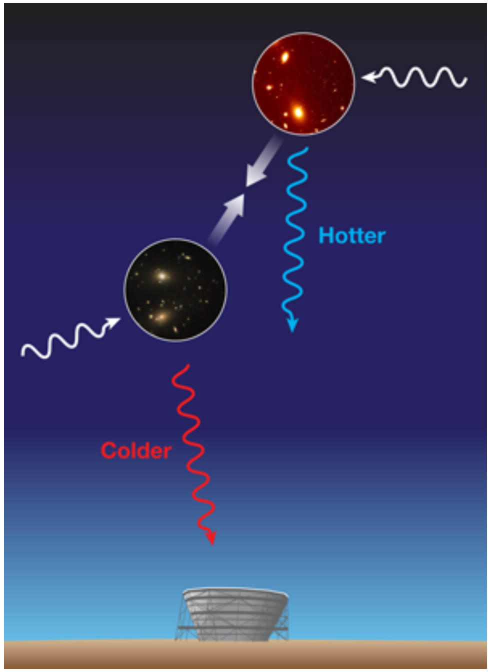
kSZ Cosmology and Astrophysics with Future Surveys

Simone Ferraro
(Miller Fellow, UC Berkeley)

CMB S4 Meeting
09/21/2016

Kinematic 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)

$$\approx -\tau_{\rm cluster}\ v_r$$

Preserves Black Body spectrum of CMB!

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

Fraction of free electrons

Large scale velocity

$$\mathbf{v} \approx f_g \left(aH \frac{i\mathbf{k}}{k^2} \right) \delta$$

Growth rate

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

$$\gamma = 0.55 \; + \; 0.05(1 + w)$$

Linder (2005)

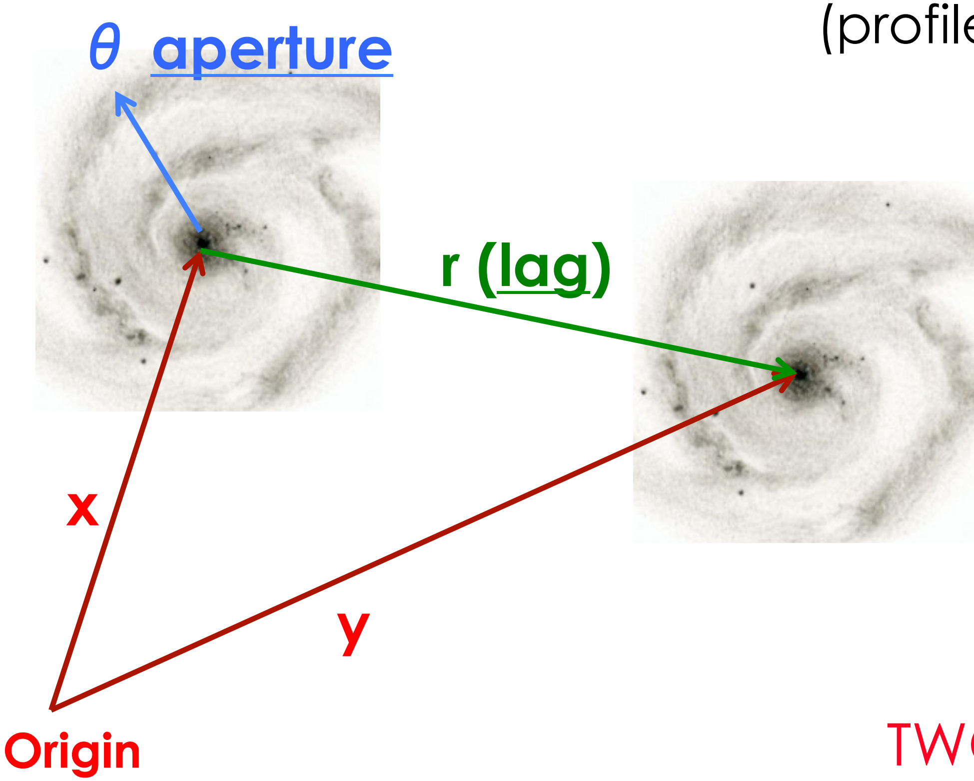
GR/Modified gravity

Dark Energy

What do we measure?

$$\left(\frac{\Delta T}{T}\right)_{\mathrm{kSZ}}(\mathbf{x}+\boldsymbol{\theta}) = -\underbrace{\tau(\boldsymbol{\theta})}_{\text{optical depth (profile)}}\ \underbrace{v_r(\mathbf{x})}_{\text{`bulk' radial velocity}}$$

(+ 2-halo)



- Vary **r** at fixed $\boldsymbol{\theta}$ → velocity field on large scales
- Vary $\boldsymbol{\theta}$ at fixed **x** → gas profile and abundance.

TWO different measurements!

Large scale velocity

$$\xi_{Tv} = \left\langle \frac{\Delta T}{T}(\mathbf{x}) \;\; v_r^{\rm rec}(\mathbf{y}) \right\rangle = -\bar{\tau} \; \underbrace{\langle v_r^{\rm true}(\mathbf{x}) \;\; v_r^{\rm rec}(\mathbf{y}) \rangle}_{\text{Velocity correlation}}$$

"reconstructed" velocity from δ_{3D} + continuity eq

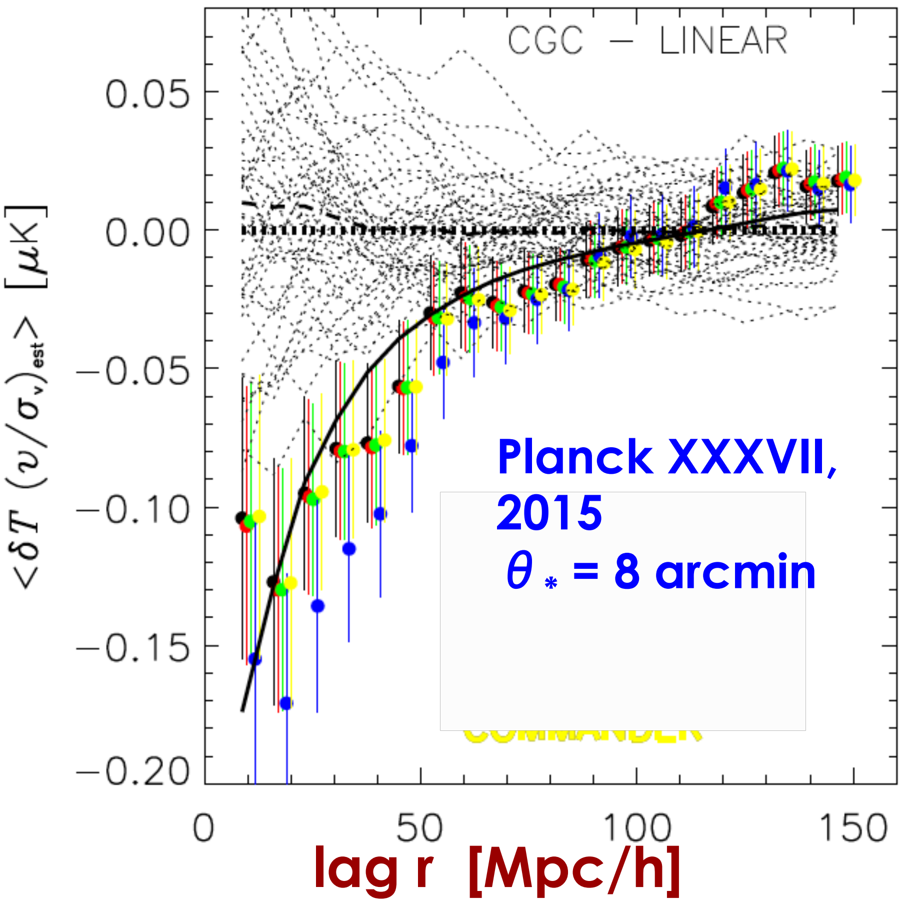
This is $\xi_{Tv}(r) \propto \;\bar{\tau} \; \left(\frac{f_g^{\rm true}}{f_g^{\rm fid}} \right) \; \xi_v^{\rm fid}(r) \propto \underline{\bar{\tau} \;\, f_g^{\rm true} \sigma_8}$

- Amplitude degenerate with tau
- Scale dependence independent of tau
  - Scale dependent modified gravity
  - Massive neutrinos

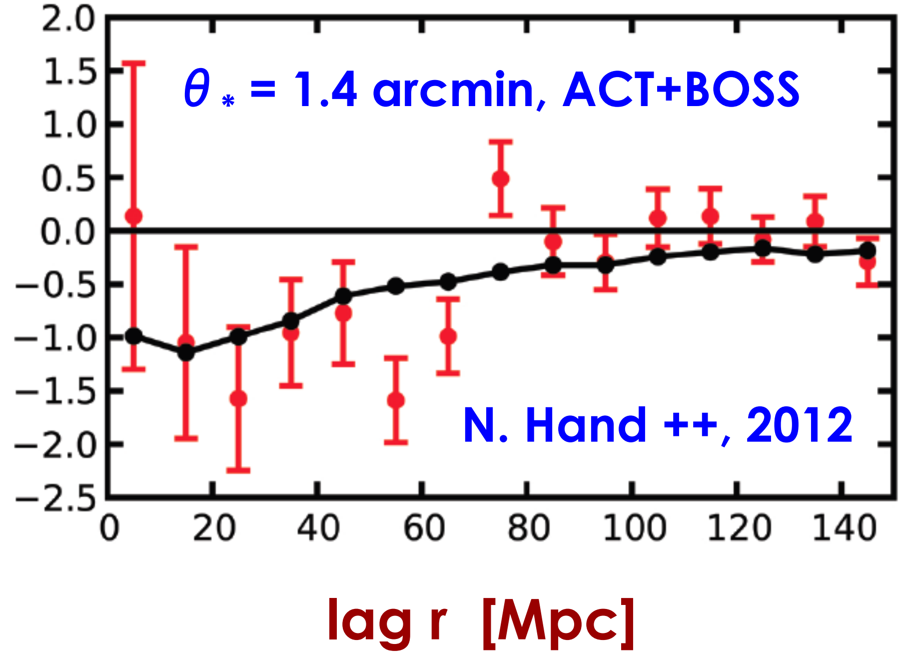
Velocity correlation

- Amplitude → growth factor, modified gravity. Degenerate with tau
- Scale dependence → scale dependent growth, neutrinos

"velocity reconstruction"

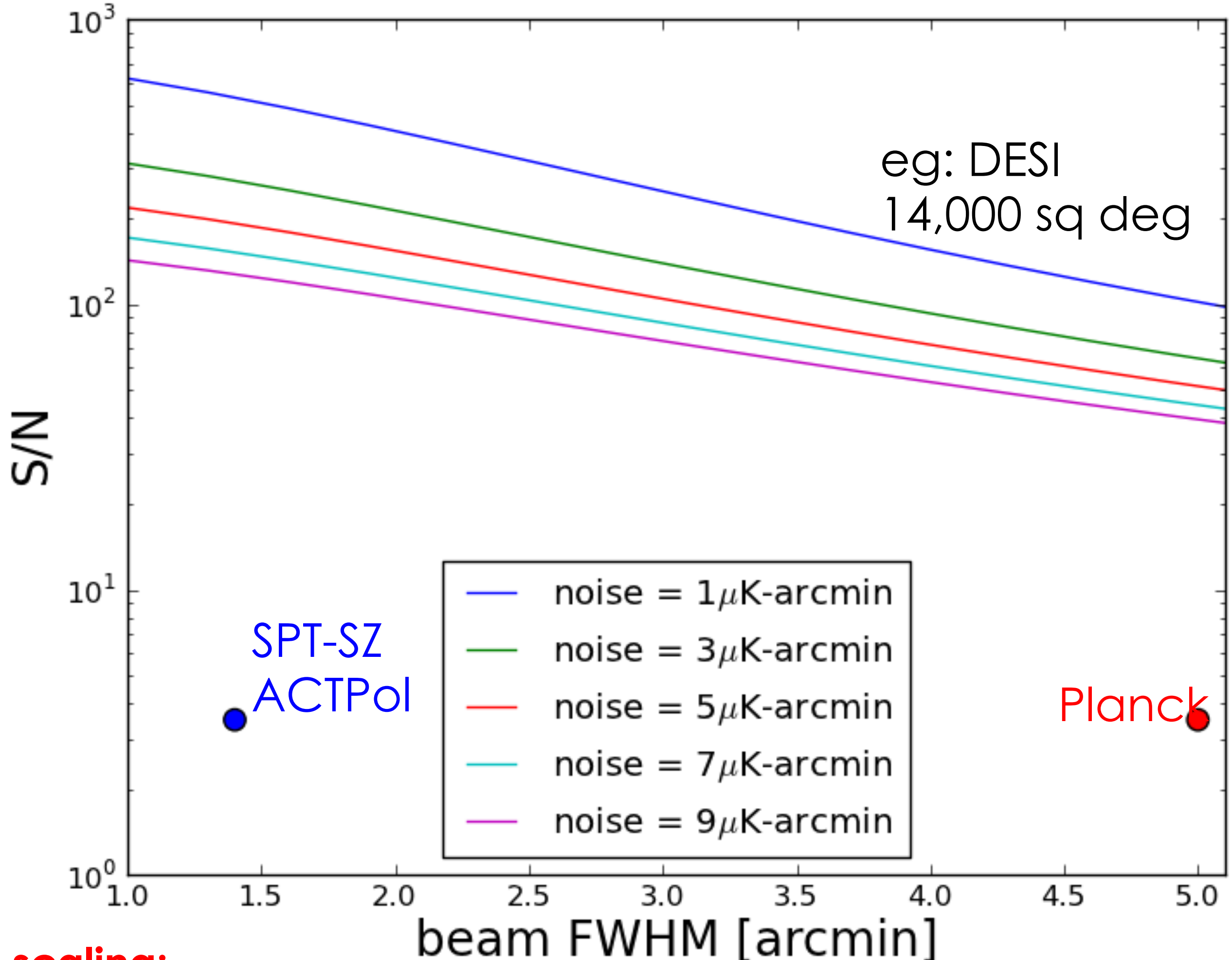


"Pairwise momentum"



Simone Ferraro (Berkeley)

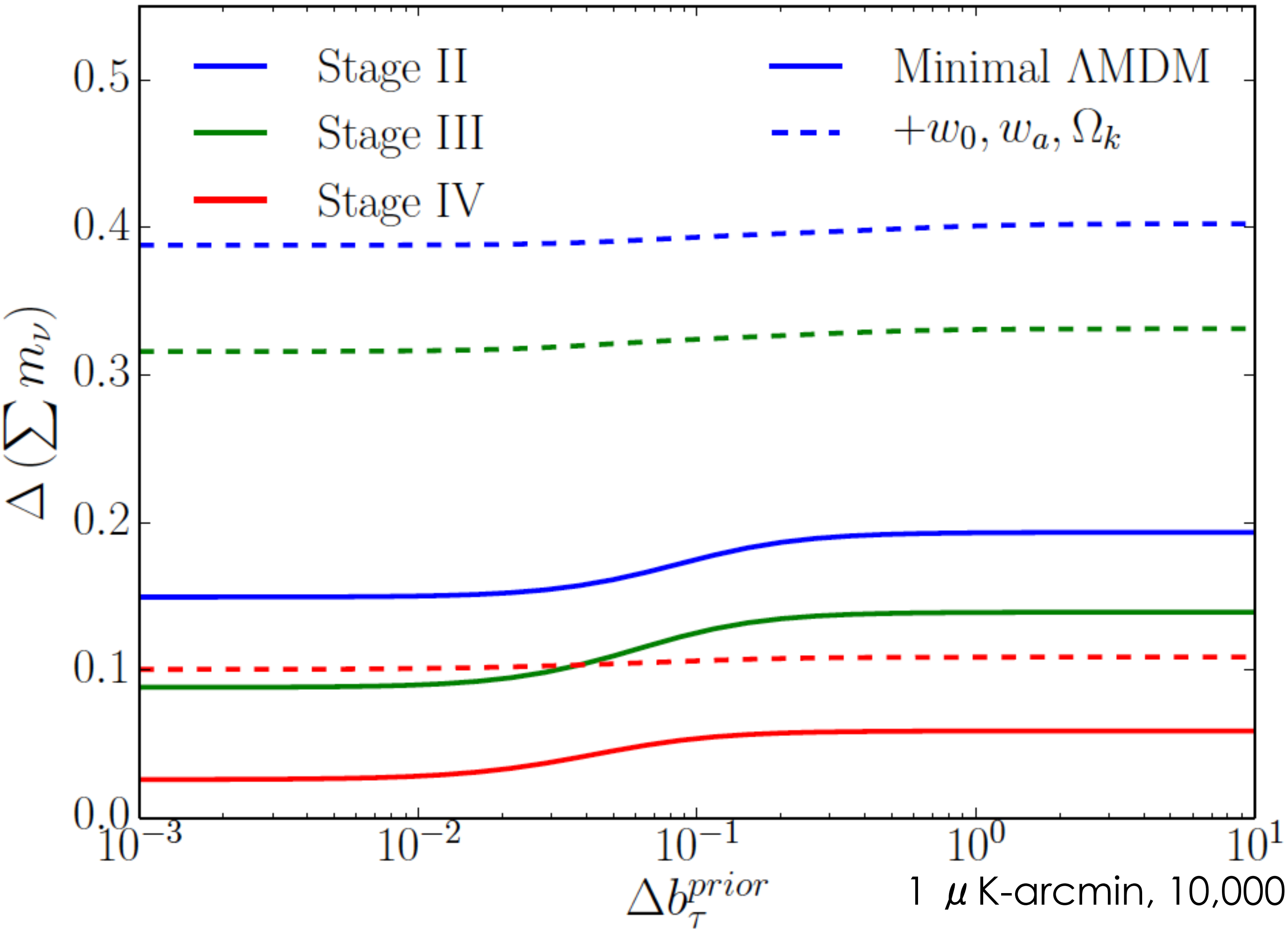
Forecasts



Rough scaling:

$$\left(\frac{S}{N}\right) \sim \sqrt{\mathrm{Area}} \times \ (\mathrm{map\ noise})^{-0.5} \times (\mathrm{FWHM})^{-1}$$

Eg: Neutrino masses



1 μ K-arcmin, 10,000 sq deg

Mueller, de Bernardis ++ (2014)

Breaking the tau degeneracy

- **<y> – <tau>** relation. Known to ~10%. (Battaglia 2016)
- Suppression of primary anisotropy (T and P)
- Linear polarization from scattering of primordial quadrupole → patchy tau estimators
- Angular dependence (octupole and dipole) (Sugiyama+ 2016)
- CMB and galaxy lensing (need to fix ionization fraction)?

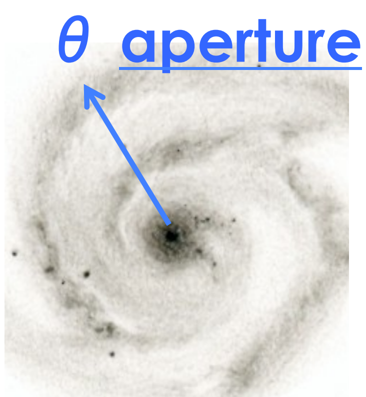
Gas profile

Measure at zero-lag (r = 0) [i.e. stacking] and vary aperture θ

zero lag

aperture

$$\left\langle \frac{\Delta T}{T}(\mathbf{x}) \quad v_r^{\mathrm{rec}}(\mathbf{x}) \right\rangle (\theta) = \sigma^2_{v_r} \;\; \tau(\theta)$$

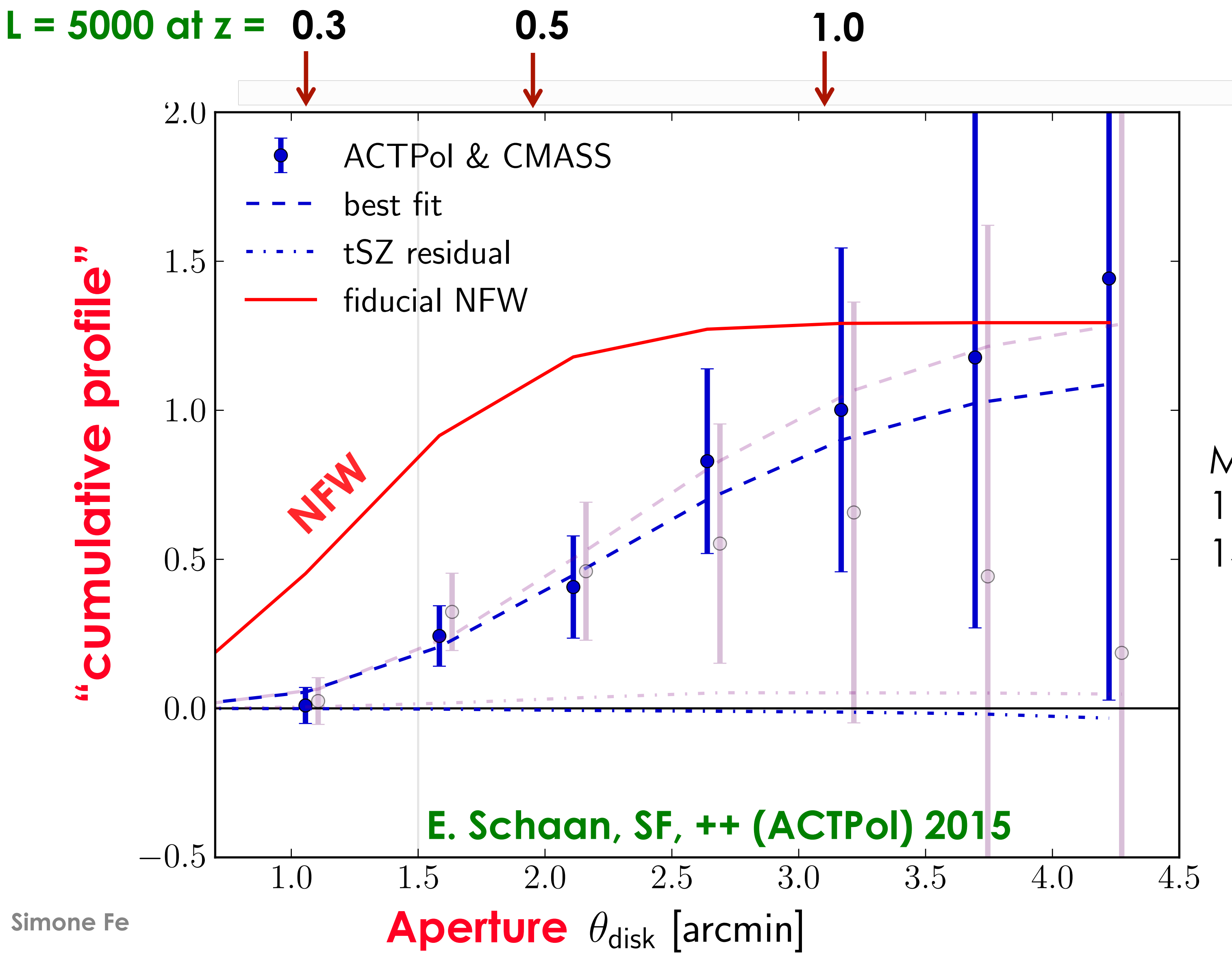


cosmology (independent of θ)

optical depth (profile)

- Can measure profile and optical depth
- Cosmology is just a normalization (independent of θ)

Gas profile: baryons don't trace the dark matter



M ~ 2 x 10^{13} M_{sun}
1.2 % of the sky
14 μK-arcmin

Other science

- Constrain thermal & non-thermal pressure, energy injection and feedback. Combine with tSZ, X-ray, lensing.
- Compare different populations! Mass, redshift, color, presence of AGN, …
- Galaxy formation
- Ellipticity, filaments, etc
- Reionization (Kendrick's talk)
- …

LSS survey requirements
Number of tracers

$$k_{\rm kSZ} = (\ell = 3000)/\chi(z = 0.6)$$

$$\bar{n} P_m(k_{\rm kSZ}) \approx 0.002 \left(\frac{\bar{n}}{3 \times 10^{-4} h^3/{\rm Mpc}^3} \right) \underline{\underline{\ll 1}}$$

Deep in the **SHOT NOISE** dominated regime

$$\bar{\tau} \propto \bar{M}_{\rm halo}$$

$$\left(\frac{S}{N} \right) \propto \bar{M}_{\rm halo} \sqrt{N_{\rm halo}}$$

Far from saturation! Scaling independent of the CMB map

Additional penalty if $\bar{n} < 10^{-4} h^3/{\rm Mpc}^3$

LSS survey requirements: Spectroscopy?

Ideally $$\Delta r = \frac{c\Delta z}{H(z)} \ll 50\ \mathrm{Mpc} \qquad \Delta z \lesssim 10^{-3}$$

$R \gtrsim 1000$ → "perfect" redshifts $\qquad R = \frac{\lambda}{\Delta\lambda}$

$R \sim 100$ → good photometric redshift
order 1 degradation in S/N

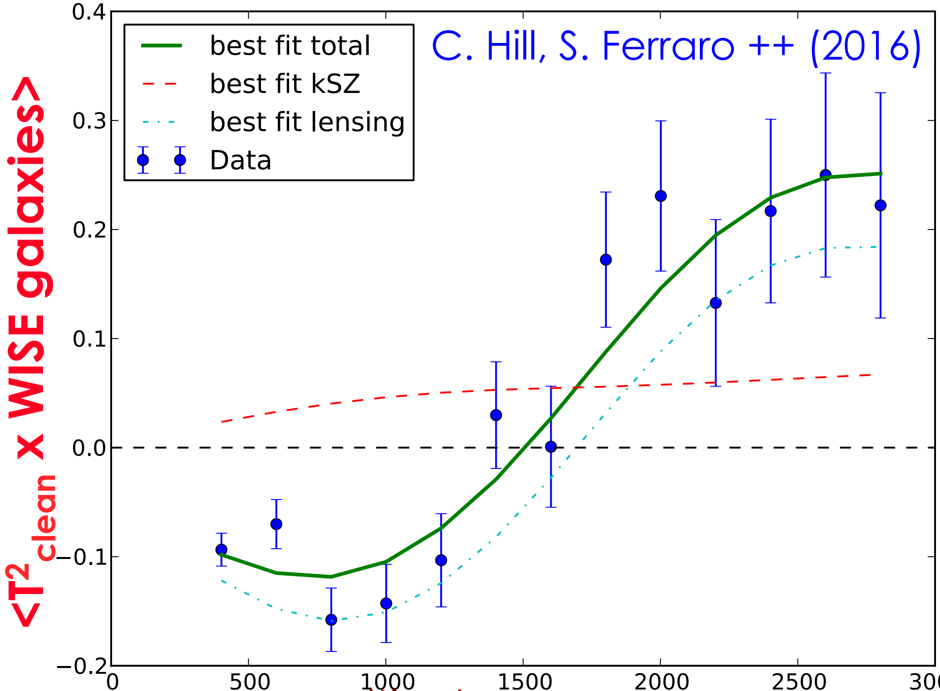
$R \sim 30$ → Most of the information lost
Need different technique (<u>projected fields</u>)

Projected fields

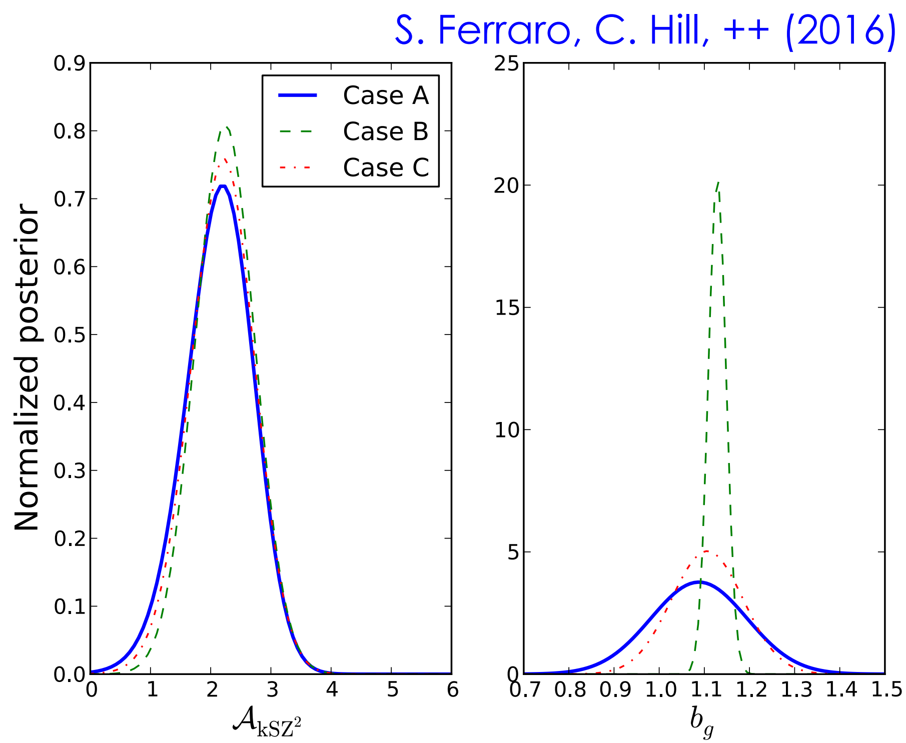
$$\langle T_{\rm CMB}\ \delta_{\rm tr}\rangle \approx 0 \quad \text{because of} \quad v_r \rightarrow -v_r$$

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

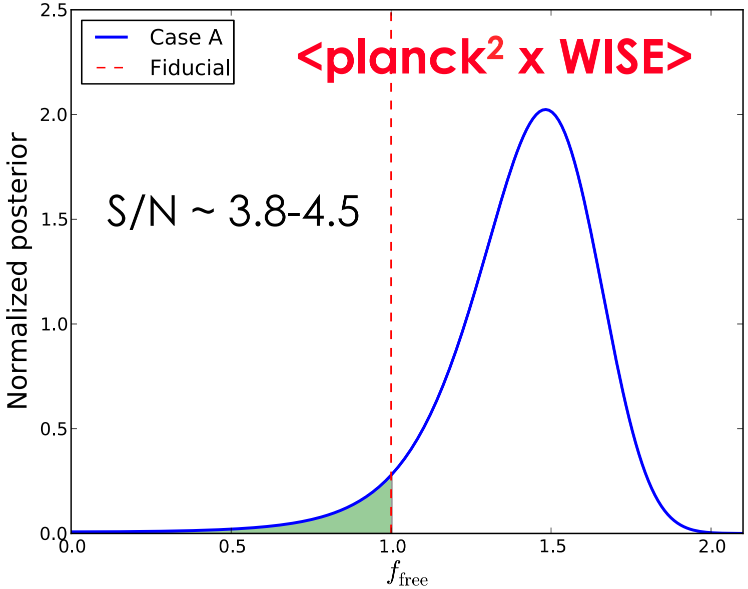
Doré et al (2003)

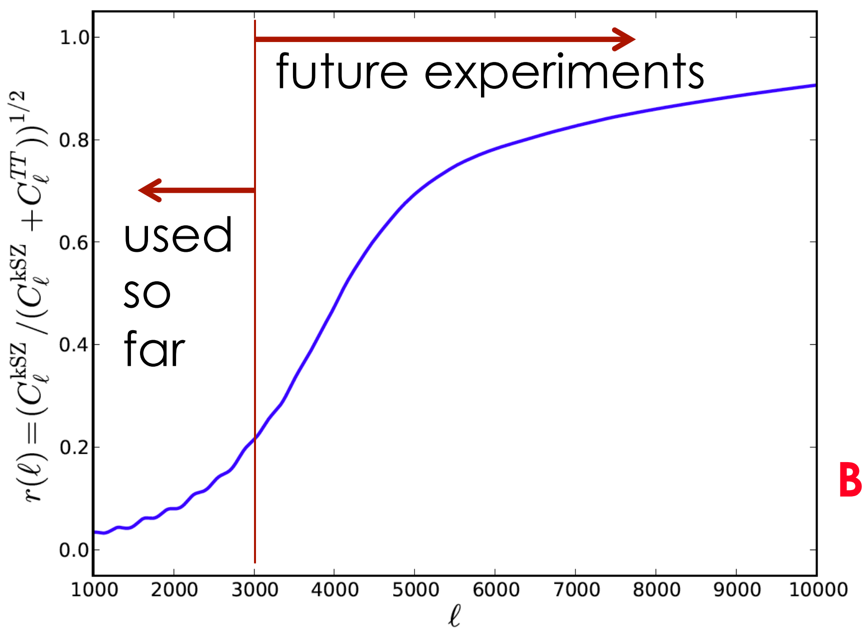


F.T. of aperture



kSZ with projected fields





CMB experiment	beam FWHM [arcmin]	effective noise[a] Δ_T [μK-arcmin]
Planck (2015 LGMCA map)	5	47
Advanced ACTPol	1.4	10
CMB-S4 (case 1) [b]	3	3
CMB-S4 (case 2)	1	3
CMB-S4 (case 3)	3	1
CMB-S4 (case 4)	1	1

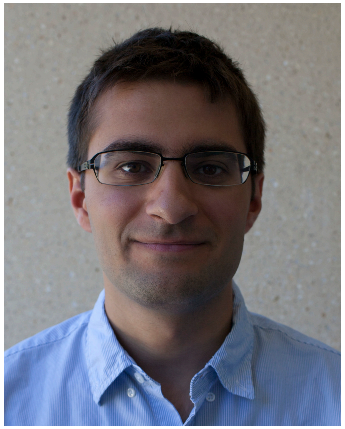
LSST 26 gal/arcmin^2 (preliminary)

x AdvACT	326
x CMB-S4 (case 1)	402
x CMB-S4 (case 2)	1032
x CMB-S4 (case 3)	1006
x CMB-S4 (case 4)	1230

BUT CAREFUL with SYSTEMATICS (foregrounds!)

S. Ferraro, C. Hill, ++ (2016)
C. Hill, S. Ferraro, ++ (2016)

My collaborators



EMMANUEL SCHAAN

KENDRICK SMITH

DAVID SPERGEL

COLIN HILL

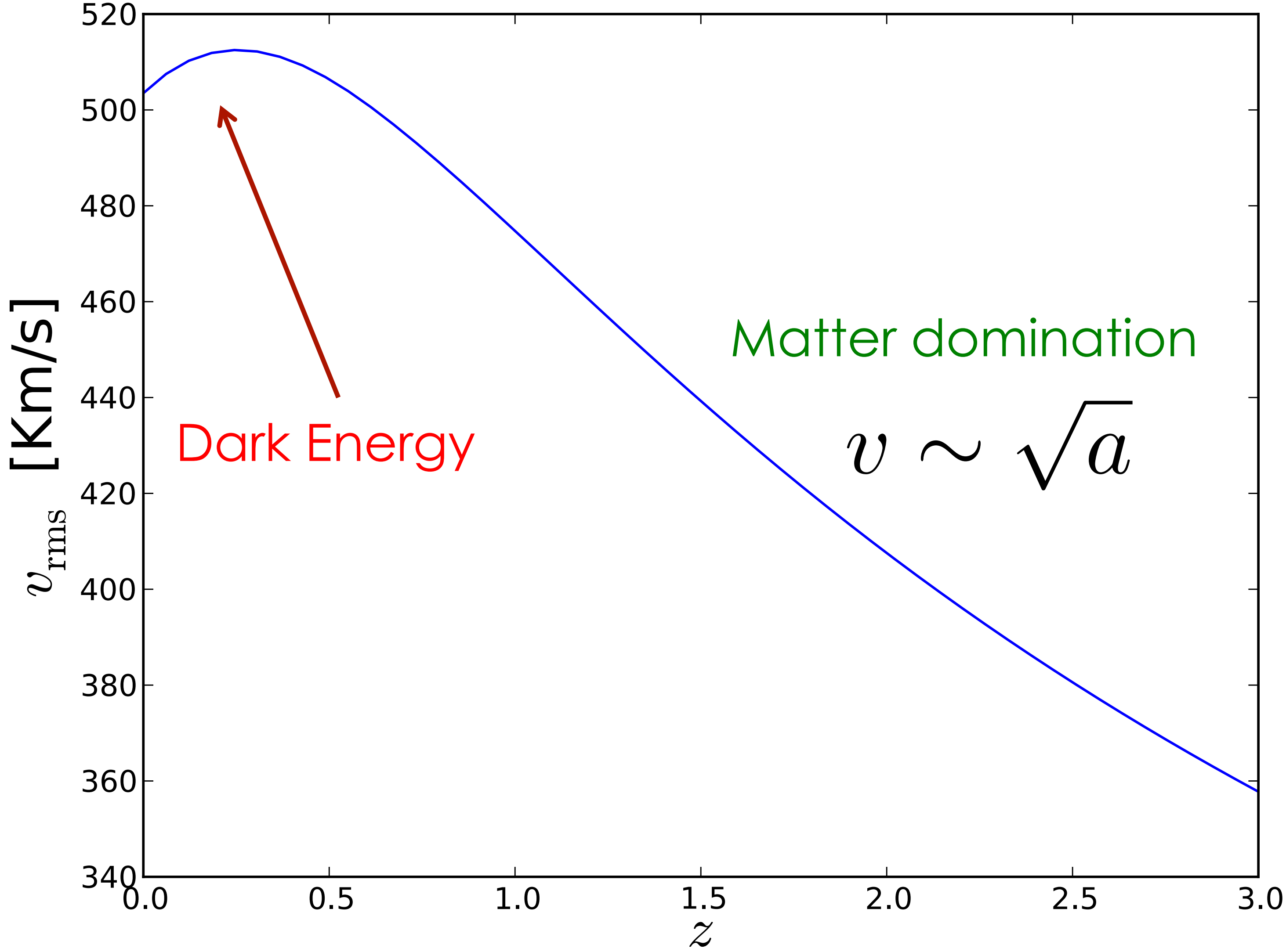
NICK BATTAGLIA

THE ACTPol TEAM

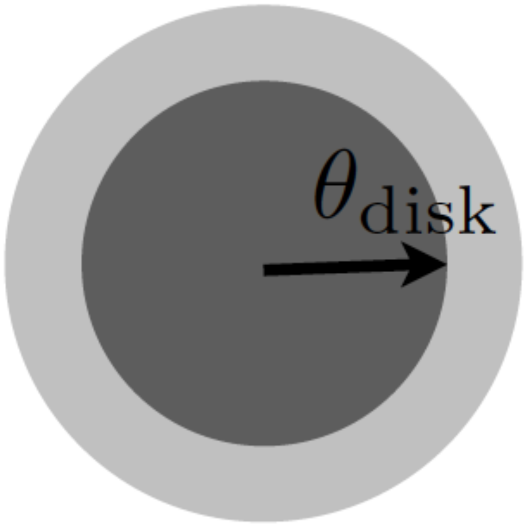
AND MANY OTHERS!

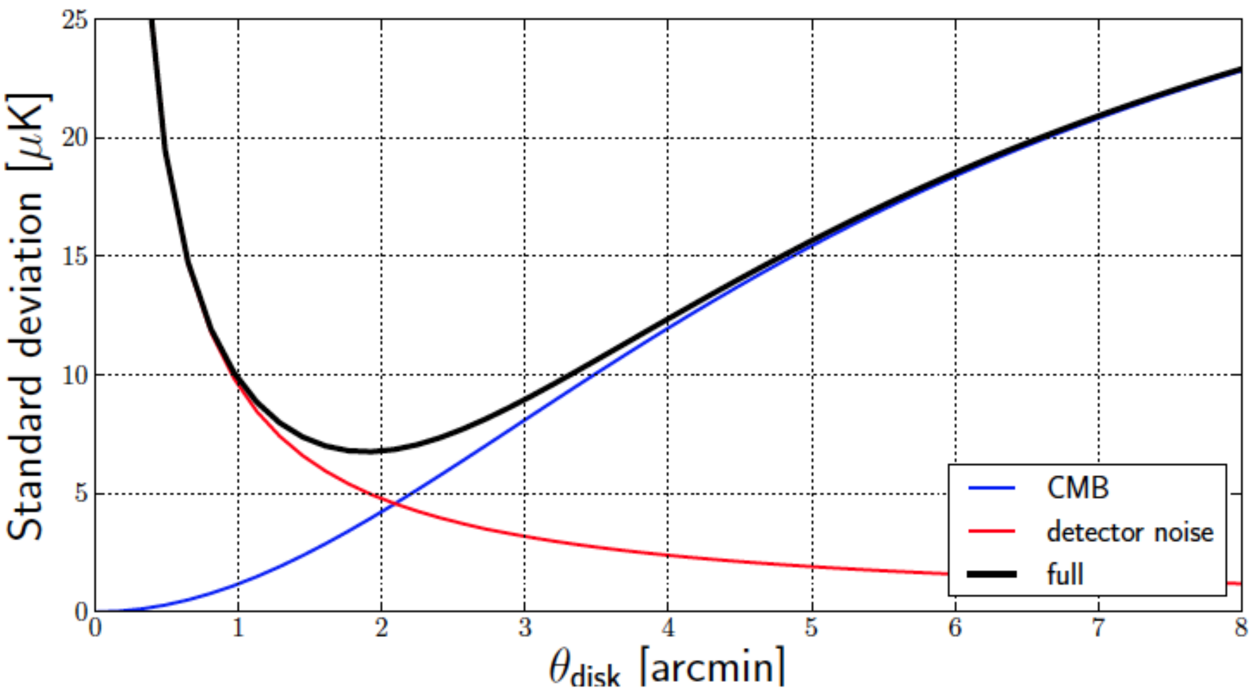
BACKUP SLIDES

RMS velocity



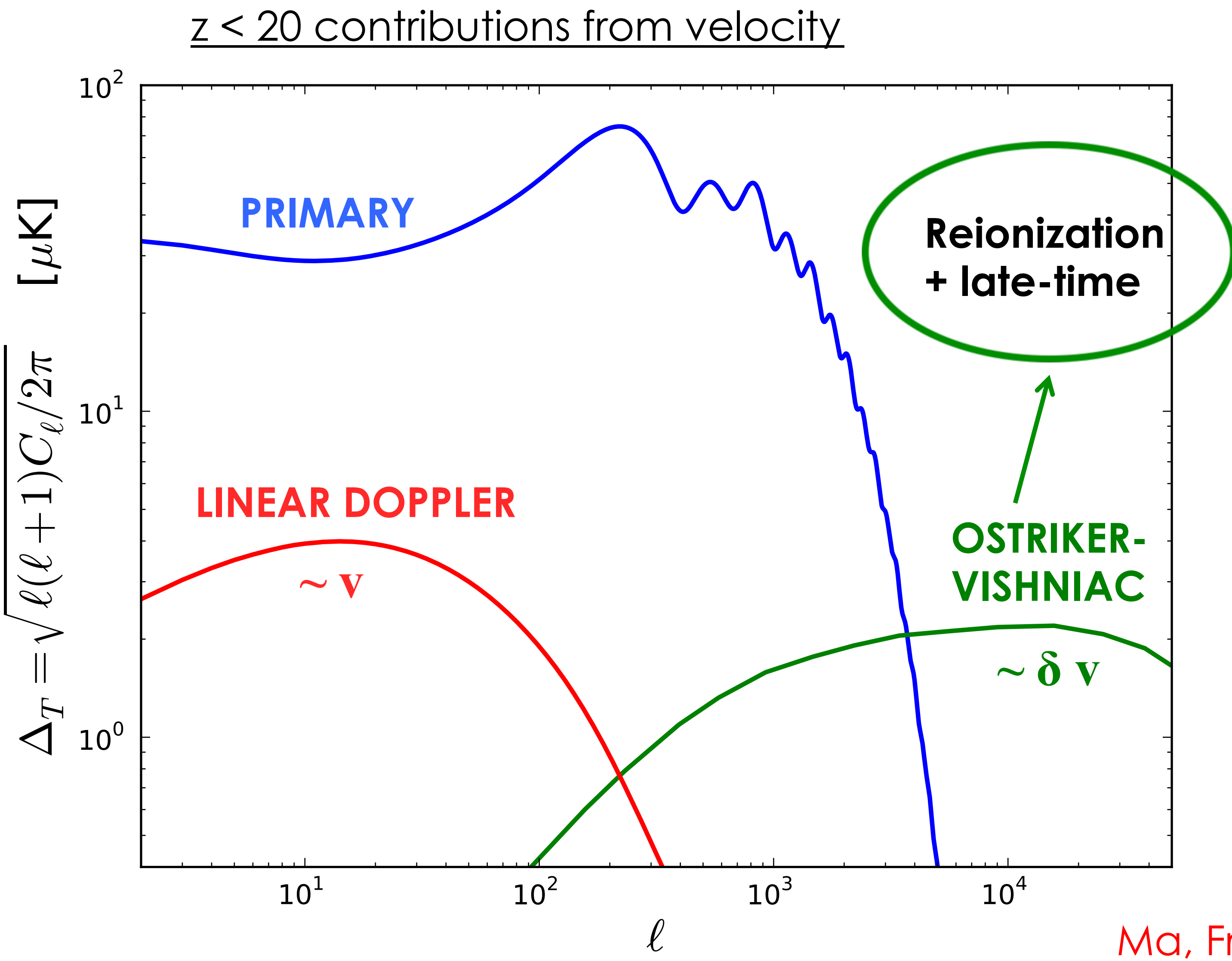
Aperture photometry





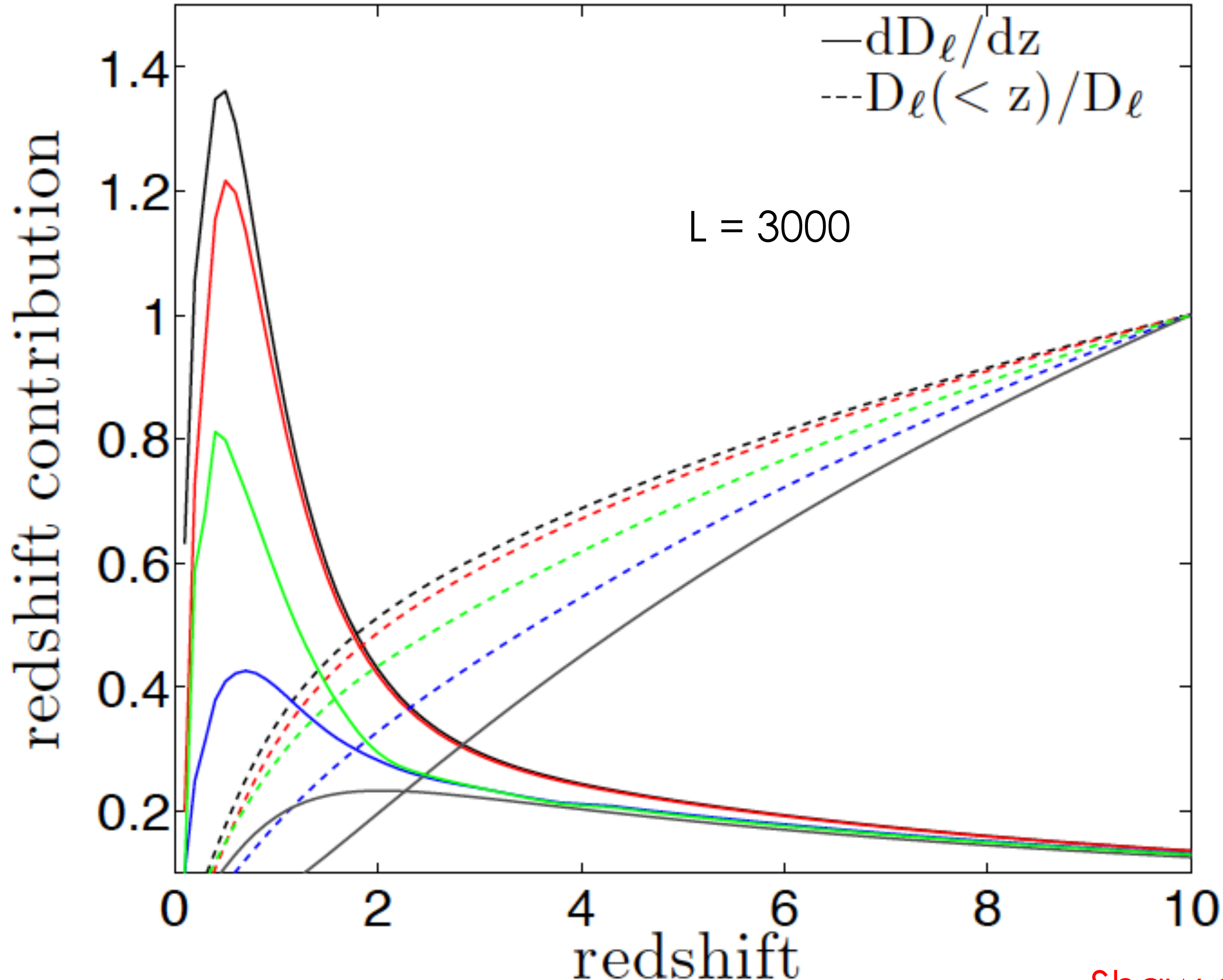
$$\Delta T = \bar{T}_{\rm disk} - \bar{T}_{\rm ring}$$

The kSZ power spectrum



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

Where does it come from?



Shaw et al (2011)