(Source-subtracted) CIB fluctuations and early populations

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with

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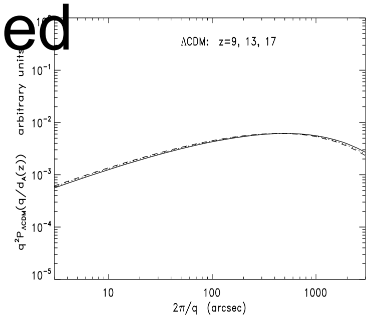
CIB fluctuations contain contributions from sources spanning the entire cosmic history
Including sources inaccessible to direct telescopic studies (now approaching z~6-8).

One particularly important class of these are sources from first star epochs, z>10 or so.

Where these sources Pop 3 stars, BHs, and in what proportions, when and how many?

Reasons why Pop 3 should produce significant CIB fluctuations

- If massive, each unit of mass emits $L/M \sim 10^5$ as normal stars ($\sim L_\odot/M_\odot$)
- Pop 3 era spans a smaller volume ($\Delta t <\sim 0.5$ Gyr), hence larger relative fluctuations
- Pop 3 systems form out of rare peaks on the underlying density field, hence their correlations are amplified



Population 3 could leave a unique imprint in the CIB structure
Measuring it would offer evidence of and a glimpse into
the Pop 3 era (Cooray et al 2004, Kashlinsky et al 2004)

CIB anisotropies contain two terms:

- Shot noise

from galaxies occasionally entering the beam

$\delta F/F \sim 1/N_{beam}^{1/2}$

(specifically : $P_{SN} = \int S^2(m)\, dN/dm\, dm \sim S\, F_{CIB} \sim n\, S^2$)

- Clustered component

Reflects clustering of the emitters, their epochs and how long their era lasted

Evaluated using the Limber equation: depends on the underlying 3-d power spectrum (LCDM) and the rate of flux production integrated over the z-span of emitters

Early pre-Spitzer attempts

- Shectman (1973,1974) was the first to deduce EBL from optical fluctuations measurements
- Kashlinsky et al (1996a,b,2000) applied similar methods to measure/constrain CIB fluctuations at ~0.5 deg from DIRBE data ***– large beam, no foreground galaxies can be removed***
- Matsumoto et al (2000) measured power spectrum of CIB fluctuations on ~ degree scales from IRTS data – ***again, large beam, no foreground galaxies can be removed***
- Kashlinsky et al (2002), Odenwald et al (2003) applied them to deep 2MASS at J,H, K bands (1-2 micron) – foreground galaxies remove sources to ~ m_{Vega}~18.5 on sub-arcmin scales. ***But atmospheric fluctuations in these ground-based data prevent measurements on larger angular scales or further foreground galaxy removal.***
- Thompson et al (2007) reconstructed CIB fluctuations from galaxy populations observed in HUDF data at 1.6 mic***. Good agreement with deep 2MASS-based detections, but cannot measure fluctuations at scales > 1 arcmin as the field is small.***

- **HENCE, ON TO *Spitzer:***

First results on cosmic infrared background fluctuations from deep Spitzer images (cryogenic era)

A. Kashlinsky, R. Arendt, J. Mather & H. Moseley

(Nature, 2005, 438, 45; ApJL, 2007, 654, L1; 654, L5; 666, L1 – KAMM1-4)

R. Arendt, A. Kashlinsky, H. Moseley & J. Mather

(2010, ApJS, 186,10 – AKMM)

Results briefly:

- Source-subtracted IRAC images contain significant CIB fluctuations at 3.6 to 8μm.
- These fluctuations come from populations with significant clustering component but only low levels of the shot-noise component.
- There are no correlations between source-subtracted IRAC maps and ACS source catalog maps (< 0.9 μm).
- These imply that the CIB fluctuations originate in populations in either 1) 1st 0.5 Gyr or z>6-7 (t<0.5 Gyr), or 2) very faint more local populations not yet observed.
- If at high z, these populations have projected number density of up to a few arcsec^{-2} and are within the confusion noise of the present-day instruments.
- JWST can resolve them (beam<0.04”).
- ***But so far there is no direct info on the epochs of these populations***

Requirements for CIB fluctuations studies – in order to measure signals as faint as those expected from P3 era

MAP ASSEMBLY

- Maps must be assembled removing artifacts to below ~ 0.01-0.02 nW/m^2/sr
- No correlations should be introduced in map construction
- Filters (e.g. median) which remove confusion populations *must* be avoided

ANALYSIS TOOLS

- Instrument noise (A-B) must be evaluated and subtracted from P(q)
- Proper tools must be used for computing the signal: FFT only when >70% of pixels are left; correlation functions otherwise
- Beam must be reconstructed and its small and large-scale properties evaluated

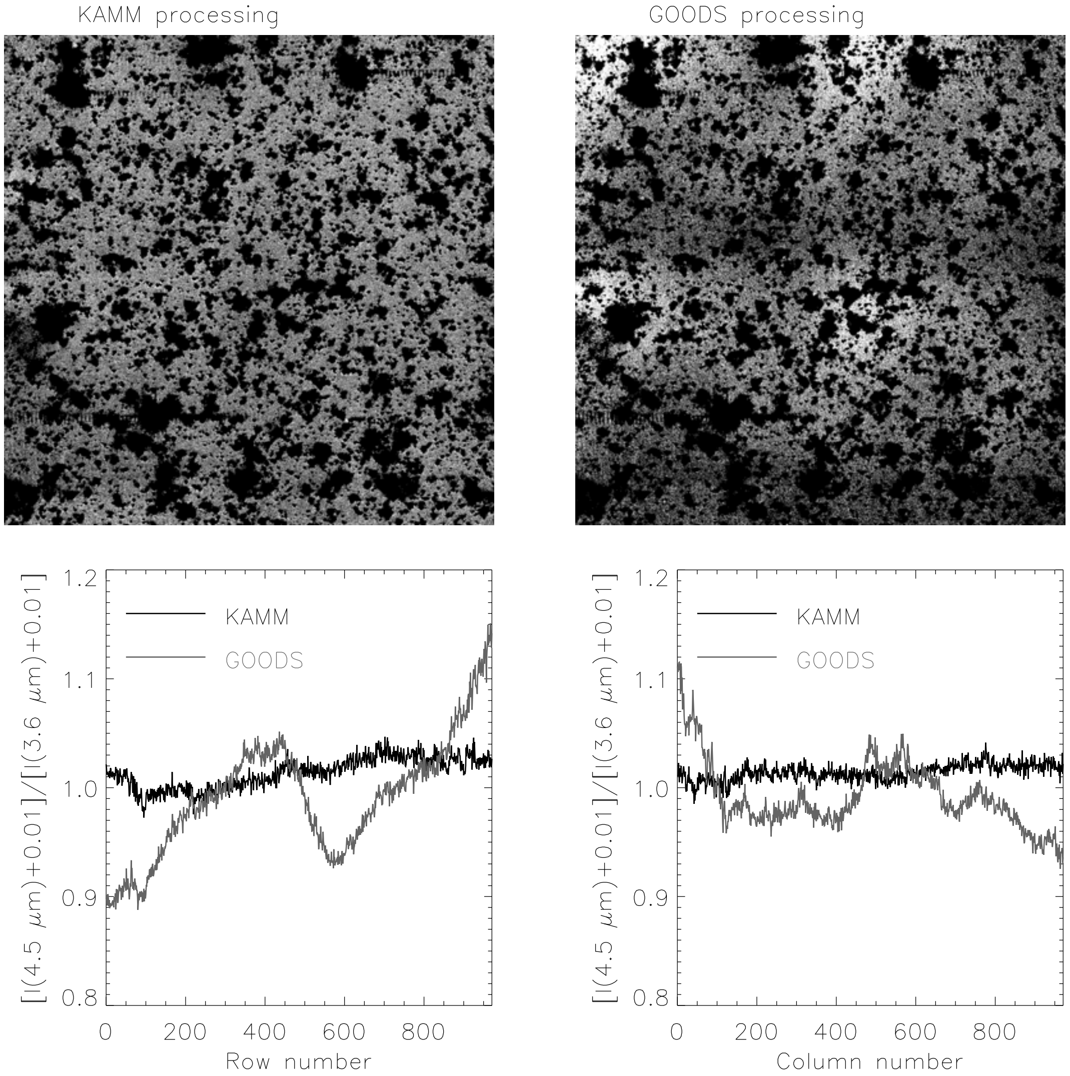
INTERPRETATION

- Cosmological signal must be tested for isotropy wherever possible
- End-to-end simulations must be done to prove that no artifacts mimic the signal
- Foreground contributions must be estimated: cirrus (e.g. 8μm) and zodi (via E1-E2)
- Observations need to be done in one epoch to avoid zodiacal gradients

IRAC image processing:

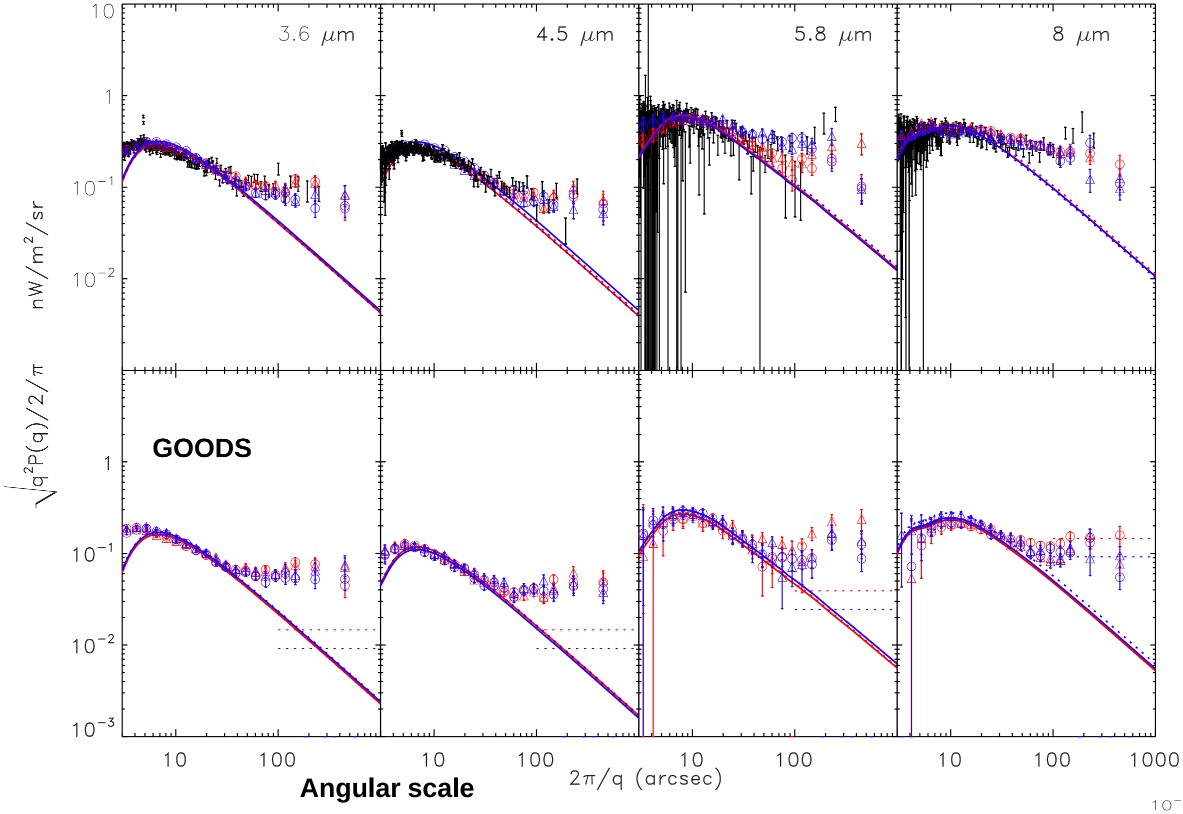
- Data were assembled using a least-squares self-calibration methods from Fixsen, Moseley & Arendt (2000).
- Selected fields w. homogeneous coverage.
- Individual sources have been clipped out at $>N_{cut}\sigma$ w N_{mask} =3-7
- Residual extended parts were removed by subtracting a “Model” via CLEAN algorithm iteratively identifying brightest pixel and subtracting a fixed fraction of normalized PSF from that location in image.
- Clipped image minus Model had its linear gradient subtracted, FFT’d, muxbleed removed in Fourier space and P(q) computed.
- Using SExtractor constructed a source catalog to identify the magnitude ceiling of the removed sources (and remaining shot noise)
- In order to reliably compute FFT, the clipping fraction was kept at >75% (N_{cut}=4)
- Noise was evaluated from difference (A-B) maps
- With GOODS data find the same signal at different detector orientations
- Note: for GOODS data E1 and E2 data must be treated separately because of the (very) different zodiacal gradients.

Comparison of self-calibration w standard image assembly



(Median across the array) From Arendt et al (2010)

Results for GOODS (4 fields - color symbols) and QSO1700 field (black symbols)



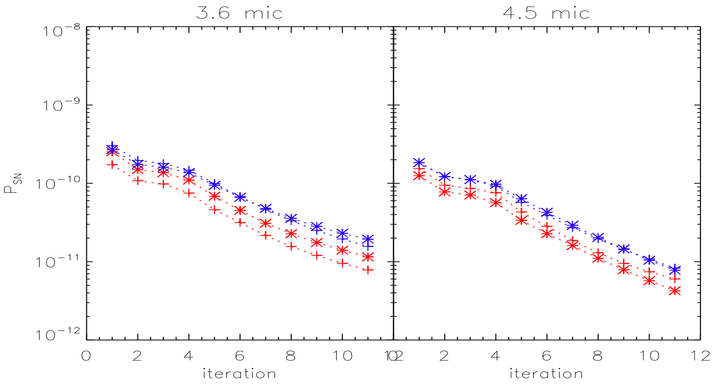
Sources are removed to m_{AB}~25-26

Shot noise reached in QSO1700

P_{SN} (3.6μm) ≈ 6 x 10^{-11} nW²/m⁴/sr

Shot noise reached in GOODS:
HDFN-E1, HDFN-E2
CDFS-E1, CFDS-E2

P_{SN} (3.6μm) ≈ 2 x 10^{-11} nW²/m⁴/sr



Fluctuations are made up of two components:

1) Remaining shot noise (scales < 20 arcsec)
2) Fluctuations arising from clustering (>0.5 arcmin)

Remaining shot noise is : $P_{SN} = \int S^2(m)\, dN/dm\, dm$

Different datasets must be compared at the same P_{SN}.

Spitzer/IRAC GOODS vs *HST*/ACS GOODS

(Kashlinsky, Arendt, Mather & Moseley 2007, Ap.J.Letters, 666, L1)

- GOODS fields were observed by ACS/*HST* at B,V,i,z (0.4 to 0.9 micron)
- We selected four regions (HDFN-E1,2; CDFS-E1,2) of 972 0.6” pixels on side (10’)
- Used ACS source catalog (Giavalisco et al 2004) to produce ACS maps for the fields
- Convolved ACS source maps with IRAC 3.6 and 4.5 beams
- Processed IRAC maps as in KAMM and computed fluctuations and cross-correlation

Results

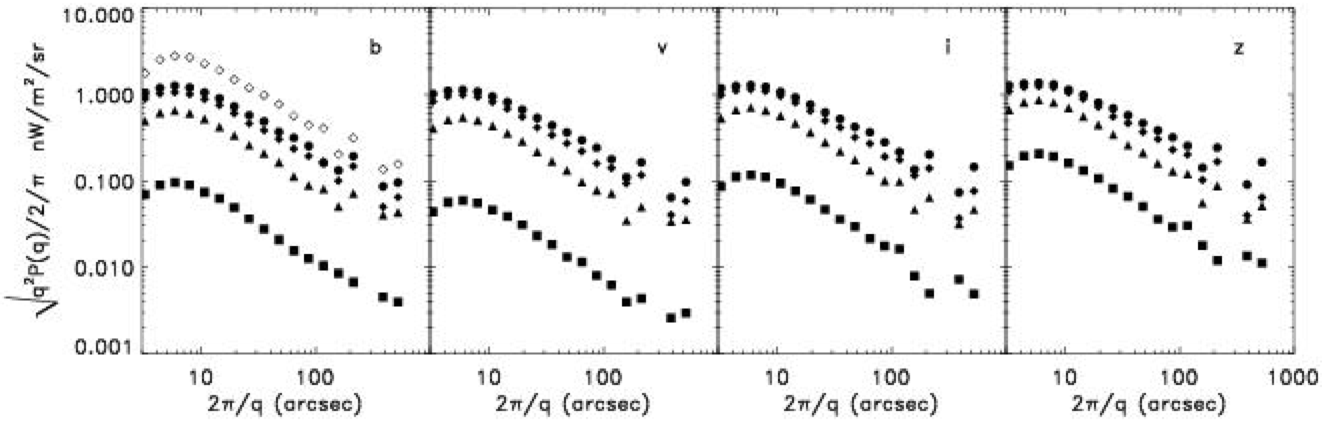
- Source-subtracted IRAC maps have different power spectra than those in ACS
- The amplitude of CIB fluctuations than can be contributed by ACS sources is small
- There are very good correlations between ACS sources and the sources removed by KAMM, but
- Completely negligible correlations between ACS and source-subtracted IRAC maps

Conclusions

- ACS sources cannot contribute significantly to KAMM IRAC fluctuations

No correlations with ACS maps out to ~0.9 micron (Kashlinsky et al 2007c – KAMM4

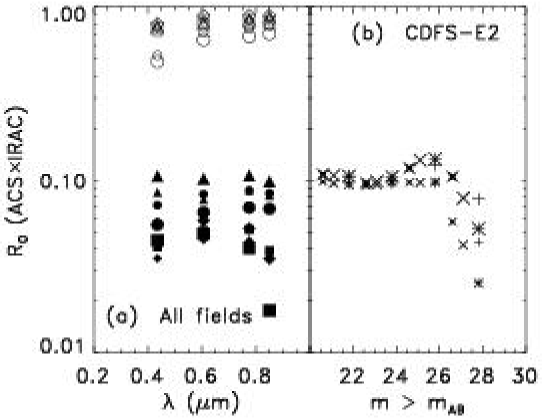
ACS source maps.
• $m_{AB}>22$
♦ $m_{AB}> 24$
▲ $m_{AB} > 26$
■ $m_{AB} > 28$
◊ $m_{AB} > 24$, no mask

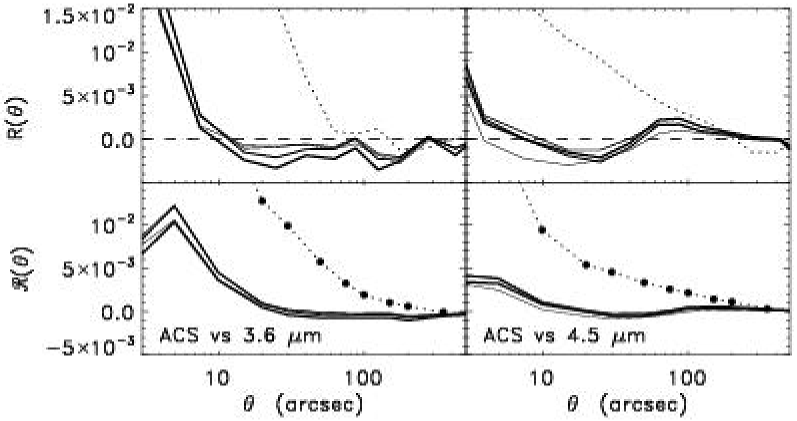


Cross-correlation
$R(\theta)=\langle\delta_{IRAC}(x)\delta_{ACS}(x+\theta)\rangle/\sigma_{IRAC}\sigma_{ACS}$

ACS vs KAMM sources (open symbols).
ACS source maps vs source subtracted IRAC data (filled).

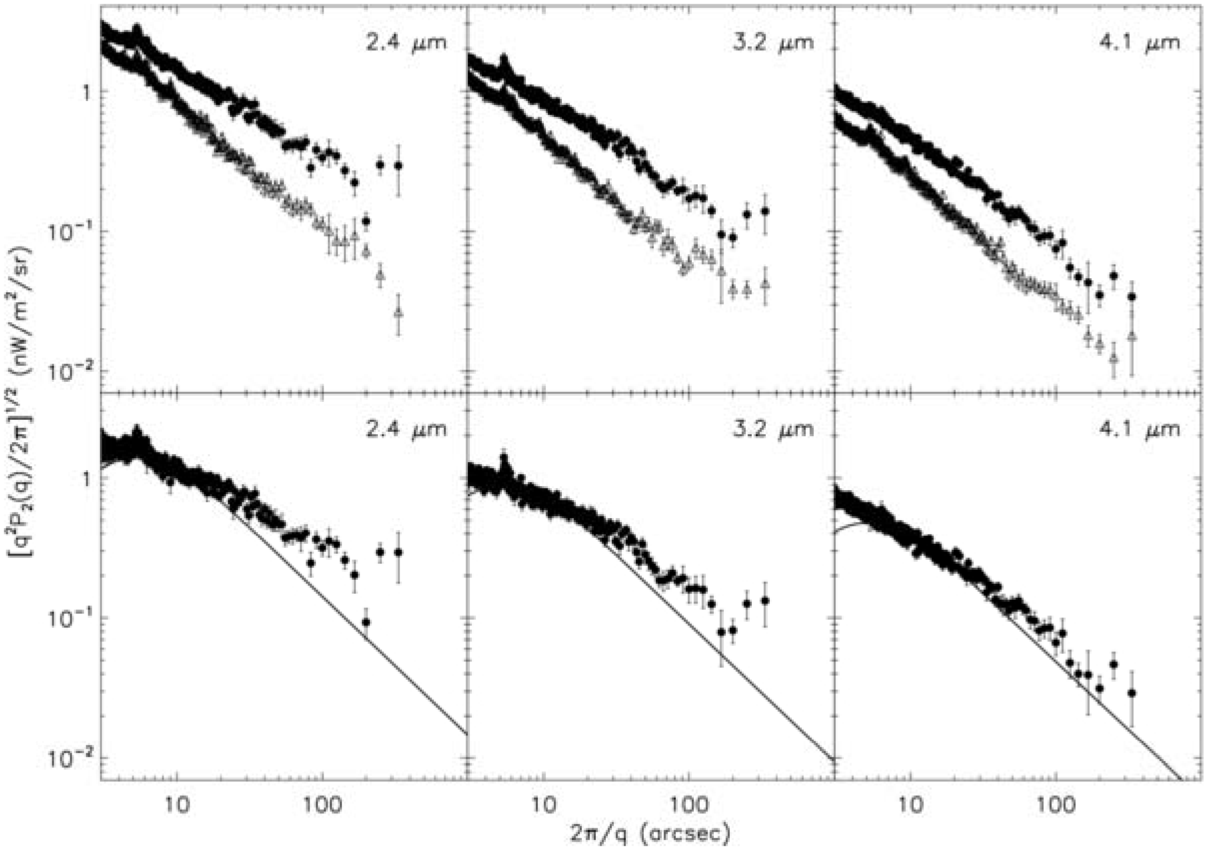
Solid lines: ACS B,V,I,z,
Dotted line: IRAC Ch 1



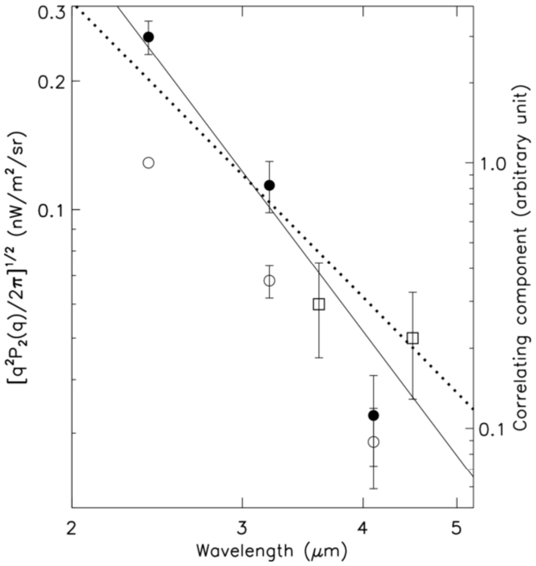


AKARI results (Matsumoto et al 2011)

Different instrument, three channels. Remove sources to m_{AB} ~23-24 and find similar CIB fluctuation excess to 300 arcsec.



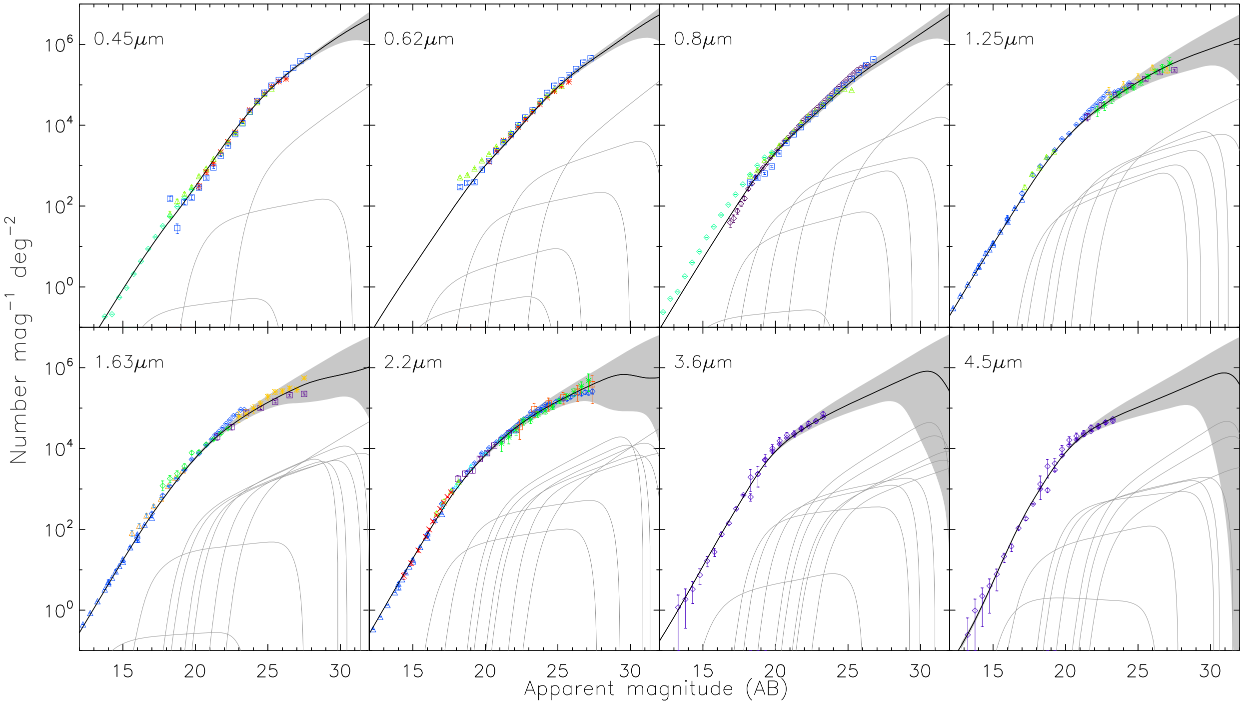
Color from 2.4 to > 4 mic is consistent with high-z sources:



Contributions from ordinary galaxies (Helgason et al 2012)

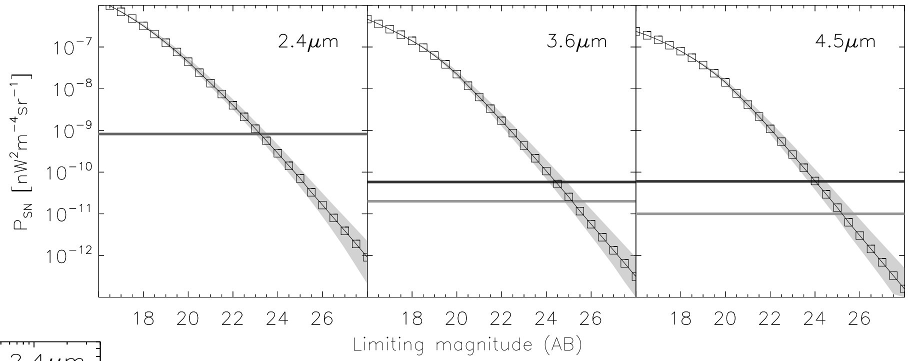
- Use 230 (!) LF datasets spanning 1) wavelengths from UV to 4.5 mic, 2) z from 0 to ~5, 3) m to ~27 AB
- Finds overall consistency between the data with Schechter-type LF w evolving parameters
- Reconstruct the emission over the (λ, z) plane and shift them to the observer NIR from 1-5 mic
- Check for and find consistency with galaxy counts from 0.45 to 4.5 mic (and other data as well)

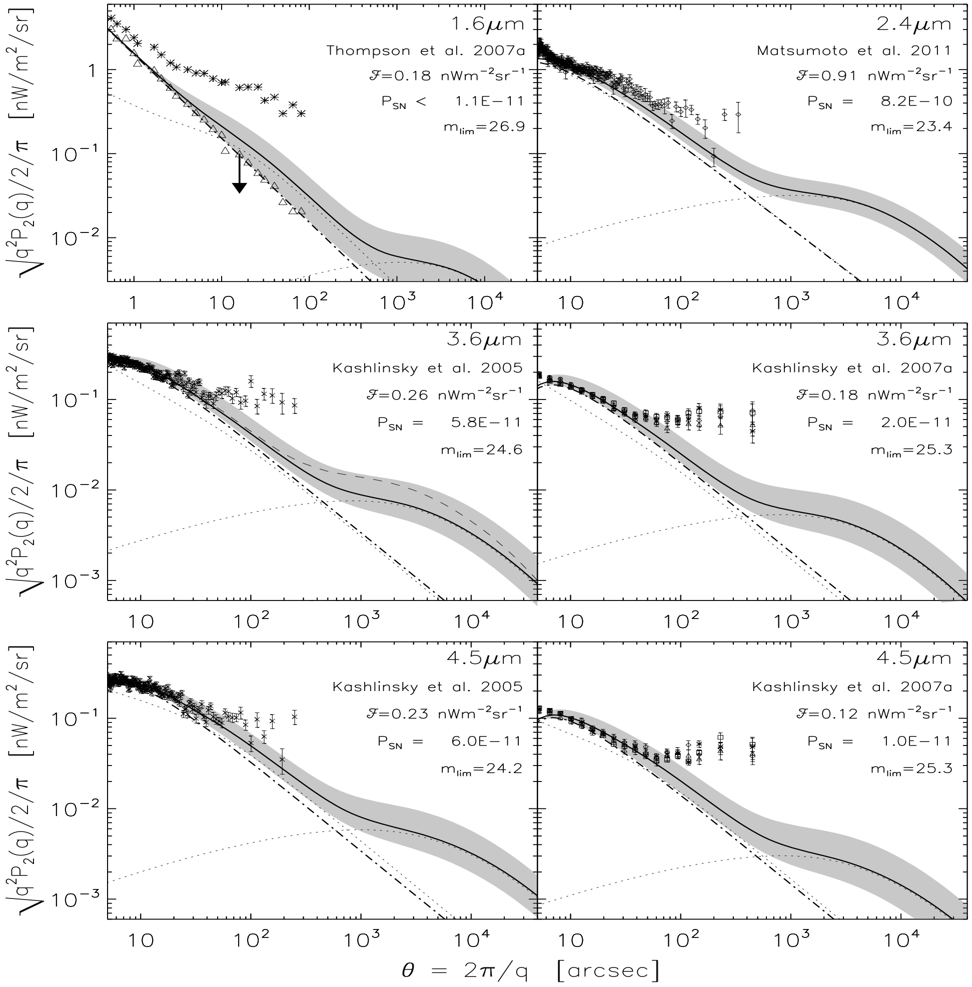
- *Then with that input can robustly compute the remaining (at the measured snot-noise) CIB fluctuations at NIR observer bands assuming the established LCDM power spectrum with 1) high-faint end of the LF data and 2) low-faint end.*



Fits to the observed counts from 0.45 to 4.5 mic. Shaded region spans the low-faint end to high-faint end allowed limits of the LF data.

Shot-noise vs AB magnitude compared to Spitzer and AKARI levels.





CIB fluctuations from ordinary (known) galaxy populations at observed shot-noise levels compared to measurements from 1.6 to 4.5 micron. Shaded region shows the spread due to high/low-faint end of LF data.

The excess at scales > 20-30 armin is obvious.

From Helgason et al (2012).

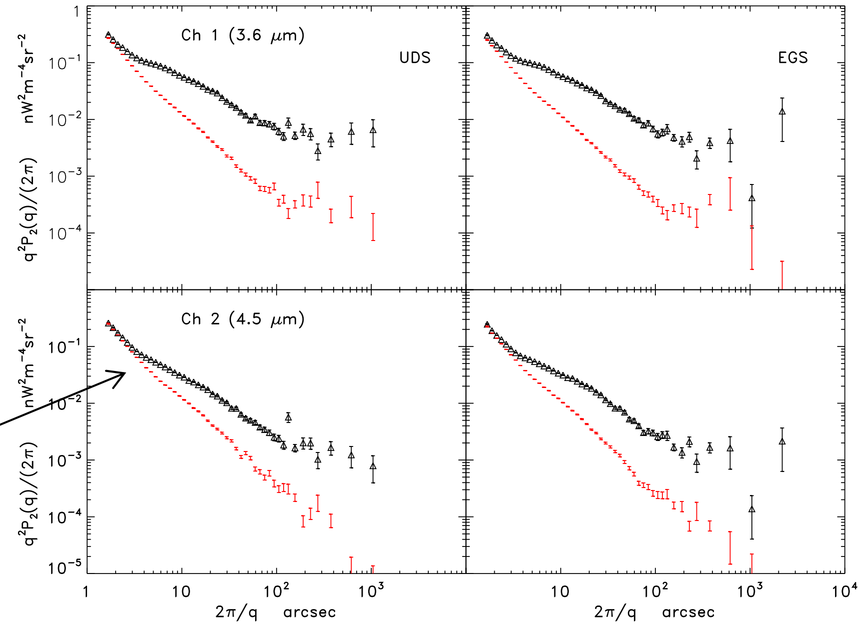
New ***Spitzer/SEDS*** results (Kashlinsky et al 2012, arxiv:1201.5617)

Two regions, UDS and EGS, observed at 3 epochs (separated by 6 months) during Spitzer warm mission.

Integration ~ 12 hrs/pixel (total)

UDS: square of 21’ on the side
EGS: rectangle of 8’ x 1 deg

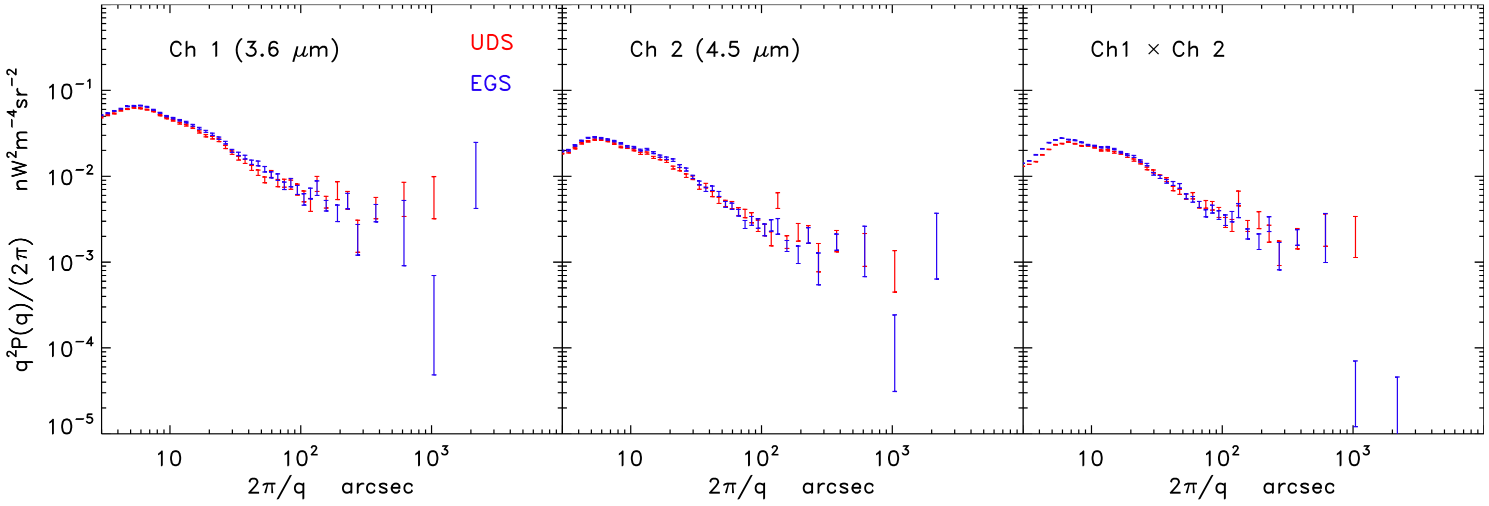
P_{A+B} in black; P_{A-B} in red



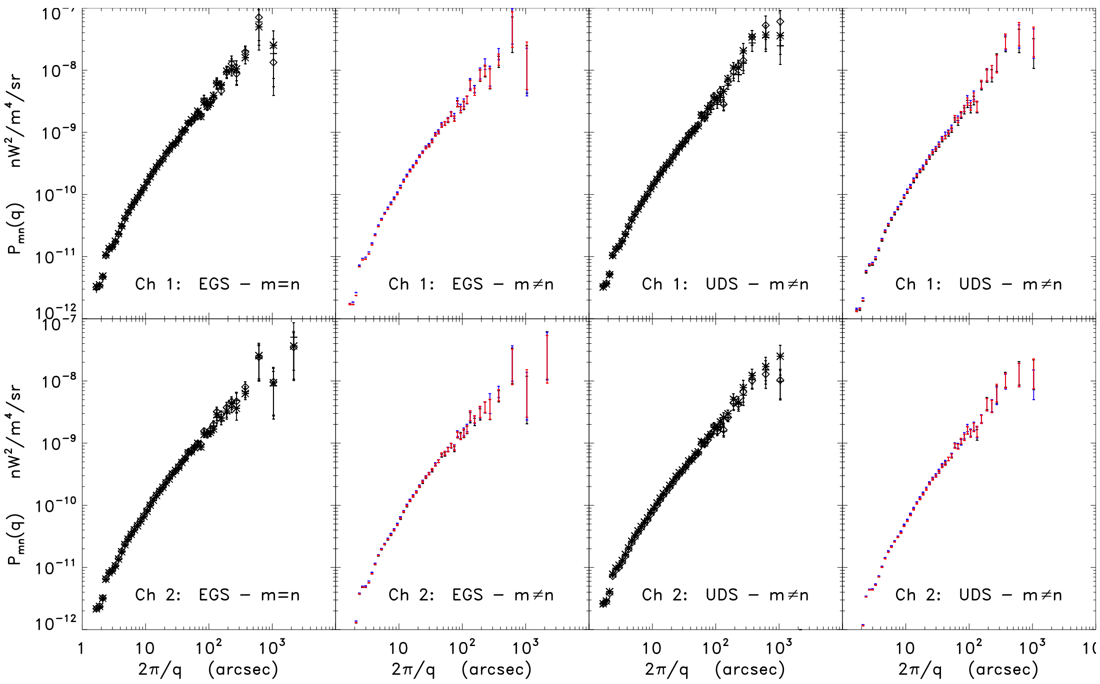
After subtracting noise:

$P = P_{A+B} - P_{A-B}$

Same signal appears in Ch1 and 2 !



From Kashlinsky et al (2012) - continued

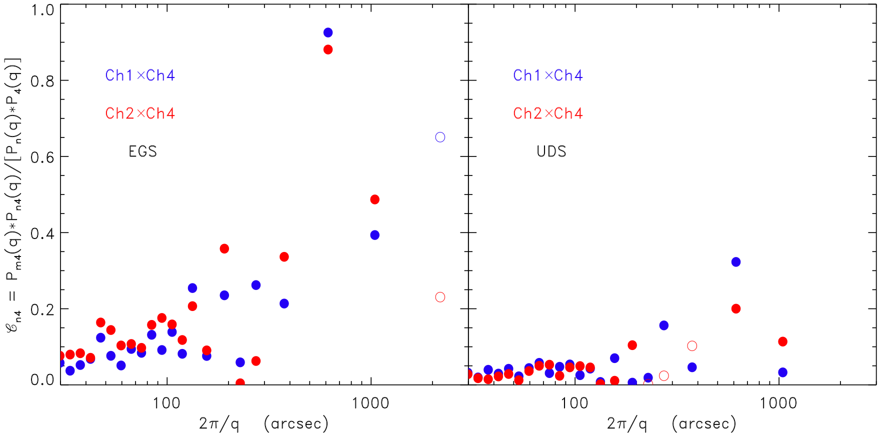


Cross-correlation P(q) between three epochs.

No sign of zodi

No sign of appreciable instrument effects

Numerous other tests confirm this.

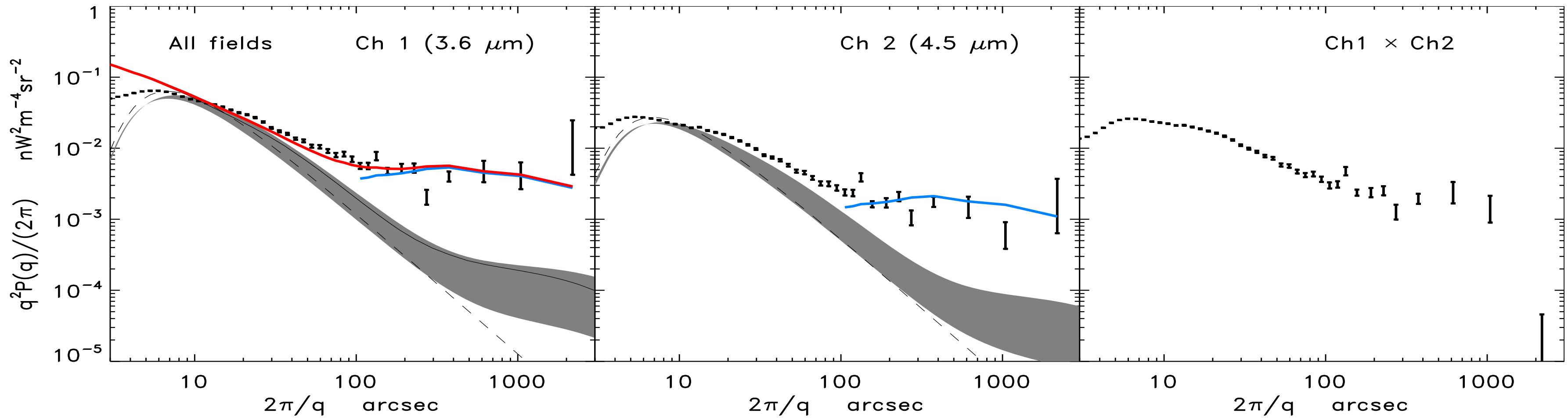


Cross-correlation with 8 mic (which traces cirrus) data is very small. Cirrus contribution is small at 3.6 and 4.5 mic.

Other tests confirm this.

From Kashlinsky et al (2012) - continued

Averaged over two fields. Signal is now measured to ~ 1 deg



- Measurement is now extended to ~ 1deg
- Shaded region is contribution of remiaining ordinary galaxies (low/high faint end of LF)
- CIB fluctuations continue to diverge to more than 10 X of ordinary galaxies.
- Blue line correspond to toy-model of LCDM populations at z>10
- Fits are reasonable by high-z populations coniciding with first stars epochs

Nature of the new populations

- Fluctuations significantly exceed expected signal from remaining galaxies at 2.4 to 4.5 micron
- CIB maps at 3.6/4.5 mic do not correlate with ACS sources
- Color of the fluctuations increases rapidly toward shorter wavelengths (and drops at ACS wavelengths<0.9 mic)
- Angular spectrum at 3.6/4.5 mic now measured to 1^{o} is consistent w high-z LCDM population

- The signal is produced by populations with only low shot noise (P_{SN}~30-50 nJy nW/m^2/sr) and significant clustering component (δF ~ 0.05-0.1 nW/m^2/sr)
- If at high z clustering component implies net F_{CIB} >~ 1 nW/m^2/sr
- If at low z, sources would have to be very faint/small and cluster very differently from normal galaxies. Such populations have never been observed.
- Either way we are talking about new populations.

- These sources would have individual flux S~ P_{SN}/F_{CIB} <~ 10-30 nJy, or m_{AB}>~28-30

- The surface density of these new populations would be ~ P_{SN}/S^2 ~ a few arcsec^{-2}
- They would be within confusion noise and care must be taken when assembling images not to filter them out (no median filtering).

CONCLUSIONS

- There exist source-subtracted CIB fluctuations significantly exceeding those from known galaxy populations
- Color of these fluctuations is very blue to ~ 2 micron consistent with production in early very hot sources
- Fluctuations spectrum has now been measured accurately to ~ 1deg and is consistent with high z LCDM distributed sources
- First stars?