Understanding large-scale structure from the CMB

Calibrating shear with CMB lensing
Gas physics from the kSZ effect

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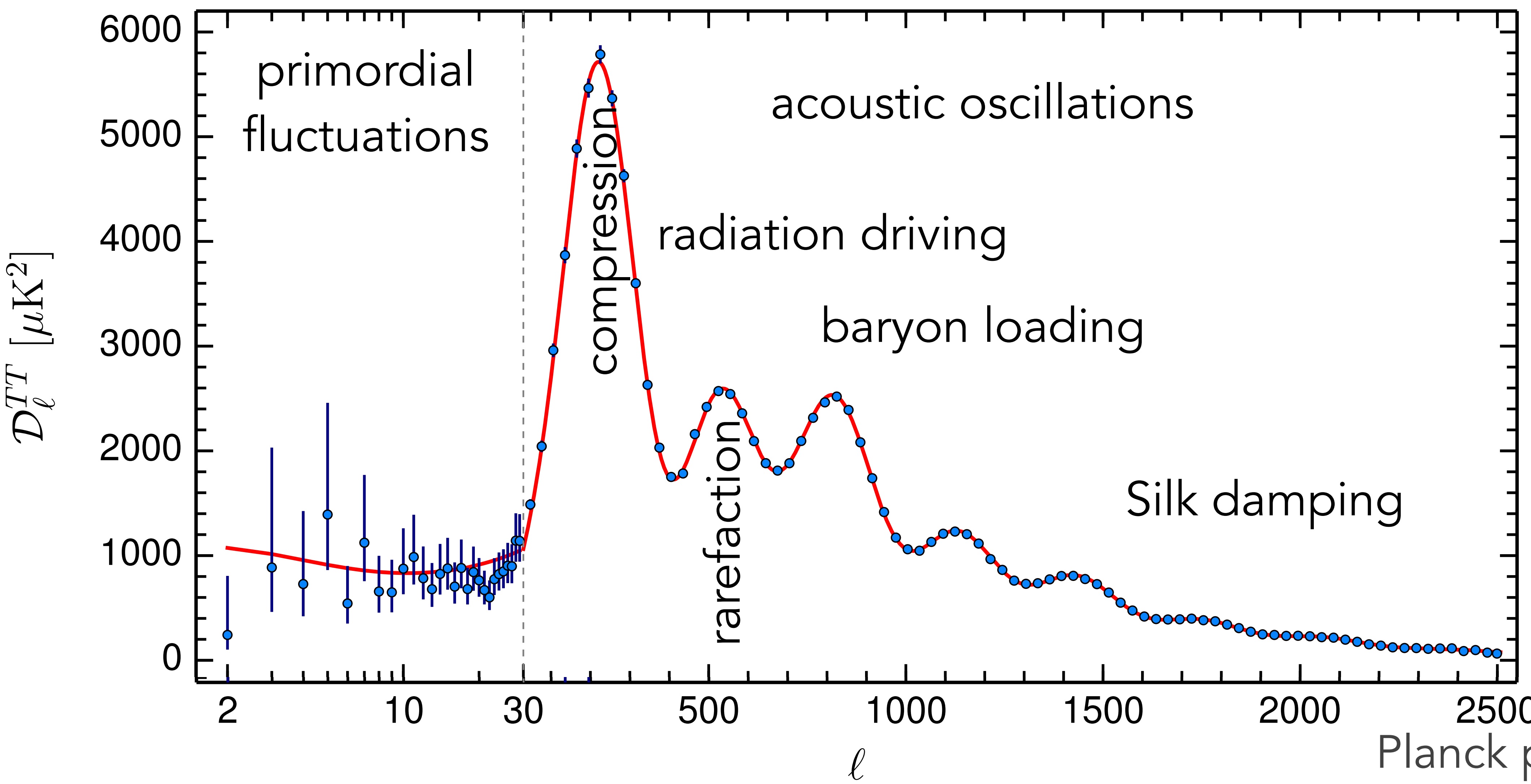
Primary anisotropies — Only one CMB sky

- **Linear physics:** acoustic waves



Planck param. 15

- **Gaussian statistics** (<~10^{-3} from Planck)

- **Primary anisotropies measured to ~ cosmic variance** with Planck (But number of relat. species, primordial gravitational waves…)

Large-scale structure: Tantalus's ordeal

Gigantic statistical power, but…

$N_{modes} \propto (k_{max}/k_{min})^3$ versus $(l_{max}/l_{min})^2$

Non-linear physics

larger perturbations but harder to predict

Non-Gaussian statistics

larger Shannon info but harder to extract

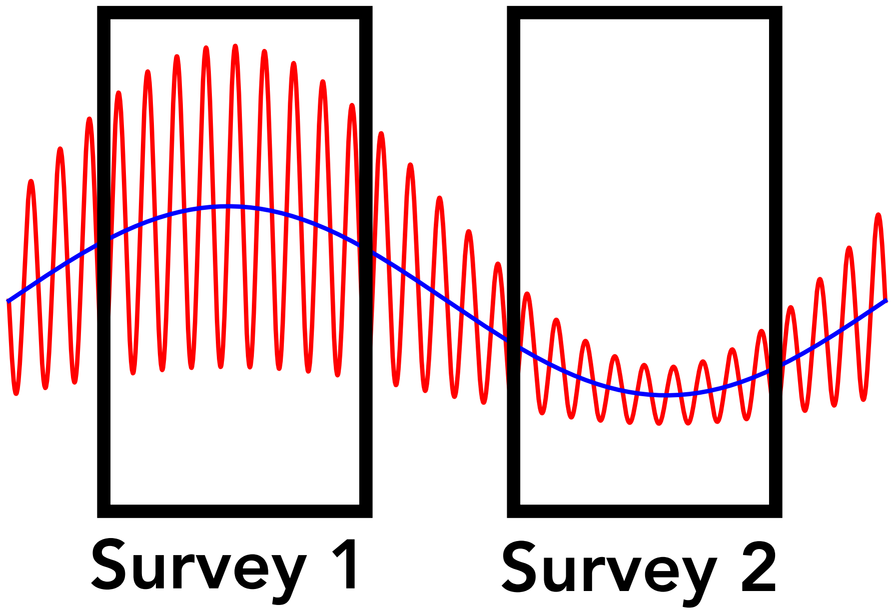
Complex baryonic effects

biasing, star formation and feedback

Complex observables

often systematics-limited

Not this talk…

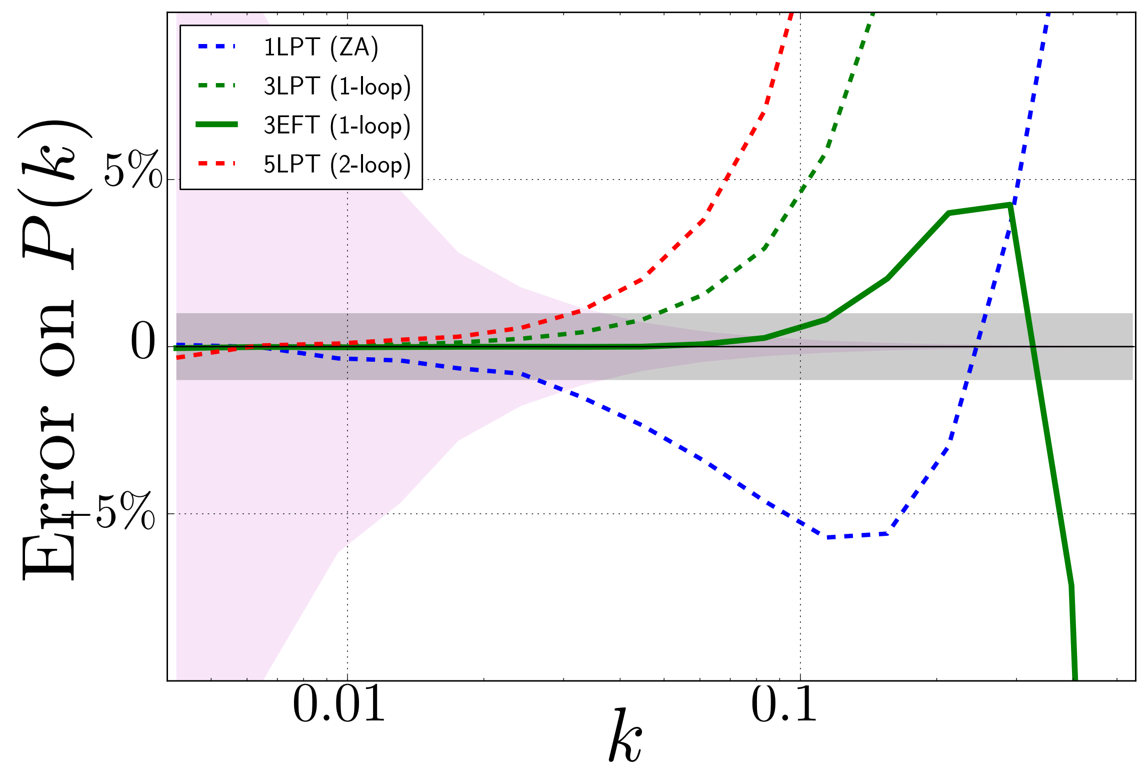


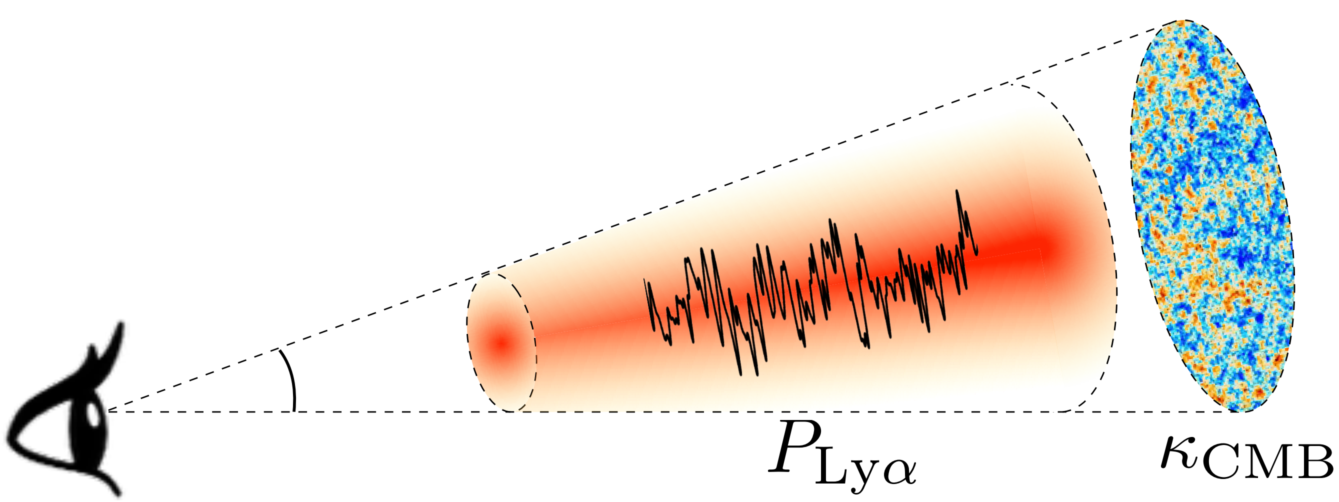
Statistics: Non-Gaussian covariances for n-point functions and halo counts

ES Takada Spergel 14, PRD, 1406.3330

Non-linearities: EFT of the large-scale structures

Baldauf ES Zaldarriaga 15a,b, JCAP, 1505.07098, 1507.01583





Baryons: First detection of the <$P_{\mathrm{Ly}\alpha}\kappa_{\mathrm{CMB}}$> bispectrum

Doux ES+14, PRD?, 1607.03625

Please come talk to me!

Looking through the same lens: Shear calibration with CMB lensing

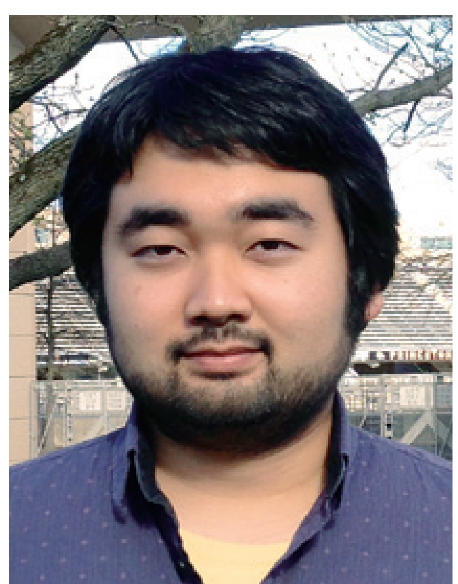
Collaborators

arXiv:1607.01761

Elisabeth Krause

Tim Eifler

Olivier Doré

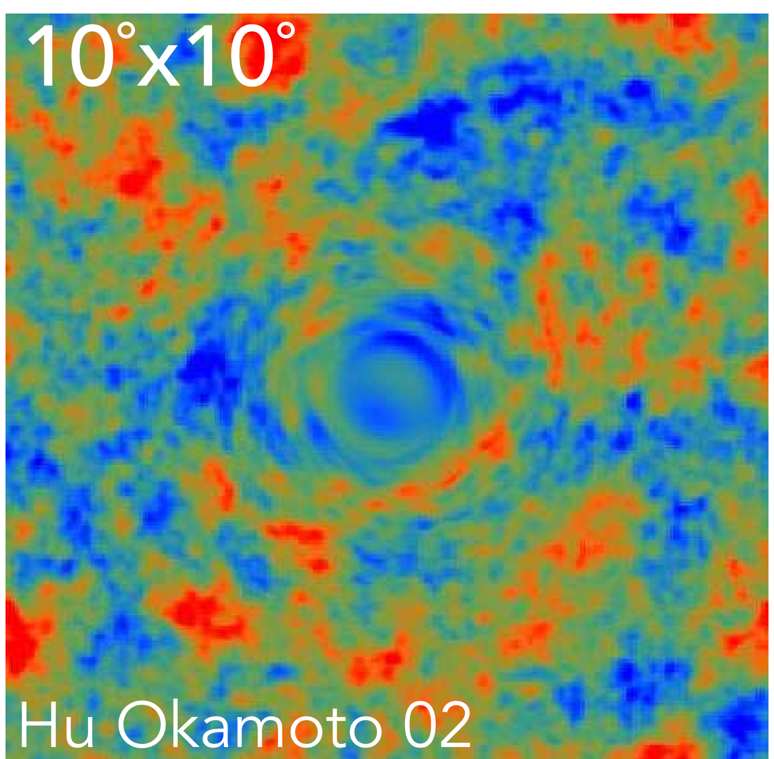


Hironao Miyatake

Jason Rhodes

David Spergel

Weak gravitational lensing



Galaxy lensing

perfect disk   shear ~1%   shape ~20%

→ SNR~5% for one galaxy,

SNR~10^3 with 10^9 galaxies

CMB lensing

Arcmin deflections, coherent on degree scale

Smoothed peaks, extra power, E→B, correlates modes

Complementary with clustering

geometry+growth

tests of GR: $\Psi+\Phi$ versus Φ

probes all the mass

biasing issue

Shear calibration: the case for redundancy

$$< e >= (1 + m)\, \gamma_{\rm true} + \alpha\, e_{\rm PSF} + c$$

Heymans+06
Taylor Kitching 16

Scary: m(z) degenerate with growth, hence dark energy EOS

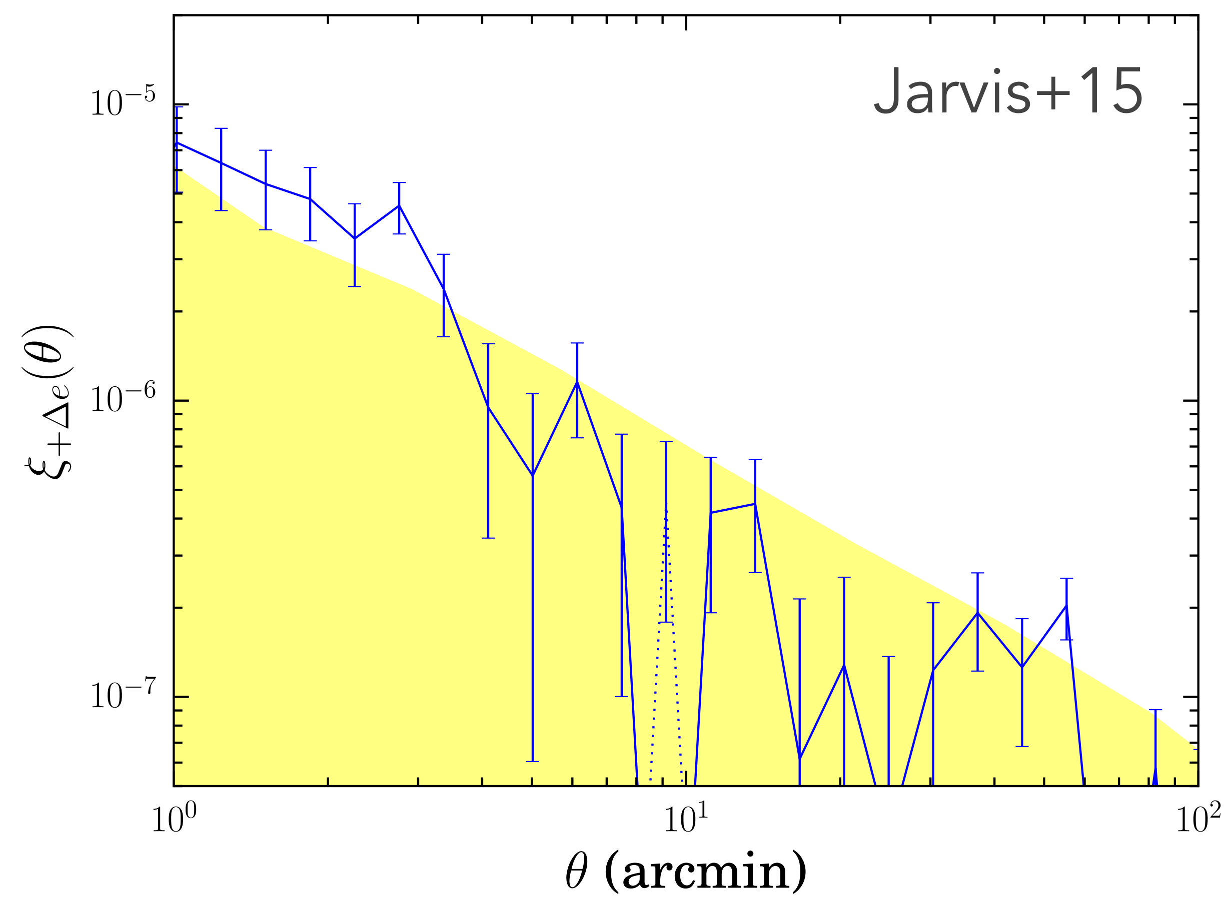
"Required" for LSST: < 0.5% (Huterer+06, Massey+12, Schaan+16)

Image simulations: 3-5% DES (Jarvis+15), 1% KiDS (Fenech-Conti+16)

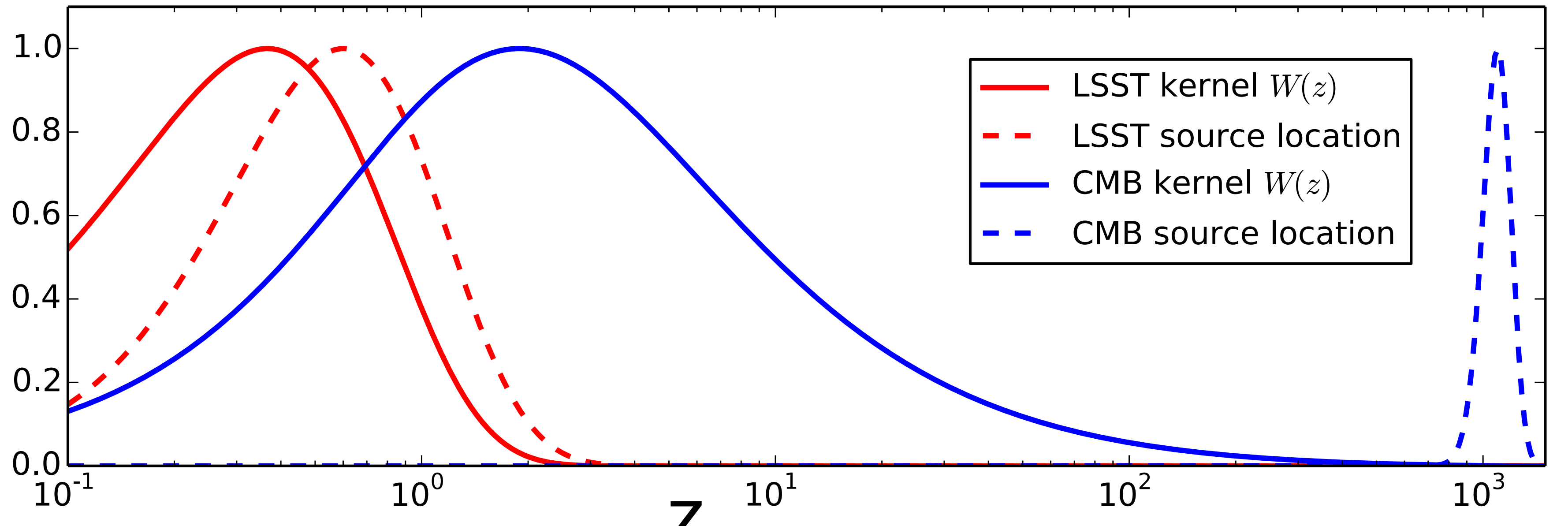
Difficult:

- Noise/Model biases
- Selection bias: simulate below the detection limit (Hoekstra+15)
- Mode coupling: simulate below the image resolution
- PSF size error

→ **Redundancy is valuable**



Shear calibration with CMB lensing



Madhavacheril, CMB S4 science book

Principle:

Vallinotto12,13, Das+13

$\kappa_{gal} \sim (1+m)\ \sigma_8$

$\kappa_{CMB} \sim \sigma_8$

Value:

Purely empirical, self-calibration

No assumption on galaxy population/morphologies

Just the beginning!

Liu+16, Baxter+16, Miyatake Madhavacheril+16, Singh+16

~10-20% calibration, (mostly) fixed cosmology & nuisances

Questions:

Competitive with image simulations / requirements?

Varying cosmology & nuisance?

Robustness to photo-z, IA?

What combination is best?

Large Synoptic Survey Telescope

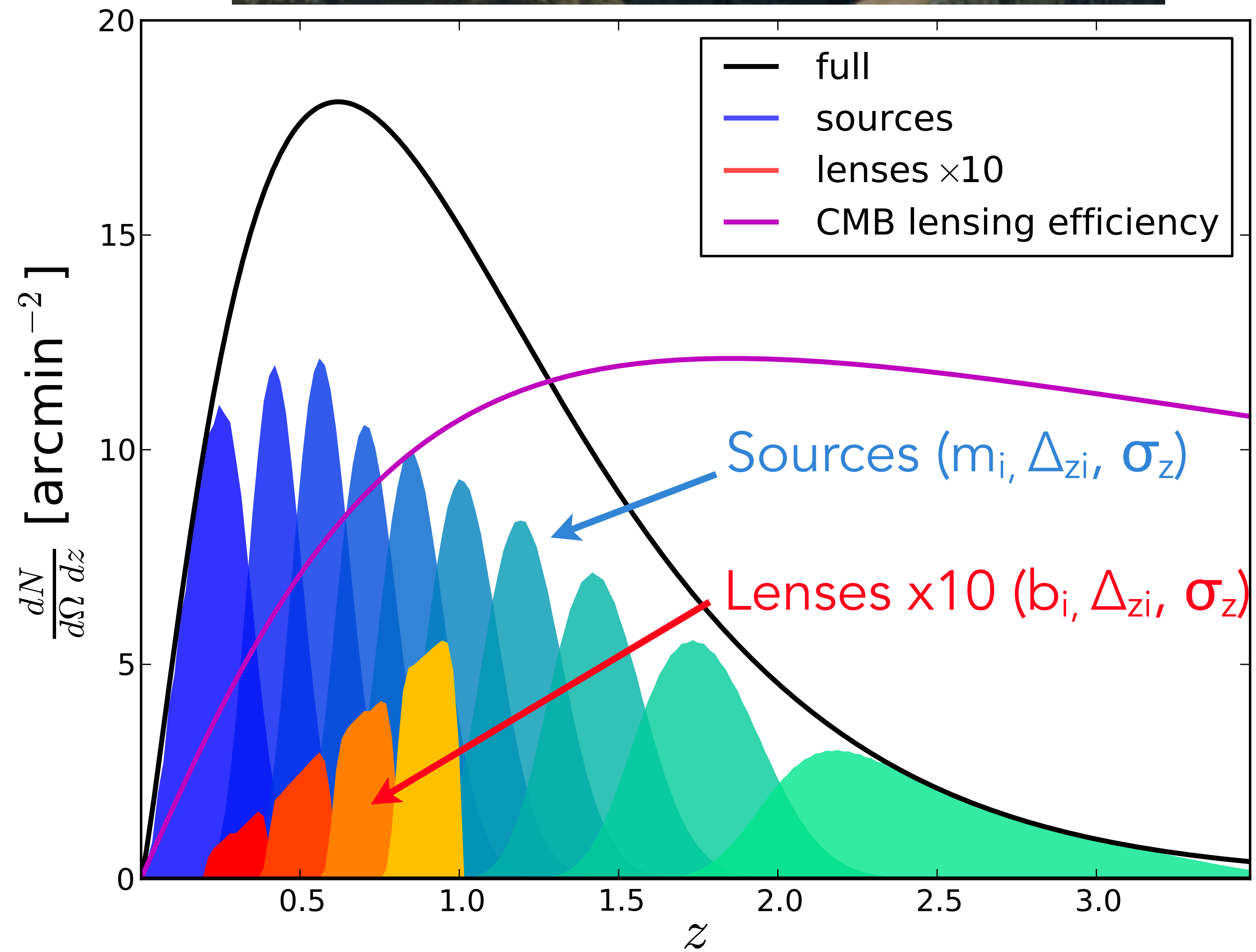
8.4m telescope in Chile

Survey starts 2022-23

~ half the sky

Sources: 26 arcmin^{-2}

Lenses: redmagic-like



18,000 deg^2, 26 sources/arcmin^2, 0.25 lenses/arcmin^2, shape noise = 0.26

$\sigma_z/(1+z)$ = 5% for sources, known to 0.2% for sources

$\sigma_z/(1+z)$ = 1% for lenses, known to 0.06% for lenses

CMB Stage 4

Stage 4: ~500,000 detectors

Beam: 1′

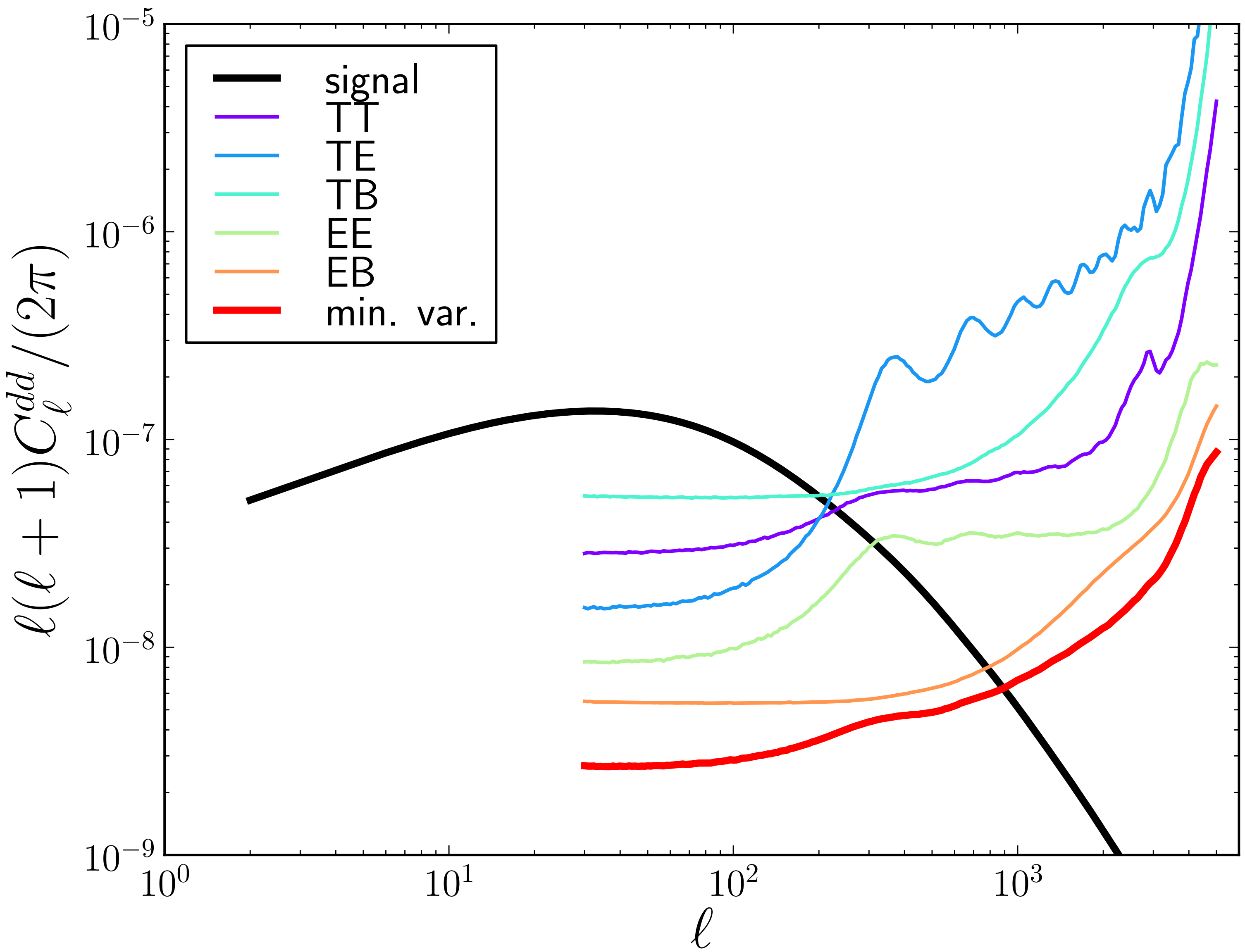
Sensitivity: 1μK′

l_{min}=30,

$l_{max,T}$=3000, $l_{max,E,B}$=5000

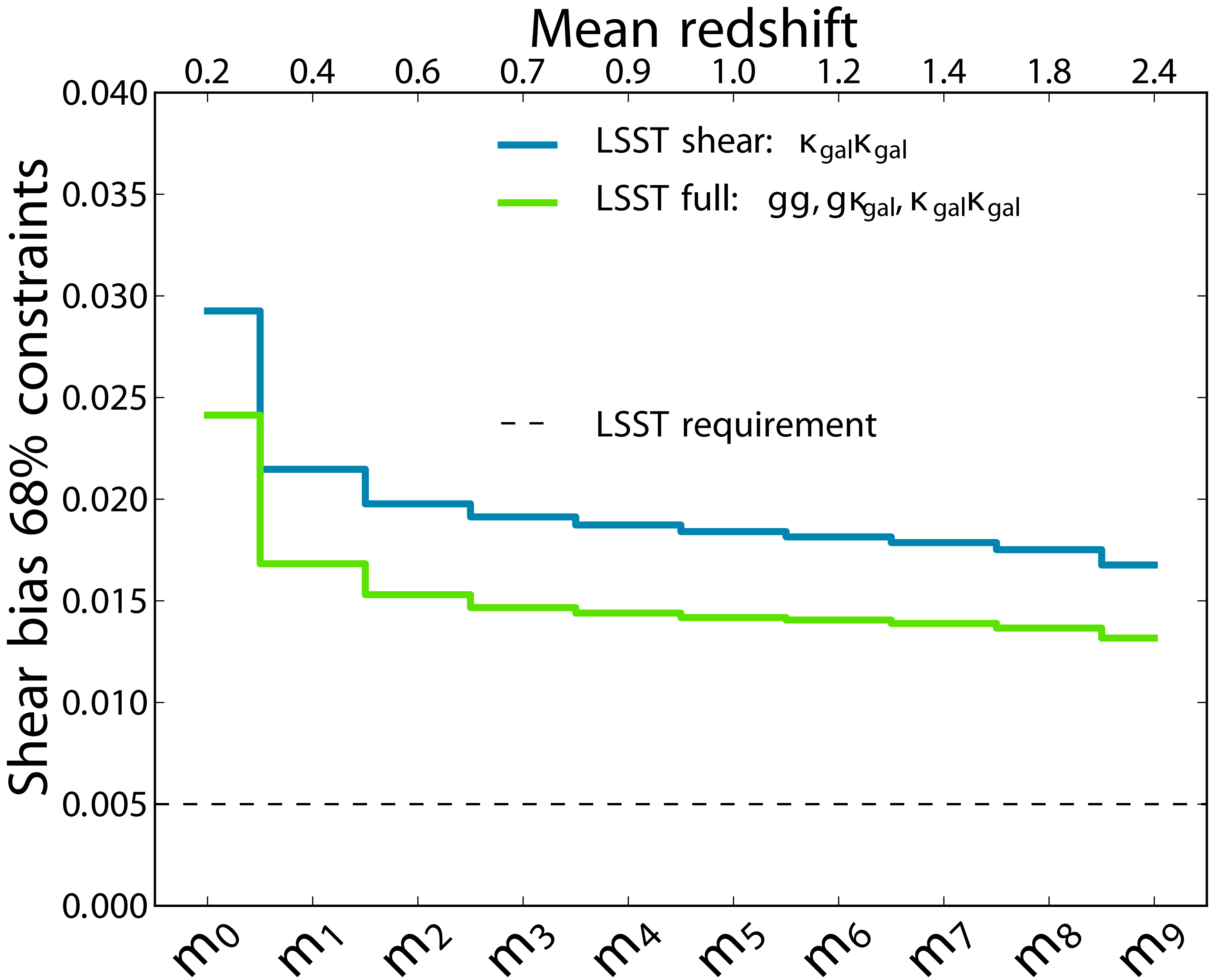
Foreground cleaned input map

Assumed no systematics



Forecast

- **Data:** all combinations of $\{g, \kappa_{gal}, \kappa_{CMB}\}$
- **Constrain:** cosmology, b_i, m_i, Δ_{zi}, $\boldsymbol{\sigma}_z$
  No prior on b_i , m_i. Priors on Δ_{zi}, $\boldsymbol{\sigma}_z$.
- **Realistic/conservative:**
  Full non-Gaussian covariances
  Explore likelihood with MCMC
- **Built on CosmoLike (Eifler Krause+14)**
  Extended to include CMB lensing
  Soon to be public!

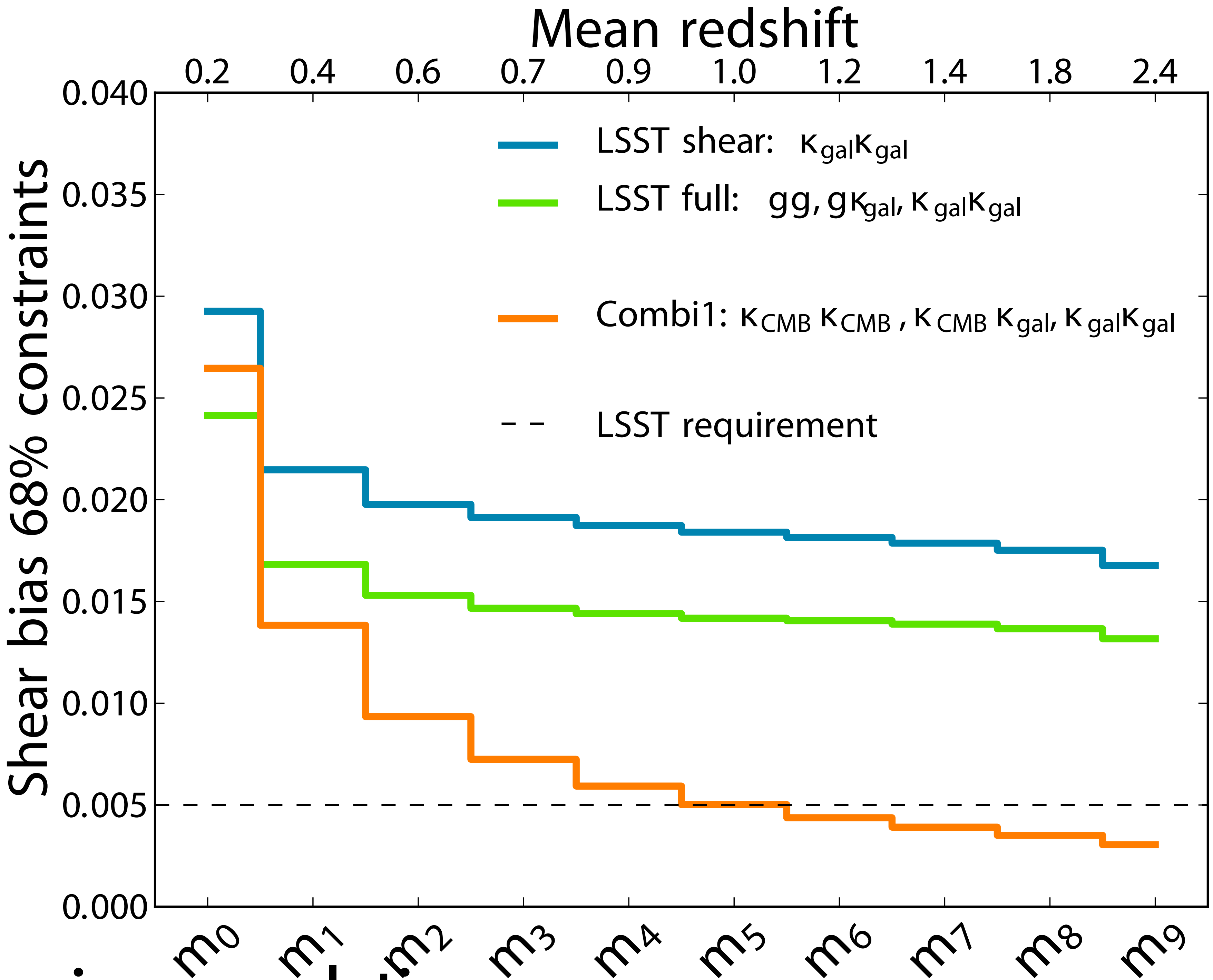


Schaan+16

Shear alone/LSST alone:

Self-calibration to ~2%

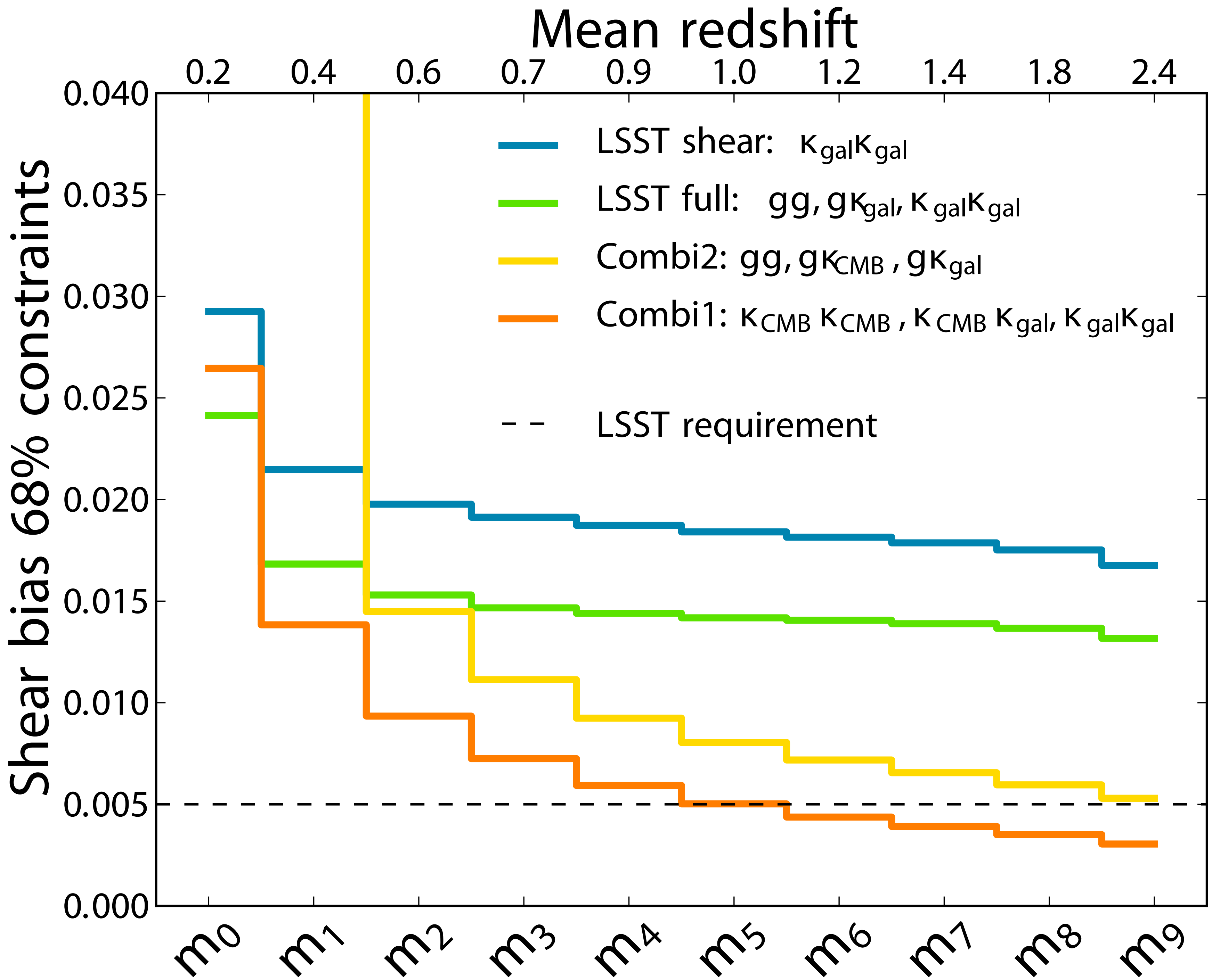
Relies on mildly non-linear scales



Schaan+16

Lensing-lensing correlations:

- requires auto spectra
- IA always present
- fixed angular scale ← arbitrary small physical scales



Schaan+16

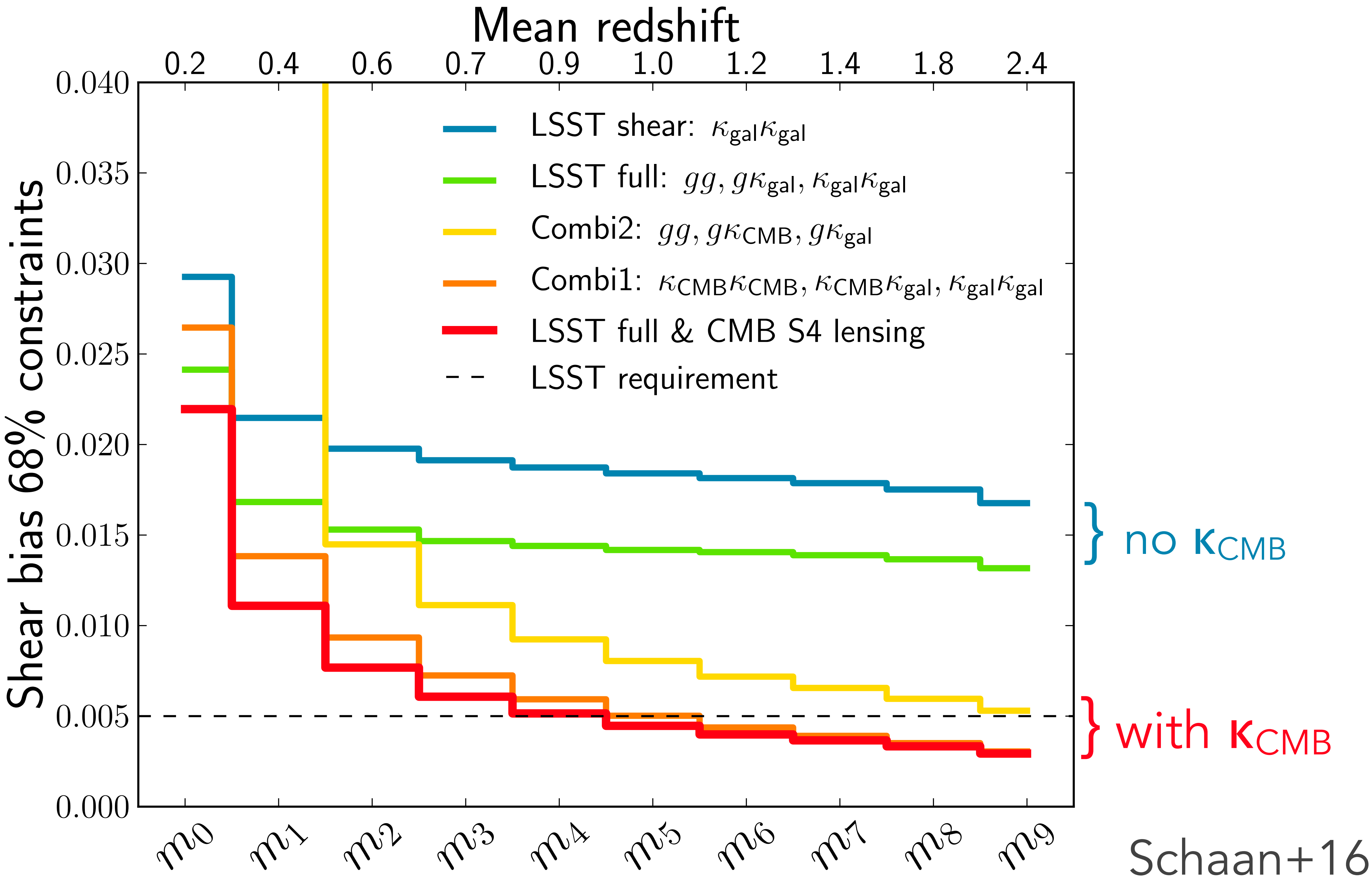
Tracer-lensing correlations:

+ no lensing auto

+ fairly insensitive to cosmology (distance ratios)

+ no IA if perfect photo-z

+ fixed angular scale ← **not** arbitrary small physical scales



CMB S4 lensing can calibrate the shear ~ requirements

while varying cosmo & nuisance params

better at high z where most challenging

purely empirical, self-calibration

Robustness

- **IA contamination:**
  Unaccounted IA in the data produce $<1\sigma$ bias in m_i, without mitigation

- **Non-linearities/baryons:**
  Varying l_{max} beyond 1000 does not affect m_i much

- **Wider photo-z errors:**
  Weakening prior on photo-z only weakens m_i constraints in the lower z-bins

- **CMB S4 specs:**
  m_i constraints are sensitive to noise, but not much to l_{max} or resolution
  → possible with AdvACT, SPT-3G

Summary: Shear calibration with CMB lensing

arXiv:1607.01761

- **CMB S4 lensing can constrain the shear bias to 0.5% ~ LSST requirements**
- **Purely empirical, self-calibration, no assumption on galaxy population/morphologies**
- **Works best at high z where most difficult**
- **Possible with AdvACT, SPT-3G, Simons Observatory**
- Robust to IA, photo-z degradation, non-linearities & baryons, CMB S4 specs
- In the works: "delensing" with CIB, iterative reconstruction, photo-z outliers, correlated mi

kSZ detection &
gas physics in clusters

Collaborators

arxiv:1510.06442

Simone Ferraro

Mariana Vargas-Magaña

Kendrick Smith

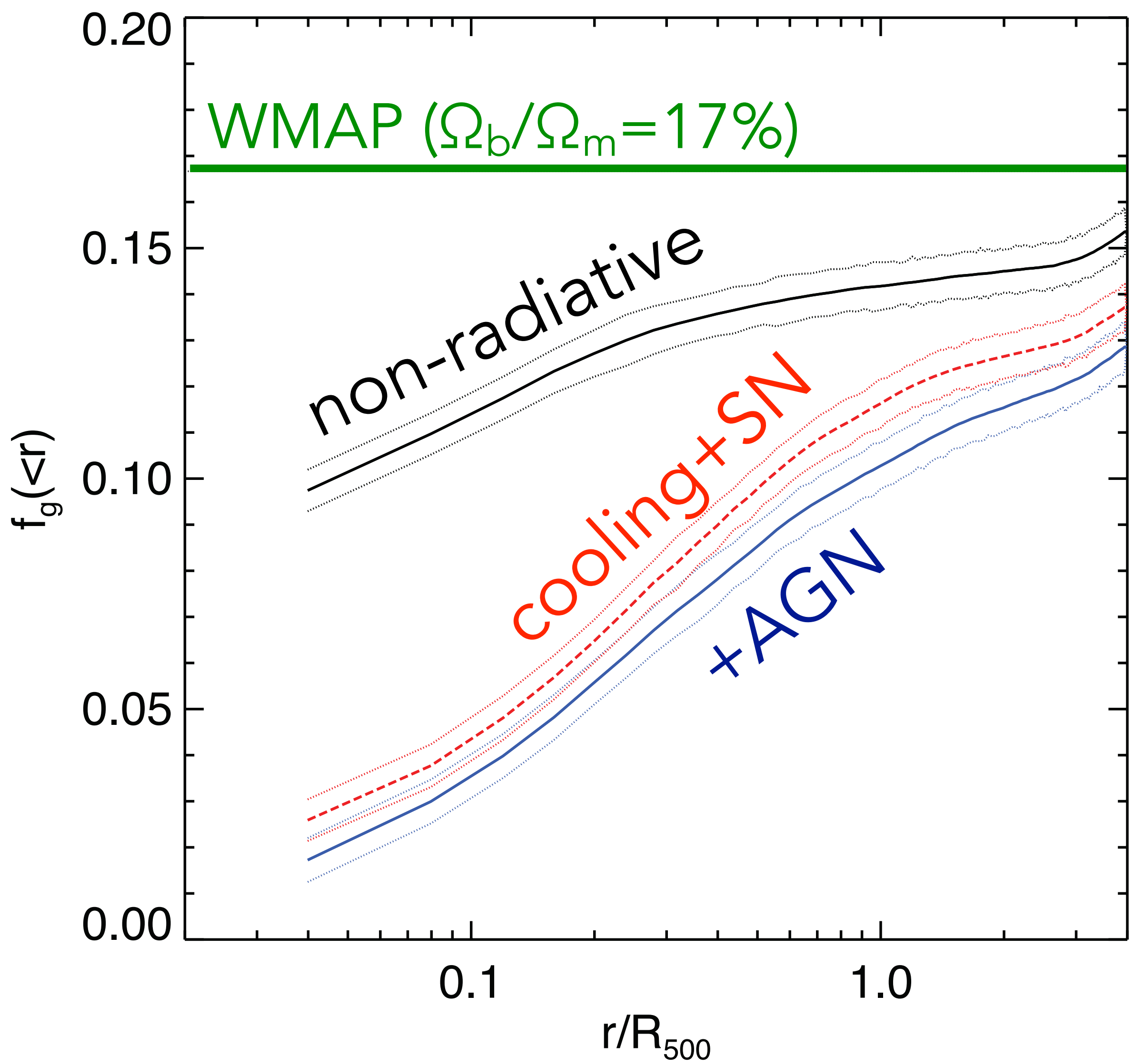
Shirley Ho

David Spergel

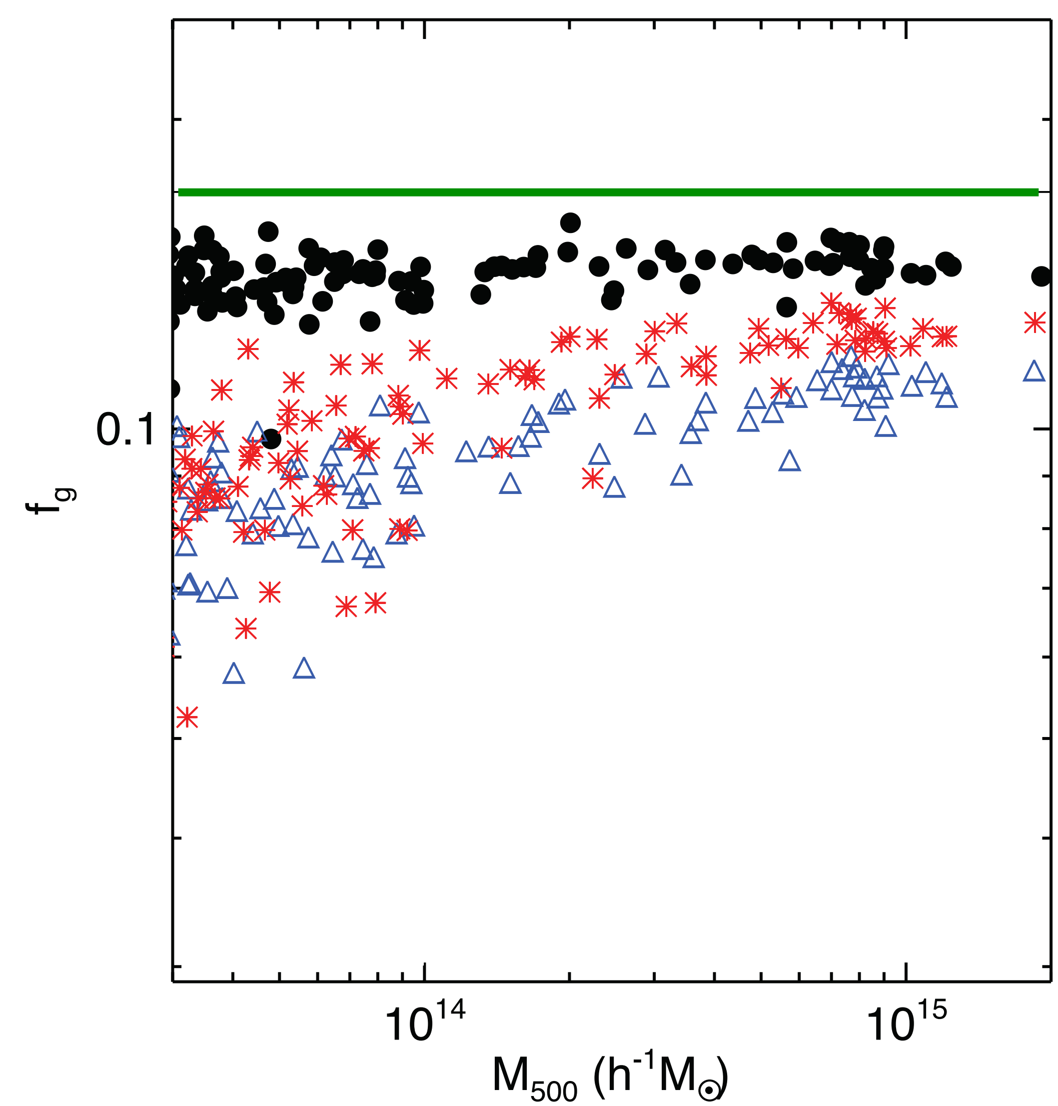
Nick Battaglia

Gas in clusters & galaxy formation

Profile



Abundance



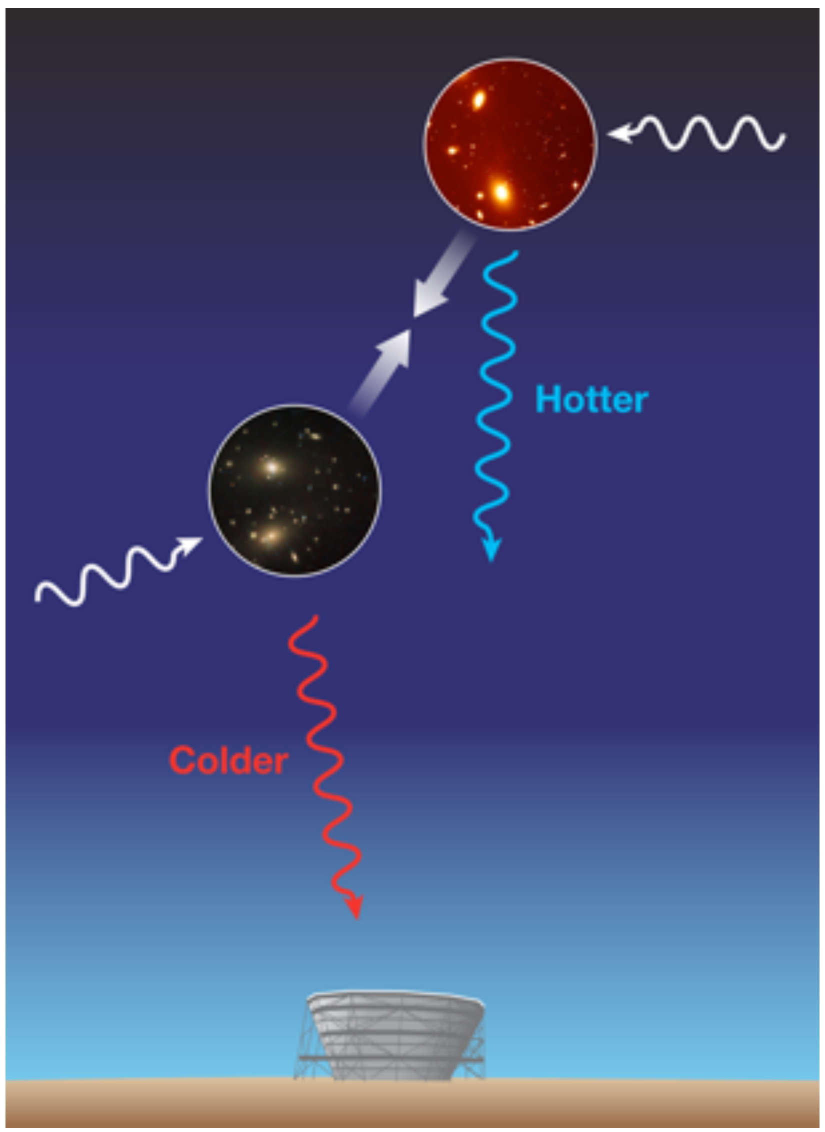
from Planelles+13

→ Measuring gas profile and abundance can constrain feedback mechanisms

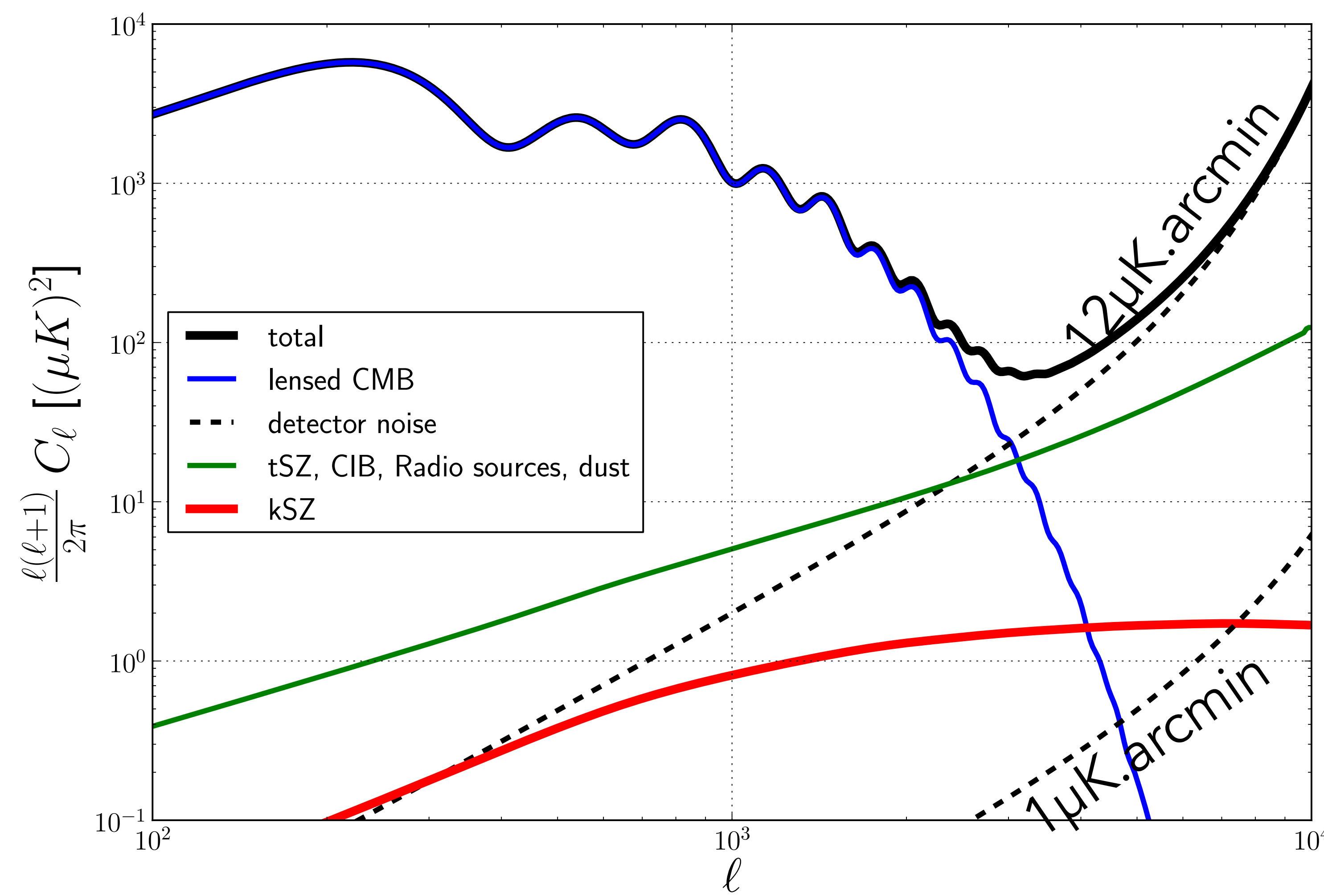
Kinematic Sunyaev-Zel'dovich effect

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

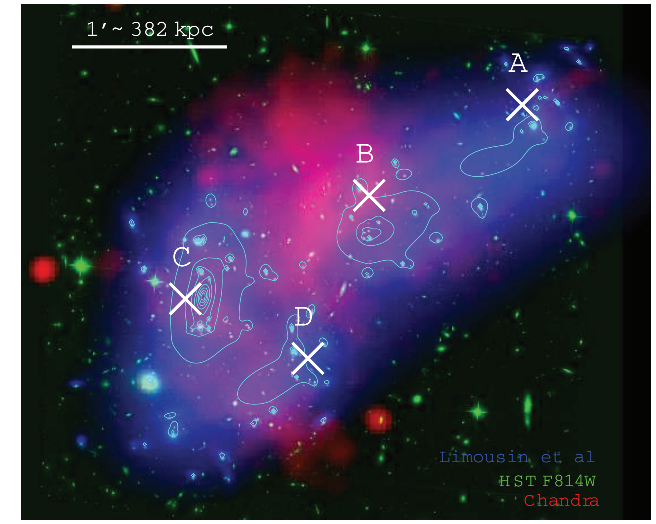
- Counts all free electrons
- Lower mass halos at higher z
- Small size: $\delta T_{\mathrm{kSZ}} \sim 0.1\mu\mathrm{K}, \delta T_{\mathrm{CMB}} = 110\mu\mathrm{K}$
- Blackbody spectrum
- Handle on v?



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



Detection methods



Individual (monster) cluster

Sayers+13, 14

Pairwise velocities

Hand+12, Planck15, Soergel+16, de Bernardis+16

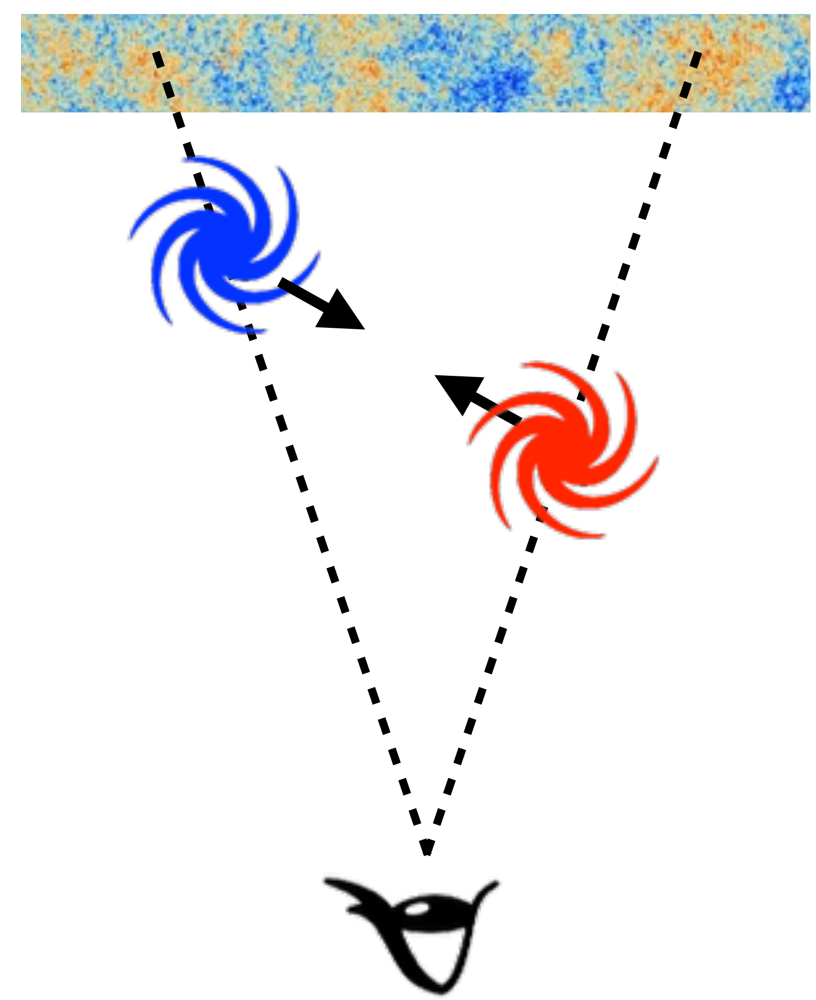
Velocity reconstruction

Planck15, ES Ferraro+16

<T^2 x tracer>, Hill+16, Ferraro+16

T Power spectrum, George Reichardt+14

T^2 power spectrum, Smith Ferraro 16



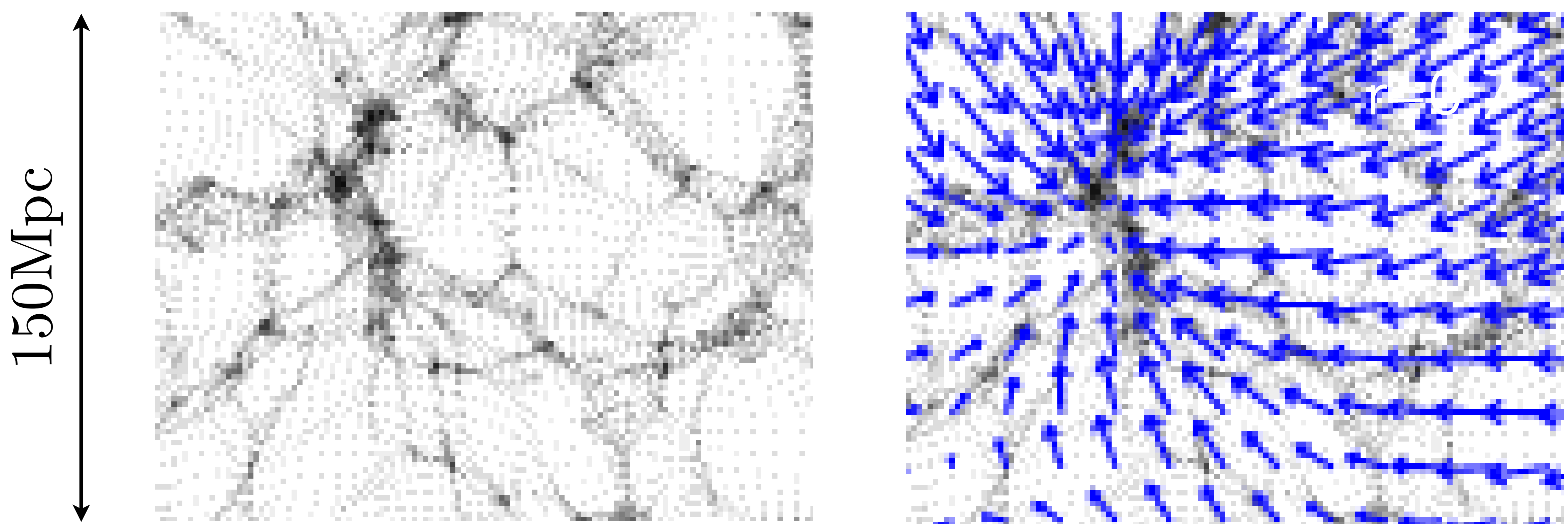
Velocity reconstruction

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

Mass conservation + linear approx.

$$\dot{\delta} + \vec{\nabla} \cdot \vec{v} = 0 \ \Rightarrow \ \vec{v} = -aHf \ \vec{\nabla}\Delta^{-1}\delta$$

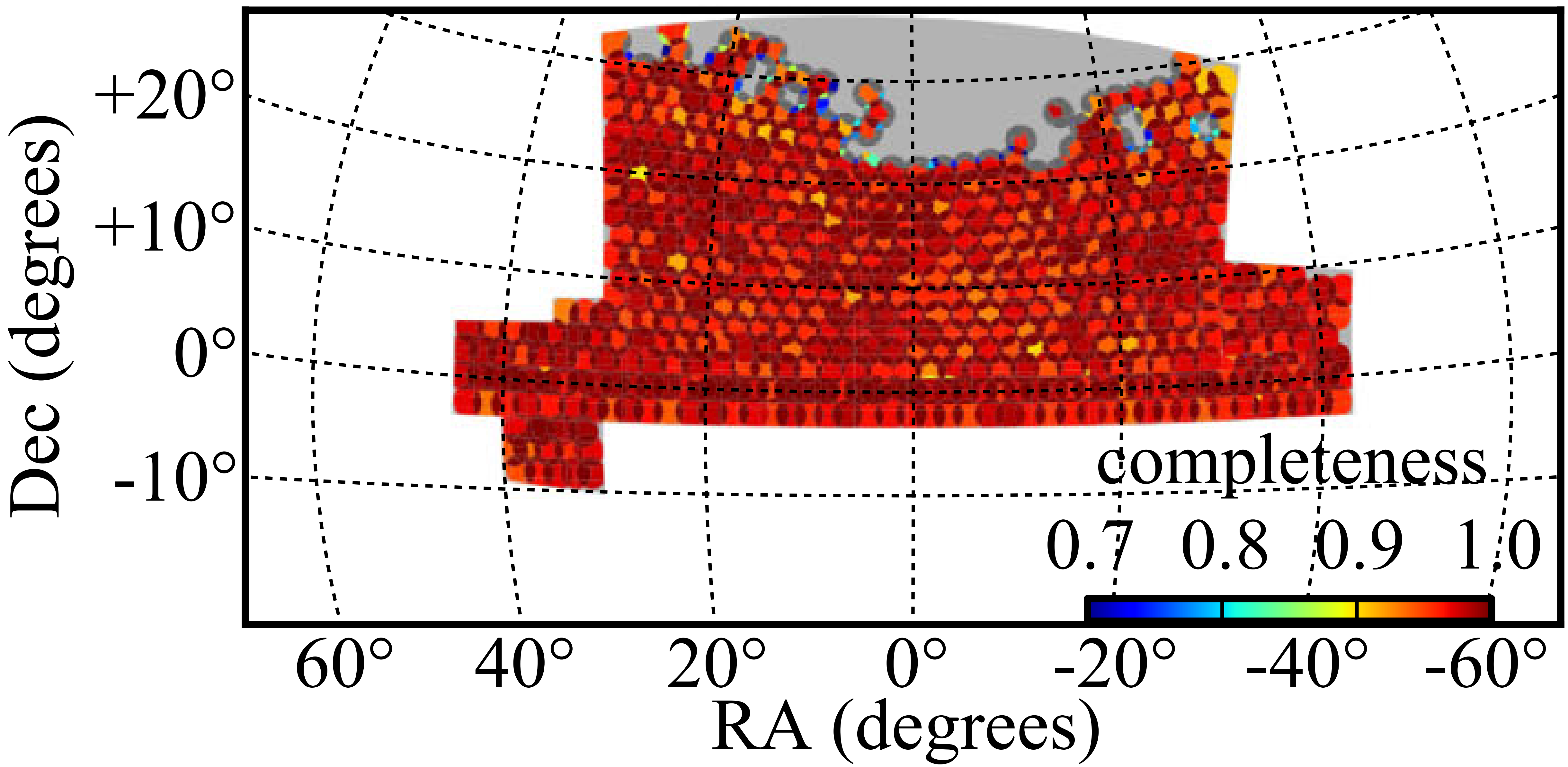
$$\rightarrow v_{\rm rms\ 1d} \sim 300 \ {\rm km/s}$$



Padmanabhan et al. 2014

Velocity reconstruction

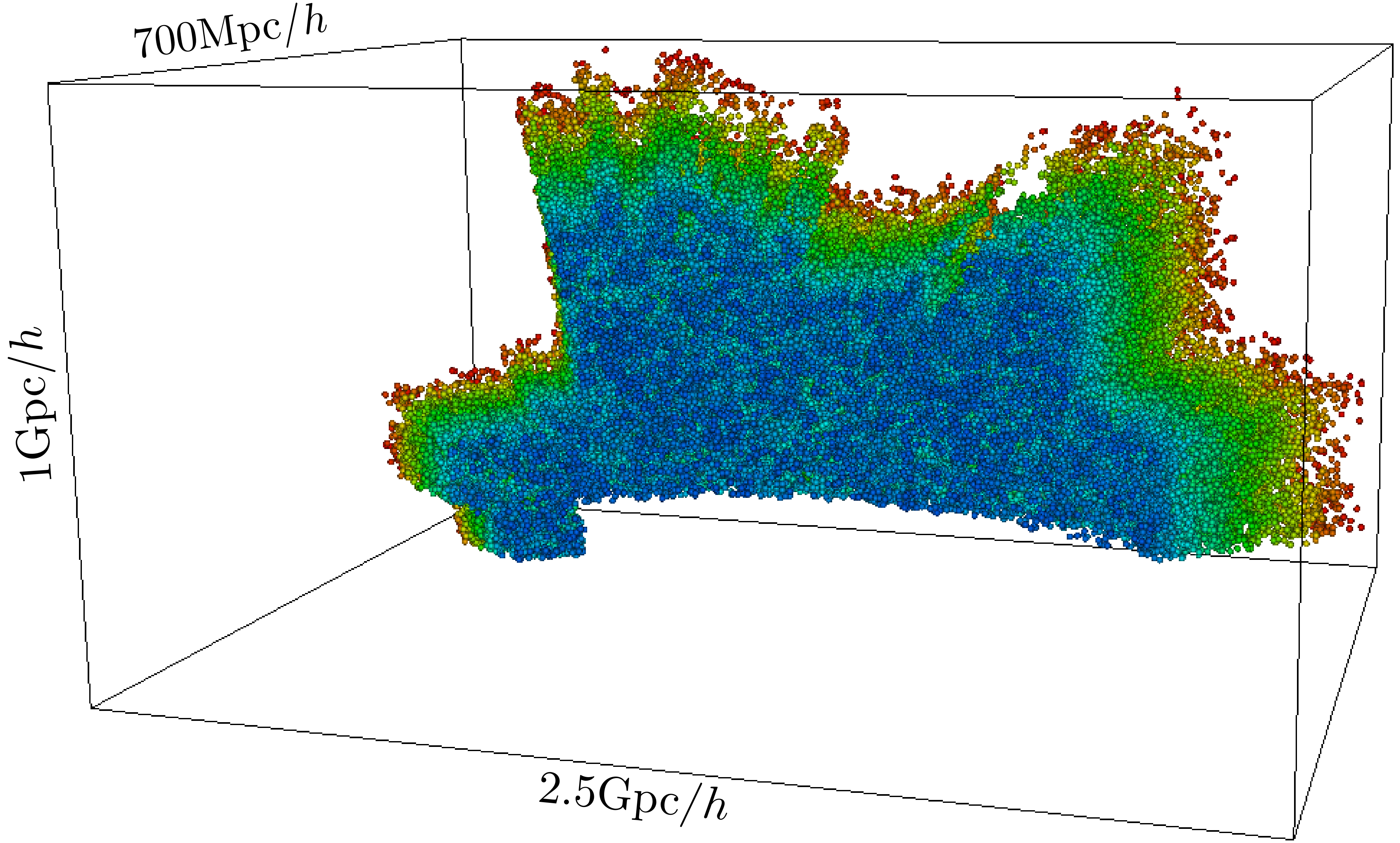
$$\vec{v} = -aHf\ \vec{\nabla}\Delta^{-1}\delta$$



BOSS CMASS South DR11 footprint (sdss.org)

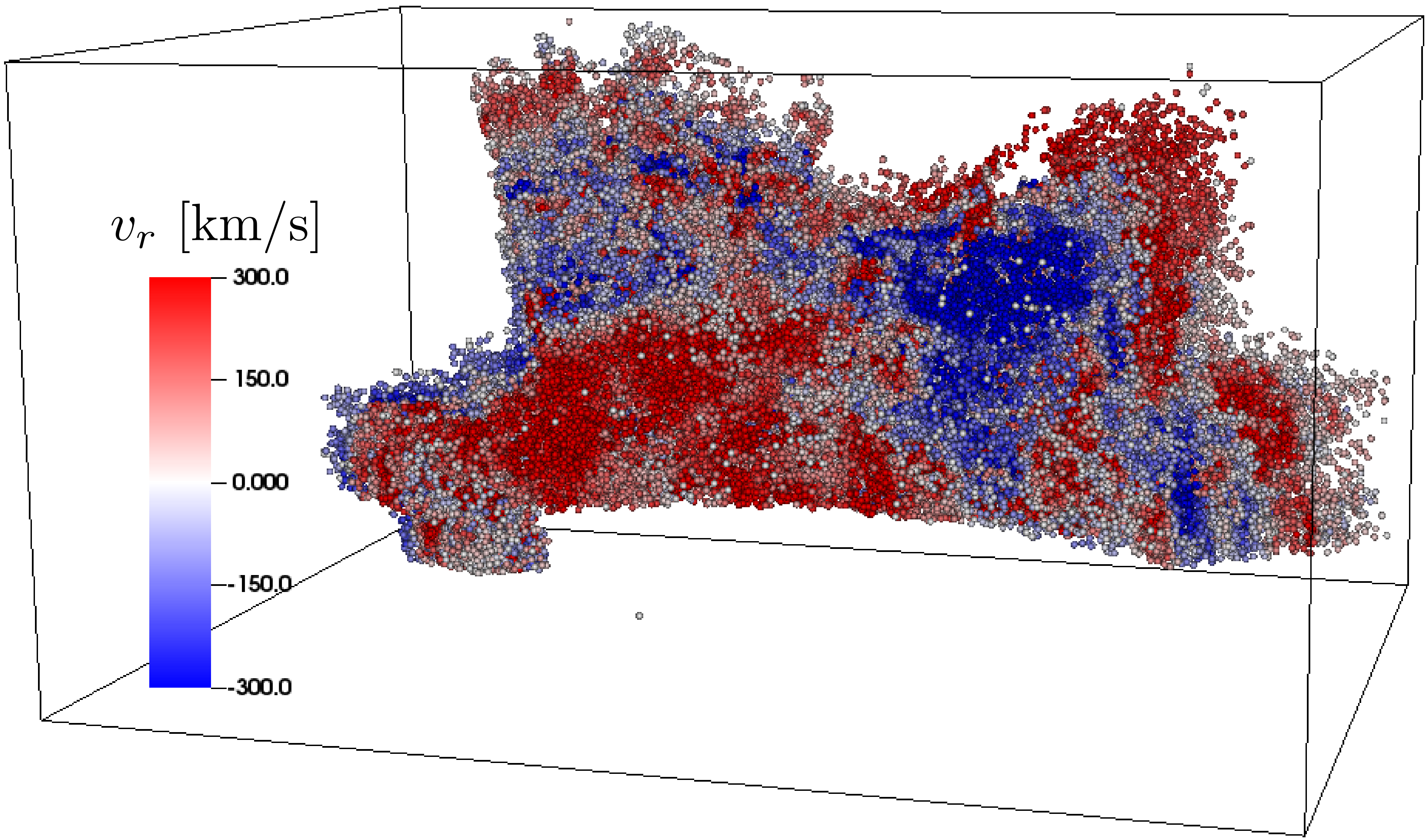
Velocity reconstruction

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



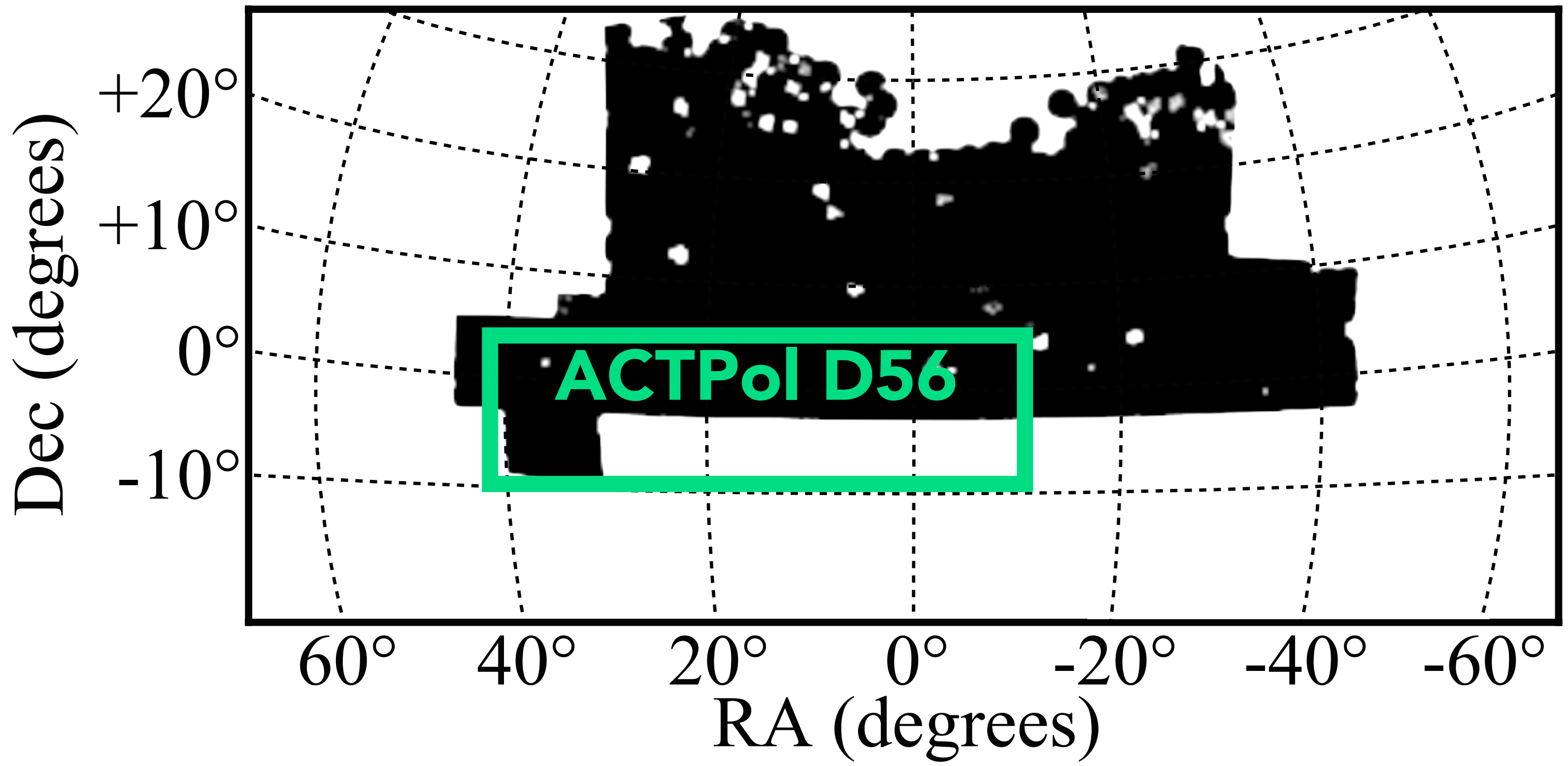
Velocity reconstruction

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



Velocity data from Smith, Vargas-Magaña, Ho

"Halos" from BOSS CMASS



25,000 CMASS DR10 galaxies, 0.4<z<0.7

Central fraction 85%

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 (K. Smith , M. Vargas-Magaña, S. Ho)

→ τ and v_{rec} for each halo

Temperatures from ACTPol

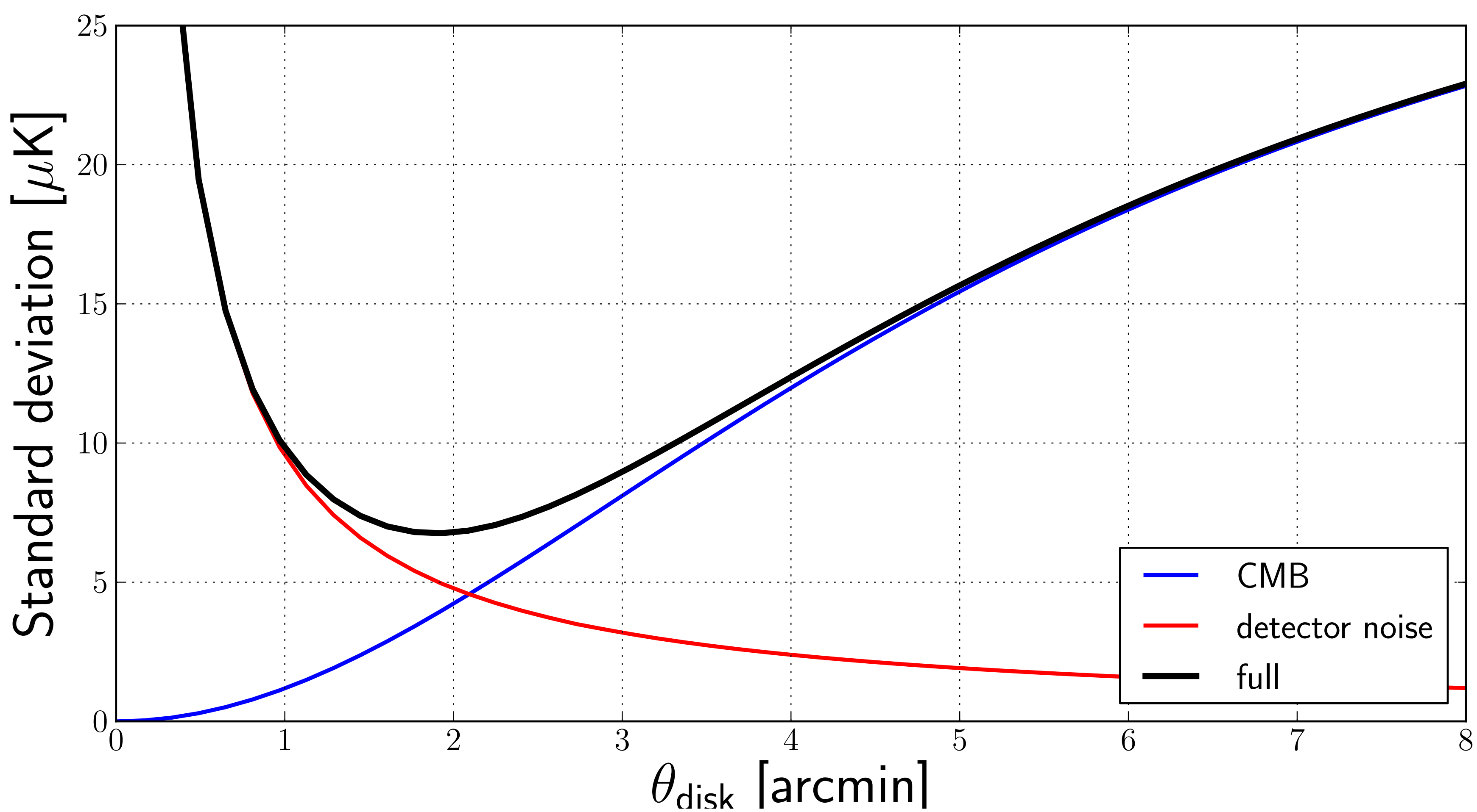
Map at 148GHz

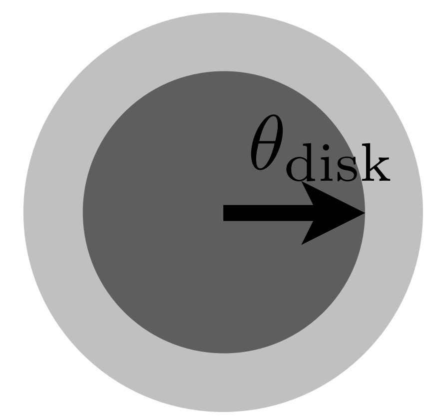
Area 600 sq. deg.

Noise 12muK.arcmin

Beam FWHM 1.4arcmin

Aperture photometry





→δT for each halo

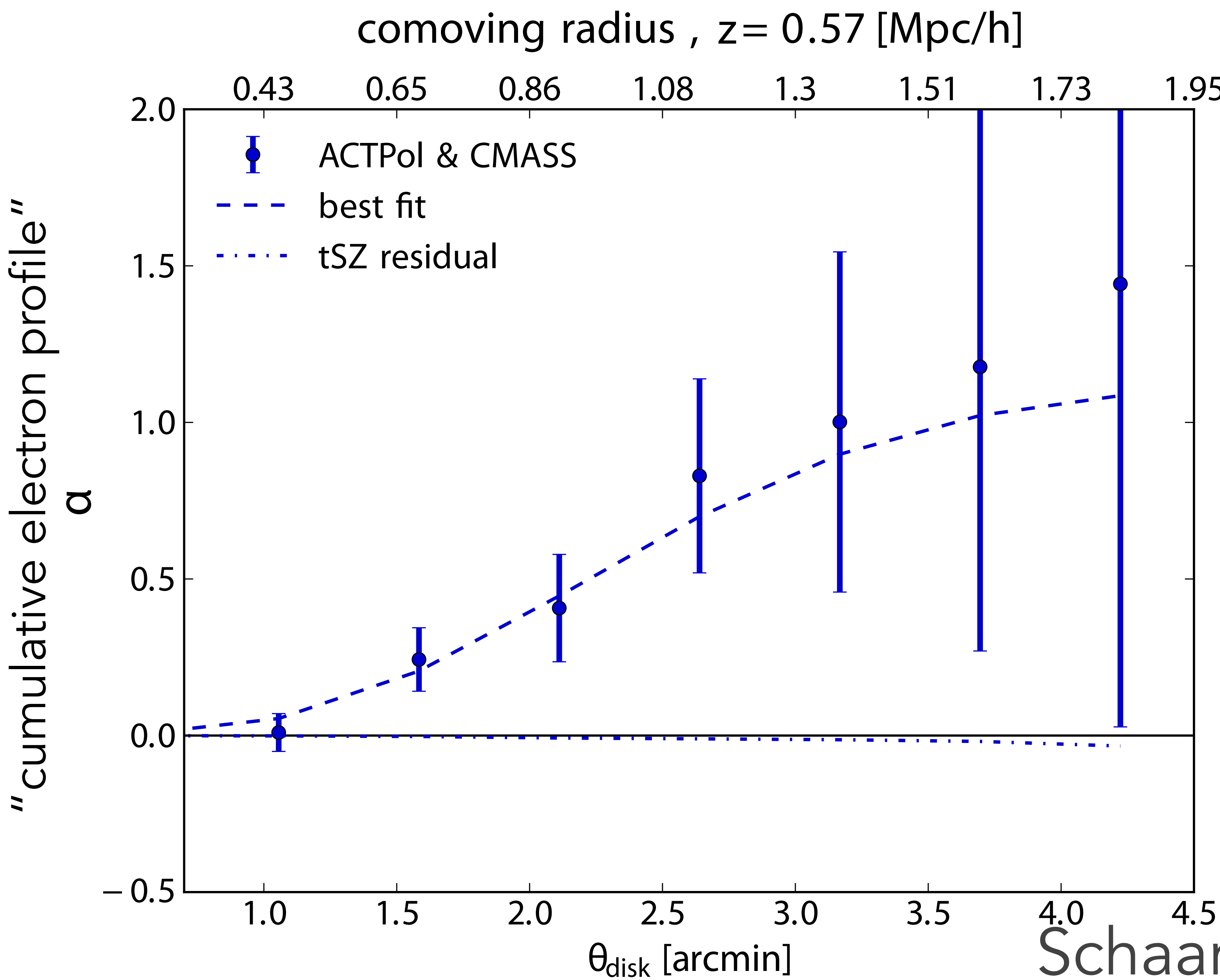
Baryon abundance & profile

Hypothesis: $\delta T \stackrel{?}{=} \alpha\, \tau\, v_{rec} + \text{noise}$

$$\rightarrow \alpha = \frac{\langle \delta T_{(\theta_{\rm disk})} \times \tau v_{\rm rec} \rangle}{\langle \tau v_{\rm rec} \times \tau v_{\rm rec} \rangle}$$

- $\alpha \simeq 0 \Leftrightarrow$ no detection
- $\alpha \simeq 1 \Leftrightarrow$ cosmological baryon abundance
- varying $\theta_{disk} \rightarrow$ profile information

Gas profile of CMASS halos

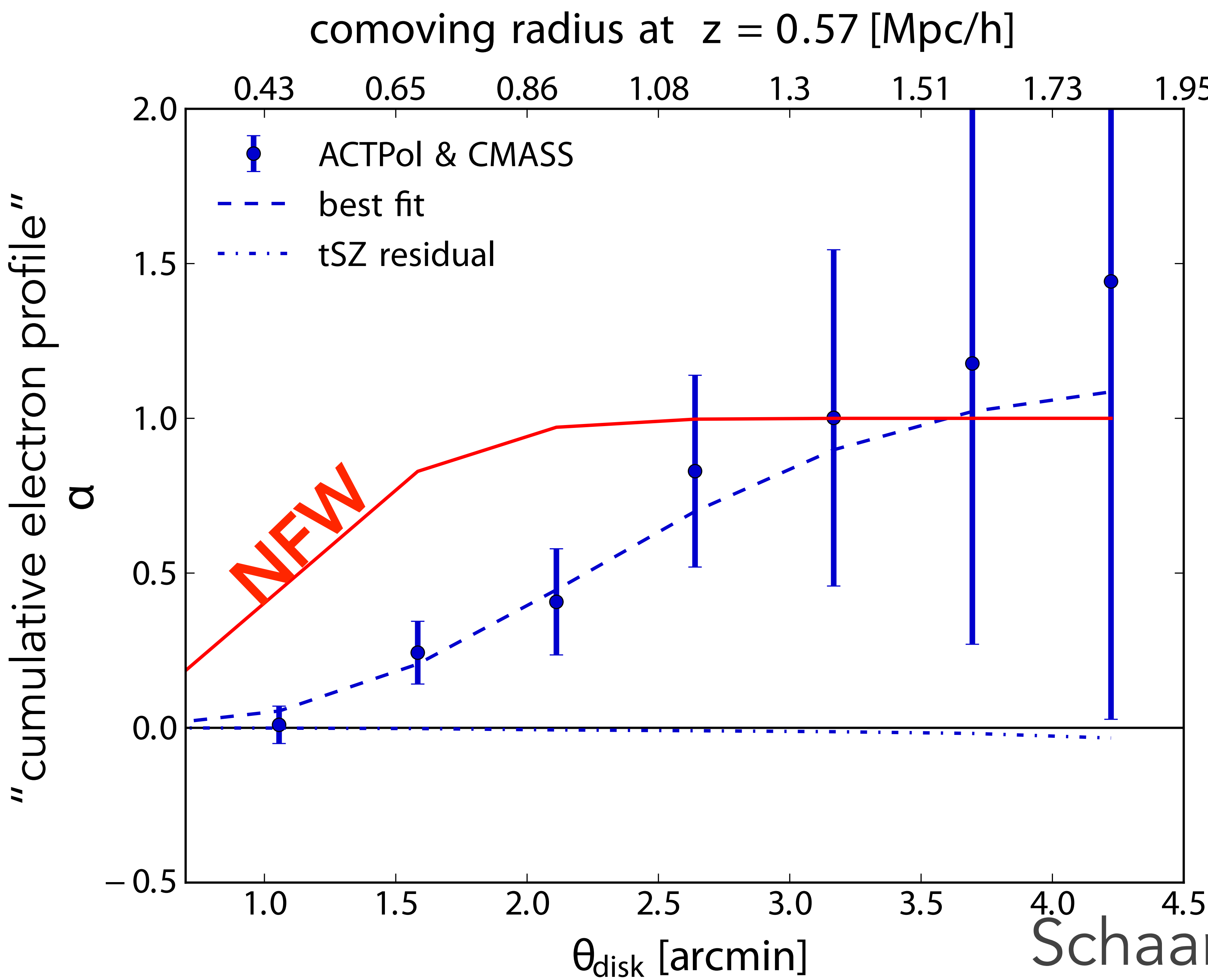


Schaan Ferraro +15

→ kSZ model preferred over null at 3 σ

→ Proxy for gas profile in clusters

Gas profile of CMASS halos



Schaan Ferraro +15

→ kSZ model preferred over null at 3 σ

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Future prospects

Tracer sample: SNR ~ (1 to 2) * ($M_h/10^{13}M_{sun}$) * sqrt($N_{obj}/10^4$)

- this study (CMASS) 3×10^4 gal, $0.4<z<0.7$
- Full CMASS 4×10^5, $0.4<z<0.7$
- PFS 10^7 gal, $0.8<z<2.4$
- DESI 2×10^7 gal, $z<2$

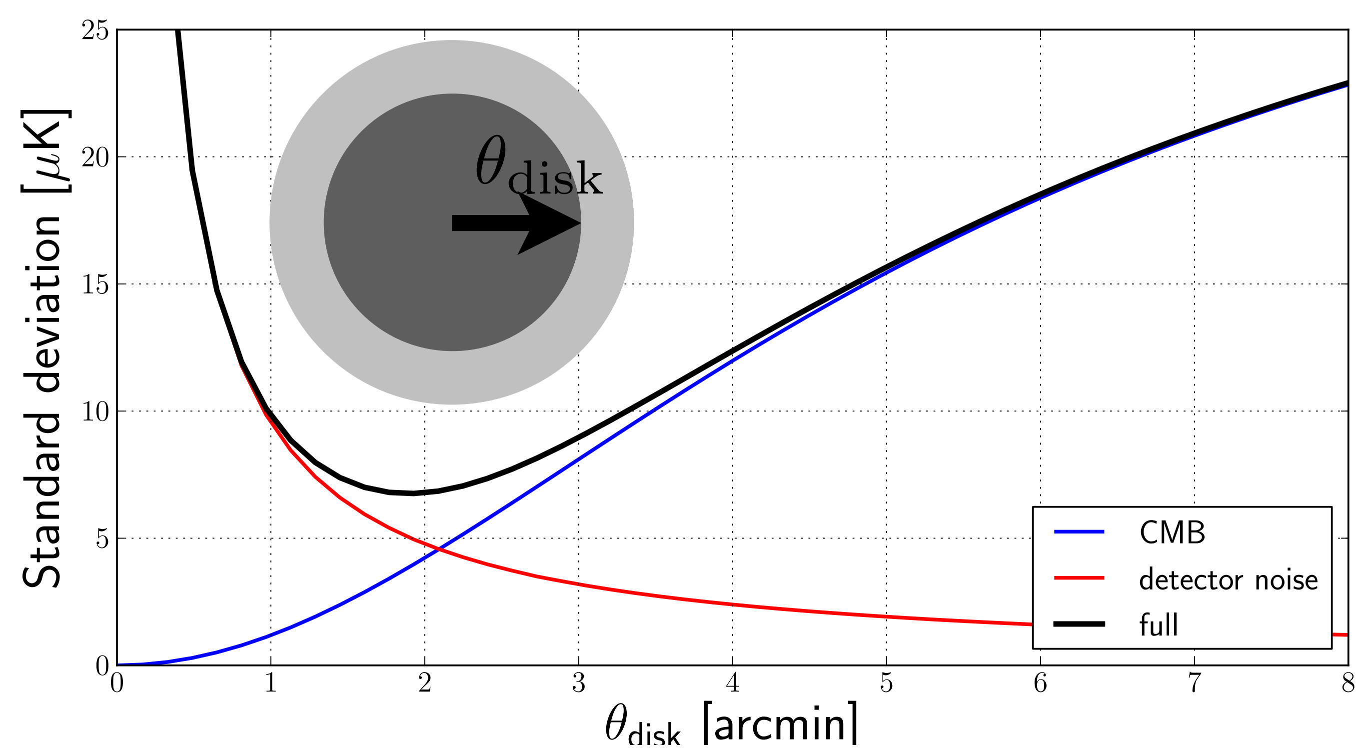
→ **SNR x 10 from number**

CMB map:

- this study (ACTPol) 14muK', 1.4',
- AdvACT 7muK', 1.4', multifreq.
- CMB S4 1muK', ?, multifreq.

→ **SNR x few from sensitivity**

→ **SNR x few from tSZ removal**



→ Large SNR: gas profile, 1h/2h, binning in mass/type

Non-thermal pressure / energy injection

$$\begin{cases} \mathrm{kSZ} = \tau \left(\frac{v_{e,LOS}}{c}\right) \propto \rho_e \text{ gas density} \\ \mathrm{tSZ} = \tau \left(\frac{v_{e,th}}{c}\right)^2 \propto P_{e,th} \text{ gas thermal pressure} \end{cases}$$

Virial theorem:

$$\Phi_{\mathrm{gas+DM/gas}} + 3\mathcal{V}\left[< P_{\mathrm{th}} > + < P_{\mathrm{non\text{-}th}} > - P_{\mathrm{surface}}\right] = 0$$

kSZ lensing tSZ

modeled from accretion rate

→ Constrain $P_{\mathrm{non\text{-}th}}$, as a function of radius

→ Constrain energy injected?

Summary: kSZ detection & gas physics in clusters

arXiv:1510.06442

- **Evidence for kSZ with ACTPol and velocity reconstruction from BOSS**
- **KSZ powerful baryometer: profile, abundance**
- **Constrain non-thermal pressure and energy injection with kSZ & tSZ?**
- CMB S4 and DESI will multiply the SNR by >10
  → bin in mass/type/color