Infrared Background and IR Anisotropies

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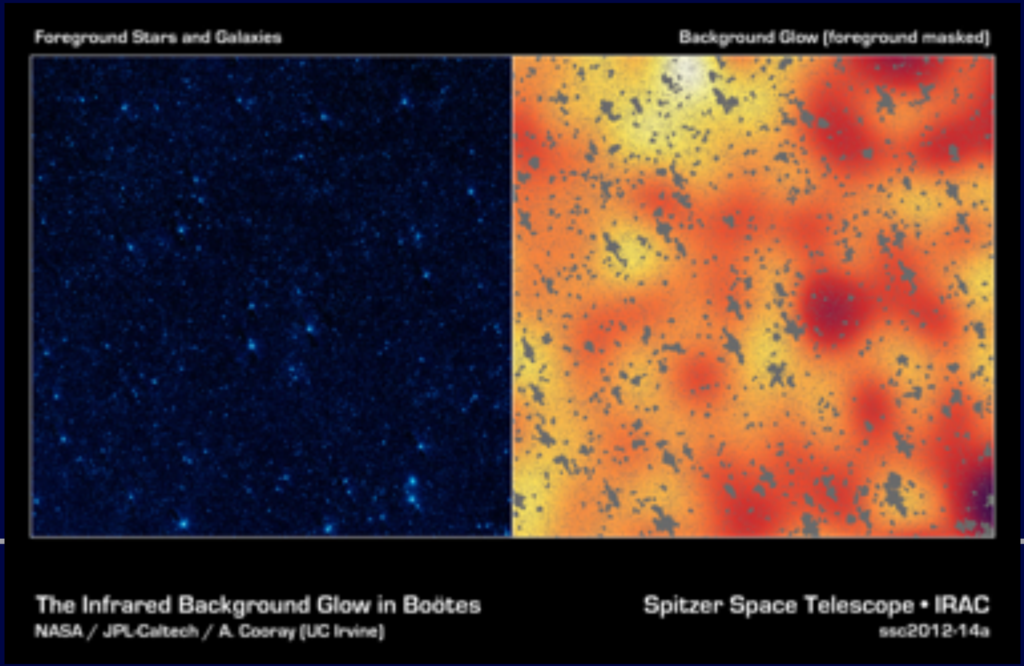
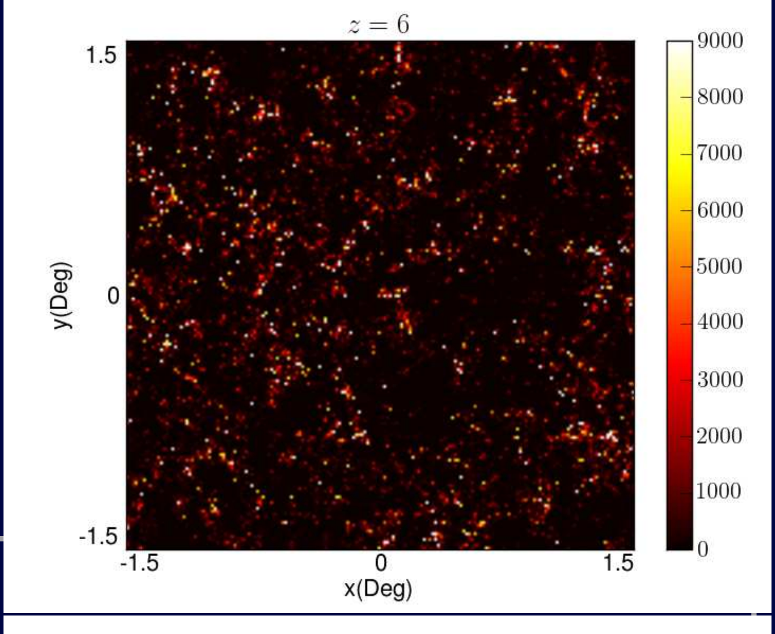


The Infrared Background Glow in Boötes
NASA / JPL-Caltech / A. Cooray (UC Irvine)

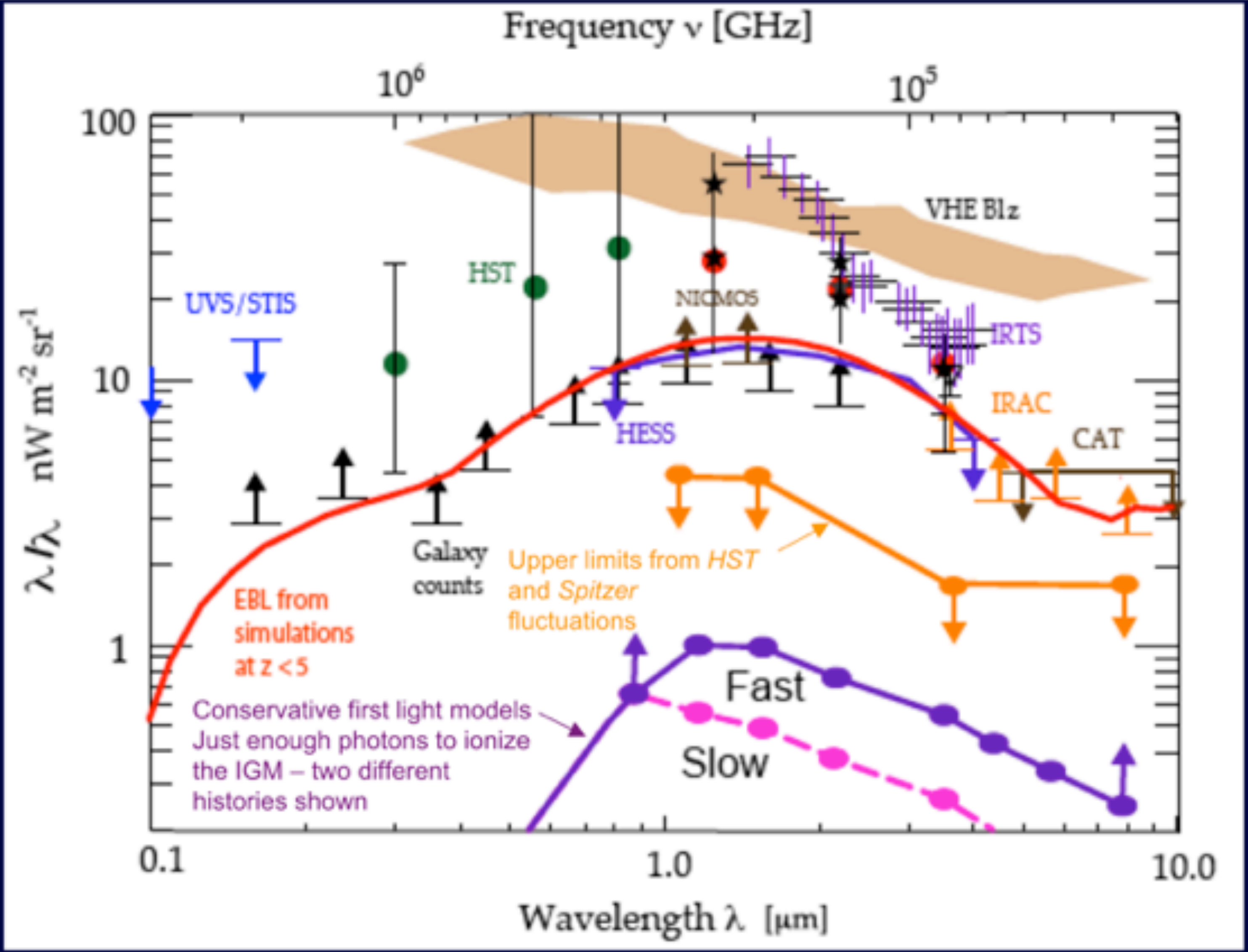
Spitzer Space Telescope • IRAC
ssc2012-14a



- Fluctuations in the near-IR background with Spitzer and Hubble *(will mention CIBER; but no results here; papers submitted)*
- CIBER (happening now) and ZEBRA (wish it is happening)
- Fluctuations in the far-IR background with Herschel
- Intensity mapping of CII in sub-mm as a probe of reionization

(Twitter summaries for each section)

Outline

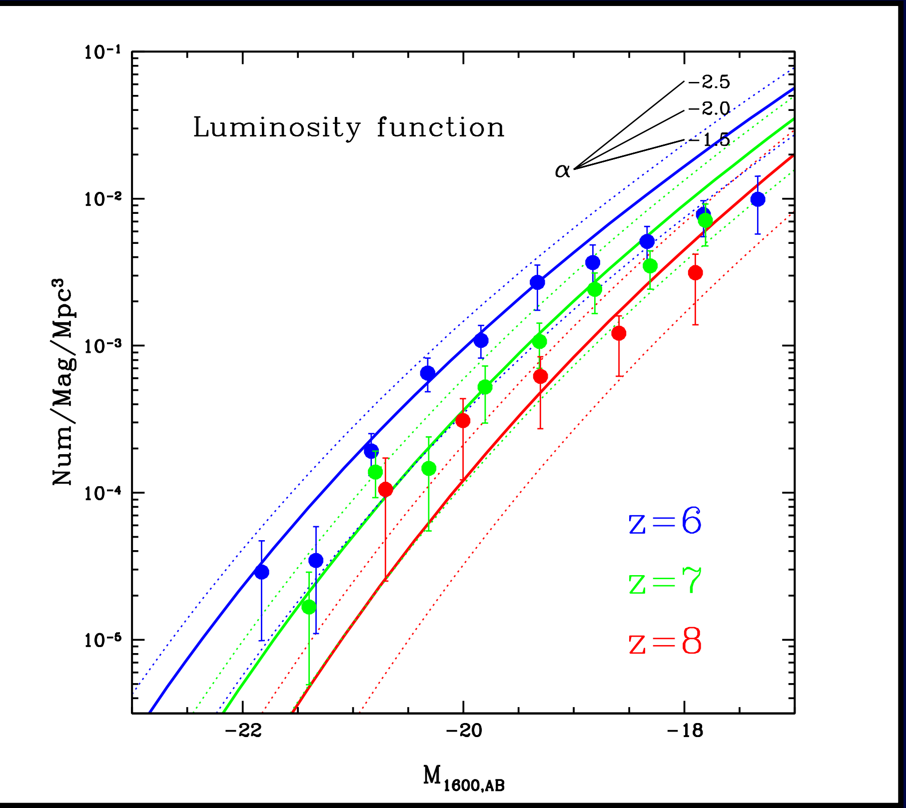


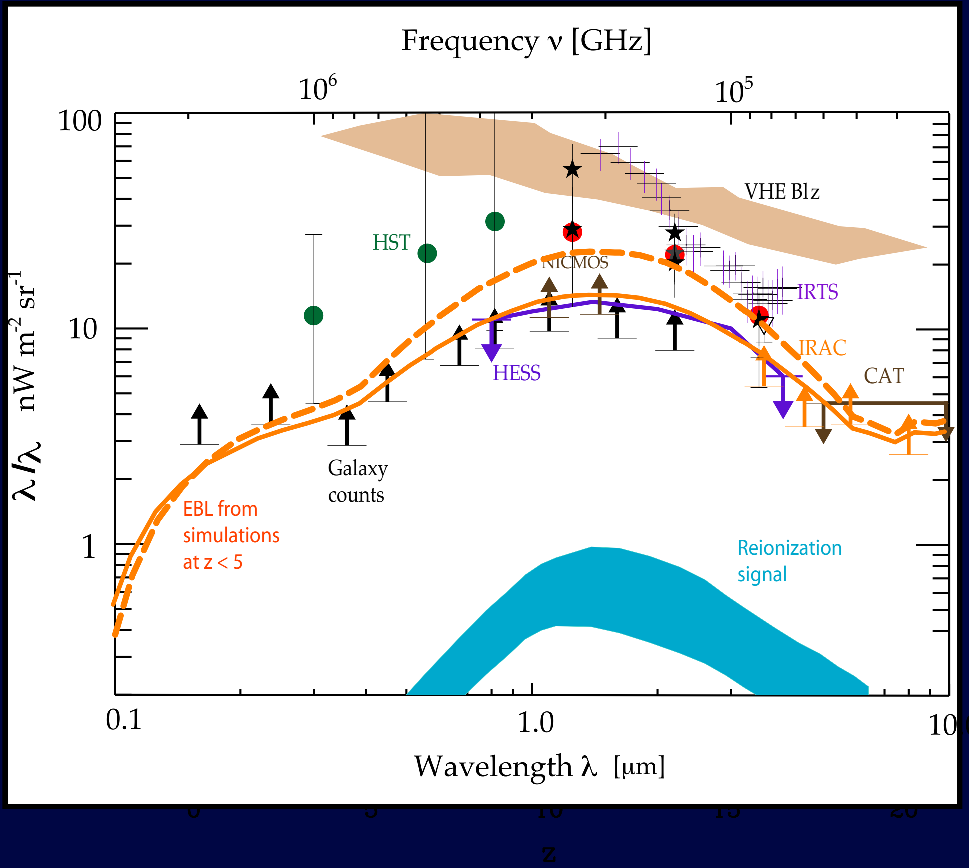
Absolute measurements completely limited by Zodiacal foreground removal

Status of Cosmic IR Background Measurements

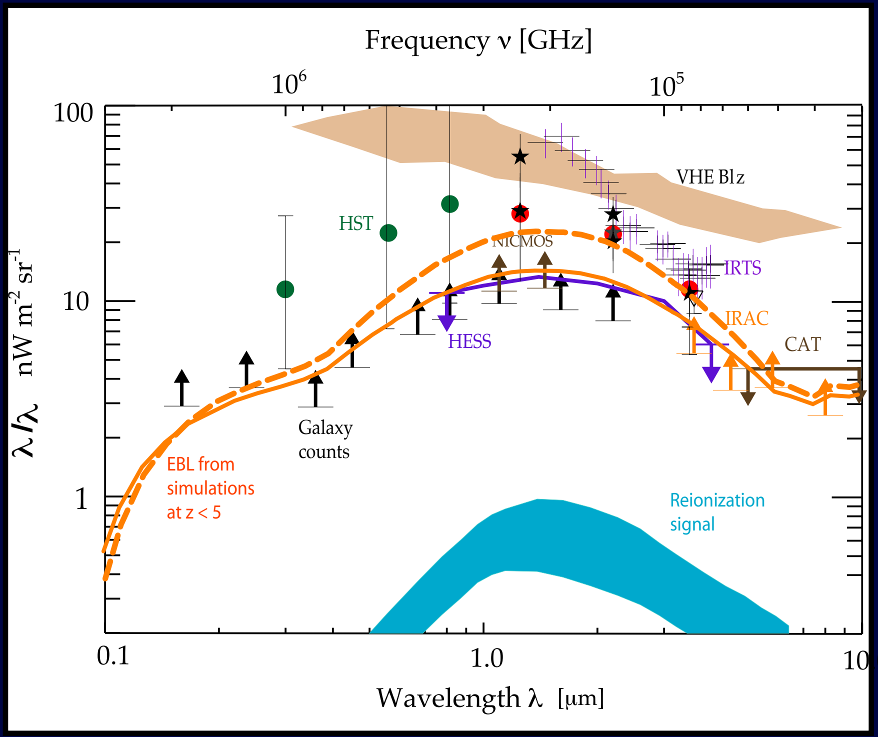
Near-IR background Light is a probe of reionization

Even if faint sources are individually undetected, their presence is visible in the absolute intensity of the near-IR background.

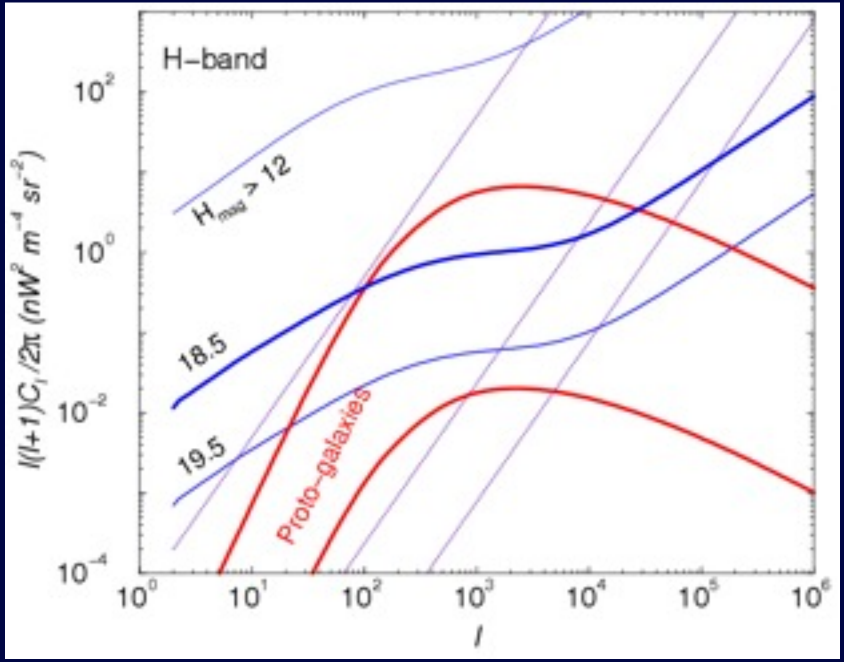




- Calculation consistent with HST/WFC3 UV LFs and reionization histories.
- ***The predicted z > 6 background intensity ~ 0.1 to 0.3 nW/m2/sr between 1 to 3 microns.***
- This is small and challenging to measure with absolute experiments at 1 AU; A small instrument outside of the zodiacal light cloud > 5 AU is necessary.



High-z galaxies? Study IRB anisotropies.

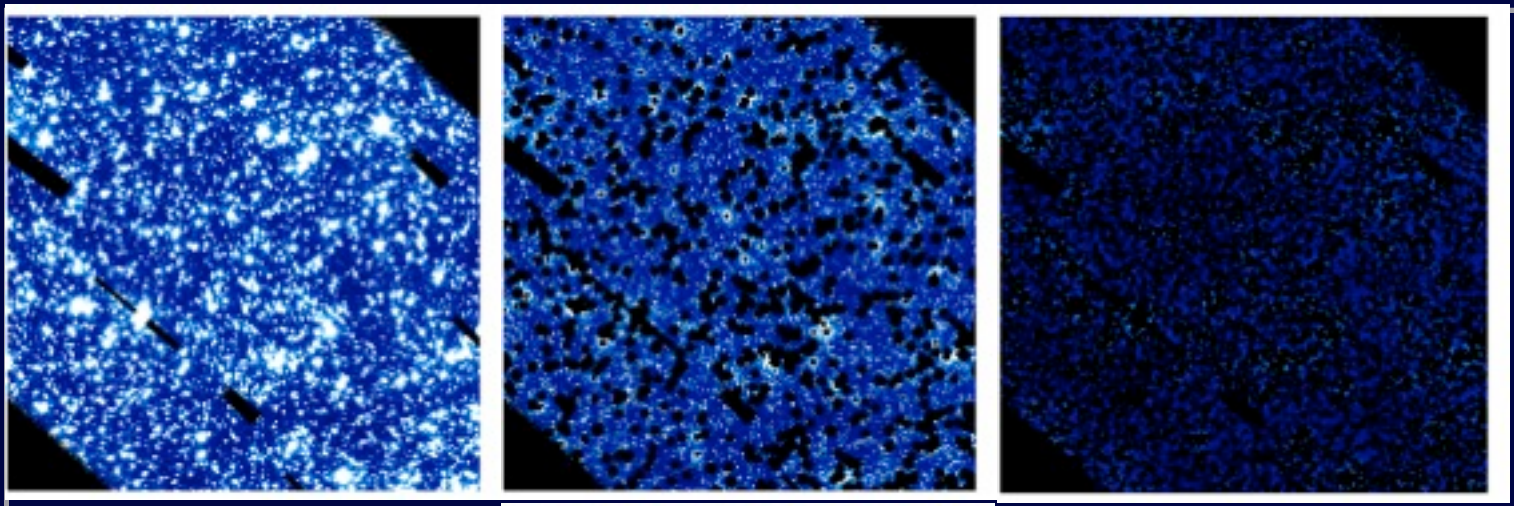


Instead of the absolute total IRB intensity, measure anisotropies or fluctuations of the intensity (just like in CMB).

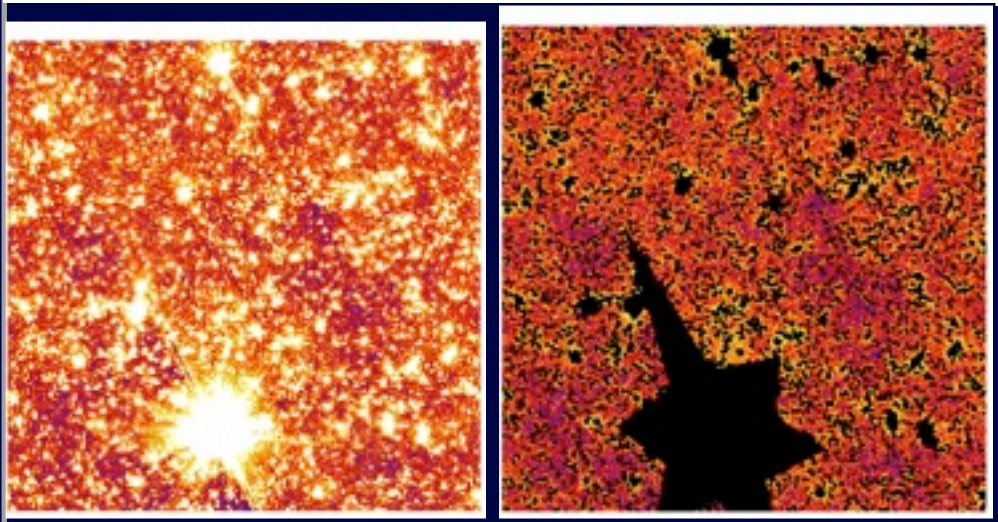
IRB anisotropies probe substantially below 0.1 nW/m2/sr intensity.

(Cooray, Bock, Keating, Lange & Matsumoto 2004, ApJ)

IR Background Fluctuations Measurements



GOODS
CDF-S



COSMOS

What do we do?

Measure statistics of “empty” pixels.

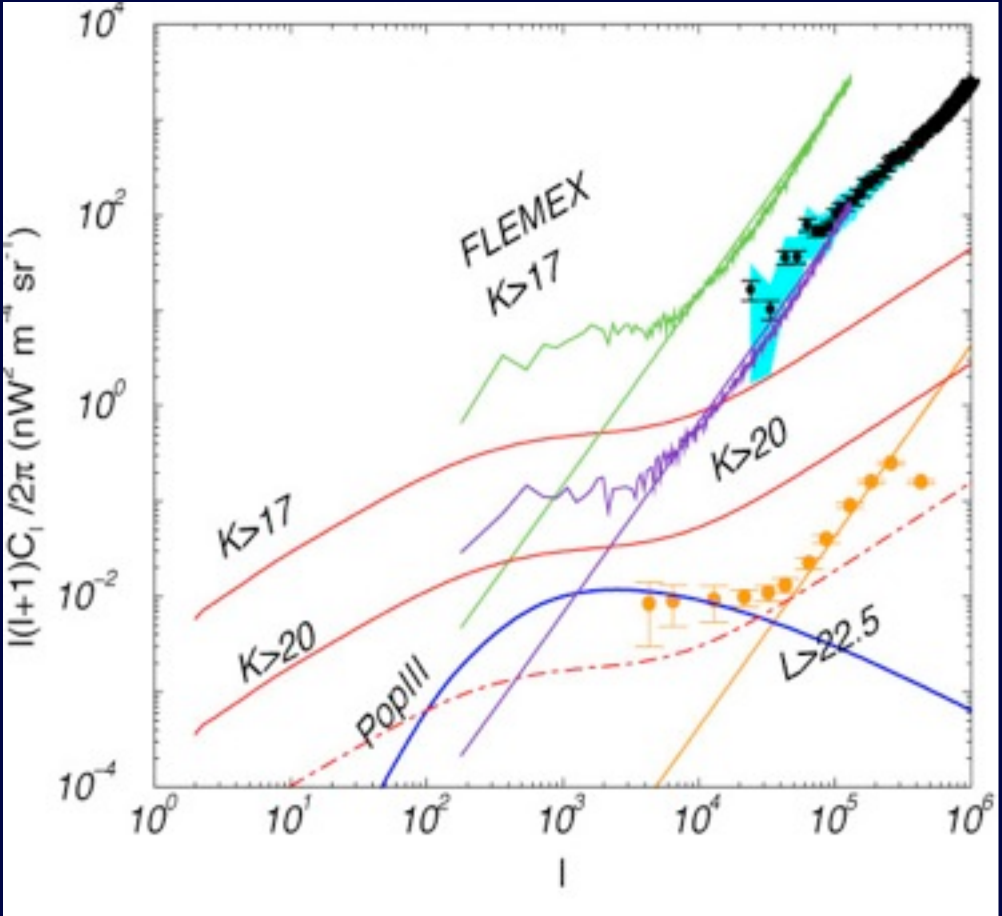
If unresolved faint galaxies are hidden in noise, then there is a clustering excess above noise

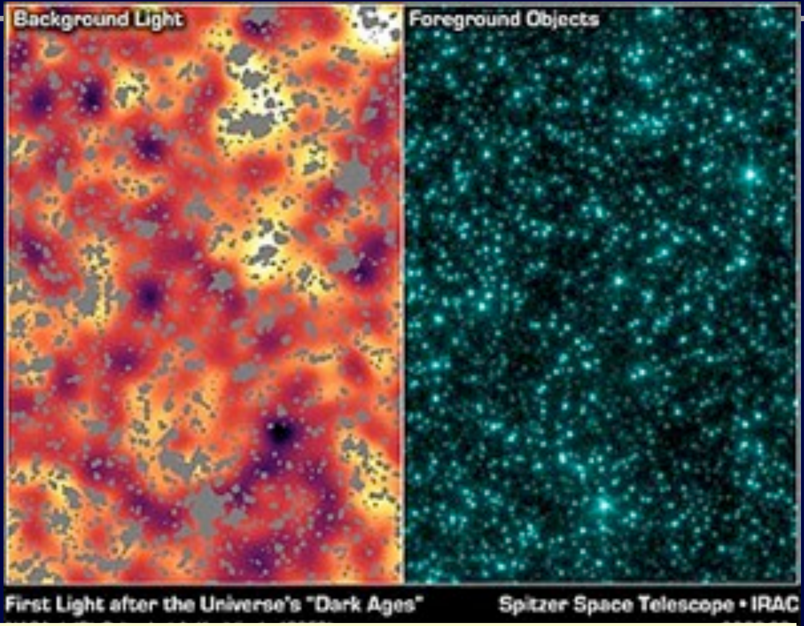
Challenges: > 10 million of pixels (higher complexity than analyzing CMB data.)

We also mask > 50% of pixels (GOODS we masked 70% of pixels).

Techniques to handle mask - borrowed from CMB analyses.

IR Background Fluctuations Measurements





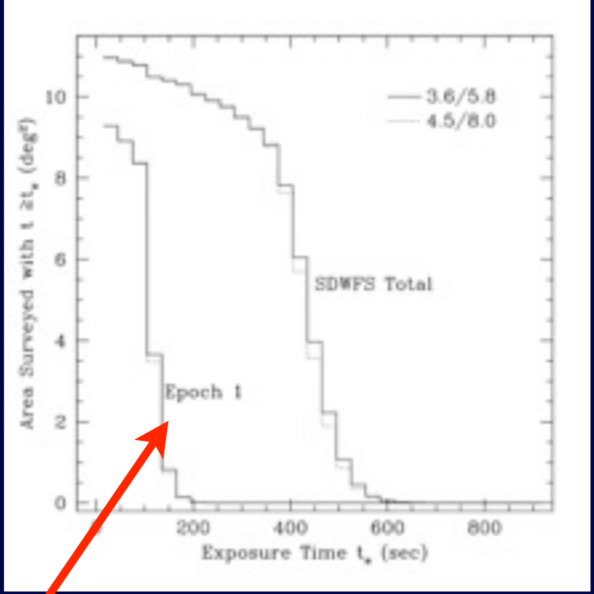
- First detection reported by Kashlinksy *et al*. 2005, Nature with Spitzer at 3.5 and 4.5 μm (also Kashlinsky *et al*. 2007, 2012)

Explained as z > 8 first-light galaxies with PopIII stars.

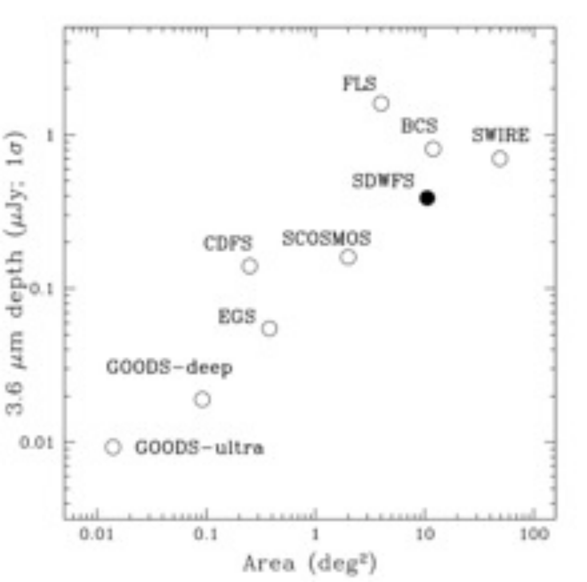
- Thompson *et al*. 2007 report HST/NICMOS measurements, which are argued to be inconsistent with Kashlinsky interpretation for z > 8 sources

IR Background Fluctuations Measurements

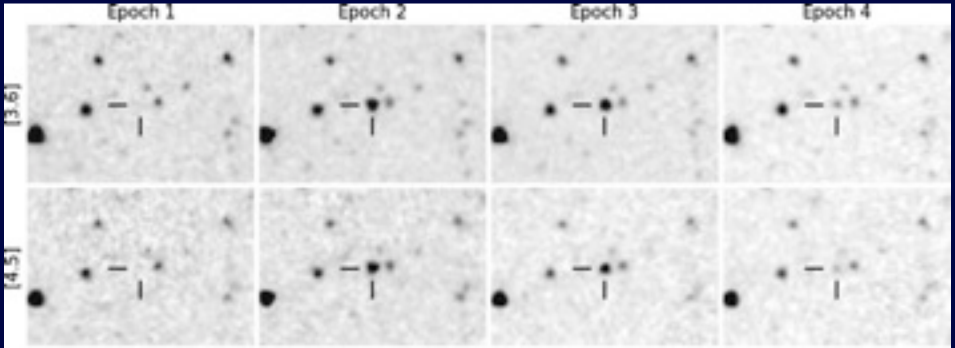
SDWFS: Spitzer Deep Wide Field Survey

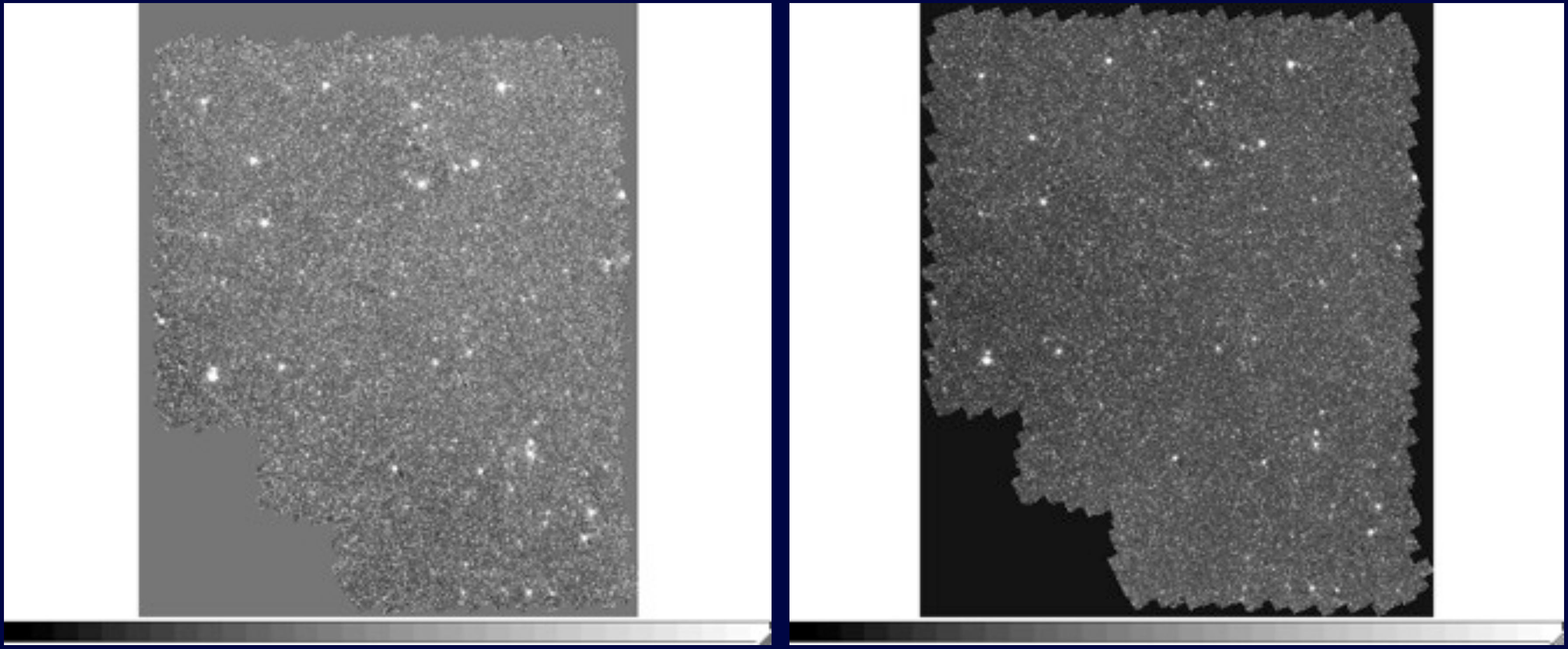


The IRAC Shallow Survey
(Eisenhardt et al. 2004)



IRAC, 4-band
~10 deg^2
4 epochs (2004-2009)
~250 hr w/ IRAC
~80,000 images
90 sec/epoch/pos'n
PI: Dan Stern (JPL)





Standard *Spitzer* software, MOPEX

Our self-calibrated mosaic

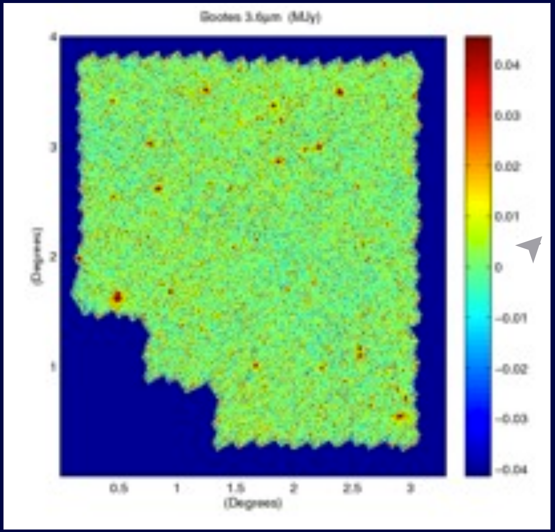
Self-calibrated mosaics are aimed at preserving the background, unlike MOPEX and HST multi-drizzle for WFC3. Based on works by Fixsen et al. 1998 & Arendt et al. 2010 (Our internal code is cross-checked against Rick Arendt's routines).

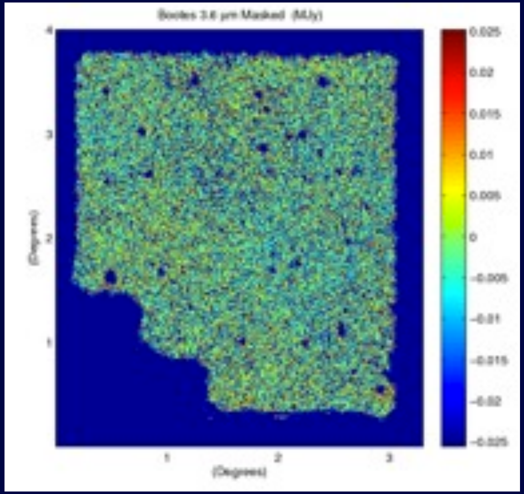
Spitzer Background Fluctuations in SDWFS

Cooray et al. 2012, Nature, 490, 514

Spitzer Background Fluctuations in SDWFS

Cooray et al. 2012, Nature, 490, 514





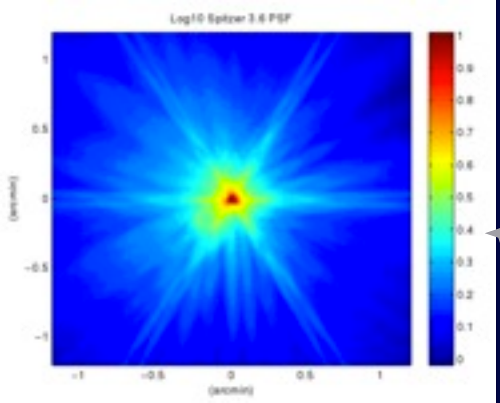
Mask map. (Sextractor)

Epoch 1 + Epoch 2

X

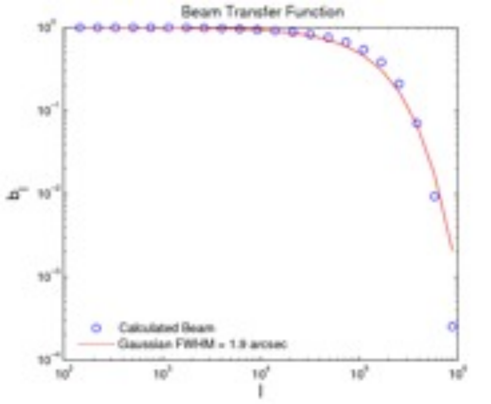
Epoch 3 + Epoch 4

Cross-Correlate Coadded Epochs



PSF

Fourier Transform



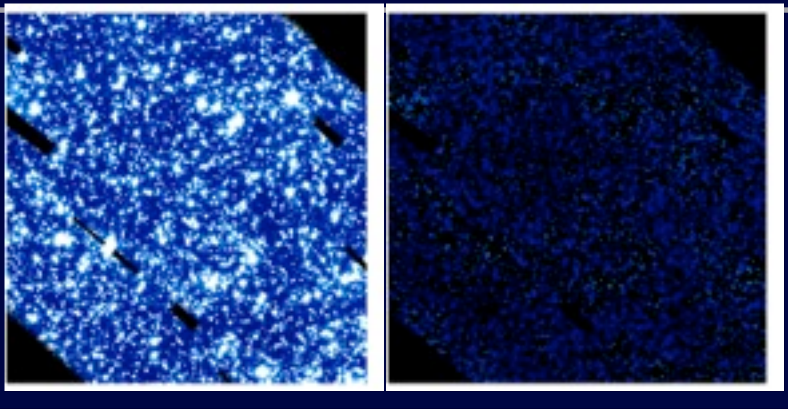
BEAM TRANSFER FUNCTION

Epoch 1 - Epoch 2

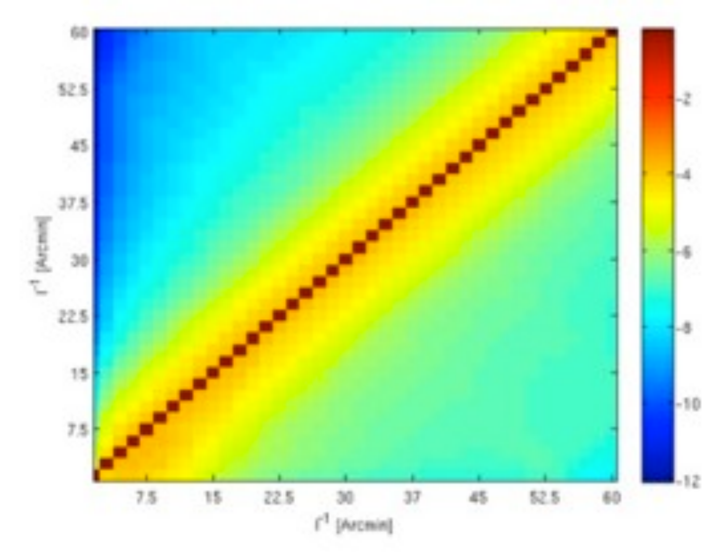
X

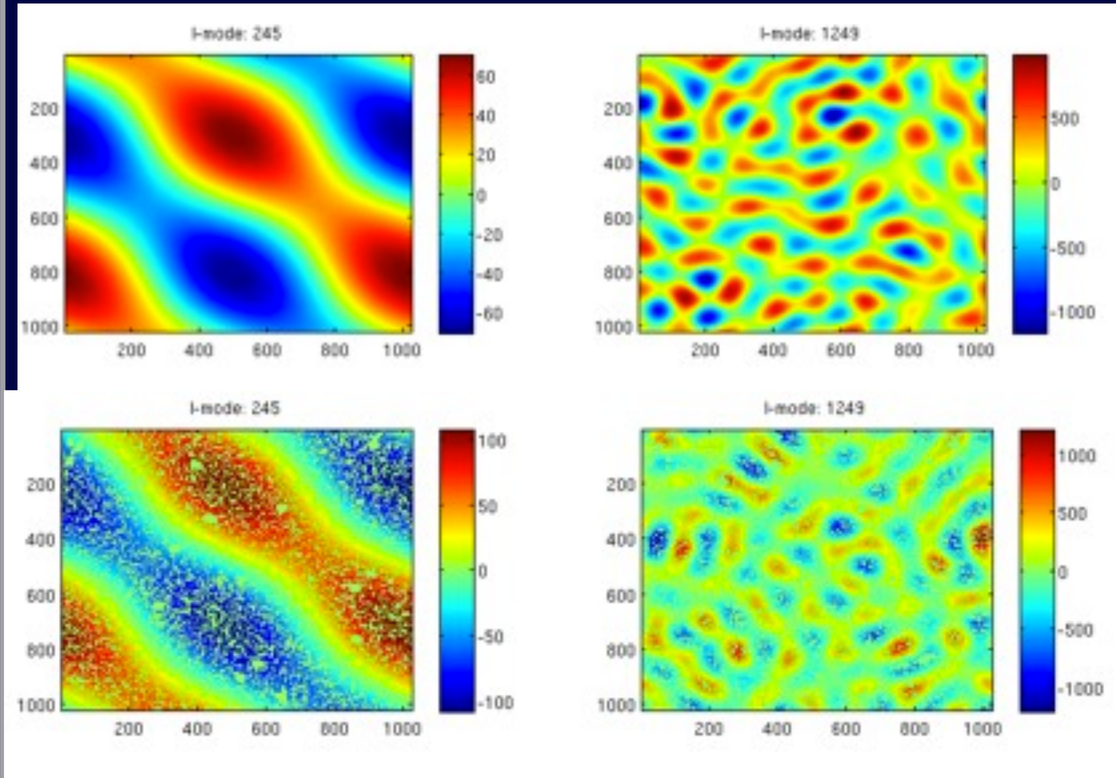
Epoch 3 - Epoch 4

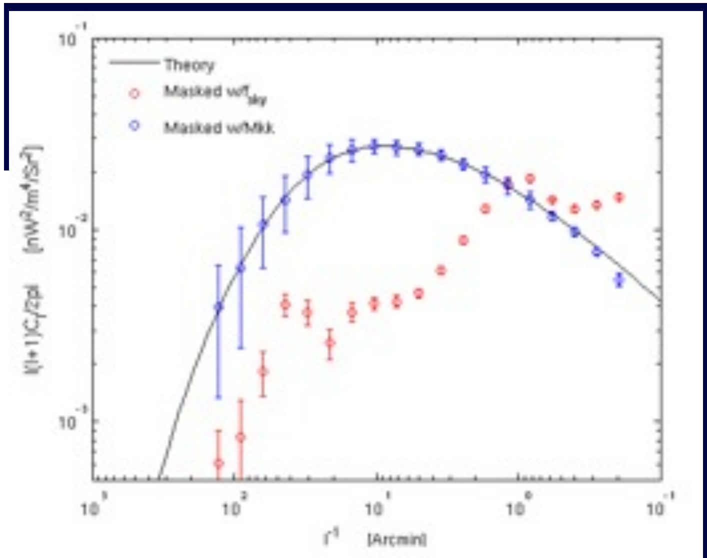
Jackknife For Noise Errors



The Matrix itself.

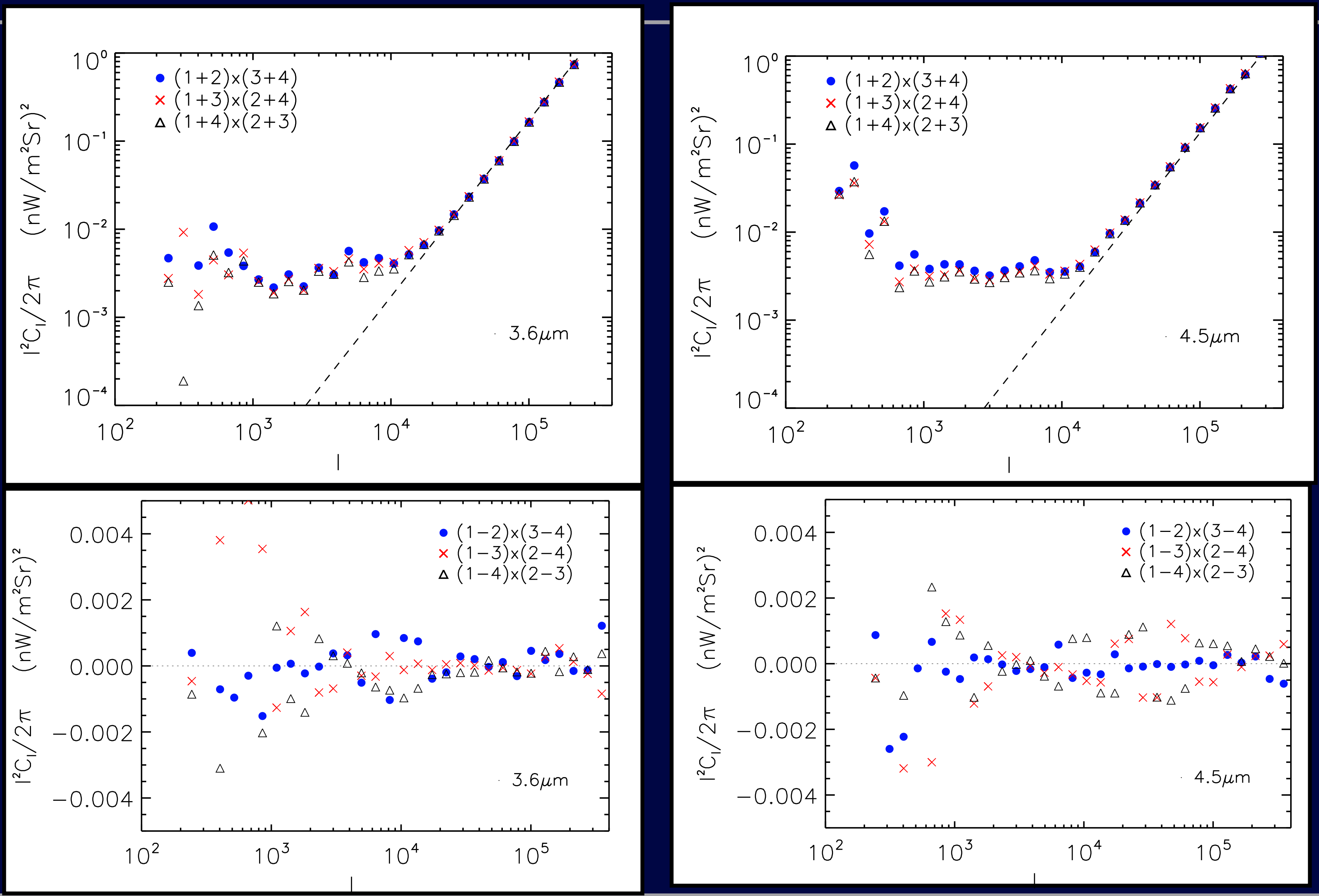






Mode-coupling due to masked sources

Cooray et al. 2012, Nature, 490, 514

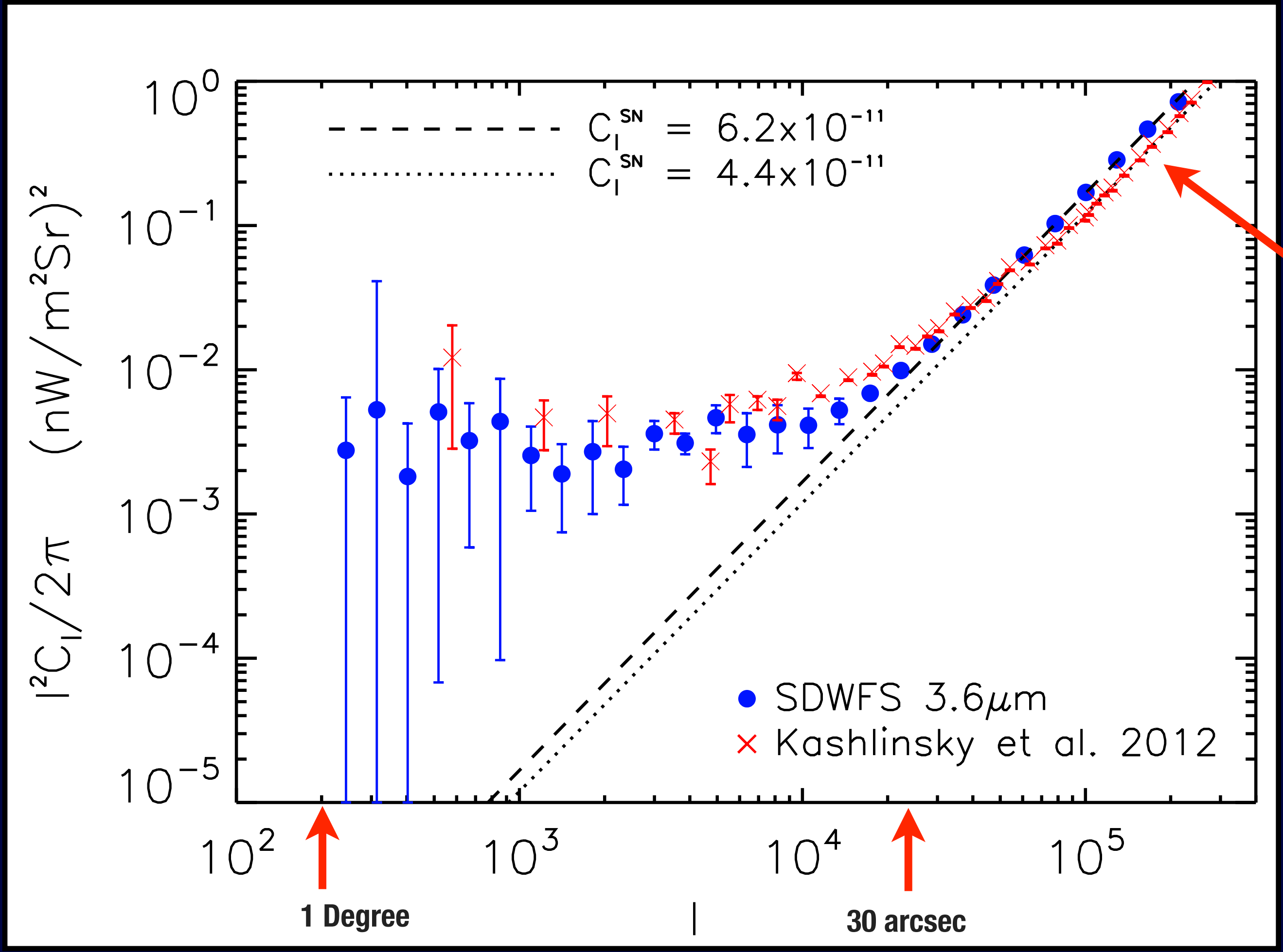


Spitzer Background Fluctuations in SDWFS

Cooray et al. 2012, Nature, 490, 514

Spitzer fluctuations are real! *Not an instrumental systematic nor zodiacal ligh*

Its extragalactic, repeatable, time-independent.

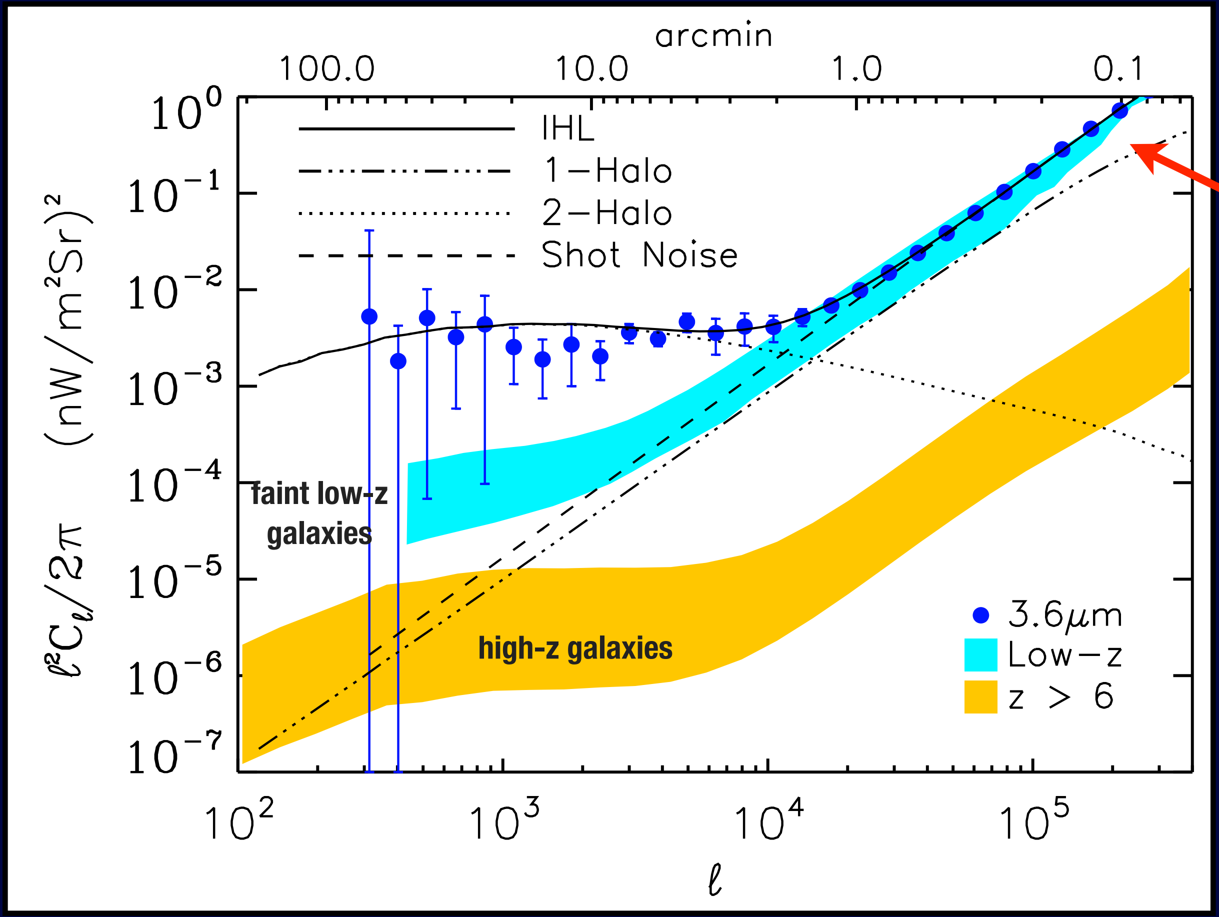


Kashlinsky et al. SEDS data are deeper than SDWFS (so more point sources are masked)

Spitzer Background Fluctuations in SDWFS

Cooray et al. 2012, Nature, 490, 514

What is the origin of these IR 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

Spitzer Background Fluctuations in SDWFS

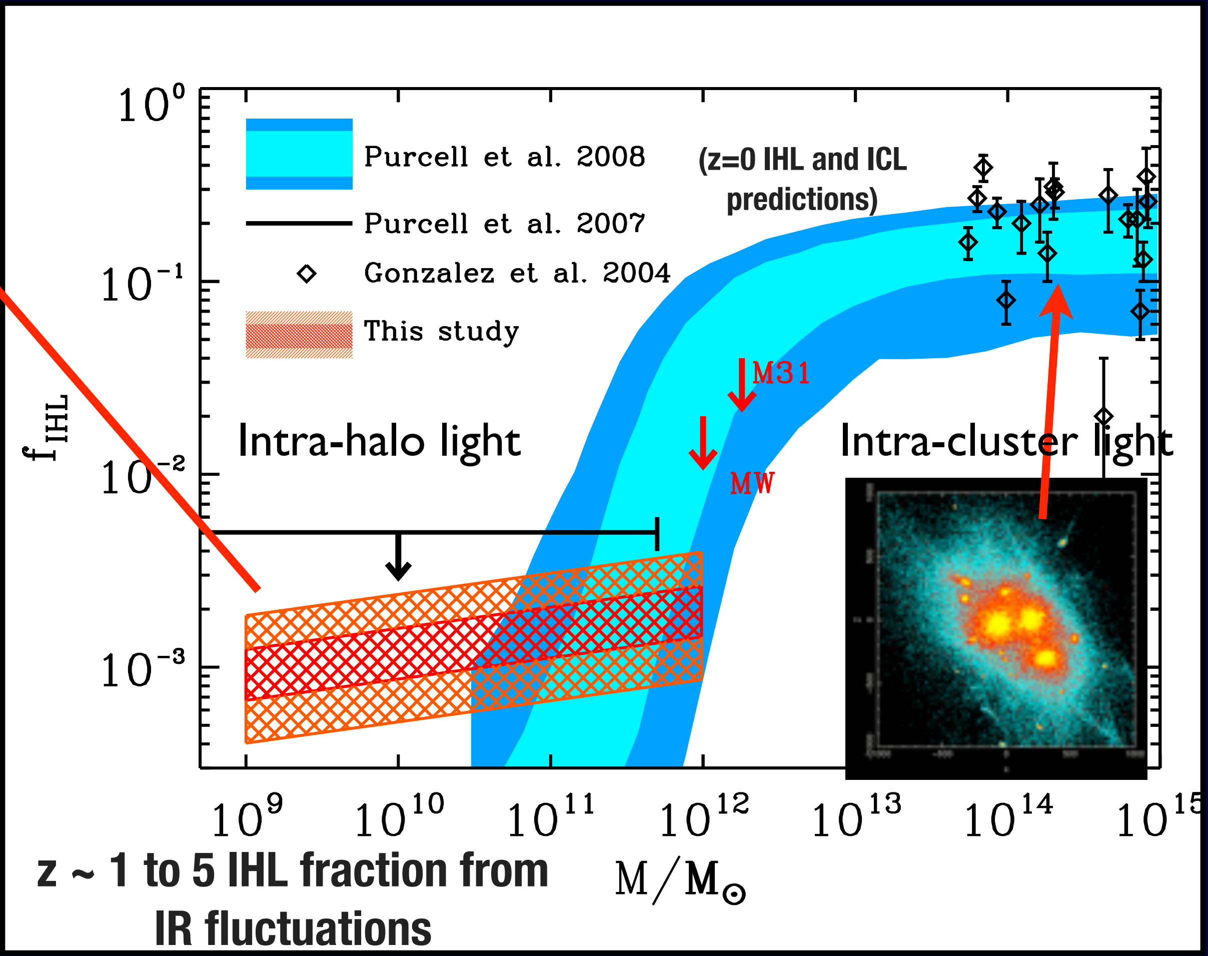
Cooray et al. 2012, Nature, 490, 514

What is the origin of these IR fluctuations?

Intra-halo light

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

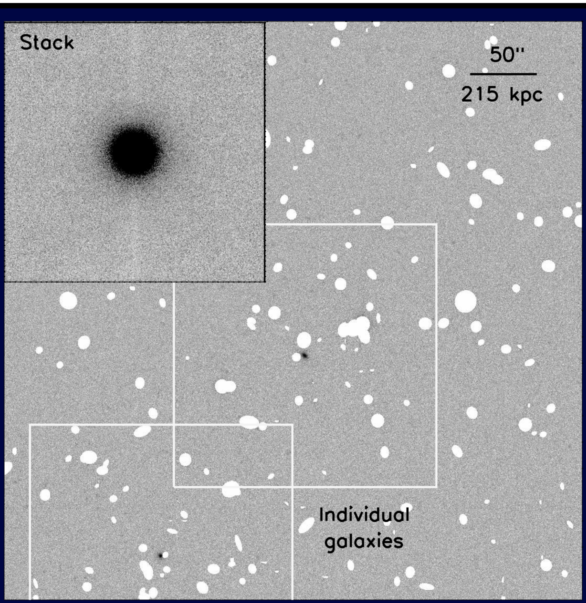


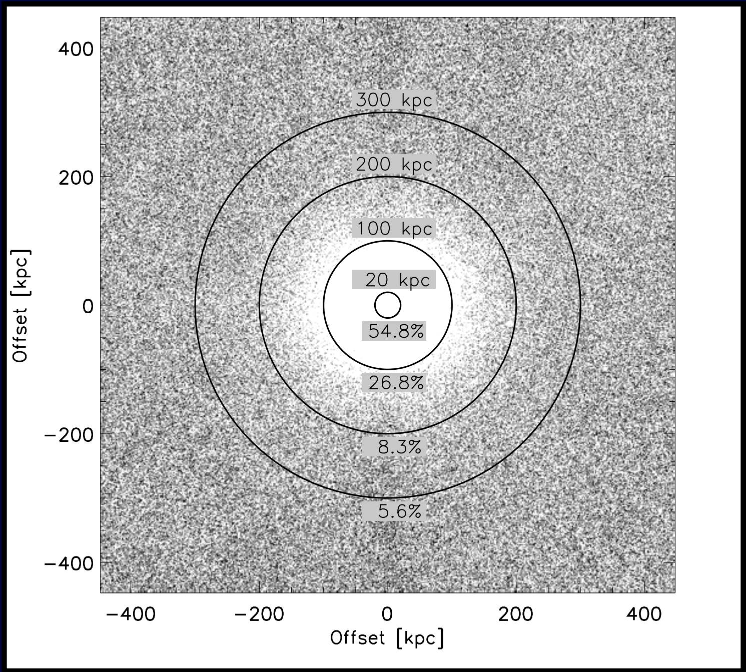
z ~ 1 to 5 IHL fraction from IR fluctuations

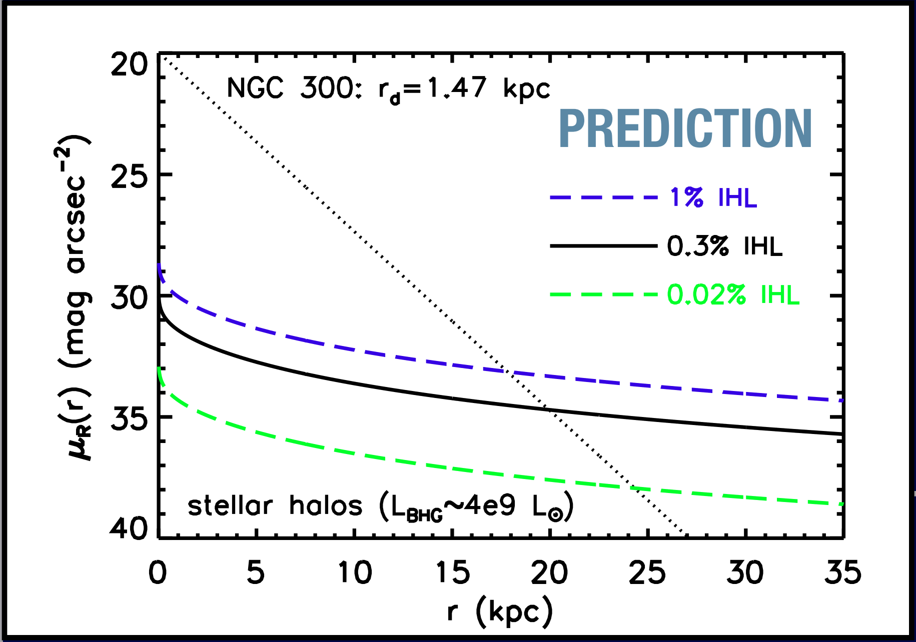
Intra-halo light in galaxy-scale dark matter halos

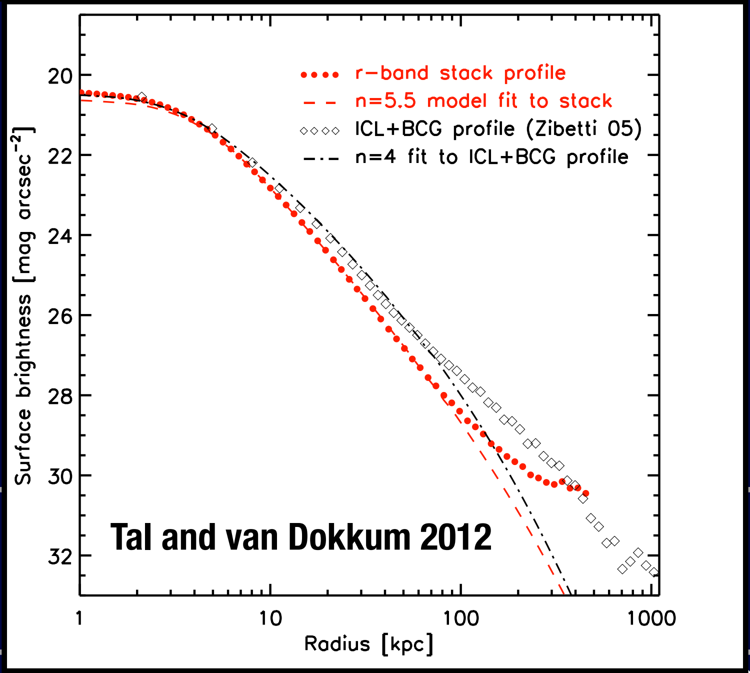
Cooray et al. 2012, Nature, 490, 514

SDSS stack of 40,000 galaxies at z=0.3









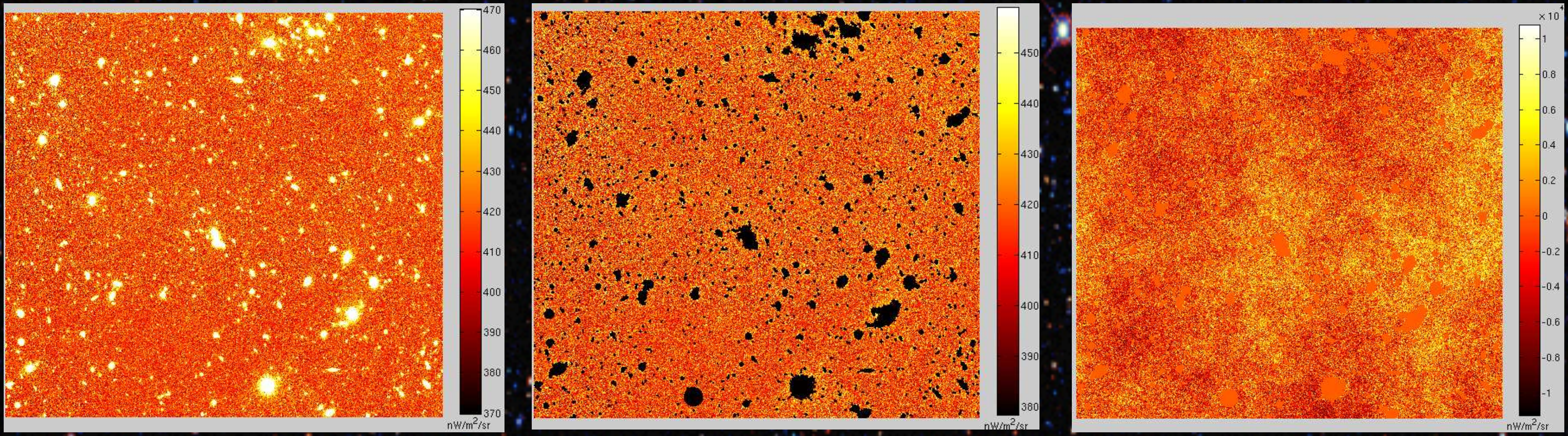
Tal and van Dokkum 2012

Twitter summary

Spitzer background fluctuations explained with 0.5% intra-halo light by @acooray #wdm14

Reionization signal in IR fluctuations?

CANDELS, a multi-cycle program with Hubble Space Telescope.
WEBSITE: CANDELS.UCOLICK.ORG



Field	Area	Program ID	Dates
UDS	210 sq arcmins	12064	11/08/10-11/25/10
		12064	12/27/10-01/10/11
EGS	90 sq arcmins	12063	04/02/11-04/08/11
		12063	05/22/11-06/02/11
COSMOS	210 sq arcmins	12440	12/06/11-02/25/12
		12440	01/23/12-04/16/12
COSMOS	1.8 sq degrees	9822/10092	10/03-5/04

Twitter summary

0.5 to 2 micron fluctuations w HST lead to integrated UV lum density at z > 6 #wdm14

CIBER

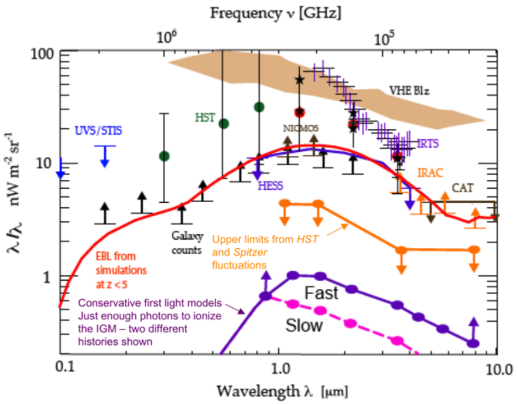
Cosmic Infrared Background ExpeRiment

UCIrvine
University of California, Irvine

JPL

ISAS JAXA

Korea Astronomy and Space Science Institute
한국천문연구원



State of NIR/Optical Extragalactic Background Measurements

Absolute measurements completely limited by Zodiacal foreground removal

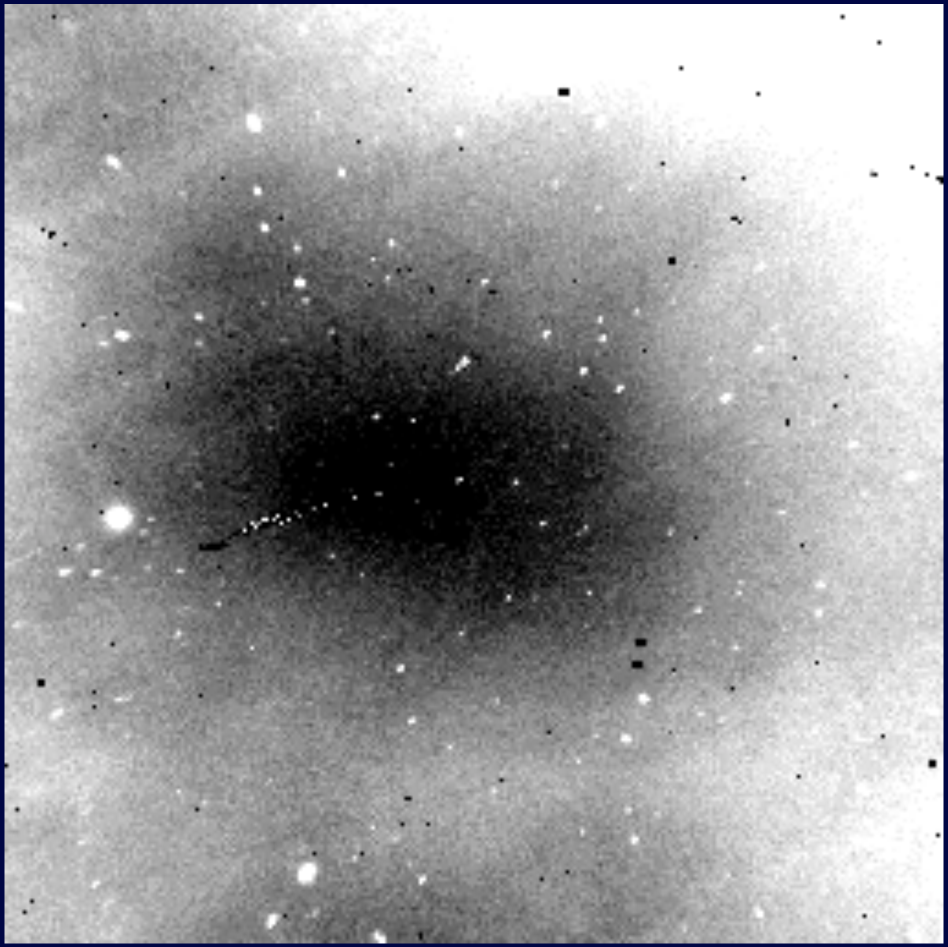
CIBER1:

First flight February 2009, second July 2010. Third flight February 2012 (all from White Sands, NM). Fourth June 2013.

Fourth flight was a non-recovery longer flight from Wallops, VA; CIBER1 payload dumped in Atlantic.

Upgrade to CIBER2 completed; pending four additional flights with NASA now.

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

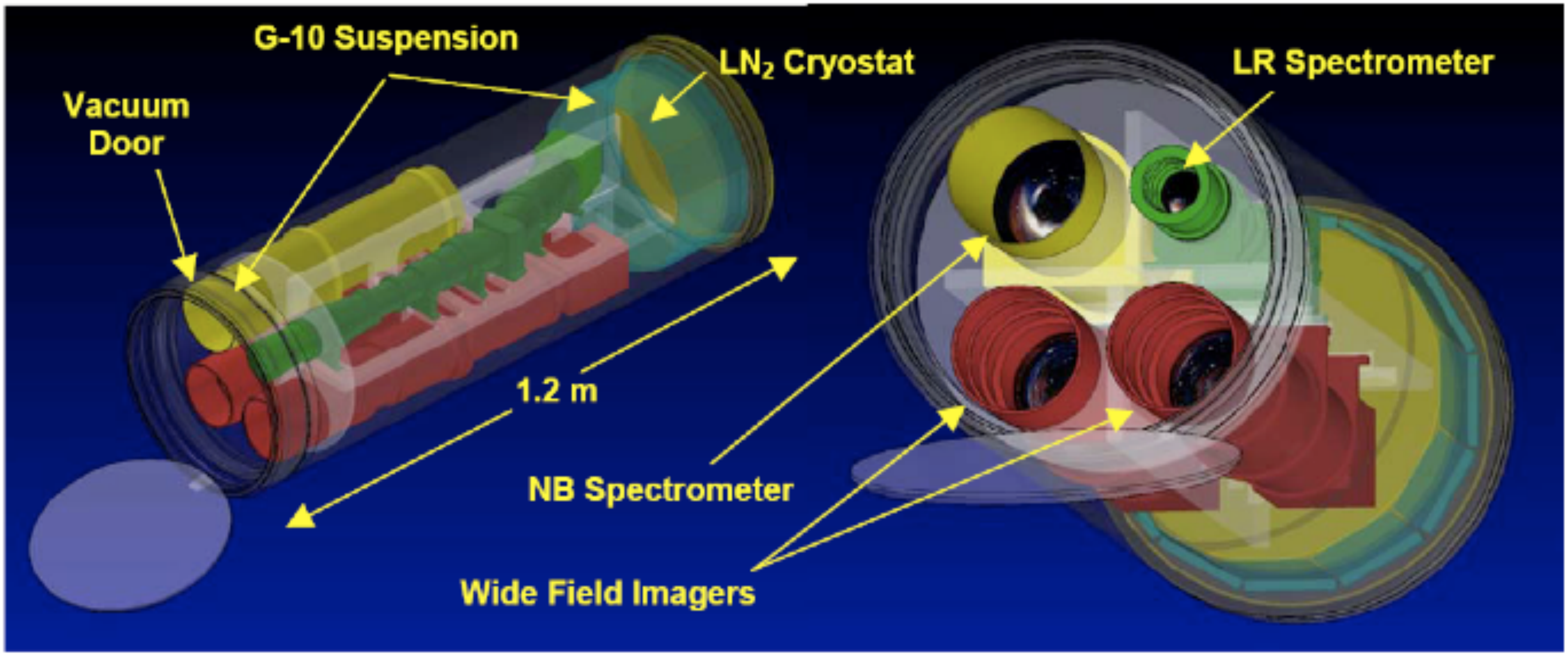
Airglow Emission

- 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

CIBER

Cosmic Infrared Background ExpeRiment

CIBER-1



Dual Wide-Field Imagers

λ = 0.8 μm & 1.6 μm $\lambda/\Delta\lambda$ = 2
2° x 2° FOV 7” pixels

Measure power spectrum from 7” to 2 degrees

Low-Resolution Spectrometer

λ = 0.8 – 2.0 μm $\lambda/\Delta\lambda \sim 20$
4° x 4° FOV 60” pixels

- Search for Ly cutoff feature in 0.8 – 1.2 μm region

Narrow-Band Spectrometer

λ = 0.8542 μm $\lambda/\Delta\lambda$ = 1000
8° x 8° FOV 120” pixels

- Use Fraunhofer lines to measure absolute Zodiacal intensity

ApJ Supplement Special Issue on CIBER Instruments, September 2012, 5 papers

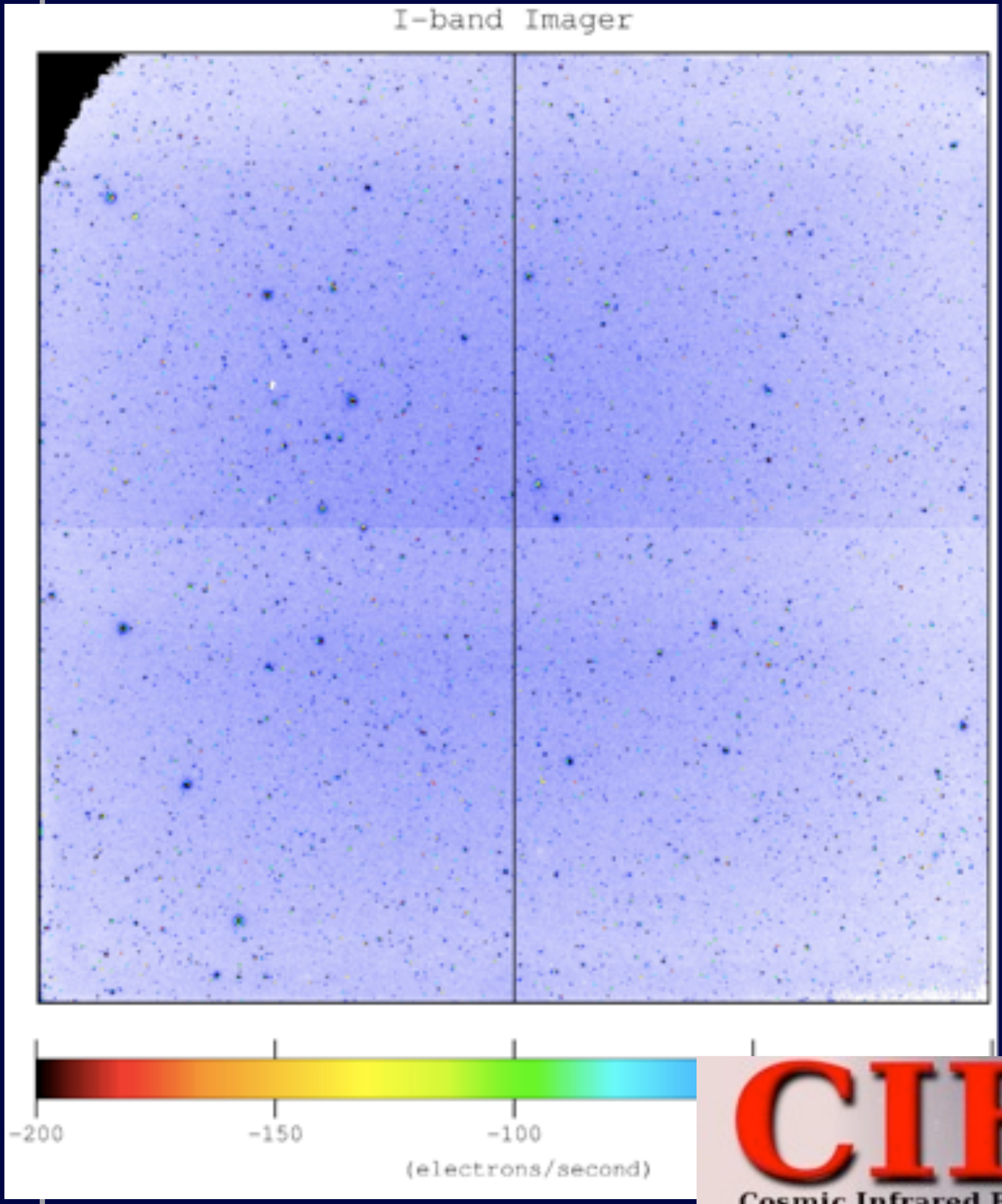
CIBER-1: before third flight

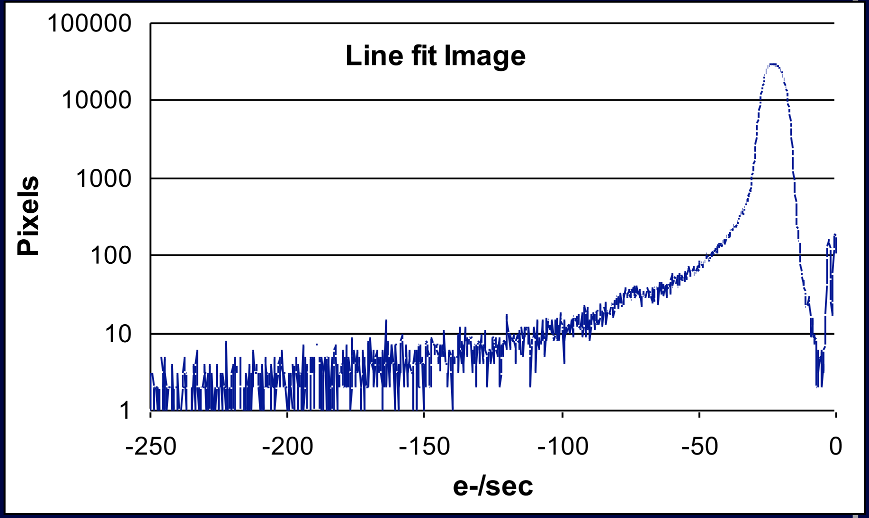
CIBER

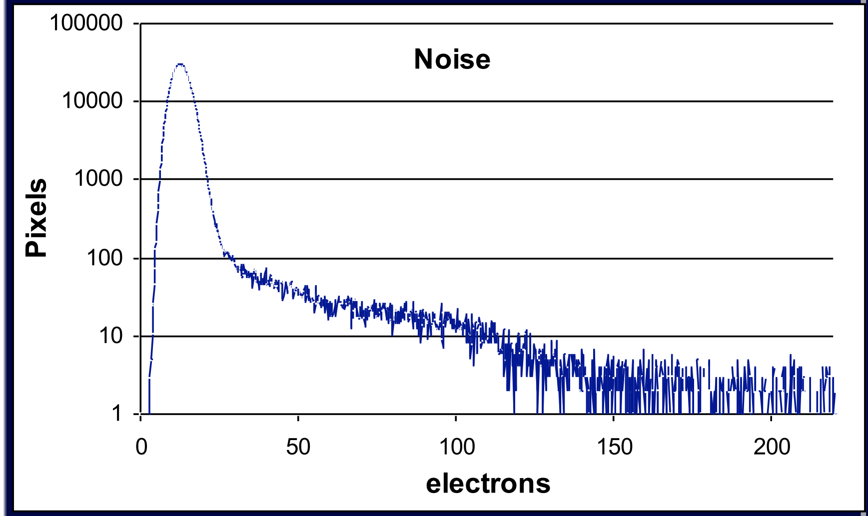
Cosmic Infrared Background ExpeRiment

CIBER: Does exist! Recovery after flights

0.9 μm Imager Data



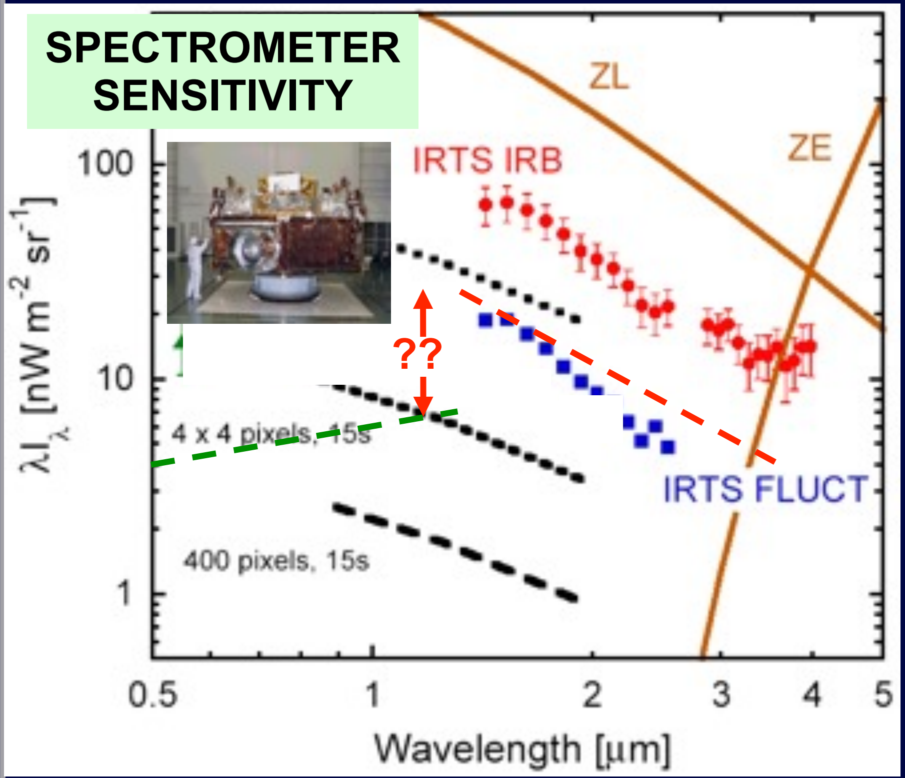




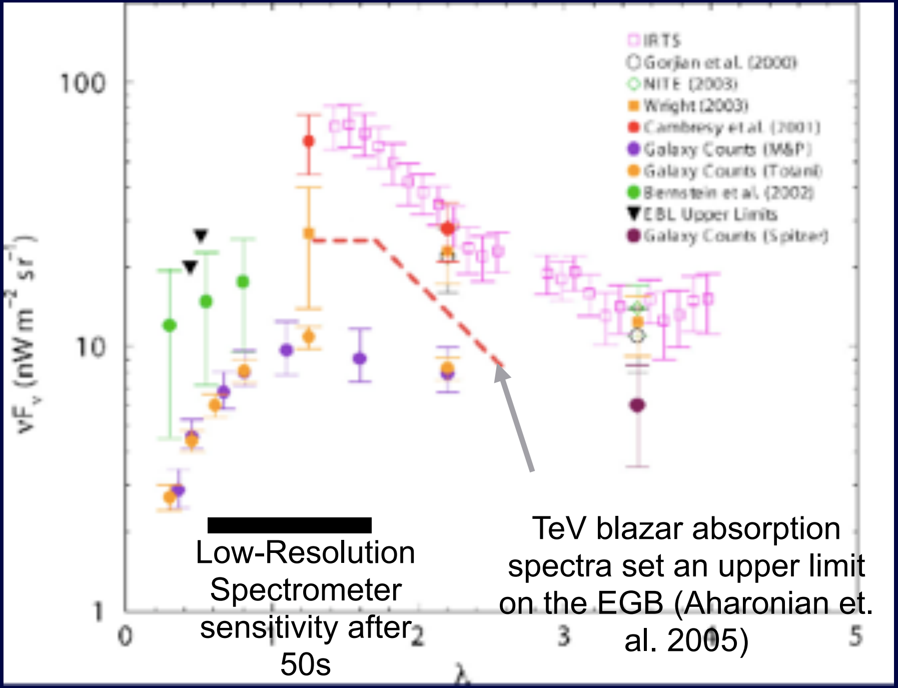
Median photocurrent = 22 e-/s
Median read noise = 12.6 e-

CIBER
Cosmic Infrared Background ExpeRiment

LOW-RESOLUTION SPECTROMETER SCIENCE



SPECTROMETER SENSITIVITY



Low-Resolution Spectrometer sensitivity after 50s

TeV blazar absorption spectra set an upper limit on the EGB (Aharonian et. al. 2005)

Is the gap between IRTS/DIRBE and HST real?

CIBER would see it easily, *without any* Zodiacal subtraction

Precisely measure Zodiacal color, link with narrow-band spectrometer

Low-resolution spectrometer sensitivity is 1-2 nW m^{-2} sr^{-1}

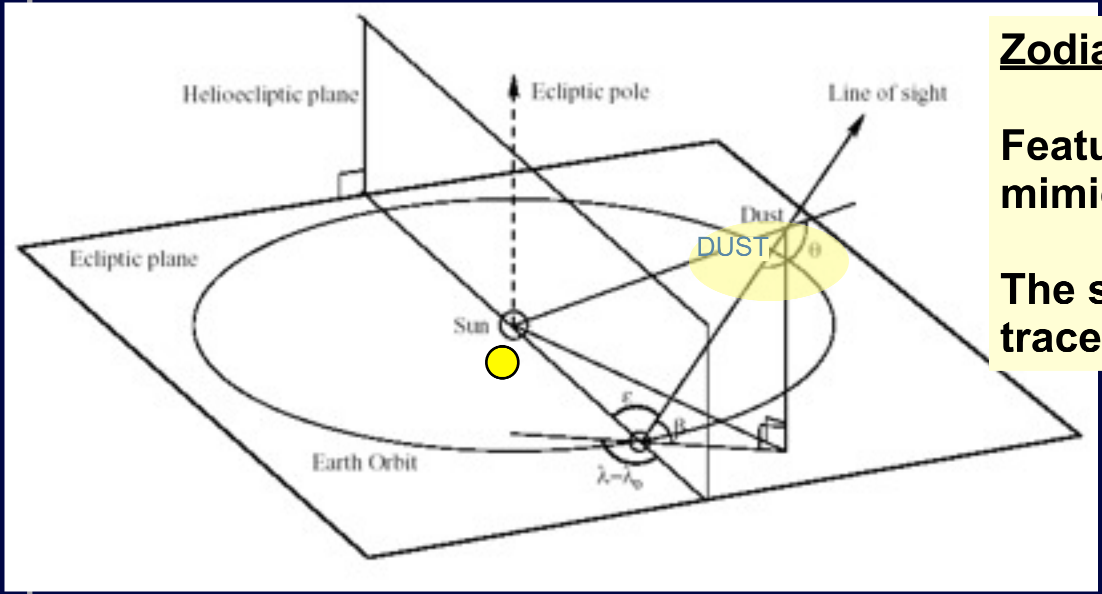
NB Spectrometer Zodiacal zero point is 3 nW m^{-2} sr^{-1} at 0.85 μm

Controversy at J-band is ~30 nW m^{-2} sr^{-1}

CIBER

Cosmic Infrared Background ExpeRiment

USING FRAUNHOFER LINES TO TRACE ZODIACAL INTENSITY



<u>Zodiacal Light is just scattered sunlight</u>

Features in the solar spectrum are mimiced in Zodiacal light

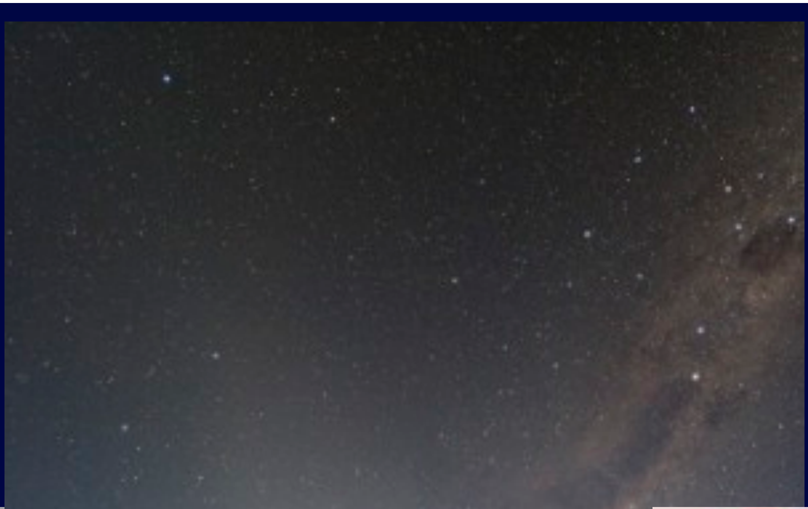
The solar spectrum gives a precise tracer of the absolute Zodiacal intensity

<u>But reality is messy</u>

Atmospheric scattering, emission, and extinction
- **scattered ZL**
- **scattered starlight**
- **airglow**
- **etc**

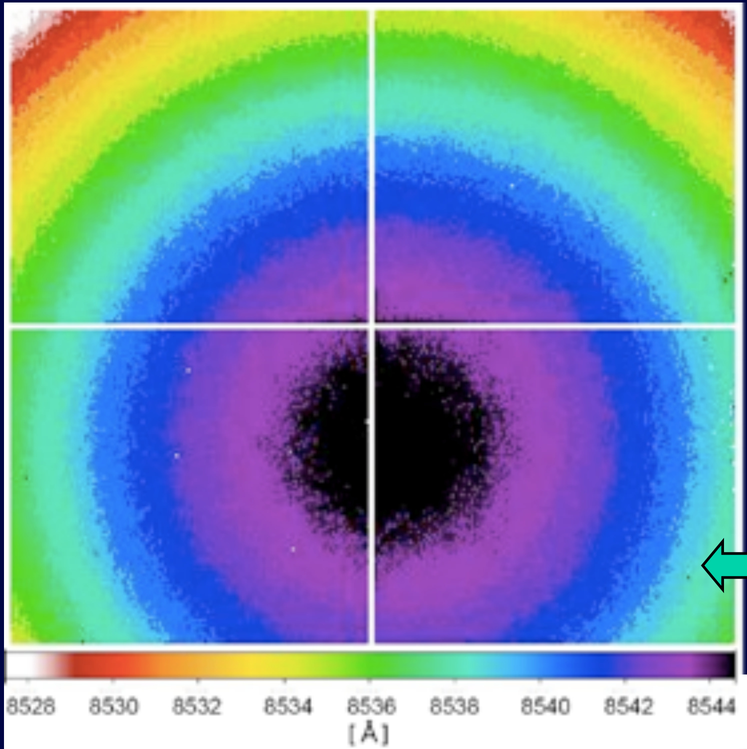
Calibration on diffuse sources

FOR DETAILS SEE: DUBE *ET AL.* 1979
BERNSTEIN *ET AL.* 2002
MATILLA 2003

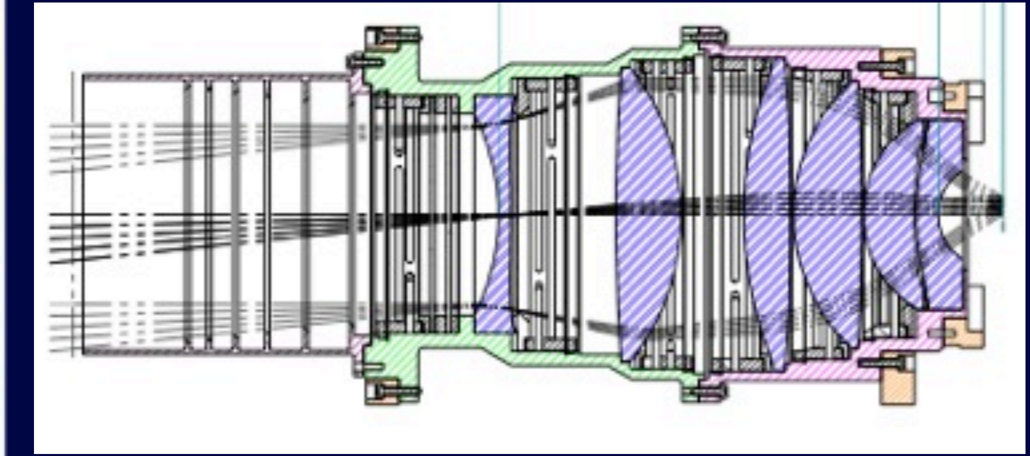


CIBER
Cosmic Infrared Background ExpeRiment

NARROW-BAND SPECTROMETER

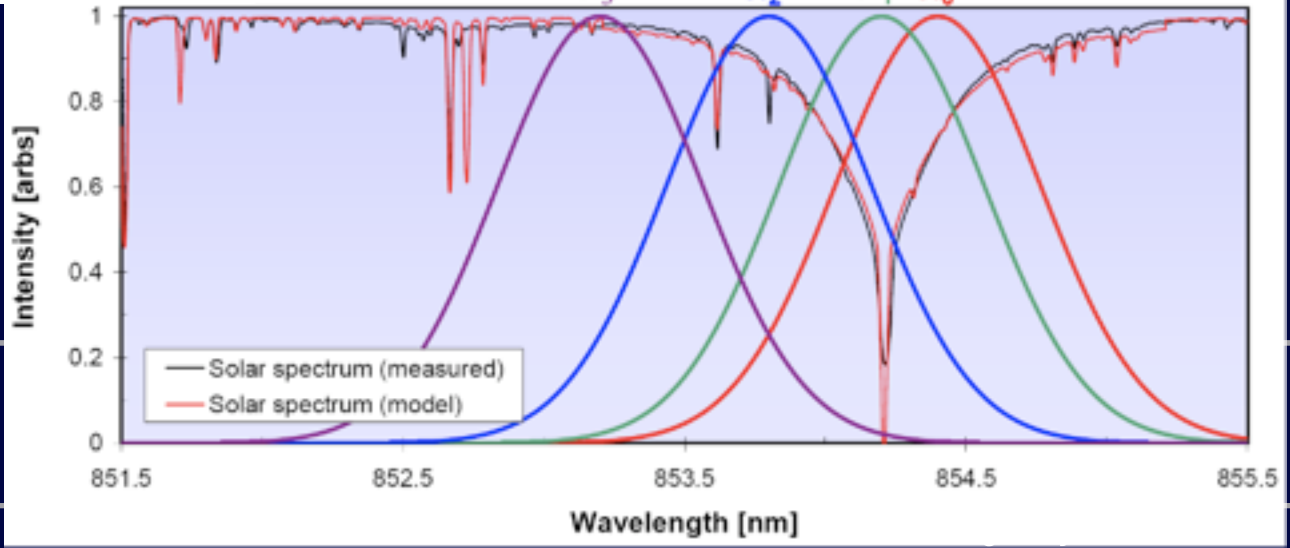


NIST calibration data
I(photo) ~ 30 e-/s



Science Goal:
Measure Fraunhofer Ca II 854.2 nm line EW to 1 % absolute

Solar Spectrum and Fraunhofer Lines

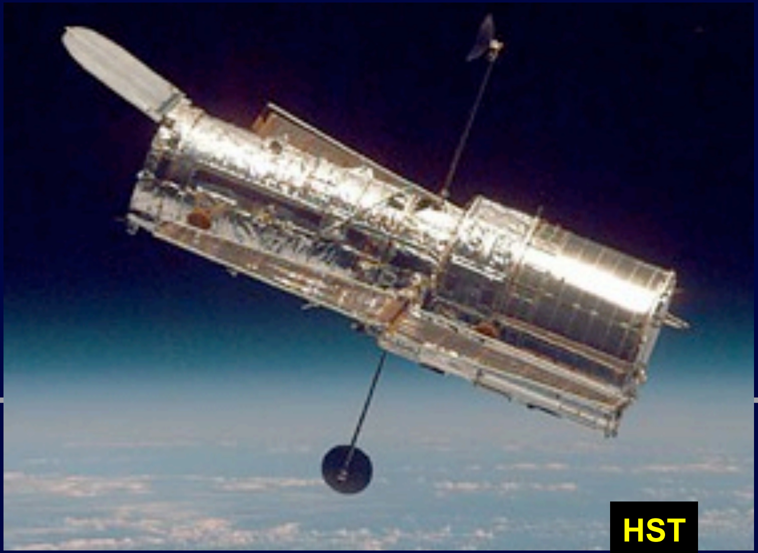


How can a rocket experiment compete with these?


SPITZER

IRTS


AKARI


HST

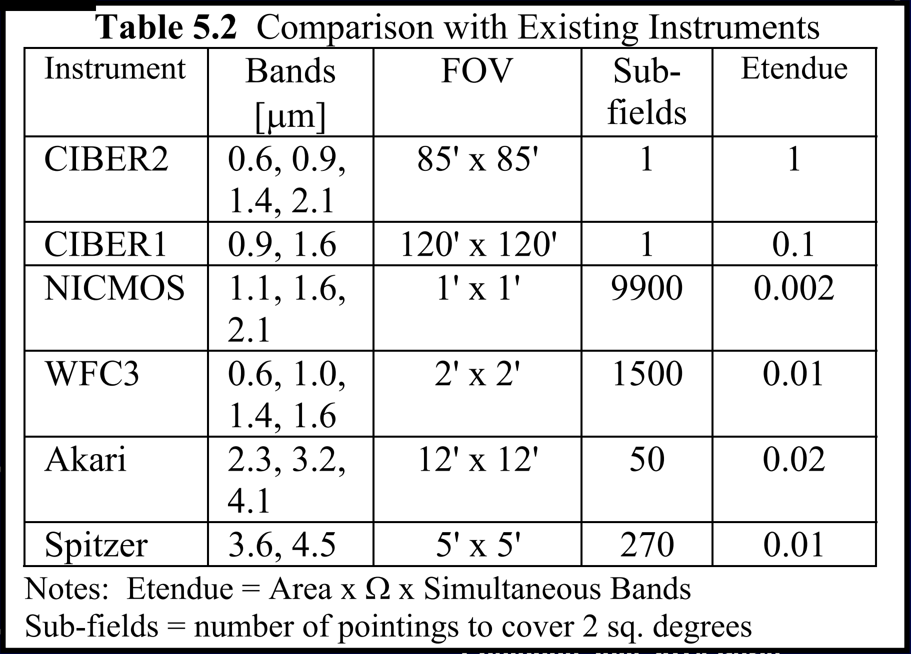


Table 5.2 Comparison with Existing Instruments

Instrument	Bands [μm]	FOV	Sub-fields	Etendue
CIBER2	0.6, 0.9, 1.4, 2.1	85' x 85'	1	1
CIBER1	0.9, 1.6	120' x 120'	1	0.1
NICMOS	1.1, 1.6, 2.1	1' x 1'	9900	0.002
WFC3	0.6, 1.0, 1.4, 1.6	2' x 2'	1500	0.01
Akari	2.3, 3.2, 4.1	12' x 12'	50	0.02
Spitzer	3.6, 4.5	5' x 5'	270	0.01

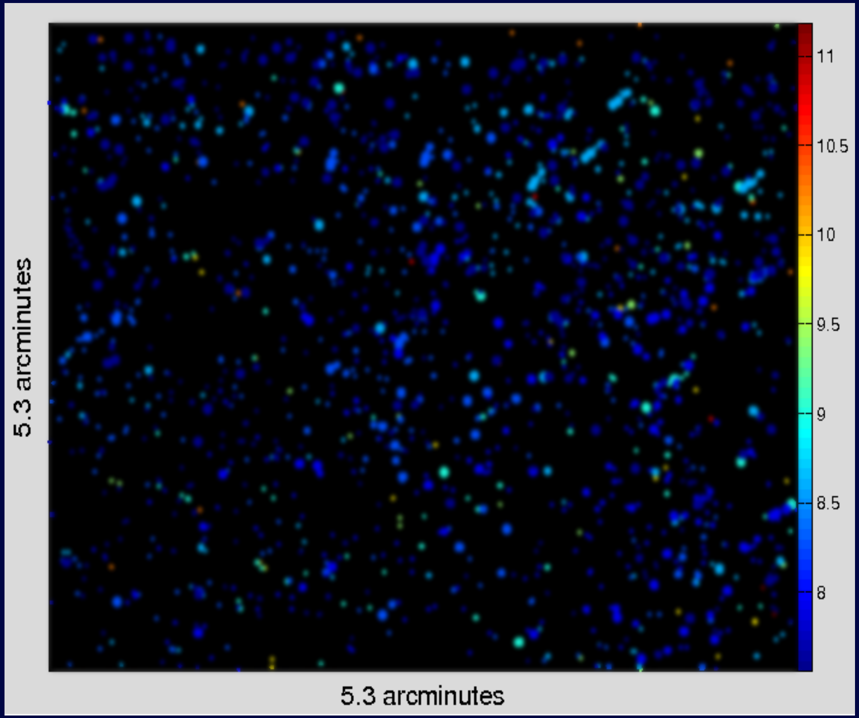
Notes: Etendue = Area x Ω x Simultaneous Bands
Sub-fields = number of pointings to cover 2 sq. degrees

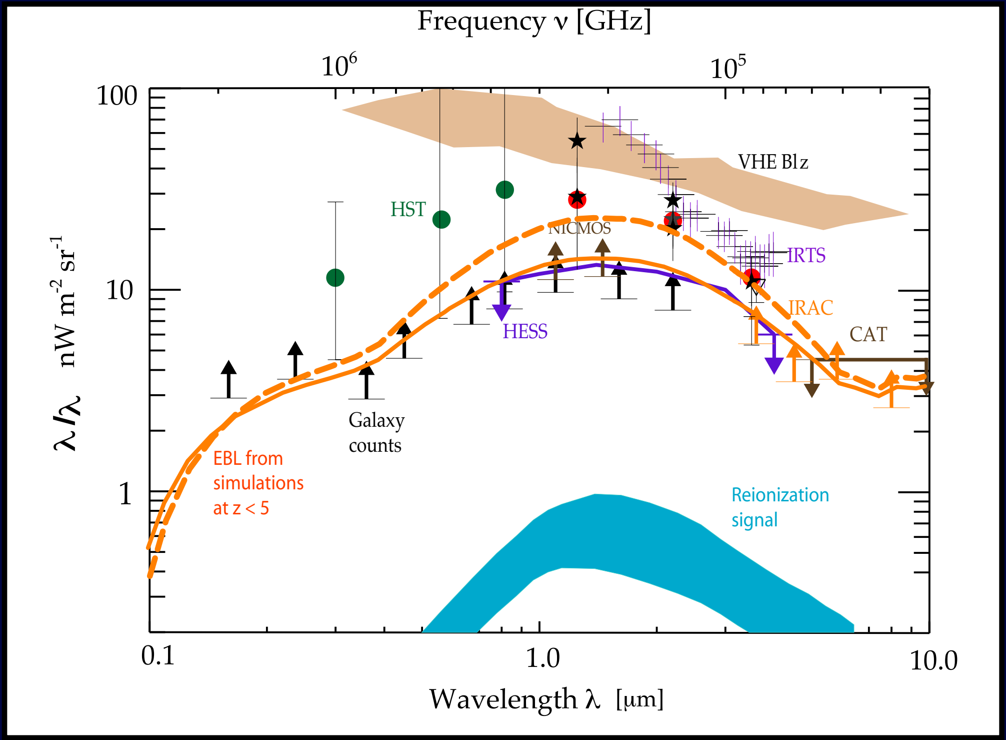
Twitter summary

CIBER will resolve controversy related to DIRBE and TeV EBL this year #wdm14

Why measure EBL to 1%?

Towards a definite signature of reionization





Two key features of the EBL reionization spectral signature:

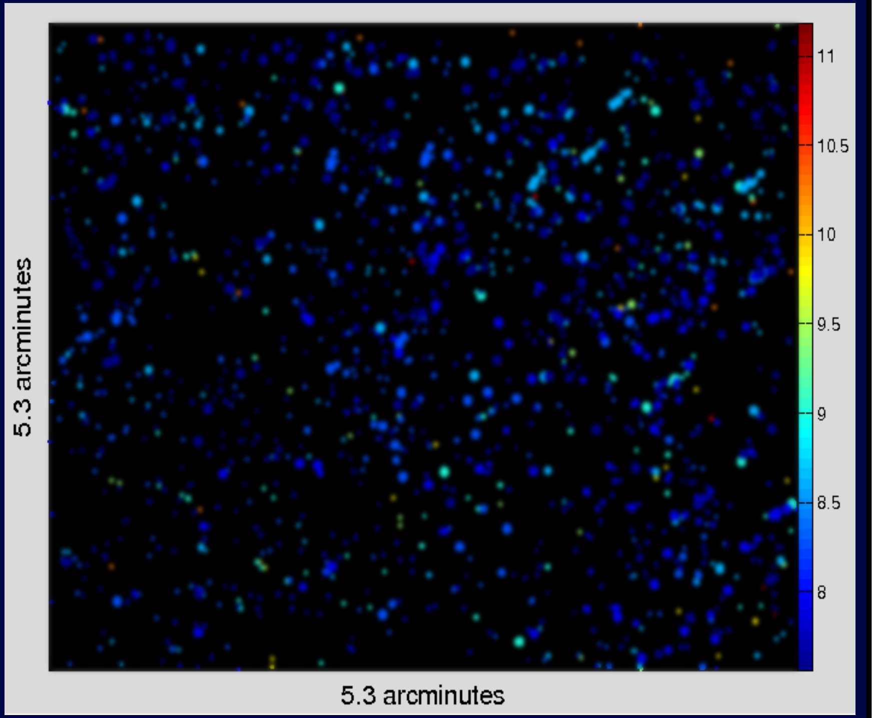
(a) Amplitude of the spectral signature probes the integrated SFR during reionization

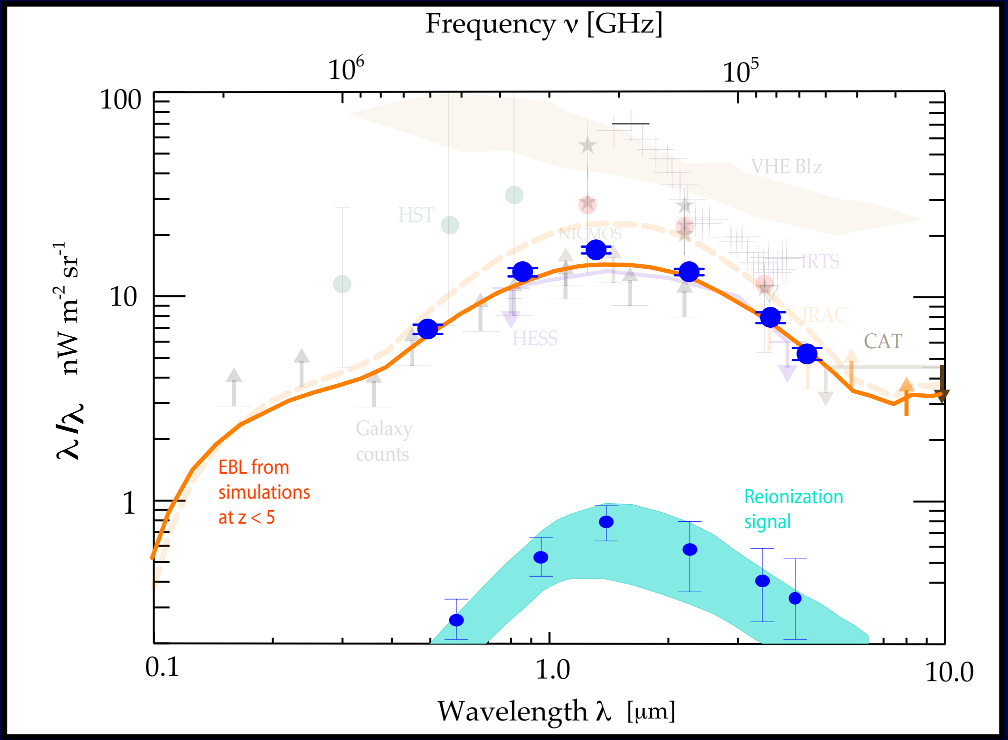
(b) Width of the spectral signature probes the redshift duration of reionization

These are complimentary to information from CMB polarization and the 21-cm background

Why measure EBL to 1%?

And the reionization signal is measurable





What do we need:

(a) A small aperture telescope with multi-wavelength coverage and observing outside of 5 AU

(b) absolute photometry and deep galaxy survey catalogs

ZEBRA

ZEBRA Mission Concept Study

Concept Study for Strategic Space Flight Science Missions

ZODIACAL DUST, EXTRAGALACTIC BACKGROUND AND REIONIZATION APPARATUS

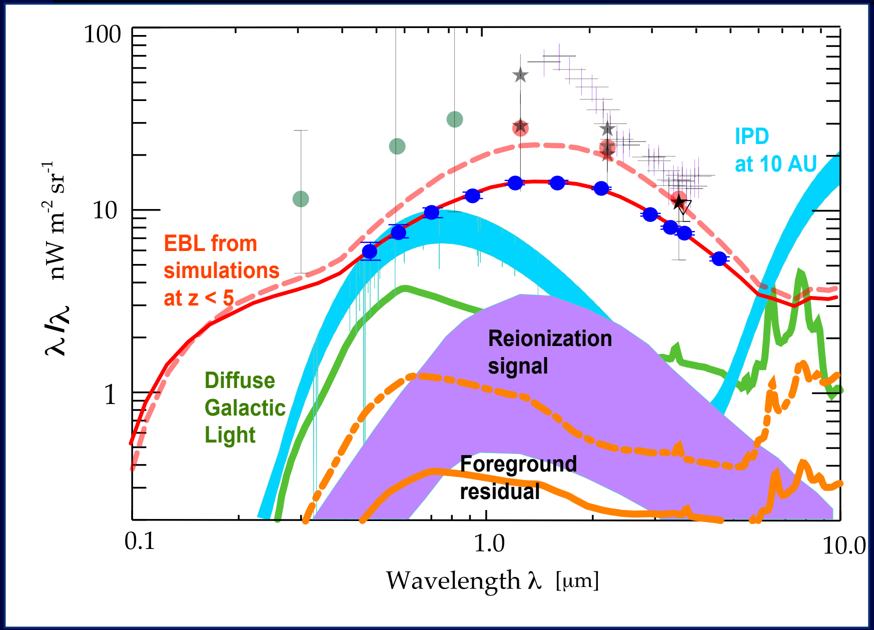
A Science Enhancement Option for an Outer Planet Discovery Mission

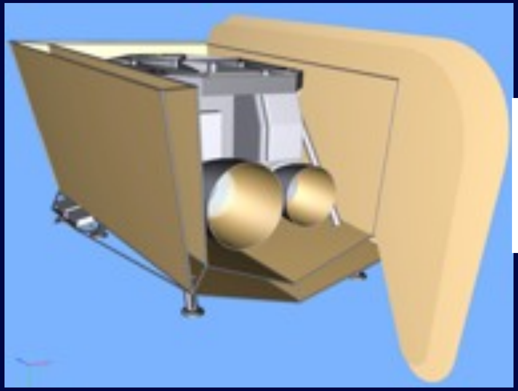
ZEBRA

Two Fundamental Science Goals in One Instrument to the Outer Planets

- **Extragalactic Background Light**
  - Measures galaxy history
  - Epoch of reionization galaxies
- **Zodiacal Dust**
  - Structure and origin of solar system dust
  - Detect and map Kuiper belt dust

- Platform: Outer planets mission to Saturn
- Description of payload instrumentation: Optical to near-infrared absolute photometer with 15 cm telescope; Wide field optical camera with 3 cm telescope
- Mission duration: 5-year outer planets cruise-phase
- Temperature: 50 K
- Pointing requirements: 0.5″ stability over 500 s.
- Data rate to ground (kbits/day): 0.5 Mbpd





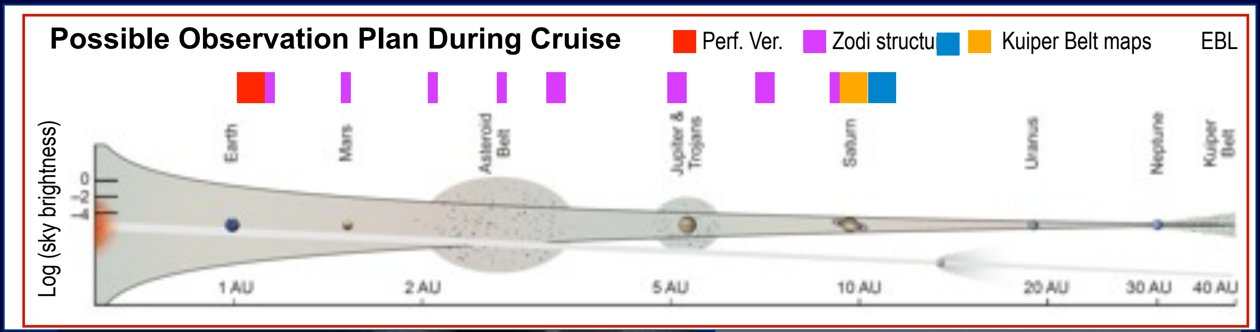
Optics: 15 cm & 3 cm off-axis
Wavelengths: 0.4 – 5 μm
Cooling: Passive to 50 K

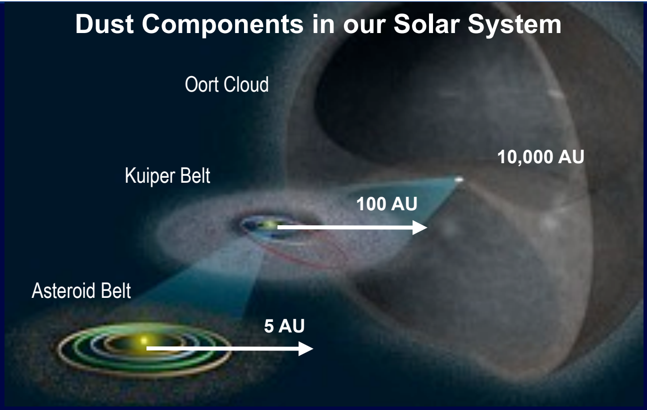
ZEBRA is a high-TRL instrument with minimum impact to host mission
- All key technologies demonstrated
- Well-defined interfaces
- ZEBRA engineers offset to net mass

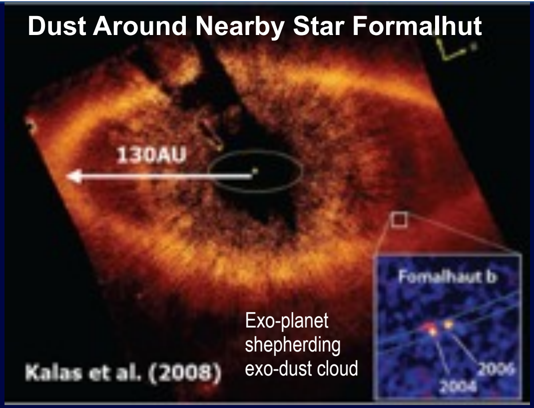
ZEBRA

Science and Hardware Implementation		
Jamie Bock	JPL/Caltech	ZEBRA PI
Robin Bruno	JPL	Project Manager
Larry Wade	JPL	Systems Engineer
Mike Zemcov	JPL	Instrument Scientist
Roger Smith	Caltech	IR Detectors
Christophe Sotin	JPL	
Kevin Hand	JPL	
Data Analysis and Archiving		
Ranga Chary	IPAC	Data archiving
Asantha Cooray	UC Irvine	EBL science
Bill Reach	USRA	Zodiacal science

Scientific Analysis and Oversight		
Chas Beichman	JPL/IPAC	Exo-Zodiacal systems
Mike Brown	Caltech	Kuiper Belt Objects
Mark Dickinson	NOAO	EBL & galaxy surveys
Eli Dwek	GSFC	EBL and Zodi modelling
Giovanni Fazio	CfA	Inst. Design; Spitzer/IRAC PI
Mike Hauser	STScI	EBL instrumentation; DIRBE PI
Carey Lisse	JHU/APL	Zodi structure & composition
Avi Loeb	Harvard	Reionization models
Brian May	Imperial	Zodi science and public outreach
Amaya Moro-Martin	SCIC	Kuiper belt dust models
Mike Werner	JPL	Spitzer PS experience for development
Ned Wright	UCLA	Zodi and stellar FGs; WISE PI


Possible Observation Plan During Cruise


Dust Components in our Solar System


Dust Around Nearby Star Formalhut

Exo-planet shepherding exo-dust cloud

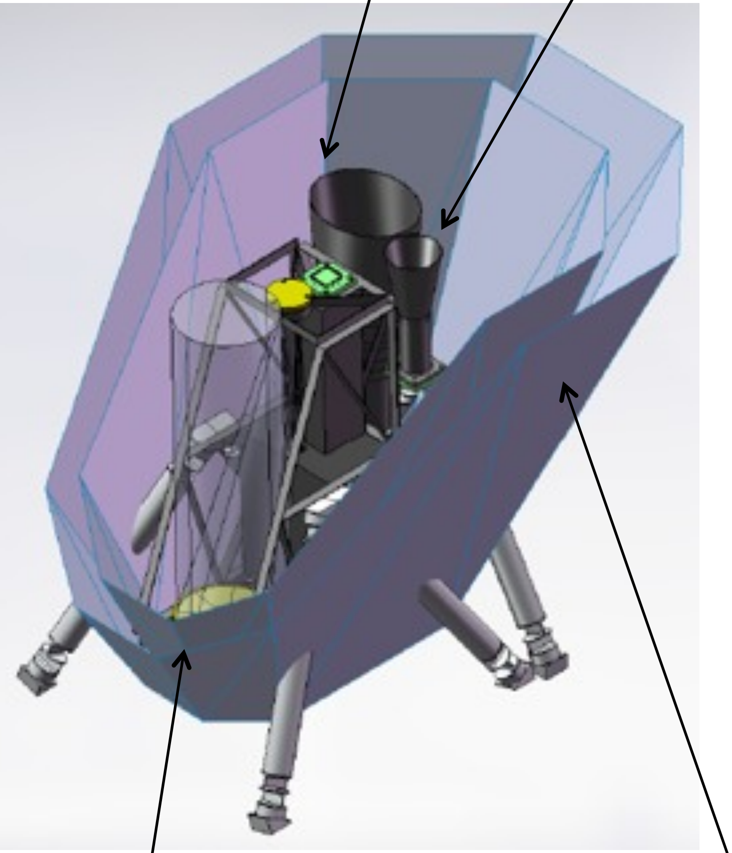
Kalas et al. (2008)

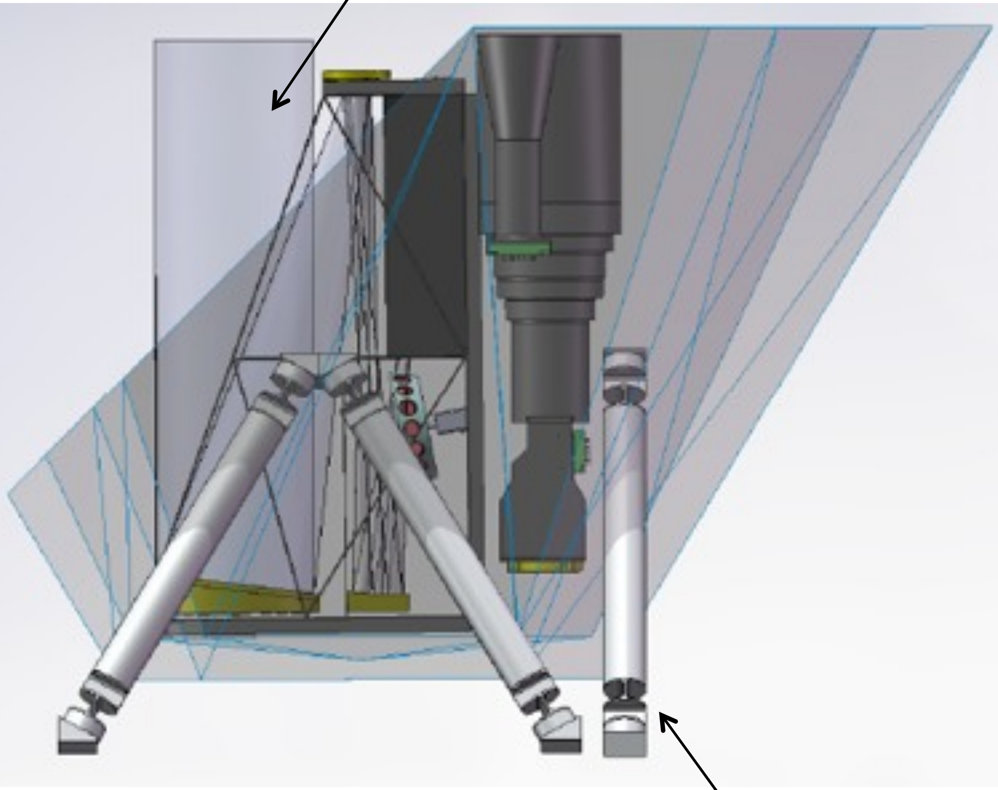
Instrument Overview

Fraunhofer Line Spectrometer

Wide-Field Camera

Absolute Photometer





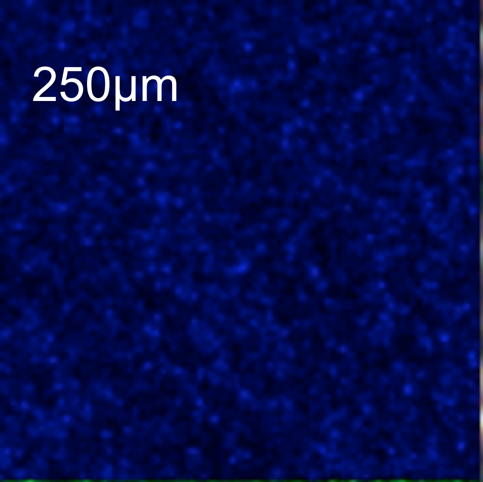
3-stage Passive Cooling System

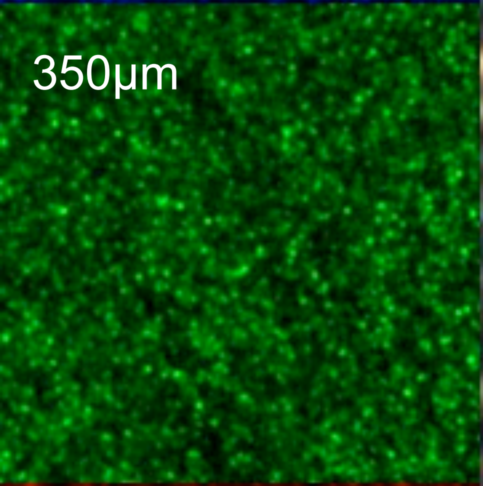
Kapton Radiation Shields (2)

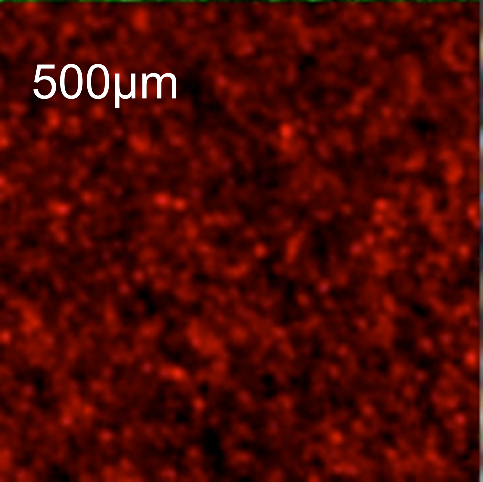
Support Struts

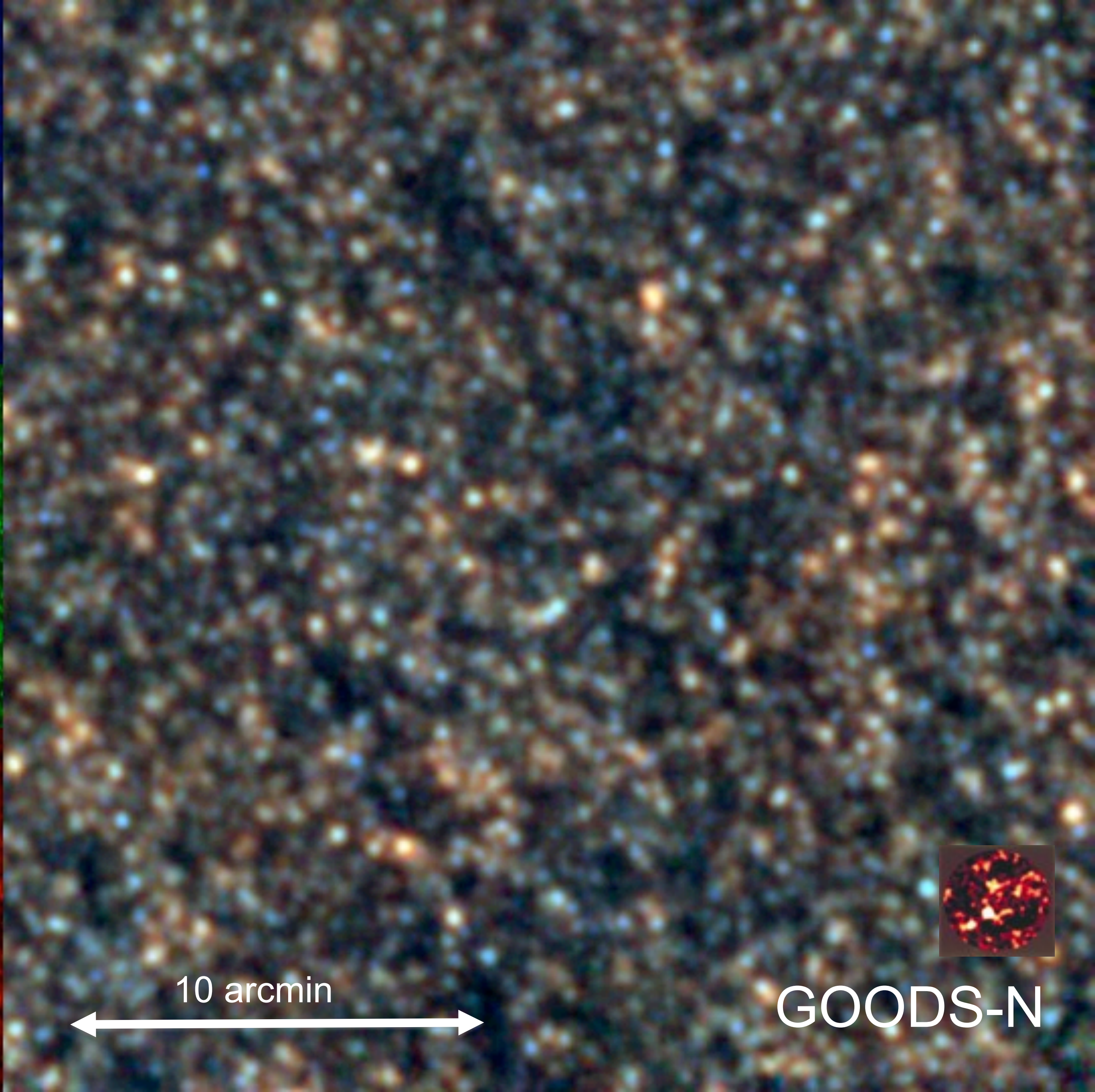
Twitter summary

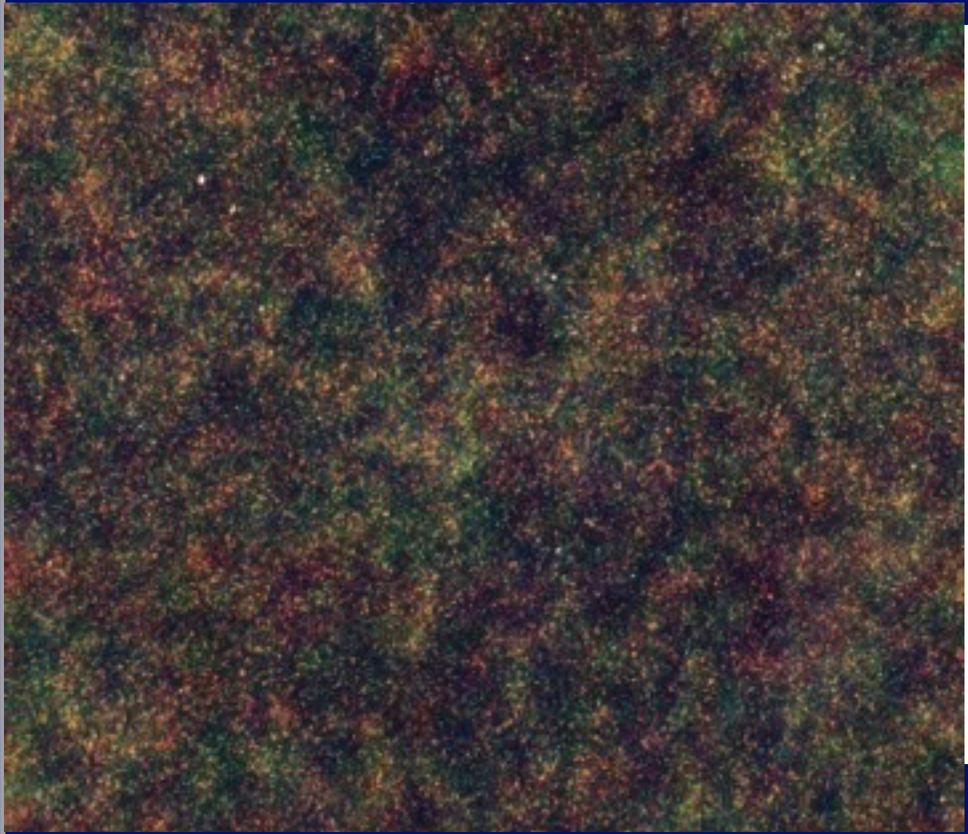
A small instrument to outer solar system is a must for a precise EBL measurement #wdm14


250μm

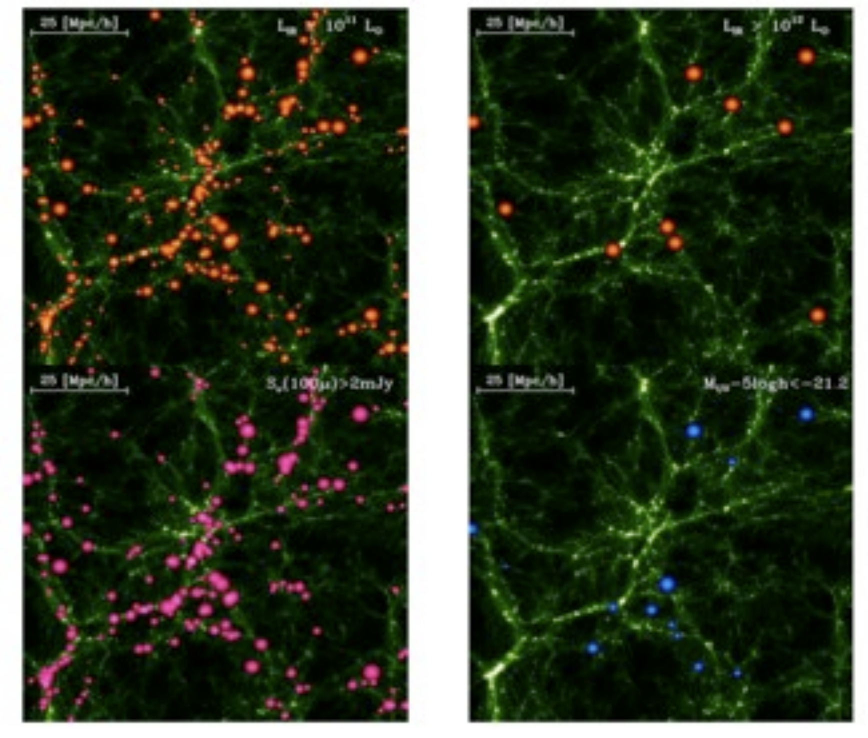

350μm


500μm


10 arcmin
GOODS-N



HerMES Lockman North



Lacey, C. et al. 2010, MNRAS, 405, 2

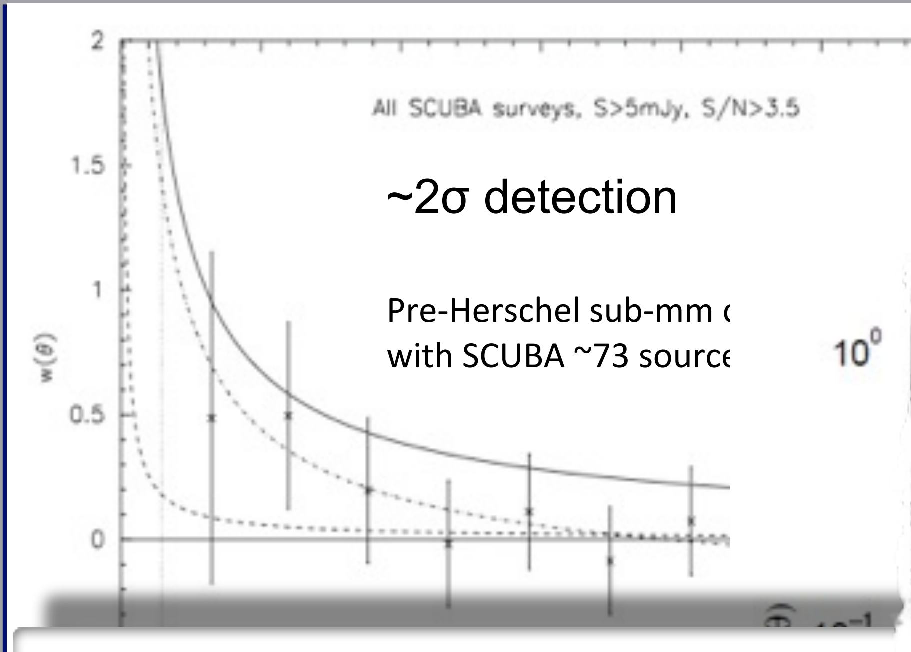
test specific predictions of clustering properties of starbursting galaxies

Where are the Starbursting Galaxies in the Universe?

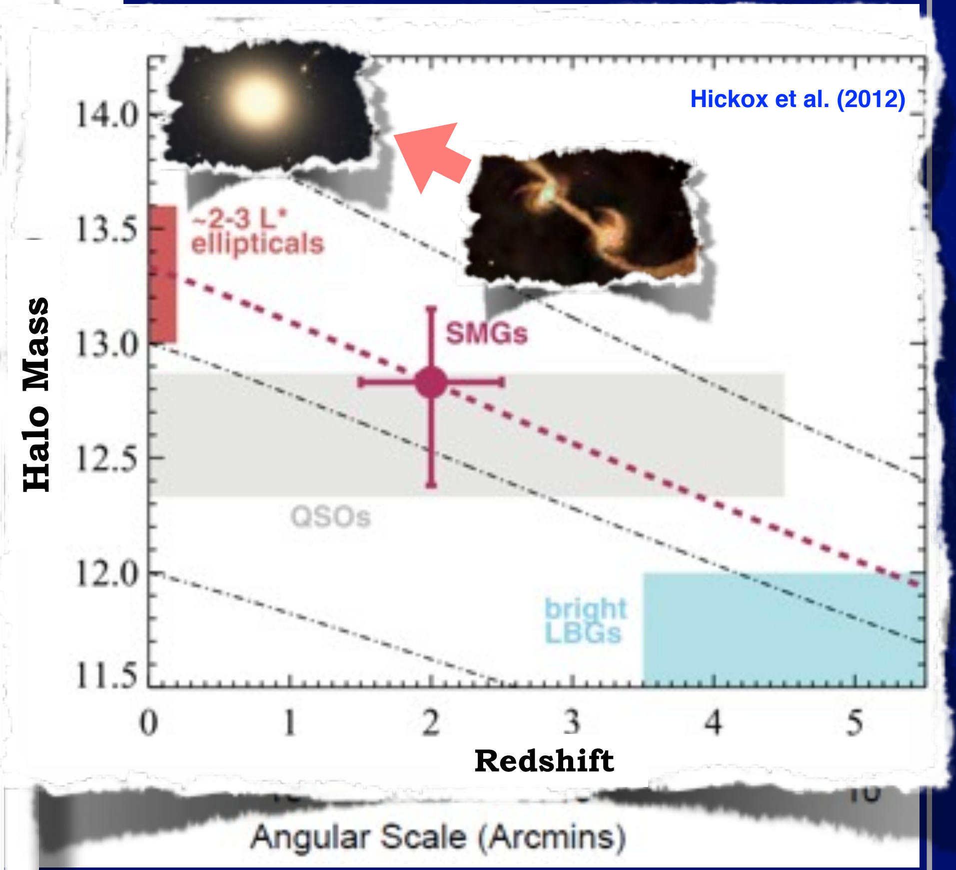
HALO MODEL REVIEW: COORAY, A. & SHETH, R. 2002, PHYSICS REPORTS, 372, 1

Angular Correlation Function

Scott, S. et al. 2006, MNRAS, 370, 1057



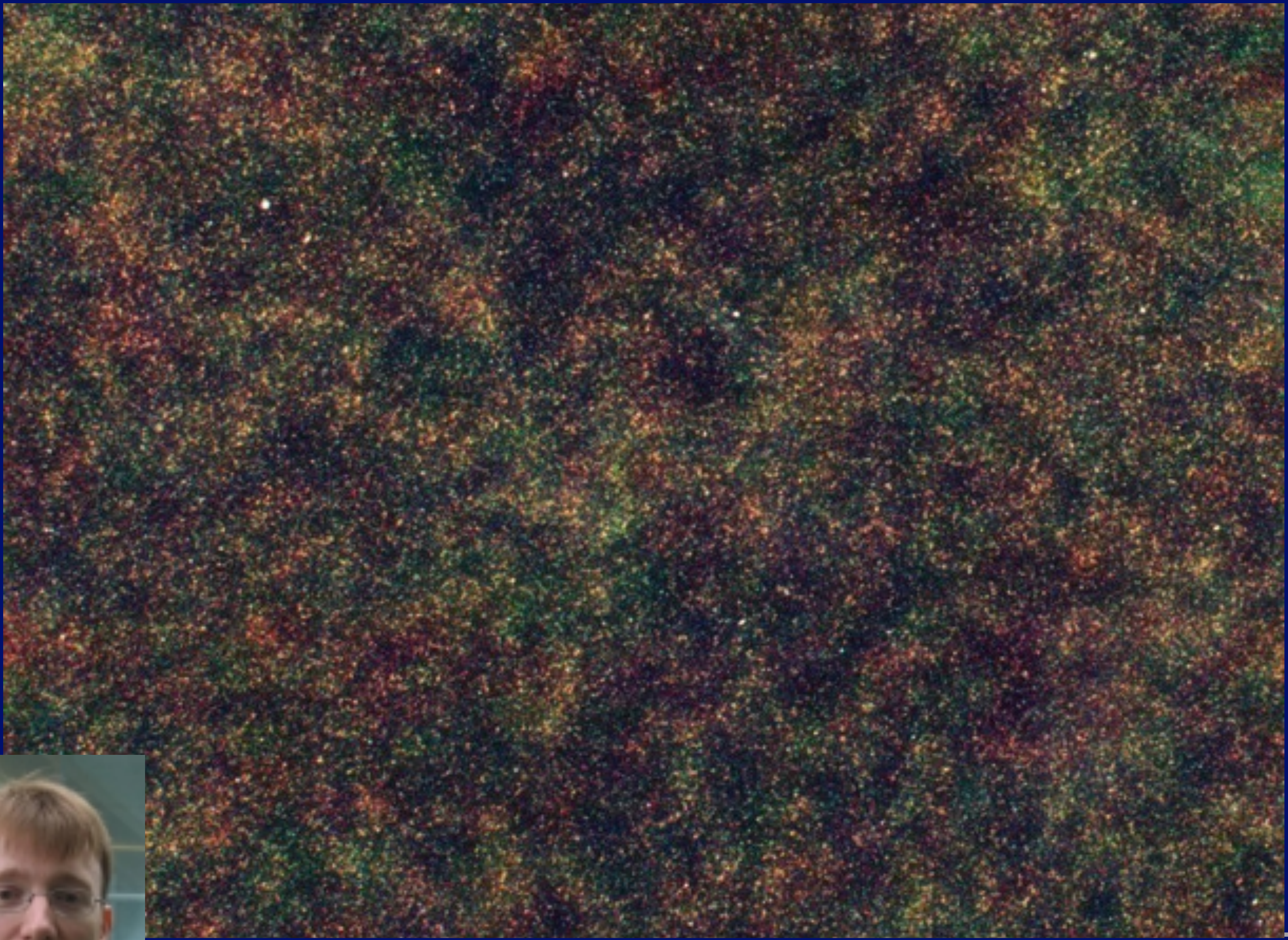
- **Dark matter halo hosting a S_{250} > 30 mJy galaxy ~ $10^{12.6}$ M_{solar}**
- **~15% appear as satellites in more massive halos ~ $10^{13.1}$ M_{solar}**
- ***Evolutionary path is z~2 S_{250} ~ 30 mJy Herschel source will evolve to be (2-5)L_{star} elliptical galaxy at z~0***



Cooray, A. et al. 2010, A&A, 518, L22

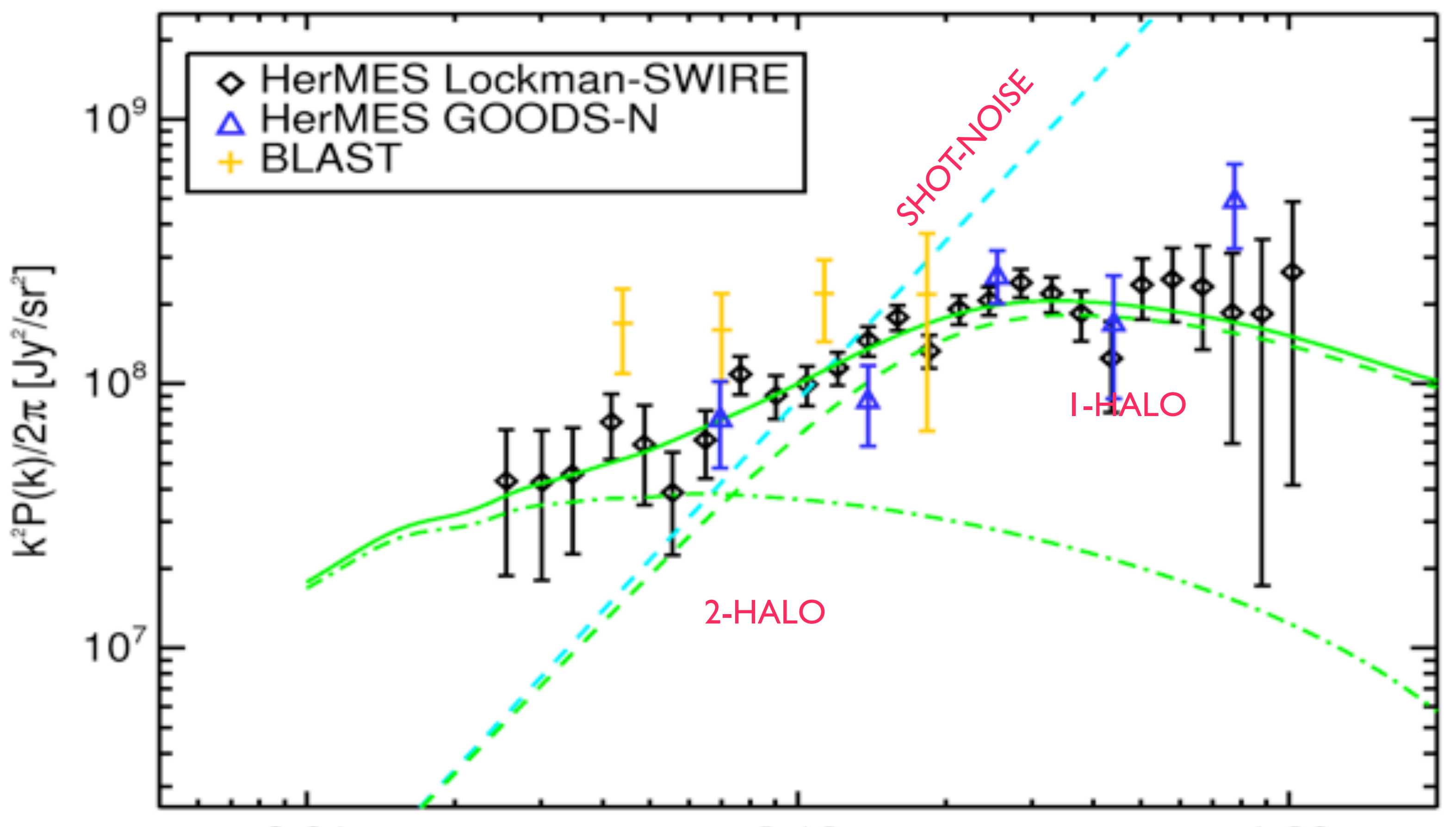
Where are the Starbursting Galaxies in the Universe?

HALO MODEL REVIEW: COORAY, A. & SHETH, R. 2002, PHYSICS REPORTS, 372, 1



Cosmic Infrared Background Fluctuations with SPIRE

Amblard et al. 2011, Nature; Thacker et al. 2013

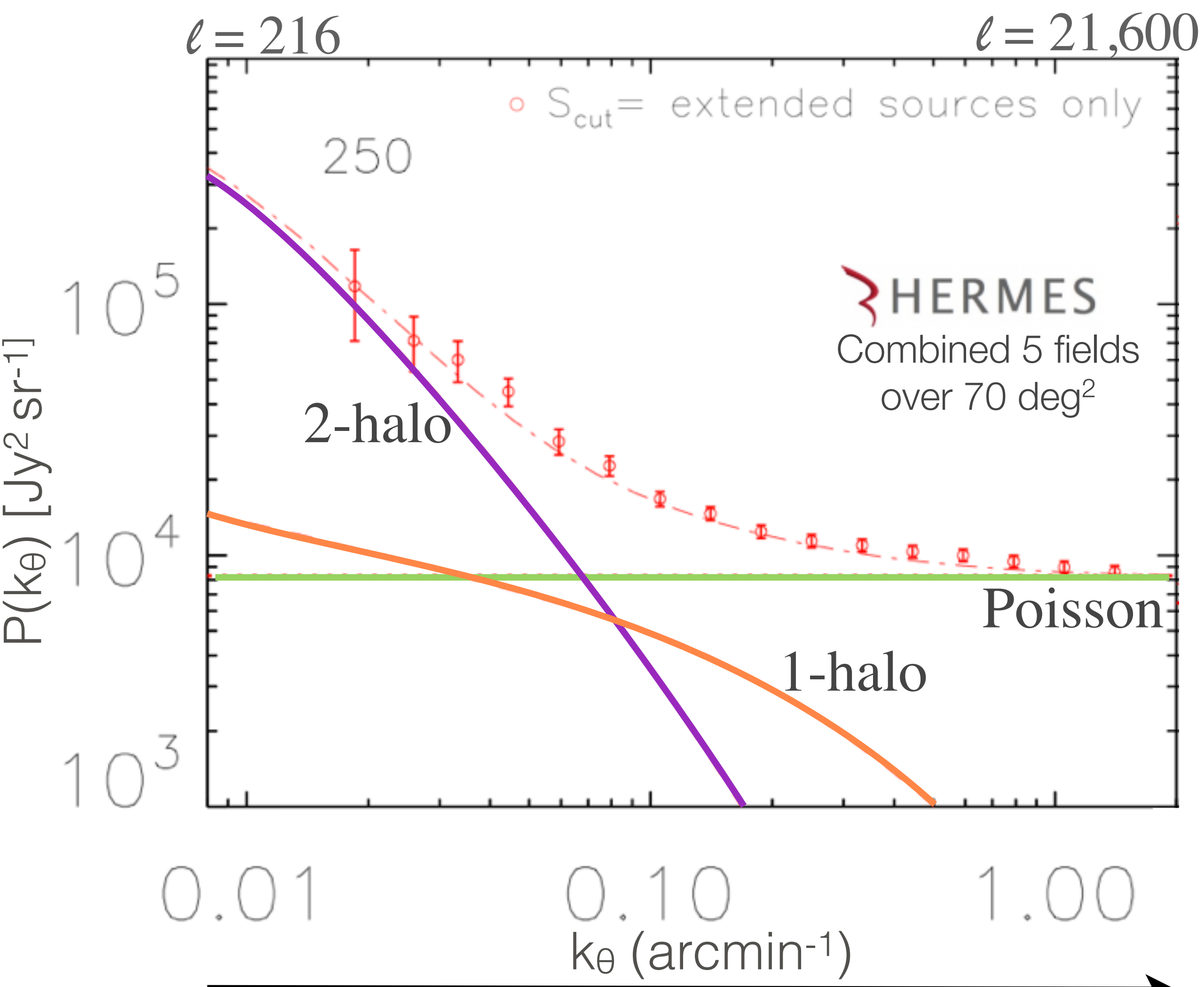


Cosmic Infrared Background Fluctuations with SPIRE

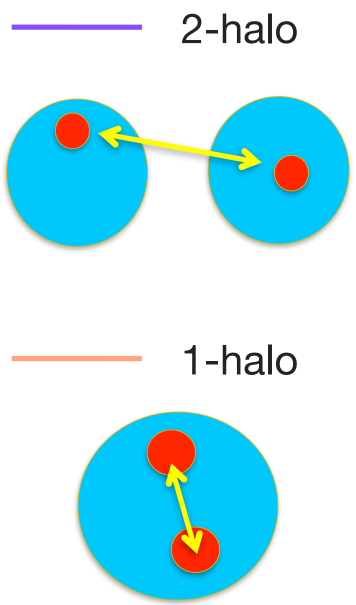
Amblard et al. 2011, Nature; Thacker et al. 2013

Cosmic Infrared Background Fluctuations with SPIRE

Viero et al. 2012



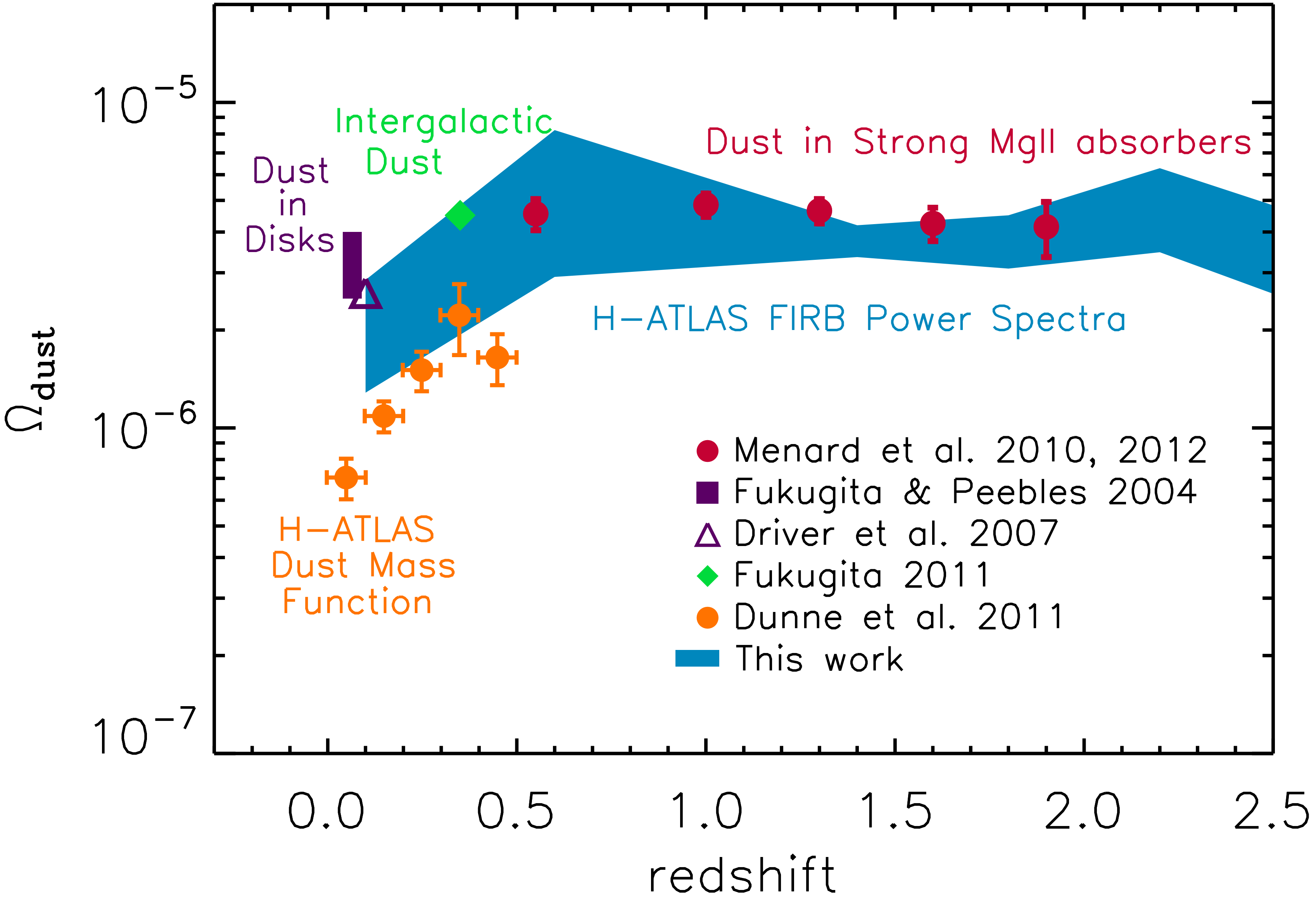
Smaller Scales



Halo Model: see e.g., Cooray & Sheth (2000), Zehavi et al. (2005, 2008)

Amblard et al. 2011, Nature; Thacker et al. 2013

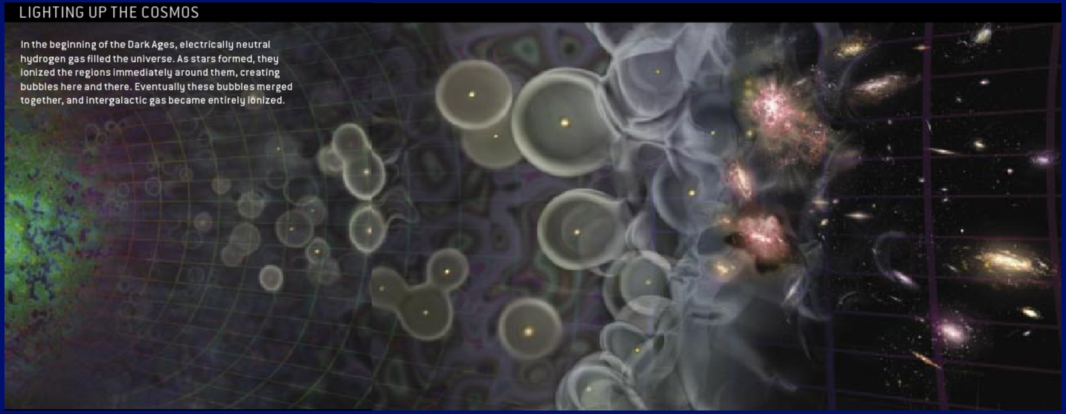
Cosmic Infrared Background Fluctuations = Dust Content



Twitter summary

Herschel anisotropies are consistent with dust abundance from SDSS QSO reddening #wdm14

Atomic and Molecular Lines as a Probe of Reionization


LIGHTING UP THE COSMOS

In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

CO probe based on

Yan Gong, Asantha Cooray, Marta Silva, Mario Santos, Philip Lubin

Probing Reionization with Intensity Mapping of Molecular and Fine Structure Lines

Astrophysical Journal Letters, 728, L46-L51 (2011).
(see also Chris Carilli, arxiv.org:1102.0745; Lidz et al. arxiv.org:1104.4800)

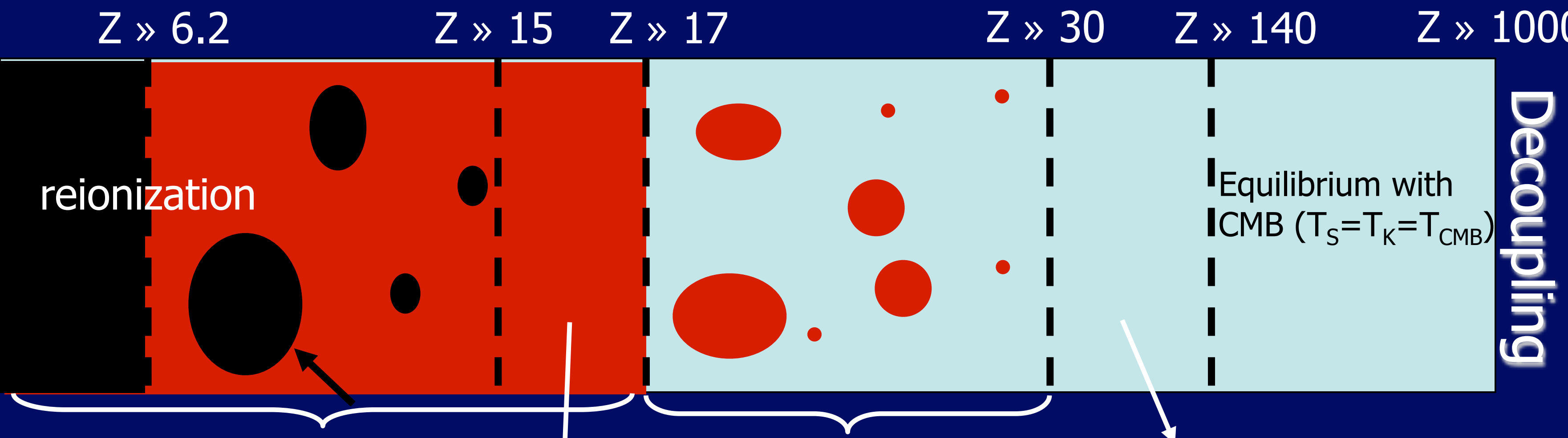
CII probe based on

Yan Gong, Asantha Cooray, Marta Silva, Mario Santos, Jamie Bock, Matt Bradford, Mike Zemcov

Intensity Mapping of the [CII] Fine Structure Line During The Epoch of Reionization

ApJ 2011, arxiv.org:1107.3553

21-cm Signal (Spin temperature)

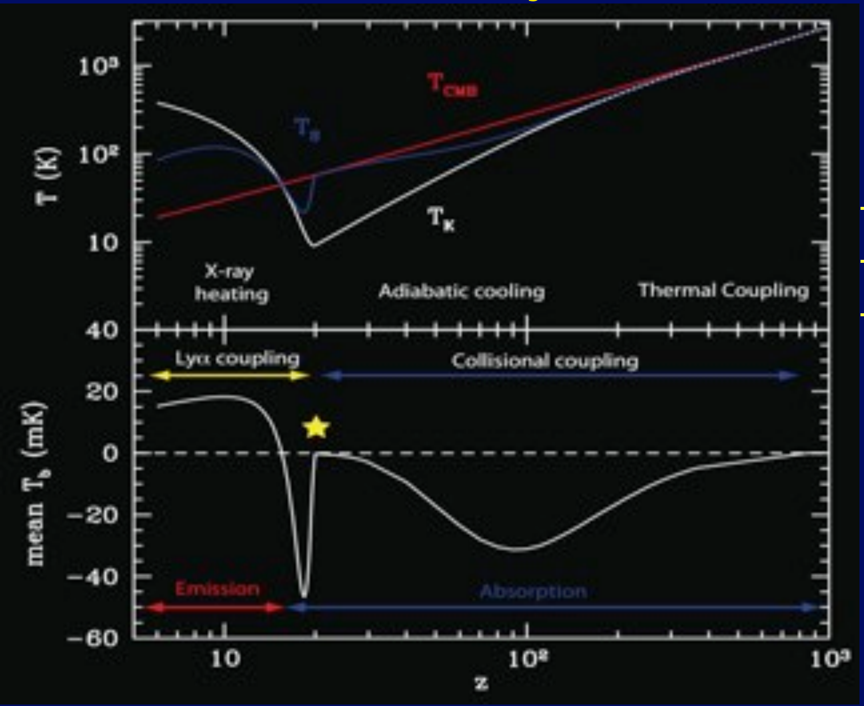


$T_S=T_K >> T_{CMB}$ (shock heating and X-ray emission)

Good for cosmology?...of interest to next-generation 21-cm

Star formation Ly$_a$: $T_S=T_{Lya}= T_K$

$T_S=T_K$ (collisions), but $T_K < T_{CMB}$ (adiabatic cooling) **Good for cosmology**! ("theory dream land") a probe of primordial density perturbations better than CMB (detection: ~SKA@Moon?)



- Useful timescales: (say at z~15)

– Radiative	$t_{rad} = T_*/A_{10}T_{cmb}$	~ 3×10^4 yrs
– Spin-changing collision	$t_c = 1/n_{HI}\langle\sigma_{10}v\rangle$	~ 3×10^5 yrs
– Hubble	$t_H = H^{-1}$	~ 7×10^8 yrs

- Spin temperature (with Lyα coupling x_α):

$$T_s^{-1} = \frac{T_{cmb}^{-1} + x_c T_k^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_c + x_\alpha};$$

$$x_c = \frac{t_{rad}}{t_c} = \frac{T_* n_{\mathrm{HI}}\langle\sigma_{10}v\rangle(T_k)}{T_{cmb}A_{10}}$$

(Mario Santos)

Experiments

LOFAR (Low-frequency Array)

Netherlands

PAPER (all sky with dipoles)

South Africa (US-led)

MWA (Mileura Wide-Field Array)

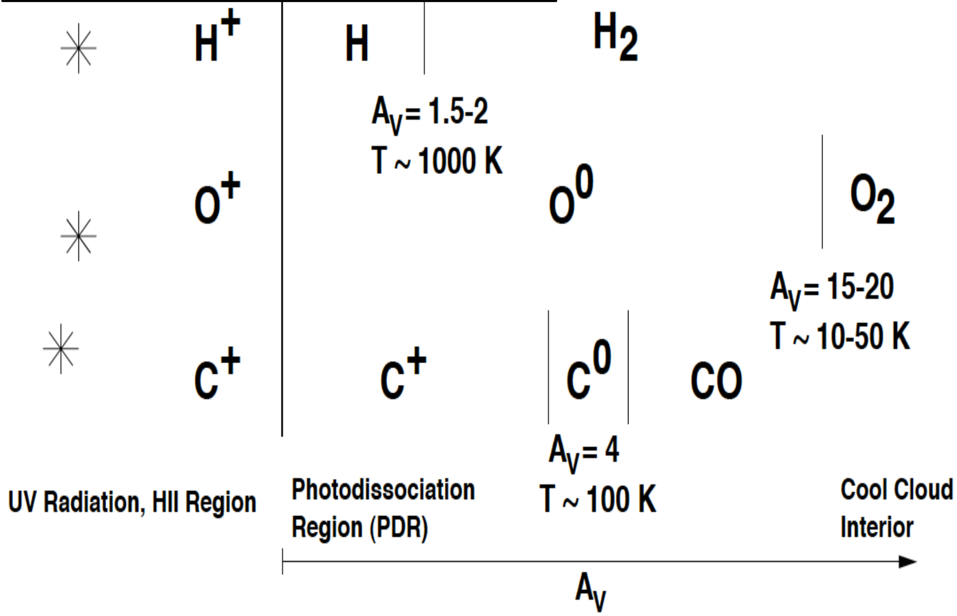
Australia (joint US-Australia)

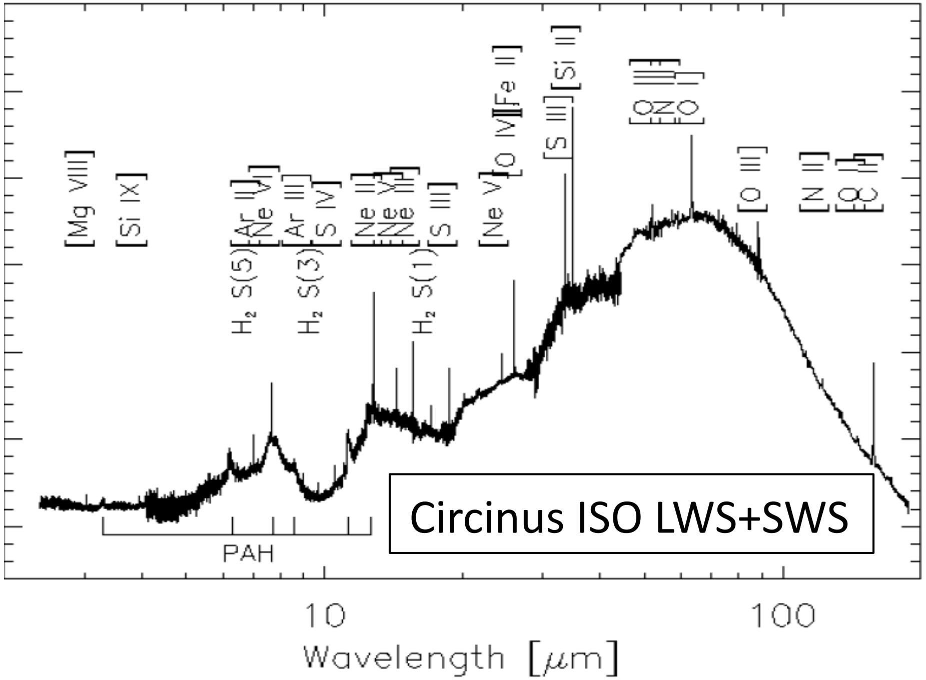
SKA (Square Kilometer Array)

International collaboartion - site testing

C+ and fine-structure lines in galaxies

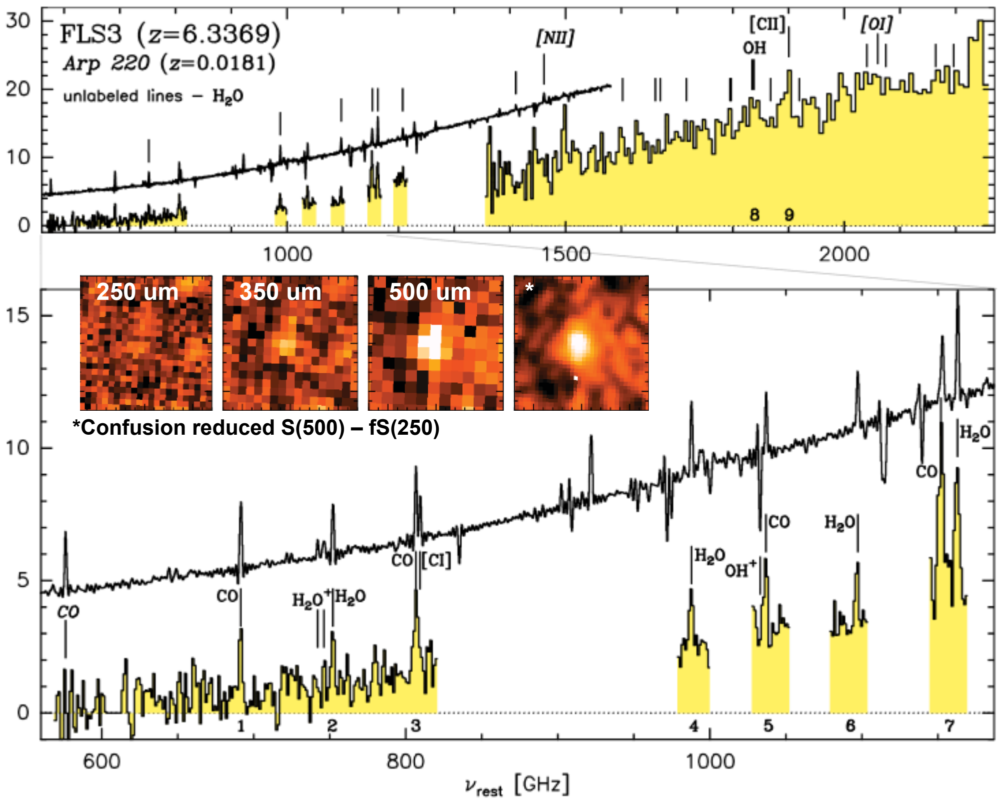
Photodissociation region

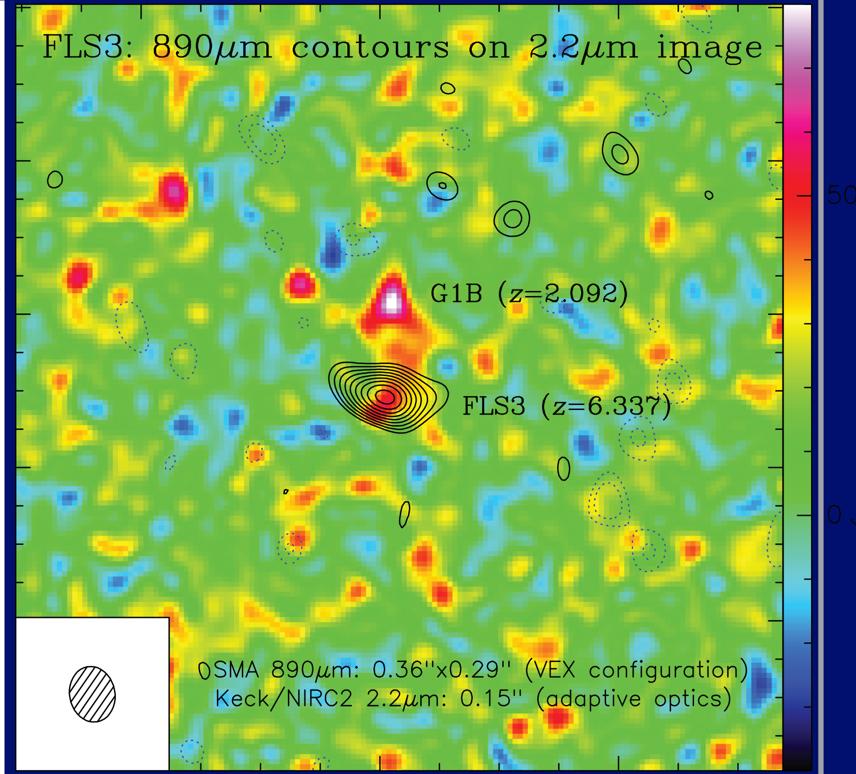




Circinus ISO LWS+SWS

- C+ ionization potential 11.6 eV, so it exists in neutral gas where much of the energy is input into the interstellar medium.
  - Easily thermalized with a critical density of 3e3 H_2 cm^{-3} or ~50 e^- cm^{-3}
  - Dense photo-dissociation regions: regions, C-ionizing photon density is set by dust extinction
    - C+ carries a large fraction of the gas cooling (30-50%, (of the 1% of the total))
  - Among the most luminous spectral line in the spectra of galaxies.
    - -> less dust to gas means more C+.
- Also traces diffuse ionized gas.





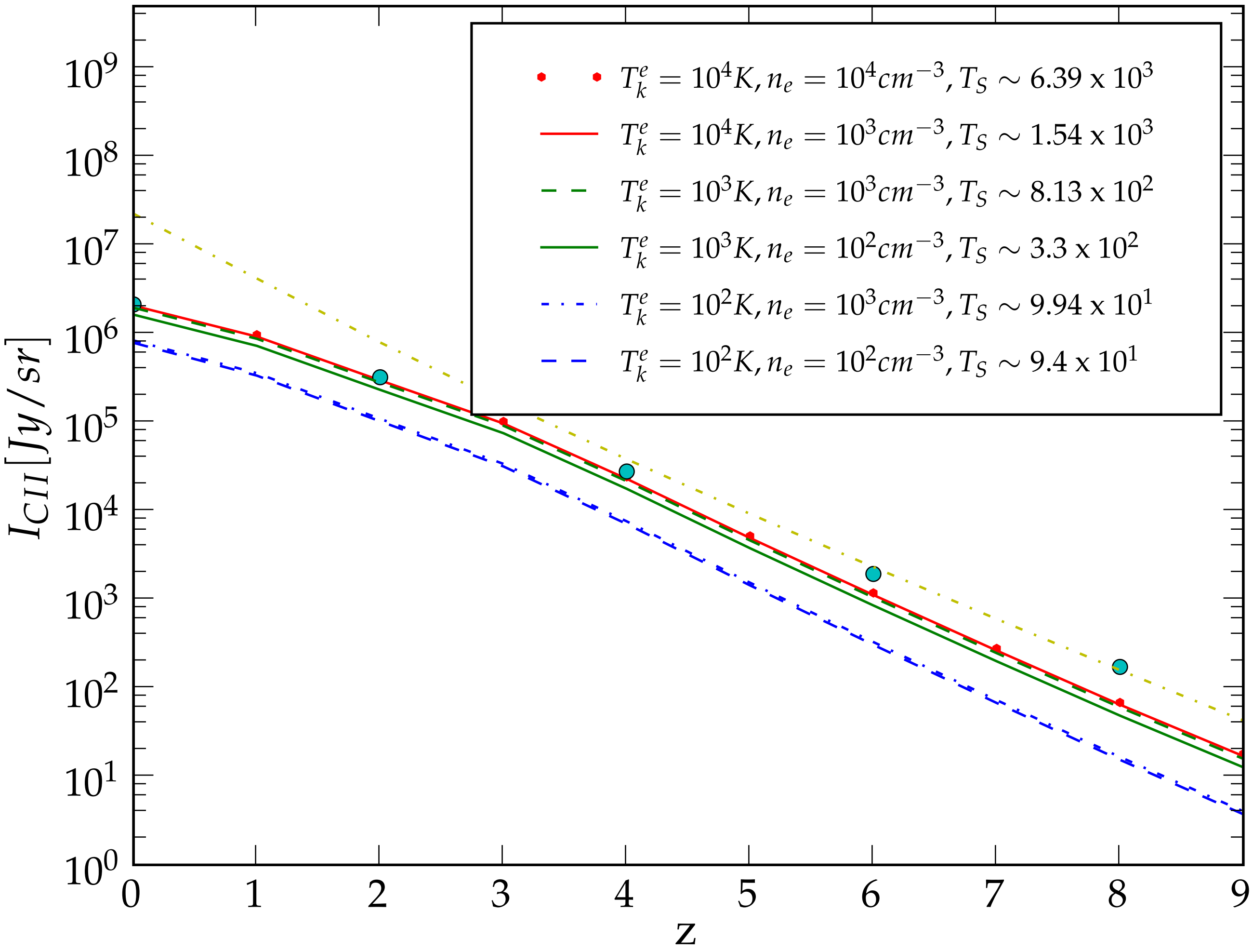
- **Highest redshift CII 158 micron detection to-date.**

- **CII intensity mapping experiment will be sensitive to fainter galaxies like these.**

z = 6.34 Dusty Starburst Galaxy in HerMES

Riechers, D., Cooray et al. 2013 Nature

Mean CII intensity as a function of redshift

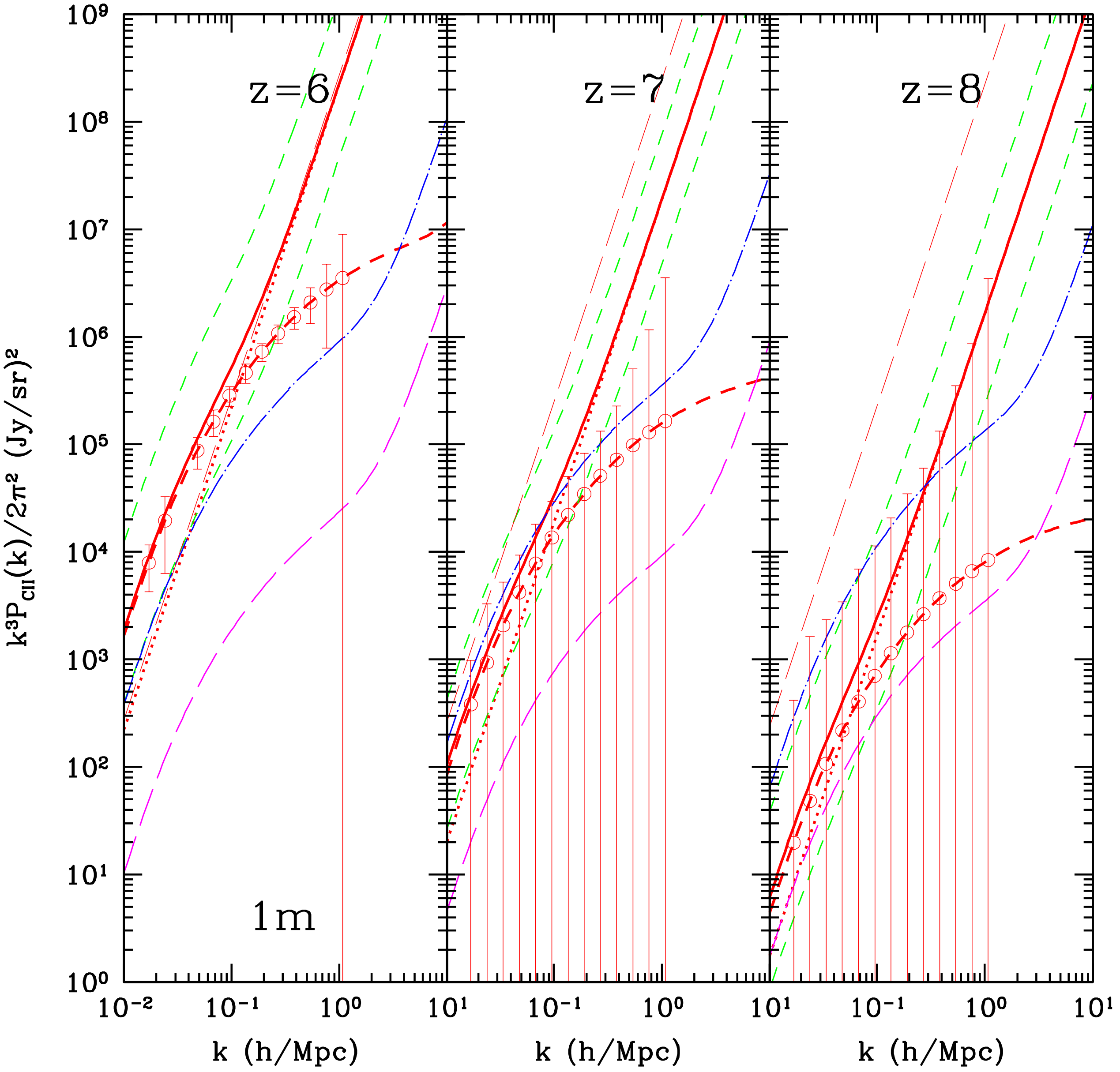


Lines analytical with
Z ~ $10^{-0.5z}$
and 30% of gas in
galaxies above critical
density

Independent estimates
agree at the level of a
factor of 10:
(a) SFR converted to CII
(b) Sub-mm number
counts + SED

Integrated signal dominated by low-luminosity galaxies
not ULIRG-type galaxies.

CII intensity fluctuations



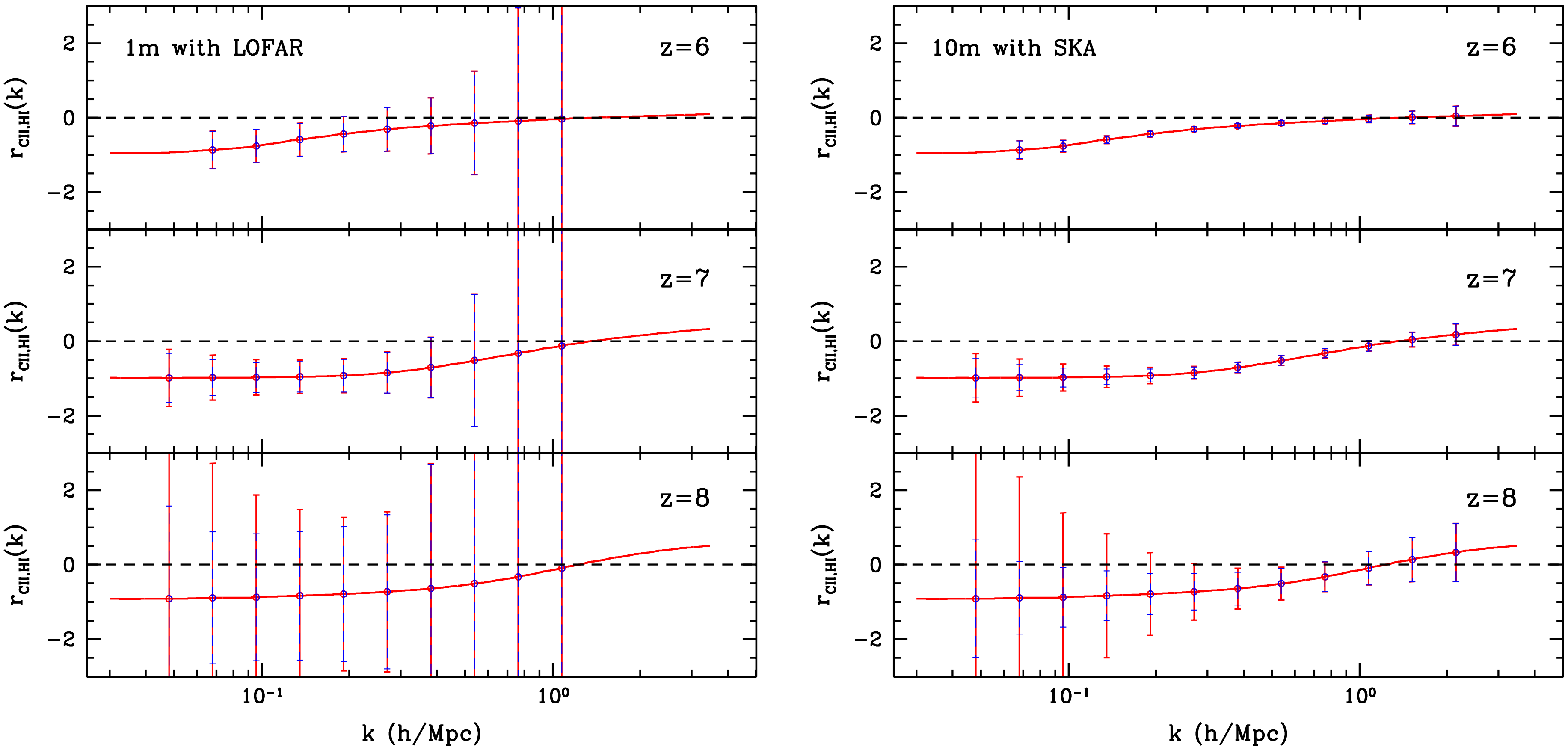
CII galaxies trace the large-scale structure

Red line our semi-analytic simulation with green lines showing uncertainty.

Blue and purple lines scale CO fluctuations to CII under assumptions on luminosity ratio.

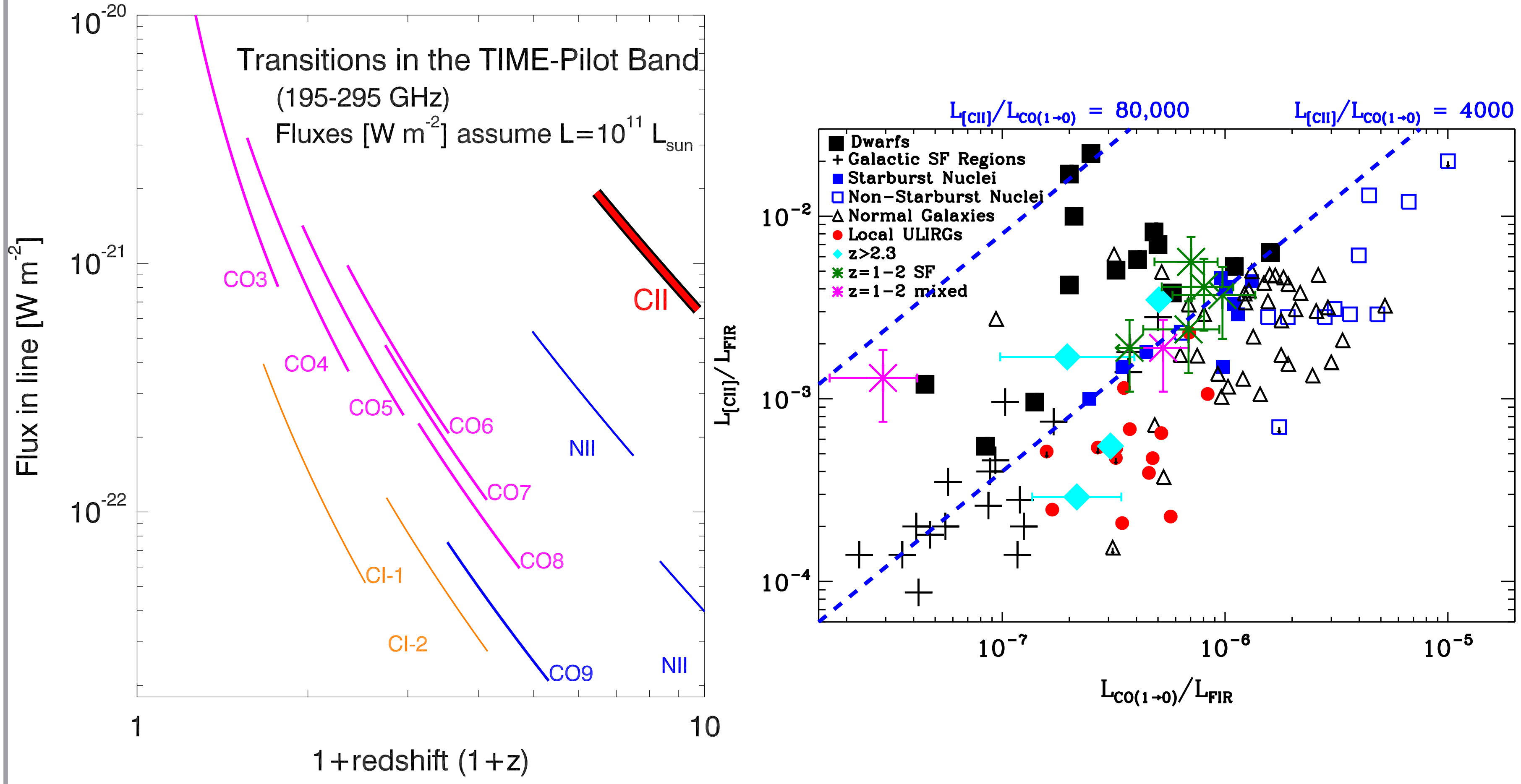
Errors from a concept experiment.

CII - 21cm cross-correlation

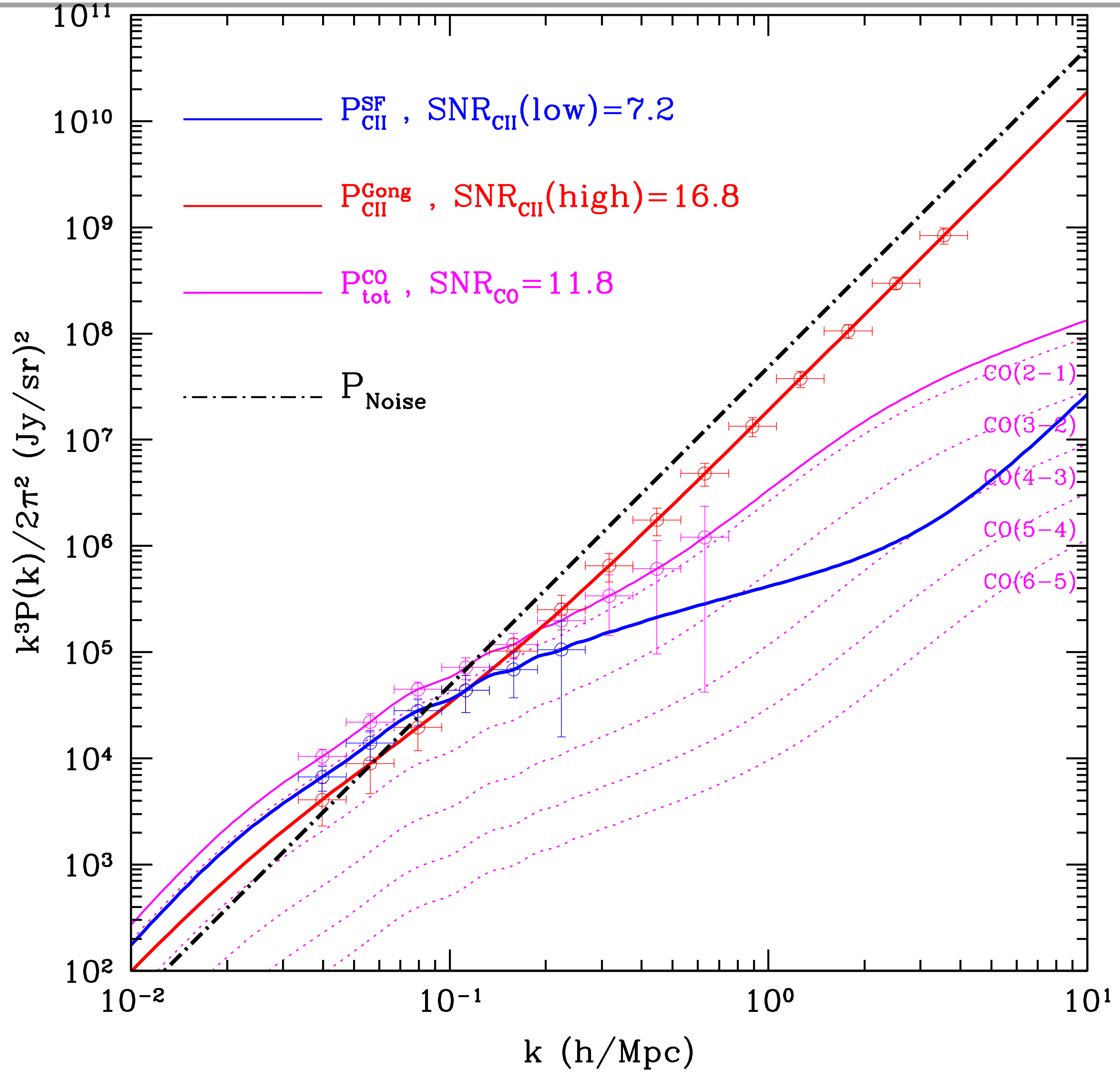


The cross-correlation allows: (a) measurement of x_i - ionized fraction, (b) the ionized bubble size, (c) the number of CII galaxies in each ionization bubble, all as a function of redshift.

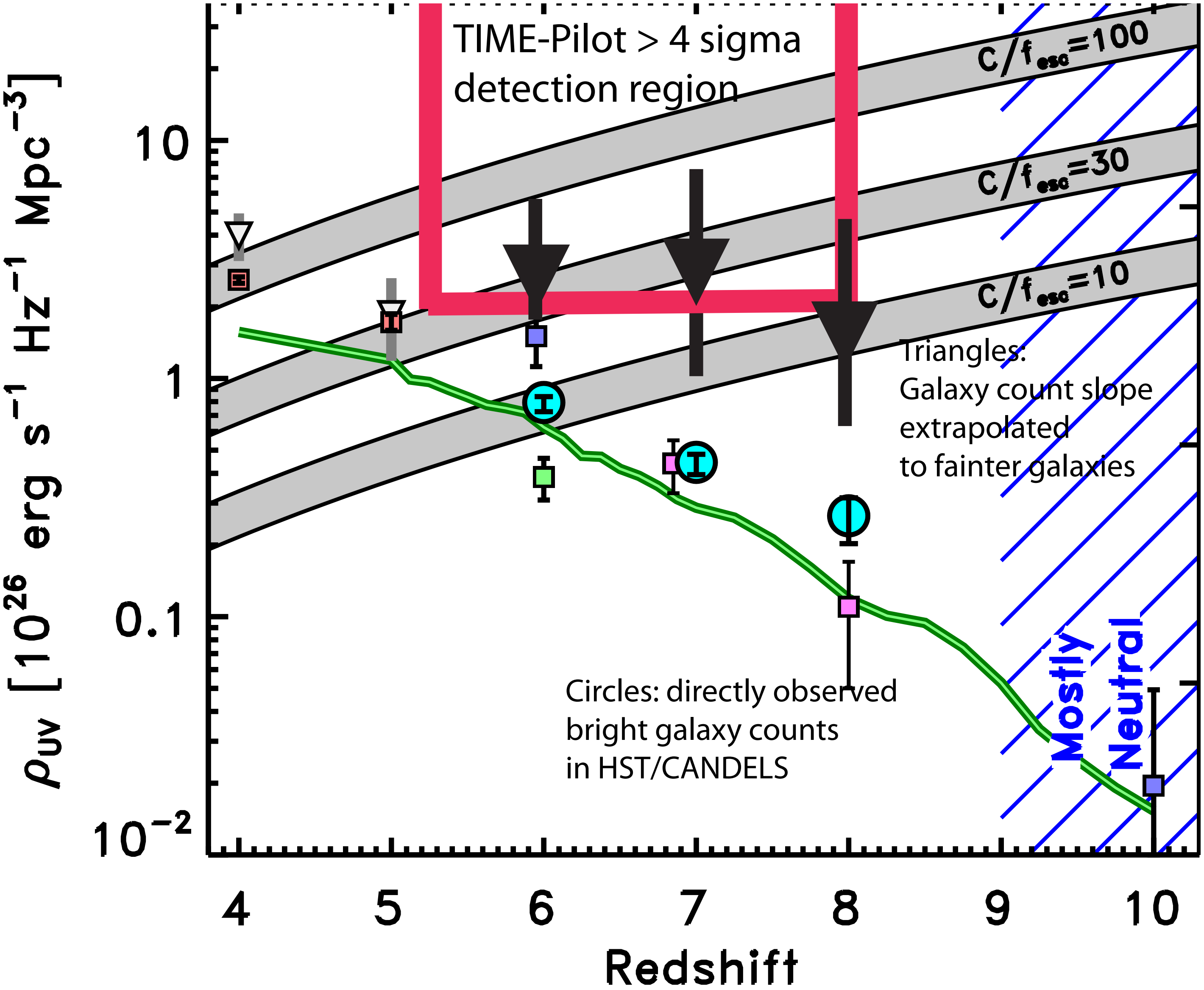
These cannot be obtained with 21-cm data alone.



TIME: Tomographic Ionized-Carbon Mapping Experiment



TIME: Tomographic Ionized-Carbon Mapping Experiment



TIME: Tomographic Ionized-Carbon Mapping Experiment

Twitter summary

TIME to start observations @ JCMT from 2017 if funded by NSF this year. #wdm14

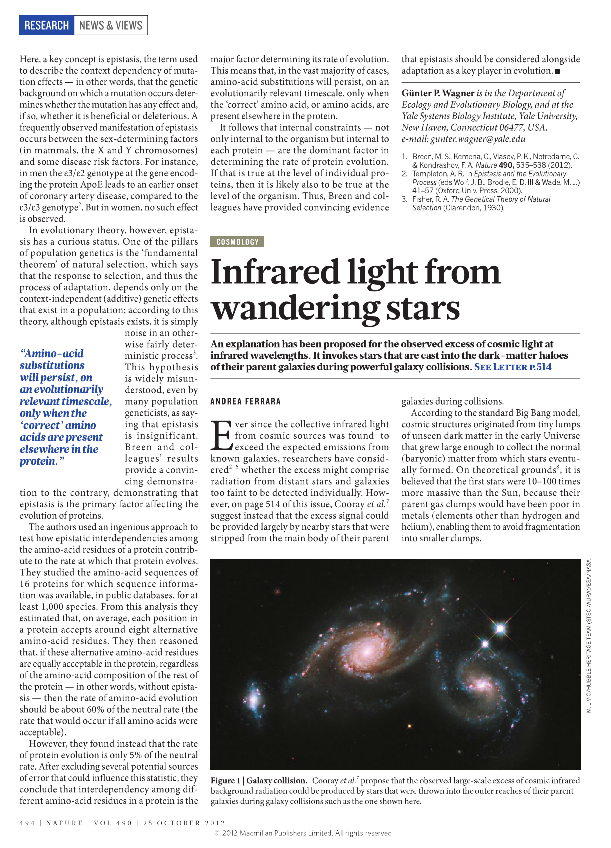
Summary

Infrared background is a probe of high-z galaxies and low-z intra-halo light.

From Spitzer fluctuations, a 0.1 to 0.5% of IHL fraction in z~1 to 5 Milky Way-like galaxies

From Hubble fluctuations, a measure of total SFRD of the Universe for the first time.

An instrument for CII fluctuations from reionization under construction to JCMT



Here, a key concept is epistasis, the term used to describe the context dependency of mutation effects — in other words, that the genetic background on which a mutation occurs determines whether the mutation has any effect and, if so, whether it is beneficial or deleterious. A frequently observed manifestation of epistasis occurs between the sex-determining factors (in mammals, the X and Y chromosomes) and some disease risk factors. For instance, in men the ε3/ε2 genotype at the gene encoding the protein ApoE leads to an earlier onset of coronary artery disease, compared to the ε3/ε3 genotype[2]. But in women, no such effect is observed.

In evolutionary theory, however, epistasis has a curious status. One of the pillars of population genetics is the 'fundamental theorem' of natural selection, which says that the response to selection, and thus the process of adaptation, depends only on the context-independent (additive) genetic effects that exist in a population; according to this theory, although epistasis exists, it is simply noise in an otherwise fairly deterministic process[3]. This hypothesis is widely misunderstood, even by many population geneticists, as saying that epistasis is insignificant. Breen and colleagues' results provide a convincing demonstration to the contrary, demonstrating that epistasis is the primary factor affecting the evolution of proteins.

> *"Amino-acid substitutions will persist, on an evolutionarily relevant timescale, only when the 'correct' amino acids are present elsewhere in the protein."*

The authors used an ingenious approach to test how epistatic interdependencies among the amino-acid residues of a protein contribute to the rate at which that protein evolves. They studied the amino-acid sequences of 16 proteins for which sequence information was available, in public databases, for at least 1,000 species. From this analysis they estimated that, on average, each position in a protein accepts around eight alternative amino-acid residues. They then reasoned that, if these alternative amino-acid residues are equally acceptable in the protein, regardless of the amino-acid composition of the rest of the protein — in other words, without epistasis — then the rate of amino-acid evolution should be about 60% of the neutral rate (the rate that would occur if all amino acids were acceptable).

However, they found instead that the rate of protein evolution is only 5% of the neutral rate. After excluding several potential sources of error that could influence this statistic, they conclude that interdependency among different amino-acid residues in a protein is the major factor determining its rate of evolution. This means that, in the vast majority of cases, amino-acid substitutions will persist, on an evolutionarily relevant timescale, only when the 'correct' amino acid, or amino acids, are present elsewhere in the protein.

It follows that internal constraints — not only internal to the organism but internal to each protein — are the dominant factor in determining the rate of protein evolution. If that is true at the level of individual proteins, then it is likely also to be true at the level of the organism. Thus, Breen and colleagues have provided convincing evidence that epistasis should be considered alongside adaptation as a key player in evolution. ■

Günter P. Wagner *is in the Department of Ecology and Evolutionary Biology, and at the Yale Systems Biology Institute, Yale University, New Haven, Connecticut 06477, USA.*
e-mail: gunter.wagner@yale.edu

1. Breen, M. S., Kemena, C., Vlasov, P. K., Notredame, C. & Kondrashov, F. A. *Nature* **490,** 535–538 (2012).
2. Templeton, A. R. in *Epistasis and the Evolutionary Process* (eds Wolf, J. B., Brodie, E. D. III & Wade, M. J.) 41–57 (Oxford Univ. Press, 2000).
3. Fisher, R. A. *The Genetical Theory of Natural Selection* (Clarendon, 1930).

COSMOLOGY

Infrared light from wandering stars

An explanation has been proposed for the observed excess of cosmic light at infrared wavelengths. It invokes stars that are cast into the dark-matter haloes of their parent galaxies during powerful galaxy collisions. SEE LETTER P.514

ANDREA FERRARA

Ever since the collective infrared light from cosmic sources was found[1] to exceed the expected emissions from known galaxies, researchers have considered[2–6] whether the excess might comprise radiation from distant stars and galaxies too faint to be detected individually. However, on page 514 of this issue, Cooray *et al.*[7] suggest instead that the excess signal could be provided largely by nearby stars that were stripped from the main body of their parent galaxies during collisions.

According to the standard Big Bang model, cosmic structures originated from tiny lumps of unseen dark matter in the early Universe that grew large enough to collect the normal (baryonic) matter from which stars eventually formed. On theoretical grounds[8], it is believed that the first stars were 10–100 times more massive than the Sun, because their parent gas clumps would have been poor in metals (elements other than hydrogen and helium), enabling them to avoid fragmentation into smaller clumps.

M. LIVIO/HUBBLE HERITAGE TEAM (STSCI/AURA)/ESA/NASA

Figure 1 | Galaxy collision. Cooray *et al.*[7] propose that the observed large-scale excess of cosmic infrared background radiation could be produced by stars that were thrown into the outer reaches of their parent galaxies during galaxy collisions such as the one shown here.

See general intro to the subject Andrea Ferrara, Nature, News & Views, 490, 494 (Oct 25 2012)