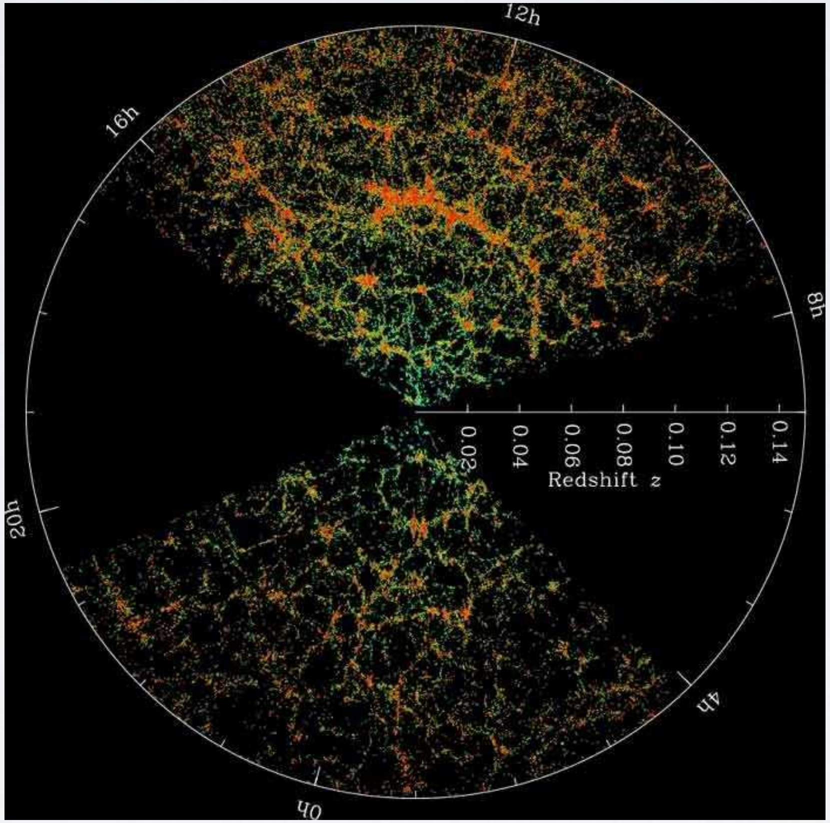
Camille Bonvin



Credit: M. Blanton, SDSS

CERN theory retreat, les Houches
November 2015

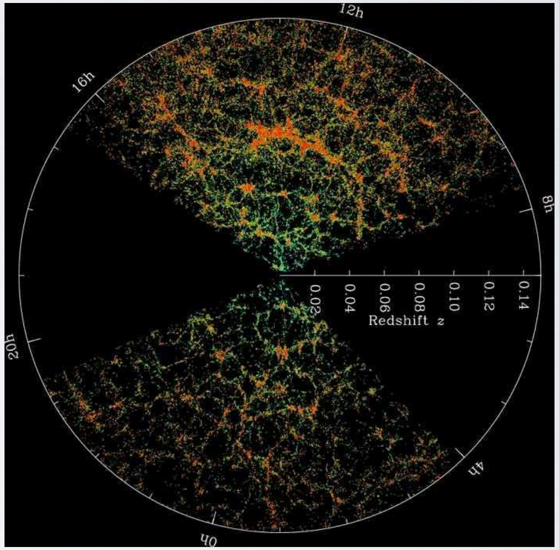
Large-scale structure

I am interested in the **large-scale structure** of the universe and its use to test **gravity** and **dark energy**.

Observationally:

- Measure of the **positions** of galaxies

  → 3D map



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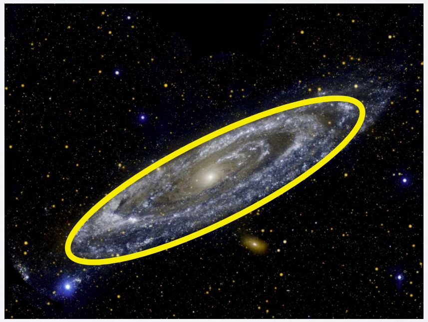
- Measure of the **shape** and **size**



Link with theory

From 3D maps we extract: $\Delta = \frac{N - \bar{N}}{\bar{N}}$ N number of galaxies

We relate it to fluctuations in the **dark matter** distribution

$$\Delta = \frac{\delta\rho}{\bar{\rho}}$$

We need to account for the fact that we observe in **redshift space**: Doppler shift Kaiser 1987

By measuring Δ we are sensitive to:

- the **growth** of fluctuations: test of gravity and dark energy
- the **velocity**: test Einstein's equations

Link with theory

From 3D maps we extract: $\Delta = \frac{N - \bar{N}}{\bar{N}}$ $\quad N$ number of galaxies

We relate it to fluctuations in the **dark matter** distribution

$$\Delta = \frac{\delta\rho}{\bar{\rho}} - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})$$

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By measuring Δ we are sensitive to:

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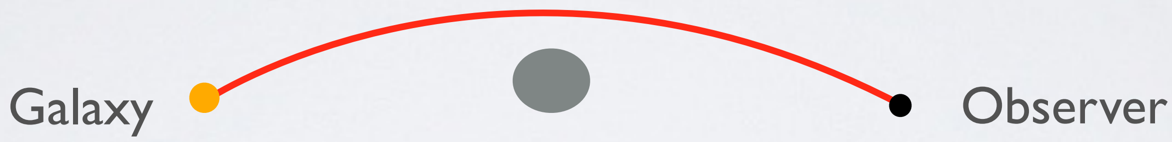
Link with theory

From the size and shape of galaxies we measure **gravitational lensing**.

Inhomogeneities along the trajectory bent the geodesic



This amplifies the **size** of galaxies and generate additional **ellipticity**.

The distortions are sensitive to: $$\int_0^{r_s} dr \frac{r_s - r}{2 r r_s} \Delta_\Omega (\Phi + \Psi)$$

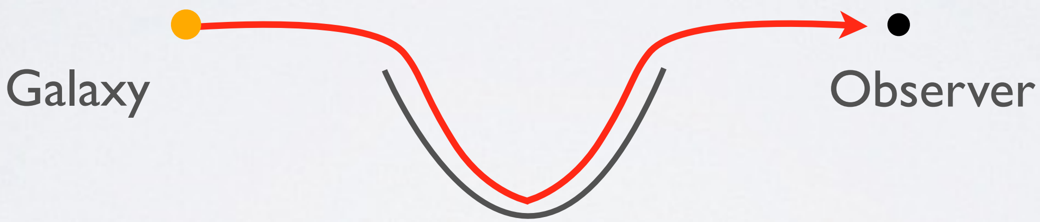
We can test gravity by comparing **potentials** with **density**.

All observations are compatible with **LCDM**.

Beyond Newtonian approximations

Current expressions for Δ and lensing are based on **Newtonian approximations**.

Our observations are affected by **relativistic effects**.



- Change the length of the geodesic: Shapiro time delay
- Change the energy of the photons: redshift

Systematic calculation of our observables in the framework of **General Relativity**.

Result

Yoo et al (2010)
CB and Durrer (2011)
Challinor and Lewis (2011)

density — redshift space distortion — lensing — Doppler — gravitational redshift

$$\Delta(z,\mathbf{n}) = b\cdot\delta - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})$$
$$- \int_0^r dr'\frac{r-r'}{rr'}\Delta_\Omega(\Phi+\Psi)$$
$$+\left(1-\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}-\frac{2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\partial_r\Psi$$
$$+\Psi-2\Phi+\frac{1}{\mathcal{H}}\dot{\Phi}-3\frac{\mathcal{H}}{k}V+\frac{2}{r}\int_0^r dr'(\Phi+\Psi)$$
$$+\left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{2}{r\mathcal{H}}\right)\left[\Psi+\int_0^r dr'(\dot{\Phi}+\dot{\Psi})\right]$$

→ potential

Neglecting magnification bias and evolution bias

Result

CB 2008
CB, Andrianomena, Bacon, Clarkson, Maartens and Bull in preparation

The convergence κ is a measurement of the observed size of galaxies

Gravitational lensing

Doppler lensing

$$\kappa = \frac{1}{2r}\int_0^r dr' \frac{r-r'}{r'}\Delta_\Omega(\Phi+\Psi) + \left(\frac{1}{r\mathcal{H}}-1\right)\mathbf{V}\cdot\mathbf{n}$$
$$-\frac{1}{r}\int_0^r dr'(\Phi+\Psi) + \left(1-\frac{1}{r\mathcal{H}}\right)\int_0^r dr'(\dot\Phi+\dot\Psi)$$
$$+\left(1-\frac{1}{r\mathcal{H}}\right)\Psi+\Phi$$

Integrated terms

Sachs Wolfe

Isolating the relativistic effects

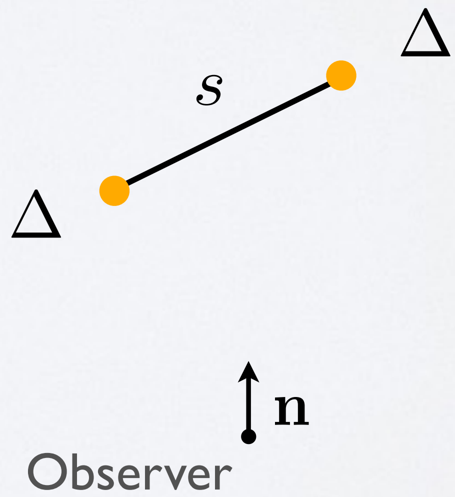
I am constructing new observables to **isolate** the relativistic effects: CB, Hui and Gaztanaga (2013)

- There are **subdominant** with respect to the Newtonian terms.
- We want to use them to test the **consistency** of General Relativity.

We can look at the two-point correlation function:

Dark matter fluctuations

→ isotropy



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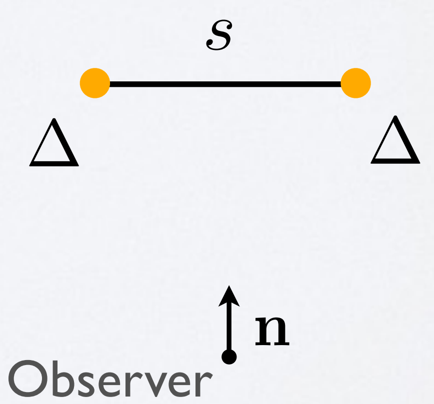

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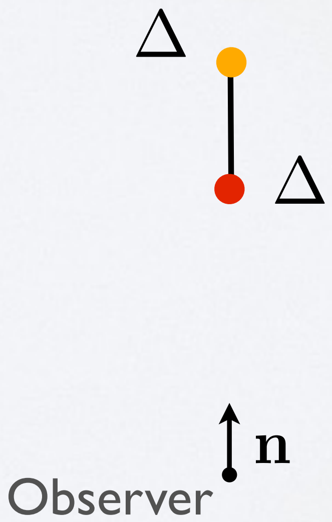

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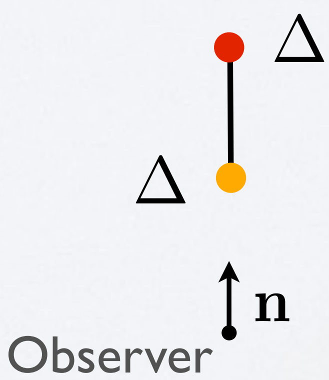

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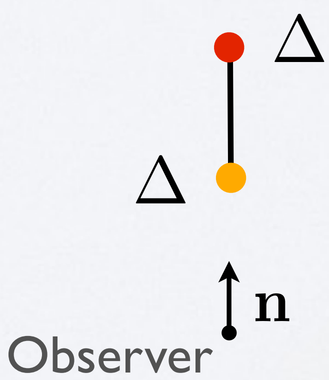
- There are **subdominant** with respect to the Newtonian terms.

> Which new tests of gravity can we do with the relativistic effects?

Relativistic effects

→ breaking of symmetry

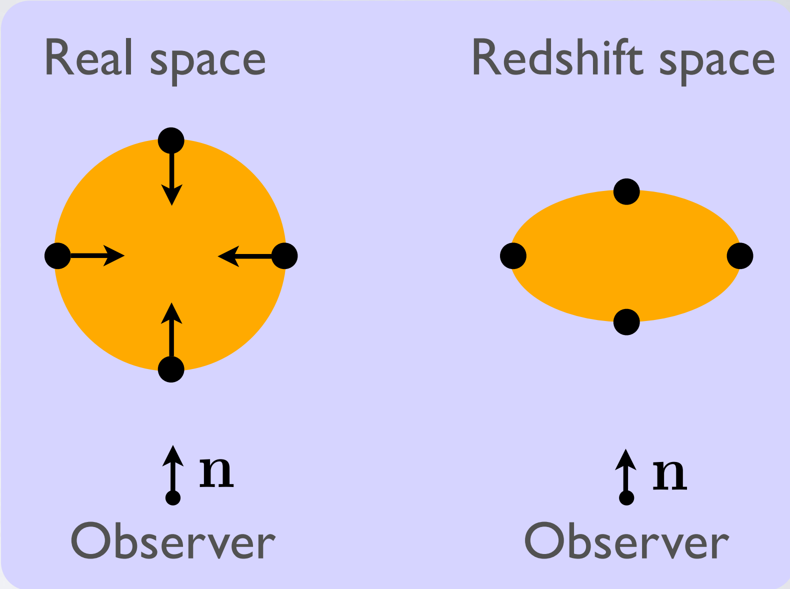


Backup

Redshift distortions

Redshift distortions **break the isotropy** of the correlation function.

$$\Delta = b \cdot \delta - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})$$



They generate a **quadrupole** and an **hexadecapole** Lilje and Efstathiou (1989), McGill (1990), Hamilton (1992)

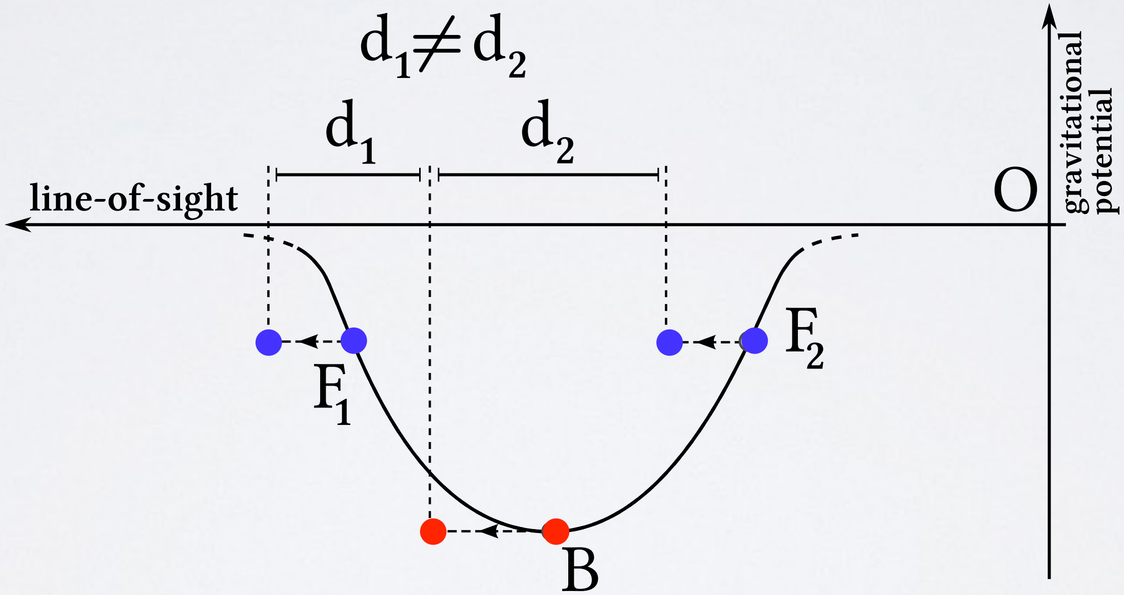
$$\xi_2 = -\left(\frac{4bf}{3}+\frac{4f^2}{7}\right)\frac{1}{2\pi^2}\int dk k^2 P(k,z) j_2(k\cdot d)\, P_2(\cos\beta)$$

$$\xi_4 = \frac{8f^2}{35}\frac{1}{2\pi^2}\int dk k^2 P(k,z) j_4(k\cdot d)\, P_4(\cos\beta)$$

Cross-correlation

The following terms **break** the **symmetry**:

$$\Delta_{\rm rel} = \left(1 - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - \frac{2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n} + \frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n} + \frac{1}{\mathcal{H}}\partial_r\Psi$$

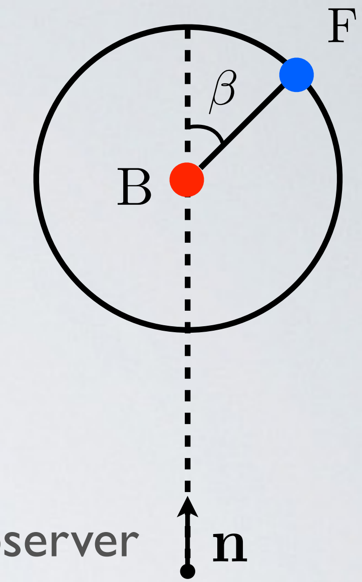


Similar to measurements of gravitational redshift in **clusters**.

Wojtak, Hansen and Hjorth (2011), Sadeh, Feng and Lahav (2015)

Dipole in the correlation function

CB, Hui and Gaztanaga (2013)



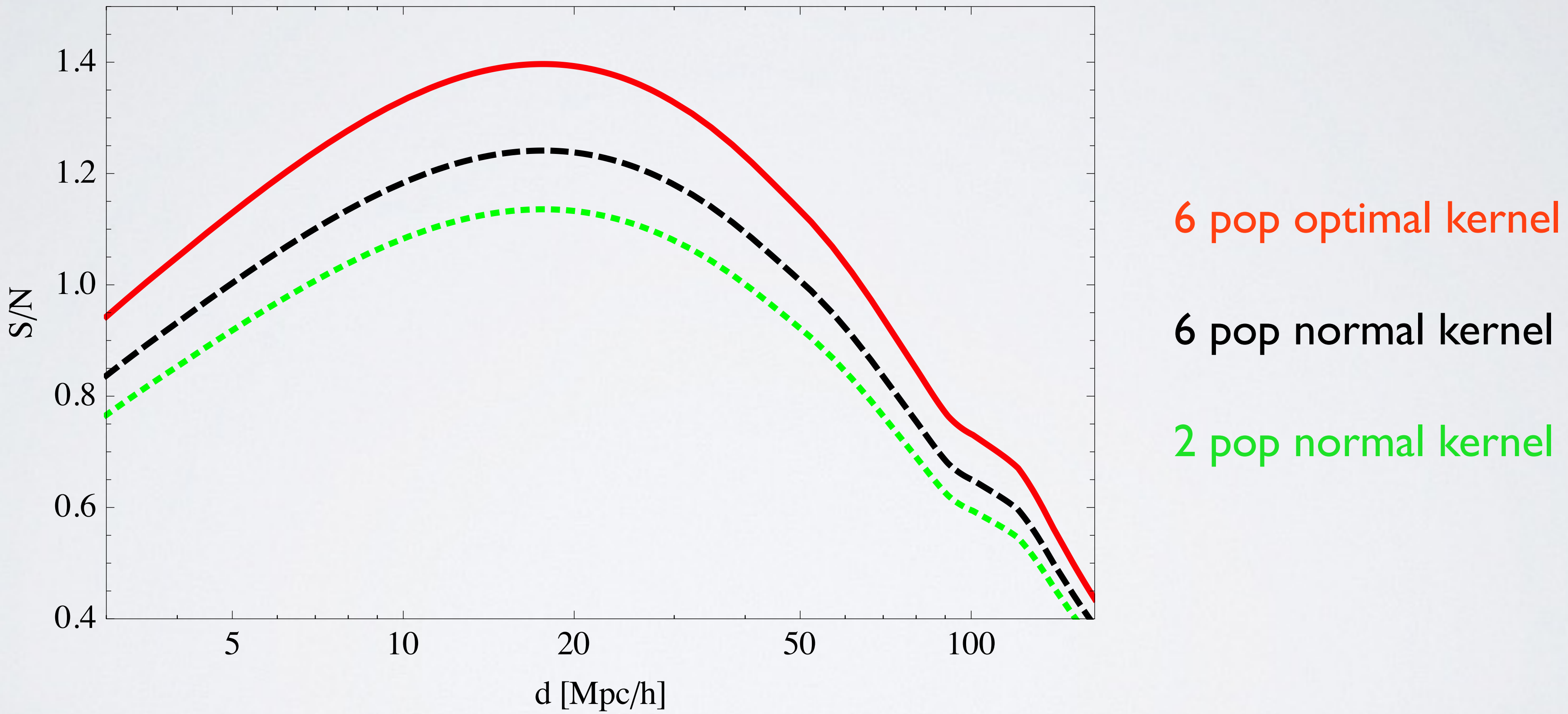
$$\xi(d,\beta) = D_1^2\, f \frac{\mathcal{H}}{\mathcal{H}_0}\left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r\mathcal{H}}\right)(b_{\rm B} - b_{\rm F})\nu_1(d)\cdot\cos(\beta)$$

$$\nu_1(d) = \frac{A}{2\pi^2}\int \frac{dk}{k}\left(\frac{k}{H_0}\right)^{n_s-1} T_\delta(k)T_\Psi(k)\, j_1(k\cdot d)$$

By fitting for a **dipole** in the correlation function, we **isolate** the relativistic effects. We get rid of the dominant monopole and quadrupole generated by density and velocities.

Result SDSS DR5

Measurement of the bias and the number density for **6 populations** with different luminosities Percival et al (2007)



Using the optimal kernel **increases** the signal-to-noise by **23 percents**.

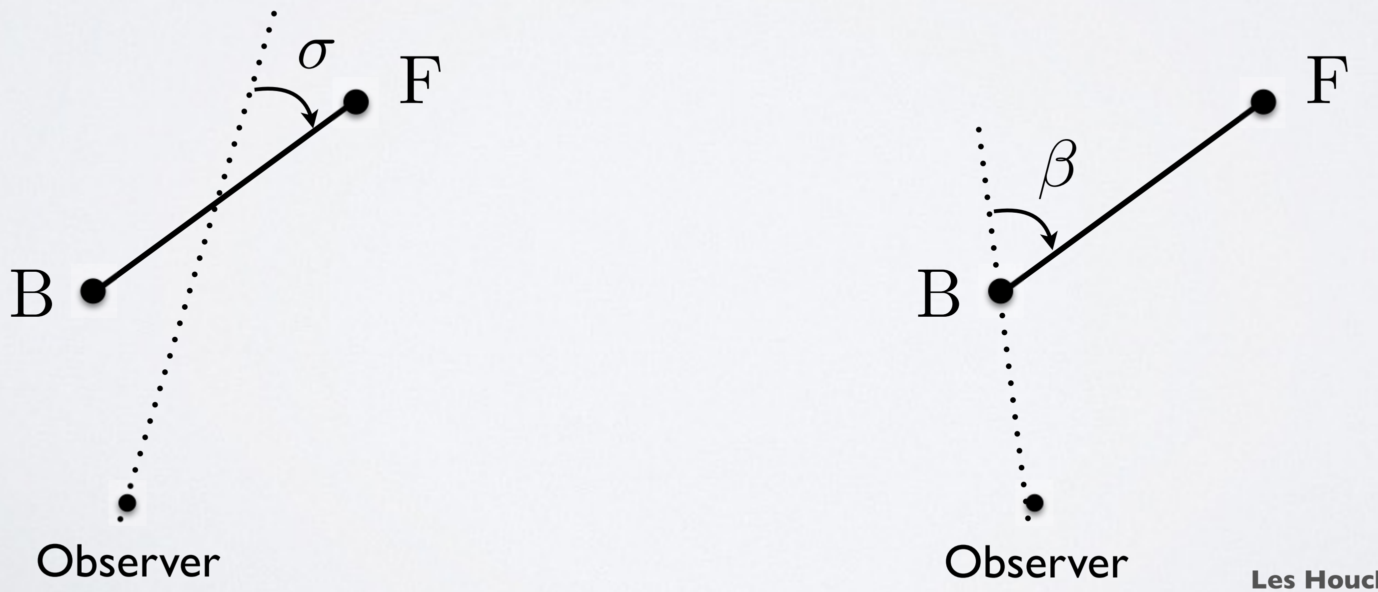
Measurements with BOSS

Two samples: LOWz $z = 0.32$ and CMASS $z = 0.57$

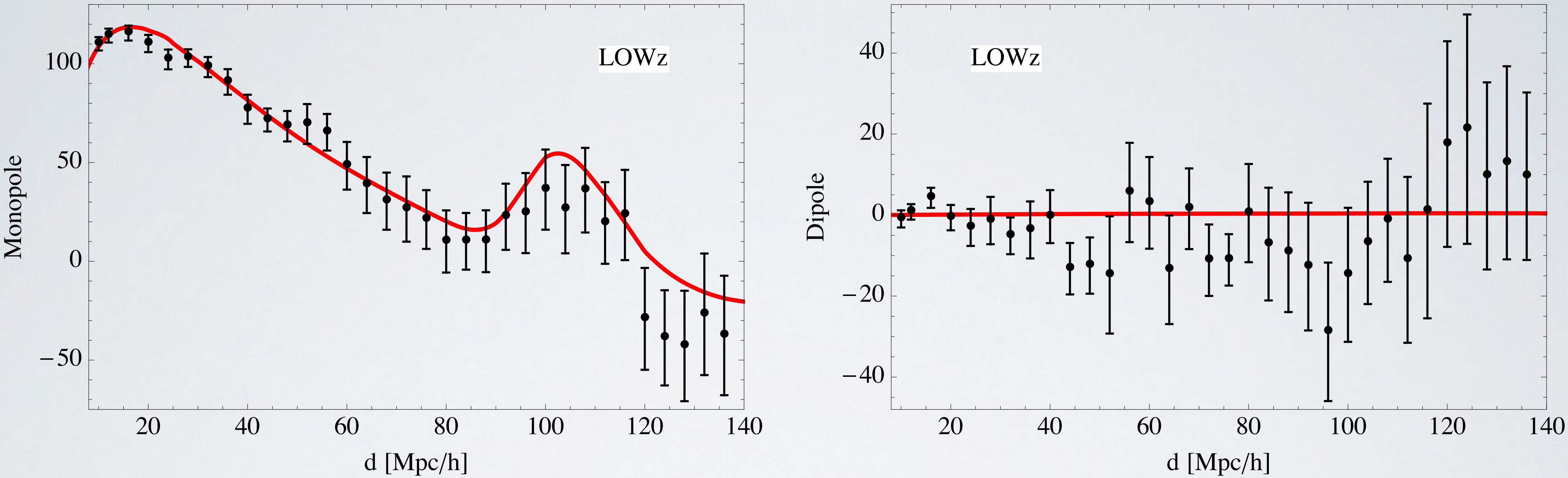
Simple case: two populations and standard kernel

$$\hat{\xi} = \sum_{ij} \sum_{L_i L_j = \mathrm{B,F}} \cos\gamma_{ij}\, \delta n_{L_i}(\mathbf{x}_i)\delta n_{L_j}(\mathbf{x}_j)\delta_K(d_{ij} - d)$$

We have different ways of **choosing** the **angle**:



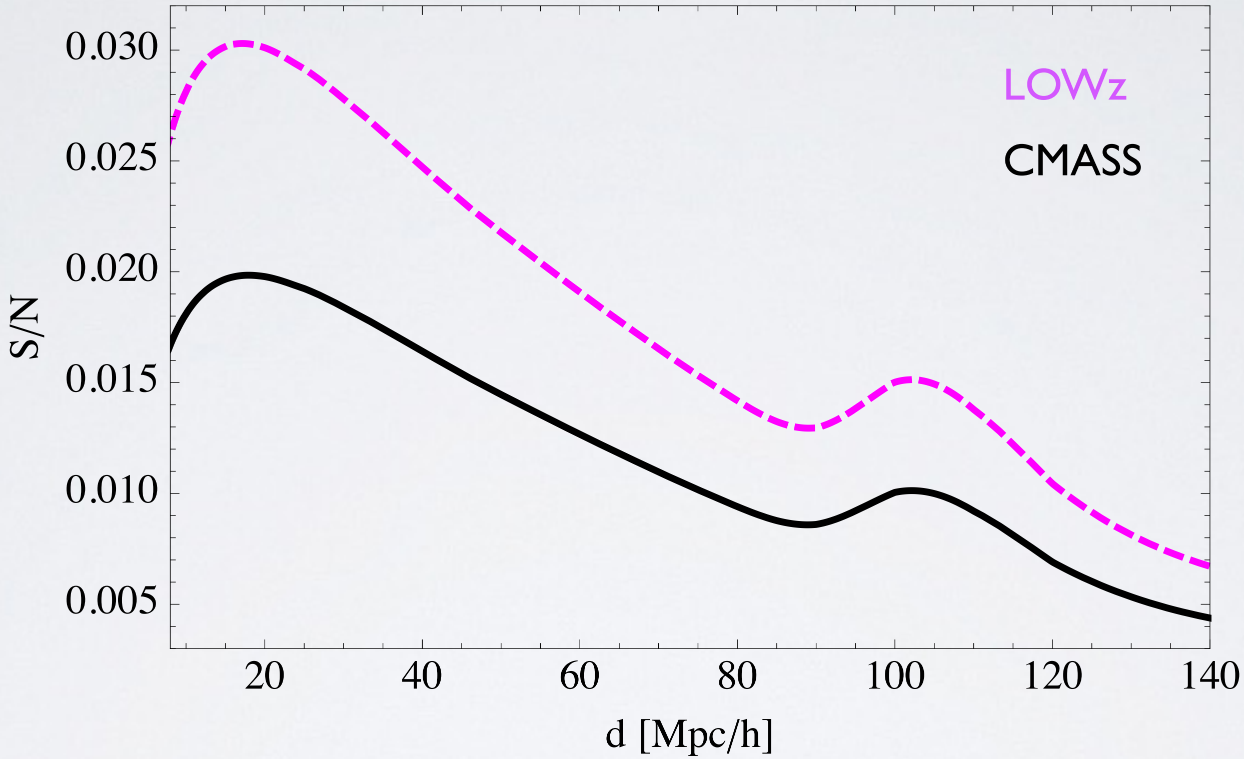
Measurement with the median angle



Predictions: we measure **separately** the monopole for the **bright** and **faint** populations and compare with predictions to fit for the bias.

The dipole is **compatible** with **zero**.

Signal-to-noise with the median angle



The signal-to-noise is much smaller than one:
no detection possible.

$z = 0.25$

Multipoles