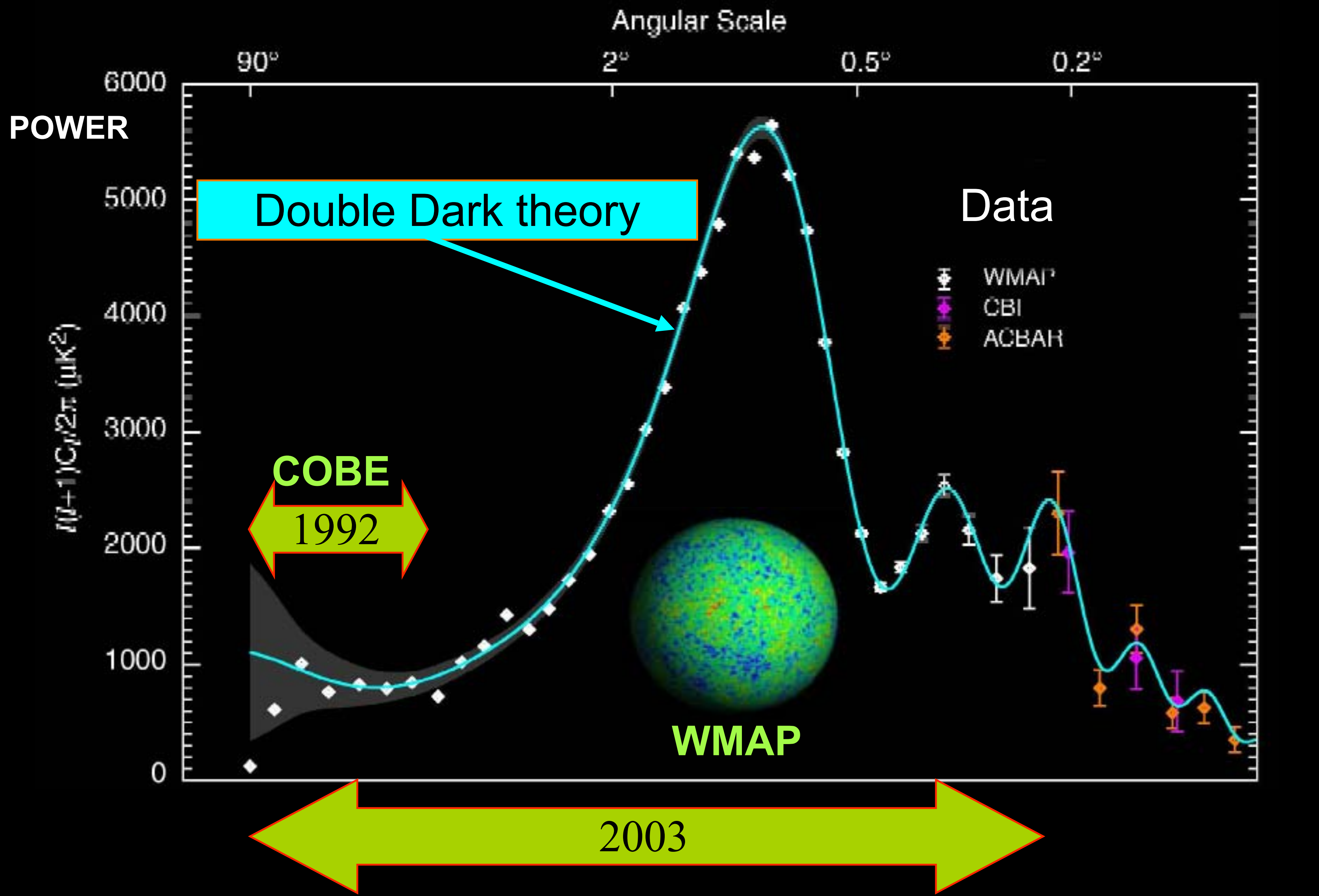
- cosmological parameters are now well constrained by observations, except possibly for σ_8



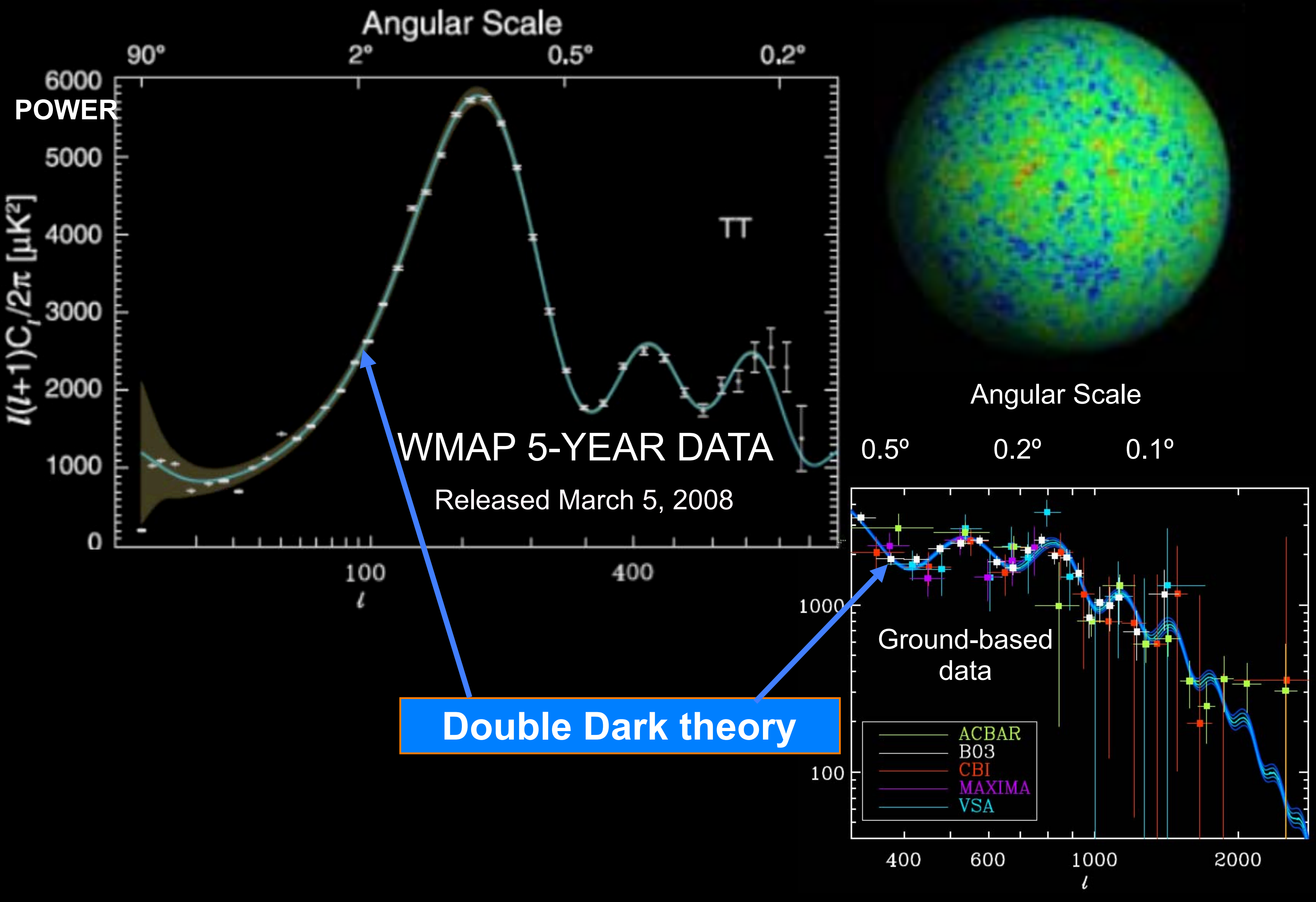
Present status of ΛCDM "Double Dark" DE + DM cosmology:

- cosmological parameters are now well constrained by observations, except possibly for σ_8

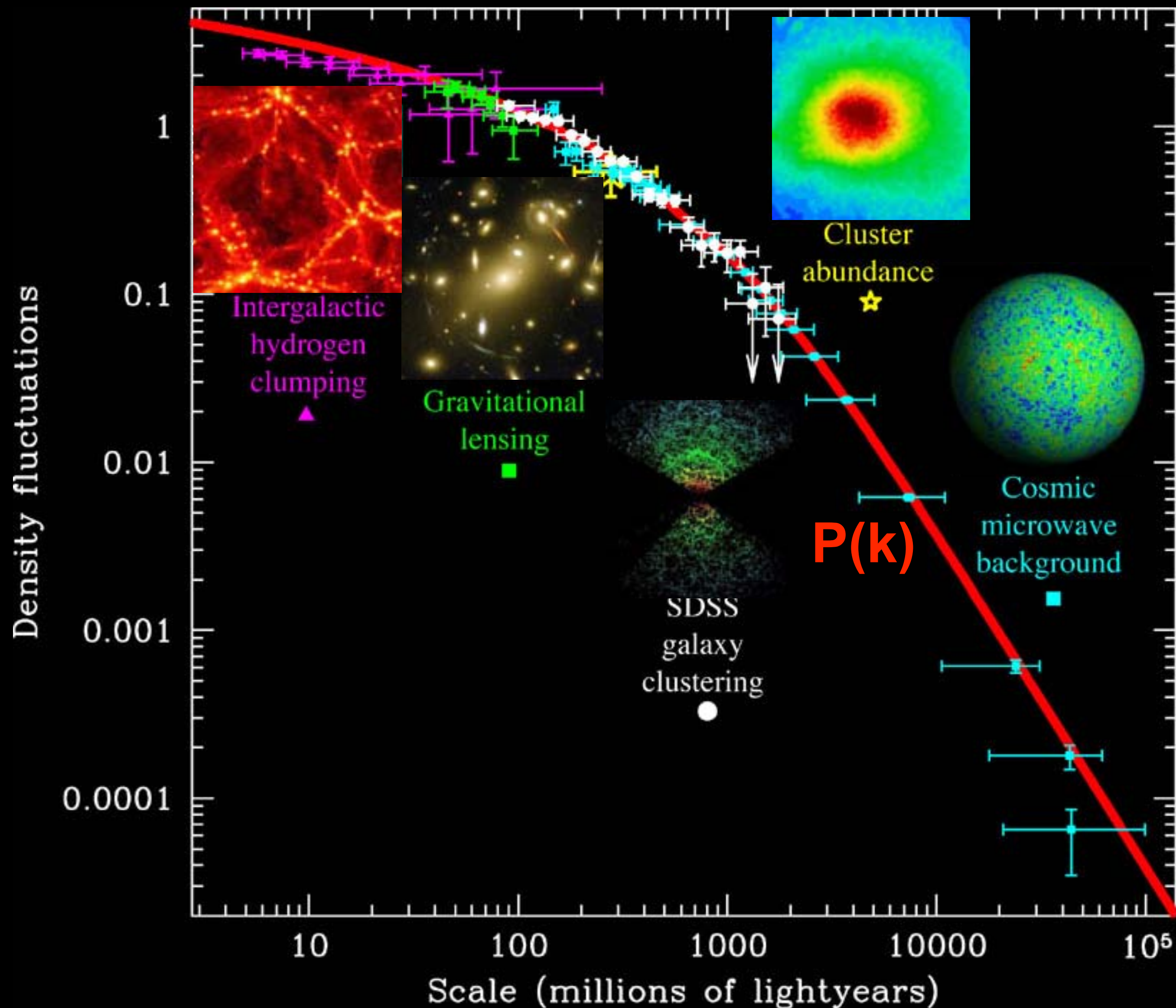
Big Bang Data Agrees with Double Dark Theory!



Latest Big Bang Data Strengthens the Agreement!



Distribution of Matter
Also Agrees with Double Dark Theory!



Max Tegmark

Forward Evolution

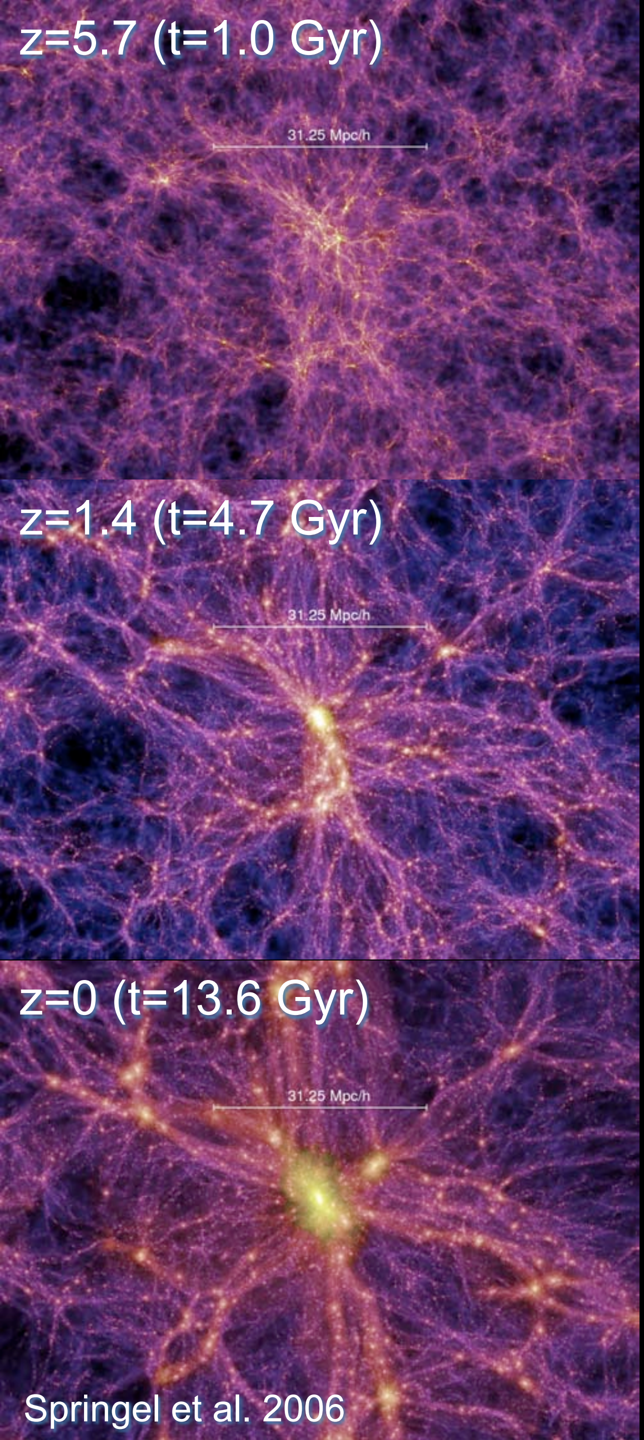
Present status of ΛCDM "Double Dark" DE + DM cosmology:

- cosmological parameters are now well constrained by observations, except possibly for σ_8

WMAP1 $\sigma_8=0.90$

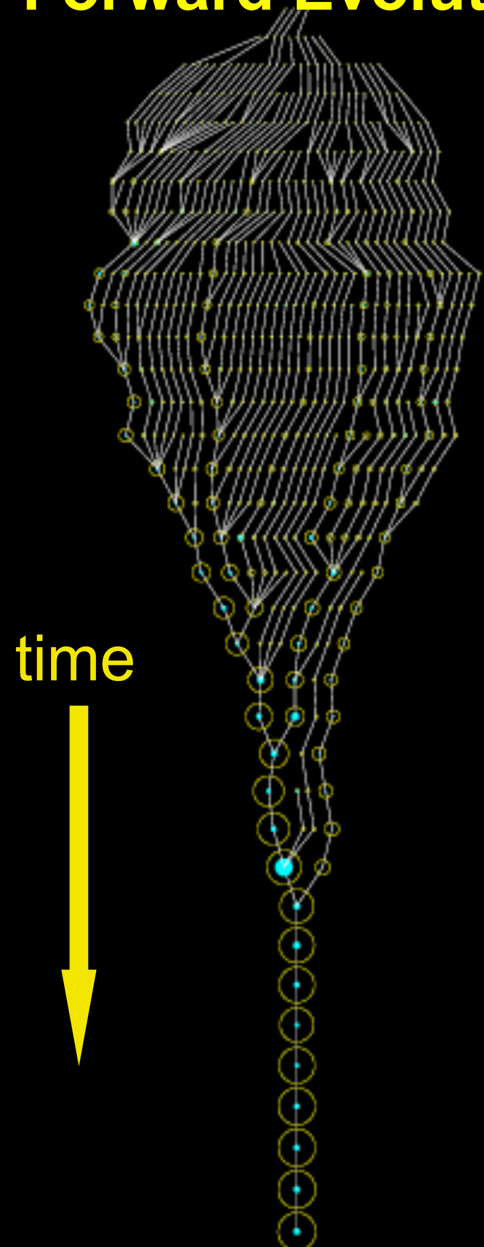
WMAP3 $\sigma_8=0.75$

WMAP5 $\sigma_8=0.82$



Springel et al. 2006

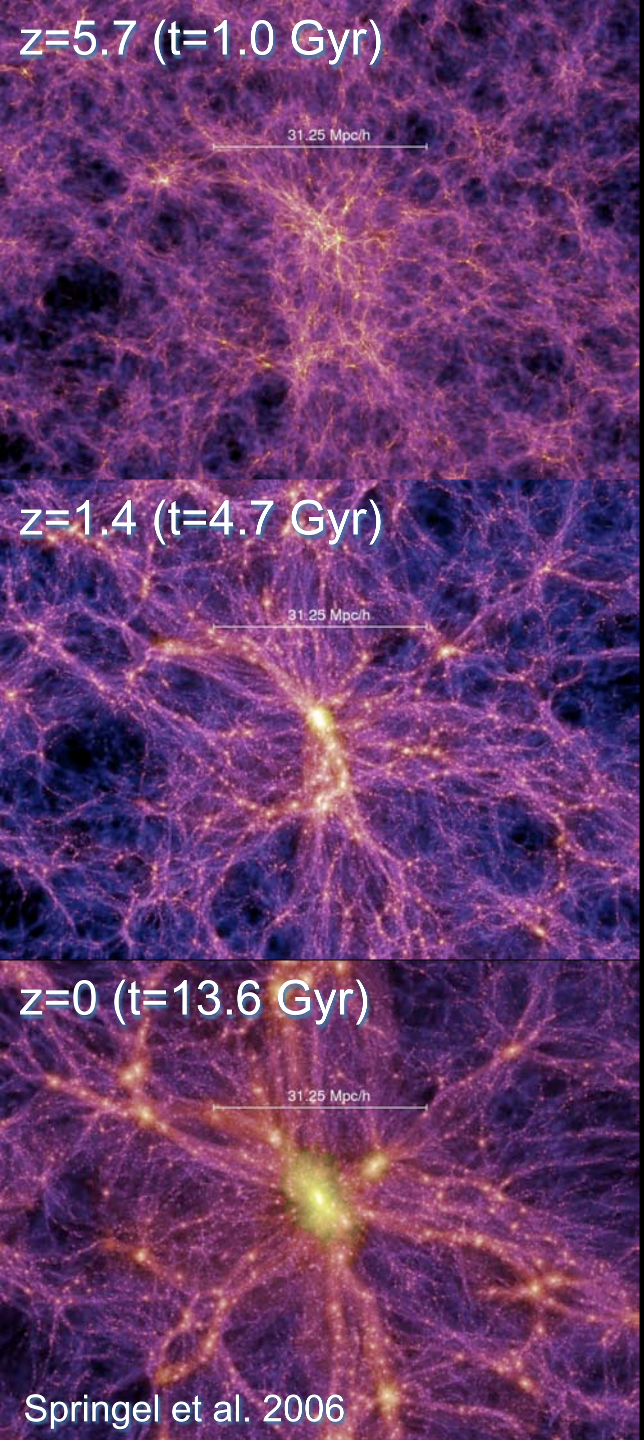
Forward Evolution



Wechsler et al. 2002

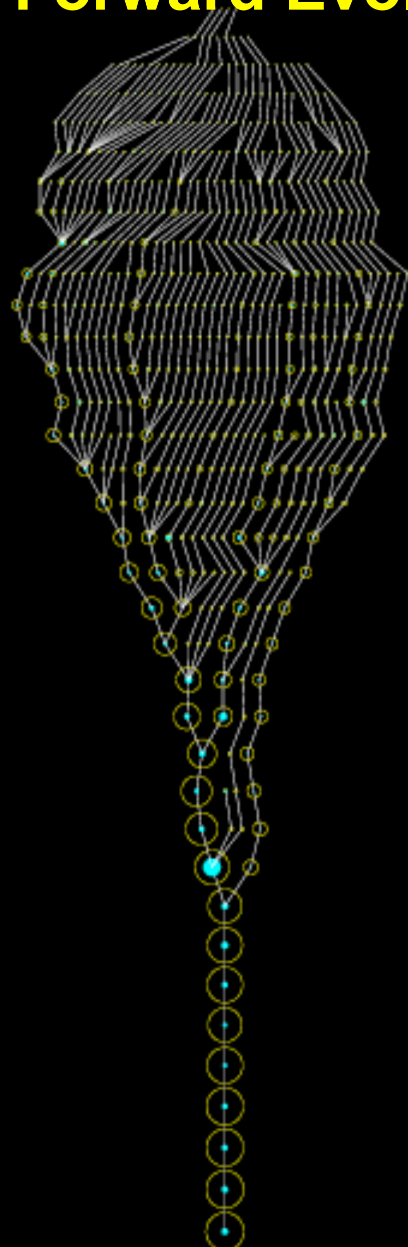
Present status of ΛCDM "Double Dark" theory:

- cosmological parameters are now well constrained by observations, except possibly for σ_8
- structure formation in dominant dark matter component accurately quantified
- mass accretion history of dark matter halos is represented by 'merger trees'



Springel et al. 2006

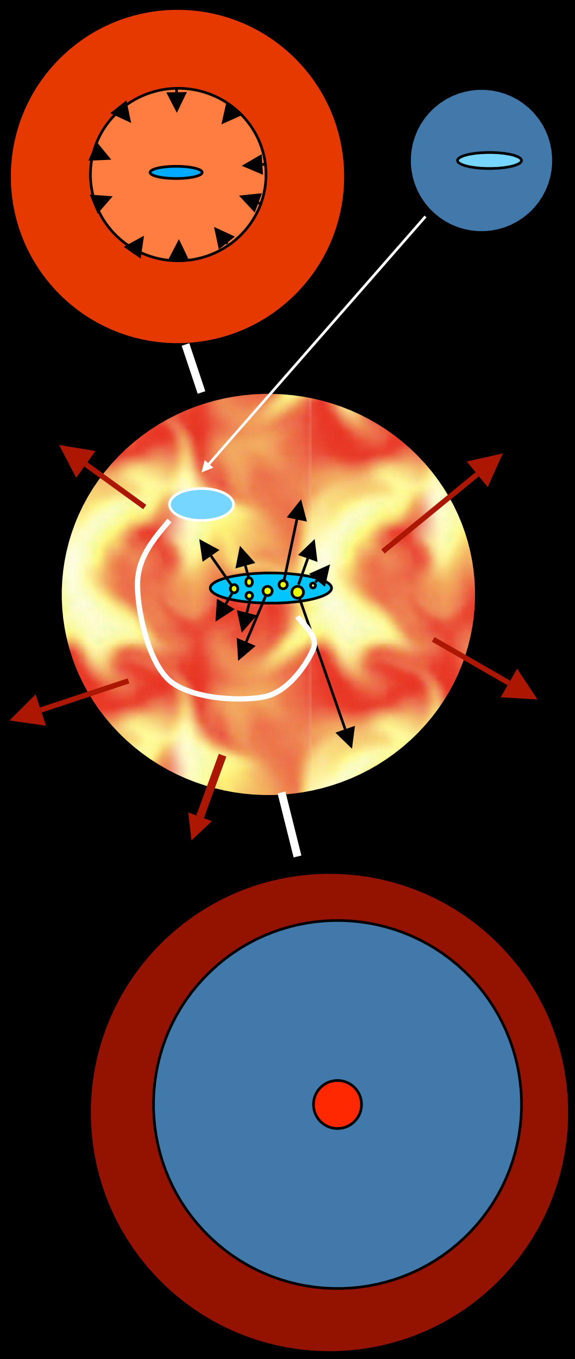
Forward Evolution


Wechsler et al. 2002

Astrophysical processes modeled:

- shock heating & radiative cooling
- photoionization squelching
- merging
- star formation (quiescent & burst)
- SN heating & SN-driven winds
- AGN accretion and feedback
- chemical evolution
- stellar populations & dust

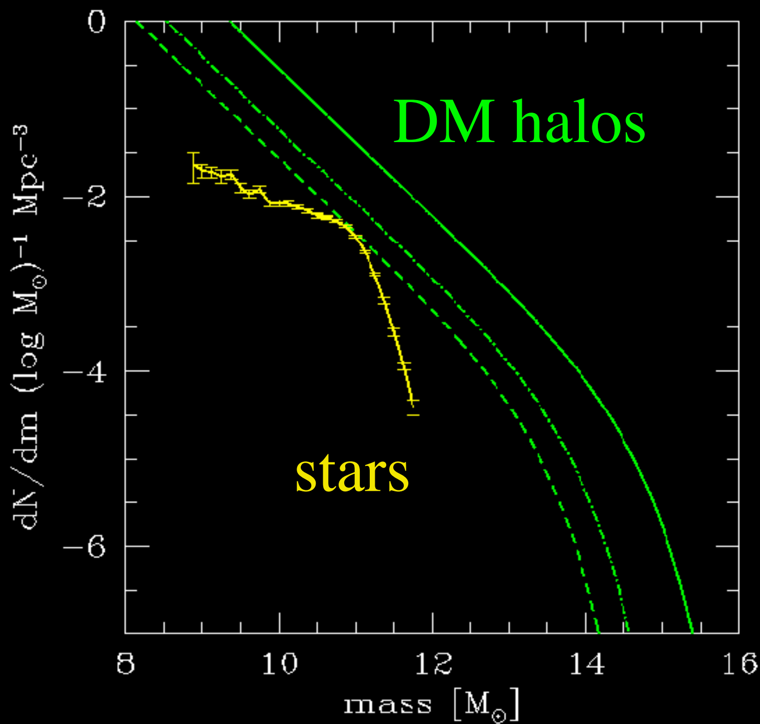
Galaxy Formation in CDM



- 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 expel?) cold gas and some metals
- galaxy mergers trigger bursts of star formation; 'major' mergers transform disks into spheroids

White & Frenk 1991; Kauffmann et al. 1993; Cole et al. 1994; Somerville & Primack 1999; Cole et al. 2000; Somerville, Primack, & Faber 2001; Somerville et al. 2008

Mapping Dark Matter to Baryons



- in order to reconcile CDM (sub)halo mass function with galaxy LF or stellar MF, cooling/star formation must be inefficient overall
- baryon/DM ratio must be a strongly non-linear (& non-monotonic) function of halo mass

Somerville & Primack 1999;
Benson et al. 2003

Empirical mapping of dark matter halos to galaxies
in the spirit of Kravtsov et al. 2004, Tasitsiomi et al. 2004,
Conroy et al. 2006

Forward Evolution

- Earlier CDM-based galaxy formation models suffered from a set of interlinked problems
  - overcooling/cooling flow problems in galaxies and clusters
  - failure to produce observed color bimodality
- ‘Bright Mode’ AGN feedback may regulate BH formation & temporarily quench star formation, but is not a viable ‘maintenance’ mechanism
- Low-accretion rate ‘Radio Mode’ feedback is a promising mechanism for counteracting cooling flows over long time scales
- New self-consistent ‘hybrid’ models based on physical scaling from numerical simulations and calibrated against empirical constraints now enable us to predict/interpret the relationship between galaxies, BH, and AGN across cosmic history

The Galaxy Color-Magnitude Diagram

old red/dead massive galaxies

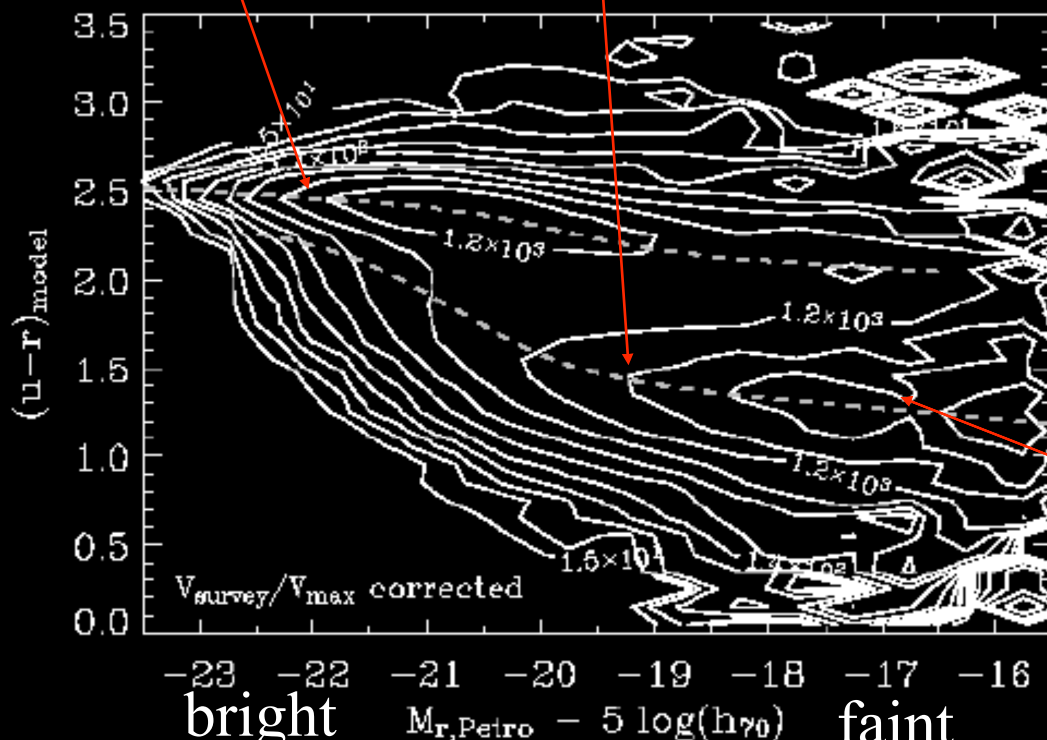
star forming galaxies

Local Universe: galaxies are **bimodal** in color & morphology

red

color

blue

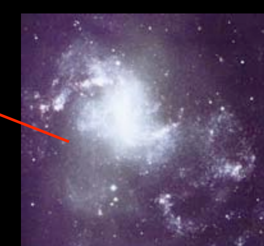


bright

faint

luminosity

young stars

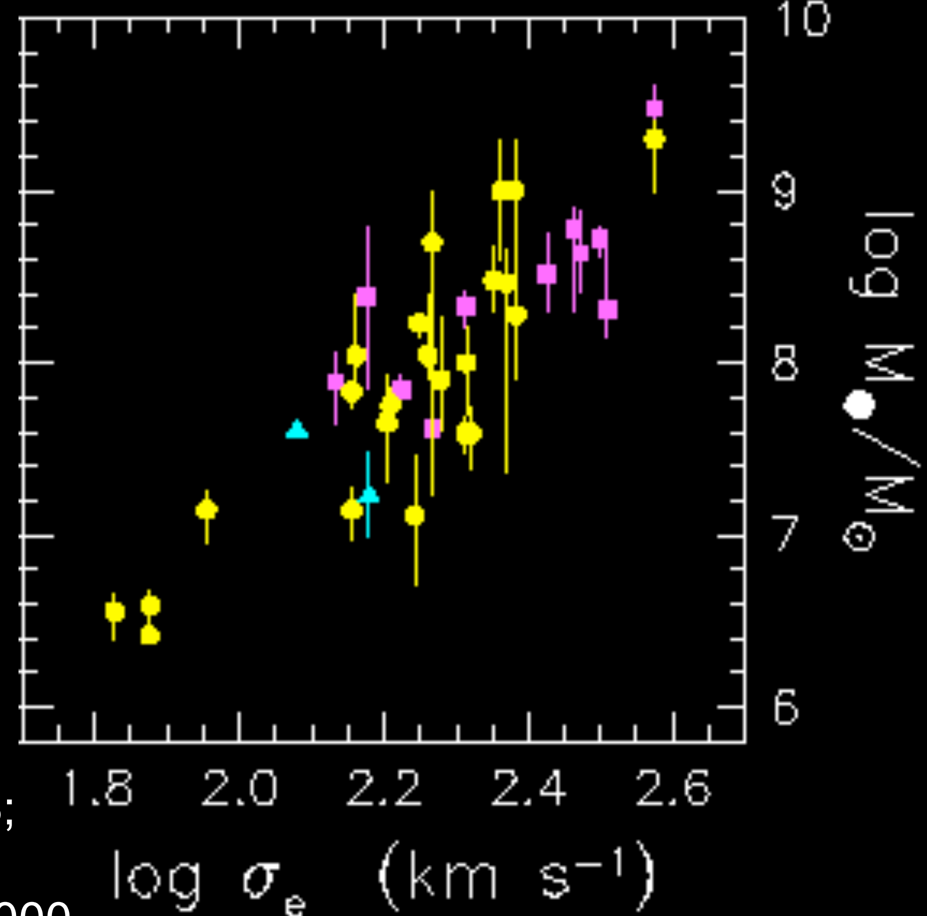


SDSS

Baldry et al. 2003

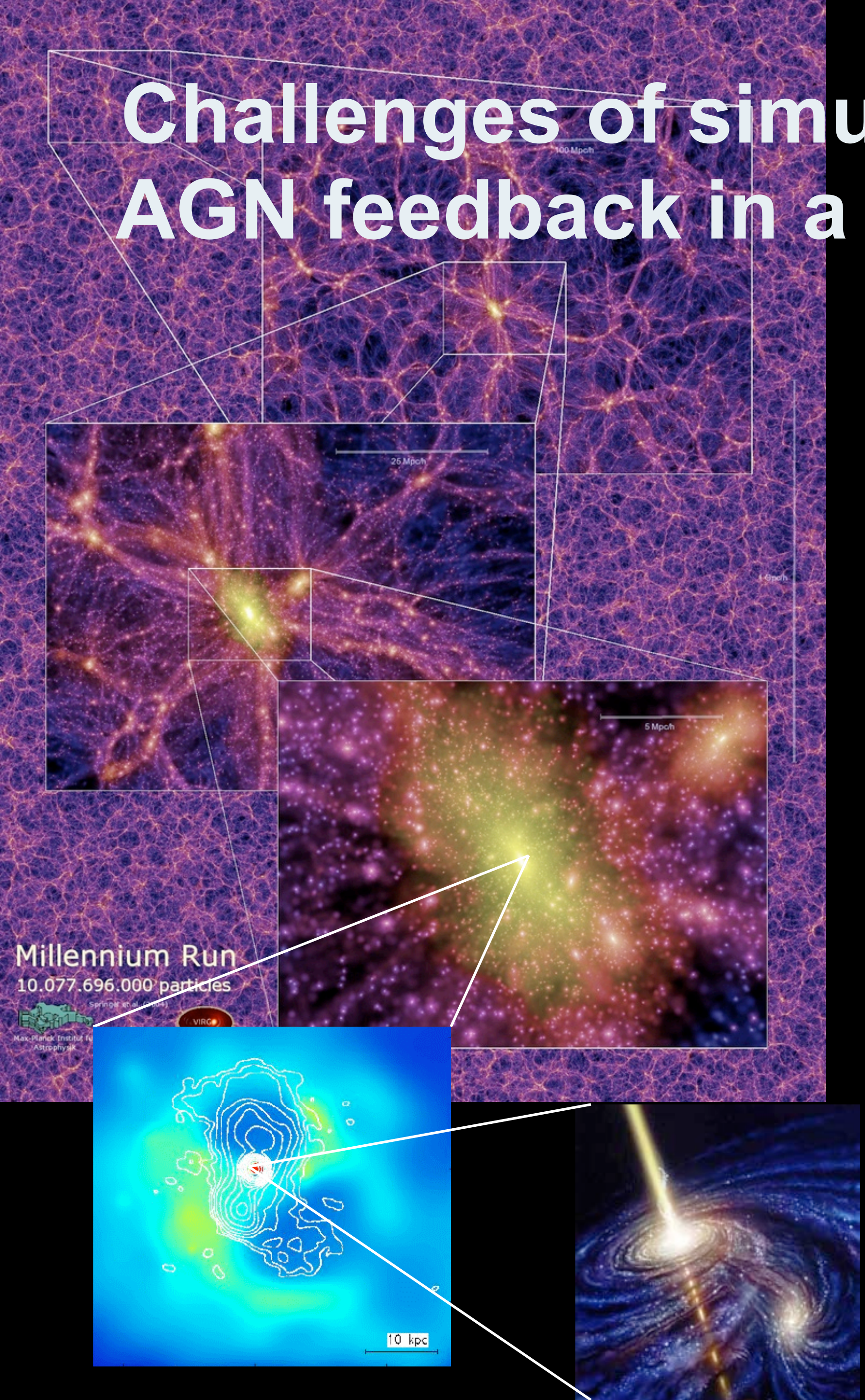
BH Formation and AGN Feedback: the Missing Link?

- Need mechanism to
  - quench star formation in massive galaxies
  - stop cooling in clusters
- SN feedback inadequate: not enough energy, little star formation in red galaxies
- BH mass closely connected with host galaxy's spheroid mass
- bigger BH ⇒ more energy



Magorrian et al. 1998; Gebhardt et al. 2000, Ferrarese & Merritt 2000

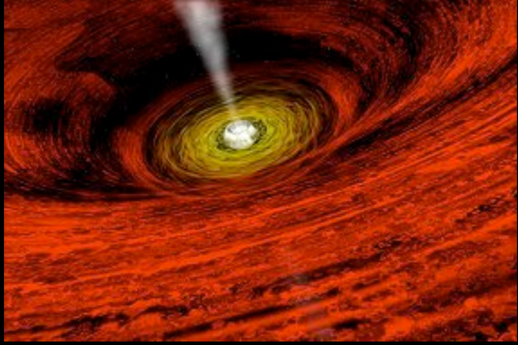
Challenges of simulating BH growth and AGN feedback in a cosmological context



- Huge dynamic range:
  - Gpc (luminous QSOs)
  - few 100 Mpc (LSS)
  - 10's of kpc (ICM, jets)
  - sub-kpc (star formation, stellar feedback)
  - few 100 pc (nuclear gas inflows, starbursts, AGN feeding, winds)
  - pc & sub-pc (accretion disk, BH mergers, etc.)
- Poorly understood physics:

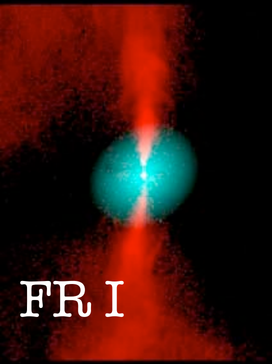
  B-fields, conduction, cosmic ray pressure, turbulence, feeding problem, ...

AGN feedback 1: Bright Mode

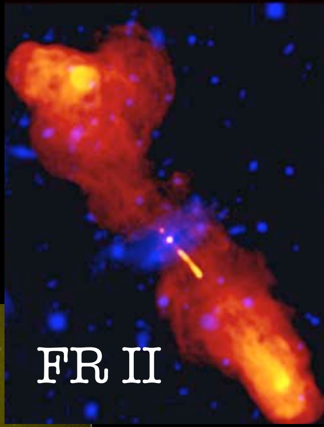


- Optical/X-ray luminous AGN/QSO, produced during periods of efficient feeding (mergers?)
- High accretion rates (0.1-1 L_{Edd}), fueled by cold gas via thin accretion disk ⇒ BH grows rapidly
- Rare ⇒ duty cycle short
- Thermal coupling of AGN energy with ISM is probably fairly weak (<5%)

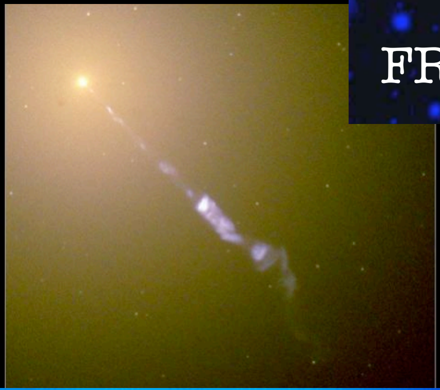
Di Matteo, Springel & Hernquist 2005

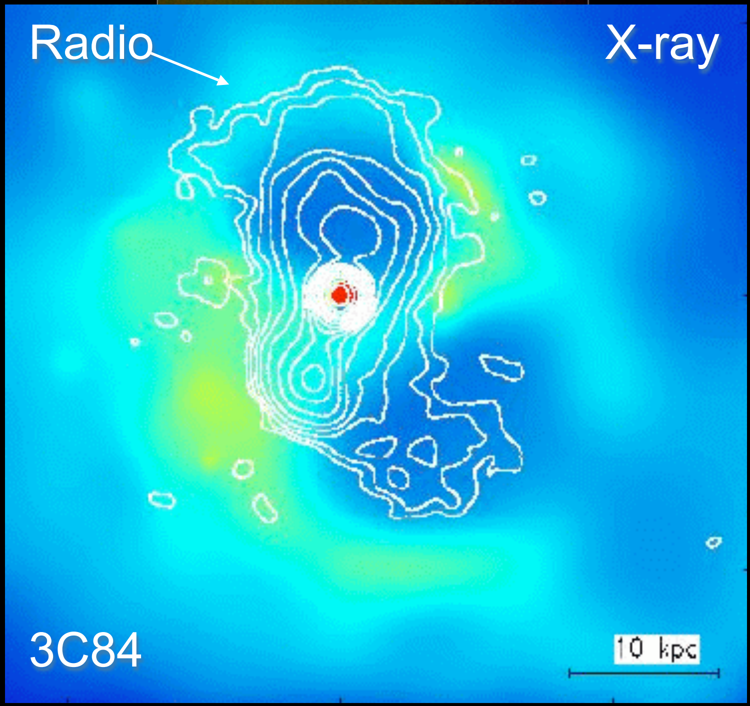


AGN Feedback 2: Radio Mode

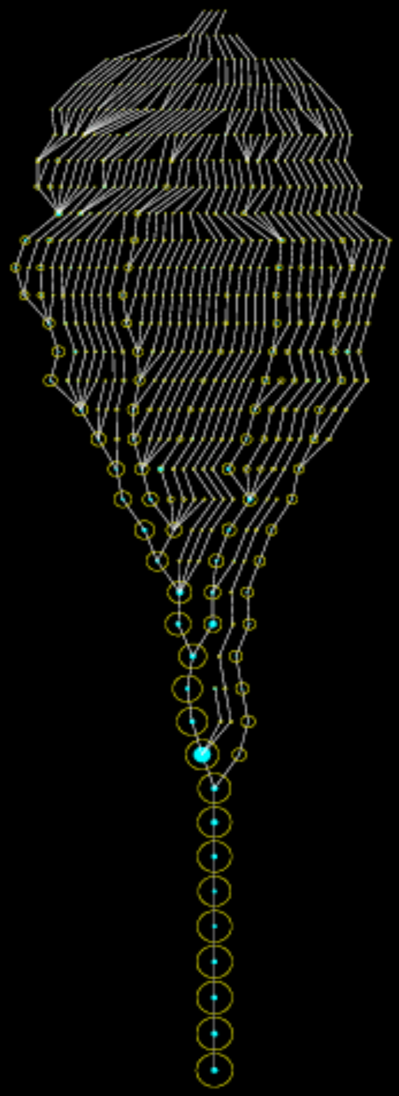


- Many massive galaxies are 'radio loud'
- Radio activity believed to be associated with BH's in 'low accretion state' (low Eddington ratio, $<10^{-3}$) -- (spherical, Bondi accretion or ADAF?)
- Jets often associated with cavities visible in X-ray images
- Coupling of jet energy with hot gas very efficient





NEW Self-Consistent Model for the Co-Evolution of Galaxies, Black Holes, and AGN



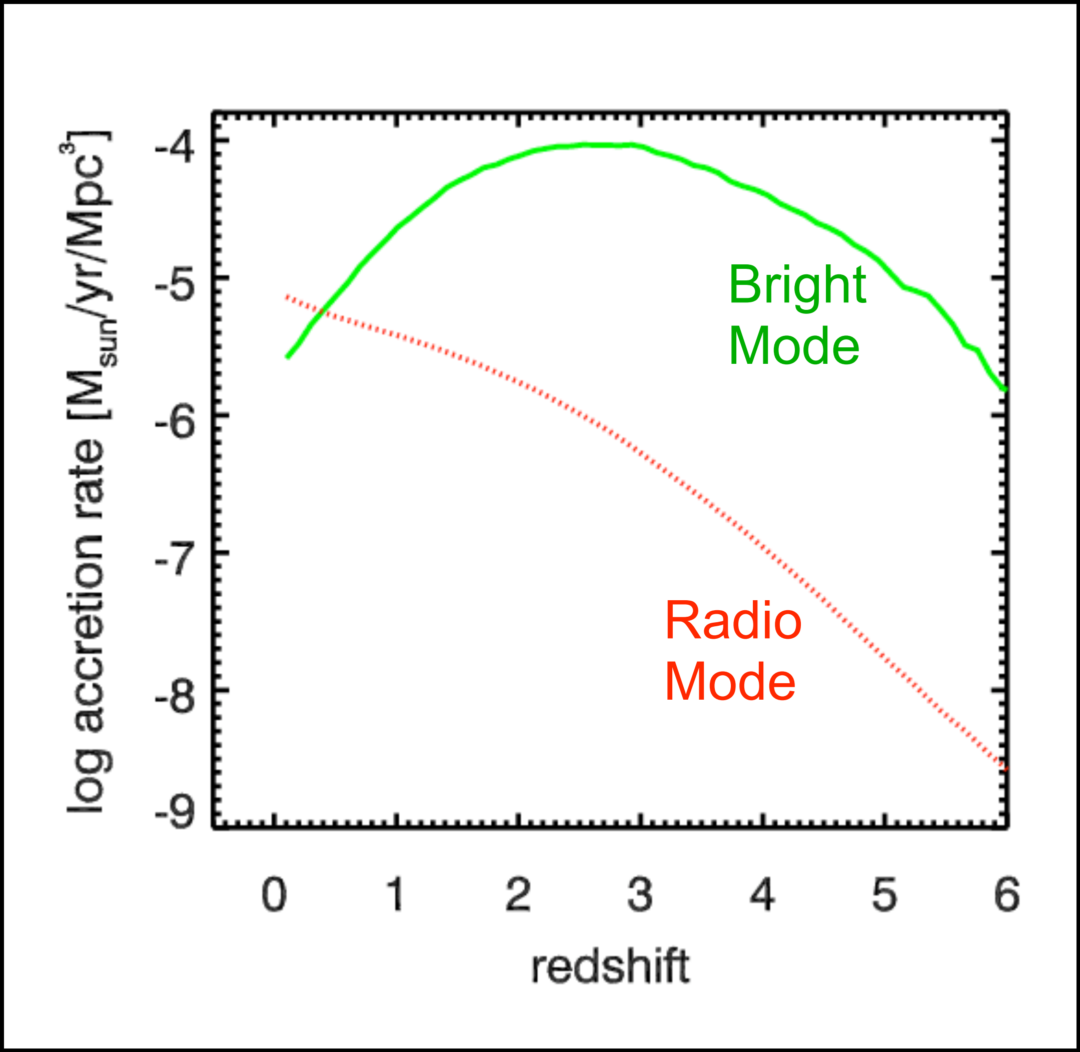
- Top-level halos start with a ~100 M_{sun} seed BH
- Mergers trigger bursts of star formation and accretion onto BH; efficiency and timescale parameterized based on hydrodynamical merger simulations (μ, B/T, V_c, f_g, z; Cox et al., Robertson et al.)
- BH accrete at Eddington rate until they reach ‘critical mass’, then enter ‘blowout’ (power-law decline) phase

$$dm_{acc}/dt = m_{Edd}/[1+(t/t_Q)^{\beta}]$$

- Energy released by accretion drives a wind
- BH merge when their galaxies merge; mass is conserved

Somerville, Hopkins, Cox, et al. 2008 MN in press

Bright vs. Radio Mode Accretion



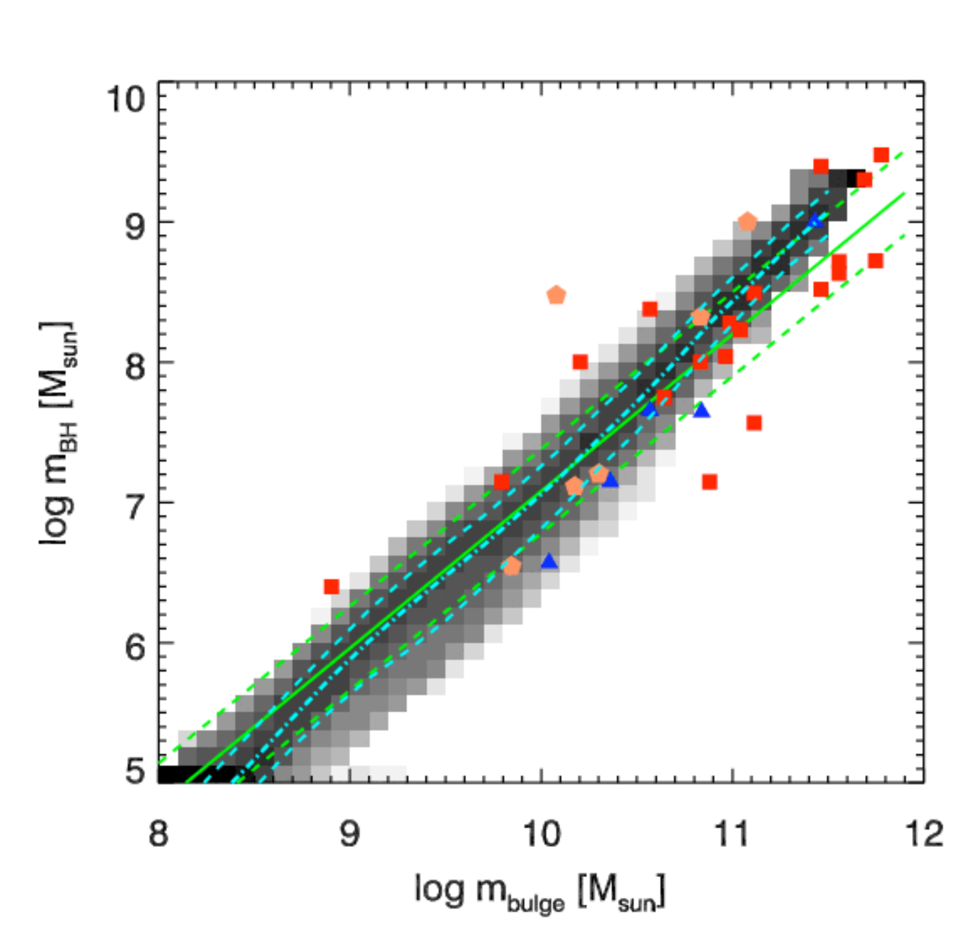
BH growth over early cosmic history is dominated by bright mode, in agreement with Soltan arguments

Radio mode becomes more important at late times ($z<1$)

Somerville et al. 2008

Predicted M_{BH}-M_{bulge} Relationship

In our model, arises from 'bright mode' feedback



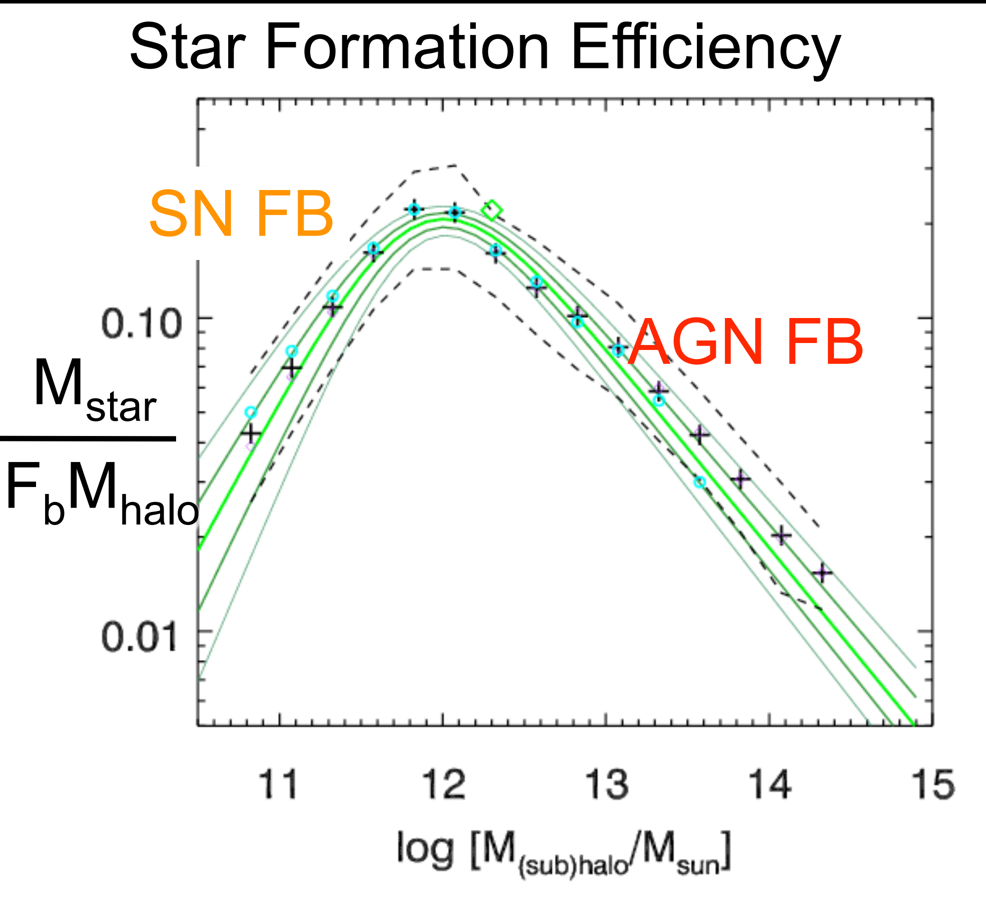
Matches slope & scatter of observed relation

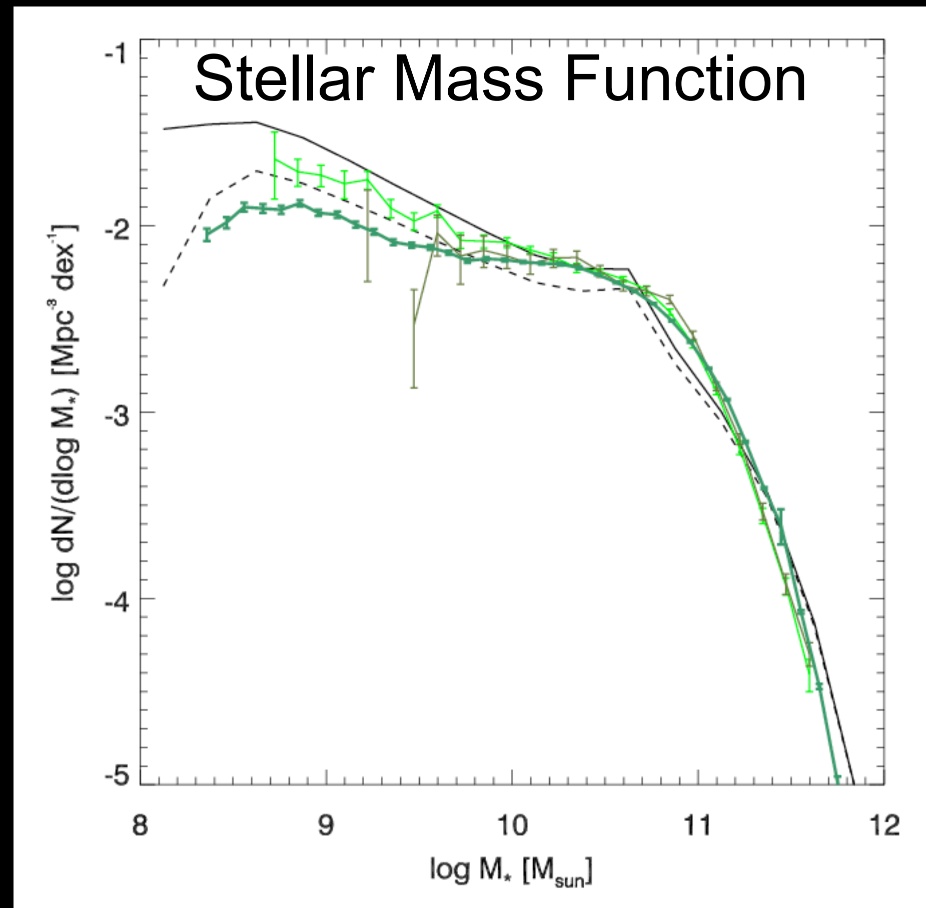
Large symbols:
Haering & Rix data
green: H&R fit + scatter
intrinsic scatter: 0.3 dex

Cyan: predicted median, 10th, & 90th percentile
predicted scatter:
~0.15 dex

Somerville et al. 2008

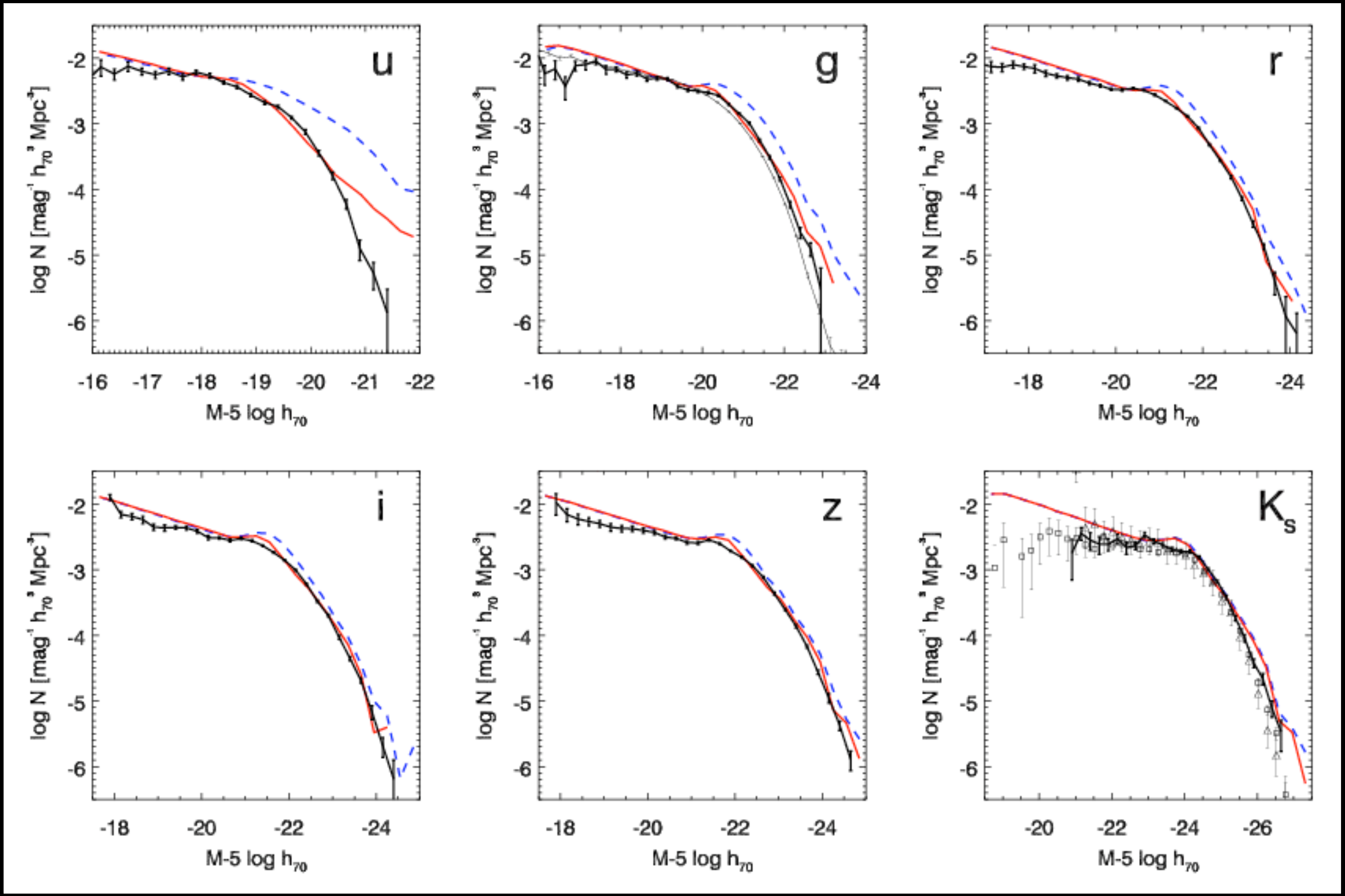
AGN Heating Leads to Galaxy Mass Functions at z~0 in Agreement with Observations





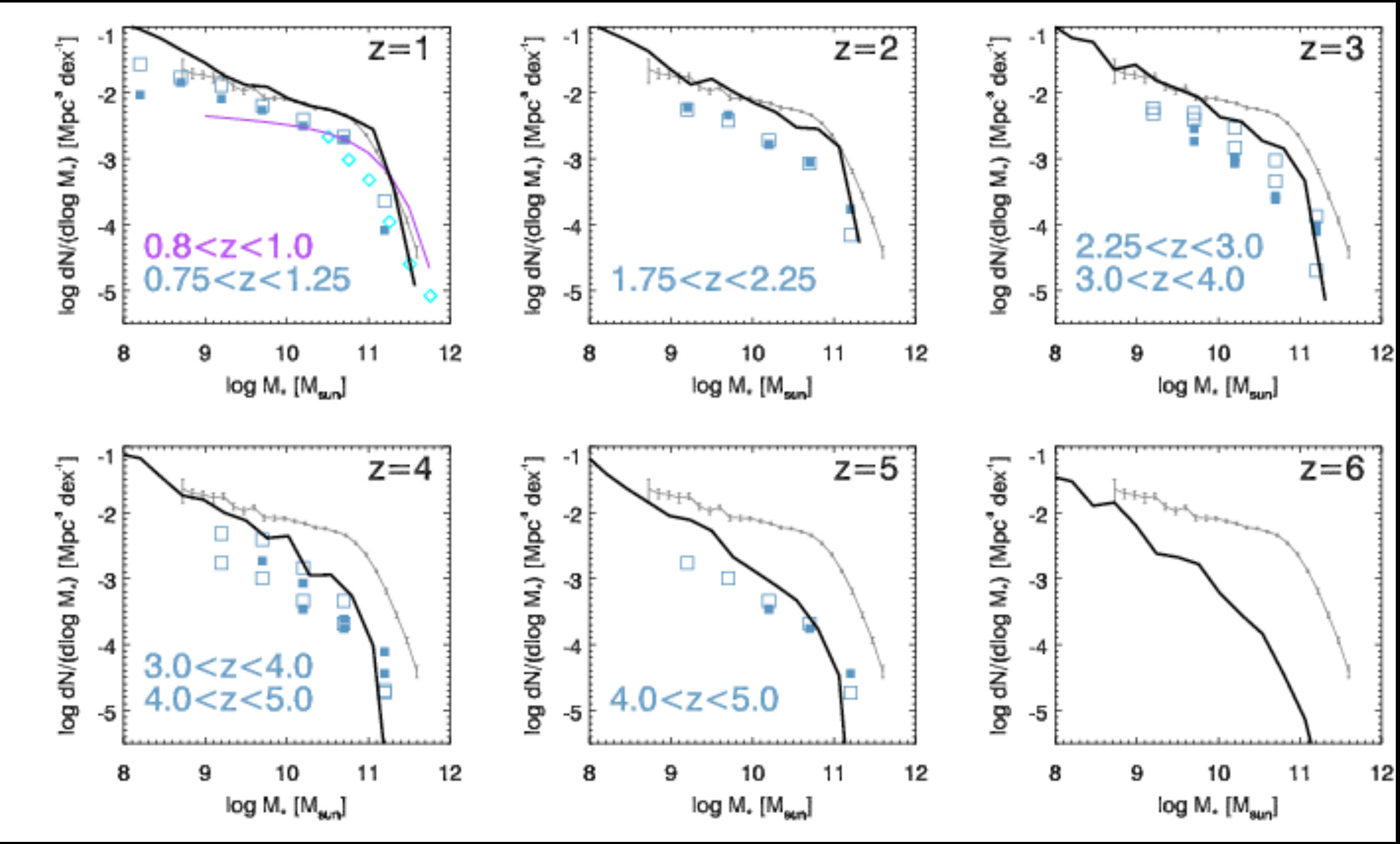
Somerville et al. 2008

z~0 Luminosity Functions



Somerville et al. 2008

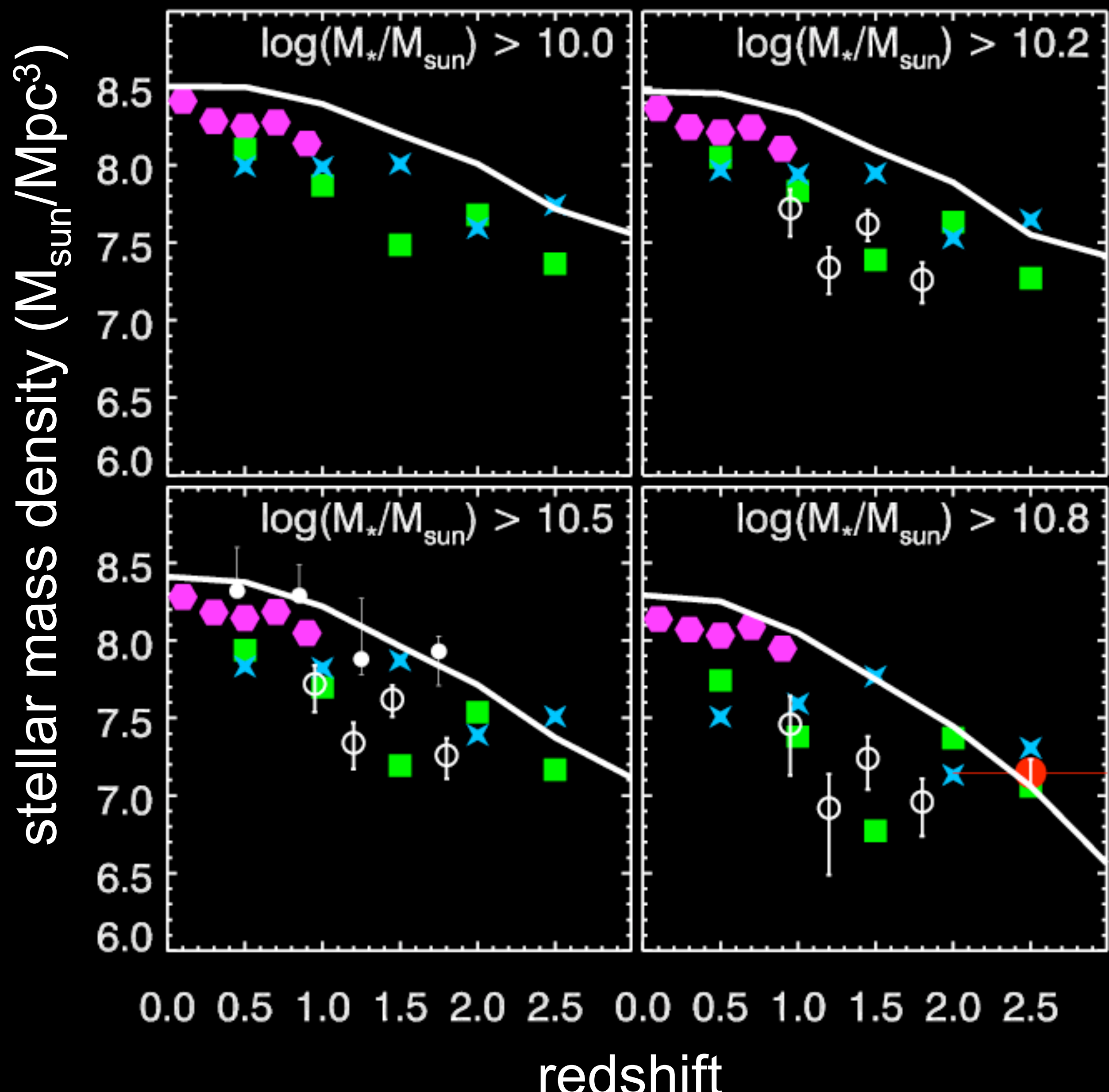
Stellar Mass Function Evolution



data from Borch et al. (COMBO-17);
Drory et al. (MUNICS, GOODS, FDF)

Somerville et al. in prep

We Still Produce Enough Massive Galaxies at High Redshift

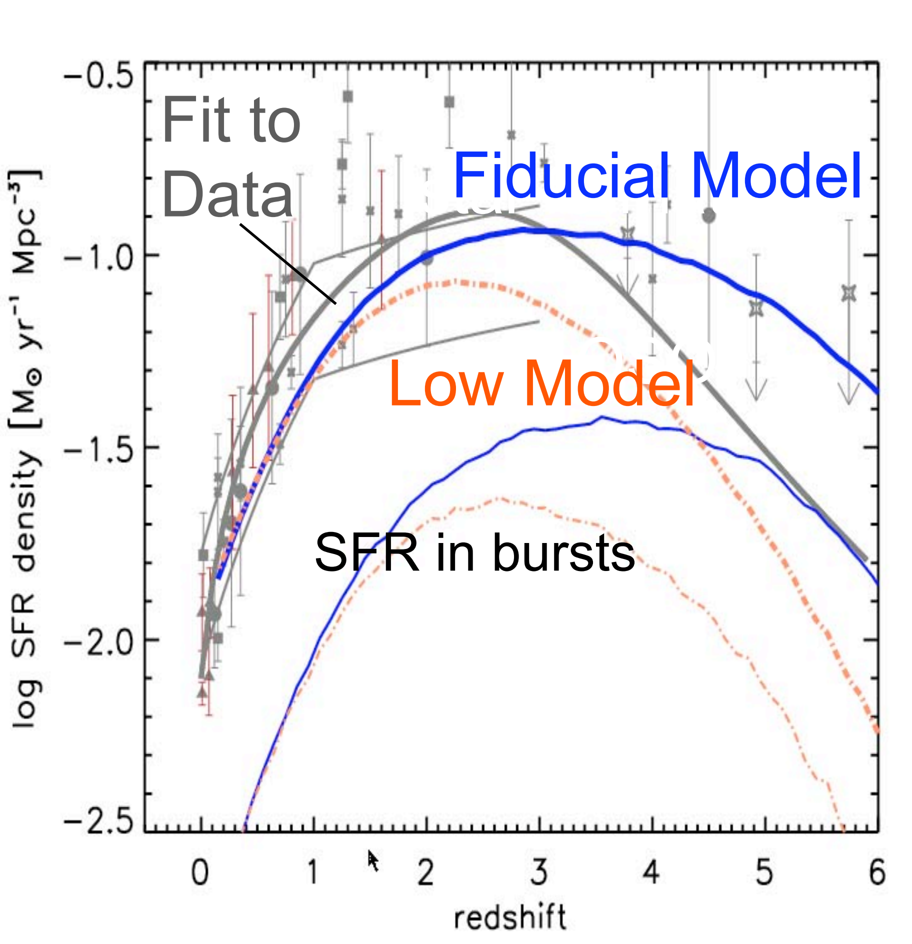


observations:
Borch et al. (COMBO-17)
Drory et al. (GOODS)
Glazebrook et al. (GDDS)
Fontana et al. (K20)
Papovich et al. (GOODS DRGs)

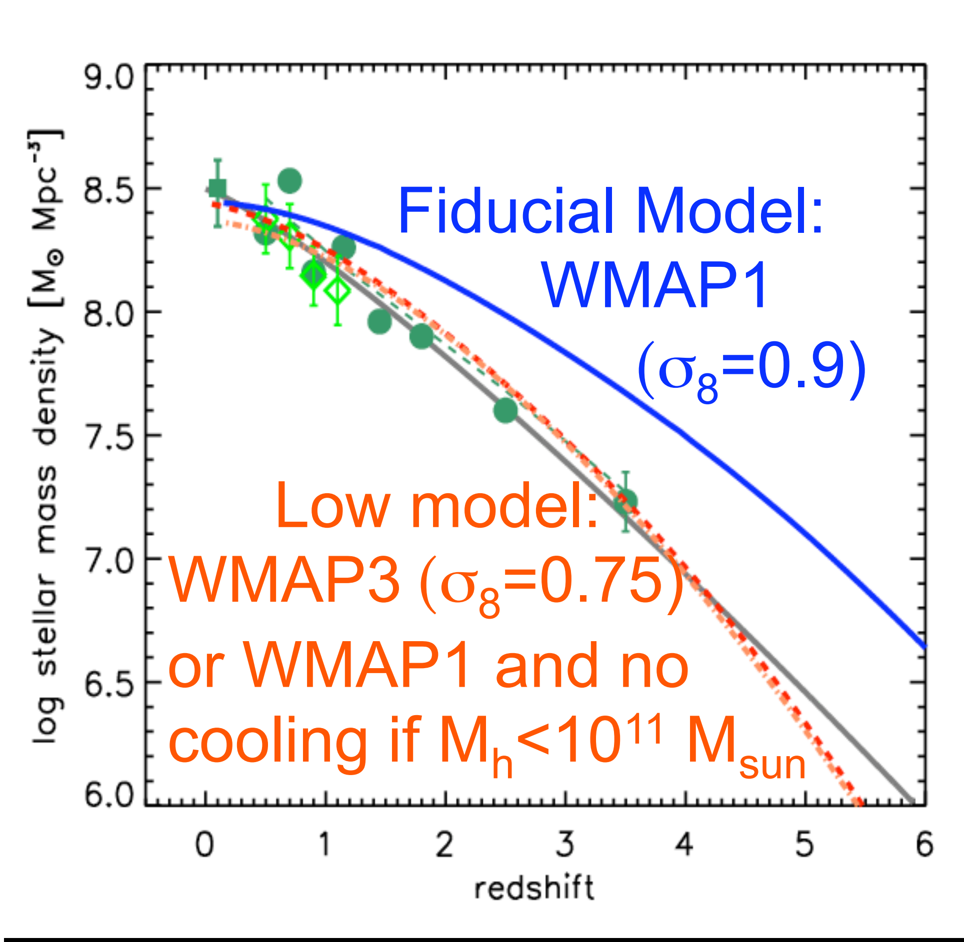
Somerville et al. 2008;
also Bower et al. 2006;
Kitzblicher & White 2006

History of Star Formation and Stellar Mass Build-up

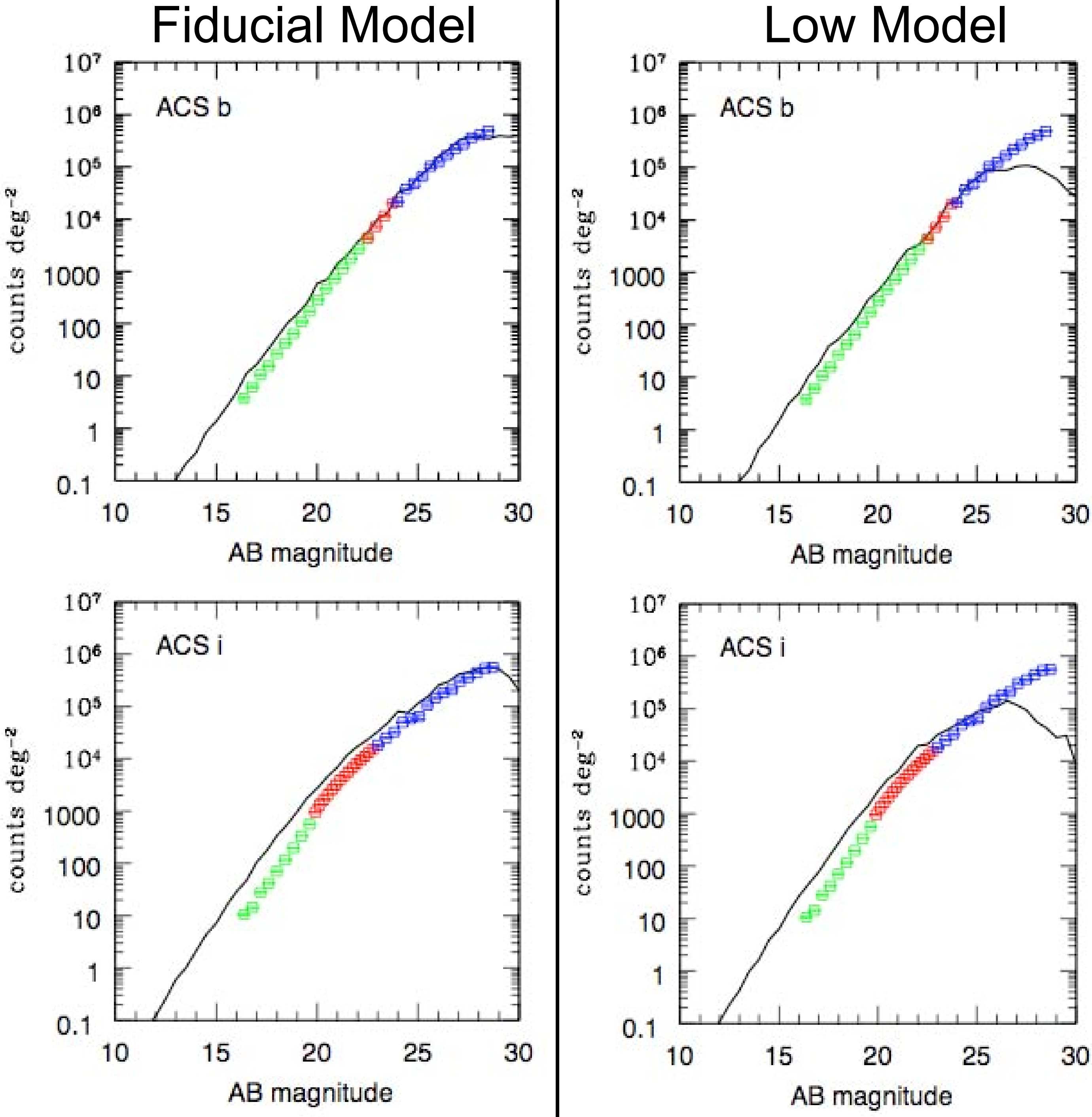
Star Formation History



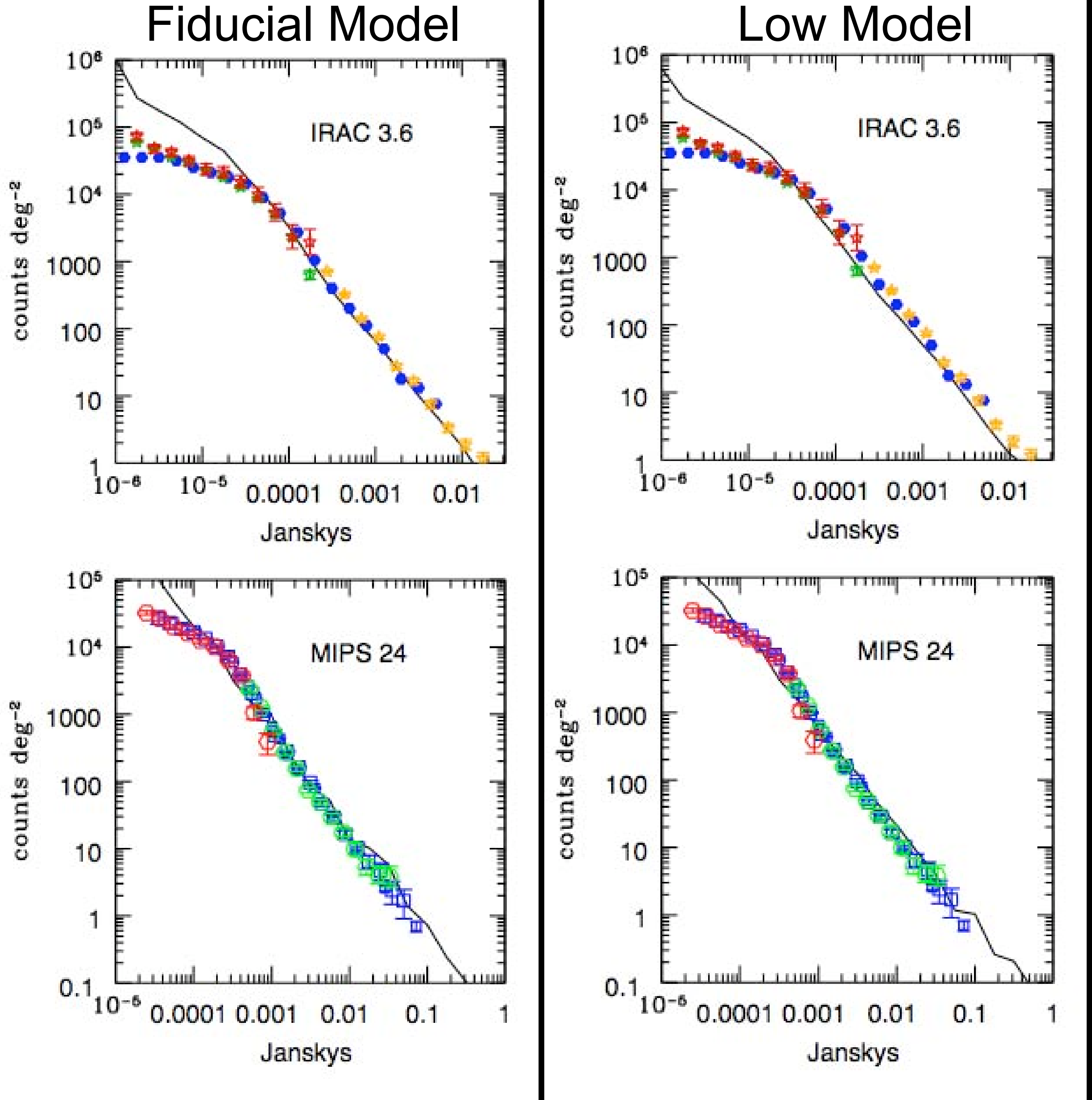
Stellar Mass Build-up



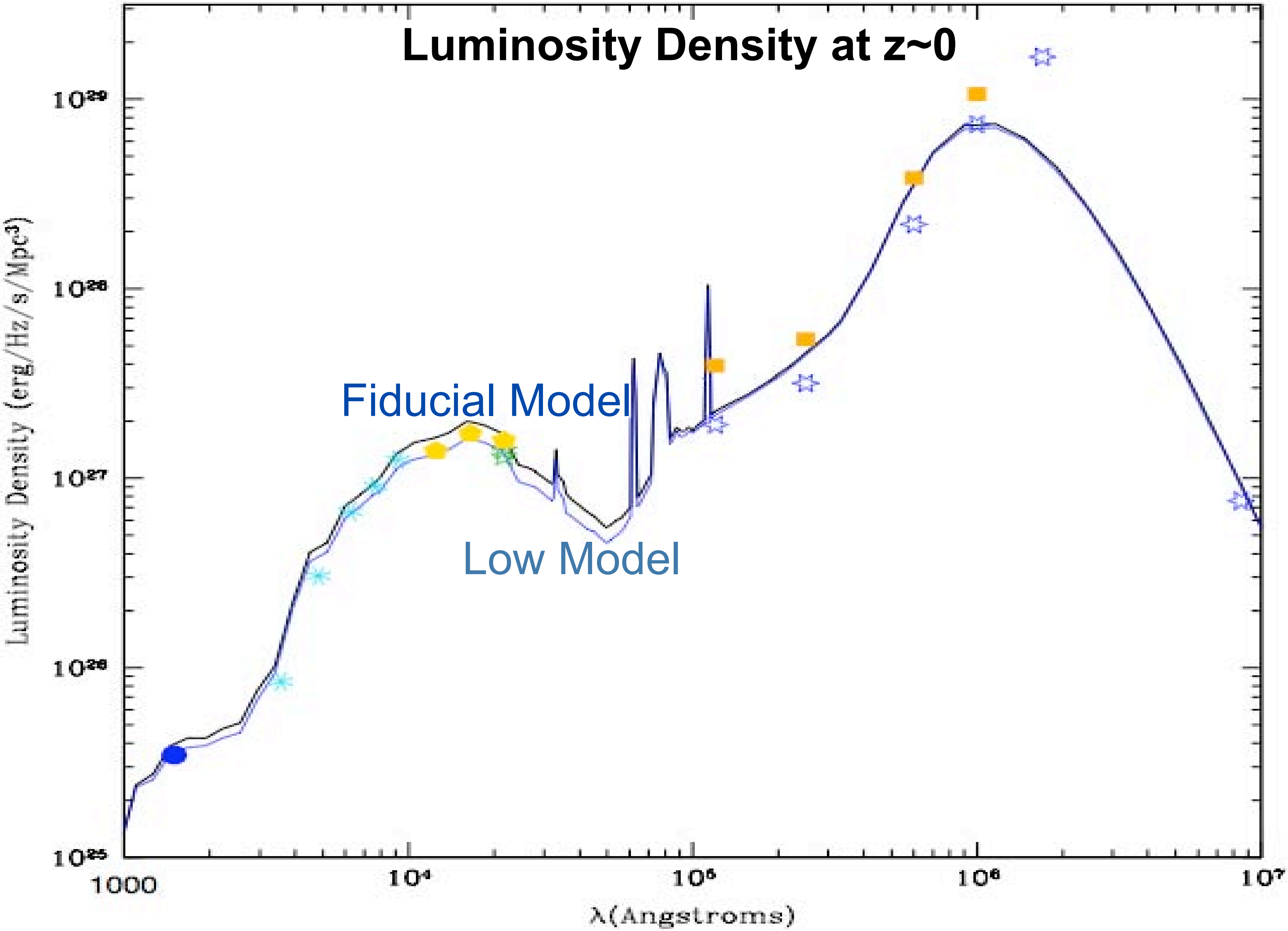
Somerville et al. 2008



Fiducial Model
Low Model
ACS b
ACS i
counts deg^{-2}
AB magnitude
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10
15
20
25
30

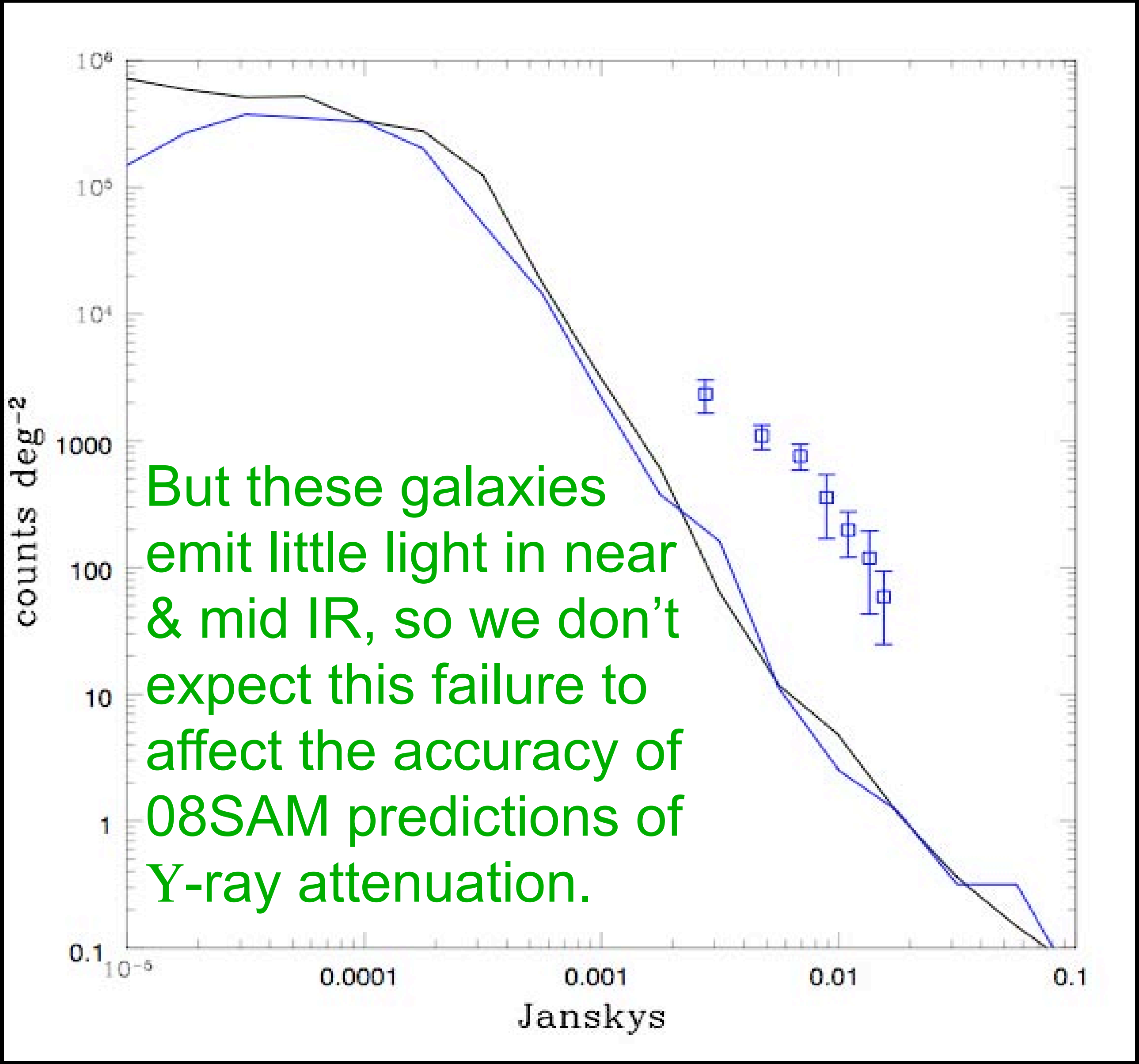


Fiducial Model
Low Model
IRAC 3.6
MIPS 24
counts deg^{-2}
Janskys



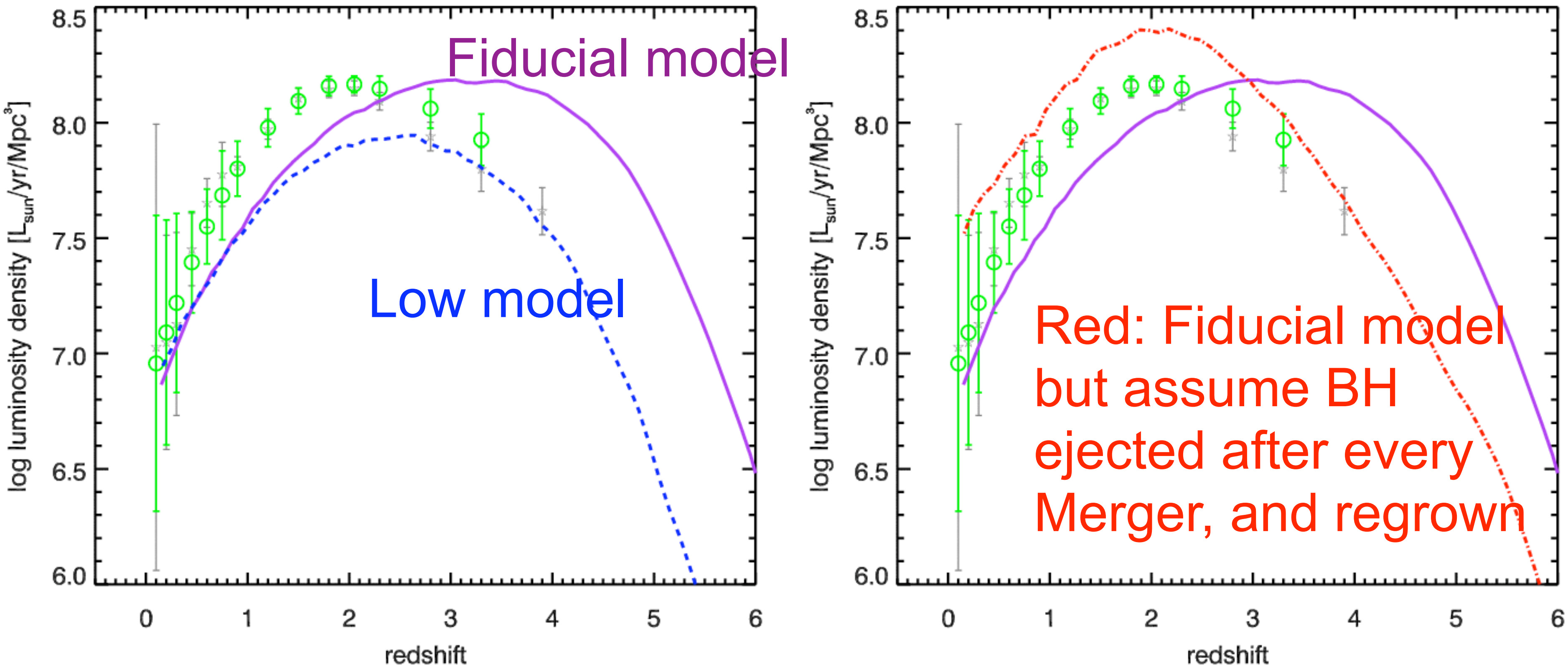
Luminosity Density at z~0
Fiducial Model
Low Model
Luminosity Density (erg/Hz/s/Mpc³)
λ(Angstroms)
1000
10⁴
10⁵
10⁶
10⁷
10²⁵
10²⁶
10²⁷
10²⁸
10²⁹

08SAM Fails to Predict Observed 850 μm Number Counts



But these galaxies emit little light in near & mid IR, so we don't expect this failure to affect the accuracy of 08SAM predictions of γ-ray attenuation.

BH Accretion History



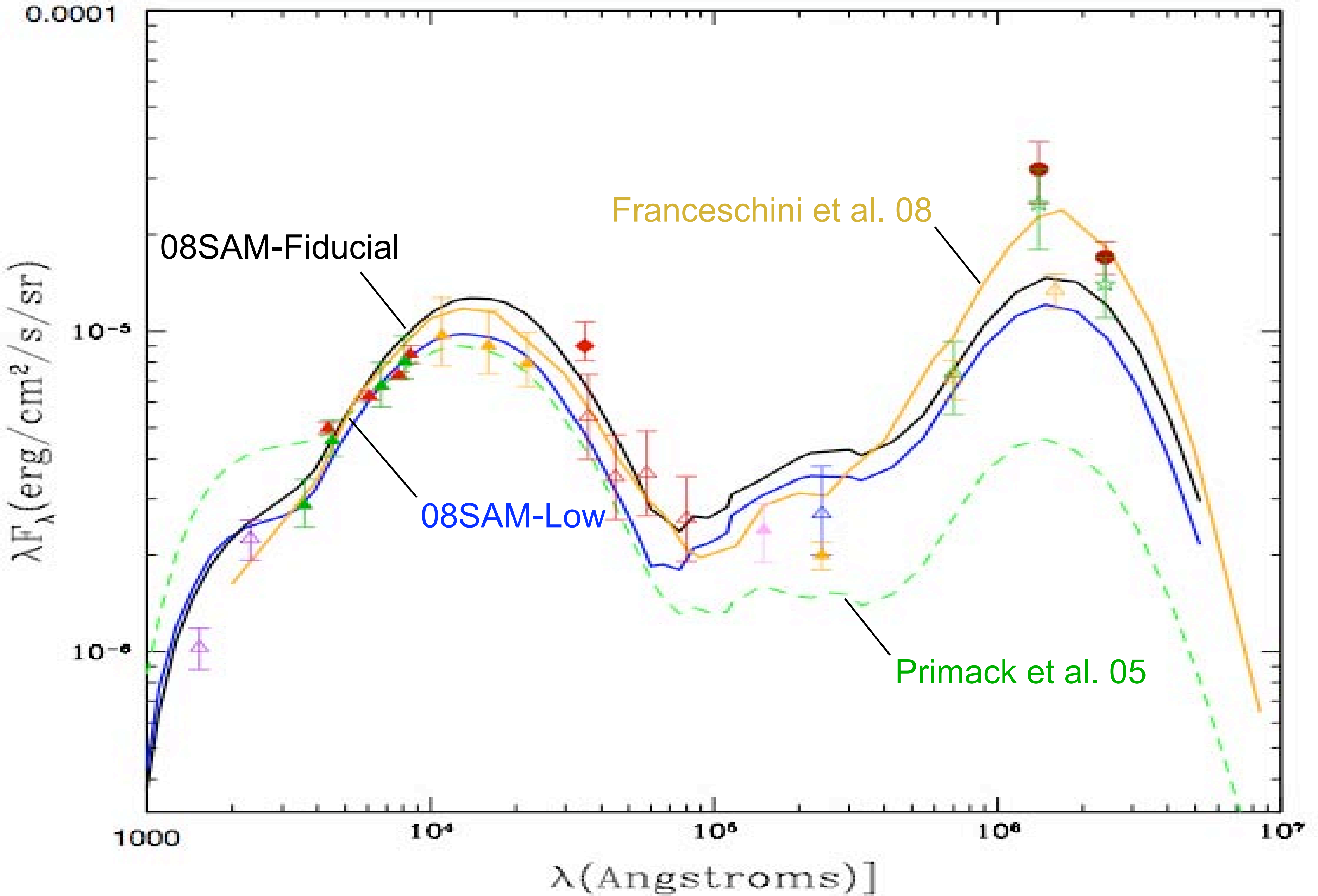
Green dots: observational estimates of bolometric QSO luminosity density.

Explanation: many late ($z<1.5$) mergers already contain a big spheroid ($M_* > M_{crit}$), so their BHs are quenched almost immediately ⇒ too few bright AGN.

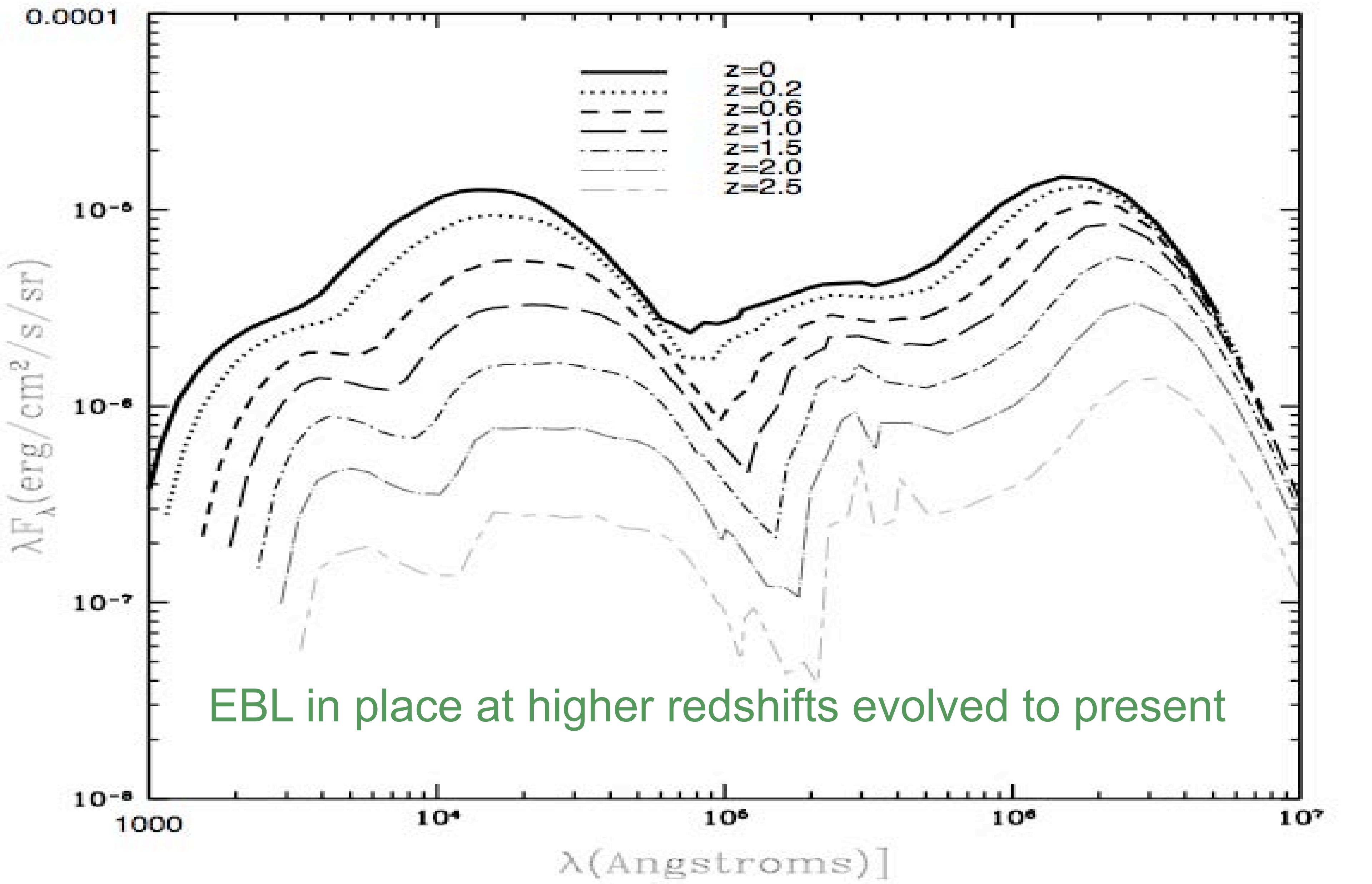
New Improved Semi-Analytic Model Works!

- Earlier CDM-based galaxy formation models suffered from a set of interlinked problems
  - overcooling/cooling flow problems in galaxies and clusters
  - failure to produce observed color bimodality
- 'Bright mode' AGN feedback may regulate BH formation & temporarily quench star formation, but is not a viable 'maintenance' mechanism
- Low-accretion rate 'radio mode' feedback is a promising mechanism for counteracting cooling flows over long time scales
- New self-consistent 'hybrid' models based on physical scaling from numerical simulations and calibrated against empirical constraints now enable us to predict/interpret the relationship between galaxies, BH, and AGN across cosmic history

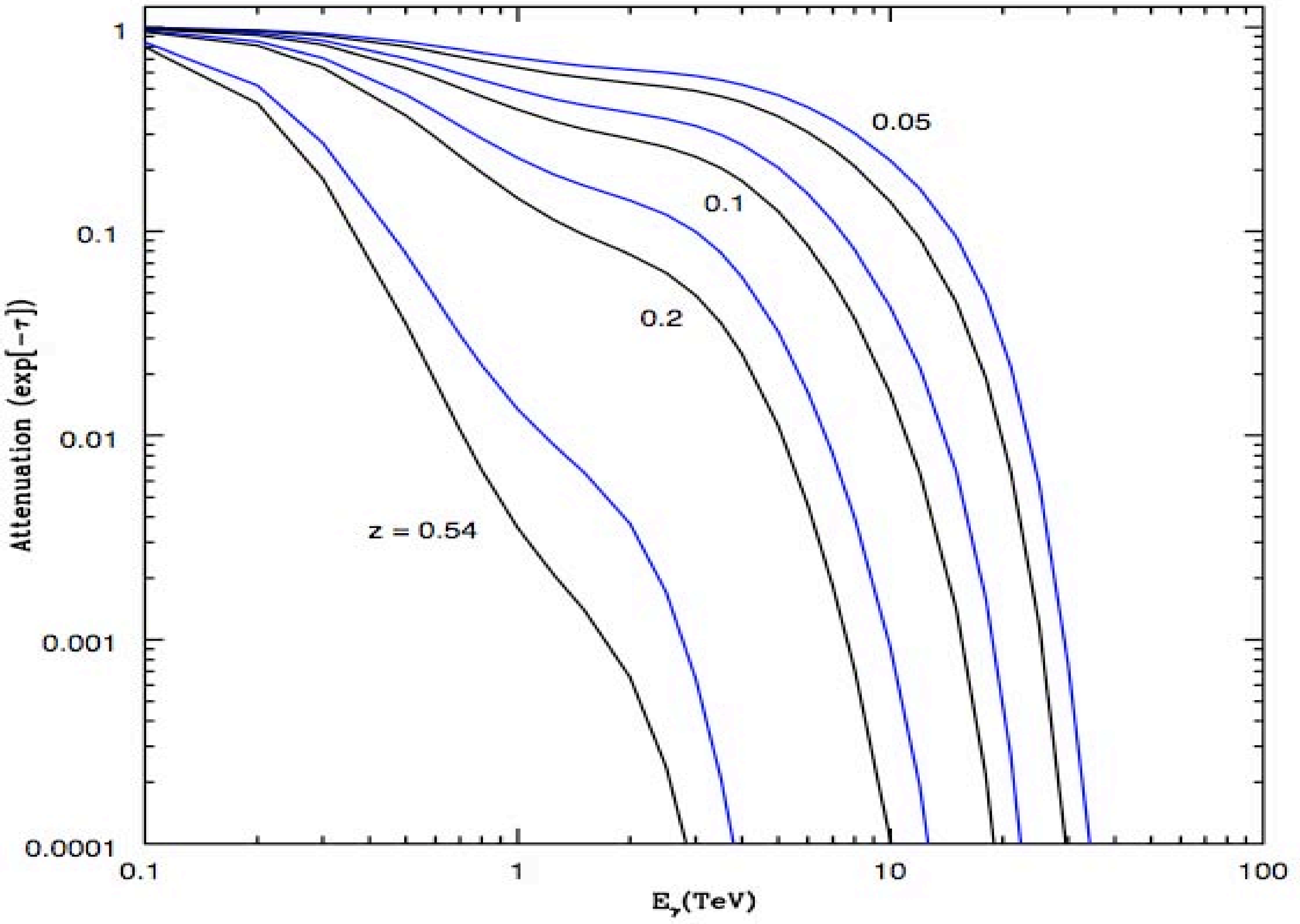
Forward Evolution EBL



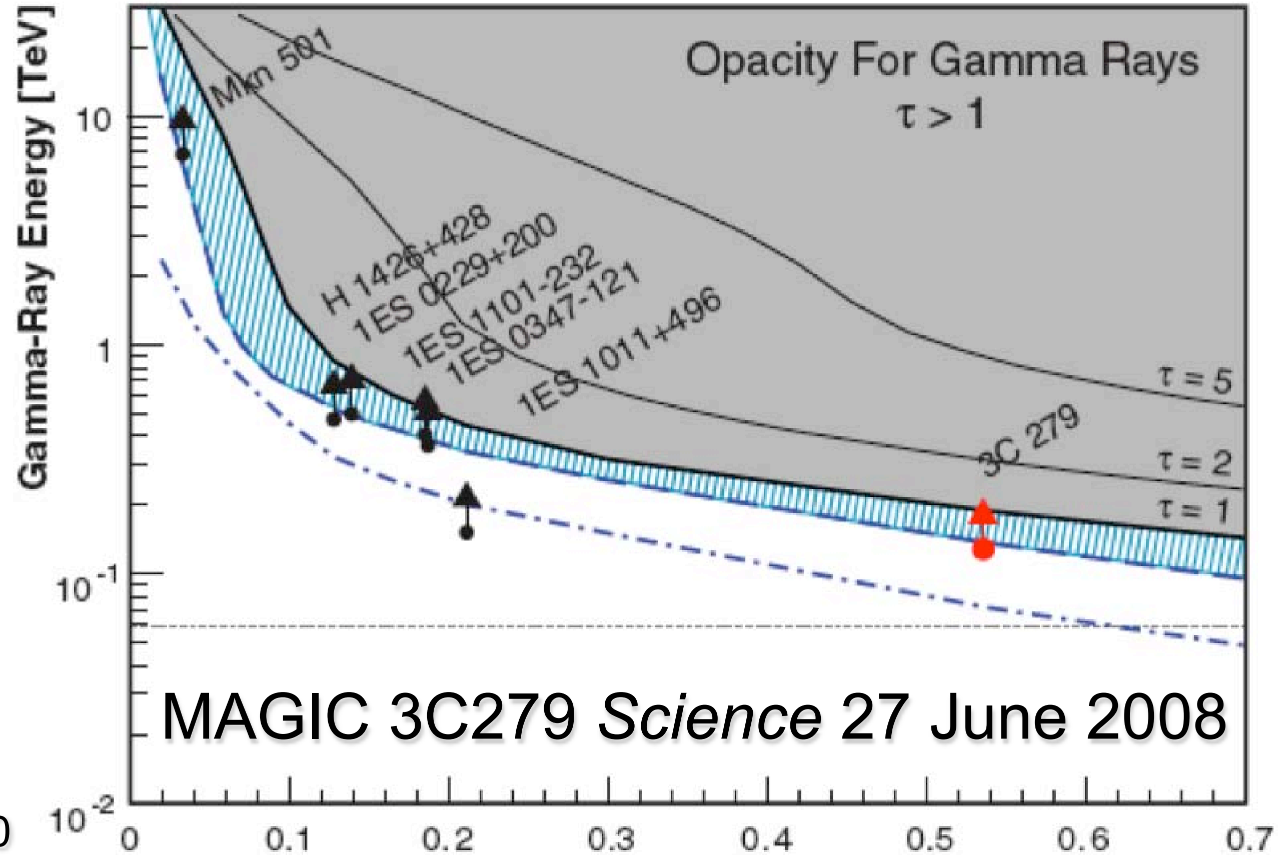
Forward Evolution Build-up of the EBL

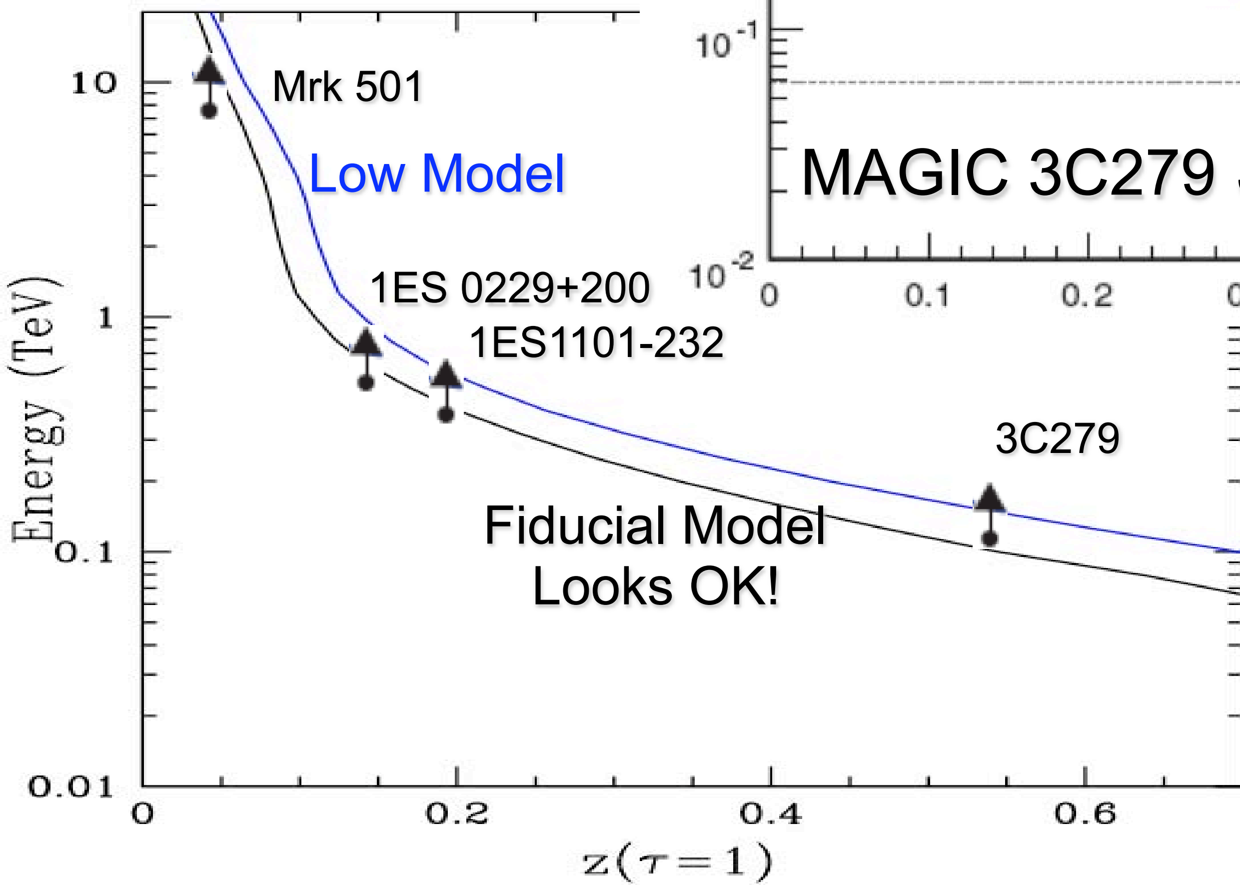


Gamma Ray Attenuation Due to Fiducial and Low Models



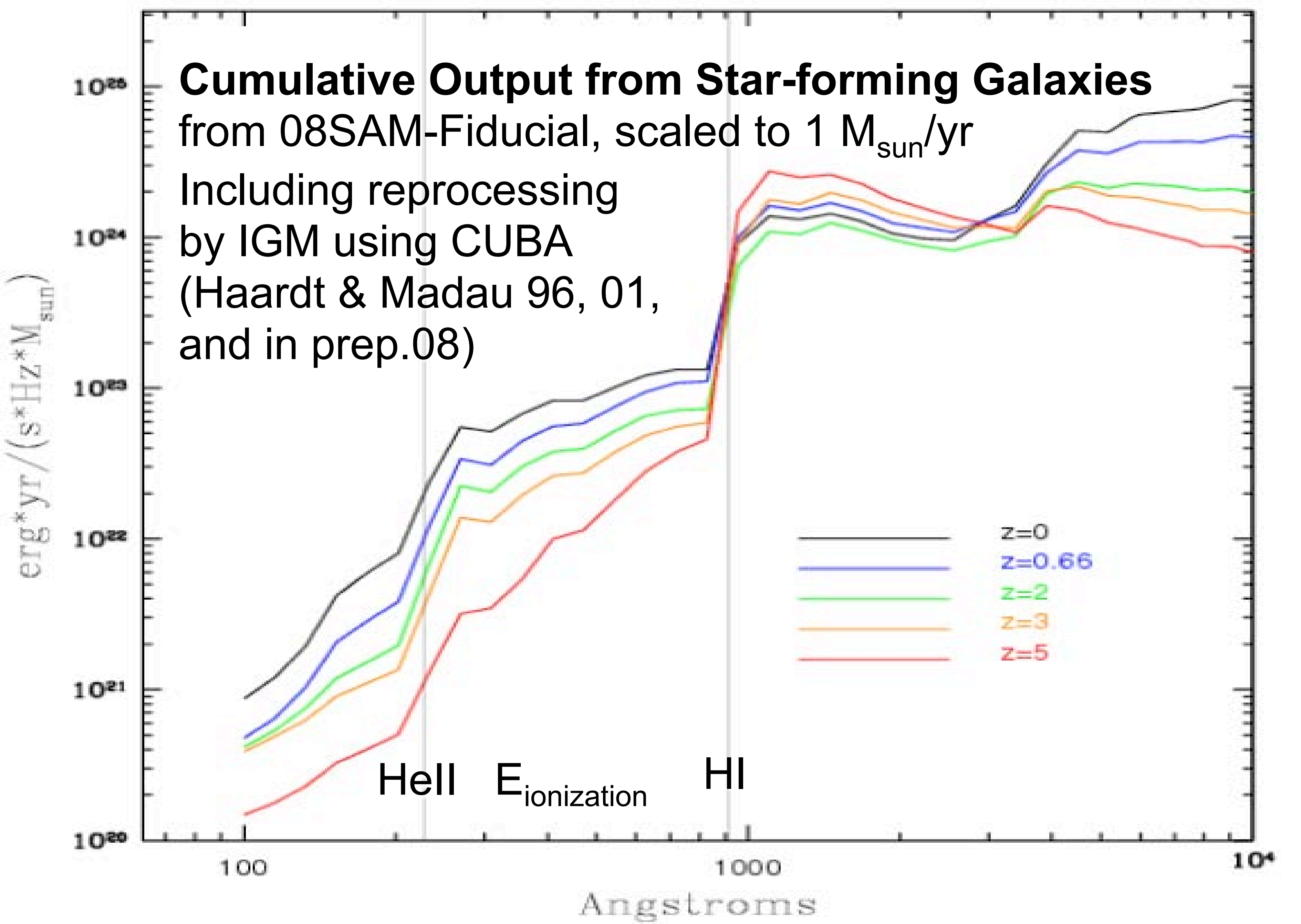
Gamma Ray Attenuation Due to **Fiducial** and Low Models



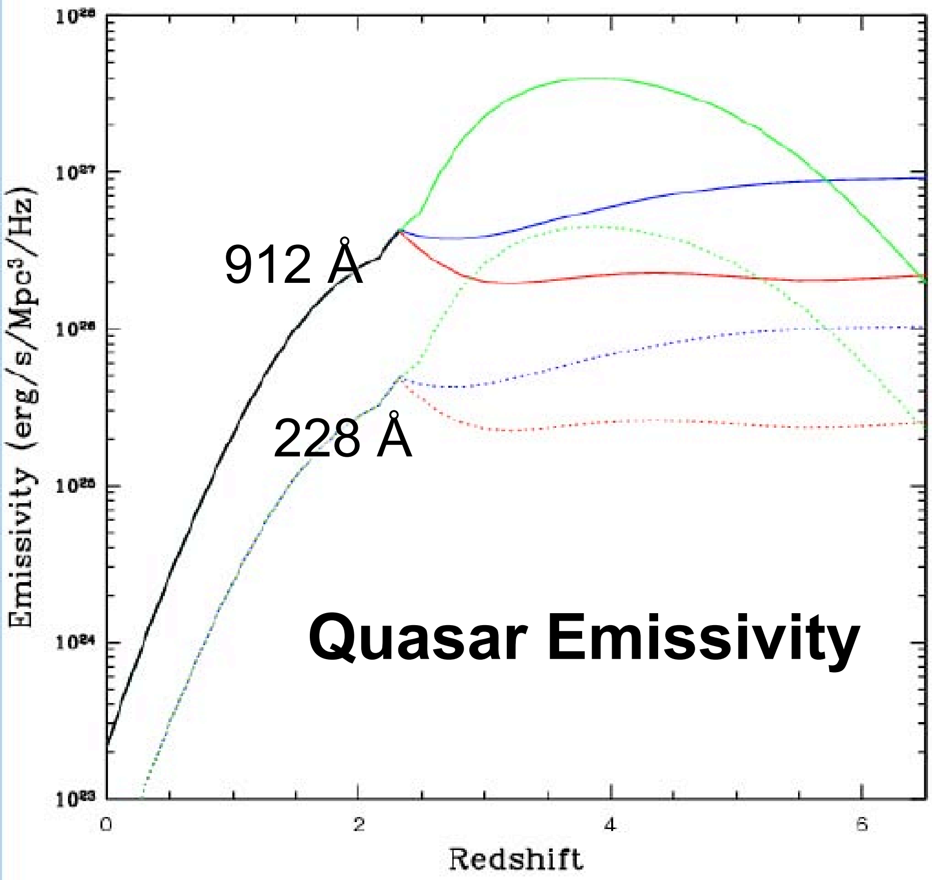


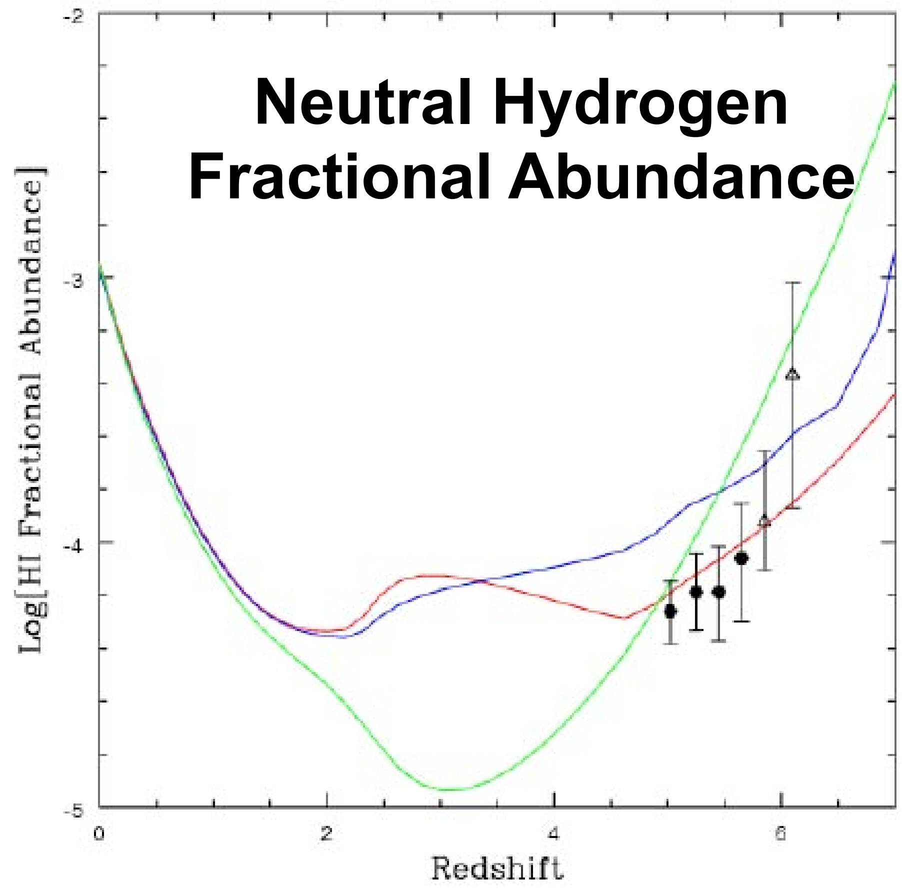
UV EBL and GLAST Gamma-Ray Attenuation

Little is known from direct measurements about the EBL at energies above the Lyman limit. Most ionizing photons from star-forming galaxies are absorbed by local cold gas and dust, with an uncertain fraction f_{esc} escaping to the intergalactic medium. Predicting optical depths to lower energy photons is further complicated by the fact that the attenuation edge for an optical depth of unity increases to redshifts of several, meaning that the evolution of ionizing sources must be understood to high redshift. Uncertainty in star-formation rates and efficiency, evolution of the quasar luminosity function and spectrum, and possibility of changing escape fraction or initial mass function make predicting optical depths for gamma rays at high redshift much more difficult than studies of local absorption at TeV energies. Here we consider three models, compare the ionization that they predict for hydrogen and helium with relevant observations, and show the predictions for gamma ray attenuation. **See also poster18 by Rudy Gilmore, Piero Madau, Rachel Somerville, and me.**



Cumulative Output from Star-forming Galaxies
from 08SAM-Fiducial, scaled to 1 M$_{sun}$/yr
Including reprocessing
by IGM using CUBA
(Haardt & Madau 96, 01,
and in prep.08)
HeII
E$_{ionization}$
HI
z=0
z=0.66
z=2
z=3
z=5
10^{25}
10^{24}
10^{23}
10^{22}
10^{21}
10^{20}
100
1000
10^4
Angstroms
erg*yr/(s*Hz*M$_{sun}$)

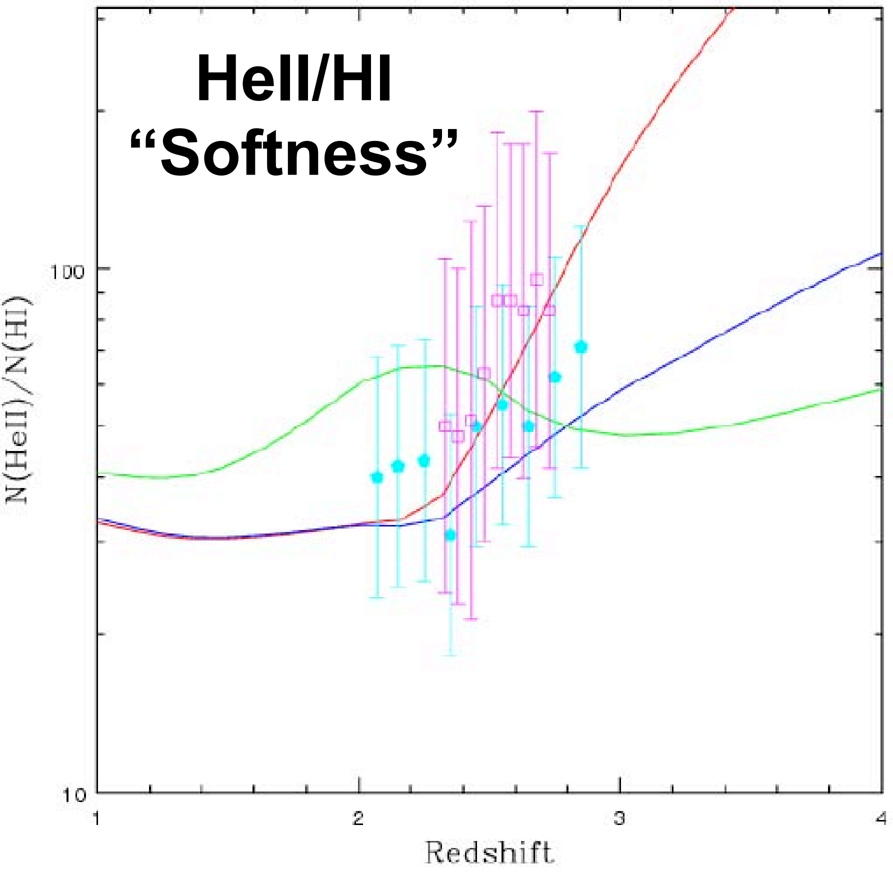


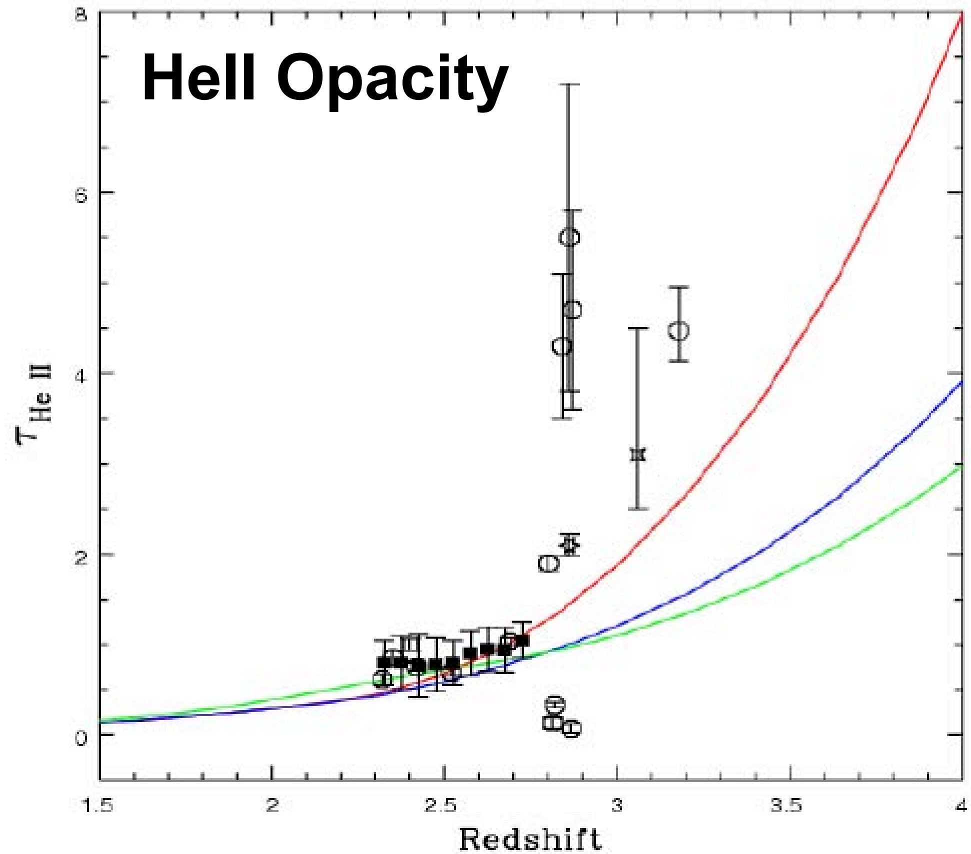


Model A (Red): Uses the 'A' quasar evolution model of Schirber and Bullock (2003) (S&B), with an evolving escape fraction for photons from star-forming galaxies that increases linearly from 0.05 at z=0 to 0.3 at z=5 (Siana+07), and is flat thereafter. Highest star/quasar ratio.

Model B (Blue): Uses the 'B' model of S&B, with a low escape fraction 0.05, and assumes that the star formation rate remains constant above z = 5, ⇒ more γ-ray attenuation for z>5.

Model C (Green): Uses S&B 'C' quasar model, together with a minimal stellar contribution to the ionizing background, with escape fraction 0.02 at all z. Most quasar-dominated.





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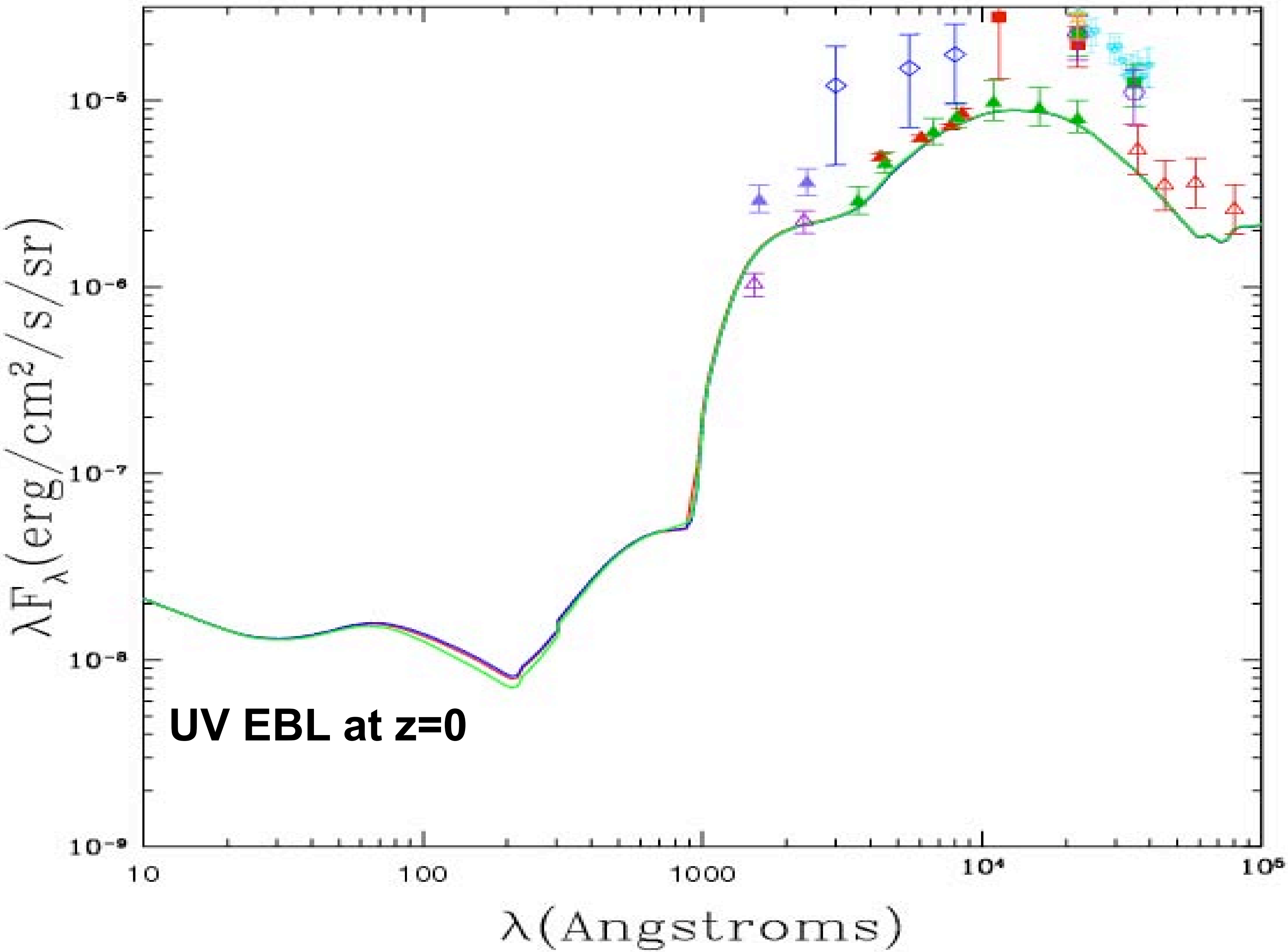
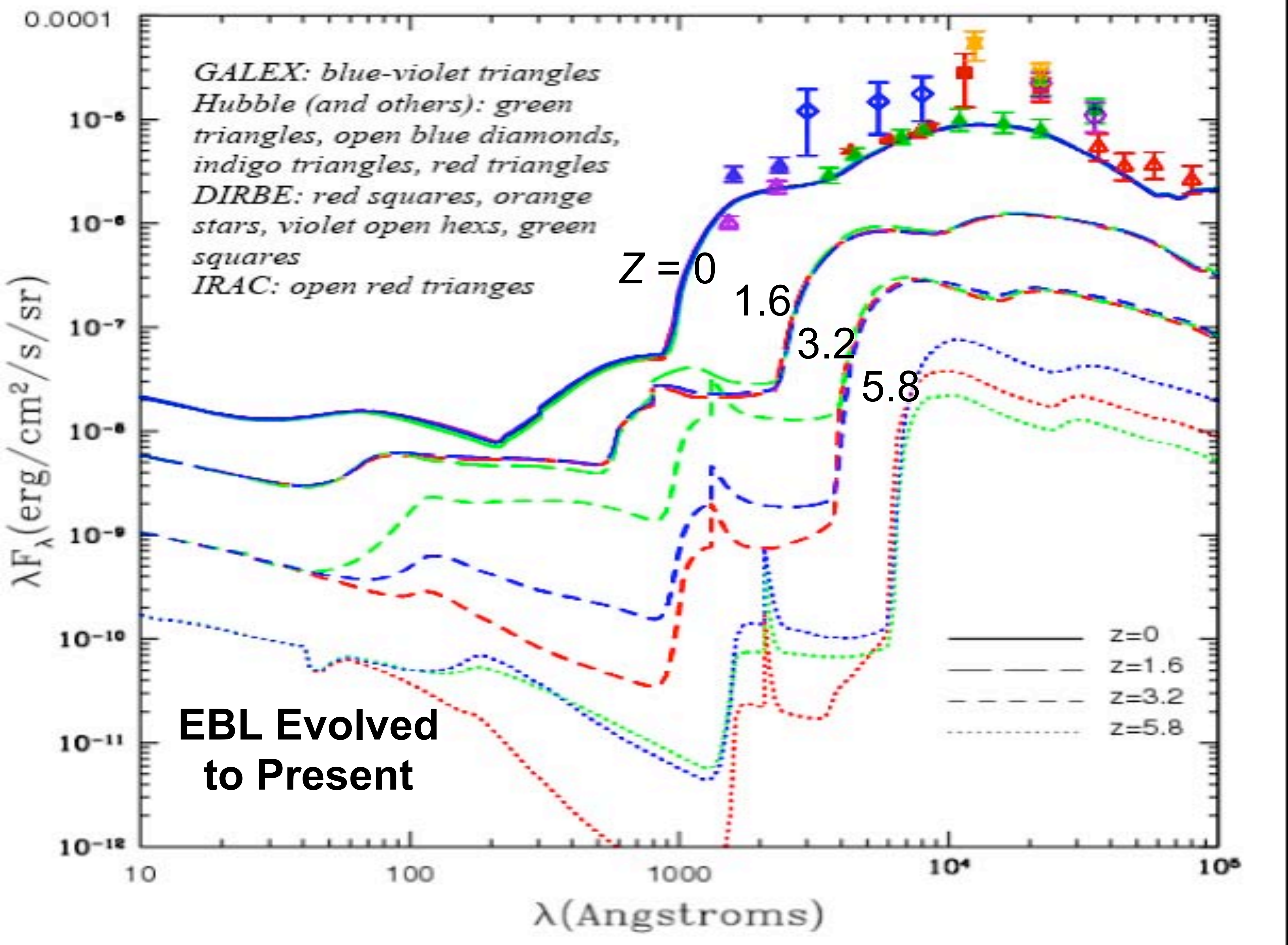
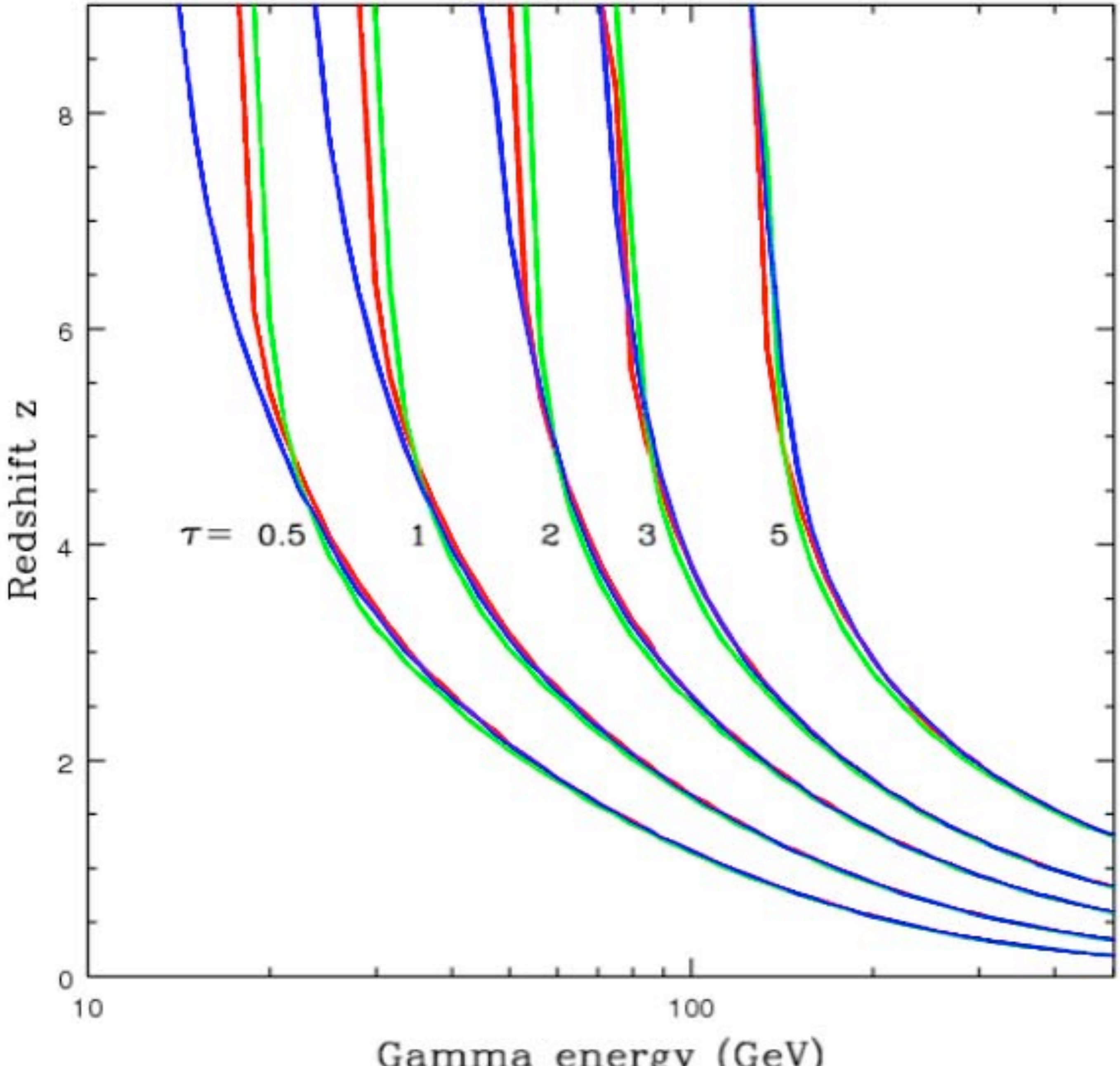


10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
λF_λ(erg/cm²/s/sr)
UV EBL at z=0
10
100
1000
10⁴
10⁵
λ(Angstroms)



GALEX: blue-violet triangles
Hubble (and others): green triangles, open blue diamonds, indigo triangles, red triangles
DIRBE: red squares, orange stars, violet open hexs, green squares
IRAC: open red trianges
Z = 0
1.6
3.2
5.8
z=0
z=1.6
z=3.2
z=5.8
EBL Evolved to Present
λF_λ(erg/cm²/s/sr)
λ(Angstroms)
0.0001
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10
100
1000
10⁴
10⁵

Gamma-Ray Attenuation Edge



Conclusions

- New self-consistent semi-analytic galaxy formation models based on physical scaling from numerical simulations and calibrated against empirical constraints now enable us to predict/interpret the relationship between galaxies, BH, and AGN across cosmic history.
- Such models accurately predict number counts and luminosity functions in all spectral bands and all redshifts except for sub-mm galaxies. They should therefore allow us to predict the EBL rather reliably.
- The predicted range of EBLs is consistent with the best estimates of EBL evolution inferred from observations.
- The UV EBL is more uncertain because we do not yet know the relative importance of ionizing radiation from AGN vs. stars and the redshift evolution of both, but we hope our three models will be helpful.