(Source-subtracted) CIB fluctuations and early populations

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  with
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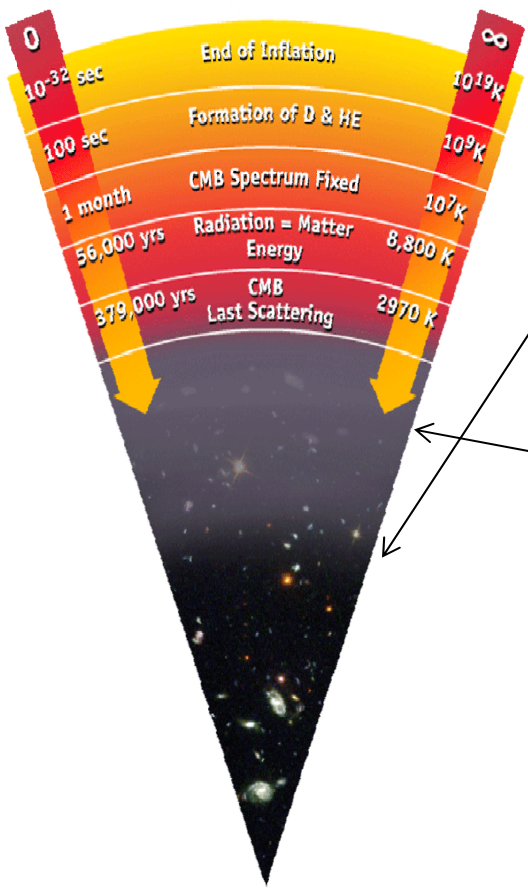
Why/what Pop3?



- Galaxies are now found out to z ~ 6
- Star formation increases rapidly between z=0 and ~1
- Systems are metal rich early on
- Colours show ‘normal’ stellar populations
- Typical mass ~0.3-1 $M_{\odot}$ (and less than ~30 $M_{\odot}$)

- Population III:
- What were they? (Stars/Black holes?)
- When did they form?
- How long did their era lasted?
- Etc

Early thinking: opacity limited fragmentation

- $M_{Jeans} \propto T^{3/2}\, \rho^{-1/2}$ $(nkT < \rho GM/r)$
- Collapse starts and proceeds when $t_{cooling} << (G\rho)^{-1/2}$
- In this case T=const and Jeans mass decreases with t
- Cloud fragments into progressively smaller M_J as $\rho\uparrow$ and T=const
- As ρ rises enough, $\tau\sim1$, photons are trapped, $M_J\uparrow$, fragmentation stops
- For present day composition $T\sim10K$ and $\tau=1$ is reached at $M_J\sim0.1M_\odot$
- For primordial composition (H,He,Li) collapse proceeds at $T\sim10^4K$ (H cooling) (if H_2 form $T\sim10^3K$)
- Hence first starts were likely massive. But…

(Rees 1977)

$M_J = (\pi k_B T/\mu m_p G)^{3/2} \rho^{-1/2}$ Jeans Mass

$\sim(GM^2/r)\ 1/(G\rho)^{-1/2}$ required rate of radiation of binding energy

$aT^4c(4\pi r^2)$ *maximal* cooling radiation rate

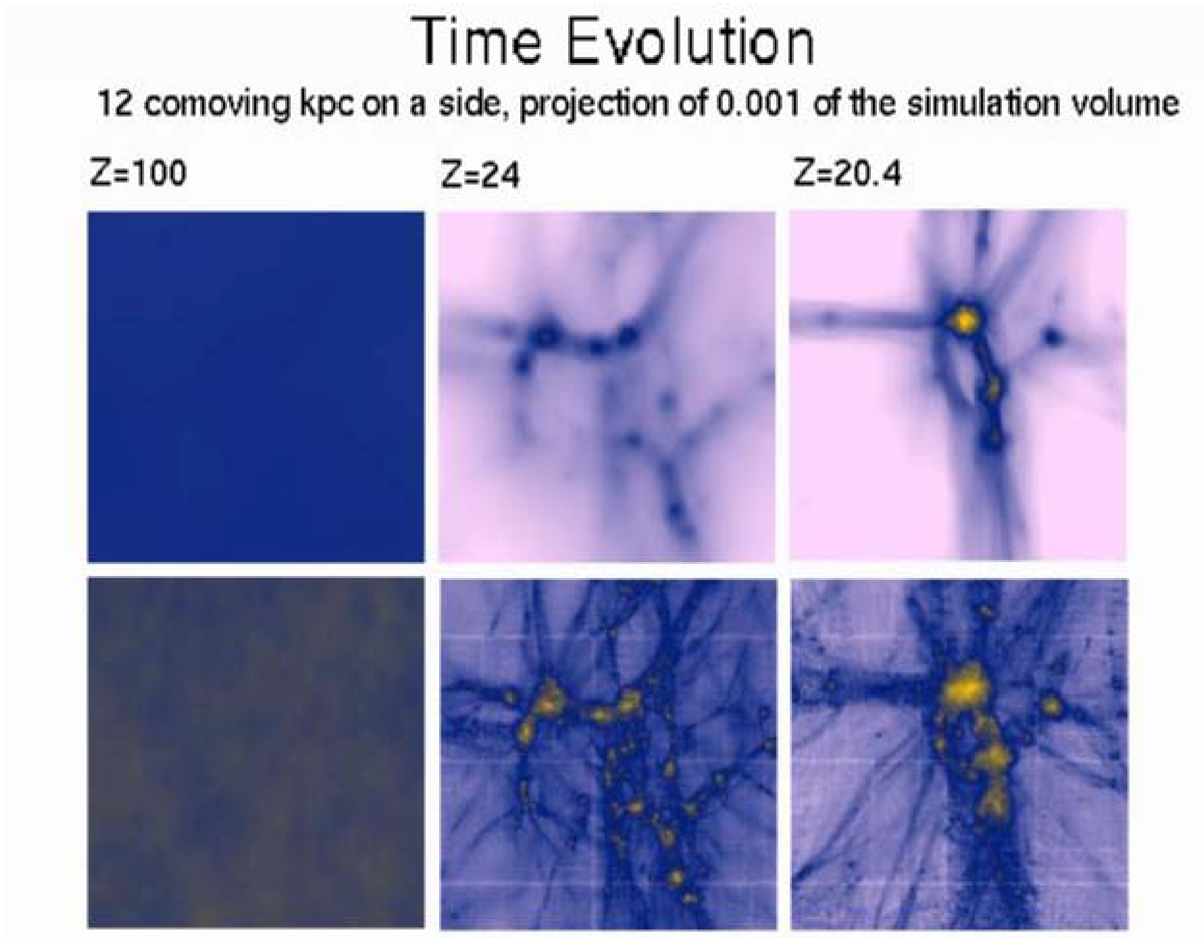
This leads to the minimal/final fragment mass of

$M_{F,min} \sim M_{Chandra}\ \mu^{-9/4}\ (k_B T/m_p c^2)^{1/4} \propto T^{0.25}$ only (!)

(here $M_{Chandra} = (\hbar c/G m_p^2)^{3/2}\ m_p = 1.44\ M_\odot$ is the Chandrasekhar mass)

So are the first stars of low mass after all? (So-called Jupiters).

Simulations of ΛCDM Universe and Pop 3
(Abel et al, Bromm et al 2000-2004)



Pop 3 – what they are, where they are, how they live, how they die

- They are expected to be very massive and form with no fragmentation
- In ΛCDM they form in mini-haloes of 10^5-10^6 solar masses
- From WMAP they form at z~20
- Their SED is black body at $T \sim 10^{4.3-5}$ K

- They radiate at Eddington limit:

$$L = L_{Edd} = 4\,\pi G m_p c/\sigma_T\, M = 1.38 \times 10^{38}\, M/M_\odot \text{ erg/sec}$$

- Their life is brief and independent of mass:

$$t_L = \varepsilon M c^2/L \sim 3 \times 10^6 (\varepsilon/0.007) \text{ yr}$$

- If they are > 240 $M_\odot$, they do not enrich IGM with metals

Diffuse background from Pop 3 (Kashlinsky et al 2004)

$\int M\, n(M)\, dM = \Omega_{baryon}\, 3H_0^2/8\pi G\, f_*$ f_* fraction in Pop 3

$$\frac{dF}{dt} = \frac{\int Ln(M)dM}{4\pi d_L^{\ 2}} \frac{dV}{dt}(1+z)$$

$dV = 4\,\pi\, c d_L^2 (1+z)^{-1}\, dt$; $L \approx L_{Edd} \propto M$; $t_L = \varepsilon\, Mc^2/L << t(z=20)$

$$\nu I_\nu = \frac{3}{8\pi}\frac{1}{4\pi R_H^{\ 2}}\frac{c^5}{G}\varepsilon\Omega_{baryon} f_* \cong 1.2\times 10^4 \frac{\Omega_{baryon}}{0.044}\frac{\varepsilon}{0.007} h^2 f_* \frac{nW}{m^2 sr}$$

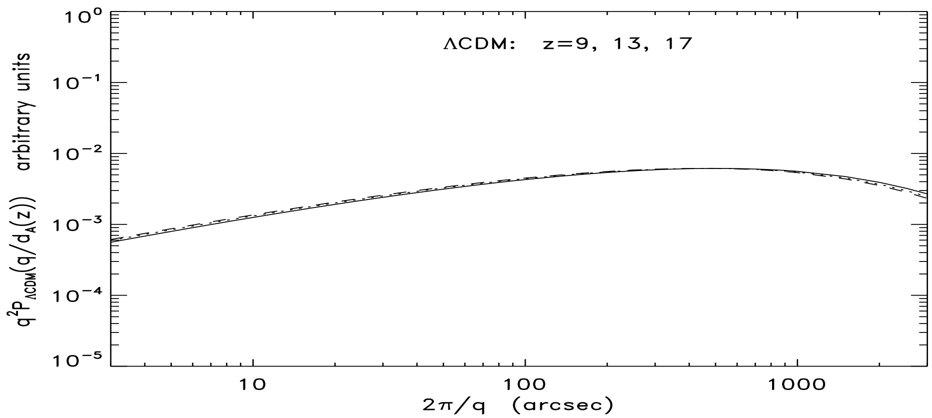
- See more detailed analyses by Santos et al (2002), Salvaterra & Ferrara (2003), Dwek et al (2005), Fernandez & Komatsu (2007)
- *IMPORTANT: nothing above depends on these objects being stars as opposed to e.g. accreting black holes*
- CIB would also have unique pattern of fluctuations.

CIB fluctuations contain contributions from sources spanning the entire cosmic history

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 , so measuring it would offer evidence of and a glimpse into the Pop 3 era (Cooray et al 2004, Kashlinsky et al 2004, Fernandez et al 2011)

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

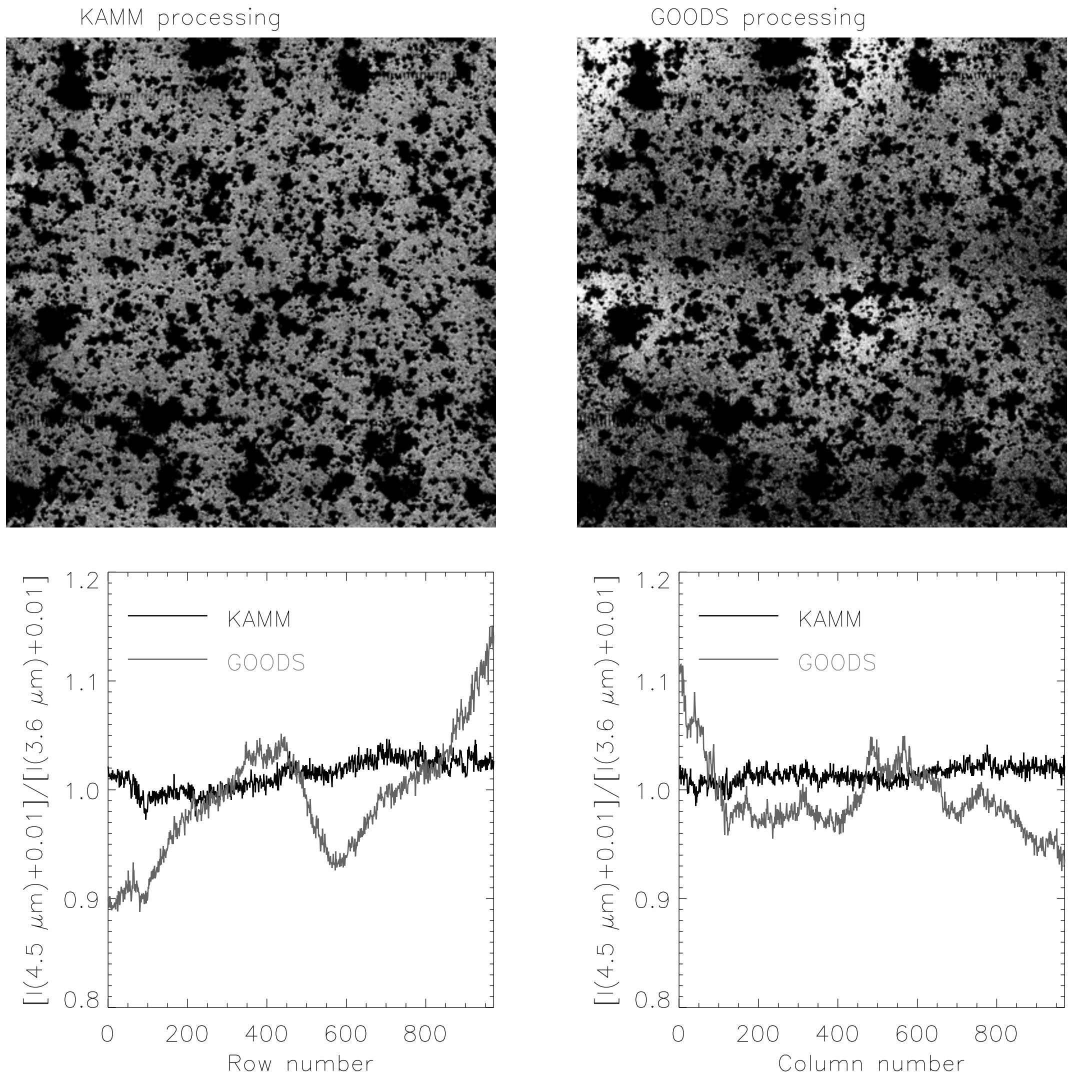
INTERPRETATION

- 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:

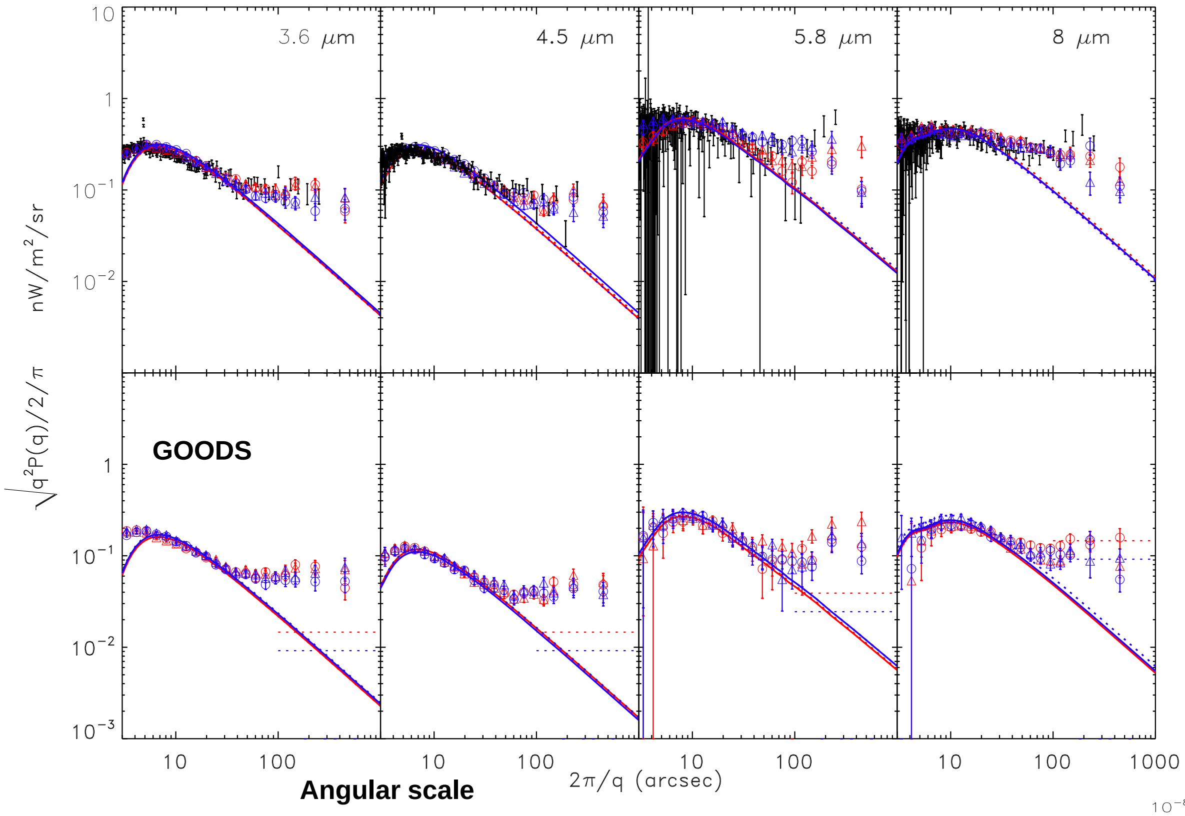
- Data were assembled using a least-squares self-calibration methods from Fixsen, Moseley & Arendt (2000).
- Selected fields w. homogeneous coverage.
- Individual sources have been clipped out at $>N_{cut}\sigma$ w N_{mask} =3-7
- Residual extended parts were removed by subtracting a "Model" via CLEAN 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

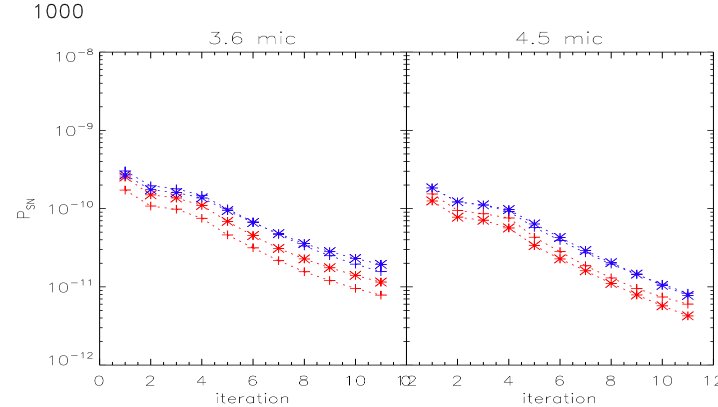
Shot noise reached in QSO1700

P_{SN} (3.6μm) ≈ 6 x 10^{-11} nW^2/m^4/sr

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

P_{SN} (3.6μm) ≈ 2 x 10^{-11} nW^2/m^4/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

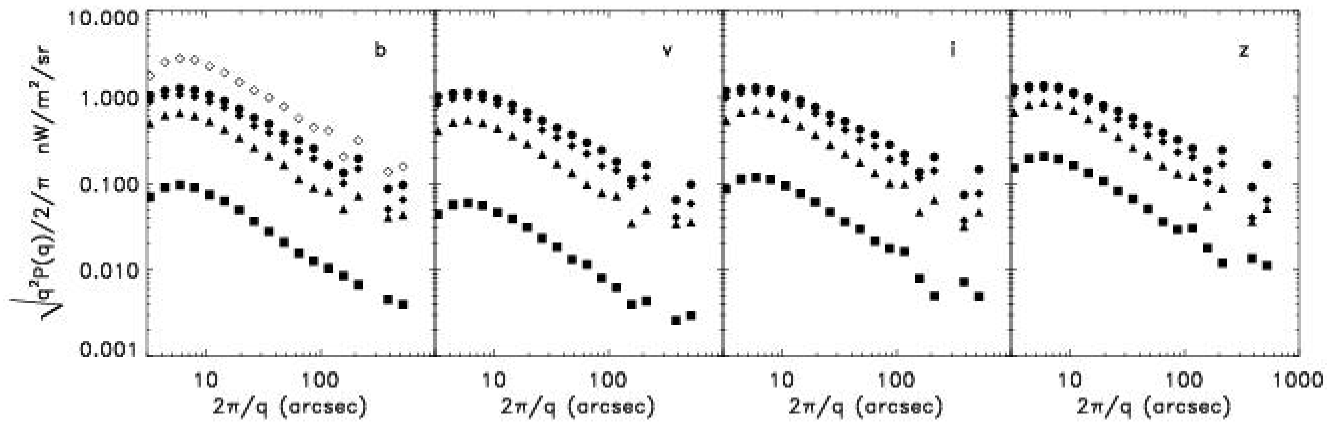
- Source-subtracted IRAC maps have different power spectra than those in ACS
- The amplitude of CIB fluctuations than can be contributed by ACS sources is small
- There are very good correlations between ACS sources and the sources removed by KAMM, but
- Completely negligible correlations between ACS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

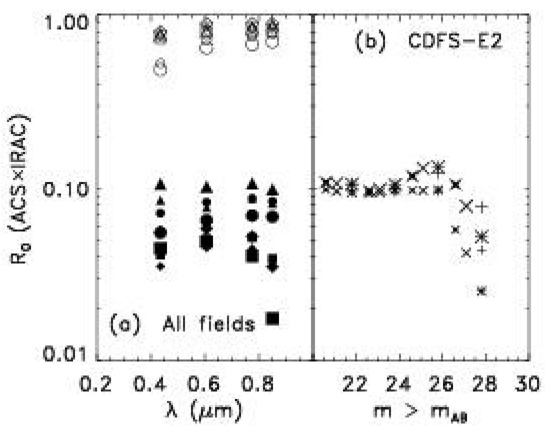


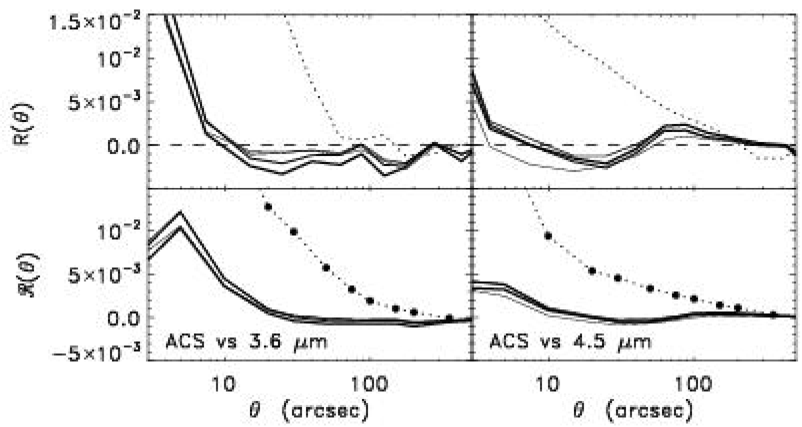
Cross-correlation

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

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

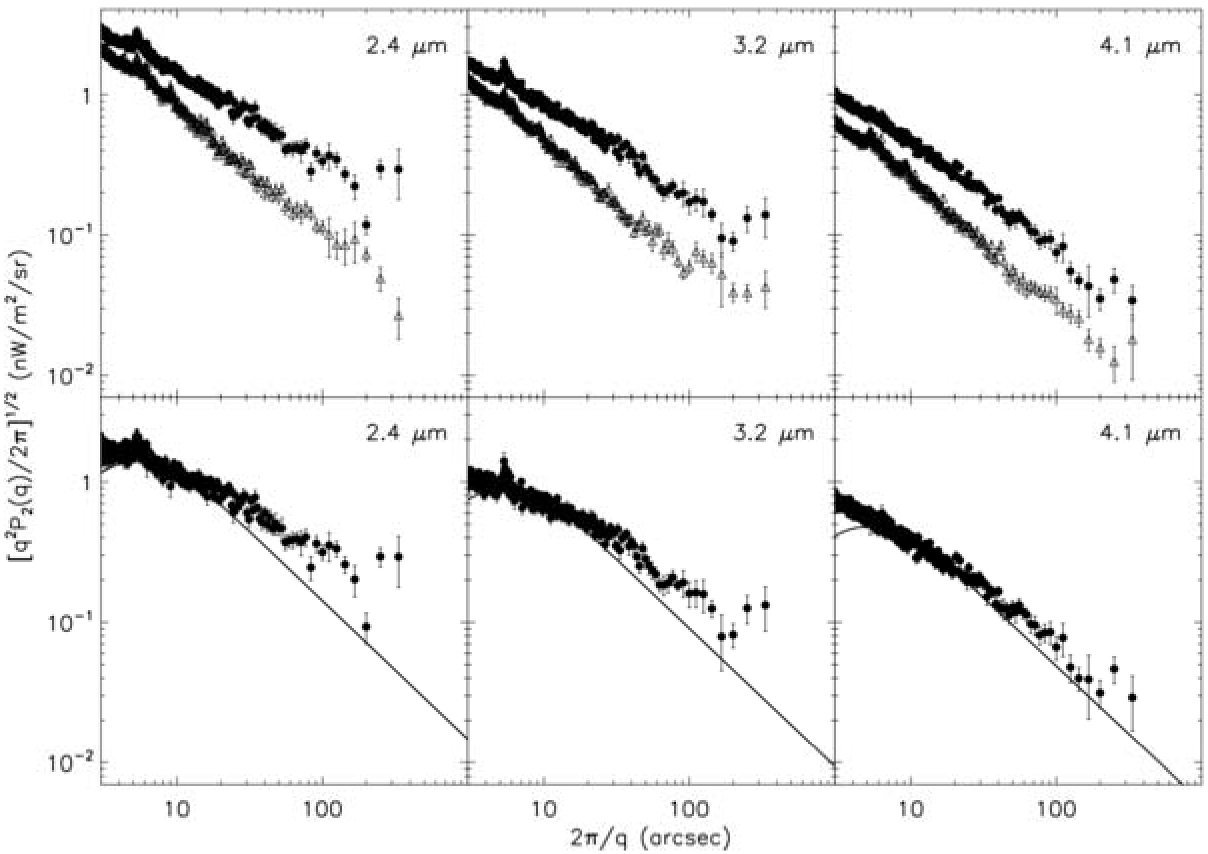
Solid lines: ACS B,V,I,z,
Dotted line: IRAC Ch 1



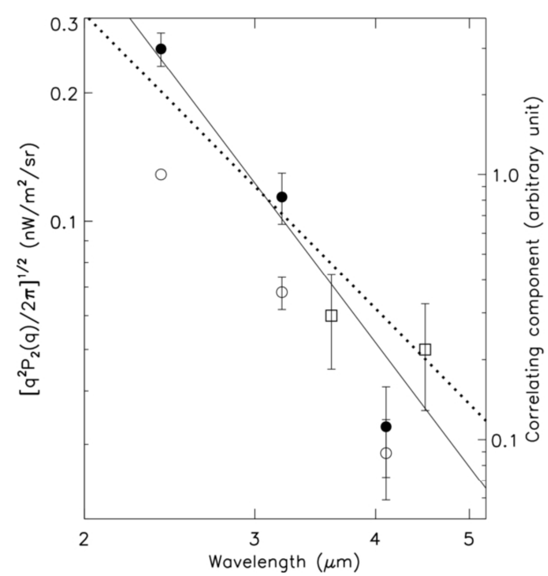


AKARI results (Matsumoto et al 2011)

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



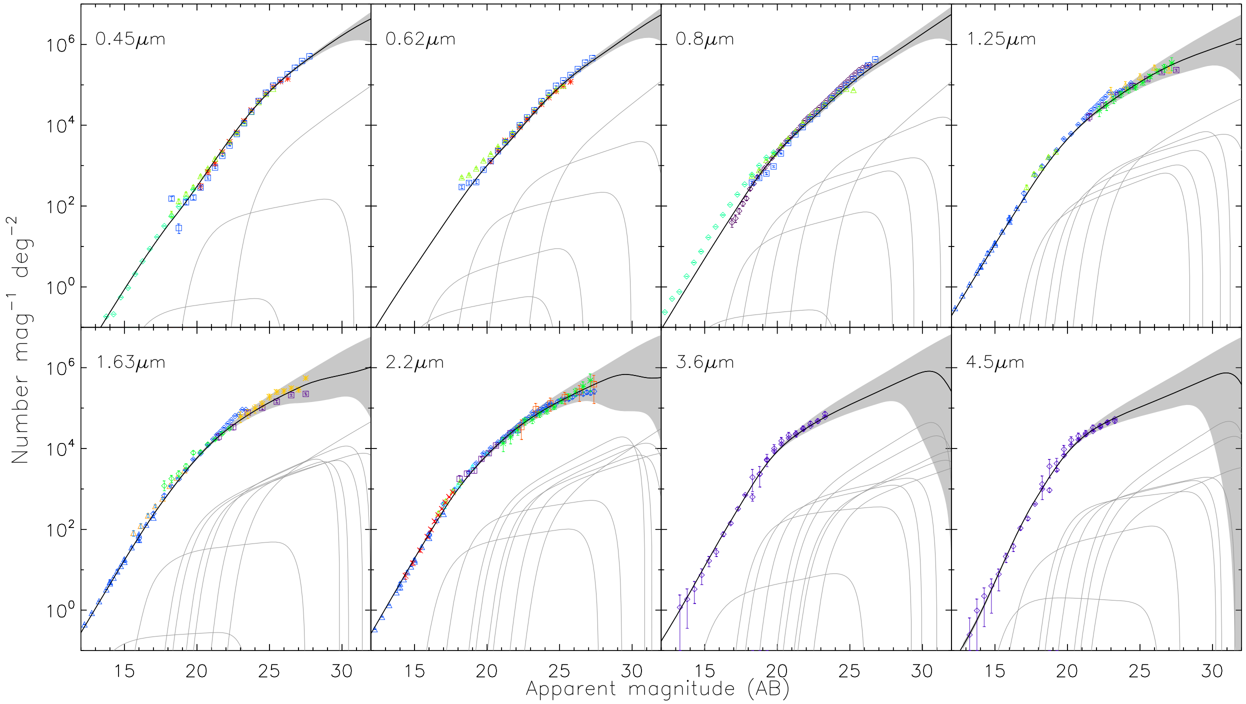
Color from 2.4 to > 4 mic is consistent with high-z sources:



Contributions from ordinary galaxies (Helgason et al 2012)

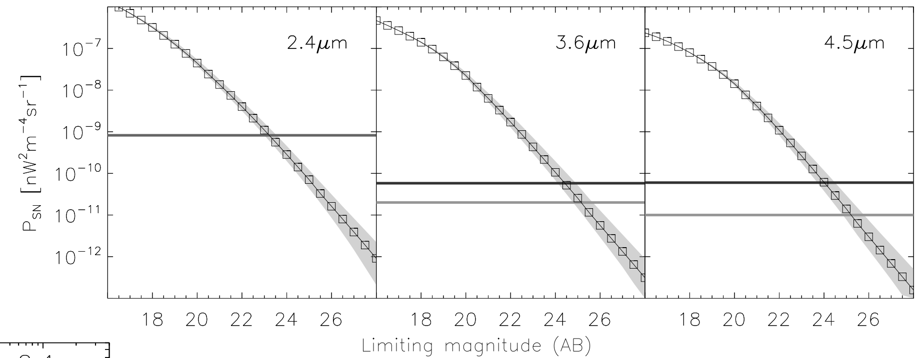
- Use 230 (!) LF datasets spanning 1) wavelengths from UV to 4.5 mic, 2) z from 0 to ~5, 3) m to ~27 AB
- Finds overall consistency between the data with Schechter-type LF w evolving parameters
- Reconstruct the emission over the (λ, z) plane and shift them to the observer NIR from 1-5 mic
- Check for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

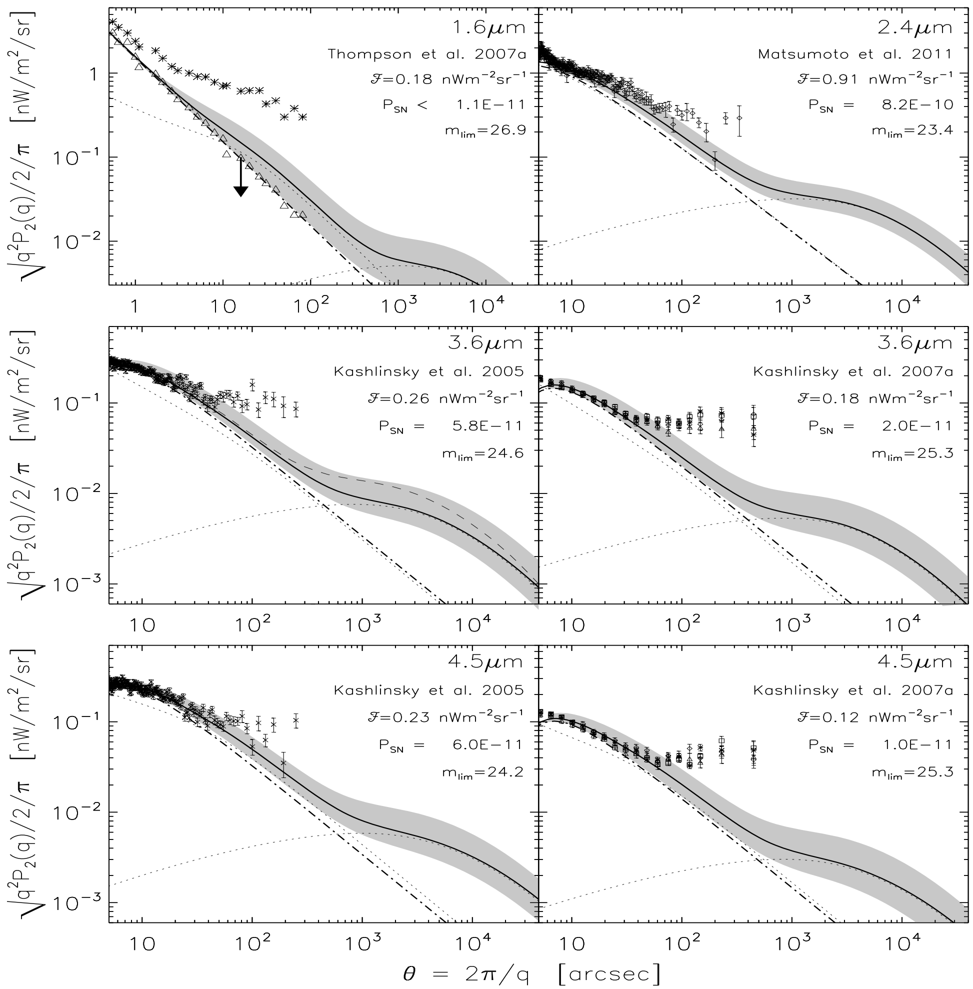
- *Then with that input can robustly compute the remaining (at the measured snot-noise) CIB fluctuations at NIR observer bands assuming the established LCDM power spectrum with 1) high-faint end of the LF data and 2) low-faint end.*



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).

Moving to larger (subdegree) angular scales:

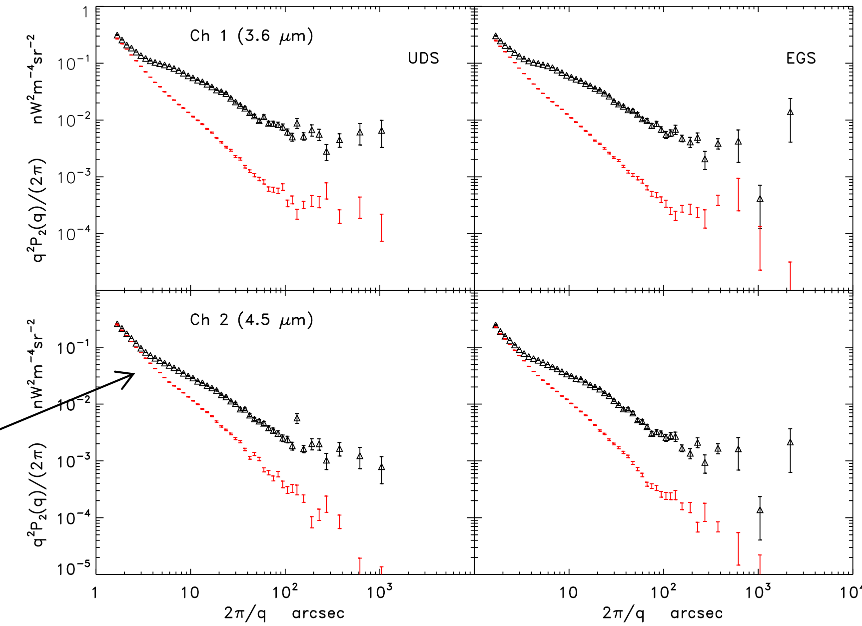
New ***Spitzer/SEDS*** results (Kashlinsky et al 2012, arxiv:1201.5617)

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

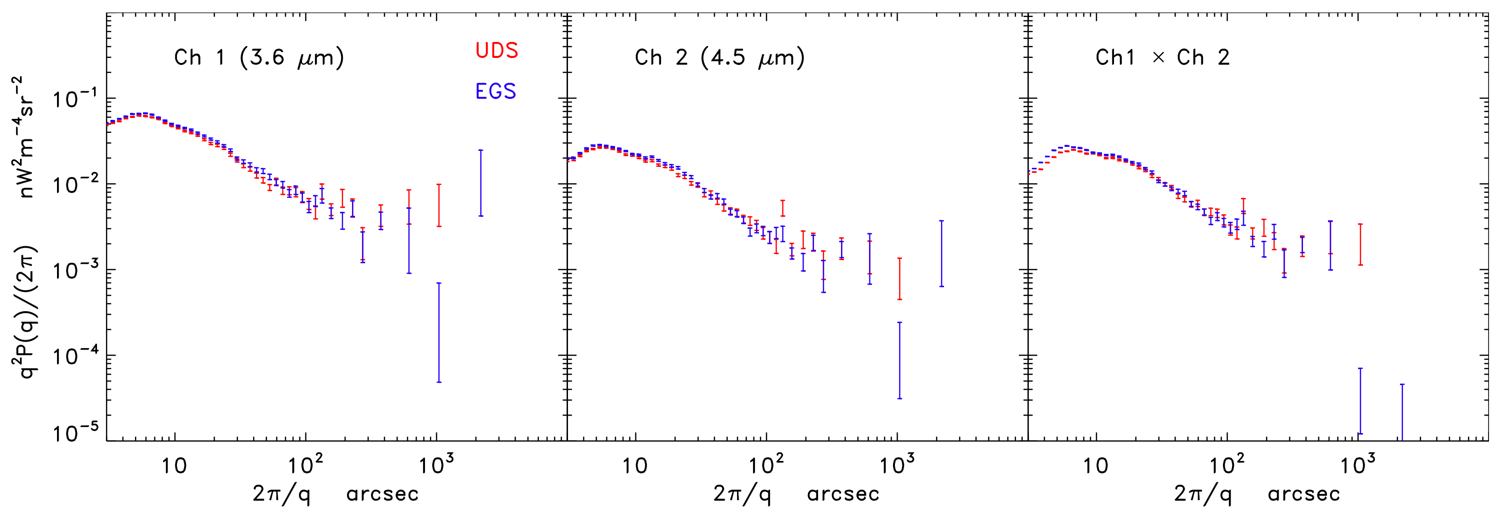
P_{A+B} in black; P_{A-B} in red



After subtracting noise:

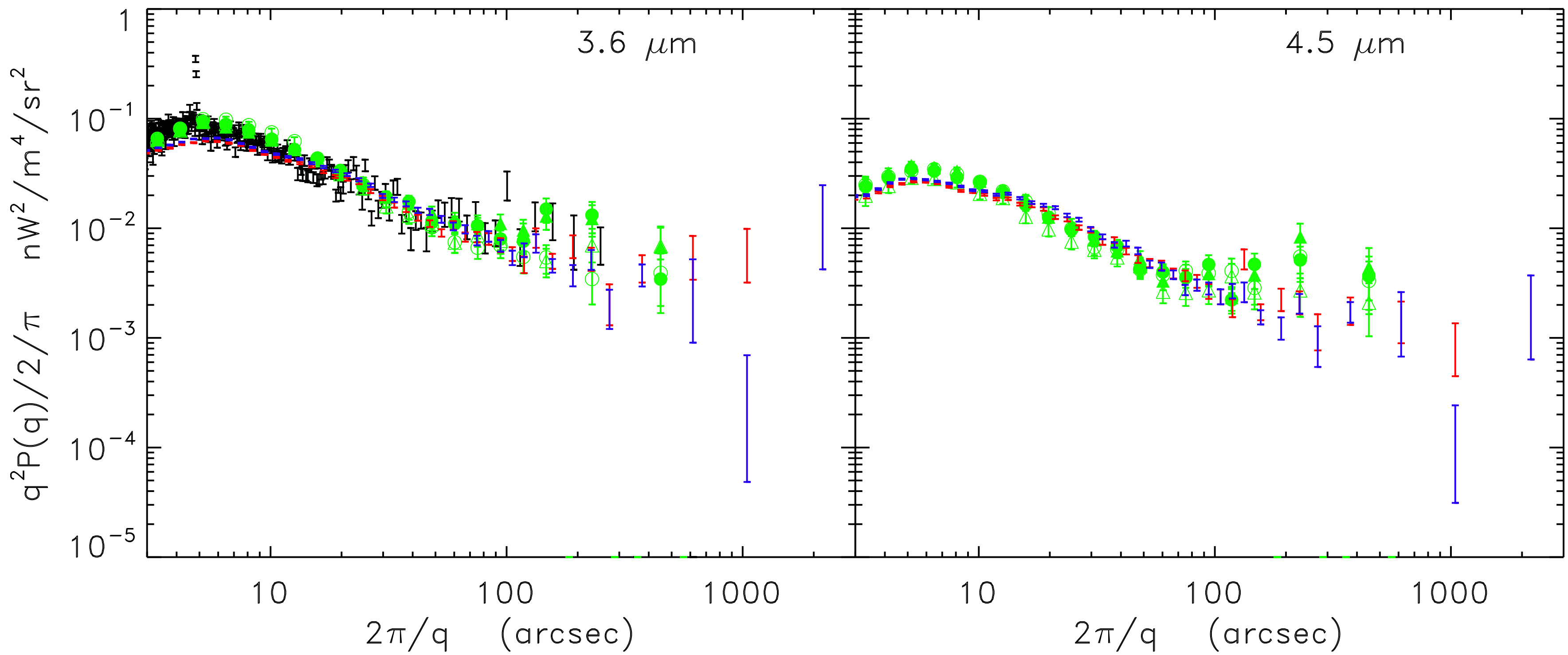
$P=P_{A+B} - P_{A-B}$

Same signal appears in Ch1 and 2 !



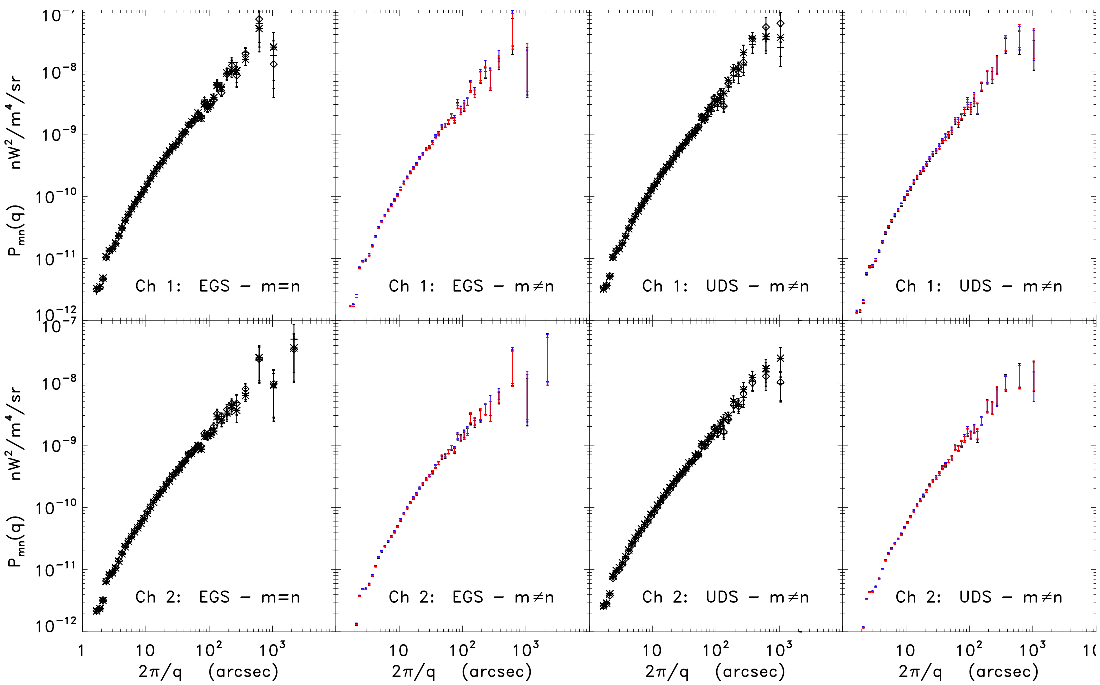
COMPARISON WITH EARLIER MEASUREMENTS

7 fields in total: QSO1700, HDFN-E1, HDFN-E2, CDFS-E1, CDFS-E2, UDS, EGS



The measured fluctuations appear highly isotropic over 7 different fields/locations.
This by itself shows the sky signal to be of cosmological origin.

From Kashlinsky et al (2012) - continued

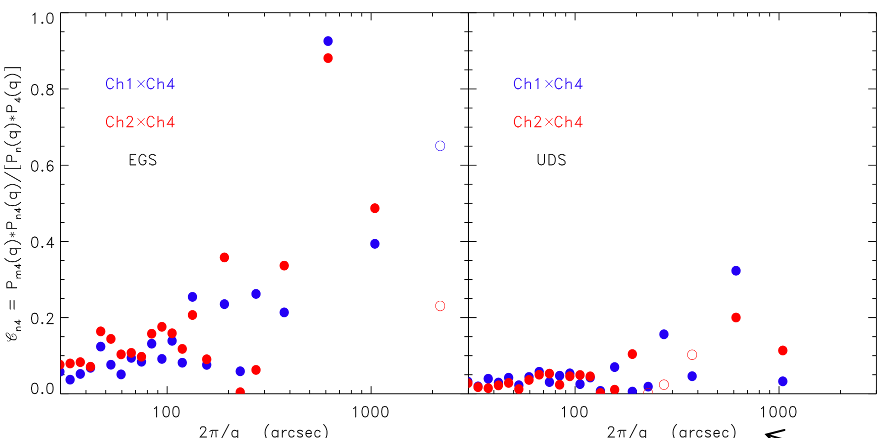


Cross-correlation P(q) between ***three*** epochs.

No sign of zodi

No sign of appreciable instrument effects

Numerous other tests confirm this.



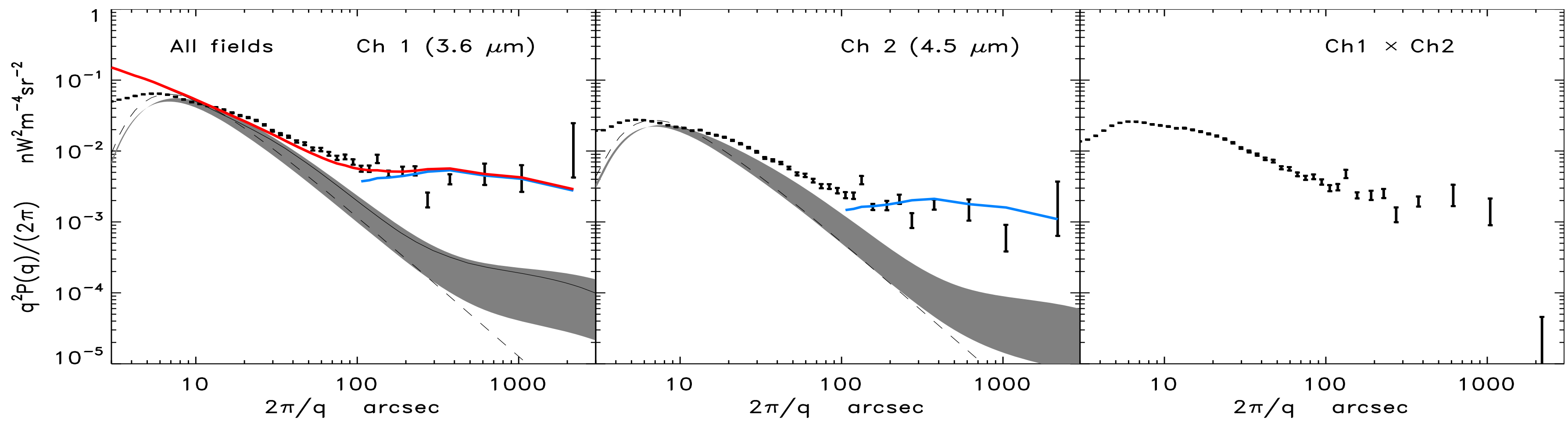
Cross-correlation with 8 mic (which traces cirrus) data is very small. Cirrus contribution is small at 3.6 and 4.5 mic.

Other tests confirm this.

Coherence = $P_{n4}P_{n4}/P_n/P_4 << 1$

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

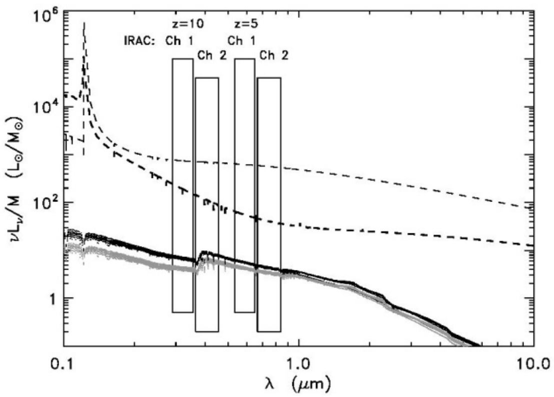
- The signal is produced by populations with only low shot noise (P_{SN}~30-50 nJy nW/m^2/sr) and significant clustering component (δF ~ 0.05-0.1 nW/m^2/sr)
- If at high z clustering component implies net F_{CIB} >~ 1 nW/m^2/sr
- If at low z, sources would have to be very faint/small and cluster very 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).

What are the populations producing the CIB fluctuations?

t(z=8)=0.6 Gyr; t(z=20)=0.2 Gyr, so $\Delta t < 1$Gyr



For comparison at z=0:

$\mathcal{L}(0.4\text{-}0.8\mu m) \sim 0.1 \mathcal{L}_*$

$\Omega_{stars}(z=0) \sim 2\times10^{-3}$

This requires comoving luminosity density at ~0.6-0.8[(1+z)/6]μm:

$$\mathcal{L}_* \approx \frac{4\pi}{c} F_{CIB} (\Delta t)^{-1} (1+z) \approx 7\times10^8 L_{Sun} Mpc^{-3} \frac{1Gyr}{\Delta t} \frac{1+z}{6} \frac{F_{CIB}}{nW/m^2/sr}$$

This corresponds to Γ = M/L << $(M/L)_{SUN}$ in order to reproduce reasonable Ω_*:

$$\Omega_* = 5\times10^{-3} \frac{F_{CIB}}{nW/m^2/sr} \frac{\Gamma}{\Gamma_{Sun}} \left(\frac{1Gyr}{\Delta t}\right) \frac{1+z}{6}$$

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?