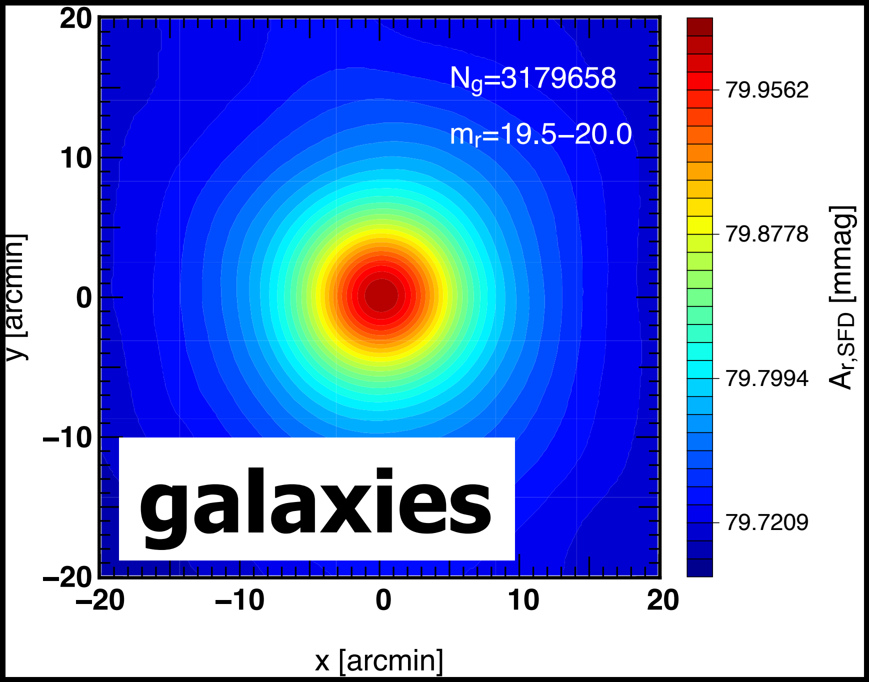
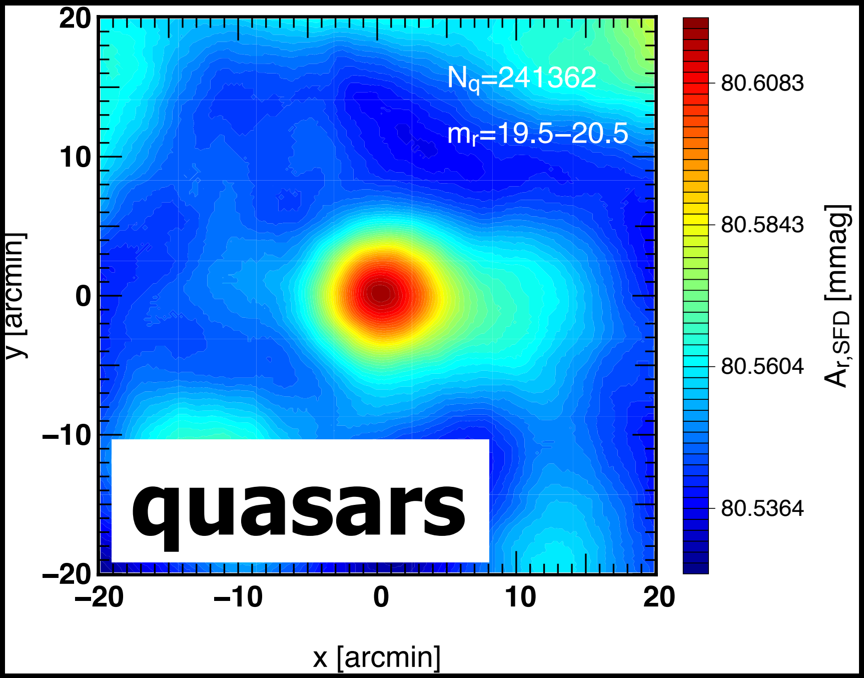
Far-Infrared Emission from Galaxies and Quasars in the Galactic Extinction Map by Stacking Analysis





Yasushi Suto *Department of Physics, The University of Tokyo*
& Global scholar, Dept. of Astrophysical Sci., Princeton University

12:00-13:00 September 30, 2013

Cosmology lunch talk@dome room, Peyton Hall

This talk is based on

- *Detection of Far Infrared Emission from Galaxies and Quasars in the Galactic Extinction Map by Stacking Analysis*
  - **T.Kashiwagi,** K.Yahata & YS
  - Publ.Astron.Soc.Japan 65 (2013)43
- *The effect of FIR emission from SDSS galaxies on the SFD Galactic extinction map*
  - K.Yahata, A.Yonehara, YS, E.L.Turner, T.Broadhurst, & D.P. Finkbeiner
  - Publ.Astron.Soc.Japan 59(2007)205

Top cited refereed astronomy papers published in 1900-2013 (ADS): 1st-5th

	authors	citation	title
1	Schlegel, Finkbeiner & Davis (1998)	8223	Maps of Dust Infrared Emission for Use in Estimation of Reddening and Cosmic Microwave Background Radiation Foregrounds
2	Perdew & Zunger (1981)	7330	Self-interaction correction to density-functional approximations for many-electron systems
3	Perlmutter et al. (1999)	7322	Measurements of Omega and Lambda from 42 High-Redshift Supernovae
4	Spergel et al. (2003)	7278	First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters
5	Riess et al. (1998)	7208	Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant

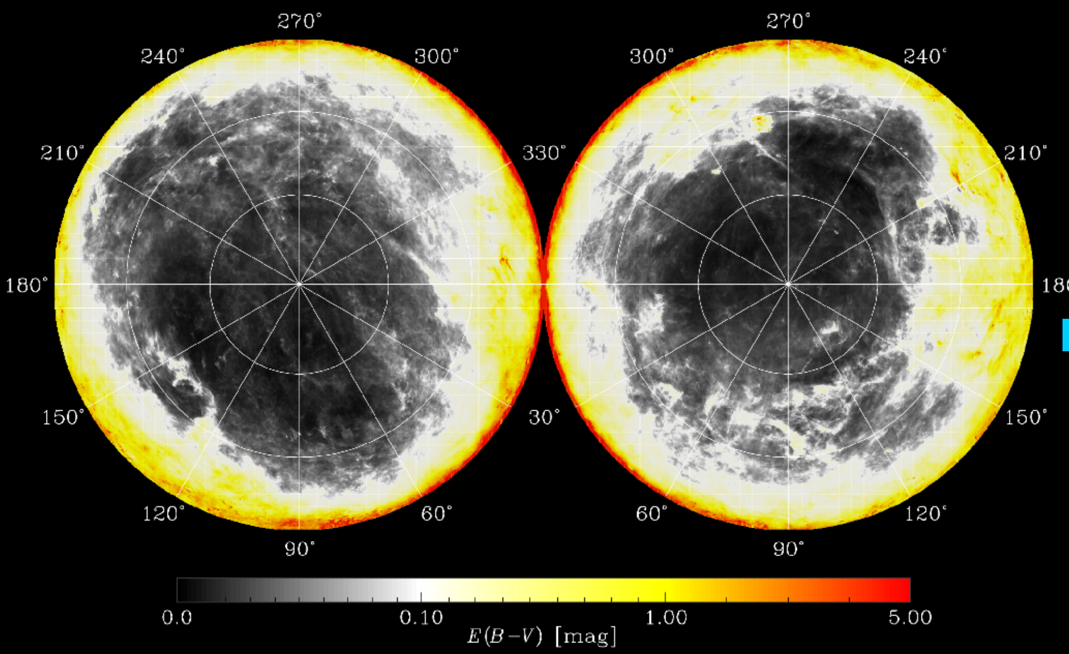
Top cited papers: 6th-12th

	paper	citation	title
6	Shakura & Sunyaev (1973)	6135	Black holes in binary systems. Observational appearance
7	Anders & Grevesse (1989)	5626	Abundances of the elements - Meteoritic and solar
8	Spergel et al. (2007)	5538	Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology
9	Randall & Sundrum (1999)	5019	Large Mass Hierarchy from a Small Extra Dimension
10	Cardelli, Clayton & Mathis (1989)	4976	The relationship between infrared, optical, and ultraviolet extinction
11	Guth (1981)	4427	Inflationary universe: A possible solution to the horizon and flatness problems
12	Navarro, Frenk & White (1997)	4266	A Universal Density Profile from Hierarchical Clustering

Testing reliability of SFD map on the basis of SDSS galaxy number counts

- K.Yahata, A.Yonehara, YS, E.L.Turner, T.Broadhurst, & D.P. Finkbeiner
  Publ.Astron.Soc.Japan 59(2007)205
- T.Kashiwagi
  Master thesis (2011) submitted to U.Tokyo

SFD Galactic extinction map



Galactic extinction E(B-V) map (Schlegel, Finkbeiner & Davis 1998; SFD)

- The most fundamental dataset for all astronomical observations
- True large-scale structures revealed only after the extinction correction
- Its reliability is of vital importance in precision cosmology

SFD procedure to construct the Galactic extinction map

- COBE 100 μm+240 μm maps (0.7deg.pixel)
  - Remove zodiacal light and cosmic infrared background
  - Dust temperature map ⇒ temperature-dependent emissivity corrected 100 μm map
- Calibration of higher angular-resolution IRAS 100 μm map (5 arcmin. pixel)
- Assume

  $$E(B\text{-}V)=pI_{100\mu m}X(T)$$

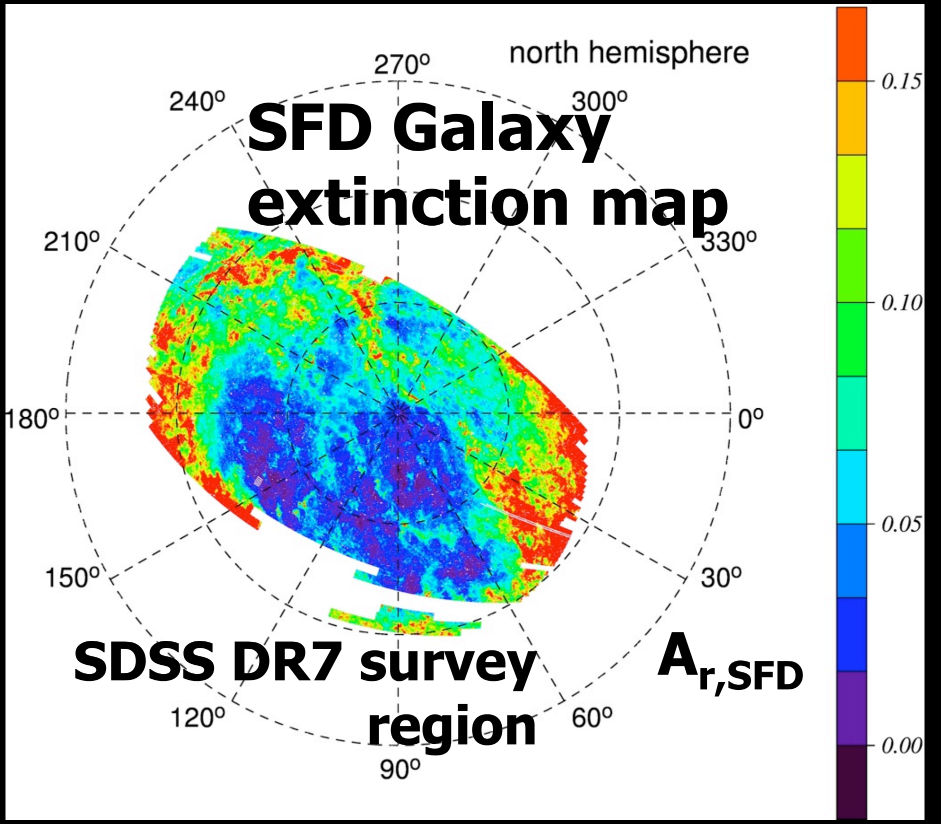
  dust temperature correction factor

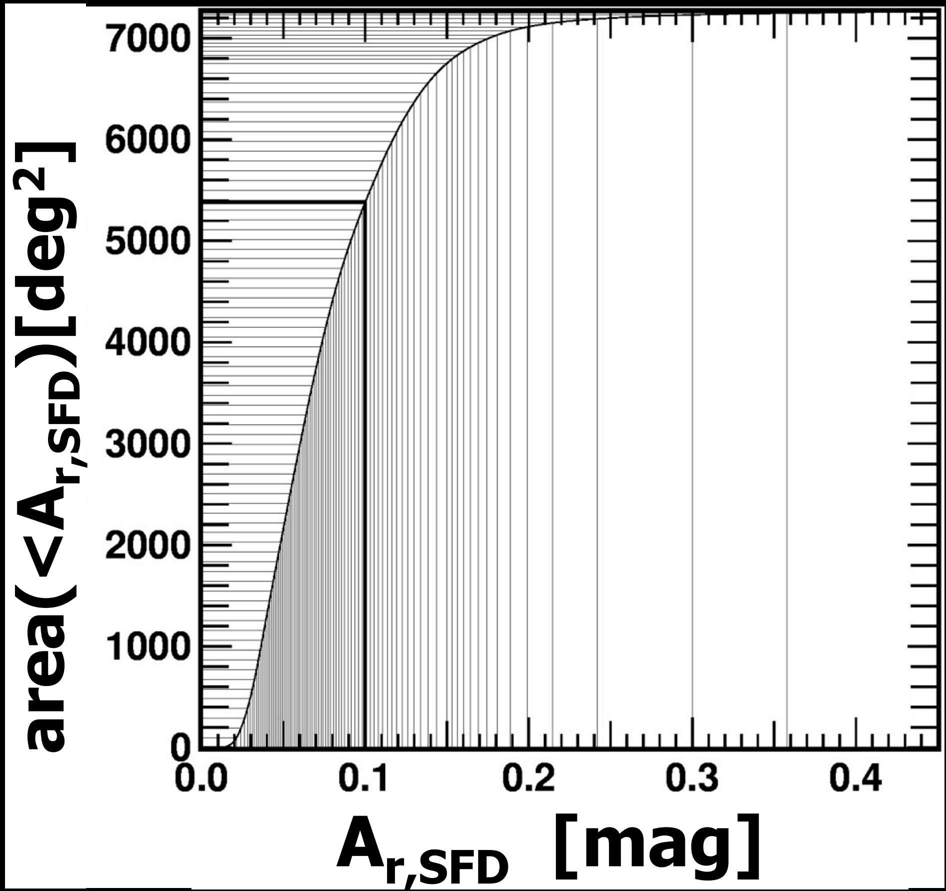
at each region and determine p～0.0184 from the data

- Convert E(B-V) to A_{band} adopting $R_V=A_V/E(B\text{-}V)=3.1$

A_{SFD} map in SDSS DR7 survey region

3.6×10^6 galaxies ($17.5<r<19.4$) in 7270 deg^2 from SDSS DR7 photometric catalog

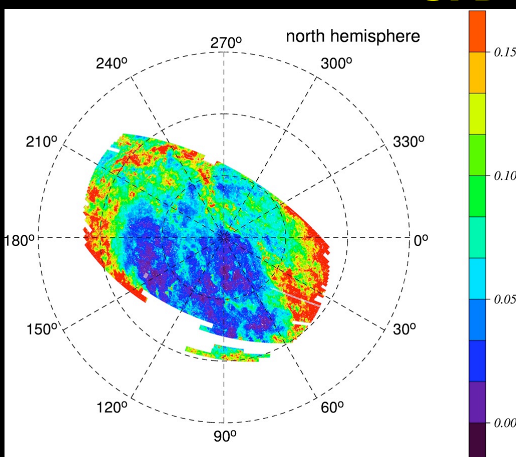


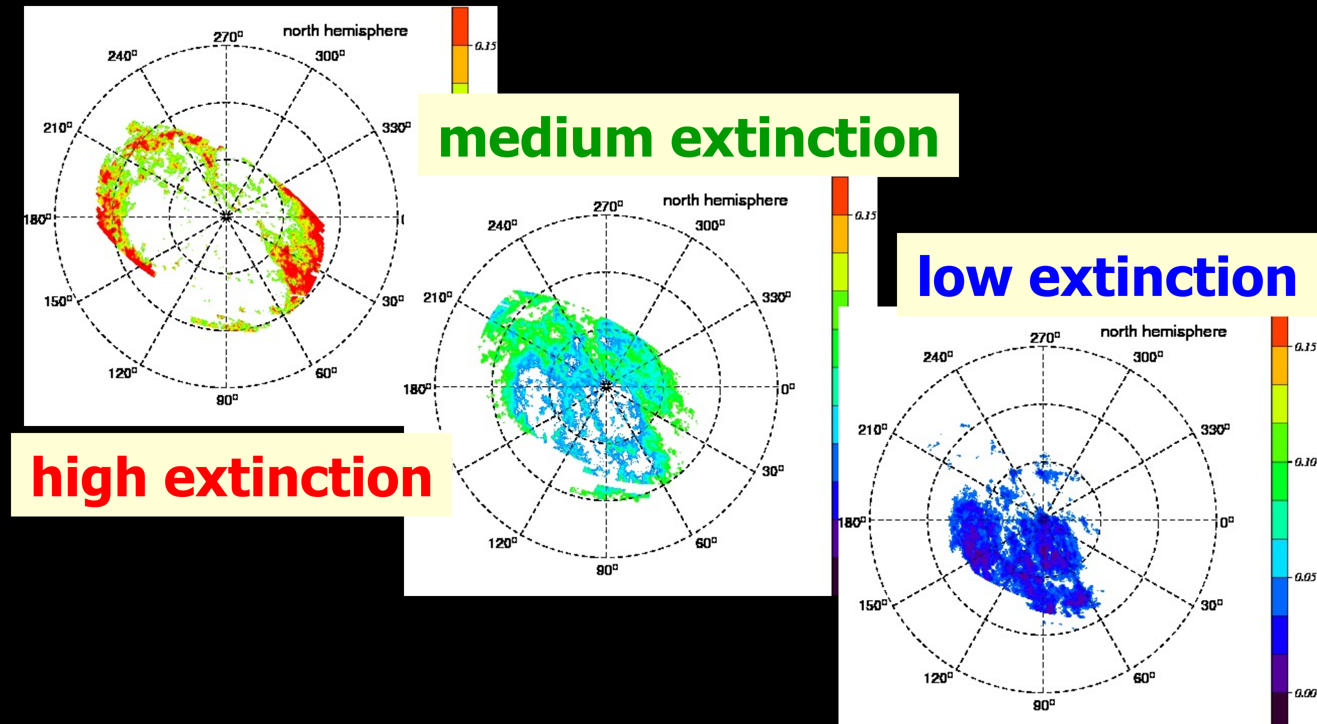


Kashiwagi (2011), Yahata et al.(2007)

Estimating Galactic extinction from SDSS galaxy surface density

SDSS DR7 survey area (color coded according to A_{SFD})

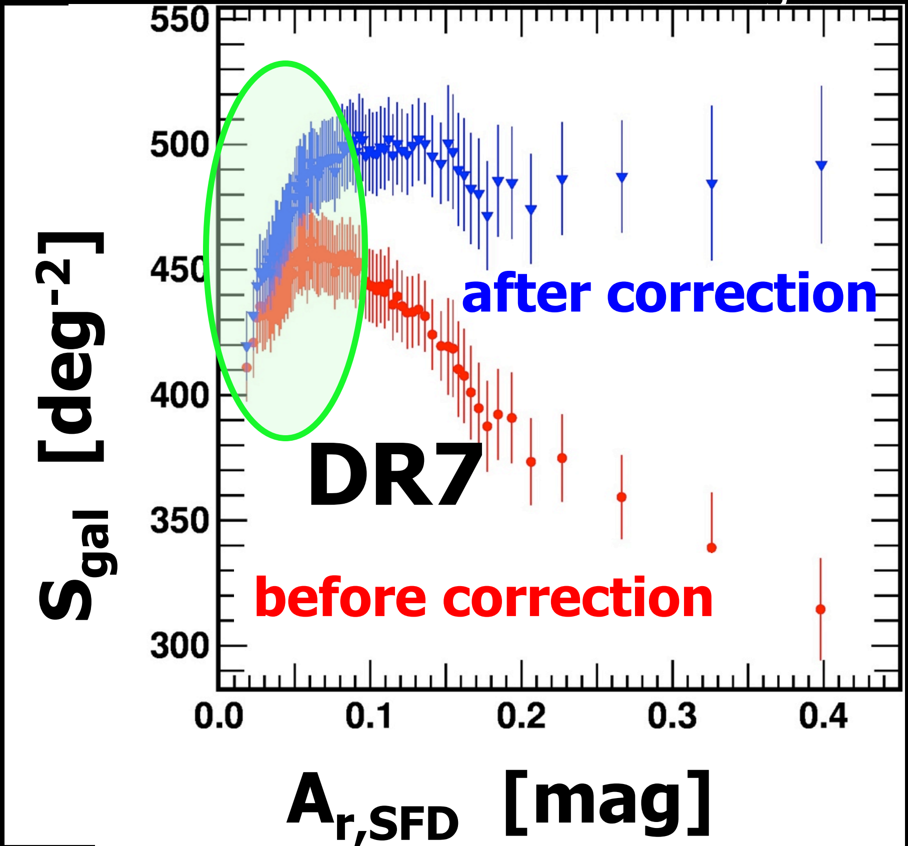




- divide the SDSS DR7 survey area into many small regions according to A_{SFD}
- combine those non-contiguous regions into 84 bins for A_{SFD} with $\sim$100 deg^2 each
- compute the SDSS galaxy number density S_{gal} for those bins

Anomalous behavior of SDSS galaxy surface density S_{gal} as a function of A_{SFD}

- ***If A_{SFD} is perfect, we expect that***
  - Before correction: S_{gal} should monotonically decrease as a function of A_{SFD}
  - After correction: S_{gal} should be constant



(cosmological principle!)

- OK for A_{SFD} >0.1, but *quite the opposite for A_{SFD} <0.1*
  - ~70% of the SDSS survey area has A_{SFD} <0.1 !
- First pointed out by Yahata et al. (2007) for DR4, and confirmed by Kashiwagi (2011) for DR7

Origin of the anomaly

- A_{SFD} is estimated assuming that the reddening is proportional to the FIR emission flux (100 μ m)
  - the anomaly indicates the positive correlation between galaxy surface density and the FIR flux at least where the real extinction is small
- 100 μ m flux = Galactic dust + galaxies
  - contamination by the FIR emission from galaxies proposed by Yahata et al. (2007); indeed originally suggested by Ed Turner

Testing the hypothesis of galaxy FIR emission contamination to explain the anomaly of SFD map

- T.Kashiwagi
  Master thesis (2011) submitted to U.Tokyo
- T.Kashiwagi & YS
  in preparation

Mock simulations to test the FIR emission hypothesis

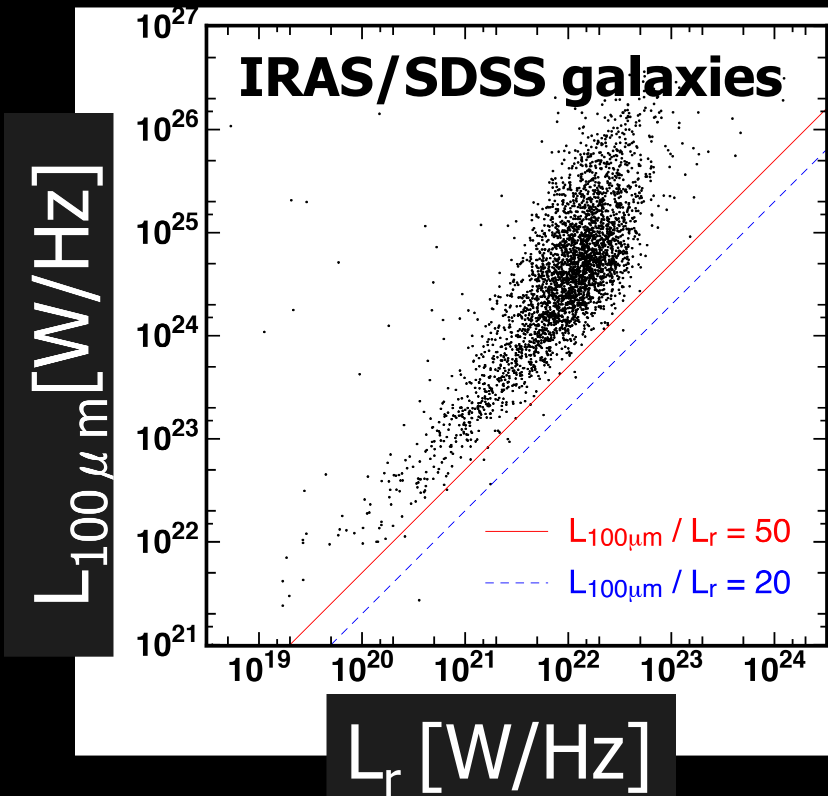
- Distribute random particles over the DR7 region
  - the same number and the same r-band magnitude distributions as SDSS galaxies
- Assign 100 μ m flux to each particle sampled from the log-normal distribution of $L_{100\mu m}/L_r$
- Add the 100 μ m flux to the original SFD map and compute the extinction

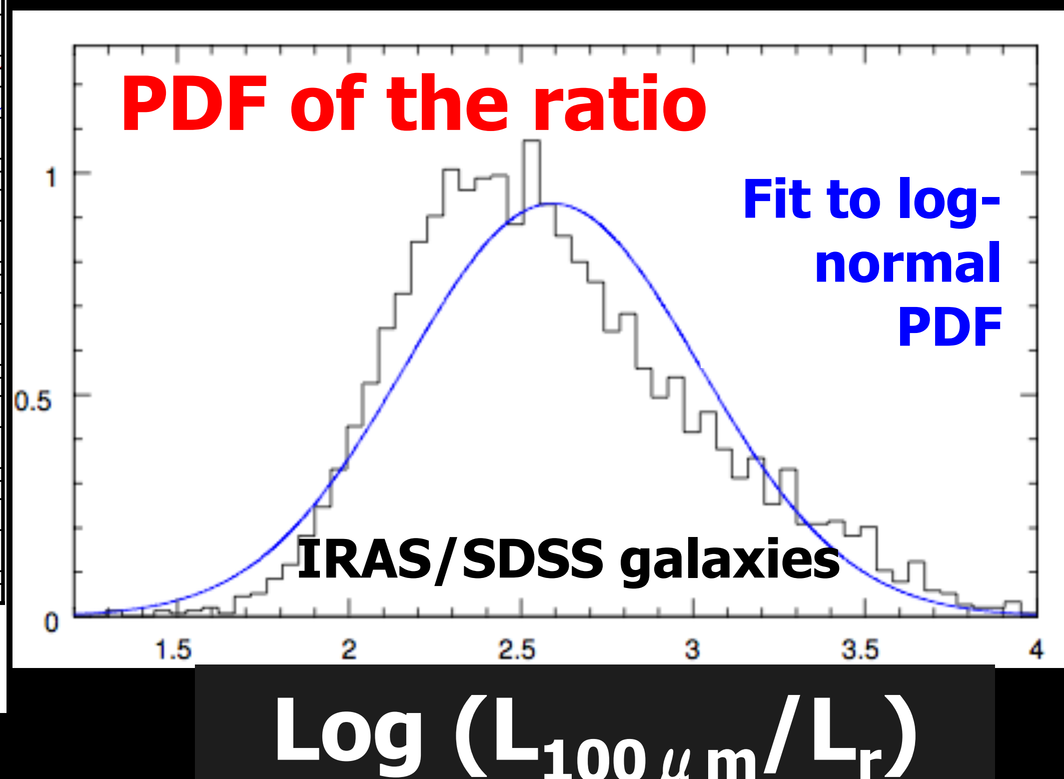
$$A_{SFD} \Rightarrow A_{SFD} + \Delta A_{mock}$$

  at each pixel (5' x5')
- Compute particle surface density as a function of $A_{SFD} + \Delta A_{mock}$ at each pixel

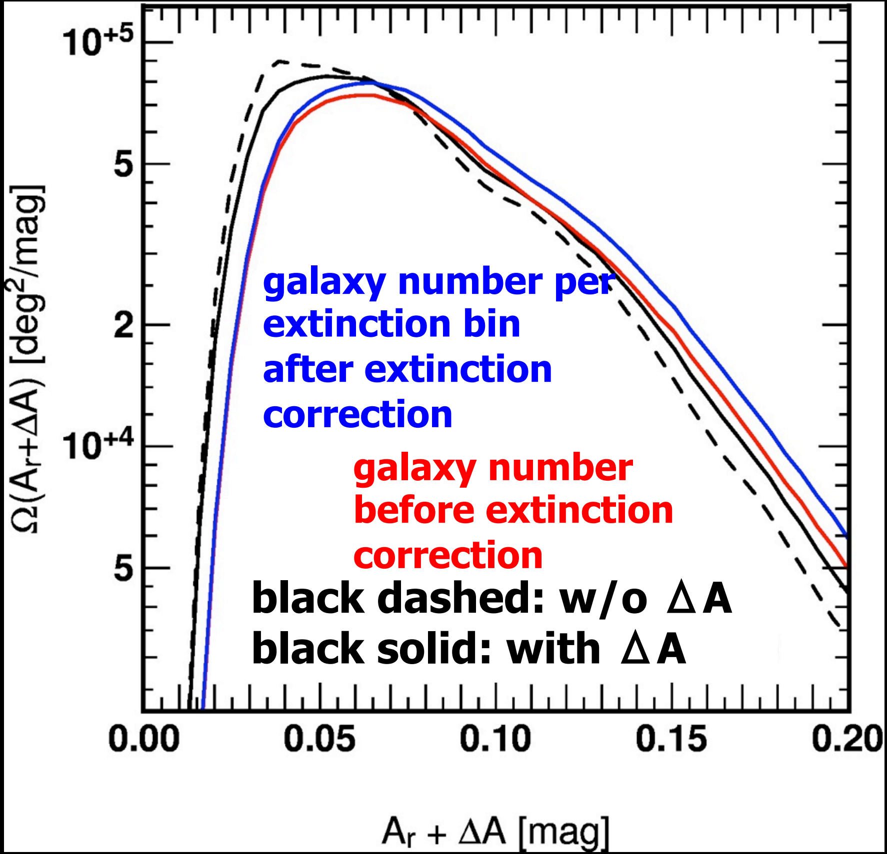
Observed correlation between $L_{100\mu m}$ and L_r

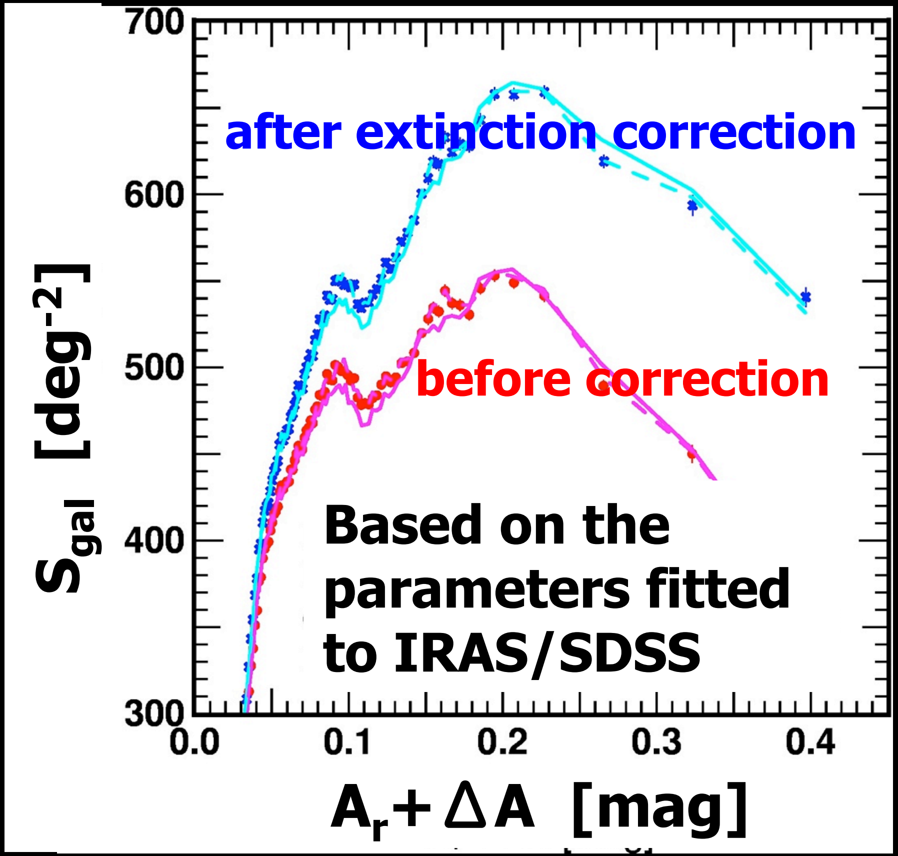
- Distribution function of galaxy luminosities in IRAS 100 μm vs. SDSS r-band for overlapped (bright) galaxies (～3700gals)
  - a biased sample for the entire SDSS galaxies





Mock simulation result





- the trend of the observed anomaly is reproduced, but too strong if the mean and standard deviation of the ratio $L_{100\mu m}/L_r$ of IRAS/SDSS are adopted

An analytic model for surface density

$P_1(\Delta A)$ PDF of extra extinction **ΔA** due to FIR flux of one galaxy

$$P_N(\Delta A) = \int_0^{\Delta A} dx\, P_1(x) P_{N-1}(\Delta A - x)$$

Conditional PDF that a pixel with N galaxies has the total extra extinction ΔA

$P(N|\bar{N})$ PDF of N galaxies per pixel given its expectation value $\bar{N}$ ⇒ Poisson assumed

Area and galaxy number after contamination

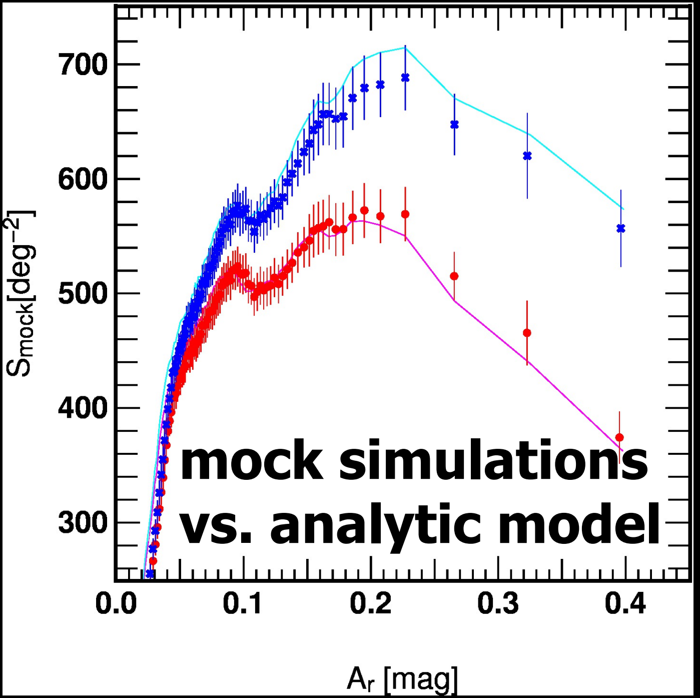
$$\Omega'(A) = \sum_{N=0}^{\infty} \int_0^A d(\Delta A)\, \Omega(A - \Delta A) P_N(\Delta A) P(N|\bar{N})$$

$$N'_{gal}(A) = \sum_{N=0}^{\infty} \int_0^A d(\Delta A)\, N \frac{\Omega(A-\Delta A)}{\Omega_{pixel}} P_N(\Delta A) P(N|\bar{N})$$

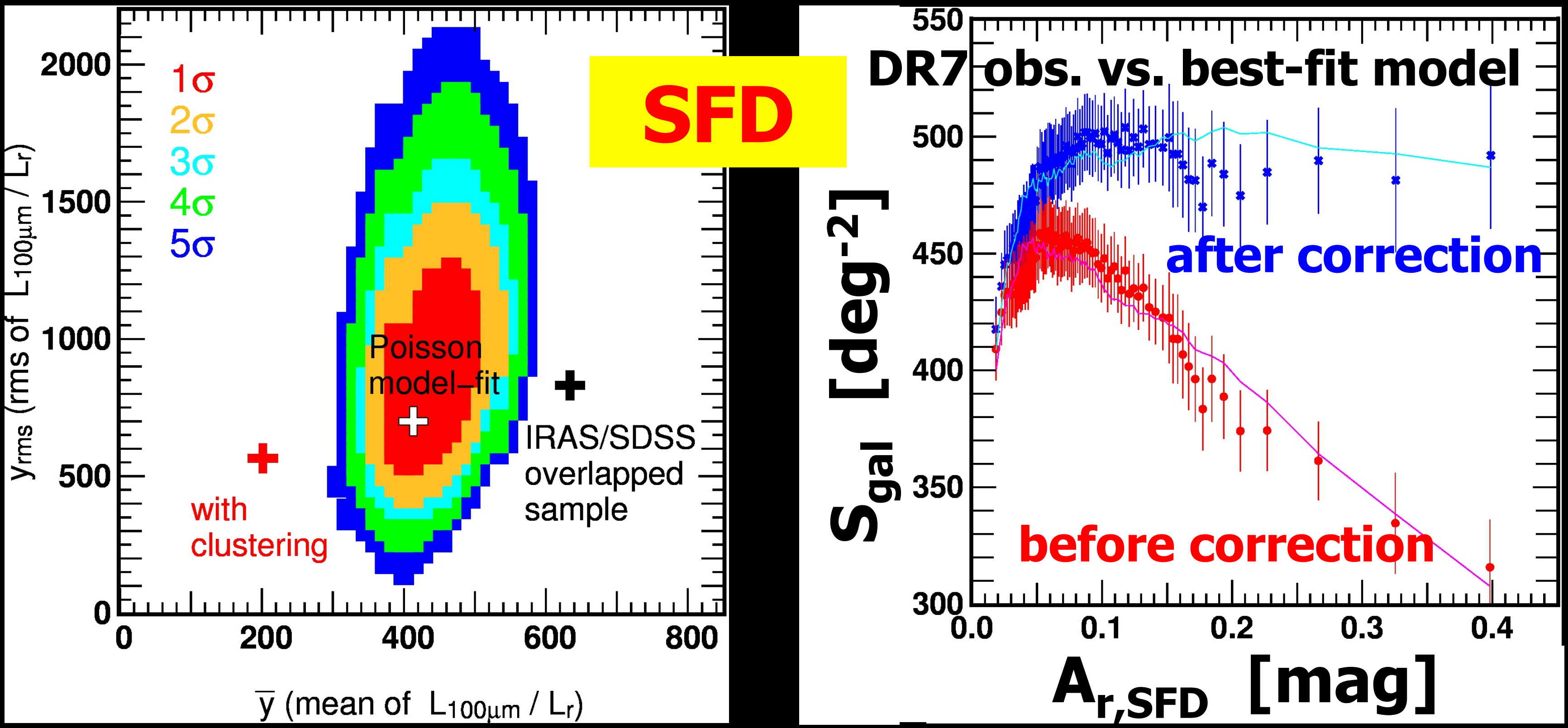
$\times 10^{\gamma(\Delta A - A)}$ without correction

$\times 10^{\gamma(\Delta A)}$ with correction

$$\Rightarrow S'_{gal}(A) = N'_{gal}(A) / \Omega'(A)$$

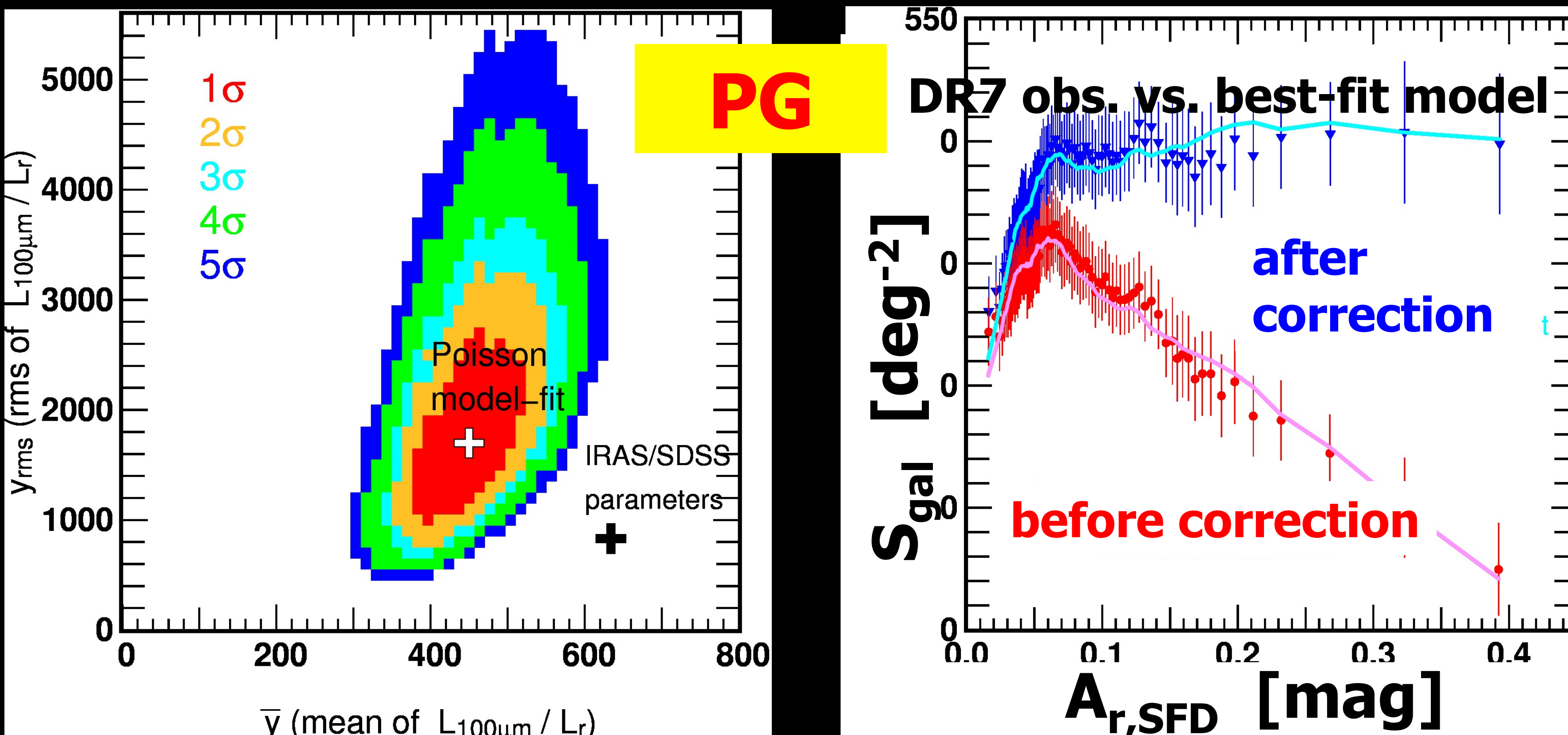


Fit to the observed anomaly using an analytic approximation model



- Observed trend is well reproduced by the model
  - (1/3-2/3) of the mean ratio $L_{100\mu m}/L_r$ of IRAS/SDSS overlapped sample (biased towards the higher value)

Fit to the observed anomaly using an analytic approximation model



- Corrected map by Peek & Graves (2010)
  - the anomaly still exists but agrees better with our model prediction than the original SFD map

Can we directly detect the FIR emission of galaxies ? - Stacking analysis of SDSS galaxies -

- T.Kashiwagi, K.Yahata & YS

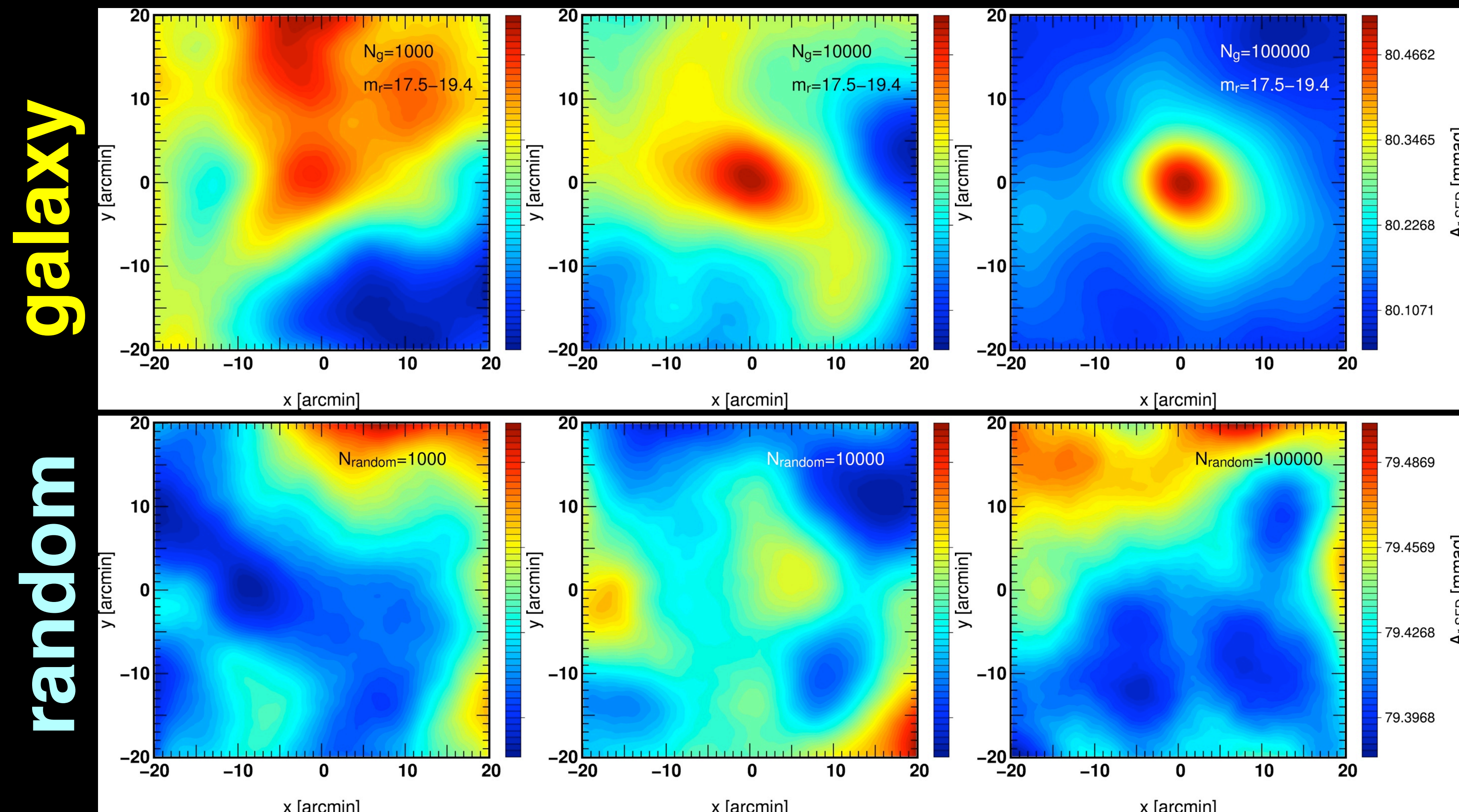
  Publ.Astron.Soc.Japan 65(2013)43

Direct detection of FIR emission of galaxies

- FIR emission of a majority of SDSS photometric galaxies is weak and cannot be detected individually.
- Can we detect their FIR emission statistically through stacking SDSS galaxies over the SFD map ? ⇒ *Yes !*

Kashiwagi, Yahata & YS
Publ.Astron.Soc.Japan 65 (2013)43

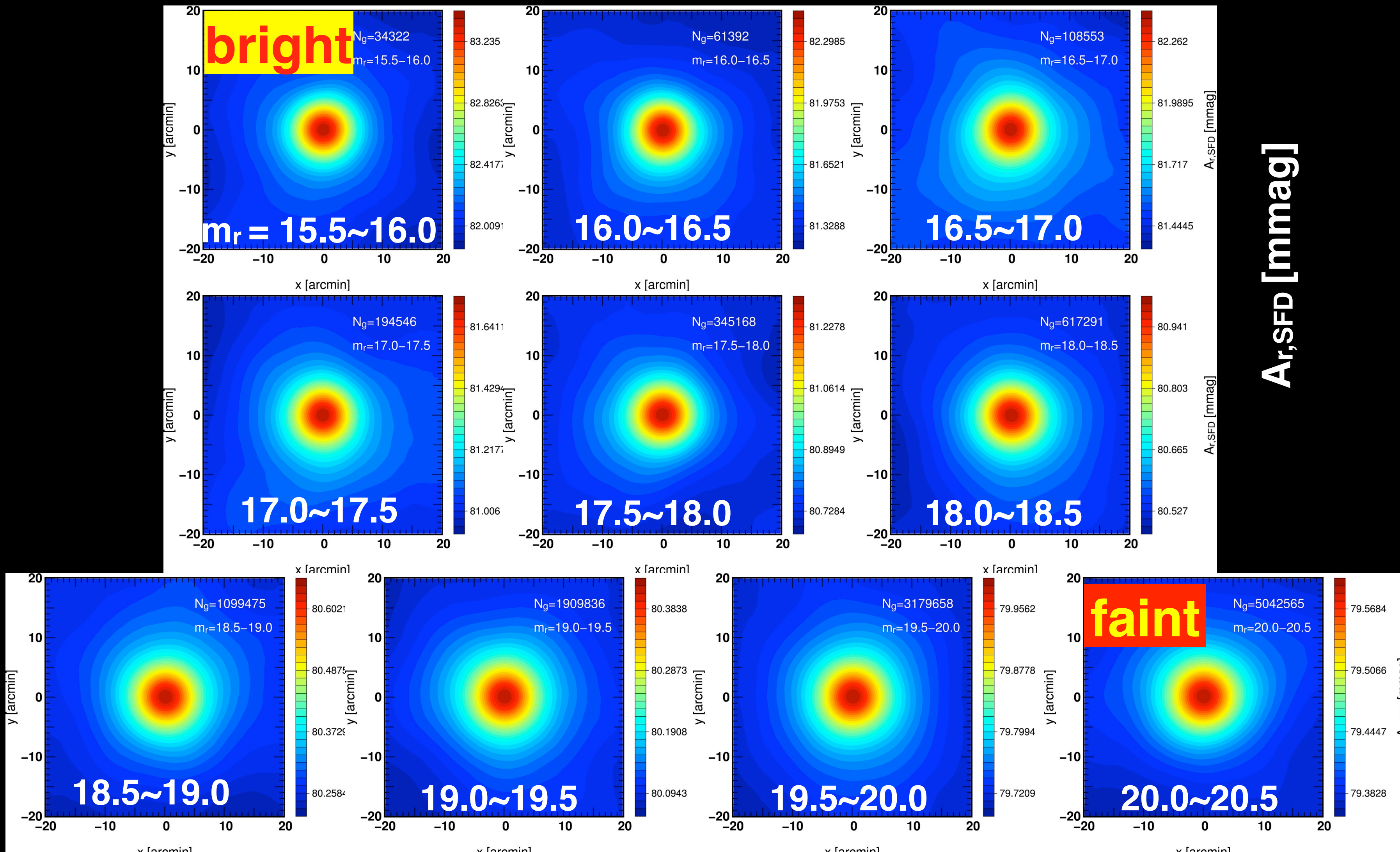
Stacking analysis of SDSS galaxies on the SFD map



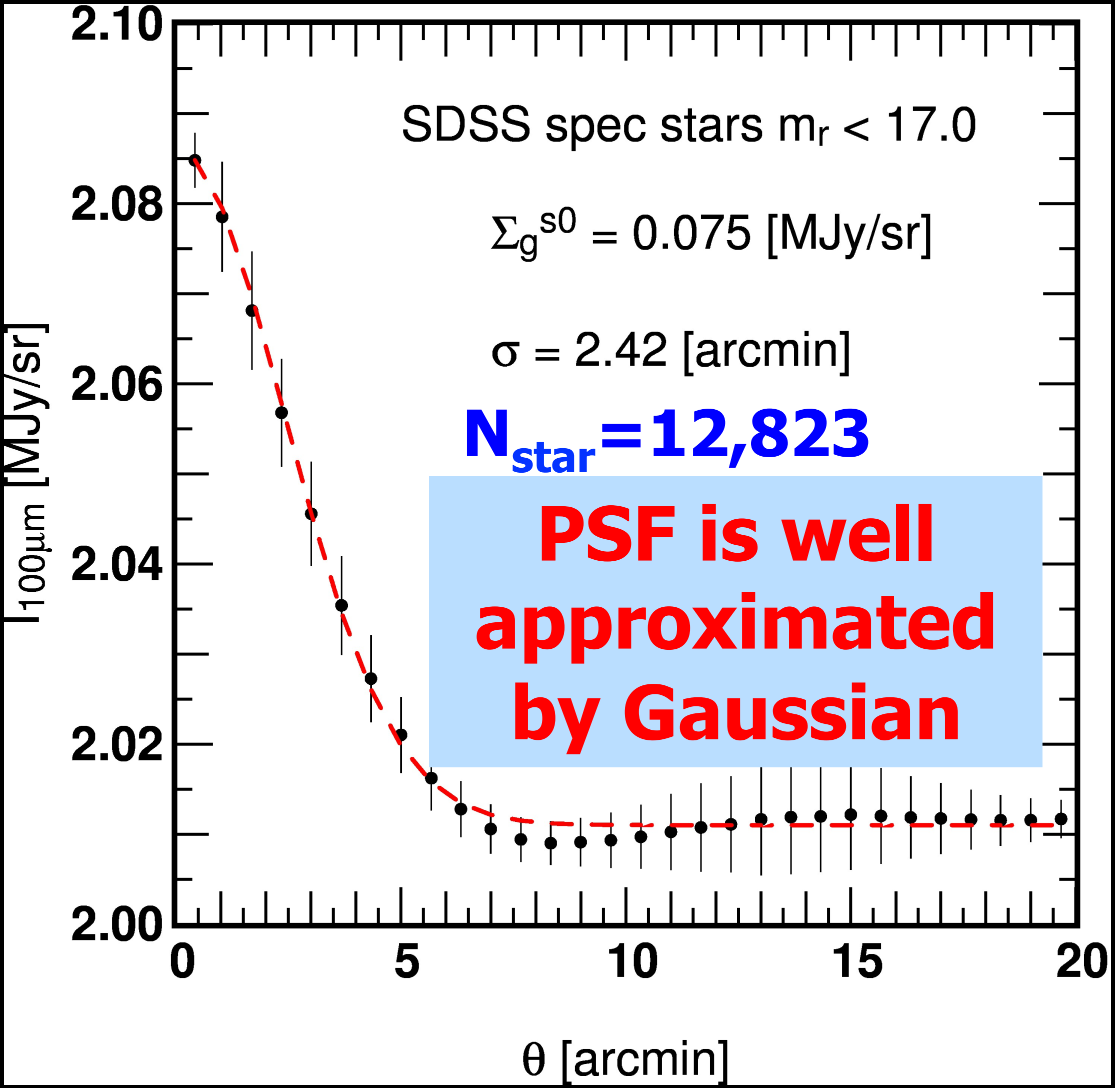
$N = 10^3$ $N = 10^4$ $N = 10^5$

Magnitude dependence

Stacking SDSS galaxies ($15.5 < m_r < 20.5$) over SFD map according to their r-band magnitude ($\Delta m_r = 0.5$)

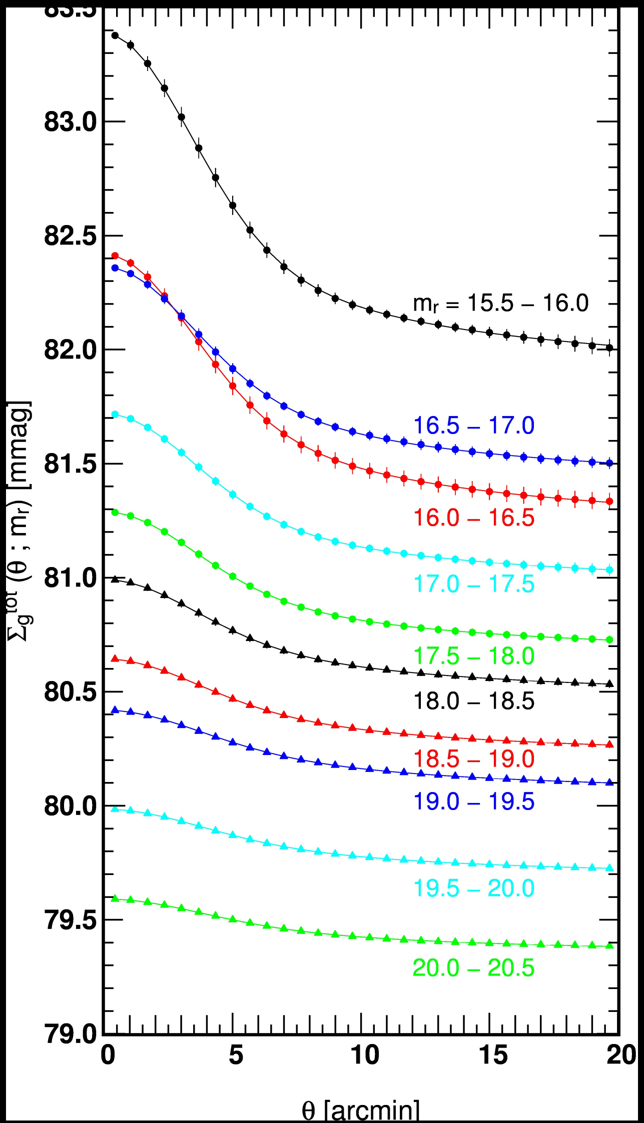


Point spread function of IRAS 100 μ m map



- Angular resolution of SFD (IRAS) is low, but we need to its PSF to understand the stacked profile
- PSF is difficult to measure on SFD map since most of point sources are removed
- We use the original IRAS 100 μ m diffuse map, and stack stars with r<17 mag.

Decompositions into single galaxy and clustering terms



$$\Sigma_{\rm g}^{\rm tot}(\theta;m_r) = \Sigma_{\rm g}^{\rm s}(\theta;m_r) + \Sigma_{\rm g}^{\rm c}(\theta;m_r) + C$$

$$\Sigma_{\rm g}^{\rm s}(\theta;m_r) = \Sigma_{\rm g}^{\rm s0}(m_r)\exp\left(-\frac{\theta^2}{2\sigma^2}\right)$$

$$\Sigma_{\rm g}^{\rm c}(\theta;m_r) = \iint dm'd\varphi\ \Sigma_{\rm g}^{\rm s}(\theta-\varphi;m') \times w_{\rm g}(\varphi;m',m_r)\frac{dN_{\rm g}(m')}{dm'}$$

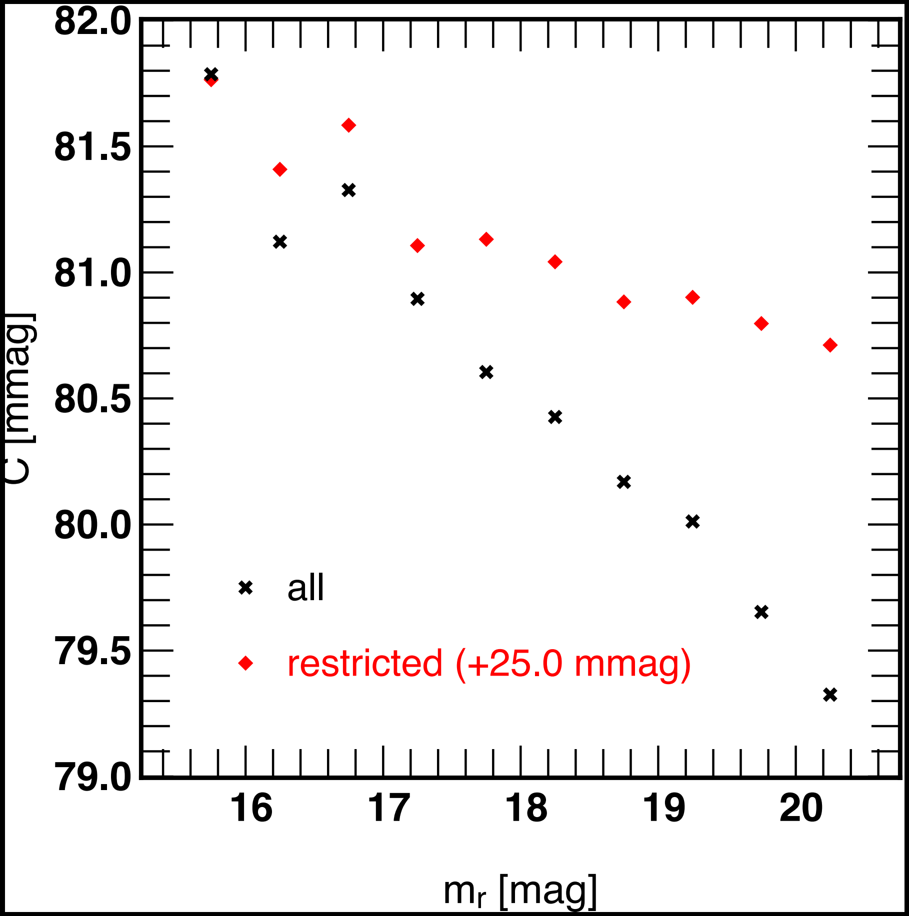
$$w_{\rm g}(\varphi;m',m_r) = K(m',m_r)(\varphi/\varphi_0)^{-\gamma},$$

$$\Sigma_{\rm g}^{\rm c}(\theta;m_r) = \Sigma_{\rm g}^{\rm c0}(m_r)\exp\left(-\frac{\theta^2}{2\sigma^2}\right) \times {}_1F_1\left(1-\frac{\gamma}{2};1;\frac{\theta^2}{2\sigma^2}\right)$$

simultaneous fit ⇒ $\sigma = 3.1'$

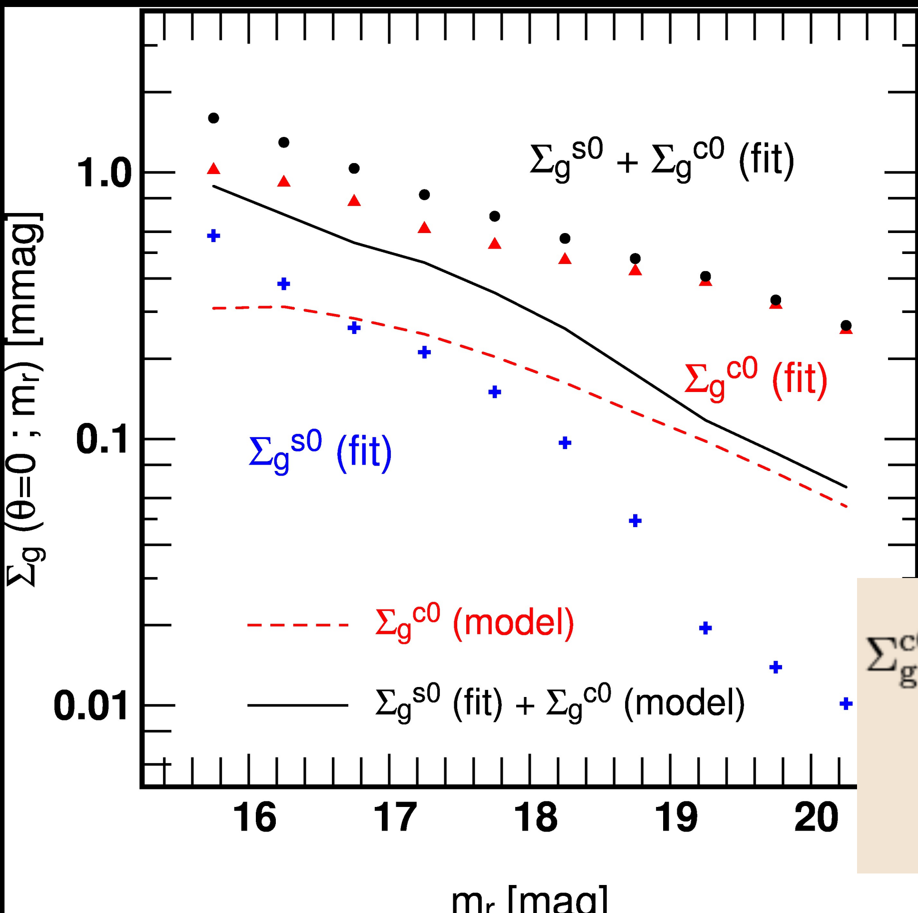
The reason why the fitted C is not constant

$$\Sigma_g^{tot}(\theta; m_r) = \Sigma_g^s(\theta; m_r) + \Sigma_g^c(\theta; m_r) + C$$



- This is largely due to the cfa Great Wall that is preferentially located in relatively high-extinction region of Galaxy.
  - The trend disappears when we remove the cfa Great Wall region.

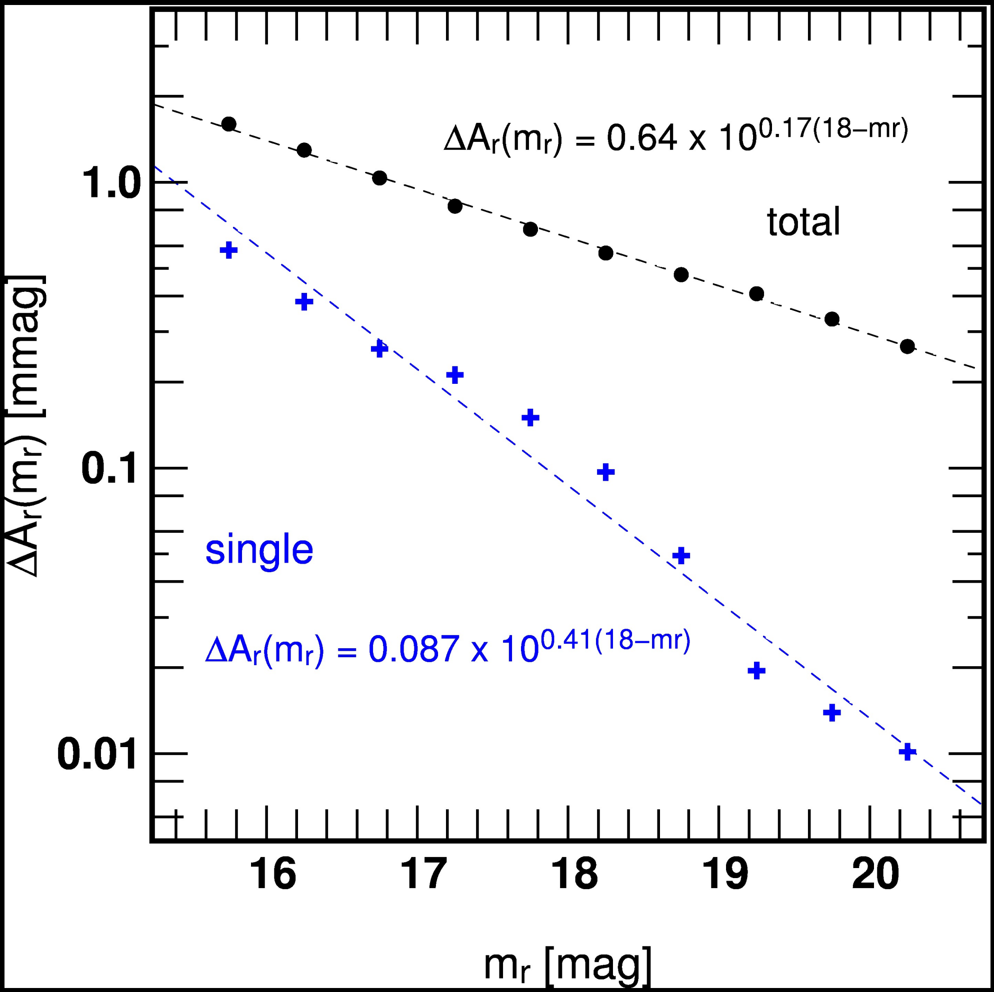
Extended dust emission around the halo hosting the central galaxy and/or contribution from unresolved galaxies ?



- The fitted clustering term is a factor of 2-3 larger than that expected from the measured angular correlation functions of resolved SDSS galaxies

$$\Sigma_{\rm g}^{\rm c0}(m_r) = 2\pi\sigma^2 \left(\frac{\varphi_0}{\sqrt{2}\sigma}\right)^{\gamma} \Gamma\left(1-\frac{\gamma}{2}\right) \times \int dm' \Sigma_{\rm g}^{\rm s0}(m') K(m', m_r) \frac{dN_{\rm g}(m')}{dm'}$$

Average contribution to A_r against m_r of the central galaxy (SDSS)



- Could be used as an empirical correction for the SFD extinction of a galaxy with m_r
  - But this is tiny and just statistical
  - not clear if this correction itself is important

c.f. Peek & Graves(2010)

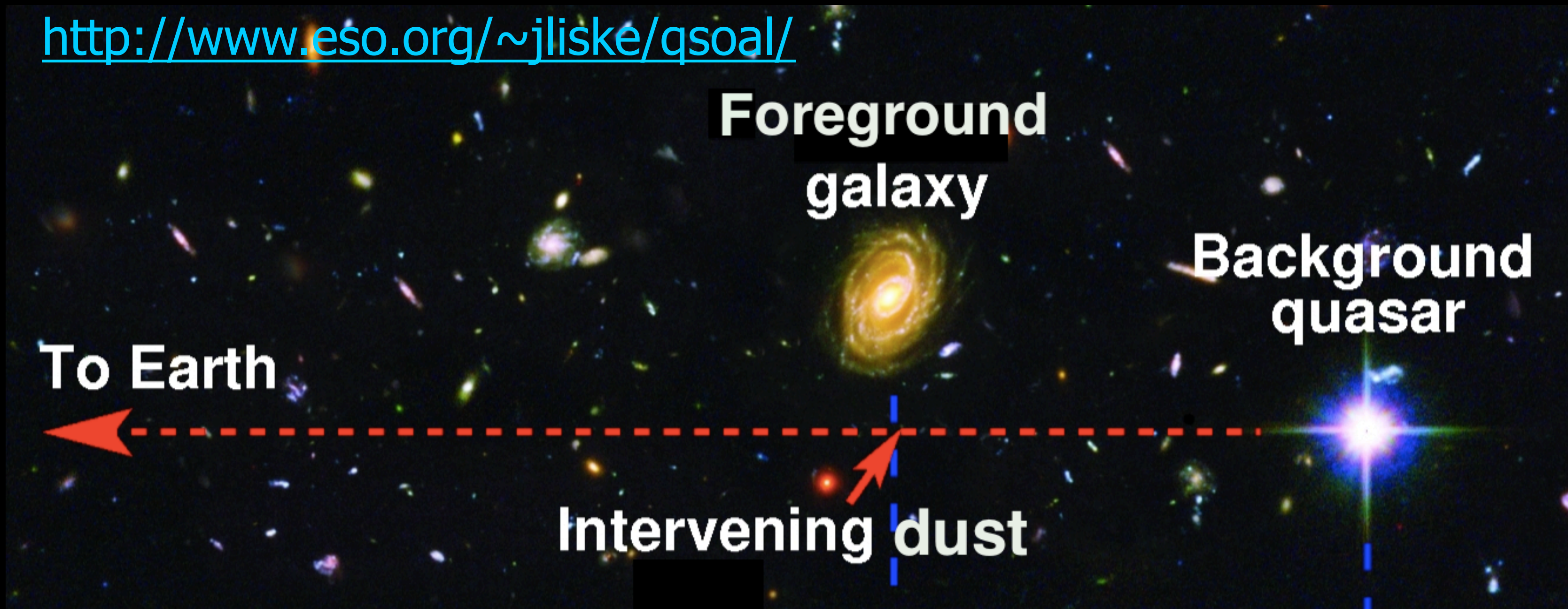
The spatial extent of the dust:

- associated with individual galaxies or extended over their common halos ? -

- T.Kashiwagi & YS: in preparation

Very preliminary !

Intergalactic dust is universal?



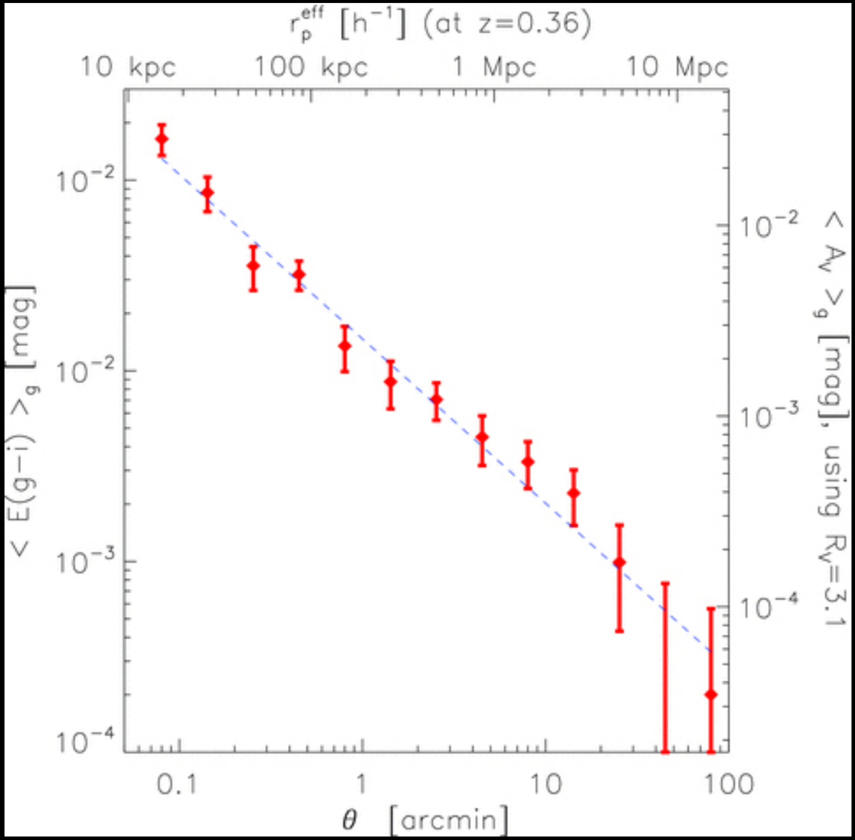
- Ménard, Scranton, Fukugita & Richards: MNRAS 405 (2010) 1025
  - Measure the reddening of background quasars due to the dust of SDSS galaxies from $<\delta m_Q(\Phi)\,\delta_g(\Phi+\theta)>$
  - Detected the presence of dust from 20kpc to several Mpc

Spatial distribution of intergalactic dust ?

$$\langle E(g-i)\rangle(\theta) = (1.5 \pm 0.4) \times 10^{-3} \left(\frac{\theta}{1\,\mathrm{arcmin}}\right)^{-0.86 \pm 0.19}$$

Menard et al. (2010)

- Extended much beyond each galaxy ?
- Sum of dust associated with galaxies ?
  - Very similar to the galaxy angular correlation function power-law…



Stacking IRAS map to detect 100 μ m emission of SDSS galaxies

- MSFR measure the ***absorption*** of dust
- Combining with the measurement of the ***emission*** of dust of galaxies, we constrain the dust temperature, which would distinguish intragalaxy and intracluster dust.
- Repeat the same stacking procedure
  - SDSS galaxies with $17<m_i<21$ that MSFR use
  - Decomposition into three terms

$$I_{\rm total}(\theta, m_i) = I_{\rm single}(\theta, m_i) + I_{\rm clustering}(\theta, m_i) + C$$

Emission and absorption of dust

- Optical depth (extinction=scattering+absorption)

$$\tau(\theta,\lambda) = \kappa_{\rm ext}(\lambda)\Sigma_{\rm d}(\theta)$$

- Color excess

$$E_{g-i}(\theta,z) = \frac{2.5}{\ln 10}\left[\tau\Big(\theta,\lambda_g^{\rm rest}(z)\Big) - \tau\Big(\theta,\lambda_i^{\rm rest}(z)\Big)\right]$$

- Emission (optically thin approximation)

$$I(\lambda_{100\mu m},\theta,z) \quad = \quad \frac{1}{(1+z)^4}B\Big(\lambda_{100\mu m}^{\rm rest},T_{\rm d}(z)\Big)\tau(\lambda_{100\mu m}^{\rm rest}(z))$$

- Emission/absorption

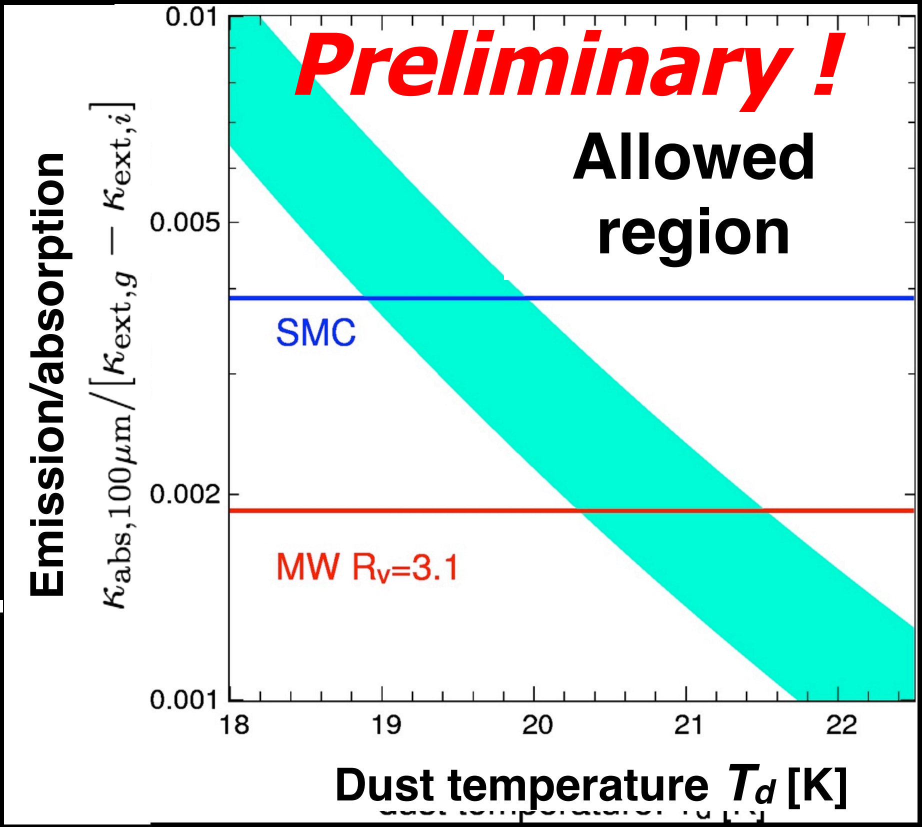
$$\frac{I(\lambda_{100\mu m},\theta,\bar{z})}{E_{g-i}(\theta,\bar{z})} = \frac{\ln 10}{2.5}\frac{1}{(1+\bar{z})^4}B(\lambda_{100\mu m}^{\rm rest}(\bar{z}),T_{\rm d}(\bar{z}))\frac{\kappa_{\rm abs}(\lambda_{100\mu m}^{\rm rest}(\bar{z}))}{\kappa_{\rm ext}\Big(\lambda_g^{\rm rest}(\bar{z})\Big) - \kappa_{\rm ext}\Big(\lambda_i^{\rm rest}(\bar{z})\Big)}.$$

constraining the dust temperature

- The ratio of emission and absorption compared with MW and SMC models (Weingartner & Draine 2001)

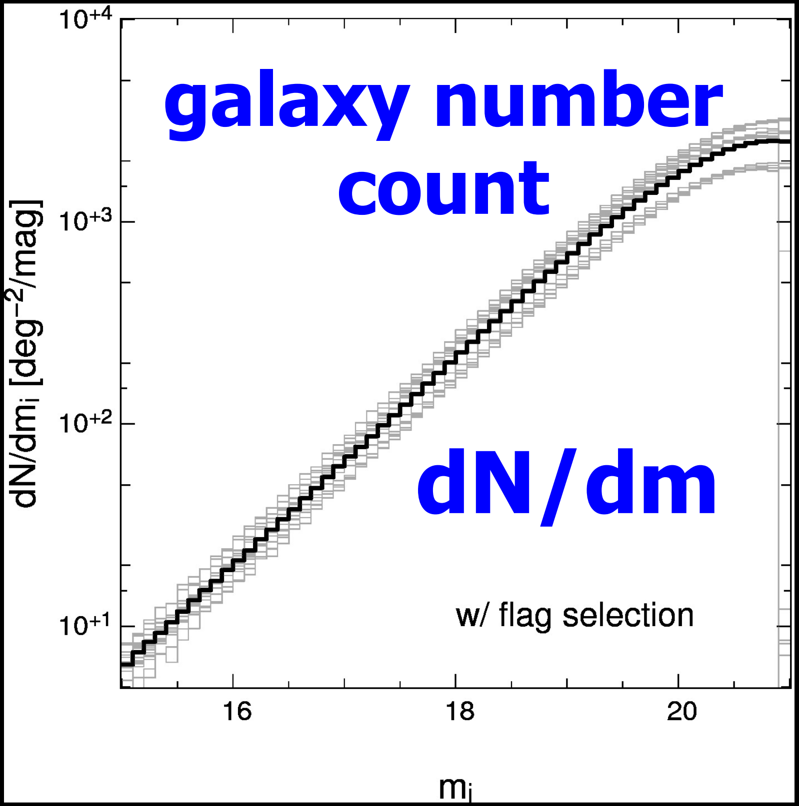
  http://www.astro.princeton.edu/~draine/dust/dustmix.html

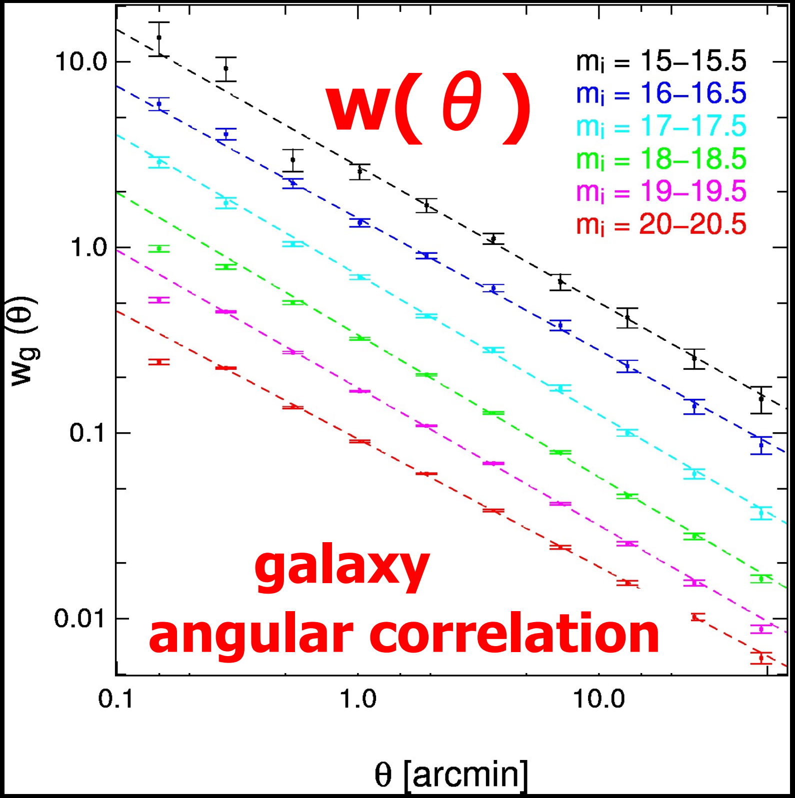
- **consistent with typical dust temperature of galaxies (~20K)**
  - **MSFR and we observed the absorption and emission of the same component, respectively.**
  - **Temperature of dust in clusters ???**



Contribution of SDSS galaxies to the 100 μm emission $I_{clustering}(\theta, m_i)$

$$I_{\rm clustering}(\boldsymbol{\theta}, m_i) = \int dm' \frac{dN(m')}{dm'} \int d\boldsymbol{\varphi}\; I_{\rm single}(\boldsymbol{\theta} - \boldsymbol{\varphi}; m') w(\boldsymbol{\varphi}; m', m_i)$$

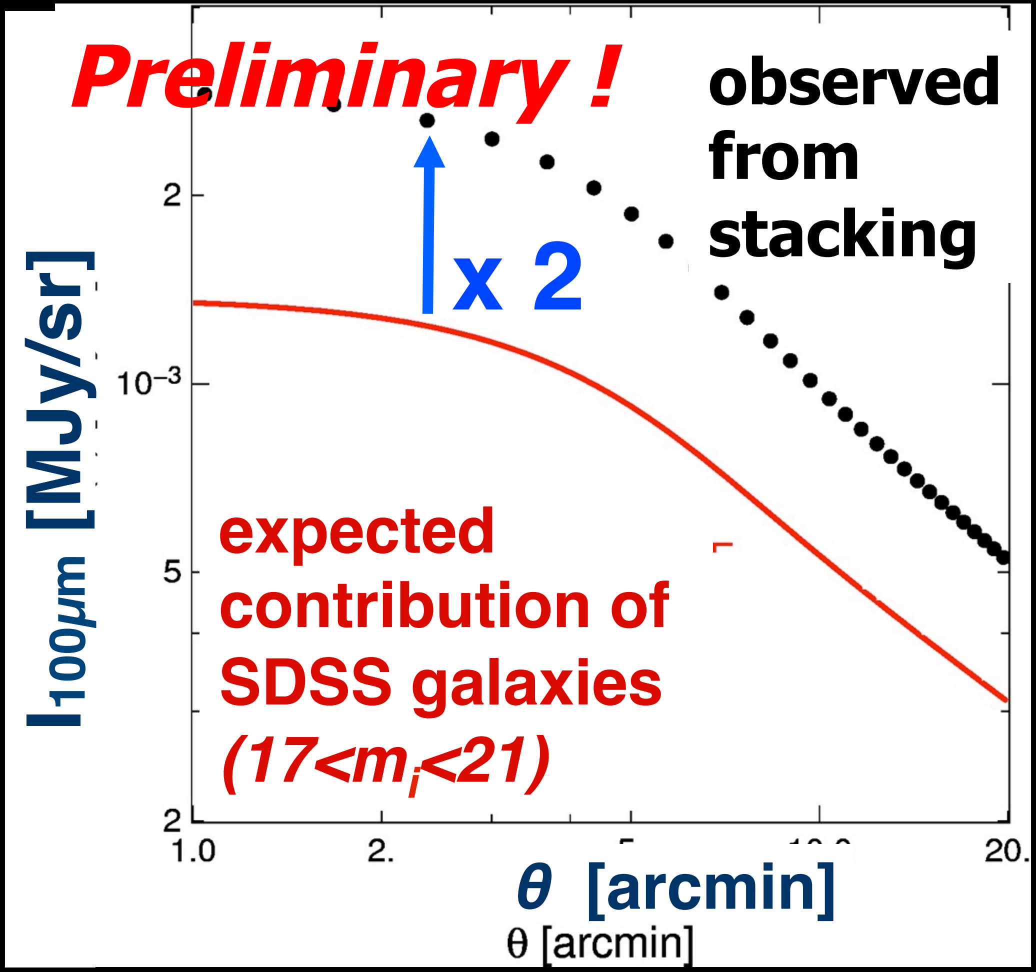




~50% is from SDSS galaxies

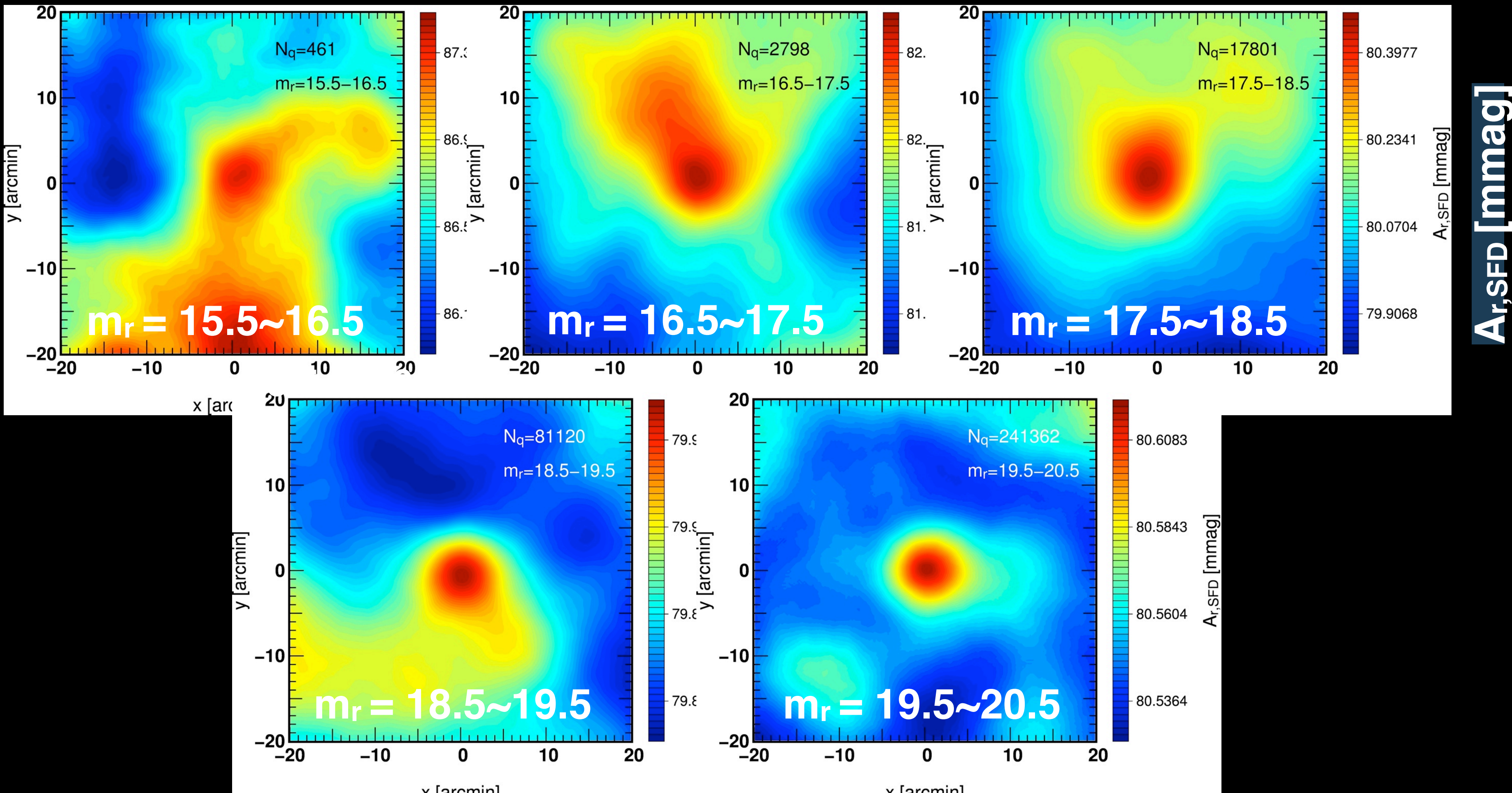
$$I_{\rm clustering,MSFR}(\theta) = \int_{17.0}^{21.0} I_{\rm clustering}(\theta; m_i') \frac{dN}{dm_i'} dm_i' \times \left(\int_{17.0}^{21.0} \frac{dN}{dm_i'} dm_i' \right)^{-1}$$

- SDSS galaxies explain 50% of the FIR flux
- The rest may be
  - extended dust component over cluster scales ?
  - sums of optically faint infrared galaxies ?

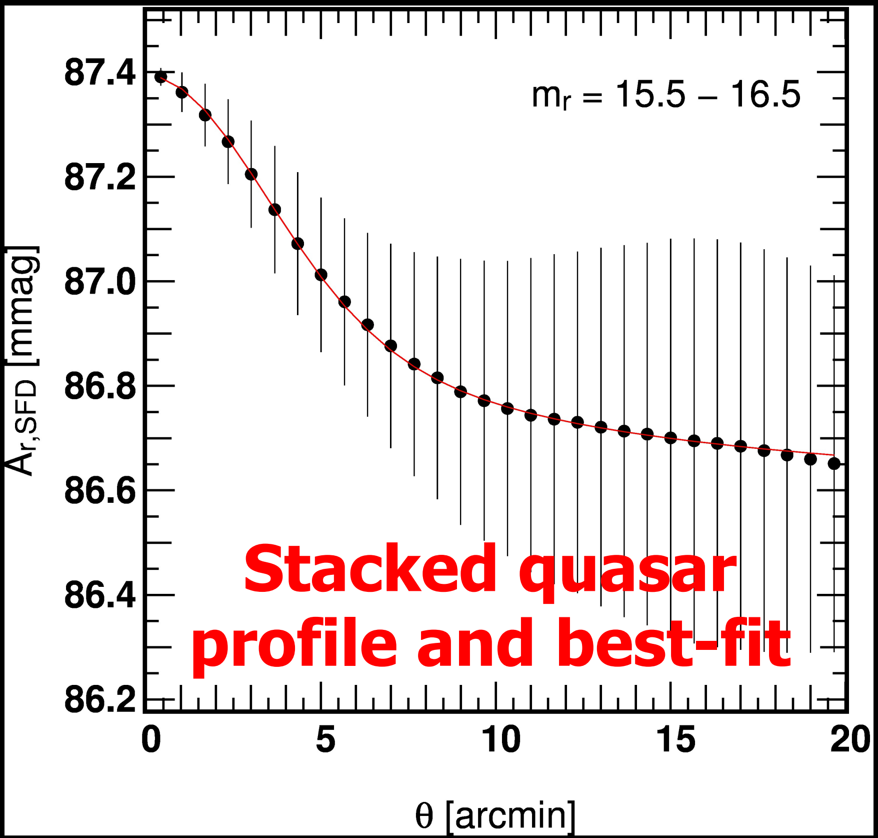


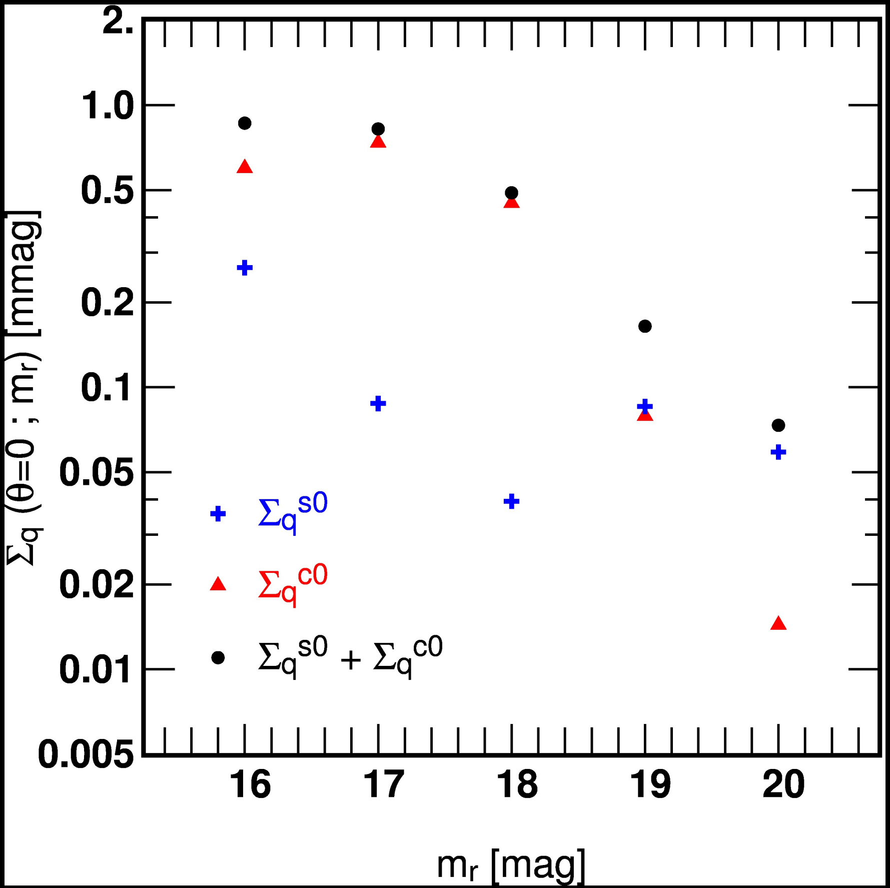
Stacking SDSS quasars

Similar stacking analysis of SDSS photometric quasar catalogue (Richards et al. 2009) indicates the FIR signals as well.



Profiles of stacked quasar images





Best-fit decomposition into the single and clustering terms

Quasars stacking should deserve further study

Comments/suggestions would be highly appreciated

Summary of the first part

- Detection of FIR emission from SDSS galaxies by stacking analysis over the SFD map（～ IRAS 100μm map)
  - Largely explain the anomaly of SDSS galaxy number counts as a function of A_{SFD} discovered by Yahata et al.(2007)
  - Possible correction to the SFD map and future Galactic extinction map with Planck
  - A new probe of unresolved (dusty) galaxy correlations or dust profile of the hosting halo

Preliminary Summary of the second part

- Sum of dust associated with SDSS galaxies explains ∼50% of the amount discovered via absorption by Menard et al.(2010)
- Where is the remaining 50% ?
  - Associated with non-SDSS galaxies ?
  - Not directly associated with individual galaxies, but extended over cluster scales ?
- FIR emission from SDSS quasars detected, but not fully explored yet. Comments and suggestions are very welcome