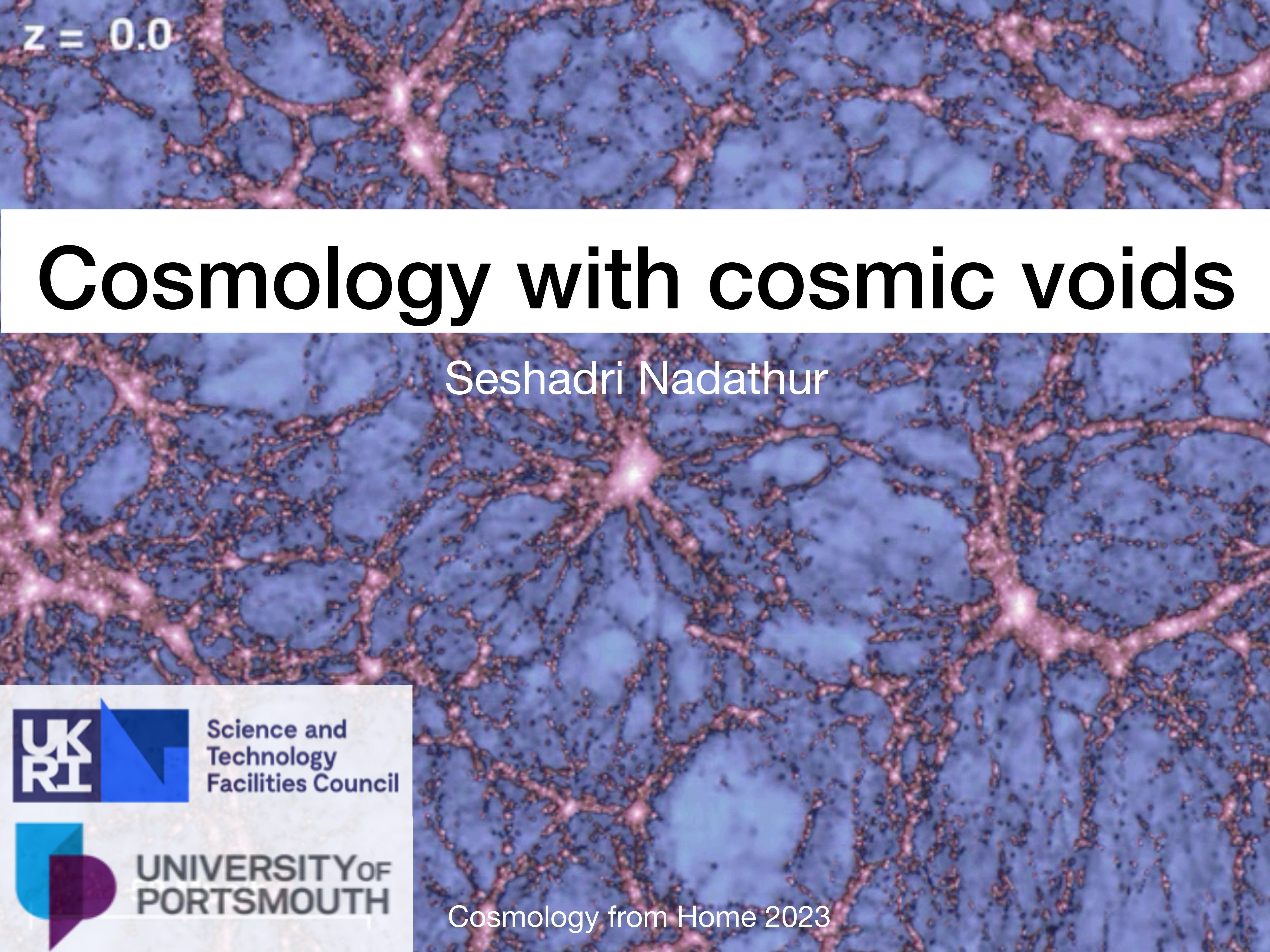

Cosmology with cosmic voids

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Science and Technology Facilities Council

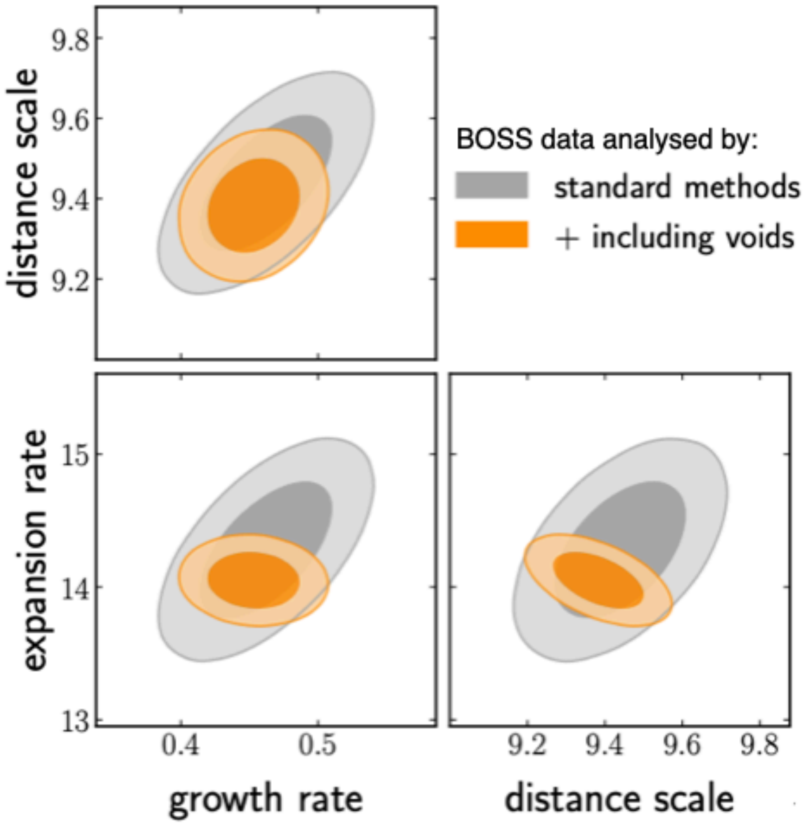
UNIVERSITY OF PORTSMOUTH

Cosmology from Home 2023

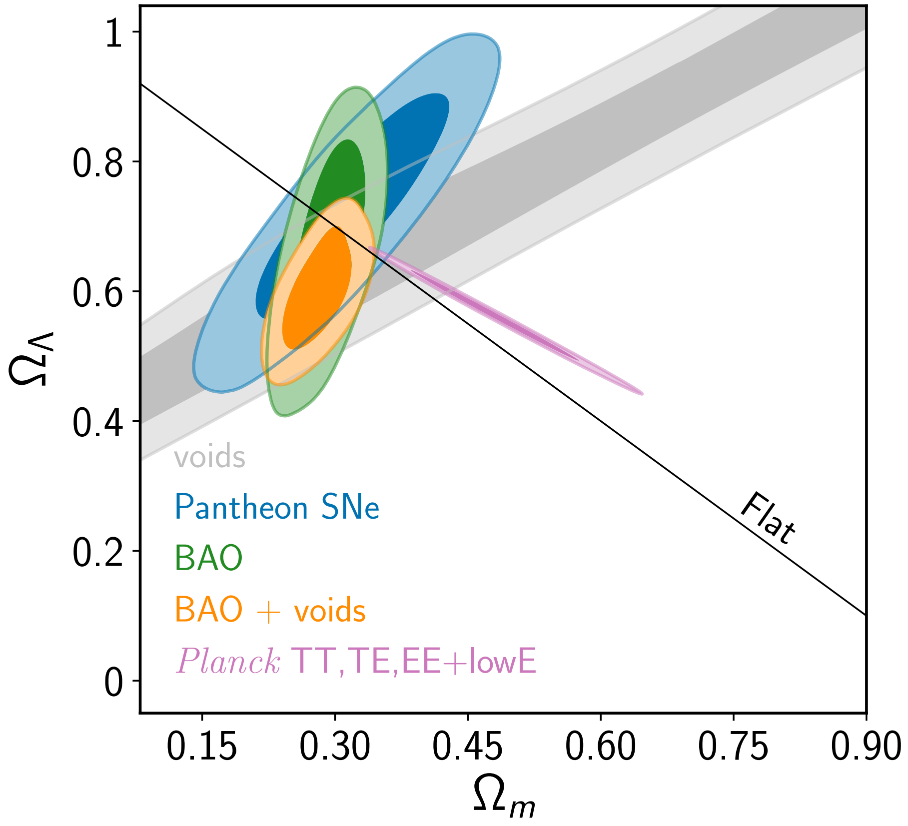
Why voids?

Voids contain *extra* cosmological information

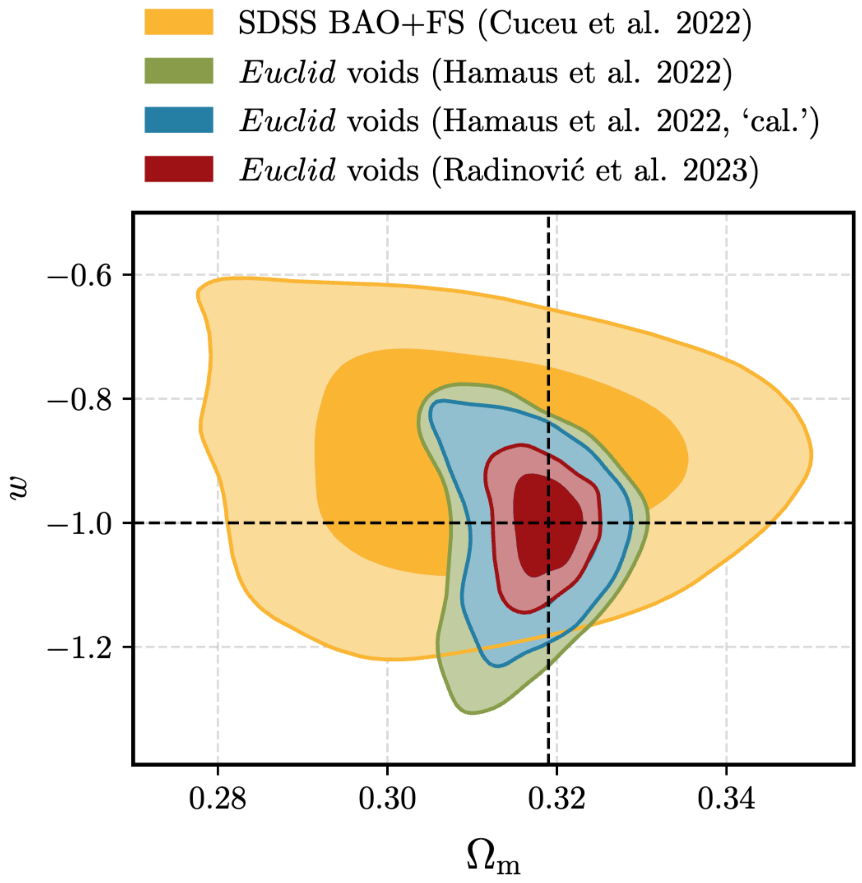
Some recent examples:



adapted from SN *et al.*, 1904.01030



SN *et al.*, 2001.11044



Radinovic *et al.*, 2302.05302

This talk: **where** this information comes from and **how** to access it

Outline

- What *are* voids?

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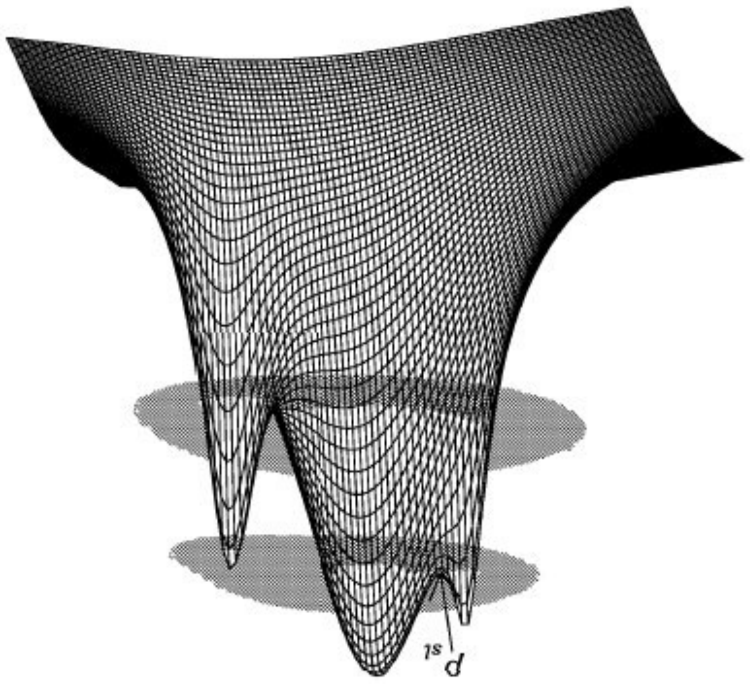
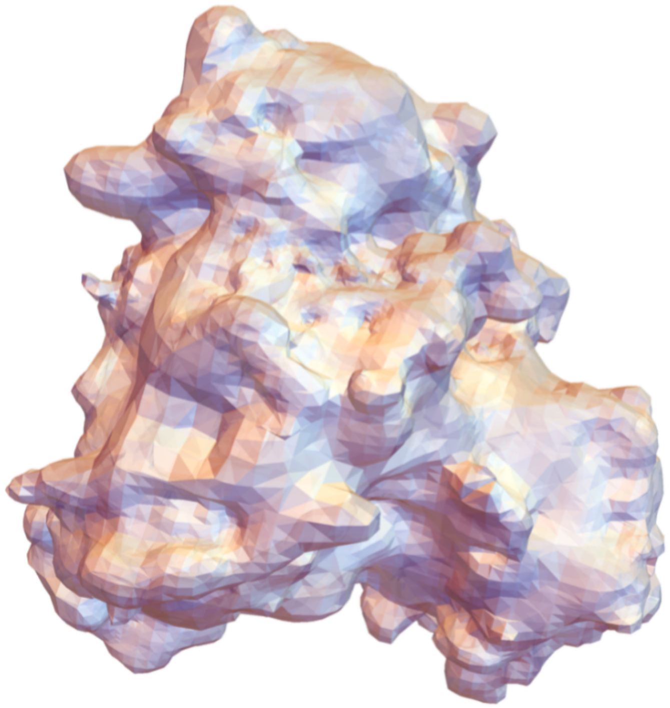
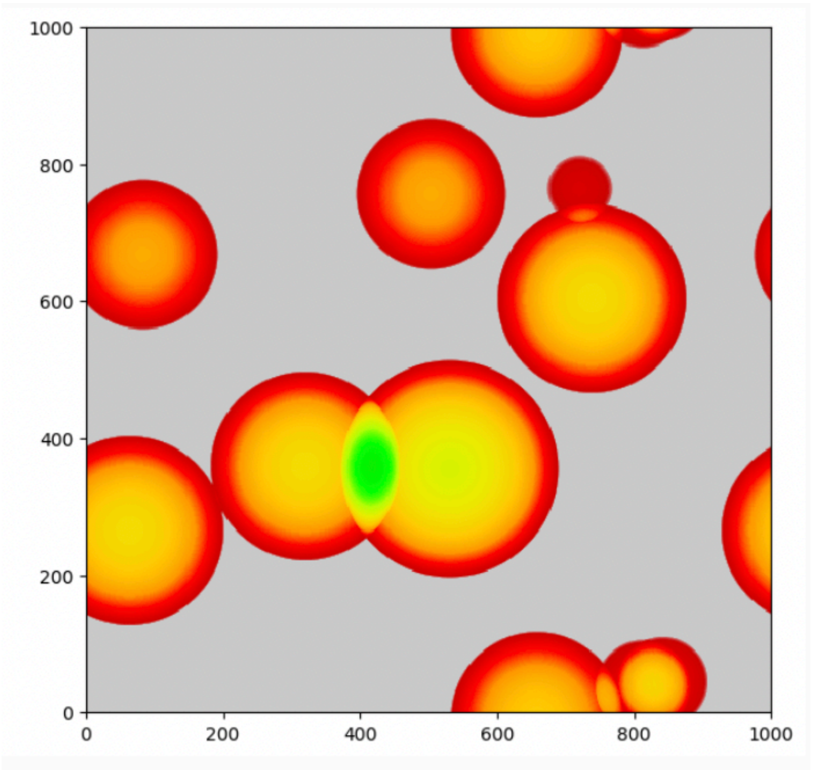
- What *are* voids?



Neyrinck *et al*., astro-ph/0402346
Neyrinck, 0712.3049



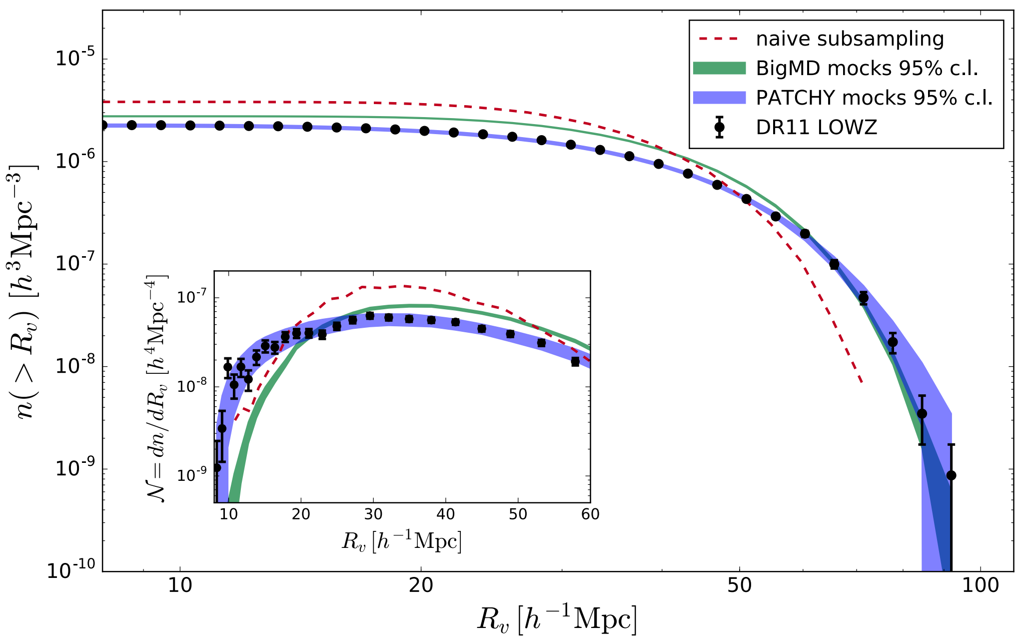
SN, 1602.04752



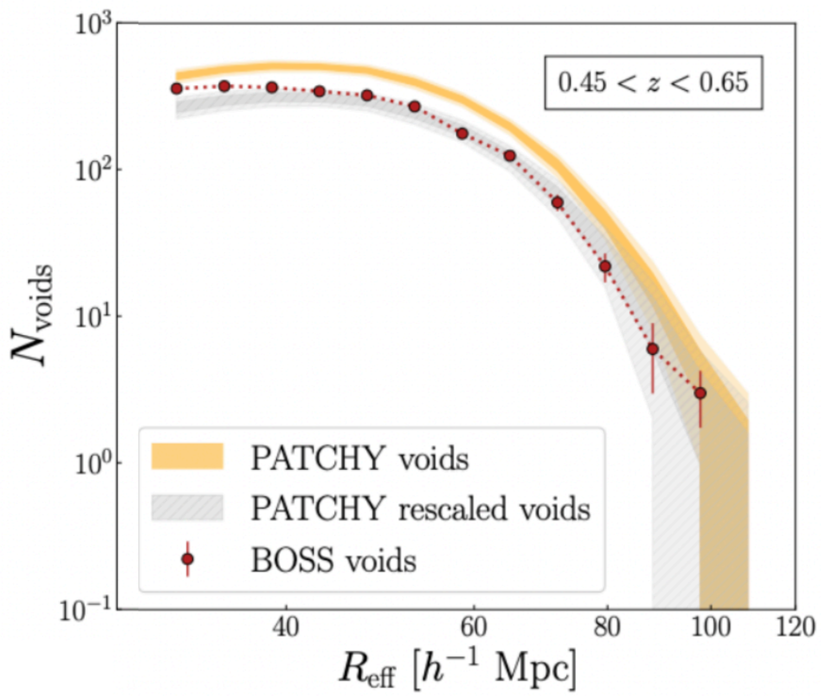
Banerjee & Dalal, 1606.06167
implemented in PYLIANS code

Outline

- What *are* voids?
- Cosmological information from voids:
  - 1-point functions (numbers)



SN, 1602.04752



adapted from Contarini *et al*., 2212.03873

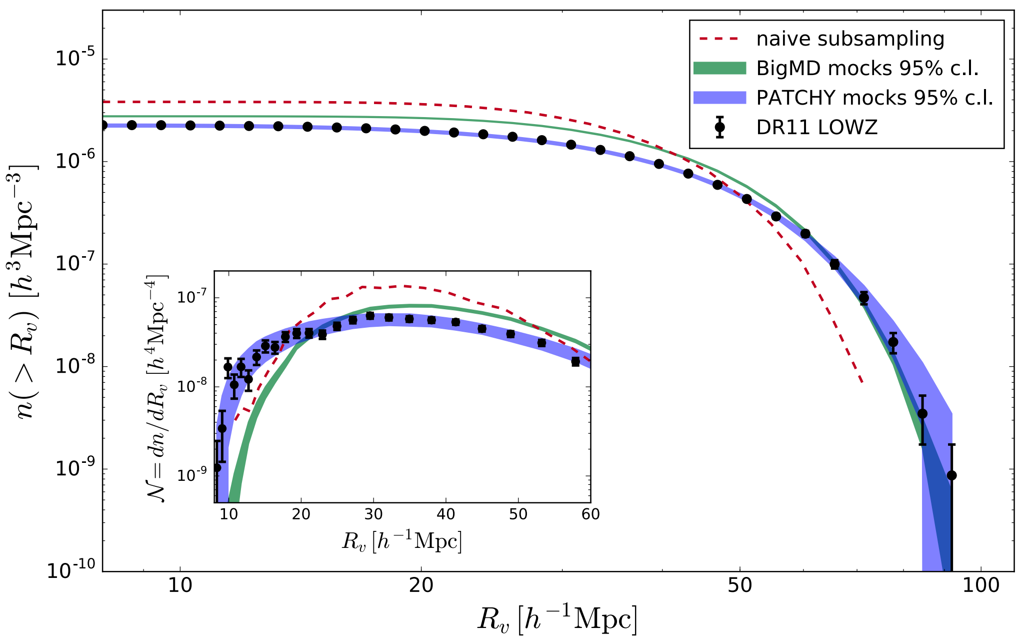
Outline

- What *are* voids?

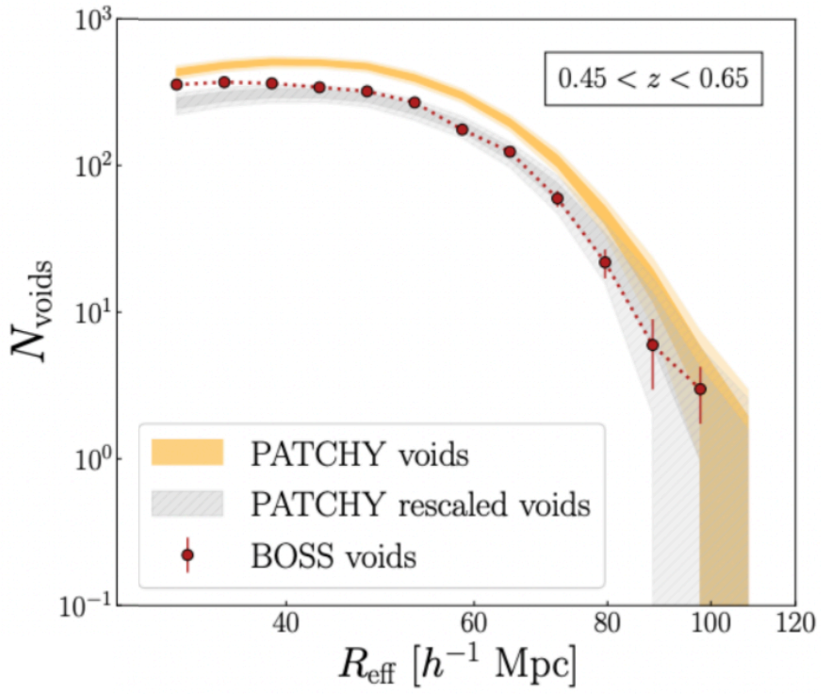
- Cosmological information from voids:

    - ~~1-point functions (numbers)~~

Not in this talk, but perhaps in the discussion



SN, 1602.04752



adapted from Contarini *et al.*, 2212.03873

Outline

- What *are* voids?
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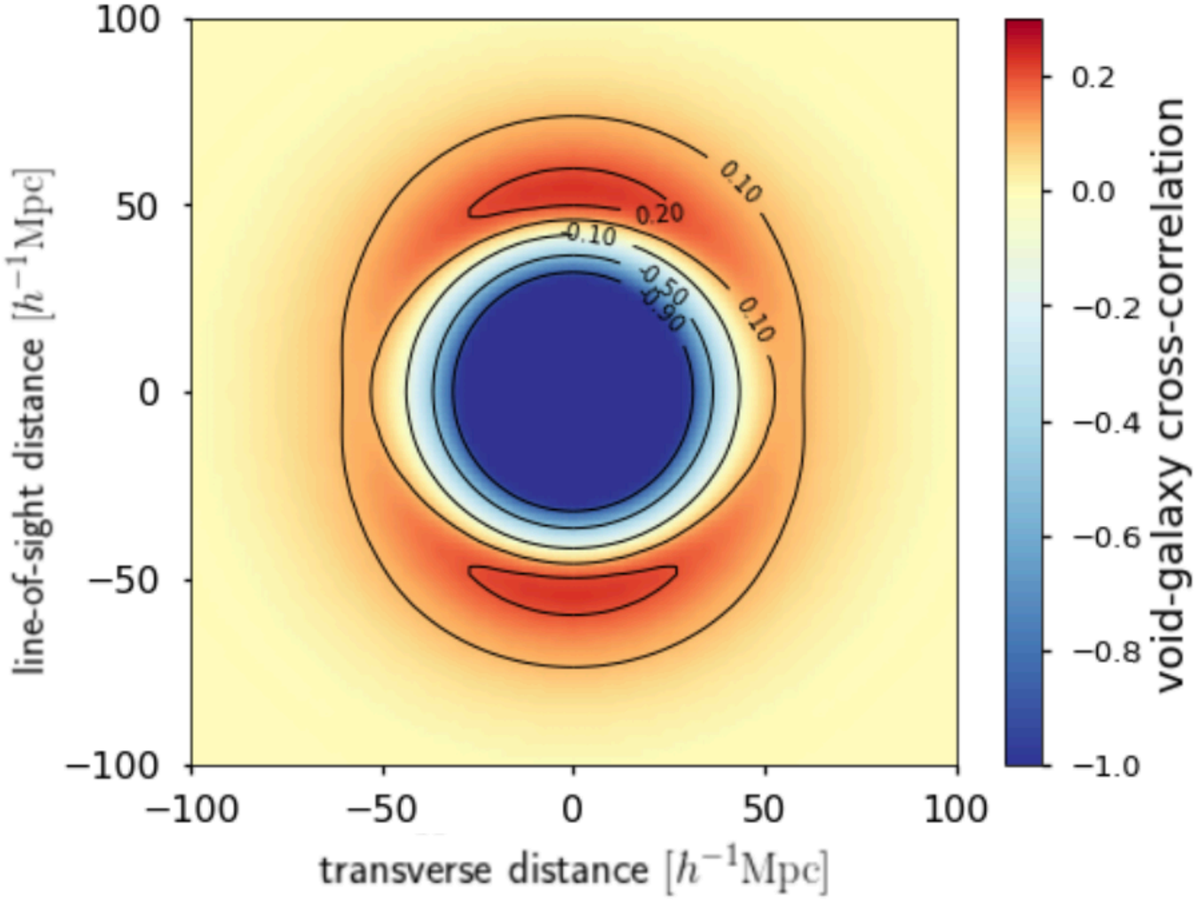
  - ~~1-point functions (numbers)~~
  - 2-point functions (correlations)



Outline

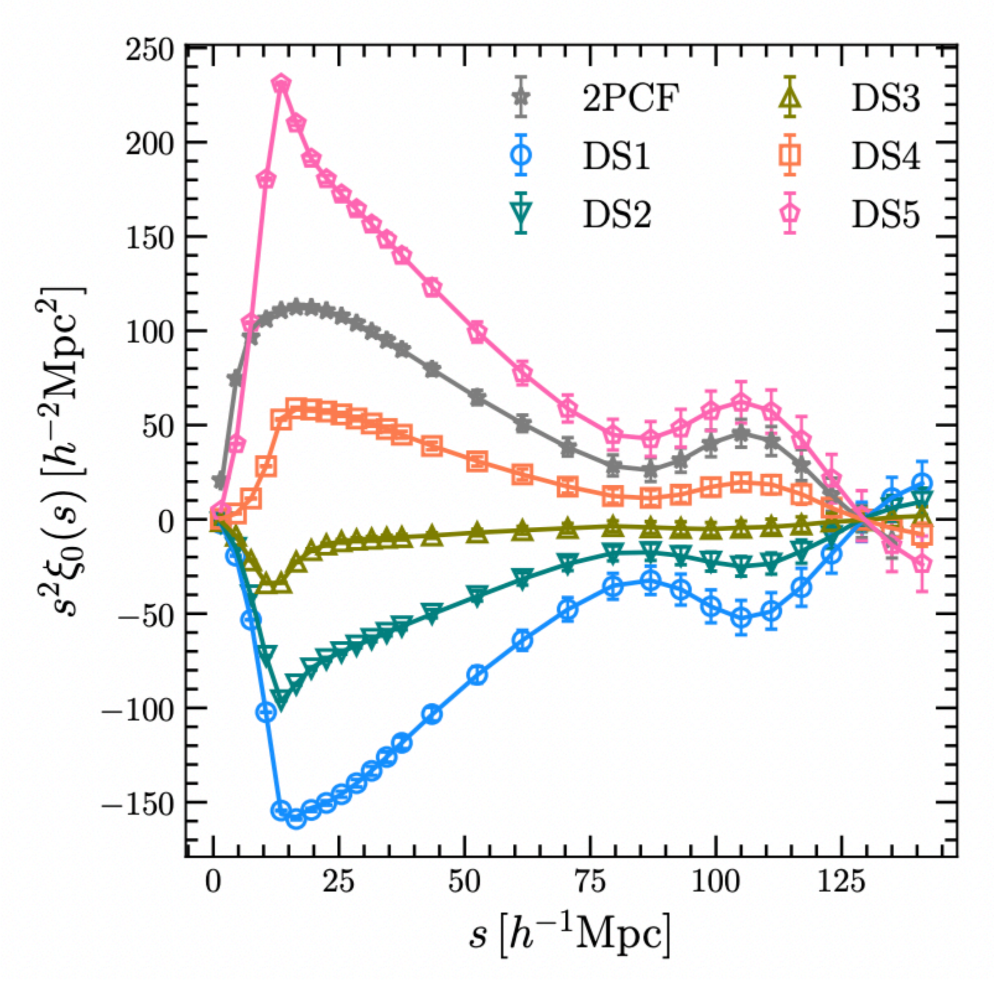
- What *are* voids?

- Cosmological information from voids:

  - ~~1-point functions (numbers)~~

  - 2-point functions (correlations)

- Beyond voids



Paillas *et al.*, 2101.09854

Outline

- What *are* voids?
- Cosmological information from voids:
    - ~~1-point functions (numbers)~~
    - 2-point functions (correlations)
- Beyond voids
- Progress required to use voids in future surveys

What are voids?

Things to remember about voids:

1. They are regions of low galaxy density

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About the only thing everyone can agree on!

What are voids?

Things to remember about voids:

1. They are regions of “low” galaxy density

About the only thing everyone can agree on!

But what counts as “low”? How to estimate local galaxy density?

Any other conditions to impose? How to define aggregate properties?

What are voids?

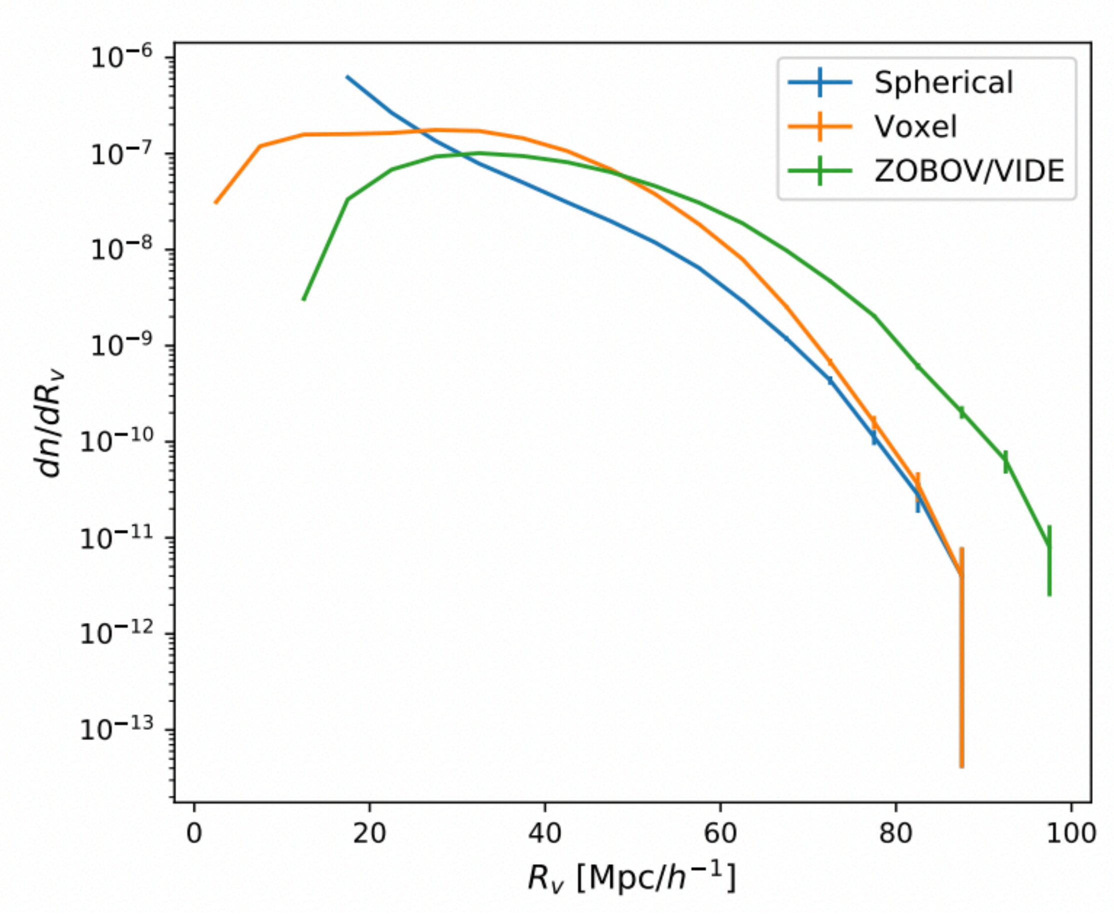
Things to remember about voids:

1. They are regions of “low” galaxy density

There are *at least 6 different** public void-finding codes available and in common use.

They produce vastly different results!

An example, comparing the void size function obtained from just 3 different codes:



Massara *et al.*, 2206.14120

*And another which places selection cuts on voids from other codes

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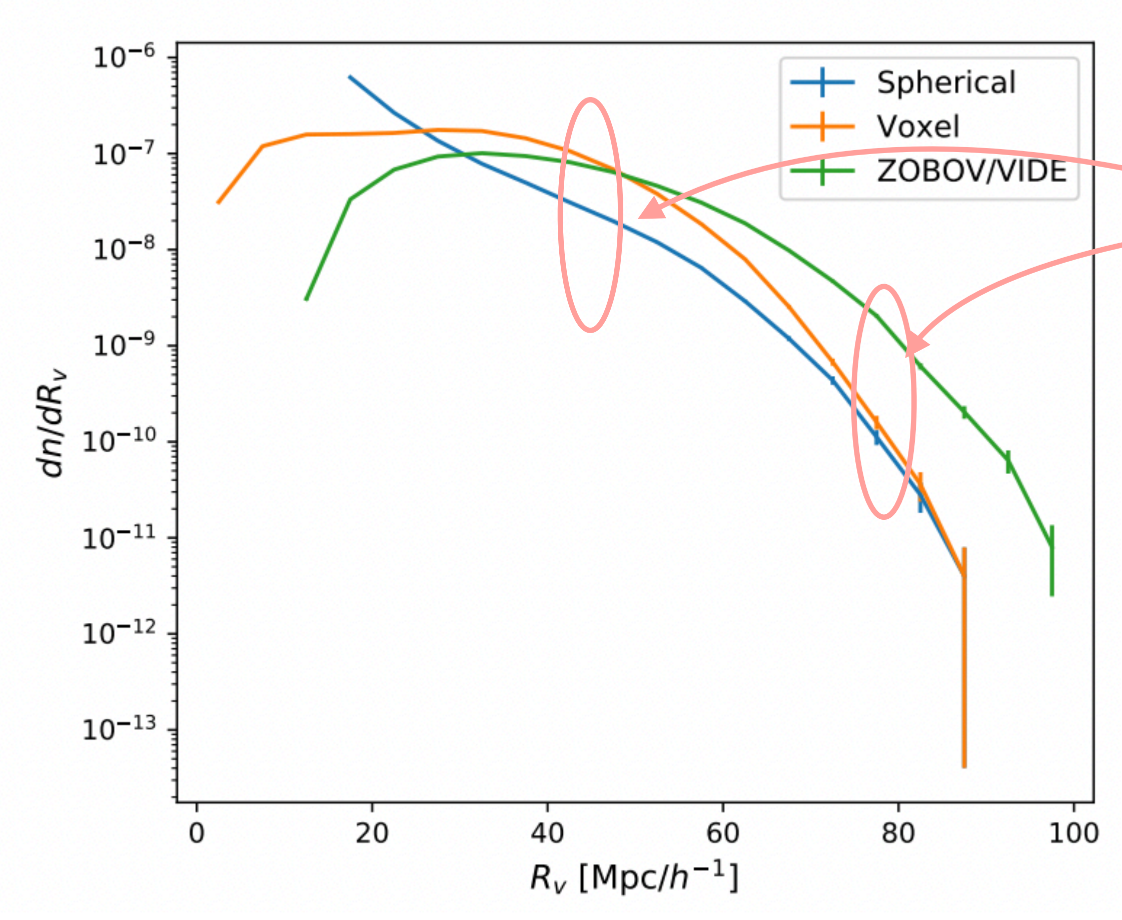


These are order-of-magnitude differences!

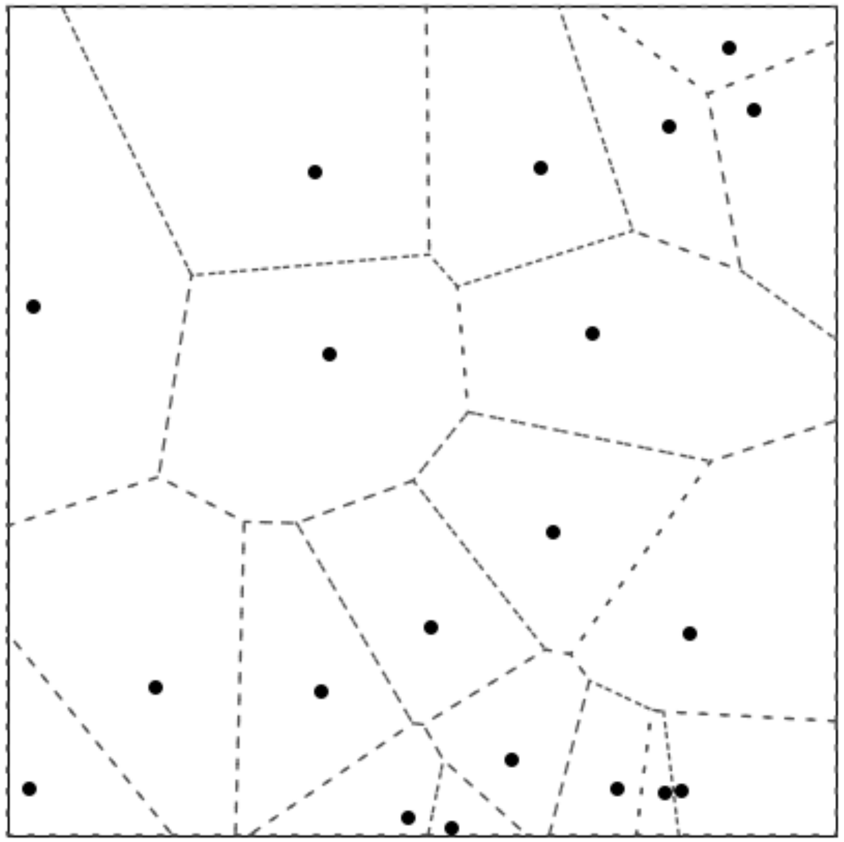
Massara *et al.*, 2206.14120

*And another which reprocesses voids from other codes to add selection cuts

What are voids?

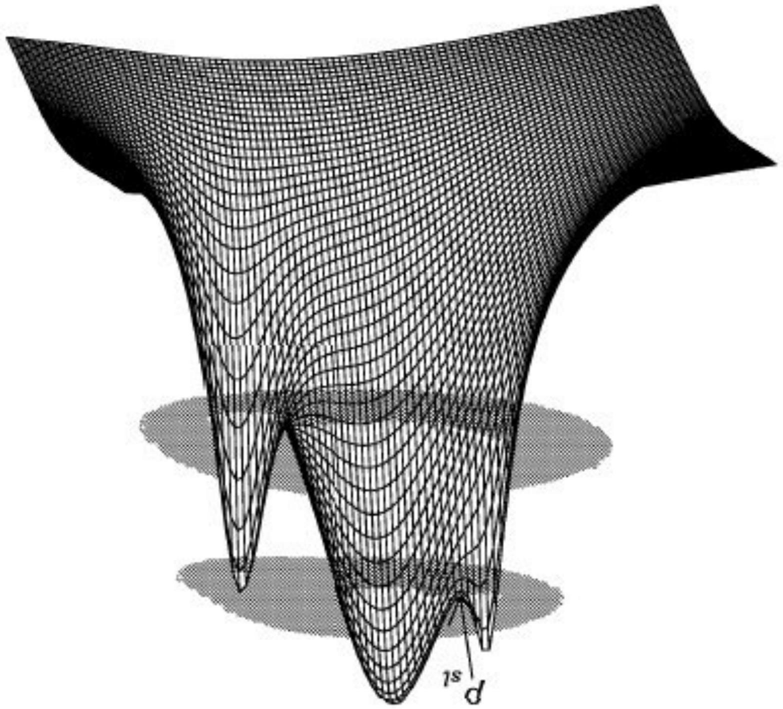
Example: tessellation-based watershed void-finders e.g. Zobov, VIDE, REVOLVER

Step 1: Voronoi tessellation to estimate local density



$$\frac{\rho_i}{\bar{\rho}} = \frac{\bar{V}}{V_i}$$

Step 2: Density minima = voids



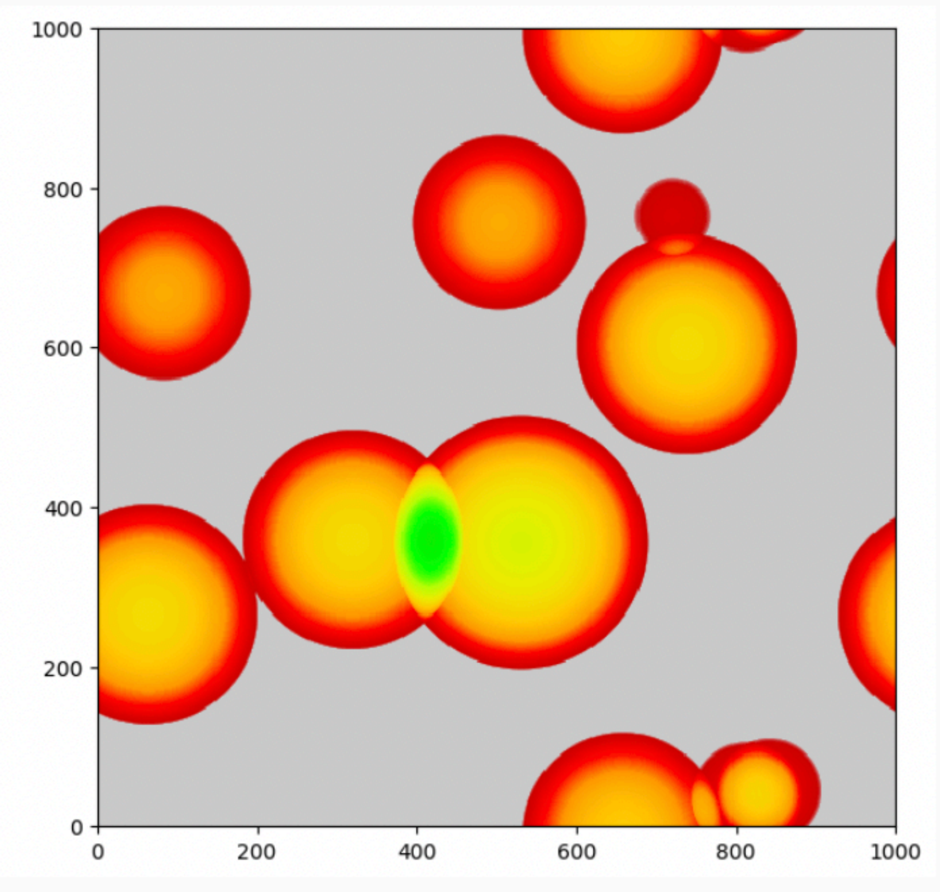
What are voids?

Another example: spherical underdensity codes e.g. PYLIANS

Step 1: Estimate local density from projection on a grid (CIC/TSC/other interpolation scheme)

Step 2: Convolve with a spherical filter (e.g., top-hat)

Step 3: Spheres passing a density threshold = voids



Some other void codes to check out:

- VAST (implementing VOIDFINDER and V^2)
- DIVE / pydive
- CosmoBolognaLib

What are voids?

Things to remember about voids:

1. They are regions of “low” galaxy density
2. But also, ***voids are not real***

What are voids?

Things to remember about voids:

1. They are regions of “low” galaxy density
2. But also, ***voids are not real***
    - Galaxies are real, voids are not
    - A “void” is just some non-linear, possibly non-local, transformation of the galaxy/matter density field
    - We are free to choose different transformations for different purposes … but these are not physical objects!
    - Just because they are not real doesn’t mean they aren’t useful
    - The key is to *be consistent* in defining your transformation and understanding implications

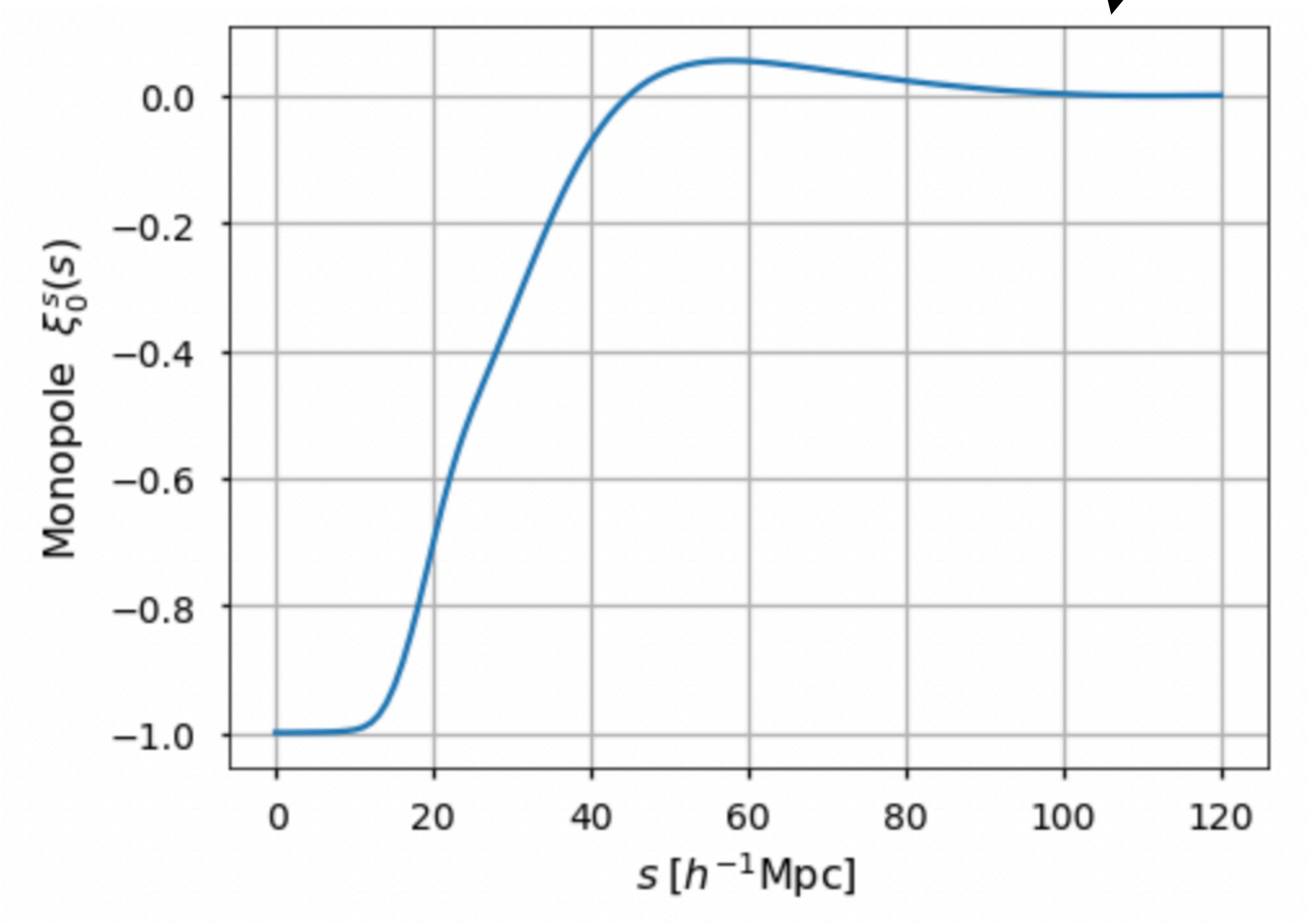
Void-galaxy cross-correlations

Void-galaxy cross-correlations

That is, the cross-correlation of void centre positions with galaxies

- “void centre” is not unambiguously defined! One useful definition is void centre = position of minimum density
- cross-correlation is then a constrained galaxy 1-pt function, i.e. the galaxy number density around regions of low density/density minima

In 1D, should look qualitatively something like this

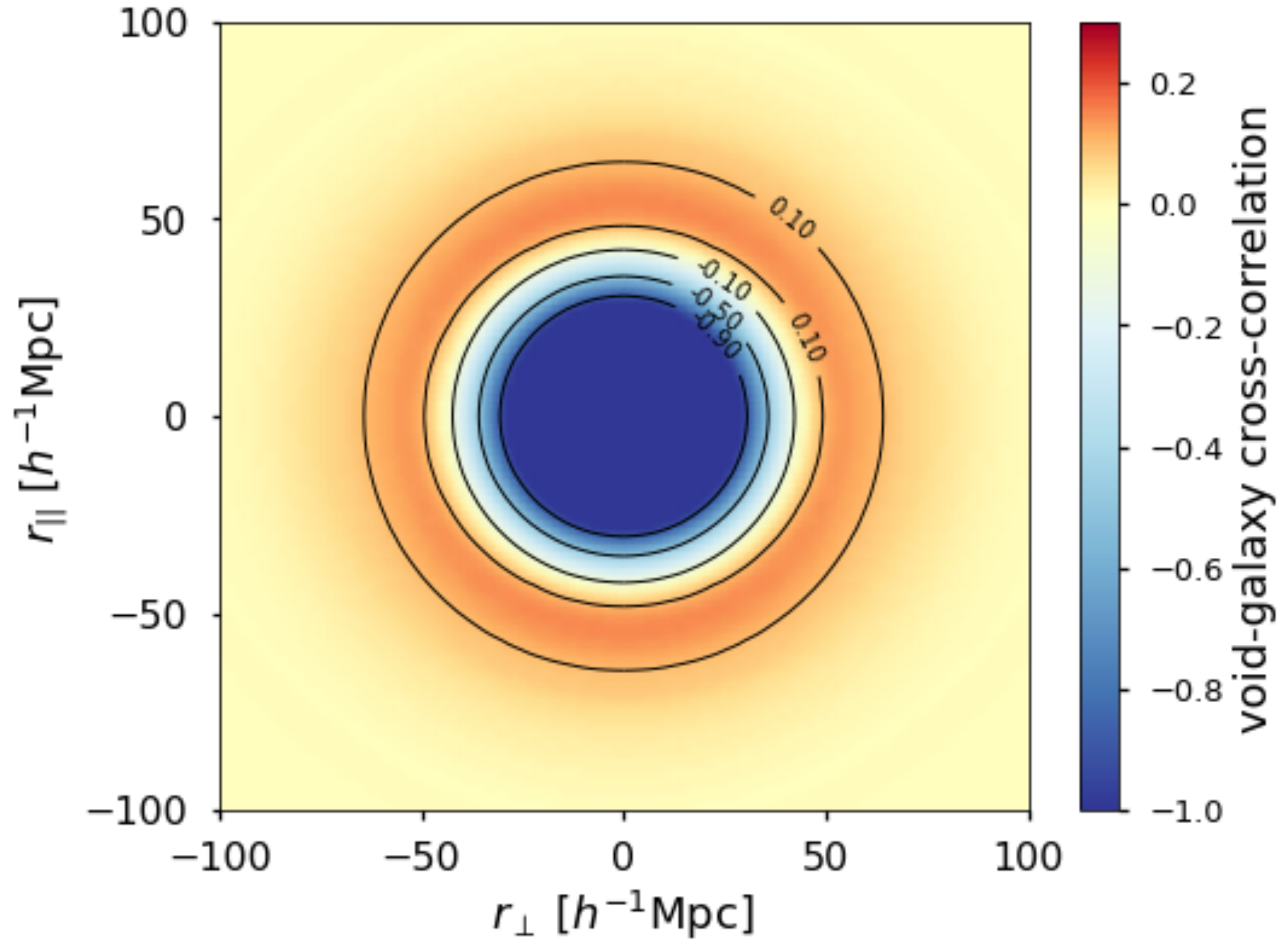


The CCF in real space

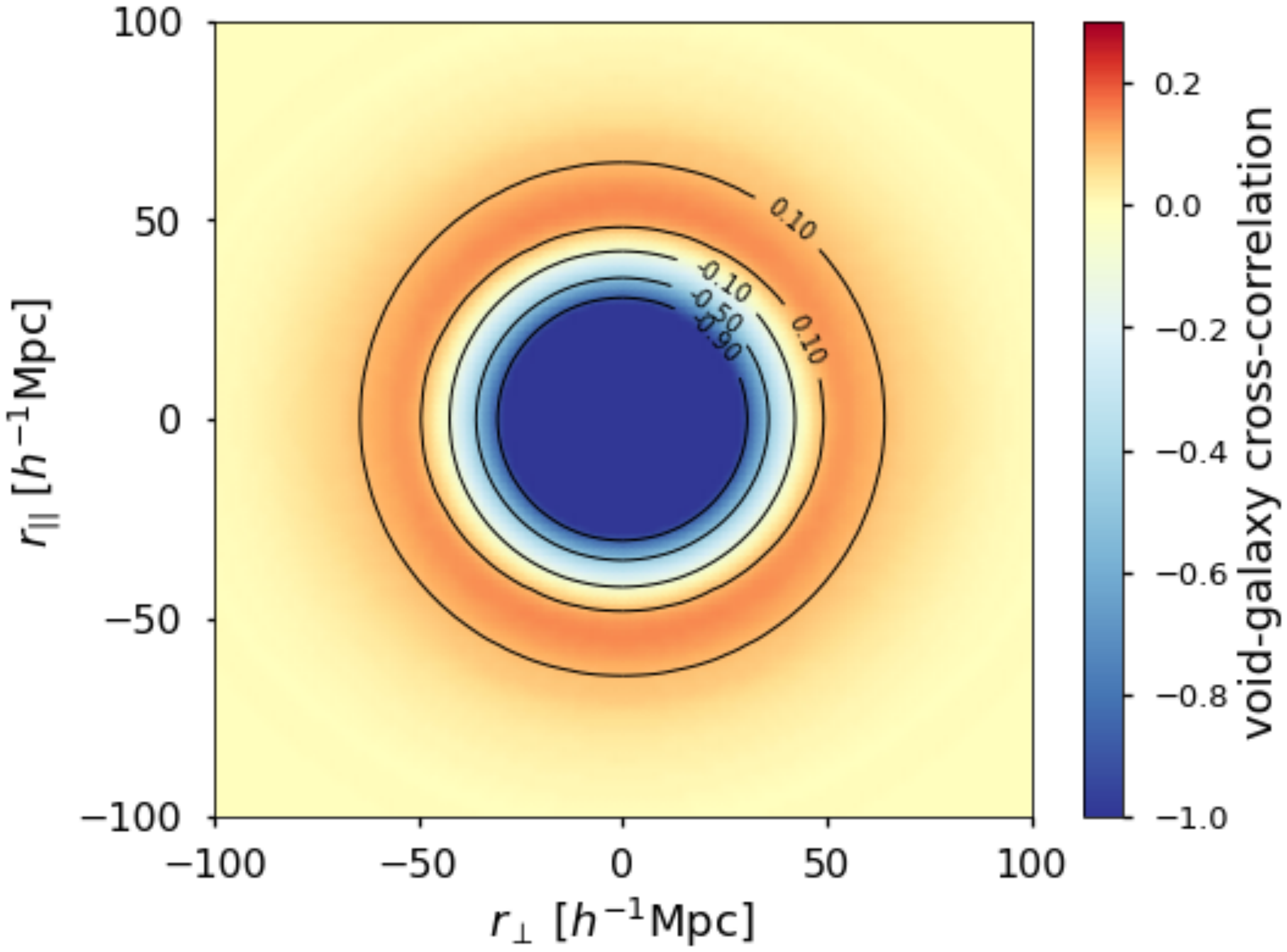
Individual voids can be far from spherical. But assuming:

1. Statistical homogeneity + isotropy
2. redshift ↔ distance conversion matches true cosmology (i.e., no Alcock-Paczynski effect)
3. All void orientations/alignments equally likely to be selected
4. Sufficiently large number of voids (~ few thousand)

CCF in real space should be spherically symmetric:



The CCF in real space

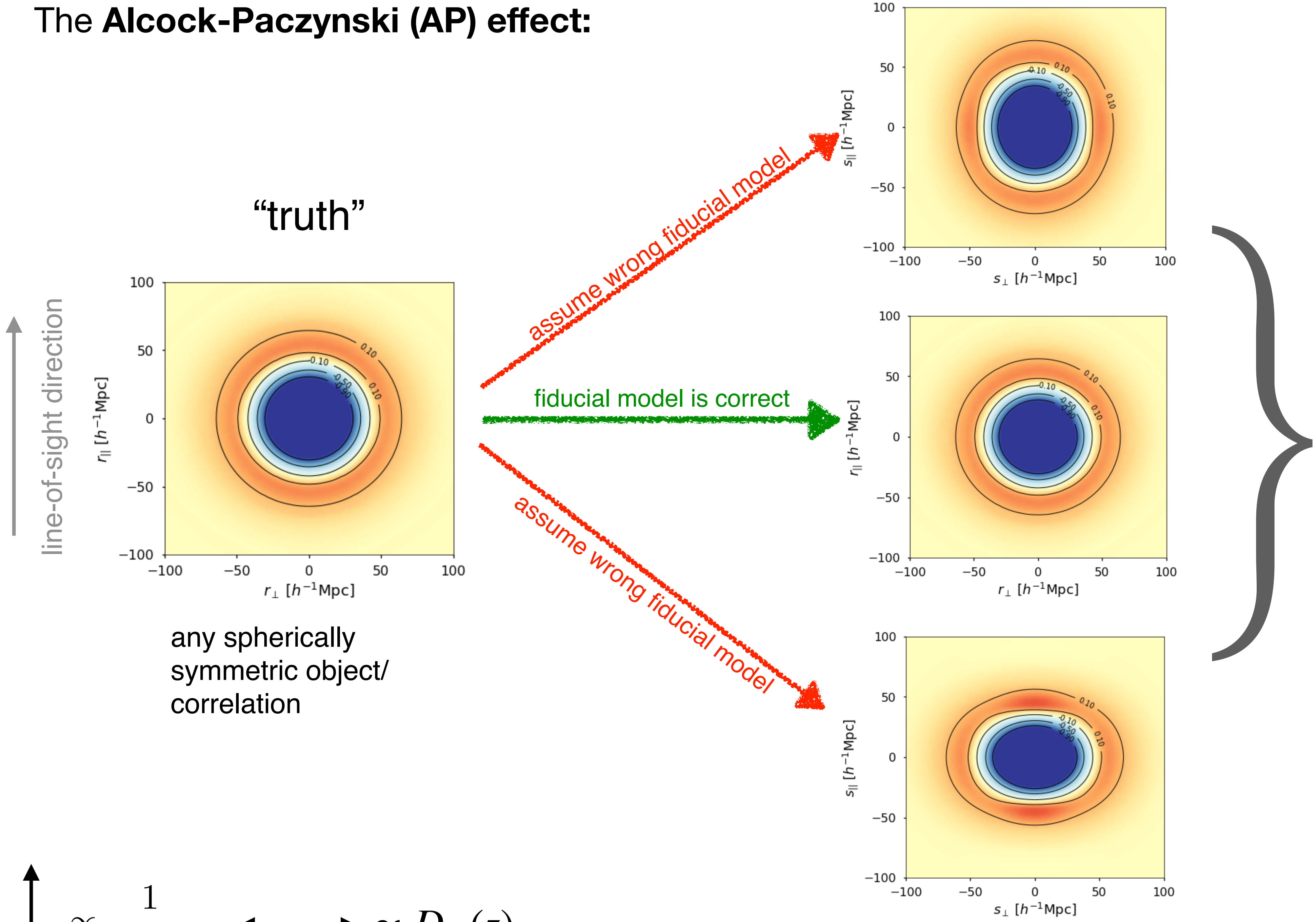


$\Longrightarrow$ can use CCF as a **standard sphere**

Standard spheres and the AP test

We only measure angles and redshifts of galaxies. Conversion to distance requires assuming a background cosmology.

The **Alcock-Paczynski (AP) effect:**



any spherically symmetric object/ correlation

“observation”

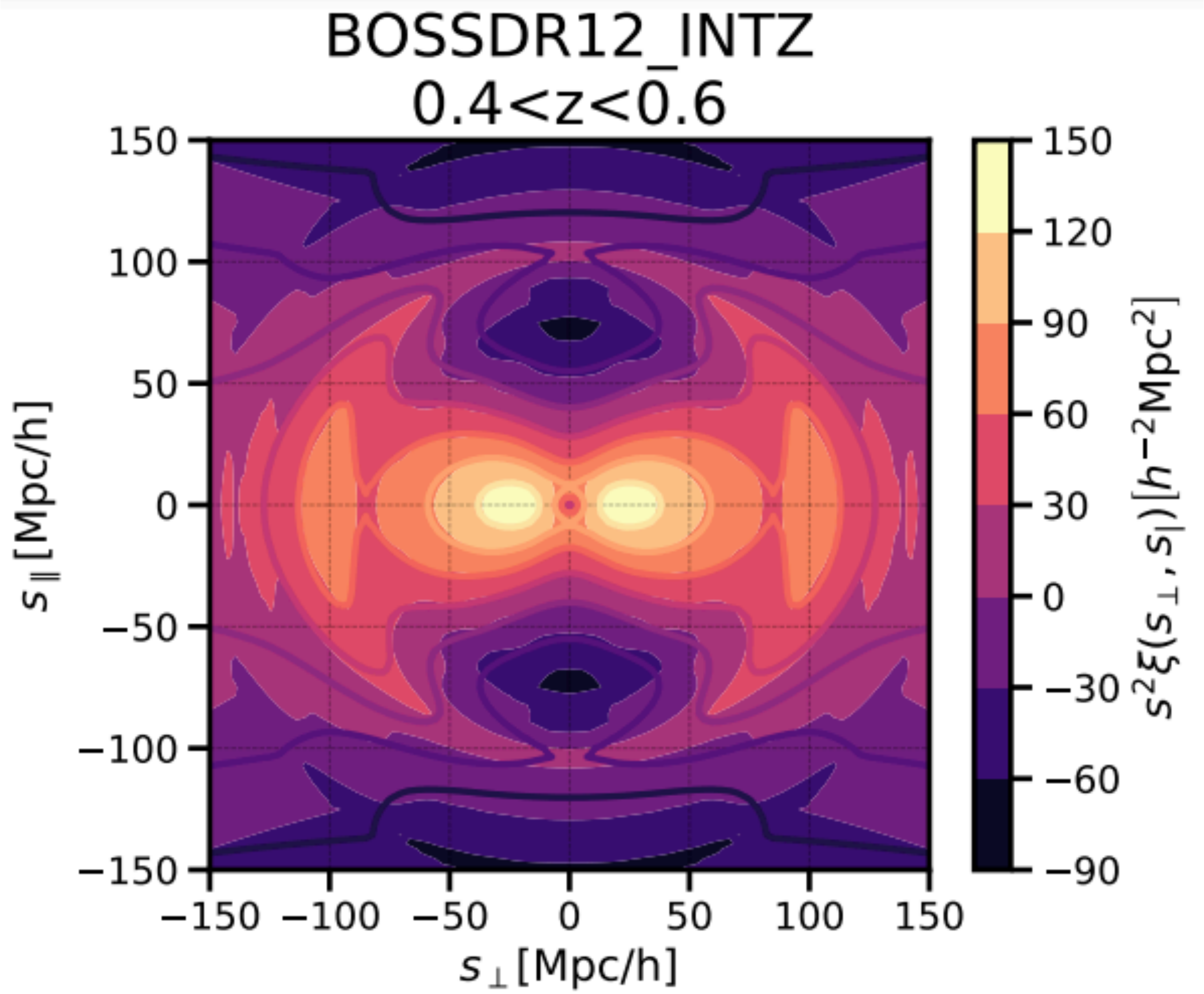
need not be spherically symmetric!

distortion measures the ratio $D_M(z)H(z)$

$\updownarrow \propto \frac{1}{H(z)}$ $\longleftrightarrow \propto D_\mathrm{M}(z)$

Other sources of anisotropy

Peculiar velocities lead to **redshift-space distortions (RSD)**

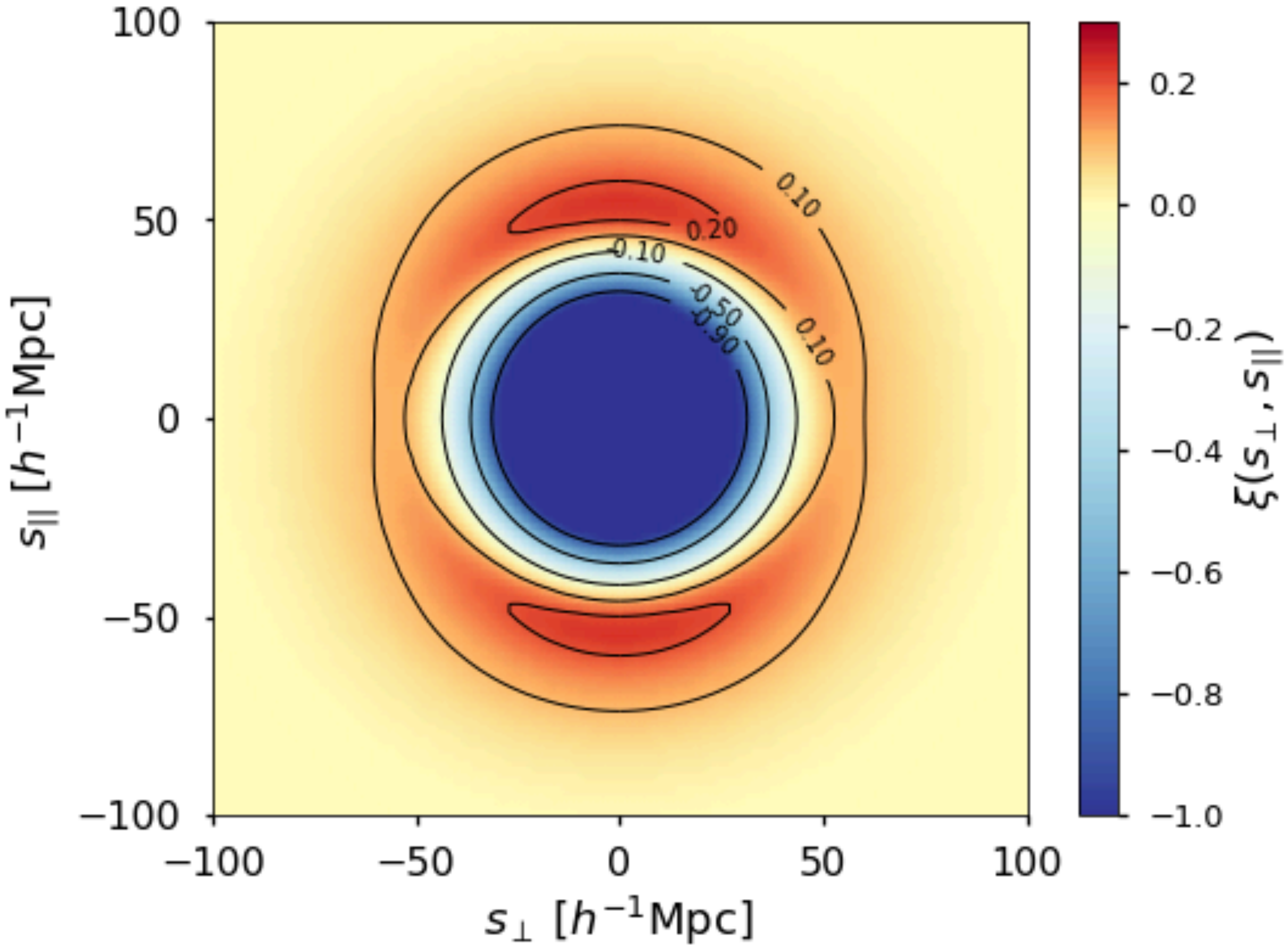


BOSS collaboration (MNRAS 470, 2617; 2017)
(plot by Jiamin Hou, MPE)

RSD in the galaxy auto-correlation

Other sources of anisotropy

Peculiar velocities lead to **redshift-space distortions (RSD)**



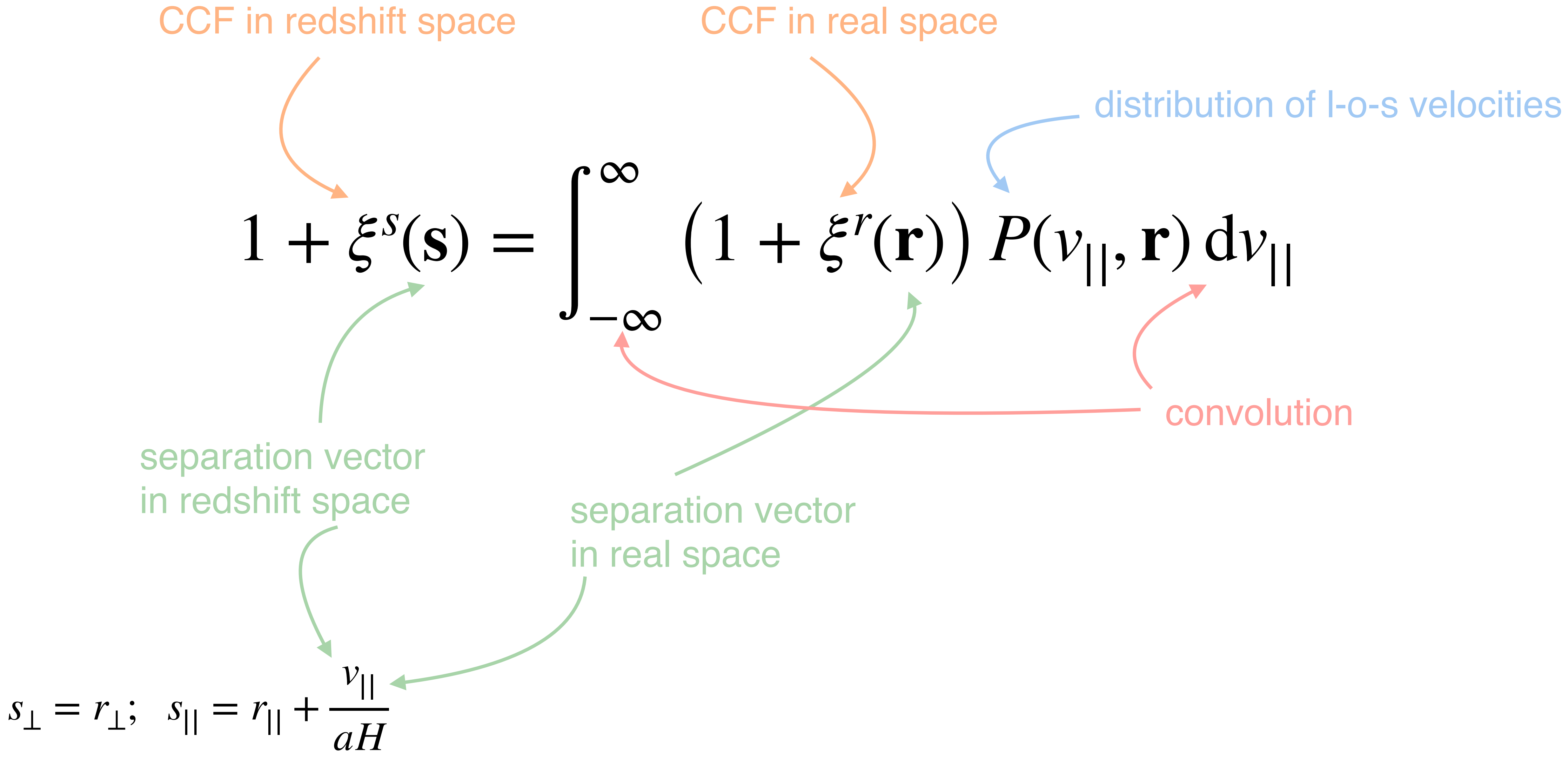
RSD in the void galaxy cross-correlation

Need to disentangle RSD from AP to use standard sphere test!

Modelling RSD in the void-galaxy CCF

$$1 + \xi^s(\mathbf{s}) = \int_{-\infty}^{\infty} \left(1 + \xi^r(\mathbf{r})\right) P(v_{||}, \mathbf{r})\, \mathrm{d}v_{||}$$

Modelling RSD in the void-galaxy CCF



CCF in redshift space

CCF in real space

distribution of l-o-s velocities

$$1+\xi^s(\mathbf{s}) = \int_{-\infty}^{\infty}\left(1+\xi^r(\mathbf{r})\right)P(v_{||},\mathbf{r})\,\mathrm{d}v_{||}$$

convolution

separation vector
in redshift space

separation vector
in real space

$$s_\perp = r_\perp;\quad s_{||} = r_{||} + \frac{v_{||}}{aH}$$

Completely* general expression!

*there is one assumption

Modelling RSD in the void-galaxy CCF

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Modelling RSD in the void-galaxy CCF

$$1 + \xi^s(\mathbf{s}) = \int_{-\infty}^{\infty} \left(1 + \xi^r(\mathbf{r})\right) P(v_{||}, \mathbf{r})\, \mathrm{d}v_{||}$$

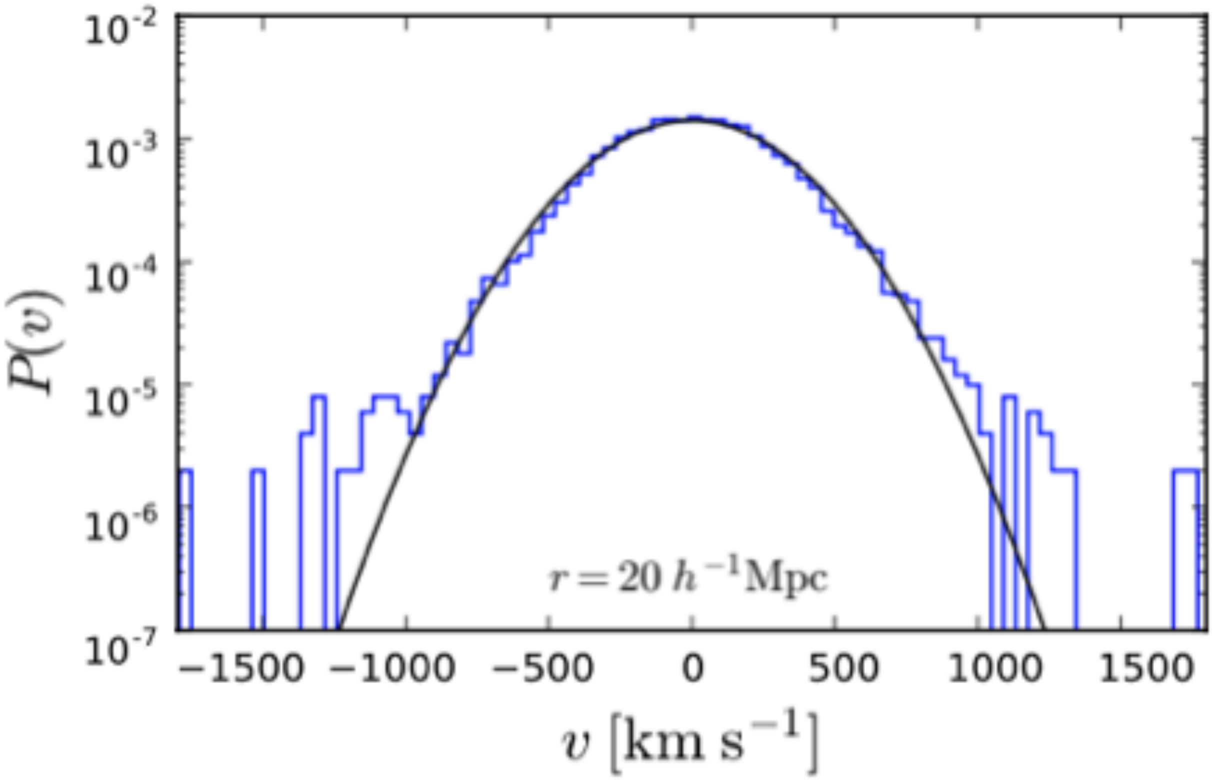
- $v_{||}$ is relative velocity between galaxies and voids, but voids do not move *by construction*

Remember, voids are not real! There is no physical object at the void centre position!

Modelling RSD in the void-galaxy CCF

$$1 + \xi^s(\mathbf{s}) = \int_{-\infty}^{\infty} \left(1 + \xi^r(\mathbf{r})\right) P(v_{||}, \mathbf{r}) \, \mathrm{d}v_{||}$$

- $P(v_{||}, \mathbf{r})$ is found to be very close to a Gaussian in simulations



SN & Percival, 1712.07575

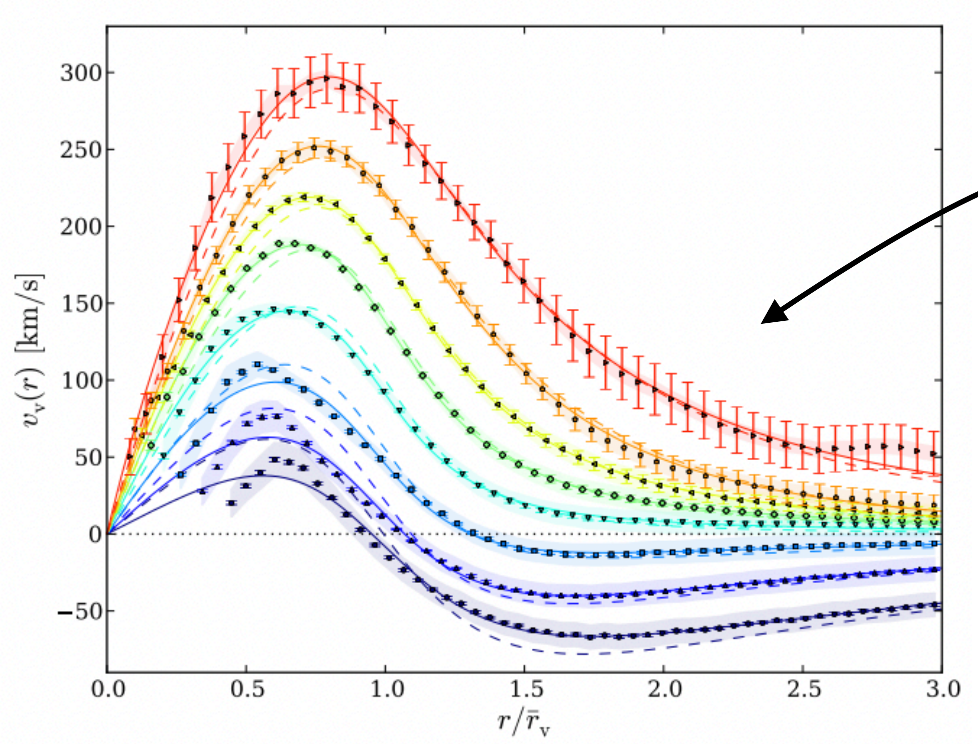
So can be specified by just a mean and variance (both generally position-dependent)

This is then a *Gaussian streaming model*

Modelling RSD in the void-galaxy CCF

$$1+\xi^s(\mathbf{s}) = \int_{-\infty}^{\infty} \left(1+\xi^r(\mathbf{r})\right) P(v_{||},\mathbf{r})\,\mathrm{d}v_{||}$$

- Mean velocity is directed radially outward from void centre (assumption of sphericity!) → dependence on $\mu = \cos\theta$
- Can model mean velocity with simple linearised form: $v_r(r) = -\frac{1}{3} f a H r \Delta(r)$



works reasonably well* for voids in simulations

*but not always and not for all void definitions!
See Massara *et al*., 2206.14120

Hamaus *et al*., 1403.5499
also SN & Percival, 1712.07575

Modelling RSD in the void-galaxy CCF

$$1 + \xi^s(\mathbf{s}) = \int_{-\infty}^{\infty} \left(1 + \xi^r(\mathbf{r})\right) P(v_{||}, \mathbf{r})\, \mathrm{d}v_{||}$$

Template-based approach to modelling mean and variance of velocity PDF:

- Calibrate templates from fixed-cosmology simulations
- Introduce terms to modify amplitude/shape of templates with changing cosmology (primarily $f\sigma_8$)

SN & Percival, 1712.07575, SN *et al.*, 1904.01030, Radinovic *et al.*, 2302.05302

All models are related!

$$1 + \xi^{s}(\mathbf{s}) = \int_{-\infty}^{\infty} \Big(1 + \xi^{r}(\mathbf{r})\Big)\, P(v_{||}, \mathbf{r})\, \mathrm{d}v_{||}$$

All models are related!

$$1 + \xi^s(\mathbf{s}) = \int_{-\infty}^{\infty} \left(1 + \xi^r(\mathbf{r})\right) P(v_{||}, \mathbf{r})\, \mathrm{d}v_{||}$$

$$\Big\downarrow$$

change variables $\tilde{v} \equiv v_{||} - v_r(r)\mu_r$

Derived in Woodfinden *et al.*, 2205.06258

$$1 + \xi^s(\mathbf{s}) = \int_{-\infty}^{\infty} \left(1 + \xi^r(r)\right) \left[1 + \frac{v_r}{raH} + \frac{rv_r' - v_r}{raH}\mu_r^2\right]^{-1} P(\tilde{v}, r)\mathrm{d}\tilde{v}$$

Model of SN & Percival, 1712.07575

All models are related!

$$1 + \xi^s(\mathbf{s}) = \int_{-\infty}^{\infty} \left(1 + \xi^r(r)\right) \left[1 + \frac{v_r}{raH} + \frac{rv_r' - v_r}{raH}\mu_r^2\right]^{-1} P(\tilde{v}, r)\mathrm{d}\tilde{v}$$

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Model of SN & Percival, 1712.07575

assume distribution → zero width

$$1+\xi^{s}(\mathbf{s}) = \left(1+\xi^{r}(r)\right) \left[1+\frac{v_r}{raH}+\frac{rv_r'-v_r}{raH}\mu_r^2\right]^{-1}$$

Also from SN & Percival, 1712.07575

“Kaiser model”

All models are related!

$$1 + \xi^s(\mathbf{s}) = \left(1 + \xi^r(r)\right)\left[1 + \frac{v_r}{raH} + \frac{r v_r' - v_r}{raH}\mu_r^2\right]^{-1}$$

Also from SN & Percival, 1712.07575

All models are related!

$$1 + \xi^s(\mathbf{s}) = \left(1 + \xi^r(r)\right)\left[1 + \frac{v_r}{raH} + \frac{rv_r' - v_r}{raH}\mu_r^2\right]^{-1}$$

Also from SN & Percival, 1712.07575

drop “second-order” terms

$$\xi^s(\mathbf{s}) = \xi^r(r) - \frac{v_r}{raH} - \frac{rv_r' - v_r}{raH}\mu_r^2$$

e.g., model of Hamaus *et al*., 2007.07895

All models are related!

$$\xi^s(\mathbf{s}) = \xi^r(r) - \frac{v_r}{raH} - \frac{rv_r' - v_r}{raH}\mu_r^2$$

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e.g., model of Hamaus *et al*., 2007.07895

assume coordinate shift can be neglected in CCF argument, $\xi^s(\mathbf{s}) \simeq \xi^s(\mathbf{r})$

$$\xi^s(\mathbf{r}) = \xi^r(r) - \frac{v_r}{raH} - \frac{rv_r' - v_r}{raH}\mu_r^2$$

e.g., Cai *et al*., 1603.05184
Hamaus *et al*., 1705.05328
Aubert *et al*., 2007.09013

Even more modelling options:

- Add extra nuisance parameters Hamaus *et al*., 2007.07895
- Add nuisance parameters + modify coefficients of some terms

Hamaus *et al*., 2108.10347

Adding AP distortion to the model

Define:

$$\alpha_\perp \equiv \frac{D_M(z)}{D_M^{\rm fid}(z)}, \;\; \alpha_{||} \equiv \frac{D_H(z)}{D_H^{\rm fid}(z)} = \frac{cH^{\rm fid}(z)}{cH(z)}$$

and model:

$$\xi^s(s_\perp, s_{||}) = \xi^{s,{\rm fid}}(\alpha_\perp s_\perp^{\rm fid}, \alpha_{||} s_{||}^{\rm fid})$$

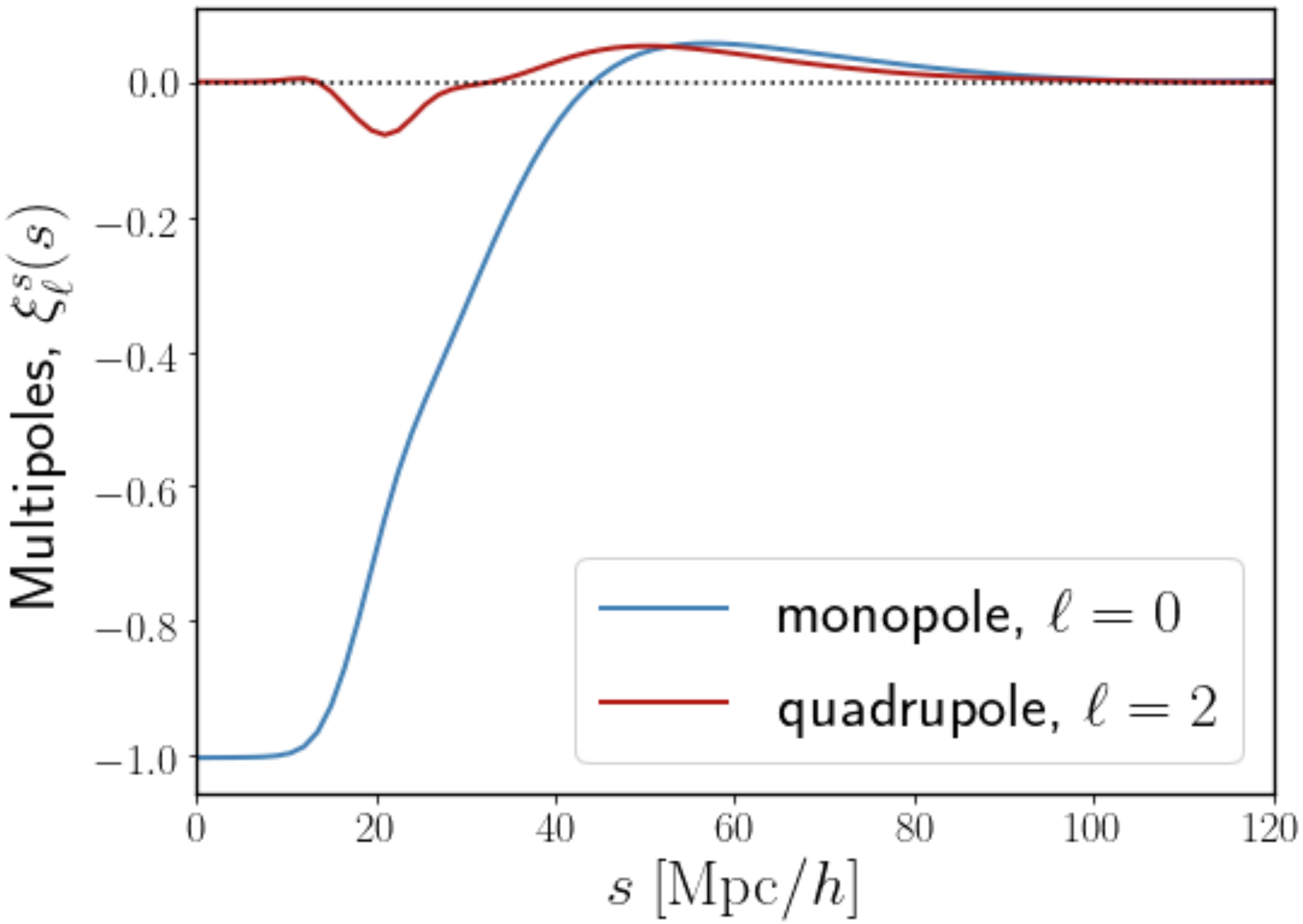
At the end of the day, key model dependencies:

– growth rate, $f(z)\sigma_8(z)$

– AP parameter, $F_{\rm AP} = \frac{D_M(z)}{D_H(z)}$

equivalently, $\epsilon \equiv \frac{\alpha_\perp}{\alpha_{||}}$

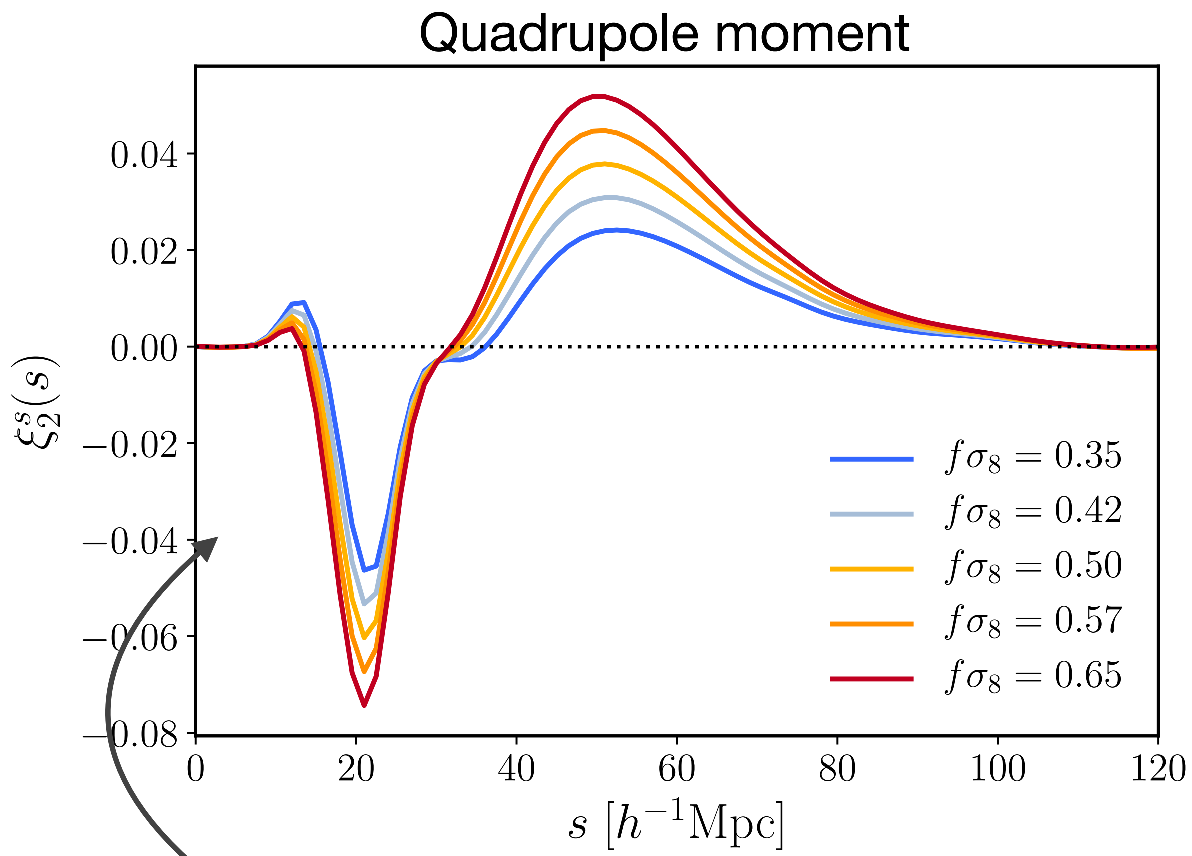
What does this look like?



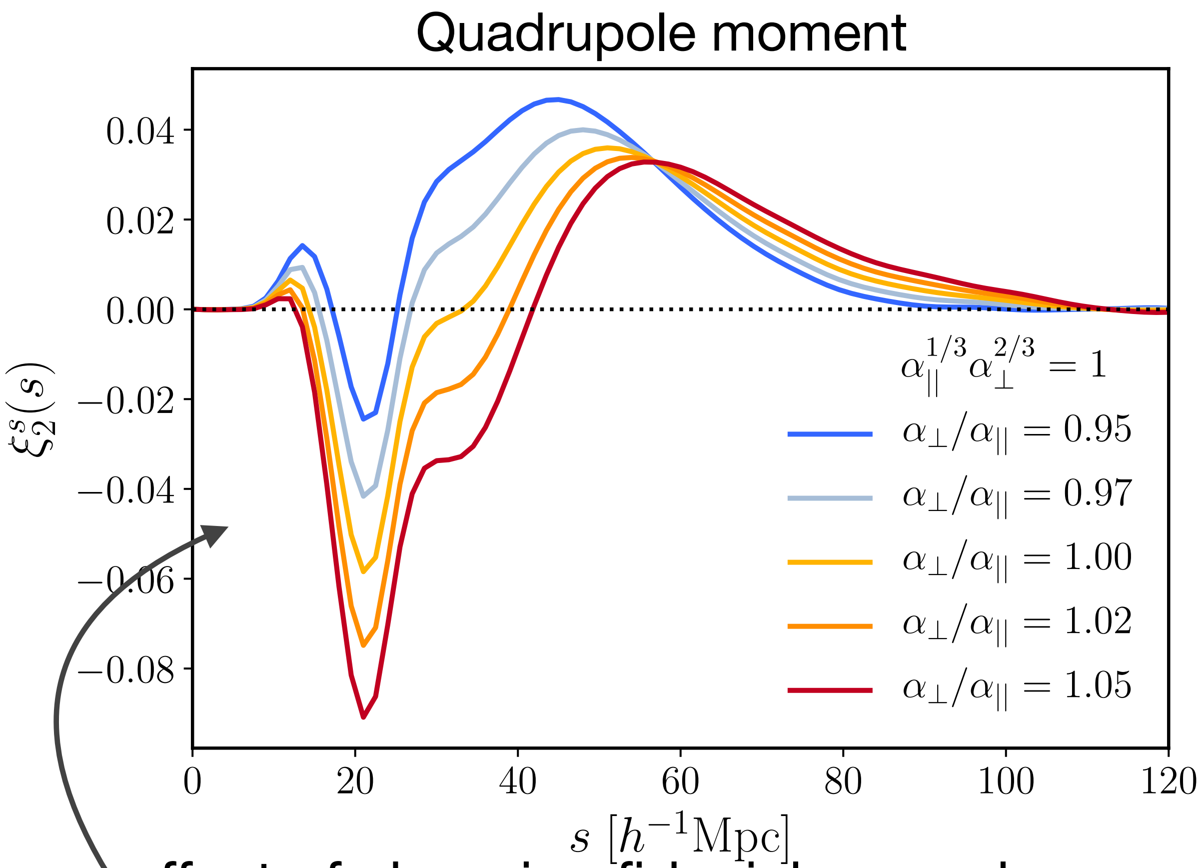
Legendre multipoles, $\xi^s_\ell(s) = (2\ell + 1)\int_0^1 \xi^s(s,\mu)L_\ell(\mu)\,\mathrm{d}\mu$

Breaking the RSD-AP degeneracy

Unlike in the galaxy 2PCF, in the void-galaxy CCF the two effects are easily distinguished at intermediate scales:

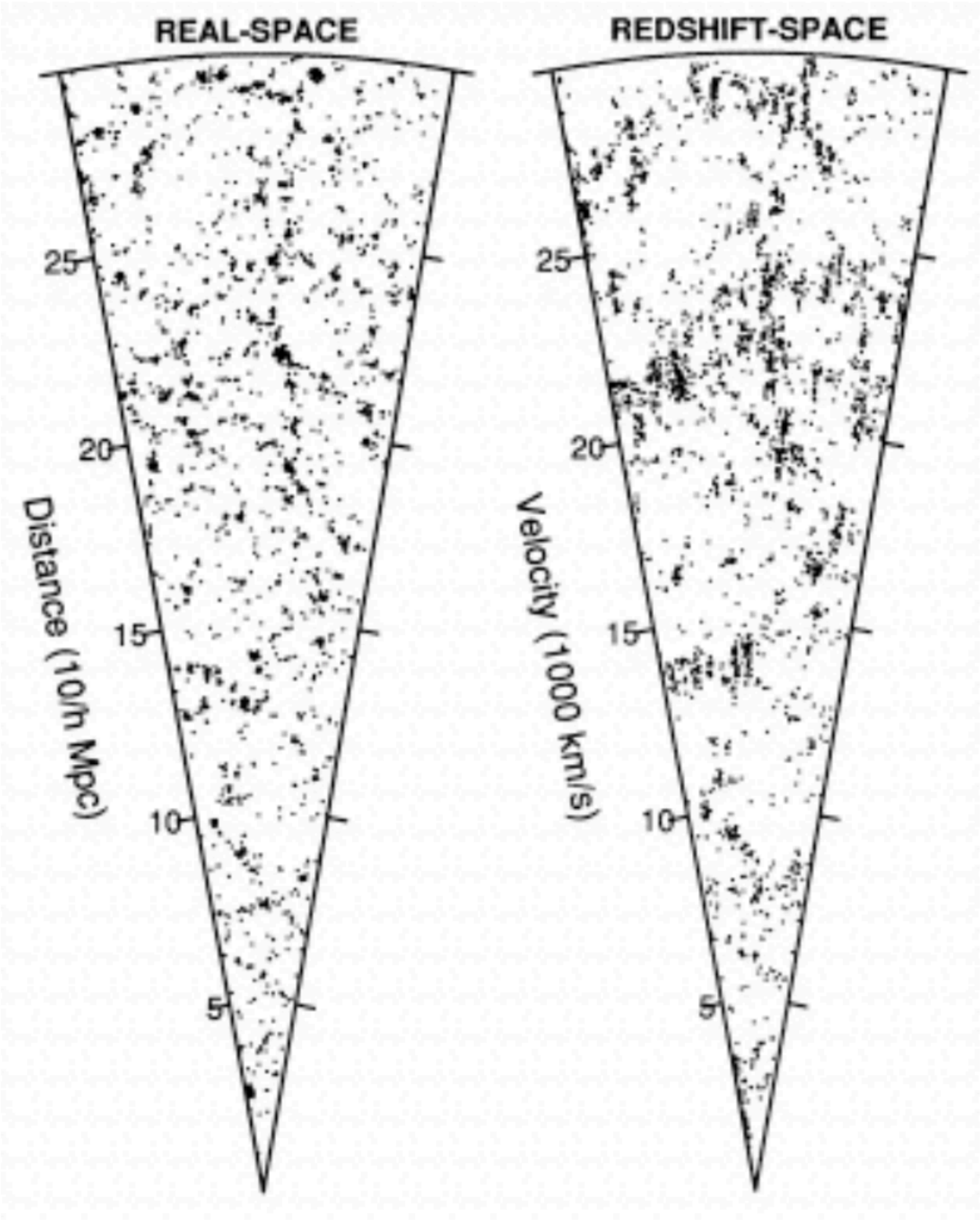

Quadrupole moment

effect of changing growth rate


Quadrupole moment

effect of changing fiducial cosmology

Practical difficulty: selection biases

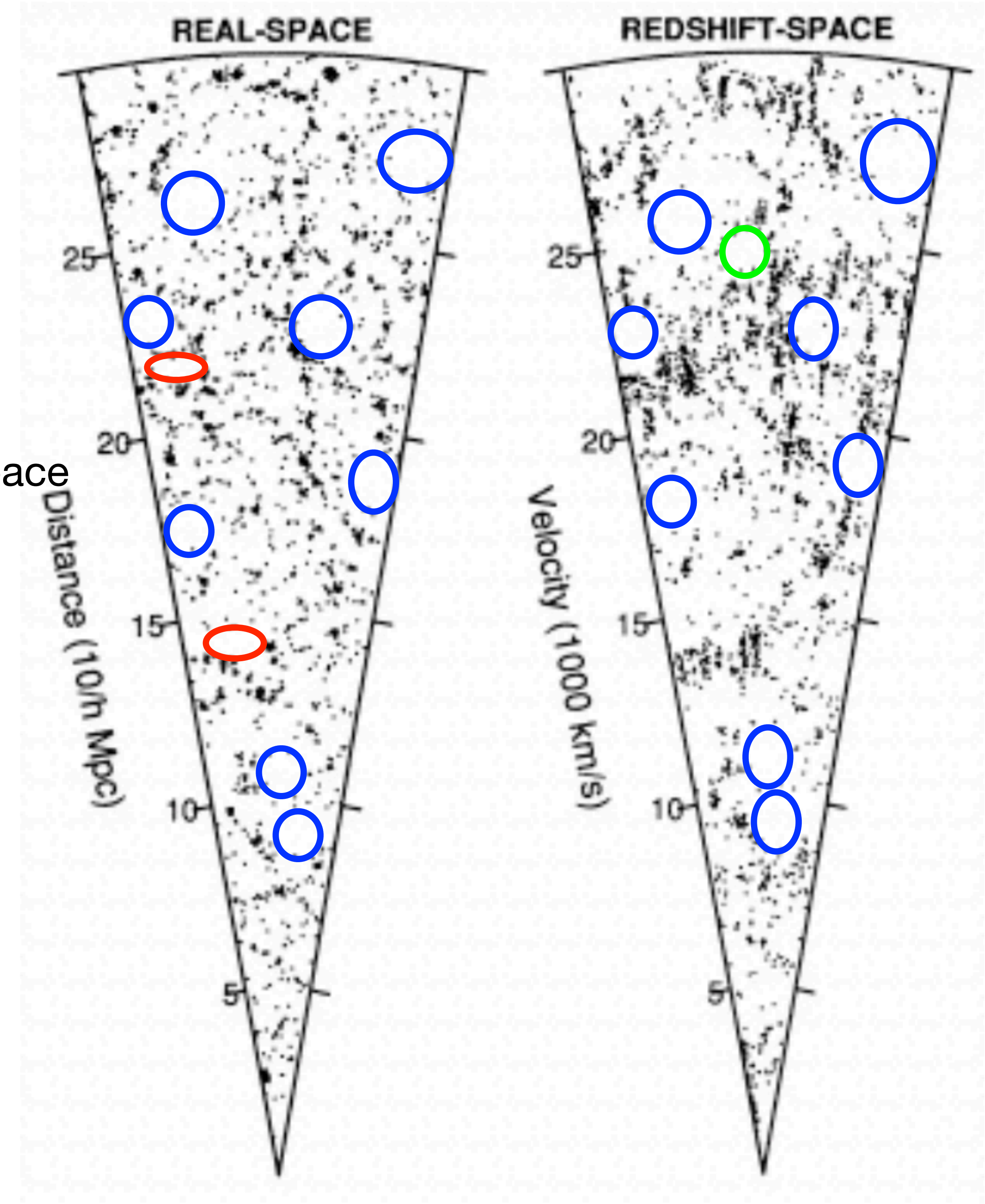


Practical difficulty: selection biases

🔵 : void in real space and redshift space

🔴 : void in real space but disappears in redshift space

🟢 : appears as void only in redshift space



In redshift space, probability of identifying a void depends on orientation!

Consequences of selection biases

In redshift space, probability of identifying a void depends on orientation!

“True” correlation is not intrinsically isotropic

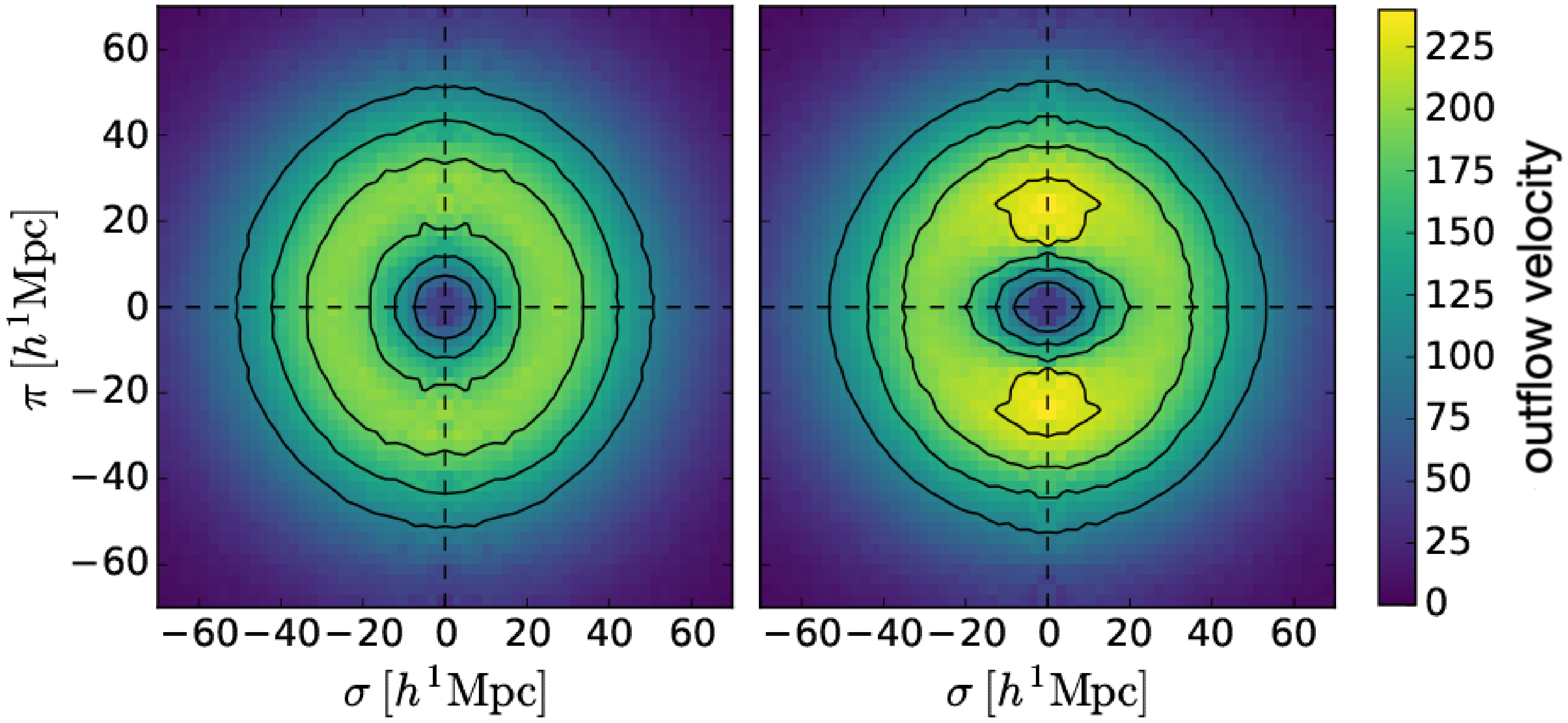
⟹ Mean outflow velocity is not spherically symmetric

SN, Carter, Percival, 1805.09349
Correa *et al.*, 2107.01314

All previous modelling breaks down

voids found in real-space galaxies

voids found in redshift-space galaxies



Consequences of selection biases

In redshift space, probability of identifying
a void depends on orientation!

Solution: use reconstruction in data analysis pipeline SN, Carter, Percival, 1805.09349

- estimate real-space positions of galaxies by reconstructing velocity field
- find voids in real-space field to avoid selection bias
- reconstruction depends on model parameters!
- → inference becomes trickier (but still possible!)

Consequences of selection biases

In redshift space, probability of identifying a void depends on orientation!

Solution: use reconstruction in data analysis pipeline

SN, Carter, Percival, 1805.09349

1. Solve Zeldovich equation for displacement $\boldsymbol{\Psi}$ (same as for BAO reconstruction!)

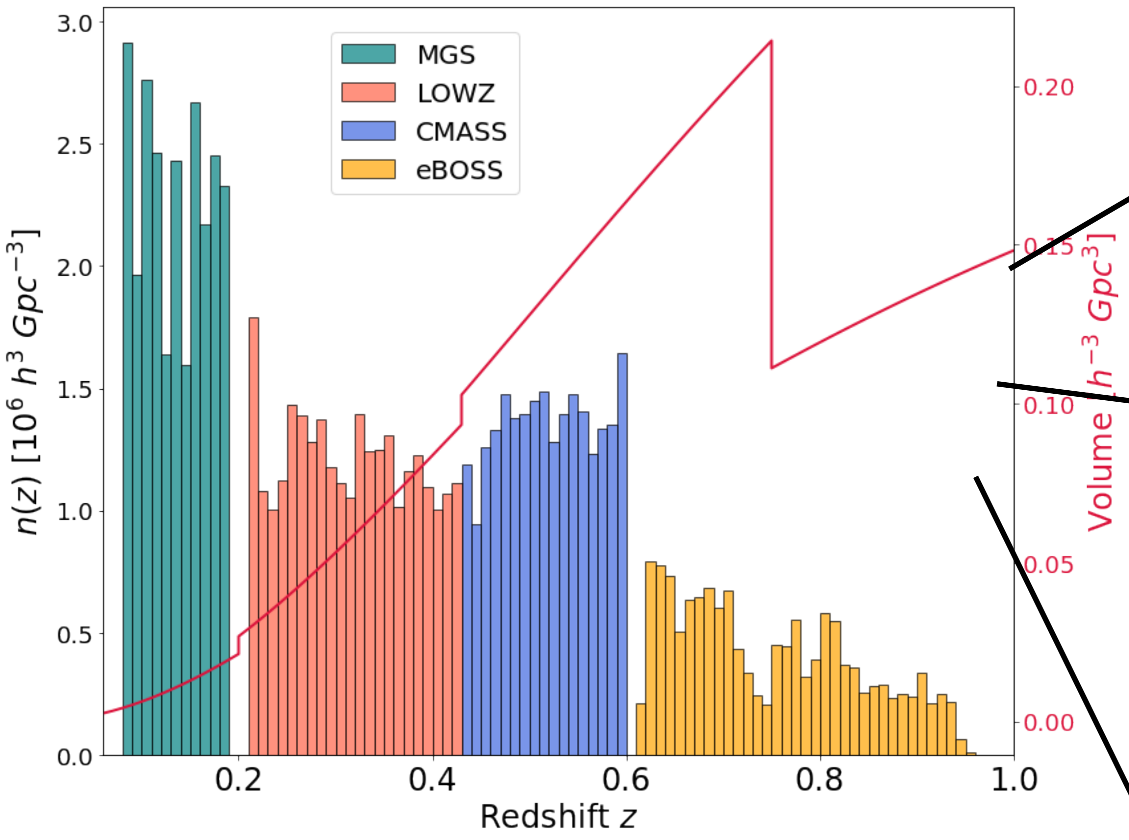
$$\nabla \cdot \boldsymbol{\Psi} + \frac{f}{b} \nabla \cdot (\boldsymbol{\Psi} \cdot \hat{\mathbf{r}}) \hat{\mathbf{r}} = -\frac{\delta_g}{b}$$

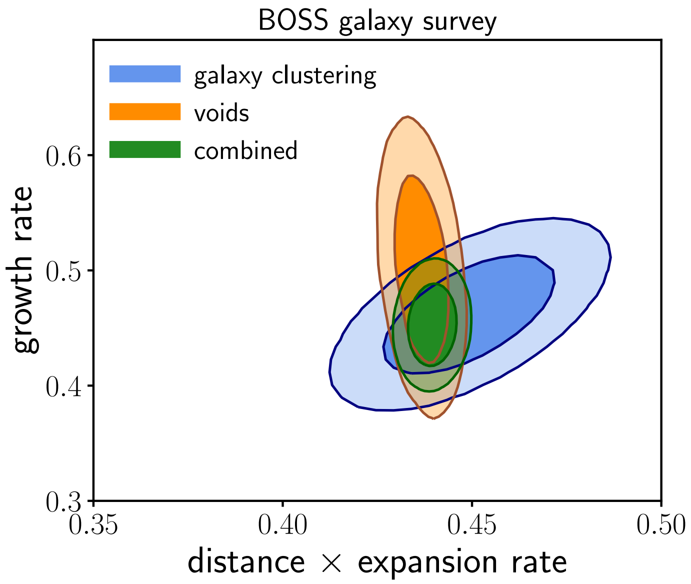
2. Estimate large-scale RSD from $\boldsymbol{\Psi}_{\mathrm{RSD}} = -f(\boldsymbol{\Psi} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}},$
3. Shift galaxies to approximately undo RSD and recover real-space positions
4. Find voids as transformation of **real-space** field
5. Cross-correlate voids with **redshift-space** galaxy field

REVOLVER code allows one to perform these steps

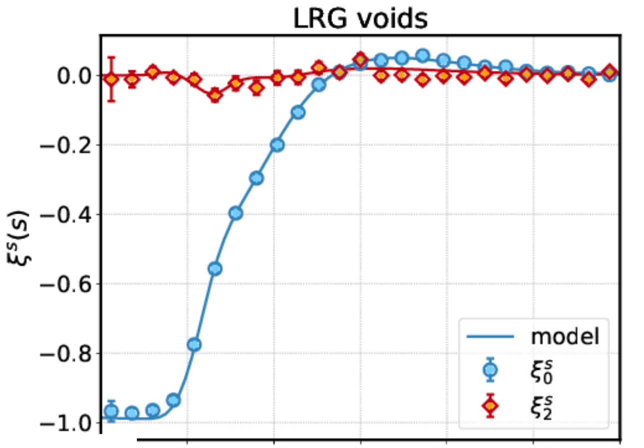
Results from SDSS

Galaxy samples from SDSS surveys





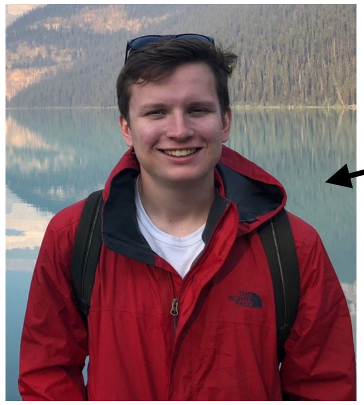
SN *et al*., 1904.01030

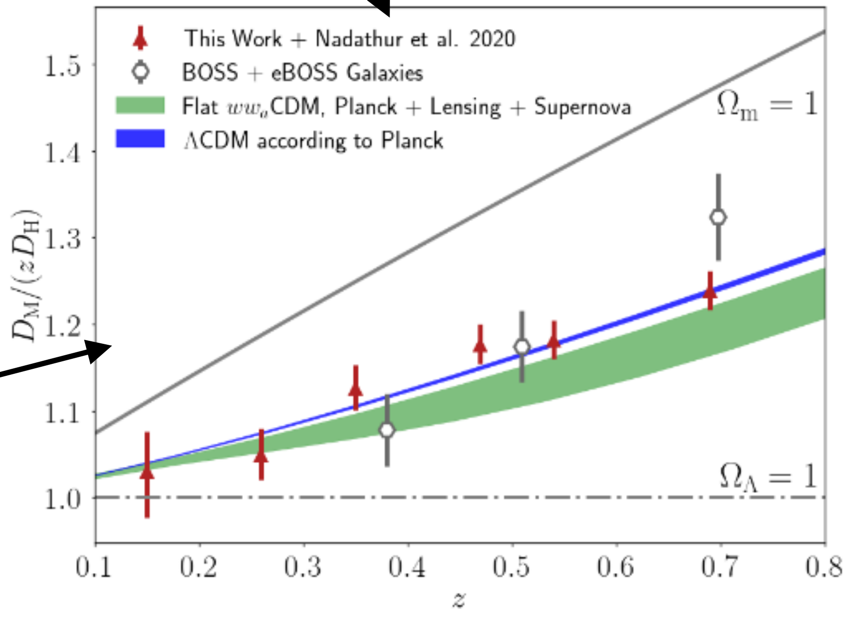


et al. (2020)

SN *et al*., 2008.06060

Alex Woodfinden

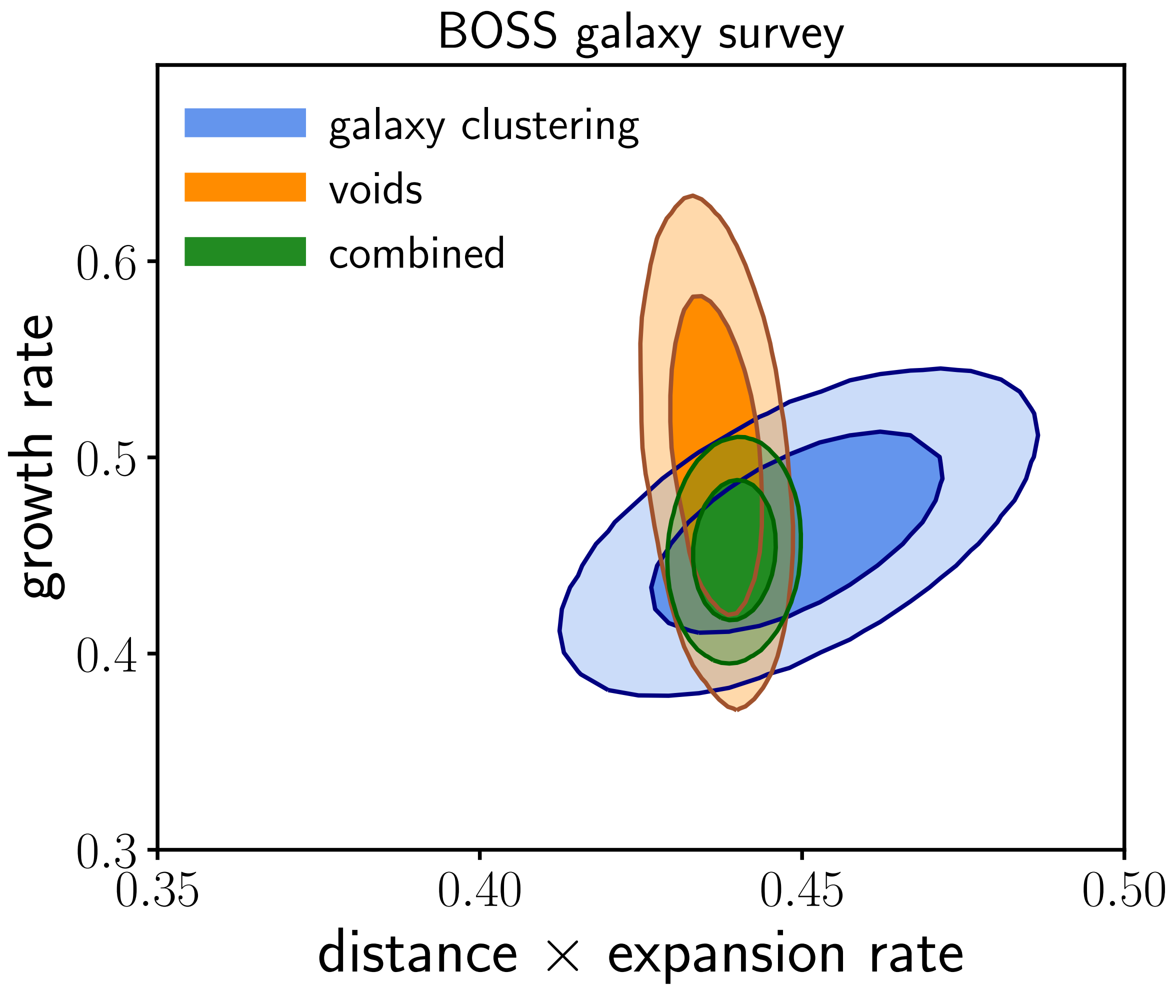




Woodfinden *et al*., 2205.06258

Results from SDSS

Voids measure the AP parameter **much** (factor of ~ few) better than galaxy clustering



SN *et al.*, 1904.01030

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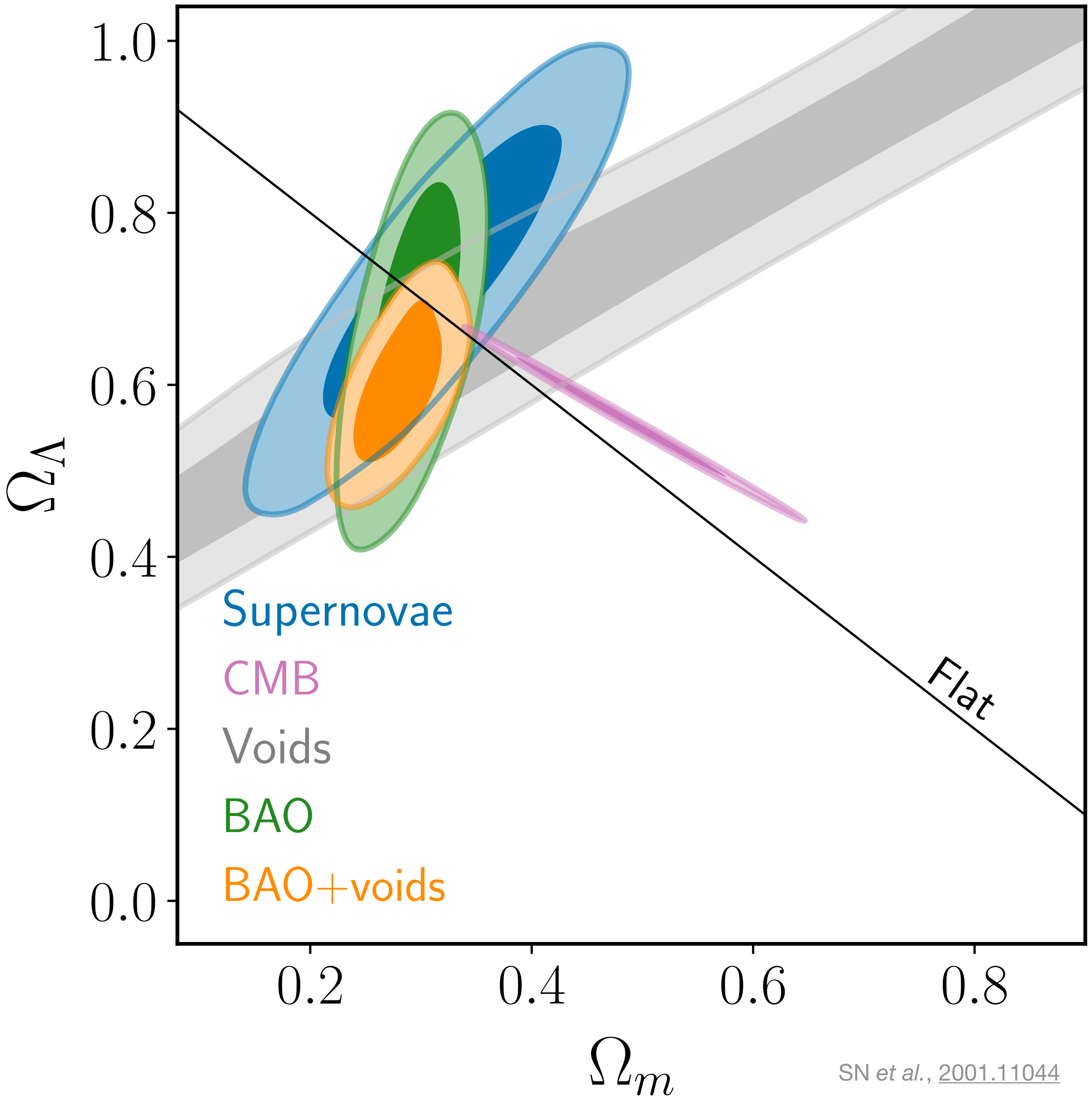
Within ΛCDM, allows better CMB-independent measurement of parameters



SN *et al.*, 2001.11044

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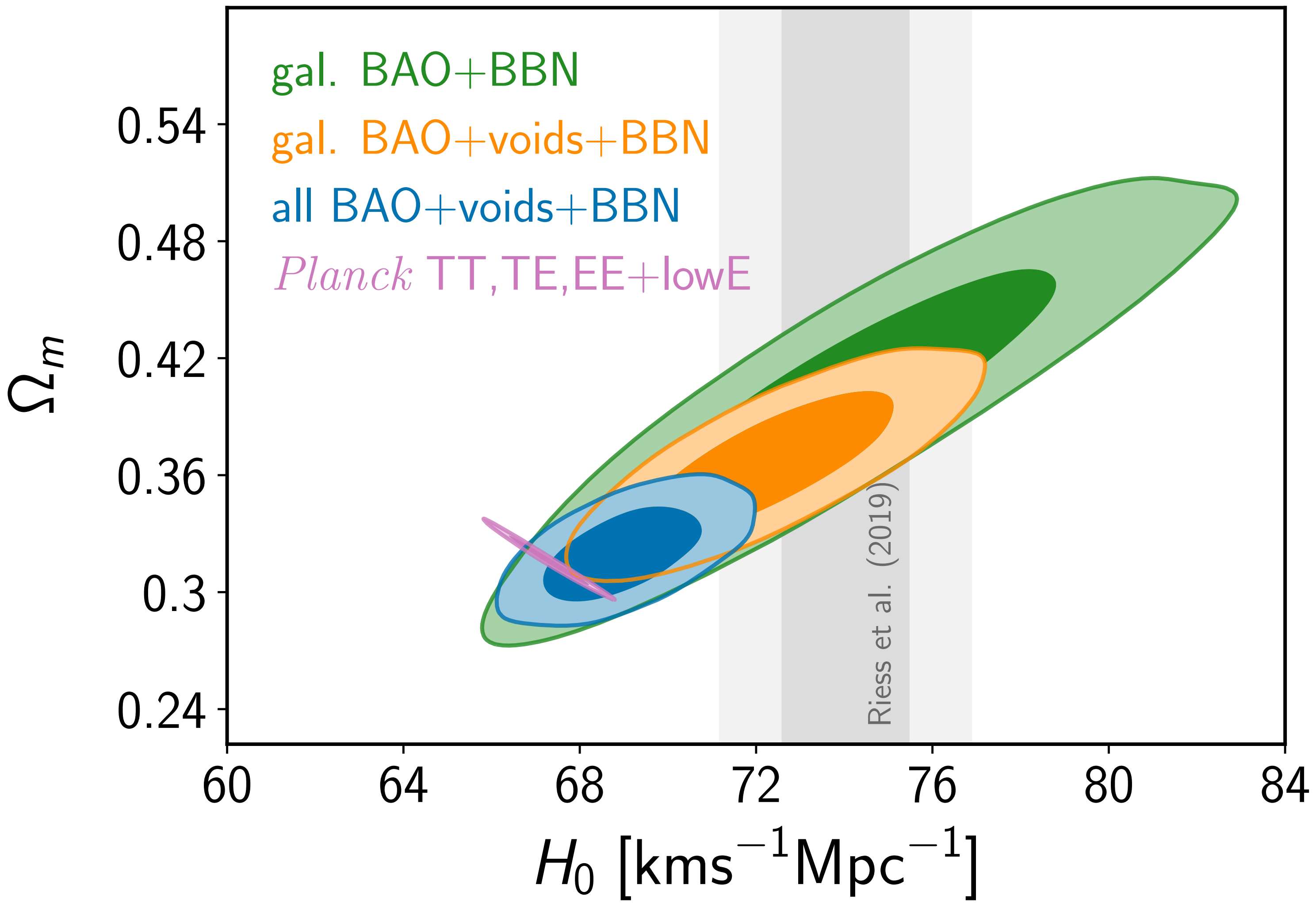
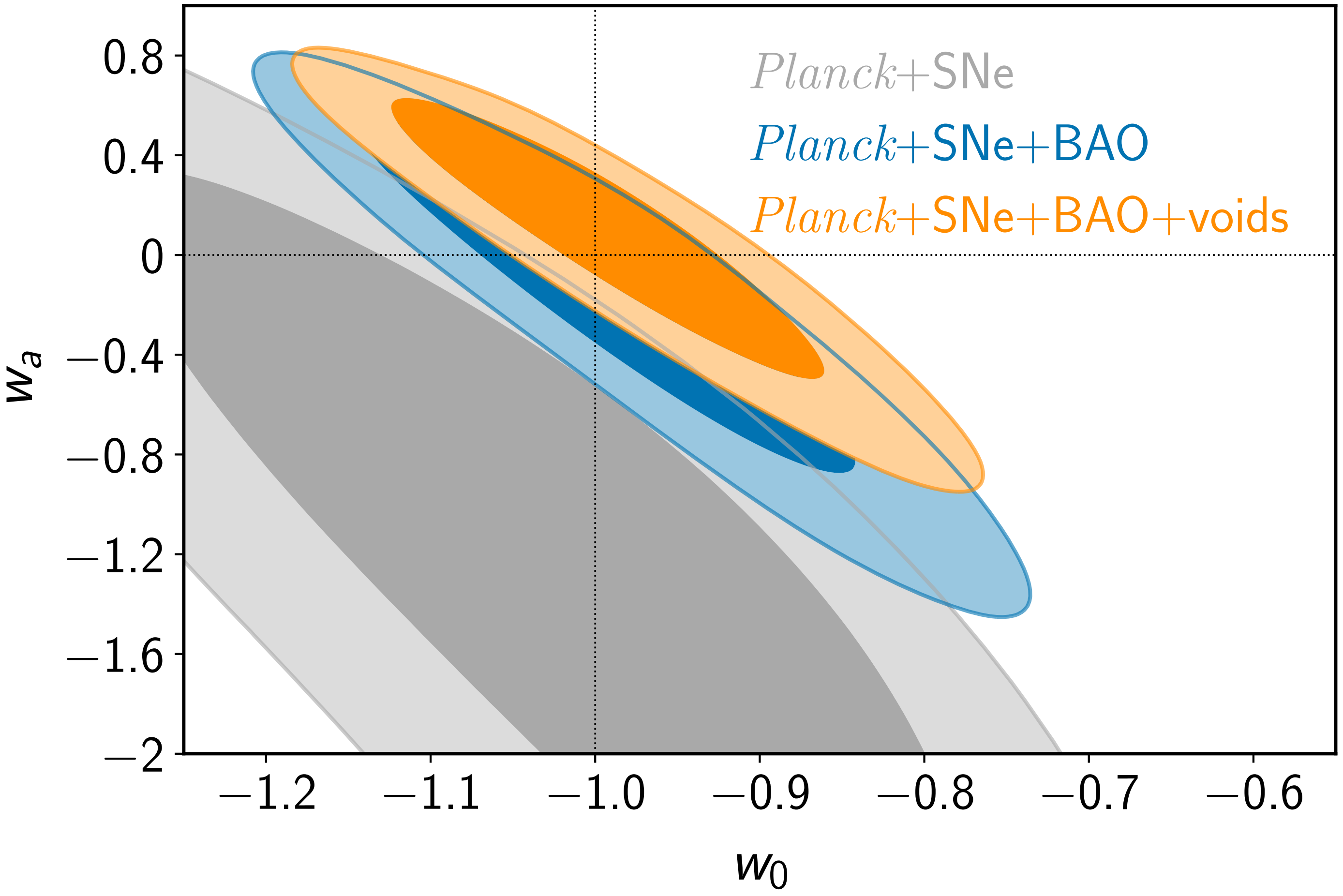


SN *et al.*, 2001.11044

Results from SDSS

Voids measure the AP parameter **much** (factor of ~ few) better than galaxy clustering

In more general models, it helps break degeneracies



40% better Figure of Merit from adding voids

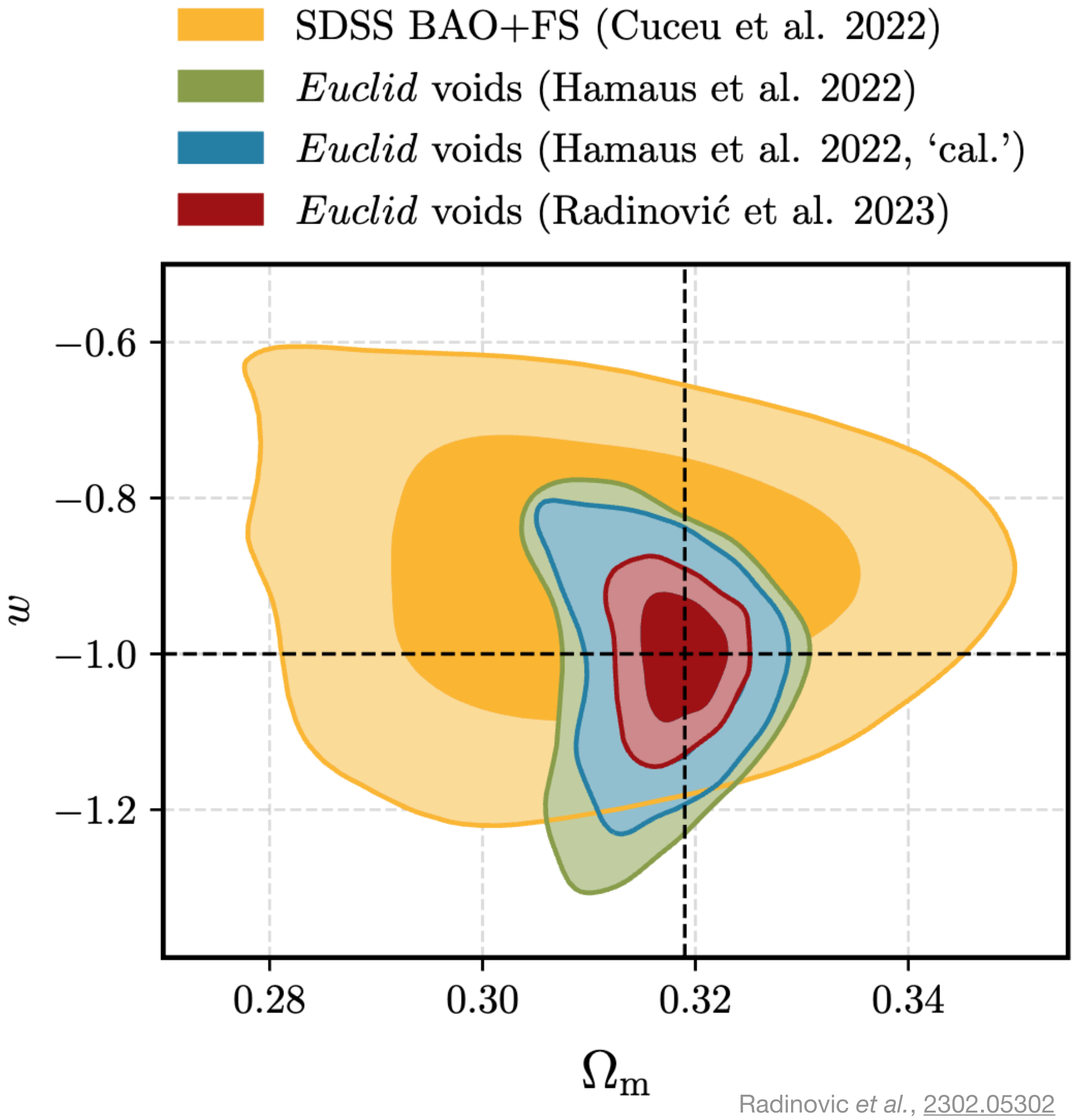
SN *et al.*, 2001.11044

Results from SDSS

Voids measure the AP parameter **much** (factor of ~ few) better than galaxy clustering

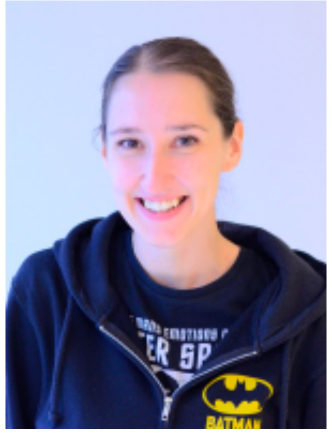
With data from upcoming surveys, it can perform even better:

Euclid forecast:



Radinovic *et al.*, 2302.05302

Sladana Radinovic



Moving beyond voids

Why stick with just voids? More generally, study galaxy clustering conditioned upon different local density environments

→ “density-split” (DS) clustering Paillas *et al*., 2101.09854

Enrique Paillas

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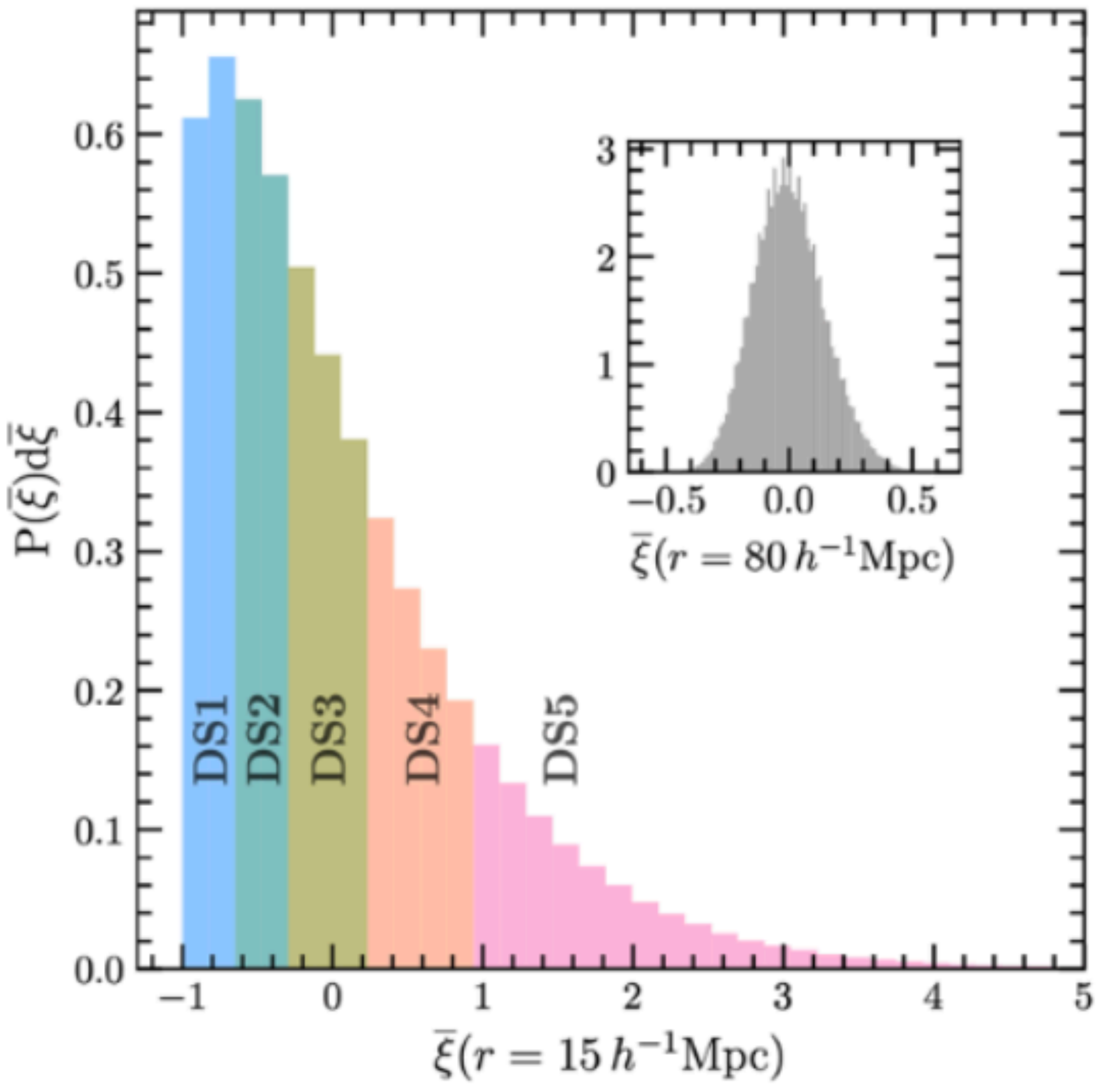

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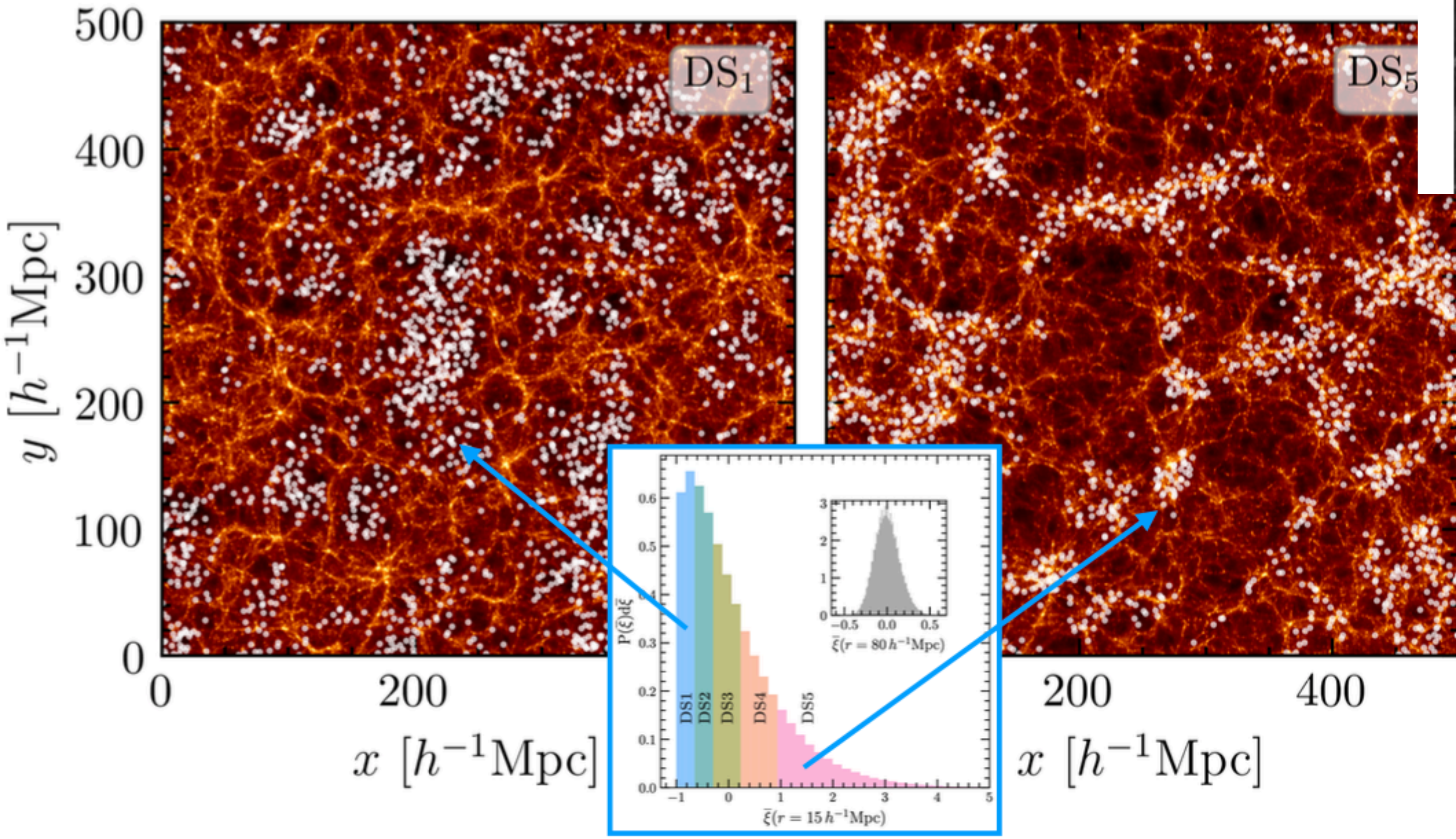

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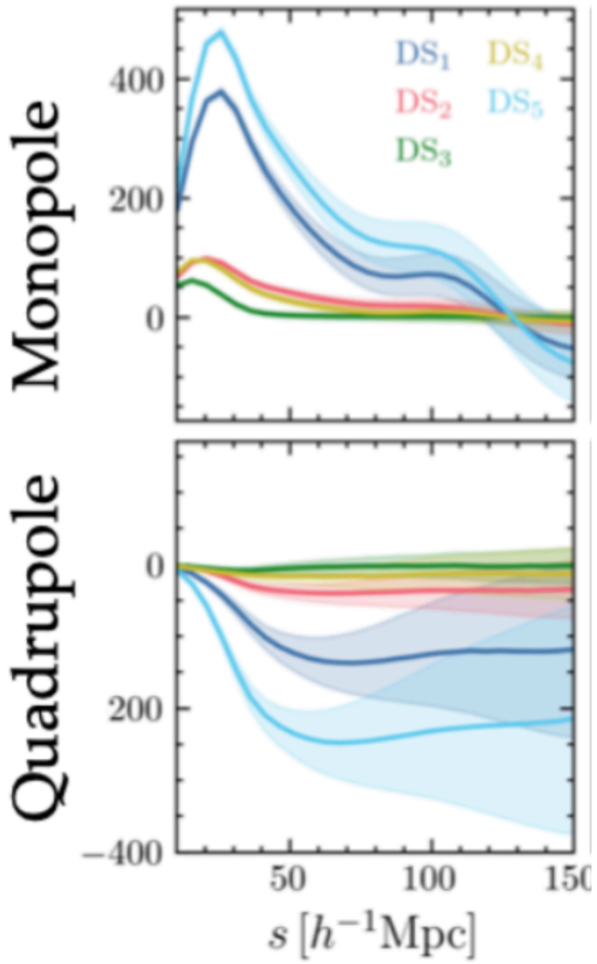
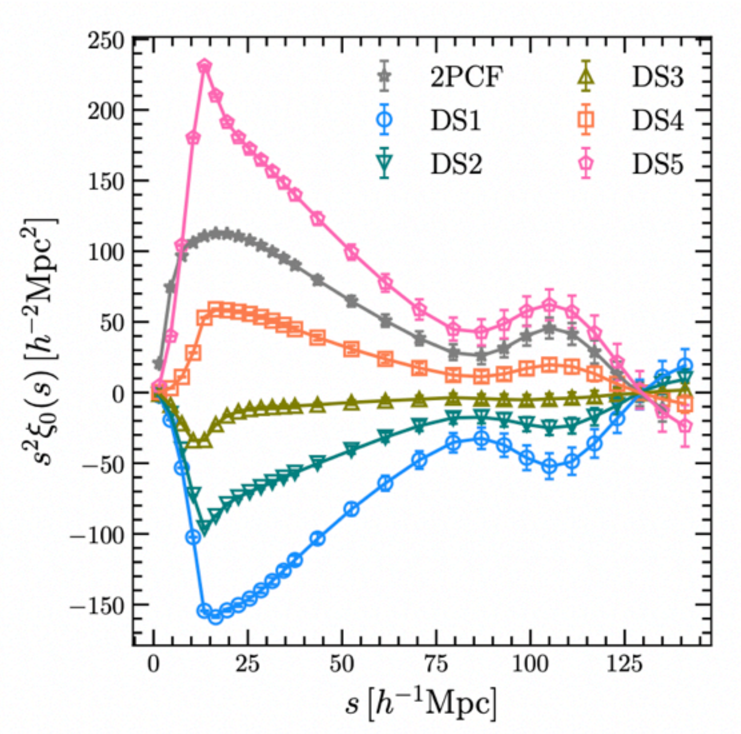


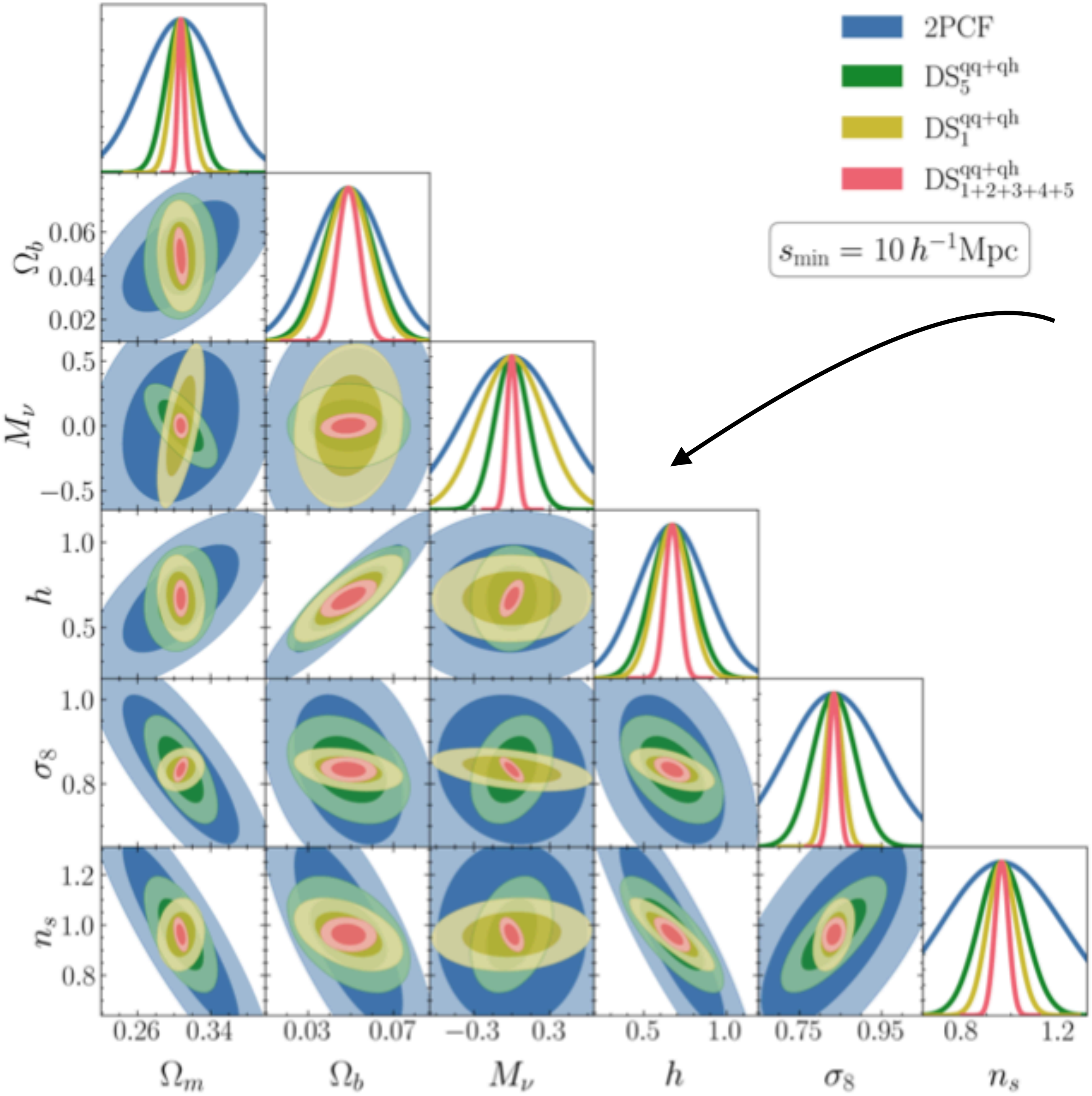
Auto-correlation of quintiles



Cross-correlation of quintiles with galaxies

Comparison to voids

Assuming we can model it, DS has *much more* information than voids (and also than galaxy clustering).



Information content based on results of a numerical Fisher forecast

Paillas *et al*., 2209.04310

Comparison to voids

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Can we model it?

- For voids, we had some form of analytical modelling (though limited in scope)
- For DS, the approximations used for voids are less good so analytic modelling less tractable
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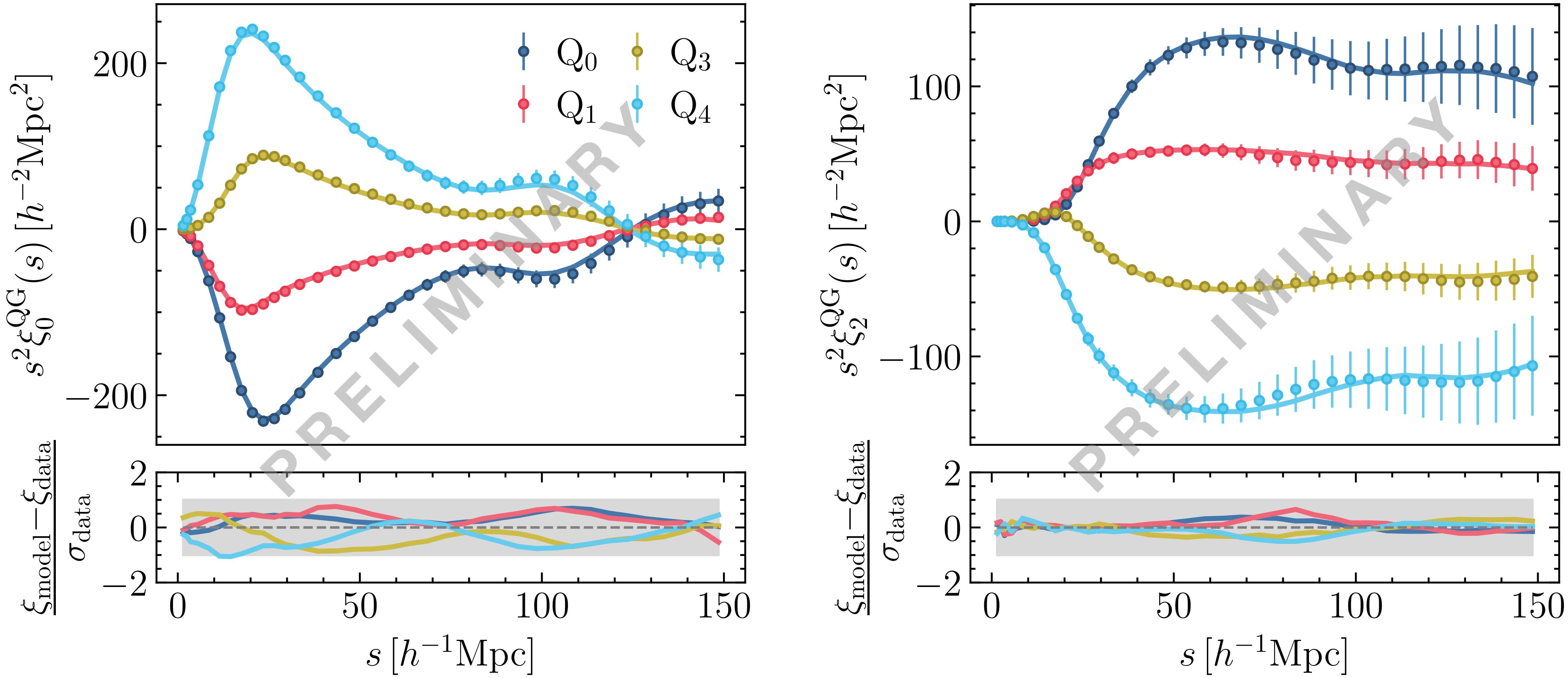
Emulators to the rescue!

Enrique Paillas

Carol Cuesta-Lazaro

Emulating DS statistics

An emulator for DS auto and cross multipoles, successfully trained for BOSS data:



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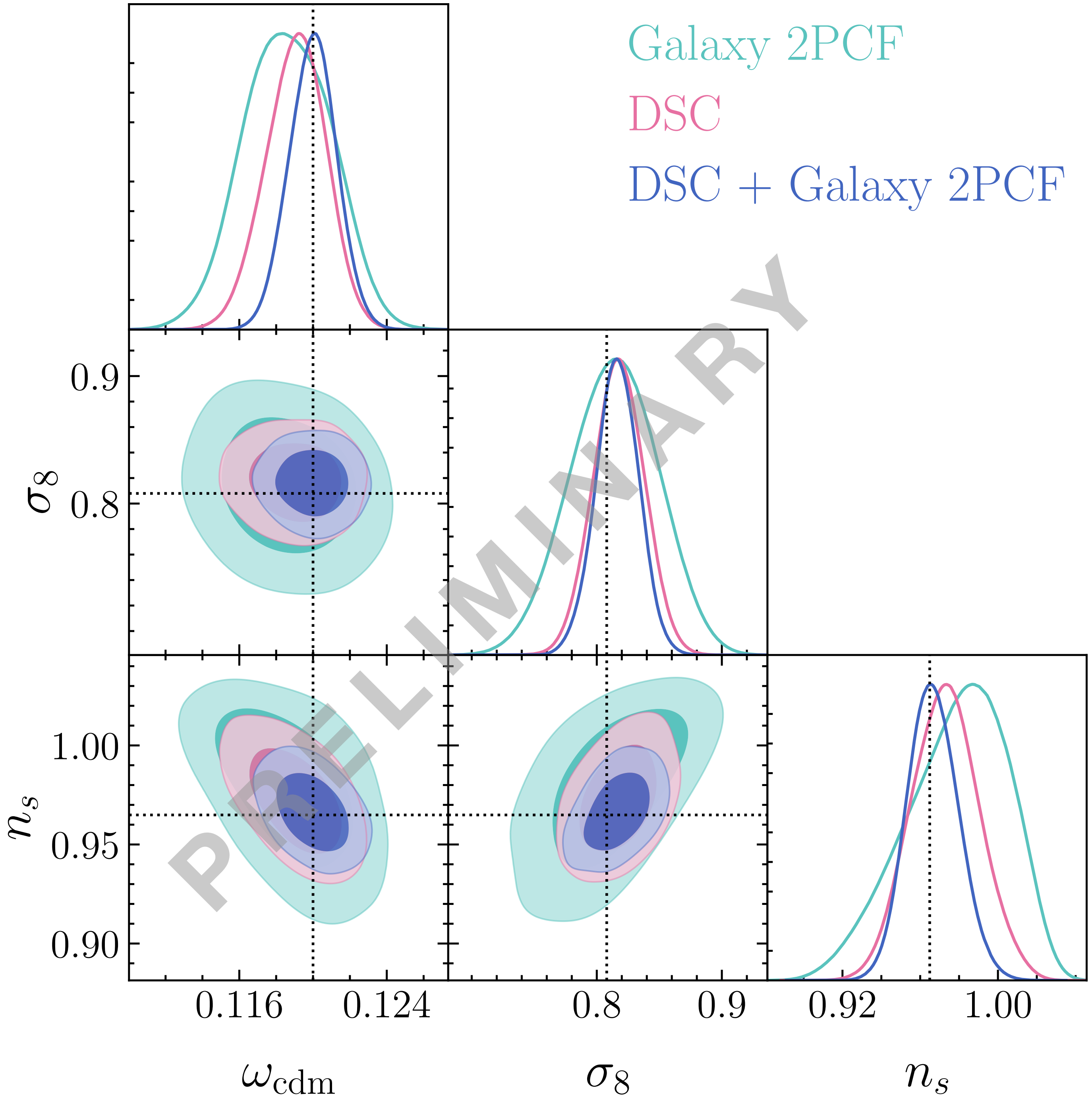

What do we need to do in the future?

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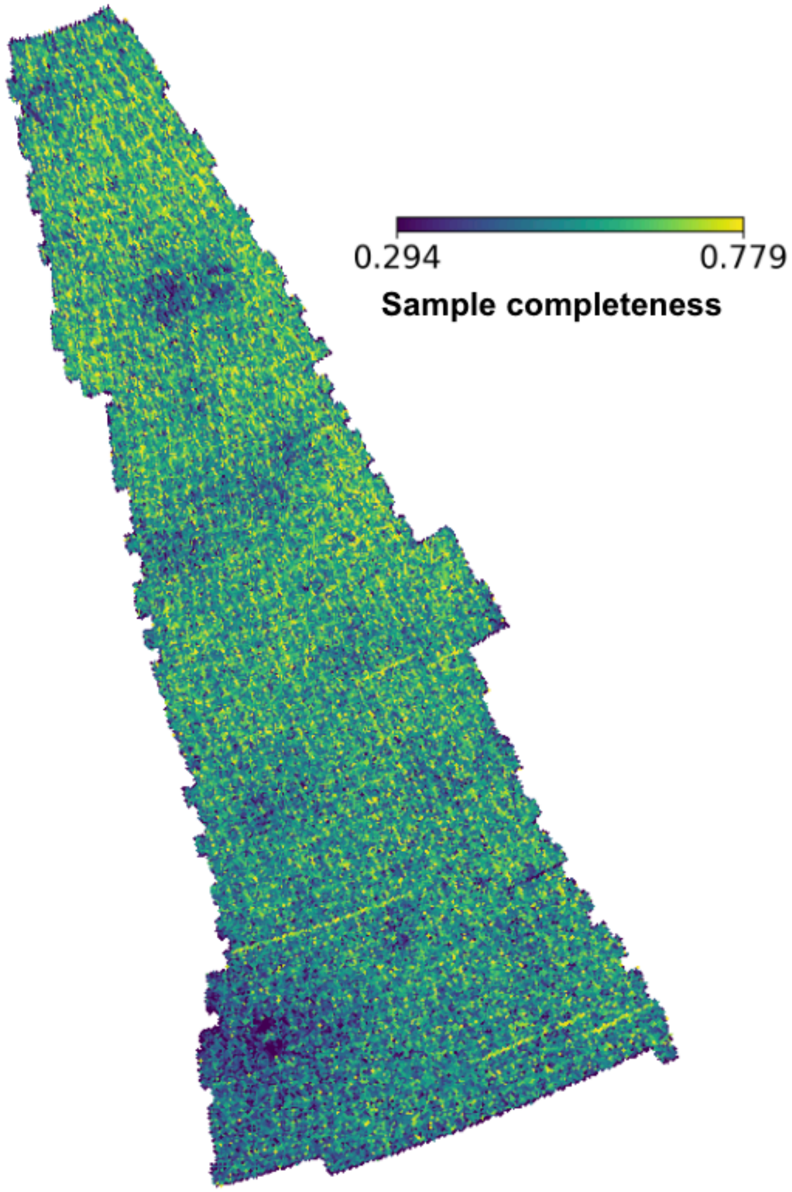
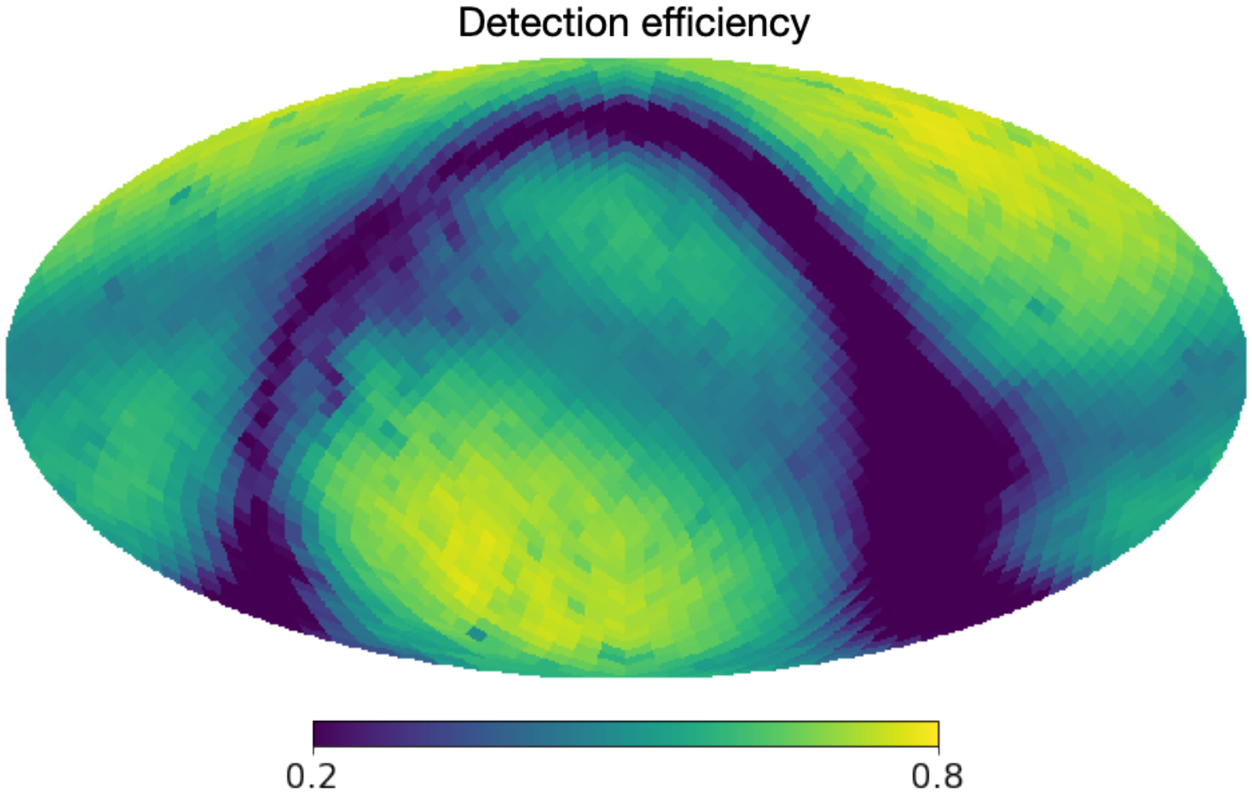
Data from DESI and Euclid will be much more complicated than current SDSS





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- We need to design + transition to void-finders that can handle this complexity! (Currently not all can)
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Emulators will likely play a major role in the future!

- We need to design + transition to algorithms that work equivalently on simulation boxes and survey data (currently none do!)
- [Enables emulators to be trained on cubic simulation boxes – massively reduces computational cost]
- Need a major focus on robustness, training on a wide variety of mocks