Cosmology beyond BAO: voids, dark energy and the cosmic web

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with many thanks to F. Leclercq, N. Hamaus, G. Lavaux, J. Jasche, A. Pisani, P. Sutter

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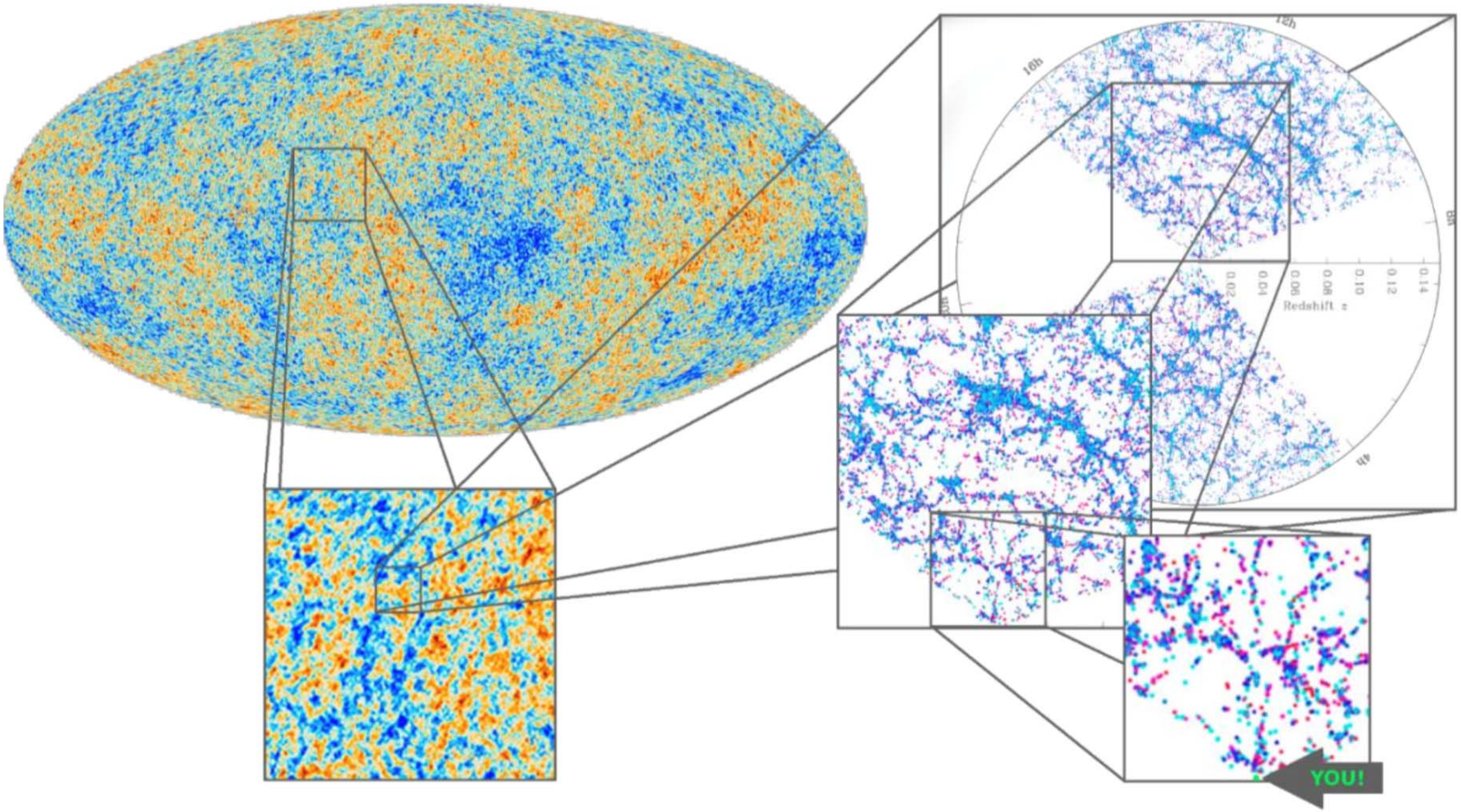
Large Scale Structure



The goals of Large Scale Structure analysis

- How did the universe begin?
  - Nature of primordial perturbations
- What does it contain?
  - Dark matter
  - Dark energy
  - Baryonic physics
- How did it evolve
  - Expansion history
  - Growth of structure

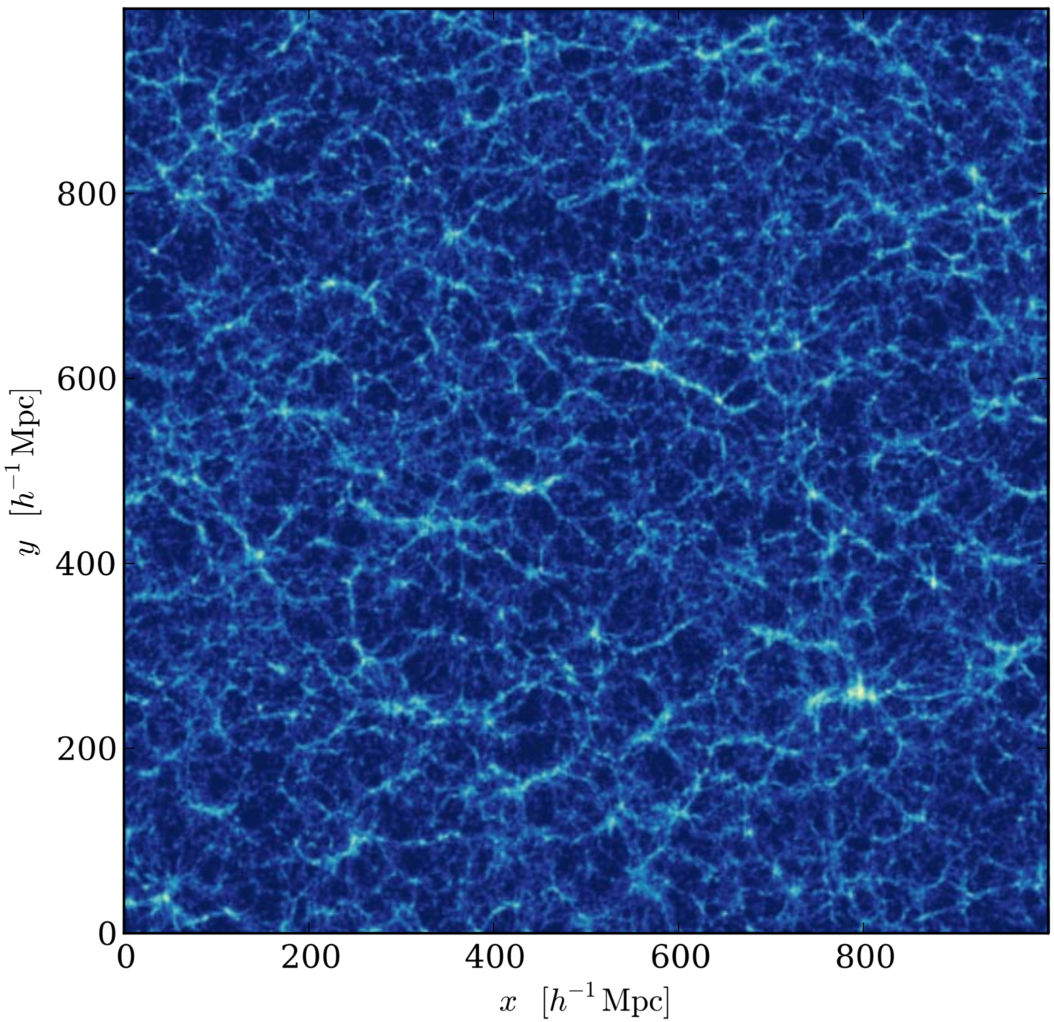
The large scale structure challenge

- ***Problem: to access the small scales need to deal with non-linearity and bias***

- Possible approaches:
  - **Avoid:** Observe at high redshift before density contrast became non-linear
  - **Attack:** Full, physical & statistical forward model of the survey
  - **Adapt:** Focus on less complicated parts of the Universe, e.g. those that retain more memory of the initial conditions: cosmic voids

How do we summarize this?
In terms of the soap or the bubbles?

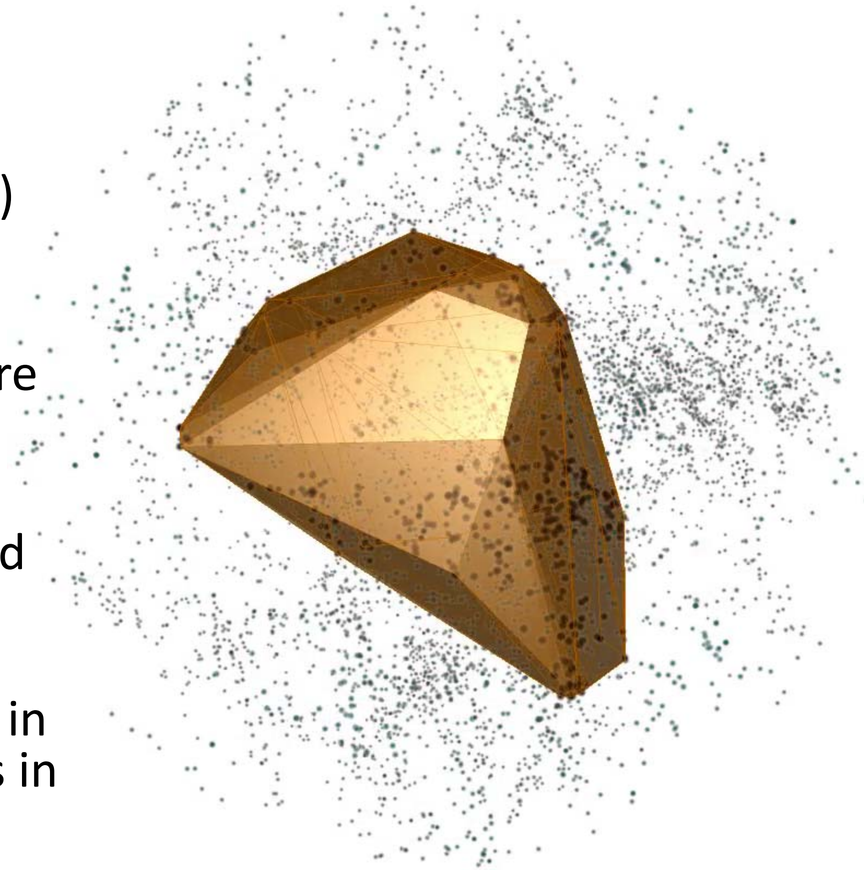
Redshift space



Why cosmic voids?

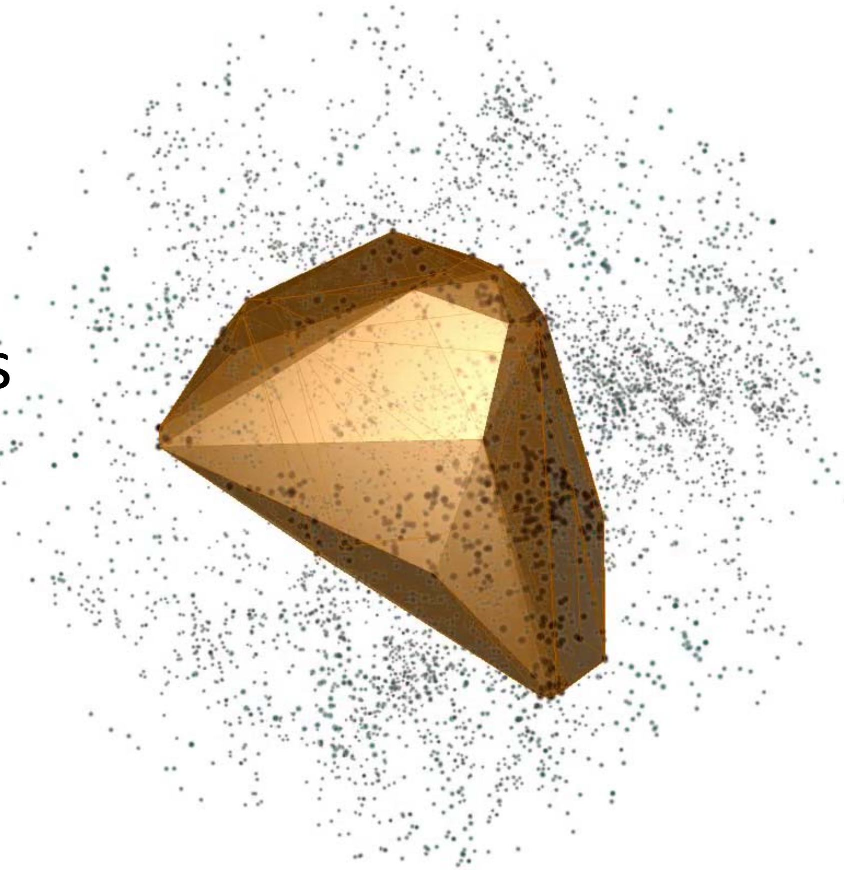
- Biggest "objects" in the Universe – fill most of the volume!
- Simpler dynamics and evolution than high density regions (see *Horizon AGN*)
- Easier to link luminous objects to underlying dark matter
- The first regions in the universe that are dominated by dark energy
- Neutrino signatures in profile?
- If acceleration of the universe is caused by modified gravity it should act most strongly in voids
- A free, additional observational probe in current and future surveys: ~10^5 voids in Euclid!

Several active groups and a rapidly growing body of work

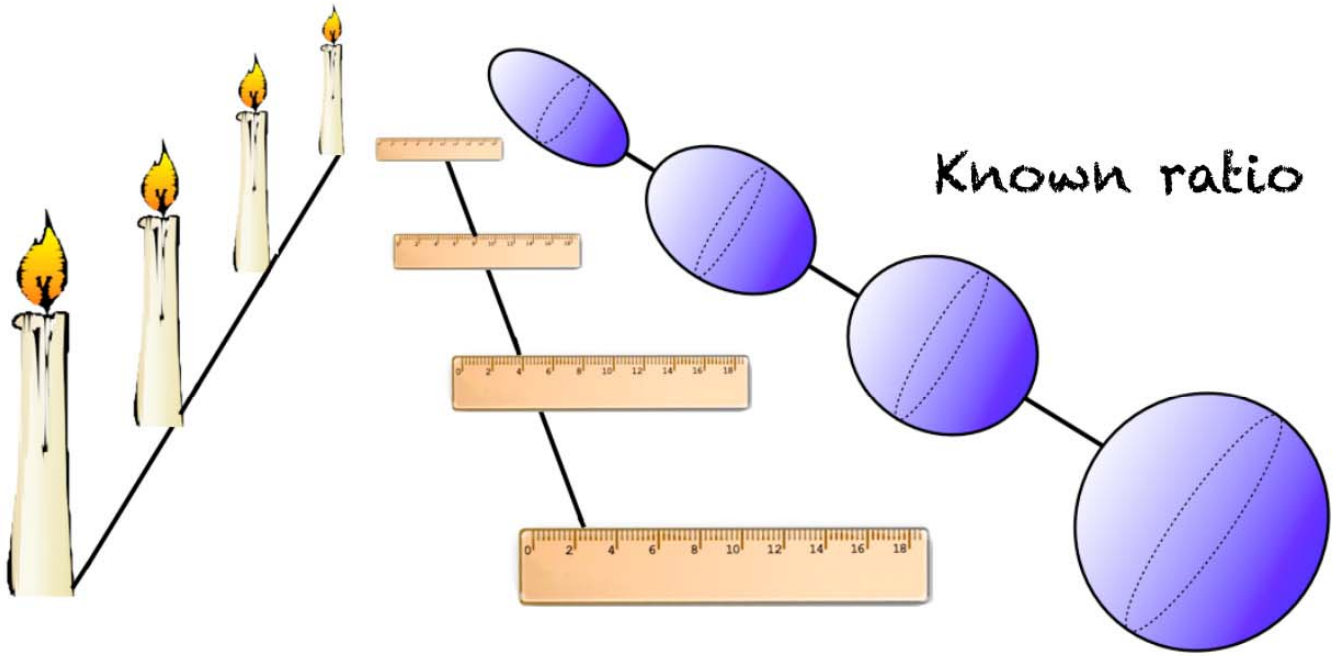


Classical cosmography with voids

- Can be used to define cosmological tests:
  - Alcock-Paczynski (Lavaux & Wandelt 2010, Hamaus et al., arXiv:1602.01784)
  - New "static ruler" (Hamaus et al., arxiv:1307.2571)



Cosmography with the Alcock-Pazcynski test



Known ratio $\frac{\text{radial size}}{\text{angular size}}$

Known luminosity

Known length

Standard "spheres"

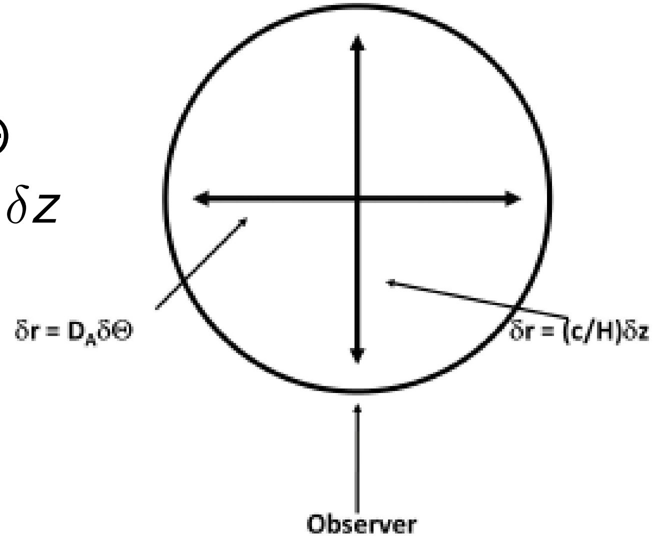
Standard "candles"

Standard "rulers"

Alcock-Paczynski test

Perform *Alcock-Paczynski test* to constrain cosmological parameters:

- Angular separation $\delta r_\perp = D_A(z)\,\delta\Theta$
- Radial separation $\delta r_\parallel = cH^{-1}(z)\,\delta z$



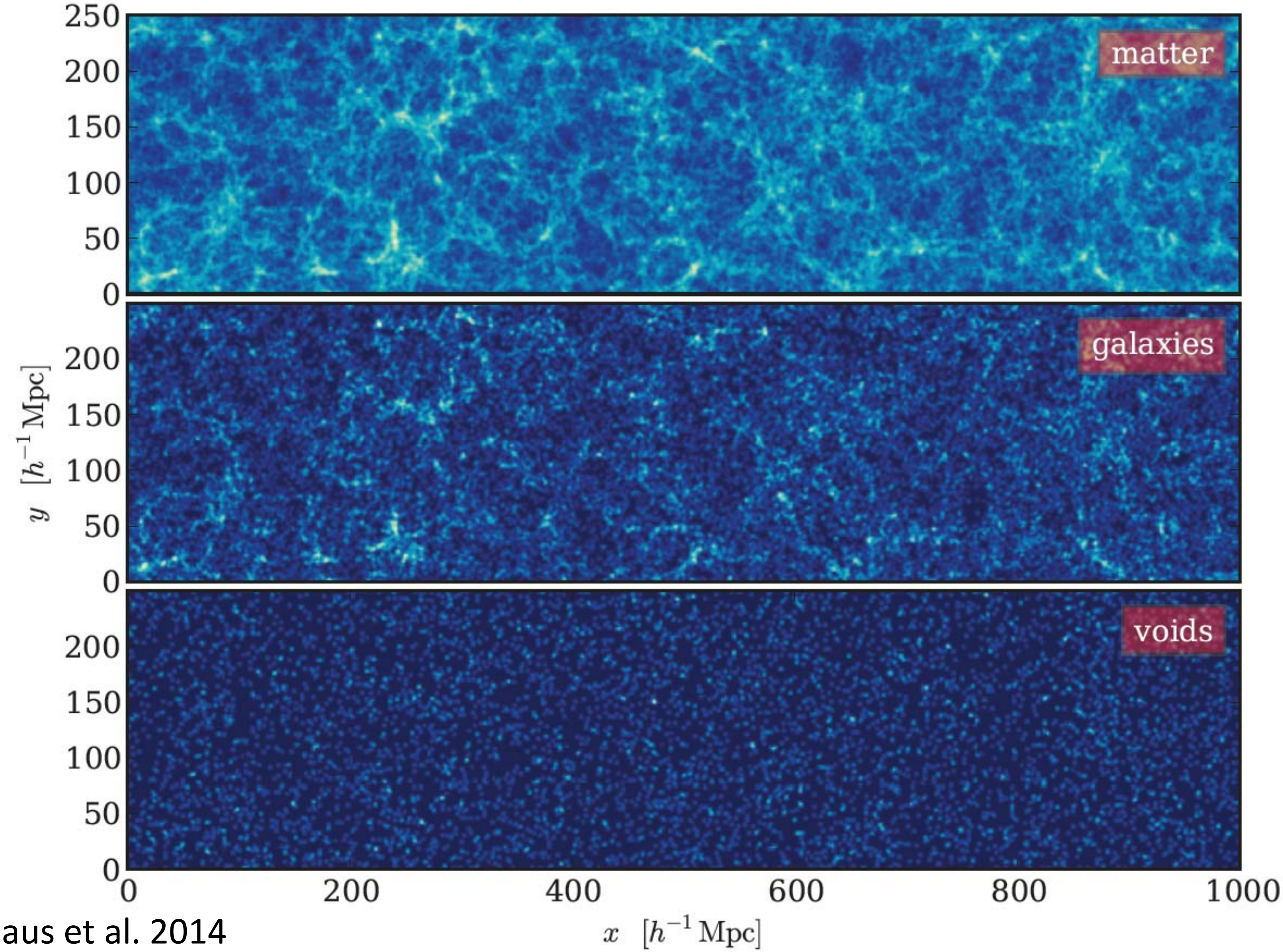
ANGULAR DIAMETER DISTANCE & HUBBLE RATE

$$D_A(z) = c\int_0^z H^{-1}(z')\,\mathrm{d}z' \quad , \quad H(z) = H_0\sqrt{\Omega_\mathrm{m}(1+z)^3 + \Omega_\Lambda}$$

Any deviation from the fiducial cosmology causes geometric distortions. ⇒ Determine ellipticity ε via

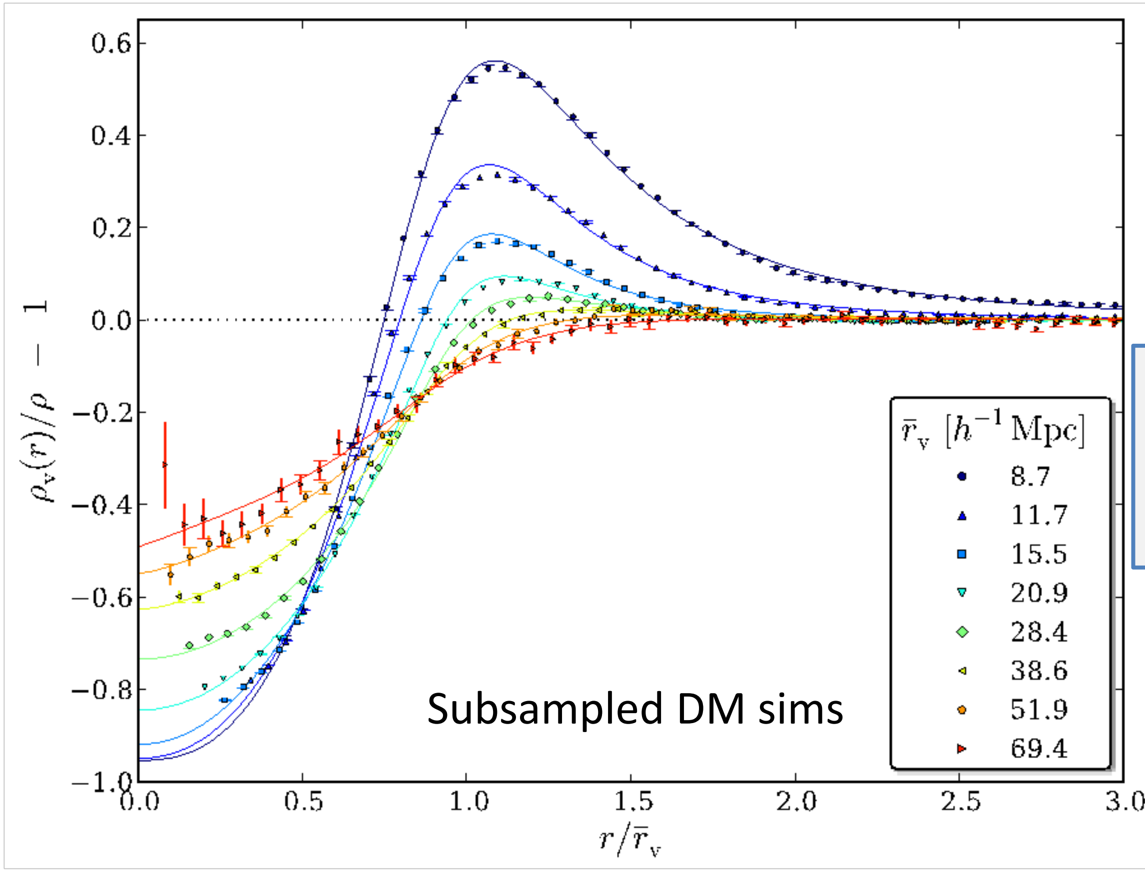
$$\varepsilon = \frac{\delta r_\parallel}{\delta r_\perp} = \frac{D_A^\mathrm{true}(z)H^\mathrm{true}(z)}{D_A^\mathrm{fid}(z)H^\mathrm{fid}(z)}$$

Matter, galaxies, voids in simulation



Hamaus et al. 2014

A universal profile for voids

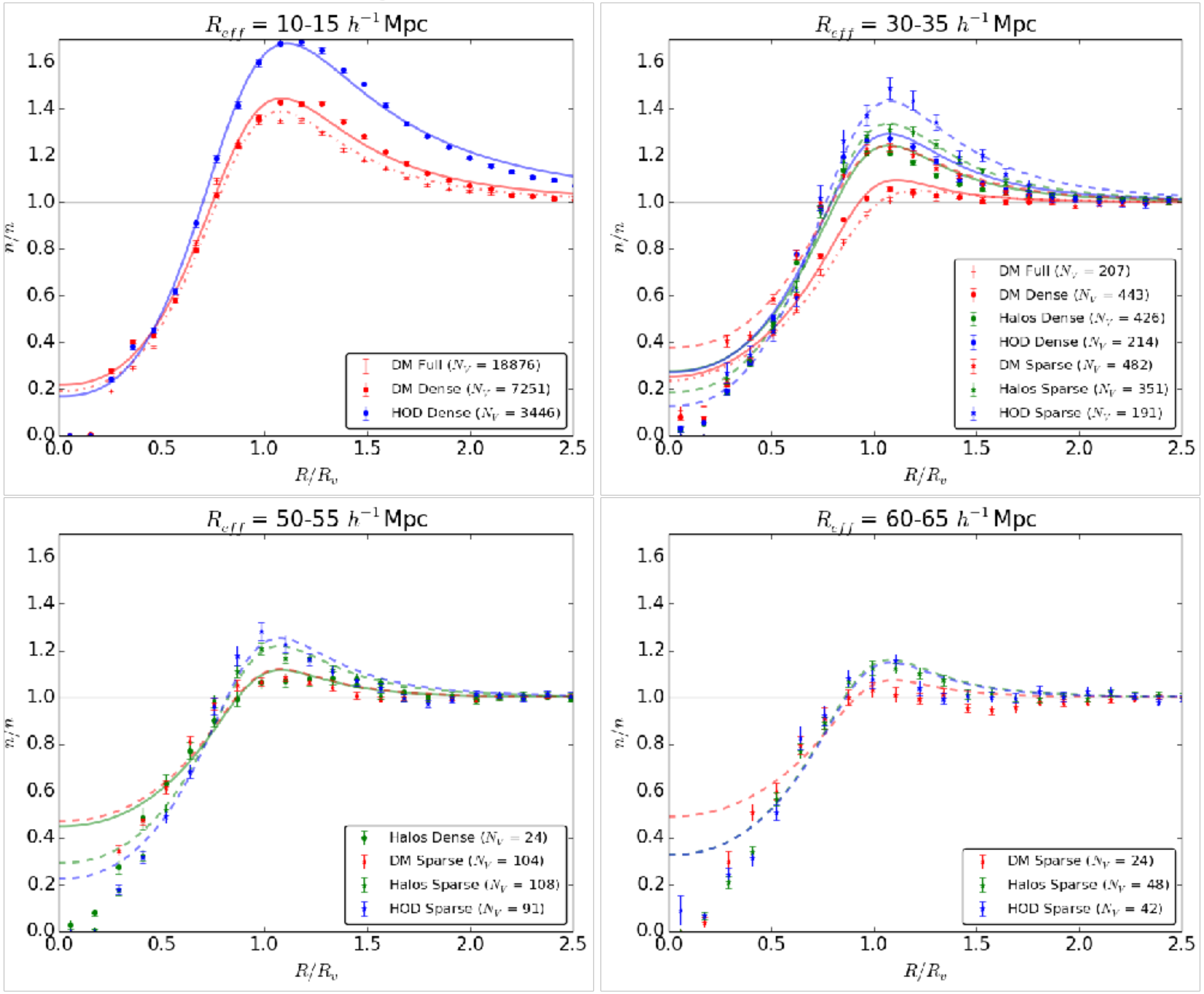


$$\frac{\rho_v(r)}{\bar{\rho}} - 1 = \delta_c \frac{1-(r/r_s)^{\alpha}}{1+(r/r_v)^{\beta}}$$

Scaling properties of voids allow reduction from 4 to 2 params

Hamaus, Sutter & Wandelt PRL 2014, arxiv:1403.5499

The profile fits DM voids, halo voids, "galaxy" voids



Sutter et al., arxiv:1309.5087; Hamaus, Sutter & Wandelt, arxiv:1403.5499

Void ρ and v profile

Estimate density and velocity profile by "stacking" tracer particles around void centers

$$\rho_{\rm v}(r) = \frac{3}{4\pi} \sum_i \frac{m_i(\boldsymbol{r}_i)}{(r+\delta r)^3 - (r-\delta r)^3}$$

EMPIRICAL BEST-FIT MODEL (4 PARAMETERS)

$$\frac{\rho_{\rm v}(r)}{\bar{\rho}} - 1 = \delta_c \frac{1-(r/r_s)^\alpha}{1+(r/r_{\rm v})^\beta}\,, \qquad r_{\rm v} \equiv (3V_{\rm v}/4\pi)^{1/3}$$

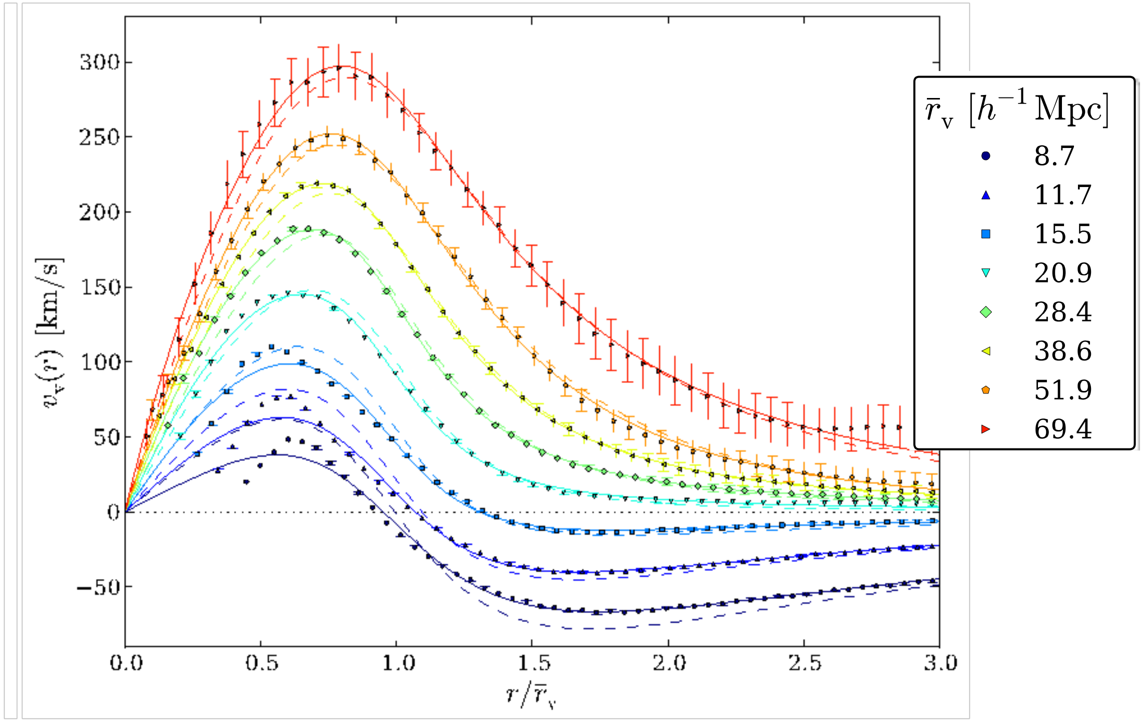
$$v_{\rm v}(r) = \frac{1}{N(r)} \sum_i \boldsymbol{v}_i(\boldsymbol{r}_i) \cdot \frac{\boldsymbol{r}_i}{r_i}$$

MASS CONSERVATION TO LINEAR ORDER

$$v_{\rm v}(r) = -\frac{1}{3}\frac{f(z)H(z)}{1+z} r\Delta_{\rm v}(r)\,, \quad \Delta_{\rm v}(r) \equiv \frac{3}{r^3}\int_0^r \left(\frac{\rho_{\rm v}(s)}{\bar{\rho}} - 1\right) s^2 {\rm d}s$$

In General Relativity: $f(z) = \Omega_{\rm m}^{0.55}(z)$

An astonishing result: *density profile fit* **+** *linear theory* predicts velocity profile!



Simple dynamics: easy to model in redshift space!

Hamaus, Sutter & Wandelt PRL 2014, arxiv:1403.5499

Void profiles in redshift space

Void-galaxy cross-correlation function in redshift space:

$$1+\tilde{\xi}_{\mathrm{vg}}(\tilde{\mathbf{r}}) = \int \mathcal{P}\left(\mathbf{v},\mathbf{r}\right)\left[1+\xi_{\mathrm{vg}}(\mathbf{r})\right]\,\mathrm{d}^3 v = \int_{-\infty}^{\infty} \mathcal{P}\left(v_{\|},\mathbf{r}\right)\frac{\rho_{\mathrm{v}}(r)}{\bar{\rho}}\,\mathrm{d}v_{\|}$$

Assume a Gaussian pairwise velocity distribution with mean $v_{\mathrm{v}}(r)\frac{r_{\|}}{r}$

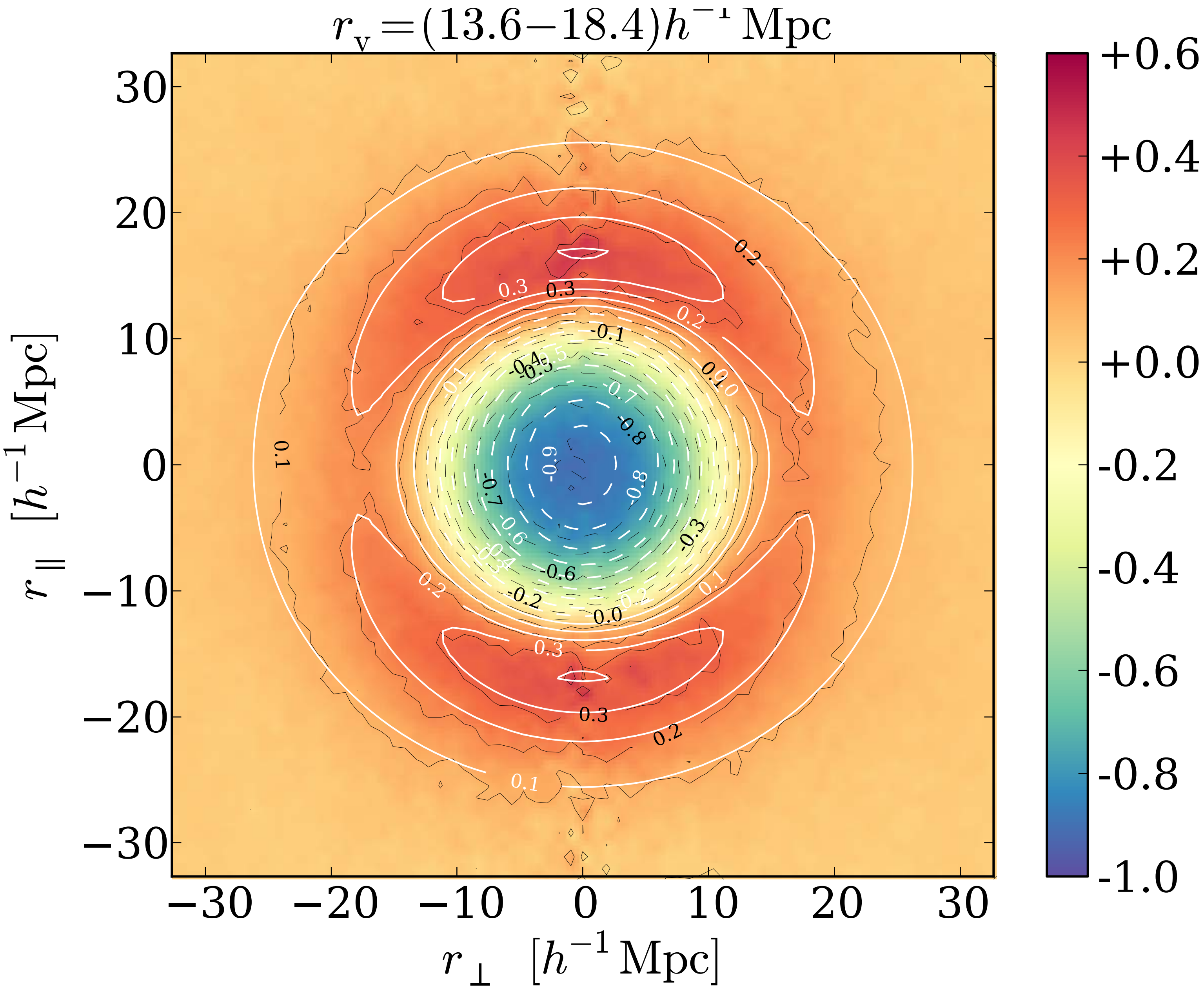
$$\mathcal{P}\left(v_{\|},\mathbf{r}\right) = \frac{1}{\sqrt{2\pi}\sigma_v(\mathbf{r})}\exp\left[-\frac{\left(v_{\|}-v_{\mathrm{v}}(r)\frac{r_{\|}}{r}\right)^2}{2\sigma_v^2(\mathbf{r})}\right]$$

and with velocity dispersion

$$\sigma_v^2(\mathbf{r}) = \sigma_{\|}^2(r)\frac{r_{\|}^2}{r^2}+\sigma_{\perp}^2(r)(1-\frac{r_{\|}^2}{r^2})$$

Assume:

$$\sigma_{\|,\perp}(r)\equiv\sigma_v = \mathrm{const.}$$

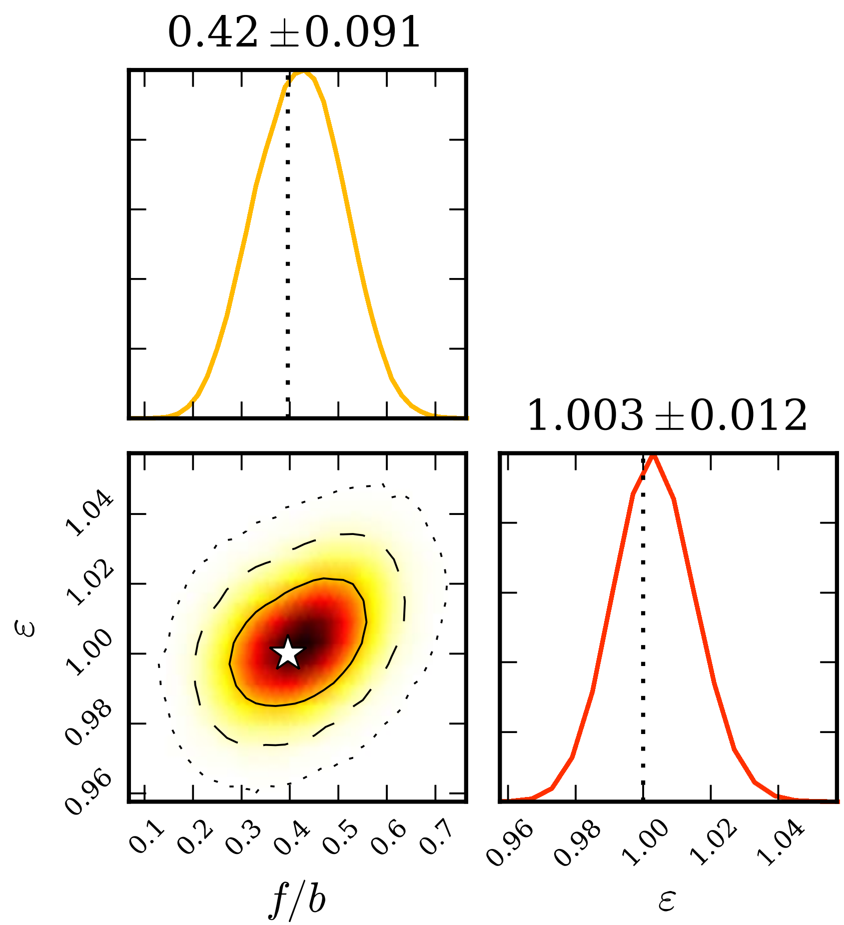


$r_v = (13.6-18.4)h^{-1}$ Mpc
$r_\parallel \ [h^{-1}$ Mpc$]$
$r_\perp \ [h^{-1}$ Mpc$]$
+0.6
+0.4
+0.2
+0.0
-0.2
-0.4
-0.6
-0.8
-1.0

Joint measurement of growth f/b and on *Alcock-Paczynski* parameter ε

Using BOSS data. AP measuremet is 4 times tighter than RSD from SDSS DR12 galaxy clustering analysis!

(Gil-Marin *et al.* arXiv:1509.06386)

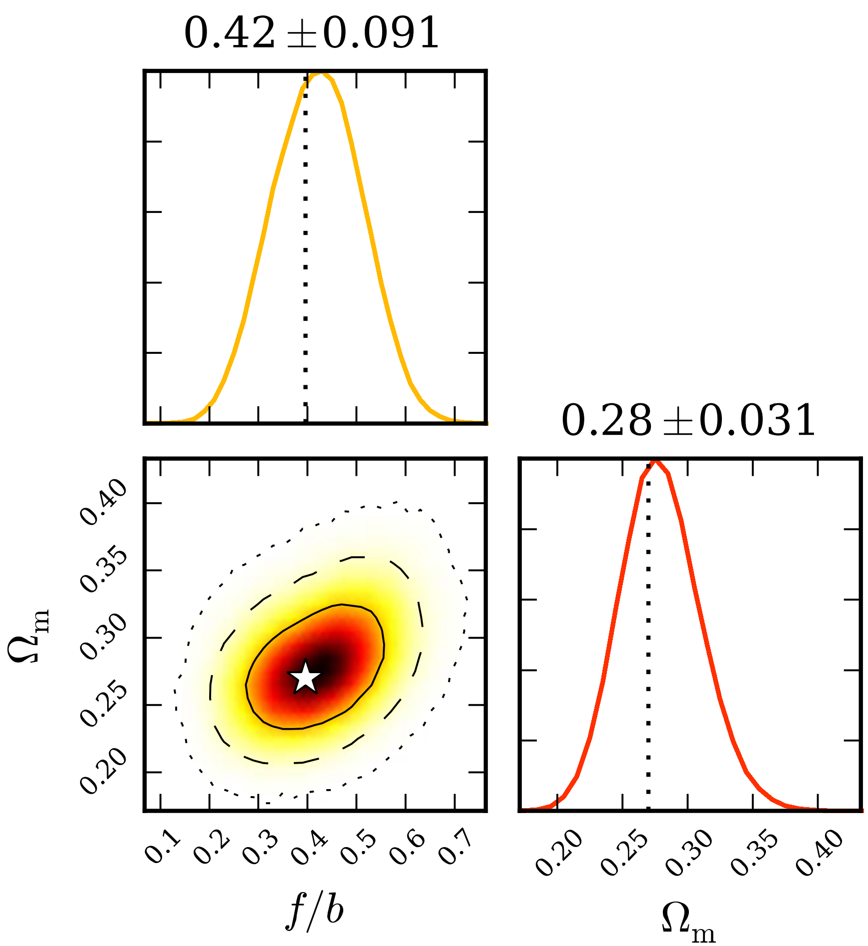


Preliminary Euclid forecasts => 30 times higher Figure of merit than standard BAO

Hamaus et al. arXiv:1602.01784

Joint constraint on growth f/b and on matter density

Assumes LCDM



Hamaus et al. arXiv:1602.01784

Bright future for cosmic voids

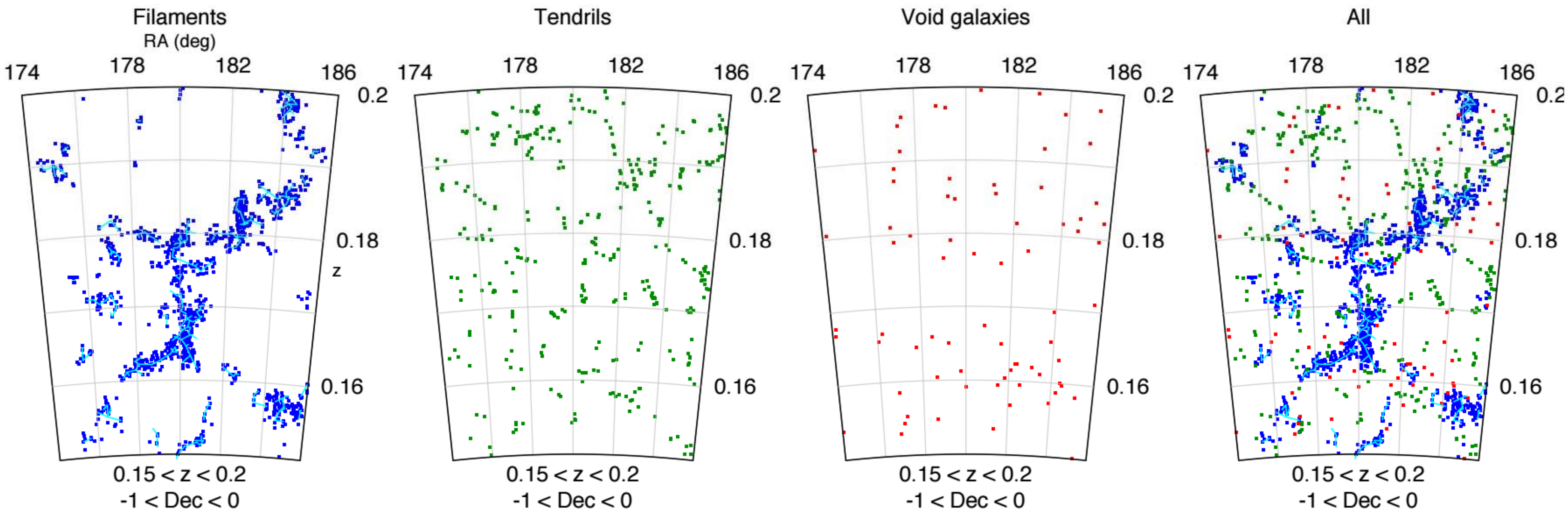
- Voids are not empty! Substructure in voids
  - Probes nature of dark matter
  - Contains information about small-scale primordial spectrum frozen in
  - Gives additional dynamical information, if clumps contain neutral gas

Galaxy and Mass Assembly (GAMA): Fine filaments of galaxies detected within voids

Mehme... nny[3],
Simon ... r[5],
Benne ...
Maritz...
Kevin ...

ABSTRACT

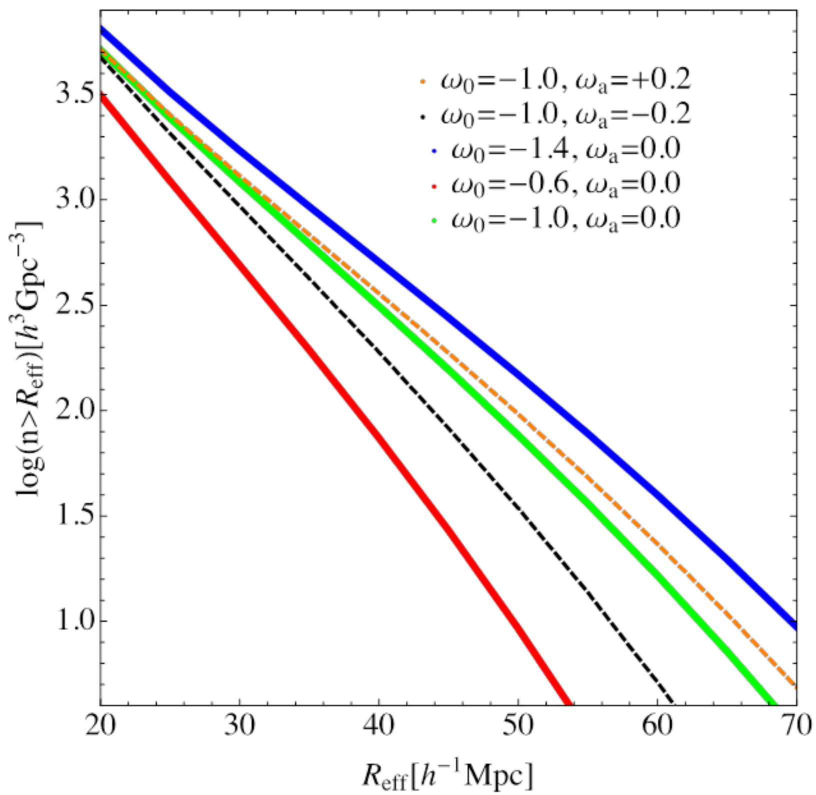
Based on data from the Galaxy and Mass Assembly (GAMA) survey, we report on the discovery of structures that we refer to as 'tendrils' of galaxies: coherent, thin chains of galaxies that are rooted in filaments and terminate in neighbouring filaments or voids. On average, tendrils contain 6 galaxies and span 10 h^{-1} Mpc. We use the so-called line correlation function to prove that tendrils represent real structures rather than accidental alignments. We show that voids found in the SDSS-DR7 survey that overlap with GAMA regions contain a large number of galaxies, primarily belonging to tendrils. This implies that void sizes are strongly dependent on the number density and sensitivity limits of a survey. We caution that galaxies in low density regions, that may be defined as 'void galaxies,' will have local galaxy number densities that depend on such observational limits and are likely higher than can be directly measured.



Bright future for cosmic voids

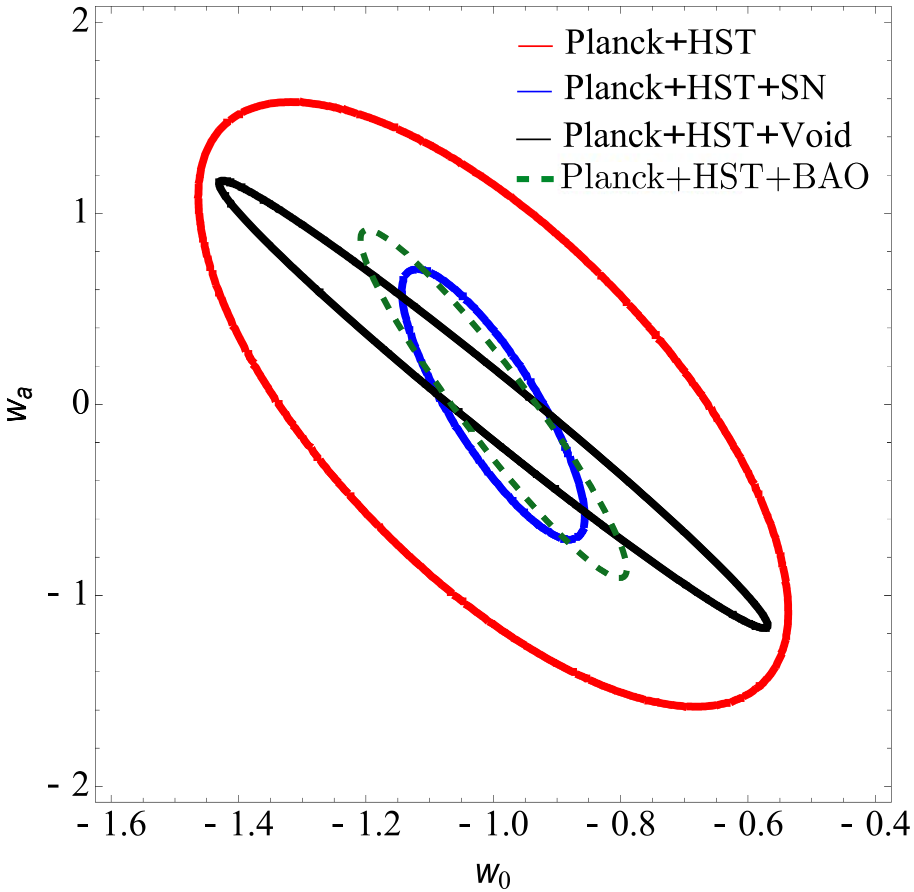
- Voids as a cosmic tracer
  - Void centers have sub-Poissonian statistics
  - Low noise tracer of large scale structure
    - E.g. BAO with voids (Liang et al 2015)
- Gravitational Lensing from voids
  - First measurement Melchior et al. 2013 (SDSS)
  - Latest: Sánchez et al. 2016 (DES SV)

Counting voids to probe dark energy



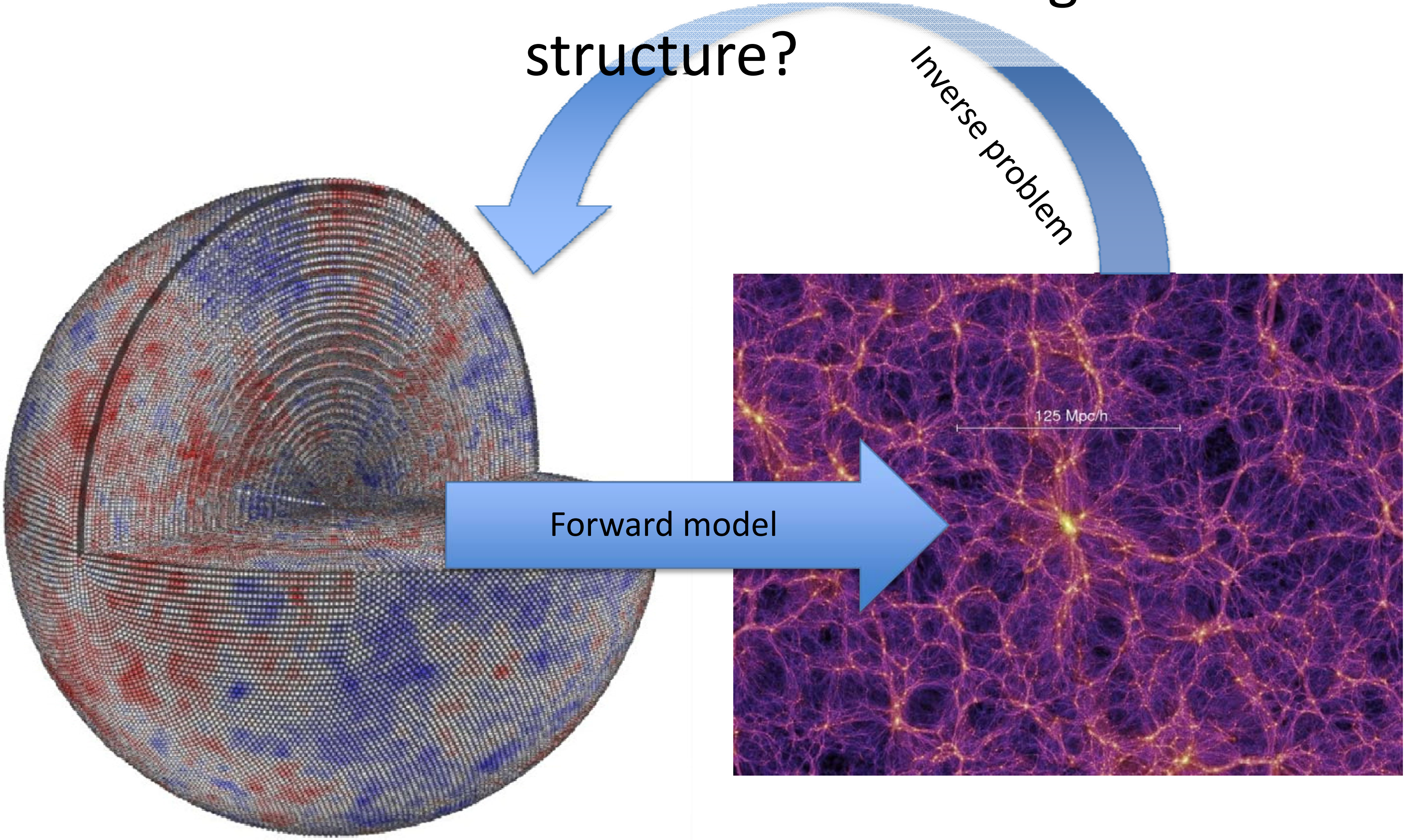
Pisani Sutter, Hamaus, Alizadeh, Biswas, Wandelt, Hirata
arXiv: 1503.07690

Fisher forecast of void abundance constraints from Euclid



Pisani Sutter, Hamaus, Alizadeh, Biswas, Wandelt, Hirata
arXiv: 1503.07690

Going from "Adapt" to "Attack" mode: can invert a full forward model of the Large scale structure?

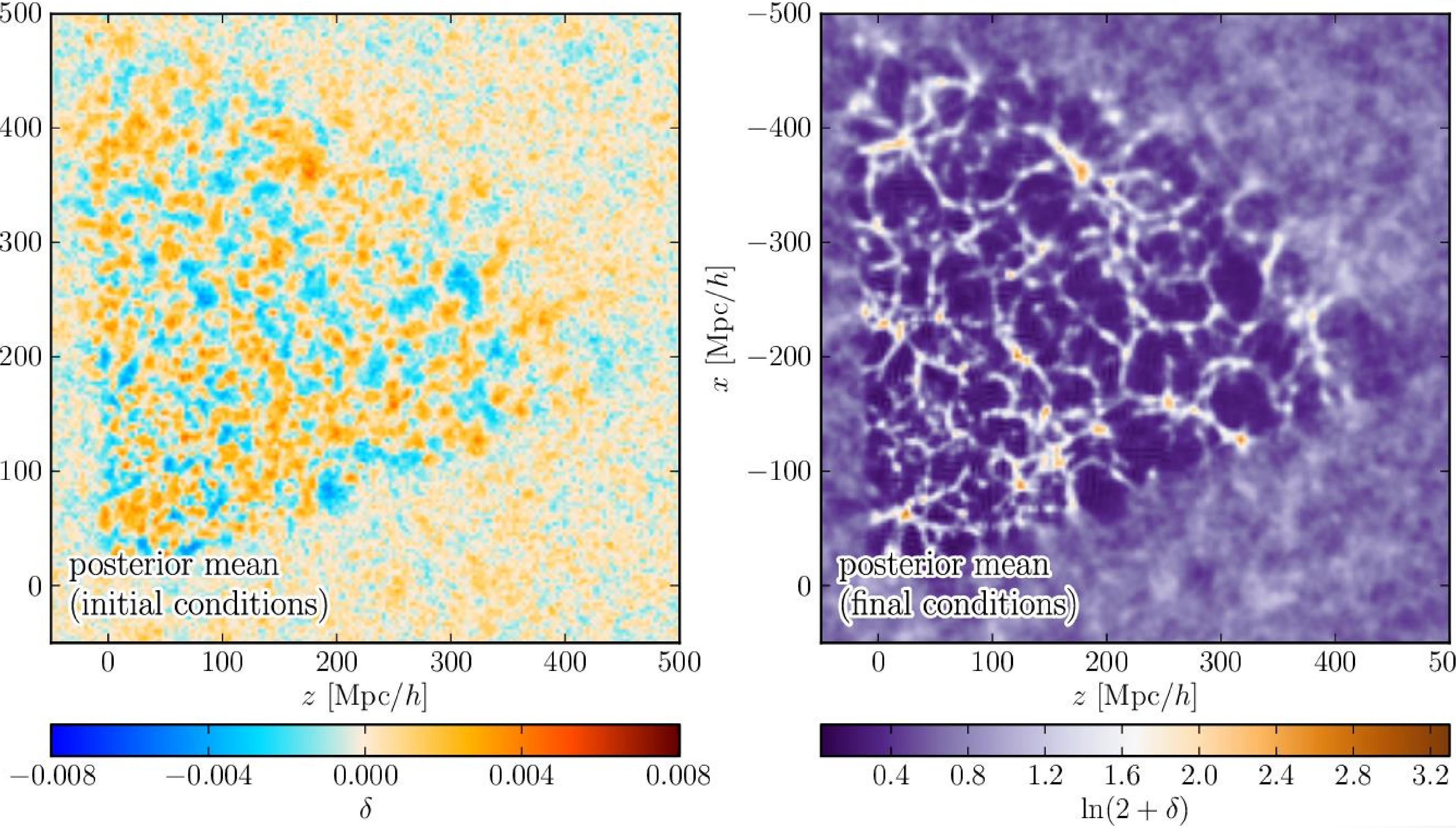


The BORG SDSS run

- 334,074 galaxies from the NYU-VAGC based on SDSS DR7
- Comoving cubic box of side length 750 Mpc/*h*, with periodic boundary conditions
- 256^3 grid, resolution 3 Mpc/*h* → ≈17 millions parameters
- 12,000 samples, four-dimensional maps
- ≈3 TB disk space
- 10 months wallclock time on 16-32 cores

Jasche, Leclercq, BDW 2015

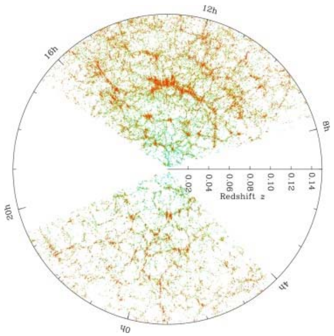
Bayesian chronocosmography from SDSS



How did we get that?

BORG: *Bayesian Origin Reconstruction from Galaxies*

- **Data model**: Gaussian prior – Second-order Lagrangian perturbation theory (2LPT) – Poisson likelihood
  (and also: luminosity-dependent galaxy bias, automatic noise level calibration)
- **Sampler**: Hamiltonian Markov Chain Monte Carlo method



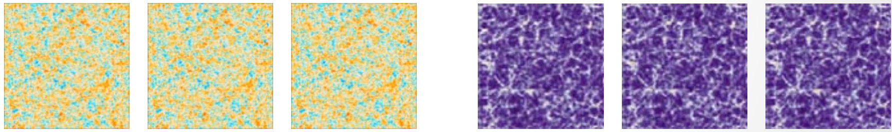
Observations

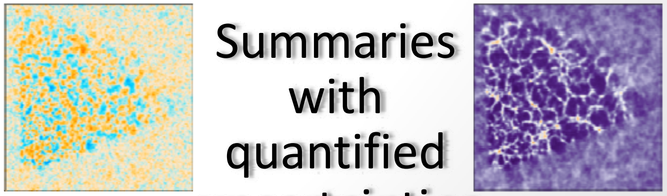
(galaxy catalog + meta-data: selection functions, completeness...)

→ BORG →

Inferred dark matter densities

z=100 z=0





Summaries with quantified uncertainties

Jasche & Wandelt 2013, arXiv:1203.3639

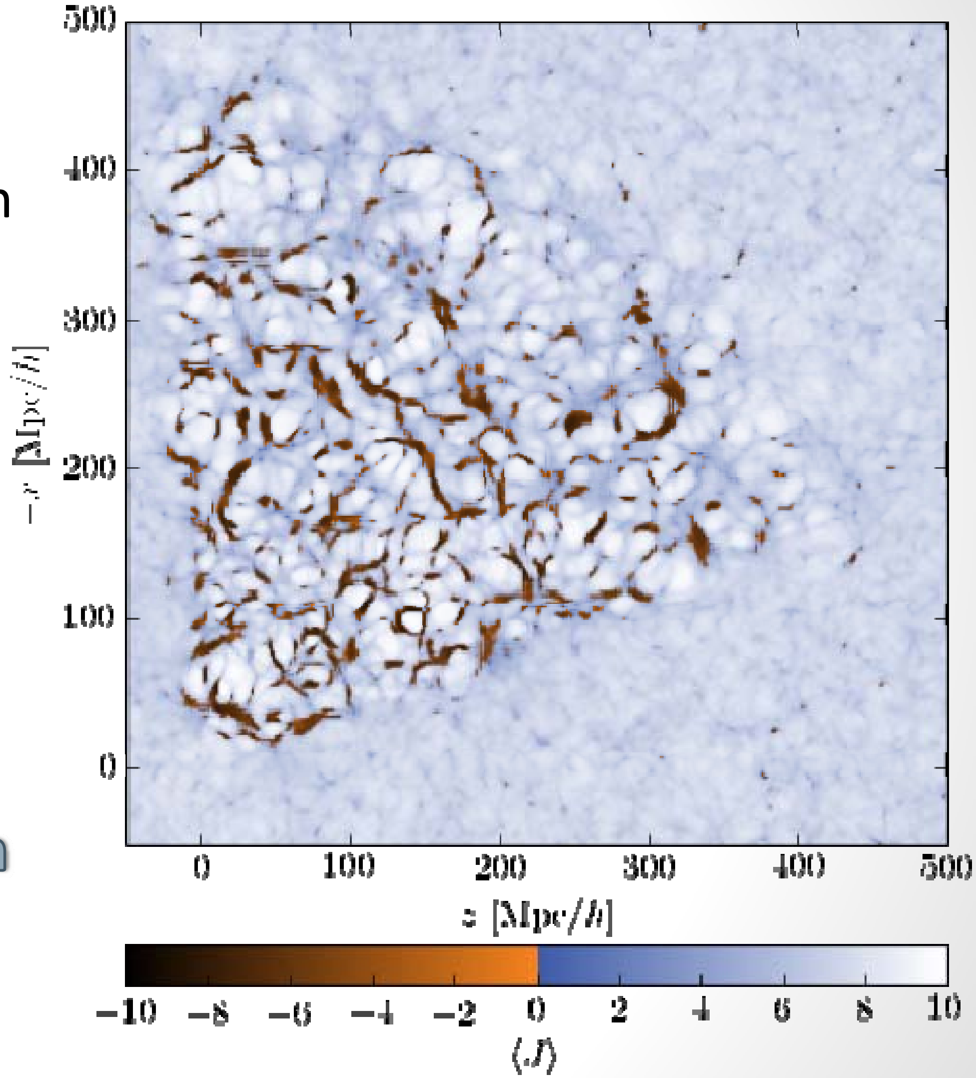
Jasche, FL & Wandelt 2015, arXiv:1409.6308

Inference of the dark matter phase-space sheet

- The dark matter phase-space sheet has been studied so far in simulations

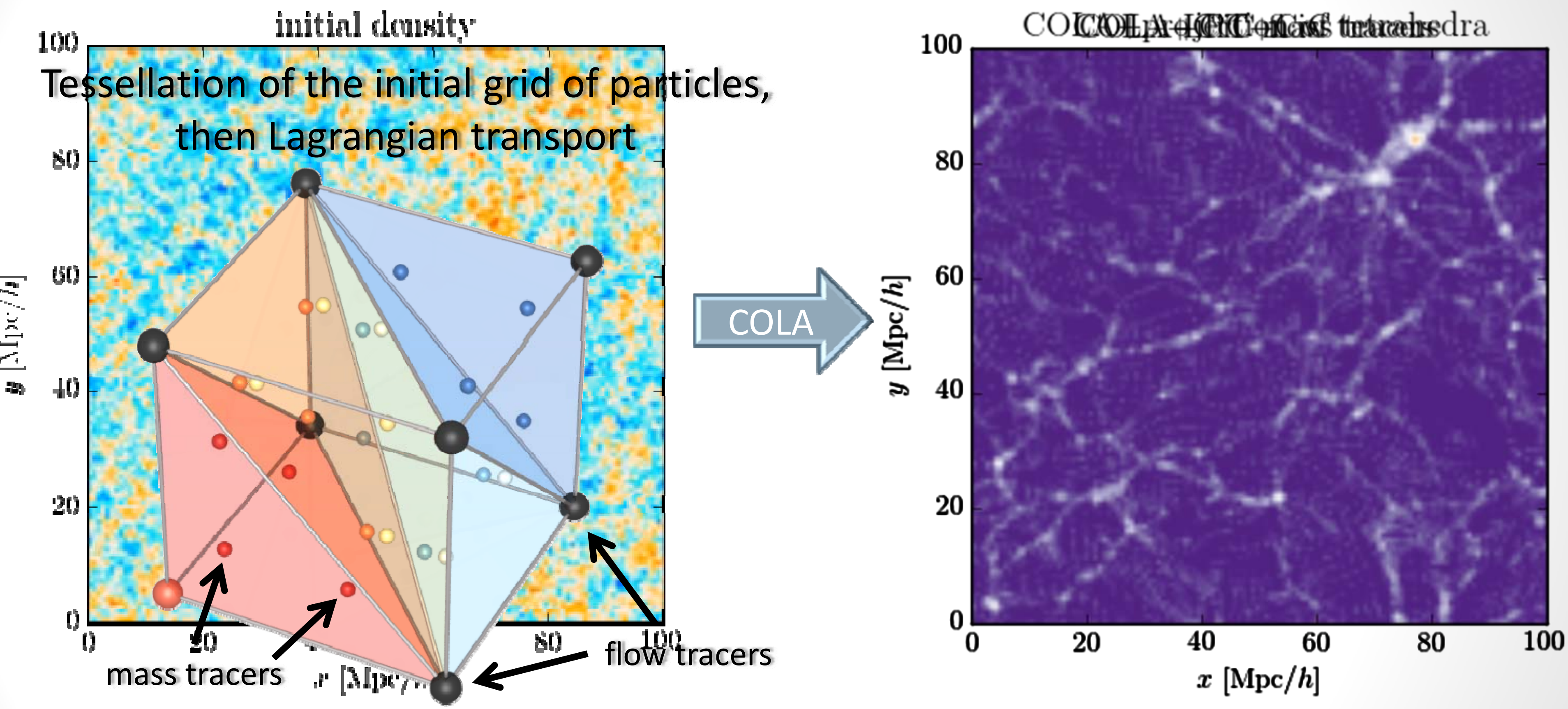
e.g. Neyrinck 2012, arXiv:1202.3364
Abel, Hahn & Kaehler 2012, arXiv:1111.3944
Shandarin, Habib & Heitmann 2012, arXiv:1111.2366

- BORG infers **Lagrangian dynamics** in real data
- Identified structures have a direct **physical interpretation**



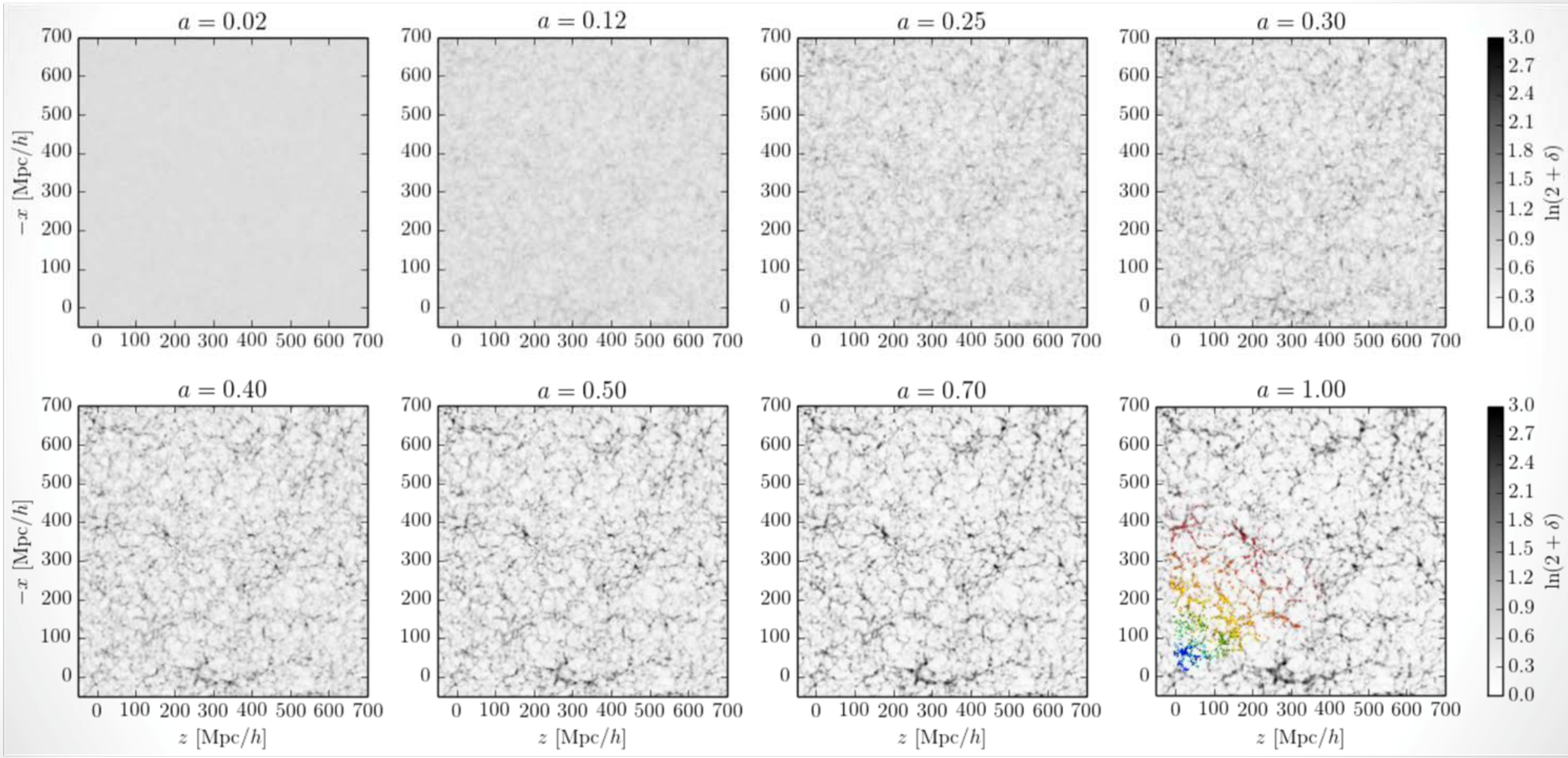
FL, Jasche, Lavaux & Wandelt 2016, arXiv:1601.00093

Exploiting Lagrangian space dynamic analysis

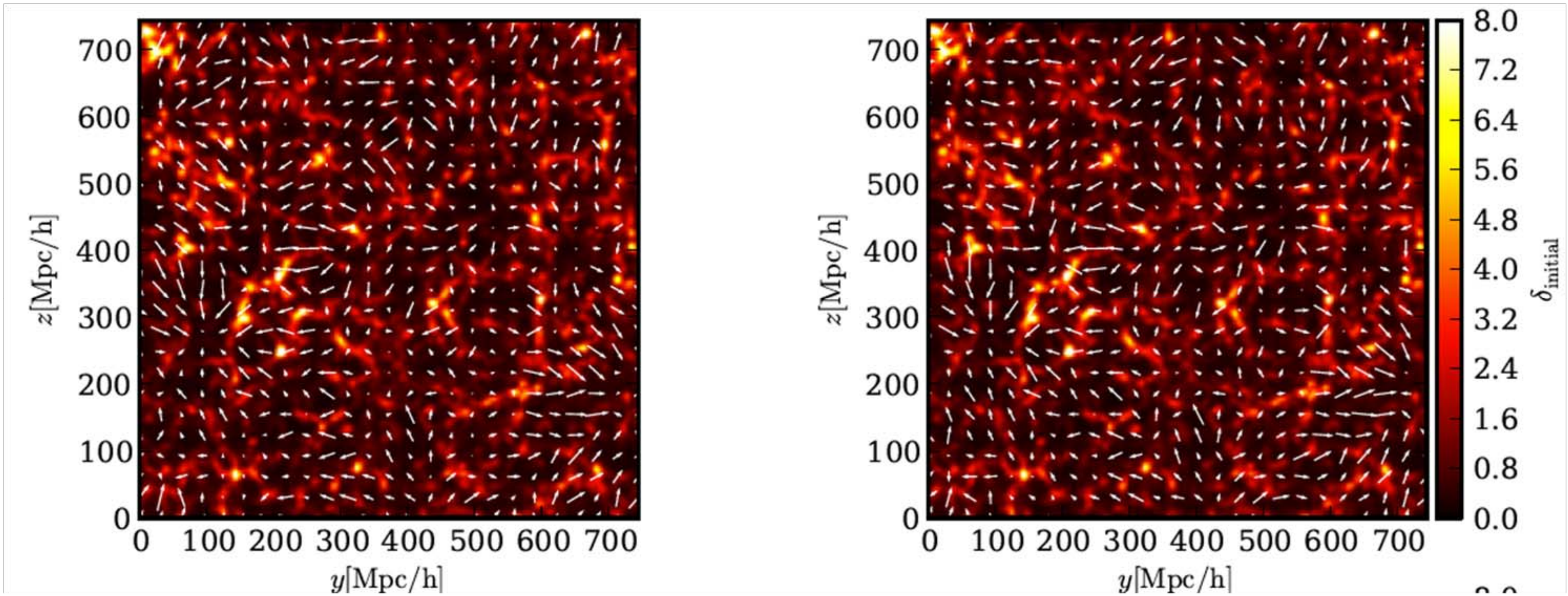


Hahn, Abel & Khaeler, arXiv:1210.6652

Consistent histories of cosmic structure evolution



Dynamical velocities



How do we find beyond-BAO Large Scale Structure statistics that inform us about cosmology?

- Example: what can the mildly non-linear regime (the *cosmic web*) teach us about dark energy?

Physical cosmic web classification

- The **T-web**:

void, sheet, filament, cluster?

uses the sign of μ_1, μ_2, μ_3: eigenvalues of the tidal field tensor, Hessian of the gravitational potential: $T_{ij}(\mathbf{x}) = \partial_i \partial_j \Phi(\mathbf{x})$

Hahn *et al*. 2007, arXiv:astro-ph/0610280

- **DIVA**:

uses the sign of $\lambda_1, \lambda_2, \lambda_3$: eigenvalues of the shear of the Lagrangian displacement field: $R_{\ell m}(\mathbf{q}) = \partial_m \Psi_\ell(\mathbf{q})$

Lavaux & Wandelt 2010, arXiv:0906.4101

- **ORIGAMI** :

uses the dark matter "phase-space sheet" (number of orthogonal axes along which there is shell-crossing)

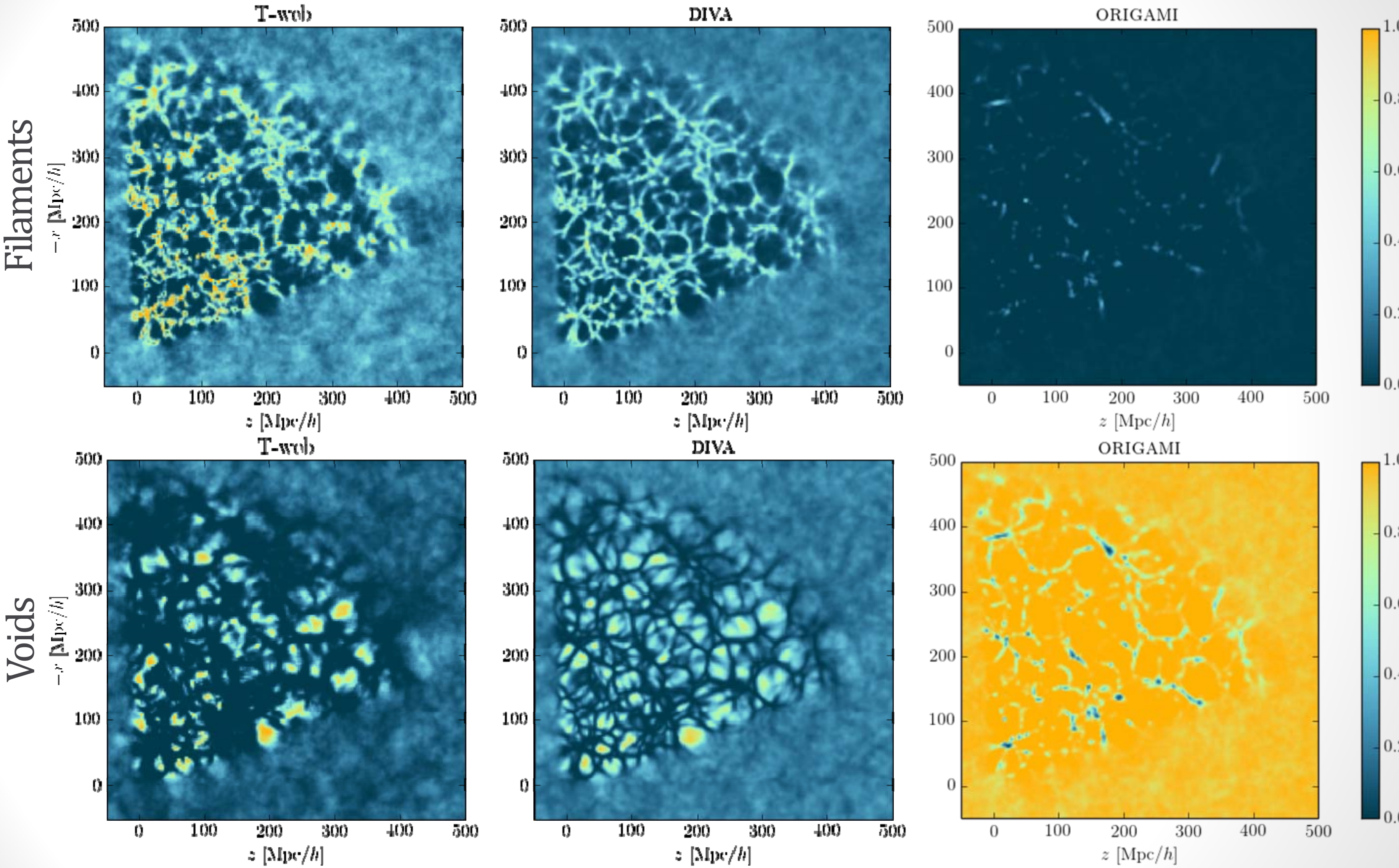
Falck, Neyrinck & Szalay 2012, arXiv:1201.2353

} Lagrangian classifiers

now usable in real data!

and many others…

Comparing classifiers



FL, Jasche & Wandelt 2015, arXiv:1502.02690

FL, Jasche, Lavaux & Wandelt 2016, arXiv:1601.00093

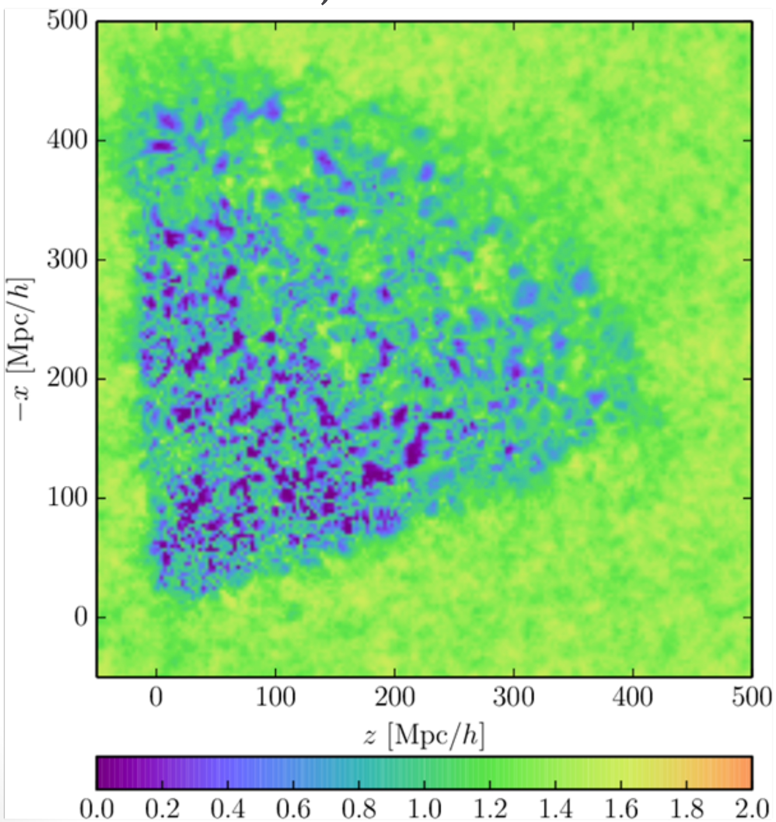
What is the information content of these maps?

Shannon entropy

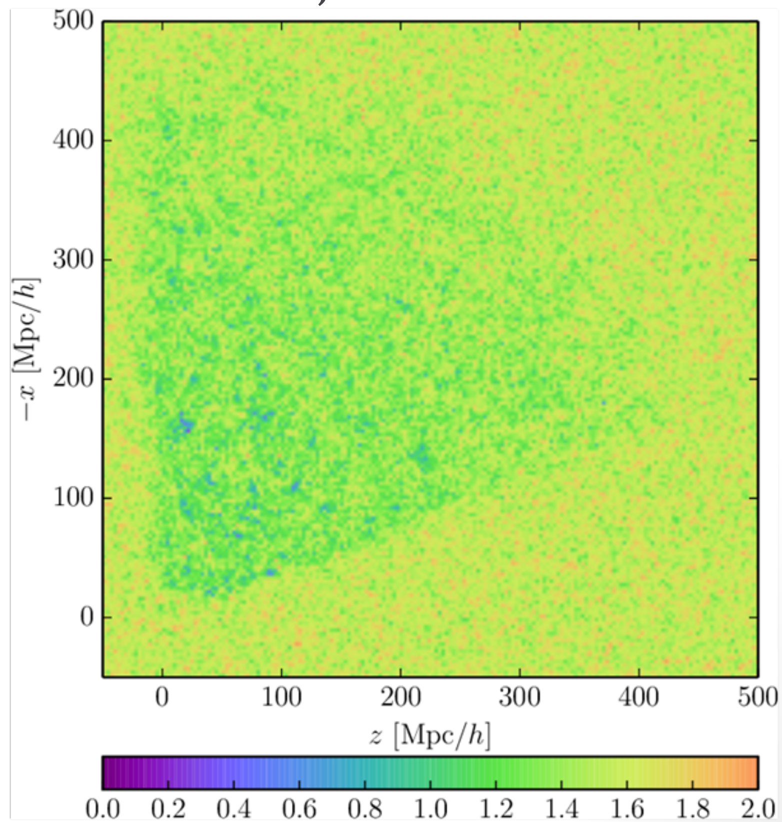
$$S = -\sum_i p_i \log_2 p_i$$

$$H\left[\mathcal{P}(\mathrm{T}(\vec{x}_k)|d)\right] = -\sum_{i=0}^{3} \mathcal{P}(\mathrm{T}_i(\vec{x}_k)|d)\log_2(\mathcal{P}(\mathrm{T}_i(\vec{x}_k)|d))$$ in shannons (Sh)

T-web, final conditions



T-web, initial conditions



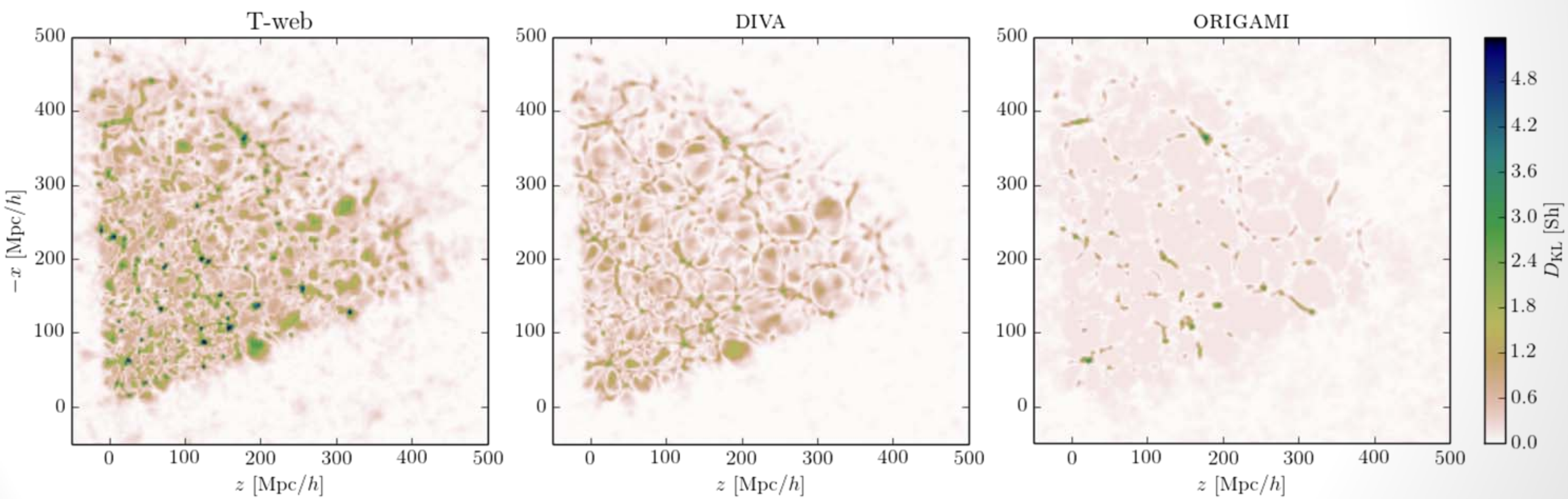
FL, Jasche & Wandelt 2015, arXiv:1502.02690

How much did the data surprise us?

information gain a.k.a. relative entropy or Kullback-Leibler divergence posterior/prior

$$D_{\mathrm{KL}}\left[P\|Q\right] = \sum_i p_i \log_2\left(\frac{p_i}{q_i}\right)$$

$$D_{\mathrm{KL}}\left[\mathcal{P}(\mathrm{T}(\vec{x}_k)|d)\|\mathcal{P}(\mathrm{T})\right] = \sum_i \mathcal{P}(\mathrm{T}_i(\vec{x}_k)|d) \log_2\left(\frac{\mathcal{P}(\mathrm{T}_i(\vec{x}_k)|d)}{\mathcal{P}(\mathrm{T}_i)}\right)$$ in Sh



(more about the Kullback-Leibler divergence later)

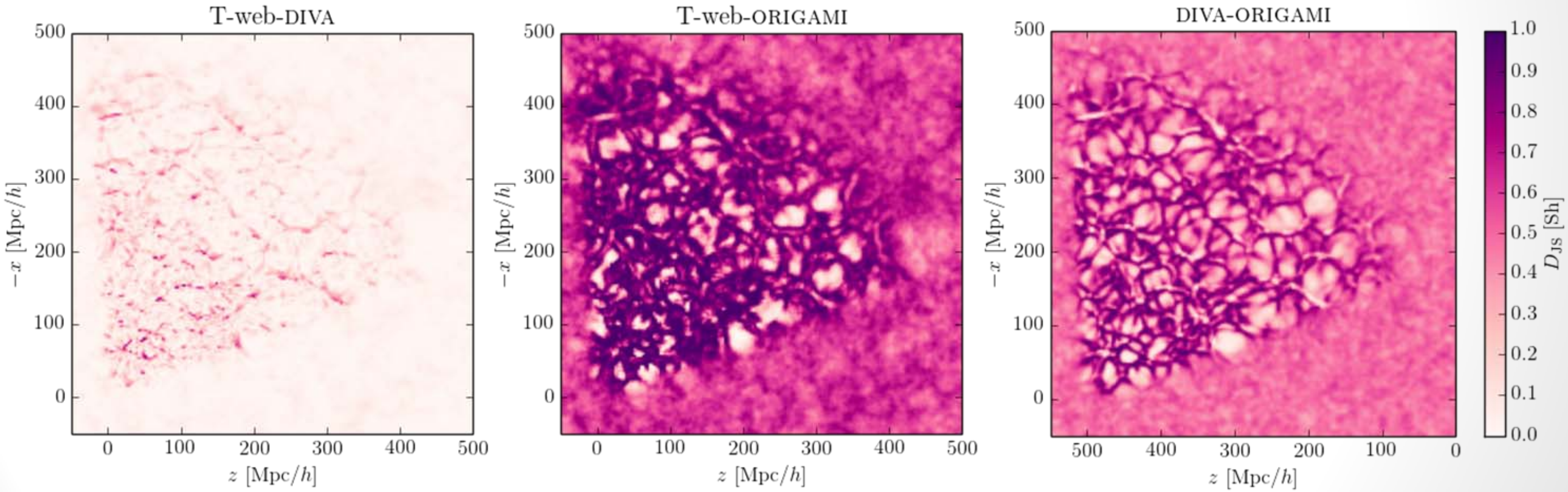
FL, Jasche & Wandelt 2015, arXiv:1502.02690

How similar are different classifications?

Jensen-Shannon divergence

$$D_{\mathrm{JS}}[\mathcal{P}:\mathcal{Q}] \equiv \frac{1}{2} D_{\mathrm{KL}}\left[\mathcal{P} || \frac{\mathcal{P}+\mathcal{Q}}{2}\right] + \frac{1}{2} D_{\mathrm{KL}}\left[\mathcal{Q} || \frac{\mathcal{P}+\mathcal{Q}}{2}\right]$$

in Sh,
between 0 and 1



(more about the Jensen-Shannon divergence later)

FL, Lavaux, Jasche & Wandelt 2016, arXiv:1606:06758.

Which is the best classifier?

- **Decision theory**: a framework to classify structures in the presence of uncertainty.
  Can we extend the decision problem to the space of classifiers?
- Idea: maximize a utility function

$$U(\xi) = \langle U(d, \mathrm{T}, \xi) \rangle_{\mathcal{P}(d,\mathrm{T}|\xi)}$$

- An important notion: the **mutual information** between two random variables

$$I\left[X:Y\right] \equiv D_{\mathrm{KL}}[\mathcal{P}(x,y)||\mathcal{P}(x)\mathcal{P}(y)]$$
$$= \sum_{x\in\mathcal{X},y\in\mathcal{Y}} \mathcal{P}(x,y)\log_2\left(\frac{\mathcal{P}(x,y)}{\mathcal{P}(x)\mathcal{P}(y)}\right)$$

- Property: $$I\left[X:Y\right] = \langle D_{\mathrm{KL}}[\mathcal{P}(x|y)||\mathcal{P}(x)]\rangle_{\mathcal{P}(Y)}$$

Mutual information is the expected information gain about X due to observing Y

FL, Lavaux, Jasche & Wandelt 2016, arXiv:1606:06758.

Utility for model selection:
example: dark energy equation of state

- **Example:** *Let us consider three dark energy models with*

$$w = -0.9, w = -1, w = -1.1 \ .$$

Which classifier separates them best?

- The **Jensen-Shannon divergence** between posterior predictive distributions can be used as an approximate **predictor for the change in the Bayes factor**

Vanlier *et al.* 2014, BMC Syst Biol 8, 20 (2014)

- In analogy: $U_2(d,\xi)(\vec{x}_k) = D_{\mathrm{JS}}\left[\mathcal{P}(\mathrm{T}(\vec{x}_k)|d,\mathcal{M}_1) : \mathcal{P}(\mathrm{T}(\vec{x}_k)|d,\mathcal{M}_2)|\xi\right]$

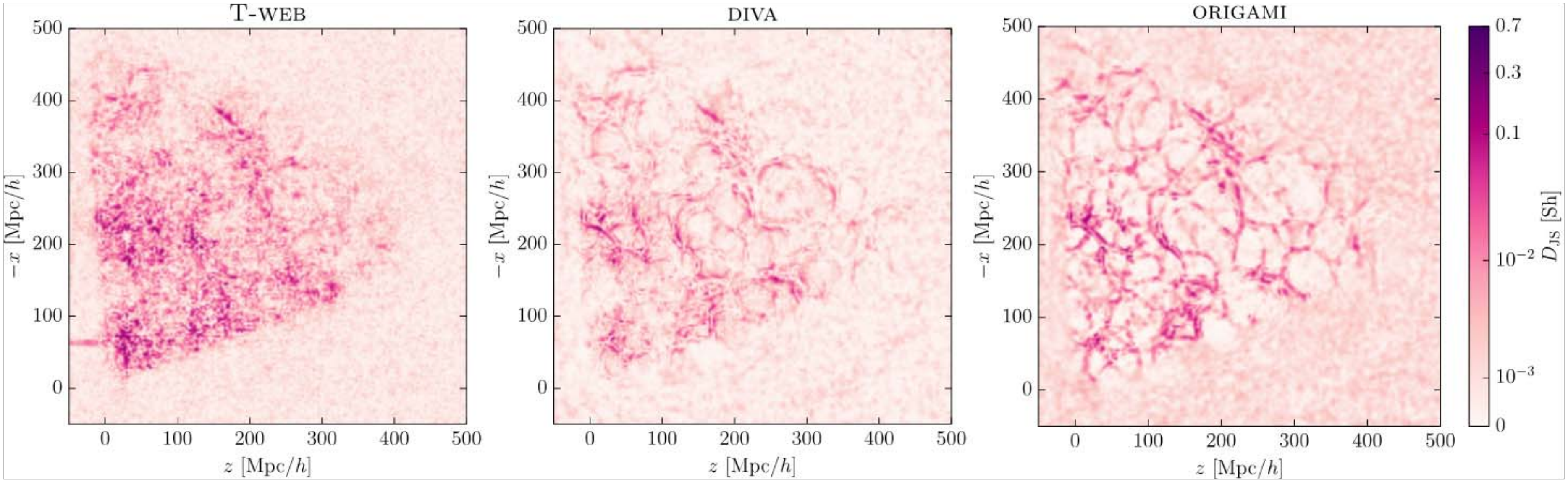
$$U_2(\xi) = I\left[\mathcal{M} : \mathcal{R}(d)|\xi\right]$$

model classifier ($\mathcal{M}$) — mixture distribution ($\mathcal{R}(d)$)

$$\mathcal{R}(d) \equiv \frac{\mathcal{P}(\mathrm{T}(\vec{x}_k)|d,\mathcal{M}_1) + \mathcal{P}(\mathrm{T}(\vec{x}_k)|d,\mathcal{M}_2)}{2}$$

FL, Lavaux, Jasche & Wandelt 2016, arXiv:1606:06758.

Information about DE equation of state in web type classification



Recent progress

- Lavaux and Jasche (in prep.)
- Now includes ***redshift space distortions***
- **~10 times faster sampling**
- Example:
  - 2M++ catalog (67, 224 galaxies from the (based on 2MRS, 6dF and SDSS-DR7))
  - Comoving cubic box of 677.7 Mpc/h
  - 256^3 grid, resolution 2.64 Mpc/h => 17 million parameters
  - 3 bias parameters and mean galaxy density sampled, each per subcatalog
  - 4 luminosity bins

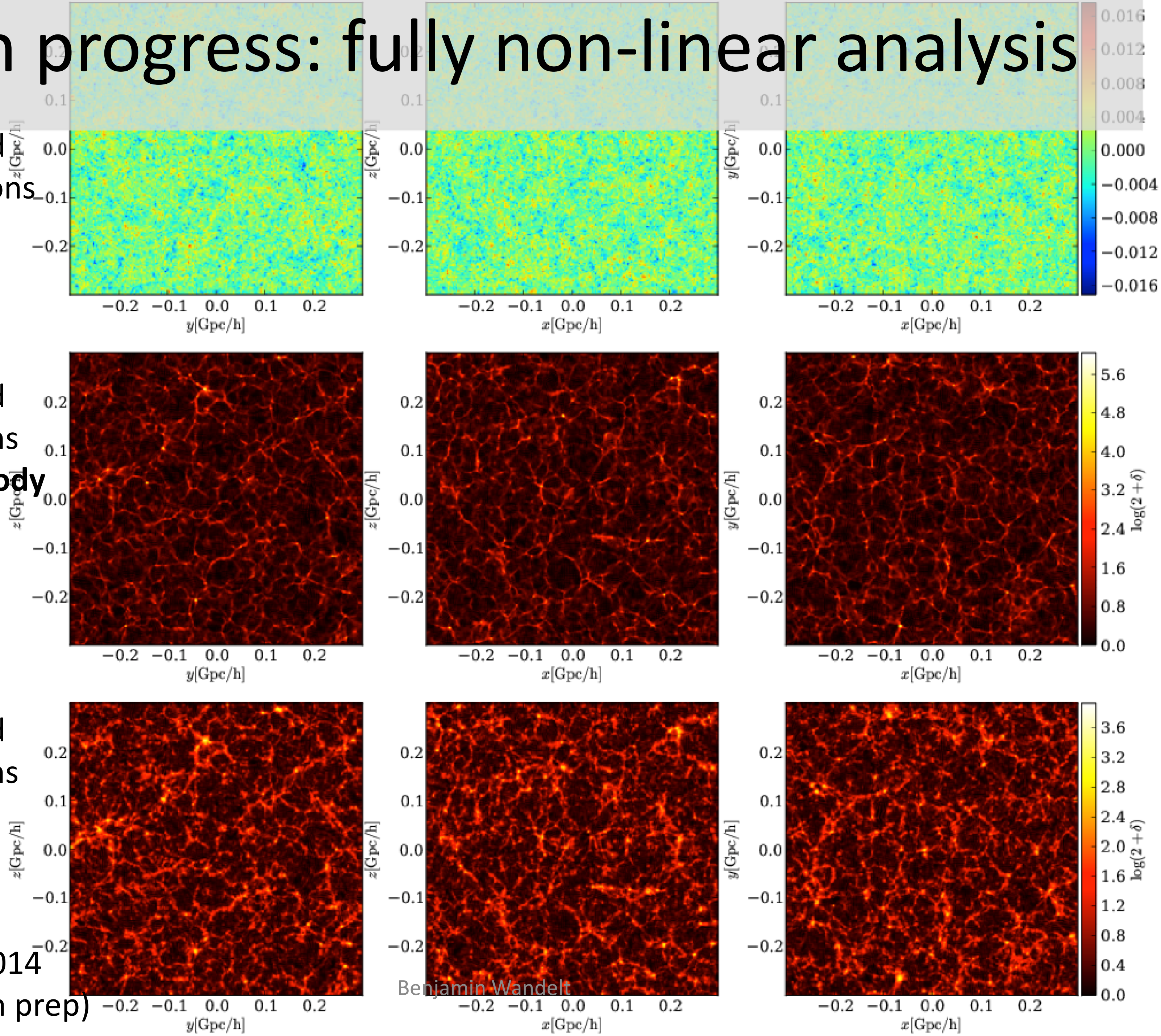
In progress: fully non-linear analysis

Reconstructed initial conditions

Reconstructed final conditions using **full N-body** dynamics

Reconstructed final conditions using **2LPT** dynamics

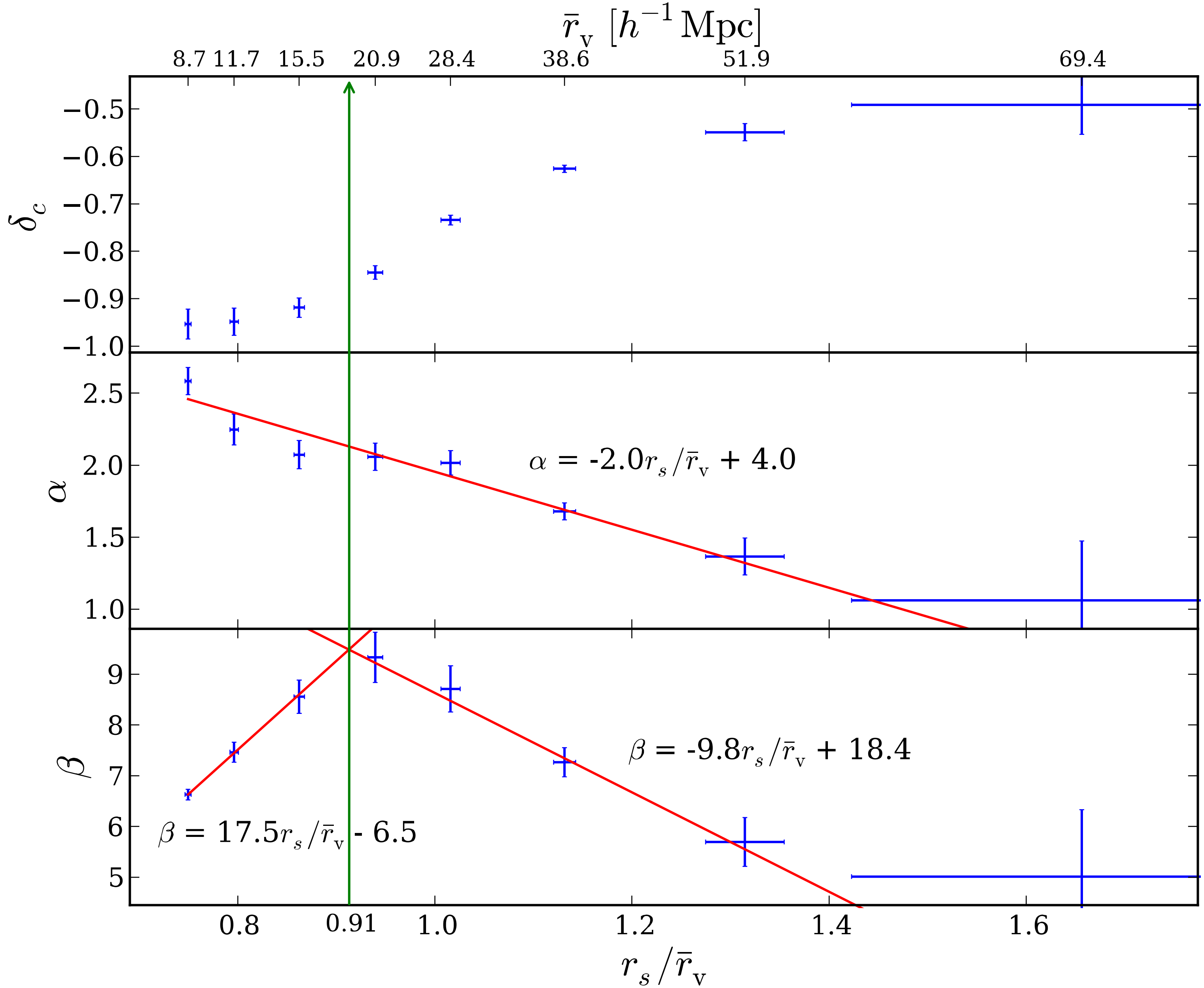
(Wang et al 2014
Jasche et al, in prep)



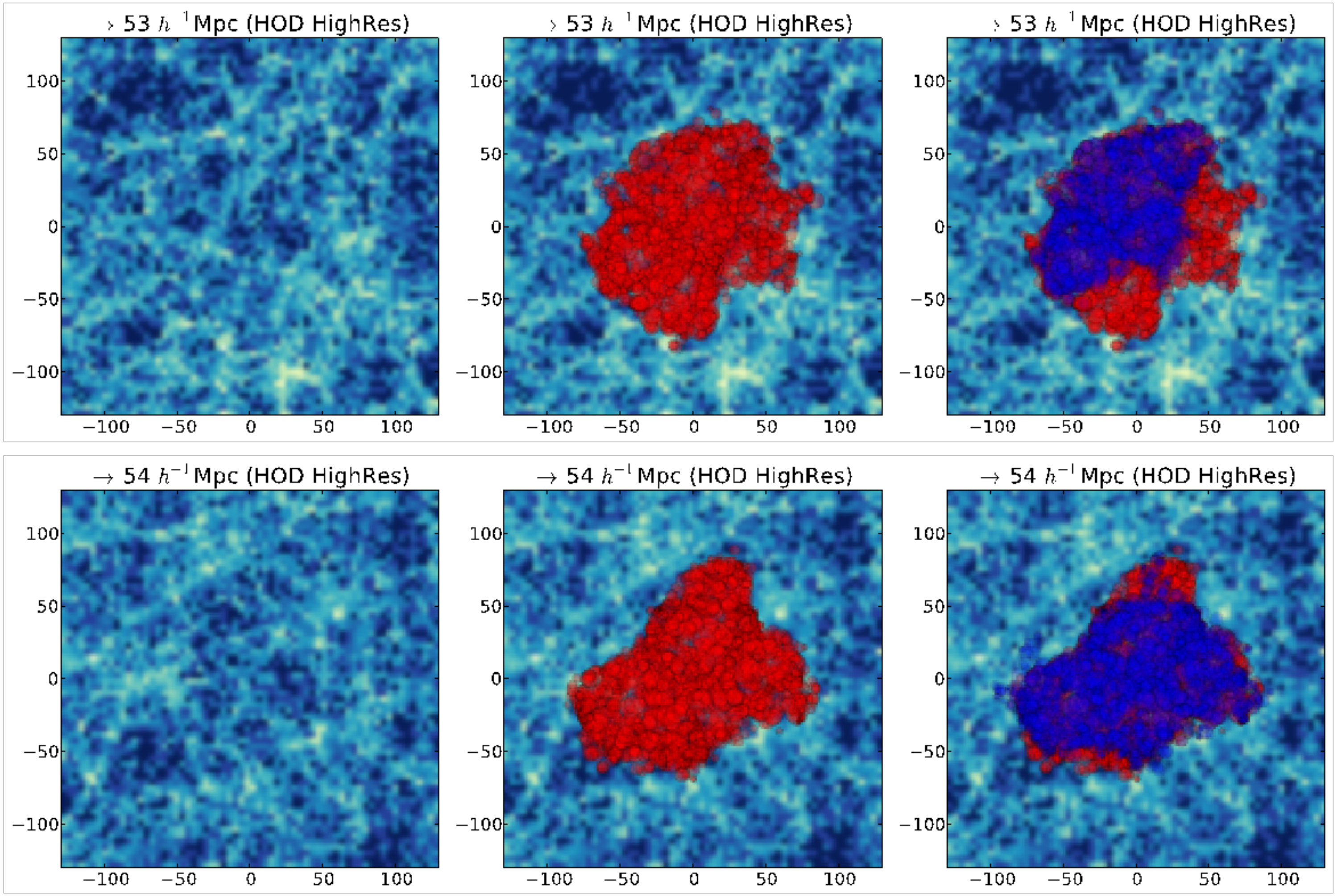
Conclusions

- Voids are a promising new line of attack for large scale structure inference for
  - Precision cosmology
  - Tests of gravity
- A new era of principled analysis of the *observable structure*, the *dynamics* and *initial conditions* of the Universe
- Information theory provides a framework for quantifying the most informative observations and data summaries beyond the power spectrum

Parameters in the void-profile



Controlling z-systematics



Pisani *et al.*, arXiv: 1506.07982