Title: Astrophysical and Cosmological consequences of recent and future kSZ measurements

Date: Feb 16, 2016 11:00 AM

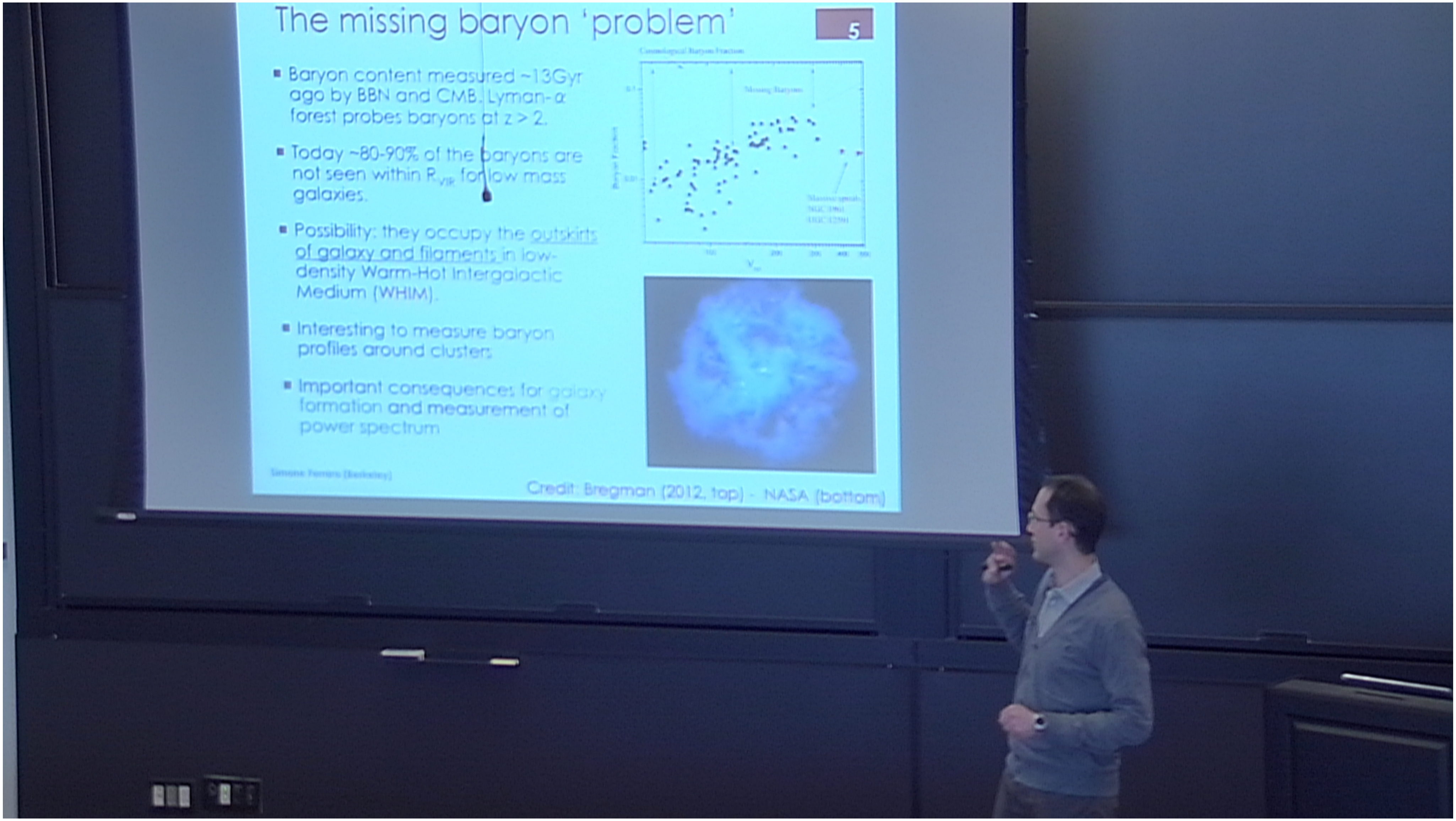
URL: http://pirsa.org/16020089

Abstract: <p>The kinetic Sunyaev-Zel'dovich effect is a direct probe of the distribution and velocity of electrons on cosmological scales. Recent progress in Cosmic Microwave Background observations allow statistical detections of this subtle effect originating from a number of different tracers populations. In my talk, I will review the observational status, highlight the consequences for astrophysics and cosmology and discuss future directions.</p>

Astrophysical and Cosmological consequences of kSZ measurements

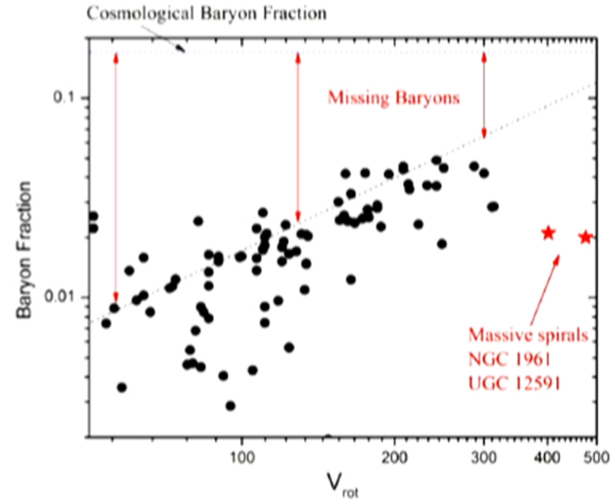
Simone Ferraro
(Miller Fellow, UC Berkeley)

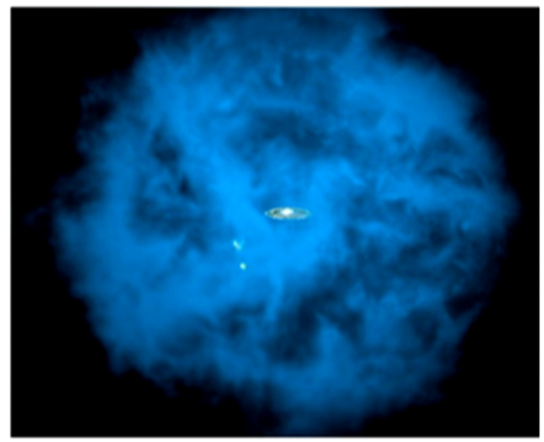
Perimeter Institute
Feb 16, 2016


The missing baryon 'problem'
5
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 for low mass galaxies.
Possibility: they occupy the outskirts of galaxy and filaments in low-density Warm-Hot Intergalactic Medium (WHIM).
Interesting to measure baryon profiles around clusters
Important consequences for galaxy formation and measurement of power spectrum
Credit: Bregman (2012, top) - NASA (bottom)

The missing baryon 'problem'

- 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} for low mass galaxies.
- Possibility: they occupy the outskirts of galaxy and filaments in low-density Warm-Hot Intergalactic Medium (WHIM).
- Interesting to measure baryon profiles around clusters
- Important consequences for galaxy formation and measurement of power spectrum





Simone Ferraro (Berkeley)

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

Cosmic velocities

6

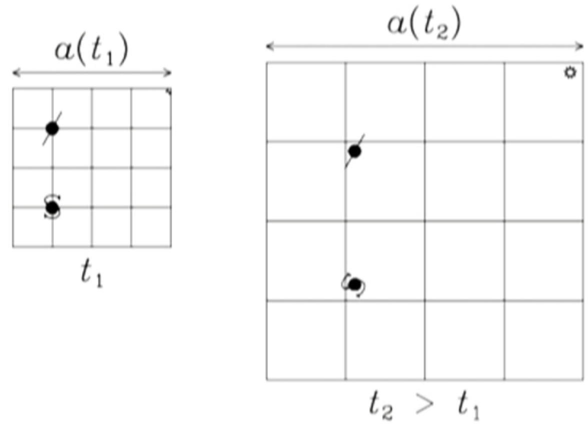
- Peculiar velocity $$\mathbf{v} = \frac{d\mathbf{x}}{d\eta} = \frac{d\mathbf{r}}{dt} - H(t)\mathbf{r}$$

- Related to density (continuity eq):

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

- In linear theory:

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



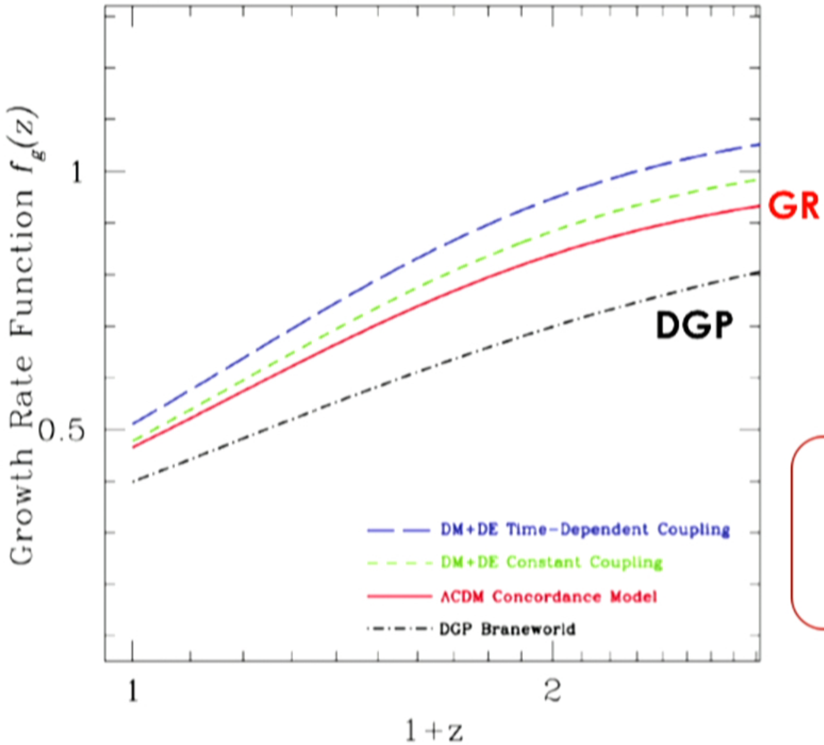
Growth rate $$f_g = \frac{d\ln\delta}{d\ln a} \approx [\Omega_m(z)]^\gamma$$

$\gamma \approx 0.55$ in GR

Linder (2005)

Growth factor as a probe of GR

7



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

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

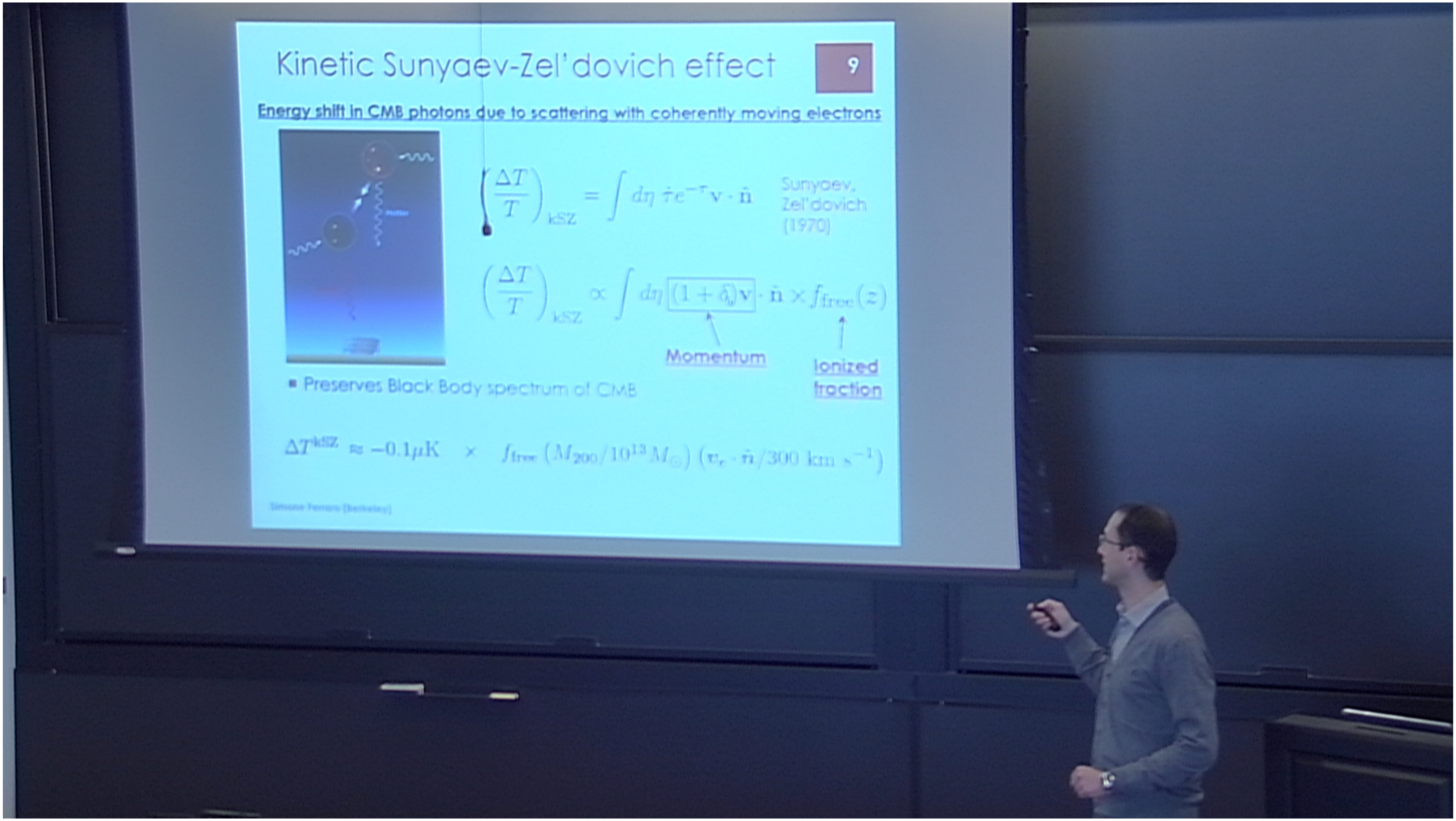
Growth factor:

- sensitive probe of gravity
- Cosmological information

Guzzo et al (2005)

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

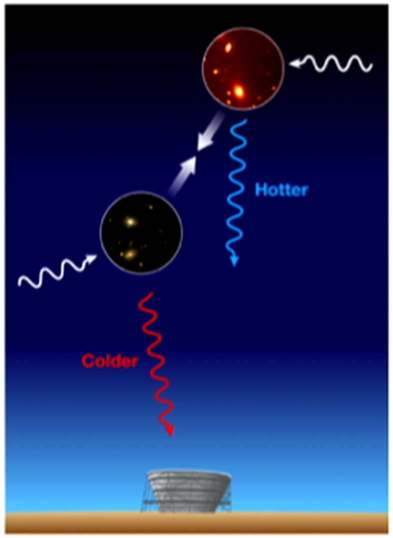
Simone Ferraro (Berkeley)


Kinetic Sunyaev-Zel'dovich effect
9
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)
$\left(\frac{\Delta T}{T}\right)_{\rm kSZ} \propto \int d\eta\, (1+\delta_e)\mathbf{v} \cdot \hat{\mathbf{n}} \times f_{\rm free}(z)$
Momentum
Ionized fraction
Preserves Black Body spectrum of CMB
$\Delta T^{\rm kSZ} \approx -0.1\mu{\rm K} \times f_{\rm free}\,(M_{200}/10^{13} M_\odot)\,(v_r \cdot \hat{n}/300\ {\rm km\ s^{-1}})$

Kinetic Sunyaev-Zel'dovich effect

9

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



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

Sunyaev, Zel'dovich (1970)

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

Momentum — $(1 + \delta_b)\mathbf{v}$

Ionized fraction — $f_{\mathrm{free}}(z)$

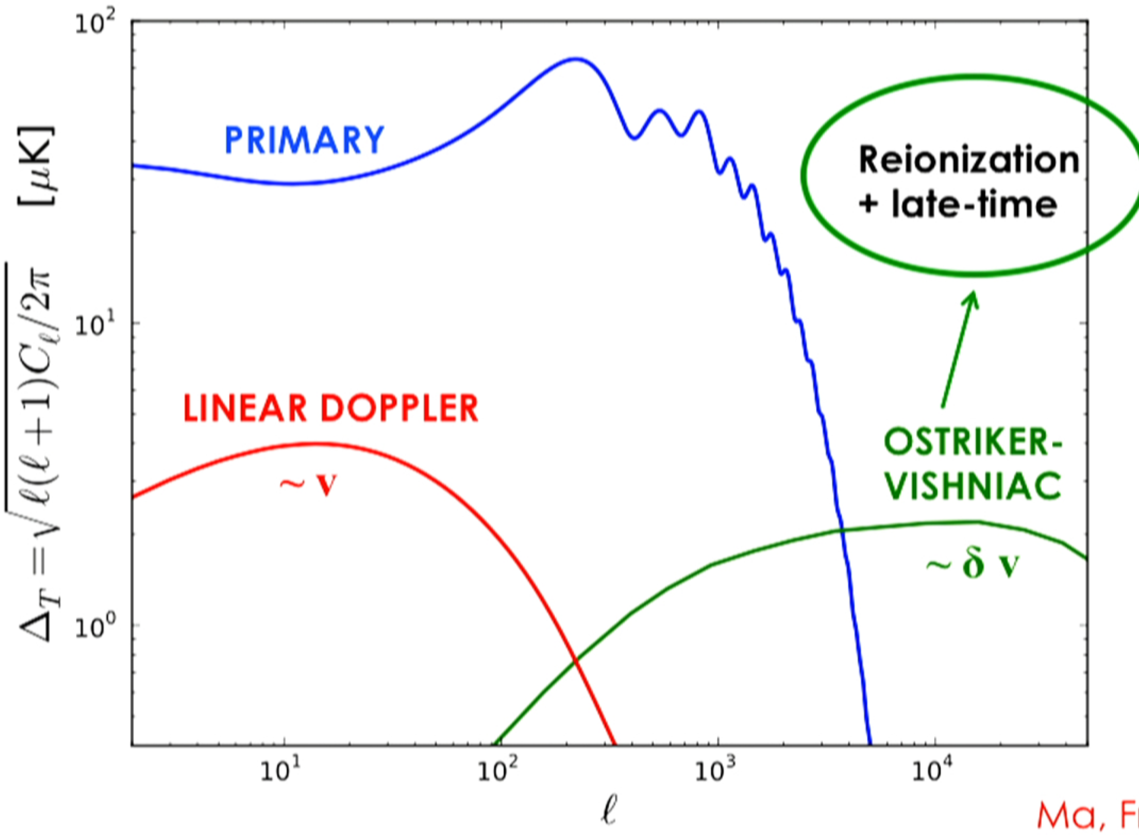
- Preserves Black Body spectrum of CMB

$$\Delta T^{\mathrm{kSZ}} \approx -0.1\mu\mathrm{K} \quad \times \quad f_{\mathrm{free}} \left(M_{200}/10^{13} M_{\odot} \right) \left(\boldsymbol{v}_e \cdot \hat{\boldsymbol{n}} / 300 \ \mathrm{km\ s}^{-1} \right)$$

Simone Ferraro (Berkeley)

The kSZ power spectrum

z < 20 contributions from velocity

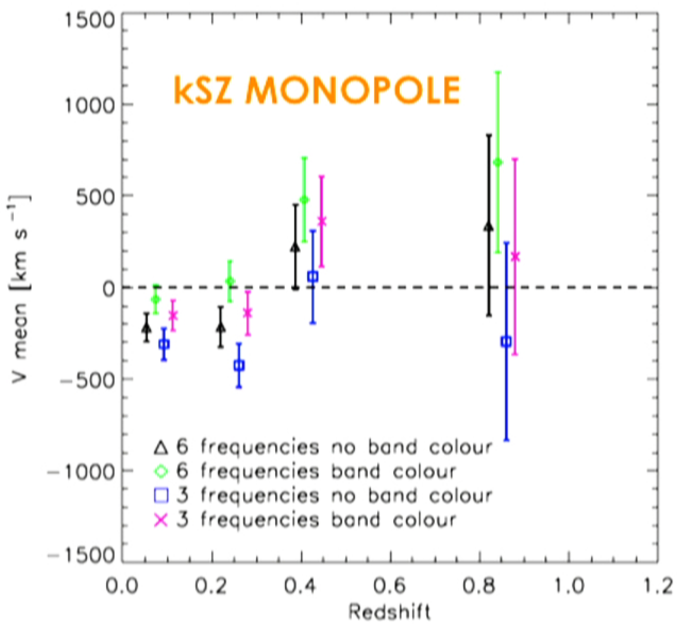


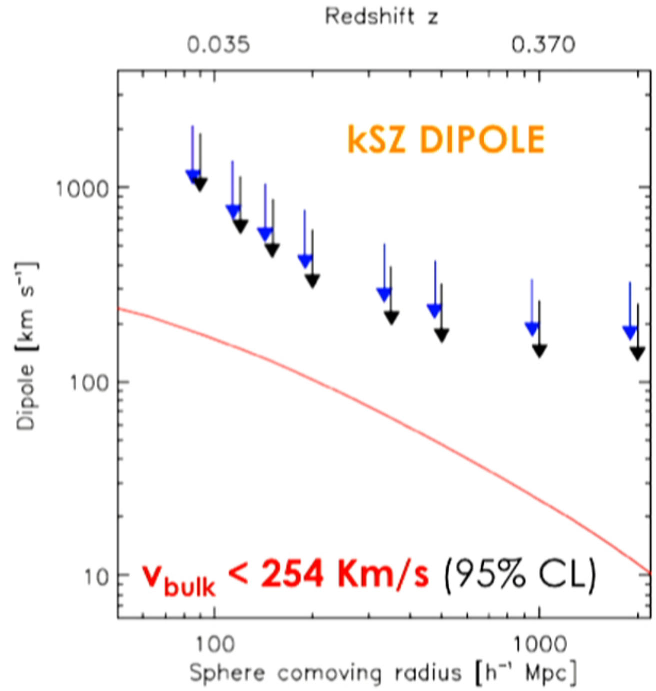
Ma, Fry (2002)
Hu, White (1996)

Simone Ferraro (Berkeley)

Planck Intermediate Results XIII:
Constraints on bulk flows and inhomogeneous universes

12





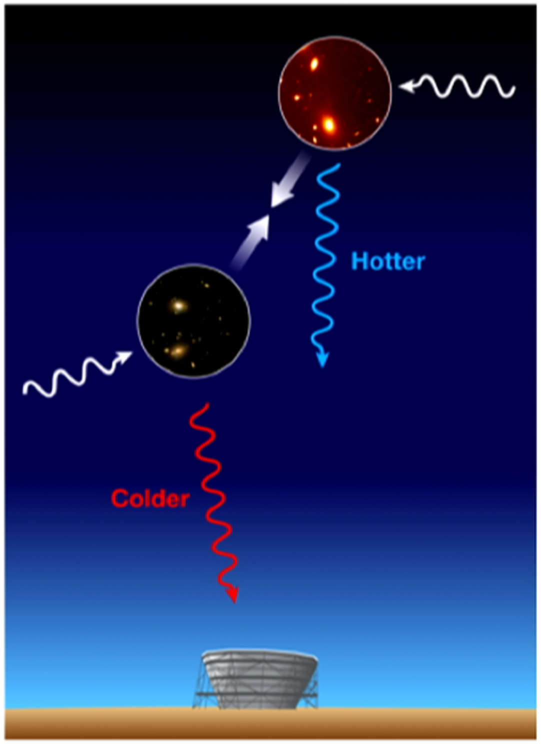
Measure v_r = 72 ±60 Km/s

Need $v_r \sim 10^4$ Km/s for void models

arXiv:1303.5090

Simone Ferraro (Berkeley)

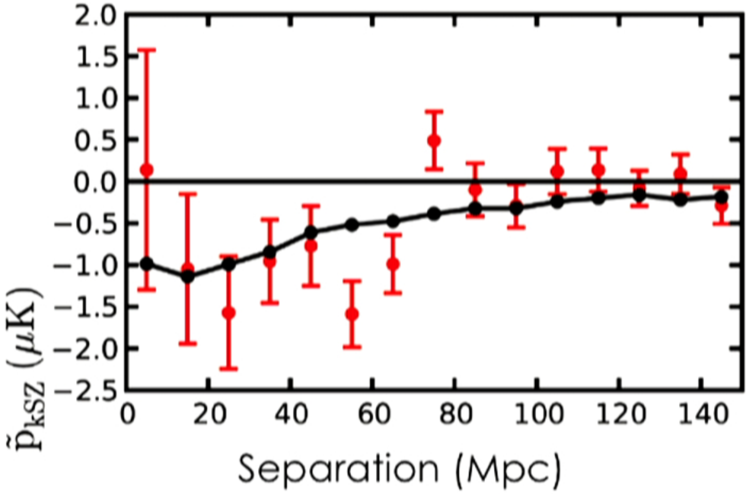
The first detection: galaxy pairs



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

$$\tilde{p}_{\rm pair}(r) = \frac{\sum_{i<j} (\mathbf{p}_i \cdot \hat{\mathbf{r}}_i - \mathbf{p}_j \cdot \hat{\mathbf{r}}_j) c_{ij}}{\sum_{i<j} c_{ij}^2}$$

$$c_{ij} \equiv \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2}$$



Simone Ferraro (Berkeley)

Hand et al (2012)

Direct detection – velocity reconstruction

15

$$T_{\rm CMB} = T_{\rm primary} + T_{\rm kSZ} + T_{\rm noise} + \ldots$$

$\langle T_{\rm CMB}\ \delta_{\rm tr}\rangle \approx 0$ because of $v_r \rightarrow -v_r$

Cubic estimator

$$\mathcal{E} \sim \langle \delta_e\ v_{rec}\ T \rangle$$

$\sim \frac{k_z}{k^2}\delta$ and/or $\frac{T}{\tau}$

Pairwise sum

Ho et al (2008)
Shao et al (2011)
SF, Smith (in prep)

Simone Ferraro (Berkeley)

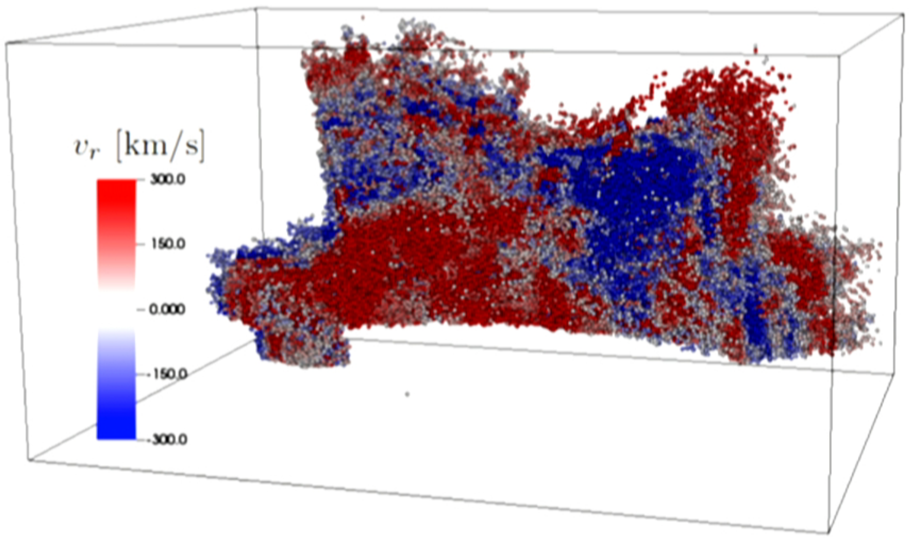
Spectroscopic z regime

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

Build a noisy kSZ template $\hat{T}_{\mathrm{kSZ}} \sim \int d\eta \; (1+\delta)\mathbf{v}_{\mathrm{rec}} \cdot \hat{n}$

Compute $\langle T_{\mathrm{CMB}} \; \hat{T}_{\mathrm{kSZ}} \rangle$

BONUS:
Foreground contamination highly suppressed!

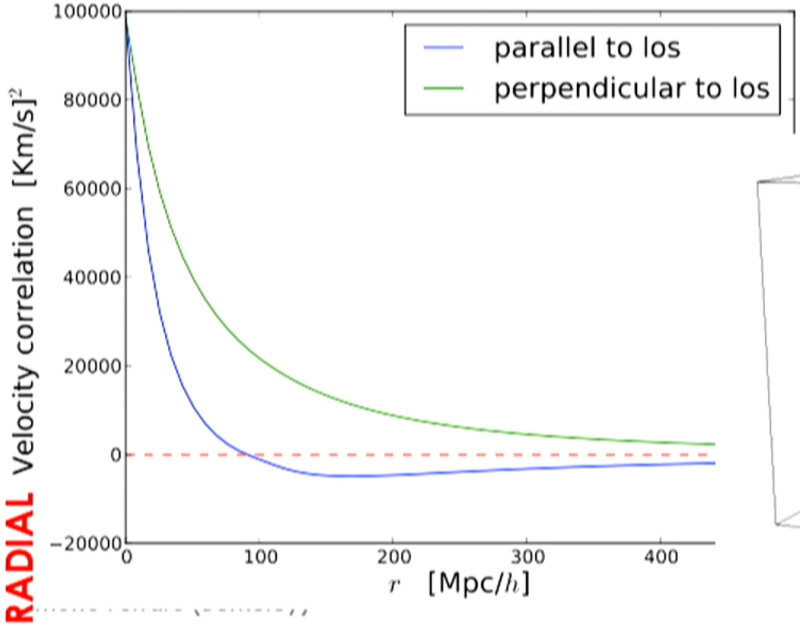


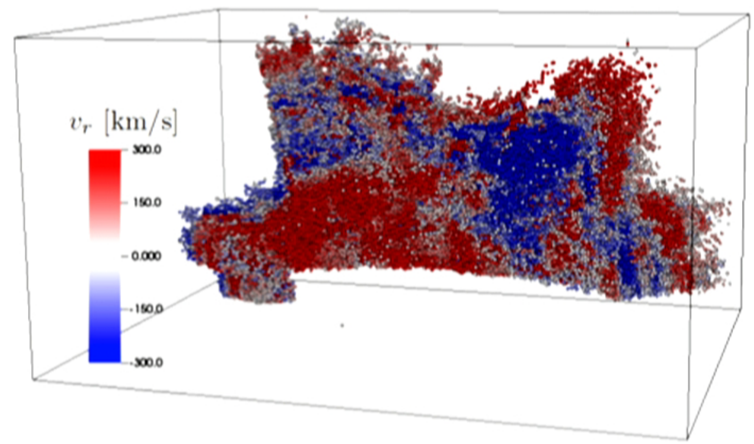
Simone Ferraro (Berkeley)

Spectroscopic z regime

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

$$\langle v_{\hat{n}}(0) v_{\hat{n}}(\mathbf{r})\rangle = \psi_0(r) + \psi_2(r)\left(\frac{3}{2}(\hat{n}\cdot\hat{r})^2 - \frac{1}{2}\right)$$





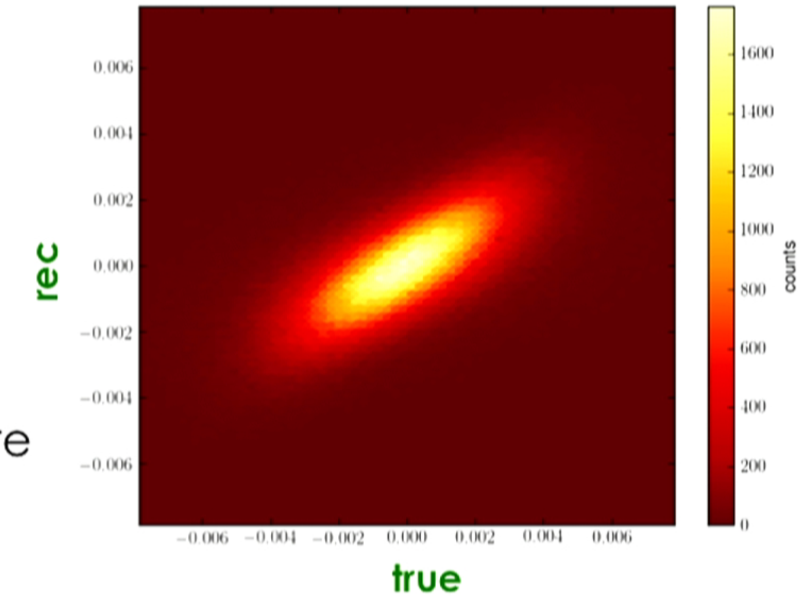

Correlation coefficient
19
We use 2 different reconstruction methods
Correlation coefficient between true and reconstructed
r ~ 0.7
Note that rec velocities are biased low (because of Wiener filter) such that
$r \frac{\sigma_{\rm true}}{\sigma_{\rm rec}} = 1$
rec
true
CMASS SOUTH mocks
Simone Ferraro (Berkeley)
credit: Kendrick Smith

Correlation coefficient

We use 2 different reconstruction methods

Correlation coefficient between true and reconstructed

r ~ 0.7



CMASS SOUTH mocks

Note that rec velocities are biased low (because of Wiener filter) such that

$$r \; \frac{\sigma_{\rm true}}{\sigma_{\rm rec}} = 1$$

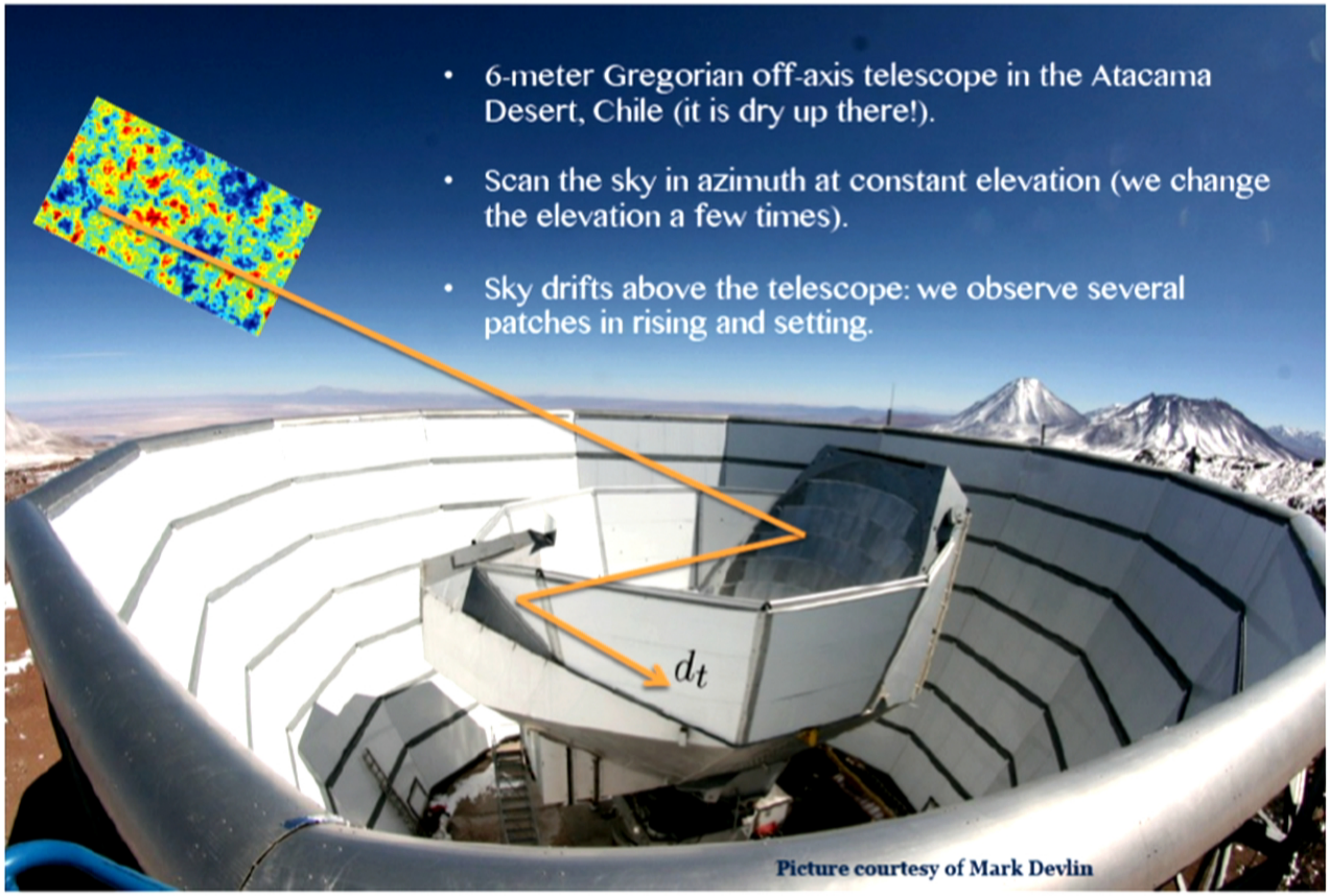
Simone Ferraro (Berkeley)

credit: Kendrick Smith

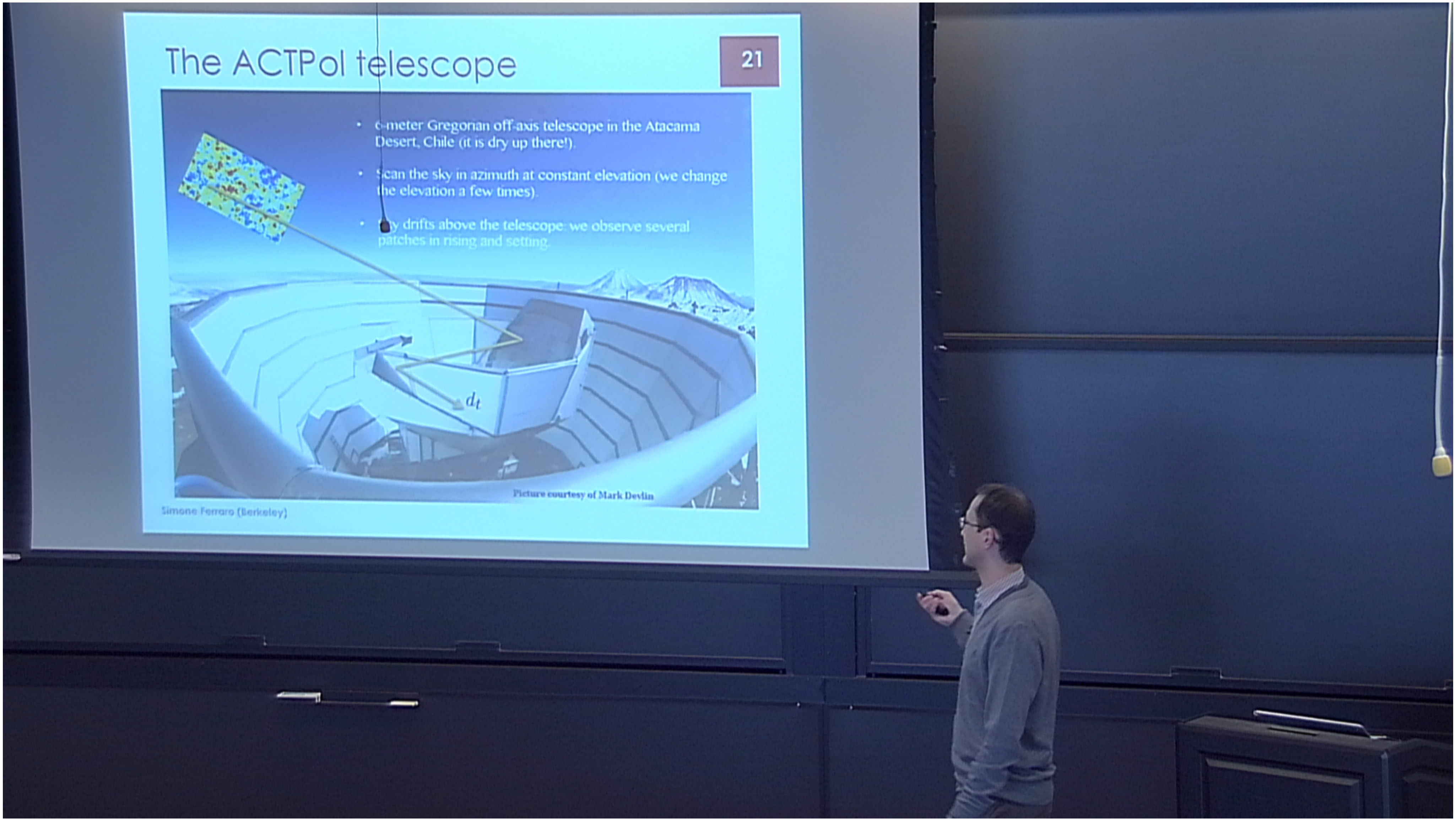
Forecasts for 'Optimal' analysis

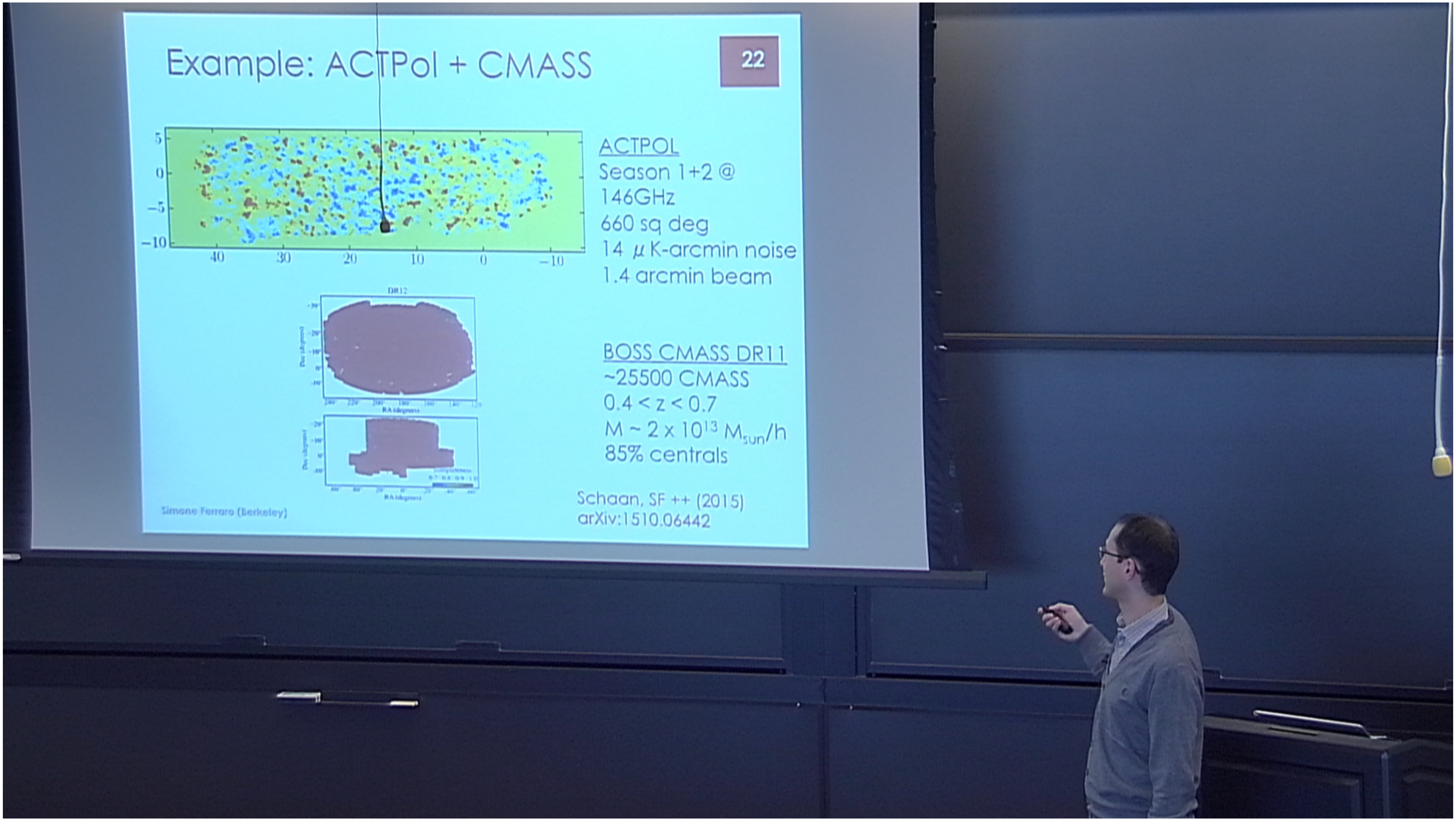
- Planck + 24000 clusters: S/N ~ 7.7 on SDSS footprint (Li et al, 2014)
- ACTPol/SPTPol + BOSS Galaxies: S/N ~ 6 for a 500 sq deg patch (about 30000 galaxies)
- ACTPol + MaxBCG: S/N ~ 5 on every 500 sq deg patch
- Dependent on assumption about gas profile/ distribution

The ACTPol telescope

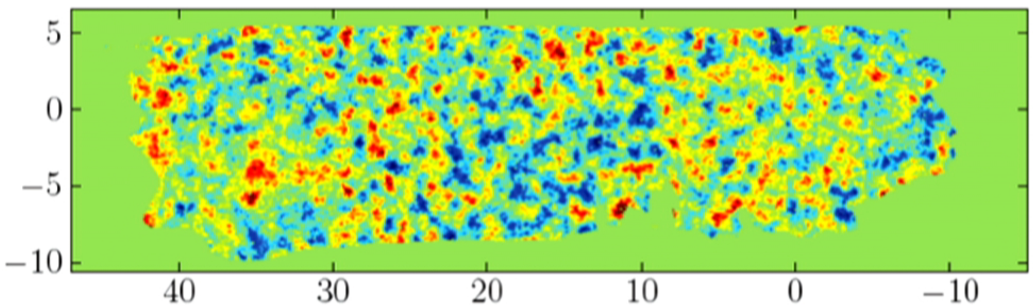


Simone Ferraro (Berkeley)

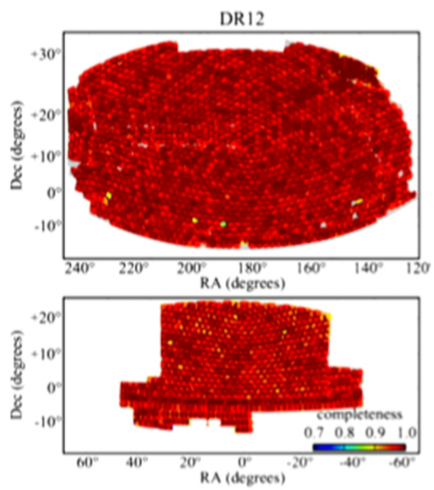

The ACTPol telescope
21
-meter Gregorian off-axis telescope in the Atacama Desert, Chile (it is dry up there!).
can the sky in azimuth at constant elevation (we change
he elevation a few times).
y drifts above the telescope: we observe several patches in rising and setting.
d_t
Picture courtesy of Mark Devlin
Simone Ferraro (Berkeley)


Example: ACTPol + CMASS
22
ACTPOL
Season 1+2 @
146GHz
660 sq deg
14 μK-arcmin noise
1.4 arcmin beam
BOSS CMASS DR11
~25500 CMASS
0.4 < z < 0.7
M ~ 2 x 10^13 M_sun/h
85% centrals
Schaan, SF ++ (2015)
arXiv:1510.06442
Simone Ferraro (Berkeley)

Example: ACTPol + CMASS



ACTPOL
Season 1+2 @
146GHz
660 sq deg
14 μK-arcmin noise
1.4 arcmin beam

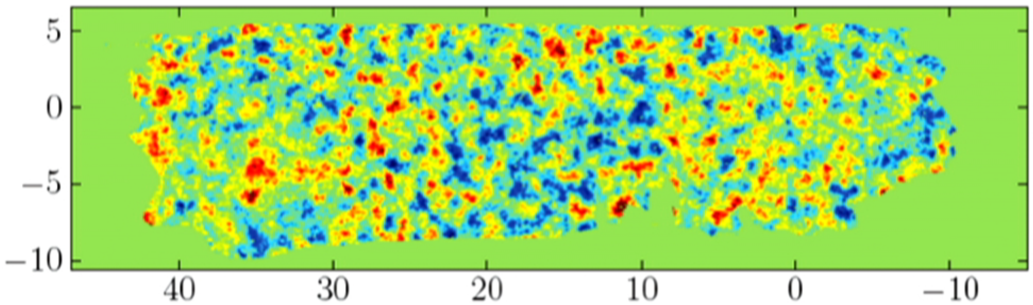


BOSS CMASS DR11
~25500 CMASS
$0.4 < z < 0.7$
$M \sim 2 \times 10^{13}\ M_{sun}/h$
85% centrals

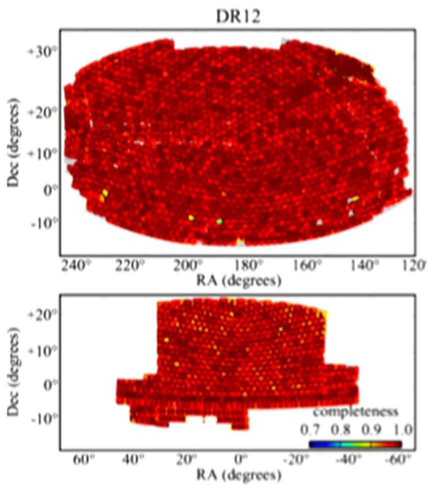
Schaan, SF ++ (2015)
arXiv:1510.06442

Simone Ferraro (Berkeley)

Example: ACTPol + CMASS



ACTPOL
Season 1+2 @
146GHz
660 sq deg
14 μK-arcmin noise
1.4 arcmin beam

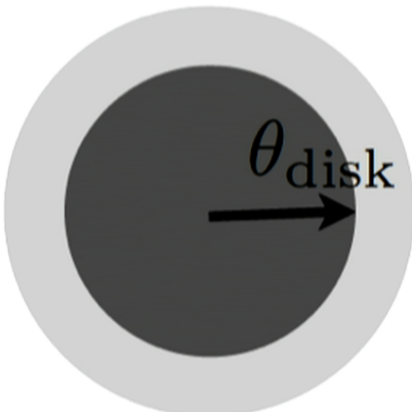


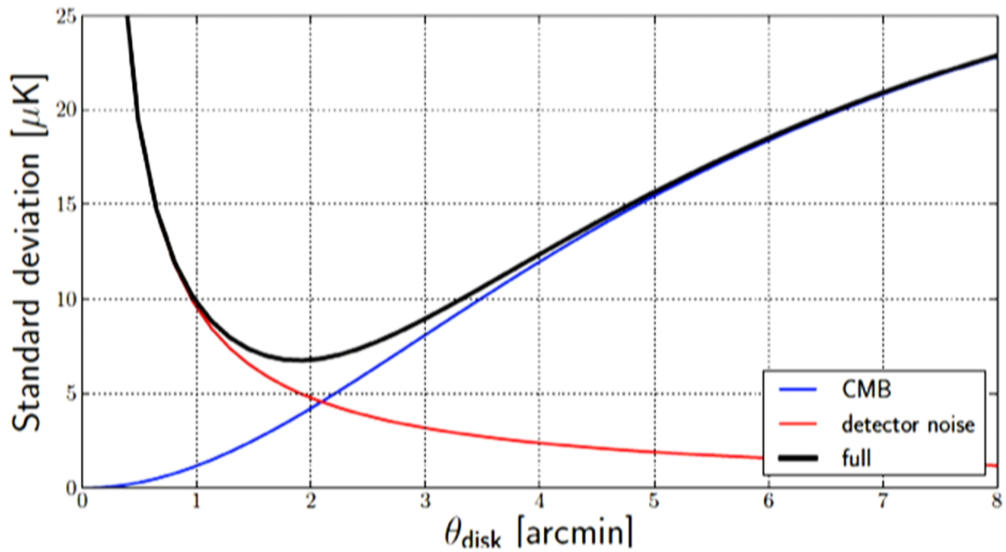
BOSS CMASS DR11
~25500 CMASS
$0.4 < z < 0.7$
$M \sim 2 \times 10^{13} M_{sun}/h$
85% centrals

Schaan, SF ++ (2015)
arXiv:1510.06442

Simone Ferraro (Berkeley)

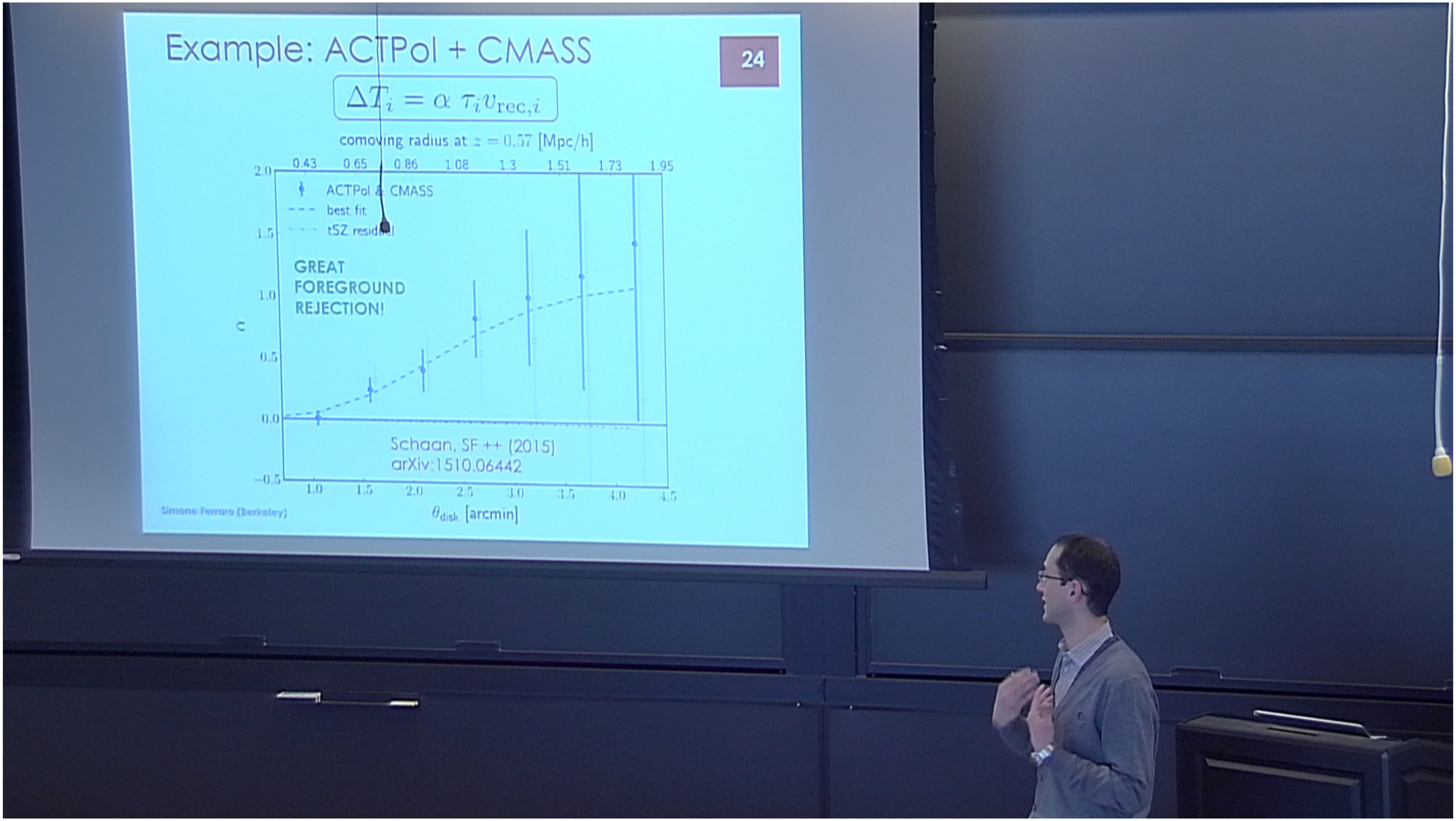
Aperture photometry





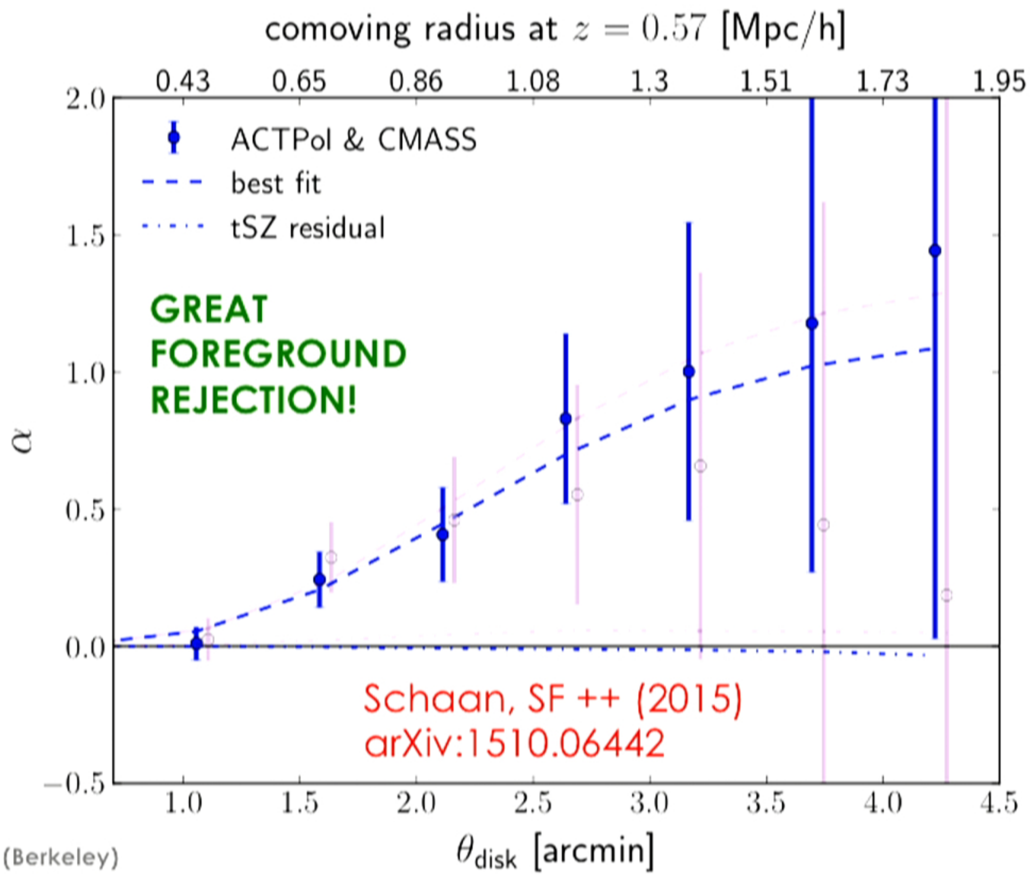
$$\Delta T = \bar{T}_{\rm disk} - \bar{T}_{\rm ring}$$

Simone Ferraro (Berkeley)


Example: ACTPol + CMASS
24
$\Delta T_i = \alpha\ \tau_i v_{\mathrm{rec},i}$
comoving radius at $z = 0.57$ [Mpc/h]
ACTPol & CMASS
best fit
tSZ residual
GREAT
FOREGROUND
REJECTION!
Schaan, SF ++ (2015)
arXiv:1510.06442
θ_{disk} [arcmin]
Simone Ferraro (Berkeley)

Example: ACTPol + CMASS

$$\Delta T_i = \alpha \ \tau_i v_{\mathrm{rec},i}$$



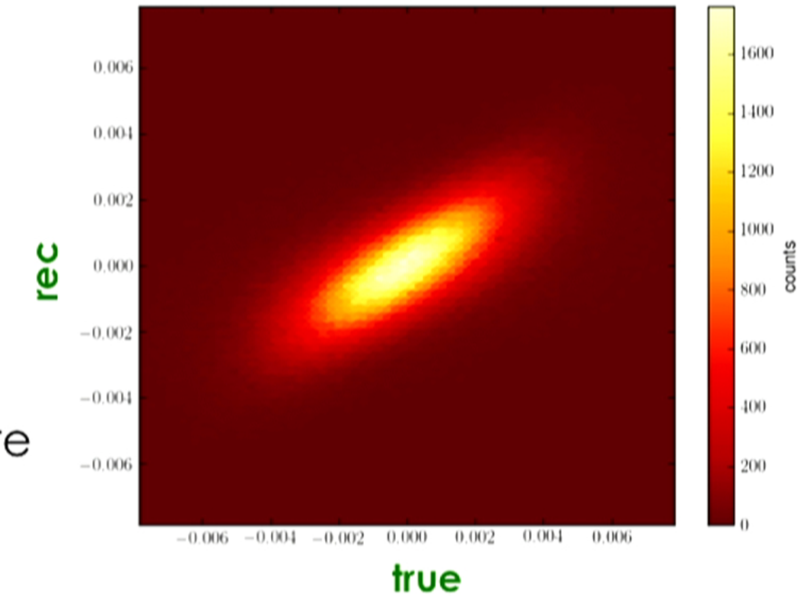
Simone Ferraro (Berkeley)

Correlation coefficient

We use 2 different reconstruction methods

Correlation coefficient between true and reconstructed

r ~ 0.7



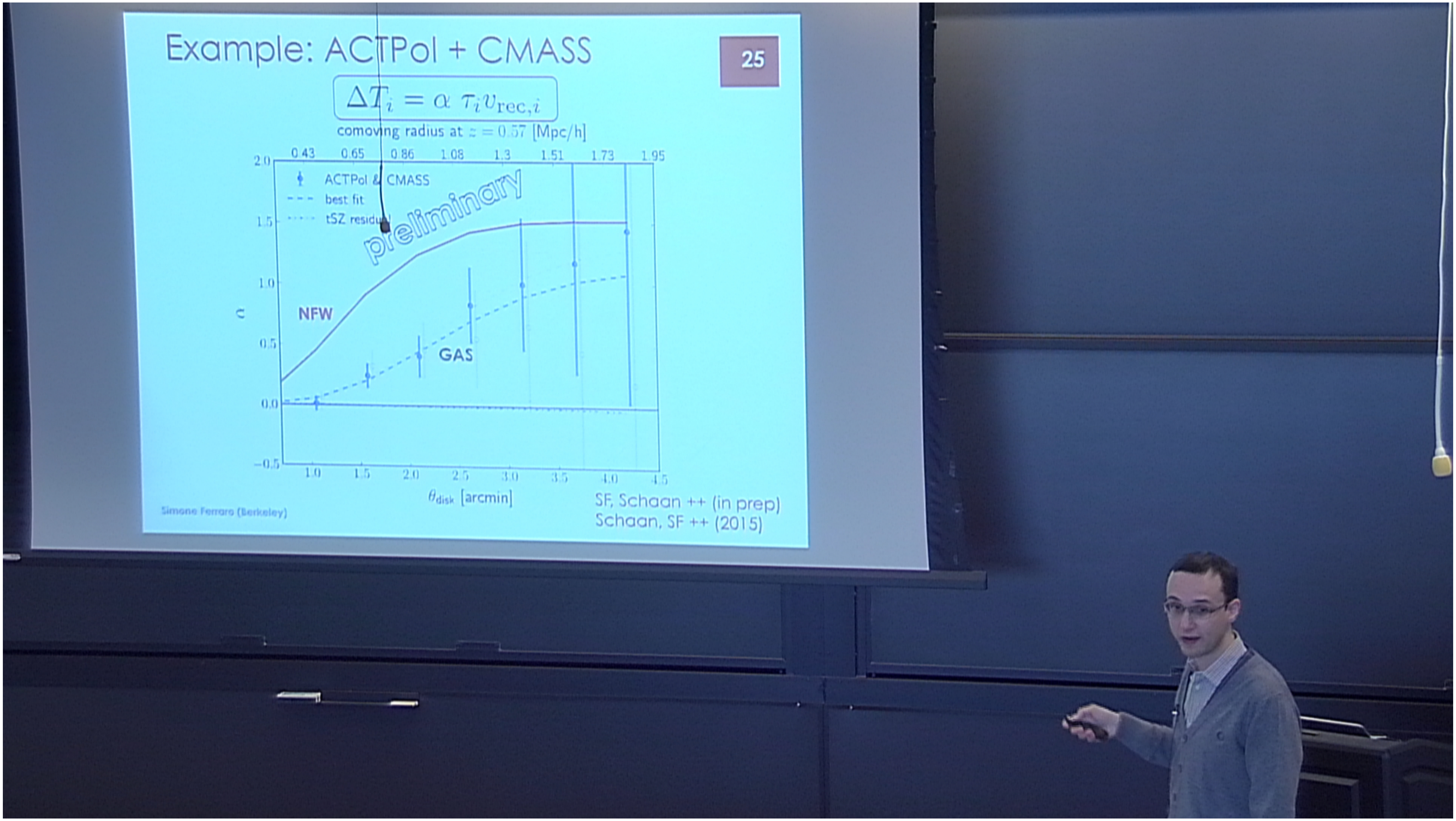
CMASS SOUTH mocks

Note that rec velocities are biased low (because of Wiener filter) such that

$$r \; \frac{\sigma_{\rm true}}{\sigma_{\rm rec}} = 1$$

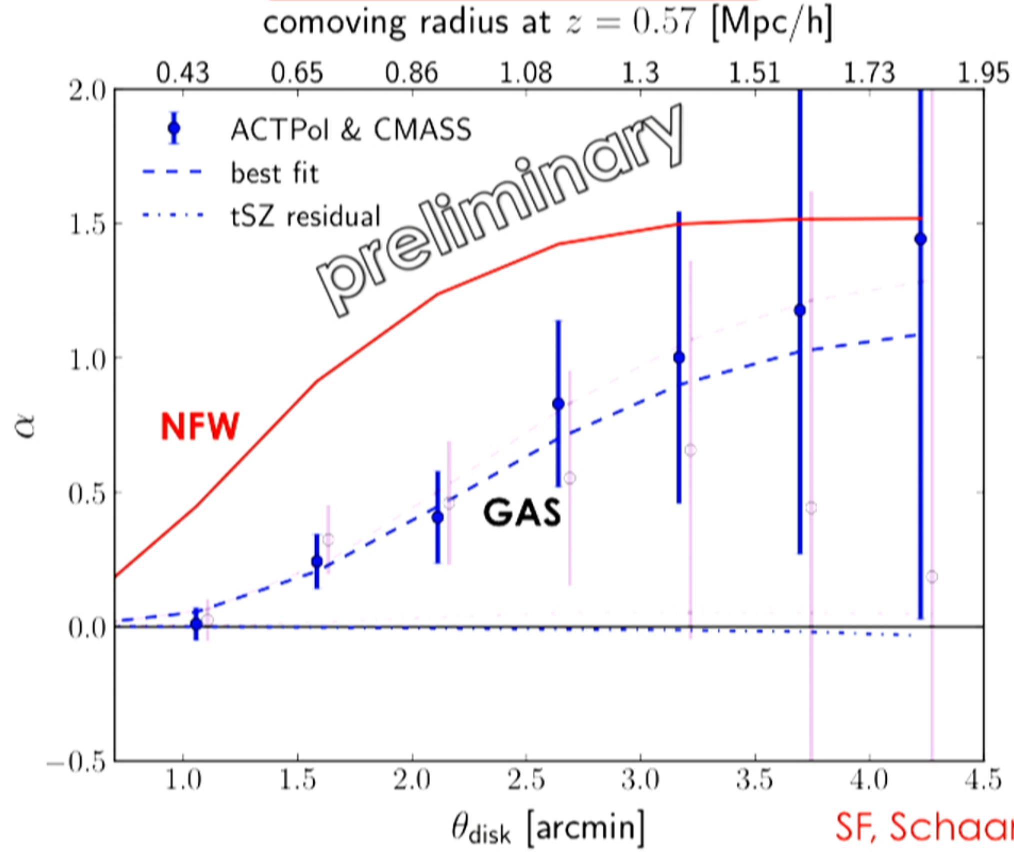
Simone Ferraro (Berkeley)

credit: Kendrick Smith


Example: ACTPol + CMASS
25
$\Delta T_i = \alpha \; \tau_i v_{\mathrm{rec},i}$
comoving radius at $z = 0.57$ [Mpc/h]
ACTPol & CMASS
best fit
tSZ residual
preliminary
NFW
GAS
α
θ_{disk} [arcmin]
Simone Ferraro (Berkeley)
SF, Schaan ++ (in prep)
Schaan, SF ++ (2015)

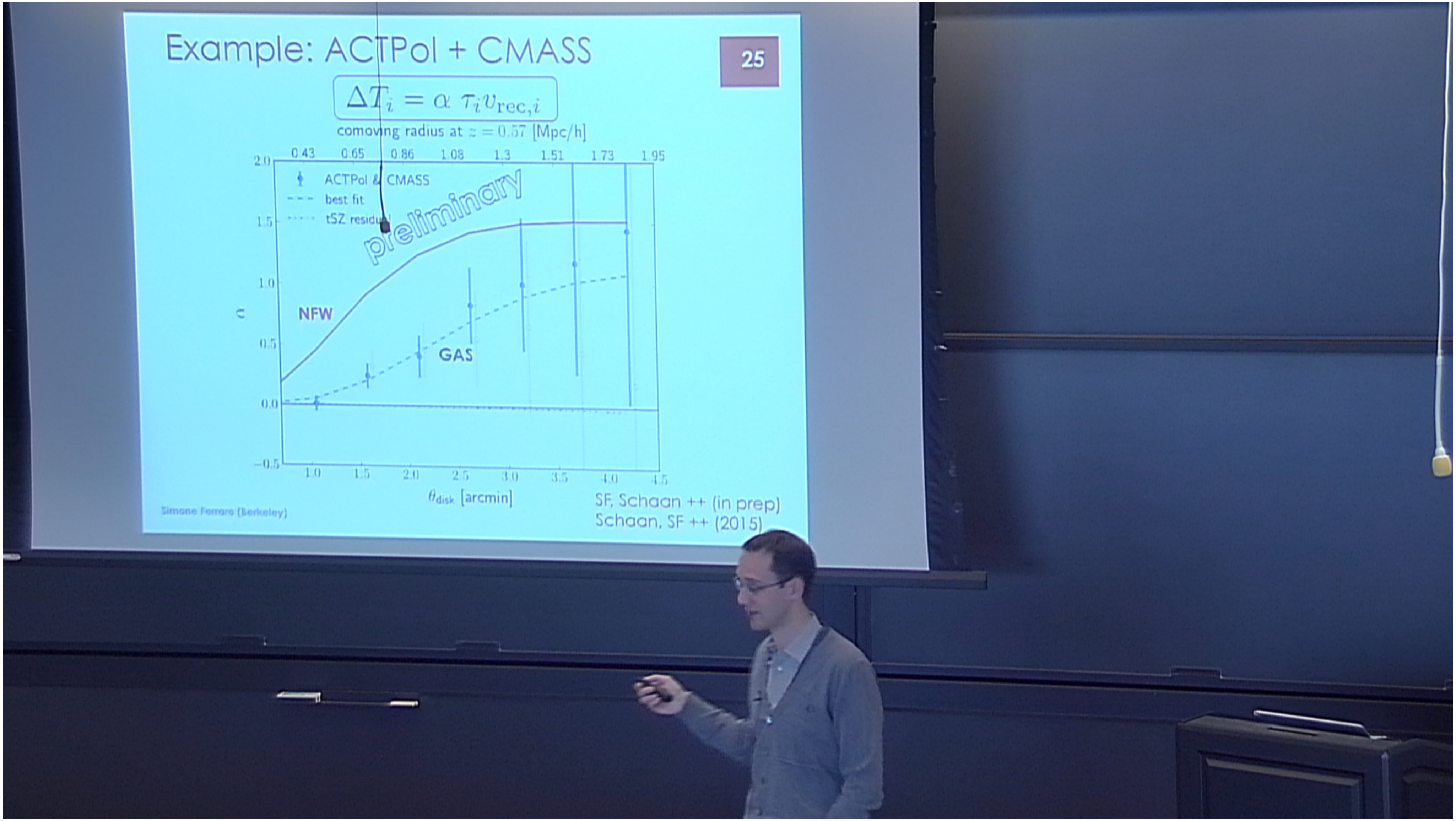
Example: ACTPol + CMASS

$$\Delta T_i = \alpha \; \tau_i v_{\mathrm{rec},i}$$

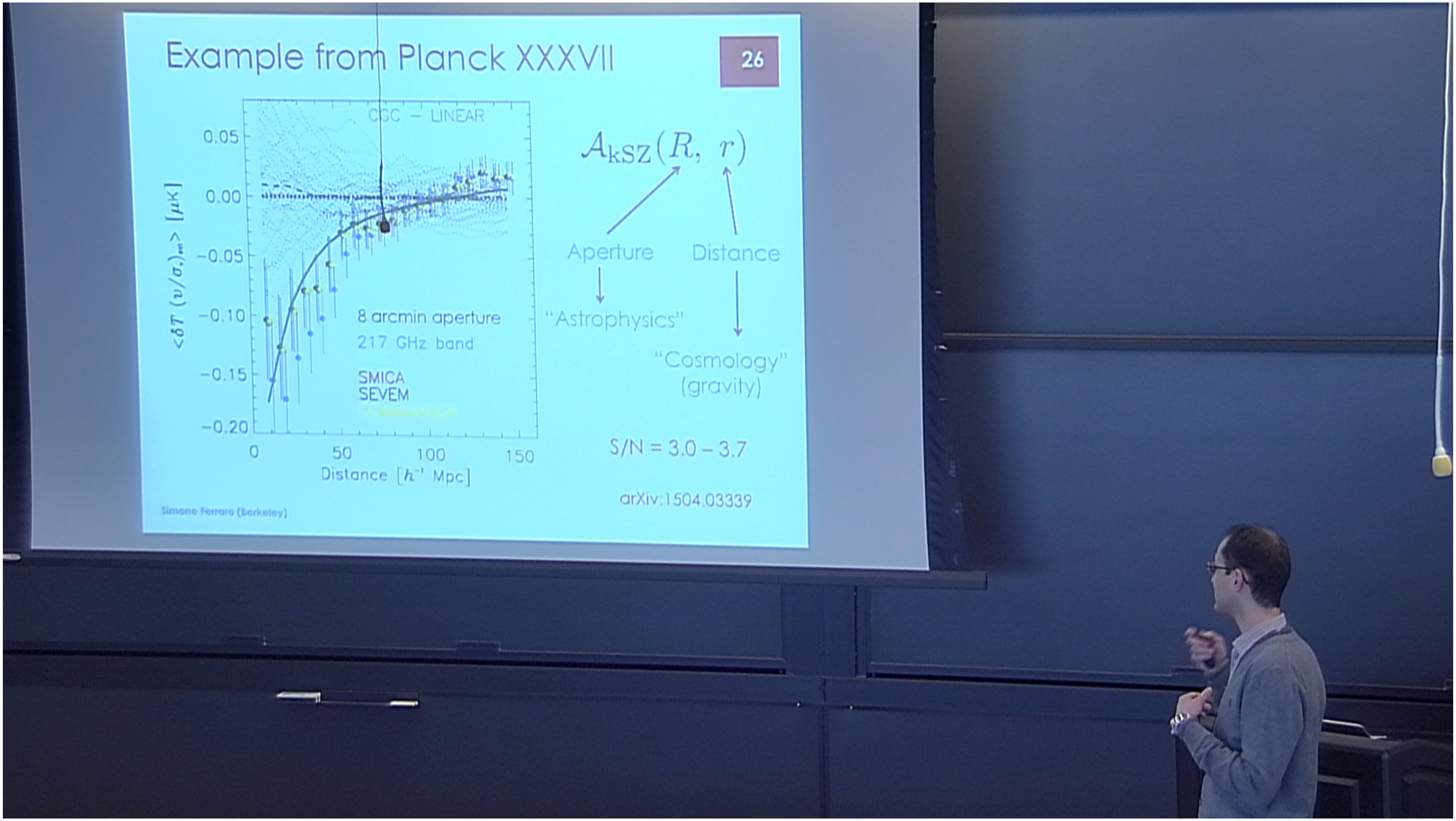


SF, Schaan ++ (in prep)
Schaan, SF ++ (2015)

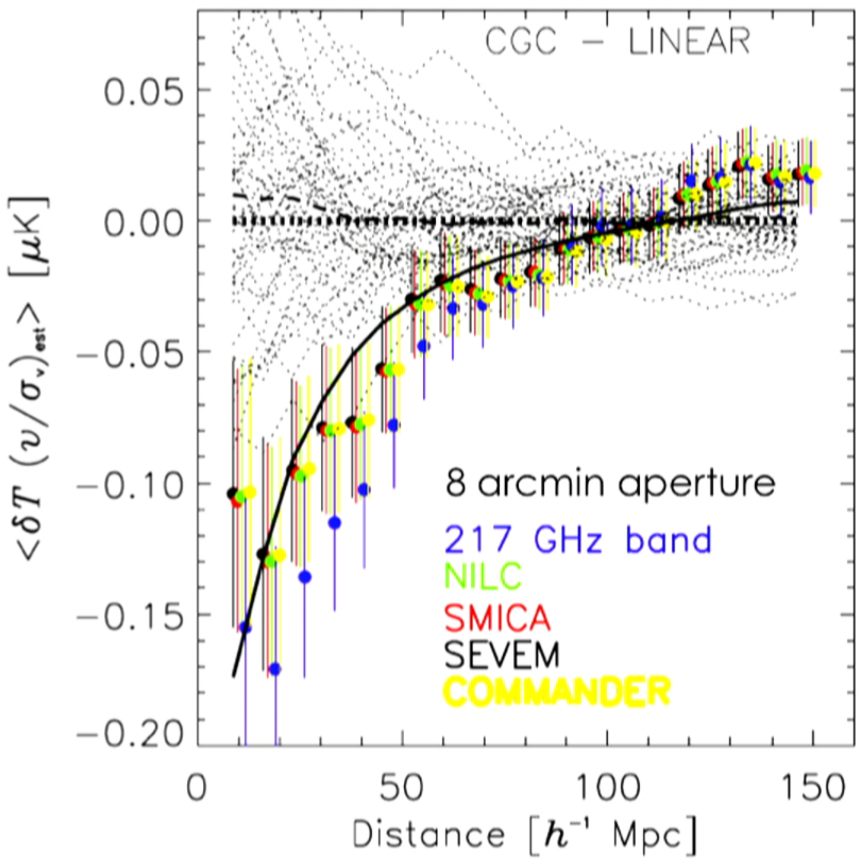
Simone Ferraro (Berkeley)



Example: ACTPol + CMASS
25
$\Delta T_i = \alpha \; \tau_i v_{\mathrm{rec},i}$
comoving radius at $z = 0.57$ [Mpc/h]
0.43
0.65
0.86
1.08
1.3
1.51
1.73
1.95
ACTPol & CMASS
best fit
tSZ residual
preliminary
NFW
GAS
α
$\theta_{\rm disk}$ [arcmin]
SF, Schaan ++ (in prep)
Schaan, SF ++ (2015)
Simone Ferraro (Berkeley)


Example from Planck XXXVII
26
CGC – LINEAR
0.05
0.00
−0.05
−0.10
−0.15
−0.20
0
50
100
150
Distance [h^{-1} Mpc]
<δT (v/σ_v)_m> [μK]
8 arcmin aperture
217 GHz band
SMICA
SEVEM
$\mathcal{A}_{\rm kSZ}(R,\ r)$
Aperture
Distance
"Astrophysics"
"Cosmology" (gravity)
S/N = 3.0 – 3.7
arXiv:1504.03339
Simone Ferraro (Berkeley)

Example from Planck XXXVII



$$\mathcal{A}_{\rm kSZ}(R,\ r)$$

Aperture → "Astrophysics"

Distance → "Cosmology" (gravity)

S/N = 3.0 – 3.7

arXiv:1504.03339

Simone Ferraro (Berkeley)

Measuring f_{free} – possible systematics

27

- Cluster miscentering and satellite galaxies
- tSZ contamination: mass cut and correction
- scatter in mass / error in mass
- cluster overlap (importance of the 2-halo term)
- velocity reconstruction

A different way (absent or poor redshifts)

$$T_{\rm CMB} = T_{\rm primary} + T_{\rm kSZ} + T_{\rm noise} + \ldots$$

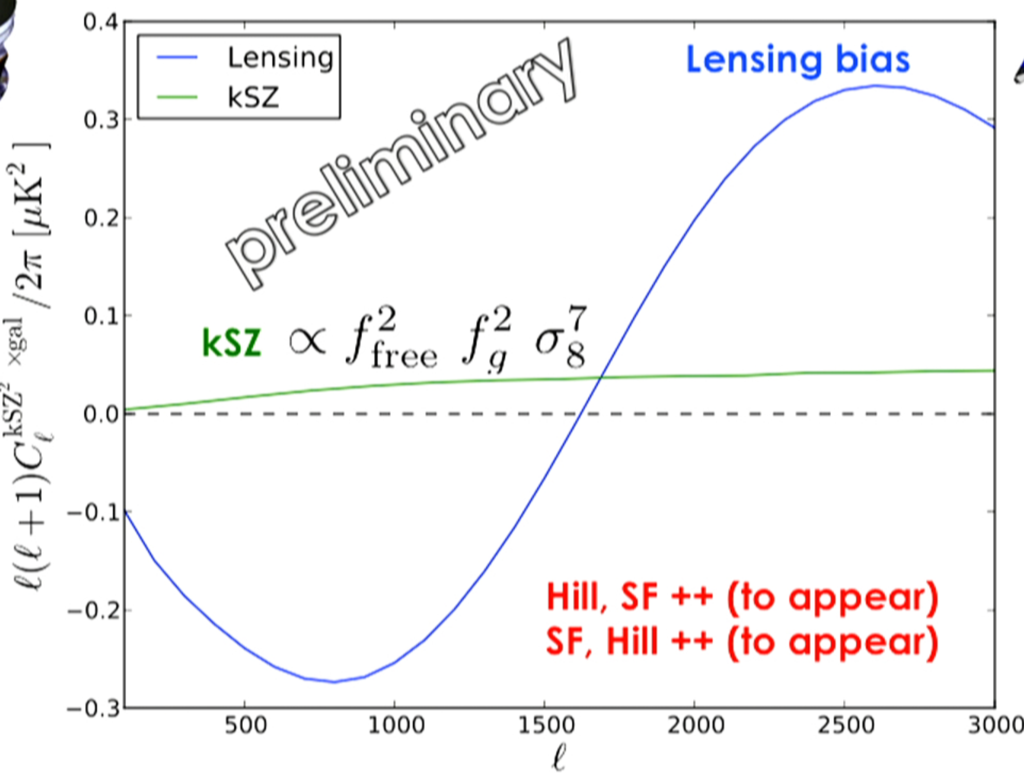
$\langle T_{\rm CMB}\ \delta_{\rm tr}\rangle \approx 0$ because of $v_r \to -v_r$

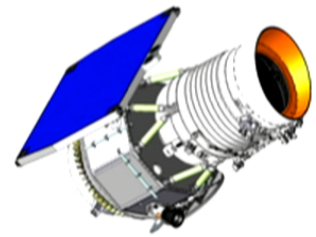
But... $\langle T^2_{\rm CMB}(\mathbf{x})\ \delta_{\rm tr}(\mathbf{y})\rangle \neq 0$

Doré et al (2003)
DeDeo et al (2005)
Hill, Ferraro et al (to appear)

Example: Planck x WISE

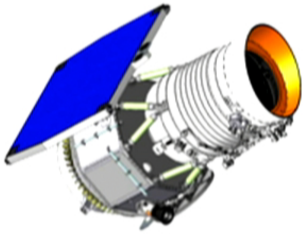
31

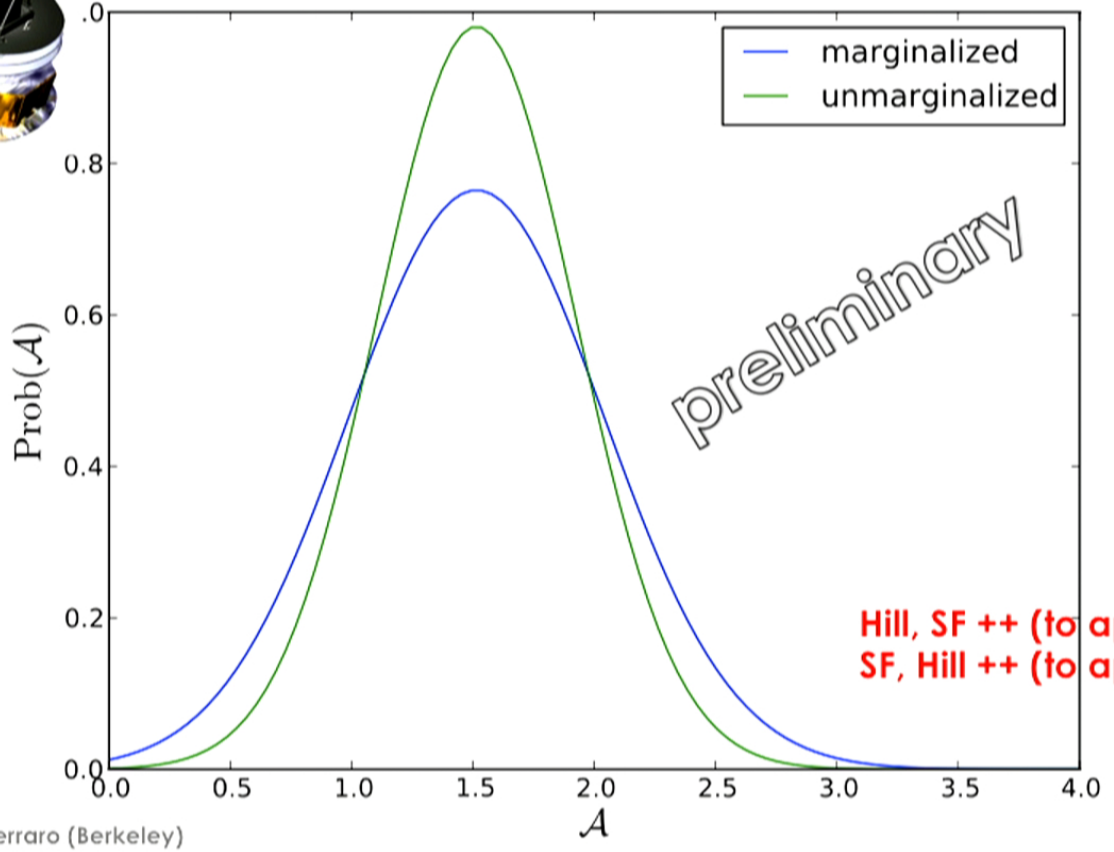




Simone Ferraro (Berkeley)

Example: Planck x WISE





Hill, SF ++ (to appear)
SF, Hill ++ (to appear)

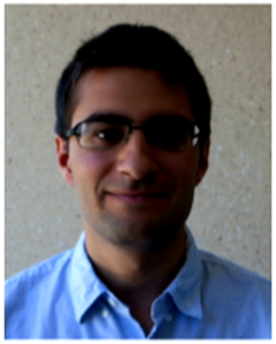
Simone Ferraro (Berkeley)

Conclusions

- Kinetic Sunyaev-Zel'dovich effect measures the abundance and distribution of free electrons.
- Independent probe of growth of perturbation/initial conditions
- Can use as a probe of reionization
- Great improvement over the near future:
  - High resolution CMB on large areas of sky
  - PFS (~10M gal, 1400 sq deg, $0.8 < z < 2.4$)
  - DESI (20M gal, 14000 sq deg, $z < 2$)
  - Spherex? (300M gal, full sky, $z < 1.5$)

Simone Ferraro (Berkeley)

My collaborators



EMMANUEL SCHAAN

KENDRICK SMITH

DAVID SPERGEL

COLIN HILL

THE ACTPol TEAM

Thank you!

AND MANY OTHERS!