Moving lens: detection prospects

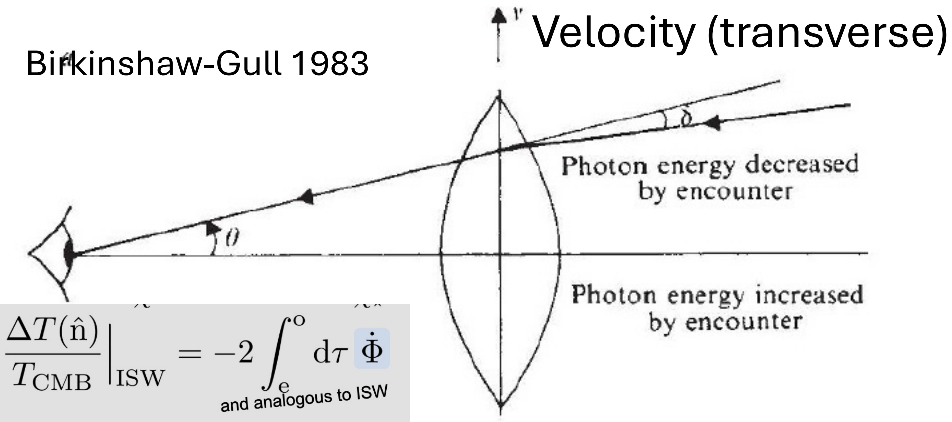
Elena Pierpaoli (USC)

Hotinli & EP arXiv:2401.12280
Hotinli, EP, Ferraro, Smith arXiv:2305.15462

What it is, motivation, and naïve estimates

- What: Dipolar temperature change in the direction of a halo:

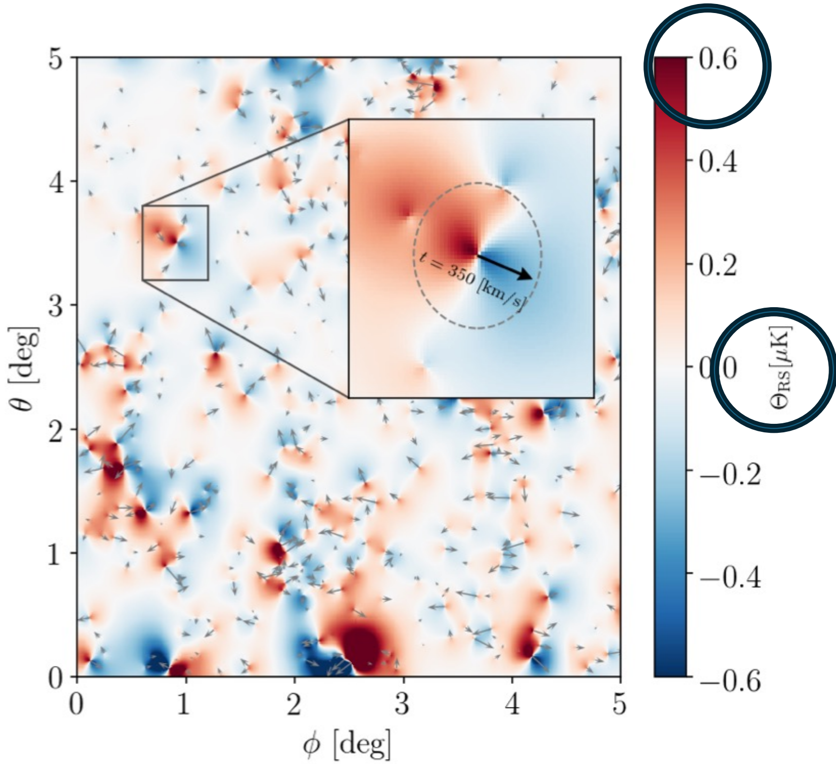
Birkinshaw-Gull 1983



$$\left.\frac{\Delta T(\hat{n})}{T_{\rm CMB}}\right|_{\rm ISW} = -2\int_e^o d\tau\, \dot{\Phi}$$

and analogous to ISW

- Why:
  - one of the two ways of measuring transverse velocities (other: polarized SZ, affected by different systematic effects)
  - Potential for making 3D velocity reconstruction
  - Potential of constraining cosmology (e.g. modified gravity)



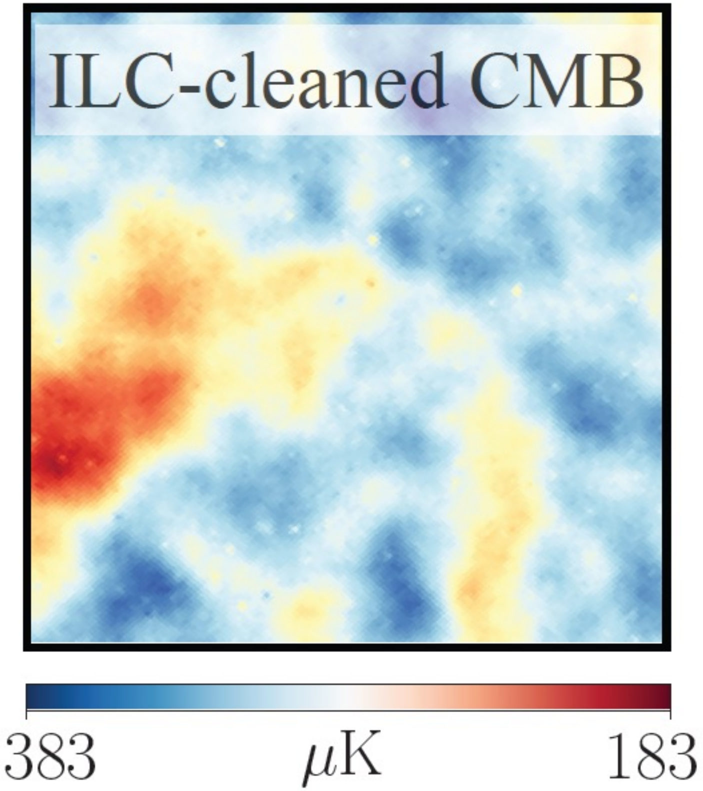
- **Small** dipolar signal
- Same frequency dependence as CMB
- Extended (beyond the virial radius)
- It depends on mass and velocity of halos

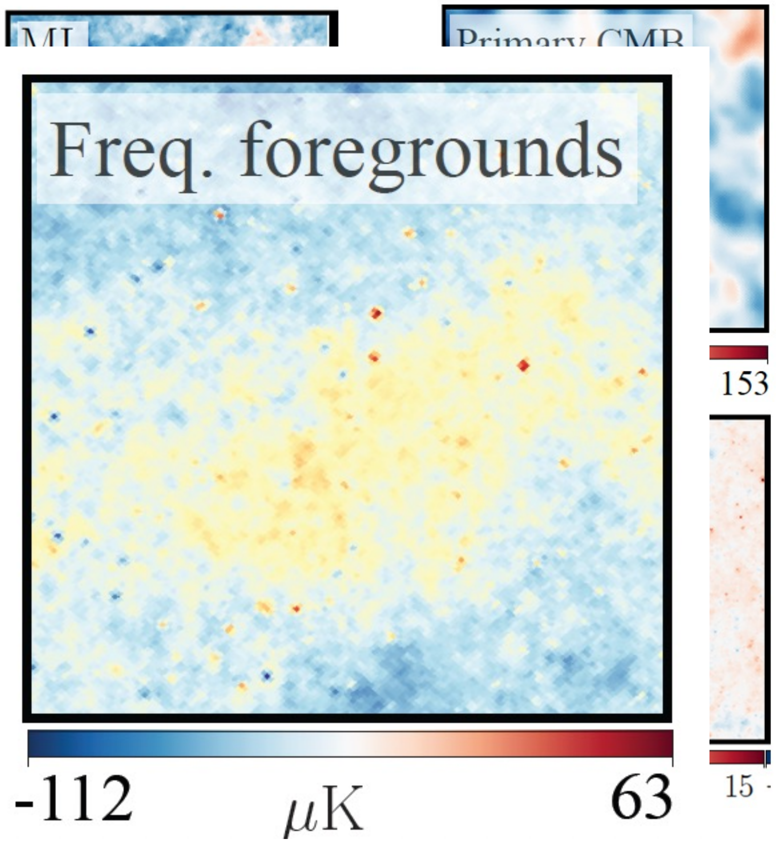
Small, but detectable with upcoming surveys (Hotinli et al 2019, Yasini, Mirzatuny, EP 2019)

Real Univers

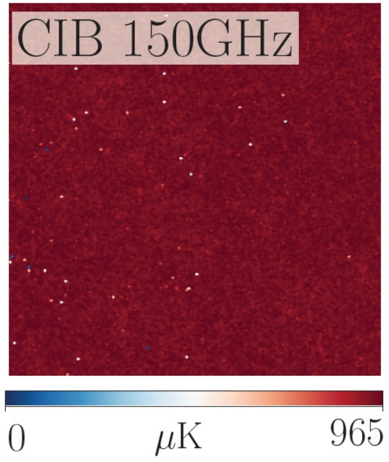
- Confusion by the same sign
- Competing signals with the
  - CMB anisotropies
  - Halo lensing (also inducing
  - Kinetic SZ (kSZ,spherical sh
- Other competing signals:
  - Cosmic Infrared backgroun
  - Thermal SZ effect (tSZ)
  - Radio point sources

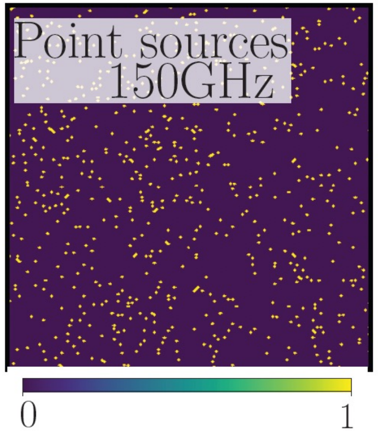
n)

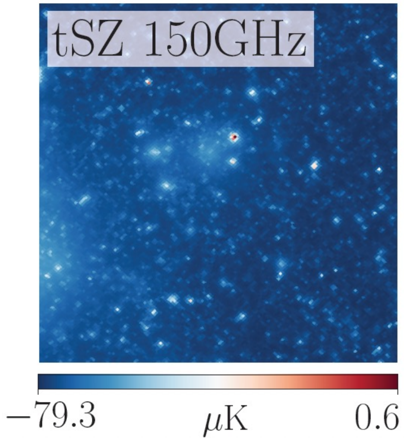




- Component s
  mandatory
- Even with perfect component separation, detecting velocities is challenging





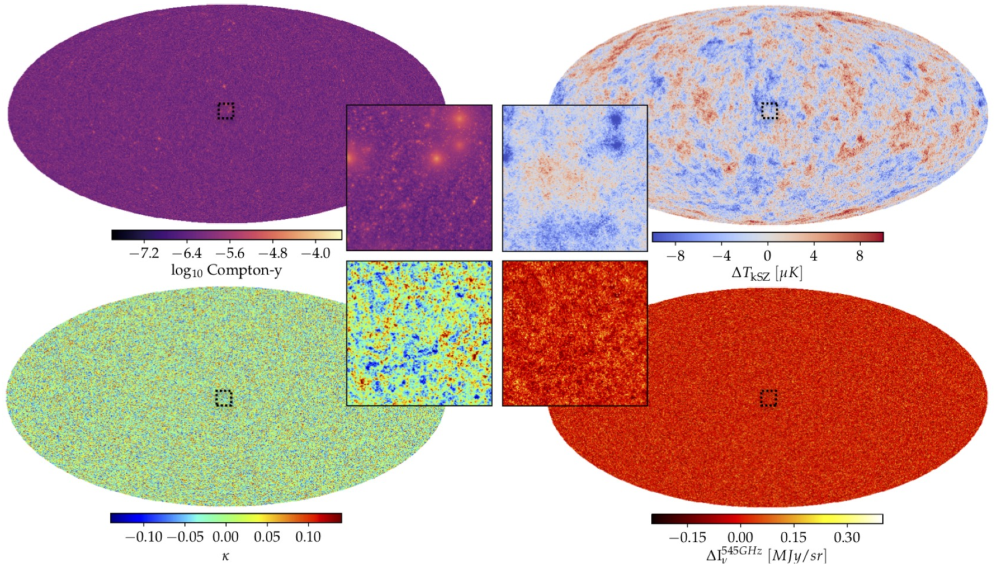


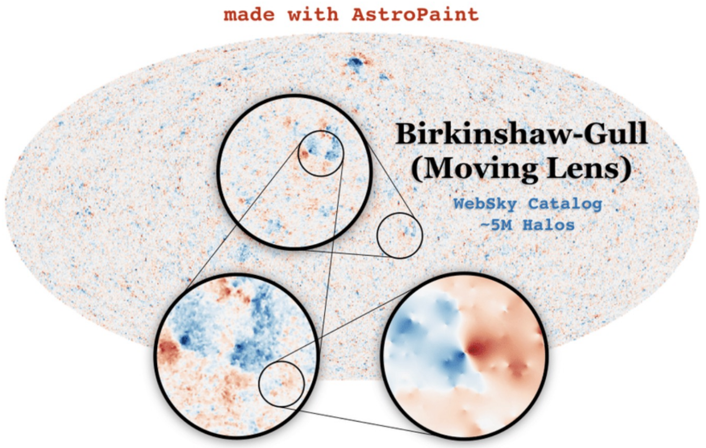
Detection strategies

- No detection of ML at the moment
- Single- Halo detection? Difficult.
- Statistical detection:
  - Stacking analysis
  - Pairwise velocity
- Practically:
  - Generate simulated frequency sky maps for all relevant [correlated and uncorrelated] signals
  - Perform component separation with ILC to extract the component that has a black-body spectrum.
  - Apply either stacking or pairwise velocity to detect ML.

Simulated maps

WebSky simulations for halos:
tSZ, kSZ, CIB, (Stein et al 2020)
radio point sources (Li et al 2022)





Astropaint (Yasini et al 2022) for ML and halo lensing

Map of the Birkinshaw-Gull effect painted with AstroPaint using the WebSky catalog * corresponding author

How can we detect the moving lens?

- The signal is too small to be detected on a cluster-by-cluster basis for a large number of objects. It needs to be detected statistically.

Component separation

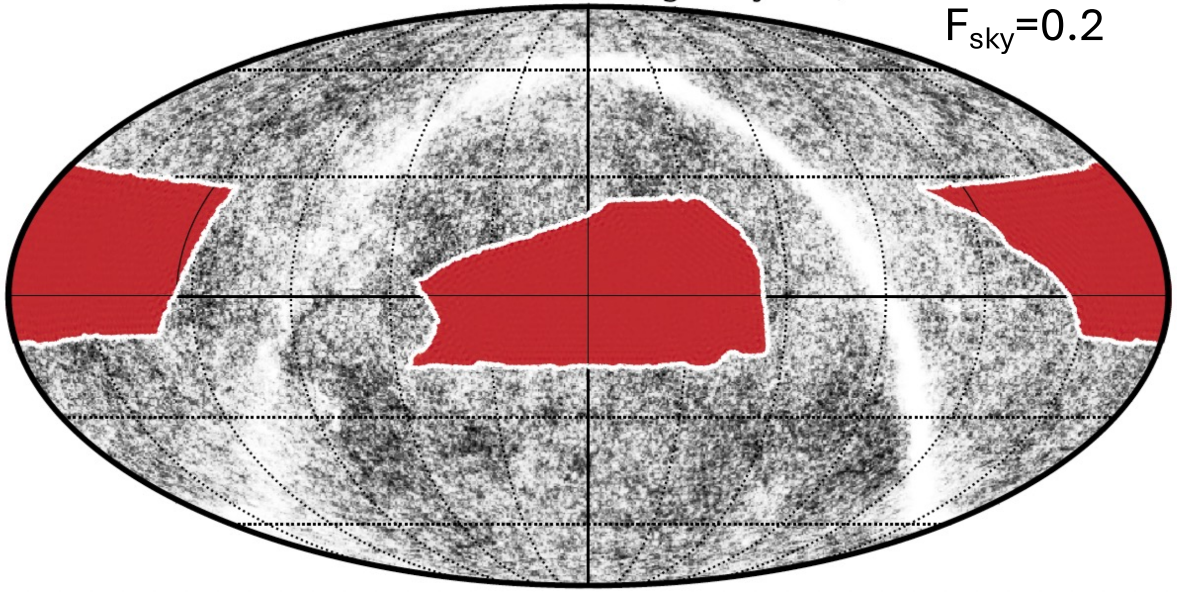
Multi-frequency observed maps → Black-body signals map (CMB, ML, Halo lensing,kSZ + residual tSZ, CIB, point sources)

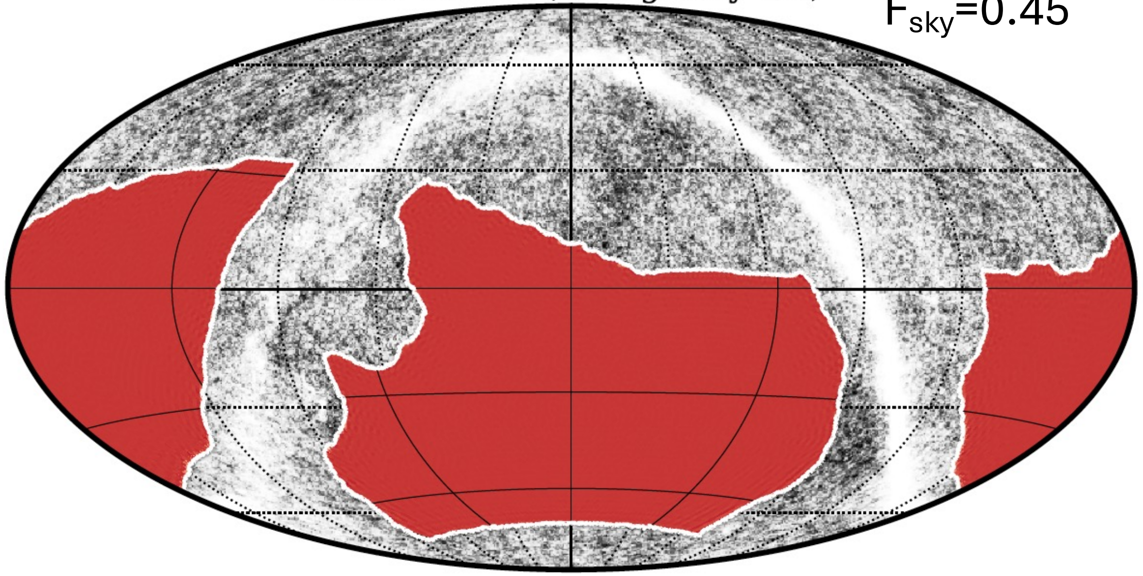
→ Oriented stacking along velocity direction

→ Matched filtering + pairwise velocity

- The final result will depend on the component separation method and on the detection method (and from the experiment's technical specifications)

Experiments considered





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CMB Experiment	Frequency in GHz =	40	90	150	220	Sky fraction
CMB-S4	$\theta_{\rm FWHM}$ [arcmin] =	5.5	2.3	1.4	1.0	0.7
	Δ_T [$\mu K'$] =	21.8	12.4	2.0	6.9	
Simons Observatory (SO)	$\theta_{\rm FWHM}$ [arcmin] =	5.5	2.3	1.4	1.0	0.4
	Δ_T [$\mu K'$] =	27.0	5.8	6.3	15.0	

Table 1. The CMB white noise parameters used in this analysis that match CMB-S4 and SO experimental specifications.

LSS Experiment	Redshift z =	0.26	0.38	0.50	0.64	0.79	0.96	1.14	1.35	1.58	1.84	2.15
LSST	$dn_{\rm gal}(z)/dz$ [1/arcmin^2] =	15.4	20.8	22.9	21.8	18.6	14.4	10.0	6.34	3.57	1.77	0.75
DESI	$dn_{\rm gal}(z)/dz$ [1/arcmin^2] =	0.15	0.18	0.24	0.36	0.56	0.47	0.45	0.36	0.14	0.02	0.0

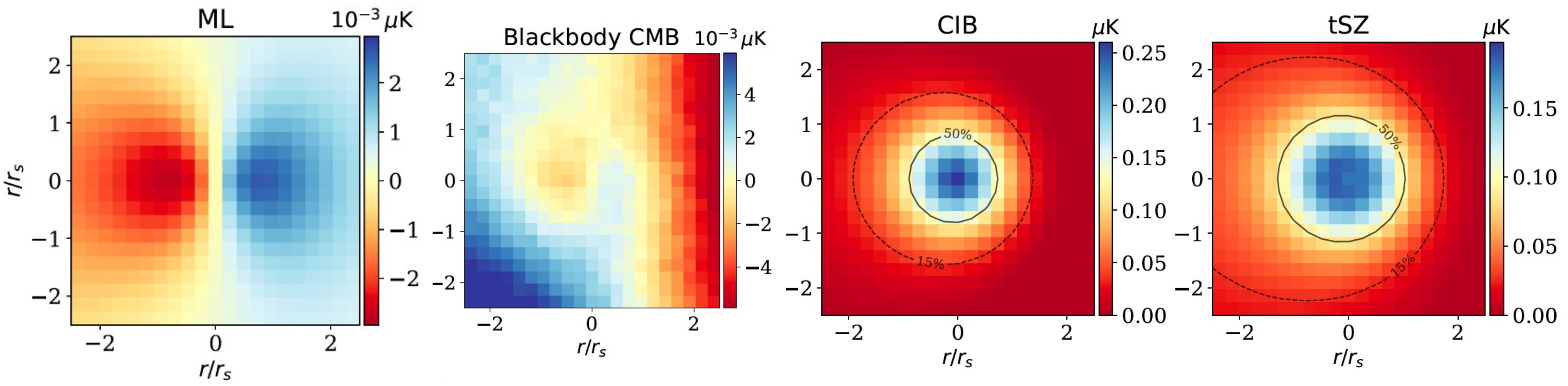
Table 2. The galaxy number counts we use that match LSST ($m_{\rm lim} \gtrsim 26$) and DESI surveys.

Overlap generated with code from Coulton et al 2022

Stacking

- Procedure:
  - Take the galaxy survey and use the continuity equation to get the velocity field from the density field as traced by galaxies
  - Take submaps around halos out of the ILC component separated CMB map
  - Orient and rescale the halos so that the velocities have the same directions
  - Cross fingers that all other signals aside from ML are averaged out.

BAD LUCK! CIB and tSZ residuals are large and show a correlated signal with velocity direction

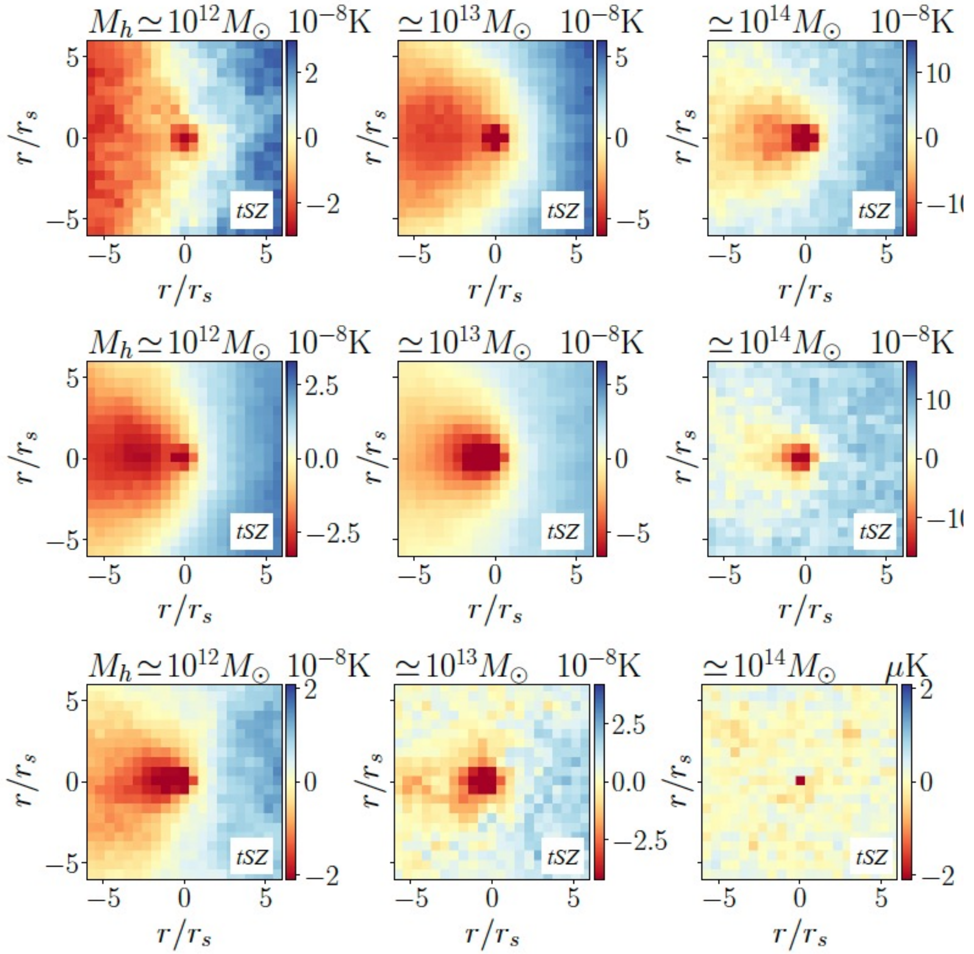


Bad luck or good luck?

This physical effect is in the simulations, and it is mass and redshift dependent

If ignored: substantial potential bias on velocity determination from single-frequency observation.

Clusters @ 150 GHz

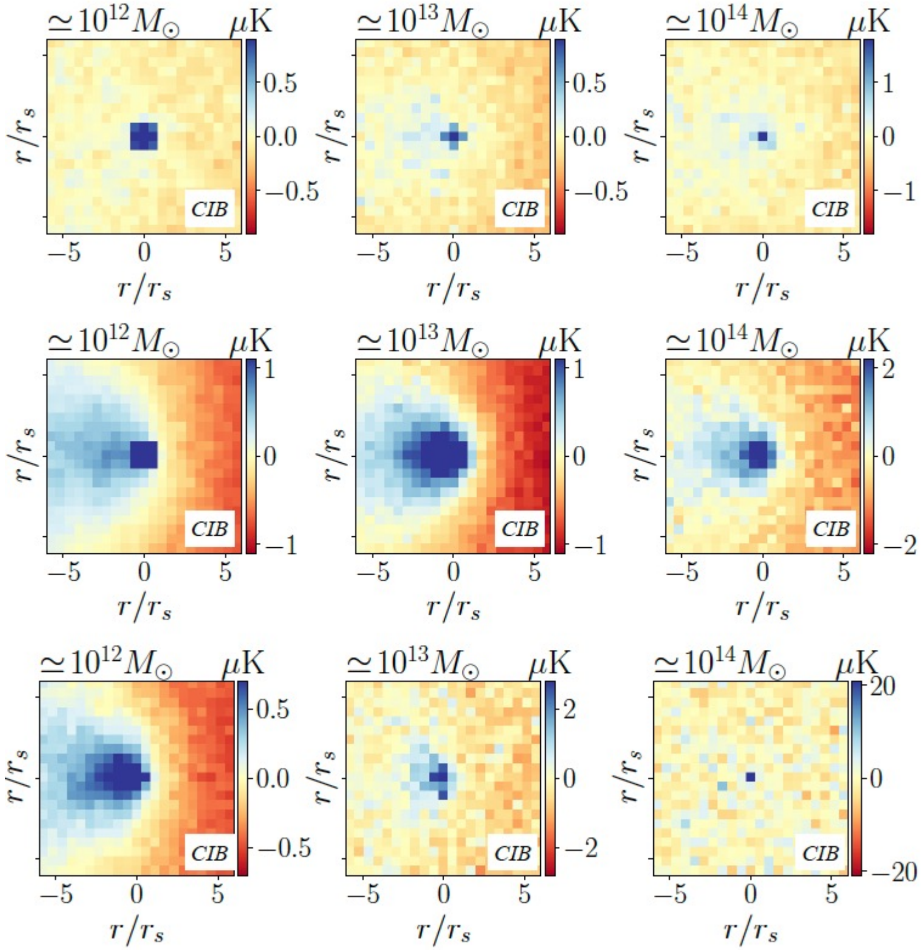


CIB @ 220 GHz

0<z<0.5

1.4<z<1.8

2.5<z<3

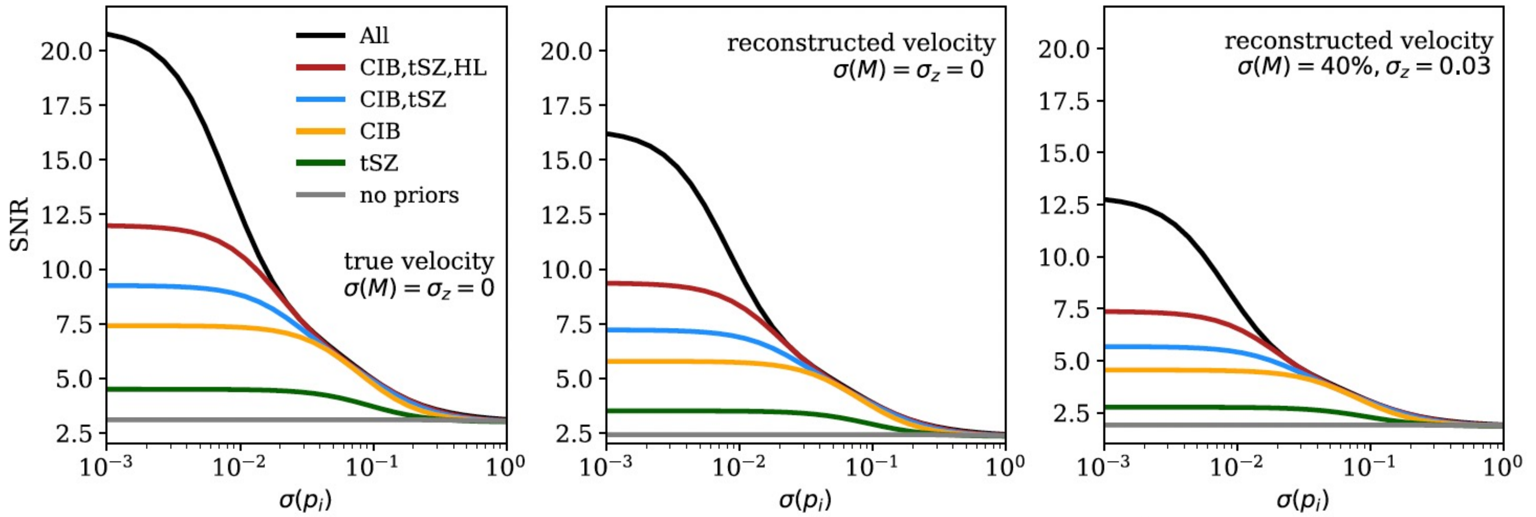


Results with stacking

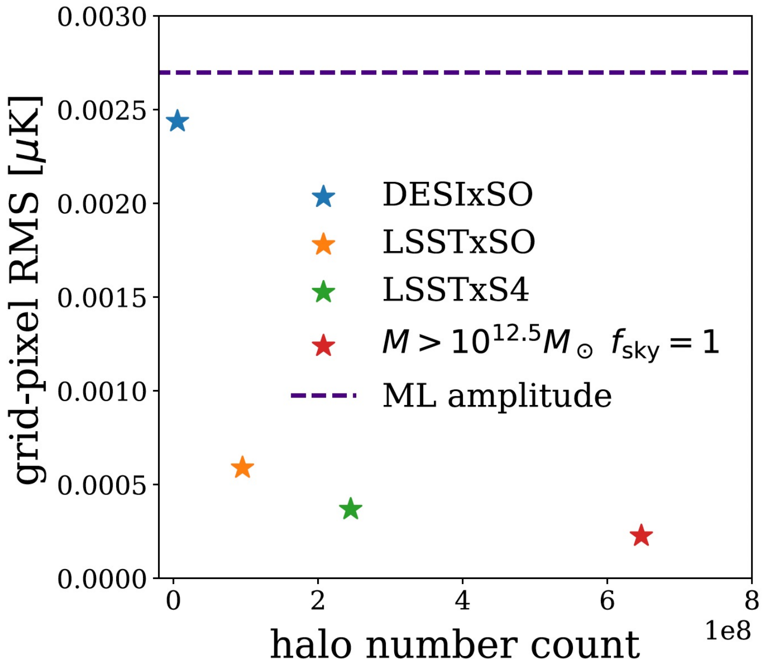
Estimates of S/N via Fisher Matrix $\pi = \{A_{\mathrm{ML}}, A_{\mathrm{lCMB}}, A_{\mathrm{kSZ}}, A_{\mathrm{HL}}, A_{\mathrm{CIB}}, A_{\mathrm{tSZ}}\}$

Results for CMB-S4+LSST

- No foreground knowledge: no detection
- Good knowledge of CIB and tSZ: 5-12.5 σ detection
- No error in M and z: adds about 3 σ
- Perfect velocity: adds about 3 σ

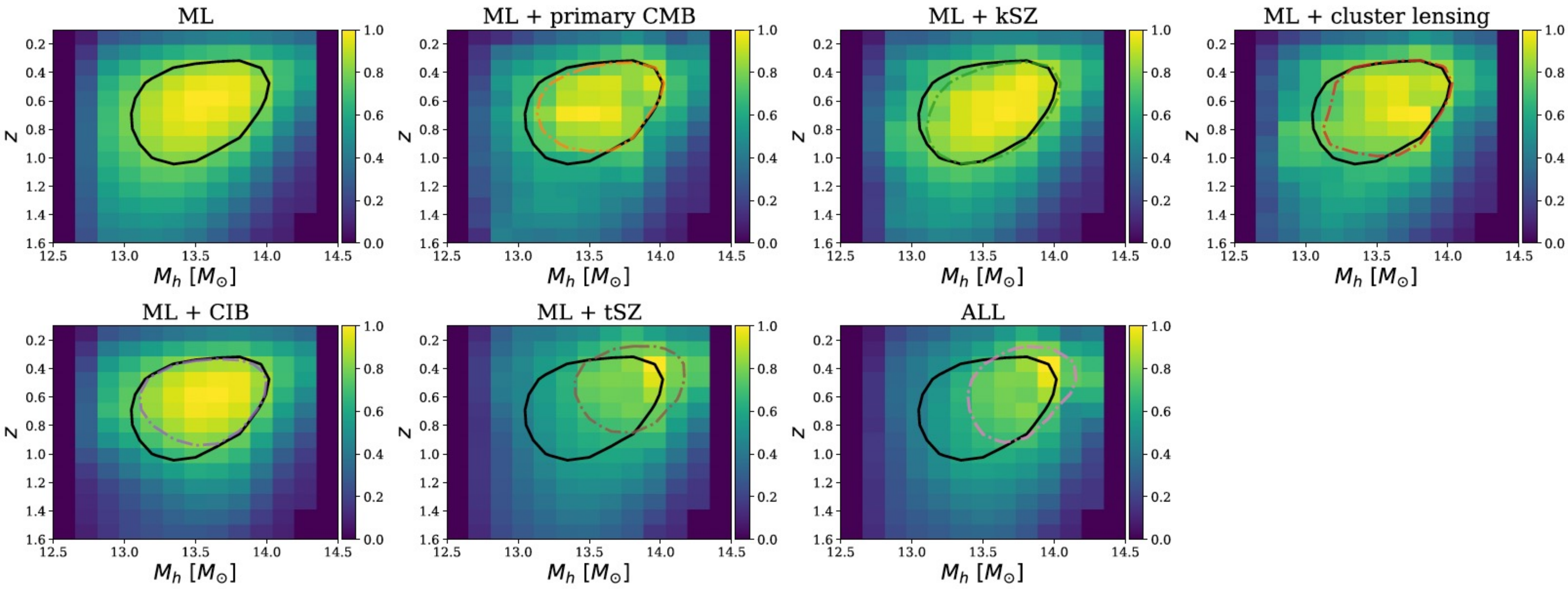


- RMS in ILC-cleaned CMB maps: improves significantly with halo number count in overlapping regions.

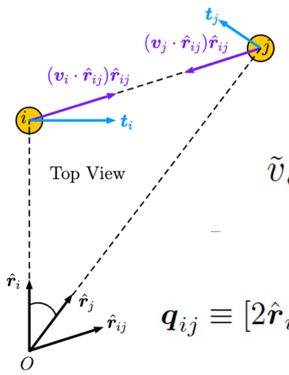


Which halos contribute the most to the detection

- Relative contribution of halos to the total SNR shifts towards lower redshifts and higher masses as all disturbing signals are included.



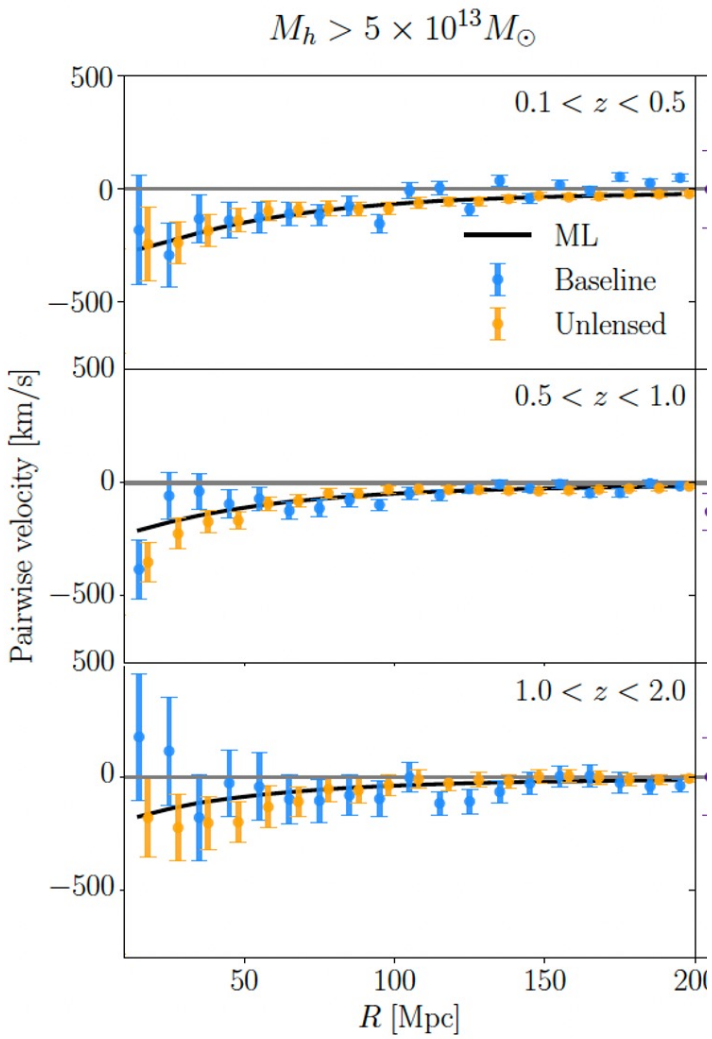
Pairwise velocities



$$v_{\langle ij\rangle}(r) \equiv \langle \boldsymbol{v}_{ij}(r) \cdot \hat{\boldsymbol{r}}_{ij} \rangle$$

$$\tilde{v}_{\langle ij\rangle} = \frac{\sum_{ij}(\tilde{\boldsymbol{t}}_i - \tilde{\boldsymbol{t}}_j) \cdot \boldsymbol{q}_{ij}}{\sum_{ij} |\boldsymbol{q}_{ij}|^2}$$

$$\boldsymbol{q}_{ij} \equiv [2\hat{\boldsymbol{r}}_{ij} - \hat{\boldsymbol{r}}_i(\hat{\boldsymbol{r}}_{ij} \cdot \hat{\boldsymbol{r}}_i) - \hat{\boldsymbol{r}}_j(\hat{\boldsymbol{r}}_{ij} \cdot \hat{\boldsymbol{r}}_j)]$$



- NB: This is NOT kSZ pairwise! (transverse velocities, and lensing - not baryon physics).
- Same procedure as for stacking, plus matched filtering to get velocities.

- CMB-S4 + LSST will be able to detect the transverse velocities. SO+DESI no.
- CIB and tSZ less (or not) of an issue. Main problem: halo lensing.
- Mass and redshift determination don't seem to be very relevant

- VERY computationally demanding - better strategy needed?

LSST+CMB-S4

$M_h > 5 \times 10^{13} M_\odot$.

SNR	$z \in [0.1, 0.5]$			$z \in [0.5, 1.0]$			$z \in [1.0, 2.0]$			
$R \in$	< 150Mpc	> 150Mpc	All	< 150Mpc	> 150Mpc	All	< 150Mpc	> 150Mpc	All	Total
baseline	5.17	-	5.17	6.31	2.84	7.11	3.14	0.99	3.25	9.4
unlensed	9.2	3.82	9.72	8.38	3.76	9.23	4.11	1.71	4.38	14.1

Conclusions and developments

- Yes ML will be detected, despite the ugliness of the real world
- Best perspectives for detection:
  - Better component separation (more tailored strategy)
  - higher resolution CMB experiments with good frequency coverage to facilitate component separation
  - Different detection strategies/methodology

  - Increased number density of galaxies
  - Better redshift determination for the galaxies

  - All of the above elements are intertwined, so it is hard to provide at this point actual quotes for improvements for cases not yet studied.

  - Really good simulations of various correlated effects are very important for these types of studies.