Possible Searches for non-Gaussianity at high redshifts

Asantha Cooray

KICP - June 2007

Outline

At low-z's gravitational non-Gaussianity >> primordial.

To understand primordial non-Gaussian perturbations, push as high in z as possible (but not clear how to connect theory on primordial NG to actual measurements)

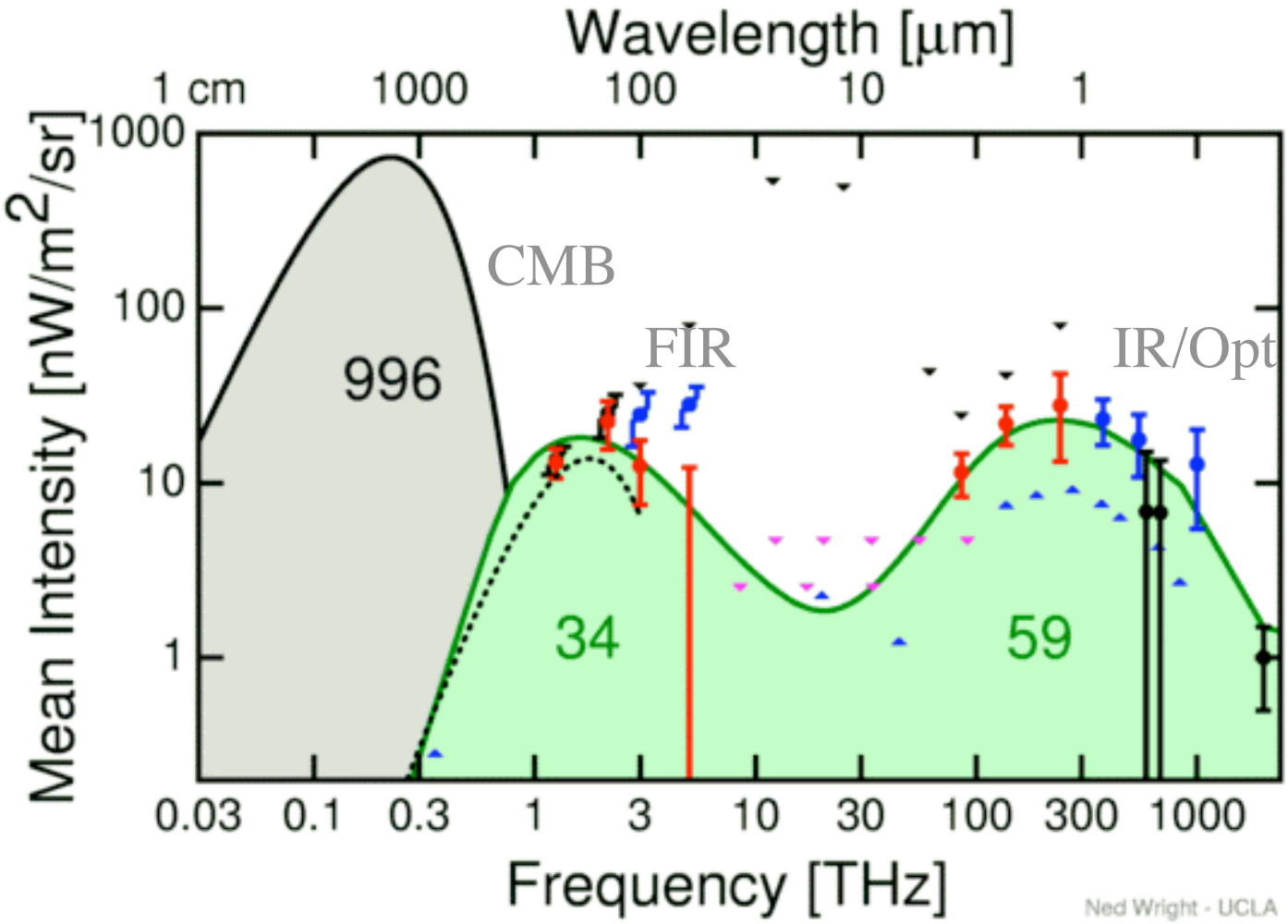
Possibilities for measurements:

z of 1 to 2: Non-Gaussianities of the far-IR background with Herschel

z > 7: near-IR background with Spitzer/NICMOS/CIBER/WFC3

z > 15: 21-cm background with ???? (MWA/SKA/21CMA/LOFAR)

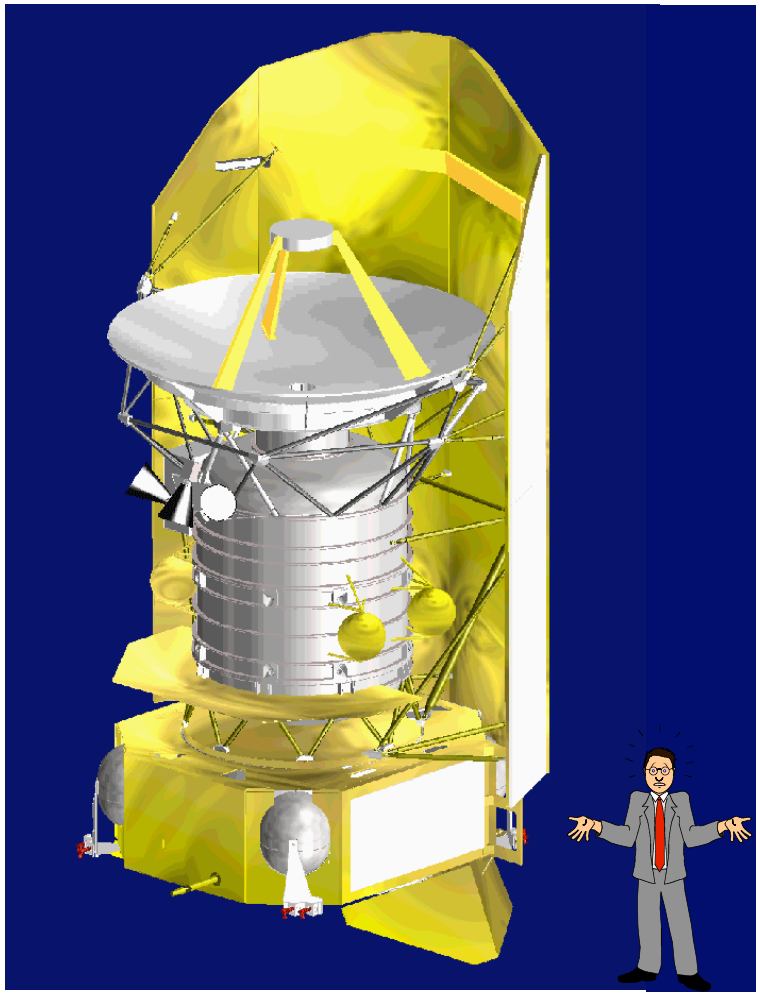
Cosmic Backgrounds



IR/Opt: Direct emission from stars

FIR: Processed emission of Opt/IR light by dust

Extragalactic Far-IR Background Studies with Hershcel-SPIRE



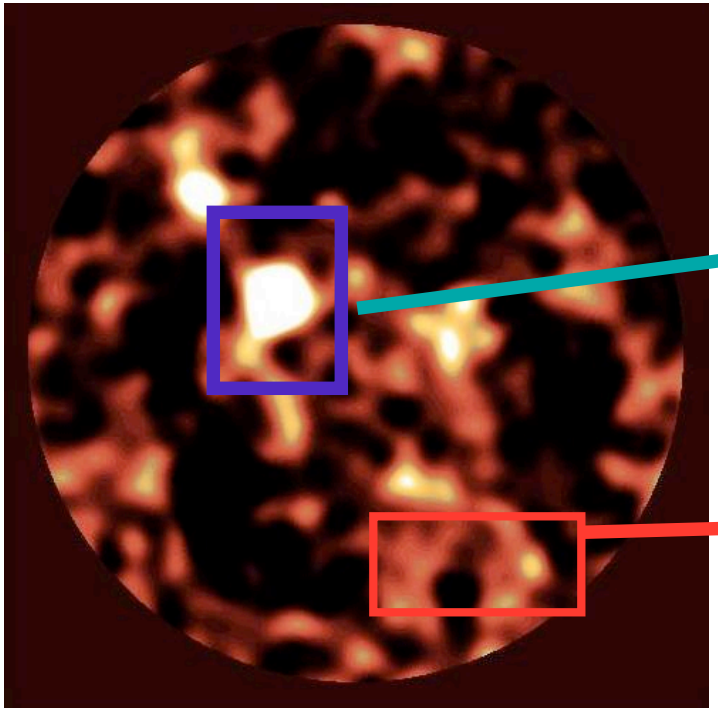
- Herschel is an astronomical observatory for photometry and spectroscopy over the spectral range 80 – 670 μm
- Large (3.5m), cold (80K), low-emissivity (4%) telescope
- Focal plane cooled to 4K using liquid He (as in ISO)
- Launch: August'08 on Ariane 5 with Planck in same pay load; Sun-Earth L2 point; 1000 days of nominal observations
- Primarily ESA mission. Instrumental contributions from NASA though JPL (bolometers for SPIRE)

Photometry with Herschel

	PACS			SPIRE		
λ_{cent}	75μm	110μm	170μm	250μm	350μm	500μm
$\Delta\lambda$	60-90	90-130	130-210	210-290	290-400	410-580
Sensitivity mJy,5s,1h	3	3	3	1.1	1.2	1.5
FOV (arcmin)	1.8x3.5	1.8x3.5	1.8x3.5	4x8	4x8	4x8
Angular res.	5″	8″	12″	17″	24″	35″

SPIRE: Survey instrument
Poor resolution. Confusion limited easily.
Can only resolve < 10% of EBL at 350 μm

Clustering Studies of Far-IR Background with Hershcel-SPIRE



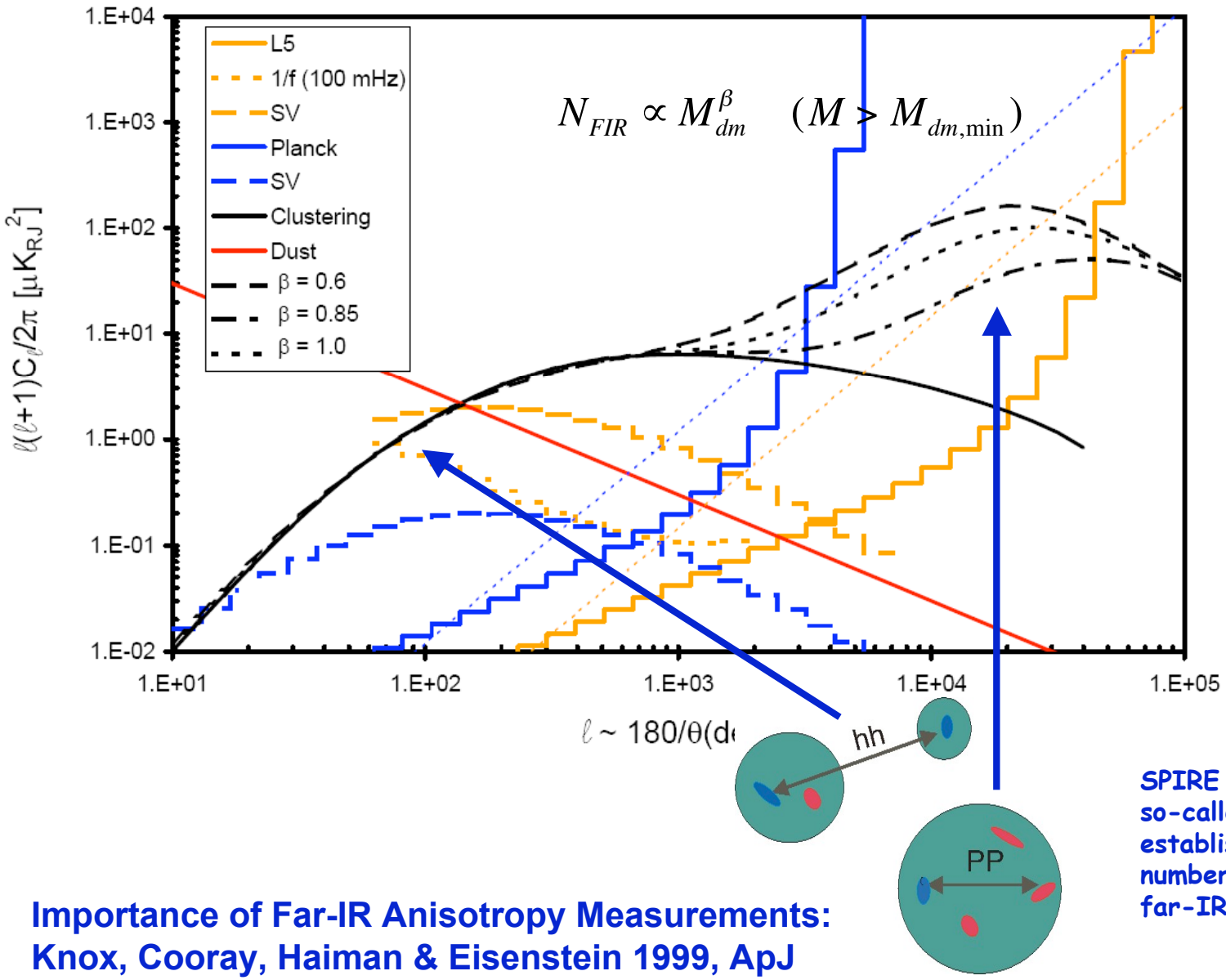
Resolved sources

Measure angular C_l's
If z's known, measure
P(k) - 3d power spectrum

Unresolved background

Measure angular C_l's
treat as in CMB
(no z-information)

Clustering of Unresolved Background



SPIRE can probe the so-called 1-halo term to establish halo occupation number of unresolved far-IR galaxies

Importance of Far-IR Anisotropy Measurements: Knox, Cooray, Haiman & Eisenstein 1999, ApJ

Extragalactic Background/Galactic Dust separation

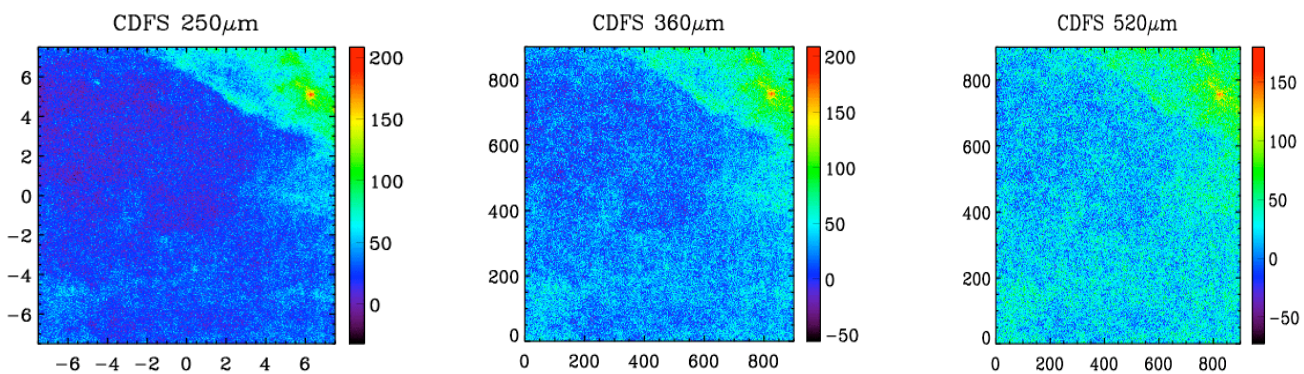
The signal received at each frequency can be modeled as the sum of the different signals contribution, and separated with a linear combination for each mode in spherical harmonic space :

$$a_{\ell m} = \sum_{freq=i} w_\ell^i a_{\ell m}^i \quad \text{with} \quad a_{\ell m}^i = c_{\ell m} + s_{\ell m}^i + d_{\ell m}^i + n_{\ell m}^i$$

Far-IR **CMB** **Dust** **Noise**

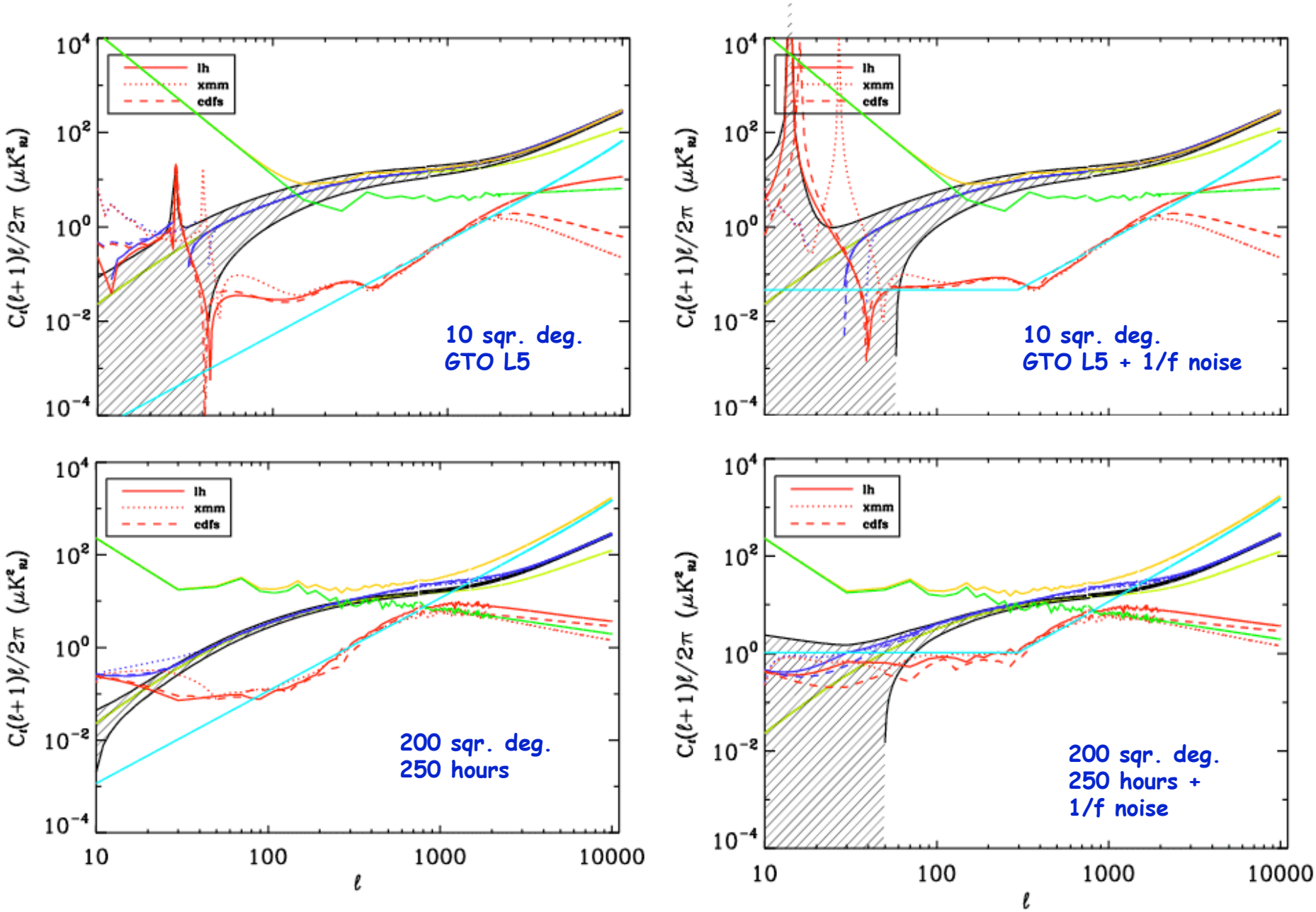
Then we minimize the resulting C_l for far-IR anisotropies

(modified from Tegmark et al. for CMB foreground removal)



Amblard & Cooray 07

Anisotropy power measurement



SPIRE Instrument Team's GTO Survey: Extragalactic Studies

Sciences:

How and when galaxies form

Search for unknown populations of high z IR galaxies

AGN contribution to Far-IRB

Star formation rates

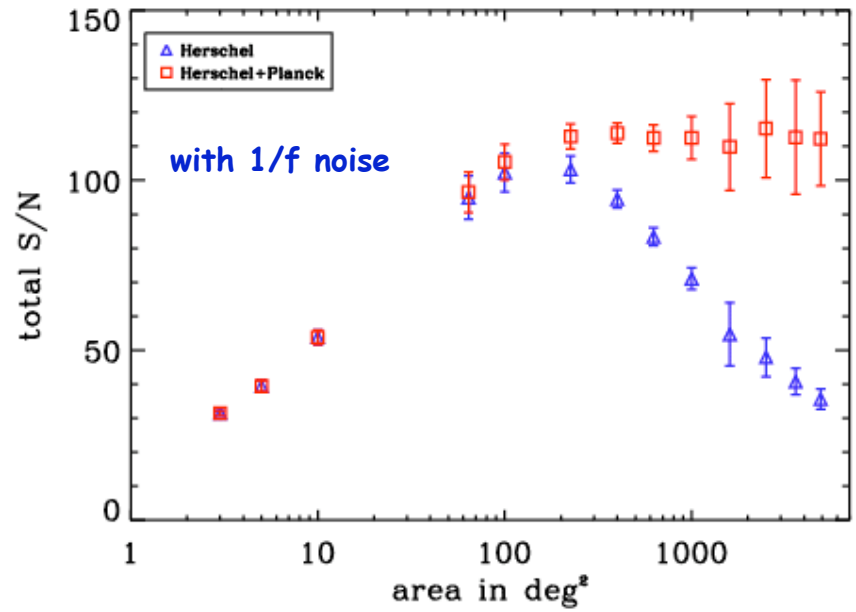
Clustering/correlations/Fluctuations

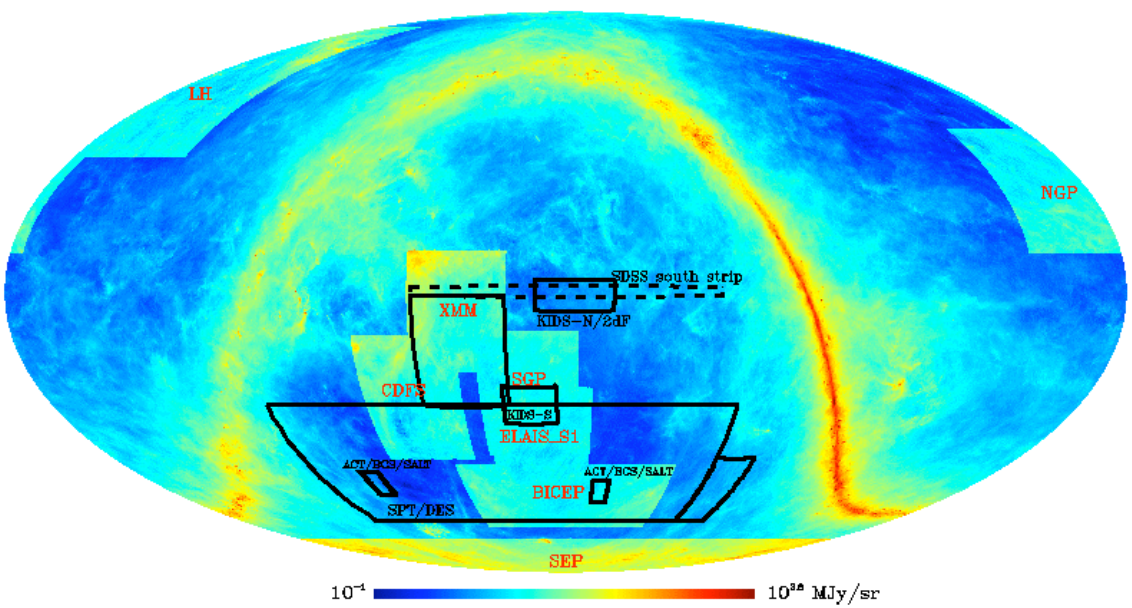
Hervé Aussel	SAp, Saclay, France
Andrew Blain	Caltech, Pasadena, USA
James Bock (a, b)	JPL, Pasadena, USA
Véronique Buat	LAM, Marseille, France
Jordi Cepa	IAC, Canaria, Spain
Sarah Church	Stanford U., Palo Alto, USA
Dave Clements	ICSTM, London, UK
Asantha Cooray	UC Irvine, Irvine, USA
Steve Eales	Cardiff U., Cardiff, UK
David Elbaz	SAp, Saclay, France
Alberto Franceschini	U. Padua, Padua, Italy
Ken Ganga	C. France, Paris, France
Walter Gear (b)	Cardiff U., Cardiff, UK
Jason Glenn (b)	U. Colorado, Boulder, USA
Matt Griffin (c)	Cardiff U., Cardiff, UK
Bruno Guiderdoni	IAP, Paris, France
Mark Halpern	UBC, Vancouver, Canada
Martin Harwit	Cornell U. (emeritus), Ithaca, USA
Evanthia Hatziminaoglou	IAC, Canaria, Spain
Kate Isaak	Cardiff U., Cardiff, UK
Rob Ivison	ATC, Edinburgh, UK
Guilaine Lagache	IAS, Orsay, France
Suzanne Madden	SAp, Saclay, France
Bruno Maffei	Cardiff U., Cardiff, UK
Phil Maloney	U. Colorado, Boulder, USA
Hien Nguyen	JPL, Pasadena, USA
Seb Oliver (a)	U. Sussex, Brighton, UK
Alain Omont	IAP, Paris, France
Mat Page	MSSL, Surrey, UK
Pasquale Panuzzo	IFSI, Rome, Italy
Ismael Perez-Fournon	IAC, Tenerife, Spain
Michael Rowan-Robinson (b)	ICSTM, London, UK
Richard Savage	U. Sussex, Brighton, UK
Bernhard Schulz	IPAC, Pasadena, USA
Douglas Scott	UBC, Vancouver, Canada
Jason Stevens	U. Hertfordshire, Herts, UK
Laurent Vigroux (c)	SAp, Saclay, France
Ian Waddington	U. Sussex, Brighton, UK
Tim Waskett	Cardiff U., Cardiff, UK

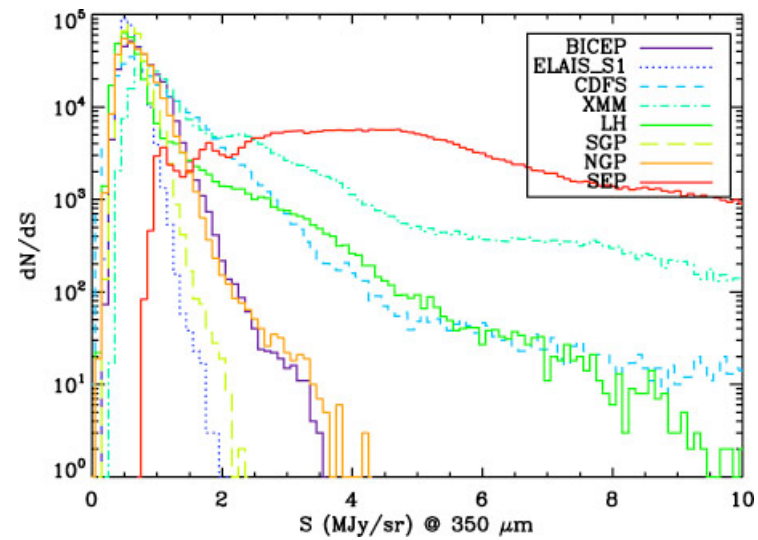
Large-Scale Structure Surveys

ESA has a proposal call out now for Herschel open-time key projects for 2nd year and later observations (after GTO) (equivalent to Legacy programs)

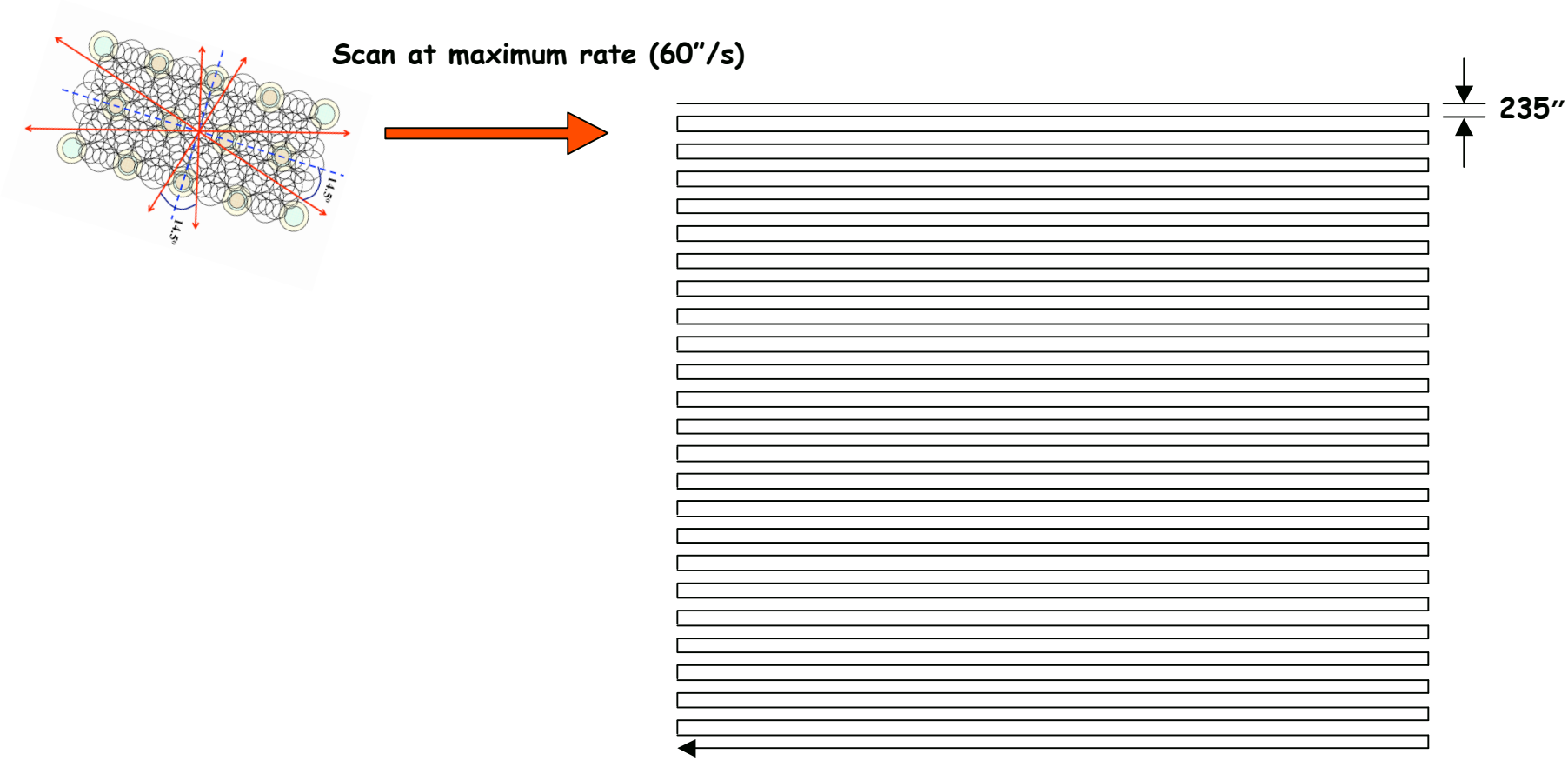
Shallow, wide survey
~2000 deg^2, 2000 hours
Low-cirrus fields (KIDS-S/N probably)
Led by Cardiff (PI: Steve Eales),
UC Irvine & Saclay (Puget/Lagache) lead
anisotropy measurements





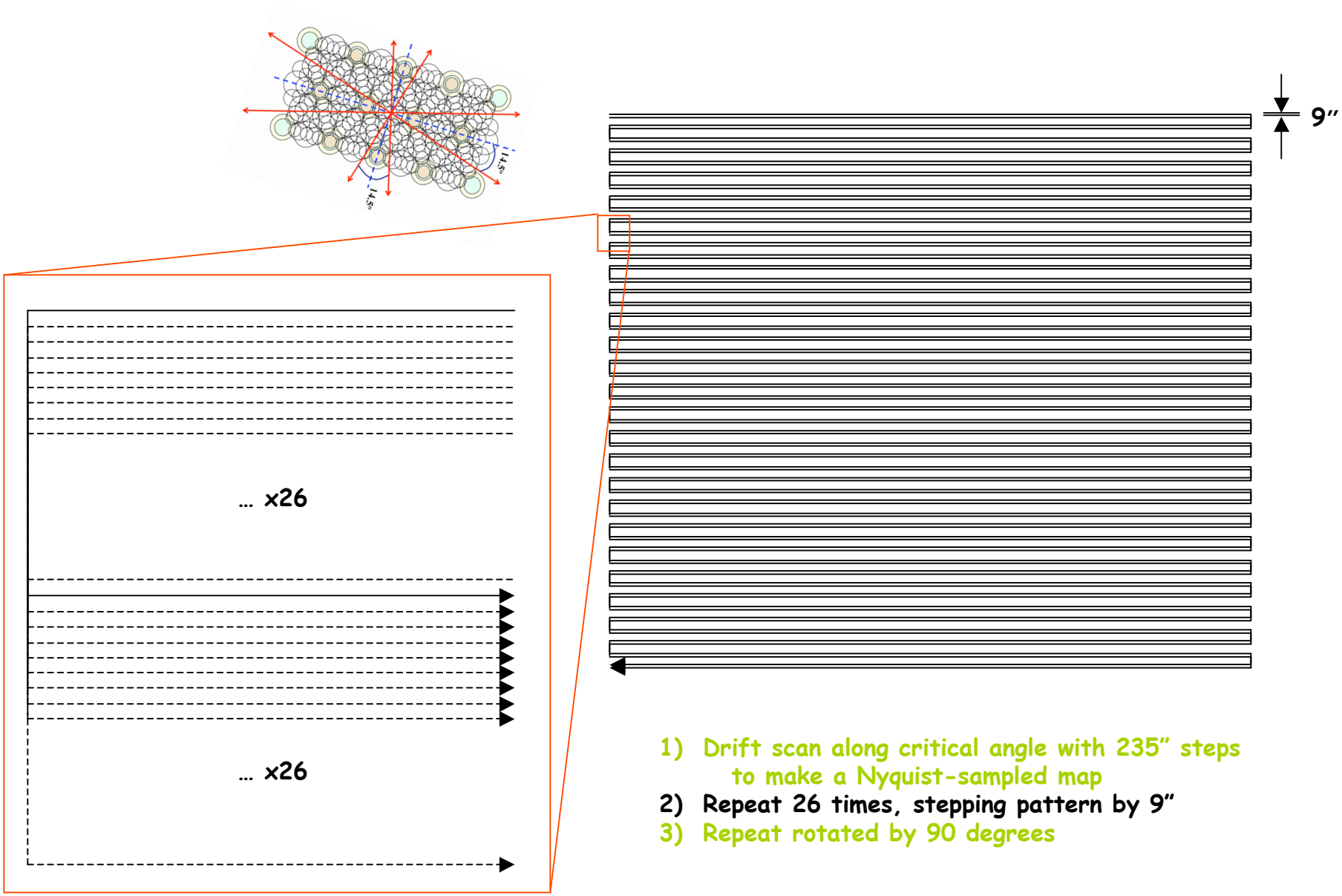


L5 Baseline Scan Strategy (1)



1) Drift scan along critical angle with 235" steps to make a Nyquist-sampled map
2) Repeat 26 times, stepping pattern by 9"
3) Repeat rotated by 90 degrees

L5 Baseline Scan Strategy (2)



1) Drift scan along critical angle with 235″ steps to make a Nyquist-sampled map
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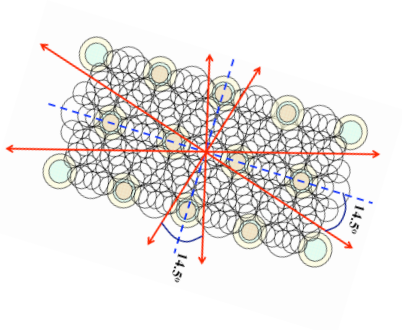
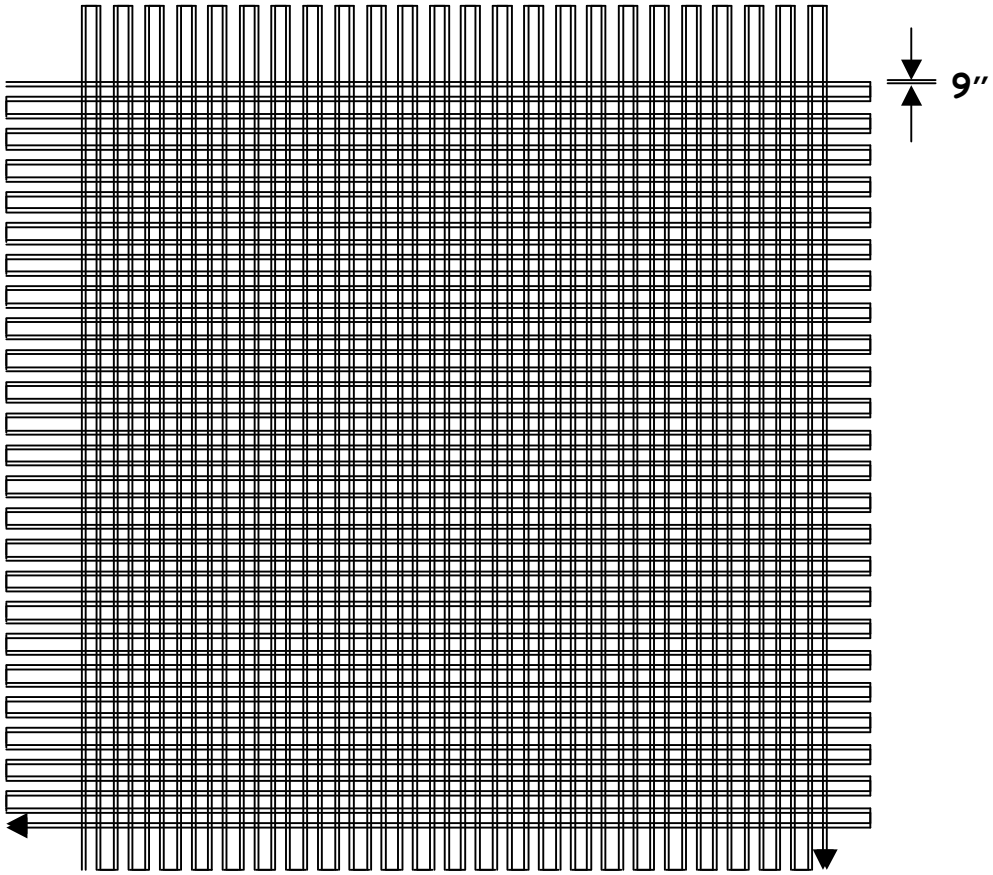
L5 Baseline Scan Strategy (3)

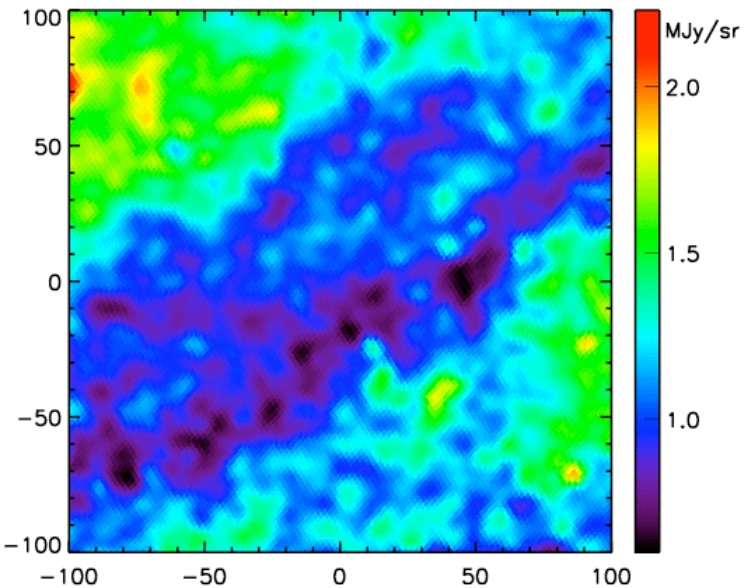


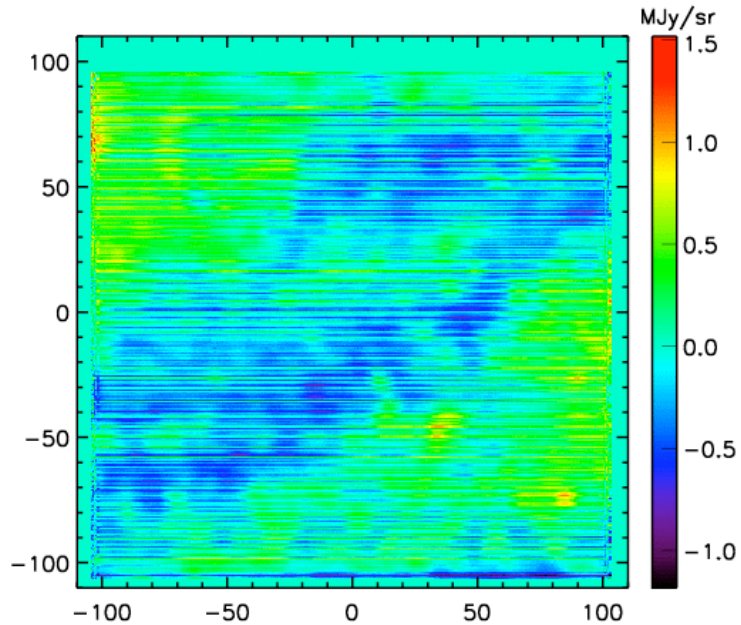


1) Drift scan along critical angle with 235″ steps to make a Nyquist-sampled map
2) Repeat 26 times, stepping pattern by 9″
3) Repeat rotated by 90 degrees

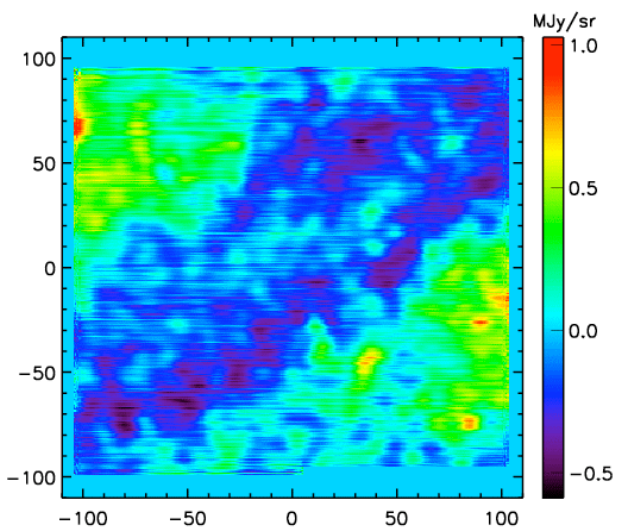
Where we are….

Simulate surveys & Characterize systematics





Input (11 deg^2)

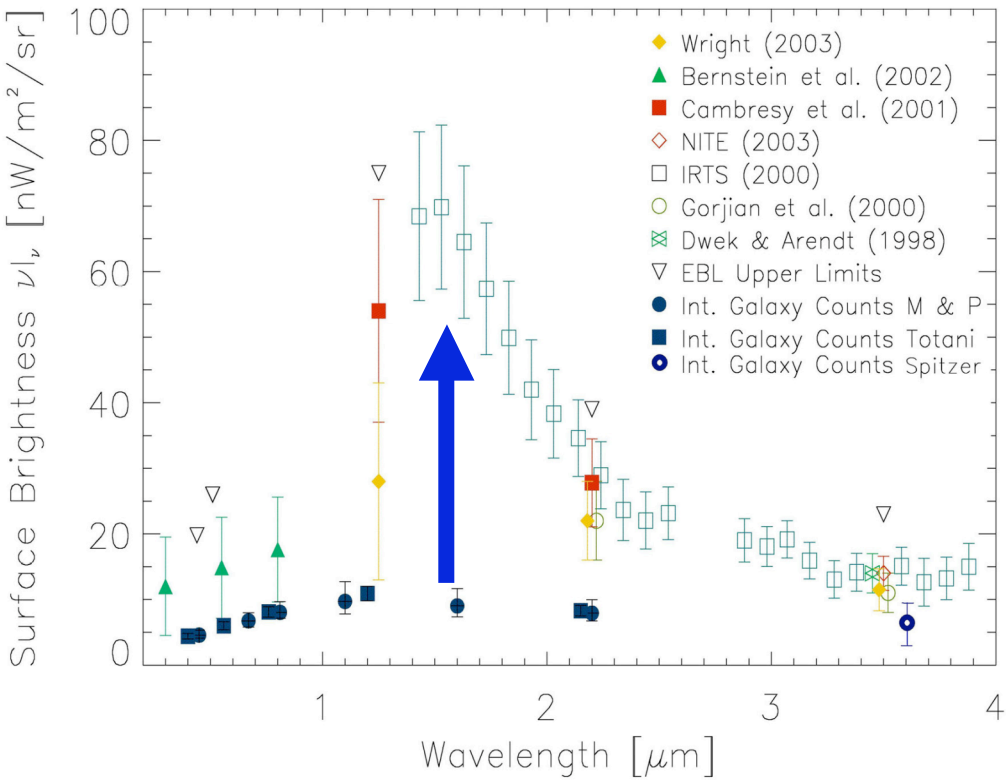


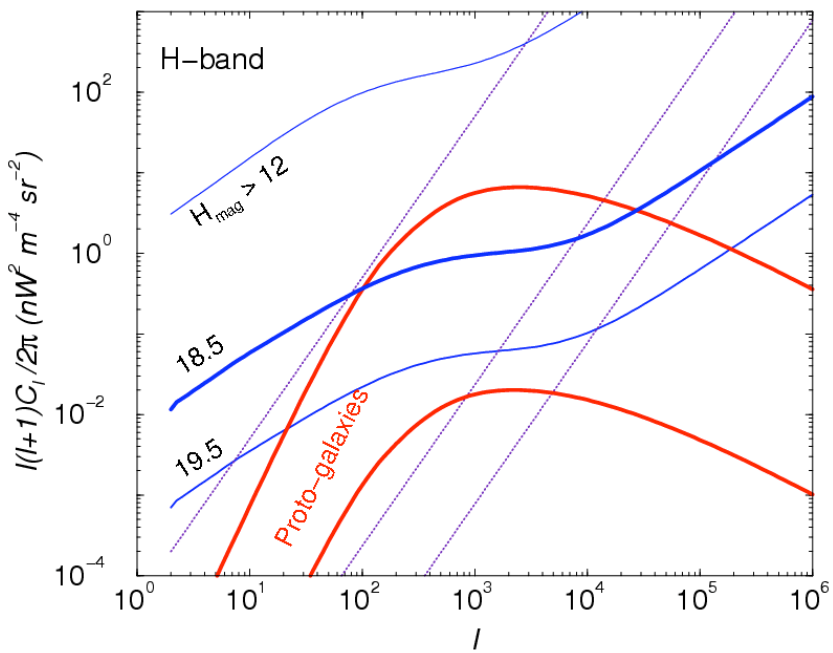
Output (1/f noise dominated)

Post-processed time stream data (still in progress)

We will measure power spectrum and bispectrum in these maps. Also cross-correlate with CMB for z=1 ISW and also do lensing studies.

Near-IR Background as a probe of z>5 galaxies





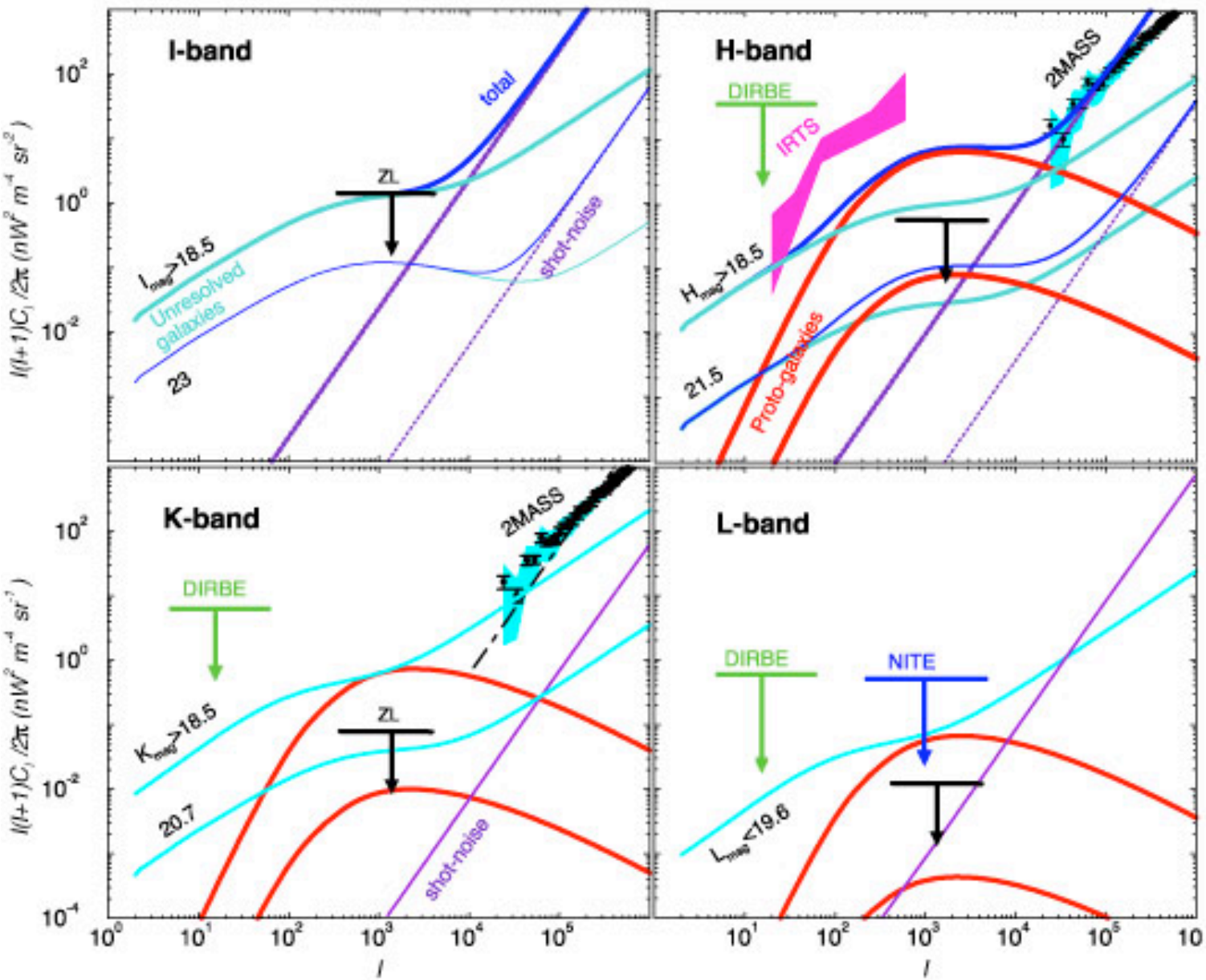
High-z galaxies? Study IRB anisotropies.

Attempts have been made to explain the excess background light as due to "first galaxies"

Zodiacal light is a major contaminant for absolute background measurements. Instead of total intensity, study fluctuations.

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

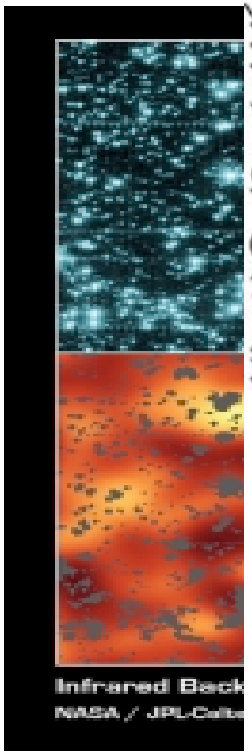
Background Fluctuation Measurements before 2005

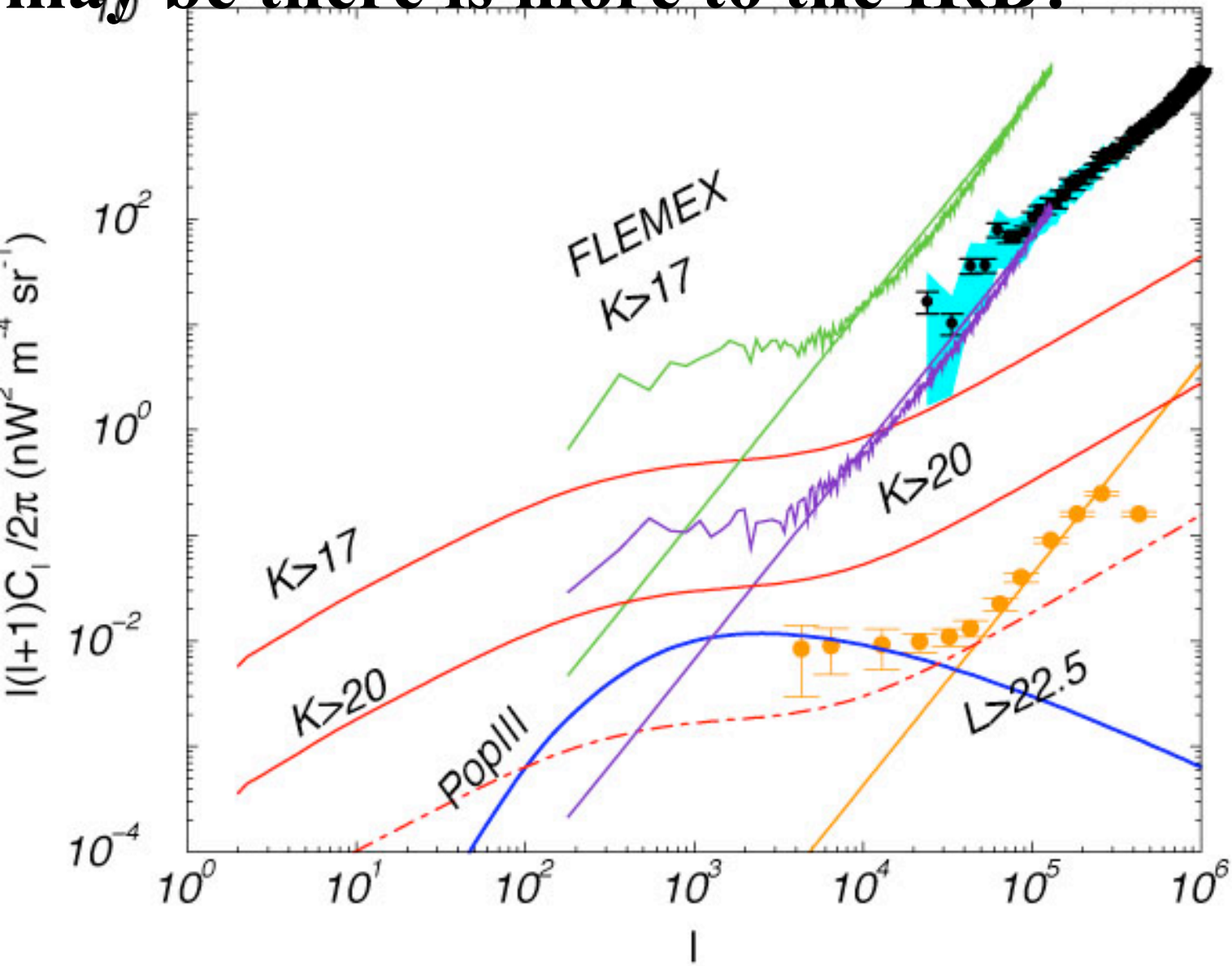


Vol 438|3 November 2005|doi:10.1038/nature04143 nature

Or, may be there is more to the IRB?

Trac
the
A. Kashlin





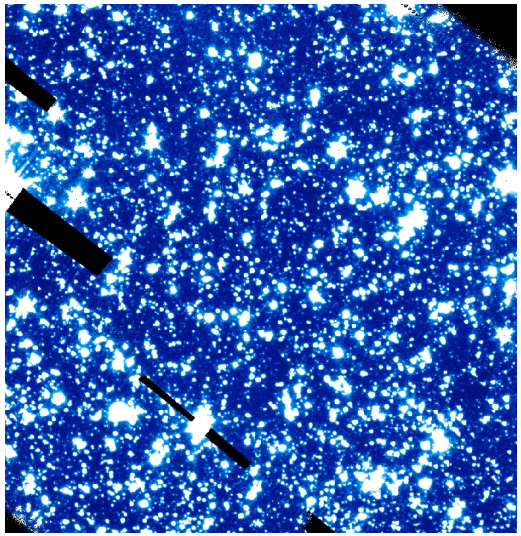
Our Recent Works: Spitzer IRAC Shallow Survey + GOODS + NUDF

IRAC Spitzer Bootes field

8.5 square degrees

(6200 pointings; ~2 weeks)

Large, but a shallow survey



IRAC Spitzer GOODS field

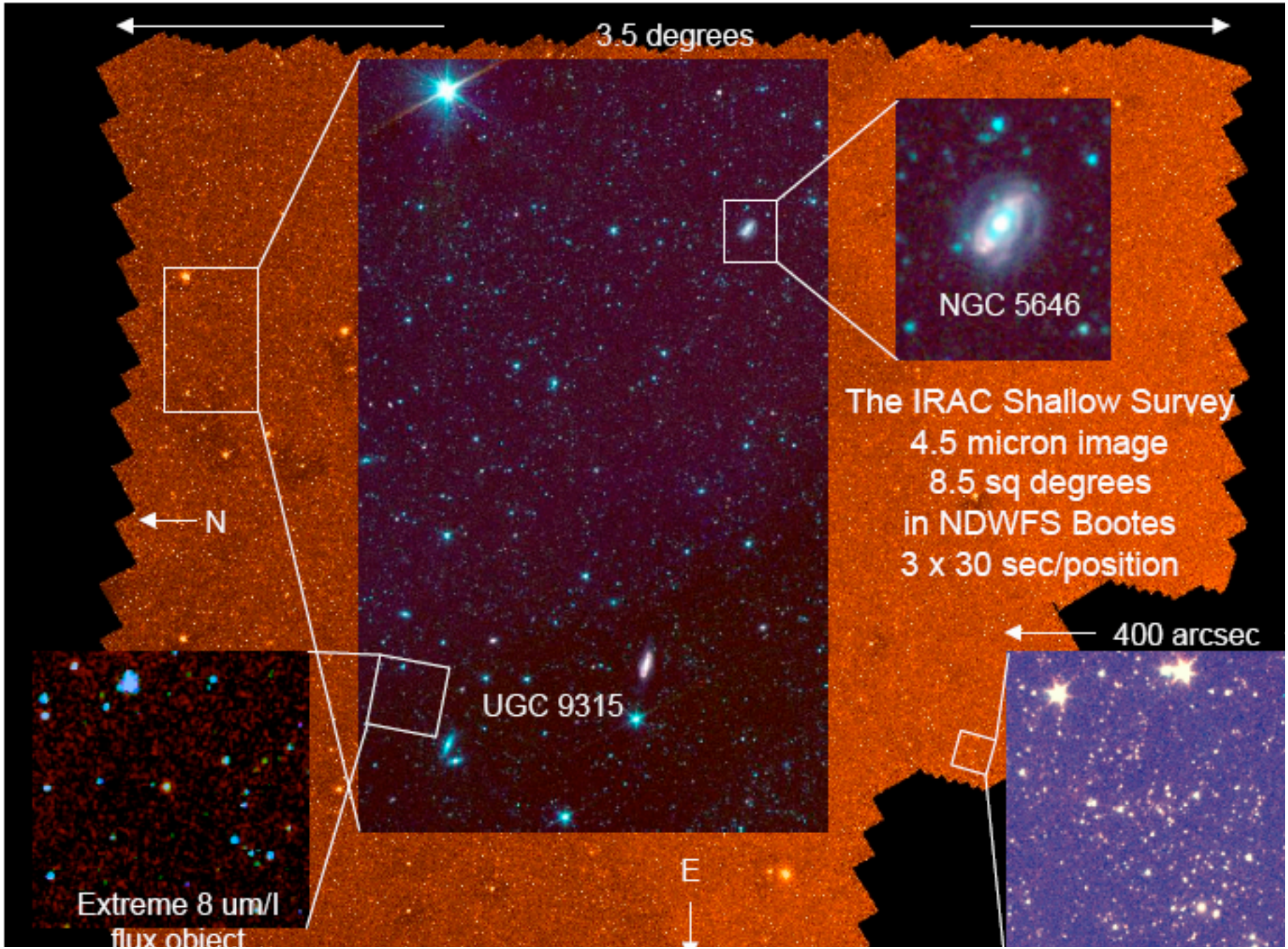
2x0.05 square degrees

HDF-N/CDF-S

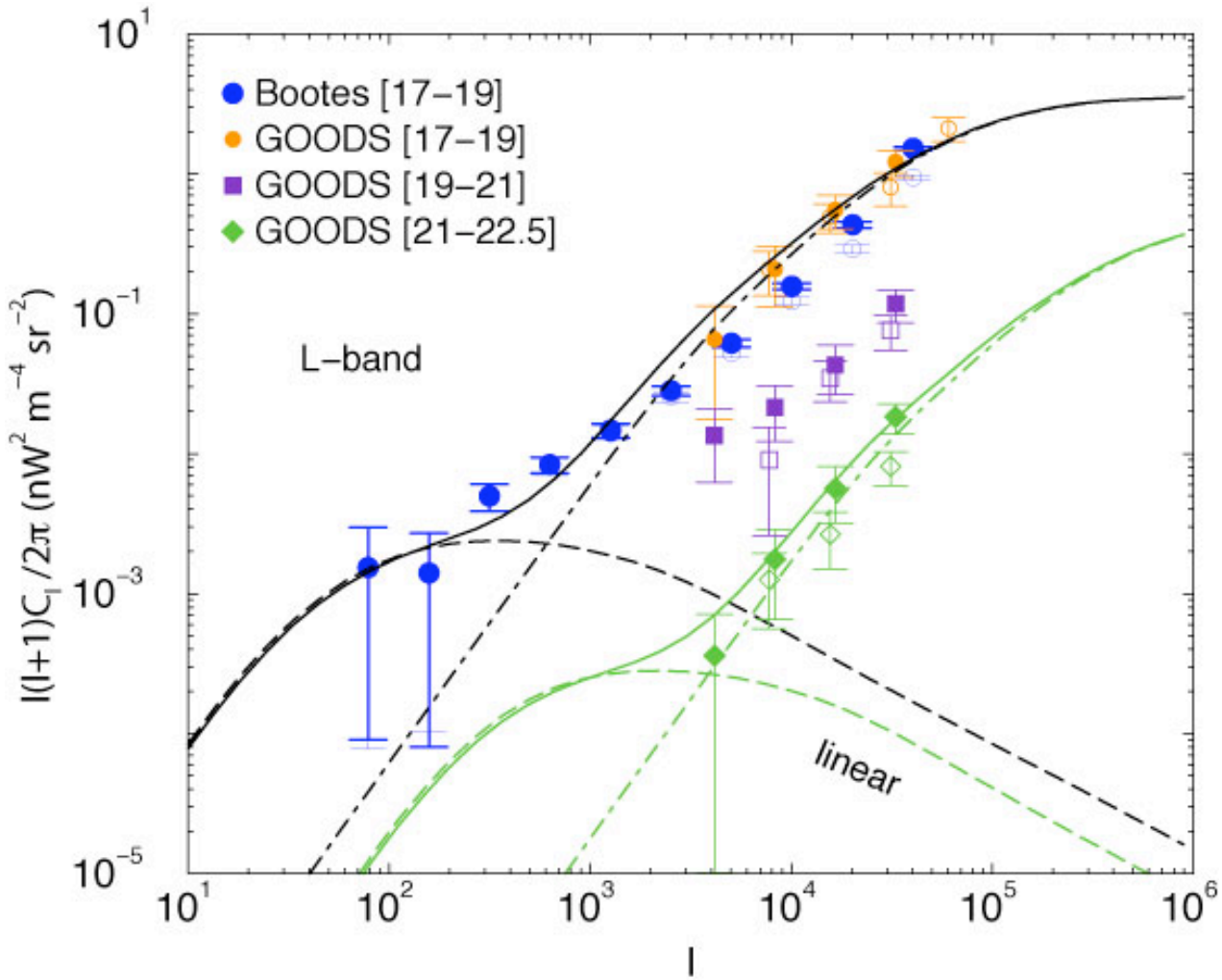
Very deep, but a narrow survey

Unpublished works with NICMOS Deep Fields and Spitzer-COSMOS

(Sullivan et al. in prep)

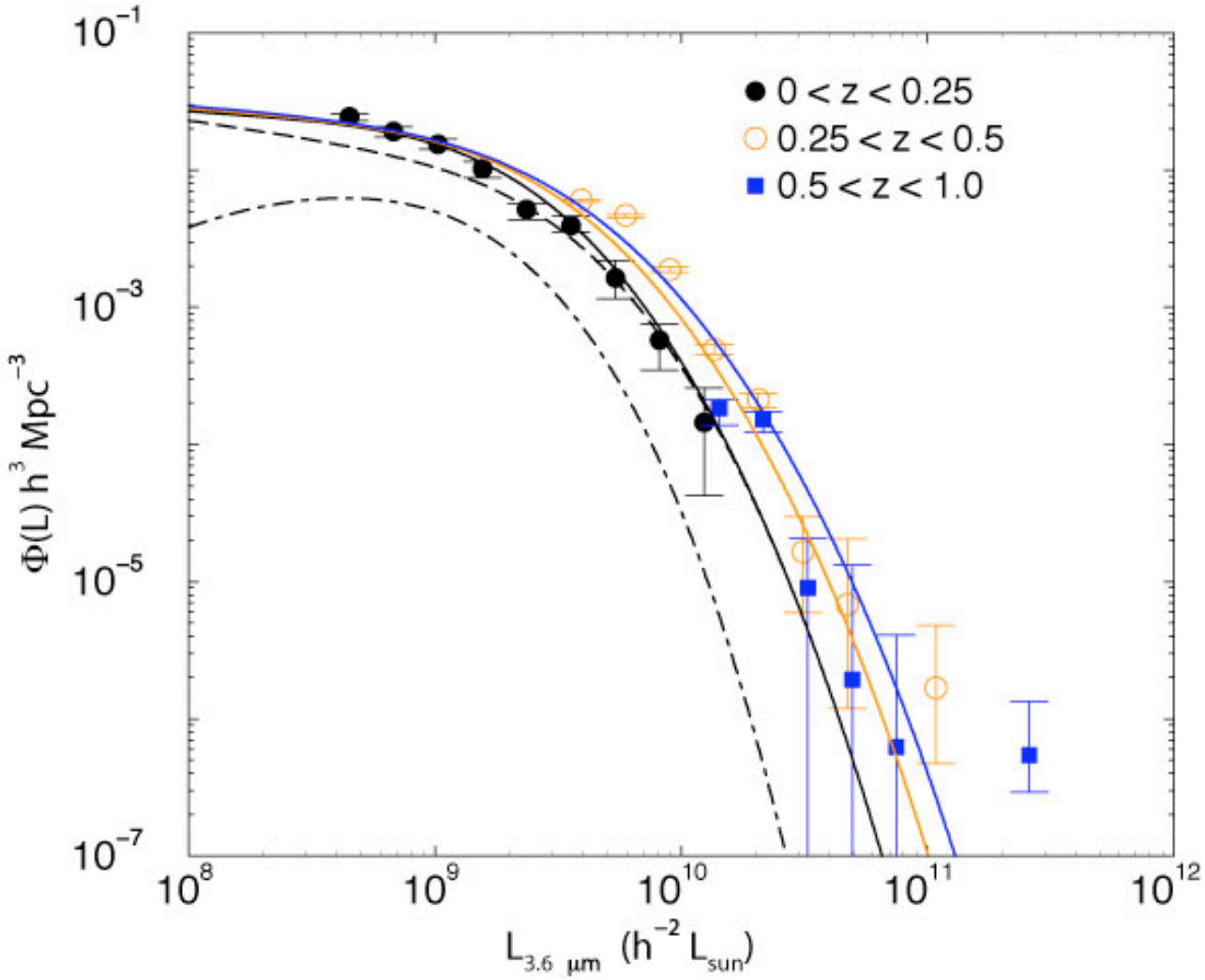

3.5 degrees
NGC 5646
The IRAC Shallow Survey
4.5 micron image
8.5 sq degrees
in NDWFS Bootes
3 x 30 sec/position
N
400 arcsec
UGC 9315
E
Extreme 8 um/I
flux object

Clustering in Bootes/GOODS: Resolved Sources



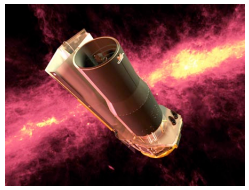
Lines: model predictions from the conditional luminosity functions based halo model.

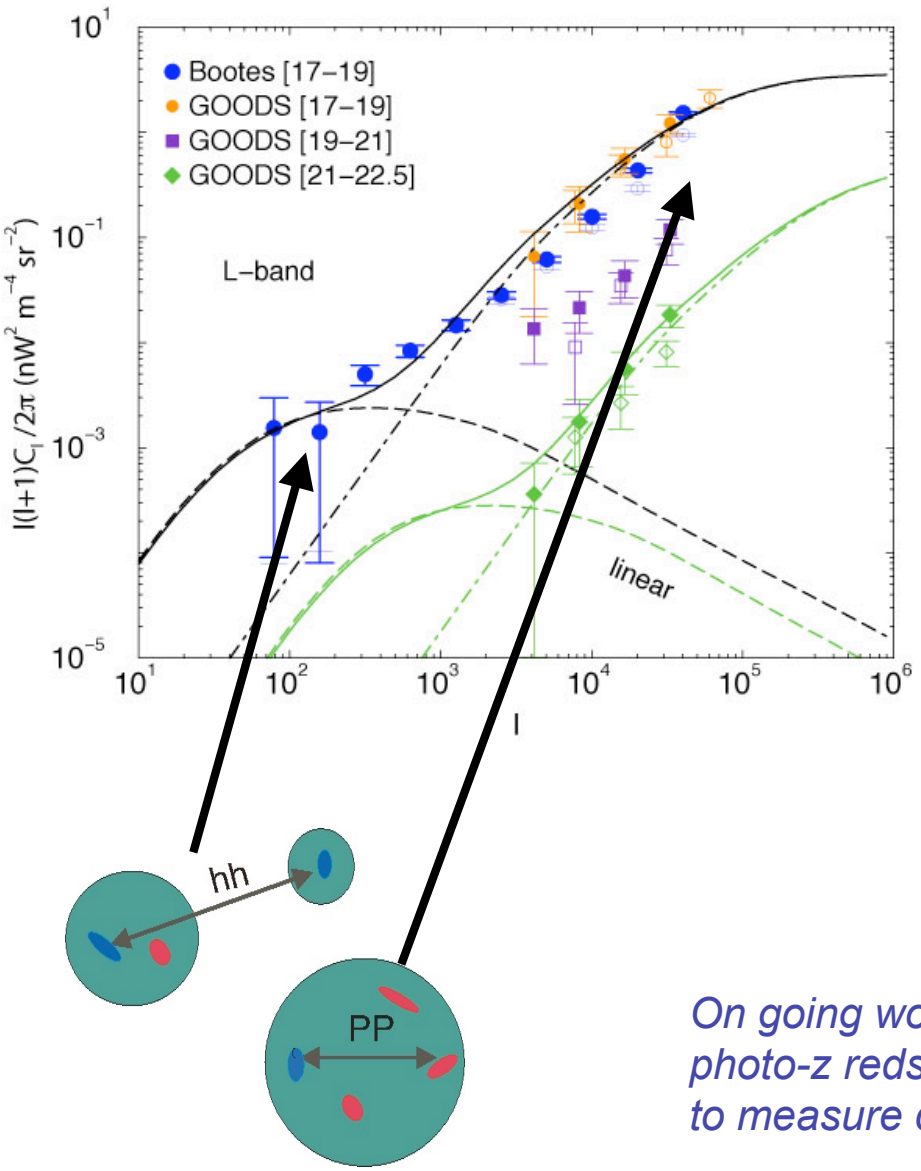
Finally, what shapes the luminosity function?

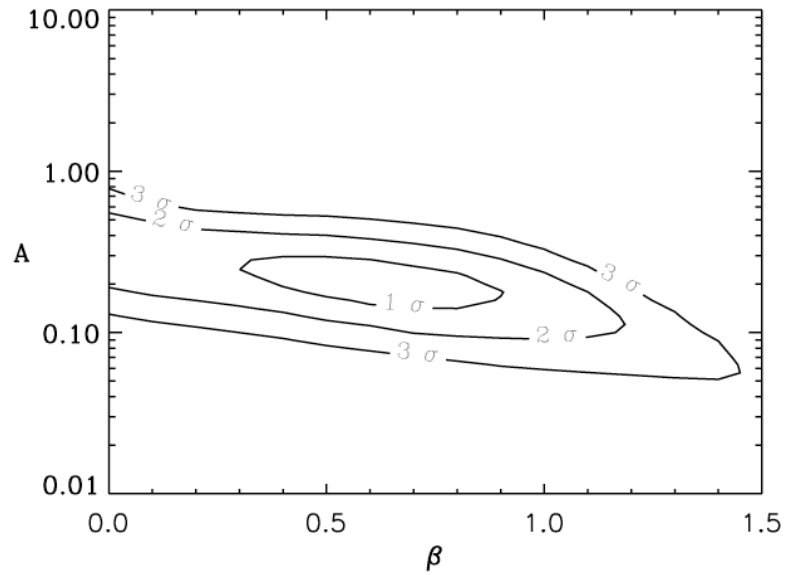


Sullivan et al. 2006: Model for SWIRE IR LFs (at L-band) from Babbedge et al. using conditional LF models.

Clustering in Bootes





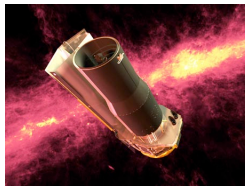


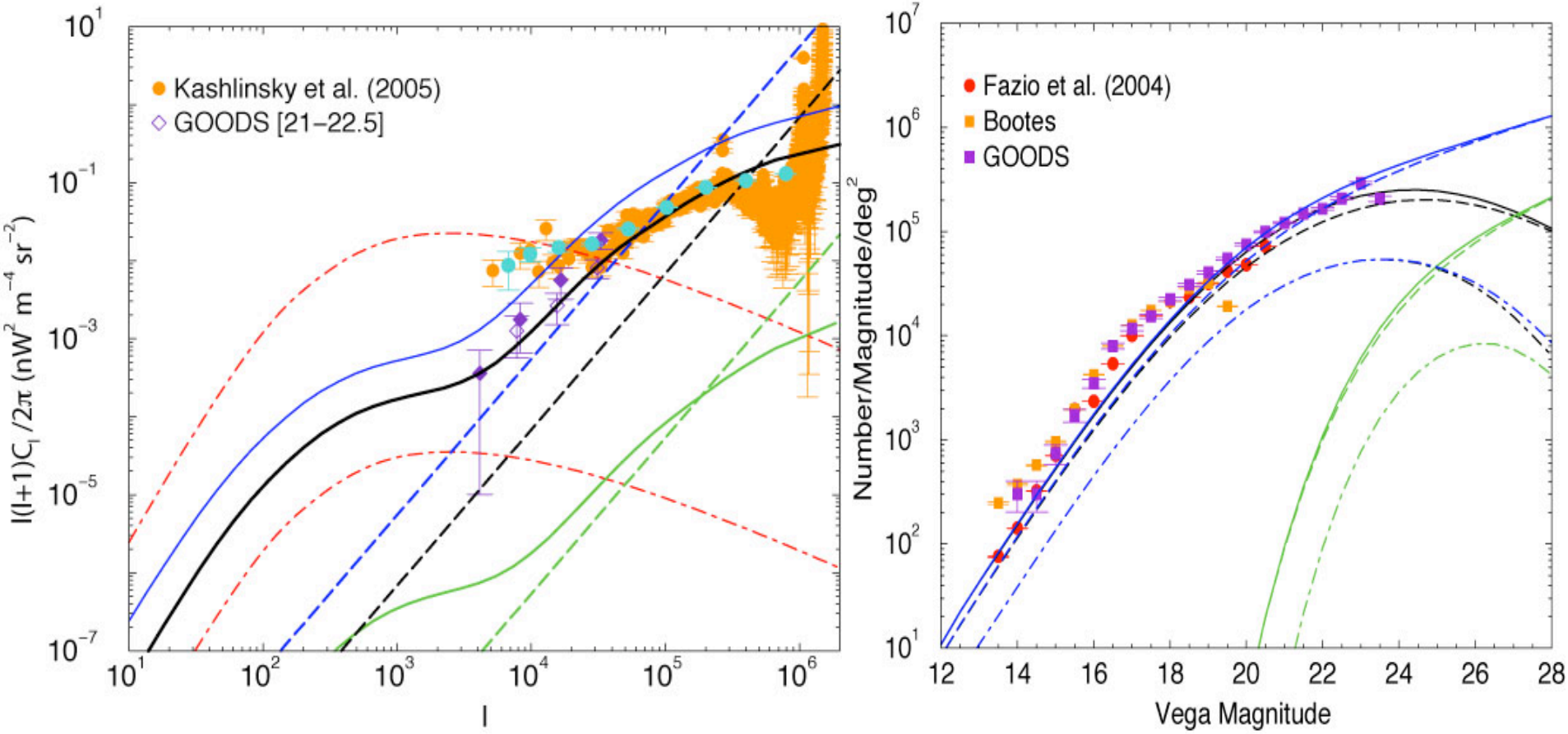
Establish the mass scale for L~17 to 19 IR galaxies at z of 1

~ 5×10^{11} M_{sun}

On going work: to combine IR galaxy bias as a function of photo-z redshifts from 0.5 to 2 + WMAP + z~0 SDSS/2DF to measure cosmology (Tristan Smith et al. in prep)

Number counts of IR galaxies

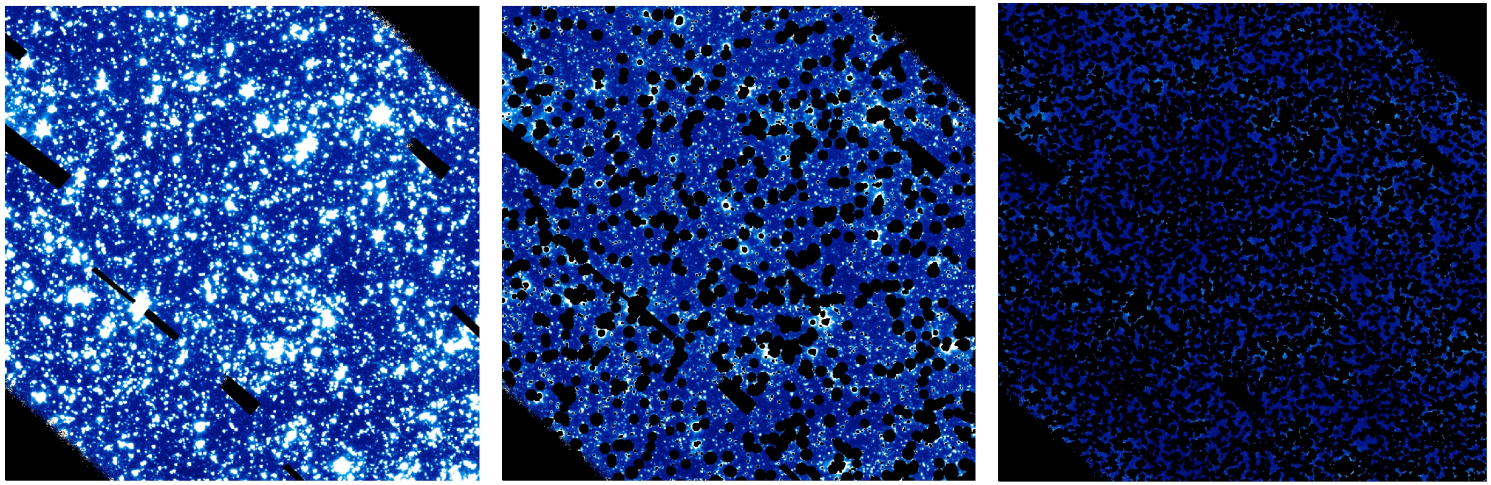




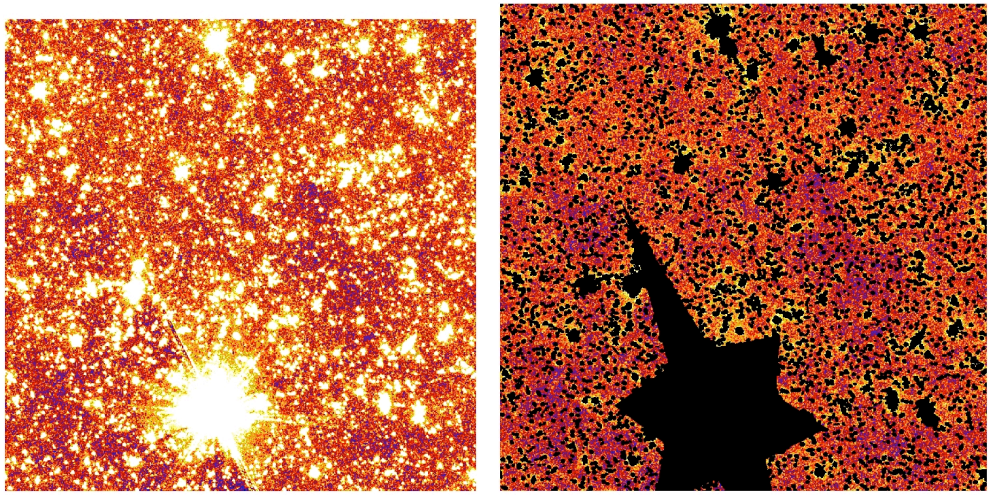
Prediction based on CLF/halo model: clustering measurement require L-band counts to flatten below the point-source detection level of deep Spitzer images.

Sullivan et al. 2006

Unresolved Clustering in Spitzer and deep IR fields



GOODS
CDF-S



COSMOS

What do we do?

Measure statistics of “empty” pixels.

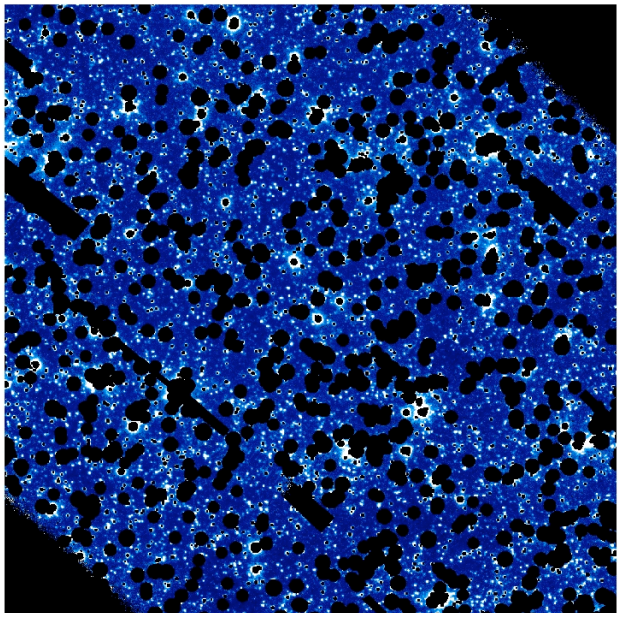
If unresolved faint galaxies are hidden in noise, then there is a clustering excess to noise (due to clustering of those sources)

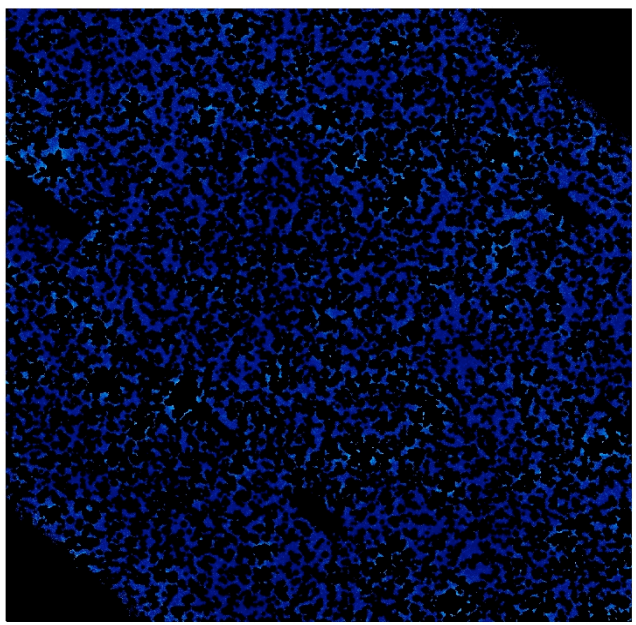
Challenges: > 40 million of pixels

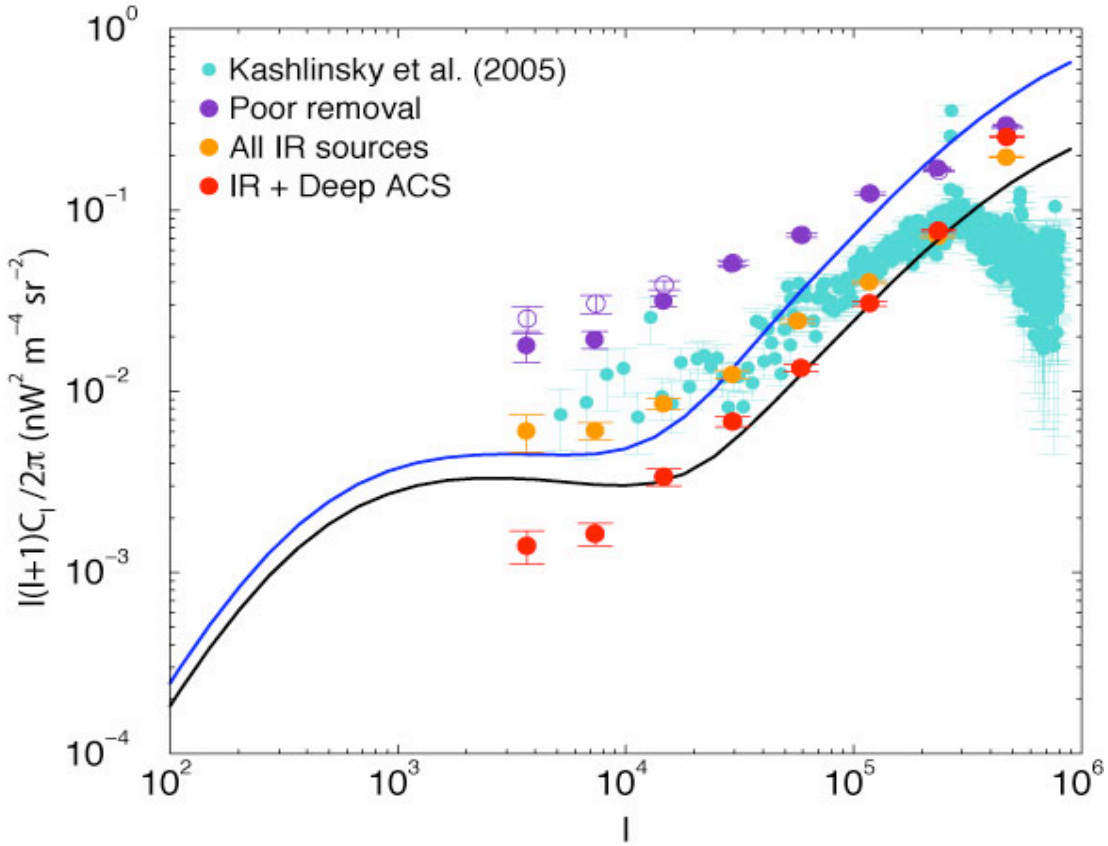
We also mask > 50% of pixels

Likelihood analysis borrowed from CMB techniques. A modified e-spice (Szapudi) for correlation functions.

First stars?: Unresolved Clustering in GOODS







Fluctuations level consistent with Kashlinsky et al. after masking IR-based detections.

But, we masked pixels of faint ACS sources with no IR counterparts. This removes power at arcminute scales.

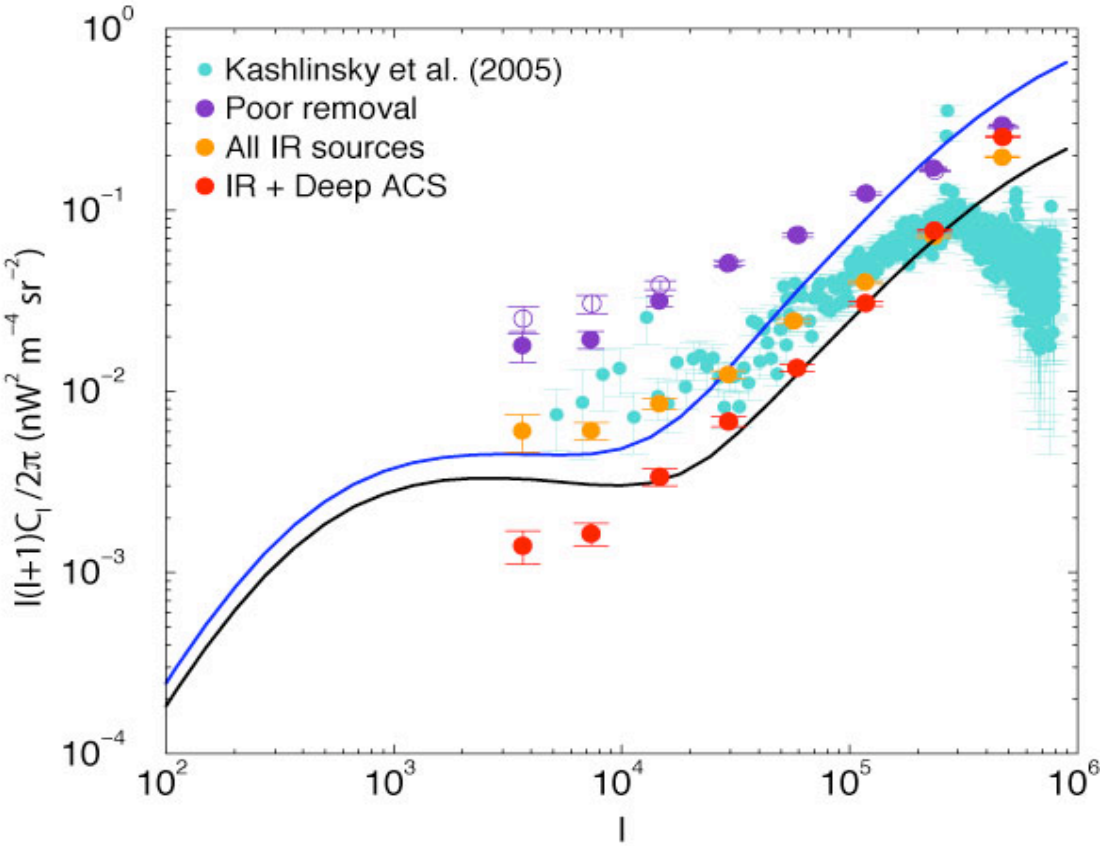
First stars?: Unresolved Clustering in GOODS

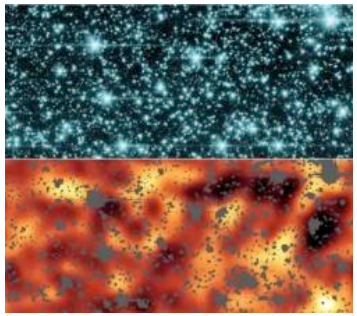
We argued against the claim in Kashlinsky et al. papers. (One in Nature, 2 in ApJ Letters)

Our suggestion:

Excess clustered fluctuations In deep IR images are from faint unresolved galaxies at z of 1 to 4.

We limit the L-band total IR intensity to be below 7 nW m^{-2} sr^{-1} , while DIRBE~11-14 nW m^{-2} sr^{-1}

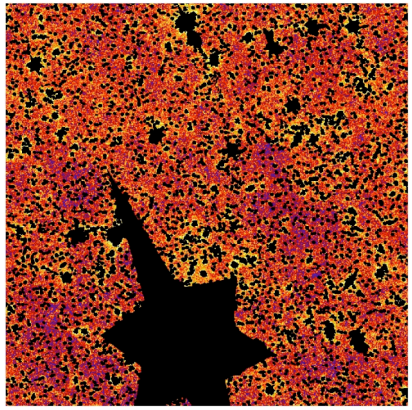


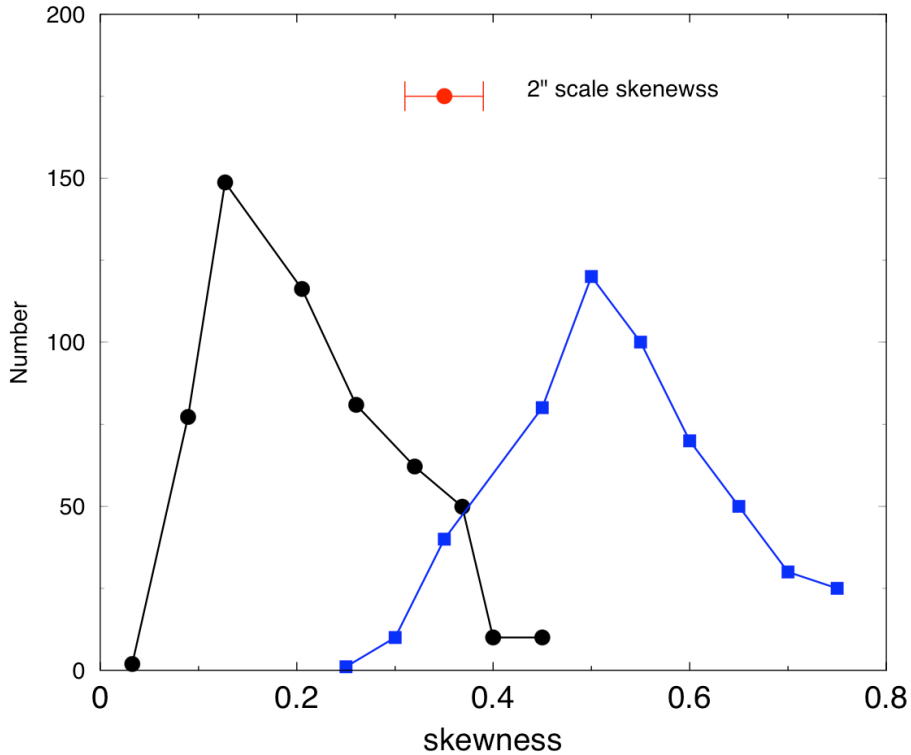


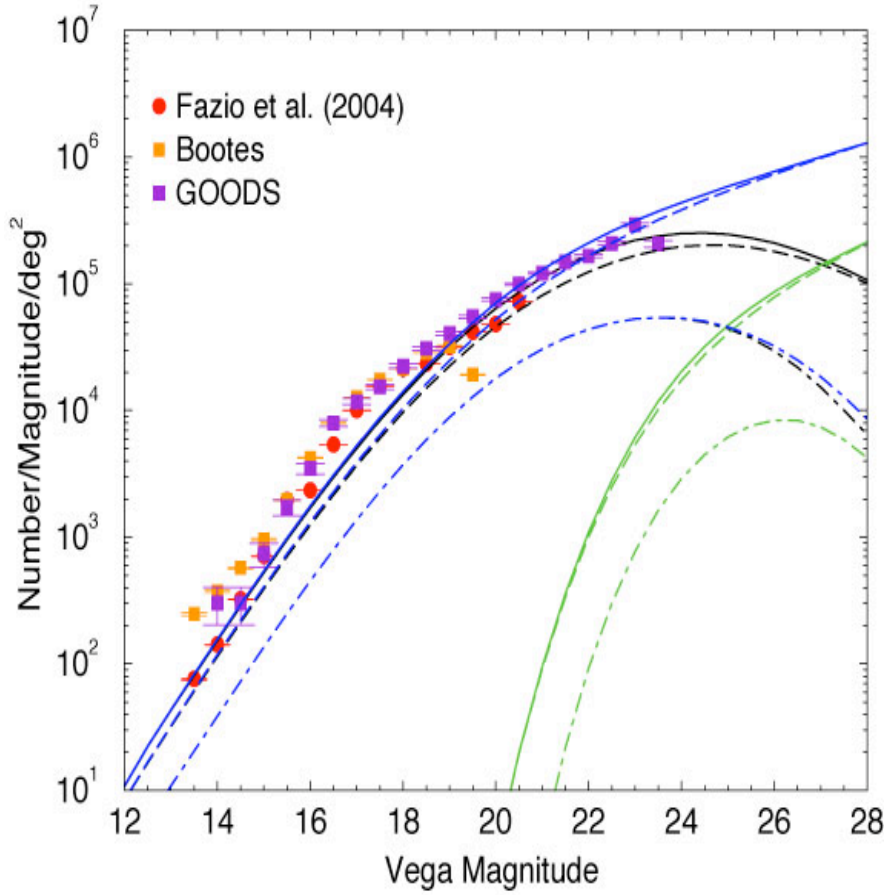
Earliest starlight detection disputed

20:41 19 December 2006
NewScientist, Maggie McKee

Non-Gaussianities in Deep IR Images







Non-Gaussian statistics can help constrain number counts of faint-end sources below the point-source detection level.

Sullivan et al. in prep

Mon. Not. R. astr. Soc. (1974) **171**, 375–379.

ON THE POSSIBILITY OF RADIOASTRONOMICAL INVESTIGATION OF THE BIRTH OF GALAXIES

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Space Research Institute, USSR Academy of Sciences, Profsoyuznaya 88, Moscow, 117485, USSR

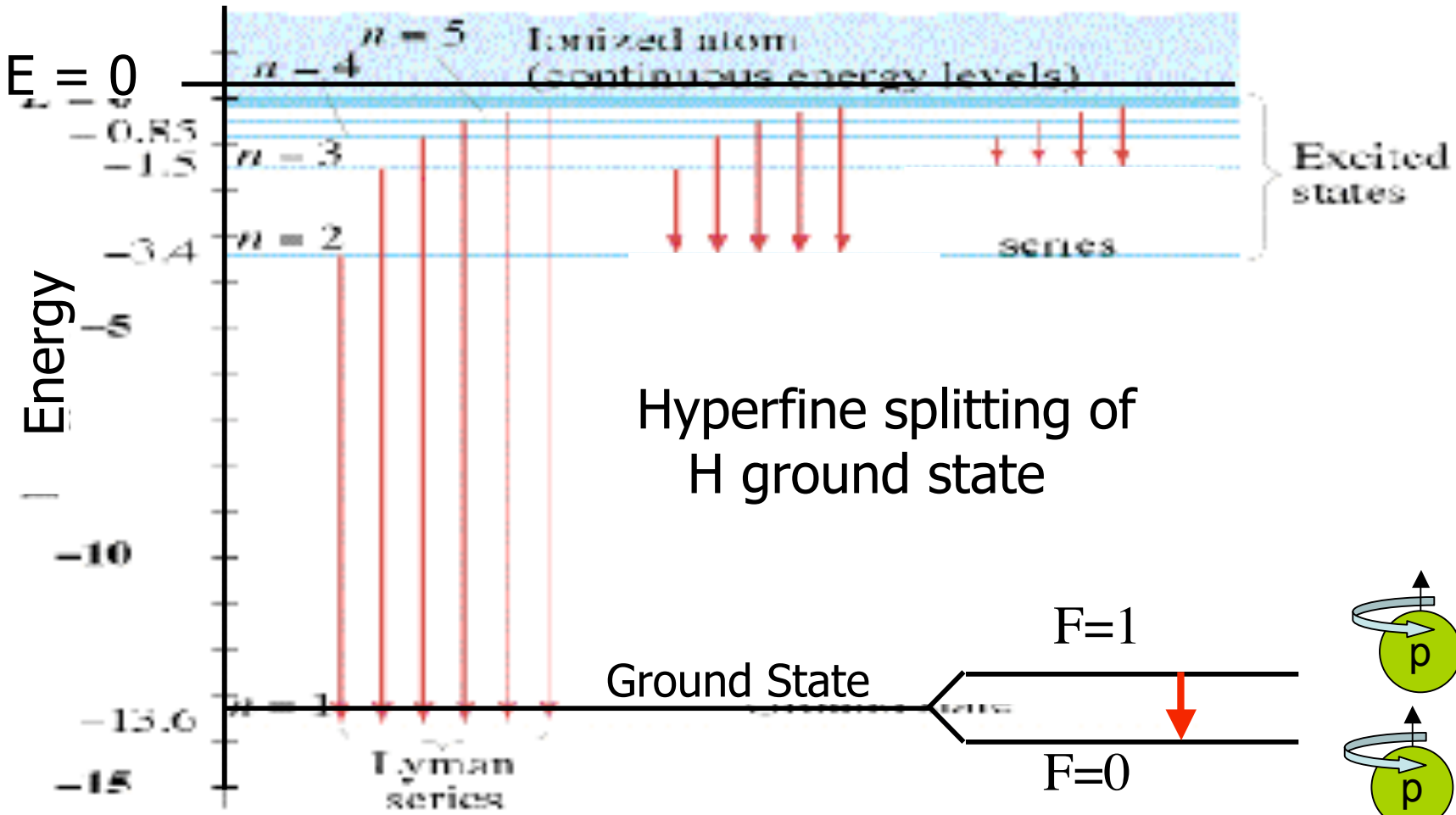
Institute of Applied Mathematics, Miusscaya pl., 4, Moscow 125047, USSR

(Received 1974 November 19)

SUMMARY

During the prestellar epoch, protogalaxies were composed mainly of neutral hydrogen with mass approximately 100 times the mass of interstellar gas in galaxies today. Protogalaxies and protoclusters of galaxies therefore radiated strongly in the 21-cm line of neutral hydrogen. Due to cosmological redshift this line will be shifted to the metre wavelength band, so detection of redshifted 21-cm lines from protogalaxies may provide the possibility of finding the epoch of galaxy formation and the properties of protogalaxies.

The birth of galaxies and clusters of galaxies is far from being clear and an observational approach to this problem is of the utmost importance, both for determining the parameters of the process and also for distinguishing between different theoretical schemes. For instance, were globular clusters born first and did they then join into galaxies? Or did the first step consist of the separation and compression of giant gas clouds (with $M \sim 10^{13}$–$10^{15}\,M_{\odot}$)—protoclusters of galaxies—which later disintegrated into smaller structural units: galaxies, globular galaxies, individual stars? At what redshift z did these processes occur? What was the density and temperature of the gas which transformed into galaxies?



$$\Delta E = \frac{4}{3}\alpha^4 g_p \frac{m_e}{m_p} m_e c^2 = 5.9\mu\text{eV} = h(1420\text{MHz}) \quad \text{or} \quad \lambda = 21\text{ cm}$$

Both F=0 and F=1 have positive parity, so this is a magnetic dipole transition. It has a very long lifetime:

$$\tau_{1\to 0} = A^{-1} = \frac{81}{64 g_p^3 \alpha^{13}} \left(\frac{m_p}{m_e}\right)^3 \frac{h}{m_e c^2} = 1.1\times 10^7 \text{ yr}$$

Cosmic 21 cm Signal

- Emission or absorption depending on whether spin temperature T_s *is > or < the CMB temperature.*

$$\frac{n_{F=1}}{n_{F=0}} = 3e^{-\Delta E/kT_s} = 3e^{-T_*/T_s} \qquad T_* = \frac{\Delta E}{k} = 68.2 \text{ mK}$$

- $T_s > T_{cmb}$ *appears as emission*
- $T_s < T_{cmb}$ *appears as absorption*
- *If gas is substantially heated,* $T_s >> T_*$. *The signal is then (c.f. Field 1959)*

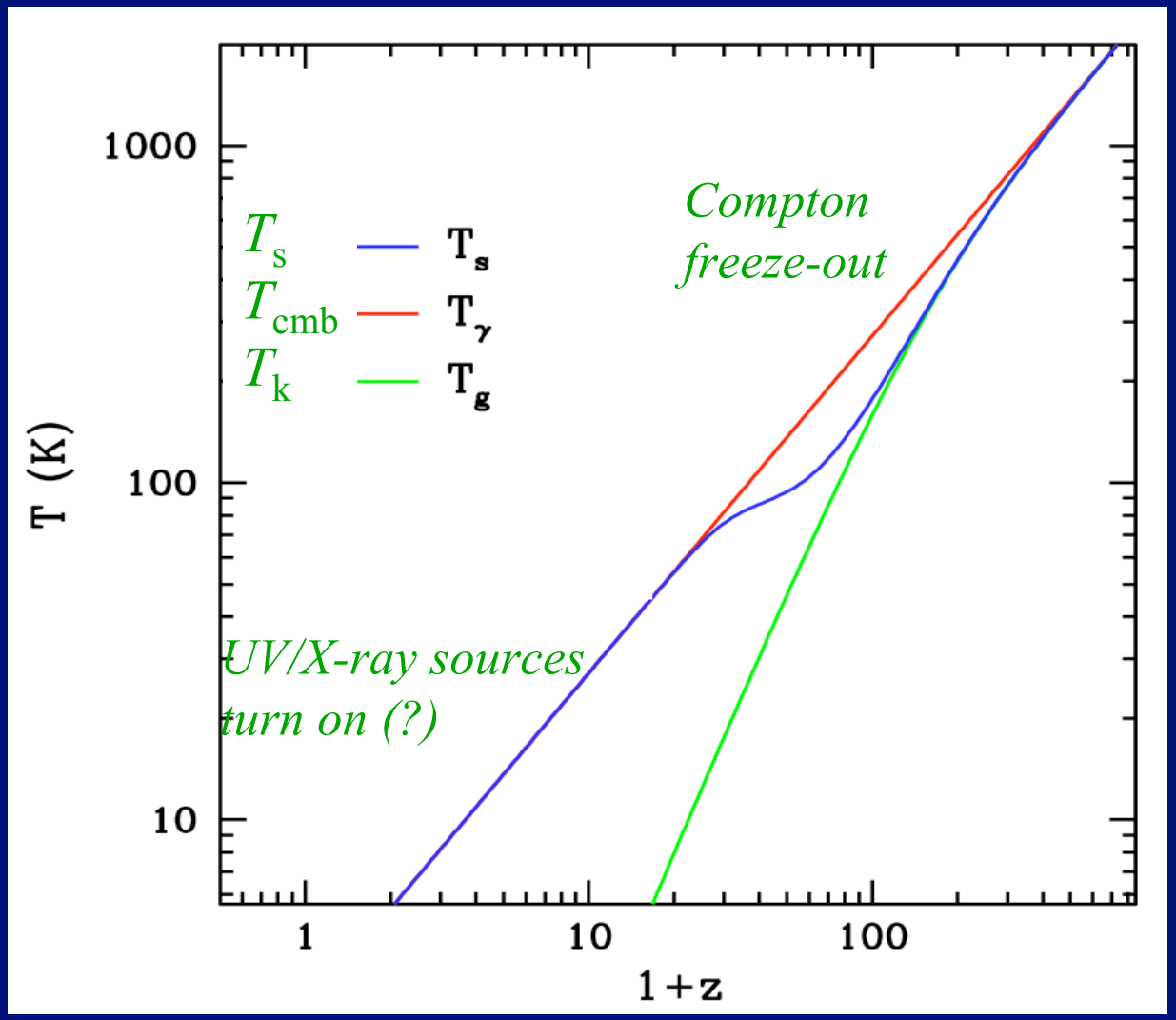
$$\Delta T = \frac{3 n_{\rm HI} \lambda^3 T_*}{32\pi H \tau_{1\to 0}(1+z)}\left(1 - \frac{T_{cmb}}{T_s}\right)$$

$$= 22\text{mK}\; x_{\rm HI}(1+\delta_b)\left(\frac{1+z}{10}\right)^{1/2}\left(1 - \frac{T_{cmb}}{T_s}\right)$$

If $T_s = T_{CMB}$, *no signal (gas in equilibrium with CMB radiation)*

Spin temperature evolution

Loeb & Zaldarriaga etc



Model dependent

Robust prediction: pure collisions

History of 21cm Background

$200 < z < 50$
$7\ \text{MHz} < \nu < 30\ \text{MHz}$

HI appears in absorption against the CMB

$15 < z < 30$
$50\ \text{MHz} < \nu < 90\ \text{MHz}$

First sources turn on and Lya coupling of spin temperature to kinetic temperature and X-ray heating of gas

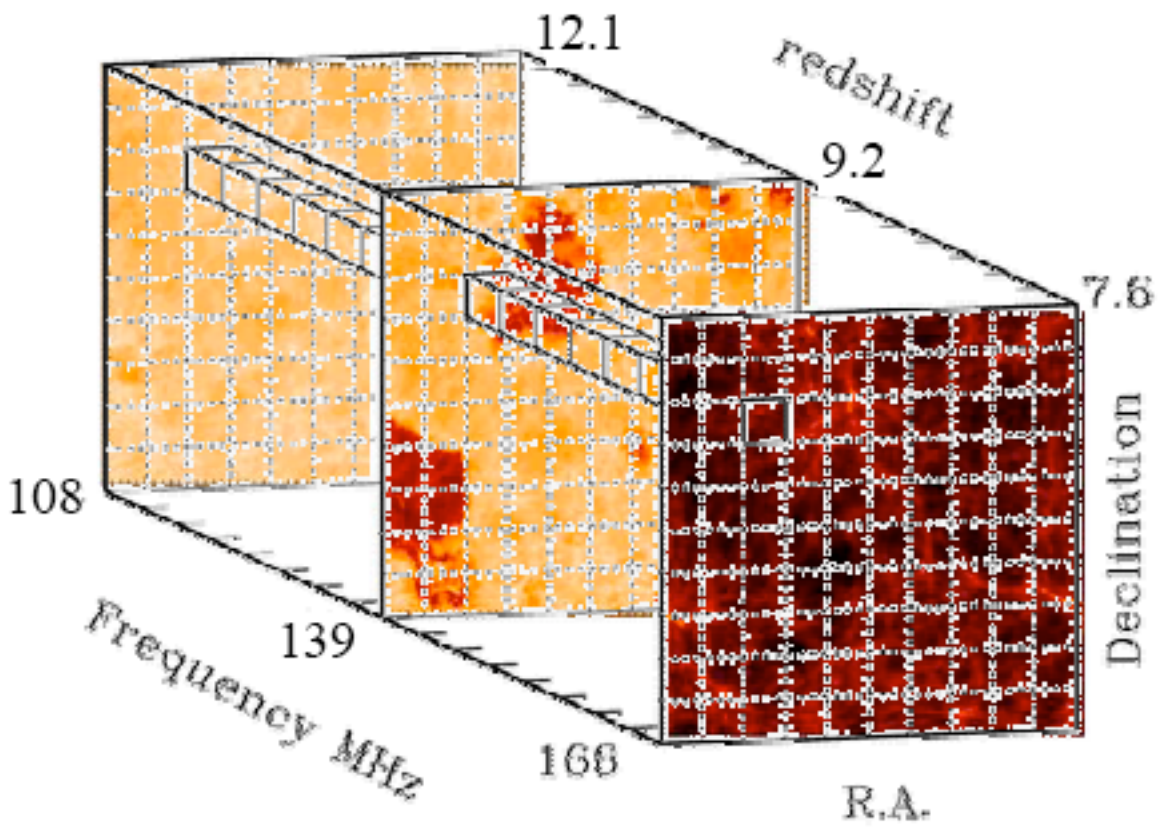
HI appears first in absorption and then in emission with heating against the CMB

$6 < z < 15$
$90\ \text{MHz} < \nu < 200\ \text{MHz}$

Reionization: 21cm signal gradually disappears as H ionized

Technique to remove foregrounds

- Make use of the smoothness in frequency space of foregrounds



Morales

21-cm cube (as a function of frequency)

Foregrounds remain the same (in the same line of sight)

Techniques developed but not clear how they work - currently tested in simulations

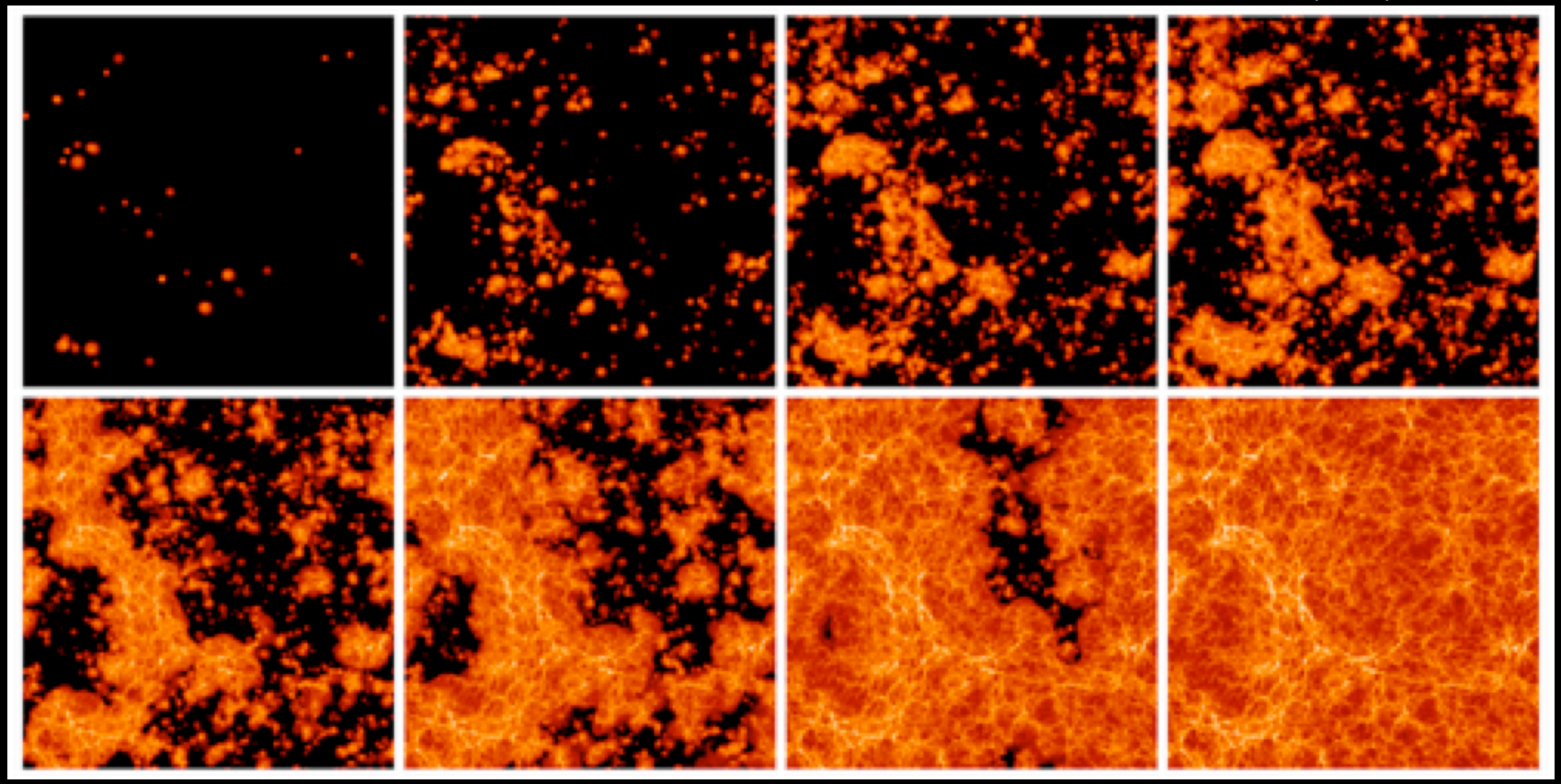
Santos, Cooray & Knox 2005 ApJ; Wang & Hu 2006 etc

On Going Work: Simulations

Ionization Fraction

Large volume
(100 Mpc)^3

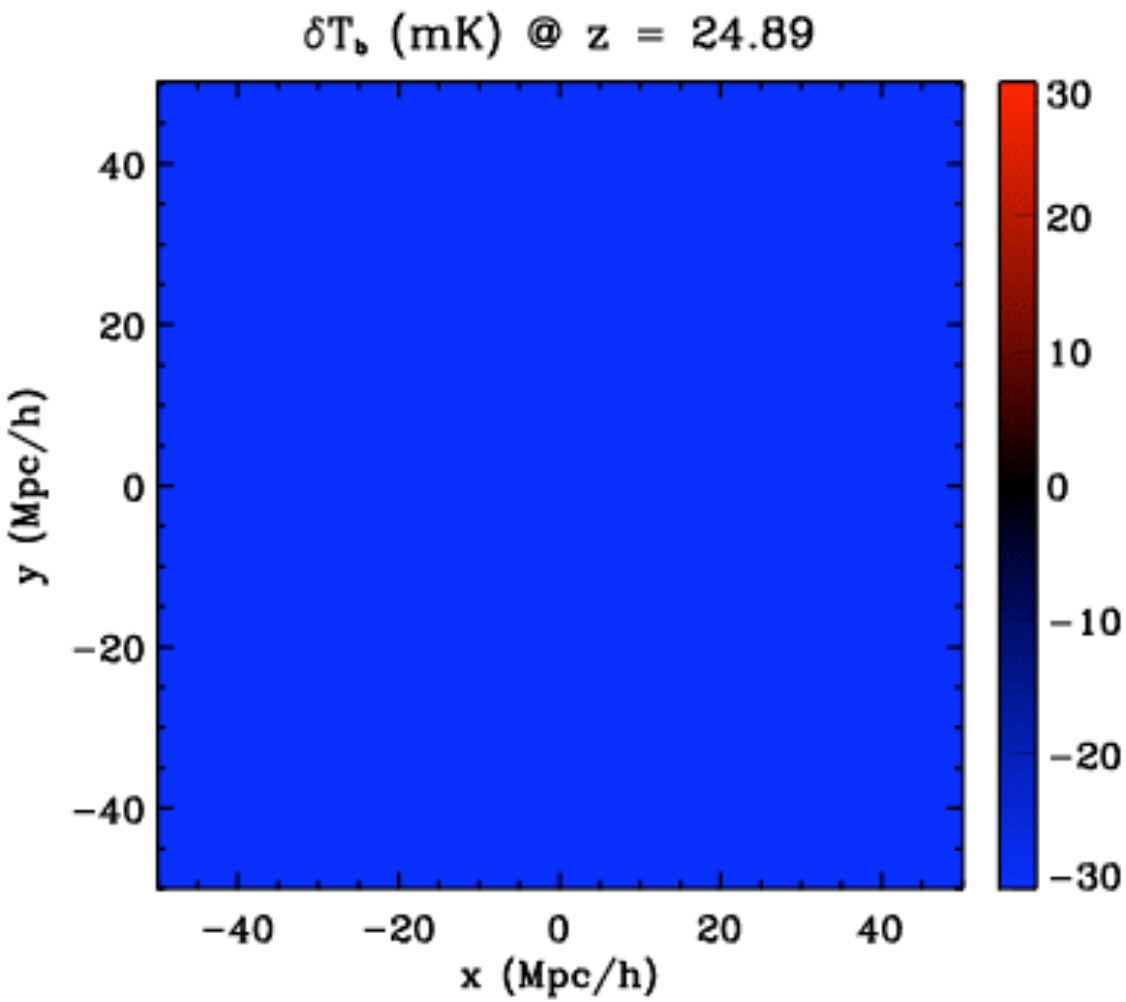
High number
of particles
(2048)^3



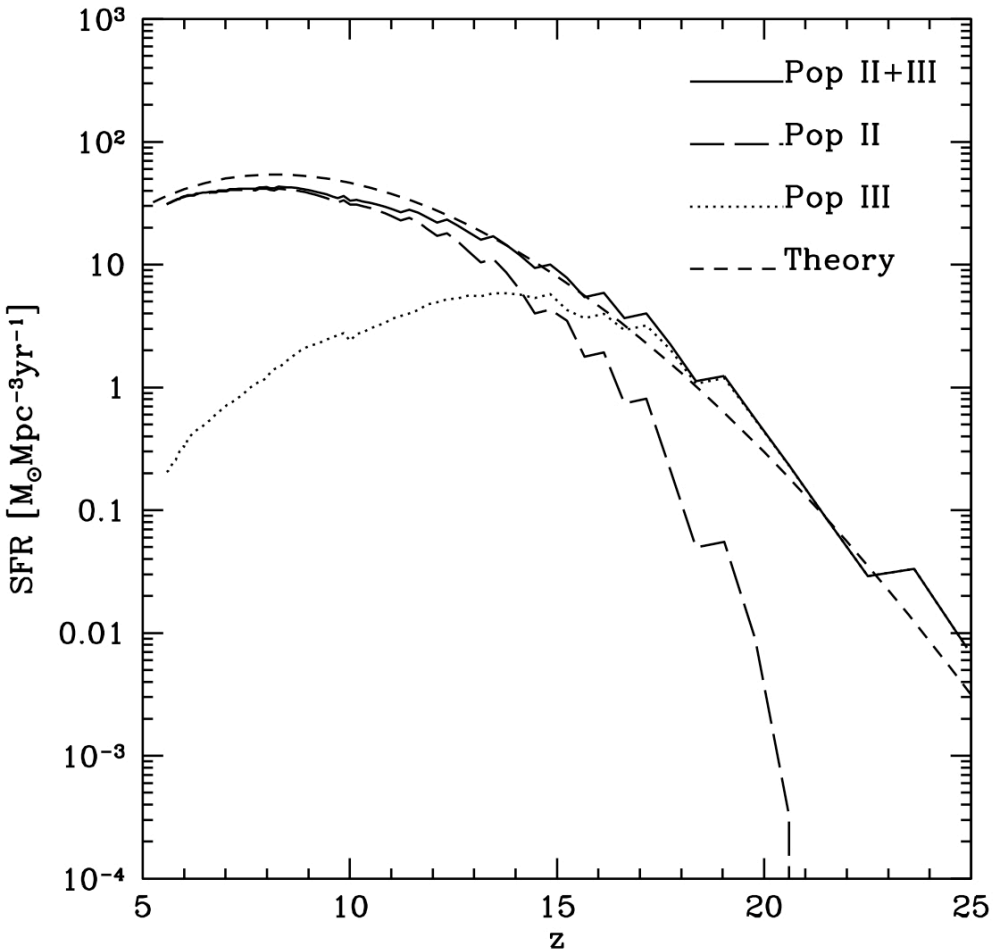
Simulations using a new hybrid radiative transfer code for cosmological reionization developed by Hy Trac

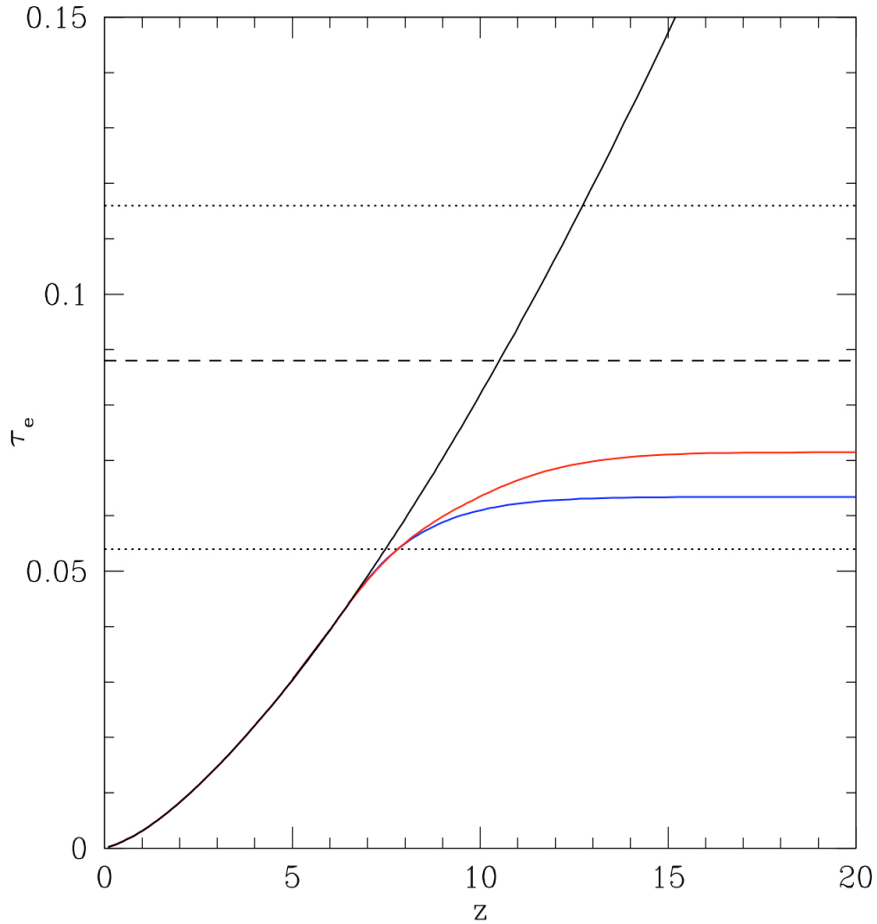
Amblard, Santos, Pritchard, Trac, Cen, Cooray 2007

Movies

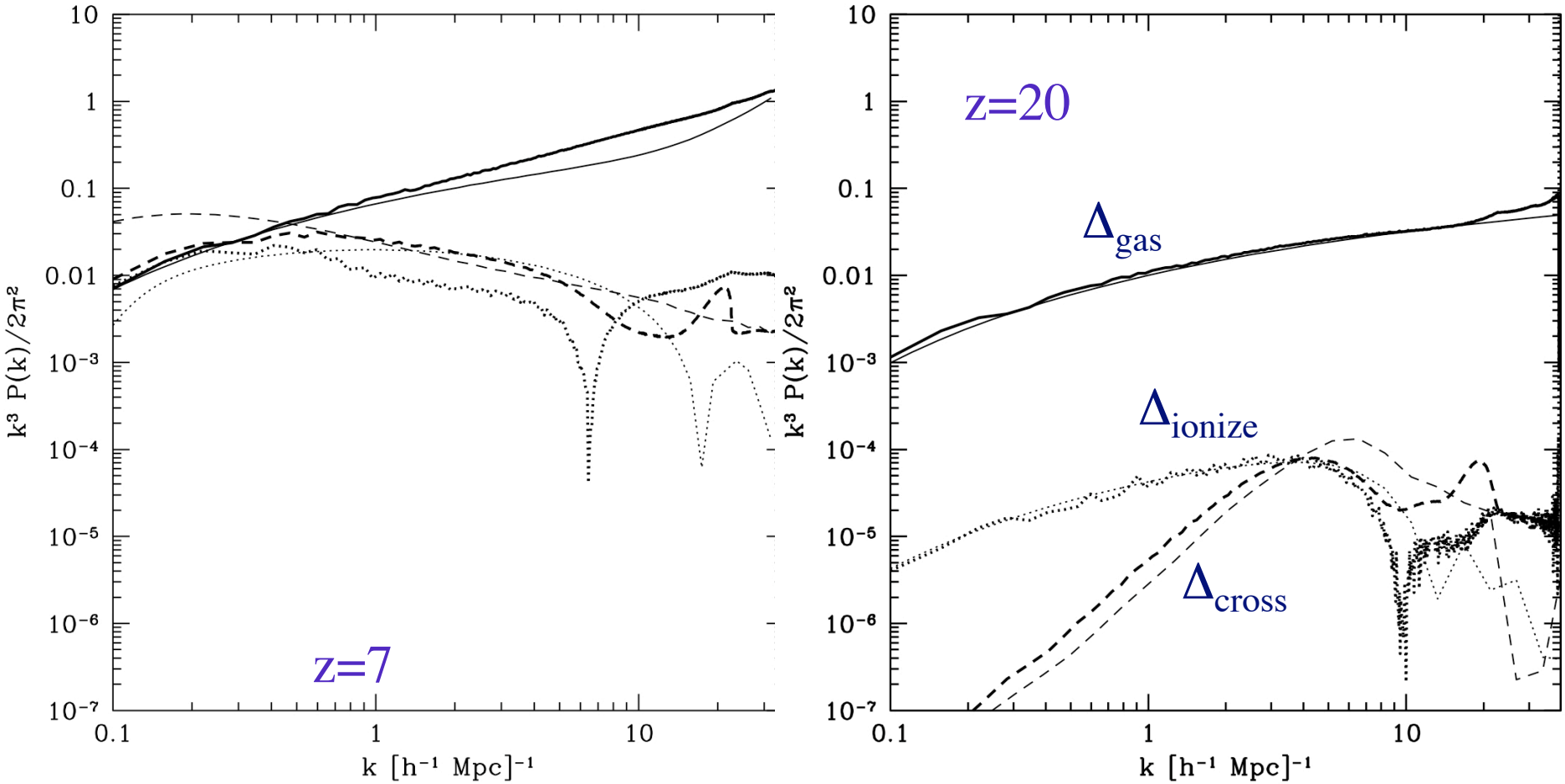

δT_b (mK) @ z = 24.89
y (Mpc/h)
x (Mpc/h)
40
20
0
−20
−40
−40
−20
0
20
40
30
20
10
0
−10
−20
−30

Basic simulation parameters

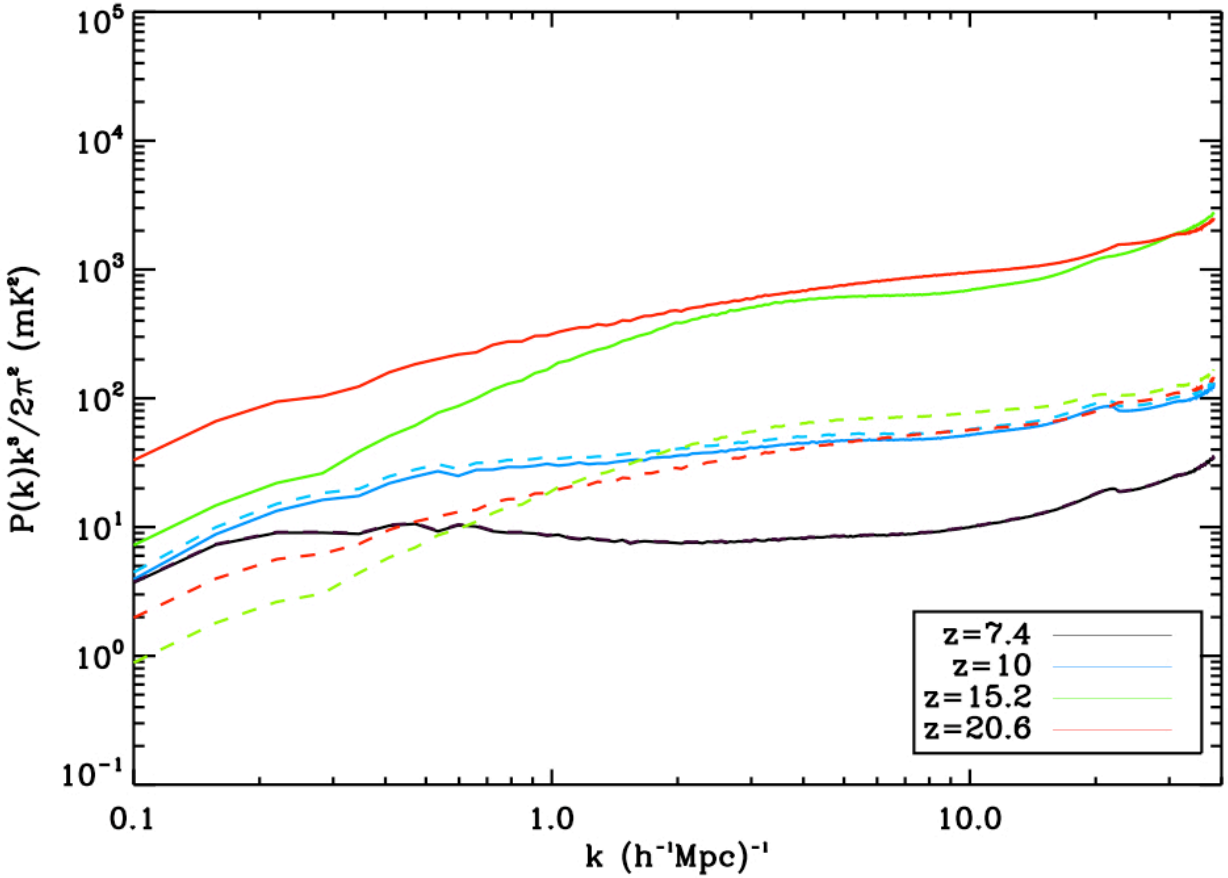




P(k) comparison between simulations and FZH04 model



Comparison between a X-ray heating model in simulation and setting $T_s >> T_{CMB}$ in the simulation box.



Applications of 21-cm: Cosmic Non-Gaussianity

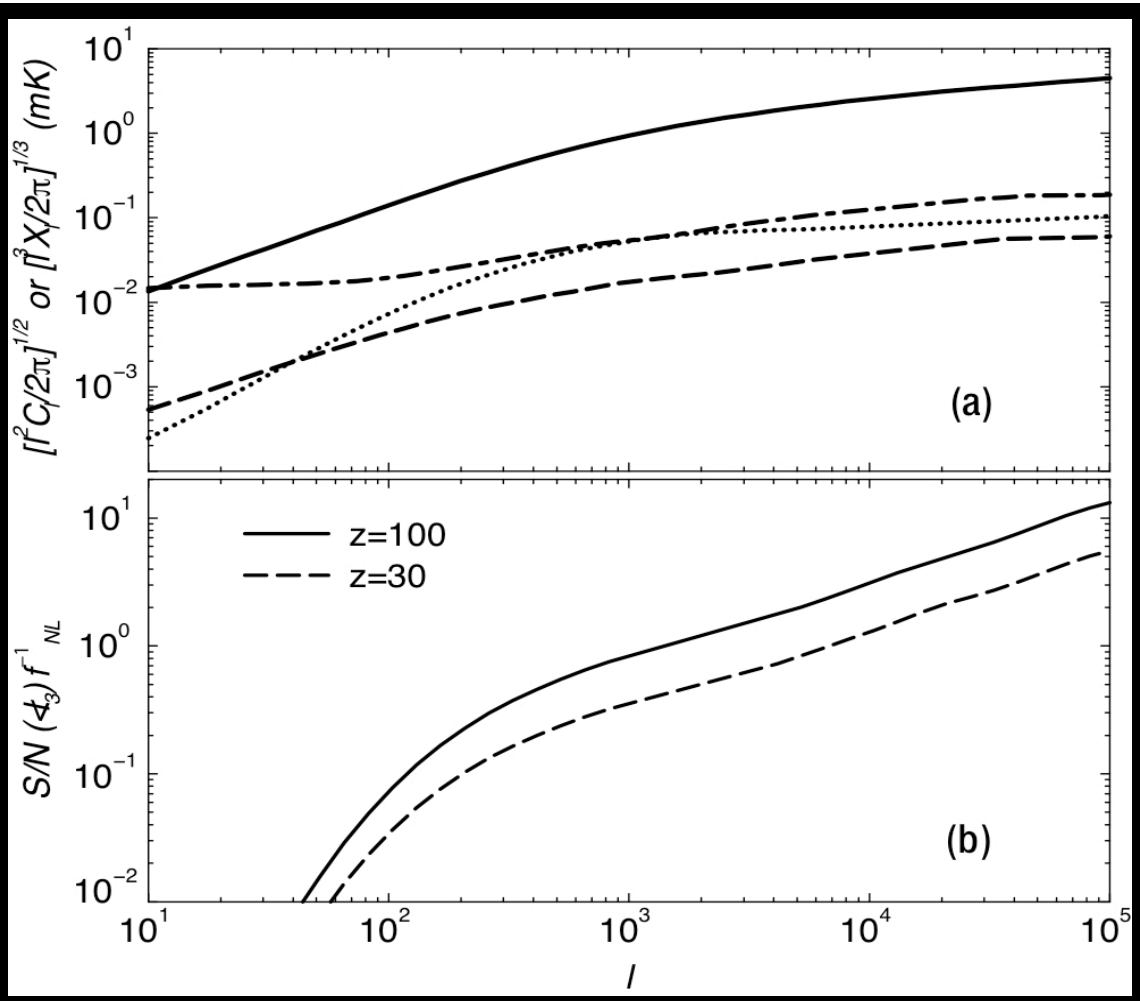
z < 15 during reionization - non-Gaussianity due to partial reionization and secondary corrections to 21-cm (coupling of density and ionization fraction etc) Cooray 06; Bharadwaj & Panday 06

z > 15 well before reionization - fully neutral, mean temp in absorption relative to CMB, and possibly the best probe of primordial non-Gaussianity (?) Pillepich et al. 07; Cooray 07

21-cm vs. CMB

CMB is a 2d map at z of 1100 while *21-cm is 3d* from z of 200 to z of 15. CMB is damped at arcminute scales, while 21-cm extends to sub-arcsecond scales.

21-cm, in principle, allows a study of f_{nl} << 0.1 (all-sky, no detector noise down to $l \sim 10^5$)



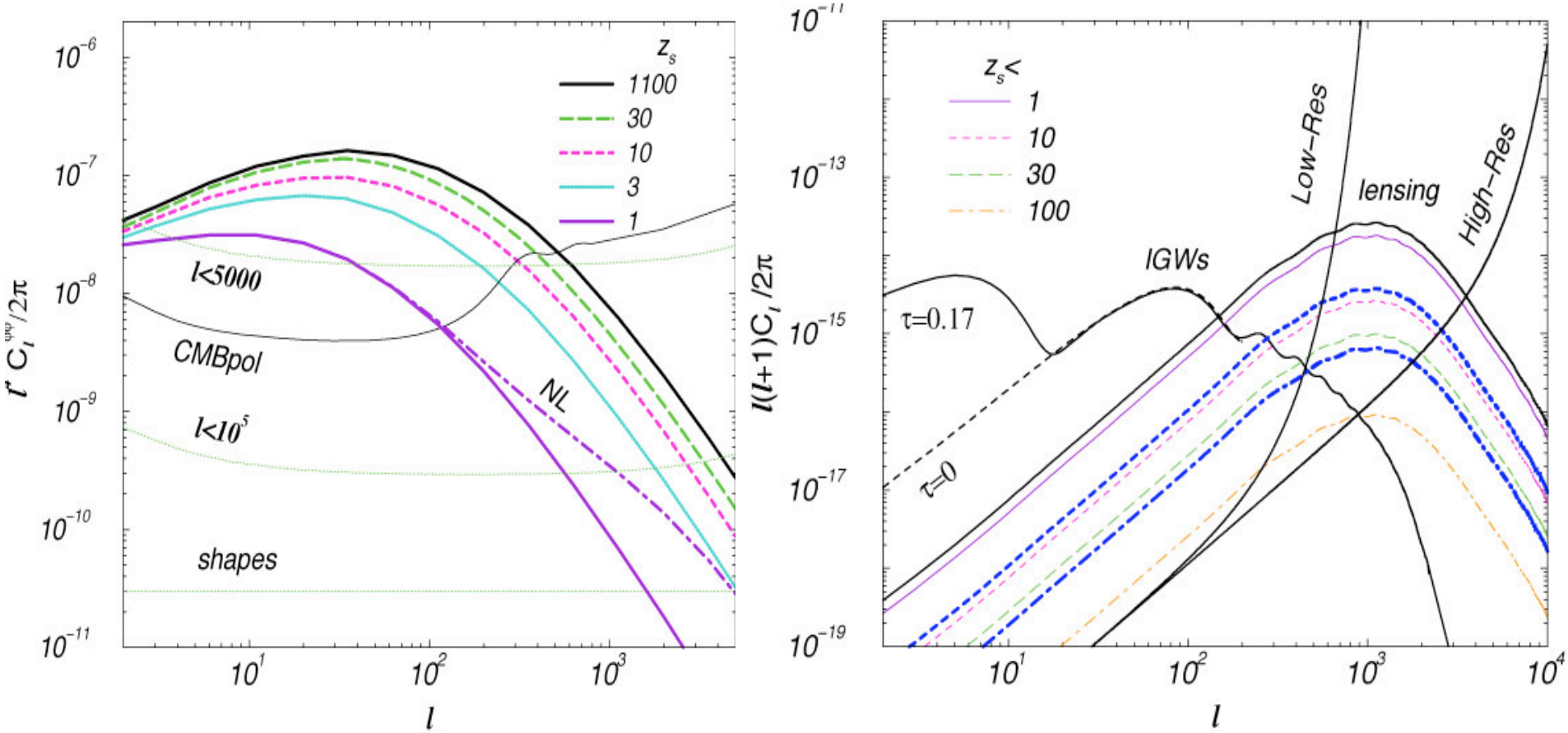
Must separate non-Gaussianity from non-linear gravitational evolution.

But, primordial and gravitational bispectra have different structure in the multipole space.

Ways to separate? Optimized bispectrum detection through a statistic based on the 2 to 1 correlator $X_l=\langle a_{lm}^2-a_{lm}\rangle$ Cooray 01

But, lensing of 21-cm is probably the biggest confusion. Can be analyzed jointly with high-res CMB for primordial non-Gaussianity. Li & Cooray in prep

Application of 21-cm: CMB lensing confusion



Galaxy lensing cannot be used to correct polarization, but 21 cm fluctuations at z > 20 can.

A low-resolution CMB satellite + a low-frequency 21 cm array may be the way to dig deep on the tensor-to-scalar ratio

Sigurdson & AC, 2005

Measurement Possibilities for Non-Gaussianity at high redshifts

- z~1 to 3 Far-IR background with Herschel - not-likely to be all that helpful, non-Gaussianity from lensing.

- z > 5: near-IR background with deep IR images. Non-Gaussianity captures some information about first-light sources.

- 21-cm at z < 15 (as probed by first-generation experiments): secondary/non-linear effects of reionization

- 21-cm at z > 15: Probably some information on primordial non-Gaussianity, 3d information down to arcsecond scales help, but challenging to measure experimentally.

Full talk and details at http://www.cooray.org.

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