Title: Cosmic Flows: cosmology and astrophysics from galaxy velocities

Date: Nov 25, 2014 11:00 AM

URL: http://pirsa.org/14110182

Abstract: <p>Velocity fields are a powerful probe of structure formation and the energy content of our Universe. Additionally, the motion of ionized gas on intermediate scales can be used to measure the clustering of baryons and shed light on galaxy formation and feedback mechanisms. I will discuss techniques that can be used to both constrain cosmology and measure baryon properties. I will also present some preliminary results.</p>

What this talk is NOT about

- Primordial non-Gaussianity and Large Scale Structure
  (arXiv: 1408.3126, 1209.2175, 1209.2173, 1110.1594, 1106.0503)
- Relative velocity between Dark Matter and baryons
  (arxiv: 1110.2182)
- ISW (still open puzzles!) and relation to kSZ
  (arXiv: 1401.1193 + SF & Spergel to appear)
- Clusters in modified gravity
  (arXiv:1011.0992)
- ....

I am at PI today and tomorrow morning (office 255)
if interested, come and talk to me!

Simone Ferraro (Princeton)

sferraro@princeton.edu

Contents

- Velocities in cosmology
- Probing the growth of structure
- The missing baryon problem
- Kinetic Sunyaev-Zel'dovich effect
- New techniques
- Preliminary results

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Cosmic velocities as a tool for…

Measuring growth of structure

Baryon properties
(clustering, ionization fraction)

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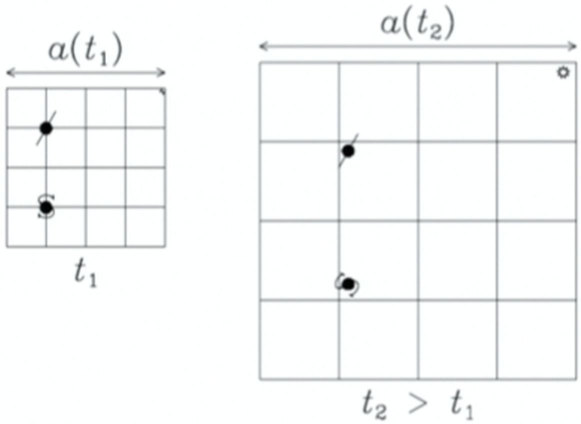
Cosmic velocities

- Peculiar velocity $\mathbf{v} = \frac{d\mathbf{x}}{d\eta} = \frac{d\mathbf{r}}{dt} - H(t)\mathbf{r}$

- Related to density (continuity eq):

$$\dot{\delta} + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$



- In linear theory:

$$\mathbf{v} \approx \frac{i\mathbf{k}}{k^2}\dot{\delta} = aH\ f_g\ \frac{i\mathbf{k}}{k^2}\delta$$

Growth rate $f_g = \frac{d\ln\delta}{d\ln a} \approx [\Omega_m(z)]^\gamma$

$\gamma \approx 0.55$ in GR
Linder (2005)

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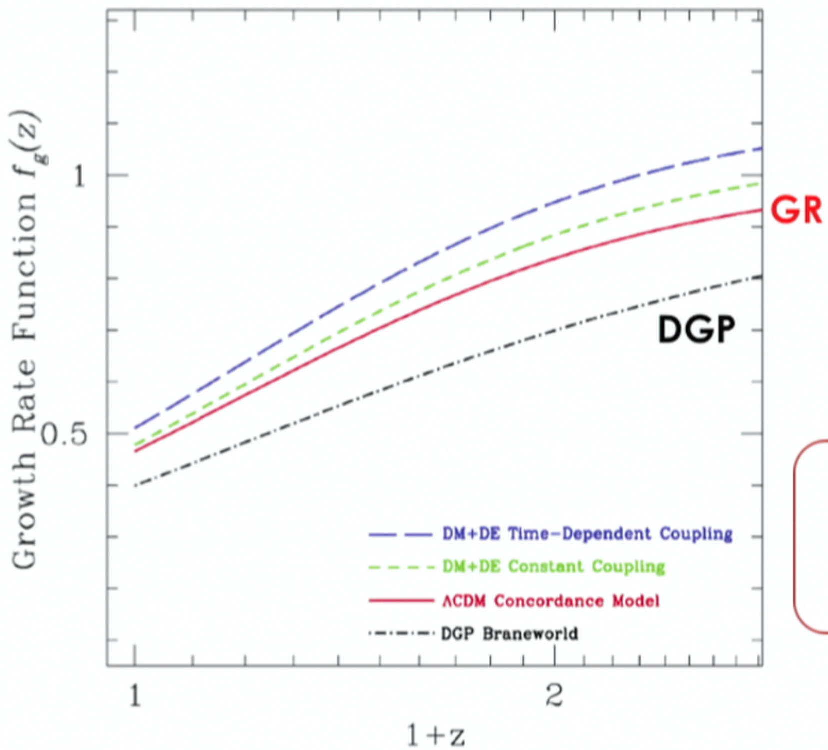
Growth factor as a probe of GR

8



$$\mathbf{v} \approx aH\ f_g\ \frac{i\mathbf{k}}{k^2}\delta$$

$$f_g = \frac{d\ln\delta}{d\ln a}$$

Growth factor:

- sensitive probe of gravity
- Cosmological information

Guzzo et al (2005)

DGP: Lue et al (2004); DM+DE models: Di Porto et al (2007)

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Growth factor as a probe of GR

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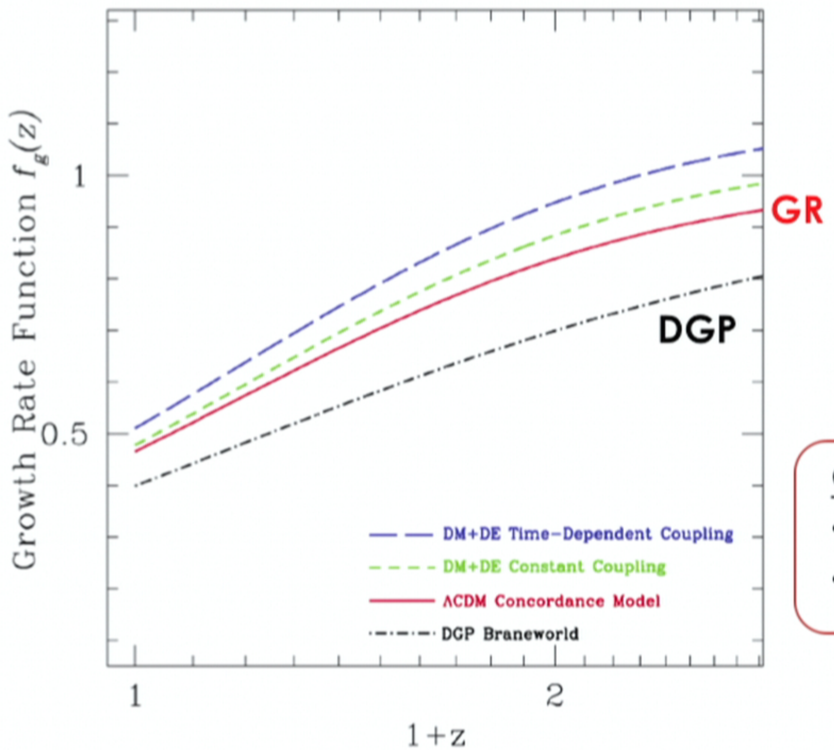

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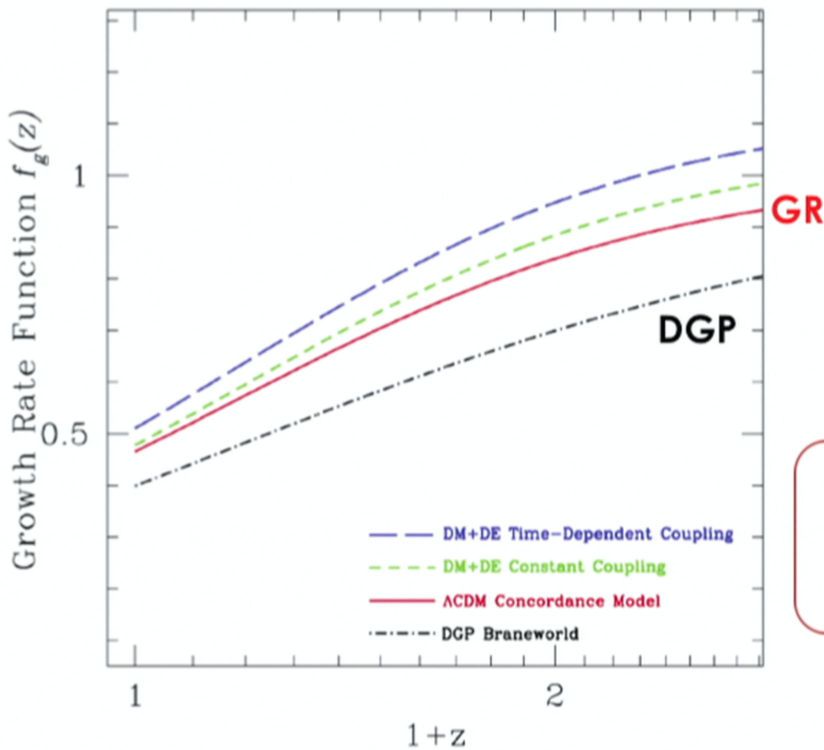

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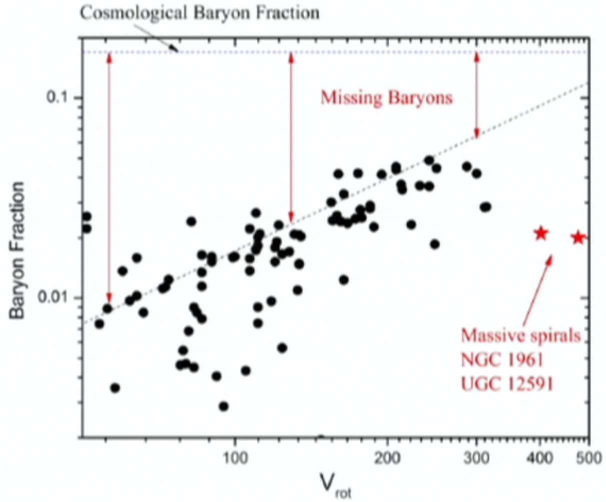
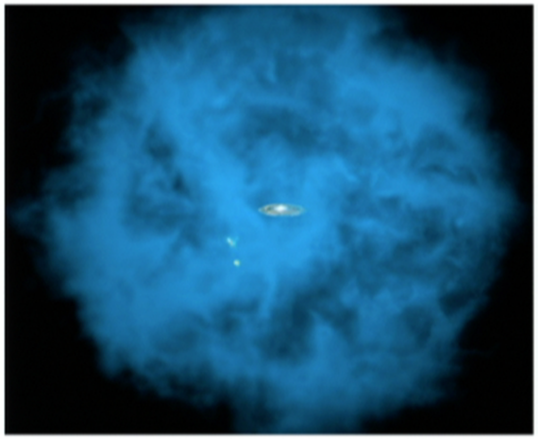
The missing baryon 'problem'

9

- Baryon content measured ~13Gyr ago by BBN and CMB. Lyman-α forest probes baryons at $z > 2$.
- Today ~80-90% of the baryons are not seen within R_{VIR}.
- Thought to occupy the <u>outskirts of galaxy and filaments</u> in low-density Warm-Hot Intergalactic Medium (WHIM).
- $R_{gas} \geq 1$ Mpc ($4 \times R_{VIR}$)
- Important consequences for galaxy formation.





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Credit: Bregman (2012, top) - NASA (bottom)

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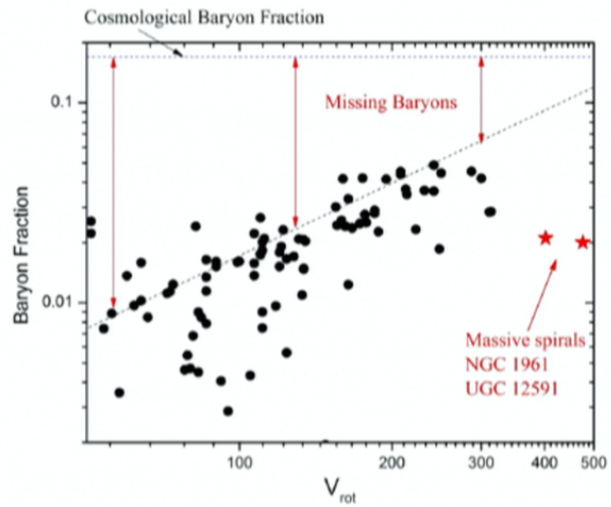

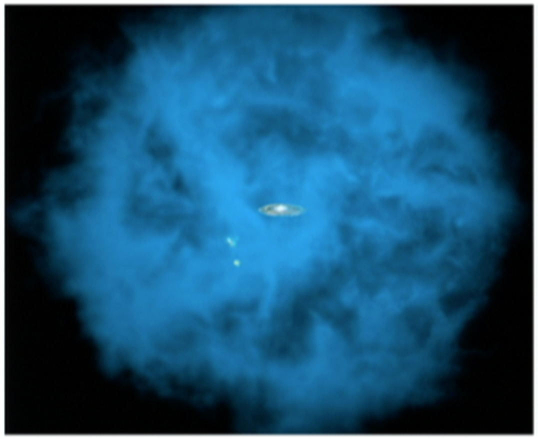

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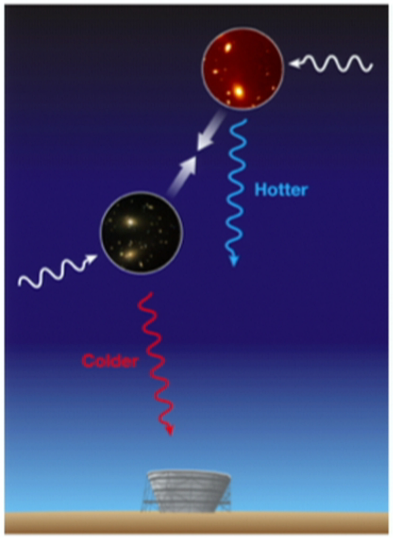
Credit: Bregman (2012, top) - NASA (bottom)

Kinetic Sunyaev-Zel'dovich effect

Energy shift in CMB photons due to scattering with coherently moving electrons



$$\left(\frac{\Delta T}{T}\right)_{\rm kSZ} = \int d\eta \; \dot{\tau} e^{-\tau} \mathbf{v} \cdot \hat{\mathbf{n}}$$

Sunyaev, Zel'dovich (1970)

$$\left(\frac{\Delta T}{T}\right)_{\rm kSZ} \propto \int d\eta \; \boxed{(1+\delta_b)\mathbf{v}} \cdot \hat{\mathbf{n}} \; \times f_{\rm ionized}$$

Momentum

Ionized fraction

- Preserves Black Body spectrum of CMB
- For a large cluster $v \sim 10^{-3}$, $\tau \sim 10^{-2}$ $\quad \Delta T_{\rm kSZ} \sim \tau v \sim 10 \; \mu{\rm K}$
- Sensitive to all of the ionized gas. Can help find the 'missing baryons'

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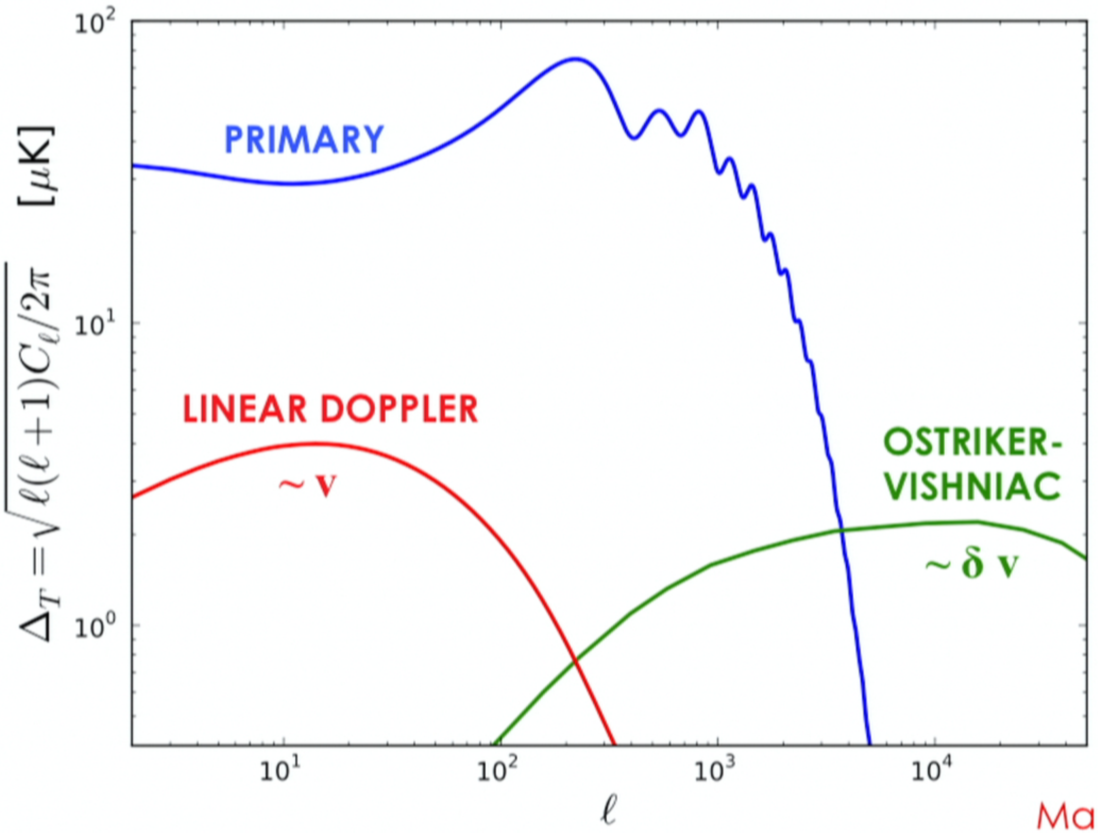
The kSZ power spectrum

'Late' time (z < 20) contributions from velocity



Ma, Fry (2002)
Hu, White (1996)

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The first detection: galaxy pairs

12

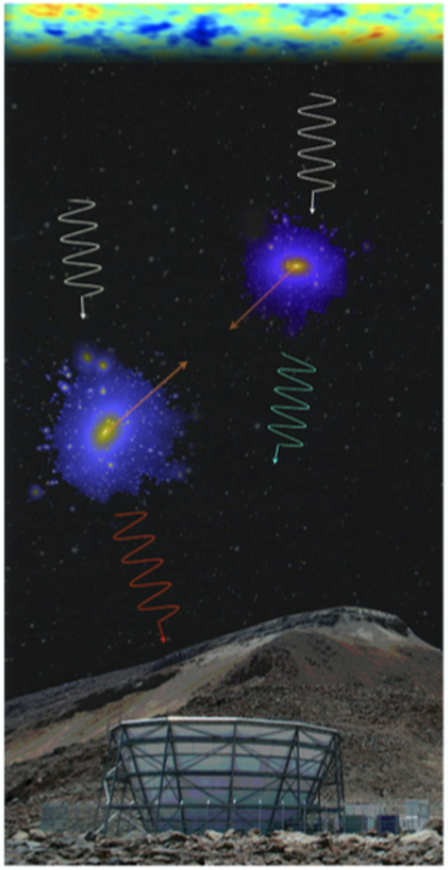
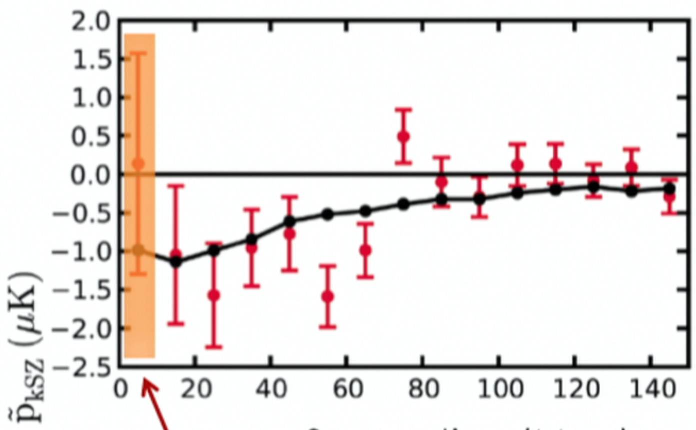


Image by Sudeep Das

$$p_{\rm pair}(r) \equiv \langle (\mathbf{p}_i - \mathbf{p}_j) \cdot \hat{\mathbf{r}}_{ij} \rangle$$



We will focus here
(1 – 10 Mpc)

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Hand + ACT collaboration (2012)

The first detection: galaxy pairs

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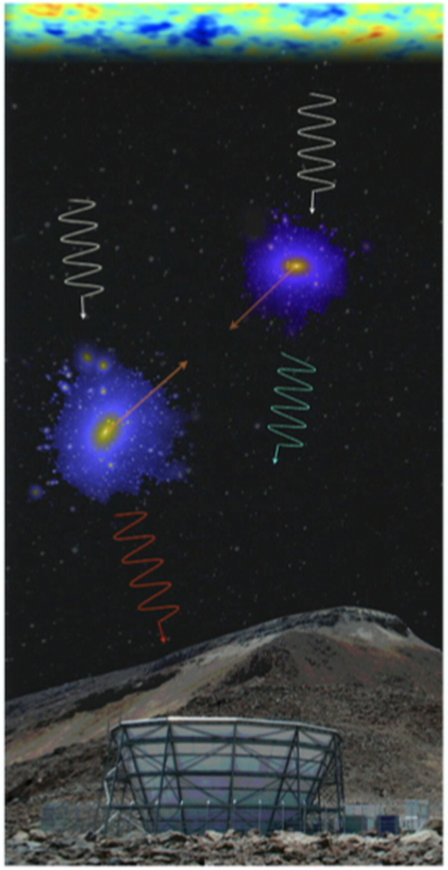

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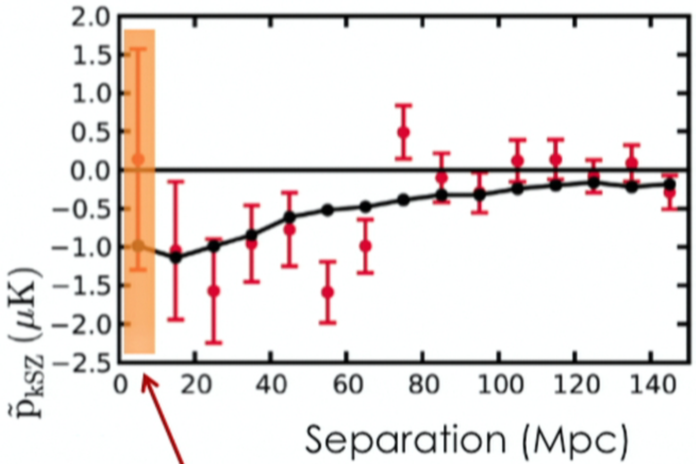

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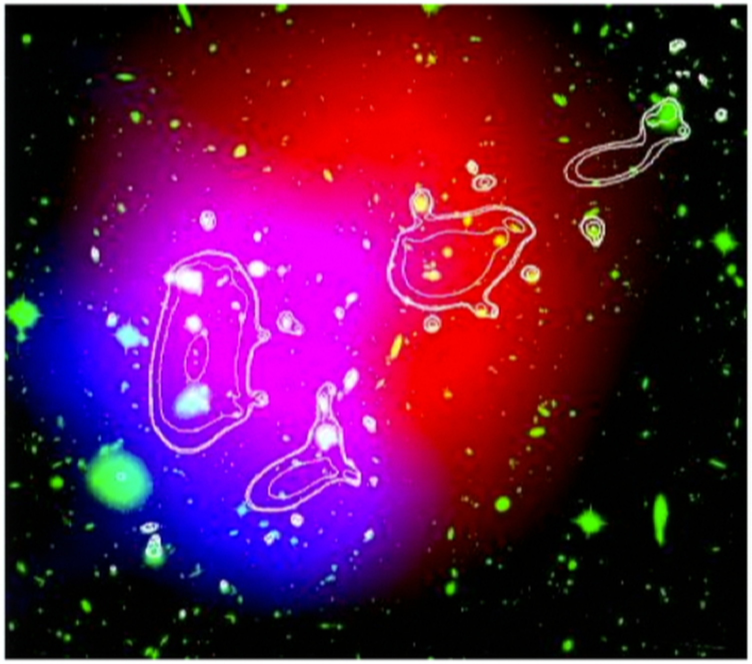
Detection from individual objects: MACS J0717.5+3745

14



Bolocam observations at 140 and 268 GHz

+ Hubble, Herschel, Chandra, XMM

V_z = **3450** ± 900 Km/s

V_{rms} = 515 Km/s

Tension with LCDM?

Sayers et al (2013)

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T^2 cross low-z tracers

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- $\langle T\ \delta_{\rm tr}\rangle \approx 0$ on small scales, but…
- Consider $\langle T_f^2(\mathbf{x})\ \delta_{\rm tr}(\mathbf{y})\rangle$

Filtered temperature squared in real space

Matter tracer (galaxies, AGNs, lensing convergence…)

- Can work on small scales
- Doesn't need redshifts
- Sensitive to cosmology, especially σ_8 and w
- Sensitive to baryon distribution
- Needs good control over foregrounds

Doré et al (2003)
DeDeo et al (2005)
SF et al (to appear)

Simone Ferraro (Princeton)

T^2 cross low-z tracers

- Consider $\langle T_f^2(\mathbf{x})\ \delta_{\rm tr}(\mathbf{y})\rangle$

<u>Filtered temperature</u>
squared in real space

<u>Matter tracer</u>
(galaxies, AGNs,
lensing convergence…)

- If only kSZ: $\sim \langle \delta v\ \delta v\ \delta_g \rangle$

$\delta_g \rightarrow b\delta$ for galaxies

$$\sim \langle vv\rangle\langle\delta\delta\delta_g\rangle + \langle v\delta\rangle\langle v\delta\delta_g\rangle + \ldots$$

↓ Fourier Transform
Project along line of sight

$$C_\ell^{\mathrm{kSZ}^2 \times \delta_g}$$

Assumptions (for now):

- Linear bias
- NL bispectrum fit
- Linear theory for $\delta \rightarrow v$
- Planck parameters

Doré et al (2003)
DeDeo et al (2005)
SF et al (to appear)

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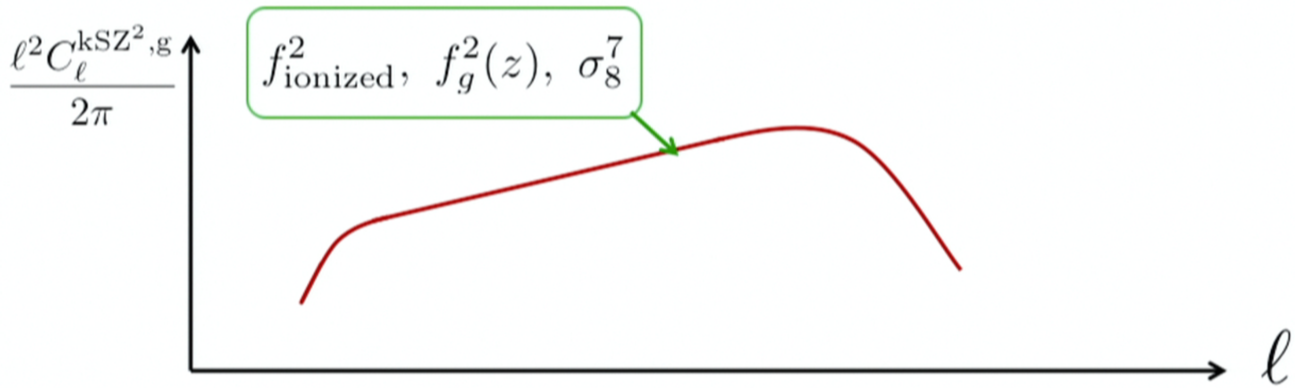
Detailed comparison with hydro simulations under way



Expect high S/N with high resolution experiments!

Doré et al (2003)
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SF et al (to appear)

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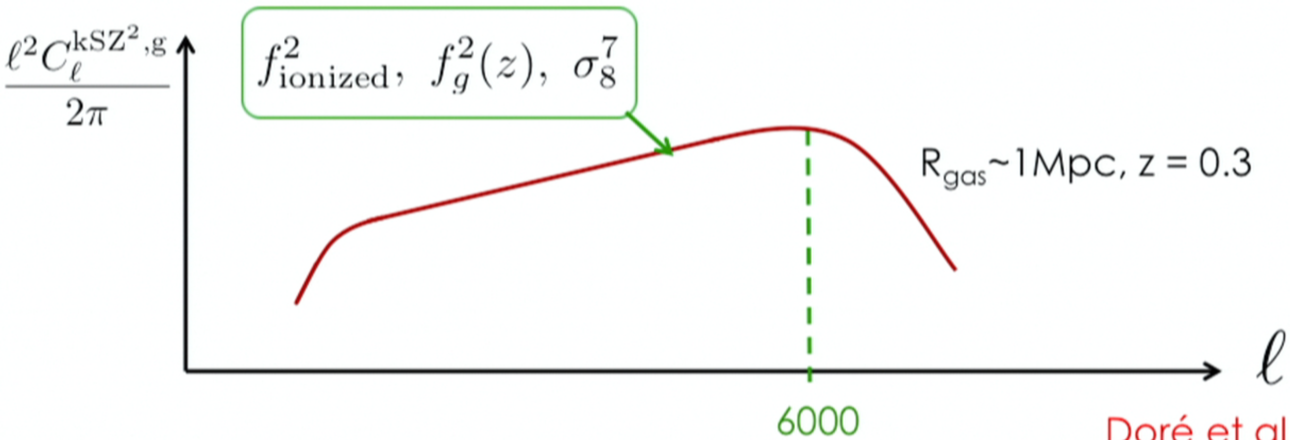

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SF et al (to appear)

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PRELIMARY RESULTS

with Colin Hill, Nick Battaglia, David Spergel, Jia Liu

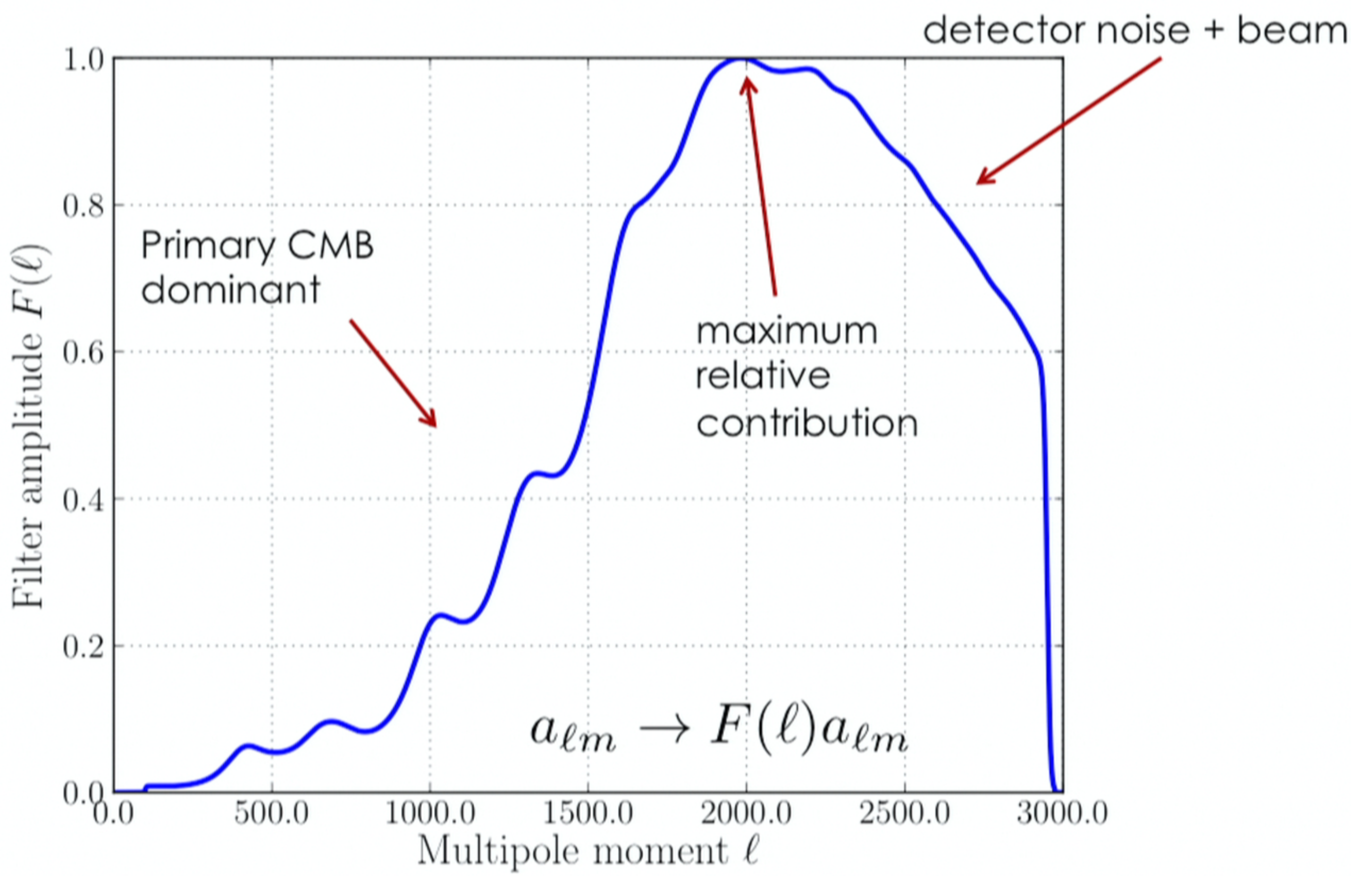
What we need:

- High resolution (foreground cleaned) CMB map
- Filter to maximize the kSZ contribution
- Low-redshift tracers.

SF, et al. (to appear)
Hill, SF, et al. (to appear)

Wiener Filter

$$F(\ell) \propto \frac{C_\ell^{\text{signal}}}{C_\ell^{\text{tot}}}$$



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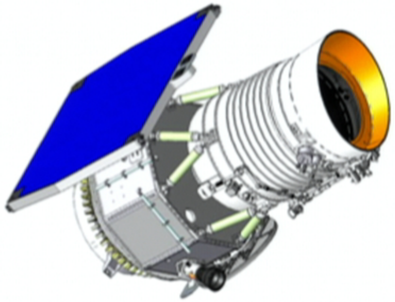
The WISE survey

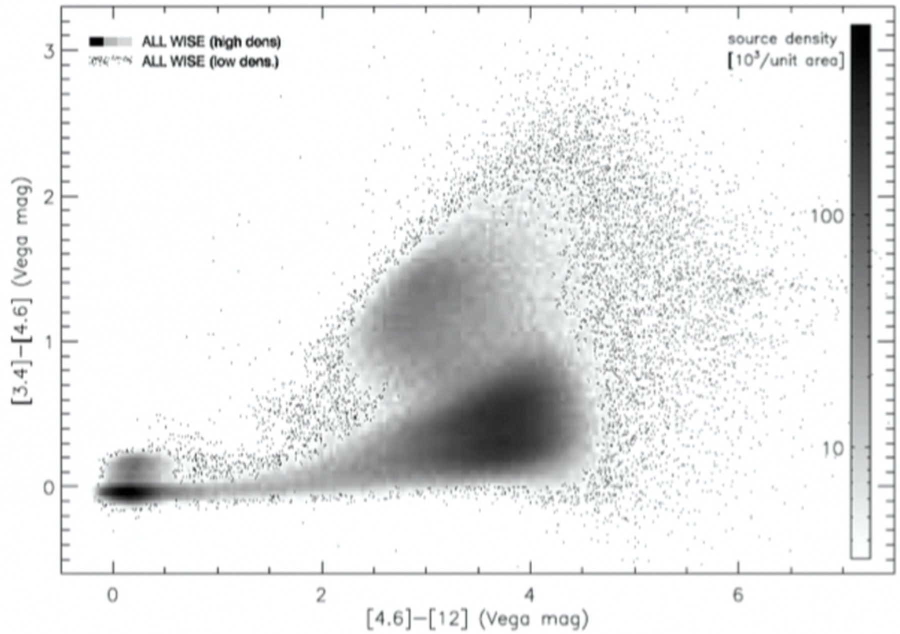
- Wide-field Infrared Survey Explorer (WISE)
- Mission 2009 → 2011 (and 2013 → present)



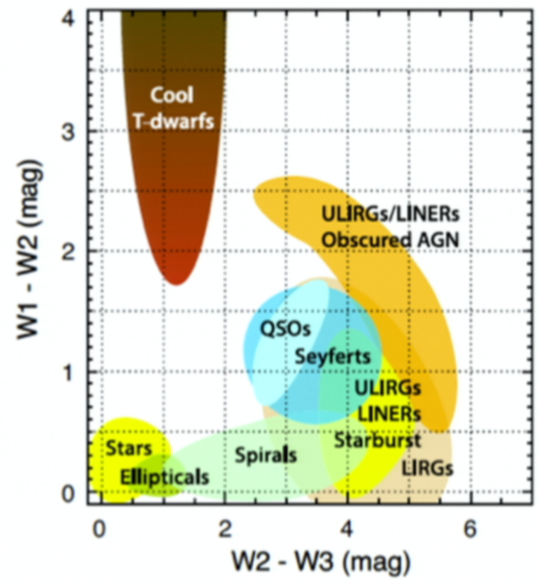
- Full sky
- 40cm mirror
- 4 IR bands: 3.4, 4.6, 12 and 22 μm (W1, W2, W3, W4)
- WISE source catalog: 5 x 10^8 objects with S/N > 5 in at least one band

Population selection

- Color-color selection effective in distinguishing stars/galaxies/AGNs



Yan et al. (2012)



Lake et al. (2011)

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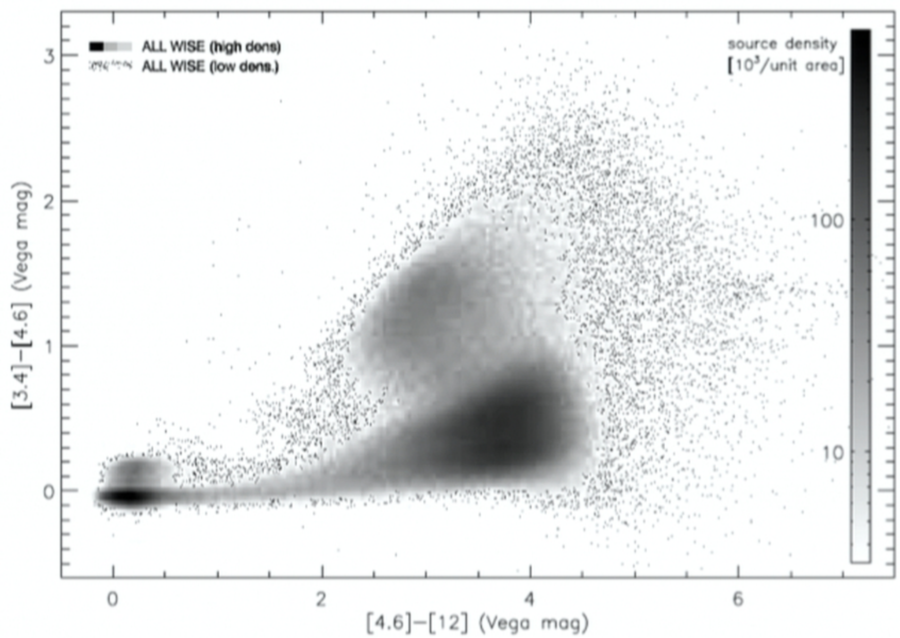

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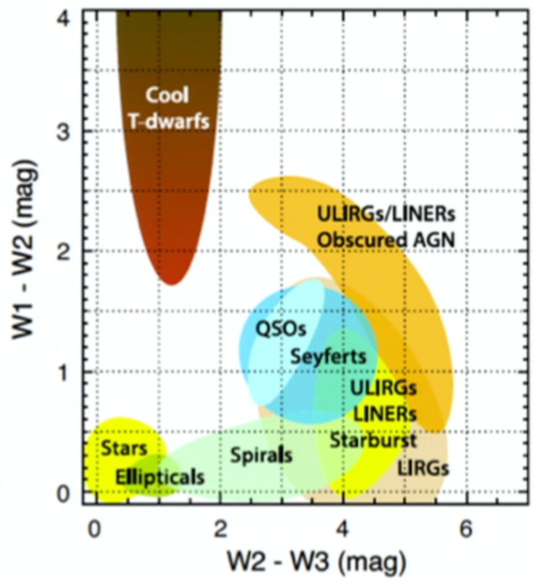

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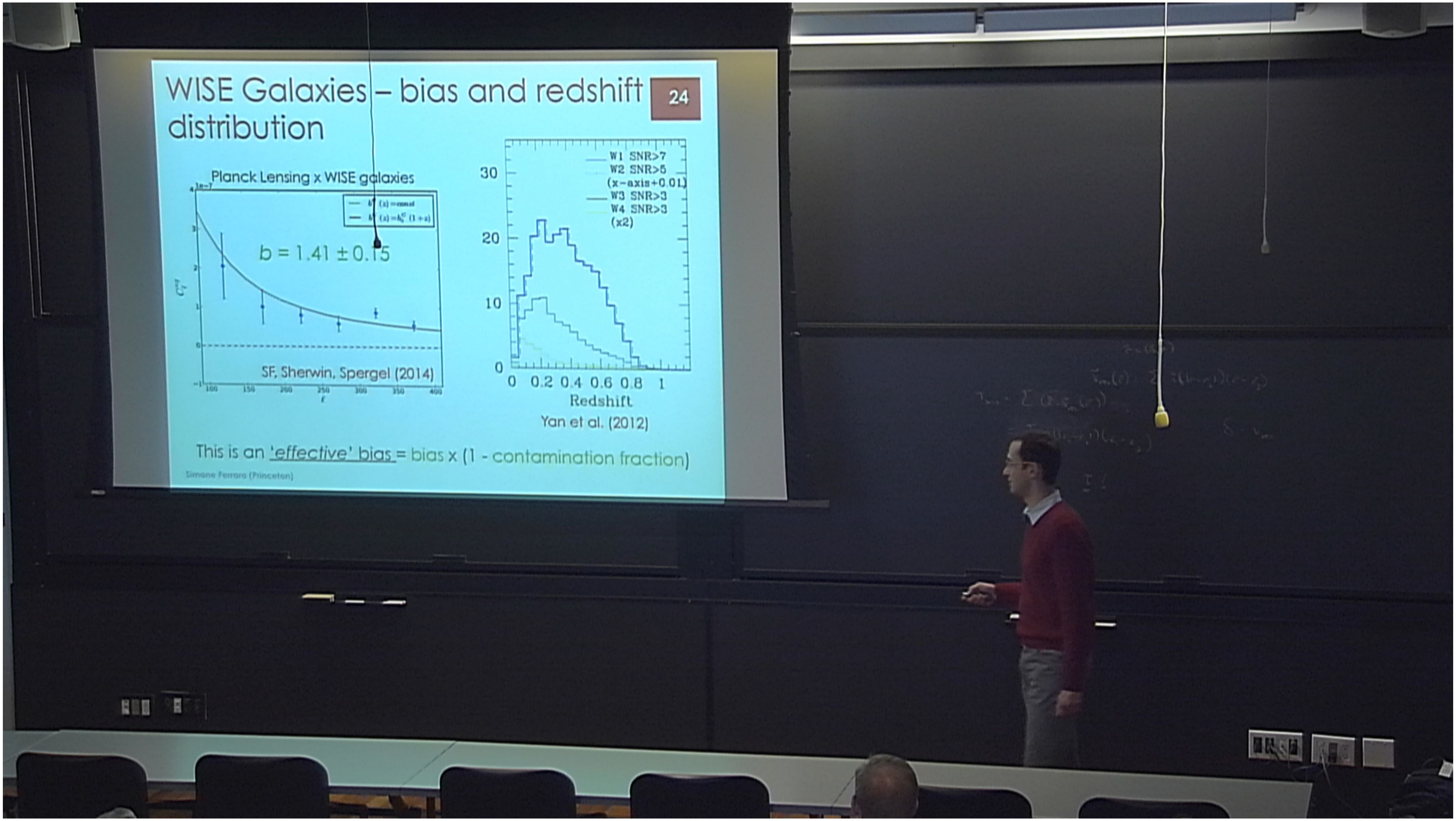

WISE Galaxies – bias and redshift distribution
24
Planck Lensing x WISE galaxies
b = 1.41 ± 0.15
SF, Sherwin, Spergel (2014)
W1 SNR>7
W2 SNR>5
(x-axis+0.01)
W3 SNR>3
W4 SNR>3
(x2)
Redshift
Yan et al. (2012)
This is an 'effective' bias = bias x (1 - contamination fraction)
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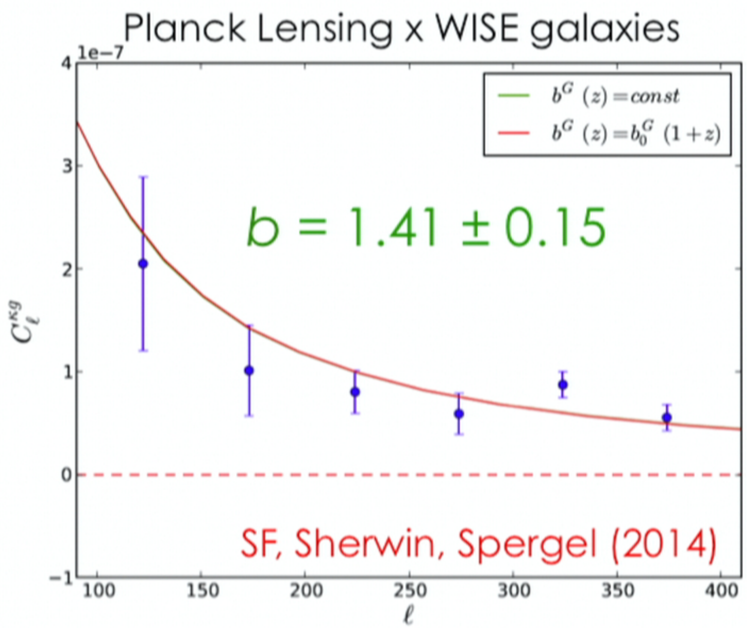
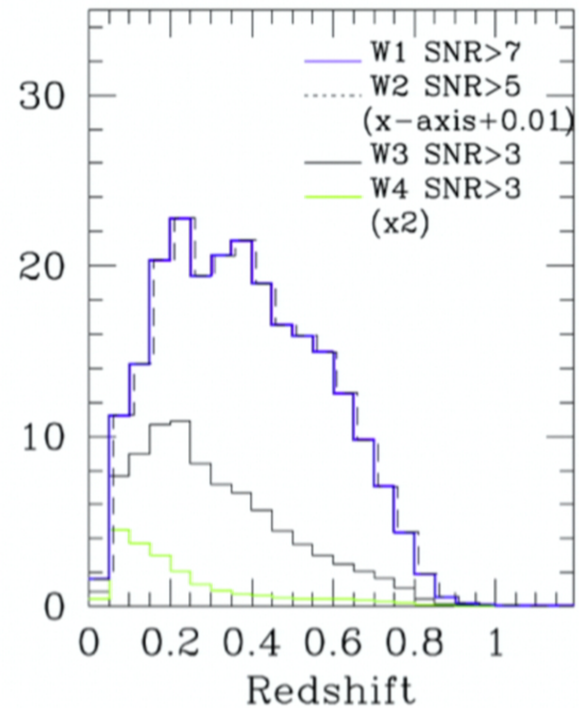
WISE Galaxies – bias and redshift distribution





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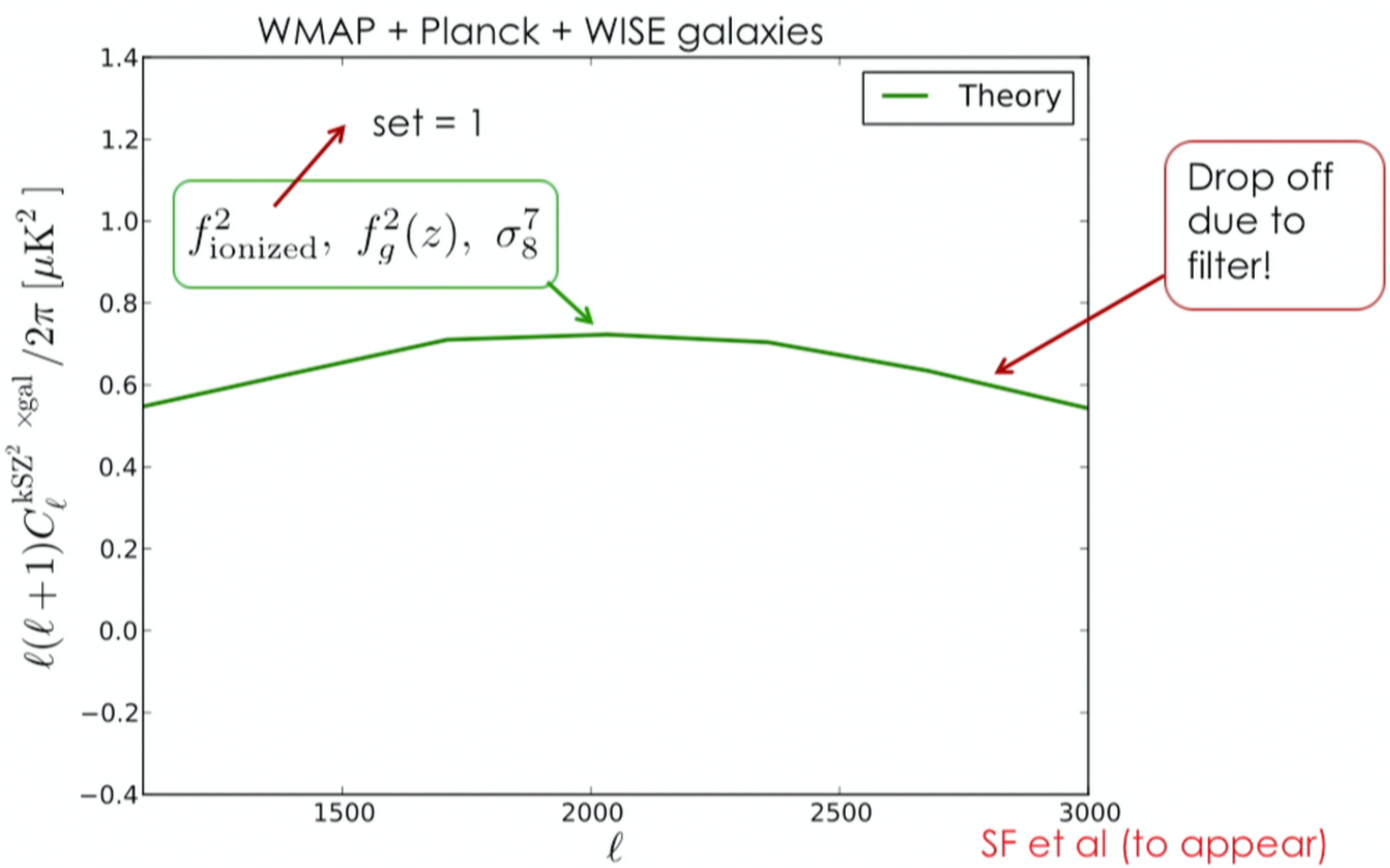
Results – WISE galaxies

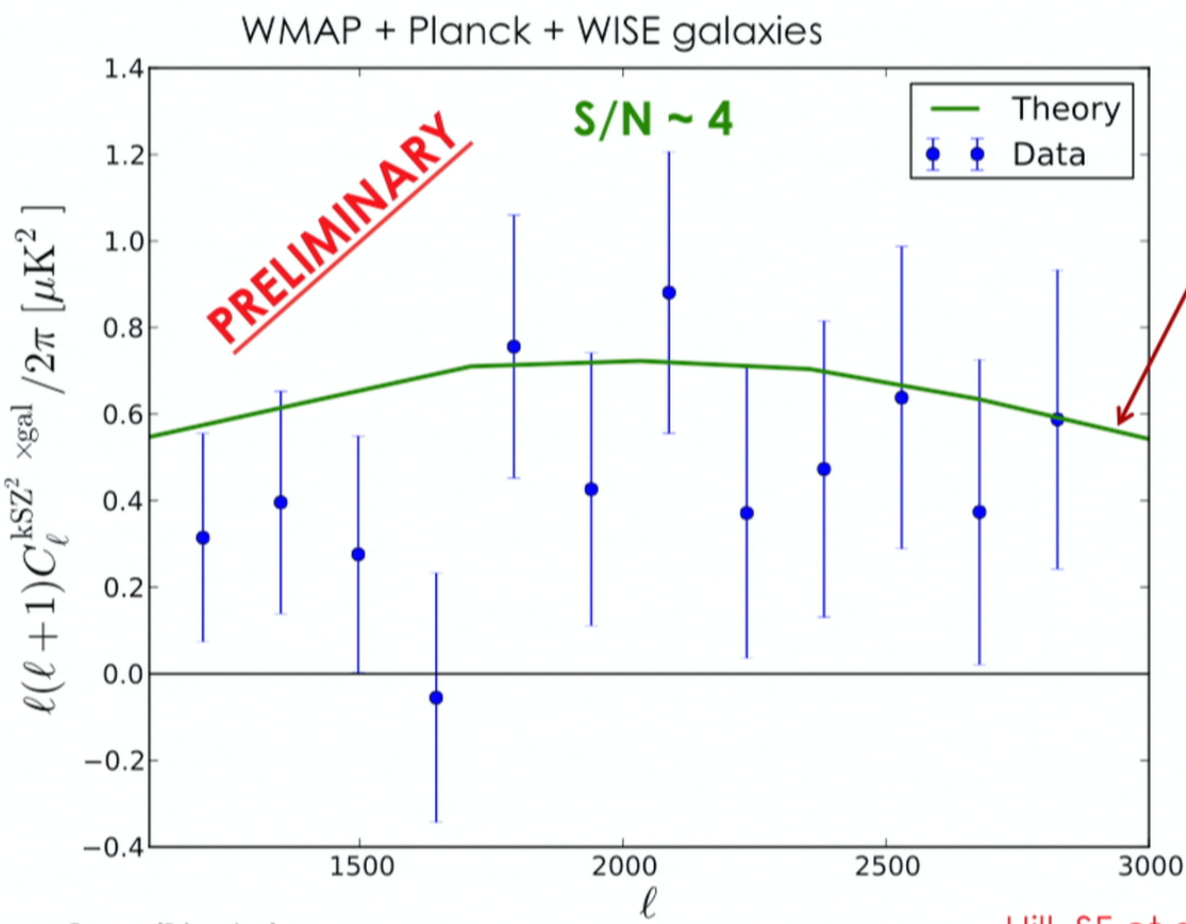
25



SF et al (to appear)
Hill, SF et al (to appear)

Results – WISE galaxies

26



Theory curve with $f_{ionized} = 1$

See all of the baryons !!

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Hill, SF et al (to appear)

Results – WISE galaxies

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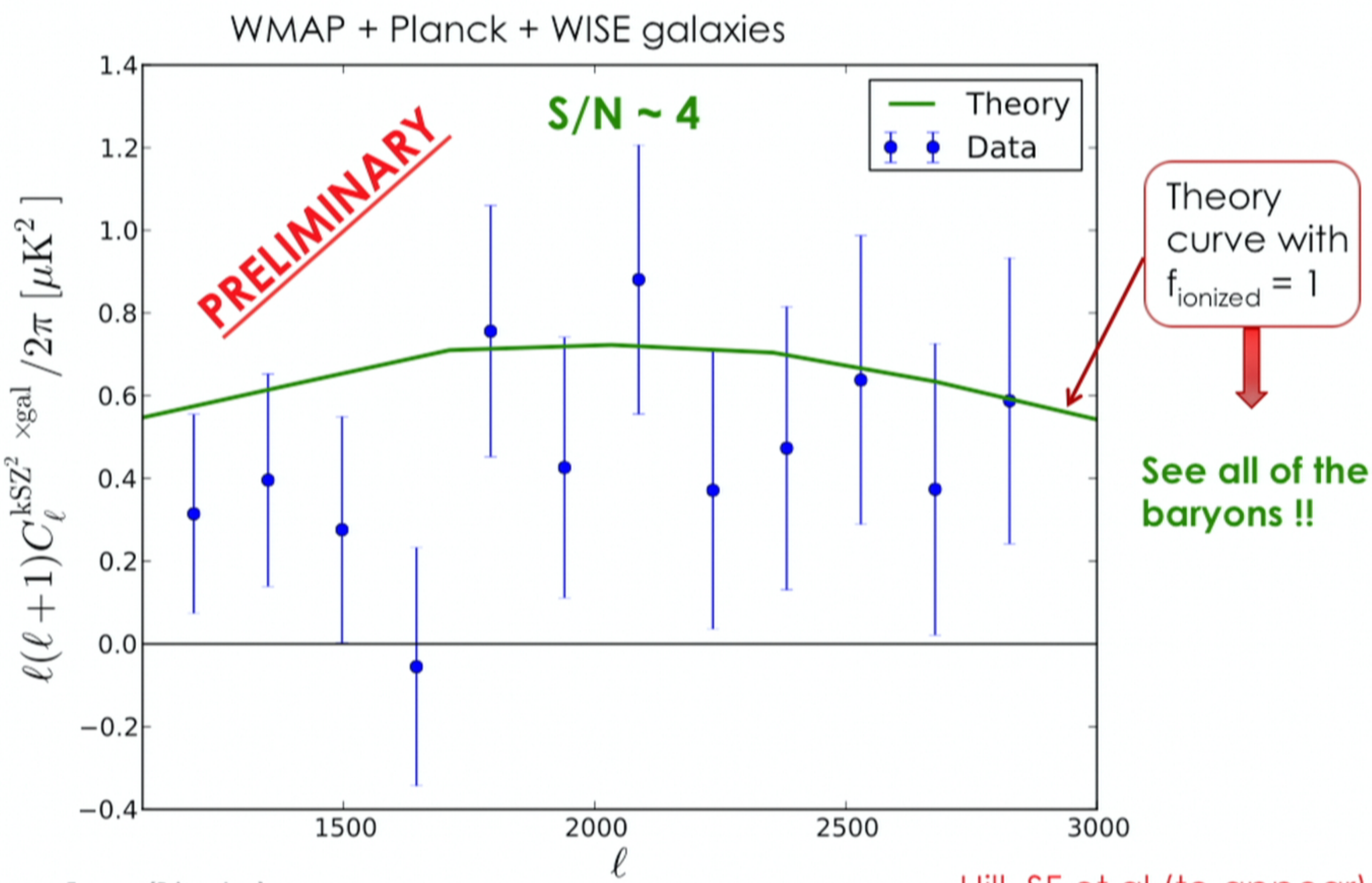

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Hill, SF et al (to appear)

Systematic Checks

Large number of systematic checks and null tests

Possible contaminats:

- Weak Lensing of the CMB
- Residual CIB or tSZ
- Galactic dust
- Variation in spectral index for CIB or radio emission (!)
- …

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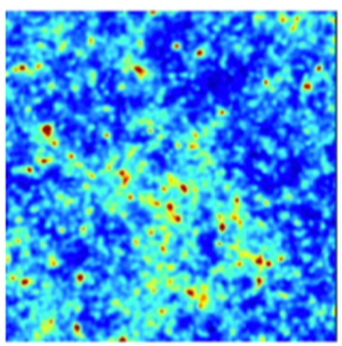
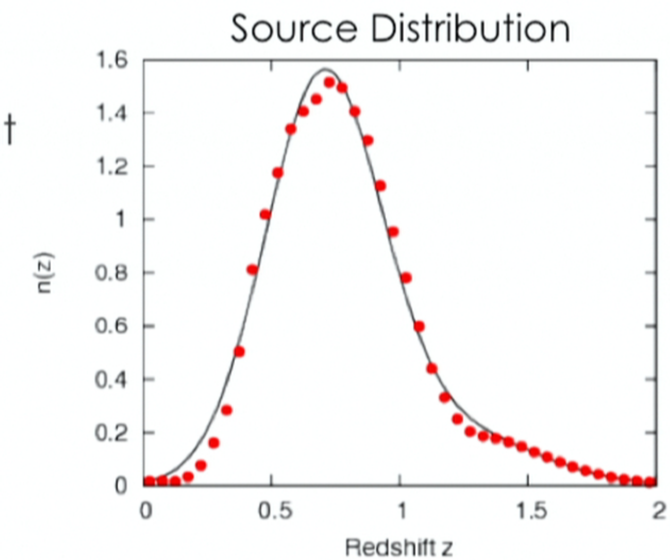
CFHTLenS lensing convergence

- 3.6 meter optical/infrared telescope
- 154 sq deg (in 4 patches)
- broad redshift distribution
- Independent pipeline developed at Columbia University



Liu et al (2014)



Van Waerbeke et al (2013)

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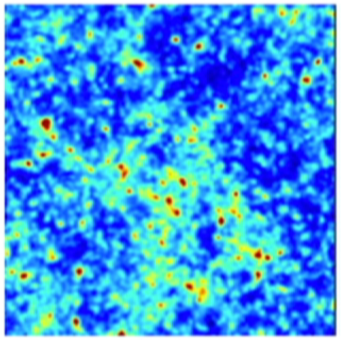

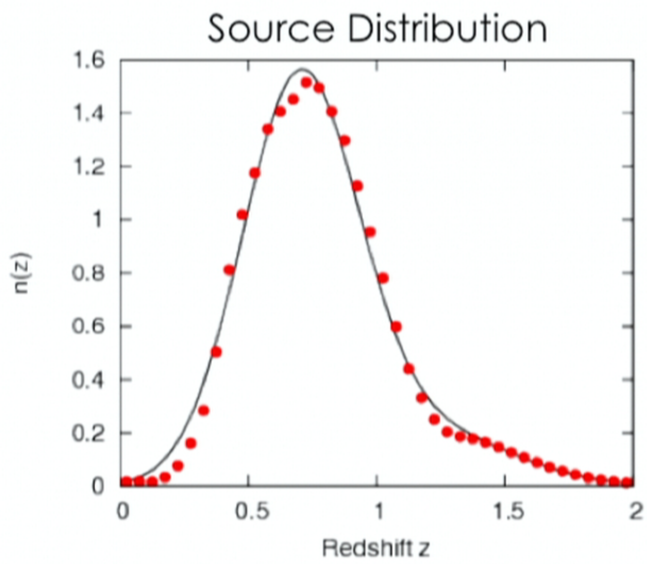

Van Waerbeke et al (2013)

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Liu et al (2014)

Results – CFHTLenS convegence

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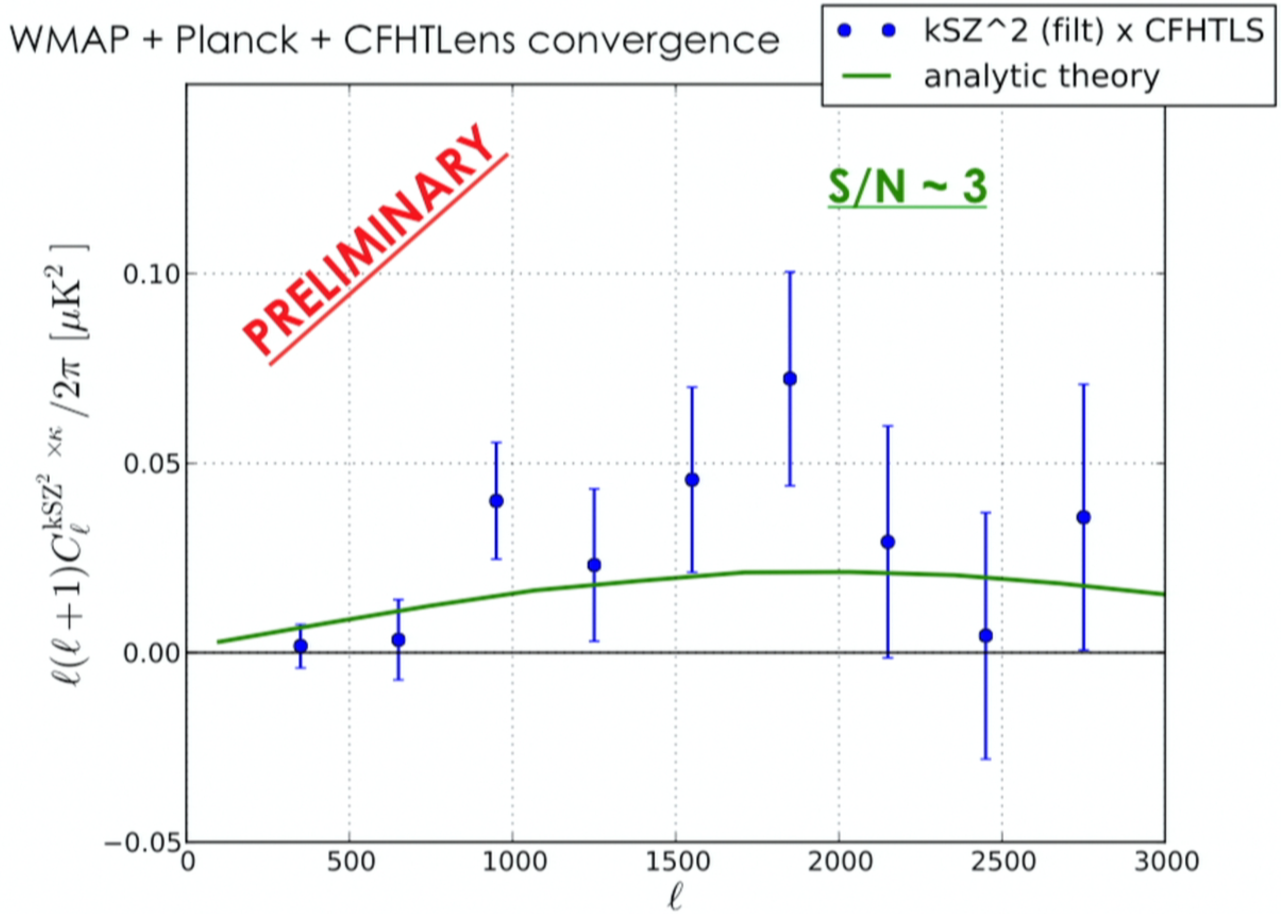

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Hill, SF et al (to appear)

What's next?

30

- Better understanding of theory/sims on small scales
- Baryon content and distribution as a function of galaxy type and redshift
- Small scale experiments → push to L ~ 10000. Can extract the signal in real space S/N ~ 0.5 per cluster for M ~ 10^{14} M_{sun}
- kSZ maps. Cosmological applications
- Constraints on reionization

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Temperature Wiener Filter

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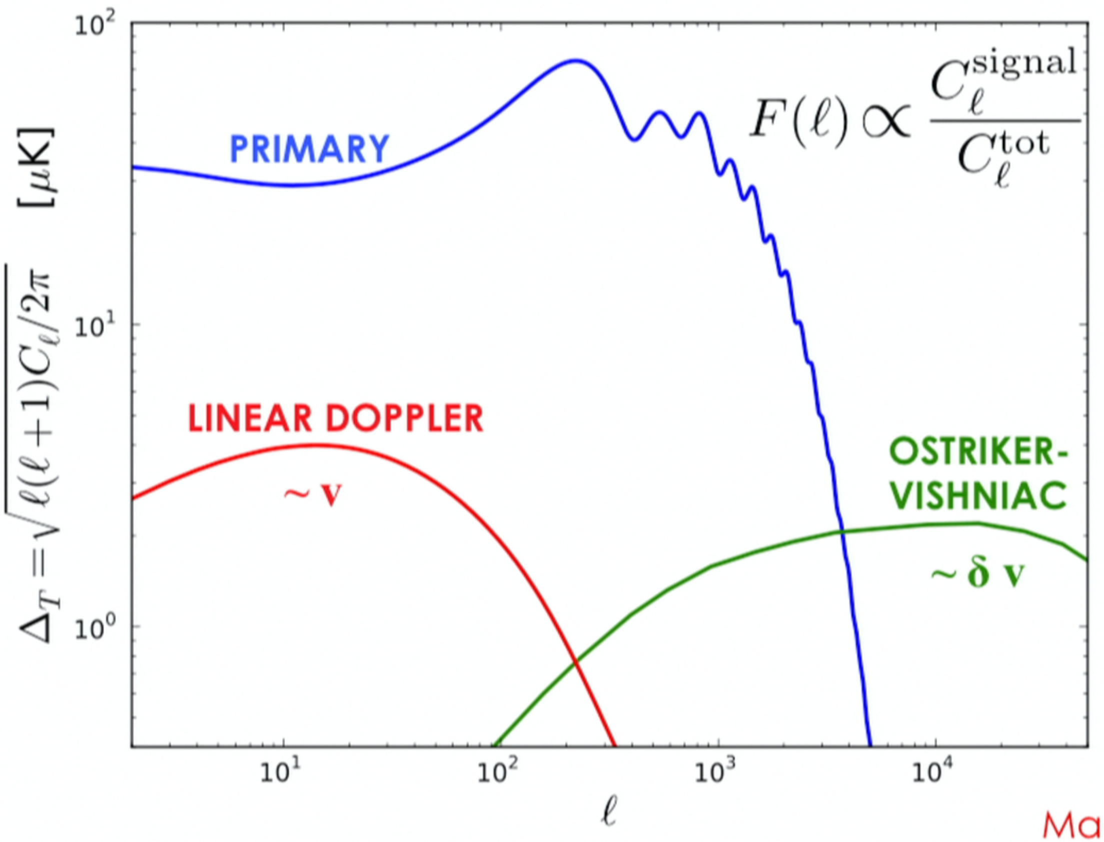

Ma, Fry (2002)
Hu, White (1996)

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Conclusions

- Kinetic Sunyaev-Zel'dovich effect measures the abundance and distribution of free electrons.
- Baryons trace the Dark Matter down to ~ 2 Mpc and abundance consistent with BBN + CMB
- Independent probe of growth of perturbation/initial conditions
- Probe of reionization
- This is just the beginning. Great improvement over the next few years!
- A lot of work in progress

Thank you!

Simone Ferraro (Princeton)