Institute for Computational Cosmology

Testing gravity with large scale structure in future galaxy redshift surveys

Elise Jennings
Durham University

C. M. Baugh & S. Pascoli

MARIE CURIE ACTIONS

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Durham University

Outline

Future galaxy redshift surveys will probe the nature of dark energy/modified gravity by measuring the expansion history of the Universe and the growth of structure.

- Dark energy or modified gravity?

- Measuring the growth rate of structure

- N-body simulations of consistent models

- Models for redshift space distortions

E. Jennings, C.M. Baugh, R.E. Angulo & S. Pascoli, 2010, MNRAS, 401. [arXiv:0908.1394]

E. Jennings, C.M. Baugh, & S. Pascoli, 2010, MNRAS in press.

E. Jennings, C.M. Baugh, & S. Pascoli, 2010, in prep.

Dark energy surveys

KEY Q's :

Is dark energy a constant or does it evolve with the expansion history of the Universe?

Is dark energy a breakdown of General Relativity on large scales?

Missions to study the dark sector need precise measurements:

Expansion history to better than 1%

Growth rate of structures to ~2%

EUCLID, JDEM,SDSS-II, PanStarrs, WFMOS, SKA etc...

Large volume N-body simulations are essential to determine

-effects of nonlinear fluctuation growth, peculiar motions, nonlinear and scale dependent bias

-how well can we constrain w(z)? (see Angulo et al. 2008)

-accuracy in measuring growth rate f

Dark energy or Modified gravity

Anything that can simultaneously explain

- **Angular diameter distances (BAO, CMB)**
- **Luminosity distances (Supernovae Ia)**

can be called "dark energy" but could be the result of modified gravity!

H(z): Current constraints **H(0) = 71.0 +- 2.5 km/s/Mpc** (WMAP 7yr)

Measuring the expansion history alone will not distinguish modified gravity from dark energy!

Need to break the degeneracy with measurements of **growth factor**

Dark energy $\longrightarrow H(z) \longleftarrow$ Modified gravity

e.g Quintessence

e.g. parametrised by
$\mu^2 = G/G_N$ and
$\zeta = 1-\Psi/\Phi$ "slip parameter"

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Within GR growth of density perturbations grows according to

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G_N \rho_m \delta = 0$$

If gravitational constant varies & g = δ/a

$$\frac{d^2 g}{da^2} + \left(5 + \frac{1}{2}\frac{d\ln H^2}{d\ln a}\right)\frac{1}{a}\frac{dg}{da} + \left(3 + \frac{1}{2}\frac{d\ln H^2}{d\ln a} - \frac{3}{2}\frac{\tilde{G}(a)}{G_N}\Omega_{m(a)}\right) g = 0$$

Dark energy → $H(z)$ ← Modified gravity

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$$\frac{\mathrm{d^2g}}{\mathrm{da^2}} + \left(5 + \frac{1}{2}\frac{\mathrm{dlnH^2}}{\mathrm{dlna}}\right)\frac{1}{a}\frac{\mathrm{dg}}{\mathrm{da}} + \left(3 + \frac{1}{2}\frac{\mathrm{dlnH^2}}{\mathrm{dlna}} - \frac{3}{2}\frac{\tilde{G}(a)}{G_N}\Omega_{\rm m(a)}\right)g = 0$$

Each model will give rise to a different growth rate

$$f(a) = \frac{\mathrm{dln}\delta}{\mathrm{dlna}}$$

Idea:

Take a **modified gravity model** (e.g parametrised extended quintessence)
and a construct a **dark energy** (quintessence) model which has the **same expansion history**.

Then using **N-body simulations** of each model test the idea that we can distinguish the two cosmologies by **measuring f using redshift space distortions**

Dark Energy: Quintessence

Scalar fields solve both the coincidence problem and cosmological constant problem in ΛCDM

Lots of choice for potential V

$$H^2 = \frac{8\pi G}{3}\left(\rho_{\rm m} + \rho_{\rm r} + \frac{\dot{\phi}^2}{2} + V(\phi)\right)$$

$$w(\phi) = \frac{P_\phi}{\rho_\phi} = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

Use one **DE equation of state w(a)** to describe different models

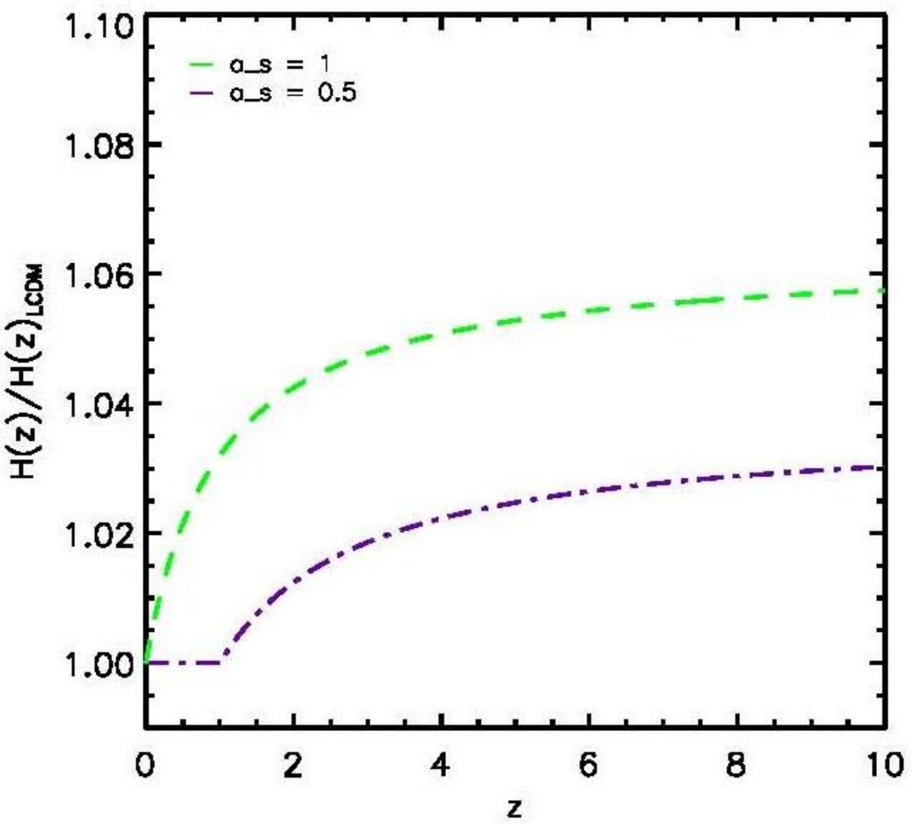
e.g.

2-parameter equation of state

$$w = w_0 + (1-a)w_a$$

Chevallier & Polarski (2001) Linder (2003)

Modified Gravity: Time-varying G



$$\tilde{G} = \mu^2 G_N$$

$$\mu^2 = \begin{cases} \mu_0^2 & \text{if } a < a_* \\ 1 - \frac{a_s - a}{a_s - a_*}(1 - \mu_0^2) & \text{if } a_* \geq a \leq a_s \\ 1 & \text{if } a > a_s\,. \end{cases}$$

Variation consistent with CMB, SS constraints etc. (Umezu et al 2005)

Spacetime varying gravitational constants arise in e.g **Extended Quintessence**

$$S = \int \mathrm{d}^4\mathrm{x}\sqrt{-\mathrm{g}}\{\frac{1}{2\kappa}\mathrm{f}(\phi, \mathrm{R}) - \frac{1}{2}\mathrm{k}(\phi)\phi^{;\mu}\phi_{;\mu} - \mathrm{V}(\phi) + \mathrm{L}_{\mathrm{matter}}\}$$

N-Body Simulations:

Modify N-body code : L-Gadget 2 (Springel 2005)

$N_p = 1024^3 \sim 1 \times 10^9$ particles

L_{box} = **1500 h^{-1} Mpc** - **27 times volume of Millennium simulation**

~4 days on 128 processors

Cosmological parameters
(A. Sánchez at al. 2009)

$$\Omega_m = 0.261$$

$$h = 0.715$$

$$\sigma_8 = 0.8$$

Need to modify expansion history & calculation of growth rate in N-body code

Dark Energy: Quintessence

$$H^2(a) = H_0^2 \left(\frac{\Omega_0}{a^3} + \Omega_{\mathrm{DE}} e^{-3w_a(1-a)} a^{-3(1+w_0+w_a)} \right)$$

and modify force calculation

Modified Gravity: Time-varying G

$$H^2 = H_0^2 \frac{\tilde{G}}{G_N} \left(\frac{\Omega_{\mathrm{m}}}{a^2} + \Omega_{\mathrm{DE}} e^{3 \int_a^1 \mathrm{dlna}'[1+\mathrm{w}(\mathrm{a}')]} \right)$$

Redshift space distortions

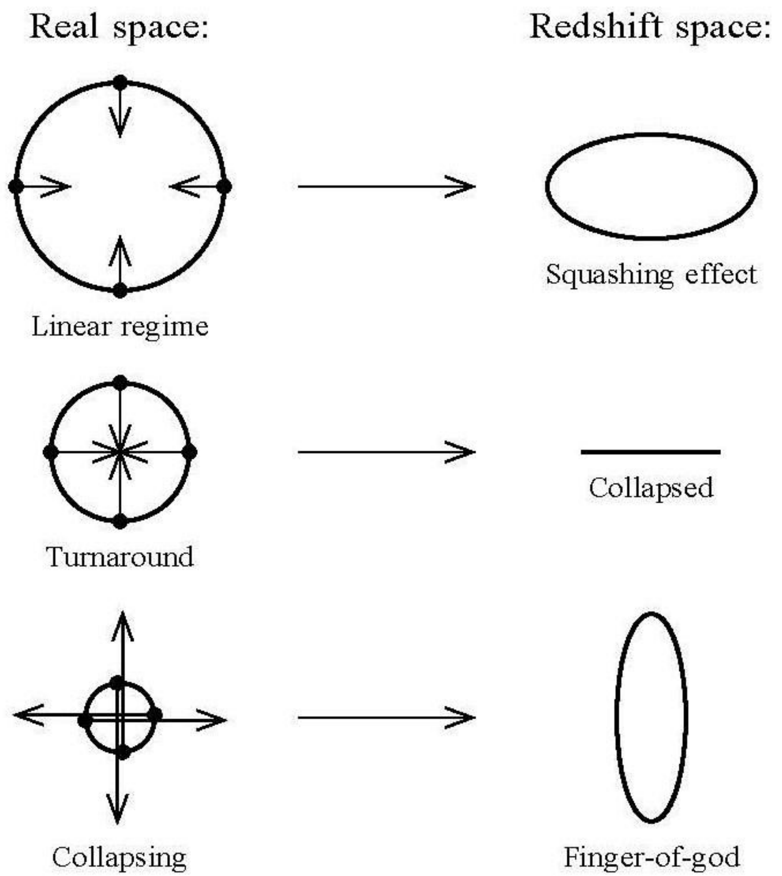
Peculiar velocities affect the inferred distance to an object

$$s = r + v$$

redshift distance | true distance | peculiar velocity

$$\delta_s(r) = \delta_r(r)(1 + \mu^2 \beta)$$

Coherent peculiar motions on large scales distort P(k) measured in redshift space compared to real space.



Hamilton (1997)

$$P_z(k) = (1 + 2/3\beta + 1/5\beta^2)P_r(k)$$

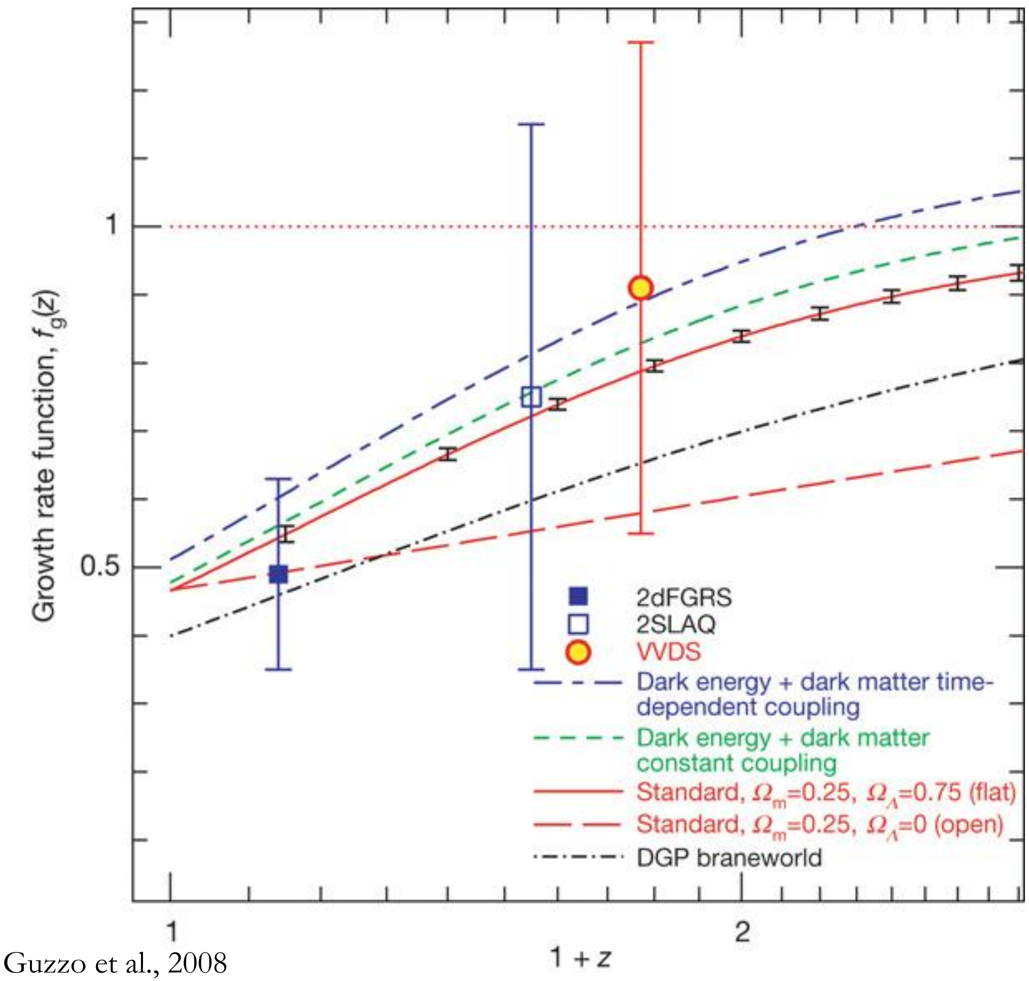
$$\beta = f/b$$

Kaiser (1987)

Redshift space distortions

Current measurements: VIMOS-VLT Deep Survey (VVDS) using 100,000 galaxies out to z~2.

f = 0.91 +/- 0.36 at z = 0.8 (Guzzo et al 2008)



Guzzo et al., 2008

Two things to test

1. How good are the current models for RSD.

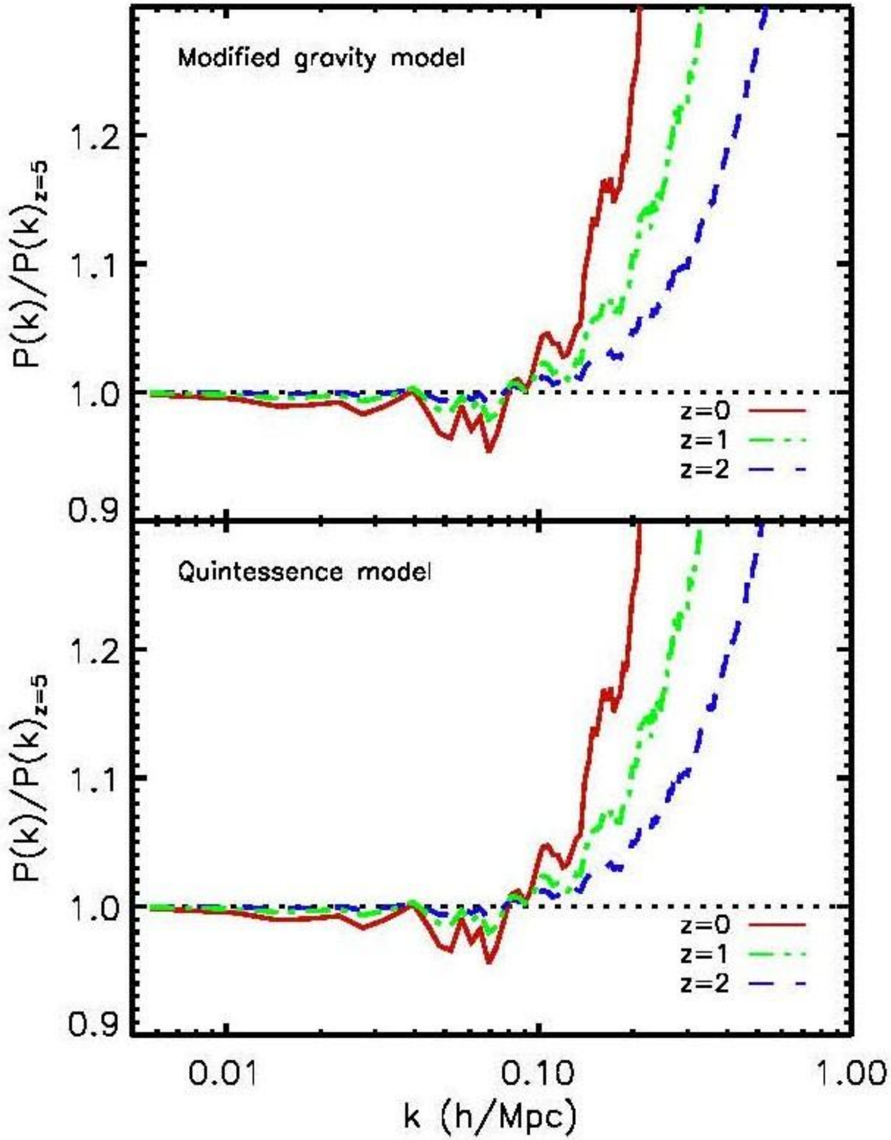
2. Can we distinguish a dark energy model from a MG model if they have the same H(z)?

Measuring the power spectrum from the simulations

$$P(k) = < |\delta_{\rm m}(k)|^2 >$$

Consistency checks of code:
linear theory

$$P(k,z) = \frac{D^2(z)}{D^2(\tilde{z})} P(k,\tilde{z})$$



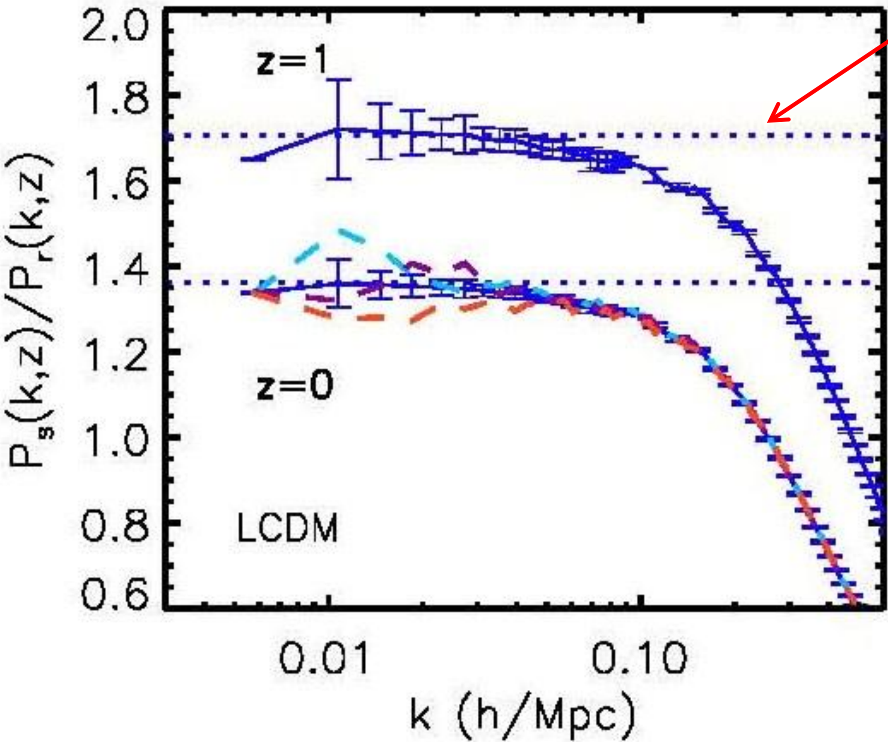
Measuring f from P(k)

LCDM

$$f = \Omega_{\rm m}^{0.55}$$

$$P_0^s(k) = (1 + 2/3f + 1/5f^2)P_r(k)$$

Kaiser linear theory



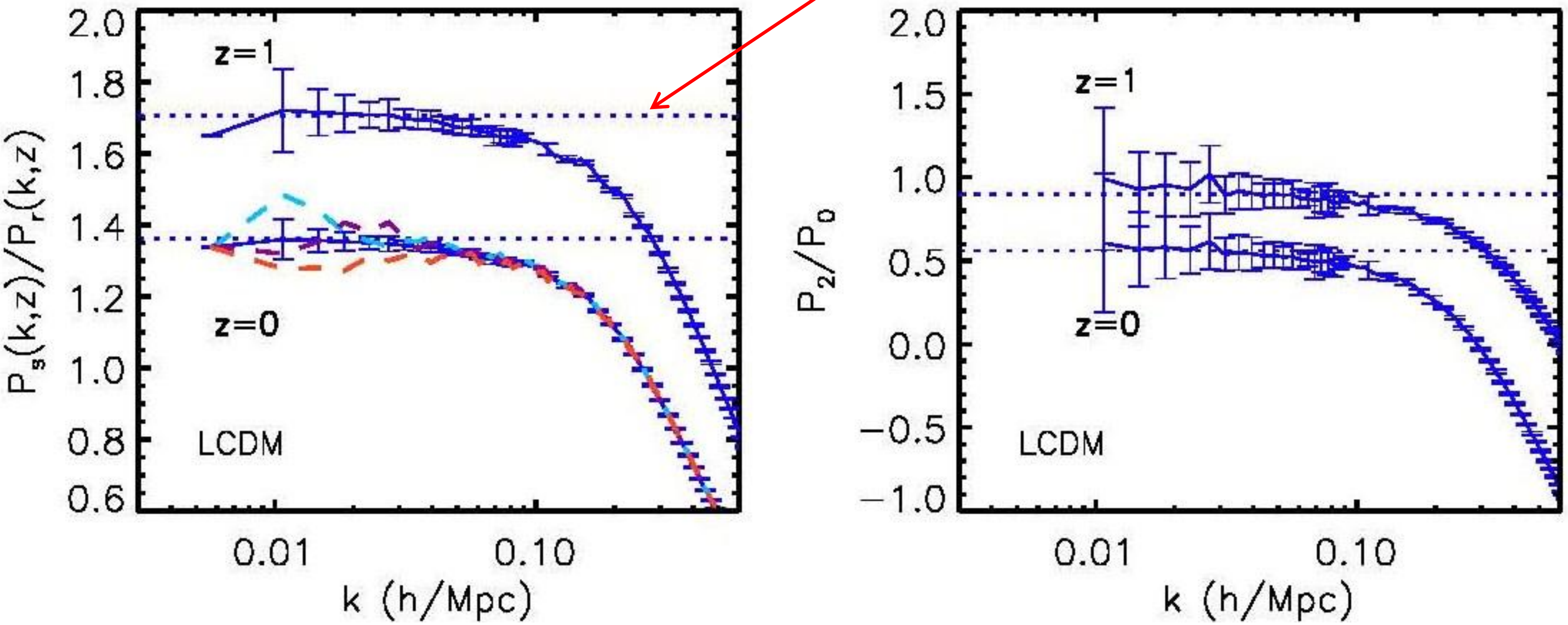
Measuring β from P(k)

LCDM

$$f = \Omega_{\rm m}^{0.55}$$

$$P_0^s(k) = (1 + 2/3f + 1/5f^2)P_r(k)$$

Kaiser linear theory



Quadrupole to monopole ratio

$$P^s(k,\mu) = P_0(k) + 1/2(3\mu^2 - 1)P_2(k) + \cdots$$

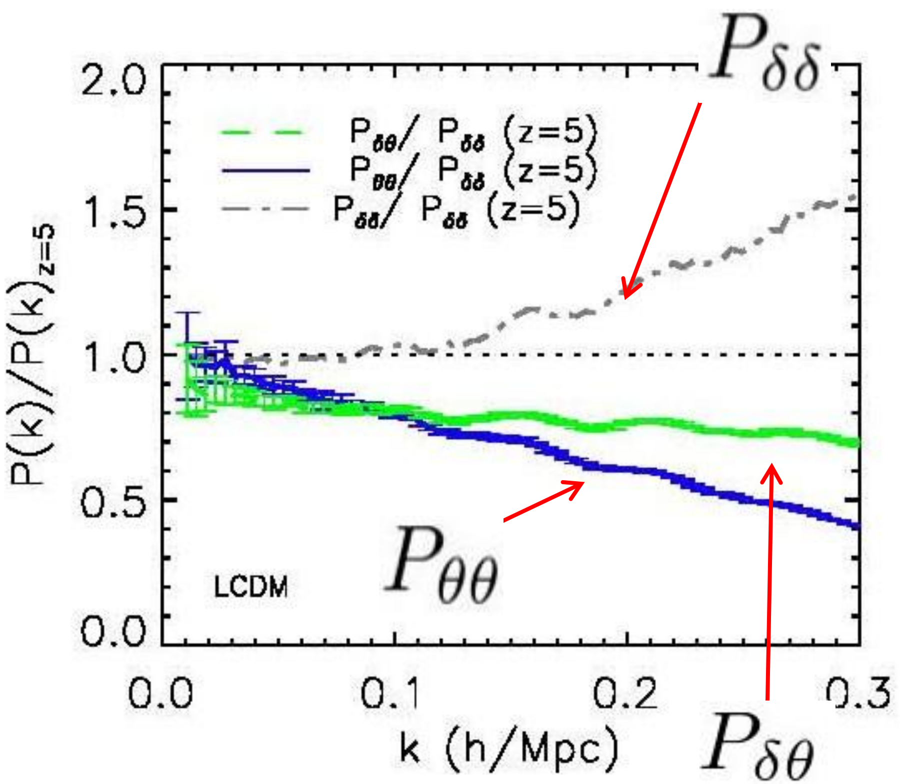
Kaiser formula assumes **velocity divergence non-linearities** can be neglected. Linear continuity eq. ⇒

$$\vec{\nabla}\cdot\vec{v} = \theta = -Hf(a)\delta(a)$$

$P_{\delta\delta}$ Matter power spectrum

$P_{\theta\theta}$ Velocity divergence auto power spectrum

$P_{\delta\theta}$ Velocity divergence cross power spectrum



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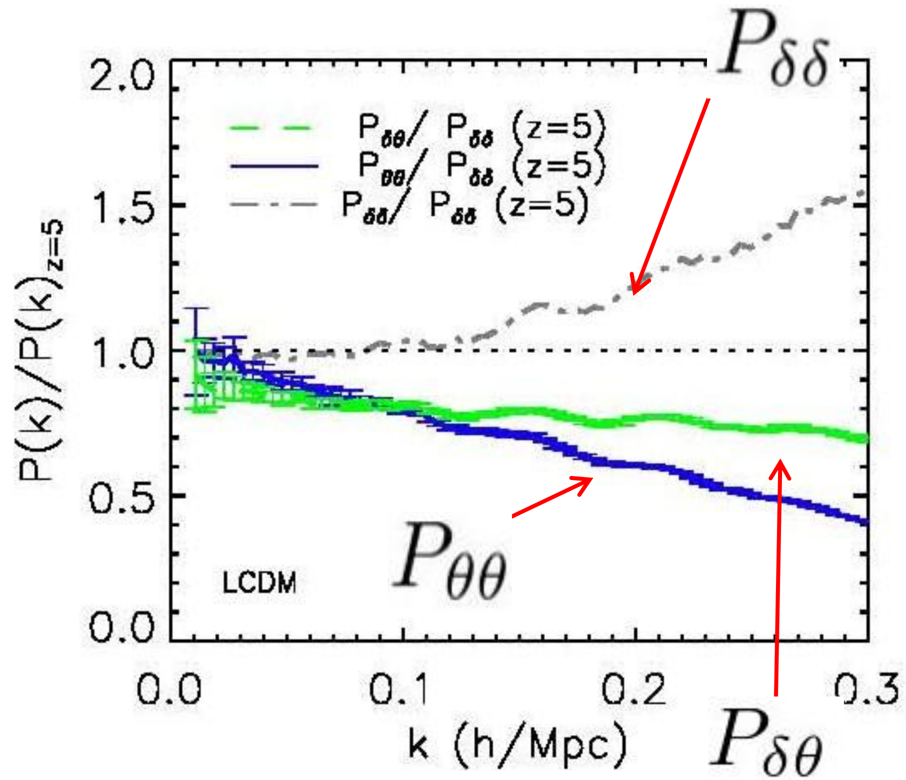

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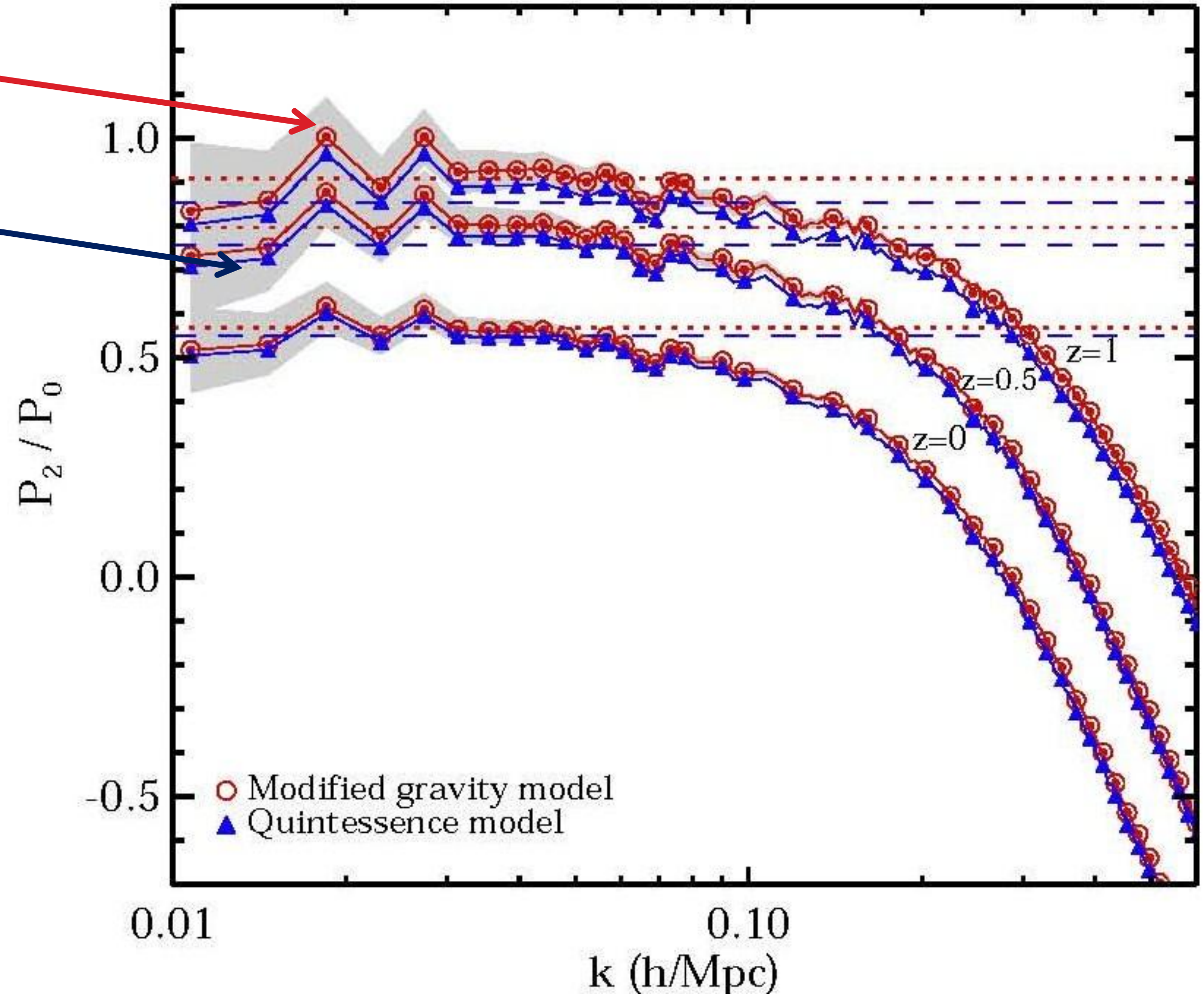
Improved model for redshift space P(k):

$$\boxed{P_s(k,\mu) = P_{\delta\delta}(k) + 2\beta(z)\mu^2 P_{\delta\theta} + \beta^2(z)\mu^4 P_{\theta\theta}(k)}$$

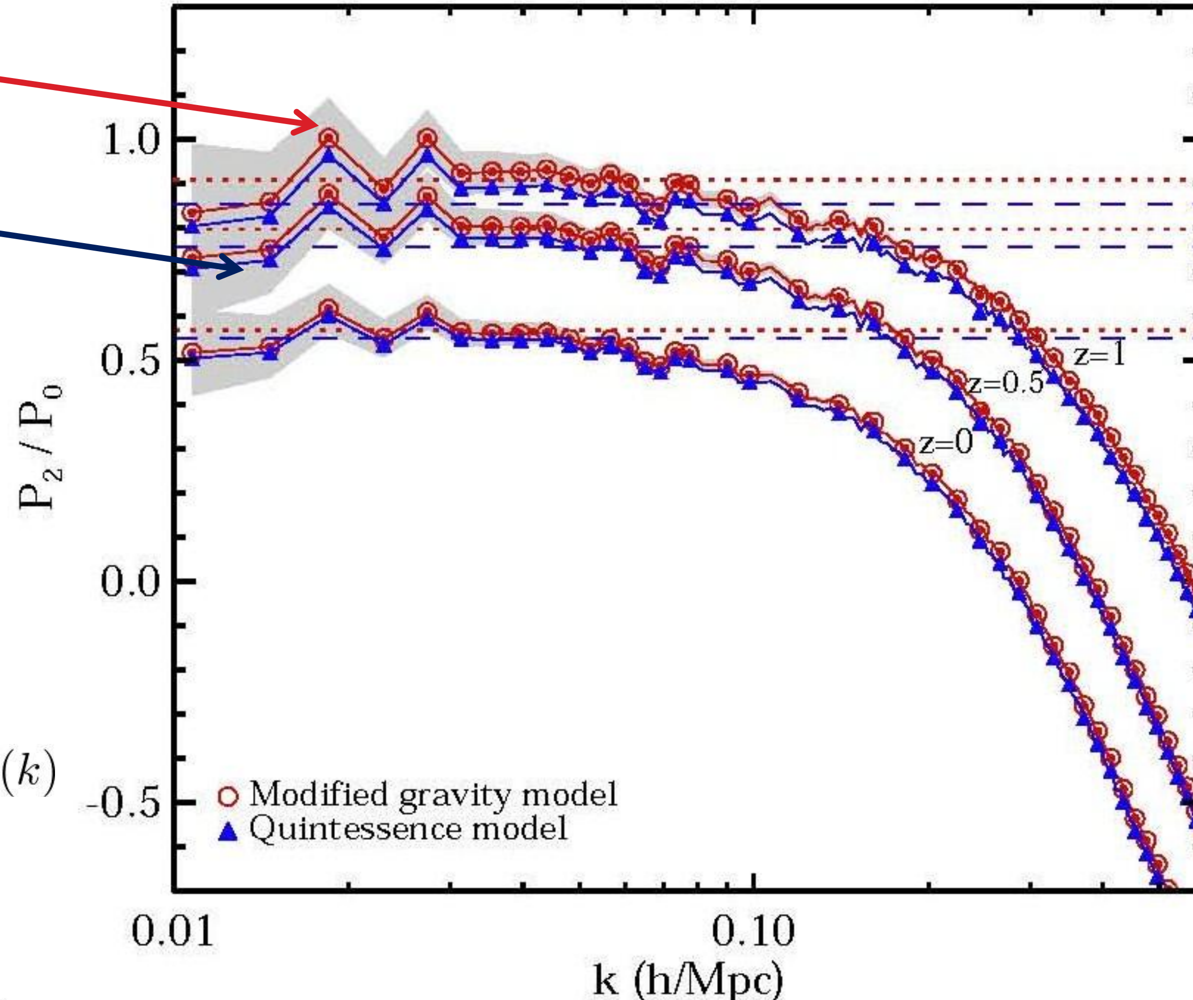
Modified gravity model

Quintessence model



Modified gravity model

Quintessence model



Fit to these ratios using models

Kaiser formula:

$$P_z(k) = (1 + 2/3\beta + 1/5\beta^2)P_r(k)$$

Gaussian model:

$$P^s(k,\mu) = P^r(k)(1+\beta\mu^2)^2 \exp(-\kappa\ \mu\ \sigma_{\mathrm{p}})$$

Velocity divergence model:

$$P^s(k,\mu) = \left(P_{\delta\delta}(k) + 2f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k)\right) e^{-(fk\mu\sigma_v)^2}$$

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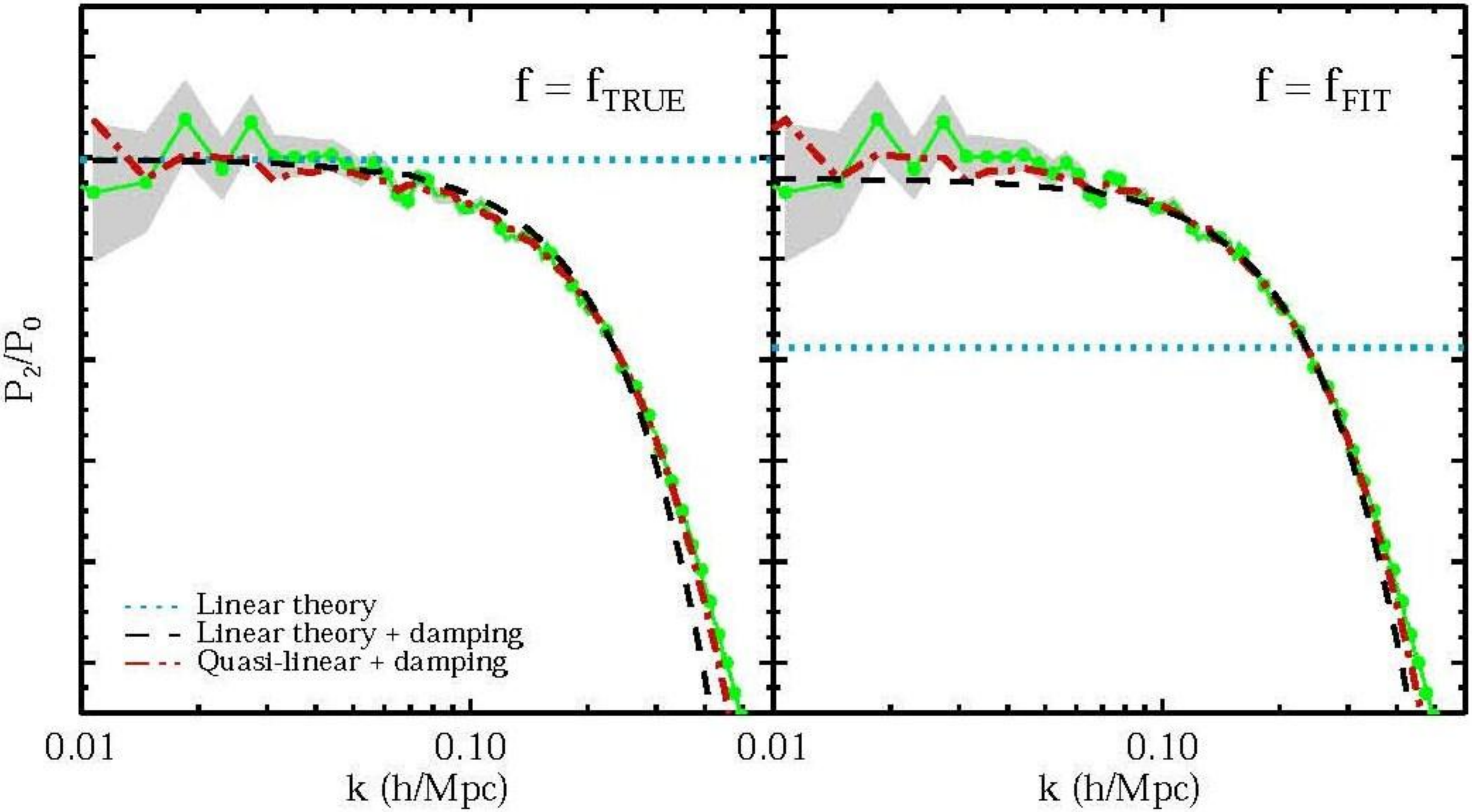
Modelling redshift space distortions



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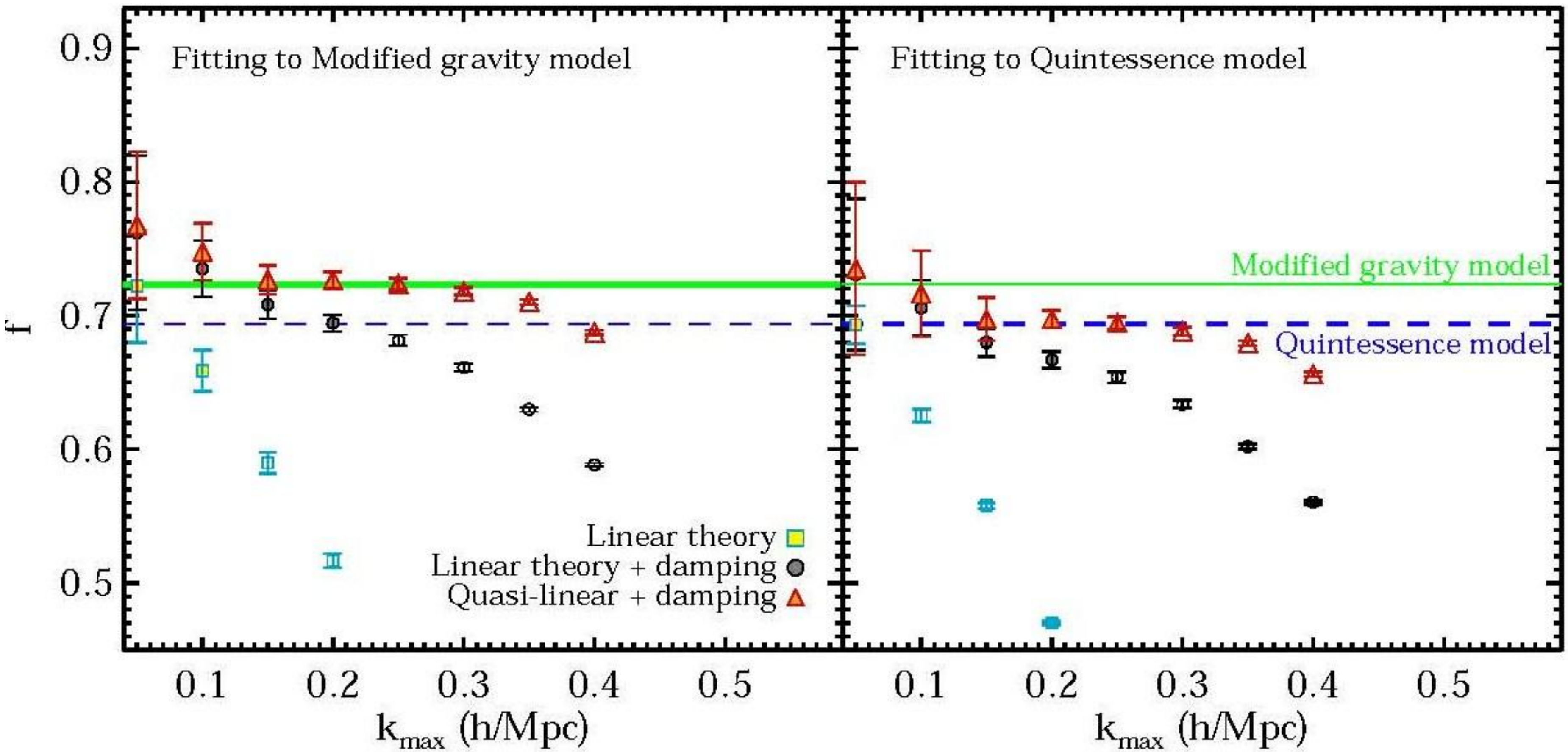
Fitting for f to P_2/P_0 over different intervals in k space

$0.01 < k < k_{max}$



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Summary

Future Dark Energy surveys require precise models

– linear theory predictions no longer good enough

Departures from linear theory due to: non-linear growth, bias, redshift space distortions

Accurate simulations of dark energy/modified gravity are essential

Improved model of redshift space distortions

include non-linear velocity terms

Dark energy model can be distinguished from modified gravity model with same expansion history

Fitting for f on $0.01 < k(h/\mathrm{Mpc}) < 0.3$

Need $H(z)$ to ~4% and f to ~2%

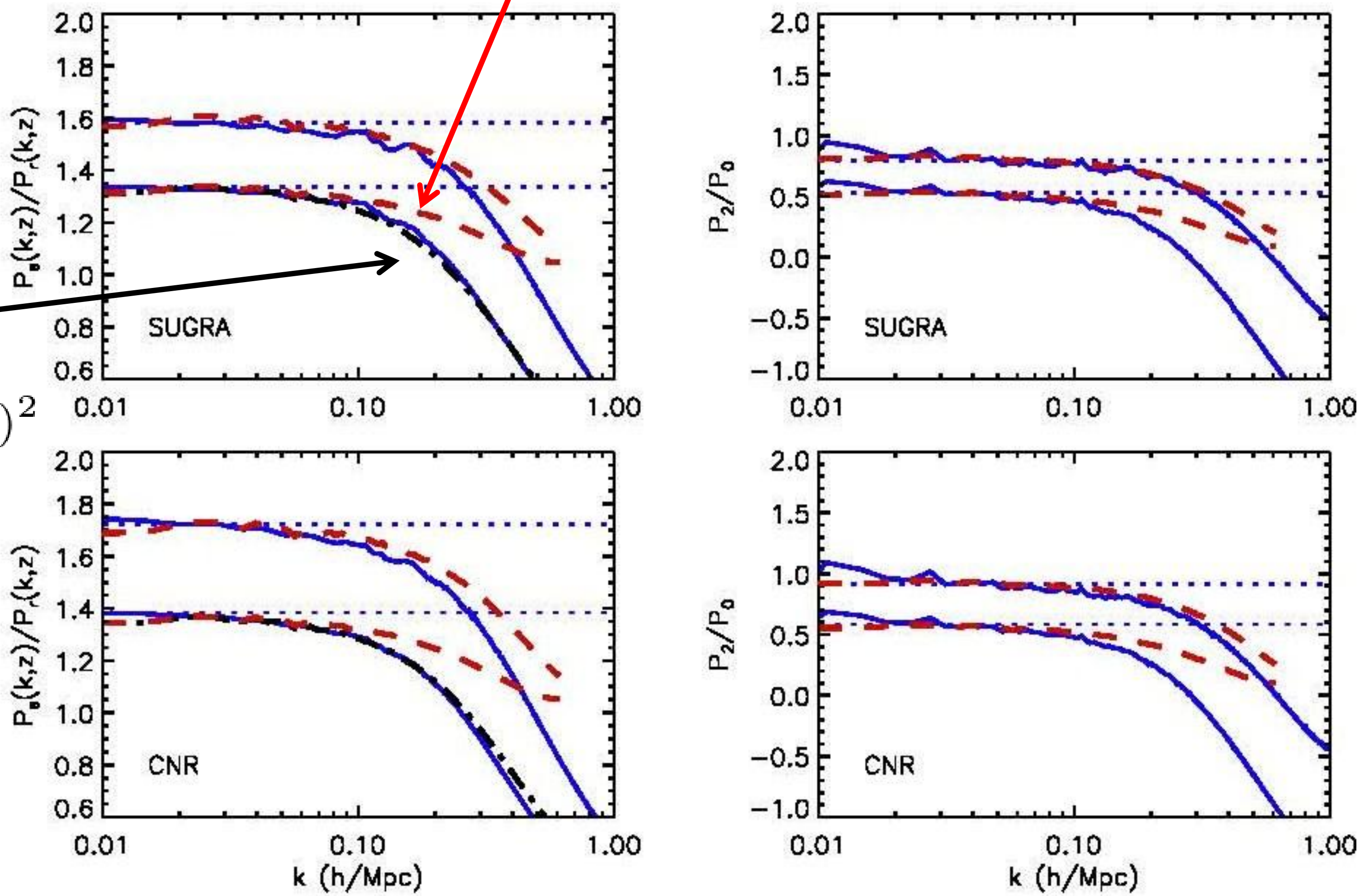
Measuring β from P(k)

Include velocity divergence auto and cross P(k)

$$P_s(k,\mu) = P_{\delta\delta}(k) + 2\beta(z)\mu^2 P_{\delta\theta} + \beta^2(z)\mu^4 P_{\theta\theta}(k)$$

damping term

$$\times e^{-(fk\mu\sigma_v)^2}$$



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