In mid-infrared bands, AKARI found zodiacal light is very smooth

Fluctuation can be explained by

- **photon noise (dots) ,**
- **DGL (black) and**
- **faint sources**

Upper limit of 0.02 % of the sky brightness at the angular scale >100 arcsec, 18μm.

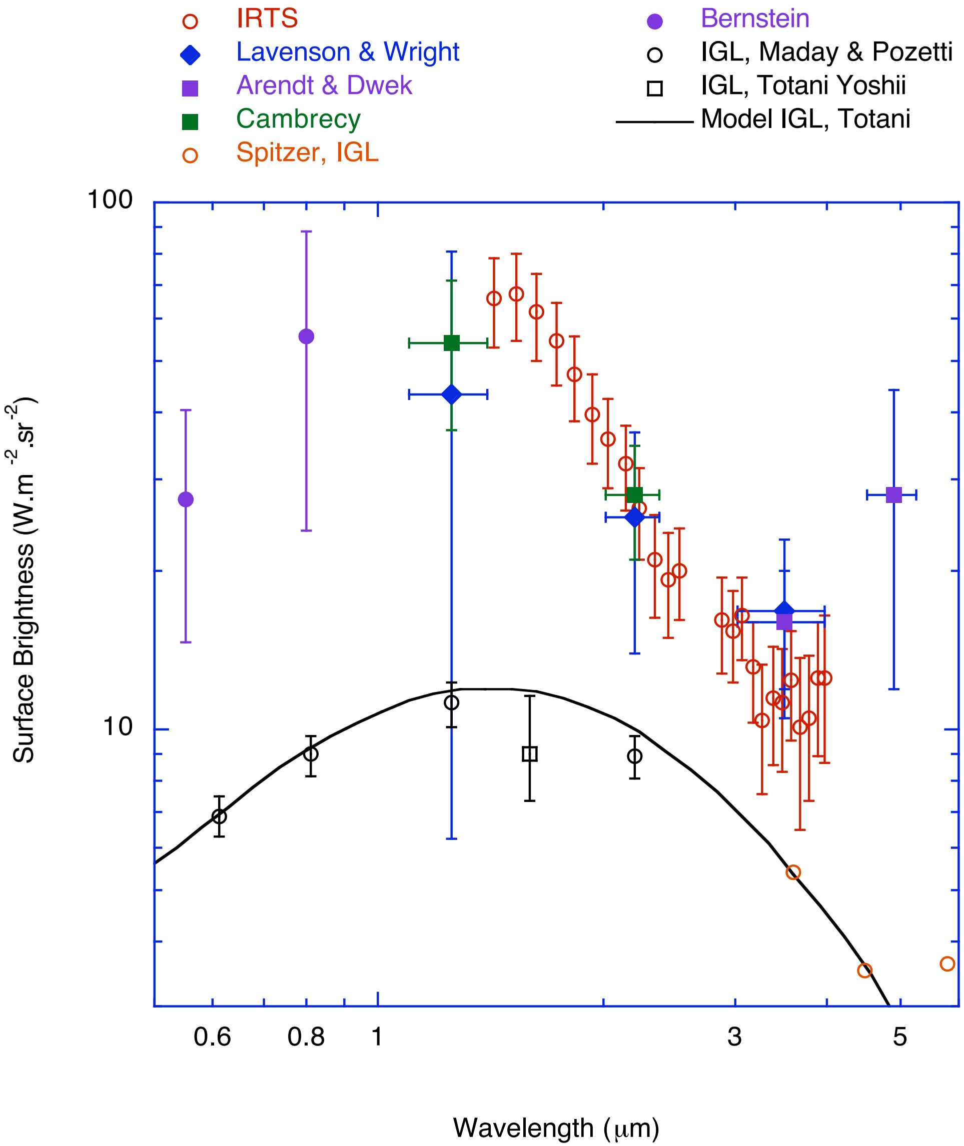
AKARI Observation of the Fluctuation of the Near-infrared Background

Matsumoto, Toshio

Institute of astronomy and Astrophysics, Academia Sinica, Taiwan
ISAS/JAXA

Collaborator: H. J. Seo, W.-S. Jeong, H. M. Lee, S. Matsuura, H. Matsuhara, S. Oyabu, J. Pyo, and T. Wada

Excess emission is significantly brighter than integrated light of faint galaxies



Pop.III origin?

Redshifted *Ly* α?

Problem

TeV γ

Too high star formation rate

Uncertainty of the ZL model?

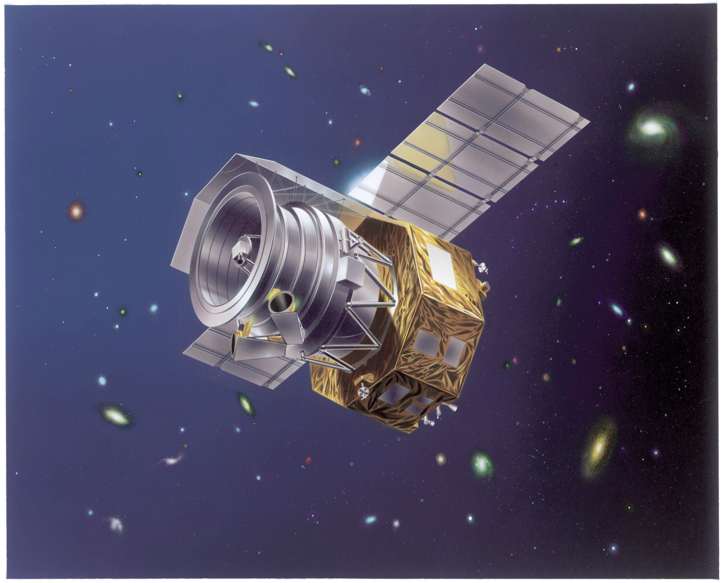
New observation: Fluctuation of the sky

Fluctuation provides model independent information

- IRAS, COBE, ISO tried to detect fluctuation of zodiacal emission, but only upper limits were obtained.
- Lowest upper limit is 0.2% of sky brightness at 25 μm , 3 arcmin scale (ISO).

Fluctuation may provide information on structure formation at pop.III era

AKARI: First Japanese Infrared astronomy satellite



70cm cooled infrared telescope

Launch : February 22, 2006

Orbit : sun synchronous orbit, 750km altitude

Observation terminated on May 2011

Instruments

IRC (Infrared Camera)

512x412 InSb array camera, 1.5"/pixel

NIR imaging observation at 2.4, 3.2, and 4.1 μm

low resolution spectroscopy

256x256 SiAs array, 2.4"/pixel

MIR imaging observation at 7~24 μm

low resolution spectroscopy

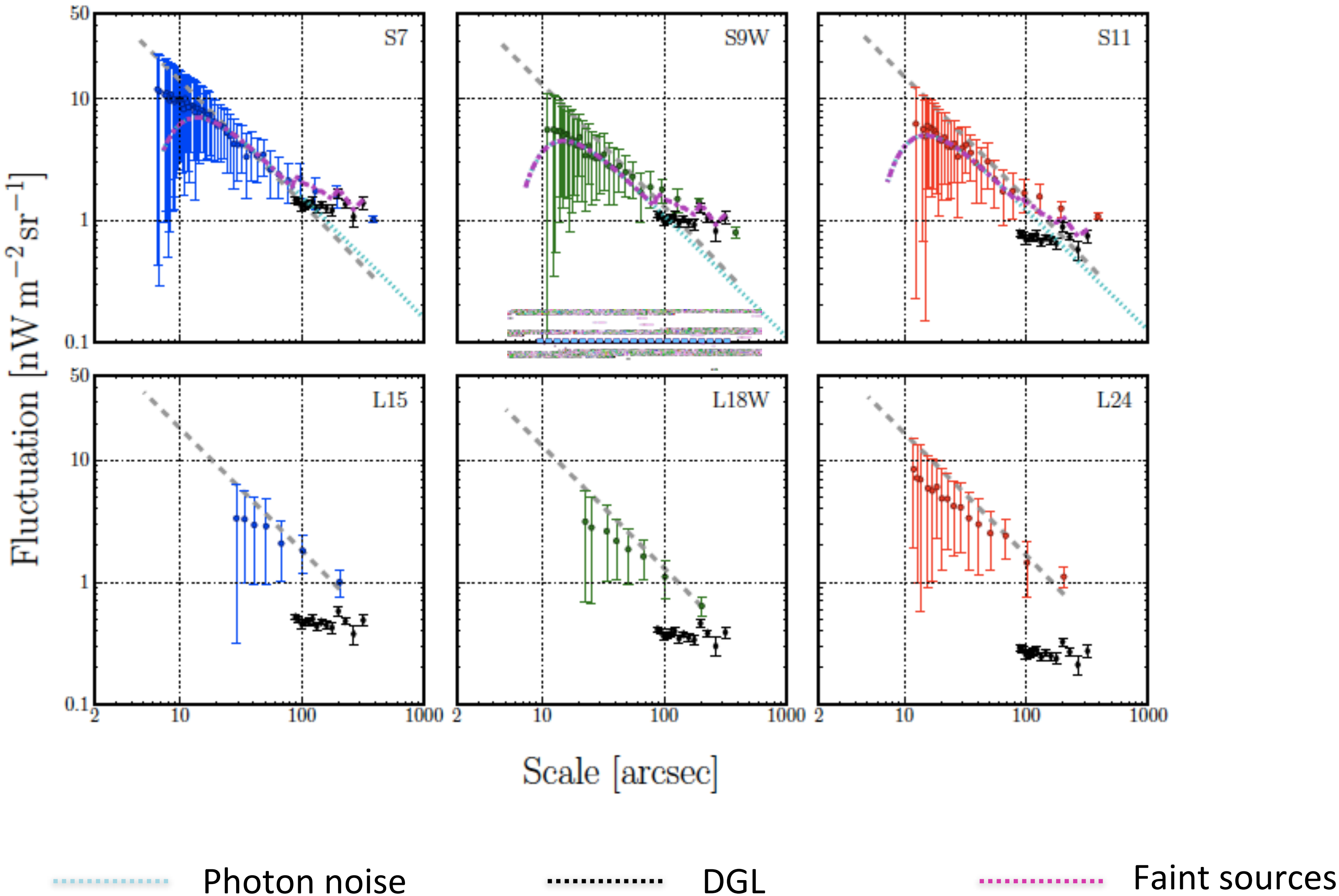
FIS(Far Infrared Surveyor)

How smooth zodiacal light?

- IRAS, COBE, ISO tried to detect fluctuation of zodiacal emission, but only upper limits were obtained.

- Lowest upper limit is 0.2% of sky brightness at 25 μm , 3 arcmin scale (ISO).

AKARI observed fluctuation of mid-IR sky
(Pyo et al. 2012)



AKARI found mid-infrared sky is very smooth!

Observed fluctuation can be explained by

Photon noise

Diffuse galactic light

Faint sources

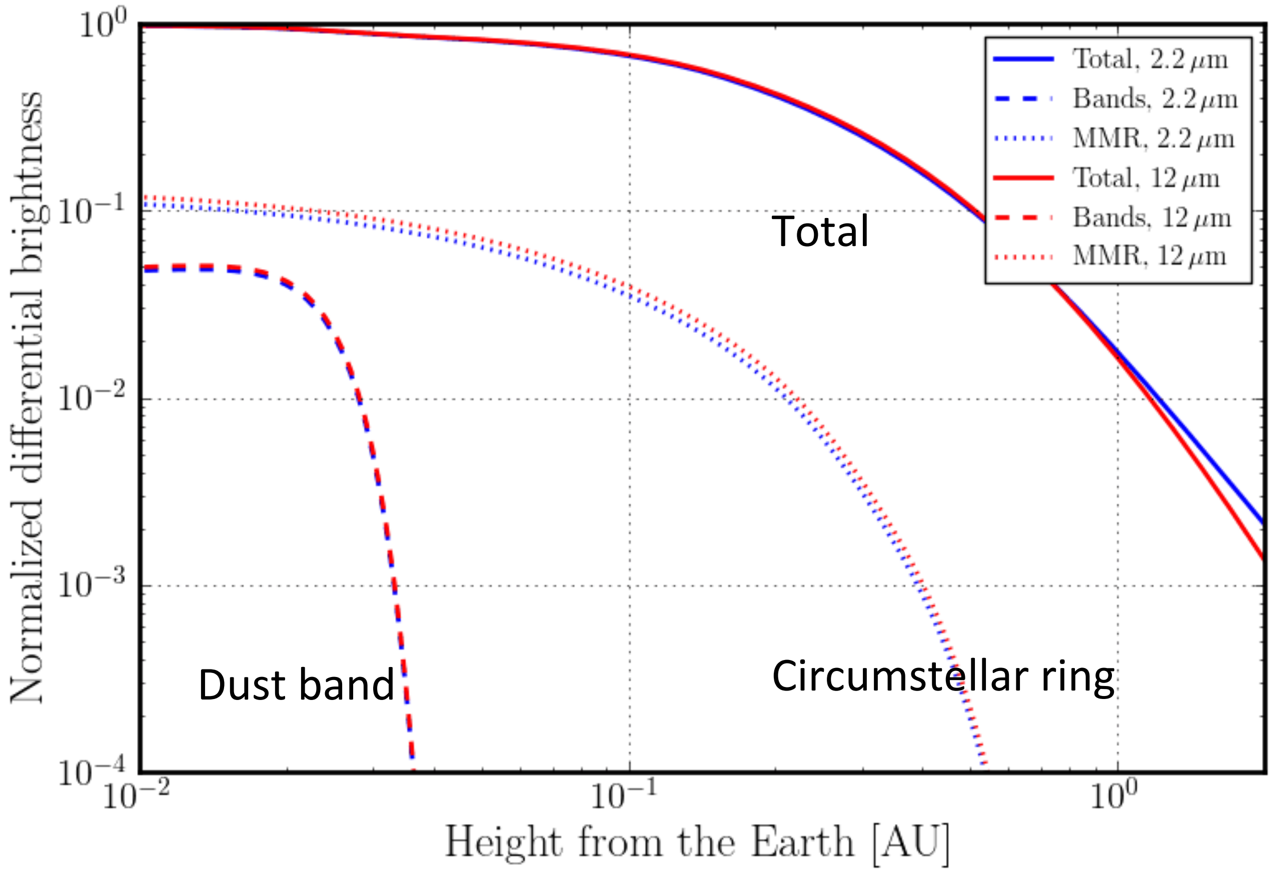
Upper limit of fluctuation is

0.02% at the angular scale >200 arcse

of zodiacal emission

Fluctuation of zodiacal light must be same as zodiacal emission

Distribution of volume emissivity for zodiacal light (2.2 μm, blue) and zodiacal emission (12 μm, red) towards NEP



Fluctuation of zodiacal light is < 0.02%

AKARI NEP survey

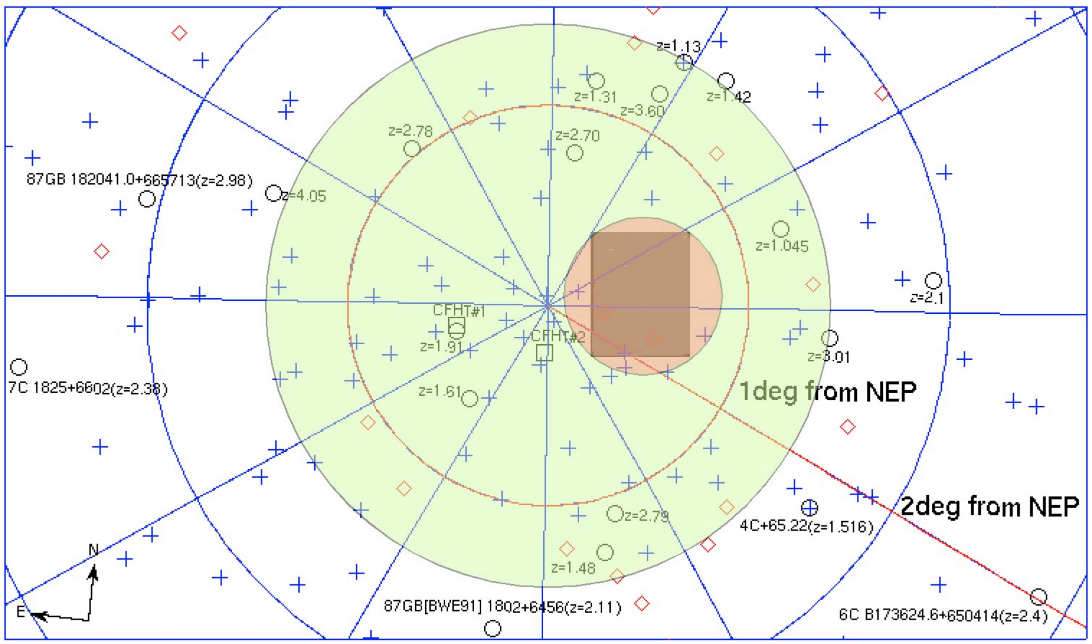
IRC/AKARI observed

NEP monitor field: ~2 times in a month with all filter bands

NEP wide field: shallow survey over ~2.5 degree circle around

Compared with Spitzer

- Dark frame can be well obtained with cold shutter
- AKARI has 2 μm band
- Larger array, Large field of view, Single frame (monitor field)
- Larger pixel scale (1.49”/1.2”), bad PSF

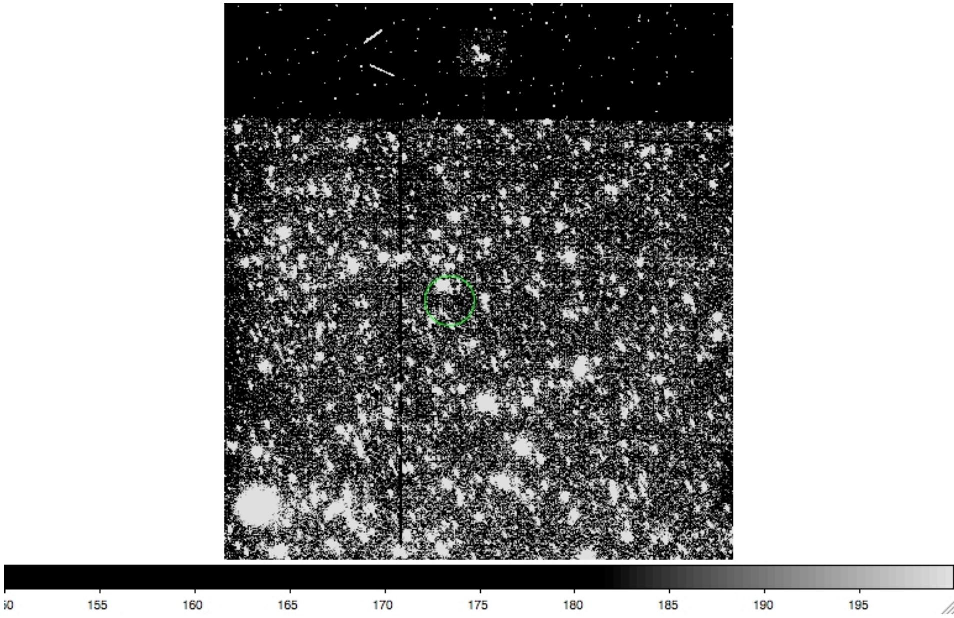


Fluctuation of the sky at NEP monitor field

Images of good quality for the NEP monitor field were stacked, and foreground sources are masked. For these maps, the fluctuation analysis was performed.

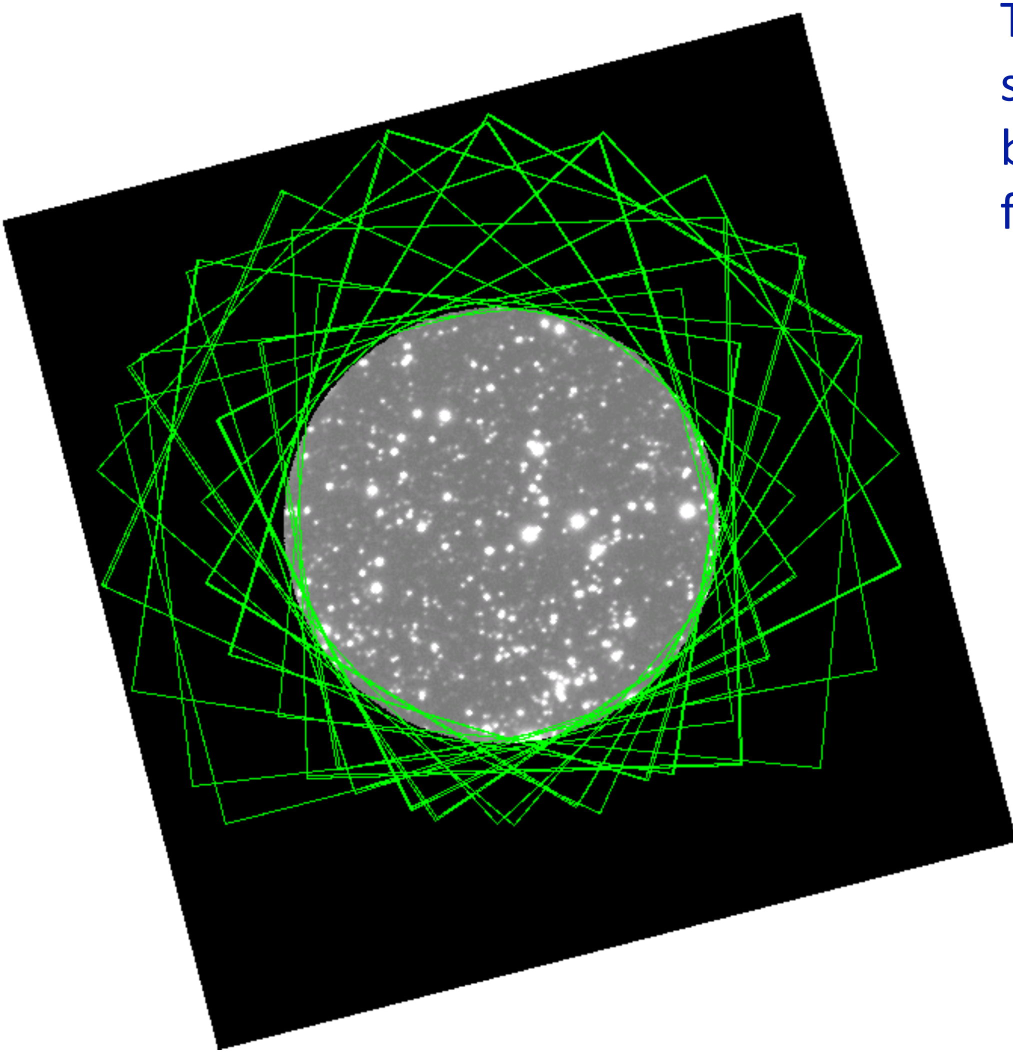
10 arcmin x 10 arcmin

1.5 arcsec/pixel

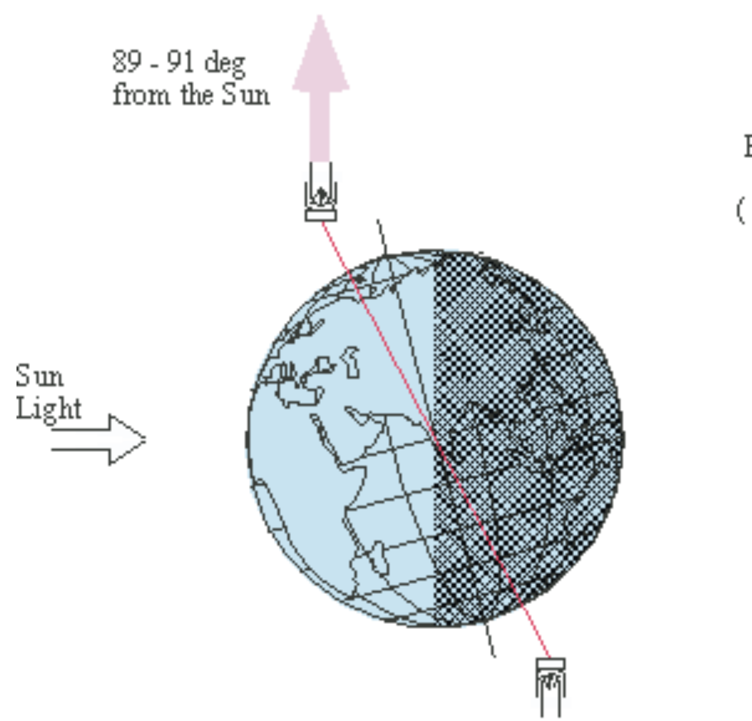


Typical image, N2

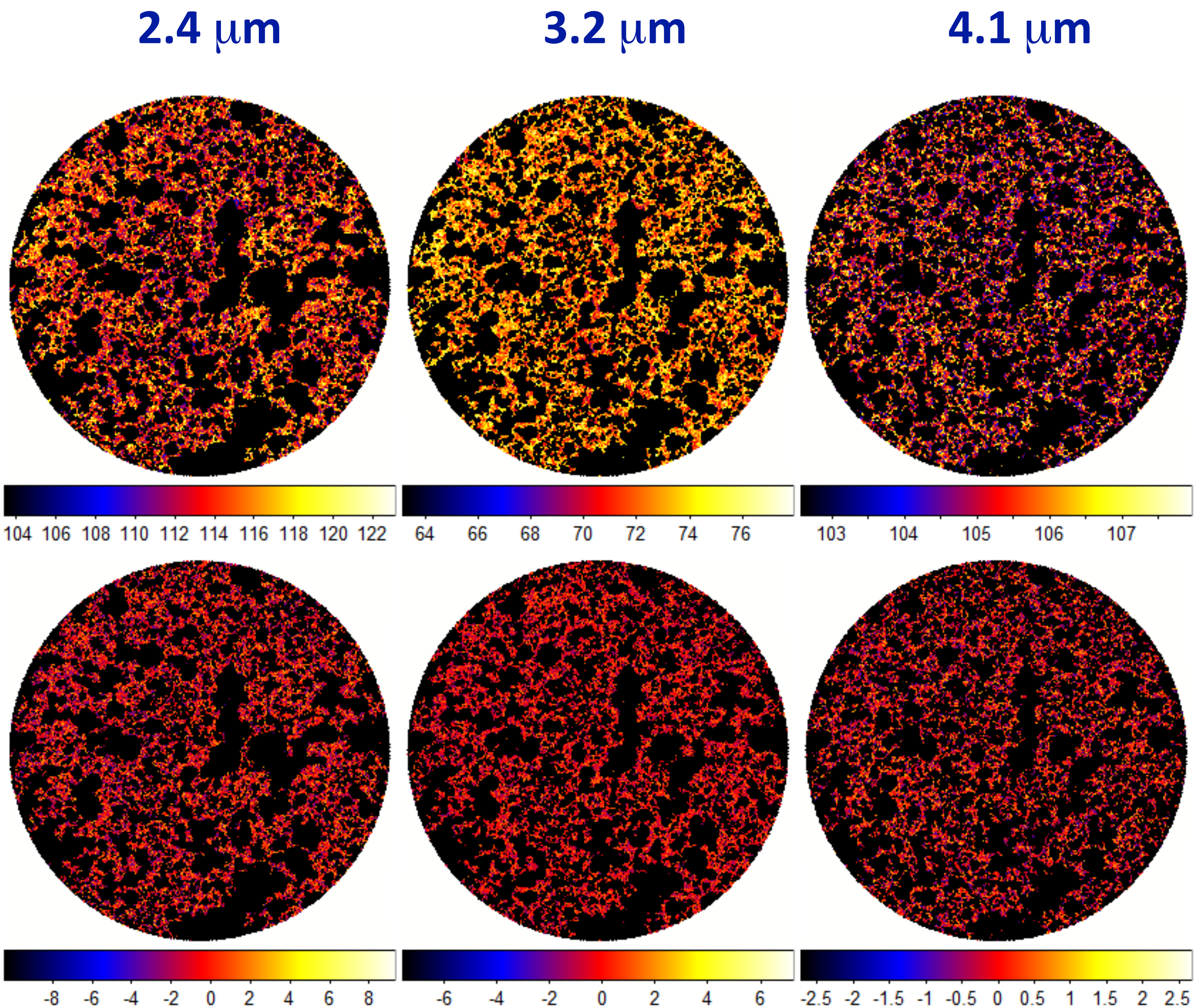
Stacked image is circular (600 arcsec diameter), since position angle changes from season to season.



This process loses some pixels, but smears out sensitivity fluctuation between pixels, instrument noise and fluctuation of zodiacal light if exists.



Stacked image of the sky and dark image



Some results

Filter band	N2	N3	N4
Wavelength, μm	2.4	3.2	4.1
Number of stacked image	40	39	24
Number of remaining pixels, %	39.2	37.9	34.8
Limiting magnitude (AB mag)	22.8	23.3	23.9
Sky brightness, $nW.m^{-2}.sr^{-1}$	114	73	105
1 σ fluctuation of sky, $nW.m^{-2}.sr^{-1}$	2.57	1.54	0.86
1 σ of dark, $nW.m^{-2}.sr^{-1}$	1.69	0.98	0.49

Power spectrum analysis
2-dimensional Fourier transform

$$P(\mathbf{k}) = |\delta I_k(\mathbf{k})|^2$$

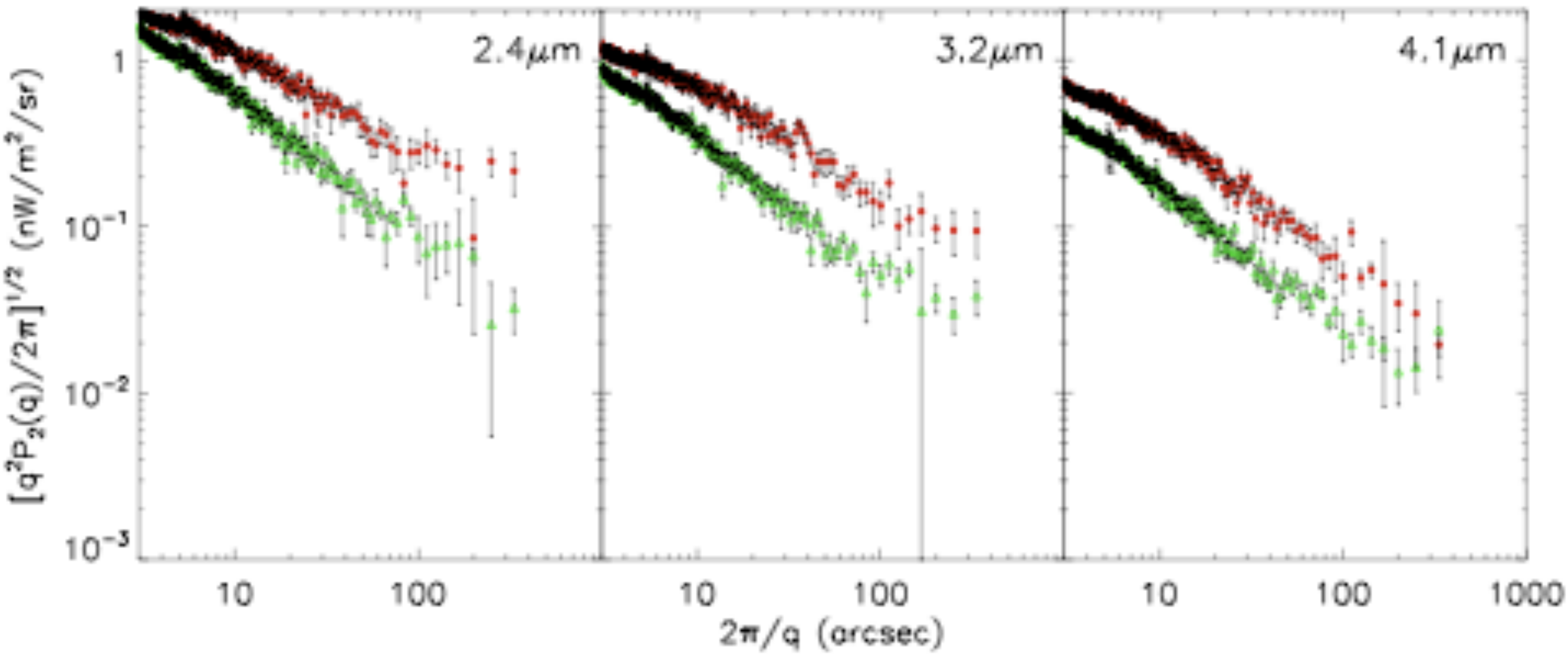
$$\delta I_k(\mathbf{k}) = \frac{1}{L_x L_y} \int \delta I(\mathbf{x}) \exp(-i\mathbf{x} \cdot \mathbf{k})\, d^2\mathbf{x}.$$

Fluctuation

$$F^2(k) = \frac{L_x L_y}{(2\pi)^2} 2\pi k^2 P(k)$$

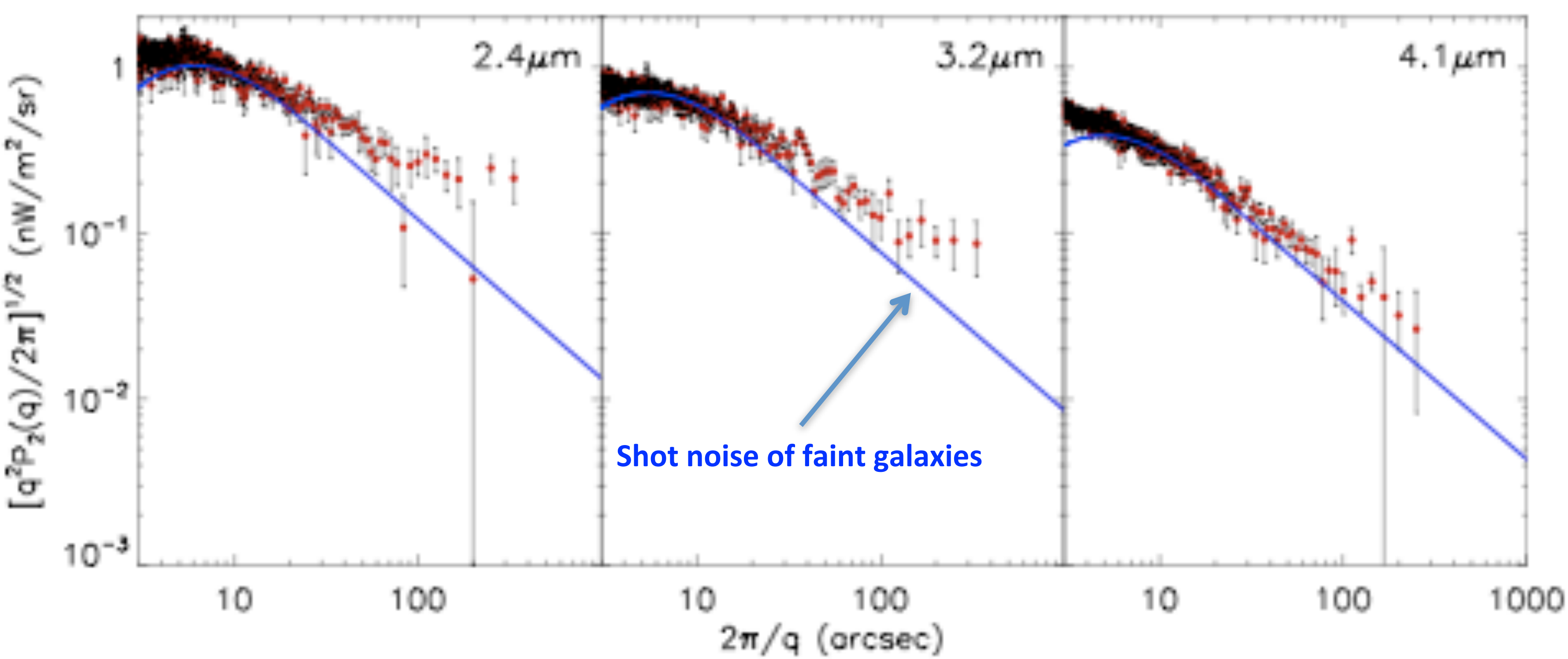
Fluctuation spectrum

2 dimensional Fourier transformation was applied both for image and dark frame.

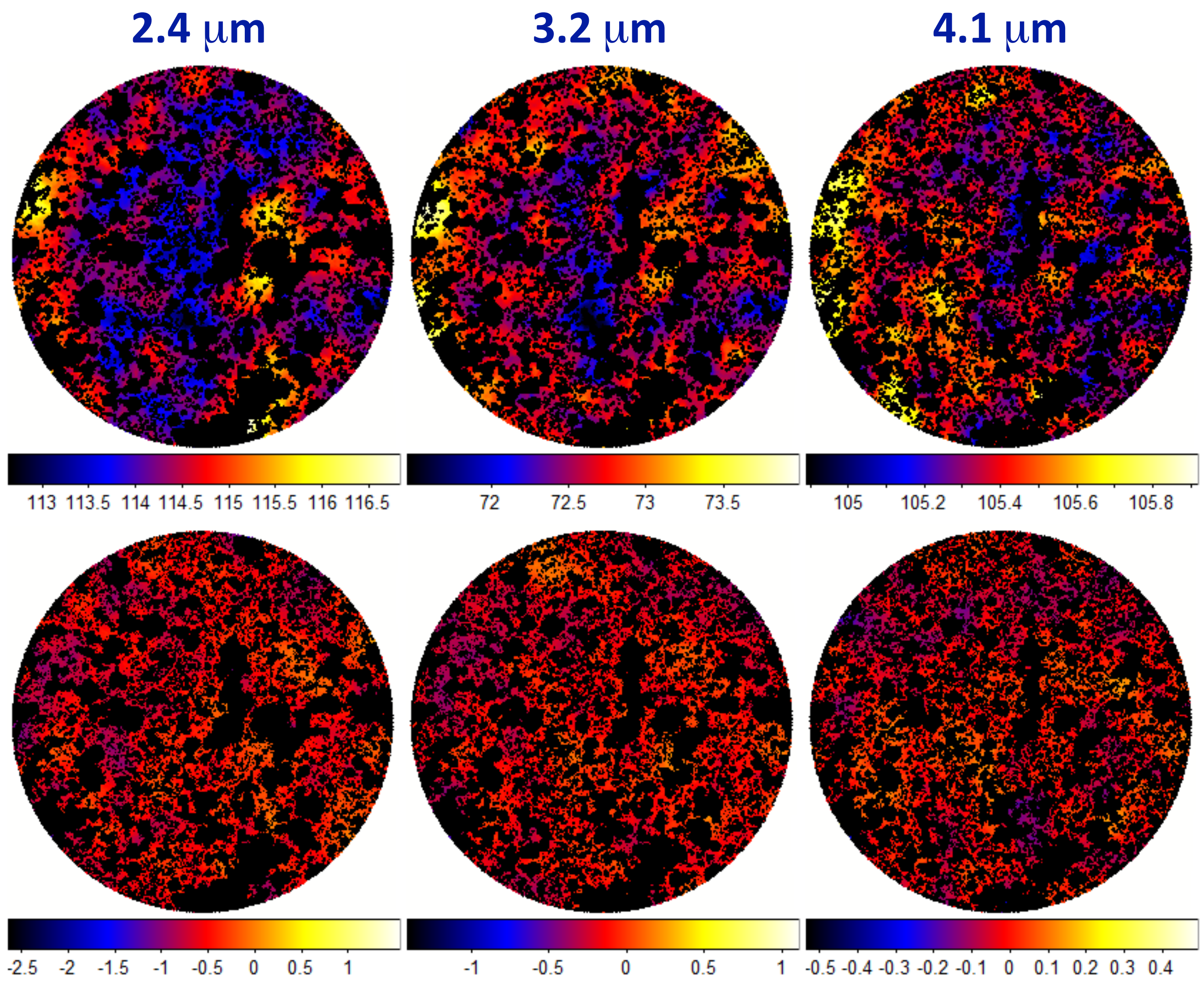


Fluctuation spectrum of the sky

Fluctuation of the dark image was subtracted

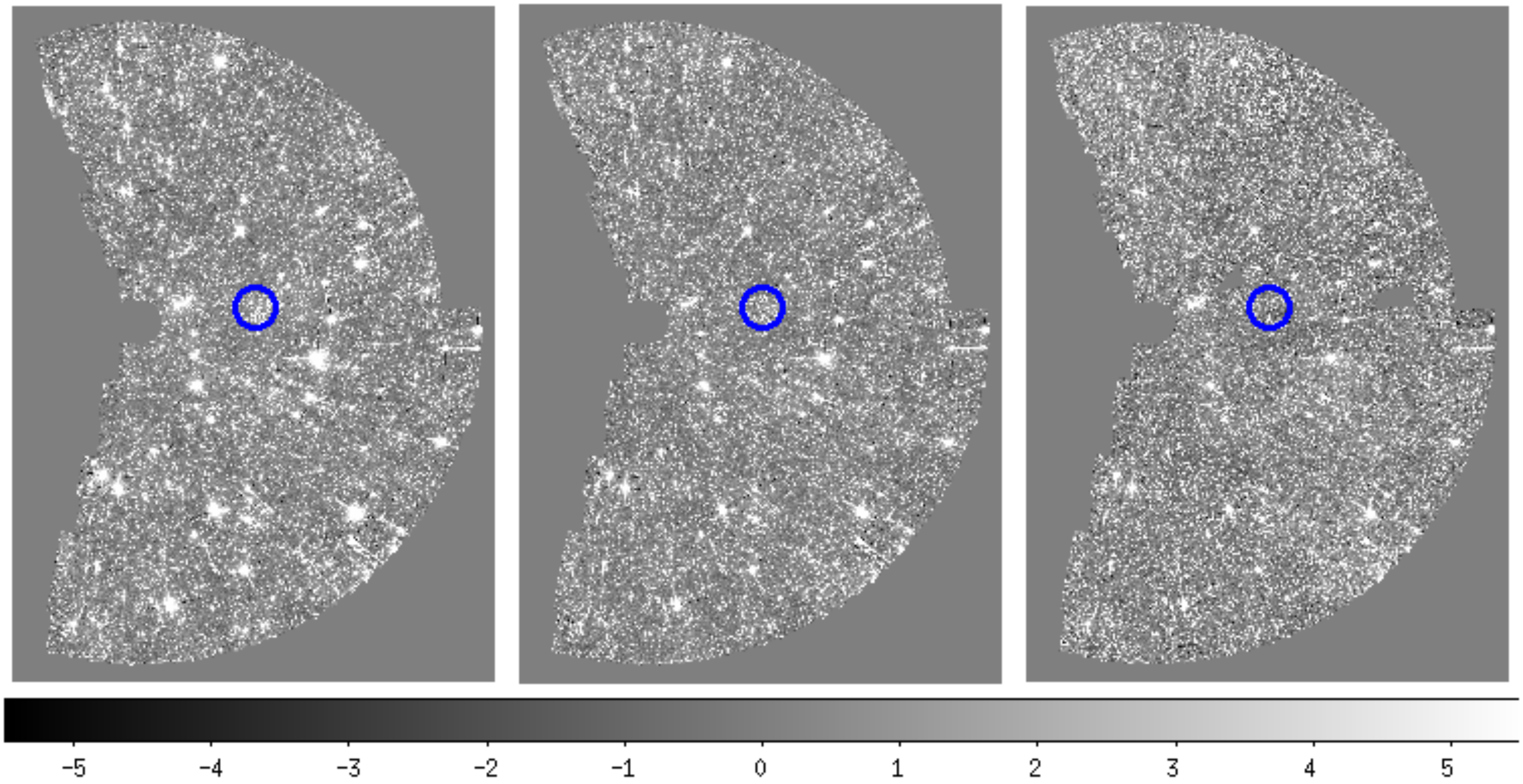


Smoothed sky image (angular resolution~50”)



Large scale structure is clearly seen!

Analysis of NEP-Wide Field

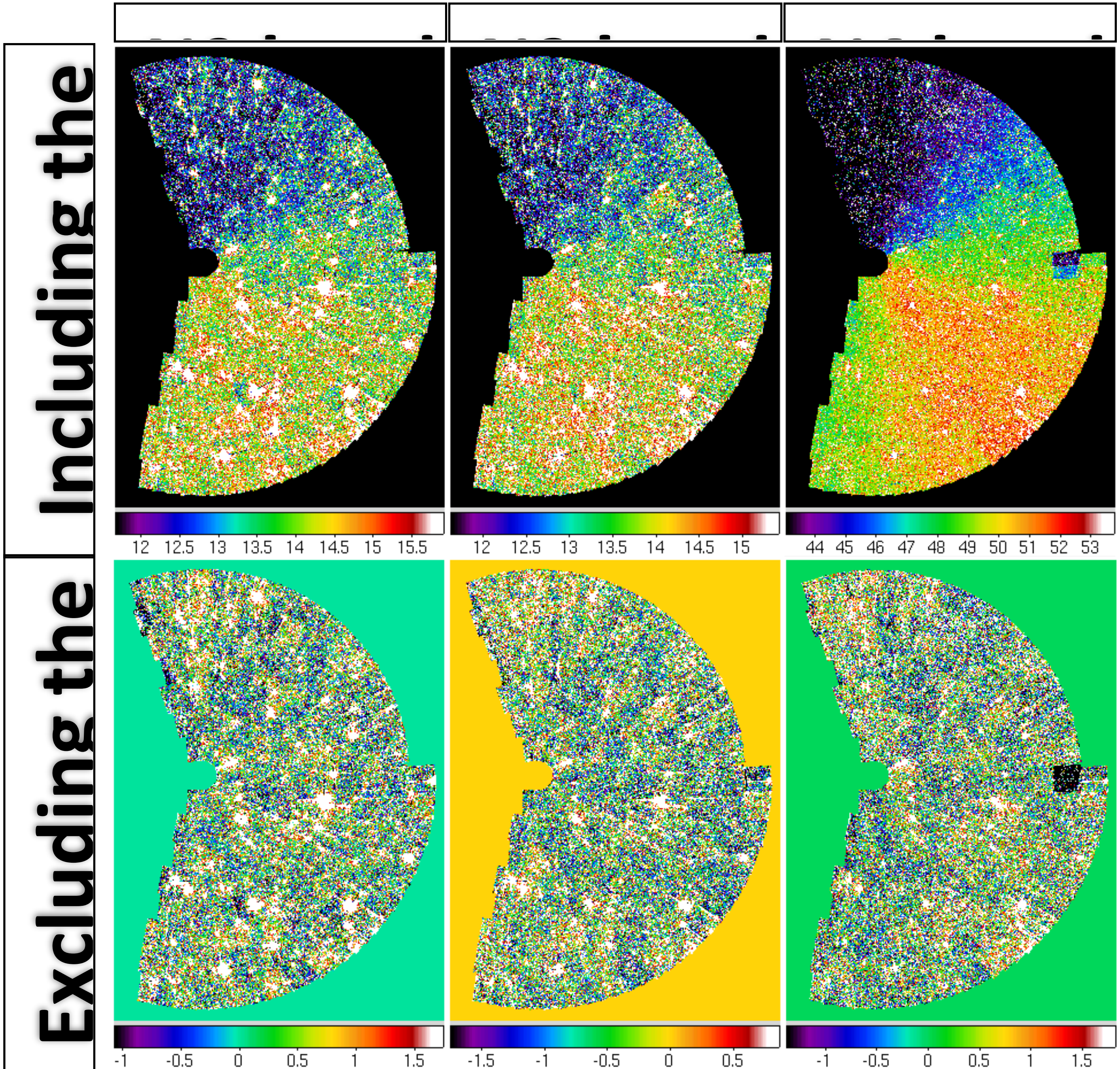


2.5 degree scale
Construct mosaic image
Stacking: 6 images (2.4 and 3.2 μm), 4 images (4.1 μm)

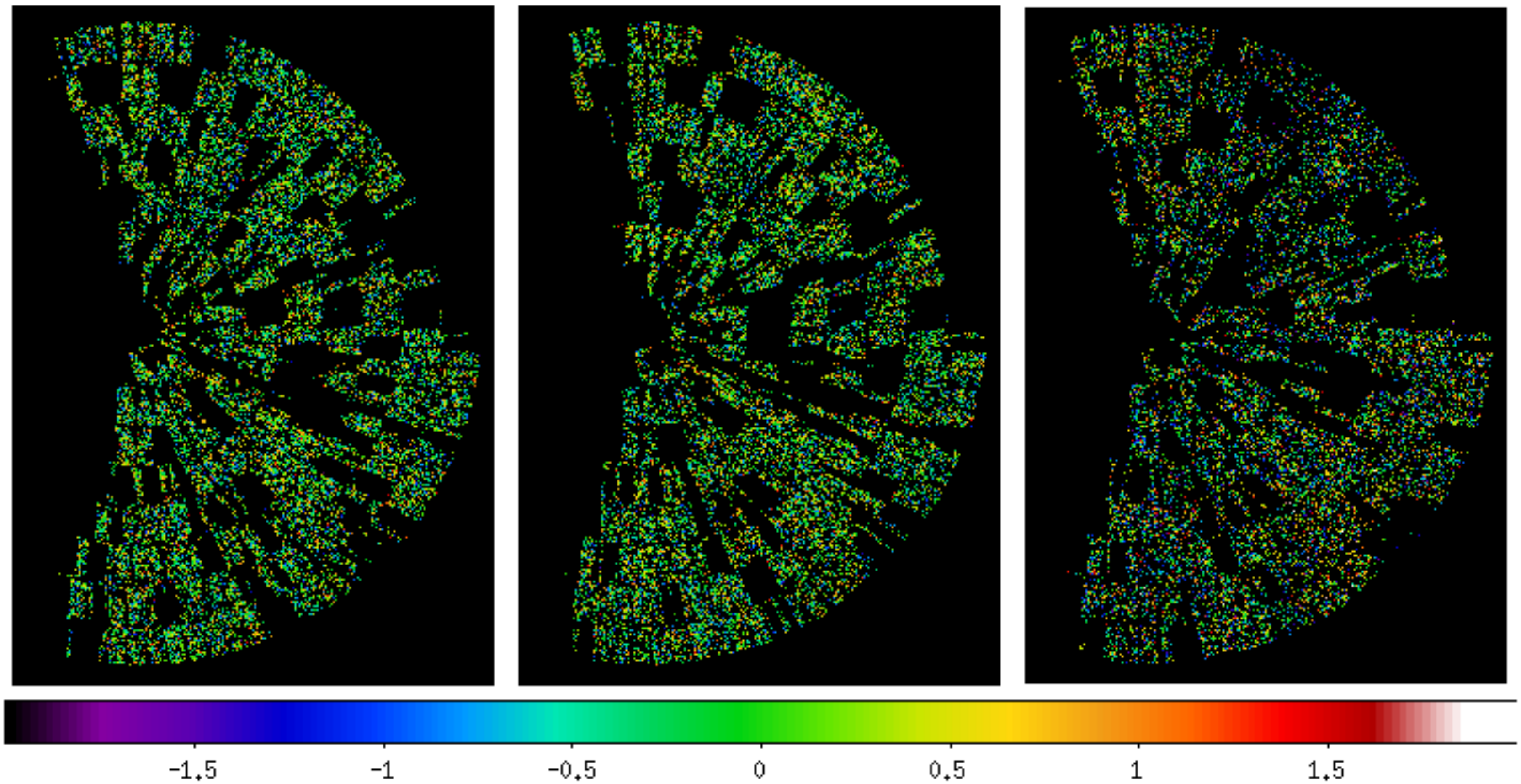
Additional careful analysis!

- Seasonal variation of zodiacal light
  Subtract zodiacal light with sinusoidal fitting
- Subtraction of dark level
  Dark level was estimated based on subsets difference
- Sky matching with using overlapped sky
- Muxbleed problem: Masked affected pixels

Mosaic image (the contribution of zodiacal light)



Final images of NEP wide field

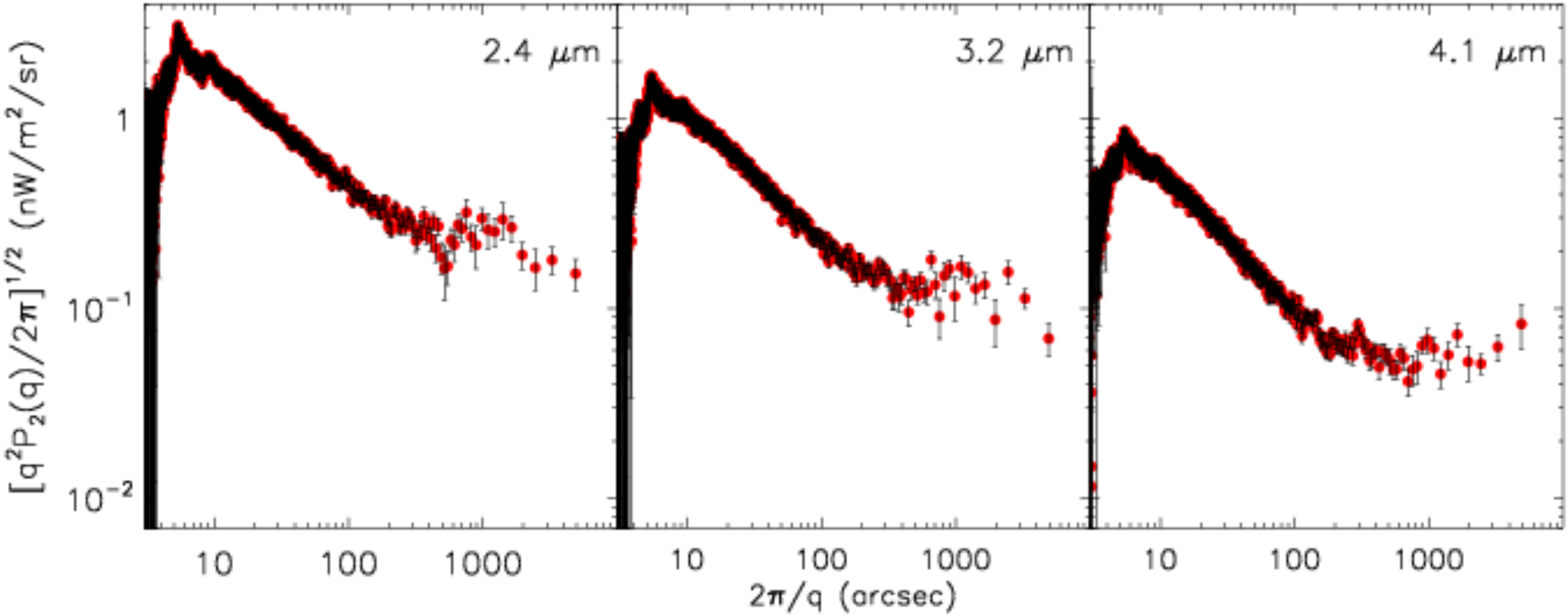


Remaining pixel ratio
: 23.3 %
Limiting mag. 21.5 (AB)

Remaining pixel ratio
: 22.6 %
Limiting mag. 22.0 (AB)

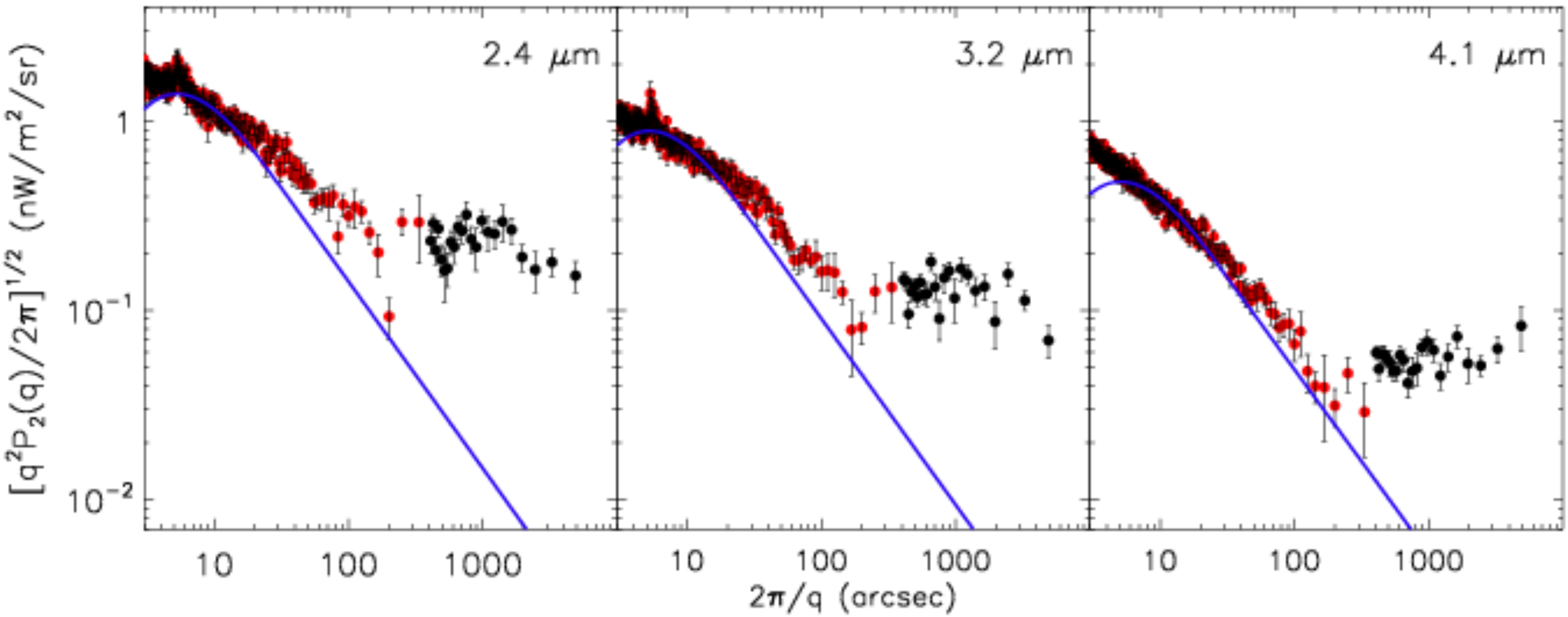
Remaining pixel ratio
: 18.4 %
Limiting mag. 22.7 (AB)

Fluctuation spectra of NEP wide field



Excess fluctuation was observed up to degree scale

Fluctuation spectrum combined with NEP monitor fields



Result of NEP wide field is consistent with that of NEP monitor field

What is the origin of large scale fluctuation?

- Zodiacal light
- Diffuse galactic light
- Clustering of galaxies, Red dwarf galaxies at z=1~2

Zodiacal light is very smooth

MIR fluctuation of zodiacal emission is < 0.02 % at >200 arcsec
Fluctuation of zodiacal light is same level
Stacking process reduces the fluctuation of zodiacal light, if it exists.

	2.4μm	3.2μm	4.1μm
Expected ZL fluctuation ($nW.m^{-2}.sr^{-1}$)	< 0.007	< 0.004	< 0.006
Observed excess fluctuation at >100 arcsec ($nW.m^{-2}.sr^{-1}$)	0.19	0.08	0.051

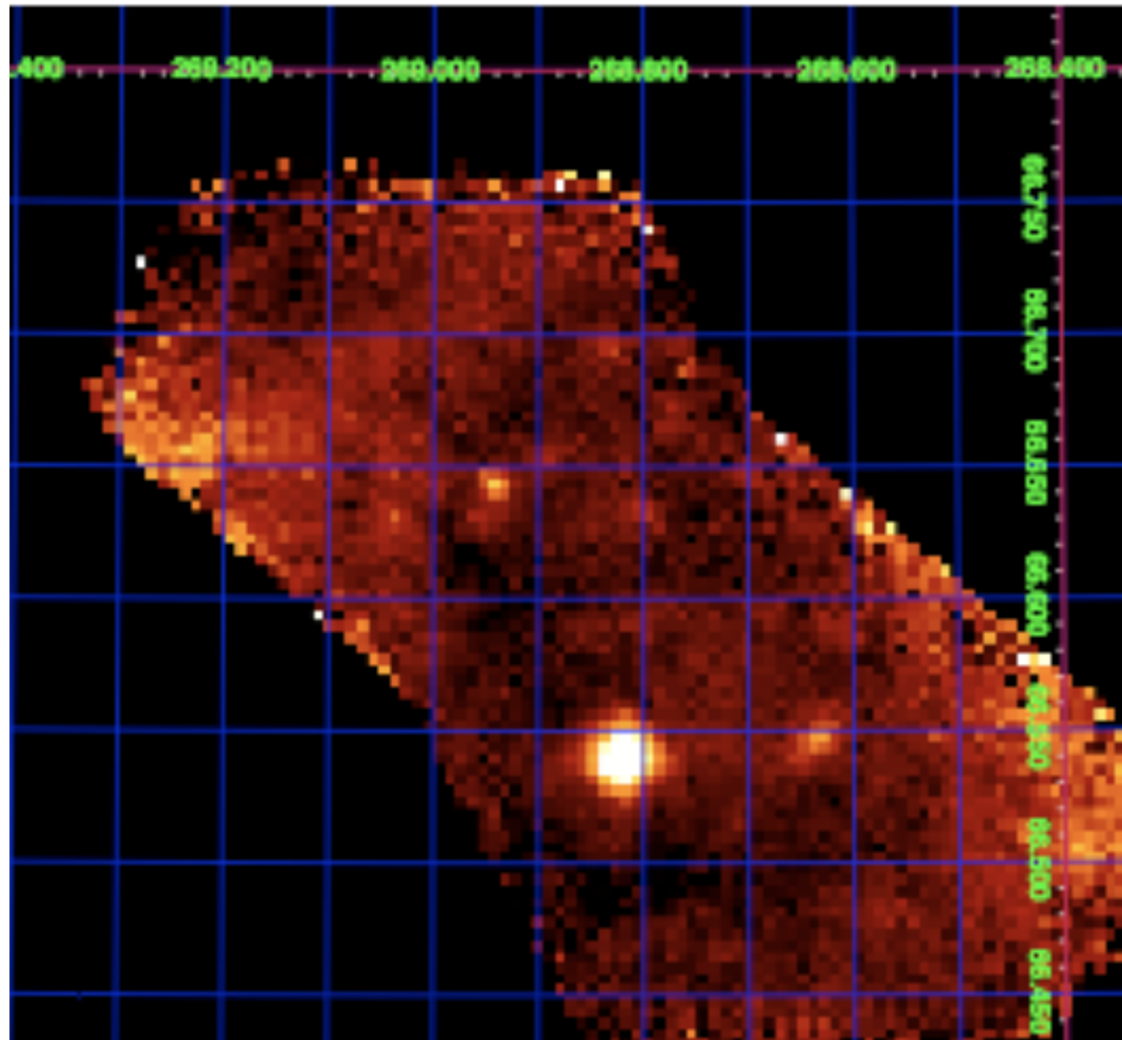
Observed fluctuation is much larger than that of zodiacal light!

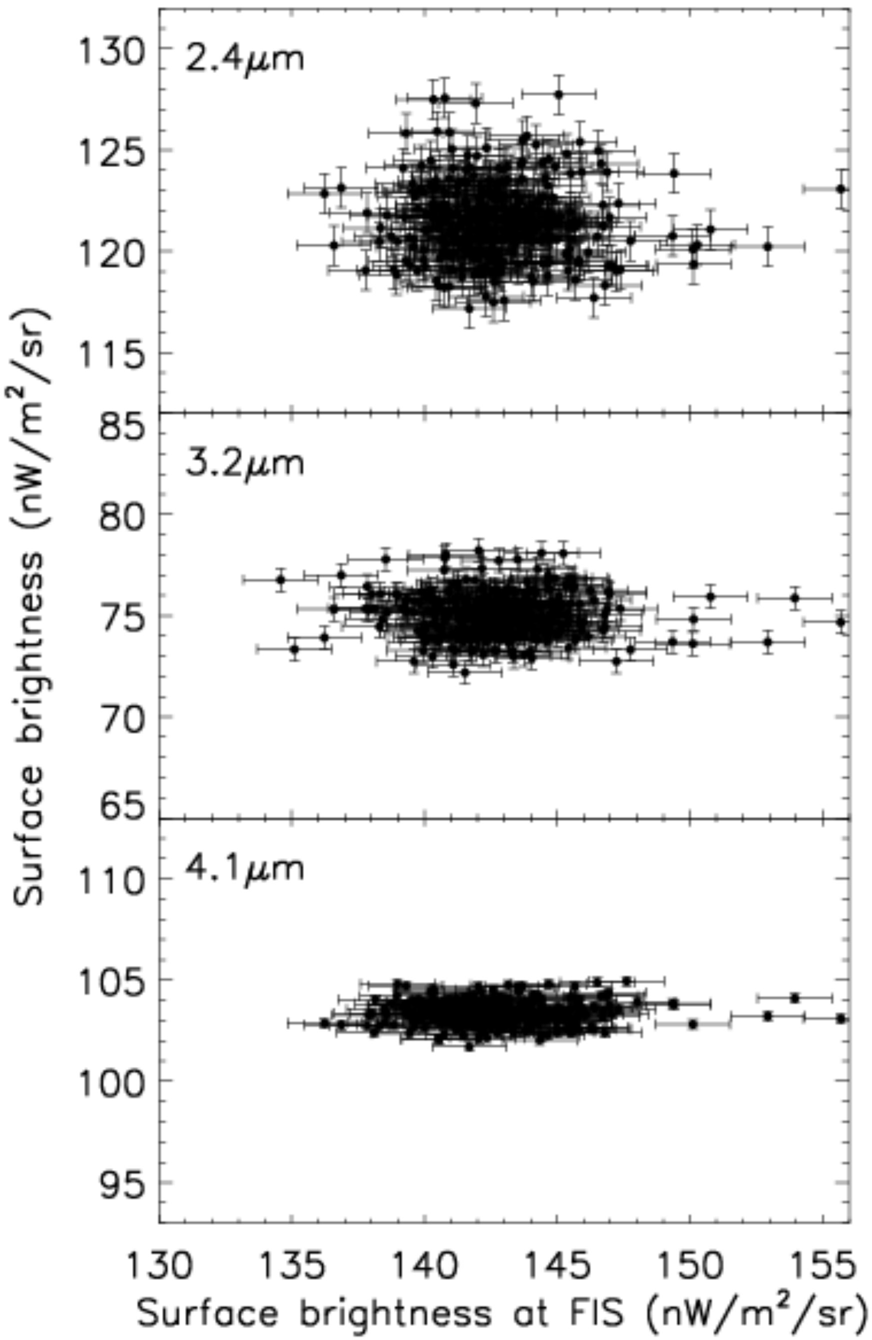
Origin of fluctuation: Diffuse Galactic Light (DGL)?

DGL is scattered star light by interstellar dust and thermal emission of dust

Dust column density correlates with thermal emission of dust

Comparison with AKARI FIS deep survey toward NEP!





There is no correlation between AKARI fluctuation and FIR emission

Fluctuation observed by AKARI is not the galactic origin!

Origin of fluctuation: clustering of faint galaxies?

Chary et al. (2008) claimed red dwarf galaxies at *z*=1~2 are origin of observed fluctuation by Spitzer

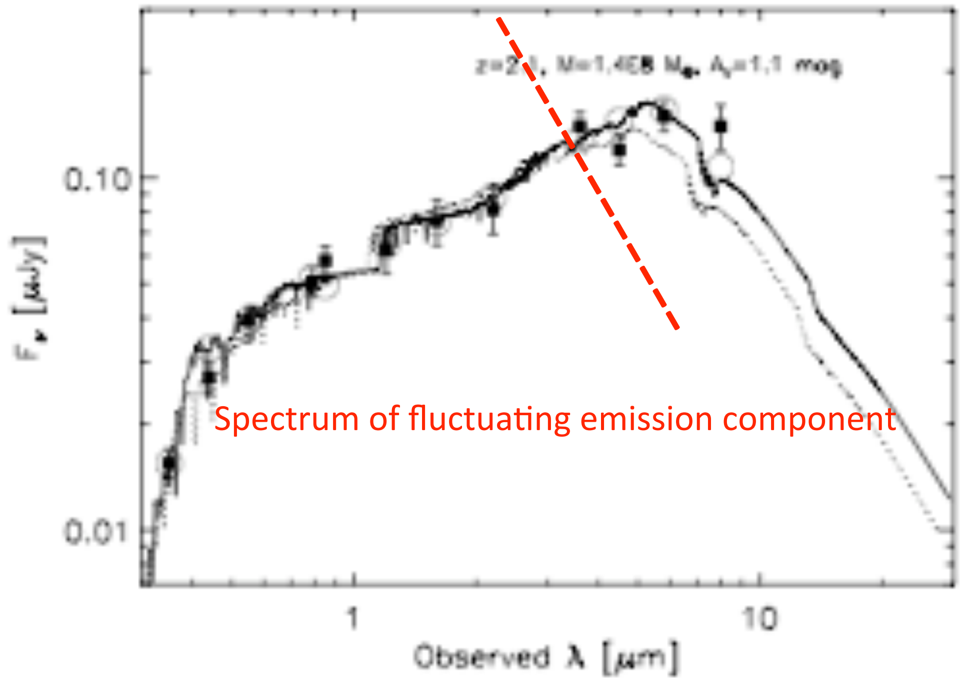
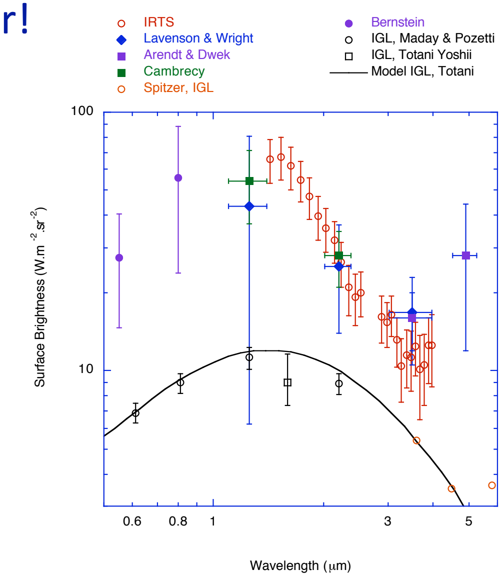


FIG. 2.—Stacked ultraviolet-to-IR flux SED of faint galaxies detected by ACS, but not detected individually by *Spitzer* IRAC in GOODS-S (*solid line and data points*). The SED is consistent with the sub-$L_{*,UV}$ galaxy population at $z \sim 2.5$. The parameters of the stacked galaxy for GOODS-S are as shown in the legend. The convolution of the fit SED with the different passbands is shown with circles. The stacking in GOODS-N results in a best-fit redshift of $z \sim 1.9$, and the SED is shown as the dotted line (See text for details).

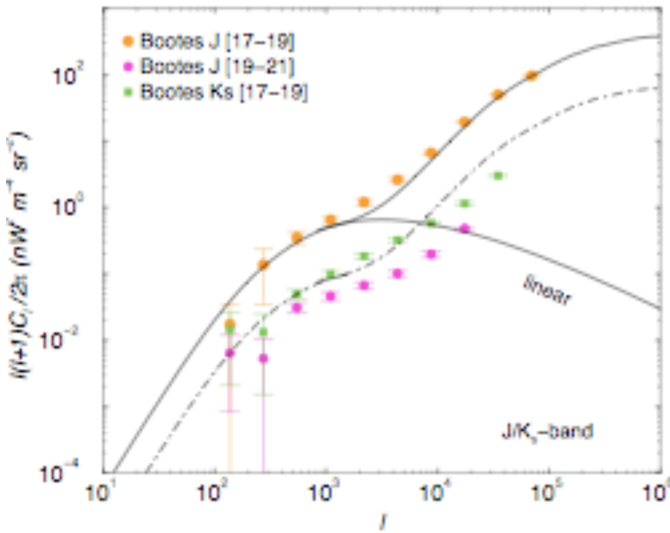
Spectrum of red dwarf galaxies is quite different from the spectrum of observed fluctuating component.

Red dwarf galaxies can not be the origin of the observed fluctuation

Ordinary low redshift galaxies have redder color!



Sullivan et al.(2007) estimated fluctuating power due to faint galaxies.

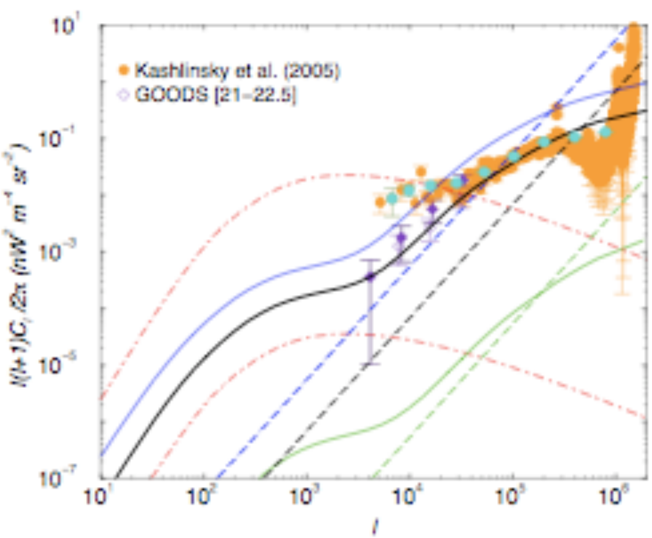


Expected fluctuation of galaxies fainter than Ks(Vega)>21 mag

0.03 nW.m^{-2}.sr^{-1} at l~1000 (600")

AKARI observation at 2.4 μm

0.2 nW.m^{-2}.sr^{-1}



At the L band

Power observed by Spitzer is significantly higher than that due to faint galaxies

Clustering is not the source of the observed fluctuation!

Expected fluctuations of zodiacal light, DGL and clustering of galaxies are significantly smaller than the observed fluctuation.

Most probable source of fluctuation is pop.III stars, and/or early population stars.

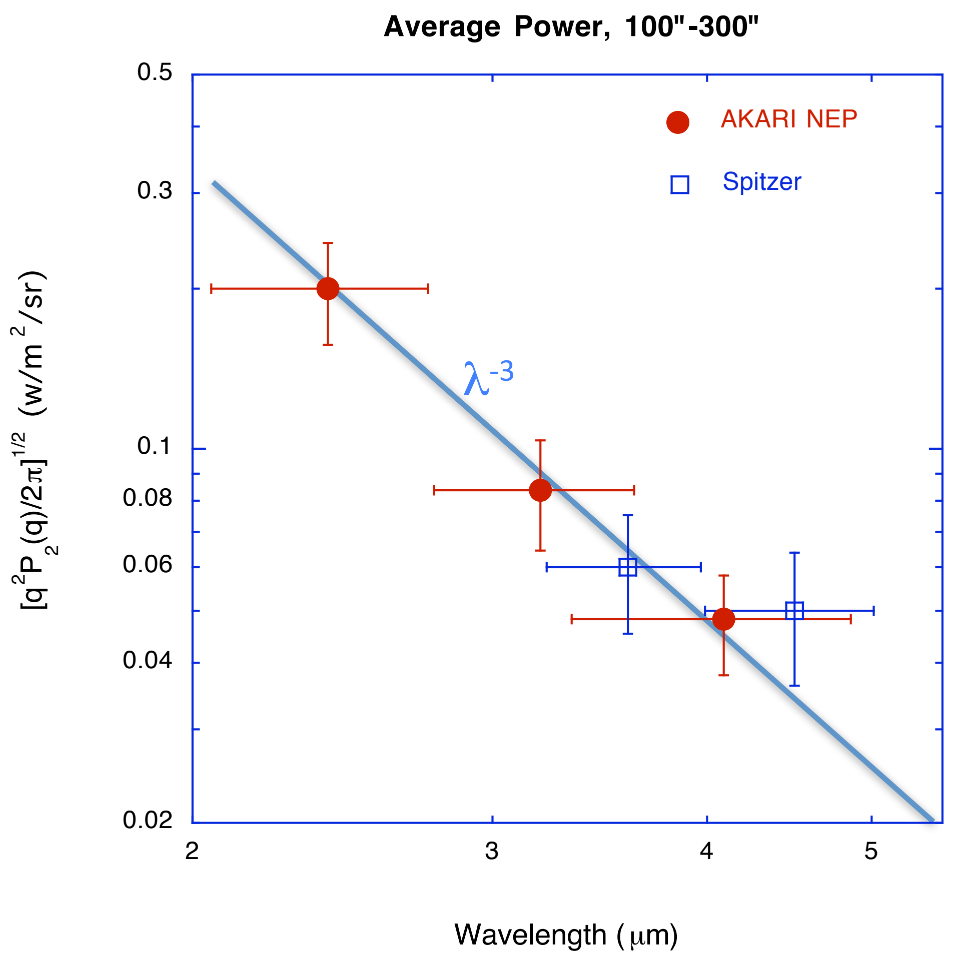
What implication on first stars AKARI fluctuation provide?

Spectrum of fluctuating component is very blue

Consistent with Spitzer result

Spectrum of fluctuating component (average value of power at >100 arcsec)

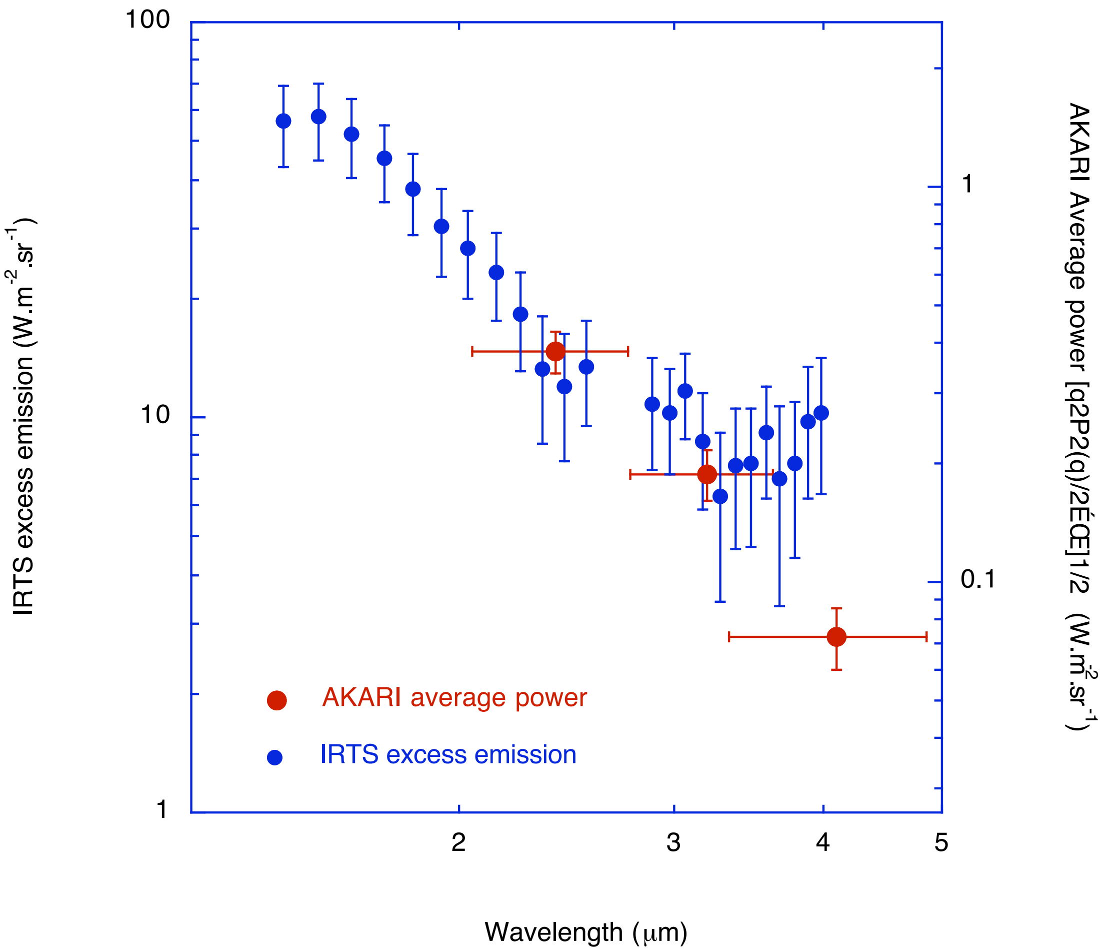
Rayleigh Jeans like spectrum ($\propto \lambda^{-3}$)

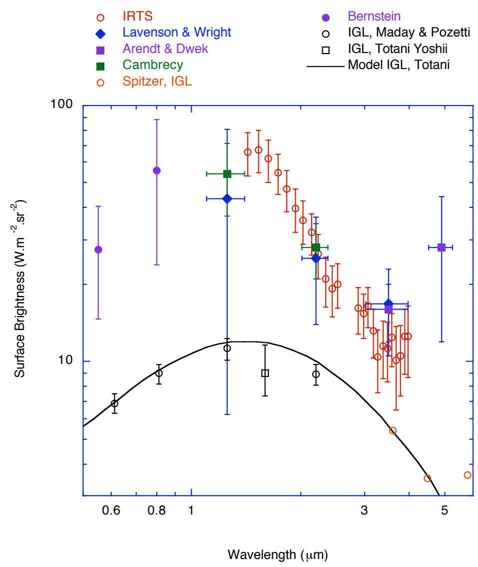


AKARI fluctuation is also consistent with NICMOS/HST (~0.4 $nW.m^{-2}.sr^{-1}$ at 1.6μm)

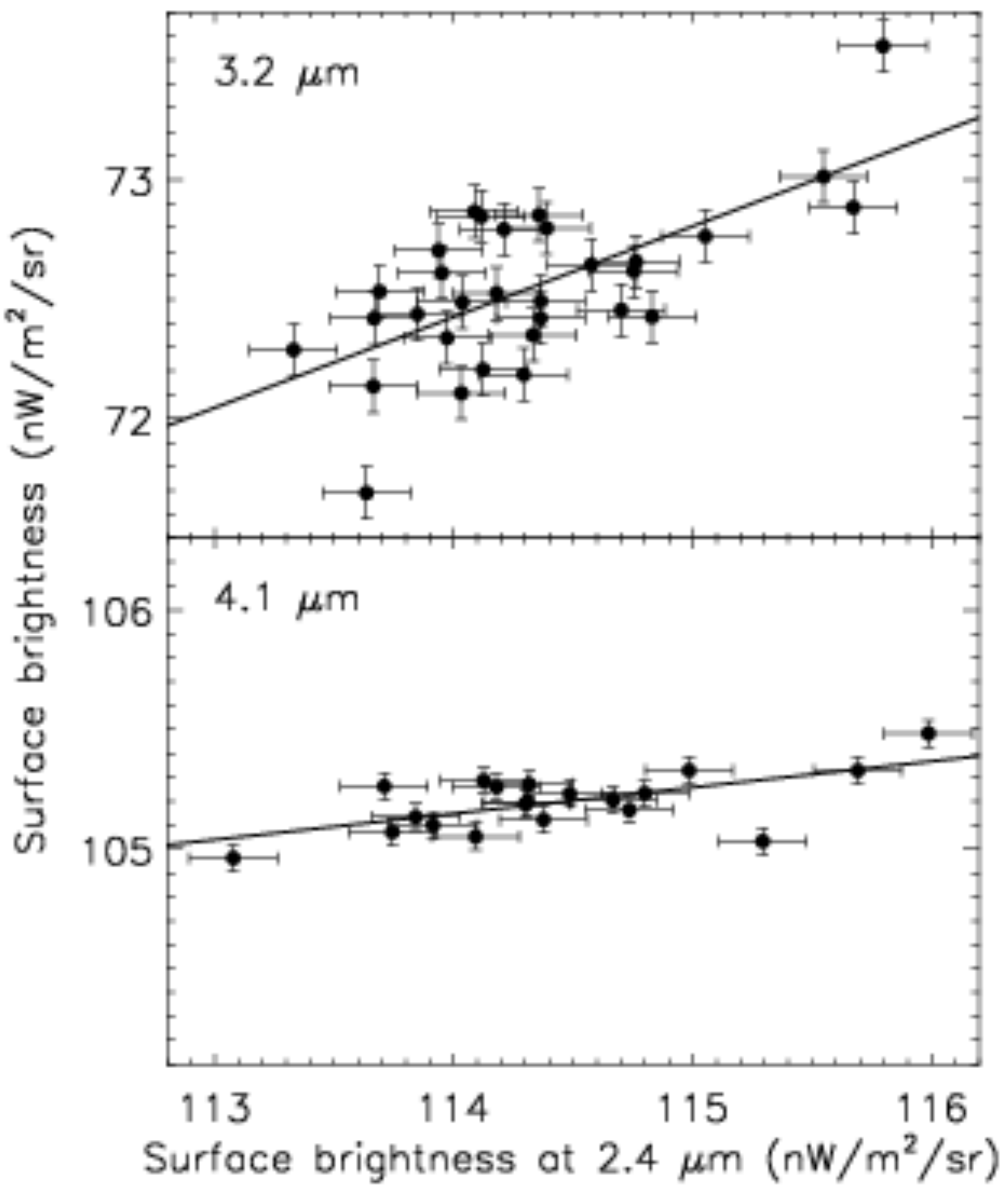
if we take small angular scale (<85 arcsec) into account.

Spectrum of large scale fluctuating component is similar to that of excess emission observed by IRTS



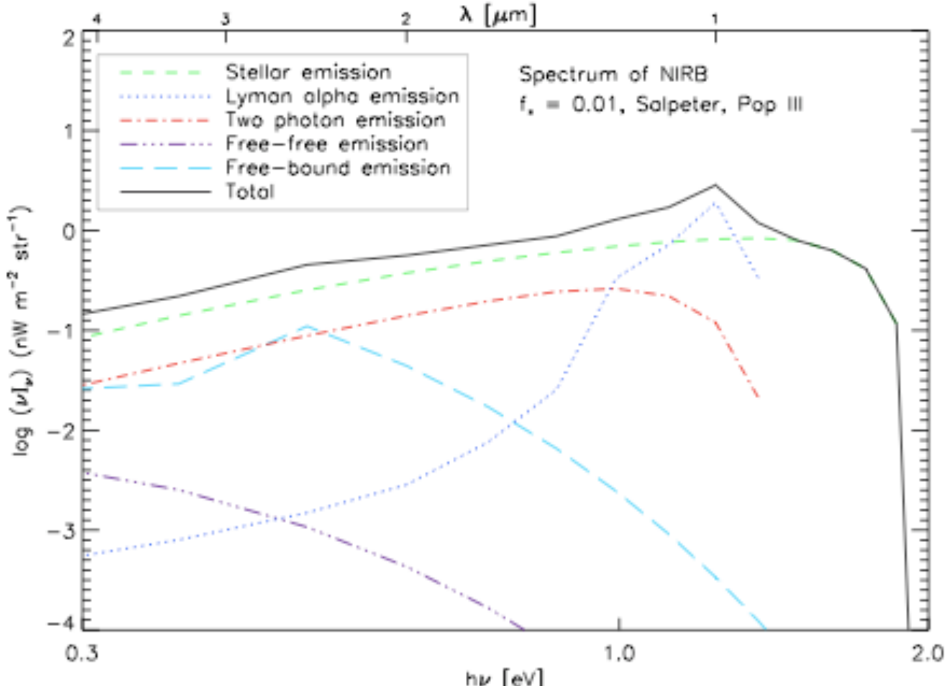


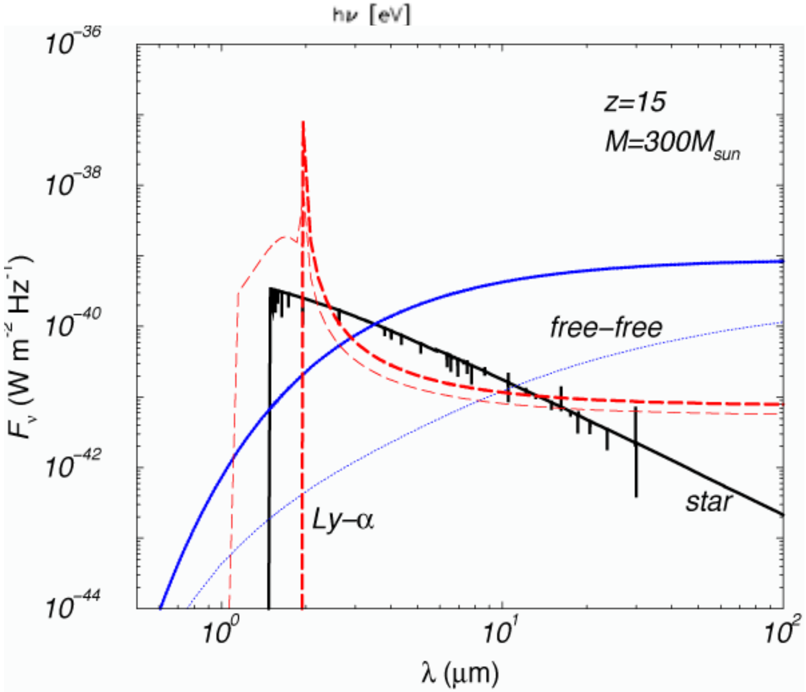
Correlation between wavelength bands



Slope : 0.380
R=0.67

Slope : 0.109
R=0.62





Spectrum
Fernandez et al. (2010)

Observed $\lambda \cdot I_\lambda \quad \sim \lambda^{-3}$

Fernandez at al. $\quad \sim \lambda^{-2}$

but model dependent

Emission source of the fluctuation AKARI detected is stars

-> good correlation between wavelength bands

Detection of **Redshifted Lyα** is important

Implication of the observed fluctuation
Comparison with theory

Cooray, Bock, Keating, Lange and Matsumoto ApJ **606**, 611 (2004)

Analytical estimation of CNB fluctuation

Linear theory

Biased star formation which traces dark matter

Fernandez, Komatsu, Iliev and Shapiro ApJ **710**, 1089 (2010)

Fernandez, Iliev, Komatsu and Shapiro ApJ **750**:20 (2012)

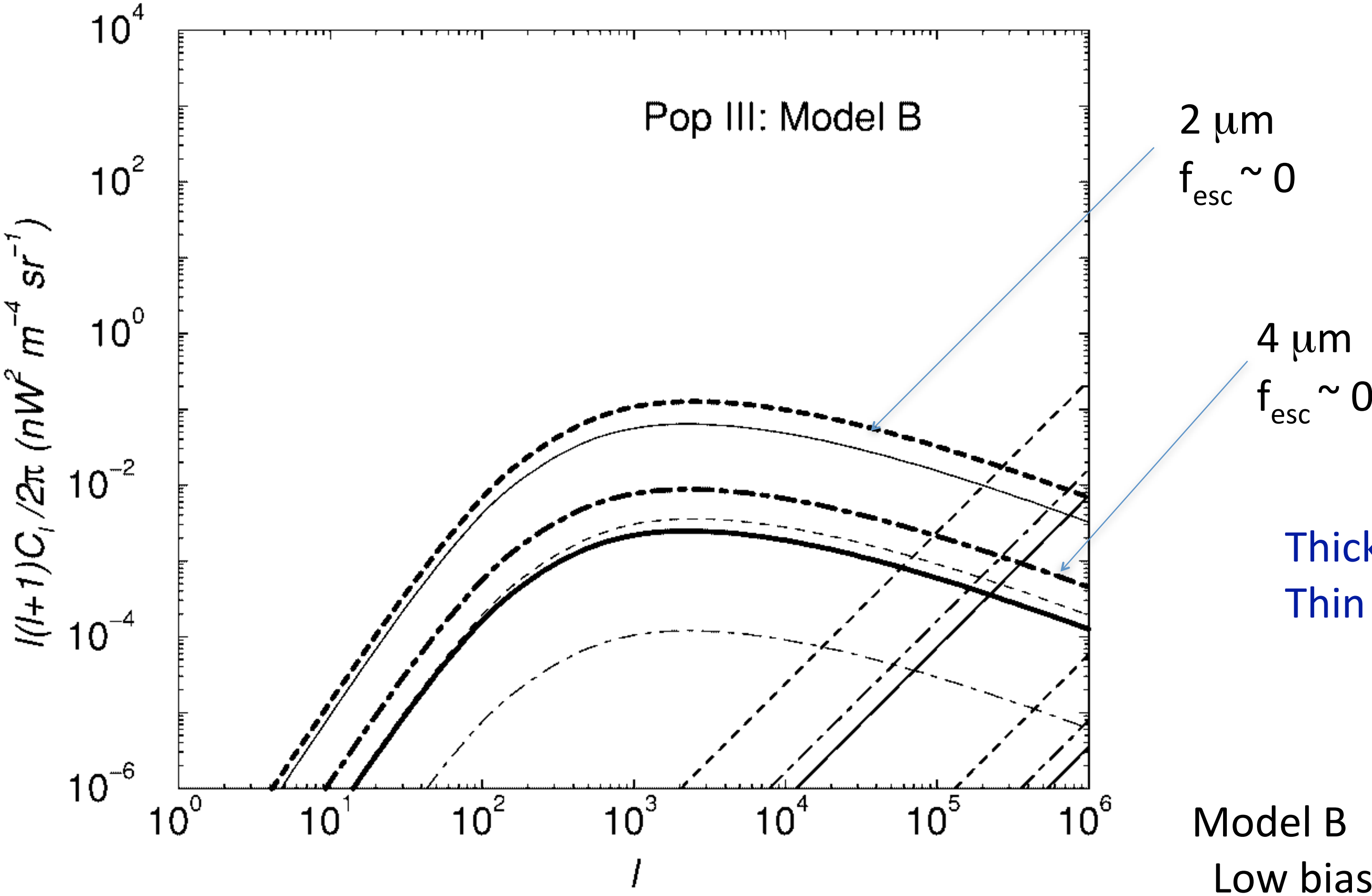
N body simulation, radiation transfer

Non linear effect

Halo mass ~ 10^8 - 10^9 solar mass

IMF Salpeter, Larson

pop.III and pop. II



Thick line fesc ~ 0
Thin line fesc ~ 1

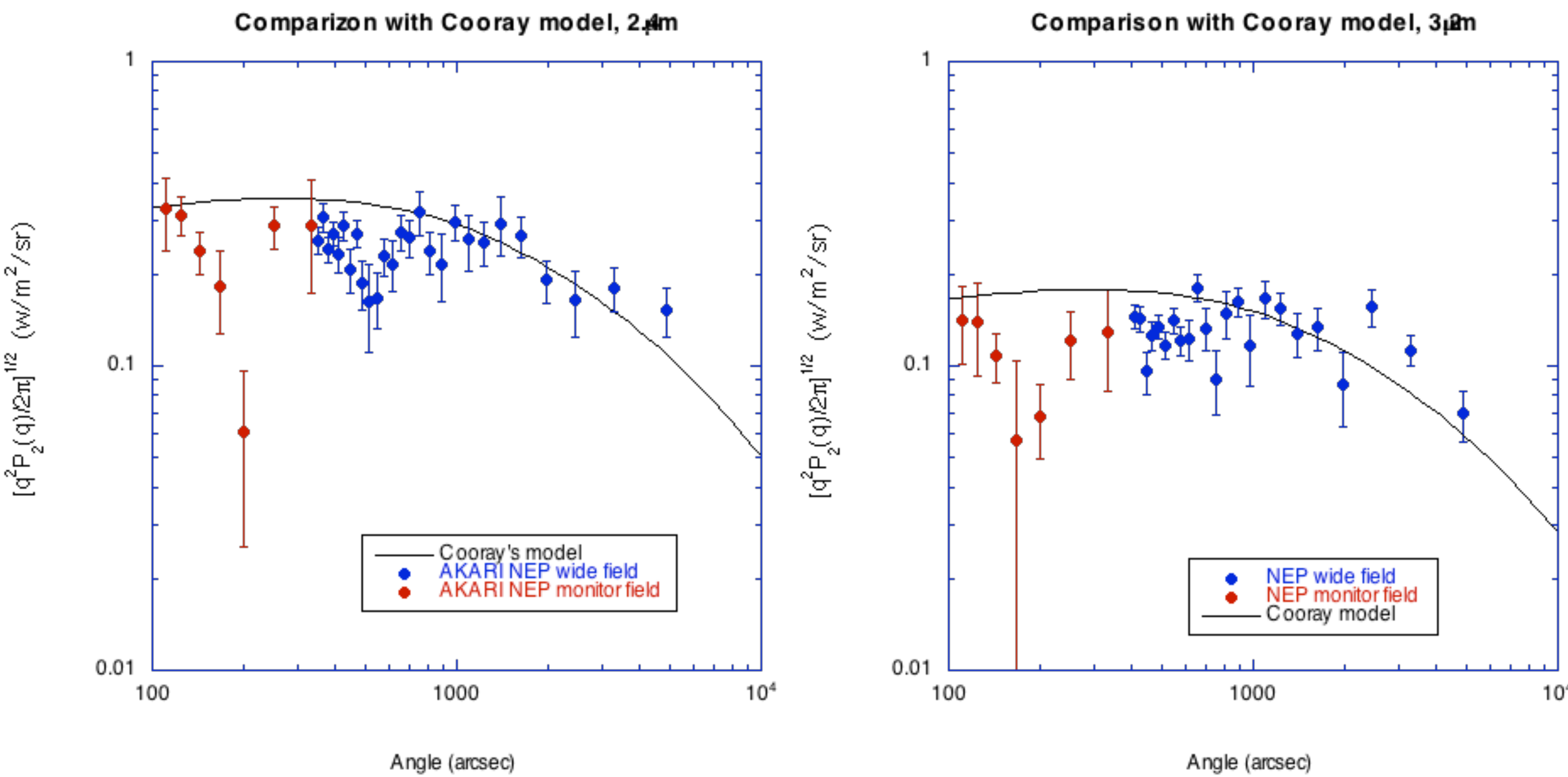
Model B (pessimistic model)
Low bias factor, T>5000K
$z_{min} \sim 15$
η (star formation rate) ~ 0.1

Prediction by Cooray et al. 2004

Peak (turn over) at several tens arcminutes

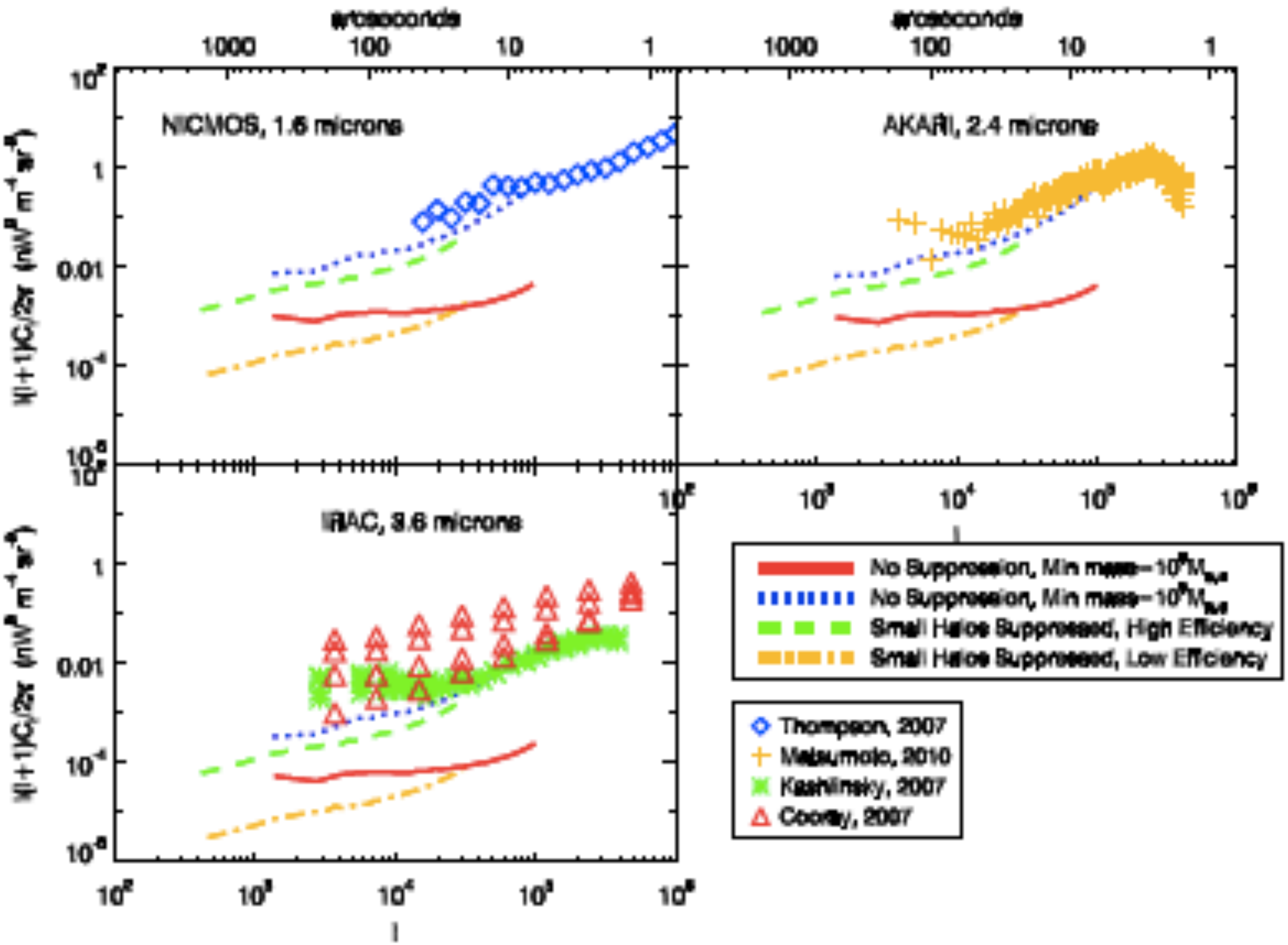
Biased star formation which traces dark matter

Comparison with theory (Cooray, private communication)



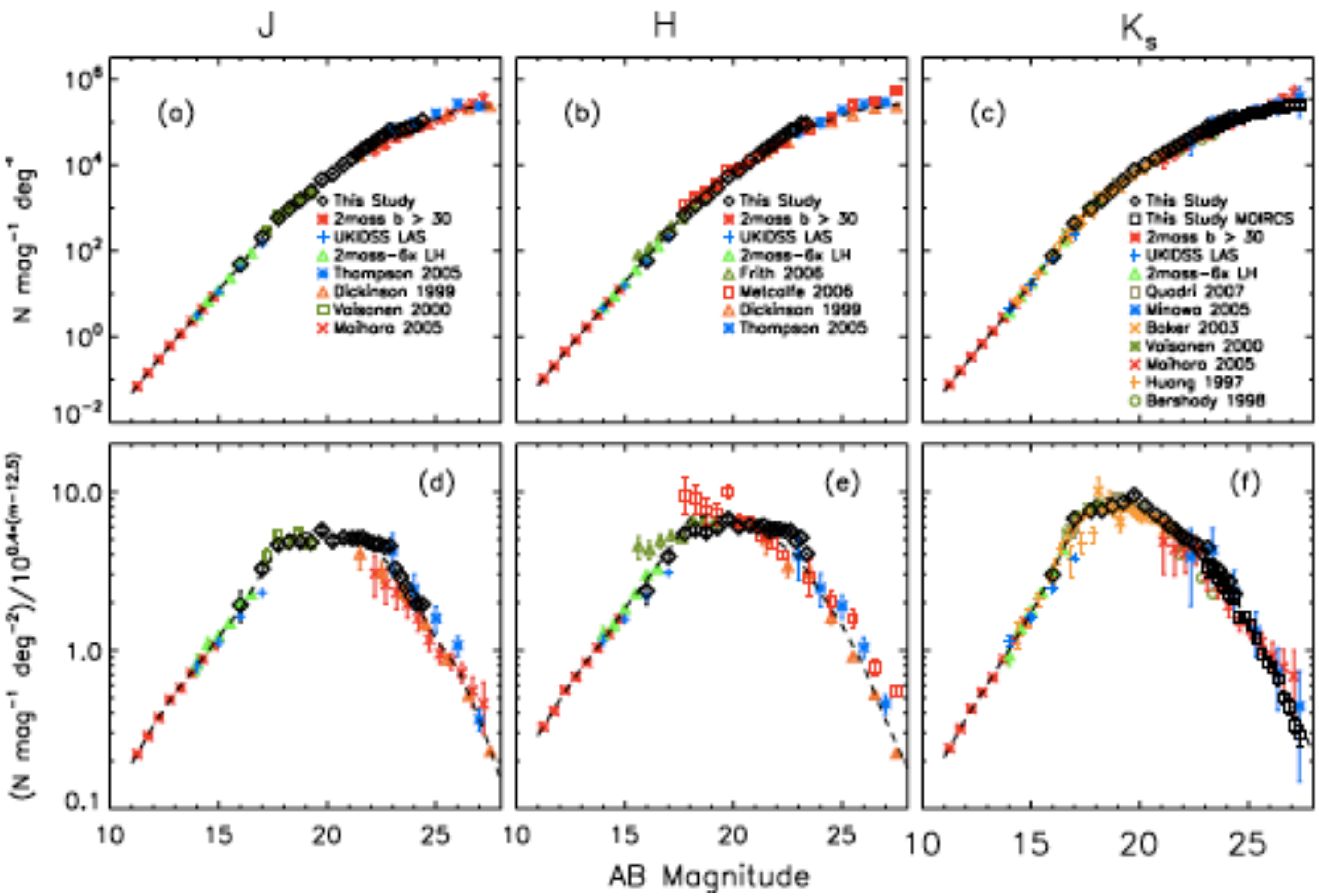
Turn over at large angles is not so clear. Observation at few degree is required. ->MIRIS

Prediction by Fernandez et al. (2012)



Absolute brightness of CNB?

Observed fluctuation is very high!



Keenan et al. （2010）

EBL (Integrated light of galaxies) amounts to ~10 nW.m^{-2}.sr^{-1} at K

Largest contribution to EBL is 17~18 mag.

Fainter galaxies than 17~18 mag have less contribution to EBL

EBL due to faint galaxies and excess fluctuation

	EBL(Keenan et al. 2010)	Fluctuation	
AKARI, 2.4 μm (lim. mag. ~23)	0.7	0.2	$nW.m^{-2}.sr^{-1}$
NICMOS/HST, 1.6 μm (lim. mag. ~28.5)	~0.04	0.4	$nW.m^{-2}.sr^{-1}$
Sullivan et al. 2.2 μm (17-19mag)	4	0.1	$nW.m^{-2}.sr^{-1}$

Simple extrapolation of logN/logS is difficult to explain observed fluctuation

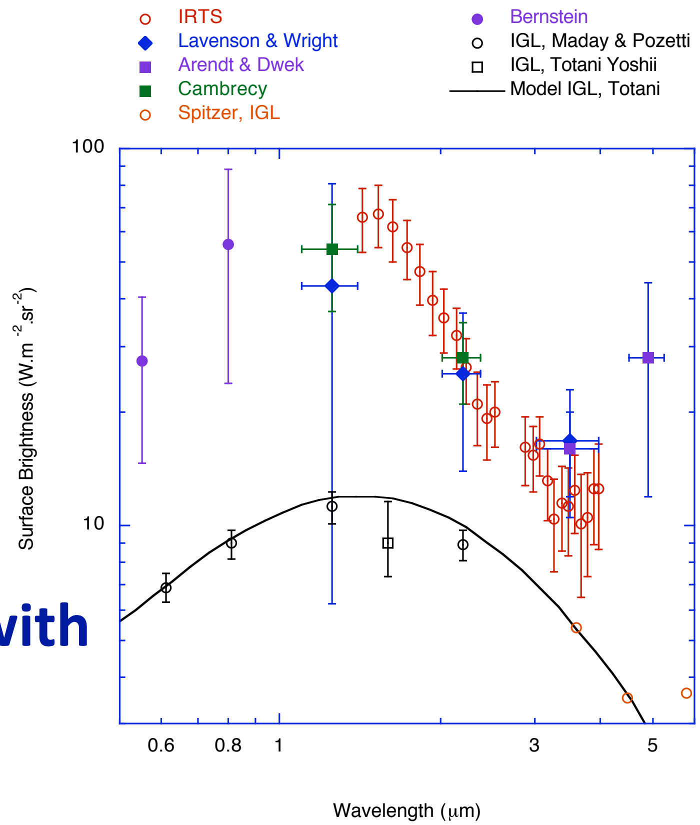
New component is required at faint end

Fernandez et al. predict $I/\Delta I > 50$

This suggests high CNB brightness

$\Delta I \sim 0.2$ nW.m^{-2}.sr^{-1}

$I > 10$ nW.m^{-2}.sr^{-1}



Consistent with excess emission observed with IRTS and COBE

Fluctuation measurement with AKARI supports high level of CNB

Conclusion

- AKARI detected excess fluctuation at large angular scale, 100 arcsec ~1.3 degree
- Detected excess fluctuation is larger than that of foreground emission sources, zodiacal light, diffuse galactic light and clustering of low redshift galaxies.
- Excess fluctuation shows flat feature, and does not show clear turn over at large angles.
- Observed fluctuation is fairly high and requires new faint sources at > 28 mag
- First star (pop.III star) is one of possible origins of observed fluctuation (10 arcmin corresponds 30 Mpc at z~10).
- Blue color of wavelength dependence of fluctuation, and good correlation between wavelength bands are consistent with model of first stars.