Title: Precision Cosmology with Voids

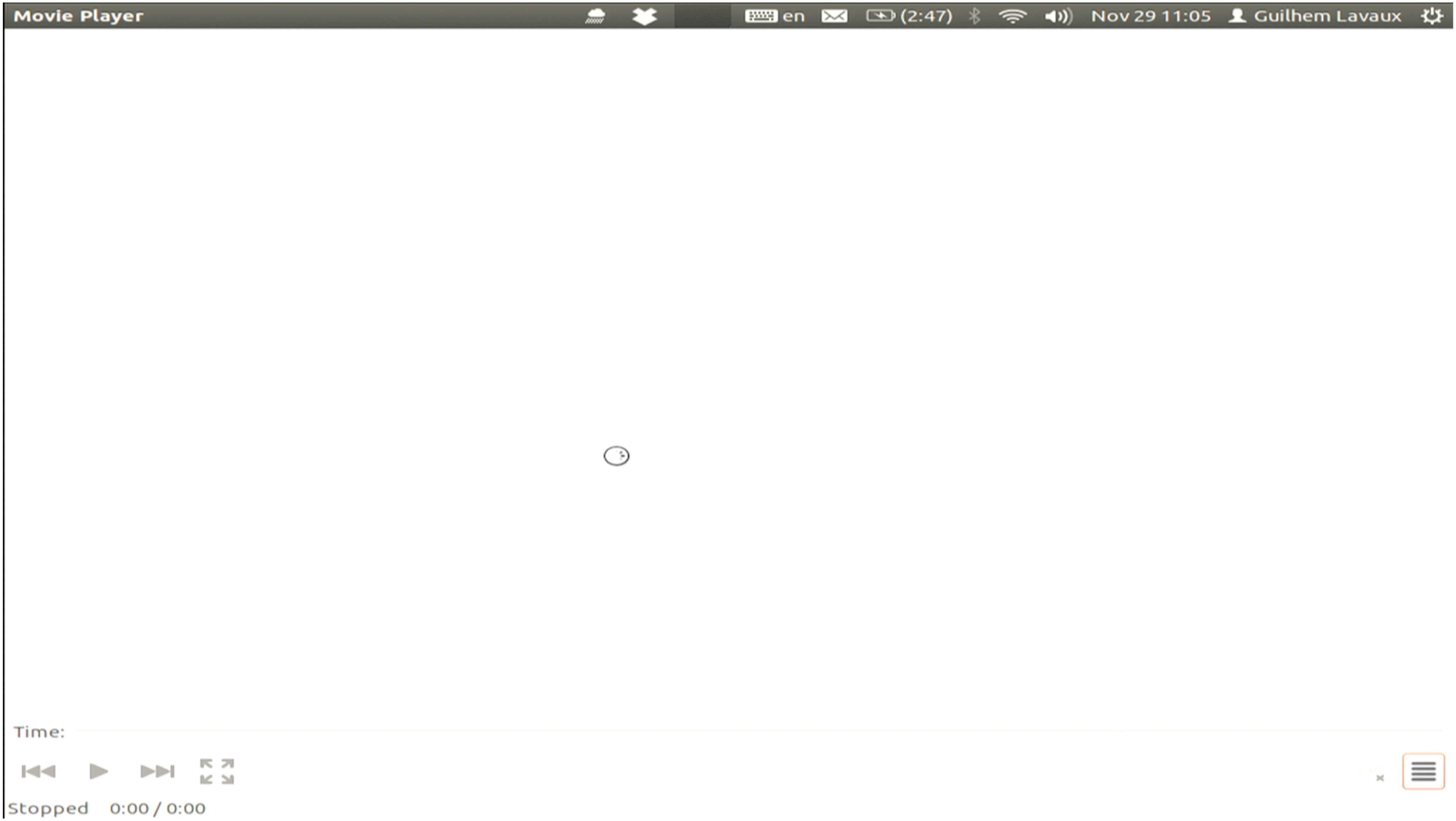
Date: Nov 29, 2011 11:00 AM

URL: http://pirsa.org/11110098

Abstract: The advent of large spectroscopic surveys of galaxies in the early 1980s has shown us that galaxies assemble in large scale structures. Recently, cosmic voids have received more attention through the availability wide and deep galaxy surveys. Voids have a simple phase space structure and thus are easier to model than cluster of galaxies.

I will present two important applications of the precise analysis of voids in the context of constraining the equation of state of dark energy. First I will discuss how they could be used to have a much better determination of the expansion factor than using traditional methods, like Baryonic Acoustic Oscillations. Second, I will show that voids is maybe the only large-scale structure for which the dynamics can be finely modelled, notably through the use of the Monge-Ampere-Kantorovitch orbit reconstruction method.

For the two above cases, I will present how we can mathematically define cosmic voids, the methods that have been developed to find them and some results based on N-body simulations for constraining the Dark Energy equation of state.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Nov 29 11:05
Guilhem Lavaux
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Why voids for doing cosmology ?

Evolution of Large Scale Structures

Void observations

Counting — Easy ?

Shape — Easy ?

Depends on void definition
+
Distortion by expansion
but
Easy dynamics

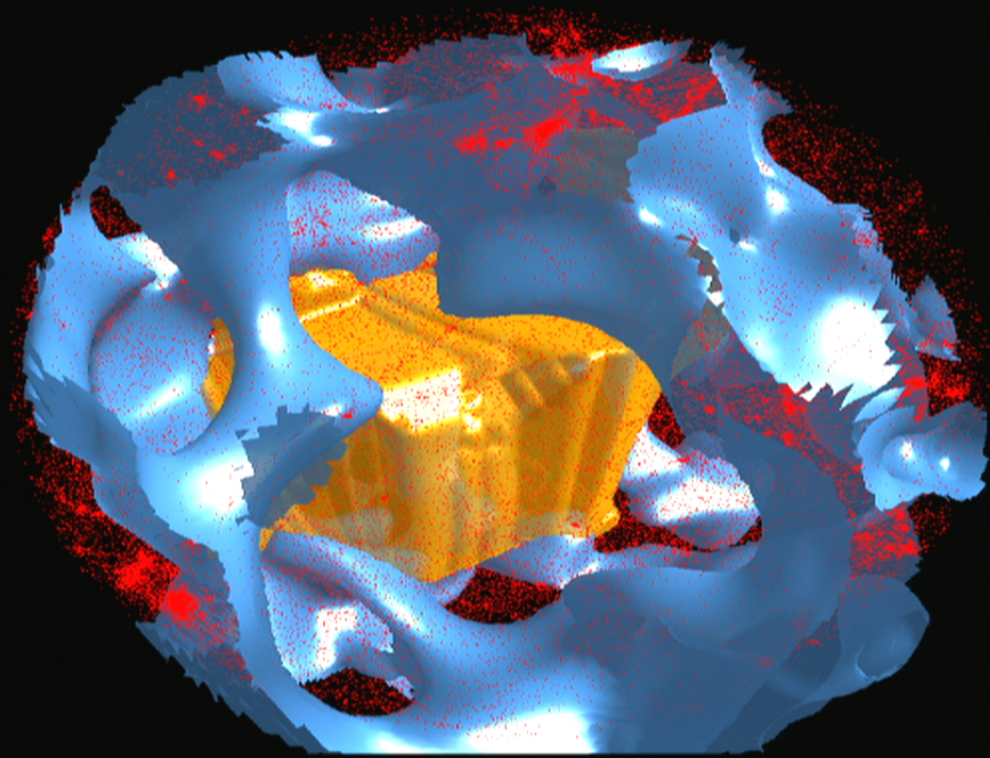
Cluster observations

Counting — Easy

Shape — Difficult
Loss of information

Less dependent on definition
but
Complicated dynamics
Strong redshift distortions

Outline

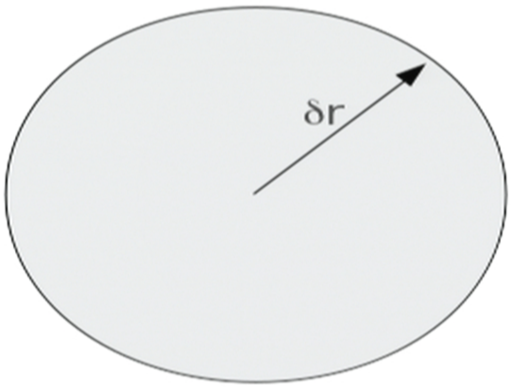


1.
Voids as cosmic stopwatches

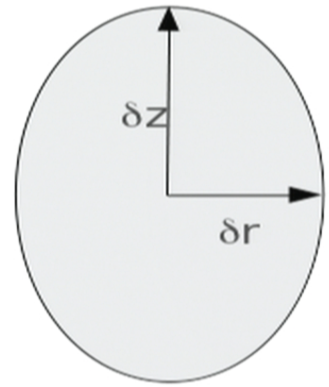
2.
Voids as tracers of the dynamics

The Alcock-Paczynski test

Physical structure



Actual observed shape



The redshift depth-vs-angular size relation

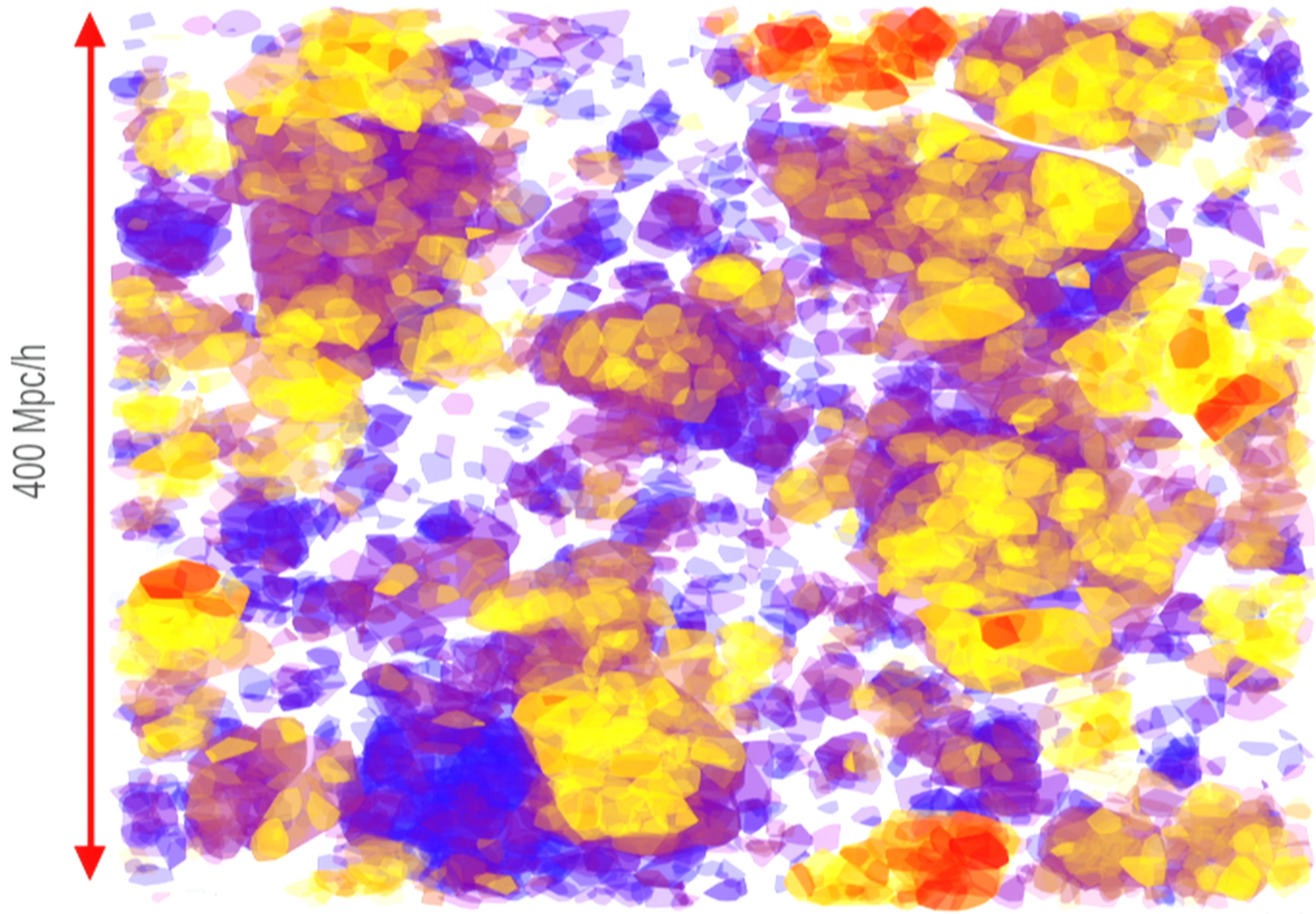
$$\frac{\delta z}{\delta r} = \underbrace{\left(\frac{D_A(z)}{z f'_k(\chi(z))}\right)}_{\text{Weaker cosmological dependence}} \underbrace{\frac{H(z)}{H(z=0)}}_{\text{Hubble constant}}$$

Weaker cosmological dependence

Hubble constant
Depends on Ω_m, Ω_X, w_i

Ryden (1995), Lavaux & Wandelt (2011)

A-P test on voids : directly no

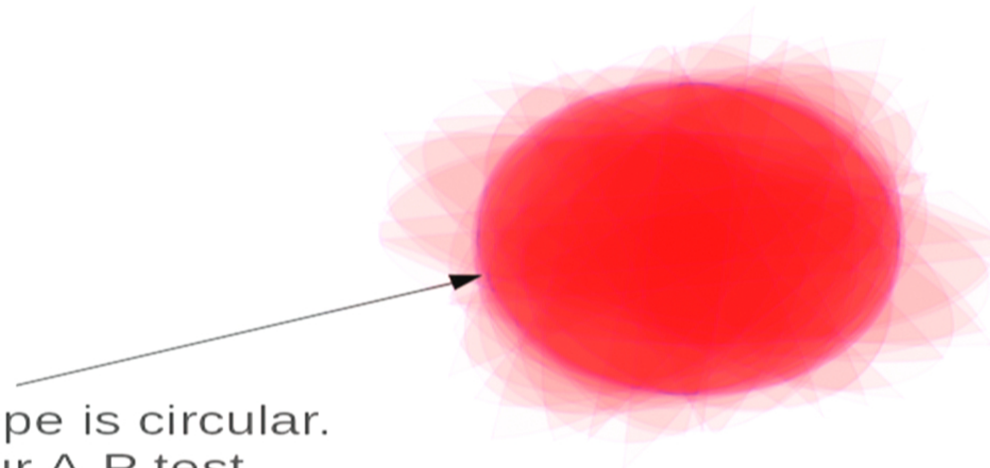


Various size and shape for voids

No clear physical scale

Lavaux & Wandelt (2011, submitted to ApJ)

A-P test on stacked voids



This envelope is circular.
We have our A-P test.

Stacking voids algorithm

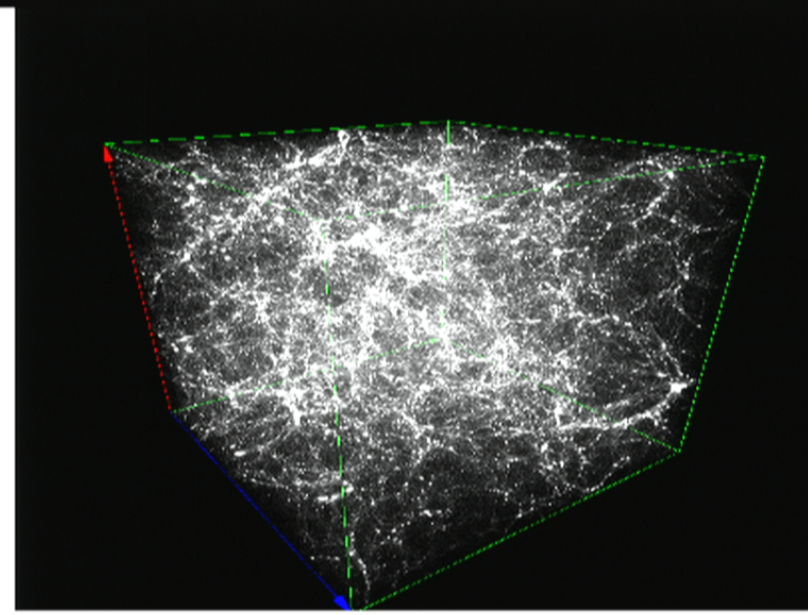
Density tracers (galaxies, particles)

↓

Put in (r,z) coordinates

↓

Extract a parallelepipedic volume mapped to a cube



Stacking voids algorithm

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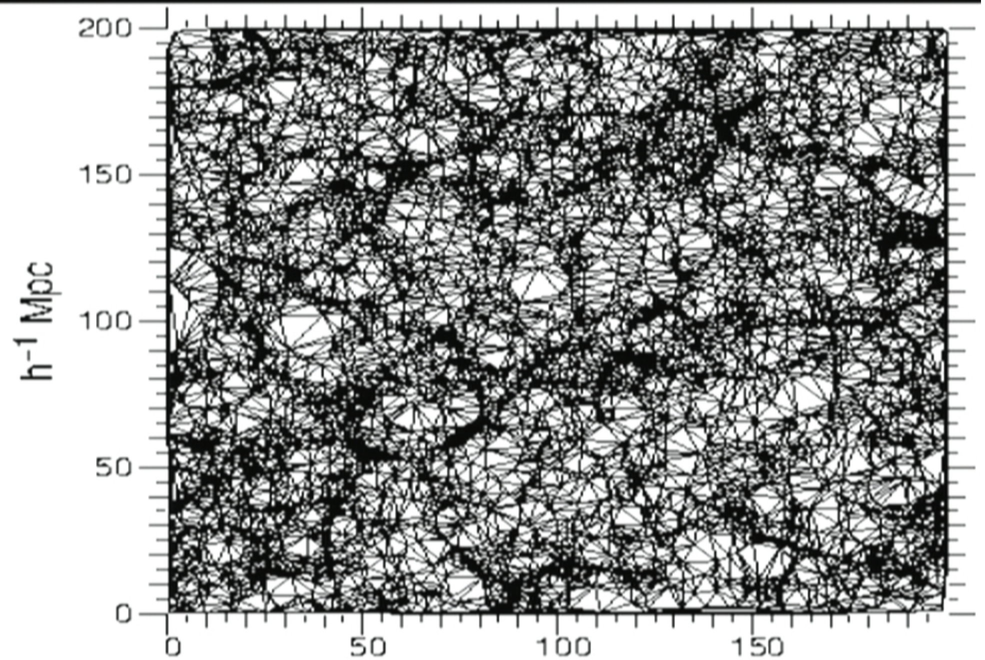
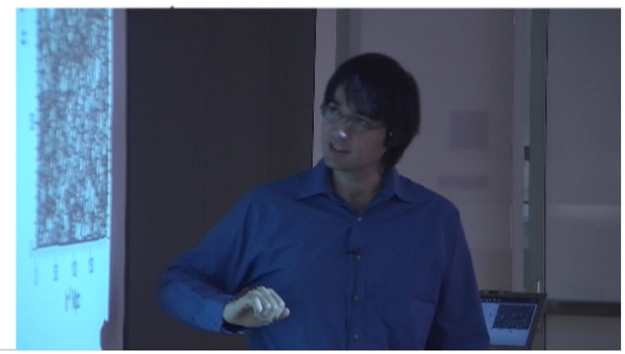
ZOBOV (Neyrinck 2008)





Stacking voids algorithm

Density tracers (galaxies, particles)

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Extract a parallelepipedic volume mapped to a cube

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ZOBOV

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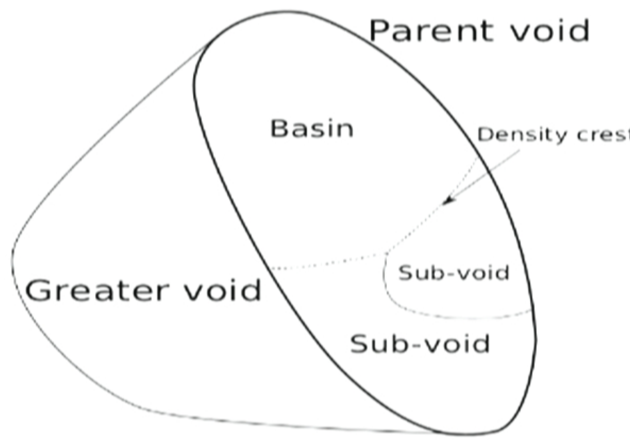
Organize voids in a tree



Stacking voids algorithm

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Extract a parallelepipedic volume mapped to a cube

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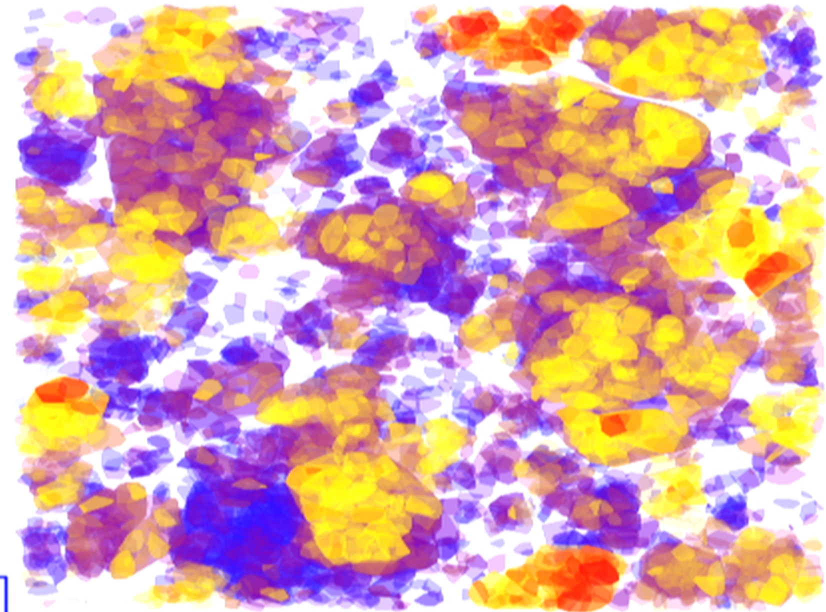
ZOBOV

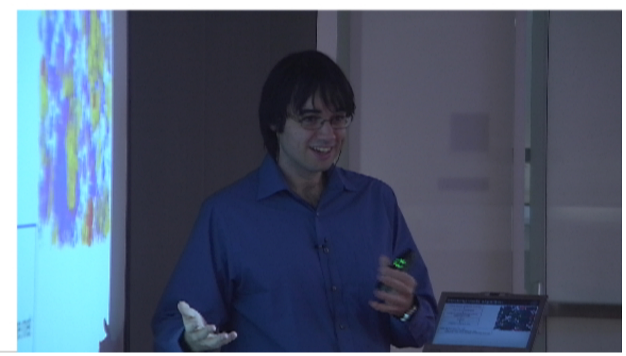
↓

Organize voids in a tree

↓

Walk the tree from the root :
- stop if volume constraints are met
- optionally, stop when density constraints are met





Stacking voids algorithm

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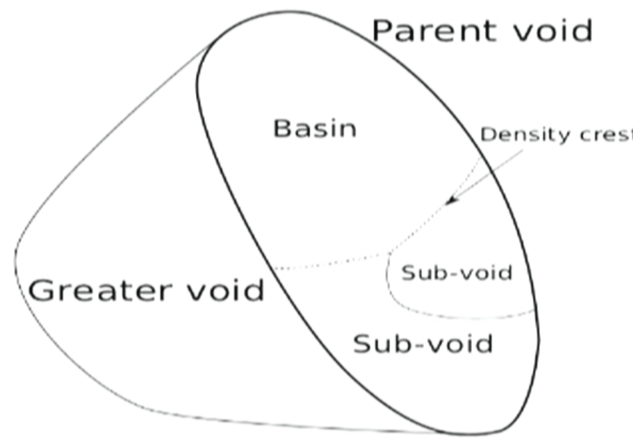
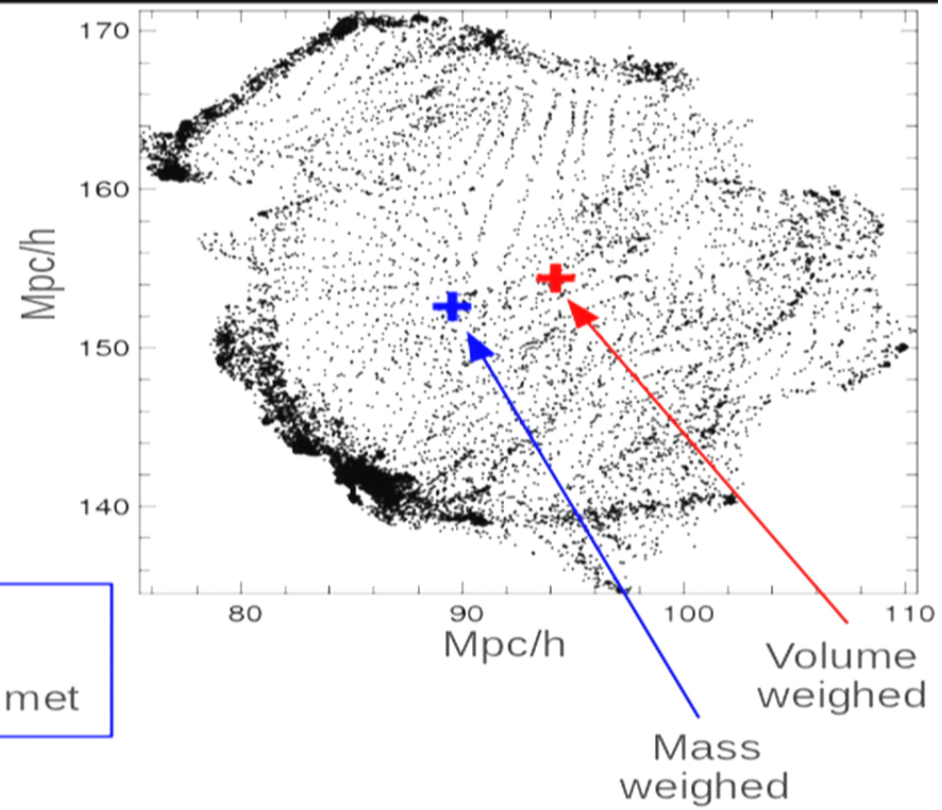


Stacking voids algorithm

- Density tracers (galaxies, particles)
- Put in (r,z) coordinates
- Extract a parallelepipedic volume mapped to a cube
- ZOBOV
- Organize voids in a tree
- Walk the tree from the root :
  - stop if volume constraints are met
  - optionally, stop when density constraints are met
- Compute volume barycenter of selected voids



Stacking voids algorithm

Density tracers (galaxies, particles)

↓

Put in (r,z) coordinates

↓

Extract a parallelepipedic volume mapped to a cube

↓

ZOBOV

↓

Organize voids in a tree

↓

Walk the tree from the root :
- stop if volume constraints are met
- optionally, stop when density constraints are met

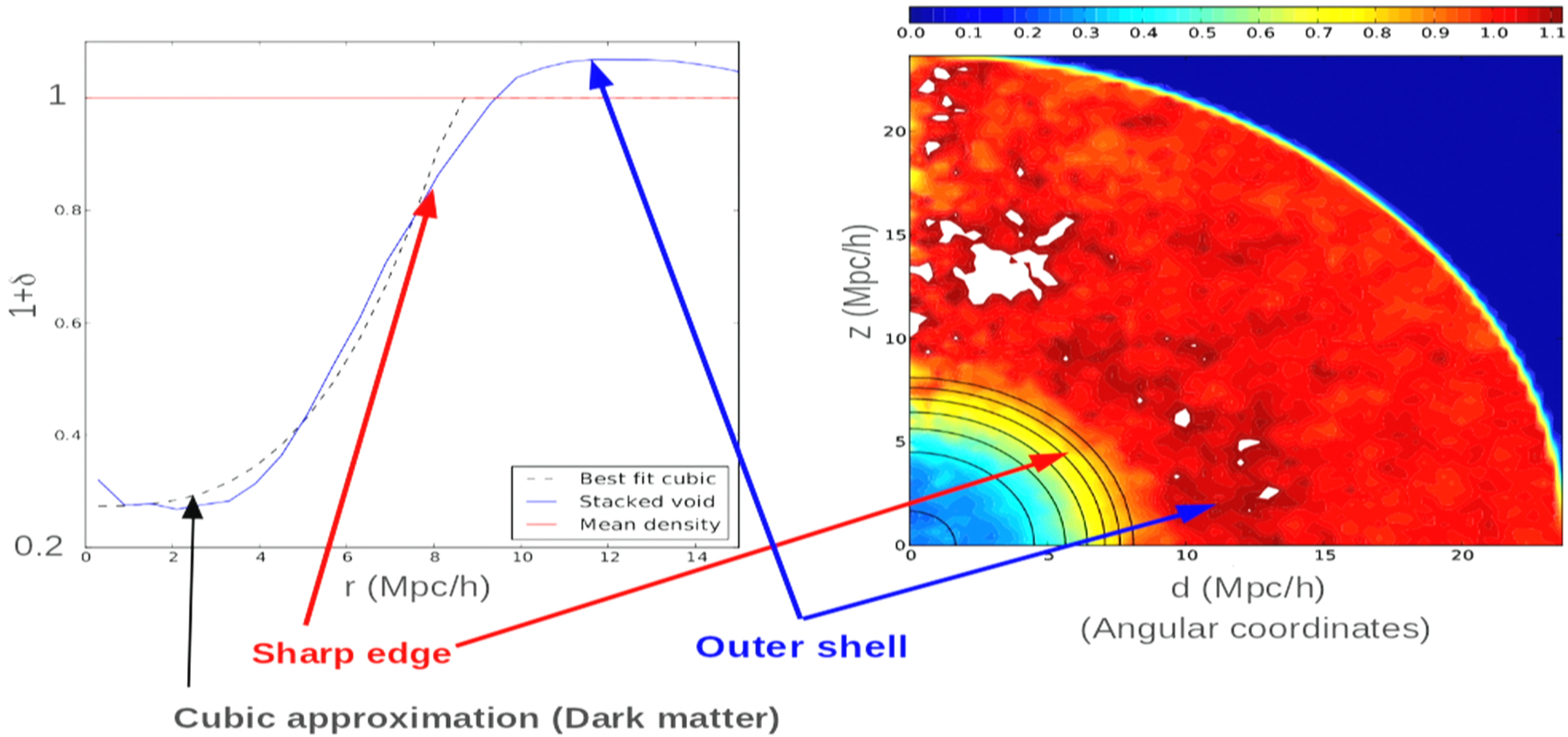
↓

Compute volume barycenter of selected voids

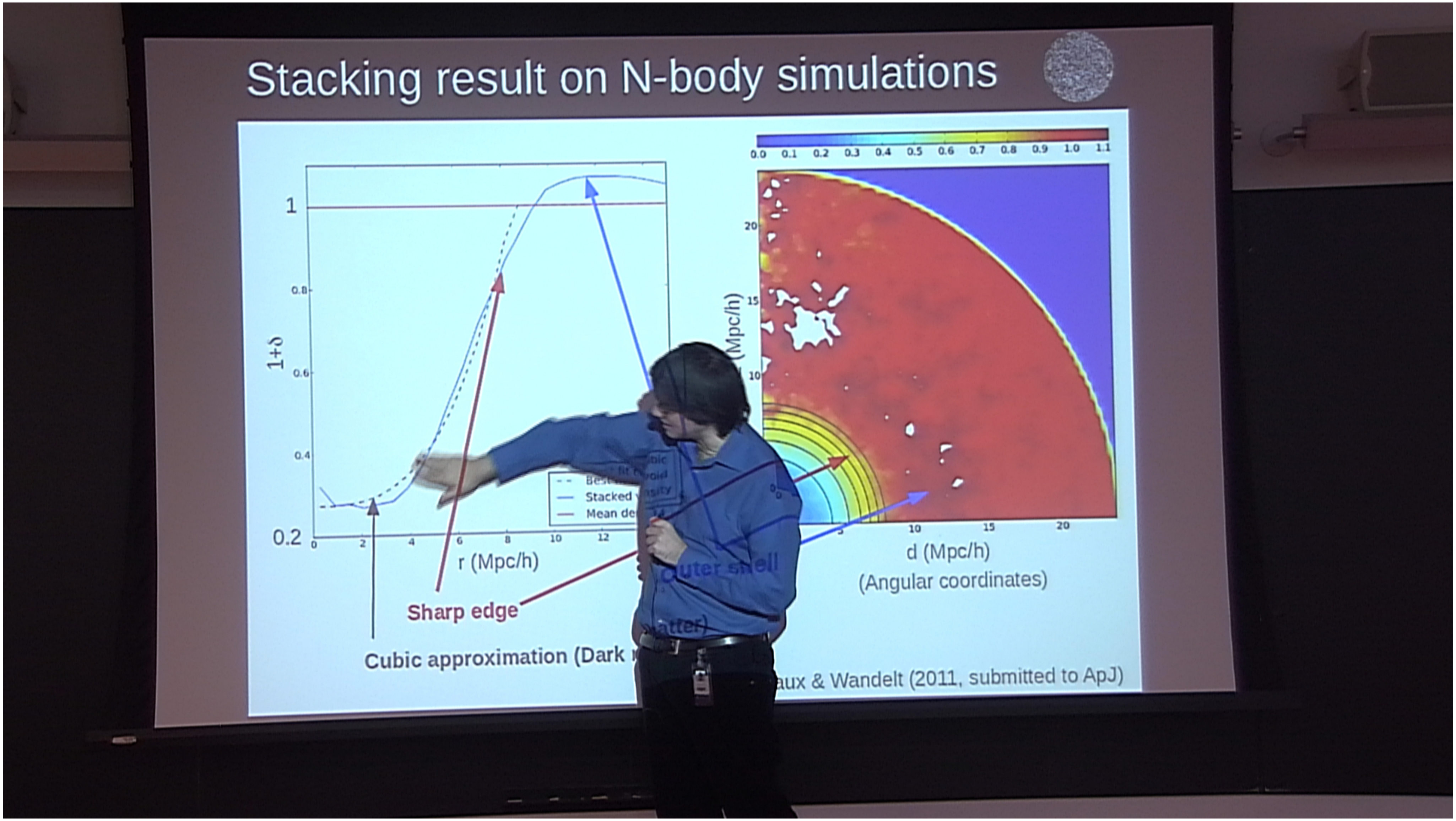
↓

Extract spheres in (r,z), centred on barycenters

Stacking result on N-body simulations

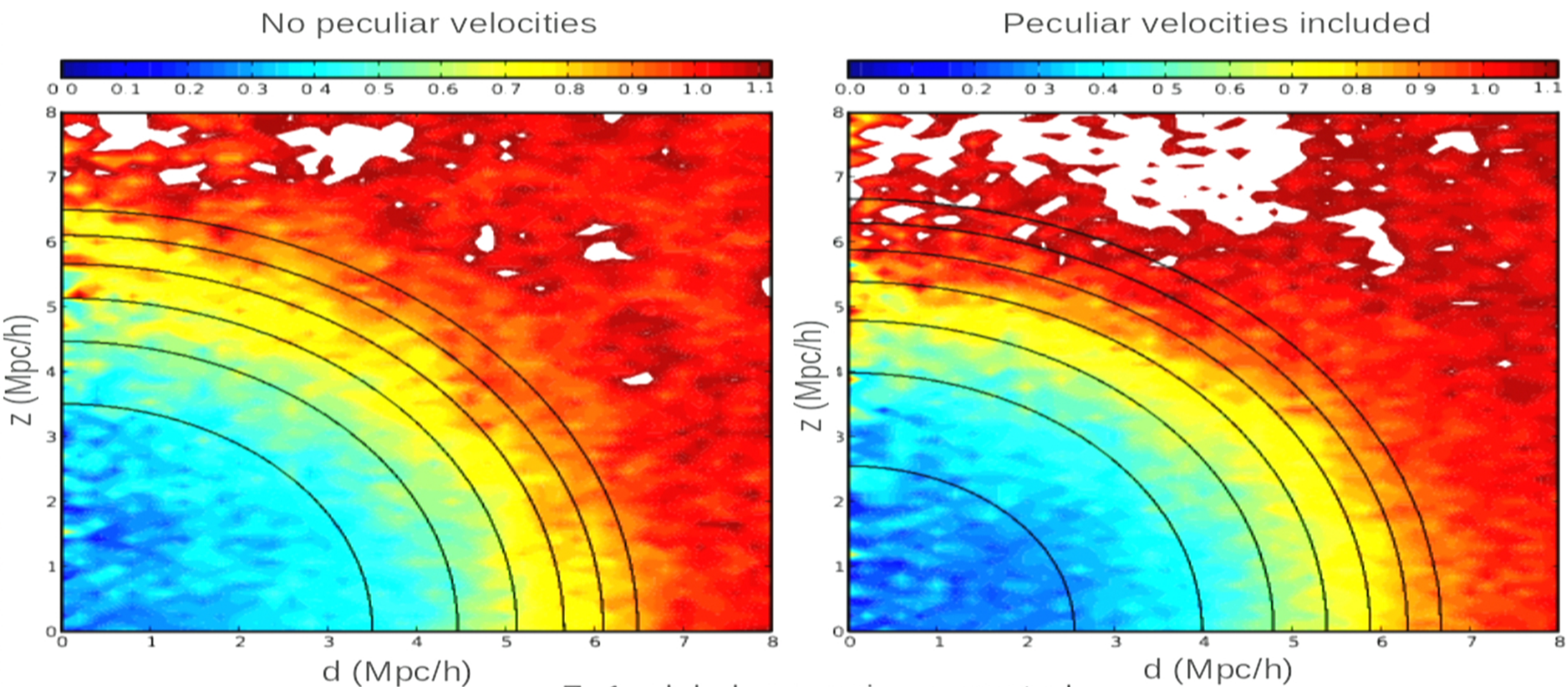


Lavaux & Wandelt (2011, submitted to ApJ)



Stacking result on N-body simulations
1+δ
r (Mpc/h)
Stacked
Mean de
d (Mpc/h)
(Angular coordinates)
Sharp edge
Cubic approximation (Dark
aux & Wandelt (2011, submitted to ApJ)

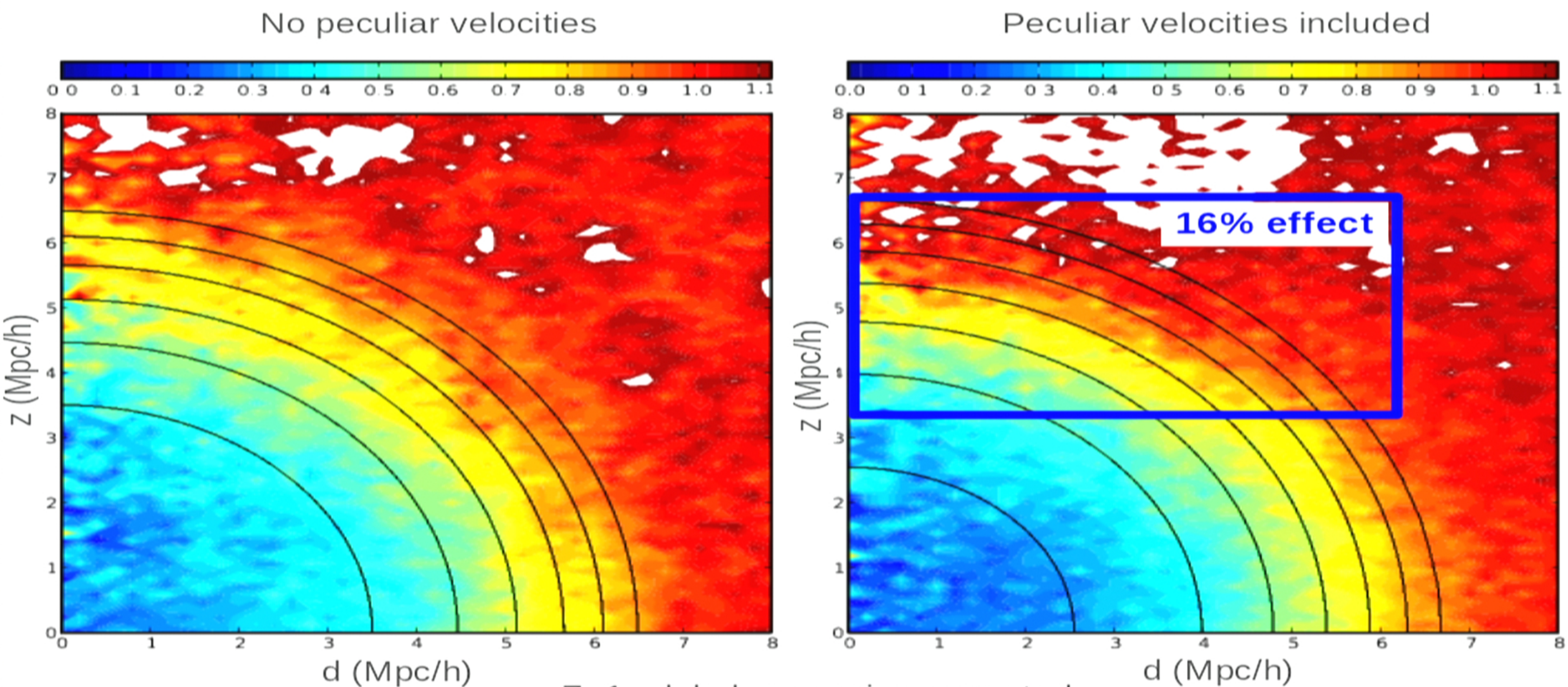
Redshift distortion contamination



Z=1, global expansion corrected

Lavaux & Wandelt (2011, submitted to ApJ)

Redshift distortion contamination



Z=1, global expansion corrected

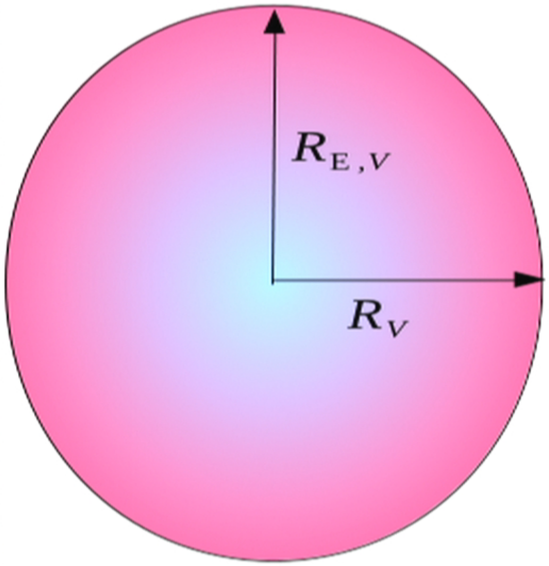
Lavaux & Wandelt (2011, submitted to ApJ)

Shape measurement

Statistical estimation of the shape

$$\chi^2(A, \mathbf{R_V}, \mathbf{R_{E,V}}, \sigma_0, \sigma_1) = \sum_p S_p \left[\frac{(n_p - \mathbf{n}(r_p, z_p))^2}{\sigma^2(r_p, z_p, n(r_p, z_p))} + \log \sigma(r_p, z_p, n(r_p, z_p)) \right]$$

Pixel mask → S_p



Void profile model

$$n_0(r) = A + B\left(\frac{r}{R_V}\right)^3$$

Stretched void profile model

$$n(d, z) = n_0\left(\sqrt{\left(\frac{d}{R_V}\right)^2 + \left(\frac{z}{R_{E,V}}\right)^2}\right)$$

$$\sigma(d, z) = \begin{cases} \sigma_0 \sqrt{\dfrac{1\ \mathrm{Mpc/h}}{d}} & \text{if } n(d, z) < n_{\max} \\ \sigma_1 & \text{otherwise} \end{cases}$$

Expansion : $E = \dfrac{R_{E,V}}{R_V}$ → Cosmology

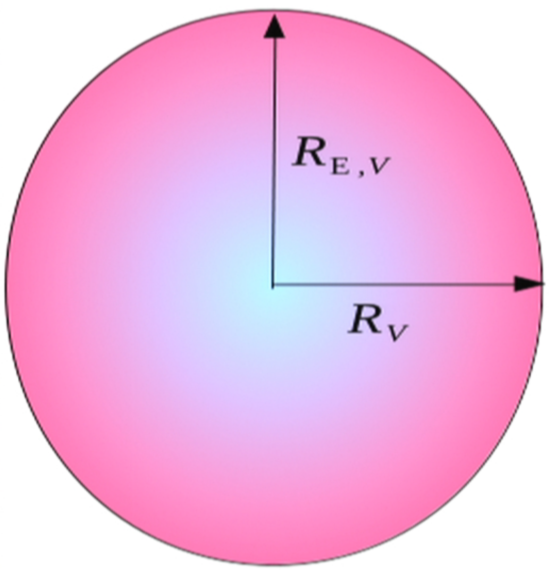
RUN

Shape measurement

Statistical estimation of the shape

$$\chi^2(A, \mathbf{R_V}, \mathbf{R_{E,V}}, \sigma_0, \sigma_1) = \sum_p S_p \left[\frac{(n_p - \mathbf{n}(r_p, z_p))^2}{\sigma^2(r_p, z_p, n(r_p, z_p))} + \log \sigma(r_p, z_p, n(r_p, z_p)) \right]$$

Pixel mask → S_p



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→

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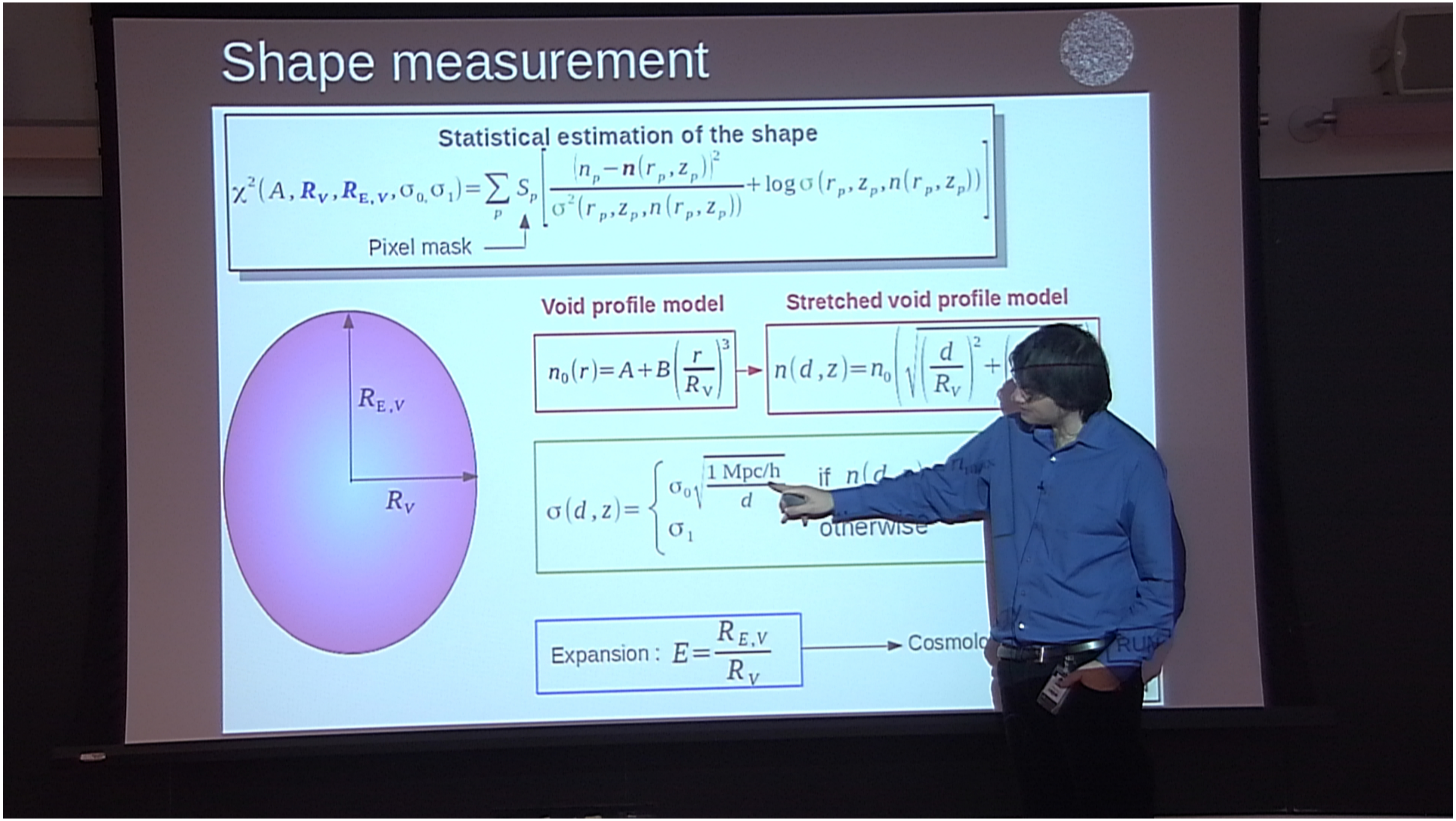
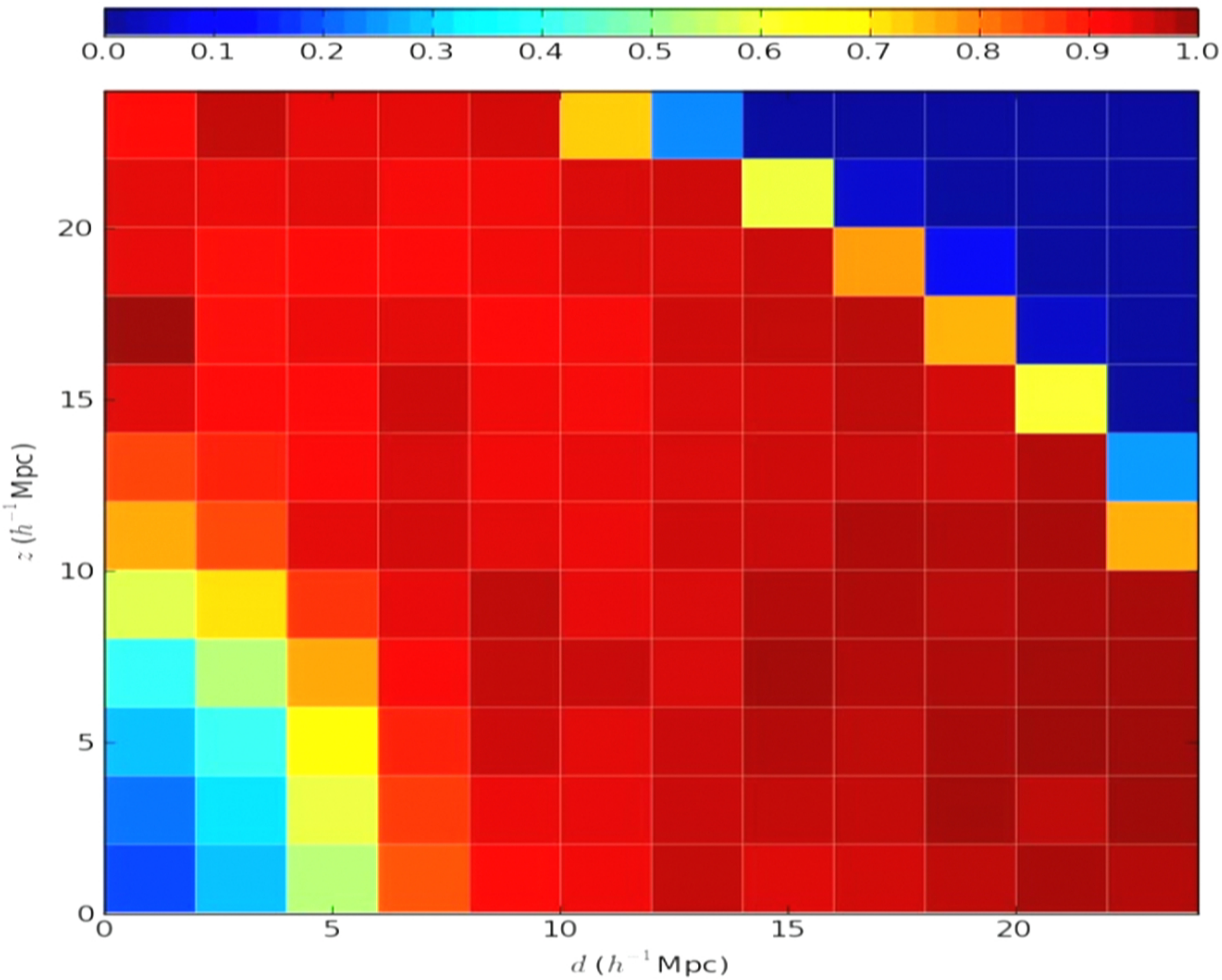
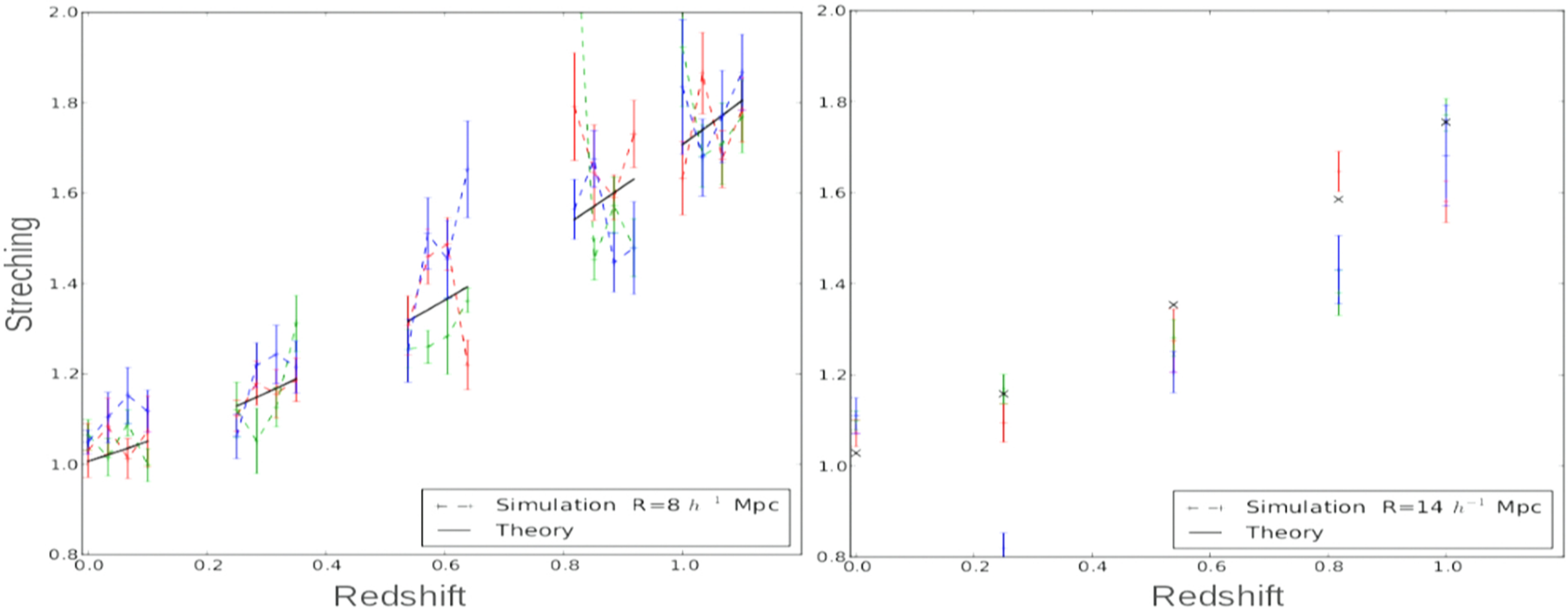
RUN


Shape measurement
Statistical estimation of the shape
$\chi^2(A, R_V, R_{E,V}, \sigma_0, \sigma_1) = \sum_p S_p \left[\frac{(n_p - n(r_p, z_p))^2}{\sigma^2(r_p, z_p, n(r_p, z_p))} + \log \sigma(r_p, z_p, n(r_p, z_p)) \right]$
Pixel mask
Void profile model
Stretched void profile model
$n_0(r) = A + B\left(\frac{r}{R_V}\right)^3$
$R_{E,V}$
R_V
Expansion : $E = \frac{R_{E,V}}{R_V}$
otherwise


0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
0 5 10 15 20
z (h^{-1} Mpc)
0 5 10 15 20
d (h^{-1} Mpc)

Hubble diagram for voids

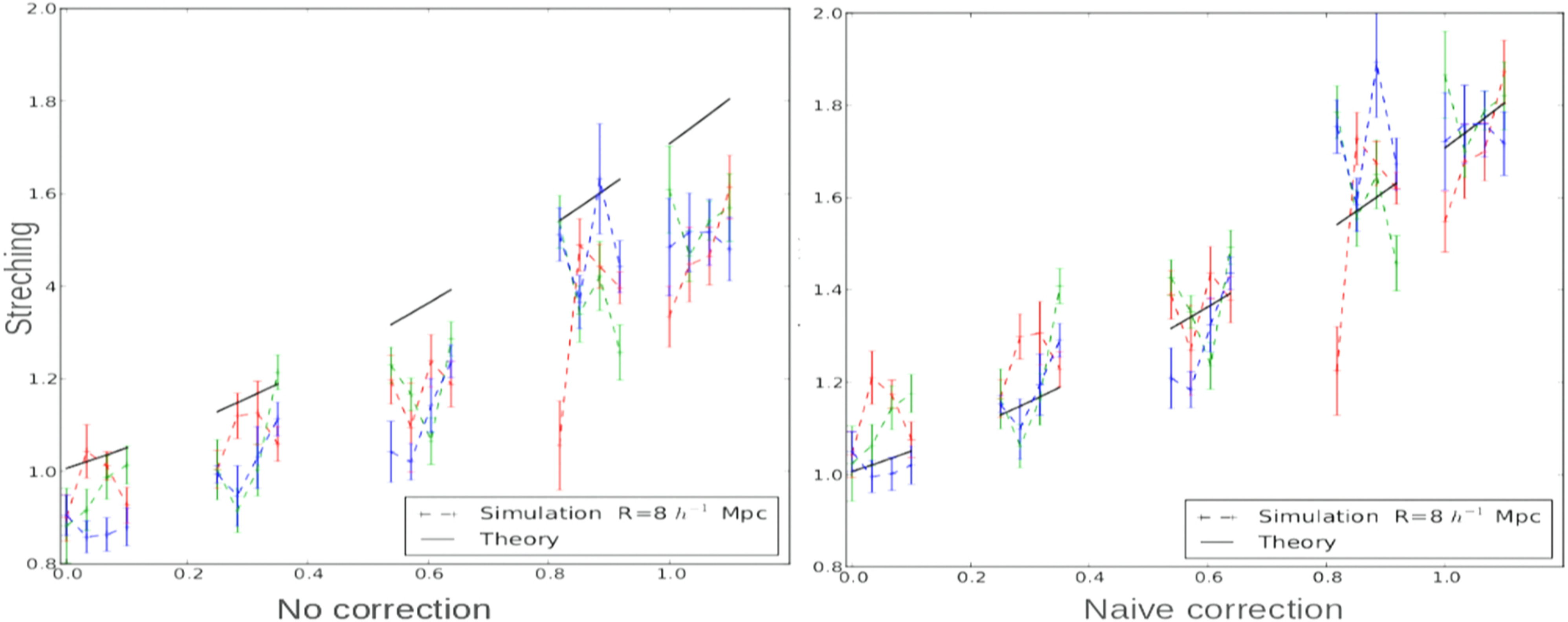


6 Mpc/h voids

14 Mpc/h voids

Lavaux & Wandelt (2011, submitted to ApJ)

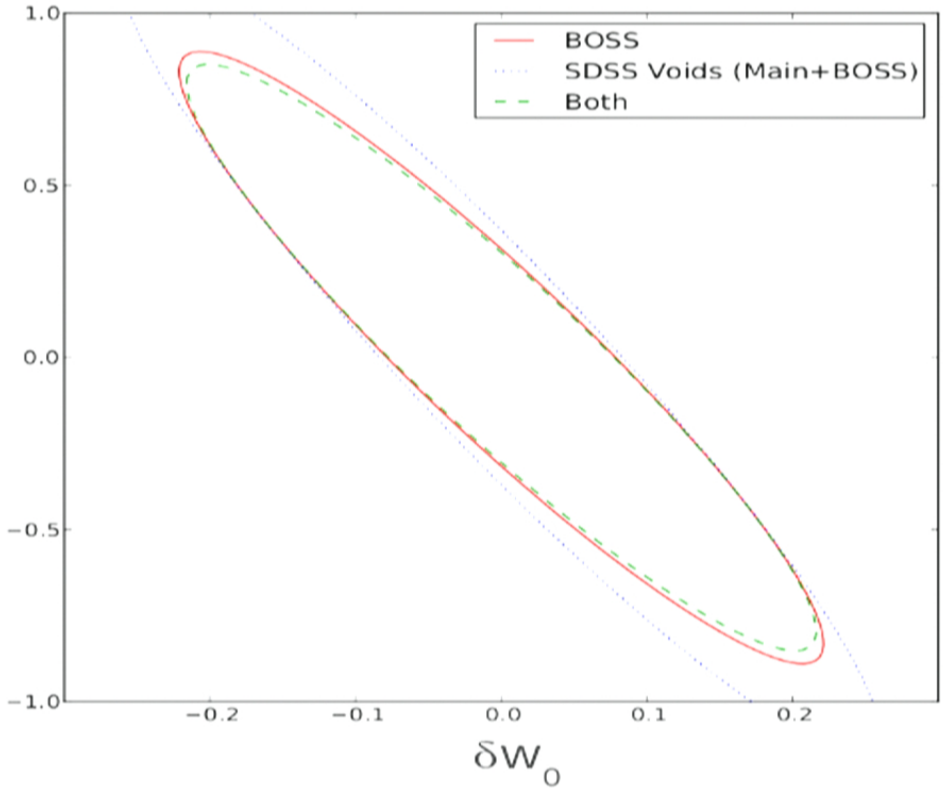
Correction needed for peculiar velocities



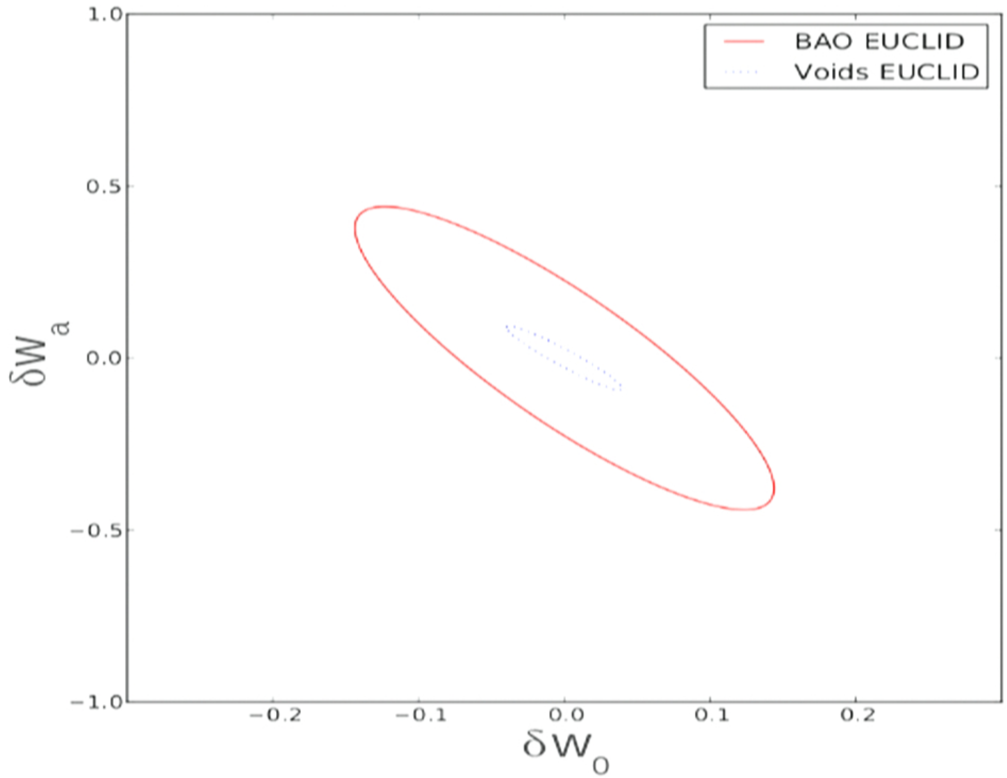
8 Mpc/h

Lavaux & Wandelt (2011, submitted to ApJ)

Fisher-Matrix analysis



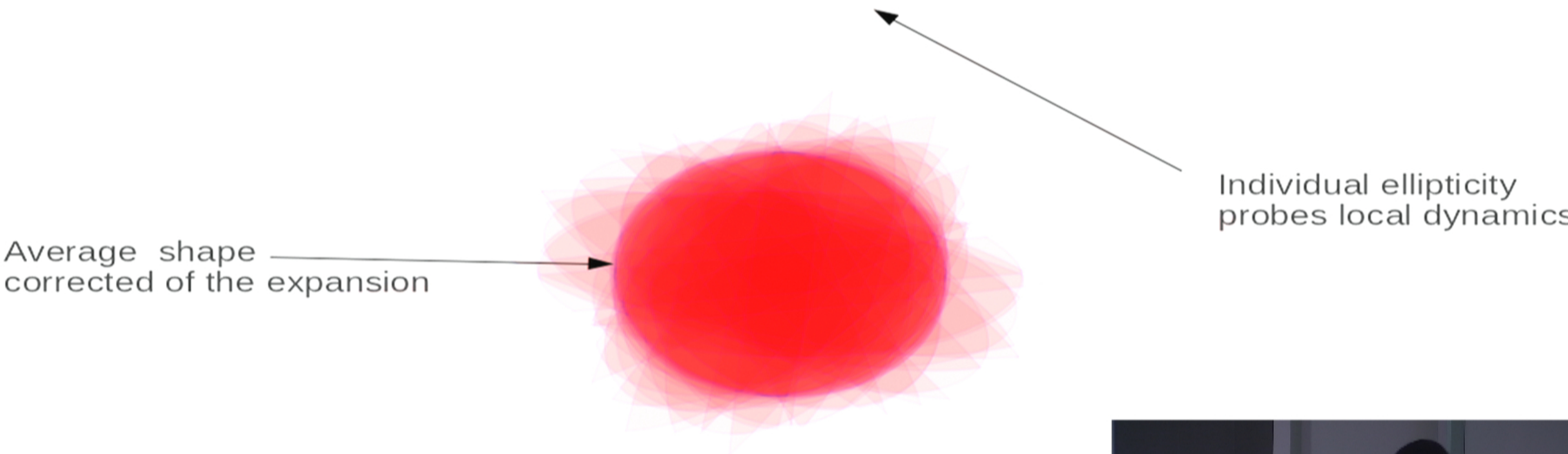
FoM voids/BAO = 0.73

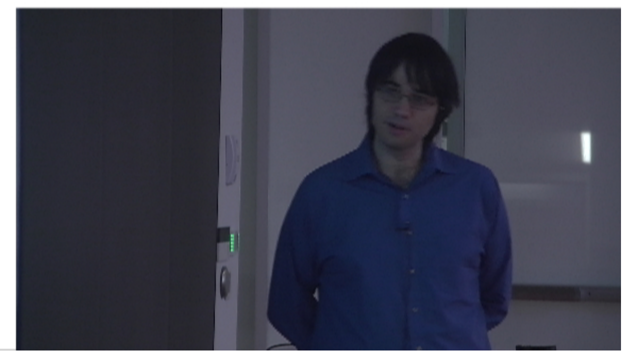


FoM voids/BAO ~ 60

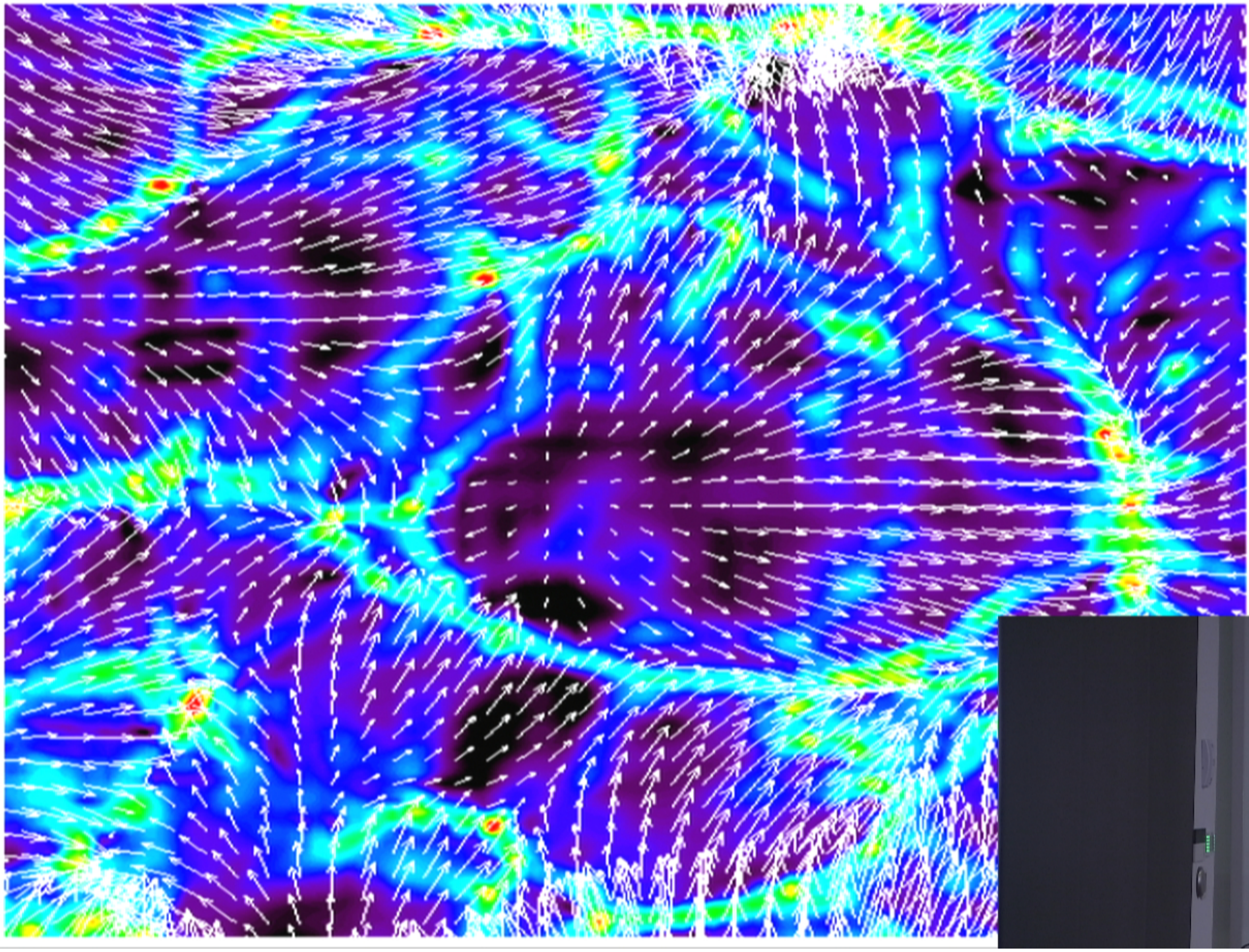
Lavaux & Wandelt (2011, submitted to ApJ)

Dynamics on top of the expansion



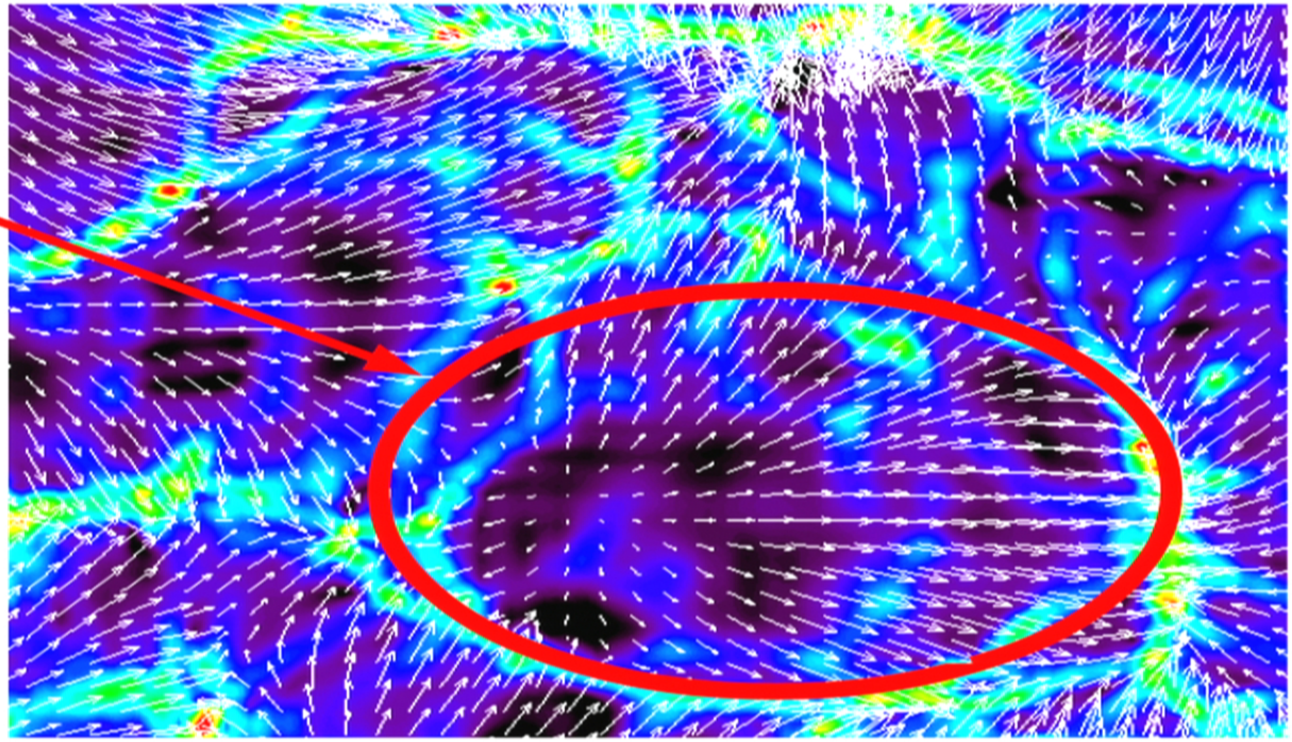


Velocity field and voids



Velocity field and voids

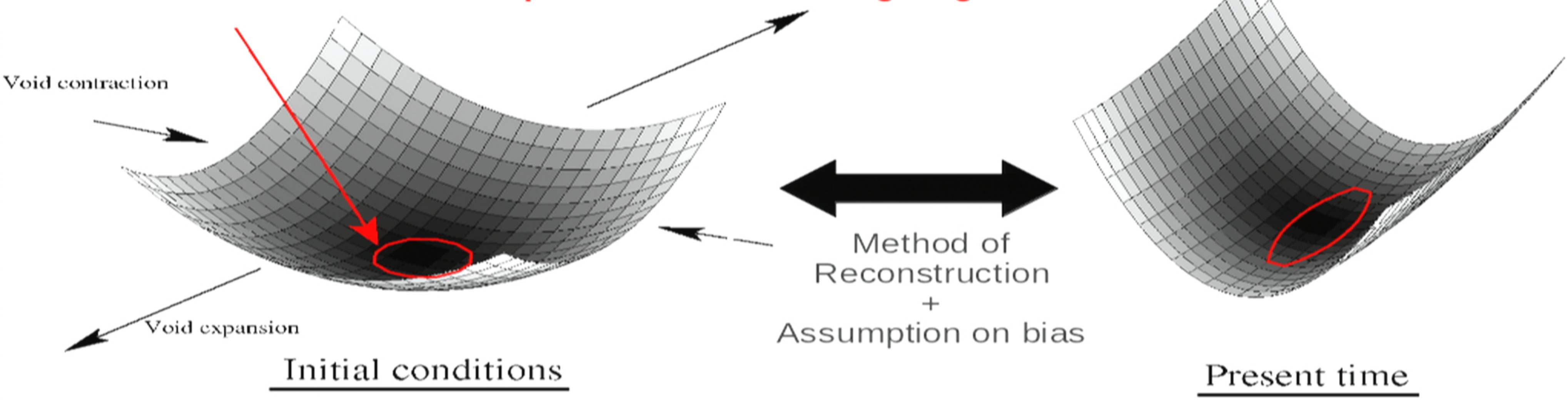
Ellipticity ε



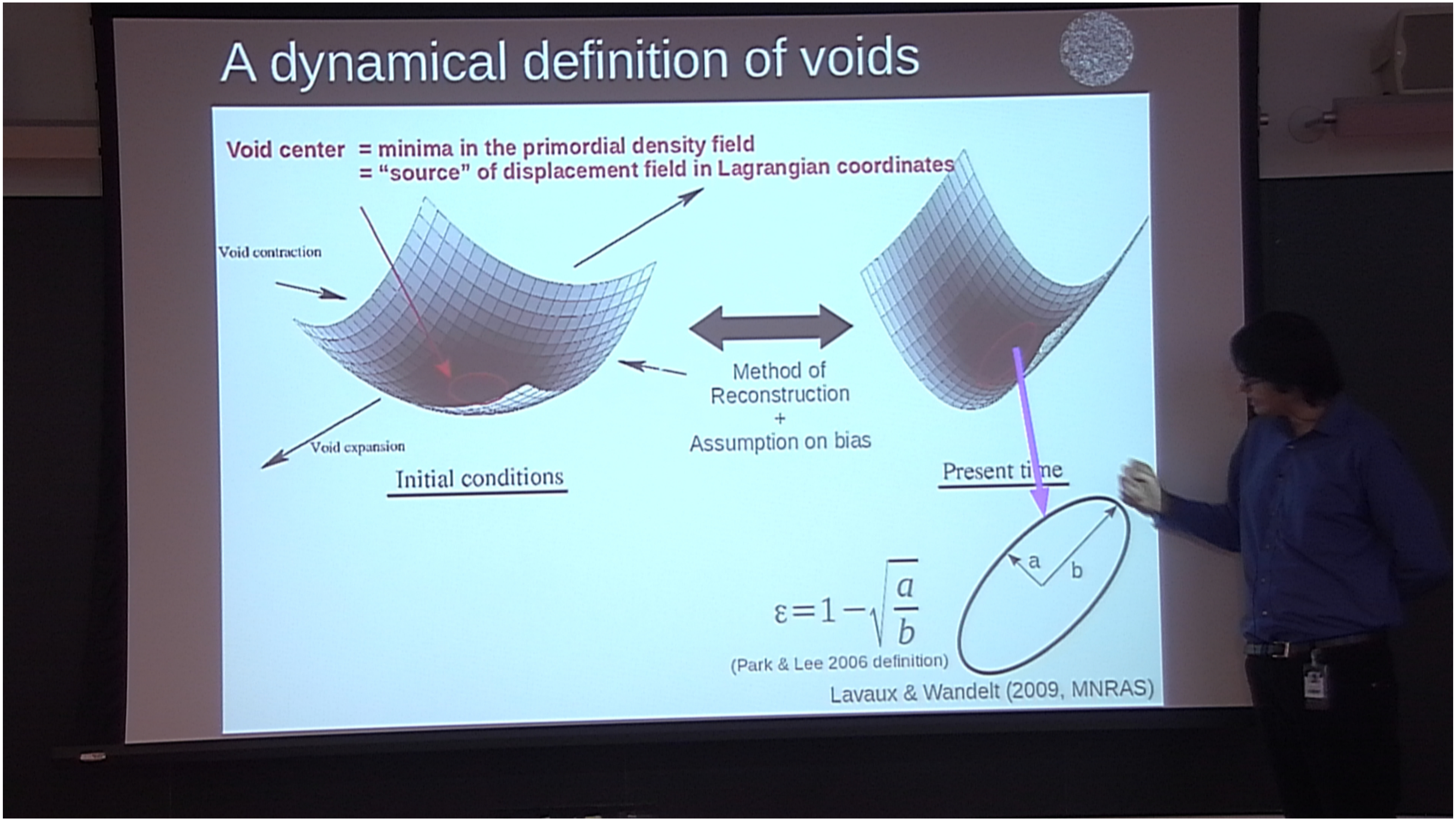
Local dynamical criterion → Require a different class of « void finder »

A dynamical definition of voids

Void center = minima in the primordial density field
= "source" of displacement field in Lagrangian coordinates



Lavau


A dynamical definition of voids
Void center = minima in the primordial density field
= "source" of displacement field in Lagrangian coordinates
Void contraction
Void expansion
Initial conditions
Method of
Reconstruction
+
Assumption on bias
Present time
a
b
$\varepsilon = 1 - \sqrt{\frac{a}{b}}$
(Park & Lee 2006 definition)
Lavaux & Wandelt (2009, MNRAS)

Algorithm for reconstructing orbits of galaxies (MAK)

Hypothesis Convex potential mapping between Lagrangian (q) and Eulerian (x) coordinates

⇔**no** shell crossing

Physics principle Mass conservation

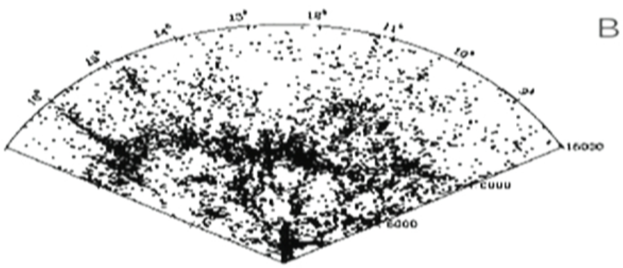
Monge-Ampère

$$\left|\frac{\partial^2 \Phi}{\partial x_i \partial x_j}\right|_{i,j} = \frac{\rho(\vec{x})}{\rho_{\text{initial}}}$$

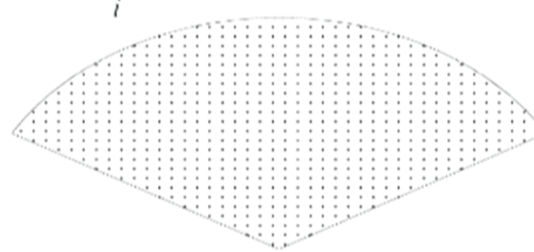
Monge-Kantorovitch

$$\begin{cases} I[\boldsymbol{q}(\boldsymbol{x})] = \int \rho(\boldsymbol{x}) |\boldsymbol{x} - \boldsymbol{q}(\boldsymbol{x})|^2 d^3 \boldsymbol{x} \\ S_\sigma = \sum_i (\vec{\boldsymbol{x}}_{i,\text{final}} - \vec{\boldsymbol{x}}_{\sigma(i),\text{initial}})^2 \end{cases}$$

Brenier et al. 2003



Final



Initial

Least action principle

Algorithm for reconstructing orbits of galaxies (MAK)

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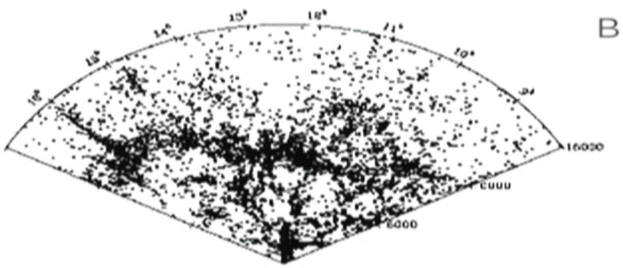
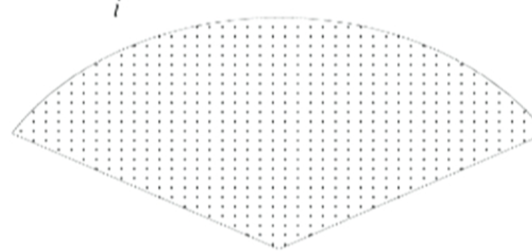


Final



Initial

Least action principle

Ellipticity statistics

Gaussian random field statistics (Doroschkevich 1970)

$$P(\lambda_1, \lambda_2, \lambda_3|\sigma) = \frac{3375}{8\sqrt{5}\sigma^6\pi} \exp\left[\frac{3\left(2K_1^2 - 5K_2\right)}{2\sigma^2}\right] |(\lambda_1 - \lambda_2)(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)|$$

$$K_1 = \lambda_1 + \lambda_2 + \lambda_3 \qquad K_2 = \lambda_1\lambda_3 + \lambda_1\lambda_2 + \lambda_2\lambda_3$$

Ellipticity statistic: $\varepsilon_{\mathrm{DIVA}} = 1 - \sqrt{\frac{1+\lambda_1}{1+\lambda_3}}$ $\longrightarrow$ $P(\varepsilon_{\mathrm{DIVA}}|\sigma)$

Lavaux & Wandelt (2009, MNRAS)

Ellipticity statistics

Gaussian random field statistics (Doroschkevich 1970)

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$$K_1 = \lambda_1 + \lambda_2 + \lambda_3 \qquad K_2 = \lambda_1\lambda_3 + \lambda_1\lambda_2 + \lambda_2\lambda_3$$

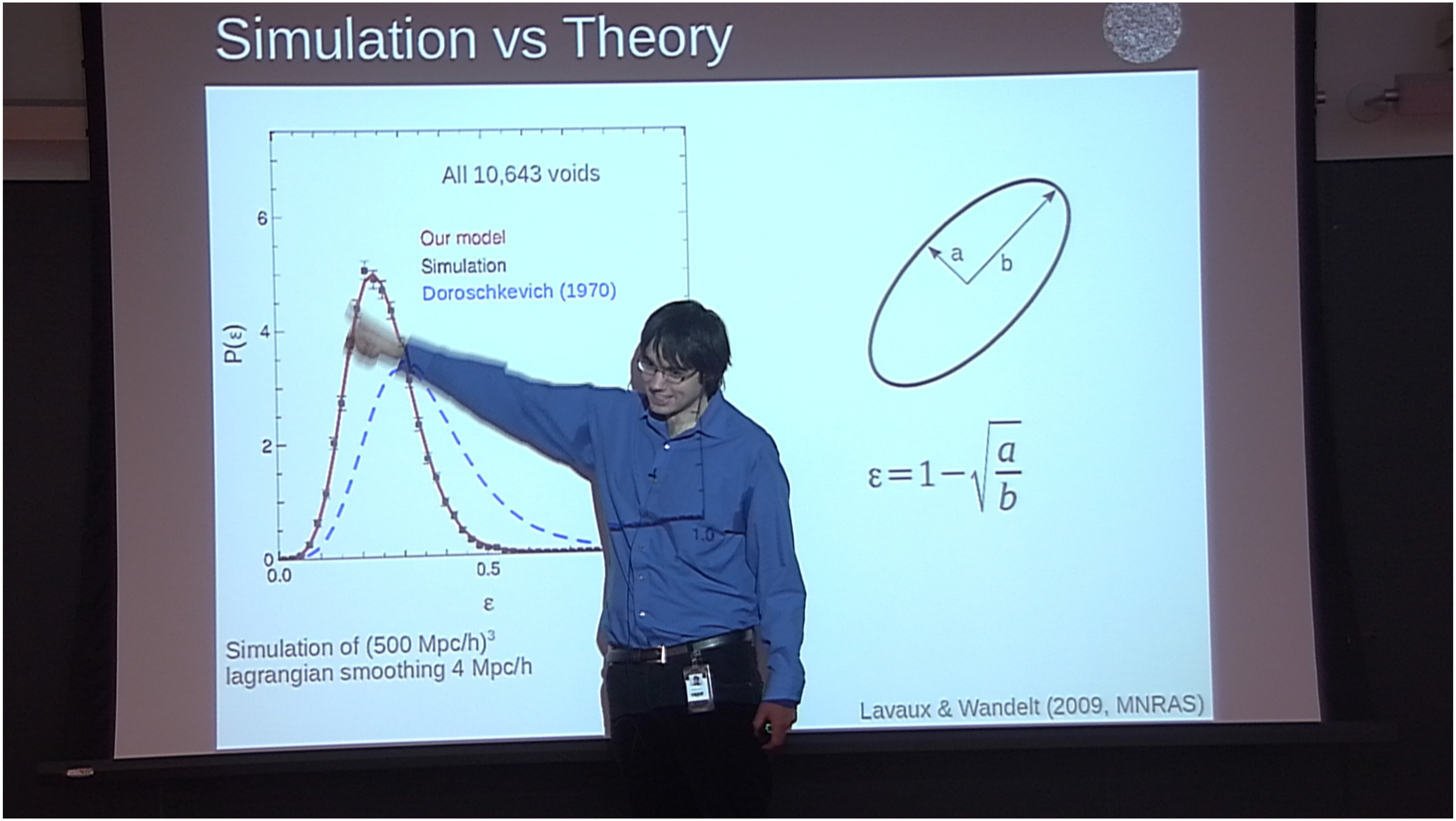
Ellipticity statistic: $\varepsilon_{DIVA} = 1 - \sqrt{\frac{1+\lambda_1}{1+\lambda_3}}$ → $P(\varepsilon_{DIVA}|\sigma)$ **WRONG !**

Void selection → Maximum of $\mathrm{div}\,\Psi$ → Curvature ***H*** of $\mathrm{div}\,\Psi < 0$

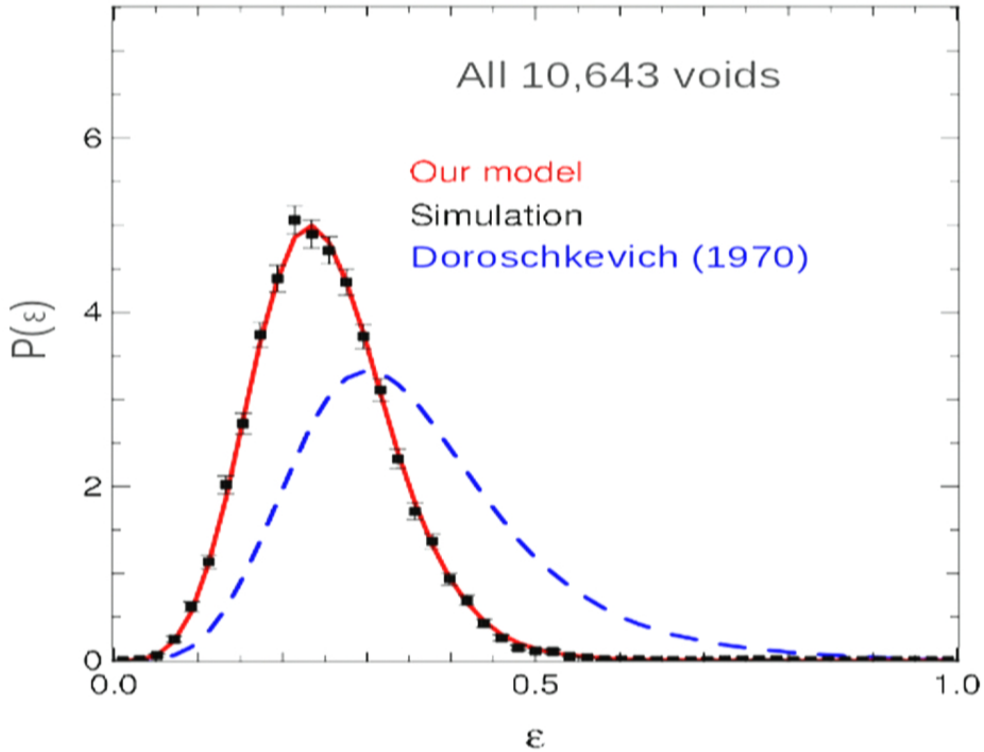
Correct quantity is: $P(\lambda_1, \lambda_2, \lambda_3 | \sigma, H > 0)$ Monte-Carlo evaluated

→ $P(\varepsilon_{DIVA}|\sigma, r)$

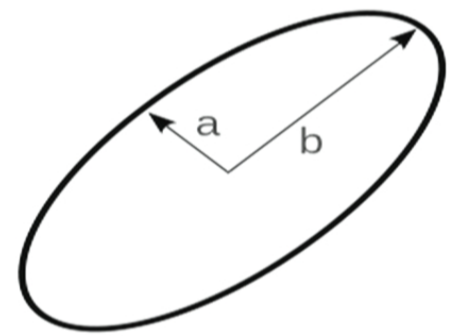
Lavaux & Wandelt (2009, MNRAS)


Simulation vs Theory
All 10,643 voids
Our model
Simulation
Doroschkevich (1970)
P(ε)
6
4
2
0
0.0
0.5
1.0
ε
Simulation of (500 Mpc/h)³
lagrangian smoothing 4 Mpc/h
a
b
ε=1−√(a/b)
Lavaux & Wandelt (2009, MNRAS)

Simulation vs Theory



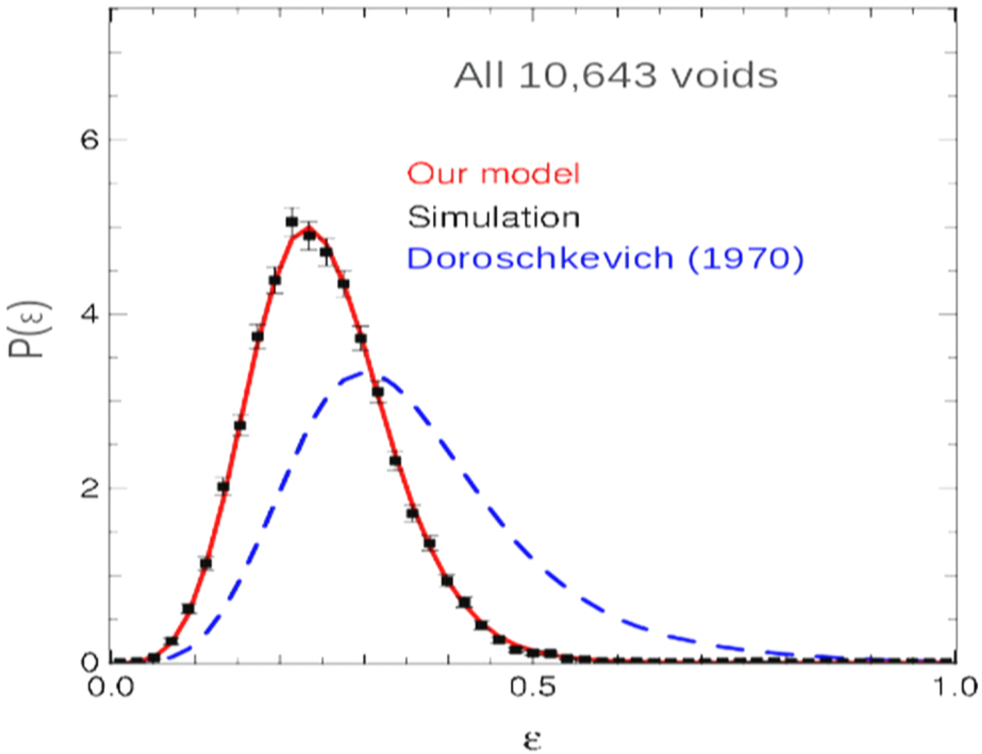
Simulation of (500 Mpc/h)^3
lagrangian smoothing 4 Mpc/h



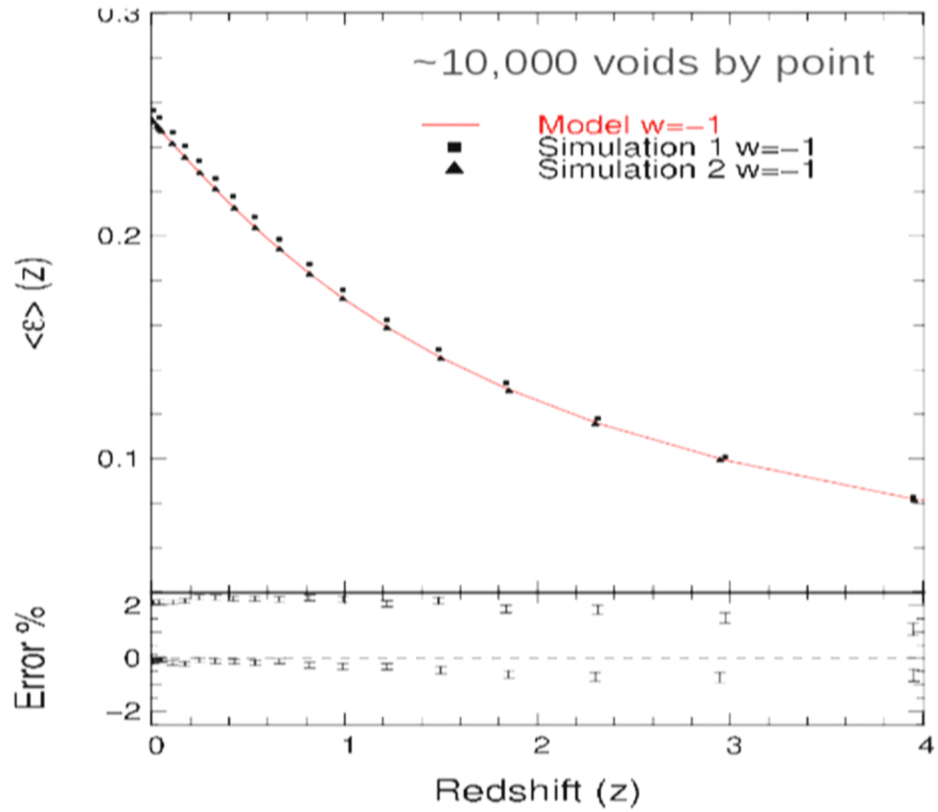
$$\varepsilon = 1 - \sqrt{\frac{a}{b}}$$

Lavaux & Wandelt (2009, MNRAS)

Simulation vs Theory

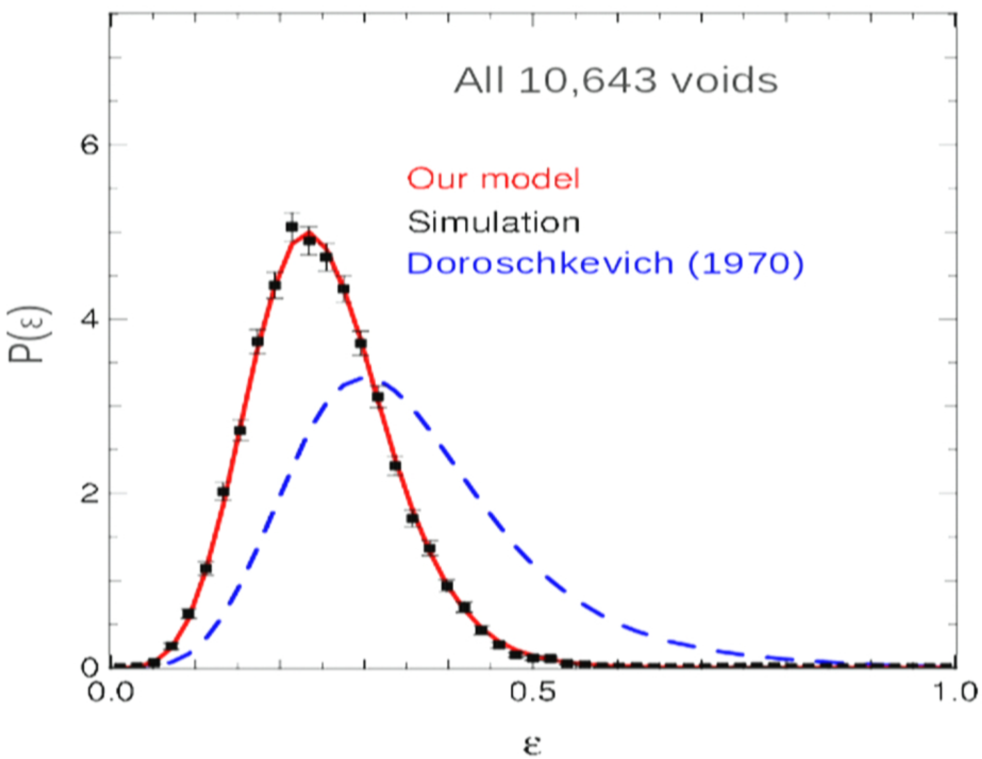


Simulation of (500 Mpc/h)^3
lagrangian smoothing 4 Mpc/h

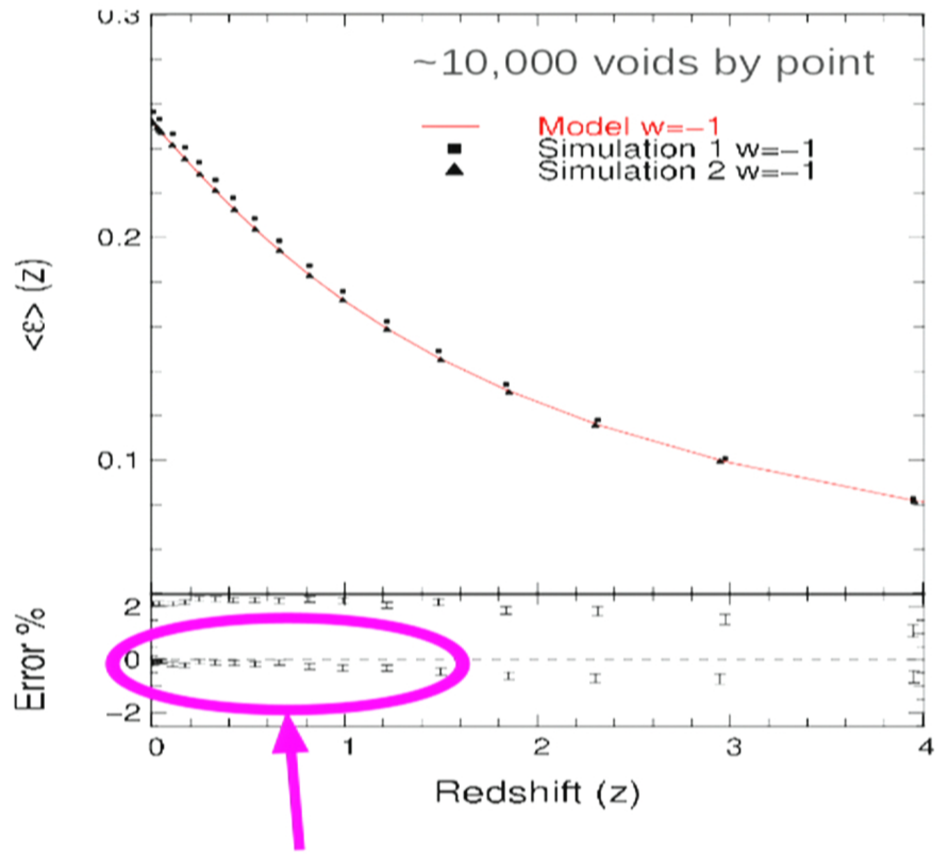


Lavaux & Wandelt (2009, MNRAS)

Simulation vs Theory



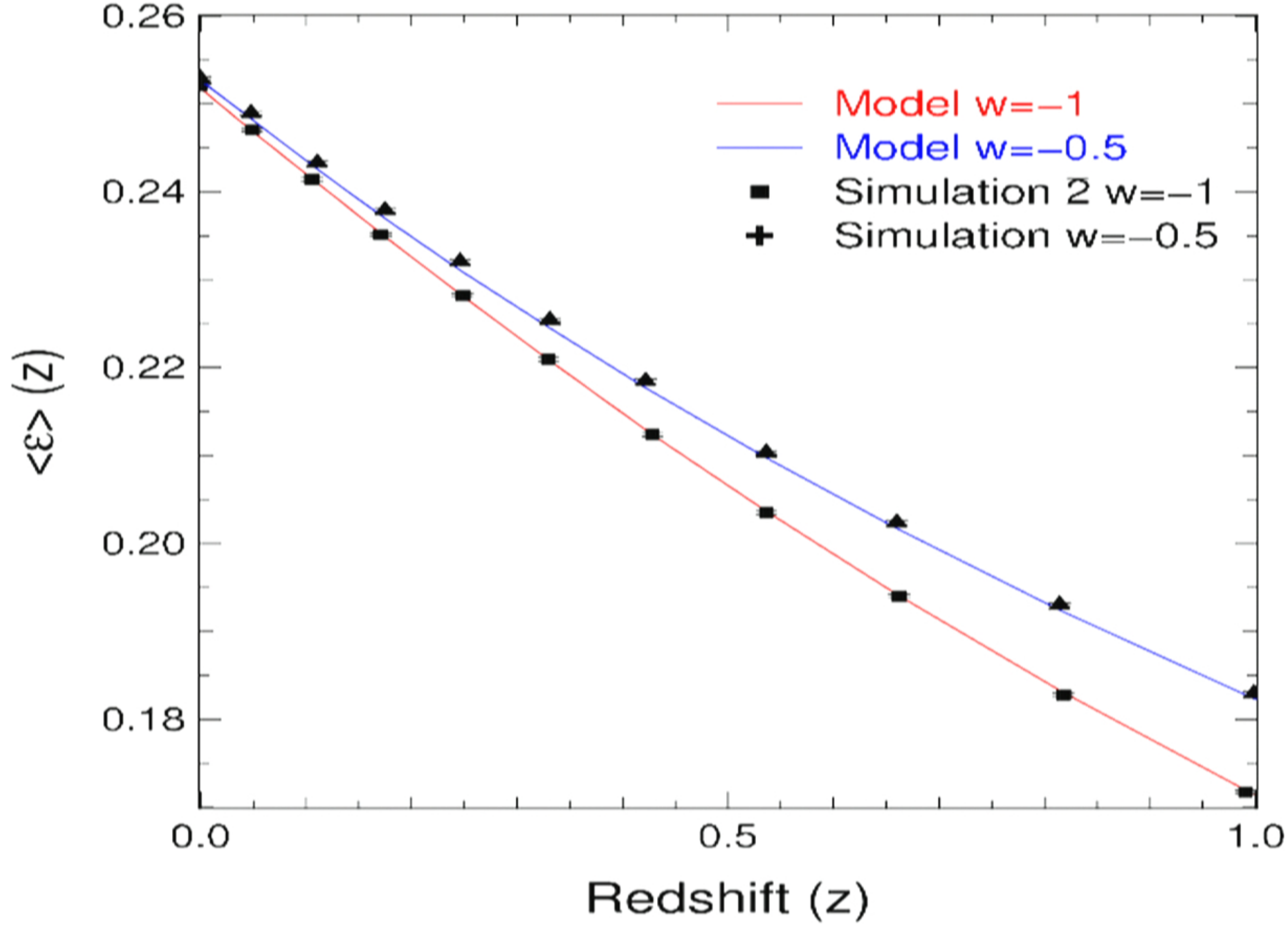
Simulation of (500 Mpc/h)^3
lagrangian smoothing 4 Mpc/h



~0.1% error

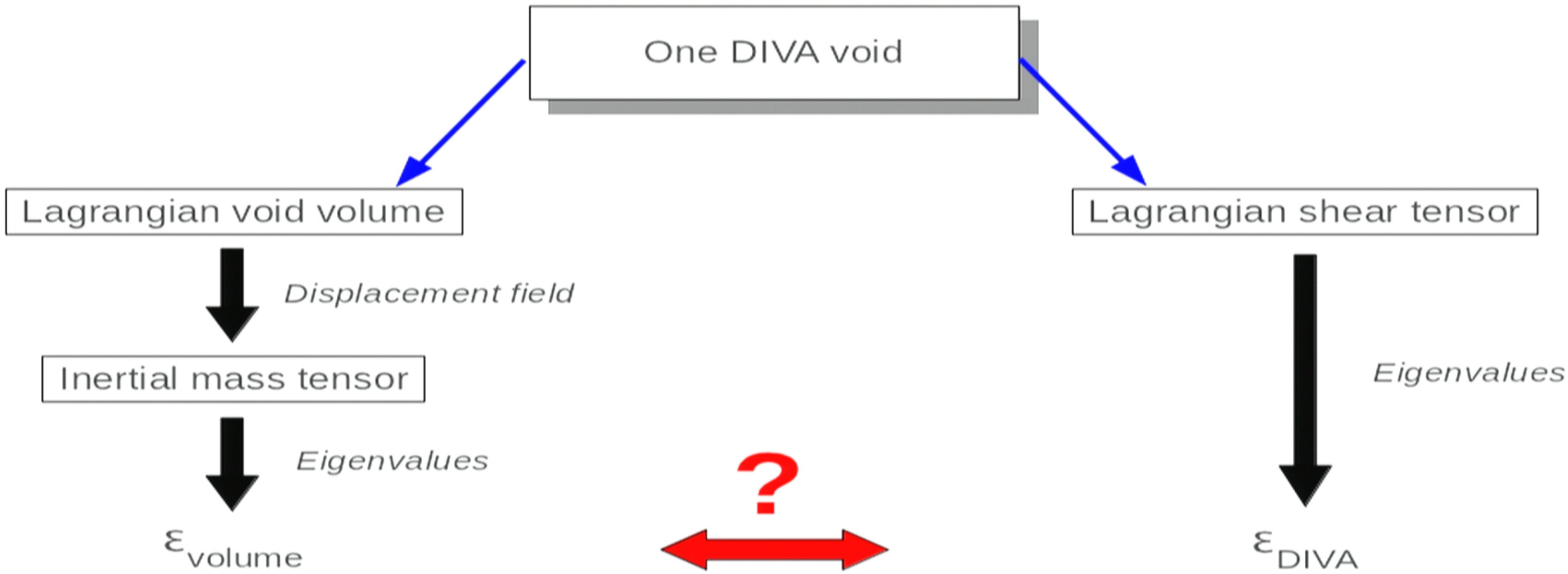
Lavaux & Wandelt (2009, MNRAS)

Mean ellipticity for different *w*CDM



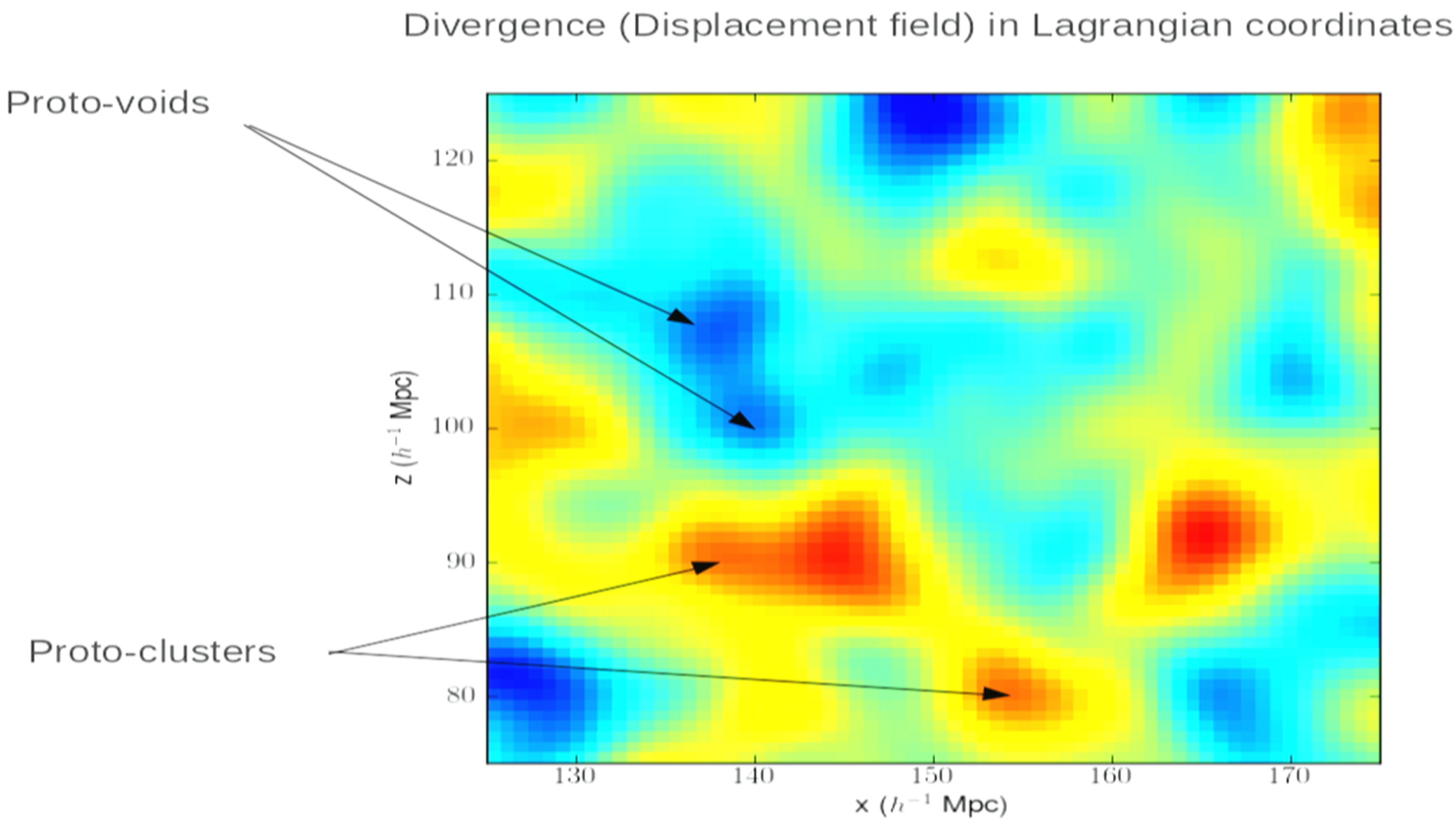
Lavaux & Wandelt (2009, MNRAS)

Relation with volume ellipticity ?

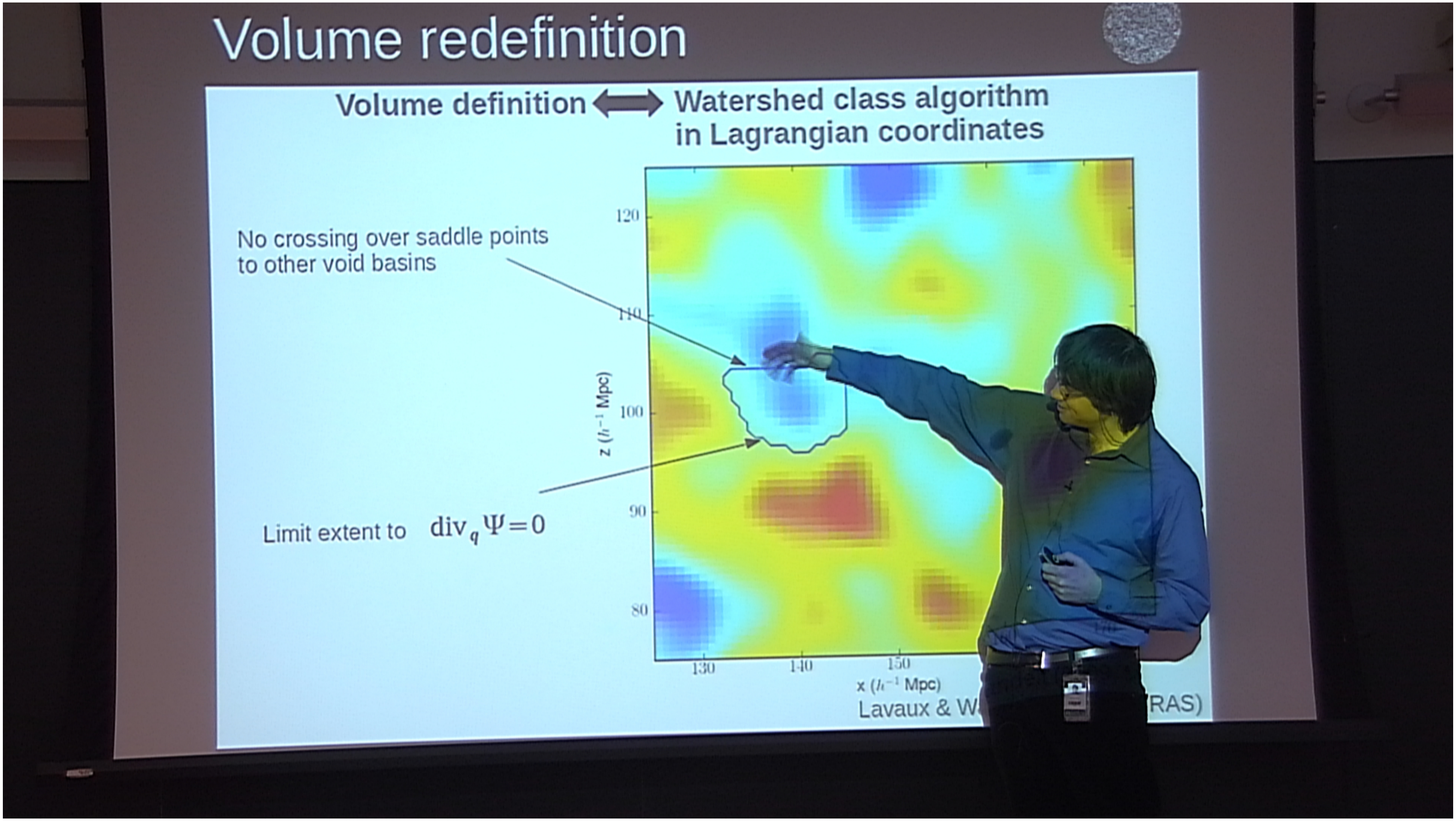


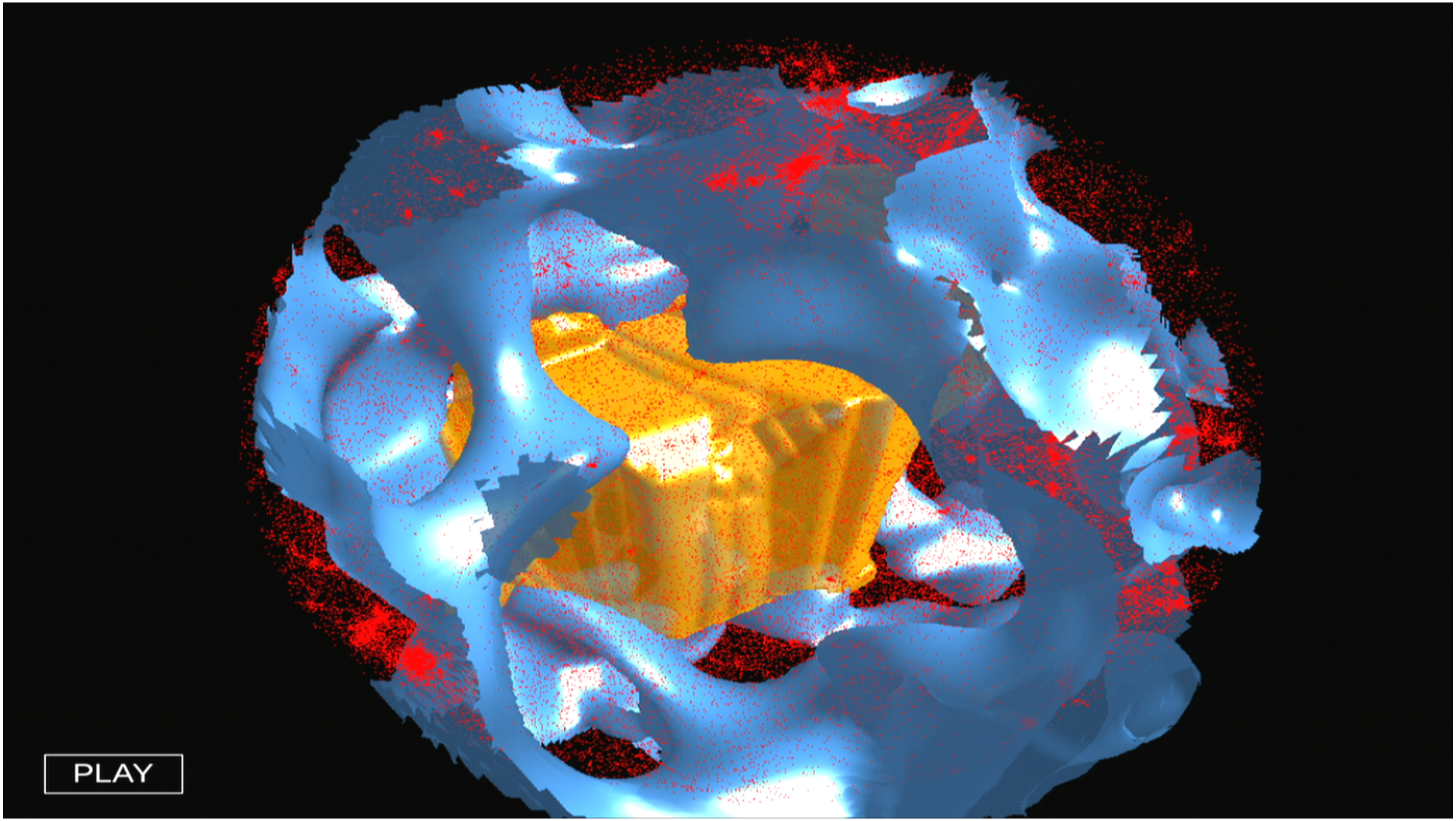
At first order they should be the same

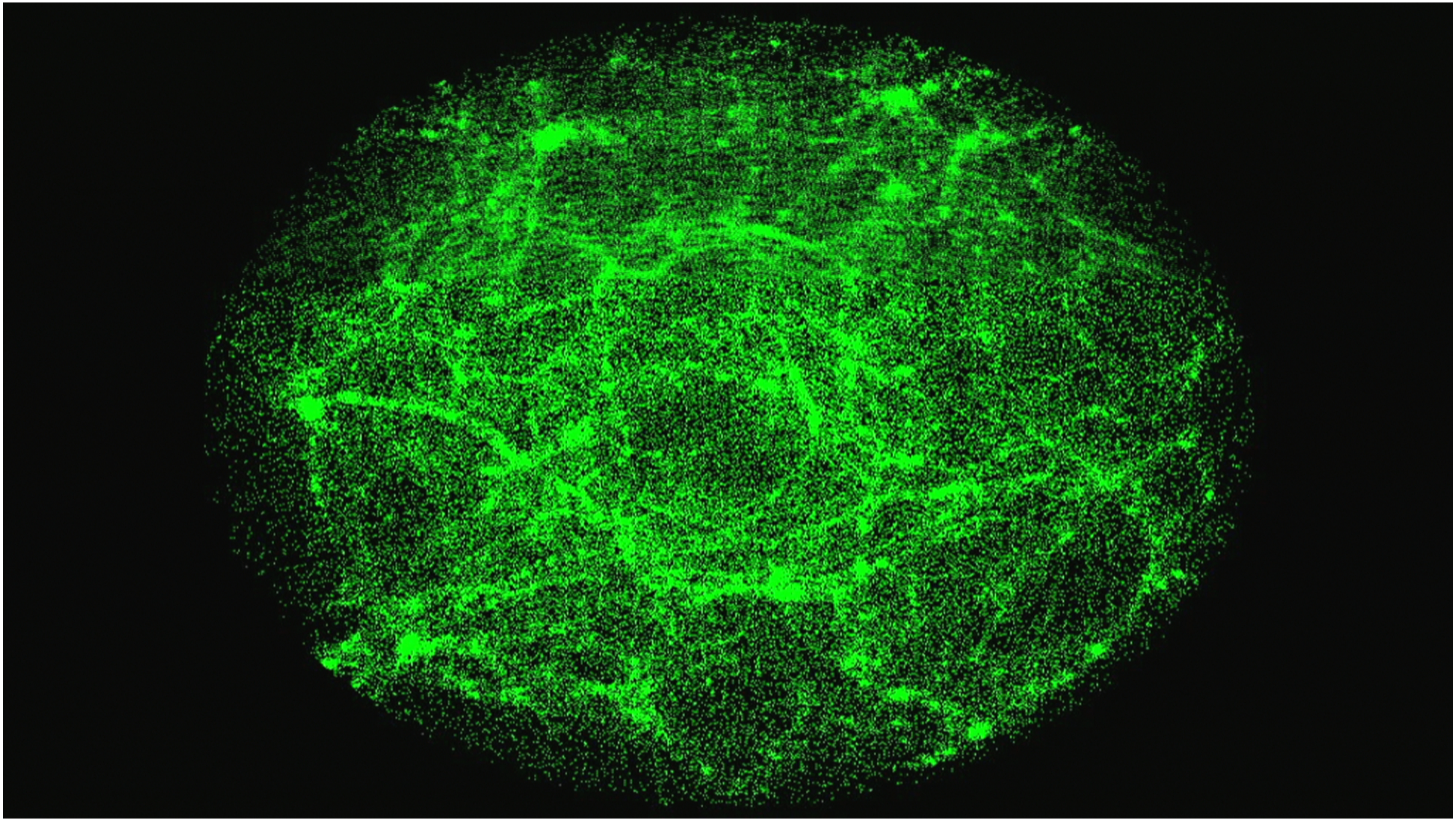
Volume redefinition

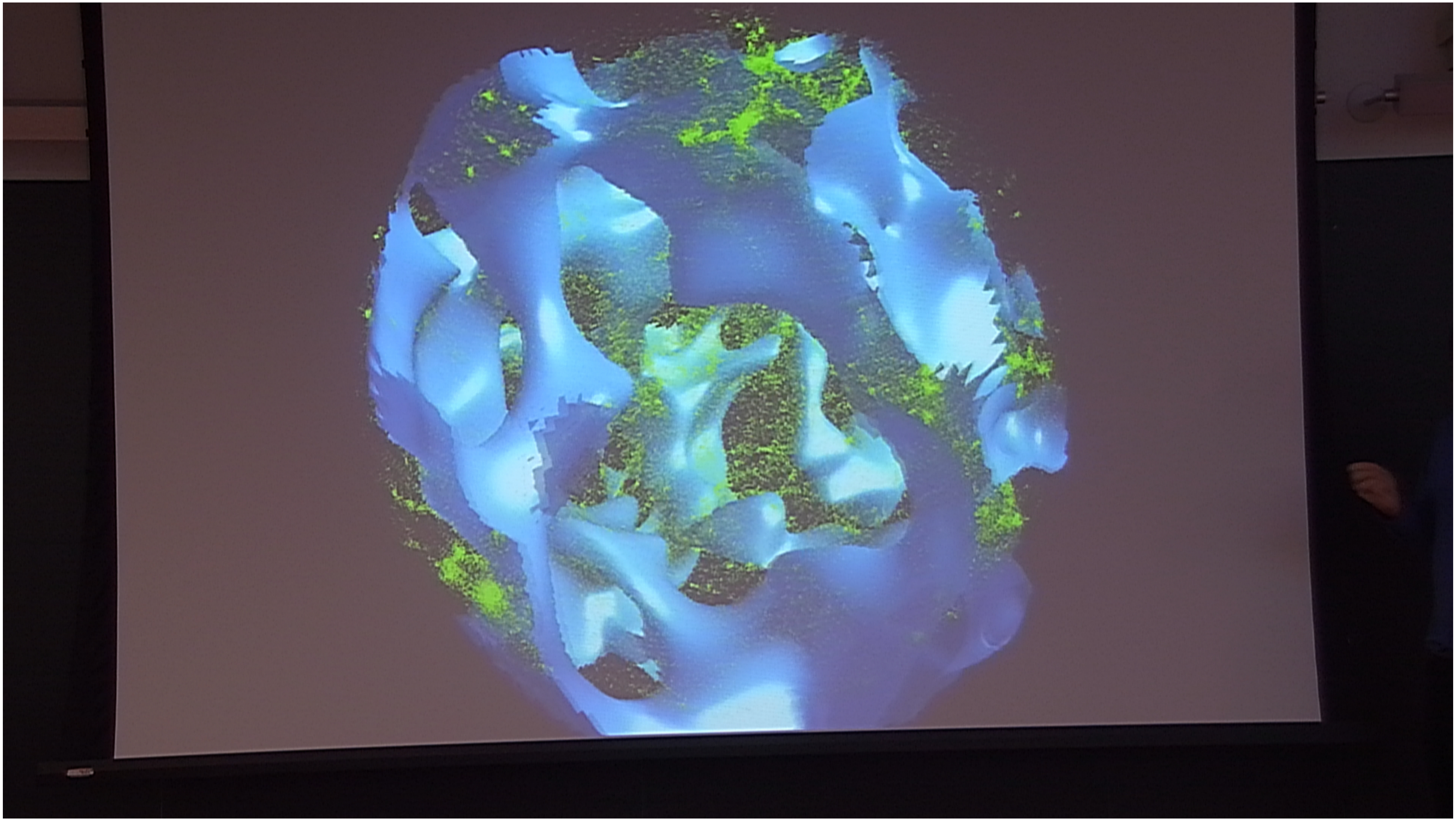


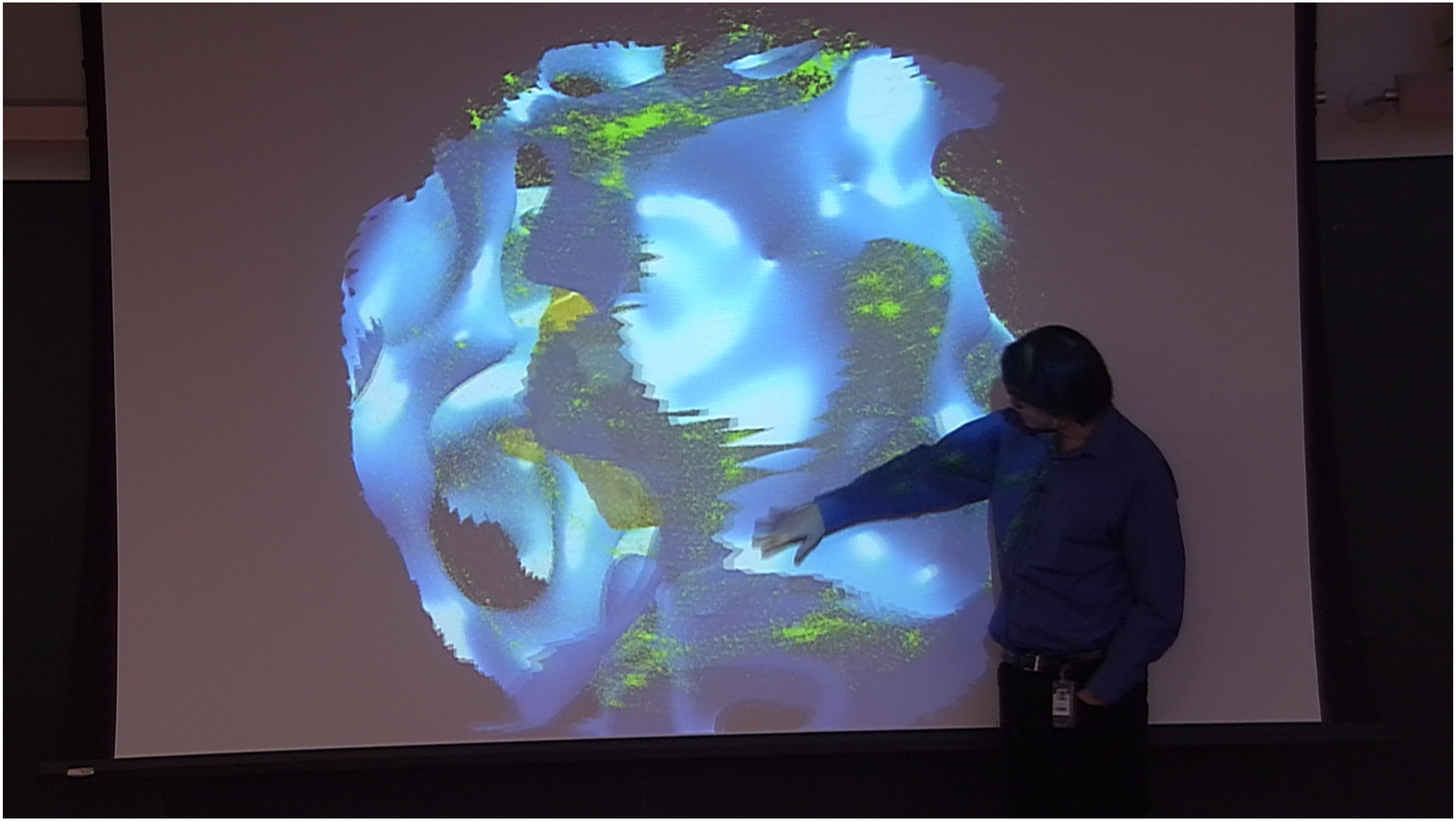
Lavaux & Wandelt (2009, MNRAS)

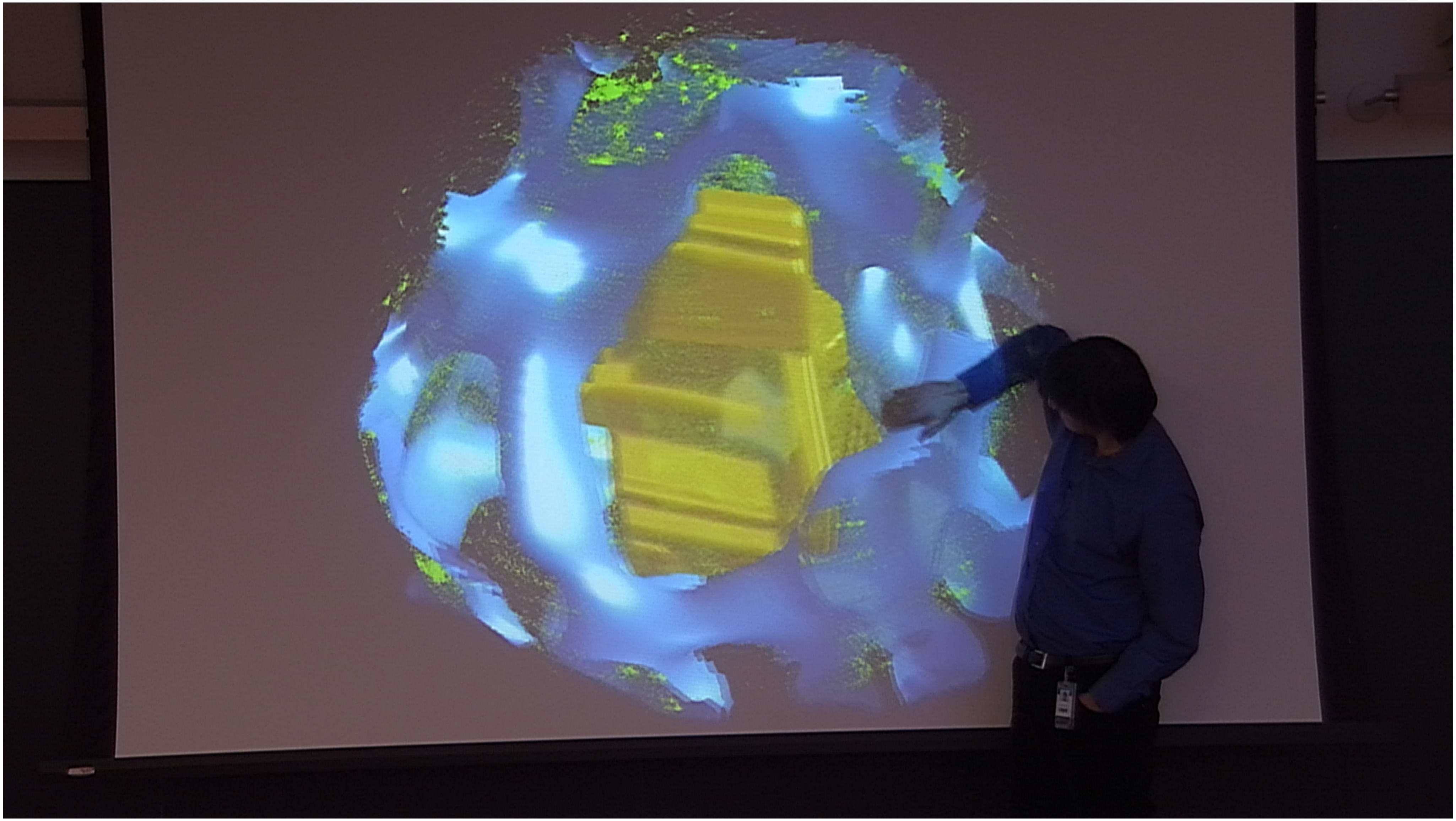

Volume redefinition
Volume definition
Watershed class algorithm
in Lagrangian coordinates
No crossing over saddle points
to other void basins
Limit extent to $\mathrm{div}_q \Psi = 0$
120
110
100
90
80
z (h^{-1} Mpc)
130
140
150
x (h^{-1} Mpc)


PLAY

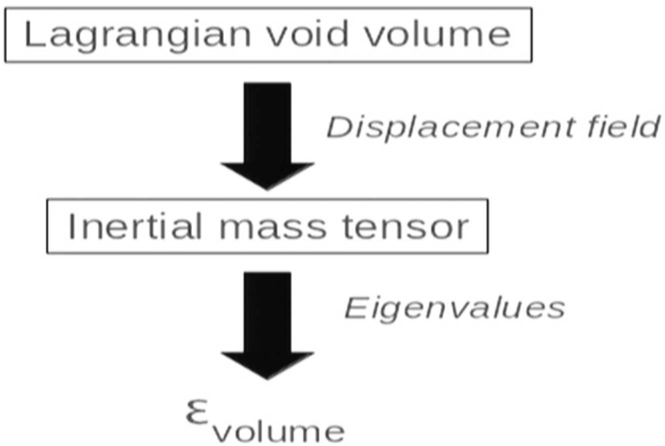


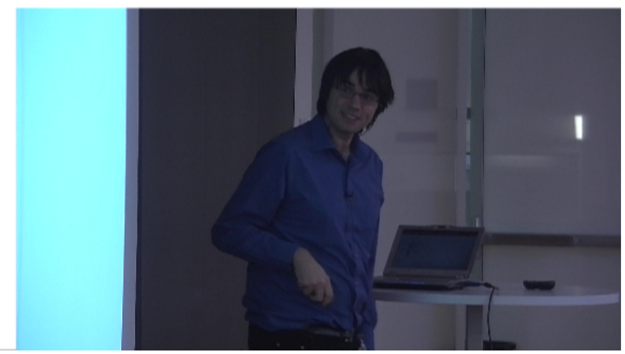






Relation with volume ellipticity





Relation with volume ellipticity

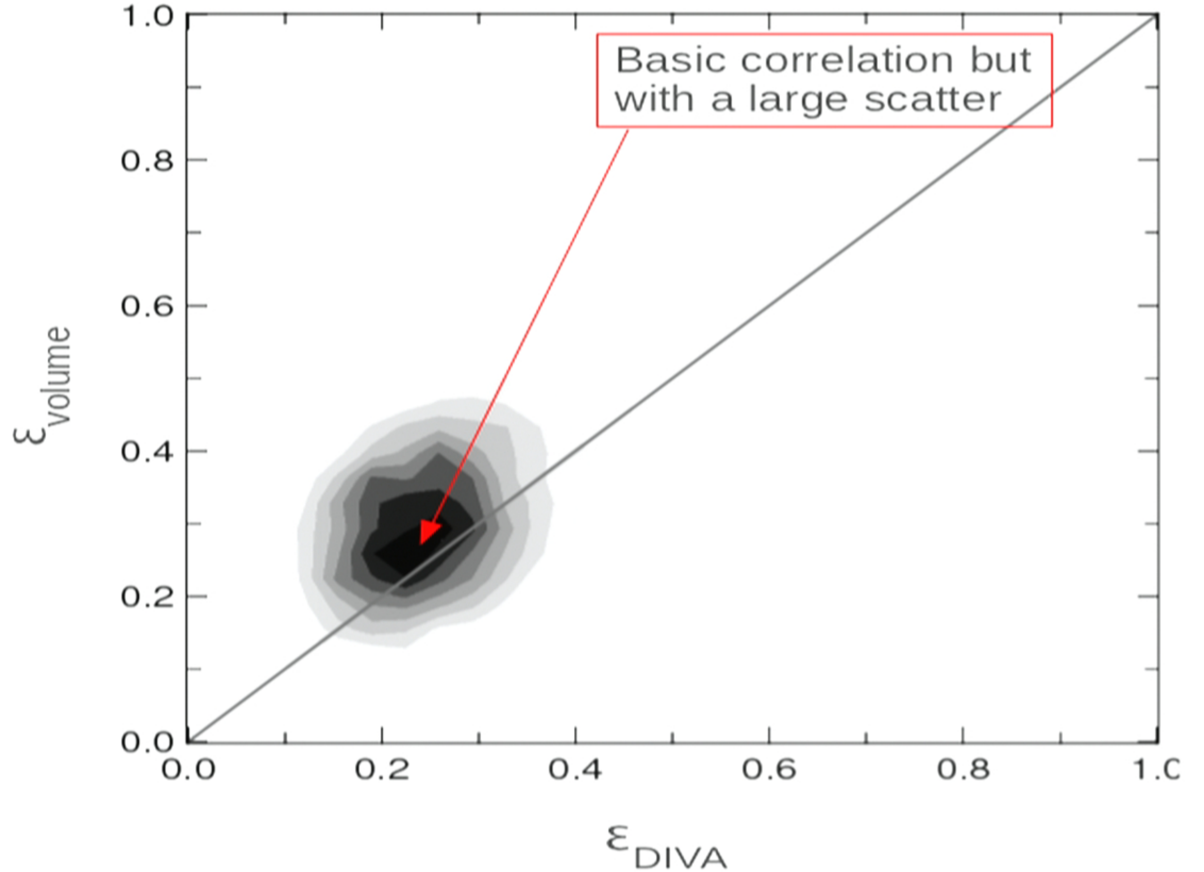
Lagrangian void volume

↓ *Displacement field*

Inertial mass tensor

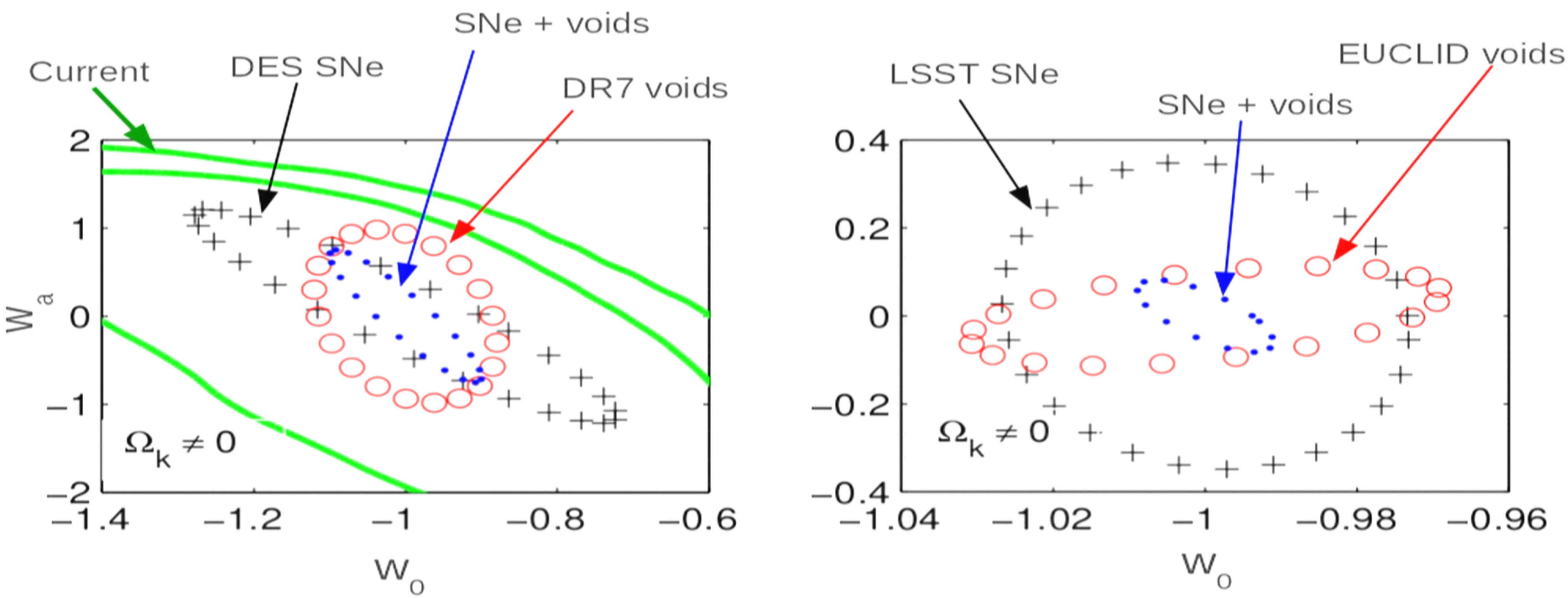
↓ *Eigenvalues*

ε_{volume}



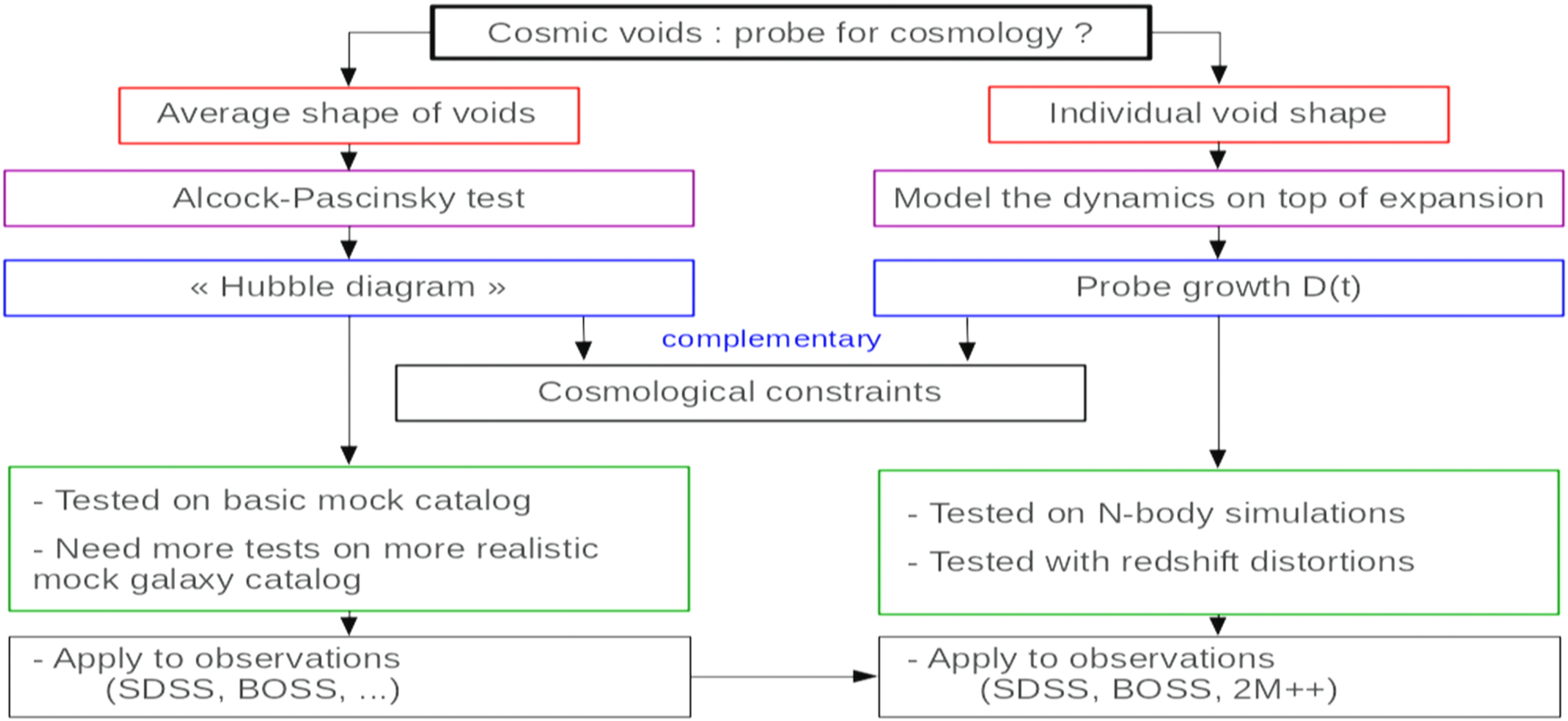
Lavaux & Wandelt (2009, MNRAS)

Fisher matrix



Biswas, Alizadeh & Wandelt (2010)

Conclusion



Lavaux & Wandelt (2011, submitted)

Lavaux & Wandelt (2009, MNRAS)