First Results on the Star Formation and Dust Extinction of Local Galaxies from *AKARI* All-Sky Survey

Tsutomu T. TAKEUCHI
Institute for Advanced Research, Nagoya University, JAPAN

Fang-Ting, YUAN, Katsuhiro L. MURATA
Division of Particle and Astrophysical Science, Nagoya University, JAPAN

Véronique BUAT, Élodie GIOVANNOLI, Denis BURGARELLA
Laboratoire d'Astrophysique de Marseille, OAMP, FRANCE

Jorge Iglesias-Páramo
Instituto de Astrofísica de Andalucía, CSIC, SPAIN

Sébastien HEINIS
Department of Physics and Astronomy, The Johns Hopkins University, USA

Agnieszka POLLO, Piotr RYBKA
Instytut Problemów Jądrowich im. Andrzeja Sołtana, POLAND

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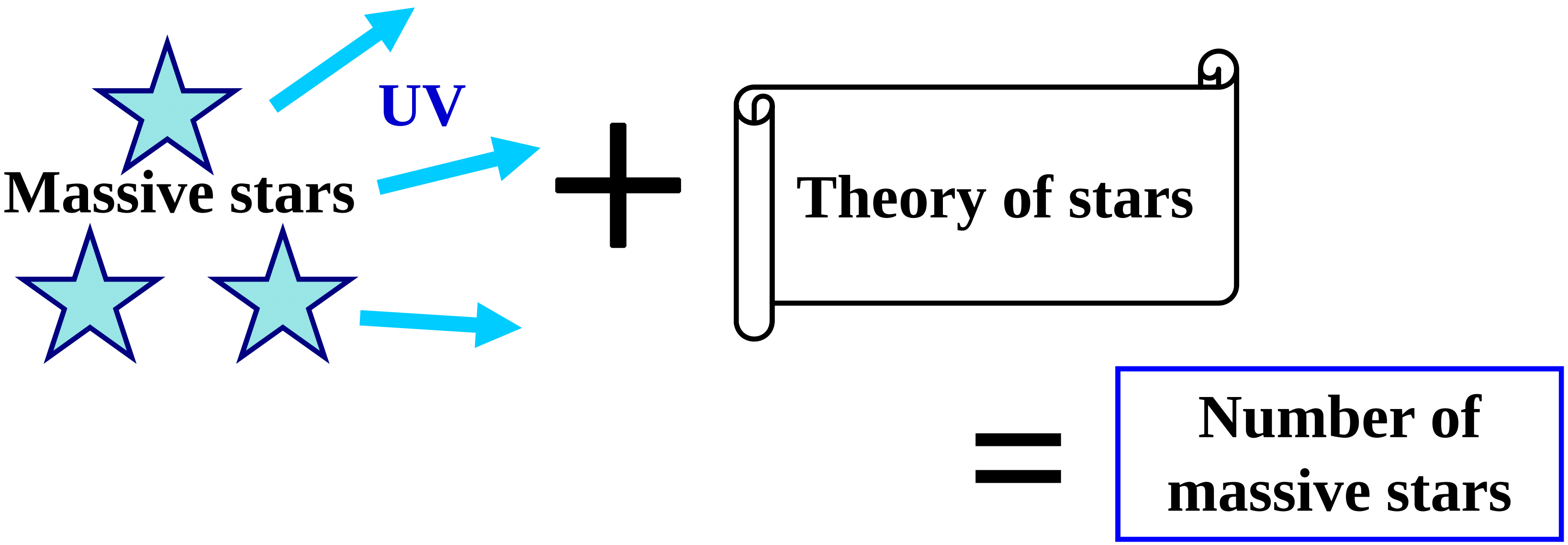
1. The Star Formation History in the Universe

1.1 How to Estimate the SFR from Observations

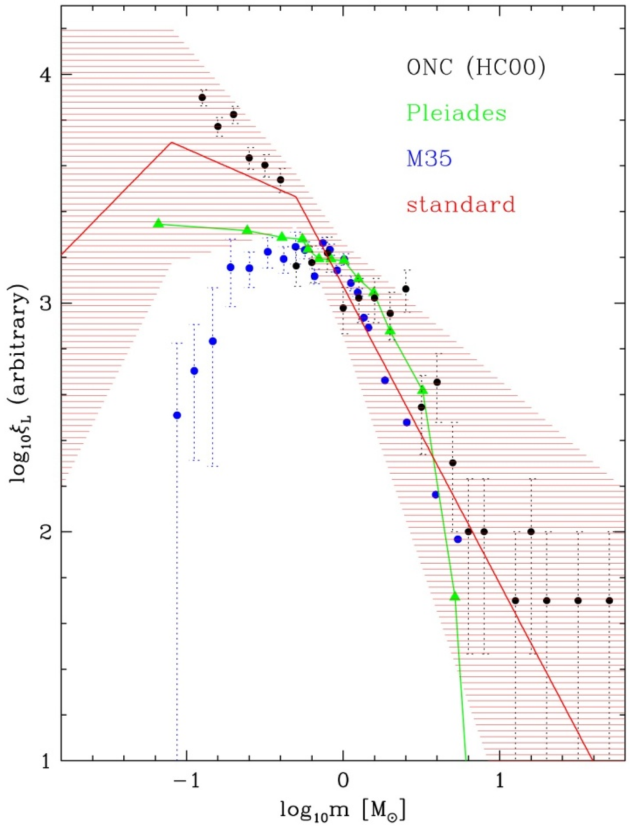
The SFR of galaxies is estimated based on the measurement of the total ultraviolet (UV) light from massive stars.



Since the lifetime of massive stars (~ 10^6 yr) is much shorter than the age of galaxies, their number can be regarded as the current SFR.

1.1 How to Estimate the SFR from Observations

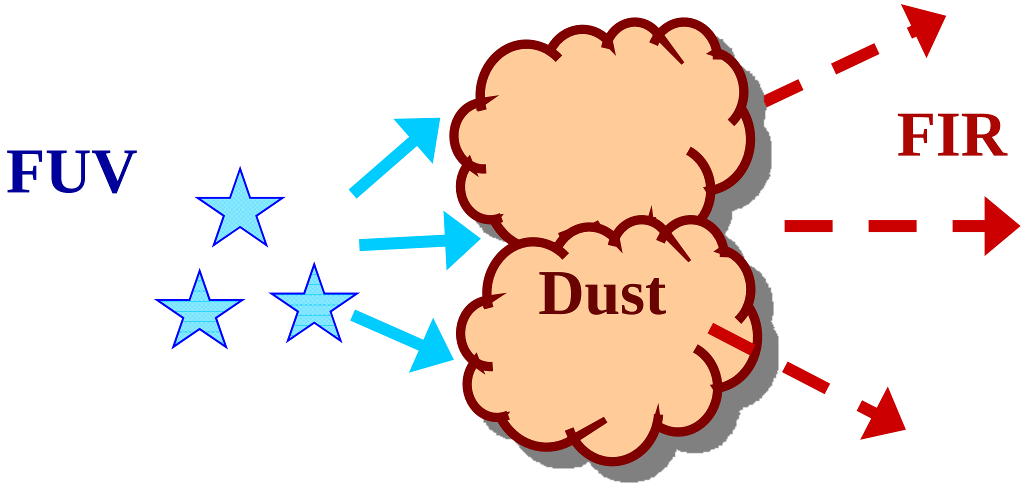
By using a mass distribution function of stars at their birth (initial mass function: IMF), we can convert the number of massive stars (current massive SFR) to the total number of newly born stars, i.e., the total SFR.



Some examples of the IMF estimated from observations. The IMF is often approximated by a power-law form with reasonable lower and upper masses.

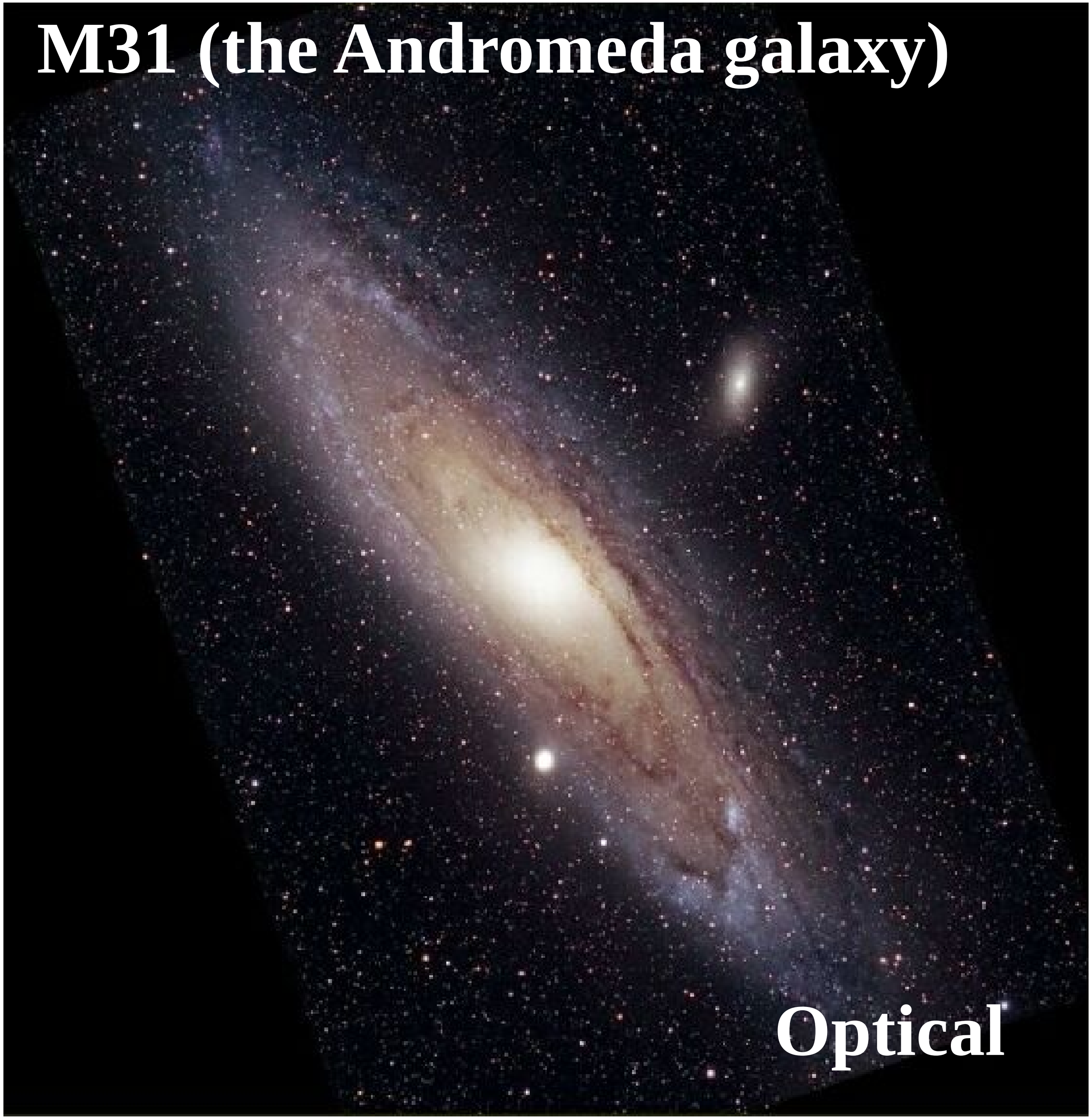
(Kroupa 2002)

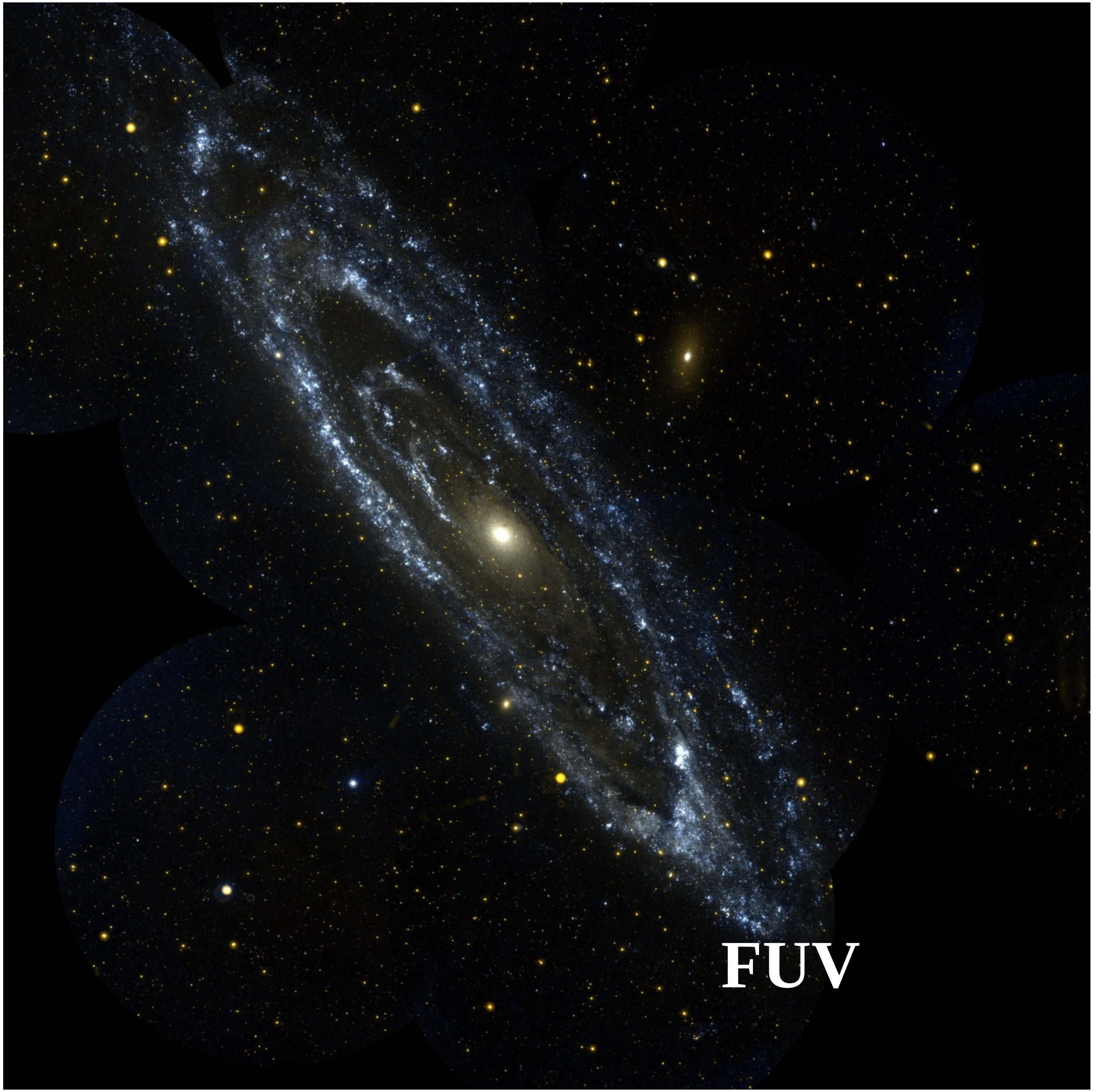
1.2 Problem in the Estimation of SFR from UV

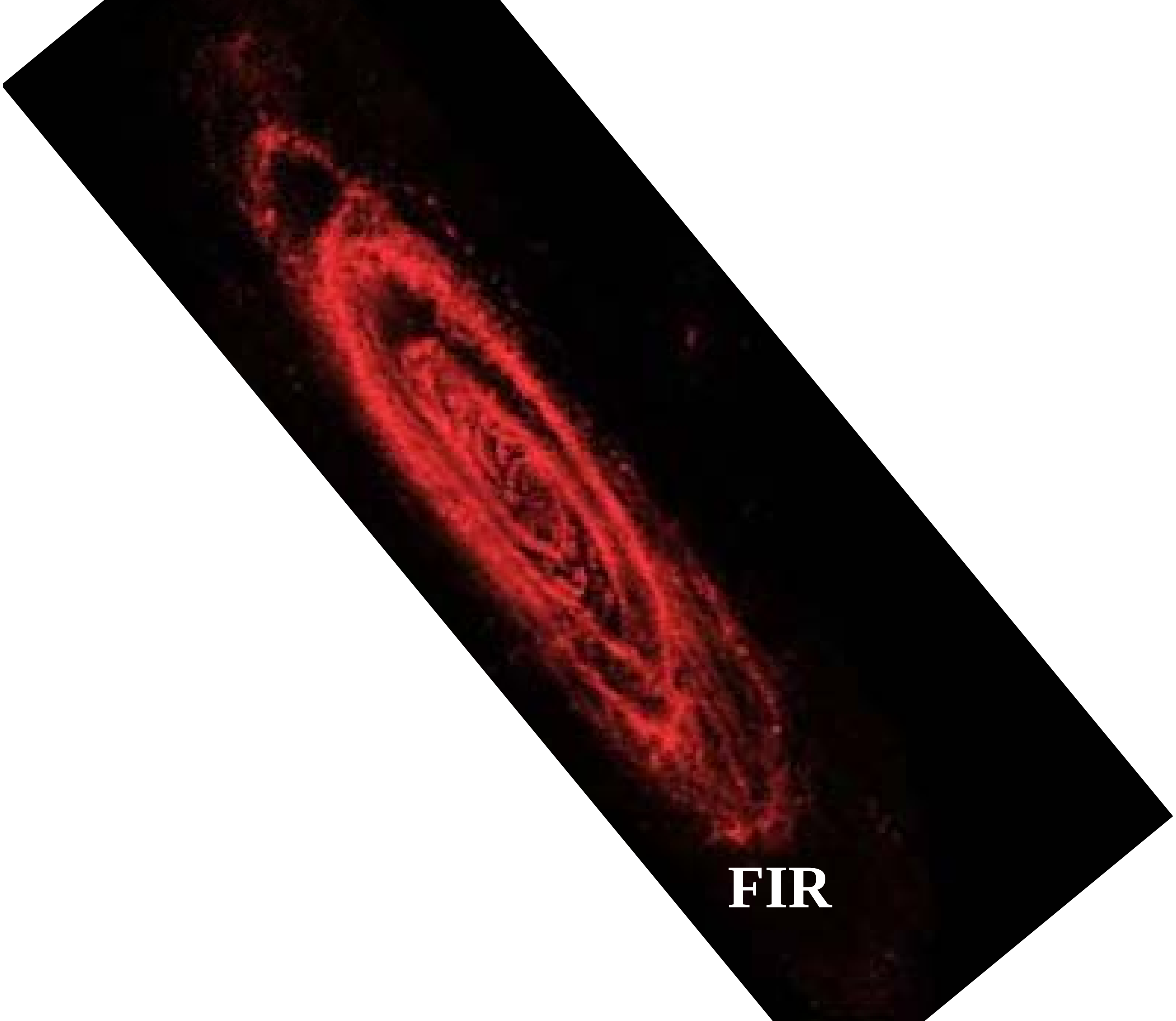


Short-wavelength photons like UV are scattered and absorbed by small solid grains, i.e., dust (referred to as “extinction”), and re-emitted from dust at far-infrared (FIR).

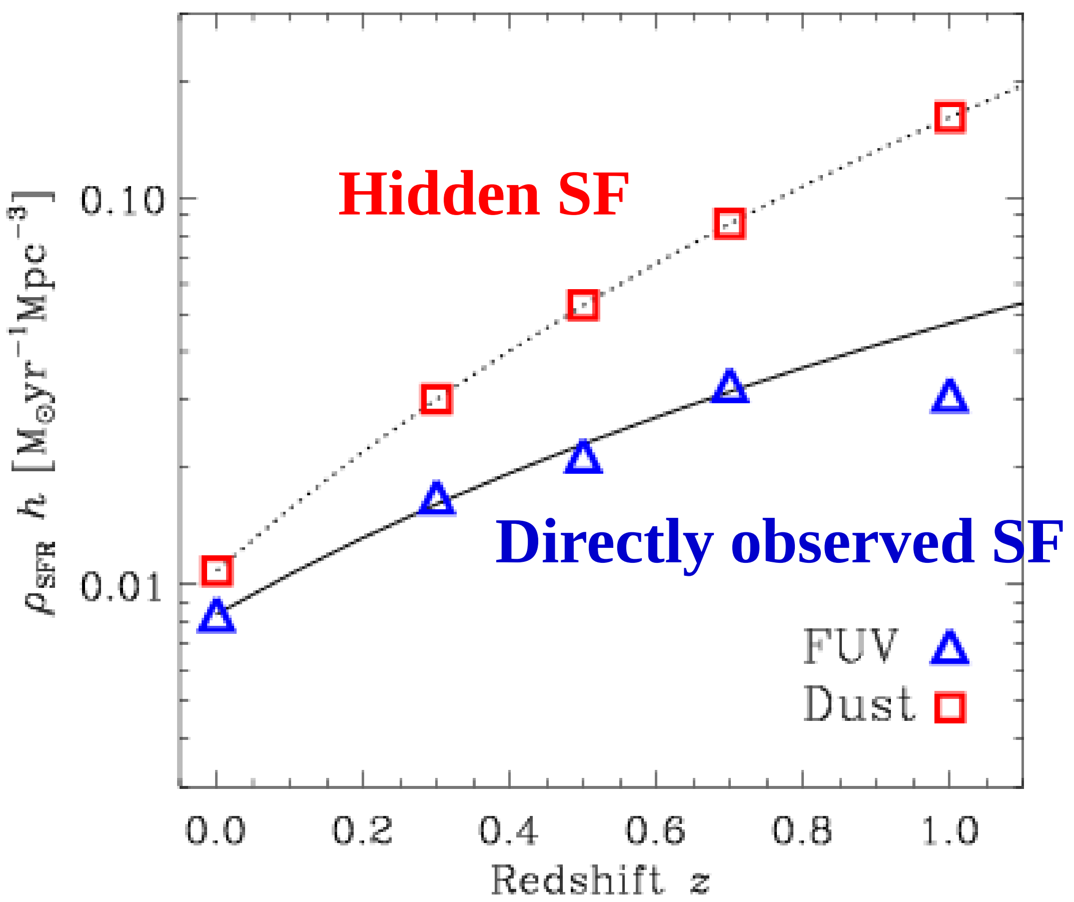
Hence, to obtain an unbiased view of the cosmic star formation, it is crucial to treat the information of both FUV and FIR.


M31 (the Andromeda galaxy)
Optical


FUV


FIR

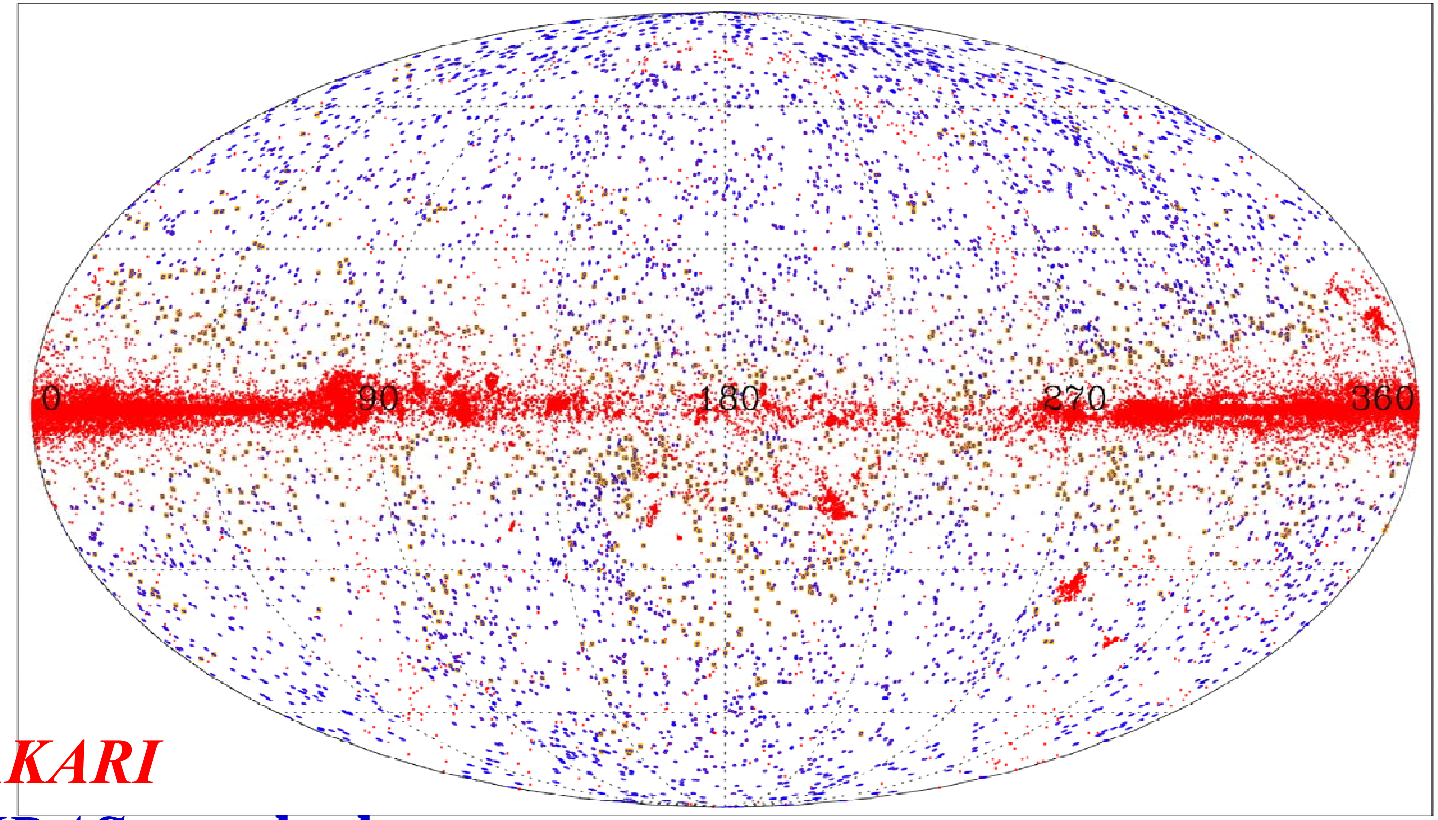
1.3 The cosmic star formation history at $z < 1$



The local fraction of the hidden SF is 50-60%, while the fraction at z=1 reaches around 80% (Takeuchi et al. 2005a).

2. Multiband Galaxy Sample from *AKARI* ASS

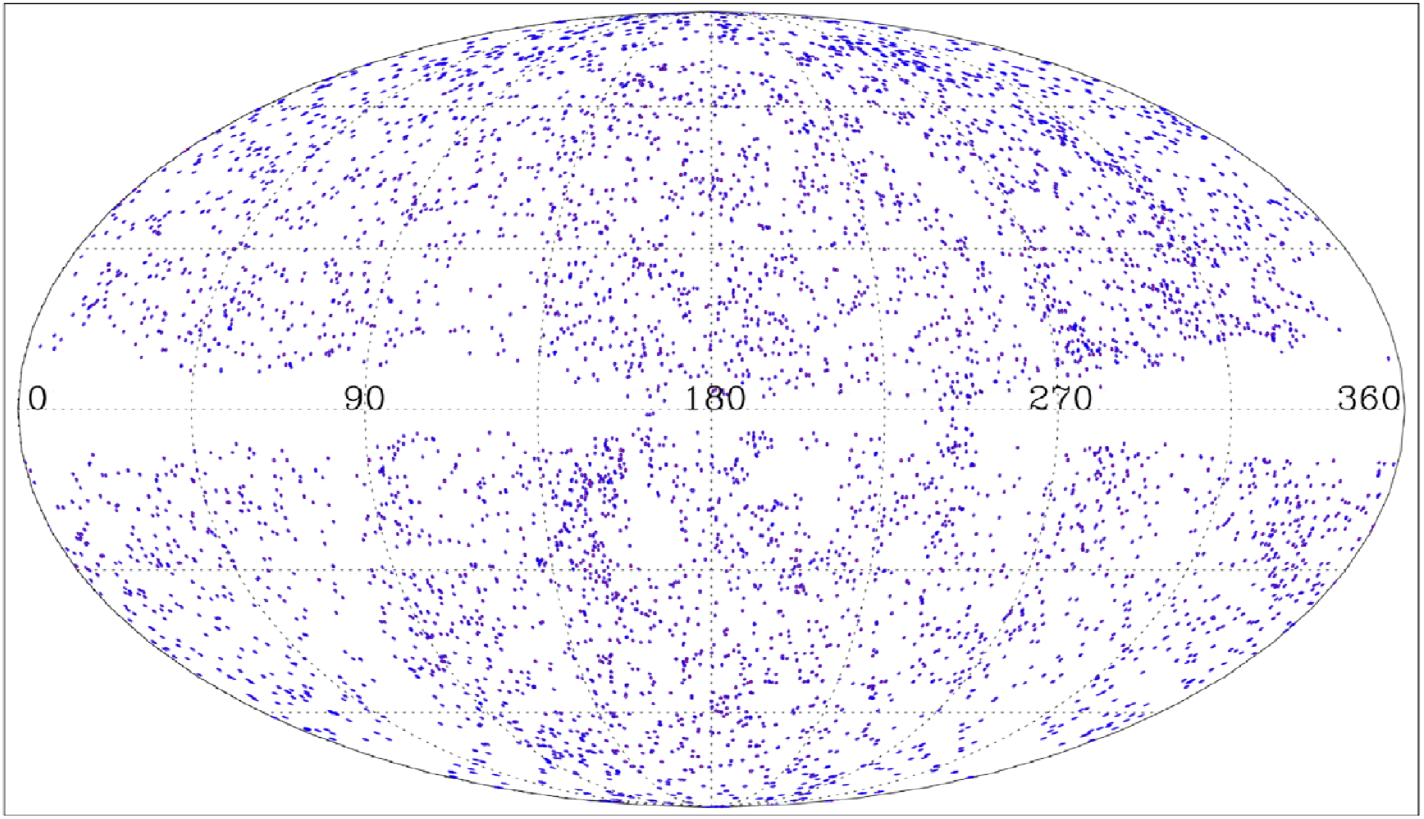
2.1 Construction of the sample



Red: *AKARI*
Blue: *IRAS* matched

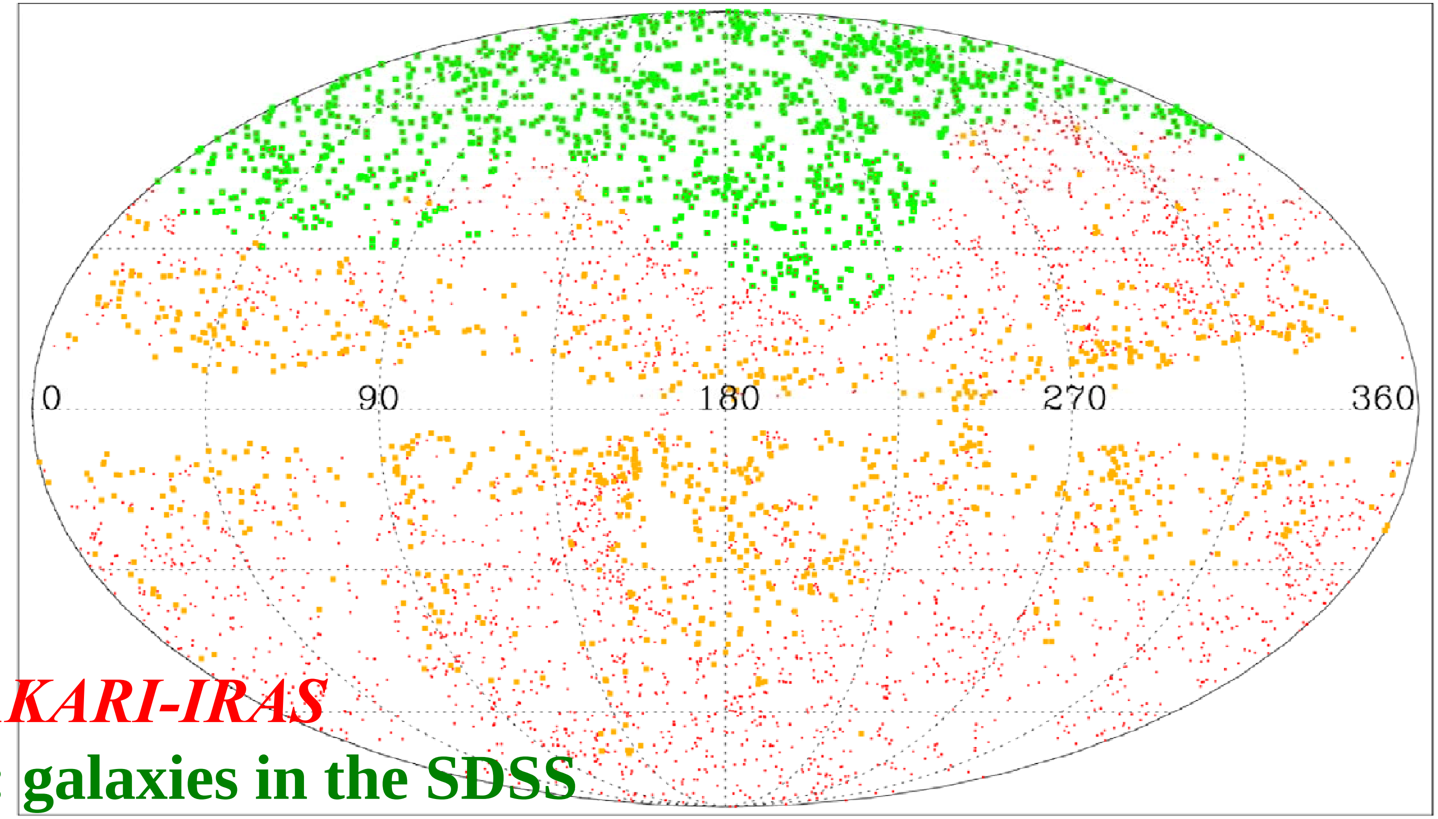
First, *AKARI* Bright Source Catalog sample (β-1.1)was matched with *IRAS* PSC*z* (60μm selected redshift survey: confirmed galaxies) (by YUAN Fang-Ting).

2.1 Construction of the sample



Parent sample (~ 6000 galaxies).

2.1 Construction of the sample



Red: ***AKARI-IRAS***
Green: galaxies in the SDSS
Yellow: cirrus-contaminated

Select galaxies in the SDSS DR7 (optical survey) region (~ 8000 deg^2). This selection automatically excluded galaxies in high-cirrus sky regions. 1186 galaxies were selected.

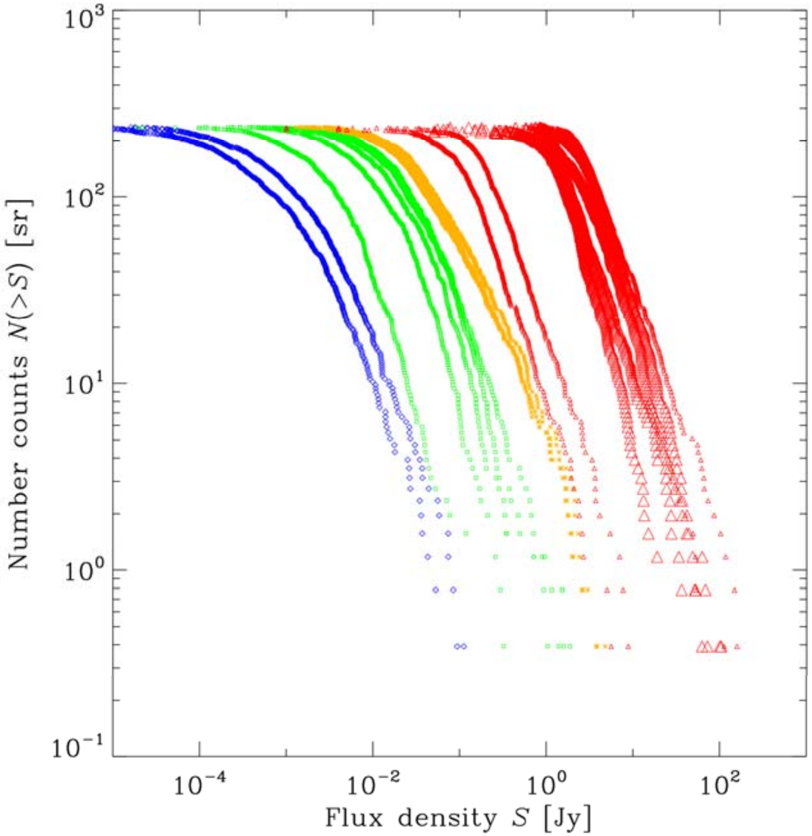
2.1 Construction of the sample

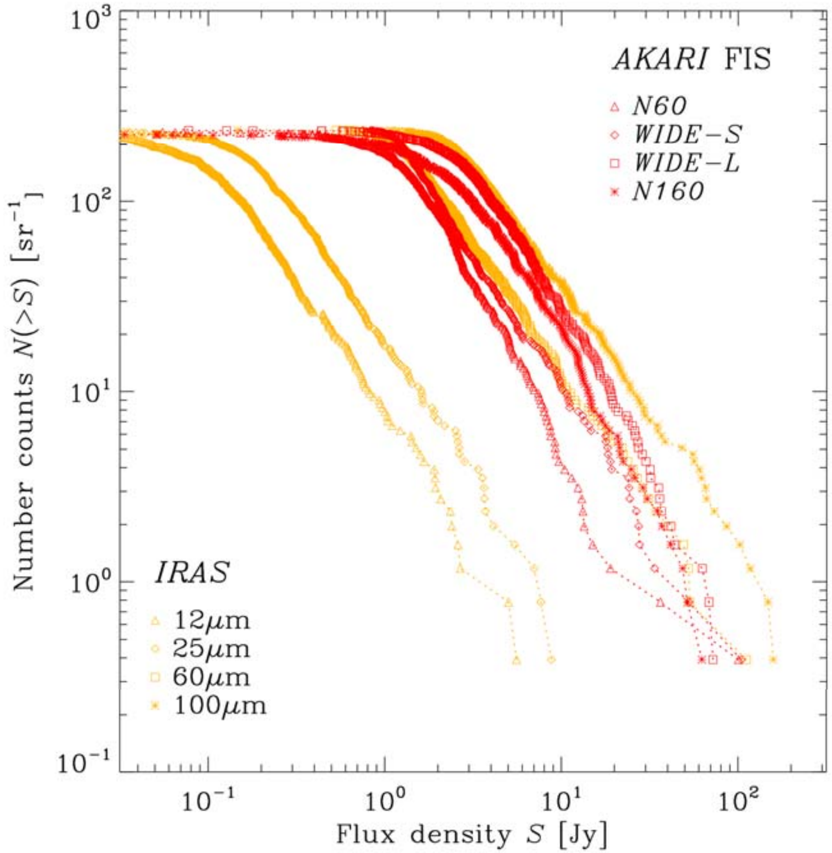
The parent sample was further matched with
1. *GALEX*: all-sky ultraviolet (UV) survey at 1530Å and 2315Å
2. SDSS: large optical survey at *u*, *g*, *r*, *i*, *z*
3. 2MASS: all-sky near-infrared (NIR) survey at *J*, *H*, *K*

Final sample consists of 607 galaxies with good quality flux measurement at UV-optical-NIR-MIR-FIR.

2.2 Properties of the sample galaxies

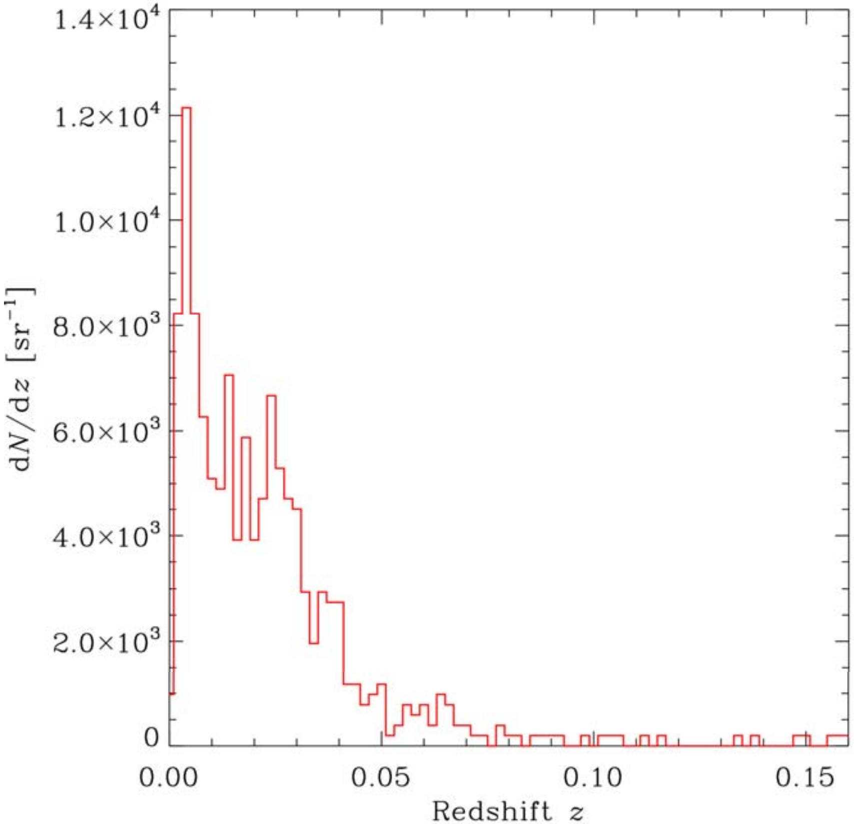
Number counts from UV to FIR

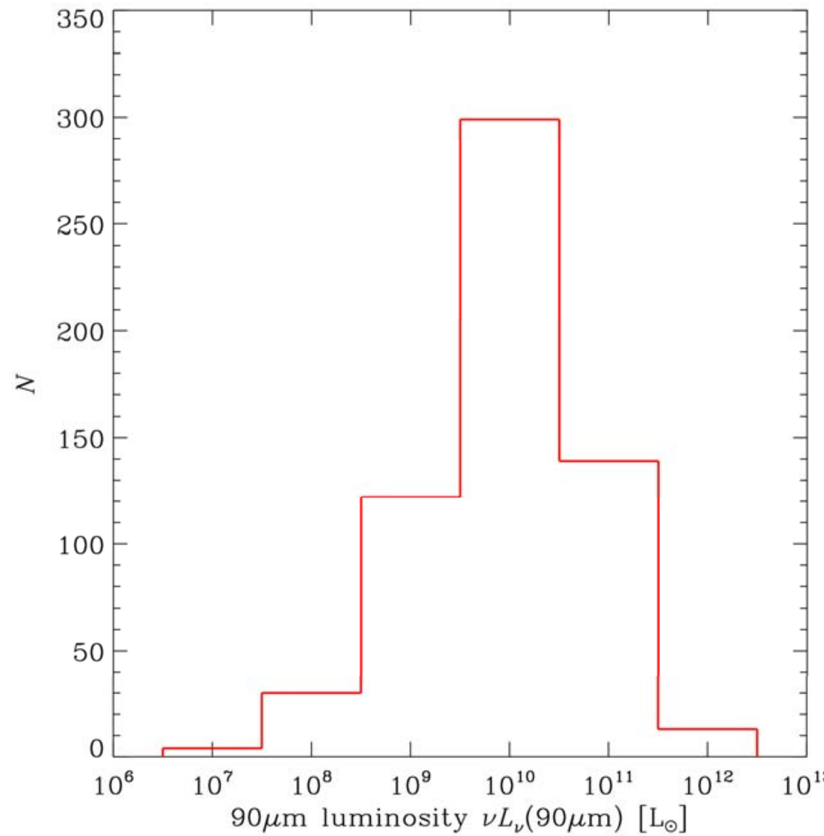




Number count slope becomes steeper and steeper from UV to FIR.
The effective detection limit at 90μm is ~ 0.8 Jy.

Redshift and 90μm luminosity distributions





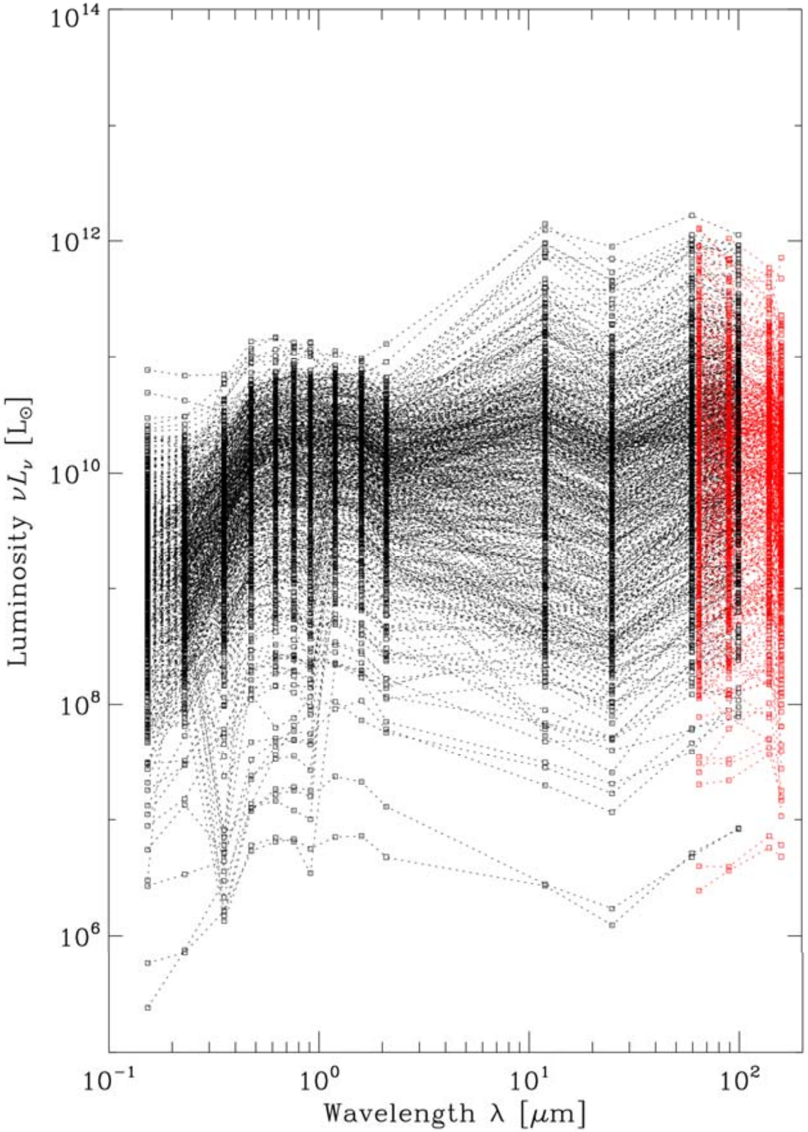
Since the *AKARI* BSC β-1 is rather shallow, most of the galaxies in the sample are local (z < 0.05). FIR luminosities range from 10^6 to $10^{12}L_\odot$. In this sample, a few are ULIRGs.

2.3 Basic Results from the Sample

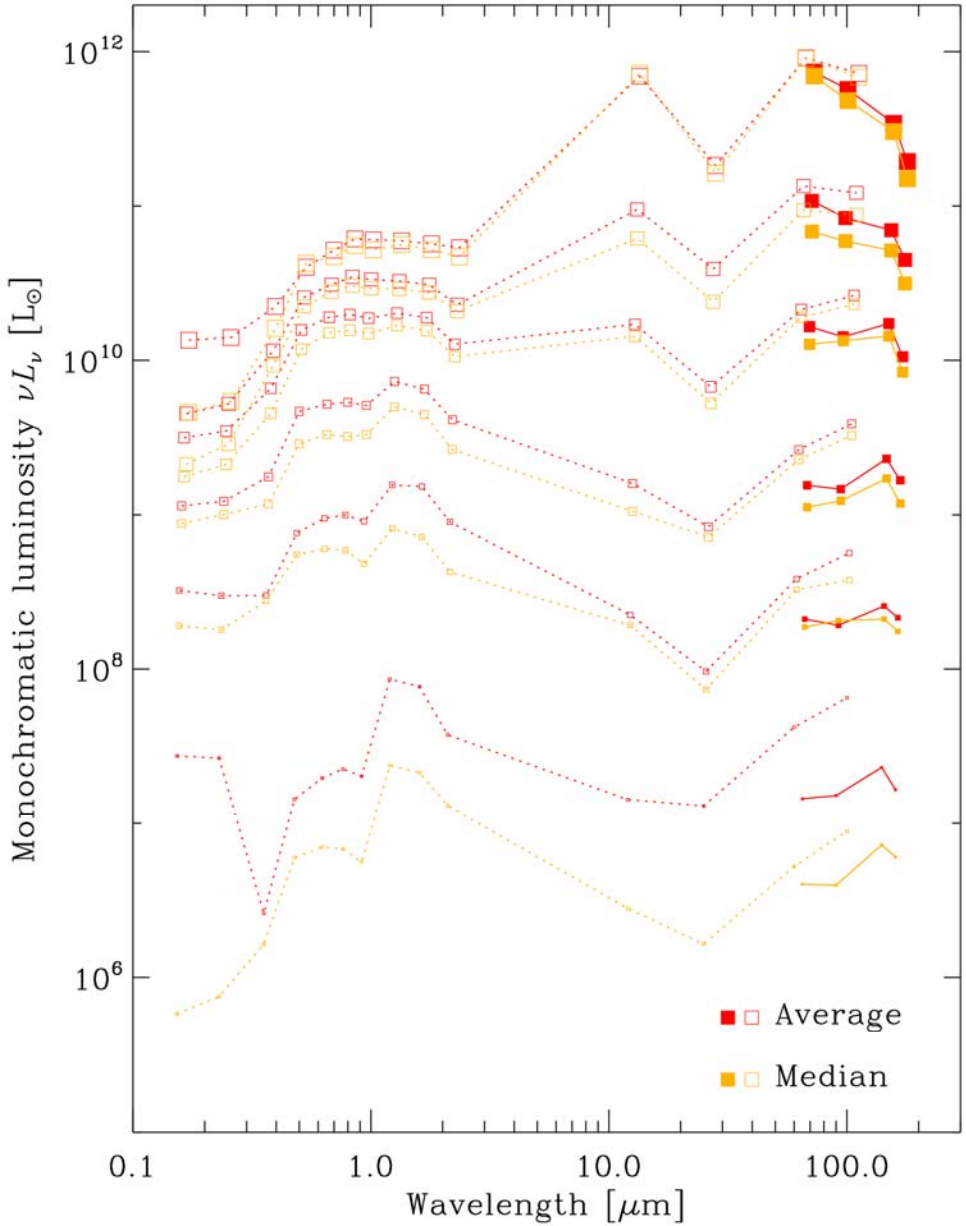
Spectral energy distributions (SEDs) of the sample

Red symbols and lines are SEDs obtained by *AKARI* FIS, and black ones are from *GALEX*, SDSS, 2MASS, and *IRAS*.

The sample galaxies have a large variety of SEDs.



Average SEDs as a function of 90μm luminosity



We find a clear trend of the shape of SEDs as a function of 90μm luminosity, even though we have various SEDs in each 90μm luminosity bin (see the difference between the average and median values).

Low L_{90} galaxies have bluer SEDs, while high-L_{90} ones have redder.

A formula to estimate the total IR luminosity from FIS flux

To calculate star-formation and extinction related quantities of galaxies, total IR luminosity is necessary.

FIR (λ=44 – 122μm: Helou et al. 1988)

$$L_{\rm FIR} \equiv 3.29 \times 10^{-22} \times (2.58\mathcal{L}_\nu(60\mu{\rm m}) + \mathcal{L}_\nu(100\mu{\rm m}))\ \ [L_\odot]$$

Total IR (λ=3 – 1100μm: Dale et al. 2001)

$$L_{\rm TIR} \equiv L_{\rm FIR} \times 10^{a_0+a_1x+a_2x^2+a_3x^3+a_4x^4}\ \ [L_\odot]$$

$$x \equiv \log(S_{60}/S_{100})$$

$$(a_0, a_1, a_2, a_3, a_4) = (0.2738, -0.0282, 0.7281, 0.6208, 0.9118)$$

Total IR (λ=3 – 1100μm: Dale & Helou 2002)

$$L_{\rm TIR2} \equiv 2.403\nu\mathcal{L}_\nu(25\mu{\rm m}) - 0.2454\nu\mathcal{L}_\nu(60\mu{\rm m}) + 1.6381\nu\mathcal{L}_\nu(100\mu{\rm m})\ [L_\odot]$$

Total IR (λ=8 – 1000μm: Sanders & Mirabel 1996)

$$L_{\rm IR} \equiv 4.93 \times 10^{-22}[13.48\mathcal{L}_\nu(12\mu{\rm m}) + 5.16\mathcal{L}_\nu(25\mu{\rm m}) + 2.58\mathcal{L}_\nu(60\mu{\rm m}) + \mathcal{L}_\nu(100\mu{\rm m})]\ \ [L_\odot]\ .$$

A formula to estimate the total IR luminosity from FIS flux

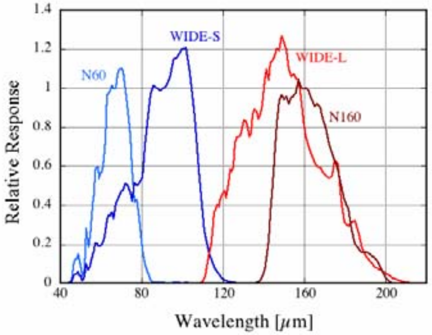
Hirashita et al. (2008) proposed a formula to estimate the FIR flux from *N60*, *WIDE-S*, and *WIDE-L* fluxes:

$$L_{AKARI} = \Delta\nu(N60)L_{65\mu m} + \Delta\nu(WIDE\text{-}S)L_{90\mu m} + \Delta\nu(WIDE\text{-}L)L_{140\mu m}$$

$$\Delta\nu(N60) = 1.58\times10^{12}\ [\mathrm{Hz}]$$

$$\Delta\nu(WIDE\text{-}S) = 1.47\times10^{12}\ [\mathrm{Hz}]$$

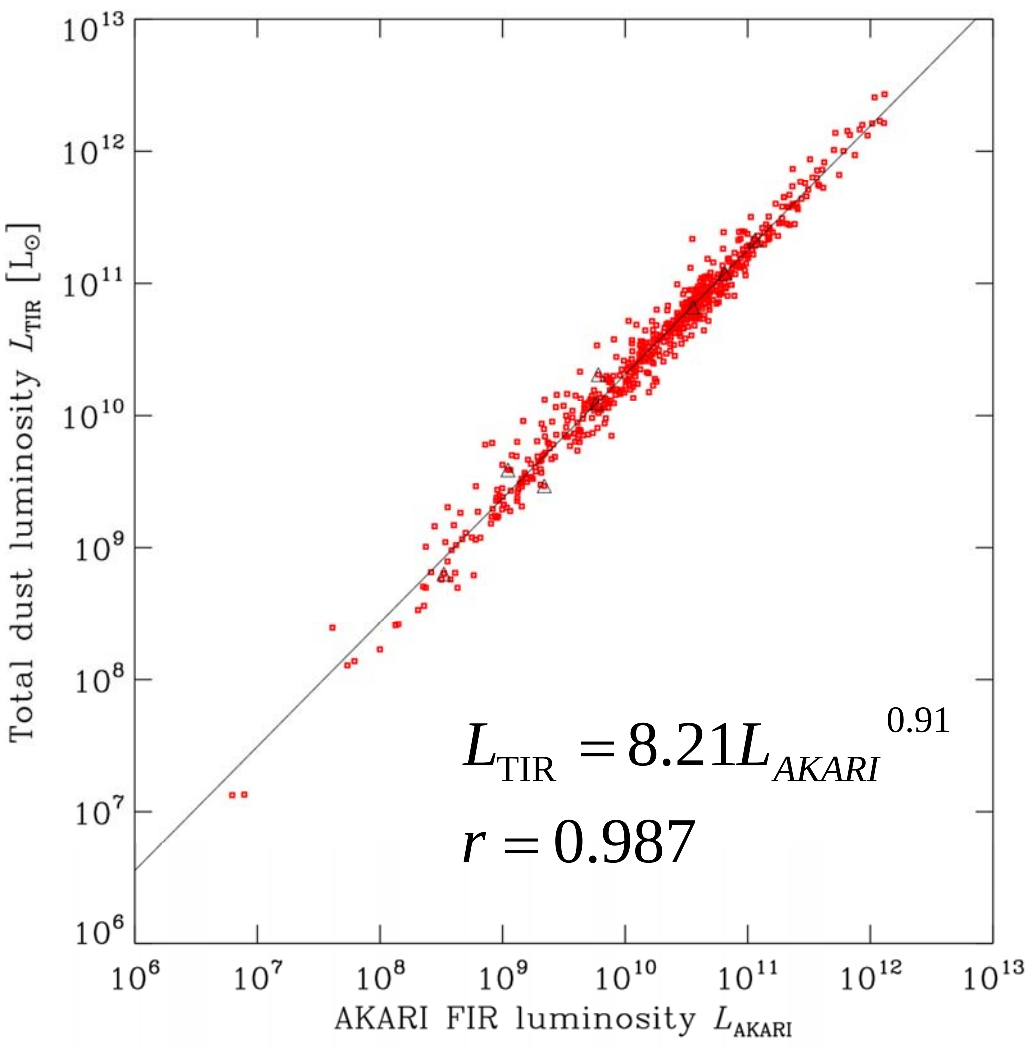
$$\Delta\nu(WIDE\text{-}L) = 0.831\times10^{12}\ [\mathrm{Hz}]$$



(*N.B.* Thanks to the continuous bands of FIS, this formula was constructed without any interpolation).

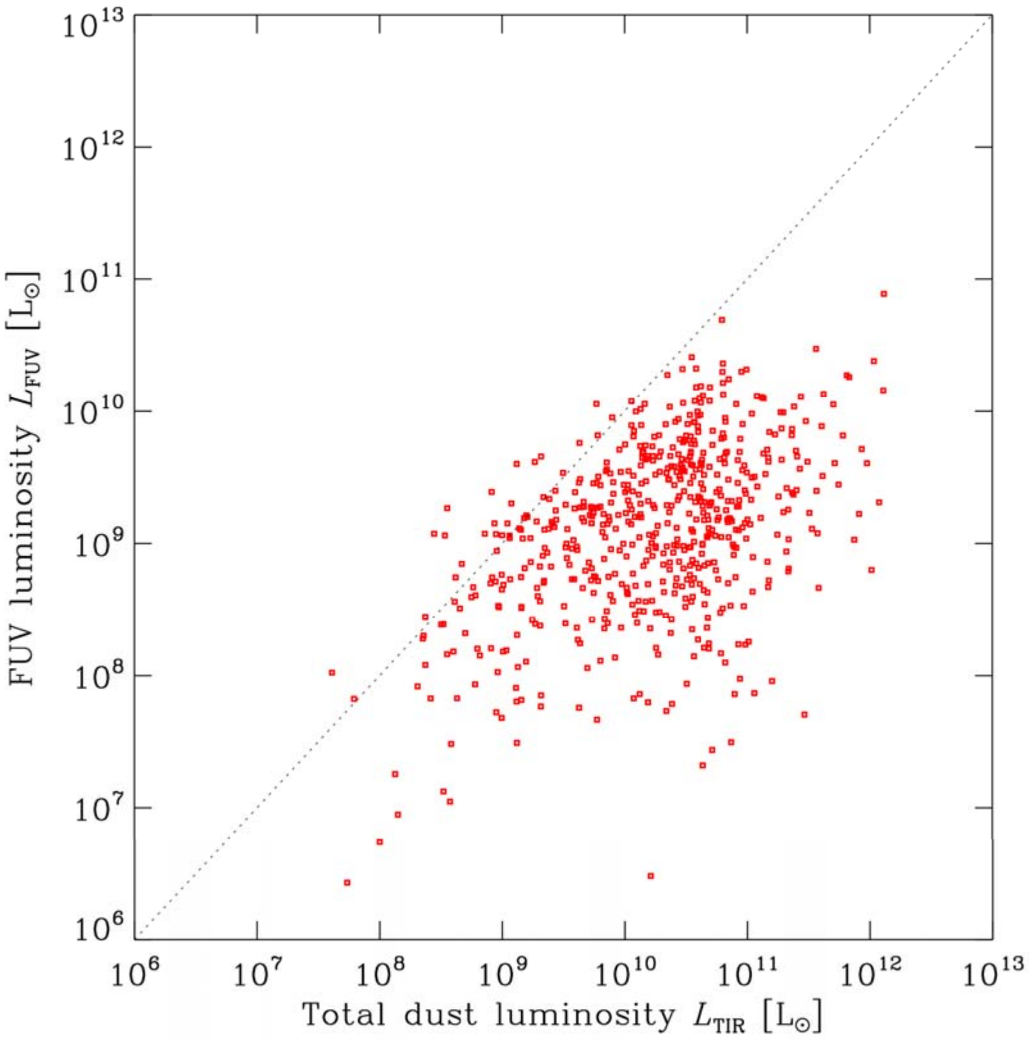
Since we have both *AKARI* FIS and *IRAS* fluxes, we can construct the desirable formula by comparing L_{AKARI} and L_{TIR}.

A formula to estimate the total IR luminosity from FIS flux



AKARI **IRC ASS will be used to explore this issue further.**

Total IR (dust) luminosity vs. FUV luminosity



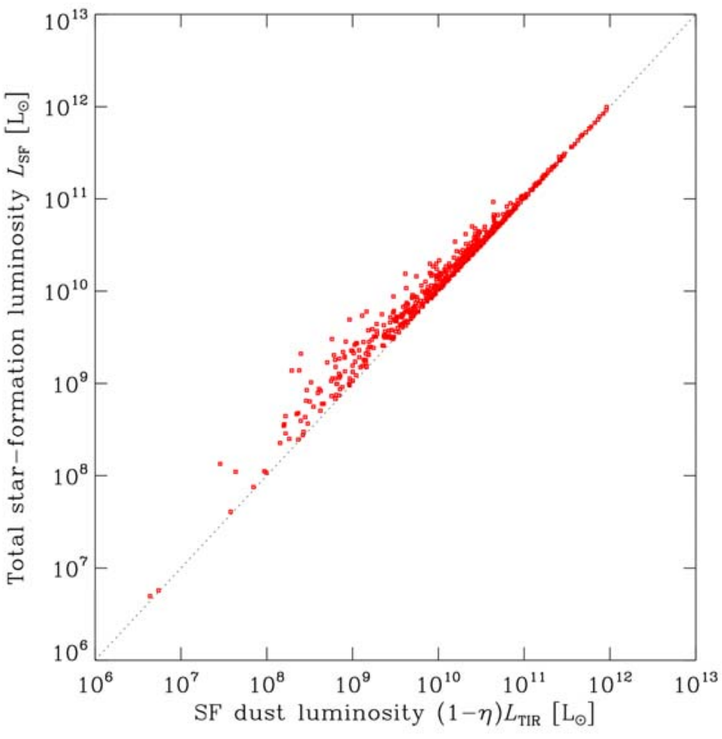
Total dust luminosity L_{TIR} is much higher than the FUV luminosity L_{FUV}.

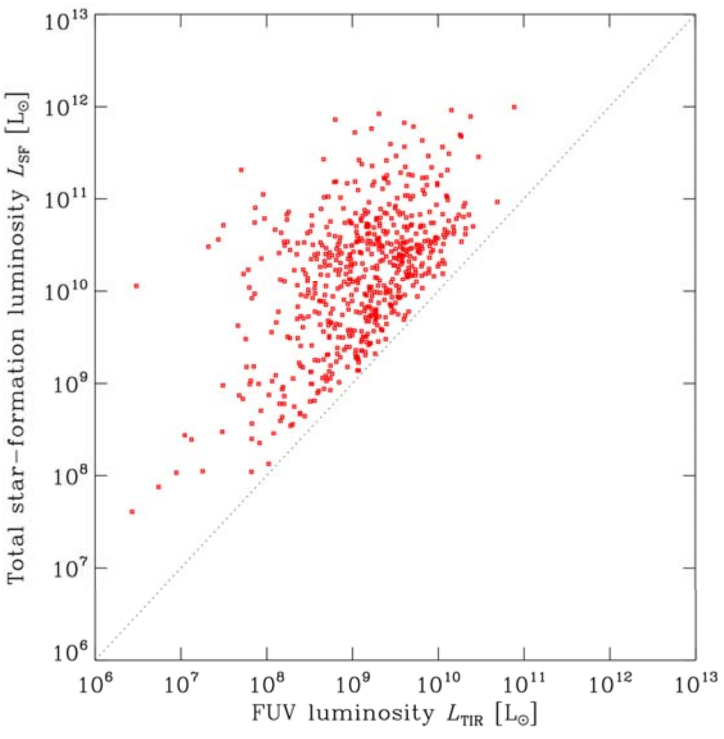
Star-formation luminosity

Since we have both FUV and FIR fluxes, we can obtain the total luminosity contribution from newly forming stars. We refer to it as the star-formation luminosity L_{SF}:

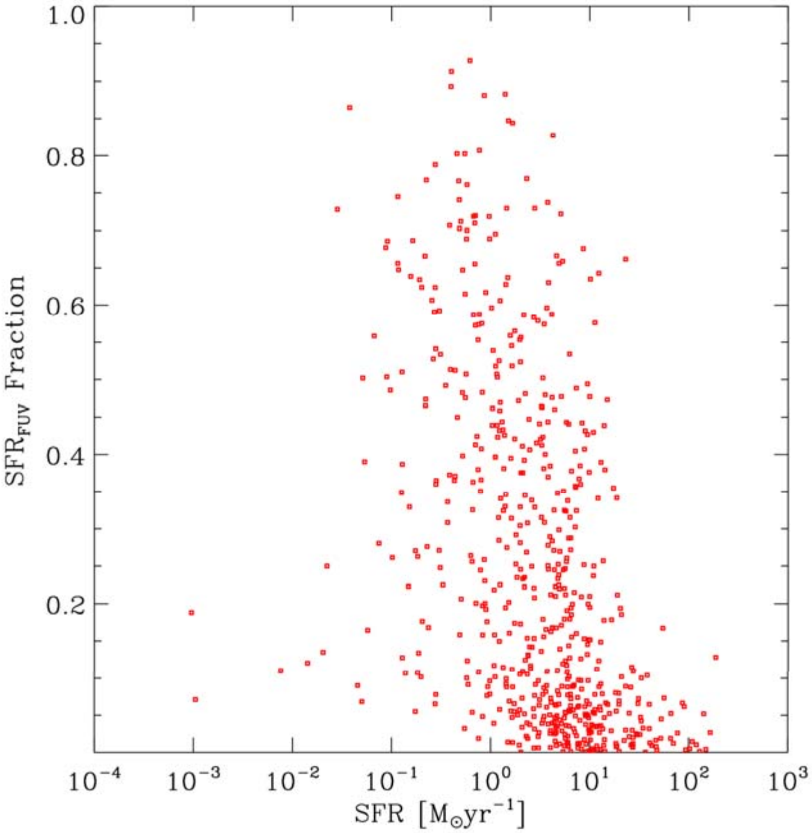
$$L_{SF} = L_{FUV} + 0.7 L_{TIR}$$

(0.7: correction for old stars)





Star formation rates (SFRs) estimated from FUV and IR



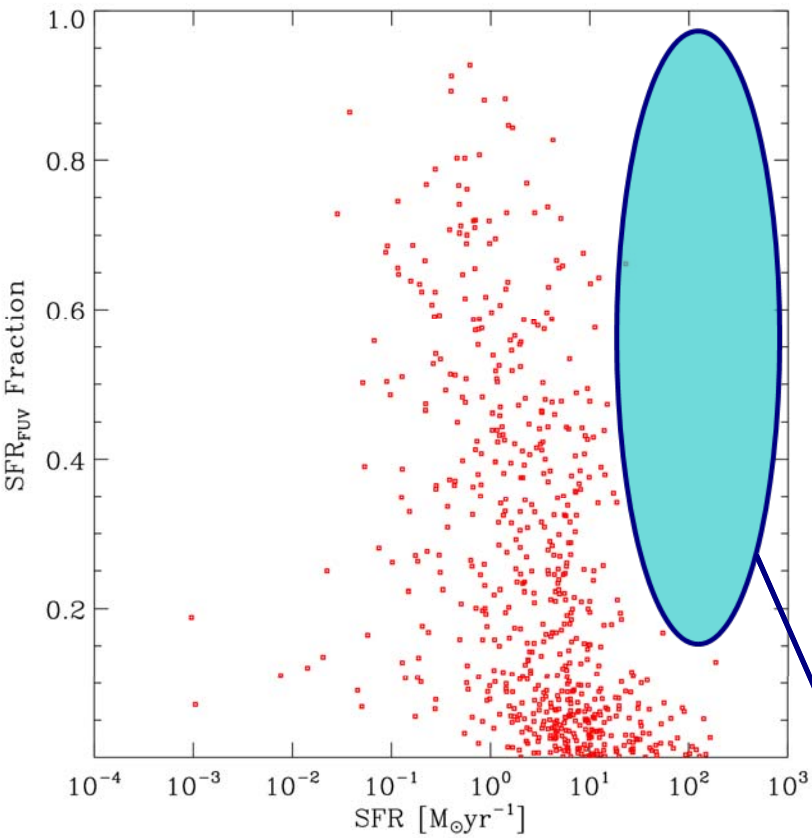
Assuming the Salpeter IMF, we have conversion formulae from FUV/dust luminosities to the SFR.

$$\log \mathrm{SFR}_{\mathrm{FUV}} = \log L_{\mathrm{FUV}} - 9.51$$

$$\log \mathrm{SFR}_{\mathrm{dust}} = \log L_{\mathrm{TIR}} - 9.75 - \log(1-\eta)$$

$$\mathrm{SFR} = \mathrm{SFR}_{\mathrm{FUV}} + \mathrm{SFR}_{\mathrm{dust}}$$

Star formation rates (SFRs) estimated from FUV and IR



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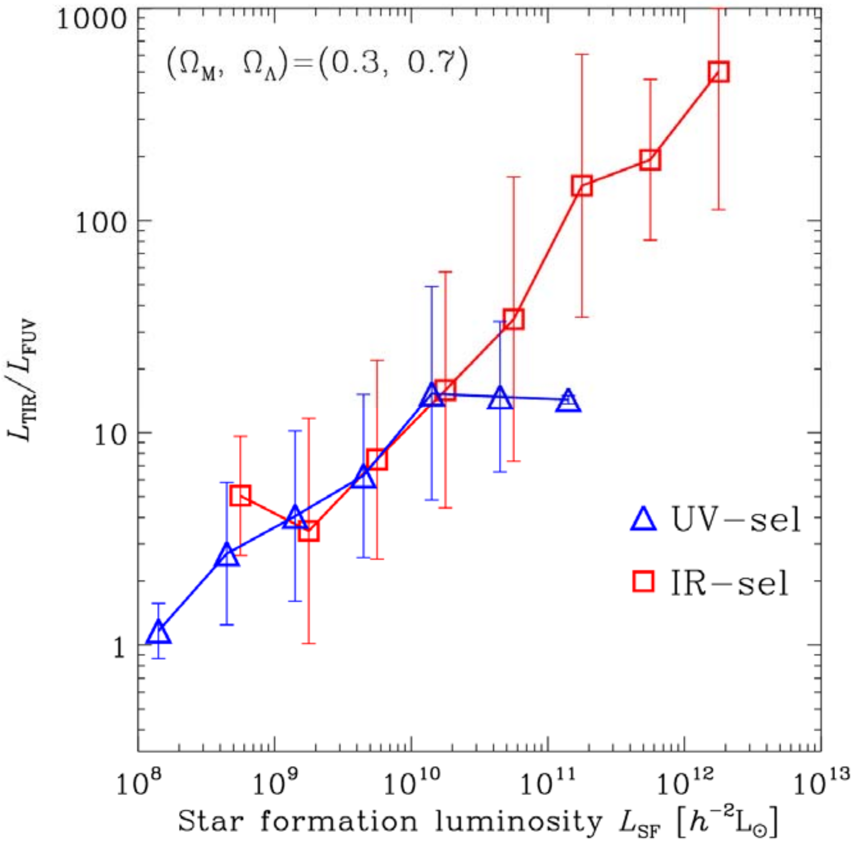
$$\mathrm{SFR} = \mathrm{SFR}_{\mathrm{FUV}} + \mathrm{SFR}_{\mathrm{dust}}$$

No galaxies have SFR_{FUV} fraction > 0.2 if SFR > 2×10 $M_{\odot} yr^{-1}$.

The average extinction trend as a function of L_{SF}: *IRAS* result



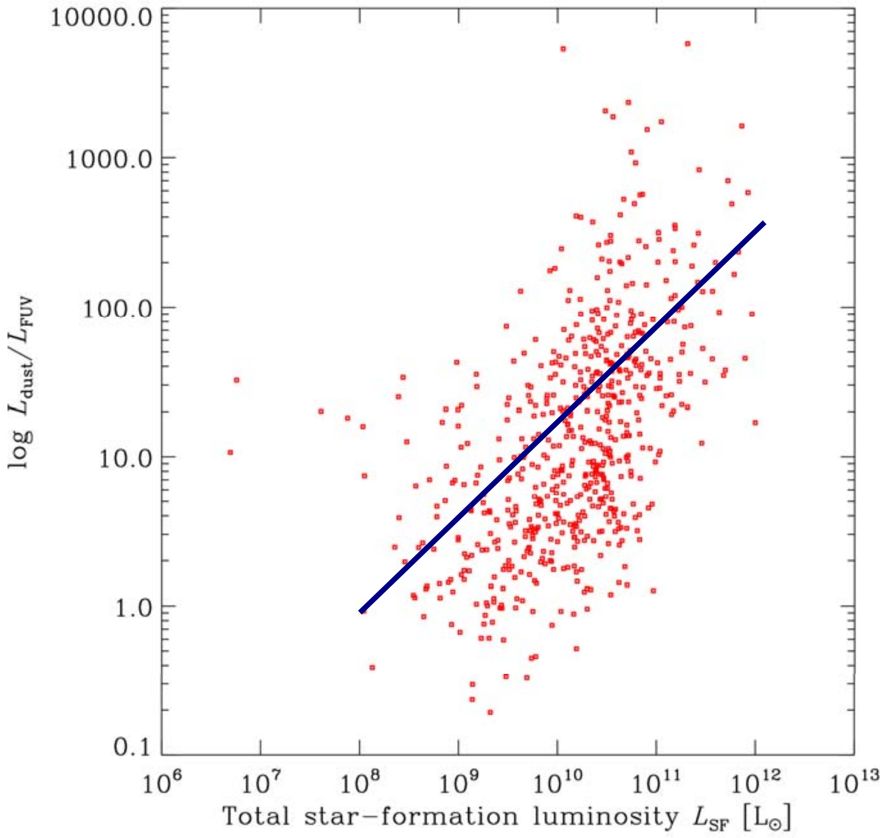
Dust attenuation at FUV, A_{FUV}, is uniquely determined by the dust-to-FUV luminosity ratio.

The relation is approximated as

$$\log\left(\frac{L_{TIR}}{L_{FUV}}\right) = 0.64 \log L_{SF} - 5.5$$

i.e., the more the SF is active, the more the galaxy is extinguished. The extinction of the UV and IR selected samples agree with each other.

The average extinction trend as a function of L_{SF}: *AKARI* result



$$\log\left(\frac{L_{TIR}}{L_{FUV}}\right) = 0.64 \log L_{SF} - 5.5$$

A similar trend was found by *AKARI* for the dust extinction of galaxies.

3. To Go Further: Galaxy Selection by FIR Colors

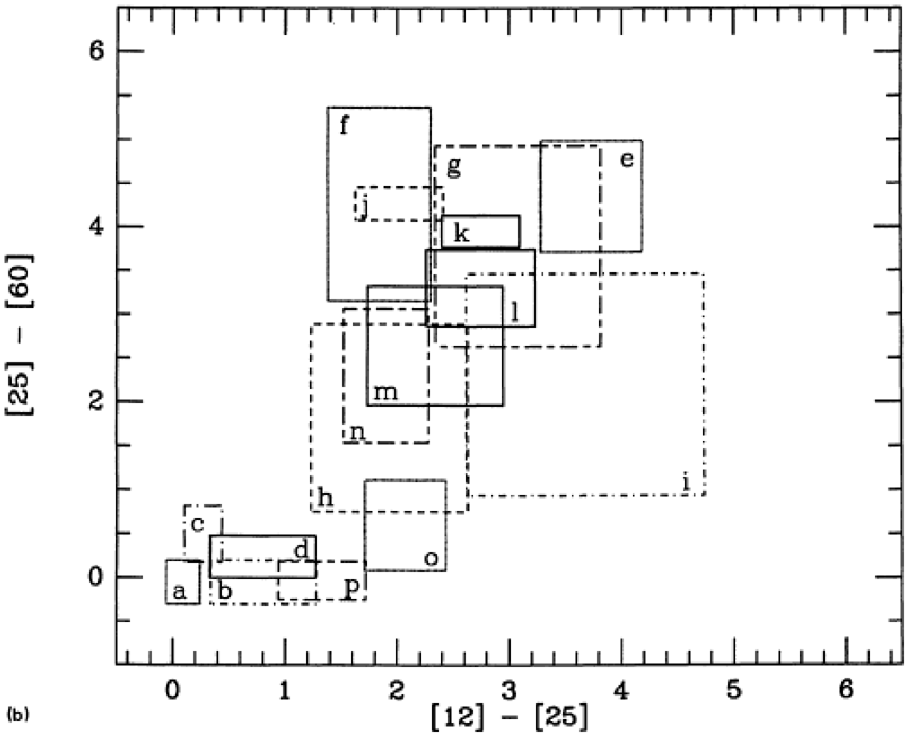
3.1 Need for Star-Galaxy Separation

As we have seen, a study with all-sky surveys is a very efficient way of exploring the general properties of galaxies. However, we had to select *confirmed* galaxies (in our case, by *IRAS* PSC*z*).

In general, when we start a systematic statistical studies on galaxies, especially when we try to measure their redshifts, we have to select good galaxy candidates; otherwise we waste observation time.

Hence, in the case of pure FIR surveys, a systematic method to extract reliable galaxy candidates is desired.

3.2 Preceding Study from *IRAS*



Source type	[12] − [25] mean	σ	#	[25] − [60] mean	σ	#	[60] − [100] mean	σ	#	Code[a]
Bright stars	0.09	±0.11	(1022)	−0.05	±0.18	(3142)	0.05	±0.29	(509)	a
O-rich stars	0.81	±0.34	(2679)	−0.05	±0.18		0.05	±0.29		b
Optical C-rich	0.27	±0.12	(308)	0.50	±0.23	(270)	0.40	±0.44	(79)	c
LRS C-rich	0.80	±0.34	(282)	0.24	±0.17	(306)	−0.18	±0.20	(52)	d
HII regions	3.73	±0.32	(42)	4.35	±0.46	(60)	1.72	±0.42	(49)	e
Blue reflection nebulae	1.84	±0.33	(31)	4.26	±0.80	(22)	2.19	±0.44	(6)	f
Red reflection nebulae	3.08	±0.53	(35)	3.78	±0.83	(27)	1.56	±0.37	(17)	g
Blue planetary nebulae	1.93	±0.50	(41)	1.82	±0.77	(41)	1.17	±1.0:	(17)	h
Red planetary nebulae	3.68	±0.76	(159)	2.20	±0.91	(170)	0.27	±0.31	(102)	i
Blue galaxies	2.02	±0.28	(179)	4.27	±0.14	(179)	1.81	±0.30	(343)	j
Red galaxies	2.75	±0.25	(95)	3.95	±0.13	(95)	1.81	±0.30		k
Seyferts	2.75	±0.35		3.30	±0.32		1.6	±0.6:		l
Quasars	2.34	±0.44	(49)	2.64	±0.49	(56)	1.56	±0.39	(37)	m
T Tau stars	1.90	±0.27	(43)	2.30	±0.55	(46)	1.50	±0.59	(16)	n
LRS=3	2.07	±0.26	(127)	0.60	±0.37	(140)	−0.23	±0.23	(21)	o
LRS=6	1.33	±0.28	(49)	−0.03	±0.16	(40)	0.24	±1.0:	(14)	p
HHES	2.99	±0.72	(26)	3.11	±0.84	(29)	1.73	±0.77	(28)	…
Bipolar nebulae	2.54	±0.82	(20)	2.84	±1.19	(21)	1.08	±0.78	(19)	…

[a] "Code" designates the letter by which the occupation zones for each type of source are identified in Figs. 1(b) and 2(b).

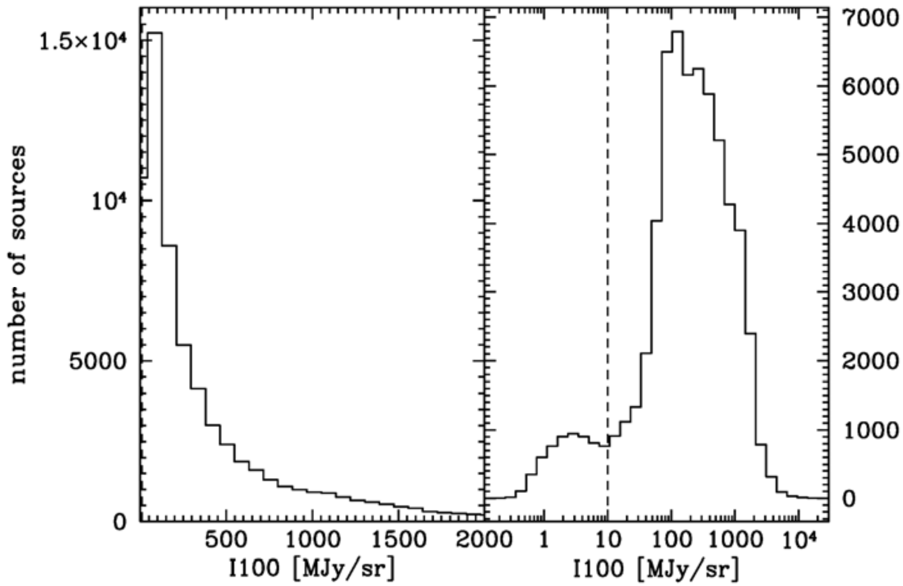
(Walker et al. 1989)

With *IRAS* four bands, a very detailed classification was possible. However, for *AKARI* FIS ASS, we must rely only on FIR bands, and this cannot be a trivial application of *IRAS* methodology.

3.3 Star-Galaxy Separation by FIS Color-Color Diagrams

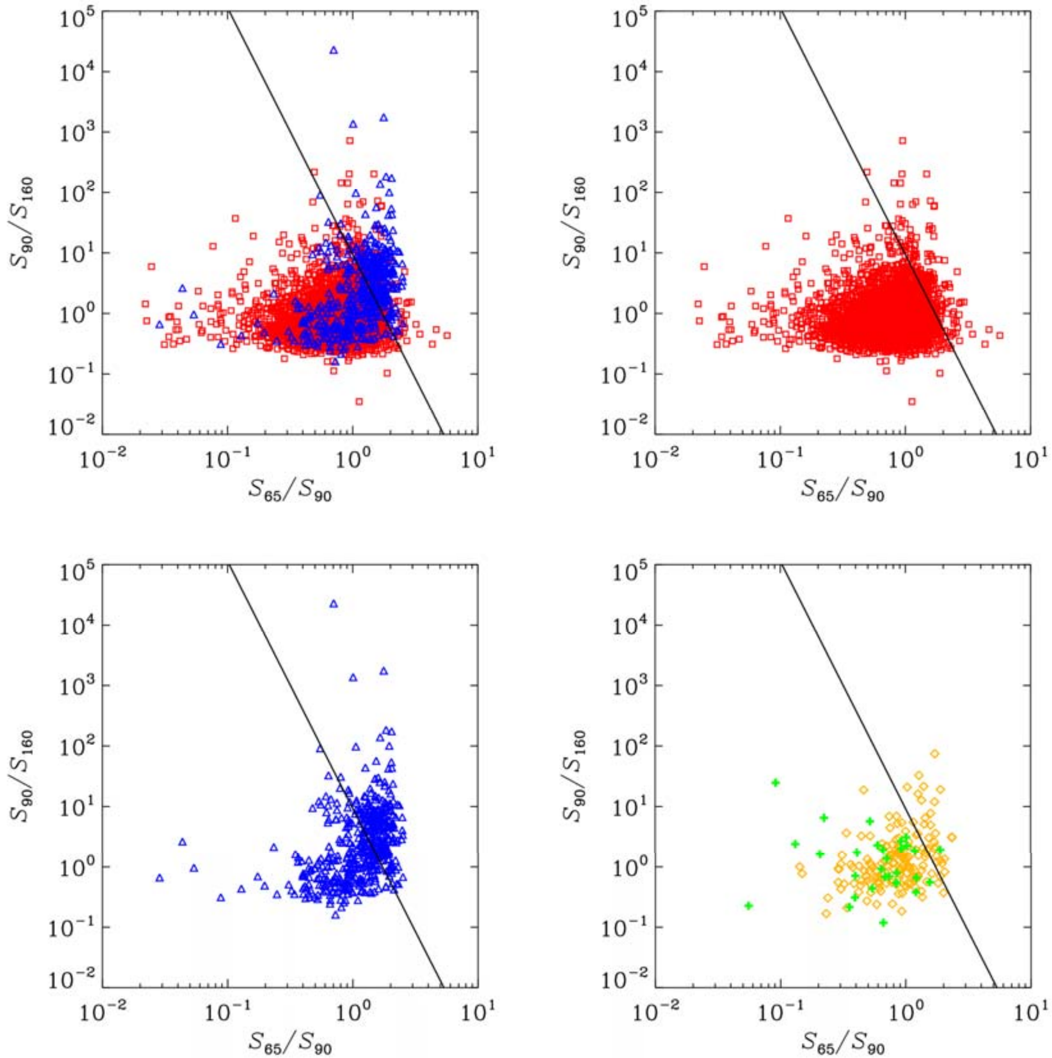
Data

1. **We selected *WIDE-S* sources in a low-cirrus region (I100 < 10 MJy sr^{-1}) on the sky to avoid contamination in FIR flux (~ 5000 objects).**



2. **The sample was matched with SIMBAD and NED (astronomical database for stars, nebulae, and galaxies).**

Color-color diagram (an example)



Red: galaxies

Blue: stars

Yellow: other Galactic objects

Green: unidentified

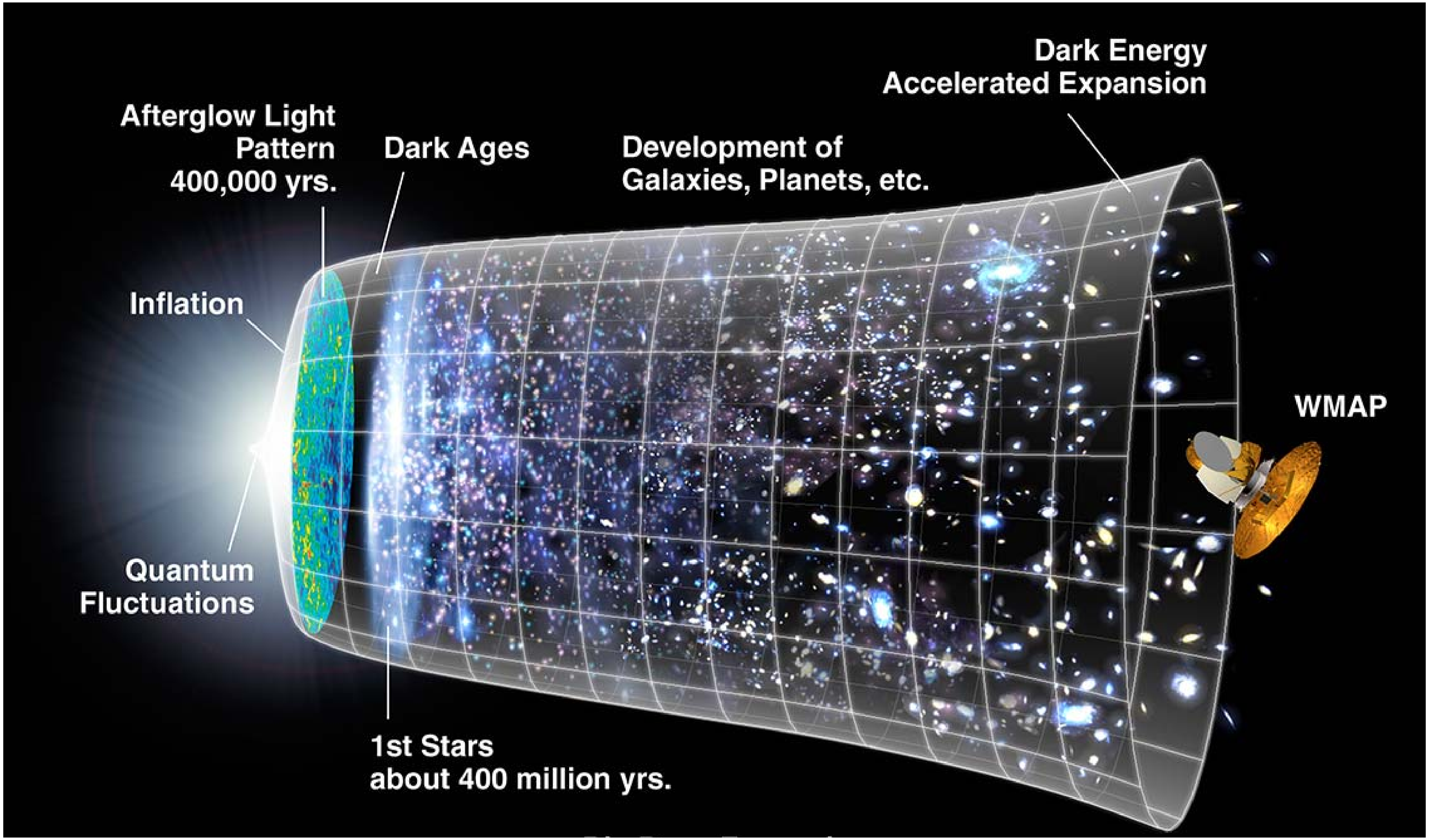
We found that we can define a separation line on the FIS color-color plot to select > 97% of galaxies (Pollo et al. A&A submitted).

4. Summary

1. **We have constructed a sample of local galaxies selected by *AKARI* WIDE-S by matching *IRAS* PSC*z* galaxies, and associated fluxes from UV to FIR (*GALEX*, SDSS, 2MASS).**
2. **By this sample, we constructed average SEDs of galaxies as a function of L_{90}.**
3. **We have established a new formula to estimate total IR (dust) emission and hidden SFR from three *AKARI* FIS bands (*N60*, *WIDE-S*, and *WIDE-L*).**
4. **Based on the formula, we found that hidden star formation dominates the star formation activity of most of the FIS selected local galaxies.**
5. **We also established a method to select galaxy candidates only from FIS color-color diagrams, with > 97% completeness.**

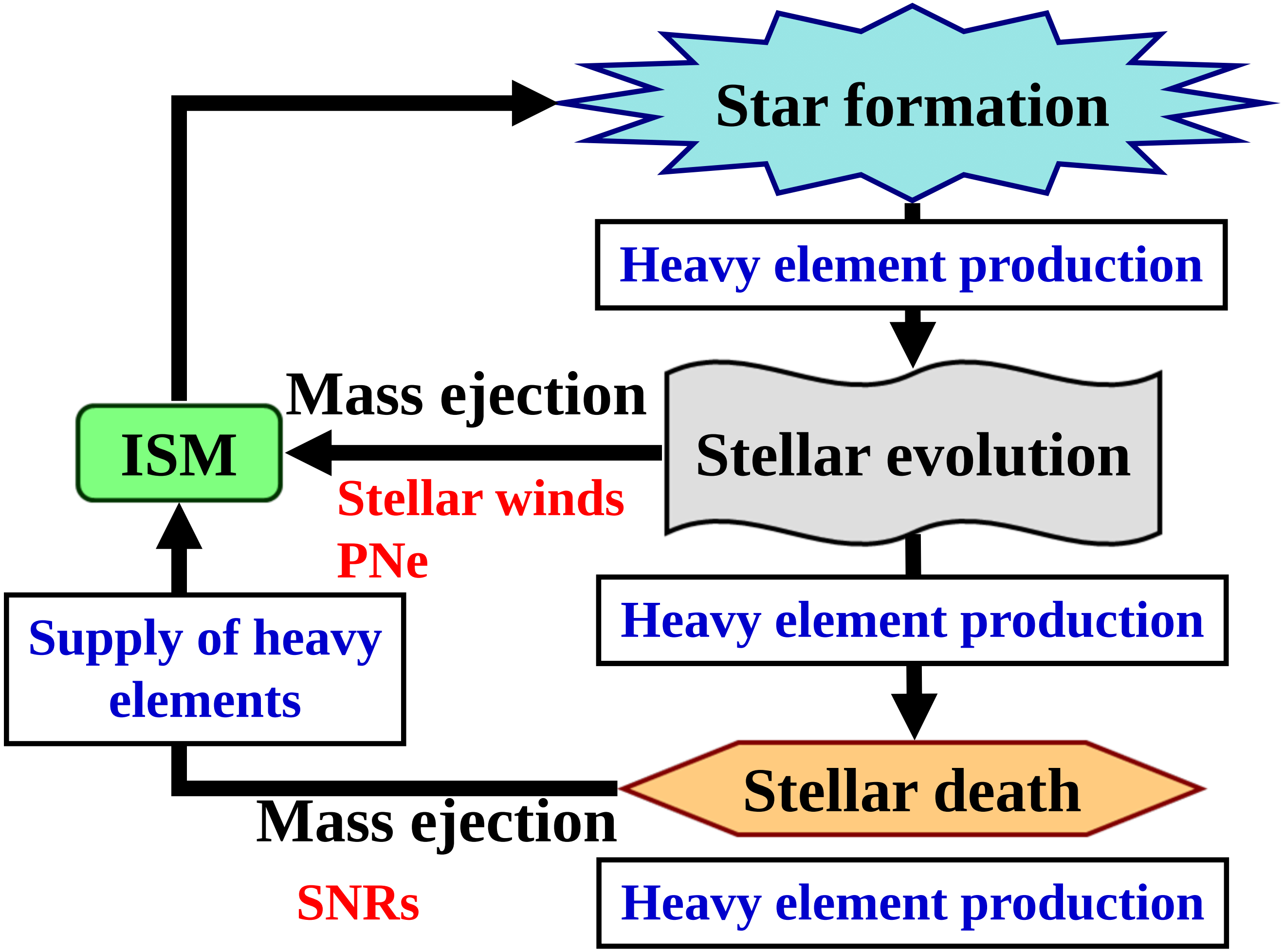
0. Introduction: the Evolution of the Universe

0.1 The Global History of the Universe



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

0.2 Chemical evolution of galaxies



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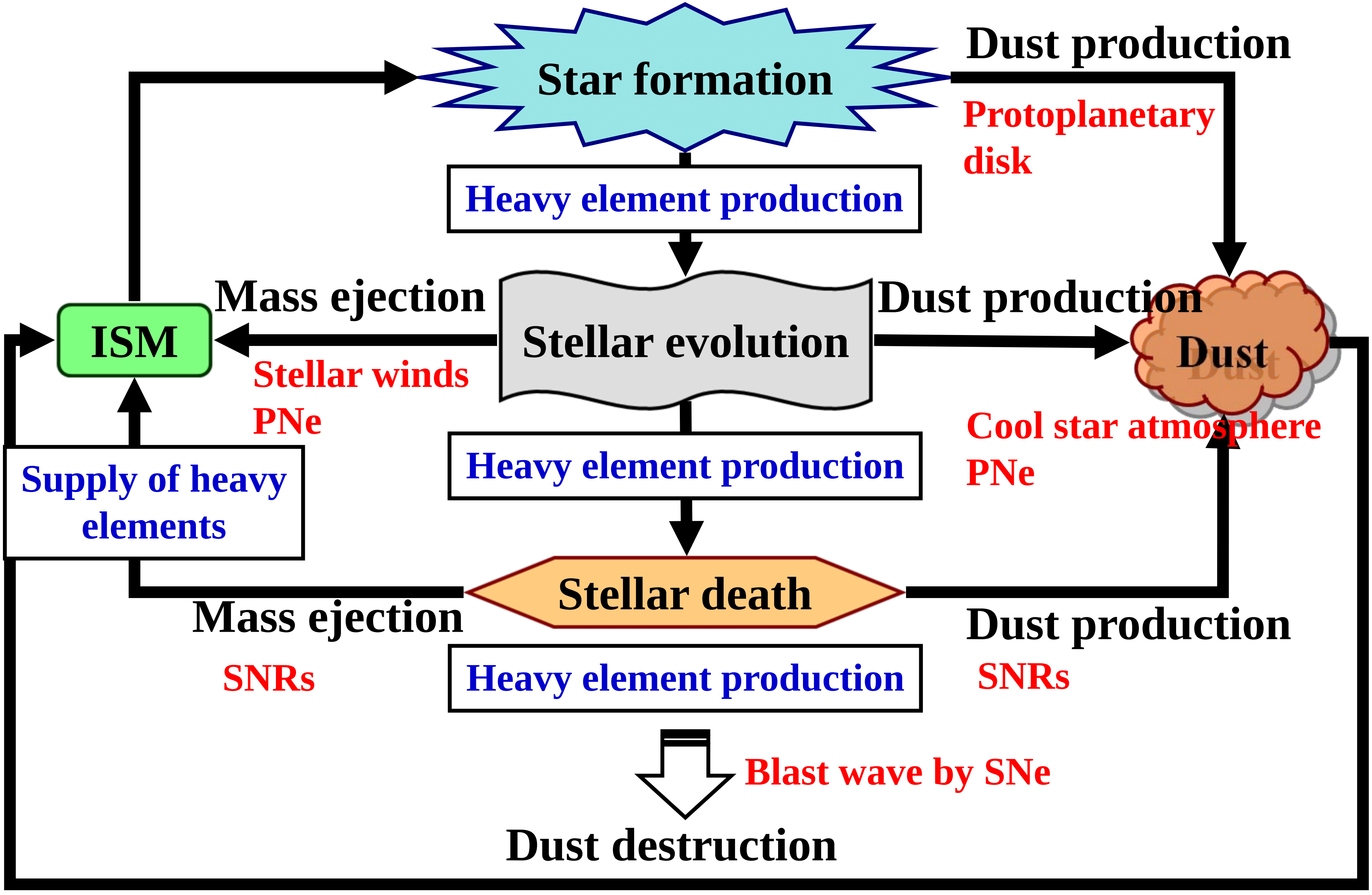
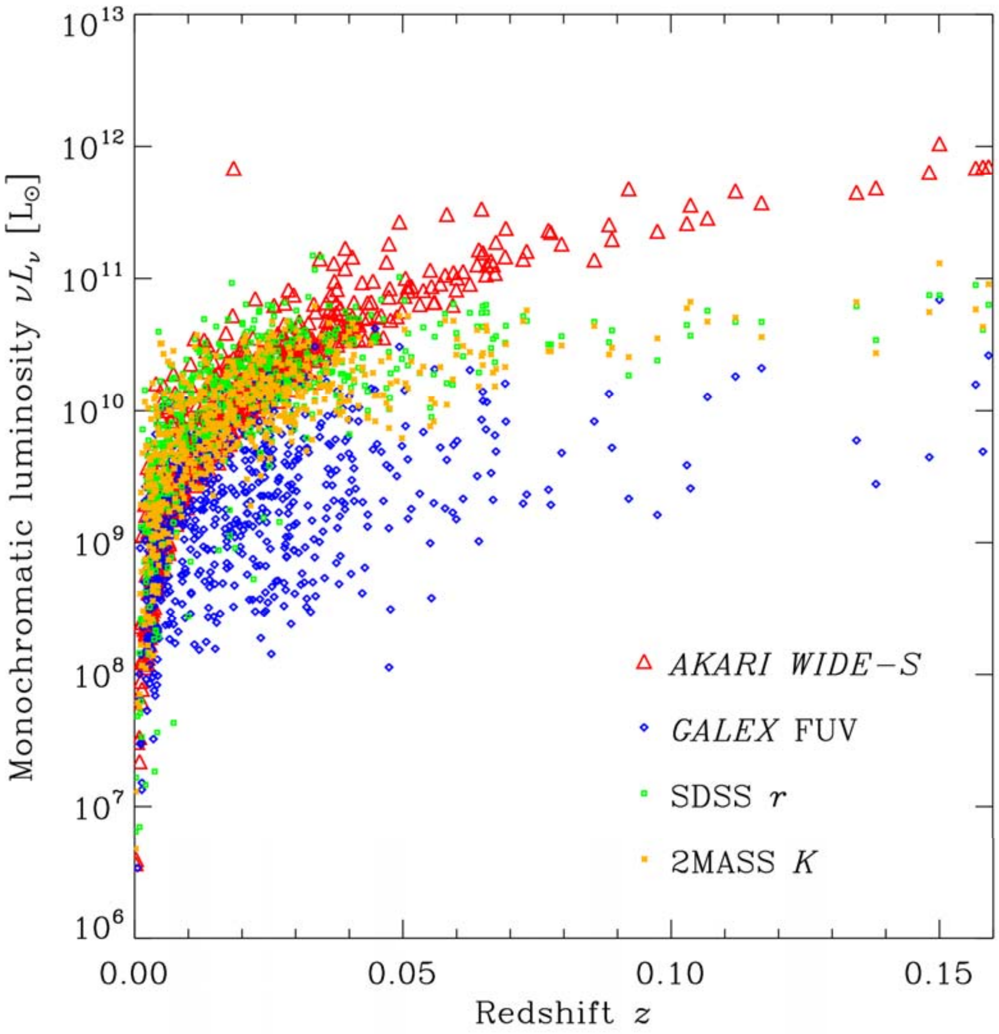
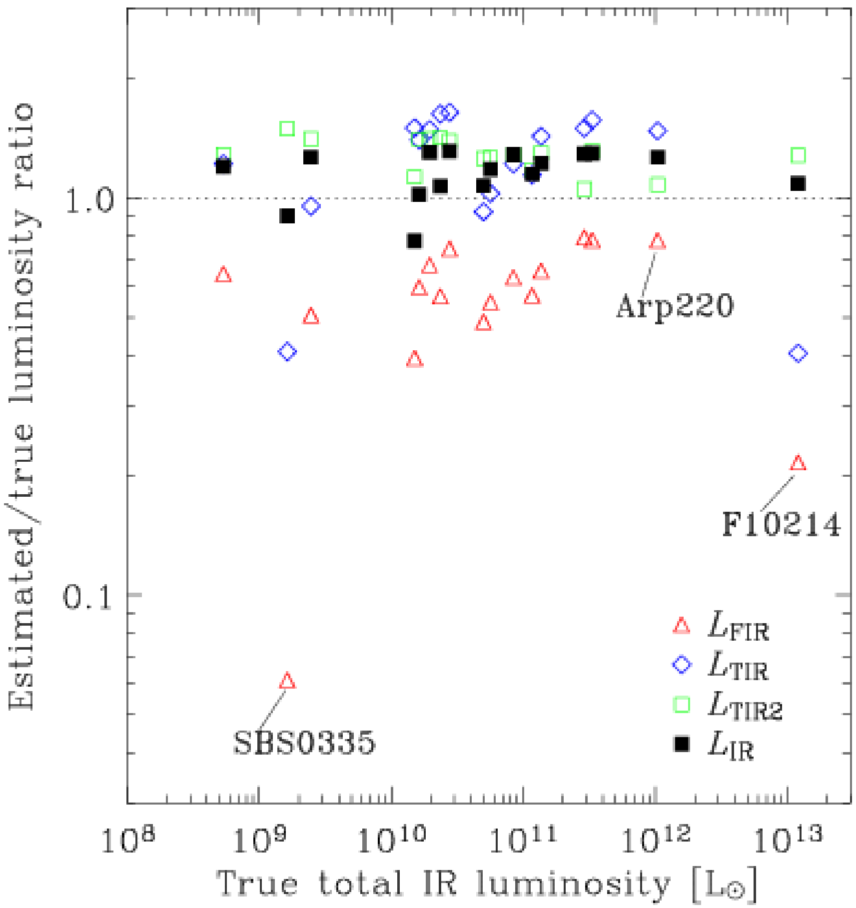


Luminosity with redshifts



FIR luminosity goes up continuously, while optical/NIR saturates (reflection of their luminosity functions). UV has large scatter.

Comparison between observed and estimated IR luminosities



(Takeuchi et al. 2005b)

The difference between L_{FIR} and true L_{IR} is important in relation to cold dust.

Relation between FUV-TIR luminosity ratio and A_{FUV}

It is known that the extinction in galaxies is expressed as a nonlinear function of the flux ratio between FIR and FUV:

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

(Buat et al. 2005)

Hence, we can see how the extinction depends on galaxy properties through the FIR/FUV luminosity ratio.

Acknowledgement

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