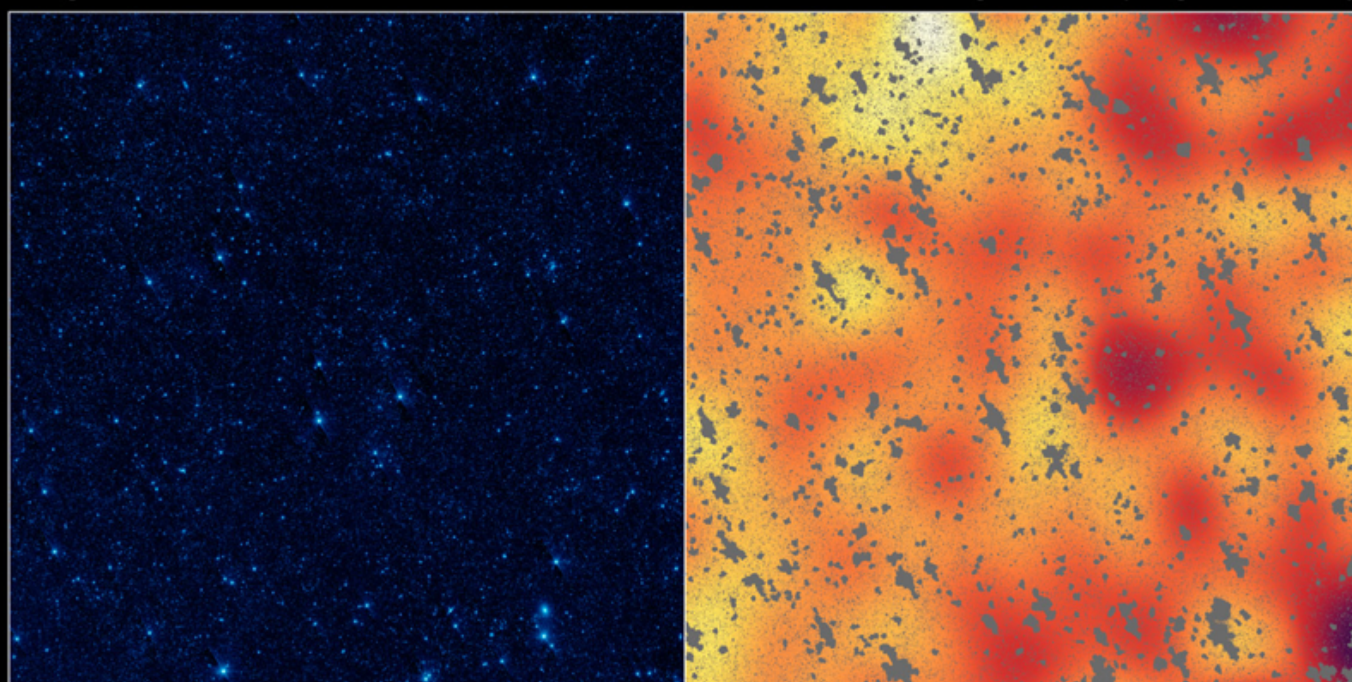
Intensity Mapping

Asantha Cooray @ARCooray on Ureka



Outline

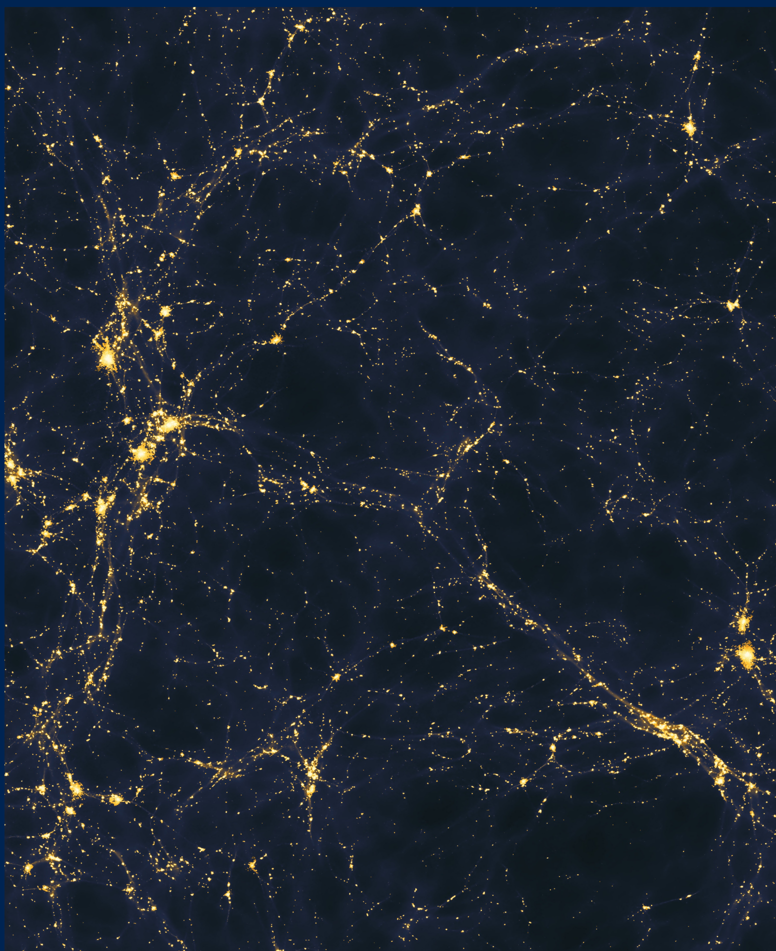
- **Intensity Mapping of Broad Band Fluctuations**
  - **Optical/IR/CIB and Cross-correlations**

- **Intensity Mapping of Spectral Lines**
  - **UV to near-IR lines: Lyman, Balmer, …**
  - **Mid-IR to mm-wave: H2, CO, CII, …**

- **Experiments: Hubble/Spitzer/Herschel-SPIRE, CIBER-I/II, CDIM; SPHEREx, TIME (-Pilot), …. see talks by Olivier and Tzu-Ching]**

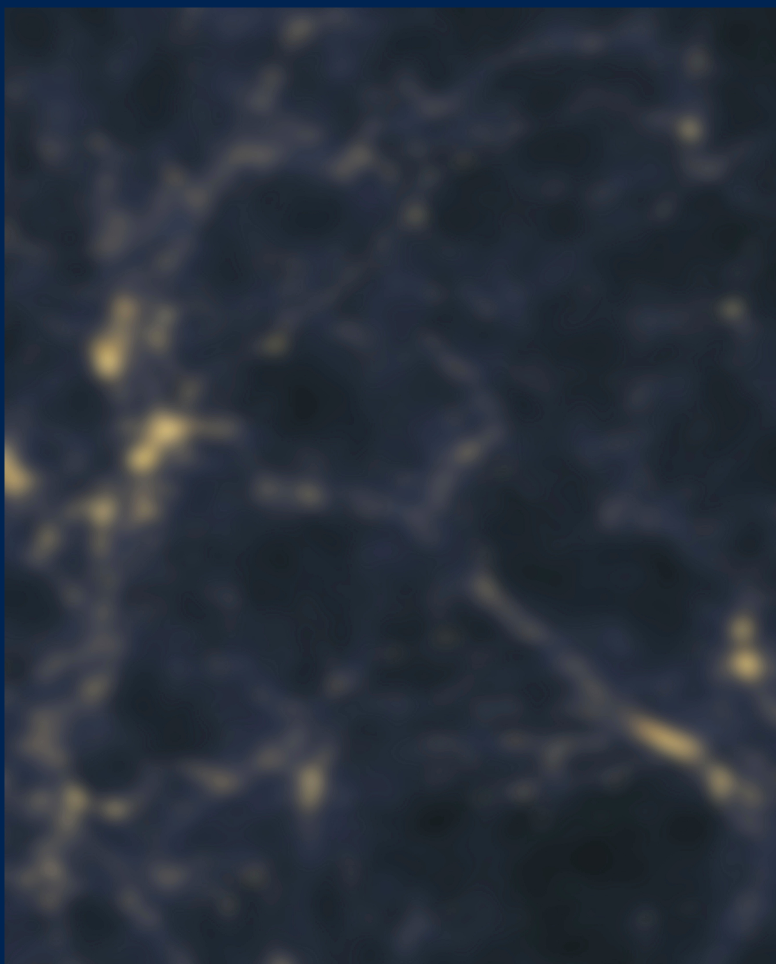
Many thanks to Mike Zemcov, Phil Korngut, Tzu-Ching Chang, and Jamie Bock for some plots and slides
Past students: Joseph Smidt, Ketron Mitchell-Wynne, Marta Silva, Caroline Heneka and Postdocs: Yan Gong, Chang Feng for plots

Intensity Mapping



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

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 $\sigma_\ell(z) \sim n_{gal}$)

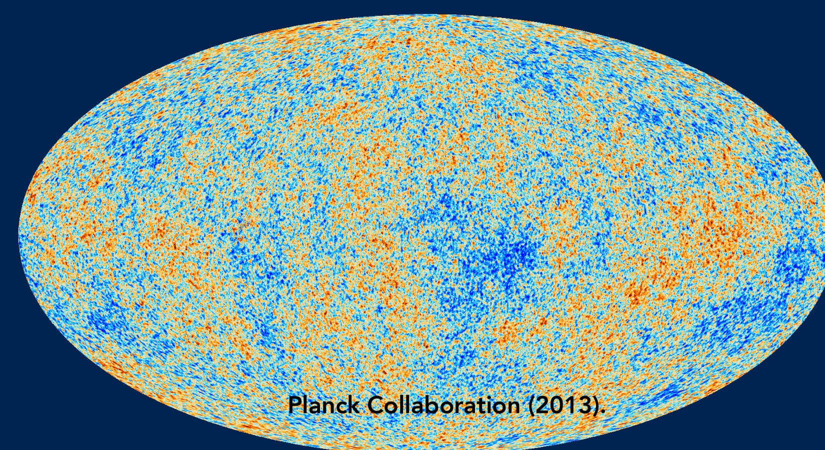
If, however:

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.

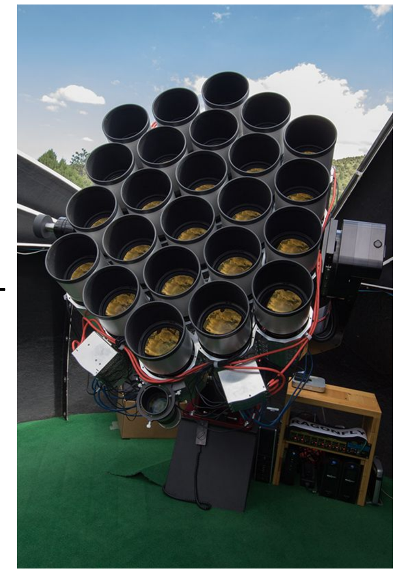
Science Applications:

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


Planck Collaboration (2013).

Intensity mapping can be done with small telescopes!

TMT, \$1B-1.4B (2008 estimate)



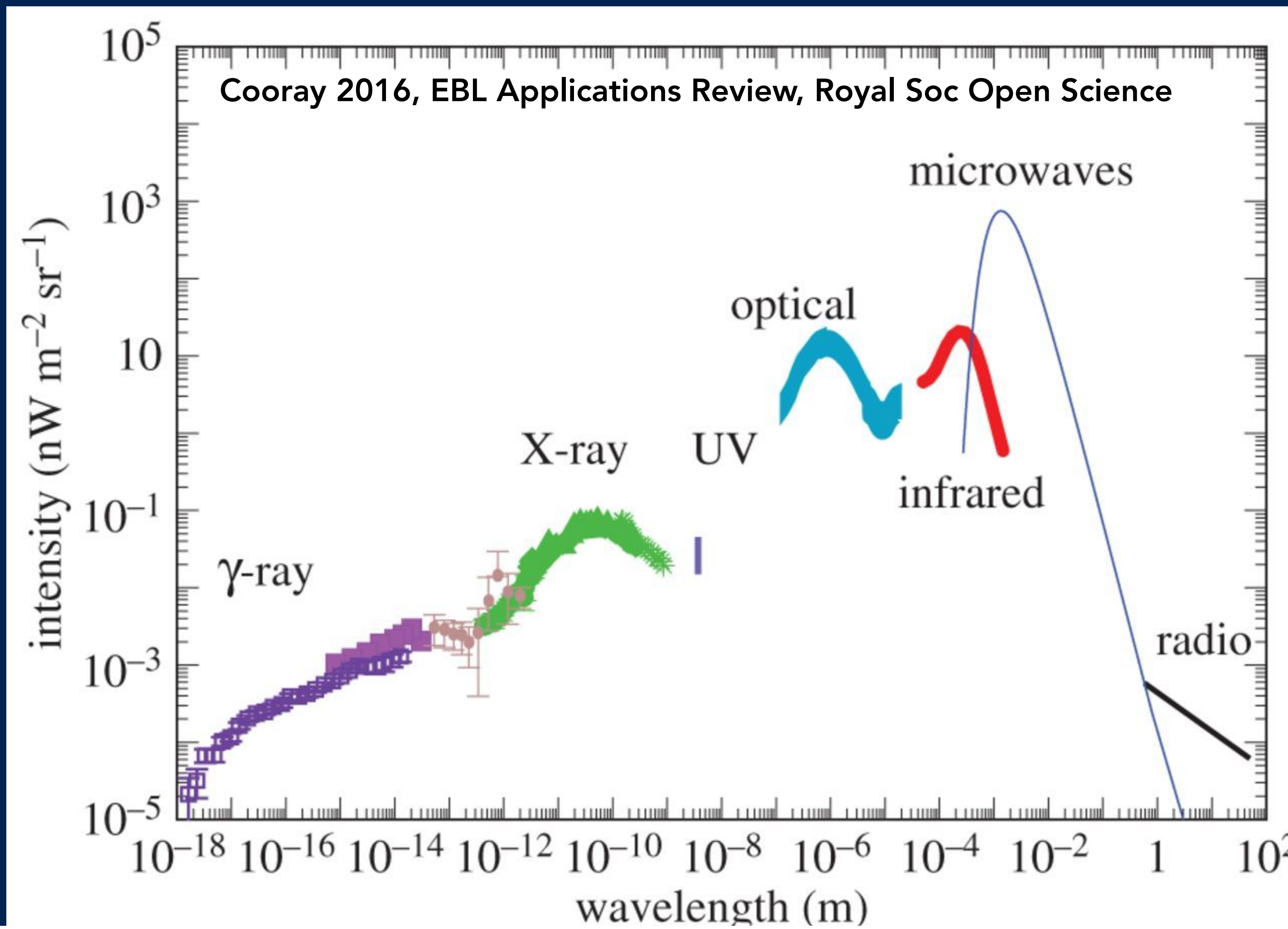
Dragonfly, Yale & UT Dunlap
24 Cannon telephoto lenses

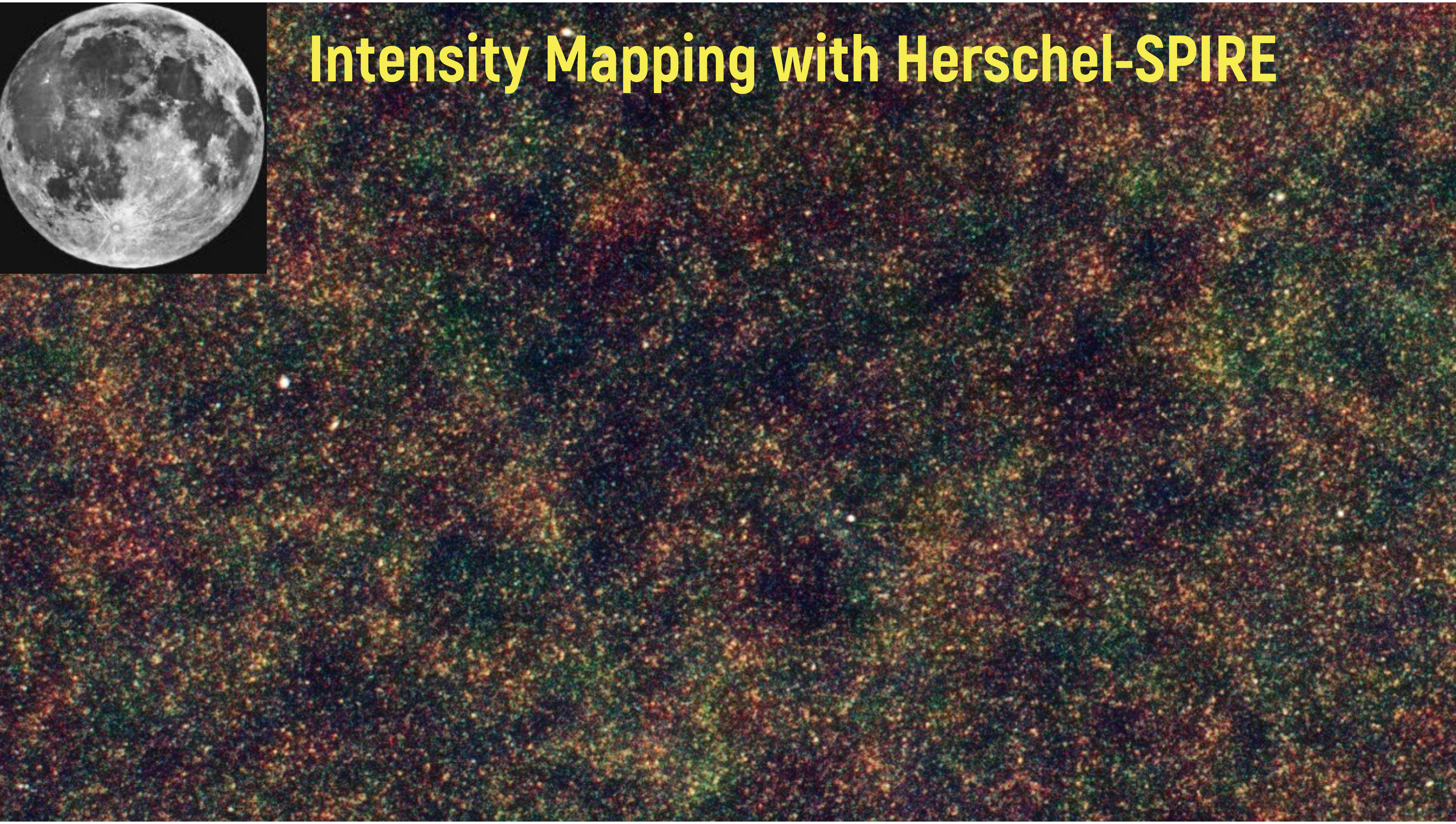
- S/N ratio on point sources goes as *d*.
- Angular resolution goes as d^{-1}.

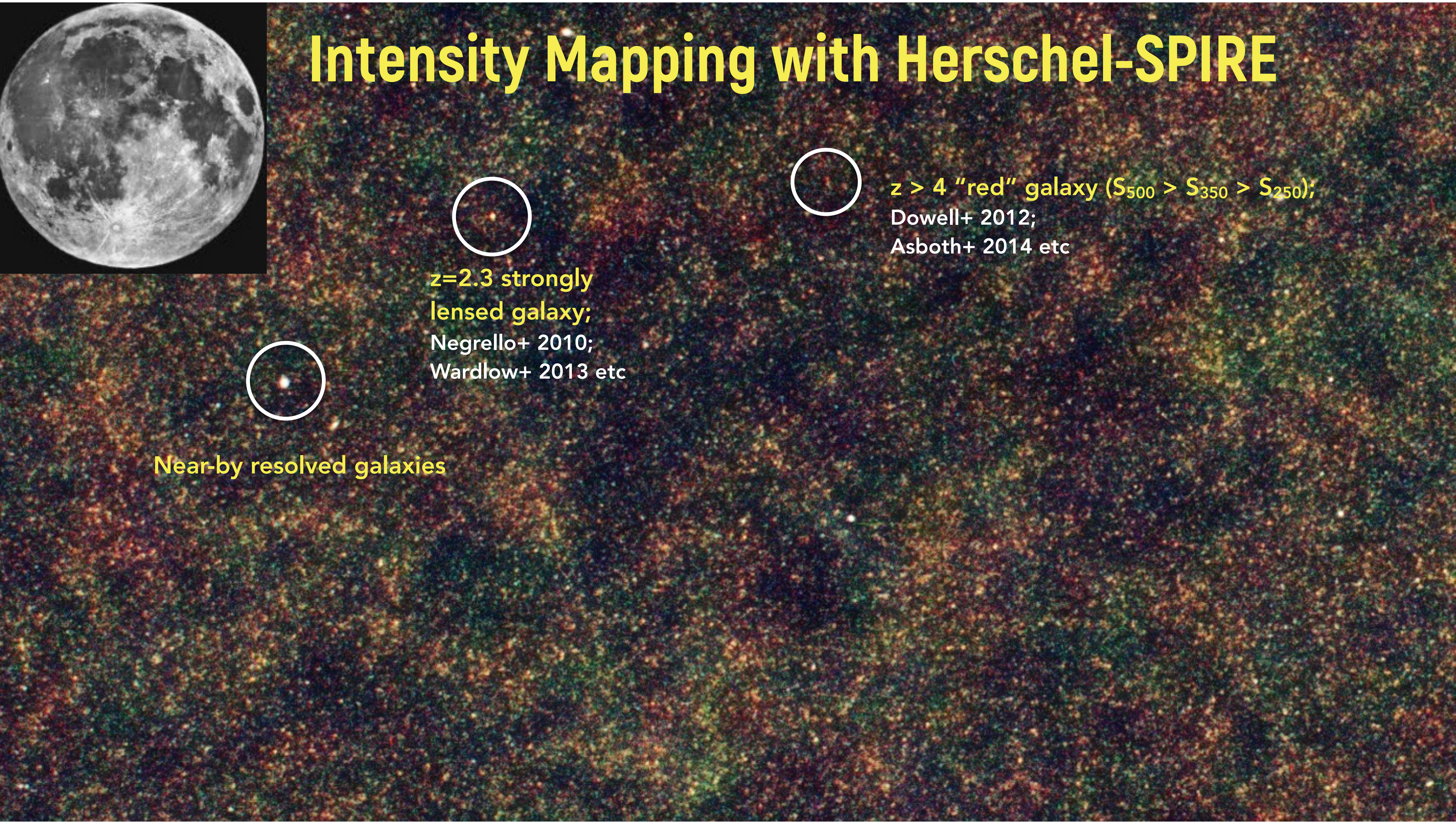
  ➡ Larger apertures are desirable for point sources.

- 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.

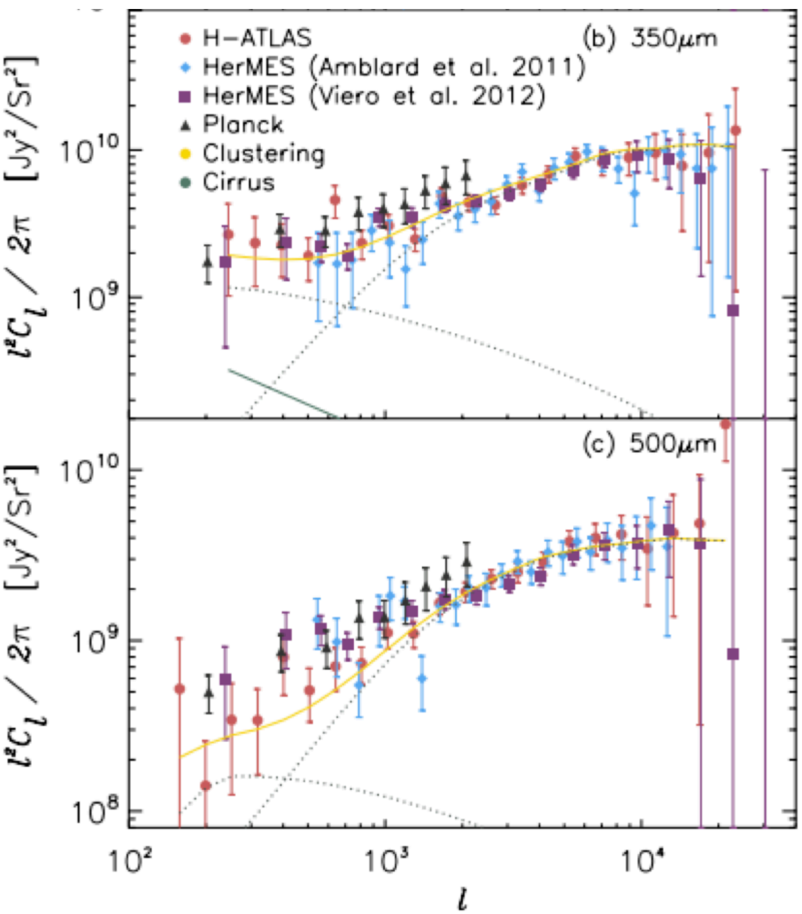
Intensity Mapping Examples, from 2D to 3D




Intensity Mapping with Herschel-SPIRE


Intensity Mapping with Herschel-SPIRE
z > 4 "red" galaxy (S_{500} > S_{350} > S_{250});
Dowell+ 2012;
Asboth+ 2014 etc
z=2.3 strongly
lensed galaxy;
Negrello+ 2010;
Wardlow+ 2013 etc
Near-by resolved galaxies

Intensity Mapping with Herschel-SPIRE



Amblard, Cooray et *al.* 2011, Nature;
+ many others + Planck CIB

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

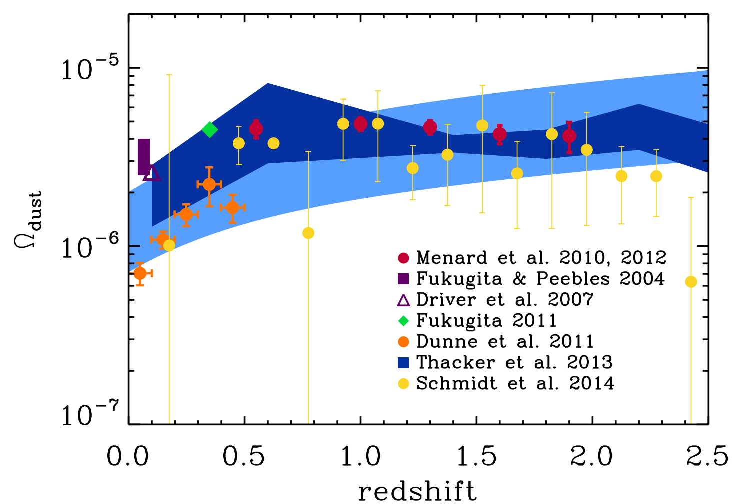
Parameter	$\log(M_{\rm min})$	$\log(M_{\rm peak})$	T	T_z	β	$\sigma^2_{L/m}$	$\log(L_0)$	η
$\log(M_{\rm min})$	10.1 ± 0.5	−0.02	0.20	−0.27	−0.10	0.02	0.26	−0.25
$\log(M_{\rm peak})$	…	12.3 ± 0.5	0.21	−0.01	−0.23	−1.00	−0.18	0.20
T	…	…	20.7 ± 1.2	−0.66	−0.92	−0.21	0.76	−0.56
T_z	…	…	…	0.2 ± 0.0	0.38	0.01	−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.

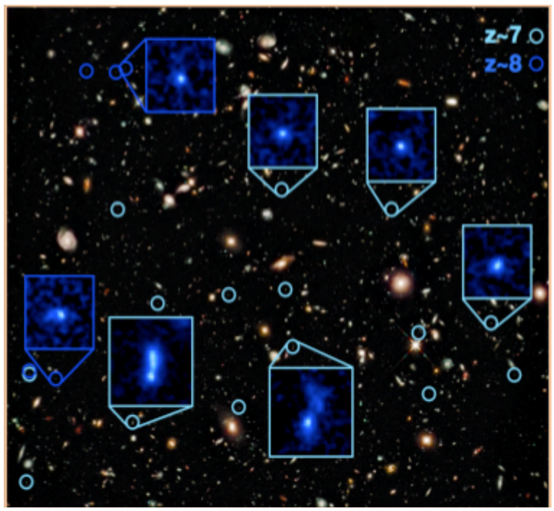
Find:
Minimum halo mass to support star formation: Log ~ 10.1
Halo mass of peak star formation efficiency: Log ~ 12.3
Some constraints on redshift evolution.

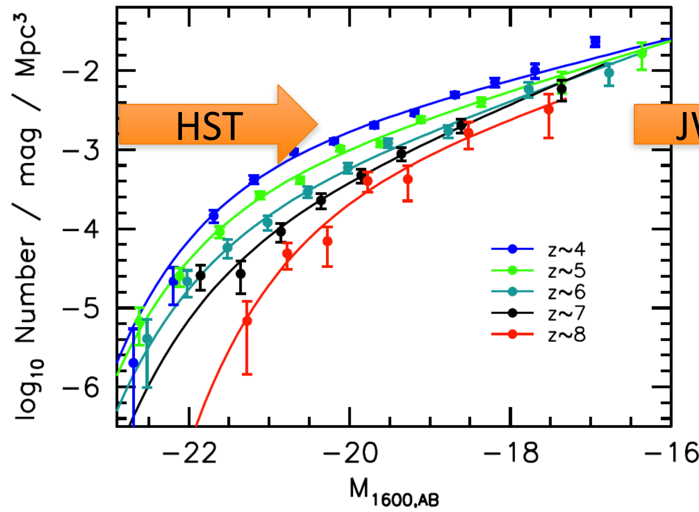


Intensity fluctuations measure the total dust content in the universe! (Thacker et al. 2013, 2014).

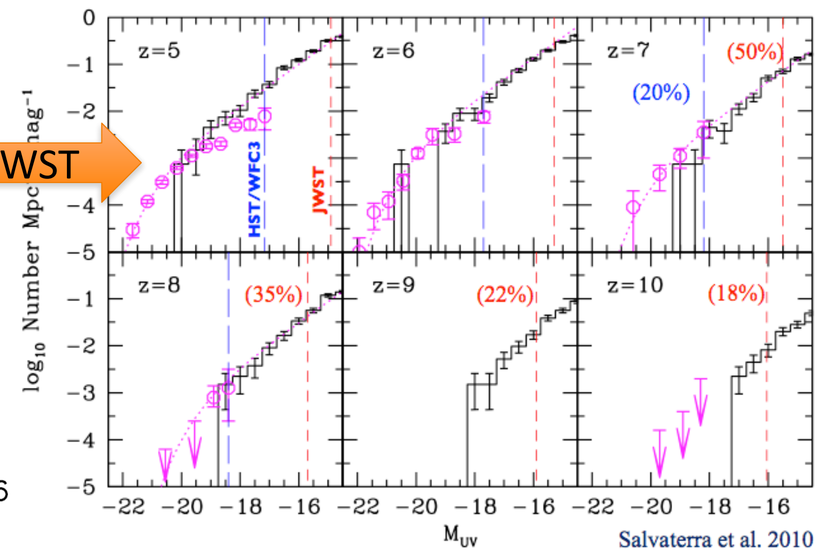
Consistent with SDSS quasar reddening-type measurements

A Near-IR Application: Searching for the Sources Responsible for Reionization





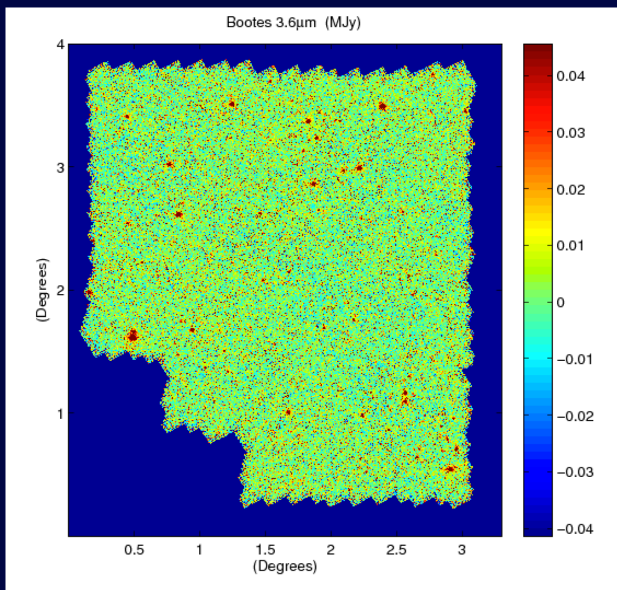
Bouwens et al. (2010,2014)



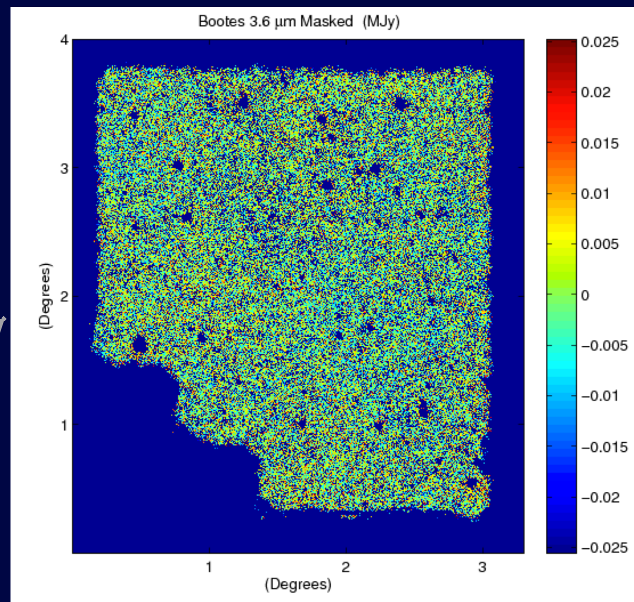
Salvaterra et al. (2010)

- Galaxy counts miss faint sources that may dominate the reionization budget.
- Estimates of the SFRD at high redshift require huge extrapolations of UV luminosity function to explain reionization.
- IM studies are sensitive to the total luminosity emitted by all galaxies -> **Intensity Mapping offers an advantage.**

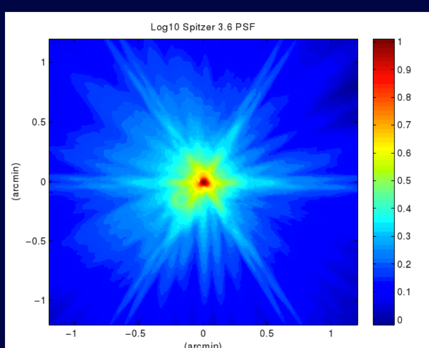
Spitzer Background Fluctuations



MOSAIC MAP

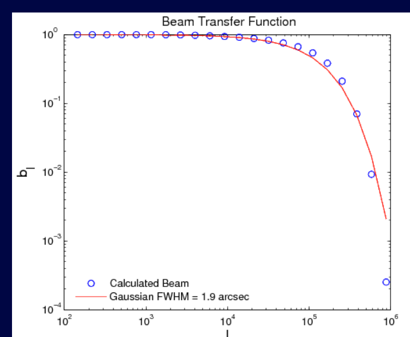


MASK MAP



PSF

Fourier Transform



BEAM TRANSFER FUNCTION

Epoch 1 + Epoch 2

X

Epoch 3 + Epoch 4

Cross-Correlate Coadded Epochs

Epoch 1 - Epoch 2

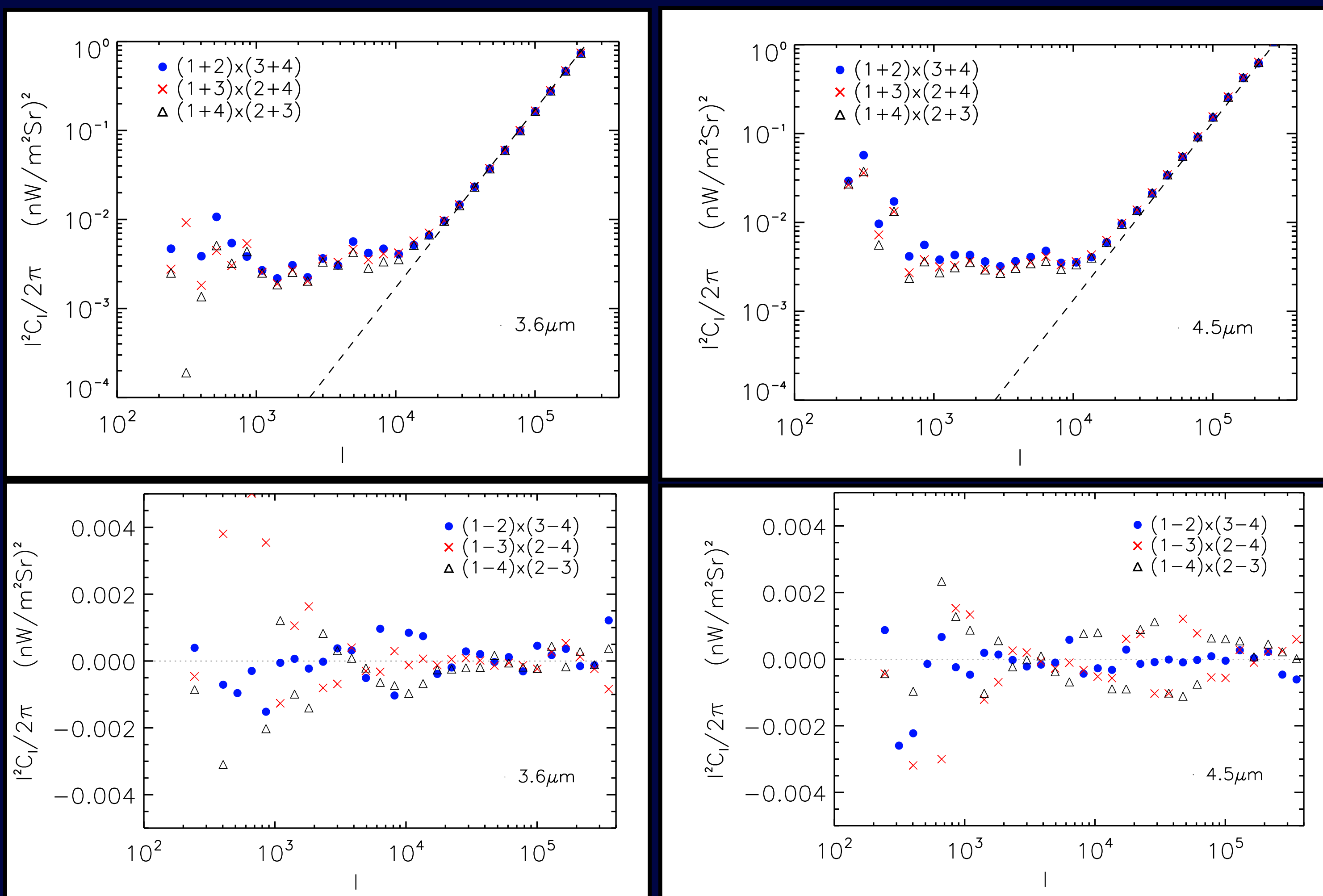
X

Epoch 3 - Epoch 4

Jackknife For Noise Errors

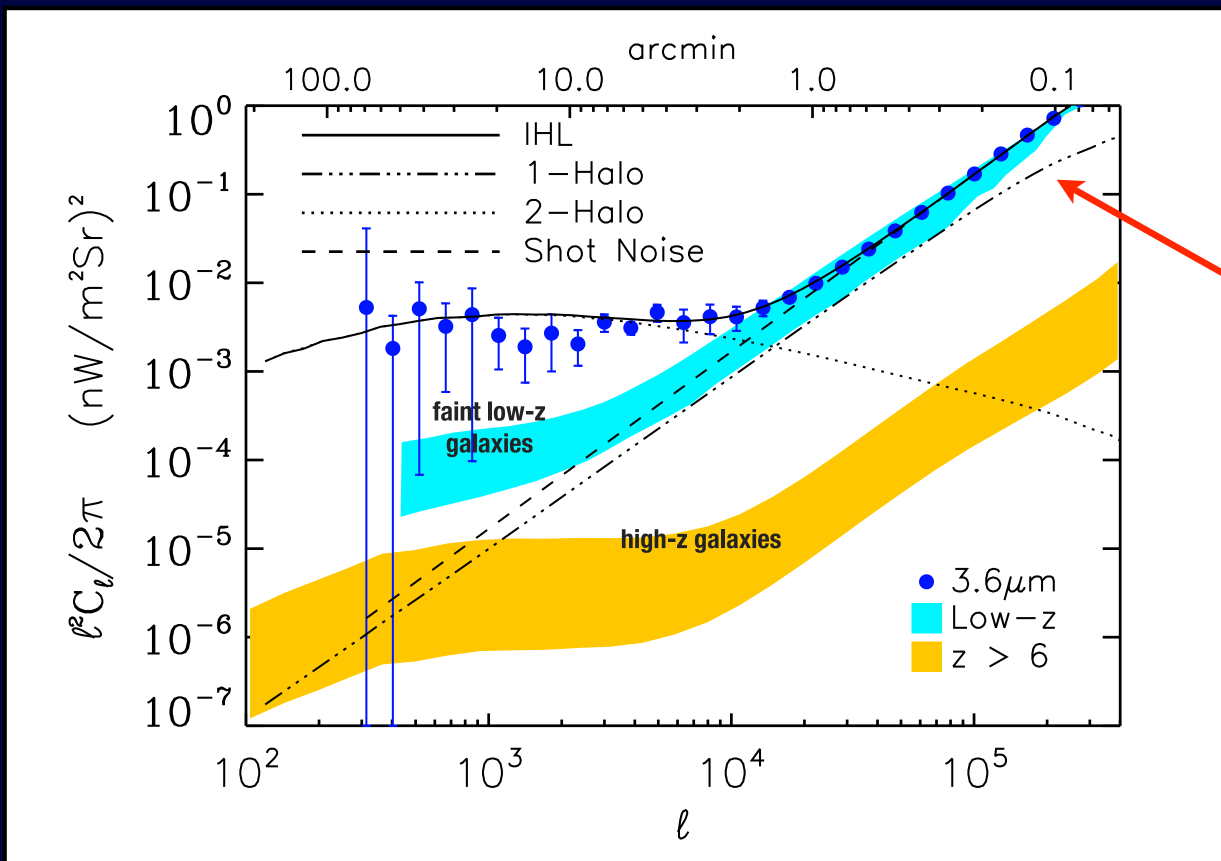
Cooray et al. 2012, Nature, 490, 514

Spitzer Background Fluctuations



Cooray et al. 2012,
Nature, 490, 514

Spitzer Background Fluctuations



Measured shot-noise agrees with prediction for faint galaxies below the detection threshold (Helgason et al. 2012)

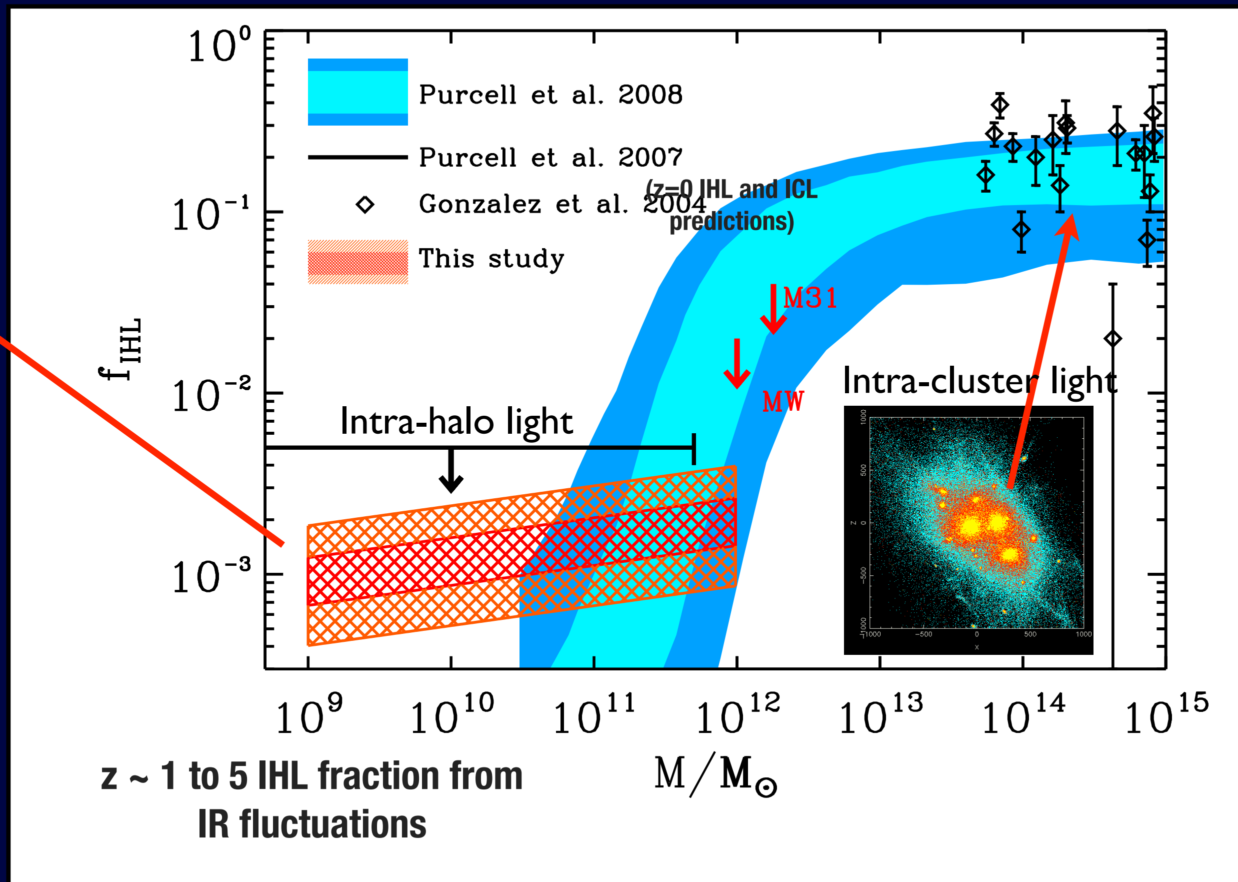
Argues against a new source population to explain the observations

Cooray et al. 2012, Nature, 490, 514

Intra-halo light in galaxy-scale dark matter halos

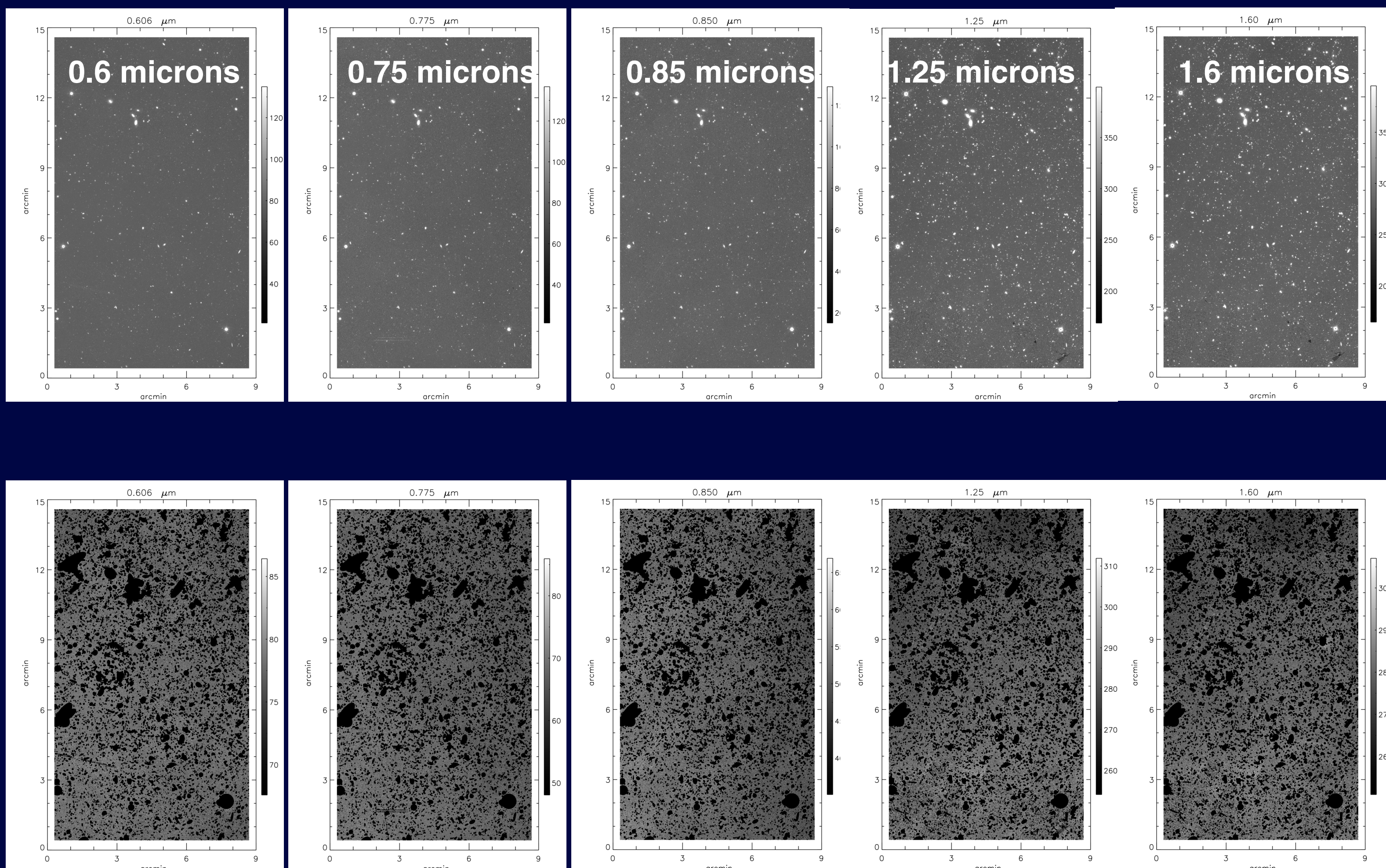
Intrahalo light:
stars outside of the galactic disks and in the outskirts of dark matter halos due to tidal stripping and galaxy mergers.

Simulation/theory predictions:
Purcell et al. 2007
Watson et al. 2012



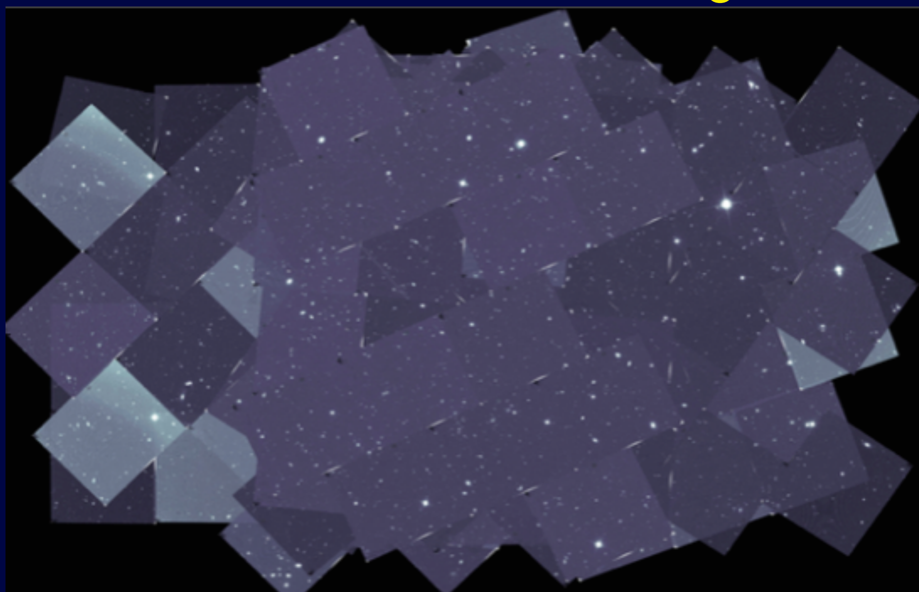
Cooray et al. 2012,
Nature, 490, 514

Hubble CANDELS fluctuations



Mitchell-Wynne et al. 2015
Nature Communications

Foregrounds – Zodiacal Light



- Sunlight scattered off dust in the solar system.
- Intensity at some point in the sky is a function of time, so observing same area at different times give different overall offset.
- Effectively a fictitious anisotropy.
- We’re looking at anisotropies, not absolute intensities. Just need to remove offsets.
- ZL power spectrum is inherently different from extragalactic signal.

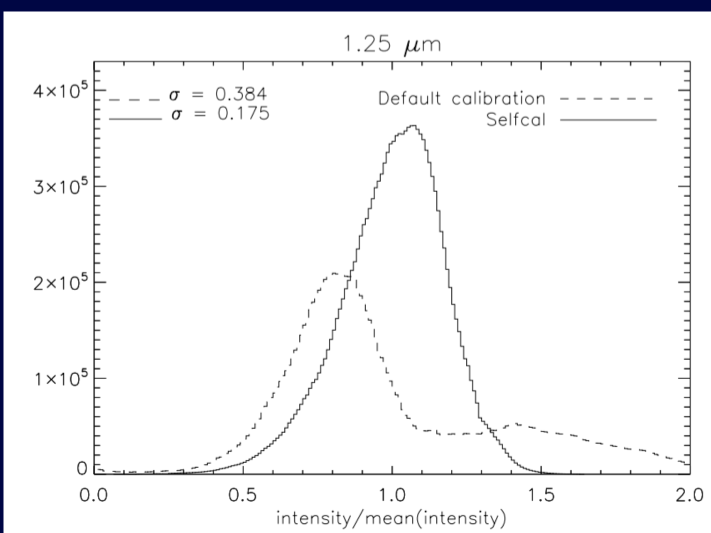
Mitchell-Wynne et al. 2015
Nature Communications

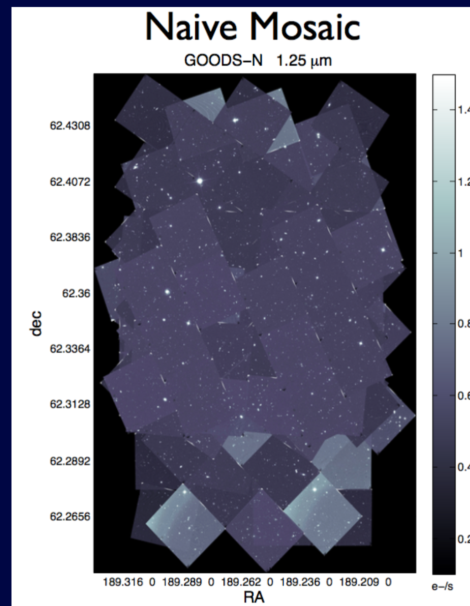
Self-Calibration vs. Default Calibration

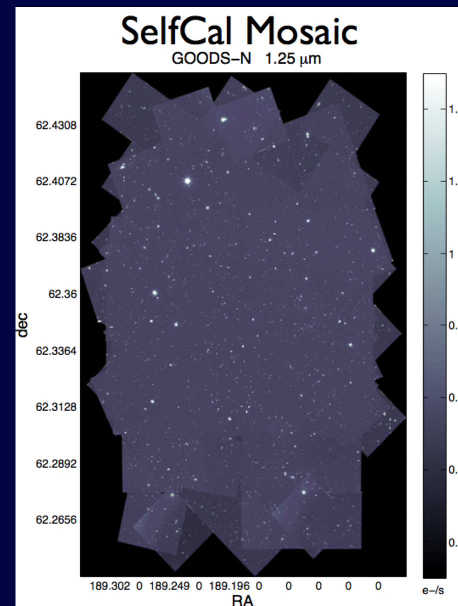
Use multiple pointings of the same sky area with different pixels to simultaneously solve for sky brightness and detector properties (non-constant gain and offset parameters) via Self-Calibration algorithm

(Fixsen, Moseley & Arendt, 2000, ApJS)

Must have sufficient pixel overlap for Self-Cal to work!





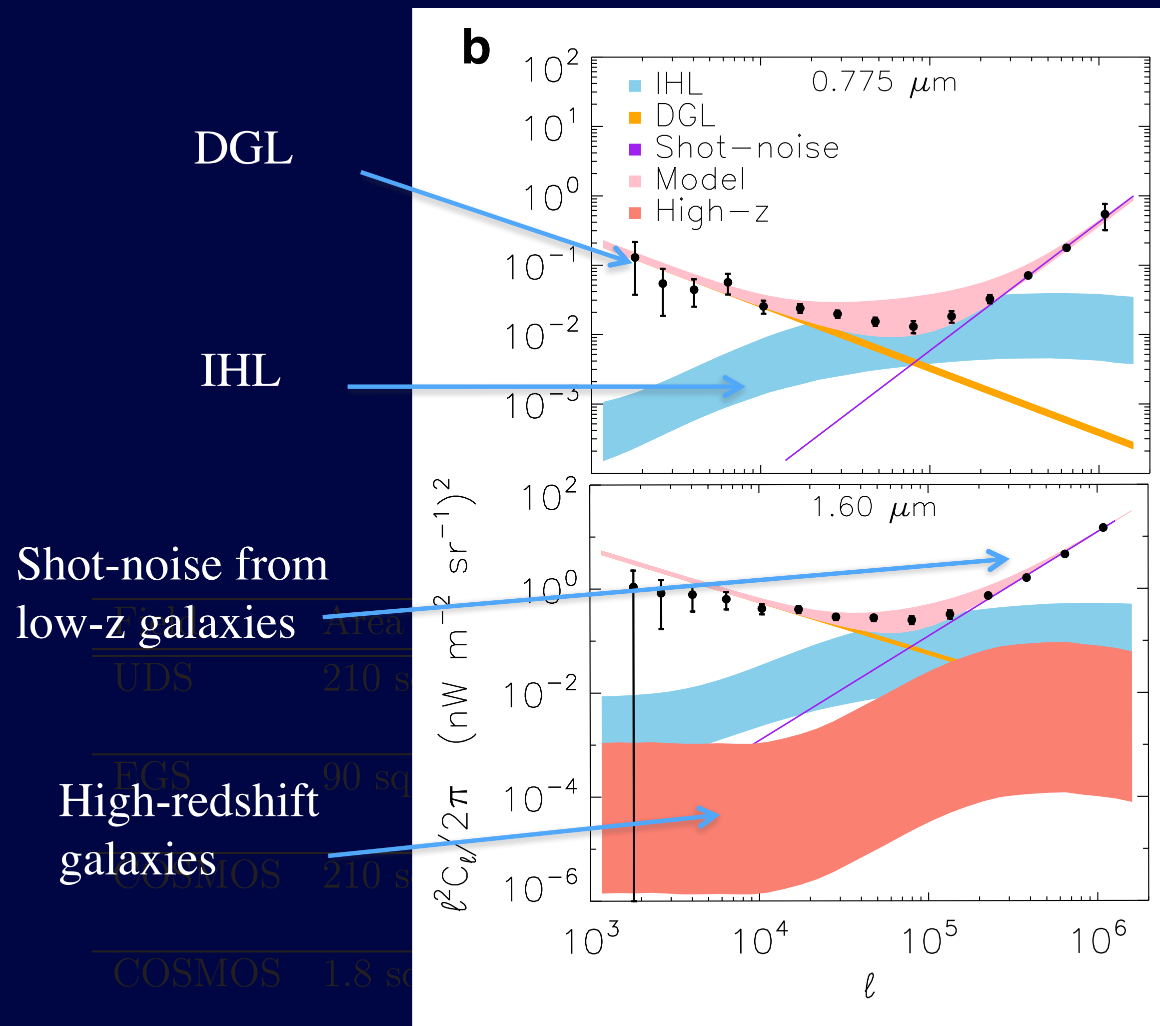


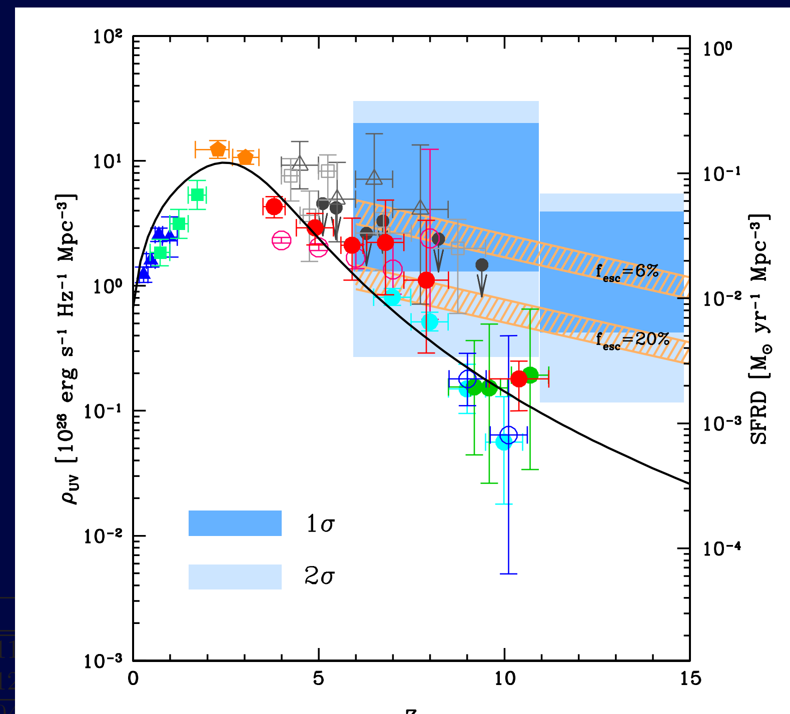

```
models the input data as  Di = Gp(1) Sa + Fp + Fq(1)
Di    = your data
Gp(1) = FIXED detector gains (per pixel)
Sa    = the actual sky intensities
Fp    = detector offsets (per pixel)
Fq(1) = variable detector or sky offsets (per frame)
```

Self-cal removes background offsets

Mitchell-Wynne et al. 2015
Nature Communications

Reionization signal in IR fluctuations

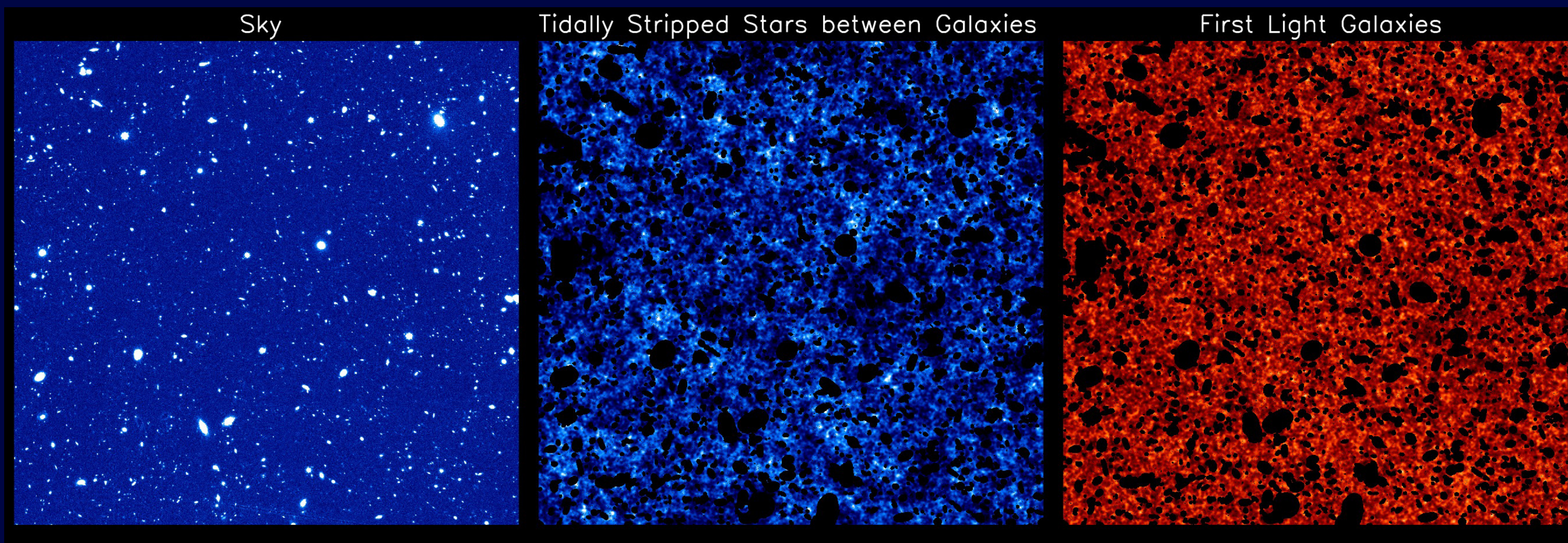




Mitchell-Wynne et al. 2015
Nature Communications

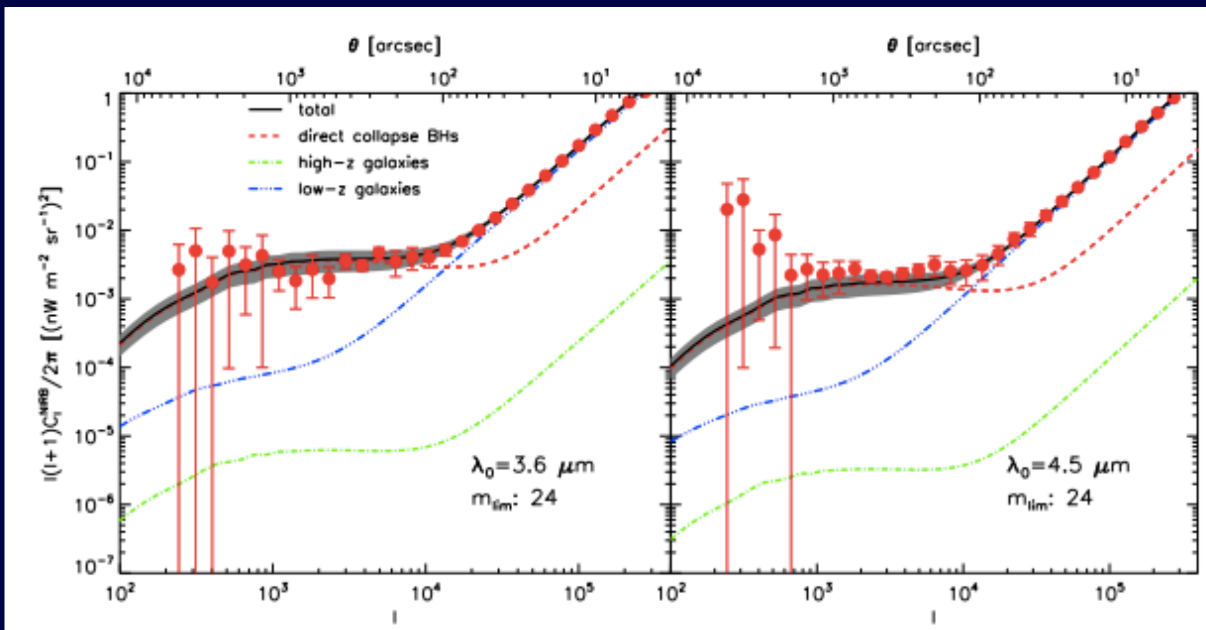
Model Component Reconstruction

What does the distribution of first light galaxies actually look like?



Mitchell-Wynne et al. 2015
Nature Communications

Direct Collapse Black hole contribution to NIRB?



Yue+ 2013 model fits of Cooray+2012 IR Background power spectra

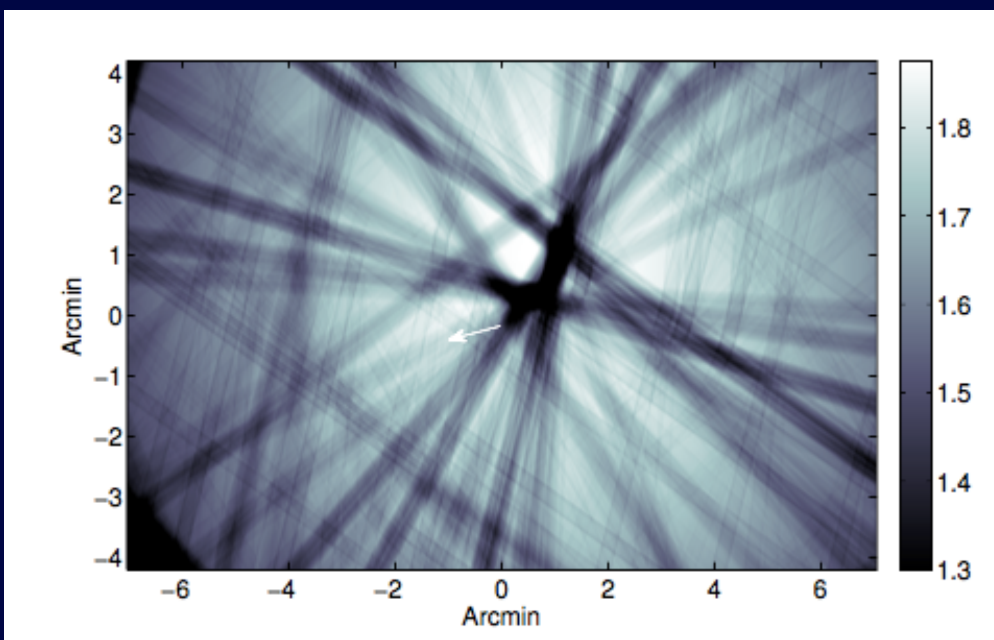
Instead of IHL Yue, Ferrara+ 2013 suggested excess fluctuations caused by massive blackholes (DCBHs) at z > 6.

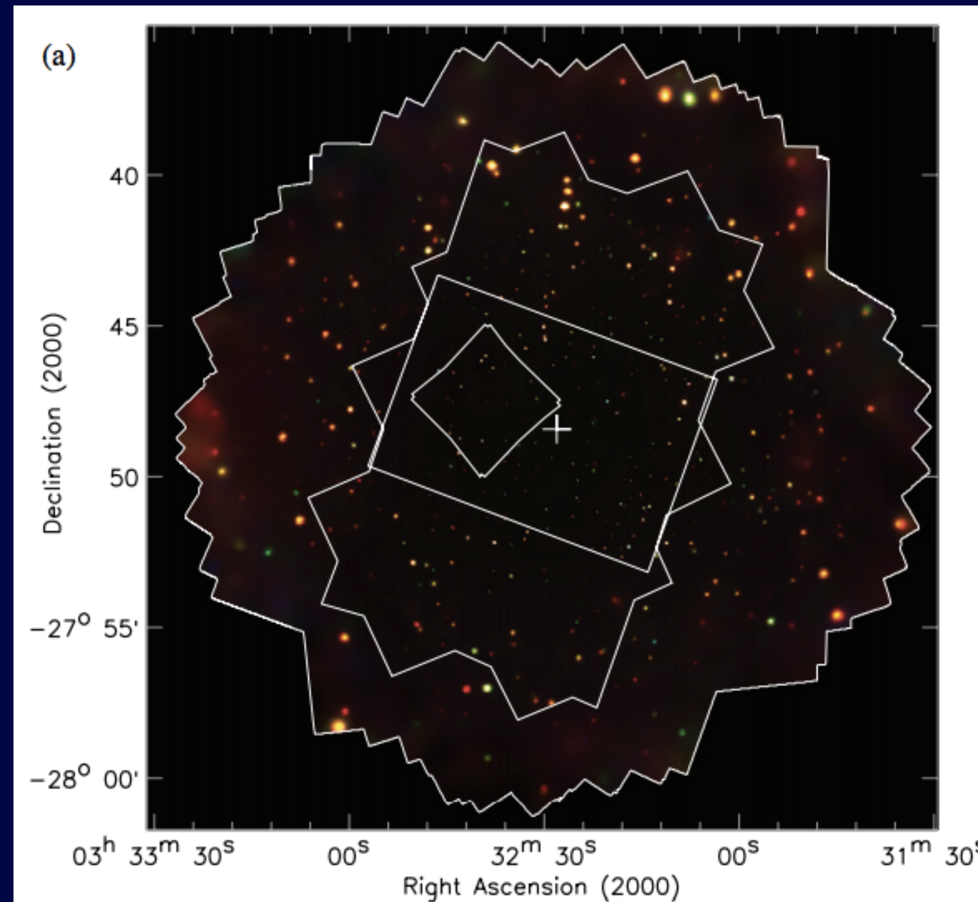
These DCBHs could be partly responsible for reionization.

- DCBHs will also emit rest-frame UV photons — ionizing photons are re-processed into optical-UV photons (free-free, free-bound, two-photon eimssions).
- DCBHs are bright in X-rays!
- If DCBHs, expect to see a significant IR - X-ray cross-correlation.

Deep Chandra Mosaics

- Chandra mosaics in three energy bands: 0.5-2 keV (“soft”), 2.5-8 keV (“hard”) and 0.5-8 keV (“full”).
- Jack-knife maps weren’t generated for other Chandra projects.
- Each jack-knife is ~2 Ms exposure.

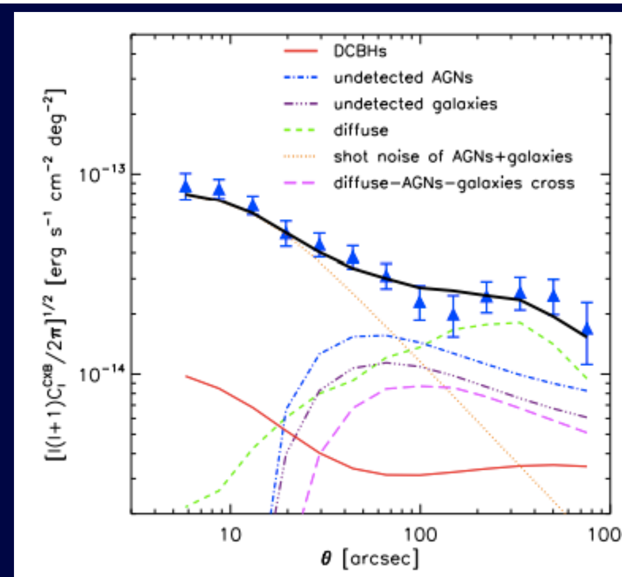


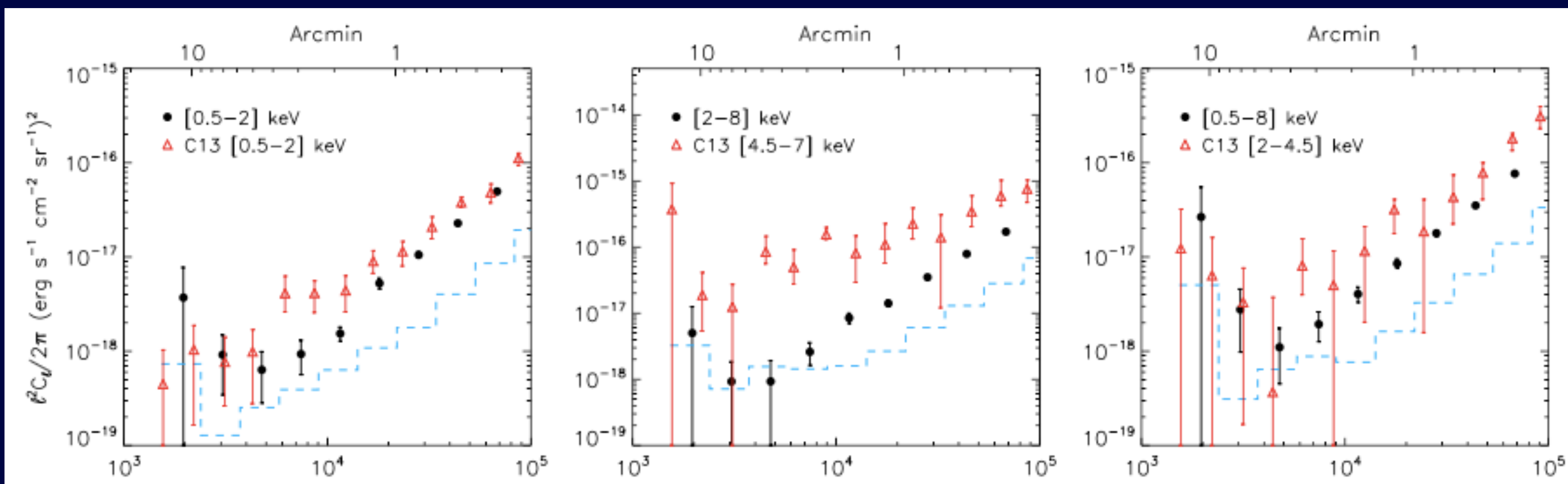


Mitchell-Wynne, Cooray, Brandt et al. 2016 ApJ

XRB Auto-correlation

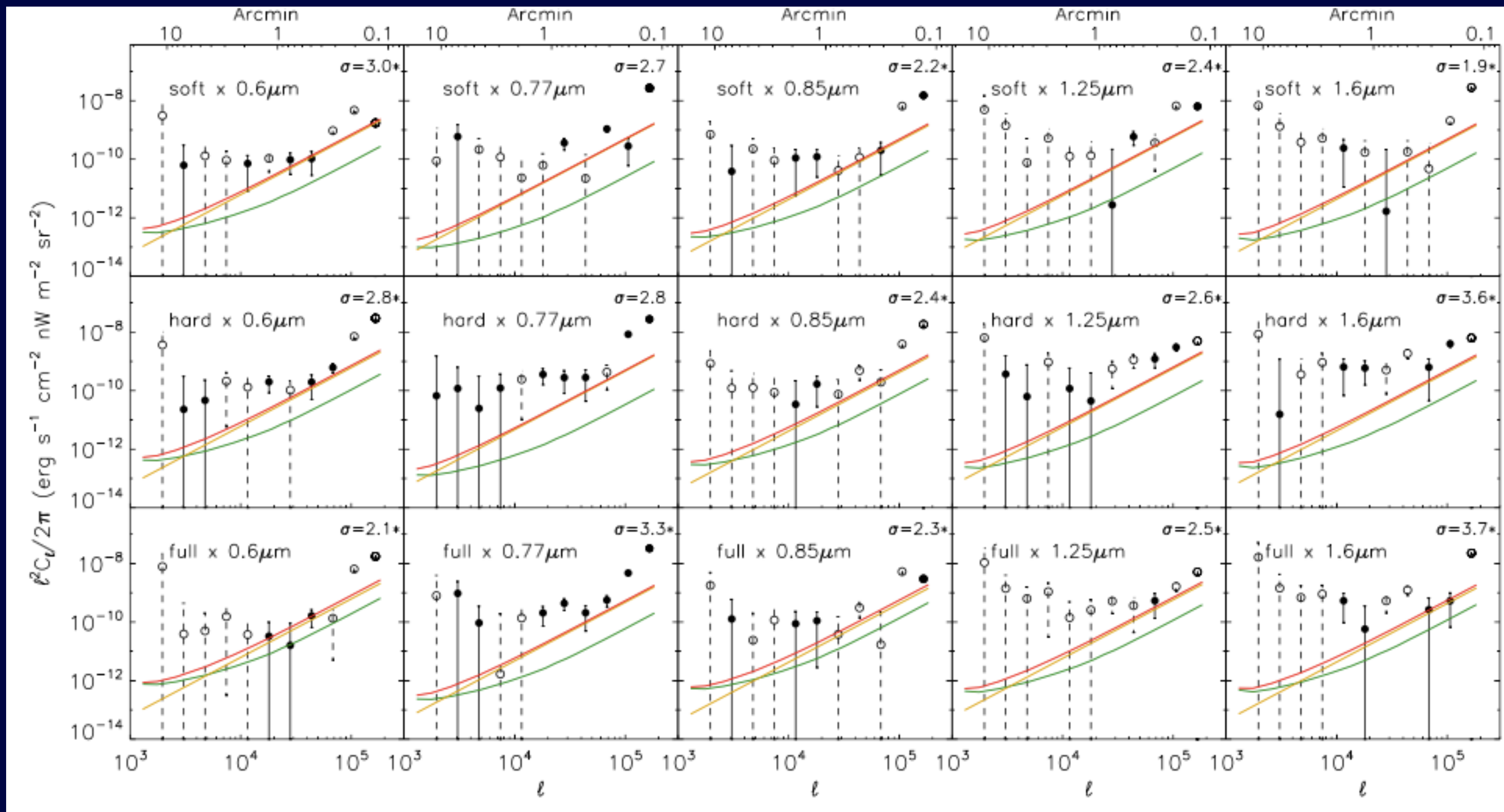
- XRB auto-correlations consistent with previous measurements.
- DCBHs are sufficiently Compton thick that they don't significantly contribute to auto-spectra.
- Auto-spectra dominated by AGN signal





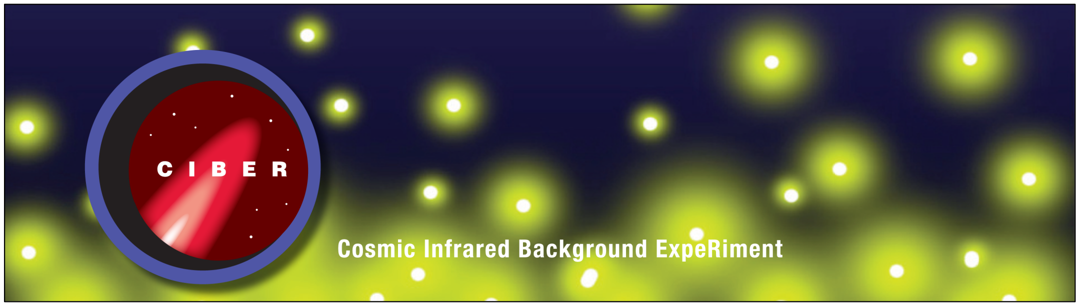
Mitchell-Wynne, Cooray, Brandt et al. 2016 ApJ

X-ray x HST optical/NIR



- XRB anti-correlated with HST. Attributed to galactic dust (X-ray absorption) in HST maps.
- Errors are sufficiently large that we can't make any new definitive statements about DCBHs.

Mitchell-Wynne, Cooray, Brandt et al. 2016 ApJ



The CIBER Collaboration

Caltech / JPL (Jet Propulsion Laboratory, California Institute of Technology): Jamie Bock, Viktor Hristov, Alicia Lanz, Phil Korngut, Peter Mason

UC Irvine: Asantha Cooray

RIT: Mike Zemcov, Chi Nguyen

JAXA: Takehiko Wada

Kwansei Gakuin: Shuji Matsuura

ASIAA: Toshio Matsumoto

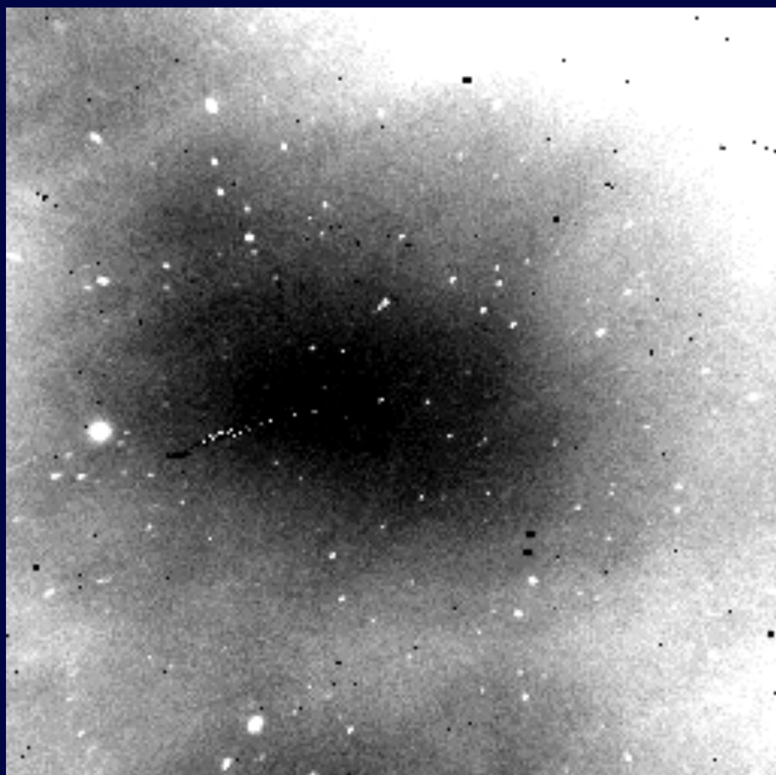
Tohoku University: Kohji Tsumura

Seoul National University: Min Gyu Kim

KASI: Dae Hee Lee

June 20, 2013 launch Wallops, VA

The Case for Space



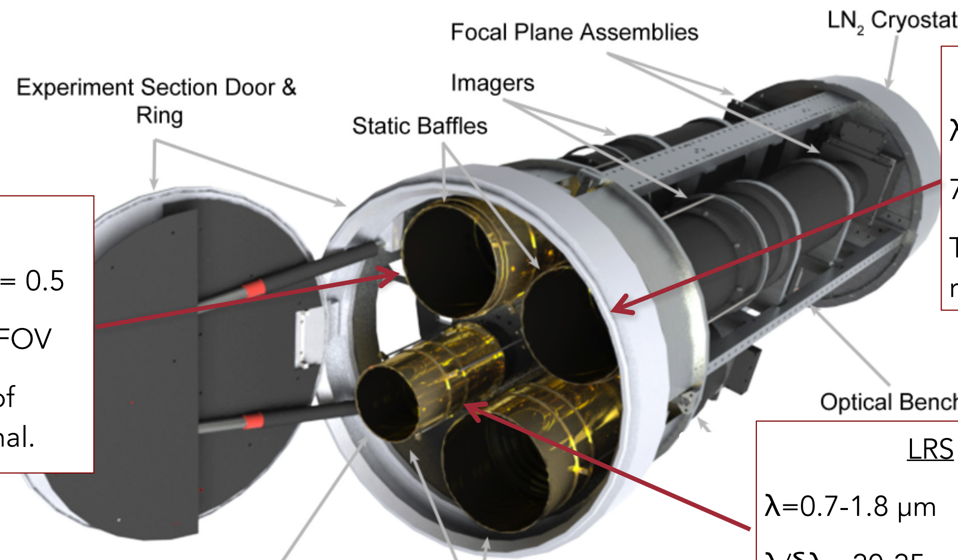
H-BAND 9º X 9º IMAGE OVER 45 MINUTES FROM KITT PEAK
WIDE-FIELD AIRGLOW EXPERIMENT: HTTP://PEGASUS.PHAST.UMASS.EDU/2MASS/TEAMINFO/AIRGLOW.HTML

CIBER
Cosmic Infrared Background ExpeRiment

Airglow Emission

- Atmosphere is **500 – 2500** times brighter than the astrophysical sky at 1-2 μm
- Airglow fluctuations in a **1-degree** patch are **10^6** times brighter than CIBER's sensitivity in 50 s
- Brightest airglow layer at an altitude of **100 km**… can't even use a balloon

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

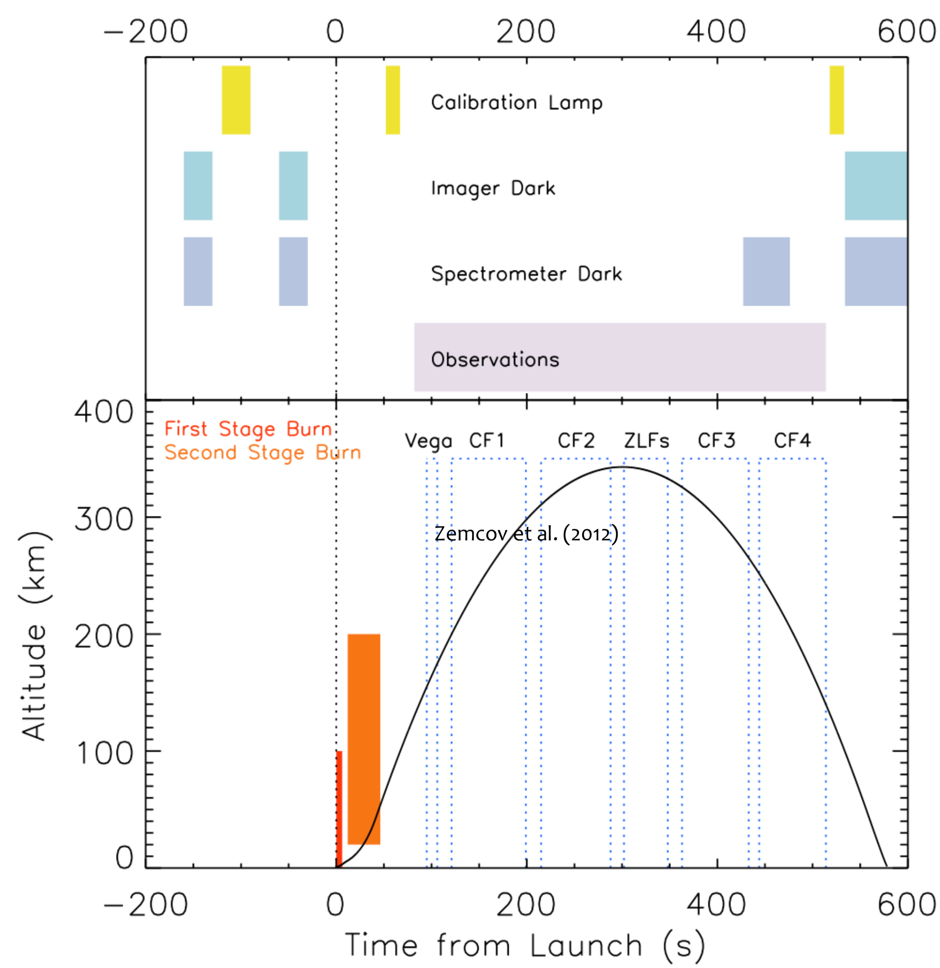
λ/δλ= 20-25

2′ pixels, 5°x0.2° FOV

Zemcov et al. (2013)

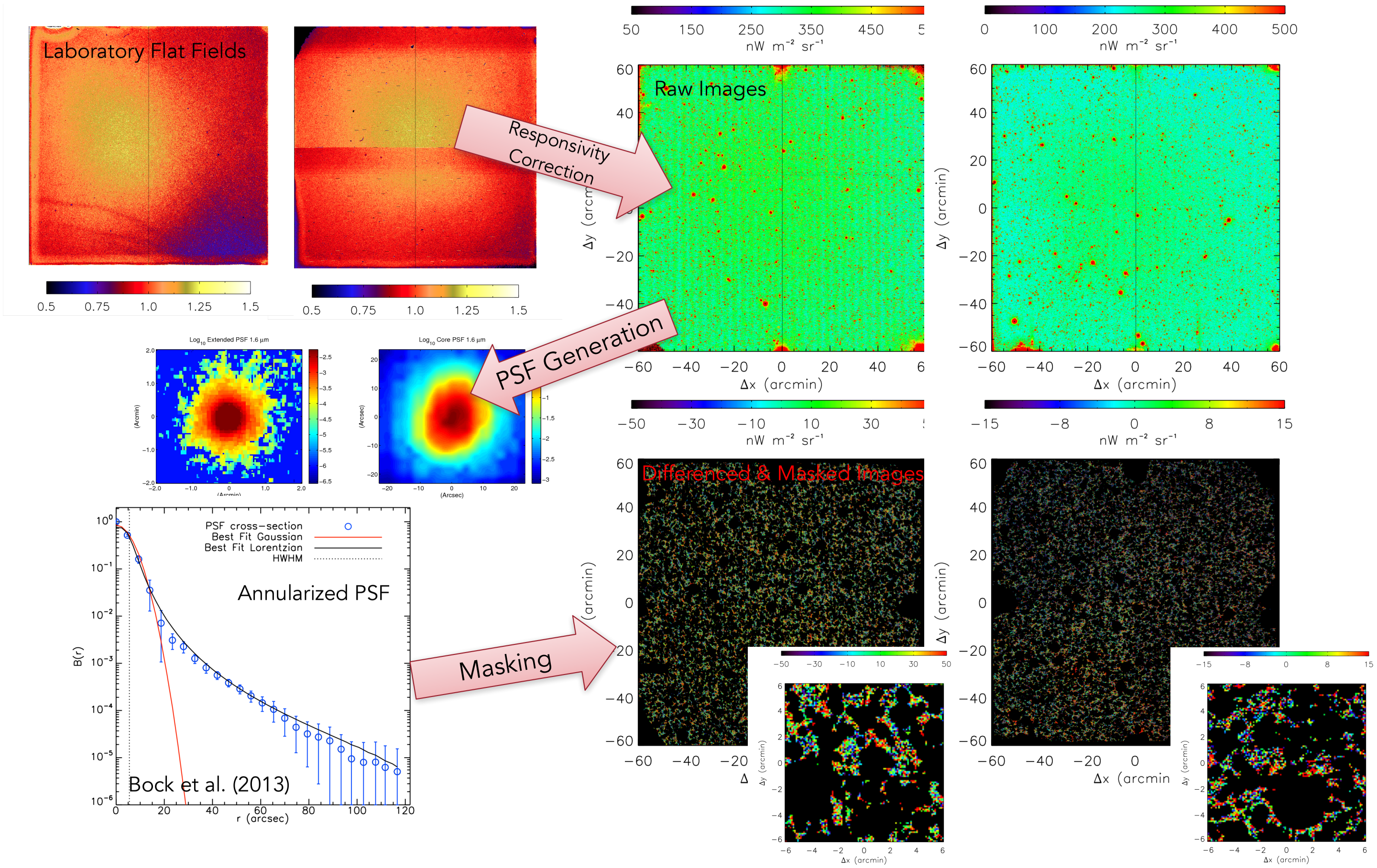
Observations

- Flight is typically 15 mins long with ~425s of data acquisition; one longer flight on a BBXII.
- Have flown CIBER four times; Feb 2009, July 2010, and Mar 2012 on BBIX and a last time in July 2013 ending in the Atlantic.
- Data quality from first flight was marginal, but last three flights very good.



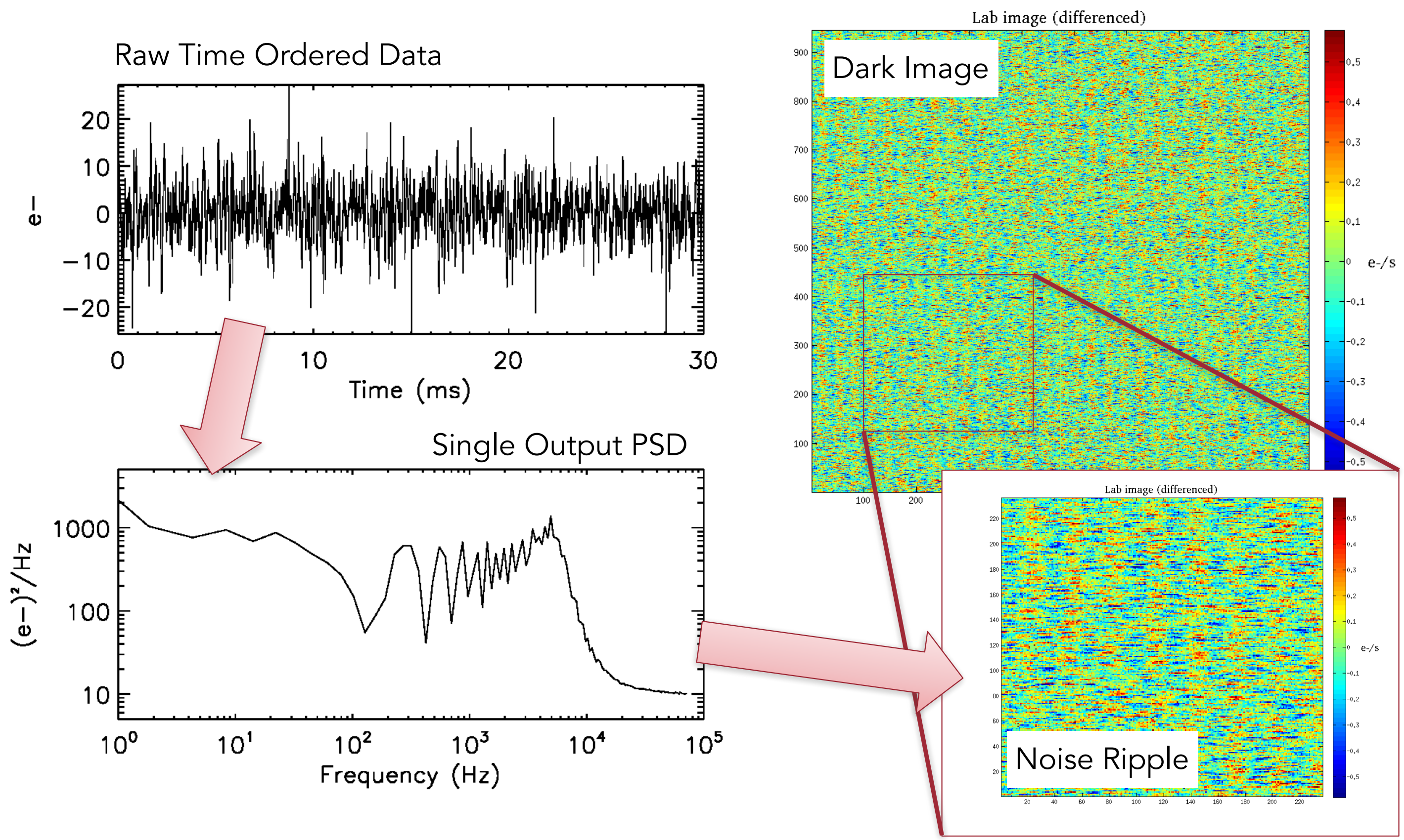
Zemcov et al. 2013, ApJ, CIBER overview

Imager Data Analysis



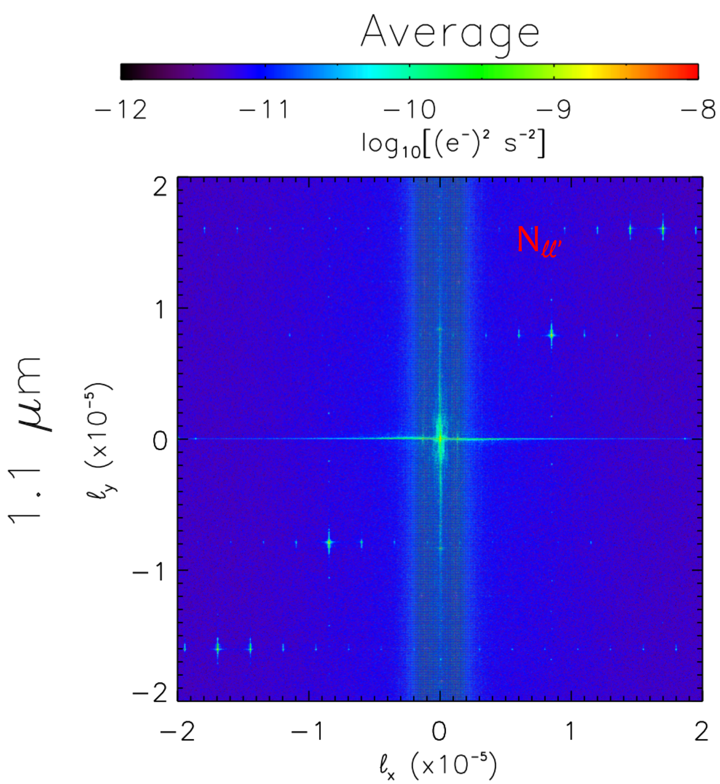
Zemcov et al. 2014, CIBER results, Science

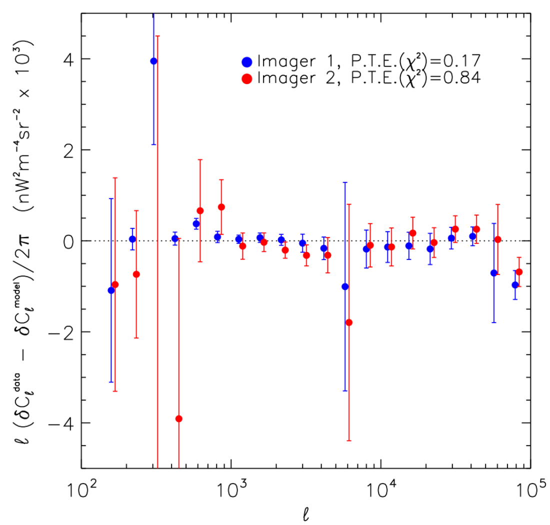
Imager Noise Properties

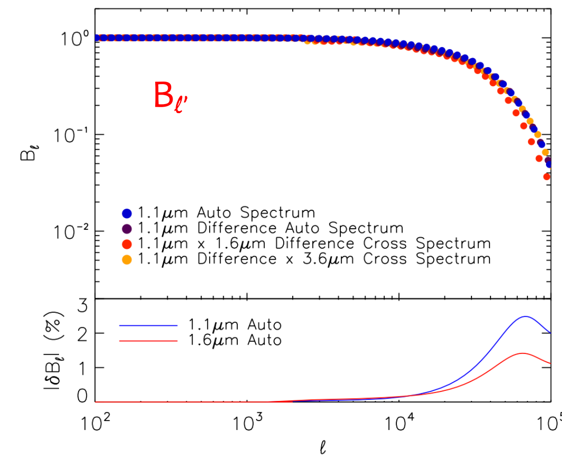


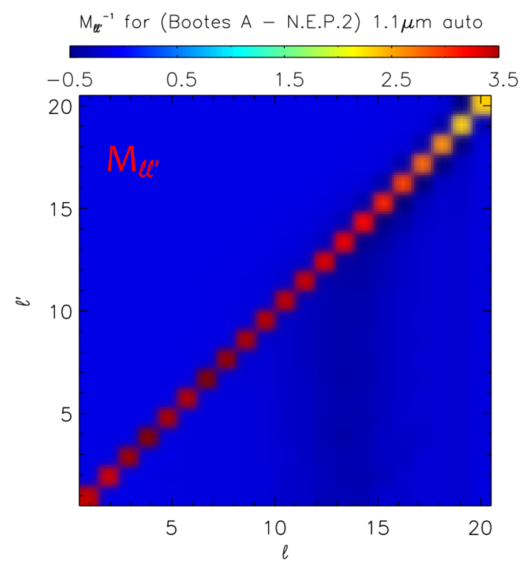
Zemcov et al. 2014, CIBER results, Science

Power Spectra & Noise Model





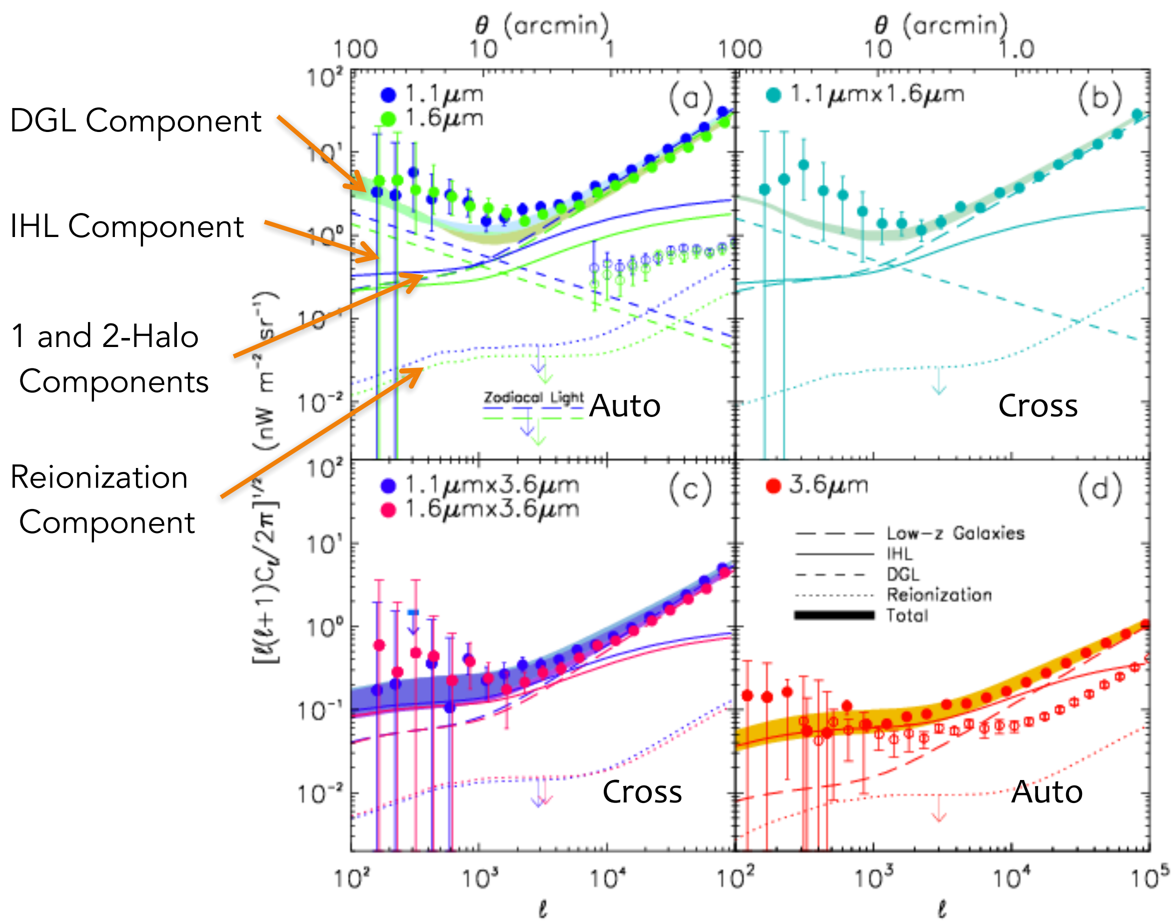




$$\widetilde{C}_\ell = \frac{\sum_{\ell'} M^{-1}_{\ell\ell'}(\langle C_{\ell'}\rangle - N_{\ell'})}{B^2_{\ell'}}$$

Zemcov et al. 2014, CIBER results, Science

Imager Results



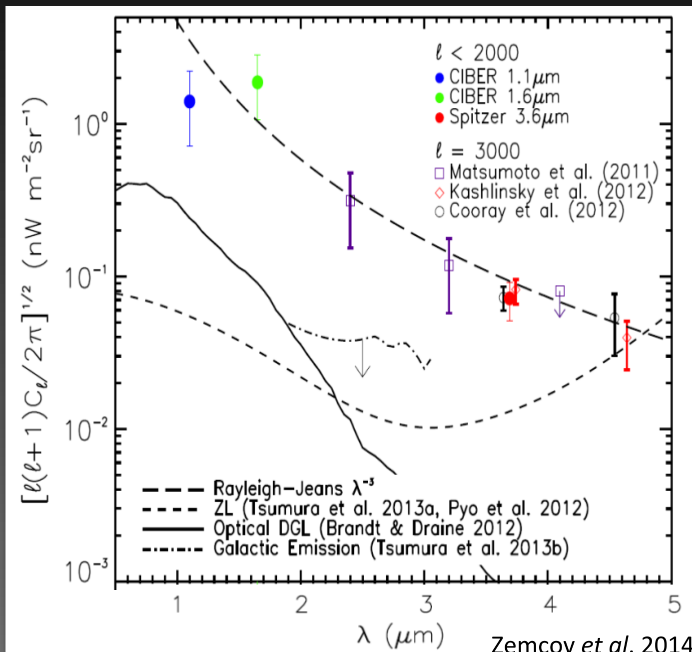
Zemcov et al. 2014, CIBER results, Science

- CIBER power spectra follow galaxies to scales of a few arcmin, and then strongly deviate.
- Behavior is well matched by Spitzer data at longer wavelengths.

Near-Infrared Clustering Fluctuations

IHL (at redshift 0-2) or EOR (at redshift 6-8)?

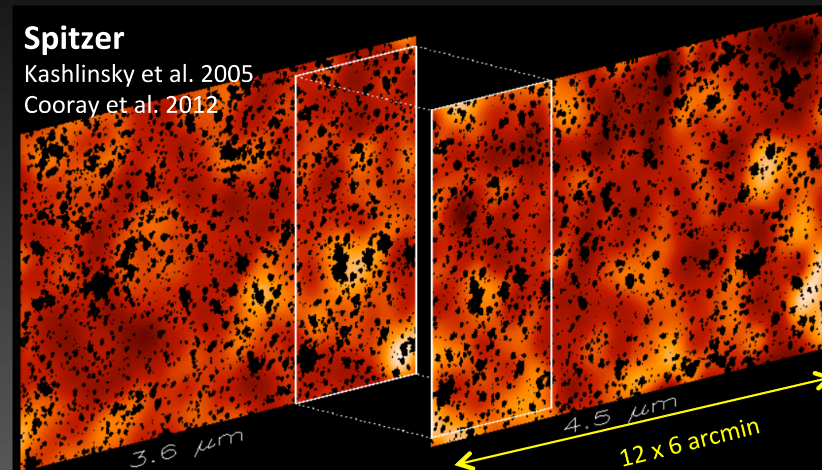
Amplitude of clustering power spectrum

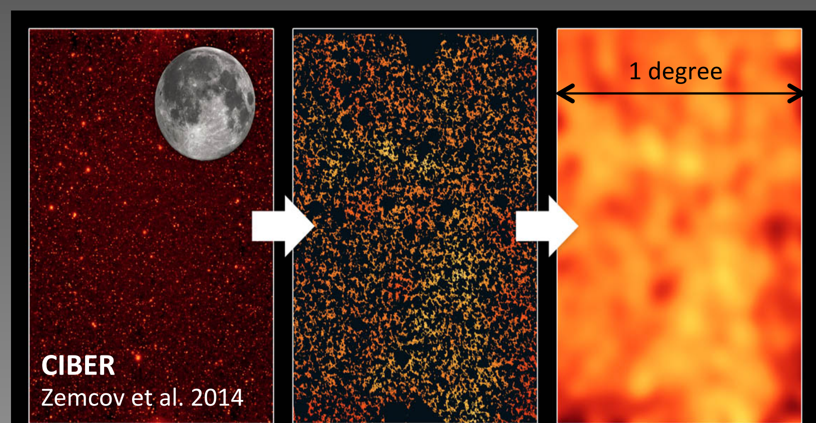


Zemcov *et al.* 2014

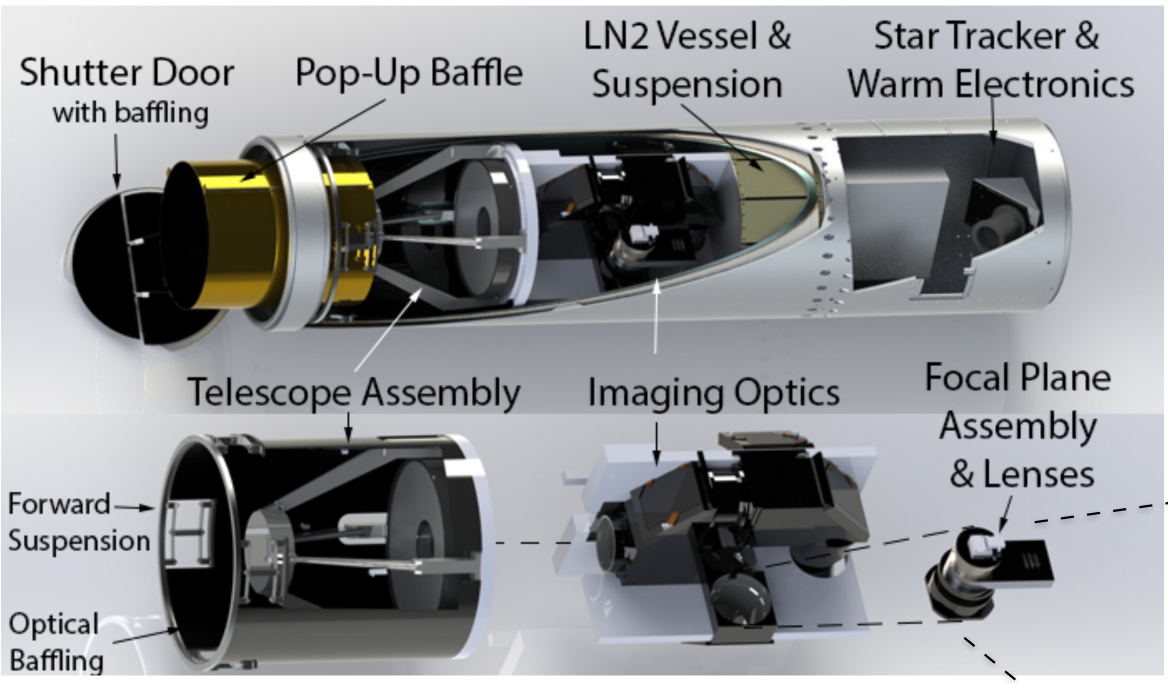
Inferred Extragalactic Background

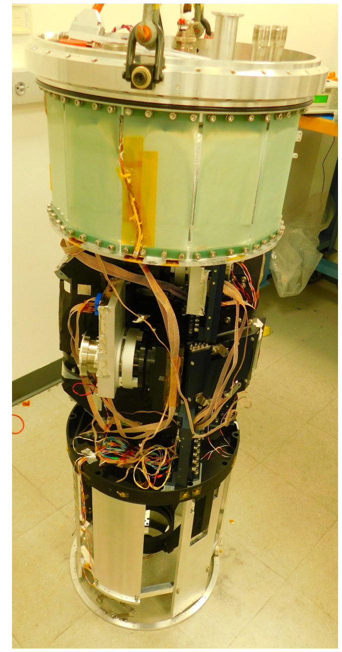
λ (μm)	Measured $\delta\lambda I_\lambda^a$ (nW m^{-2} sr^{-1})	$\frac{\lambda I_{\lambda,\mathrm{IHL}}}{\delta\lambda I_\lambda}$	$\lambda I^b_{\lambda,\mathrm{IHL}}$ (nW m^{-2} sr^{-1})	$\lambda I^c_{\lambda,\mathrm{IGL}}$ (nW m^{-2} sr^{-1})
1.1	$1.4^{+0.8}_{-0.7}$	5	$7.0^{+4.0}_{-3.5}$	$9.7^{+3.0}_{-1.9}$
1.6	$1.9^{+0.9}_{-0.8}$	6	$11.4^{+5.4}_{-4.8}$	$9.0^{+2.6}_{-1.7}$
2.4	$0.32 \pm 0.05^*$	7	2.2 ± 0.4	$7.8^{+2.0\,e}_{-1.2}$
3.6	$0.072^{+0.019}_{-0.021}$	9	$0.65^{+0.17}_{-0.19}$	5.2 ± 1.0
3.6^f	$0.049^{+0.021}_{-0.007}$	9	$0.44^{+0.19}_{-0.06}$	5.2 ± 1.0
4.5	$0.053 \pm 0.023^*$	7	0.37 ± 0.16	3.9 ± 0.8

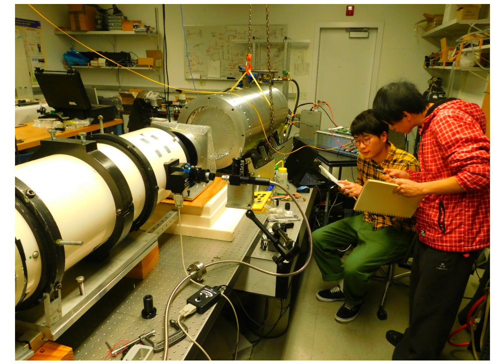


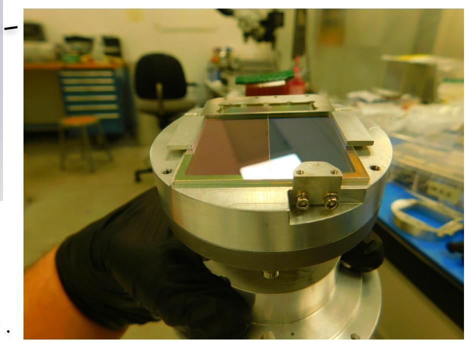


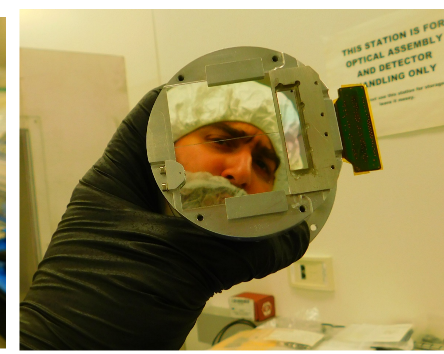
CIBER-2 (4 flights 2019-2022)









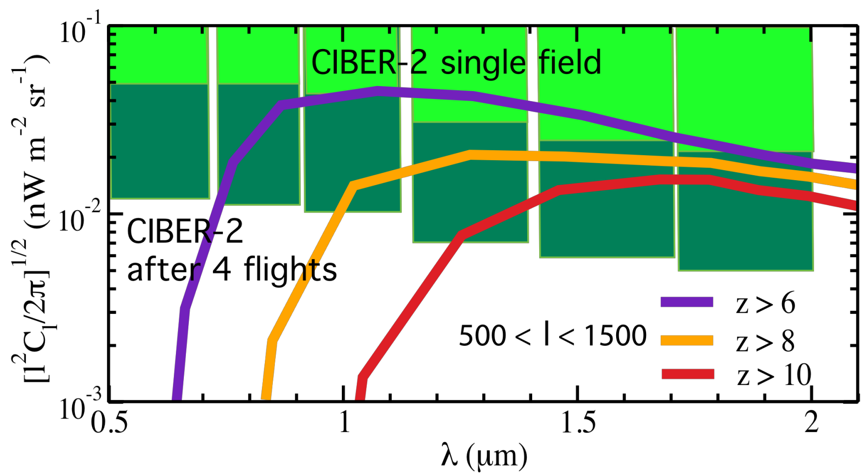


- NASA-APRA funded
- Hardware integrated at Caltech; Currently under testing. Aiming vibrational tests at NASA Wallops from mid March.
- First launch planned June 2019 from WSMR, New Mexico.

Phil Korngut and CIBER Collaboration

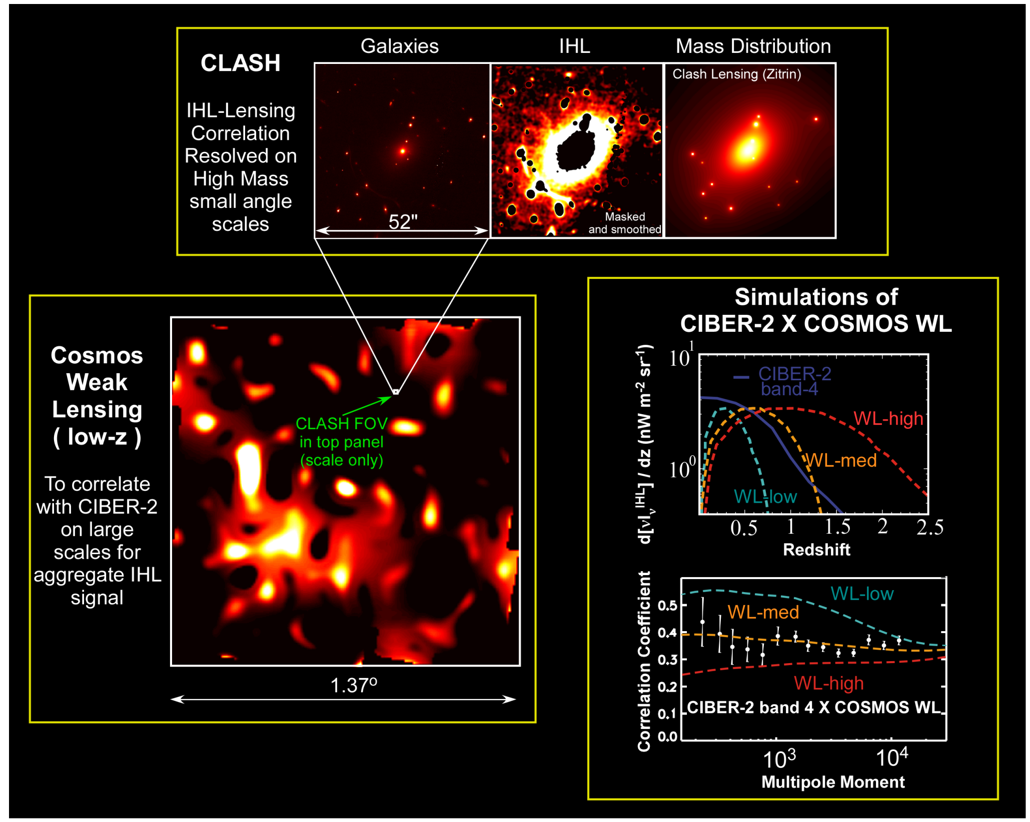
CIBER-2 (4 flights 2019-2022)

Aperture	28.5						cm
Pixel Size	4						arcsec
FOV	1.61x2.2 for imager bands, 0.4 for LVF						degrees
Array	3x 2048² H2RG						
$\lambda (\Delta\lambda/\lambda)$	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



Wavelength coverage in the optical aimed at separating IHL from EOR.

CIBER-2 improves on CIBER-1 with 6 bands and ~5x greater AΩ which maximizes sensitivity to fluctuation measurements.

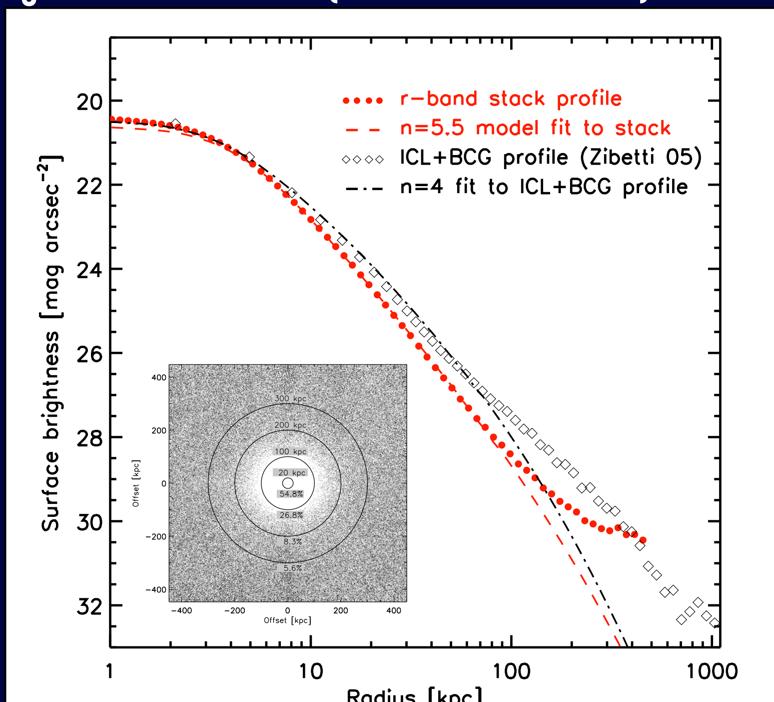


CIBER-2 aims to image 2 deg² COSMOS field; aiming to cross-correlation IR background fluctuations with existing COSMOS weak lensing mass maps to establish IHL x dark matter cross-correlation.

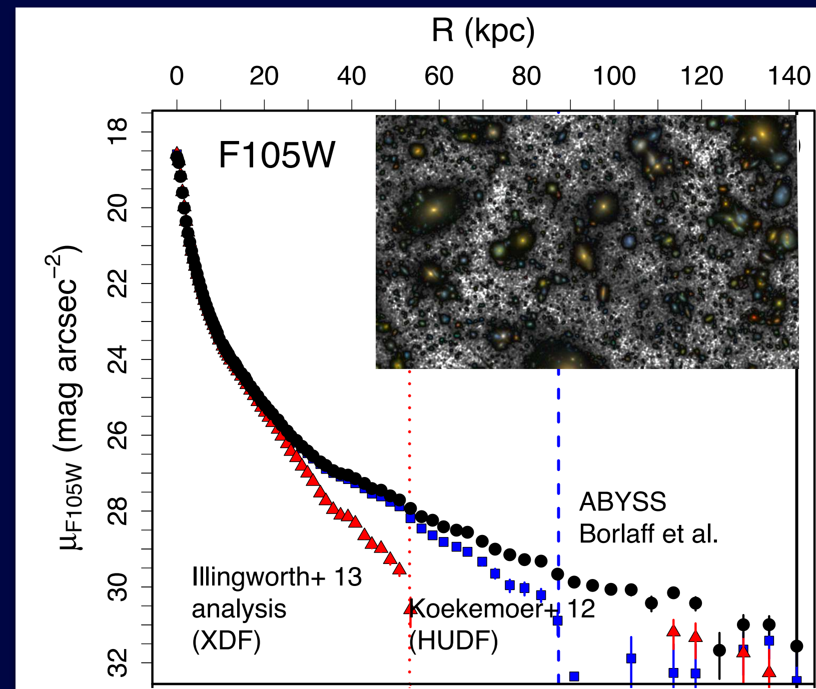
CIBER Collaboration (2014)

Is IHL Real? extended light profiles of galaxies

400k galaxies SDSS stack (Tal & van Dokkum 12)



The missing light of the HUDF (Borlaff et al. 2019)

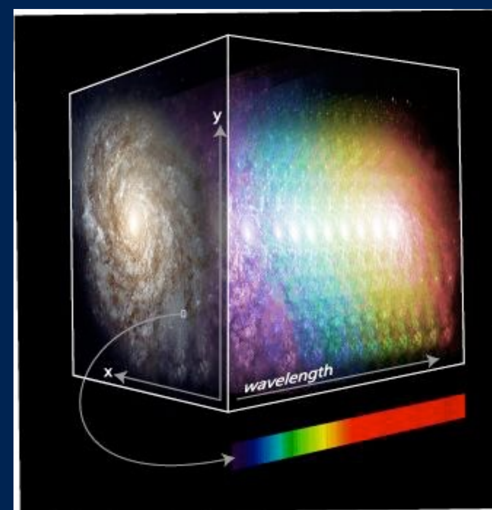


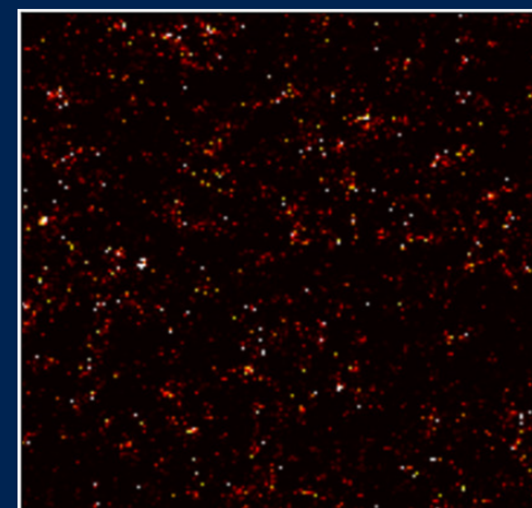
- If IHL should see extended light profiles - more in early-type galaxies (likely merger products) than late types (evidences starting to show up slowly)
- There should be clear color differences, not demonstrated yet.
- When does the galactic disk end? when does IHL start? no clear definitions of IHL/ICL yet.

3-D Intensity Mapping

Sky map at z

Intensity map at z





- No need to resolve individual sources
- Measure the collective emission from many sources
- Map large volume throughout cosmic history economically
- Astrophysical and cosmological applications from cosmological parameters, structure formation to galaxy formation.

Which lines are suitable for intensity mapping?

1. For cosmological parameters, just about any line. Currently pursued are lines in the far-infrared to mm-wavelengths.

   CO tracing molecular gas in galaxies (Carilli 2011; Gong et al. 2011; Lidz et al. 2012;)

   [CII] 158 μm - a good tracer of SF in galaxies (Gong et al. 2012; Silva et al. 2015; Yue et al. 2015)

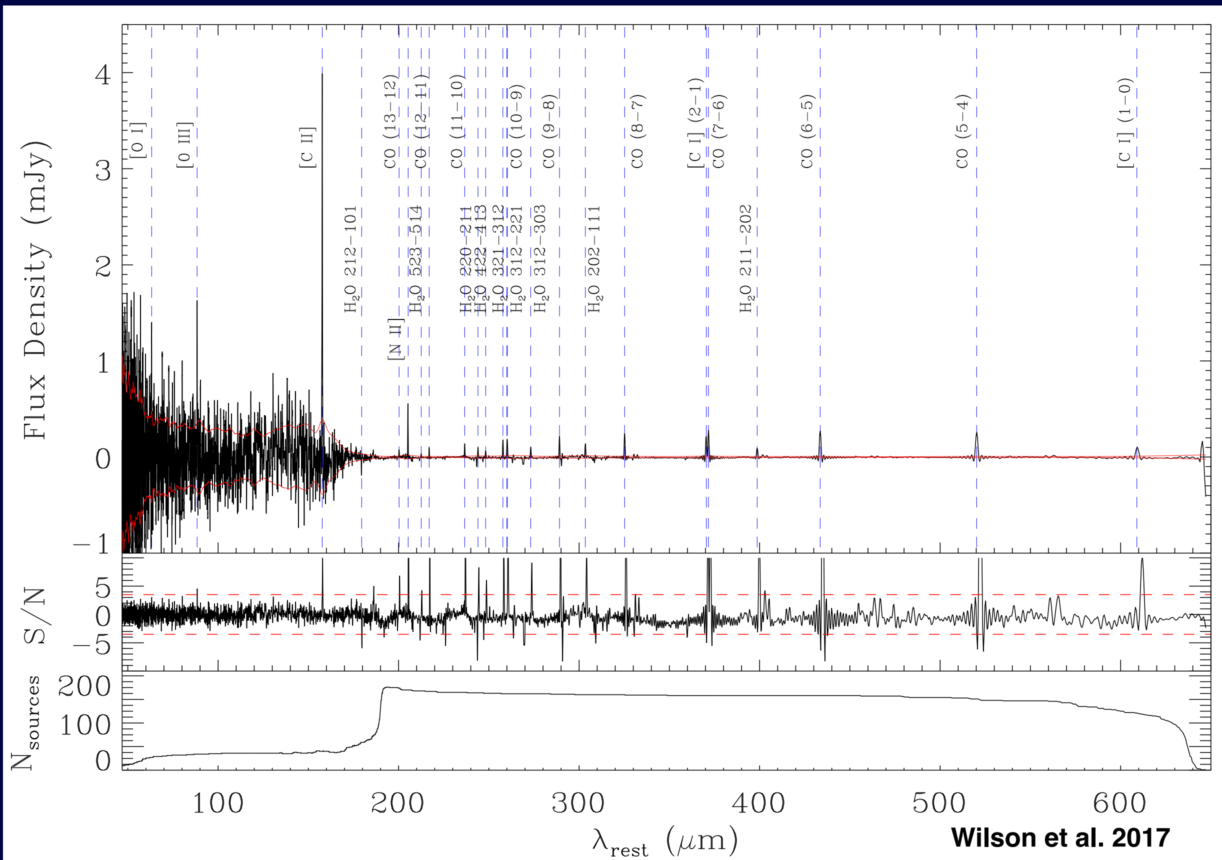
   [OI], [OIII], [NII] etc….

   - With all these lines we are detecting point sources, unresolved. Complementarity to ALMA or a large 30m+ submm-wave dish. *IM here is really a poor person's solution to an expensive project (scale, cost and technology).*

2. To understand reionization, intergalactic medium with spectral lines that are diffuse and extended, we really must do intensity mapping.

   e.g., Lyman-α both during and post reionization.
   And 21-cm during cosmic dawn/reionization.

Which lines are suitable for intensity mapping?



Wilson et al. 2017

Average stacked spectrum of a 4×10^{11} galaxy with 246 galaxies at z > 0.005 with the full Herschel SPIRE/FTS archive

Lots of line options to do IM to understand structure formation, BAOs,

But also lots of possibilities to be line confused!

Cross-correlations are critical.

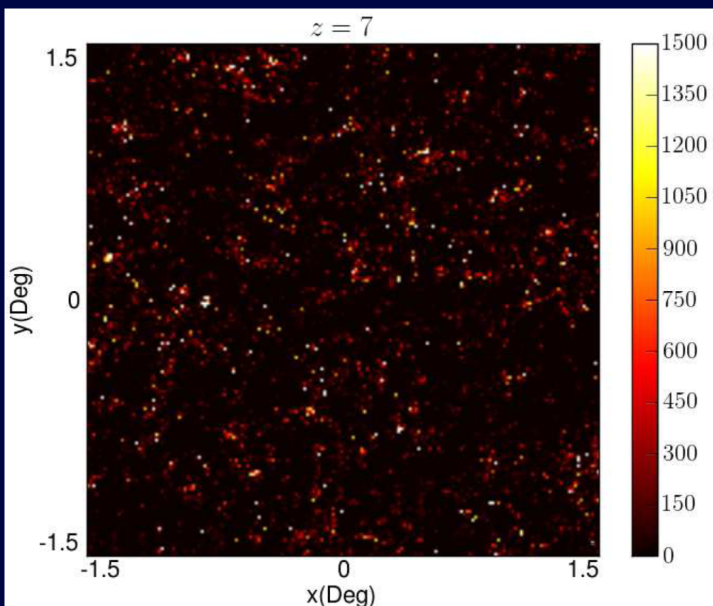
Cross-correlations must be an integral part of any analysis claiming reliable detections of one particular line.

(careful frequency/band selections; giving up some redshift ranges and focussing on overlapping redshift windows)

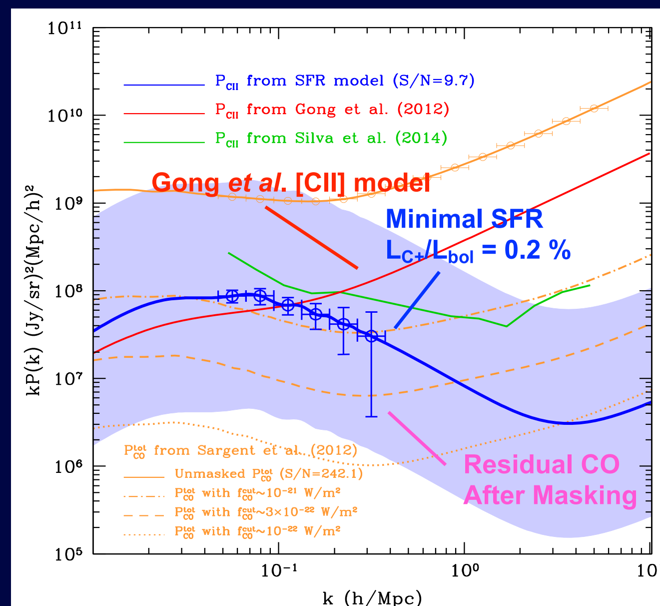
CII intensity mapping

TIME-Pilot and TIME and other CII experiments

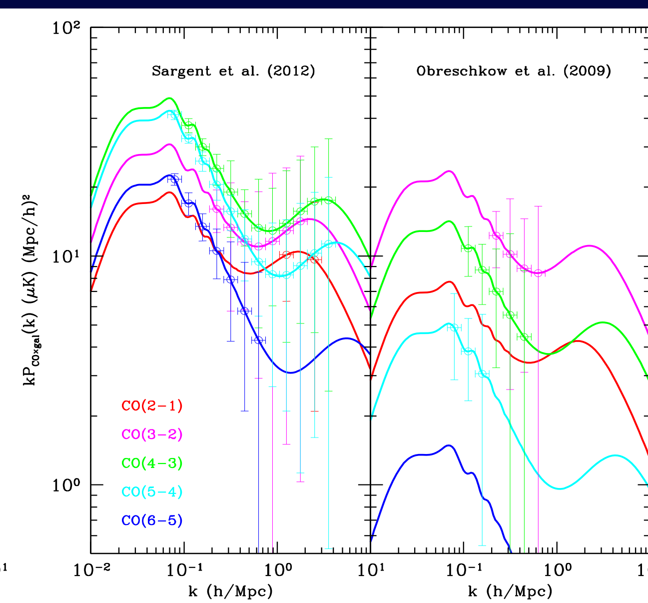
Simulated Sky in [CII]



Epoch of Reionization Science
- Detect [CII] clustering
- Detect [CII] Poisson fluctuations
- Discriminate between models



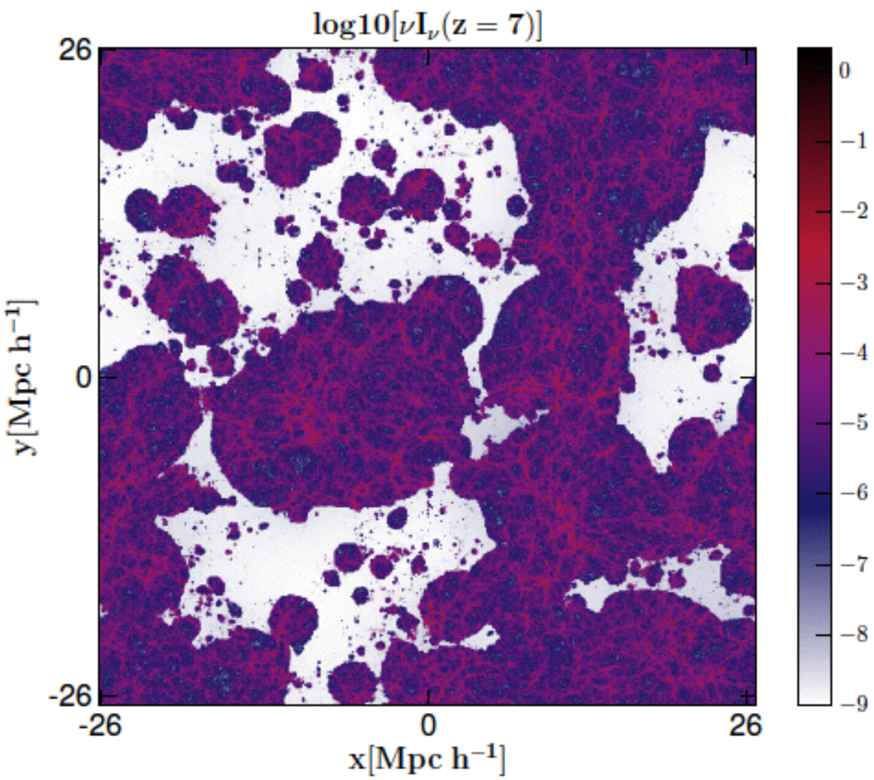
Ancillary Science
- CO clustering fluctuations
- Assess residual CO foreground
- Powerful kSZ instrument



- [CII] serves as a tracer of star formation
- The clustering signal traces total luminosity -> unlike a flux-limited galaxy survey
- Use [CII] to trace SF during the reionization epoch; cross-correlation with 21-cm

Gong et al. 2012, ApJ

Lyman-alpha intensity mapping is tracing more than just sources!



Total Ly-α intensity from galaxies and the IGM in erg s^{-1} cm^{-2} sr^{-1} at redshift 7

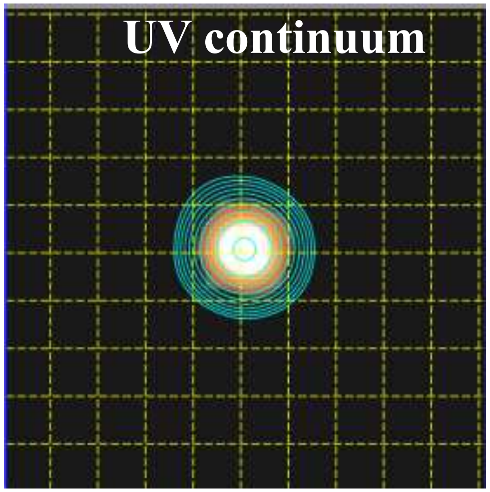
- Galaxy contributions:
  - Recombinations
  - Excitations/decays
  - gas cooling (gravitational collapse)
  - Ly-α emission from stars
- IGM contributions:
  - Recombinations
  - Excitations/decays
  - Scattering of Ly-n photons from galaxies

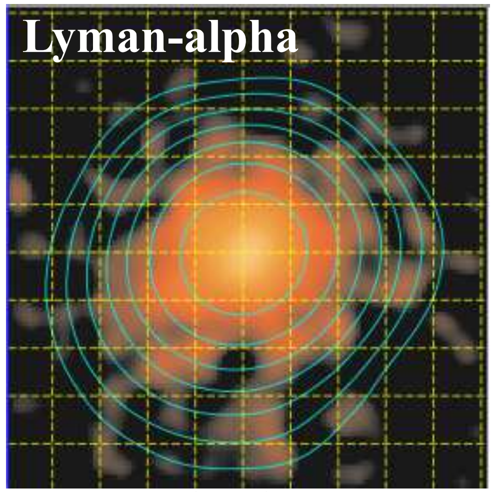
α SFR

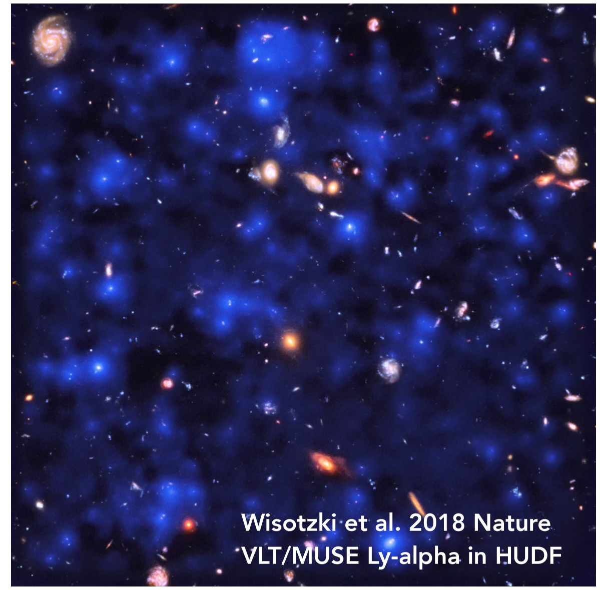
T_K, x_i

Gong et al. 2013; Pullen et al. 2013; Silva et al. 2014

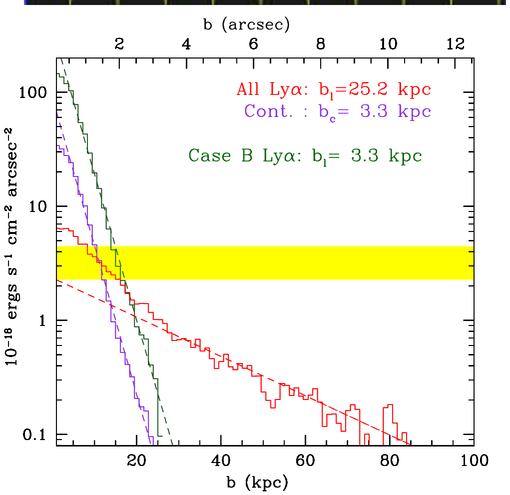
z=3 Lyman-alpha is extended!

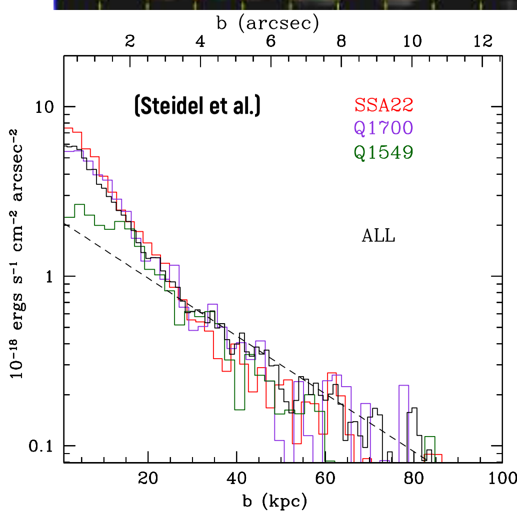


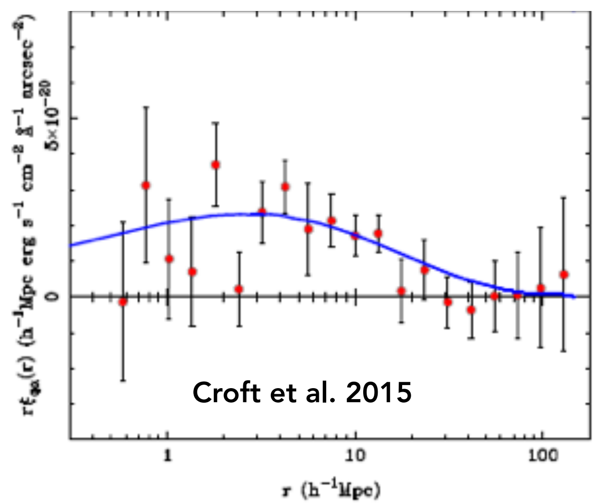




z=1-4 Lyman-alpha covers the whole sky

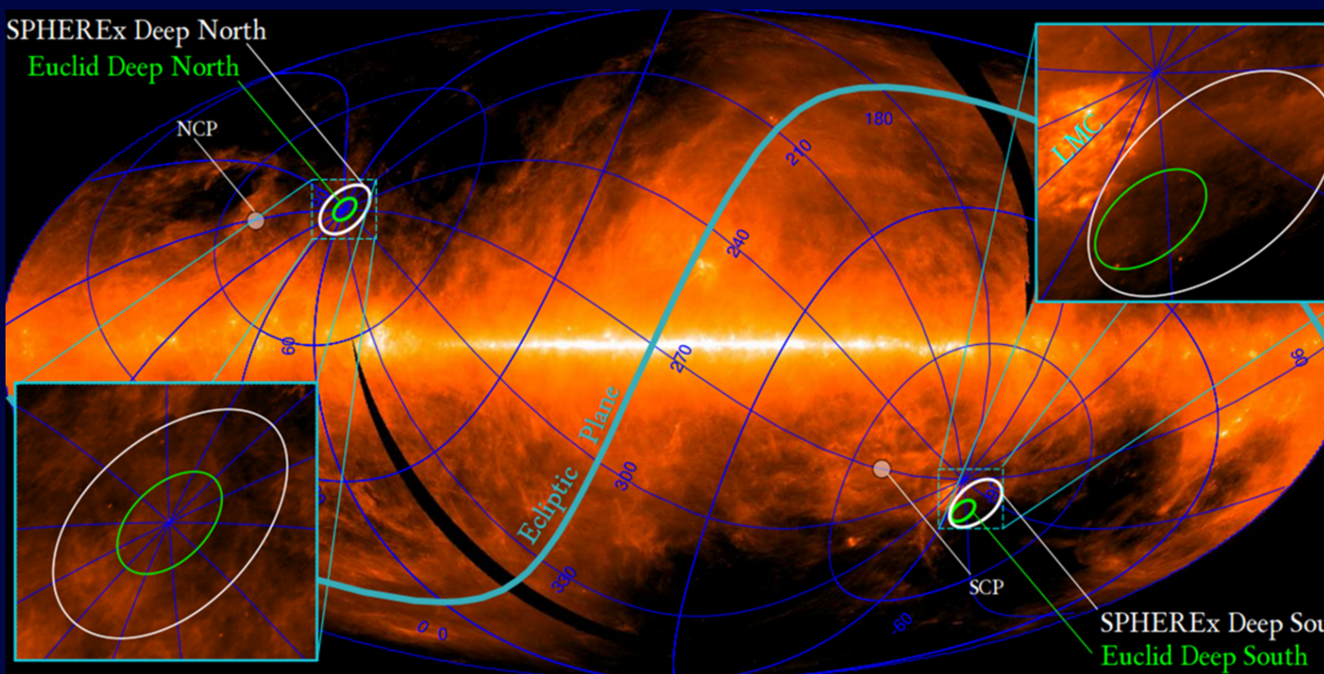


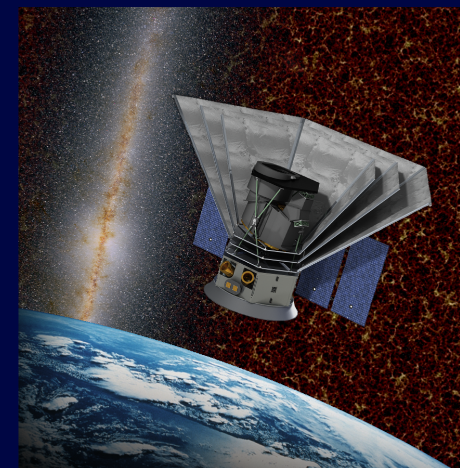


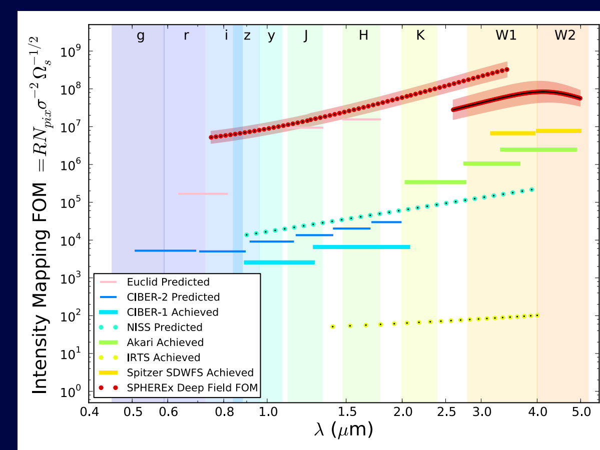


z=2 Lyman-alpha intensity mapping with SDSS

Fluctuation Measurements with SPHEREx





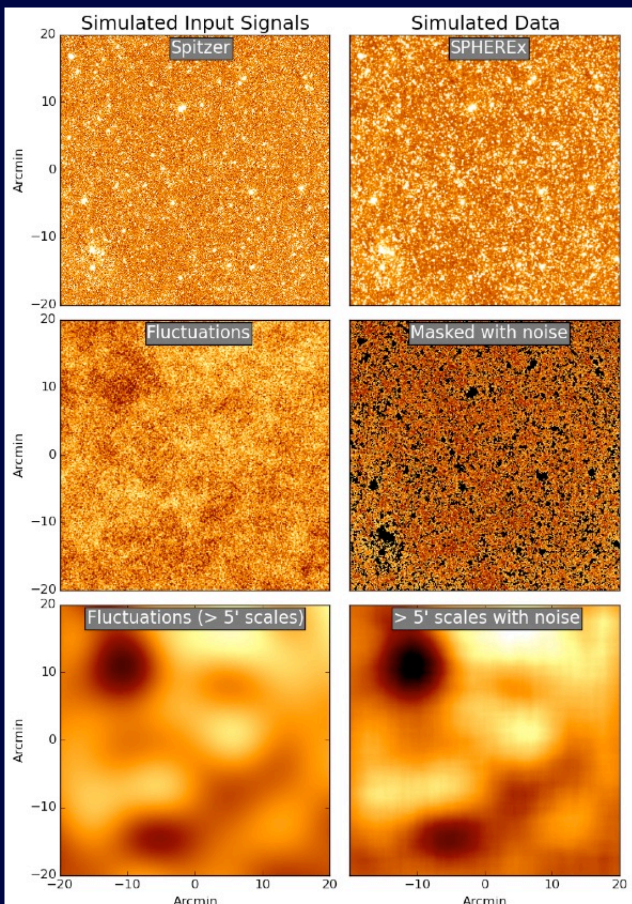


2 x 100 sq. degree regions at the poles which are ~30x deeper than the all-sky survey.

An opportunity for unique science

SPHEREx Intensity Mapping Figure of Merit

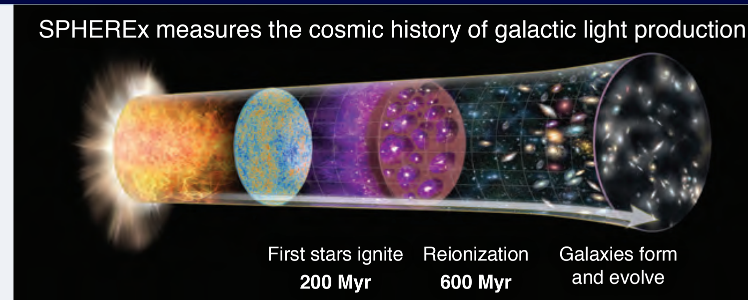
SPHEREx EBL
Continuum Fluctuations

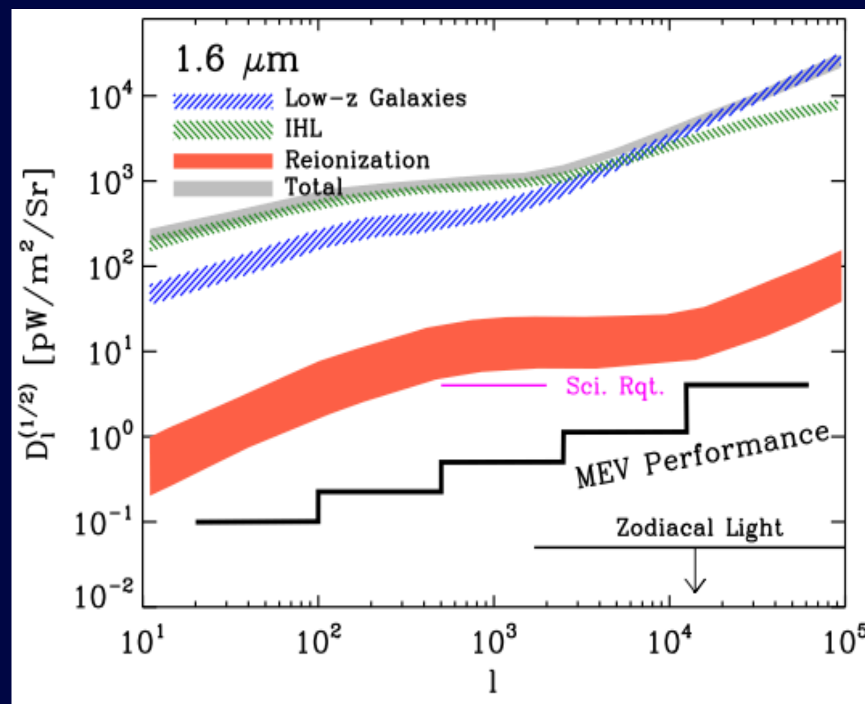


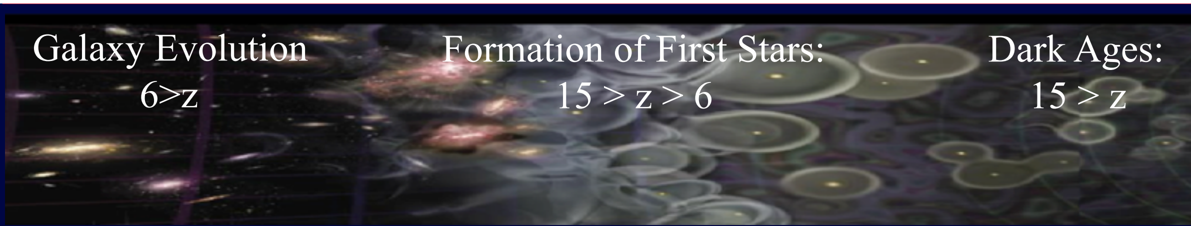
NASA GOAL

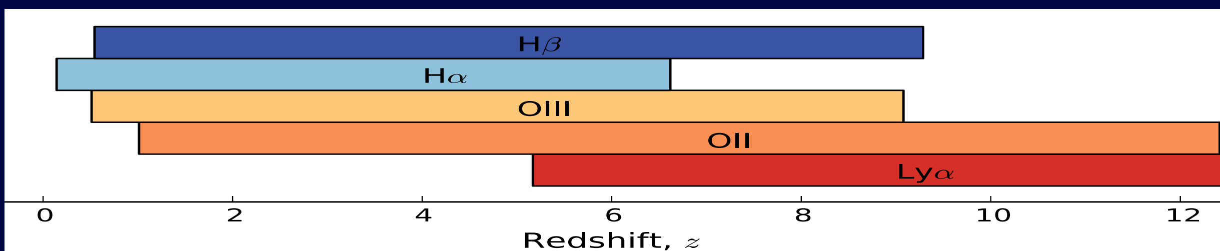
Explore the origin and evolution of galaxies

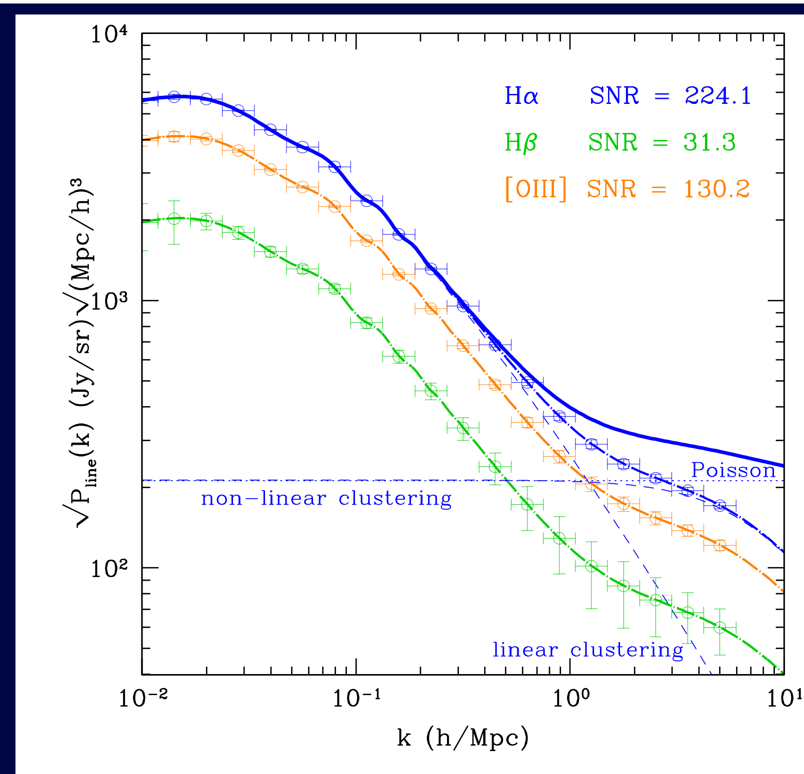
SPHEREx traces the total light emitted over cosmic time from the first stars to modern galaxies.









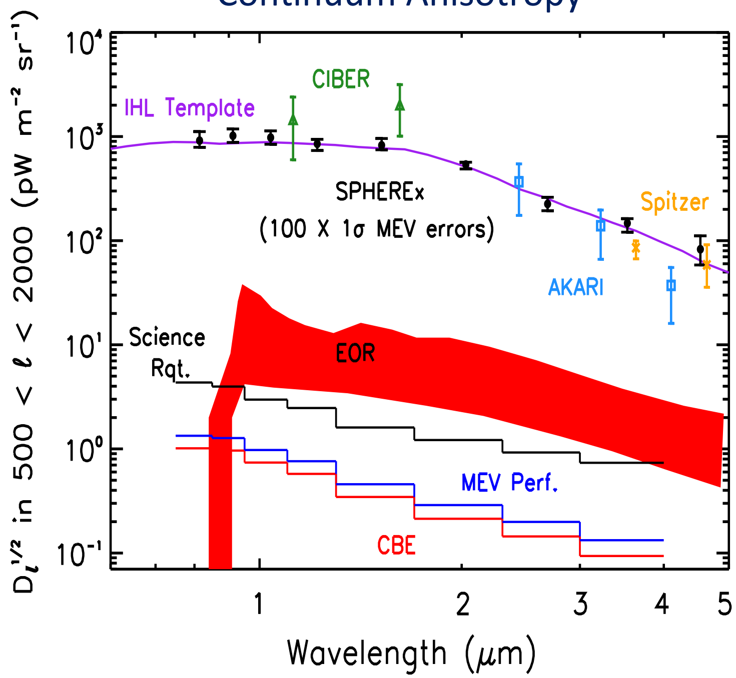


SPHEREx Spectral Line Intensity Mapping

- Our key galaxy formation science program concentrates on continuum fluctuations
- But with R~40 spectro-imaging, SPHEREx contains some spectral line information throughout the cosmic history.
- Opportunity with Hα and Hβ between 0.5 < z < 6 - combine the two to IM of dust as a function of z slices.
- Challenging to do Lyα IM at z > 6 with SPHEREx due to low S/N, but could be surprises.

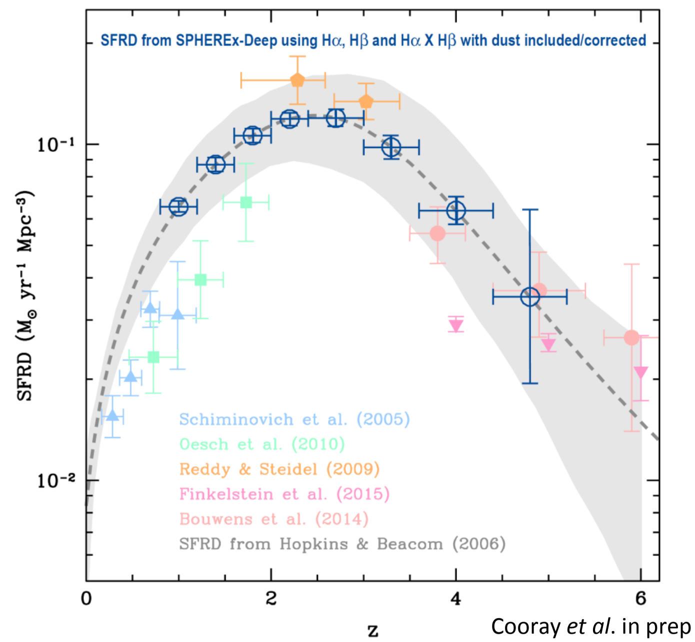
SPHEREx Measures Large-Scale Fluctuations

Continuum Anisotropy



- SPHEREx has ideal wavelength coverage and high sensitivity
- Multiple bands enable correlation tests sensitive to redshift history
- Method demonstrated on Spitzer & CIBER

Line Tomography



Cooray *et al.* in prep

- Amplitude gives line light production
- Multiple lines trace star formation history
  - High S/N in Hα for z < 5; OIII and Hβ for z < 3
  - Lyα probes EoR models for z > 6
  - Hα and Lyα crossover region 5 < z < 6
- Example above uses Hα + Hβ to solve for SFRD and dust attenuation simultaneously

CDIM

Cosmic Dawn Intensity Mapper

A Probe Class Spectro-Imaging Astrophysics Mission for Reionization

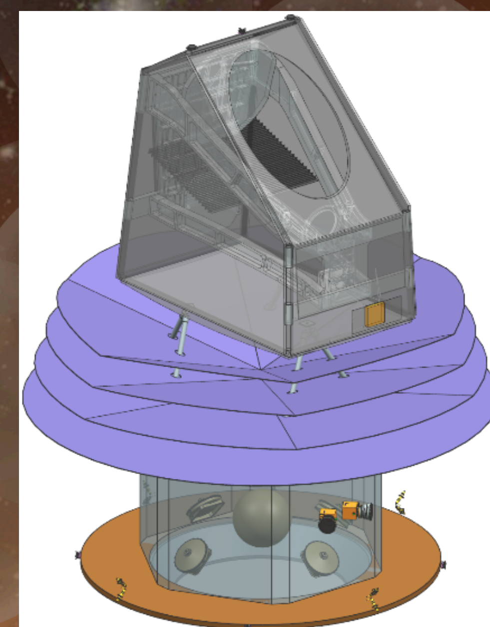
Asantha Cooray, UC Irvine (PI)
Tzu-Ching Chang, JPL (Study Scientist)
Stephen Unwin, JPL (Study Manager)

Science Team

Renyue Cen, Princeton
Ranga Ram Chary, IPAC
Olivier Doré, JPL
Xiaohui Fan, Arizona
Giovanni Fazio, CfA
Chang Feng, U Illinois
Steven Finkelstein, U T Austin
Hai Fu, U Iowa
Caroline Heneka, SNS
Hooshang Nayyeri, UC Irvine
Jason Rhodes, JPL
Mario Santos, U Western Cape
Raphael Sadoun, Osaka U
Marta Silva, U Oslo
Hy Trac, CMU
Heidi Wu, OSU
Michael Zemcov, RIT
Zheng Zheng, U Utah

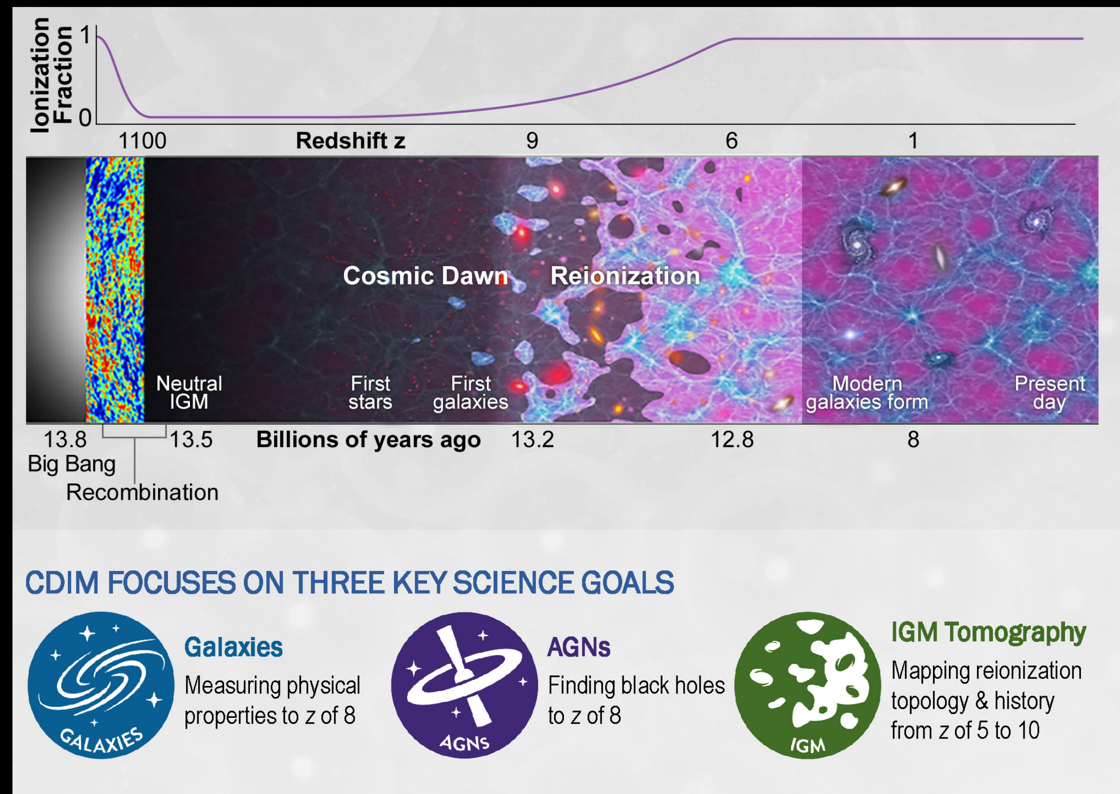
Design Team

Patrick Morrissey, JPL (Instrument)
Andrew Coffey, JPL (System engineering)
Nasrat Raouf, JPL (LVF filters)
Talso Chui, JPL (Thermal)
James McGuire, JPL (Optics)
Sarah Lipscy, Ball (Spacecraft Bus)



CDIM Summary

- 0.75 µm – 7.5 µm spectro-imaging in 840 narrow bands at R=300
- 0.83 m effective aperture (1.1 m physical)
- 7.8 sq. degree focal plane (1" pixels)
- Diffraction limited at 7.5 µm, 2" PSF
- Three-tired survey in 4 years
- Costed at JPL under 1$B (incl. 30% margin)



Cosmic Dawn and Reionization Sciences

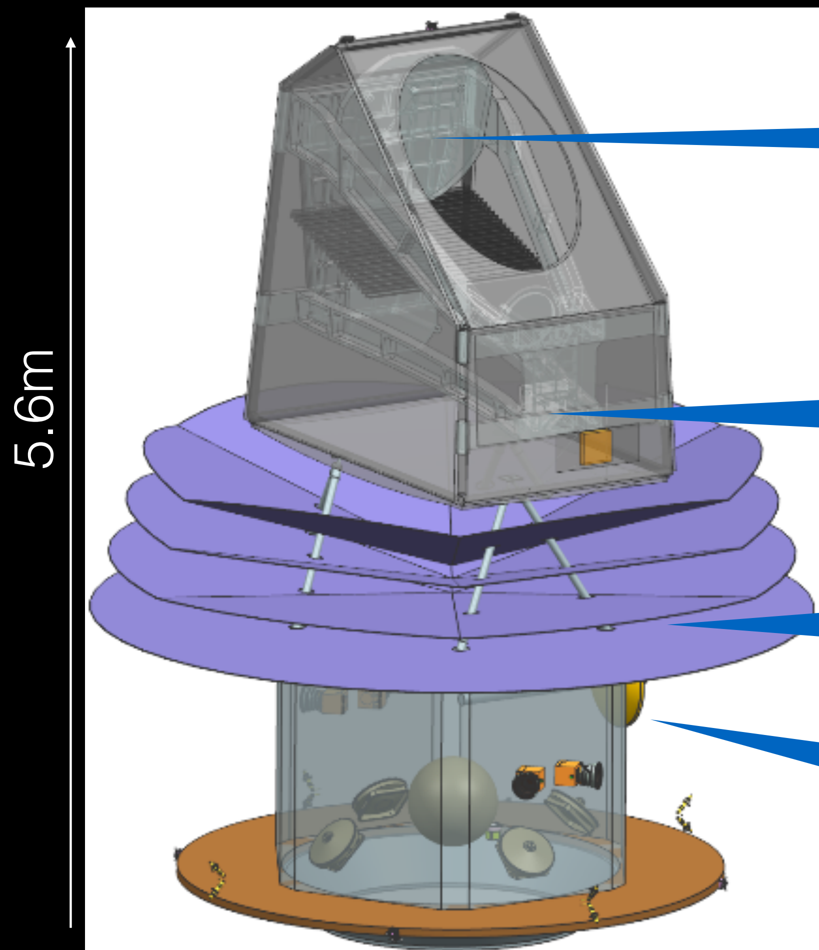
- First Galaxies: tracing Hα to z=10
- First Blackholes: finding AGNs at z=8
- Reionization Tomography: Lyα, Hα intensity mapping, and cross-correlation with 21cm EoR maps

Wavelength 0.75-7.5 microns at R=300 to separate [NII] from Hα & sensitivity to Hα at z > 5

Large field of view & Surface brightness sensitivity

Large survey area & point source sensitivity

CDIM Design

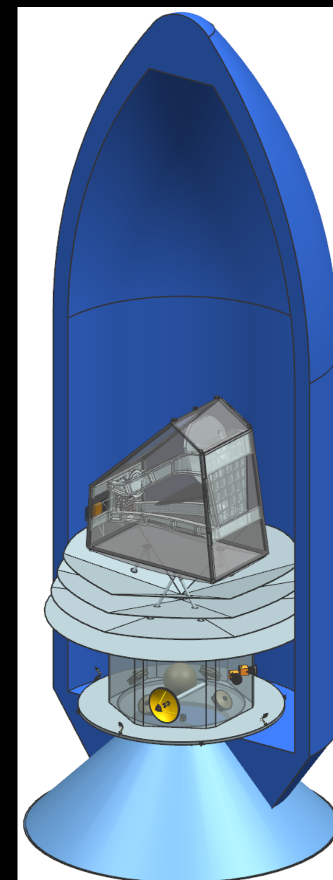


Three-mirror all-reflective design with 0.8m clear aperture

Linear Variable Filters (LVF) at R=300, 4x6 H2RG detectors

V-groove radiators, passive cooling at T<35K in L2 halo orbit

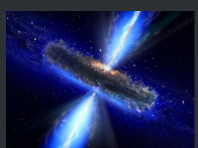
Ka-band HGA. Data rate ~400 Gbit/day, 1hr/day downlink



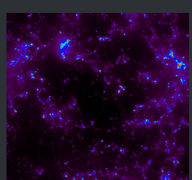
Design team & Team-X

CDIM Three-tiered Survey

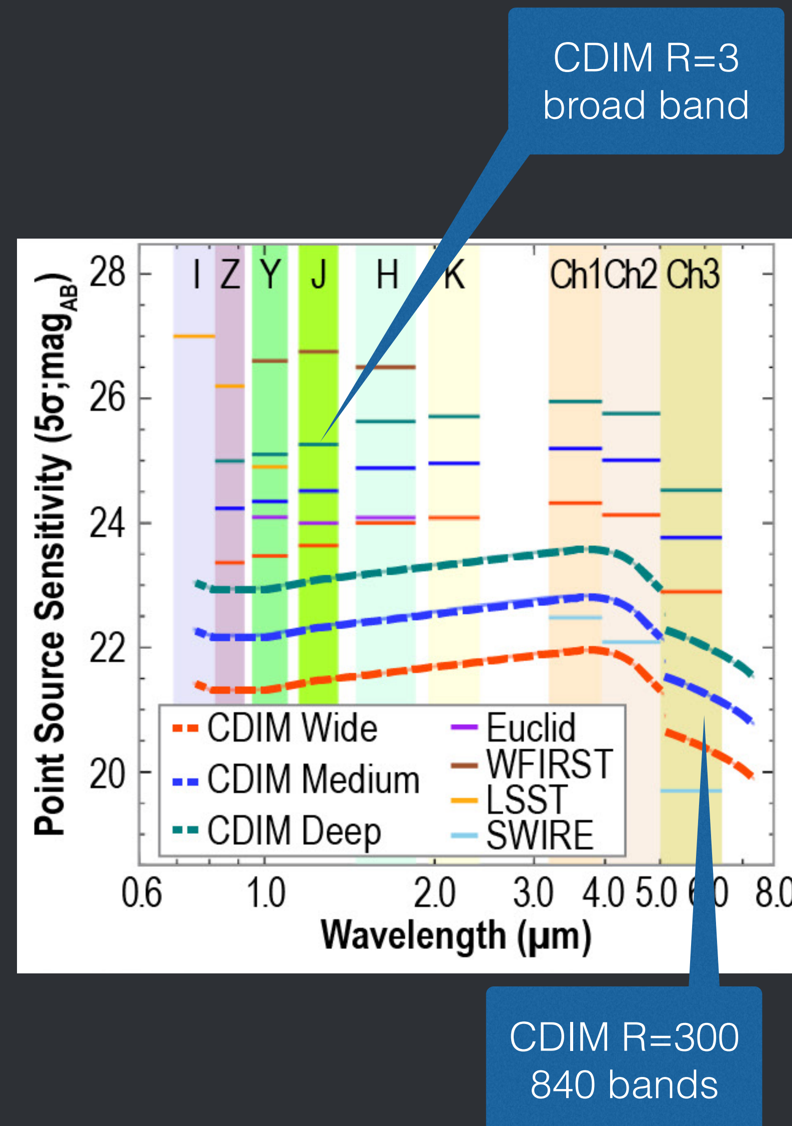
- Detecting faint, high-redshift galaxies
  - Deep survey; 15 deg^2 to overlap with WFIRST/Euclid deep fields



- Detecting bright, rare AGNs
  - Wide survey; 300 deg^2 to catch z=8 AGNs.
  - At either SEP or NEP, visible all-year round from L2, surrounding the Deep survey field



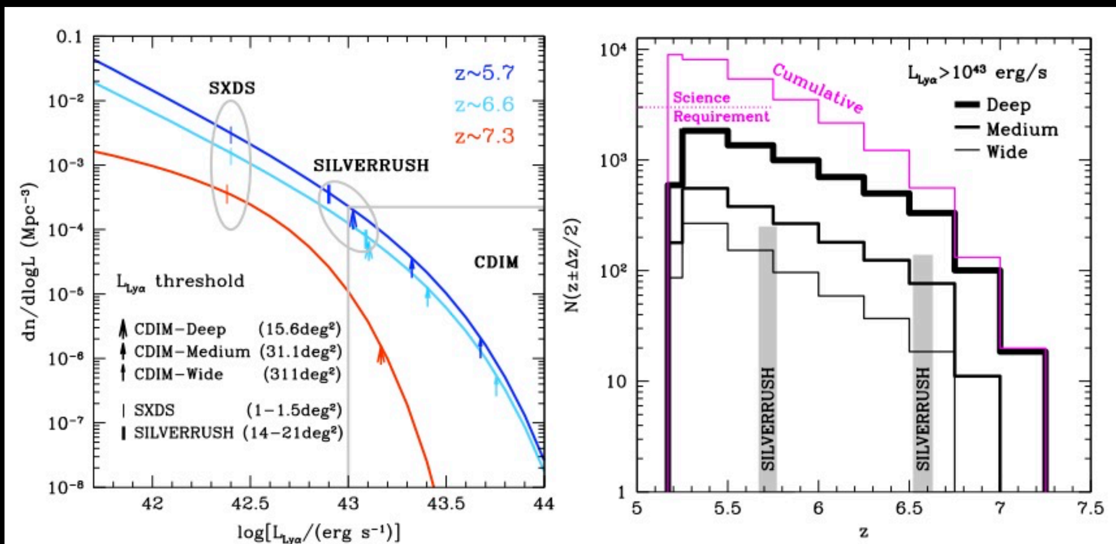
- Reionization tomography in synergy with 21cm intensity maps
  - Medium survey; 30 deg^2 to match a SKA 21cm EoR deep field likely overlapping with the ECDF-S and HERA
- Four years of survey



Lyα Emitting Galaxies

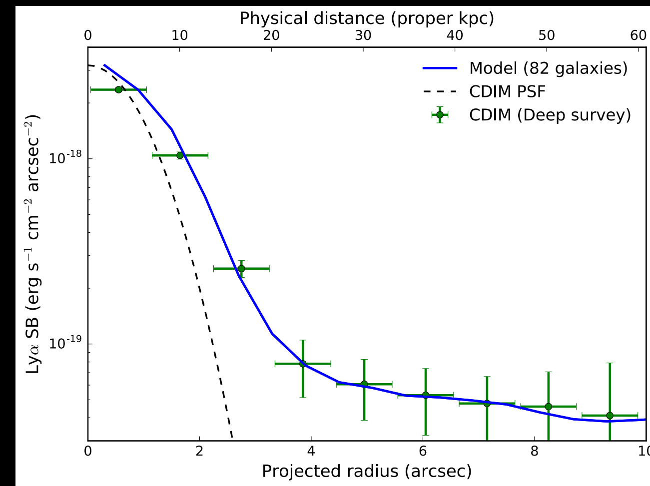
LAE luminosity function

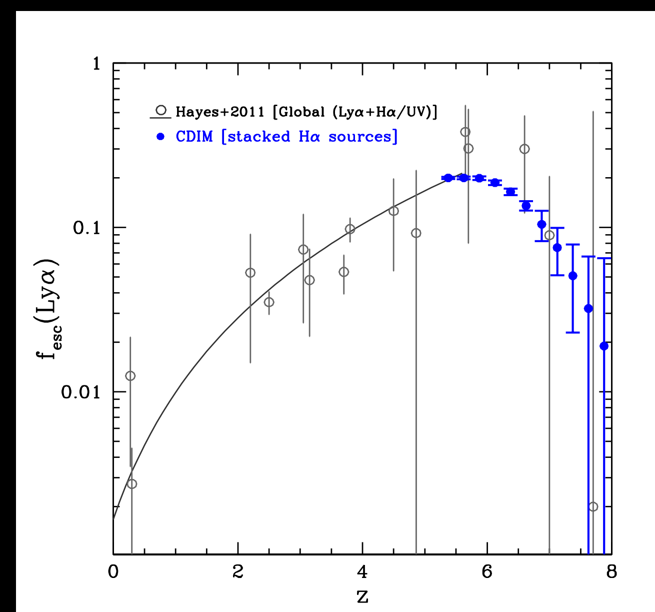
LAE number counts



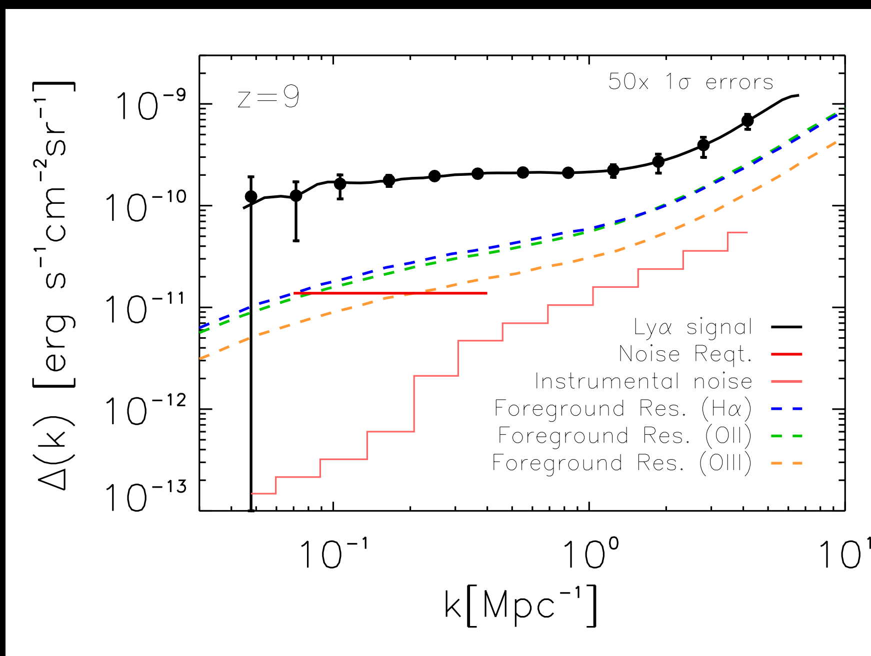
Zheng Zheng

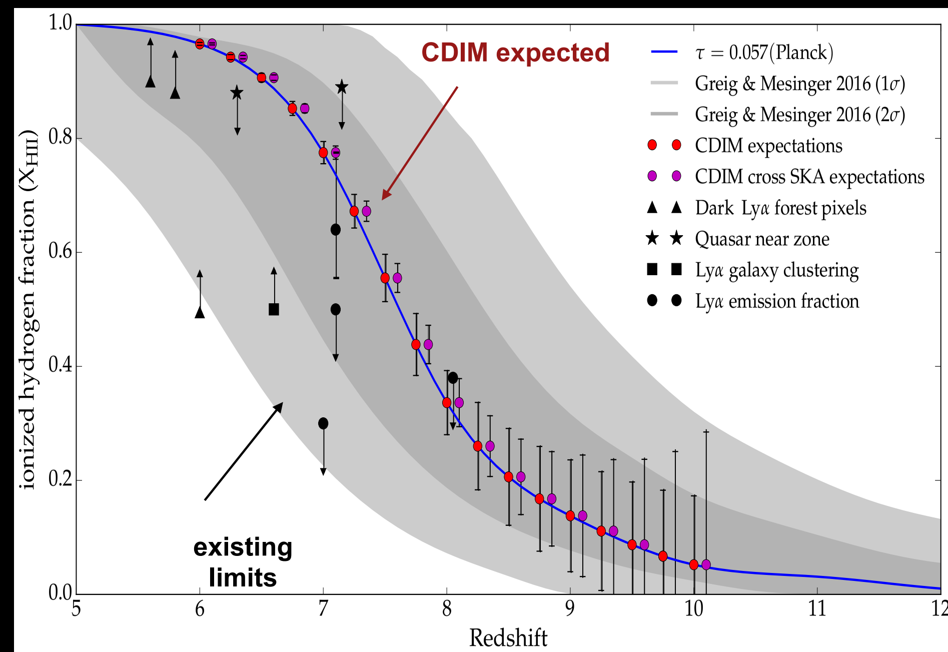
- Detect a few thousand LAEs with $L_{Ly\alpha} > 10^{43}$ erg/s
- Determine the bright end of Lyα luminosity function at 5.2 < z < 7
- Hα counter part detectable out to z~9, can stack on Hα for fainter LAEs.
- CDIM spectral resolution ~ 6 Mpc/h at z=6 v.s. Silverrush narrowband at ~30 Mpc/h
- Constrain the evolution of ionization state of IGM





CDIM Measures Reionization History



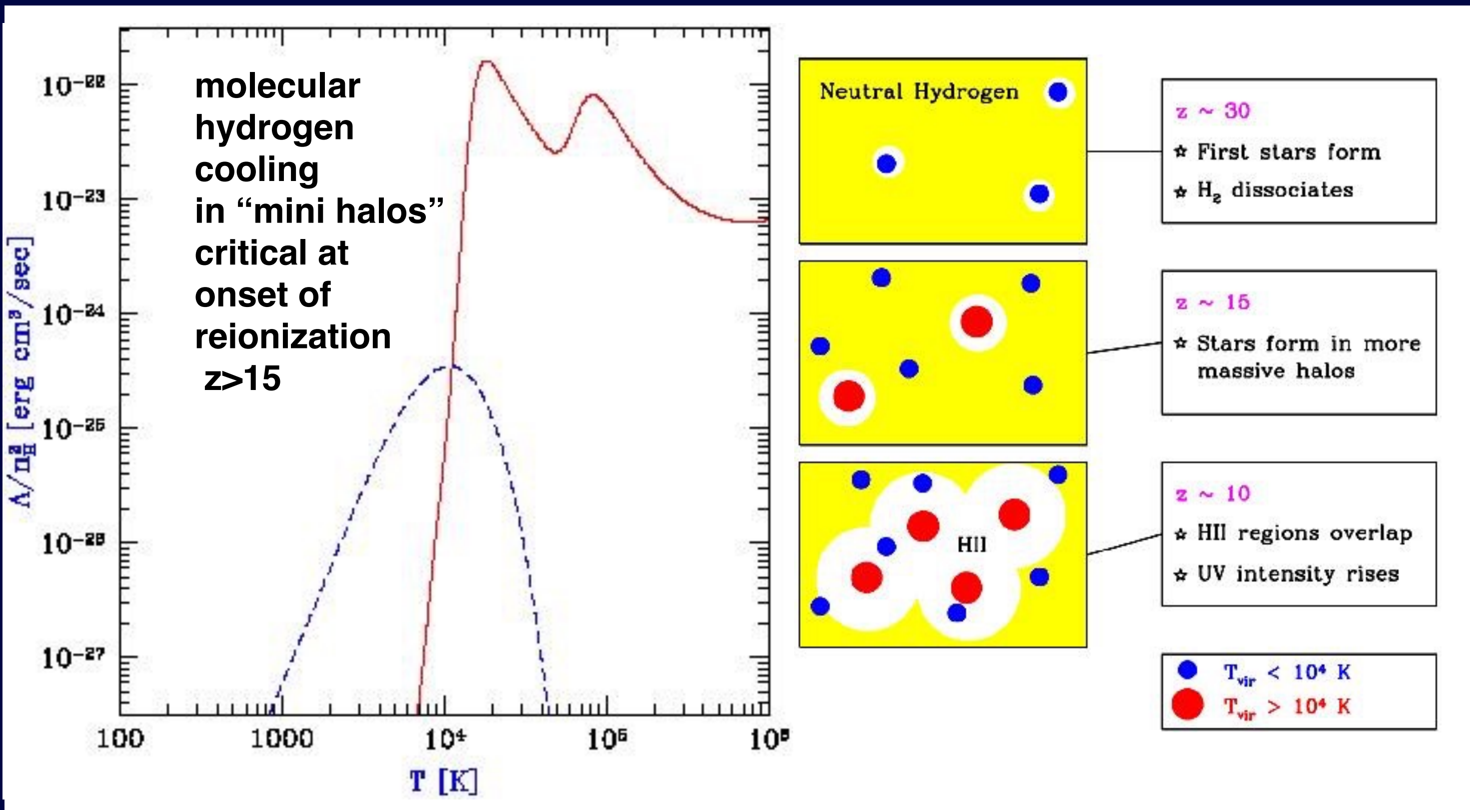


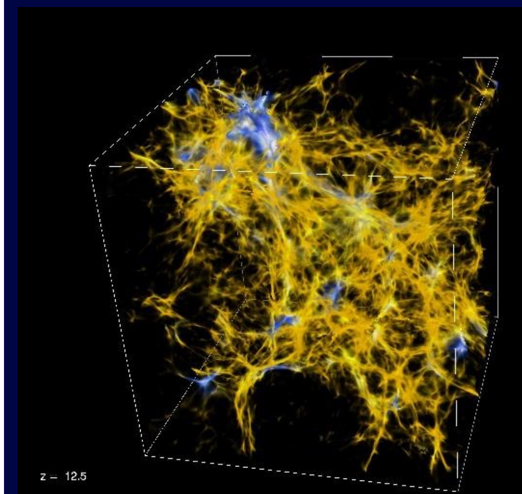
Caroline Heneka

Marta Silva

- Ionization fraction can be inferred from multiple measurements: evolution of LAEs, Hα and Lyα intensity evolution, and amplitudes of (21cm x Lyα) cross-power spectra.

Molecular Hydrogen tracing primordial cooling sites/halos





Outstanding problems at z > 6: billion to ten billion solar mass black-holes in SDSS quasars, Universe at < 600 Myr.
One solution is massive PopIII clusters collapsing - seed blackholes.
Need formation in minihalos at z > 15.

Gong et al. 2012, ApJ

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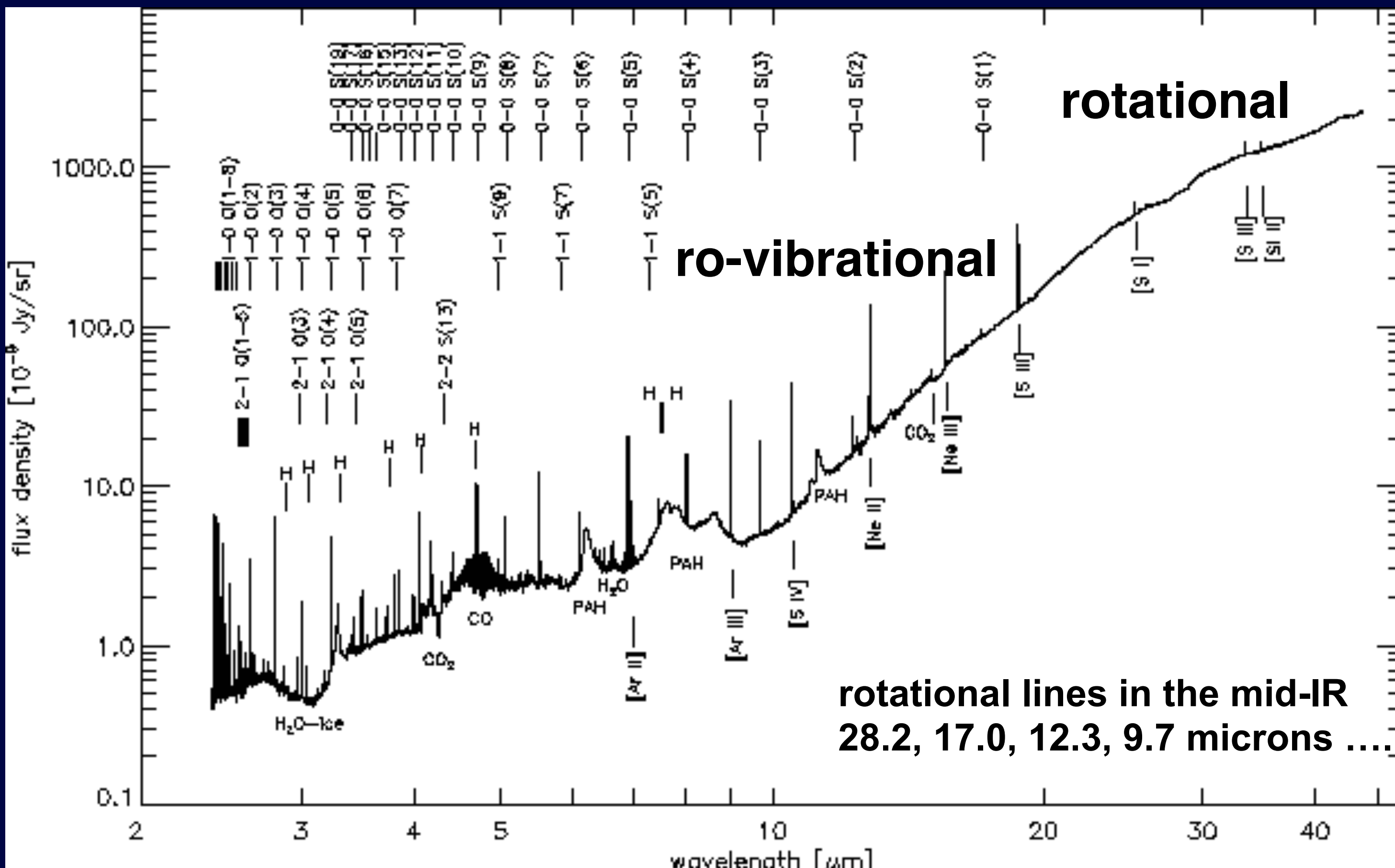
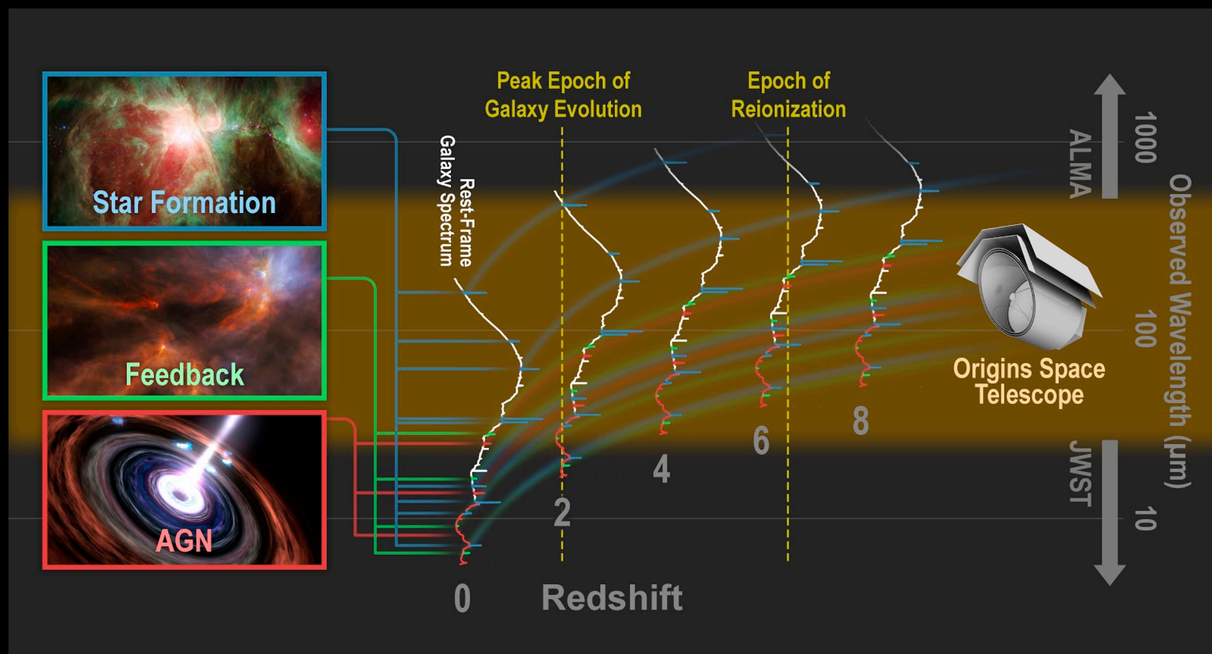


Gong et al. 2012, ApJ

From first stars to life

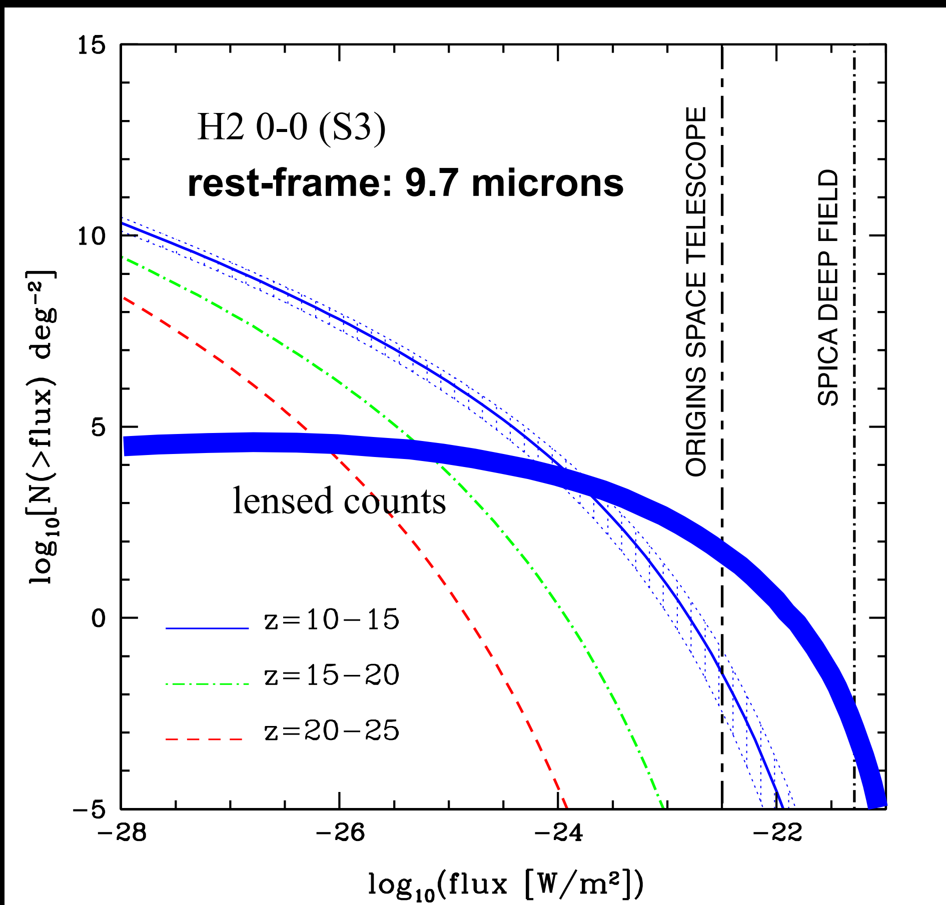
- **How do galaxies form stars, make metals, and grow their central supermassive blackholes from reionization to today?**

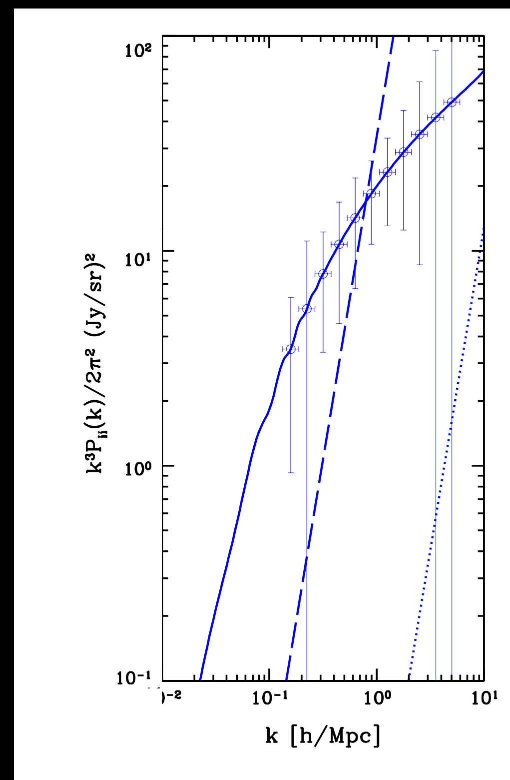


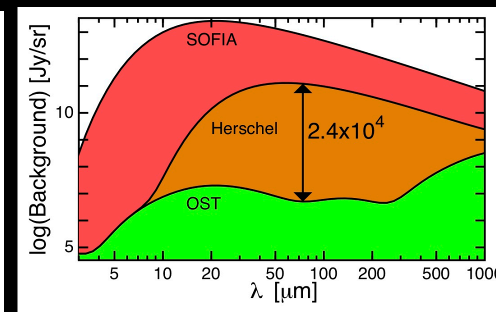
- 3-600 microns contains all necessary lines to study star-formation, blackhole activity, and the interplay between star-formation and galactic central nuclei through negative feedback. *No other wavelength regime provides simultaneous information.*
- 50-beam spectroscopy/fast scans for spectroscopic surveys not individual galaxy observations.

From first stars to life

Origins Space Telescope has **sensitivity down to 10^{-23} Wm^{-2} in a deep field integration to see rotational lines (rest-frame 12.3,17, 28 μm)**







Summary

- **Intensity Mapping of Broad Band Fluctuations**
  - With CIBER-2 improve IHL measurements and first detection of EOR, improve substantially with SPHEREx
- **Intensity Mapping of Spectral Lines**
  - With SPHEREx $0.5 < z < 5$ Hα and Hβ and combination for galactic dust
  - Interesting experiments from the ground for CII, CO etc.
  - Lyman-α has lots of information, more than just detecting point sources, but requires a new approach like CDIM.
- **Things to consider:** Foregrounds, spectral confusion -> Cross-correlations are the key.