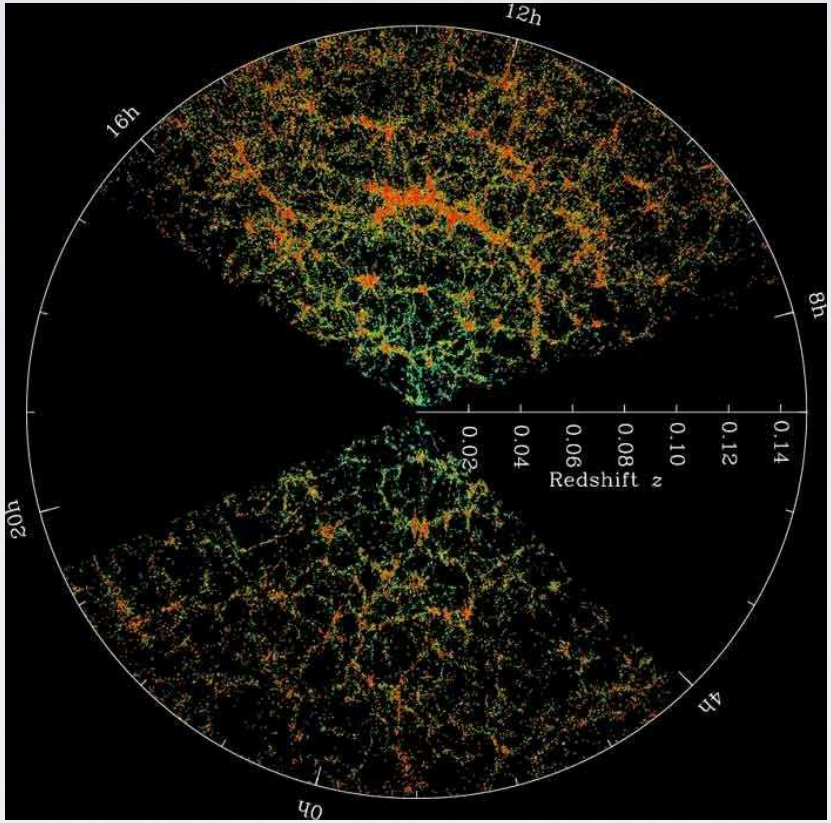
Camille Bonvin



Credit: M. Blanton, SDSS

CERN theory retreat, les Houches
November 2014

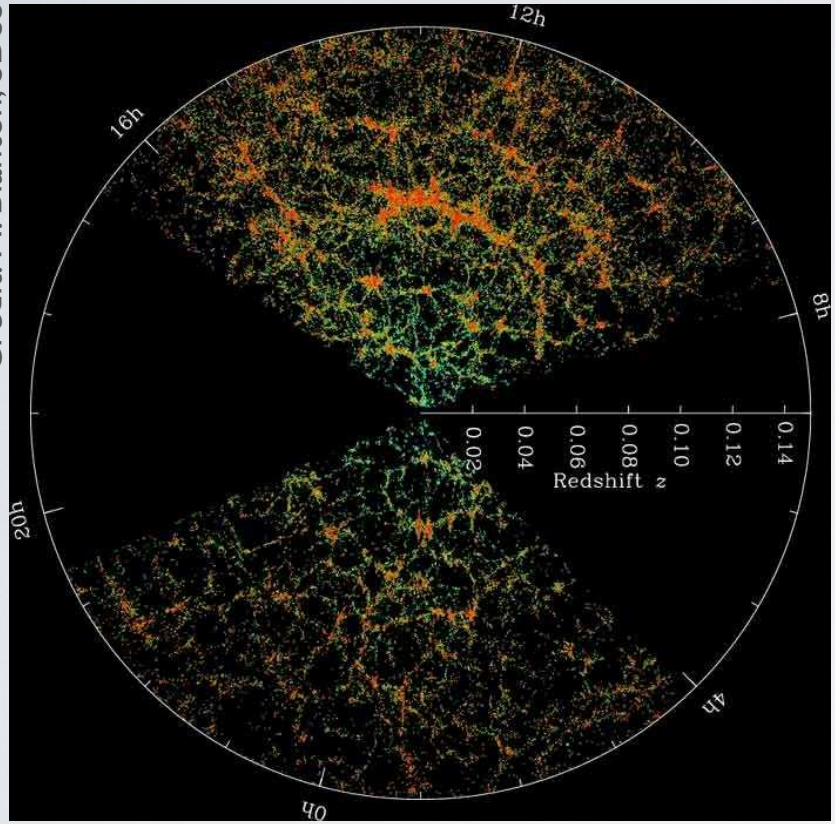
Interests

- **Large-scale structure**: how can we use it to test the theory of gravity? Motivation: understand if the acceleration of the universe is due to **dark energy** or to a break down of General Relativity.

- **Primordial magnetic fields**: what impact do they leave on the Cosmic Microwave Background (CMB). Example: **B-modes** polarisation observed by BICEP2.

Large-scale structure

The **distribution** of galaxies is determined by:



Credit: M. Blanton, SDSS

- The initial conditions.
- The theory of gravity.
- The content of the universe.

The large-scale structure contains a lot of information about the global **properties** of our universe.

Large-scale structure

Two different and complementary regimes:

- The **large-scale** regime: we can test predictions from General Relativity.

- The **small-scale regime**: we can test gravity in the non-linear regime. Many modified gravity models undergo a non-trivial transition. To test these models we need **new observables**, well adapted to extract information in the non-linear regime (e.g. **phases** of the density field).

The large-scale regime

- We usually assume that galaxies are a **tracer** of the underlying **dark matter** distribution:

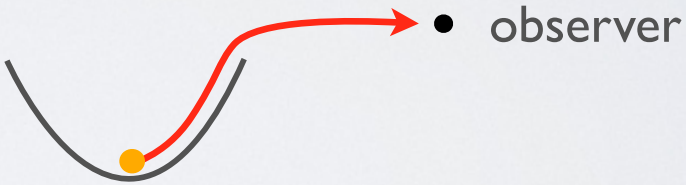
$$\Delta = \frac{N - \bar{N}}{\bar{N}} = \frac{\delta\rho}{\bar{\rho}} = \delta$$

- Incomplete picture: surveys do not provide the true positions of galaxies. They observe incoming **photons' directions** and **redshifts**.

- In a homogeneous universe:
  - light propagates on **straight line**
  - redshift is due to the **expansion**

Relativistic distortions

- Our universe is not homogeneous → this **distorts** our coordinate system.
- Interest: the distortions can be used to **test gravity**.
  - **Doppler** effect: velocity shifts the photons' frequency.
  - **Gravitational redshift**: the gravitational field shifts the photons' frequency.



- Measure of the distortions → measure of the gravitational potential → **test** of Einstein's equations: relation between the density and the gravitational field.

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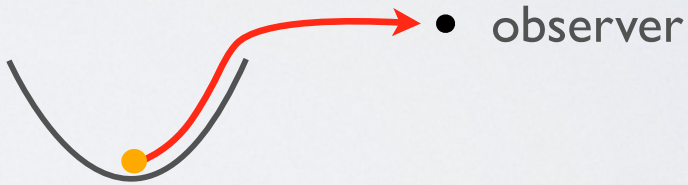

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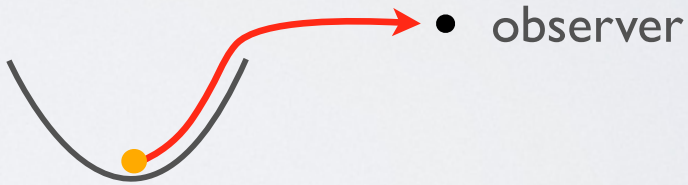

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Backup slides

Redshift

$$ds^2 = -a^2\Big[\big(1+2\Psi\big)d\eta^2 + \big(1-2\Phi\big)\delta_{ij}dx^i dx^j\Big]$$

Effect of inhomogeneities on the redshift: $1+z = \dfrac{\nu_S}{\nu_O} = \dfrac{E_S}{E_O}$

Photons travel on **null geodesics**.

$$1+z = \frac{a_O}{a_S}\Big[1 + \mathbf{V}_S\cdot\mathbf{n} - \mathbf{V}_O\cdot\mathbf{n} + \Psi_O - \Psi_S - \int_0^{r_S} dr(\dot{\Phi}+\dot{\Psi})\Big]$$

Doppler Gravitational redshift Integrated Sachs-Wolfe

Gravitational redshift:

Result

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

density

redshift space distortion

lensing

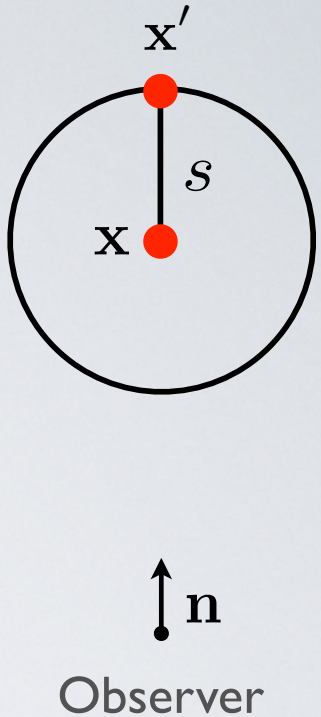
gravitational redshift

Doppler

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

Density

The **density** contribution $\Delta = b \cdot \delta$, generates an **isotropic** correlation function.



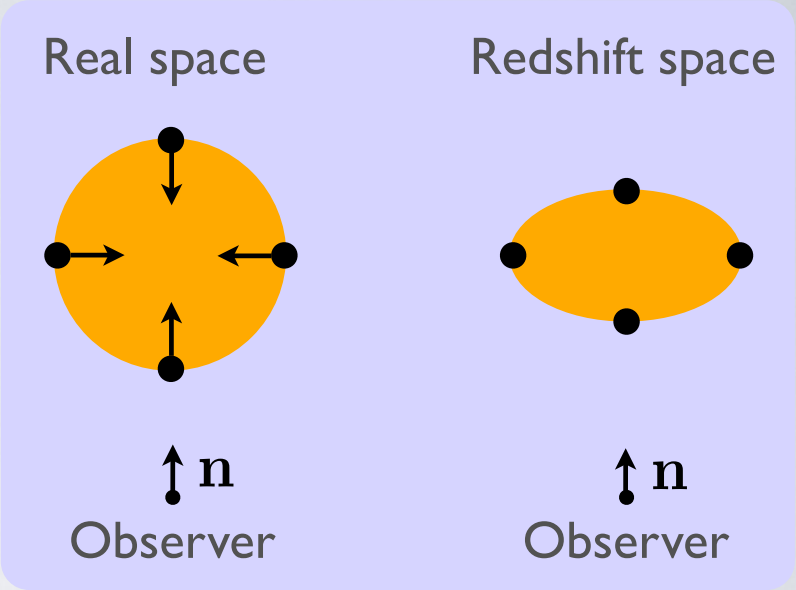
$\xi(s) = \langle \Delta(\mathbf{x}) \Delta(\mathbf{x}') \rangle$ depends only on the **separation** $s = |\mathbf{x} - \mathbf{x}'|$

$$\xi(s) = \frac{A b^2 D_1^2}{2\pi^2} \int \frac{dk}{k} \left(\frac{k}{H_0} \right)^{n_s - 1} T_\delta^2(k)\, j_0(k \cdot s)$$

Redshift distortions

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

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



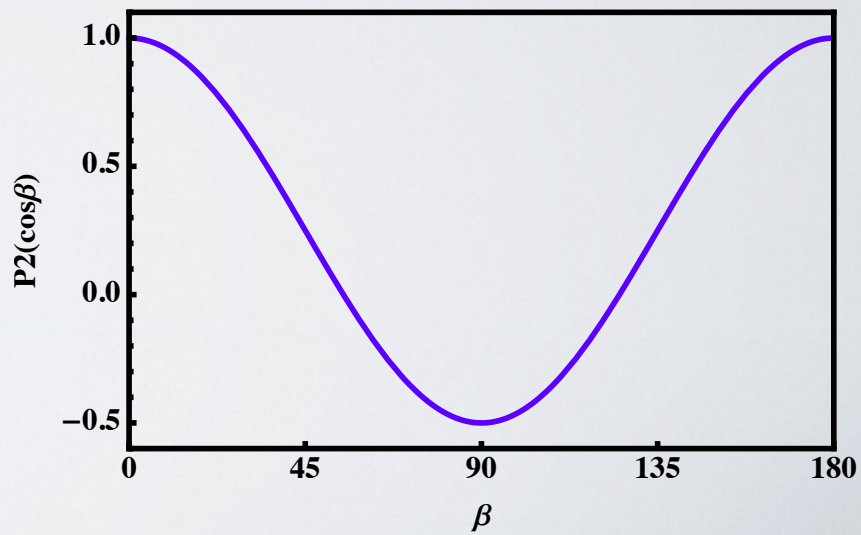
Quadrupole

Hamilton (1992)

$$P_2(\cos\beta) = \frac{3}{2}\cos^2\beta - \frac{1}{2}$$

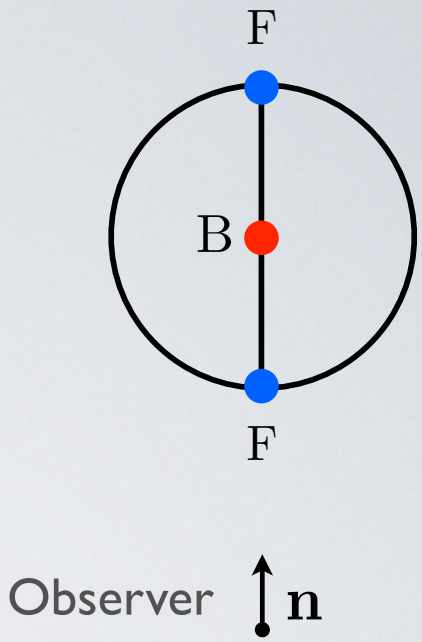
$$\xi_2 = -D_1^2 \left(\frac{4f}{3} + \frac{4f^2}{7} \right) \mu_2(s) P_2(\cos\beta)$$

$$\mu_\ell(s) = \frac{A}{2\pi^2} \int \frac{dk}{k} \left(\frac{k}{H_0} \right)^{n_s - 1} T_\delta^2(k)\, j_\ell(k \cdot s)$$



Relativistic effects

The relativistic effects break the **symmetry** of the correlation function.



The correlation function differs for galaxies **behind** or in **front** of the central one.

This differs from the breaking of **isotropy**, which is symmetric: redshift distortions have **even** powers of $\cos\beta$.

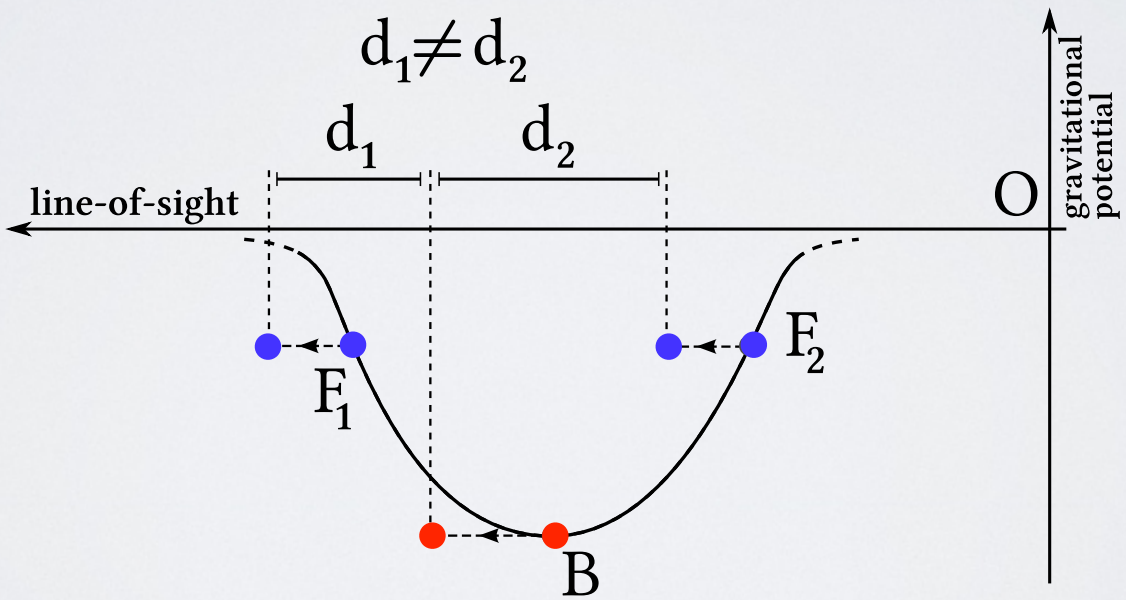
→ The amplitude is the same for $\beta = 0$ and $\beta = \pi$

To measure the asymmetry, we need **two populations** of galaxies: faint and bright.

Cross-correlation

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

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

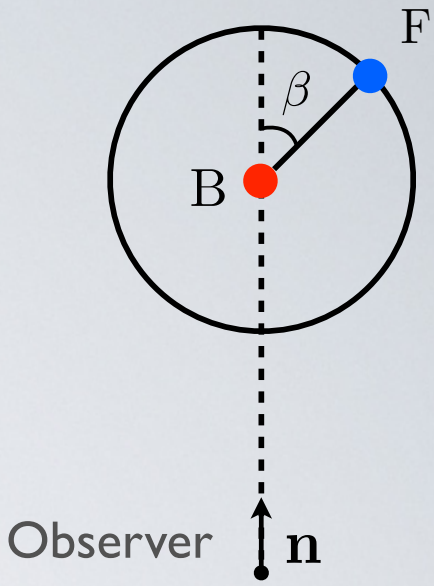


Dipole in the correlation function

CB, Hui and Gaztanaga (2013)

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

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

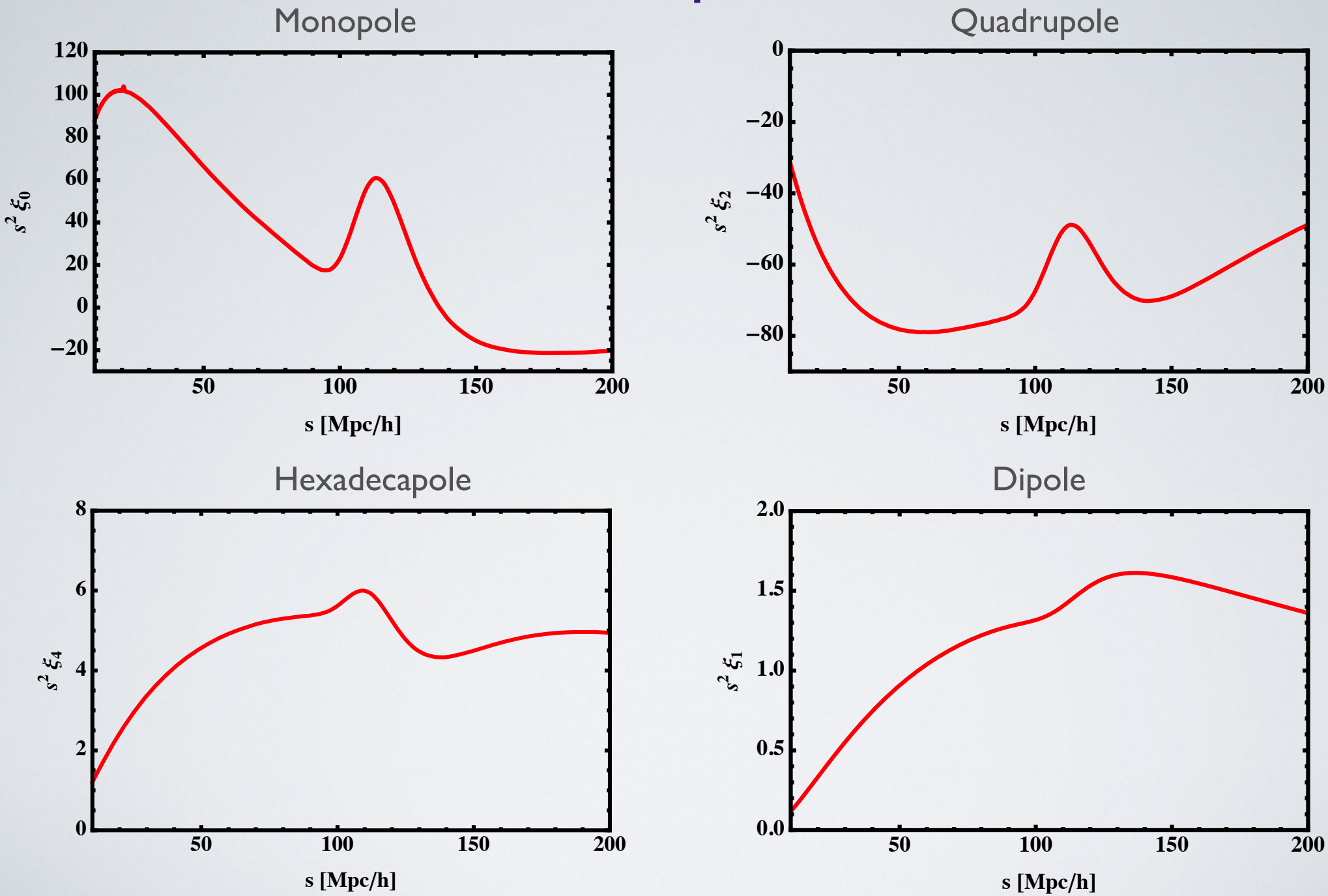


By fitting for a **dipole** in the correlation function, we can measure **relativistic effects**, and separate them from the density and redshift space distortions.

$$\xi_1(s) = \frac{3}{2}\int_{-1}^{1} d\mu\, \xi(s,\mu)\cdot\mu \qquad \mu = \cos\beta$$

Multipoles

$z = 0.25$



Interest

The dipole is sensitive to the **gravitational potential**.

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

In general relativity, Euler equation: $\dot{\mathbf{V}}\cdot\mathbf{n} + \mathcal{H}\mathbf{V}\cdot\mathbf{n} + \partial_r\Psi = 0$

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

Combining the dipole with the quadrupole, we can test **Euler equation**.