# Recent Topics on Dust in Galaxies : A Critical Review of Herschel First Results

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*Special thanks to*
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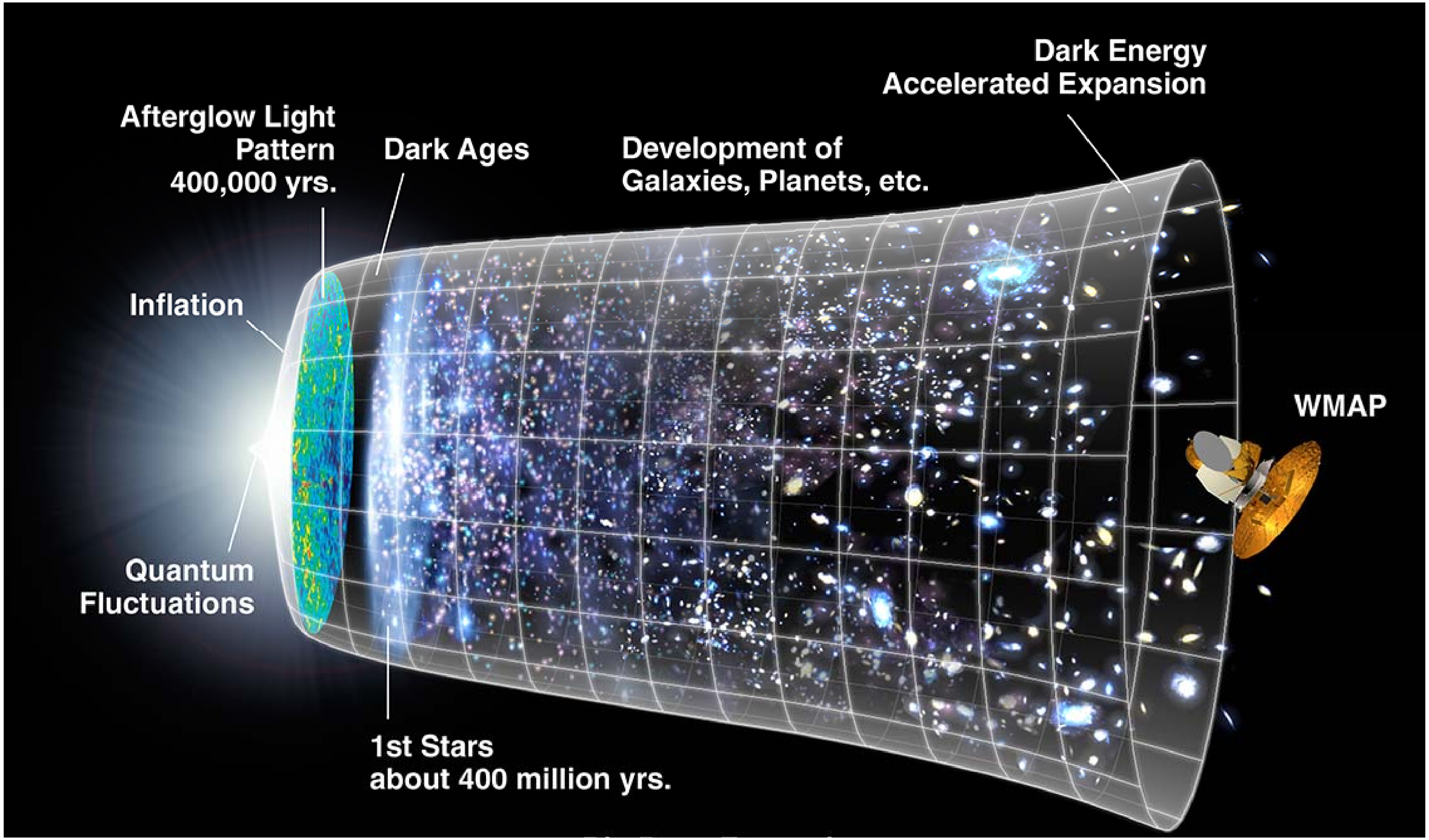
**28th Grain Formation WS/Dust in Galaxies, Kobe, 01 Sep. 2010**

# 1. The Star Formation History in the Universe

## 1.1 The global history of the Universe




http://map.gsfc.nasa.gov/m_mm.html

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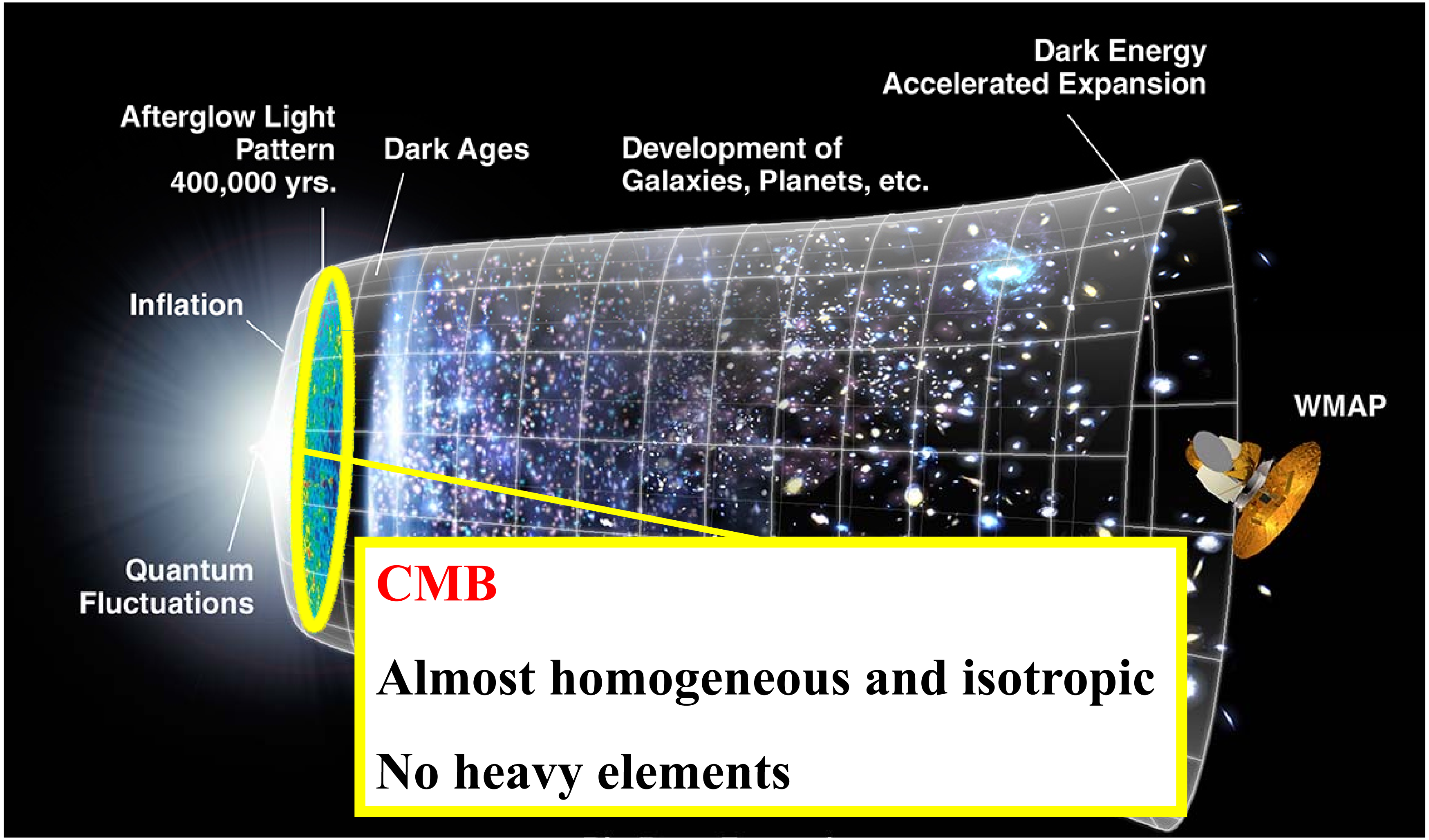


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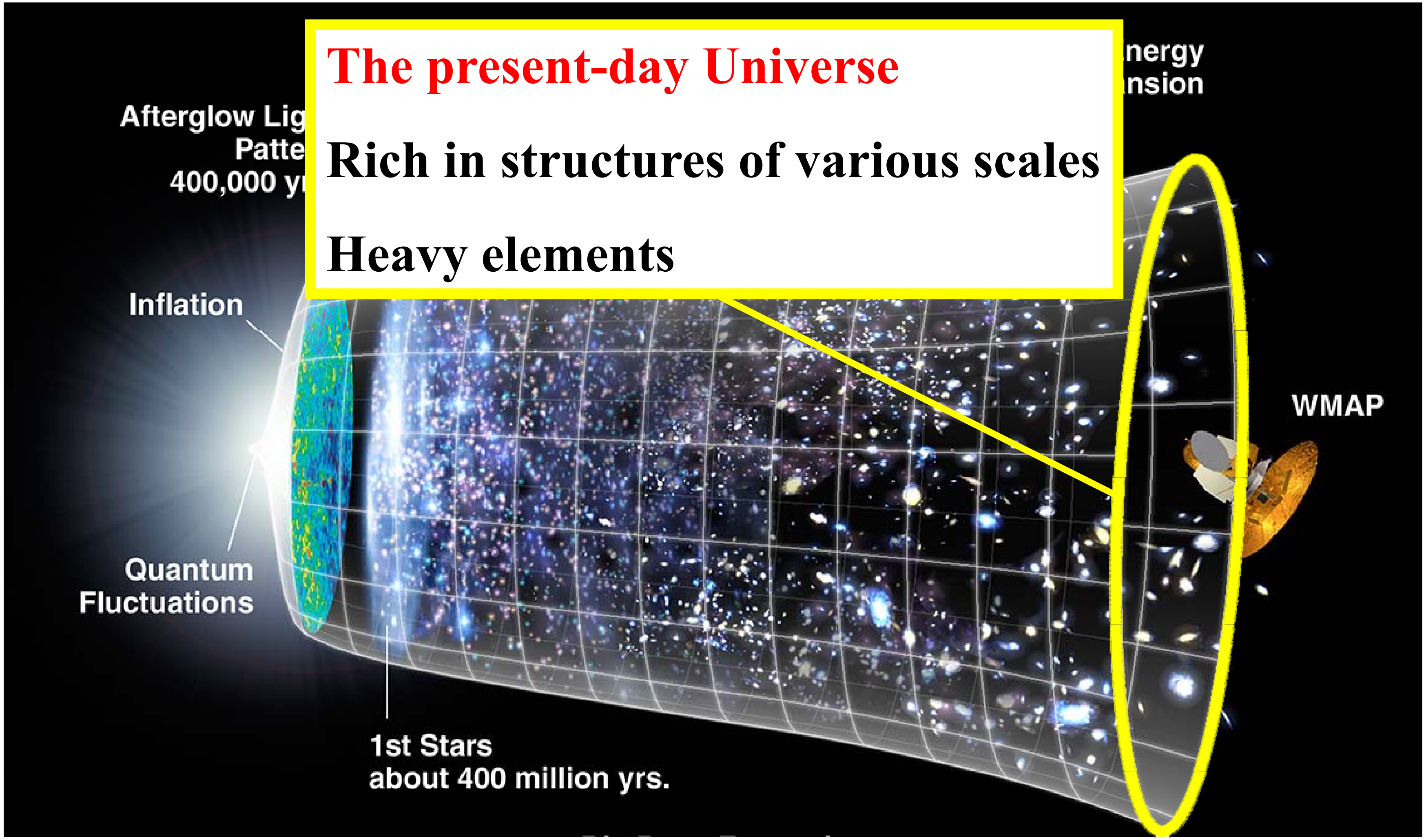


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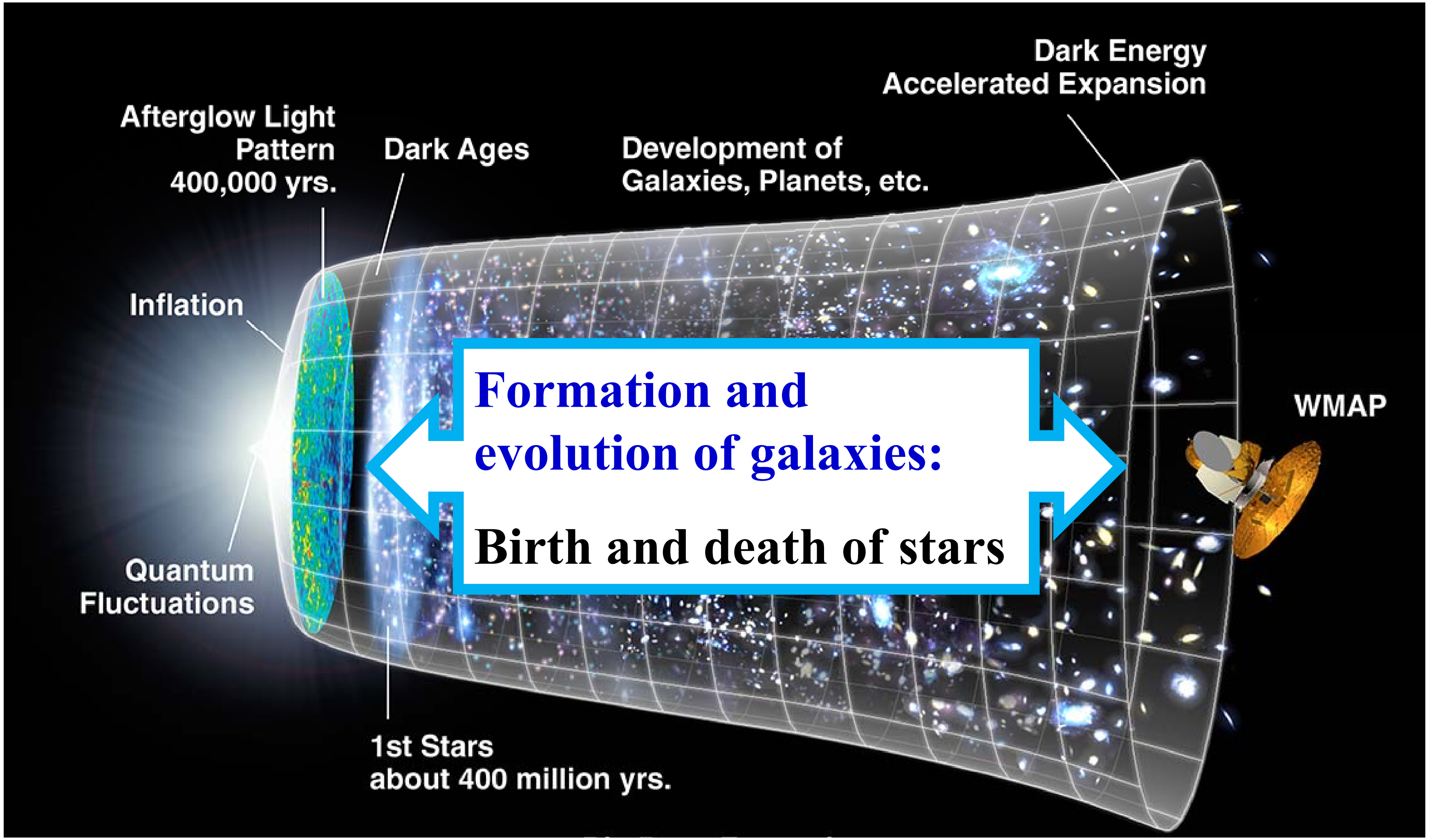
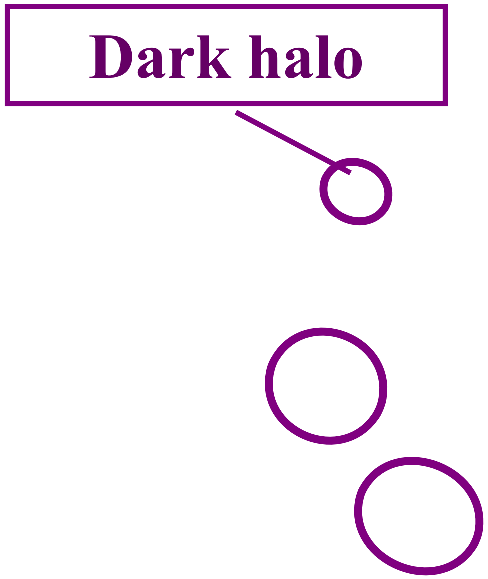



http://map.gsfc.nasa.gov/m_mm.html

# 1.2 Formation and evolution of galaxies

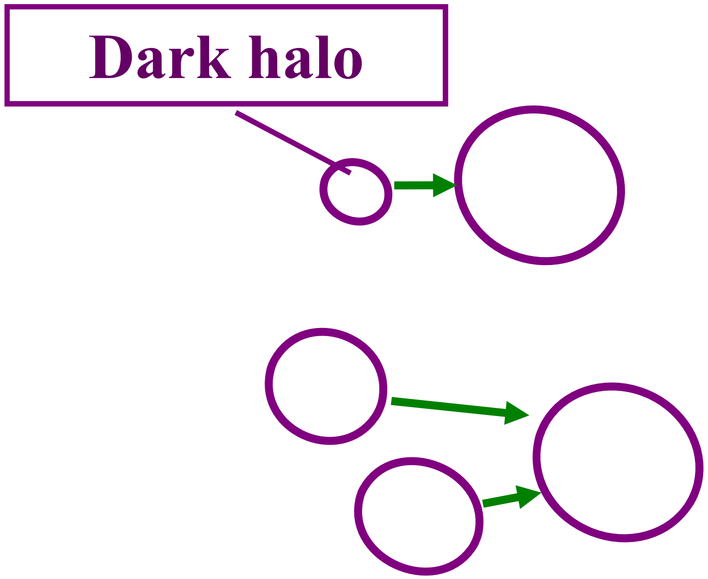
## The hierarchical structure formation

**The mass in the Universe is known to be dominated by invisible matter detected only by gravity (dark matter: DM). The initial fluctuations of DM start to grow by gravitational interactions. Resulting virialized structures are called dark halos.**



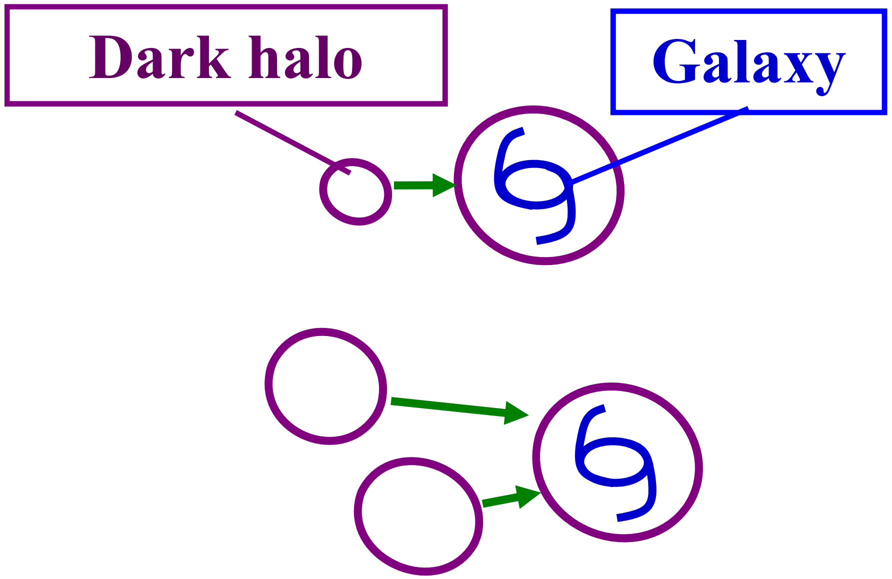
## The hierarchical structure formation

**The dark halos approach each other and finally merge to form larger halos. The formation proceeds from smaller to larger structures. This is the so-called hierarchical structure formation, currently the most reliable scenario of the structure formation in the Universe.**



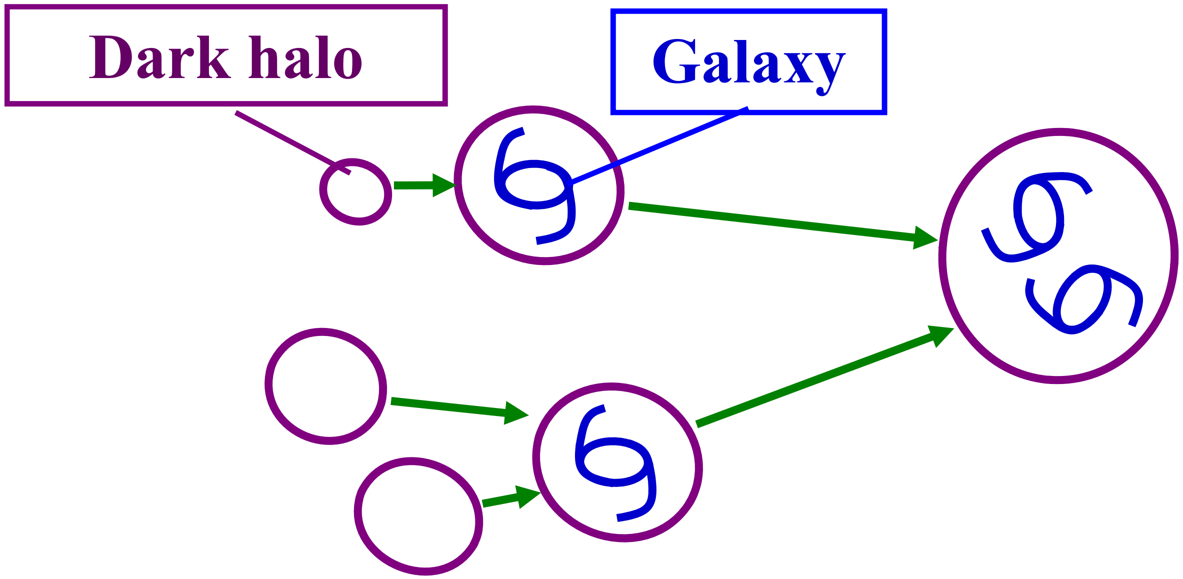
## The hierarchical structure formation

**During the merging of dark halos, the baryonic gas falls into the gravitational potential wells of DM and is compressed there. Then, the gas turns into stars, and galaxies form as large agglomerations of stars and remaining gas in dark halos.**



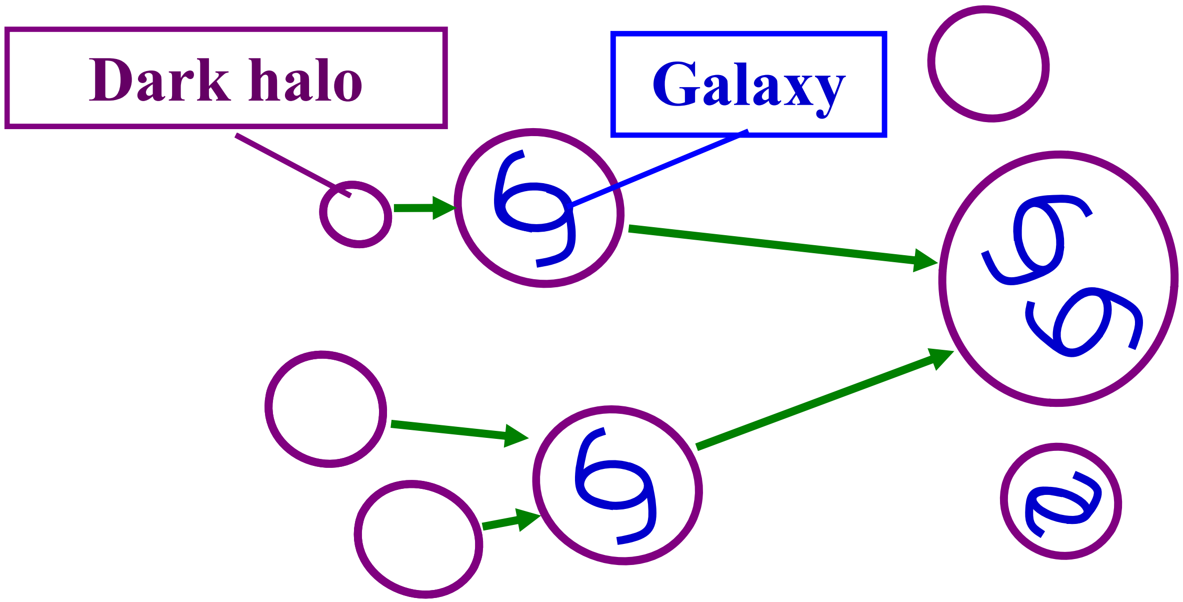
## The hierarchical structure formation

**Dark halos continue merging and form larger and larger halos. Consequently, galaxies in these halos start to cohabit in the same newly formed halos. Baryonic structures cannot merge as easily as dark halos because of gas pressure.**



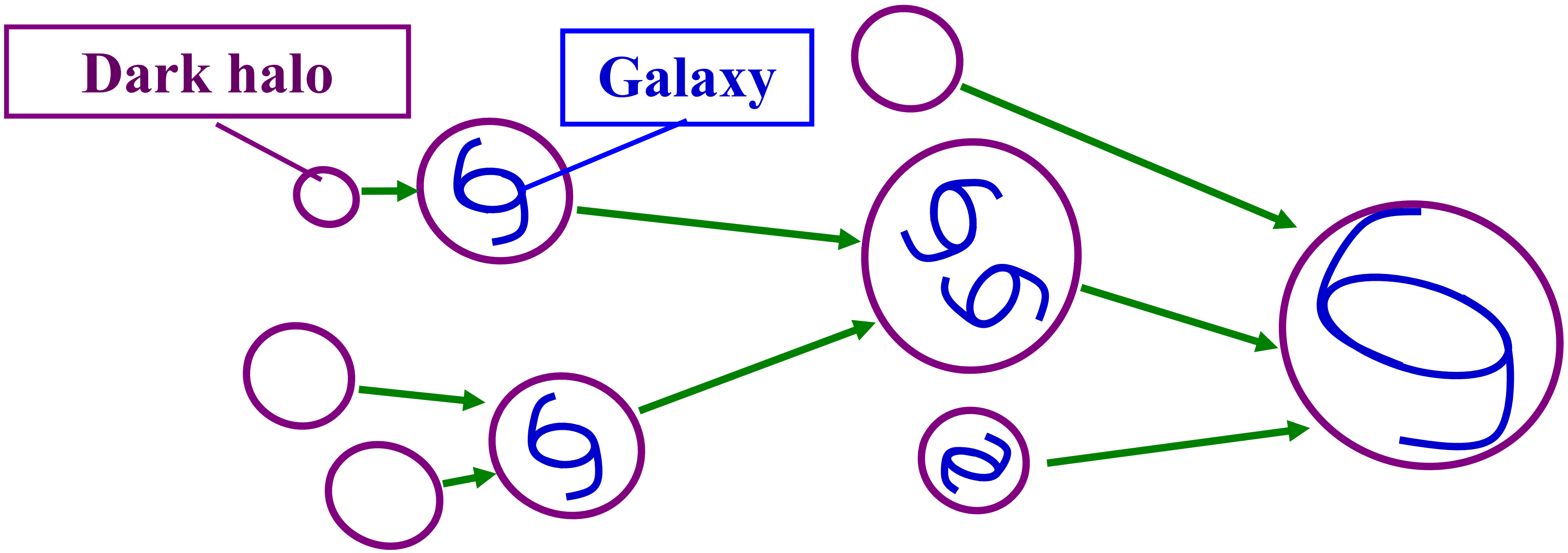
## The hierarchical structure formation

**Then, sometimes dark halos are occupied by one or more galaxies and sometimes no galaxies. The occupation number is stochastic (but loosely a function of the halo mass). Merging goes on with the cosmic time.**



## The hierarchical structure formation

**Finally, some galaxies merge and form larger galaxies. Present-day large galaxies (up to $M_{\mathrm{baryon}} \sim 10^{12}\ \mathrm{M_{sun}}$) are thought to have formed in the merger process. Strong merging process is often accompanied by an effective compression of gas, inducing star formation.**



## The hierarchical structure formation

**Important issues:**

**When, where, and how stars formed?**

**How large/small were the first galaxies?**

**How does the site of star formation depend on the surrounding?**

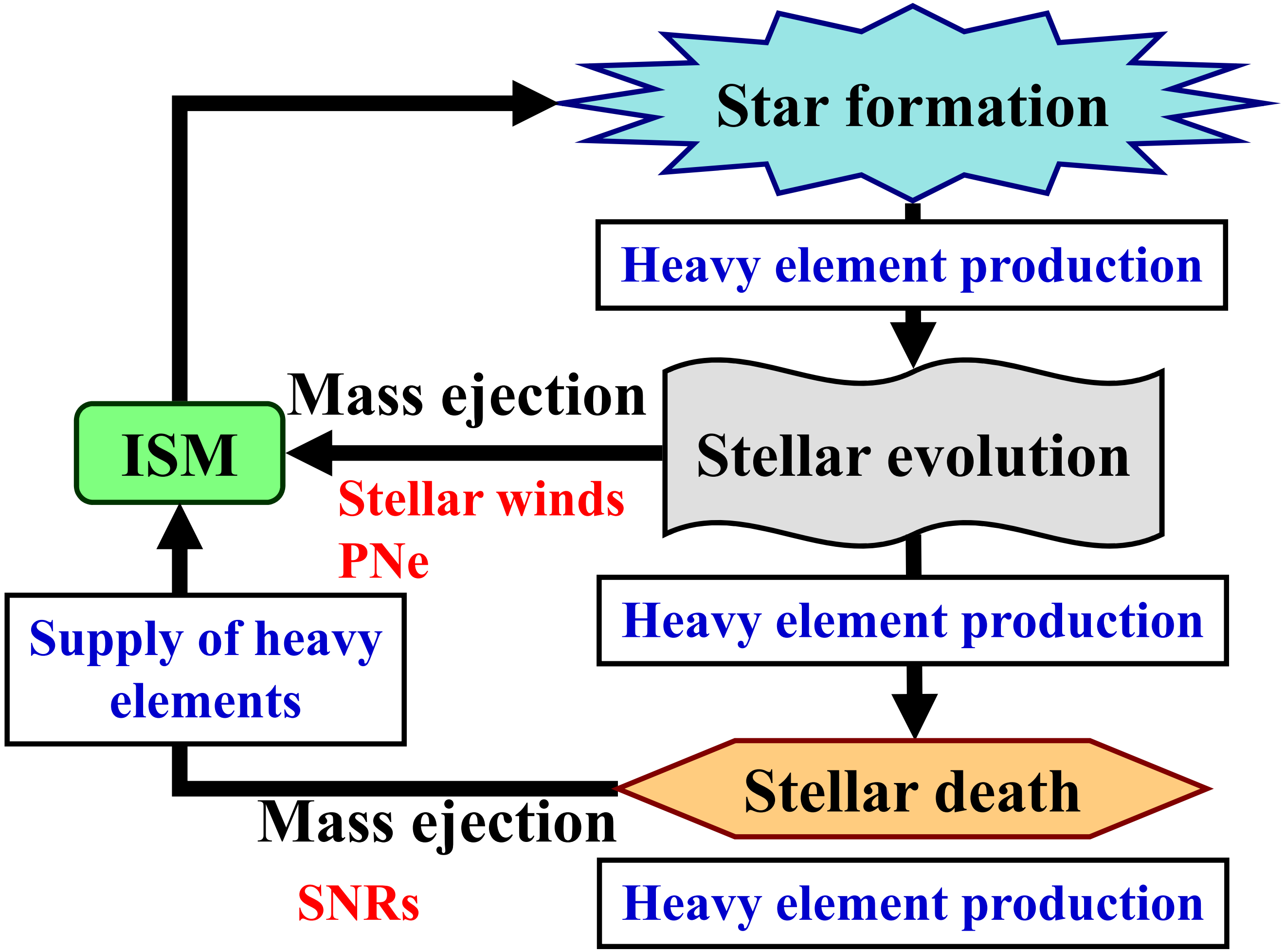
## Chemical evolution of galaxies

**After the first star formation in galaxies, all galaxies gradually accumulate heavy elements produced by their own stars.**

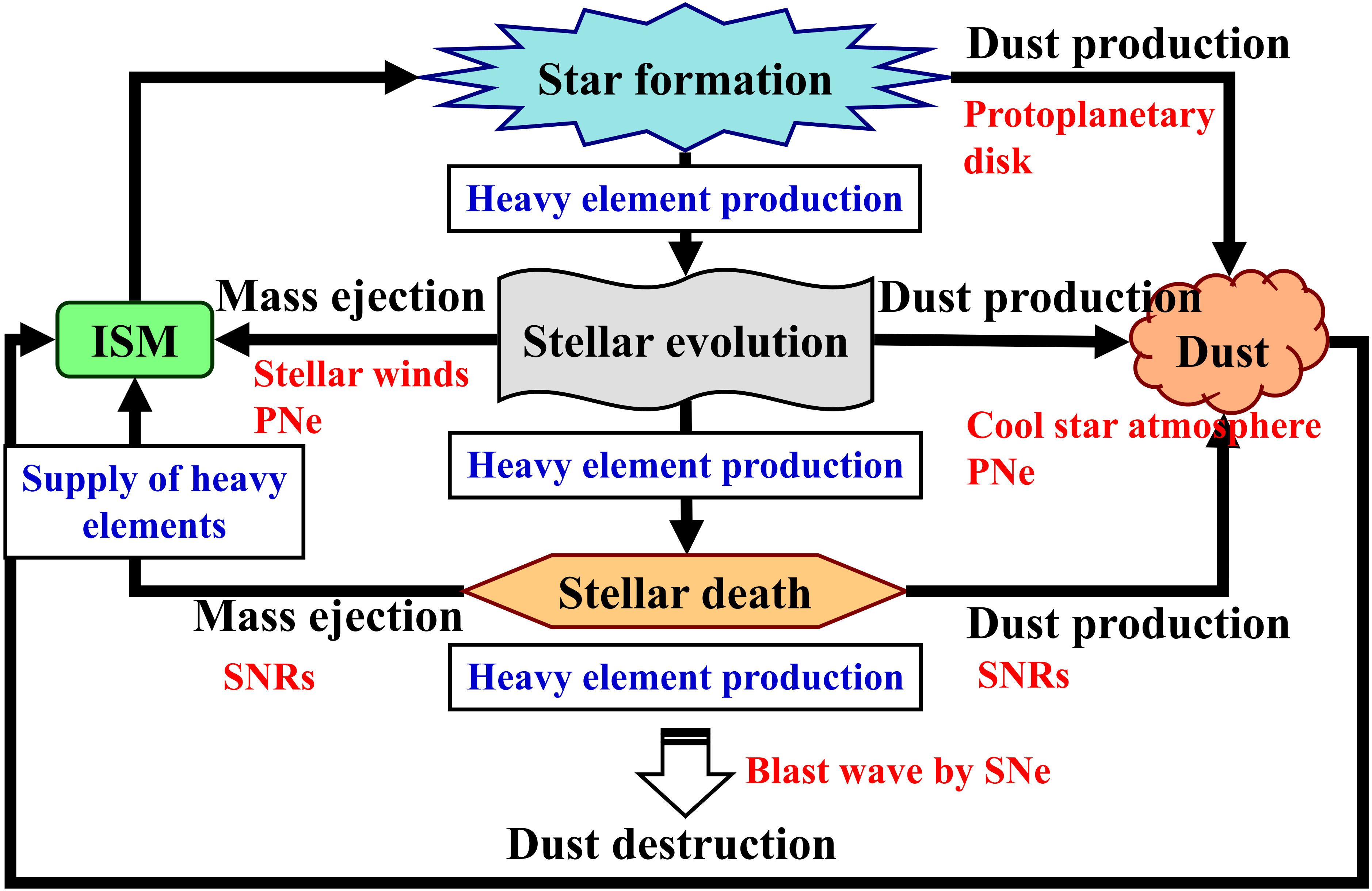
**The chemical composition of the interstellar medium (ISM) in each galaxy evolves with time as star formation proceeds: chemical evolution.**

**The efficiency of star formation is affected by the chemical composition of the ISM, i.e., the star formation in galaxies is regulated by the chemical evolution.**

## Chemical evolution of galaxies



# Chemical evolution of galaxies



## Chemical evolution of galaxies

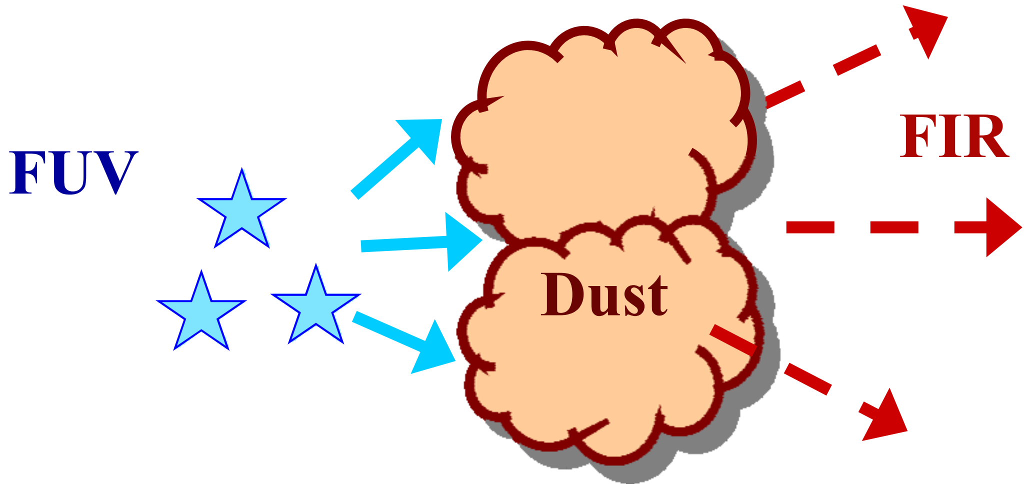
**Important issues:**

**How the heavy element and dust production proceeded?**

**How much, what kind of, and when dust formed?**

**Also discussed by the next talk (Asano et al.).**

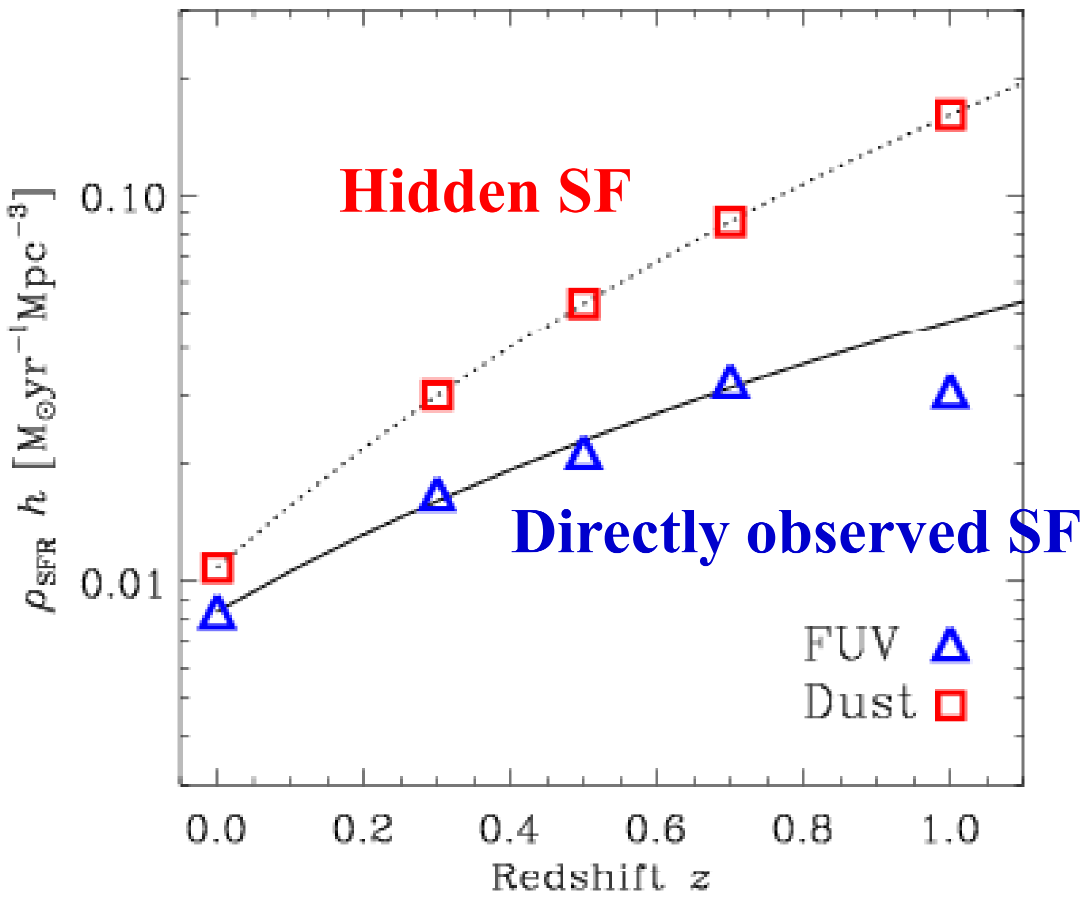
## Dust extinction and hidden star formation




**Short-wavelength photons like UV are scattered and absorbed by small solid grains, i.e., dust (referred to as "extinction"), and re-emitted from dust at far-infrared (FIR).**

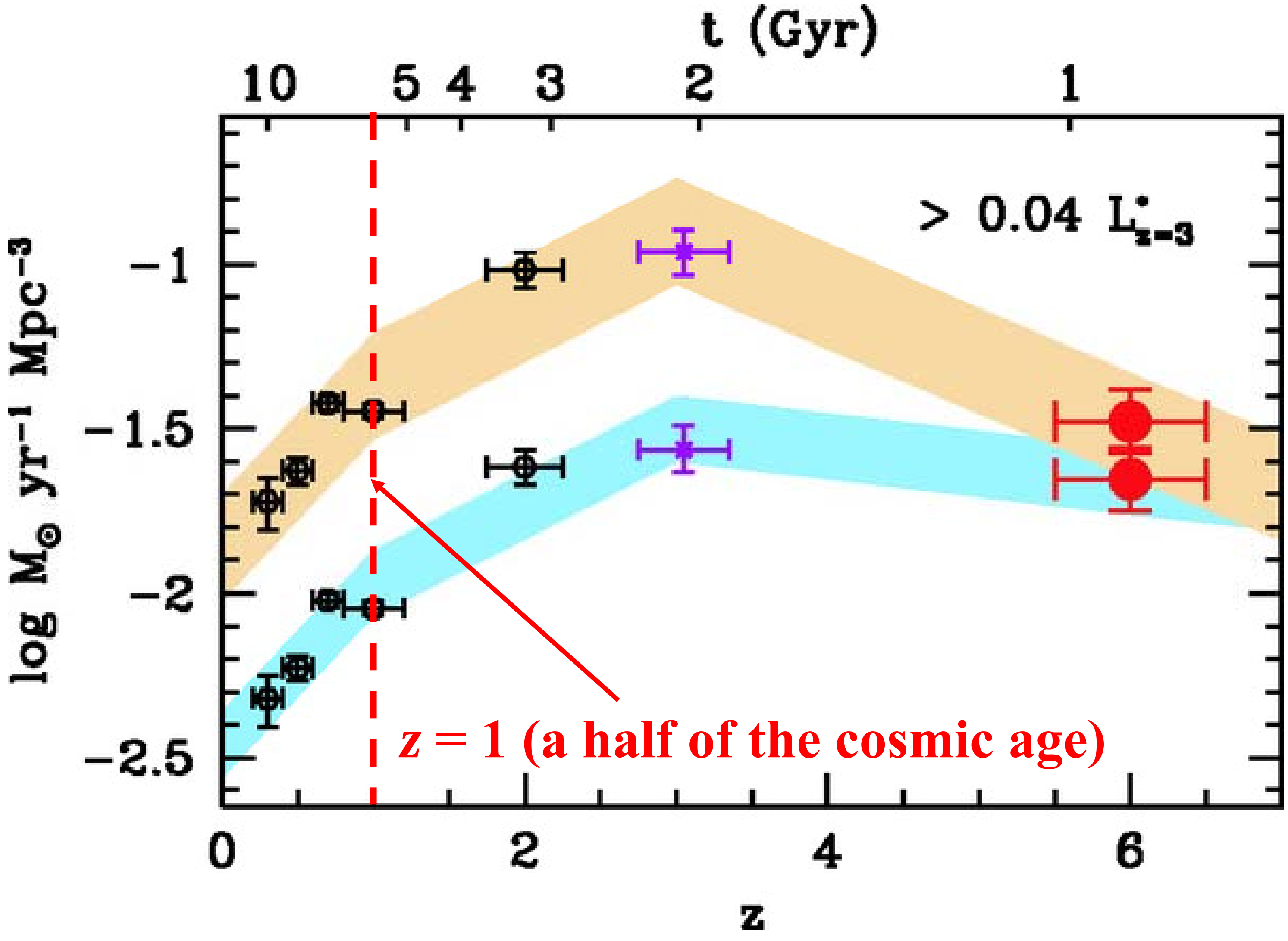
**Hence, to obtain an unbiased view of the cosmic star formation, it is crucial to treat the information of both FUV and FIR.**

# Dust extinction and hidden star formation



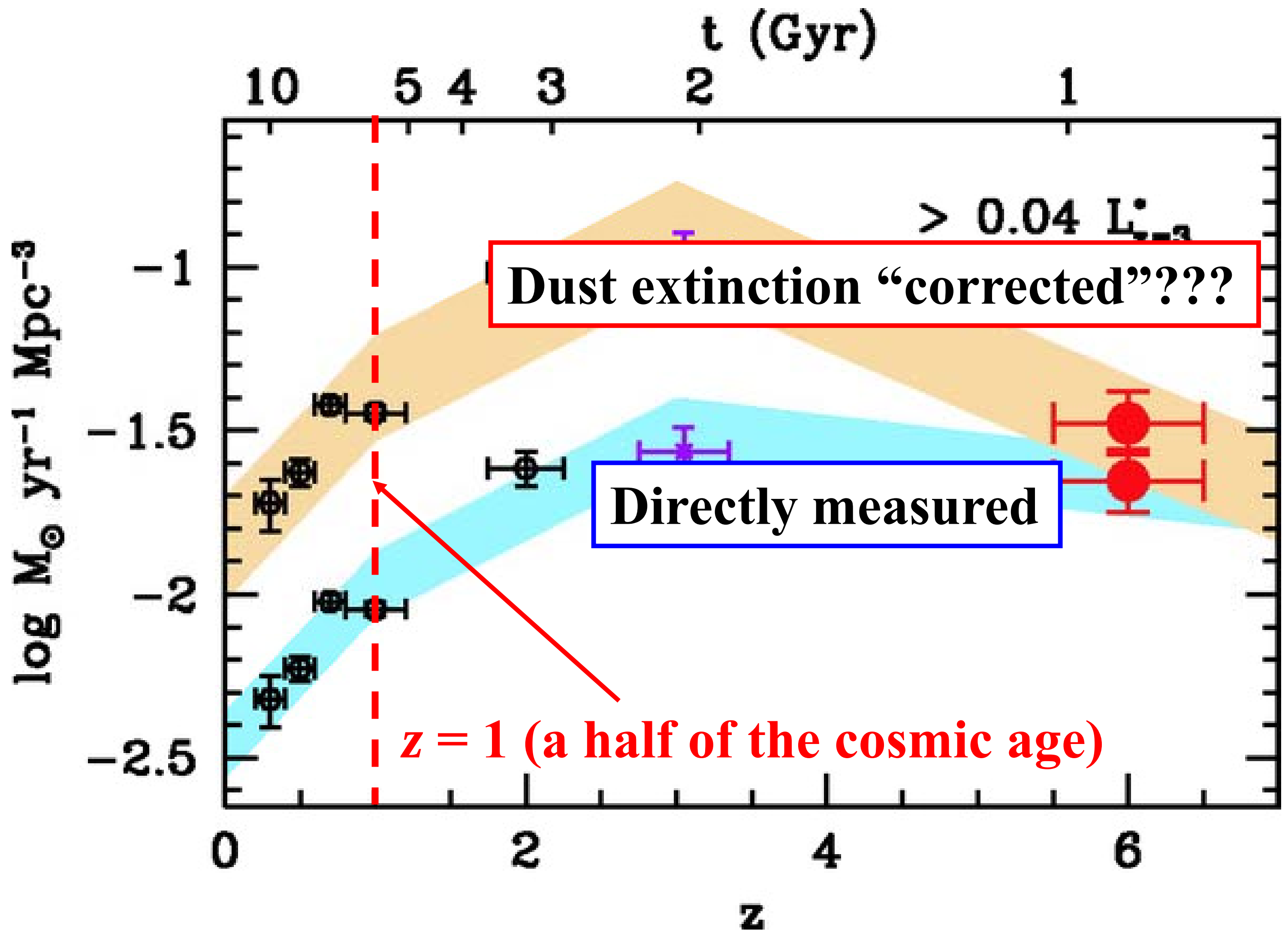

**The local fraction of the hidden SF is 50-60%, while the fraction at *z* = 1 reaches around 90% (Takeuchi et al. 2005a).**

# Dust extinction and hidden star formation




(Bouwens et al. 2006)

# Dust extinction and hidden star formation




(Bouwens et al. 2006)

## Dust extinction and hidden star formation

**Important issues:**

**How strong is the dust extinction?**

**How has the extinction evolved in the cosmic history?**

**How large is the fraction of hidden star formation?**

**Also discussed by the third talk (Ikeyama et al. and two posters Fujiwara et al. and Nagaya et al.).**

## 1.3 Issues to be investigated by dust in galaxies

1. When, where, and how stars formed?
2. How large/small were the first galaxies?
3. How does the site of star formation depend on the surrounding?
4. How the heavy element and dust production proceeded?
5. How much, what kind of, and when dust formed?
6. How strong is the dust extinction?
7. How has the extinction evolved in the cosmic history?
8. How large is the fraction of hidden star formation?

**Issues 1-3 are not perfectly traced by dust (IR), though we expect to obtain some information even if partially.**

# 2. Herschel Early Extragalactic Results

## 2.1 Herschel Space Observatory

Launch: 14 May, 2009
Wavelength: 55 – 671 μm
Main mirror ϕ: 3.5 m
Direct imaging instruments:
PACS (Poglitsch et al. 2010)
SPIRE (Griffin et al. 2010)
Heterodyne spectrometer:
HIFI (de Graauw et al. 2010)

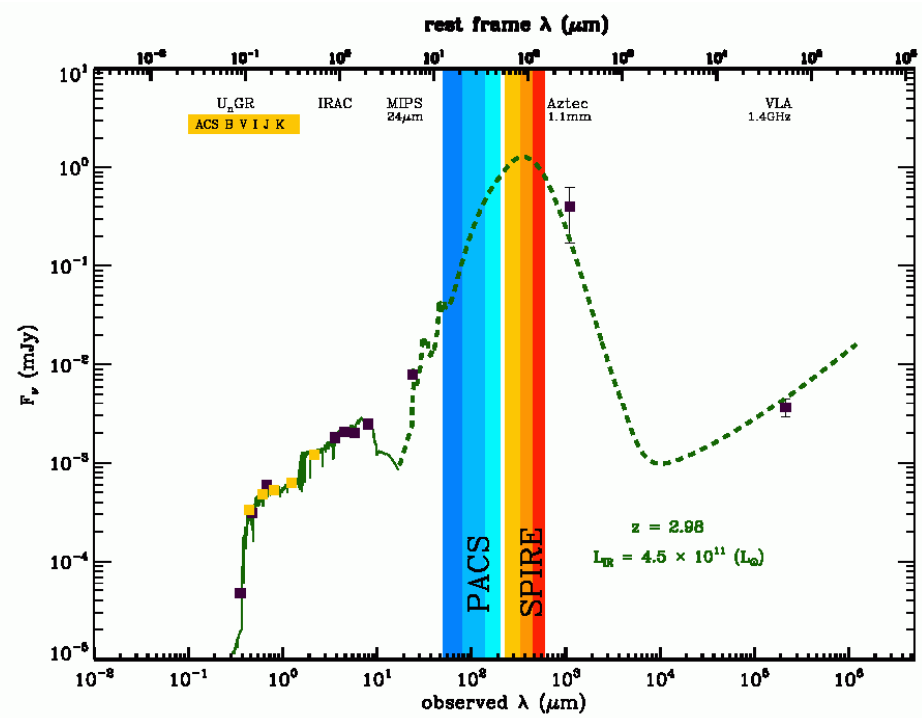
(Pilbratt et al. 2010)

Special Issues for Herschel early results:

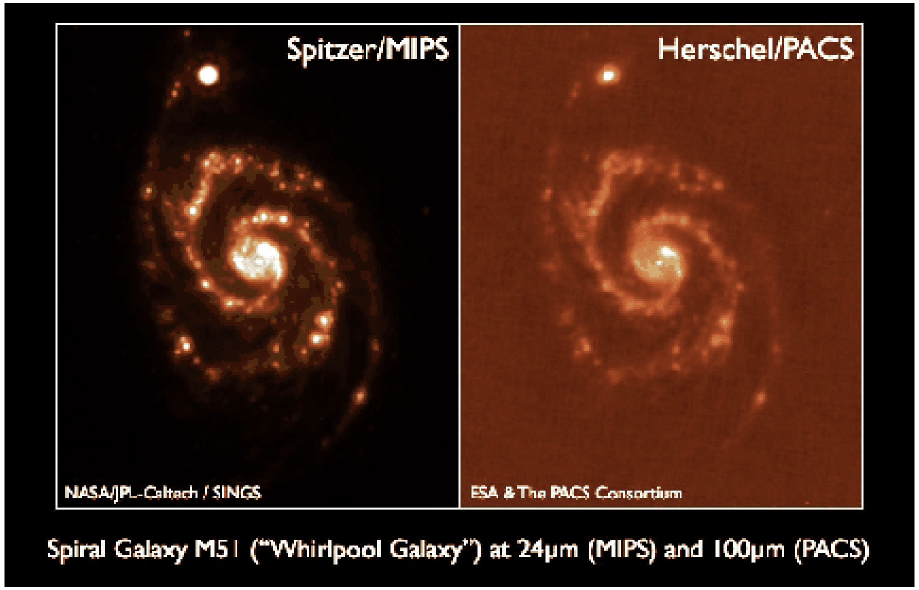
Astronomy & Astrophysics: vol. 518 (2010)

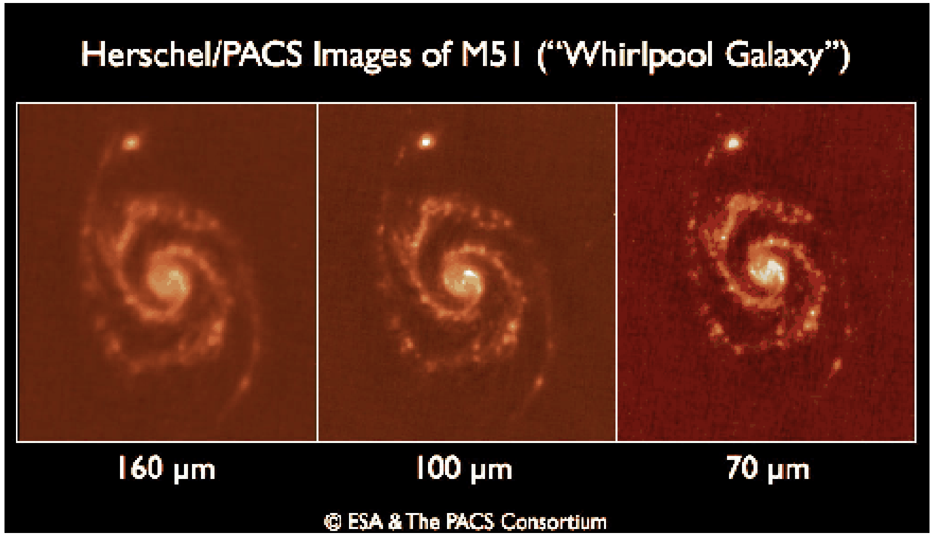
Monthly Notices of the RAS: in press (2010)

# 2.1 Herschel Space Observatory




PACS and SPIRE bands (Magdis et al. 2010a)




PACS images (Pilbratt et al. 2010)

## 2.2 Extragalactic key programs

**Herschel observation time:**

**Guaranteed time 1/3**

**Open time 2/3 (key programs + normal call)**

**Guaranteed time key programs:**

**HerMES (SPIRE GT, 900h)**

**PEP (PACS GT, 654.9h)**

**Open time key programs:**

**H-ATLAS (600h): very wide (550 deg$^2$) shallow survey**

**GOODS-Herschel (362.6h): ultradeep pencil-beam survey**

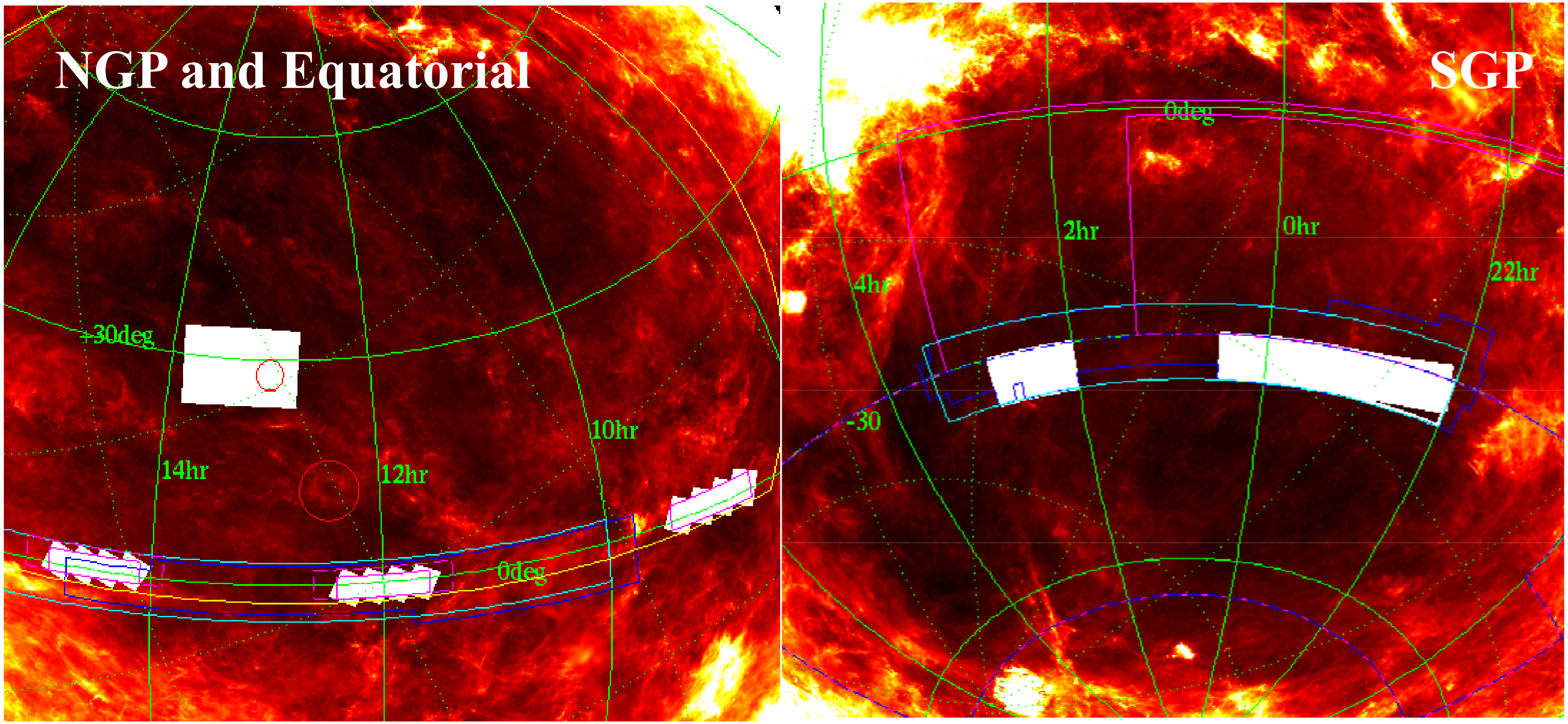
**Key project consortia must make data products and tools public at the proprietary period (1 year for the 1$^{st}$ year, and 6 months after).**

## The Herschel ATLAS (H-ATLAS)

**Astrophysical Terahertz Large Area Survey**

- **Covering 5 bands with PACS and SPIRE (110 - 500 μm) in fast parallel mode (5-σ limits: 132, 126, 33, 36 and 45 mJy/beam from 110 - 500 μm)**
- **Detect ~ $10^5$ sources up to *z* ~ 3**
- **Science demonstration phase (SD) data, maps and catalogs will be made public around mid-June 2010 through the URL:** [www.h-atlas.org](www.h-atlas.org)

# The Herschel ATLAS (H-ATLAS)




**The widest area survey with Herschel (~ 550 deg$^2$).**

# The HerMES

**Herschel Multi-tiered Extragalactic Survey**

**Clusters**

**Level 1 0.11 □°**

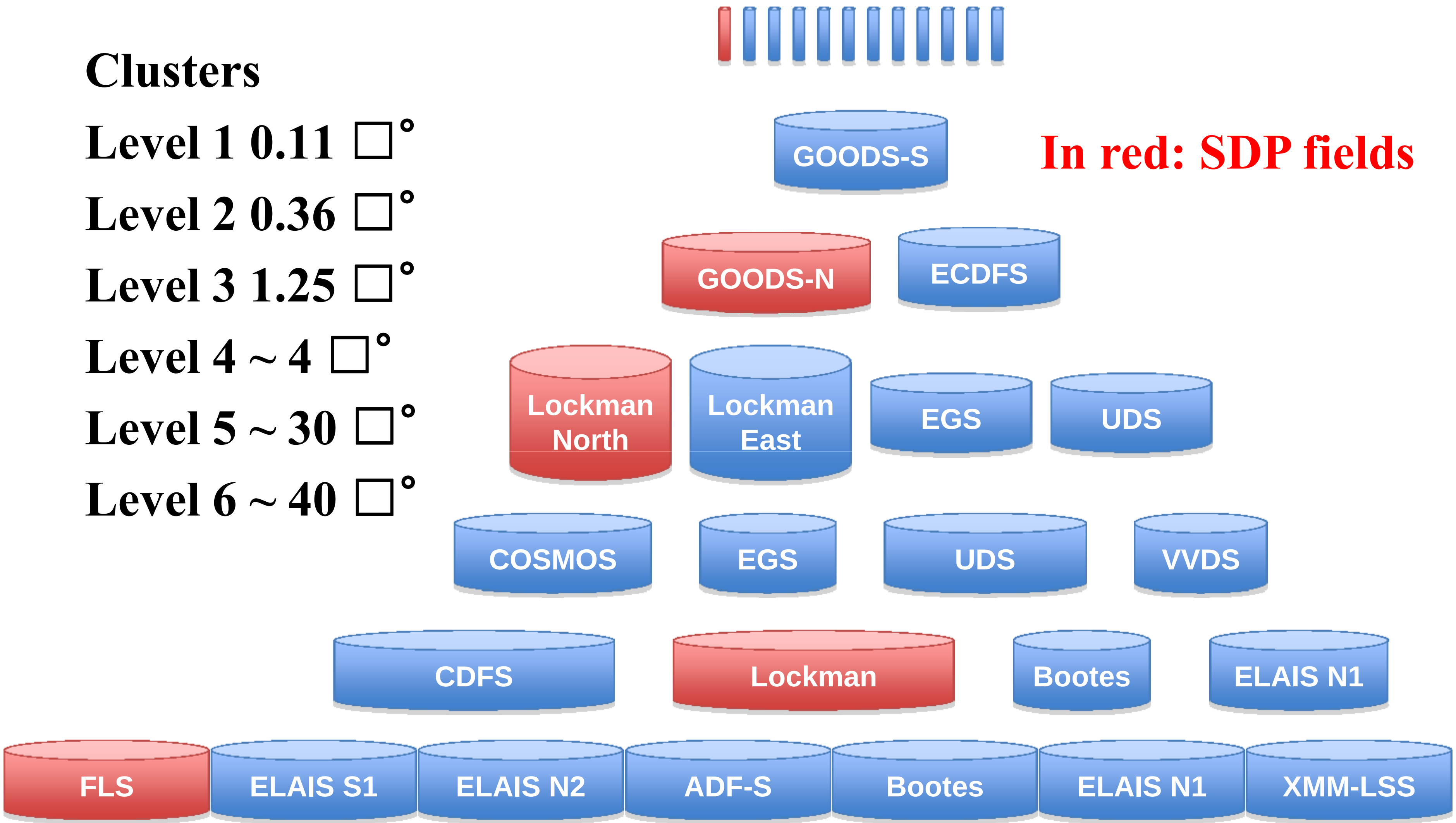
**Level 2 0.36 □°**

**Level 3 1.25 □°**

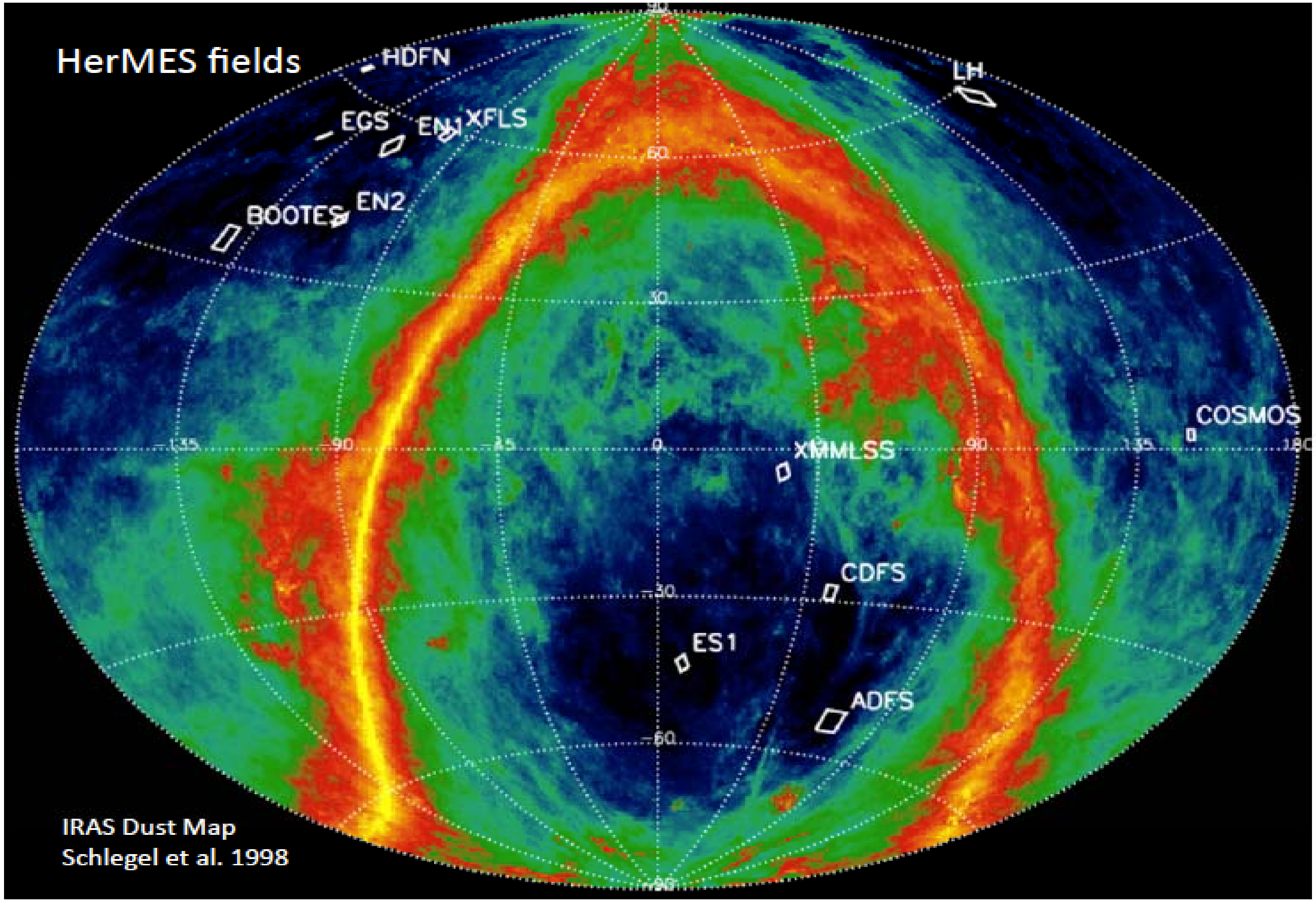
**Level 4 ~ 4 □°**

**Level 5 ~ 30 □°**

**Level 6 ~ 40 □°**

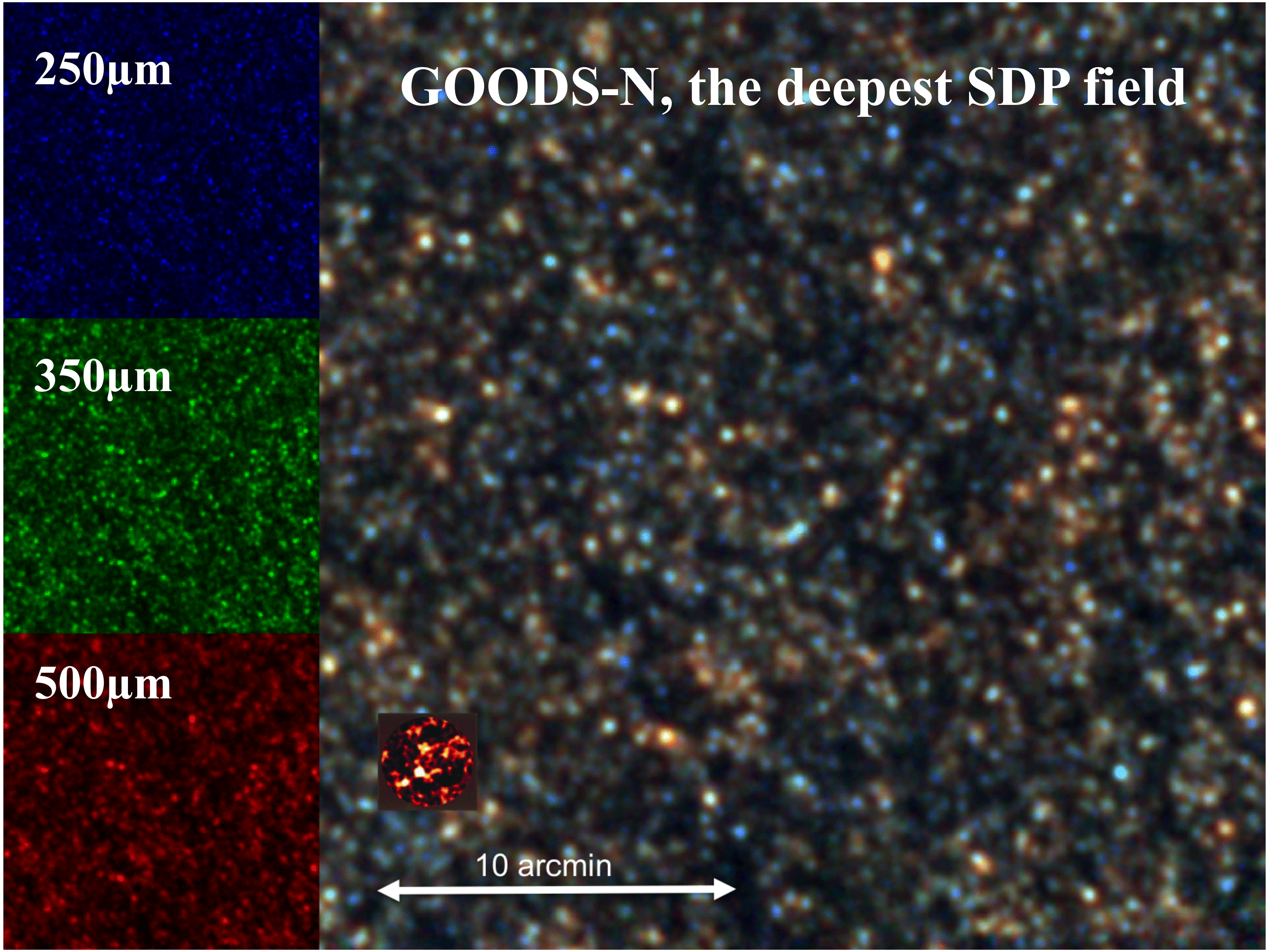


# The HerMES



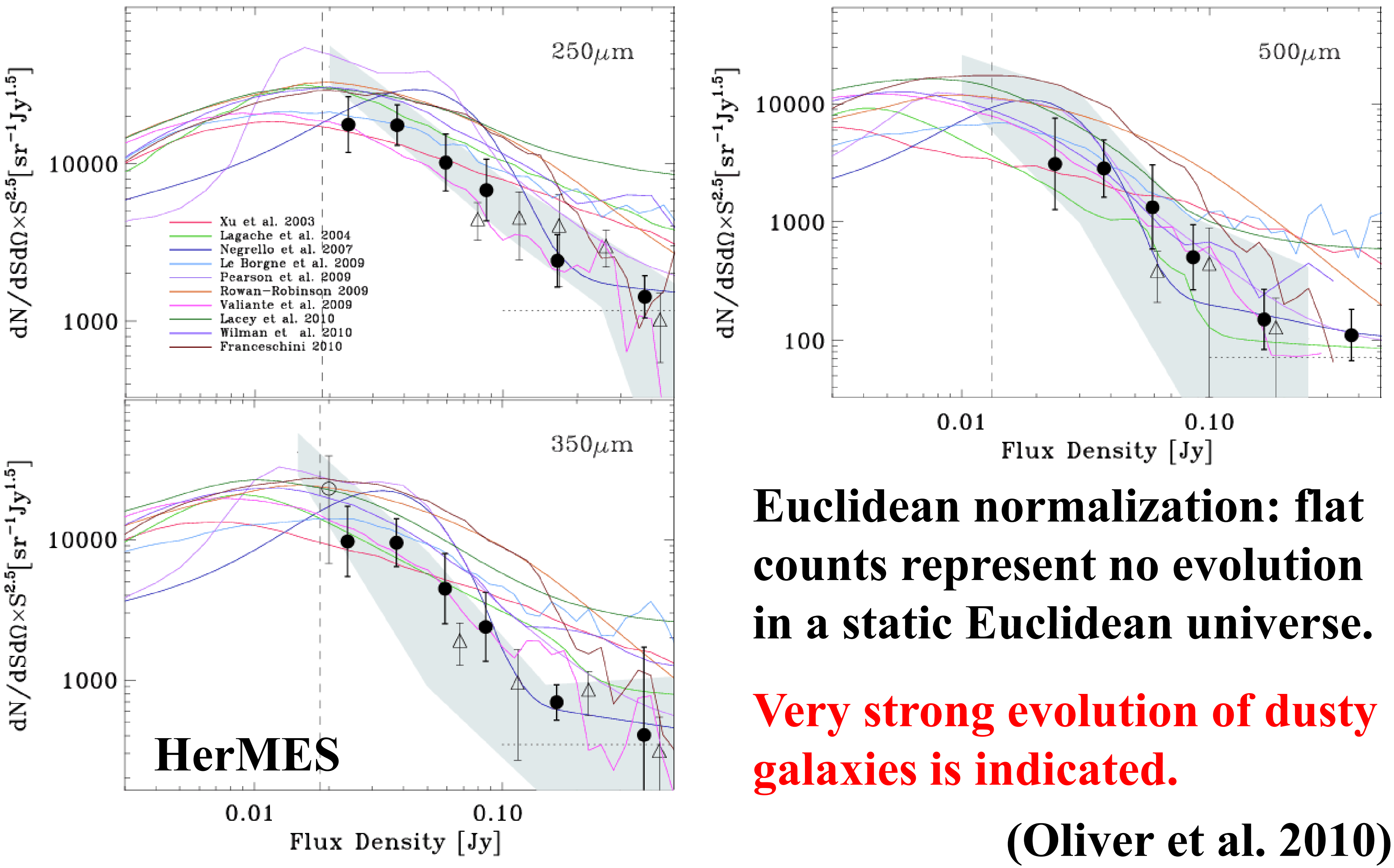

**The largest project of Herschel (850 h).**
**Data will be available via HeDaM.**

## The HerMES



# 2.3 Early extragalactic results from Herschel

## The number counts of IR galaxies

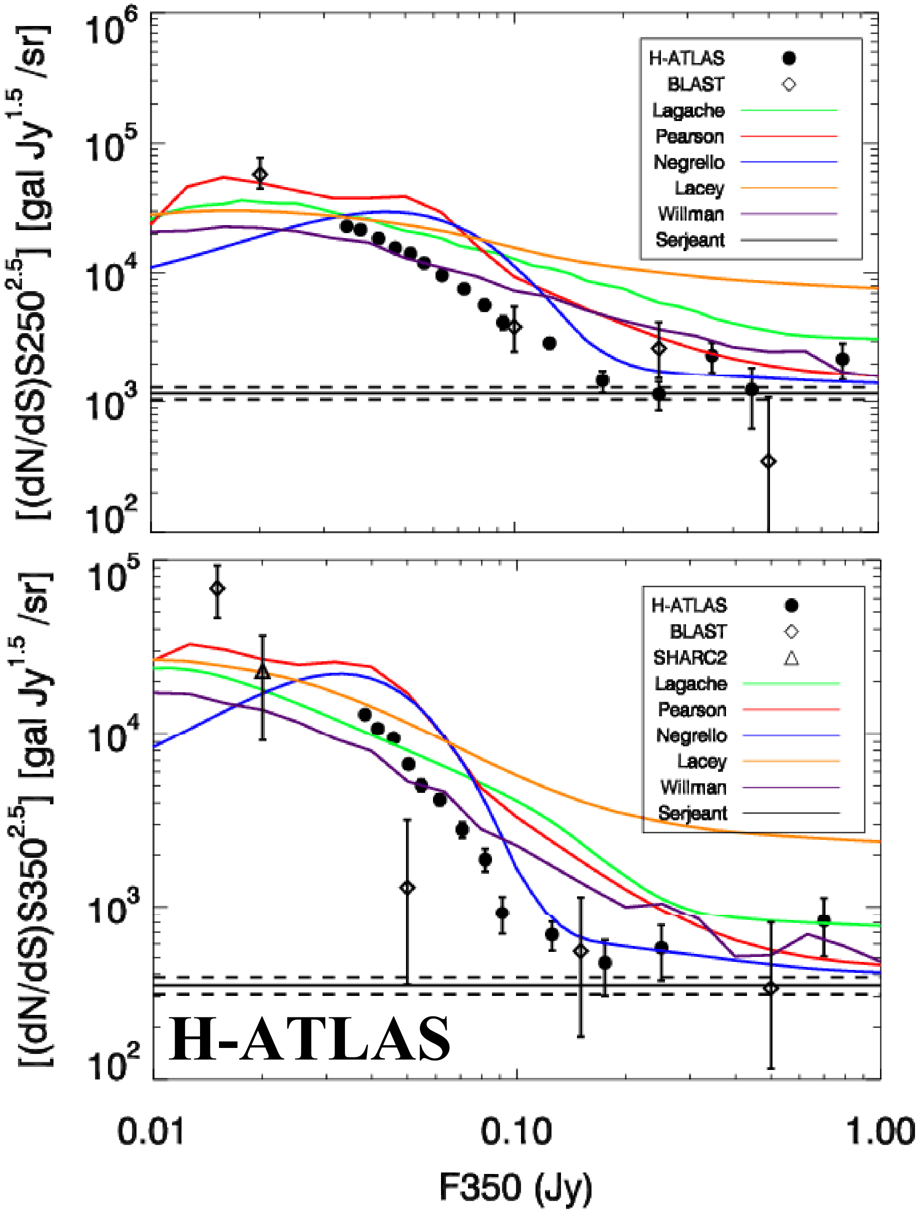


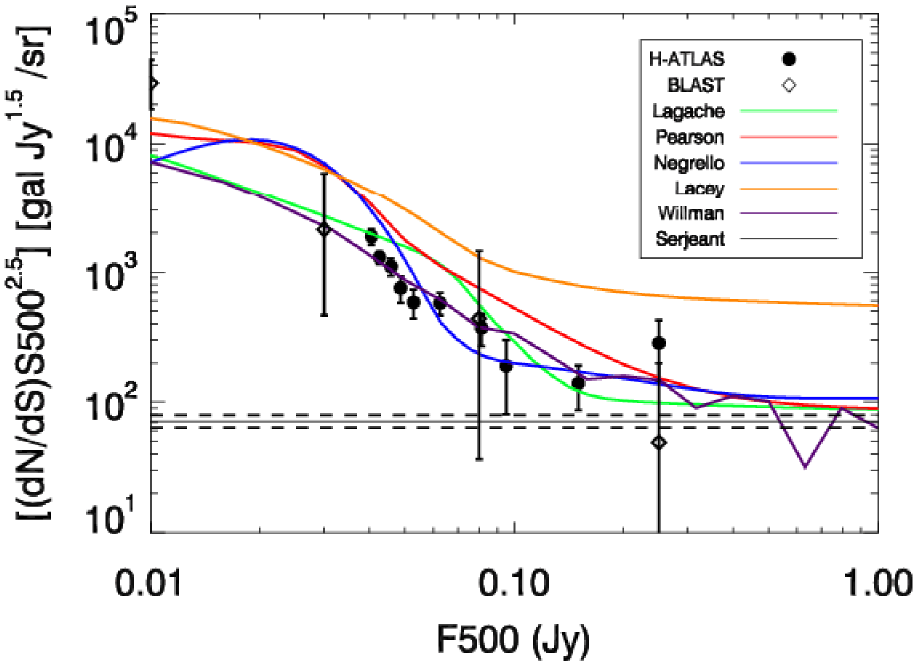

**Euclidean normalization: flat counts represent no evolution in a static Euclidean universe.**

**Very strong evolution of dusty galaxies is indicated.**

**(Oliver et al. 2010)**

# The number counts of IR galaxies

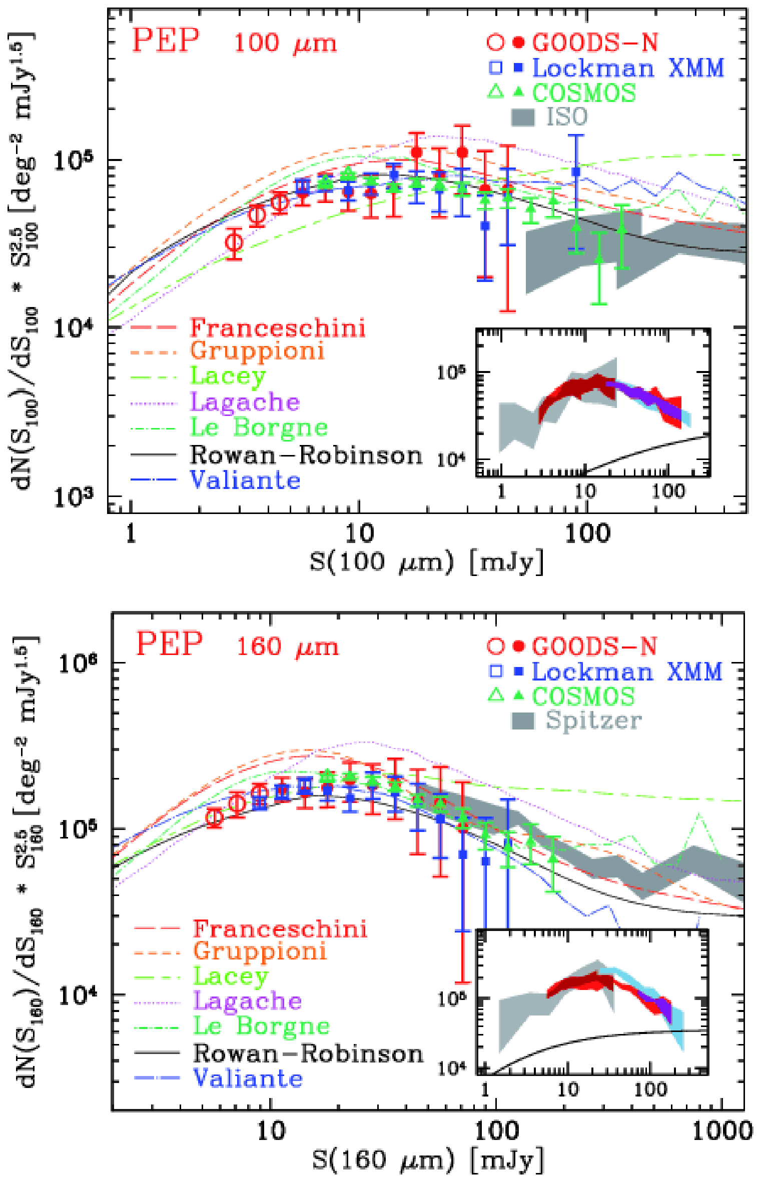


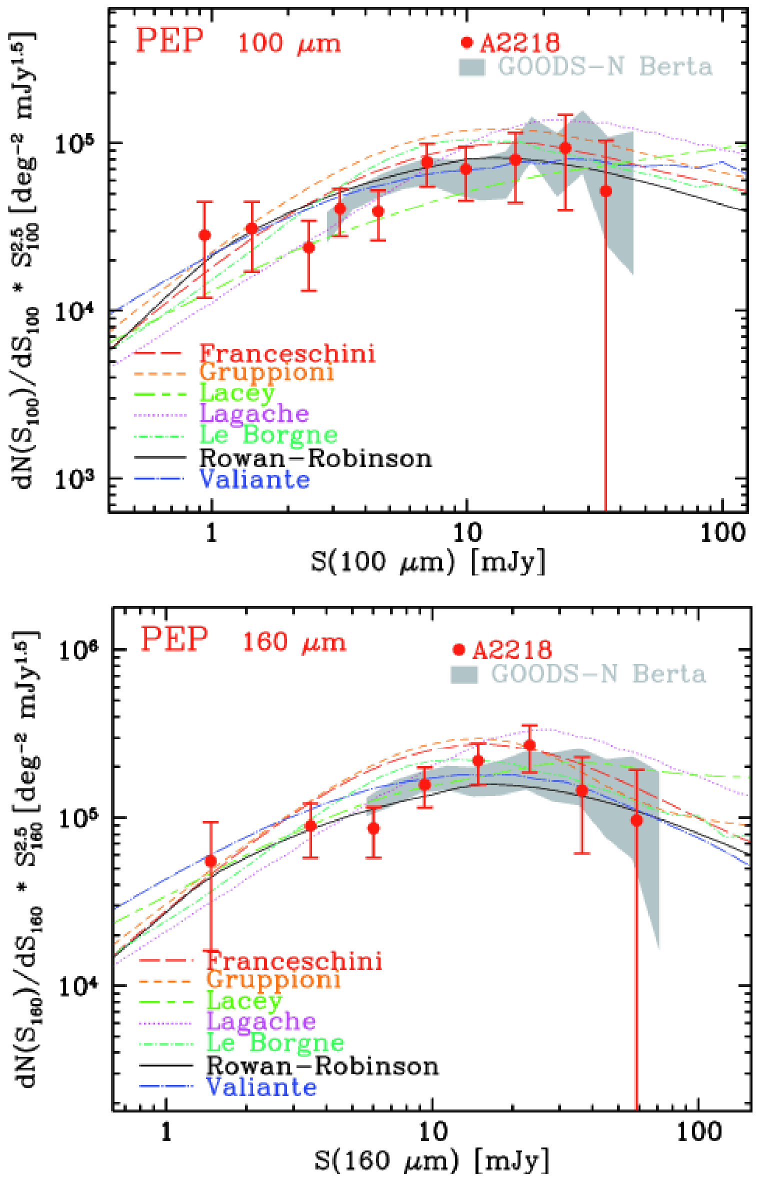




**Same as the previous study, but from H-ATLAS. Thanks to the large area, the bright counts are well determined.**

**(Clements et al. 2010)**

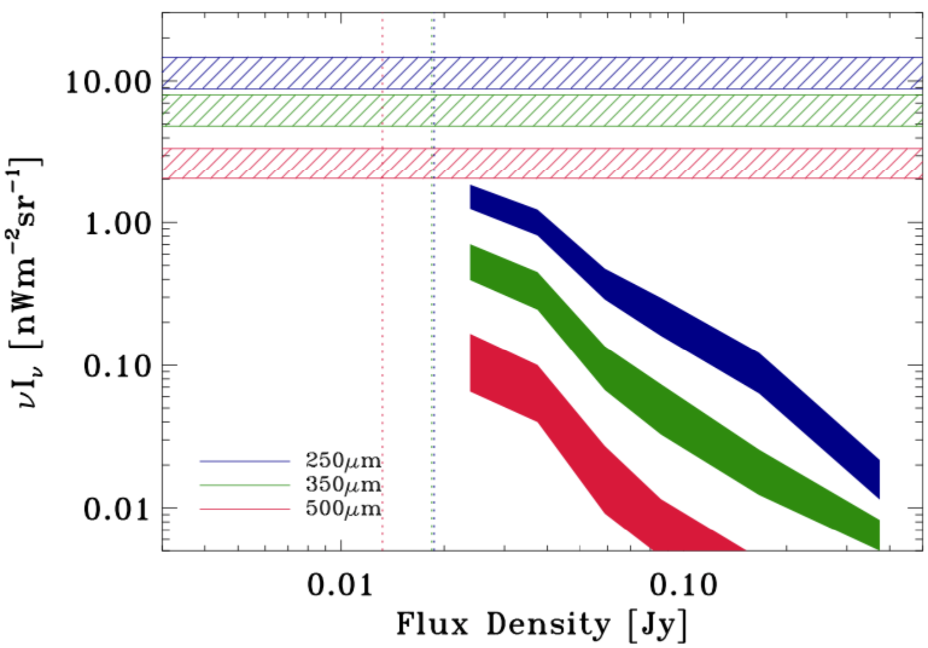
# The number counts of IR galaxies



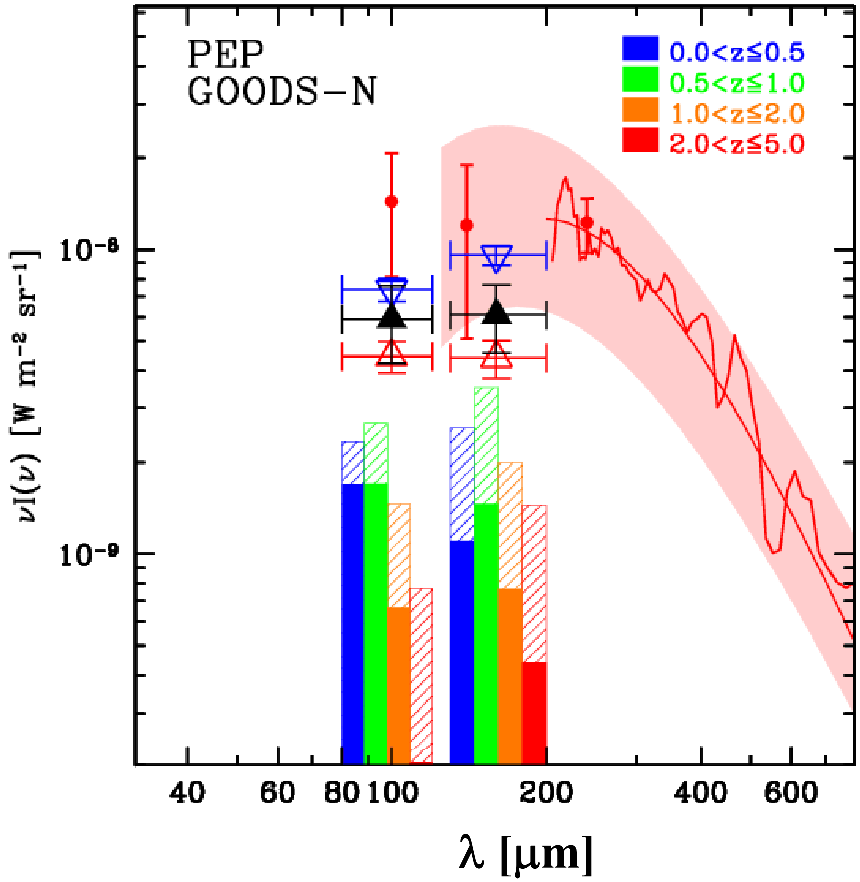




**(Berta et al. 2010)** **(Altieri et al. 2010)**

# The cosmic IR background and its origin




**15% of the CIRB is resolved from direct counts at 250 mm.** **At longer wavelengths, the fraction is higher.**

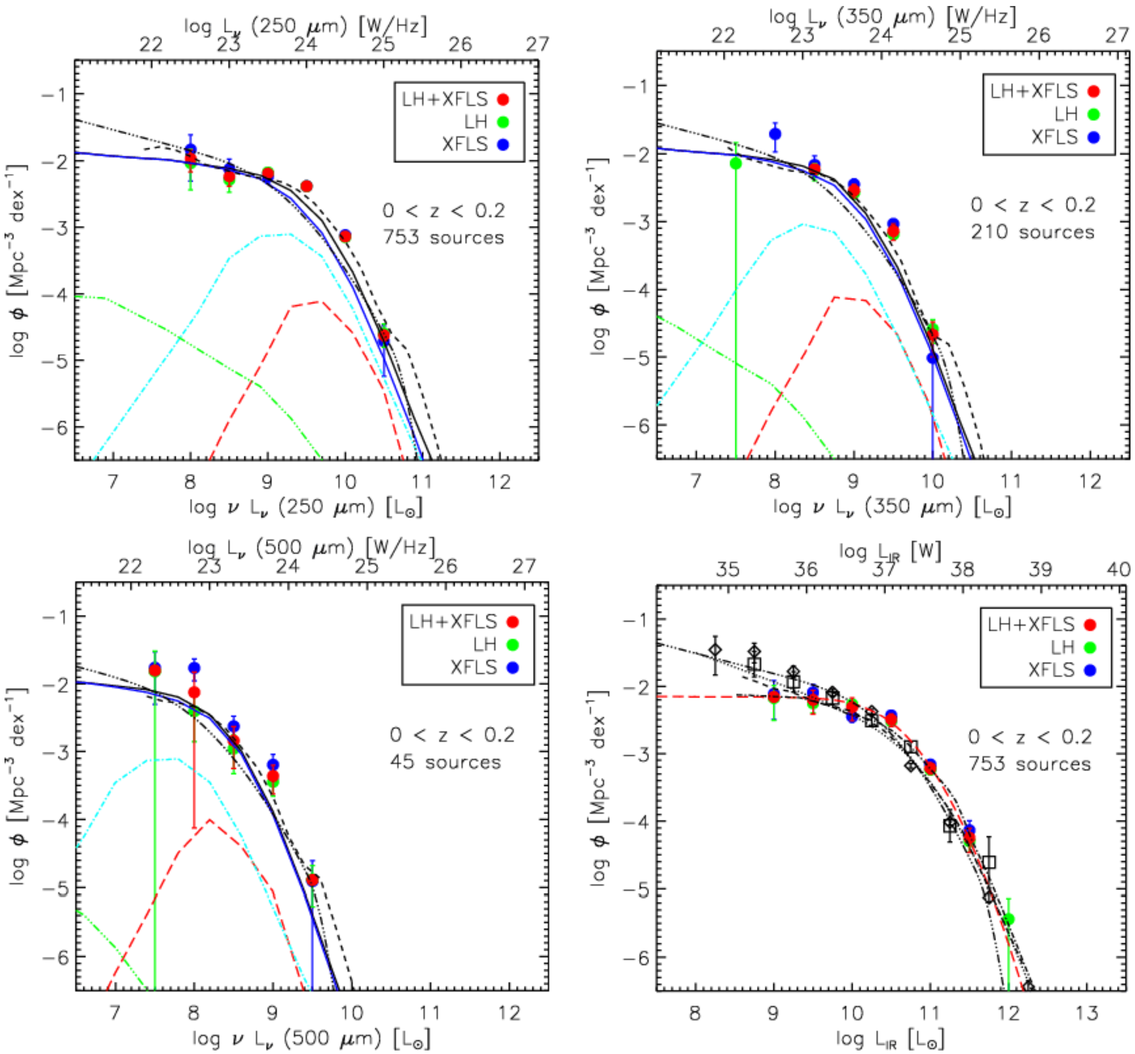



**45-50% of CIRB (100-160mm) is resolved into galaxies.** **Most of them are at *z* < 1.0.**

**(Oliver et al. 2010)**

**(Berta et al. 2010)**

# Luminosity function of dusty galaxies




(Vaccari et al. 2010)

**Local ($z$ = 0) LF**

**SDSS, 2MASS, IRAC, MIPS, and SPIRE data over 15 deg$^2$ in a portion of HerMES fields.**

***N.B.* The 1/$V_{max}$ estimator (the same for all the rest) is not appropriate to discuss the shape of the LF.**

$\rho_{IR} = 1.31 \times 10^8 L_\odot yr^{-1}$

# Luminosity function of dusty galaxies

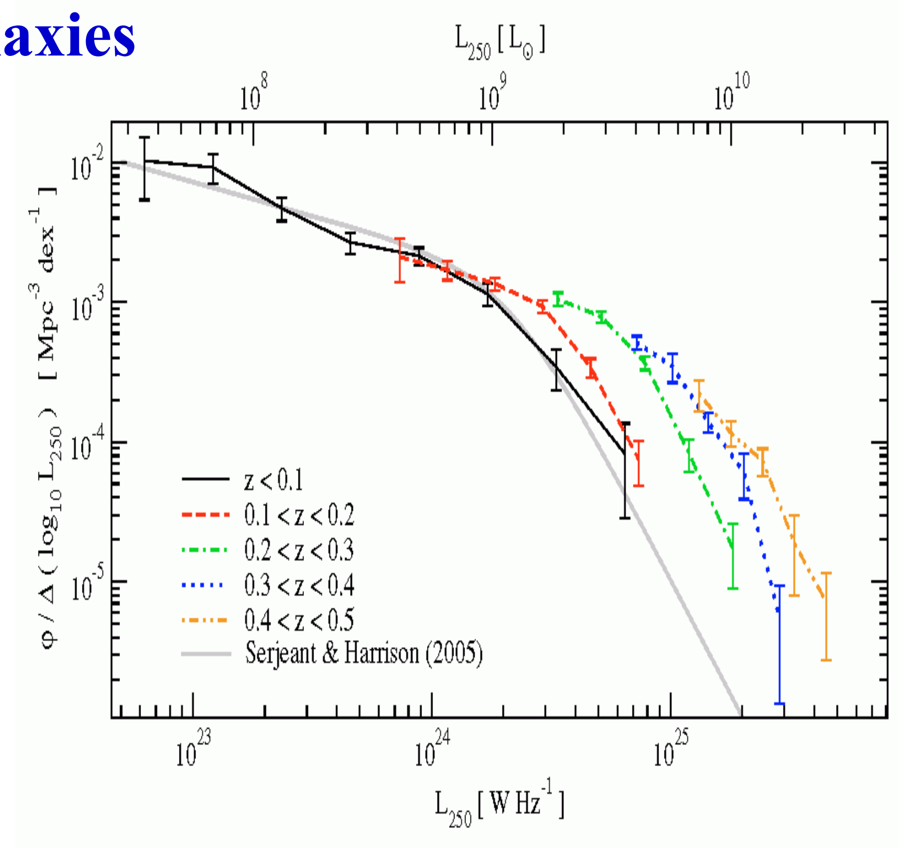
**LF at $0 < z < 0.5$**

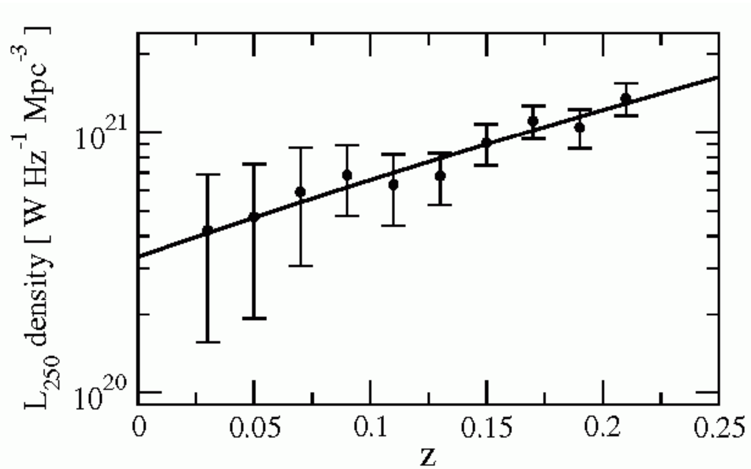
**250 μm selected in H-ATLAS.**

**They claim luminosity density evolution $\propto (1+z)^7$ up to $z = 0.5$, stronger than in HerMES (*cf.* Spitzer: $\propto (1 + z)^{3.9}$ at $z < 1$).**

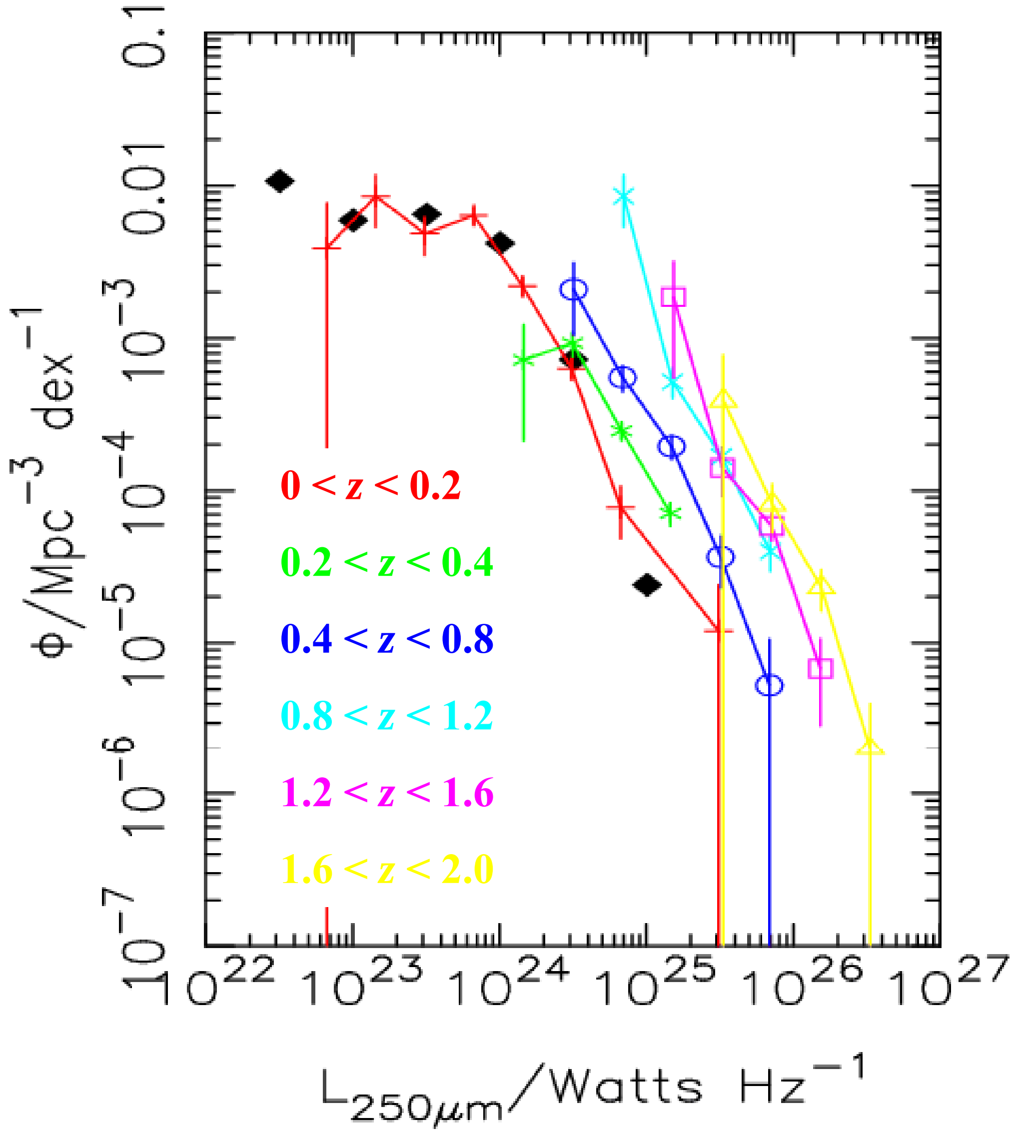
***N. B.* Since only 876 have spec-z out of 2276, photo-z uncertainty exists. Also, the faint end uncertainty hampers the estimation of integrated IR luminosity.**

**(Dye et al. 2010)**



# Luminosity function of dusty galaxies




**(Eales et al. 2010)**

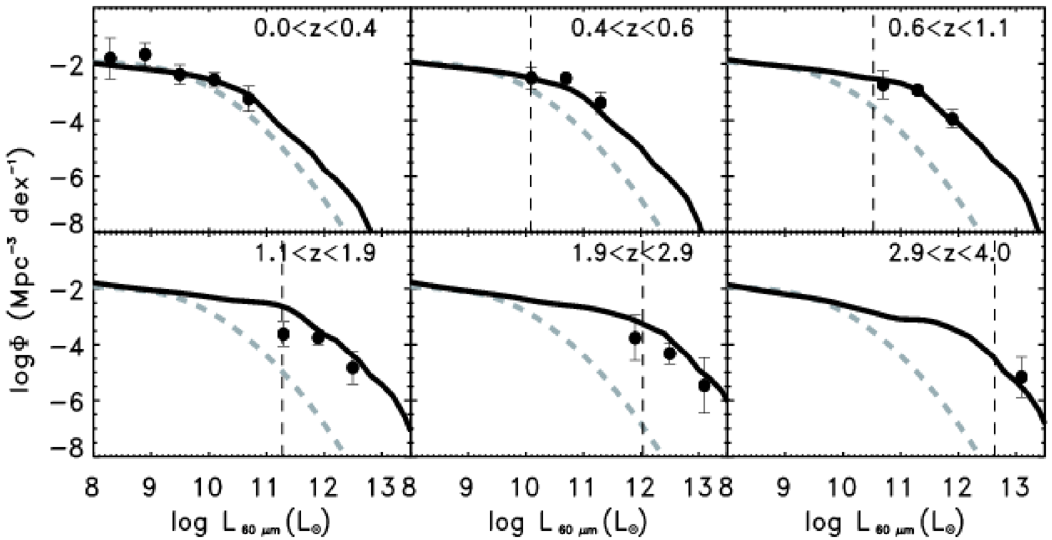
**LF at $0 < z < 2.0$**

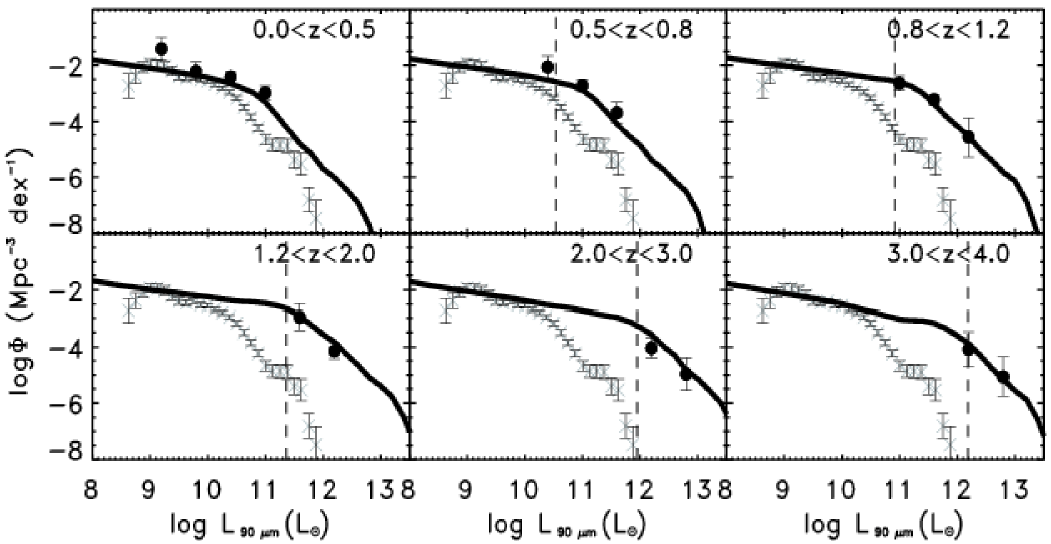
**Selection at 250 μm in the HerMES field.**

**Strong evolution at $0 < z < 1$, but at most weak evolution at $z > 1$.**

***N. B.* We should note possible redshift incompleteness at high *z* and uncertainty in photo-*z*. Also, again the faint end uncertainty hampers the estimation of integrated IR luminosity.**

# Luminosity function of dusty galaxies



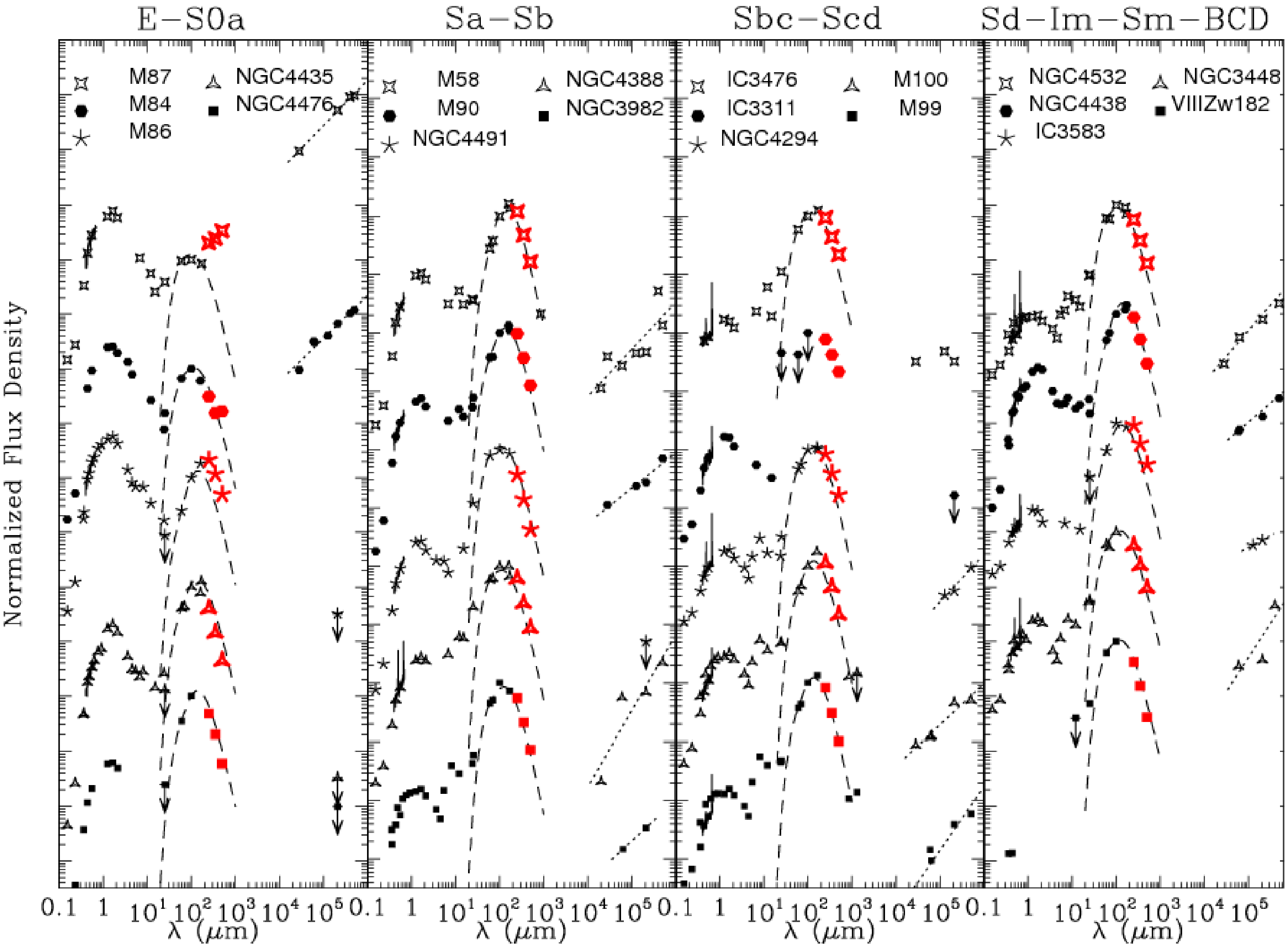

**LF at $0 < z < 4.0$**

**Selection at 100 μm and 160 μm in the PEP fields.**

**Note that there are only a few (sometimes one!) point(s) at higher redshifts.**

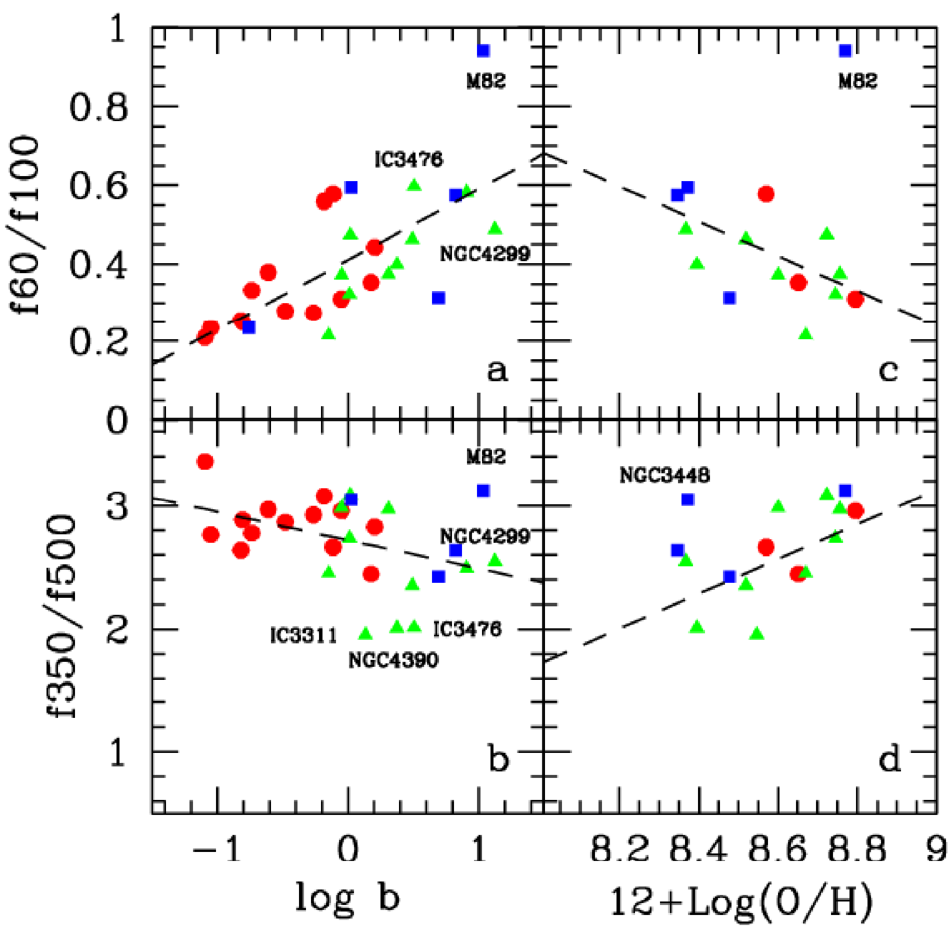
**(Gruppioni et al. 2010)**

# Spectral energy distribution of dusty galaxies




**(Boselli et al. 2010)**

# Spectral energy distribution of dusty galaxies



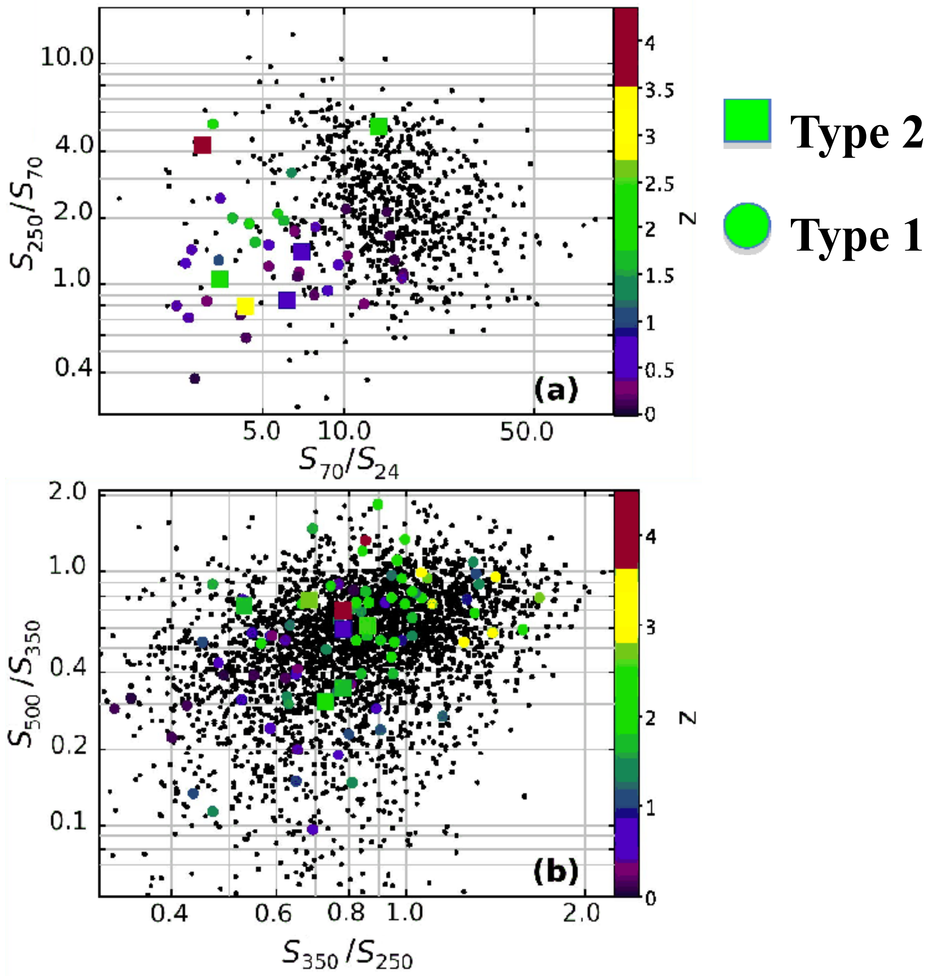

(Boselli et al. 2010)

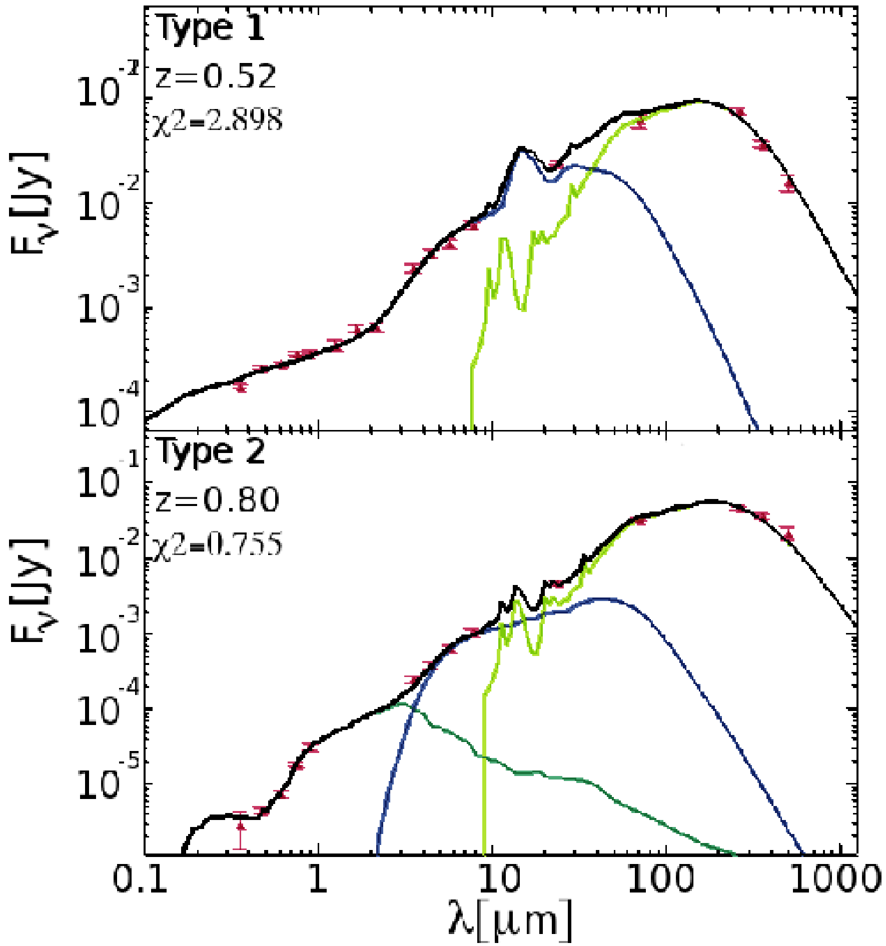
**FIR-Submm color and its dependence on physical properties**

**$S60/S100$ positively correlats with the birthrate parameter *b* (ratio between current to average star formation rates), while the $S350/S500$ correlates negatively. They also correlate with metallicity. This time the former correlates negatively, while the latter positively.**

***N. B.* M82 seems to be an outlier on the $S60/S100$-$Z$ plot.**

# Spectral energy distribution of dusty galaxies

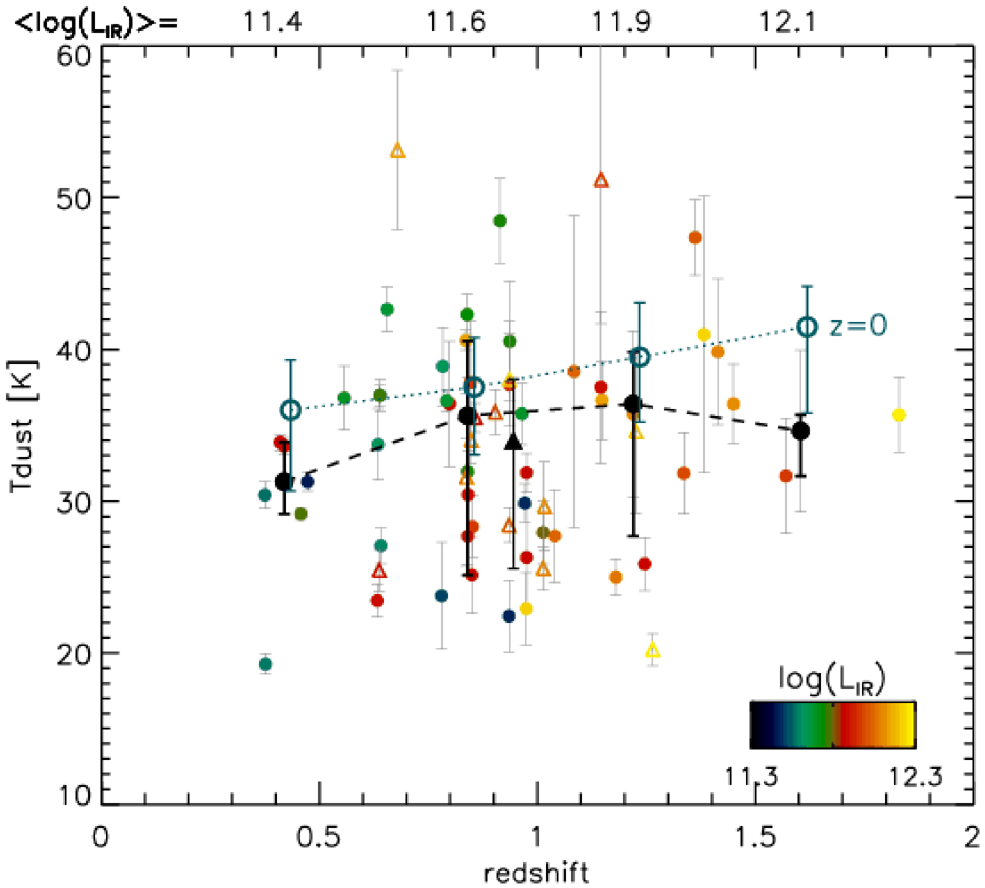



**FIR/submm ratio works well to distinguish starburst/AGN, while submm color does not. Herschel fluxes are always dominated by starburst.**

**(Hatziminaoglou et al. 2010)**

## Dust temperature



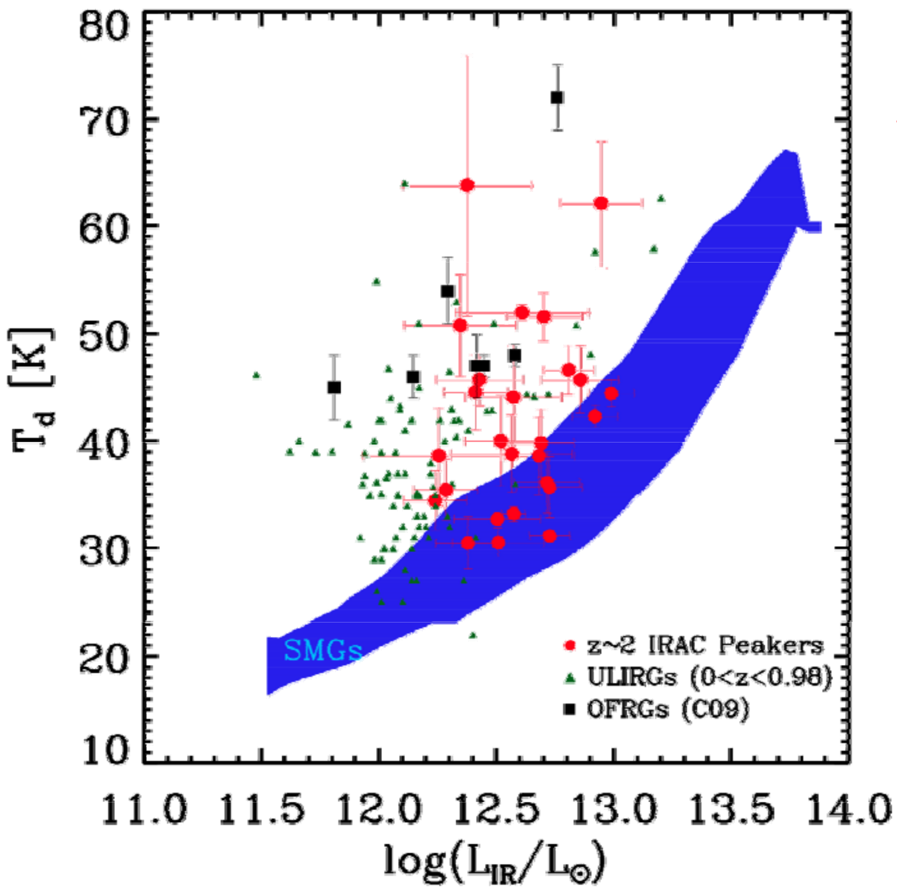

(Elbaz et al. 2010)

$T_{\rm dust}$ is "significantly" cooler than the local dusty galaxies if $L_{\rm IR}$ is the same ($T_{\rm dust}$ is defined simply by fitting of graybody $\nu^{\beta}B_{\nu}(T)$ with a fixed β).

***N.B.* The error bars are large and the claimed difference would not be statistically justified. Also, in the same paper, they claim that the SED templates should be modified.**

## Dust temperature

**$T_{dust}$ of $z \sim 2$ IRAC peakers have a large dispersion, bridging submillimeter galaxies (SMGs), and spanning Local ultraluminous IR galaxies (ULIRGs).**



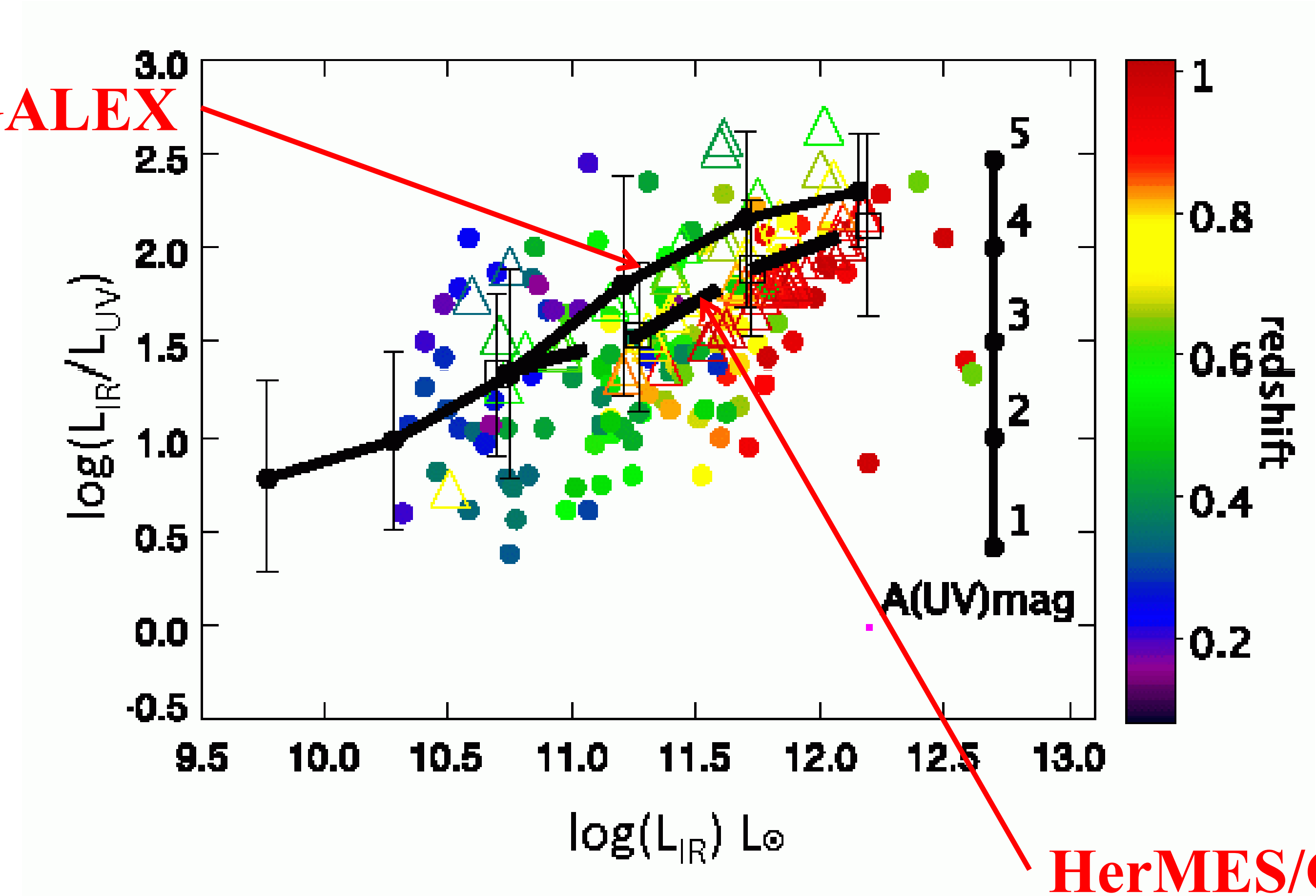

***N.B.* Again in all these works, $T_{dust}$ is defined merely by graybody fitting.**

**Another caveat is that sample selection is not carefully discussed.**

**(Magdis et al. 2010b, astro-ph/1007.4900)**

## Extinction properties and hidden star formation

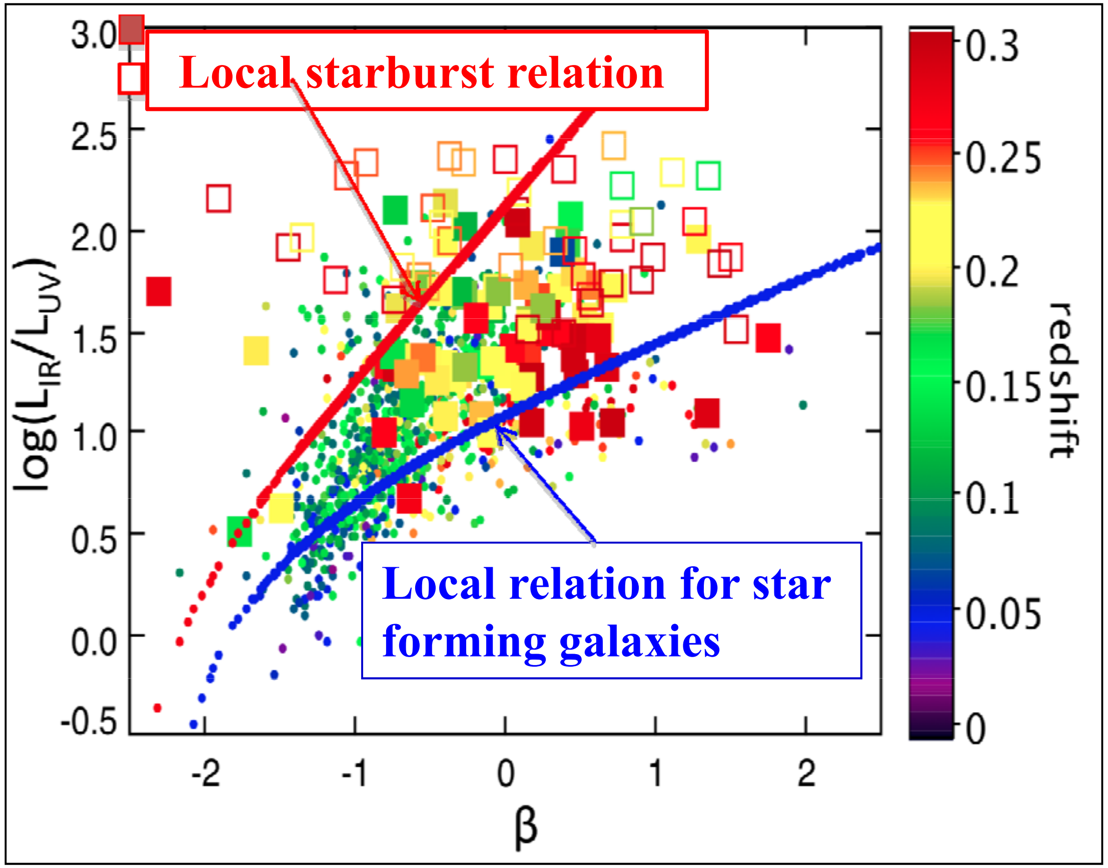
**Possible decrease of dust attenuation in distant ($z$ < 0.5) IR luminous galaxies was found.**




**(Buat et al. 2010, astro-ph/1007.1857)**

# Extinction properties and hidden star formation

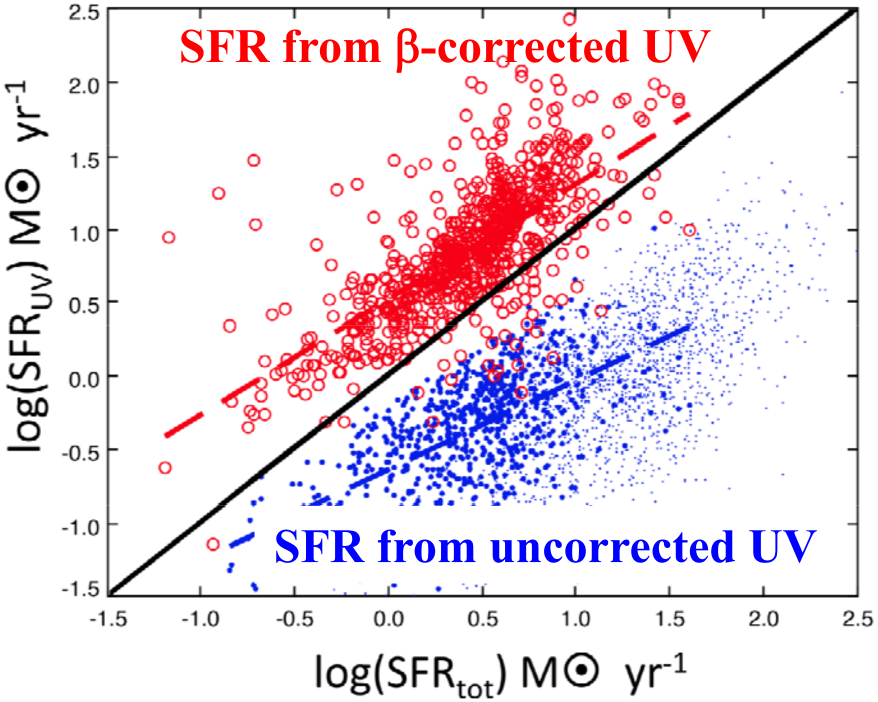
**The Local starburst law (the so called Meurer's law) overestimates dust attenuation in most of the cases (cf. talk by Ikeyama et al.).**




**(Buat et al. 2010, astro-ph/1007.1857)**

# Extinction properties and hidden star formation

$SFR_{UV} + SFR_{IR} = SFR_{TOT}$ : total star formation rate



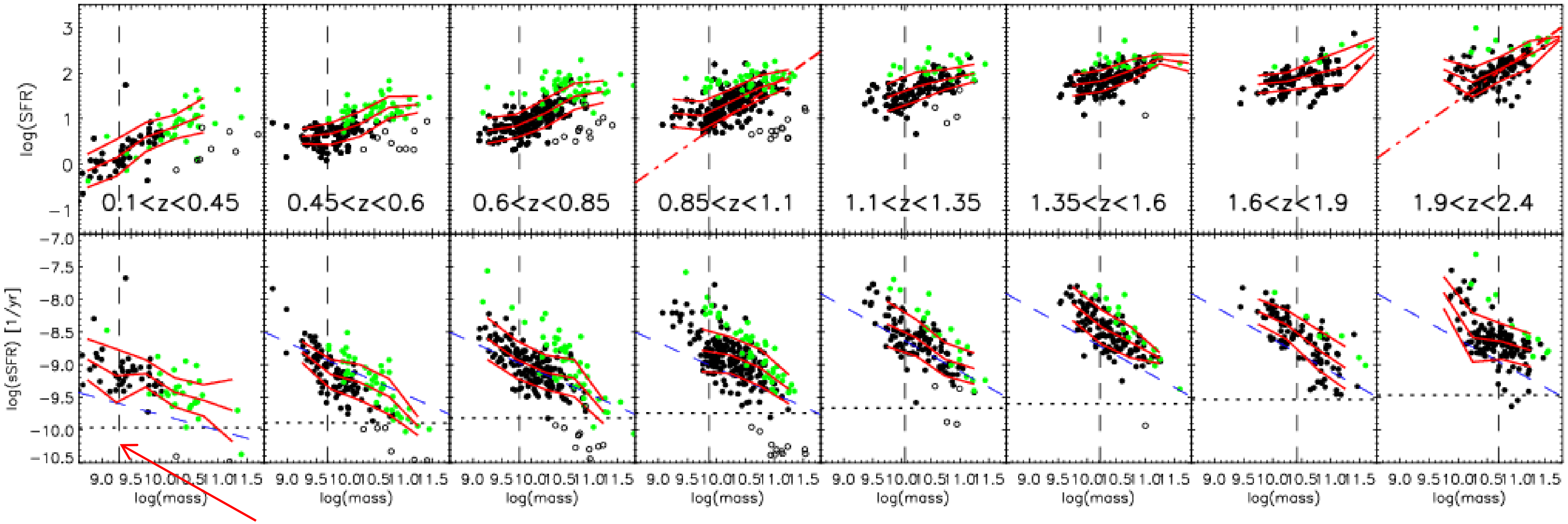

If the β-correction of UV would work well, the SFR calculated from corrected UV should have been the same as the $SFR_{TOT}$ defined above.

However, it is NOT the case: $SFR_{UV}$ underestimates $SFR_{TOT}$ by a factor of ~ 6, and the SFR from UV corrected using the UV slope β overestimates $SFR_{TOT}$ by a factor of 2-3.

(Buat et al. 2010, astro-ph/1007.1857)

# Hidden star formation and evolution of stellar mass

**The growth history of stellar mass in galaxies is one of the most important clues to understand the galaxy growth in the cosmic history. This is reflected in the SFR and specific SFR (SFR/$M_*$).**

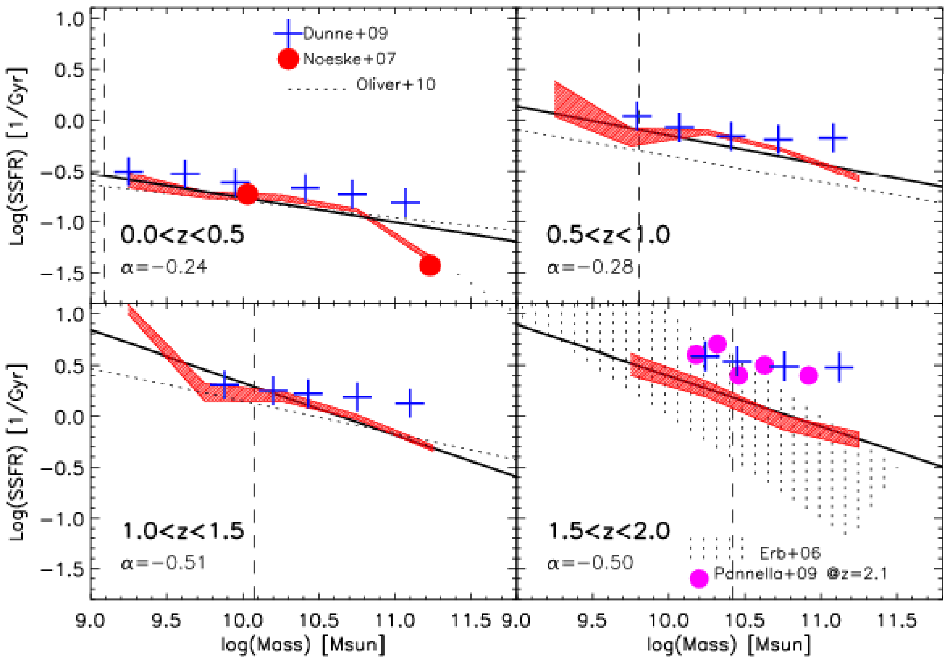


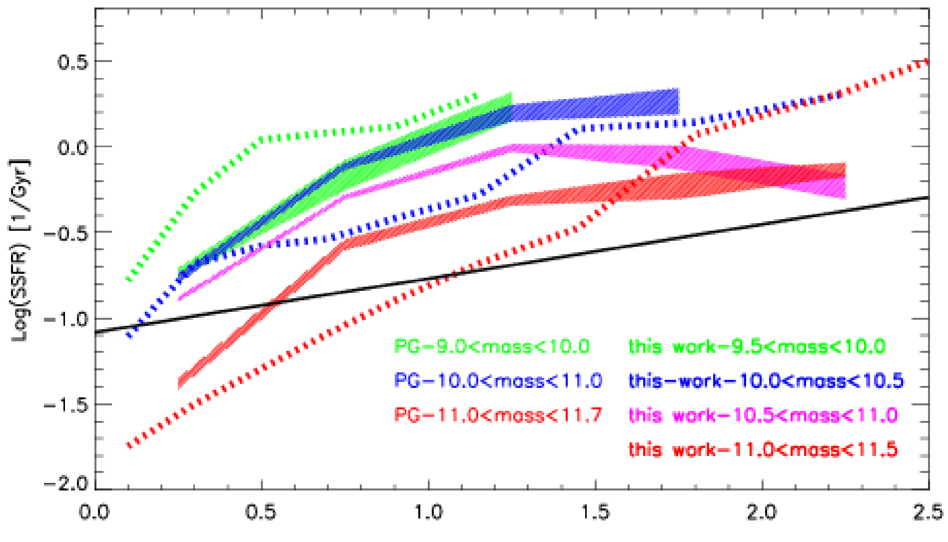

mass completeness limit

**The SFR is estimated by adding $SFR_{UV}$(optical data with model) and $SFR_{dust}$ (Herschel).**

**(Rodighiero et al. 2010)**

# Hidden star formation and evolution of stellar mass




**The decreasing trend of SSFR with $M_*$ (downsizing) is seen at any redshift range, but the slope steepens up to $z = 2$.**

***N.B.* However, still results from different studies do not agree with each other.**

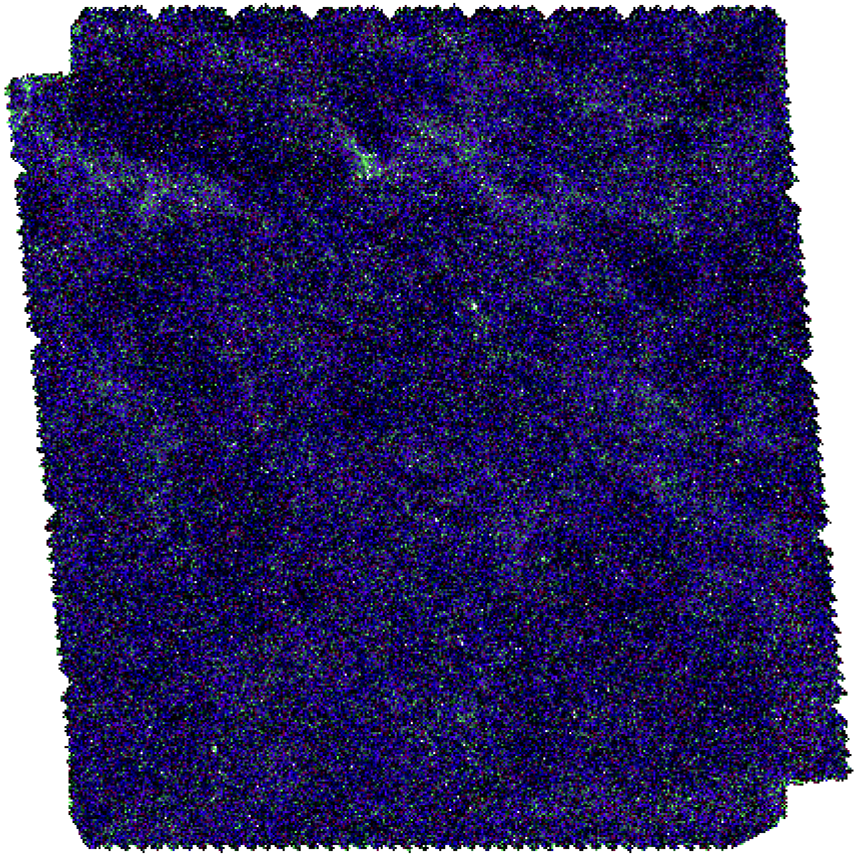
**(Rodighiero et al. 2010)**

## Clustering of dusty galaxies and structure formation

**Spatial distribution of galaxies** carry crucial information on the structure formation and galaxy formation in dark halos.

**Low-z dusty galaxies are biased to starbursts and late-type star forming ones.**

**In contrast, at higher redshifts, dusty galaxies are *speculated* to be progenitors of present-day massive elliptical galaxies.**

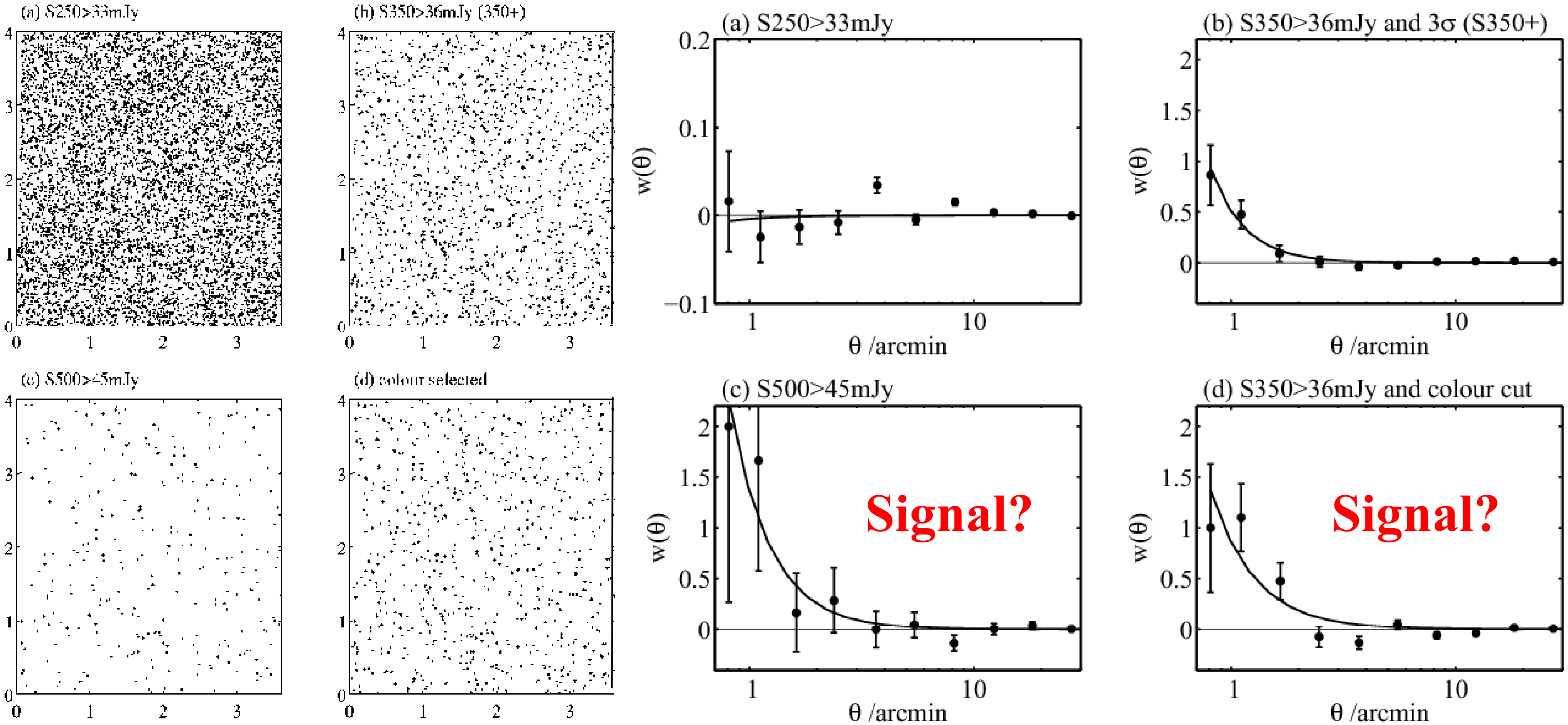


The SDP field (4 deg × 4 deg)

**H-ATLAS will provide us with ideal data. However, the currently available area is still small, and numbers of galaxy candidates are of 300-6000.**

(Maddox et al. 2010)

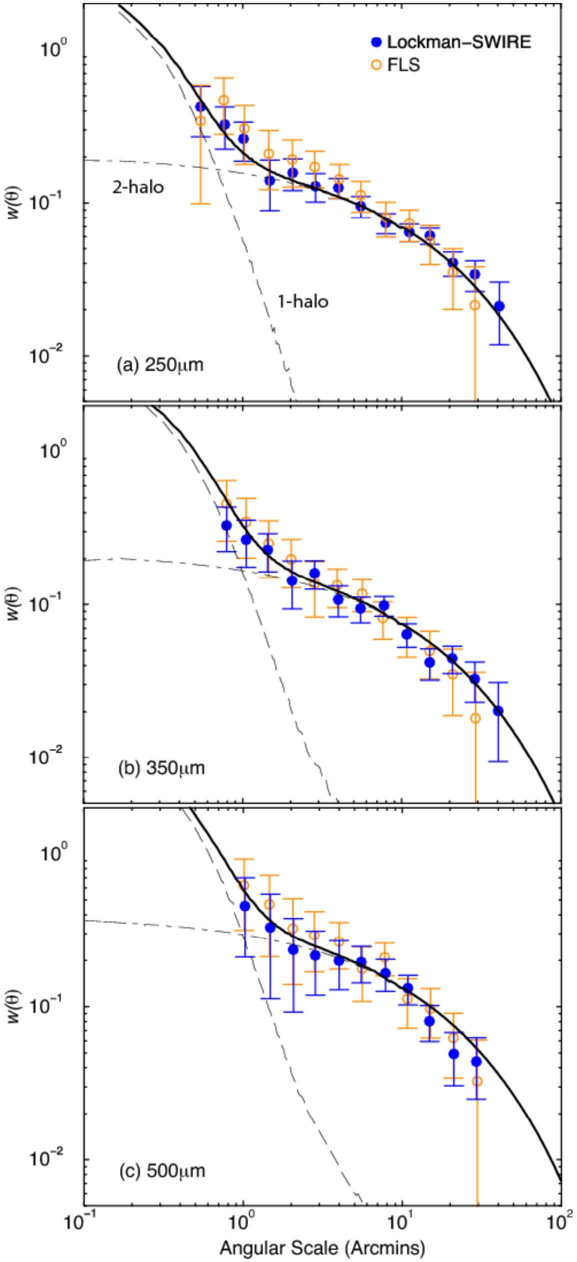
# Clustering of dusty galaxies and structure formation




**They claim that they found a clustering for brightest sources and possibly high-*z* objects. However, the minimum number of clustering analysis would be ~ 2000, i.e., in most of the analysis with the SDP data, the sample size is insufficient.**

**(Maddox et al. 2010)**

## Clustering of dusty galaxies and structure formation




**Halo model is now a fashonable simple theoretical framework to model the dark matter and dark halo distribution.**

**The basic idea is to divide the matter power spectrum into two components: clustering of halos and density profile of each halo.**

**In principle, angular clustering of dusty galaxies have information on the dark halos in which dusty galaxies reside.**

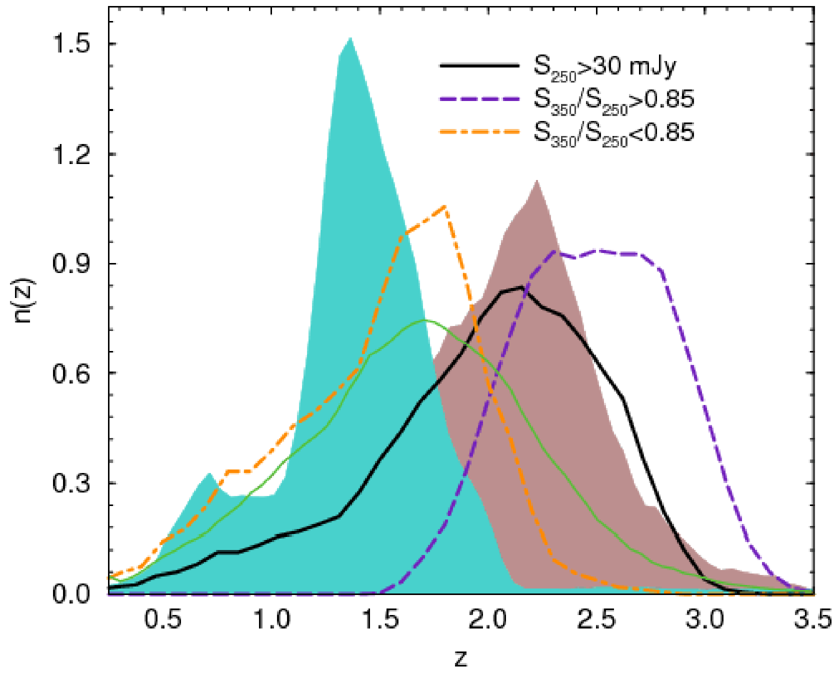
**HerMES provide relatively large number (~ 3000-8000) of dusty galaxies at *z* ~ 2.**

**(Cooray et al. 2010)**

## Clustering of dusty galaxies and structure formation

**By the halo model and observed clustering, with redshift distribution, the halo occupation distribution can be estimated.**

**From HerMES, they found that galaxies detected at 250 mm (> 30 mJy) reside in dark halos with $M_{\rm halo} > (5 \pm 4) \times 10^{12}\ M_\odot$, while 14 ± 8 % of them are satellites in more massive halos.**



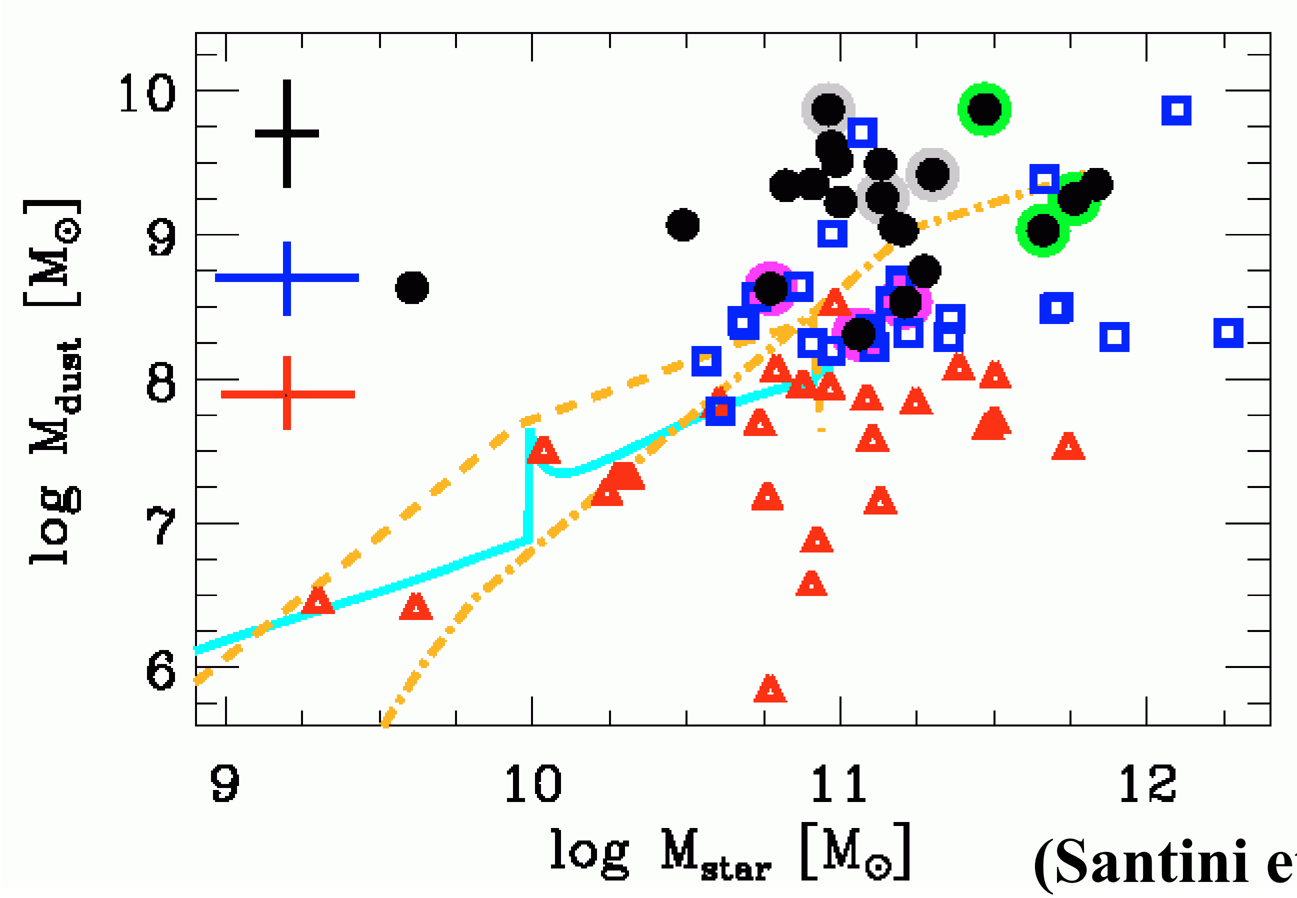

**Redhisft distribution**

***N.B.*** **this type of analysis strongly depends on the redshift distribution of the sources. The *z*-distribution is indirectly reconstructed by assuming the SED of galaxies, which are also very uncertain and to be investigated.**

**(Cooray et al. 2010)**

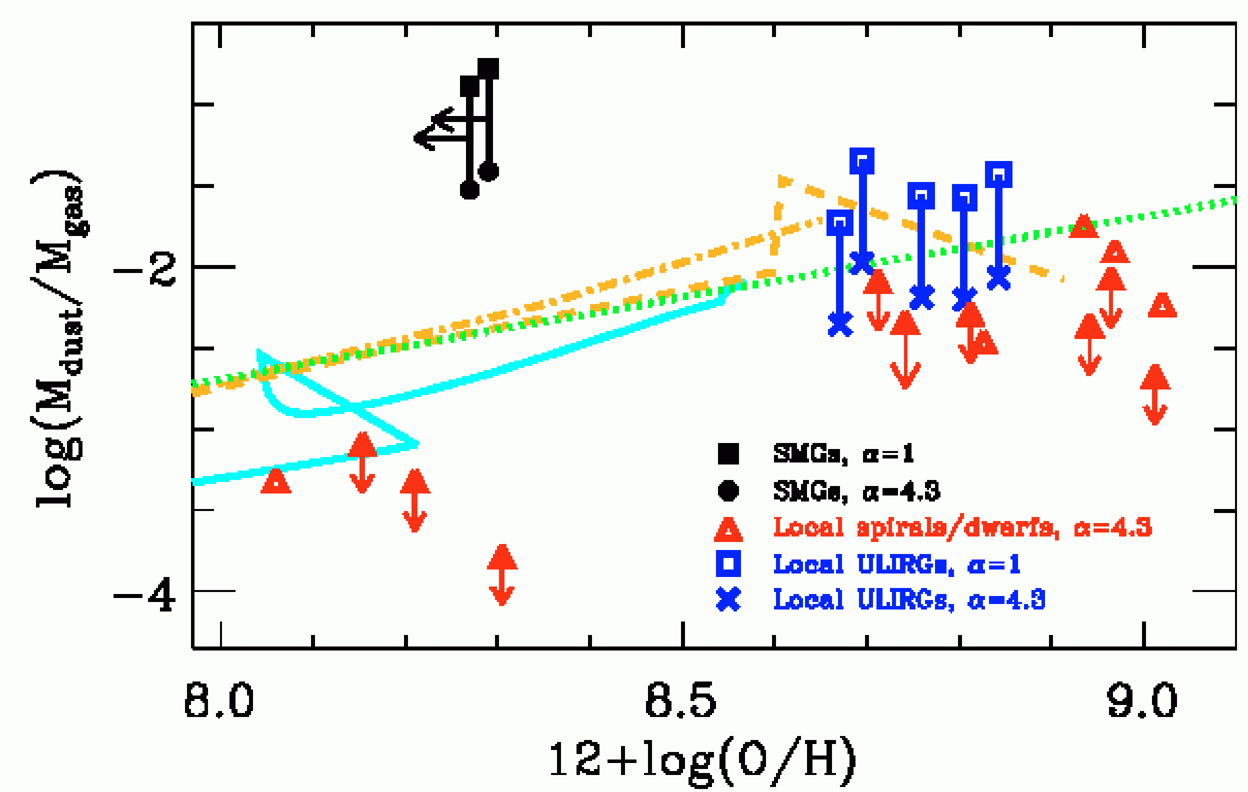
## Nature of dust in high-z galaxies

**Dust content of high-z galaxies is crucial to understand the early evolution of galaxies. Especially, dust-to-gas (or stellar) mass ratio is a key factor for theoretical modeling (cf. talk by Asano et al.).**




**(Santini et al. 2010)**

# Nature of dust in high-z galaxies




**Somewhat puzzling feature is that the dust-to-gas mass ratio of dusty starbursts and submm galaxies are much higher than that expected from their metallicity, and the Herschel PEP result confirmed this for high-z submm galaxies. The interpretation is still under debate.**

**(Santini et al. 2010)**

## Other interesting extragalactic topics

1. **Photometric observation of a Local metal-poor dwarf NGC 1705 (O'Halloran et al. 2010).**
2. **FIR-to-radio correlation (Ivison et al. 2010).**
3. **FIR (100 and 160 mm) SFR estimators (Boquien et al. 2010).**
4. **The cosmic SF history of QSO host galaxies (Serjeant et al. 2010).**
5. **Sunyaev-Zel'dovich effect at $\lambda$ < 650 $\mu$m (Zemcov et al. 2010).**
6. **PACS spectroscopy of high-z dusty galaxies (Strum et al. 2010).**
7. **Dust content of Cassiopeia A SNR (Barlow et al. 2010).**

**etc…**

# 3. Summary

1. **Metal and dust is a key factor to understand the cosmic history of galaxy formation.**
2. **Herschel is providing data with unprecedented quality at wavelengths from 100 to 500 μm, as well as spectroscopic observations. Data from the key projects will be opened to public.**
3. **Far-IR to submm number counts are very well determined in wide range of flux, from 1.0 Jy to 1 mJy. Though the counts are simple statistics, they are very useful to constrain cosmological galaxy evolution model. Also, the cosmic IR background (CIRB) is decomposed into individual sources. Now 50% of the CIRB is explained by galaxies.**
4. **Luminosity functions of submm galaxies were estimated. They can work as a stronger constraint on theoretical models, but because of the limitation in estimation method, further investigation is needed.**

# 3. Summary

5. **Galaxy SEDs are very well determined at $\lambda = 100 – 500\ \mu m$. Their metallicity dependence is also clarified. Though AGN contribution is significant at $\lambda < 100\ \mu m$, the SED is dominated by star formation at $\lambda > 100\ \mu m$.**
6. **Dust temperature is often discussed, but often very unclear in definition and/or results.**
7. **Dust extinction is quantified toward higher-z than before. High-z dusty galaxies have statistically lower extinction than the low-z counterparts. It was also found that the IR excess-UV slope ($\beta$) relation (Meurer's law) does not to work well at any redshifts.**
8. **Galaxy downsizing is confirmed up to $z \sim 2$. The slope of SSFR as a function of stellar mass shows steepening toward higher-z. However, since still many studies show discrepant results, further more careful analysis is needed.**

## 3. Summary

9. **Galaxy clustering carries crucial information on the structure formation and galaxy evolution. However, though clustering signal of dusty galaxies was found, the sample size is too small to have reliable result.**
10. **Halo model was adopted to examine the dark halo environment of dusty galaxies. For this analysis, the sample size was acceptably large, but the uncertainty of redshift distribution hampers to have a firm result.**
11. **Dust-to-gas/stellar mass ratio of dusty galaxies was examined for high-z galaxies. It is known that dusty starbursts tend to have too much dust with respect to their metallicity. This weird tendency was confirmed for Herschel sample. This problem remains to be solved.**

**The data will be public.**

**It is ourselves who will solve these problems! Let's try!**

# Acknowledgement

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