Possible Searches for non-Gaussianity at high redshifts

Asantha Cooray

KICP - June 2007
At low-z’s gravitational non-Gaussianity $\gg$ 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)
IR/Opt: Direct emission from stars
FIR: Processed emission of Opt/IR light by dust
Extragalactic Far-IR Background Studies with Herschel-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

<table>
<thead>
<tr>
<th>λ_{cent} (µm)</th>
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<th>Angular res.</th>
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SPIRE: Survey instrument
Poor resolution. Confusion limited easily.
Can only resolve < 10% of EBL at 350 µm
Clustering Studies of Far-IR Background with Herschel-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

$N_{\text{FIR}} \propto M_{\text{dm}}^B \quad (M > M_{\text{dm,min}})$

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

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:

$$a_{\ell m} = \sum_{freq=i} w_i^i a_i^i$$

with

$$a_i^i = c_{\ell m} + s_i^i + d_i^i + n_i^i$$

Far-IR | CMB | Dust | Noise

Then we minimize the resulting $C_\ell$ for far-IR anisotropies

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

- 10 sqr. deg. GTO L5
- 10 sqr. deg. GTO L5 + 1/f noise
- 200 sqr. deg. 250 hours
- 200 sqr. deg. 250 hours + 1/f noise
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

Herve Aussel
Andrew Blain
James Bock (a, b)
Véronique Buit
Jordi Cepa
Sarah Church
Dave Clements
Asantha Cooray
Steve Eales
David Elbaz
Alberto Franceschini
Ken Ganga
Walter Gear (b)
Jason Glenn (b)
Matt Griffin (c)
Bruno Guiderdoni
Mark Halpern
Martin Harwit
Evanthis Hatziminaoglou
Kate Isaak
Rob Ivison
Guilaine Lagache
Suzanne Madden
Bruno Maffei
Phil Maloney
Hien Nguyen
Seb Oliver (a)
Alain Omont
Mat Page
Pasquale Panuzzo
Ismael Perez-Fournon
Michael Rowan-Robinson (b)
Richar Savage
Bernhard Schulz
Douglas Scott
Jason Stevens
Laurent Vigroux (c)
Ian Waddington
Tim Waskett

SAP, Saclay, France
Caltech, Pasadena, USA
JPL, Pasadena, USA
LAM, Marseille, France
IAC, Canaria, Spain
Stanford U., Palo Alto, USA
ICSTM, London, UK
UC Irvine, Irvine, USA
Cardiff U., Cardiff, UK
SAP, Saclay, France
U. Padua, Padua, Italy
C. France, Paris, France
Cardiff U., Cardiff, UK
U. Colorado, Boulder, USA
Cardiff U., Cardiff, UK
IAP, Paris, France
UBC, Vancouver, Canada
Cornell U. (emeritus), Ithaca, USA
IAC, Canaria, Spain
Cardiff U., Cardiff, UK
ATC, Edinburgh, UK
IAS, Orsay, France
SAP, Saclay, France
Cardiff U., Cardiff, UK
U. Colorado, Boulder, USA
JPL, Pasadena, USA
U. Sussex, Brighton, UK
IAP, Paris, France
MSSL, Surrey, UK
IFSI, Rome, Italy
IAC, Tenerife, Spain
ICSTM, London, UK
U. Sussex, Brighton, UK
IPAC, Pasadena, USA
UBC, Vancouver, Canada
U. Hertfordshire, Herts, UK
SAP, Saclay, France
U. Sussex, Brighton, UK
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

with 1/f noise

<table>
<thead>
<tr>
<th>area in deg$^2$</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
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<tr>
<td>total S/N</td>
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<td>○</td>
<td>□</td>
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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

Scan at maximum rate (60"/s)
L5 Baseline Scan Strategy (2)

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 (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 deg²)

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

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.

Background Fluctuation Measurements before 2005
Or, may be there is more to the IRB?
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)
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.
Establish the mass scale for L~17 to 19 IR galaxies at z of 1

\[ \sim 5 \times 10^{11} \, M_{\text{sun}} \]

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

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

*Sullivan et al. in prep*
ON THE POSSIBILITY OF RADIOASTRONOMICAL INVESTIGATION OF THE BIRTH OF GALAXIES

R. A. Sunyaev and Ya. B. Zel'dovich

Space Research Institute, USSR Academy of Sciences, Profsoyuznaya 88, Moscow, 117455, USSR
Institute of Applied Mathematics, Miusskaya 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 $M \sim 10^{13}-10^{15} M_\odot$)—proto-clusters 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?
\[ \Delta E = \frac{4}{3} \alpha^4 g_p \frac{m_e}{m_p} m_e c^2 = 5.9 \mu eV = h(1420MHz) \text{ or } \lambda = 21 \text{ cm} \]

Both F=0 and F=1 have positive parity, so this is a magnetic dipole transition.

It has a very long lifetime:

\[ \tau_{1 \rightarrow 0} = A^{-1} = \frac{81}{64 g_p^3 \alpha^{13}} \left( \frac{m_p}{m_e} \right)^3 \frac{h}{m_e c^2} = 1.1 \times 10^7 \text{ yr} \]
Cosmic 21 cm Signal

• Emission or absorption depending on whether spin temperature $T_s$ is $> \ or <$ the CMB temperature.

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

• $T_s > T_{cmb}$ 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)

\[
\Delta T = \frac{3n_{HI} \lambda^3 T_*}{32\pi H \tau_{1\to0}(1+z)} \left(1 - \frac{T_{cmb}}{T_s}\right) \\
= 22\text{mK} \ x_{HI} (1 + \delta_b) \left(\frac{1+z}{10}\right)^{1/2} \left(1 - \frac{T_{cmb}}{T_s}\right)
\]

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 MHz < ν < 30 MHz

HI appears in absorption against the CMB

15 < z < 30
50 MHz < ν < 90 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 MHz < ν < 200 MHz

Reionization: 21cm signal gradually disappears as H ionized
Technique to remove foregrounds

- Make use of the smoothness in frequency space of foregrounds

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

Morales

On Going Work: Simulations

Ionization Fraction

Simulations using a new hybrid radiative transfer code for cosmological reionization developed by Hy Trac Amblard, Santos, Pritchard, Trac, Cen, Cooray 2007

Large volume $(100 \text{ Mpc})^3$

High number of particles $(2048)^3$
Basic simulation parameters
P(k) comparison between simulations and FZH04 model
Comparison between a X-ray heating model in simulation and setting $T_s >> T_{\text{CMB}}$ 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
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

• $z \sim 1$ 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.

Thanks to sponsors: NSF CAREER, NASA Herschel, HST/Spitzer