Cosmology with cosmic voids

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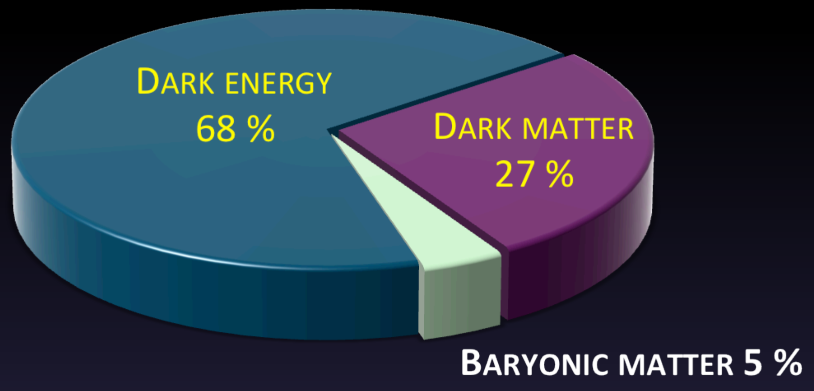
ICISE 2020

Outline

- Cosmology
- Cosmic voids
- Cosmology with cosmic voids
  - Alcock-Paczynski test
  - Redshift Space Distortions
- Perspectives and conclusion
  - Incoming and future galaxy surveys
  - Conclusion

COSMOLOGY

Cosmology:
Understanding the dark Universe



Assumption:
Homogeneous and isotropic Universe

- What is the origin of the Universe ? What is its fate ?
- What is Dark Matter ?
- What is Dark Energy ?

Dark energy

Cosmic acceleration

Λ

- Cosmological constant
- Constant of integration
- Vacuum energy

Evolving dark energy ?

- Quintessence
- k-essence
- Galileons
- Chaplygin gas

Modified gravity ?

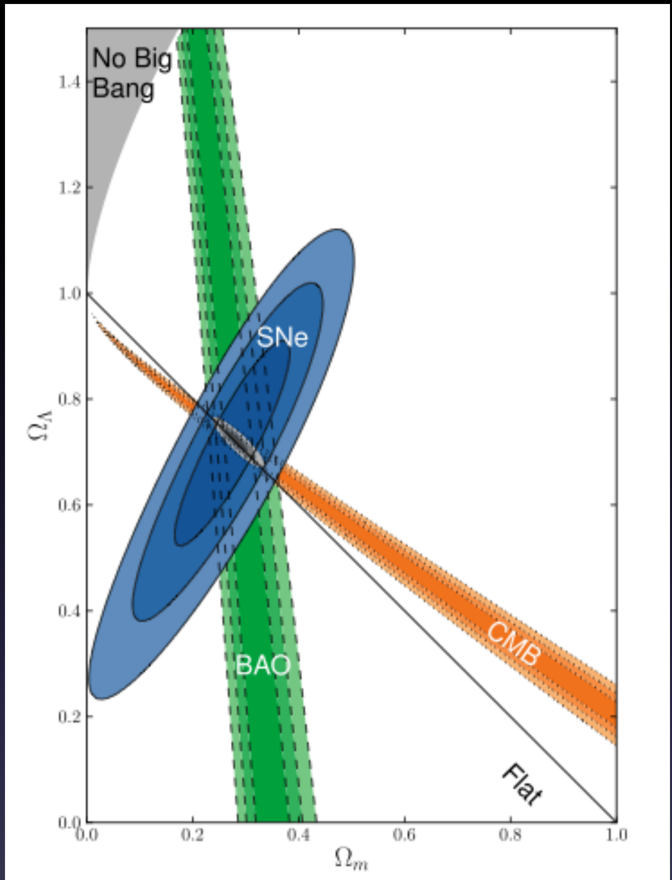
- DGP gravity
- Brane world gravity
- TeVeS theories
- F(R) theories

New assumption ?

Higher dimensions ?

New constituent ?

The concordance model



The concordance model ΛCDM

Λ : dark energy
CDM : cold dark matter

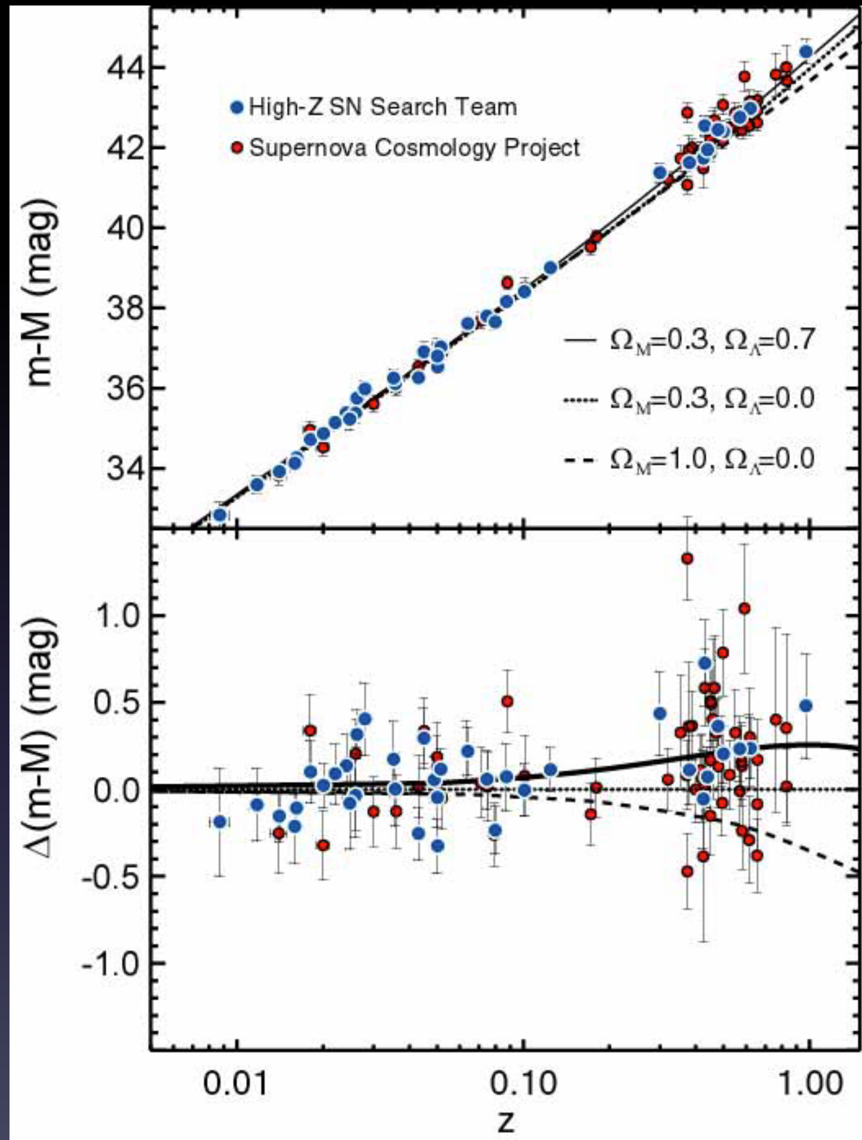
All cosmological probes converge to the same description

Cosmology: Supernovae Ia

In 1998, evidence that the expansion of the universe is accelerating

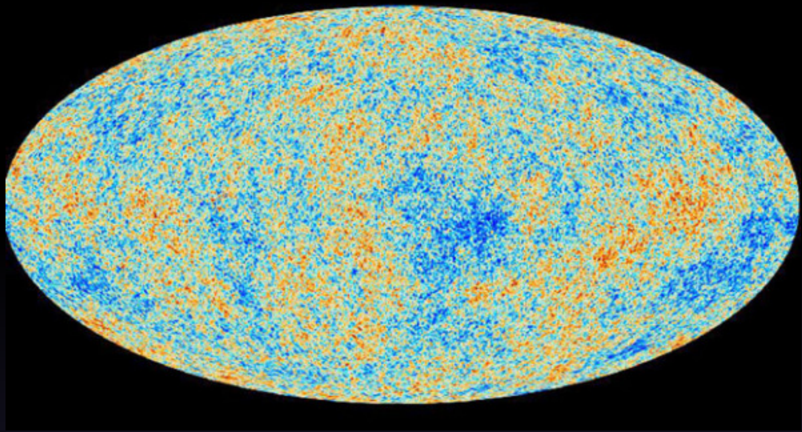
2011 Nobel Prize

See E. Gangler's talk on LSST

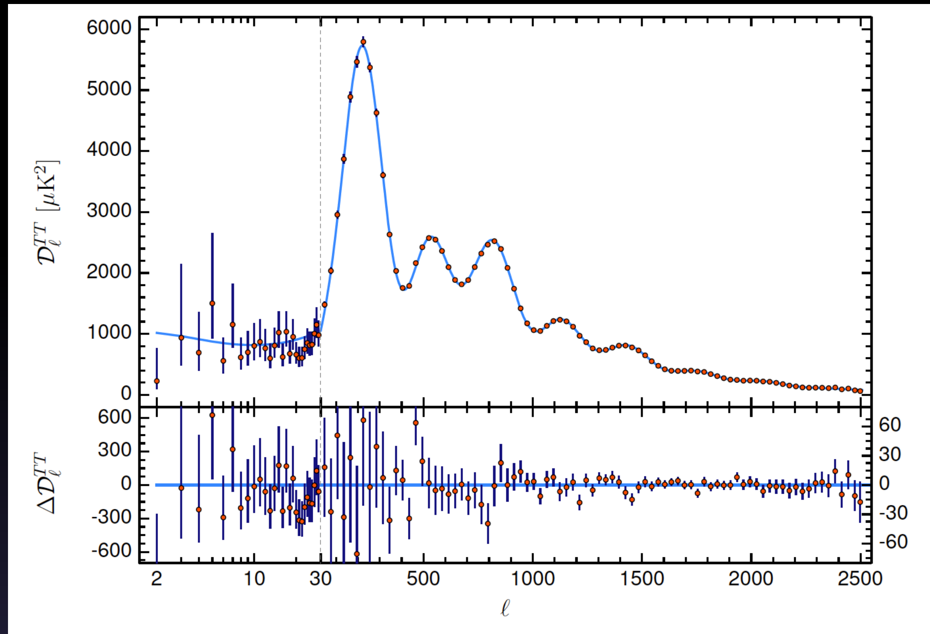


Perlmutter et al. 1999, Riess et al. 1998

Cosmology: CMB



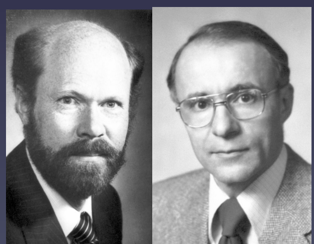
The Universe is flat



See M. Tristam's talk on LiteBIRD

Planck Coll. 2018

1978 Nobel Prize



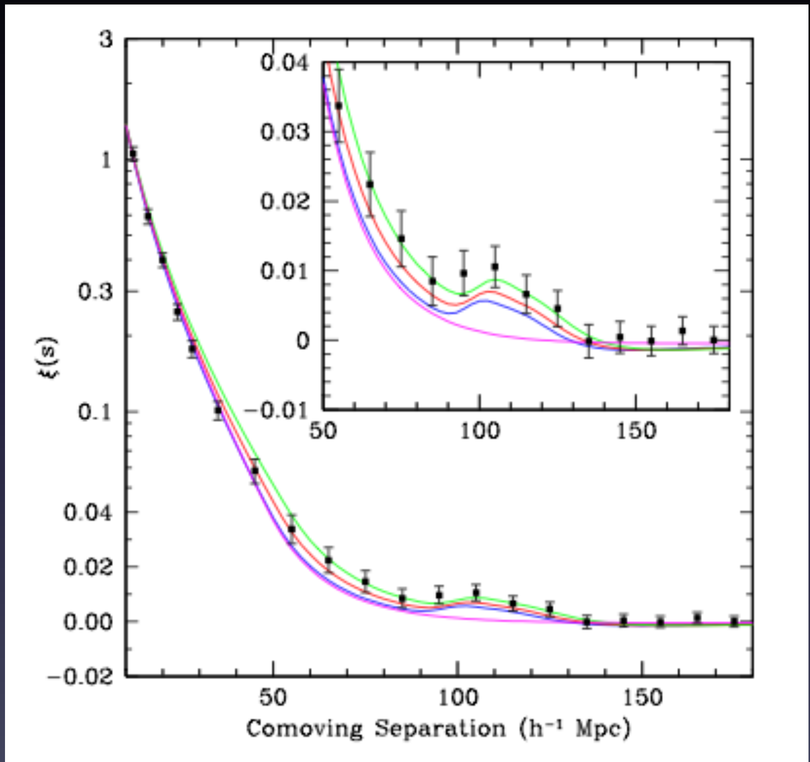
2006 Nobel Prize

2019 Nobel Prize

Cosmology: Large scale structure

The study of large scale structures is a powerful tool to understand the composition of the universe

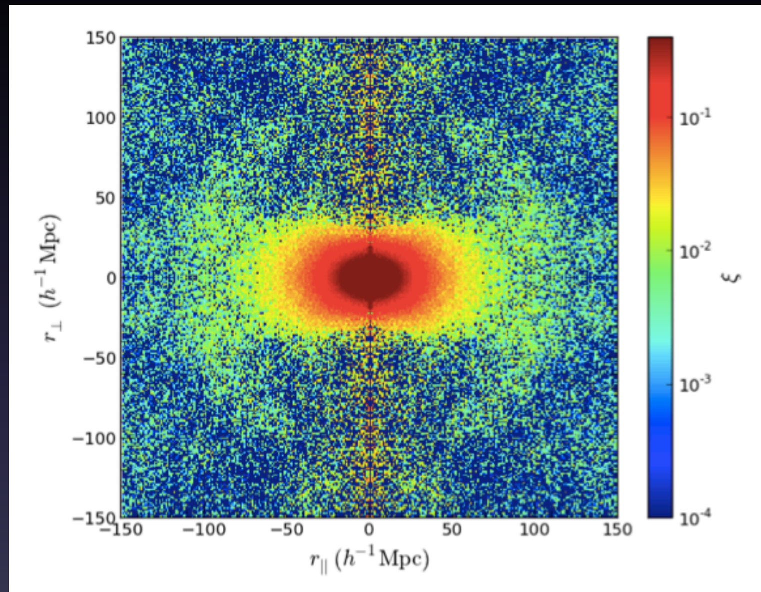
Baryon Acoustic Oscillations (BAO)
= standard ruler



Eisenstein et al. 2005

➔ $H^2(z) = H_0^2[\Omega_m(1+z)^3 + \Omega_\Lambda]$

Redshift Space Distortions (RSD)



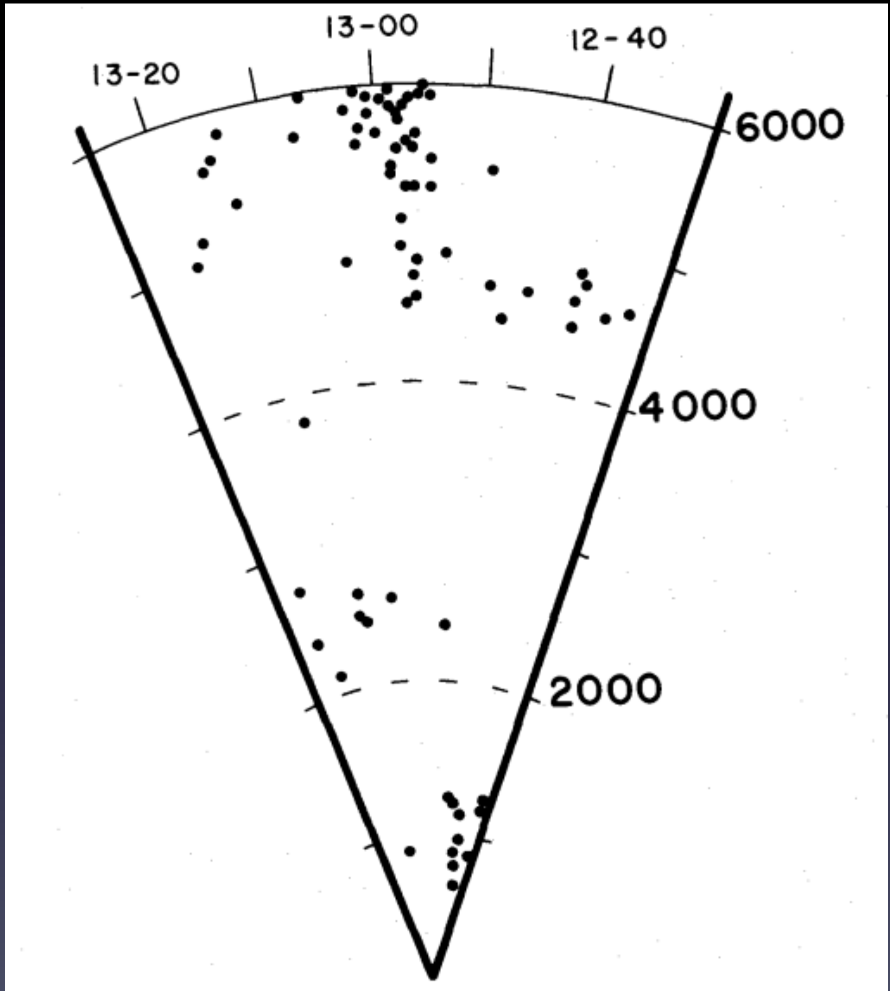
Samushia et al. 2012

➔ Growth rate of structure

COSMIC VOIDS

Galaxy redshift surveys:
Reconstructing the 3D structure of the Universe

The first 3D survey (Tifft and Gregory, 1976):



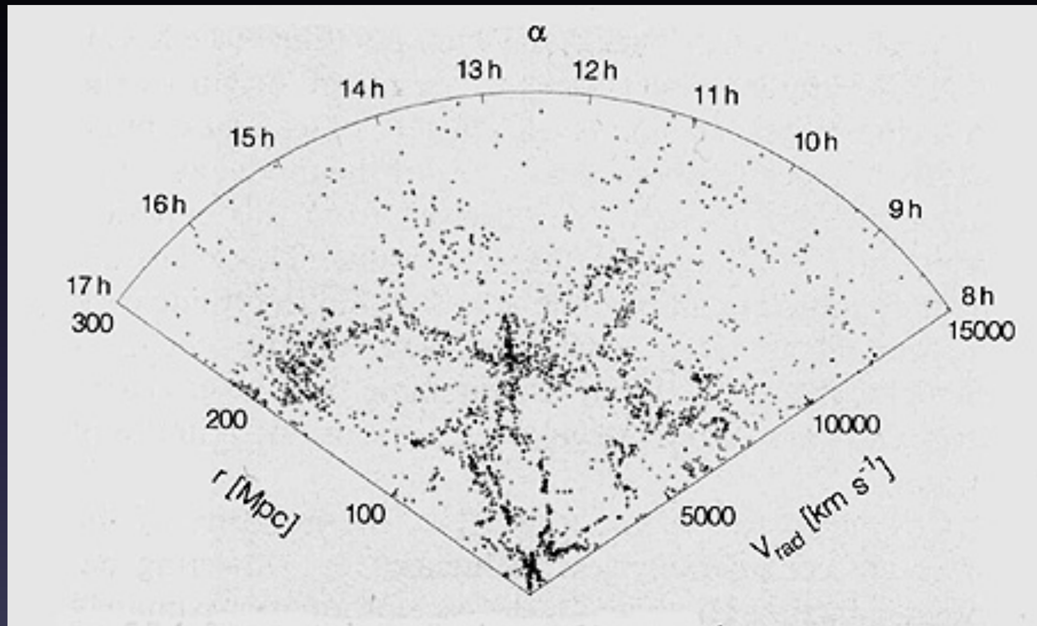
Universe is not homogeneous.

It shows some “holes”, but can be due to the nature of the magnitude-limited sample…

Galaxy redshift surveys:
Reconstructing the 3D structure of the Universe

The CfA survey revealed structures in the Universe, and the existence of the so-called "Great Wall", a supercluster of galaxies that extends over 170 h^{-1} Mpc

CfA: 2,400 redshifts
(~1989)
20% sky

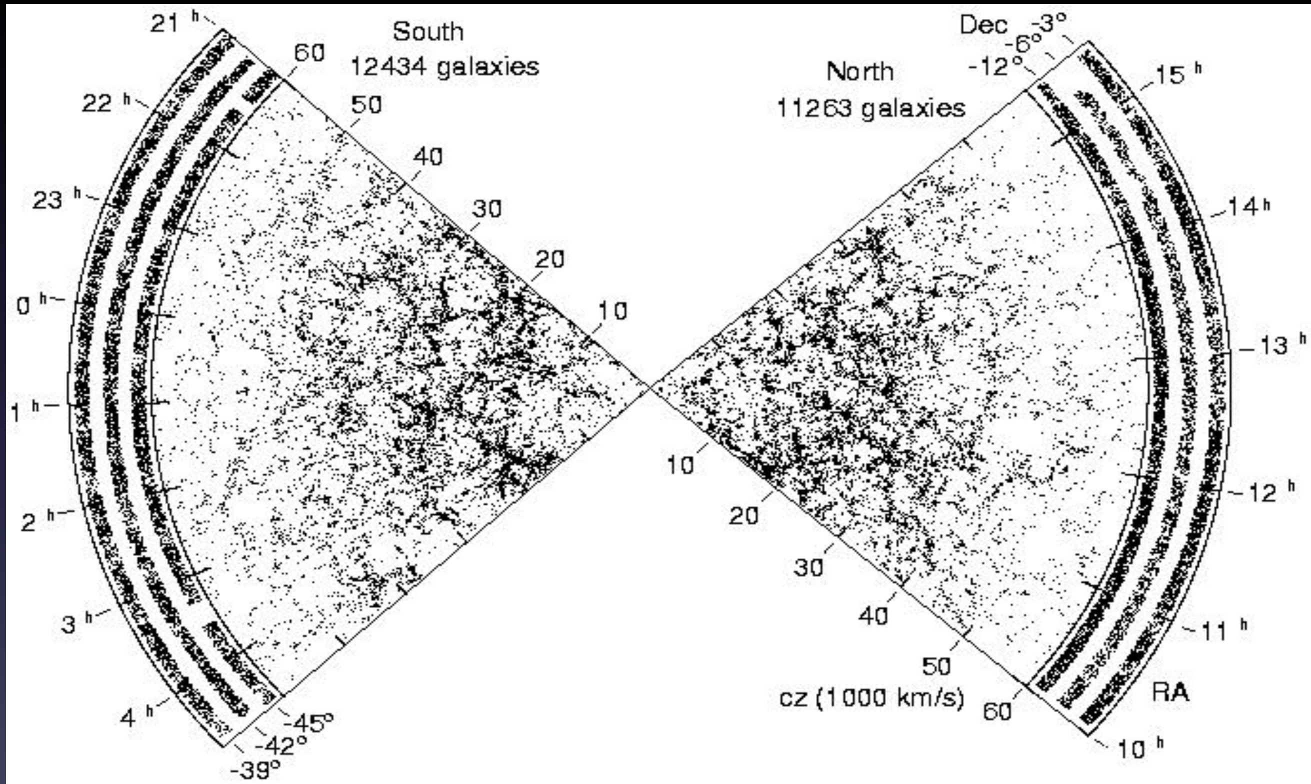


Geller et Huchra (1989), Science 246, 897.

Emptier (not empty!) regions from 10 to 100 Mpc/h:
Are these regions real voids?

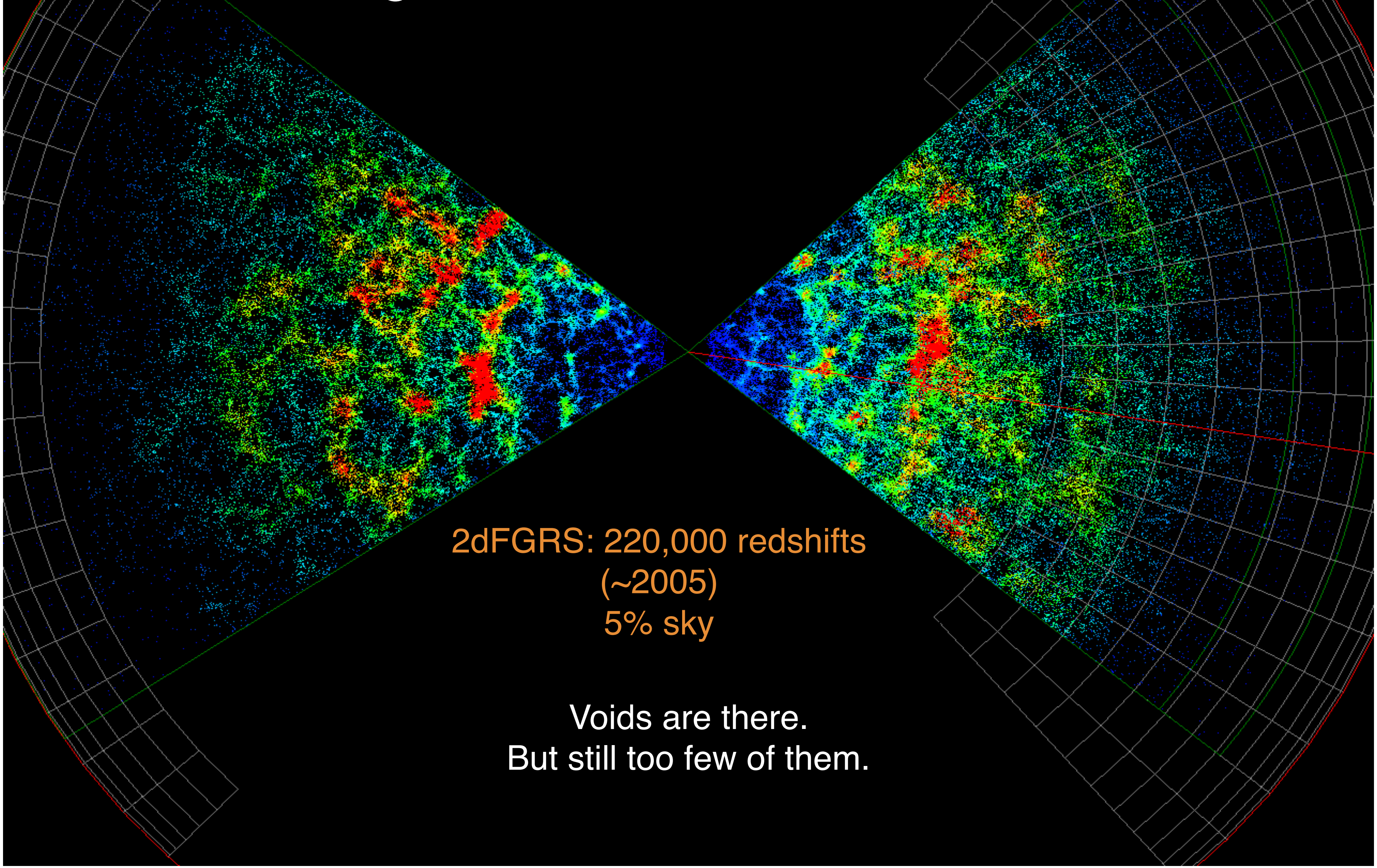
Galaxy redshift surveys:
Reconstructing the 3D structure of the Universe

Las Campanas Redshift Survey: 25,000 redshifts
(~1996)
2% sky



Voids are there.
But the survey must contain enough galaxies to accurately delineate the void walls.

Galaxy redshift surveys:
Reconstructing the 3D structure of the Universe

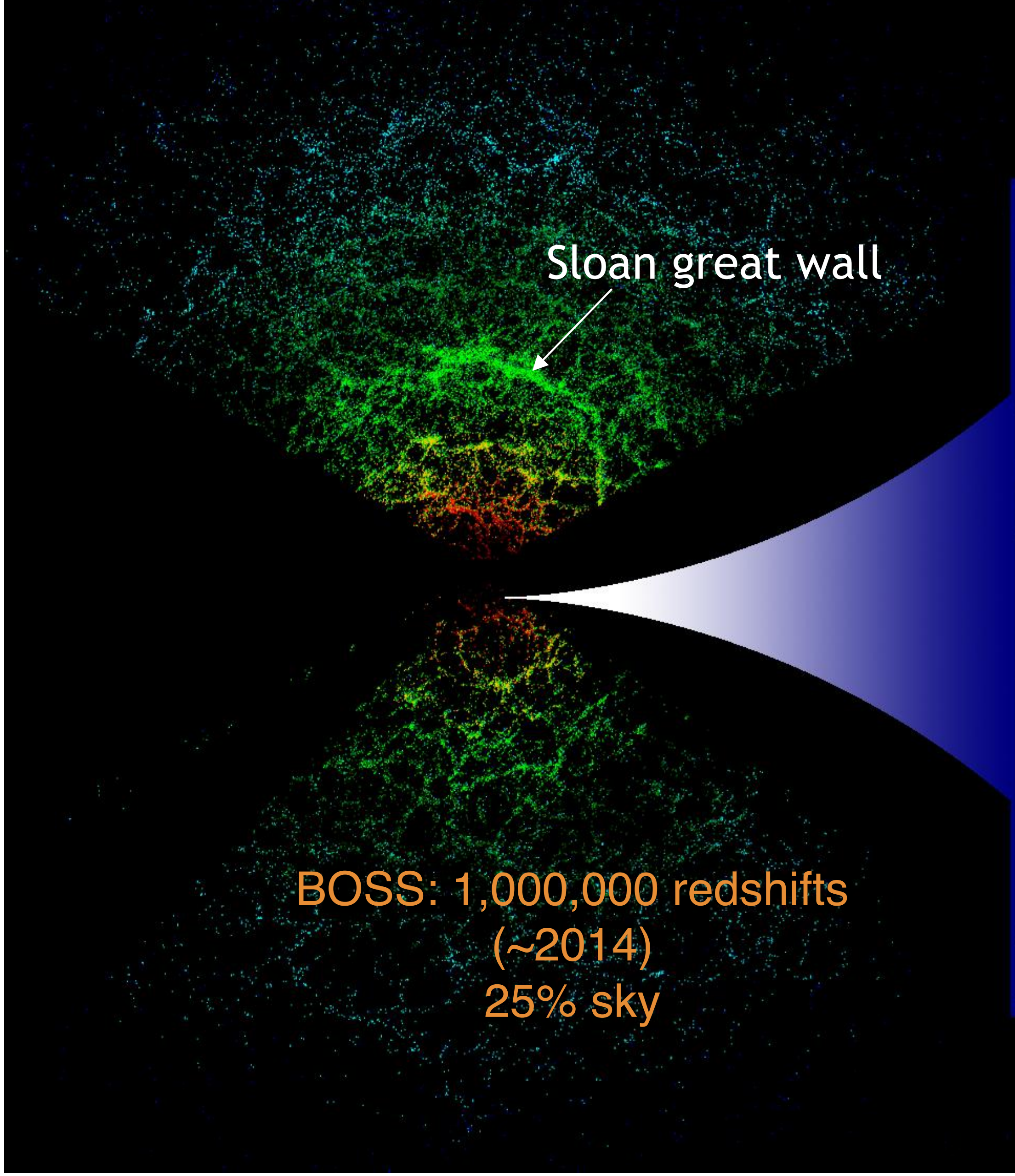


2dFGRS: 220,000 redshifts
(~2005)
5% sky

Voids are there.
But still too few of them.

Galaxy redshift surveys: Reconstructing the 3D structure of the Universe

SDSS et SDSS-II (2000-2008)



Voids are there.

And with galaxy surveys larger and larger, statistical approaches using voids become possible

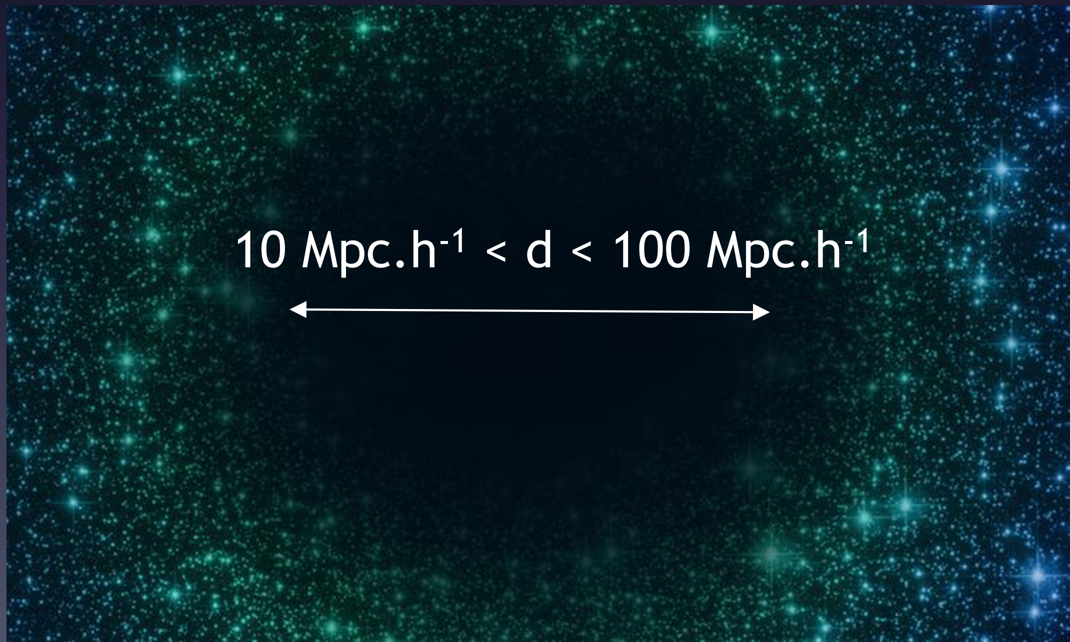
(Lavaux and Wandelt 2012):

a new era began for the study of cosmic voids

Credit: SDSS, NASA, DOE

Cosmic void

- Regions devoid of matter, in any case containing very few galaxies
- Typically have a density on the order of 1/10 of the average density of the Universe.
- Voids keep clusters of galaxies and filaments apart
- Voids account for 80% of the total volume of the observable Universe
- Have a diameter between 10 and 100 Mpc/h



Void finders

There are many definitions of cosmic voids, depending on the algorithm used to find them:

- Voronoi tesselation and watershed method (ZOBOV, VIDE) (Neyrinck 2008, Sutter 2015, Nadathur 2015)
- Growth of spherical underdensities (Padilla 2005, Micheletti 2014)
- Delaunay triangulation (DIVE) (Zhao 2016)
- …

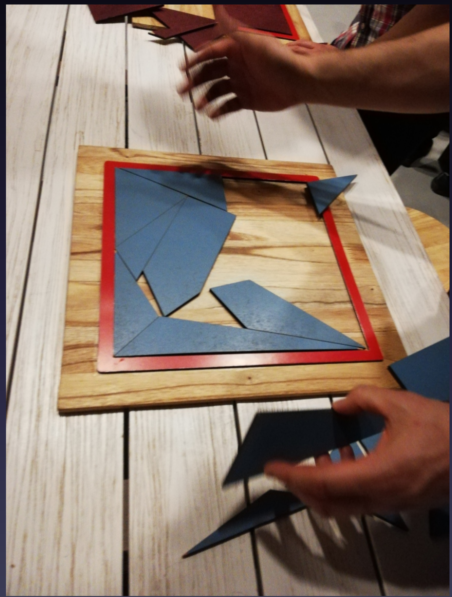
There is no right or wrong definition of voids. There are more sensitive definitions depending on the application.

Void finder : VIDE

VIDE Algorithm : Void IDentification and Examination (Sutter et al 2015)

Cosmic voids are defined from a galaxy catalog

Step 1: tesselation



Remember the visit of ExploraScience yesterday !

Not always an easy task !

Void finder : VIDE

VIDE Algorithm : Void IDentification and Examination (Sutter et al 2015)

Cosmic voids are defined from a galaxy catalog

Step 1: Voronoï tesselation

Paving into cells from a discrete set of points

Points = galaxies

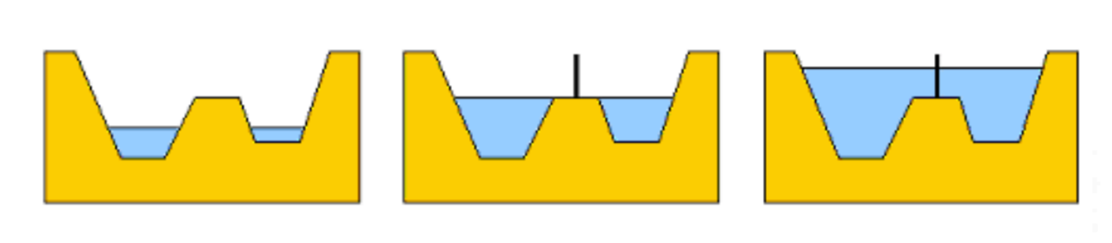
To each galaxy (cell) is associated a volume V_i, as well as a density:

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

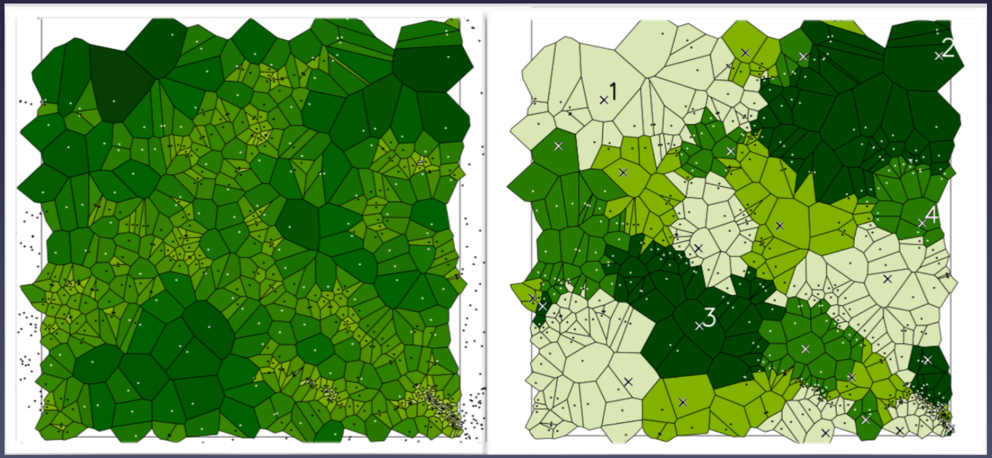
Void finder : VIDE

VIDE Algorithm : Void IDentification and Examination (Sutter et al 2015)

Step 2: Watershed transformation



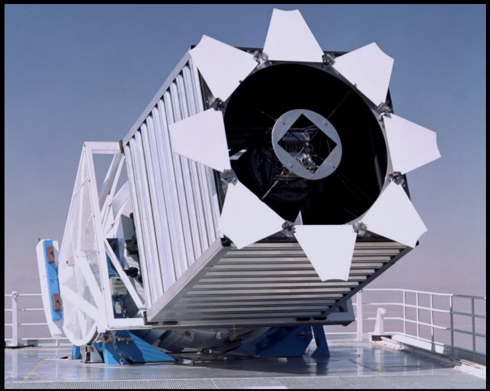
Basins are merged into a single void if the edge between them is the lower edge density.



Application to data

Baryon Oscillation Spectrscopic Survey (BOSS)
(Dawson et al. 2013)

2.5m Sloan telescope at APO in New Mexico, US

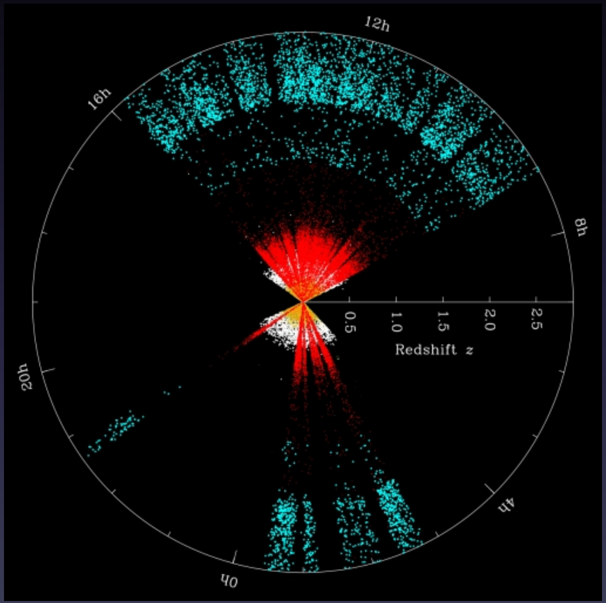


Operating: from 2010 to 2014

Area: 10 000 deg^2

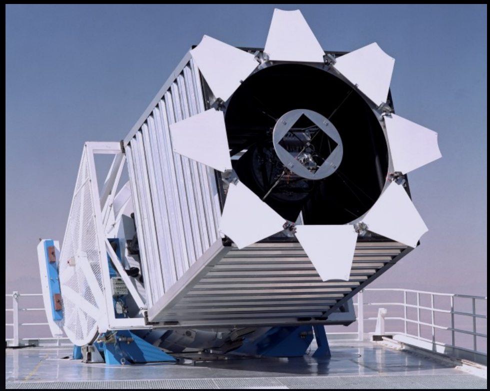
Redshift range: $0.15 < z < 0.7$
& $2 < z < 3.5$

Targets number: 1.35 million galaxies (LRG)
& 230 000 quasars Lyman-alpha



Void catalog

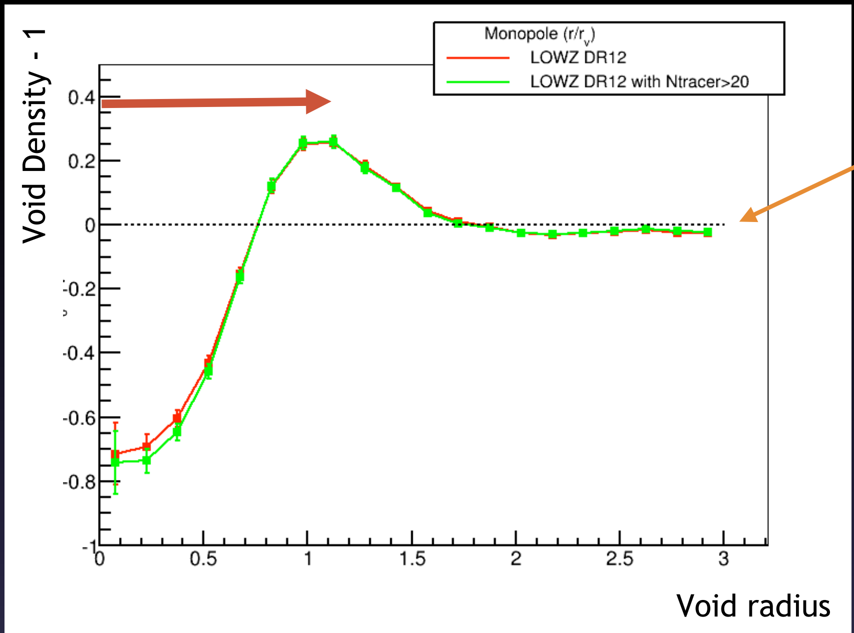
BOSS Final Data Release DR12 (Alam et al 2015):



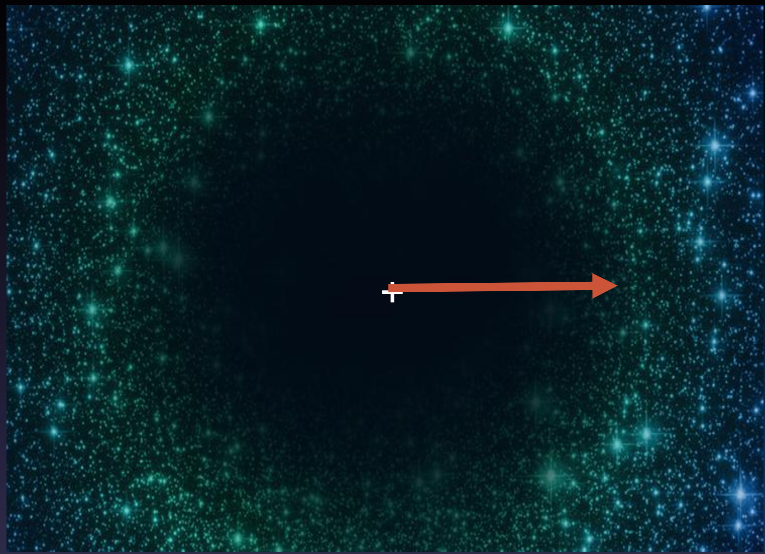
LOWZ	CMASS
$0.15 < z < 0.43$ $z_{eff} = 0.32$	$0.43 < z < 0.73$ $z_{eff} = 0.57$
361,762 galaxies	777,202 galaxies
1,448 voids	4,262 voids

Two-point statistics

Void density profile: $\xi_0^s(r)$



Average density of the Universe $\bar{\rho} - 1$



Void-galaxy cross-correlation function :

$$\xi_{vg}^s = \frac{D_v D_g - D_v R_g - D_g R_v + R_v R_g}{R_v R_g}$$

v/g: void/galaxy in the Data/Random catalog

Decomposition in Legendre polynomials:

$$\xi_\ell(s) \equiv \frac{2\ell+1}{2} \int_{-1}^{1} L_\ell(\mu) \xi(\mu, s)\, \mathrm{d}\mu,$$

Use of voids for cosmology

Some cosmological applications:

- BAO with voids (Kitaura 2016, Liang 2016)
- AP test (Mao 2016)
- RSD around voids (Hamaus 2016, Cai 2016)
- iSW effect using voids (Kovacs 2016, Nadathur 2016)
- Lensing on voids (Sanchez 2016)
- Void abundance (Pisani 2015)
- Neutrino mass (Kreish 2018)

As voids are nearly devoid of matter, they have proved to be very promising objects for exploring the imprint of possible modifications of GR

Cosmology with Cosmic voids

ALCOCK-PACZYNSKI TEST

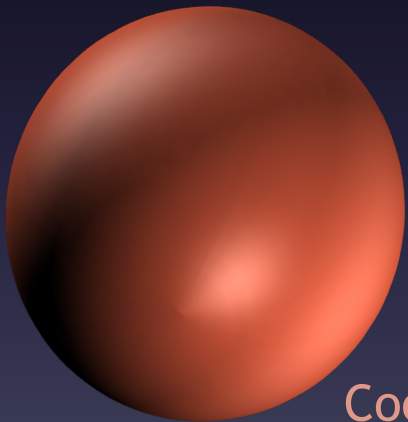
Principle

Cosmological test suggested by Alcock-Paczynski 1979

Assuming a symmetric object:

$$\Delta r_{\parallel} = \Delta r_{\perp}$$

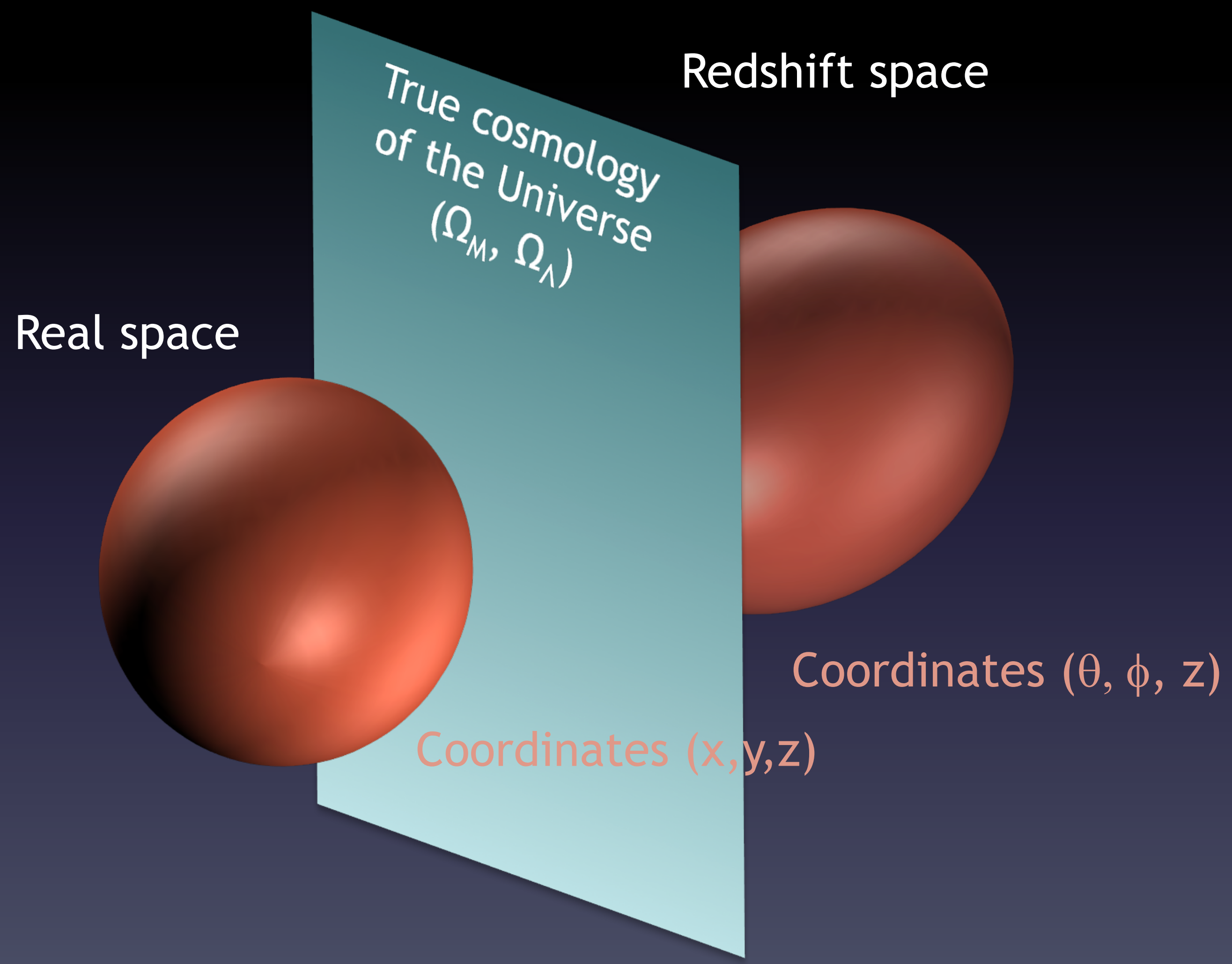
Real space



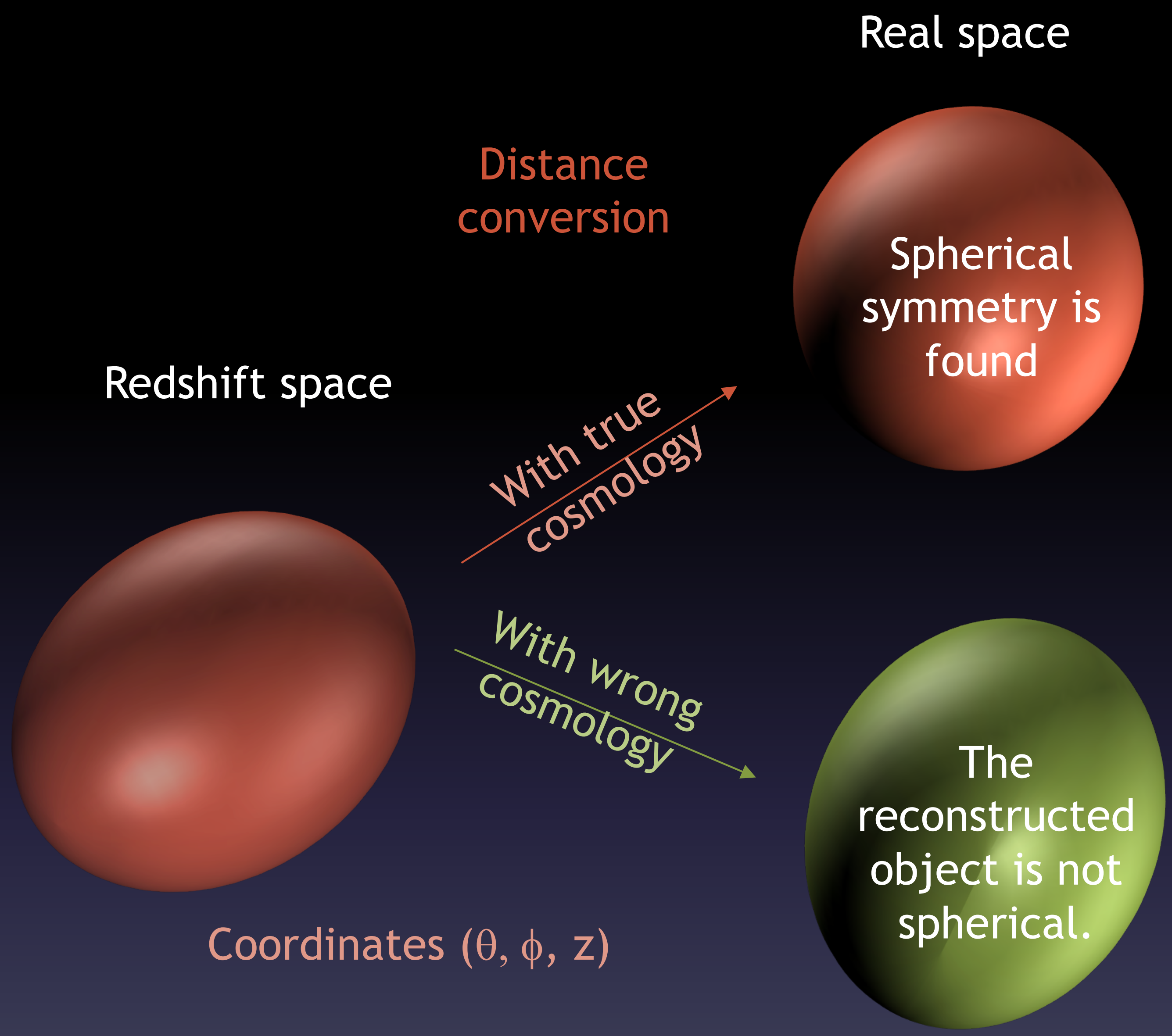
Coordinates (x,y,z)

Principle

Cosmological test suggested by Alcock-Paczynski 1979



Principle



The true cosmology is the one for which a "spherical" object is reconstructed "spherical"...

Mathematical formulation

Cosmological test suggested by Alcock-Paczynski 1979

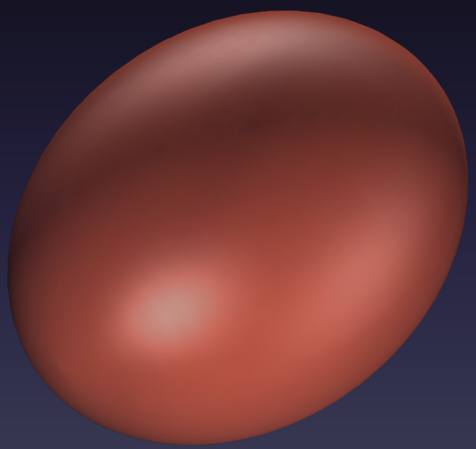
Object with size

$$\Delta r_{\perp} = D_A(z)\Delta\theta$$

$$\Delta r_{\parallel} = \frac{c\Delta z}{H(z)}$$

$D_A(z)$: angular diameter distance

$H(z)$: Hubble parameter



In case of a symmetric object, assuming:

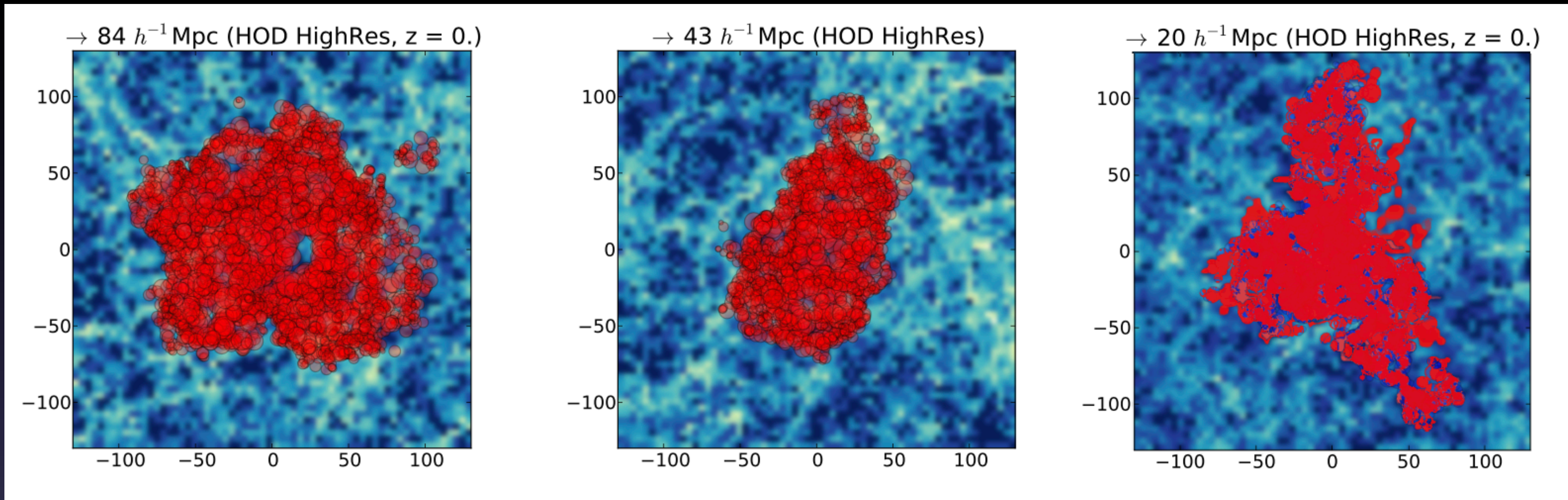
$$\Delta r_{\parallel} = \Delta r_{\perp}$$

gives :

$$\frac{c\Delta z}{\Delta\theta} = D_A(z)H(z)$$

Application to cosmic voids

Idea from Barbara Ryden : apply the AP test on voids (Ryden 1995)



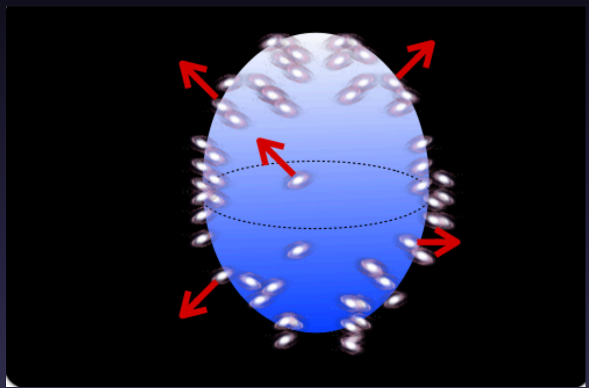
But the voids all have different shapes !!!!

And galaxy surveys in 1995 with not enough galaxies to well define voids

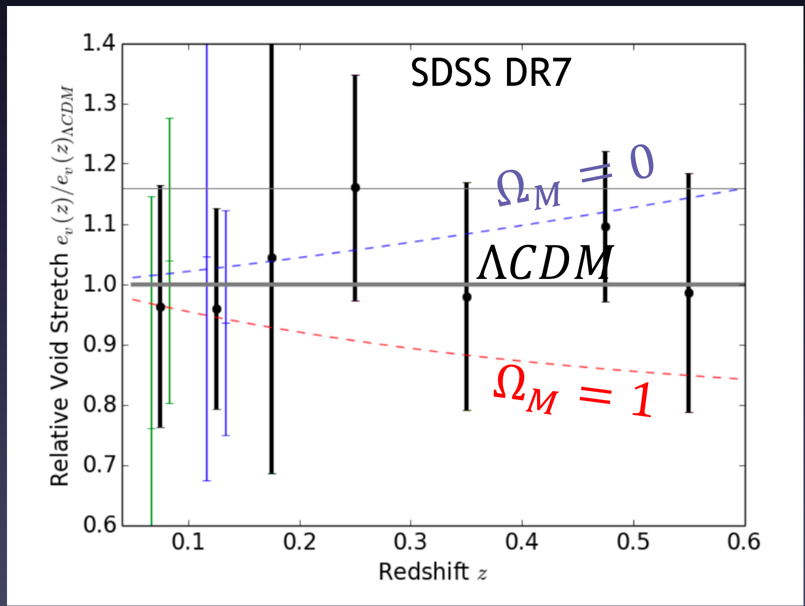
AP test on cosmic voids

With increasing large galaxy surveys, Lavaux and Wandel (2012) suggest to stack cosmic voids:

In line with the cosmological principle, in a homogeneous and isotropic Universe, voids must, on average, be spherical.



➔ AP test could be applied on cosmic voids



Sutter et al 2014

But we have to be sure that peculiar velocities do not affect AP measurement

Cosmology with Cosmic voids

REDSHIFT SPACE DISTORTIONS

Peculiar velocities

The measured redshift consists of 2 contributions

$$z = \frac{H_0 d}{c} + \frac{v}{c}\cos\theta$$

cosmological redshift
Hubble flow

Doppler redshift
Due to peculiar velocities in the LOS

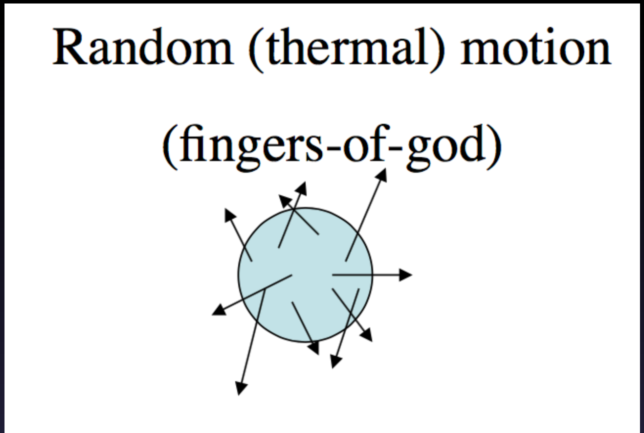
Peculiar velocities

There are two categories of redshift space distortions:

- Fingers of God (FoG):

  due to random motion within a cluster.
  Dominant effect at small scales (< 1 Mpc).

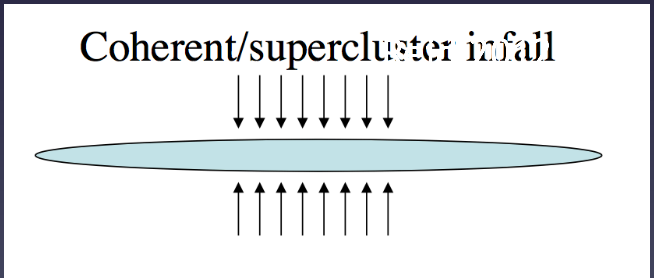
  ➔ elongation in redshift space along the line of sight within overdense regions.



- Kaiser effect :

  due to streaming motions of galaxies that are infalling onto structures that are still collapsing.
  On larger scales 5-20Mpc

  ➔ coherent motion which causes an apparent *contraction* of structure along the LOS.



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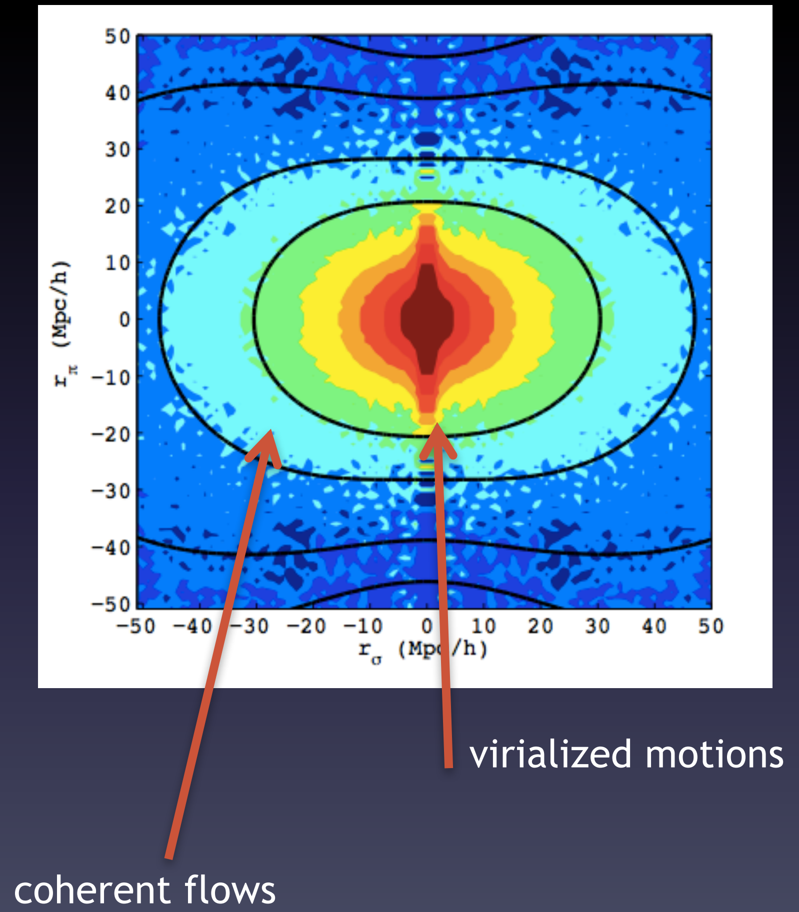
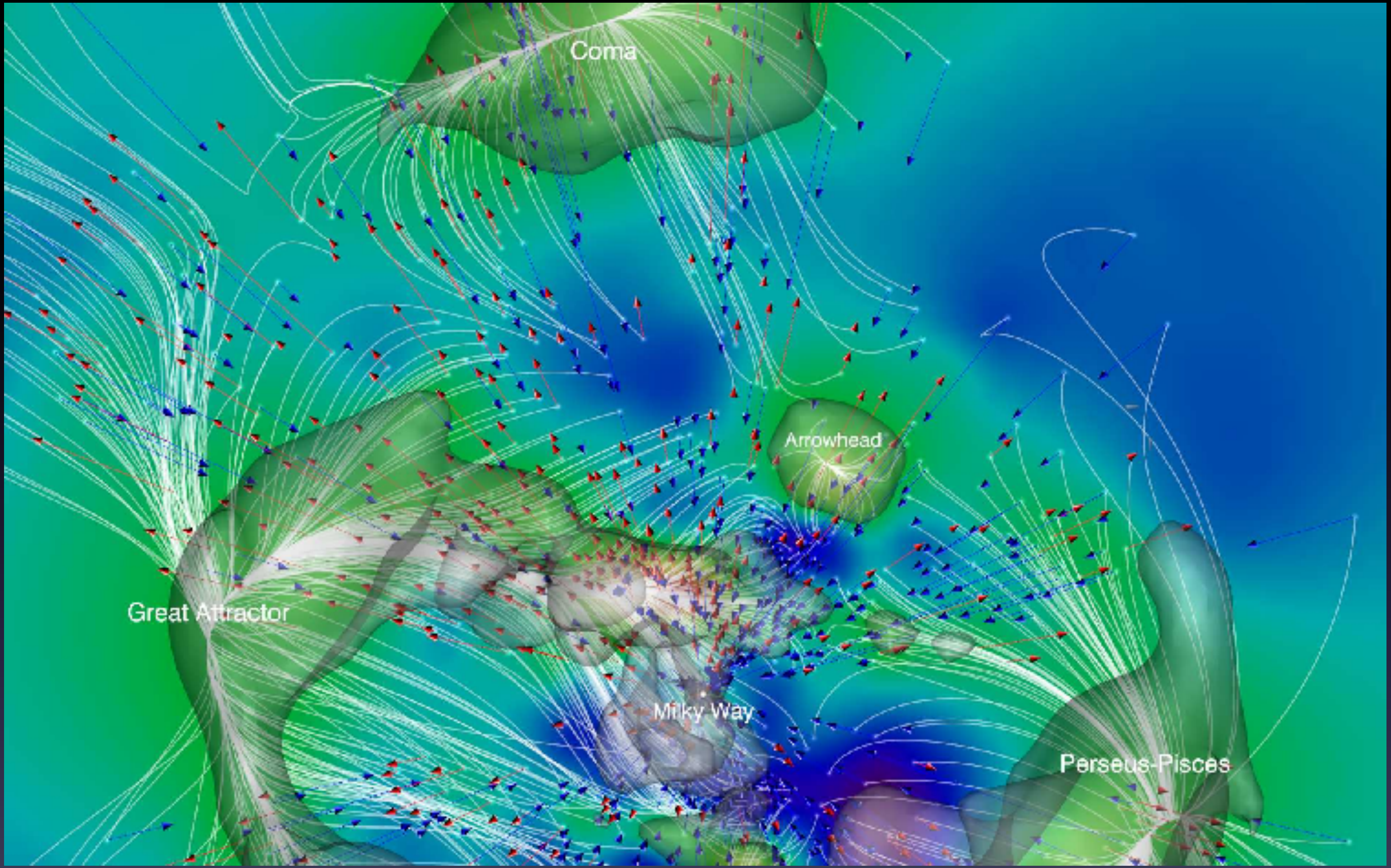
Reid 2012



Peculiar velocities



Tully et al Nature 2014

As the Kaiser effect is due to the gravitational infall of galaxies onto massive forming structures, it is sensitive to the growth of structure

Growth of structure using voids

Key test for confronting dark energy with modified gravity models

Growth of structure:

$$\beta = \frac{f}{b} = \frac{\Omega_m(z)^\gamma}{b}$$

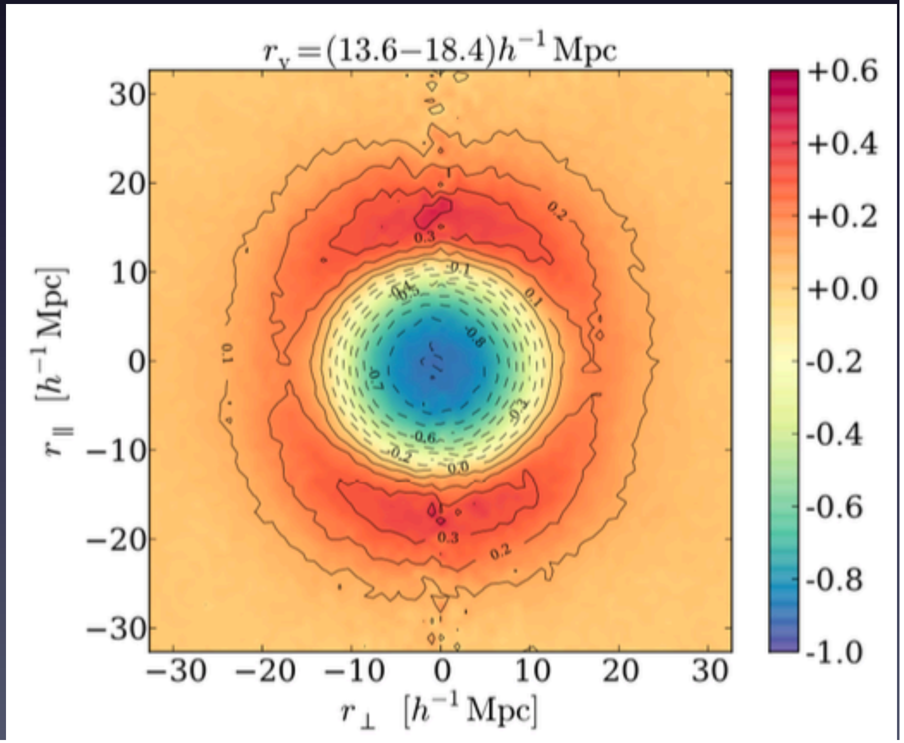
f: linear growth rate of density perturbations
b: galaxy biais

GR predicts γ = 0.55

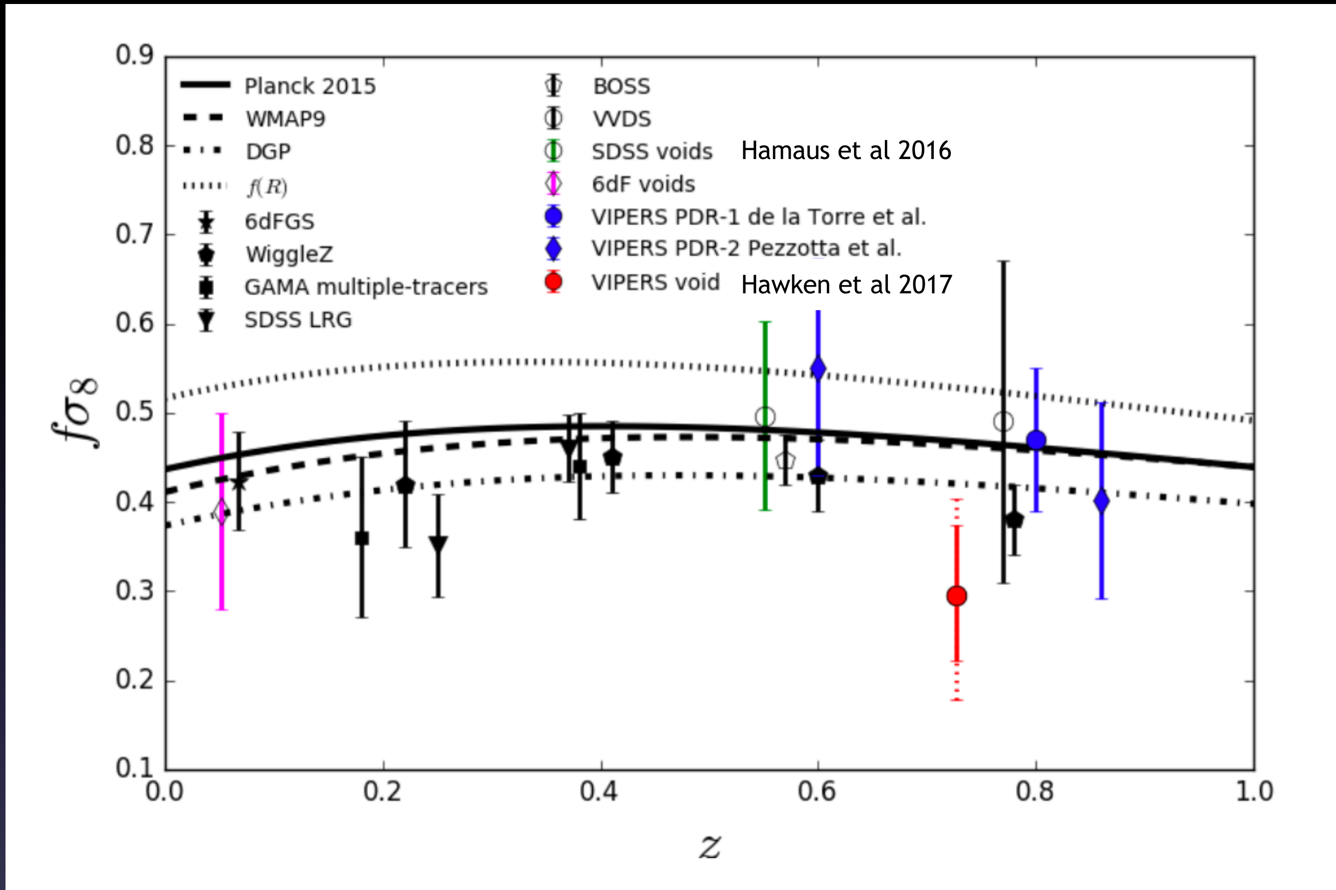
➔ any deviation from this value would be a deviation from GR

It is expected that the gravitational dynamics of galaxies around voids remain in the linear regime (Gaussian streaming model)

Hamaus et al. 2015



Growth of structure using voids



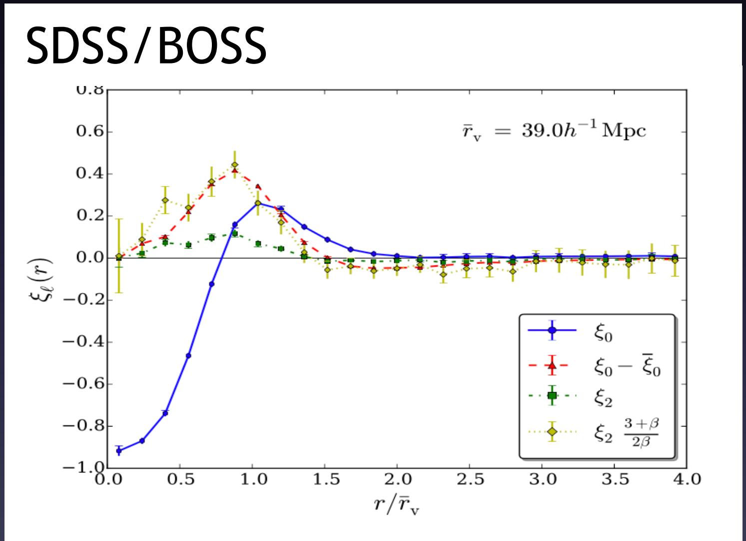
Hawken et al. 2017

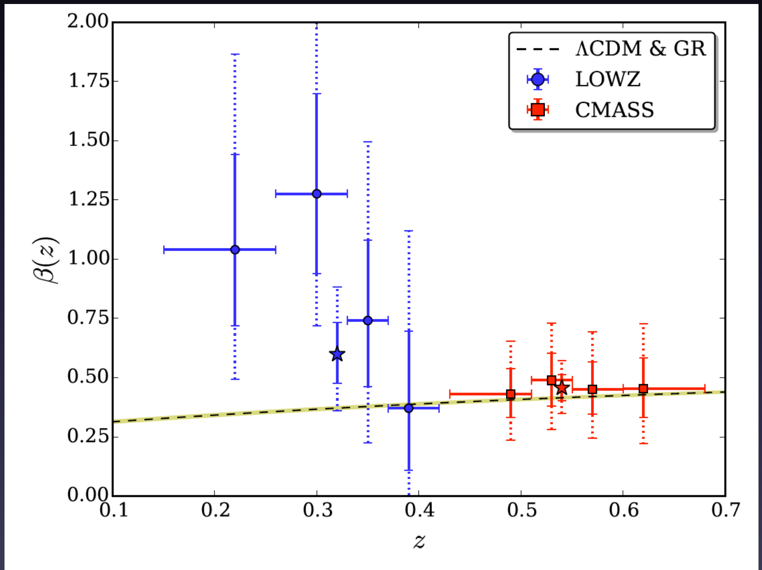
Complimentary growth rate measurements with cosmic voids compared to conventional galaxy clustering techniques

Growth of structure using voids

Estimator of the growth rate using moments of the correlation function:

$$\hat{G}(f) = \frac{\xi_2^s(r)}{\xi_0^s(r) - \frac{3}{r^3 \int_0^r \xi_0^s(r') r'^2 dr'}} = \frac{2f}{3+f}$$ (Cai et al 2016)





Hamaus et al. 2017

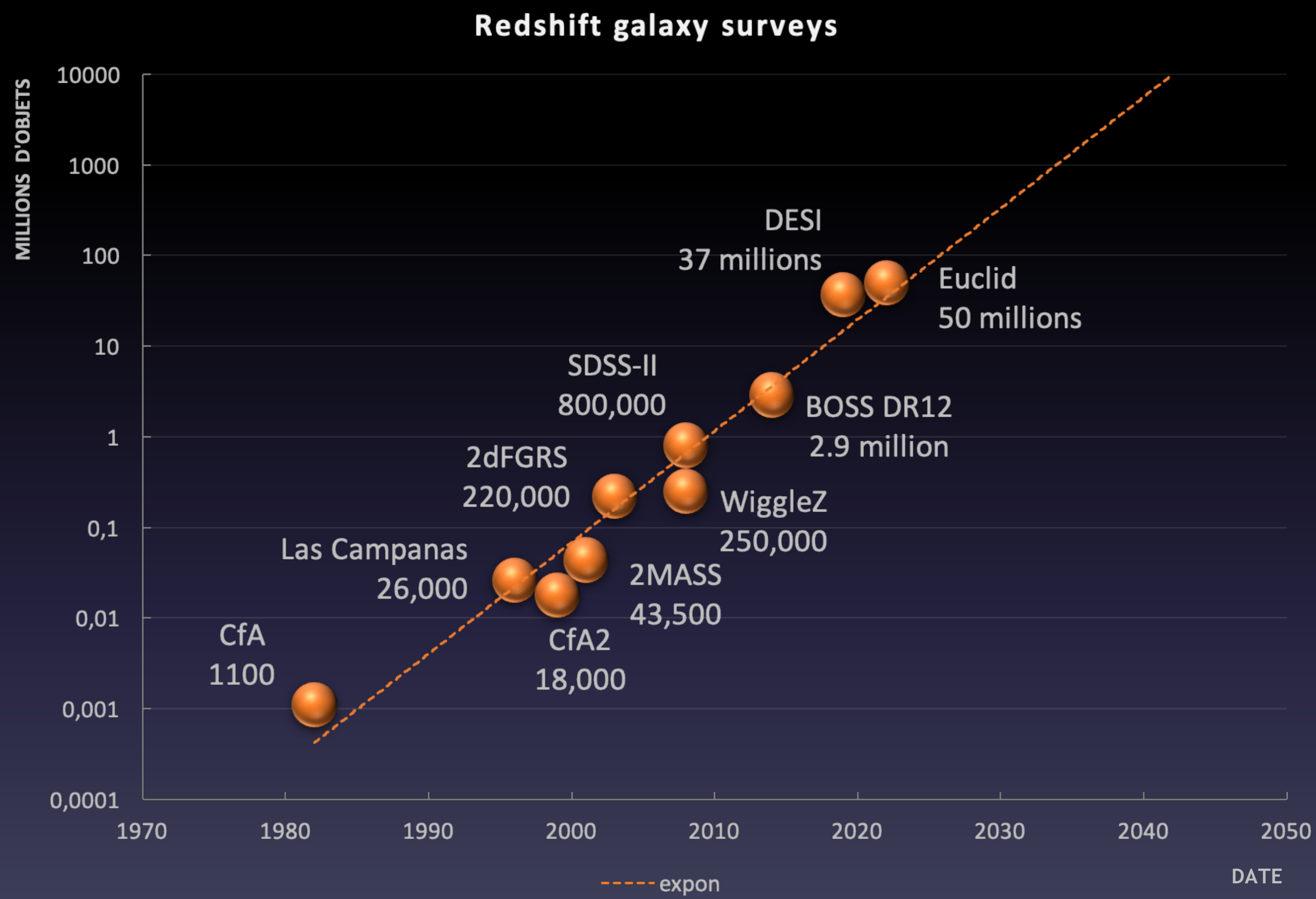
Large statistical error

➔ Need incoming massive spectroscopic galaxy surveys

Perspectives and conclusion

INCOMING & FUTURE SURVEYS

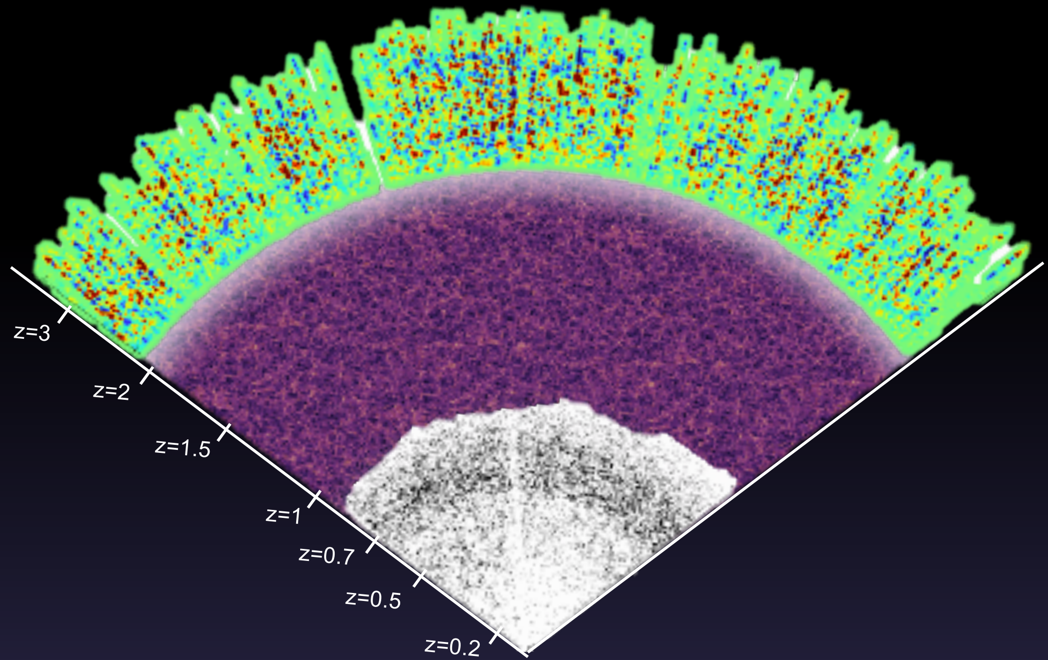
Redshift galaxy surveys

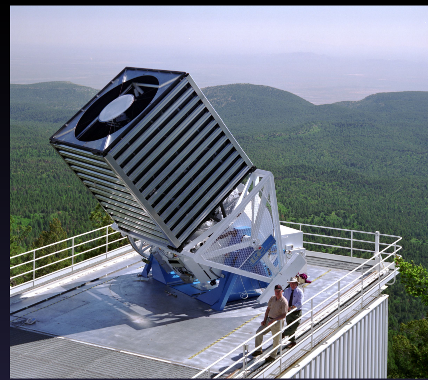


Redshift surveys increasing 10X every 10 years


Mayall 4-meter Telescope
Kitt Peak, AZ
DESI
Dark Energy Spectroscopic Instrument

The next generation is DESI
The next generation after SDSS/BOSS





3-D map of 35 million galaxies (DESI)

3-D map of 1.5 million galaxies (BOSS)

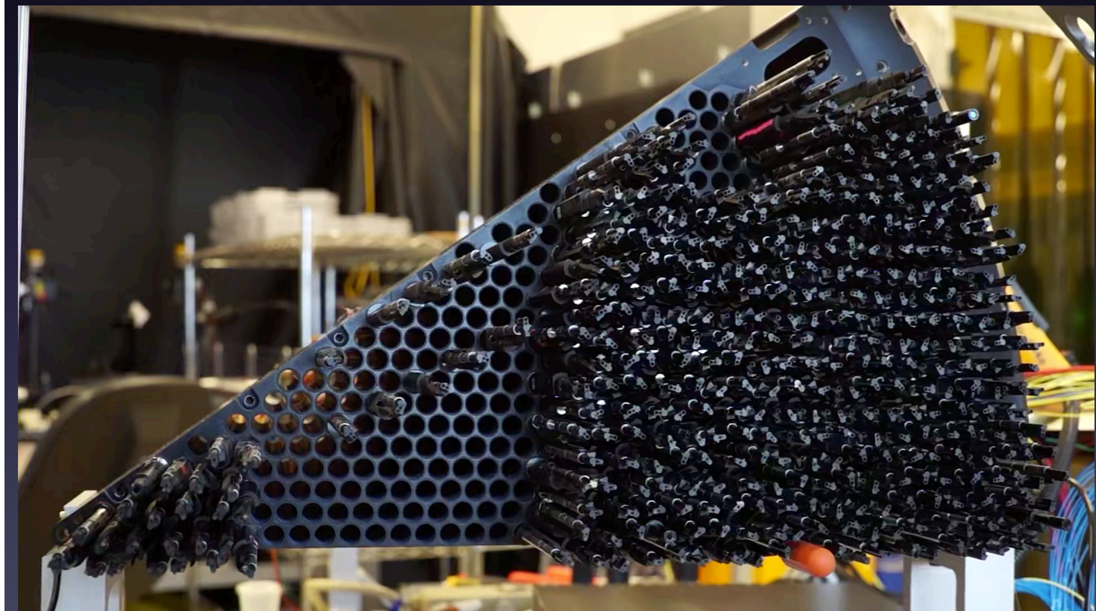
Target	Number of objects	Redshift range
Bright Galaxies (BG)	10 million	z = 0.05-0.4
Luminous Red Galaxies (LRG)	7.7 million	z = 0.4-1.0
Emission Line Galaxies (ELG)	17 million	z = 0.6-1.6
Tracer QSOs	1.7 million	z < 2.1
Ly-α QSOs	0.7 million	z > 2.1

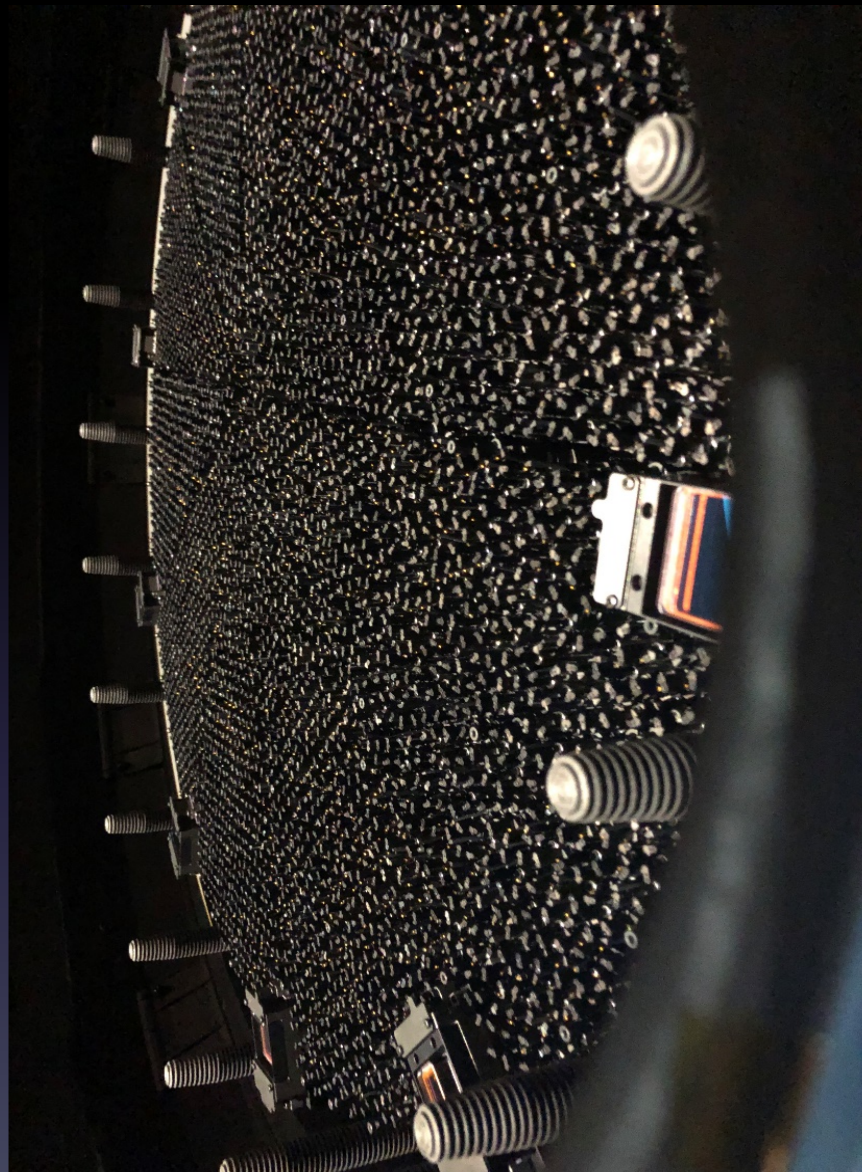
DESI will start the next leap in redshift surveys

Focal plane

Focal plane: ten petals with a total of 5000 fibers

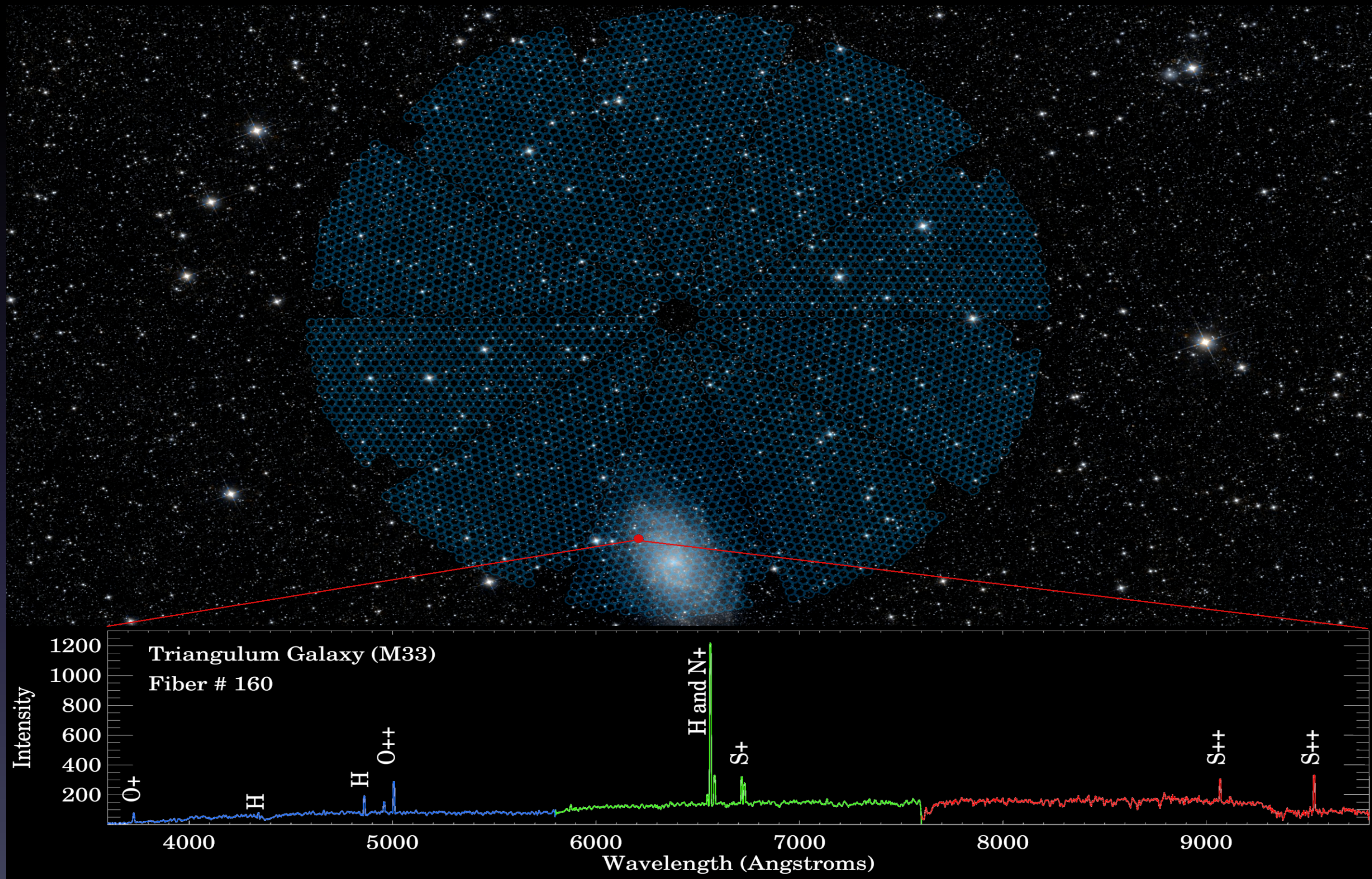
Robot positioners





Commissioning (Oct 2019 – Mar 2020)

Qualifying the spectroscopic instrument



DESI will start the 5-year survey in June 2020

The Euclid space mission

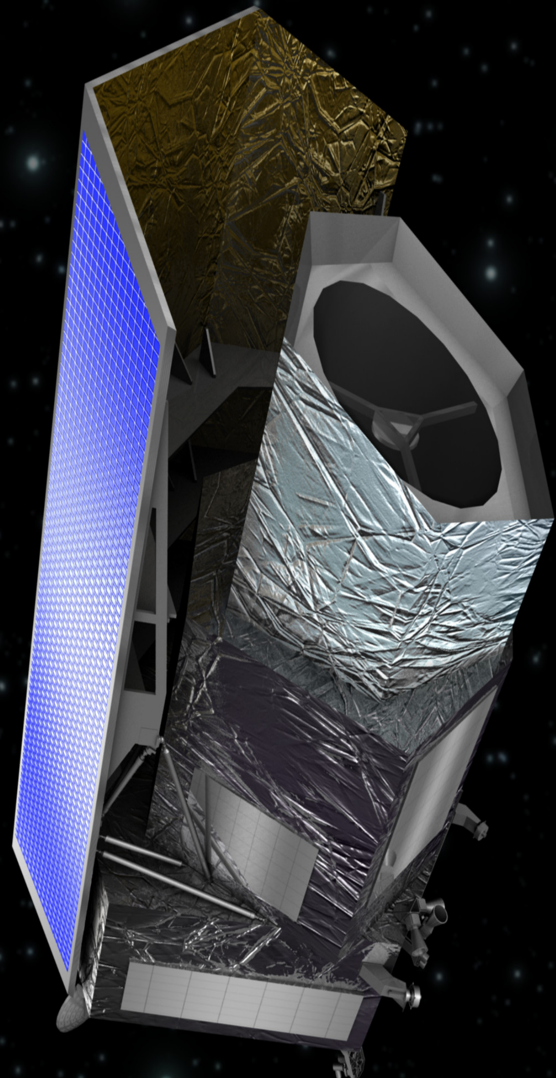
1.2 m telescope
Visible & infrared imaging
Infrared slitless spectroscopy

ΛCDM model ?

Modified gravity ?

- 15,000 deg^2 survey
- Spectra for 50 millions galaxies
- Images for 2 billion galaxies

>100,000 cosmic voids expected



European Space Agency (ESA) mission with launch in June 2022
for 6-year period.

Conclusion

- Cosmic voids are under-dense regions that account for 80% of the Universe.
- Promising cosmological probe to test gravity.
- Imminent massive influx of cosmological data soon available (DESI, Euclid, LSST) will increase the number of voids by at least one order of magnitude

Thank you for your attention