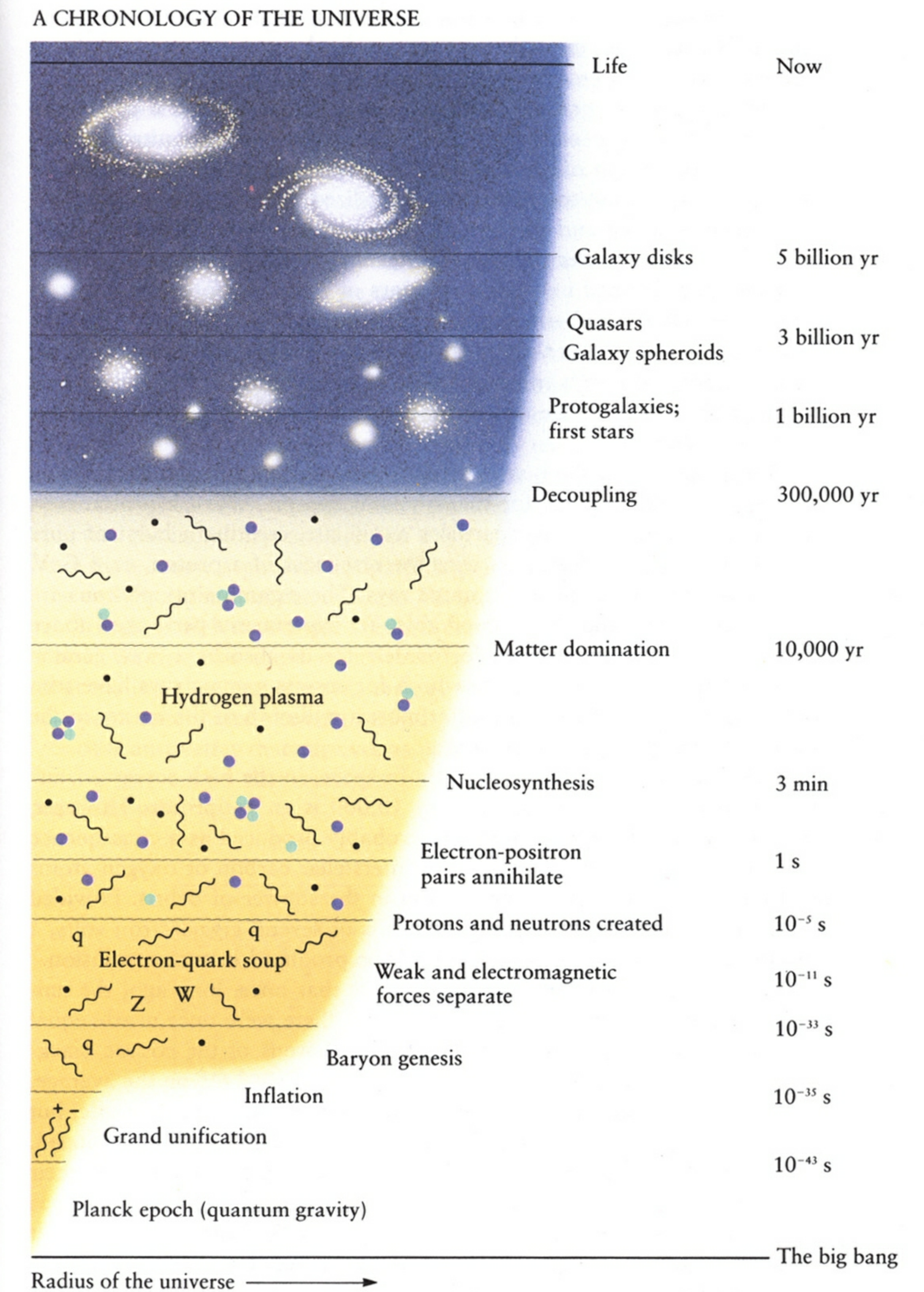
Growing galaxies from beginning to end

Lennox Cowie, IfA, U. Hawaii

Cartoon version of the growth of structure in the universe

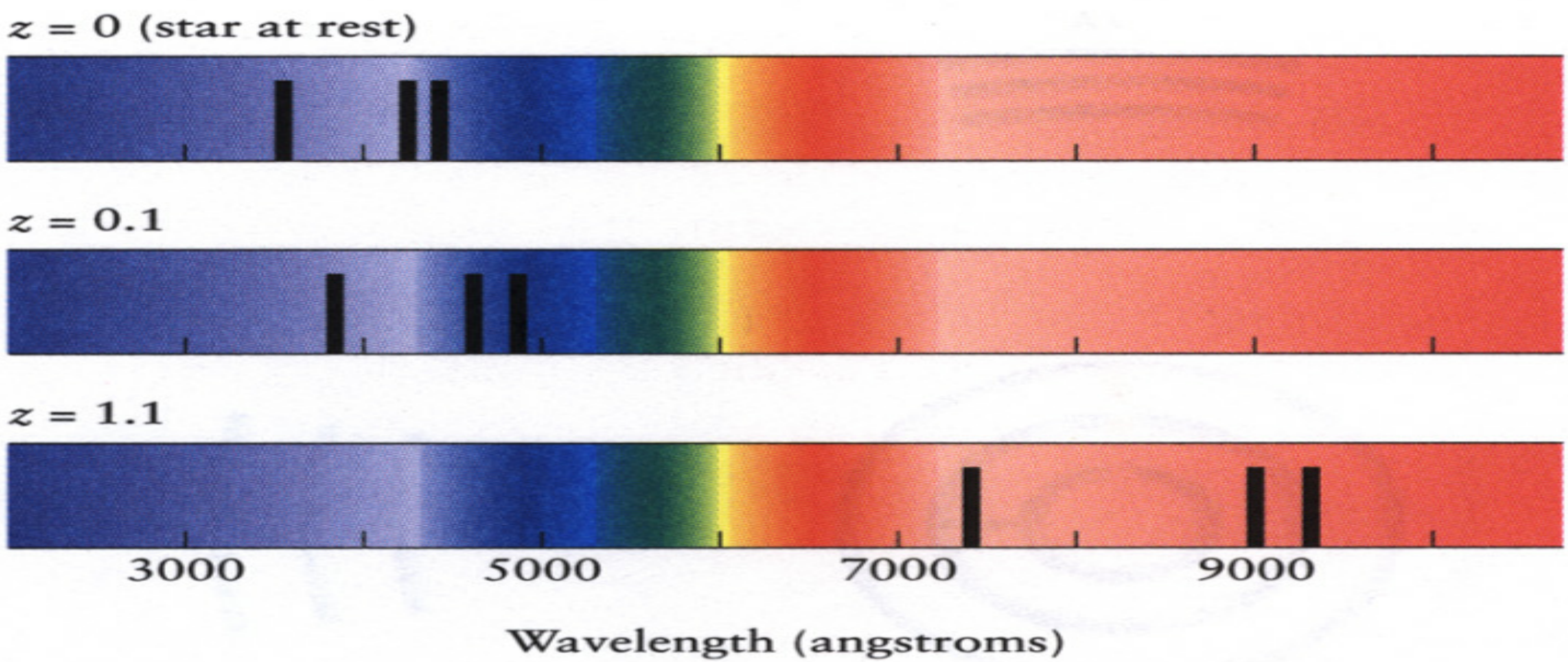


Redshift

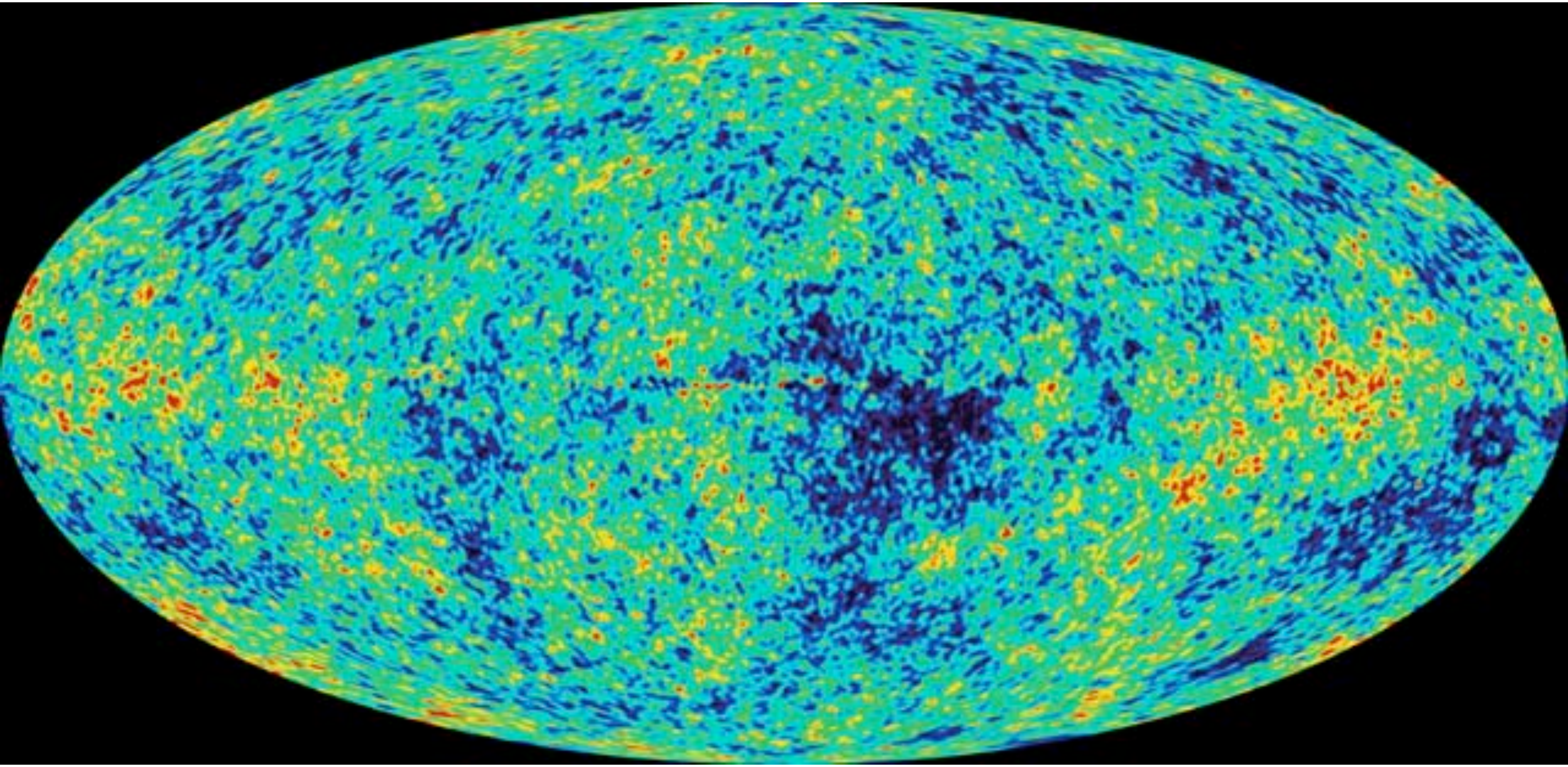
(1+z) = expansion factor

Redshift maps to distance, which maps to lookback time

at z>>1 t=0.8 Gyr ((1+z)/8)^(-1.5)
Current age = 13.7 Gyr (z=0)



How did we get from the tiny 1 part in 100,000 density fluctuations measured in the Cosmic microwave wave background at recombination

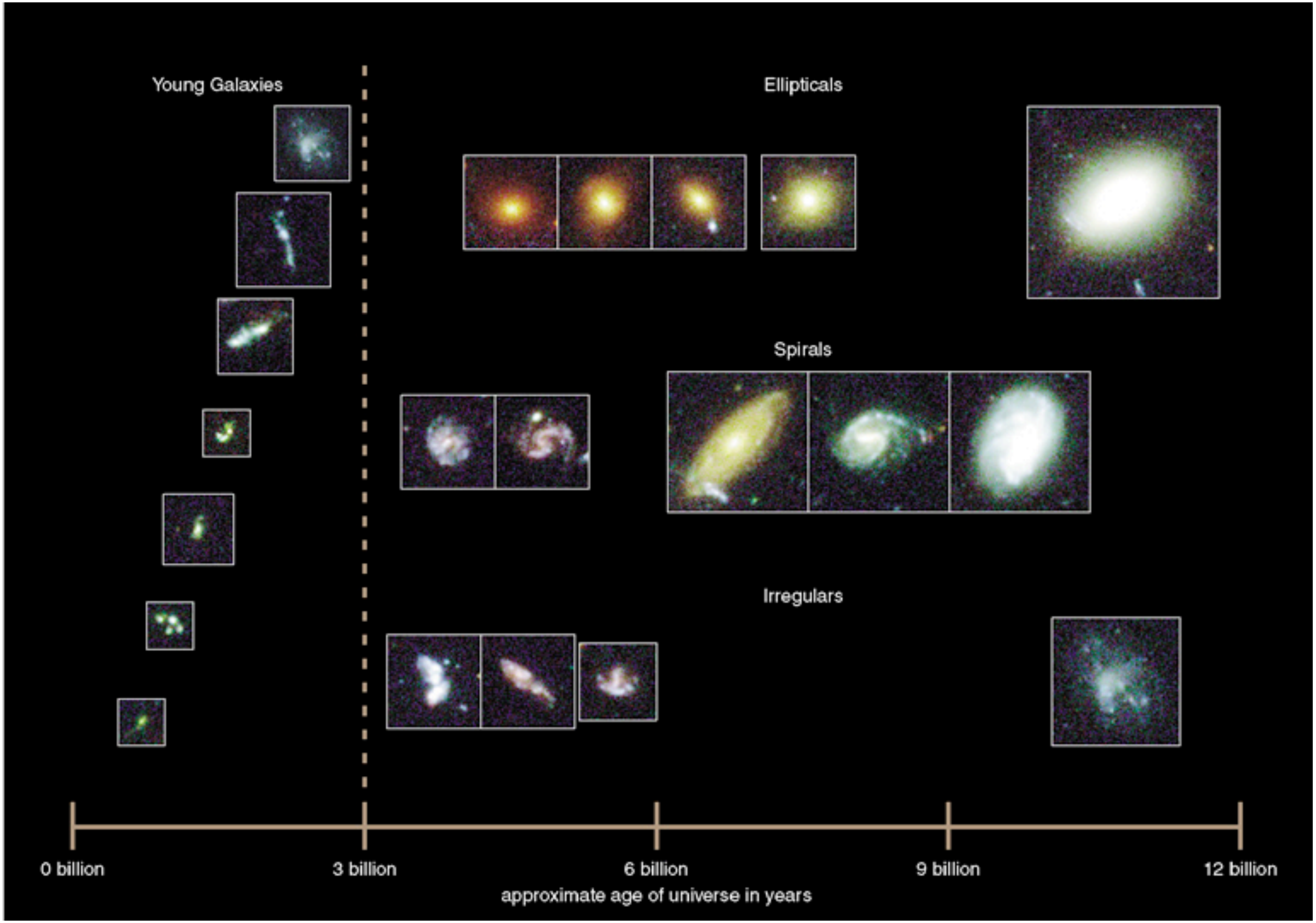


to the beautifully ordered structures we see today

E1

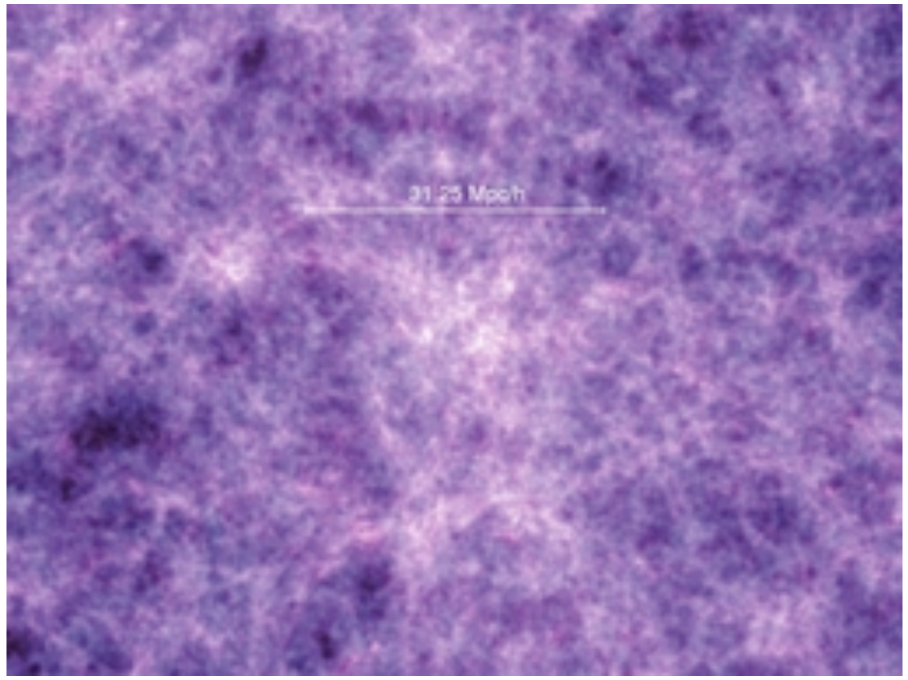
E6

GALAXIES LOOKED MUCH MESSIER AT

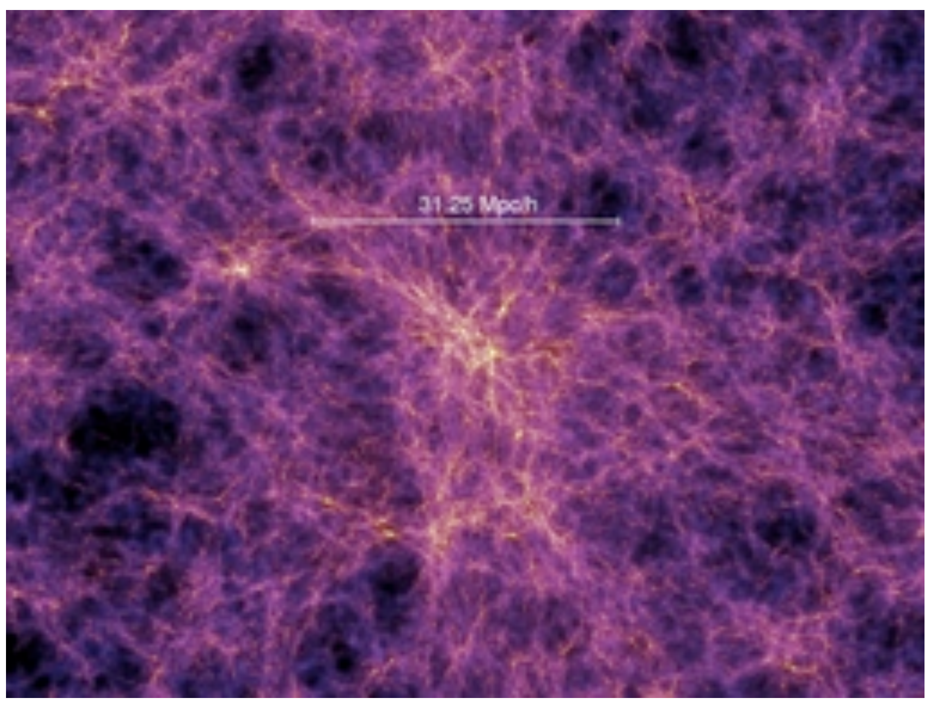


Mostly just gravity which grows a structure of filaments and nodes from the initial perturbations in the dark matter and the gaseous baryons

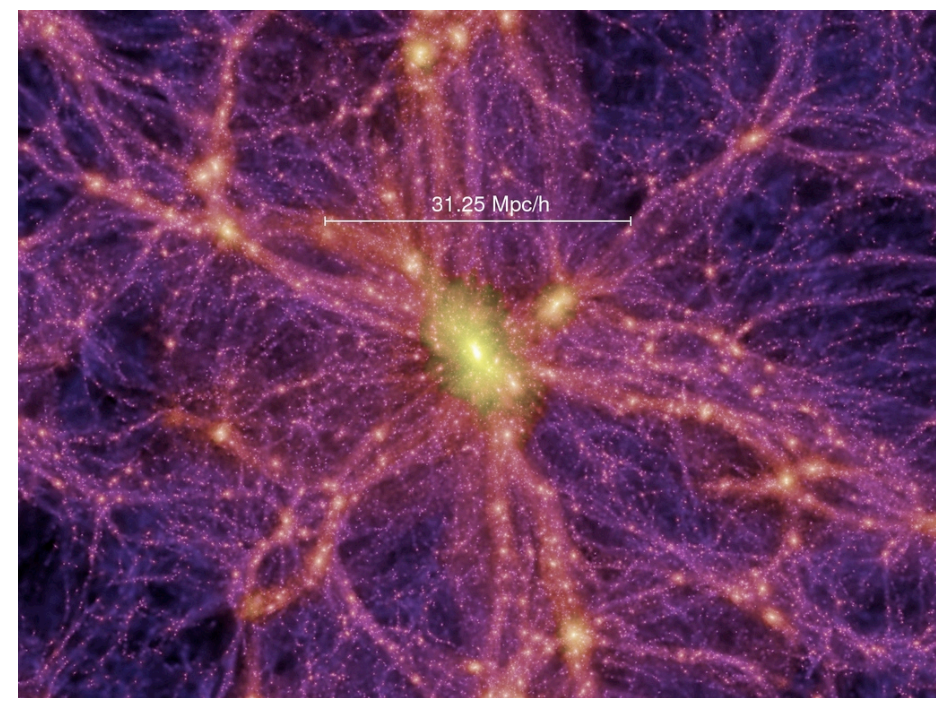
Z=18.3



Z=5.7



Z=0



Millenium Simulation

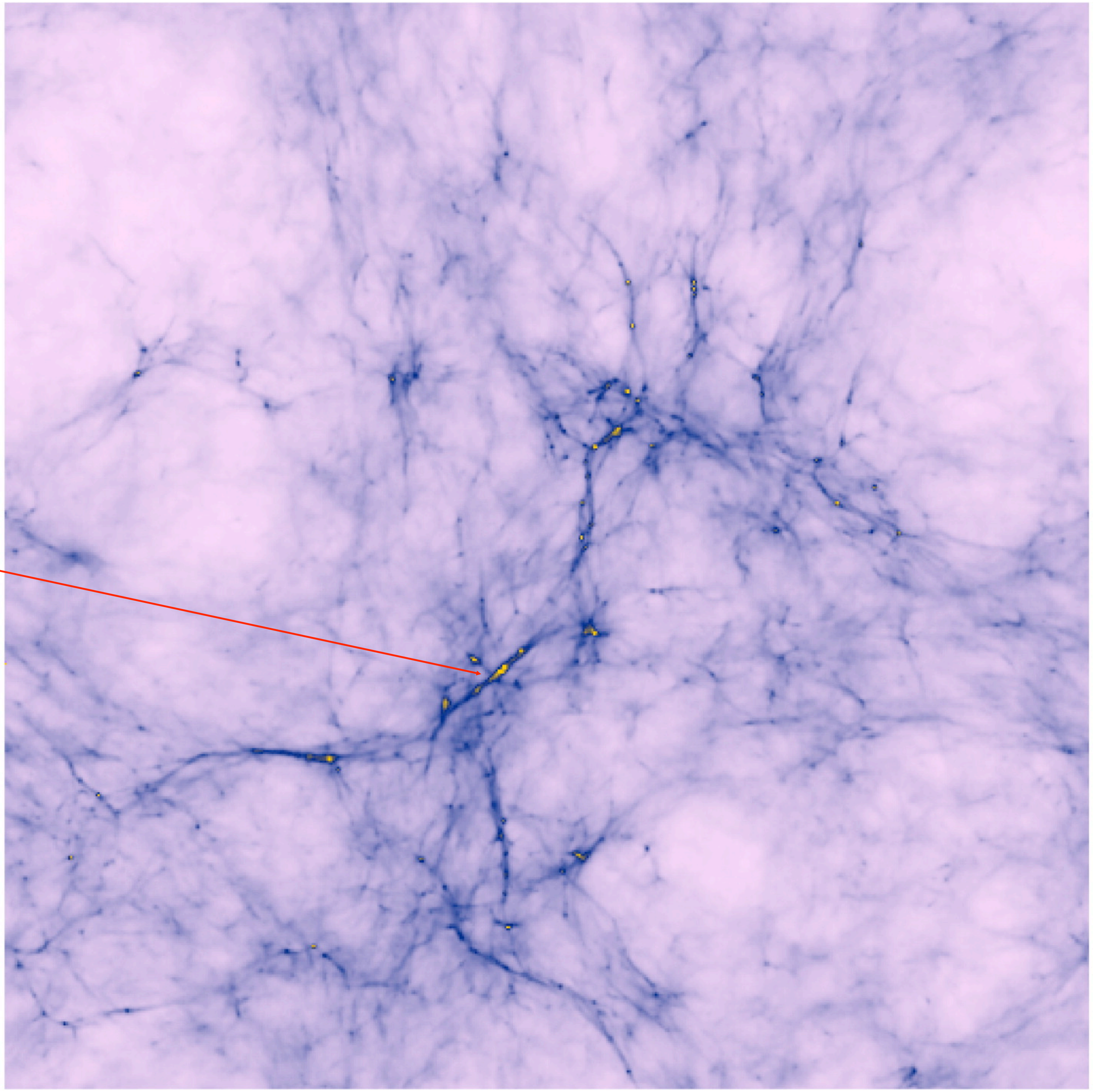
The first stars and galaxies form in the densest regions:

Yellow colors

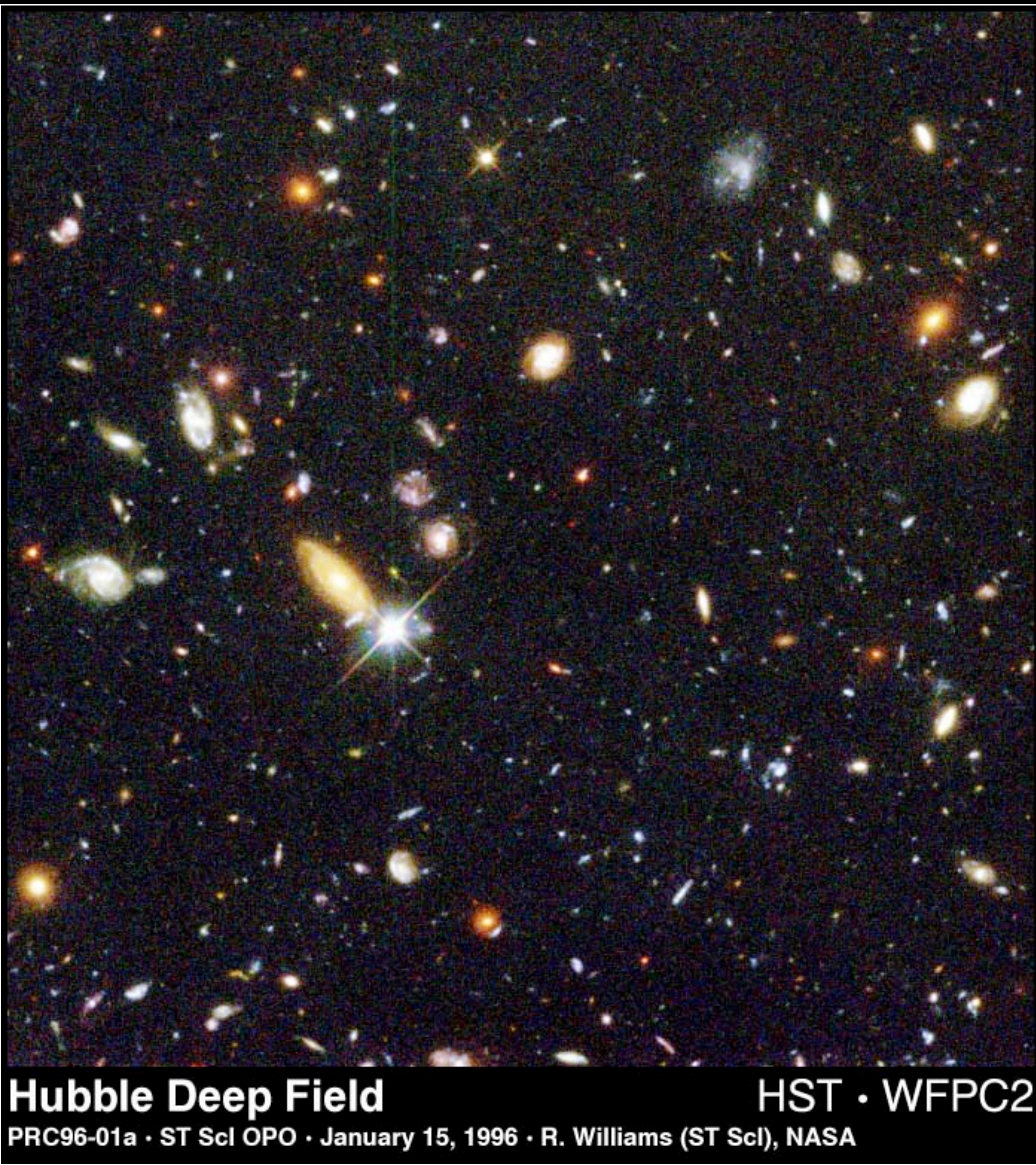
show

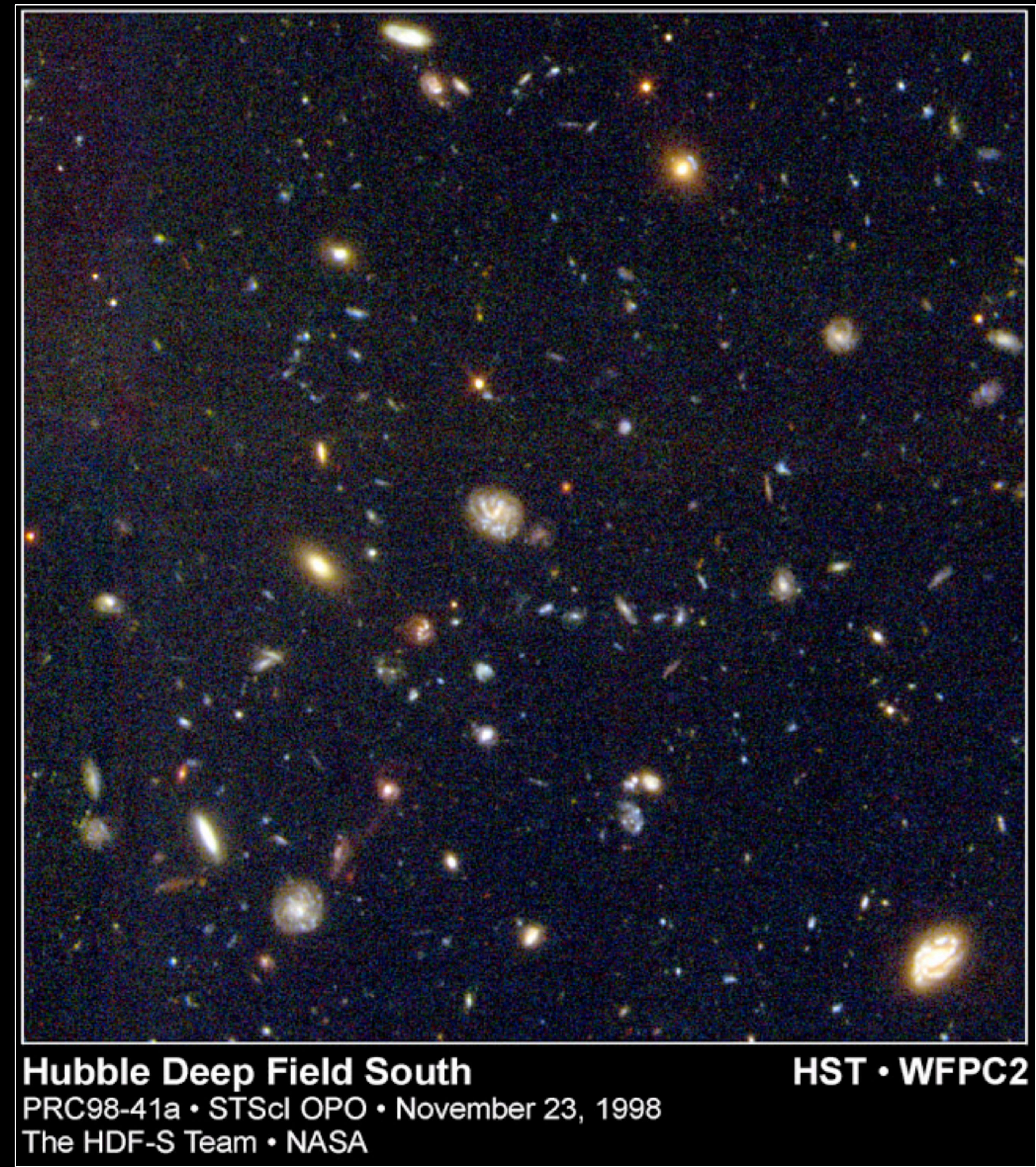
the forming

stars



The light of the universe is in





Galaxies are complex: it's very difficult to model their formation

Made up of:

Dark matter halos
Old and Young stars
Gas and Dust
Supermassive black holes

The formation of the star and black holes releases energy and modifies the environment : FEEDBACK (e..g. Ostriker and Cowie 1981)

High-redshift galaxies

In this talk I will try to outline the progress we have made in the last couple of decades in observing how galaxies form and evolve. Over the last 20-30 years the field has evolved from one with very little information to being incredibly rich and active. It would be impossible at this stage to cover all of the work going on so let me apologize in advance for all the material I'm going to miss and the many areas of research I'm going to short-change.

The road to high redshift

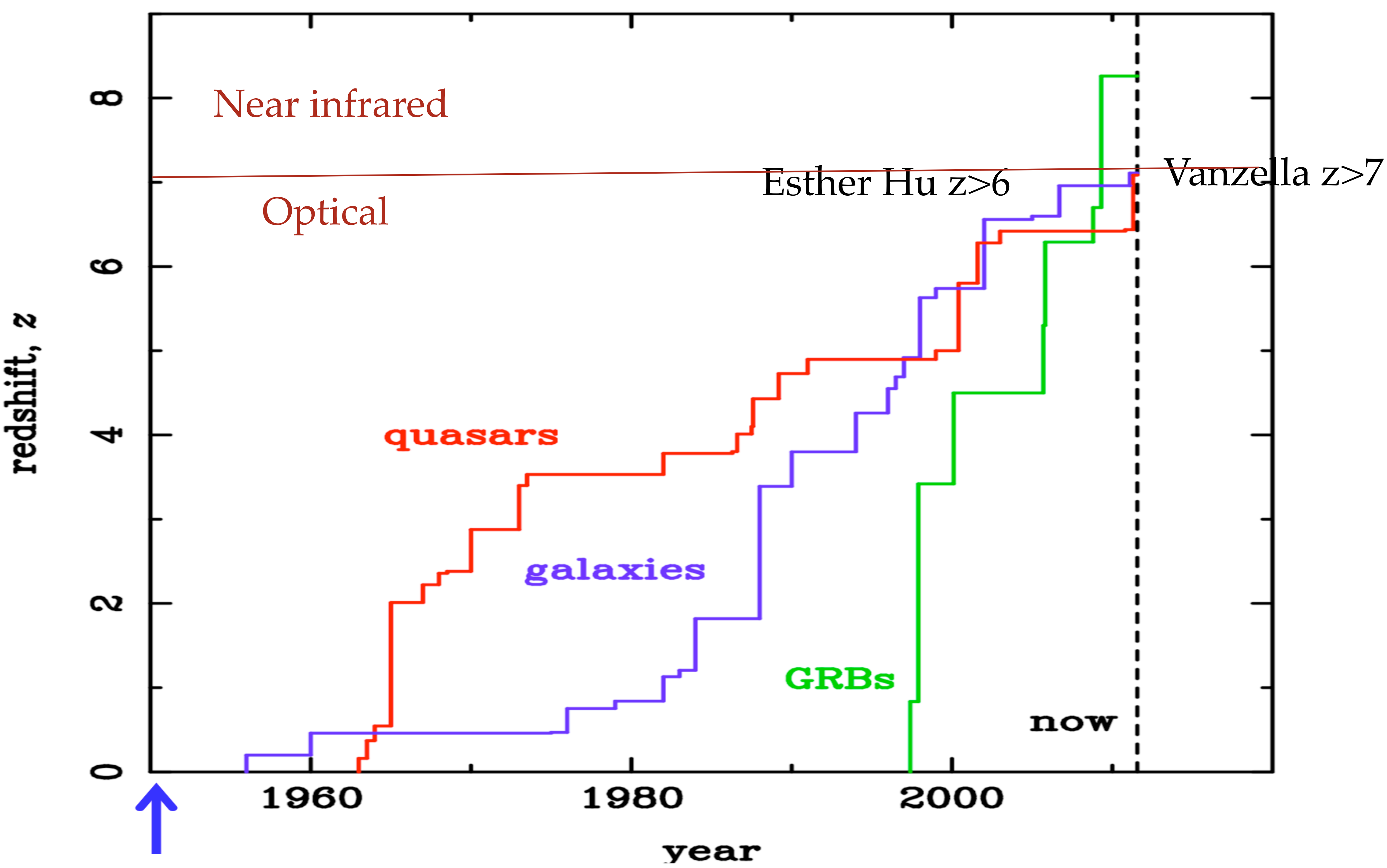


Figure adapted from Mortlock

Galaxy Populations at High Redshifts

While the most distant galaxies can provide valuable information, we must understand the more typical galaxy population at a given redshift in order to

Understand the cosmic star formation history

Understand the formation of present-day galaxies

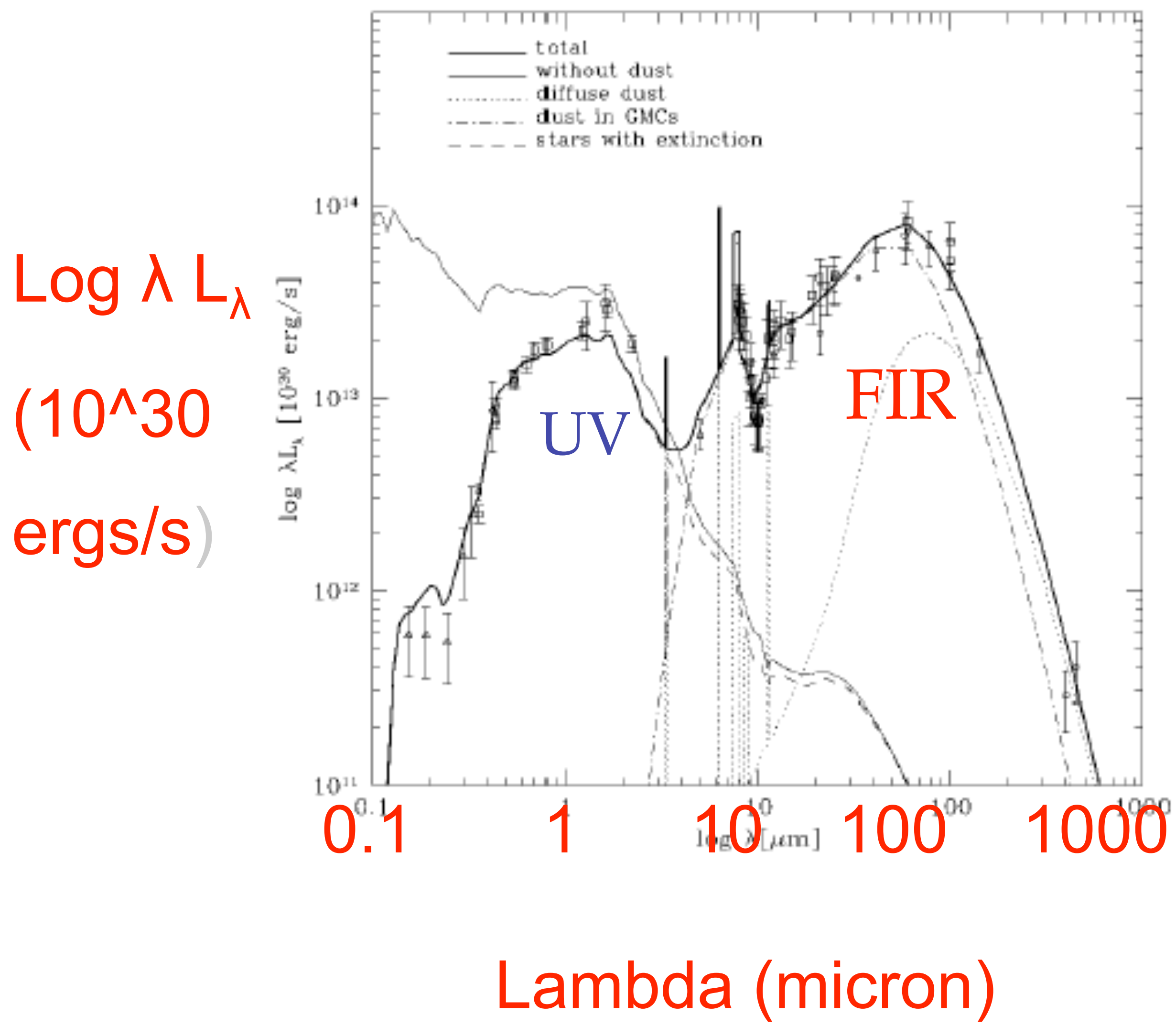
Compare with models

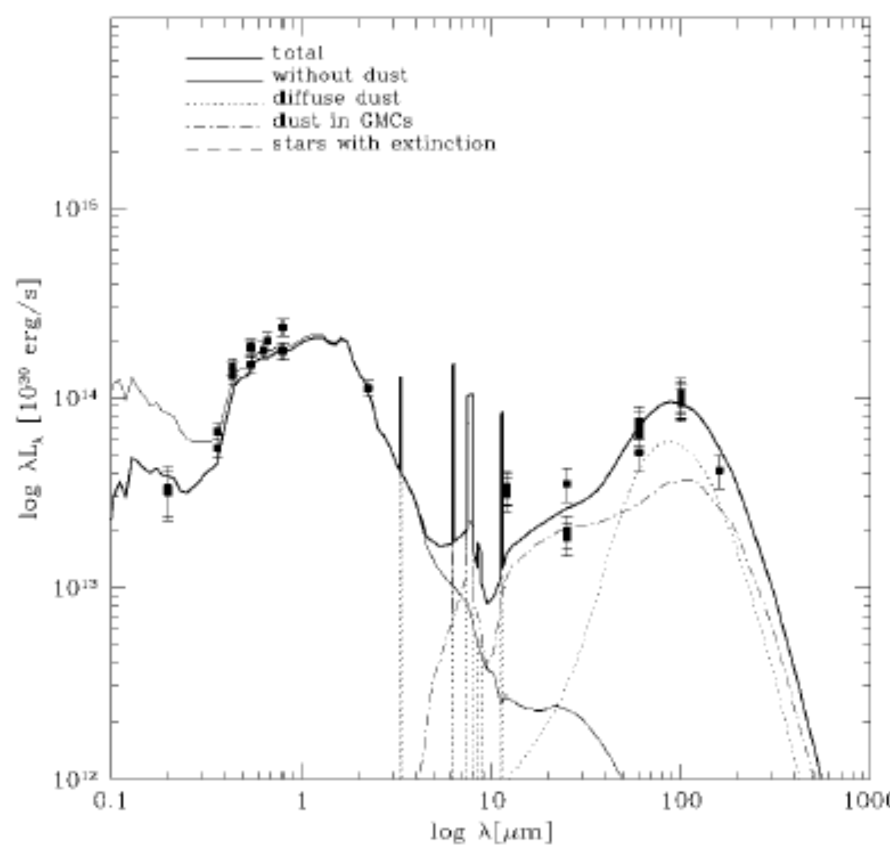
Place unusual sources in context

Massive stars in a galaxy radiate light in the ultraviolet

Part of this luminosity is absorbed by interstellar dust and re-emitted in the far-IR (10-300 micron)

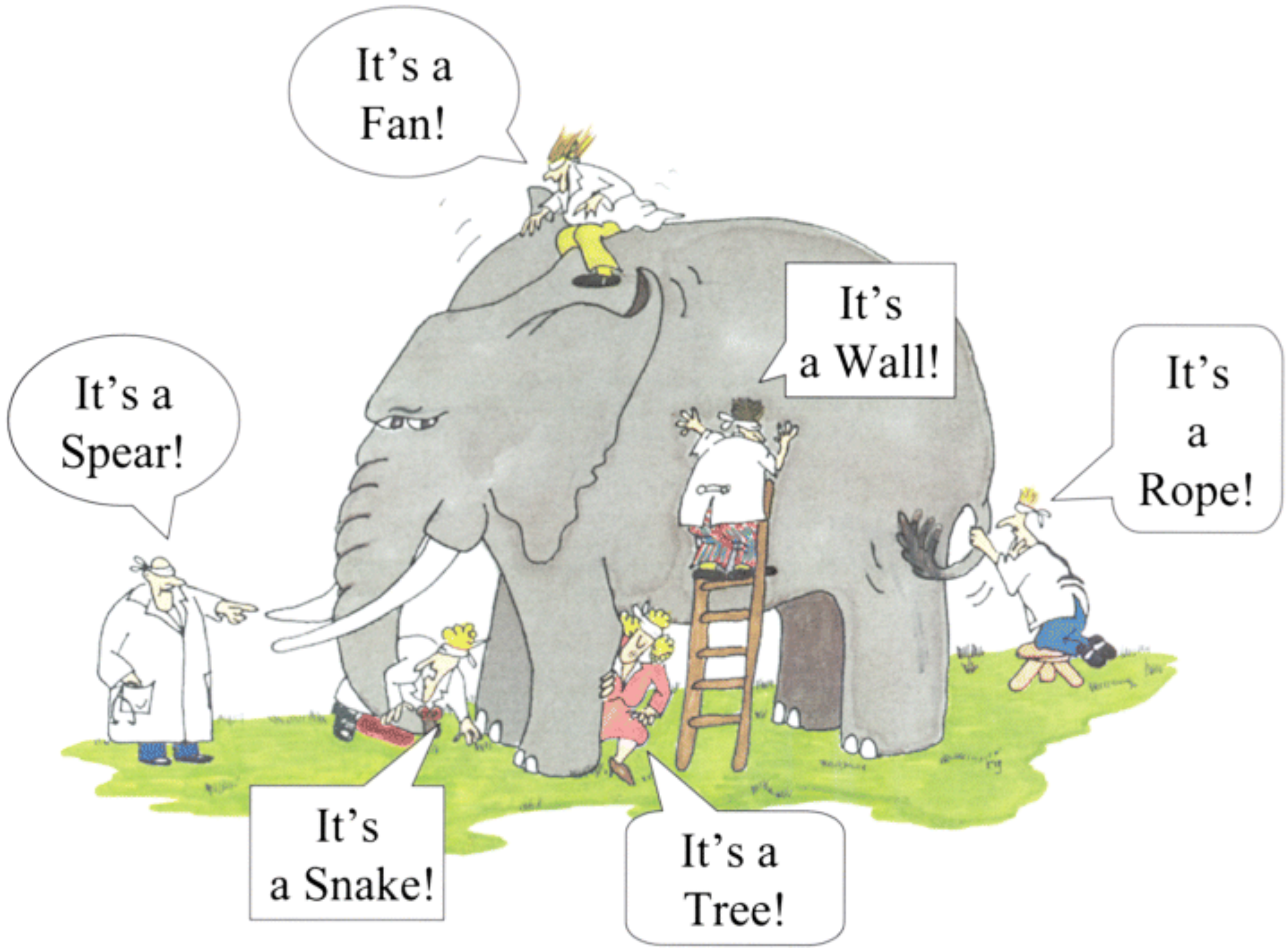
Very luminous (large) galaxies can have most of their radiation in the far-IR





Silva et al. 1998

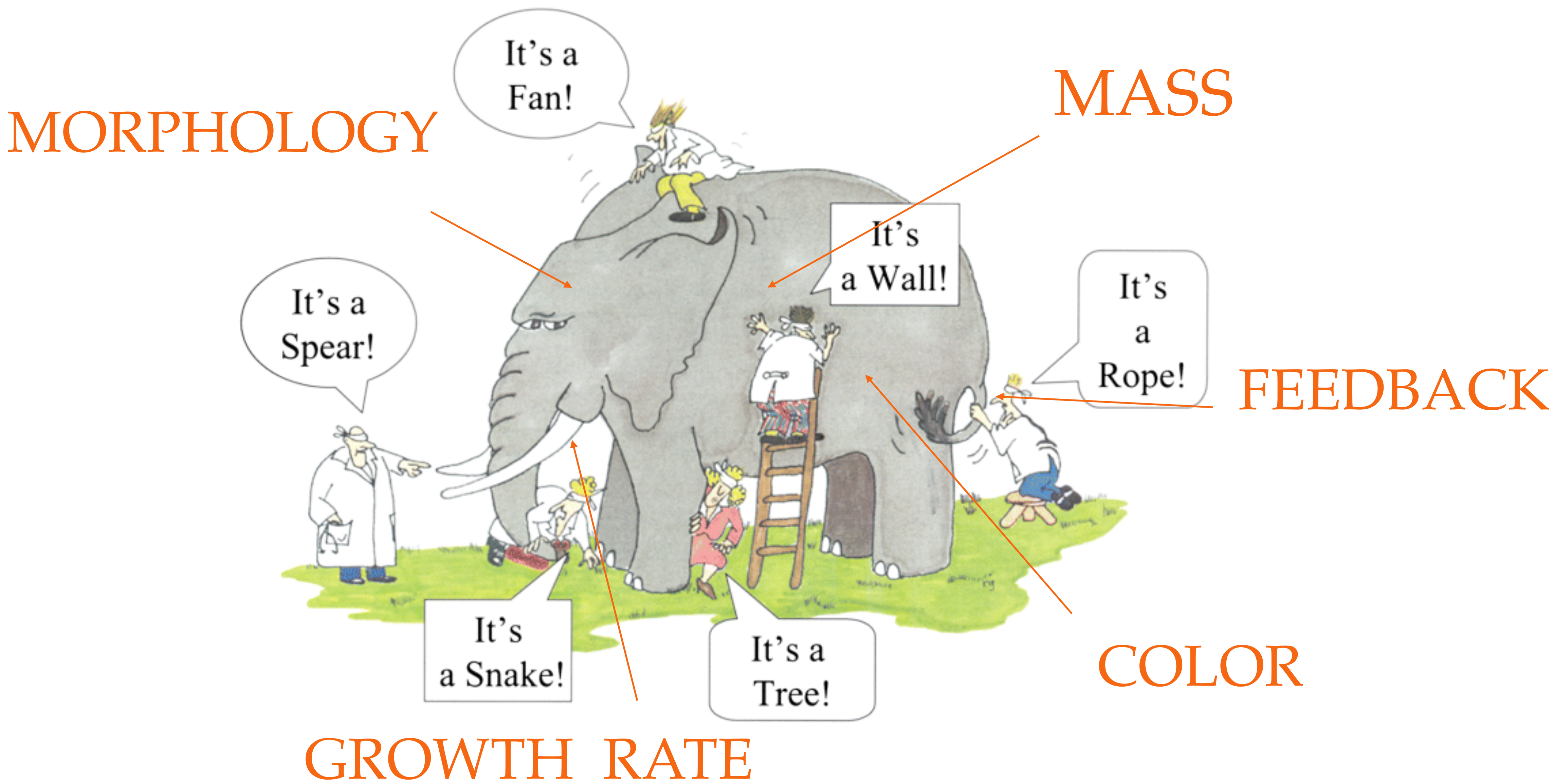
The blindfold people and the elephant



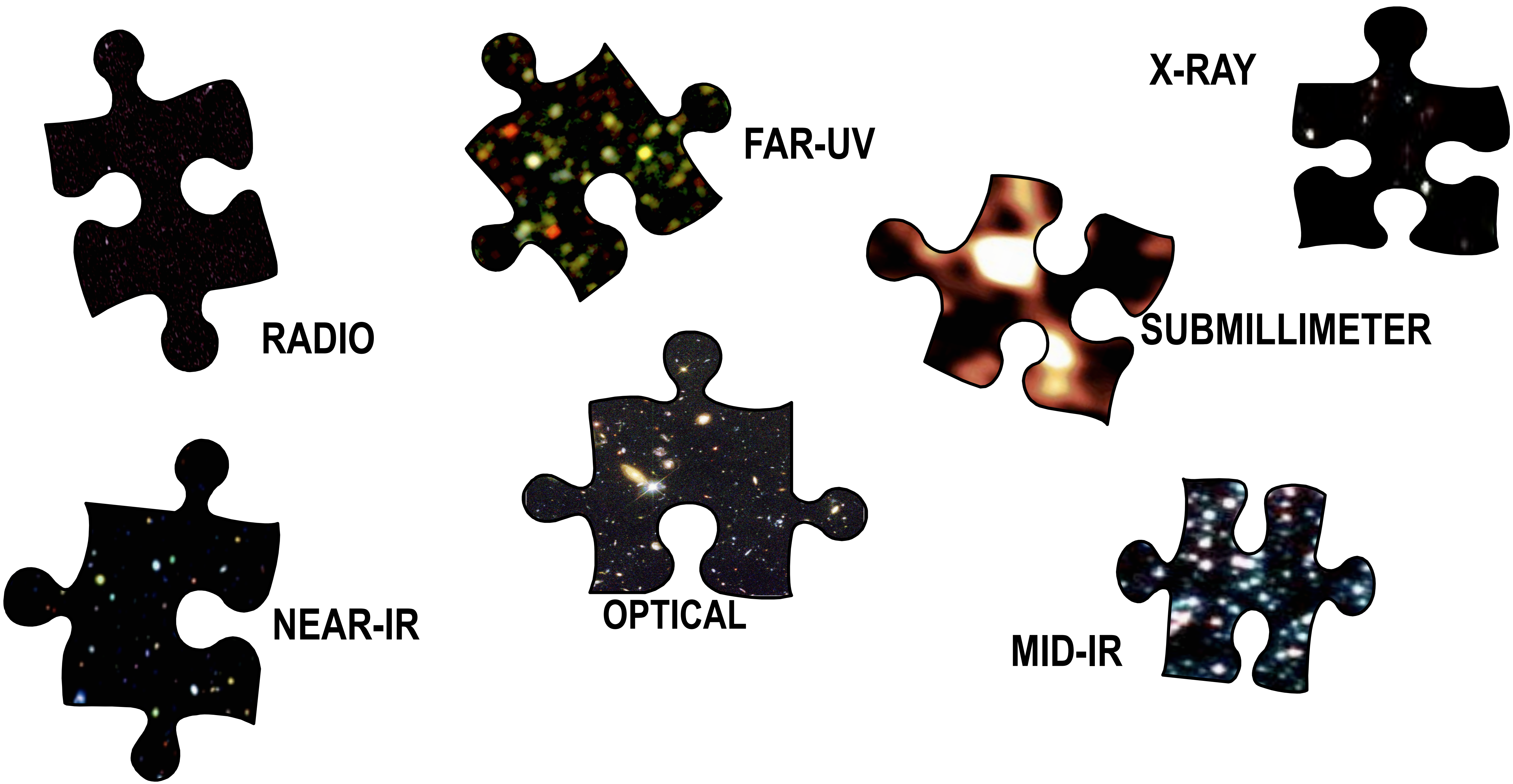
Acknowledgement to Sangeeta Malhotra

Cartoon from Nature

Astronomers and the elephant



The universe looks very different if we view it at different wavelengths....



Fundamental challenge

How do we put together all of the pieces to fully understand the history of star formation and mass assembly in galaxies?

- Where are the overlaps, and which pieces are we still missing due to our selections?
- How do supermassive black holes fit into the picture?

First we need a census

We can do this in two ways

1) We can look at all the light produced by the objects (the extragalactic background light or EBL)

2) We can count all the galaxies and active galactic nuclei (AGN) as a function of their luminosity

The Extragalactic Background Light

The *present* is the living *sum*-total of the whole *past*.

(*Thomas Carlyle)*

What does the EBL measure?

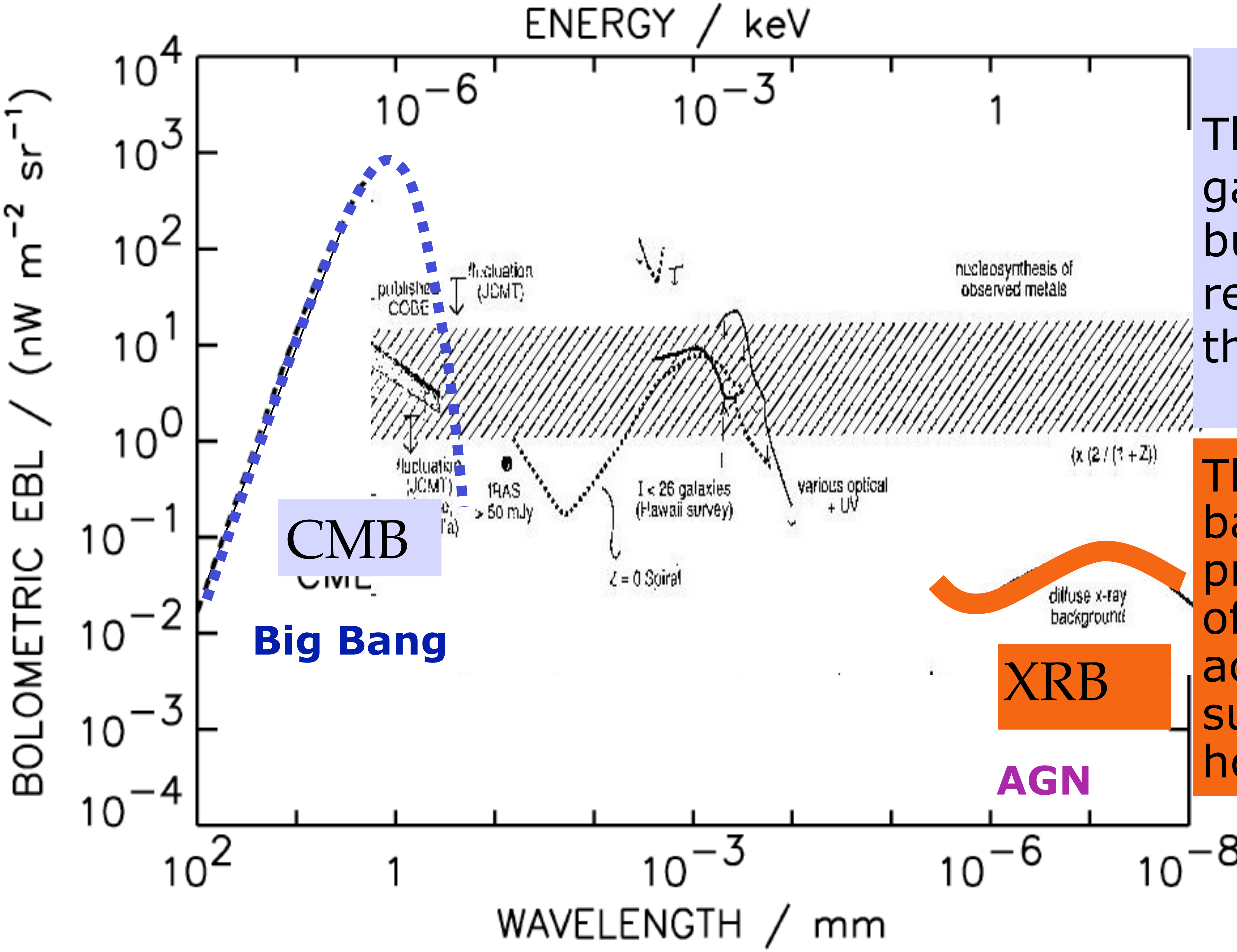
• The EBL is an integral of the total light production

• However, early light production contributes less to the EBL because of photon adiabatic expansion losses

$$I_{\mathrm{EBL}} = \frac{c}{4\pi} \int_0^{t_H} \frac{\rho_{\mathrm{bol}}(t)}{1+z} dt$$

Extragalactic Background Light circa 1990

(from Cowie 1991 Physica Scripta T36 102)

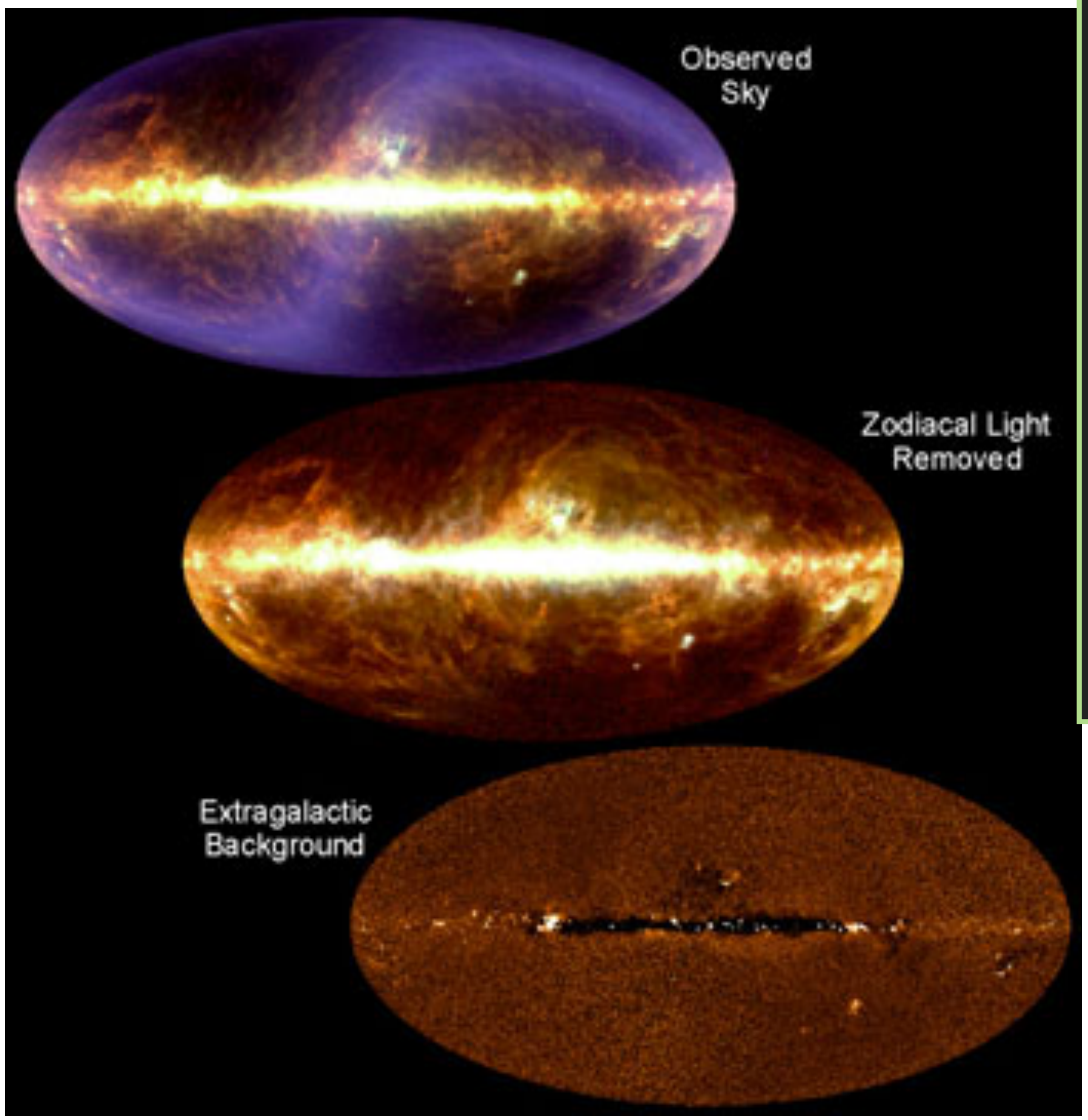


The CMB is not from galaxy light but rather from recombination of the gas

The X-ray background is primarily made up of AGN powered by accretion onto supermassive black holes

Submillimeter/Far-Infrared EBL

COBE/DIRBE



Hauser et al 1998

From FIRAS:

The submm EBL at 850 µm:
31 Jy/deg^2 (Puget et al. 1996)
44 Jy/deg^2 (Fixsen et al. 1998)

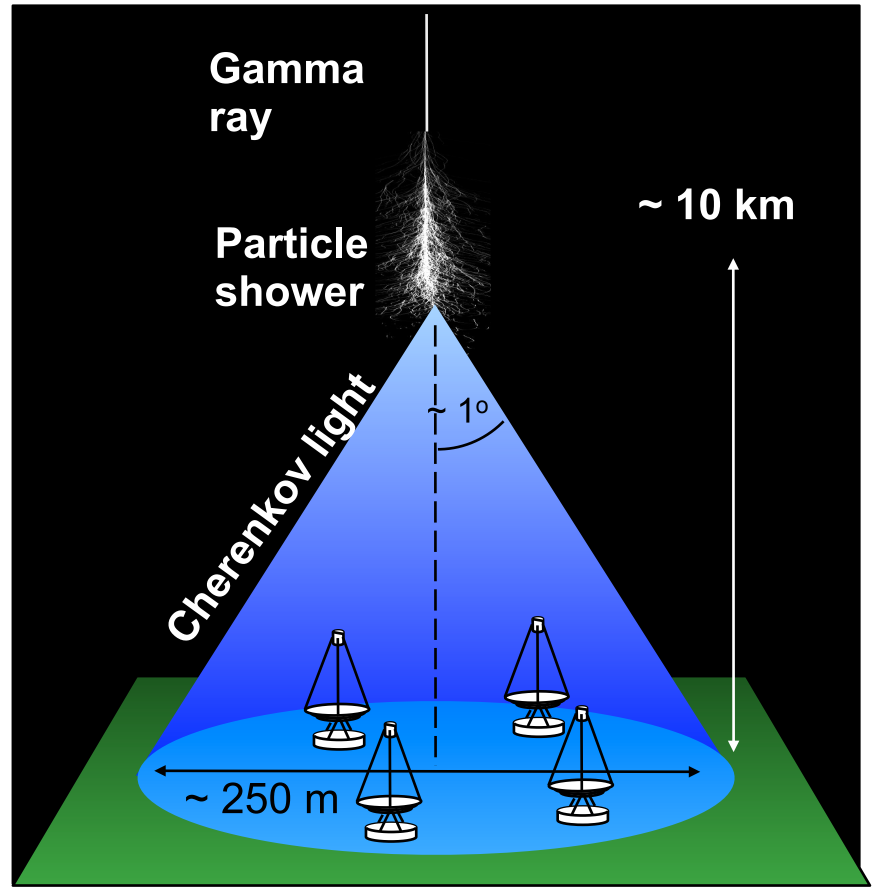
Uncertainties from foreground subtraction

Measuring the NIR/optical EBL with Tev Gamma rays

(Slide from HESS presentations)

High Energy Stereoscopic System (HESS) Windhoek, Namibia

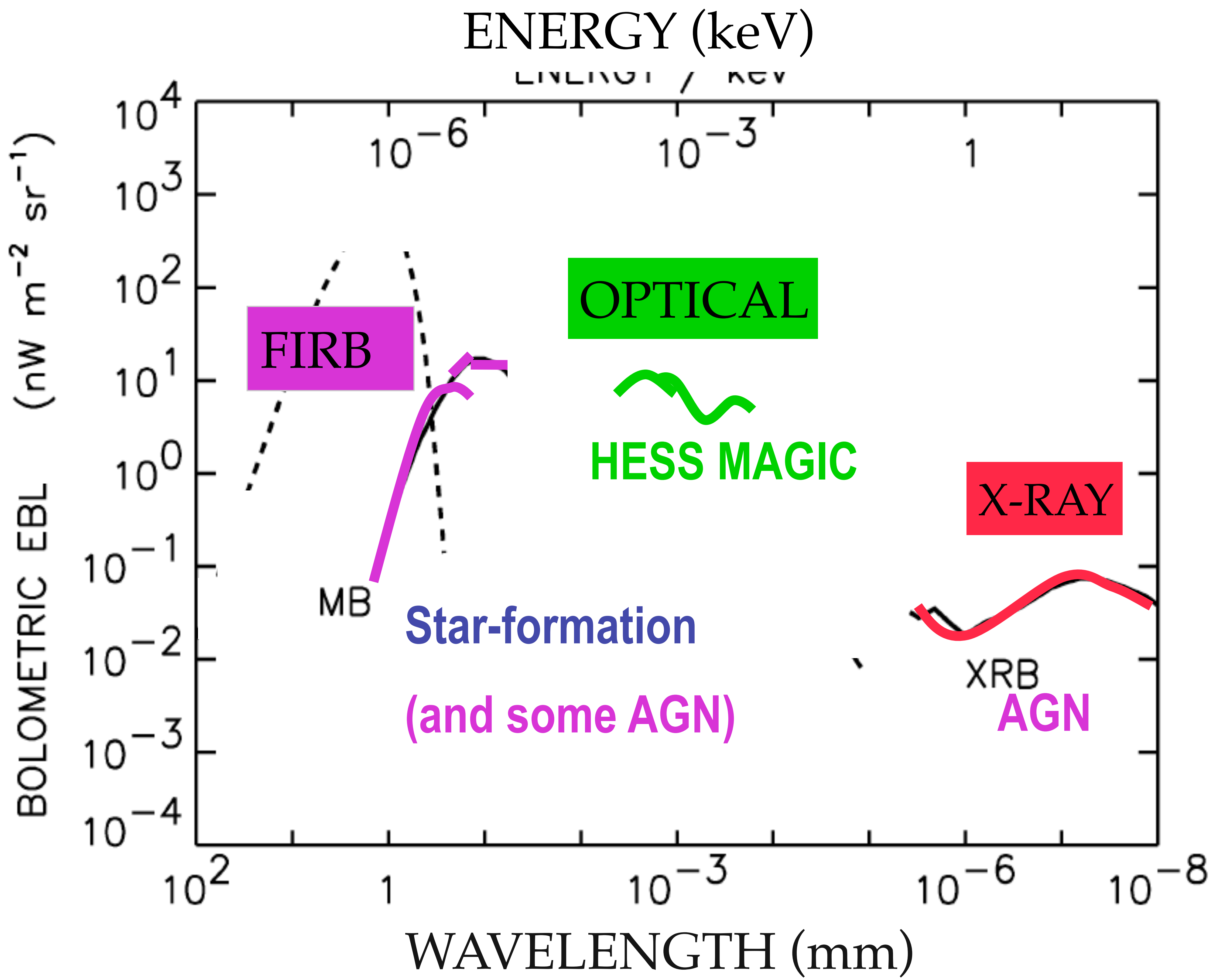
Array of 4 telescopes detecting Cerenkov radiation (particles moving faster than speed of light in air)



High-energy gamma rays are absorbed and converted into secondary particles forming an ‘air shower’. Cerenkov light is generated, a faint beam of blue light, which on the ground illuminates an area of about 250 m in diameter. The faint flash lasts a few billionths of a second

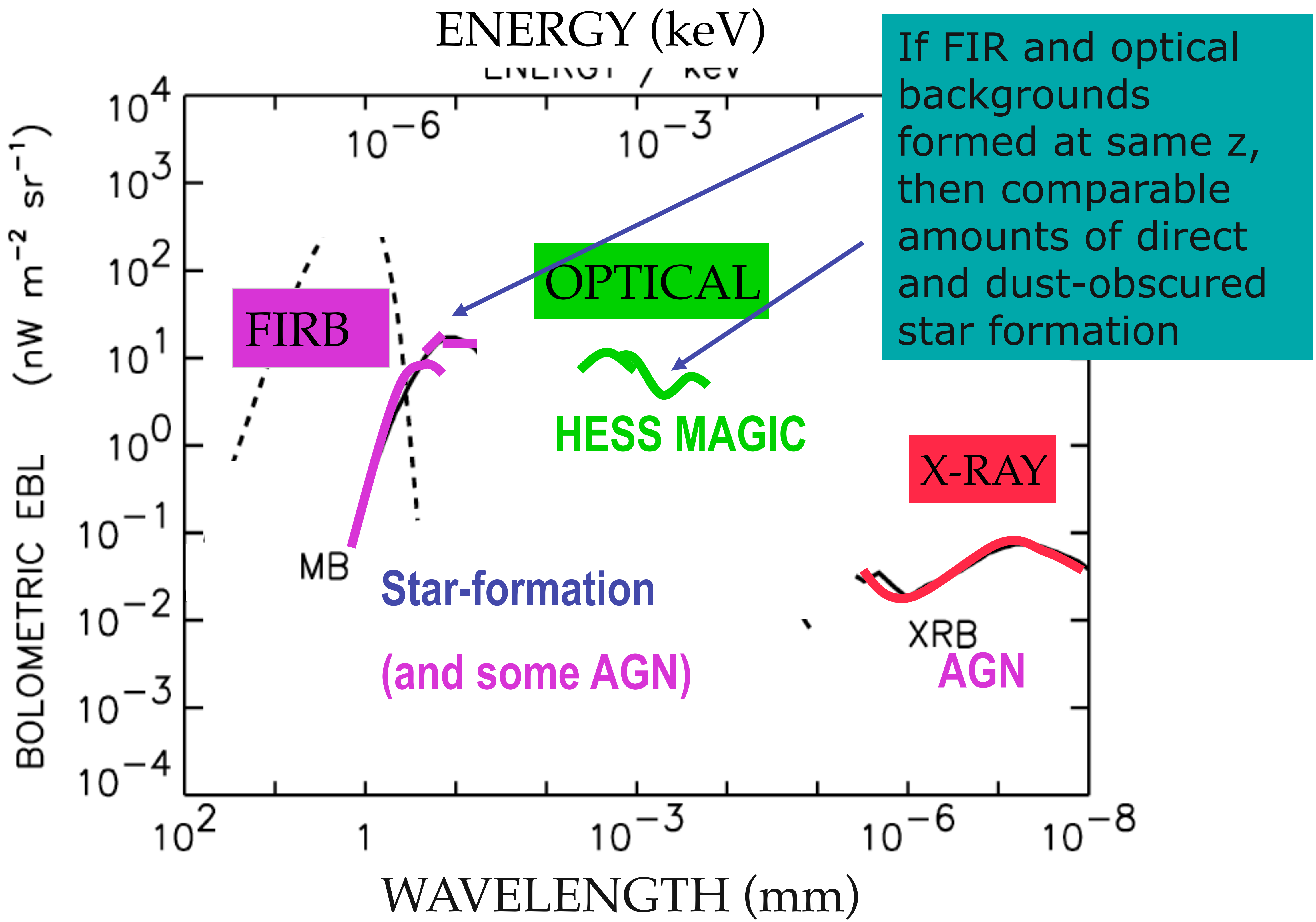
Gamma rays interact with 1-10 μm IR photons via pair creation process $(\gamma\gamma \rightarrow e^+e^-)$ producing absorption features in distant sources (e.g. blazars). Strength of the absorption indicates the ambient IR photon background (EBL)

Extragalactic Background Light circa 2010



HESS and MAGIC measurements from the summary of Mazin 2009

Extragalactic Background Light circa 2010

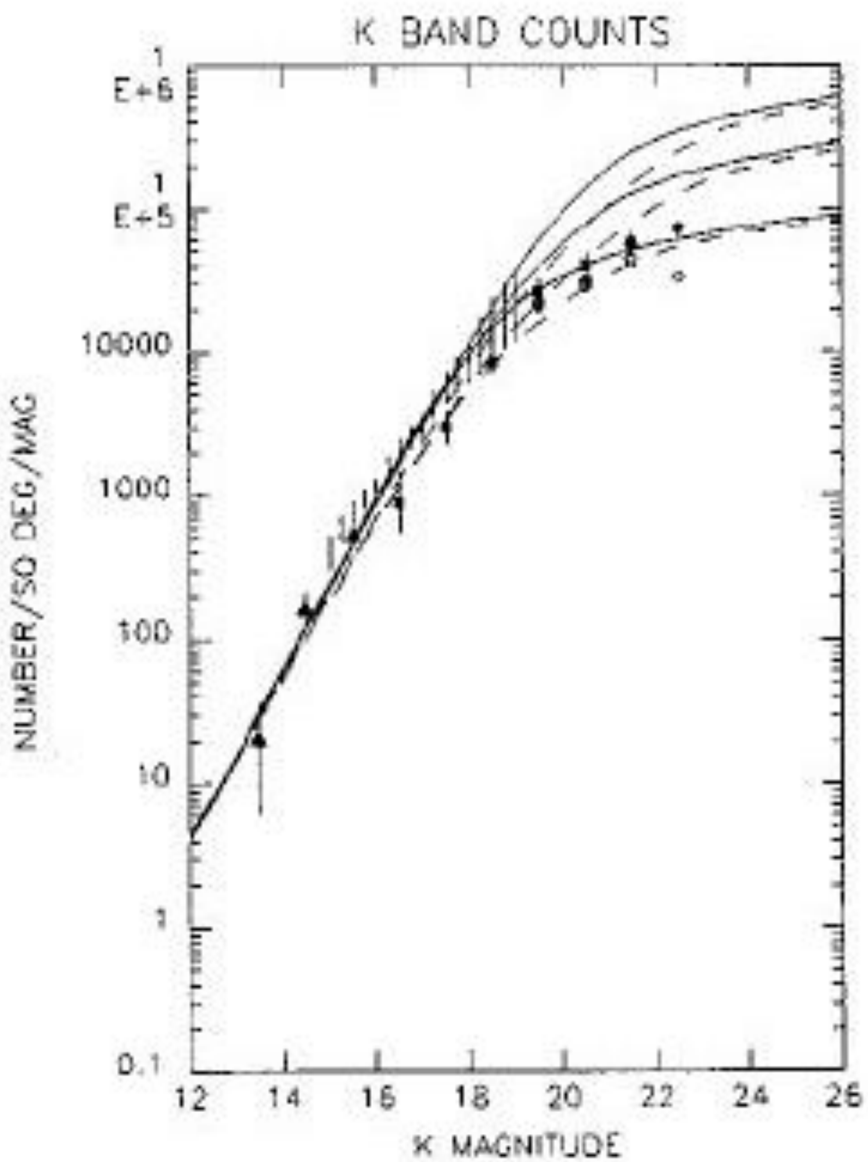


HESS and MAGIC measurements from the summary of Mazin 2009

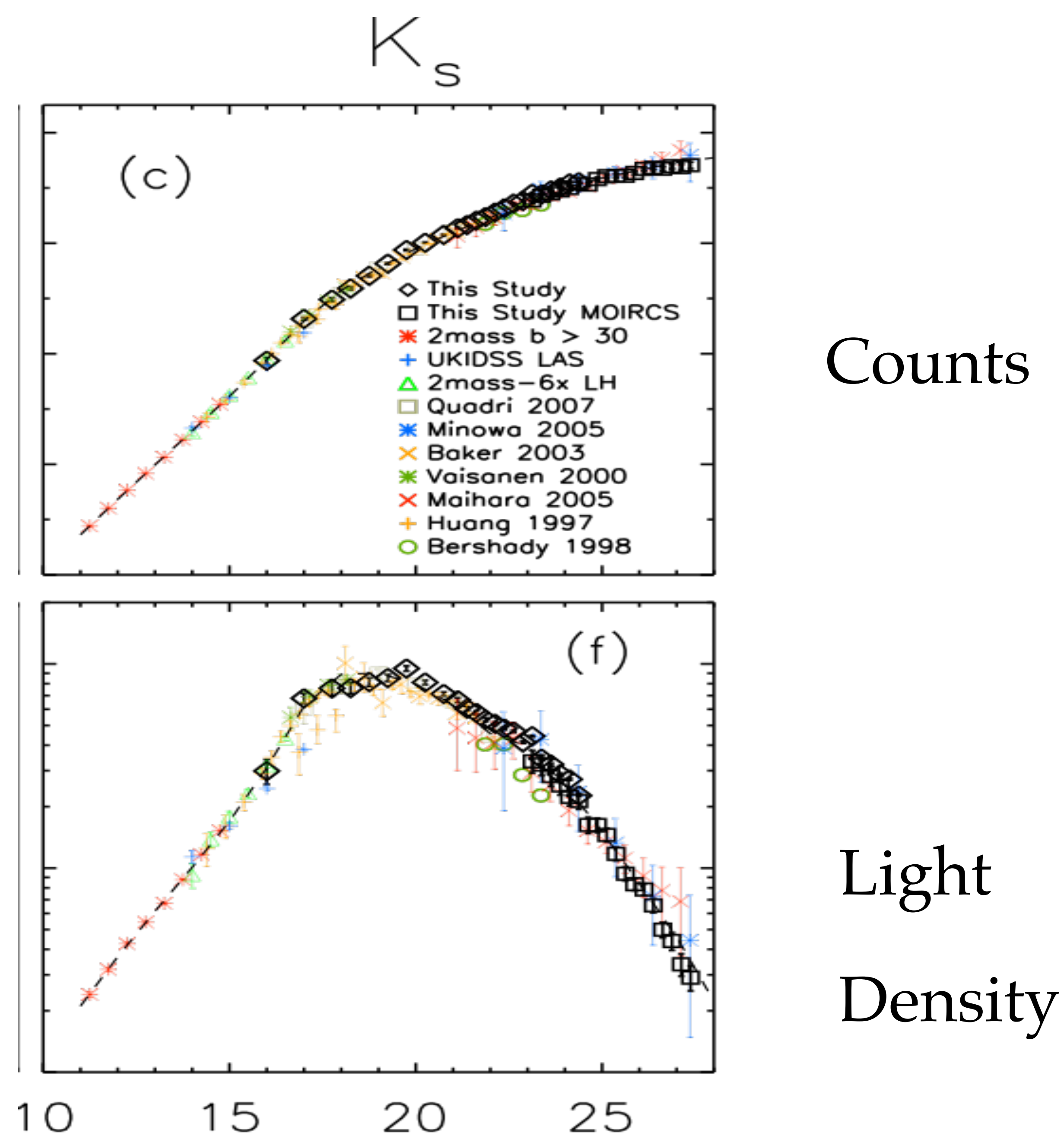
Resolving the EBL

In the optical/near-infrared the light converges at about K(Vega)=19 and B(Vega)=25

K band =2.2 micron

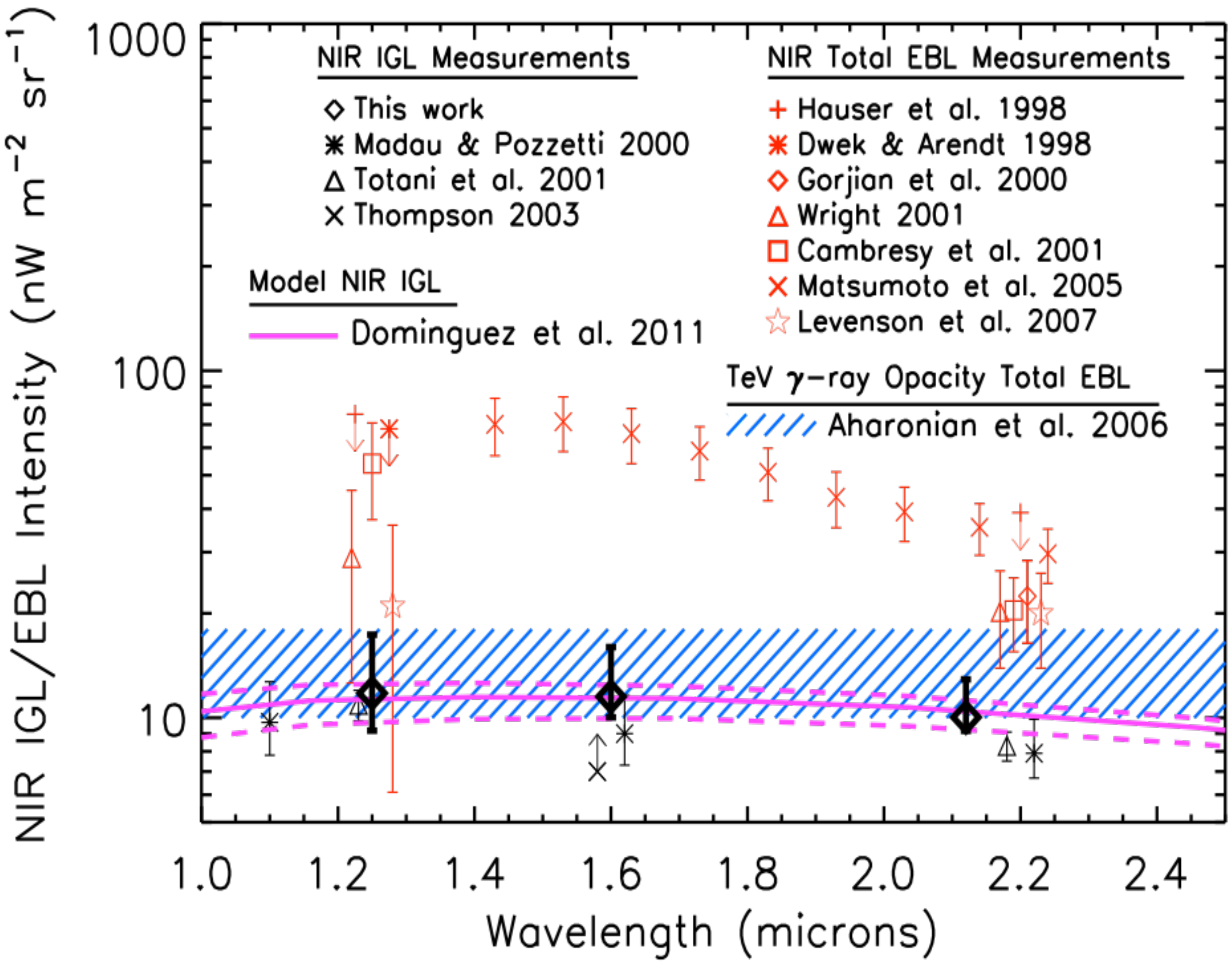


Cowie et al. 1990



Keenan, Barger, Cowie & Wang 2010

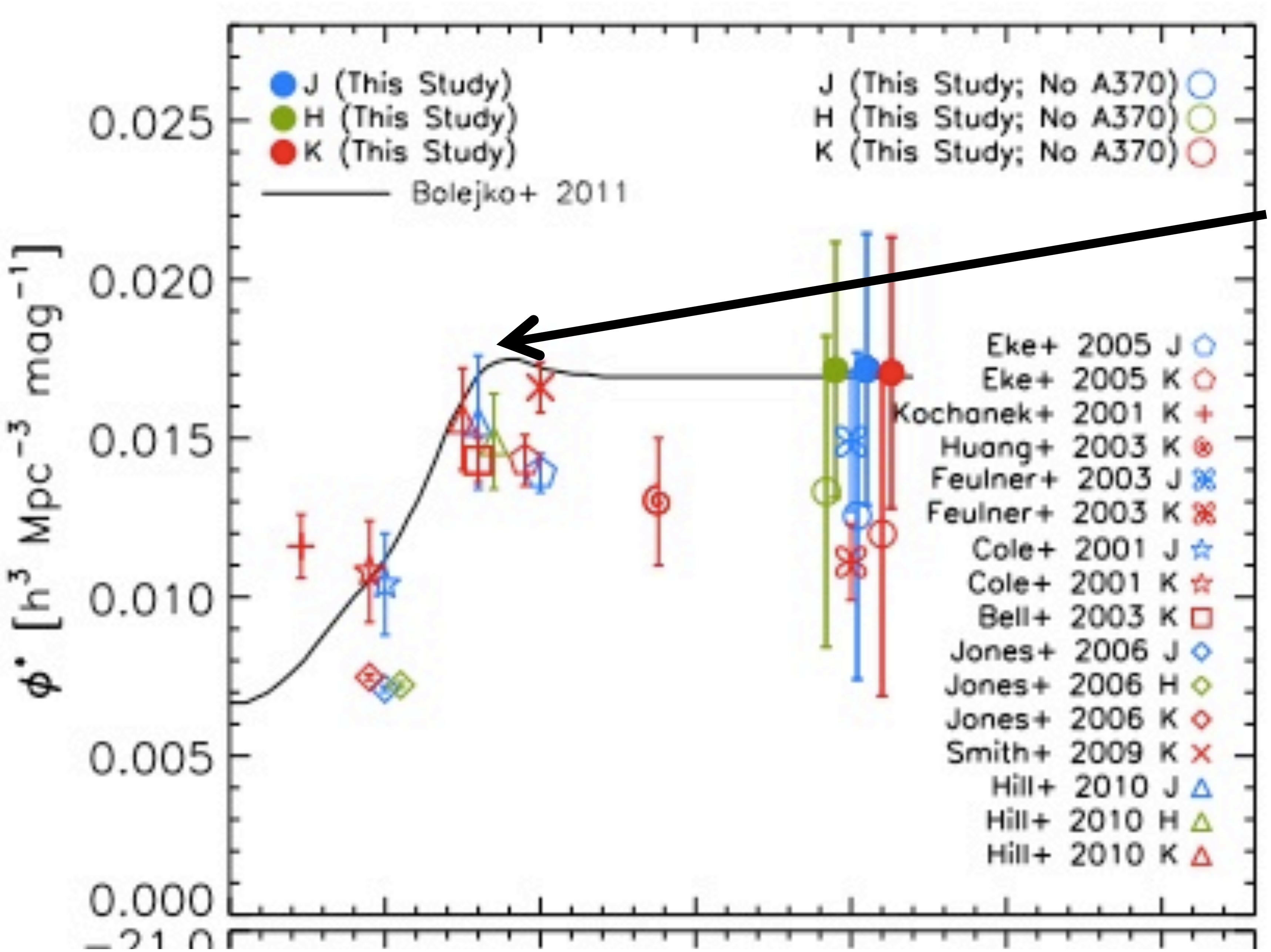
HESS/MAGIC background resolveD



TE

Keenan, Barger, Cowie & Wang 2010

Could there be a local hole which is large enough to cause problems with our measurement of the expansion?



Need about a 250 MPc void to get rid of dark energy

0.0 0.1 0.2 0.3

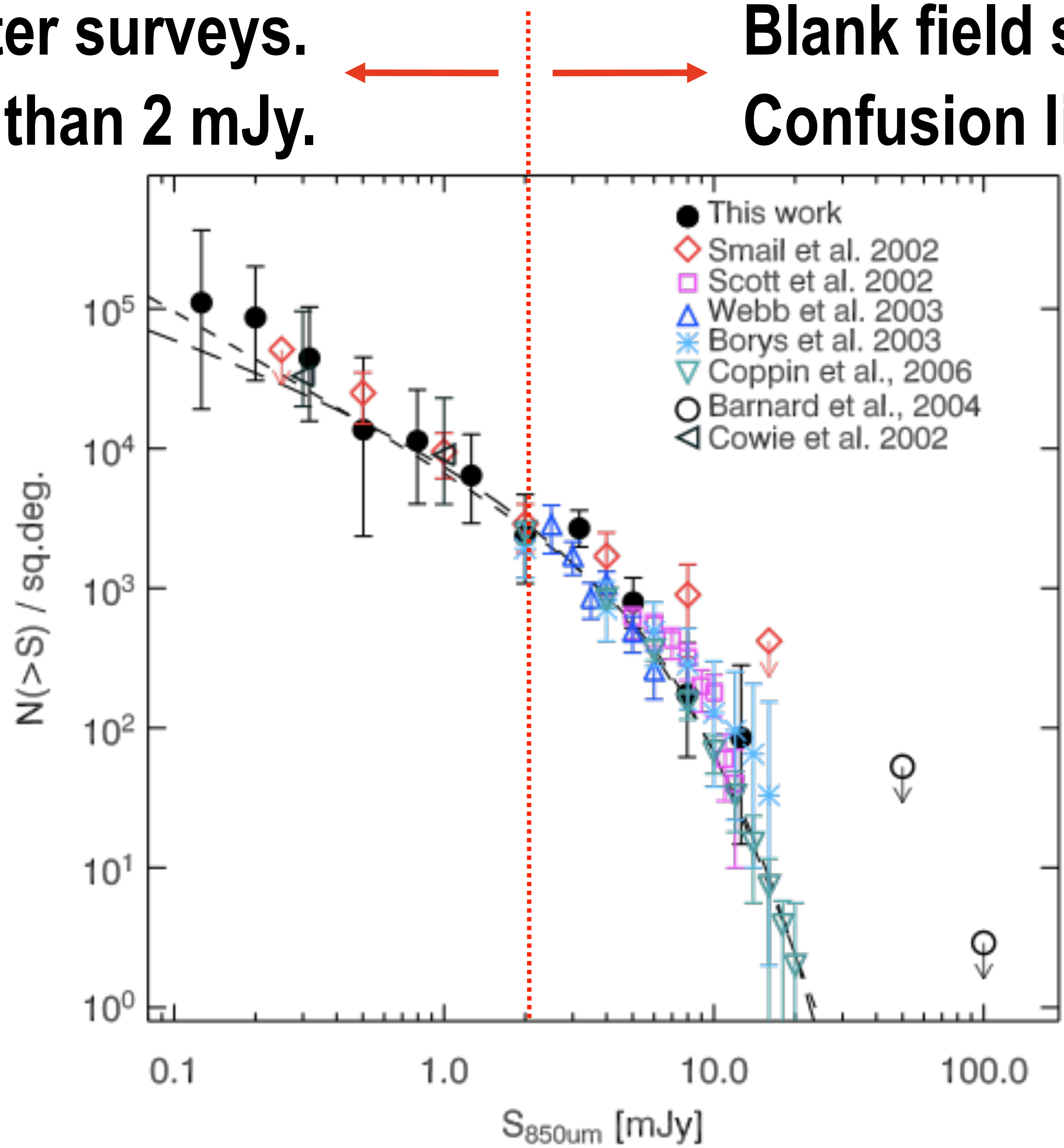
REDSHIFT

Keenan et al. 2011

850 micron number counts roughly resolve the FIR EBL

Lensing cluster surveys.
Probe fainter than 2 mJy.

Blank field surveys.
Confusion limited at 2 mJy.

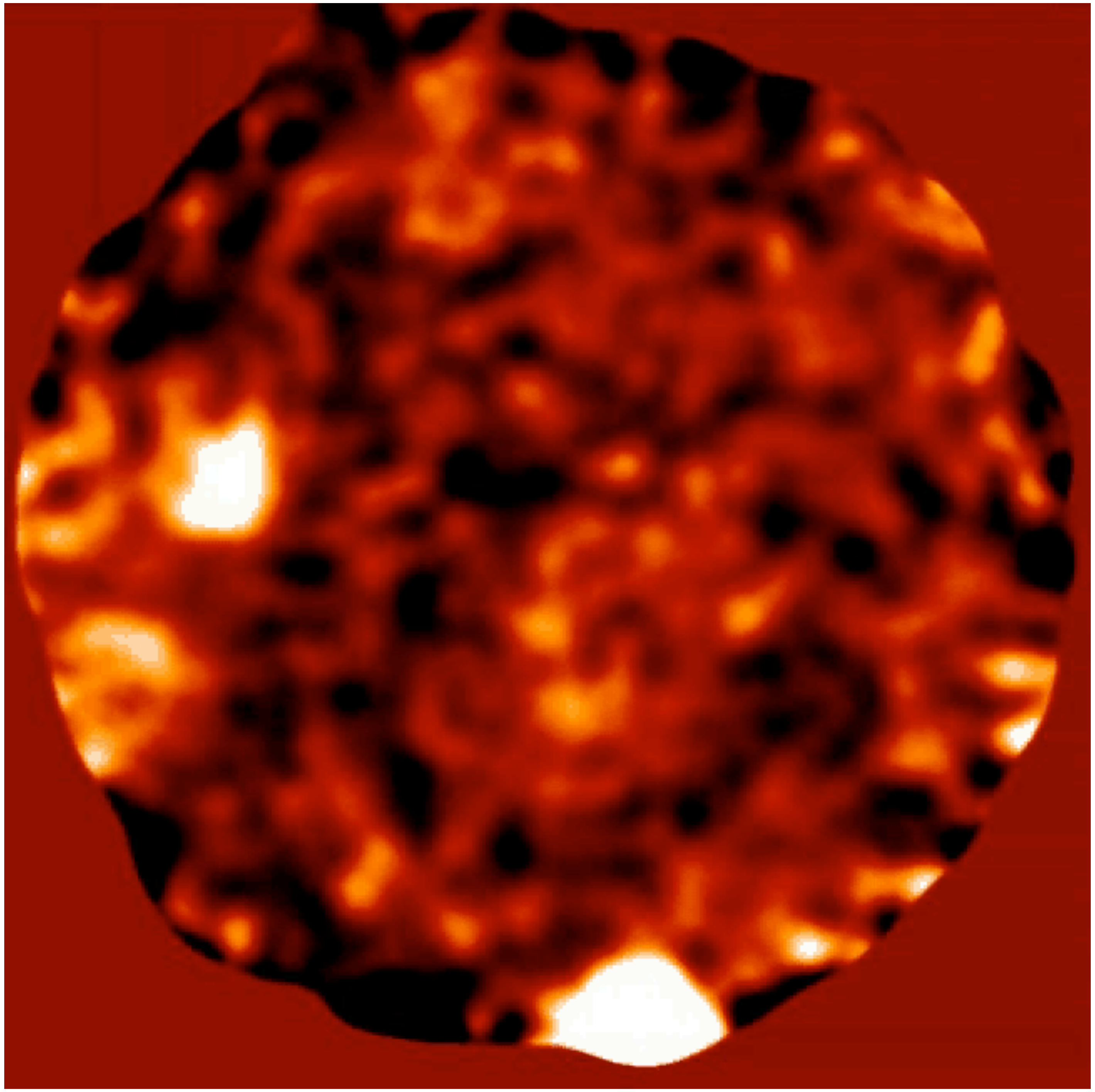


Knudsen et al. (2008)

However, there is a radical difference in the number of sources that make up the EBL at far-infrared and optical wavelengths

Hubble Deep Field-Proper

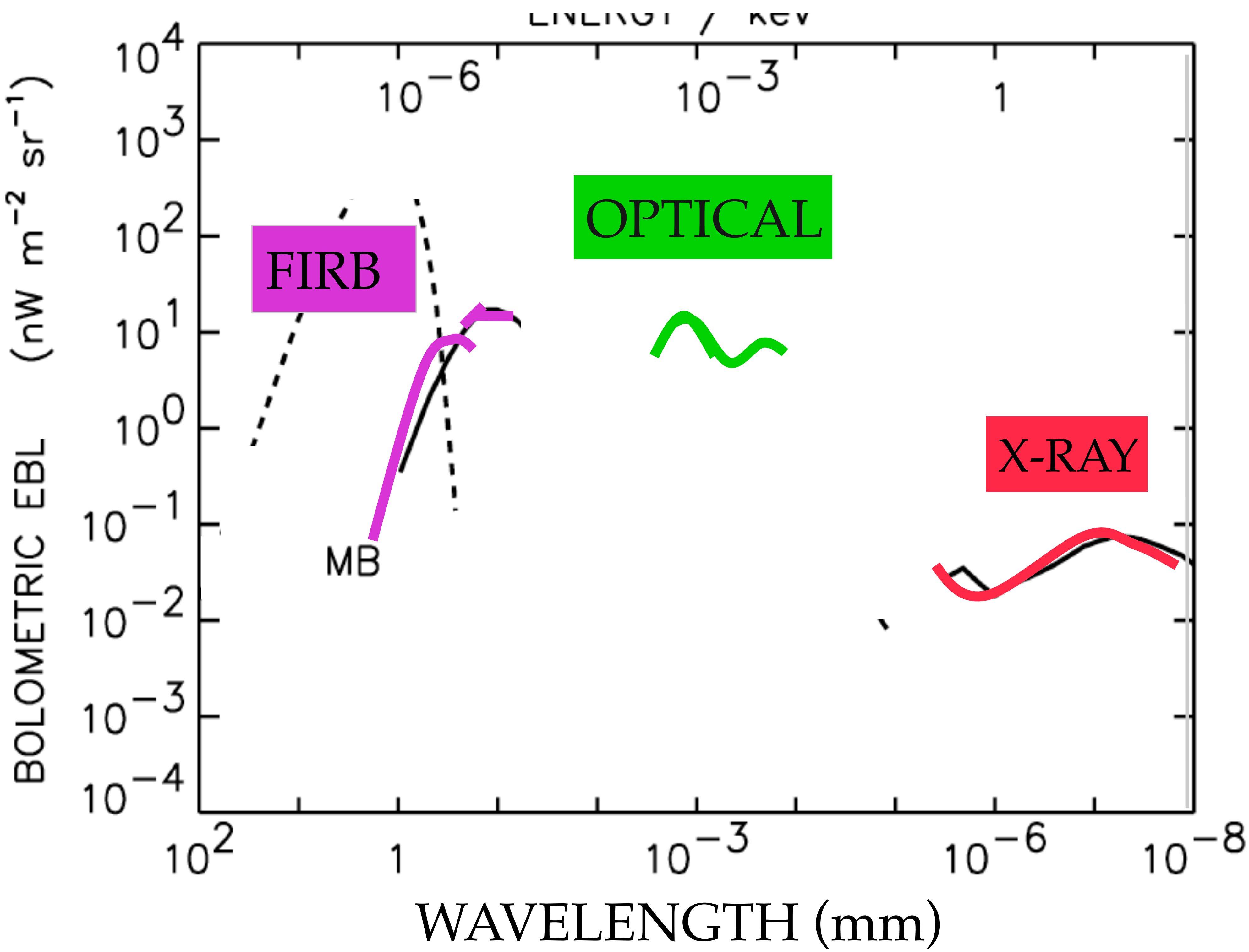
However, there is a radical difference in the number of sources that make up the EBL at far-infrared and optical wavelengths



The star-formation seen in the optical comes from a large number of galaxies

In the Far-infrared a much smaller number of much more intense star-forming galaxies contain the same amount

How much of the EBL have we resolved?



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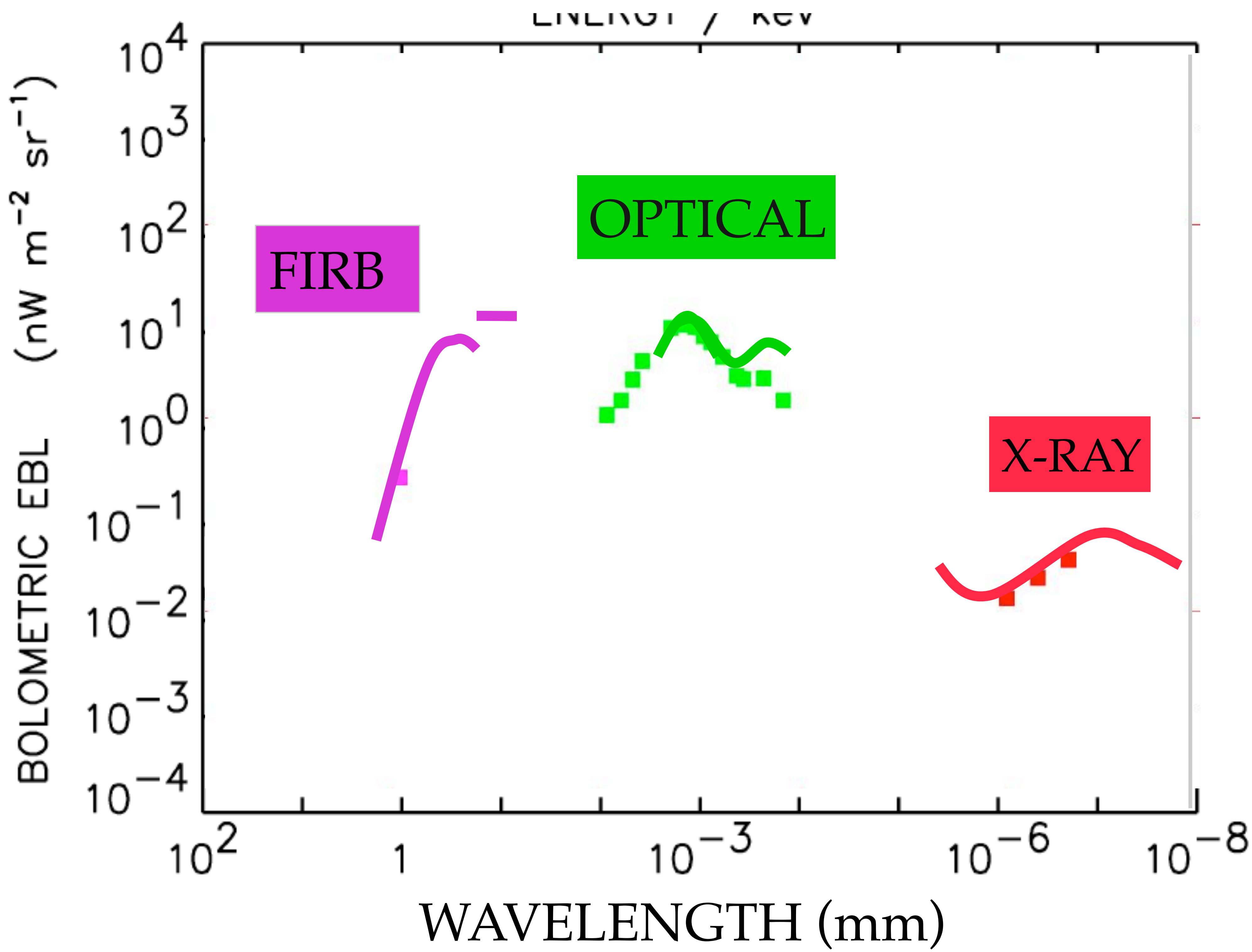
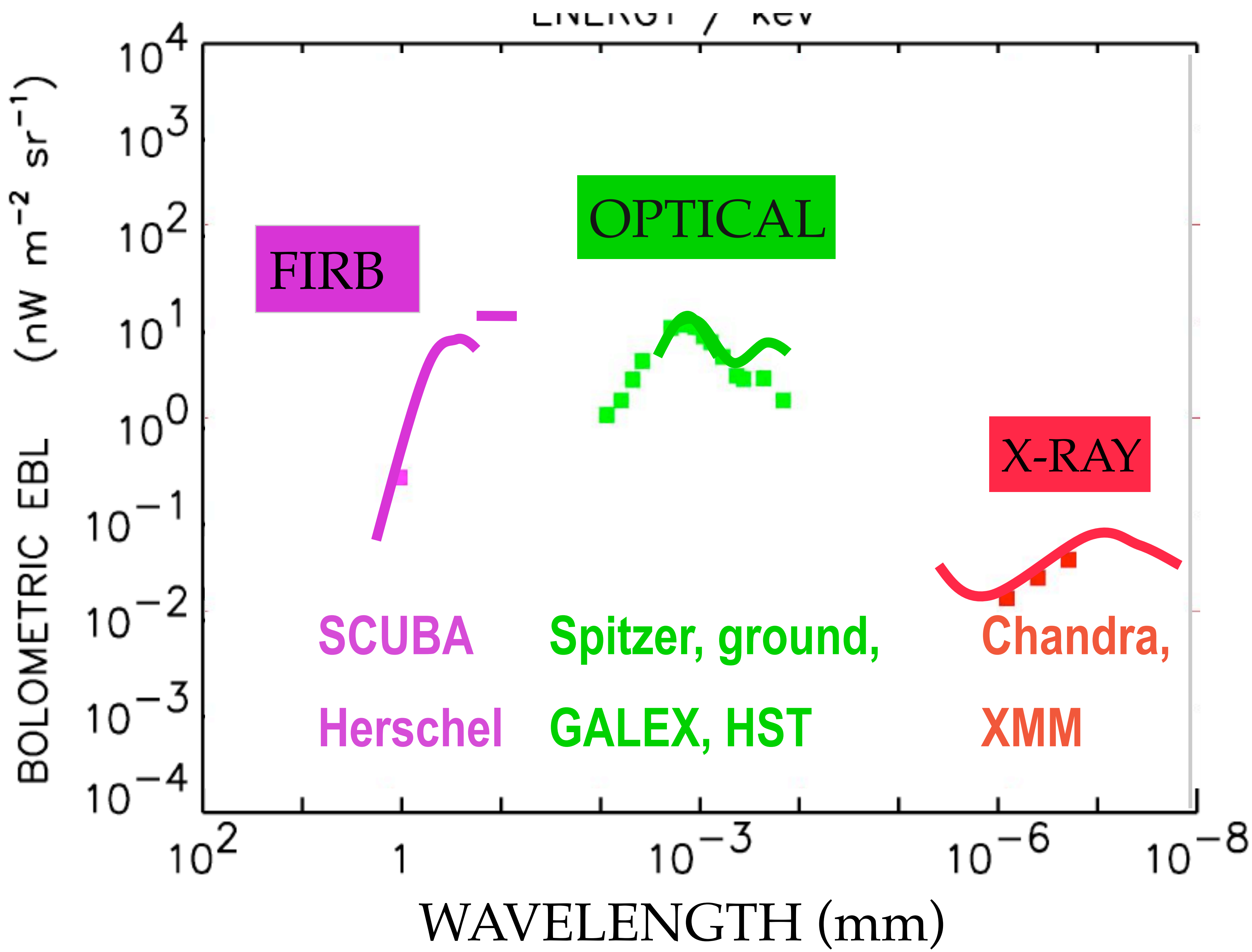
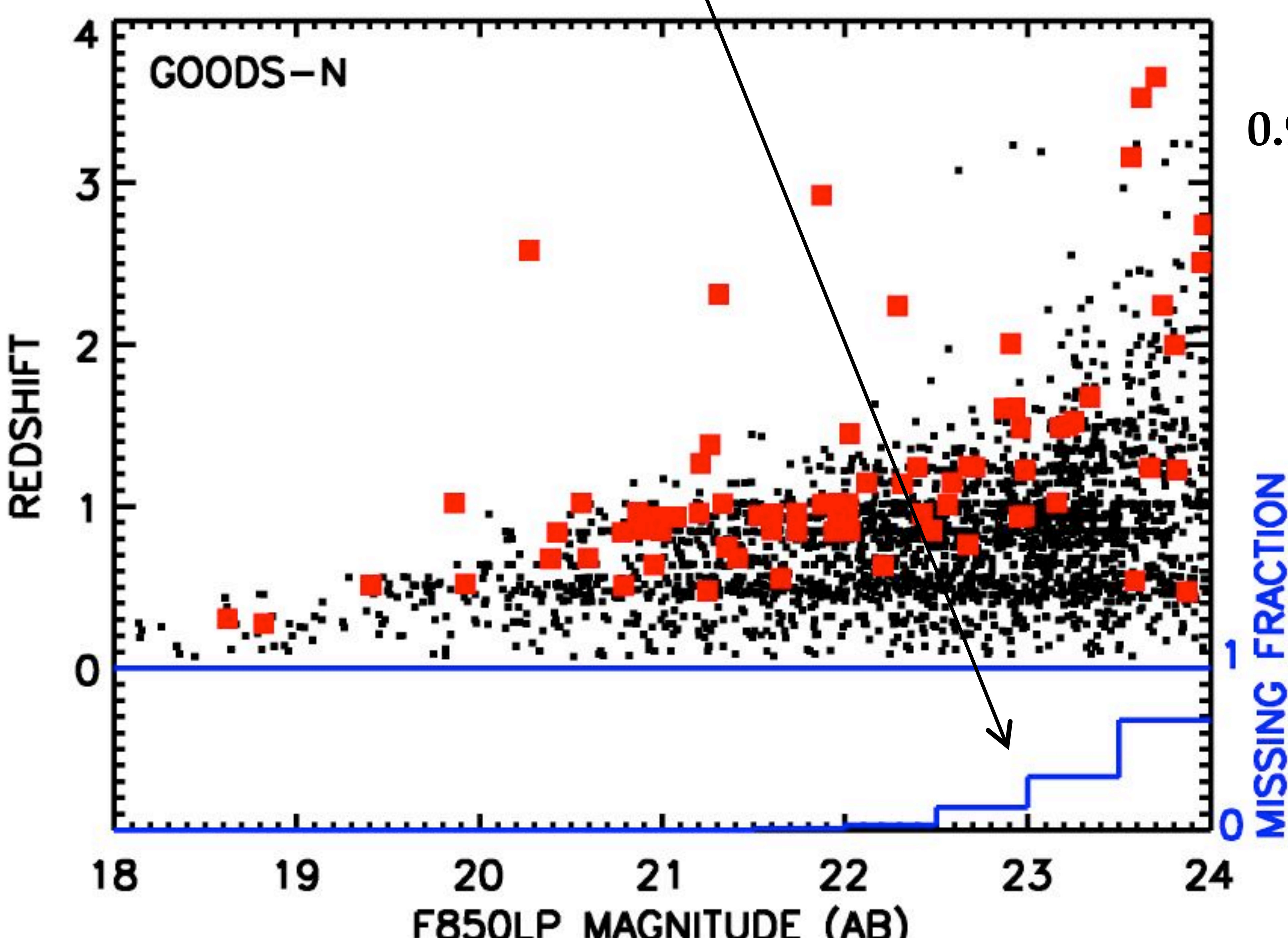


How much of the EBL have we resolved?



Redshift distribution of sources:

Spectroscopically complete to about 23rd magnitude

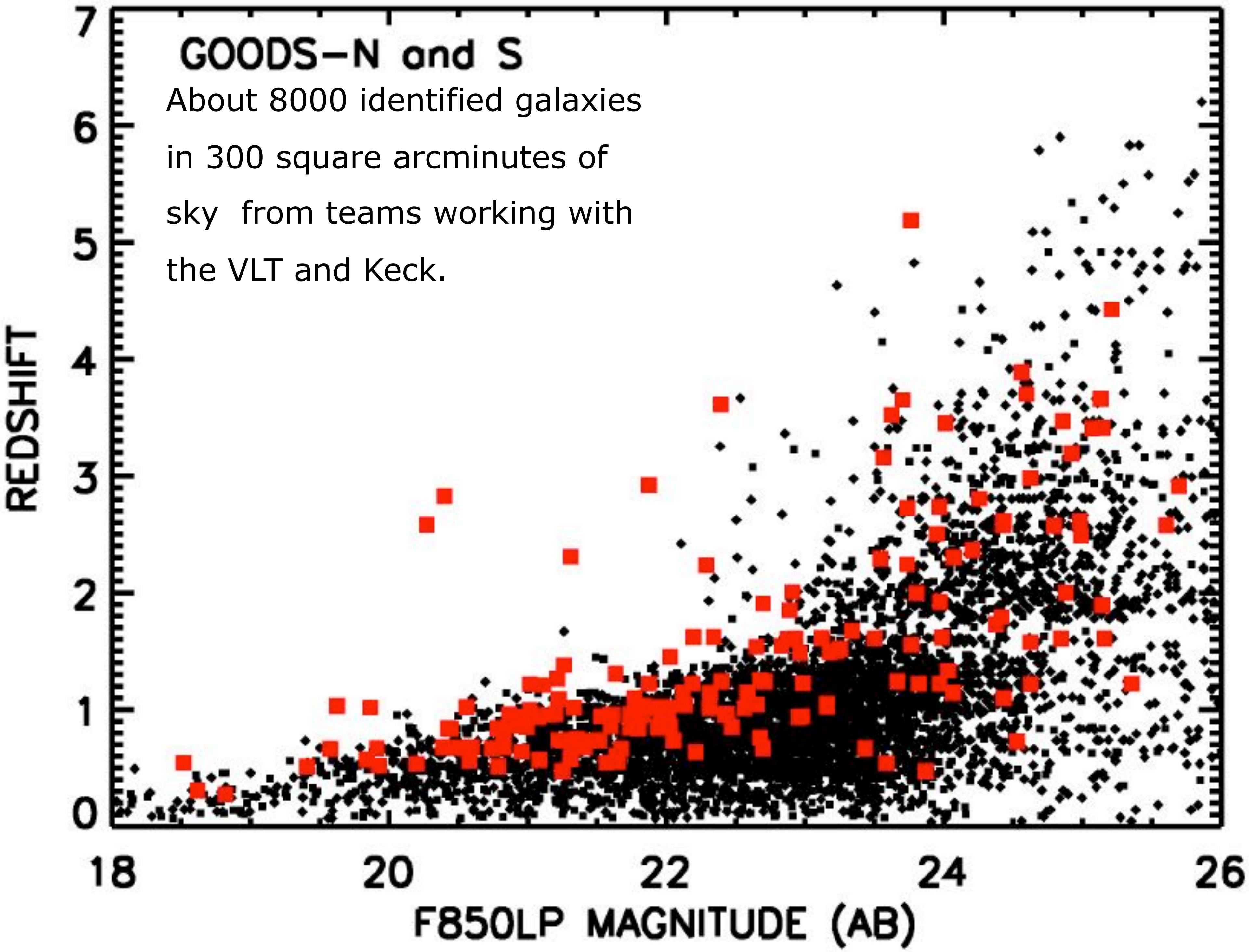


0.9 micron

LRIS and DEIMOS on Keck

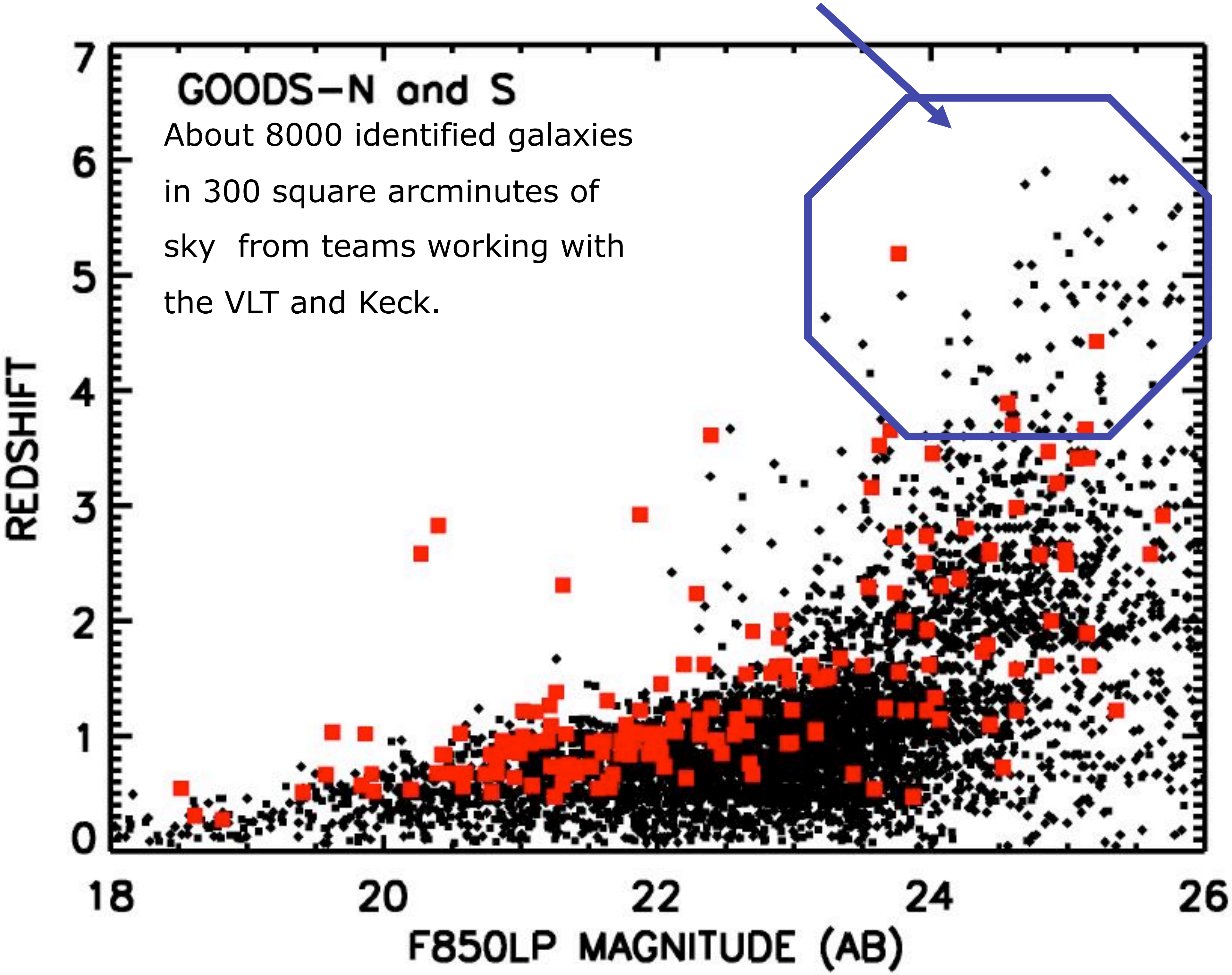
Red squares = X-ray AGN

Barger et al. 2008



Red squares = X-ray AGN

High redshift galaxies enter at faint magnitudes and have to be found with selection techniques

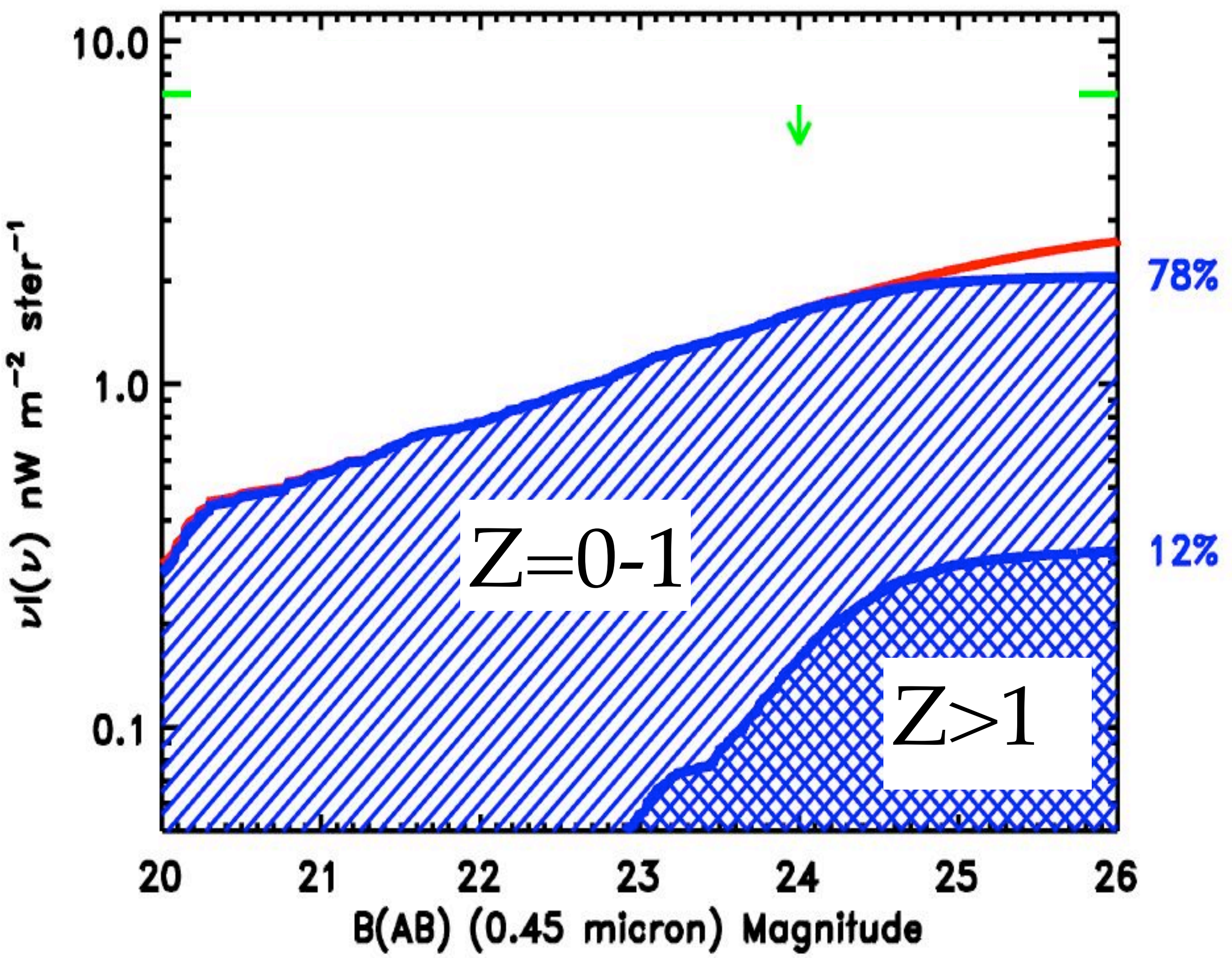


Red squares = X-ray AGN

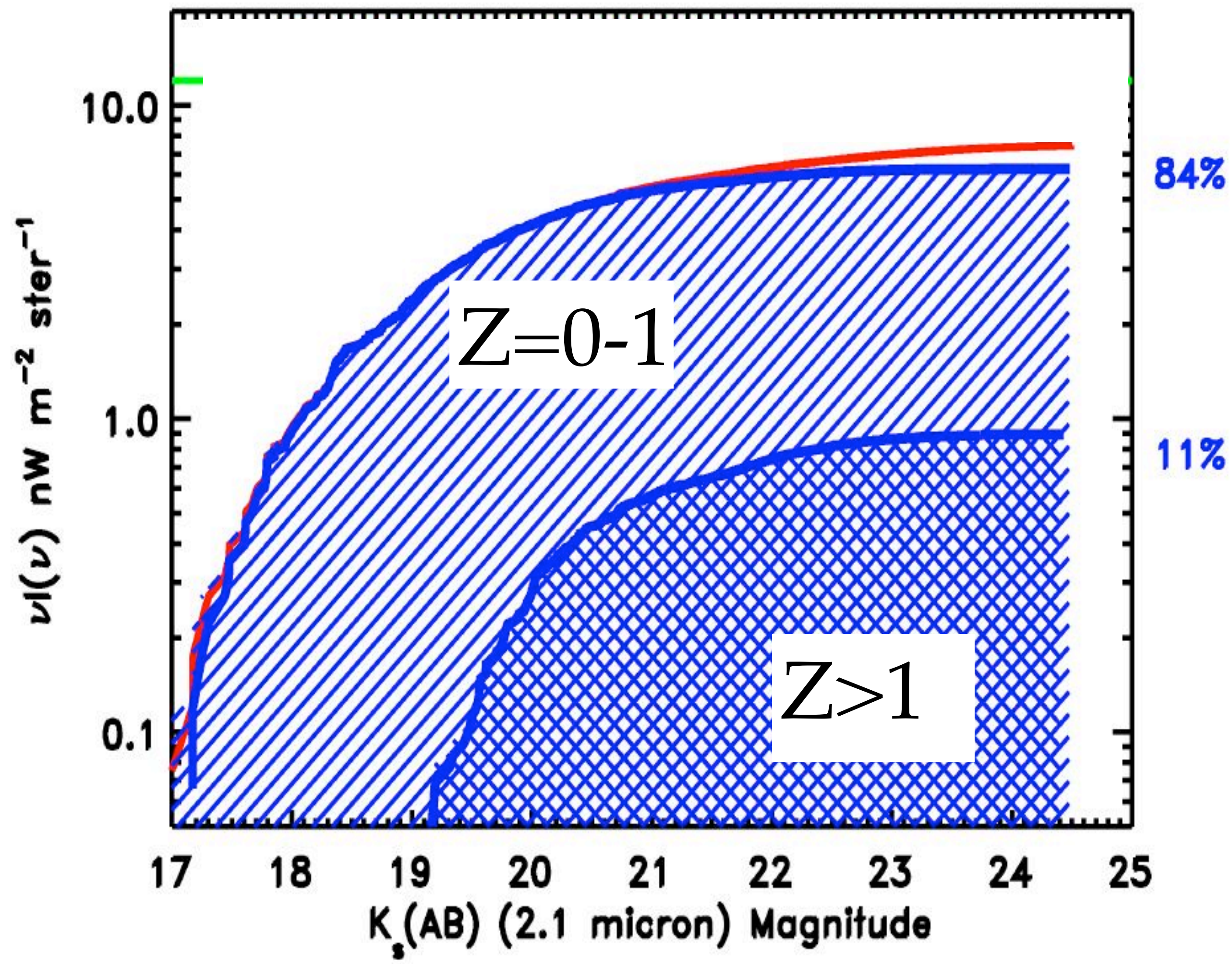
Most of the optical/IR light is spectroscopically identified

The missing galaxies are faint and lie on the converging part of the number counts versus magnitude relation

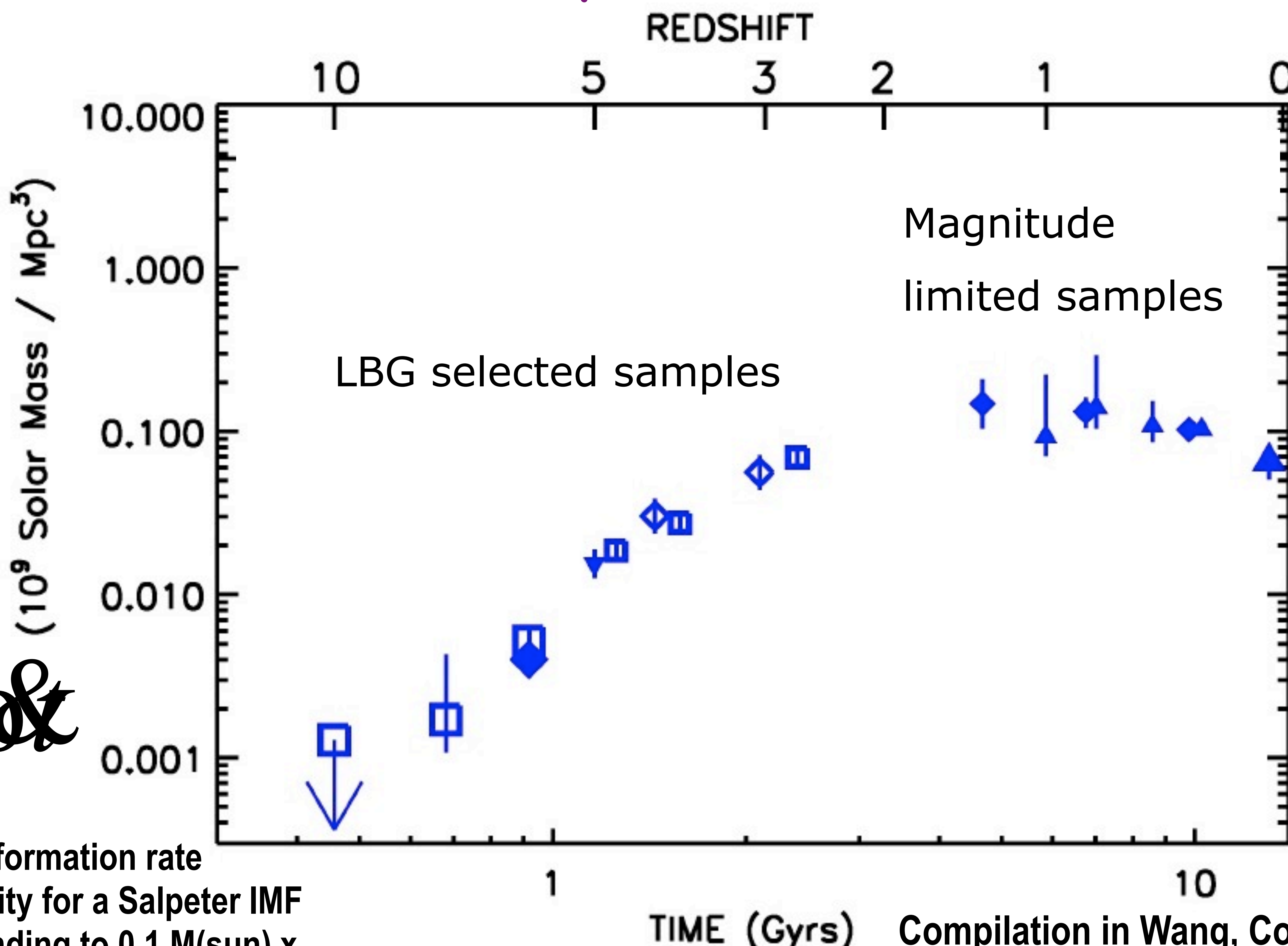
B Band 0.4 micron



K band 2.2 micron



Star formation directly seen in the rest-frame UV

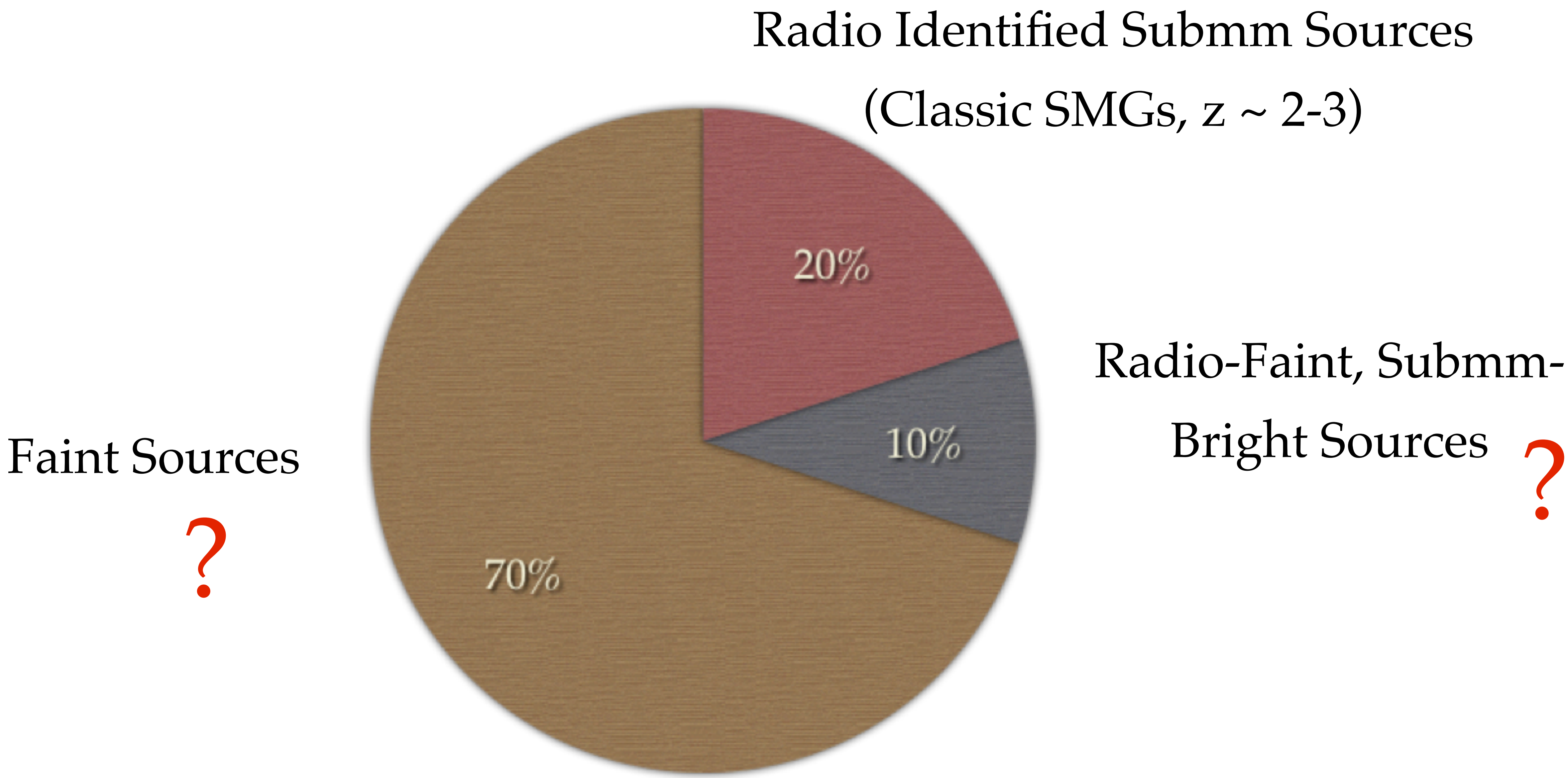


ρ&t

Star formation rate density for a Salpeter IMF extending to 0.1 M(sun) x the cosmic time

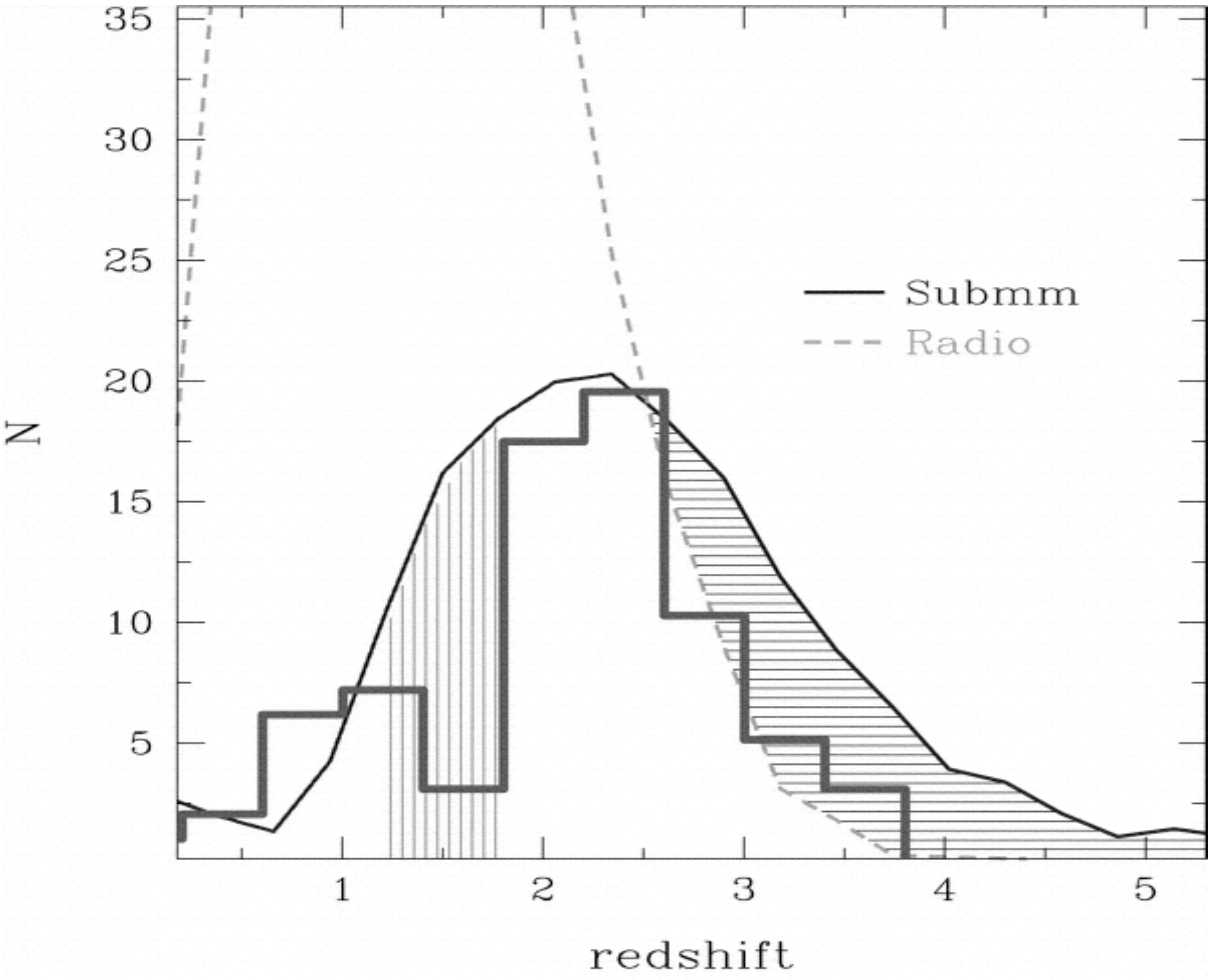
Compilation in Wang, Cowie, & Barger 2006

We still have profound problems identifying the far-infrared/submillimeter light



Total Submm EBL

Spectroscopy of Radio-Selected Submm Sources

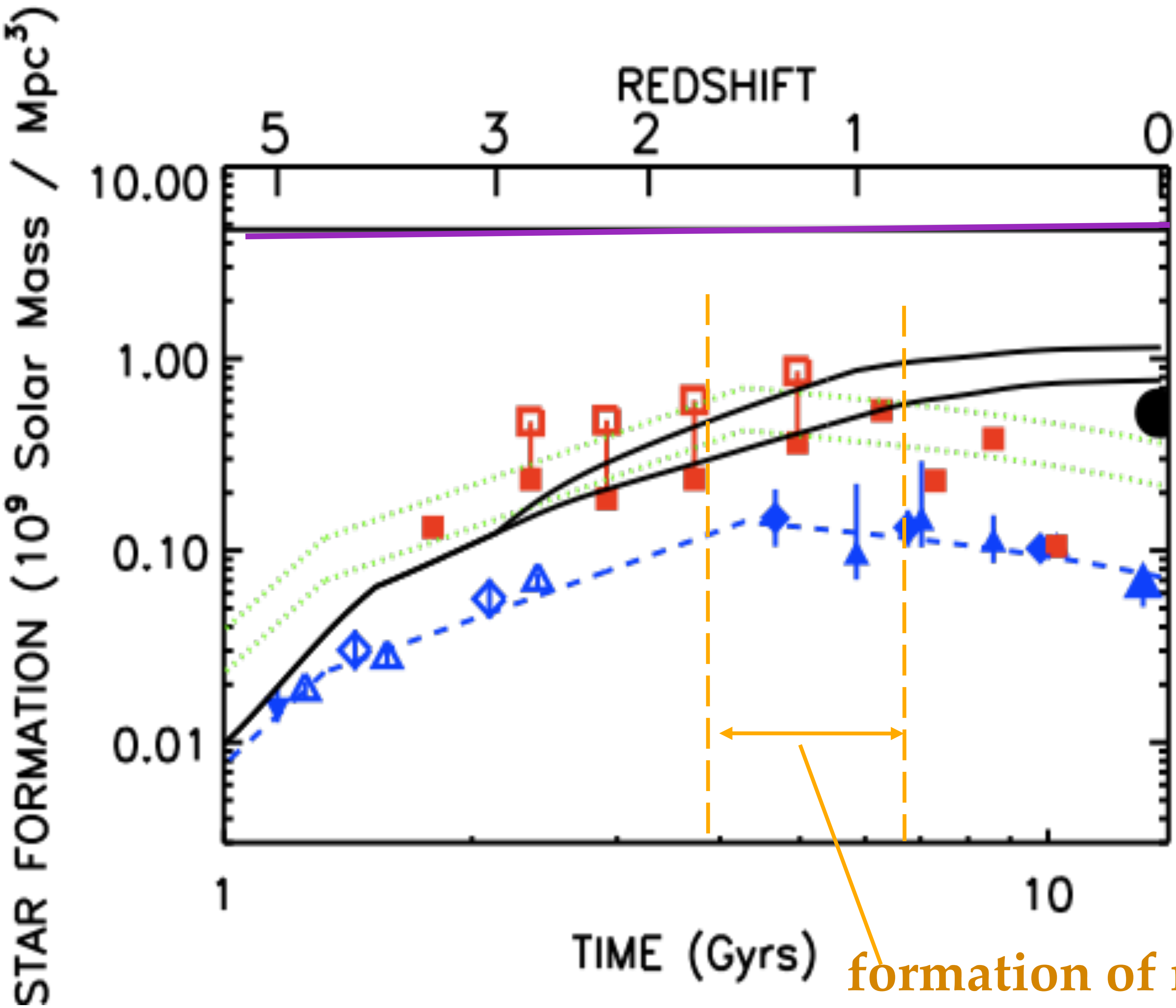


Chapman et al. (2005) median redshift of 2.2, max z=3.6

But we haven't identified 80% of the far-infrared background

- About 2/3 of the submm EBL is not detected as bright submm sources.
- It comes from submm sources fainter than the detection limit (~2 mJy) of current single-dish submm telescopes.
- These faint sources are the typical sources in the submm population.
- What are they? Are they the fainter tail of the classic submm galaxies (i.e., also at $z = 2–3$)? Or an entirely different population?

Cosmic star formation history



total baryonic mass in the universe

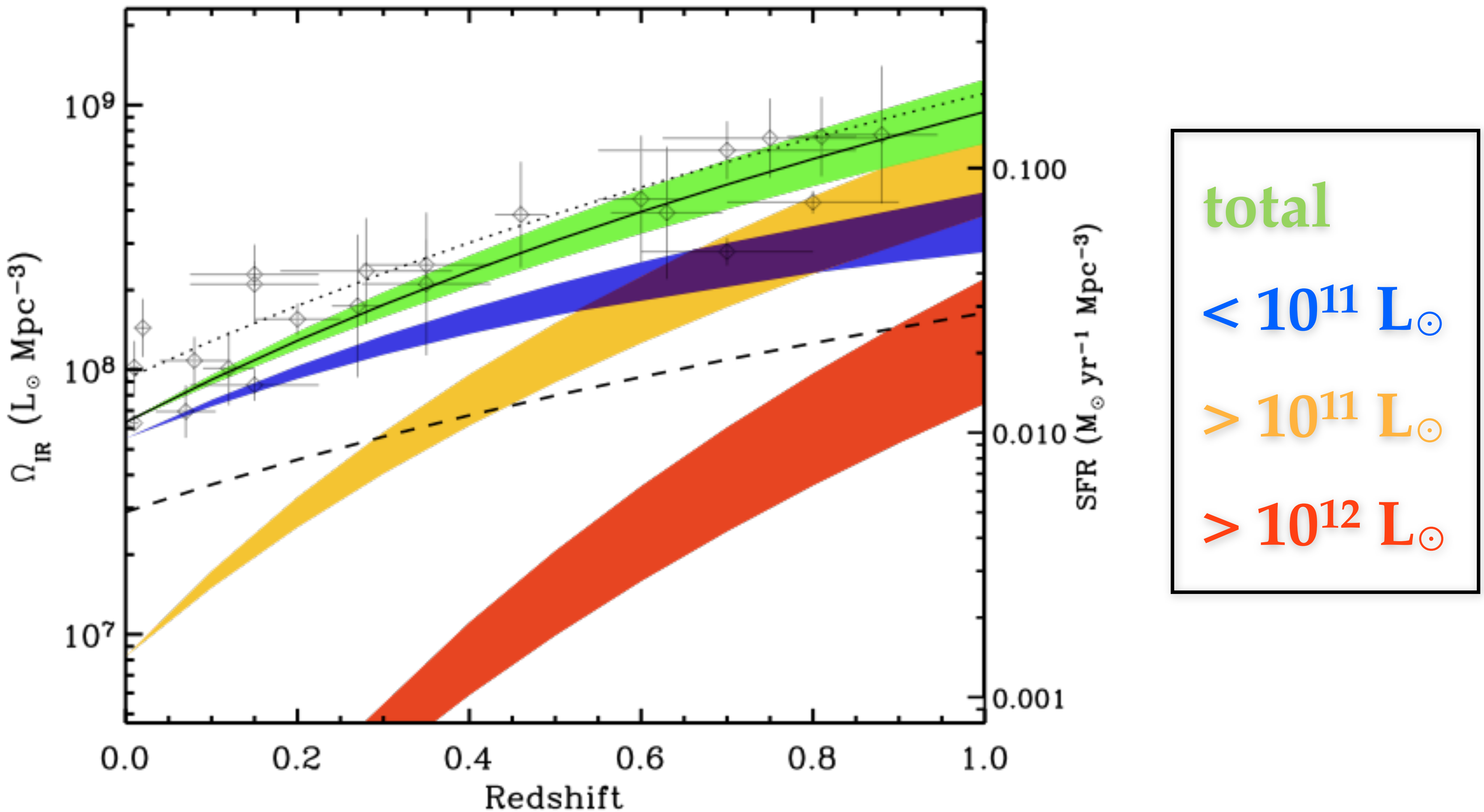
stellar baryonic mass in the present-day universe

Present day star formation is dominated by small blue galaxies

formation of most of the present-day stellar baryonic mass in the z=1-2 redshift interval

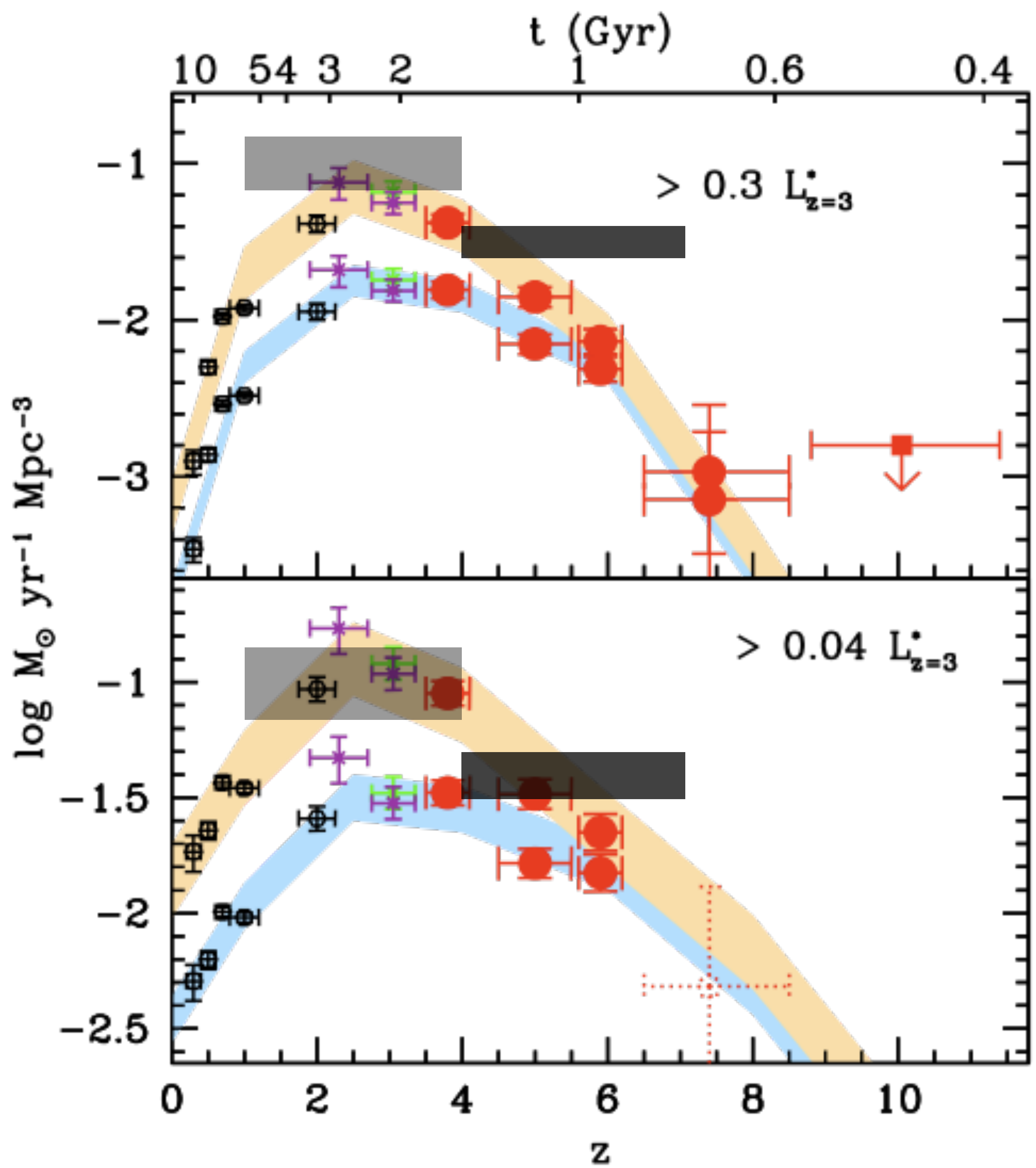
Wang, Cowie, & Barger 2006

Mid-infrared downsizing (z<1)



Le Floc'h et al. (2005)

Cosmic Star Formation History

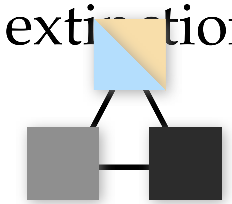


faint submm sources detected with stacking analyses

radio-faint, submm-bright sources

rest-frame UV measurements with extinction correction

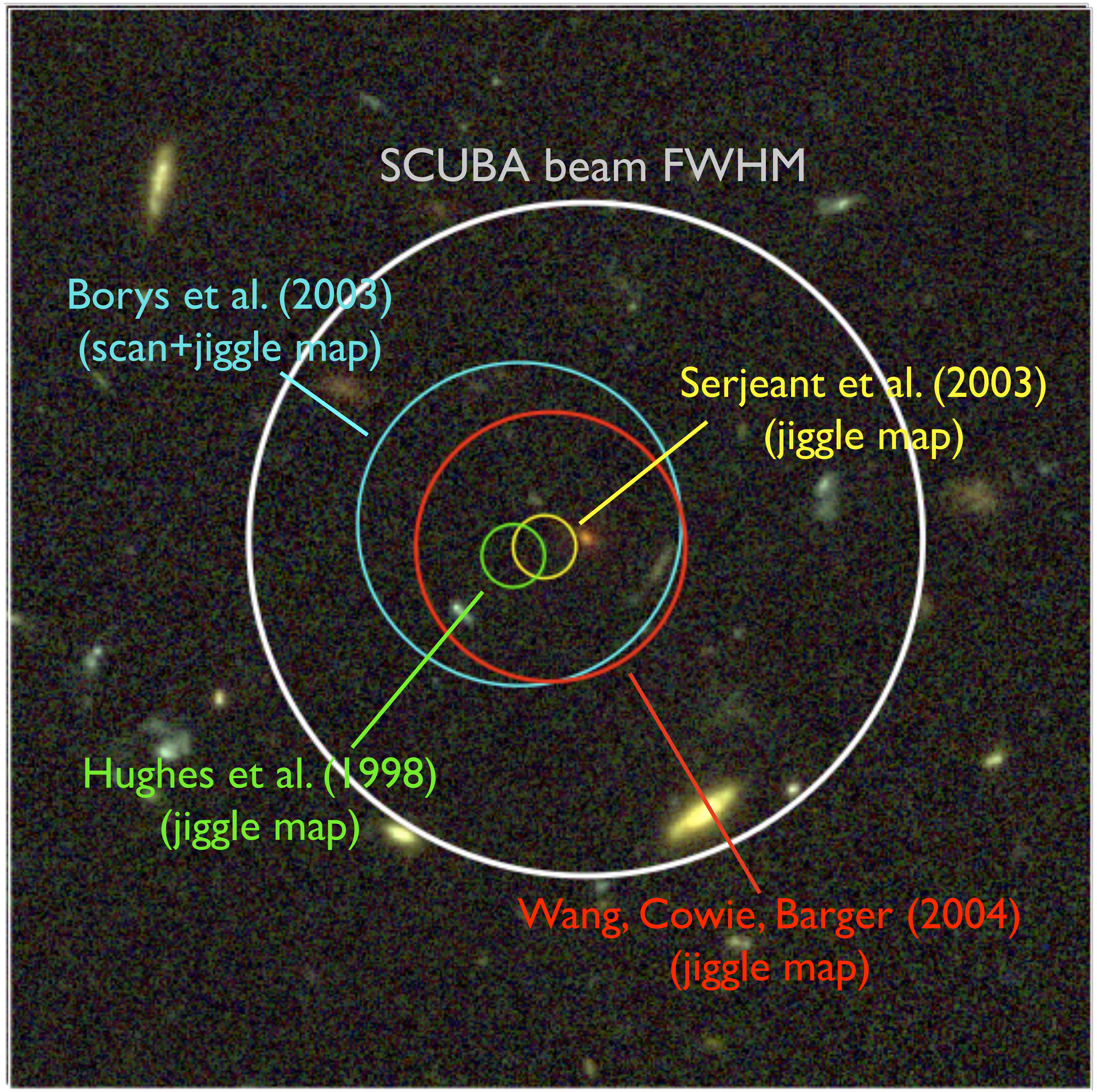
rest-frame UV measurements without extinction correction



Caution: the amount of overlap between the three populations is still unclear.

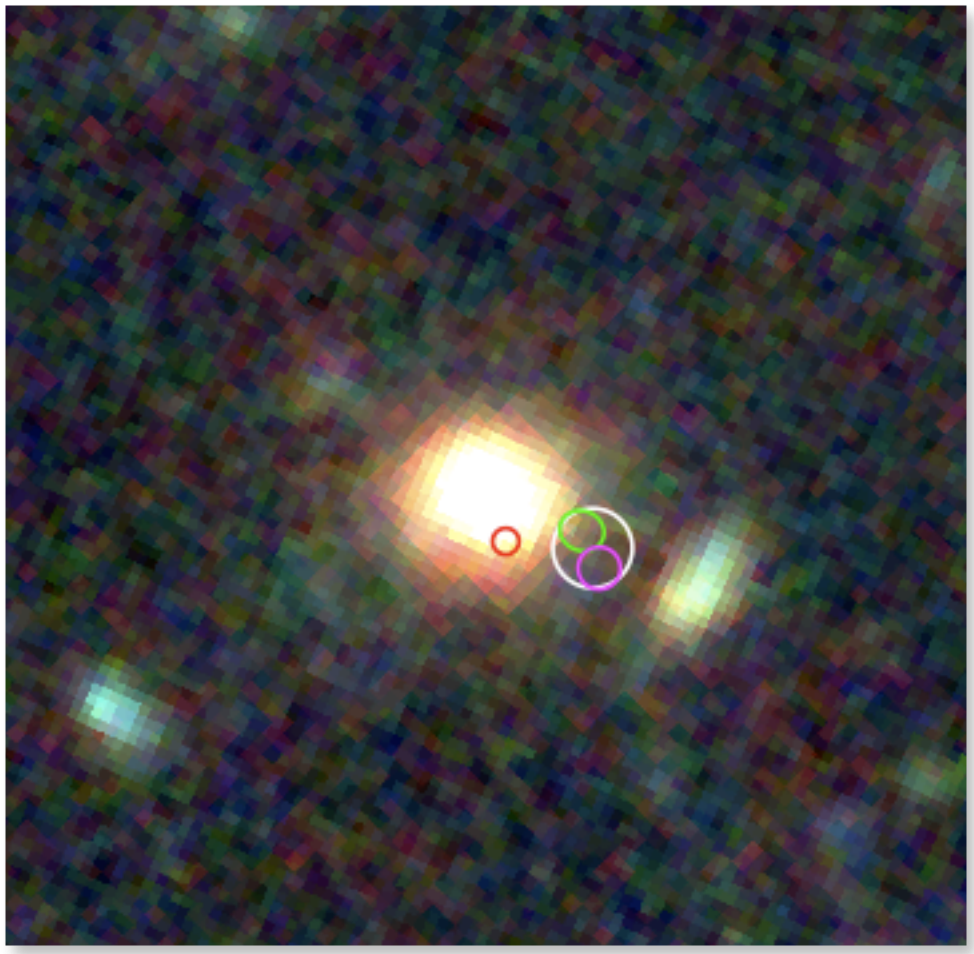
Bouwens et al. (2007)

HDF850.1: the brightest submillimeter source in the HDF proper and a poster child for the



HST ACS b,v,i,z

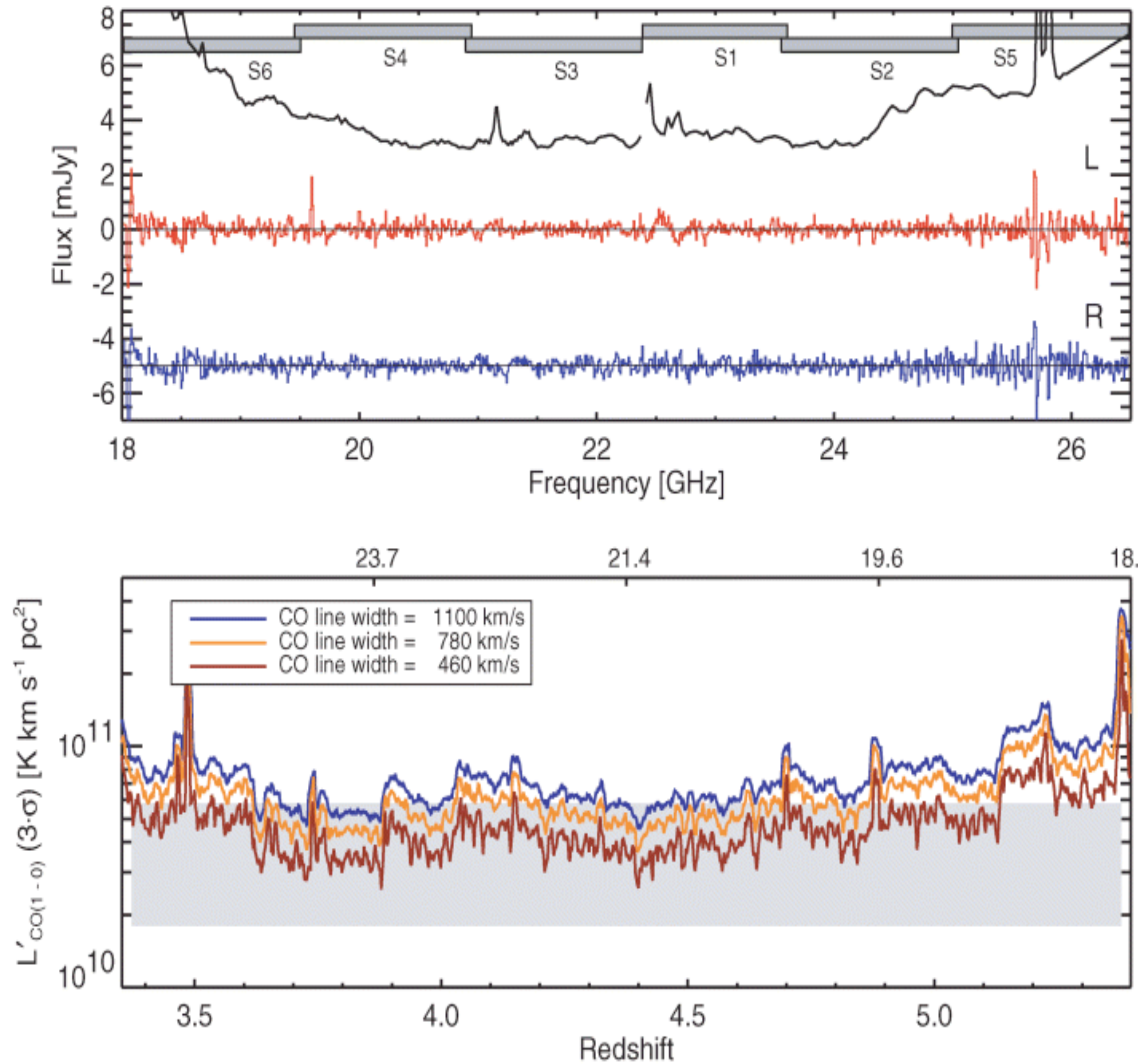
What is HDF850.1?
Radio-submillimeter estimate of z=4.5



NICMOS F110W, F160W, Subaru Ks

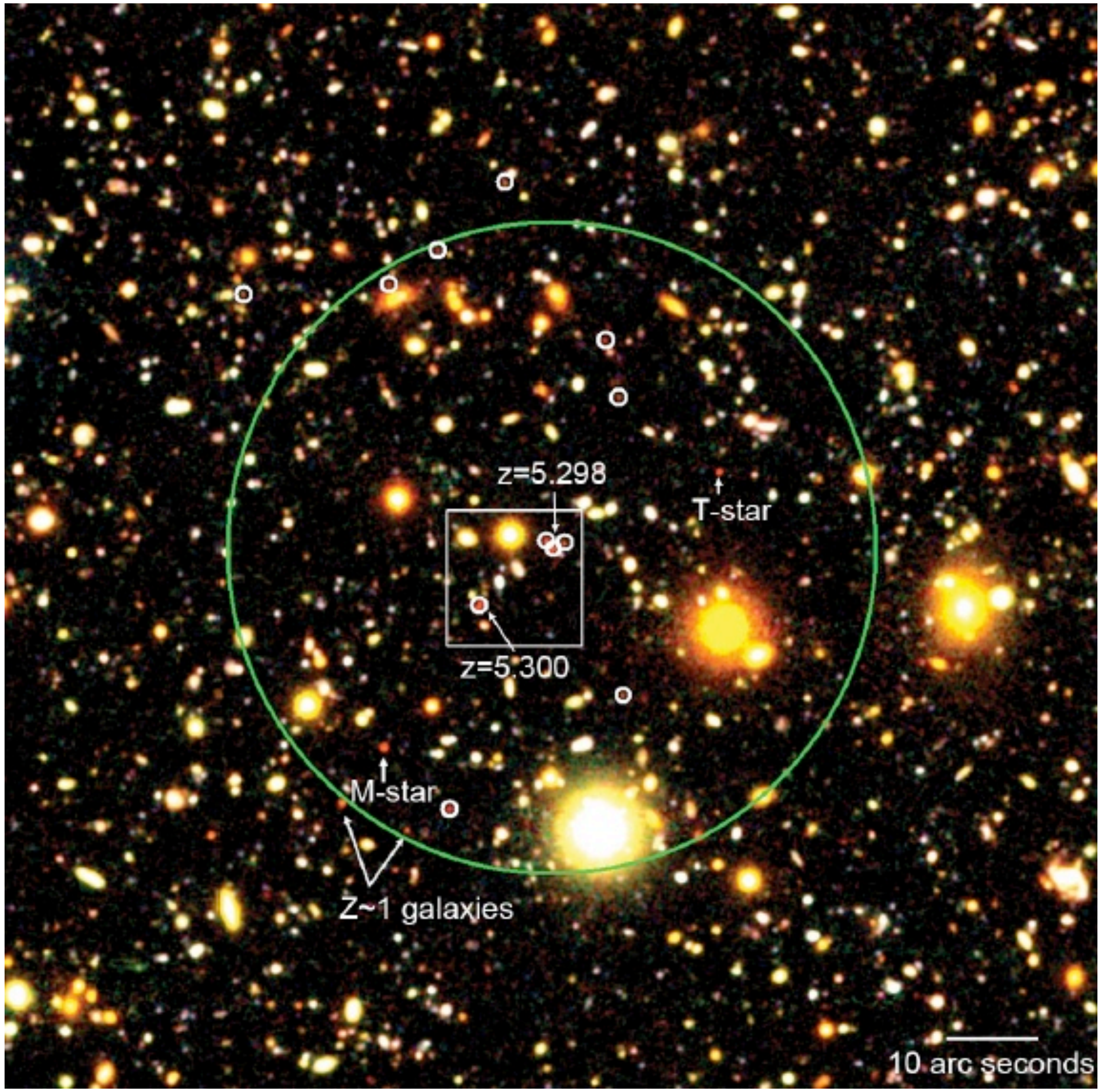
- Nothing obvious in the optical and near-IR.
- No CO emission found by GBT between z=3.3 and 5.4.

Cowie et al. 2009



Wagg et al. 2007

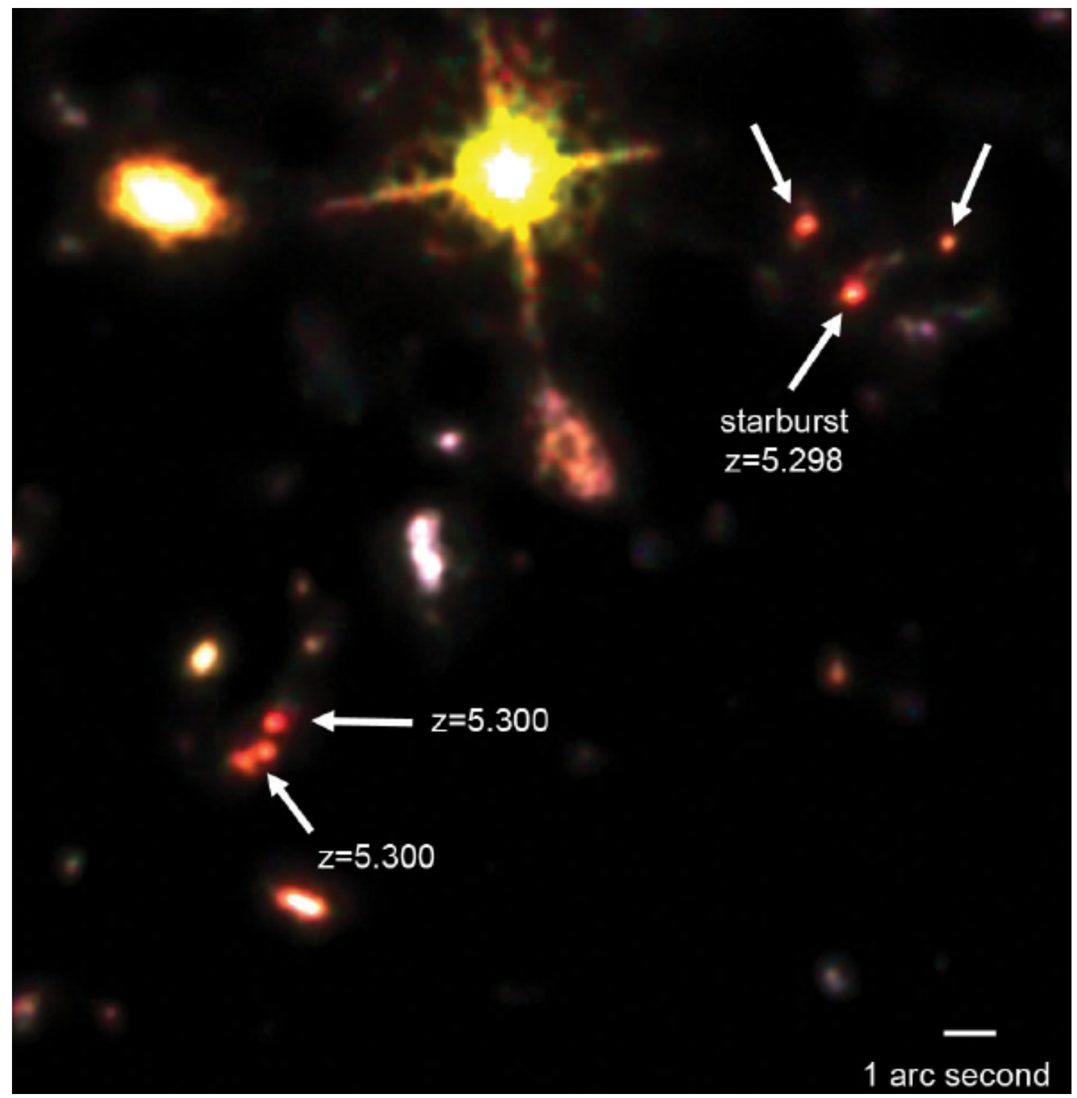
A massive protocluster at z=5.3



Protocluster region

- 13 Mpc
- Includes QSO
- SMG COSMOS

Aztec-3

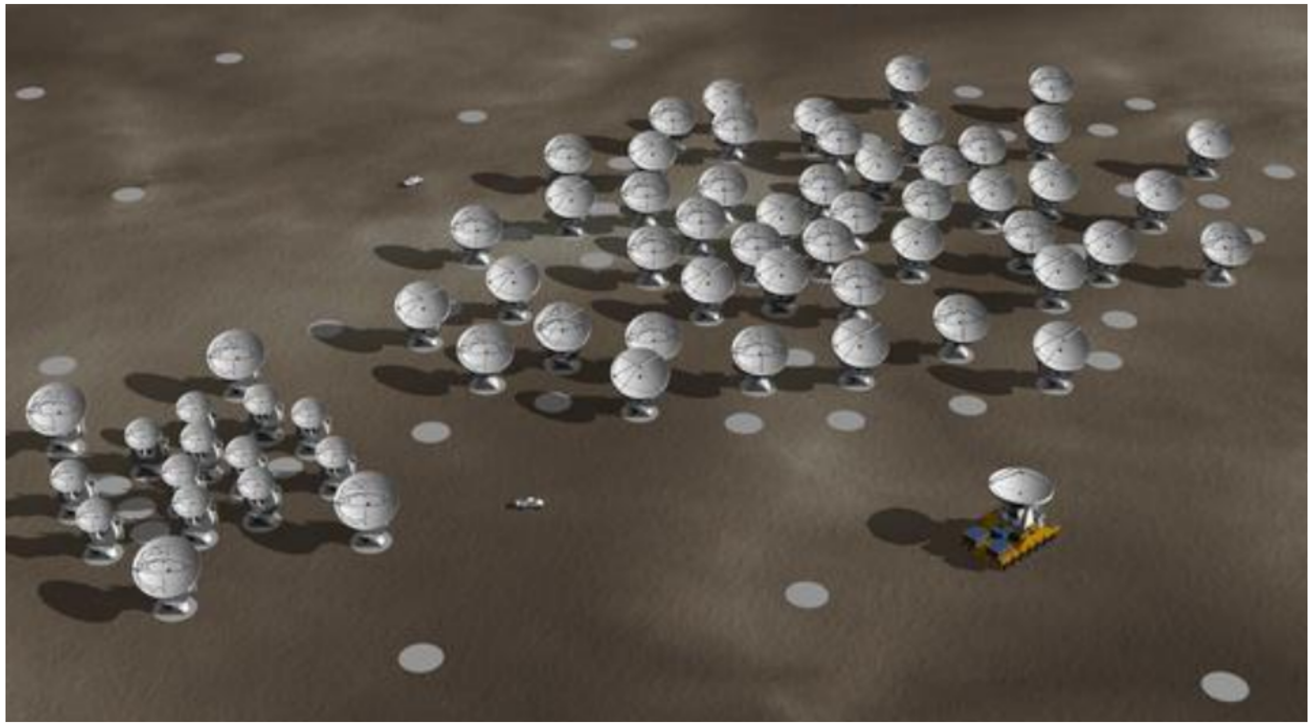


Capak et al 2011

We still are in the very early stages of

There could be considerable amounts of obscured star formation that we haven't identified yet at the highest redshifts

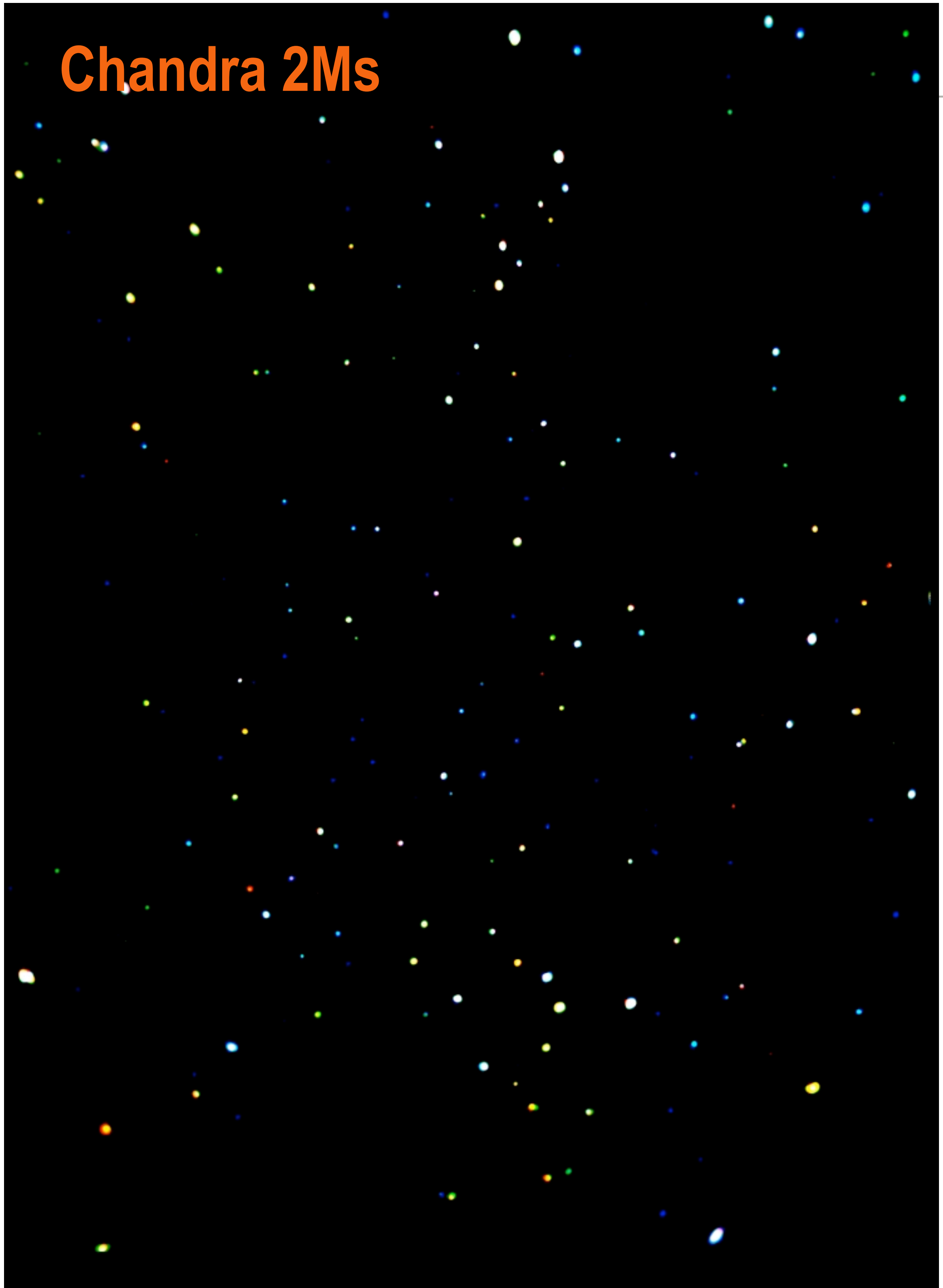
Lots of problems for new instruments and telescopes to solve particularly the ALMA interferometer and the SCUBA-2 camera on the JCMT



ALMA

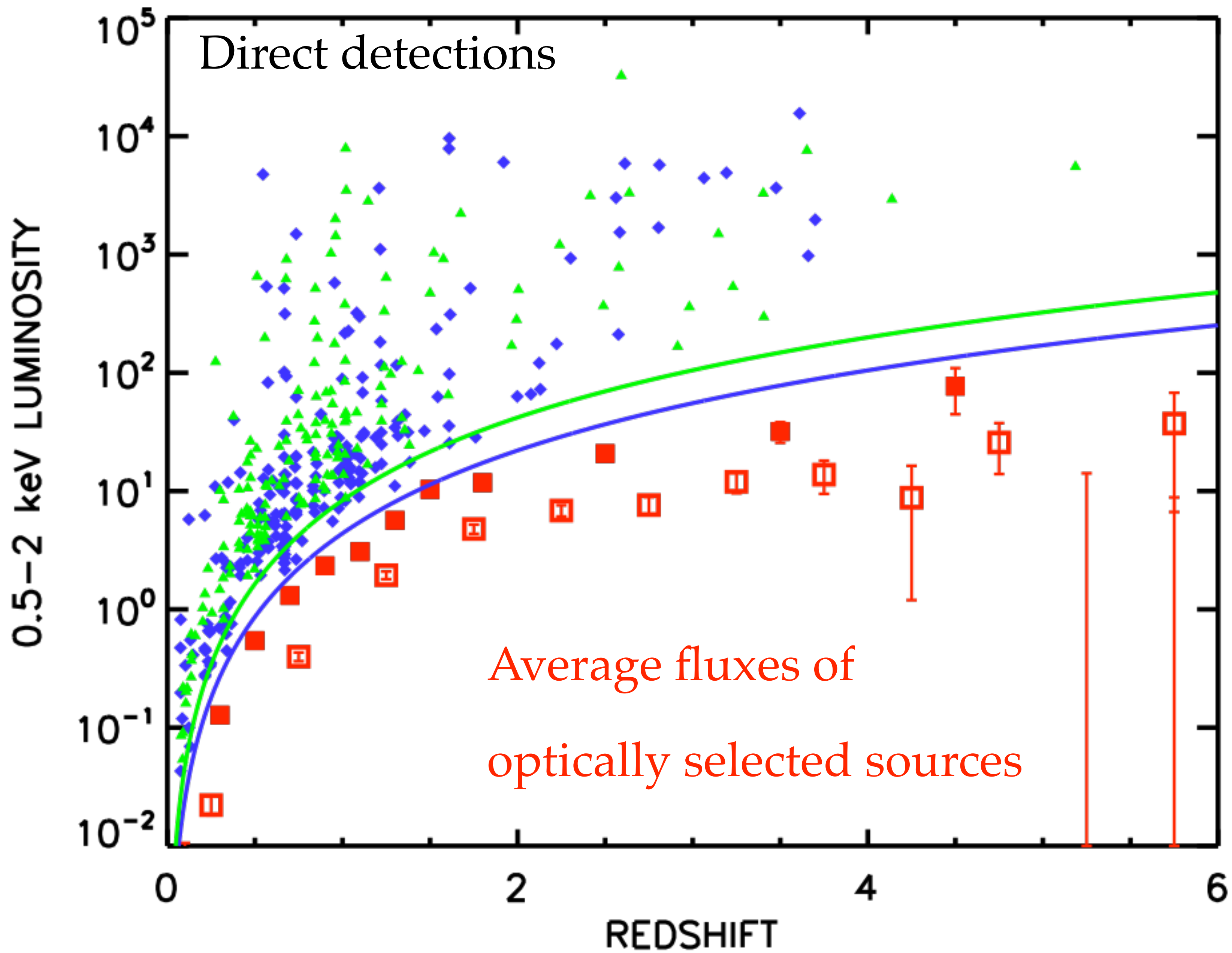
What about supermassive black holes?

The number of sources forming the X-ray background is much smaller than in the NIR or Optical (GOODS-N)



Most AGN are at LOW redshifts: AGN are rare at high redshifts

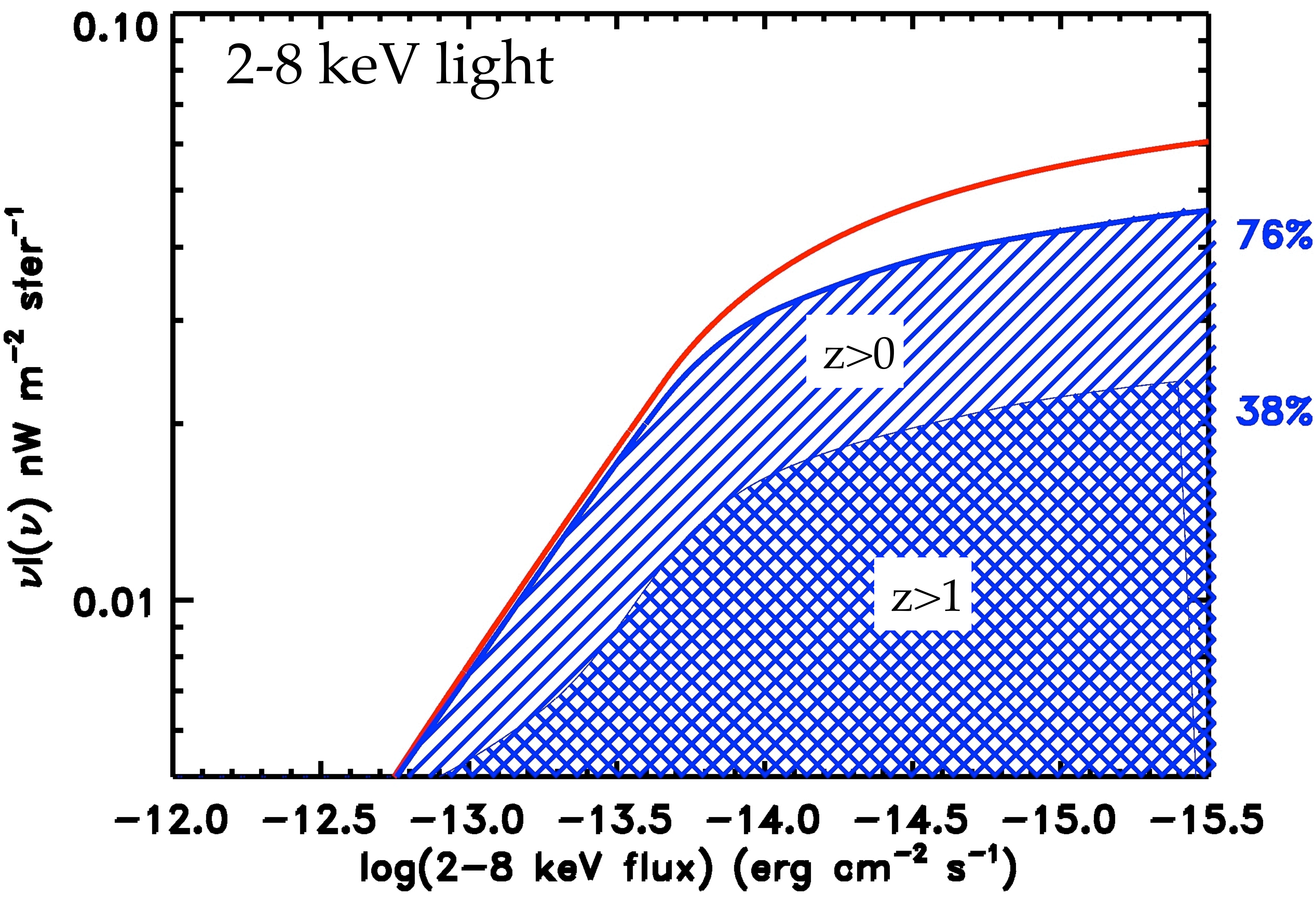
Identifications of sources in the two deepest X-ray images ever taken (CDF-N (green) and CDF-S (blue))



Cowie, Barger and Hasinger 2011

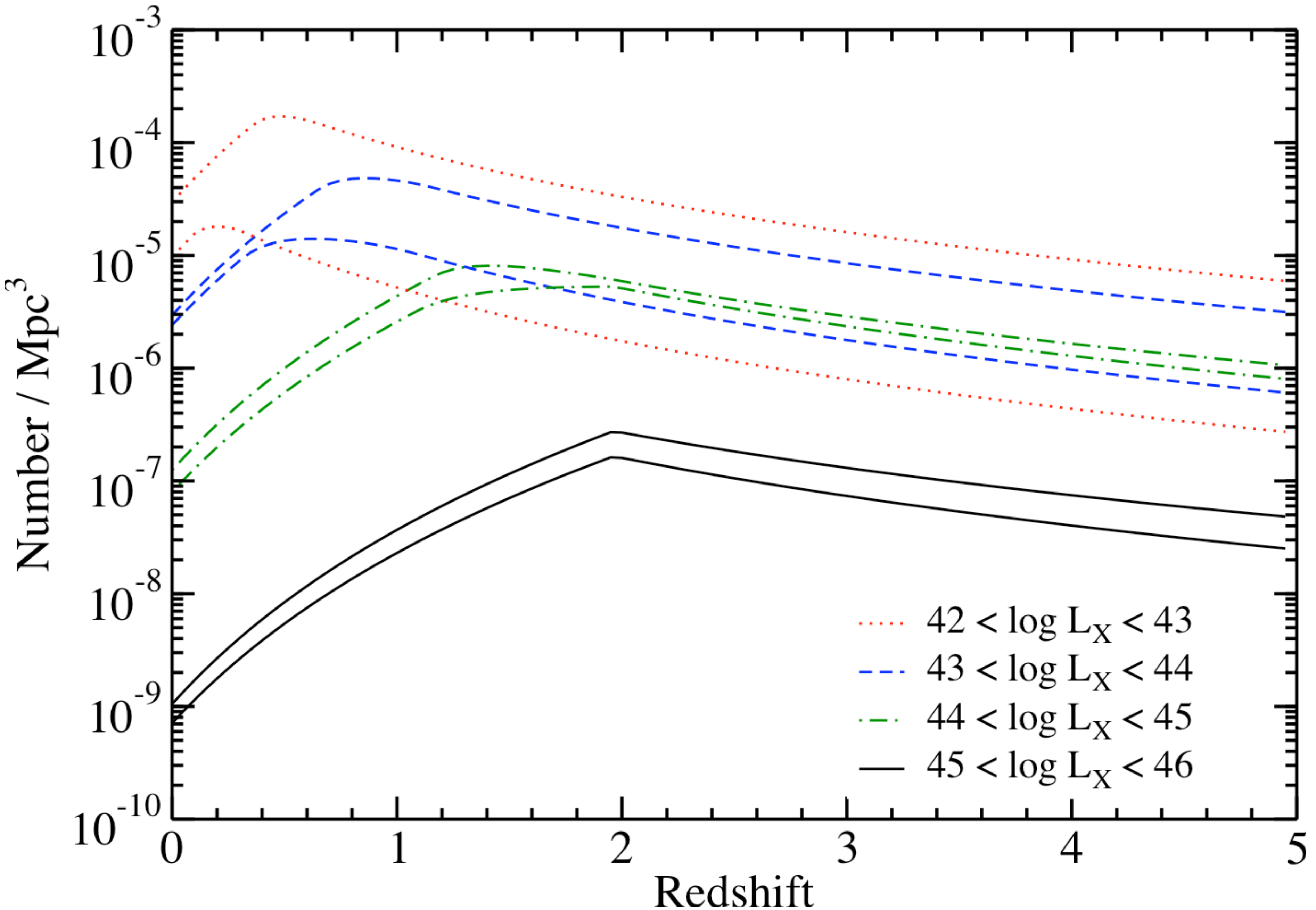
No signal above z=5 in an any sample

X-ray samples are also very spectroscopically complete. Photometric redshifts increase overall identified fraction to about 85%



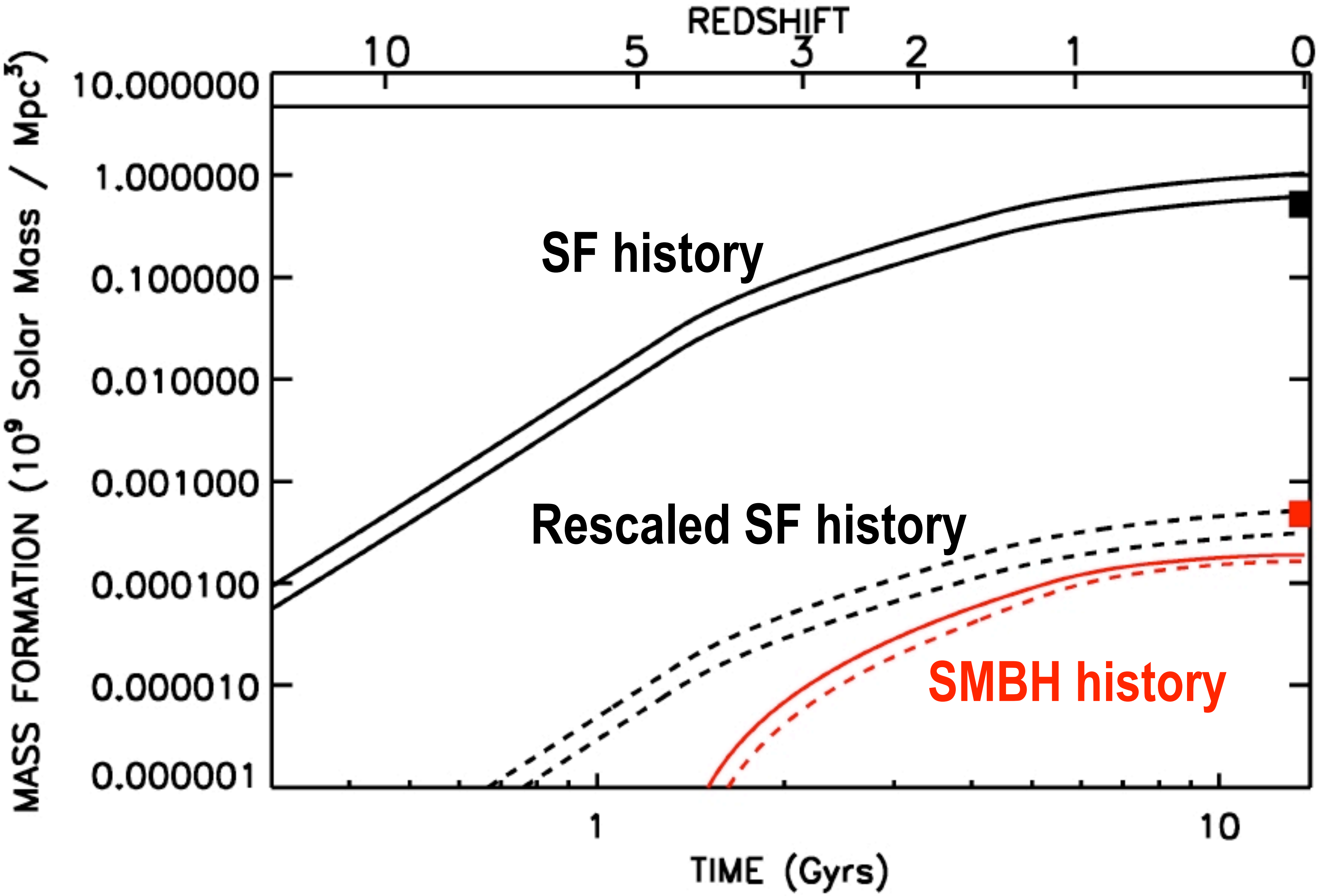
From Trouille et al. 2009

X-ray selected AGN also show downsizing effects, with the high-mass sources forming first and the lower-mass sources persisting to much later times; perhaps whatever is quenching the star formation in large



Yencho, Barger, Trouille & Winter 2009

Cumulative growth of supermassive black holes from Chandra (red curve) compared with the cumulative SFH



Both form most of their mass at late times. If AGN feedback has a significant effect, the relative histories can help diagnose that

AGN versus star formation

The star formation and accretion histories are remarkably similar in many ways:

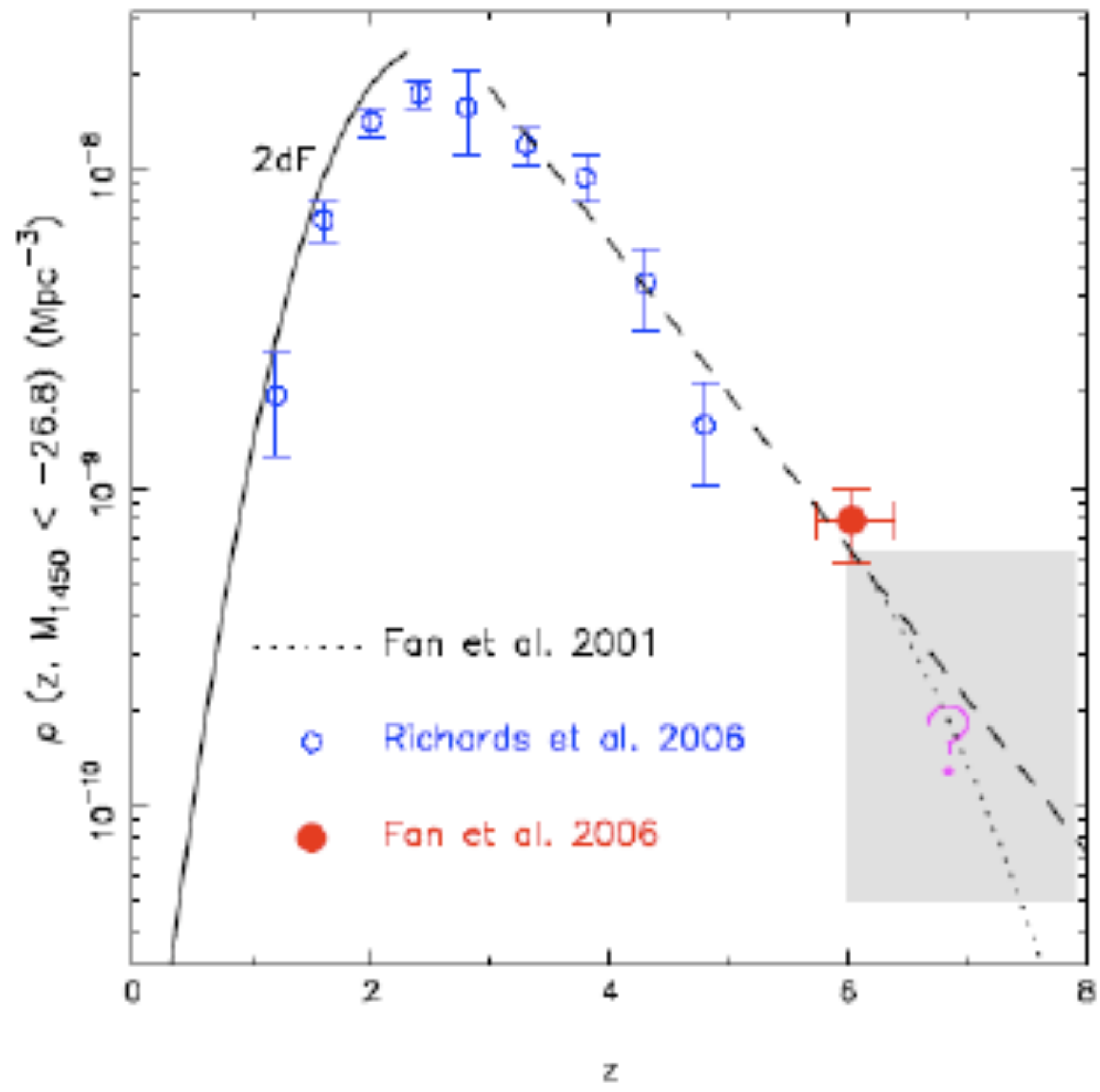
- Both show similar growth with time, peaking at about $z=1$

- Both show downsizing effects, with the high-mass sources forming first, and the lower mass sources persisting to much later times

- Perhaps whatever is quenching the star formation in large galaxies is also switching off the AGN activity (it could be the AGN themselves)

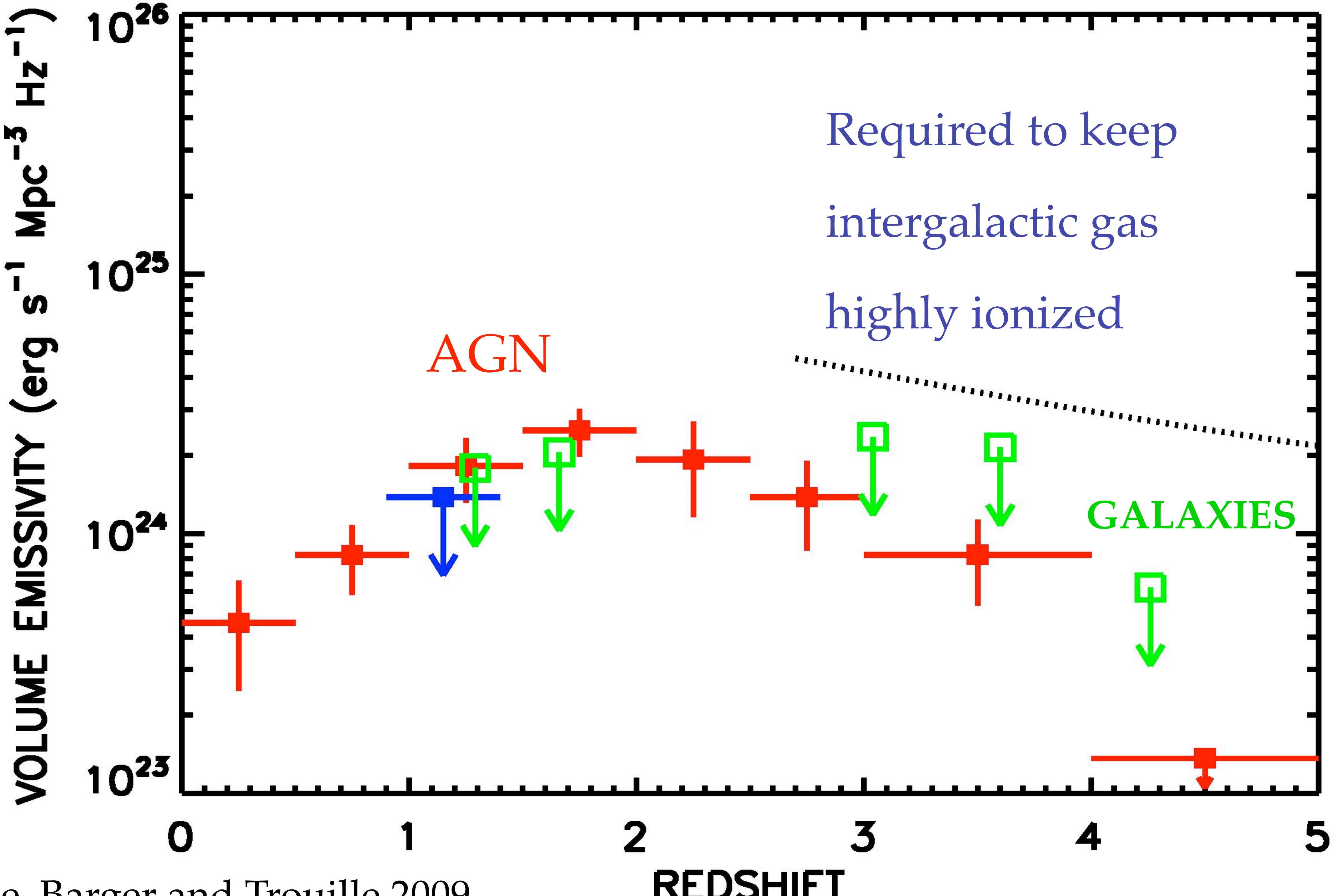
The rarity of high-z AGN

is consistent with optical studies



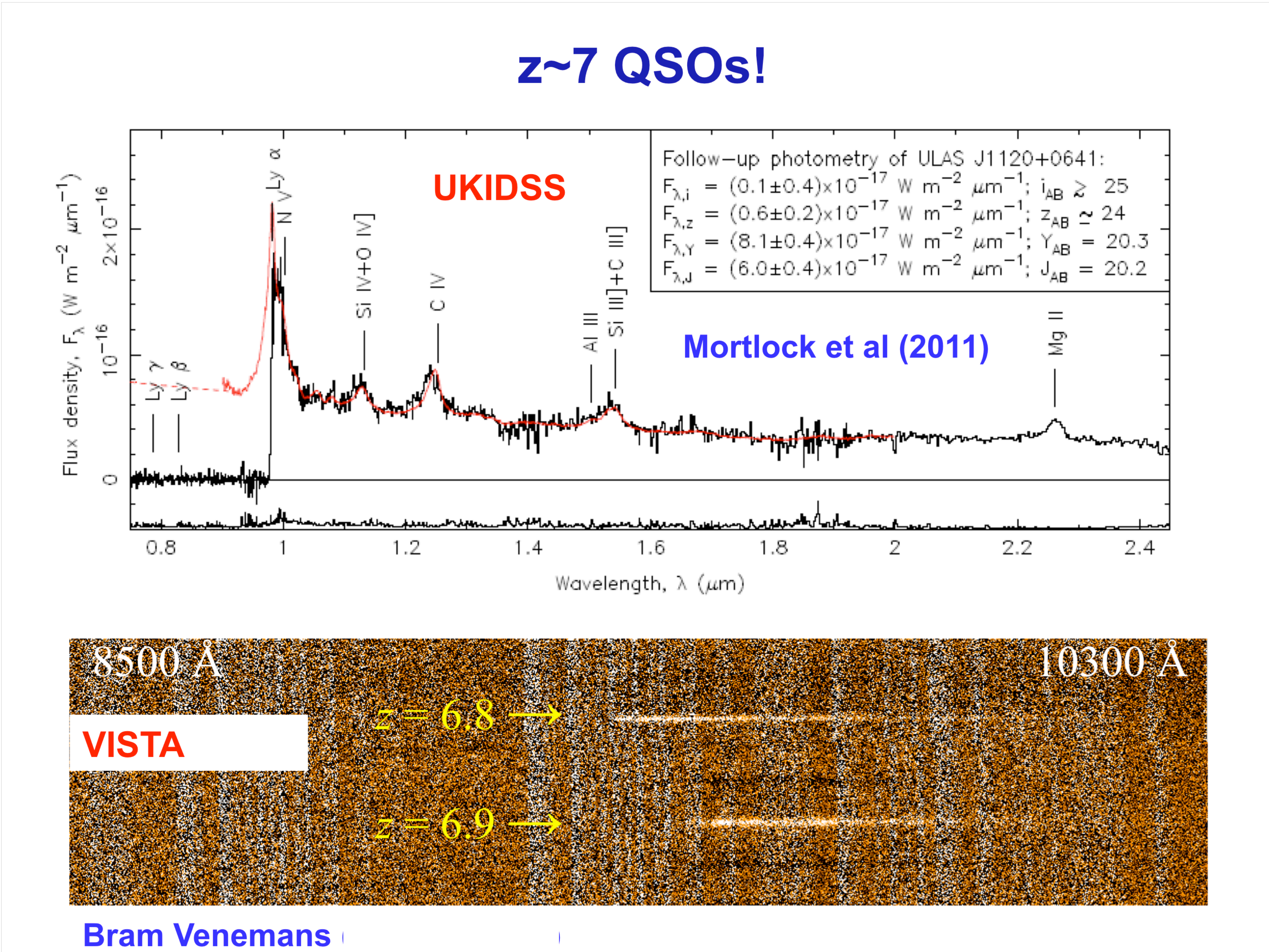
We don’t know what reionizes the intergalactic gas but we also don’t know what keeps it highly ionized at high redshifts where there are few AGN

Best guess is low luminosity galaxies below our current detection thresholds

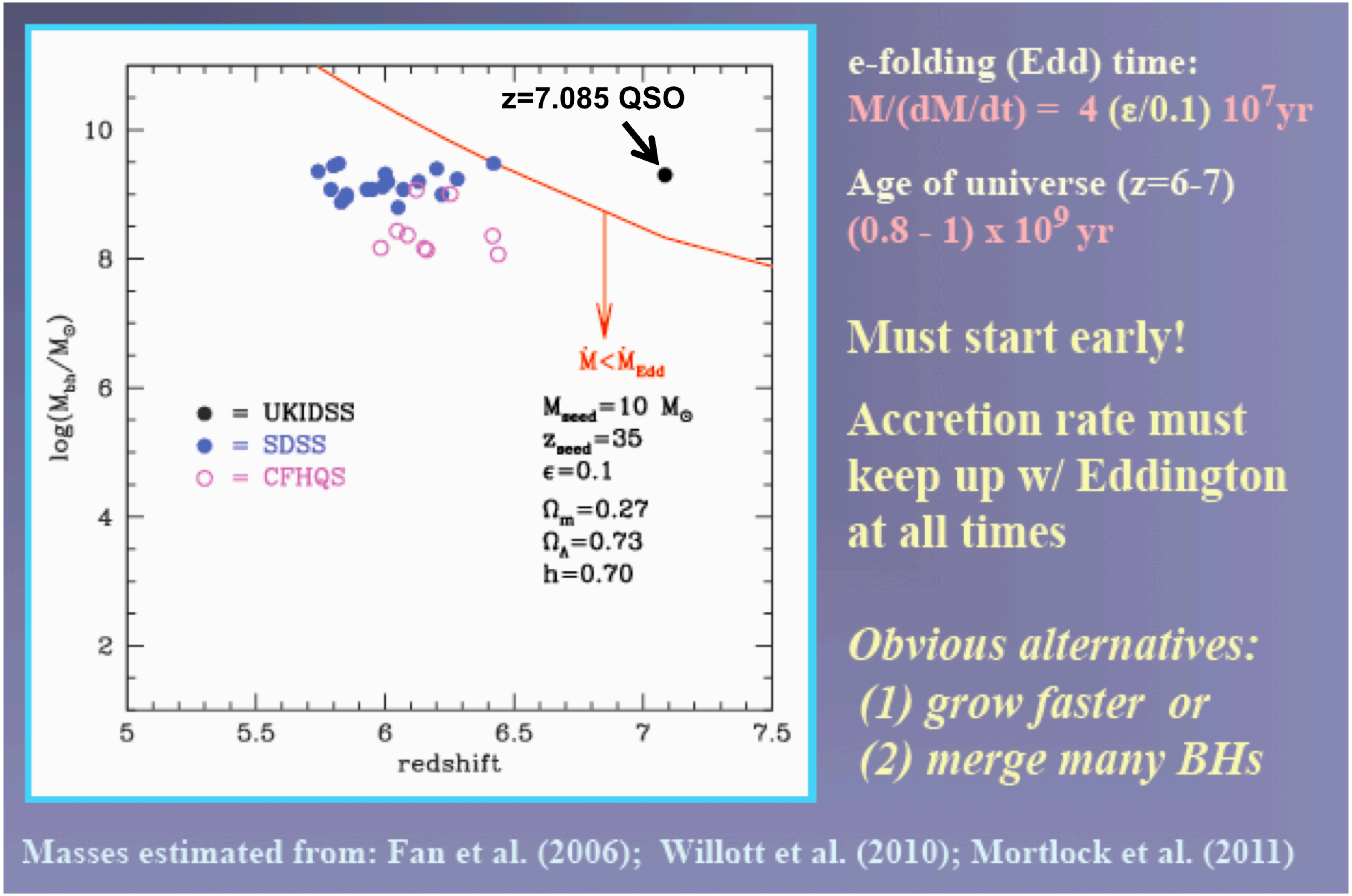


Cowie, Barger and Trouille 2009

But there are some very high redshift AGN



These observations show that supermassive black holes had to start extremely early in order to be this massive at z=7



Slide from Zoltan Haiman

Summary

Over the last 20 or so years we have developed an enormous amount of information on how galaxies evolve

Currently we are probing the boundary where galaxies were younger than a Gyr

We are still struggling with how to deal with the obscured part, which releases most of its light in the far-infrared

We don't know which galaxies or supermassive black holes produce the ionizing photons needed for the intergalactic gas

We don't know how massive quasars formed at early