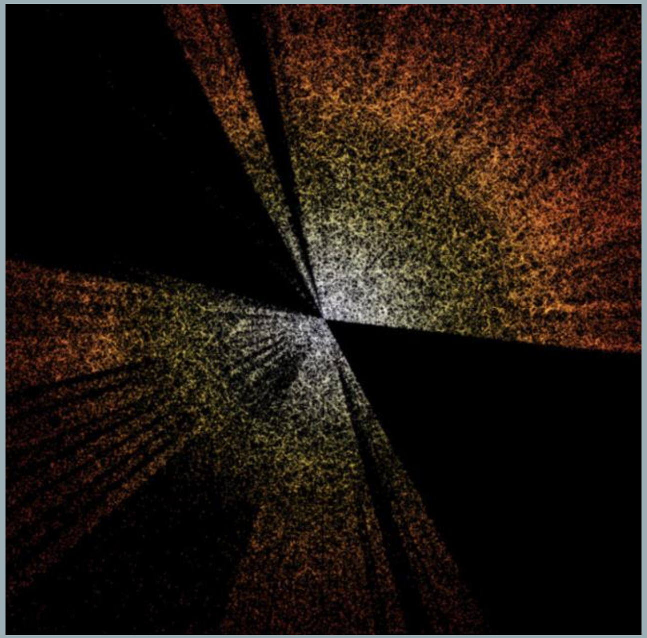
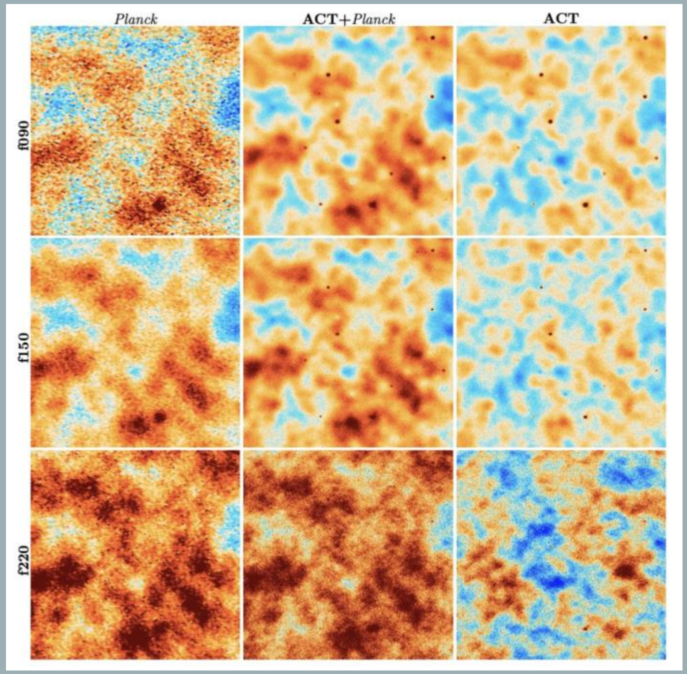
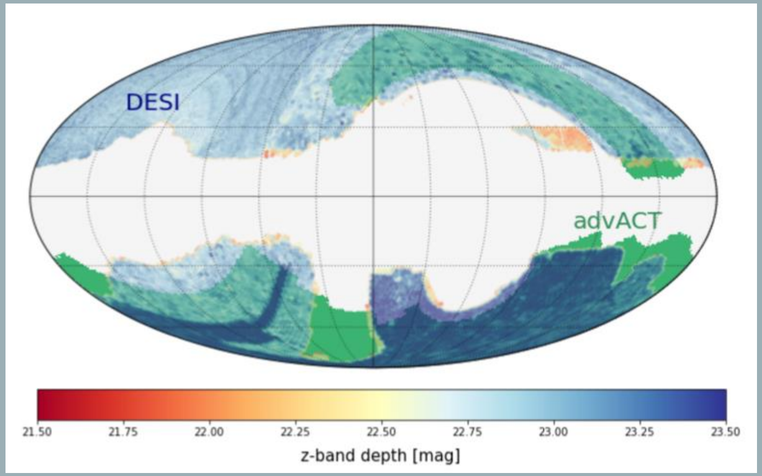
MULTI-WAVELENGTH SURVEYS AND HIGH-RESOLUTION CMB MAPS: POTENTIALS AND CHALLENGES FOR NEW ASTROPHYSICS AND COSMOLOGY

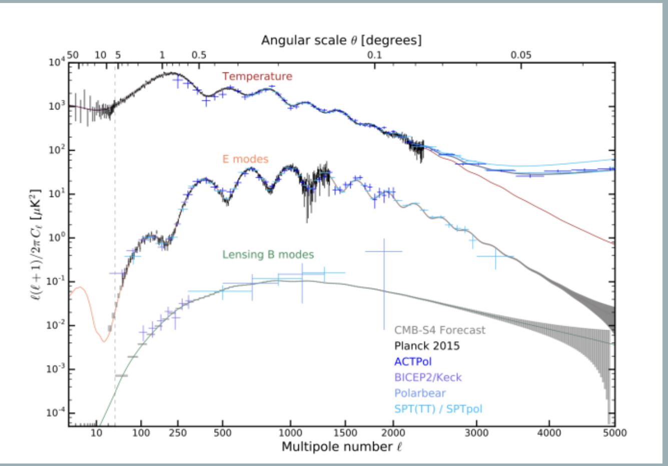


galaxy surveys (DESI, credit Schlegel)



CMB observations (ACT and Planck)
(Credit: Naess et al 2021)





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The Cosmic Web
KITP Santa Barbara, 3/13/23

TOPICS I WILL (AND WILL NOT) DISCUSS

- Considerations on cluster cosmology, multi-wavelength observation, clusters' detection and characterization

  [In collaboration with Satish Kumar (USC) and Karime Maamari (USC)]

- Future CMB surveys: what can be done in cosmology, beyond what we were able to do up to now with previous ones
  - Determining transverse velocities: the moving lens effect [with Selim Hotinli (JHU), formerly with Siavash Yasini, Sanjay Patil, Nareg Miratuny all (USC)]
  - Determining large-scale anisotropy modes from CMB polarization [with Haoyu Wu (USC), Mat Johnson (Waterloo/Perimeter), Marcelo Alvarez (LBL)]

- Will not discuss:
  - Determining clusters' physics and cosmology effect [Raghunathan et al 2022]
  - Detecting the Rees-Sciama effect [Ferraro, Schaan, Pierpaoli 2022] [yes, it is detectable at 6 sigma or so with CMB-S4 or CMB-HD and LSST]

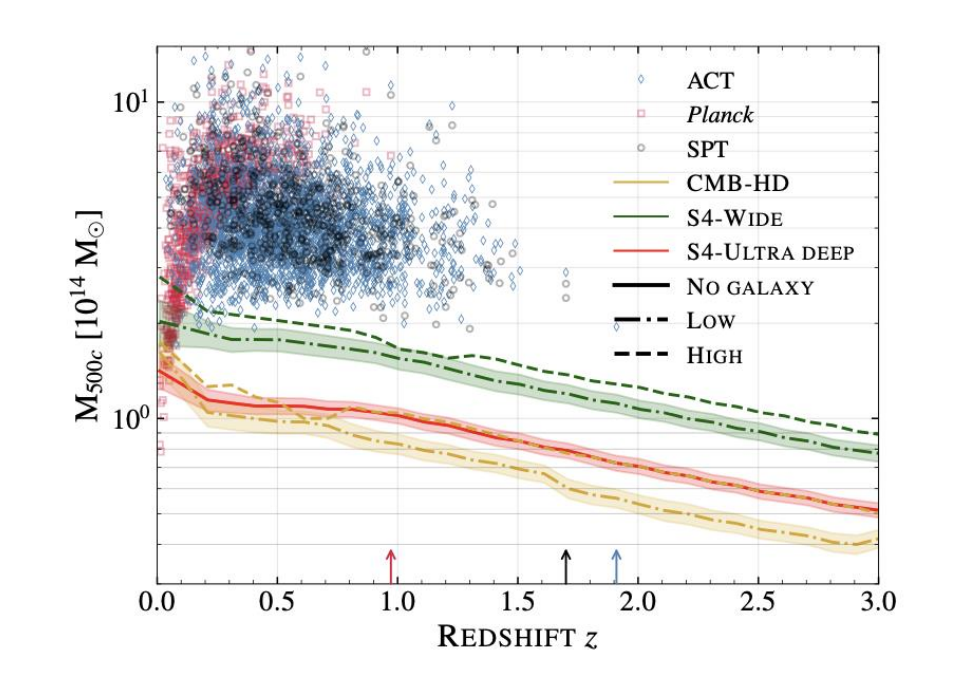
PARRT I: CLUSTER COSMOLOGY AND CLUSTER FINDING

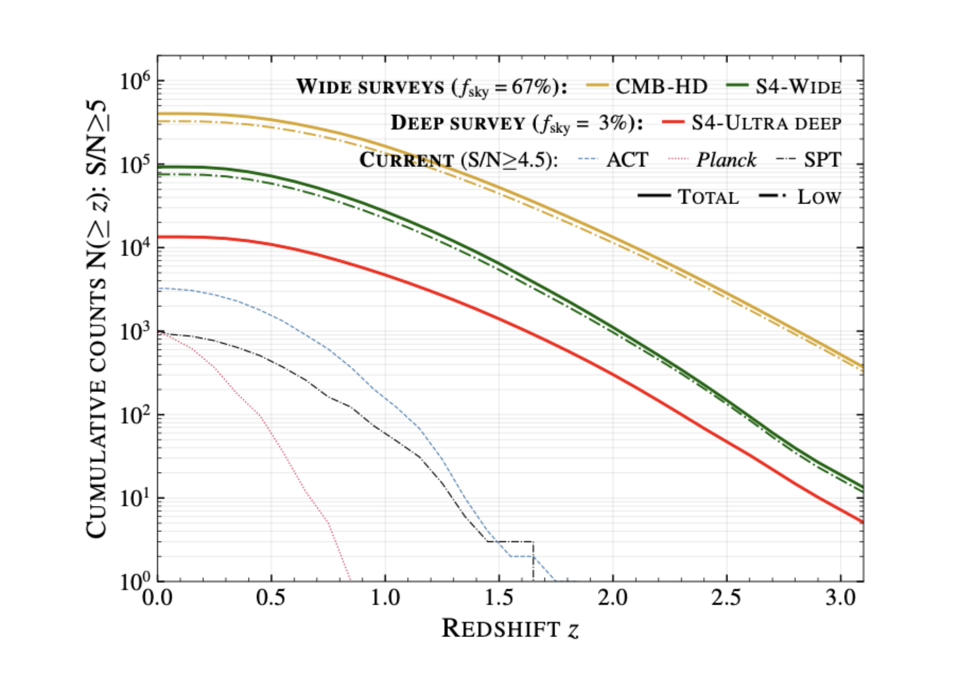
- Cluster cosmology = cluster number counts [for the longest time]
- Is it still useful, or shall we abandon it all together? Can it be made "more useful"?

CLUSTER DETECTION AND NUMBER COUNTS (TSZ)

1653 Planck detected clusters
~4000 objects with ACT and SPT

Raghunathan et al 2022





- Detection expected down to very low mass and z~3
- Enabled science:
  - Study of the growth factor (dark energy, modified gravity)
  - Neutrino masses (Future limits: $\Sigma m_\nu < 0.03$ eV (from SZ cluster counts (mass calibration from CMB lensing, current: Current limits: $\Sigma m_\nu < 0.13$ eV (95% CL, Planck + BAO))

CLUSTER COSMOLOGY AND CLUSTER FINDING

- Cluster cosmology = cluster number counts [for the longest time]
- Is it still useful, or shall we abandon it all together? Can it be made "more useful"?
  - It seems to be still useful (claimed to help with neutrino mass determination, dark energy, NG, etc)

  * If we find many objects, we can also compute the power spectrum and perform self calibration.

I truly hope I can believe my own predictions, but history in not on my side (see next slide).
Also, I don't want to wait until ~2030 (Nobody assures me I'll be around then, to begin with!)

To get there faster, we need to change the paradigm that we use to operate in this business.
We need to find more objects, and be confident of what they are.

REALITY CHECK

Figure from: Planck Blue Book 2006

~ 30,000 detection predicted (2006)

1653 actual detections (2015)

~400 used for cosmology (2015)

76 *CHAPTER 3 SECONDARY ANISOTROPIES*

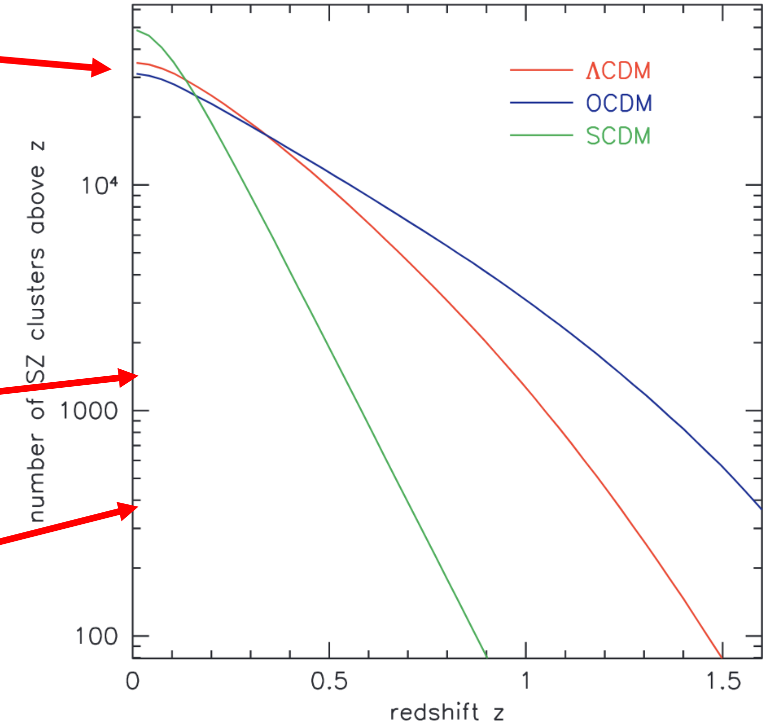


FIG 3.7.—The number of clusters *Planck* should detect at $\sim 3\,\sigma$ over the full sky at redshifts exceeding z, for three different cosmologies. For this calculation, the assumptions about the amount and structure of the intracluster medium were chosen to reproduce the SZ properties of observed low-redshift clusters. Abundance evolution is then based on large-scale numerical simulations (based on Bartelmann 2001).

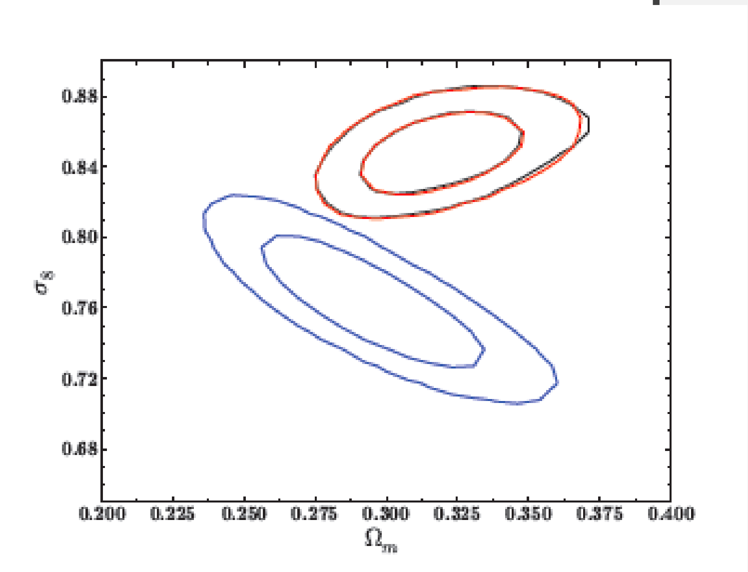
Take home message:

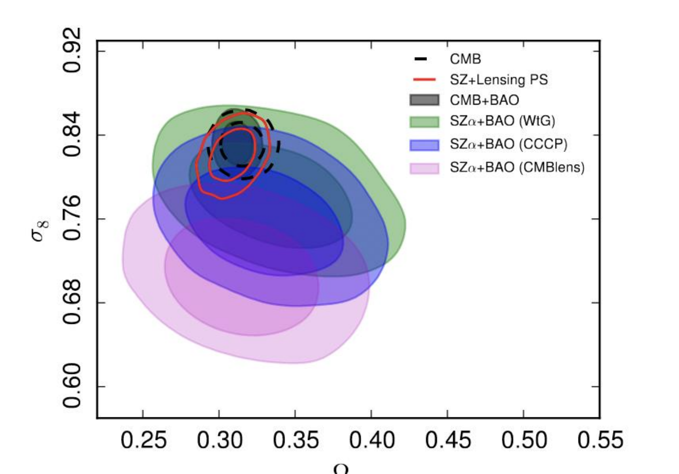
Everybody loves to be a theoretician, but life is way more complicated than typically predicted by a theoretician!

PROBLEMS

Planck Collab. 2013 and 15

- The cluster-derived measurement is discrepant with what found by CMB power spectrum studies
- Details in the analysis don't seem to matter enough. A bias of ~45% in the mass-observable relation would be needed to reconcile the two results (See also Salvati 2022 for Planck +SPT)
- Mass calibration is the main issue
- Much hope for weak lensing calibrated mass, but for low masses the scatter seems to be ~20% (Sereno et al 2020, Abbott et al 2020)
- None of the scaling relations (M–Lx, M–T, M–Yx and M–Mgas) seem to be self-similar, not even for the 120 Planck most massive clusters (Lovisari et al 2020) (see also Salvati 2022).
- More relaxed clusters are 30% more X-ray luminous than "disturbed" clusters.
- In general, selection in different wavebands yield objects with different properties (See e.g. Orlowski 2021 for ACT and MadCoWs)





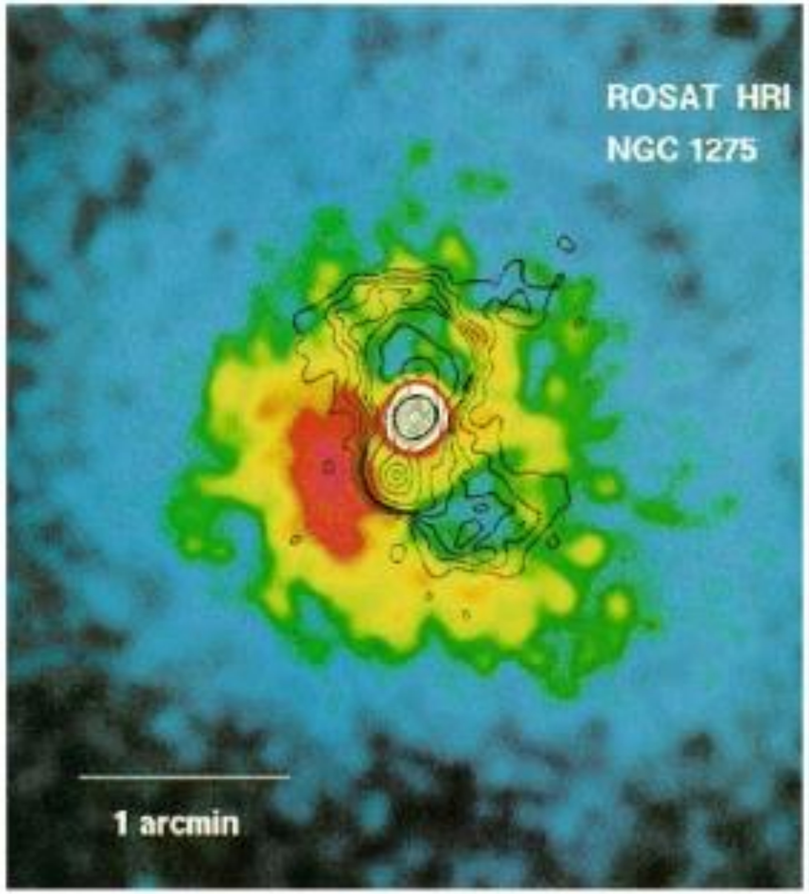
The green, blue and violet contours give the cluster constraints (two-dimensional likelihood) at 68 and 95 % for the WtG, CCCP, and CMB lensng mass calibrations, respectively

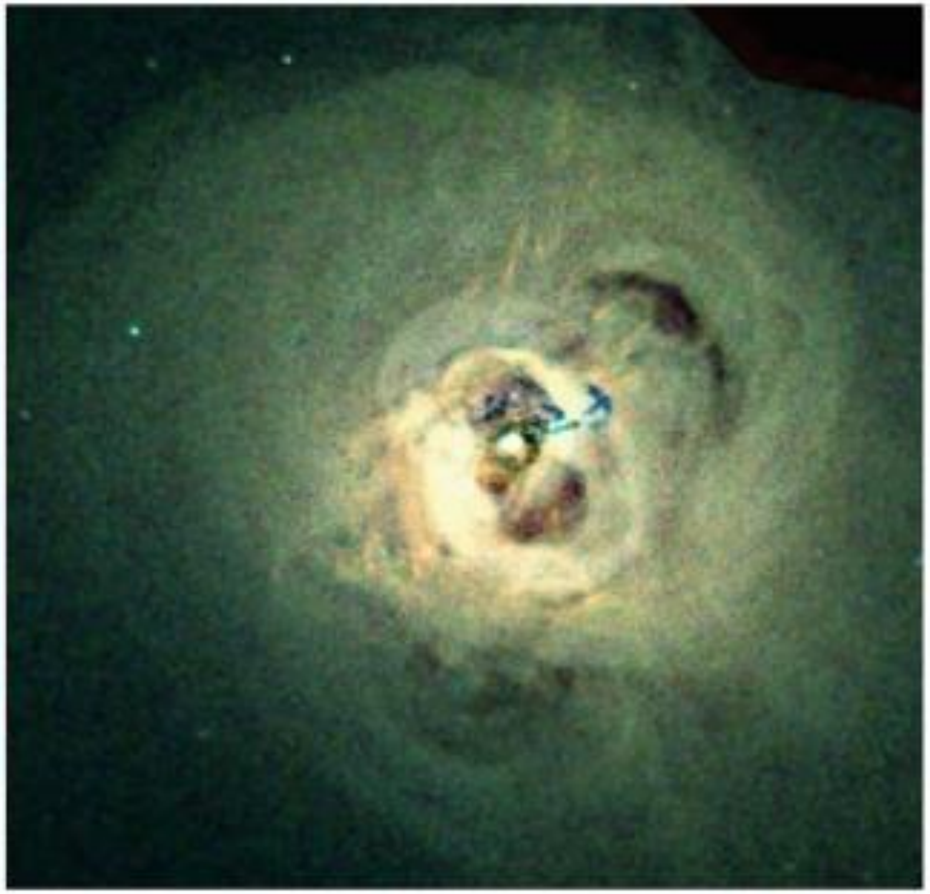
CLUSTERS ARE NOT SIMPLE OBJECTS

Example: Perseus

Black contours: radio
Color coded: Lx (ROSAT)

Fine structure of gas
Observed by Chandra





IS ``MORE" CLUSTERS ACTUALLY ALWAYS BETTER FOR COSMOLOGY?

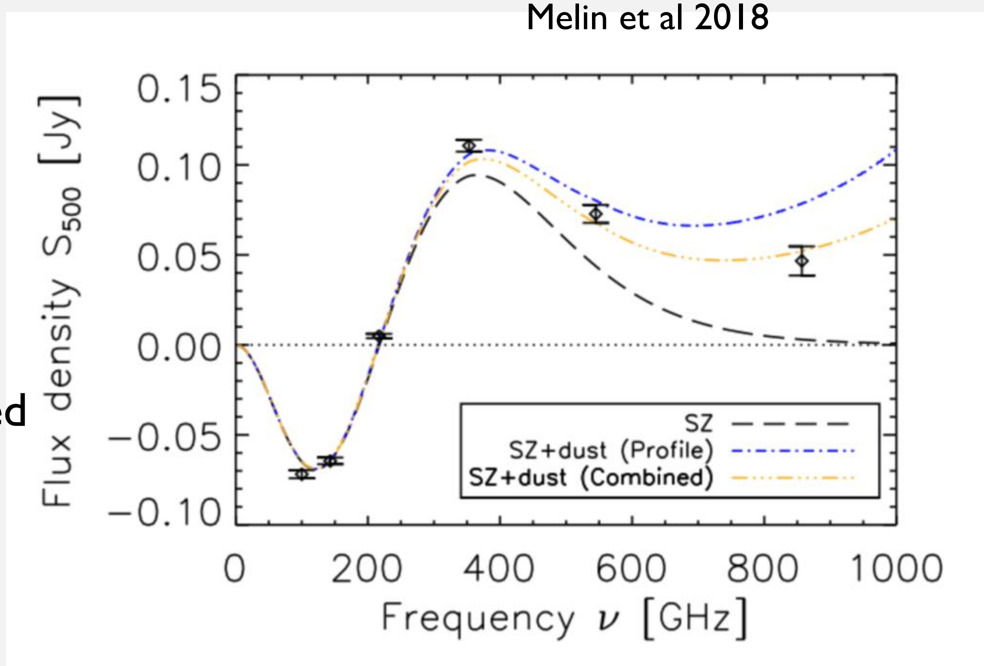
- Up to now, the answer has been "no".
- Various examples of problems on going to small masses, and also not so small: reliability of the detection, and then physical processes having a greater impact on the diversified appearance of the objects.

THE ASTROPHYSICS OF CLUSTERS

- A number of physical effects at play:
  - Merging (shocks etc)
  - star formation, dust extinction
  - Dust production and disruption
  - Galaxy formation and evolution
  - Cooling and heating of the gas
  - Gravitation processes
- there is interplay between the various components
- There are redshift dependences
- Result: Different appearances in different bands are to be expected, also depending on redshift.

RIGIDITY OF THE SZ CLUSTERS SEARCH SCHEME

Melin et al 2018



The measured emission of stacked Planck clusters at various frequencies (points with error bars). The SZ sig- nature is the black curve, and the other two curves include models with dust

Current SZ Cluster searches rely on matched filtering for the y distortion (Black line) but this is not even correct at 350 GHz, let aside 500 GHz and up.

Also, these might be point sources filling up the decrement (masked in Planck). Dicker et al 2021 show that 3%-6% of clusters have y signal significantly impacted by a point source.

Also, clusters might not be spherical.

All three points above might be more important as we search clusters at higher redshifts.

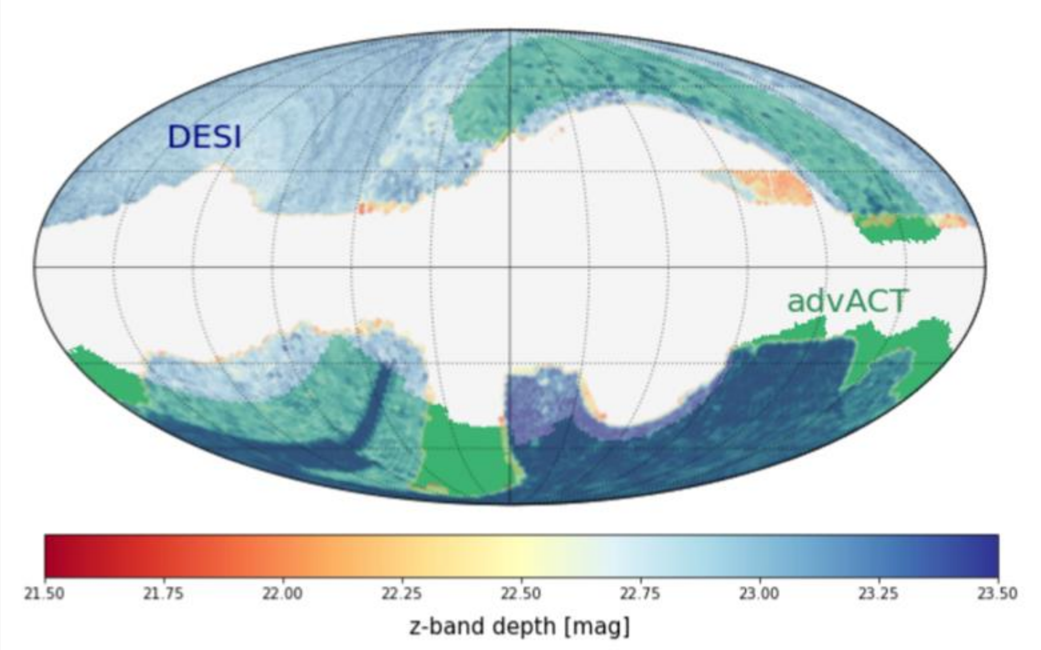
[note that the modeling "rigidity" is present also in the search at other wavelengths]

WAYS FORWARD

- Learn more from the observations:
  - multi-wavelengths teach us more. Why don't we do it? Because it is difficult. Many have tried, with fruitful results, but still with a limited set of wavelengths.
  - Allow for different strategies. Use AI.

In collaboration with Karime Maamari, Satish Kumar Thittamaranahalli.

We can do that because nowadays, there are several large overlapping regions. Let's use them.



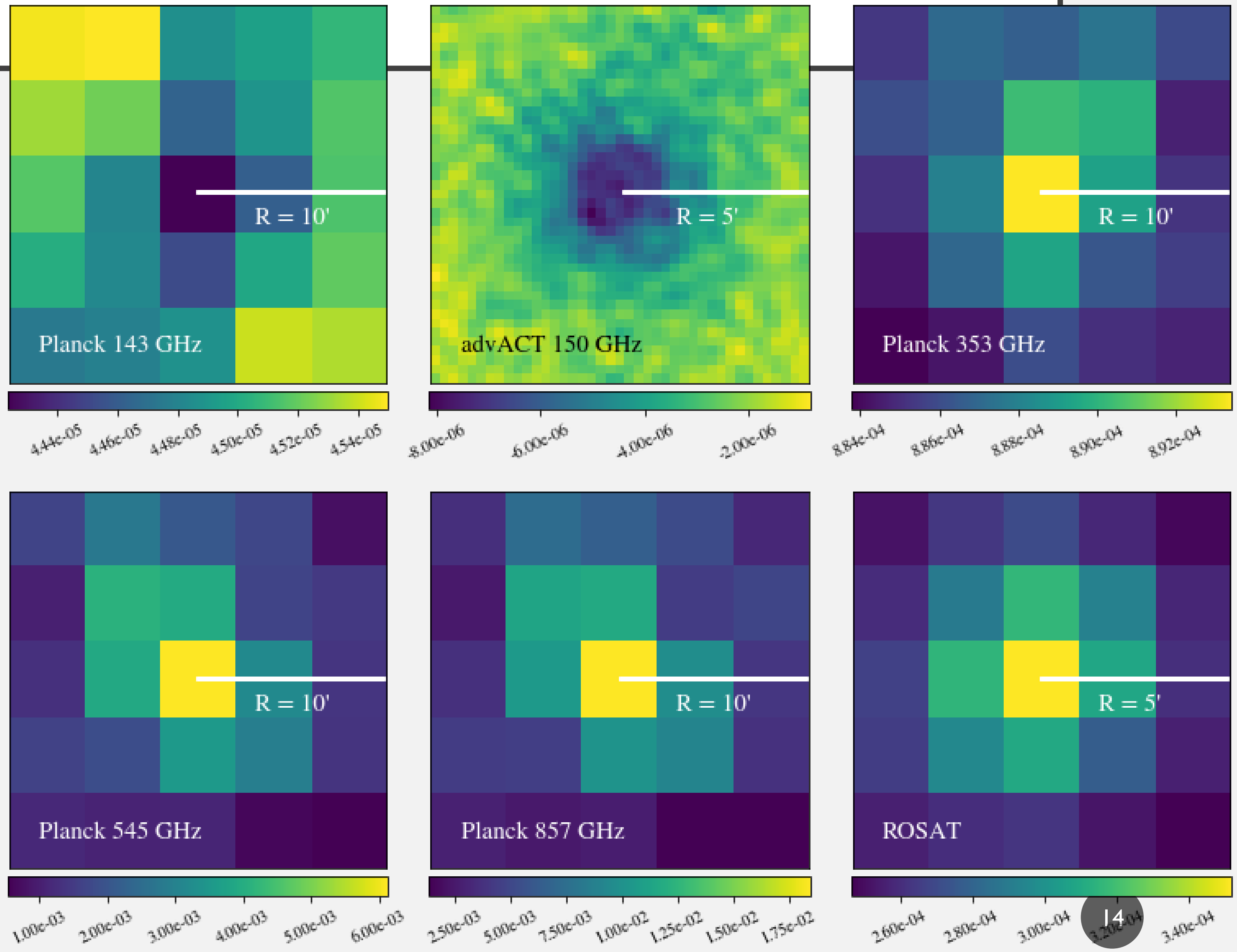
SOME CLUSTER CATALOGS

Catalog name	Observations	No. of obj.	z (median)
PSZ2	Planck	1653 [92]	≤ 1 [≥ 0.4]
y param. dist.	Planck, WISE, SDSS	3000 [1218]	≤ 0.7 [≥ 0.4]
ComPRASS	Planck, ROSAT	2323	≤ 1.2 (0.22)
PHZ	Planck (high freq), IRAS	2150	≤ 4 (2.5)
ACT clu. cat.	ACT	4000	≤ 1.9 (0.52)
SPT clu cats.	SPT	680+450+80	(0.55)
SPT+Planck	Planck, SPT	400	≤ 1.7 (0.47)
RedMapper	SDSS	26,000	≤ 0.55
WHL	SDSS	132,700	≤ 0.7
AMF	SDSS	46,400	≤ 0.7
MaDCoWS	WISE,Pan-STARRS	2800	0.7-1.5
DESI clu. cat.	DESI	540,000	≤ 1 (0.56)
WH22	DES,WISE	151K [30K]	≤ 1.5 [≥ 1]
Zou22	DES, DESI, HSC	530K, 87K, 36K	≤ 1, ≤ 1.2, ≤ 1.6
eROSITA cat.	eROSITA	542+346	0.001-1.3
MARD-Y3	ROSAT, DES	$\simeq 1500$	0.02-1.1
NORAS+REFLEX	ROSAT	$\simeq 1000$	≤ 0.3
MCXC	ROSAT+pointed-X	1740	≤ 0.8

- Optical is the wavelength where we have most detections on a large area of the sky (100k objects vs 1k of X and SZ)
- Optical (+IR) have the highest number of z clusters as of now.
- multi-wavelength searches yield more clusters than single wavelength studies. Are they real?

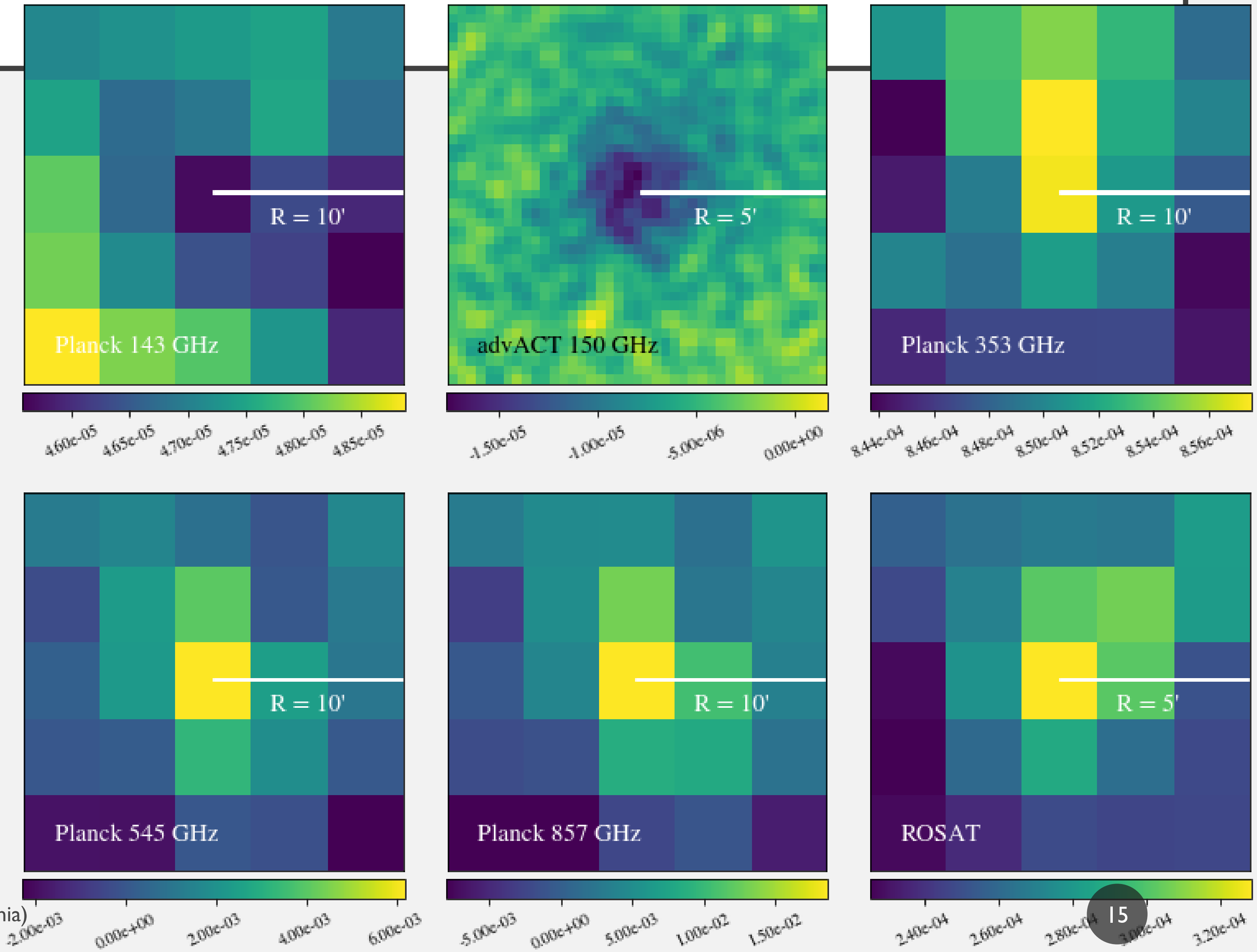
YES, THEY ARE REAL!

- Intersection between WHL, AMF (SDSS based) and DESI Clu. Cat [excluding Planck detected clusters, 31.5k objects, z<0.64]



IS THIS DOMINATED BY LOW-Z OBJECTS? NO

Z>0,48 objects only,
10% of the sample, 2676 objects

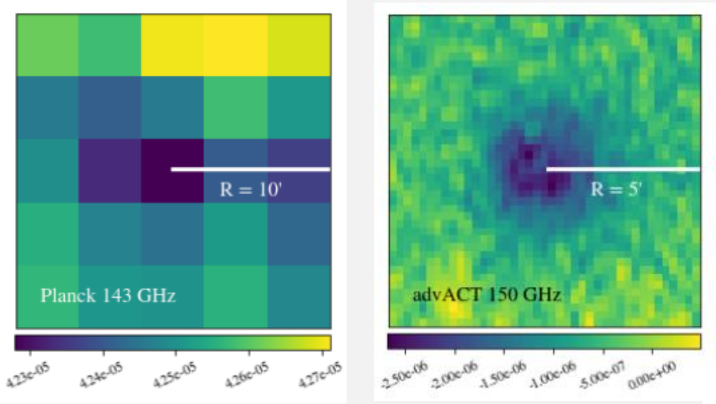


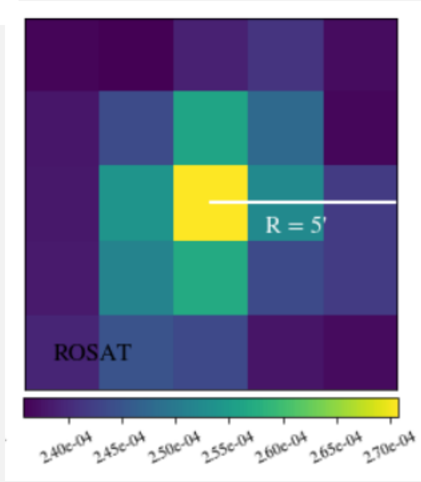
OK, but this is still pretty low redshift.
What about higher z?

WH22 (DES+WISE) CATALOG

High z: visible in the Planck (high-freq channel
not so much in ROSAT,
ACT or Planck low freq (point sources?)
.

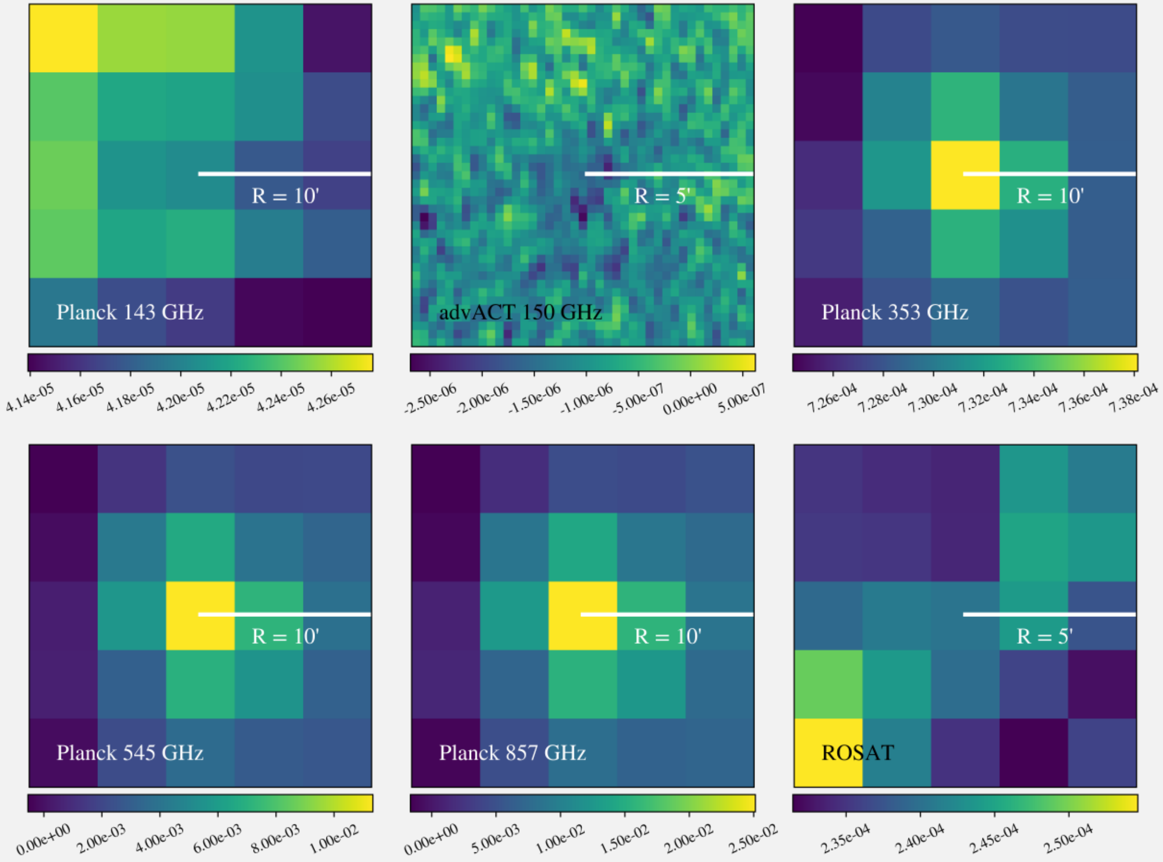
Z<1 objects





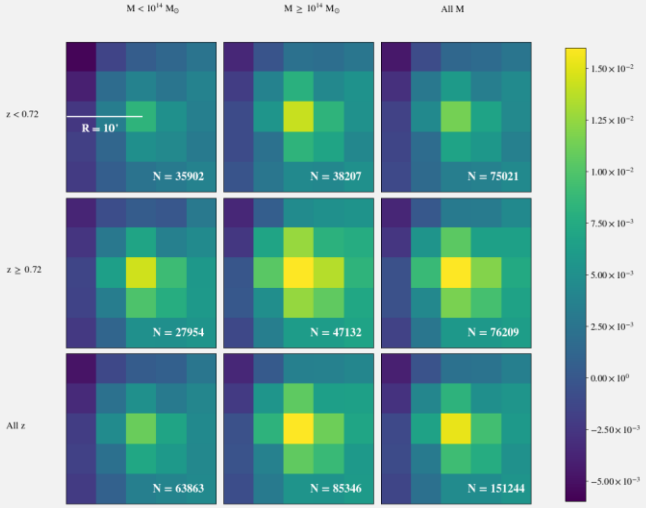
Low-z: visible in all freq.
Hints of point source signal?

Z>1 objects

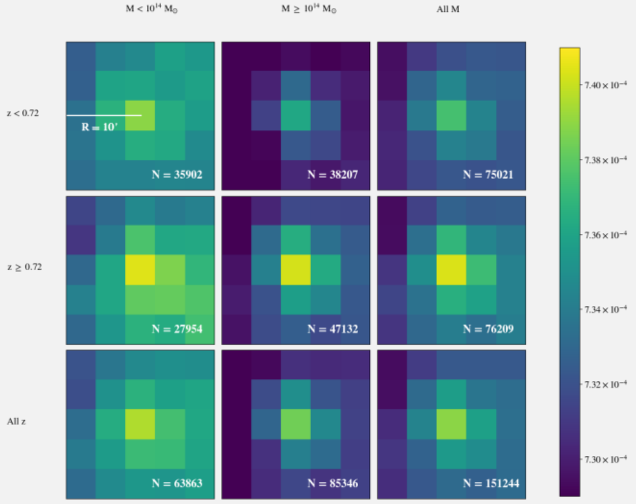


WH22 IN Z AND M BINS

857GHz



353 GHz



← Planck

220 GHz

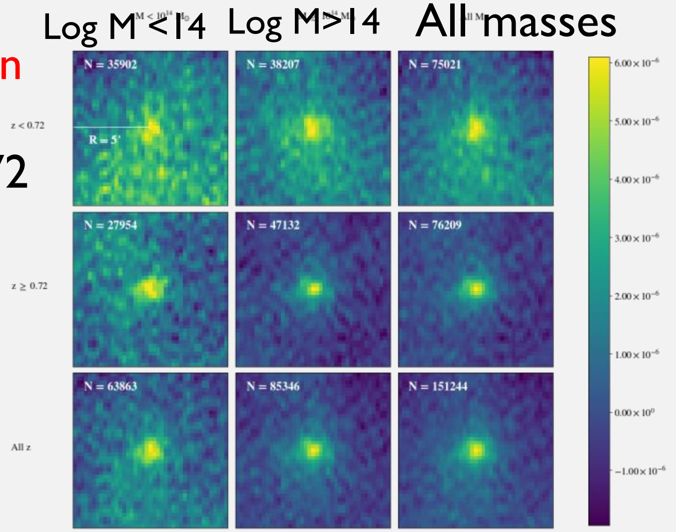
Log M<14 Log M>14 All masses

With a special dedication
To Evan….

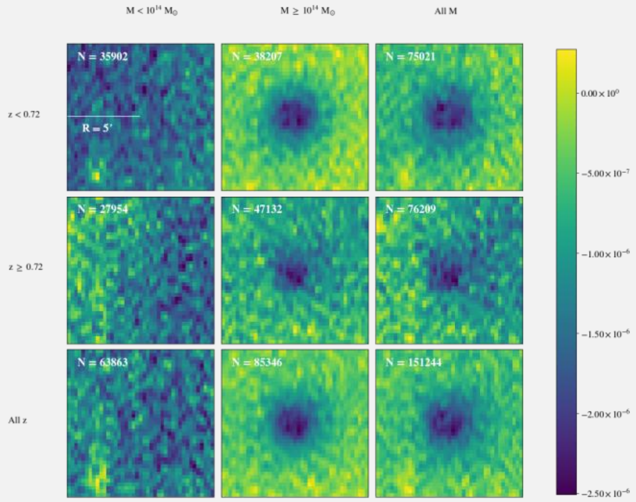
Z<0.72

ACT → Z>0.72

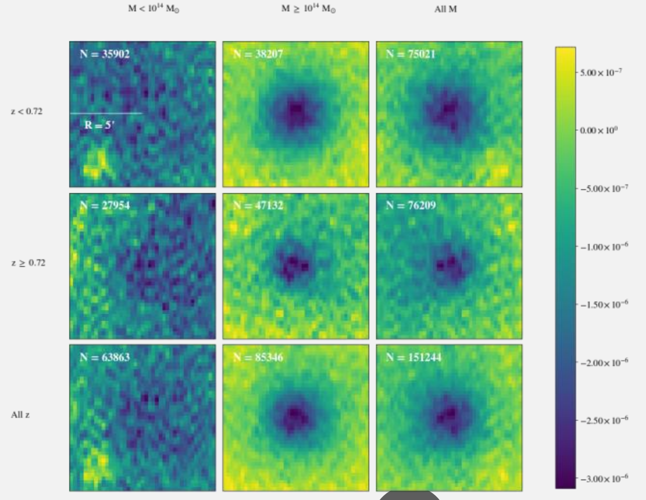
All z



150 GHz

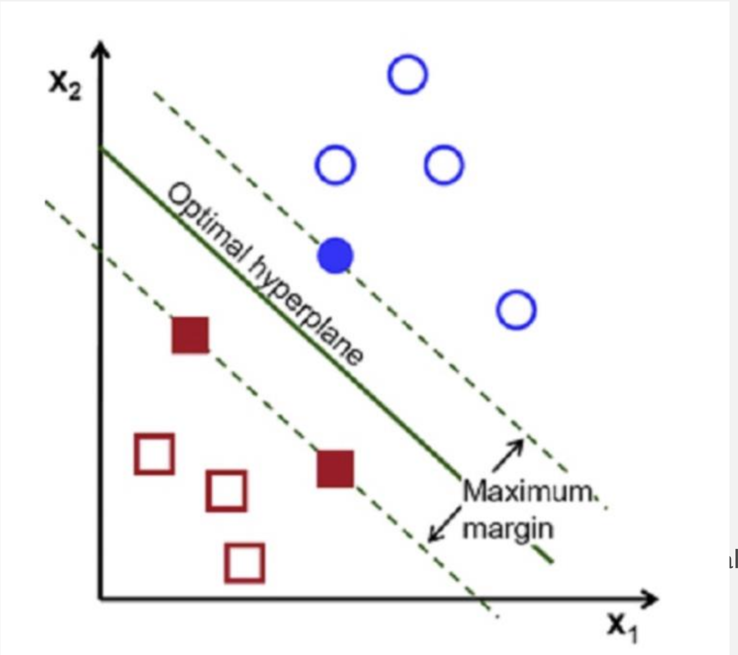


90 GHz



ALL GOOD. CAN THIS BE USED FOR DEFINING A NEW CLUSTER FINDING SCHEME? (ADVENTURES IN ML)

- Leverage on the abundance of data to characterize clusters while avoiding rigid schemes.
- Consider the integrated signal within a given radius, at each frequency.
- Classification problem: clusters versus non-clusters, using support – vector – machine algorithm (SVM).



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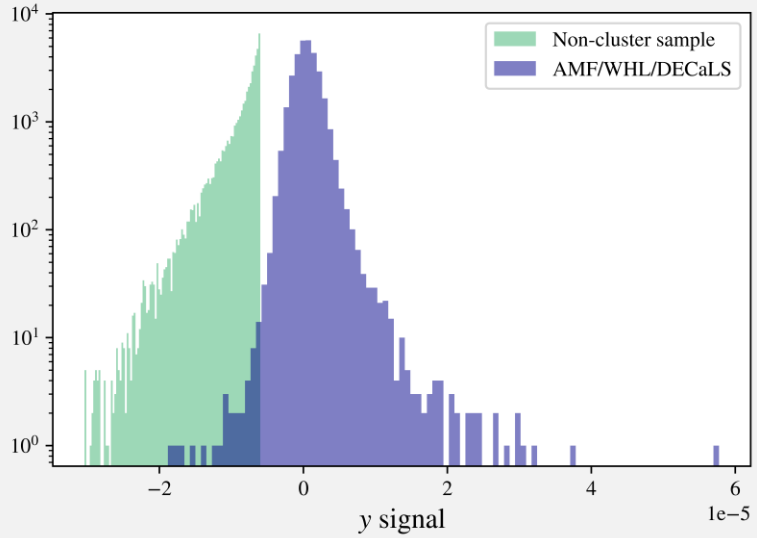


SOME RESULTS: PROBABILITIES OF THE CONTROL SAMPLE

Probabilities for actual clusters

Planck data only

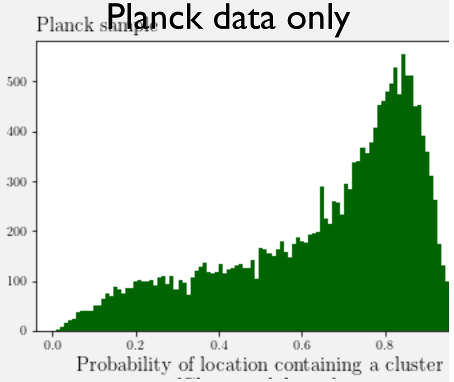


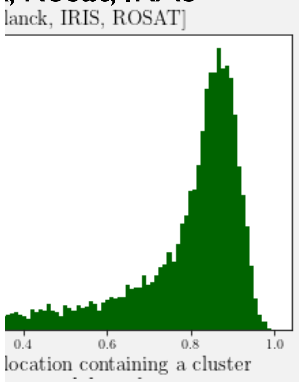
Table 2: Full (Planck, ACT, ROSAT, IRIS) sample of 25,181 clusters and non-clusters

Probability	Clusters correctly identified	Non-clusters incorrectly identified	Purity
> 80%	18386	1416	92.8%
> 85%	16546	1012	94.2%
> 90%	13484	526	96.2%
> 95%	7546	130	98.3%

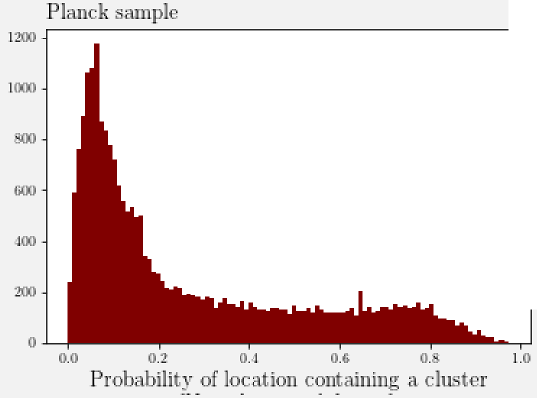
Table 3: No-ACT (Planck, ROSAT, IRIS) sample of 36,908 clusters and non-clusters

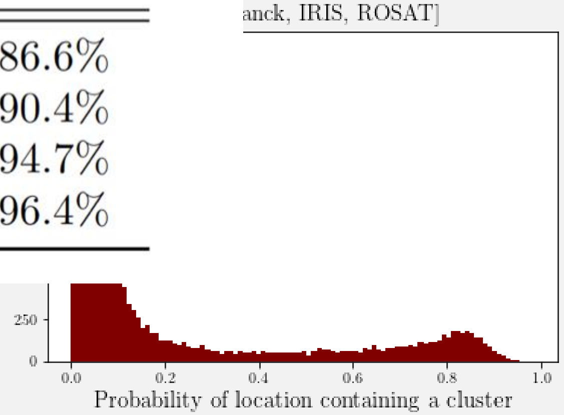
Probability	Clusters correctly identified	Non-clusters incorrectly identified	Purity
> 80%	22380	3462	86.6%
> 85%	15838	1690	90.4%
> 90%	6142	344	94.7%
> 95%	852	32	96.4%

, Rosat, IRAS



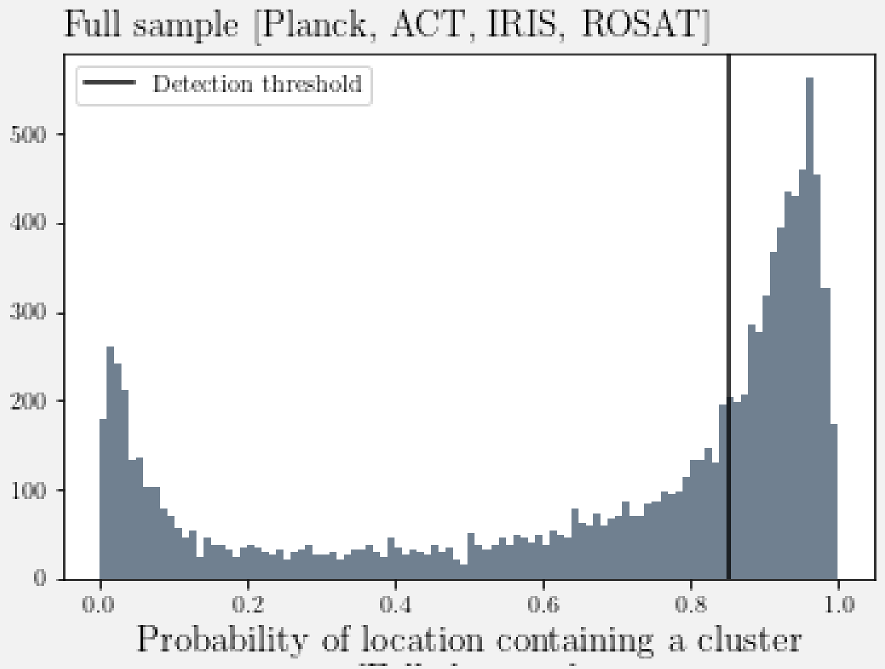
Probabilities for non-cl

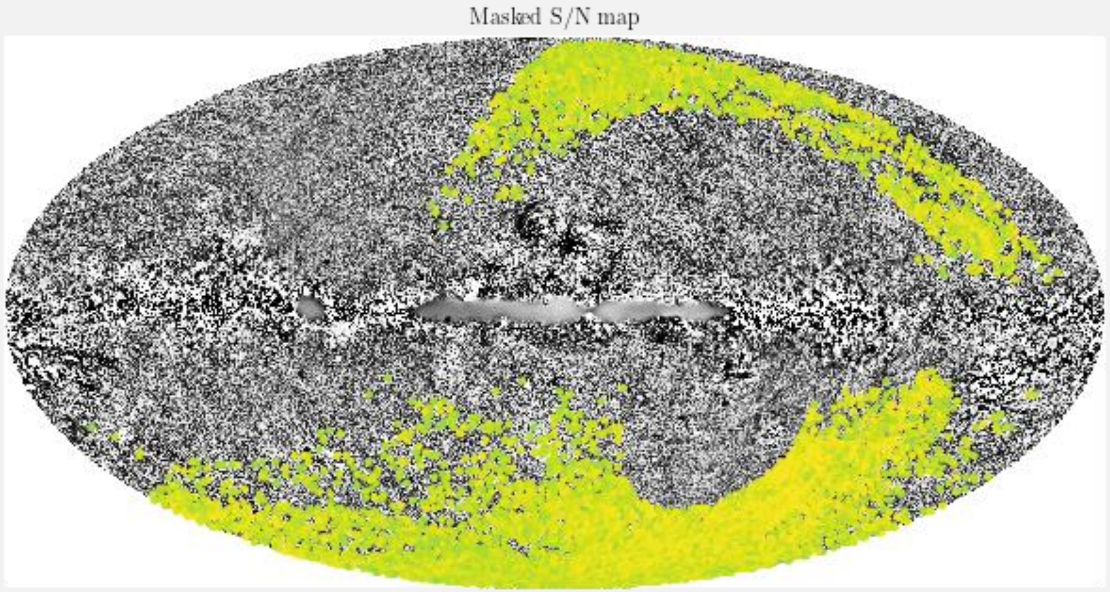




CAN WE ACTUALLY FIND CLUSTERS WITH THIS STRATEGY?

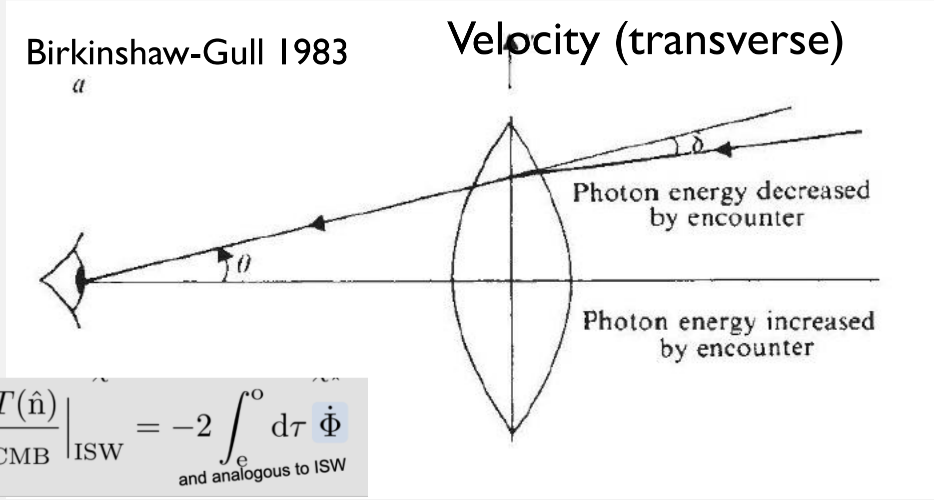
- Yes, on real data and random locations we see the bimodal distribution we expext
- It looks like we do. We are in the process of validating what we find





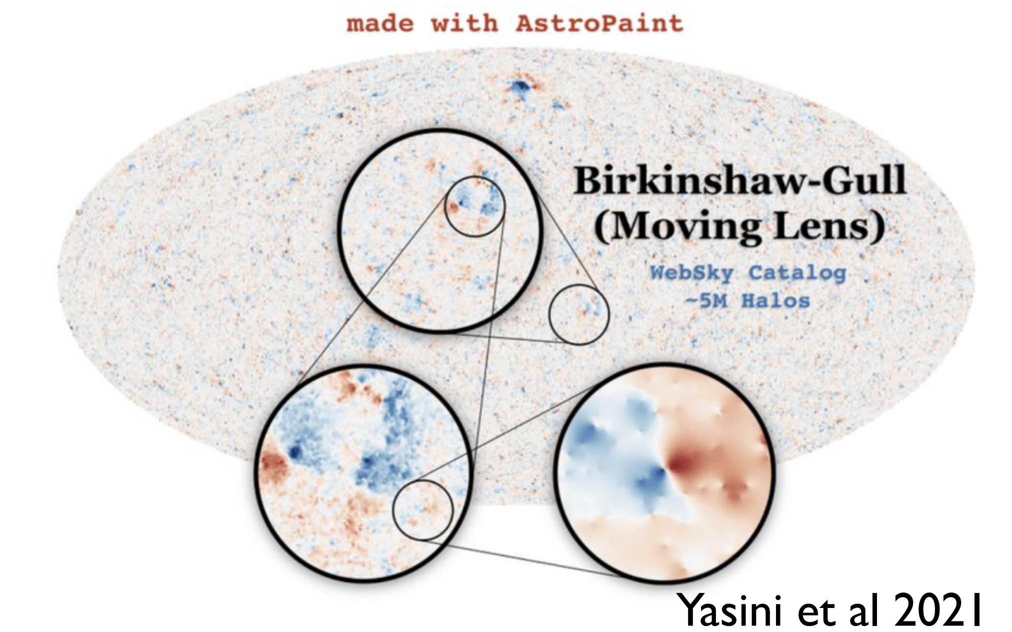
PART II: TRANSVERSE VELOCITY DETERMINATION FROM THE MOVING LENS EFFECT

- If the cluster moves transverse to our line of sight, the potential changes. A dipolar pattern appears in the CMB temperature. The signal is very small (~0.1 muK).
- It has been (theoretically) shown to be detectable with future survey via CMB-halos cross correlations (Hotinli et al, PRL 2019; Yasini Mirzatuny, EP, ApJL 2019)
- Questions:
  - Can it really, given all the correlated competing signals and confusion noise?
  - If so, which halos really help in thar respect? (more massive but more rare, less massive and more abundant…)
  - What is the best strategy to detect it:
    - Stacking
    - Pairwise velocities calculation



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

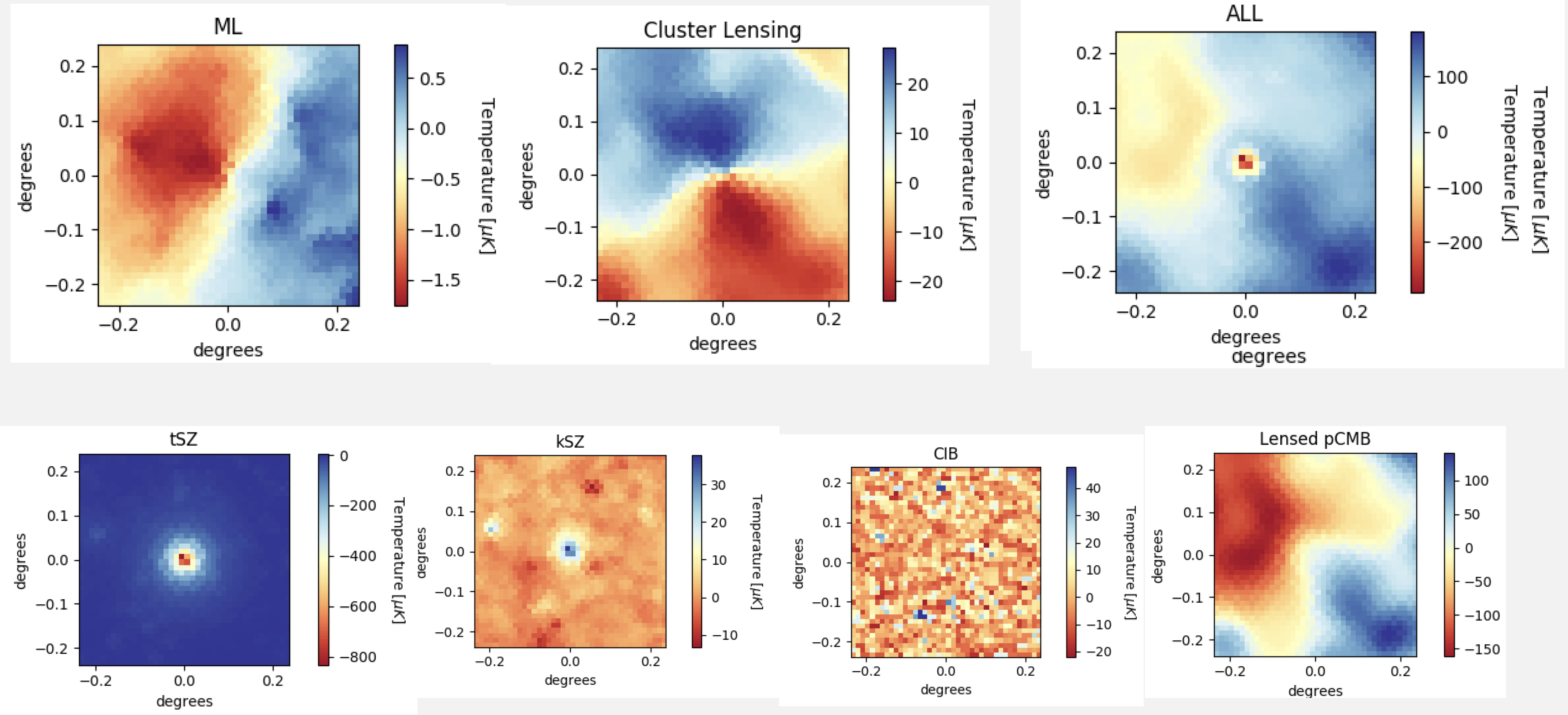
and analogous to ISW



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

Selim Hotinli

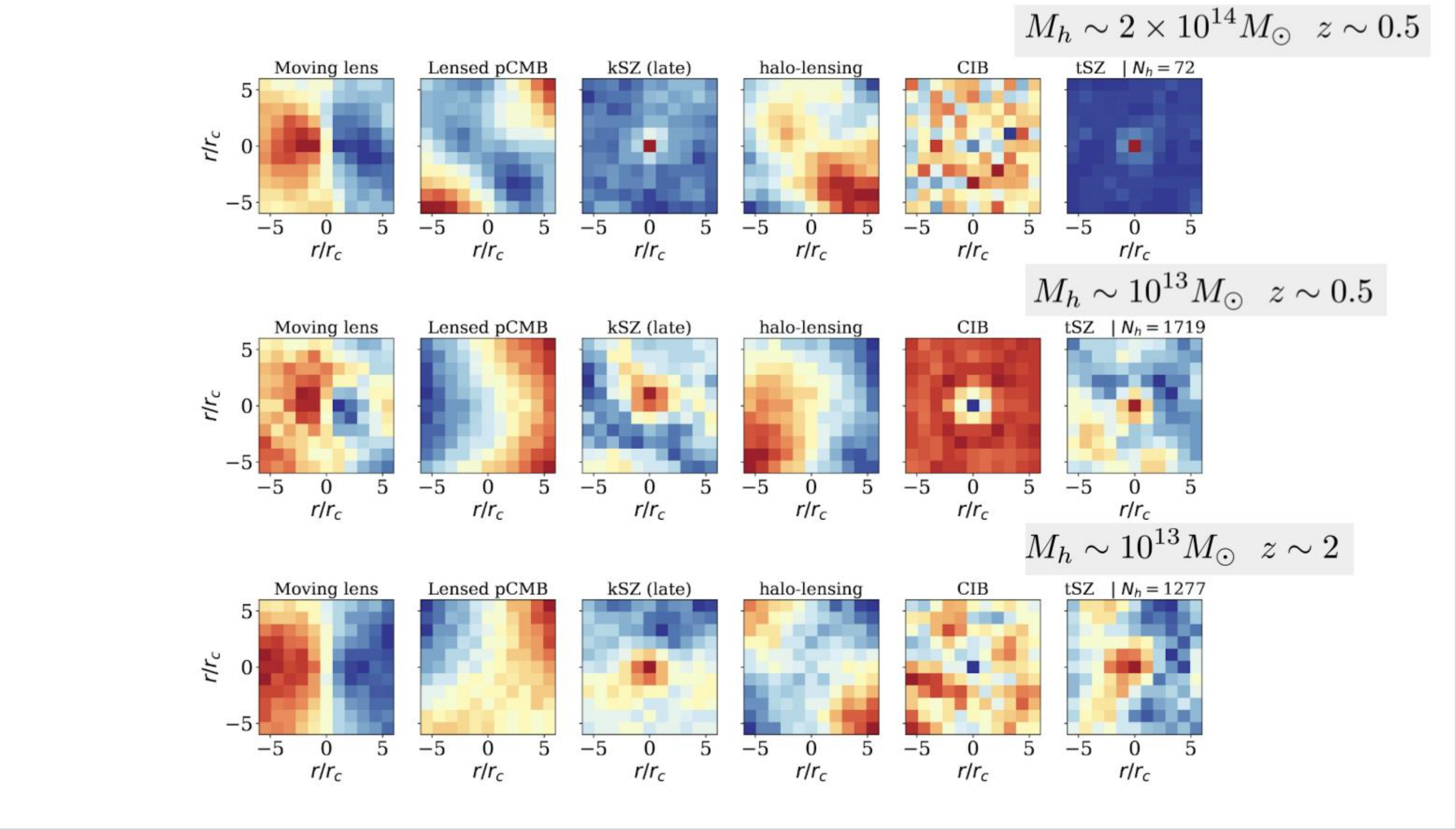
THE CHALLENGE: ONE SINGLE MASSIVE CLUSTER @ Z=0.5 AND 150 GHZ



METHOD

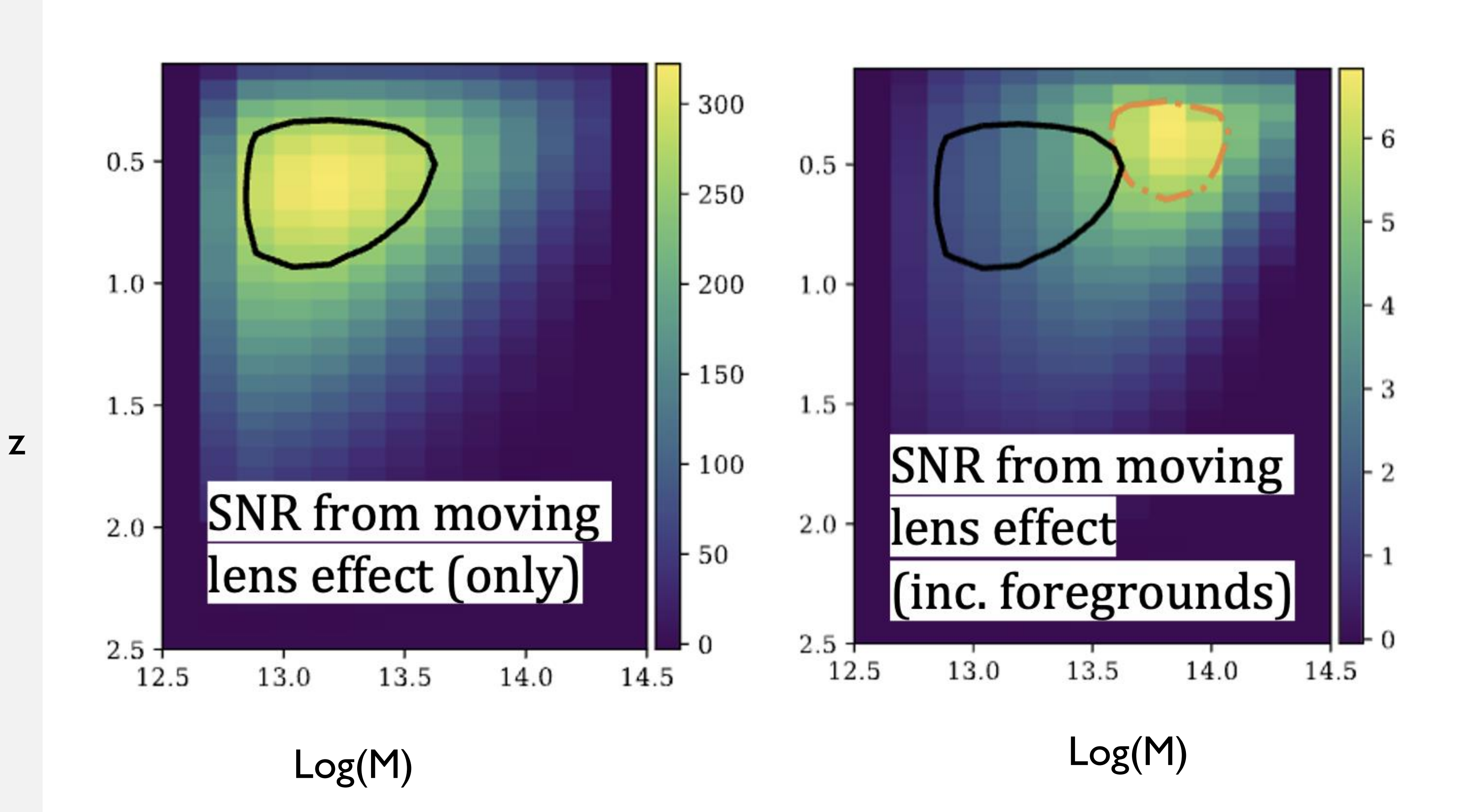
Hotinli and EP, in prep

- We created simulated observed maps for Simons Observatory and CMB-S4 based on the Websky halo catalog. These include all correlated and mildly or not correlated foregrounds and noise.
- We performed component separation to extract the "black body signals" from the observed maps.
- We used either a stacking technique or the computation of pairwise velocities to assess detection.



SOME RESULTS

Hotinli and EP, in prep

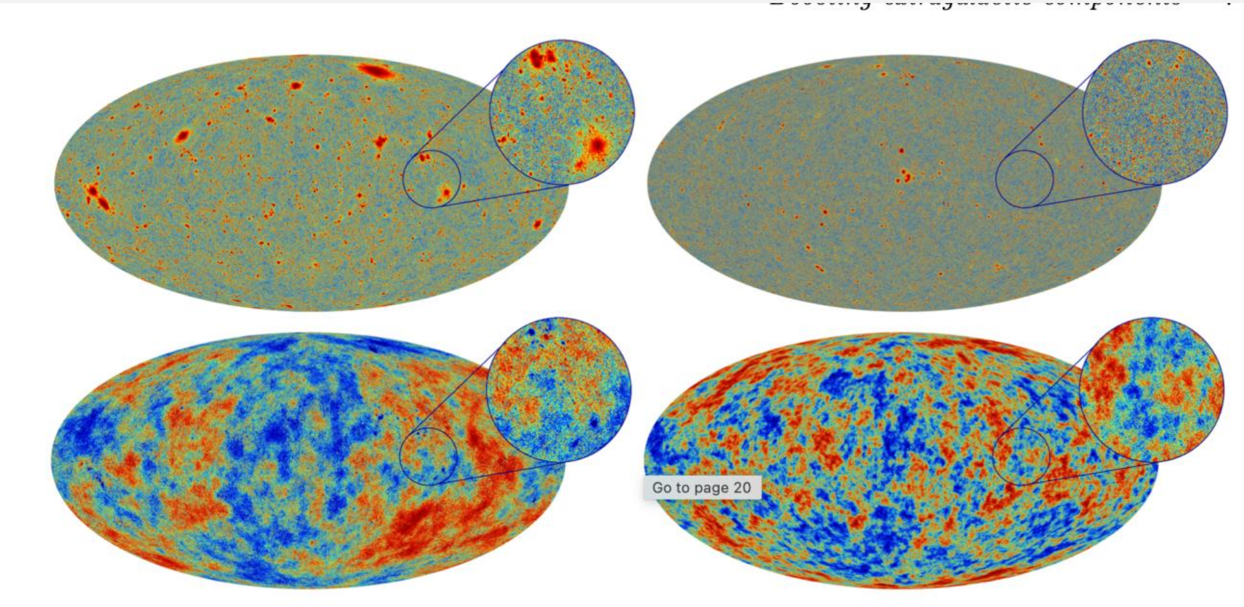


When all "complications" are added, clusters result to be the "crucial" halos in the detection of this signal.

A WORD OF CAUTION ON SIMULATION MODELING :KSZ

hydro

websky



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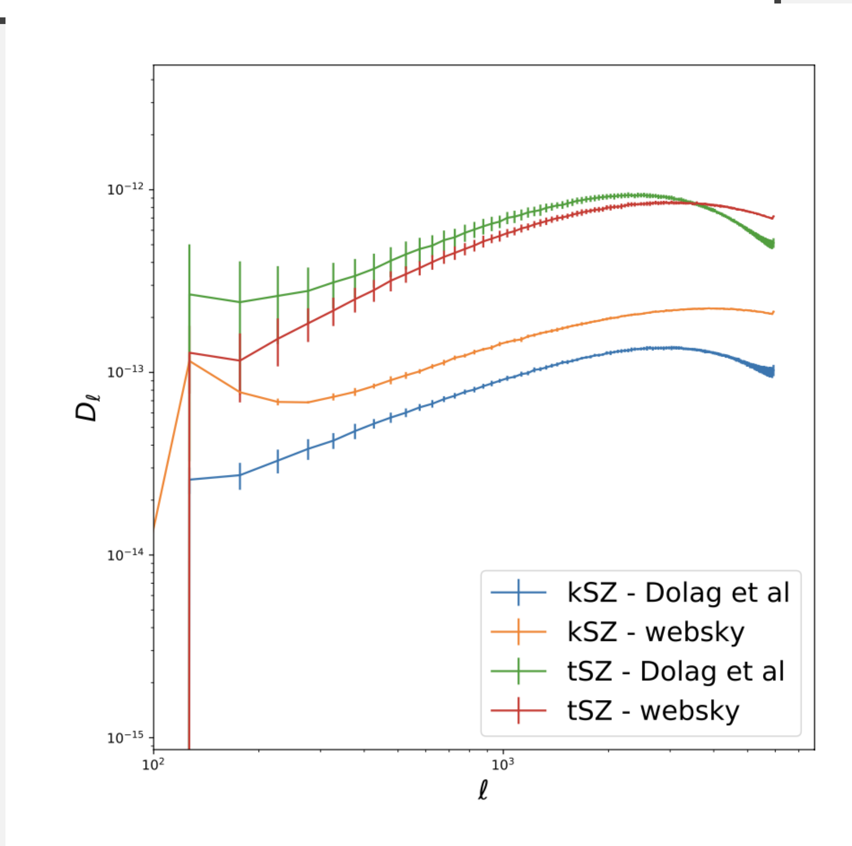
kSZ

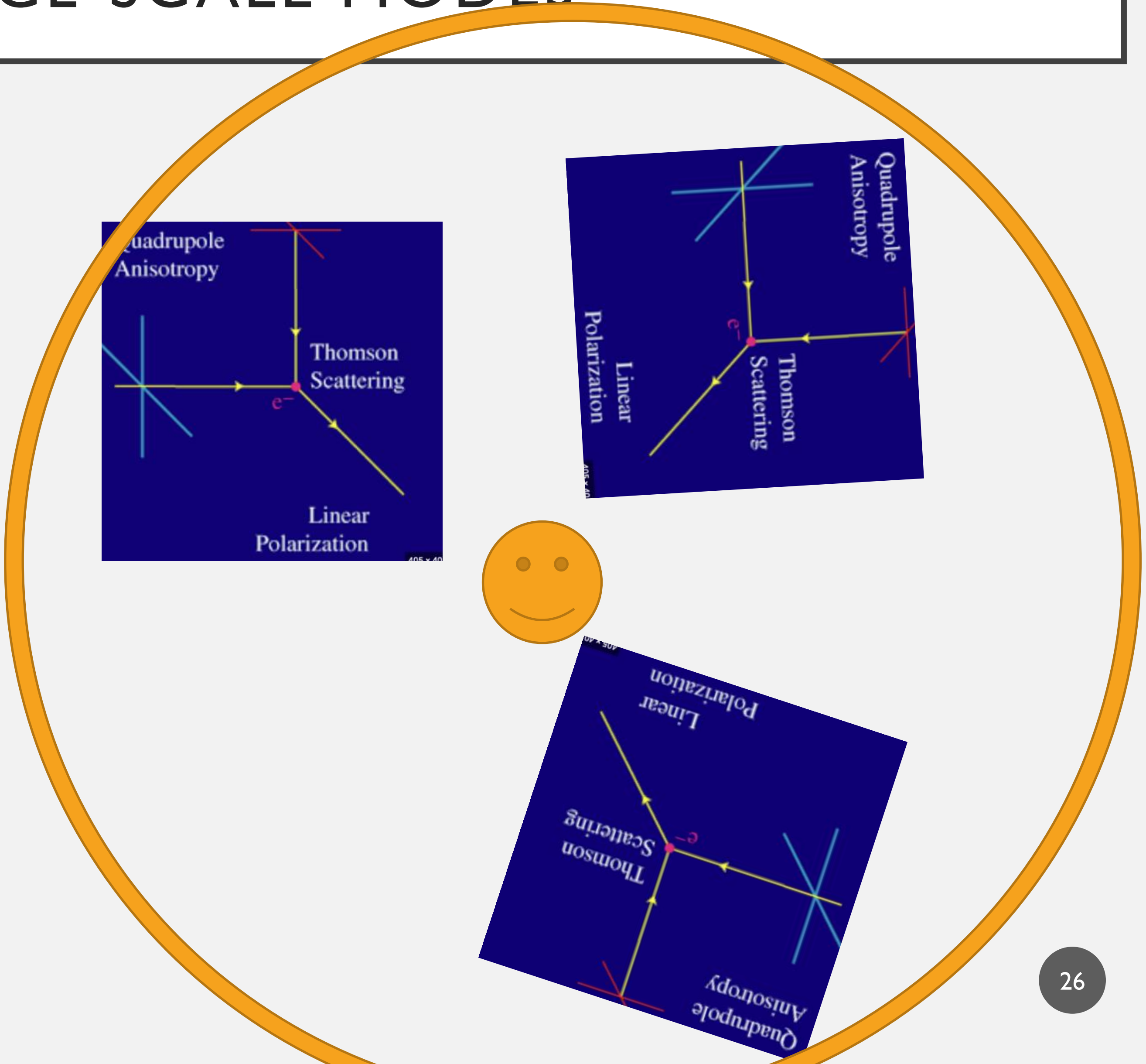


Coulton et al 2022

- Hydro sim and semi-analytical sims may yield quite different power spectra

PART III: SMALL SCALE POLARIZATION TO DERIVE LARGE-SCALE MODES

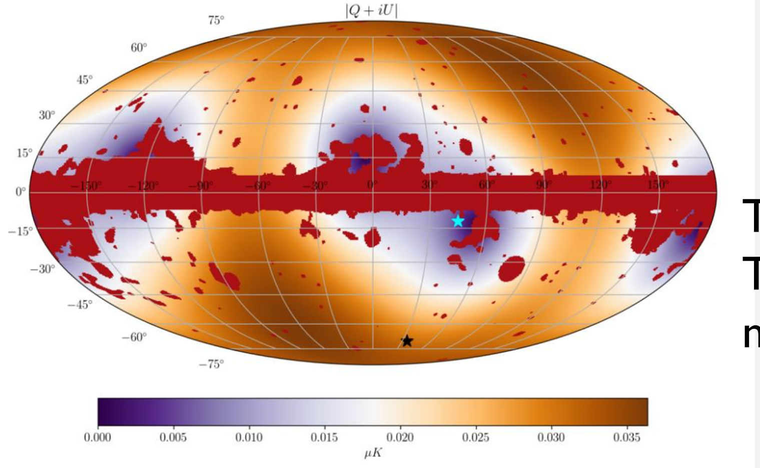
- Motivated by the high resolution and sensitivity in polarization of future CMB surveys.
- Polarized signal in clusters due to
  (Sazonov & Sunyaev 1999):
  - CMB quadrupole in the location of the cluster (no velocity involved, most prominent effect)
  - Transverse peculiar velocity of the cluster



SIMULATING THE POLARIZATION SIGNAL

[with Haoyu Wu (USC) Mat Johnson (Perimeter) Marcelo Alvarez (LBL)]

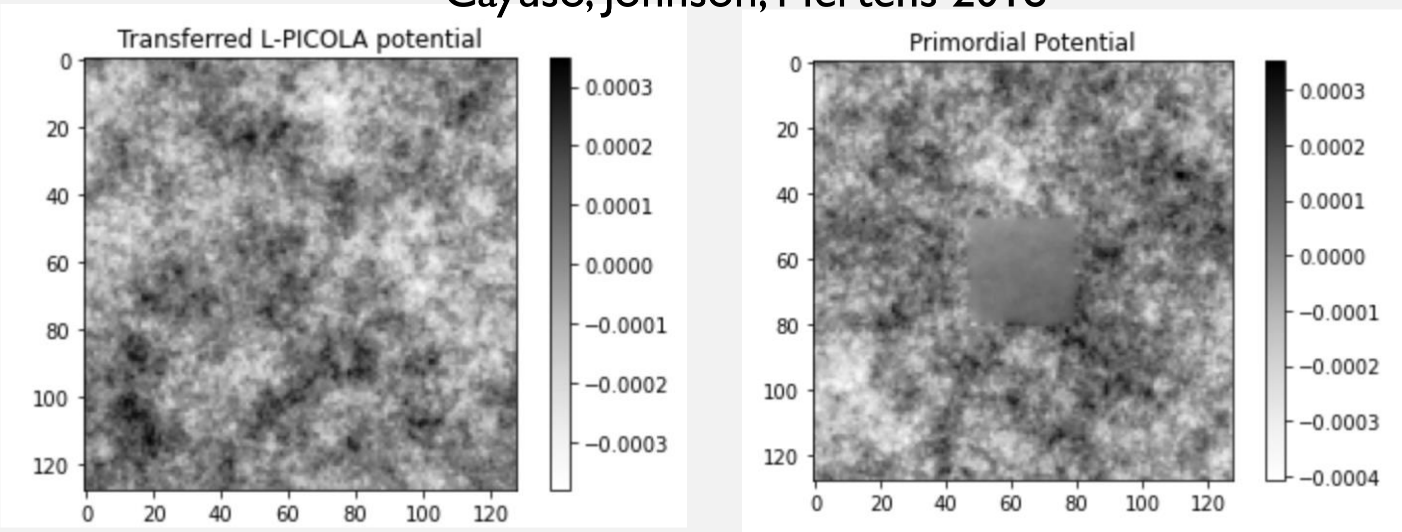
Yasini & EP 2017



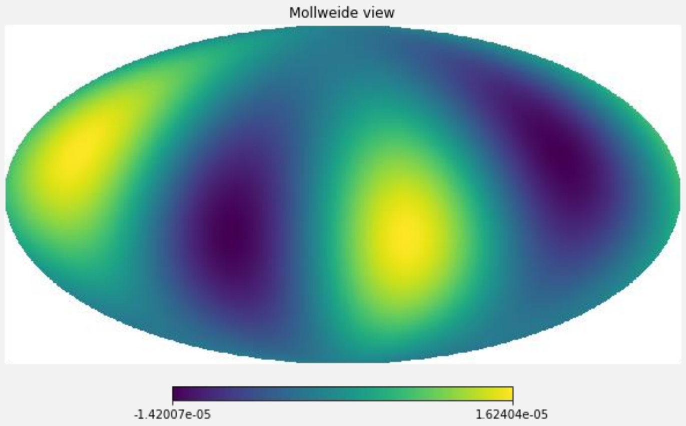
The figure shows SZ polarization signal induced by the local CMB-temp. quadrupole. The least intense areas are along the mask (so anything else will be harder to measure, unless we can subtract this signal well).

- We are working towards making realistic simulations for the Polarized SZ signal:
  - Small scales and halos
  - Large scales/CMB simulated with linear theory in a coherent way
  - Make the whole simulation compatible with the observed CMB signal we see on the sky

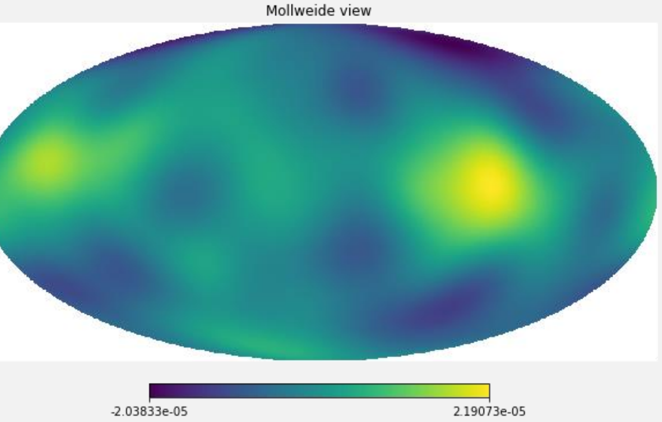
Cayuso, Johnson, Mertens 2018



Z=0

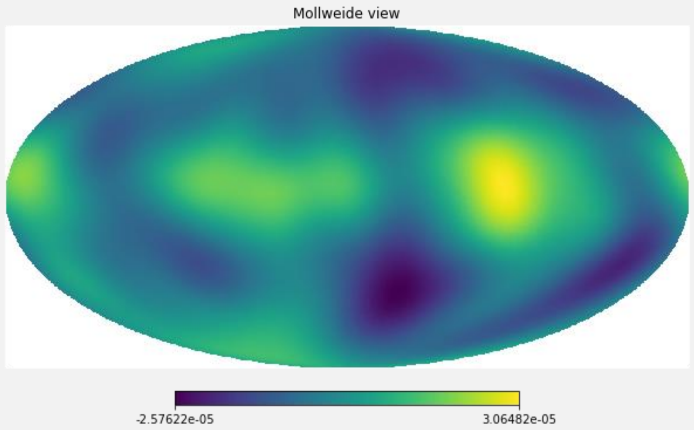


Z=1

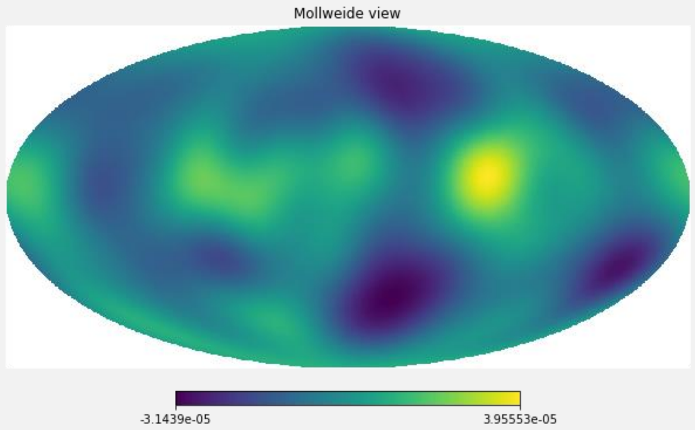


Halos at different redshifts see a different CMB quadrupole and induce a different polarization signal. The signal is progressively less correlated with z=0 as we move to higher redshift.

Z=2



Z=3



- Plan:
  - Adapt the code to use with websky simul. In order to make it compatible with the study of other cluster-related signals (done)
  - Add appropriate optical depth in the location of the cluster.
  - Adapt to correctly represent the observed quadrupole at z=0.
  - Test strategies for detection and exploitation of the signal.

SUMMARY

- We are working towards a better observational characterization and detections of clusters, which will include also SZ, but not only. This is a major endeavor, with potentially high yields.
- We are working on the possibility for detection of the moving lens effect.
- We are working towards a better modelling and realistic exploitation of the polarized SZ signal.
- There is the possibility that kSZ simulations need to be better understood.
- Some tools useful to perform simulations are already available (Astropaint, moving lens map…)

THE END