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

Niayesh Afshordi
Perimeter Institute, and University of Waterloo

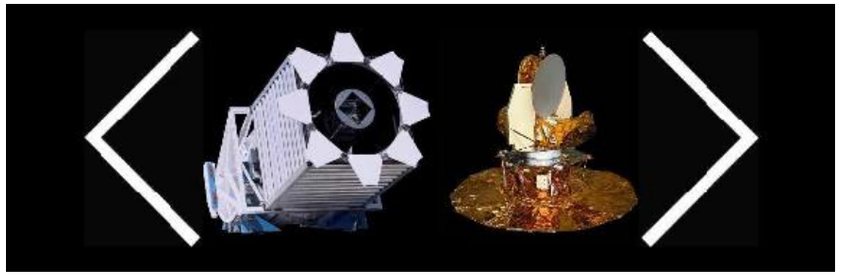
with Siavash Aslanbeigi (PI/UW)
Guilhem Lavaux (UW/PI→CNRS/IAP)
Amir Hajian (CITA)
Mike Hudson (UW)

Good Old Days!

Agenda

External Correlations of the CMB and Cosmology

May 25-27, 2006. Fermilab, Batavia, IL



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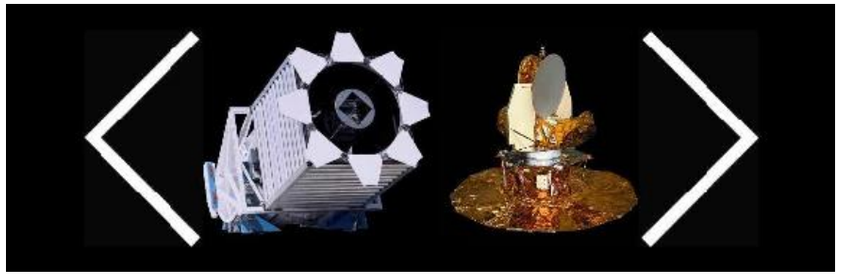

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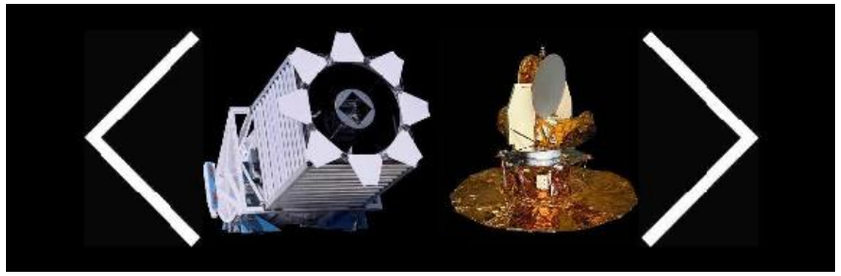

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Extending Limber

- When can we trust Limber approximation? systematic derivation?
- $\tilde{A}(\hat{\mathbf{n}}) = \int dr\ \sqrt{r}\ f_A(r) A(r\hat{\mathbf{n}}),\ \text{and}\ \tilde{B}(\hat{\mathbf{n}}) = \int dr\ \sqrt{r}\ f_B(r) B(r\hat{\mathbf{n}}).$

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

$$k = \frac{\ell + 1/2}{r}, s(k) = \frac{d\ln P_{AB}(k)}{d\ln k}, p(k) = \frac{k^2 [3P''_{AB}(k) + kP'''_{AB}(k)]}{3P_{AB}(k)}$$

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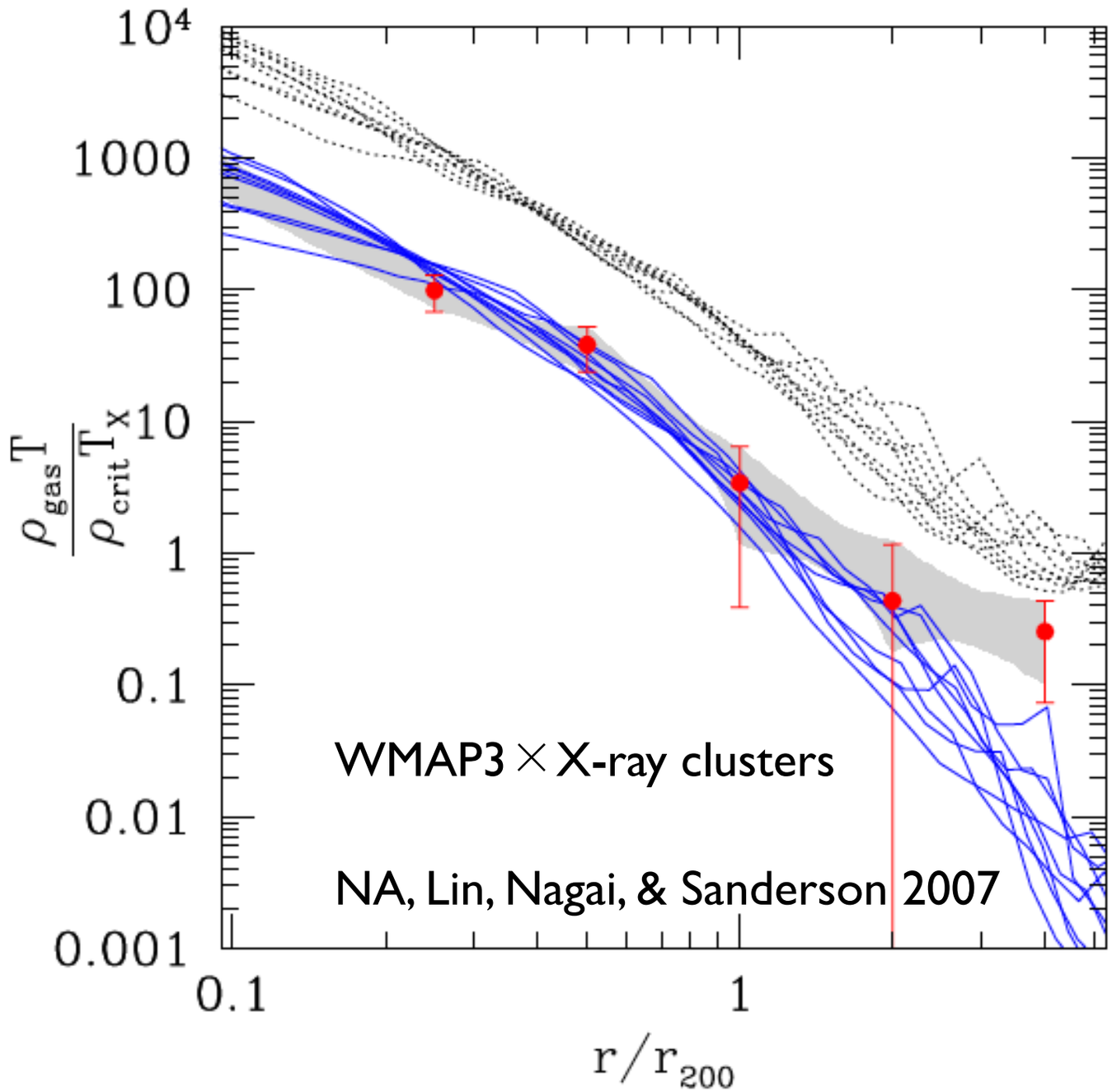
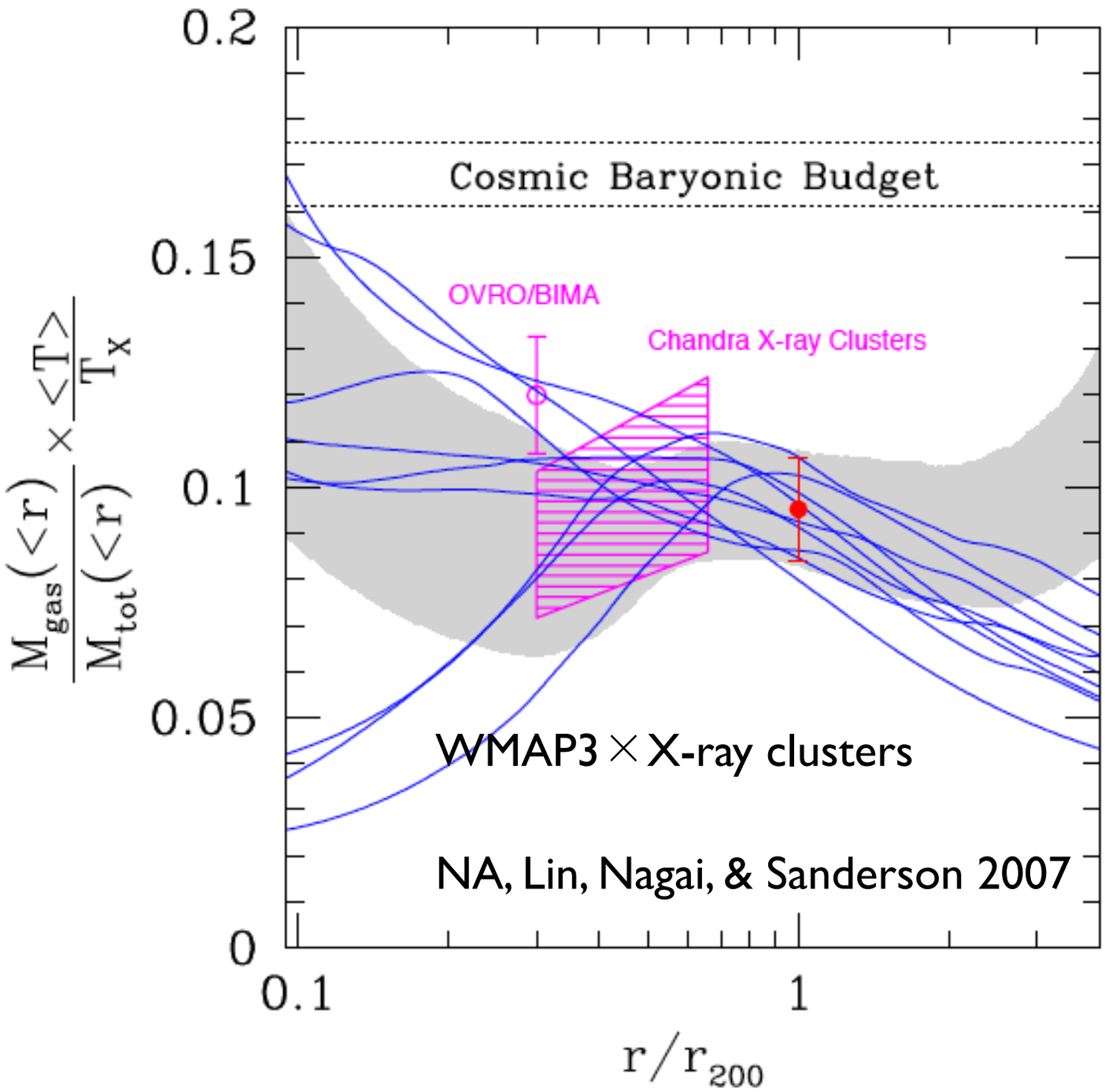
Universal Pressure Profile

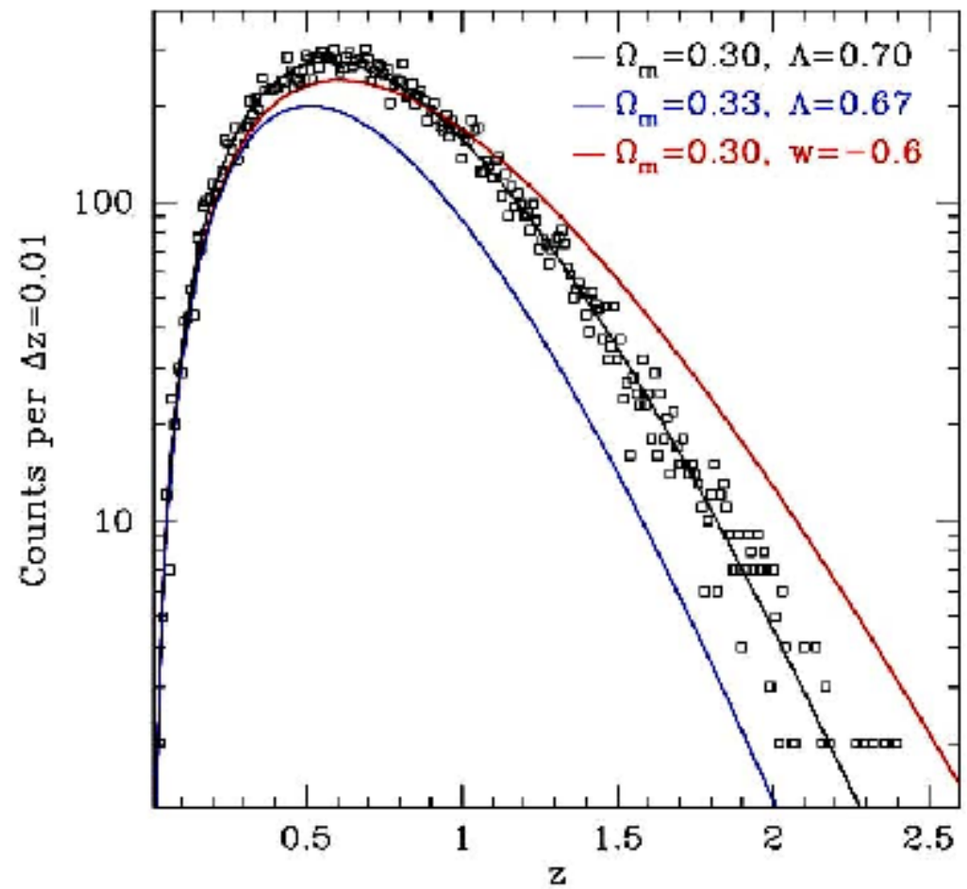


missing thermal energy?
missing baryons?



Can SZ surveys sustain the CMB dominance?

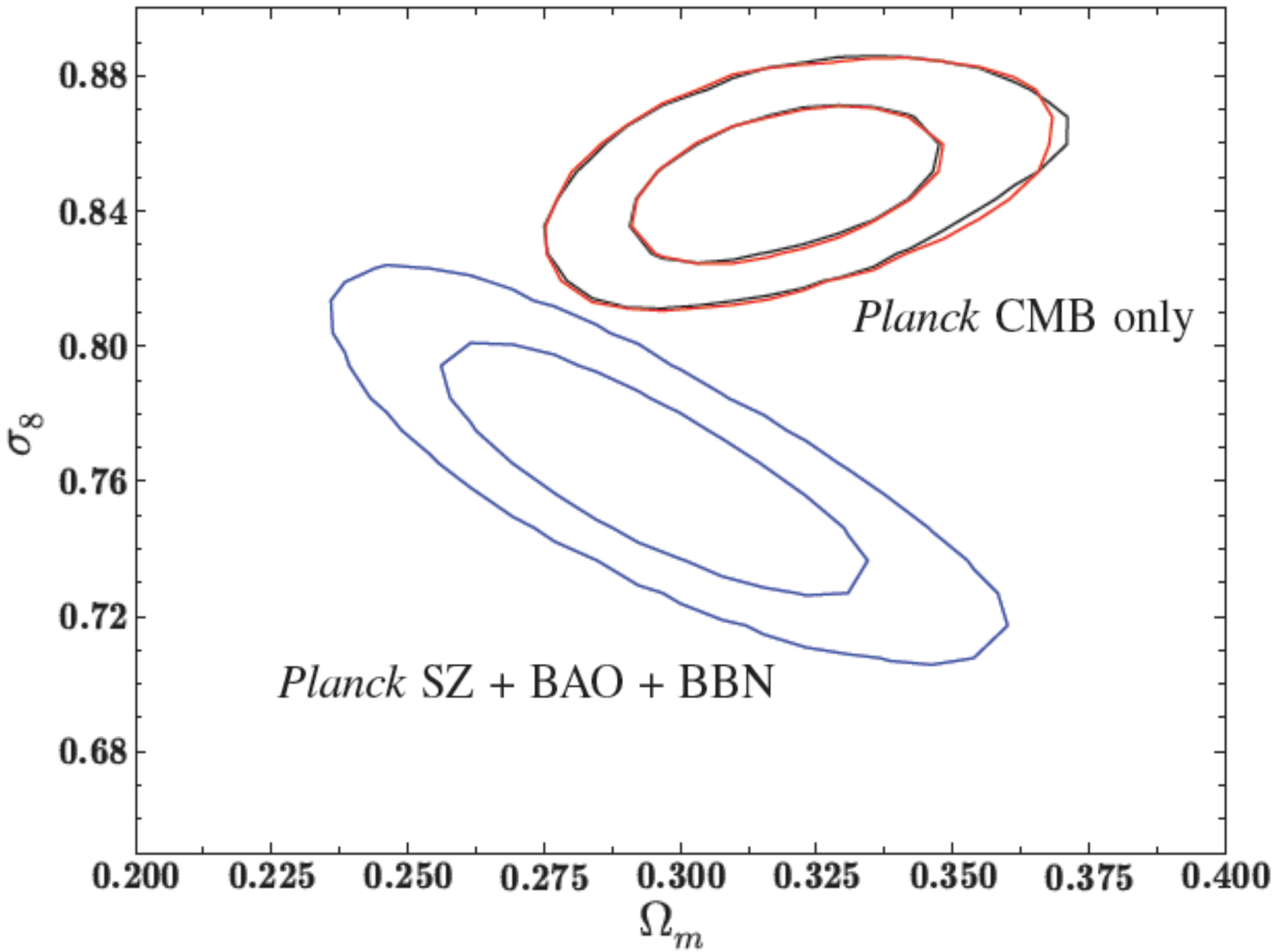
- SZ clusters can be Detected up to high redshifts
- Their number counts probe Dark Energy/Cosmology
- Many SZ surveys are underway: APEX, SZA, ACT, SPT, Planck, …
- Can they deliver? Calibration of SZ-Mass relation, Gastrophysics, …



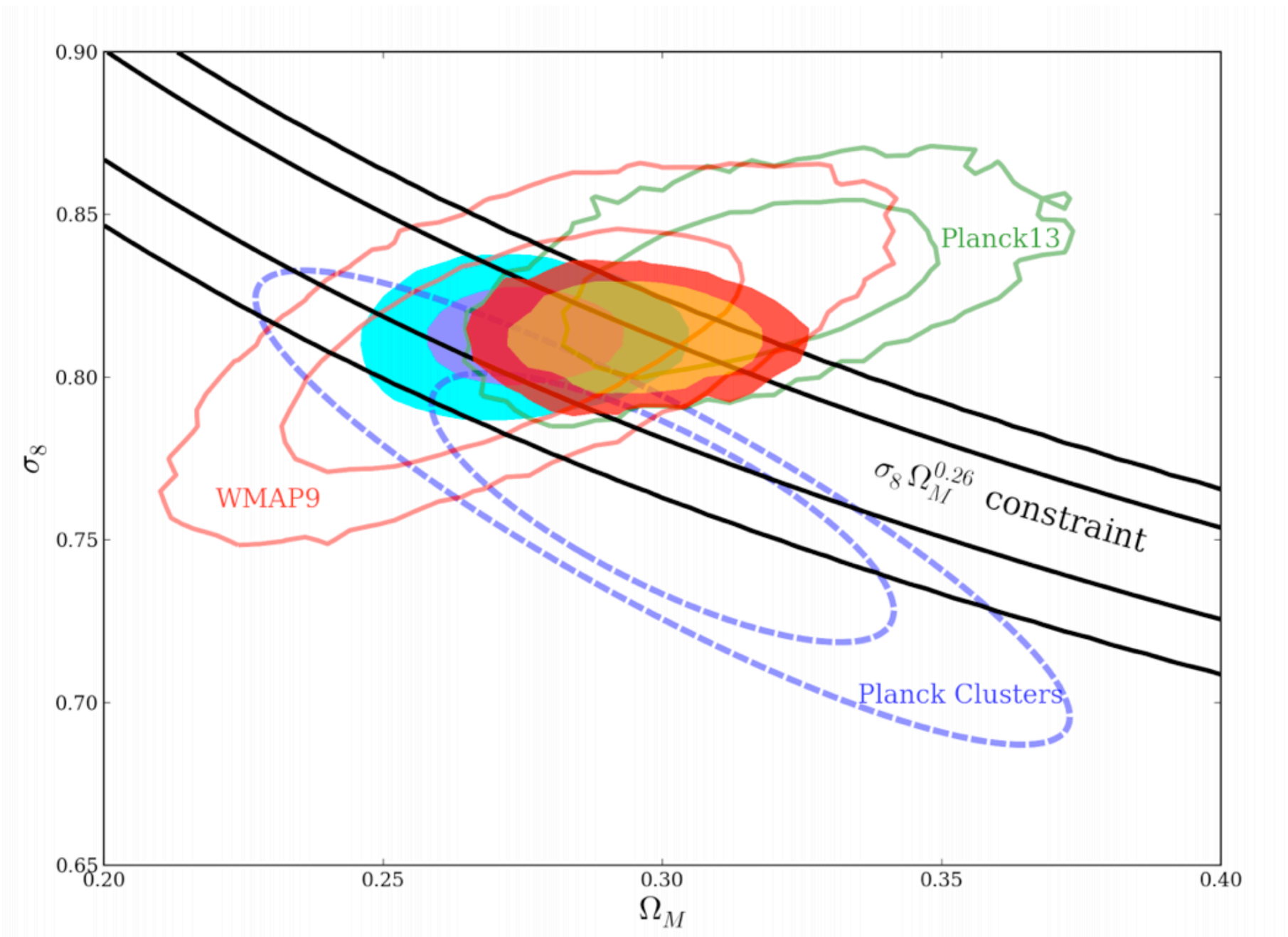
Courtesy of John Carlstrom

In the mean time …

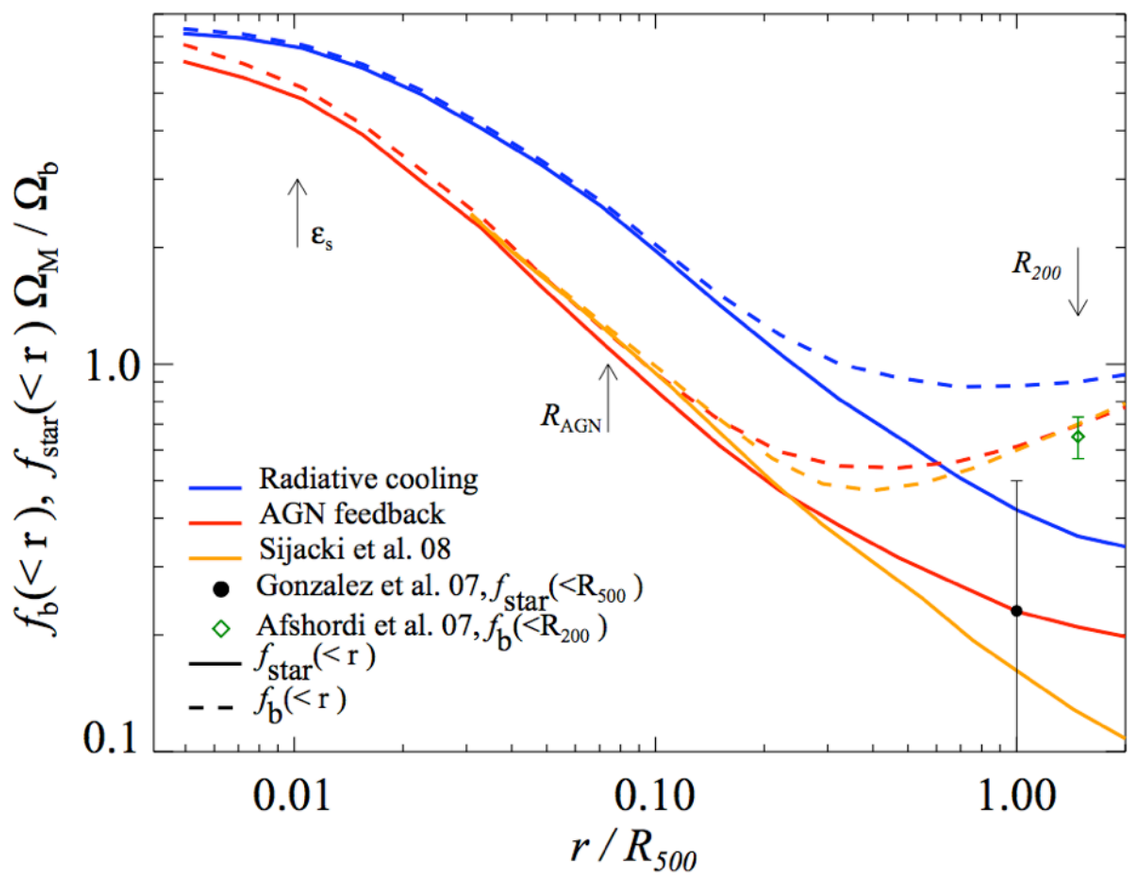
Planck 2013 results. XX. Cosmology from Sunyaev–Zeldovich cluster counts



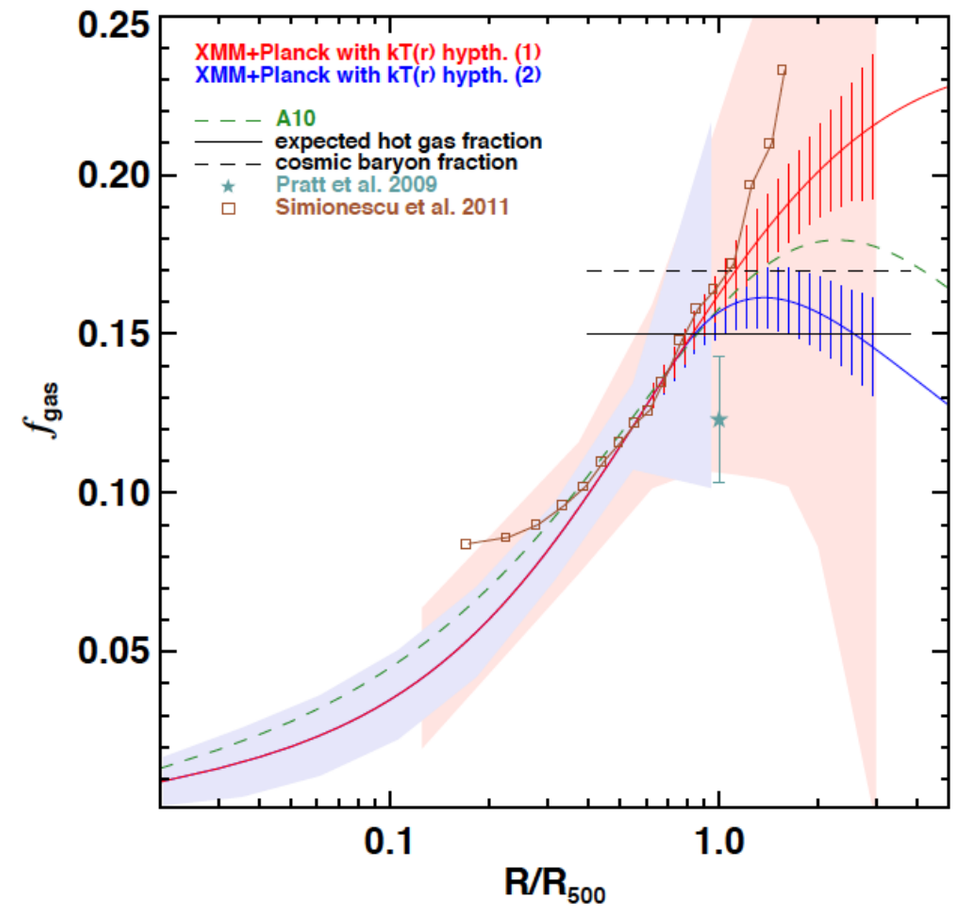
Do we have a problem, or don't we?
Hajian, et al. 2013: *Planck×ROSAT*



Gastrophysical Black Magic!



Battaglia, et al. 2010



Planck Intermediate Results. V. 2013

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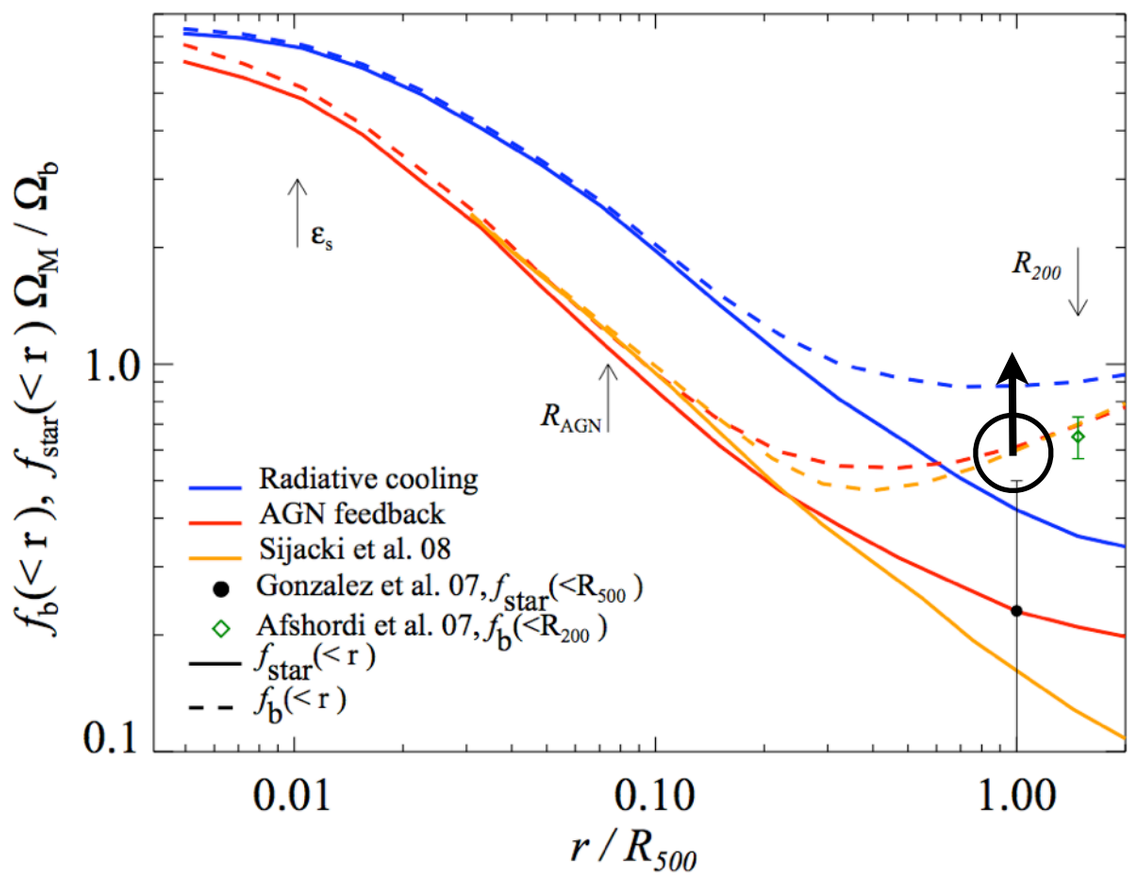

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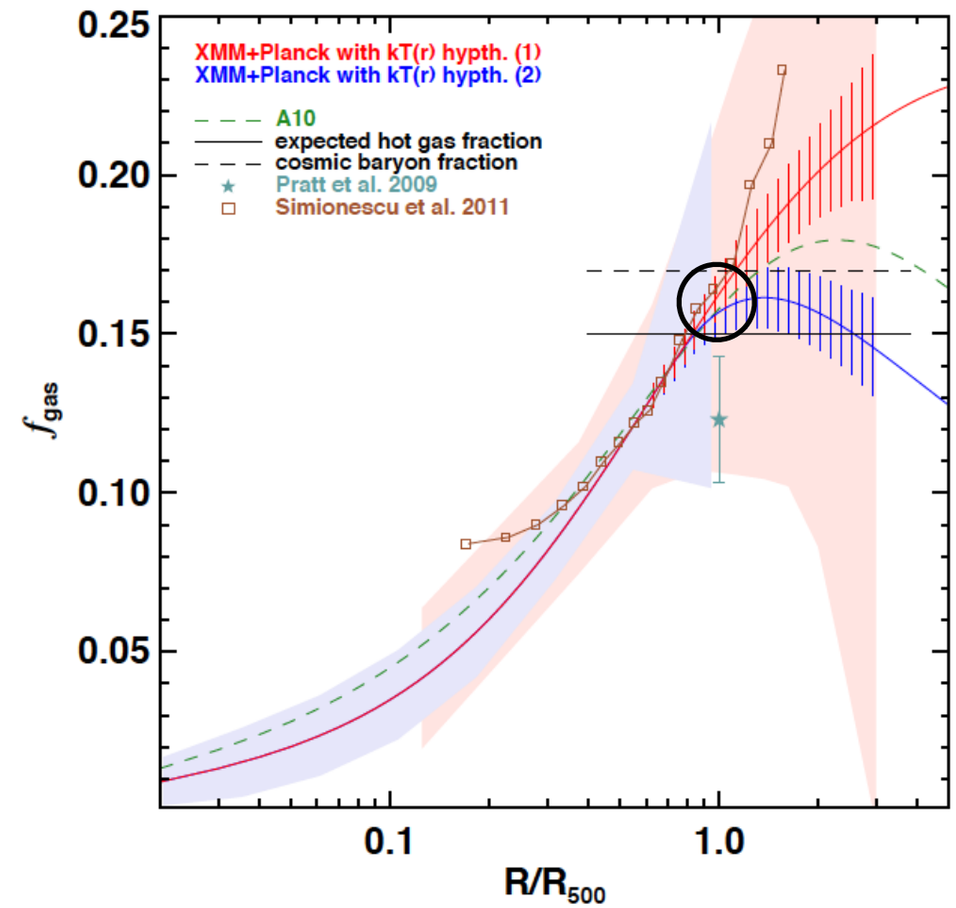

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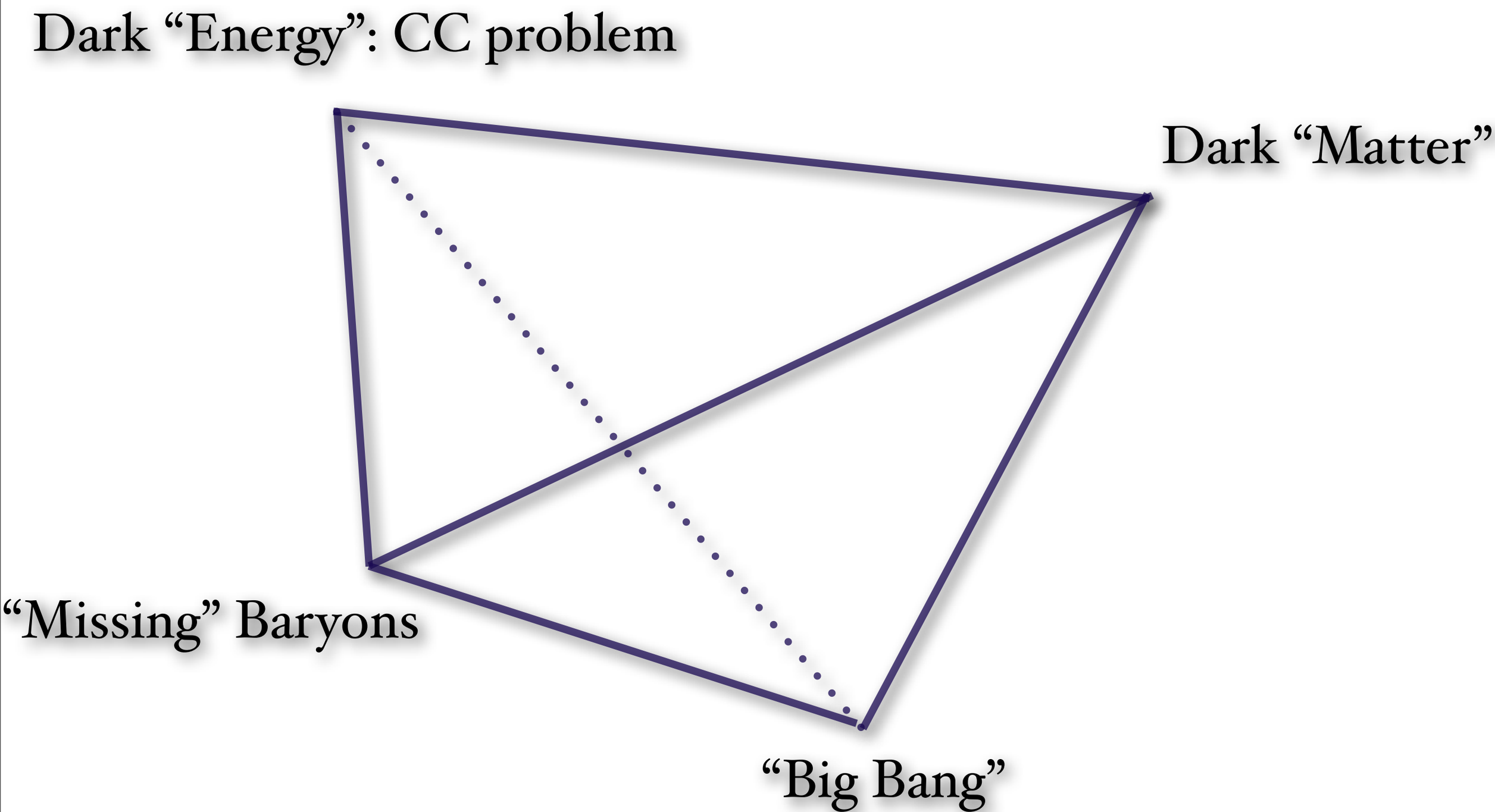
Cosmic Pyramid



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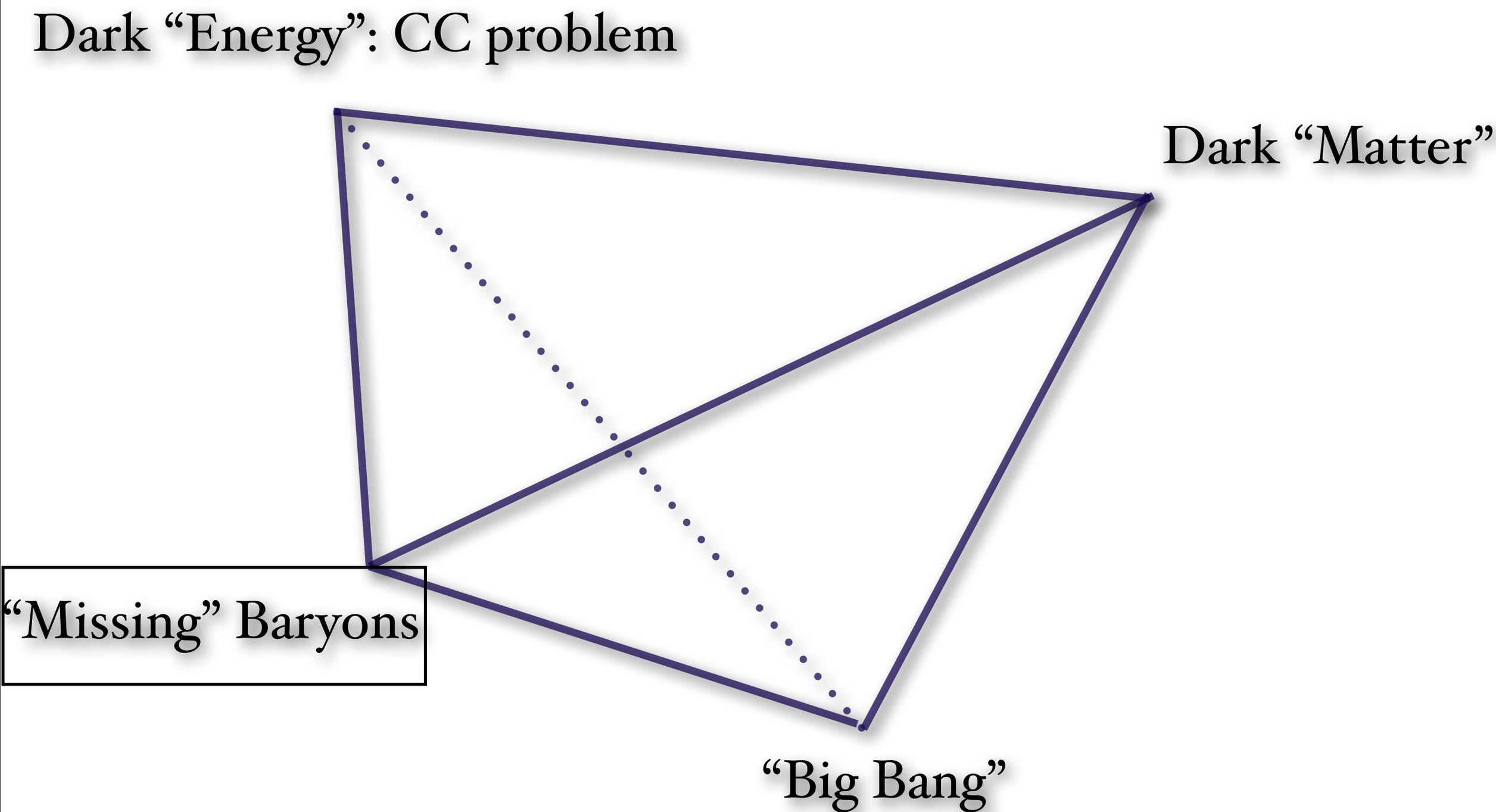

Cosmic Pyramid: *missing baryons*

- 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+...

$$\chi^2(\{\alpha_{i,\rho}\}) = \sum_{c,c'}(\boldsymbol{d}_c - \sum_i \alpha_{i,\sigma_i(c)}\mathbf{B}_c\boldsymbol{t}_{i,c})^\dagger \mathbf{C}^{-1}_{c,c'}(\boldsymbol{d}_{c'} - \sum_i \alpha_{i,\sigma_i(c')}\mathbf{B}_{c'}\boldsymbol{t}_{i,c'}),$$

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templates

data

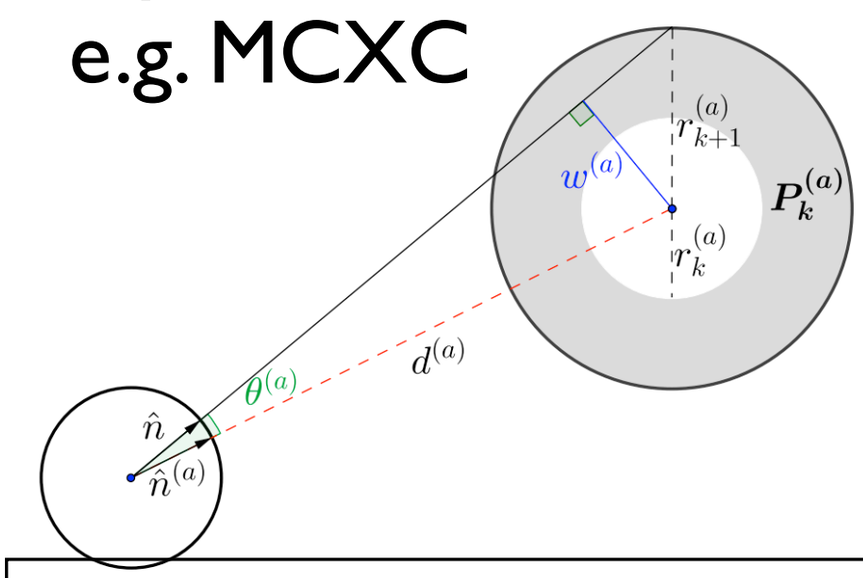
data

beams

beams

SZ done optimally: *meet the templates!*

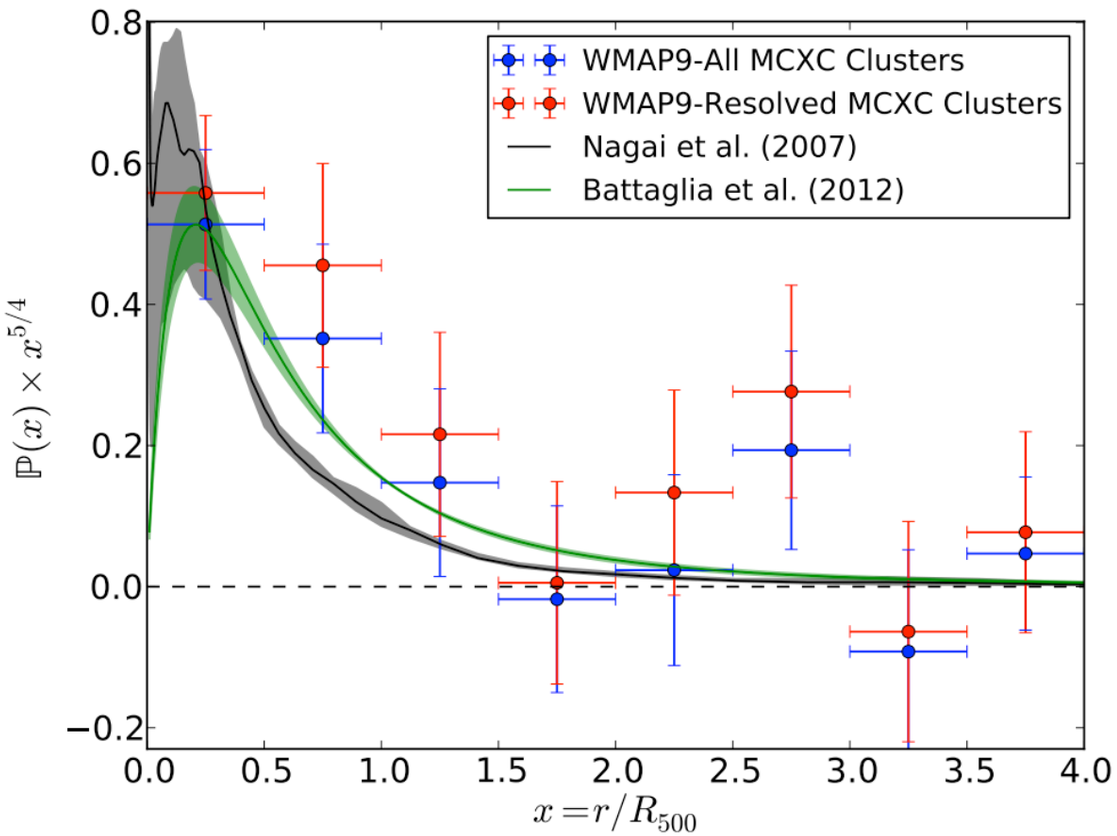
- *Thermal SZ:*
  - pressure radial bins
  - scale size/ amplitude with X-ray observables, e.g. MCXC

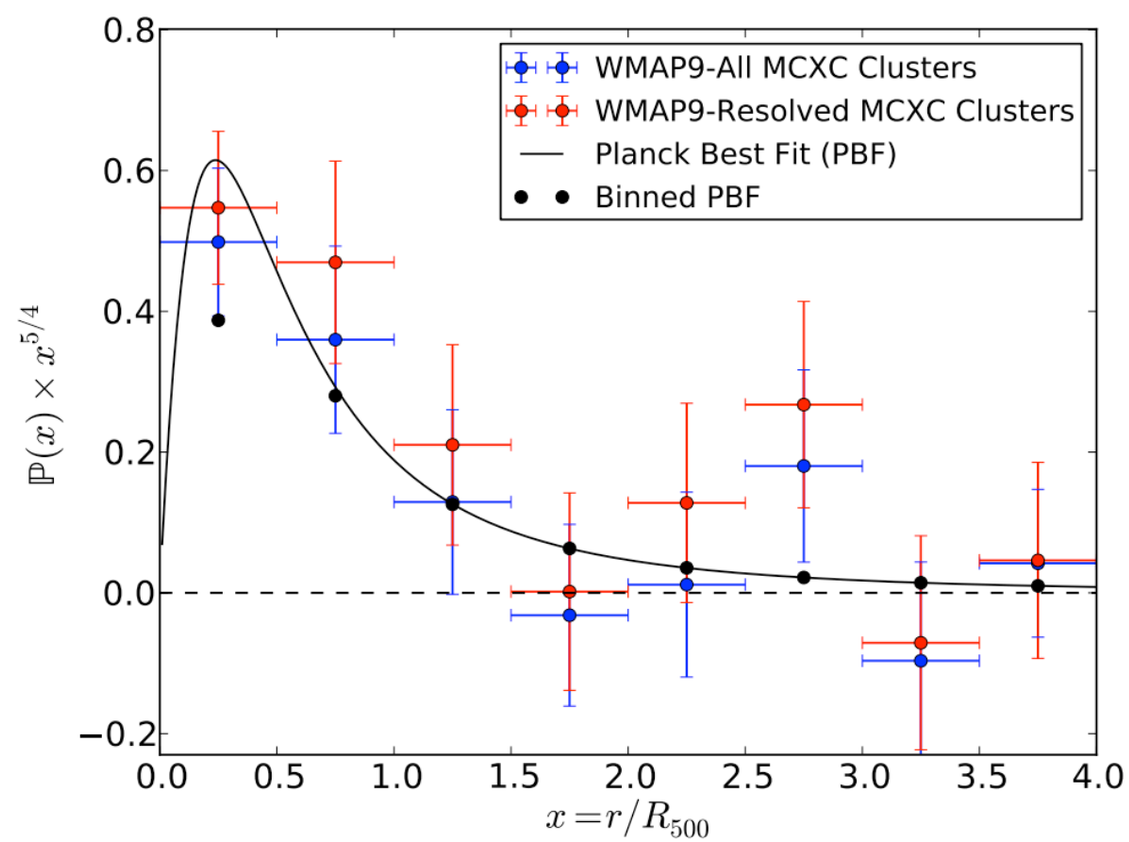


Aslanbeigi, Lavaux, NA, Hajian 2013
Lavaux, NA, Hudson 2013

- *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)

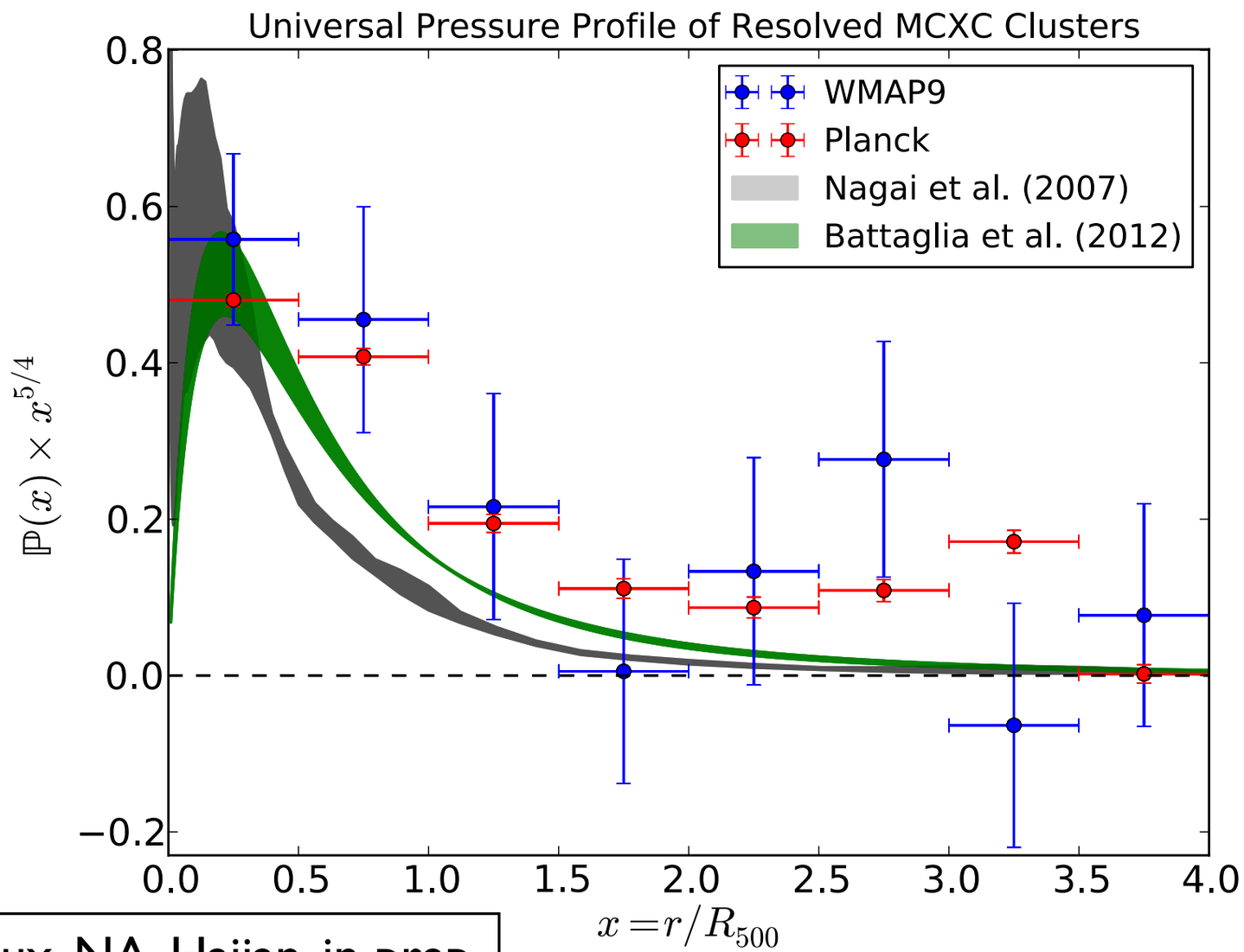
Universal Pressure Profile (WMAP9)





Aslanbeigi, Lavaux, NA, Hajian 2013

Universal Pressure Profile (WMAP9 vs Planck)



Aslanbeigi, Lavaux, NA, Hajian, in prep.

Preliminary!

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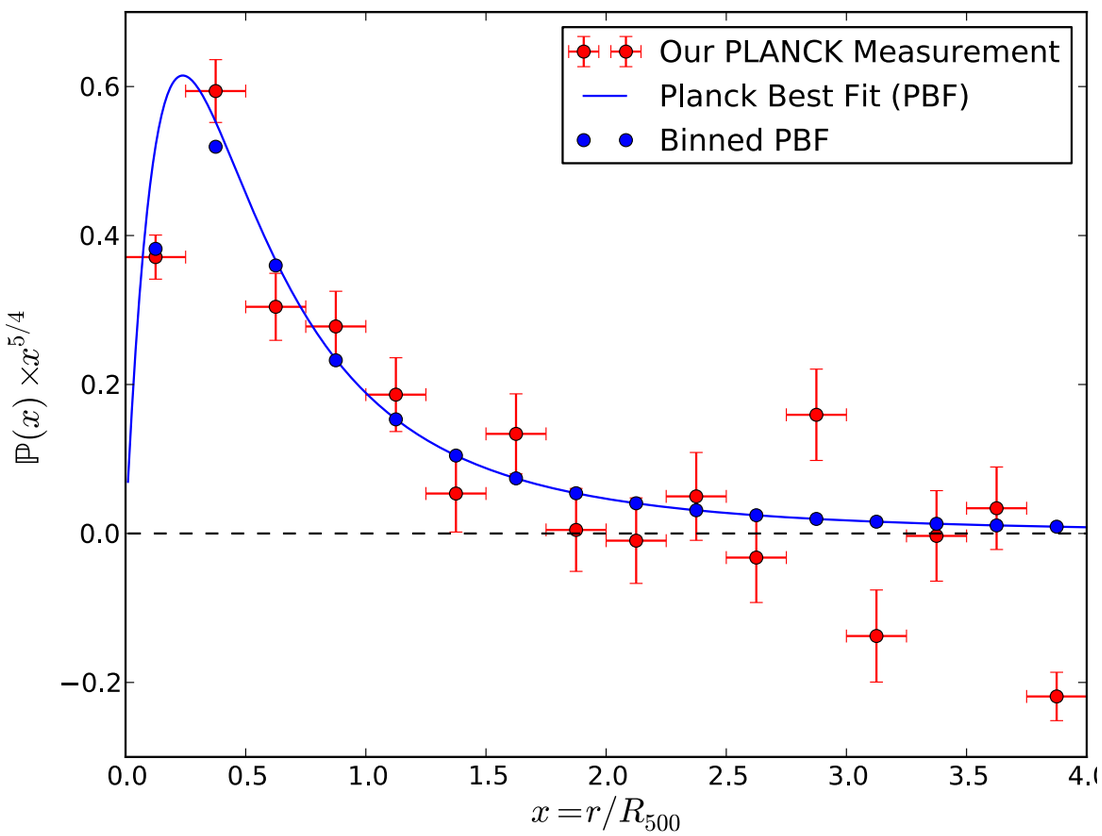

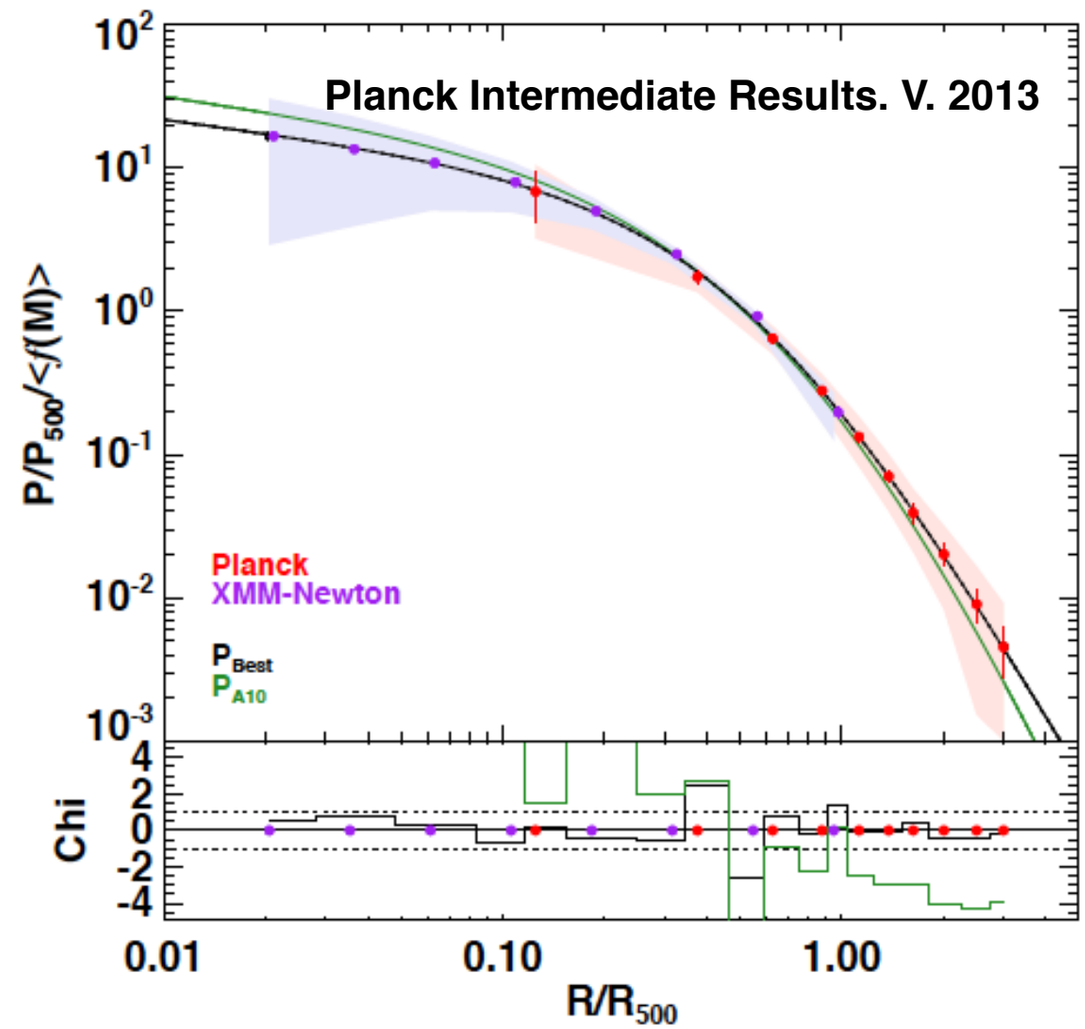

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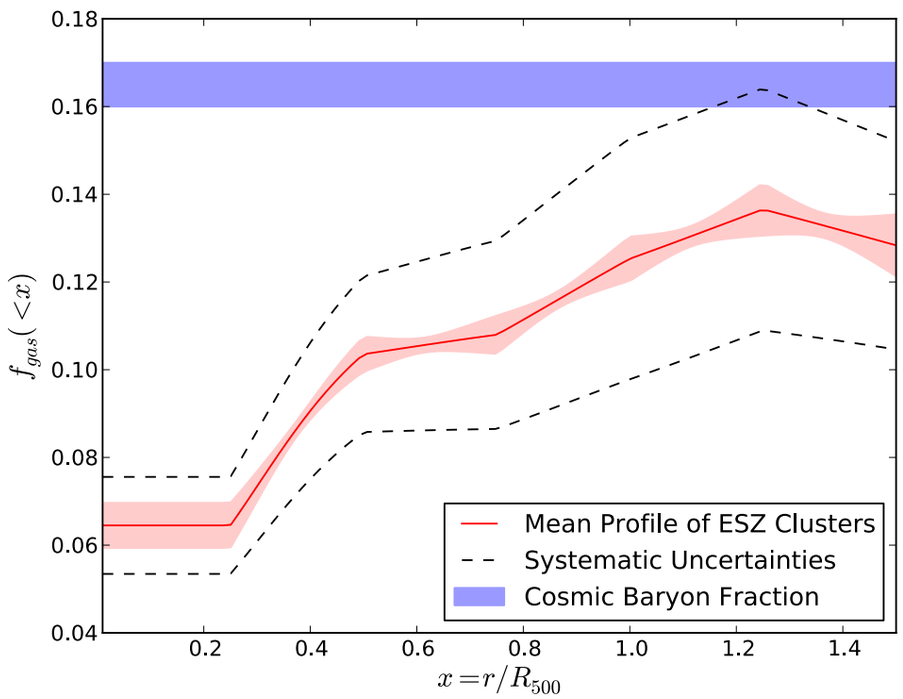
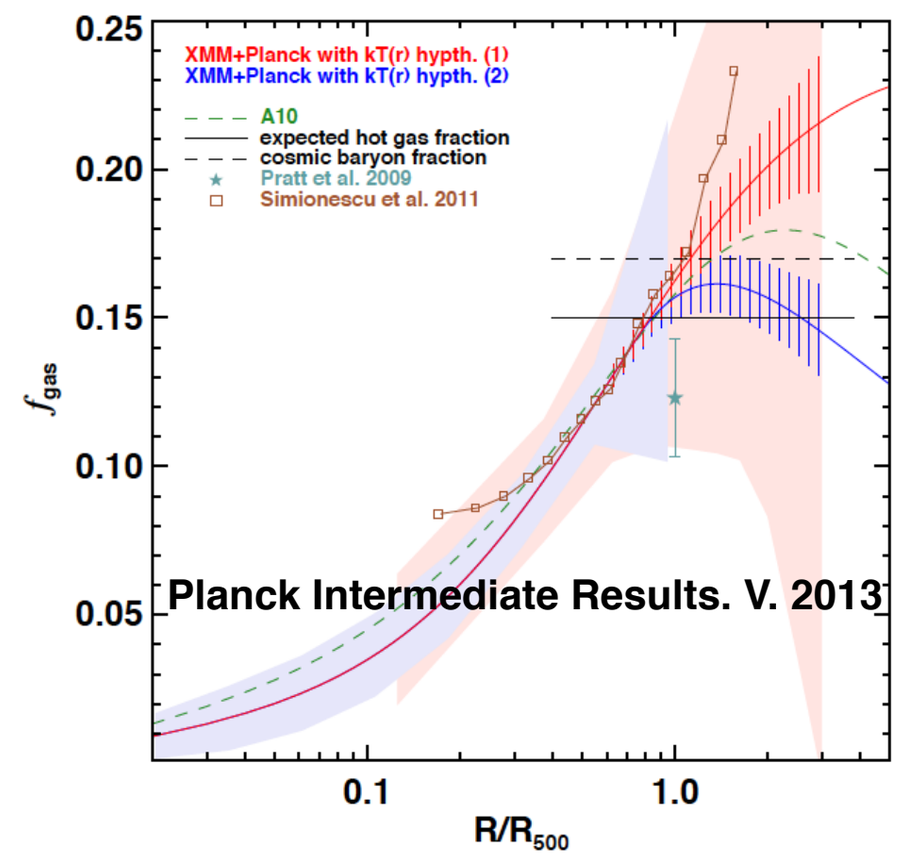
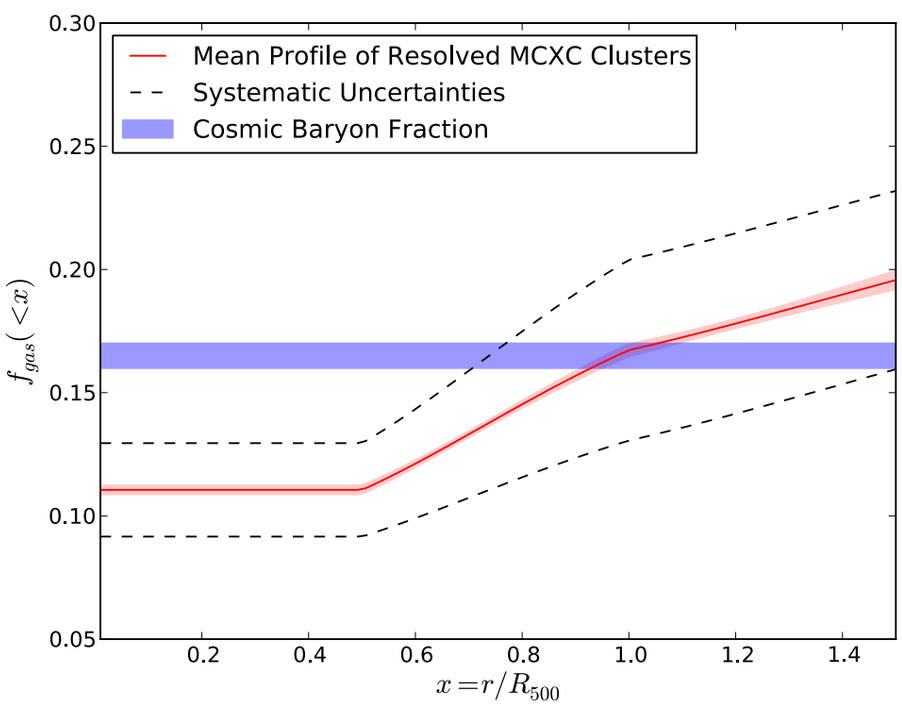
missing baryon?!





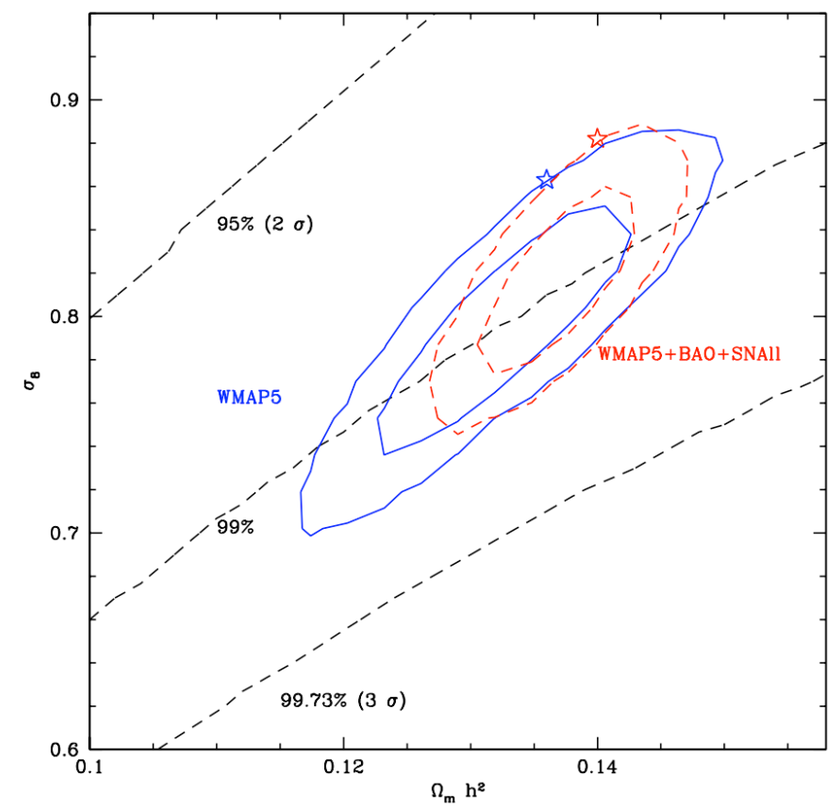


Aslanbeigi, Lavaux, NA, Hajian, in prep.

Preliminary!

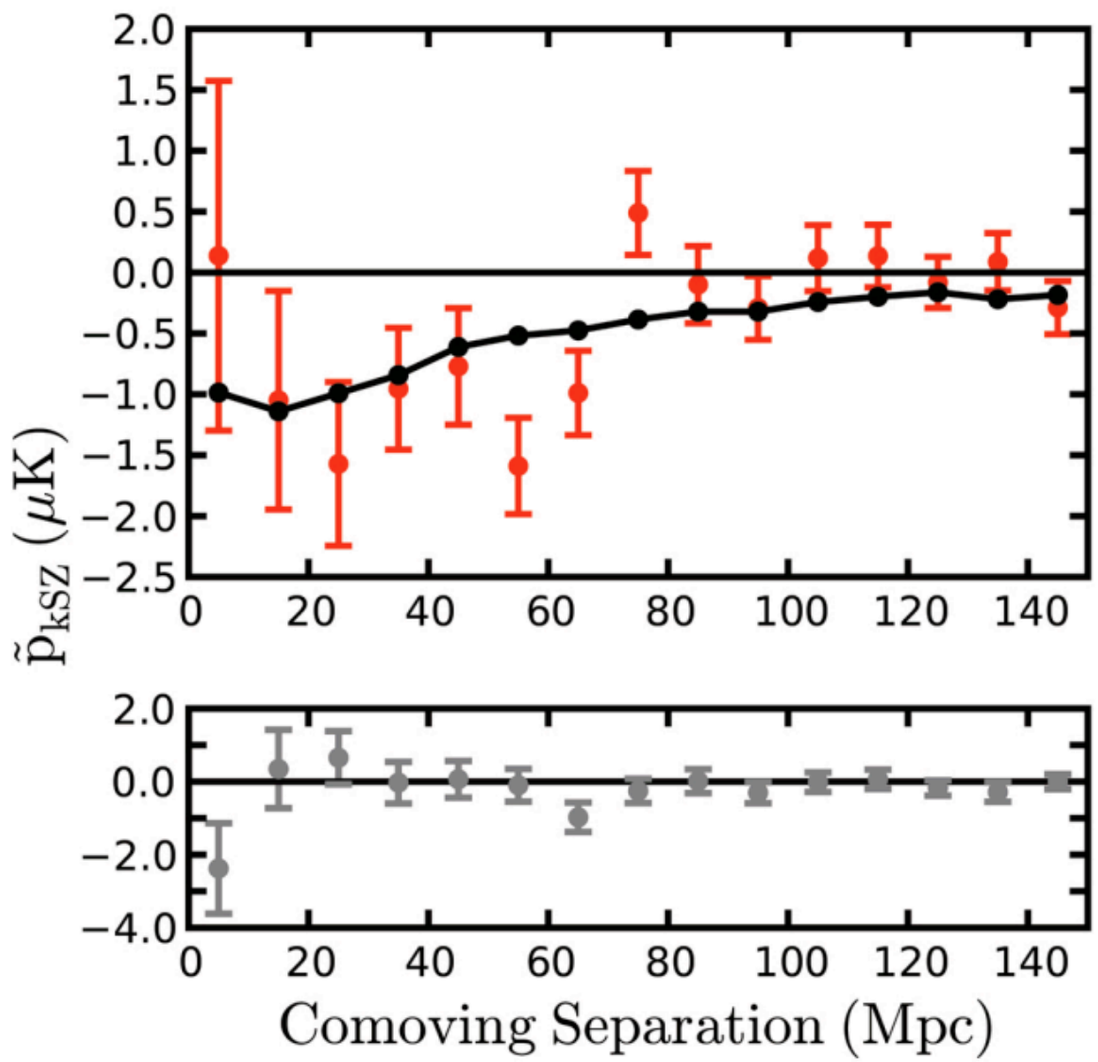
Bulk Flow Controversy

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



BOSS×ACT kSZ

- Hand et al. 2012, kSZ @ 3σ



Bulk Flow: Done Optimally

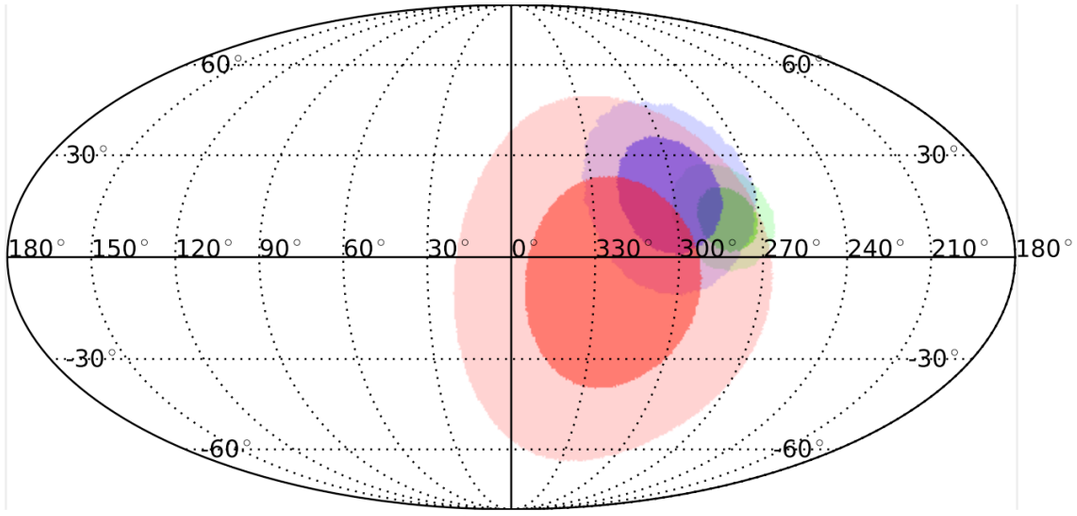
- Zhang 2010
- Most of kSZ signal comes from small scales
- Need to model/ understand baryon distribution on small scales

- *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 ($\|b\| \geq$)	kSZ depth (h^{-1} Mpc)	kSZ (km s^{-1}) V_x	V_y	V_z	χ^2	p_0 (%)
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	Typical depth (h^{-1} Mpc)	kSZ (km s^{-1}) V_x	V_y	V_z	χ^2_0	p_0 (%)	$\chi^2_{\rm KAEEK}$	$p_{\rm KAEEK}$ (%)
2MASS-XSC $K \leq 14$	470	160 ± 141	211 ± 124	-11 ± 112	4.3	23		
Kashlinsky et al. (2010)	175-260	174 ± 407	-849 ± 351	348 ± 342	7.1	7	9.1	2.8
	260-380	428 ± 375	-1029 ± 323	575 ± 316	14.7	0.2	16.3	$9\,10^{-2}$
	270-530	352 ± 304	-713 ± 262	652 ± 256	15.2	0.16	16.1	$1\,10^{-1}$

Lavaux, NA, Hudson 2013

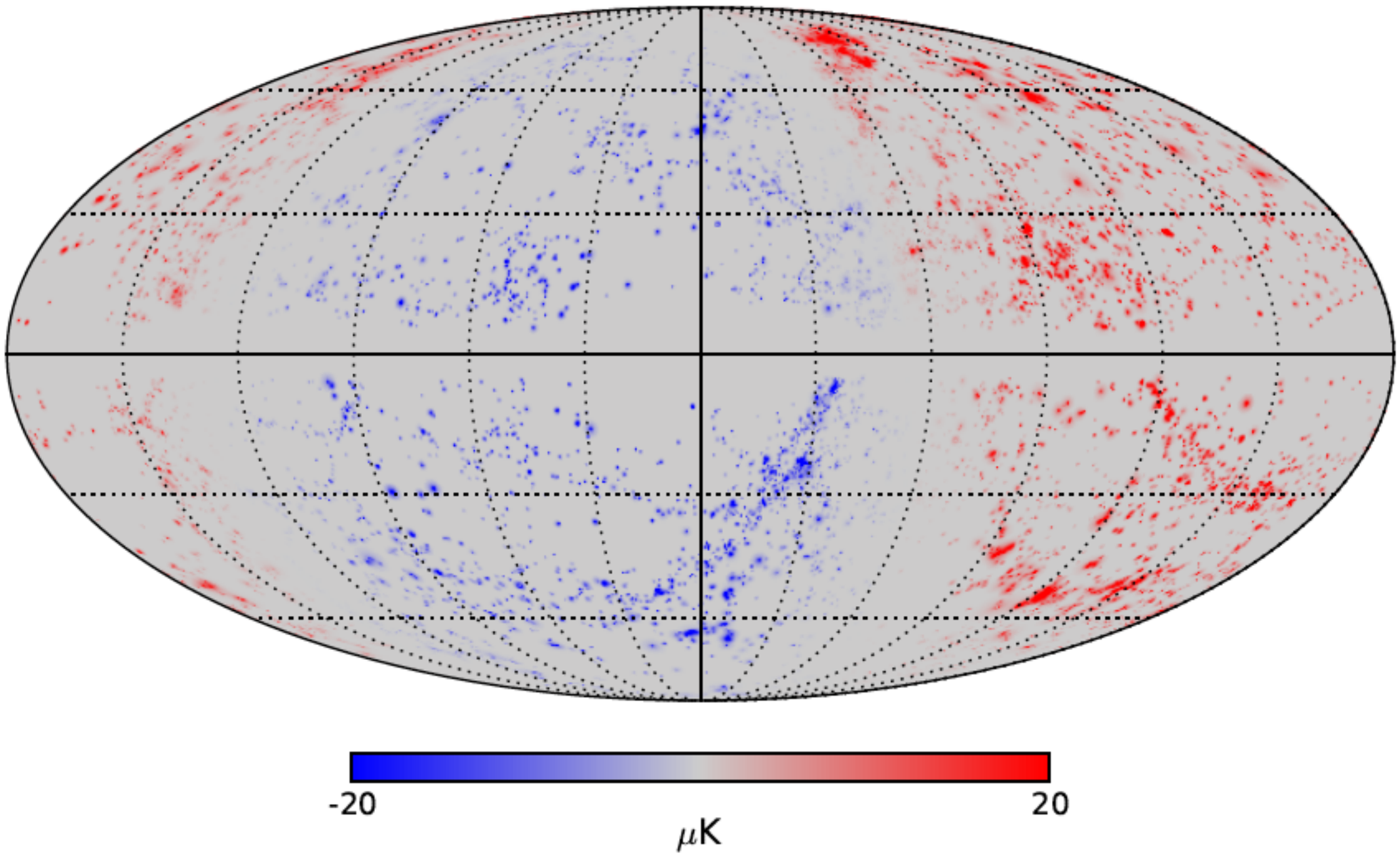
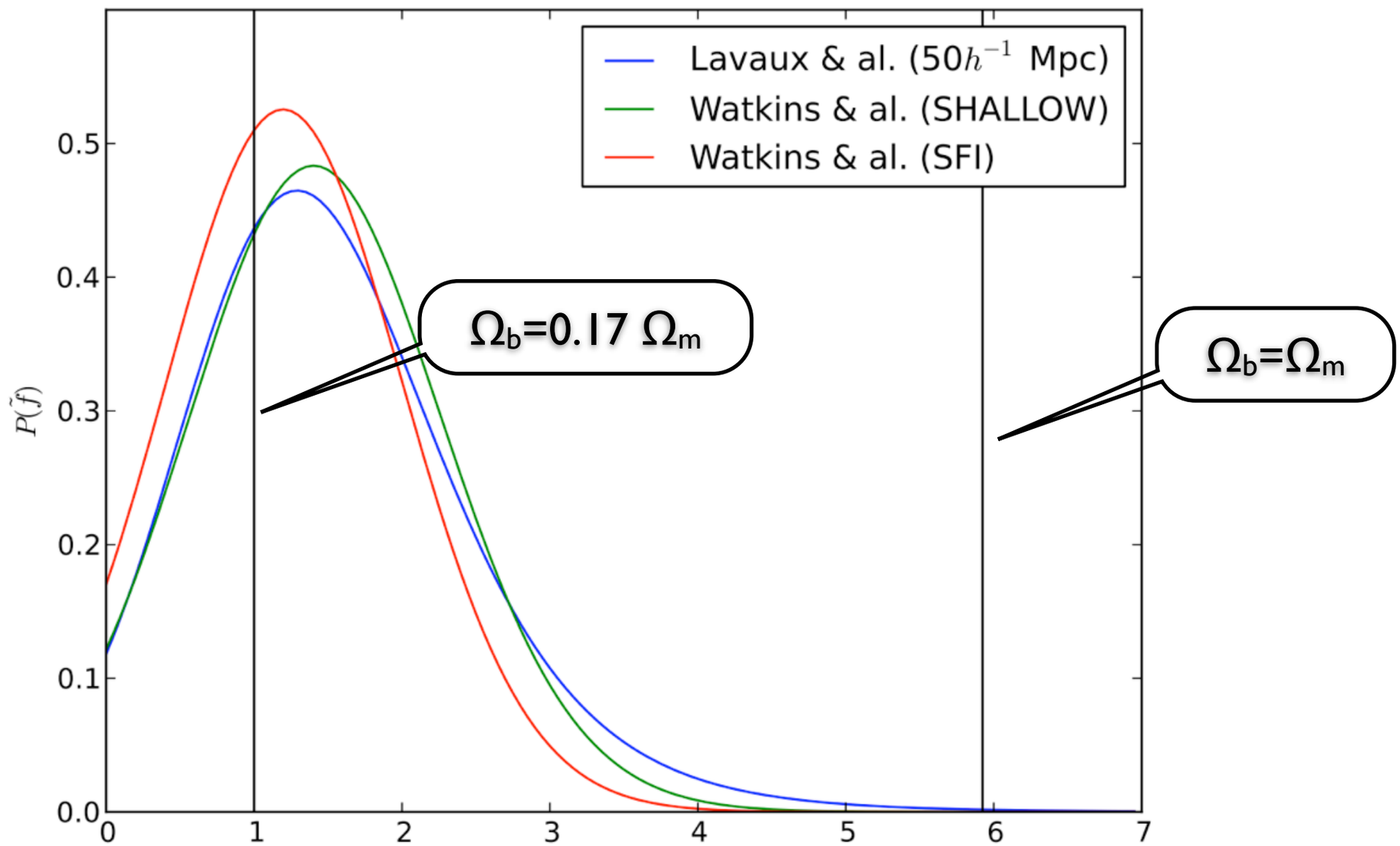


Figure 5. kSZ signal corresponding to the mean bulk-flow corresponding to the $50h^{-1}$ Mpc cut in the 2M++, limited to $|b| \geq 15°$ (line 1 of Table 1).

Baryons, missing no more!?

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



Lavaux, NA, Hudson 2013

IGM plasma density

Best is yet to come!

- Shao, Zhang, et al. 2010 predict 50σ kSZ detection in BigBOSS*x*Planck *(maybe too good!)*
- Planck forecast for bulk flow:

Component	WMAP7 obtained (km s^{-1})	WMAP7 forecast (km s^{-1})	PLANCK forecast (km s^{-1})
x	290	305	120
y	285	277	111
z	200	224	93

- 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

What next?

Dark "Energy": CC problem

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

Dark "Matter"

"Missing" Baryons

"Big Bang"