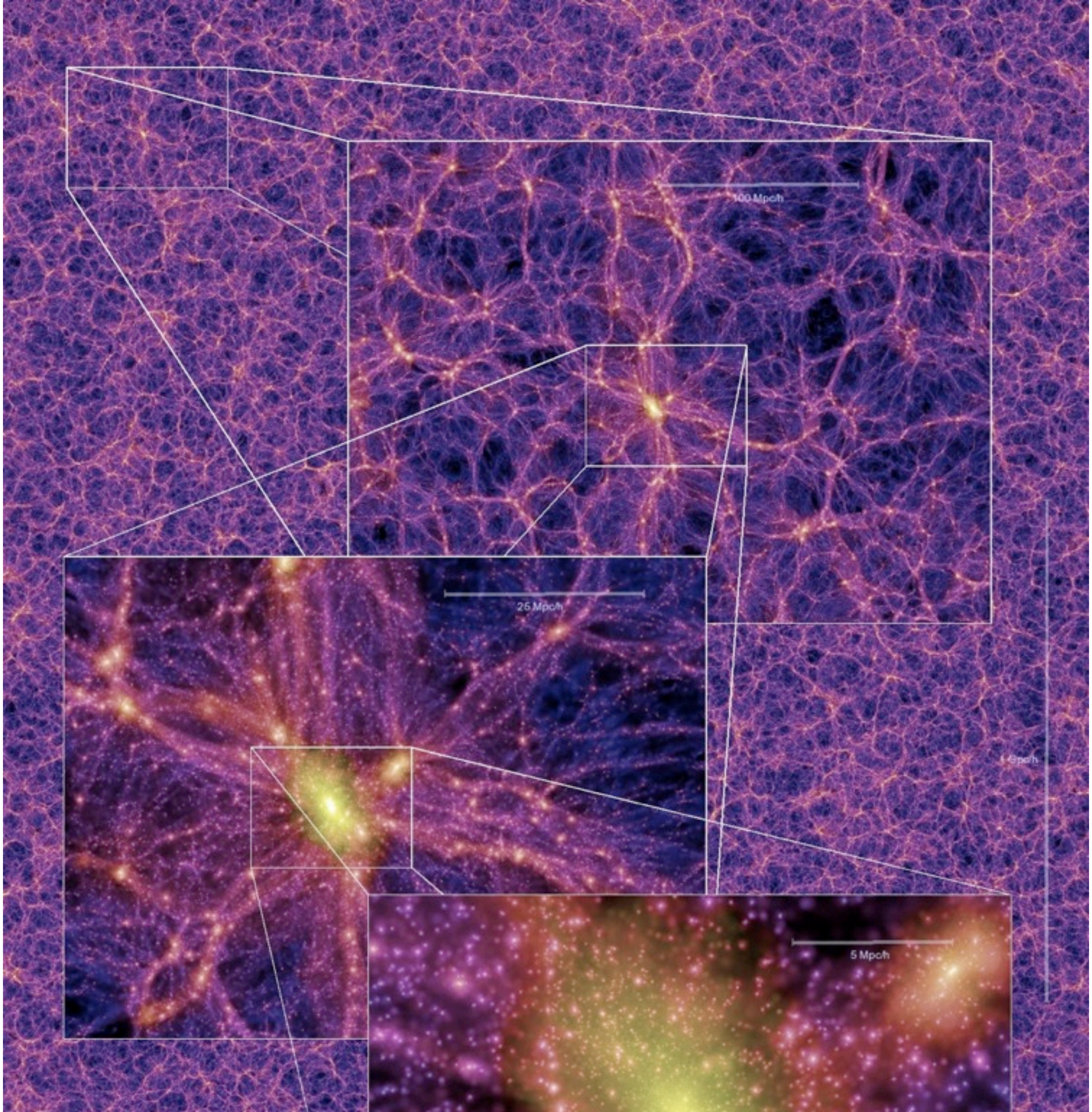
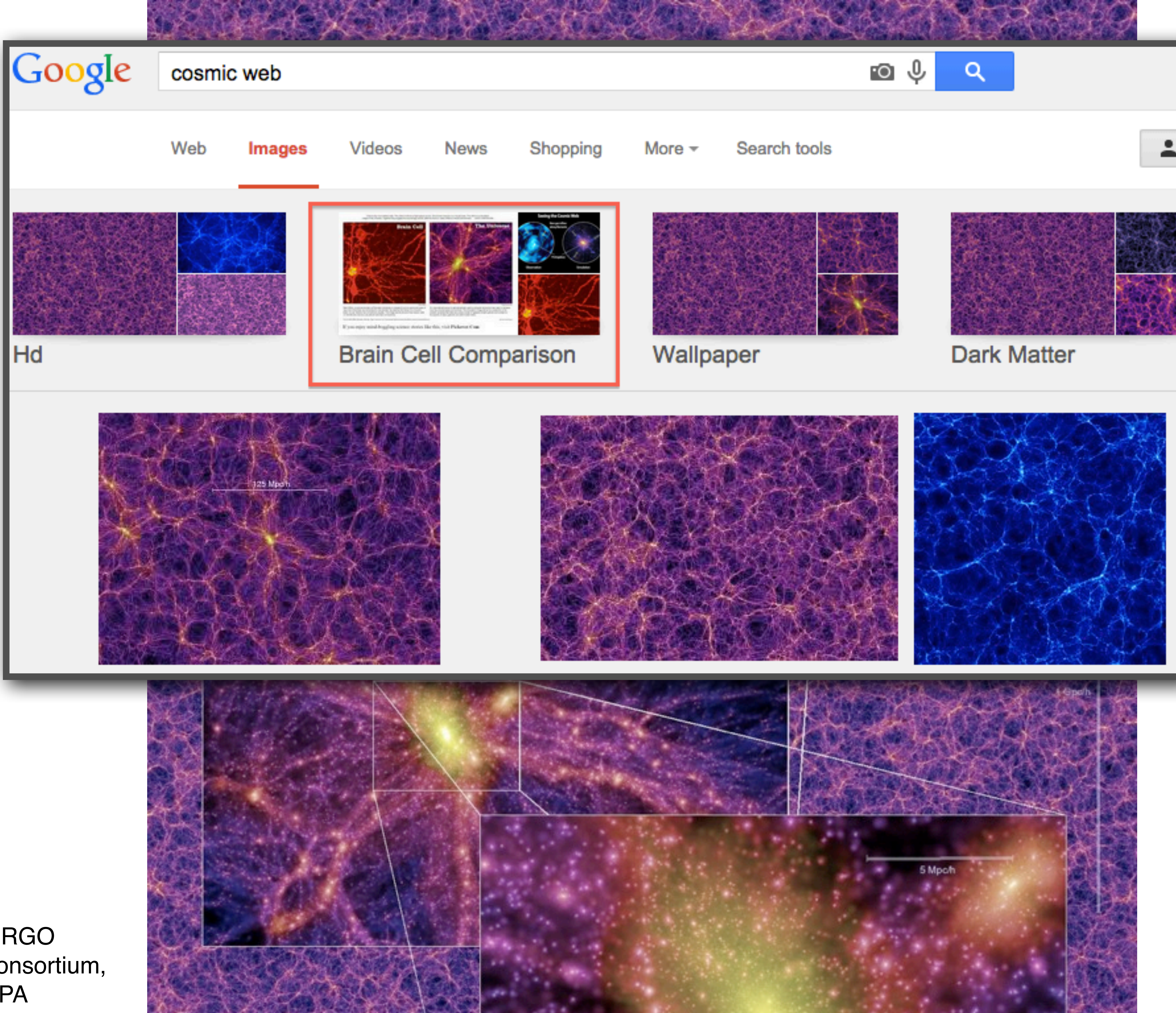
Resolving the IGM: tomographic reconstructions and hydrodynamic simulations

Casey W. Stark

work with:
Peter Nugent, Martin White, Zarija Lukić,
Andreu Font-Ribera, Joe Hennawi, Khee-Gan Lee,
Anže Slosar and Nishi Khandai



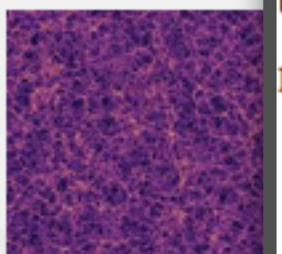
VIRGO
Consortium,
MPA



VIRGO
Consortium,
MPA

Google

cosmic web



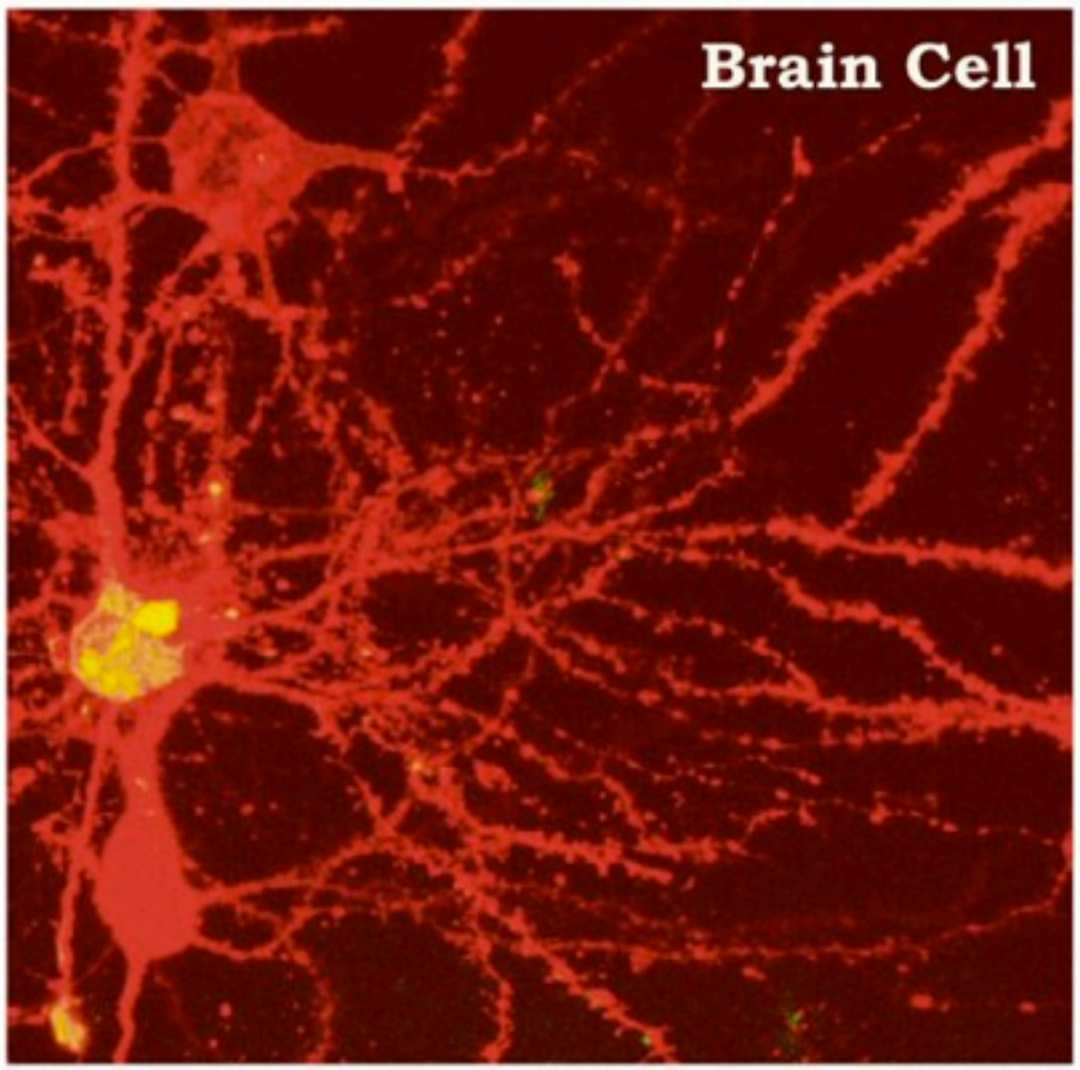
Hd

A Brain Cell is the Same as the Universe

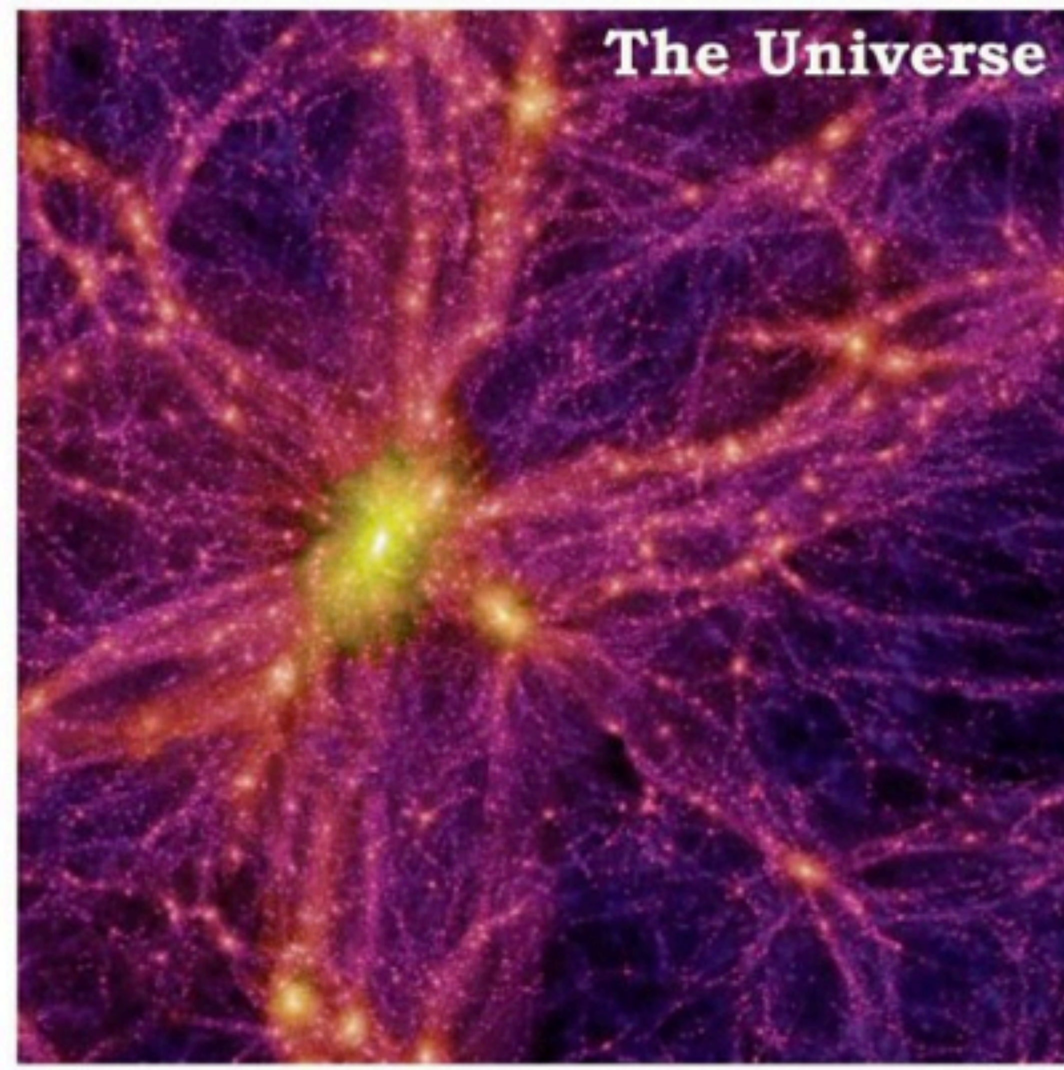
by [Cliff Pickover](), [Reality Carnival]()

Physicists discover that the structure of a brain cell is the same as the entire universe.

One is only micrometers wide. The other is billions of light-years across. One shows neurons in a mouse brain. The other is a simulated image of the universe. Together they suggest the surprisingly similar patterns found in vastly different natural phenomena. *DAVID CONSTANTINE*



Mark Miller



Virgo Consortium

Mark Miller, a doctoral student at Brandeis University, is researching how particular types of neurons in the brain are connected to one another. By staining thin slices of a mouse's brain, he can identify the connections visually. The image above shows three neuron cells on the left (two red and one yellow) and their connections.

An international group of astrophysicists used a computer simulation last year to recreate how the universe grew and evolved. The simulation image above is a snapshot of the present universe that features a large cluster of galaxies (bright yellow) surrounded by thousands of stars, galaxies and dark matter (web).

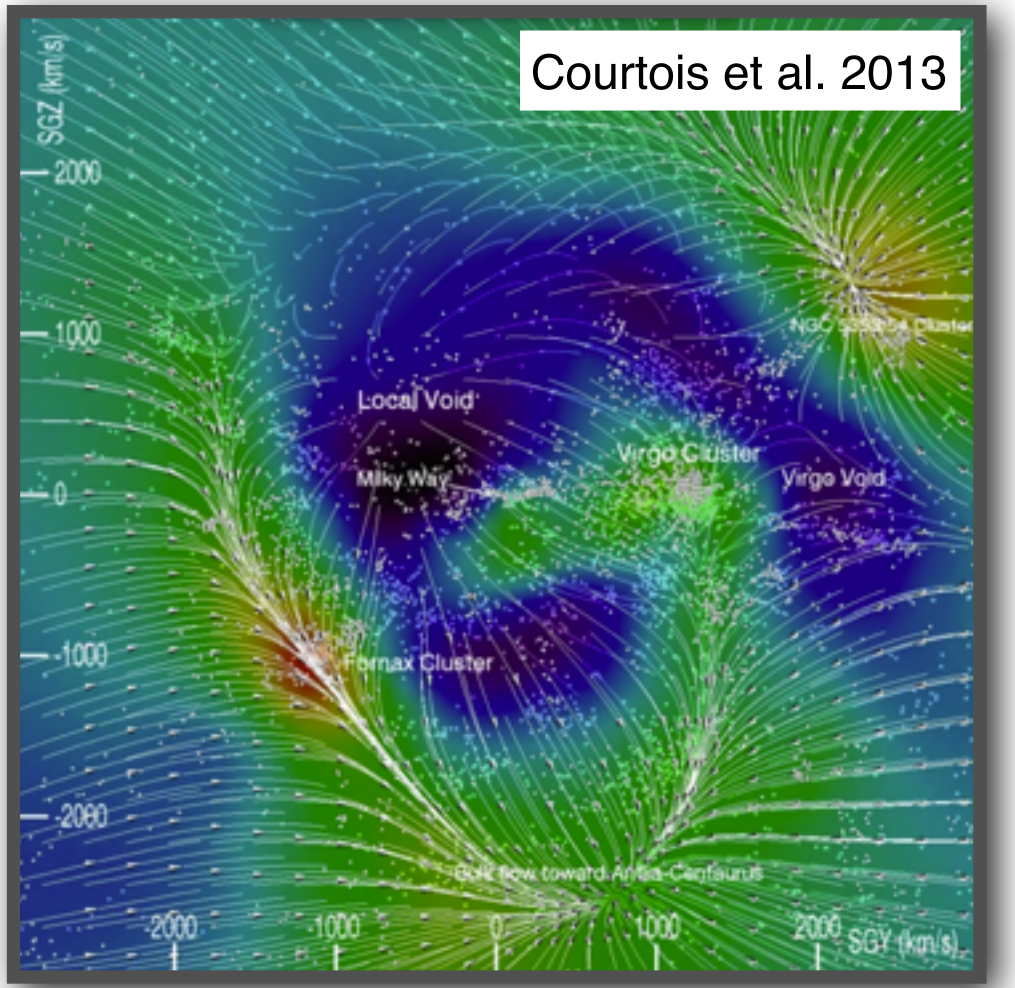
Source: Mark Miller, Brandeis University; Virgo Consortium for Cosmological Supercomputer Simulations; www.visualcomplexity.com

The New York Times

VIRGO Consortium, MPA

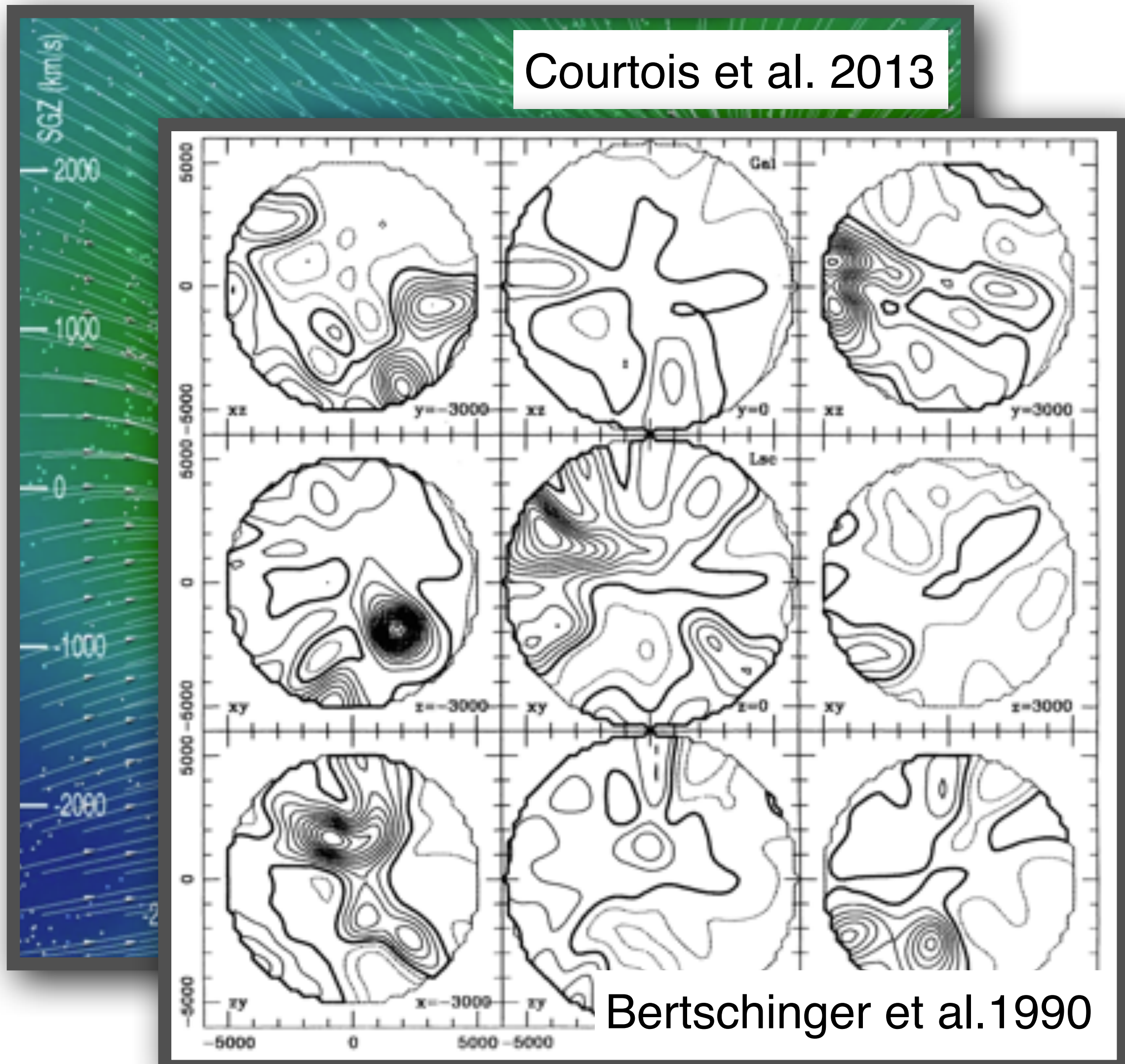
Cosmography history

Cosmography history

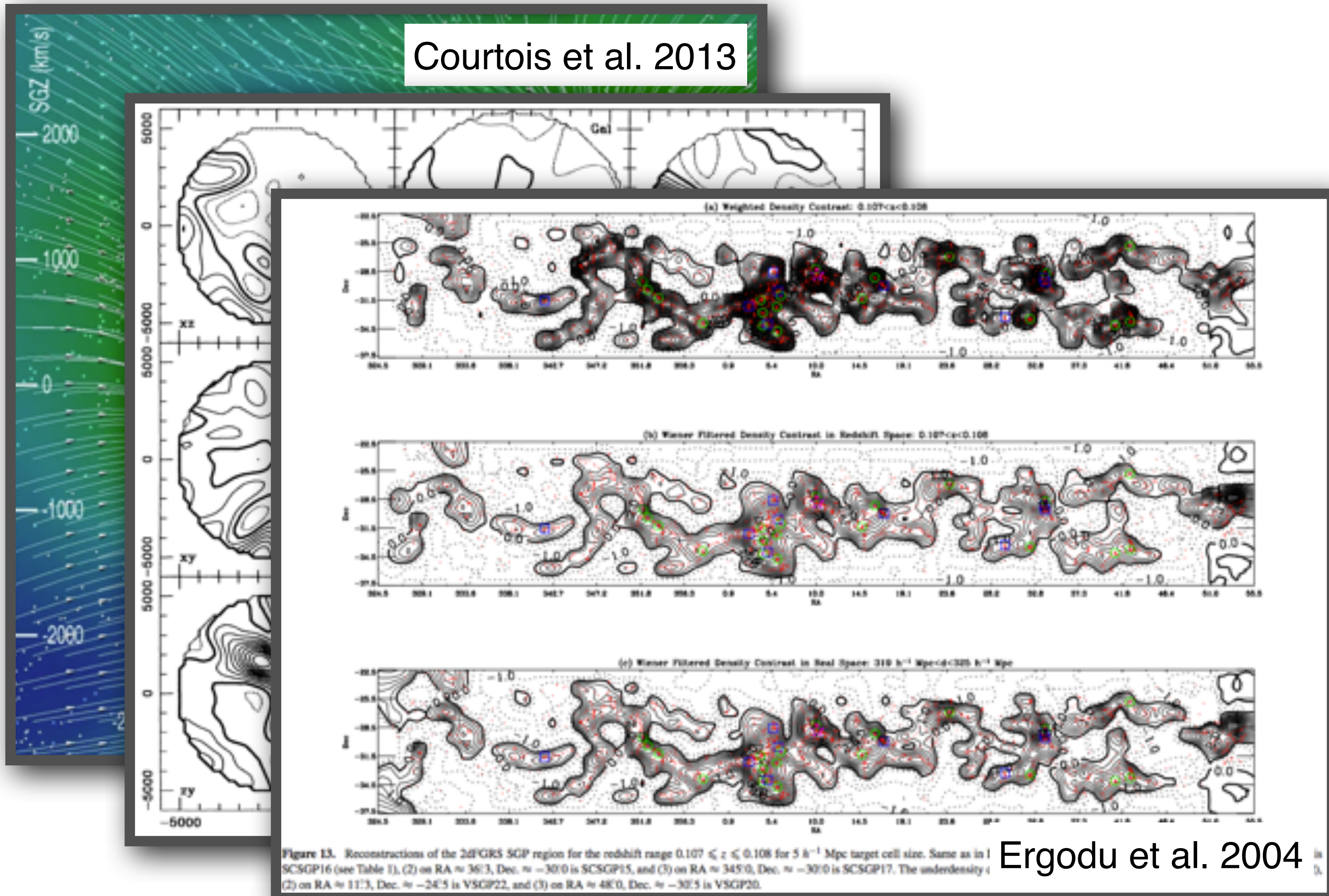


Courtois et al. 2013

Cosmography history



Cosmography history



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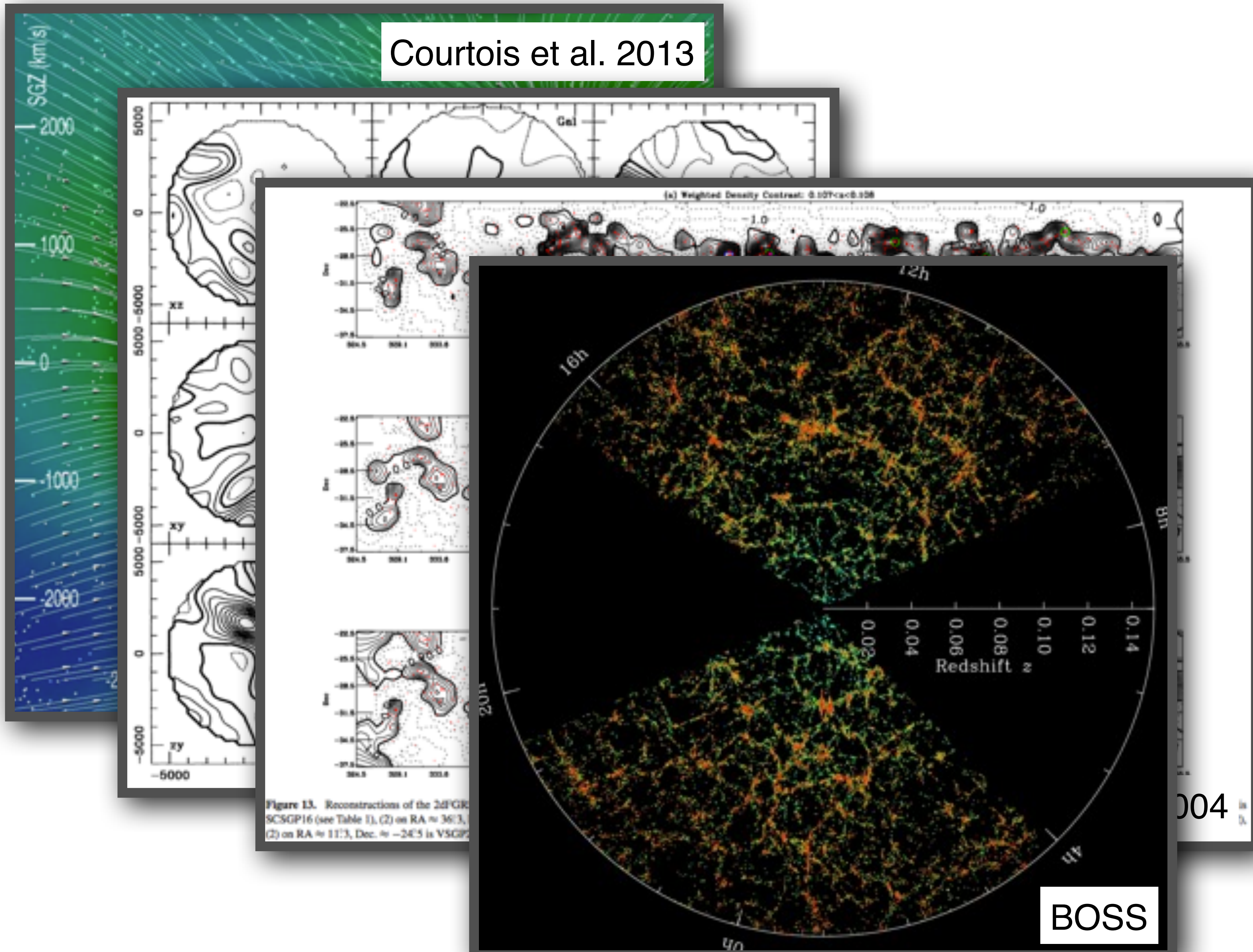
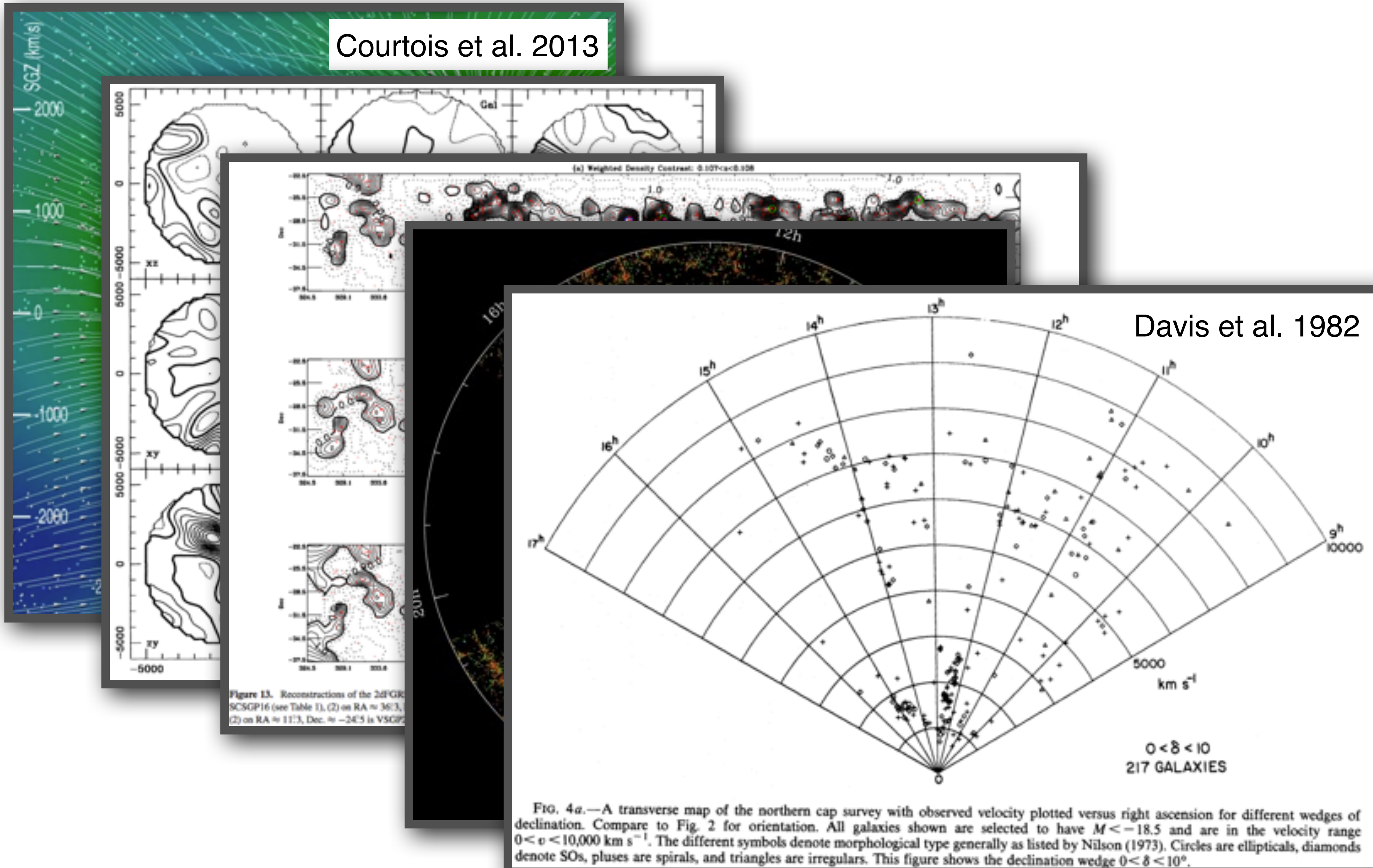
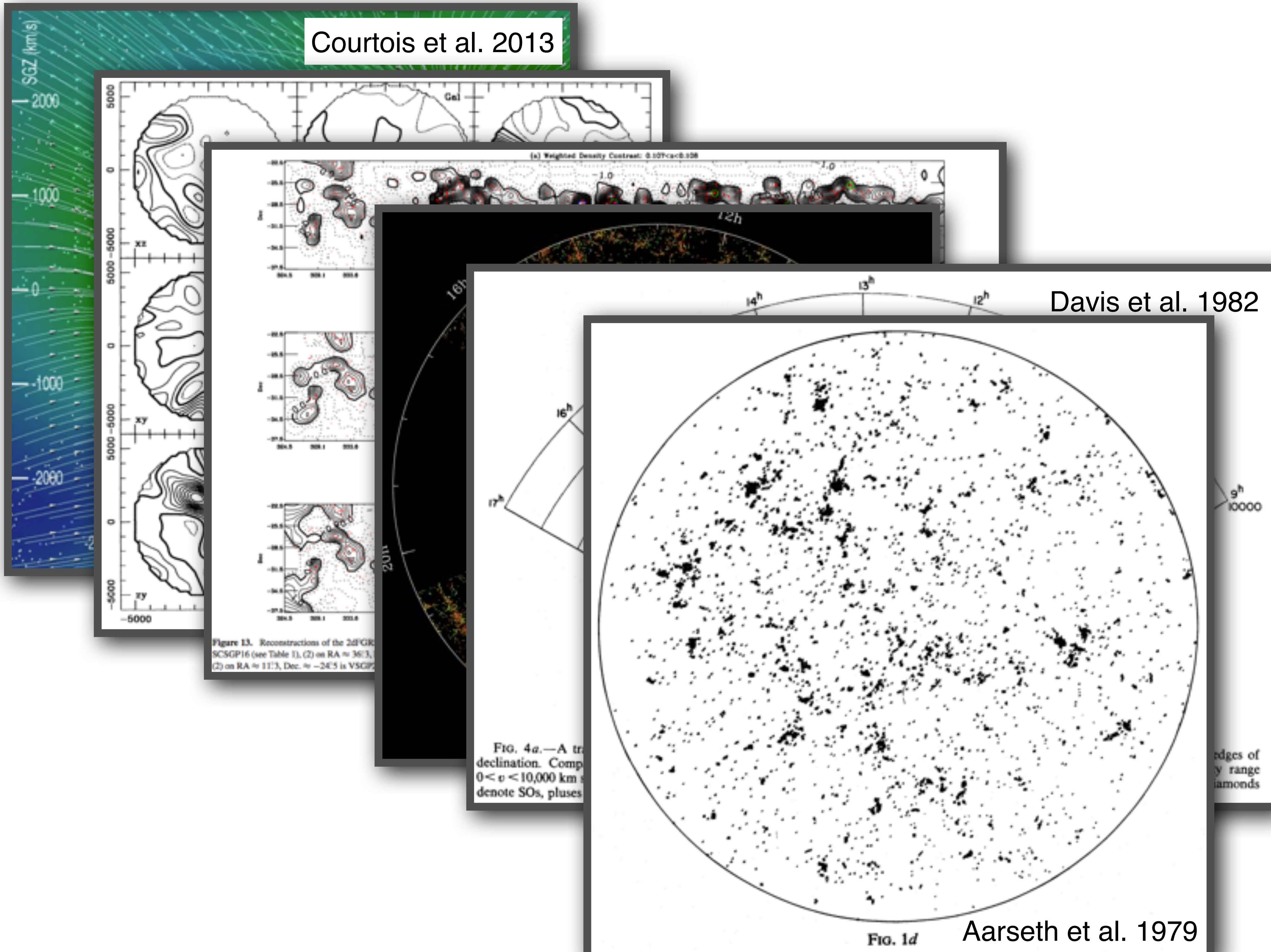


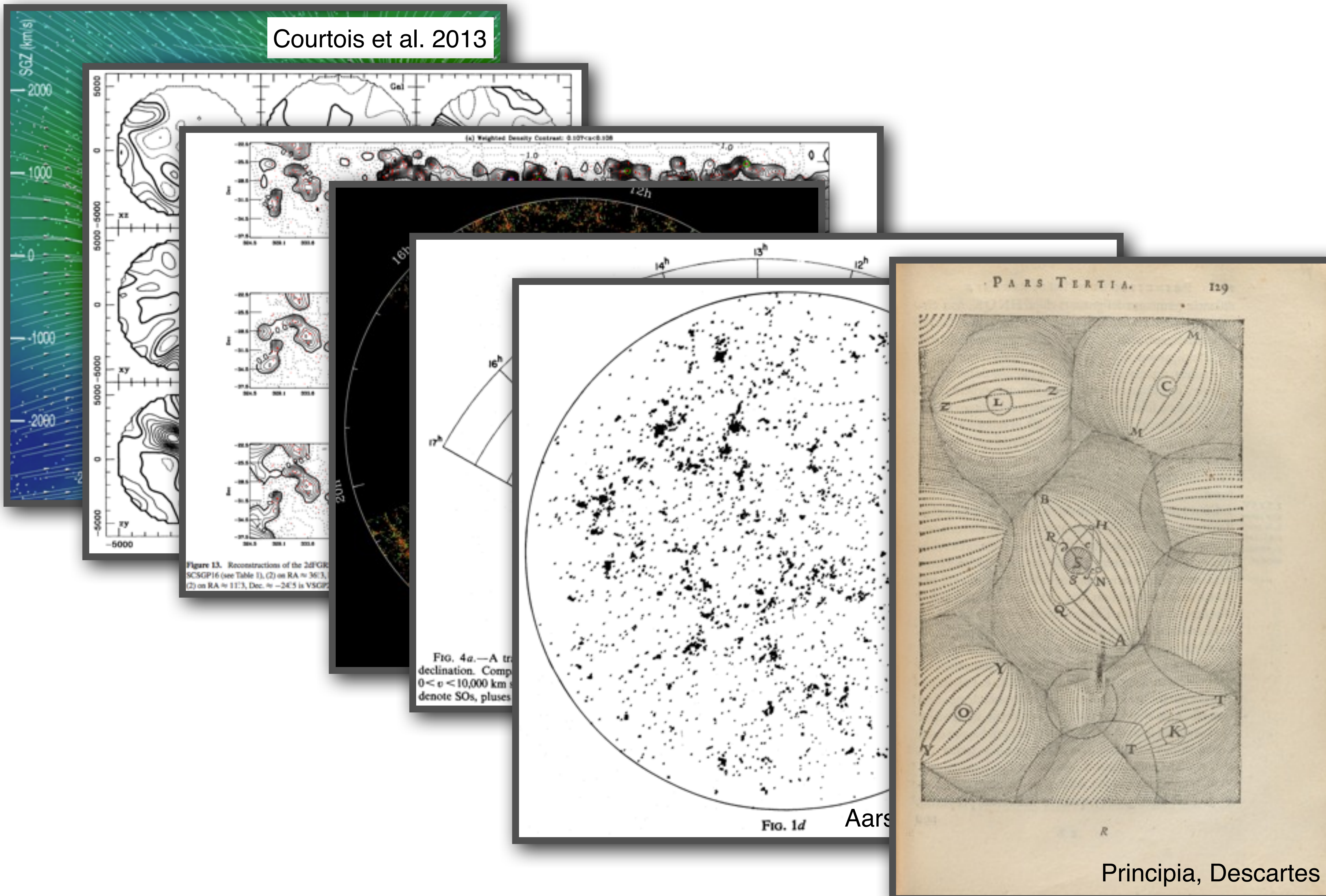
Cosmography history



Cosmography history



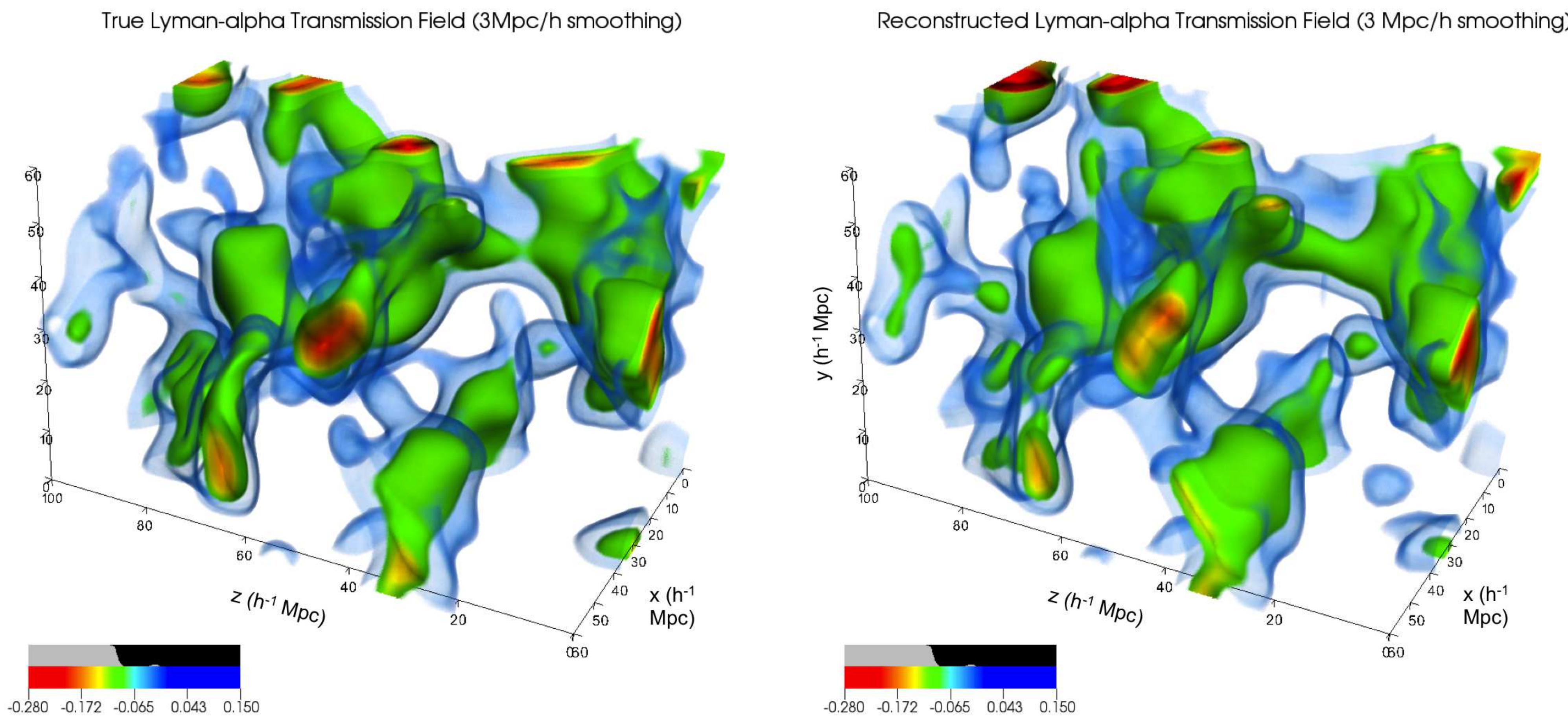
Cosmography history



KG's work on observational requirements

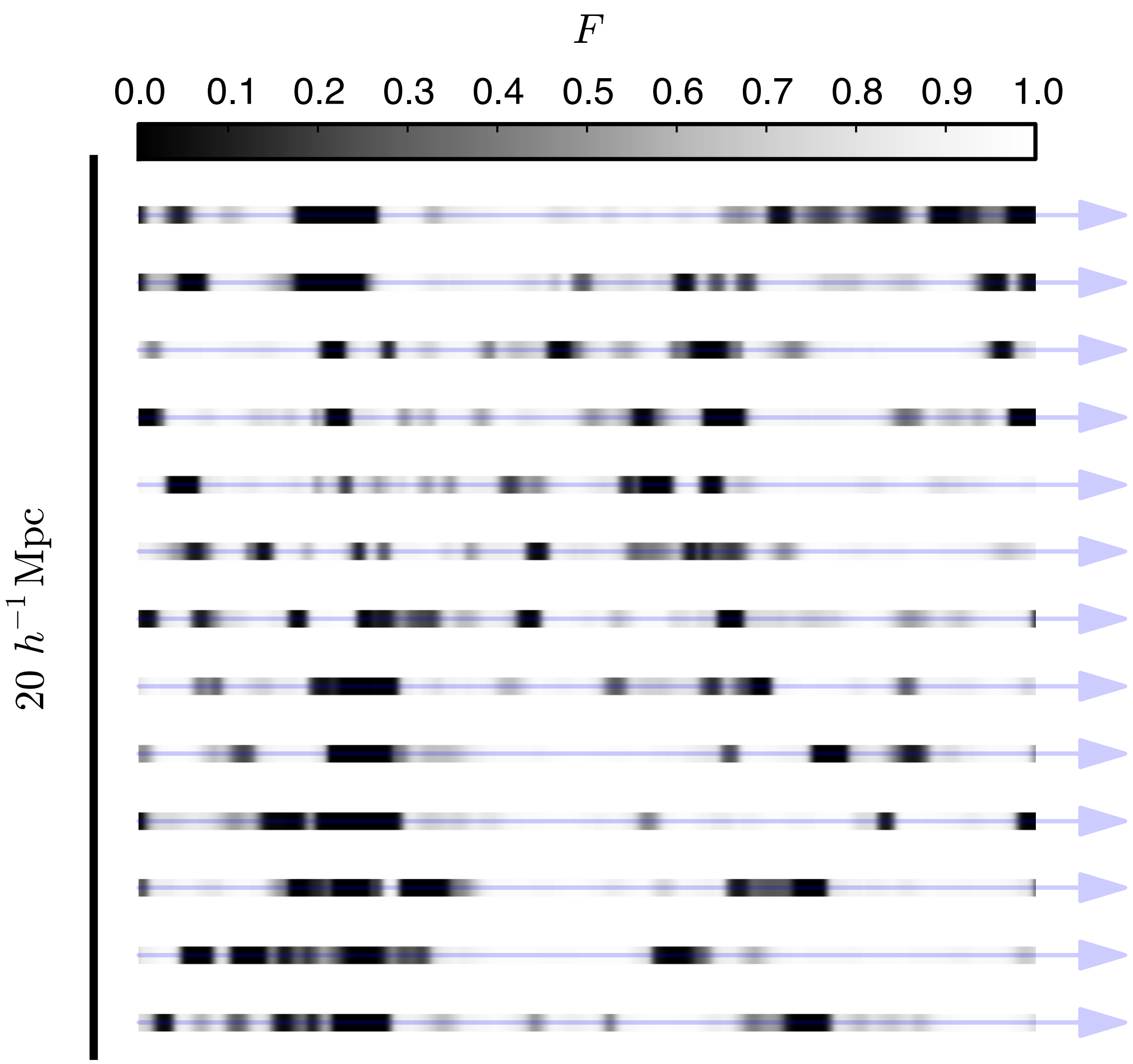
3D Visualization of IGM Tomography

'True' 3D absorption field at left; reconstruction from noisy mock spectra at right (Similar reconstruction as previous slide).



Dimensions: $(65\ \mathrm{h}^{-1}\,\mathrm{Mpc})^2 \times (100\ \mathrm{h}^{-1}\,\mathrm{Mpc})$

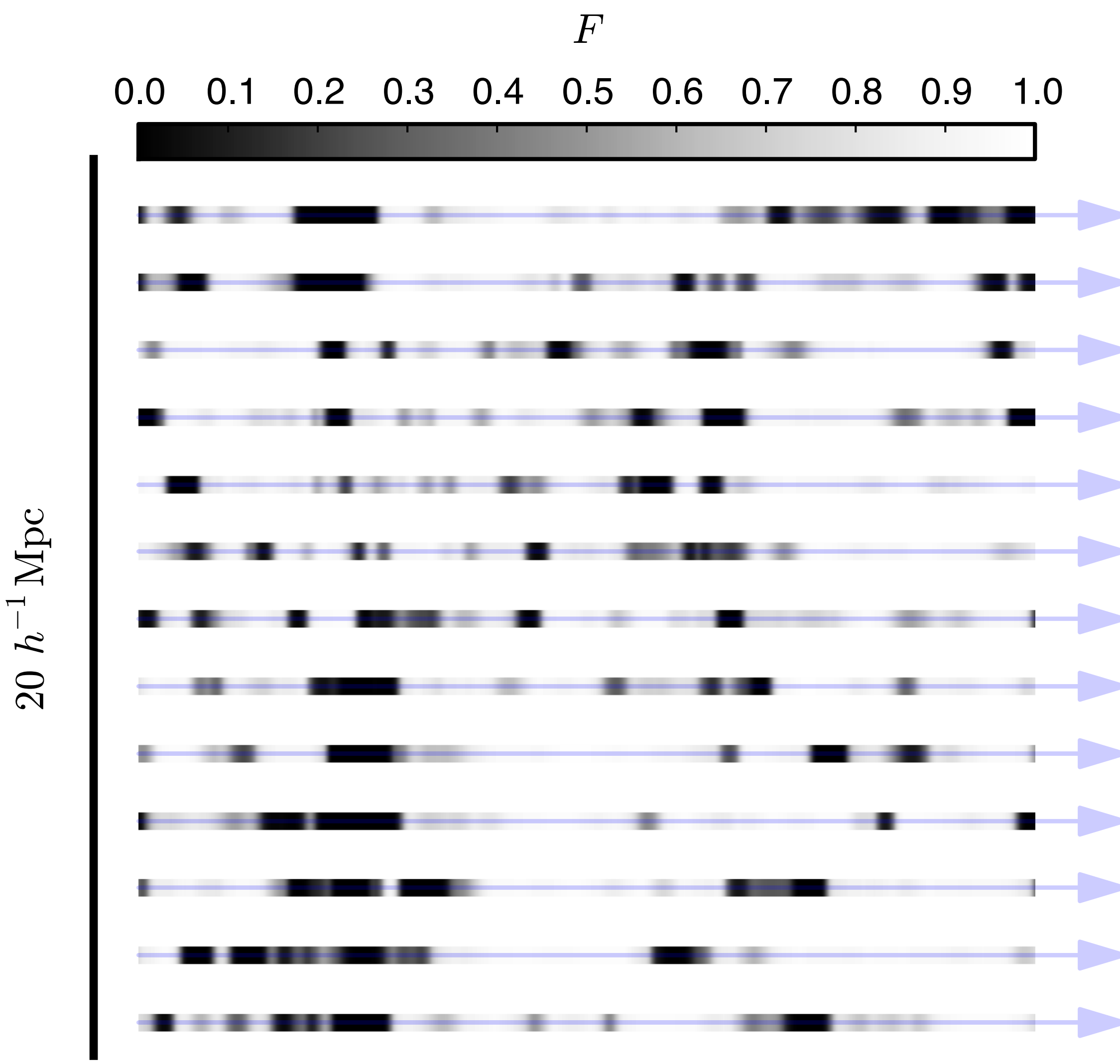
Tomography (cartoon version)



1D sampling (in same plane)

Observationally, we only sample the absorption along skewers, but the signal is everywhere and provides an excellent tracer of matter density.

Tomography (cartoon version)

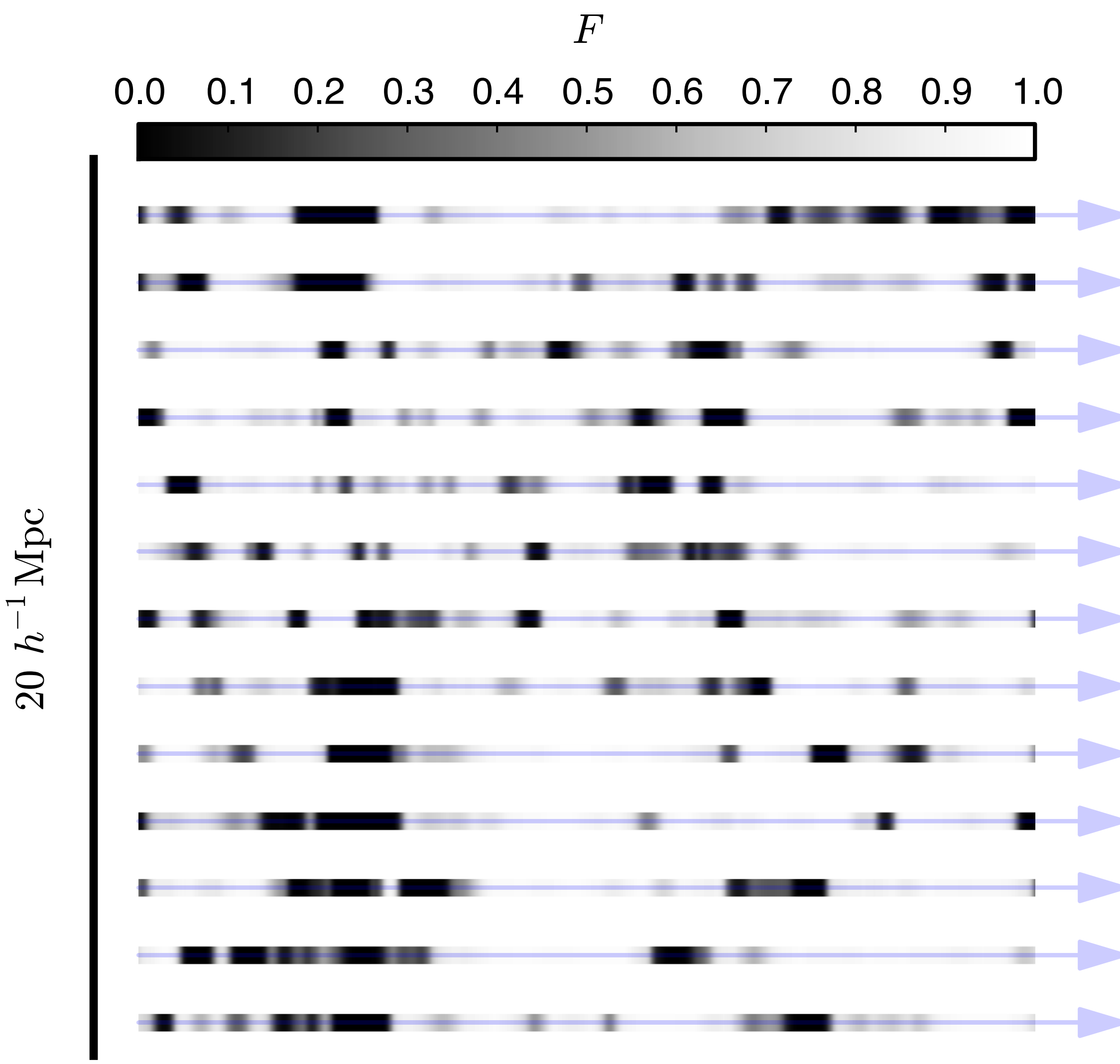


1D sampling (in same plane)

Observationally, we only sample the absorption along skewers, but the signal is everywhere and provides an excellent tracer of matter density.

Given some sparse sampling of a 3D field, you already interpolate the missing points by eye.

Tomography (cartoon version)



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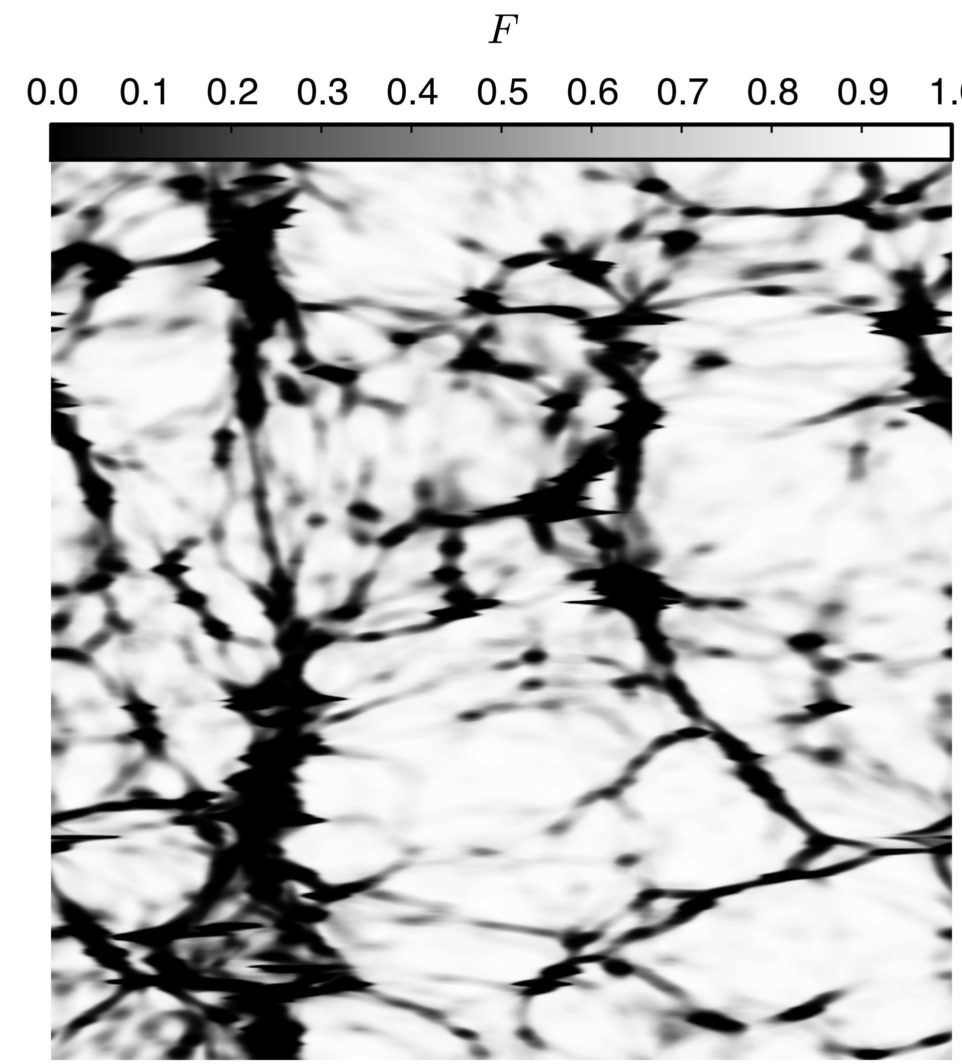
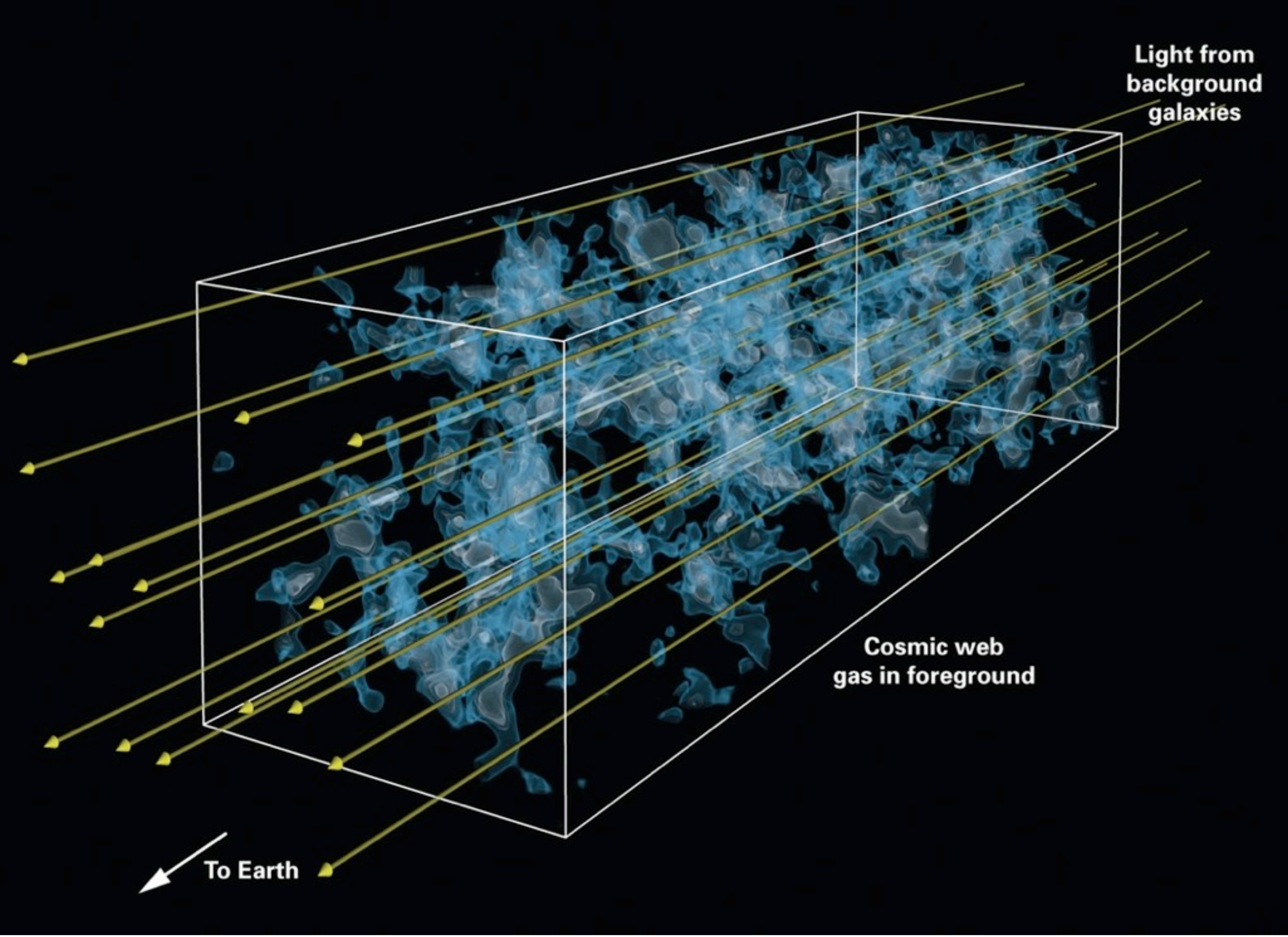


3D sampling

Observationally, we only sample the absorption along skewers, but the signal is everywhere and provides an excellent tracer of matter density.

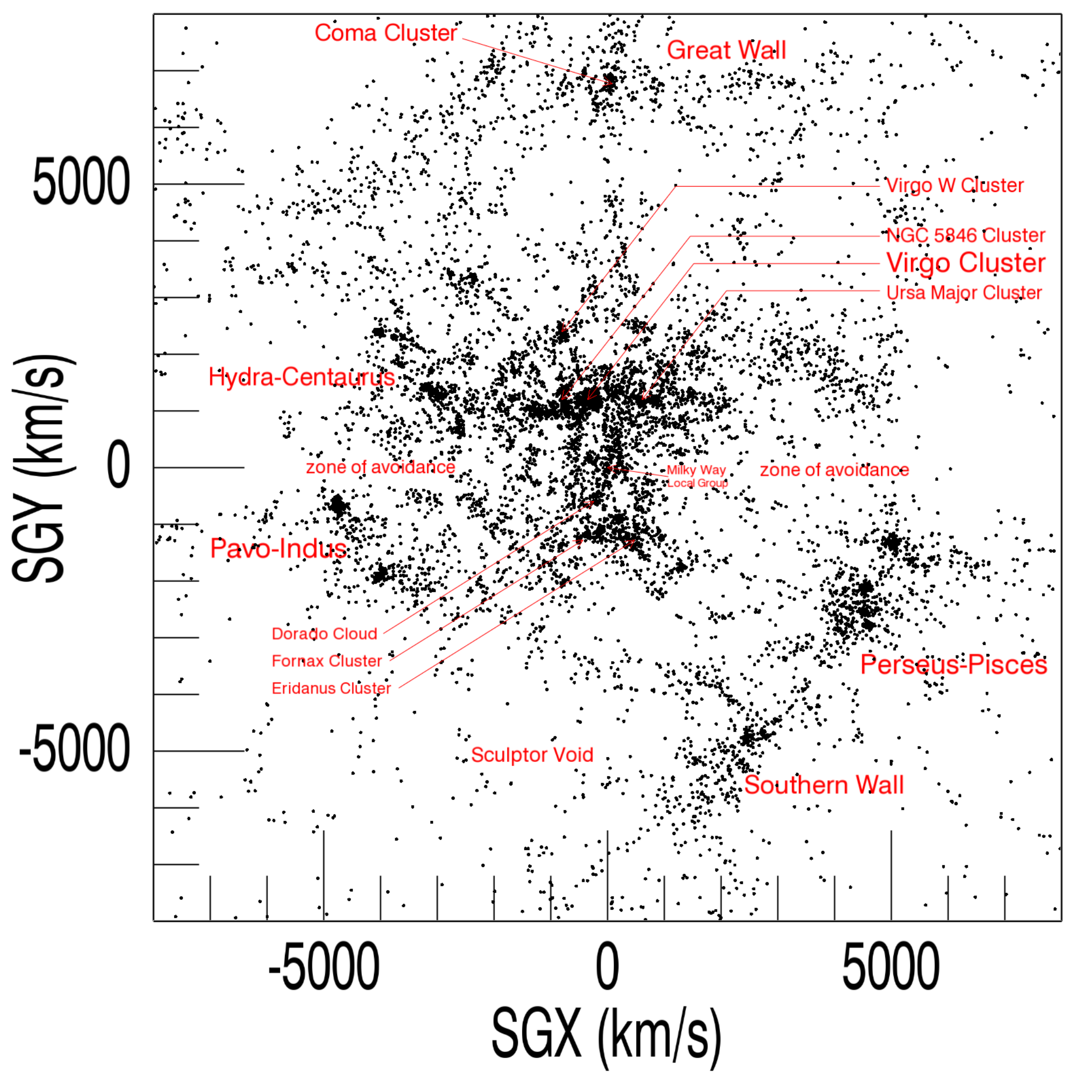
Given some sparse sampling of a 3D field, you already interpolate the missing points by eye.


Light from
background
galaxies
Cosmic web
gas in foreground
To Earth

Galaxy Redshift Maps at z = 0 and z = 2

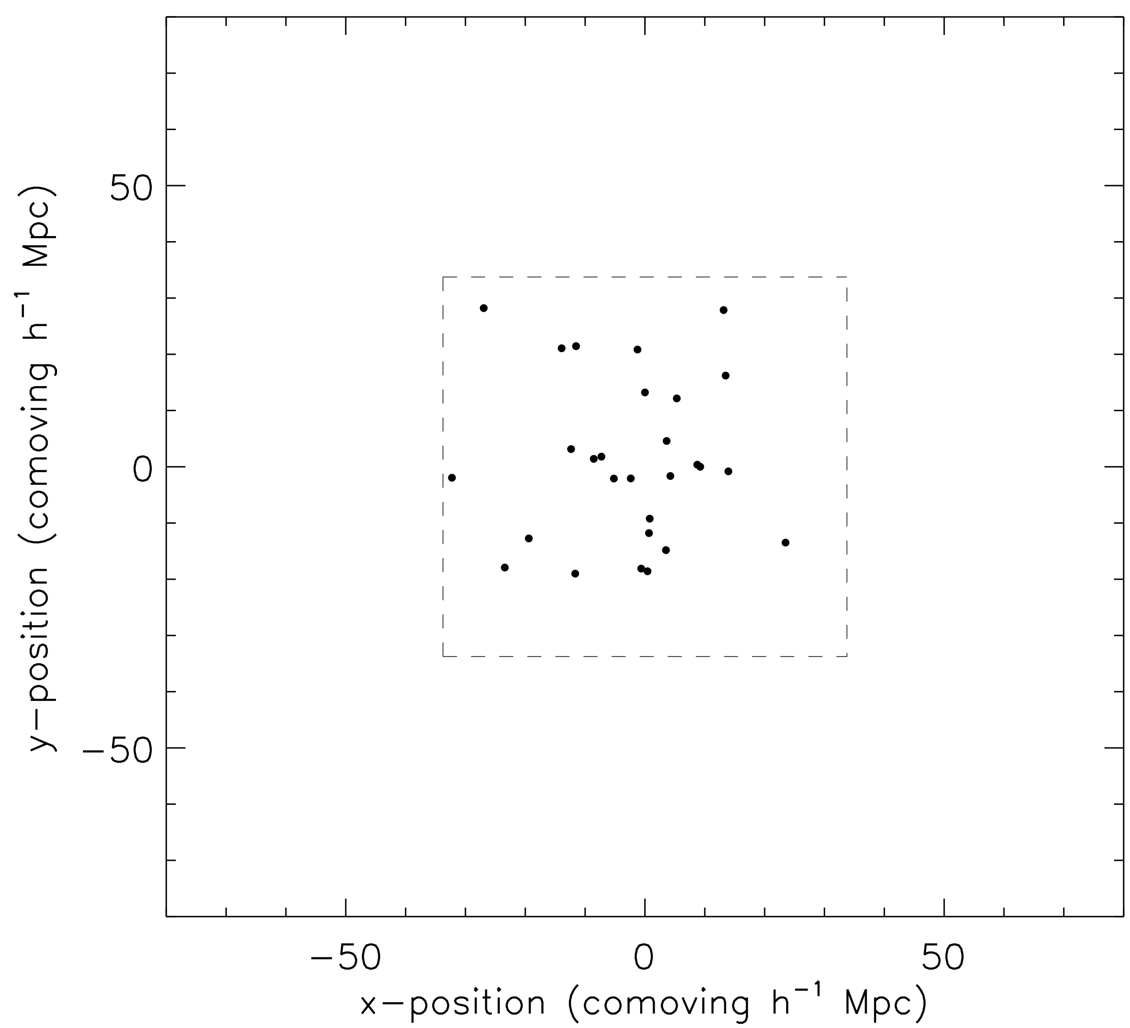
Redshifts are expensive since surface brightness goes as $(1 + z)^4$.
Going from z = 0.5 to z = 2 requires 16x more exposure time.

Local Universe
(Δv = 2000 km s^{-1} slice)



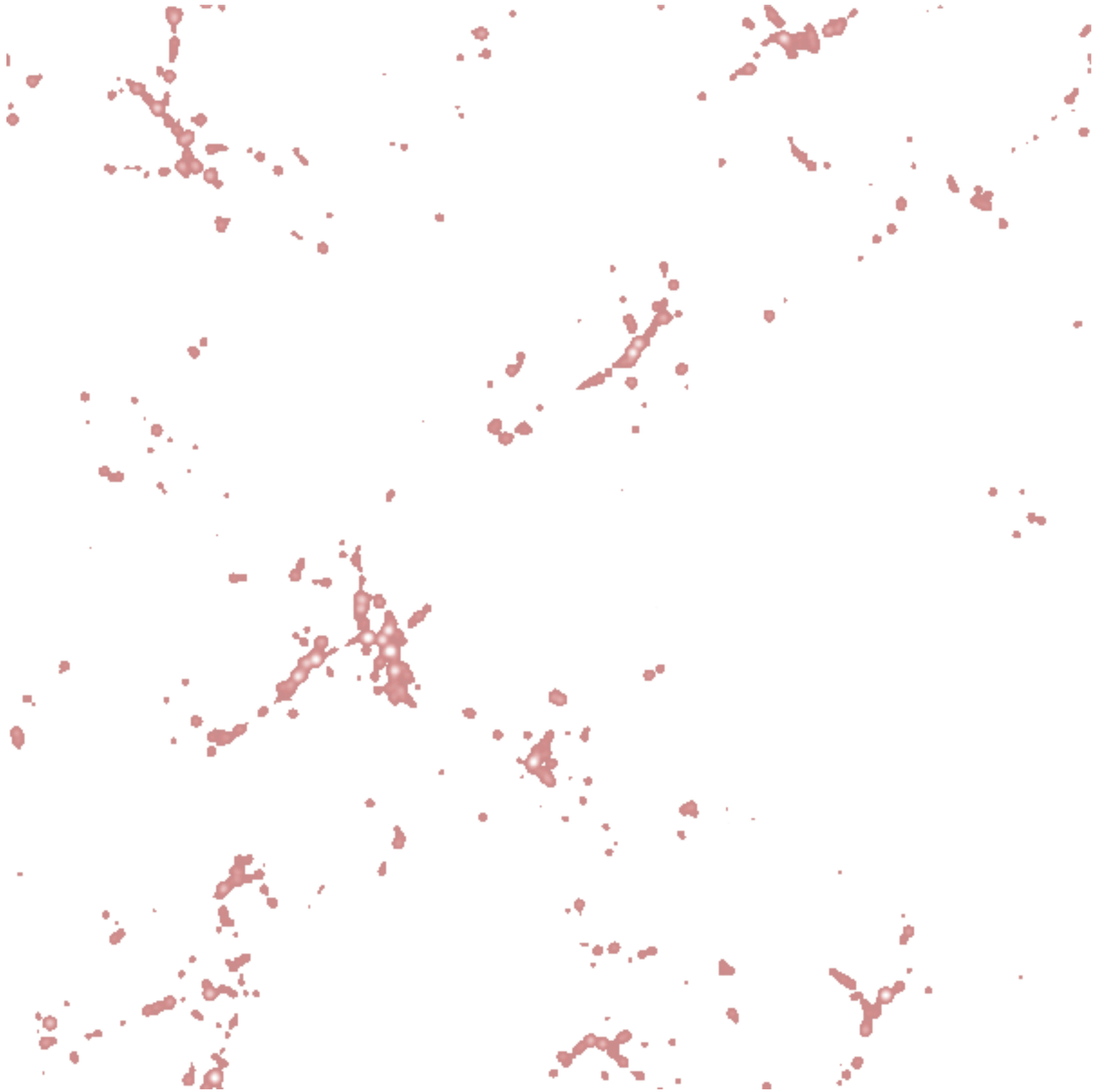
Courtois et al. 2013

COSMOS spectro-z's at z = 2.3
(Same comoving volume)

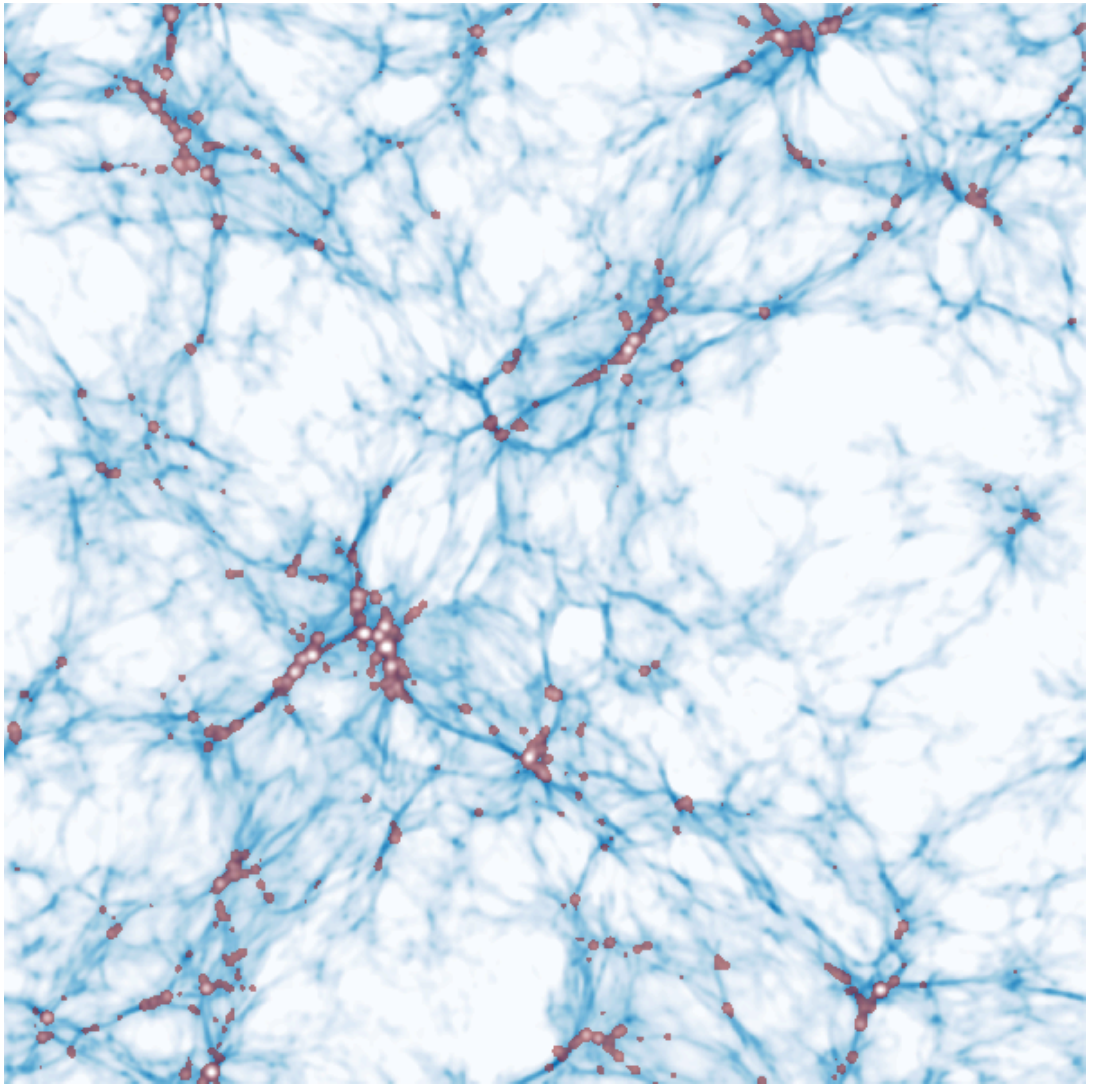


COSMOS Collaboration

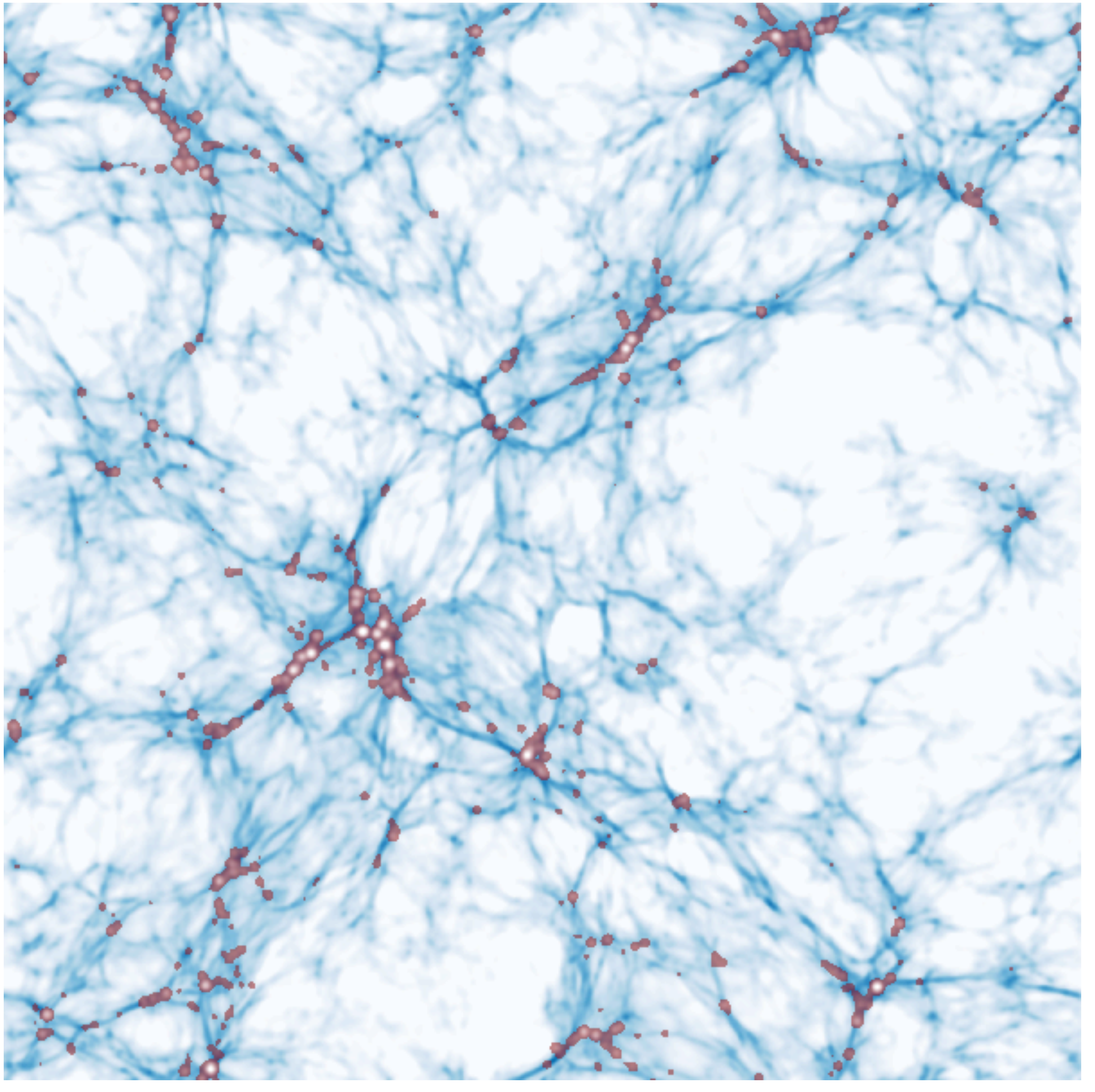
Structure in galaxies vs. IGM



Structure in galaxies vs. IGM



Structure in galaxies vs. IGM



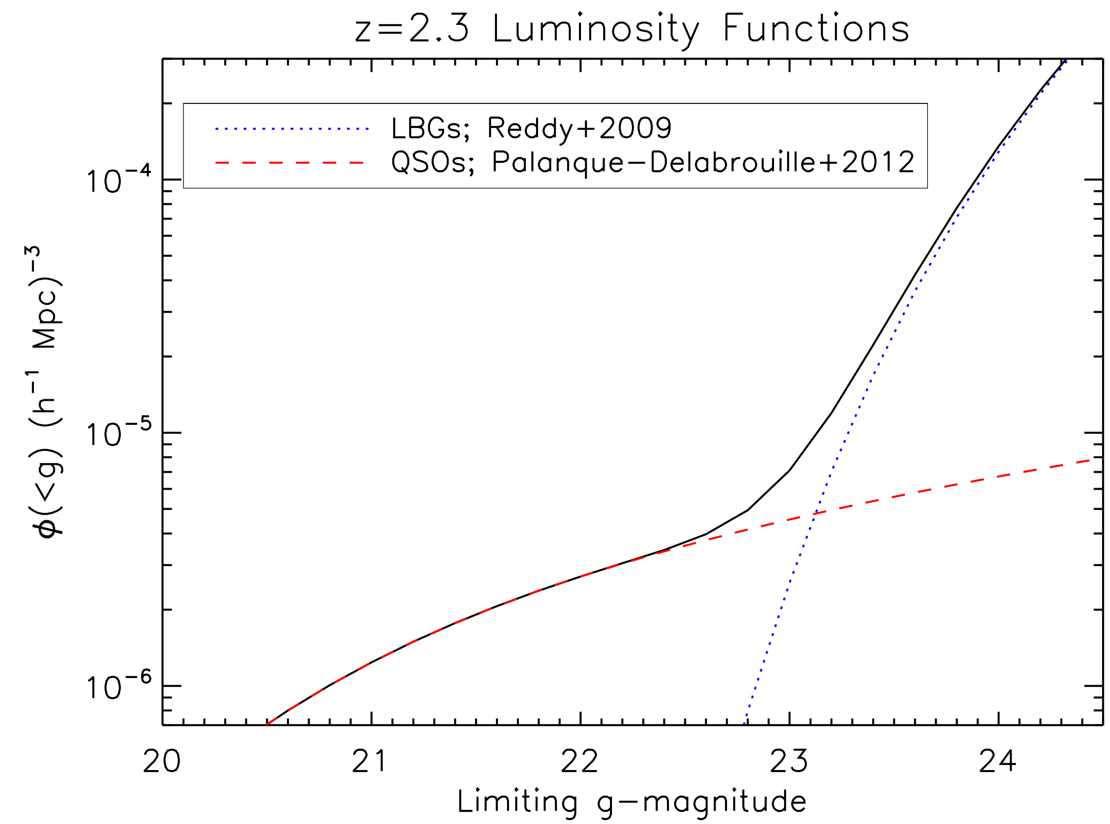
Resolving ~2 Mpc and no projection effects!

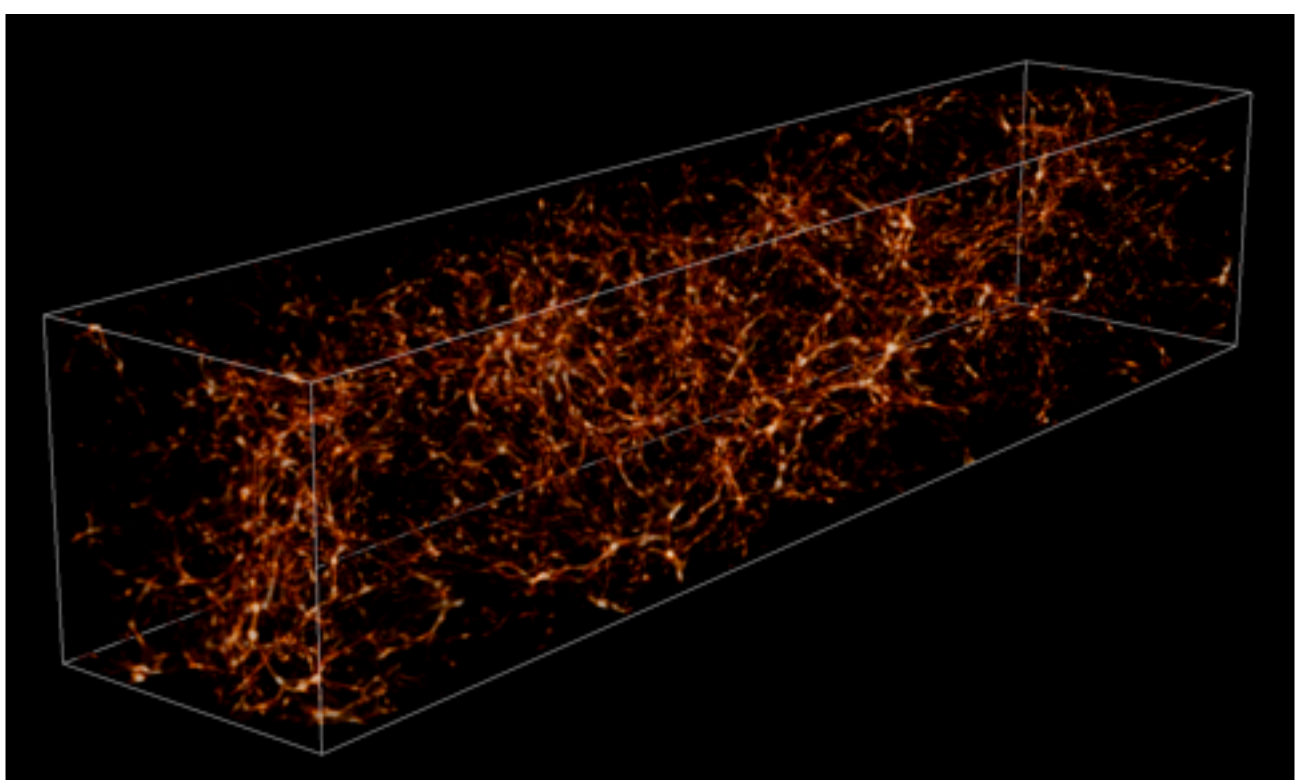
CLAMATO survey

Lyα Forest survey focused on very high sightline density.

Targeting QSO's and LBG's in COSMOS down to g = 24.7 in order to increase sightline density.

Sightline density of ~2000 per square degree, mapping 70 x 70 x 200 Mpc/h at z = 2.3.





Example of CLAMATO volume from a Nyx simulation (showing density).

Survey goal: Mpc-scale tomographic map. Previously thought to only be possible with 30m class telescopes!

Lee et al. 2014a

Reconstruction with Wiener Filtering

The Wiener filter is the minimum mean squared error estimator, assuming normal-distributed signal and known signal and noise covariances.

WF operator

$$\mathbf{m} = \mathbf{S}_{mp}(\mathbf{S}_{pp} + \mathbf{N})^{-1}\mathbf{d}$$

map

data vector

We model the correlation function as a product of two Gaussians and assume independent noise.

$$S_{ij} = \sigma_F^2 \exp\left[-\left(\frac{|\mathbf{x}_{\perp,i} - \mathbf{x}_{\perp,j}|}{l_\perp}\right)^2\right] \exp\left[-\left(\frac{x_{\parallel,i} - x_{\parallel,j}}{l_\parallel}\right)^2\right]$$

$$N_{ij} = n_i n_j \delta_{ij}$$

We want to run N = 10^6 problems regularly, so it must be fast.
Developed OpenMP-parallel implementation with $O(N^2)$ time and O(N) space complexity: github.com/caseywstark/dachshund

Previous code took 20 hrs to run $N_{pix} \sim 10^5$, now takes a few minutes.

See Pichon et al. 2001, Caucci et al. 2008, Lee et al. 2014a, Stark et al. 2014

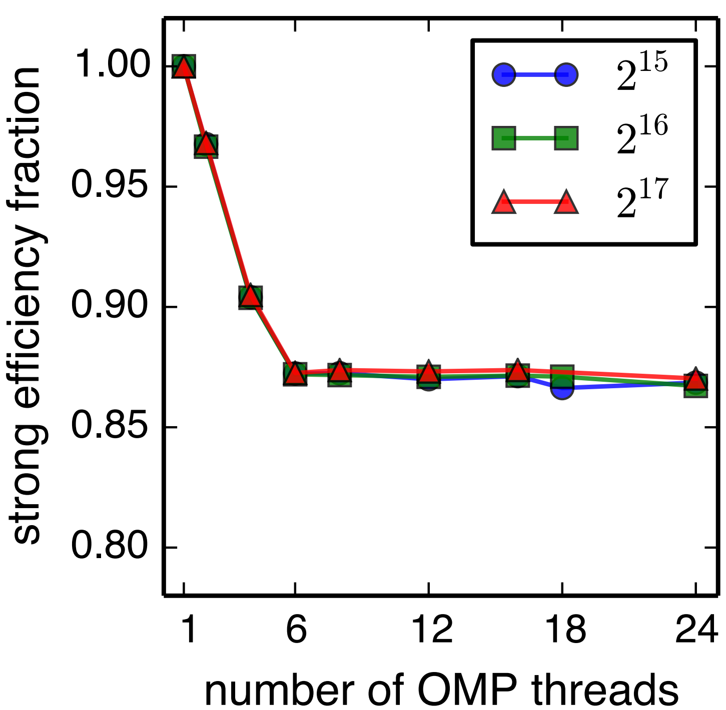
Algorithm details

WF operator broken down into:

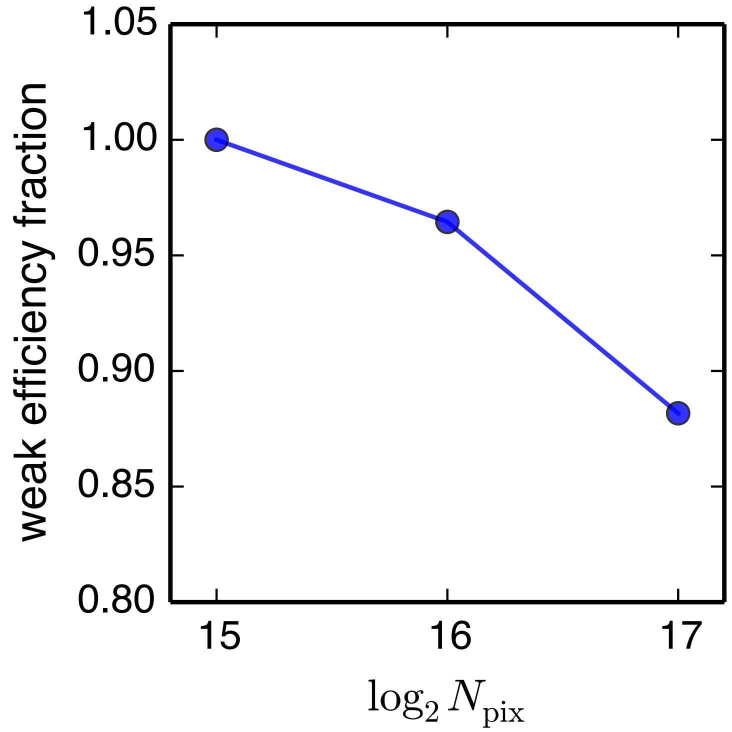
- PCG solve for $x = (S + N)^{-1} d$
- matrix-vector multiply for $m = S x$.

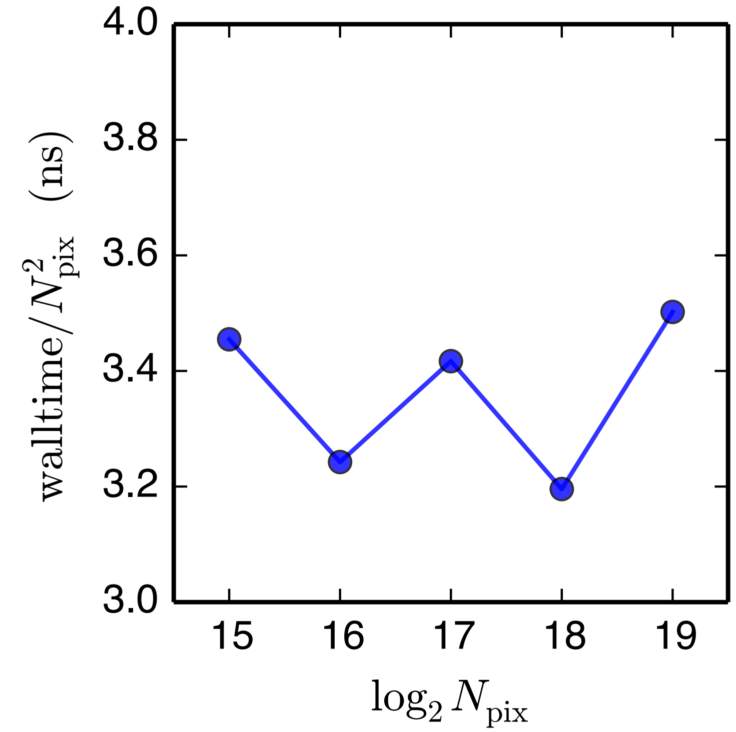
Ran mock reconstructions with:

- $\log_2 N_{pix}$ = 15, 16, ..., 19
- OMP_NUM_THREADS = 1, 2, ..., 24



NUMA boundary





24 threads,

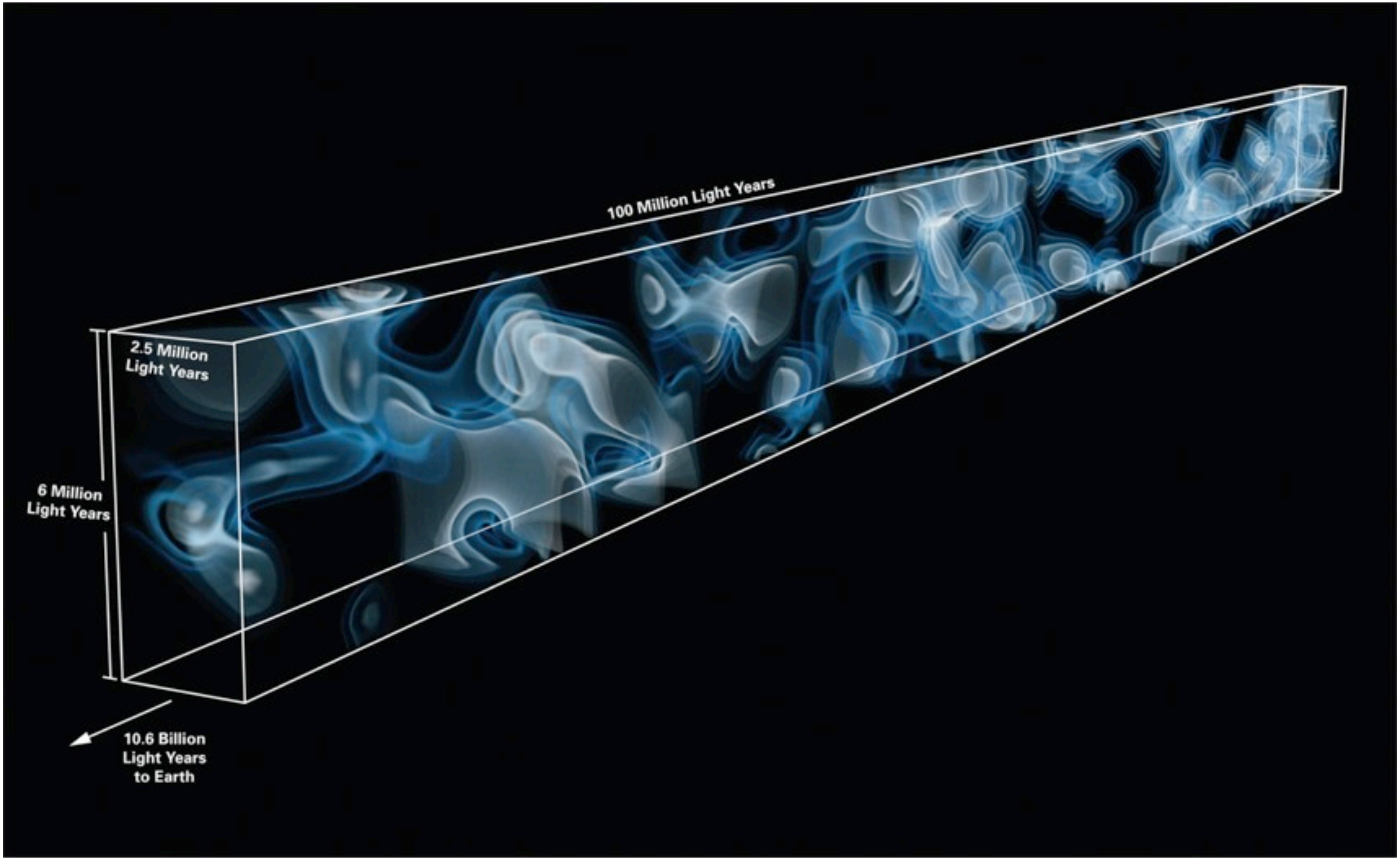
2.4 GHz,

12 or 13 PCG iterations

-> 15 cycles per element!

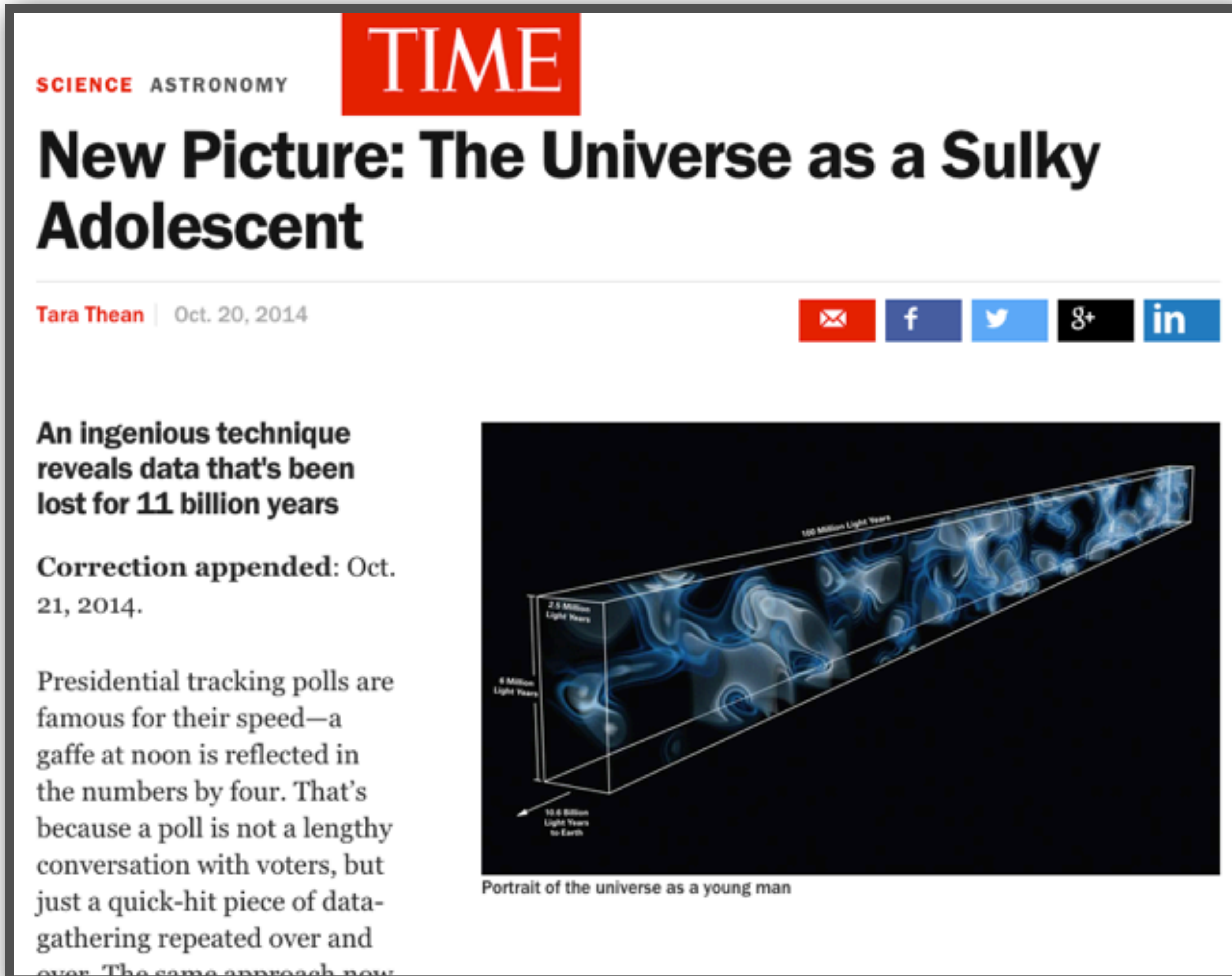
Pilot data map

4 hours on Keck LRIS got 24 sightlines to SFGs in small sky area, resulted in 6 x 14 x 230 Mpc/h map.



Lee et al. 2014b

sky area,



SCIENCE ASTRONOMY

TIME

New Picture: The Universe as a Sulky Adolescent

Tara Thean | Oct. 20, 2014

An ingenious technique reveals data that's been lost for 11 billion years

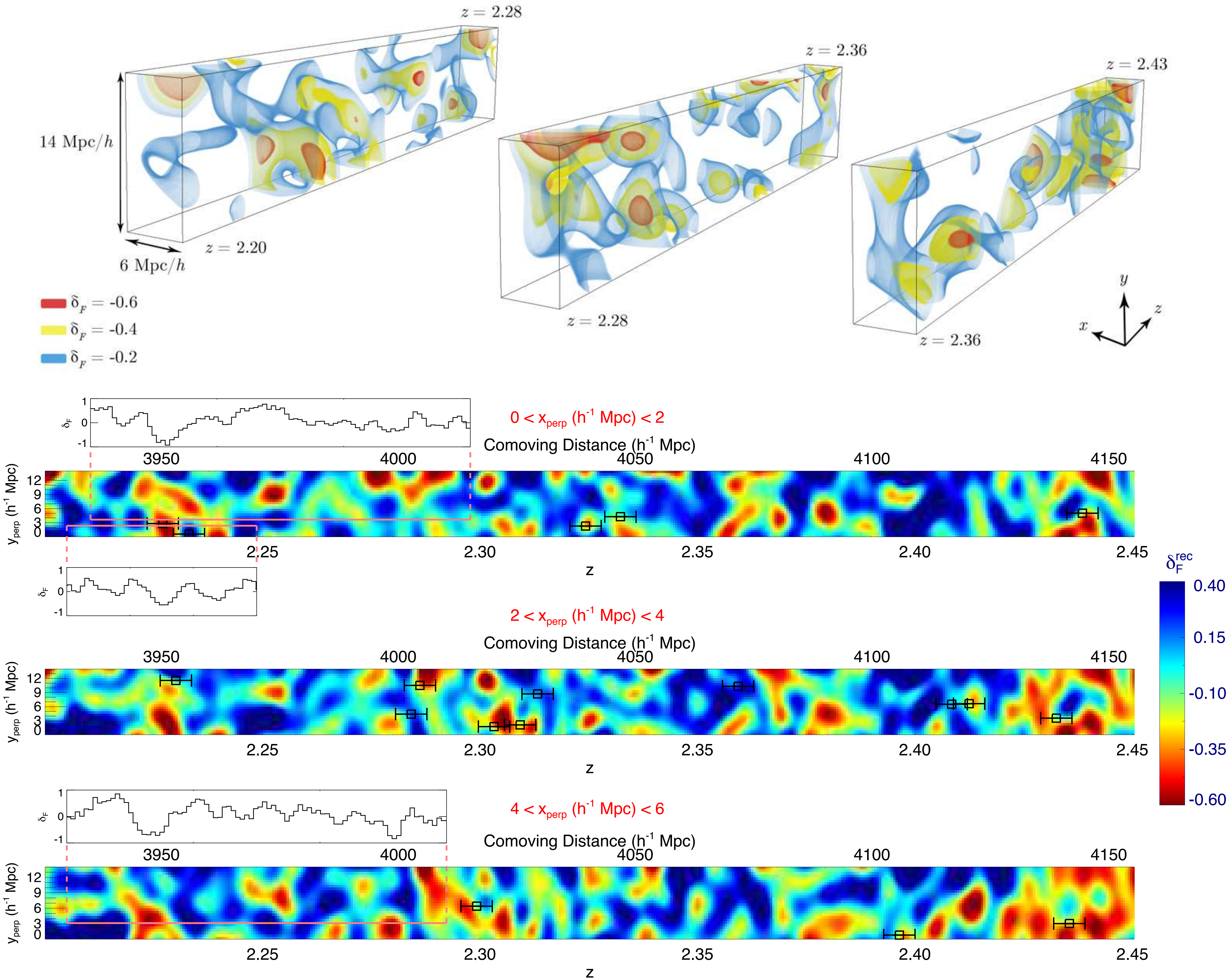
Correction appended: Oct. 21, 2014.

Presidential tracking polls are famous for their speed—a gaffe at noon is reflected in the numbers by four. That's because a poll is not a lengthy conversation with voters, but just a quick-hit piece of data-gathering repeated over and over. The same approach now

Portrait of the universe as a young man

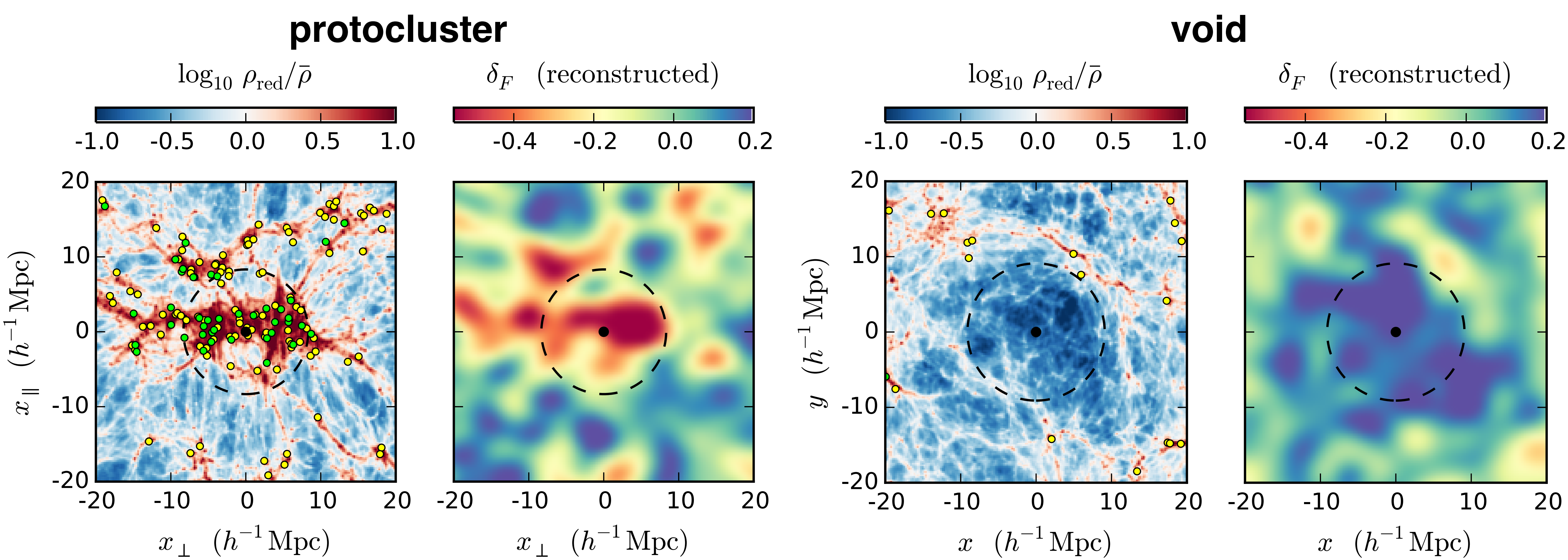
Lee et al. 2014b

Pilot data map



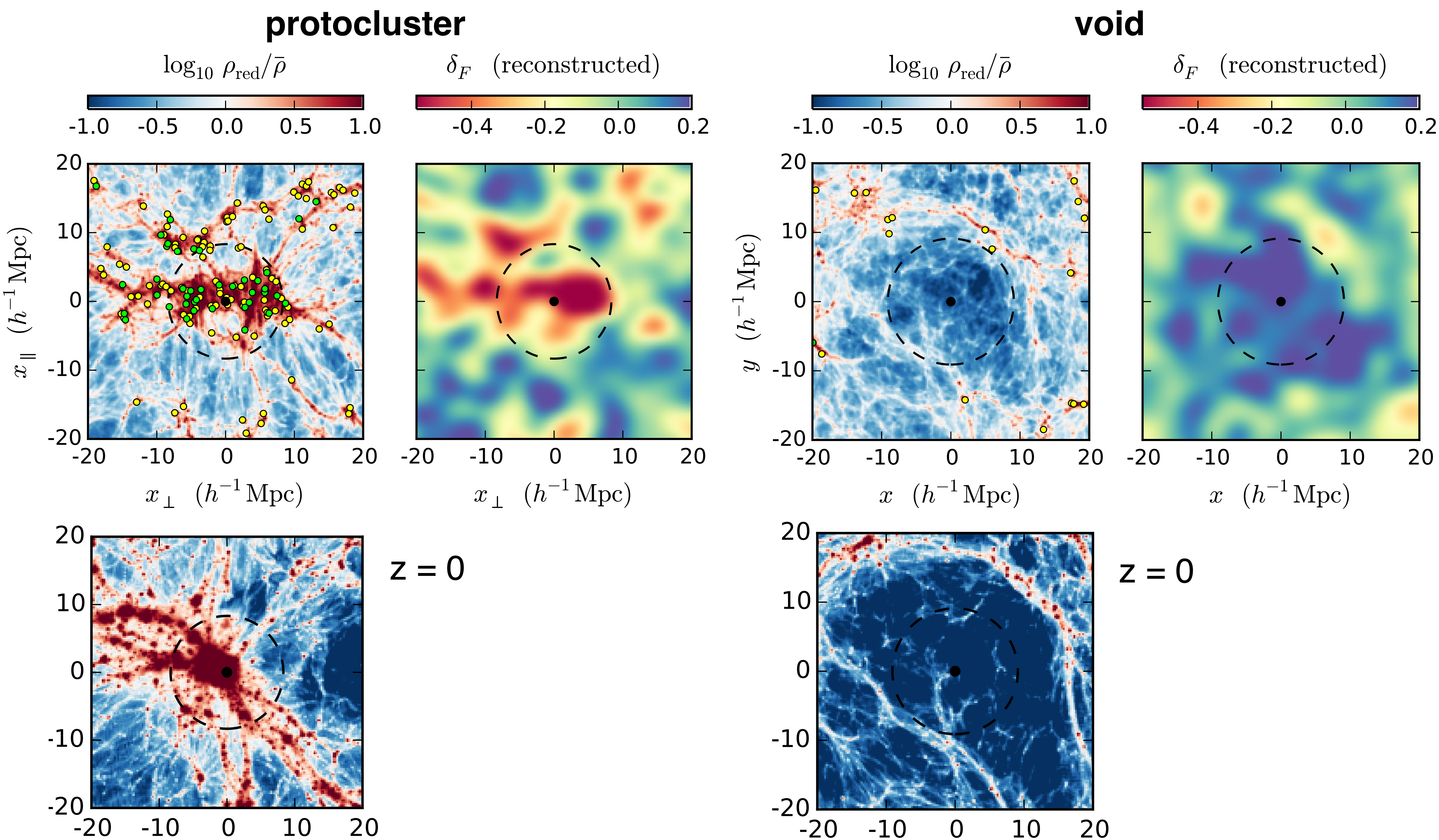
Lee et al. 2014b

Large-scale structure in tomographic maps



halos with M > 10^{12} Msun/h in green and M > 3 x 10^{11} Msun/h in yellow.

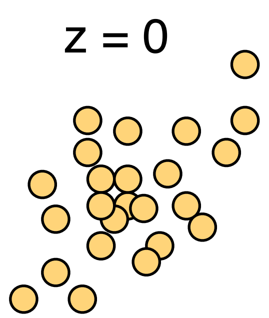
Large-scale structure in tomographic maps



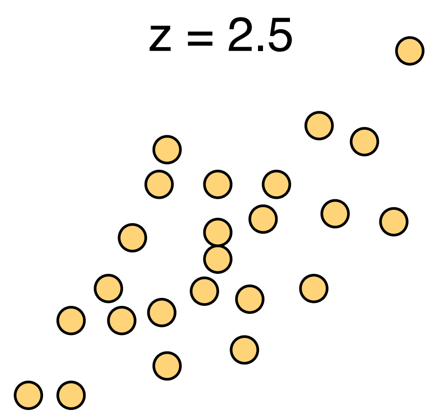
halos with M > 10^{12} Msun/h in green and M > 3 x 10^{11} Msun/h in yellow.

Finding Protoclusters

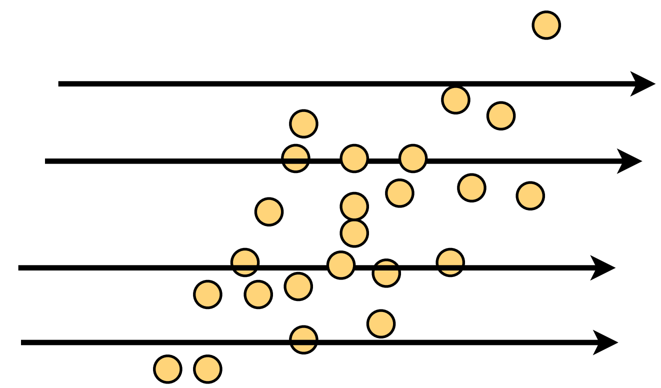
Use N-body simulation snapshots at z = 0 and z = 2.5 to find progenitors of most massive objects today.



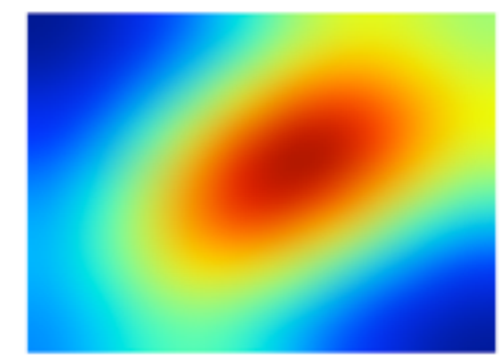
find massive FOF halos at low redshift



find progenitor at high redshift



sample flux and reconstruct



search flux field for PC signal

compare to PC catalog

Simple method:

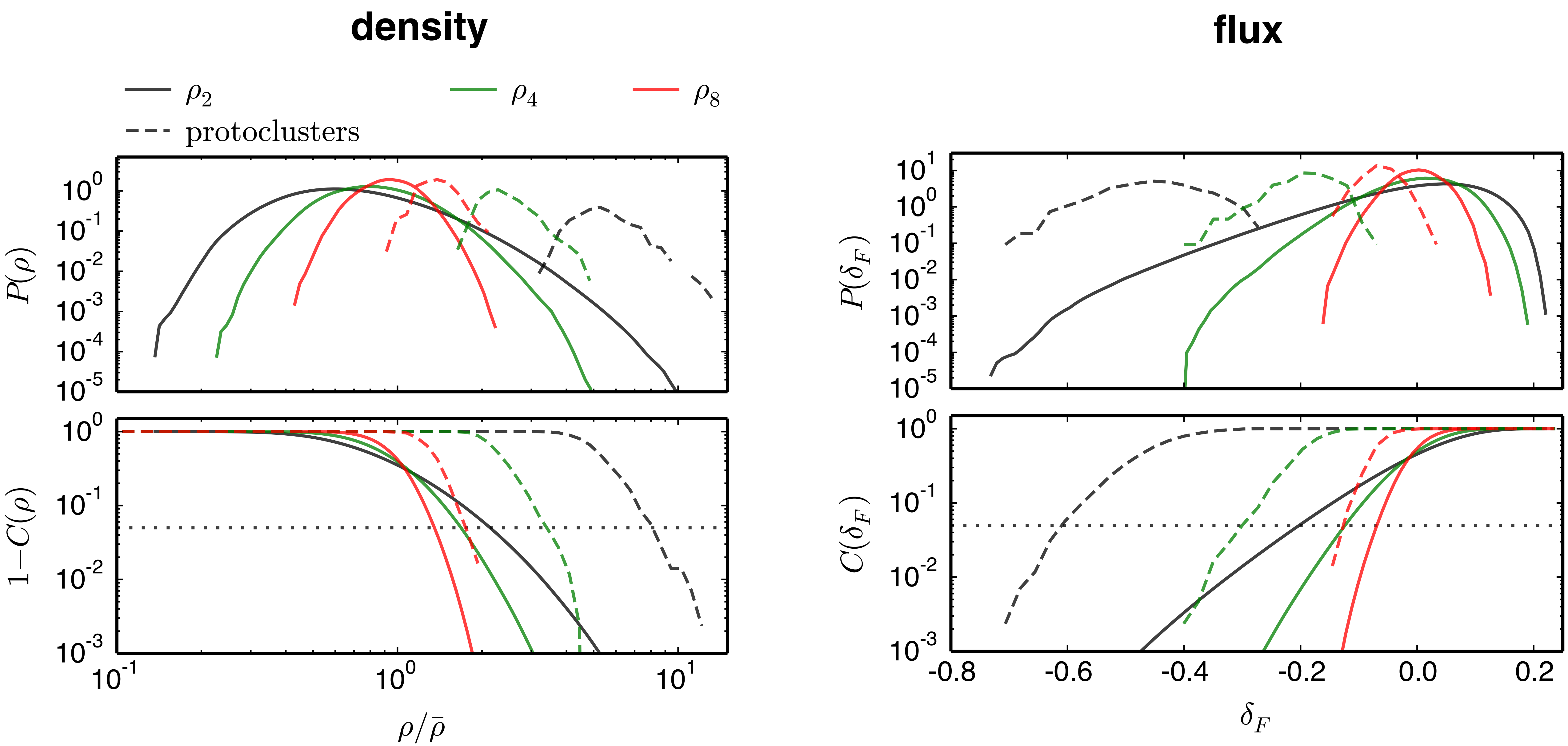
- Smooth tomographic map (crude matched filter).
- Select points above given threshold.
- Group nearby points.

Not even taking map covariance into account!

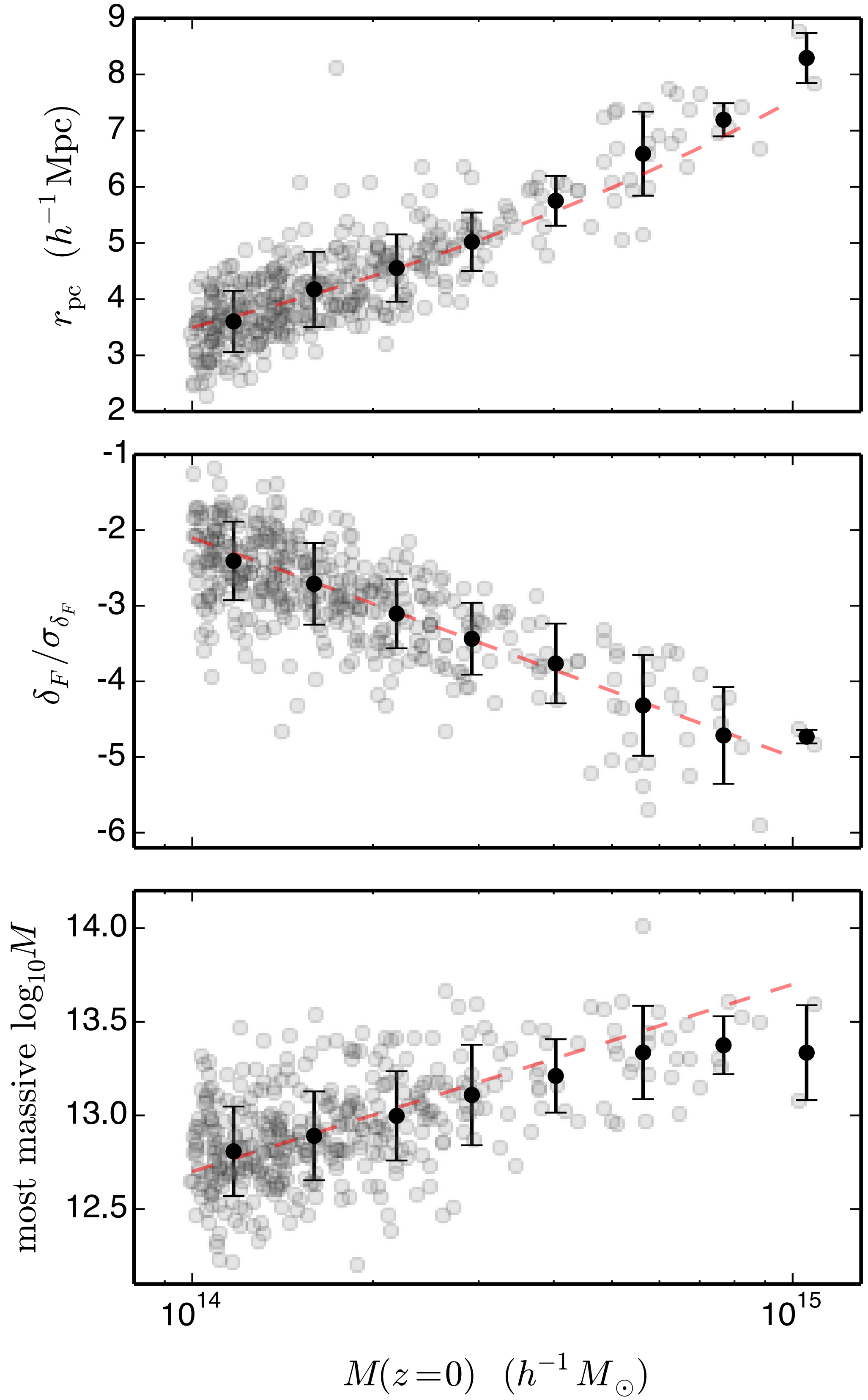
also see Chiang et al. 2013, Cai et al. 2014

Protoclusters in density and flux

Significant outliers in density and flux (as seen in different smoothings).



Protocluster trends with mass

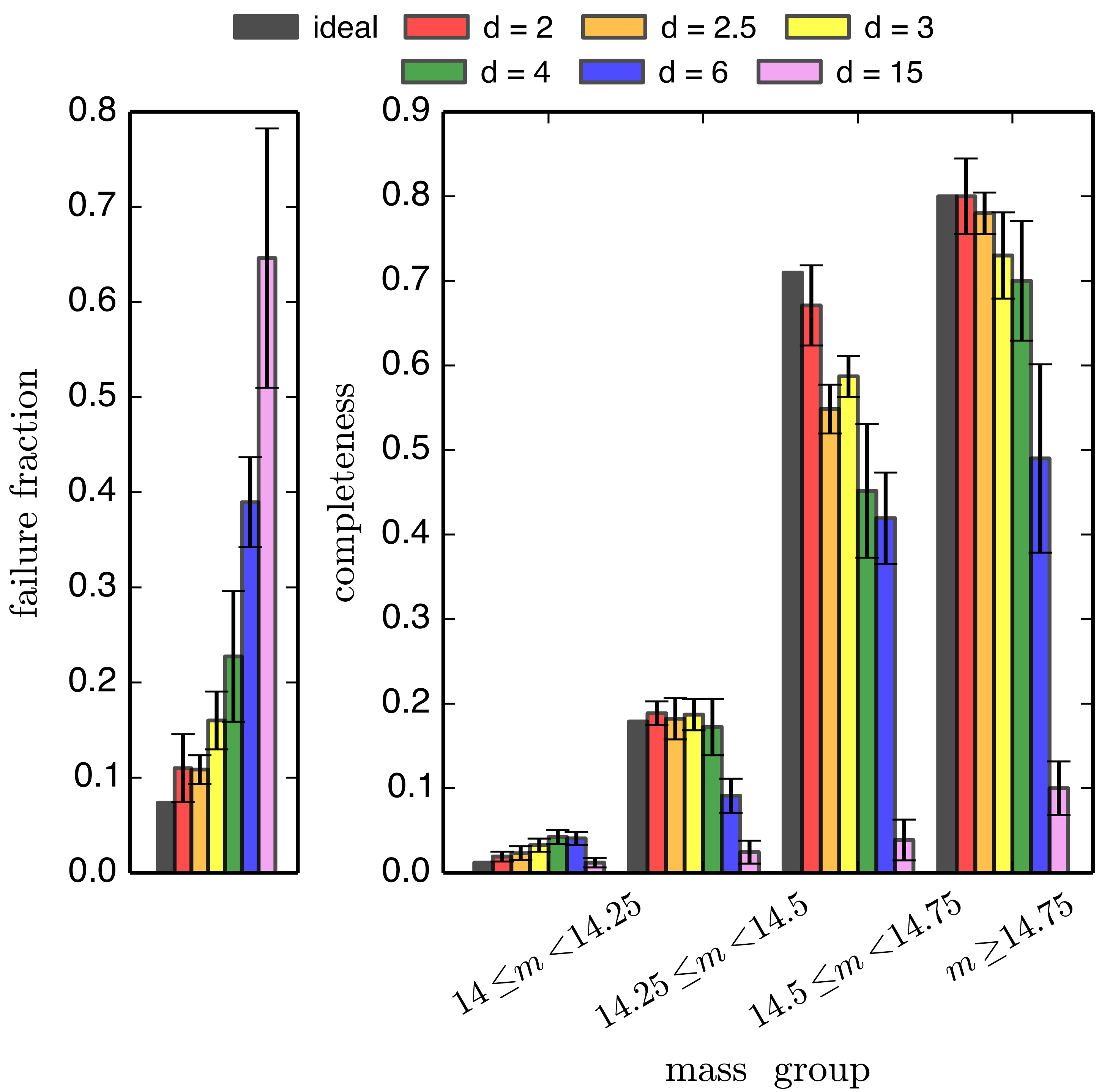


Progenitors of more massive clusters start larger,

create larger flux decrements,

and host more massive halos, likely making follow up easier.

Protocluster sample forecast



Ran mock surveys and reconstructions with various sightline spacings d = 2 to 15 Mpc/h, with 5 realizations each.

Compared to what was found in noiseless map and mock maps to full protocluster sample.

Result: simple protocluster identification method finds 70% of the massive protoclusters with 90% purity.

Void finding

Spherical underdensity

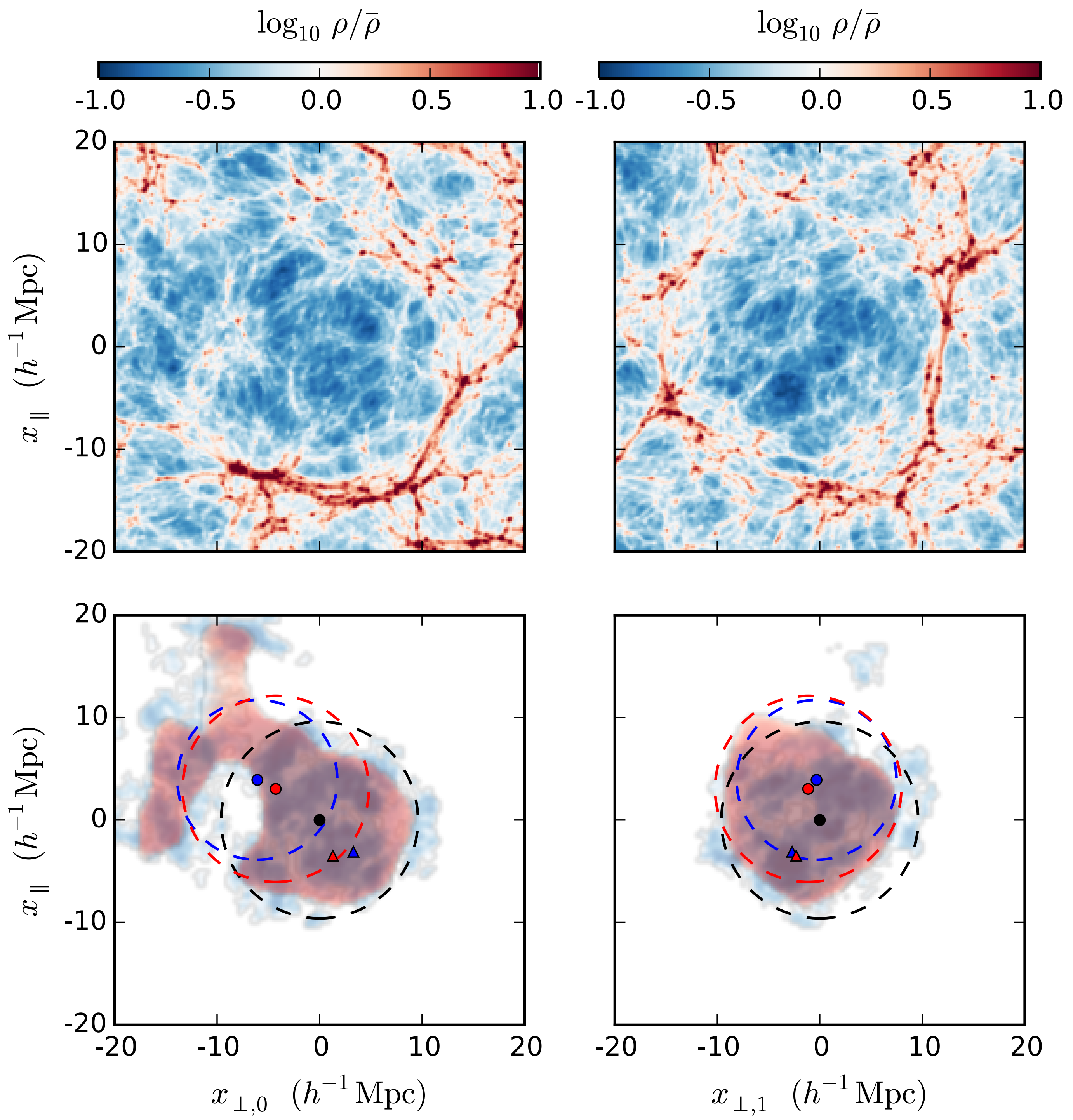
- Grow spheres around points under threshold. Stop growth based on enclosed average or value at edge.
- Handle overlaps, e.g. take largest and discard others.

Watershed (e.g. ZOBOV)

- Find point under threshold and add neighbors also under threshold.

Hessian

- Compute the eigenvalues of the Hessian of the gravitational potential.
- A point is a part of a void if there are no positive eigenvalues.
- Group points.

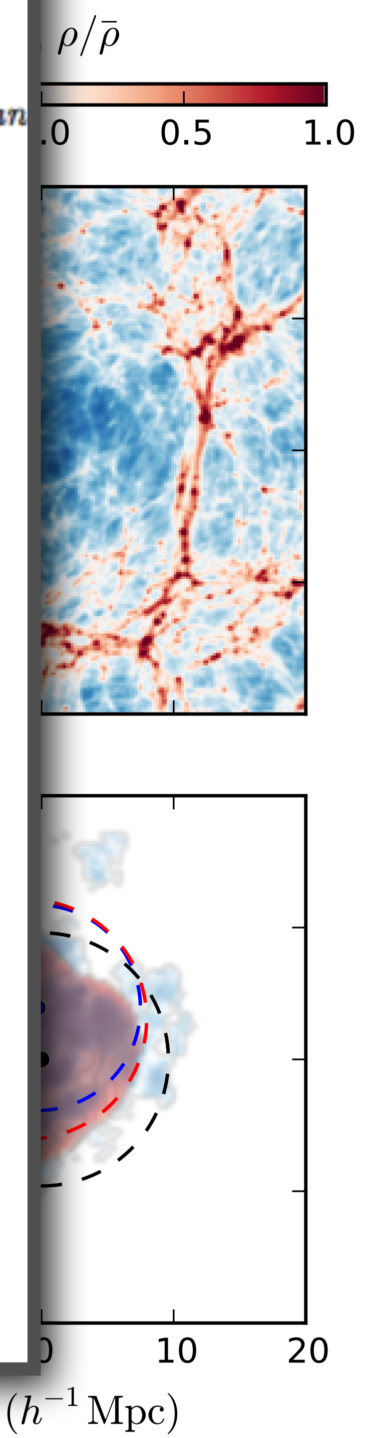


The nature of voids: I. Watershed void finders and their connection with theoretical models

S. Nadathur[1⋆] & S. Hotchkiss[2]
[1]Department of Physics, University of Helsinki and Helsinki Institute of Physics, P.O. Box 64, FIN-00014, University of Helsinki, Finlan
[2]Department of Physics and Astronomy, University of Sussex, Falmer, Brighton, BN1 9QH, UK

27 April 2015

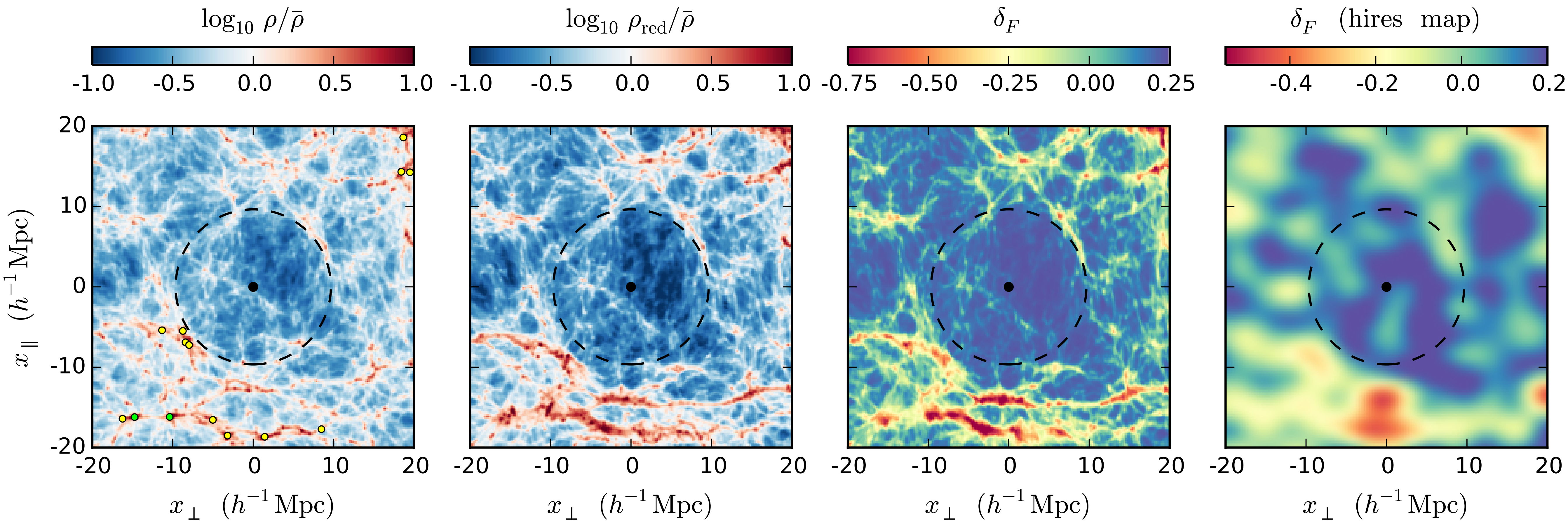
ABSTRACT
The statistical study of voids in the matter distribution promises to be an important tool for precision cosmology, but there are known discrepancies between theoretical models of voids and the voids actually found in large simulations or galaxy surveys. The empirical properties of observed voids are also not well understood. In this paper we study voids in an N-body simulation, using the ZOBOV watershed algorithm. As in other studies, we use sets of subsampled dark matter particles as tracers to identify voids, but we use the full-resolution simulation output to measure dark matter densities at the identified locations. Voids span a wide range of sizes and densities, but there is a clear trend towards larger voids containing deeper density minima, a trend which is expected for all watershed void finders. We also find that the tracer density at void locations is smaller than the true density, and that this relationship depends on the sampling density of tracers. We show that fitting functions given in the literature fail to match the density profiles of voids either quantitatively or qualitatively. The average enclosed density contrast within watershed voids varies widely with both the size of the void and the minimum density within it, but is always far from the shell-crossing threshold expected from theoretical models. Voids with deeper density minima also show much broader density profiles. We discuss the implications of these results for the excursion set approach to modelling such voids.



- Group points.

Void finding

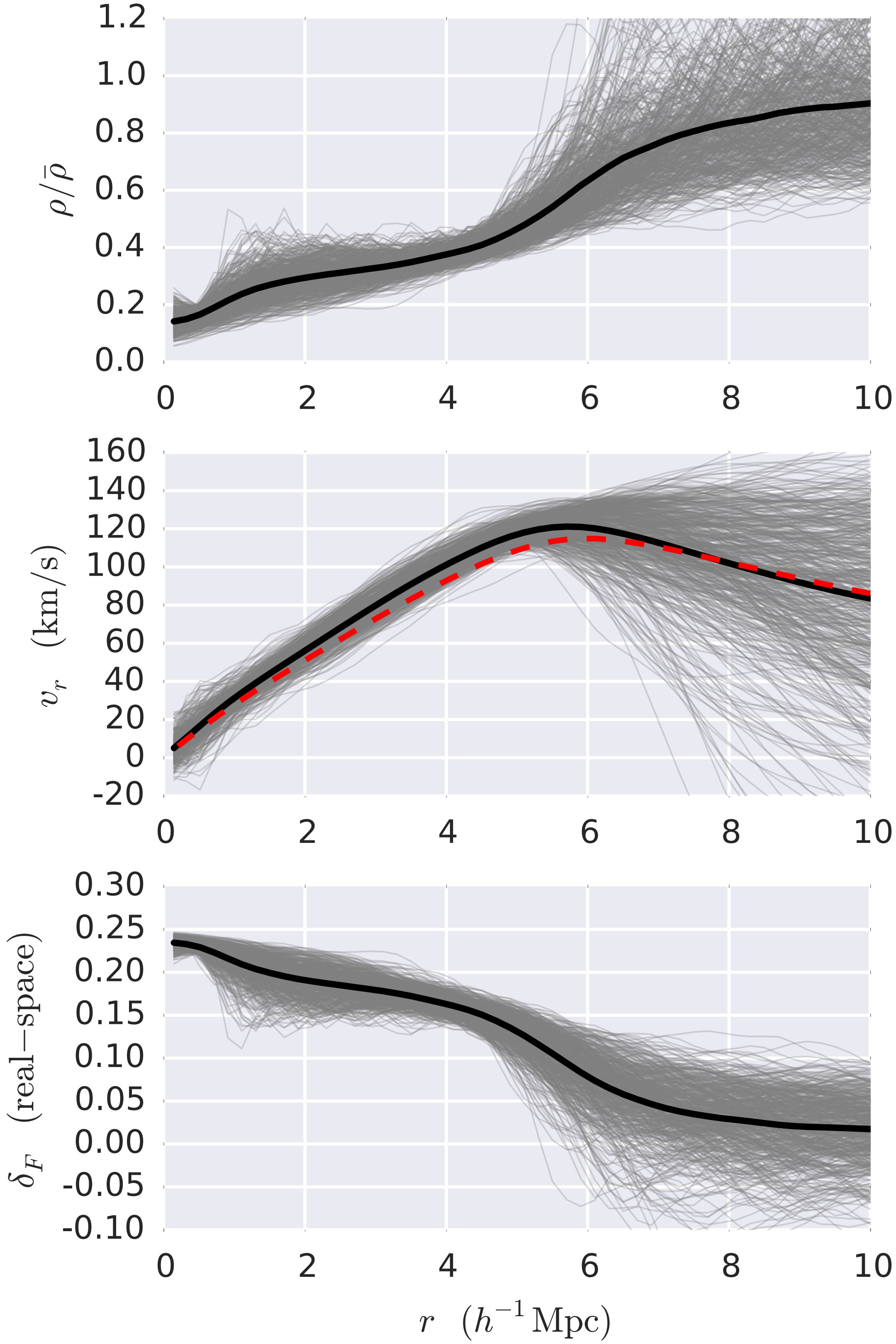
SO finder example in density, flux, and tomographic map.



Even with deep integrations, galaxies can't possibly trace the same structure.

High-redshift voids

Individual and stacked radial profiles of 5 Mpc/h < r < 6 Mpc/h voids.

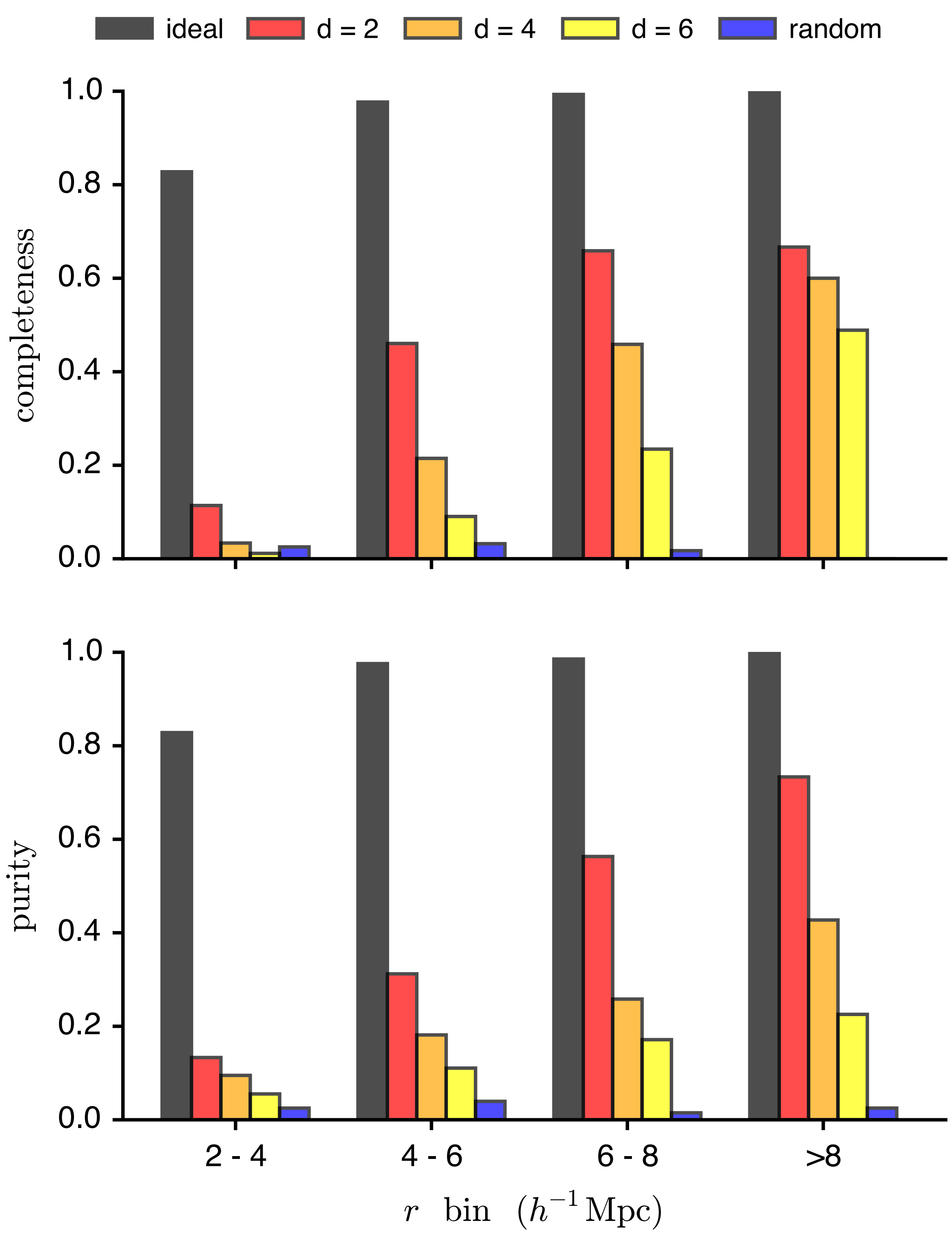


High-redshift voids are significantly underdense, but have a steeper profile than low-redshift counterparts.

Radial velocity profiles with small scatter, close to linear theory.

and similarly transmissive...

Void sample forecast



Ran SO void finder on the same mock maps, now tuned for flux.

Matched void catalogs found in density and flux based on the cut

$$\epsilon = \frac{\sqrt{(r_A - r_B)^2 + |\vec{x}_A - \vec{x}_B|^2/3^2}}{r_A} < 0.3$$

Hires map (CLAMATO-like) gives about 60% completeness with 60% purity for large voids.

Likely a lower bound for performance as we don't make use of covariance.

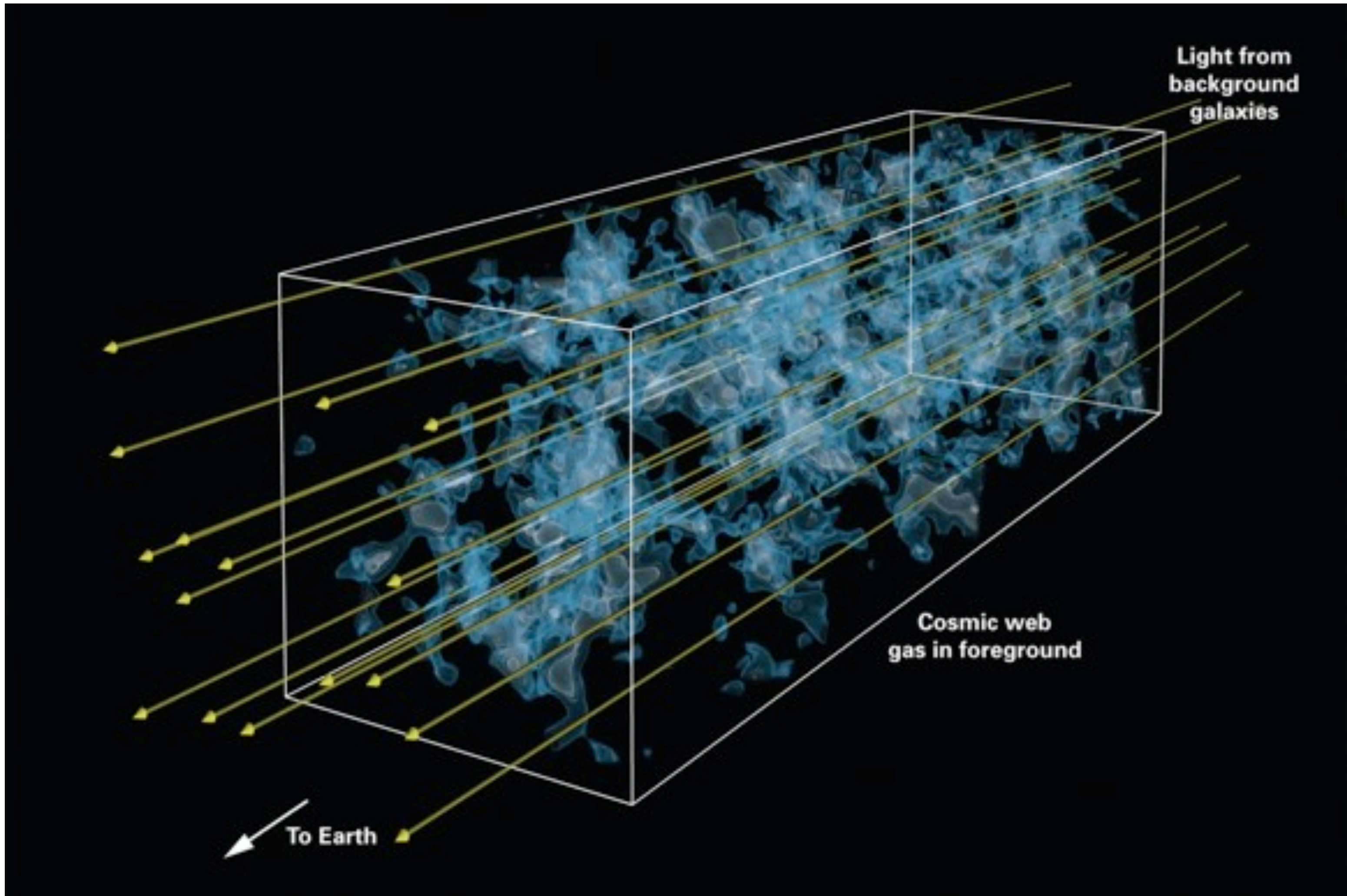
Summary

Developed high-performance tomographic reconstruction code designed to handle large numbers of pixels. Used for first Mpc-scale map at z > 2!

Used large N-body simulation to characterize protocluster and void signals in tomographic maps.

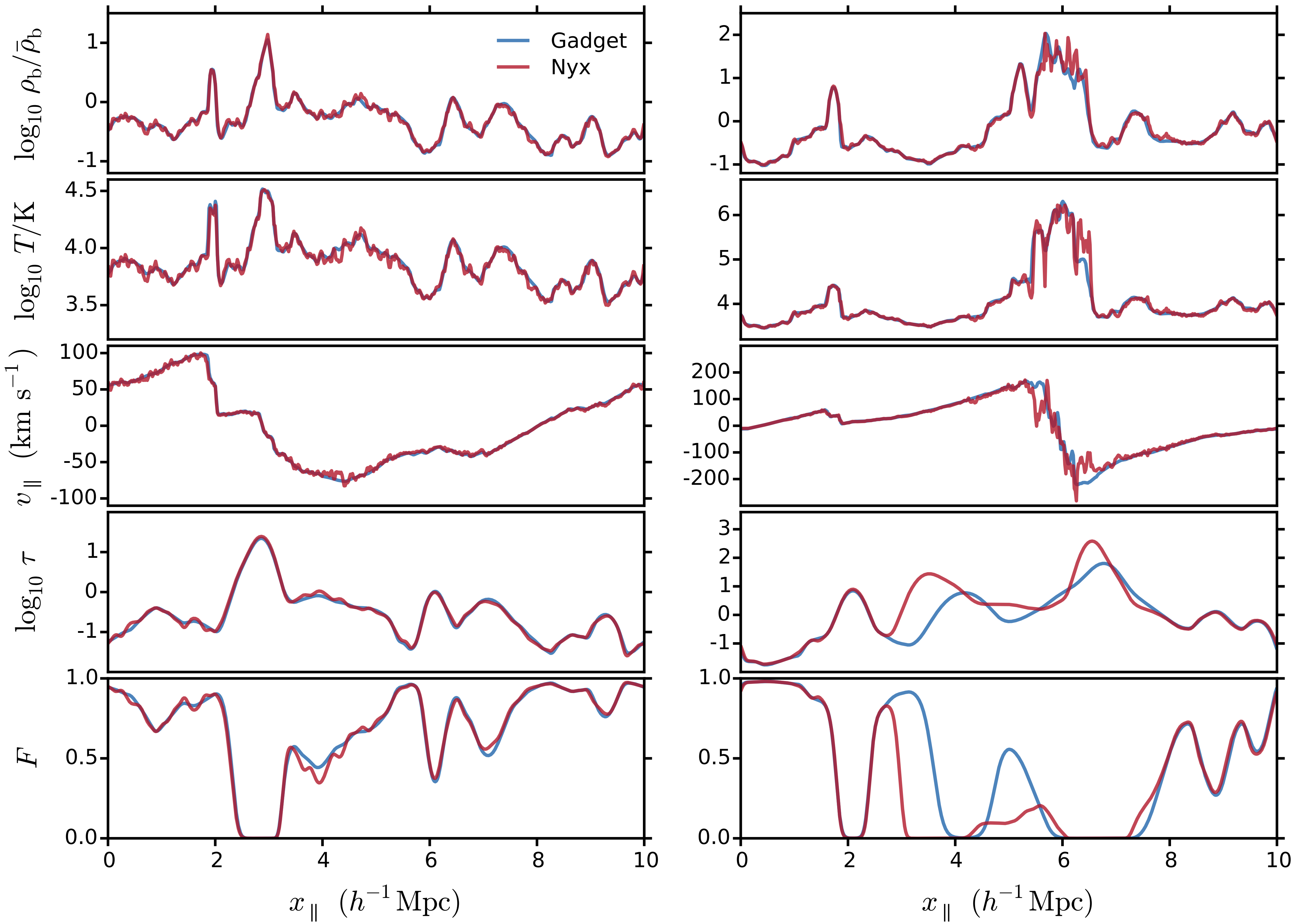
Mock surveys and reconstructions similar to ongoing CLAMATO survey demonstrated Lyα forest tomography is a promising tool for finding protoclusters and voids at z > 2.

Final CLAMATO map covering 1 deg^2 will have the volume and resolution to provides samples of 5 - 10 protoclusters and 90 voids.

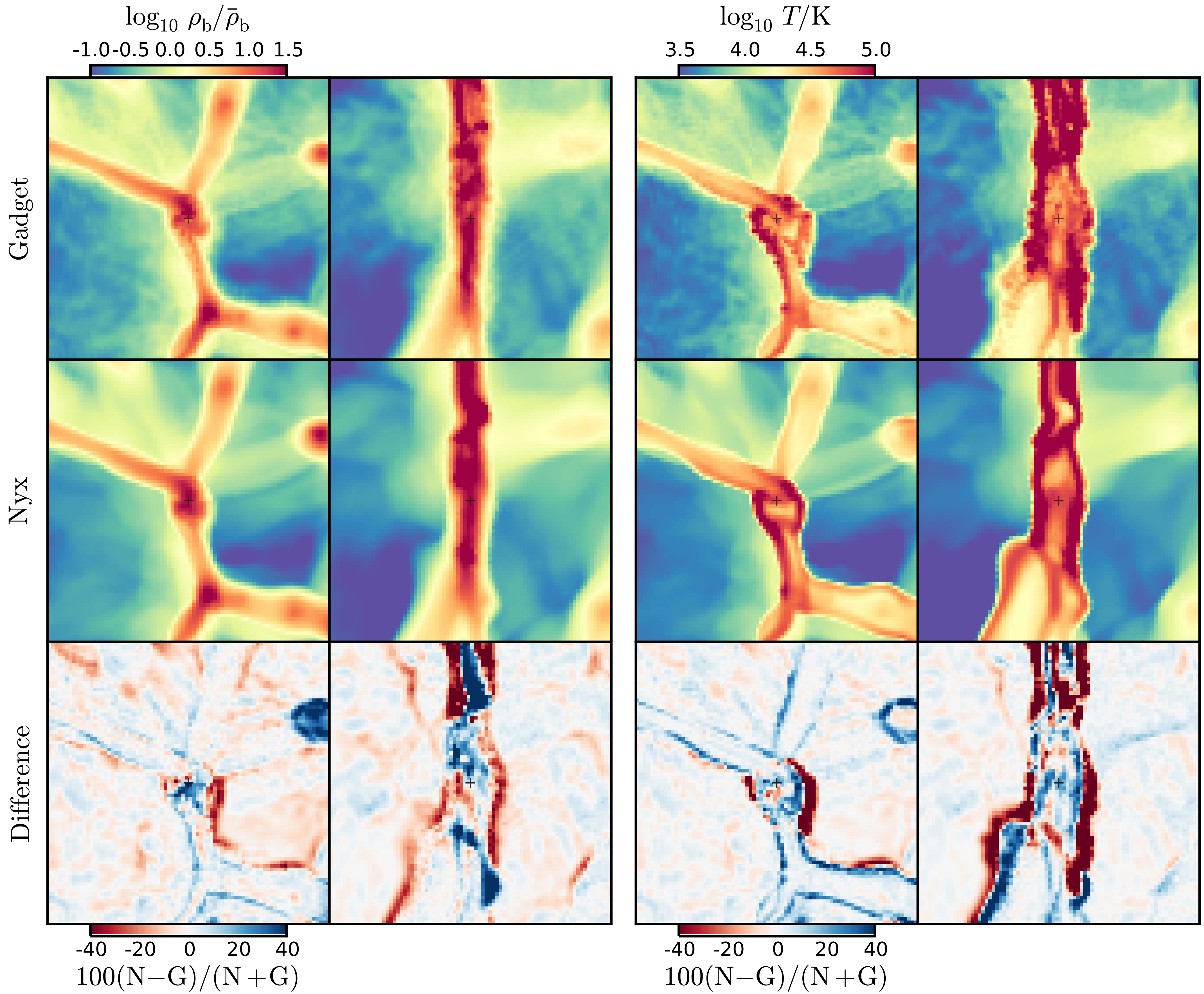


Nyx-Gadget Comparison

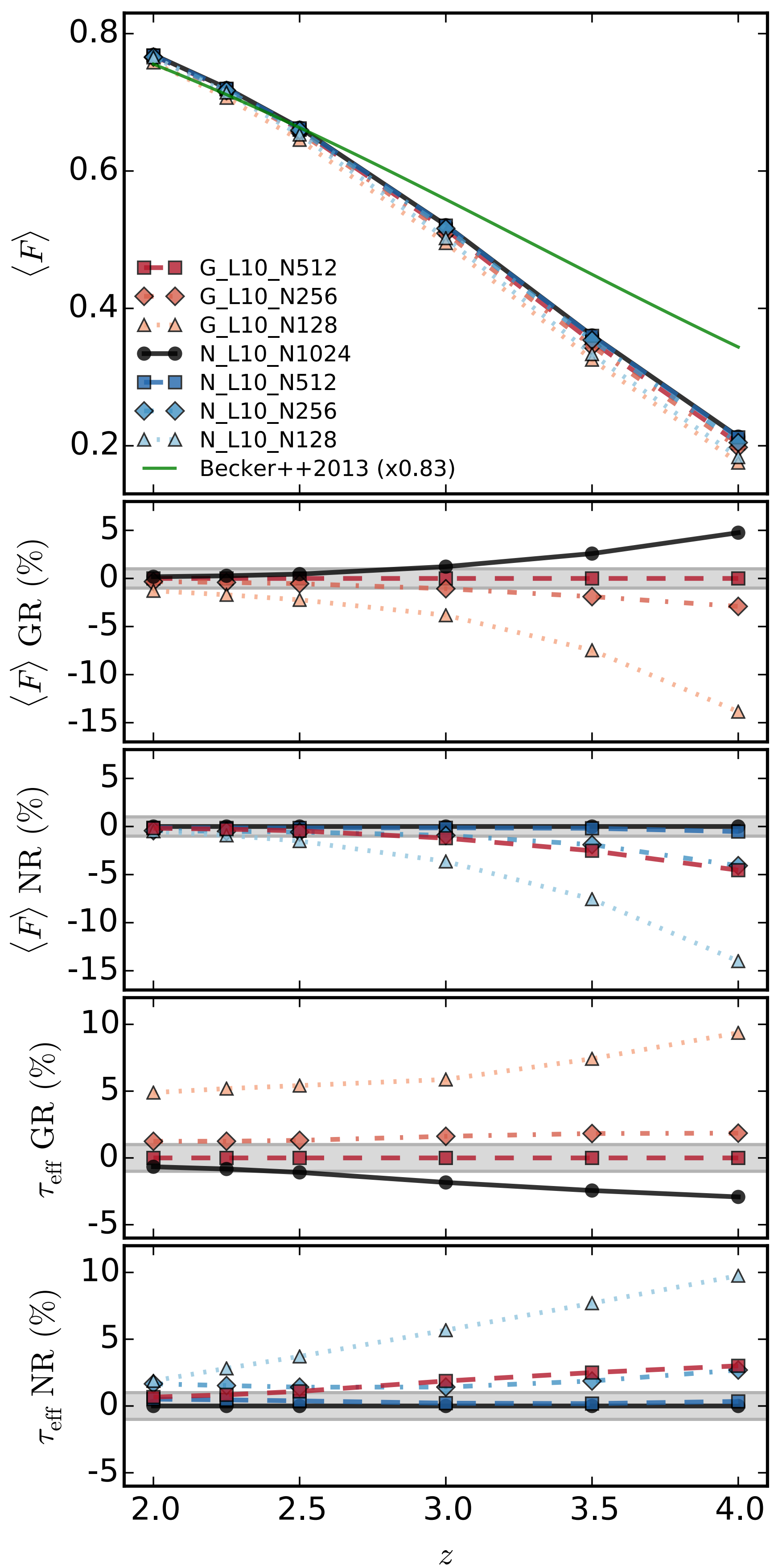
Using same initial conditions, cosmology, atomic rates, UVB rates.



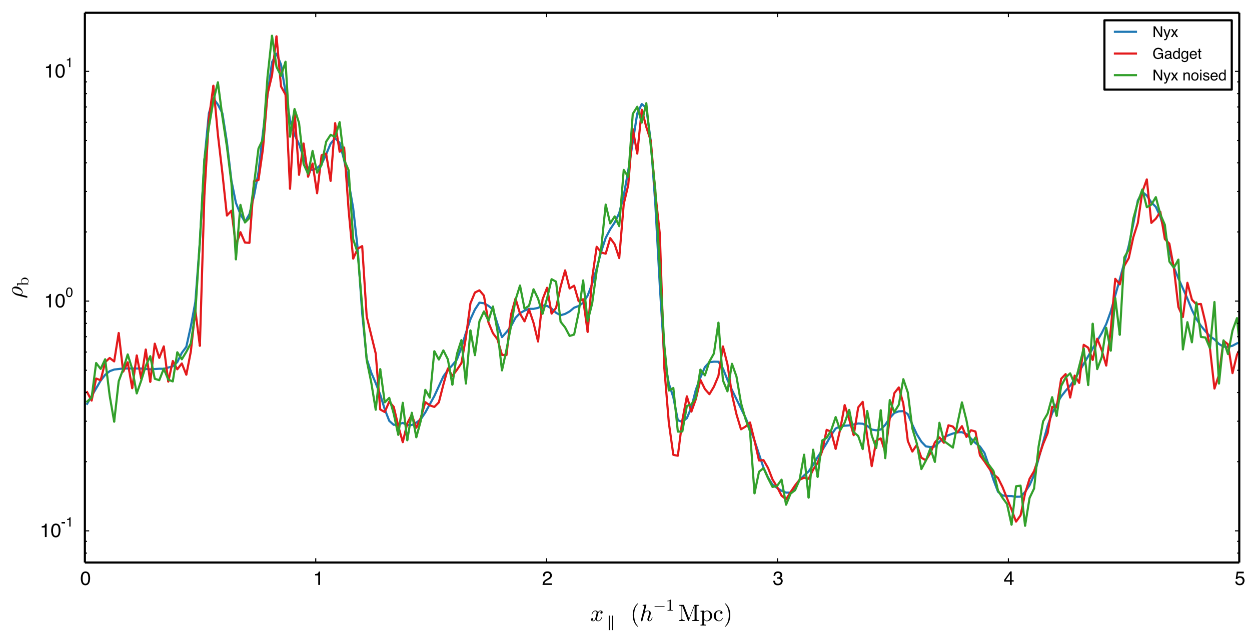
Filament comparison



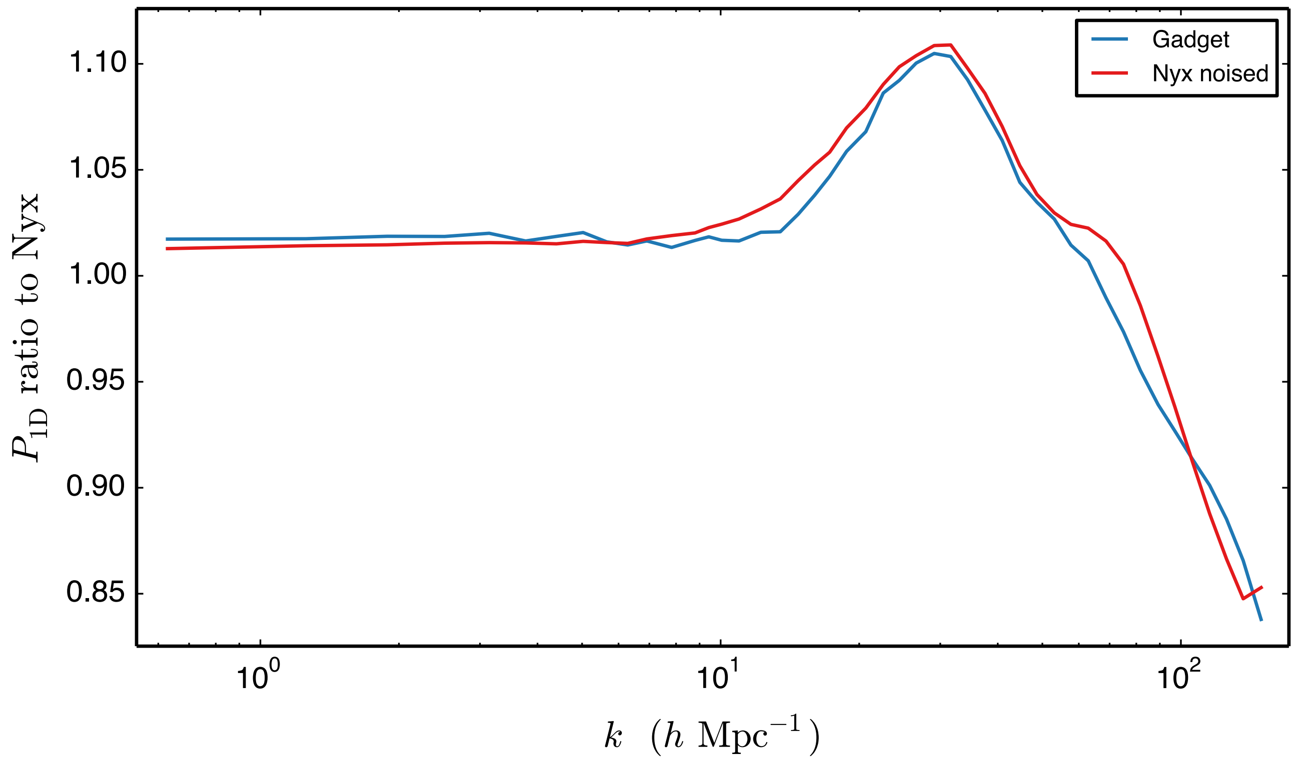
Mean flux evolution



Particle noise



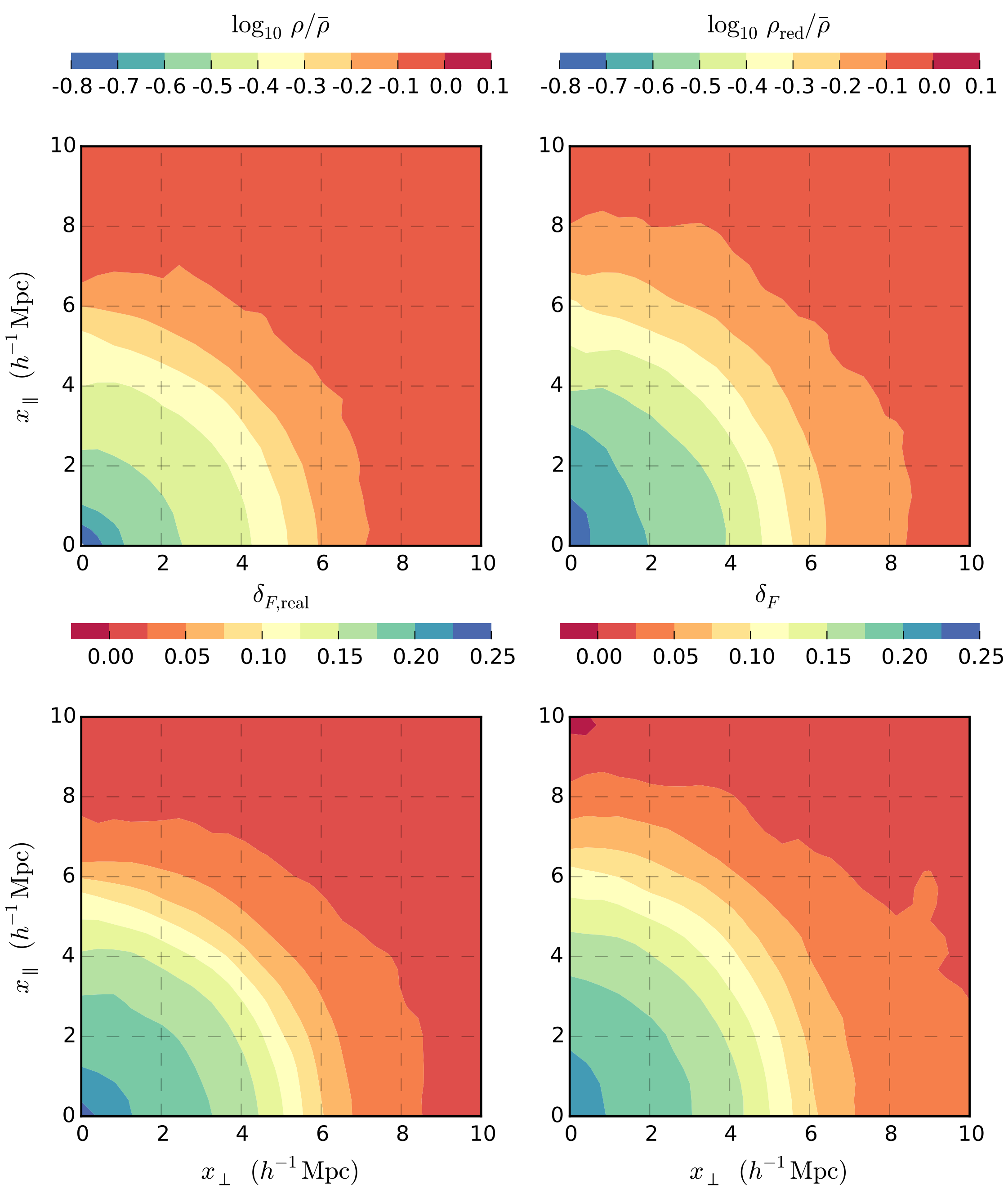
Took Nyx z = 4 data and added Gaussian random noise to density field.

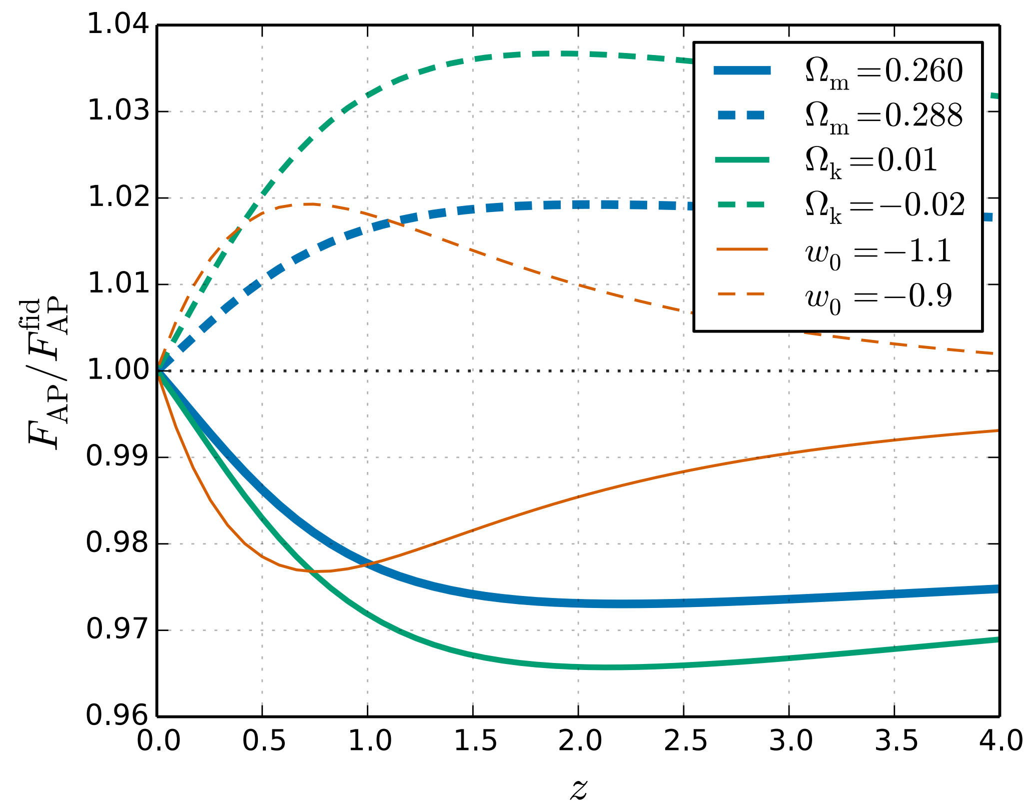


Nyx <F> = 0.1475
Gadget <F> = 0.1446
Nyx noised <F> = 0.1446

Void cosmology

Stack of about 500 voids.





Current BOSS measurements at about 5%.

Ignoring systematics in shape measurements...

$$\frac{\sigma_{\rm AP}}{F_{\rm AP}} \approx \frac{1}{\sqrt{N}}$$

Naively need 10,000 voids for 1% AP measurement!

Science with CLAPTRAP

Lyα forest tomography with CLAPTRAP can generate LSS maps at $z \sim 2$ at $\approx 3\ \mathrm{h}^{-1}$ Mpc scales over $10^6\ \mathrm{h}^{-3}$ Mpc^3

- Galaxy Environment Studies
  - Will overlap with CANDELS/3D-HST field in COSMOS
  - Study colors, morphology, SF rates, AGN activity etc as function of large-scale environment.
  - But will require theoretical interpretation from hydro simulations
- Galaxy Protoclusters
  - Progenitors of low-z $> 10^{14.5} M_\odot$ clusters are $\rho/\langle\rho\rangle \sim 3 - 4$ overdensities at $\sim 10\ \mathrm{h}^{-1}$ Mpc scales (Chiang et al 2013)
  - Expect $\sim 10 - 20$ protoclusters within 1 sq deg CLAPTRAP volume
  - Follow-up with imaging and spectroscopy to study member galaxies
- Clustering Measurements
  - Can measure $< 10\ \mathrm{h}^{-1}$ Mpc Lyα forest autocorrelation in 3D
  - Constrain σ_8, neutrino mass etc
  - Also: cross-correlation with your favorite population to measure bias