



Cross correlations and Cosmic Flows

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Why cross-correlate?

$$A = S + N_A$$

$$\langle S \rangle = \langle N_A \rangle = 0$$

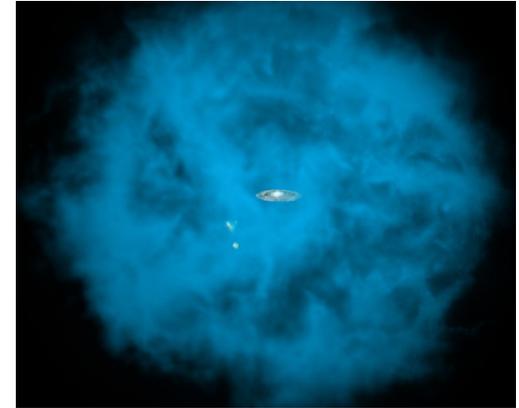
Auto-correlation $\langle A^2 \rangle = \langle S^2 \rangle + \langle N_A^2 \rangle$  **bias**

Second tracer $B = S + N_B$

Cross-correlation $\langle A B \rangle = \langle S^2 \rangle$ **unbiased if**
 $\langle N_A N_B \rangle = 0$

- Bias \rightarrow Noise
- More robust to systematics
- Can isolate only part of the signal (eg. coming from a given redshift or population)
- Can enhance S/N

Kinematic Sunyaev-Zel'dovich effect



Cosmic velocities:
Growth of structure
Dark Energy/Modified gravity
Neutrinos

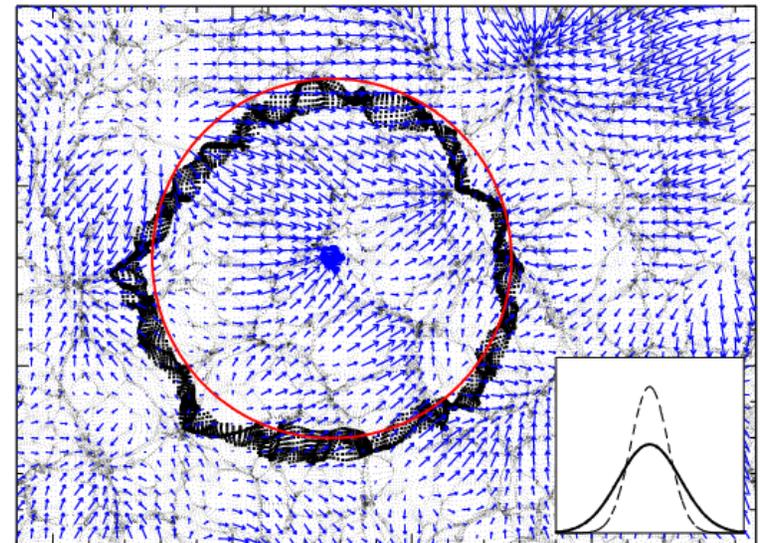
Astrophysics:
Missing baryons
Star formation
....

Cosmic velocities

Velocity related to density (continuity equation):

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

$$\mathbf{v} \approx \frac{i\mathbf{k}}{k^2} \dot{\delta} = aH \underbrace{f_g}_{\text{Growth rate}} \frac{i\mathbf{k}}{k^2} \delta$$



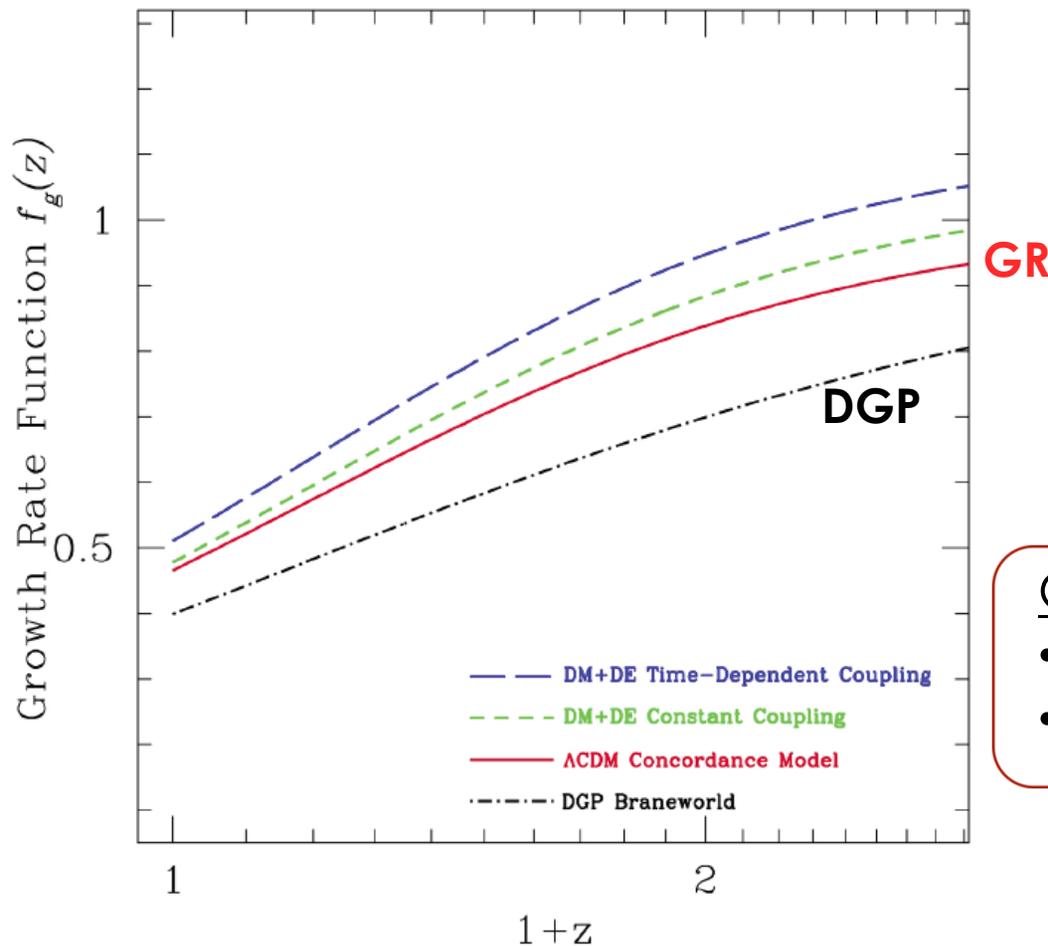
Growth rate $f_g = \frac{d \ln \delta}{d \ln a} \approx [\Omega_m(z)]^\gamma$

$$\gamma \approx 0.55 \text{ in GR}$$

Linder (2005)

Growth factor as a probe of GR

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

Growth factor:

- Sensitive probe of gravity
- Cosmological information

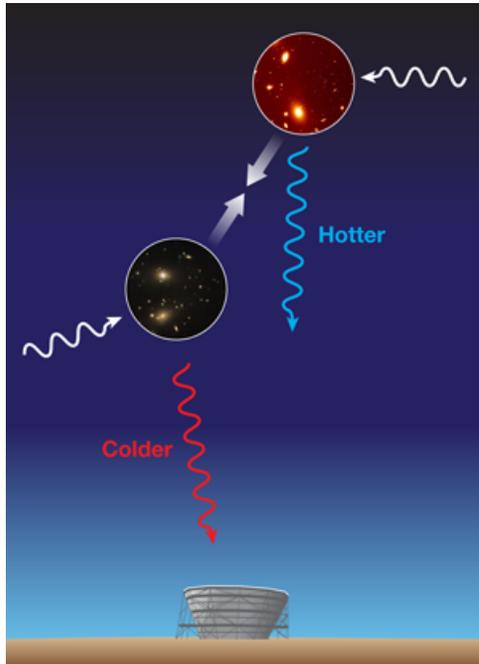
Guzzo et al (2005)

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

Kinematic Sunyaev-Zel'dovich effect

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



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

Sunyaev,
Zel'dovich
(1970)

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

Preserves Black Body spectrum of CMB!

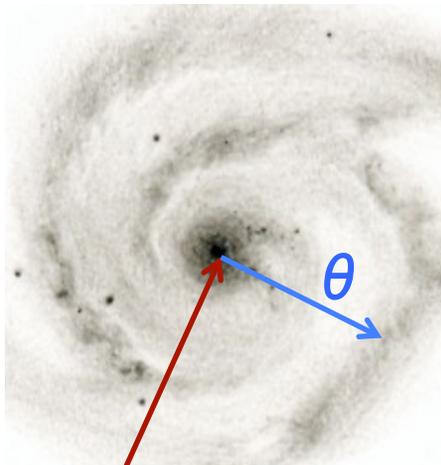
$$\Delta T^{\text{kSZ}} \approx \underline{\underline{-0.1 \mu\text{K}}} \times f_{\text{free}} \left(M_{200}/10^{13} M_{\odot} \right) \left(v_e \cdot \hat{\mathbf{n}}/300 \text{ km s}^{-1} \right)$$

Fraction of free electrons

What do we measure?

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$$\left(\frac{\Delta T}{T}\right)_{\text{kSZ}}(\mathbf{x} + \boldsymbol{\theta}) = -\tau(\boldsymbol{\theta}) v_r(\mathbf{x}) \quad (+ 2\text{-halo})$$



Origin

gas profile

$$\tau(\boldsymbol{\theta}) = \int dl n_e(\boldsymbol{\theta}, l) \sigma_T$$

Only ionized gas contributes

Azimutally averaged

$$\tau(\boldsymbol{\theta}) = \bar{\tau} u(\boldsymbol{\theta})$$

'bulk' radial velocity

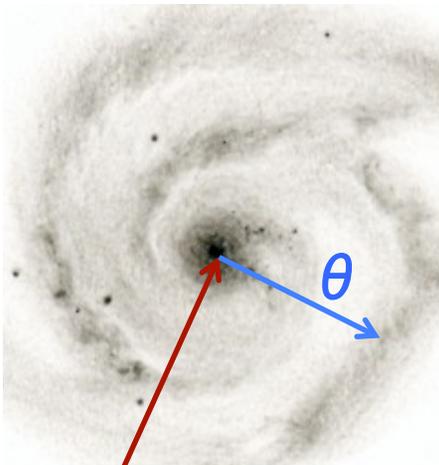
Velocity of center of mass

Assumed independent of θ

Large coherence length (~ 50 Mpc)

Two cross correlations

$$\left(\frac{\Delta T}{T}\right)_{\text{kSZ}}(\mathbf{x} + \boldsymbol{\theta}) = -\tau(\boldsymbol{\theta}) v_r(\mathbf{x}) \quad (+ 2\text{-halo})$$



- Vary \mathbf{x} at fixed $\boldsymbol{\theta}$ \rightarrow cosmology
Probe velocity field on large scales
- Vary $\boldsymbol{\theta}$ at fixed \mathbf{x} \rightarrow astrophysics
Probe gas profile and abundance.

Independent of each other, except for overall normalization.

Origin

Probing cosmology

If we know the cluster optical depths τ_i . Fix $\theta = \theta_*$

$$\left\langle \frac{\Delta T}{T}(\mathbf{x}_i; \theta_*) \bar{\tau}_j v_r^{\text{rec}}(\mathbf{x}_j) \right\rangle = \bar{\tau}_i \bar{\tau}_j u(\theta_*) \underbrace{\langle v_r^{\text{true}}(\mathbf{x}_i) v_r^{\text{rec}}(\mathbf{x}_j) \rangle}_{\text{Velocity correlation with lag } r = |\mathbf{x}_i - \mathbf{x}_j|}$$

Fixed “aperture” \nearrow “reconstructed” velocity from δ_{3D} + continuity eq

$$\text{This is } \xi_{pT}(r) \propto \bar{\tau}_i \bar{\tau}_j u(\theta_*) \left(\frac{f_g^{\text{true}}}{f_g^{\text{fid}}} \right) \xi_v^{\text{fid}}(r)$$

NOTES:

- Normalization is astrophysics dependent!
- May be able to break the degeneracy with external probes of optical depth and profile (tSZ, X-rays, ...)
- More work needed

Probing cosmology

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$$\xi_{pT}(r) \propto \bar{\tau}_i \bar{\tau}_j u(\theta_*) \left(\frac{f_g^{\text{true}}}{f_g^{\text{fid}}} \right) \xi_v^{\text{fid}}(r)$$

BUT... scale dependence is independent of astrophysics!

$$\frac{\xi_{pT}(k_1)}{\xi_{pT}(k_2)} = \left(\frac{f_g^{\text{true}}(k_1)}{f_g^{\text{true}}(k_2)} \right) \frac{\xi_v^{\text{fid}}(k_1)}{\xi_v^{\text{fid}}(k_2)}$$

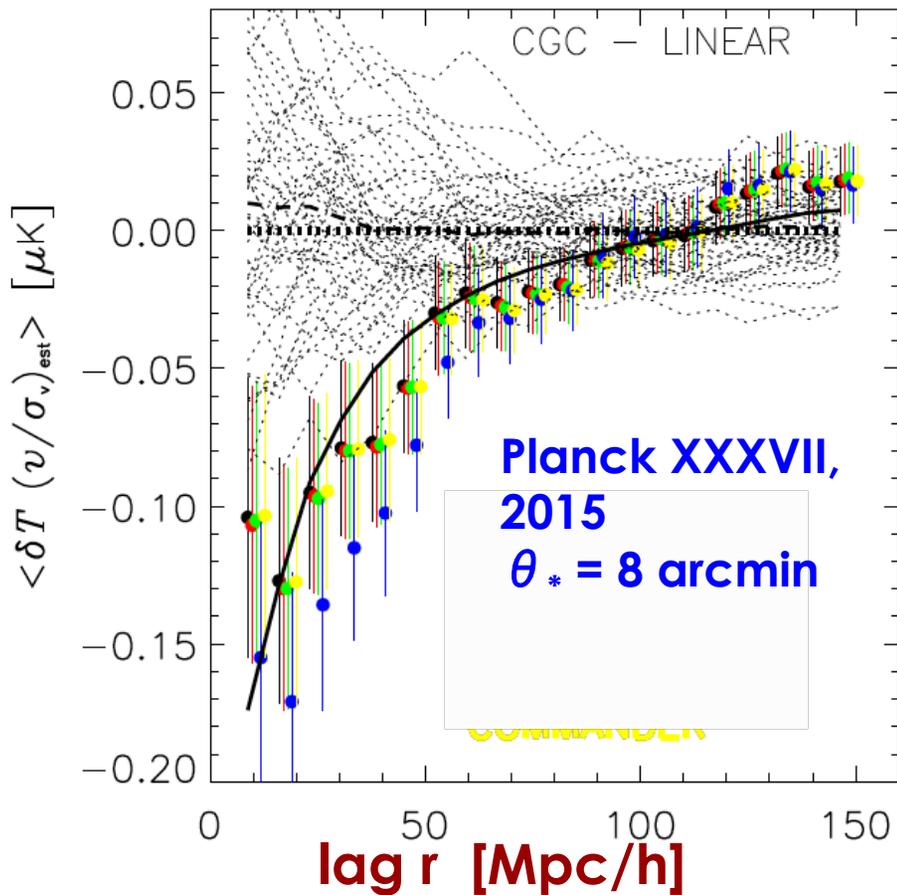
Robust probe of scale dependent growth: massive neutrinos and scale dependent modified gravity / Dark Energy

ALSO: v^{true} and v^{rec} depend on the same modes → can measure f_g with no/reduced cosmic variance!

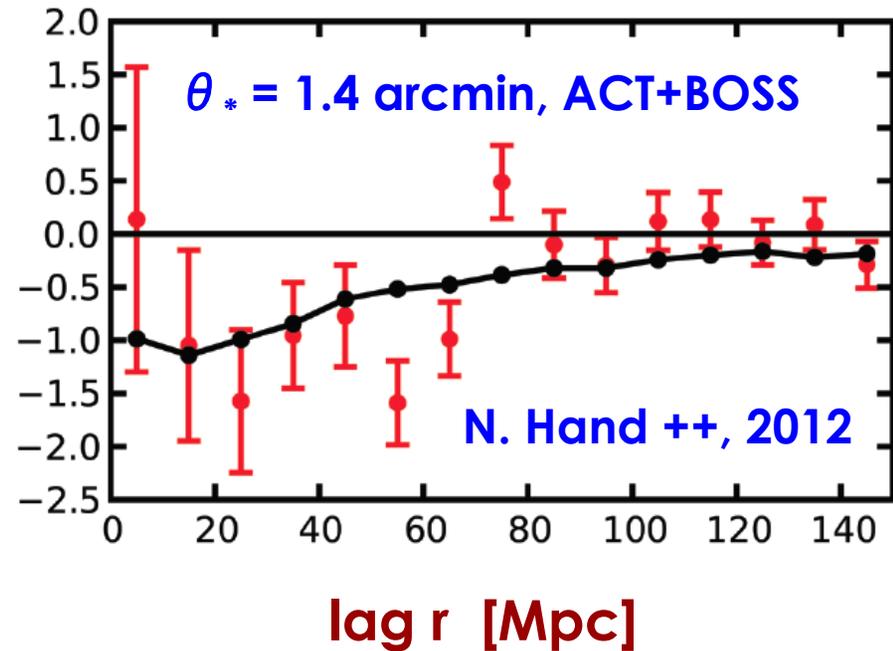
Cosmology examples

$$\left\langle \frac{\Delta T}{T}(\mathbf{x}_i; \theta_*) \bar{\tau}_j v_r^{\text{rec}}(\mathbf{x}_j) \right\rangle = \bar{\tau}_i \bar{\tau}_j u(\theta_*) \langle v_r^{\text{true}}(\mathbf{x}_i) v_r^{\text{rec}}(\mathbf{x}_j) \rangle$$

“velocity reconstruction”



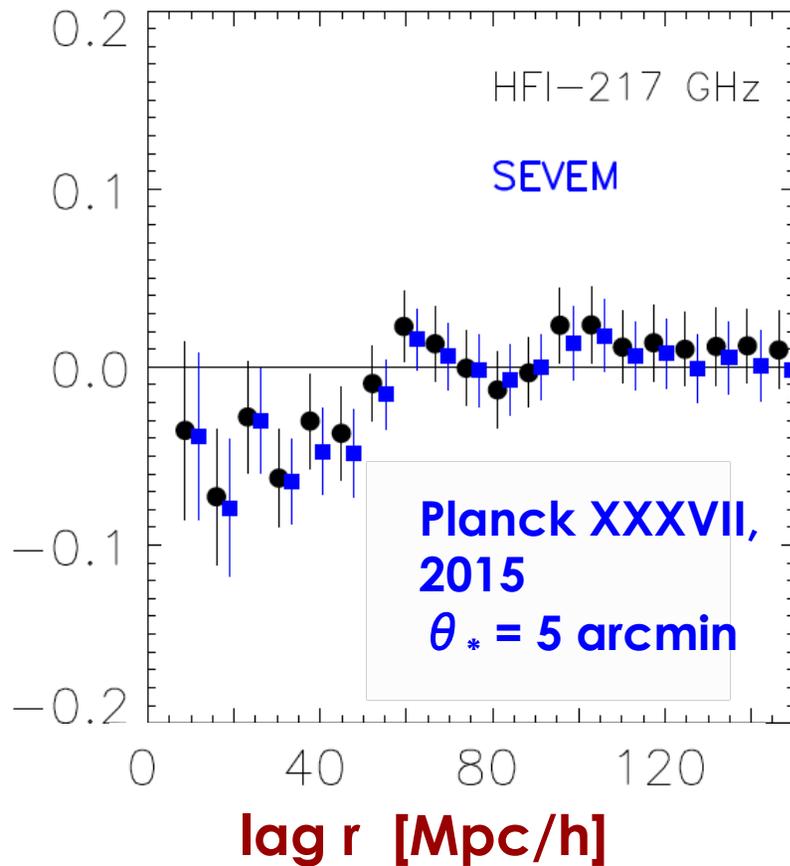
“Pairwise momentum”



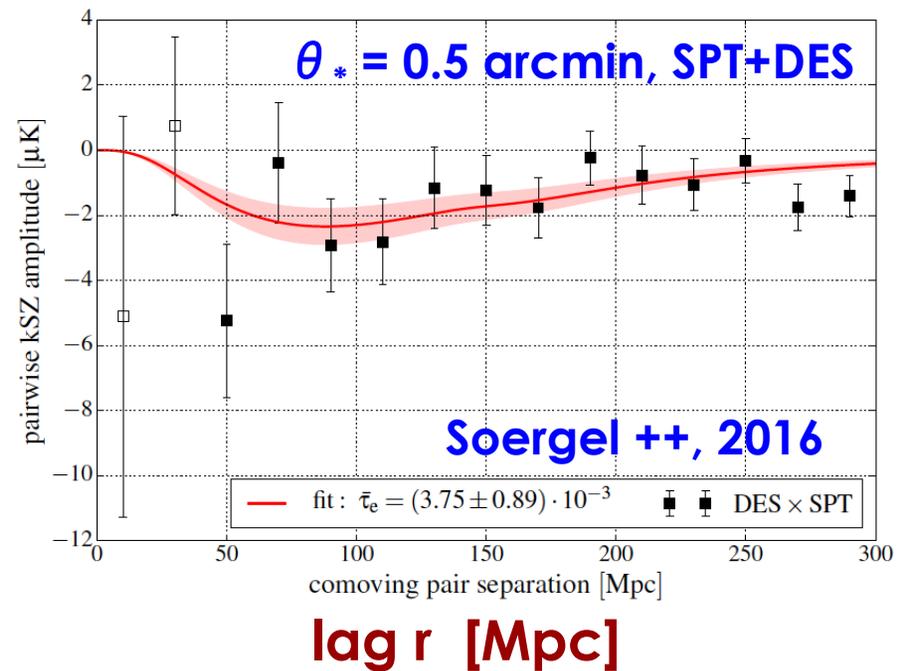
Cosmology examples

$$\left\langle \frac{\Delta T}{T}(\mathbf{x}_i; \theta_*) \bar{\tau}_j v_r^{\text{rec}}(\mathbf{x}_j) \right\rangle = \bar{\tau}_i \bar{\tau}_j u(\theta_*) \langle v_r^{\text{true}}(\mathbf{x}_i) v_r^{\text{rec}}(\mathbf{x}_j) \rangle$$

“Pairwise momentum”

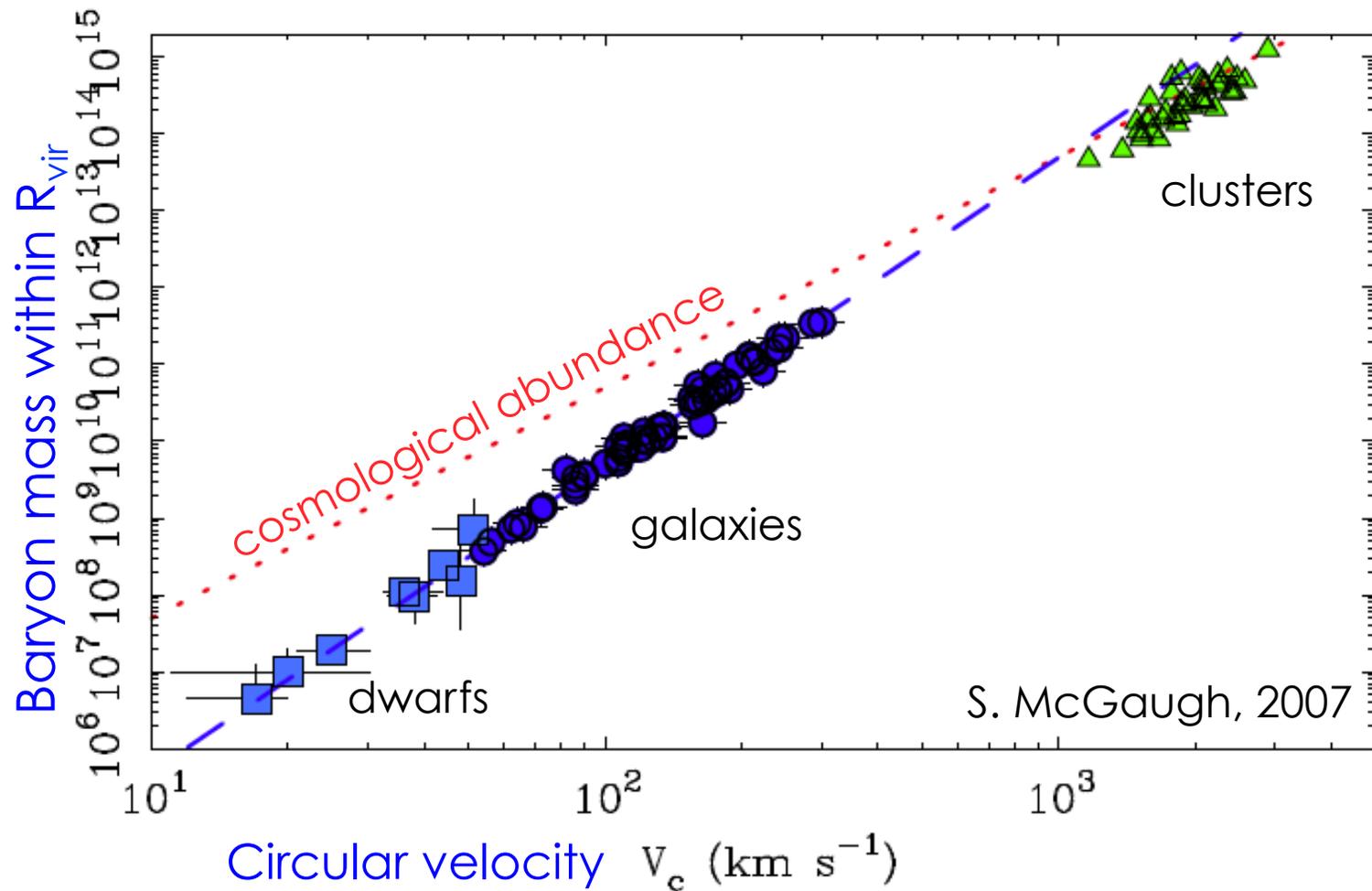


“Pairwise momentum”



Astrophysics and the missing baryons

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Baryons don't trace Dark Matter within R_{vir} !

$$\left\langle \frac{\Delta T}{T}(\mathbf{x}; \theta) \overline{\tau} v_r^{\text{rec}}(\mathbf{x}) \right\rangle (\theta) = \sigma_{v_r}^2 \overline{\tau}^2 u(\theta)$$

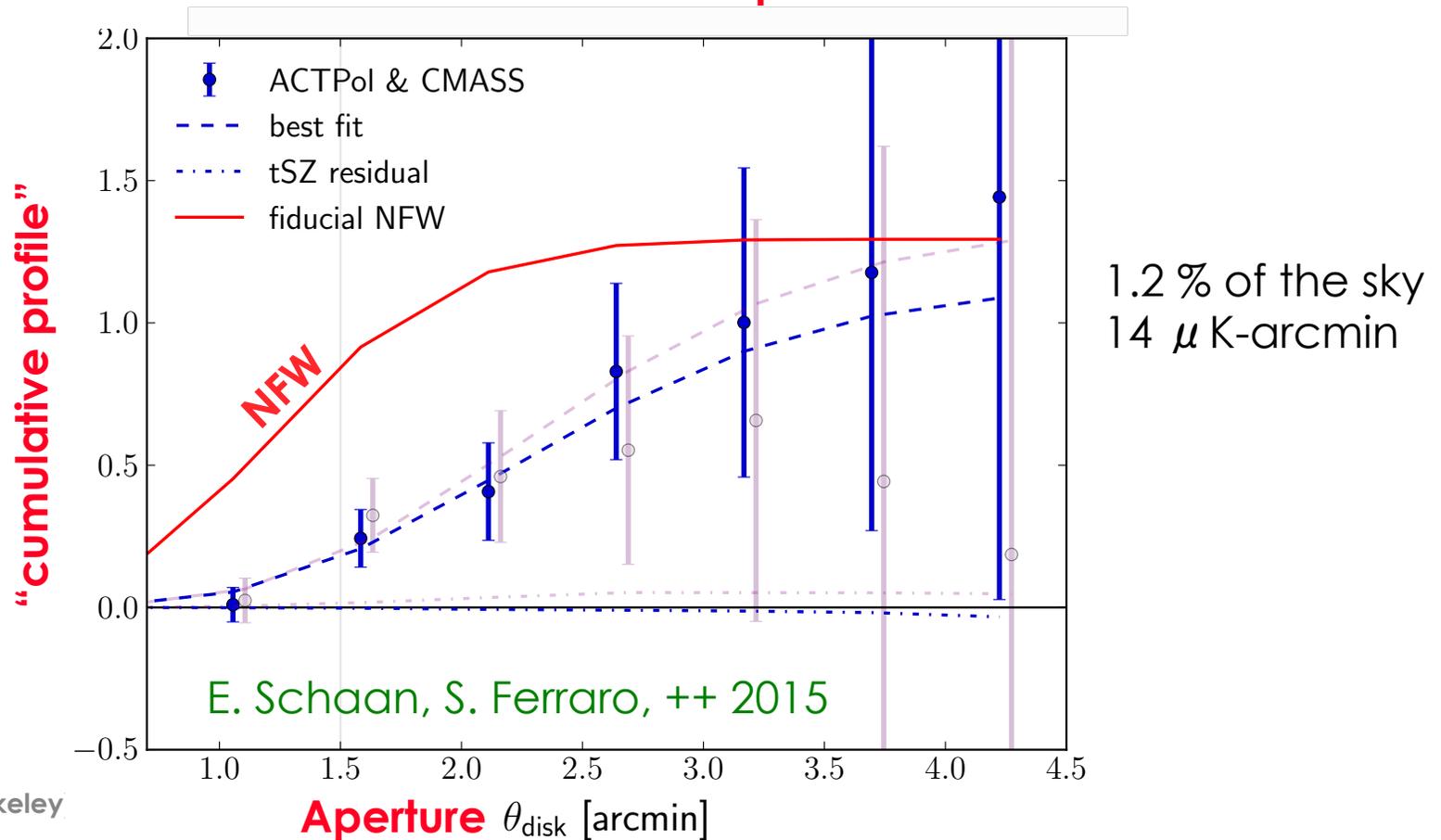
Annotations:

- “aperture” (points to θ)
- zero lag (bracketed above the correlation function)
- 1D velocity dispersion (independent of θ) (points to $\sigma_{v_r}^2$)
- optical depth (points to $\overline{\tau}^2$)
- profile (points to $u(\theta)$)

- Measure at zero-lag ($r = 0$) and vary aperture θ
- Can measure profile and optical depth
- Cosmology is just a normalization (independent of θ)
- (normalized) profile is independent of cosmology

Astrophysics example

$$\left\langle \frac{\Delta T}{T}(\mathbf{x}; \theta) \overbrace{\bar{\tau} v_r^{\text{rec}}(\mathbf{x})}^{\text{zero lag}} \right\rangle (\theta) = \sigma_{v_r}^2 \overbrace{\bar{\tau}^2}^{\text{optical depth}} \underbrace{u(\theta)}_{\text{profile}}$$



Astrophysics

- Profile and optical depth
- Compare different populations! Mass, redshift, color, presence of AGN, ...
- Complementary to tSZ, X-ray, lensing → can constrain thermal & non-thermal pressure, energy injection and feedback
- Ellipticity, filaments, etc
- Very nice foreground properties (foregrounds uncorrelated with velocity average out)

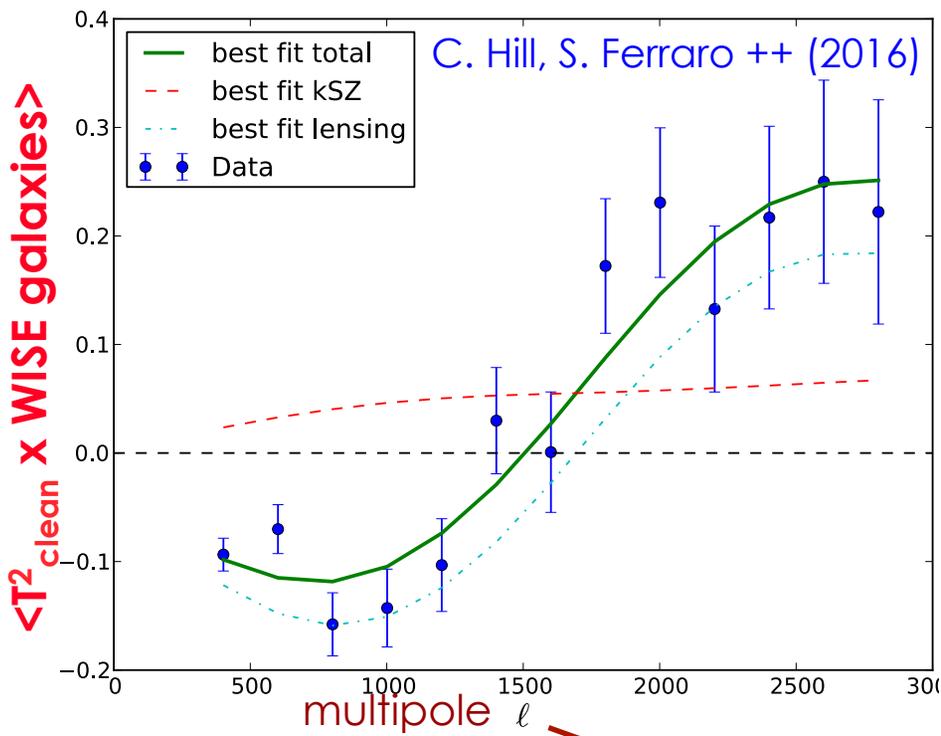
Do we need accurate redshifts?

Can use projected fields!

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

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

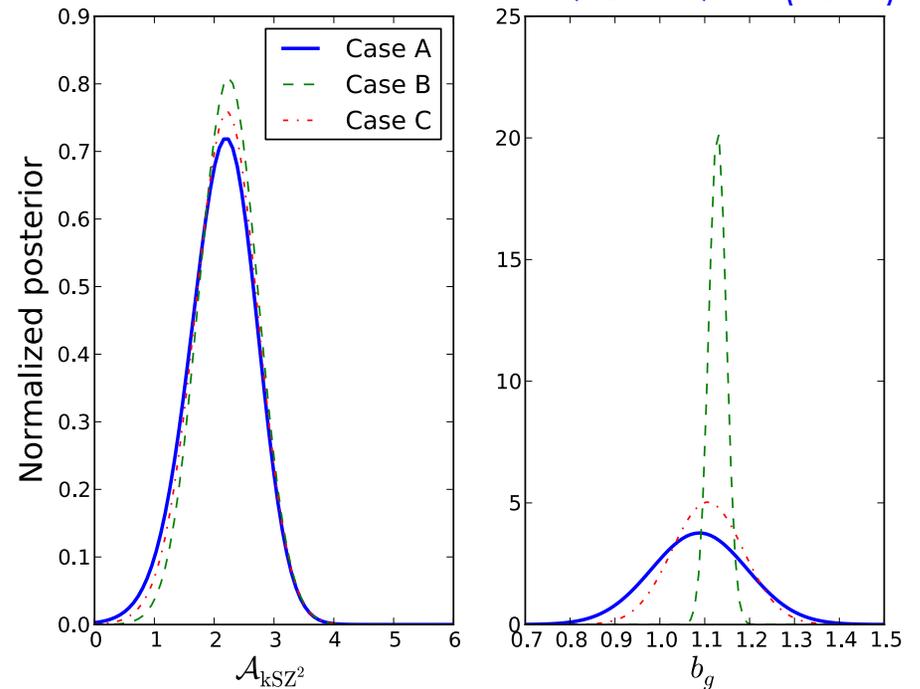
Doré et al (2003)



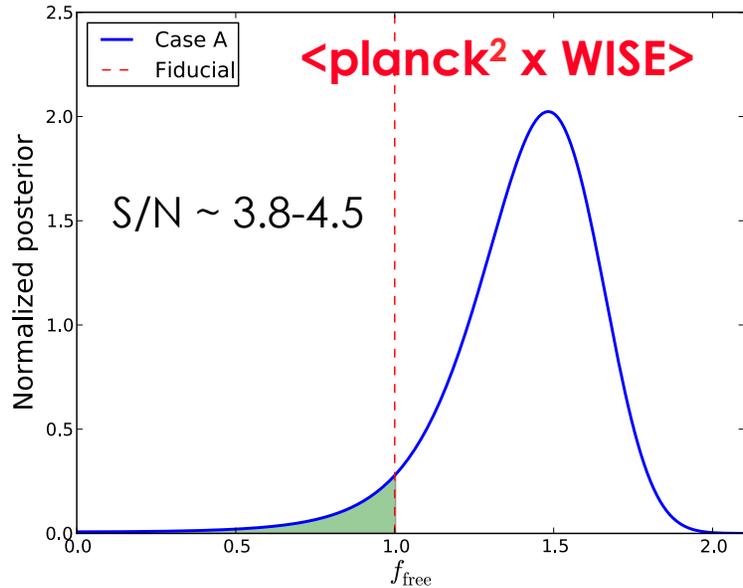
Simone Ferraro (Berkeley)

F.T. of aperture

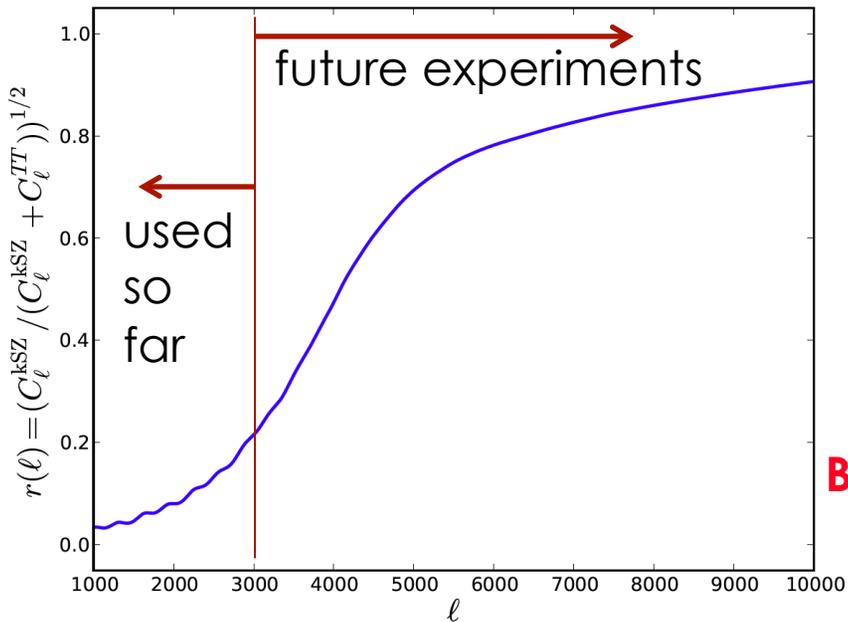
S. Ferraro, C. Hill, ++ (2016)



kSZ with projected fields



CMB experiment	beam FWHM [arcmin]	effective noise ^a Δ_T [$\mu\text{K}\cdot\text{arcmin}$]
<i>Planck</i> (2015 LGMCA map)	5	47
<i>Advanced ACTPol</i>	1.4	10
<i>CMB-S4</i> (case 1) ^b	3	3
<i>CMB-S4</i> (case 2)	1	3
<i>CMB-S4</i> (case 3)	3	1
<i>CMB-S4</i> (case 4)	1	1



	f_{sky}	ℓ range	$(\frac{\Delta f_{\text{free}}}{f_{\text{free}}})^{-1}$
<i>Planck</i> \times <i>WISE</i>	0.7	100 - 3000	5.2
<i>Planck</i> \times <i>SPHEREEx</i>	0.7	100 - 3000	5.4
<i>Advanced ACTPol</i> \times <i>WISE</i>	0.5	100 - 8000	232
<i>Advanced ACTPol</i> \times <i>SPHEREEx</i>	0.5	100 - 8000	280
<i>CMB-S4</i> (case 1) \times <i>WISE</i>	0.5	100 - 8000	296
<i>CMB-S4</i> (case 1) \times <i>SPHEREEx</i>	0.5	100 - 8000	356
<i>CMB-S4</i> (case 2) \times <i>WISE</i>	0.5	100 - 8000	704
<i>CMB-S4</i> (case 2) \times <i>SPHEREEx</i>	0.5	100 - 8000	866
<i>CMB-S4</i> (case 3) \times <i>WISE</i>	0.5	100 - 8000	702
<i>CMB-S4</i> (case 3) \times <i>SPHEREEx</i>	0.5	100 - 8000	858
<i>CMB-S4</i> (case 4) \times <i>WISE</i>	0.5	100 - 8000	822
<i>CMB-S4</i> (case 4) \times <i>SPHEREEx</i>	0.5	100 - 8000	1014

BUT CAREFUL with SYSTEMATICS (foregrounds!)

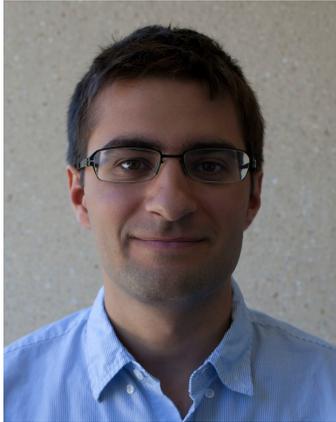
S. Ferraro, C. Hill, ++ (2016)

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

Conclusions

- kSZ is a function of two variables
- Degeneracy between optical depth & growth
- Scale dependence of growth not affected
- Can potentially cancel cosmic variance
- Learn about cluster physics/feedback
- Looking ahead:
 - now: $S/N \sim 4$
 - 1 year: $S/N \sim 10-20$
 - 3 years: $S/N \sim 50-100$
 - 5 years: $S/N \sim 100++$
- Constrain [reionization](#)!

My collaborators



**EMMANUEL
SCHAAN**



**KENDRICK
SMITH**



DAVID SPERGEL



COLIN HILL



NICK BATTAGLIA



**THE ACTPol TEAM
AND MANY OTHERS!**

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