Missing Baryons: how much? how hot? how fast?

Niayesh Afshordi
Perimeter Institute, and University of Waterloo

with Siavash Aslanbeigi (PI/UW)
Guilhem Lavaux (UW/PI→CNRS/IAP)
Amir Hajian (CITA)
Mike Hudson (UW)
# Agenda

**External Correlations of the CMB and Cosmology**  
May 25-27, 2006. Fermilab, Batavia, IL

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## AGENDA

Click on title for presentation file (except Asantha's)

<table>
<thead>
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**Thursday May 25**

**Friday May 26**

**Good Old Days!**

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### Wednesday, 16 October, 13
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## GOOD OLD DAYS!

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<td>G. Mathews</td>
<td>Scientific CMB Lensing - Mean Magnification and Variance</td>
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<td>B. Wandelt</td>
<td>Constraints on Resonant Particle Production and Primordial Magnetic</td>
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<td>R. Bean</td>
<td>Fields from the CMB and LSS on Small Angular Scales</td>
</tr>
<tr>
<td>6:00</td>
<td>Workshop Dinner @ Chez Leon</td>
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**Saturday May 27**

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**Scientific Contact:** stebbins@fnal.gov  
**Administrative Contact:** sazama_at_fnal.gov

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Wednesday, 16 October, 13
Good Old Days!

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Friday May 26

Cross-Correlation Analysis Using Gibbs Sampling
AMBA
The South Pole Telescope
The Dark Energy Survey
C(theta) from WMAP

Coffee Break

Cross-correlation of 2MASS and WMAP3: Implications for ISW
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CMB Constraints on the Intracluster Medium
SZE Signals in Cluster Models
An In-Depth Comparison Between X-ray Emission and WMAP Observation of the SZ Effect Among 31 Nearby Clusters

Extreme Correlations: SZ, 21-cm and the high-z Universe with CMB
Cross-Correlation Between the 21cm and the CMB

Coffee Break

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Extending Limber

• When can we trust Limber approximation? systematic derivation?

\[ \tilde{A}(\hat{n}) = \int dr \sqrt{r} f_A(r) A(r\hat{n}), \text{ and } \tilde{B}(\hat{n}) = \int dr \sqrt{r} f_B(r) B(r\hat{n}). \]

\[
C_{AB}(\ell) = \int \frac{dk}{k} P_{AB}(k) f_A(r) f_B(r) \left\{ 1 + \frac{2}{(2\ell + 1)^2} \left[ \frac{d\ln f_A}{d\ln r} \frac{d\ln f_B}{d\ln r} s(k) - p(k) \right] + O(\ell^{-4}) \right\}
\]

\[
k = \frac{\ell + 1/2}{r}, \quad s(k) = \frac{d\ln P_{AB}(k)}{d\ln k}, \quad p(k) = \frac{k^2[3P''_{AB}(k) + kP'''_{AB}(k)]}{3P_{AB}(k)}
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• Trick: Laplace transform of Bessel function

LoVerde & NA 2008; included in CAMB (July 2013)
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• Trick: Laplace transform of Bessel function
  LoVerde & NA 2008; included in CAMB (July 2013)
Universal Pressure Profile

$\rho_{\text{gas}} T / \rho_{\text{crit}} T_x$

$\times\, r / r_{200}$

WMAP3 × X-ray clusters

NA, Lin, Nagai, & Sanderson 2007

Wednesday, 16 October, 13
missing thermal energy?
missing baryons?

\[
\frac{M_{\text{gas}}(<r)}{M_{\text{tot}}(<r)} \times \frac{<T>}{T_X}
\]

Cosmic Baryonic Budget

OVRO/BIMA
Chandra X-ray Clusters

WMAP3 \times X\text{-}ray clusters

NA, Lin, Nagai, & Sanderson 2007

\(r/r_{200}\)
Can SZ surveys sustain the CMB dominance?

- SZ clusters can be detected up to high redshifts
- Their number counts probe Dark Energy/Cosmology
- Many SZ surveys are underway: APEX, SZA, ACT, SPT, Planck, …
- Can they deliver? Calibration of SZ-Mass relation, Gastrophysics, …
In the mean time ...
Planck 2013 results. XX. Cosmology from Sunyaev–Zeldovich cluster counts

\[ \sigma_8 \quad \Omega_m \]

- Planck CMB only
- Planck SZ + BAO + BBN
Do we have a problem, or don’t we?

Hajian, et al. 2013: \textit{Planck} $\times$ \textit{ROSAT}
Gastrophysical Black Magic!

Battaglia, et al. 2010

Planck Intermediate Results. V. 2013
Gastrophysical Black Magic!

Battaglia, et al. 2010

Planck Intermediate Results. V. 2013
Cosmic Pyramid

Dark “Energy”: CC problem

“Missing” Baryons

“Big Bang”

Dark “Matter”
Cosmic Pyramid: missing baryons

• How much? We only see 10-20% of baryons at low z.

• How hot? What are the energetic processes that affect Intergalactic plasma?

• How fast? Where are the baryons going?
SZ done optimally!

- Maximize likelihood for physical parameters, given data
- Covariance = CMB + Noise + ...
• Maximize likelihood for physical parameters, given data

\[
\chi^2(\{\alpha_{i,\rho}\}) = \sum_{c,c'}(d_{c} - \sum_{i} \alpha_{i,\sigma_i(c)} B_{c,t_{i,c}})^\dagger C_{c,c'}^{-1} (d_{c'} - \sum_{i} \alpha_{i,\sigma_i(c')} B_{c',t_{i,c'}}),
\]

• Covariance = CMB + Noise + ...

Tuesday, 16 October, 13
SZ done optimally: meet the templates!

- **Thermal SZ:**
  - pressure radial bins
  - scale size/amplitude with X-ray observables, e.g. MCXC

- **Kine(ma)tic SZ:**
  - truncated singular isothermal around each galaxy (Fukugita & Peebles 06)
  - scale size/amplitude with luminosity, e.g. 2M++
  - velocity: linear reconstruction or constant (bulk flow)
Universal Pressure Profile (WMAP9)

Aslanbeigi, Lavaux, NA, Hajian 2013
Universal Pressure Profile
(WMAP9 vs Planck)

Aslanbeigi, Lavaux, NA, Hajian, in prep.

Preliminary!
Universal Pressure Profile (Planck)

Preliminary!

Aslanbeigi, Lavaux, NA, Hajian, in prep.
missing baryon?!

Aslanbeigi, Lavaux, NA, Hajian, in prep.

Preliminary!
Bulk Flow Controversy

- *pre-history*: Lauer & Postman 1994
- Kashlinsky, et al. 2008-2011 (several $\sigma$ discrepant)
- Watkins, Feldman, Hudson 2009 ($\sim 3\sigma$ discrepant)

- ...
BOSS×ACT kSZ

• Hand et al. 2012, kSZ @ 3σ
Bulk Flow: Done Optimally

- Zhang 2010
- Most of kSZ signal comes from small scales
- Need to model/understand baryon distribution on small scales

- *Kine(ma)tic SZ:*
  - truncated singular isothermal around each galaxy (Fukugita & Peebles 06)
  - scale size/amplitude with luminosity, e.g. 2M++
  - velocity: linear reconstruction or constant (bulk flow)
**Bulk Flow from WMAP7**

**Table 1.** Kinetic Sunyaev-Zel’dovich estimates from WMAP7 maps.

| Line | Sky cut (|b| ≥) | kSZ depth ($h^{-1}$ Mpc) | kSZ ($km \ s^{-1}$) | $\chi^2$ | $p_0$ (%) |
|------|-----------|--------------------------|---------------------|---------|-----------|
|      |           | $V_x$                    | $V_y$               | $V_z$   |           |
| 1    | 15°       | 50                       | 559 ± 290           | −412 ± 285 | −93 ± 200 | 6.1       | 11        |
| 2    | 100       | 305 ± 223                | 7 ± 222             | −119 ± 151 | 2.5       | 47        |
| 3    | 200       | 365 ± 207                | 183 ± 206           | −141 ± 143 | 5.0       | 17        |

**Experiment**

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<tr>
<th>Typical depth ($h^{-1}$ Mpc)</th>
<th>kSZ ($km \ s^{-1}$)</th>
<th>$\chi^2$</th>
<th>$p_0$ (%)</th>
<th>$\chi^2_{KAEK}$</th>
<th>$p_{KAEK}$ (%)</th>
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<tr>
<td>470</td>
<td>160 ± 141</td>
<td>211 ± 124</td>
<td>−11 ± 112</td>
<td>4.3</td>
<td>23</td>
</tr>
<tr>
<td>175-260</td>
<td>174 ± 407</td>
<td>−849 ± 351</td>
<td>348 ± 342</td>
<td>7.1</td>
<td>7</td>
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<tr>
<td>260-380</td>
<td>428 ± 375</td>
<td>−1029 ± 323</td>
<td>575 ± 316</td>
<td>14.7</td>
<td>0.2</td>
</tr>
<tr>
<td>270-530</td>
<td>352 ± 304</td>
<td>−713 ± 262</td>
<td>652 ± 256</td>
<td>15.2</td>
<td>0.16</td>
</tr>
</tbody>
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Lavaux, NA, Hudson 2013
Figure 5. kSZ signal corresponding to the mean bulk-flow corresponding to the $50h^{-1}$ Mpc cut in the 2M++, limited to $|b| \geq 15^\circ$ (line 1 of Table 1).
Baryons, missing no more!? 

- Compare kSZ and standard candle bulk flows 
- Planck will do ~3 times better 

\[ \Omega_b = \Omega_m \]

Lavaux, NA, Hudson 2013
Best is yet to come!

- Shao, Zhang, et al. 2010 predict 50σ kSZ detection in BigBOSS×Planck (*maybe too good!*)

- Planck forecast for bulk flow:

<table>
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<tr>
<th>Component</th>
<th>WMAP7 obtained (km s⁻¹)</th>
<th>WMAP7 forecast (km s⁻¹)</th>
<th>PLANCK forecast (km s⁻¹)</th>
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<td>x</td>
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<td>305</td>
<td>120</td>
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<tr>
<td>y</td>
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<td>277</td>
<td>111</td>
</tr>
<tr>
<td>z</td>
<td>200</td>
<td>224</td>
<td>93</td>
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- Planck × 2M++ bulk flows (and more) in progress
What next?

• Imaging coronae of galaxies
• Temperature profiles, shock fronts
• fundamental plane (NA 2008)
• bulk flow in polarization? (Roebber & Holder 2013)
• cosmology?! precision!
• measurement vs understanding
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