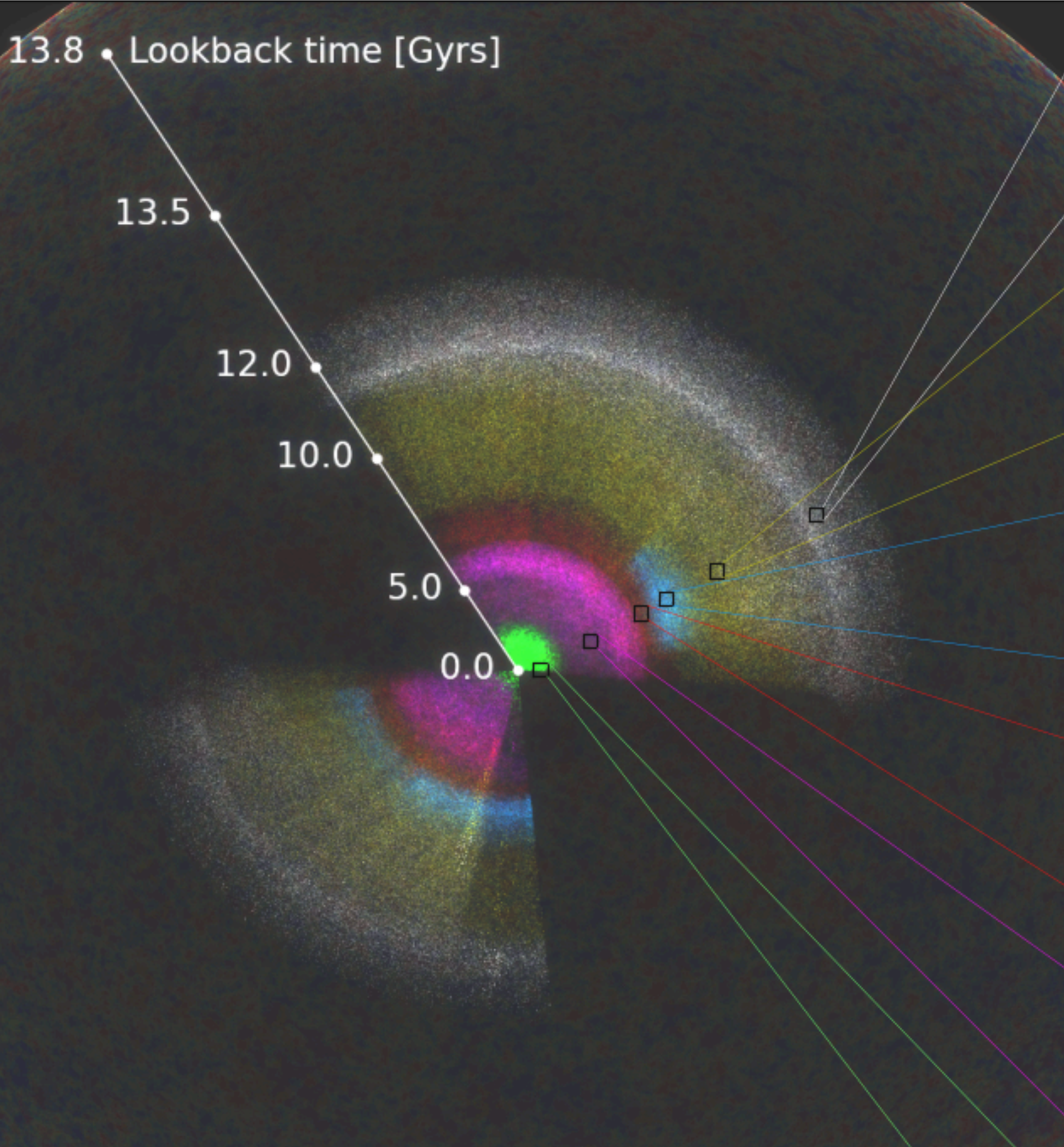
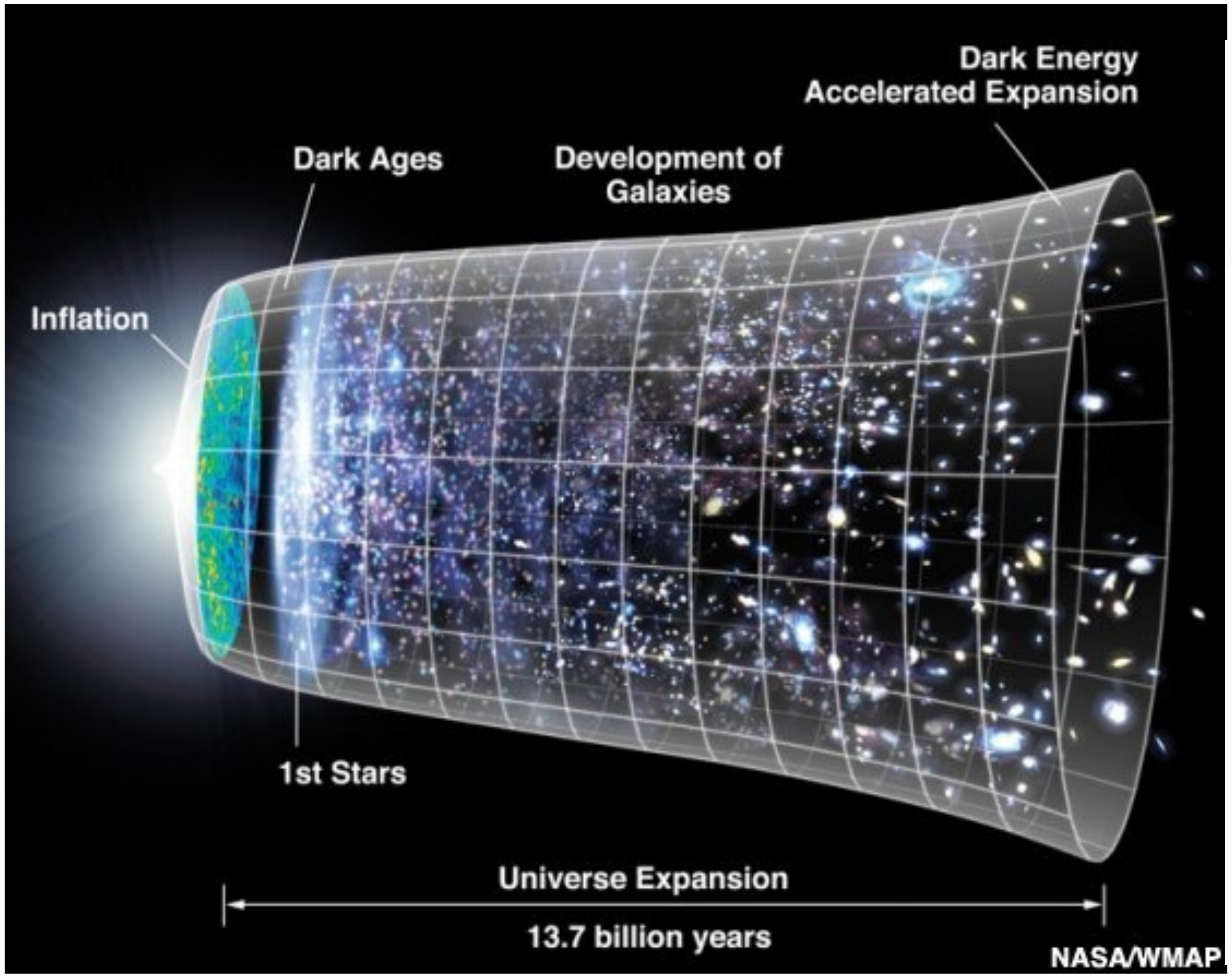
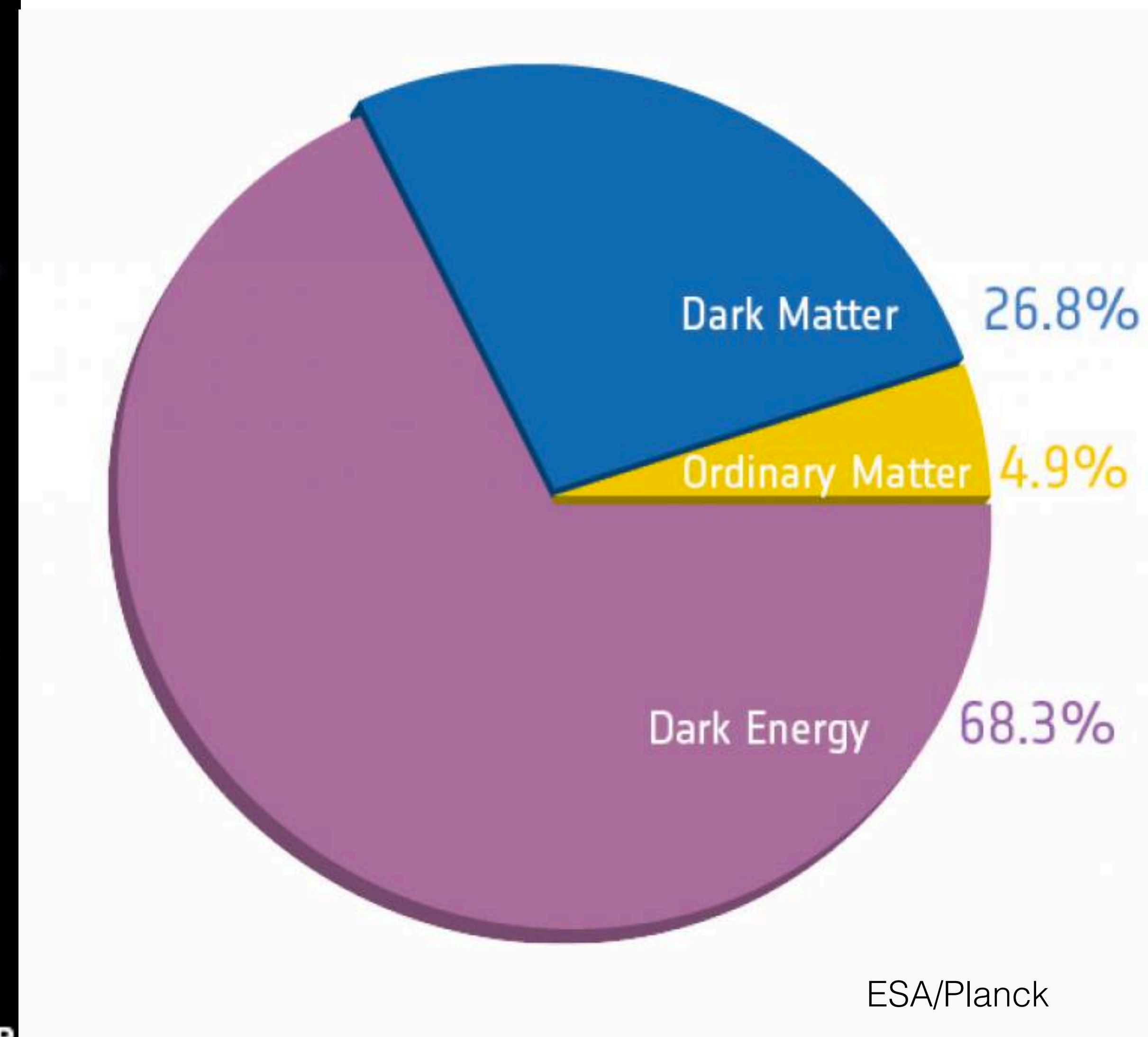


Beyond BAO: Cosmology with voids in BOSS and eBOSS

Seshadri Nadathur

The state of cosmology today



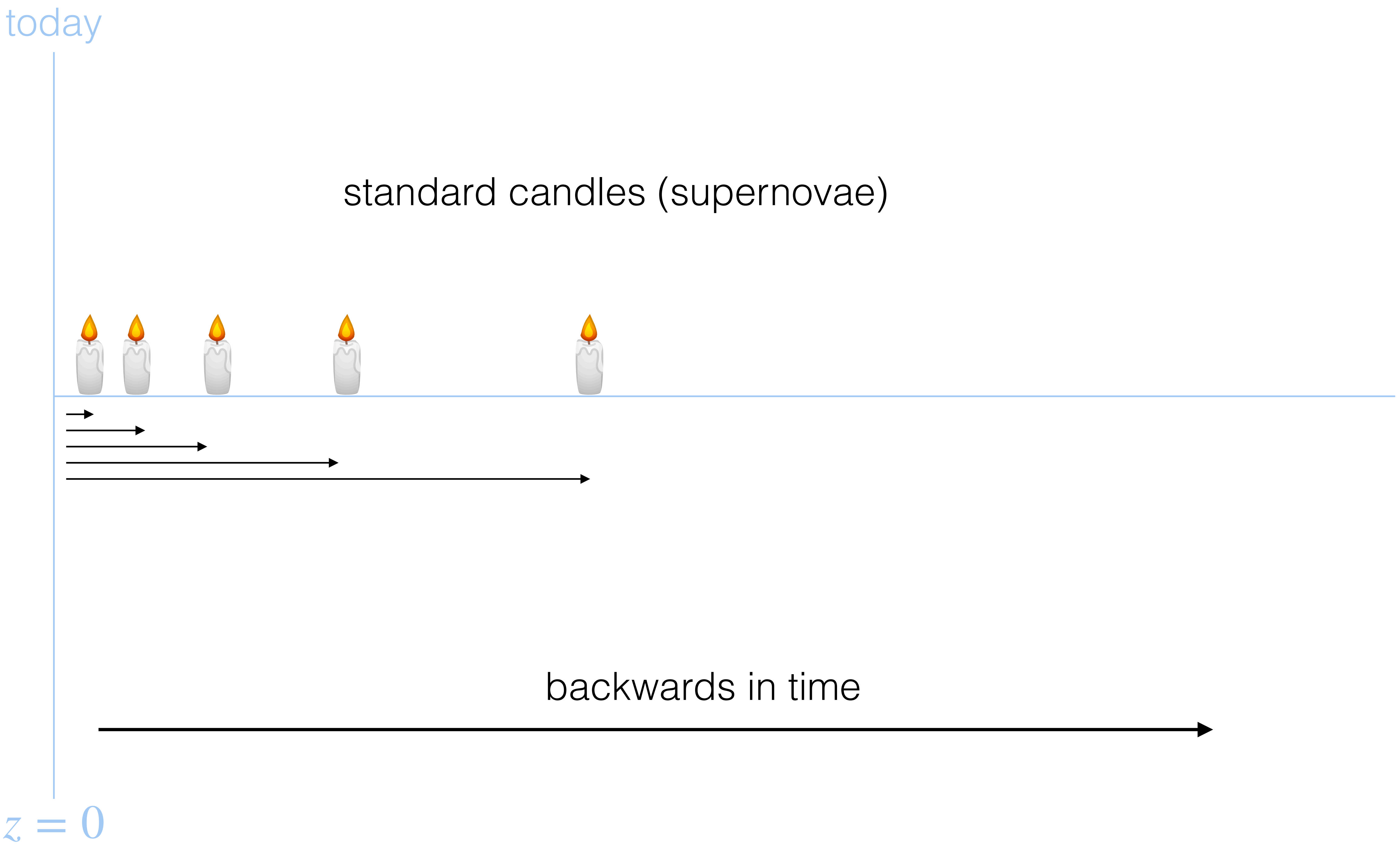


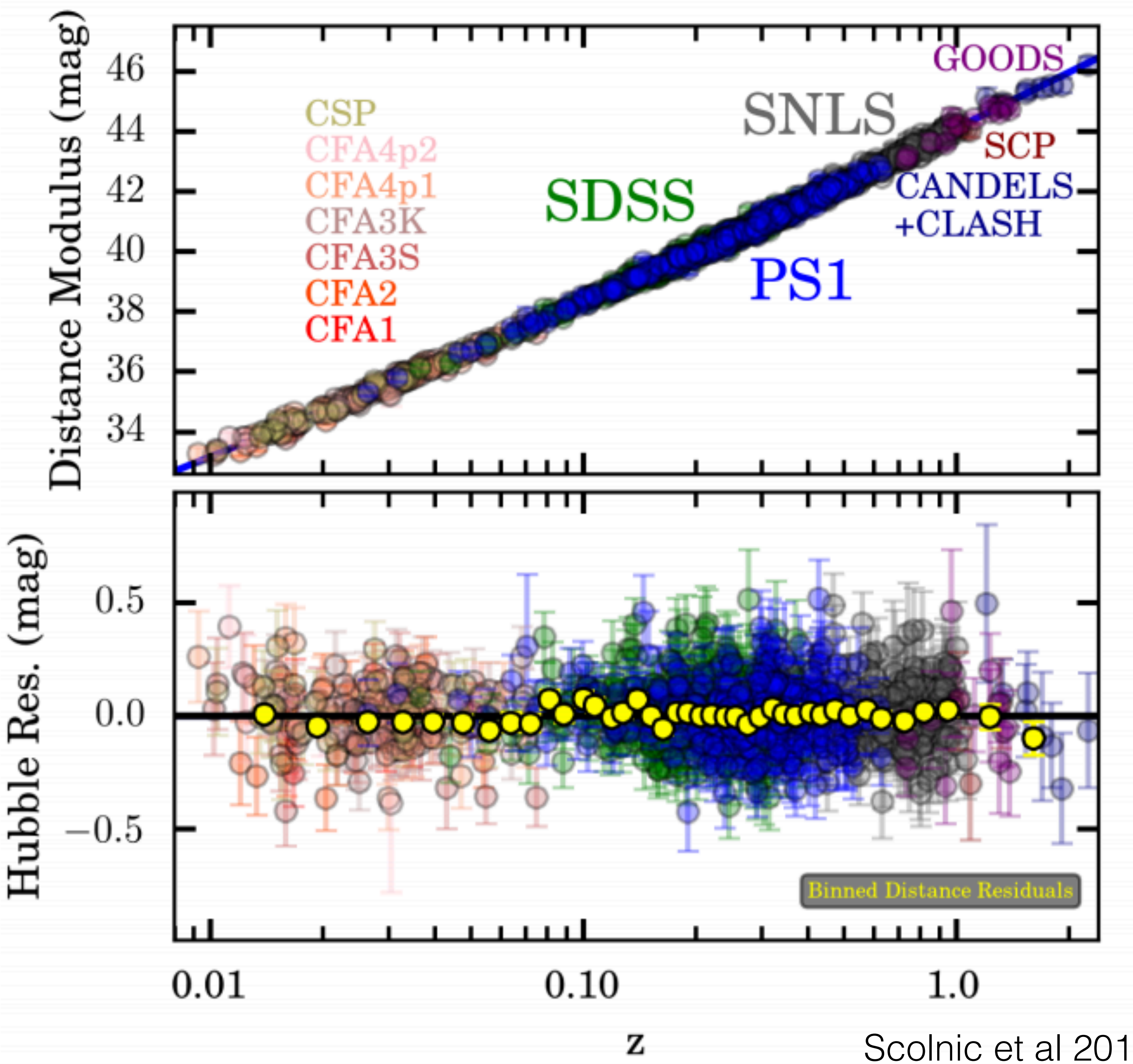
standard Λ cold dark matter model

- What is dark energy?
  - we don’t know! (cosmological constant, quintessence, MG …)
- How can we learn about dark energy?
  - measure the acceleration!
- How to measure acceleration?
  - measure distances and how they change with time

Measuring acceleration

Classic example of measuring distances is with Type Ia supernovae:



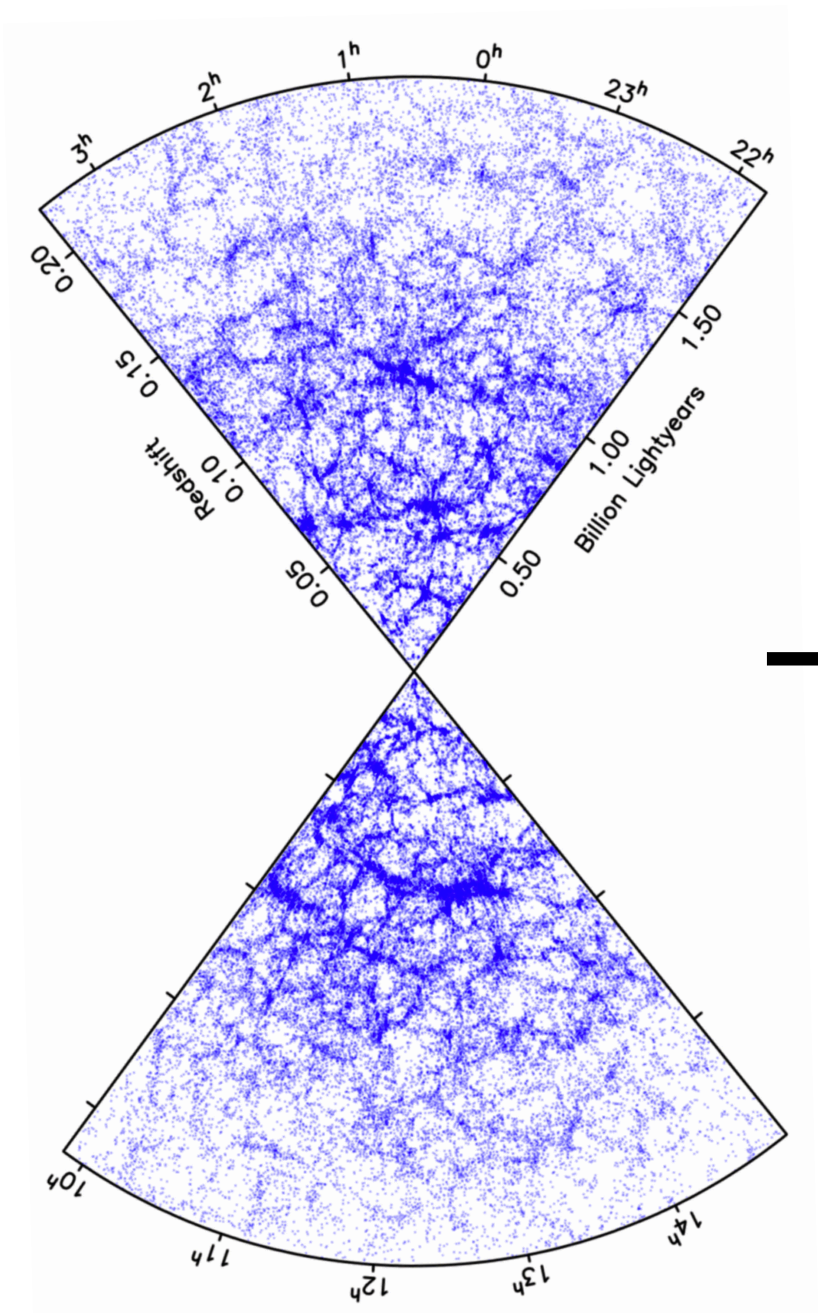


Scolnic et al 2018 (Pantheon dataset)

Traditionally the best method for directly measuring acceleration?

Galaxy survey science

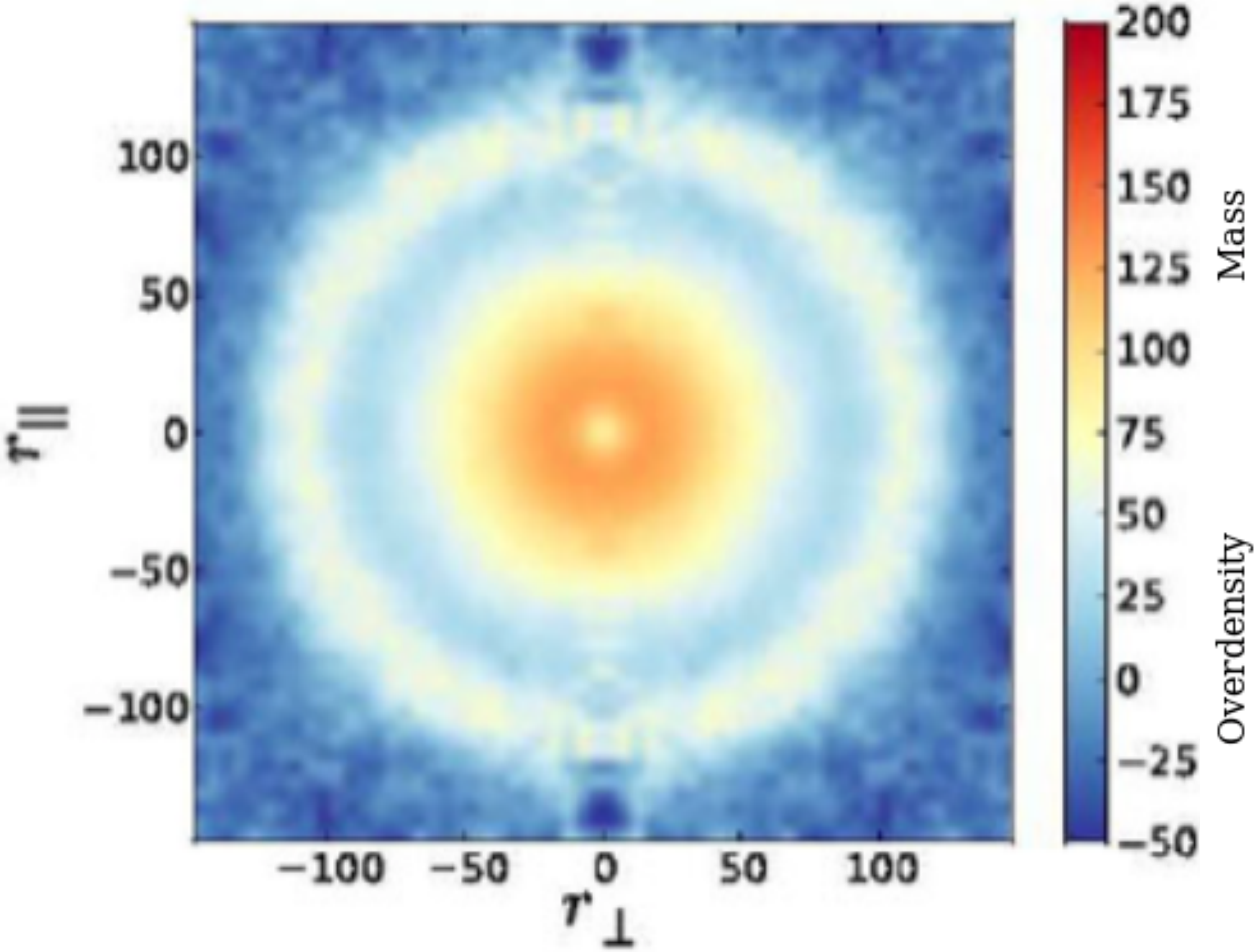
3D maps of galaxies used to measure fundamental cosmological quantities

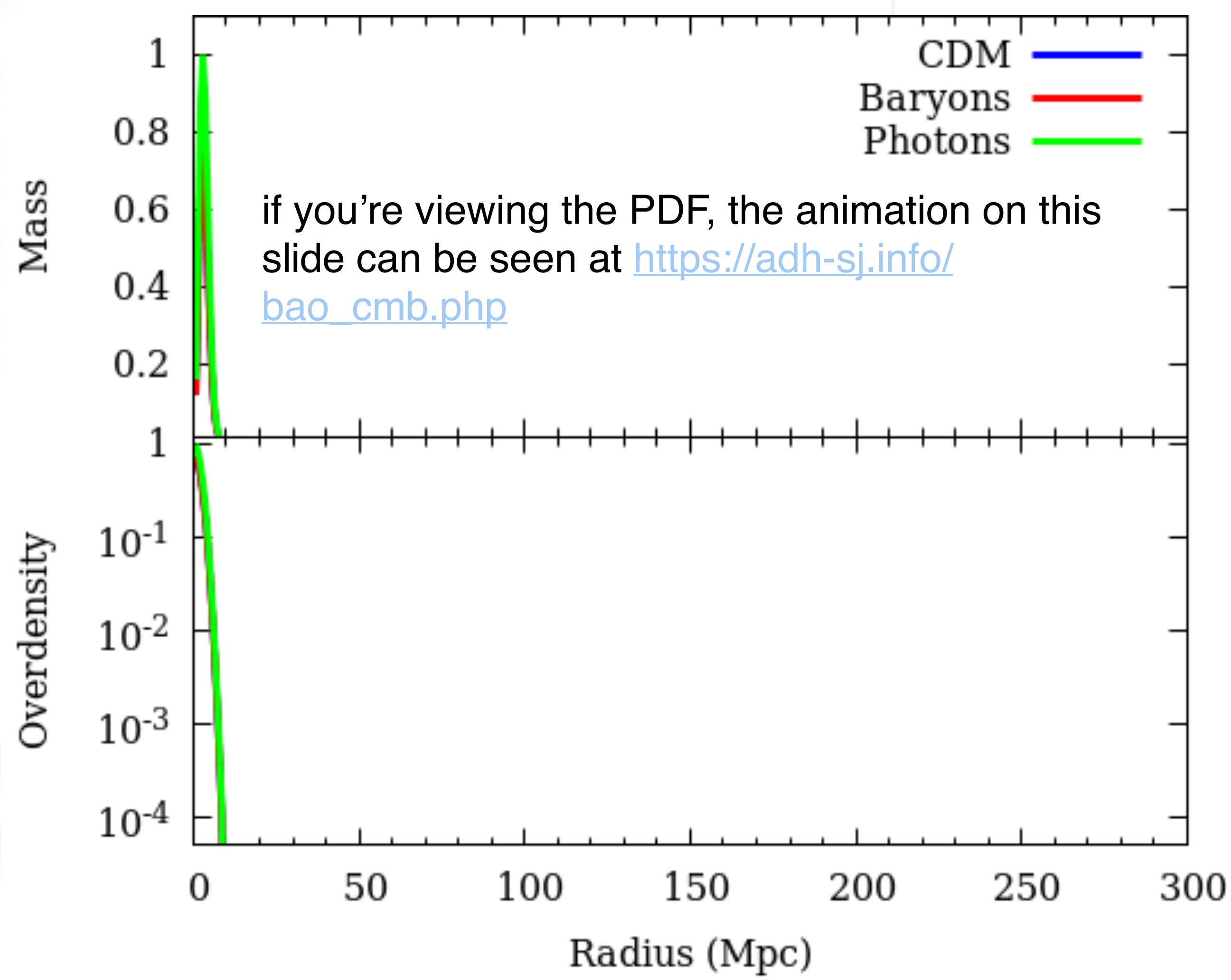


distance + expansion rate

standard methods: baryon acoustic oscillations (BAO)

Baryon Acoustic Oscillations (BAO)



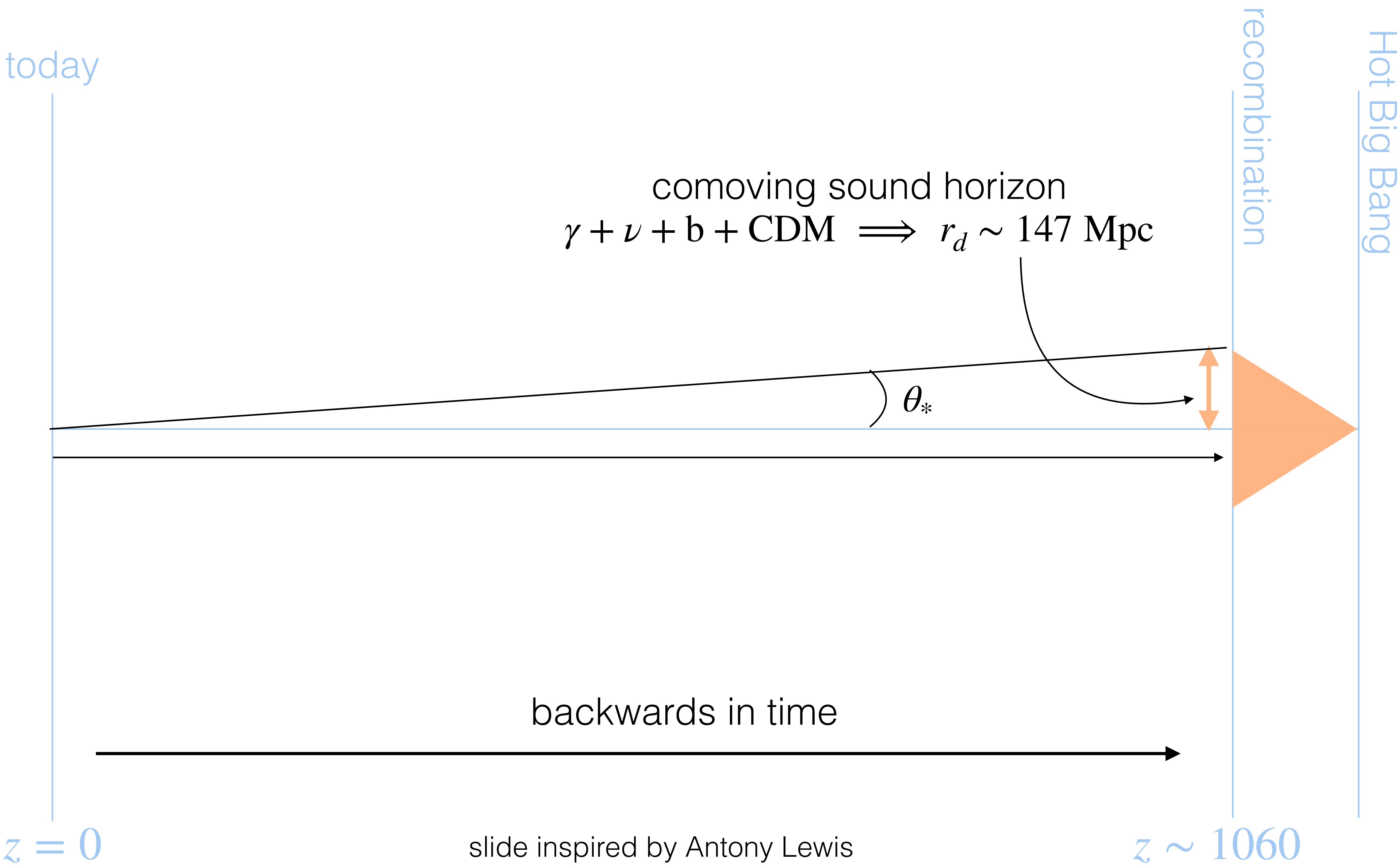


if you're viewing the PDF, the animation on this slide can be seen at https://adh-sj.info/bao_cmb.php

animation by Adam Hincks

Measuring acceleration

We can also measure the scale of the BAO:

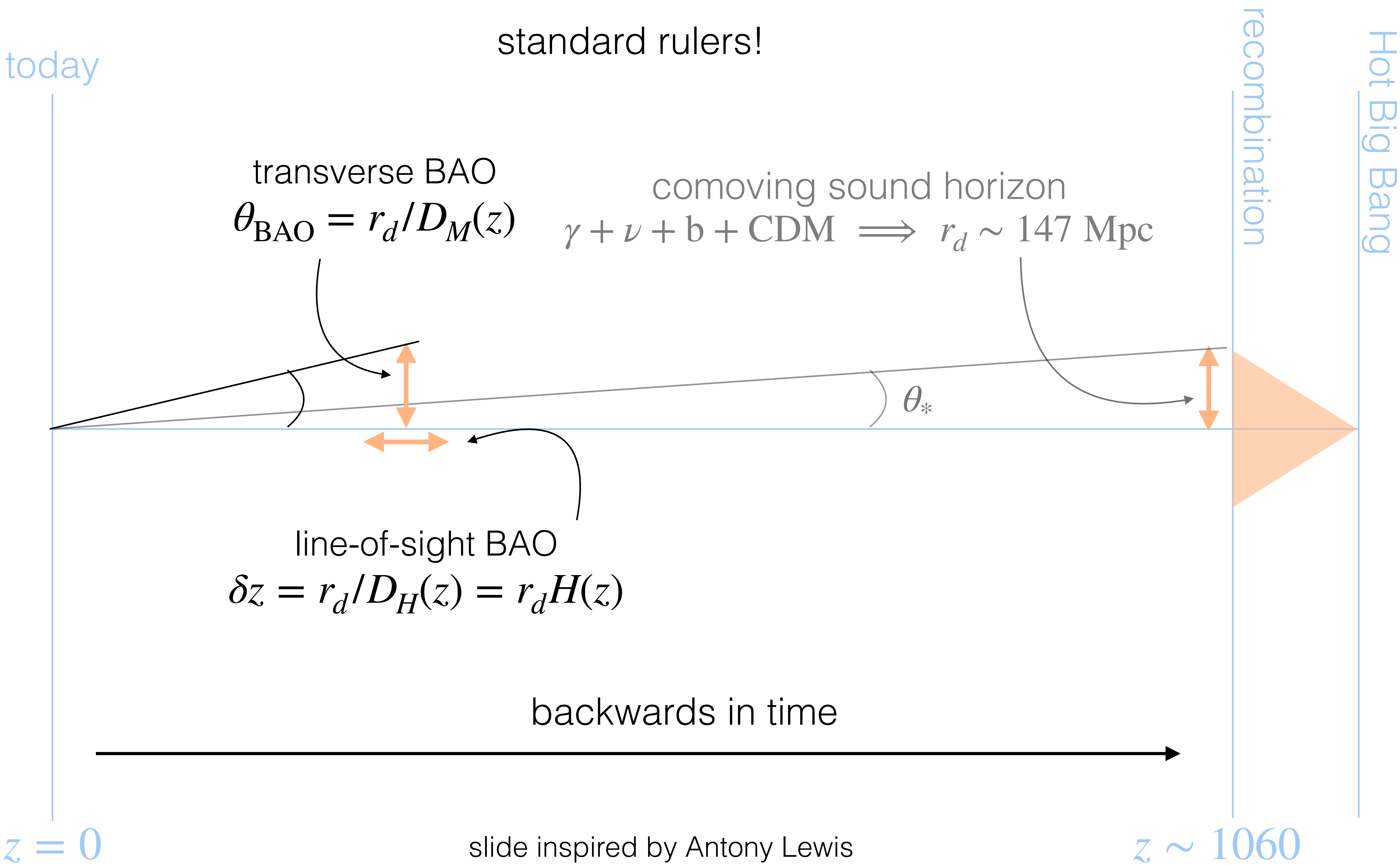


slide inspired by Antony Lewis

Measuring acceleration

We can also measure the scale of the BAO:

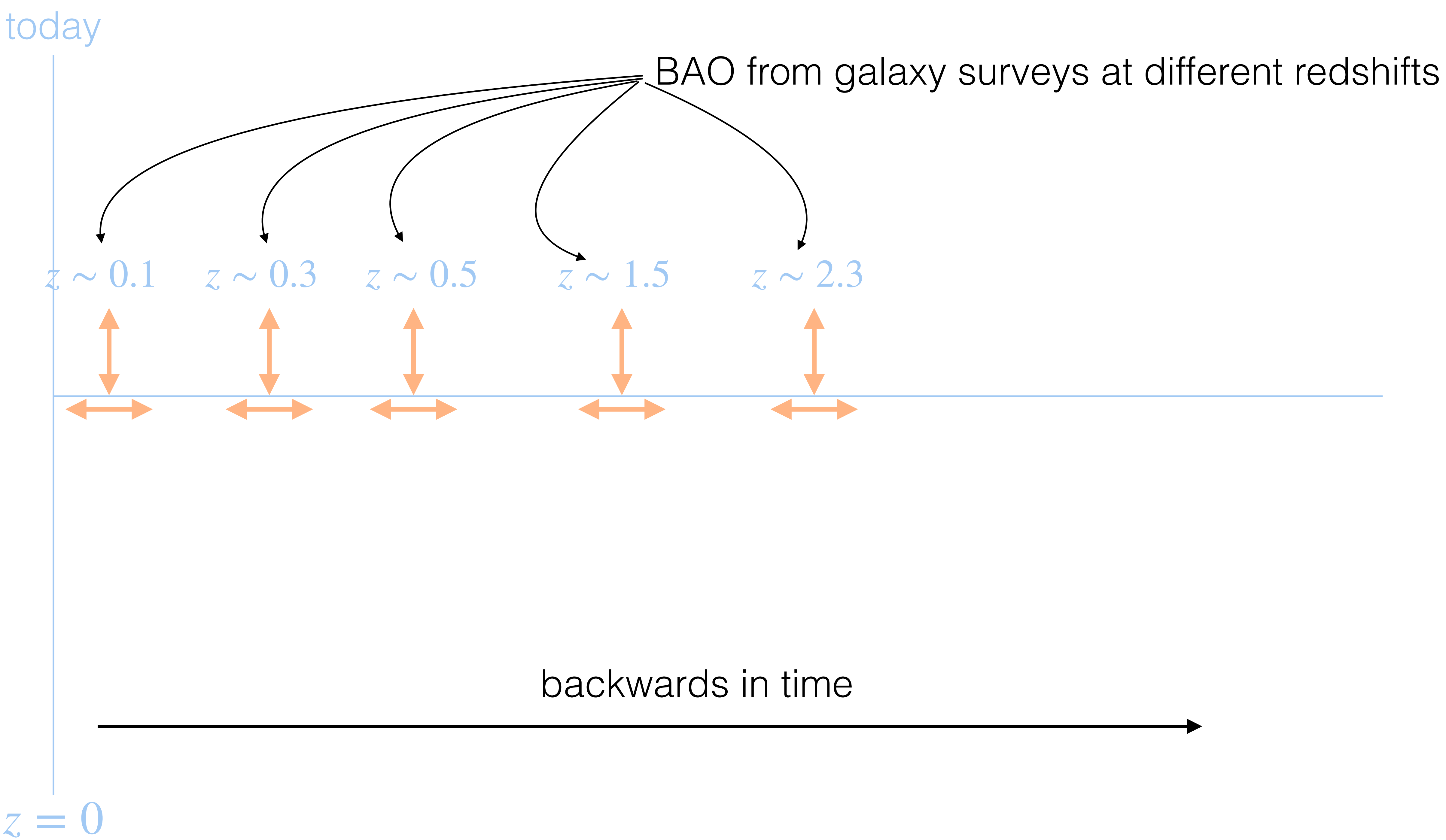
standard rulers!



slide inspired by Antony Lewis

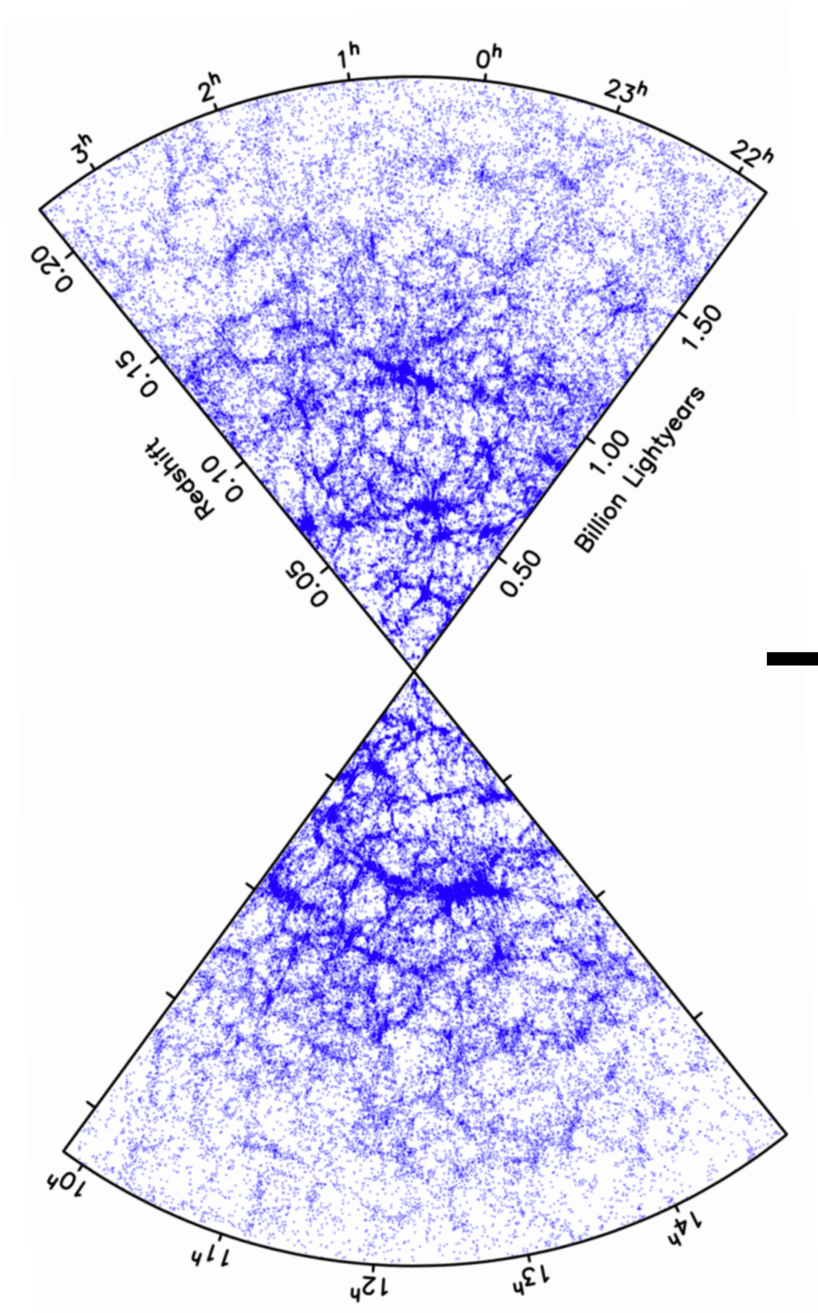
Measuring acceleration

We don’t even need to calibrate this ruler as we see many of the same!



Galaxy survey science

3D maps of galaxies used to measure fundamental cosmological quantities



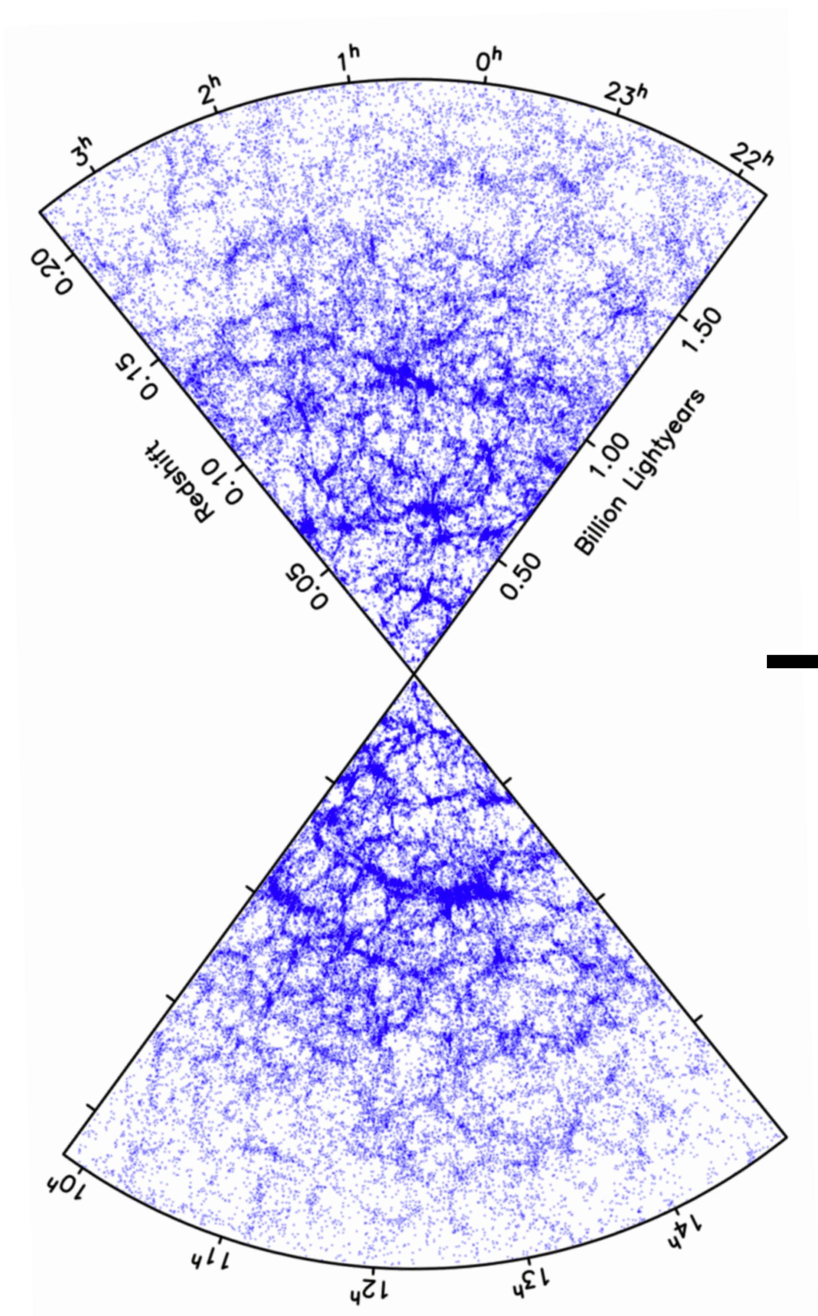
→ distance + expansion rate + growth rate

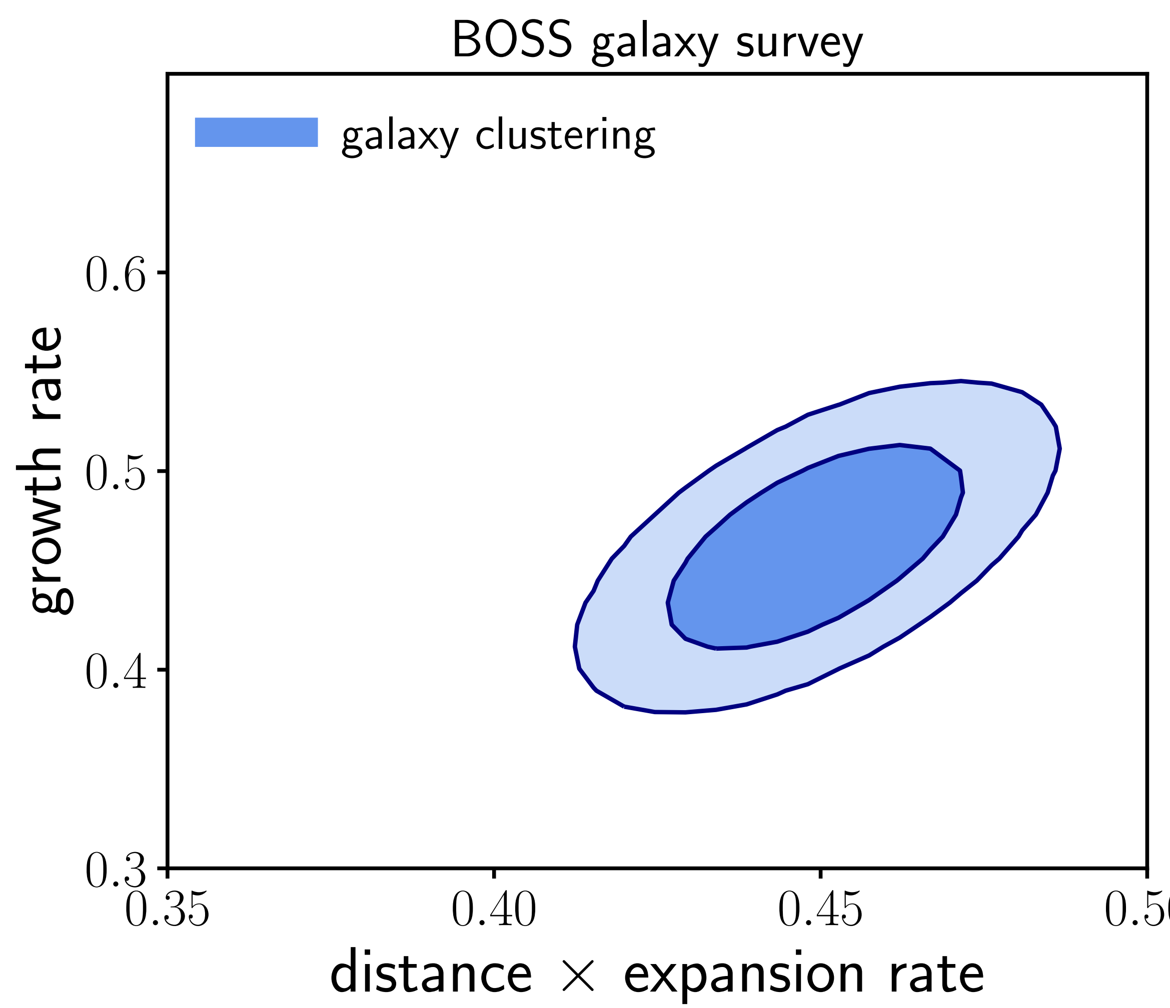
full shape of galaxy clustering 2-pt statistics $P(k)$ or $\xi(r)$

standard methods: BAO, redshift-space distortions

Galaxy survey science

3D maps of galaxies used to measure fundamental cosmological quantities



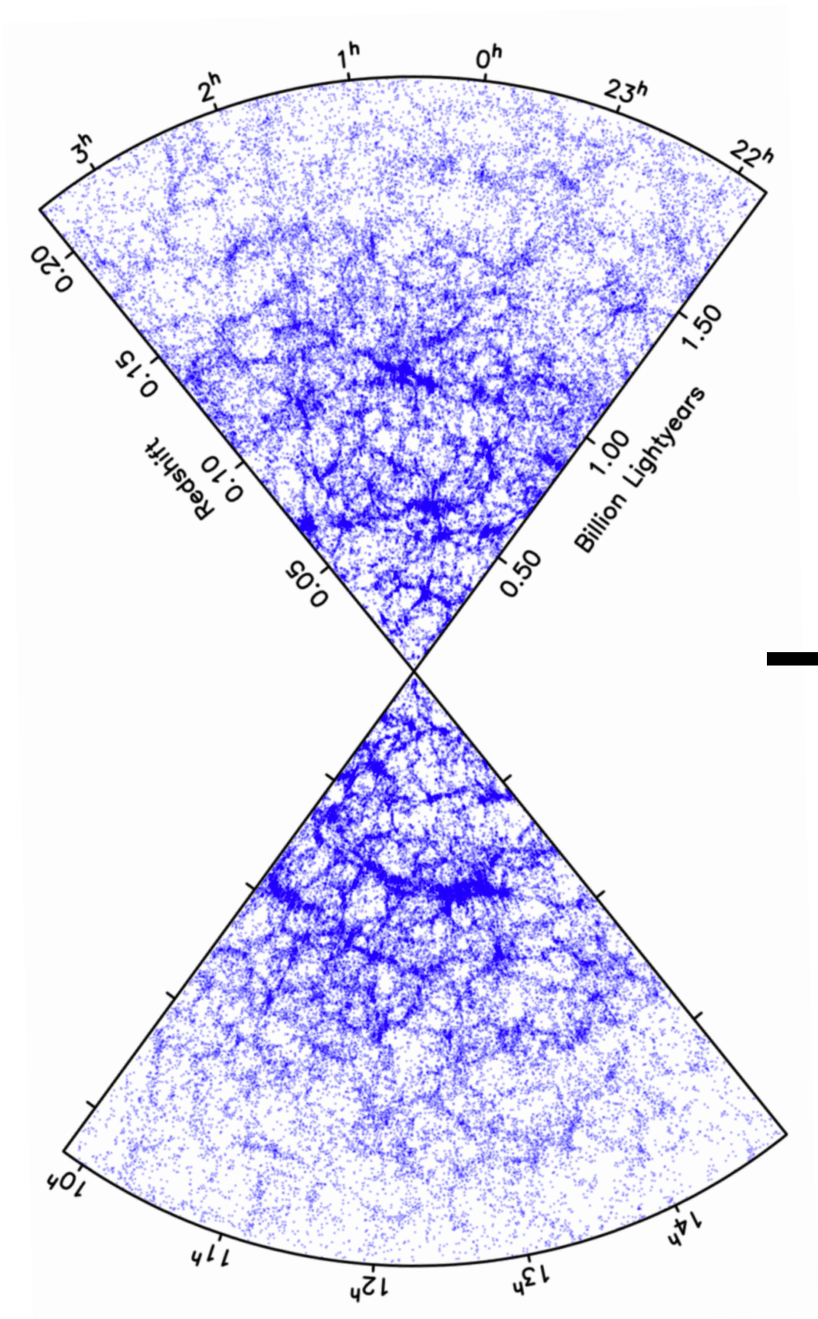


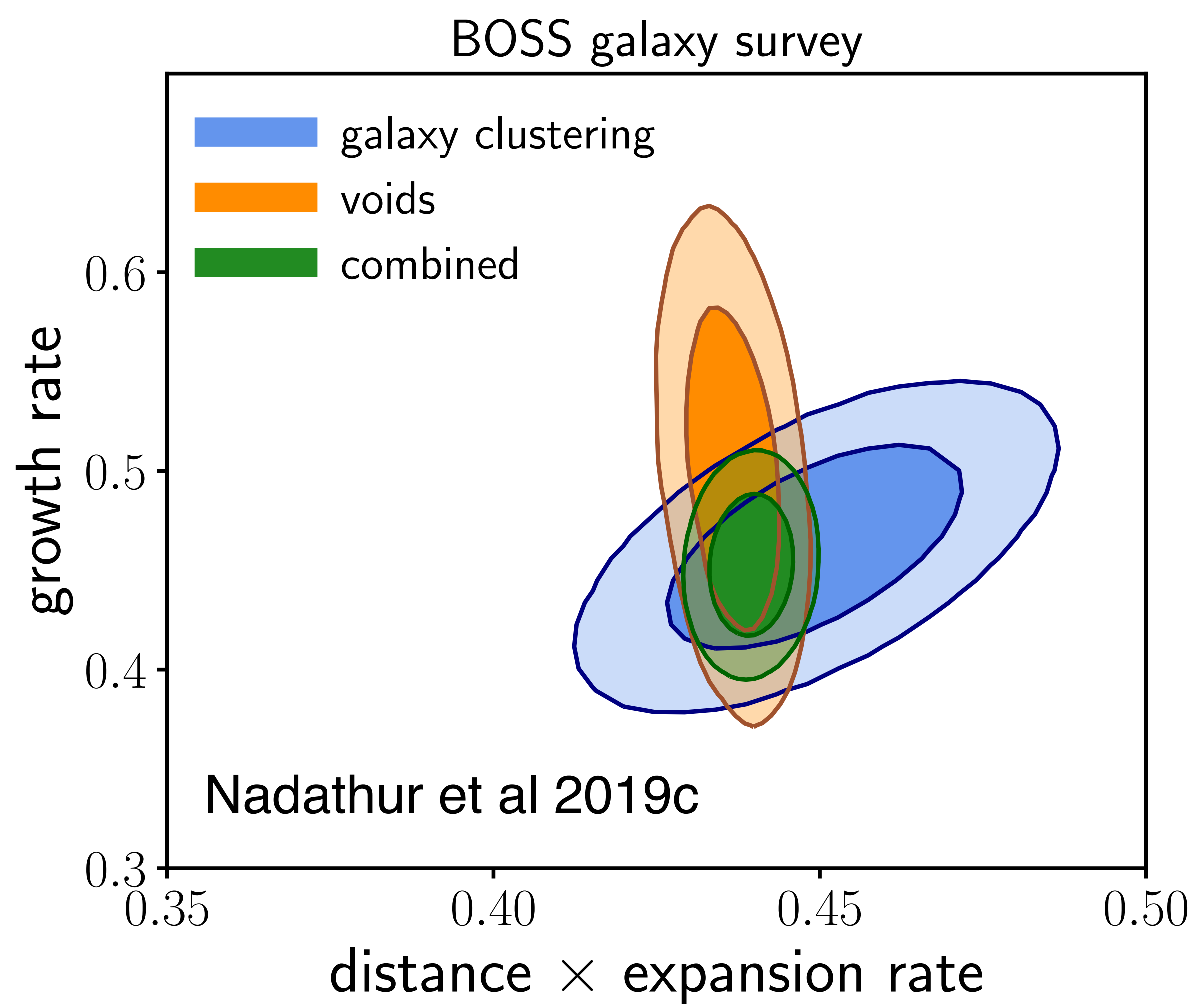
standard methods: BAO, redshift-space distortions

Galaxy survey science

3D maps of galaxies used to measure fundamental cosmological quantities

New idea: use voids in same maps to get much more information

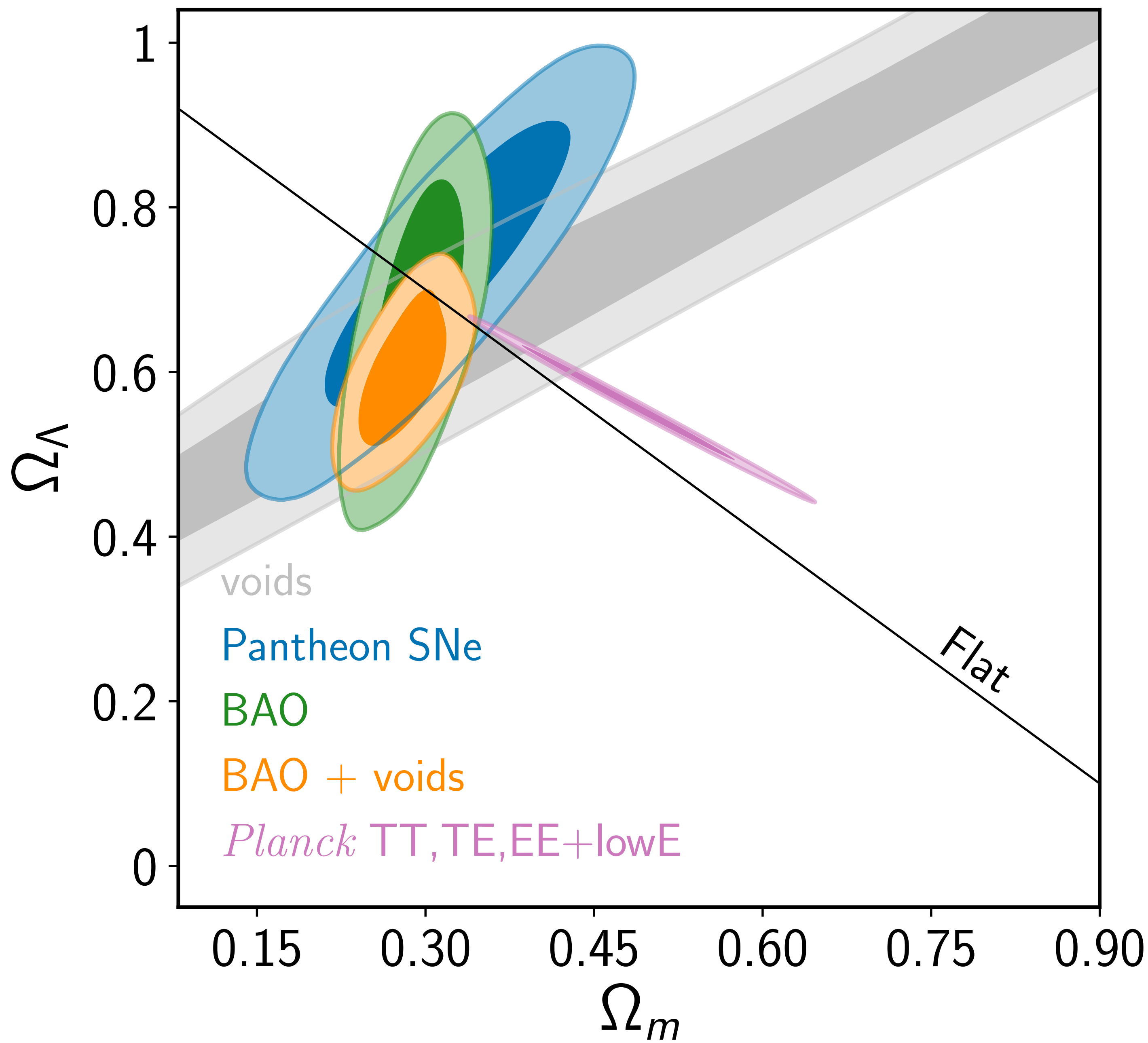




SN+, arXiv:1904.01030

voids + BAO + redshift-space distortions

What can we get from this?



SN+, PRL *2020 (arXiv:2001.11044)*

How does using voids work?

Main idea:

- Use cosmological-sized objects that should be spherically symmetric
- Gives a realisation of the Alcock-Paczynski test

Published: 01 October 1979

An evolution free test for non-zero cosmological constant

Charles Alcock & Bohdan Paczyński

Nature **281**, 358–359(1979) | Cite this article

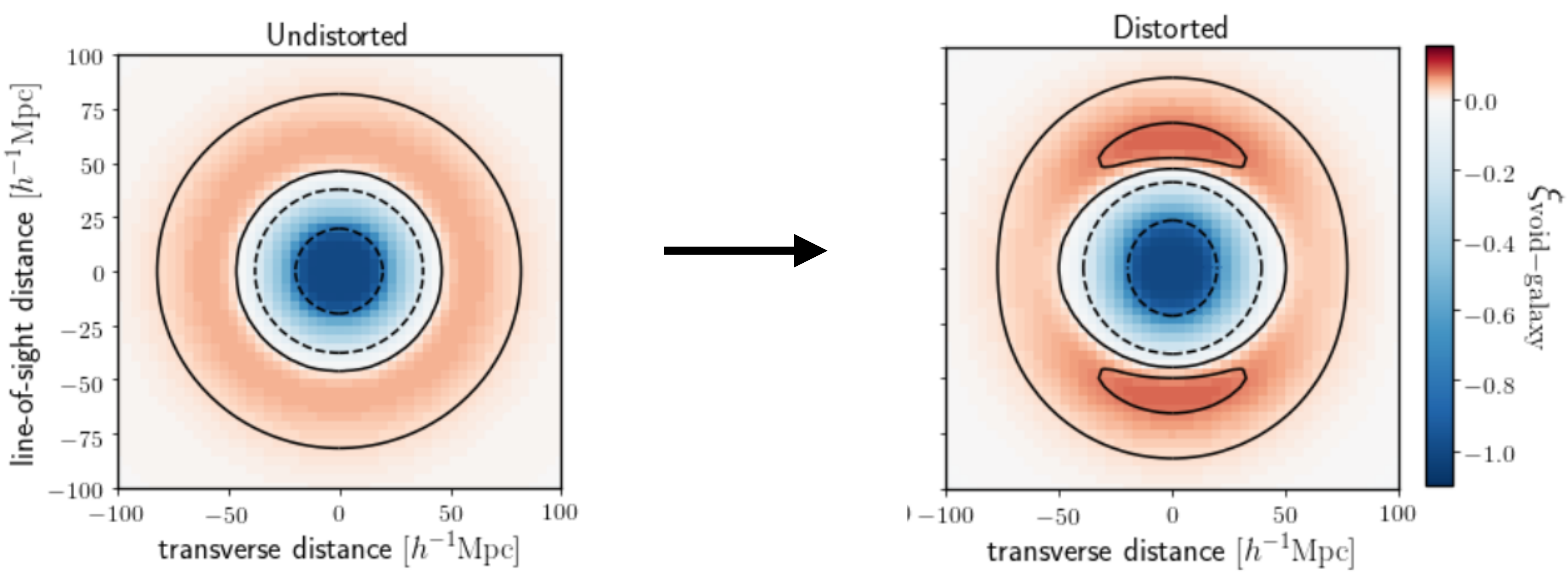
663 Accesses | **569** Citations | **5** Altmetric | Metrics

In practical terms, we measure the **void-galaxy cross-correlation**

Void-galaxy correlation

Voids
- regions of few galaxies & low matter density
- algorithmically identified from 3D galaxy maps
- closer to Zeldovich behaviour

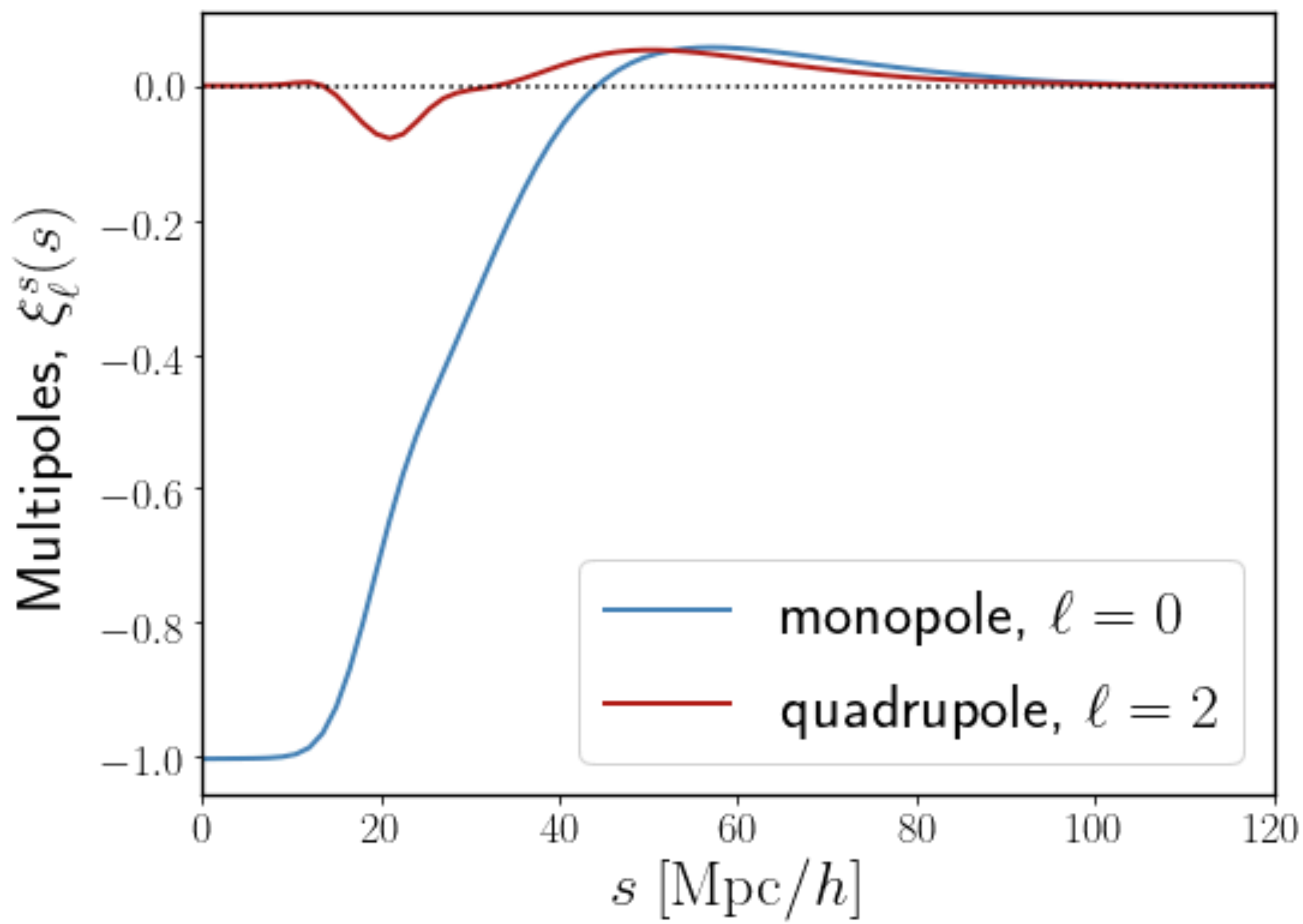
Void-galaxy correlation
- cross-correlation of void centres* with galaxies
  *for our purposes, void centre = position of minimum density
- = galaxy number density around voids
- (mildly) anisotropic in redshift-space: redshift distortions



Multipole decomposition

Standard compression of measured anisotropic correlation function $\xi^s(\mathbf{s})$ into Legendre multipoles:

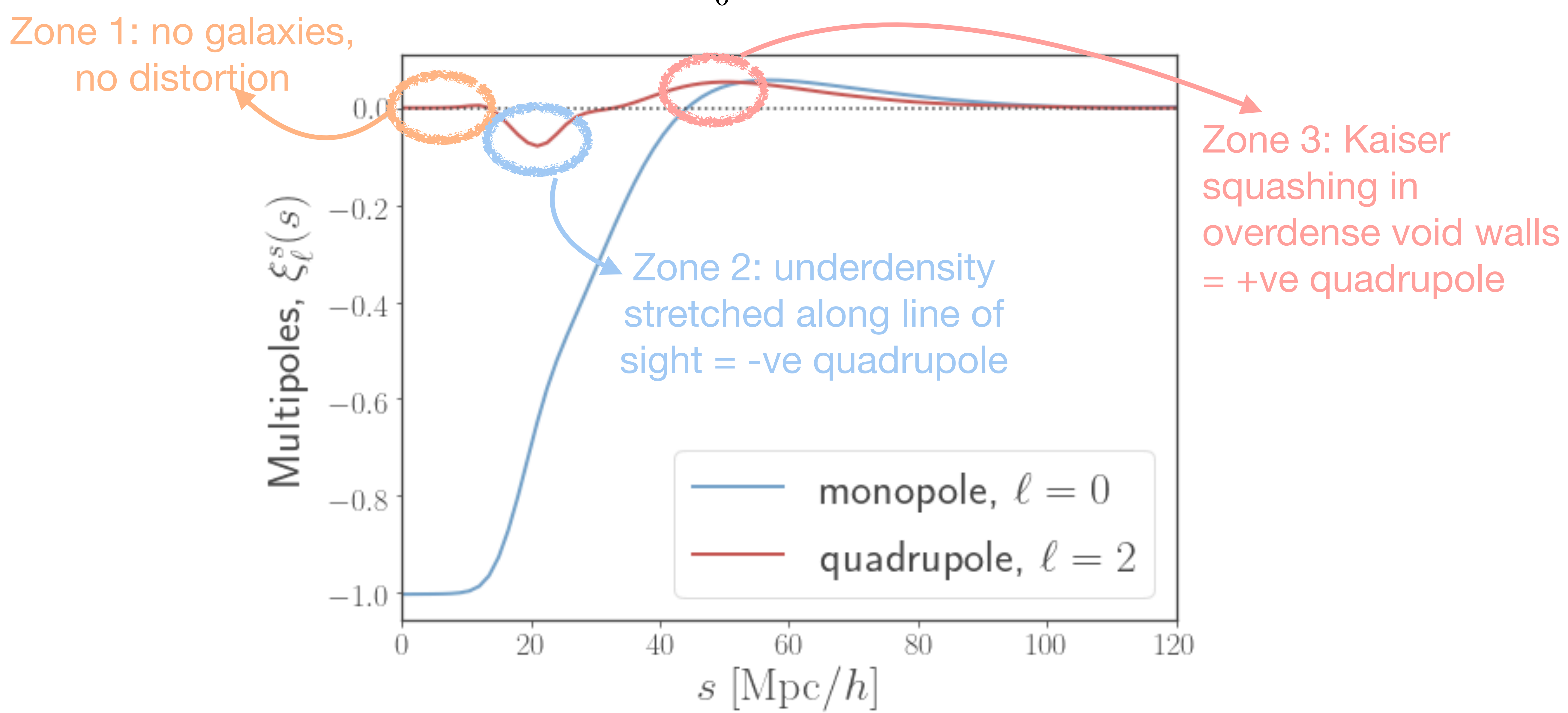
$$\xi^s_\ell(s) = (2\ell + 1) \int_0^1 \xi^s(s, \mu) L_\ell(\mu) \, \mathrm{d}\mu$$



Multipole decomposition

Standard compression of measured anisotropic correlation function $\xi^s(\mathbf{s})$ into Legendre multipoles:

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



RSD and Alcock-Paczynski

RSD: distortions introduced due to shifts in galaxy redshifts caused by velocity outflows from voids

$$\text{distortion} \propto f\sigma_8$$

AP effect: distortion introduced due to transforming measured redshifts to distances using the wrong cosmological model *(c.f. BAO)*

$$s_\perp = \alpha_\perp s_\perp^{\text{fid}}, \;\; s_{||} = \alpha_{||} s_{||}^{\text{fid}}$$

Both affect the quadrupole term, but in very distinct ways

Modelling the correlation

Basic model:

Jacobian of coordinate transform

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

redshift-space correlation

real-space correlation

radial velocity outflow from void
(modelled by linear perturbation theory)

Advanced model: basic model + convolution with pdf for random l-o-s velocity component (i.e., adds a dispersion around coherent outflow)

Basic model: Cai et al, 1603.05184
Advanced model: SN & Percival, 1712.07575

Modelling: the gory details

Model AP effect:

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

applied on top of fiducial RSD model:

$$1 + \xi^{s,\mathrm{fid}}(s, \mu) = \int \left(1 + \xi^{r}(\tilde{r})\right) \left[1 + \frac{\tilde{v}_r}{\tilde{r}aH} + \frac{\tilde{r}\tilde{v}_r' - \tilde{v}_r}{\tilde{r}aH}\mu^2\right]^{-1} P(v_{||})\mathrm{d}v_{||}$$

using:

$$v_r(r) = -\frac{1}{3} faHr\Delta(r)$$ (linear theory) + $$P(v_{||}) \propto \exp\left(-\frac{v_{||}^2}{2\sigma_{v_{||}}^2(r)}\right)$$ (gaussian)

3 input functions:

$\xi^{r}(r)$: measured using RSD-removed galaxy positions

$\Delta(r),\ \sigma_{v_{||}}(r)$: basic form calibrated using N-body sims, then modified according to free parameters

RSD and Alcock-Paczynski

RSD: distortions introduced due to shifts in galaxy redshifts caused by velocity outflows from voids

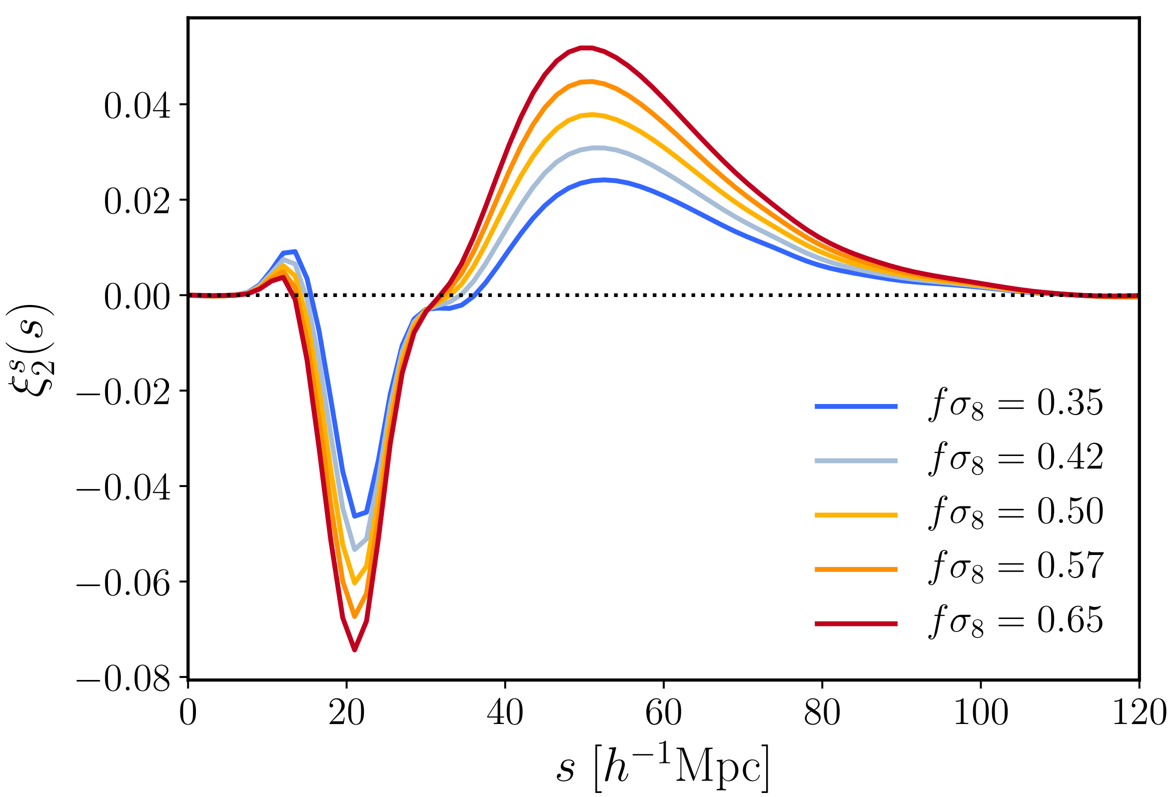
$$\text{distortion} \propto f\sigma_8$$

AP effect: distortion introduced due to transforming measured redshifts to distances using the wrong cosmological model *(c.f. BAO)*

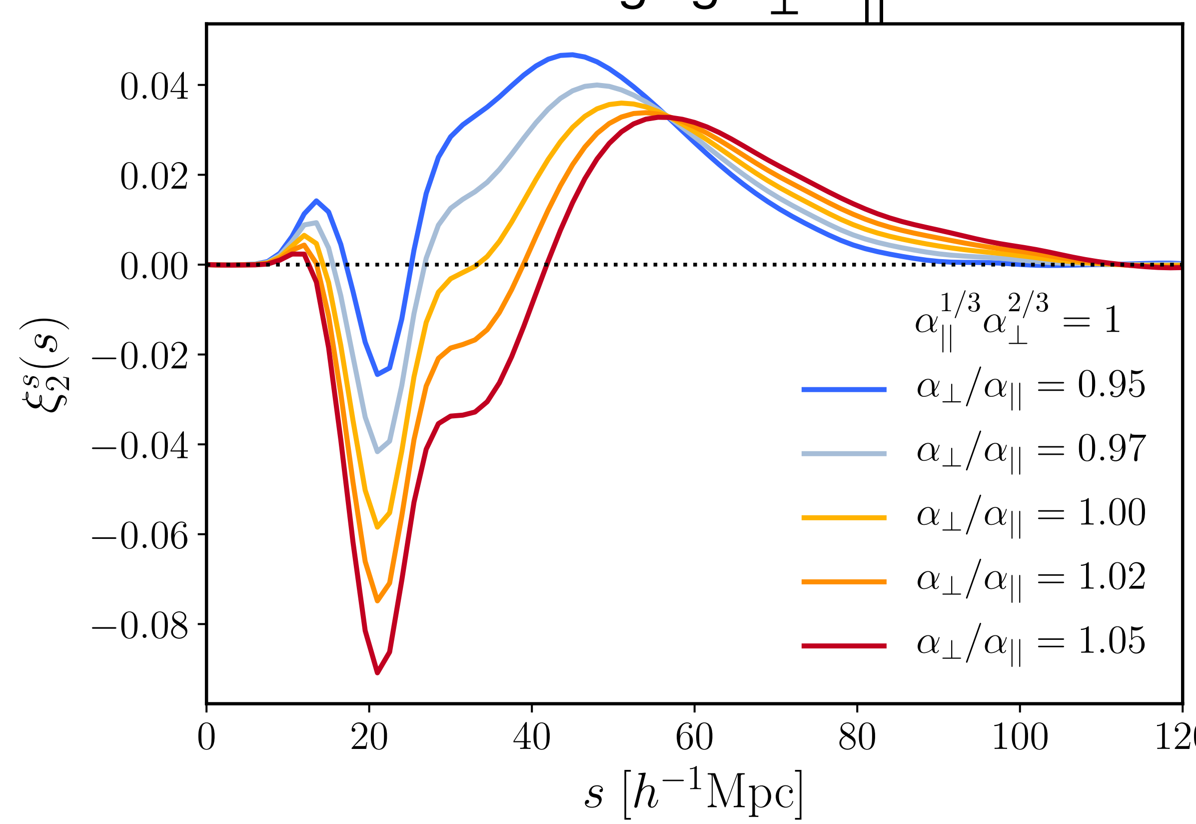
$$s_\perp = \alpha_\perp s_\perp^{\text{fid}}, \;\; s_{||} = \alpha_{||} s_{||}^{\text{fid}}$$

Both affect the quadrupole term, but in very distinct ways

changing growth rate



changing $\alpha_\perp/\alpha_{||}$



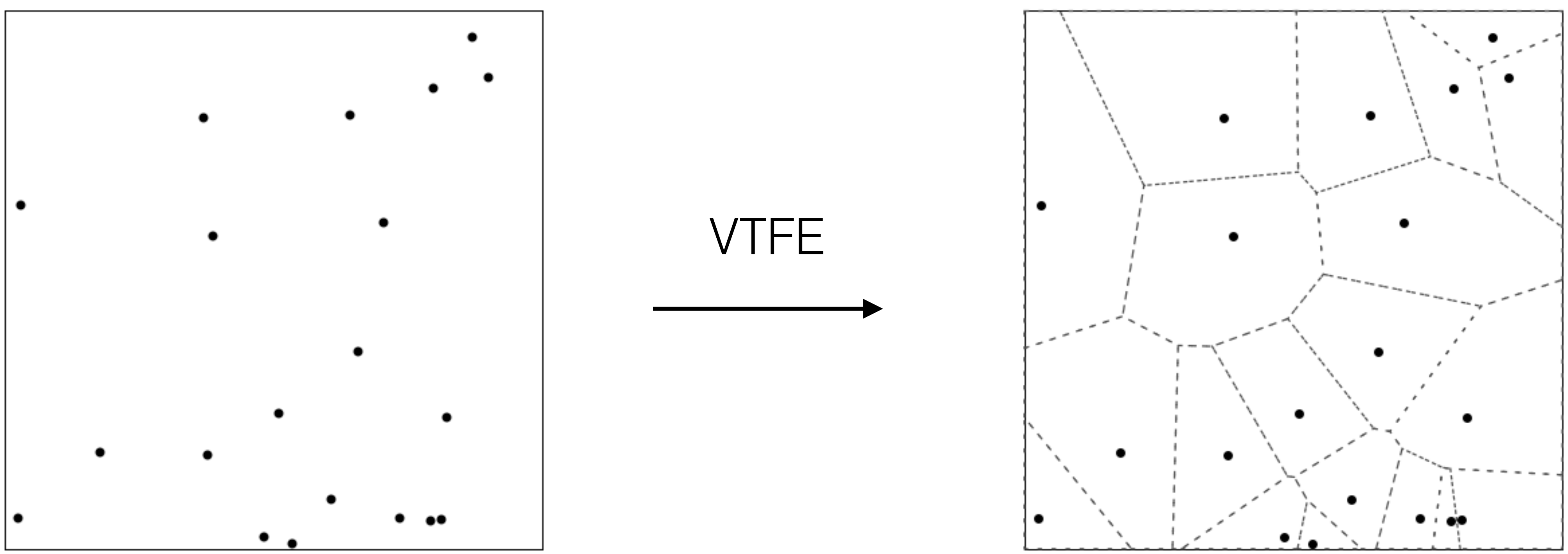
Practical void-finding

There are many void-finding algorithms, but currently most popular are *watershed algorithms* based on *Voronoi tessellations*

e.g. ZOBOV → VIDE

e.g. ZOBOV → REVOLVER

(https://github.com/seshnadathur/Revolver)



$$\rho_i = \frac{1}{V_i}$$

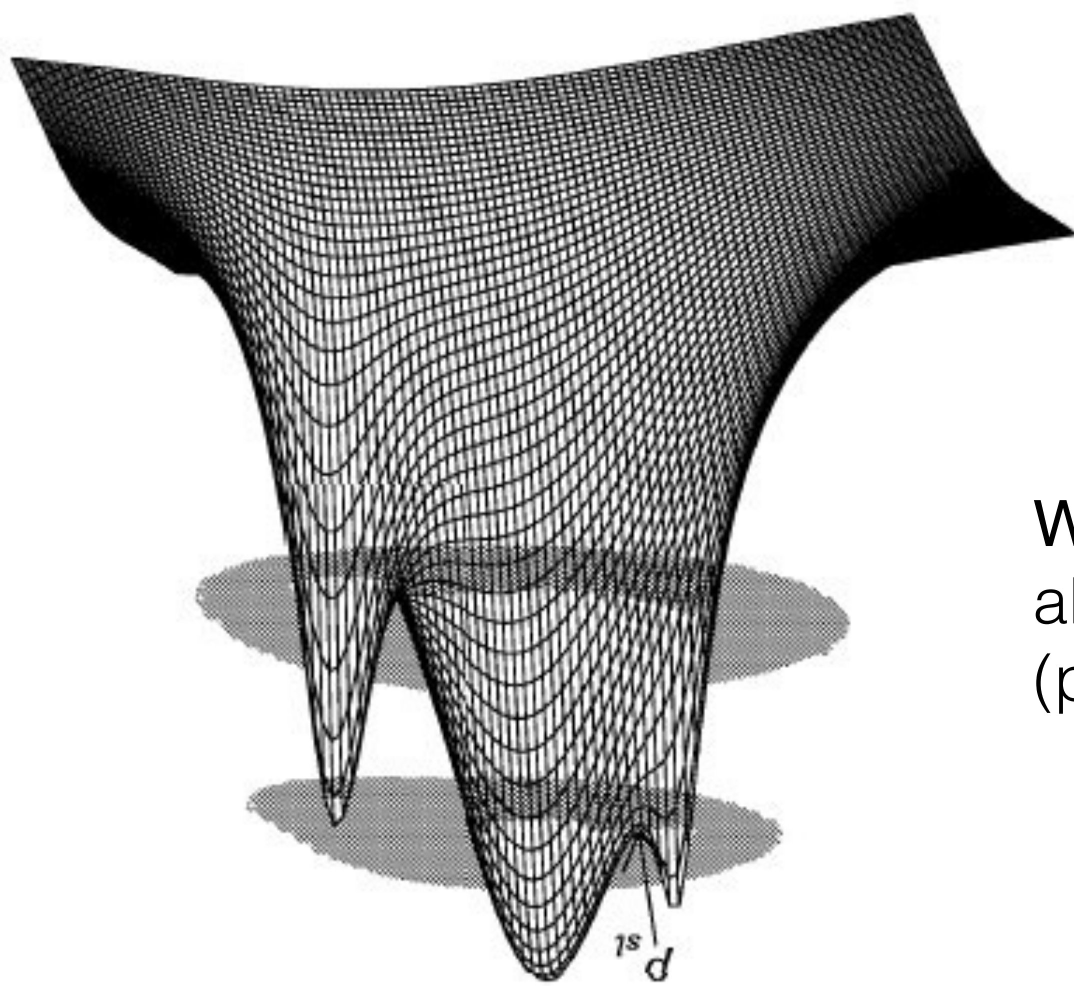
Voronoi tessellation: convenient method to estimate continuous density field, self-adaptive scaling, more resilient to shot noise

Practical void-finding

There are many void-finding algorithms, but currently most popular are *watershed algorithms* based on *Voronoi tessellations*

e.g. ZOBOV → VIDE

e.g. ZOBOV → REVOLVER (https://github.com/seshnadathur/Revolver)



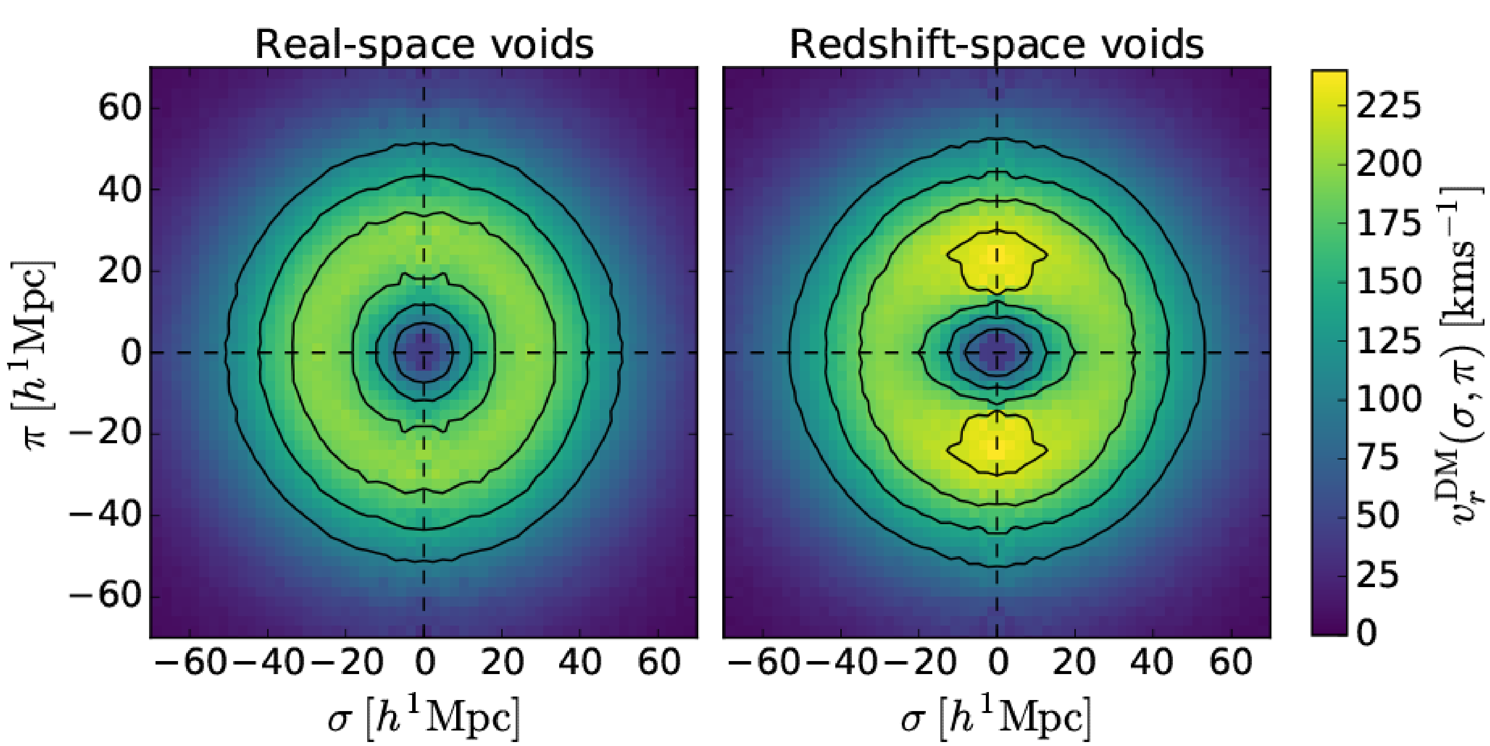
Watershed algorithm: no a priori assumptions about void shape, voids ↔ density minima, (potentially) void hierarchy

Practical void-finding

Void-finding algorithm must:

1. Be able to operate on sparse discrete galaxy tracers (robust to shot noise, obs. systematics)
2. Be agnostic about void shapes (not impose sphericity!)
3. Accurately identify minima of matter density field
4. Have **no orientation-dependent selection bias**

Orientation-dependent selection bias *always* applies for finders run on redshift-space galaxy field!



Nadathur et al, 1805.09349

Solution: **reconstruction**

approximately remove galaxy RSD *before* void-finding

Reconstruction

Solve:

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

(Zeldovich approximation in redshift space)

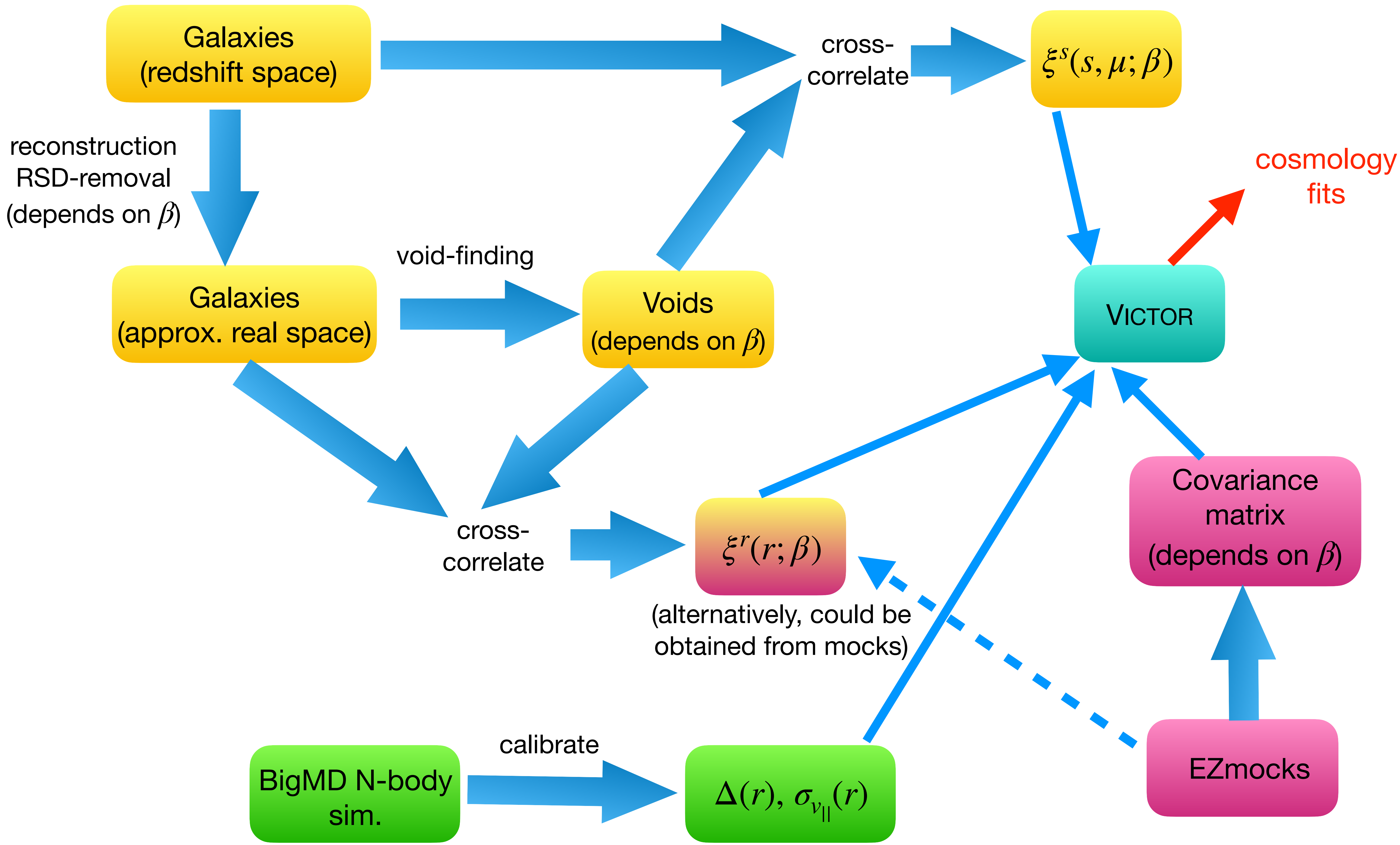
Shift galaxy positions by $-\mathbf{\Psi}_{\mathrm{RSD}} = f(\mathbf{\Psi} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}}$

Galaxies now at approximate real-space positions, so find voids

very closely related to BAO reconstruction!

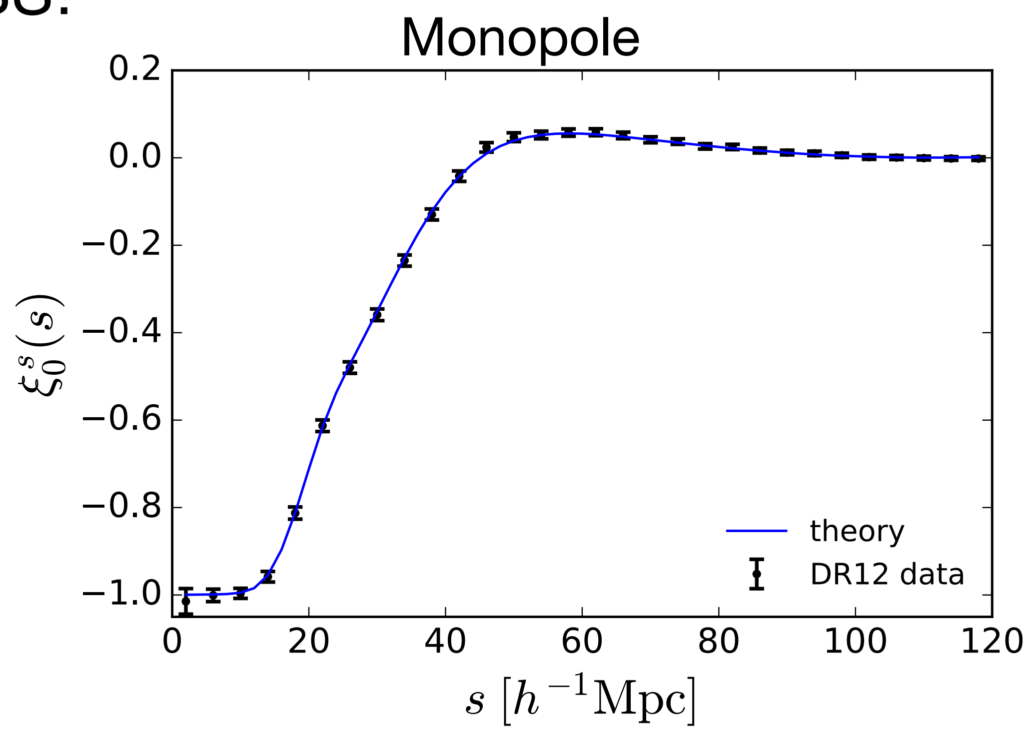
Void-finding always performed on (approximate) *real-space galaxy field*!

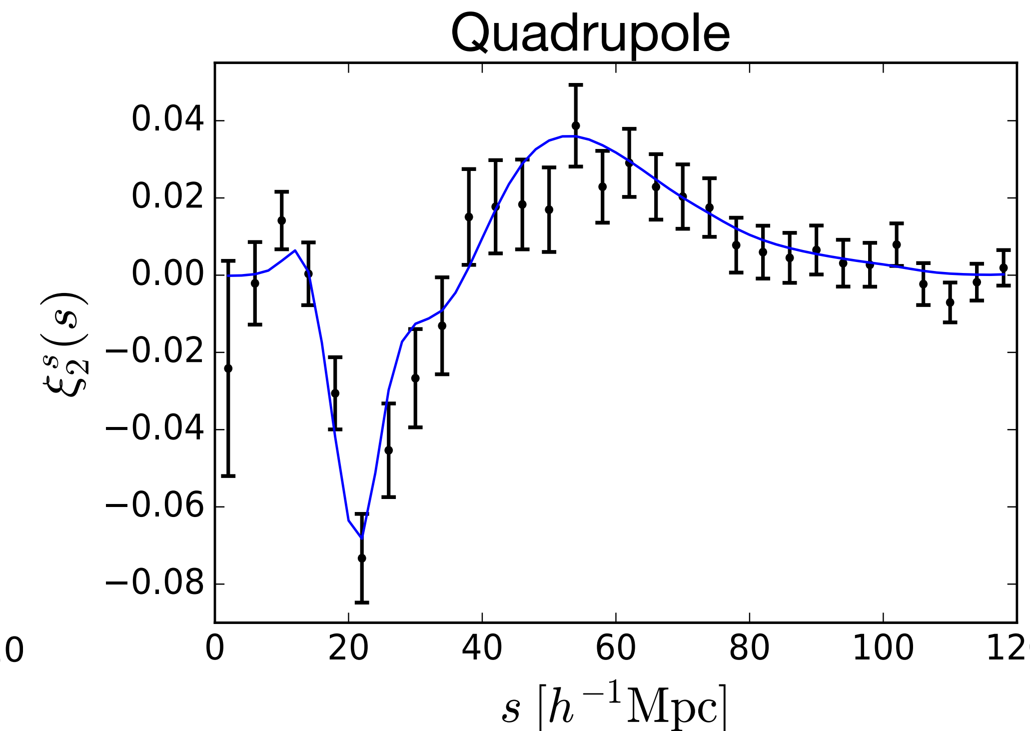
Example eBOSS pipeline



Fits to the data

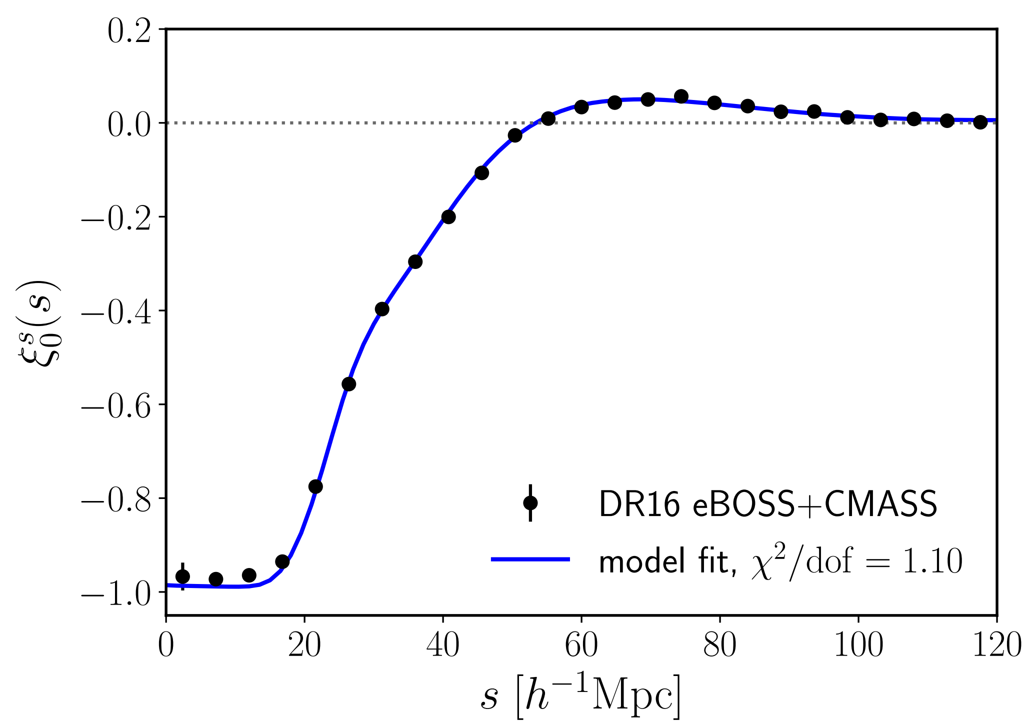
BOSS:

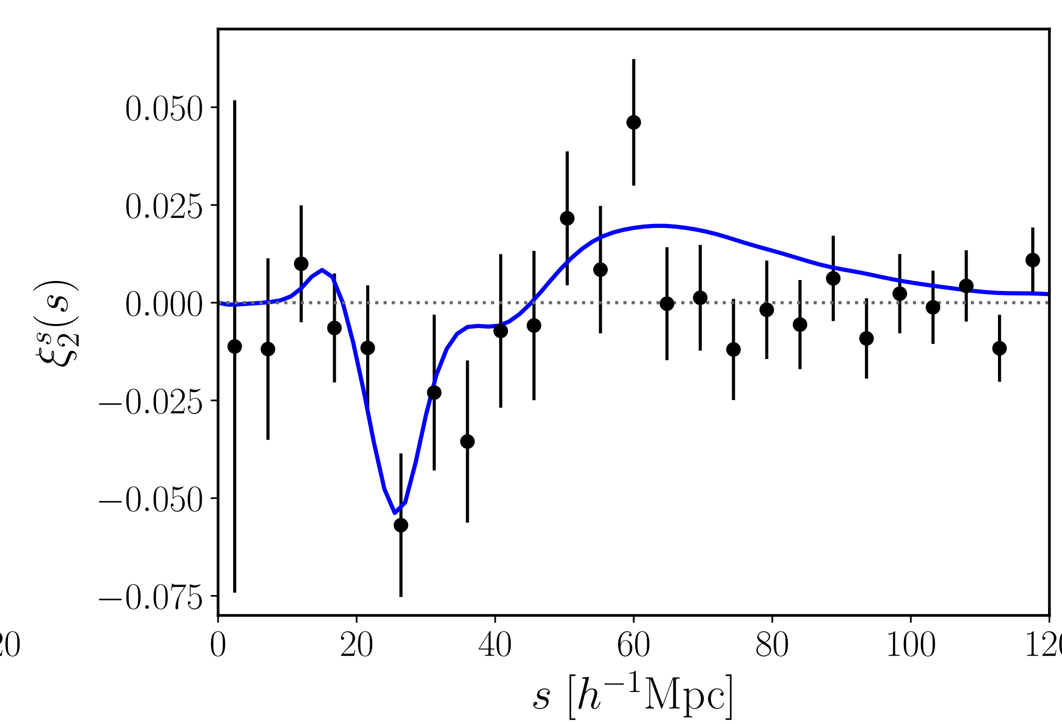




SN+, 1904.01030

eBOSS:



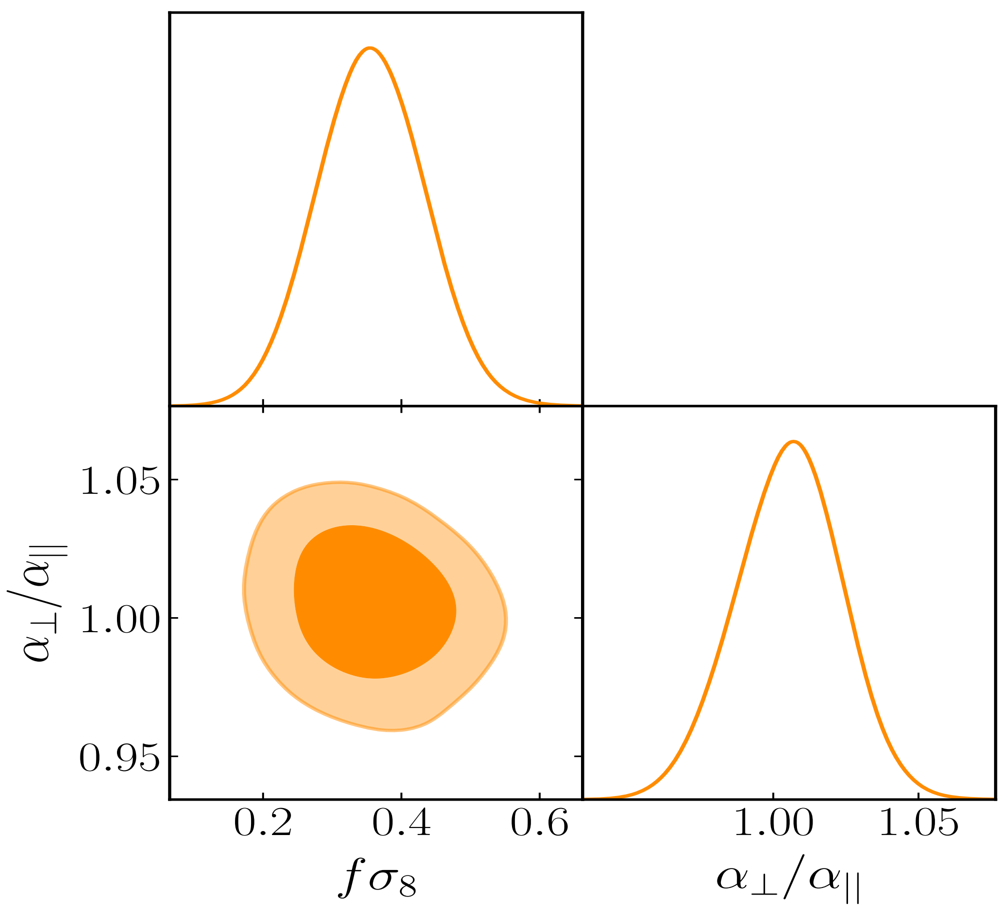


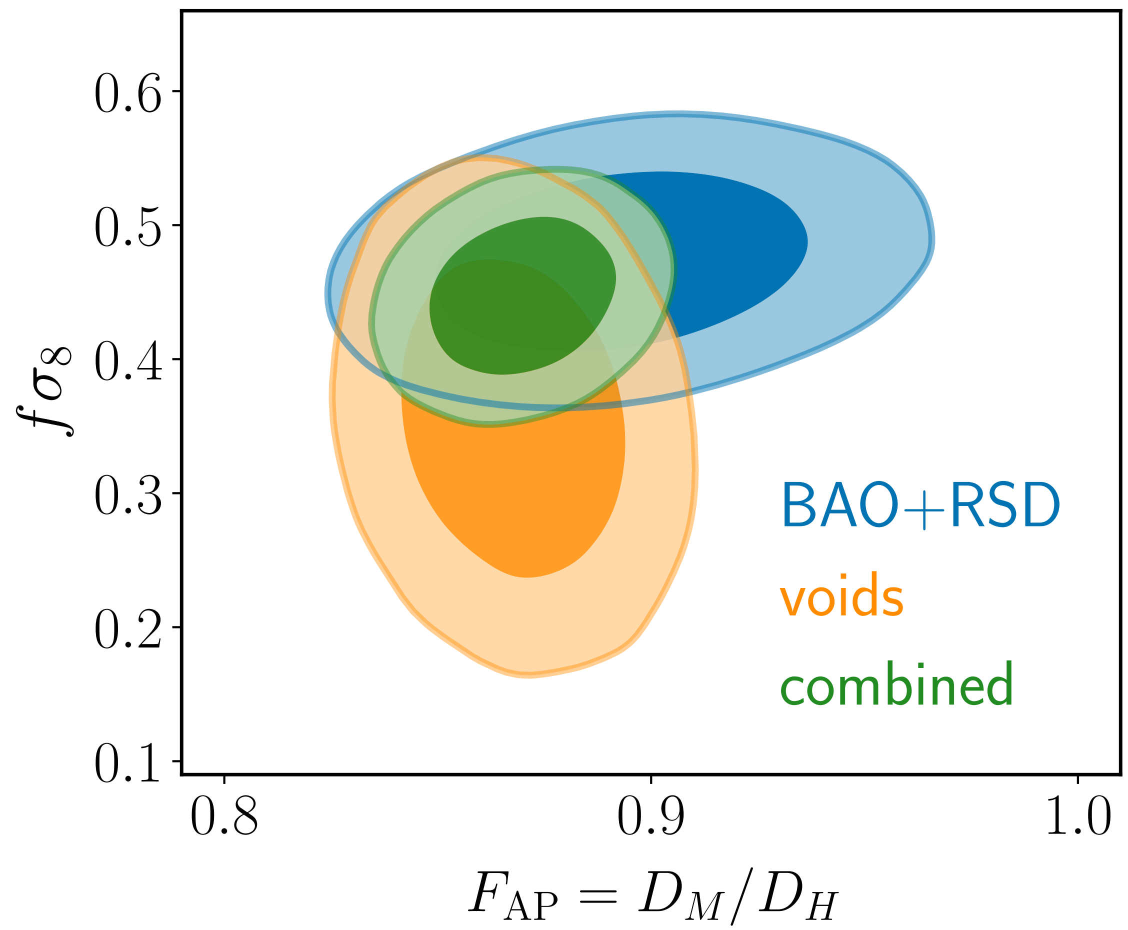
SN+, 2008.06060

Fits to the data

Model fit uses VICTOR code*

- fits for $f\sigma_8$ and $\alpha_\perp/\alpha_{||}$ + 2 nuisance parameters
- data vector & covariances depend on parameter $\beta = f/b$ via RSD-removal step: consistently accounted for in fits!
- MCMC exploration of posterior





*https://github.com/seshnadathur/victor

SN+, 2008.06060

Tests for systematic errors

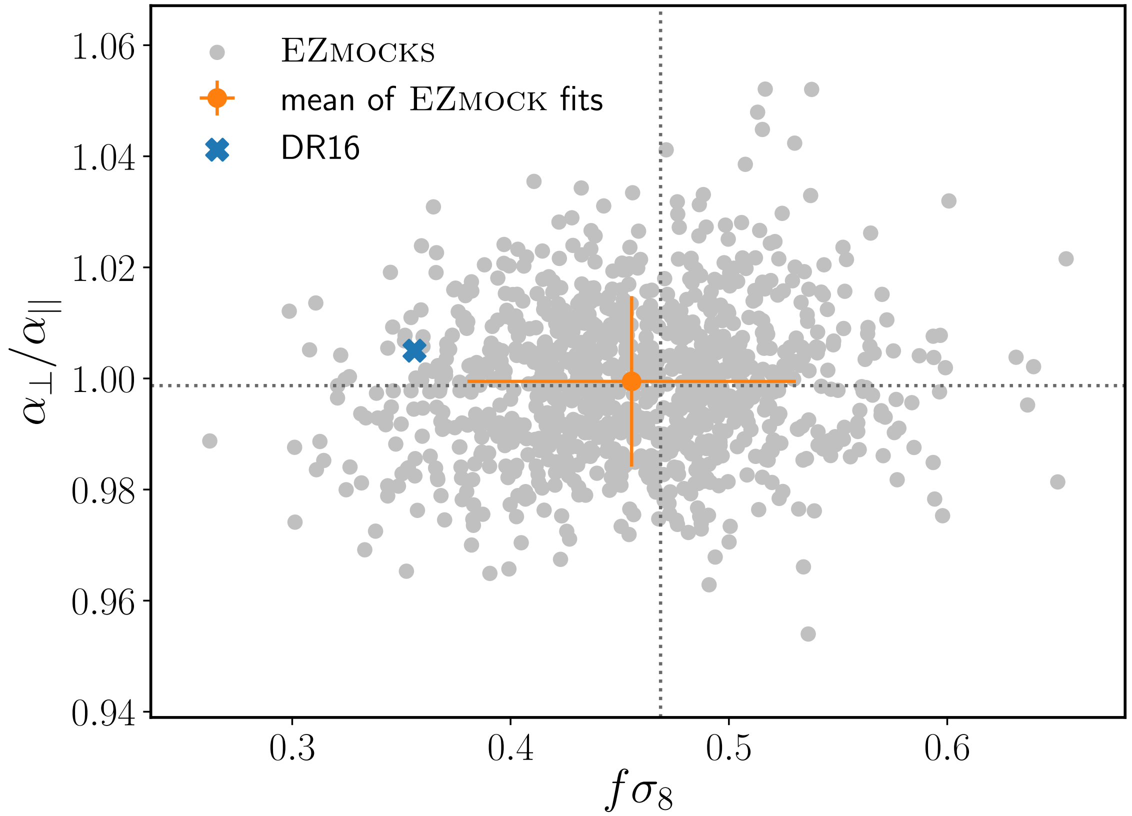
As for BAO+RSD analyses, systematics checks use simulated catalogues (fast EZMOCKS + N-body NSERIES)

Test for:

- modelling limitations + effects due to composite sample
- fiducial cosmology systematics

Systematics are small contribution to total error budget and are at $< 1\ \%$ level for $\alpha_\perp/\alpha_{||}$

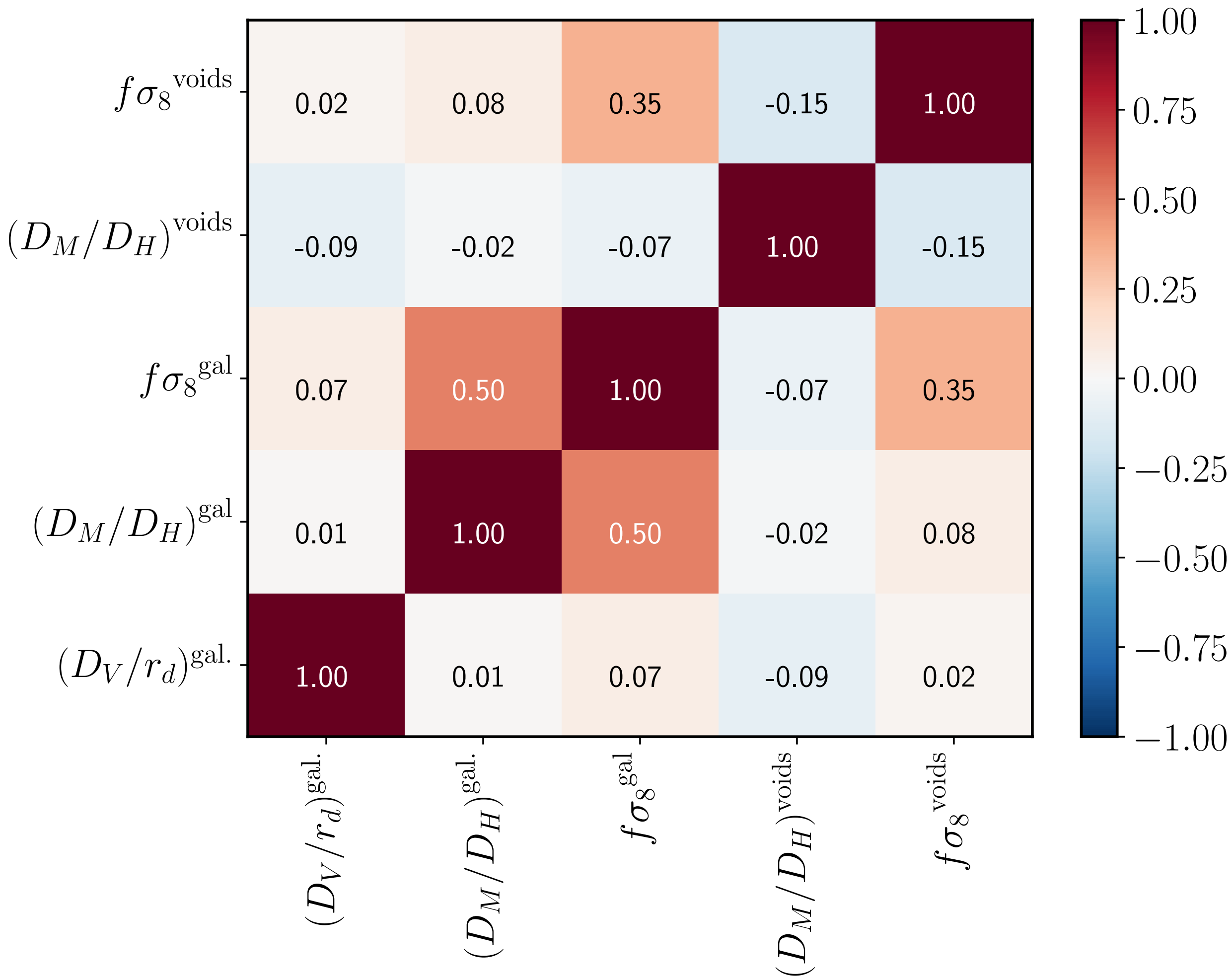
Parameter	$\sigma_{\rm syst,\,model}$	$\sigma_{\rm syst,\,cosmo}$	$\sigma_{\rm syst,\,tot}$	$\sigma_{\rm stat}$	$\sqrt{\sigma^2_{\rm syst,\,tot}+\sigma^2_{\rm stat}}$
$f\sigma_8$	0.0144	0.0075	0.0162	0.077	0.079
$\alpha_\perp/\alpha_{\|\|}$	0.0042	0.0081	0.0091	0.018	0.020

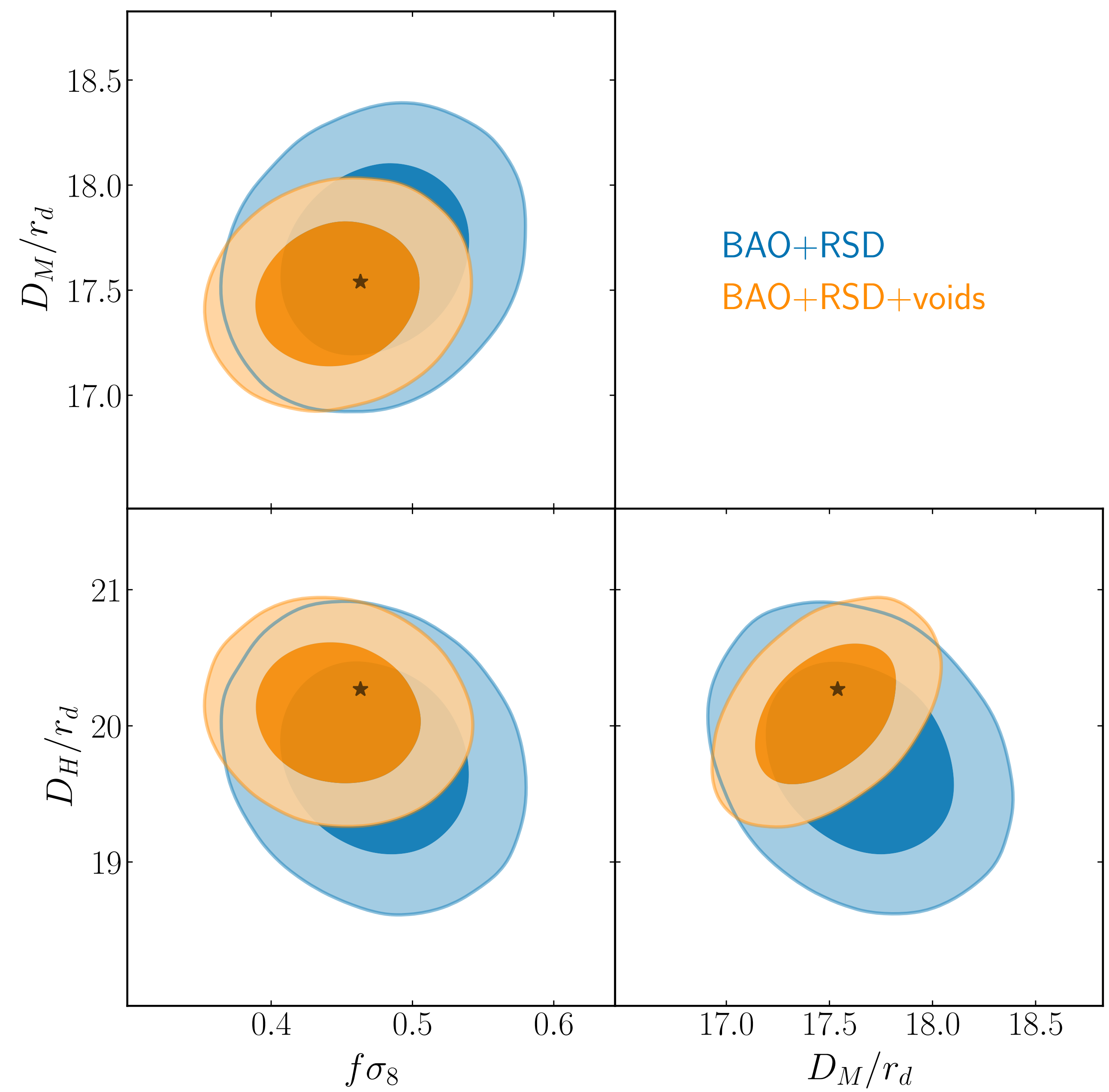


details in SN+, 2008.06060

Consensus constraints

Independent of other methods; adds LOTS of information from same data!

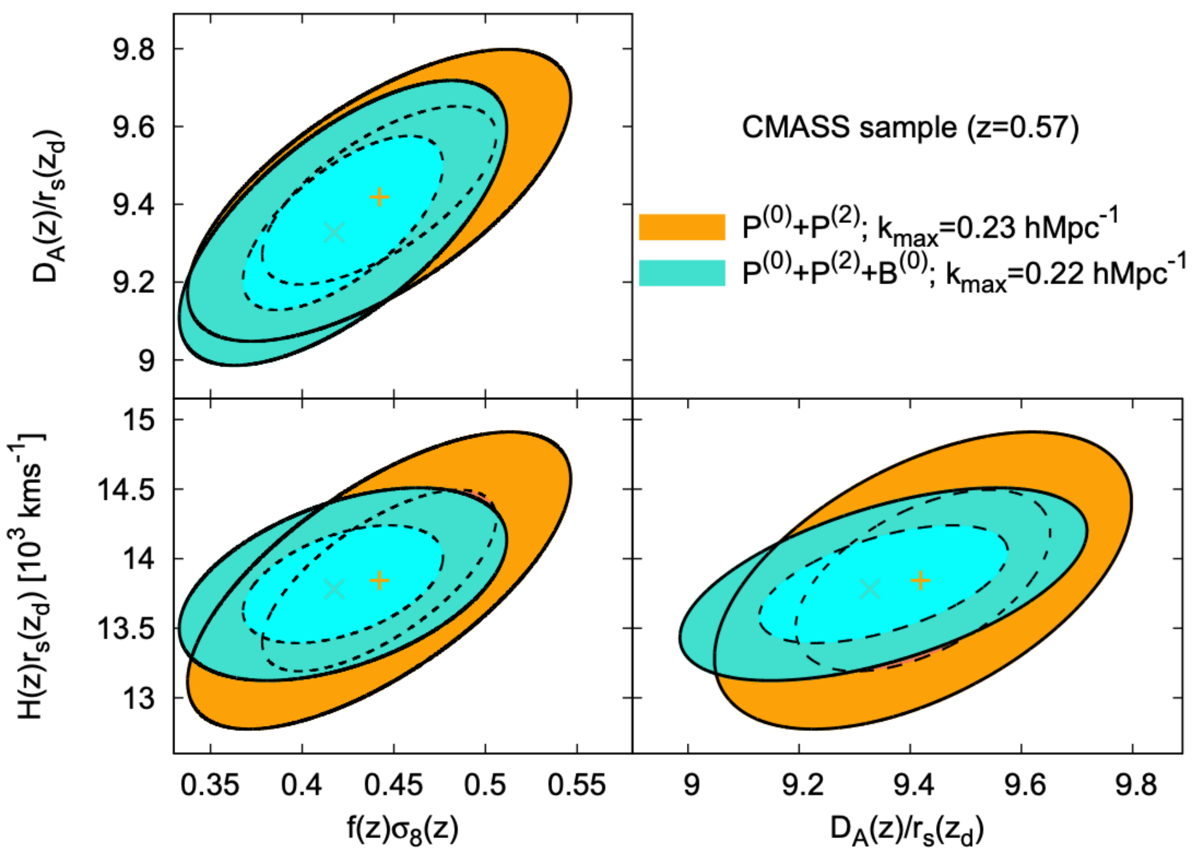




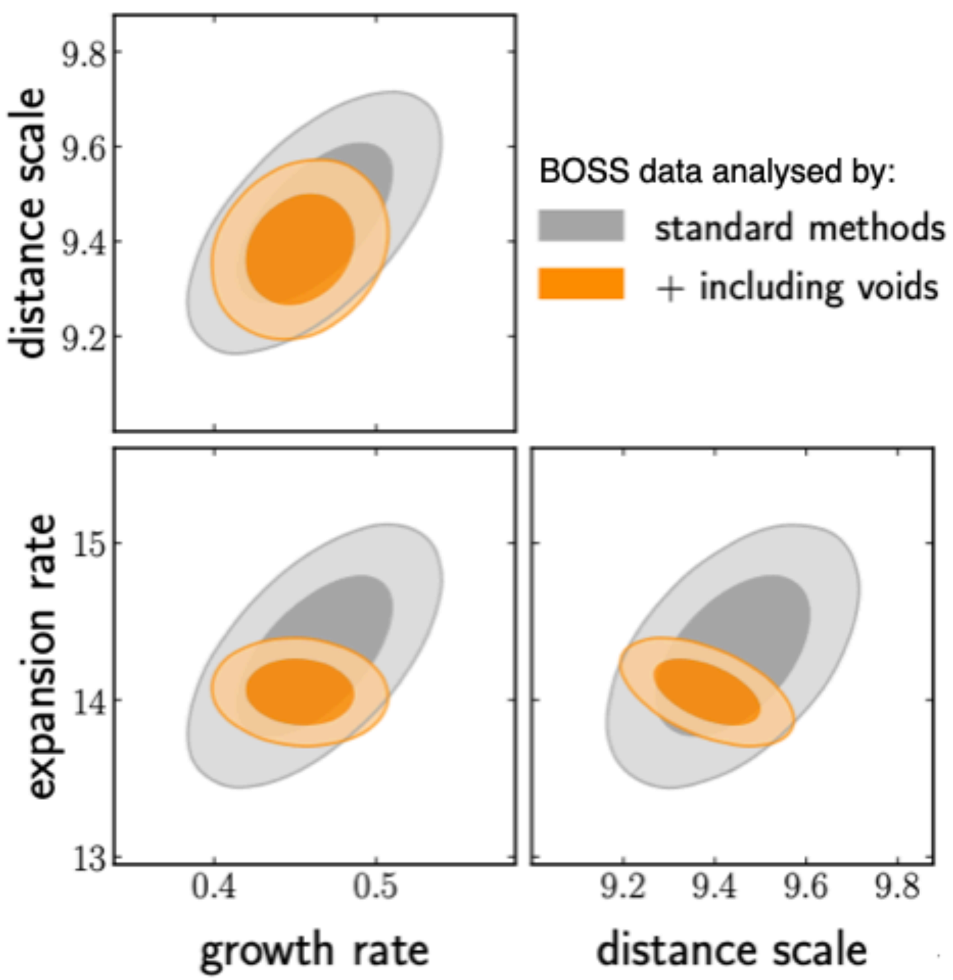
details in SN+, 2008.06060

Comparing voids to bispectrum

Different methods have been applied to same BOSS data:



taken from Gil-Marin et al, 1606.00439

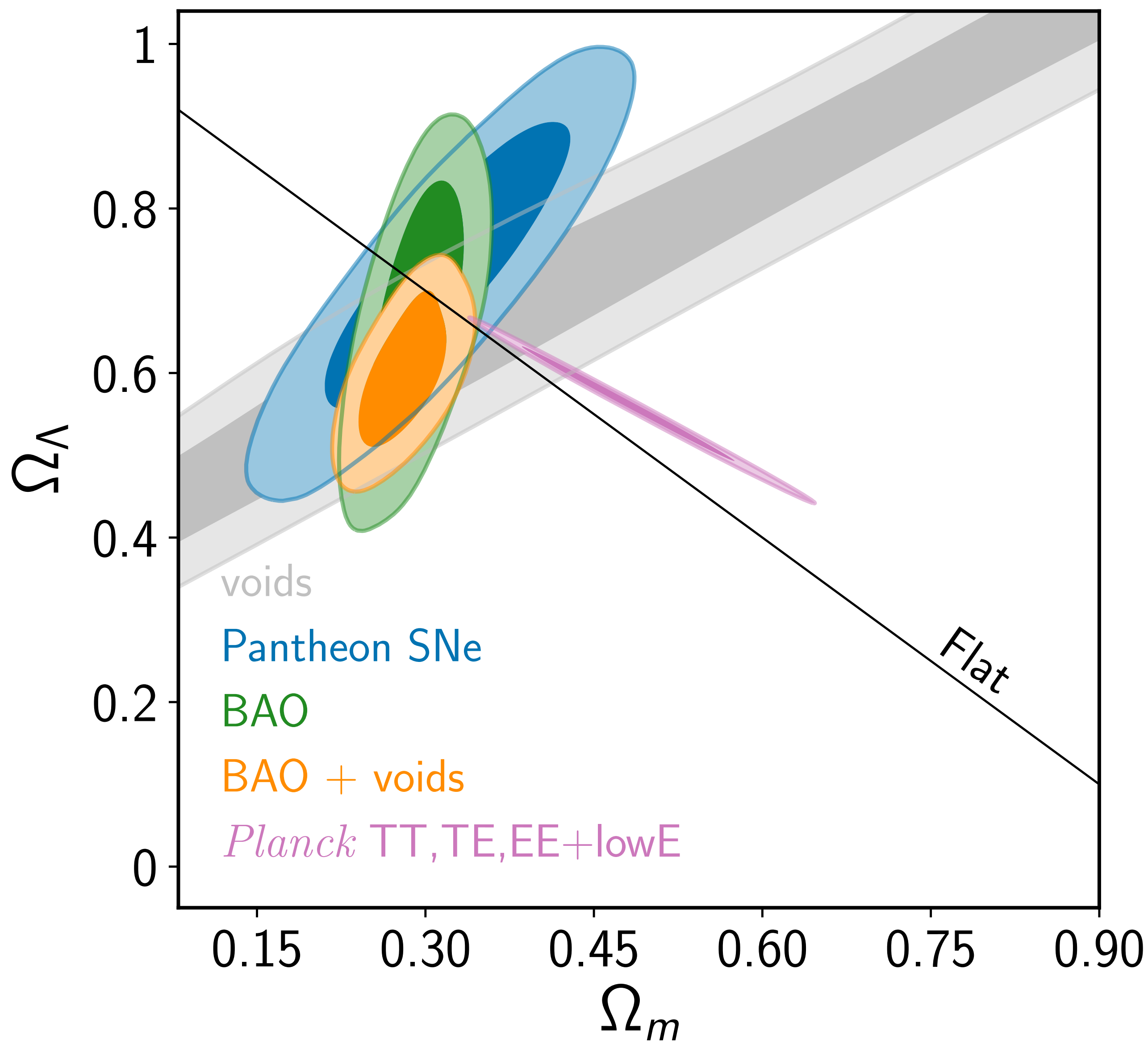


adapted from SN+, 1904.01030

void-galaxy measurement yields different information to bispectrum

Cosmological implications

Dark energy and curvature:



Direct evidence of acceleration *independent of CMB and SNIa*

- voids *alone* require $\Omega_\Lambda > 0$ at >99.99% confidence
- BAO+voids: $> 10\sigma$ evidence of acceleration (>> SNIa!)

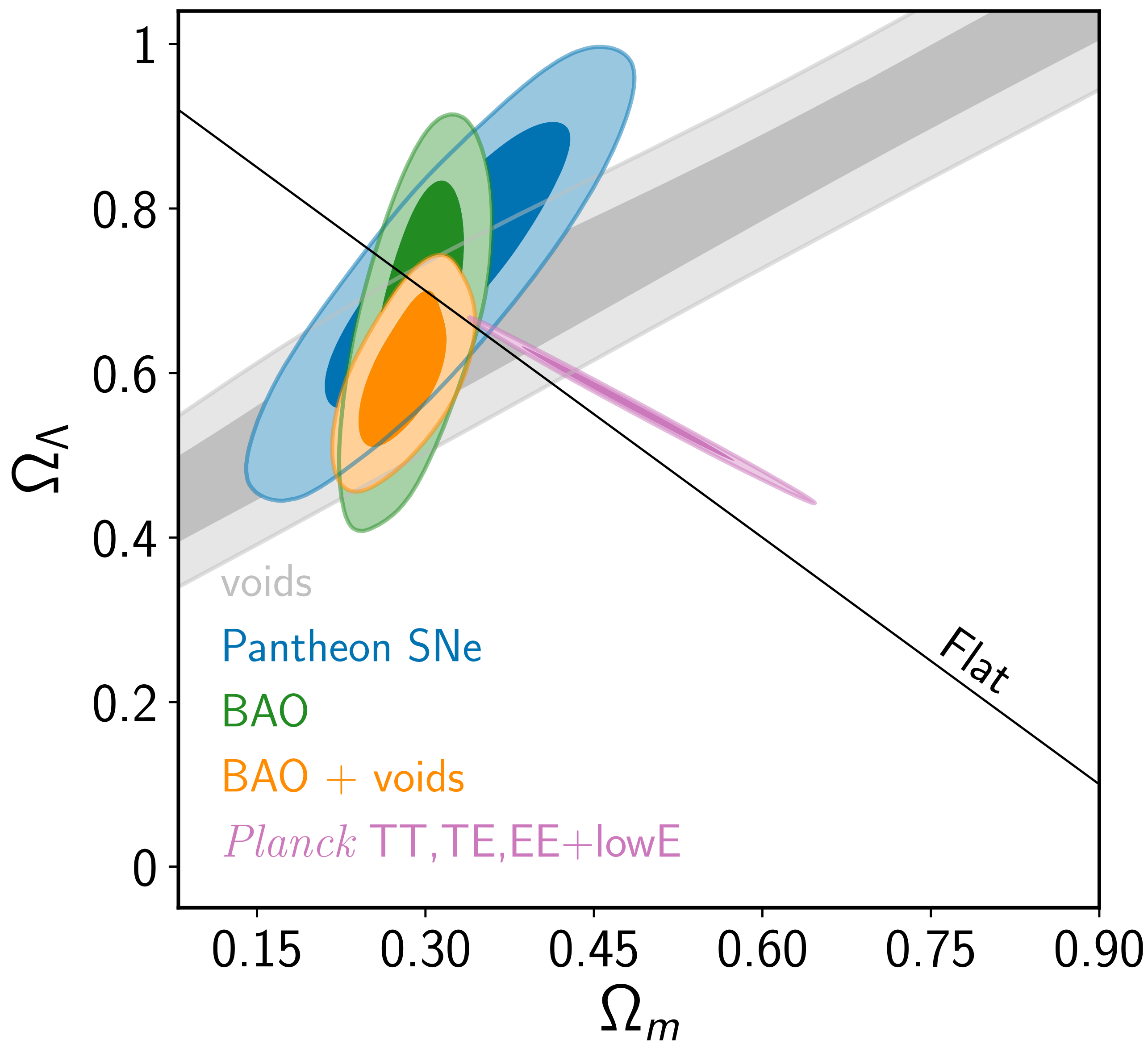
$$\Omega_\Lambda = 0.60 \pm 0.058$$

SN+ 2001.11044

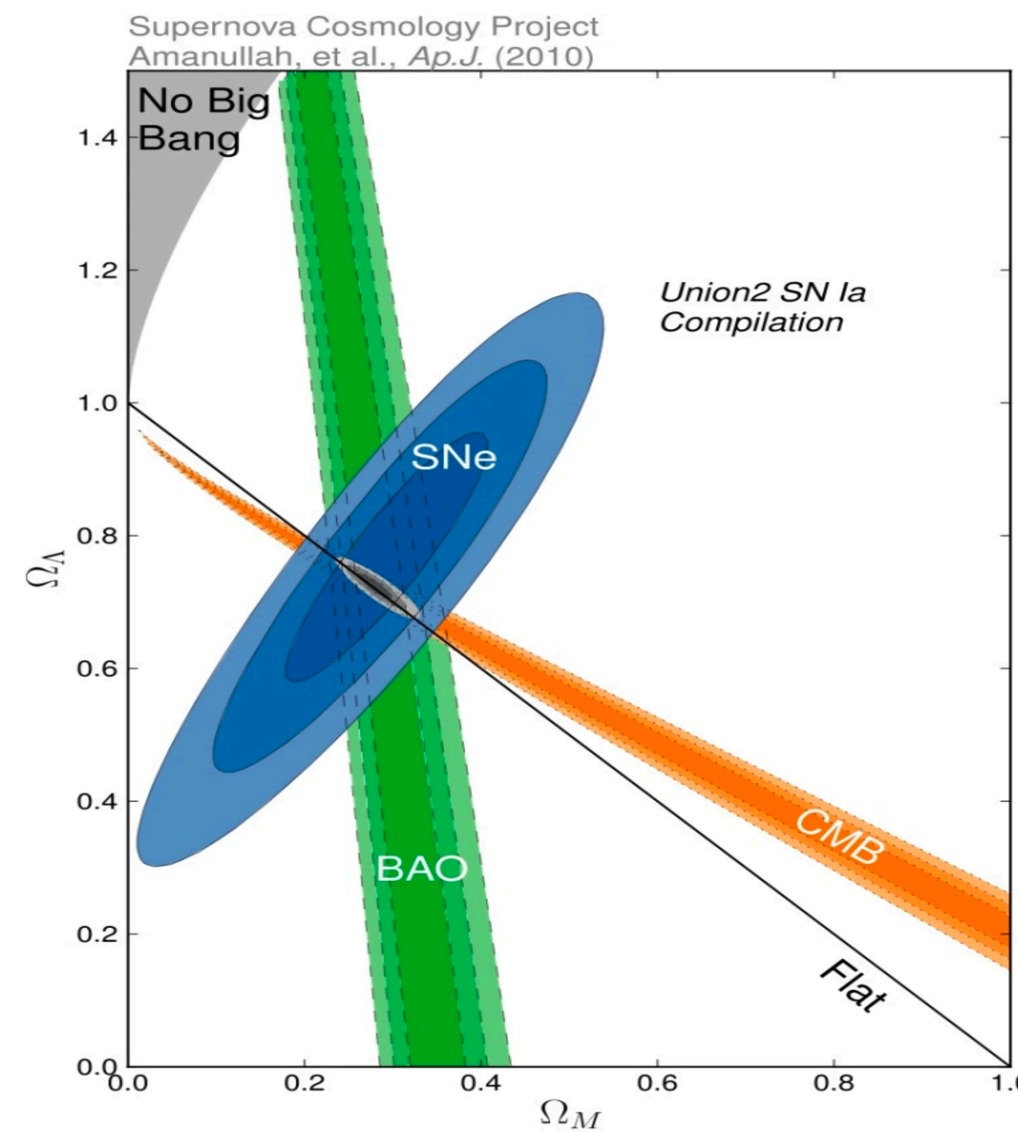
Cosmological implications

Dark energy and curvature:

2020



2010



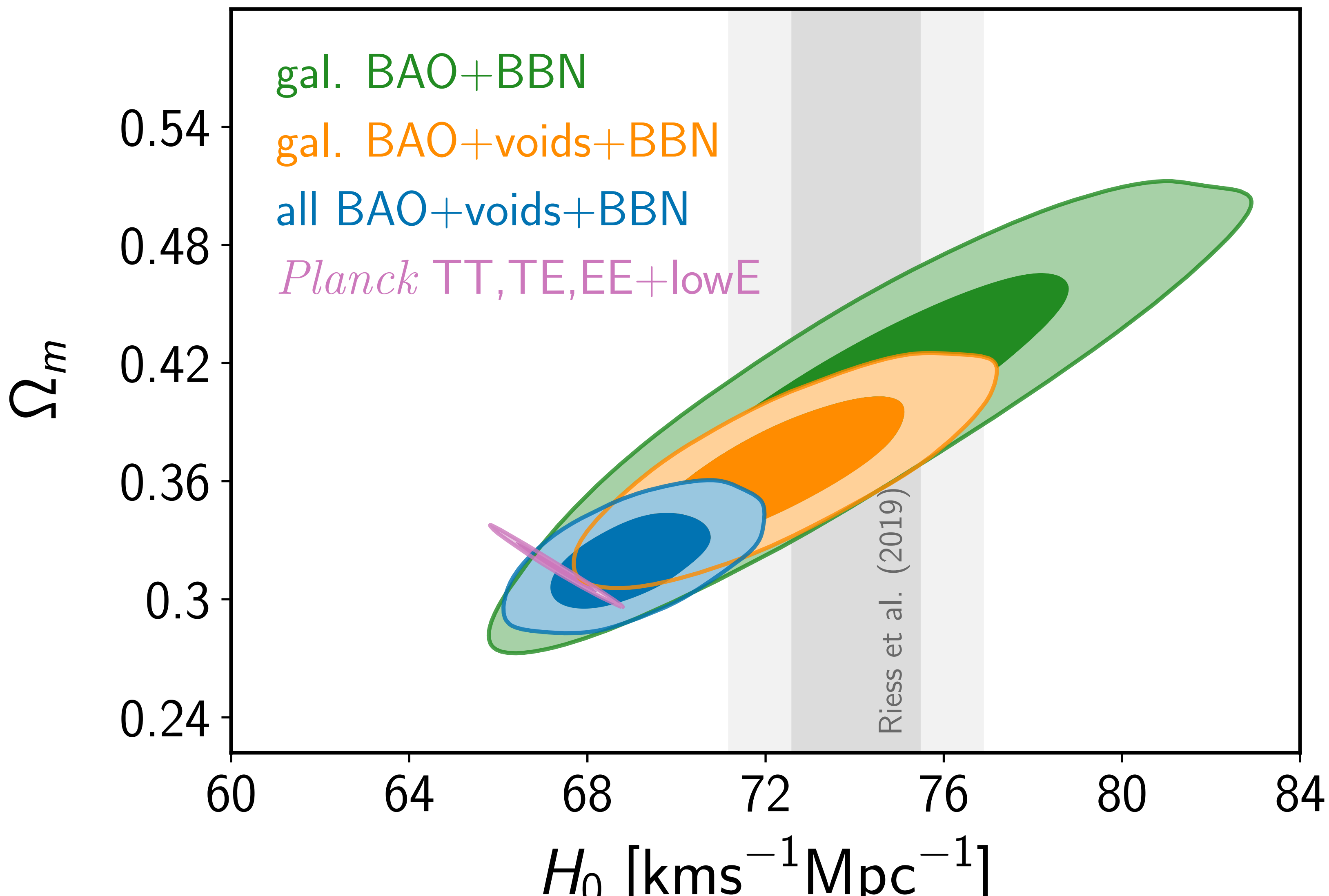
Things have changed in interesting ways in 10 years

Cosmological implications II

Hubble constant:

Measure relative *H(z)* + calibrate with anchor = get H_0

voids improve this by ~2x



BAO *(z<2)* + voids:

$$H_0 = 72.3 \pm 1.9\,\mathrm{km\,s^{-1}Mpc^{-1}}$$

BAO *(z<2)* + voids + Ly-a BAO:

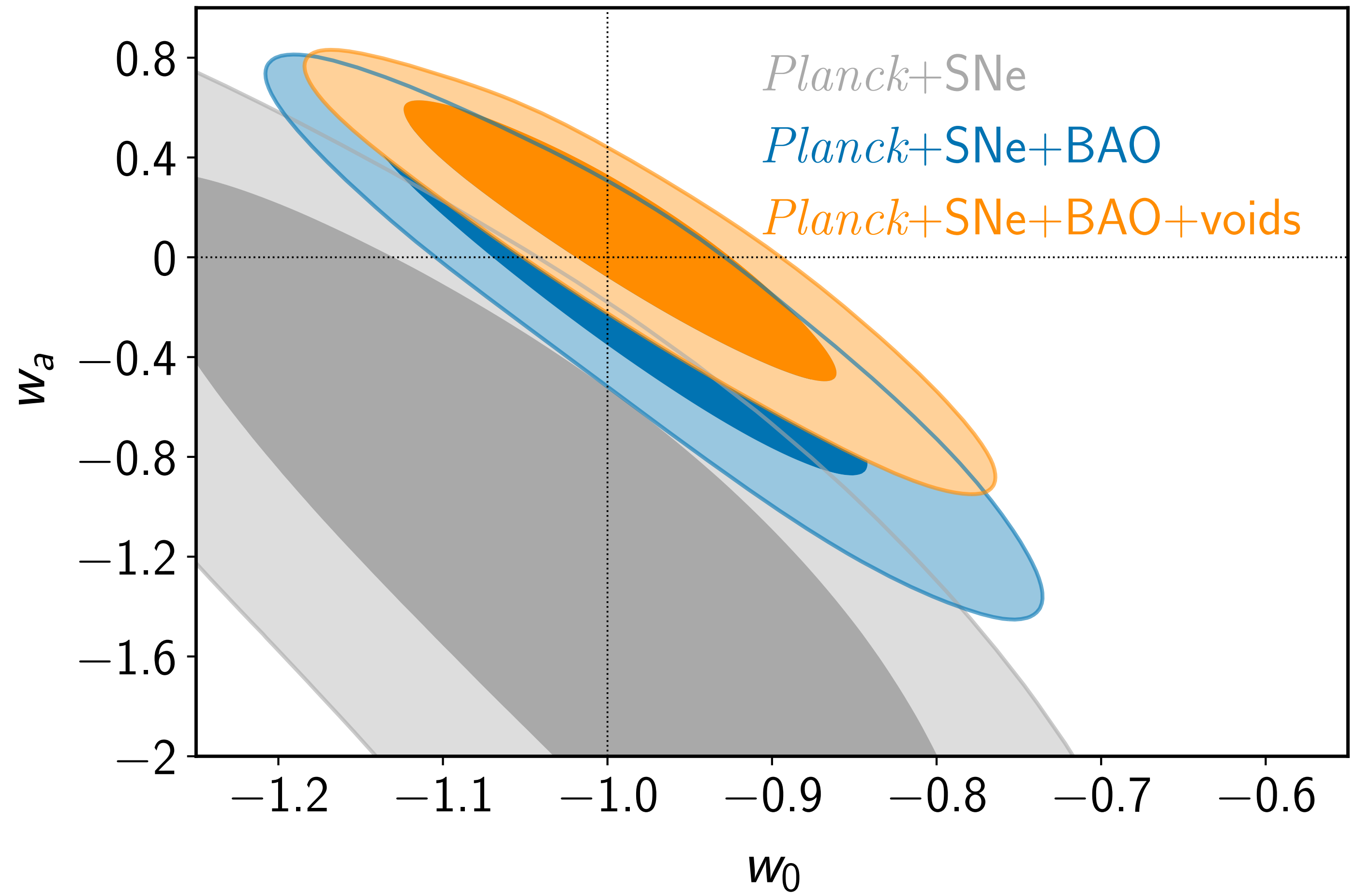
$$H_0 = 69.0 \pm 1.2\,\mathrm{km\,s^{-1}Mpc^{-1}}$$

SN+ 2001.11044

Cosmological implications III

DE **equation of state**:

$$w(z) = w_0 + w_a \frac{z}{1+z}$$



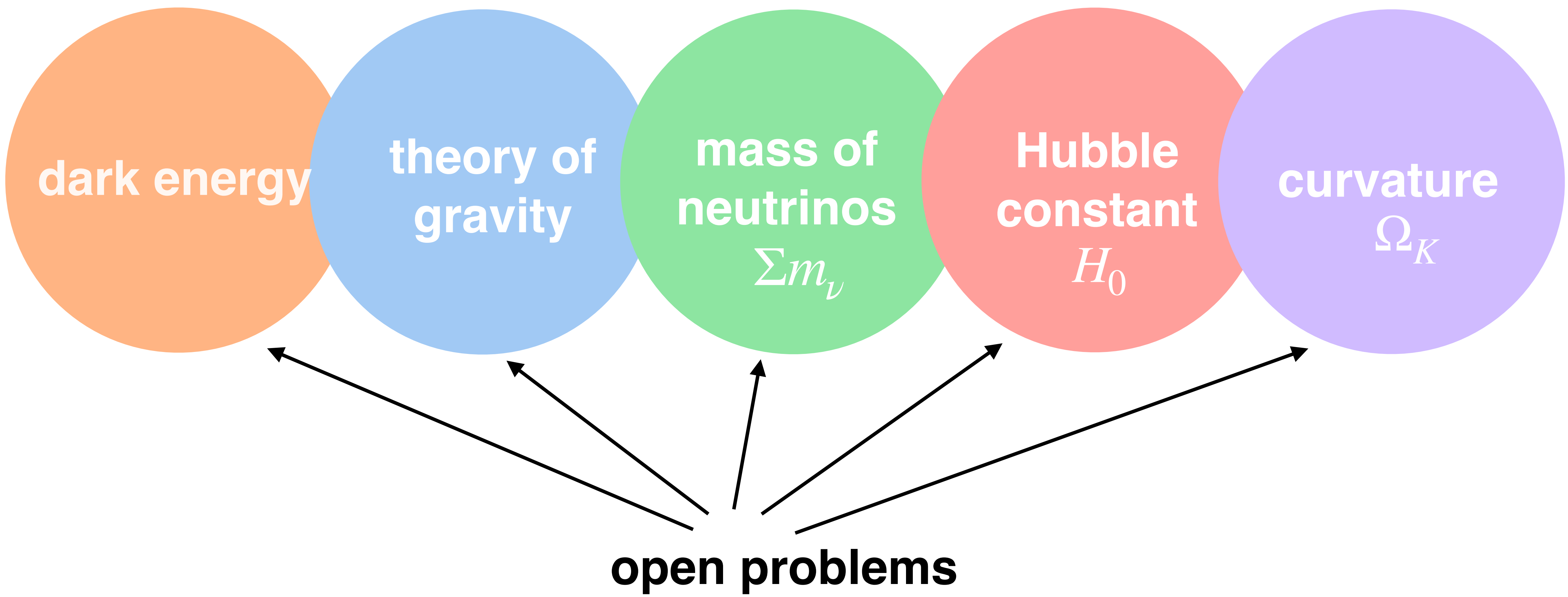
$$w_0 = -0.984^{+0.076}_{-0.097},$$
$$w_a = 0.05^{+0.44}_{-0.29},$$
$$\Omega_K = 0.0033^{+0.0034}_{-0.0041},$$

Figure of Merit: **10.9** **58.1** **82.9** → >40% better measurement with voids!

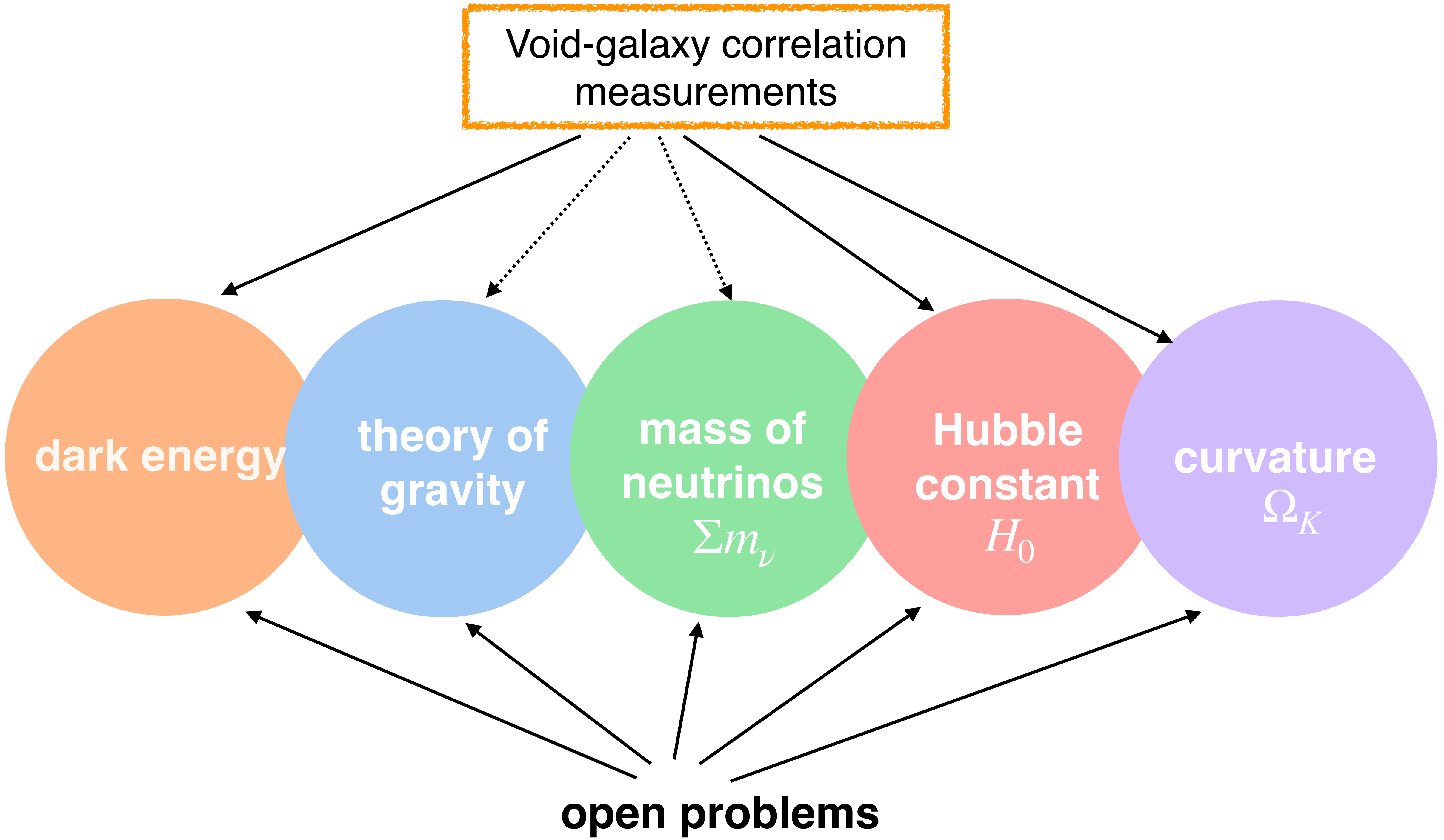
SN+ 2001.11044

Void likelihoods are public with eBOSS DR16 releases!
https://svn.sdss.org/public/data/eboss/DR16cosmo/tags/v1_0_0/likelihoods/

The Bigger Picture



The Bigger Picture



Summary

- Large-scale structure is the future for cosmology!
- Void-galaxy correlation is a key new tool – lots of new info not available from other methods
- Method demonstrated on BOSS and eBOSS data; low systematic errors
- Best current constraints on dark energy, other extended models
- Extraordinarily promising method – will become standard of LSS analysis for *all* galaxy surveys!