Probing gravity with galaxy clustering: Redshift-Space Distortions

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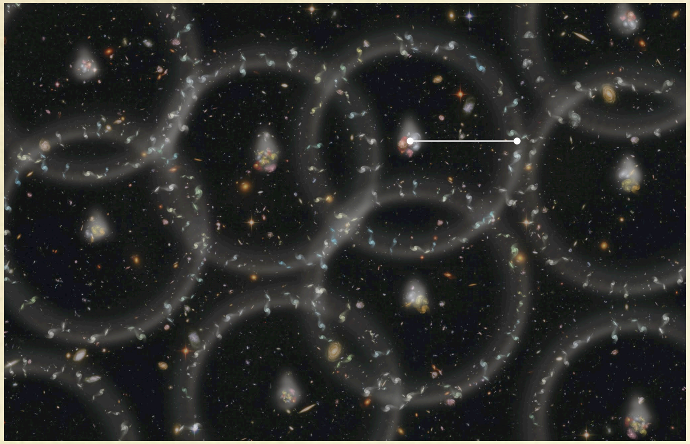
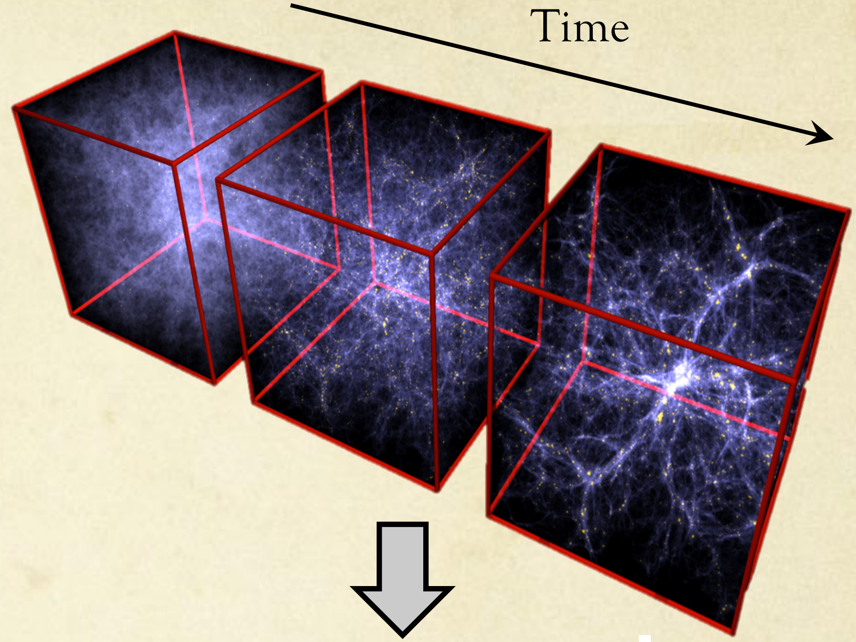
Workshop beyond six parameters

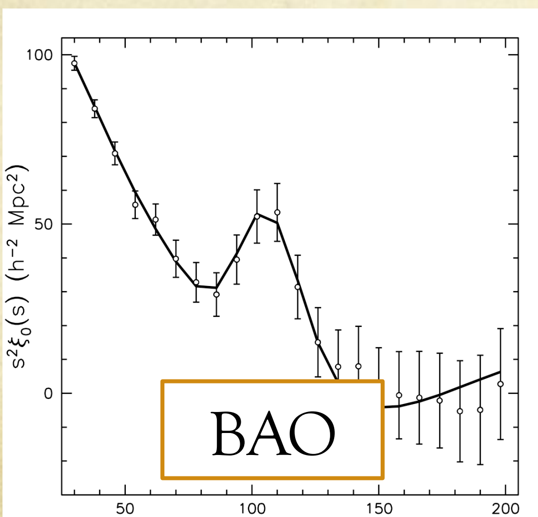
Luminy, Marseille

03/03/2015

Galaxy clustering and cosmology

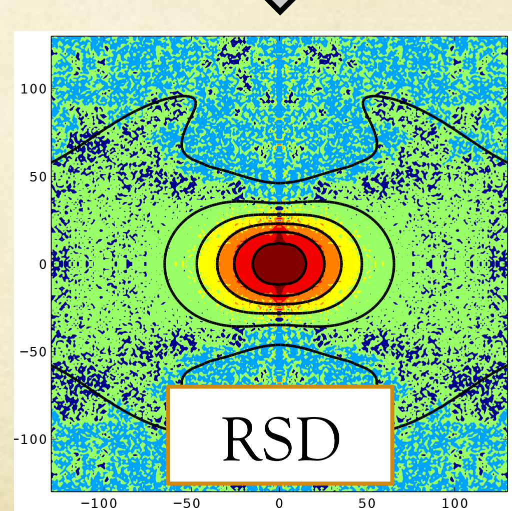






(BOSS, Anderson et al. 2013)

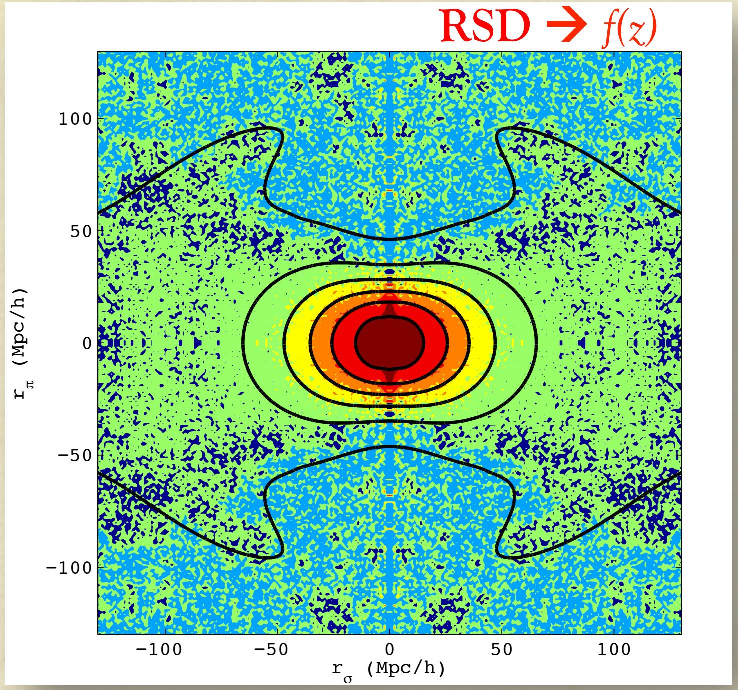
Galaxy clustering (2PCF)



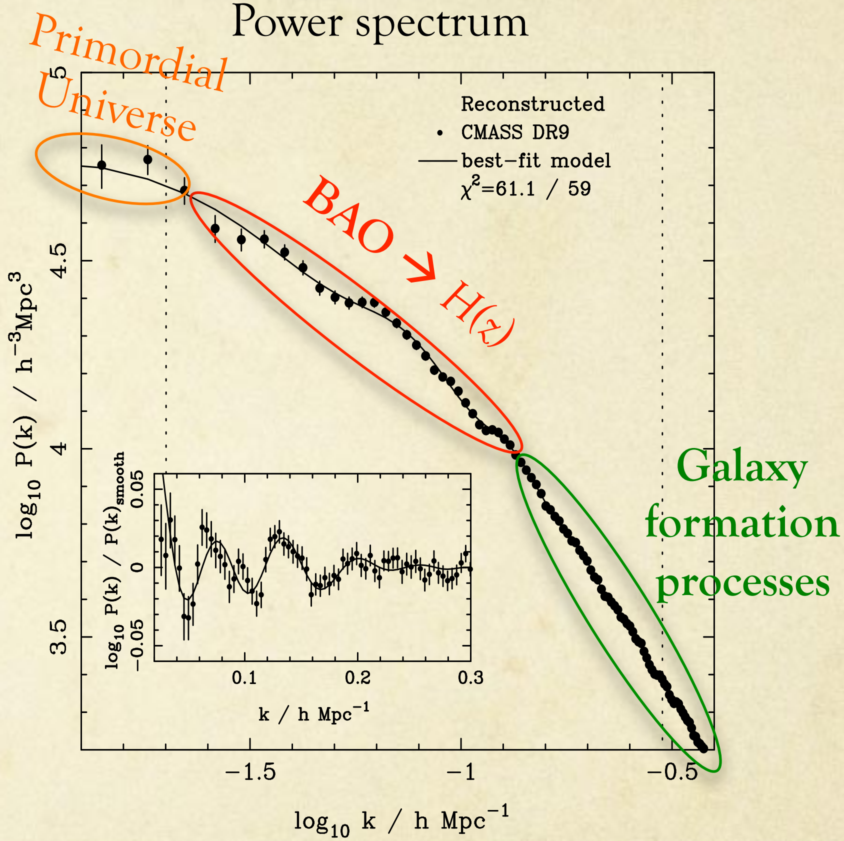
(BOSS, Reid et al. 2012)

Galaxy clustering and cosmology

Anisotropic correlation function



Power spectrum

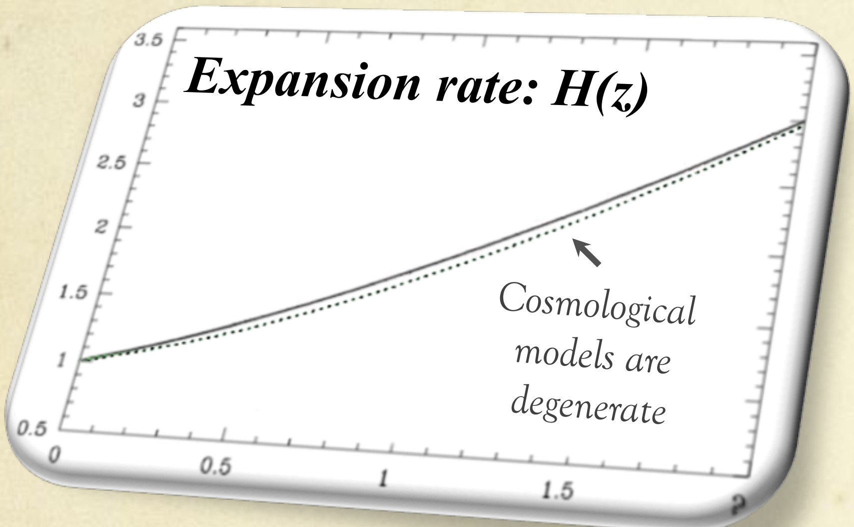


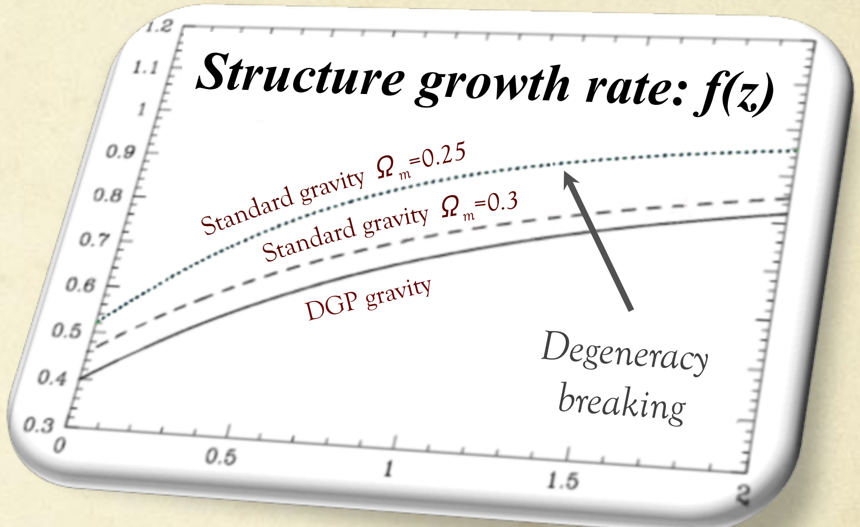
(Anderson et al. 2012, Reid et al. 2012)

Cosmic Acceleration

- The origin of cosmic acceleration is one the most important questions in cosmology and physics today:

  Dark Energy or a **modification of standard gravity** ?



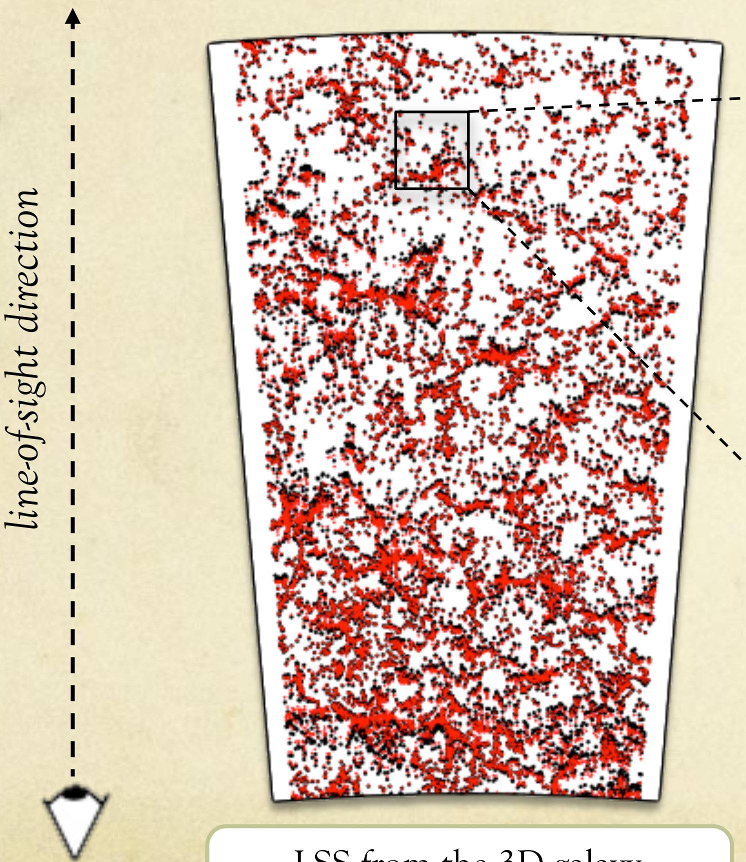


- The *growth rate of the large-scale structure* uniquely allows probing **gravity**

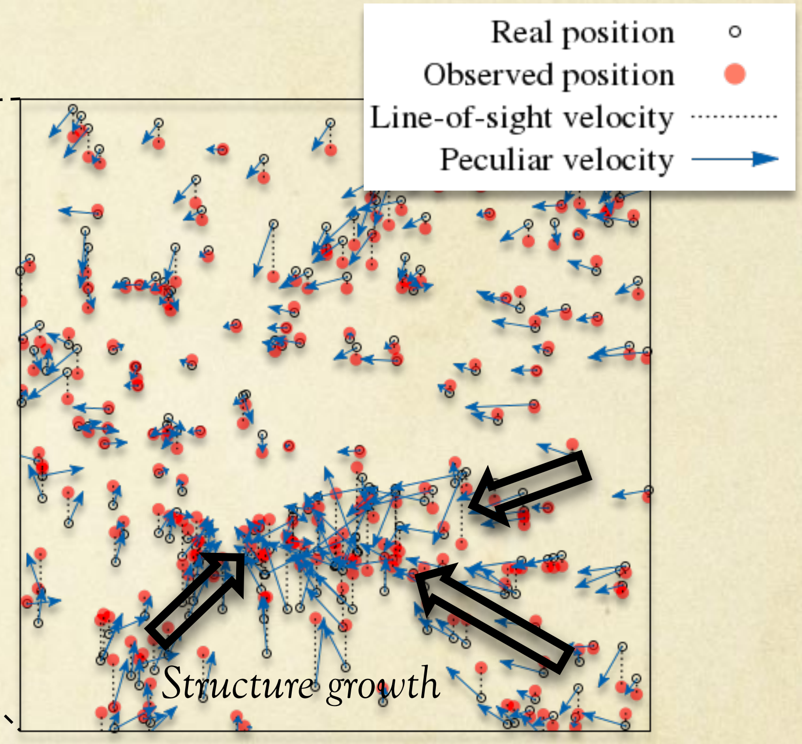
Growth rate of structure *f(z)* is crucial to break the degeneracy between cosmological models to explain cosmic acceleration

Redshift-space distortions

- **Redshift-space distortions** (RSD) in galaxy redshift surveys are unique to measure the **growth rate of structure** *f(z)*

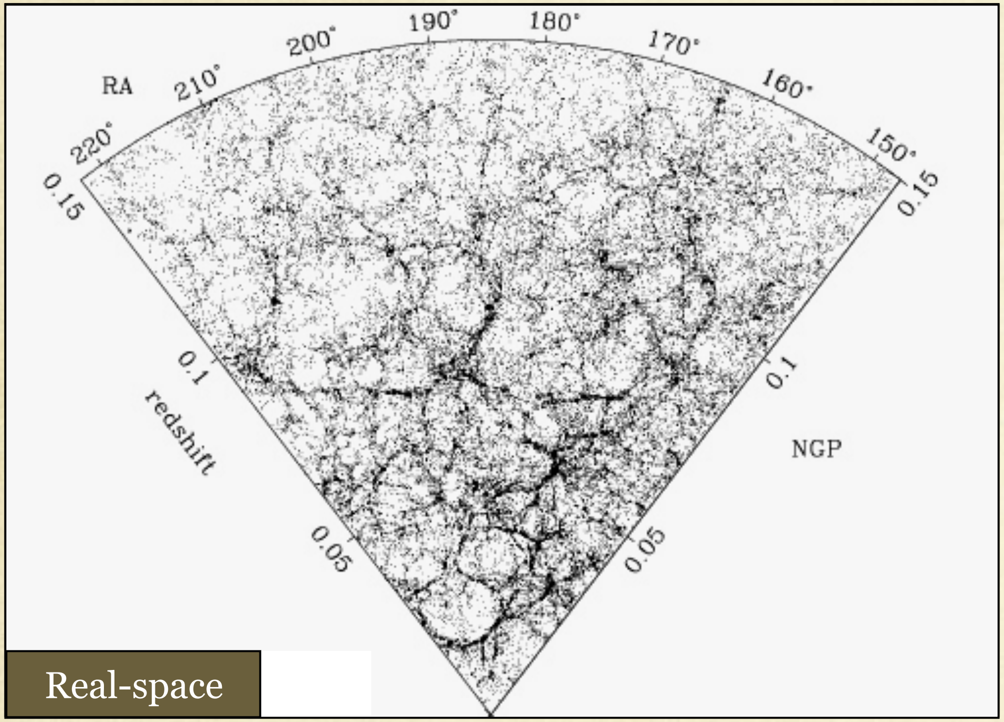


LSS from the 3D galaxy distribution in redshift survey

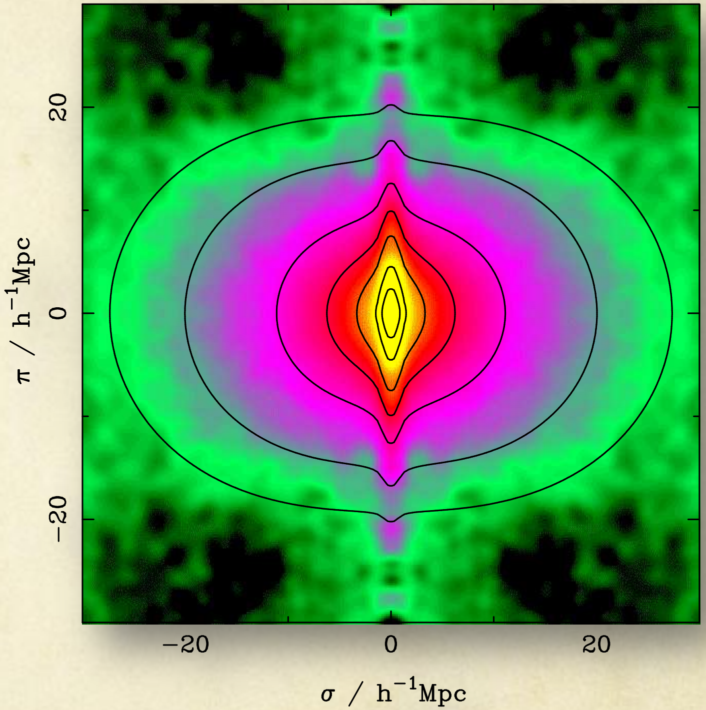


Galaxy positions are distorted by peculiar velocities induced by structure growth

Redshift-space distortions

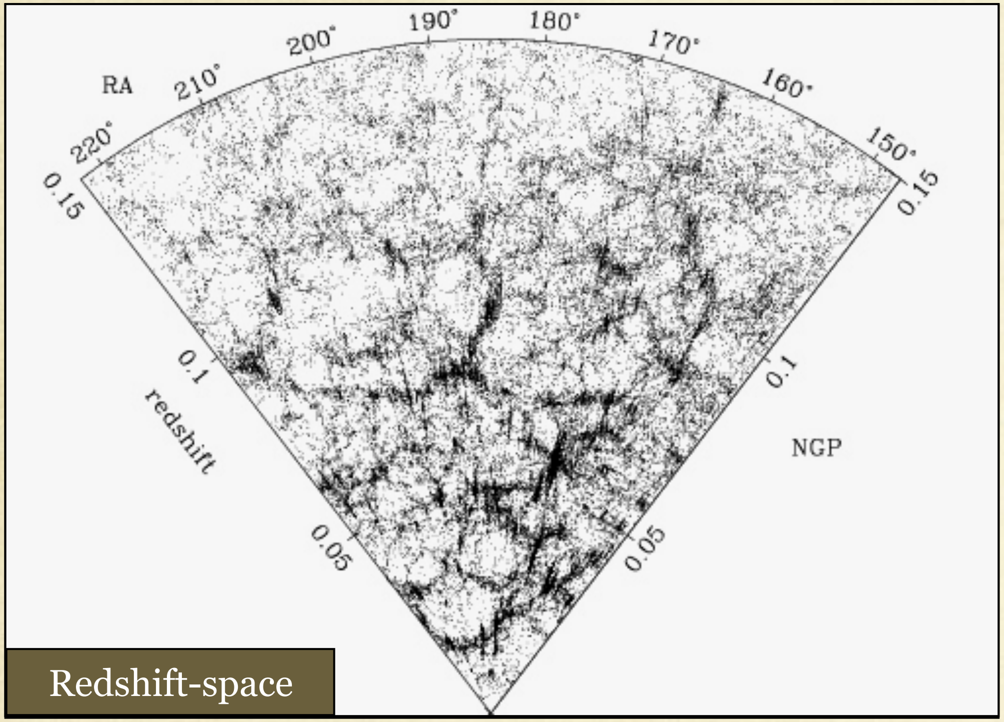


Anisotropic two-point correlation function



The linear component of these distortions maps coherent motions induced by the **growth of structure**

Redshift-space distortions



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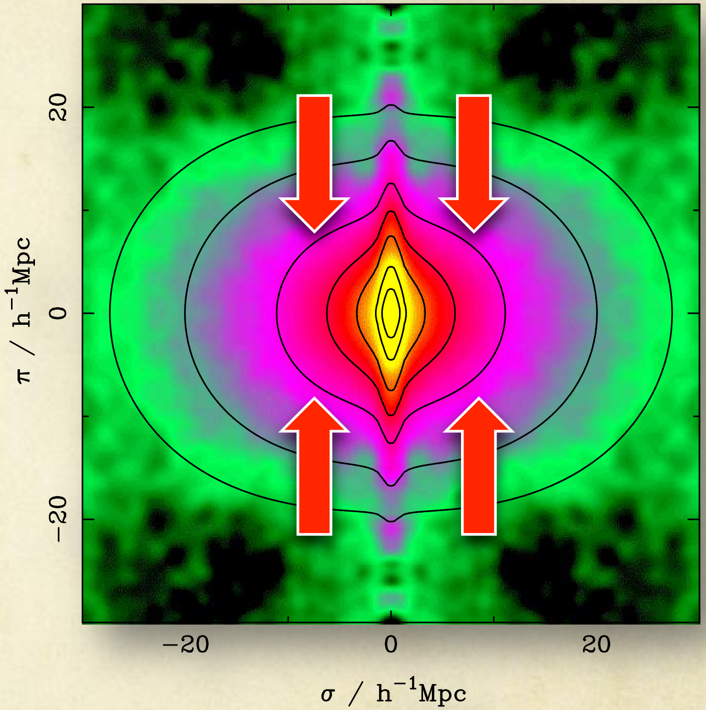
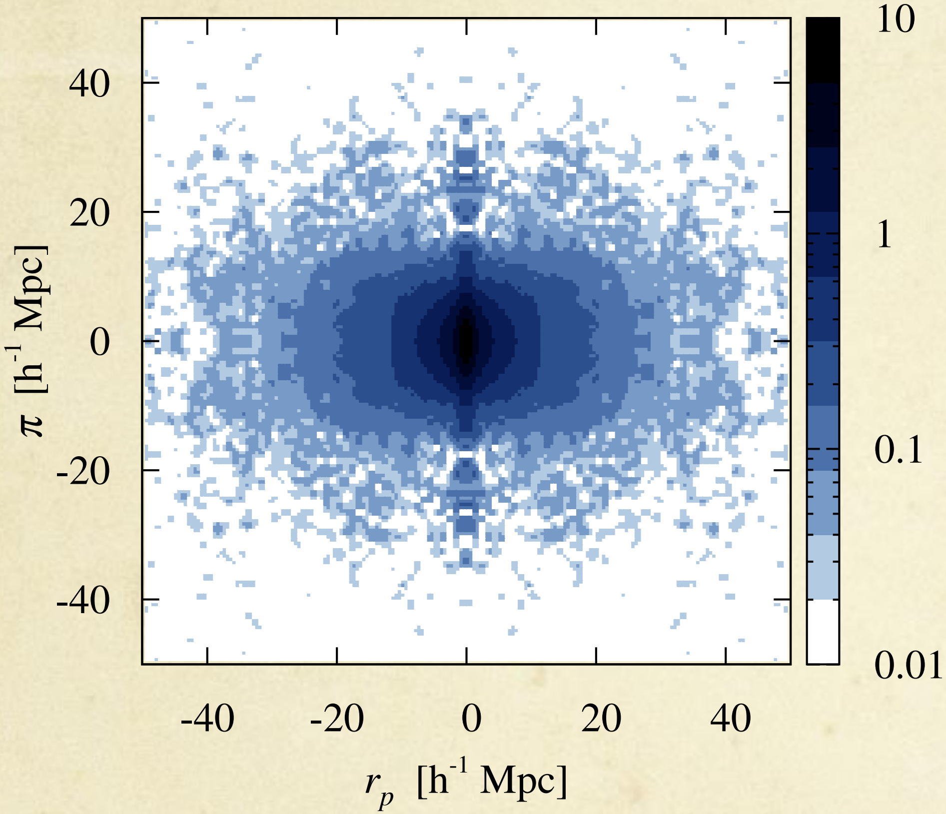


The linear component of these distortions maps coherent motions induced by the **growth of structure**

SDSS & VIPERS redshift surveys

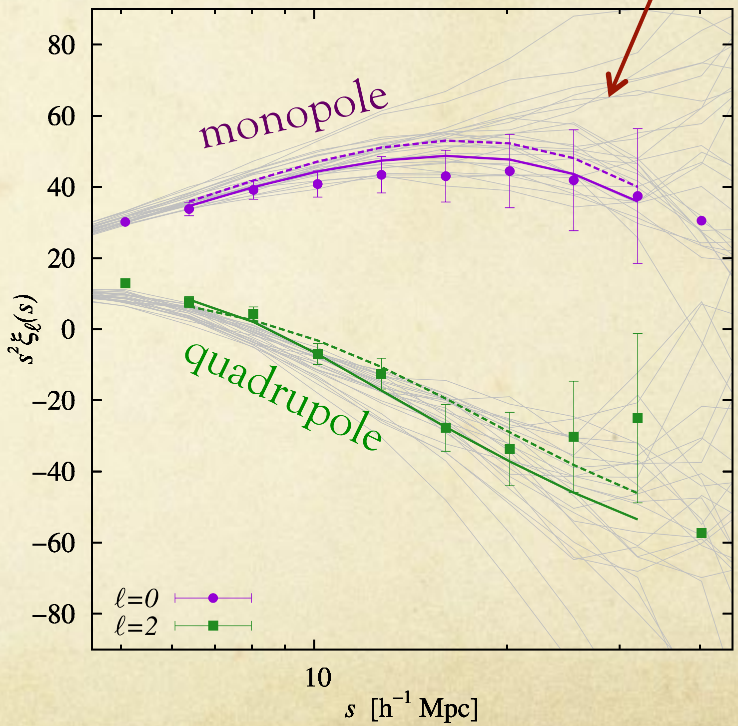
VIPERS survey analysis



Highest redshift currently probed : z=0.8

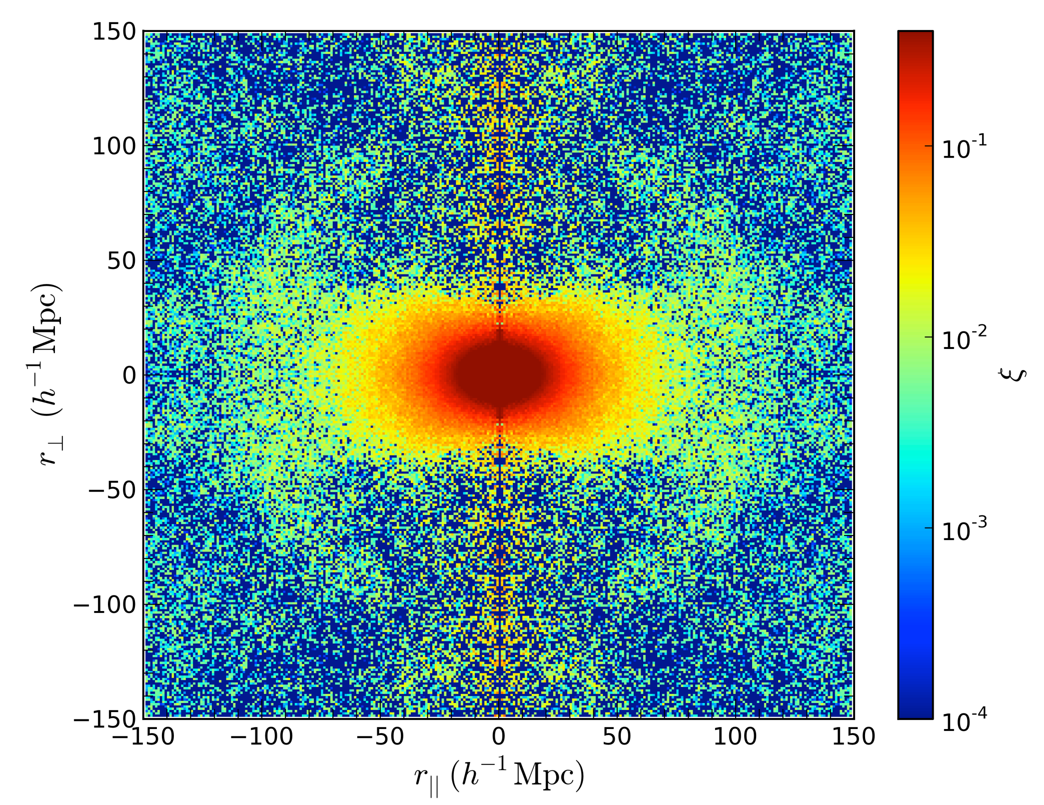
- Moments of the anisotropic correlation function:

$$\xi(r_\perp, r_\parallel) = \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} e^{i\boldsymbol{k}\cdot\boldsymbol{s}} P^s(k,\mu) = \sum_l \xi_l^s(s) L_l(\nu)$$



(de la Torre, Guzzo, Peacock et al. 2013)

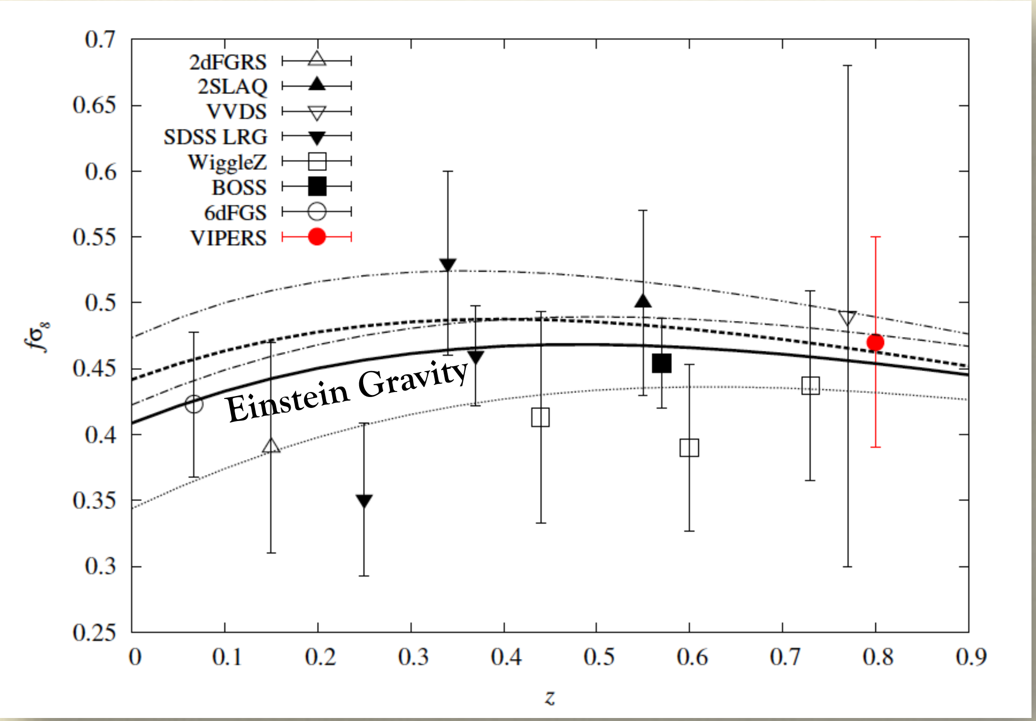
BOSS (DR11) survey analysis

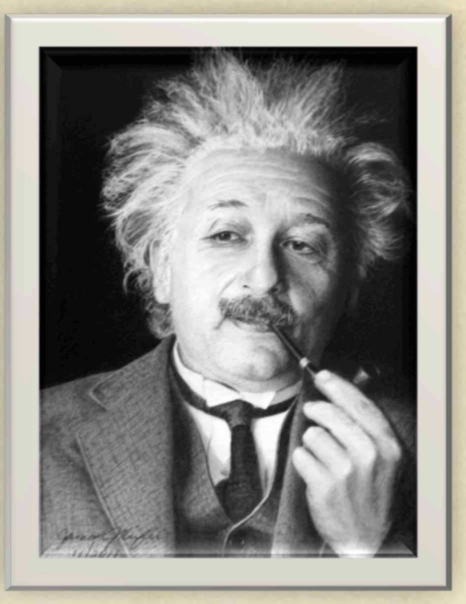


Largest volume of the Universe currently mapped

(Samushia et al. 2014)

Constraints on $f\sigma_8$





- Current measurements in agreement with ΛCDM and Einstein gravity

(de la Torre, Guzzo, Peacock et al. 2013)

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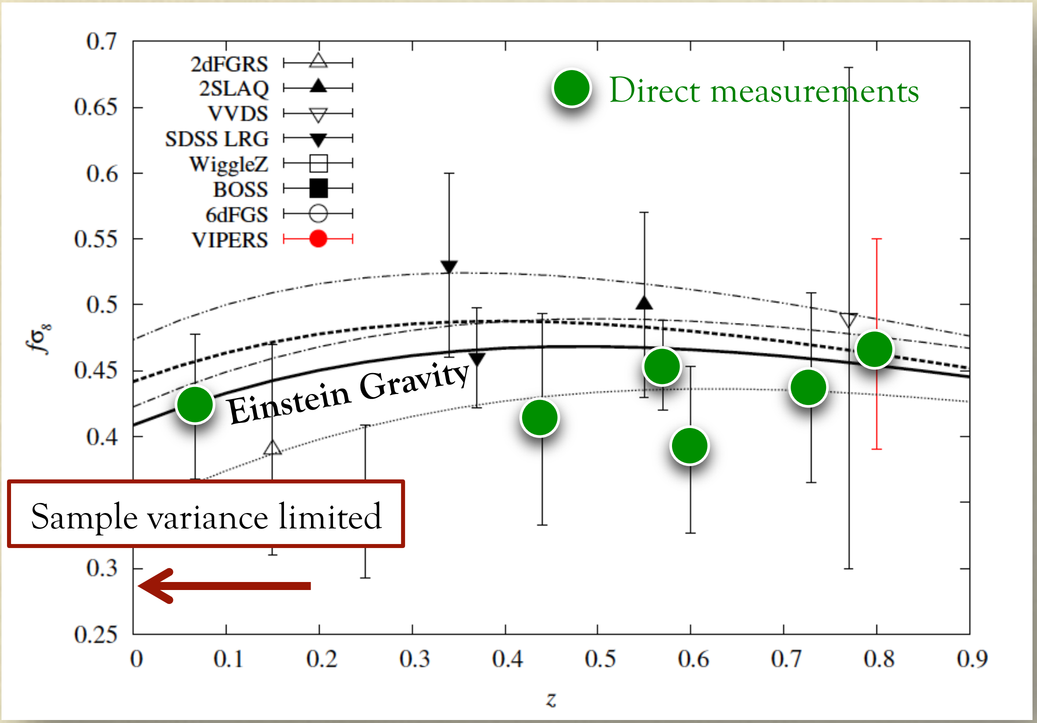

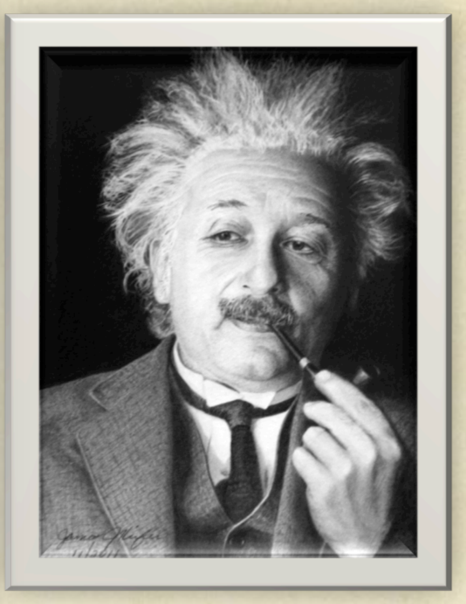

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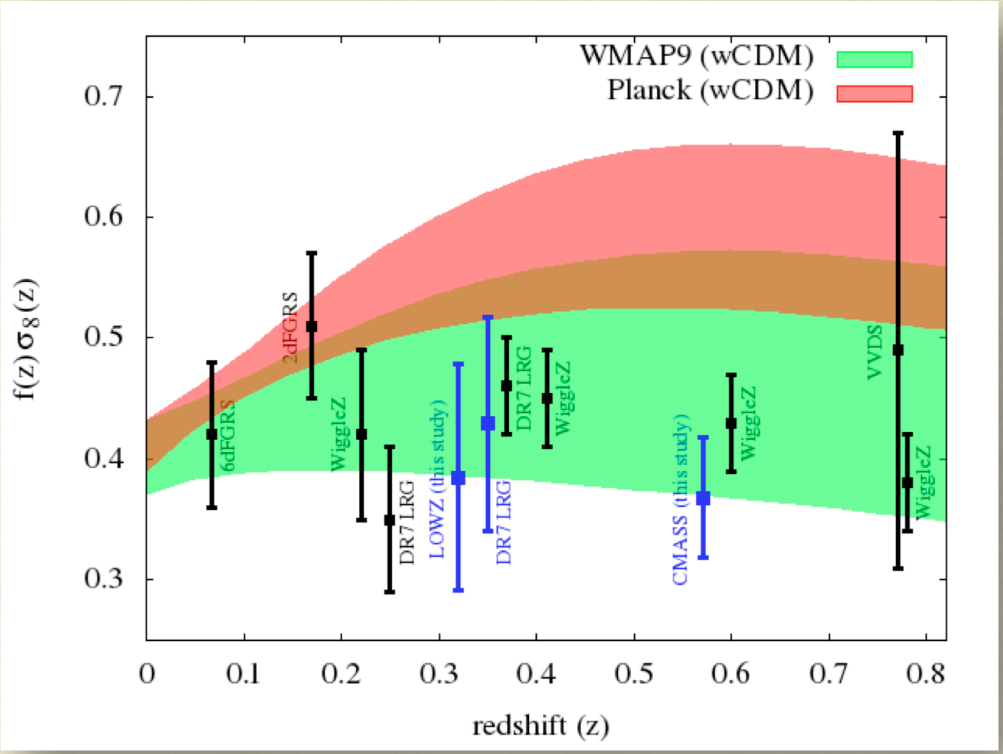
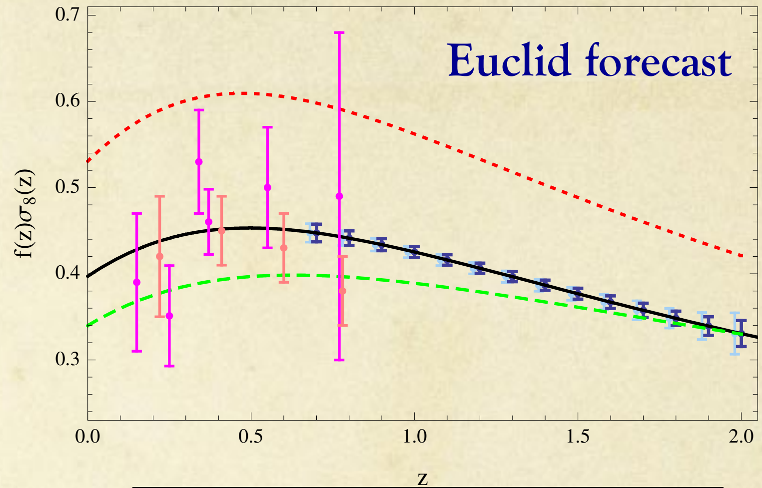


Is there a tension between Planck and *f(z)* constraints?

(Samushia et al. 2014)

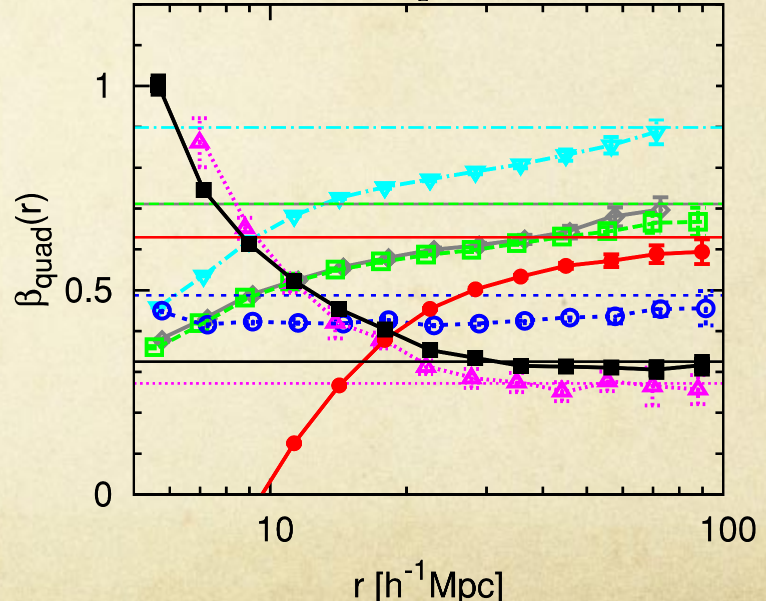
Modelling RSD



- Next-generation surveys (e.g. Euclid, DESI): **1-2% precision on $f\sigma_8$**
- Most commonly used model (Fisher et al. 1994, Peacock & Dodds 1994):

$$P_Z(k,\mu) = P_R(k)(1+\beta\mu^2)^2\left(1+\frac{k^2\sigma_k^2\mu^2}{2}\right)^{-1}$$

- But introduces systematic errors on β or f at the 10% level



(Okumura & Jing 2011; Bianchi, Guzzo et al. 2012)

RSD non-linear models

$$P^s(k,\mu) = \int \frac{d^3\boldsymbol{r}}{(2\pi)^3} e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} \left\langle e^{-ikf\mu\Delta u_\parallel} \times \right.$$
$$\left. [\delta(\boldsymbol{x}) + \mu^2 f\theta(\boldsymbol{x})][\delta(\boldsymbol{x}') + \mu^2 f\theta(\boldsymbol{x}')] \right\rangle$$

$$P_g^s(k,\mu) = D(k\mu\sigma_v) P_K(k,\mu,b)$$

$$D(k\mu\sigma_v) = \begin{cases} \exp(-(k\mu\sigma_v)^2) \\ 1/(1+(k\mu\sigma_v)^2) \end{cases}$$

$$P_K(k,\mu,b) = \begin{cases} \boxed{\mathrm{A}}:\ b^2(k)P_{\delta\delta}(k) + 2\mu^2 f b(k) P_{\delta\delta}(k) \\ +\mu^4 f^2 P_{\delta\delta}(k) \\ \\ \boxed{\mathrm{B}}:\ b^2(k)P_{\delta\delta}(k) + 2\mu^2 f b(k) P_{\delta\theta}(k) \\ +\mu^4 f^2 P_{\theta\theta}(k) \\ \\ \boxed{\mathrm{C}}:\ b^2(k)P_{\delta\delta}(k) + 2\mu^2 f b(k) P_{\delta\theta}(k) \\ +\mu^4 f^2 P_{\theta\theta}(k) + C_A(k,\mu;f,b) \\ +C_B(k,\mu;f,b) \end{cases}$$

- Building an accurate RSD non-linear model for galaxies:
  - Knowledge of **galaxy biasing**
  - Knowledge of the underlying **velocity** power spectra

(de la Torre & Guzzo 2012)

An undesirable perspective...(?)

- Non-linear RSD model by **Taruya et al. (2010)** in terms the two-point correlation function multipole moments

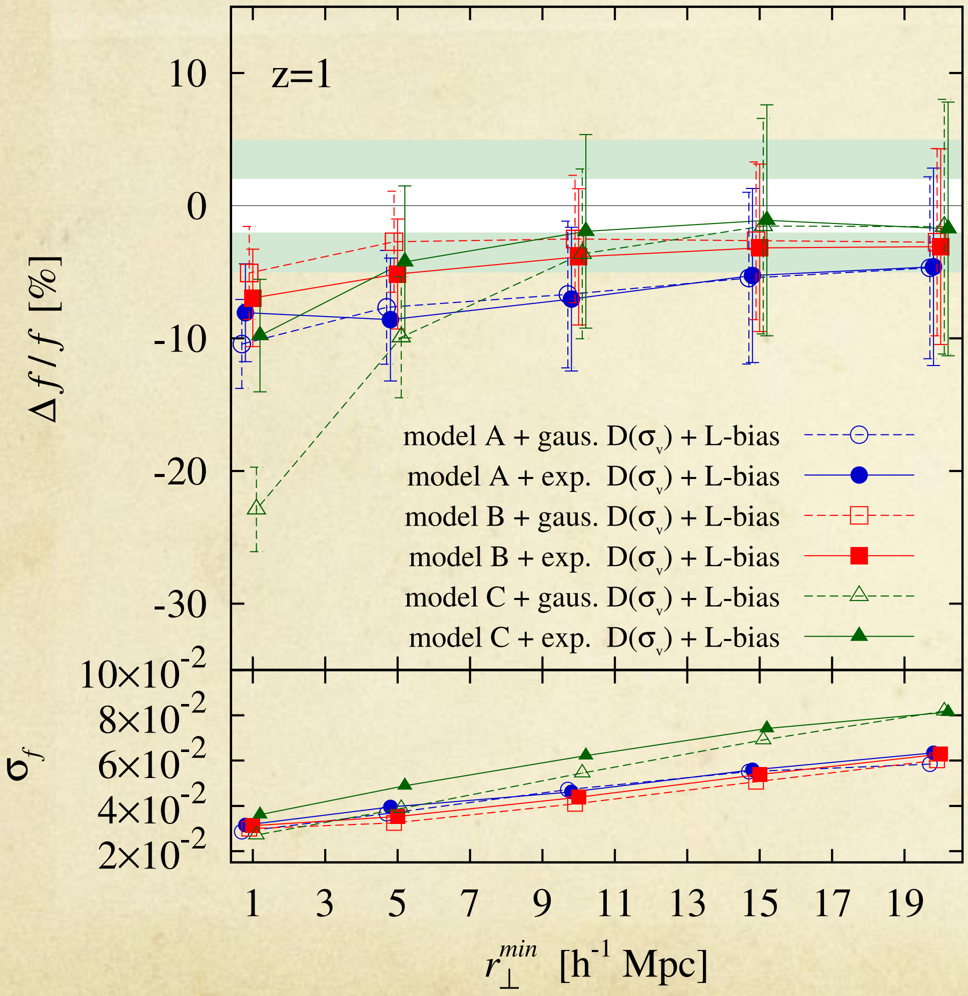
- Accurate but need to be able to predict the **non-linear density-density, velocity-div - density** and **velocity-div –velocity-div** power spectra for any cosmology.

$\longrightarrow$

$$
\begin{aligned}
\xi_0^s(s) &= b^2\xi_{\delta\delta} + bf\frac{2}{3}\xi_{\delta\theta} + f^2\frac{1}{5}\xi_{\theta\theta} \\
&\quad + b^2 f\frac{1}{3}\xi_{A11} + bf^2\frac{1}{3}\xi_{A12} + bf^2\frac{1}{5}\xi_{A22} + f^3\frac{1}{5}\xi_{A23} \\
&\quad + f^3\frac{1}{7}\xi_{A33} + b^2f^2\frac{1}{3}\xi_{B111} - bf^3\frac{1}{3}\left(\xi_{B112}+\xi_{B121}\right) \\
&\quad + f^4\frac{1}{3}\xi_{B122} + b^2f^2\frac{1}{5}\xi_{B211} - bf^3\frac{1}{5}\left(\xi_{B212}+\xi_{B221}\right) \\
&\quad + f^4\frac{1}{5}\xi_{B222} - bf^3\frac{1}{7}\left(\xi_{B312}+\xi_{B321}\right) + f^4\frac{1}{7}\xi_{B322} \\
&\quad + f^4\frac{1}{9}\xi_{B422}, \\
\xi_2^s(s) &= bf\frac{4}{3}\xi^{(2)}_{\delta\theta} + f^2\frac{4}{7}\xi^{(2)}_{\theta\theta} \\
&\quad + b^2f\frac{2}{3}\xi^{(2)}_{A11} + bf^2\frac{2}{3}\xi^{(2)}_{A12} + bf^2\frac{4}{7}\xi^{(2)}_{A22} + f^3\frac{4}{7}\xi^{(2)}_{A23} \\
&\quad + f^3\frac{10}{21}\xi^{(2)}_{A33} + b^2f^2\frac{2}{3}\xi^{(2)}_{B111} - bf^3\frac{2}{3}\left(\xi^{(2)}_{B112}+\xi^{(2)}_{B121}\right) \\
&\quad + f^4\frac{2}{3}\xi^{(2)}_{B122} + b^2f^2\frac{4}{7}\xi^{(2)}_{B211} - bf^3\frac{4}{7}\left(\xi^{(2)}_{B212}+\xi^{(2)}_{B221}\right) \\
&\quad + f^4\frac{4}{7}\xi^{(2)}_{B222} - bf^3\frac{10}{21}\left(\xi^{(2)}_{B312}+\xi^{(2)}_{B321}\right) + f^4\frac{10}{21}\xi^{(2)}_{B322} \\
&\quad + f^4\frac{40}{99}\xi^{(2)}_{B422}, \\
\xi_4^s(s) &= f^2\frac{8}{35}\xi^{(4)}_{\theta\theta} \\
&\quad + bf^2\frac{8}{35}\xi^{(4)}_{A22} + f^3\frac{8}{35}\xi^{(4)}_{A23} + f^3\frac{24}{77}\xi^{(4)}_{A33} + b^2f^2\frac{8}{35}\xi^{(4)}_{B211} \\
&\quad - bf^3\frac{8}{35}\left(\xi^{(4)}_{B212}+\xi^{(4)}_{B221}\right) + f^4\frac{8}{35}\xi^{(4)}_{B222} - bf^3\frac{24}{77}\left(\xi^{(4)}_{B312}\right. \\
&\quad \left.+\,\xi^{(4)}_{B321}\right) + f^4\frac{24}{77}\xi^{(4)}_{B322} + f^4\frac{48}{143}\xi^{(4)}_{B422}, \\
\xi_6^s(s) &= f^3\frac{16}{231}\xi^{(6)}_{A33} - bf^3\frac{16}{231}\left(\xi^{(6)}_{B312}+\xi^{(6)}_{B321}\right) + f^4\frac{16}{231}\xi^{(6)}_{B322} \\
&\quad + f^4\frac{64}{495}\xi^{(6)}_{B422}, \\
\xi_8^s(s) &= f^4\frac{128}{6435}\xi^{(8)}_{B422},
\end{aligned}
$$

(de la Torre & Guzzo 2012)

Systematic on *f* measurements



Most advanced non-linear models allow to better model RSD when going to the quasi-non-linear regime.

Taruya et al. 2010 model allows recovering ***f*** **at the 5% percent level**

→ We are not yet at the percent accuracy on the growth rate

(de la Torre & Guzzo 2012)

Summary

- RSD is a fundamental probe to test and understand the cosmological model and in particular the origin of cosmic acceleration

- Current **measurements are consistent with standard (Einstein) gravity** but are not able to distinguish between different gravity models

- Next generation massive redshift surveys such as **Euclid** will allow the measurement of $f(z)$ **to a few percent up to z=2**

  → But RSD models need to be improved to reduce systematics

- Improved non-linear prescriptions have been recently proposed but can be difficult to implement, need to converge on models