The Bright Side of Black Holes:
dark matter, primordial black holes and the cosmic infrared background

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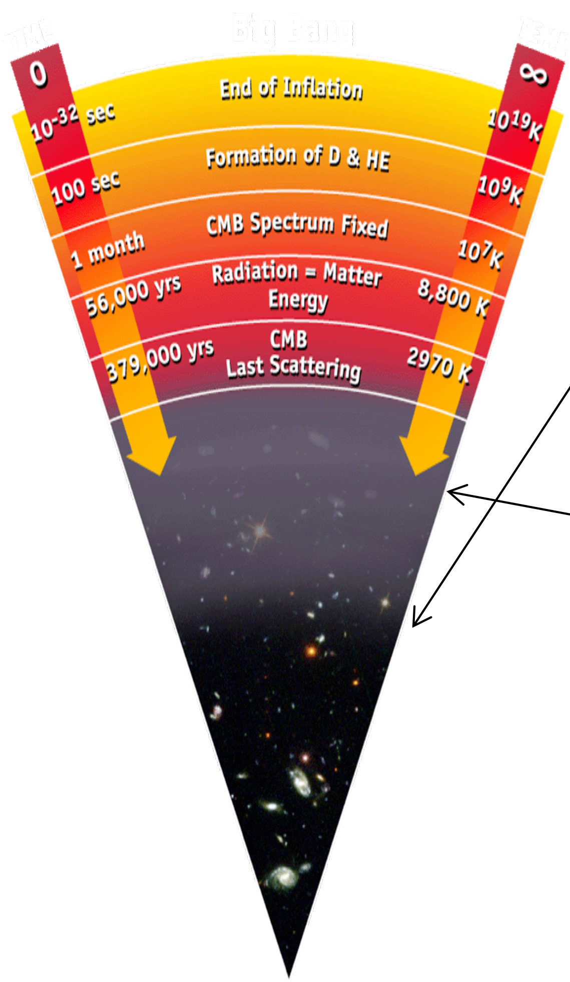
(GSFC/SSAI and Euclid)

In collaboration with R. Arendt, M. Ashby, F. Atrio-Barandela, N. Cappelluti, G. Fazio, A. Finoguenov, A. Ferrara, G. Hasinger, K. Helgason, Y. Li, J. Mather, H. Moseley. M. Ricotti and others.

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 $M_\odot$

- *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:

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

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

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

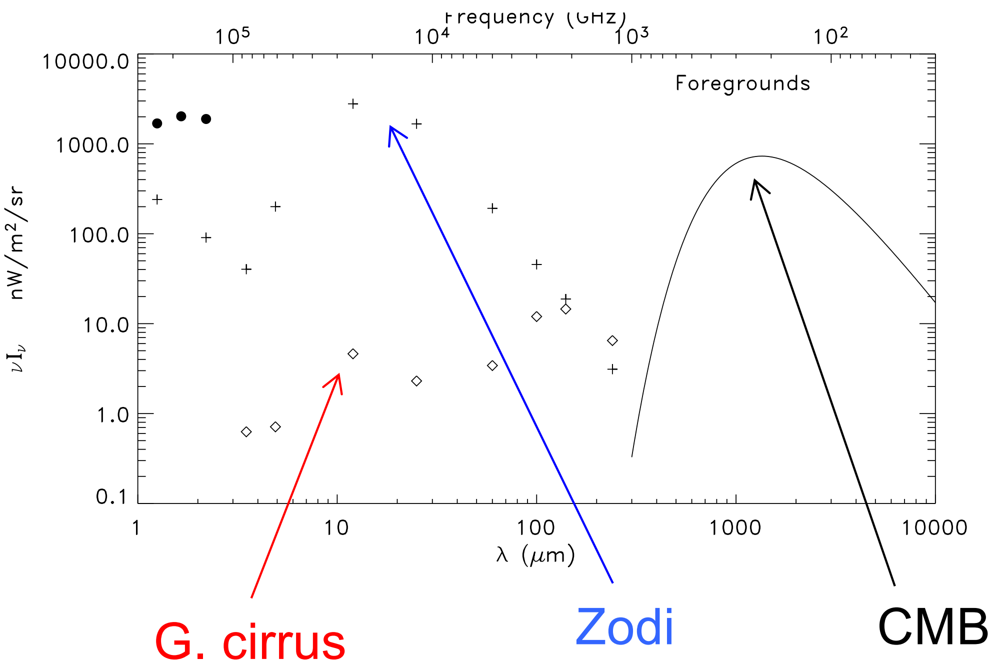
$$\nu I_\nu = \frac{3}{8\pi}\frac{1}{4\pi R_H^2}\frac{c^5}{G}\varepsilon\Omega_{baryon} f_* \nu b_{\nu'}\frac{1}{z} \cong 1.2\times10^4 \frac{\Omega_{baryon}}{0.044}\frac{\varepsilon}{0.007} h^2 \nu b_{\nu'} f_* / z \frac{nW}{m^2 sr}$$

Hubble radius area

Maximal L of any gravitating object

Emissions are cut at $\lambda > 0.1\ (1+z)\ \mu m$, or ~ $1\mu m$ for $z \sim 10$

Mean CIB is difficult to probe because of foregrounds
but Zodi and Galactic Cirrus are smooth!



Because the foregrounds are very bright, but smooth evaluate the CIB fluctuations after subtracting sources: i.e.

Source-Subtracted CIB Fluctuations

Mean squared flux $\delta F_\lambda^2 = q^2 P_\lambda(q)/(2\pi)$, power $P = \langle |FFT_{Flux}|^2 \rangle$, scales via $q(rad^{-1}) = \ell$ (multipole)

I. Shot noise component to power from sources occasionally entering the beam $\delta F/F \sim 1/N_{beam}^{1/2}$

$P_{SN} = \int S^2(m)\, dN/dm\, dm \sim S\, F_{CIB} \sim n\, S^2$. ***Units:*** $[P_{SN}]$ = nJy nW/m^2/sr (or nW^2/m^4/sr)

II. Clustering component reflects clustering of the emitters, their epochs and duration of their era.

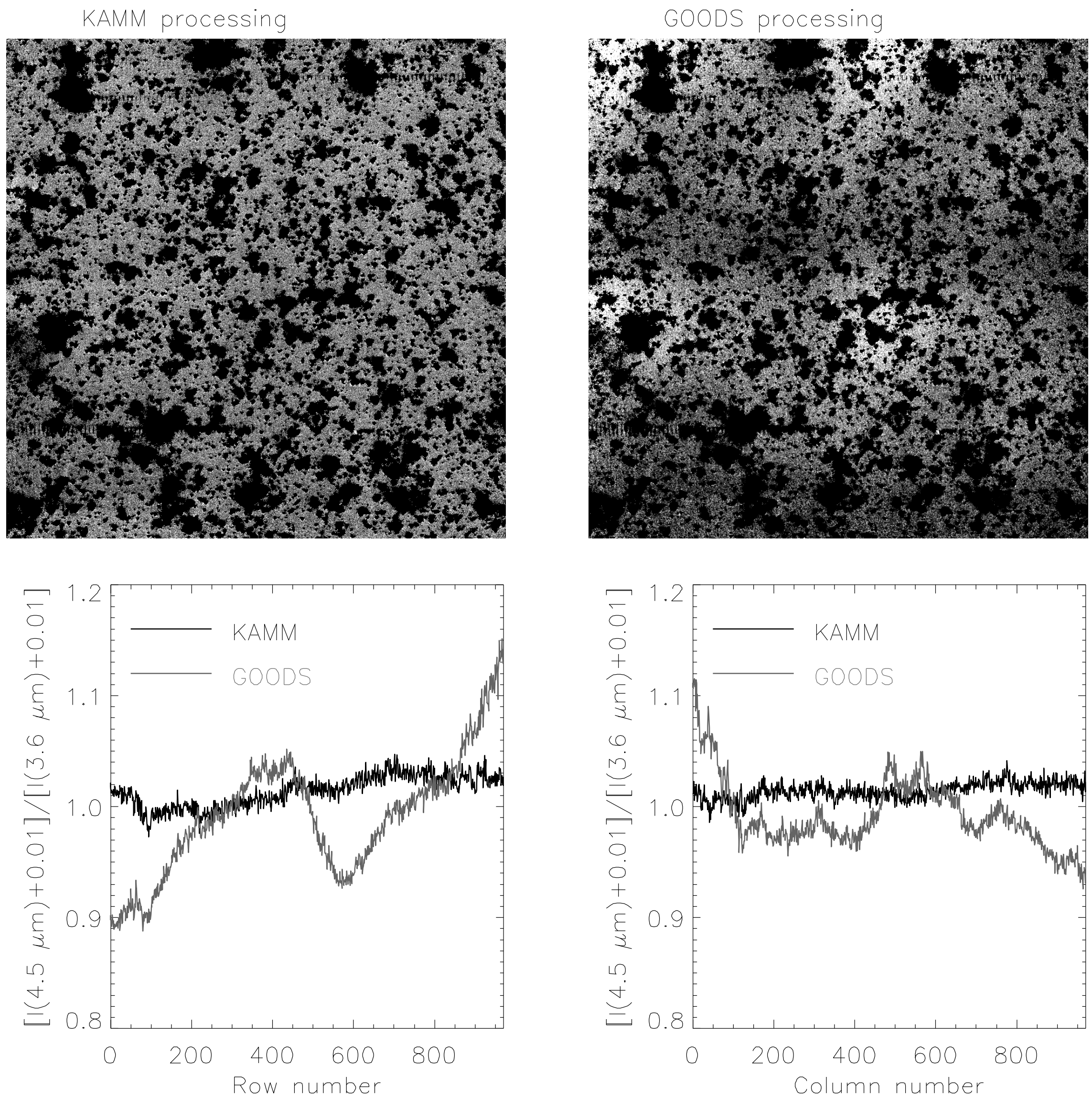
CIB fluctuations at 3-8 μm
from deep Spitzer images (cryogenic + warm era)

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)
A. Kashlinsky et al. (2012, ApJ, 753, 63)

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 *HST*/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***

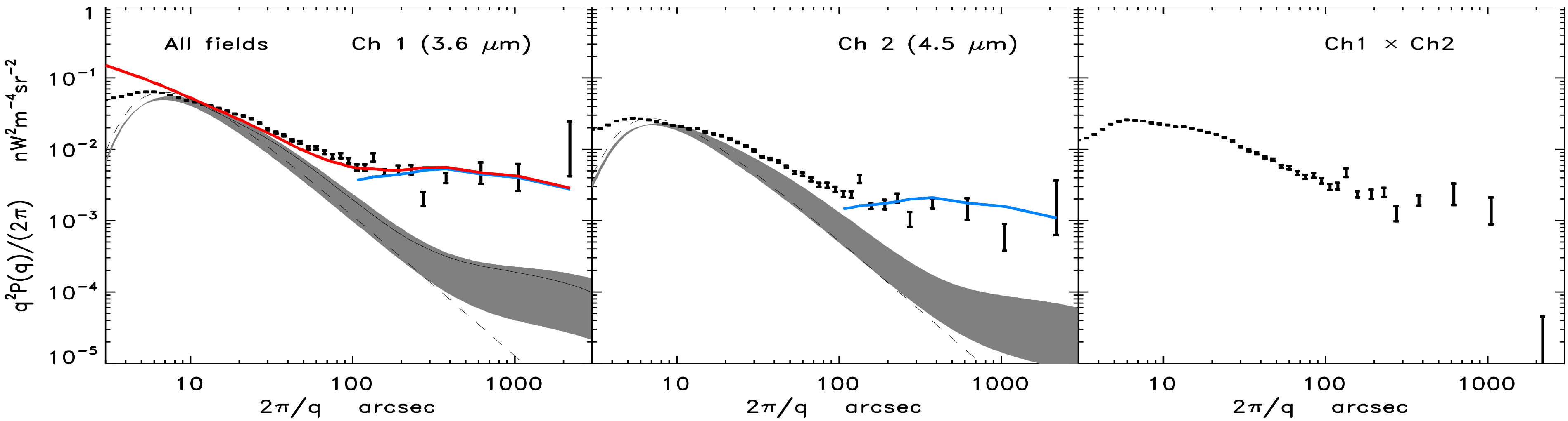
Comparison of self-calibration w standard image assembly



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

From Kashlinsky et al (2012)

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

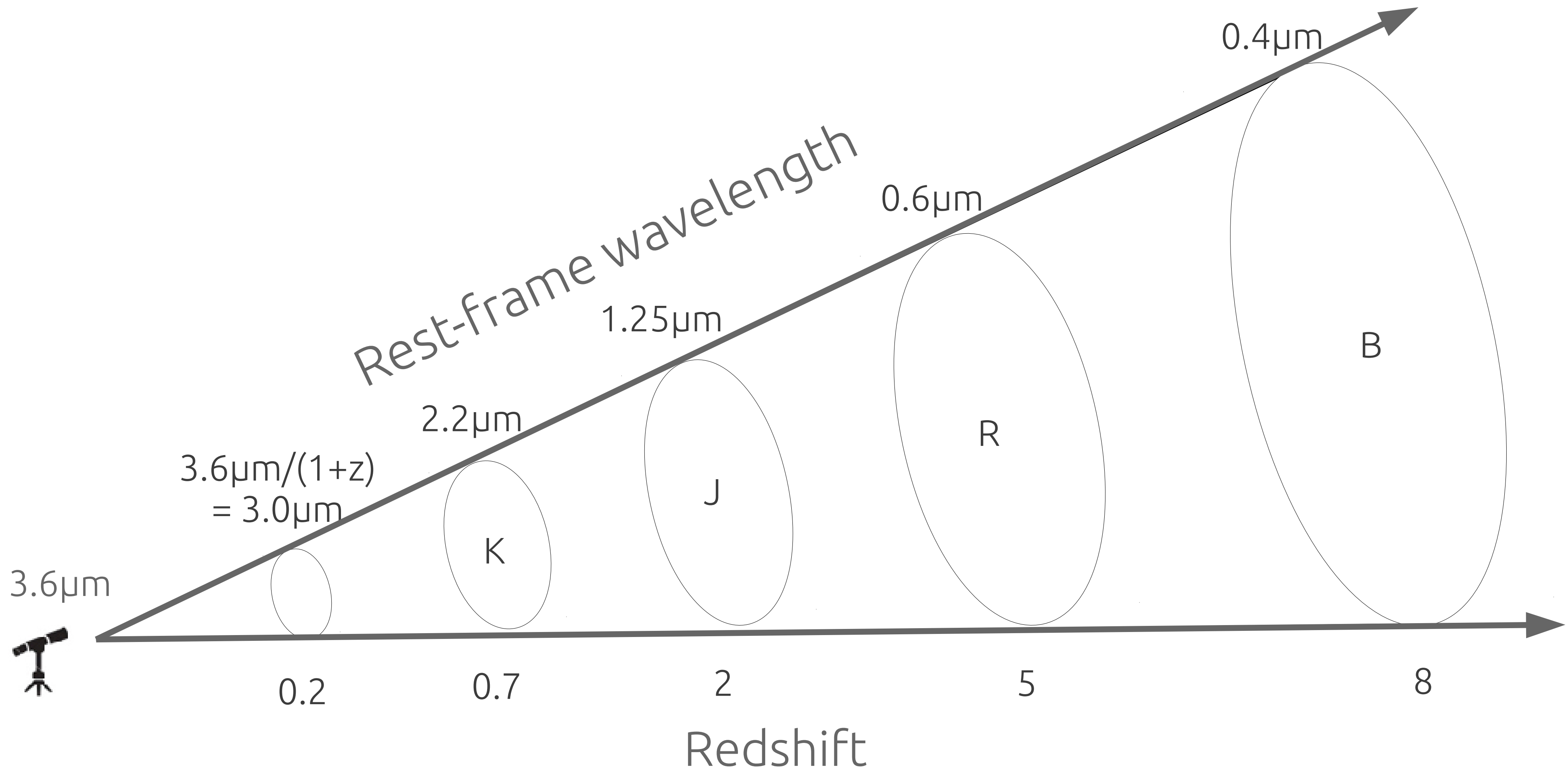


- Measurement now extends to ~ 1deg for 7+ regions
- Shaded region is contribution of remiaining ordinary galaxies (low/high faint end of luminosity function)
- CIB fluctuations continue to diverge to more than 10 X of ordinary galaxies.
- Blue line corresponds to "toy-model" of LCDM populations at z>10
- Fits are reasonable by high-z populations coinciding with first stars epochs

Estimating contribution from remaining known galaxies per

Helgason, Ricotti, Kashlinsky (HRK12)

Probing the redshift cone

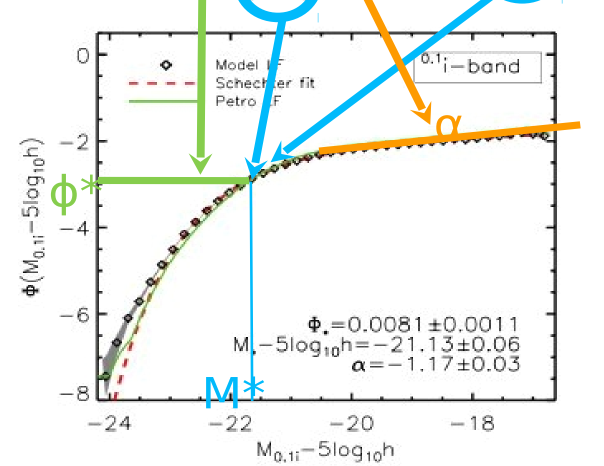


Luminosity Functions

From HRK12 – currently updated to 340+ LF surveys

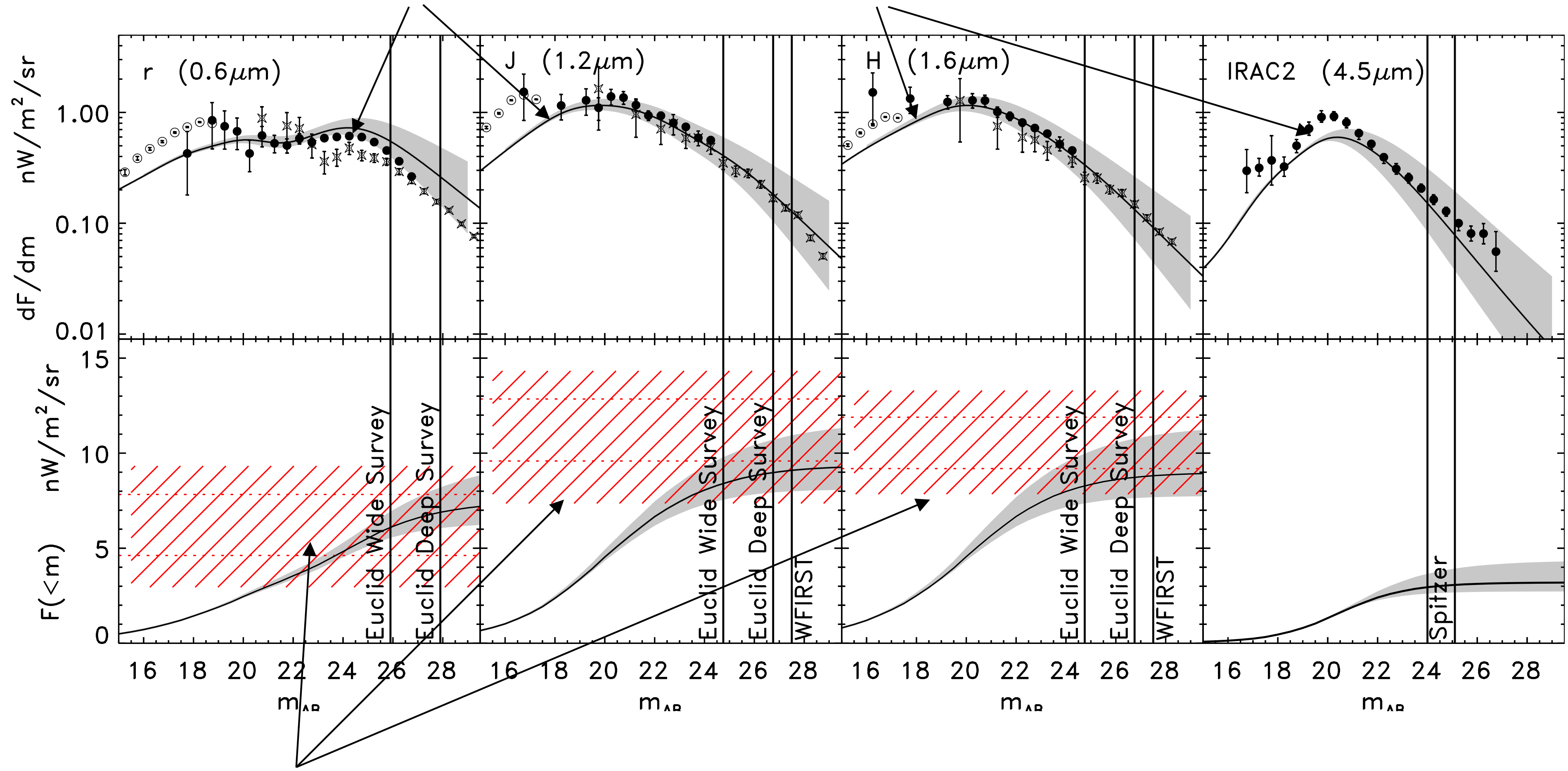
Reference	Rest-frame band	Redshift z	Sample N_{gal}	Selection $m_{lim}(AB)$	Survey Catalog / Field
Arnouts et al. (2005)	1500Å	0.2-1.2	1039	NUV<24.5	GALEX/VVDS
		1.75-3.4		F450&F606<27	HDF
Wyder et al. (2005)	NUV, FUV	0.055	896,1124	$m_{UV}<20$	GALEX/2dF
Oesch et al. (2010)	1500Å	0.5-2.5	284-403	$\lesssim$26	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

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



Reconstructing CIB from observed counts

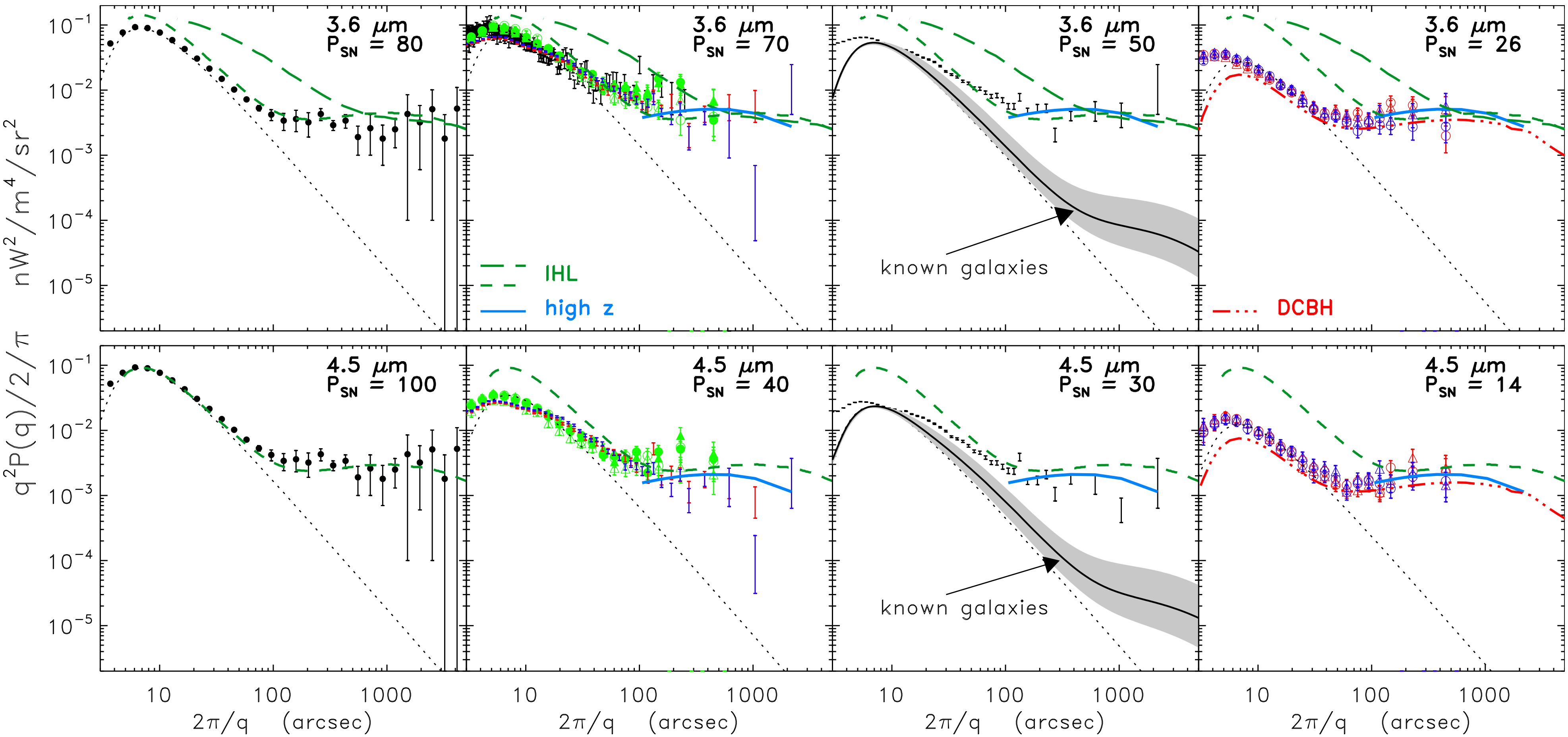
Diffuse flux from observed sources counts



γγ absorption limits

- The reconstruction fits the data well
- There is little flux left from known sources

COMPARISON of MEASUREMENTS by remaining shot noise (depth)



P_{SN} shown in nJy nW/m²/sr

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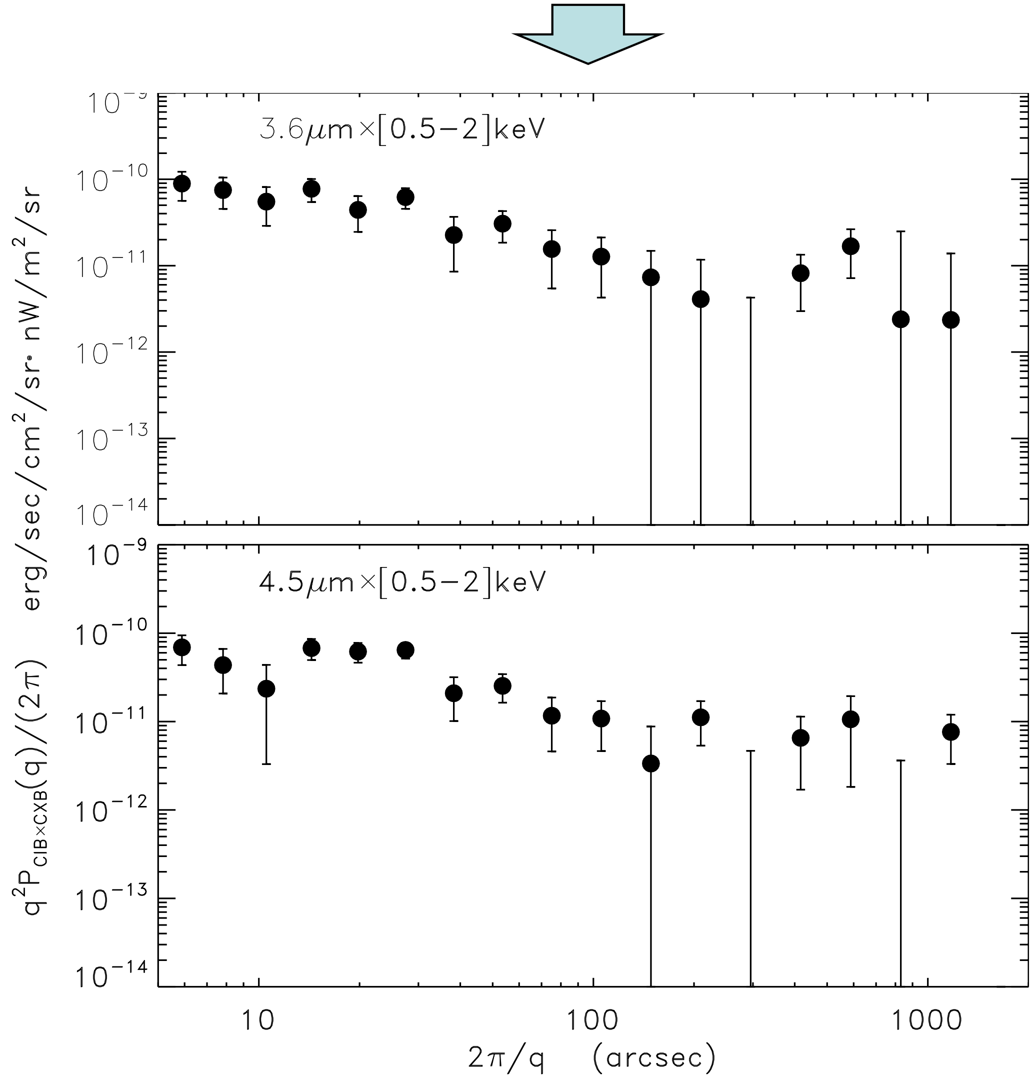
Cross-correlating CIB with CXB (Cappelluti et al 2013, 2017)

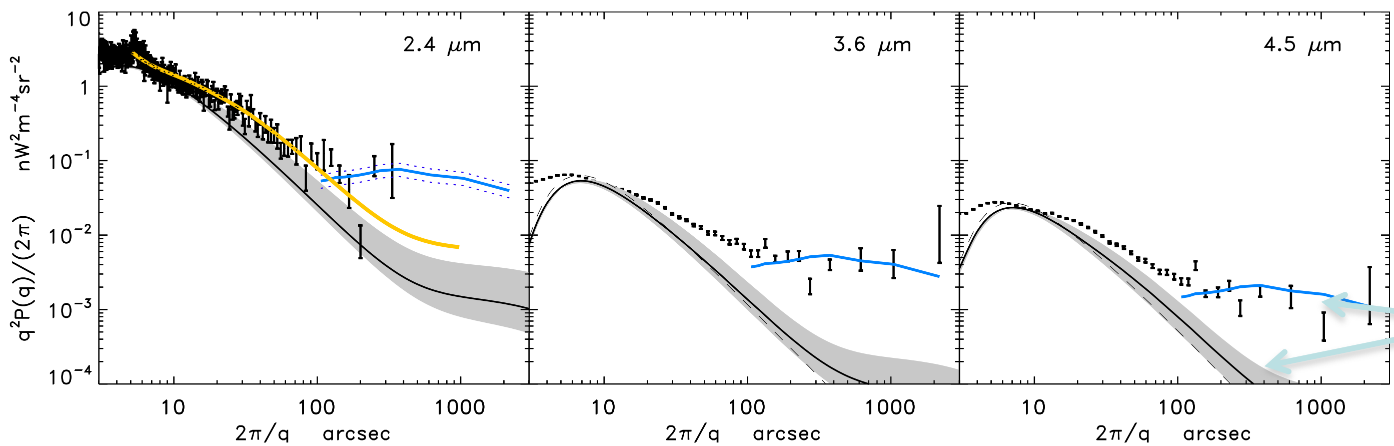
- Have constructed unresolved CXB maps using several Msec deep Chandra and Spitzer data
- There exists highly statistically significant cross-power (>5-sigma)
- **CXB-CIB coherence is**

  $C=|P_{X\text{-}IR}|^2/P_X/P_{IR} \gtrsim 0.15$
- ***Indicates at least √C~ 35% of the CIB sources are correlated with accreting sources (BHs), proportion far higher than in the present-day populations.***

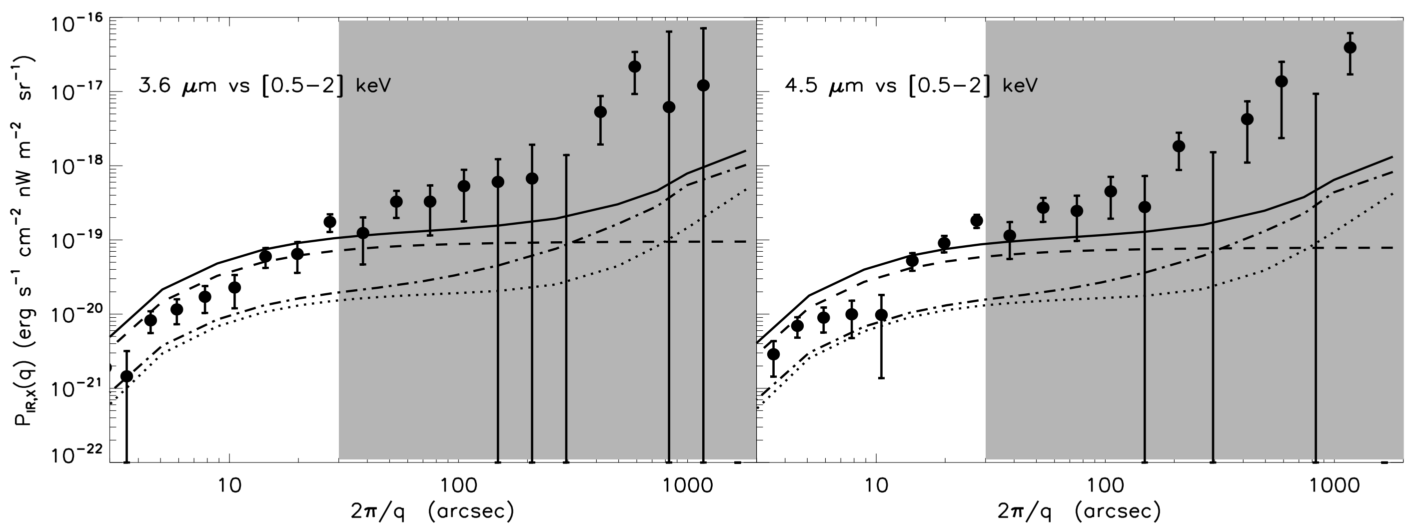
CIB-CXB cross-power/fluctuations



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).

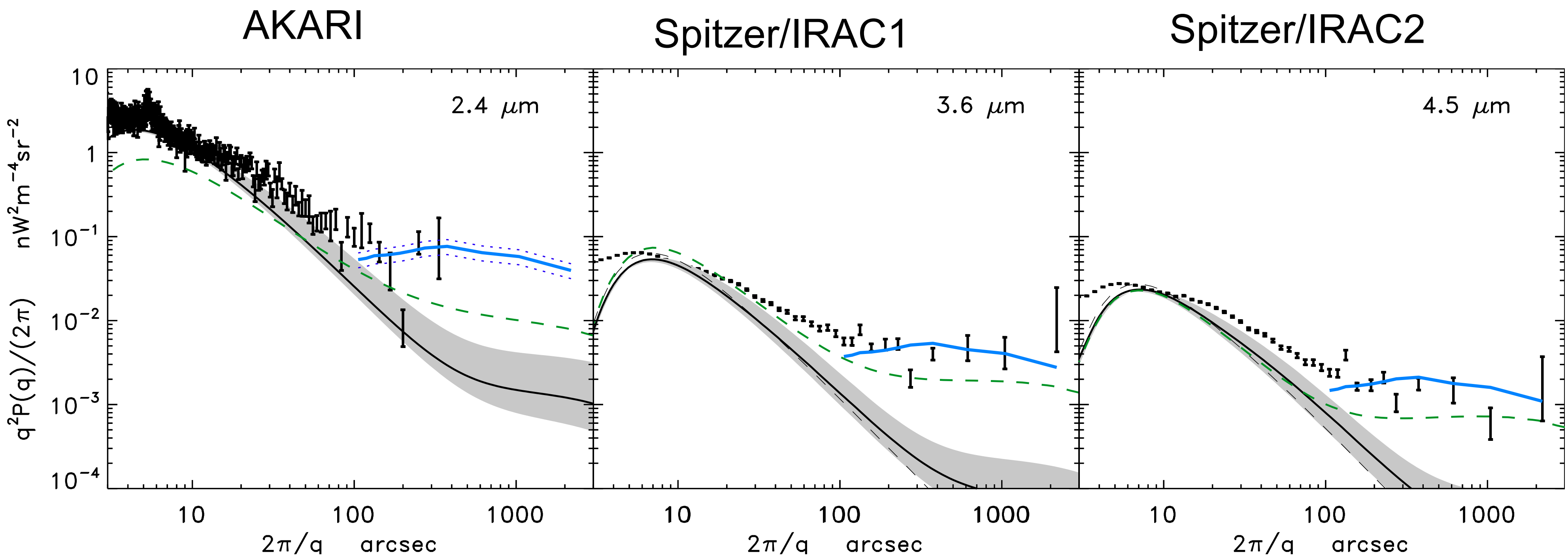
CIB at 2-5 micron: established key properties

- 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 ~25-40% of sources are accreting BHs
- 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

- No coherence between CIB and unresolved CXB at harder (>1 Kev) X-bands
- The measured coherence cannot be explained by remaining known populations
- 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 $\sqrt{P_\lambda} \propto \lambda^{-3}$:

$$\delta F_{2-5\,\mu\mathrm{m}}(5') = \int_{AKARI}^{\mathrm{IRAC}} \left(\frac{q^2 P_\lambda}{2\pi}\right)^{1/2} \frac{d\lambda}{\lambda}$$
$$= \delta F_{4.5\,\mu\mathrm{m}}(5') \left(\frac{(4.5/2.4)^\alpha - 1}{\alpha}\right)$$
$$\simeq 0.09 \text{ nW m}^{-2}\text{ sr}^{-1}$$

The sources producing these CIB fluctuations should have contributed

F_{CIB}(2-5μm) ~ 1 nW/m²/sr

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:

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

- 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):

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

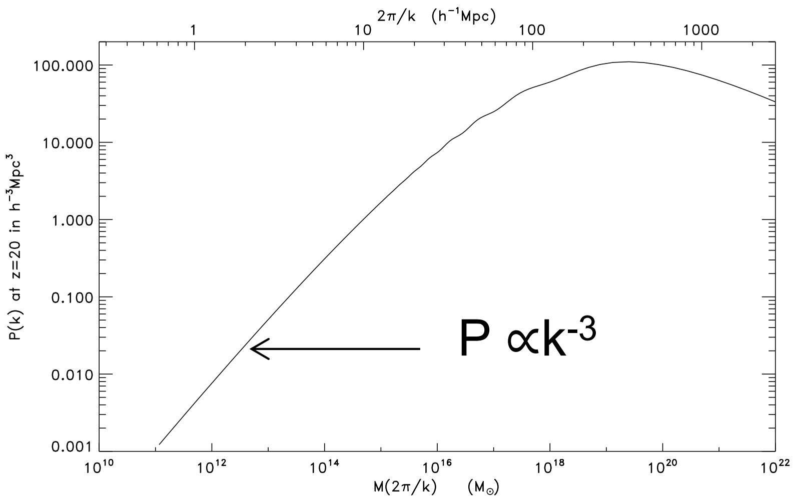
BH emissions:

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

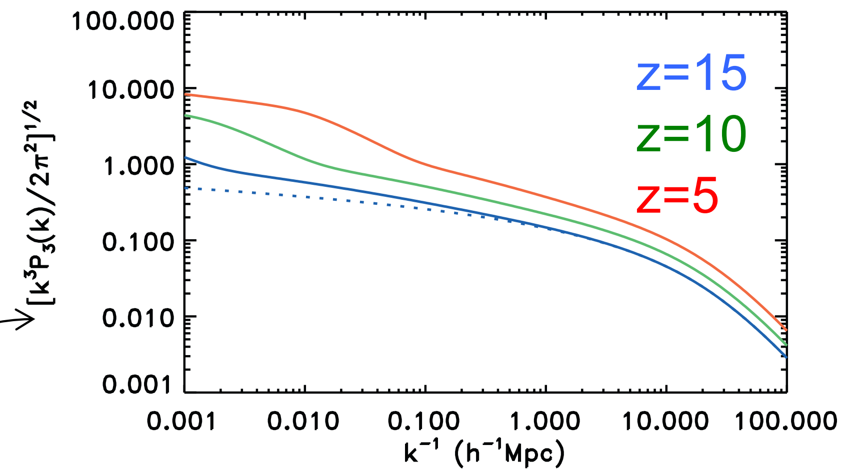
These small "reasonable" fractions possibly appear "unreasonable" in "standard" model

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

"Standard" (particle CDM) P(k)



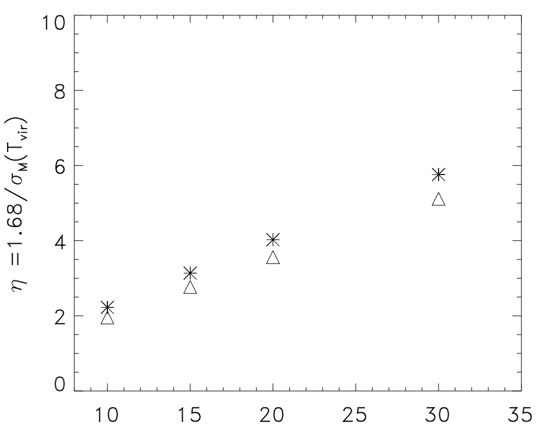
RMS mass density fluctuations



Hence baryon fraction in collapsed halos:

Z	T_{vir} = 10^4K	T_{vir}= 10^3K
25	9x10^{-5}	7x10^{-4}
20	10^{-3}	5x10^{-3}
15	8x10^{-2}	1.5x10^{-2}
10	3x10^{-2}	7x10^{-2}

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



Needed to explain CIB
$f_{Halo} f_* \sim 10^{-3}$ (z/10) (ε/10^{-2})
Whereas sims and "common sense" suggest *f_*<10%*

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PBHs and extra fluctuation power

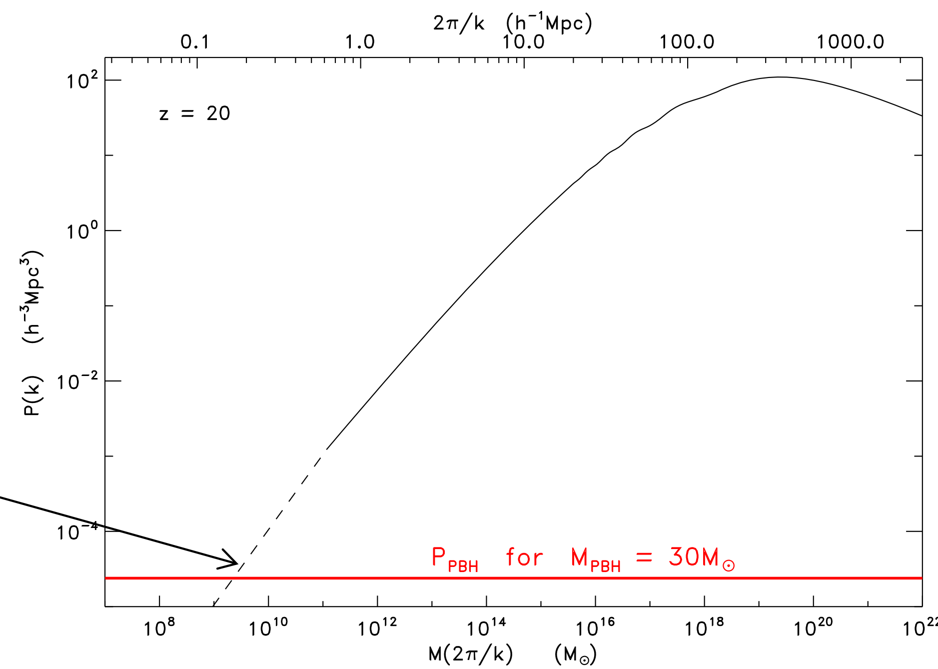
- If LIGO BHs were PBHs making up DM, there number density would be

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

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

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

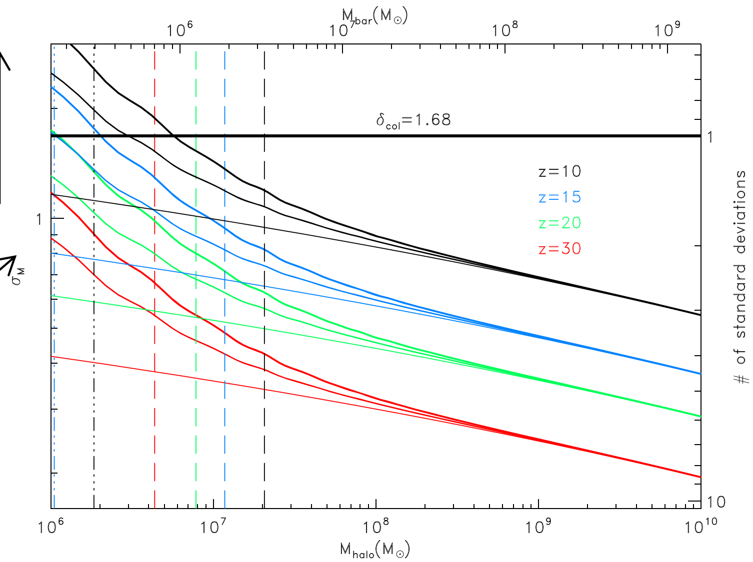
- This extra power will dominate the small scales responsible for collapse of 1st minihaloes where 1st sources form! The resultant CIB would change dramatically.



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

RMS density fluctuation vs halo mass

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

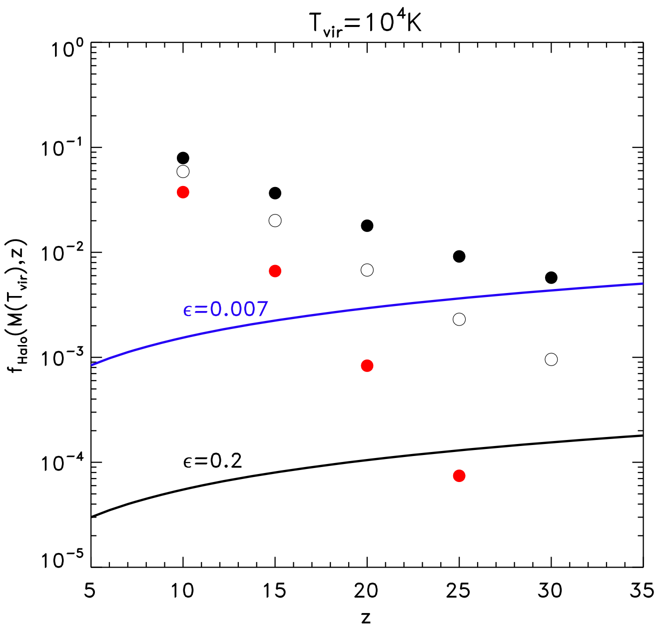


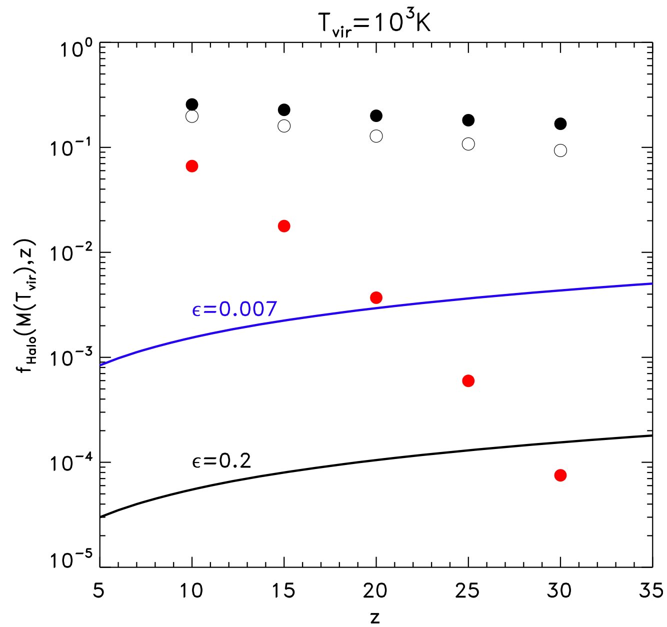
Number of standard deviations for collapsed halos of mass M at z=10, 15, 20, 30

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

•"Standard" DM

•PBH DM of M_{PBH}=30$M_\odot$





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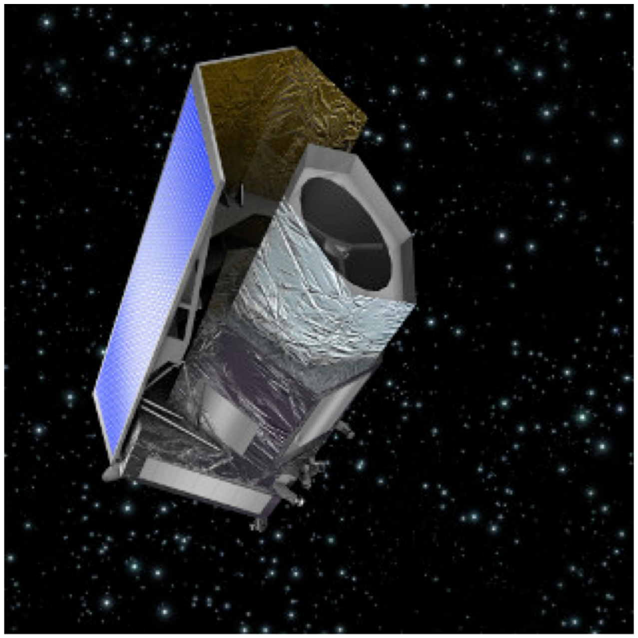
***FUTURE: Euclid** (2013-2031)*

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

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.



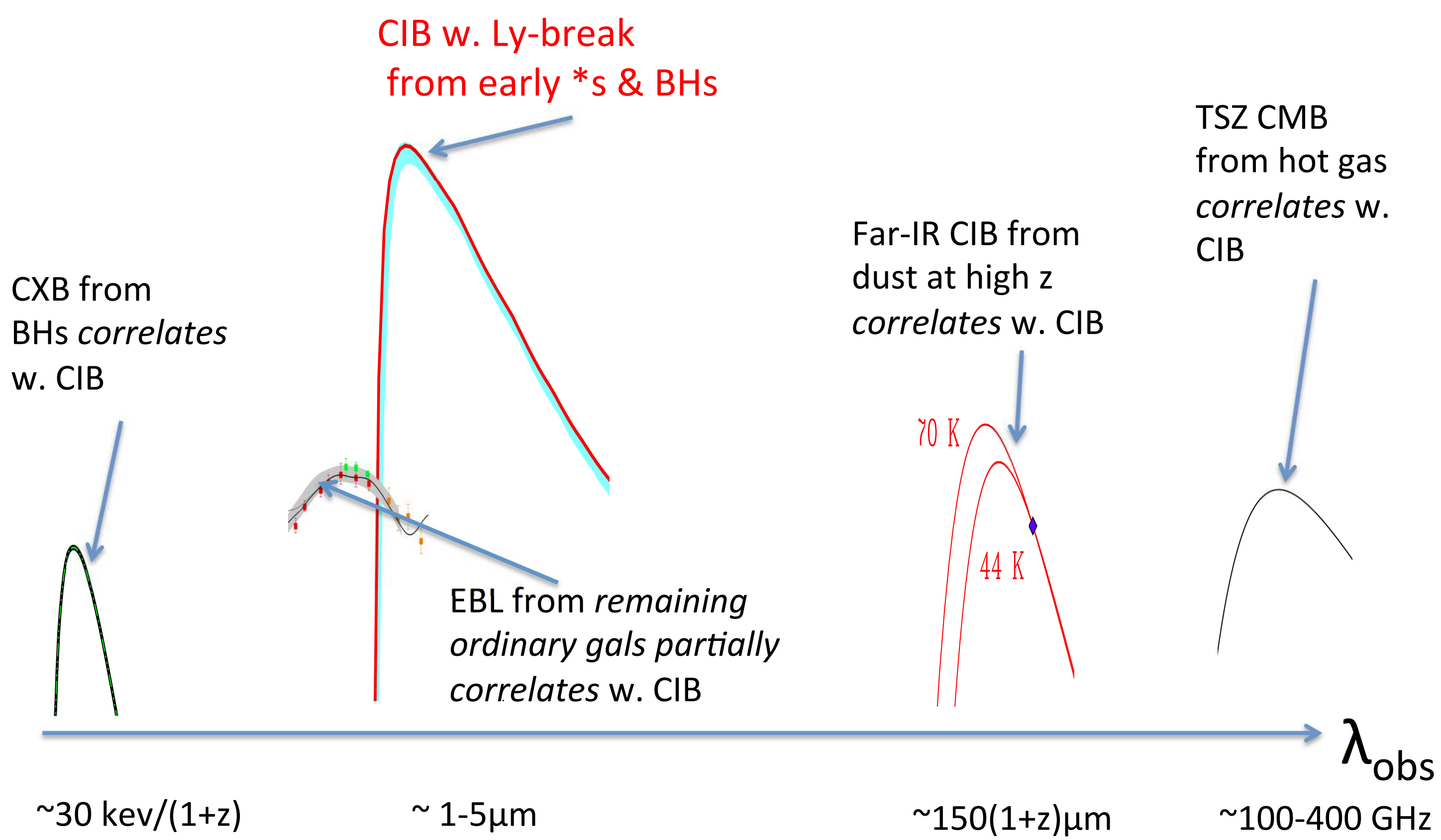
- *Launch in ~2022 for 6-yr mission at L2*
- *One visible band VIS around 0.6 mic*
- *Three NIR bands from 1 to 2 micron*
- *Instantaneous FOV ~ 0.5 deg^2*
- *Wide survey ~ 35-45% of sky to AB~26*
- *Deep survey covers 40 deg^2 to AB~28*
- *LIBRAE was selected to complement the main goal of measuring Dark Energy evolution w weak lensing and BAO*

- The project will measure all-sky CIB fluctuations with sub-percent stat accuracy
- Measure cross-power with all-sky CXB (eROSITA+) and CMB (S4+) maps
- Determine the epochs (Lyman break) of the populations
- Determine the SED of these (new) populations

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

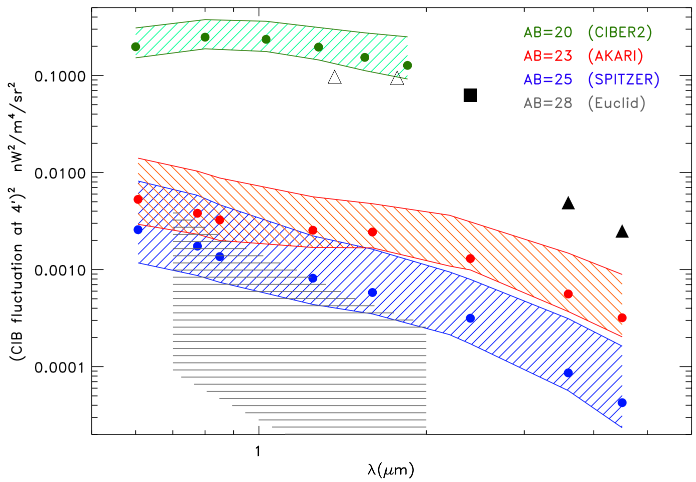
https://www.euclid.caltech.edu/page/Kashlinsky%20Team

The planned science:



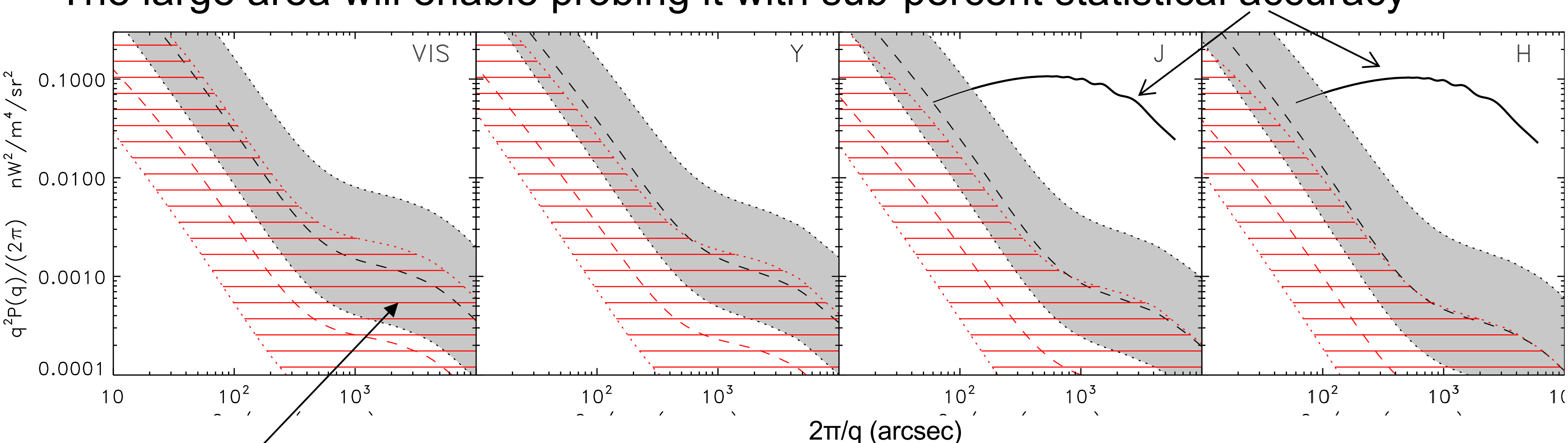
LIBRAE has 7 US-based scientists and a similarly sized contingent in Europe.
PI – A. Kashlinsky

LIBRAE: probing source-subtracted CIB and its Lyman break



- Because fluctuation in visible bands are significant compared to the remaining source-subtracted CIB ***one needs to remove sources to AB ≳ 25 to probe reliably any Lyman-break in the CIB fluctuation.***

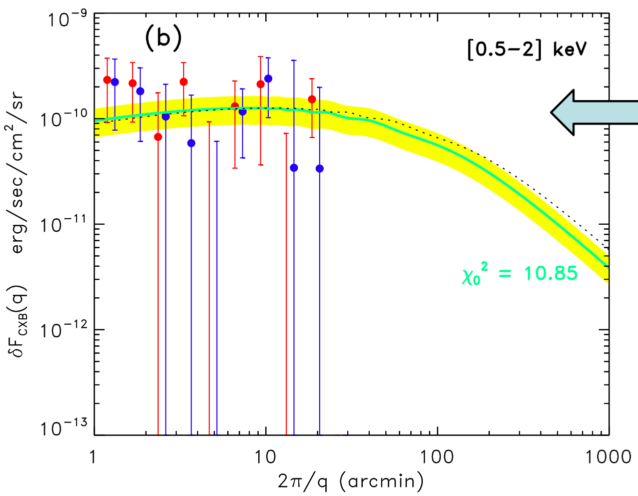
- Euclid will remove sources in VIS deep enough to comfortably probe the Lyman break of the source-subtracted CIB fluctuation.
- The large area will enable probing it with sub-percent statistical accuracy



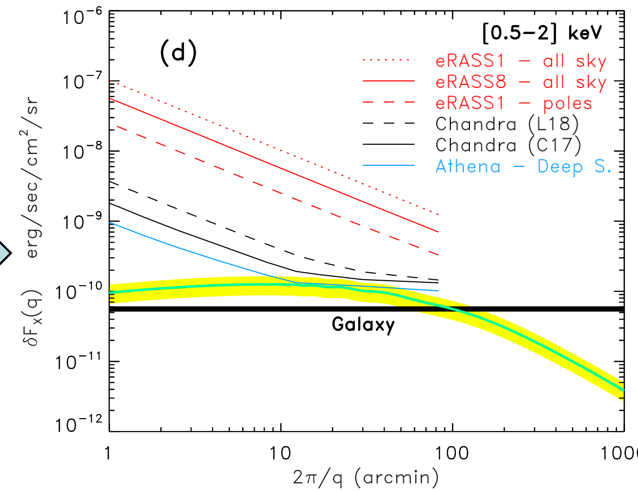
Remaining known gals (Wide/Deep Surveys)

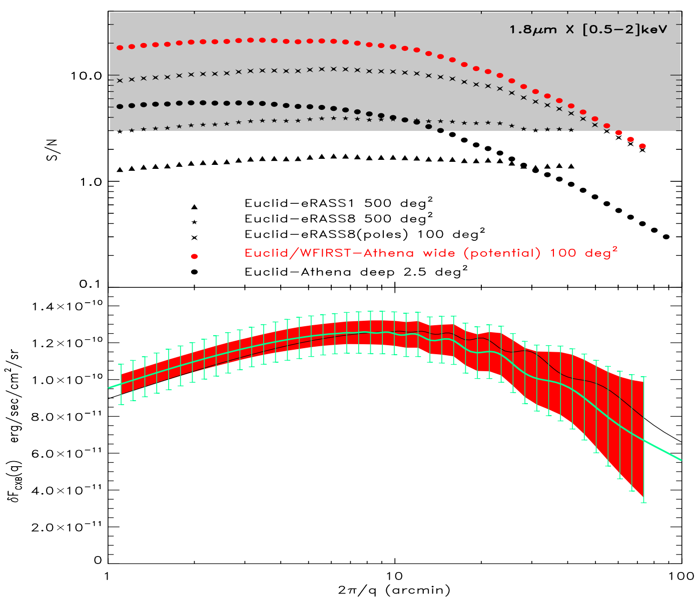
A. Kashlinsky *Brussels* *Apr 2019*

LIBRAE + eROSITA/Athena: probing 1st BHs



- CXB fluctuation implied by new pops consistent w high-z origin
- Its amplitude is such that the CXB due to these sources is hard to probe directly





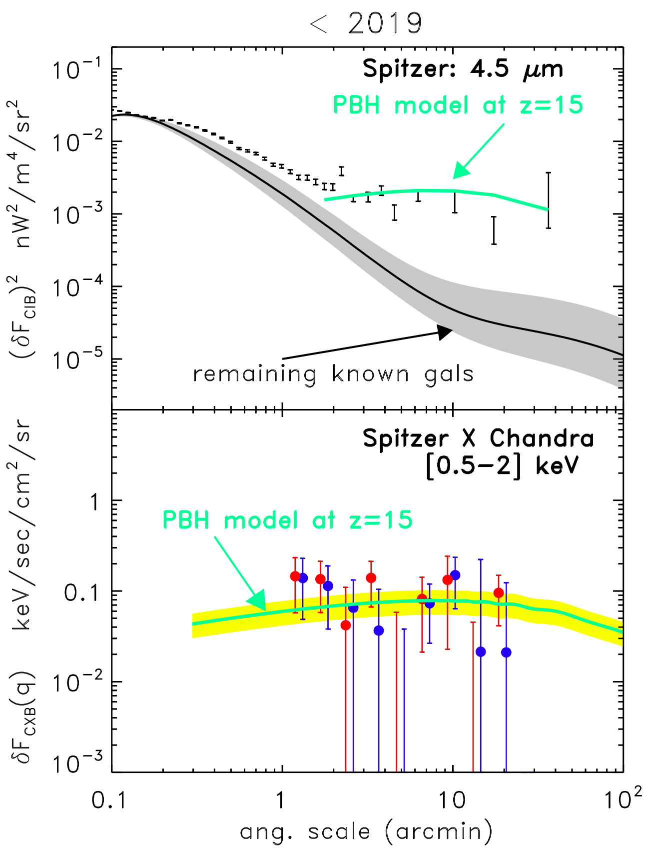
- eROSITA and Athena in conjunction with Euclid will be able to probe this CXB signal w. high fidelity between 1’ and ~2^o

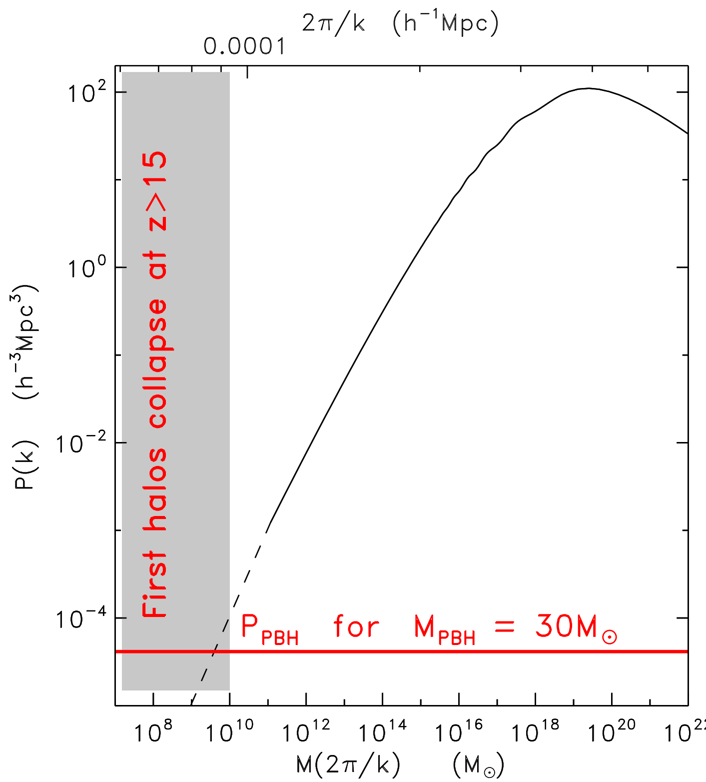
Kashlinsky et al. 2019, ApJ(Letters), **871**, L6

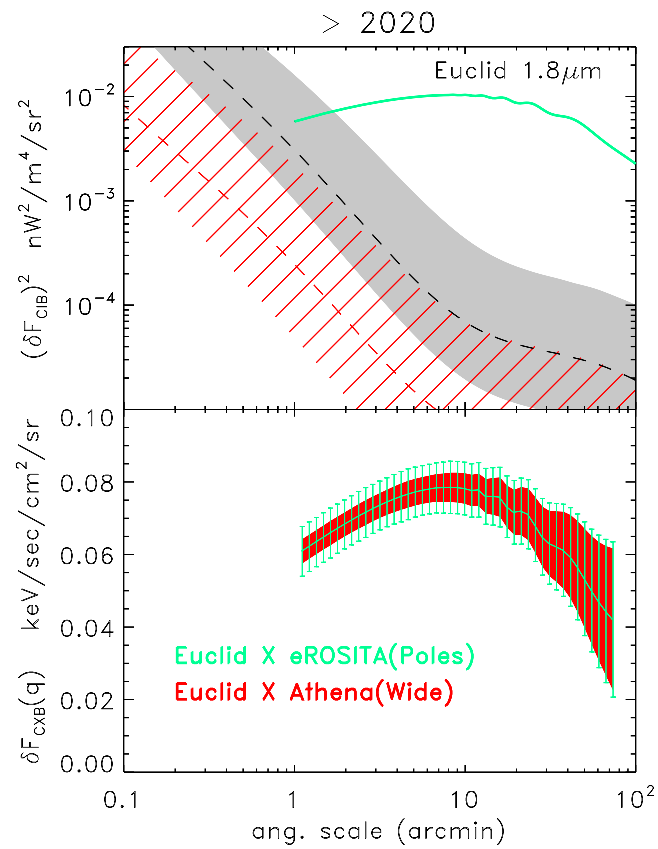
Summary of LIBRAE prospects for PBH-DM

Where we are now

Where LIBRAE can be







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Summary

- **Current measurements with Spitzer established CIB fluctuations well in excess of those from known galaxies.**
- **There appears a high coherence between unresolved CIB & CXB implying a high fraction of the sources in black holes.**
- ***The extra power implied by the source-subtracted CIB may be indicative of the PBH-DM collusion, which is further supported by the CIB-CXB coherence.***
- **There are now preparations for LIBRAE@Euclid which will resolve this CIB signal with <1% accuracy and identify the nature and epochs of the sources producing it.**
- **eROSITA/Athena will be critical for CIB-CXB probe w LIBRAE.**

- **STAY TUNED!**