Cosmology with kSZ

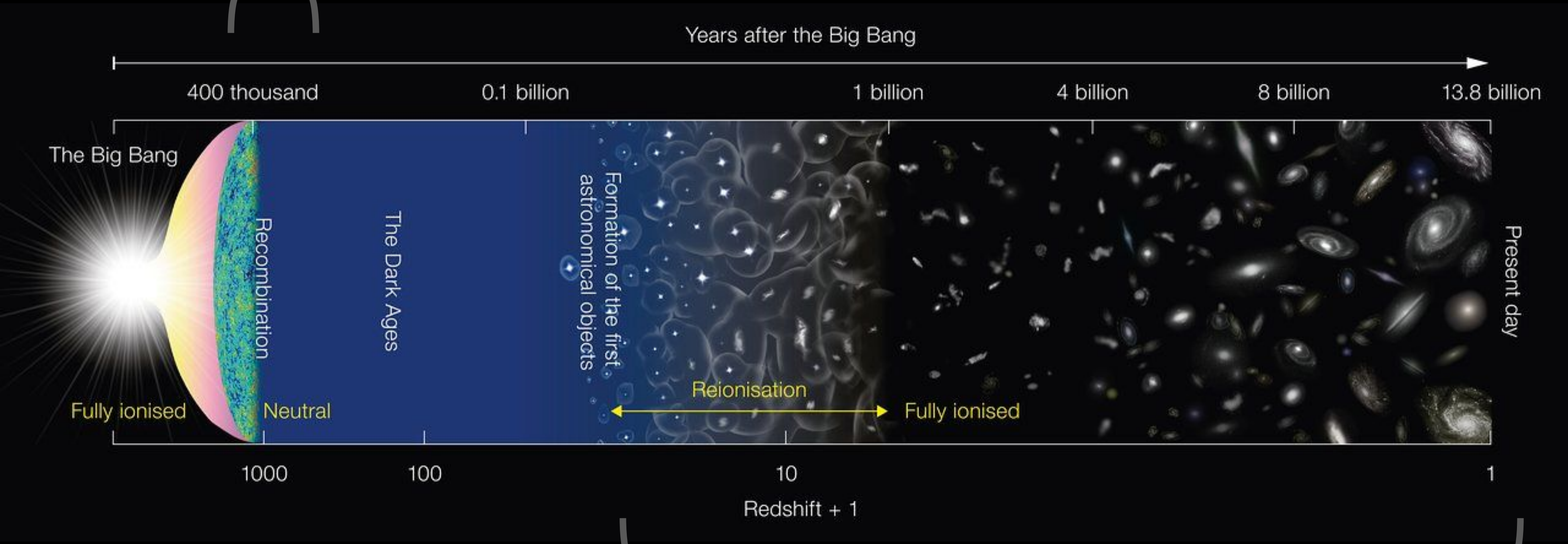
Mathew Madhavacheril

with Nick Battaglia, Colin Hill, Simone Ferraro, Utkarsh Giri, Moritz Munchmeyer, Matt Johnson, Emmanuel Schaan, Jon Sievers, Kendrick Smith

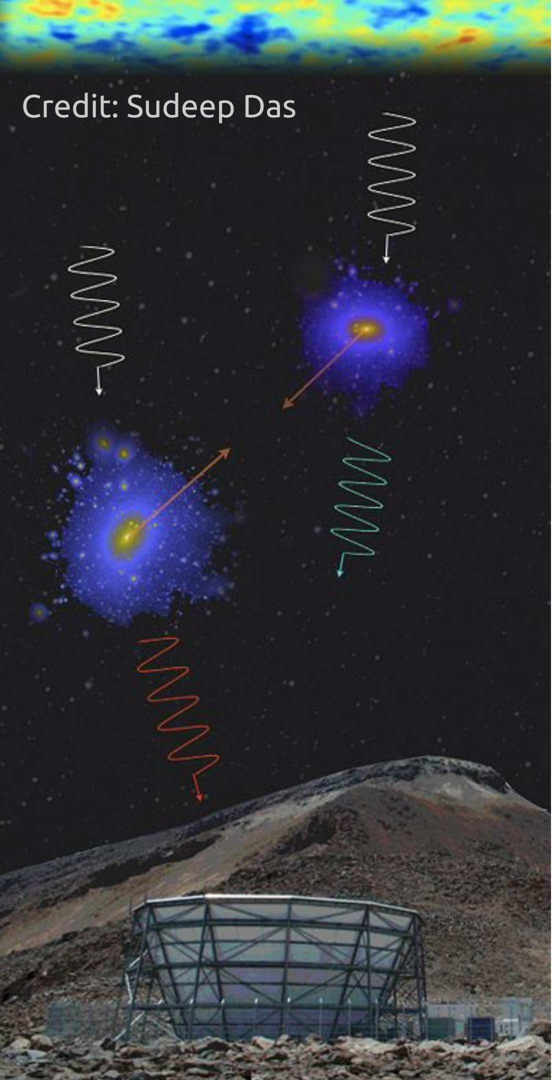
1. What does kSZ measure?
2. Bispectrum formalism — Smith, MM, Ferraro ++ 2018 arXiv:1810.13423
3. Applications
   a. Primordial Non-Gaussianity — Munchmeyer, MM, Ferraro ++ 2018 arXiv:1810.13424
   b. Cosmic growth w/ FRBs — MM, Battaglia, Smith, Sievers 2019 arXiv:1901.02418
   c. Feedback and lensing — (work in progress with Schaan, Battaglia, Ferraro, Hill, ++)

“I’ve been ionized, but I’m OK now.” -- Dr. Buckaroo Banzai

CMB backlight



Lots of (moving) free electrons

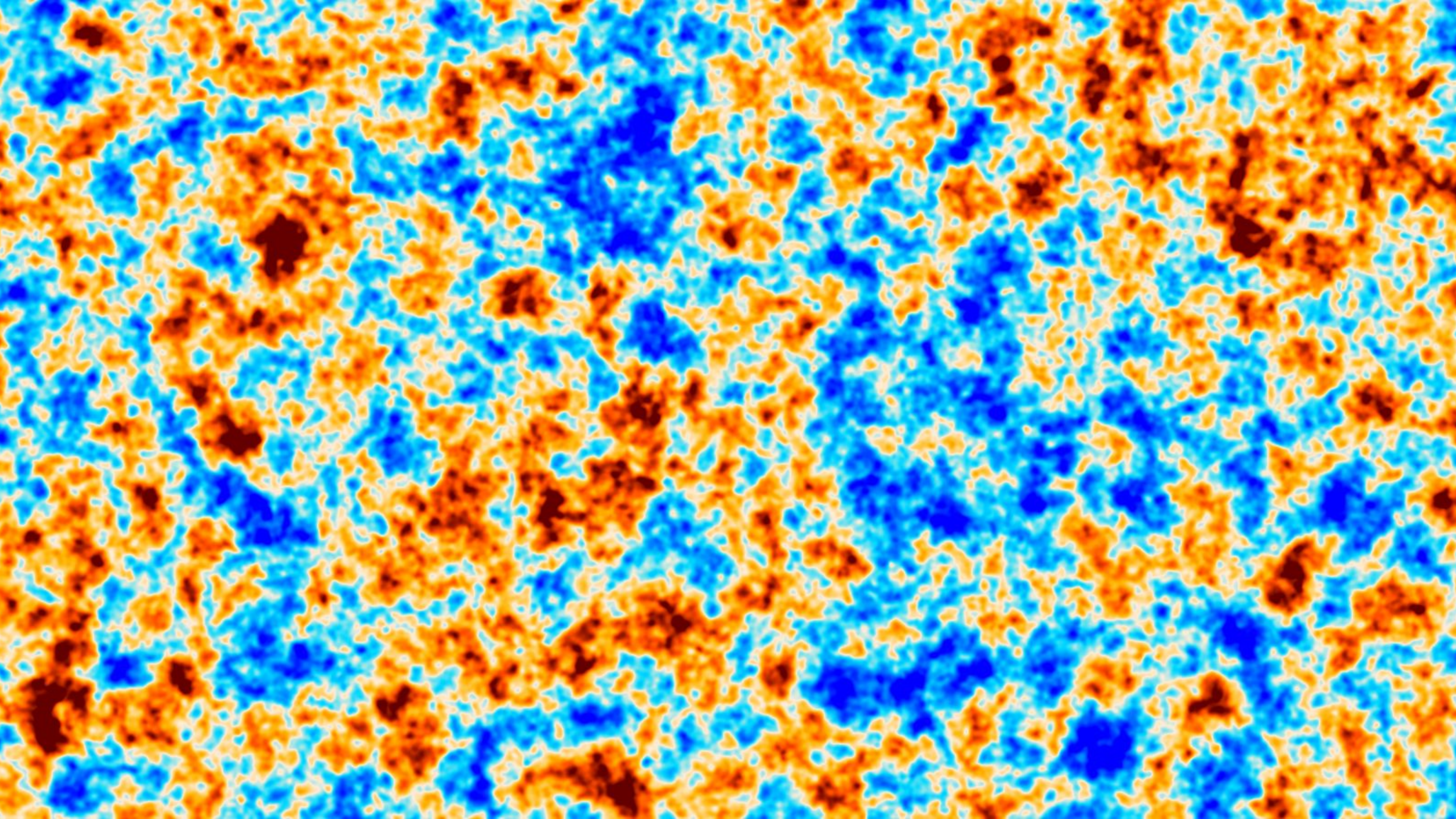


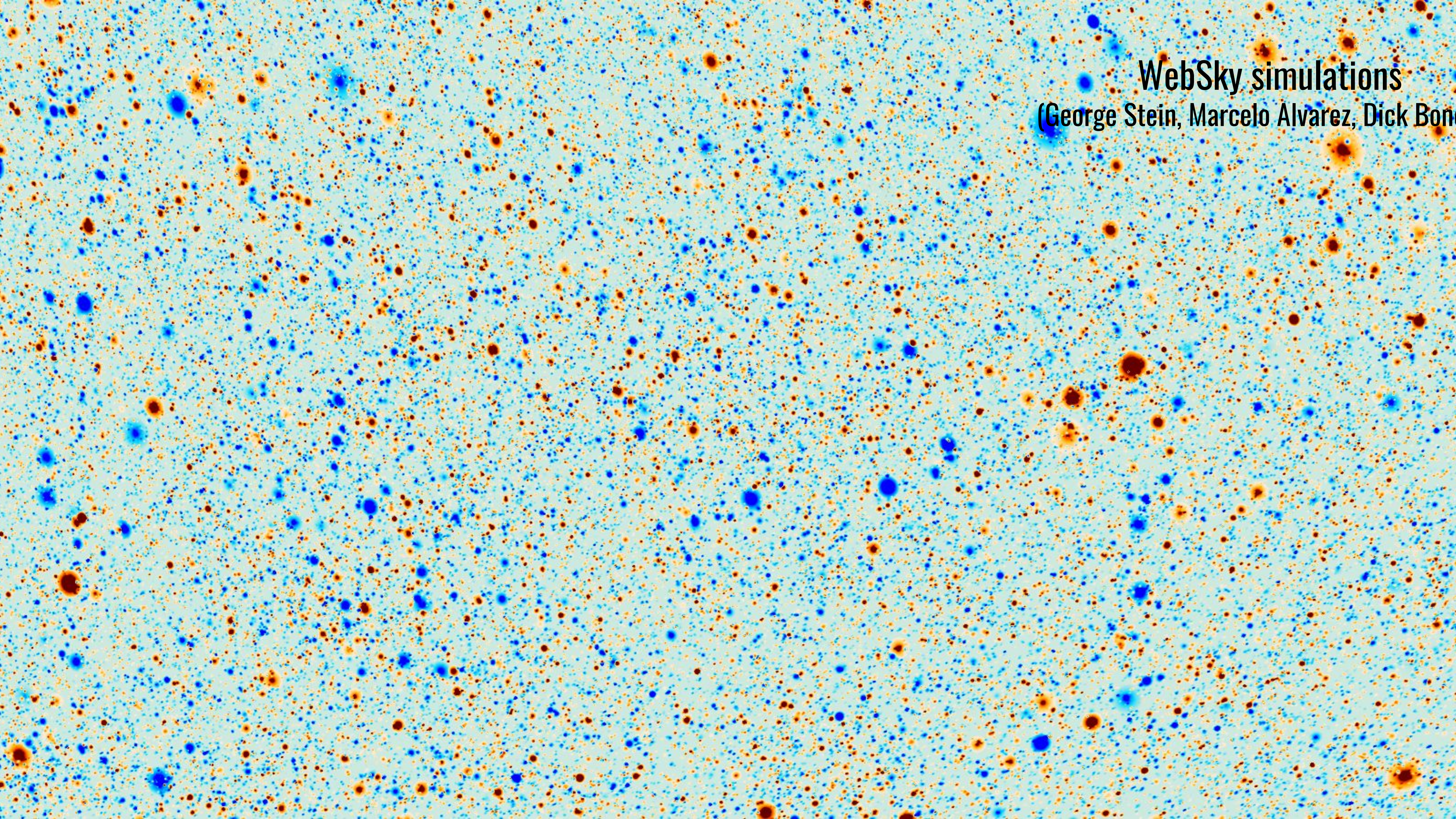
kSZ: Doppler shift of CMB photons scattering off electrons with bulk velocity

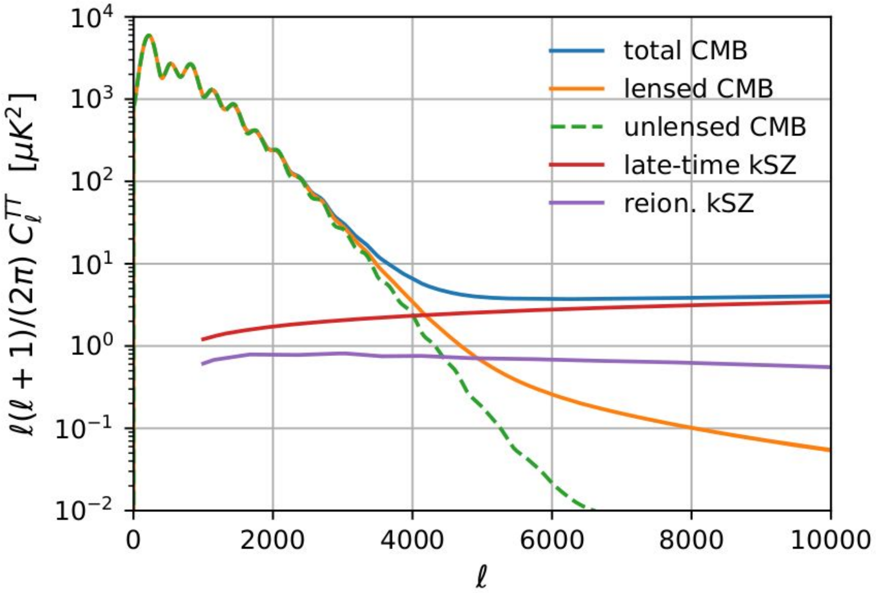
$$\frac{\Delta T_{\mathrm{kSZ}}(\vec{\mathbf{n}})}{T_{\mathrm{CMB}}} \sim \int d\chi e^{-\tau(z)} v_r \delta_e(\vec{\mathbf{n}}, \chi)$$

Contributions from

1. Reionization (from first stars) 6 < z < 20
2. **Ionized gas in and between clusters 0 < z < 6**

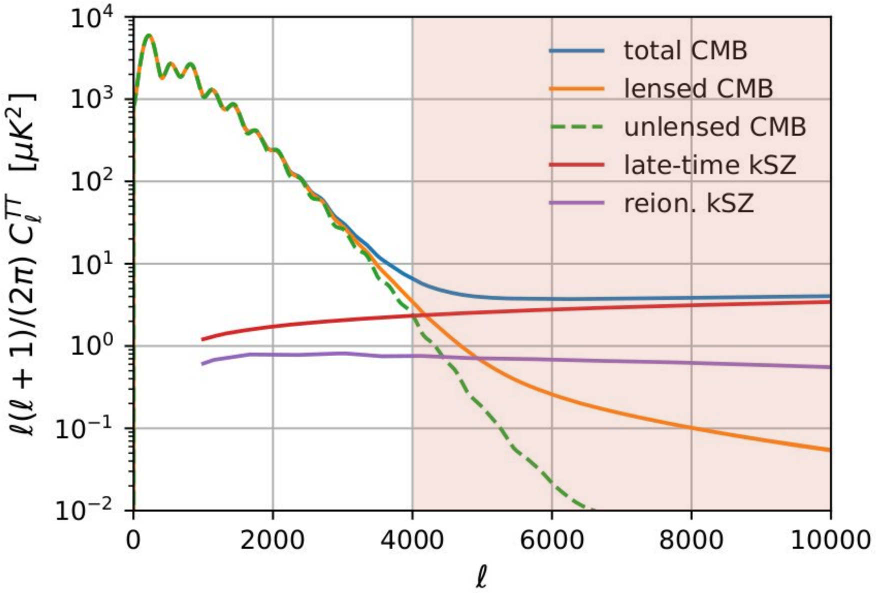



WebSky simulations
(George Stein, Marcelo Alvarez, Dick Bon



kSZ dominates CMB at ℓ>4000

Can in fact bias CMB lensing: see **Ferraro, Hill 2017**

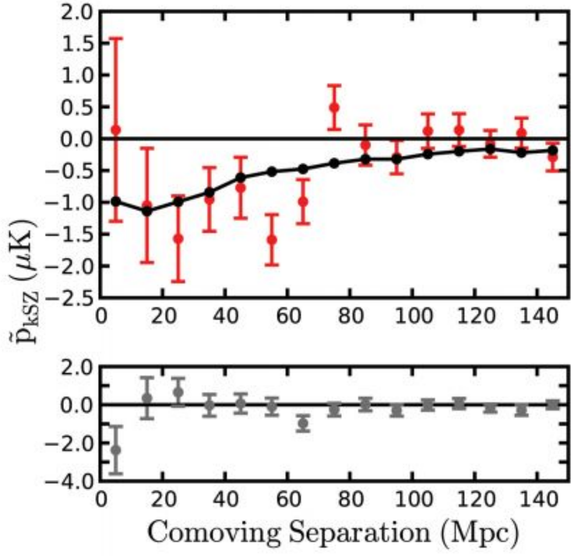


kSZ dominates CMB at ℓ>4000

Can in fact bias CMB lensing: see **Ferraro, Hill 2017**

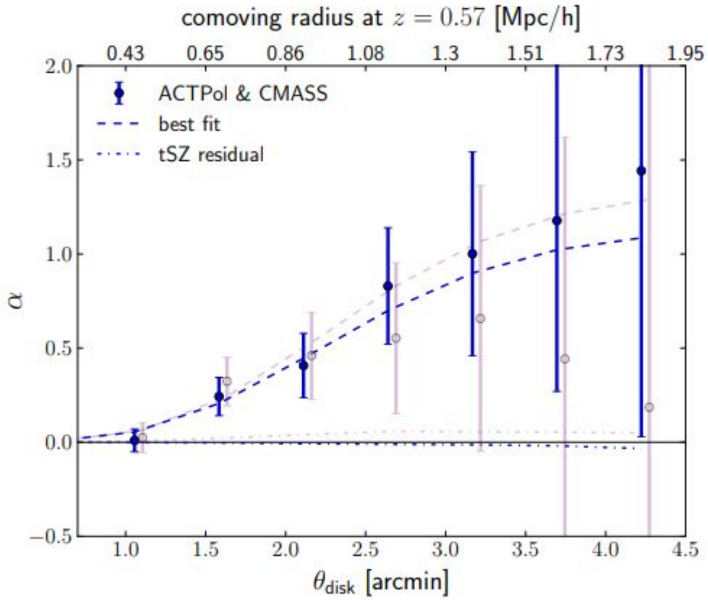
Modes to be explored by AdvACT, SPT-3G, Simons Observatory, CMB-S4

ACT x BOSS, Hand++ '12



Also:
ACT x redMaPPer, de Bernardis++ '16
SPT x DES, Soergel++ '16
Planck x SDSS, '15

ACT x BOSS, Schaan++ '15



See also: Planck x WISE, Hill++ '16

Currently detected only at the <**5 sigma** level
But expected to improve quickly with (deeper) CMB x galaxy overlap!
SNR O(100-1000) expected!

What can we learn with the kSZ effect?

$$\frac{\Delta T_{\mathrm{kSZ}}(\boldsymbol{n})}{T_{\mathrm{CMB}}} \sim \int d\chi e^{-\tau(z)} \delta_e(\boldsymbol{n}, \chi) v_r$$

Reionization
(Smith+ '17, Ferraro+ '18)

Missing baryons
(Lim+ '17, Hernández-Monteagudo+ '15)

Halo energetics and feedback
(Battaglia+ '18)

Astrophysics

Large scale anomalies
(e.g. Terrana+ '16)

Growth of structure?
- Growth rate?
  (e.g. Alonso+ '16)
  - Neutrino mass?
    (Mueller+ '14)
  - Dark energy?
    (Mueller+ '13)

+++ ...?

Cosmology?

What cosmology can kSZ potentially constrain?

$$\frac{\Delta T_{\mathrm{kSZ}}(\boldsymbol{n})}{T_{\mathrm{CMB}}} \sim \int d\chi e^{-\tau(z)} \delta_e(\boldsymbol{n}, \chi) v_r$$

- **Unbiased density modes** inferred from velocities

$$v \approx \frac{faH}{k} \delta_m$$

- Velocities respond to **growth rate f** -> neutrino mass, dark energy, modified gravity

E.g Mueller+ '14
Alonso+ '16

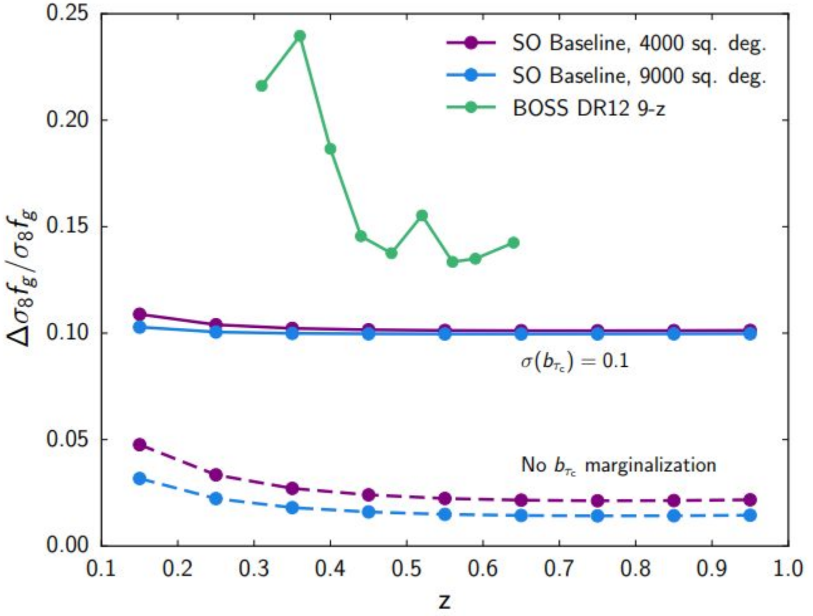
Astrophysics complicates this a bit

- Notorious "cluster optical depth"
- A catch-all term that includes our uncertainty about
    - Number density of electrons in halos associated with galaxies
    - Shape of the electron profile

$$\frac{\Delta T_{\rm kSZ}(\boldsymbol{n})}{T_{\rm CMB}} \sim \int d\chi e^{-\tau(z)} \delta_e(\boldsymbol{n}, \chi) v_r$$

But I'll show that this does **not** make it impossible to do interesting cosmology with kSZ!

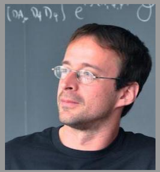
arXiv:1808.07445 SO Collab. produced by **Victoria Calafut**



Unifying Framework:
Bispectrum

Smith, MM ++ 2018 arXiv:1810.13423

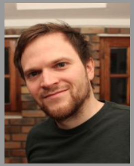
Kendrick Smith



Simone Ferarro

Utkarsh Giri

Moritz Munchmeyer



Matt Johnson

Proposed estimators for kSZ have one of these forms:

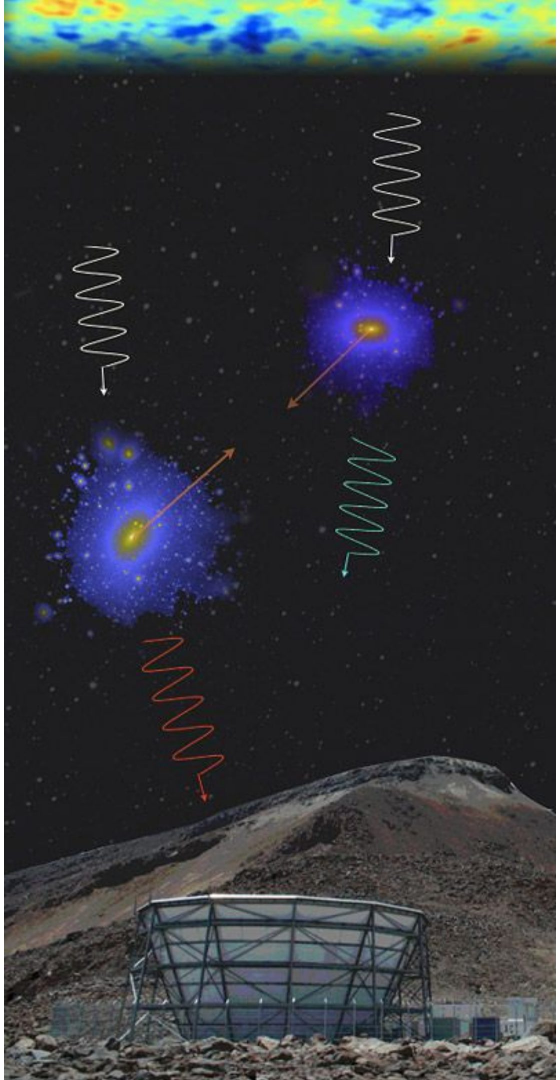
- <ggT> kSZ tomography: includes
  - **pairwise momentum (4)** — Hand++, de Bernardis++, Soergel++, Planck++
  - **template method (1)** — Schaan++ 2016
  - velocity matched filter — Li++ ‘17
  - velocity reconstruction — Deutsch++ ‘17, Smith,MM,Ferraro++ arxiv:1810.13423
- <gTT> **Projected kSZ (1)** — Hill++ ‘16, Ferraro++ ‘16
- <TTTT> patchy reionization kSZ — Smith++ ‘17, Ferraro++ ‘18

- <ggT> **kSZ tomography**: includes
  - pairwise momentum
  - template method
  - velocity matched filter
  - velocity reconstruction

These involve “cross-correlating” a CMB survey and a galaxy survey but effectively 3-point function since 2-pt cross-correlation is zero for halos equally likely to move towards or away

- <ggT>   kSZ tomography: includes
    - **pairwise momentum**
    - template method
    - velocity matched filter
    - velocity reconstruction

e.g Hand++, de Bernardis++,
Soergel++, Planck++



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  - pairwise momentum
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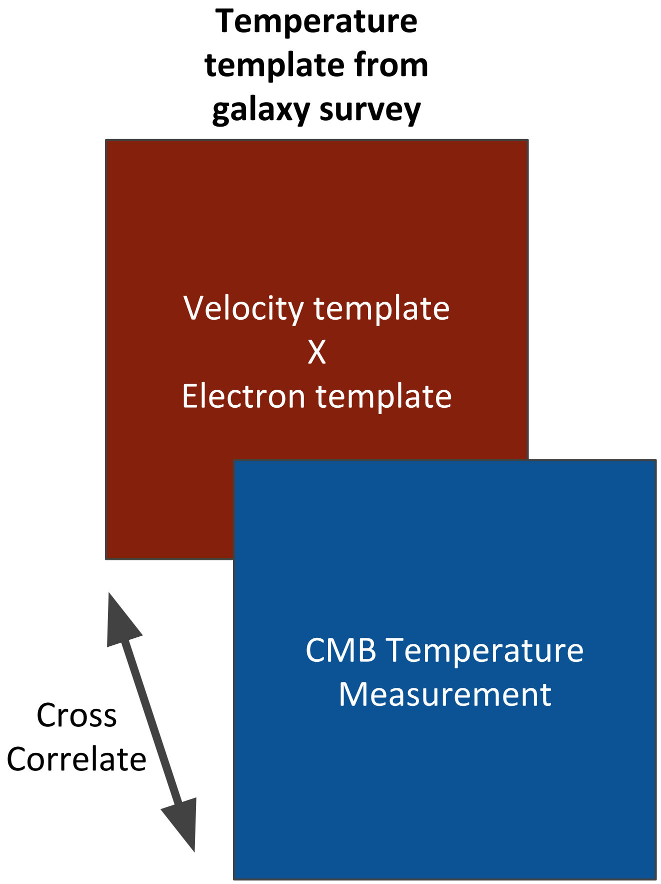
  - velocity reconstruction

e.g. Schaan++



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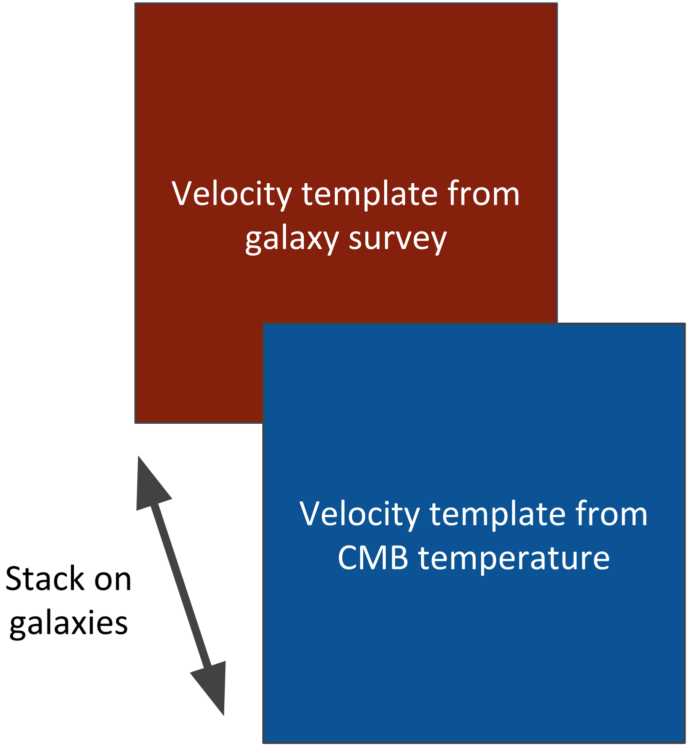

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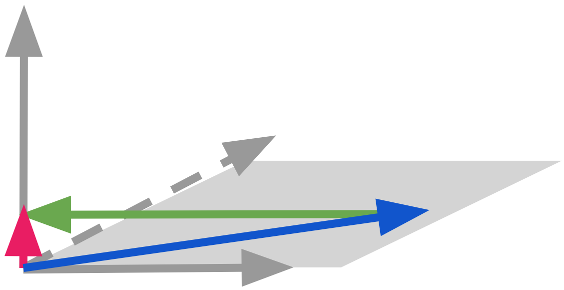


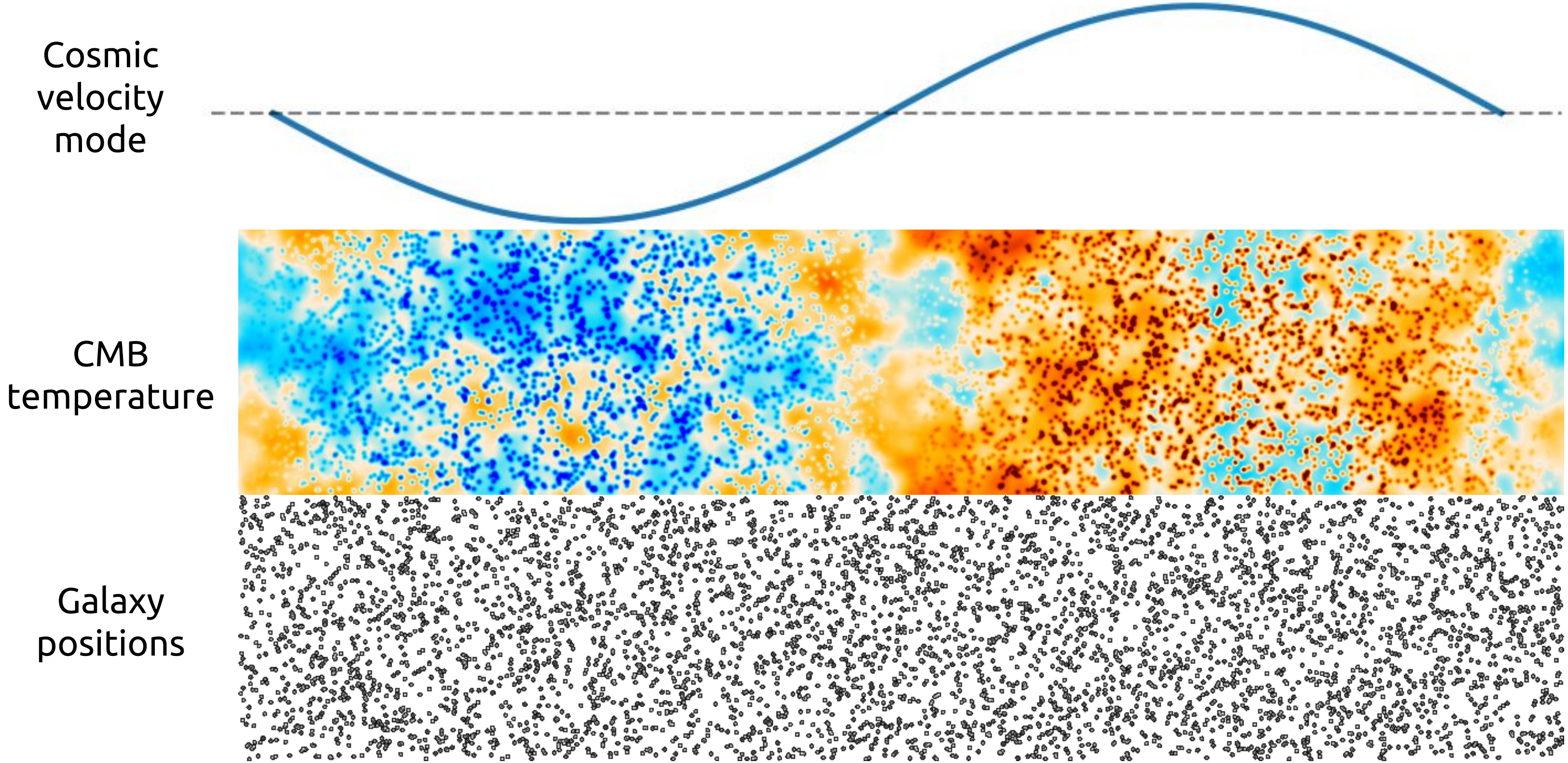
- An especially illuminating framework for cosmology is **velocity reconstruction**

- Cosmic velocity extracted from quadratic combination of galaxy positions (from BOSS, DESI, LSST) together with CMB temperature v ~ <gT>

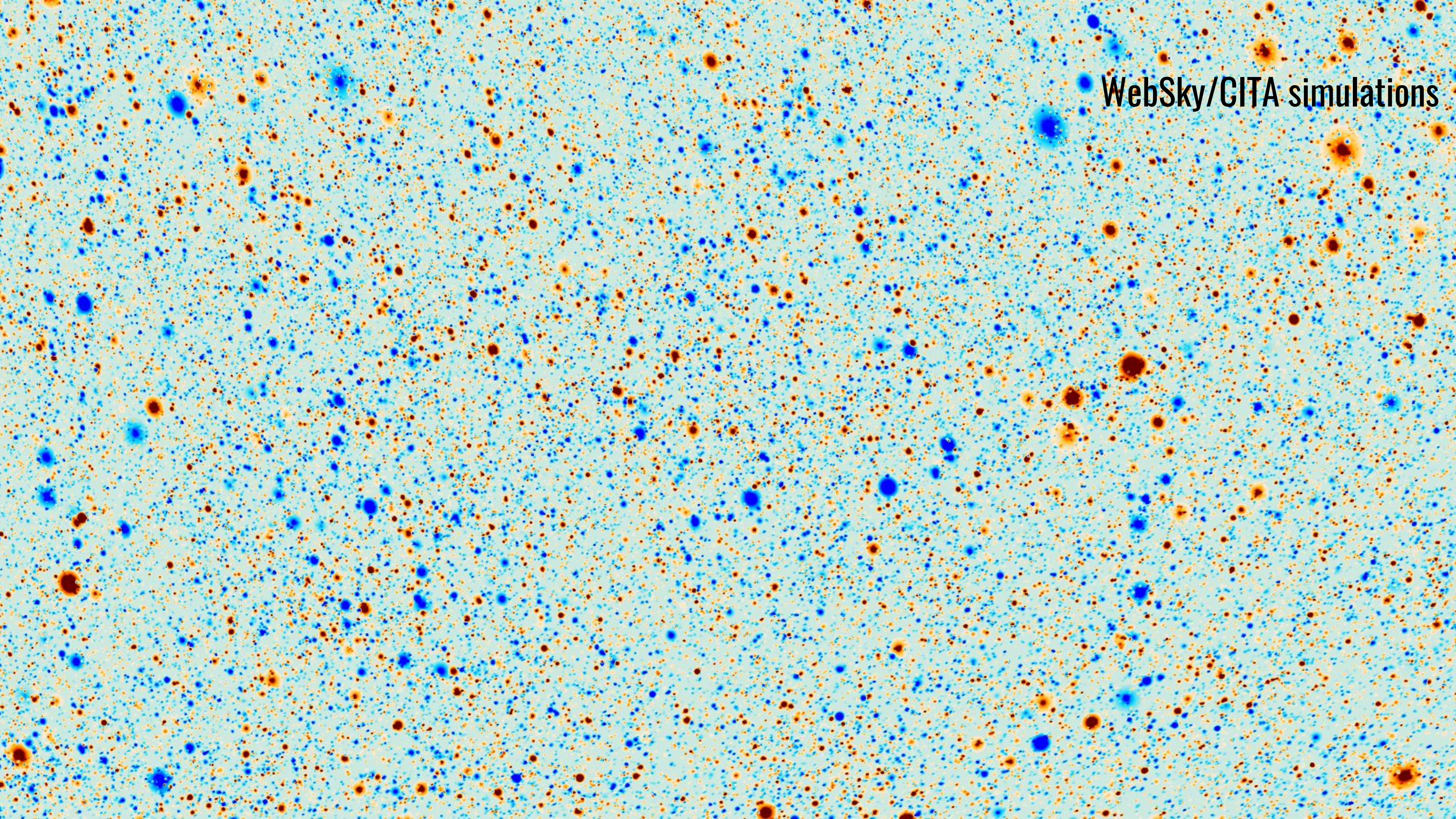
- 3D Velocity reconstruction then auto-correlated and cross-correlated with galaxy survey

- The cross-correlation with the galaxy survey <vg> realizes one possible projection of the bispectrum <gv> -> <ggT>

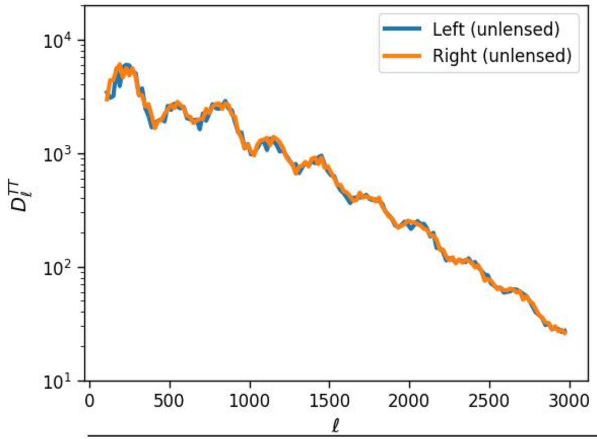
Squeezed bispectrum cartoon: **kSZ**



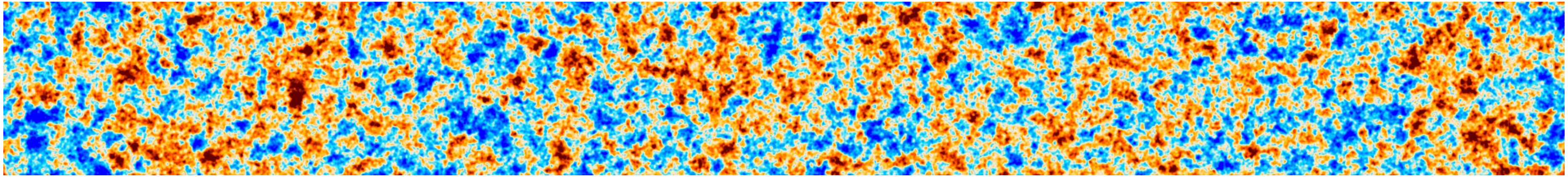
Velocities from modulation of late-time patchy kSZ cross-power with galaxies


WebSky/CITA simulations

Squeezed bispectrum cartoon: **lensing**

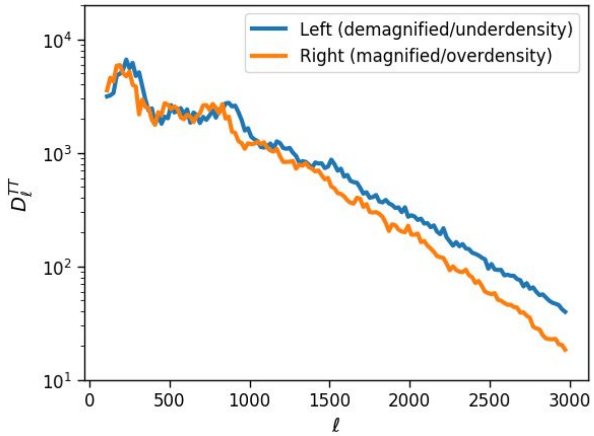


Matter overdensity mode
(zero)

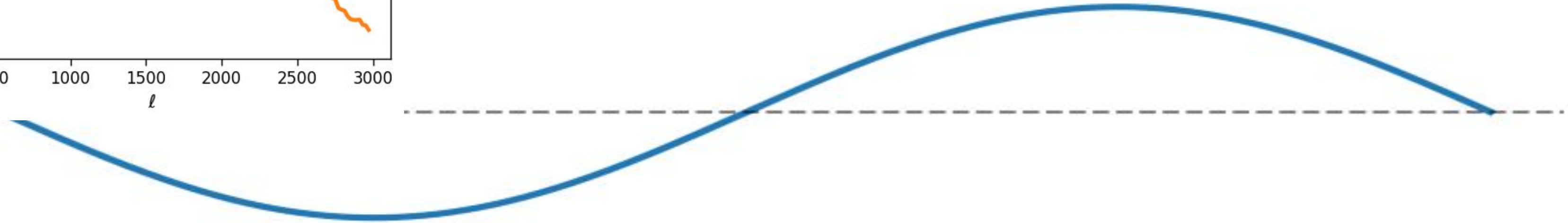


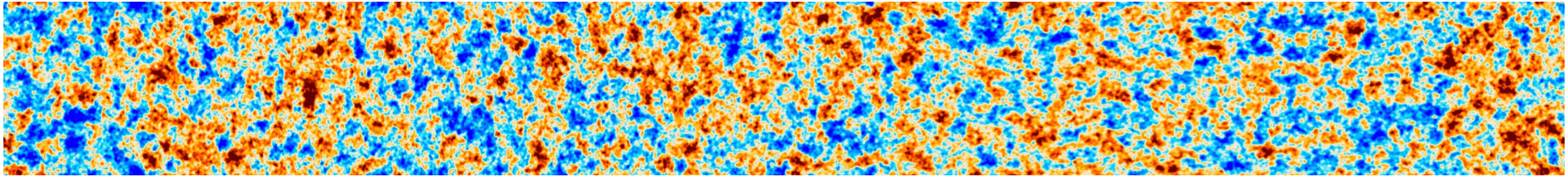
Unlensed CMB
temperature

Squeezed bispectrum cartoon: **lensing**



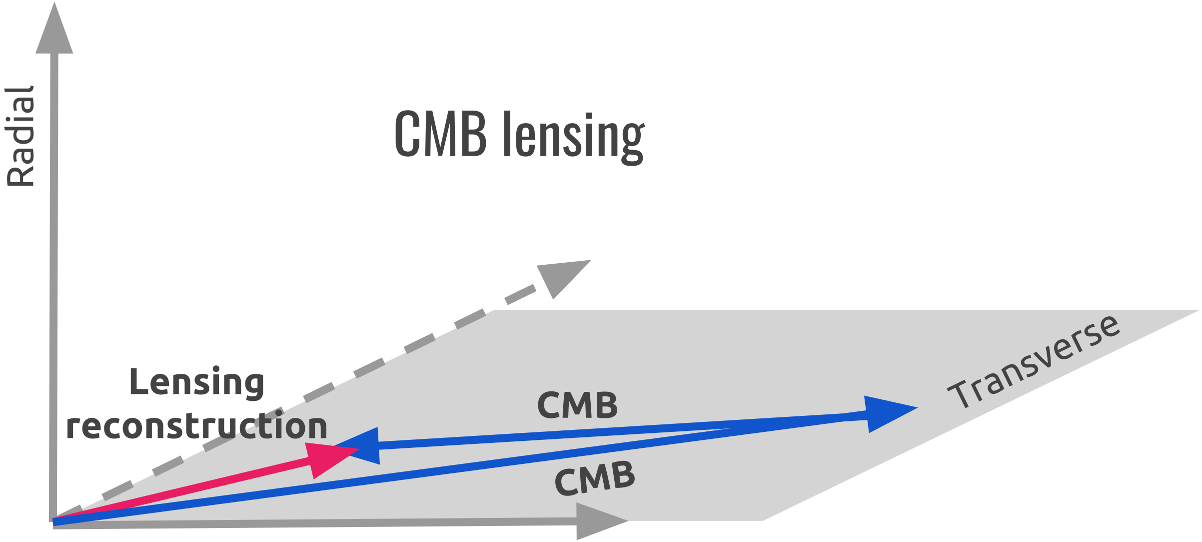
Matter overdensity mode





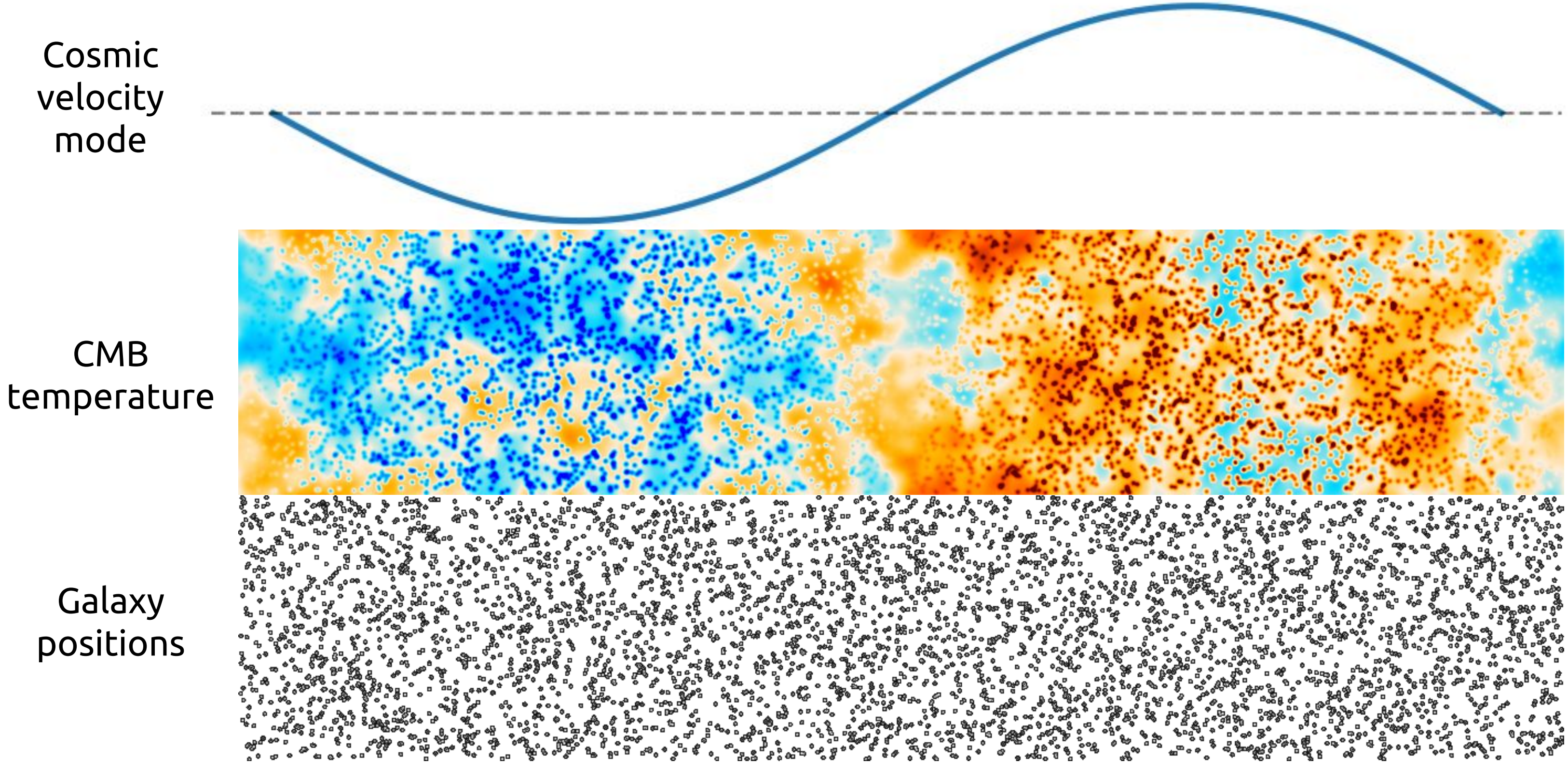
Lensed CMB
temperature

CMB lensing



$$\hat{\phi}(L) = \langle TT \rangle_{\ell}$$

Squeezed bispectrum cartoon: **kSZ**



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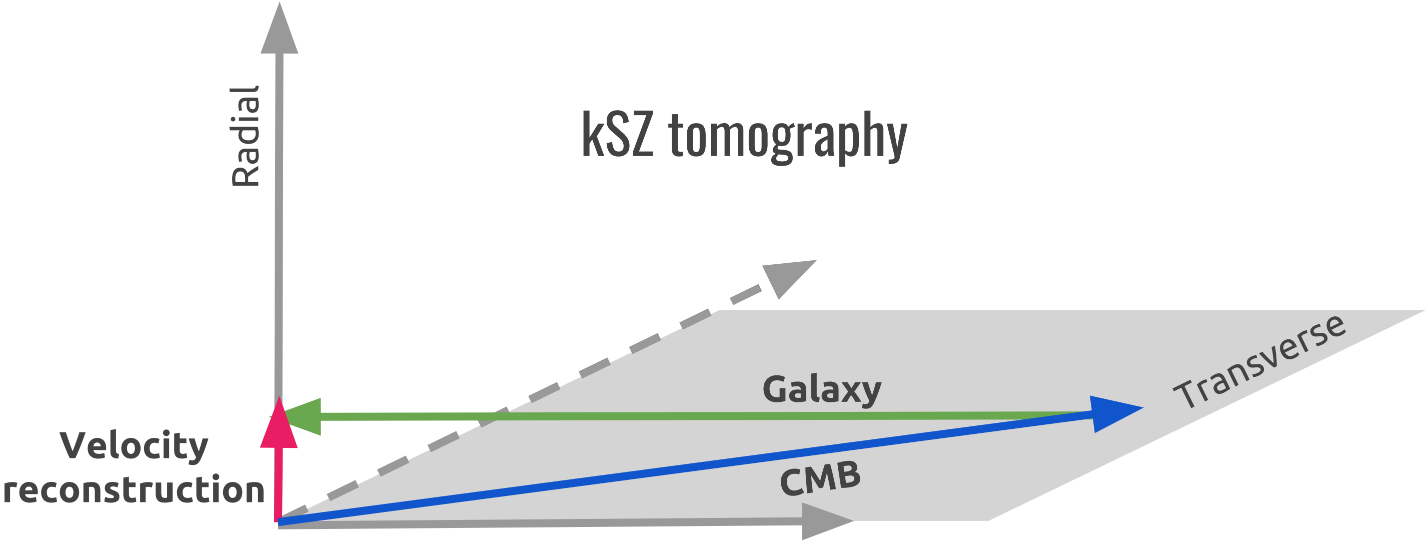


Step 1: get reconstructed velocity

$$\hat{v}_{\mathrm{rec}}(k_L) \sim \langle gT \rangle_{k_S}$$

Velocity Reconstruction Framework

- Average over quadratic pairs of modes -- effectively look for modulation of galaxy x CMB temperature power

$$T_{\mathrm{ksz}} \sim \delta_e v$$

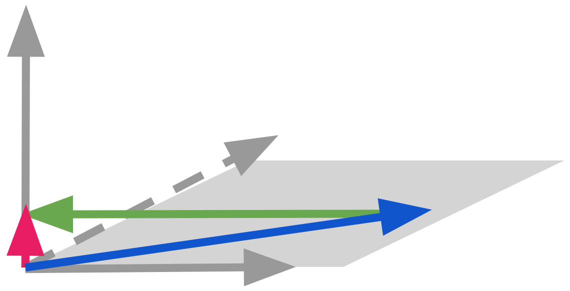
$$\begin{aligned}\hat{v}_{\mathrm{rec}}(k_L) &\sim \langle \delta_g T \rangle_{k_S} \\ &\sim \langle \delta_g(k_S)[\delta_e(k_S) v(k_L)] \rangle_{k_S} \\ &\sim \langle \delta_g(k_S)\delta_e(k_S) \rangle_{k_S} v(k_L) \\ &\sim \underbrace{v(k_L)}_{\text{Cosmology}} \underbrace{\int dk_S P_{ge}(k_S)}_{\text{Astrophysics}}\end{aligned}$$

Cosmology

Astrophysics

Scale-independent number $\mathbf{b_v}$

- <ggT>   kSZ tomography: includes
  - pairwise momentum
  - template method
  - velocity matched filter
  - **velocity reconstruction**



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- 3D Velocity reconstruction then auto-correlated and cross-correlated with galaxy survey

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After velocity reconstruction, we have two probes of matter density

$$v = \frac{b_v f a H}{k}\delta_m$$

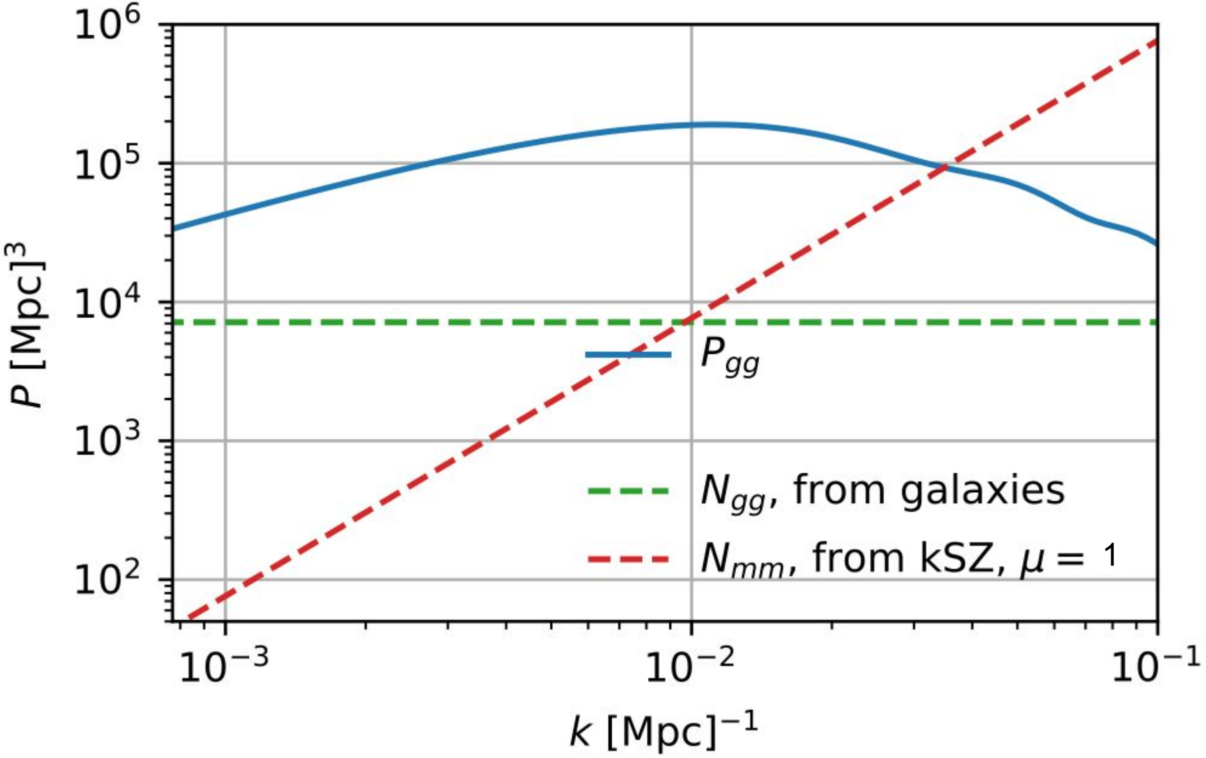
With some reconstruction noise

$$\delta_g = b_g \delta_m$$

With some shot noise

How does the noise compare between velocities and galaxies?
Squeezed limit noise is white
Convert noise on velocity to noise on matter density with k^2

Smith, **MM**++ arxiv:1810.13423



$$\delta_g = b_g \delta_m$$

$$v = \frac{faH}{k} \delta_m$$

kSZ Velocities outperform galaxy clustering at large scales!

Recap!

kSZ tomography measures the largest scale density modes

Up to an unknown scale-independent normalization (“tau”)

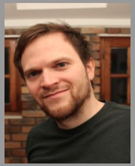
With much lower noise than galaxy surveys!

Both galaxy and velocity surveys are signal dominated and hence sample variance limited at large scales.

New application: primordial non-Gaussianity (f_{NL})

Munchmeyer, MM++ 2018 arXiv:1810.13424

Moritz Munchmeyer



Simone Ferarro

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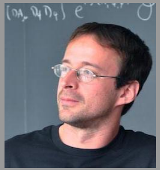


f_{NL}

Amplitude of non-gaussianity predicted generally in multi-field inflation models to be O(1)

$$\Phi_{\rm NG} = \Phi_{\rm L} + f_{\rm NL}\Phi_{\rm L}^2$$

Current best constraints:
sigma(fNL) ~ 5 from Planck CMB
Exhausted by sample variance

f_{NL} from scale-dependent galaxy bias b_g

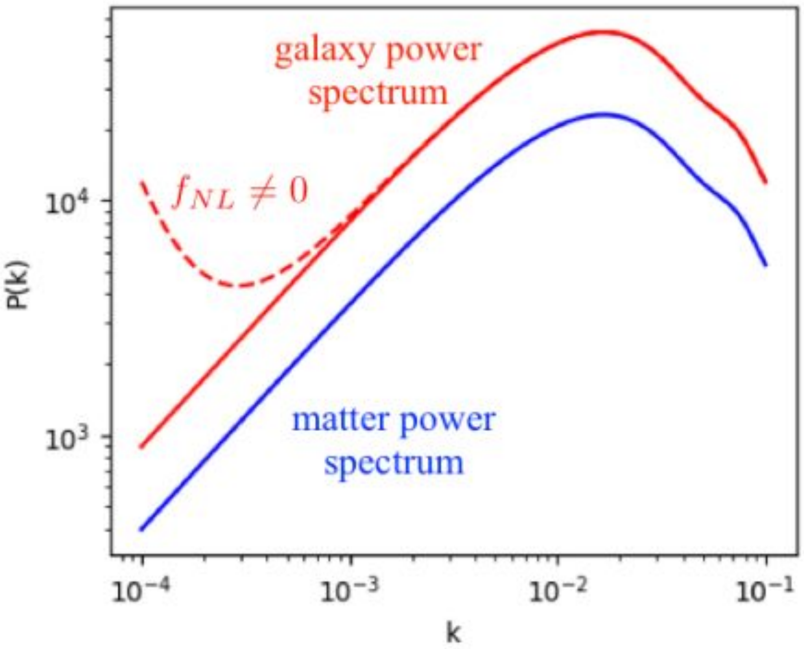
Another physical effect: **excess galaxy clustering** at large scales (Dalal++ 2008)

Galaxy surveys hope to measure bias at large scales

But constraints limited by sample variance (few modes at large scales)

sigma(fNL) ~ 1.5 forecast for LSST

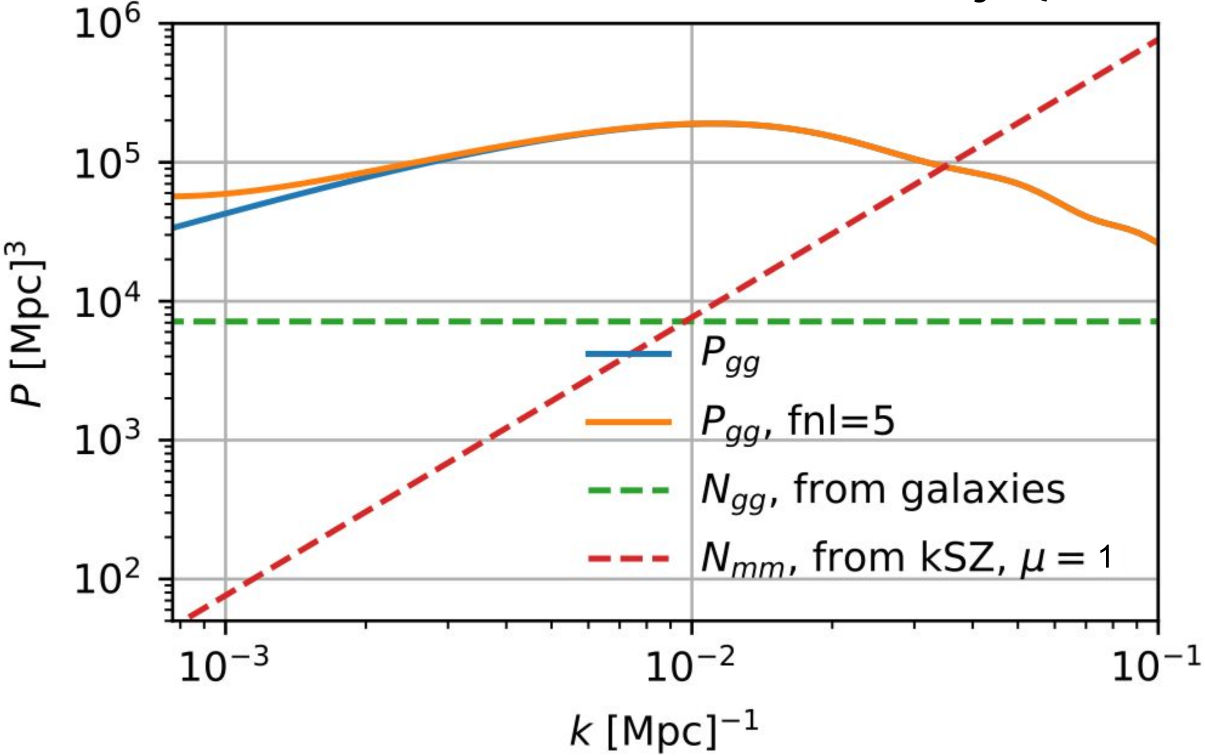
sigma(fNL) < 1 interesting models ruled out



Clustering of galaxies is scale-dependent on large scales in certain multi-field models of inflation, parameterized by f_{NL}

-

Munchmeyer,MM++ 2018



$$\delta_g = b_g \delta_m$$

$$v = \frac{b_v f a H}{k} \delta_m$$

Idea: ratio of (kSZ-)velocities and galaxies contains no matter field

$$v = \frac{b_v f a H}{k}\delta_m$$

With some reconstruction noise

$$\delta_g = b_g(f_{\rm NL}, k)\delta_m$$

With some shot noise

- Sample variance cancelled! Can measure bias without sample variance.
- Arbitrary improvement with CMB and galaxy survey noise improvement.
- Effectively done by measuring all auto and cross-correlations: Pgg, Pgv, Pvv
- Not affected by scale-independent astrophysics (tau) marginalization!

3x improvement in fNL from CMB-S4 kSZ + LSST

Galaxy clustering (LSST)	Galaxy clustering + kSZ velocities	
Pgg	Pgg, Pgv, Pvv	
$\sigma(f_{\rm NL})$ = 1.5	$\sigma(f_{\rm NL})$ = 1.0	Simons Observatory
	$\sigma(f_{\rm NL})$ = 0.5	CMB-S4

Larger improvement than similar method from CMB lensing (Schmittful, Seljak 2016) due to better correlation

3x improvement in fNL from CMB-S4 kSZ + LSST

Galaxy clustering (LSST)	Galaxy clustering + kSZ velocities	
Pgg	~~Pgg~~, Pgv, Pvv	
$\sigma(f_{\rm NL})$ = 1.5	$\sigma(f_{\rm NL})$ = 1.0	Simons Observatory
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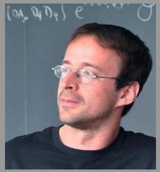
Extremely robust measurement possible -- does not need galaxy auto!

Growth rate? (f)

MM++ 2019 arXiv:1901.02418

Nick Battaglia

Kendrick Smith



Jon Sievers

What about the growth rate f ?

f(k,z) constrains neutrino mass, dark energy, modified gravity

Amplitude f(z) is degenerate with “optical depth” amplitude

$$v = \frac{b_v f a H}{k} \delta_m \qquad b_v \sim \int dk_S w(k_S) P_{ge}(k_S)$$

Breaking this degeneracy requires an external measurement of **Pge**

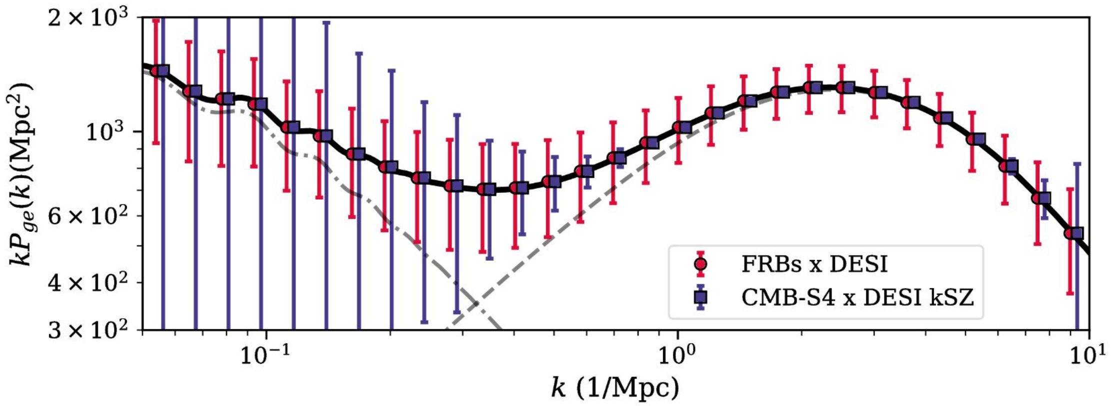
Breaking tau degeneracy requires predicting Pge

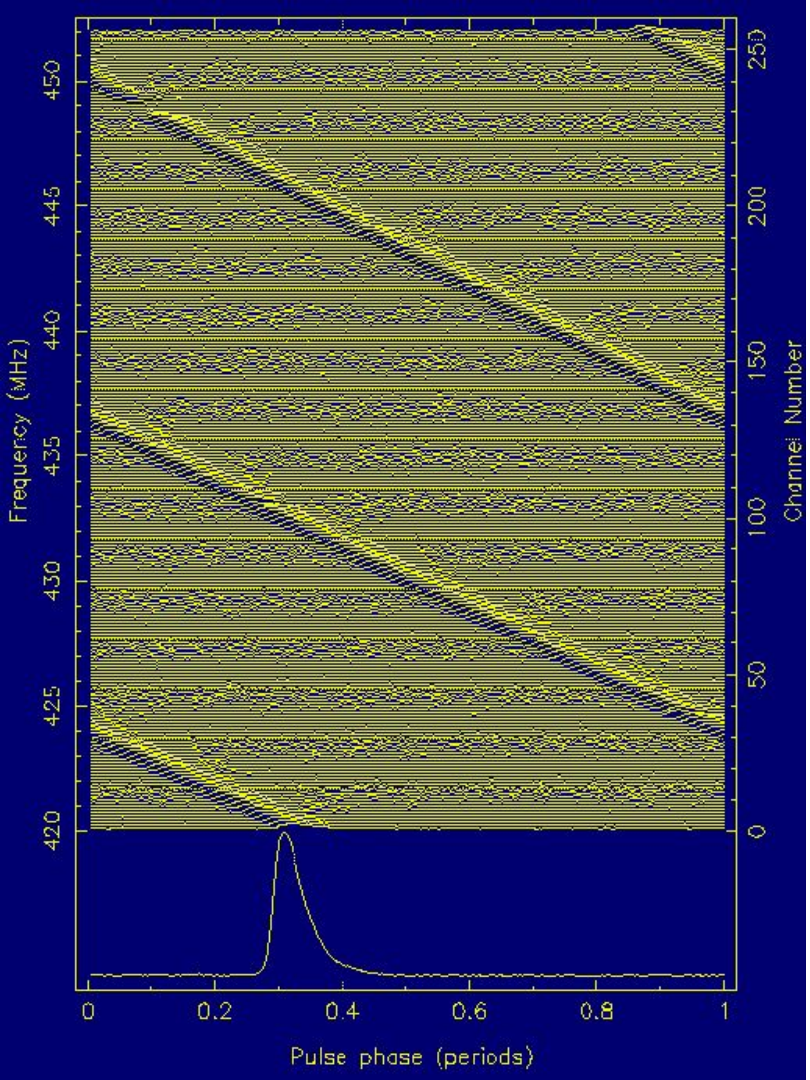
A data driven approach is to look for other effects that depend on **free electron density** and cross-correlate with the kSZ galaxy sample

Breaking tau degeneracy requires predicting Pge

A data driven approach is to look for other effects that depend on **free electron density** and cross-correlate with the kSZ galaxy sample

An ambitious possibility is:
Dispersion measures of Fast Radio Bursts (FRBs)





Radio waves from energetic sources interact with intervening ionized matter and undergo dispersion

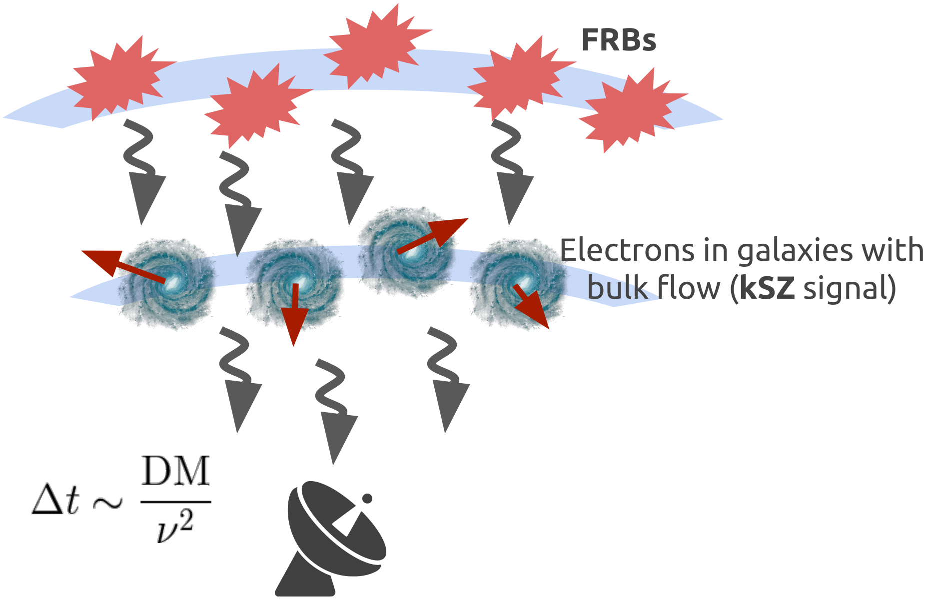
$$\Delta t \sim \frac{\mathrm{DM}}{\nu^2}$$

Higher frequencies push past free electrons and arrive earlier

Potentially **large number** of energetic sources at cosmological distances - **FRBs**

Breaking tau with FRBs

MM, Battaglia, Smith, Sievers arxiv:1901.02418

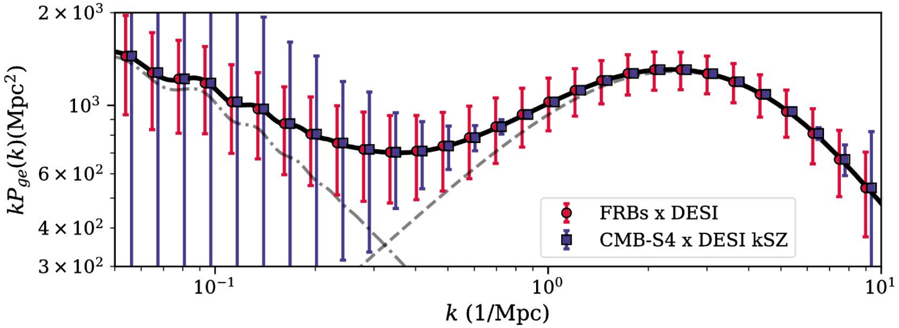


$$\Delta t \sim \frac{\mathrm{DM}}{\nu^2}$$

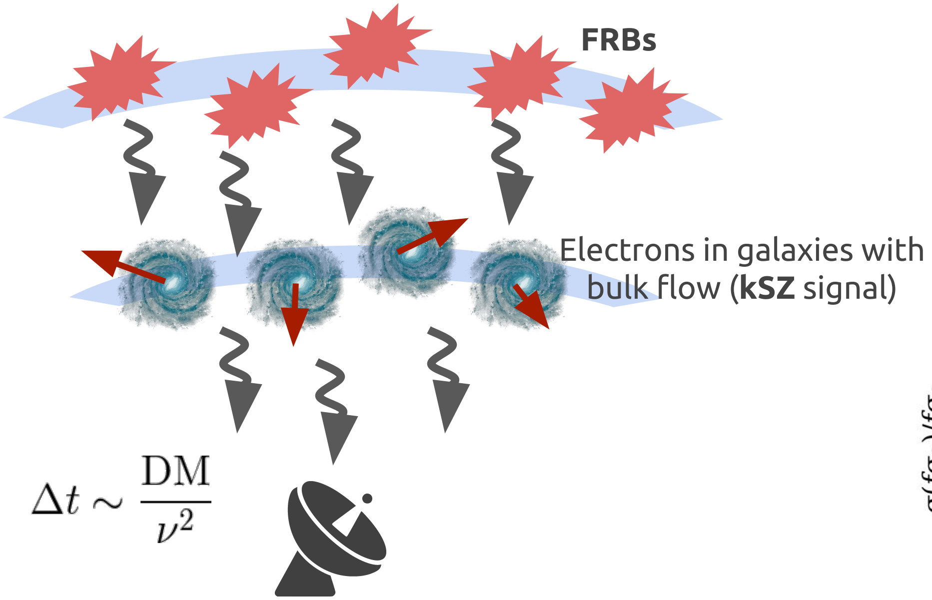
$$\mathrm{DM}(\vec{\mathbf{n}}) = \int_0^{\chi_f} d\chi (1+z)\delta_e(\vec{\mathbf{n}}, z)$$

$$\mathrm{DM}(\vec{\mathbf{n}}) \times \delta_g(\vec{\mathbf{n}}) \sim P_{ge}(k_S)$$

- FRB frequency-dependence of time delay depends on intervening electron density
- One contribution is electrons in galaxies whose “optical depth” we want to measure (apart from host galaxy and Milky Way)
- Cross-correlate DMs with galaxies used in kSZ estimator



Breaking tau with FRBs



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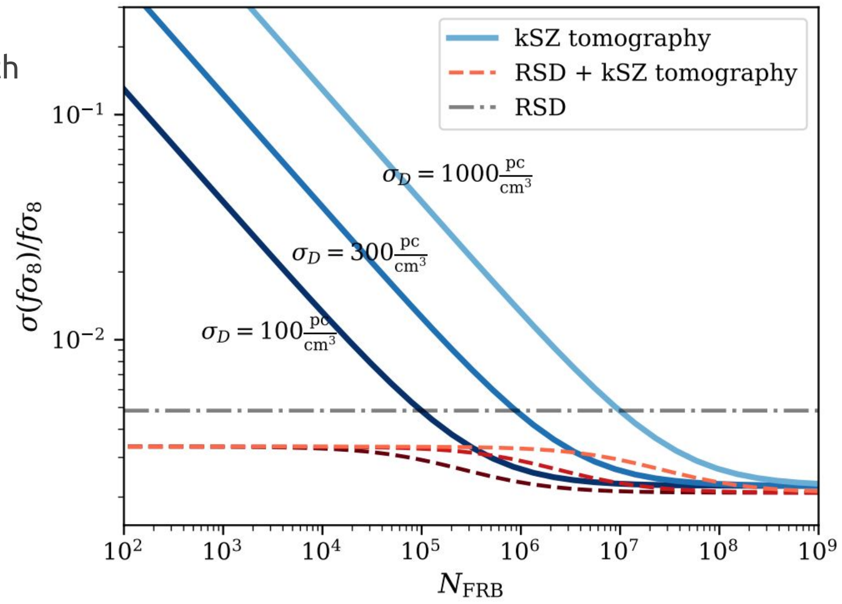


MM, Battaglia, Smith, Sievers arxiv:1901.02418

Feedback and lensing

(work in progress)

Emmanuel Schaan

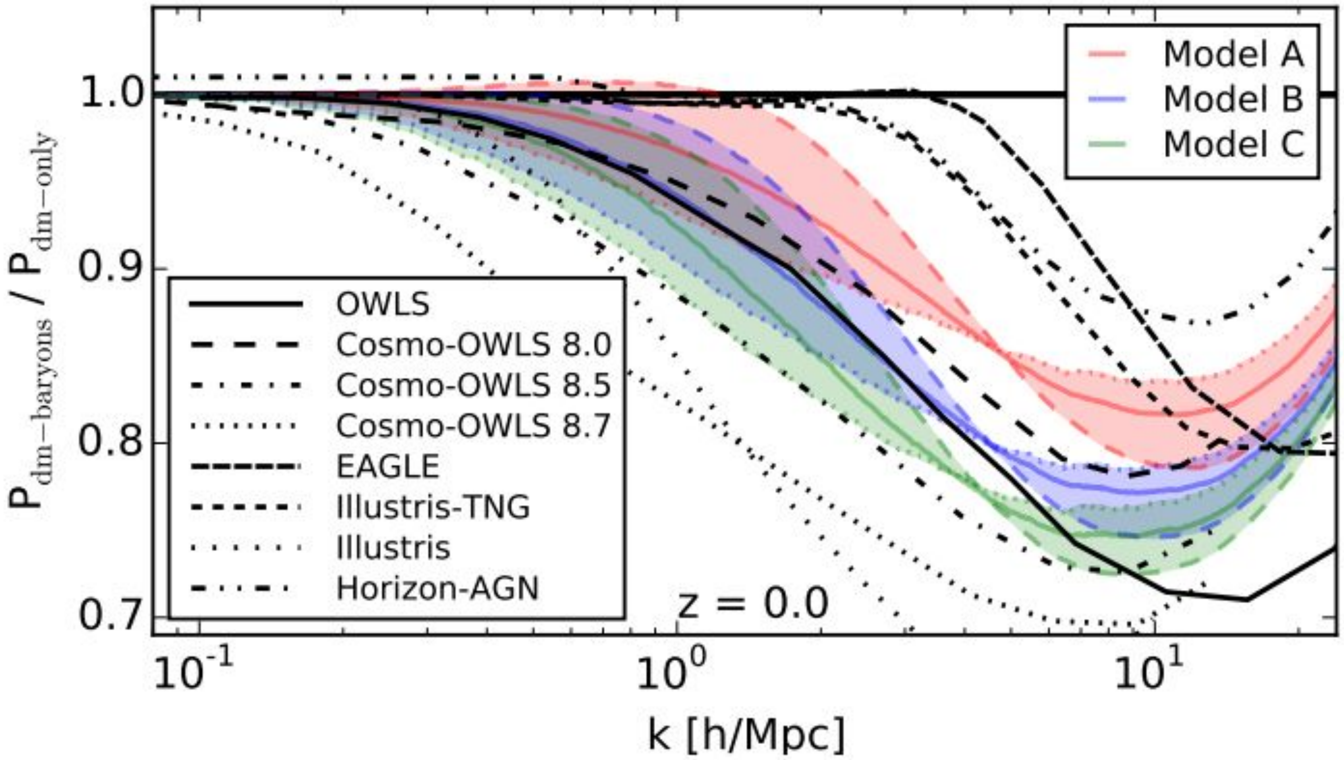
Nick Battaglia

Simone Ferarro

Colin Hill

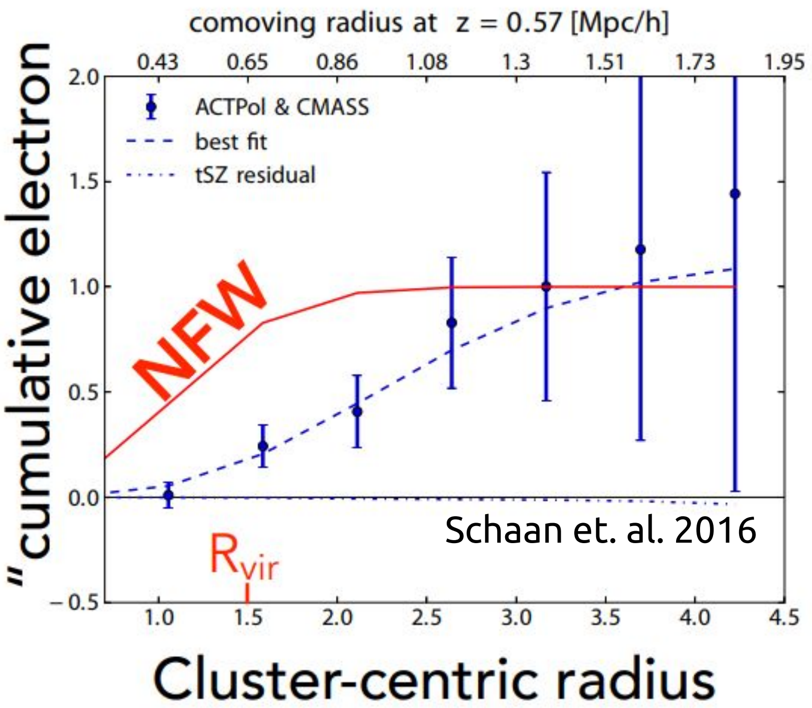
Matter power spectrum impacted by baryonic feedback

Schneider++ 2018



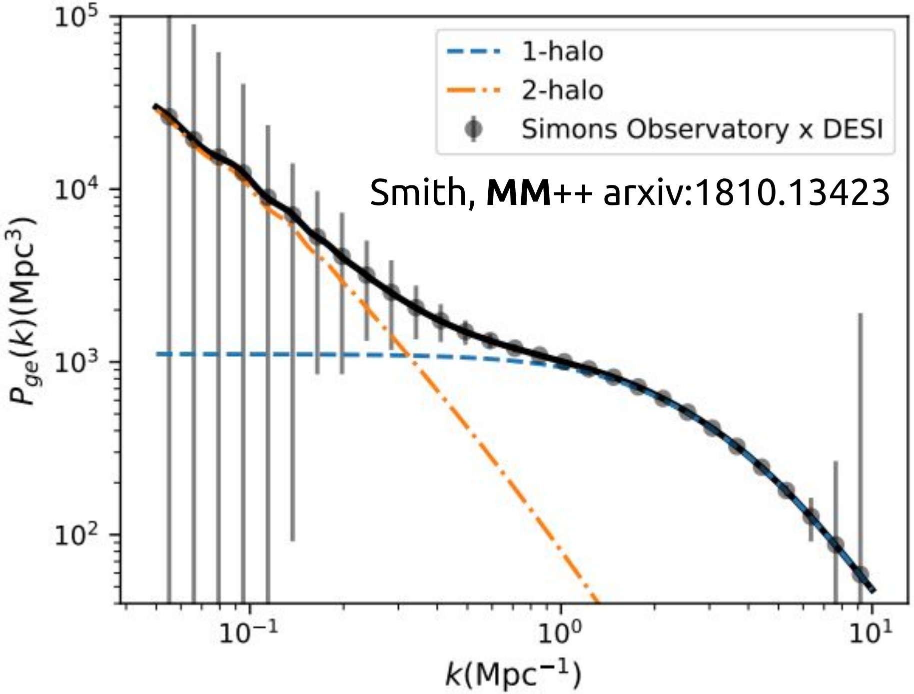
$$\delta_m = \delta_{\mathrm{cdm}} \frac{\Omega_{\mathrm{cdm}}}{\Omega_m} + \delta_{\mathrm{gas}} \frac{\Omega_{\mathrm{gas}}}{\Omega_m} + \delta_{\mathrm{s}} \frac{\Omega_{\mathrm{s}}}{\Omega_m}$$

Puffiness of gas seen in kSZ measurements



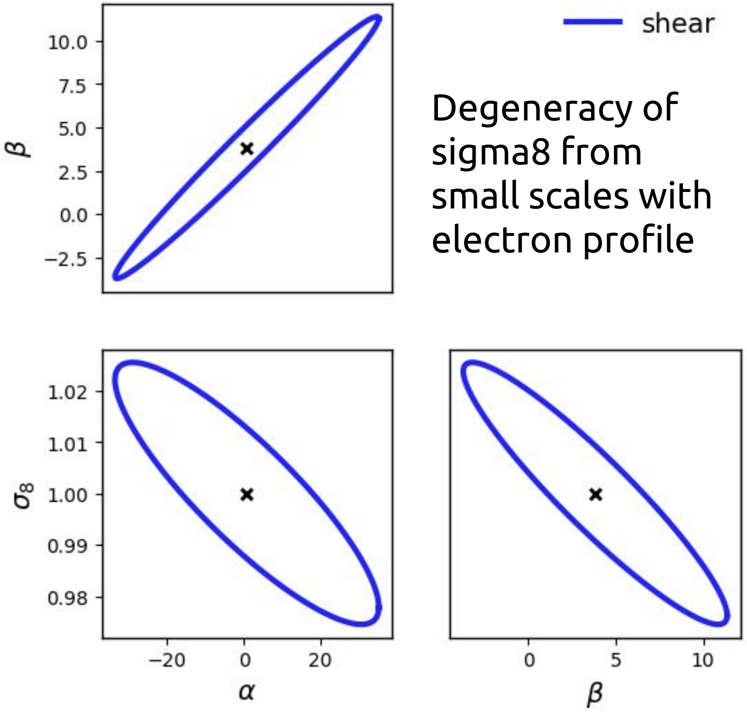
Plot from **Emmanuel Schaan** (kSZ detection)

kSZ will constrain the gas (electron) profile



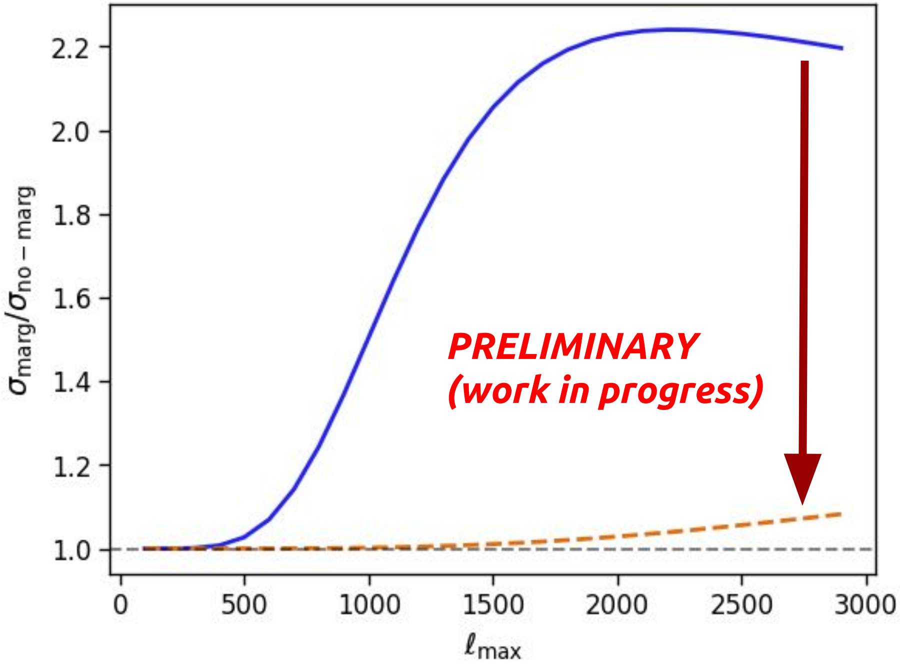
Smith, **MM**++ arxiv:1810.13423

Which can translate to improvements on cosmology



Degeneracy of sigma8 from small scales with electron profile

with Emmanuel Schaan, Nick Battaglia, Simone Ferraro, Colin Hill



Improvement on sigma8 from 5% constraint on electron profile parameters

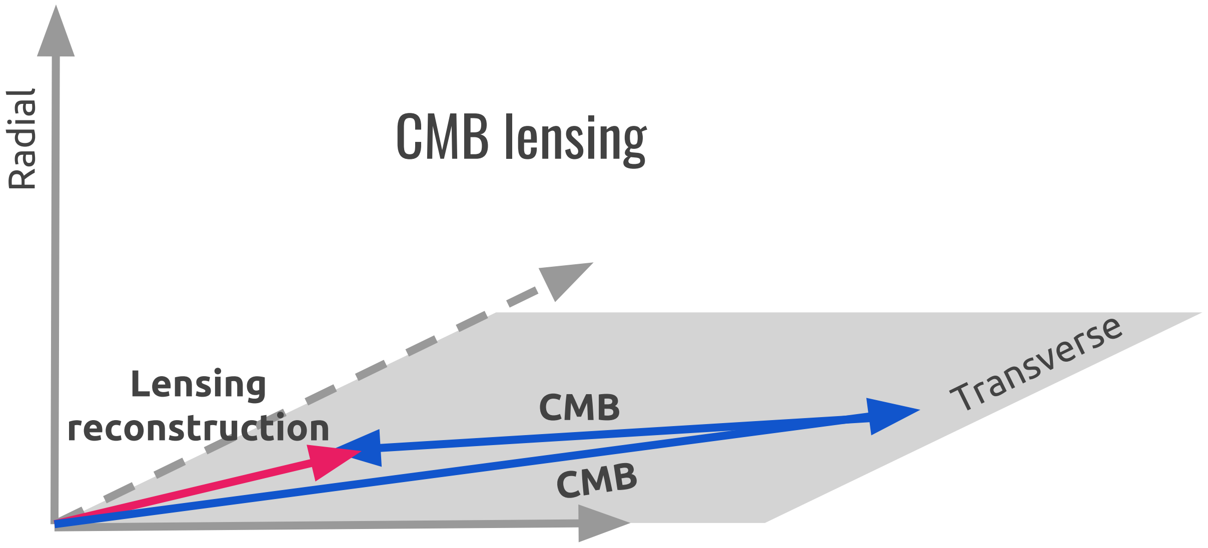
Conclusion

- Optical depth (tau) factors out as **scale-independent** uncertain amplitude
- kSZ velocity reconstruction does better than clustering at large scales
- Cosmological applications
  - Improves non-Gaussianity sigma(fnl) through **scale-dependent bias** by 3x for CMB-S4 + LSST probing multi-field inflation
  - **Amplitude of growth** rate is perfectly degenerate with tau, but degeneracy can potentially be broken with localized **FRB** dispersion measures
  - Robustly include smaller scales in **cosmic shear** and galaxy-galaxy lensing with kSZ measurements of electron profile

Thank you!

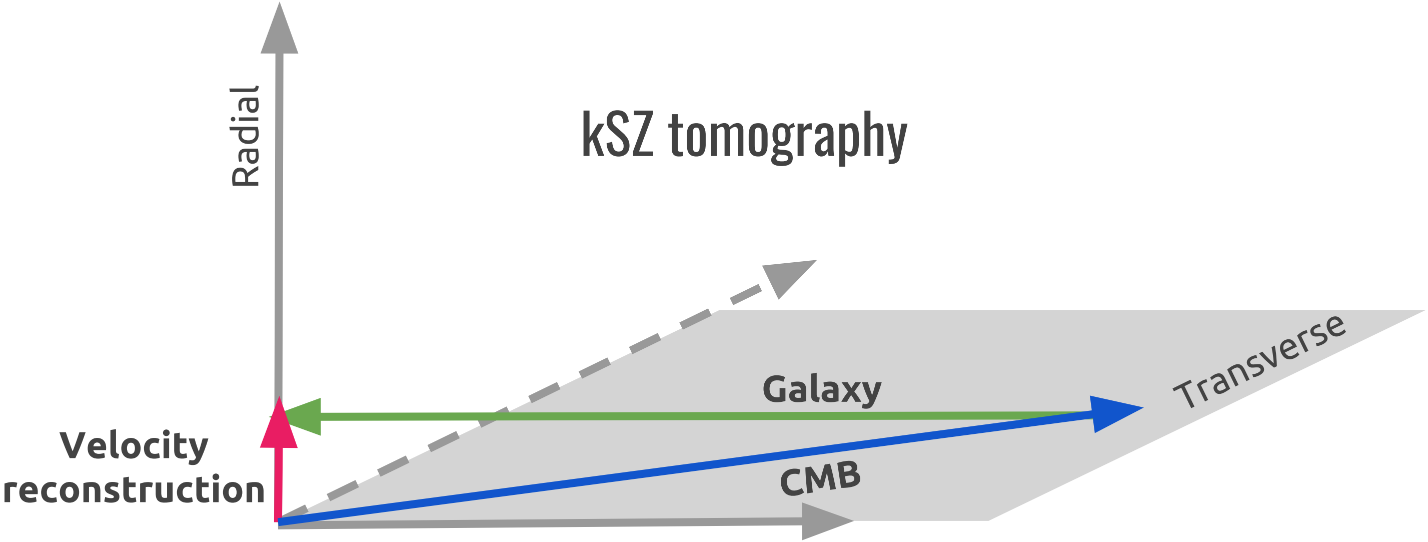
Bonus slides

CMB lensing



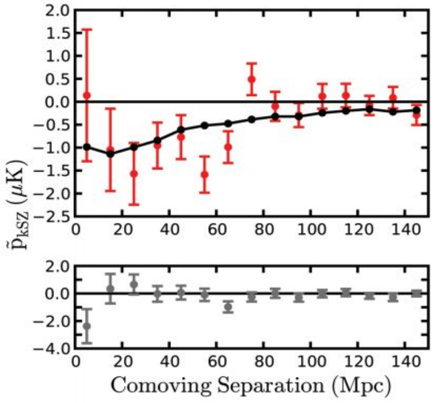
$$\hat{\phi}(L) = \langle TT \rangle_\ell$$

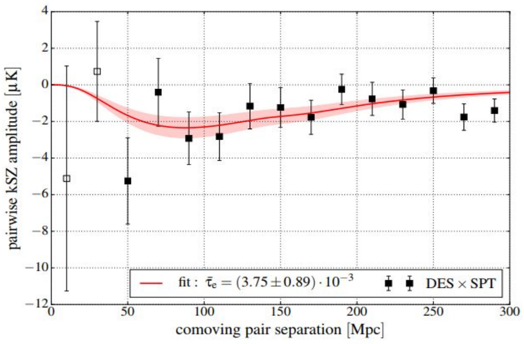
kSZ tomography

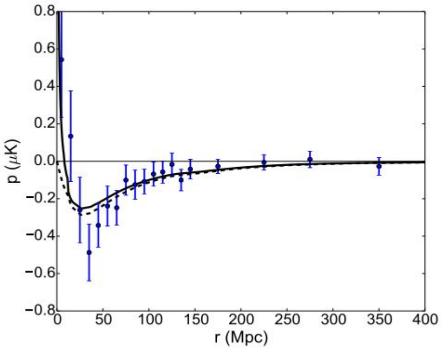


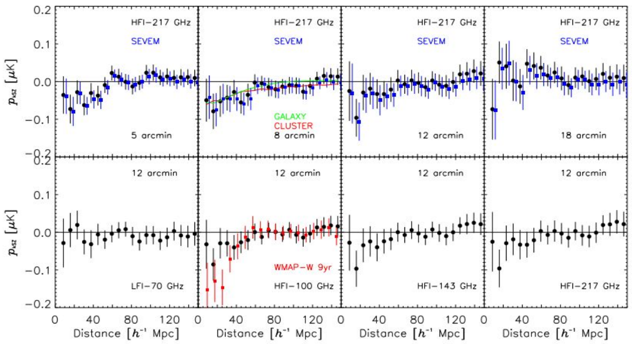
$$\langle v(k_L)\delta_g(k_S)T(\ell)\rangle$$

Bonus slide: pairwise kSZ detections









Step 2: cross-correlate velocity with galaxy pos.

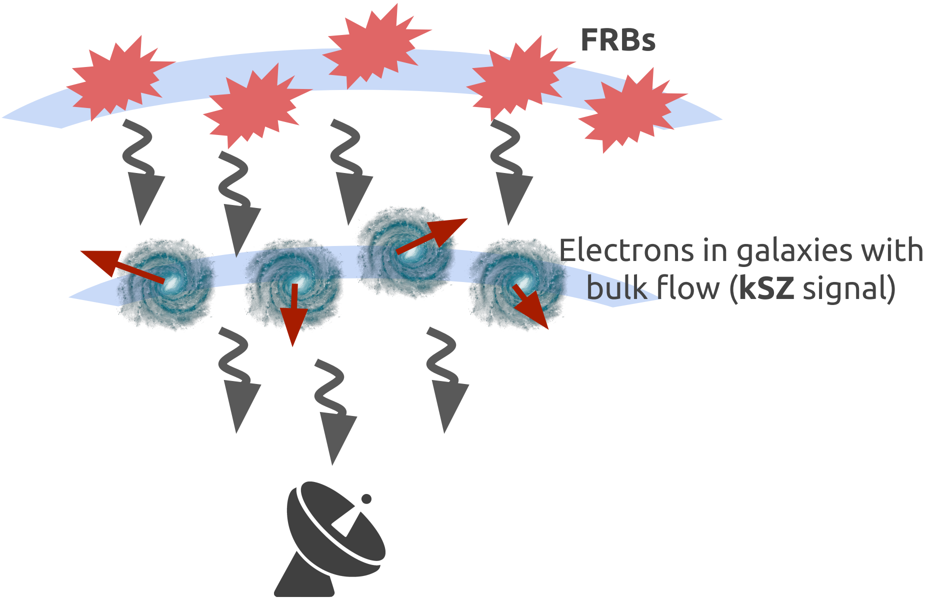
$$\langle \hat{v}\delta_g \rangle = \langle \langle \delta_g T \rangle_{k_S} \delta_g \rangle \sim \langle \langle \delta_g (v\delta_e) \rangle_{k_S} \delta_g \rangle$$

$$\sim \underbrace{P_{gv}(k_L)}_{\text{Cosmology}} \underbrace{\int dk_S P_{ge}(k_S)}_{\text{Astrophysics}}$$

Cosmology

Astrophysics

Scale-independent number


FRBs
Electrons in galaxies with
bulk flow (**kSZ** signal)