LIGO gravitational wave detection, primordial black holes and the near-IR cosmic infrared background (CIB)

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Outline

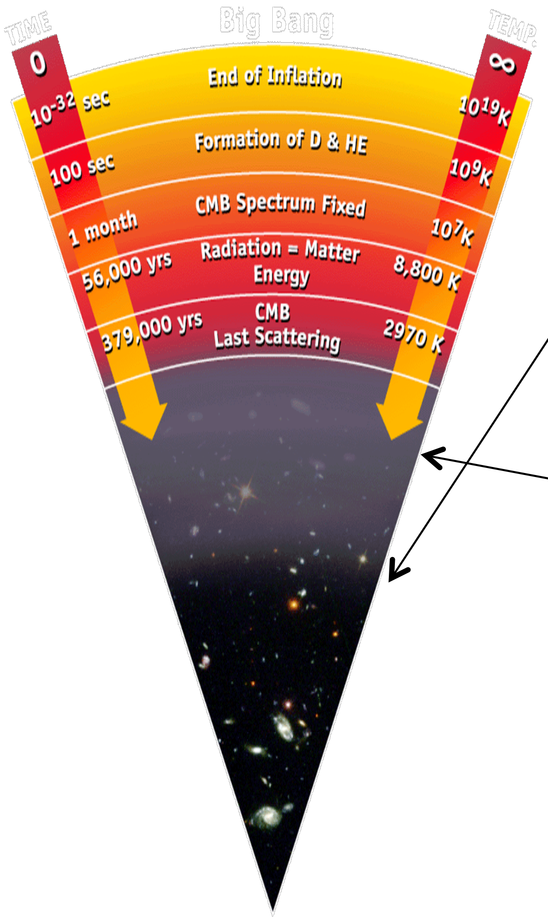
- CIB and its near-IR anisotropies: link to 1st sources

- Source-subtracted CIB anisotropies in *Spitzer* deep data
- Their measured properties and excess over known pops
- Their connection to 1st sources
- Do they arise from LIGO-type PBHs making up DM?

- Future work: LIBRAE (*Looking at Infrared Background Radiation Anisotropies with Euclid*)

- Summary

Why/what CIB and 1st stars and BHs?



- 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 $M_\odot$)

- *First stars era*:
- **What were they? (Stars/Black holes?)**
- **When did they form?**
- **How long has their era lasted?**
- **Can be detected perhaps through their unique imprint in**

cosmic infrared background (CIB)

- *LOOK FOR THESE OBJECTS IN CIB*

Diffuse background from Pop 3 and BHs (Kashlinsky et al 2004)

If first objects were massive stars or BHs radiating at the Eddington limit they would CIB as follows:

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

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

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

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

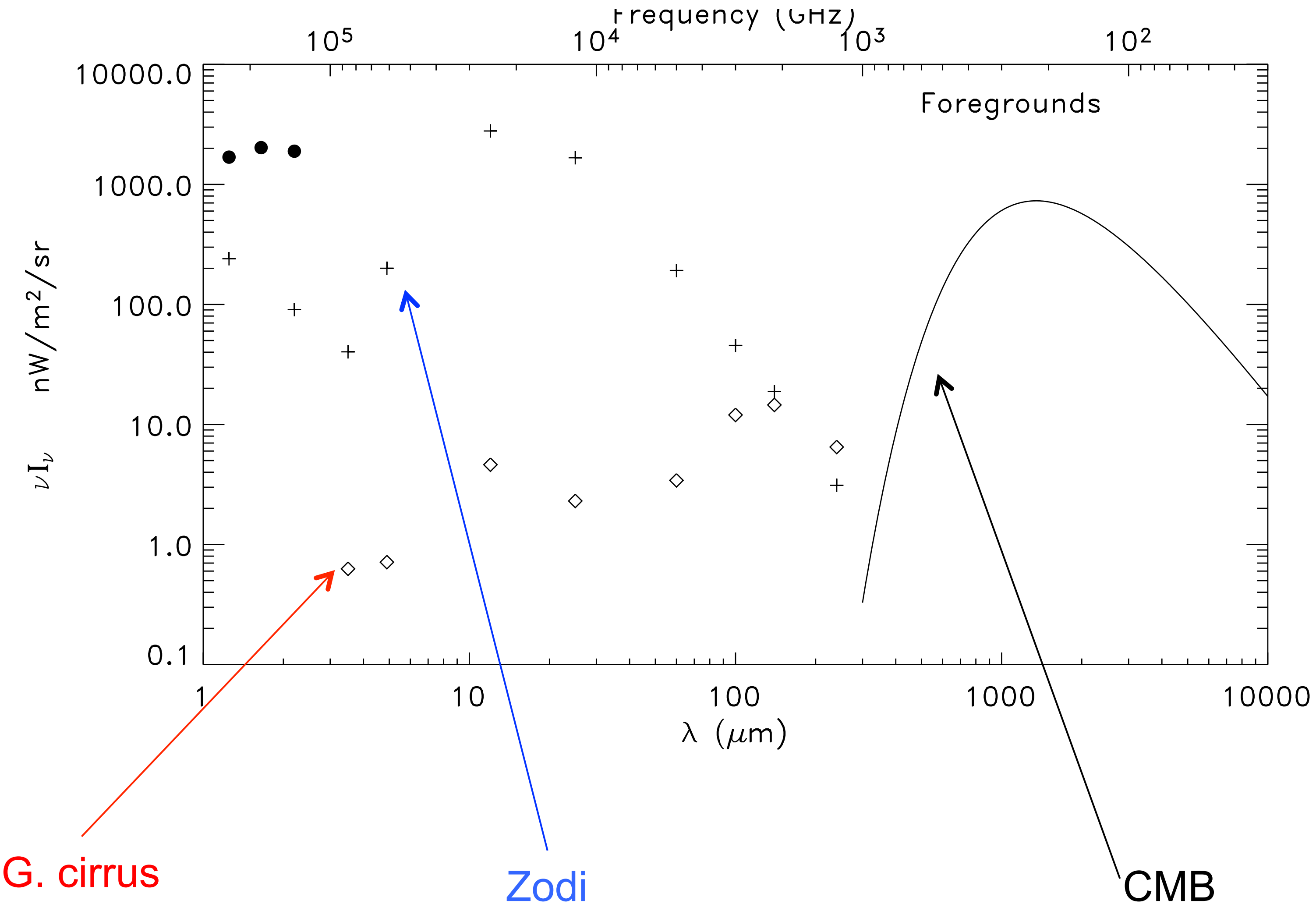
Hubble radius area

Maximal L of any gravitating object

Emissions are cut at λ > 0.1 (1+z) μm, or ~ 1μm for z~10

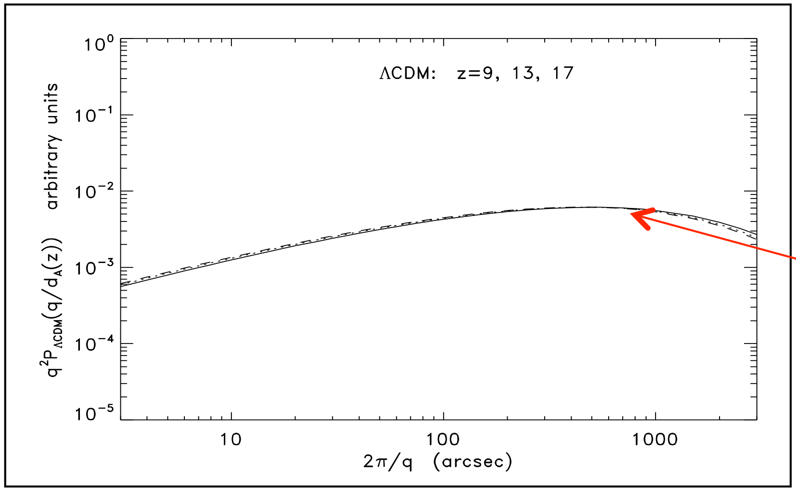
Mean CIB is difficult to probe because of foregrounds

but Zodi and Galactic Cirrus are smooth!



Pop 3 c/should produce significant CIB fluctuations

- If massive, each unit of mass emits $L/M \sim 10^5 L_\odot/M_\odot$
- 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



Peak is ~ horizon at matter radiation equality epoch projected to z_*

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

CIB anisotropies contain two terms:

- Definitions: **1)** *Mean squared flux is* $\delta F_\lambda^2 = q^2 P_\lambda(q)/(2\pi)$, **2)** *power* $P = <|FFT_{Flux}|^2>$, **3)** *scales defined via* $q(rad^{-1}) = \ell$ *(multipole)*
- *I. Shot noise*

  from sources occasionally entering the beam $\delta F/F \sim 1/N_{beam}^{1/2}$

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

  Dominates small scales near the beam.
- *II. 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

CIB fluctuations at 3-8 μm

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)

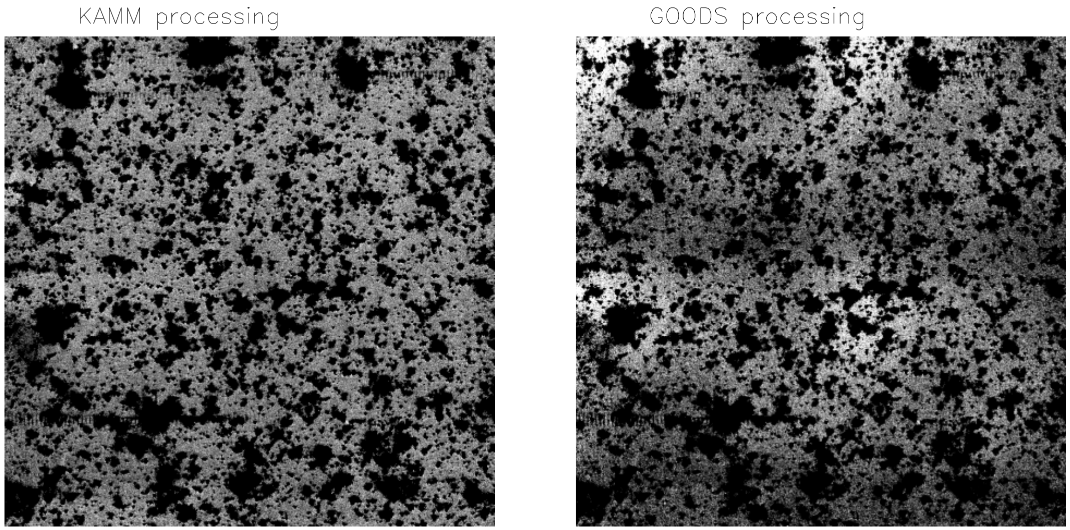
R. Arendt, A. Kashlinsky, H. Moseley & J. Mather

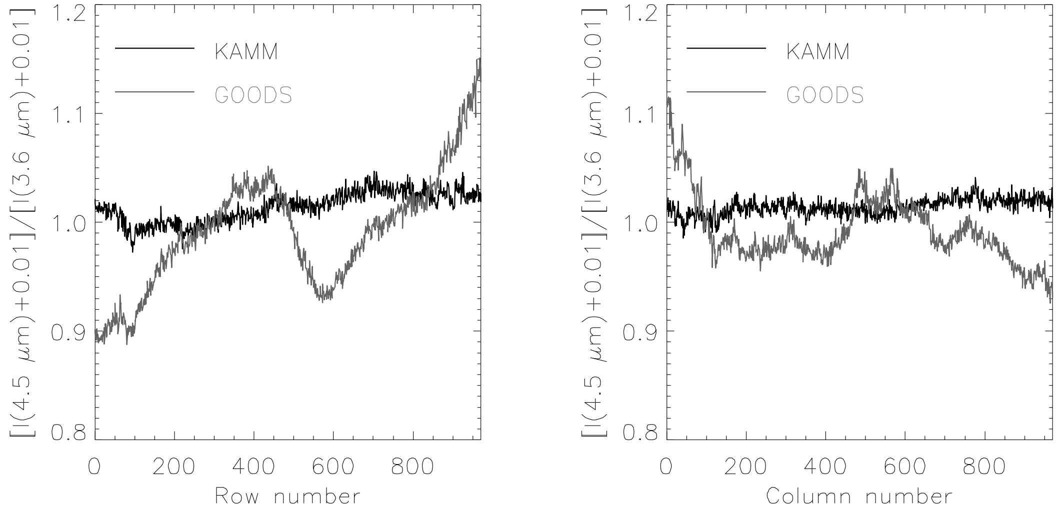
(2010, ApJS, 186,10 – AKMM)

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.
- ***But so far there is no direct info on the epochs of these populations***

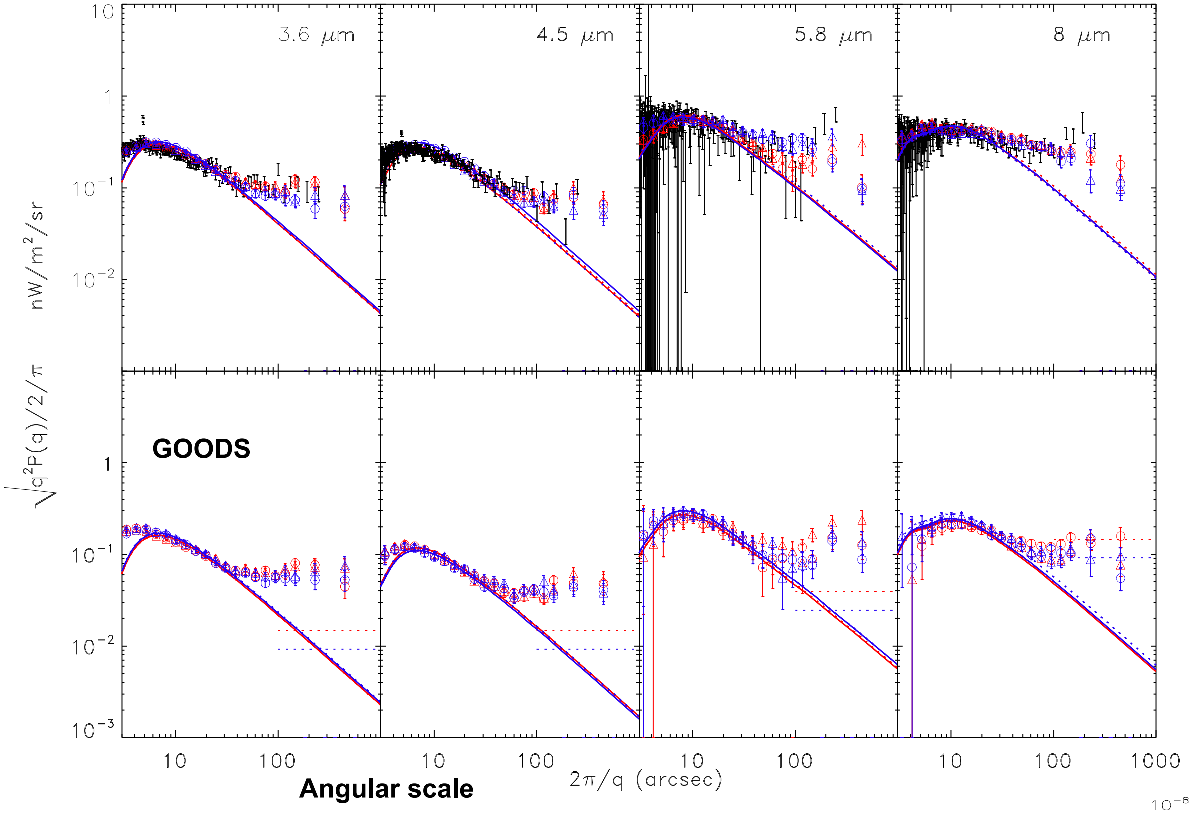
Comparison of self-calibration w standard image assembly





(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

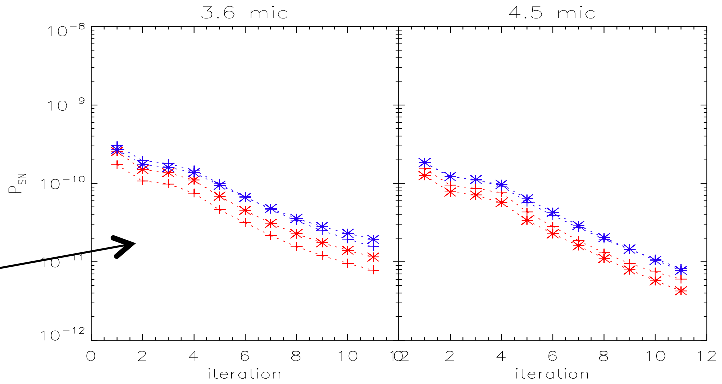
P_{SN} (3.6μm) ≈ 2 x 10^{-11} nW^2/m^4/sr

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

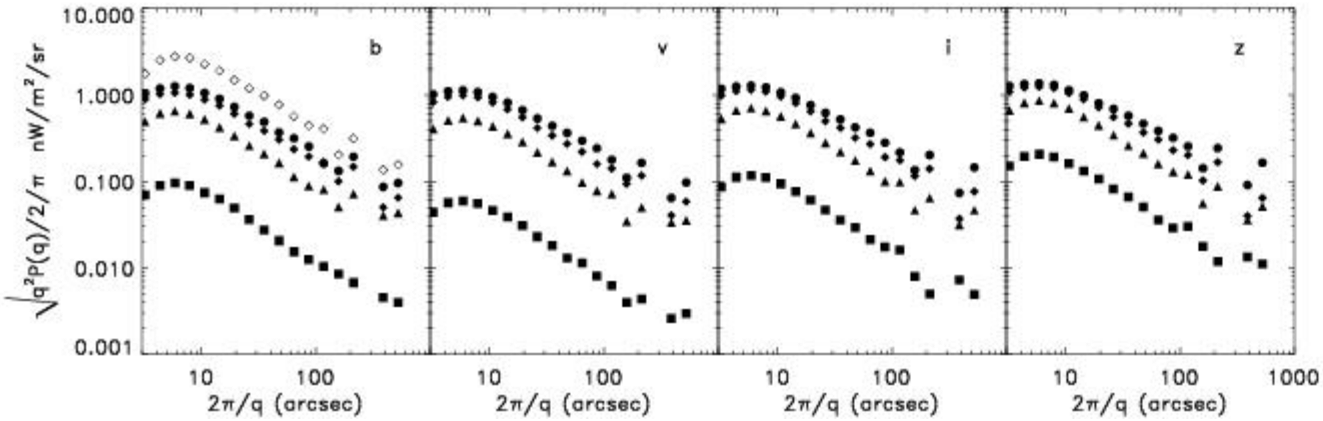
Different datasets must be compared at the same P_{SN}.



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

ACS source maps.

- • $m_{AB}>22$
- ♦ $m_{AB}> 24$
- ▲ $m_{AB} > 26$
- ■ $m_{AB} > 28$
- ◊ $m_{AB} > 24$, no mask

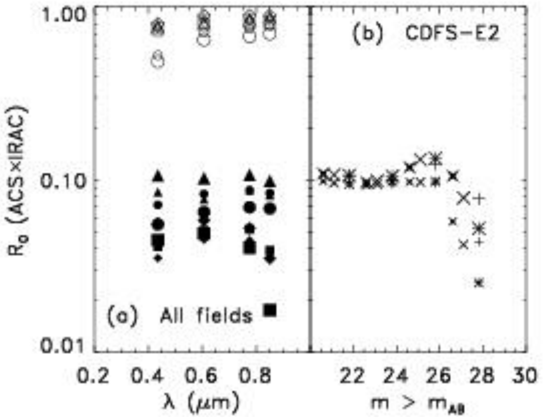


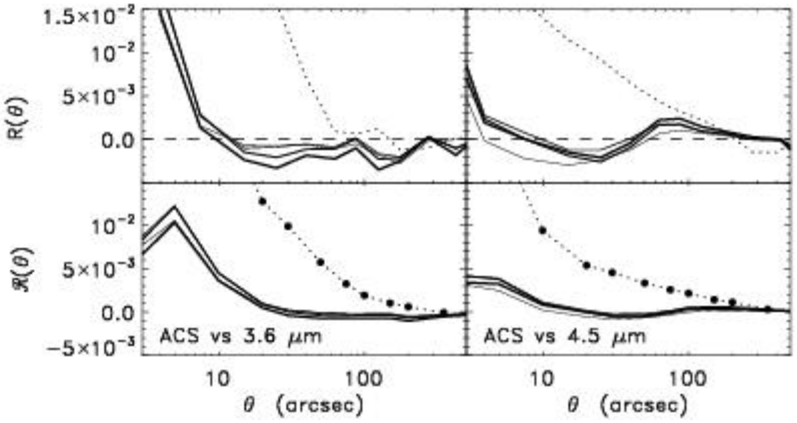
Cross-correlation

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

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

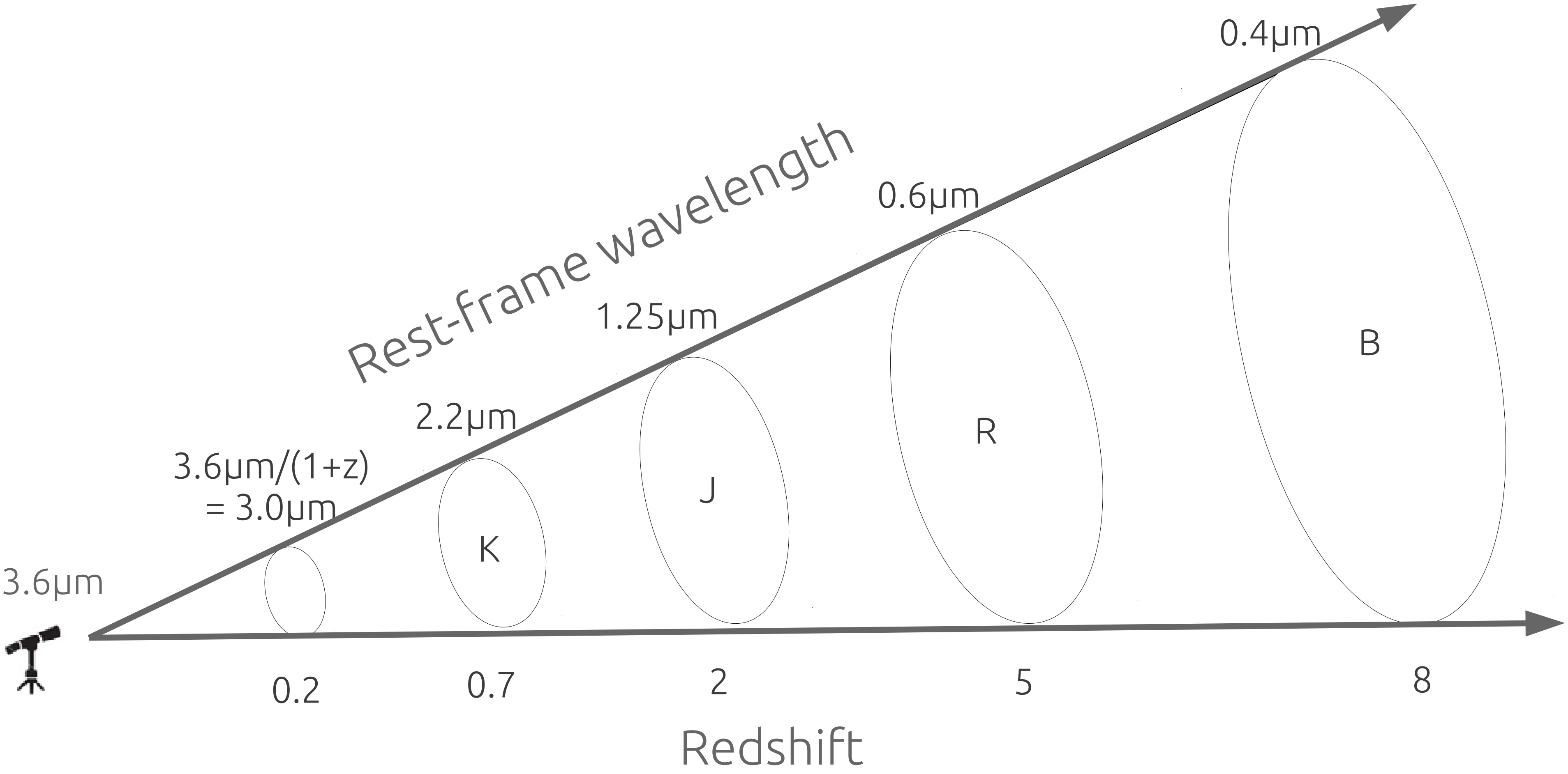
Solid lines: ACS B,V,I,z,
Dotted line: IRAC Ch 1





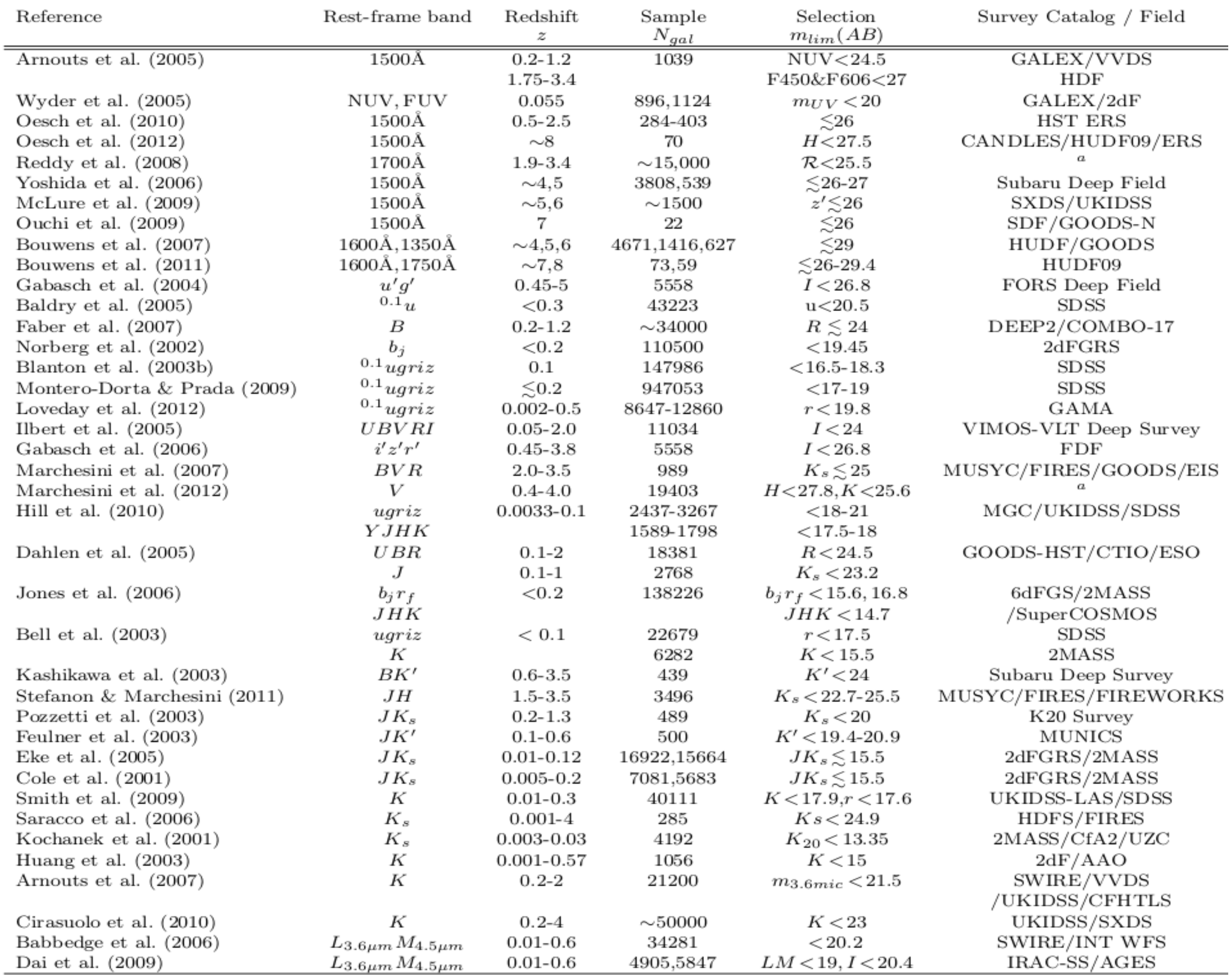
Estimating contribution from remaining known galaxies per Helgason, Ricotti, Kashlinsky (HRK12)

Probing the redshift cone

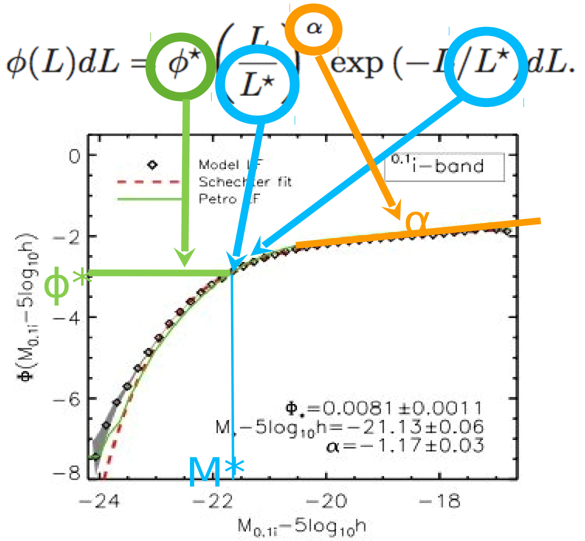


Luminosity Functions

From HRK12 – currently updated to 340+ LF surveys



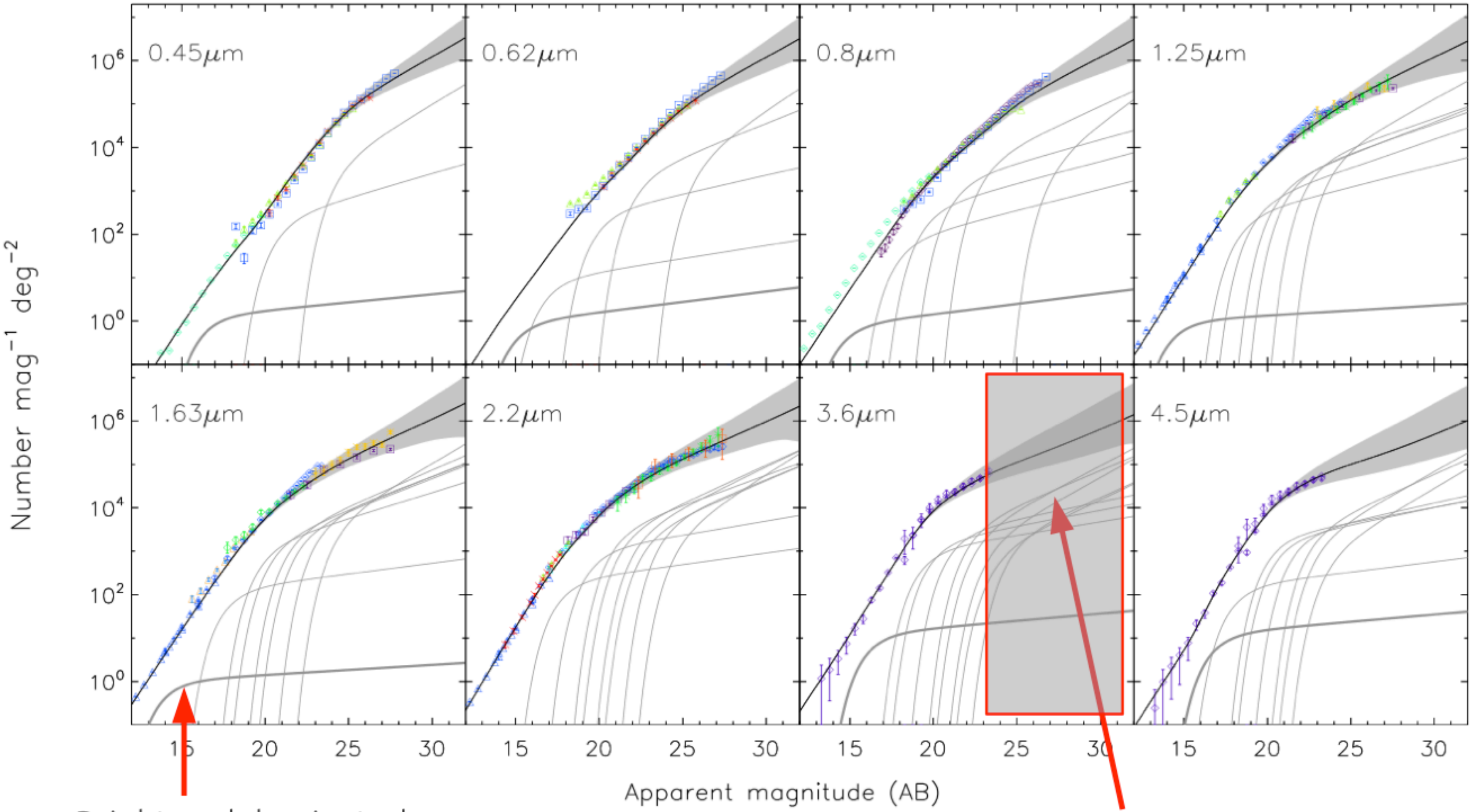
Reference	Rest-frame band	Redshift z	Sample N_{gal}	Selection $m_{lim}(AB)$	Survey Catalog / Field
Arnouts et al. (2005)	1500Å	0.2-1.2	1039	NUV<24.5	GALEX/VVDS
		1.75-3.4		F450&F606<27	HDF
Wyder et al. (2005)	NUV, FUV	0.055	896,1124	$m_{UV} < 20$	GALEX/2dF
Oesch et al. (2010)	1500Å	0.5-2.5	284-403	$\lesssim$26	HST ERS
Oesch et al. (2012)	1500Å	~8	70	H<27.5	CANDLES/HUDF09/ERS
Reddy et al. (2008)	1700Å	1.9-3.4	~15,000	$\mathcal{R}$<25.5	^{a}
Yoshida et al. (2006)	1500Å	~4,5	3808,539	$\lesssim$26-27	Subaru Deep Field
McLure et al. (2009)	1500Å	~5,6	~1500	$z' \lesssim 26$	SXDS/UKIDSS
Ouchi et al. (2009)	1500Å	7	22	$\lesssim$26	SDF/GOODS-N
Bouwens et al. (2007)	1600Å,1350Å	~4,5,6	4671,1416,627	$\lesssim$29	HUDF/GOODS
Bouwens et al. (2011)	1600Å,1750Å	~7,8	73,59	$\lesssim$26-29.4	HUDF09
Gabasch et al. (2004)	$u'g'$	0.45-5	5558	$I < 26.8$	FORS Deep Field
Baldry et al. (2005)	$^{0.1}u$	<0.3	43223	u<20.5	SDSS
Faber et al. (2007)	B	0.2-1.2	~34000	$R \lesssim 24$	DEEP2/COMBO-17
Norberg et al. (2002)	b_j	<0.2	110500	<19.45	2dFGRS
Blanton et al. (2003b)	$^{0.1}ugriz$	0.1	147986	<16.5-18.3	SDSS
Montero-Dorta & Prada (2009)	$^{0.1}ugriz$	$\lesssim$0.2	947053	<17-19	SDSS
Loveday et al. (2012)	$^{0.1}ugriz$	0.002-0.5	8647-12860	$r < 19.8$	GAMA
Ilbert et al. (2005)	$UBVRI$	0.05-2.0	11034	$I < 24$	VIMOS-VLT Deep Survey
Gabasch et al. (2006)	$i'z'r'$	0.45-3.8	5558	$I < 26.8$	FDF
Marchesini et al. (2007)	BVR	2.0-3.5	989	$K_s \lesssim 25$	MUSYC/FIRES/GOODS/EIS
Marchesini et al. (2012)	V	0.4-4.0	19403	H<27.8,K<25.6	^{a}
Hill et al. (2010)	$ugriz$	0.0033-0.1	2437-3267	<18-21	MGC/UKIDSS/SDSS
	$YJHK$		1589-1798	<17.5-18	
Dahlen et al. (2005)	UBR	0.1-2	18381	R<24.5	GOODS-HST/CTIO/ESO
	J	0.1-1	2768	K_s<23.2	
Jones et al. (2006)	$b_j r_f$	<0.2	138226	$b_j r_f < 15.6, 16.8$	6dFGS/2MASS
	JHK			$JHK < 14.7$	/SuperCOSMOS
Bell et al. (2003)	$ugriz$	< 0.1	22679	r<17.5	SDSS
	K		6282	$K < 15.5$	2MASS
Kashikawa et al. (2003)	BK'	0.6-3.5	439	$K' < 24$	Subaru Deep Survey
Stefanon & Marchesini (2011)	JH	1.5-3.5	3496	$K_s < 22.7$-25.5	MUSYC/FIRES/FIREWORKS
Pozzetti et al. (2003)	JK_s	0.2-1.3	489	$K_s < 20$	K20 Survey
Feulner et al. (2003)	JK'	0.1-0.6	500	$K' < 19.4$-20.9	MUNICS
Eke et al. (2005)	JK_s	0.01-0.12	16922,15664	$JK_s \lesssim 15.5$	2dFGRS/2MASS
Cole et al. (2001)	JK_s	0.005-0.2	7081,5683	$JK_s \lesssim 15.5$	2dFGRS/2MASS
Smith et al. (2009)	K	0.01-0.3	40111	$K < 17.9, r < 17.6$	UKIDSS-LAS/SDSS
Saracco et al. (2006)	K_s	0.001-4	285	$Ks < 24.9$	HDFS/FIRES
Kochanek et al. (2001)	K_s	0.003-0.03	4192	$K_{20} < 13.35$	2MASS/CfA2/UZC
Huang et al. (2003)	K	0.001-0.57	1056	$K < 15$	2dF/AAO
Arnouts et al. (2007)	K	0.2-2	21200	$m_{3.6mic} < 21.5$	SWIRE/VVDS
					/UKIDSS/CFHTLS
Cirasuolo et al. (2010)	K	0.2-4	~50000	$K < 23$	UKIDSS/SXDS
Babbedge et al. (2006)	$L_{3.6\mu m} M_{4.5\mu m}$	0.01-0.6	34281	< 20.2	SWIRE/INT WFS
Dai et al. (2009)	$L_{3.6\mu m} M_{4.5\mu m}$	0.01-0.6	4905,5847	$LM < 19, I < 20.4$	IRAC-SS/AGES



$$\phi(L)dL = \phi^\star \left(\frac{L}{L^\star}\right)^\alpha \exp\left(-L/L^\star\right) dL.$$

Number Counts

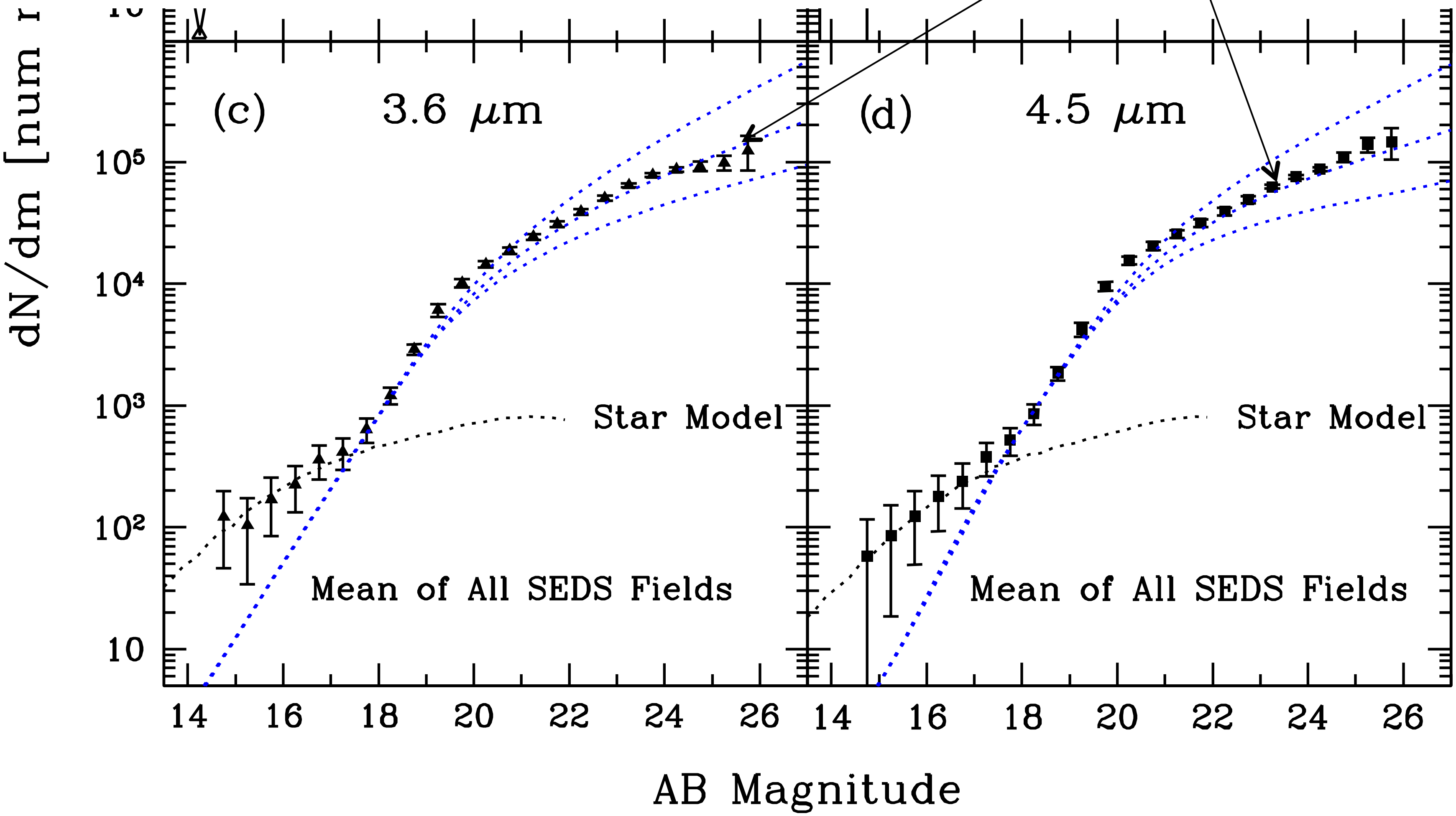
$$N(m) = \int \Phi(m|z) \frac{dV}{dz d\Omega} dz$$



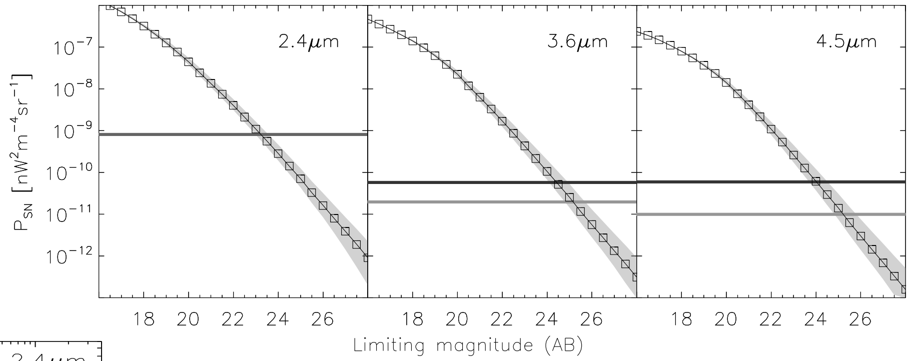
Bright-end dominated by local populations

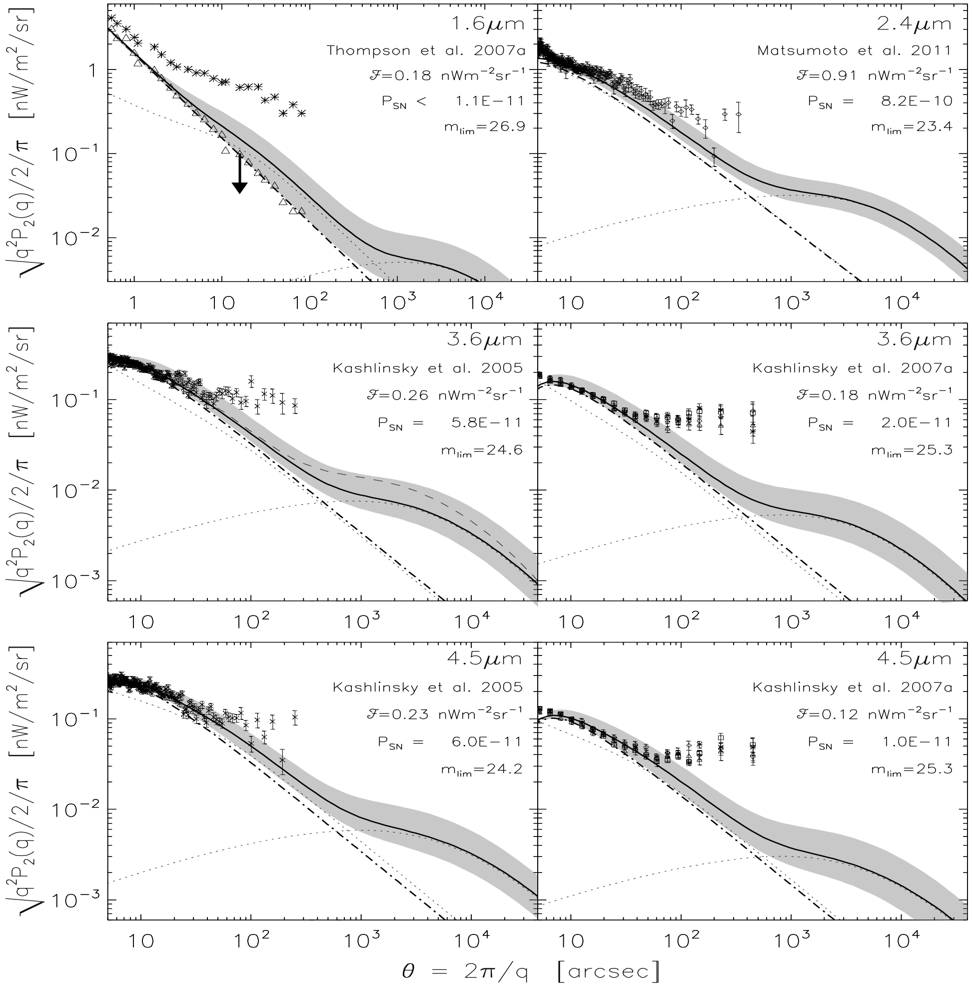
Faint-end dominated by intermediate-z populations

New deeper IRAC counts from Ashby et al (2013, 2015) confirm the Helgason et al reconstruction to a remarkable accuracy.



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).

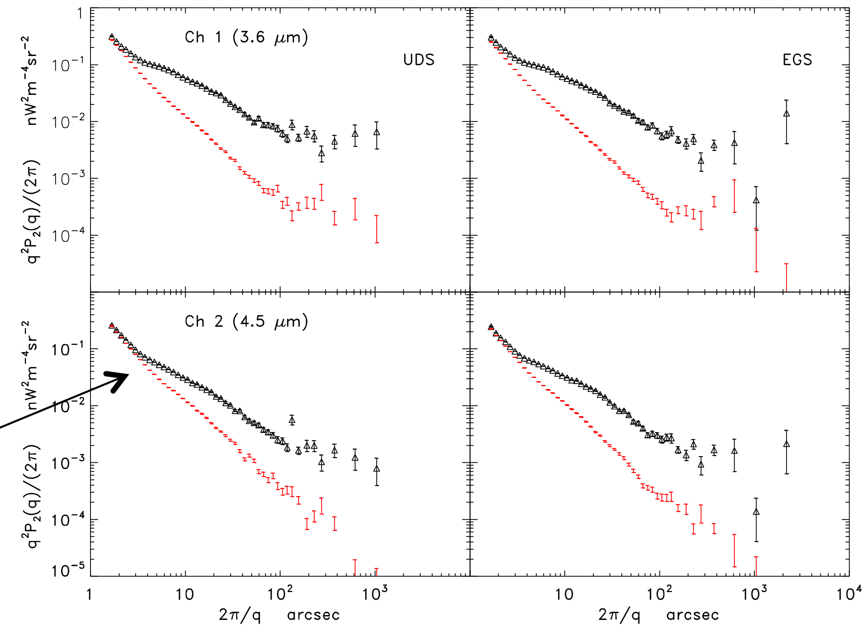
Warm mission *Spitzer CIB* results (Kashlinsky et al 2012)

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

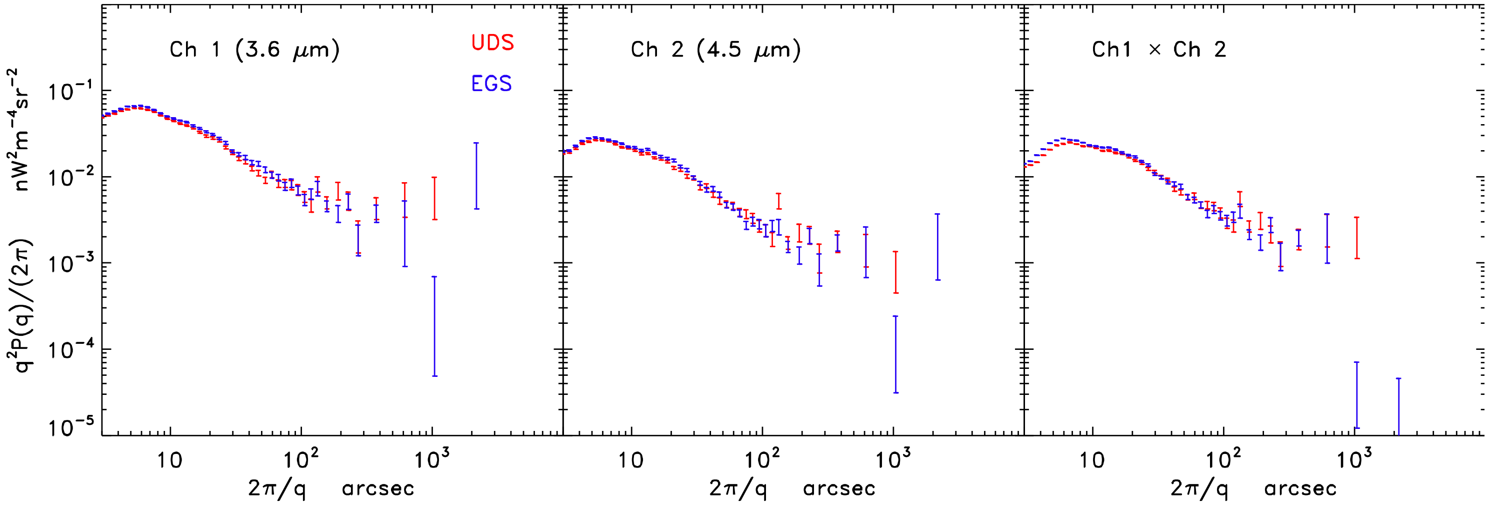
P_{A+B} in black; P_{A-B} in red



After subtracting noise:

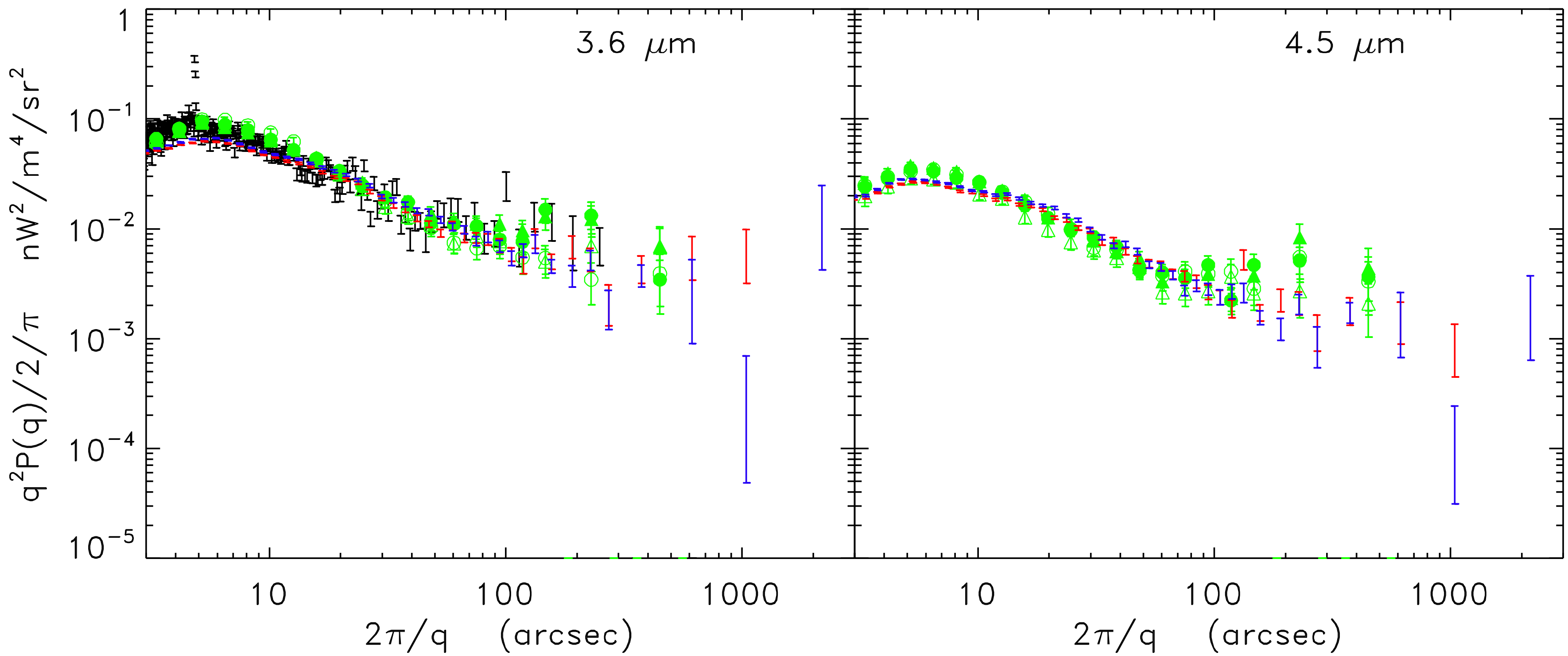
$P = P_{A+B} - P_{A-B}$

Same signal appears in Ch1 and 2 !



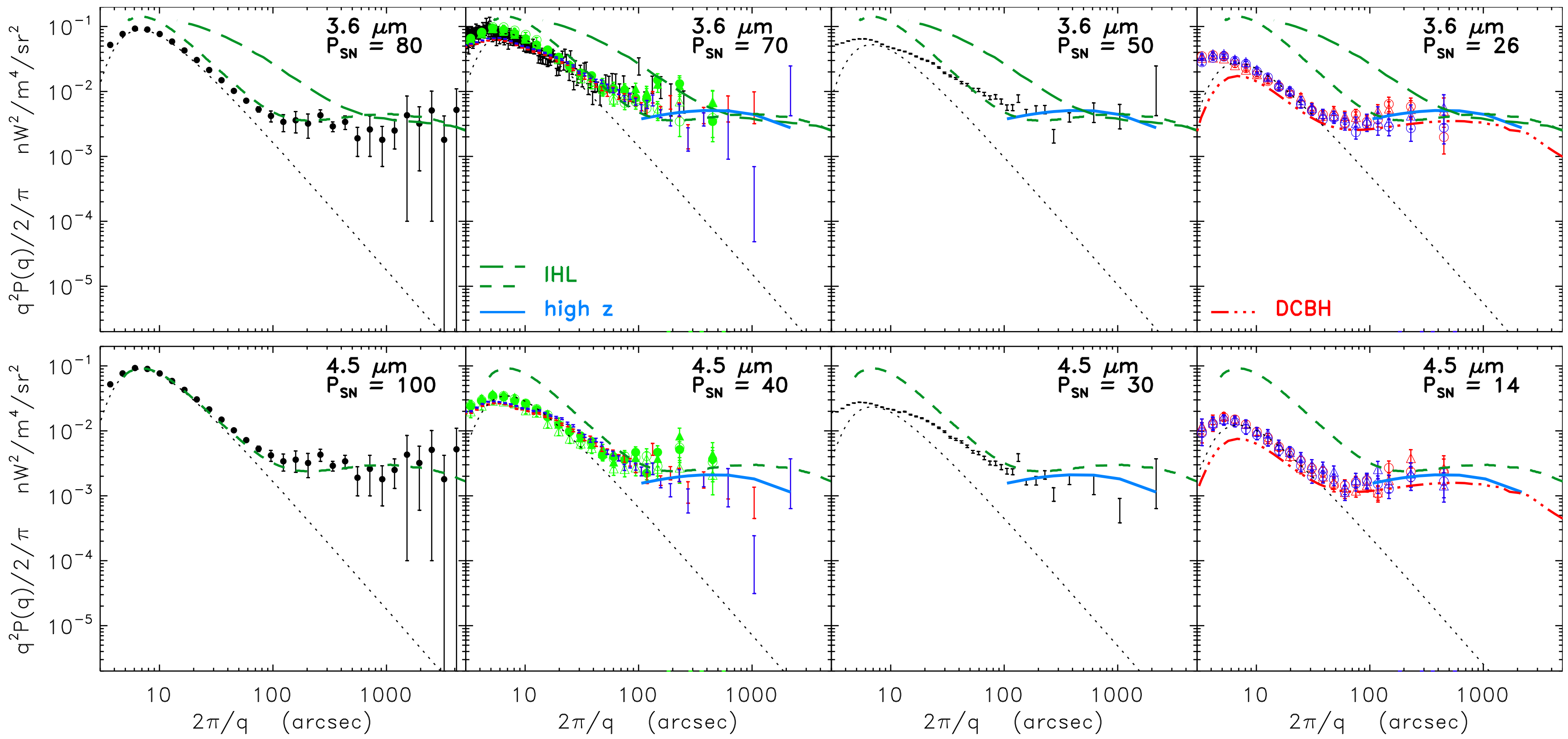
COMPARISON WITH EARLIER MEASUREMENTS

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



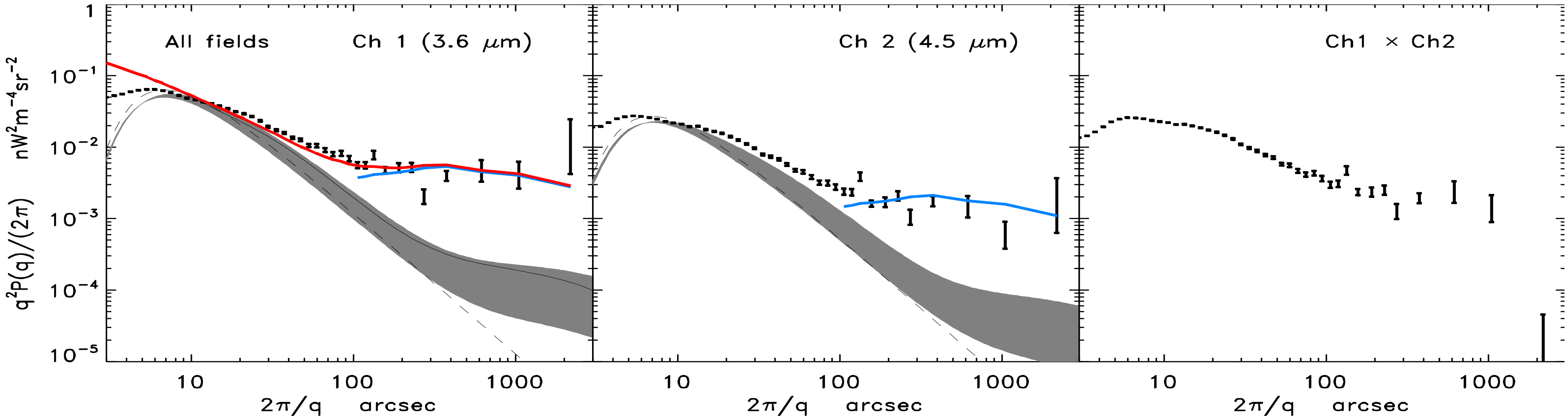
The measured fluctuations appear isotropic over 7 different fields/locations. This by itself shows the sky signal to be of cosmological origin.

Clustering component does not yet decrease with shot-noise



From Kashlinsky et al (2012)

Averaged over fields. Signal, inc the 3.6x4.5 µm cross-power, is measured to ~ 1°

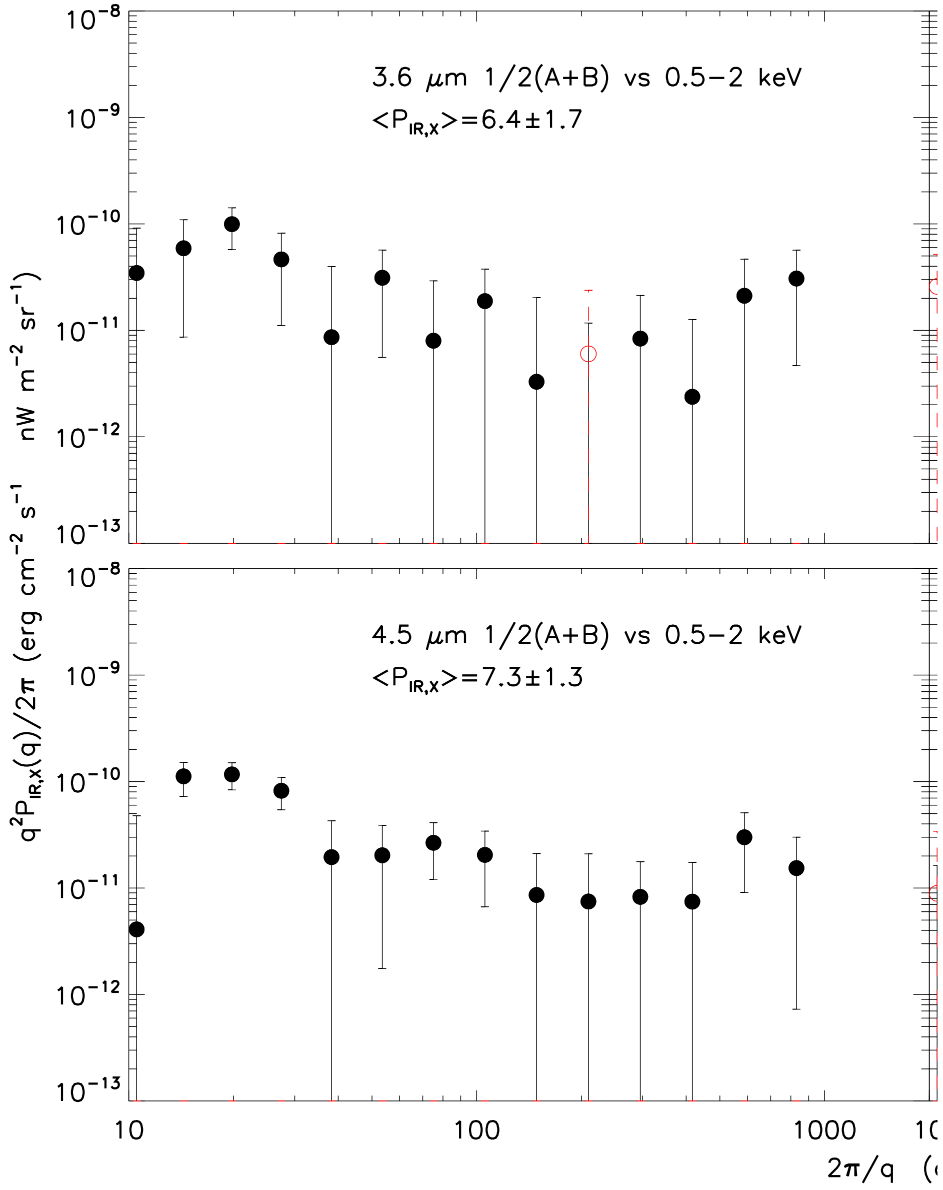


- Measurement is now extended to ~ 1deg
- Shaded region is contribution of remiaining ordinary galaxies (low/high faint end of LF)
- CIB fluctuations continue to diverge to more than 10 X of ordinary galaxies.
- Blue line correspond to toy-model of LCDM populations at z>10
- Fits are reasonable by high-z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

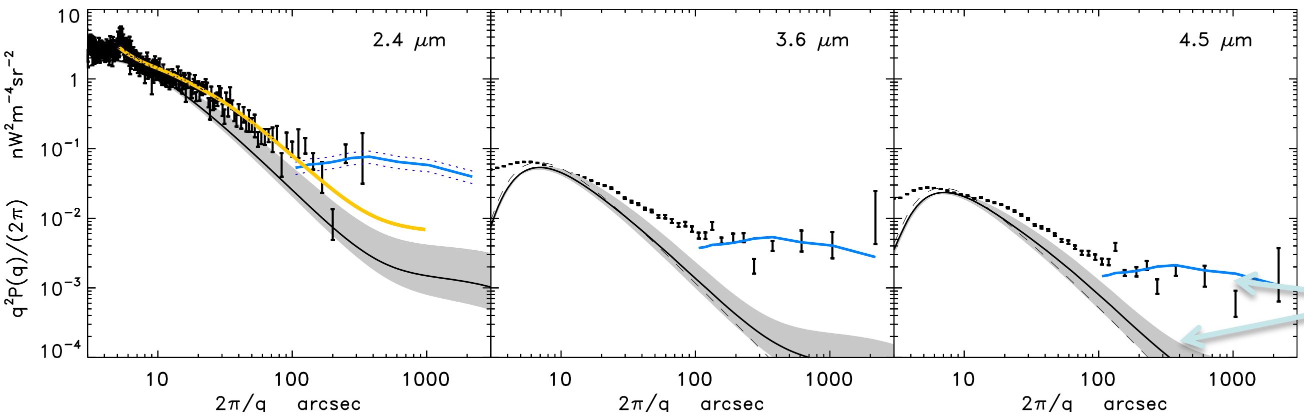
Cross-correlating CIB with CXB (Cappelluti et al 2013)

- Have constructed unresolved CXB maps using Chandra Msec observations in the EGS/AEGIS filed and Spitzer/SEDS data
- There exists highly statistically significant cross-power (>5-sigma)
- **CXB-CIB coherence is**

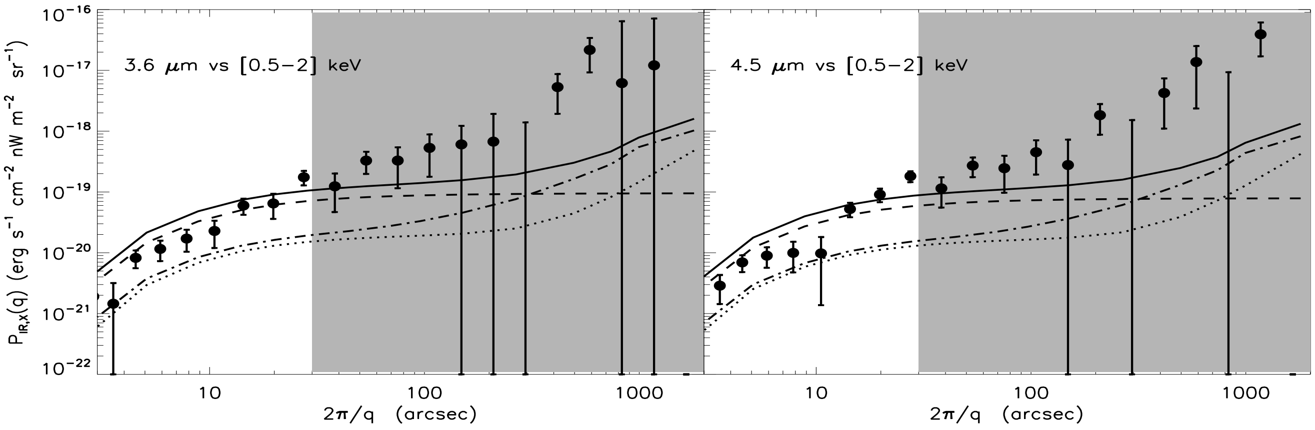
  $C=|P_{X\text{-}IR}|^2/P_X/P_{IR}$ >~0.04
- ***Indicates at least √C~ 20% of the CIB sources are correlated with accreting sources (BHs), proportion far higher than in the present-day populations.***



Observational motivation established with Spitzer, AKARI + Chandra data:



- Spitzer and AKARI measurements uncovered source-subtracted CIB fluctuations significantly in excess of those by remaining known gals. Power consistent with high-z LCDM



- There exists CXB-CIB crosspower in Spitzer+ Chandra data exceeding at ***>5σ significance*** the cross-power from known sources and indicating high BH proportion (>1:5) among the CIB sources.

Two current models successfully explain the measurements: 1) direct-collapse-BHs (DCBHs, Yue et al 2013) and 2) primordial LIGO-type BHs making up dark matter (Kashlinsky 2016).

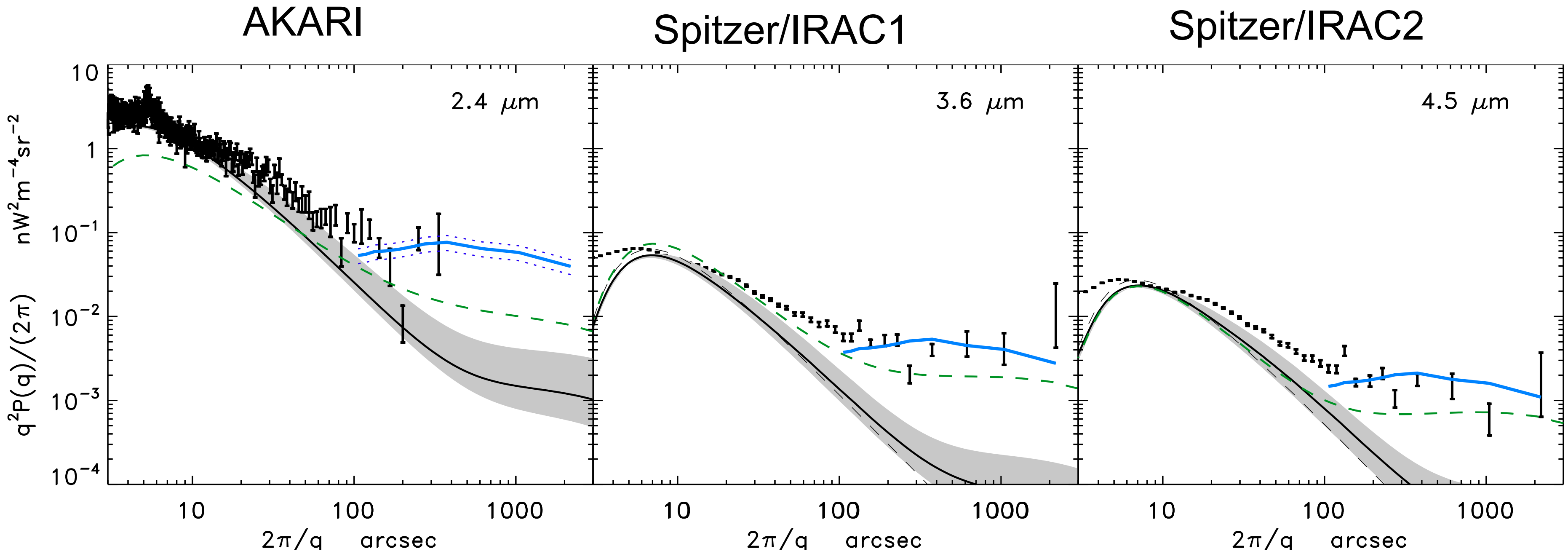
CIB at 2-5 micron: established key properties

- Two components: shot-noise at small scales and clustering component
- Shot noise is from remaining galaxies, but clustering component indicates new pops

- Large-scale component cannot be accounted for by remaining known galaxies
- SED consistent with λ^{-3} from hot Rayleigh-Jeans sources
- Angular spectrum to 1 deg consistent with high-z LCDM-distributed population
- Fluctuations are **coherent** with unresolved soft-X band (0.5-1keV) CXB indicating at least ~15-25% of sources are accreting BHs

- No coherence between CIB and unresolved CXB at harder (>1 Kev) X-bands
- The measured coherence cannot be explained by remaining known populations
- The clustering component does yet appear to start decreasing as the shot noise is lowered from 7.8 hr/pix to > 21 hr/pix exposures
- Diffuse maps do ***not*** correlate with either removed sources or extended mask

Summary of current CIB measurements: 2-5 micron (Spitzer and AKARI)



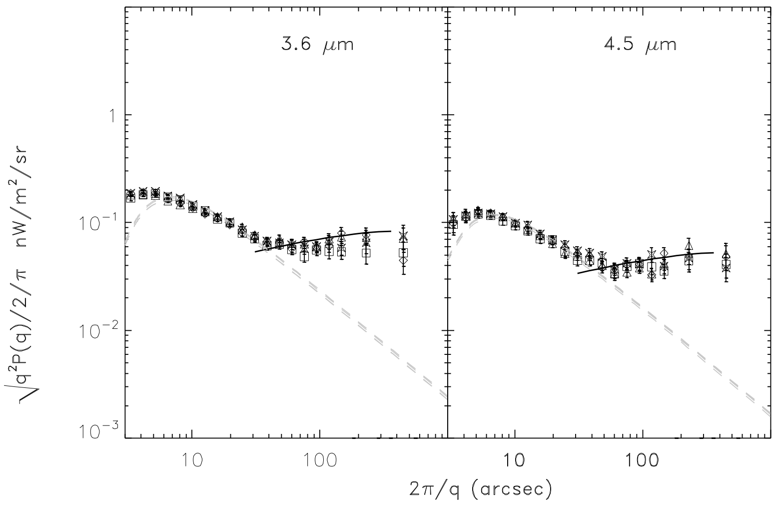
The integrated ("quasi-bolometric") excess CIB flux fluctuation from data, w $\sqrt{P_\lambda} \propto \lambda^{-3}$:

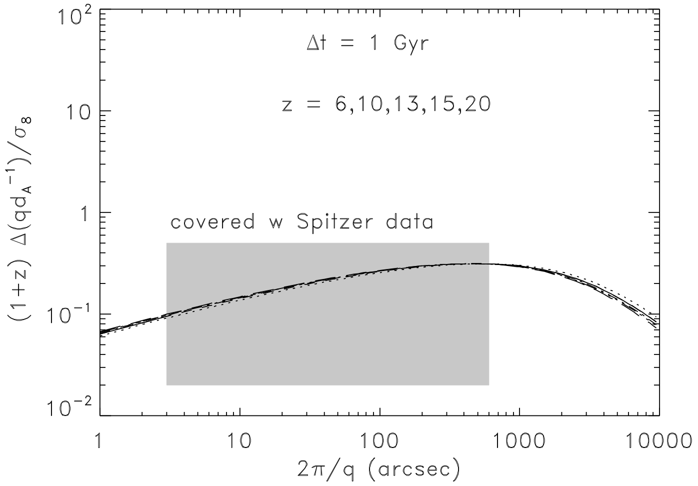
$$\delta F_{2-5\,\mu\mathrm{m}}(5') = \int_{AKARI}^{\mathrm{IRAC}} \left(\frac{q^2 P_\lambda}{2\pi}\right)^{1/2} \frac{d\lambda}{\lambda}$$

$$= \delta F_{4.5\,\mu\mathrm{m}}(5') \left(\frac{(4.5/2.4)^\alpha - 1}{\alpha}\right)$$

$$\simeq 0.09 \text{ nW m}^{-2}\text{ sr}^{-1}$$

What does this CIB 2-5 µm excess mean: 1. clustering component





1. At 3.6 mic the fluctuation is δF~ 0.1 nW/m^2/sr at θ≥ 1 arcmin
2. At 20>z>5 angle θ=1\` subtends between 2.2 and 3 Mpc
3. Limber equation requires:

$$\delta F_{CIB} = F_{CIB}\Delta(qd_A^{-1}(\langle z\rangle)) \qquad \text{w.} \qquad \Delta^2(k) = \frac{1}{2\pi^2}\frac{k^2P_3(k)}{ct_*}$$

4. Concordance CDM cosmology with reasonable biasing then requires
   Δ of at most 5-10 % on arcmin scales
5. ***Hence, the sources producing these CIB fluctuations should have F_{CIB} ~ 1 nW/m^2/sr***

2. Shot noise: clues to where the signal comes from.

$P_{SN}=\int S^2(m)\, dN(m)$ and $F_{CIB}=\int S(m)\, dN(m)$ hence:

$$P_{SN}= \int S(m)\, dF_{CIB}(m) = S(<m>)\, F_{CIB}(m>m_{lim})$$

where $S(m)=f_0 10^{-0.4m}$ and $dF=S(m)dN(m)$.

At 3.6,4.5 mic $P_{SN}<(1,2)\times10^{-11}$ nW^2/m^4/sr and the level of clustered component of fluctuations indicates F> 1 nW/m^2/sr. The fluctuations arise from population with relatively strong clustering component, which has only a weak shot-noise level. SO:

1. For F_{CIB}~1 nW/m^2/sr, the SN levels indicates the sources contributing to fluctuation must have m_{AB}>28-29.

2. These sources must be abundant at $n_2 \sim F^2_{CIB}/P_{SN} >\sim 10^{11}$ /sr

3. What are the populations producing the CIB fluctuations if at high z?

Ly-break being at > 0.9 mic today requires z>~7-8, so the time available to produce the CIB:

$$t(z=8)=0.6\ \mathrm{Gyr};\ t(z=20)=0.2\ \mathrm{Gyr},\ \text{so}\ \Delta t< 0.5\text{-}1\mathrm{Gyr}$$

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

$$\mathcal{L}_* \approx \tfrac{4\pi}{c} F_{CIB} (\Delta t)^{-1} (1+z) \approx 7\times 10^8 L_{Sun} Mpc^{-3} \frac{1Gyr}{\Delta t} \frac{1+z}{6} \frac{F_{CIB}}{nW/m^2/sr}$$

Or in terms of density in *'s

(Today $\Omega_* \sim 2\mathrm{x}10^{-3}$)

$$\Omega_* = 5\times 10^{-3} \frac{F_{CIB}}{nW/m^2/sr} \frac{\Gamma}{\Gamma_{Sun}} \left(\frac{1Gyr}{\Delta t}\right) \frac{1+z}{6}$$

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

This means that these sources had to have very large L/M – may be P3 stars, but also may be BHs as well (or have an admixture of less massive *'s).

Can this CIB be produced by high-z sources?

(Kashlinsky et al 2015, ApJ, 804, 99)

- The net CIB fluctuation integrated between 2 and 5 μm is ***$\delta F_{2\text{-}5\mu m}$=0.1 nW/m²/sr***
- The net "bolometric" flux produced by sources at high $z_{\rm eff}$ emitting radiation at efficiency ε:

$$F_{\rm tot} \simeq \frac{\epsilon f}{z_{\rm eff}} \frac{c}{4\pi} \rho_{\rm bar} c^2 \simeq 9.1 \times 10^5 \frac{\epsilon f}{z_{\rm eff}} \frac{\Omega_{\rm bar} h^2}{0.0227} \ {\rm nW\ m^{-2}\ sr^{-1}}$$

- If P3 then ε~0.007, if P2 then ε~0.0007, if BH then one can reach ε~0.2
- Hence to produce the measured *$\delta F_{2\text{-}5\mu m}$ ~ 0.1 nW/m²/sr* with relative amplitude $\Delta_{5'}$~0.1 around 5' one needs:

Pop 3 (massive *s):

$$f_{P3} \sim 1.4 \times 10^{-3} \left(\frac{z_3}{10}\right) \left(\frac{\Delta_{5'}}{0.1}\right)^{-1}$$

Pop 2 (normal IMF *s):

$$f_{P2} \gtrsim 0.01 \left(\frac{\epsilon}{7 \times 10^{-4}}\right) \left(\frac{z_3}{10}\right) \left(\frac{\Delta_{5'}}{0.1}\right)^{-1}.$$

BH emissions:

$$f_{\rm BH} \sim 5 \times 10^{-5} \left(\frac{z_3}{10}\right) \left(\frac{\Delta_{5'}}{0.1}\right)^{-1} \left(\frac{\epsilon}{0.2}\right)^{-1}$$

These small "reasonable" fractions possibly appear "unreasonable" in "standard" model

*Regimes of * formation in 1st metal-free halos at z>10*

Less massive/more numerous halos

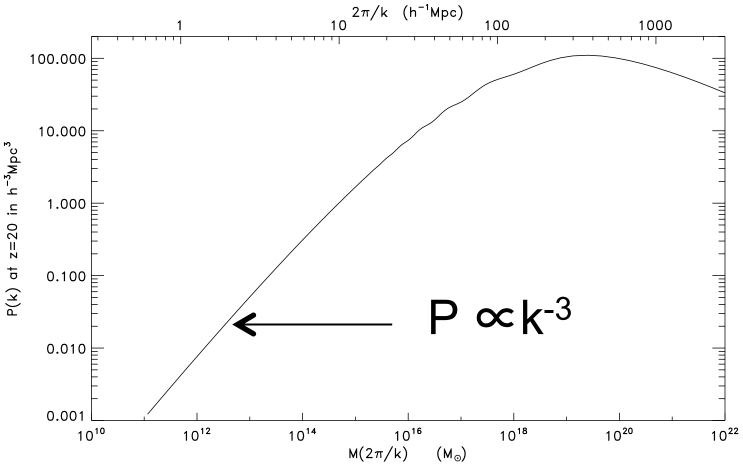
- T_{vir}~1,000K
- H_2 forms and cools gas
- Gas collapses isothermally
- Forms 1st stars at $n \sim 10^4$ cm^{-3}
- 1st stars are massive
- Emit Lyman-Werner radiation at 11.2-13.6 eV
- LW photons dissociate H_2
- * formation in the halo cannot be sustained and ceases

More massive/less numerous halos

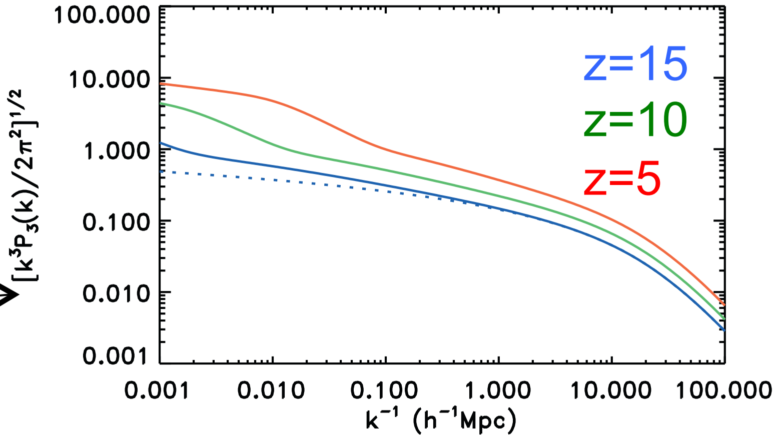
- $T_{vir}>10^4$K
- No H_2 forms
- Ionized H provides cooling
- Gas collapses at $T=10^4$K
- Forms stars
- * formation can be ongoing as in “galaxies”
- These 1st galaxies would be very few in number for standard cosmology

*Formation of 1^{st} *s and CIB in "standard" DM cosmology*

"Standard" (particle CDM) P(k)



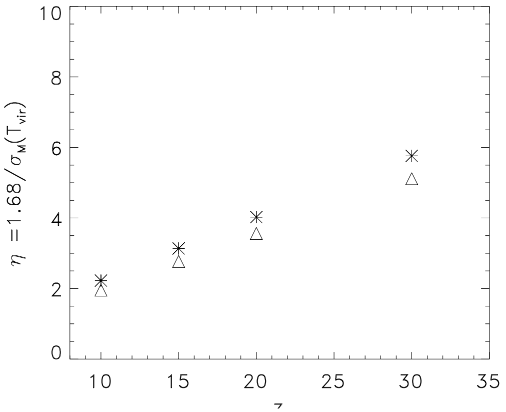
RMS mass density fluctuations



Hence baryon fraction in collapsed halos:

Z	**$T_{vir} = 10^4$K**	**$T_{vir} = 10^3$K**
25	9×10^{-5}	7×10^{-4}
20	10^{-3}	5×10^{-3}
15	8×10^{-2}	1.5×10^{-2}
10	3×10^{-2}	7×10^{-2}

\# of standard deviations in collapsing halos w $T_{vir}>10^3$K



Needed to explain CIB

$f_{Halo}f_*\sim10^{-3}$ (z/10) ($\varepsilon/10^{-2}$)

Whereas sims and "common sense" suggest *$f_*<10\%$*

LIGO's GW150914

- Two BHs: $M_1 = 36_{-4}^{+5}\,M_{sun}$ and $M_2=29\pm4\,M_{sun}$ (w no spin)
- Detected w/n 1 week of operations and imply rate of (2-400) $yr^{-1}Gpc^{-3}$
- More BHs mergers are known by now (5+).
- While these remarkably similar *and* large masses somehow may be remnants of normal *, what if…

- These two were ***primordial BHs making up dark matter*** as suggested in Bird et al, Garcia-Bellido & Clesse and Kashlinsky in 2016
- This binary may have arisen in PBHs being captured by GW emissions in dense low-velocity environments at the observed rate (more-or-less)

PBHs and extra fluctuation power

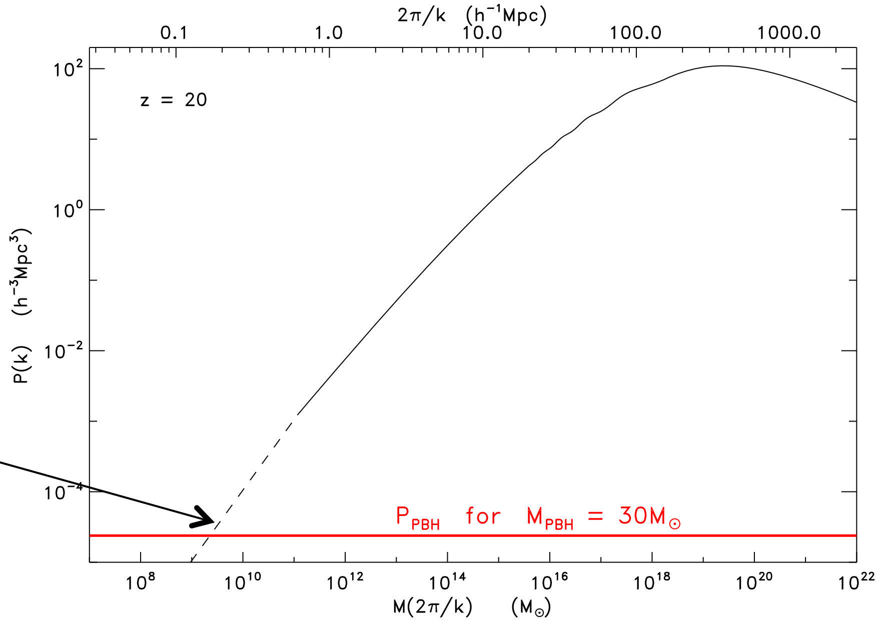
- If LIGO BHs were PBHs making up DM, there number density would be

$$n_{\rm PBH} = \frac{1}{M_{\rm PBH}} \Omega_{\rm CDM} \frac{3H_0^2}{8\pi G} \simeq 10^9 \left(\frac{M_{\rm PBH}}{30M_\odot}\right)^{-1} \left(\frac{\Omega_{\rm CDM}h^2}{0.1}\right) {\rm Mpc}^{-3}.$$

- They would then be present before z_{eq} and contribute
- Poissonian isocurvature component with the extra power at z:

$$P_{\rm PBH}(z) = \frac{9}{4}(1+z_{\rm eq})^2 n_{\rm PBH}^{-1} [g(z)]^{-2} \simeq 2 \times 10^{-2} \left(\frac{M_{\rm PBH}}{30M_\odot}\right) \left(\frac{\Omega_{\rm CDM}h^2}{0.13}\right) \left(\frac{1}{g^2(z)}\right) {\rm Mpc}^3$$

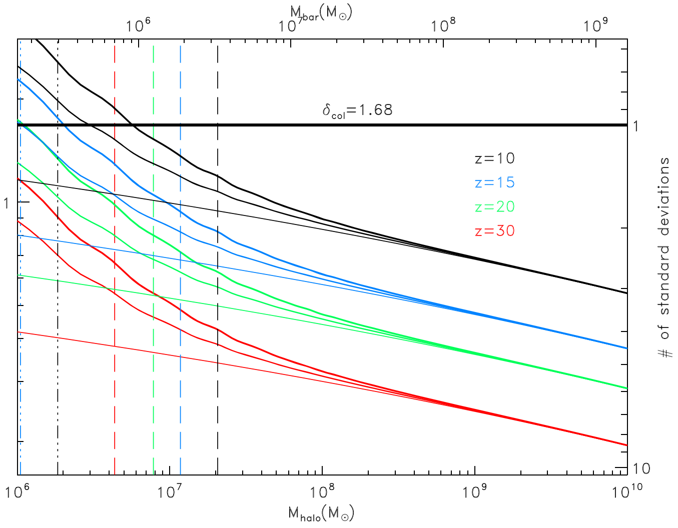
- This extra power will dominate the small scales responsible for collapse of 1st minihaloes where 1st sources form! The resultant CIB would change dramatically.



1^{st} minihalo collapse in presence of DM PBHs

RMS density
fluctuation
vs halo mass

M_{PBH}=0, 15, 30 $M_\odot$

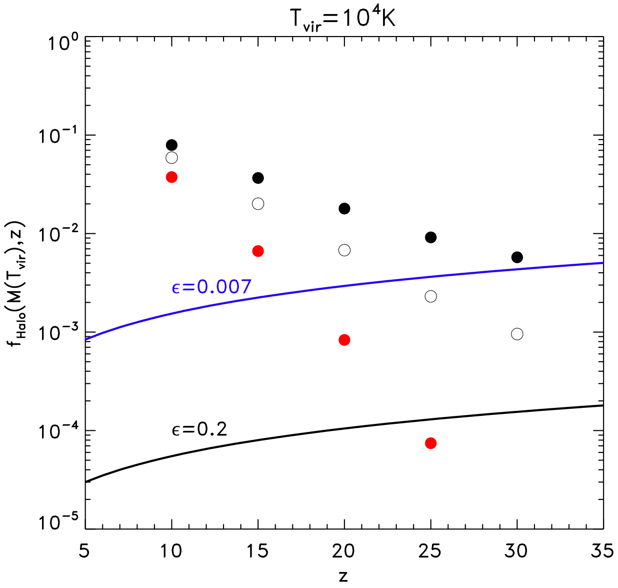


Number of standard
deviations for collapsed
halos of mass M
at z=10, 15, 20, 30

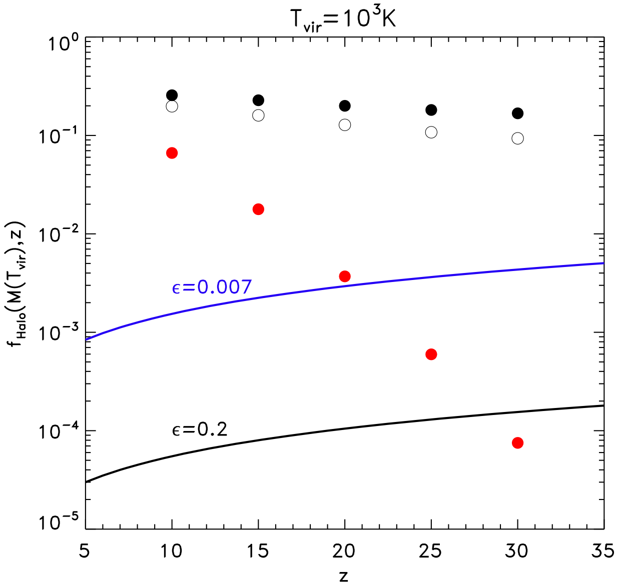
Fraction of collapsed
halos (f_{Halo}) at *z*

- "Standard" DM
- PBH DM of
  M_{PBH}=30$M_\odot$

A. Kashlinsky



CERN



May 2018

Formation of 1st sources in presence of DM PBHs

- **I. *Inevitable to produce***
- Observed CIB
- Observed CIB-CXB coherence

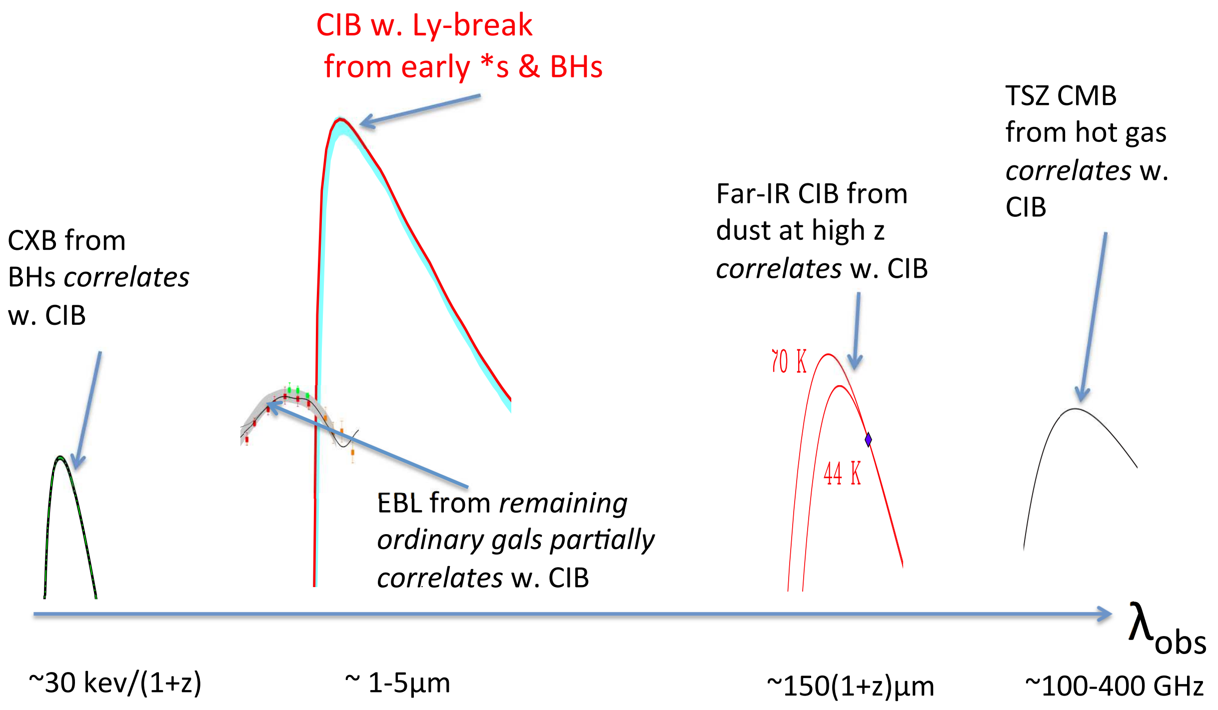
- **II. *Factors to be worked out***
- PBH accretion: may increase PBH mass by <10%
- PBH cluster evolution: evaporation – will affect later evolution
- PBH GW merger: dynamical friction + sinking leading to massive BH

- **III. *Need to study:***
- LW radiation from accreting PBHs and formation of H_2 & 1st stars
- Radiation from accreting PBHs and distortions in CMB from upcoming missions.

LIBRAE – Looking at Infrared Background Radiation Anisotropies with *Euclid*

https://www.euclid.caltech.edu/page/Kashlinsky%20Team

A NASA-selected cosmic infrared background (CIB) study to measure what were the 1st sources - Pop 3 stars, BHs, and in what proportions, when and how many - as well as probe IGM and BAOs at 10<z<20. The planned science is below:



CIB w. Ly-break
from early *s & BHs

TSZ CMB
from hot gas
correlates w.
CIB

Far-IR CIB from
dust at high z
correlates w. CIB

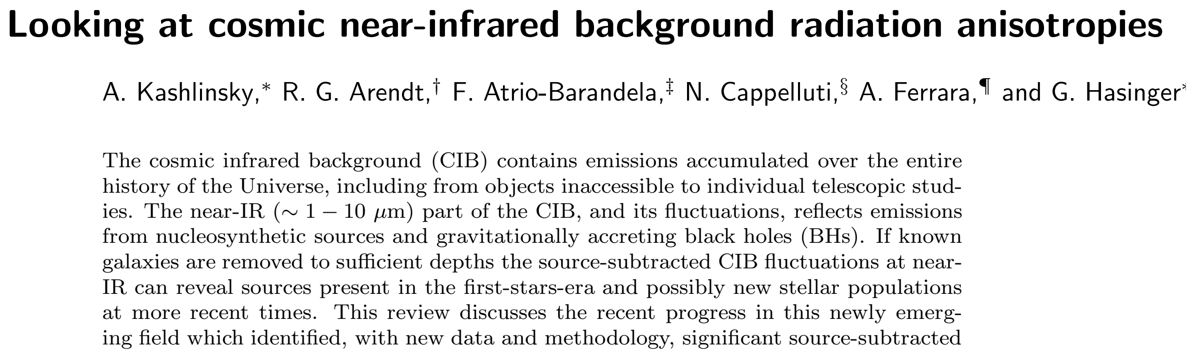
CXB from
BHs *correlates*
w. CIB

EBL from *remaining*
ordinary gals partially
correlates w. CIB

LIBRAE has 7 US-based scientists and a similarly sized contingent in Europe.
PI – A. Kashlinsky

Euclid holds substantial and unique promise for this science:

- Review on CIB for Review of Modern Physics gives details (Sec. VII)



Looking at cosmic near-infrared background radiation anisotropies

A. Kashlinsky,[*] R. G. Arendt,[†] F. Atrio-Barandela,[‡] N. Cappelluti,[§] A. Ferrara,[¶] and G. Hasinger

The cosmic infrared background (CIB) contains emissions accumulated over the entire history of the Universe, including from objects inaccessible to individual telescopic studies. The near-IR ($\sim 1 - 10\ \mu$m) part of the CIB, and its fluctuations, reflects emissions from nucleosynthetic sources and gravitationally accreting black holes (BHs). If known galaxies are removed to sufficient depths the source-subtracted CIB fluctuations at near-IR can reveal sources present in the first-stars-era and possibly new stellar populations at more recent times. This review discusses the recent progress in this newly emerging field which identified, with new data and methodology, significant source-subtracted

Arxiv:1802.07774
Rev Mod Phys, in press

- **Goal 1**: Determining source-subtracted CIB power spectrum to better than 1% statistical accuracy w NISP all-sky survey.
- **Goal 2**: Determining epochs (Lyman-break) of the contributing sources from NISP-VIS cross-power.
- **Goal 3**: Determining history of emissions and BAOs at 10<z<20 w Lyman tomography. Probing cosmological parameters at those epochs from BAOs.
- **Goal 4**: Probing CIB-CXB cross-power and BH proportions amongst the sources from Euclid+eROSITA.
- **Goal 5**: Probing condition of IGM at 10<z<20 from CIB-CMB cross-power with Euclid CIB and next stage CMB maps (AdvACTPol and CMB-S4 as well as Planck).

SUMMARY

- If PBHs of the LIGO type are DM the outlined mechanism is ***inevitable***
- If PBHs are not DM, this is ***irrelevant***
- ***Could be that the same population detected by LIGO was seen in our CIB signal***
- Fully testable and future LIGO observations over the next 1-2 (?) yrs will close the story.
- LIBRAE (Looking at Infrared Background Anisotropies w *Euclid*) will resolve the CIB anisotropies and their CXB coherence w sub-percent accuracy.