Visible and Hidden Star Formation in the Universe

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1. Introduction

1.1 The global history of the Universe

Birth

The Big-Bang fireball

The cosmic microwave background

Almost isotropic and homogeneous.

Without heavy elements.

Formation and evolution of galaxies

Birth and death of stars

→ **Production of heavy elements**

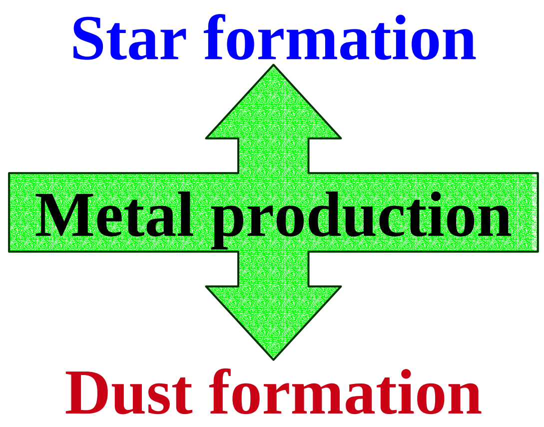
The present-day Universe

Present

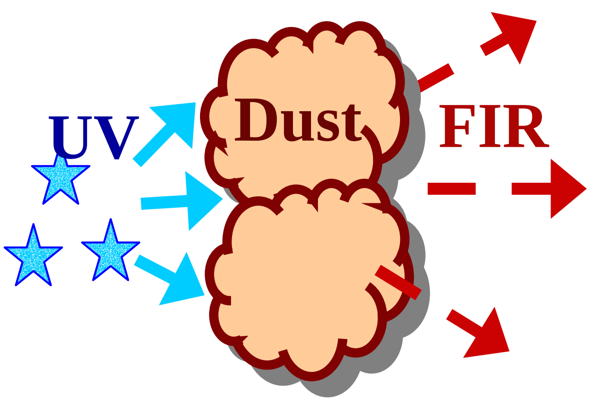
Rich in structures: planets, stars, galaxies, clusters.

Heavy elements: origin of planets, and further, the life.

1.2 The role of dust in galaxies



Star formation activity is always associated with metal production. The produced metals usually exist in a form of small solid grains, i.e., dust.



Photons, especially UV, are scattered and absorbed by dust, and re-emitted as FIR radiation.
Since UV is a direct measure of star formation, dust emission carries complementary information of the star formation hidden by dust.

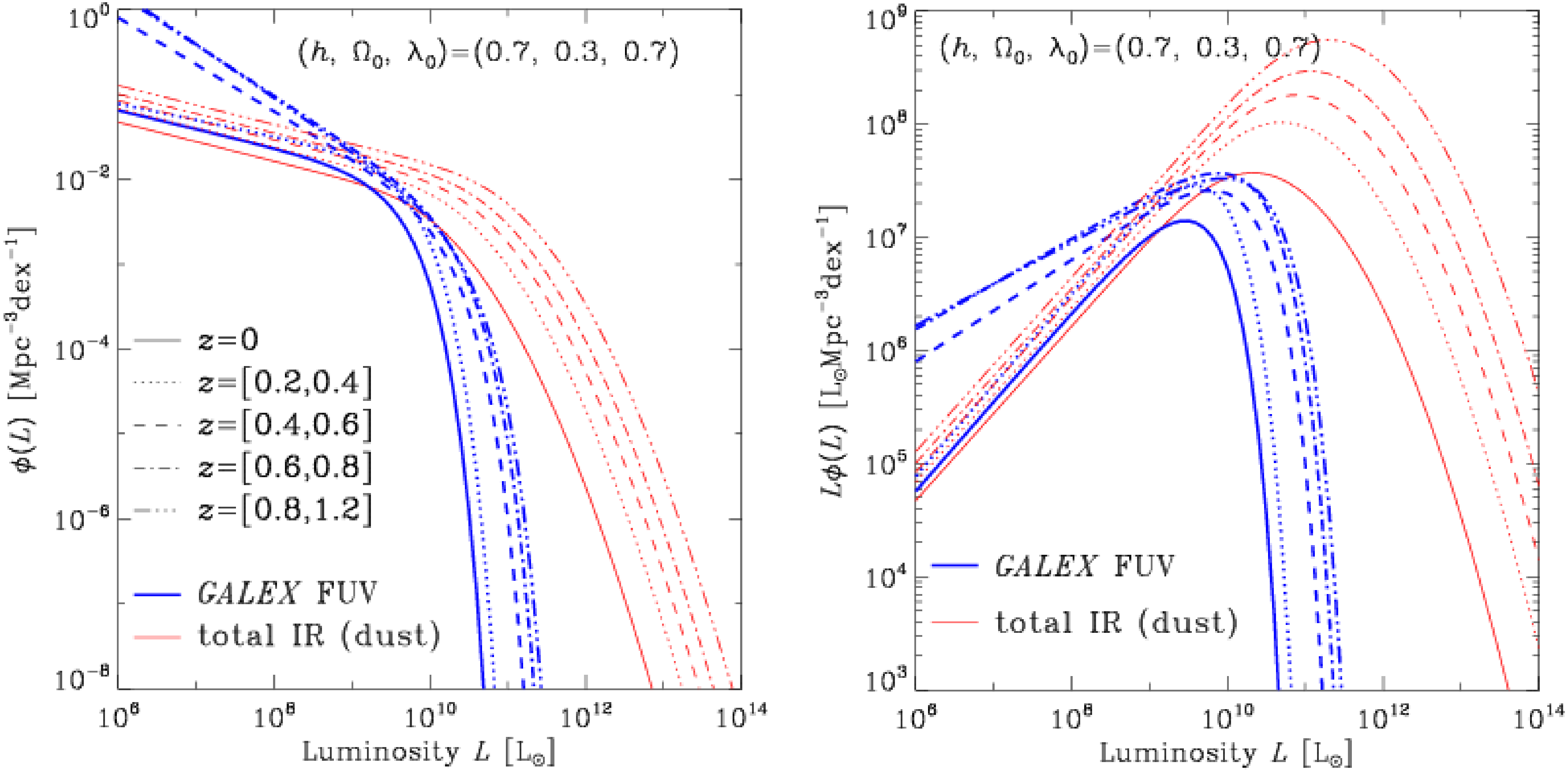
1.3 Evidence of hidden star formation

There is increasing evidence that significant amount of stars formed in galaxies is strongly obscured by dust.

Optical

Mid IR

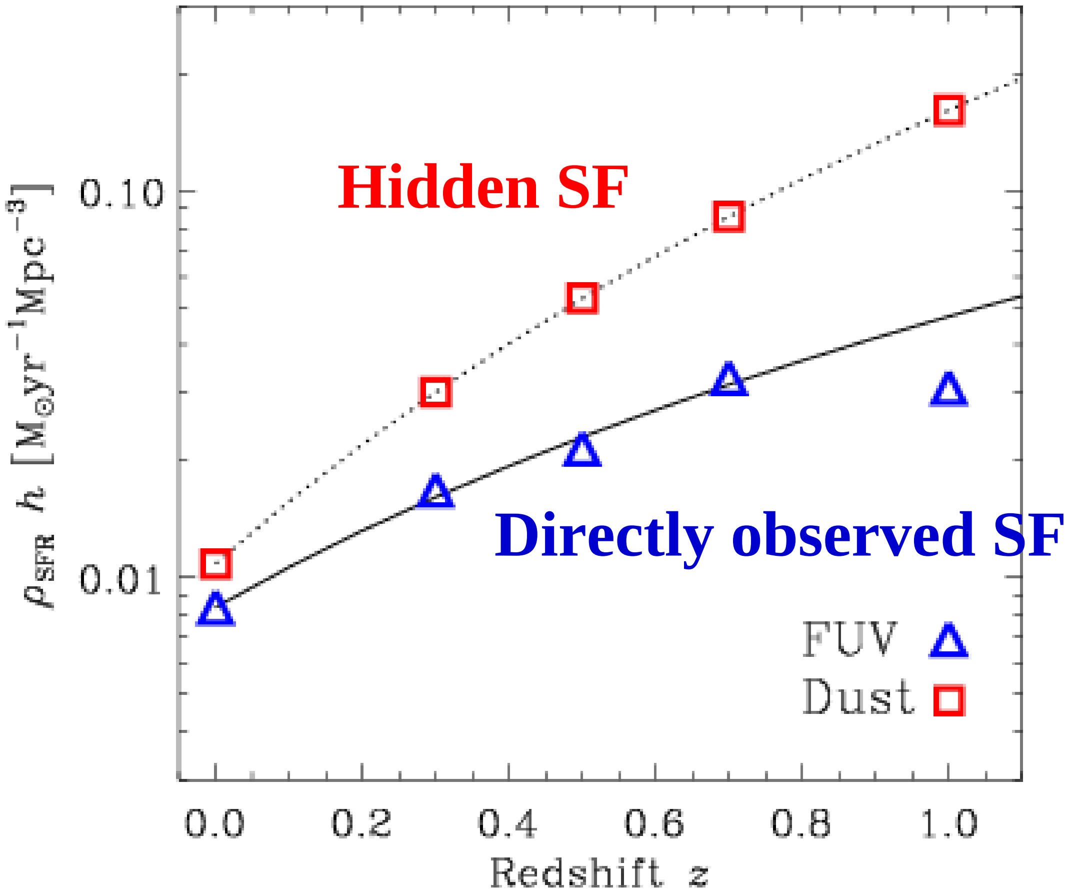
Evolution of the luminosity function in FUV and FIR



UV: *GALEX* (Arnouts et al. 2005)

IR: *IRAS* and *Spitzer* (Le Floc'h et al. 2005)

Evolution of the visible and hidden star formation densities



Though both visible and hidden SFs show strong evolution, the hidden SF evolution is much stronger than the visible SF.

(Takeuchi, Buat, & Burgarella 2005)

Fundamental Question: What is the origin of this evolution?

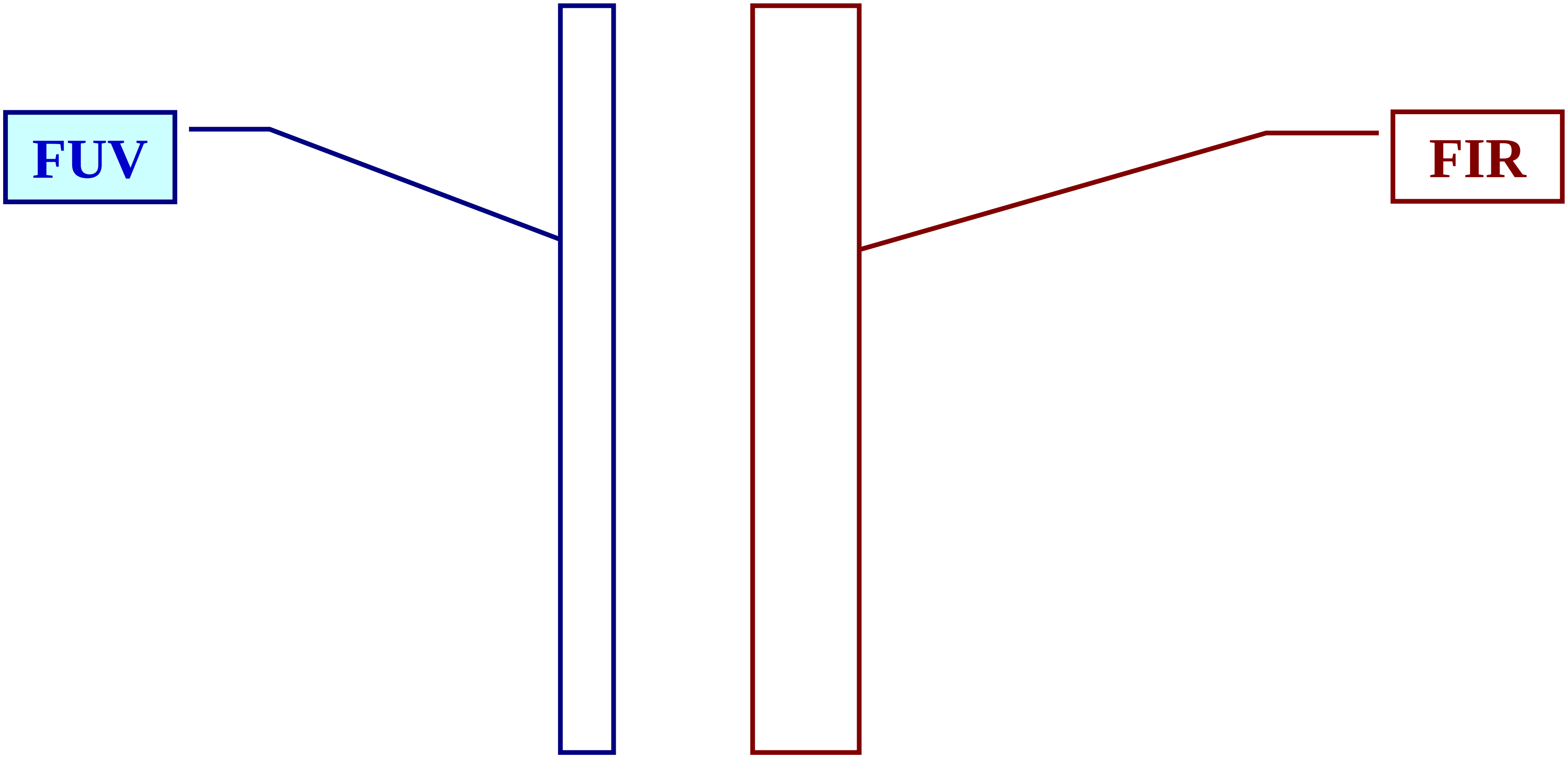
Emergence and/or diminution of a certain population?
Evolution of the property of individual galaxies?

To address this question, unbiased and well-controlled galaxy samples are required. Specially dedicated analysis is also important.

We constructed carefully selected galaxy samples from FUV and FIR satellite observational data, and performed extensive statistical studies on the star formation and dust extinction properties of galaxies.

2. Data Construction

2.1 Need of the satellite observation



FUV and FIR observations are impossible from the ground.

→ **Satellite facilities are required.**

2.2 FUV-selected sample

***GALEX* (*Tinsley Explorer*)**

A UV astronomical satellite launched at 28, Apr. 2003. All-sky surveys at 1530Å and 2315Å are now underway, as well as very deep surveys in some selected sky areas at the same bands.

Data construction procedure

1. **We selected galaxies based on the 1530Å fluxes.**
2. **We assigned FIR fluxes from *IRAS* (Local sample) and *Spitzer* (z=1 sample).**
3. **We assigned optical/NIR fluxes and redshifts from existing databases.**

2.3 FIR-selected sample

Local sample : *IRAS*

The first satellite dedicated to the all-sky survey in the FIR, launched in Jan. 1983. FIR all-sky maps are available, and various point source catalogs and follow-ups have been published.

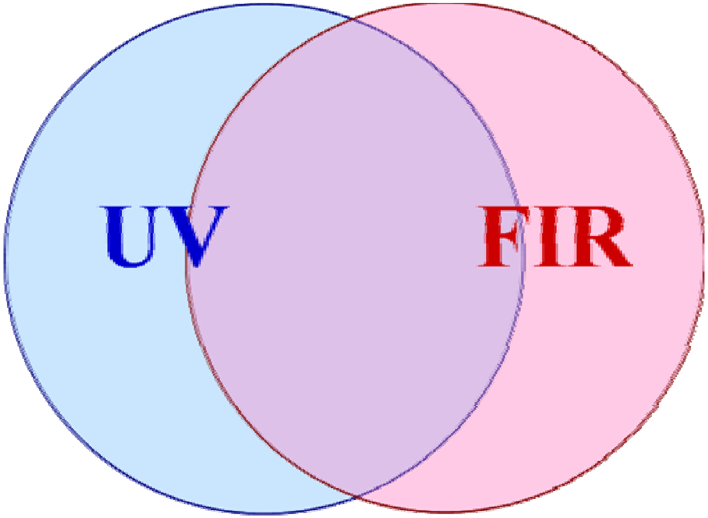
High-*z* sample : *Spitzer Space Telescope*

An IR observatory launched in Aug. 2003. A large-area deep survey (called SWIRE) is underway, and the data are being opened to public.

Data construction has been proceeded in a similar way to the FUV-selected sample, with assigning FUV fluxes by *GALEX*.

2.4 Structure of the datasets

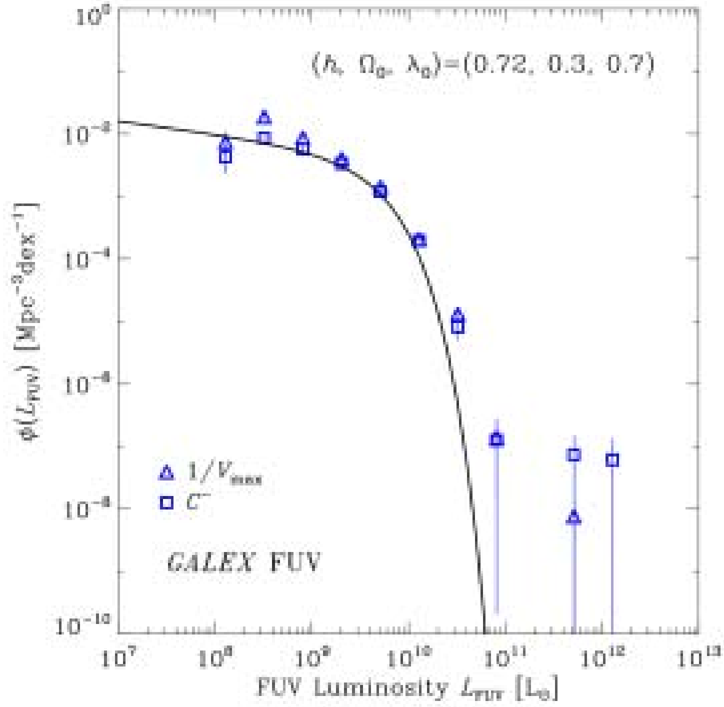
Structure of the sample is schematically described as the Venn diagram. Some galaxies are only detected in one of the two wavelengths, while others are detected both in the FUV and FIR.

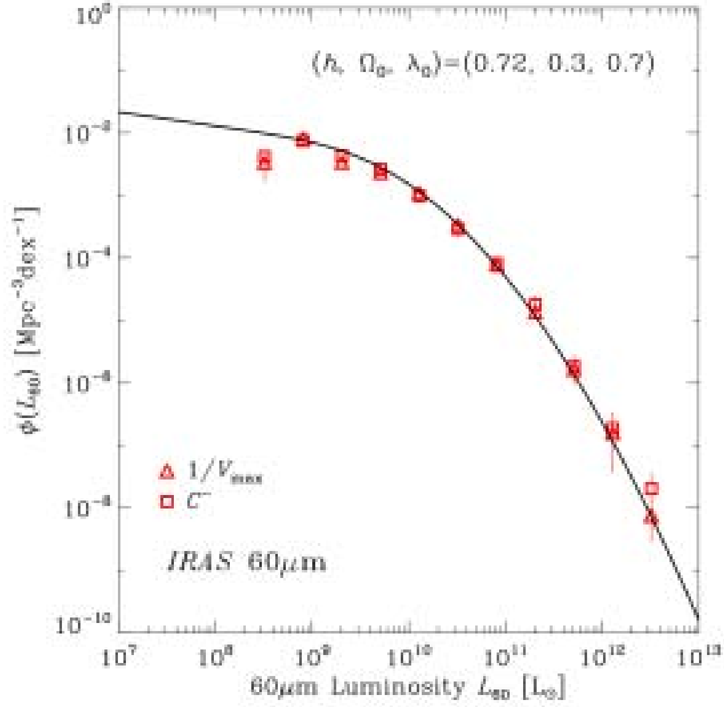


It is very important to understand how we select sample galaxies and what we see in them. We must understand clearly which property is physical and which is simply due to the selection procedure.

3. Results for the Local Universe

3.1 The univariate luminosity functions (LFs)





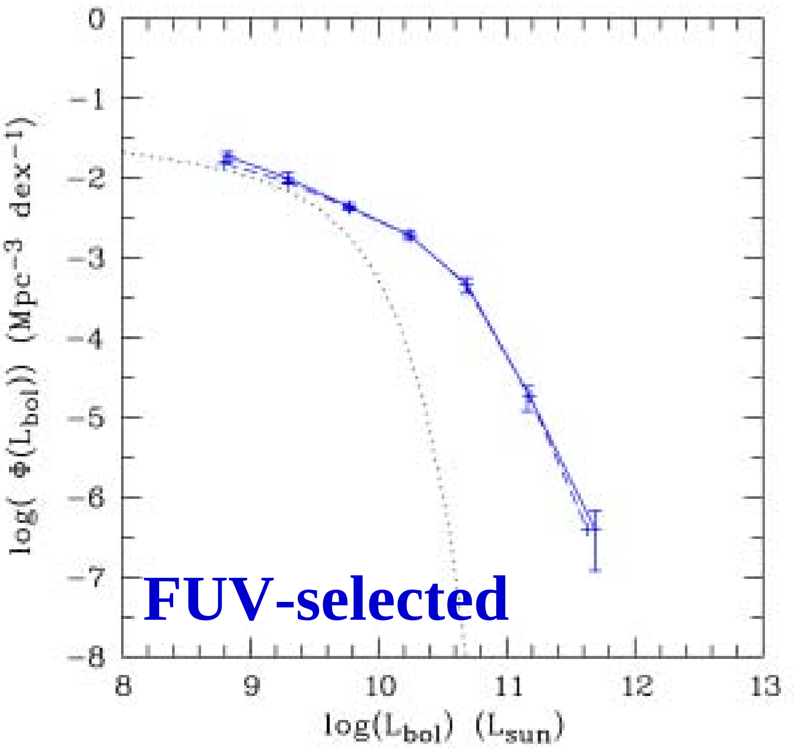
The univariate LFs of our samples show good agreement with the larger sample results. This guarantees the validity of our sample selection procedure, i.e., no significant bias was introduced.

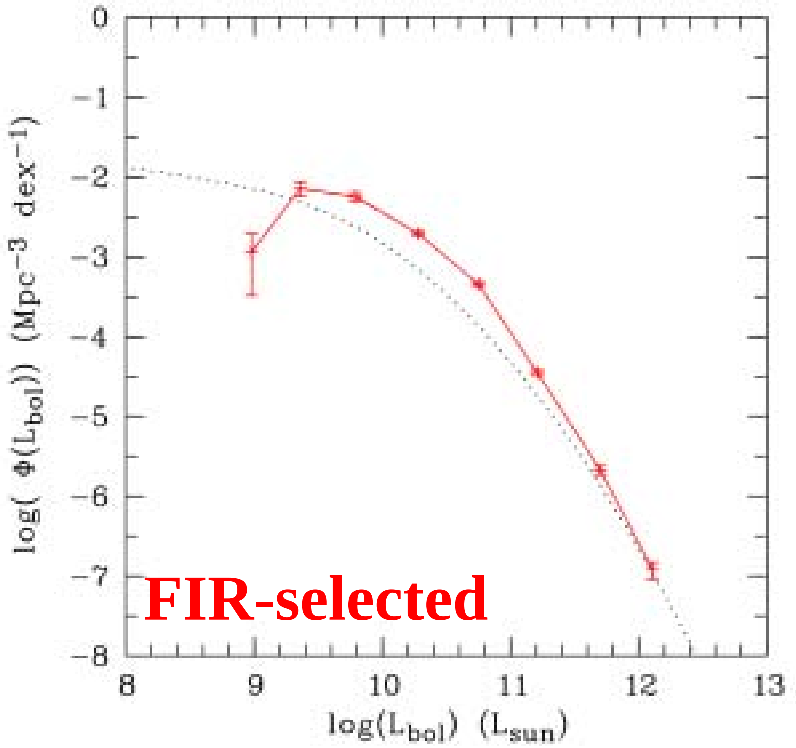
3.2 Bolometric young star luminosity functions

Since we have both FUV and FIR fluxes, we can obtain the total luminosity contribution from newly forming stars:

$$L_{bol} = L_{FUV} + 0.7\,L_{TIR}$$

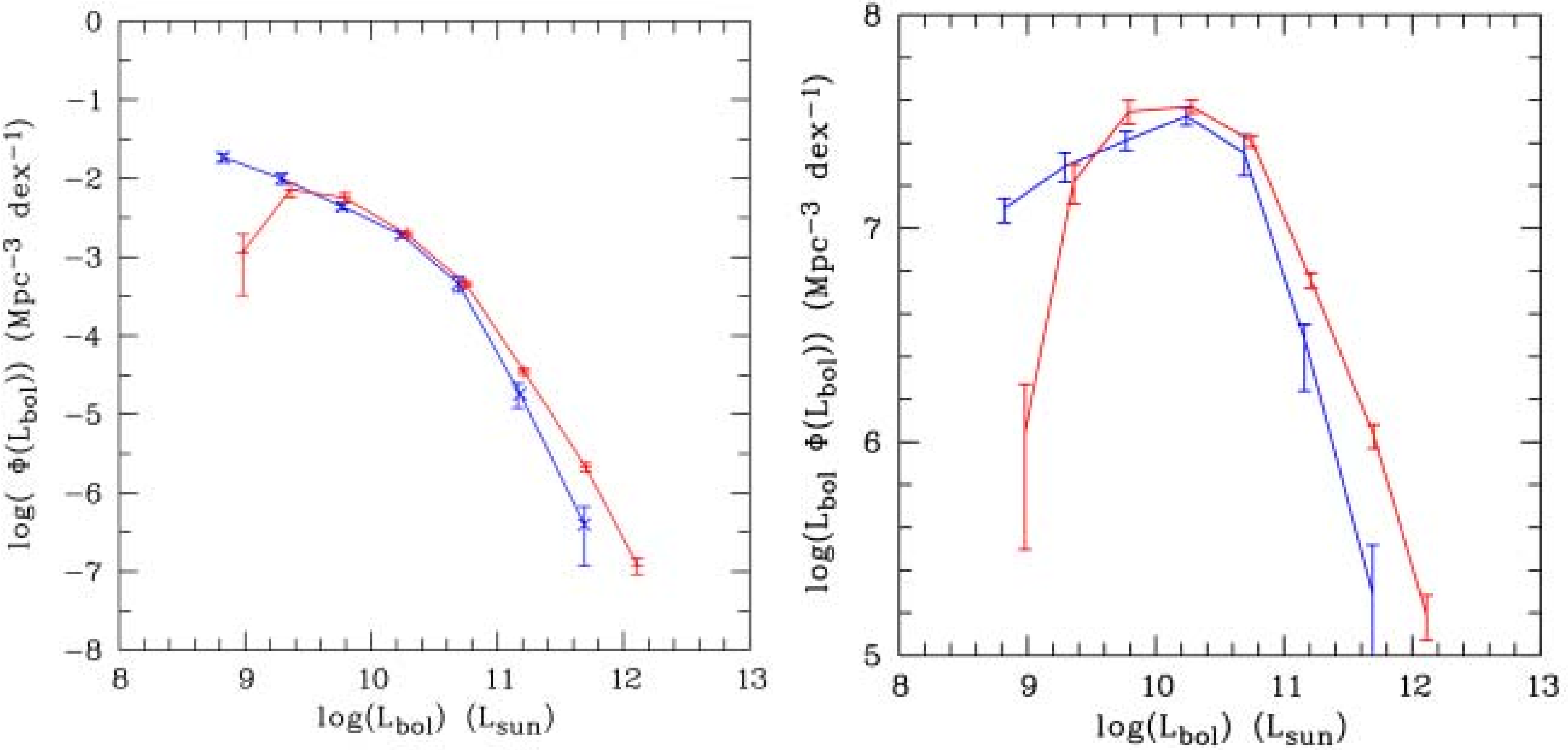
(0.7: correction for old stars)





At FUV, we only see a very small amount of young stars, especially at high luminosity, while FIR well traces them.

Comparison of bolometric LFs from FUV and FIR



The bolometric LFs from FUV and FIR agree with each other quite well except at highest luminosities. This implies a population of galaxies completely obscured by dust, but its contribution is not significant in the Local Universe.

3.3 Extinction properties of galaxies

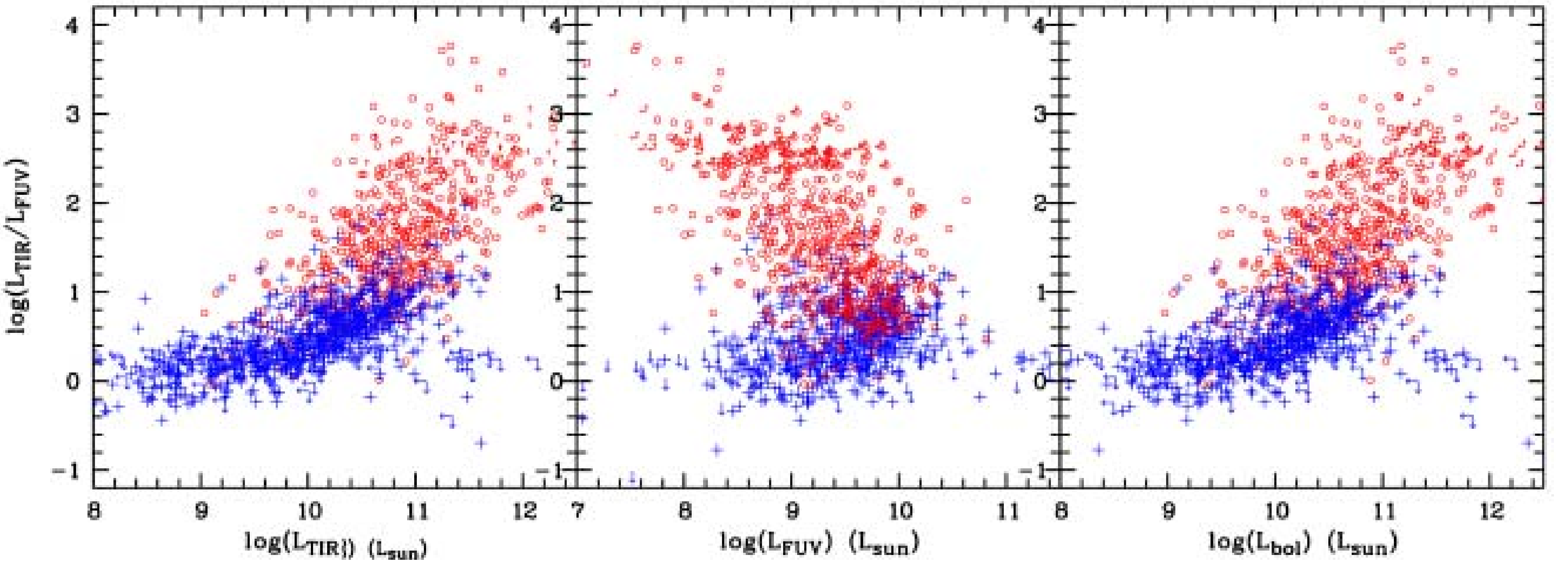
It is known that the extinction (total effect of absorption and scattering by dust) in galaxies is expressed as a nonlinear function of the flux ratio between FIR and FUV:

$$
\begin{aligned}
A(\mathrm{FUV})\ [\mathrm{mag}] \quad = \quad & -0.0333 \left(\log \frac{L_{\mathrm{TIR}}}{L_{\mathrm{FUV}}}\right)^3 \\
& +0.3522 \left(\log \frac{L_{\mathrm{TIR}}}{L_{\mathrm{FUV}}}\right)^2 \\
& +1.1960 \left(\log \frac{L_{\mathrm{TIR}}}{L_{\mathrm{FUV}}}\right) + 0.4967
\end{aligned}
$$

(Buat et al. 2005)

From the current sample, we can see how the extinction depends on galaxy properties through FIR/FUV flux ratio.

The extinction (FIR/FUV ratio) as a function of luminosity



The extinction increases with L_{FIR} and L_{bol}. The trend of FUV (blue symbols) and FIR (red symbols) selected samples are consistent. In contrast, the trends are completely different when we see the relation between FIR/FUV ratio and L_{FUV}.

To see the trend of the FIR/FUV ratio of galaxies, we must take into account the different volumes of the two samples: since FIR-selected galaxies are intrinsically more luminous, we can detect more distant galaxies at FIR.

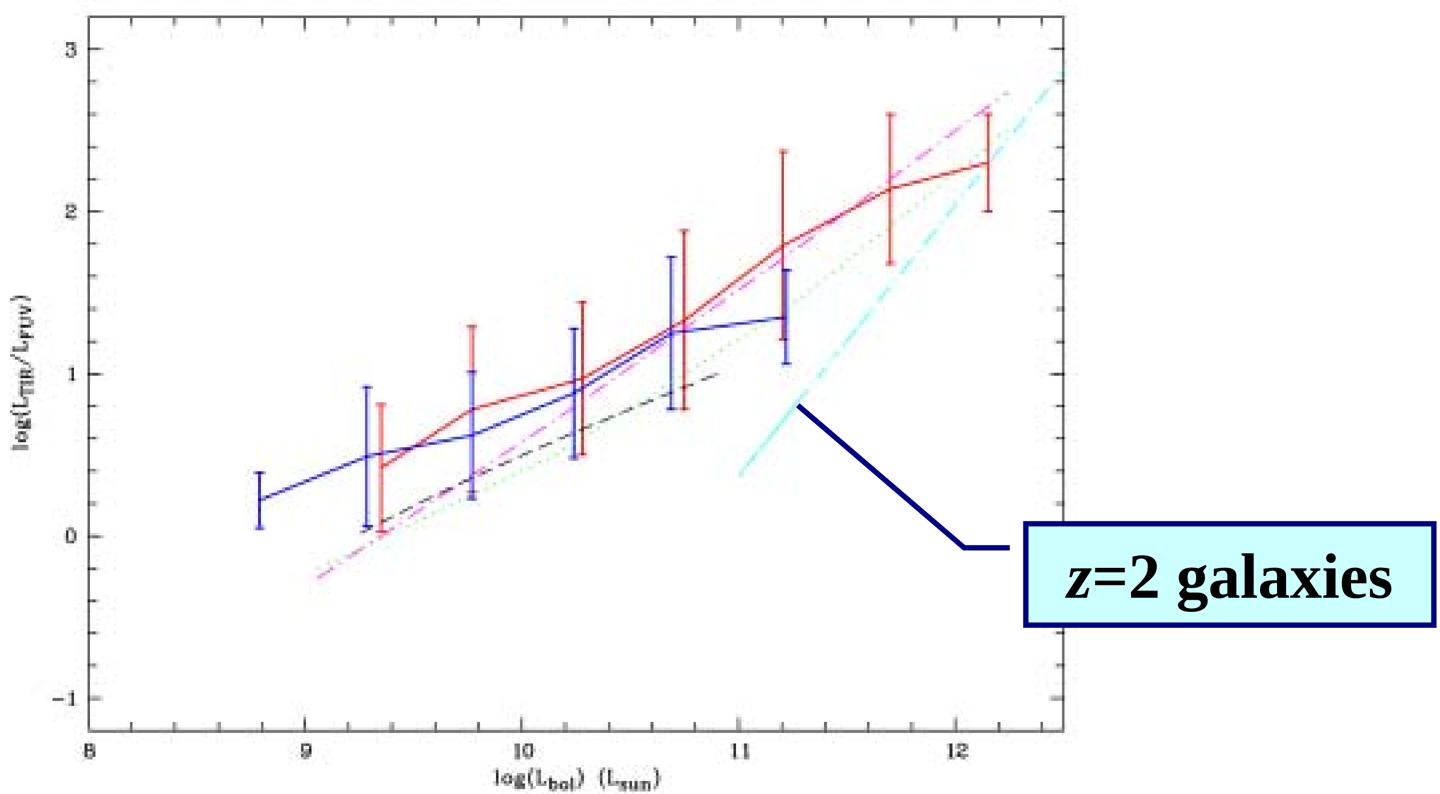
This volume effect is addressed by weighting individual galaxy contribution with the inverse maximum volume ($1/V_{max}$). The V_{max} is defined by the enclosed volume by the maximum distance to which a galaxy can be detected.

By this recipe, we can obtain the average trend of the ratio as follows:

$$\langle R(L_{\rm bol})\rangle = \frac{\sum_i w_i R_i}{\sum_i w_i} \qquad w_i = \frac{1}{V_{\rm max}}$$

where $R_i = L_{FIR}/L_{FUV}$ for a galaxy i.

The average extinction trend along L_{bol}



The trend agrees with previous studies with smaller samples. It is also interesting that the trend at the highest luminosity is consistent with higher-*z* (*z*=2) trend (Reddy et al. 2005). This suggests that the evolution of extinction trend is understood by the simple scale-up of the bolometric luminosity.

3.4 Star formation history

Specific star formation rate (SSFR)

The specific star formation rate (SSFR) is defined as a current SFR normalized by the total stellar mass M_*:

$$\mathrm{SSFR} = \frac{\mathrm{SFR}}{M_\star}$$

The SSFR practically represents the ratio between the current SFR and the average SFR in the galaxy lifetime, the so-called birthrate parameter *b*:

$$b = \frac{\mathrm{SFR}}{\langle \mathrm{SFR} \rangle}$$

This is a direct reflection of the star formation history of galaxies and hence crucial for the studies of galaxy evolution.

The downsizing effect

It is known that the SSFR monotonically decrease with stellar mass: more massive galaxies have smaller SSFR.

This implies that massive galaxies formed stars in their early phase of evolution, while less massive ones in later phase. It is a crucial property remaining to be explained.

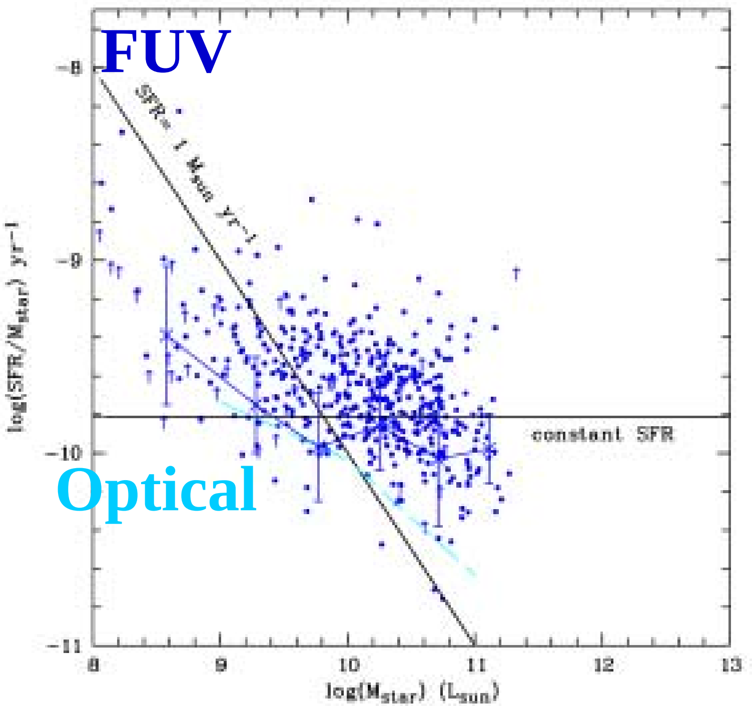
We can also obtain the average trend for the SSFR of the samples by the $1/V_{max}$ recipe:

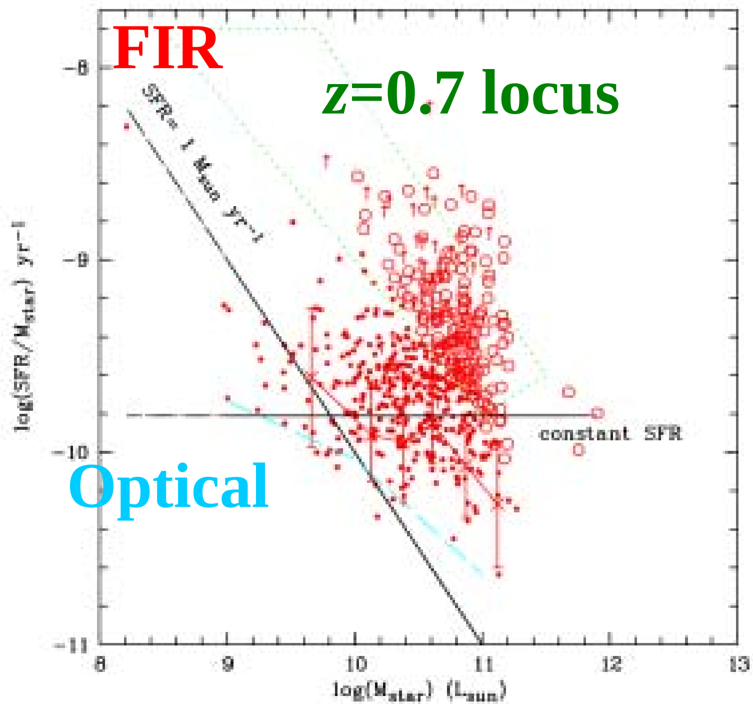
$$\langle \mathrm{SSFR} \rangle \equiv \frac{\sum_i w_i \, \mathrm{SSFR}_i}{\sum w_i} \qquad w_i = \frac{1}{V_{\max}}$$

where, with η=0.3 (again correction for old stars),

$$\mathrm{SFR_{tot}} = \mathrm{SFR}(\mathrm{FUV_{obs}}) + (1-\eta)\mathrm{SFR}(\mathrm{TIR})$$

The downsizing effect seen in FUV and FIR-selected samples

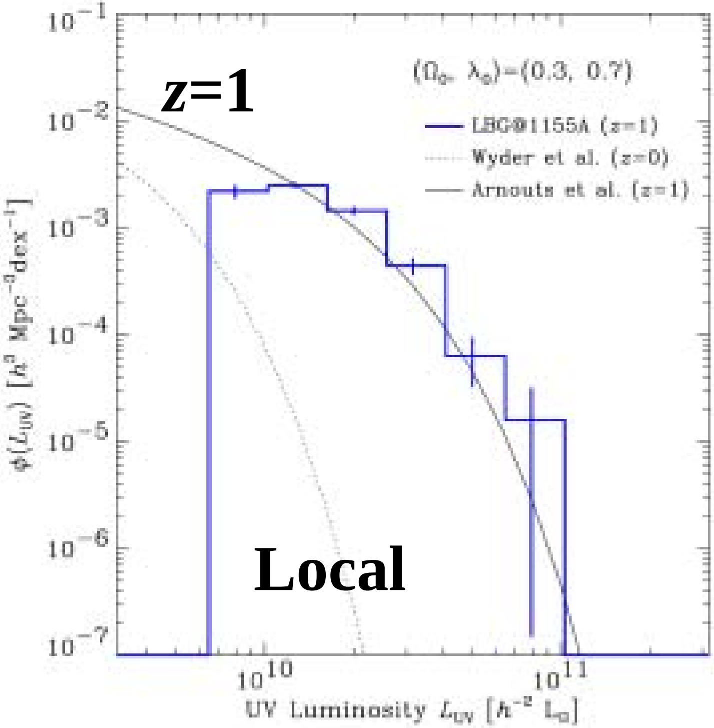




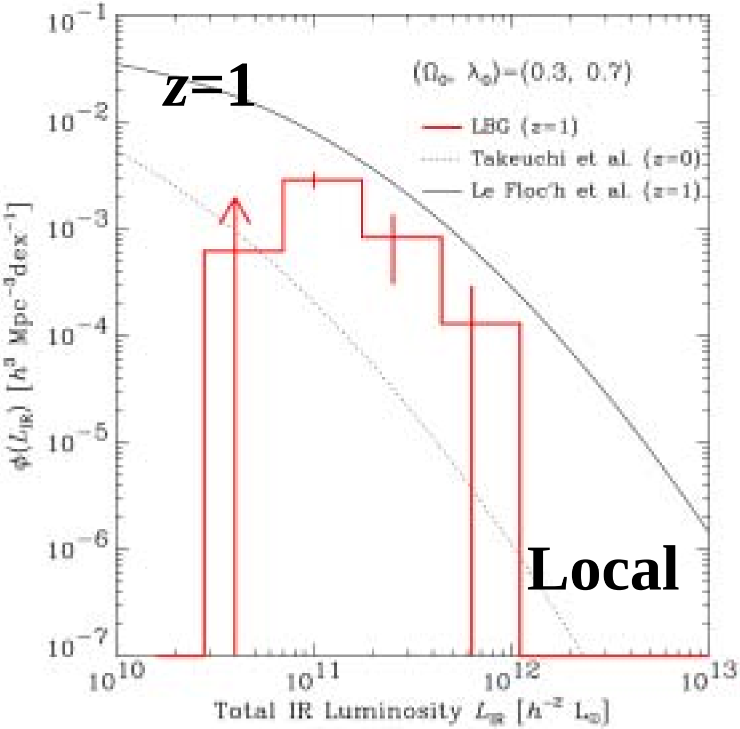
Both the FUV and FIR sample trends roughly agree with the optical study by SDSS (Brinchmann et al. 2004). In the FIR, we find a population of massive galaxies with very high SSFR, deviating from the downsizing trend. They are as active as galaxies at *z*=0.7 (Bell et al. 2005), but they are rare objects in the Local Universe.

4. Results at z=1

We report the first result from the Chandra Deep Field South (CDFS) observed by *GALEX* and *Spitzer*.



FUV univariate LF at z=1 sample



FIR LF of the FUV-selected sample, compared with the total FIR LF in the CDFS

Quick summary of the z=1 results

1. **The FUV LF at z=1 in the CDFS showed a perfect agreement with the LFs in other regions, validating that our sample selection is proper.**
2. **At z=1, the galaxy LF shows a strong evolution both at FUV and FIR.**
3. **However, though the evolution of the FIR LF of the FUV sample is strong, it is a factor of 3 lower than that of the FIR LF of the purely FIR selected sample by *Spitzer*.**

These facts implies that the contribution from the hidden galaxy population is much larger than that in the Local Universe. This is coherently understood as the increase of the FIR luminosity density along redshifts. Further refinement will be interesting.

5. Prospects to *AKARI*

AKARI **(formerly known as ASTRO-F) is a new Japanese satellite designed to carry out infrared surveys with a higher sensitivity and angular resolution than *IRAS* all-sky survey. *AKARI* was successfully launched on 22 Feb. 2006.**

MIR and FIR instruments are on board. Large area surveys will be performed, as well as pointed observations.

Large-area survey data will be opened to public after a reliable verification and calibration. Pointed observation data will also be opened to public after one-year prioritized period.

⇨ ***AKARI*** **will provide us with a huge amount of high quality data, which promises a great progress in the studies of dust in galaxies and cosmic star formation.**

6. Conclusions

1. **The bolometric LFs are consistent at the intermediate luminosity range, but differ at the highest luminosity, implying the obscured galaxy population.**
2. **The luminosity dependence of the extinction is well established. The high-*z* property is explained by simple scale-up of the luminosity.**
3. **The SSFR from the sample show the downsizing effect. We also found that massive FIR luminous galaxies are as active as galaxies at *z*=0.7.**
4. **At *z*=1, obscured galaxies are the majority of galaxies.**
5. **The *AKARI* all-sky survey data promise further understanding of hidden star formation in the Universe.**