Fluctuation measurements of the cosmic optical and infrared backgrounds

Michael Zemcov

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RIT | College of Science
School of Physics and Astronomy

c. T. Arai

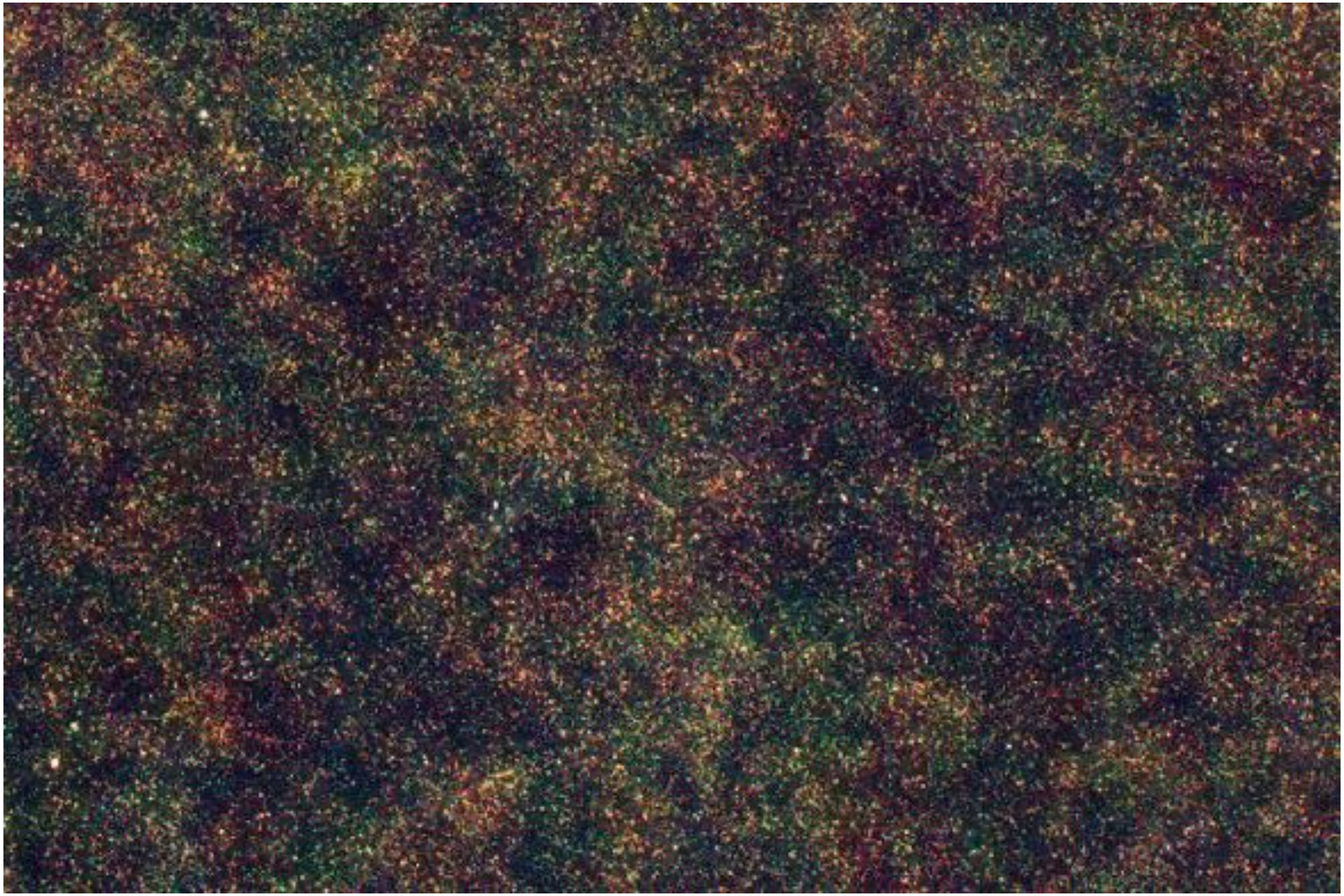
We Need Large Aperture Telescopes to do Cutting Edge Science… Or Do We?

- S/N ratio on point sources goes as *d*.
- Angular resolution goes as d^{-1}.

➡ Larger apertures are desirable for point sources.

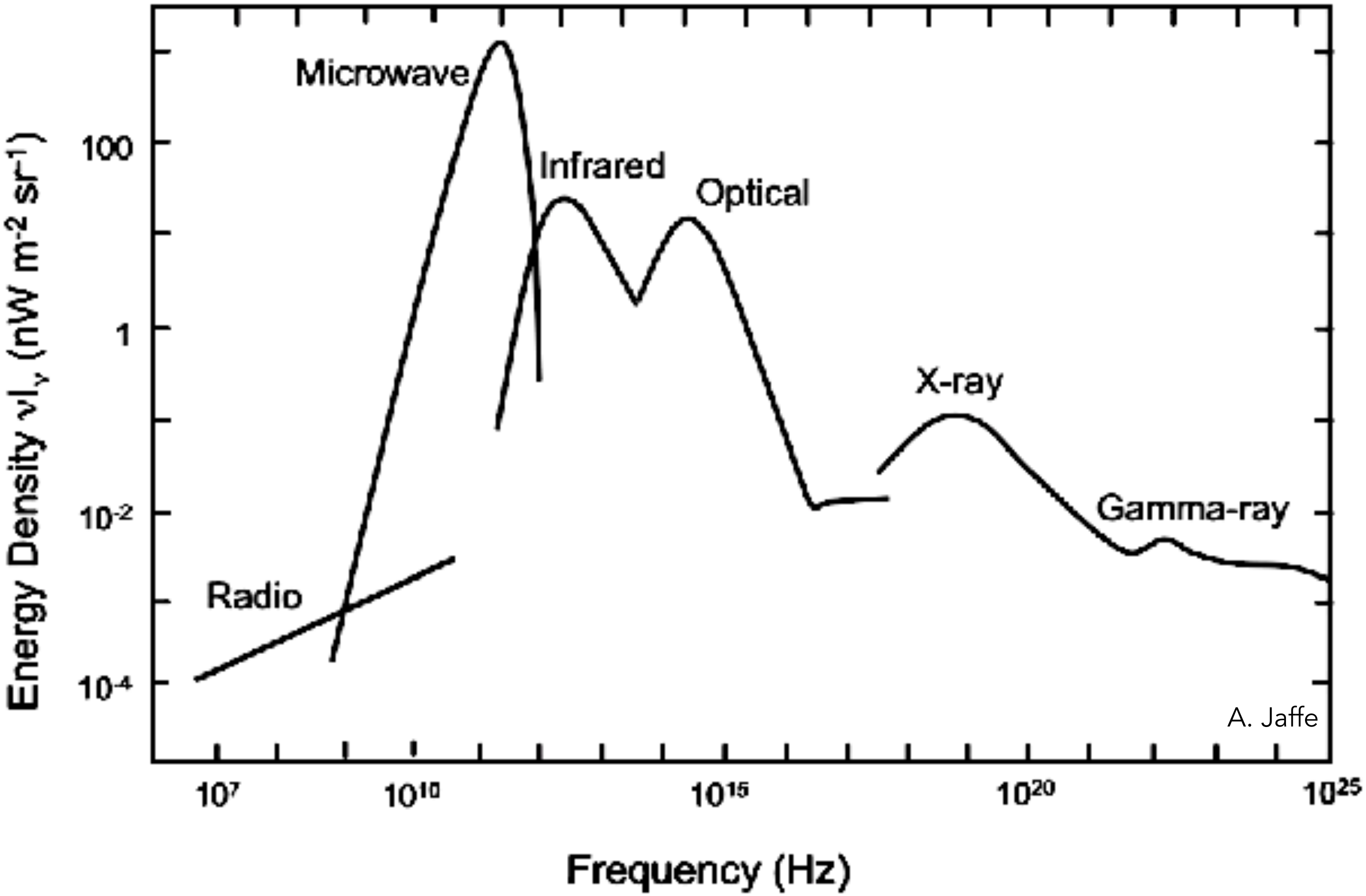
- Sensitivity to ***surface brightness*** goes as AΩ, the entendue.
- For surface brightness-based science, we can build small telescopes, as long as we maximize AΩ at a given A.

The Cosmic Background Radiation

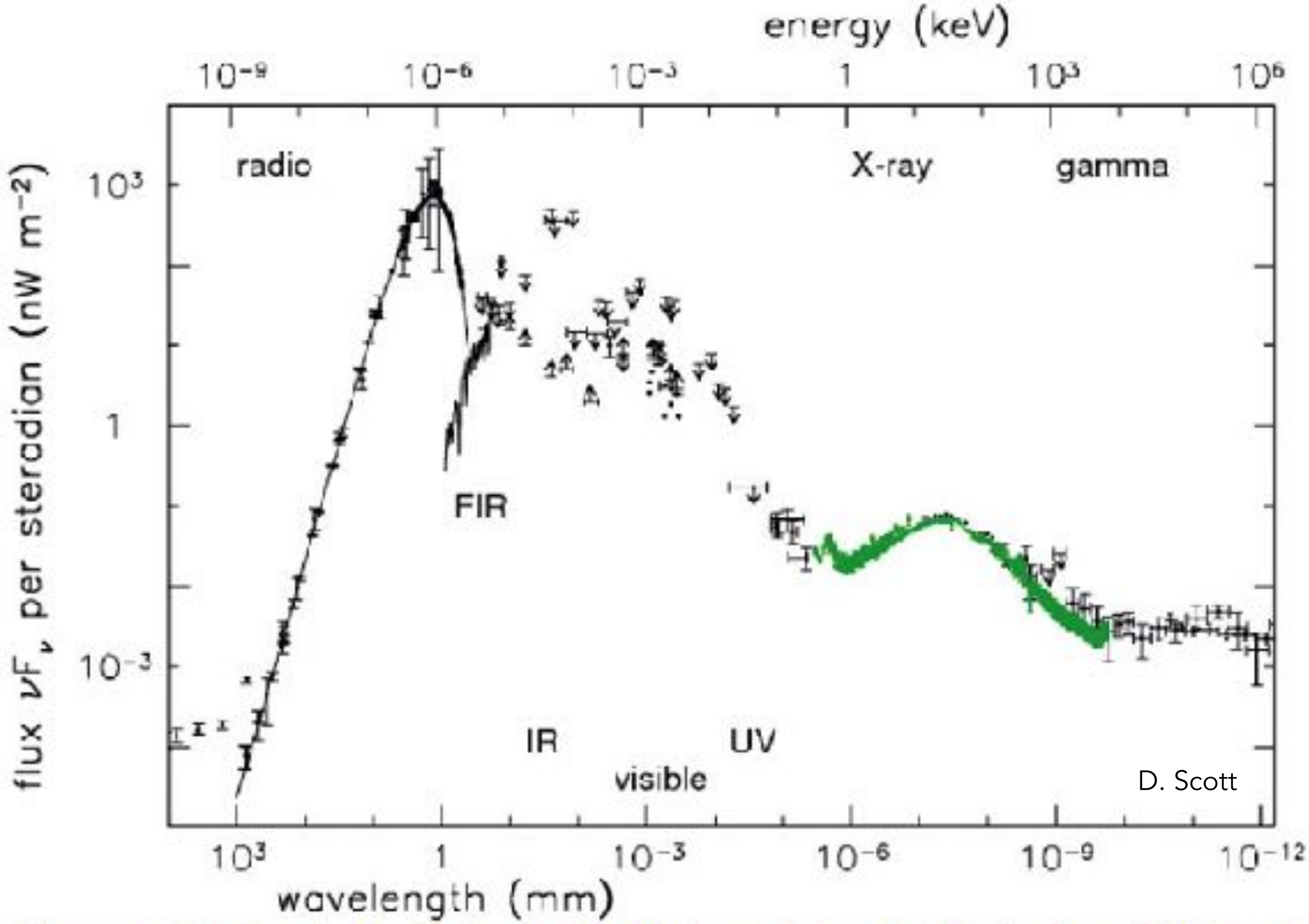


ESA/SPIRE Consortium/HerMES Consortium

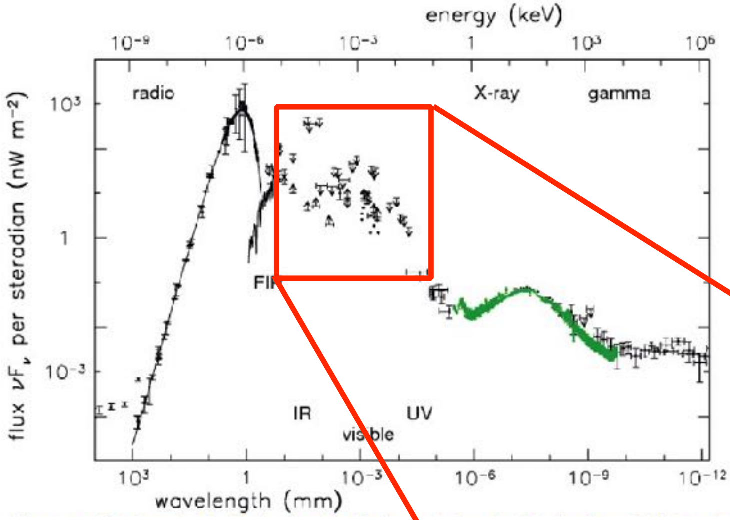
The Cosmic Background Radiation



The Cosmic Background Radiation

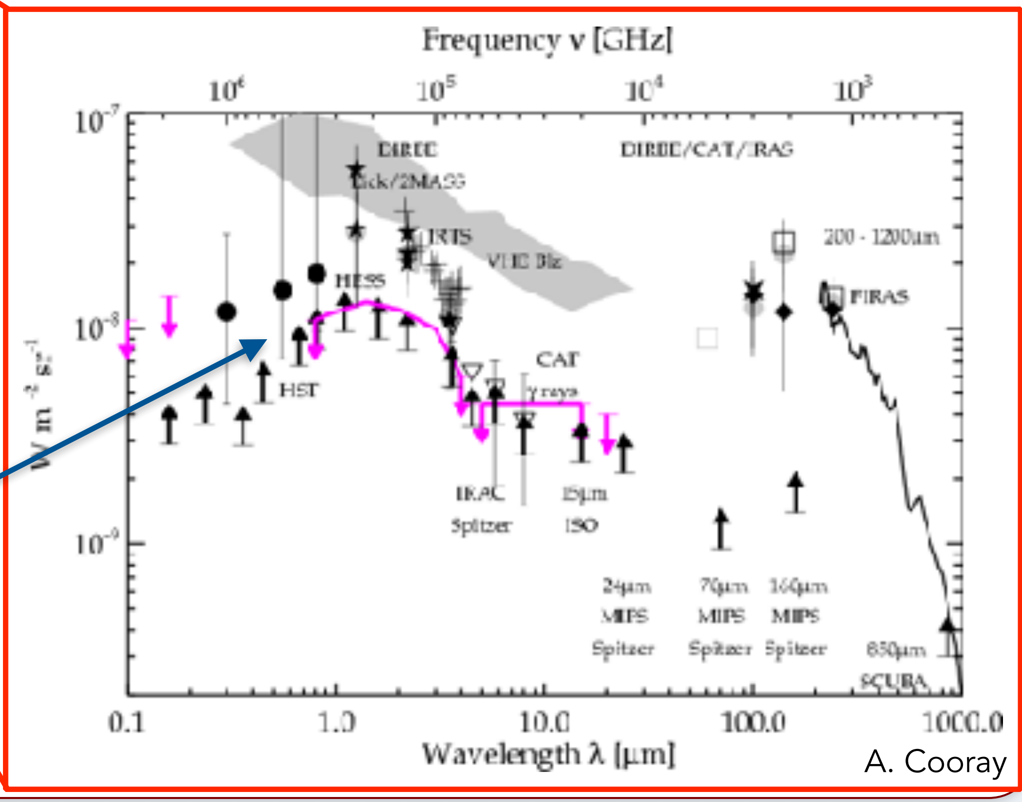


The Cosmic Optical Background

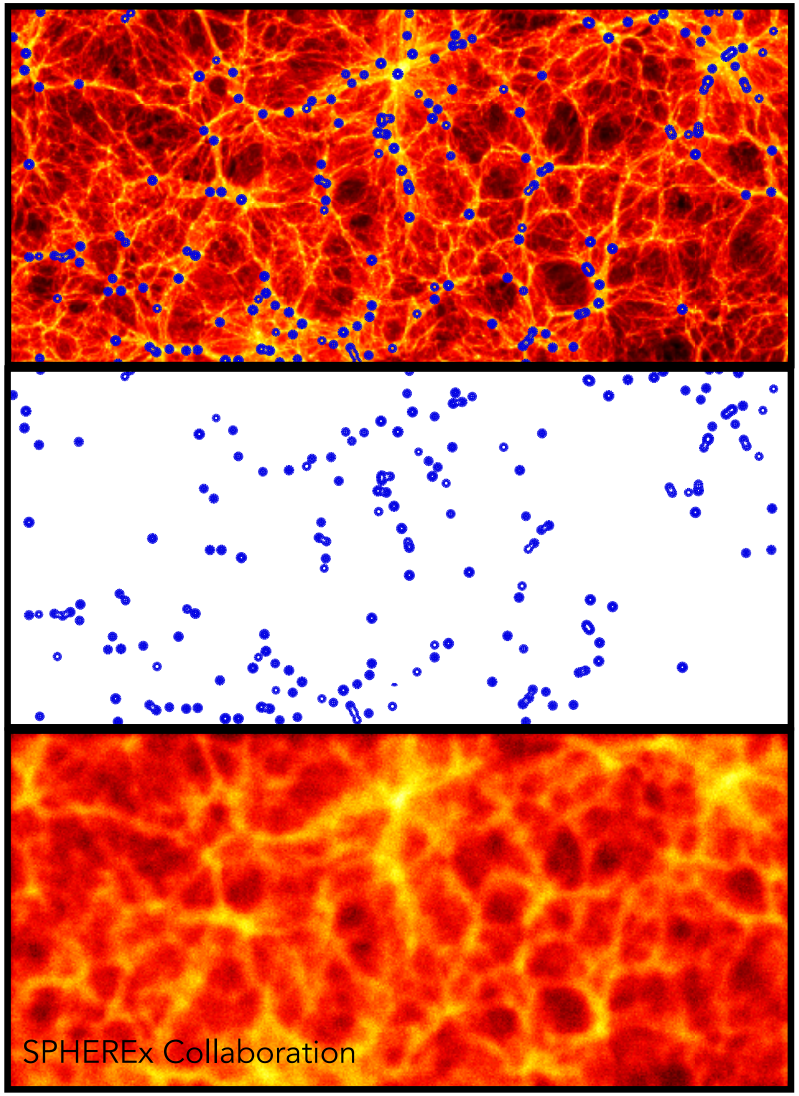


The Cosmic Optical/IR Background has been… stubborn.

But important for cosmic energetics!

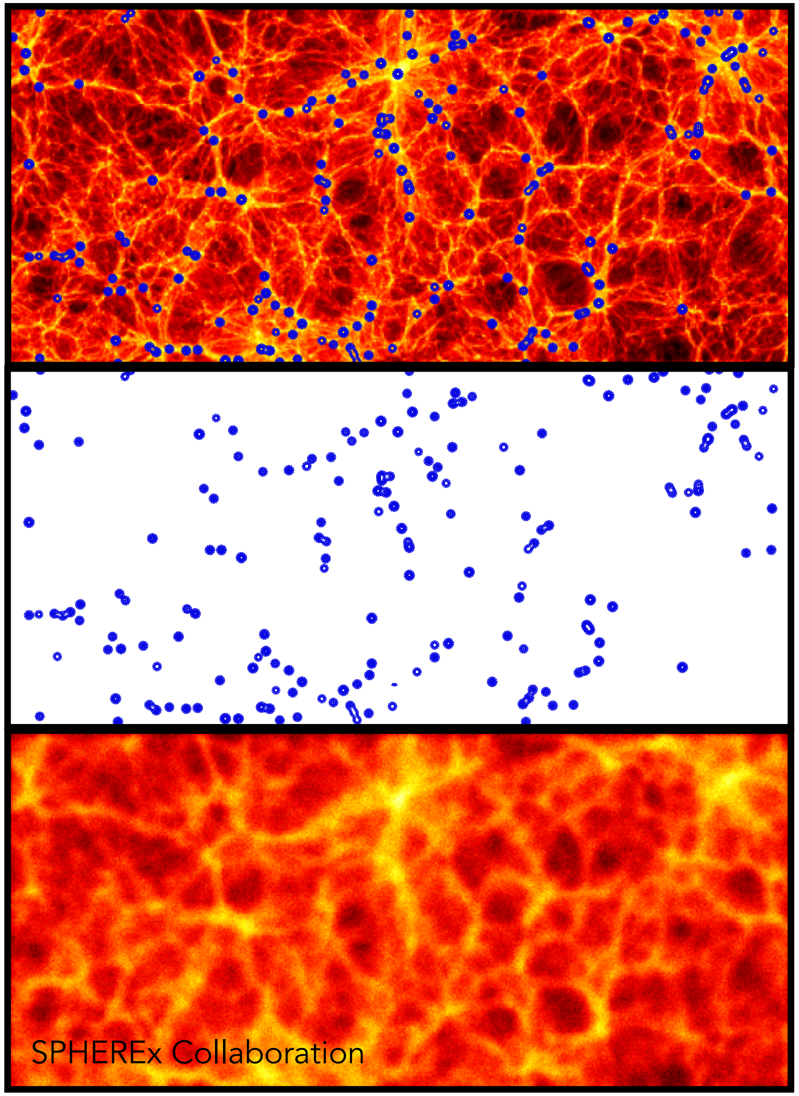


An Introduction to Intensity Mapping



- What is the large scale structure of the universe?
- To find out, we could identify individual sources of emission.

An Introduction to Intensity Mapping



- What is the large scale structure of the universe?
- To find out, we could identify individual sources of emission.
- Alternatively, we could sum all the emission in large areas and measure fluctuations.
- This is called Intensity Mapping.

Why Intensity Mapping?

When it is straightforward to measure the position of individual sources, we can measure their power spectrum with high signal to noise easily (e.g. Baryon Acoustic Oscillations) as $\sigma_\ell(z) \propto n_{gal}$.

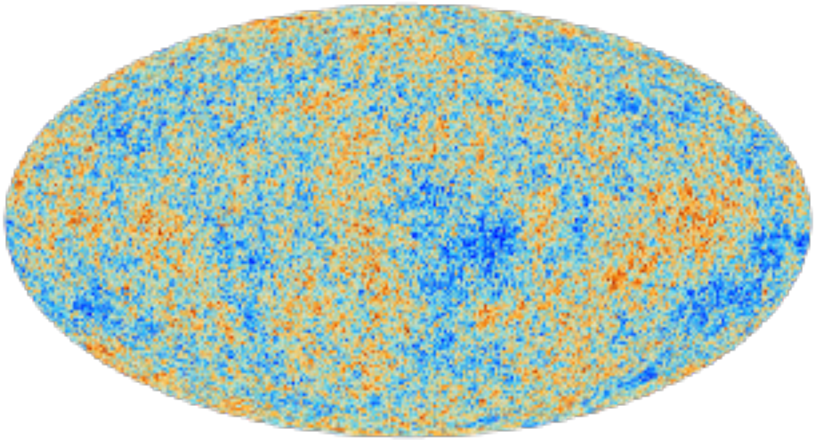
If, however:

1. Individual sources are difficult to detect (sources are intrinsically faint, large instrument beam, etc),
2. We are interested in the total power from all sources, or
3. There is truly diffuse emission,

Intensity mapping offers advantages.

Science Applications:

- Galaxy Evolution
- Dark Matter and Galaxy Formation
- Epoch of Reionization
- Baryon Acoustic Oscillations.

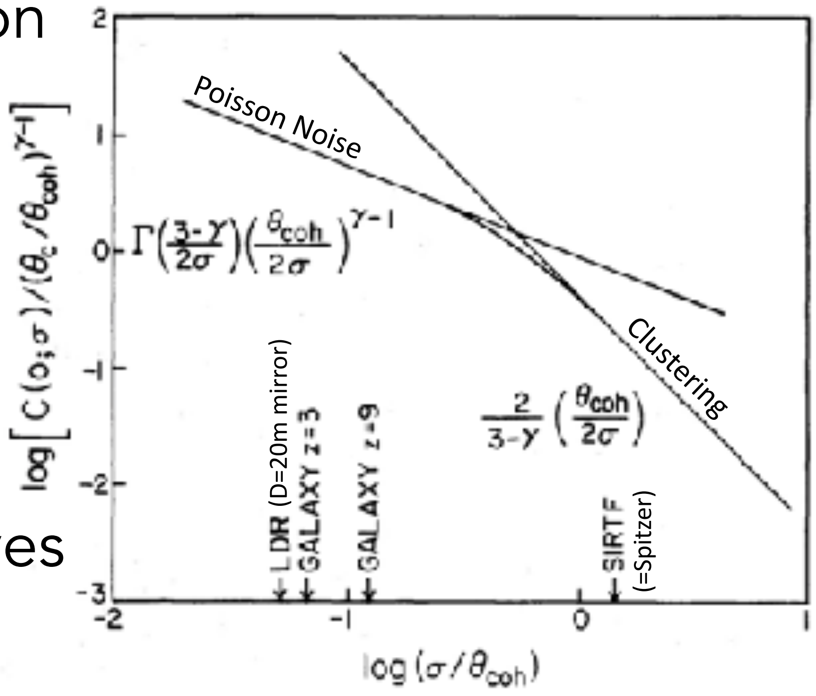


Planck Collaboration (2013).

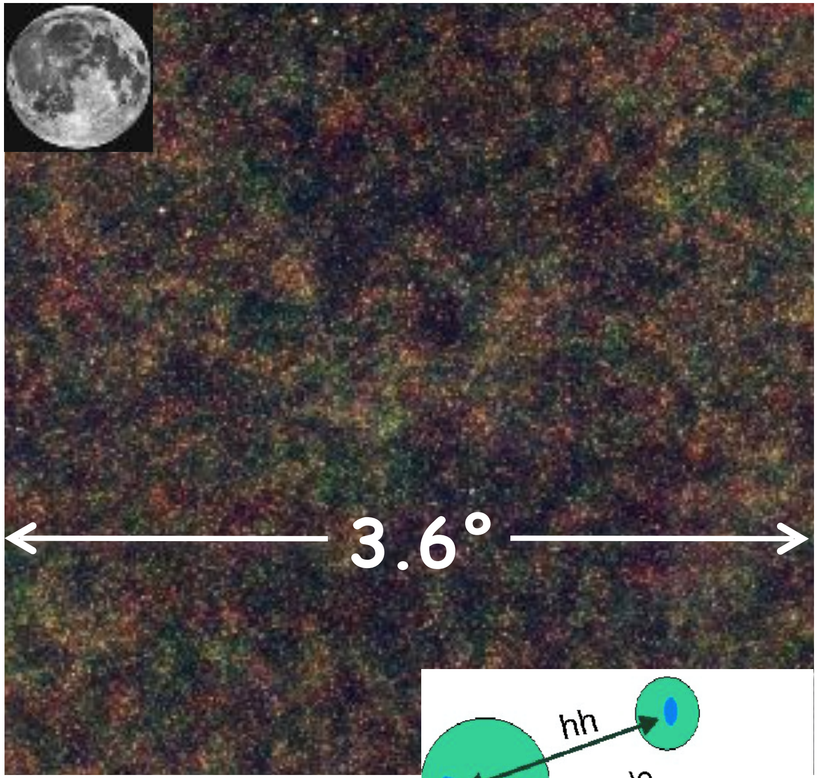
CIB Anisotropies

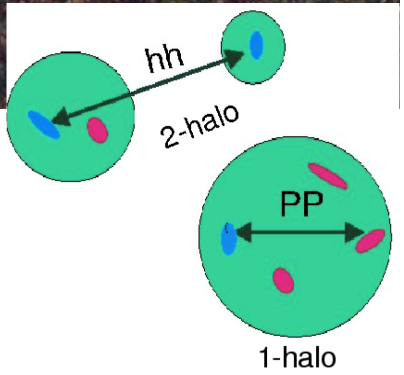
Originally predicted by Bond et al 1986. Already had insight that:

- Depends on structure formation history of the universe.
- At optical/near-IR, mostly emission from stars.
- At mid/far-IR, mostly emission from dust.
- Spatial correlation function gives information on source populations.

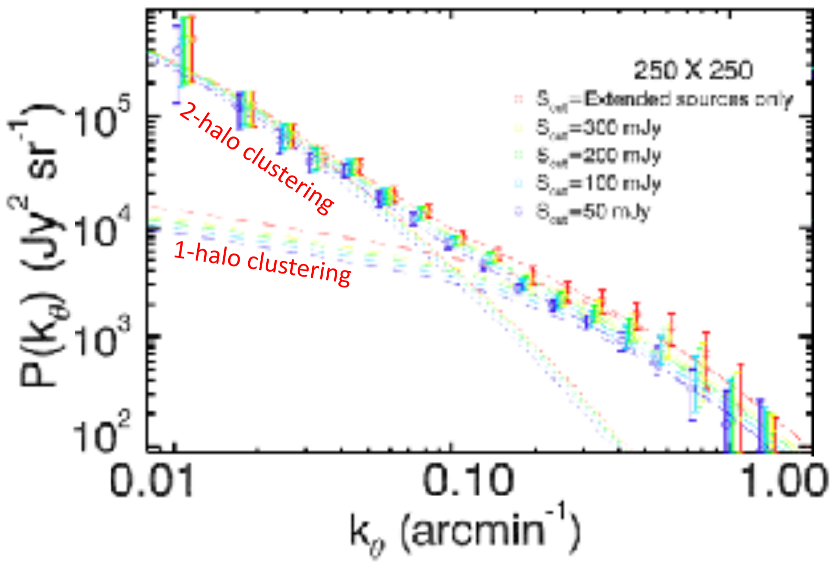


Intensity Mapping with SPIRE





Viero *et al.* 2013, ApJ
Amblard *et al.* 2011, Nature



Fitting 2-D auto- and cross-spectra (under various depth flux cuts) to halo models

Table 5
Model 2: Best-fit Parameters and Corresponding Correlation Matrix

Parameter	$\log(M_{min})$	$\log(M_{peak})$	T	T_z	β	$\sigma^2_{L/m}$	$\log(L_0)$	η
$\log(M_{min})$	10.1 ± 0.5	−0.02	0.20	−0.27	−0.10	0.02	0.26	−0.25
$\log(M_{peak})$	…	12.3 ± 0.5	0.21	−0.01	−0.23	−1.00	−0.18	0.20
T	…	…	20.7 ± 1.2	−0.66	−0.92	−0.21	0.76	−0.56
T_z	…	…	…	0.2 ± 0.0	0.38	0.01	−0.81	0.89
β	…	…	…	…	1.6 ± 0.1	0.23	−0.53	0.31
$\sigma^2_{L/m}$	…	…	…	…	…	0.3 ± 0.0	0.18	−0.20
$\log(L_0)$	…	…	…	…	…	…	-1.8 ± 0.1	−0.90
η	…	…	…	…	…	…	…	2.4 ± 0.1

SED parameters

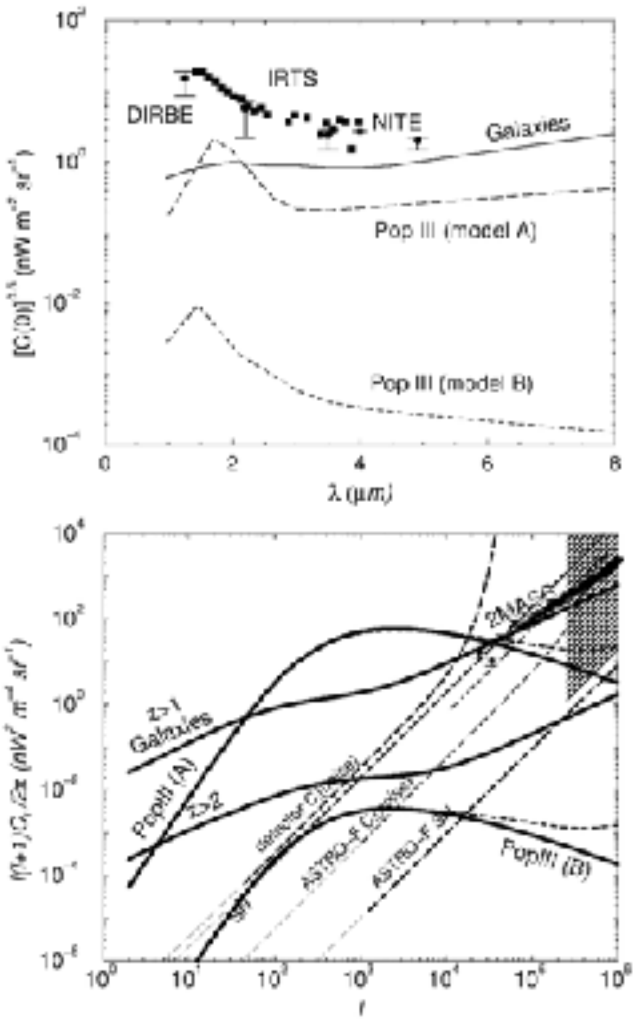
L-M relation

z-evol.

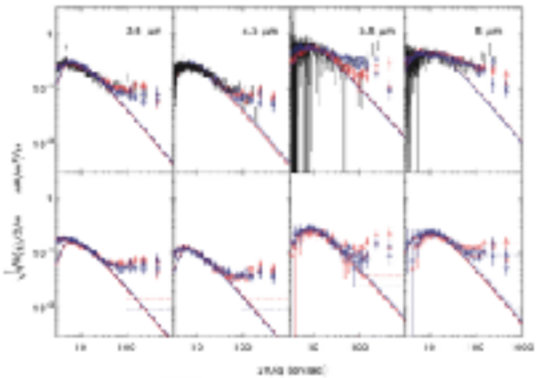
Find:
Minimum halo mass to support star formation: Log ~ 10.1
Halo mass of peak star formation efficiency: Log ~ 12.3
Some constraints on redshift evolution.

NIR Anisotropies

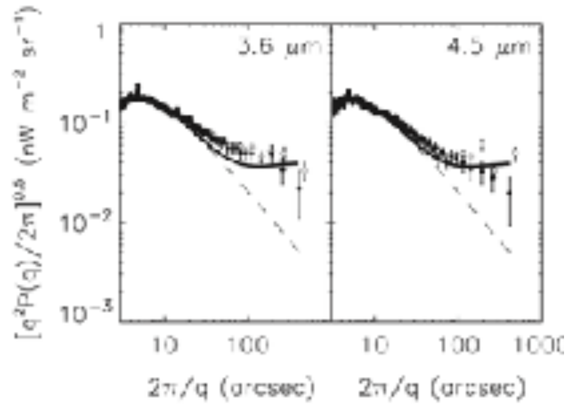
- In 2004, Cooray et al. and Kashlinksy et al. both pointed out that reionization should produce a detectable optical/IR background.
- Brightness and shape depends on reionization history.
- Lyman break provides a unique spectral feature to search.
- Fluctuations allow spectral/spatial decomposition to isolate the high-z source.



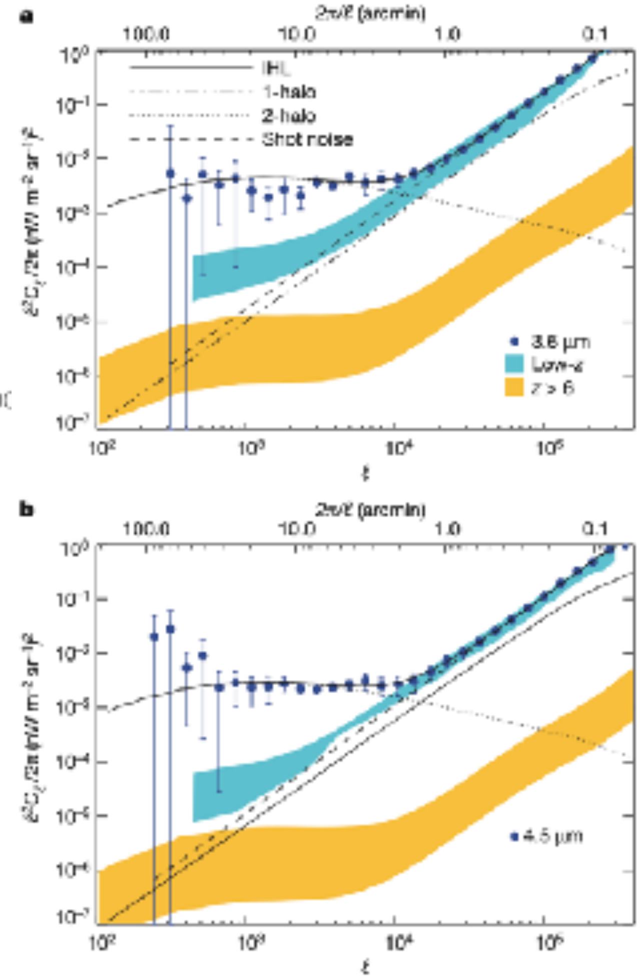
Spitzer and Akari Measurements



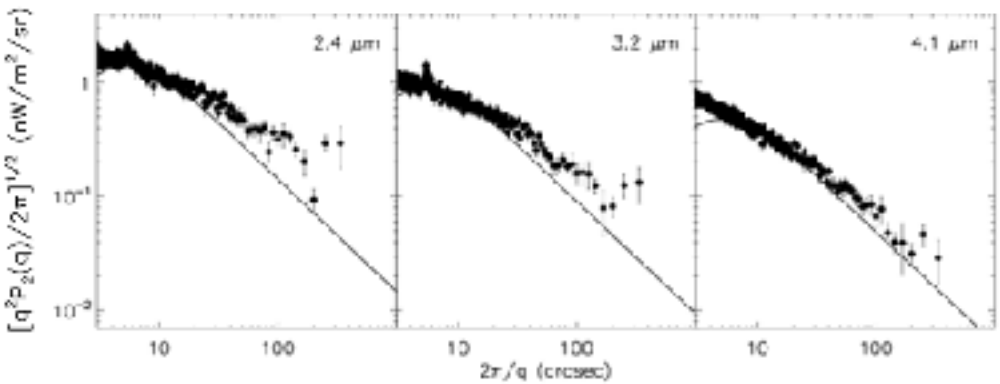
Kashlinsky et al. 2007
Kashlinsky et al. 2012



Arendt et al. 2010

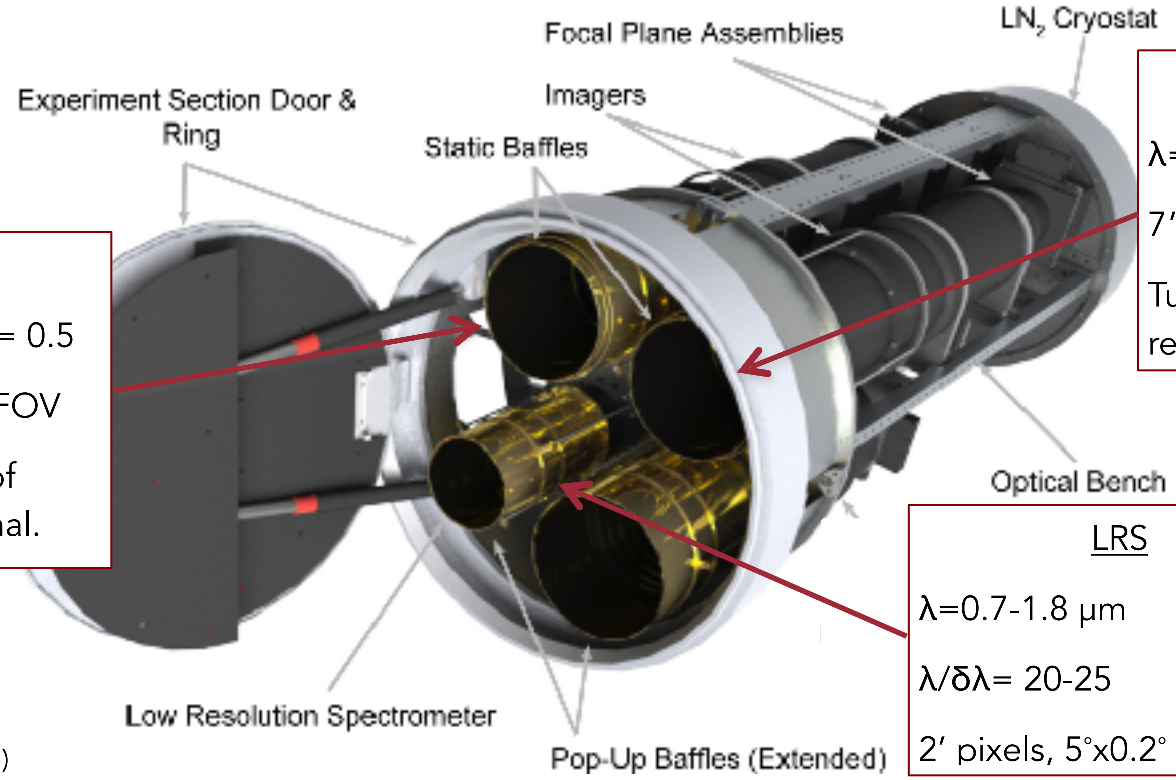


Matsumoto et al. 2011



Cooray et al. 2012

The Cosmic Infrared Background Experiment (CIBER)



H-band

λ=1.6 μm, δλ/λ= 0.5

7″ pixels, 2°x2° FOV

Tuned to peak of reionization signal.

I-band

λ=1.1 μm, δλ/λ= 0.5

7″ pixels, 2°x2° FOV

Tuned to measure low redshift signal.

LRS

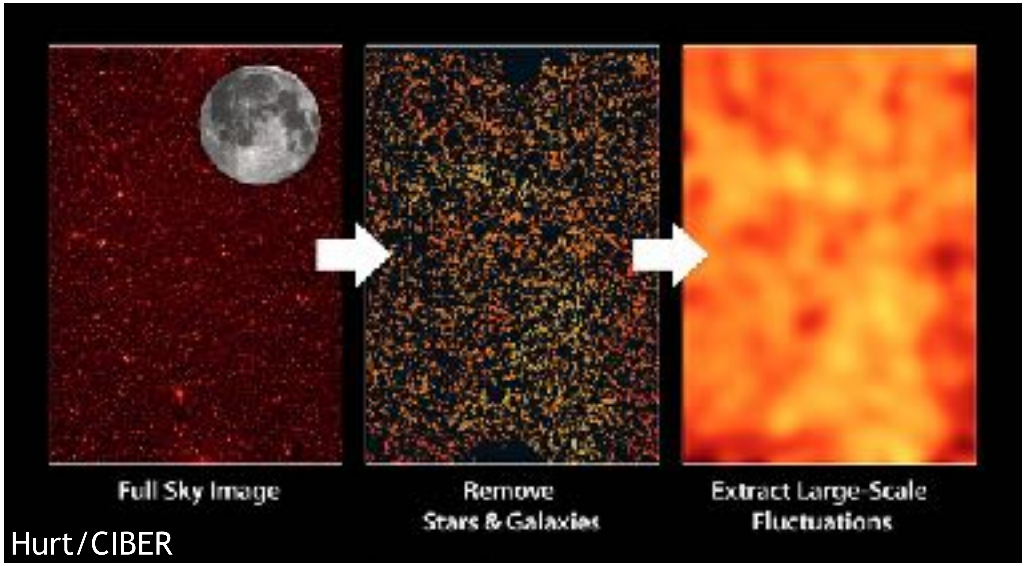
λ=0.7-1.8 μm

λ/δλ= 20-25

2′ pixels, 5°x0.2° FOV

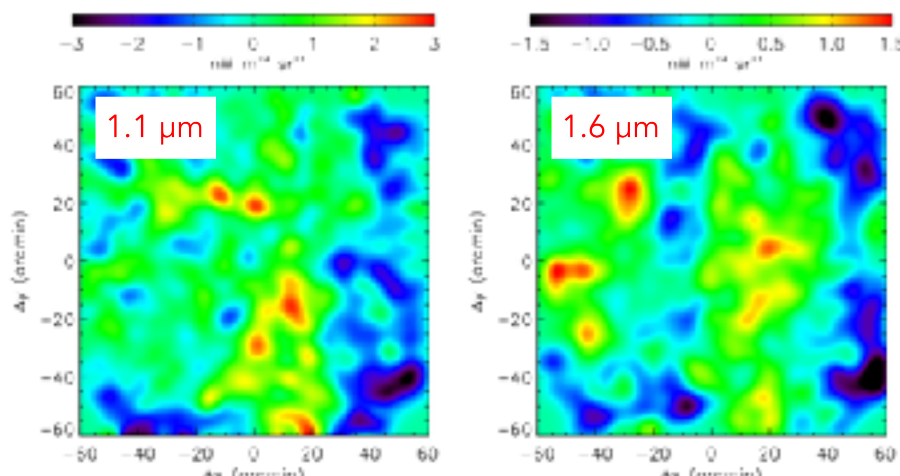
Zemcov et al. (2013)

CIBER Fluctuation Results



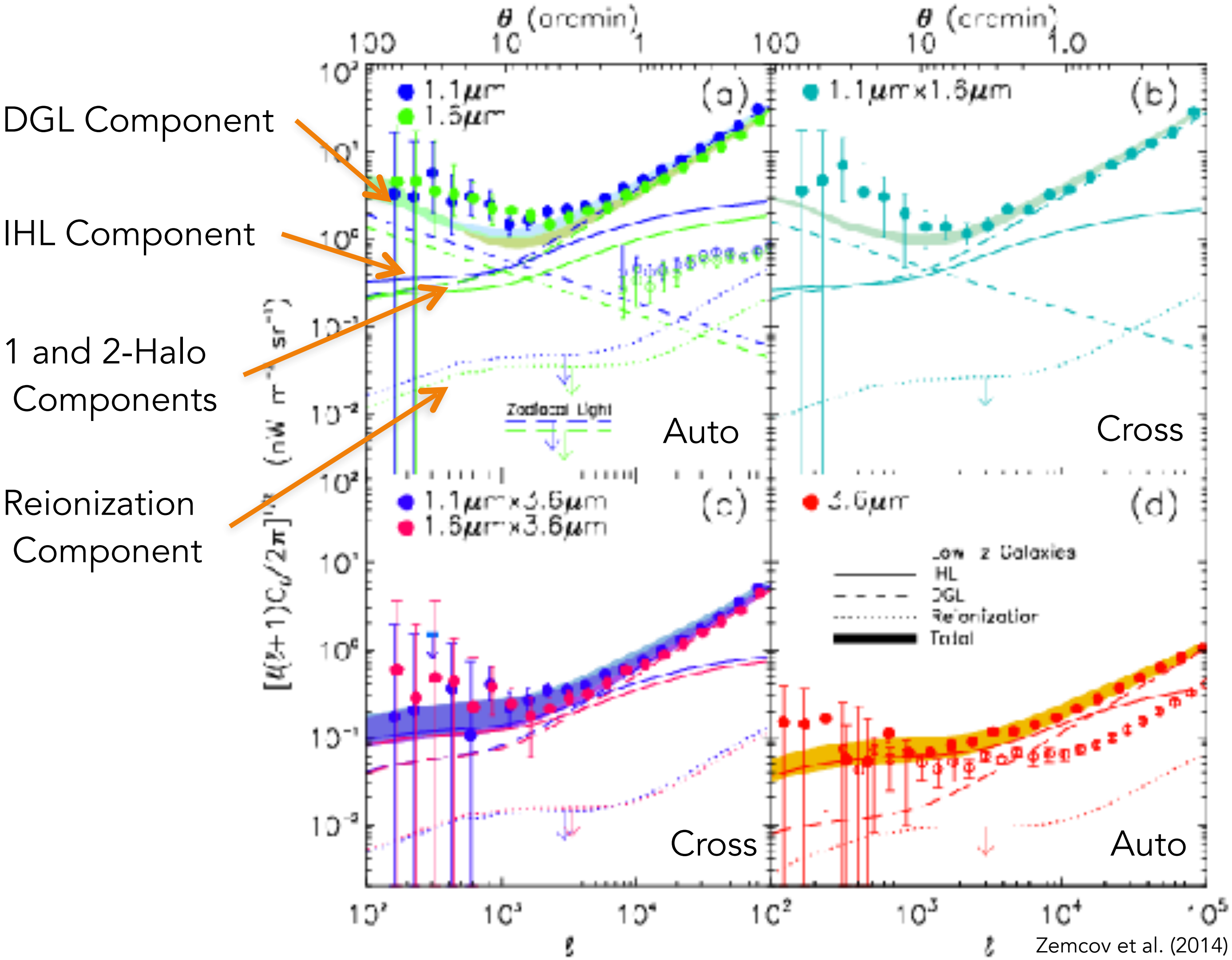
- Measured 5 good fields in two flights.
- Form 4 difference-field combinations to reduce flat field error, 2 of which are independent.
- Masked images smoothed with an ℓ=3000 Gaussian kernel show correlated fluctuations between bands.

See Zemcov et al., "On the Origin of Near-Infrared Extragalactic Background Light Anisotropy" (Science 2014) for details.



Zemcov et al. (2014)

Imager Results



CIBER is Robust to Systematic Errors

Systematic Error	Mitigation
Zodiacal Smoothness	Observe same sky in two different seasons.
Flat Field Errors	Use field difference images, laboratory flat field, Season 1 x Season 2.
1/f noise from HAWAII-1 Detector	Assess using sky differences, create detailed noise model, remove in x-correlations.
Unmasked Galaxies	Large ℓ separation from signal.
Astrophysical Foregrounds	Careful checks using ancillary data.
Anything else?	Cross-correlate with Spitzer.

Astrophysical Foregrounds

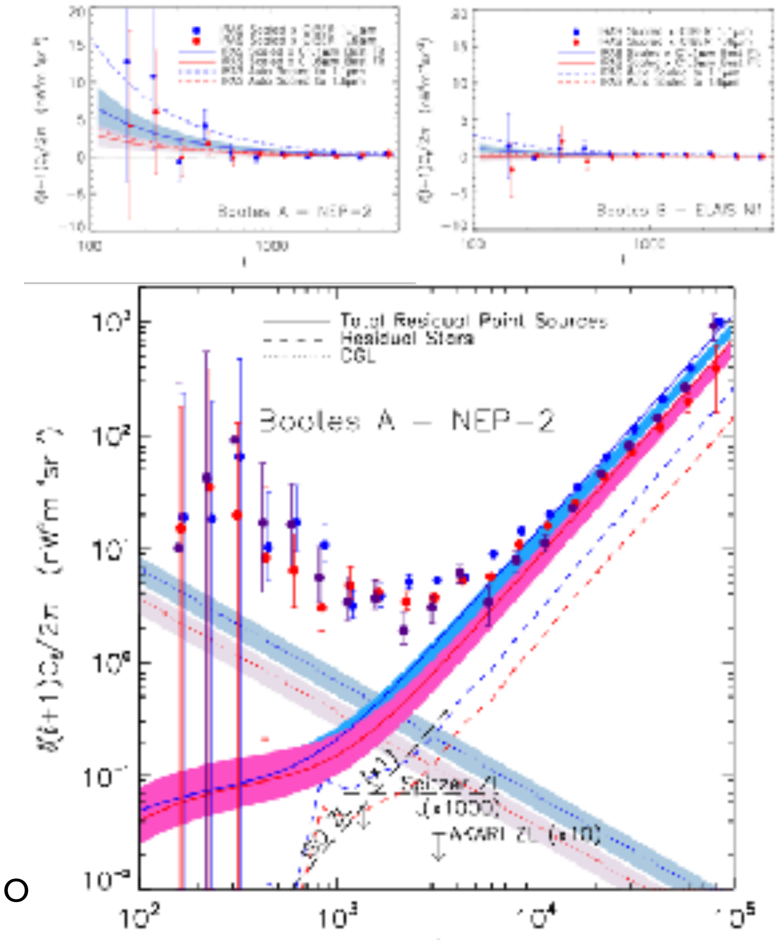
Could all this be caused by local sources of emission?

1. Dust in the solar system (Zodiacal light) ➔ very smooth on the angular scales we measure, previous limits exist.

2. Residual stars ➔ can measure this from deep surveys, this contributes 10% of the small angle power but goes as shot noise.

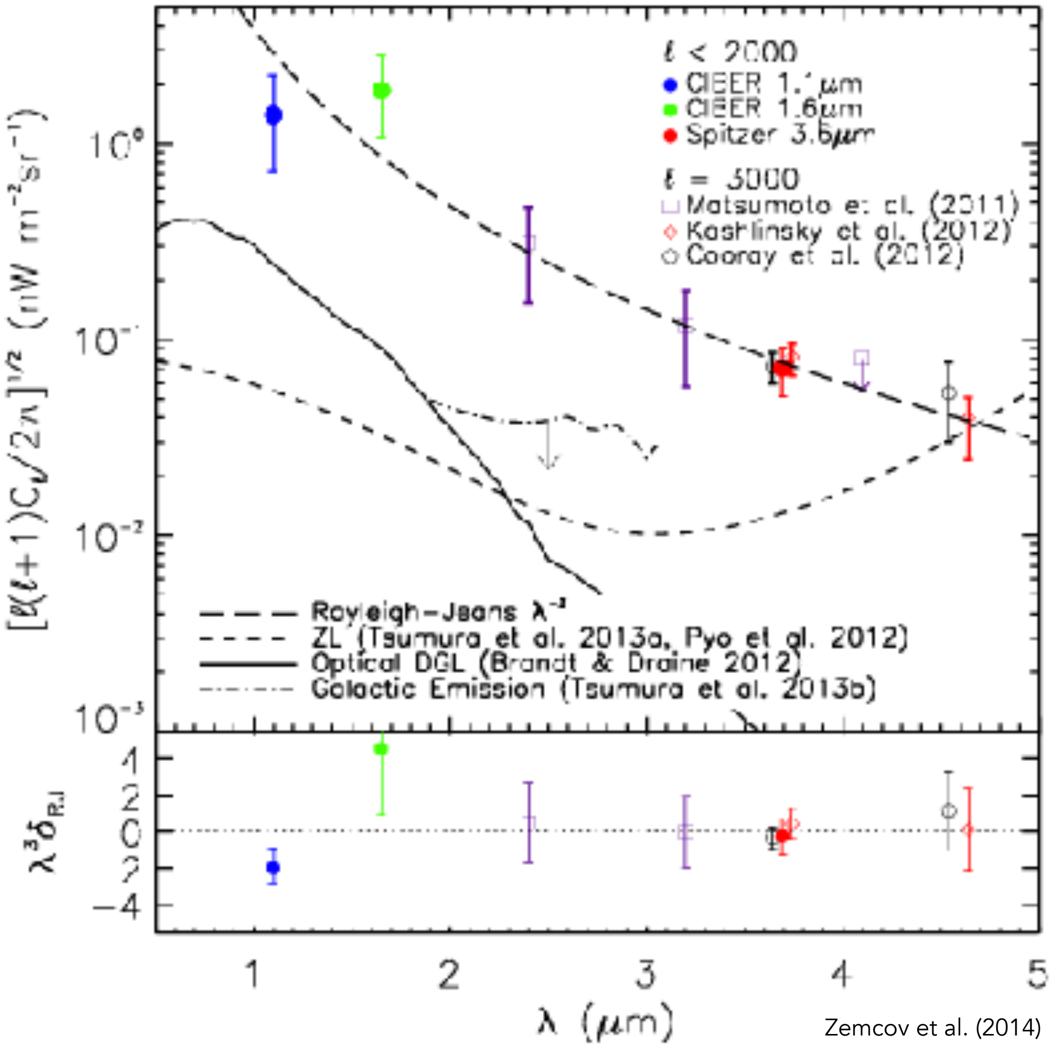
3. Diffuse galactic light ➔ we *measure* a correlation between CIBER and 100 μm, smaller than the measured fluctuations.

4. Residual galaxies ➔ most recent models do not explain power at l~10^3.



Zemcov et al. (2014)

Imager Results



Zemcov et al. (2014)

- CIBER is plotted with previous measurements from Spitzer & AKARI.
- The EM spectrum of combined data is very blue and too bright to be reionization.
- Not explained by scaled foregrounds.
- Evidence for the beginning of a turn over at 1.1 μm?

Additional Information

Measurement	Instrument/Wavelength	Result
Thompson et al. 2007	HST/NICMOS 1.4, 1.6 um	No additional source populations present to explain high NIR monopole. Later questioned by eg Donnerstein 2015
Cappelluti et al. 2013 and later Cappelluti et al. 2017, also Mitchell-Wynne et al. 2016	Spitzer-Chandra (NIR x X-ray) correlations	Correlation detected at 4-6s. Interpreted as possibly arising from high redshift black holes.
Mitchell-Wynne et al. 2015	HST/WFC3 0.6 - 1.6 um in 5 bands	Fluctuations strongly deviating from galaxy expectation at deep masking levels.
Thacker et al. 2015	Spitzer-Herschel NIRxFIR correlations	Report a correlated component between NIR and FIR at few-sigma significance.
Seo et al. 2015	Akari/2.4 and 3.2 um	NIR fluctuations consistent with earlier measurements.
Arendt et al. 2015	Spizter time correlations	Limits ZL to being a faint component sourcing NIR fluctuations.

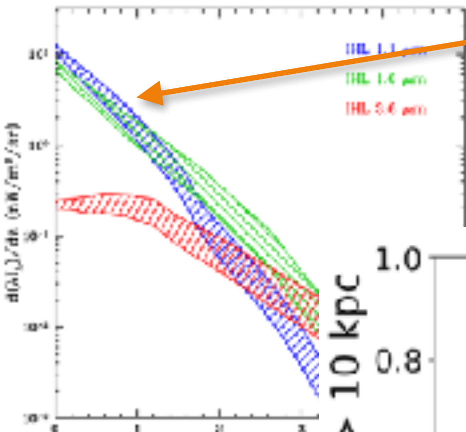
Intra-Halo Light

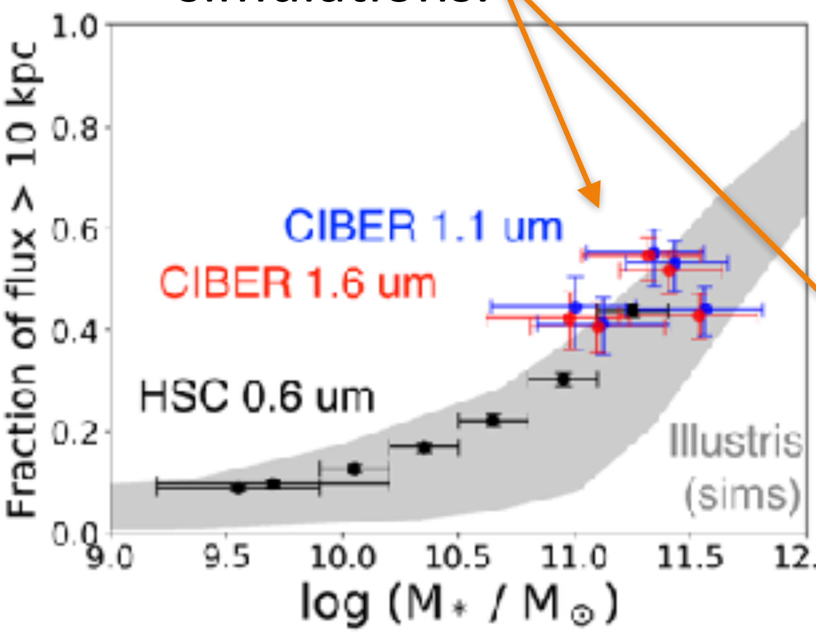
IHL Properties

IHL at NIR wavelengths is sourced nearby.

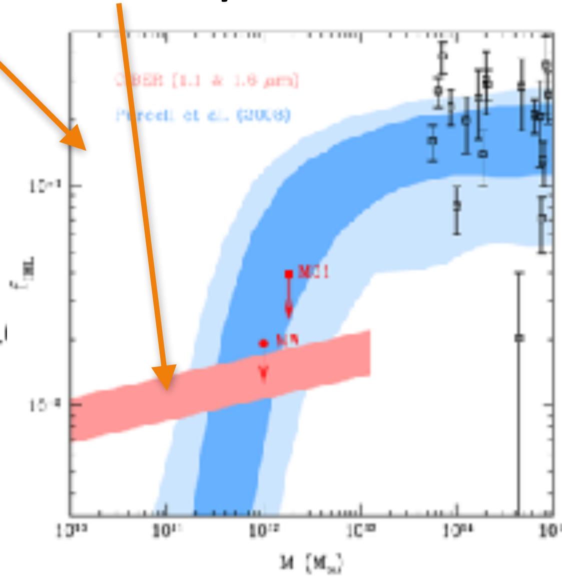
Mass distribution follows expectations from simulations.

Significant IHL fraction even in low-mass systems.





Y.T.Cheng et al. 2021



Next-generation sims by J. Mirocha reproduce fluctuation measurements well.

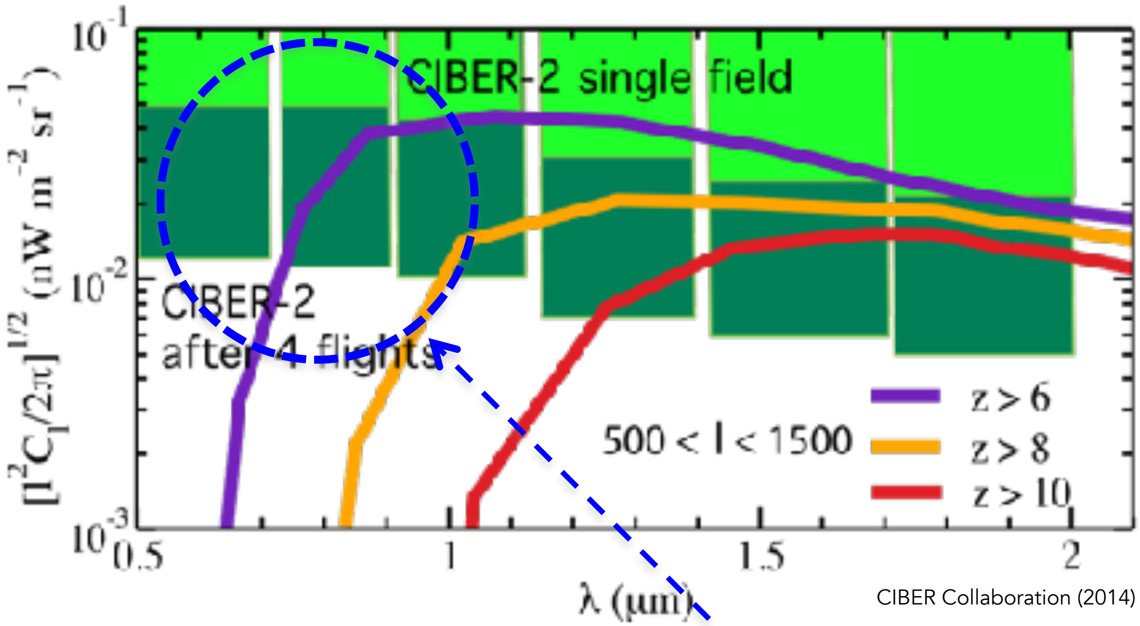
Open Questions

The 4th flight CIBER data (R. Feder, in prep) adds considerably more constraining power. Some questions that extant CIBER data can address:

- Is the color of the large-angle component different than the galaxy component? *Yes*
- Does the inter-wavelength correlation change in other fields? *No*
- Can we formulate a model which explains the colors? *In work*
- Can we detect the large angle component in an image-space analysis? *Yes (Y.T. Cheng et al. 2021)*
- Can we detect a reionization component? *Probably not.*

CIBER-2

CIBER-2 improves on CIBER-1 with 6 bands and ~10x greater AΩ which maximizes sensitivity to ℓ-modes of interest.



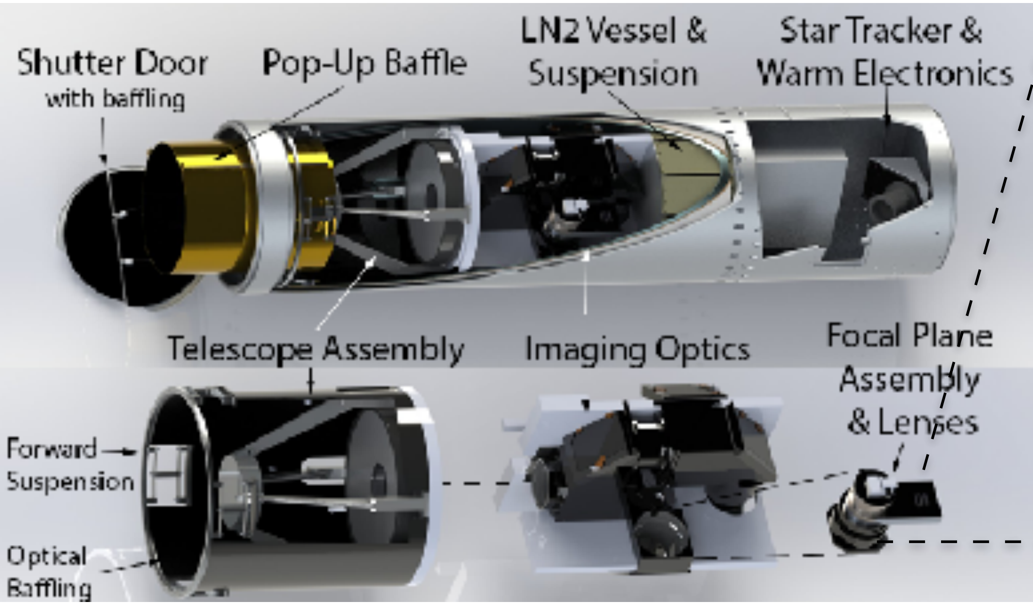
CIBER Collaboration (2014)

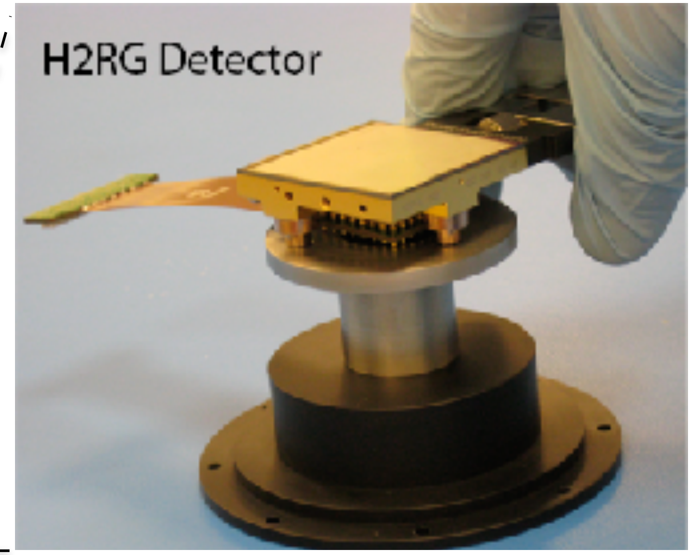
Aperture	**28.5**						**cm**
Pixel Size	4						arcsec
FOV	1.61x2.2 for imager bands, 0.4 for LVF						degrees
Array	3x 2048² H2RG						
λ (Δλ/λ)	600	800	1030	1280	1550	1850	μm
νI_ν (sky)	525	450	400	380	320	224	nW m^{-2} sr^{-1}
$\delta \nu I_\nu$ (1σ/pix)	38	45	34	31	25	23	nW m^{-2} sr^{-1}
δF_ν (3σ)	21.5	21.1	21.0	21.0	21.0	20.9	Vega mag

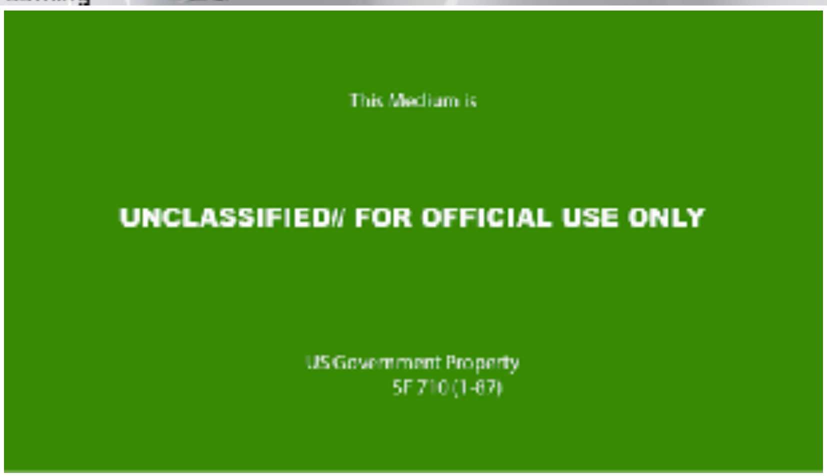
CIBER Collaboration (2014)

Coverage In the optical is critical to separate IHL from EOR.

CIBER-2







Three launches:

June 2021 - engineering flight

April 2023 - vehicle termination

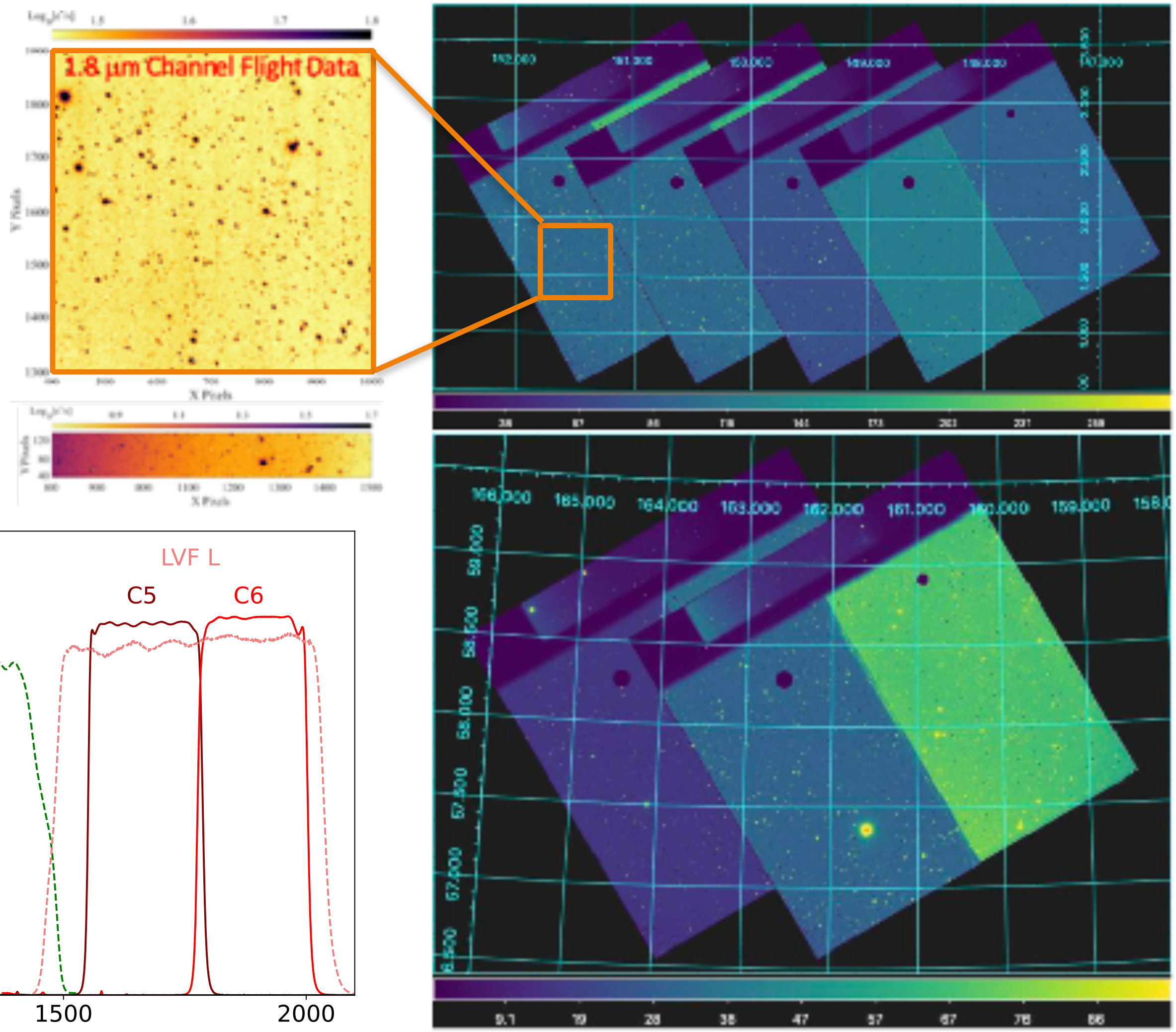
May 2024 - good data!

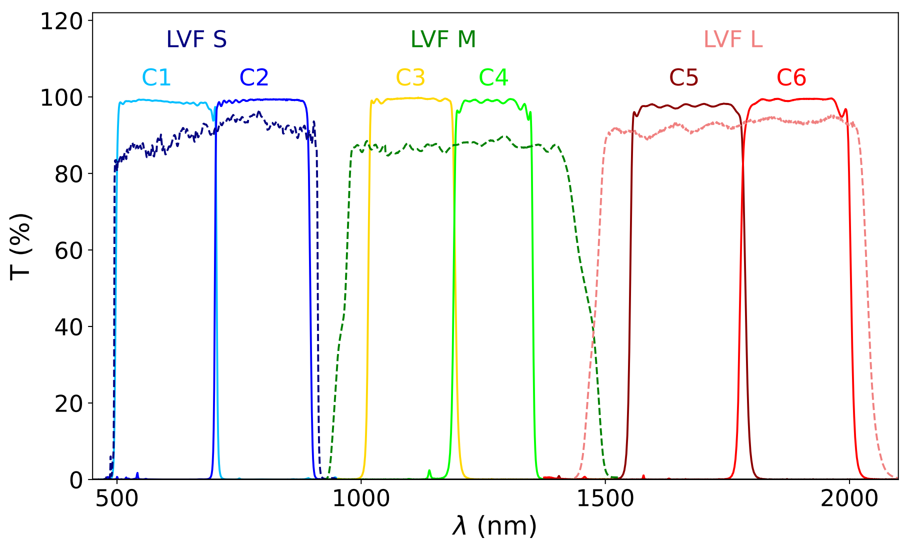
We are analyzing data now, expect first assessment of flight data soon.

Preliminary Data Analysis

Each exposure is 1.1x1.8 sq. deg per band
x 6 bands simultaneously
x 6 exposures in flight (4x COSMOS, 2x Lockman)

Lots of multi-band coverage!





Next Steps

- We expect to be done with CIBER-2 data soon.
- SPHEREx was designed, in part, to be an IM machine. Will be definitive at NIR wavelengths (see Phil's talk). Answers expected ~2027.
- Fluctuations at optical wavelengths are a question. *CIBER-2 may continue in an optical wavelength instrument.*
- Beyond that, multi-wavelength wide-area correlation will be the path forward.
- **The end goal is to isolate the reionization component from the low redshift component, and to answer whether these measurements are consistent with the absolute EBL.**

Merci Beaucoup