Title: Probing cosmic flows through the kinematic Sunyaev Zel'dovich effect

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Abstract: Beyond its primary fluctuations, the cosmic microwave background (CMB) contains a wealth of information on the large-scale structure of the universe, which it illuminates as a backlight. The baryon momentum field is thus imprinted on the CMB through the kinematic Sunyaev-Zel'dovich (kSZ) effect. Current small-scale high-sensitivity CMB experiments make this effect detectable, providing a unique handle on peculiar velocities and baryon physics.

I will report a significant detection of the kSZ effect, obtained by combining CMB intensity data with peculiar velocities reconstructed from the galaxy number density field. I will present the prospects for localizing the missing baryons, constraining baryon physics inside galaxy clusters, and measuring the growth rate of structure from the kSZ effect. I will finally explore the possibility of measuring velocities across the line of sight through the CMB moving lens effect.

Cosmic Flows in the CMB

Emmanuel Schaan, Princeton University
with Simone Ferraro, Mariana Vargas-Magaña, Shirley Ho,
Kendrick Smith & ACTPol collaboration

Perimeter Institute, August 10 2015

Motivations

Peculiar velocities

Growth rate of structure, test of GR - *Linder 05, Mueller+14*

Bulk flows - *Planck XIII*

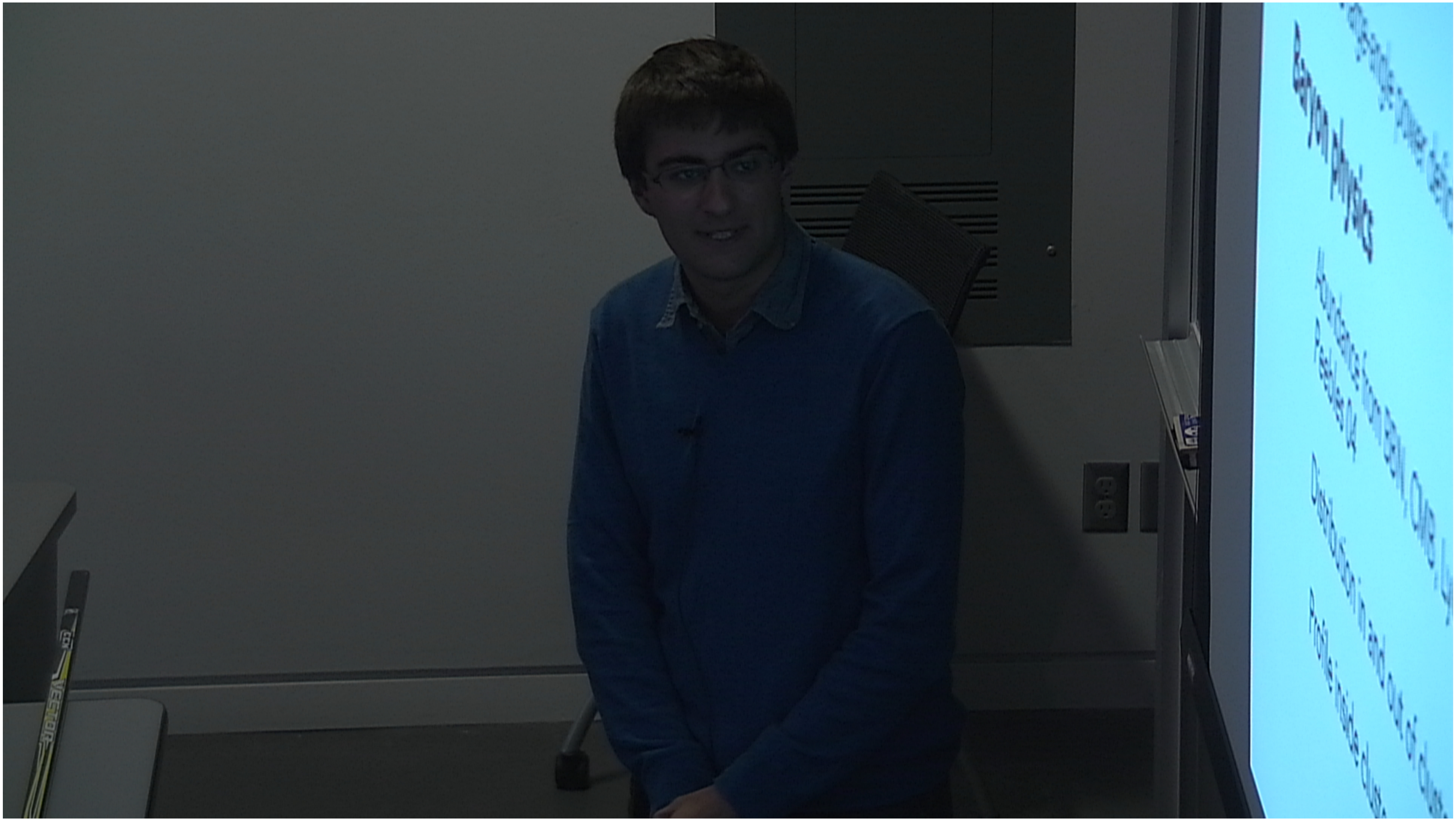
CMB large-angle power deficit

Baryon physics

Abundance from BBN, CMB, Lyα, not found at z=0 - *Fukugita Peebles 04*

Distribution in and out of clusters? (stars 7%, HI and H_2 2%)

Profile inside clusters, energy injection processes?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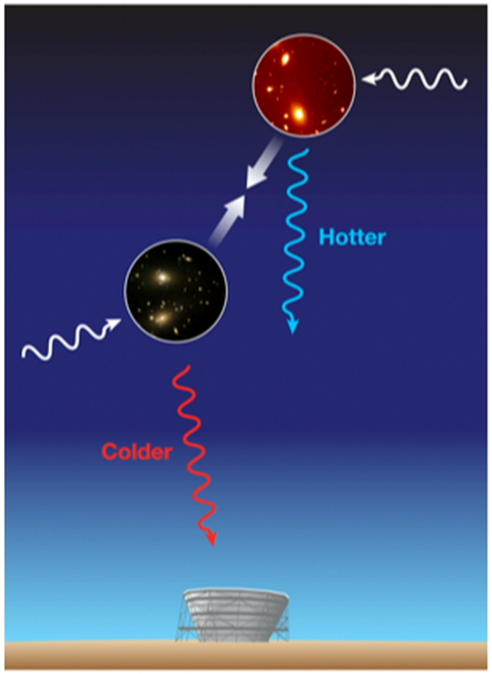
Kinematic Sunyaev-Zel'dovich effect

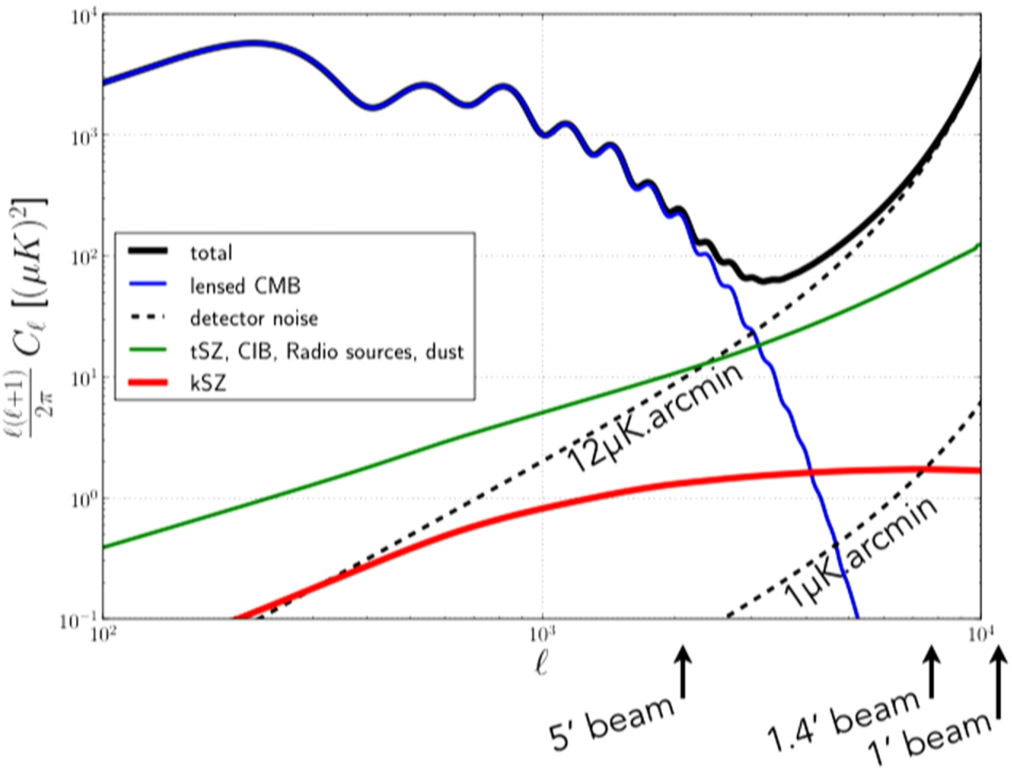


$$\frac{\delta T}{T} = \underbrace{\int \mathrm{d}l \, n_e \sigma_T}_{\tau} \frac{v}{c}$$

- sensitive to all free electrons vs Xray $\propto n_b^2$ and tSZ $\propto n_e T$
- blackbody spectrum
- small size: $\delta T_{\mathrm{kSZ}} \sim 0.1 \mu\mathrm{K}, \delta T_{\mathrm{CMB}} = 110 \mu\mathrm{K}$

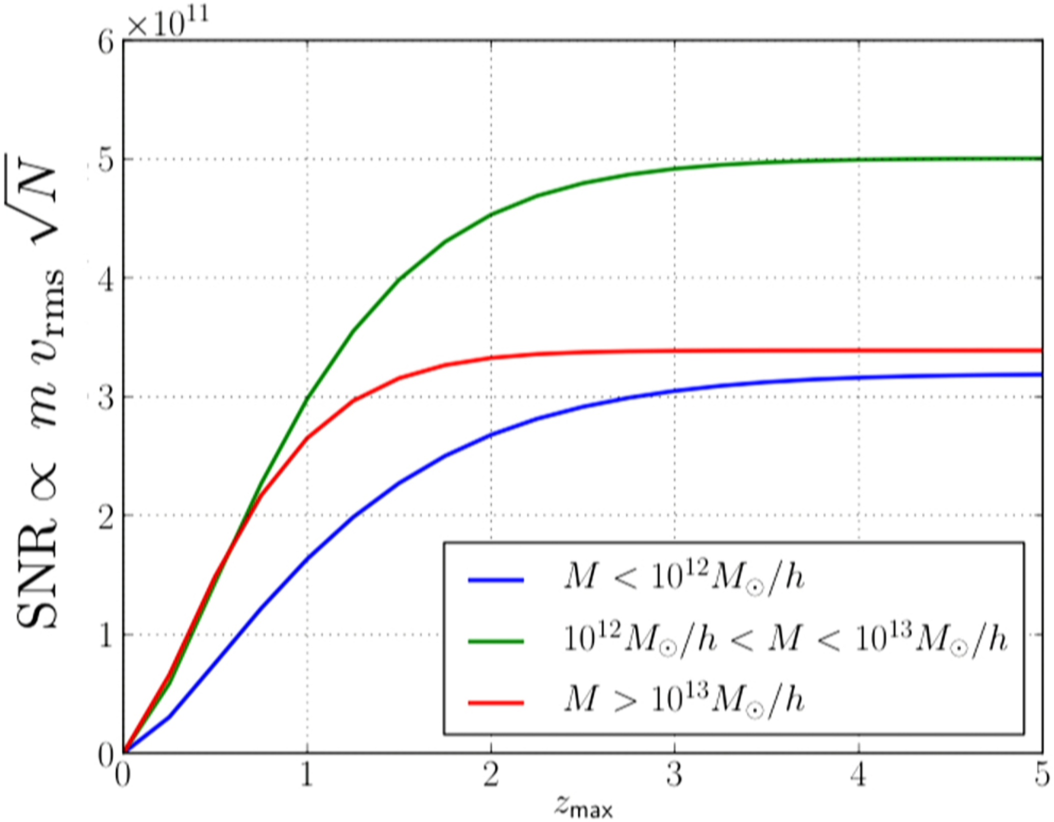
Hand et al 2012
aps.org, ESO, ESA, Hubble, NASA

Foregrounds & scale-dependence



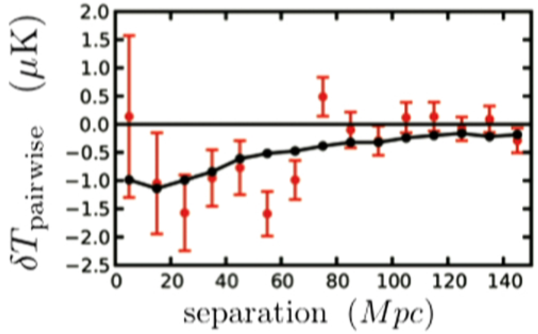
- CMB & noise dominant
- Signal peaks on very small scales
- reionization + late time

Origin of the late-kSZ signal



→ Groups and clusters up to z~2

Previous detections



Hand et al 2012

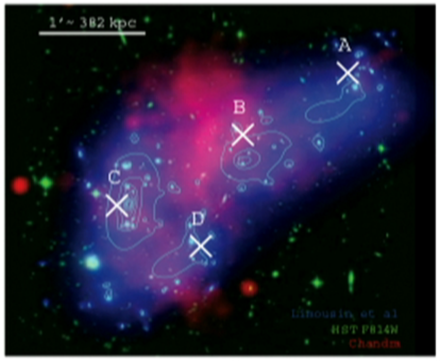
30,000 BOSS galaxies (DR9), ACT Equatorial

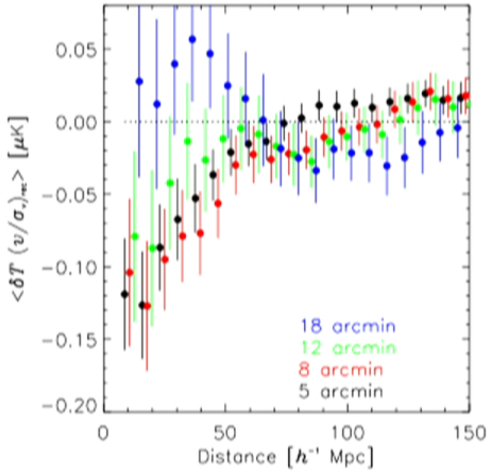
→ 3.8σ detection

Sayers et al 2013

$M = 10^{15} M_{sun}$, z=0.55, v= 3450±900 km/s

→ 4.2σ detection with Bolocam





Planck XXVII 2015

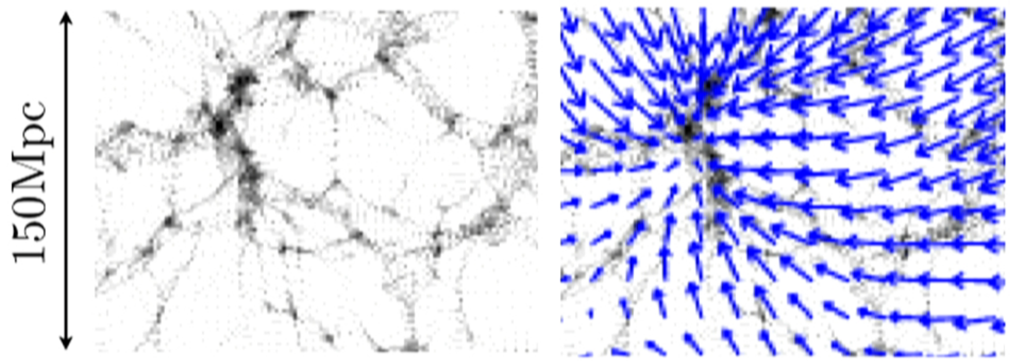
260,000 central galaxies from NYU VAGC (DR7)

Planck cleaned maps

→ 3.5σ detection

Peculiar velocities

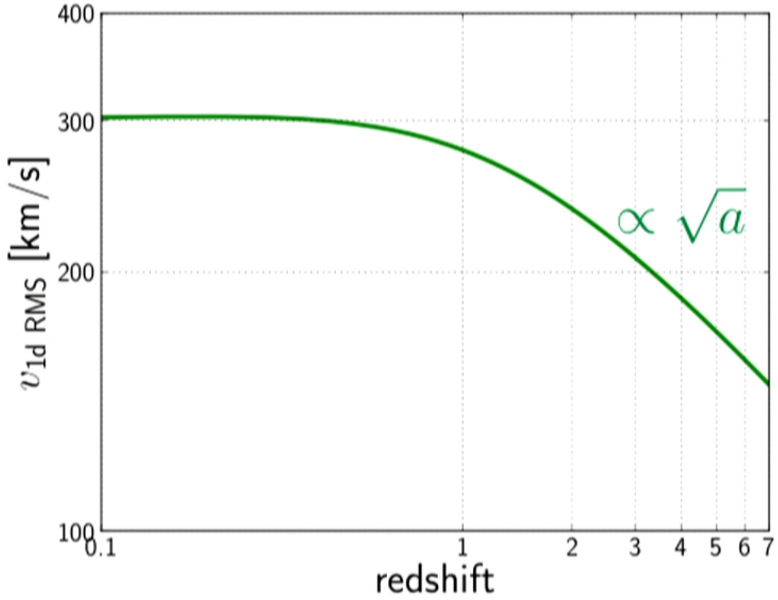
- peculiar velocity $\vec{v} = \frac{d\vec{r}}{dt} - H_{(t)}\vec{r} = \frac{d\vec{x}}{d\eta}$
- mass conservation + linear approx.
  $\Rightarrow \quad \vec{v} = aHf\ \vec{\nabla}\Delta^{-1}\delta$

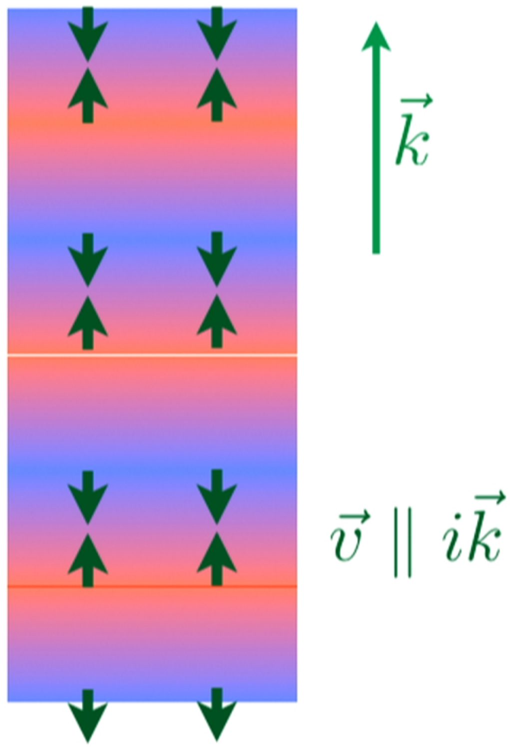


Padmanabhan et al. 2014

Velocities: time/scale dependence

$$\vec{v} = aHf\ \vec{\nabla}\Delta^{-1}\delta$$

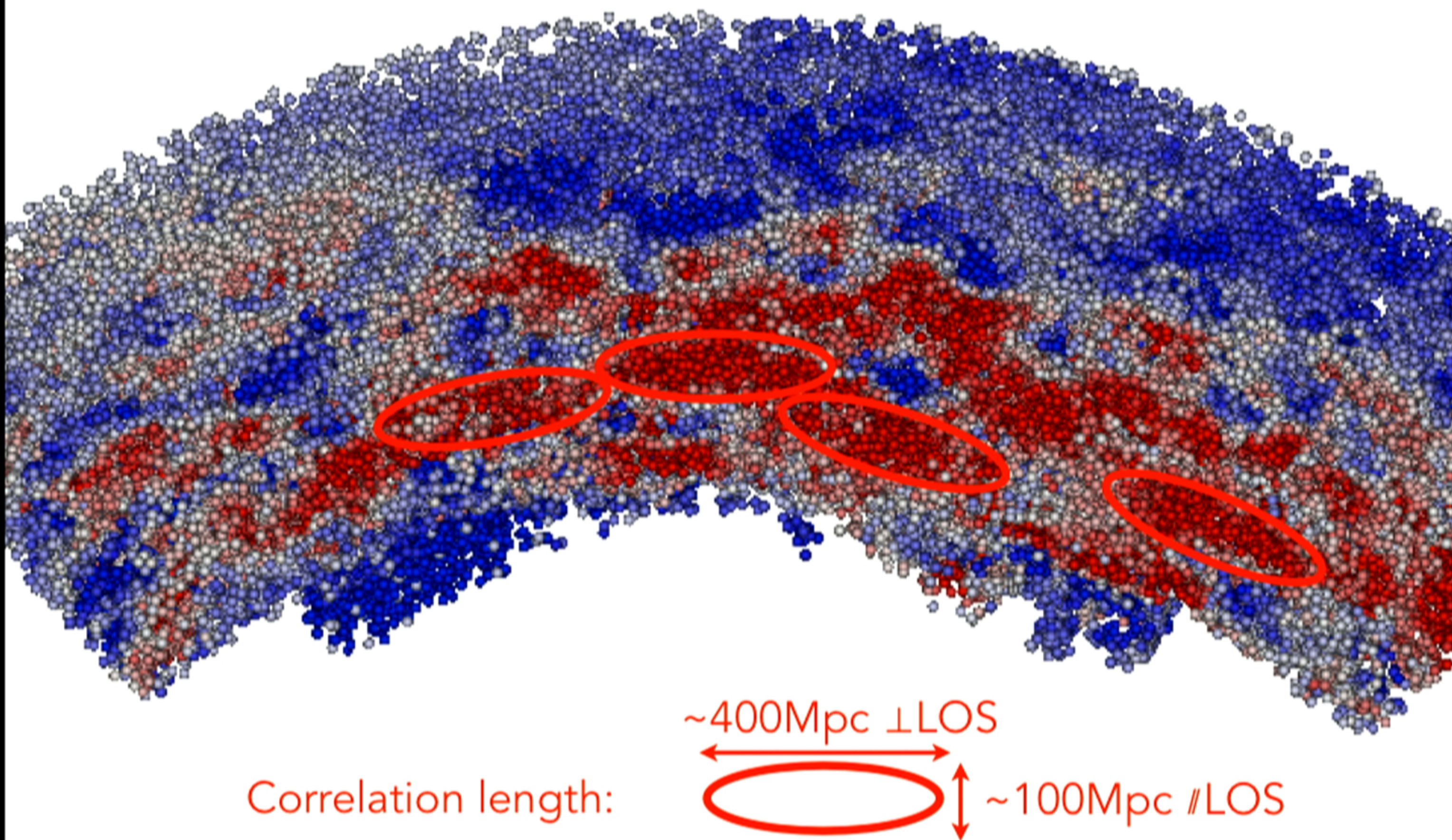




→ $v_{\rm rms\ 1d} \sim 300$ km/s

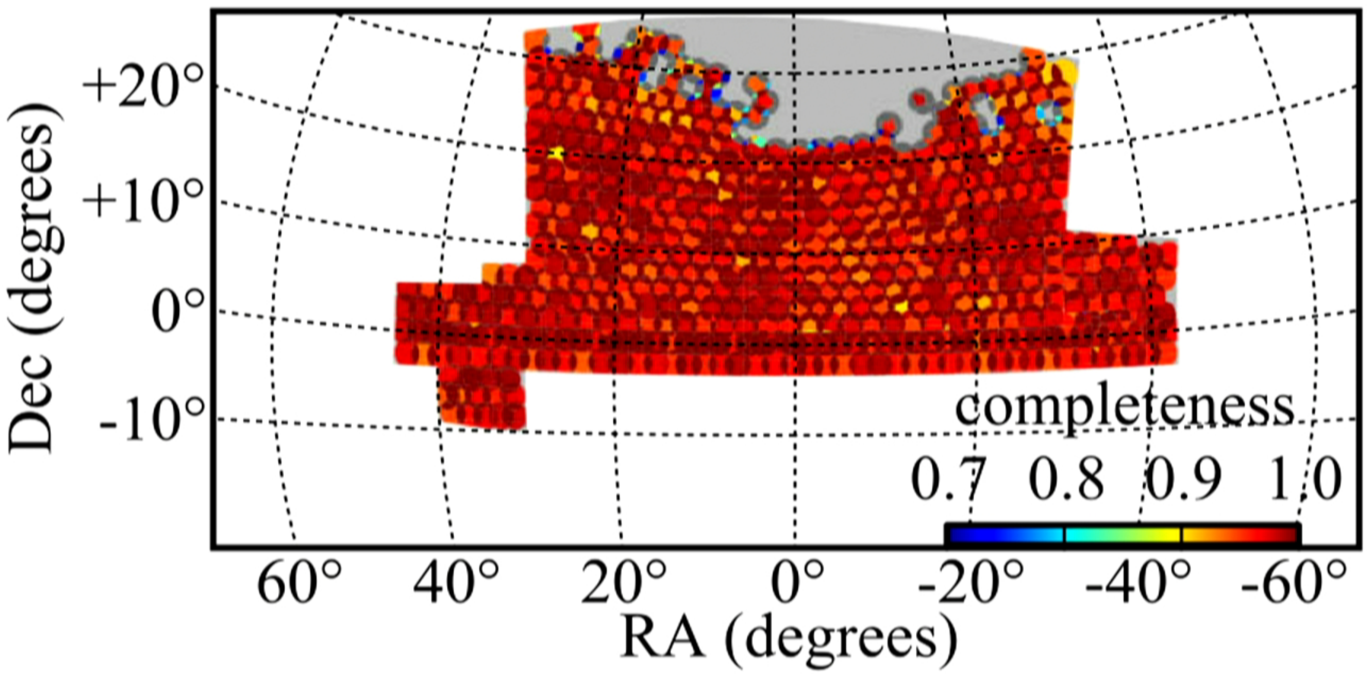
→ anisotropic scale-dependence

Velocities: anisotropic scale-dependence



Velocity reconstruction

$$\vec{v} = aHf\ \vec{\nabla}\Delta^{-1}\delta$$



BOSS CMASS South DR11 footprint (sdss.org)

Velocity reconstruction

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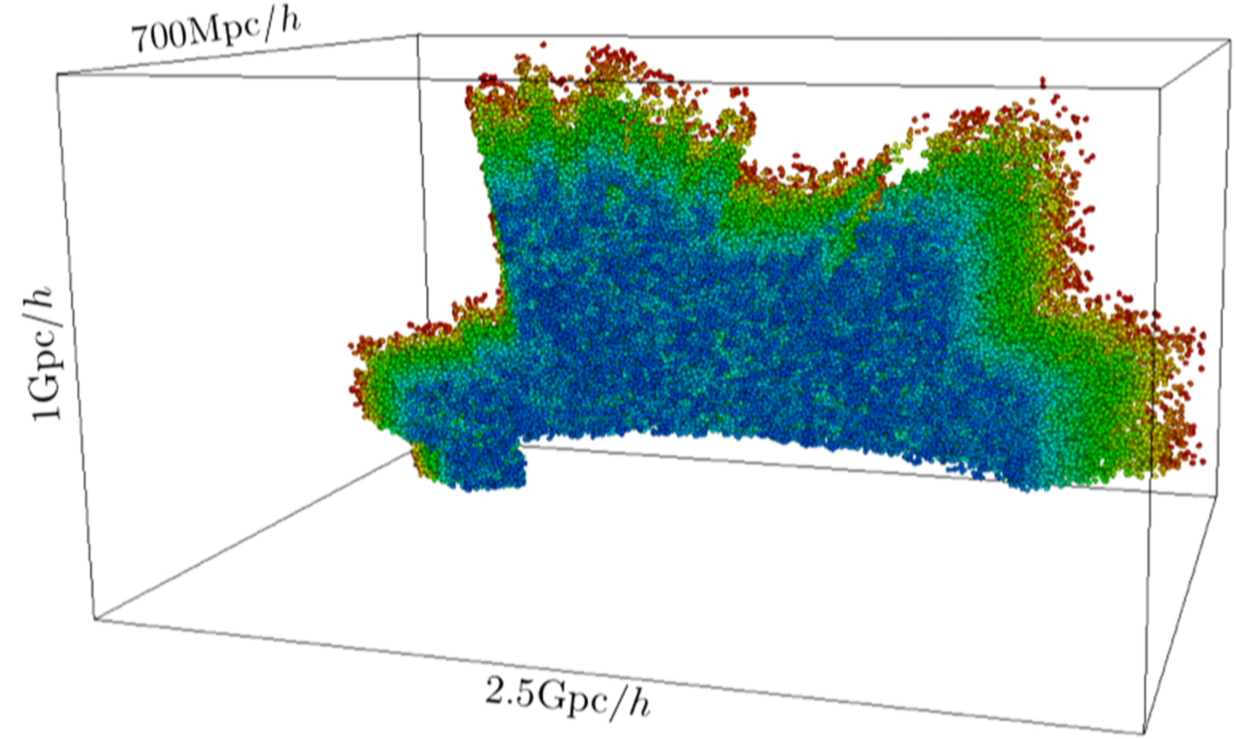

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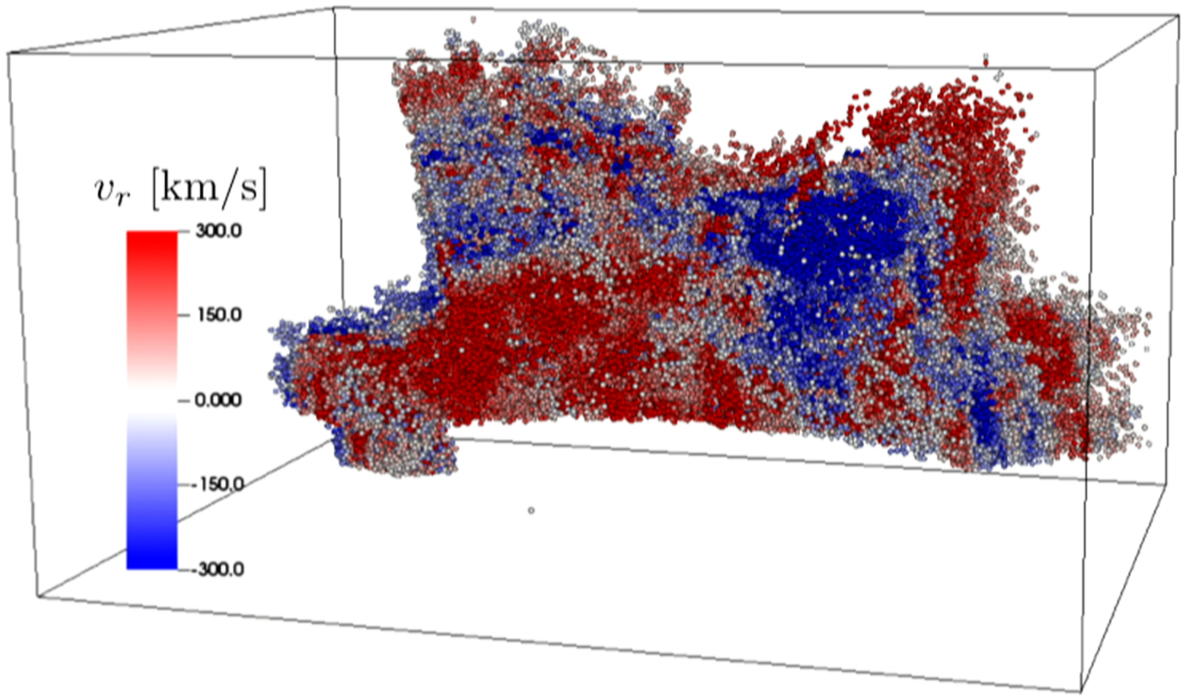
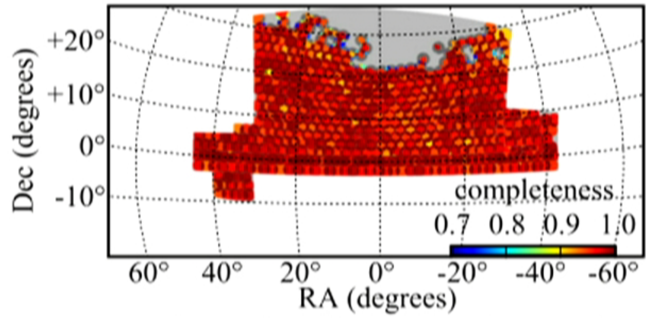


Velocity data from Smith, Vargas-Magaña, Ho

Datasets



map at 148GHz

area 600 sq. deg.

noise 12muK.arcmin

beam 1.4arcmin

aperture photometry

→δT

30,000 CMASS DR11 galaxies

0.4<z<0.7

central fraction 85%

individual stellar masses

$M_* \sim 2 \times 10^{11} M_\odot$

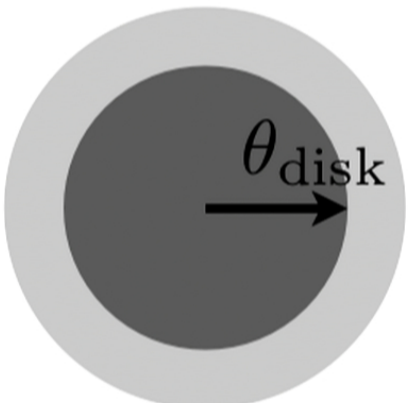
$M_{\rm halo} \sim 2 \times 10^{13} M_\odot$

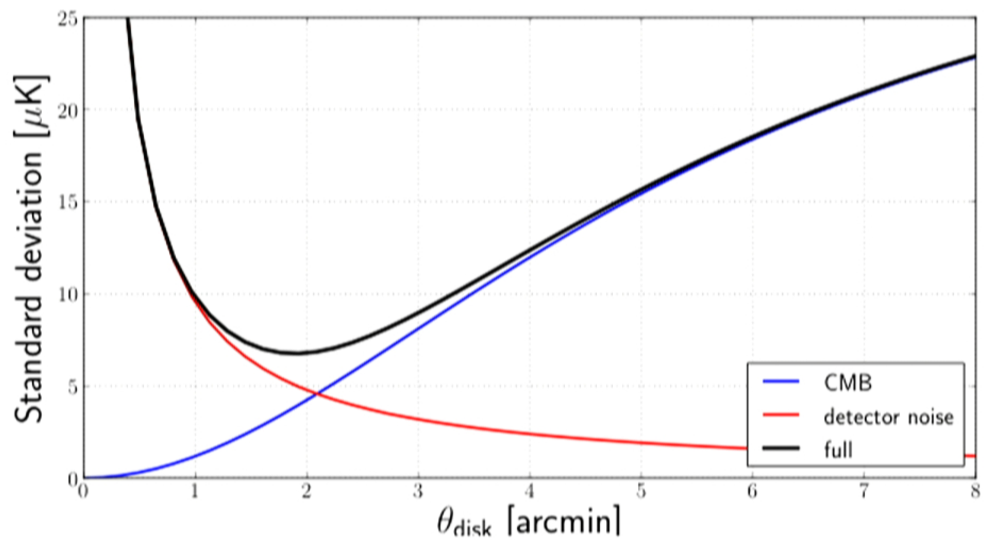
$\theta_{\rm vir} \sim 1.5 \rm arcmin$

reconstructed velocities (Kendrick Smith , Mariana Vargas Magaña, Shirley Ho))

→ τ and v

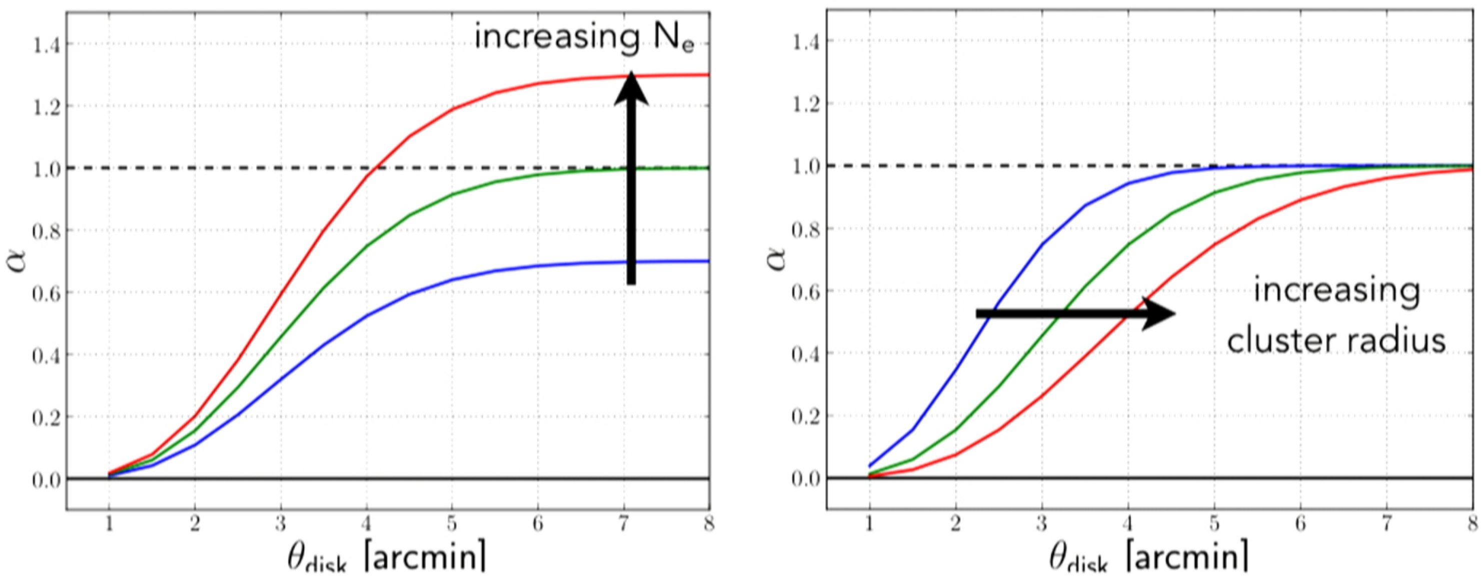
Aperture photometry





Results

$$\delta T = \alpha \tau \frac{v}{c}$$



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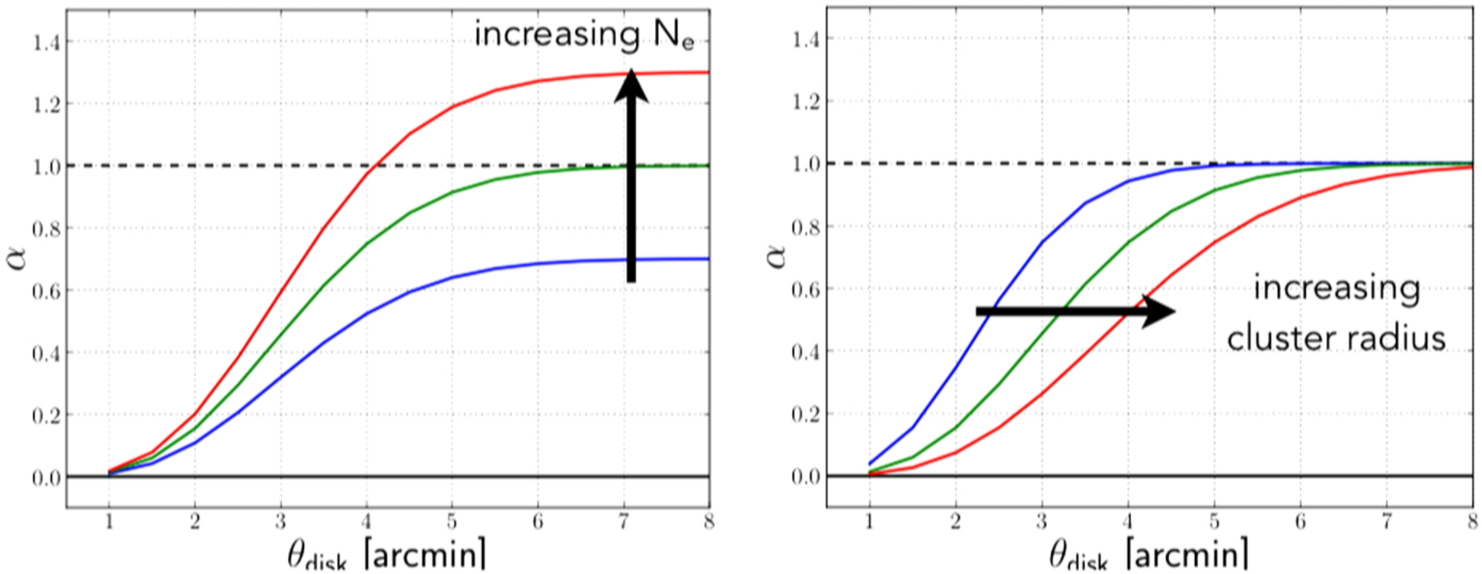

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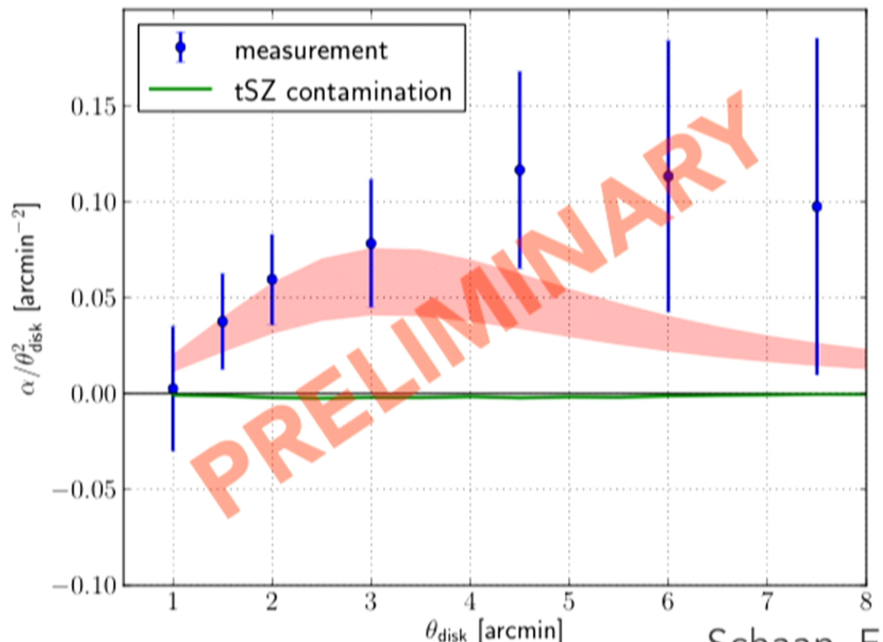


Schaan, Ferraro et al in prep.

"no kSZ" hypothesis rejected at 4 σ

Systematics

Cluster miscentering: <0.5arcmin, ~1% effect

Velocity reconstruction: SNR reduced by r=0.7

TSZ contamination: mass cut/correction

2-halo term: bias high 60%

Mass scatter: bias high 60%, fractional uncertainty on α increased by 30% (using mean mass reduces SNR by 40%)

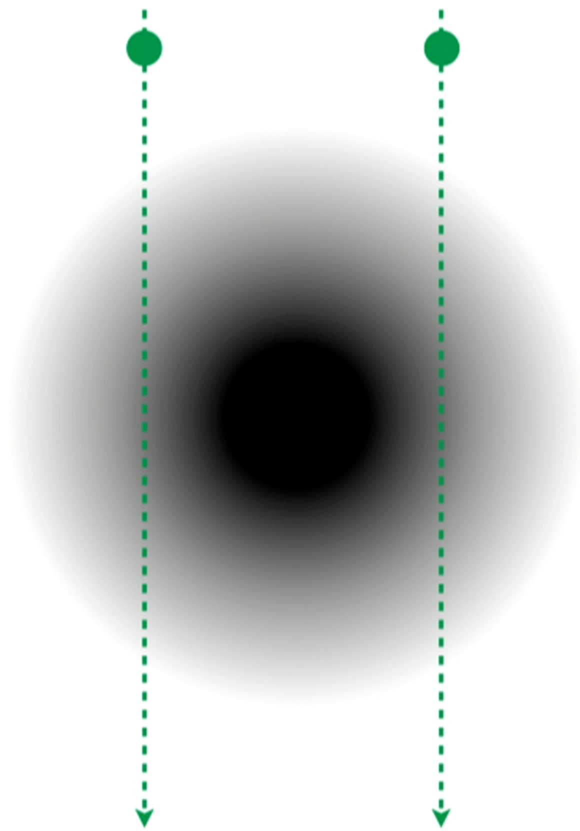
Future with kSZ

- Baryon abundance and size of gas profile
- Rapid increase in signal to noise
    - PFS: 10M gal, 0.8<z<2.4
    - DESI: 20M gal, z<2
    - CMB S4: full sky, 1arcmin, 1μK.arcmin

→ factor of 10 increase!

→ gas profile, binning in mass/type

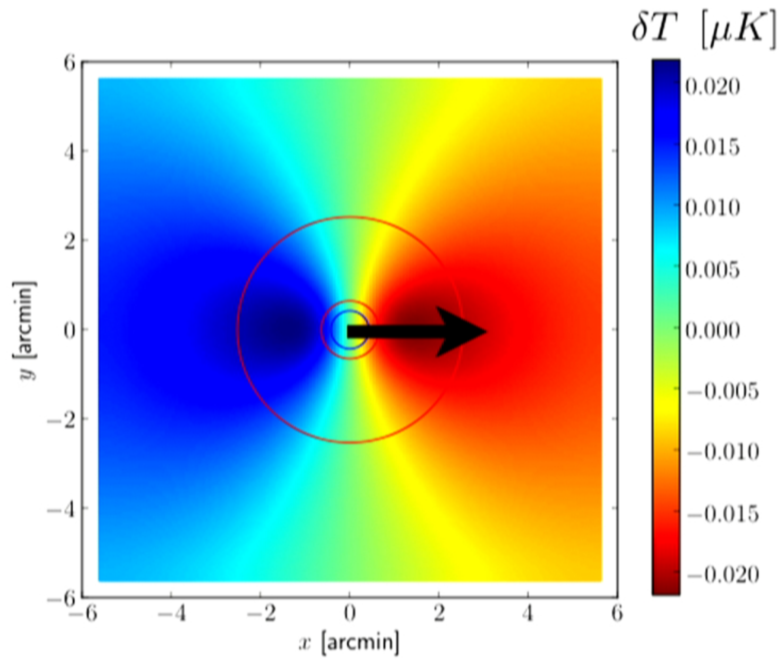
Static potential



Moving lens effect

$$\frac{\delta T}{T} = \frac{1}{c^2}\int dt\, \partial_t \Phi = \frac{\vec{v}_\perp}{c} \cdot \underbrace{\frac{1}{c^2}\int dl\, \vec{\nabla}\Phi}_{\frac{\vec{\alpha}}{(1-\chi_L/\chi_S)}}$$

lensing deflection



NFW halo: M = 10^{13} M_{sun}/h, v = 200km/s, z = 0.6

Possible confusion with cluster lensing (50x larger) and rotating kSZ, but uncorrelated directions.

Conclusion

- kSZ powerful probe of baryons (abundance & distribution)
- Upcoming 10-fold increase in SNR
  → gas profiles, binning in mass/type
- Handle on growth rate & initial conditions
- Moving lens effect soon detectable