Dusty Galaxies
Berkeley CMB Lensing Workshop - April 2011
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Optical/UV Starlight absorbed by dust

Dust re-emits in the FIR

Stellar bump from old stars

UV from young, hot stars

Chary & Elbaz (2001)
Extragalactic Background Light (EBL)

Dole et al. 2006

Extragalactic Background Light (EBL)
Negative K-correction
get this data @ http://www.ias.u-psud.fr/irgalaxies/model.php#Counts

Béthermin et al. (2011)
arXiv:1010.1150

Redshift Distribution
Infrared Background at $\lambda > 1$ mm ($< 300$ GHz) dominated by high-redshift sources

CMB bands at

- 220 GHz (1.4 mm)
- 148 GHz (2 mm)

Béthermin et al. (2011)
arXiv:1010.1150

Total Infrared Background
Béthermin et al. (2011)
arXiv:1010.1150
Most of that Star Formation occurs in LIRGS, i.e.:
$L_{\text{FIR}} = 10^{11} - 10^{12} \, M_{\odot}$

Le Floc'h et al. (2005)
Typical LIRGS at z~1-3 have flux densities $S_{250} \sim 1-10$ mJy
BIG QUESTIONS

1. How many are there?
2. Where are they?
Observing in the submillimeter
Submm Observations

MAMBO
AzTEC
SCUBA 500
SHARC 250
U-band: MUSYC
K-band: MUSYC
SPIRE 250 μm

Gaelen Marsden, UBC

10′

Confusion

U-band
~ 60 sources/arcmin²
K-band
~ 45 sources/arcmin²
SPIRE
~ 0.5 sources/arcmin²
$S > 20 \text{ mJy} : 1,200/\text{deg}^2$

$S < 20 \text{ mJy} : 480,000/\text{deg}^2$

Confusion
Recovering "Sources" in Simulations

50 brightest (top 0.5%)

70% of top 0.5% recovered

50 brightest recovered

Confusion
How do you count sources without sources to count?

1. How many are there?
Counts Histogram

$P(d)$
Measured Number Counts

Model – Béthermin et al. (2011)  
arXiv:1010.1150

Lima et al. (2010)
arXiv: 1004.4889

Lensed Sources

$S^* = 0.35 \text{ mJy, } \alpha = -1.0$

$z_s = 5.0$
$z_s = 4.0$
$z_s = 3.0$
$z_s = 2.0$
$z_s = 1.0$

SPT dust
2.0 mm
Negrello et al. (2010)
arXiv:1011.1255

SMA

Keck i-band
(SMA contours)

Lensed Sources
Strong Detections:
PdBI: CO(J=5→4)
CARMA: CO(J=3→2)
GBT: CO(J=1→0)
3. Where are they?

How do you measure clustering when most of what you see are fluctuations?
Poisson (shot) Noise

\[ P_{\text{shot}} = S^2 \frac{dN}{dS} \]
Star Forming Galaxies are biased tracers of Dark Matter
Viero et al. (2009)
arXiv: 0904.1200

Shot Noise

Herschel observation

Clustering Signal After Removal of Shot Noise

BLAST simulation...

Excess Signal from Galaxy Clustering

BLAST Power Spectrum

... Herschel observation

Viero et al. (2009)
arXiv: 0904.1200
$\chi^2/dof = 0.85$

Planck Collaboration et al. (2011)

arXiv: 1101.2028
Frequency-dependence of Power-law

\[ P(\ell) = P_{\text{shot}} + A \left( \frac{\ell}{1000} \right)^{-n} \]

Planck / ACT / BLAST
SPIRE (Amblard et al.)

Addison et al. (in prep.)
Latest Power Spectra

Planck - (2011)
Herschel - Amblard(2011)

Slope consistent with $S_\nu \sim \nu^\alpha$ with $\alpha \sim 3.4$

see also Shirokoff et al. (2010) - arXiv: 1012.4788
Millea et al. (2011) - arXiv: 1102.5195
Clustering Signal made up of two regimes
- 2-halo: Linear Regime (large scales)
- 1-halo: Non-Linear Regime (small scales)

see e.g., Cooray & Sheth (2000), Zehavi et al. (2005, 2008)
What are you actually fitting?

\[ P_{1h}(k, z) = \int_M n_{\text{halo}}(M, z) [2N_{\text{cen}}(M)N_{\text{sat}}(M)u_{\text{DM}}(k, z|M) \\
+ N_{\text{sat}}^2(M)u_{\text{DM}}^2(k, z|M)]dM/n_{\text{gal}}^2(z), \]

\[ P_{2h}(k, z) = P_{\text{DM}}(k, z) \left[ \int_M n_{\text{halo}}(M, z)N_{\text{gal}}(M, z) \\
\times b(M, z)u_{\text{DM}}(k, z|M)dM \right]^2 / n_{\text{gal}}^2(z). \]

\[ n_{\text{gal}}(z) = \int_M n_{\text{halo}}(M, z) \left[ 1 + \left( \frac{M}{M_1} \right)^{\alpha} \right]dM \]

and for each \( M_{\text{min}}-\alpha \) pair, \( M_1 \) fixed to agree to source model by requiring:

\[ \int_0^\infty \frac{dN}{dS\,dz}(S, z)\,dS = n_{\text{gal}}(z)\,dV_c(z) \]
Galaxies reside in dark matter halos with $\sim 3 \times 10^{11} \ M_\odot$

- At $z \sim 2$
  - $b_{linear} \approx 4.0$
  - $M_{eff} \approx 6 \times 10^{12} \ M_{Sun}$
  - $M_{min} \approx 3 \times 10^{11} \ M_{Sun}$
  - $b_{eff} \approx 2.4$

Using the halo model fits, we estimate the minimum dark matter mass scale for dusty star-forming galaxies at the peak of the star formation history of the universe to be $\log_{10} M_{min}/M_\odot = 11.5^{+0.7}_{-0.7}$ at 350 $\mu$m with a bias factor for the galaxies of $b = 2.4^{+0.9}_{-0.9}$. The minimum halo masses log$_{10} M_{min}/M_\odot$ at 250 and 500 $\mu$m are $11.1^{+1.0}_{-1.0}$ and $11.8^{+0.4}_{-0.4}$, respectively. The corresponding bias factors for the galaxies are $2.0^{+0.9}_{-0.9}$ and $2.8^{+0.4}_{-0.4}$ at 250 and 500 $\mu$m, respectively. The differences in the minimum halo masses and the bias factors between the three wavelengths are likely due to a combination of effects including overall calibration uncertainties, the fact that at longer wave-
Planck Collaboration et al. (2011)
arXiv: 1101.2028

Planck Halo Model
Amblard et al. (2011)
arXiv: 1101.1080

Herschel Halo Model
cmbH?
CMB

Galaxies

SZ Clusters

The high-$\ell$ CMB sky
Galaxies:
• Dusty
• Radio

Secondary CMB:
• Sunyaev-Zel’dovich (SZ)

Total Signal

CMB Foregrounds

Dunkley et al. 1009.0866
Cross-Correlations
Isolate Dusty Galaxies from the Rest

BLAST 250 μm

ACT 148 GHz
9 deg²
Cross-Correlate BLAST and ACT

Hajian & Viero et al.
arXiv:1101.1517
future surveys

image: Joaquin Vieira
SPT 100 deg\(^2\) deep field is the deepest mm map in existence and will remain so for the next decade.

Given 79 hours to map a 100 deg\(^2\) with SPIRE

Will use this field for cross-correlations in hopes of measuring the kSZ power spectrum
end