Mapping Mass with Sky Surveys

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Andrew Bradshaw (SLAC/KIPAC/UC Davis)
20200826 - Cosmology from Home

With thanks to: Tony Tyson, James Jee, Sam Schmidt, Brian Lemaux and the collaborations of DLS, DES, KiDS, Buzzard, CFHTLS, HSC and the Cosmology from Home organizers

Link to the slide deck with animations and speaker notes, or *andrewnomy.com/talks/CosmoFromHome2020*

Outline of the talk (note: script in speaker notes below)

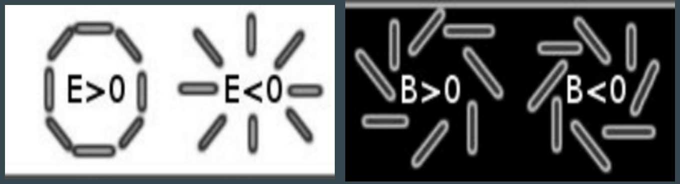
1. Background of weak lensing aperture mass maps
    a. Why aperture mass map?
    b. Optimal filter shape, E-modes and B-modes
    c. Detecting clusters with maps
2. Approximating large scale structure with cluster detections
    a. Approximated shears vs. ray-tracing N-body simulations
    b. Applying the detection & modeling method on real deep data
    c. Shear correlations & distribution functions of data vs. model
3. Mass mapping with sky surveys
    a. All sky map of survey areas and cluster catalogs
    b. Maps vs. depth, scale, method, & survey
    c. **Looking at maps!!!**

Foreground mass maps from background galaxy catalogs

- Sky surveys produce free catalogs of millions of carefully-measured galaxy shapes across thousands of square degrees, as well as simulations!

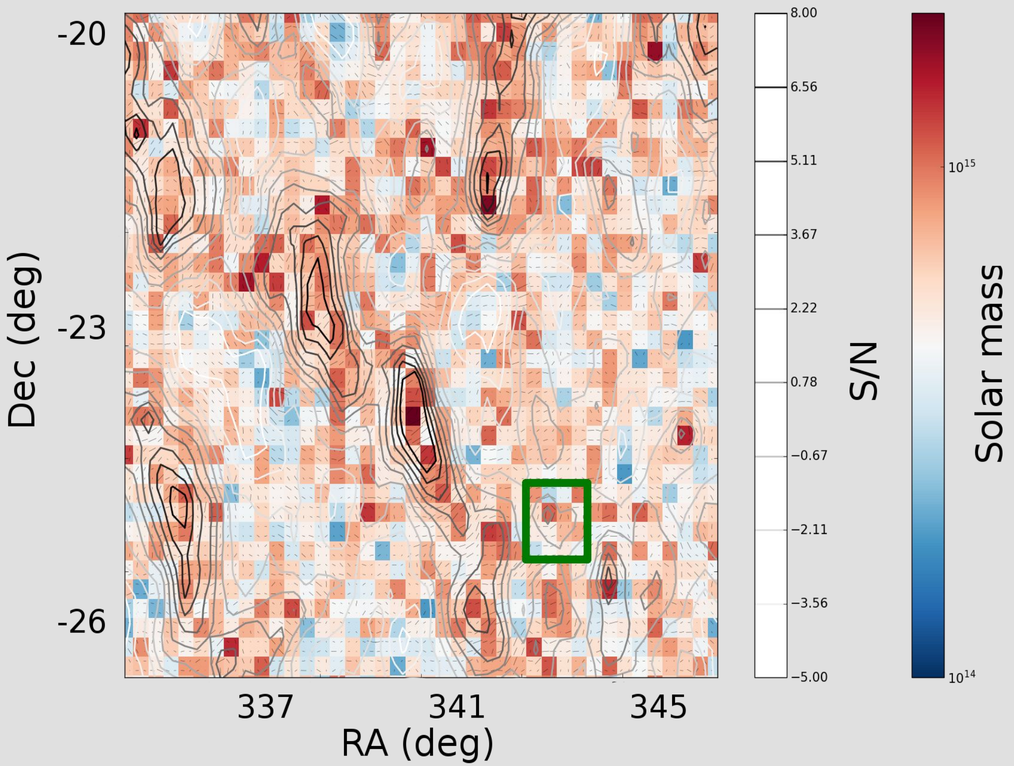
- Map foreground mass structure by optimally filtering for gravitational lensing shear patterns in background galaxy shape catalogs

E modes (+/- mass) **B-modes (≡0???)**



- Use tomographic E-mode maps to infer “cluster catalog” in 3D, and model the large scale structure and its lensing

- Can the observed B-modes be accounted for with lensing of LSS?



N-body simulation mass map → recovery of structure

Black contours: Filtered tangential shear around each point (E-modes)

Blue-to-Red pixels: Cluster catalog binned along L.o.S., in solar masses

Data from Buzzard collaboration for the DES

How to aperture mass map? Radially filter the shear catalog!

$$M_{ap}(\theta) = \int Q(|\theta|)\gamma_t(\theta)d^2\theta \qquad S_t = \frac{\sqrt{2}\sum \epsilon_{t,i}Q_i}{(\sum(\sigma_e Q_i)^2)^{1/2}}$$

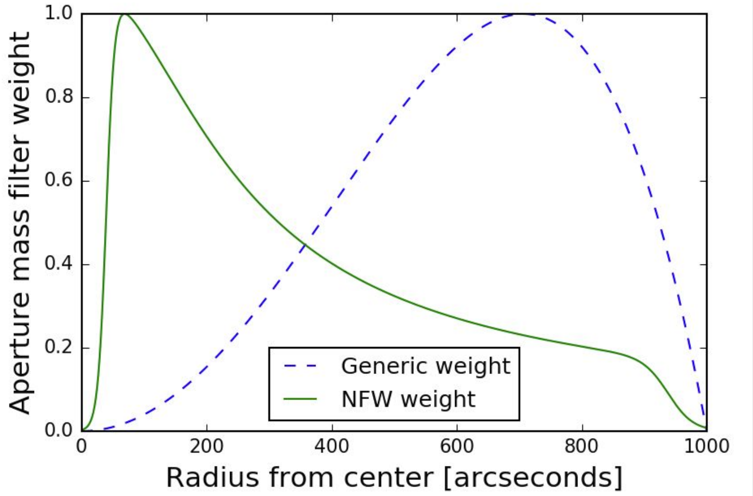
weight shear

The aperture statistic and its signal to noise, Schneider 1996

$$Q_{NFW}(x) = Q_{box}(x)\frac{tanh(x/x_c)}{x/x_c}$$

$$Q_{box}(r) = (1 + e^{6-150r/r_{out}} + e^{-47+50r/r_{out}})^{-1}$$

The apodized NFW filter, Schirmer 2007



Why aperture mass map? For fun, and maybe even science!

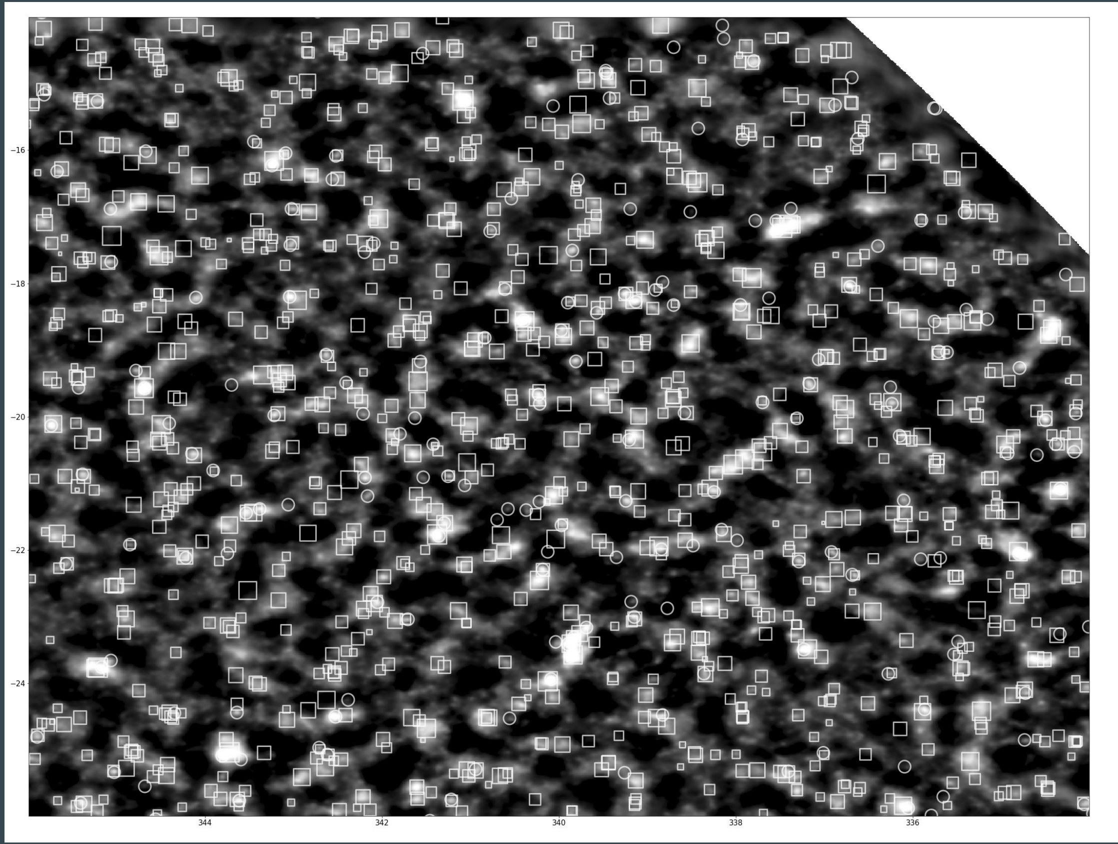
- **Using signal-matched filter (NFW) optimizes detection of clusters**
- Avoids mass-sheet degeneracy, measures “mass contrast”
- Multiplicative shear bias factors out
- Fast/simple computation → cluster scale size variation & redshift tomography
- Easy handling of masks in real space, no Fourier transforms
- Spatial analog of (filtered) shear power spectrum at a given scale

Steps for using mass maps to model Large Scale Structure

1) **Make the mass maps**
Catalogs must be deep, and include shear & phot-z

2) **Find the clusters:**
Finding peaks in fuzzy E-mode maps vs. redshift is difficult, not impossible with 3D segmentation algo.

3) **Model the lens field:**
“Forward model the cosmic shear” using detected NFW clusters + approx.



10x10 deg. E-mode map from ray-tracing Buzzard N-body simulation. -1<S/N<5 black to white. **Open circles:** known clusters from the N-body sim with mass $M>2\times10^{14}\ M_o$ and .1<z<1.0 **Open squares:** mass-map detected clusters, sensitive to map filter scale and threshold/deblending detection.

Starting simple: E- and B-modes in a small piece of Buzzard

Comparing ray-traced shears to a simple approximation

Left column: NFW filtered E/B aperture mass maps with shears from ray tracing (CALCLENS, Becker 2012) through ΛCDM N-body sim (Buzzard, DeRose et al 2019)

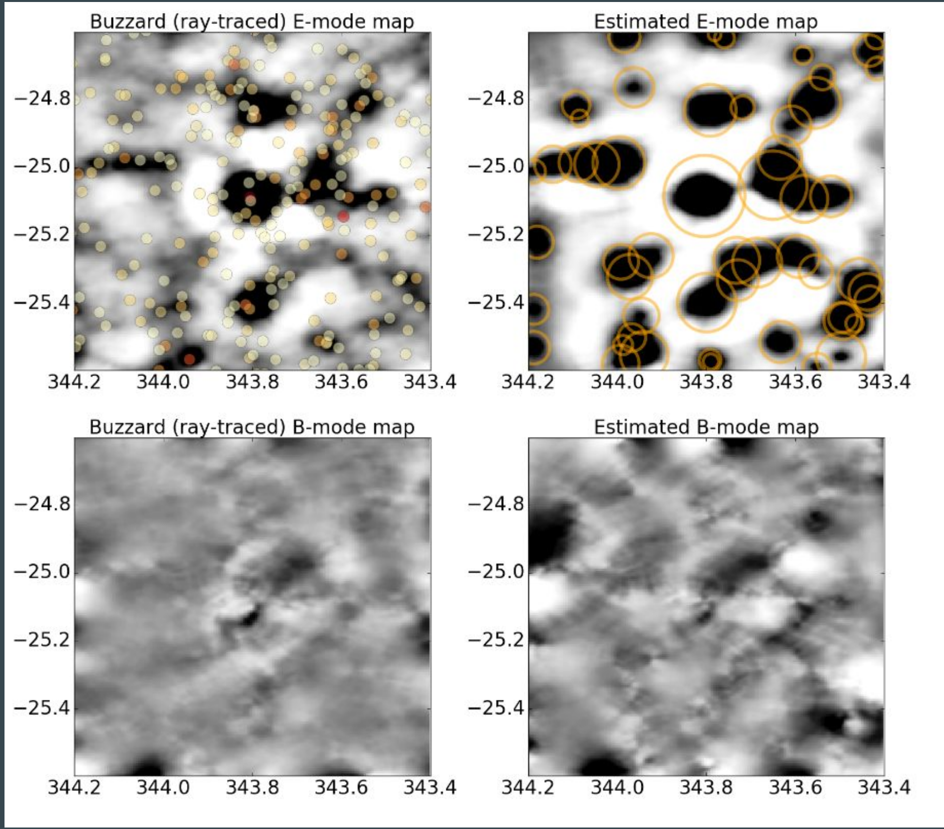
Cluster catalog members indicated by orange-red circles

Strong E modes seen at cluster locations, as well as some B-modes at edges and near clusters

Right column: E/B maps from filtering shears which are approximated by sum of shears of foreground clusters using known cluster catalog

Most large scale structure is captured by this method, though some small scale structure is lost

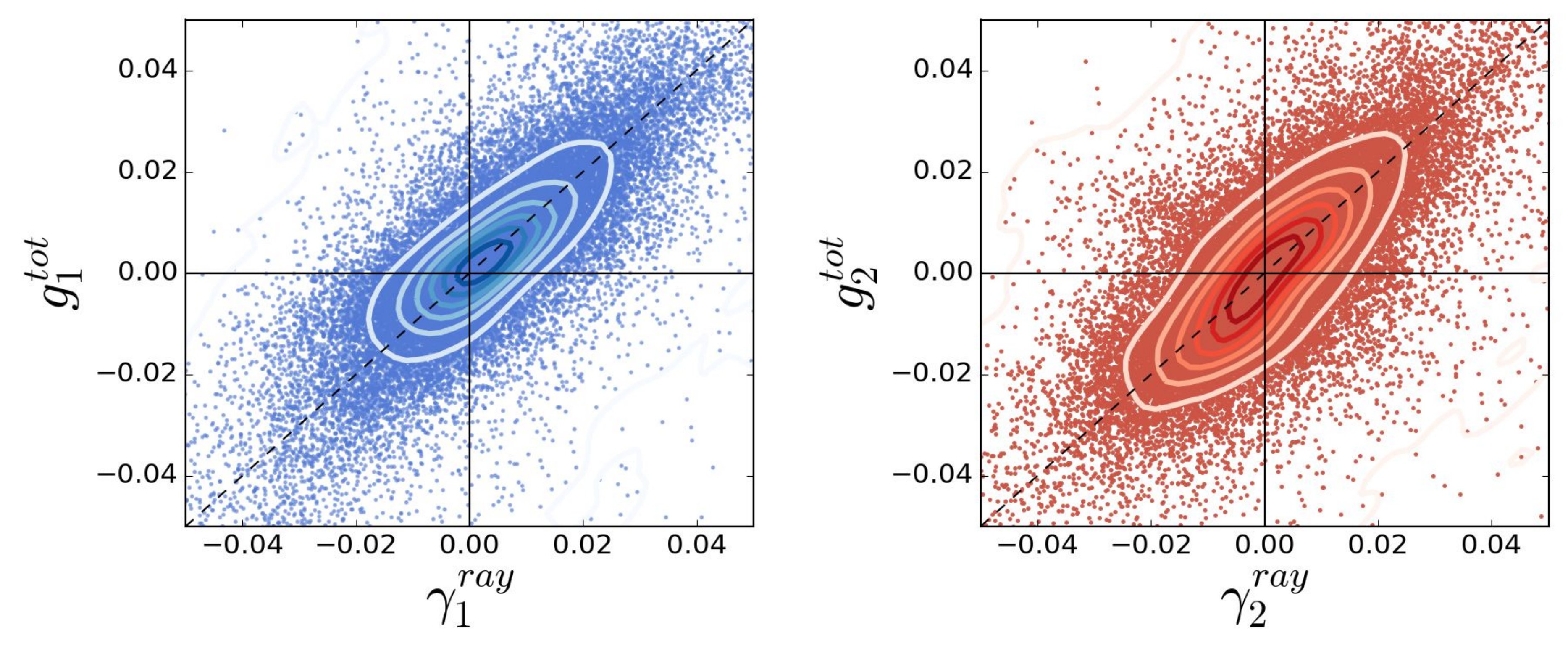
B-mode maps are similar, though slightly **overestimated**



Large scale reconstruction & ray-tracing approximation

Sum-of-shears are compared to Buzzard N-body ray-traced shears

Cosmic shear is statistically captured via a sum-of-shears method deployed on mass maps and photo-z catalogs.



Aperture mass mapping *the real sky* - Lynx North

- ~½ degree on sky, or 1 full moon
- ~5 hours of Subaru Suprime-cam
  - [B,V,R,i’,z’] filters: colors & photo-z
  - Independent [R,i’,z’] shape catalogs
  - ~27th magnitude limited, or
  - ~10 years of LSST wide/fast/deep
- Same mass mapping & cluster reconstruct method from sims
- Cluster catalog + ~ray-tracing matches maps and correlations

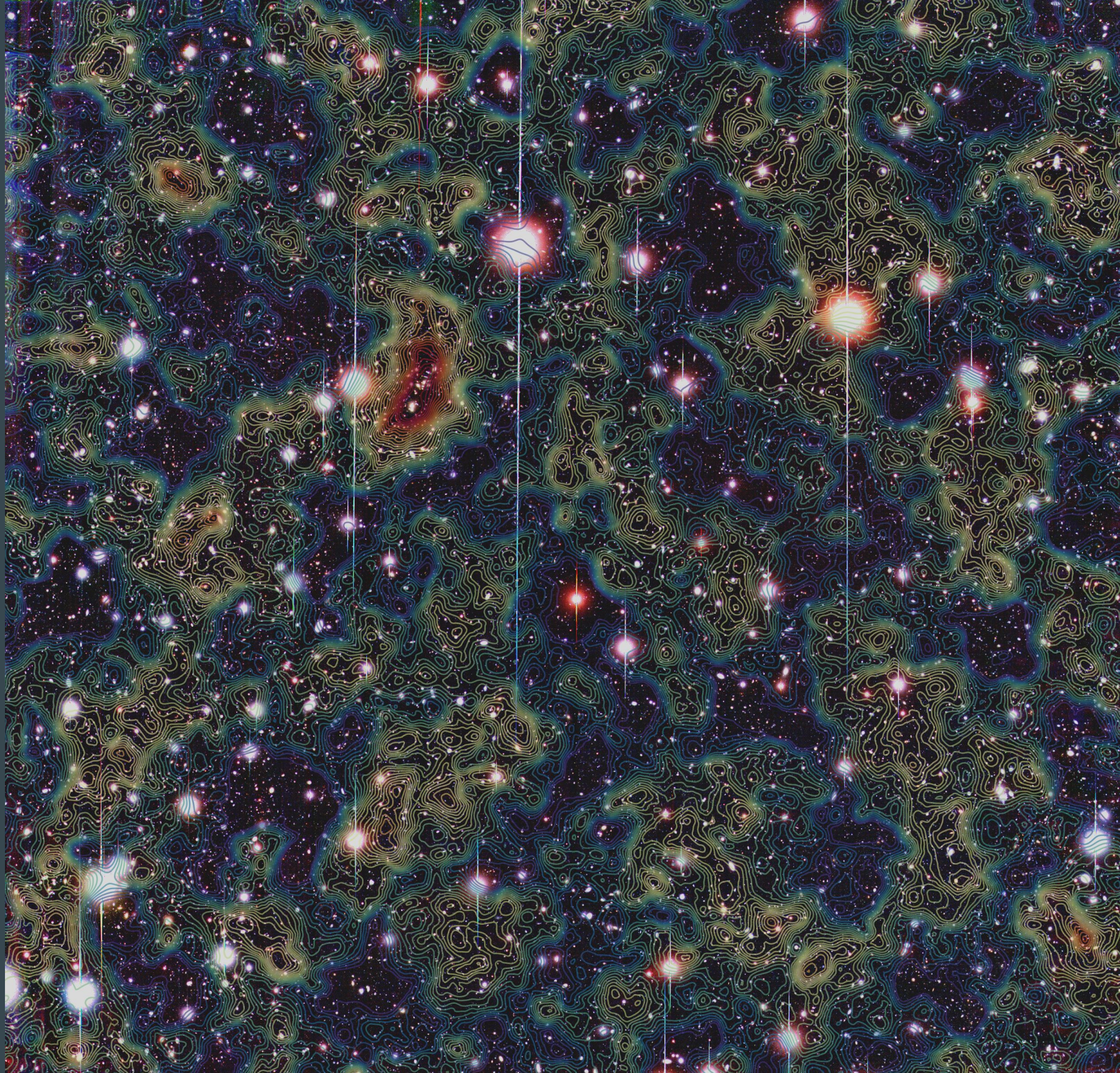


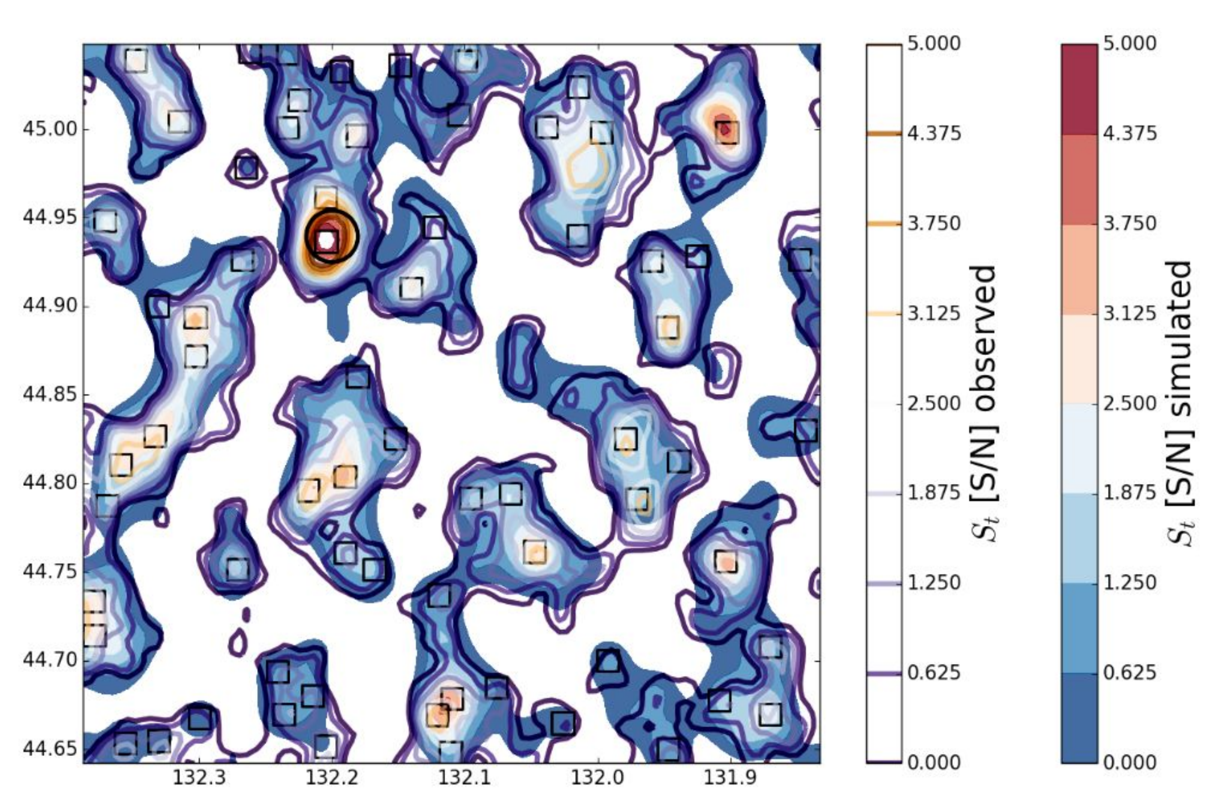
Figure: RGB (i’RV) image of the Lynx field with aperture mass mapping contours overlaid (from $-3<S/N<8$, blue-to-red). Lynx North cluster mass $M=5x10^{14}$, $z=0.55$

Lynx field aperture mass map   using 10^5 background galaxies z>0.8

Contours: real data mass map

Squares: estimated cluster catalog

Colors: approx. shear mass map

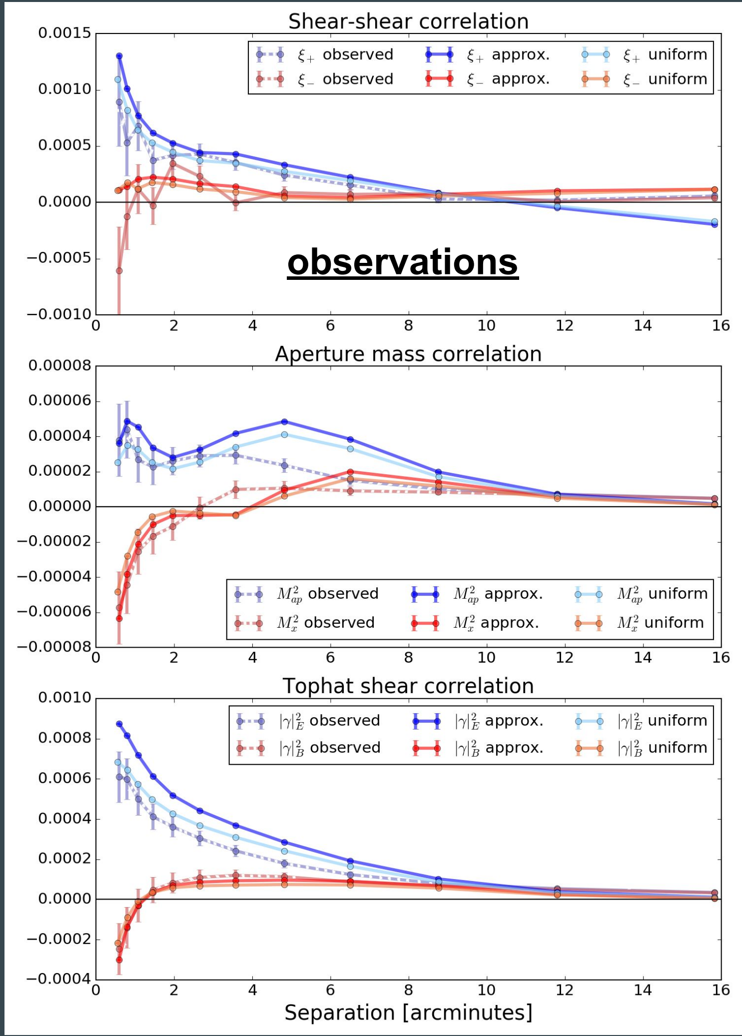


Mass map approximation works with real cluster survey images!

→ how about shear correlations?

→ will it work on all scales?

Rubin LSST will have maps across ×100,000 this area!



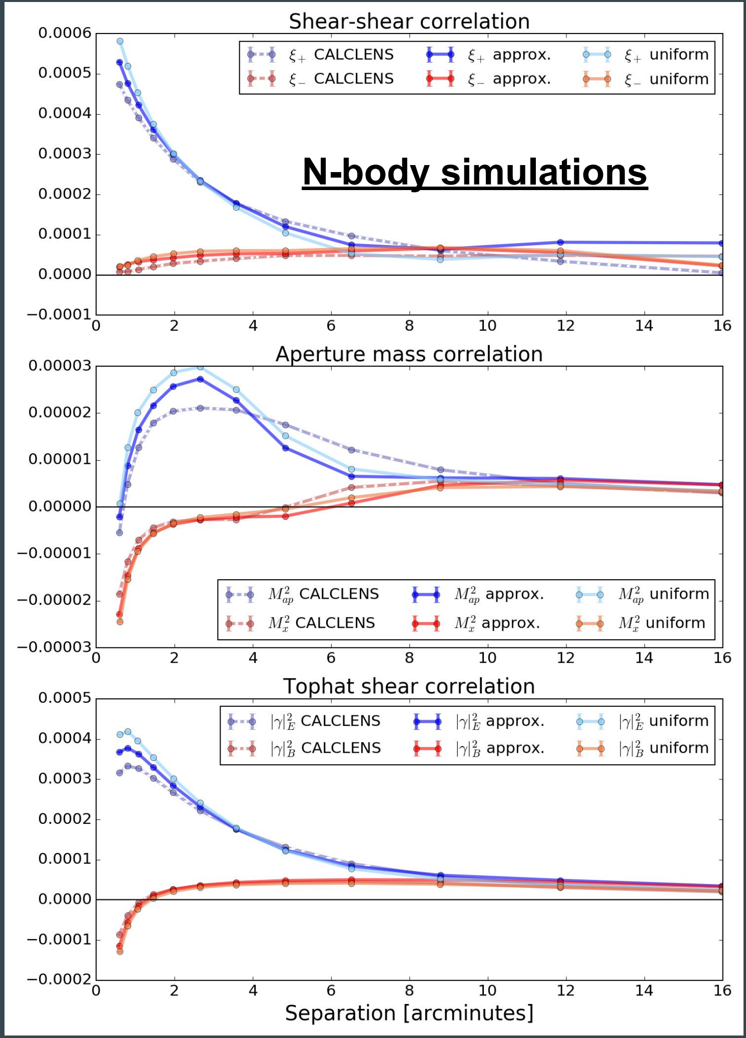
Shear correlations

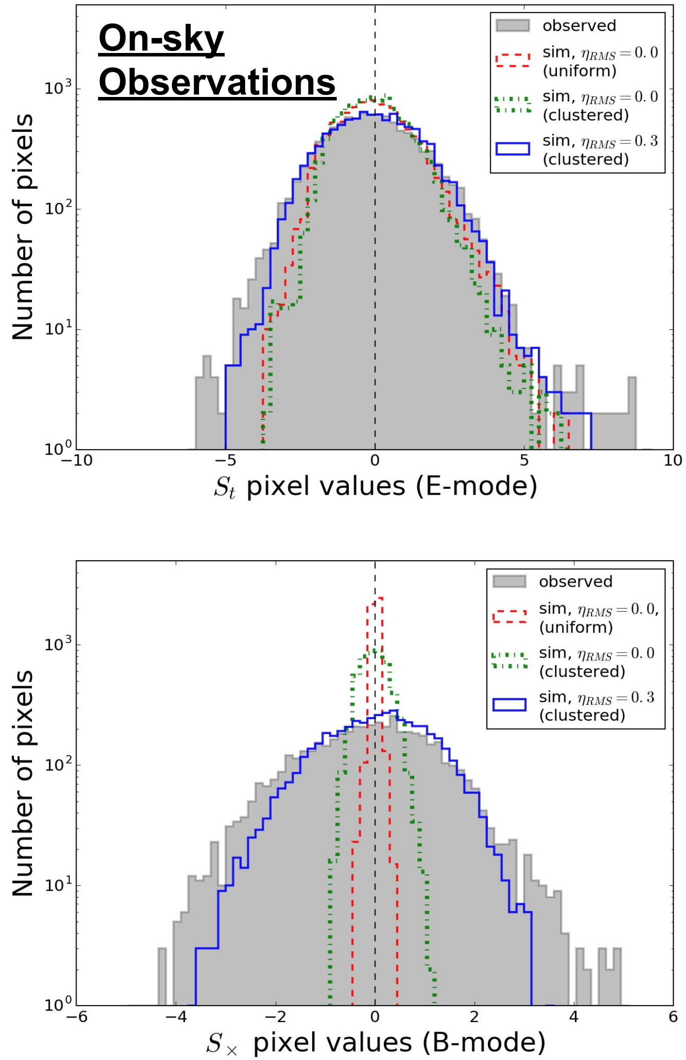
1D summary of mass maps on all scales,

Used to compare cosmological models to data

E-modes in various filters similar in shape/scale, and are well summarized by the approximation

B modes in the simulation can be ~understood as combination of lensing and mapping methods



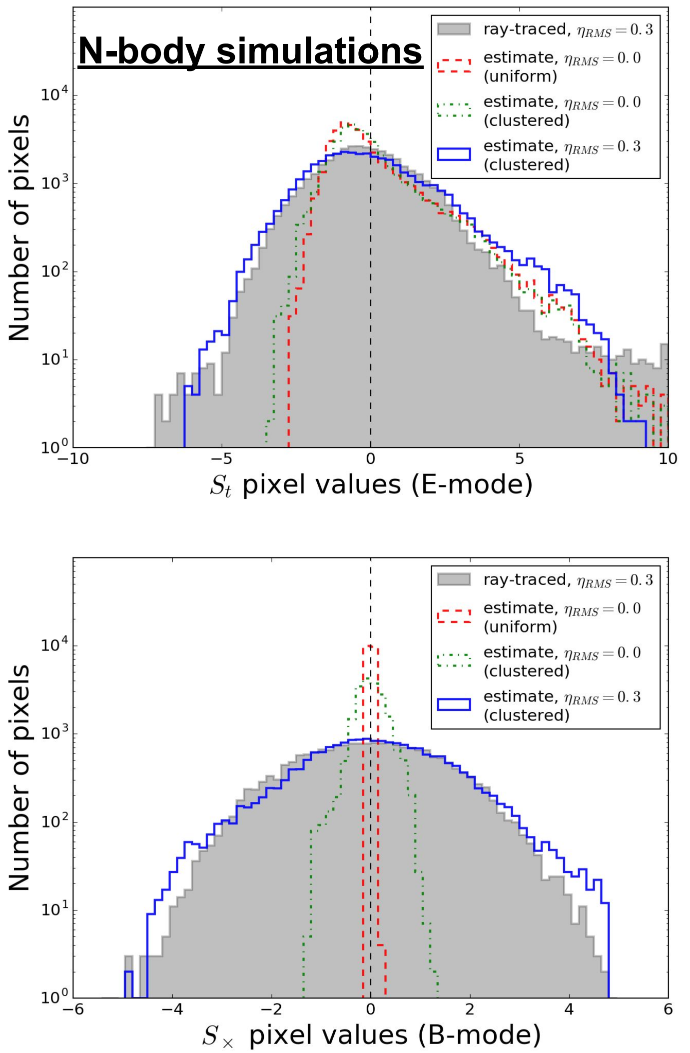


However, a curious excess remains in the distribution of on-sky B-modes

Multiple lensing?
PSF modeling?
Intrinsic alignments?
Larger-scale structure?
“External shear”?

← **Real data:** B-mode estimate **under-shoots** observed dist.

Simulated data: B-mode estimate ⟶ **over-shoots** observed (ray-traced) data



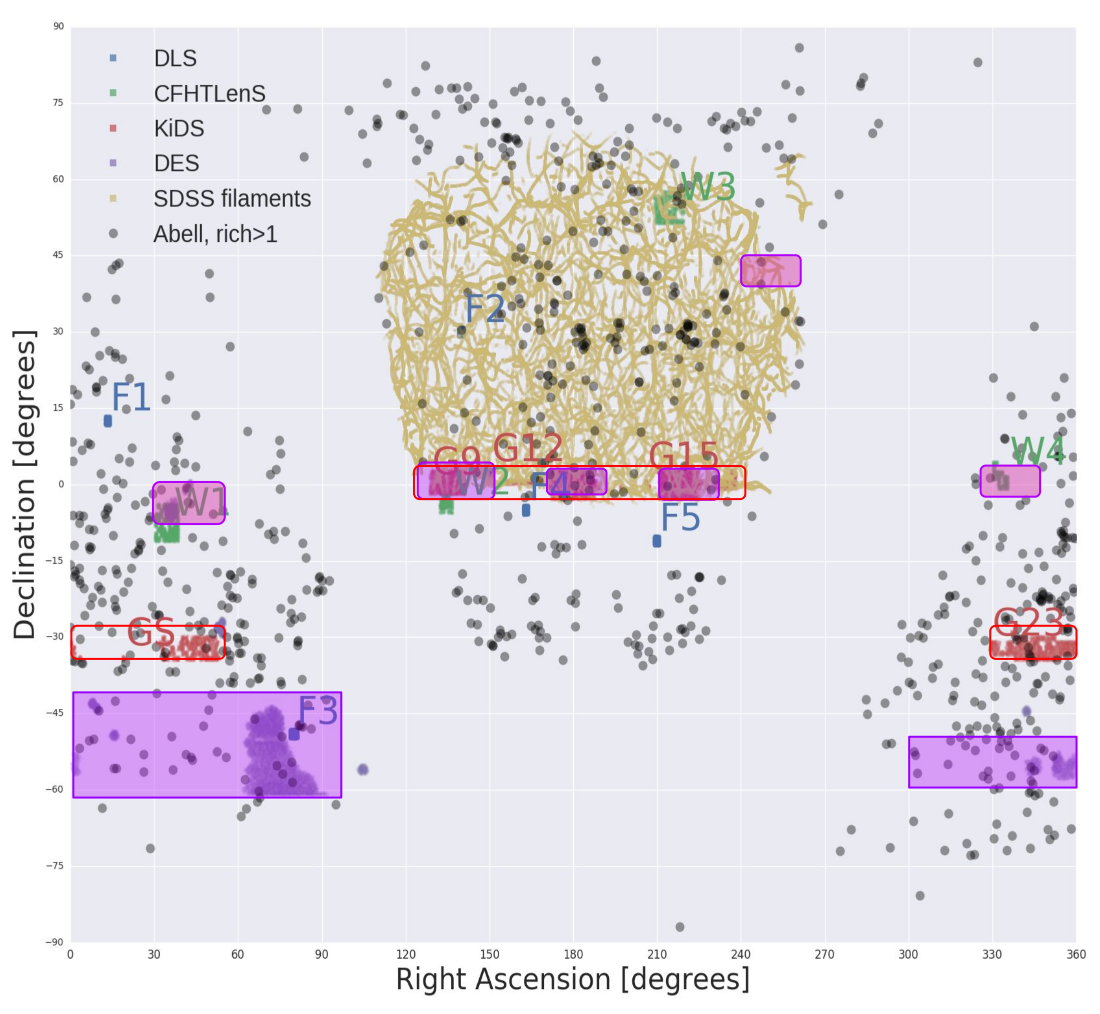
Let's map mass on the sky!

There are lots of surveys to choose from, varying in width and depth, with much overlap

We will use shape catalogs from five surveys: the Deep Lens Survey (DLS), the Canada France Hawaii Telescope Lensing Survey (CFHTLenS), the Kilo Degree Survey (KiDS), the Dark Energy Survey (DES), and the Hyper Suprime Cam Survey (HSC, an 800 megapixel camera on an 8m telescope that will survey 1400 square degrees to ~27th magnitude (LSST depth!)

Table 1.1: CCD surveys of the sky

Survey name	Camera (Megapixels)	Telescope size (m)	Start year	Area (deg^2)	Lim. Mag.
TS12	0.16	4	1983	2.5	26
BTC	16	4	1996	(1, 100, 5000)	(26,24,20)
SDSS	150	2.5	2000	15000	22.5
DLS	64	4	2002	20	26
CFHTLS (Wide/Deep)	340	3.5	2003	(150,16)	(25,25.6)
COSMOS (HST)	16	2.4	2006	2	27.2
Pan-STARRS	1,400	4x1.8	2010	30000	22.8
KiDS	300	2.7	2011	1500	24.6
DES	570	4	2013	5000	25
LSST	3,200	6.7	2019	20000	27

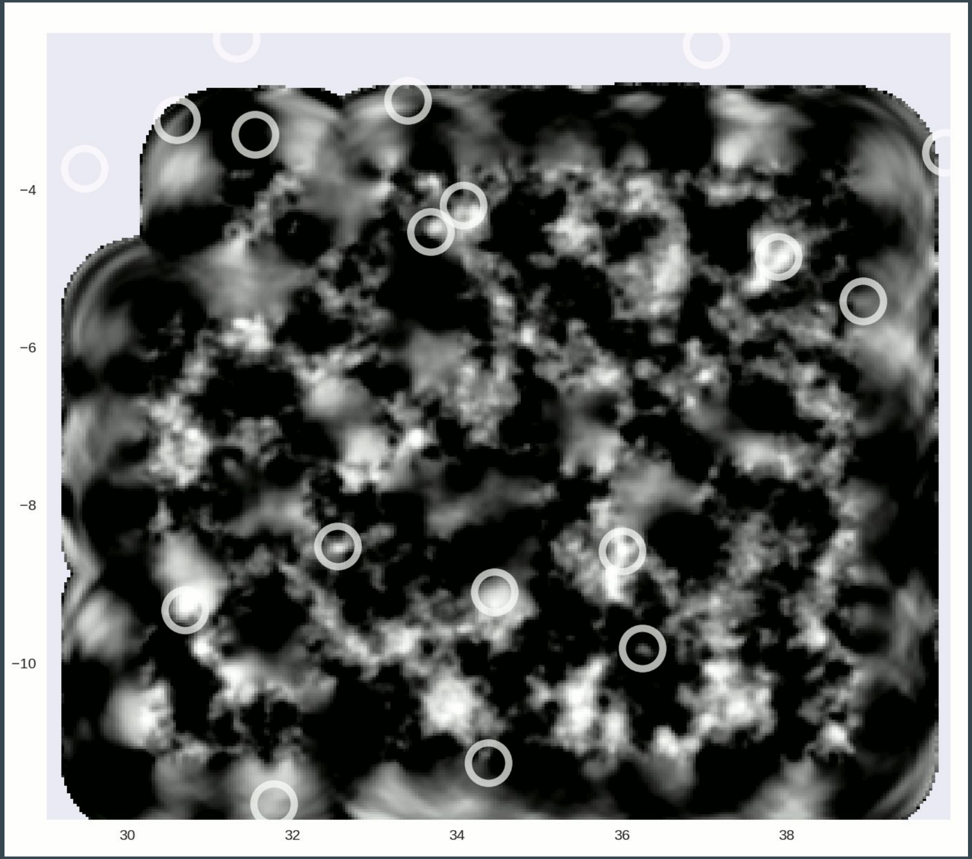


Apologies for the spaghetti plot, filaments by Chen et al 2015

E-modes

CFHTLenS

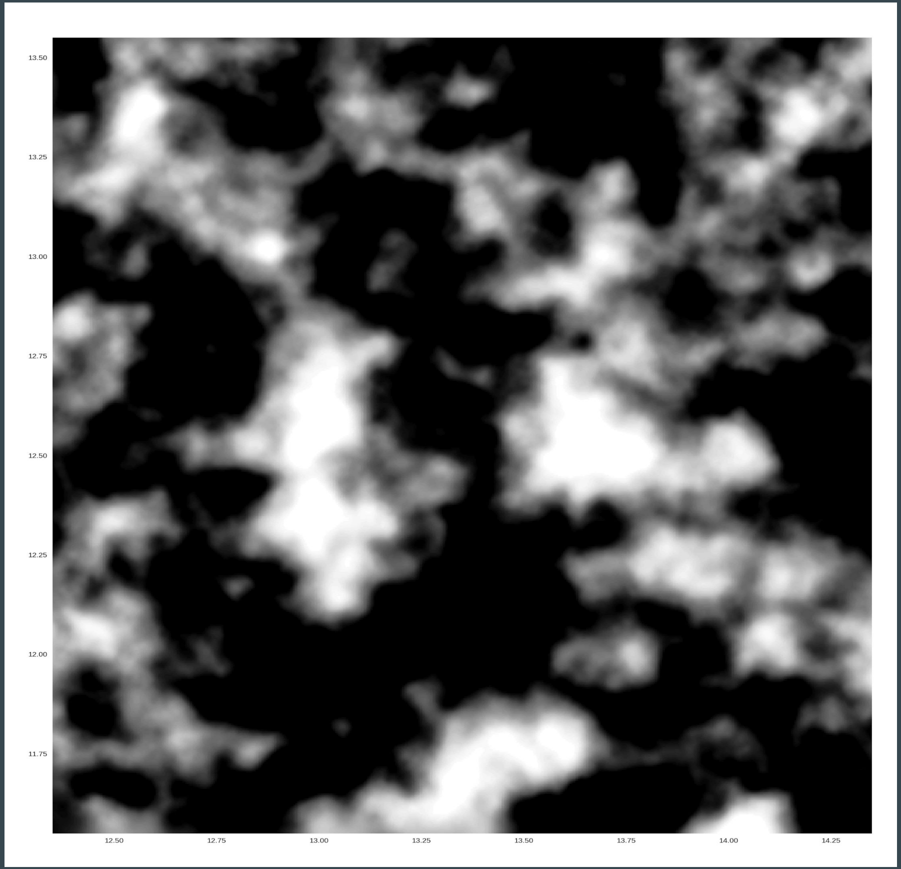
140 sq. deg to ~25th magnitude



Abell cluster locations marked by white and black circles

Deep Lens Survey

20 square degrees to ~26th magnitude



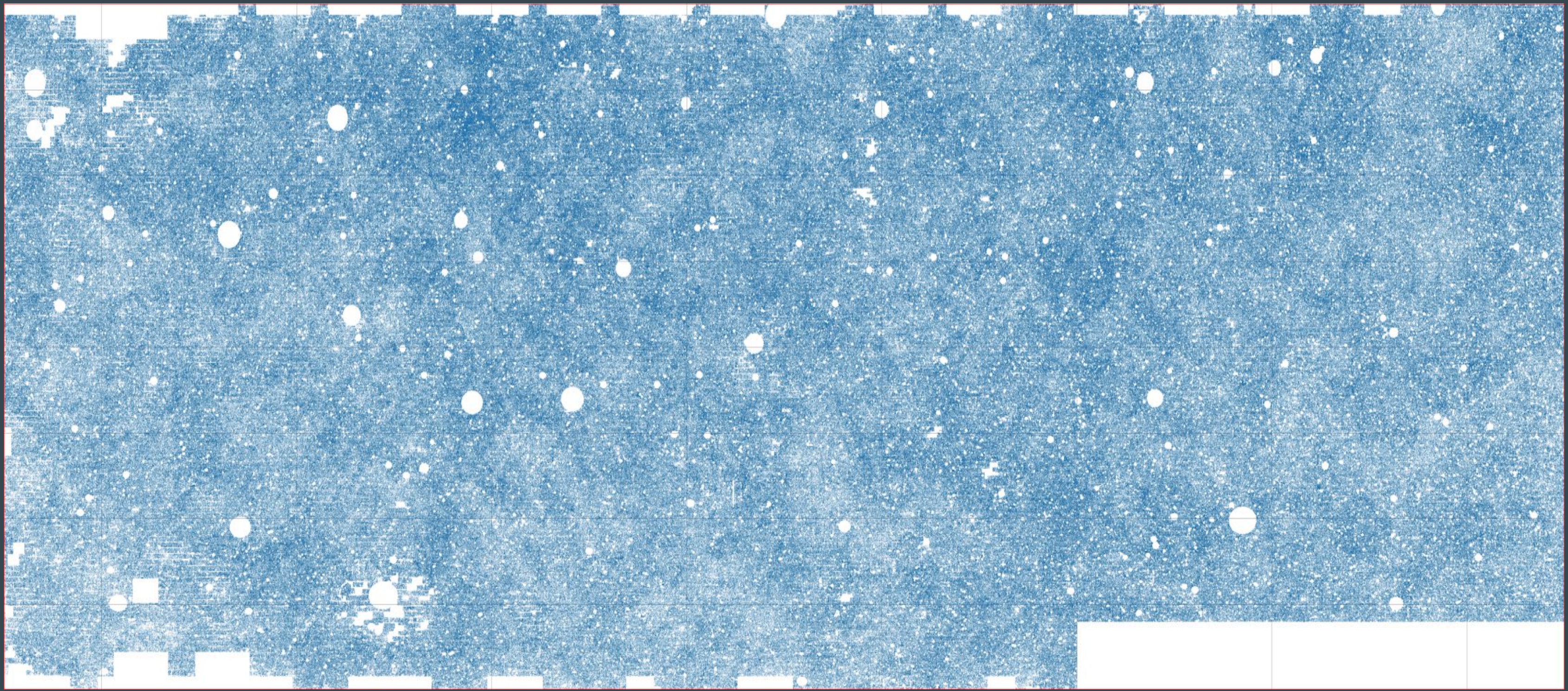
$-1<S_+<5$, $r_{max} = [1.0, 0.2°]$, $z_{src}>0.5$

Dark Energy Survey Y1 patch

$15x10^6$ background galaxies 0.3<z<1.0

[(RA),(Dec)]=[(5,85),(-60,-40)]

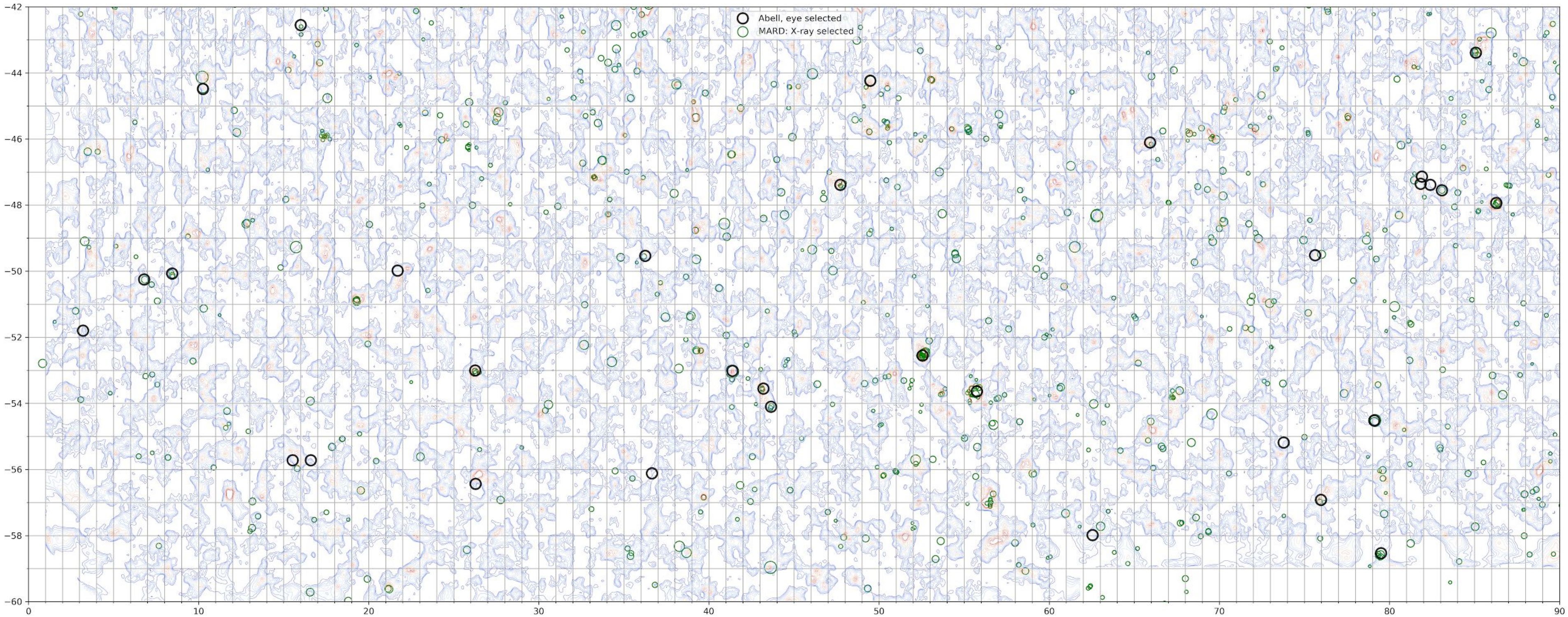
80x20 degrees



DES Y1 - NFW Aperture Mass Map

$-2<S_+<4$, r_{max}=1.0 degrees, z_{max}=1.0

Foreground Abell clusters in black circles, and X-ray selected MARD-Y3 catalog (Klein 2019) in green circles

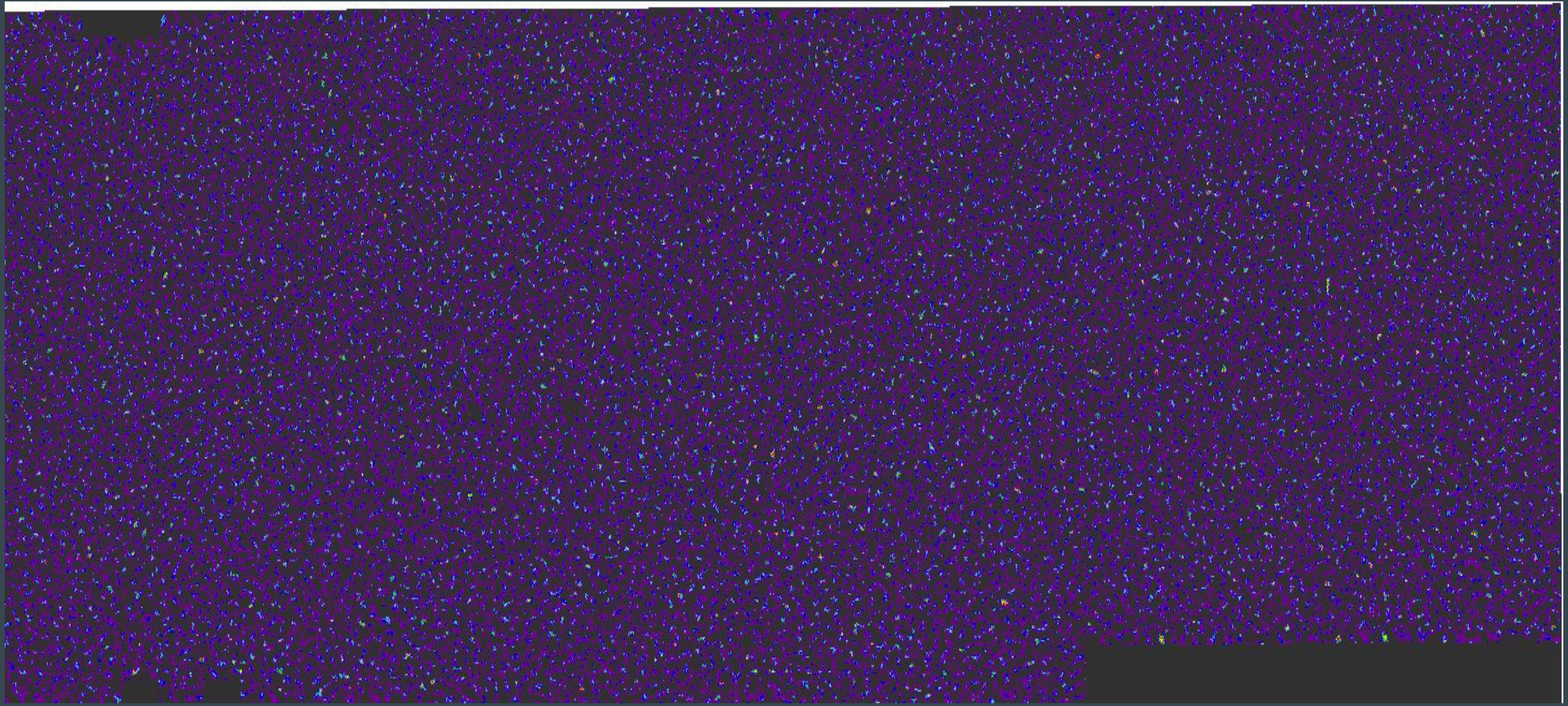


DES Y1 - Mass vs Scale

NFW Aperture Mass Map

[(RA),(Dec)]=[(5,85),(-60,-40)]

r_{max}= from 0.25 to 6.0°

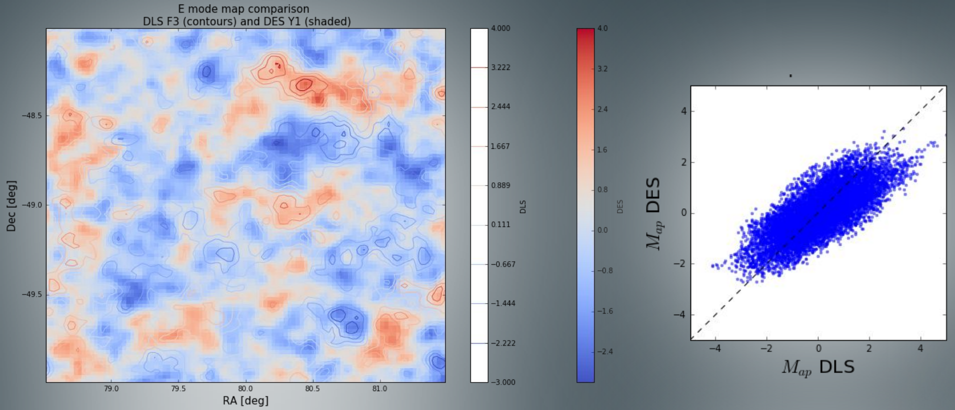


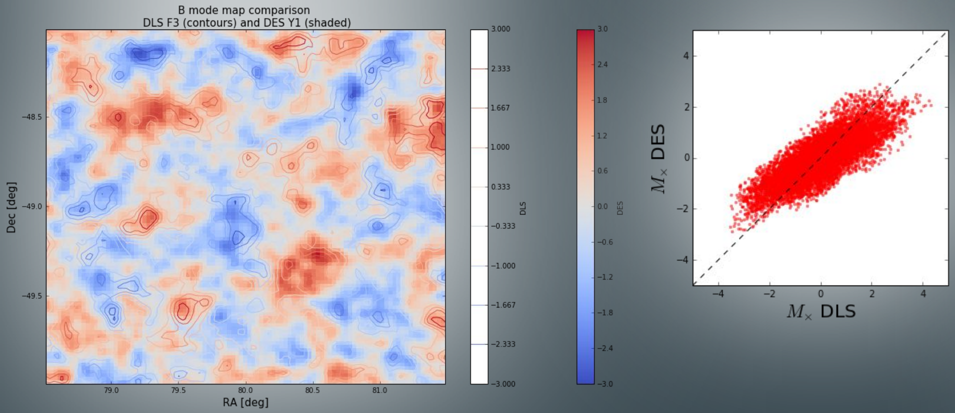
There's a lot going on at all scales, stretching homogeneity & isotropy to new limits!

Comparison: DLS F3 vs. DES Y1

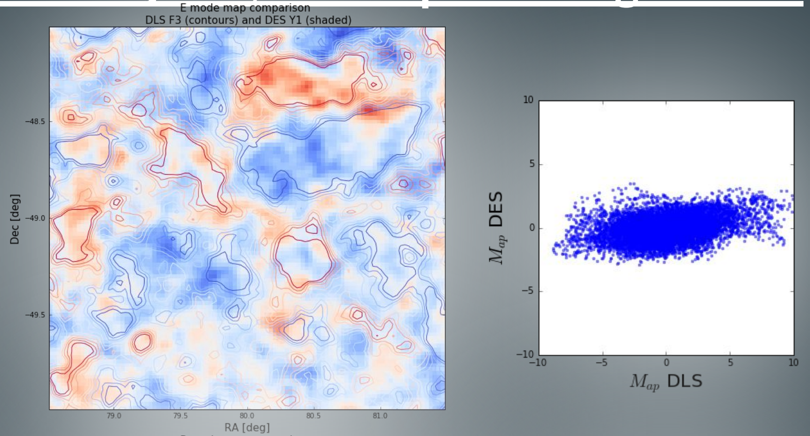
$-3 < S_+ < 4 \quad r_{max} = 0.25° \quad z_{src} > 0$

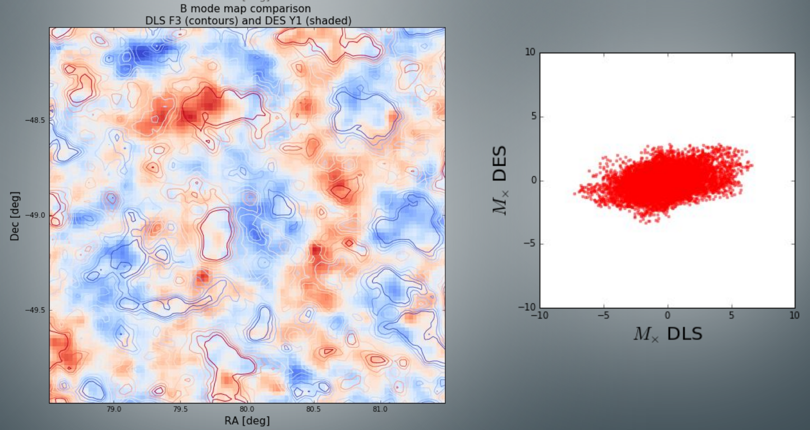
same objects, different measurements





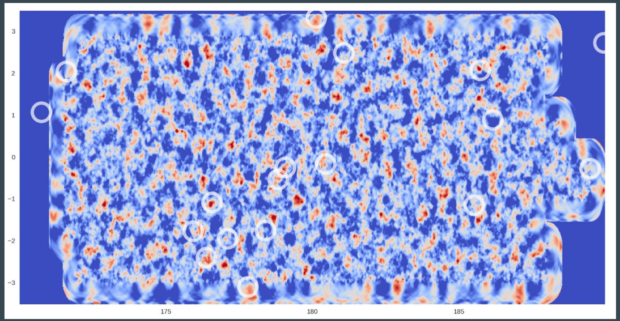
all objects, DLS depth → higher S/N

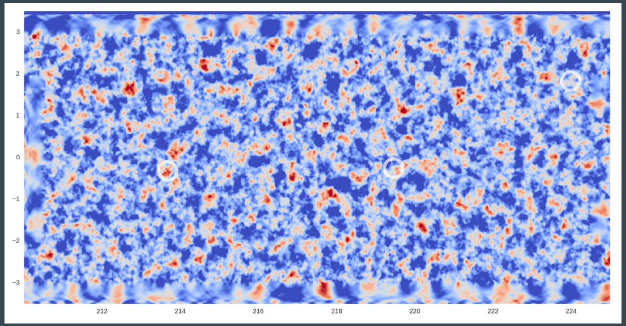


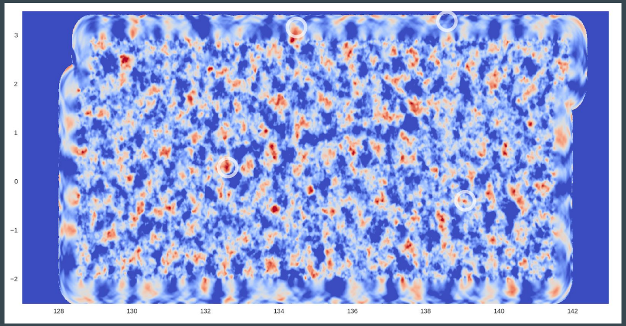


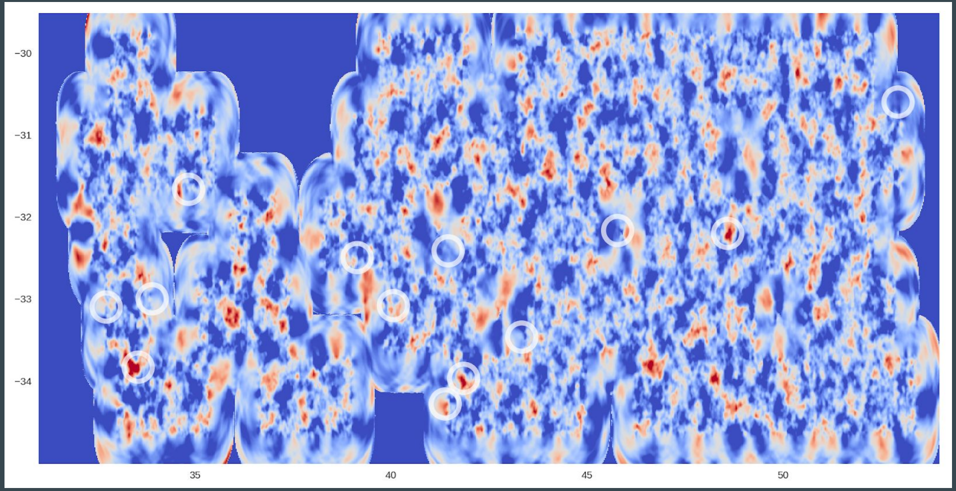
KiDS-450 E-modes

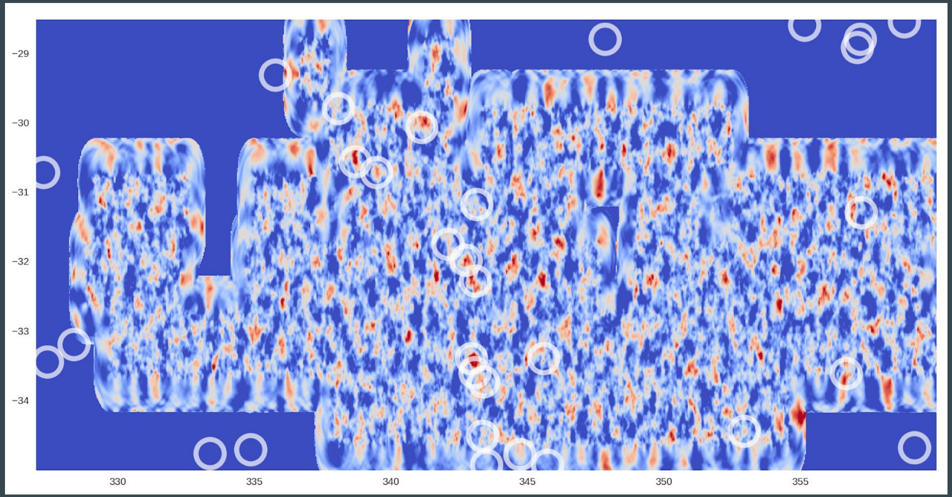
$-2<S_+<5$ $r_{max} = 0.5°$ $z_{src}>0.5$







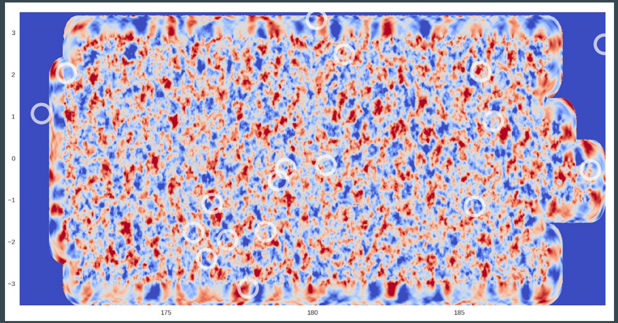


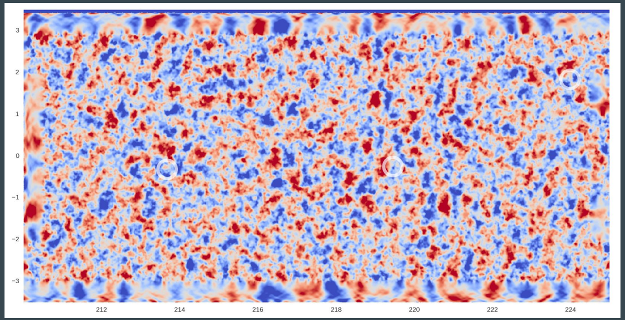


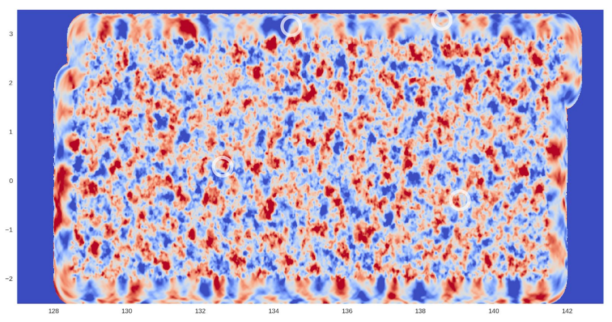
KiDS-450 B-modes

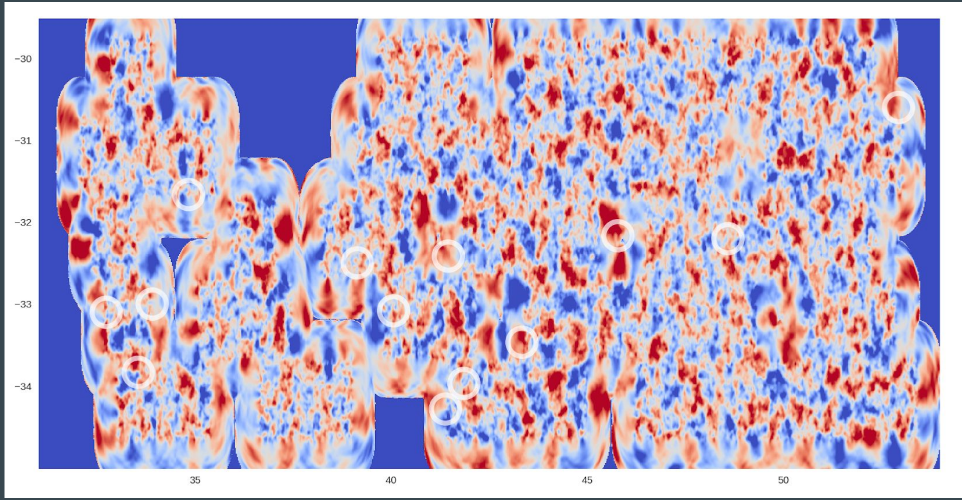
$-3<S_x<3$ $r_{max} = 0.5°$

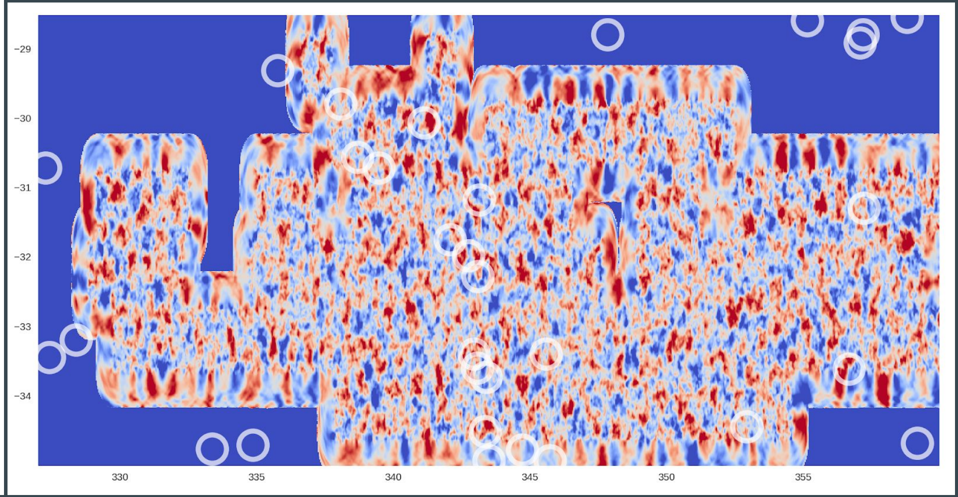
$z_{src}>0.5$





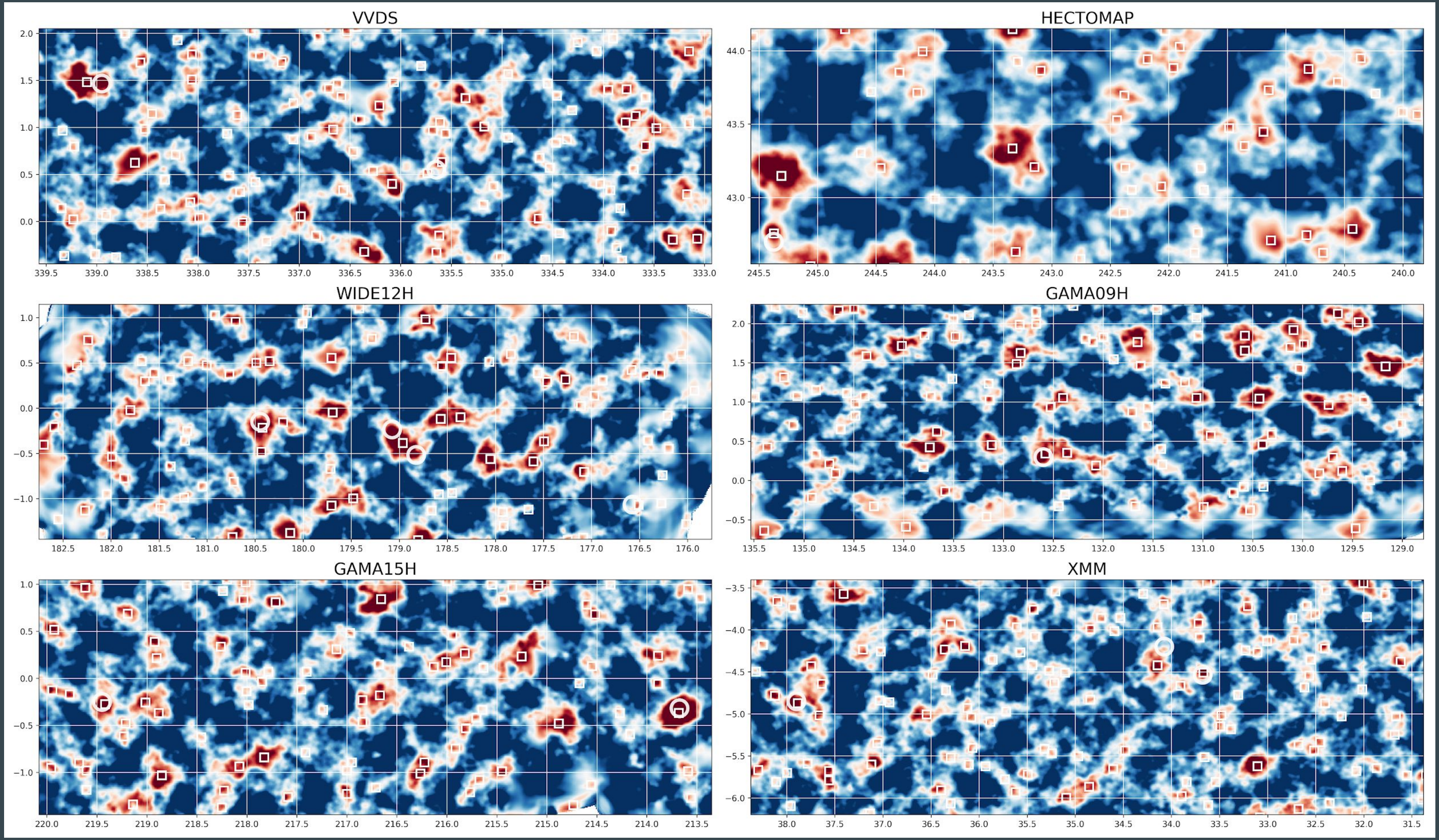






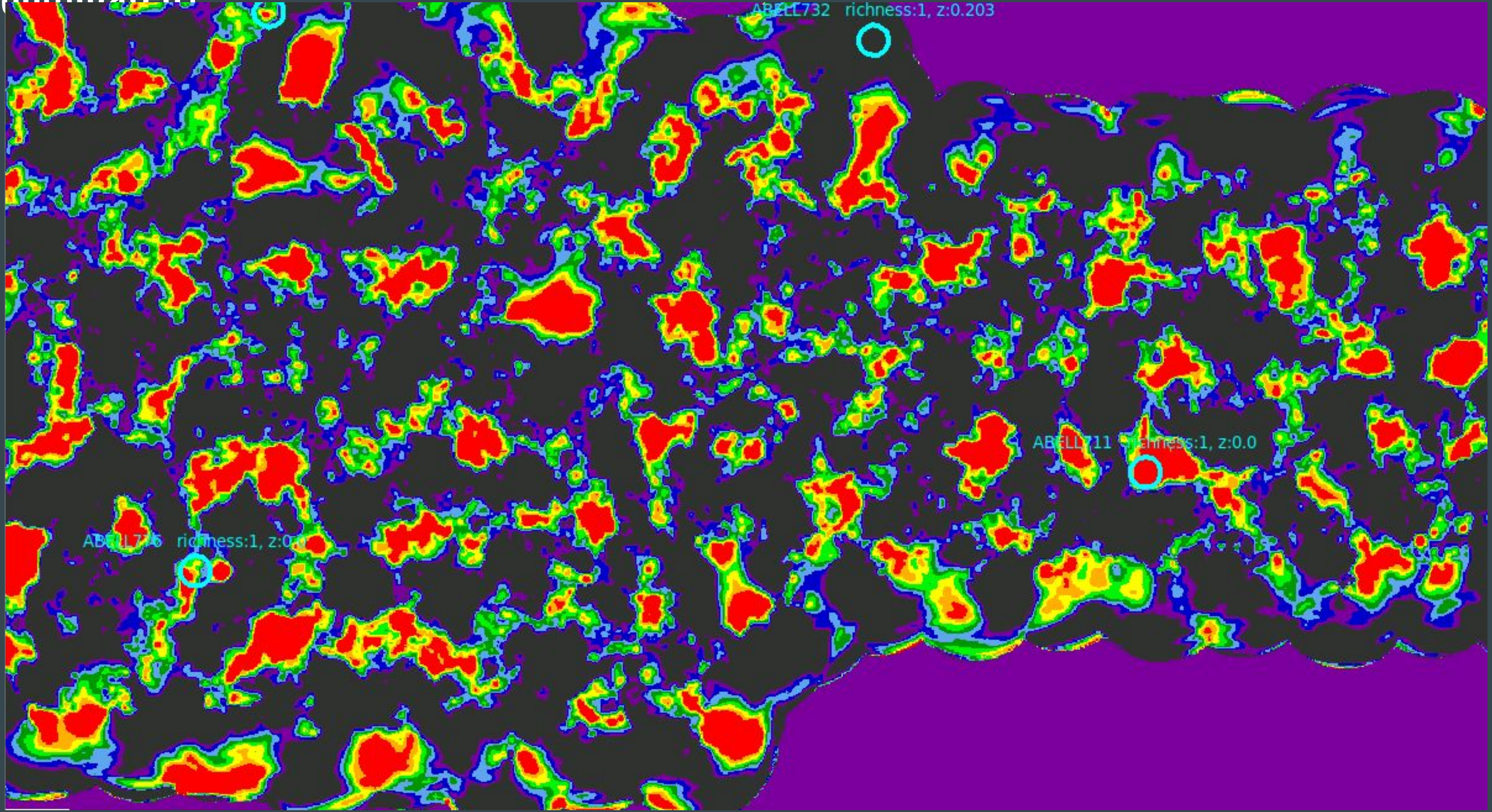
HSC S16A all fields

$-2<S_+<8$ $r_{max} = 0.5°$ $z_{src}>0.5$



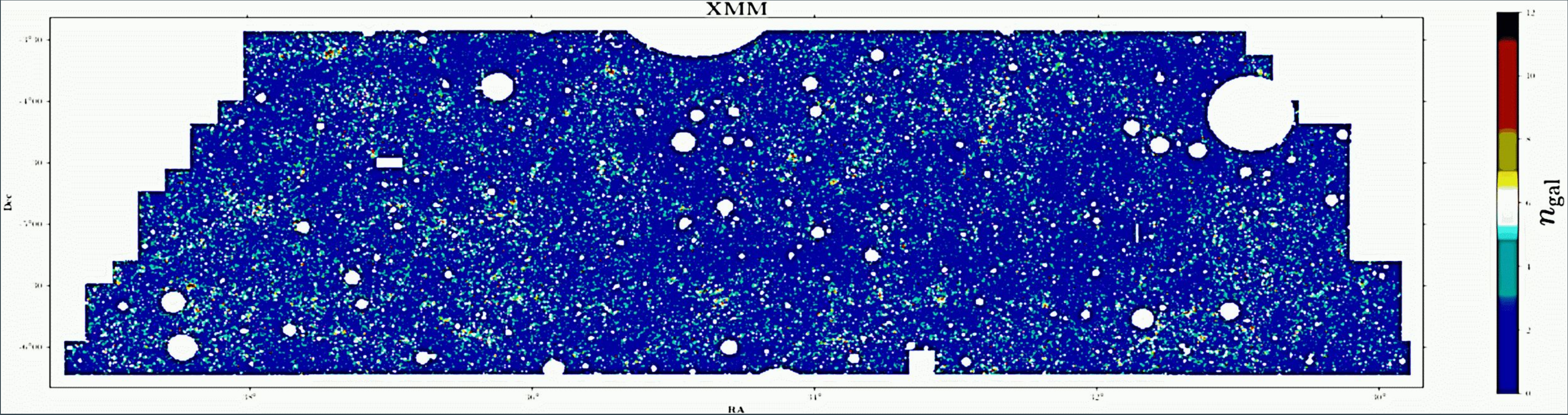
Comparison: KiDS and HSC in G9 $-1<S_+<5$ $r_{max} = 0.5°$ $z_{src}>0.5$

More depth → higher S/N, but similar structure → Maps are foreground dominated?



HSC XMM field

Mass map vs. Foreground Density (Nicola et al 2019)



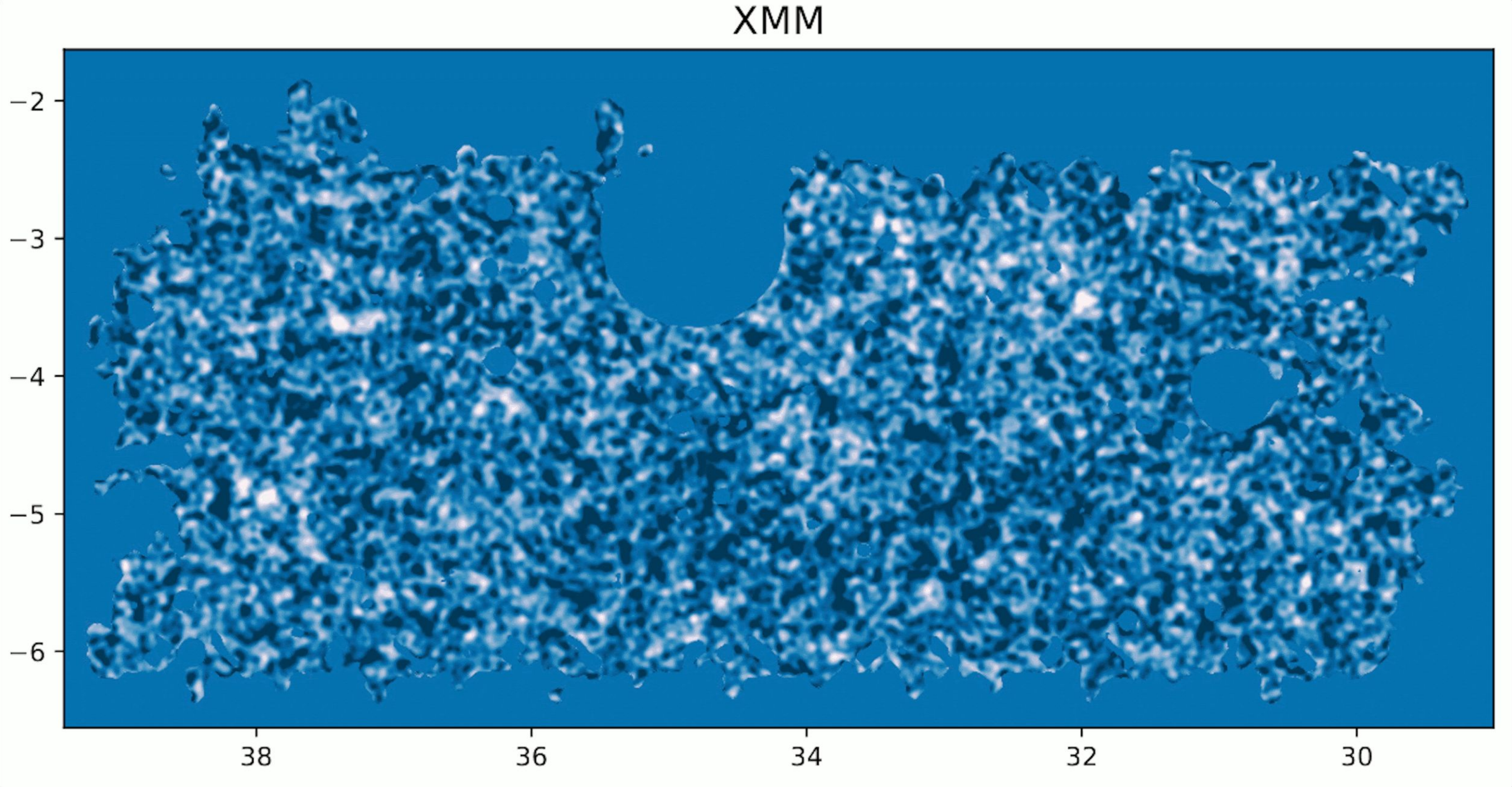
Foreground mass map made from background galaxies z>0.5

a completely independent sample and method

from the density measurement using z<0.5 galaxies

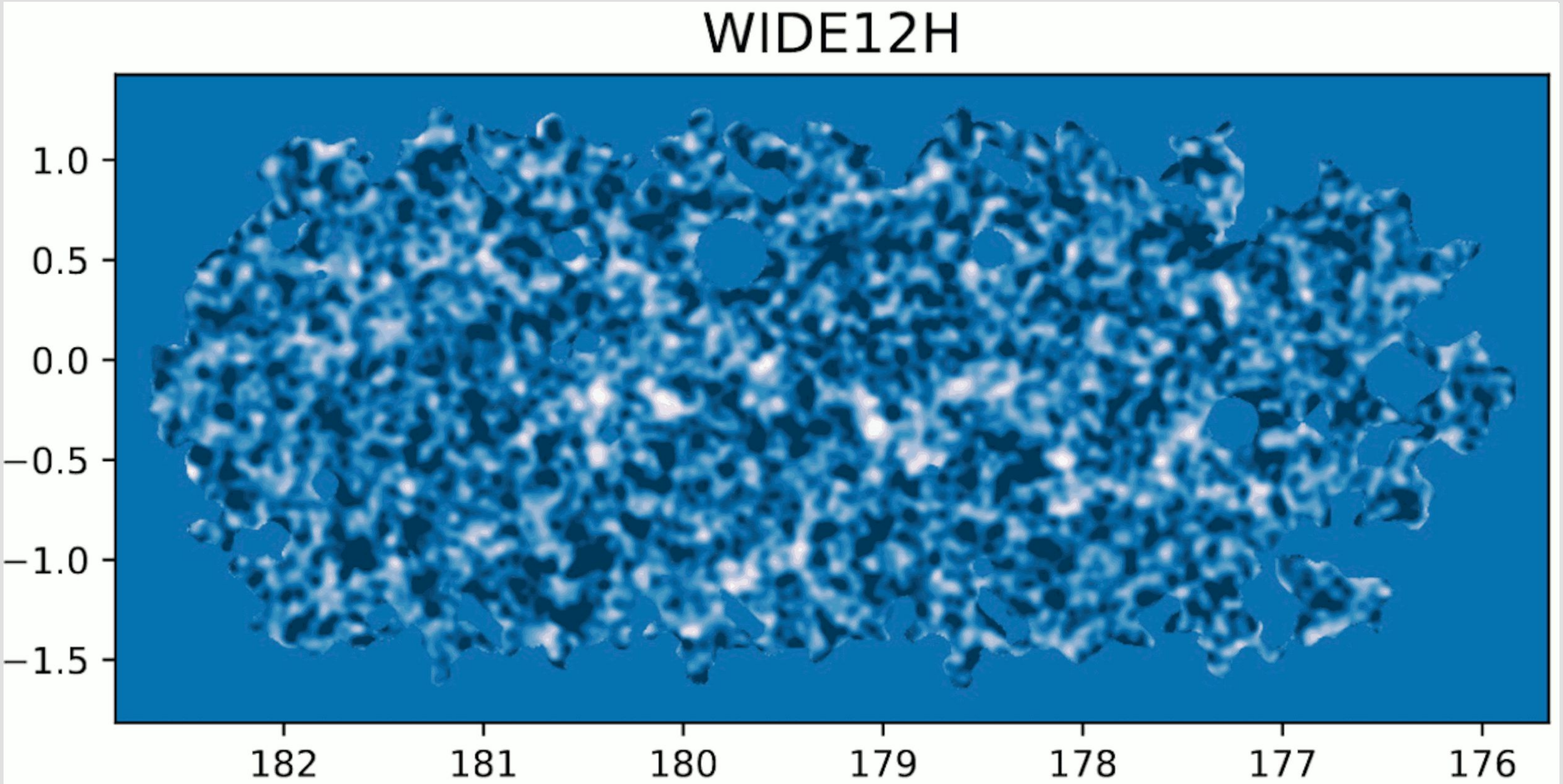
HSC XMM field

S/N map comparison - NFW aperture vs convergence S/N (Xiangchong Li et al)



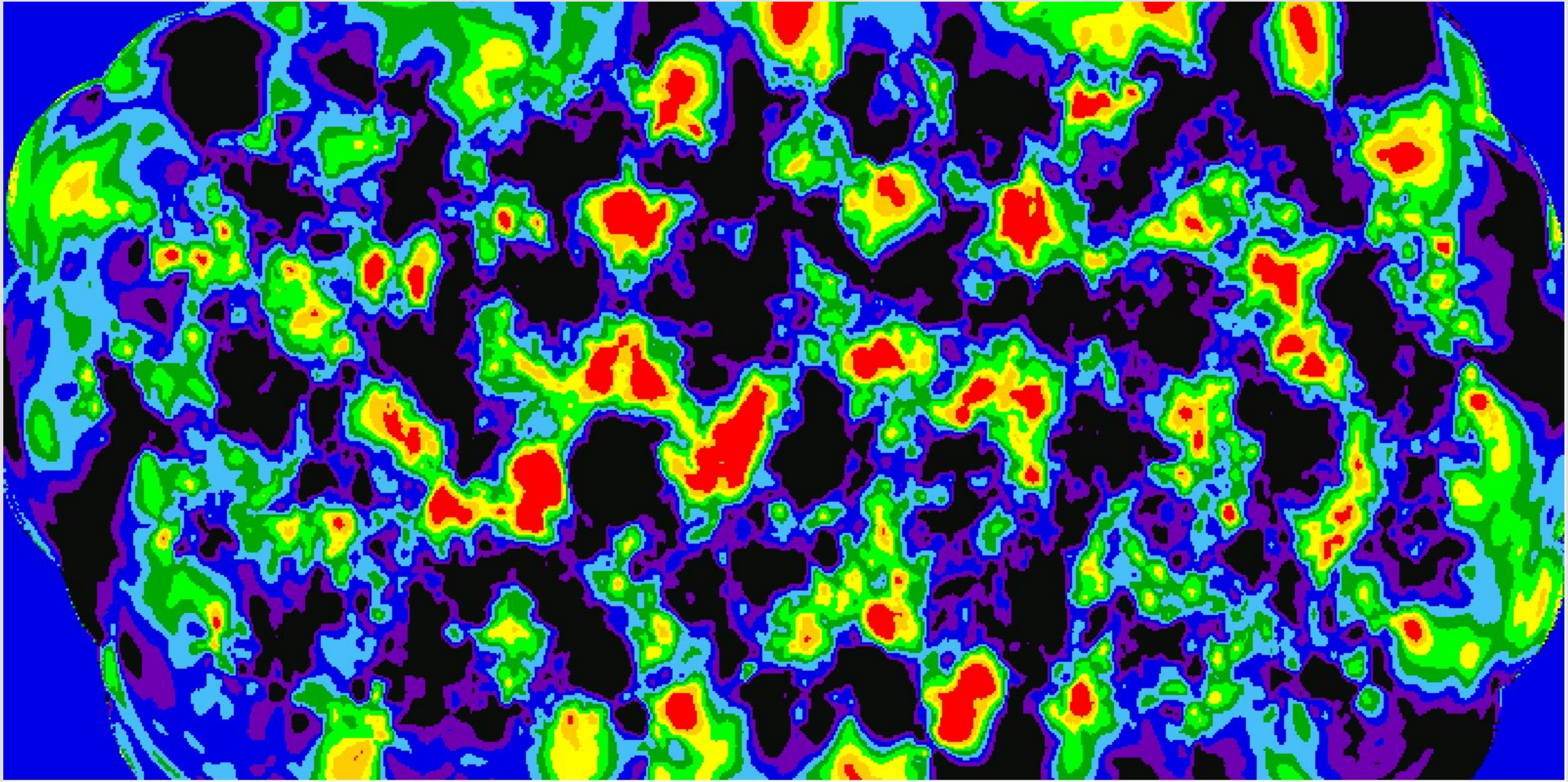
HSC WIDE12H field

S/N map comparison - NFW aperture vs convergence S/N (Xiangchong Li et al)



HSC S16A E-modes

$-2<S_+<7$ varying min. redshift z_{src} = 0.9, 0.5, 0.1



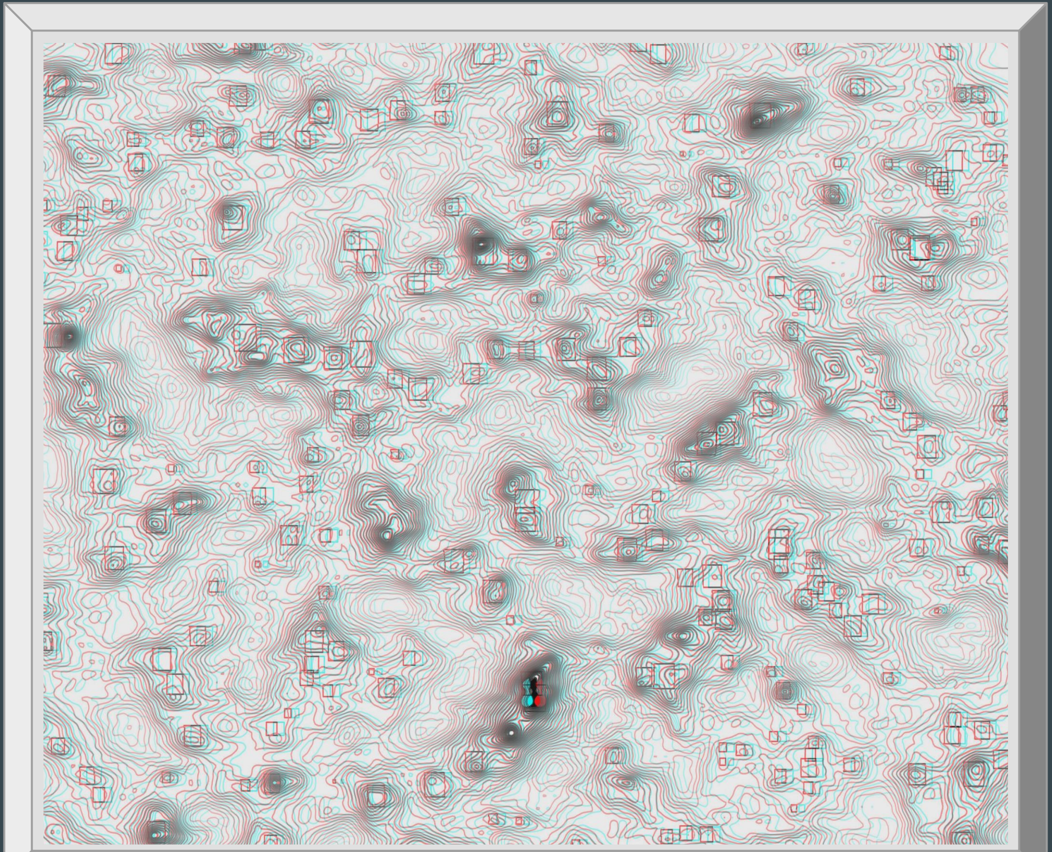
Summary

Aperture mass maps are a powerful method to optimally detect clusters and generate beautiful maps of mass on all scales

Public shape & redshift catalogs from the DLS, CFHTLenS, DES, KiDS, and HSC all show evidence of beautiful node & filament structure in NFW-filtered mass maps

Detecting & modeling large scale structure found in mass maps can enable new tests of understanding & assumptions in lensing

But mostly they are just fun to look at!



Red/blue stereographic mass map of 10x10 degree field of N-body simulation; sky surveys to come!