# Testing modified gravity beyond cosmic variance

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# Aims

- How can we distinguish between ΛCDM and alternatives?
- How can we best utilise low-redshift surveys?
- Can we overcome cosmic variance in a self-consistent way?

# The standard model

$\Lambda$CDM attributes accelerated expansion to dark energy

but could there be an alternative explanation?

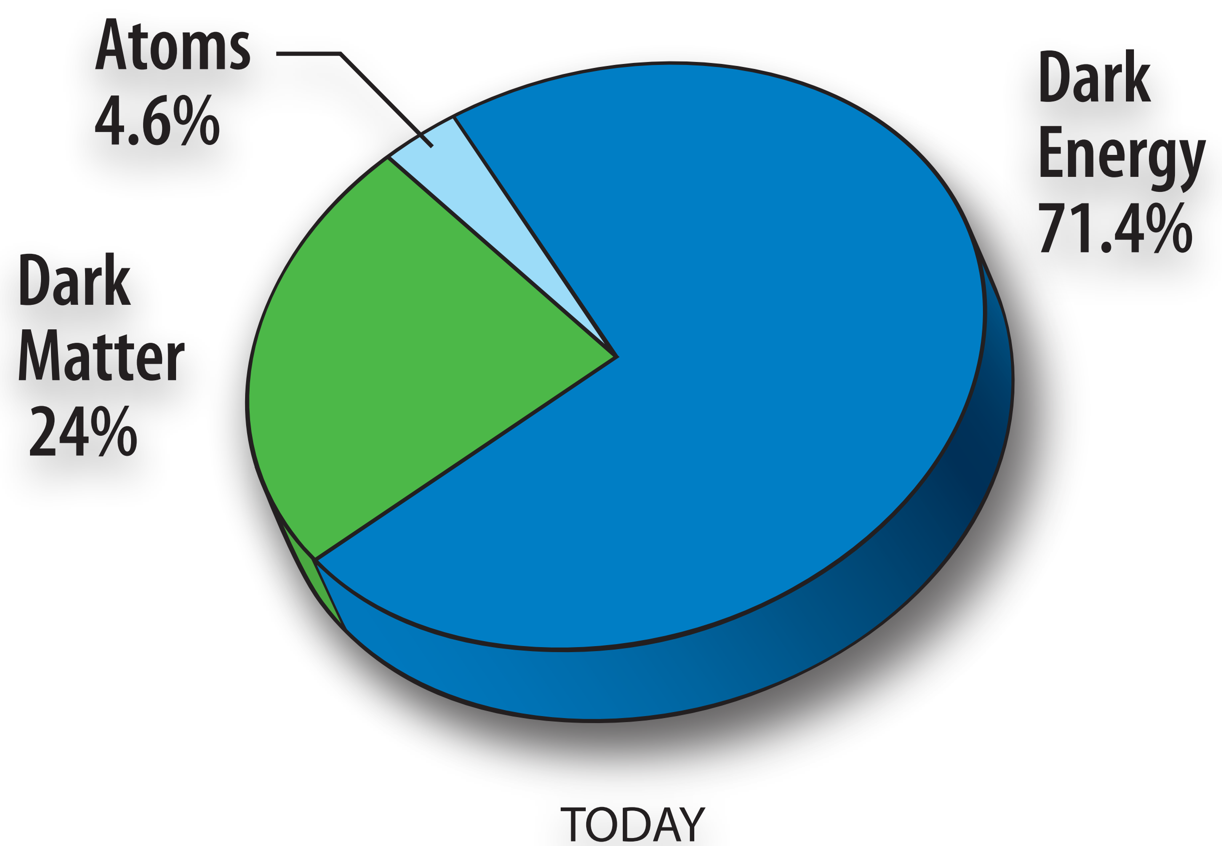



Image from NASA/WMAP

# Modified gravity

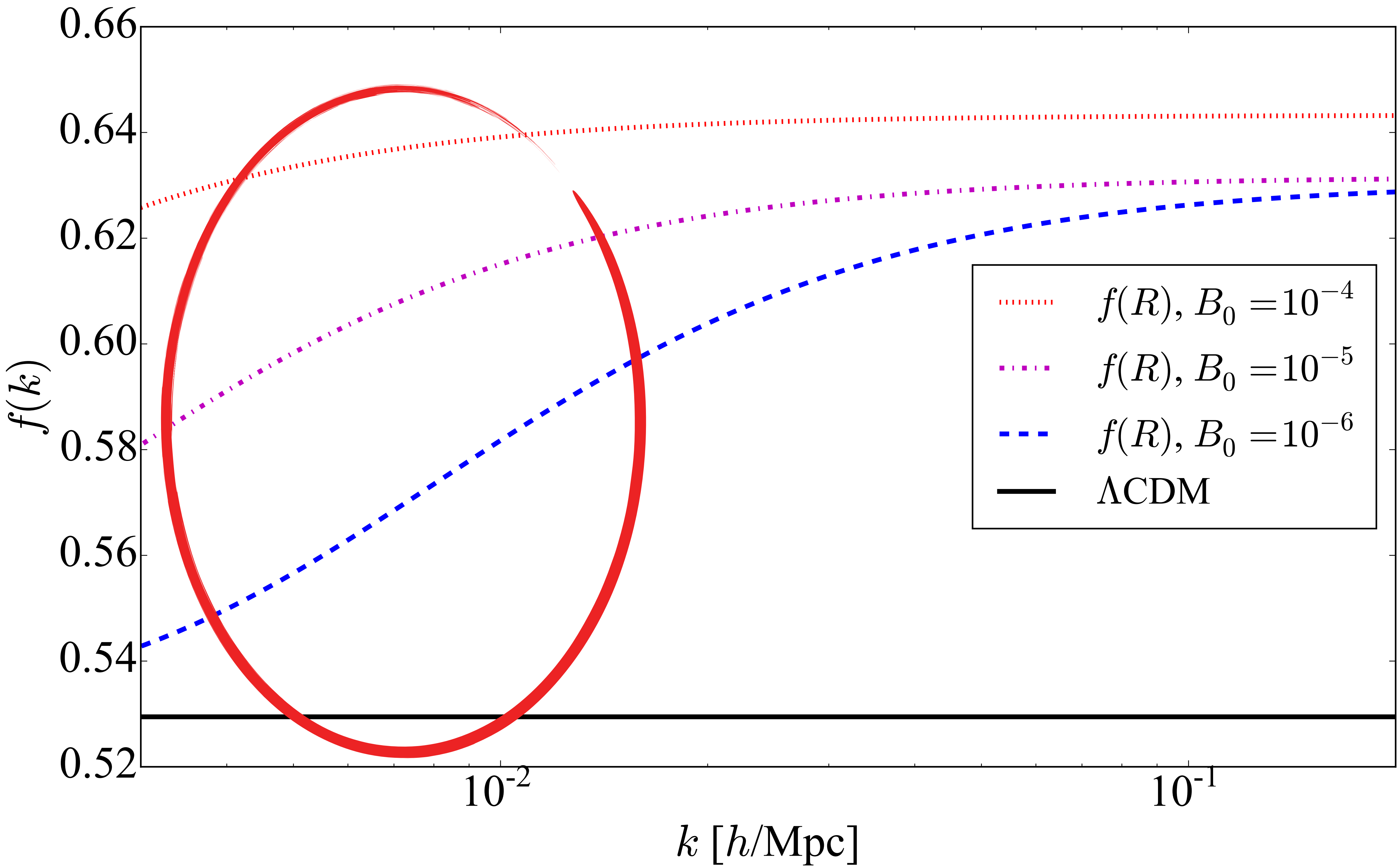
Many physicists are exploring extensions to GR

There are some well established models:

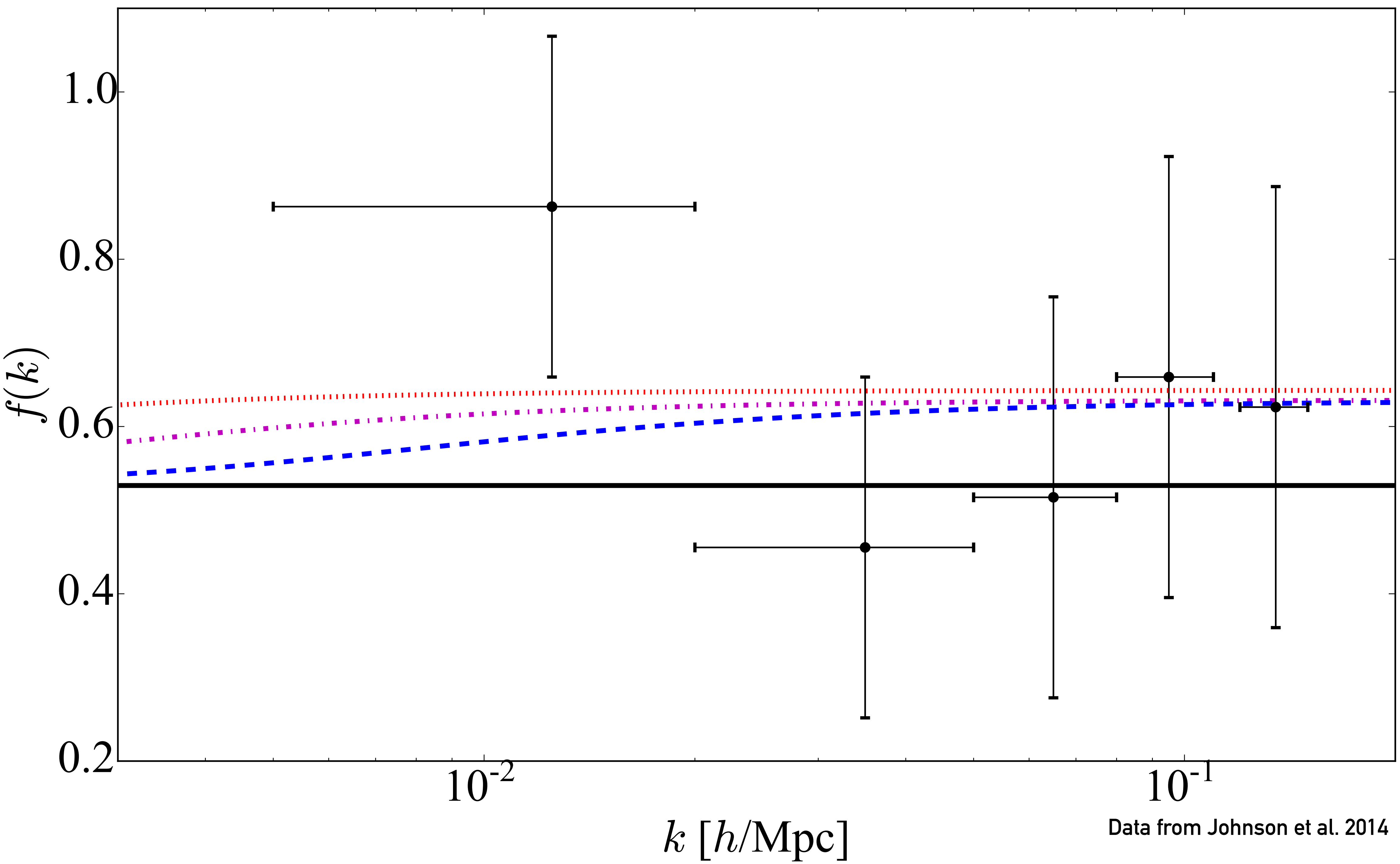
- f(R) models - extending functional form of GR
- Galileon models - addition of a scalar field
- Massive gravity models - graviton has mass

There's also work on observational predictions from generalised forms of modified gravity (Baker et al. 2014)

# Scale-dependence



# Scale-dependence: 6dFGS




Data from Johnson et al. 2014

# Cosmic variance

Measurements on large scales at low redshift are limited by sample variance from the overdensity field

$$v_p \propto f\delta_m$$

A single tracer is limited by this variance

$$\frac{v_p}{\delta_g} \propto \frac{f\delta_m}{b\delta_m} = \frac{f}{b} = \beta$$

But the ratio of tracers is not!

# Covariance model

For data vector

$$\vec{x} = \begin{pmatrix} \vec{\delta_g} \\ \vec{v_p} \end{pmatrix}$$

we can construct

$$\mathcal{L} = \frac{1}{\sqrt{2\pi|C|}} \exp\left(-\frac{1}{2}\vec{x}^T C^{-1} \vec{x}\right)$$

where

$$C = \begin{pmatrix} \Sigma_{gg} & \Sigma_{gv} \\ \Sigma_{vg} & \Sigma_{vv} \end{pmatrix}$$

# Covariance model

$$C = \begin{pmatrix} \Sigma_{gg} & \Sigma_{gv} \\ \Sigma_{vg} & \Sigma_{vv} \end{pmatrix}$$

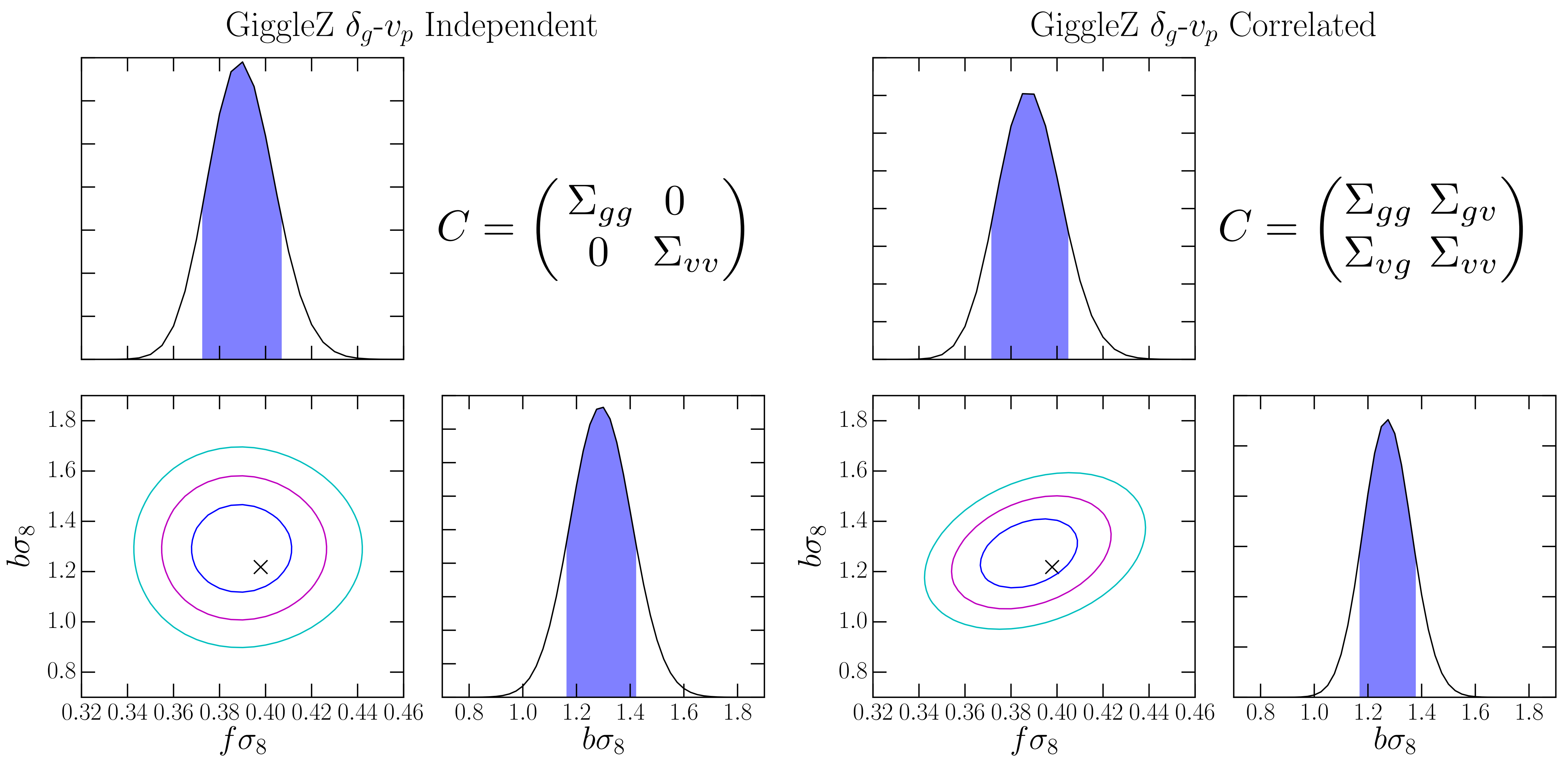
free parameters: $f\sigma_8,\ b\sigma_8,\ \sigma_v^2$

$$\Sigma_{gg}(\vec{x}_i,\vec{x}_j) = (b\sigma_8)^2 \int_0^{k_{\rm max}} \frac{k^2}{2\pi^2} P_{mm}(k) W_{gg}(k,\vec{x}_i,\vec{x}_j)\ dk\ + \delta_{ij}\frac{1}{N_{{\rm exp}_i}}$$

$$\Sigma_{gv}(\vec{x}_i,\vec{x}_j) = (fb\sigma_8^2) \int_0^{k_{\rm max}} \frac{k}{2\pi^2} P_{mm}(k) W_{gv}(k,\vec{x}_i,\vec{x}_j)\ dk$$

$$\Sigma_{vv}(\vec{x}_i,\vec{x}_j) = (f\sigma_8)^2 \int_0^{k_{\rm max}} \frac{1}{2\pi^2} P_{mm}(k) W_{vv}(k,\vec{x}_i,\vec{x}_j)\ dk\ + \delta_{ij}(\sigma^2_{{\rm obs}_i} + \sigma_v^2)$$

# Results: GiggleZ simulation

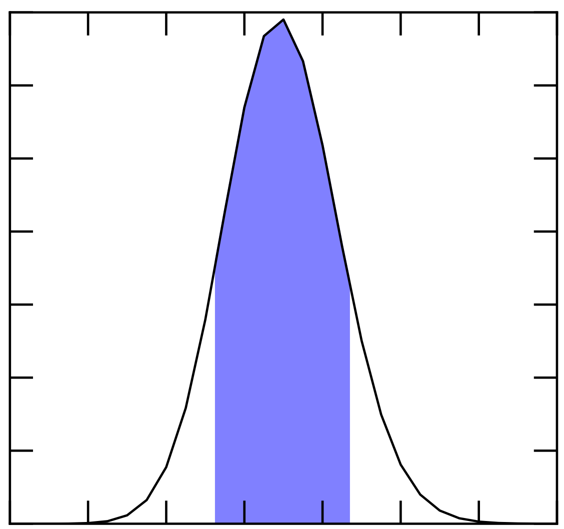



$$C = \begin{pmatrix} \Sigma_{gg} & 0 \\ 0 & \Sigma_{vv} \end{pmatrix}$$

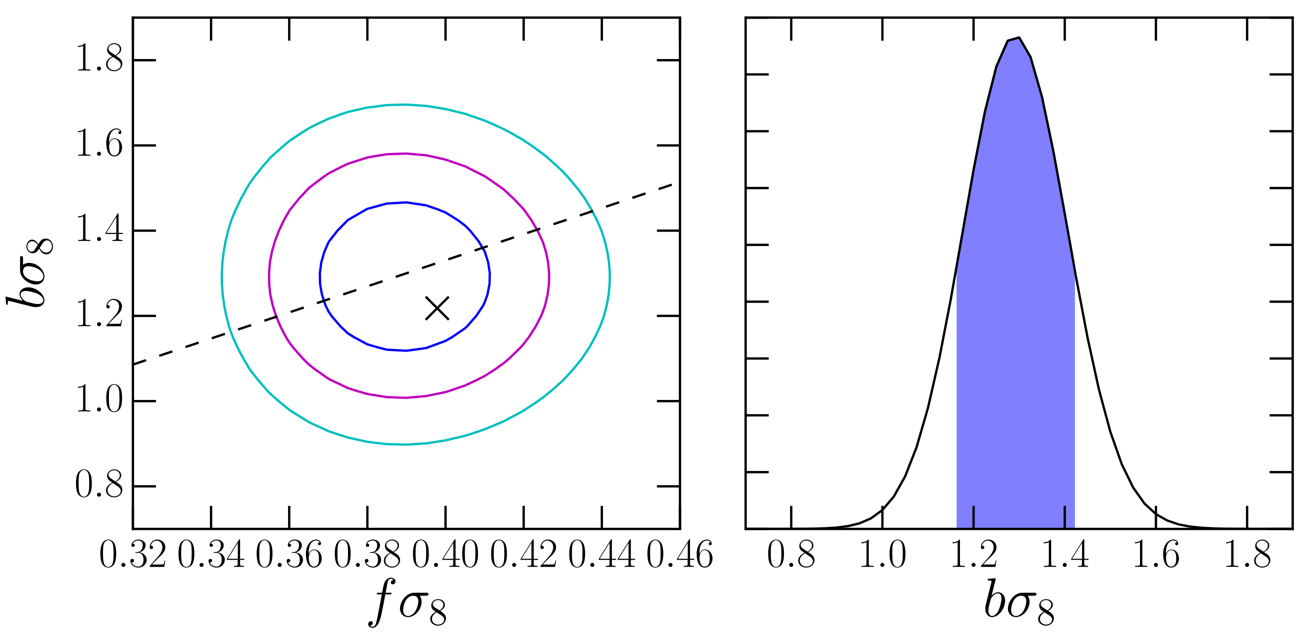
$$C = \begin{pmatrix} \Sigma_{gg} & \Sigma_{gv} \\ \Sigma_{vg} & \Sigma_{vv} \end{pmatrix}$$

# Results: GiggleZ simulation

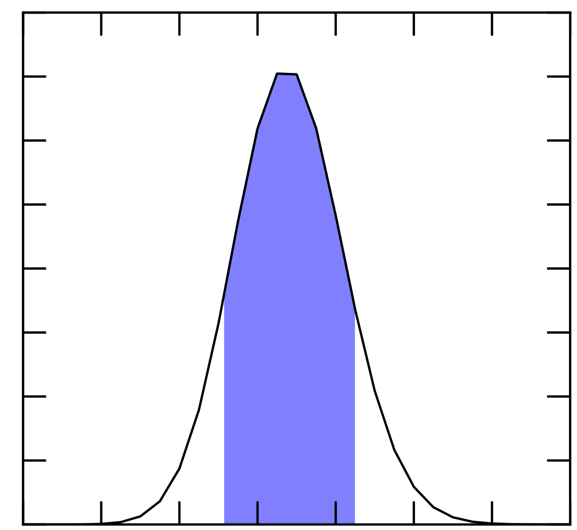
GiggleZ $\delta_g$-$v_p$ Independent



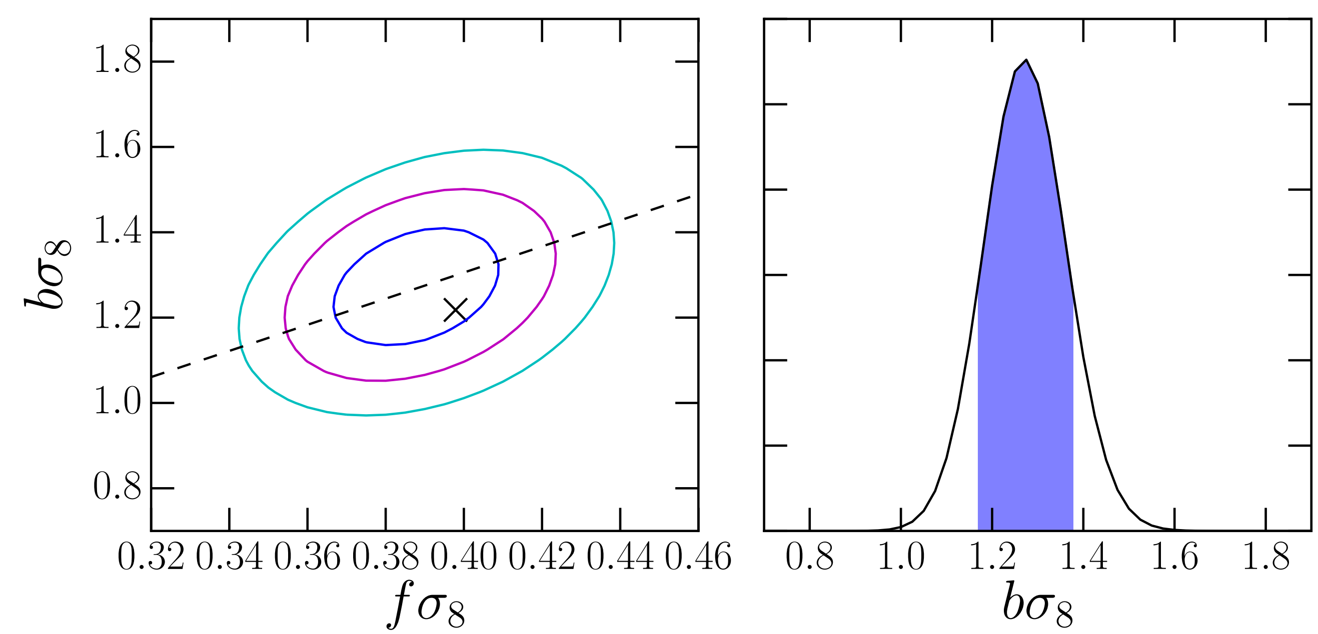
$$C = \begin{pmatrix} \Sigma_{gg} & 0 \\ 0 & \Sigma_{vv} \end{pmatrix}$$



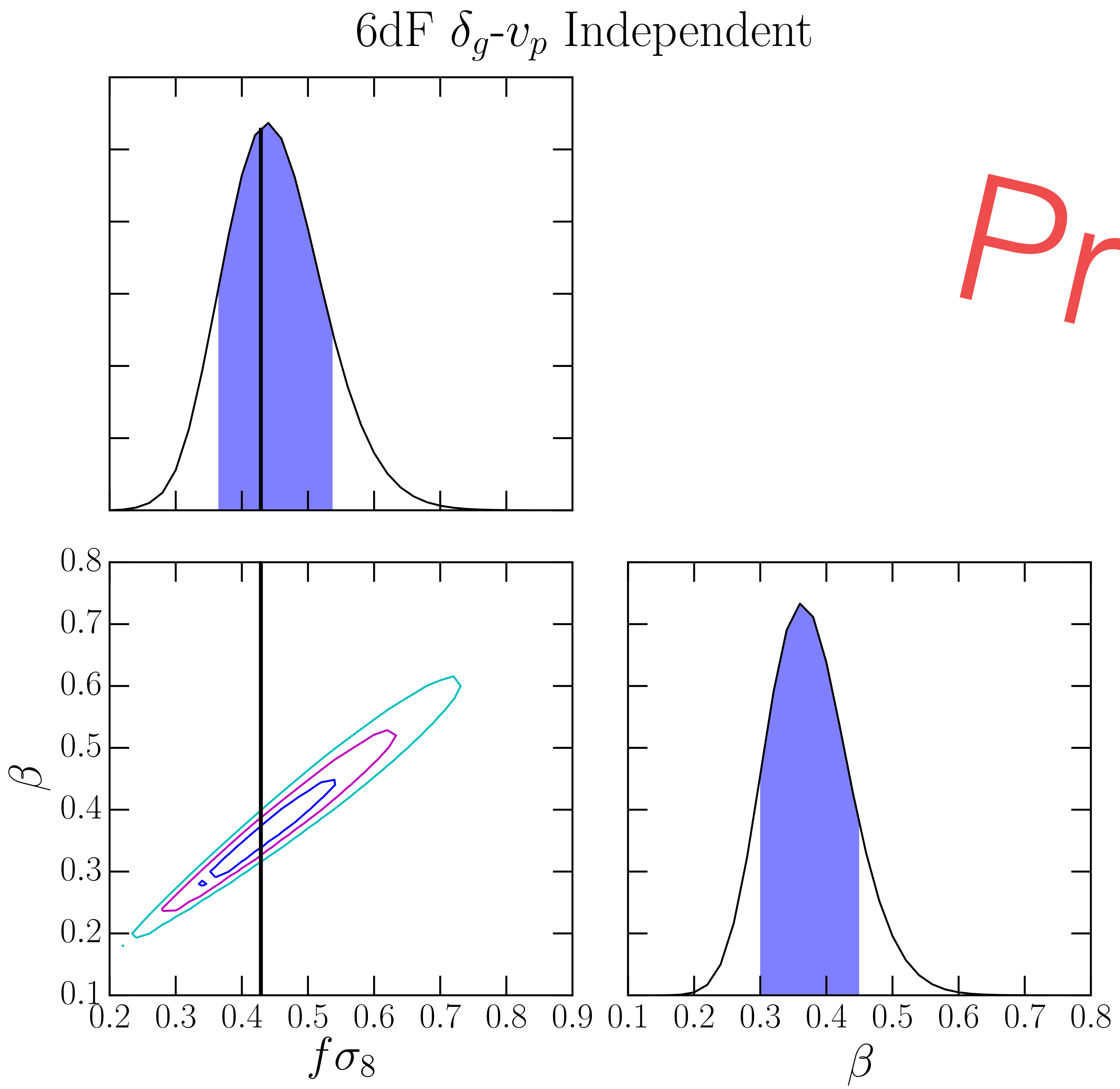

GiggleZ $\delta_g$-$v_p$ Correlated



$$C = \begin{pmatrix} \Sigma_{gg} & \Sigma_{gv} \\ \Sigma_{vg} & \Sigma_{vv} \end{pmatrix}$$



# Results: 6dFGS



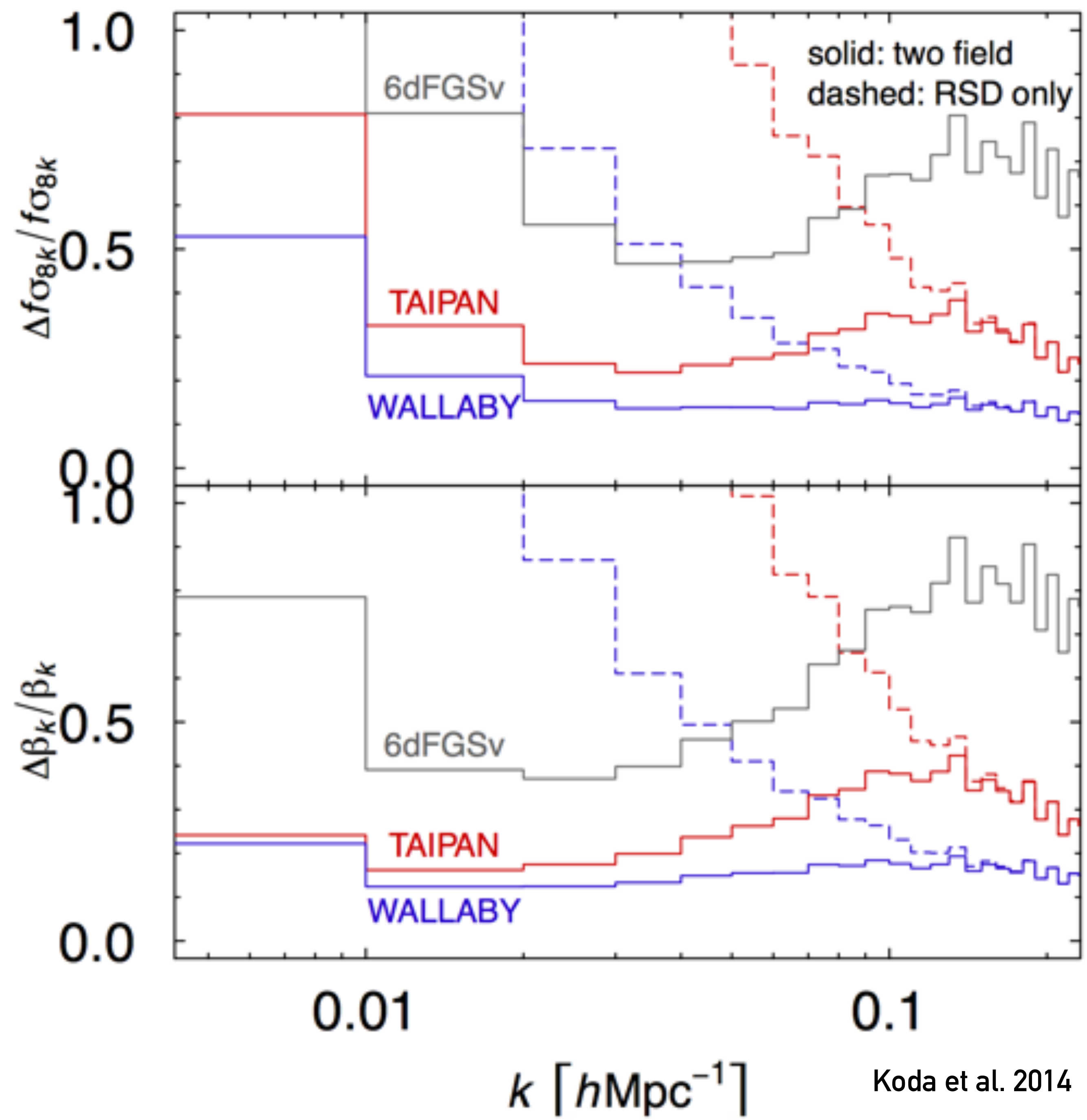

Preliminary

$$f\sigma_8 = 0.44^{+0.09}_{-0.07}$$

$$\beta = 0.37^{+0.09}_{-0.06}$$

# Upcoming: Taipan

| | Constraint (β) |
|---|---|
| 6dFGS | 16% |
| Taipan | 7.4% |
| WALLABY | 3.8% |




Koda et al. 2014

# Take home points

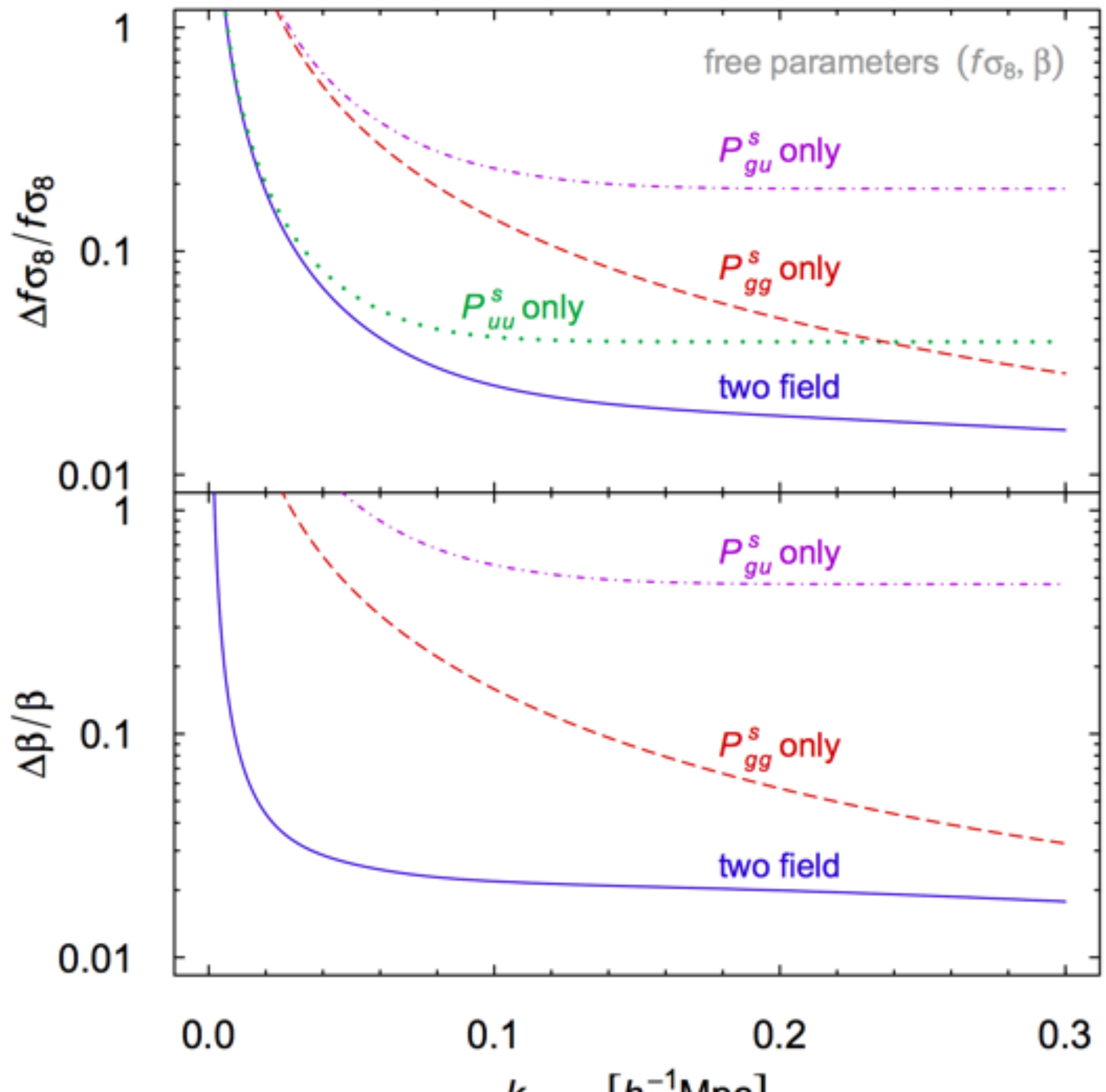
- Scale-dependent measurements can distinguish between the standard model and modified gravity models
- Modelling the covariance of velocities and overdensities will provide a measure of $\beta(k)$
- Beating down cosmic variance through multiple probes will provide tighter constraints on $f(k)$

# Bonus Slide: Peculiar velocities

In Fourier Space:

$$\vec{v_p}(\vec{k}) = -\frac{iaHf\hat{k}}{k}\delta(\vec{k})$$

1/k dependence means velocities are sensitive to large modes (small k)




Koda et al. 2014

# Bonus Slide: Peculiar velocities

Peculiar velocities are non-Gaussian, so apply a transform:

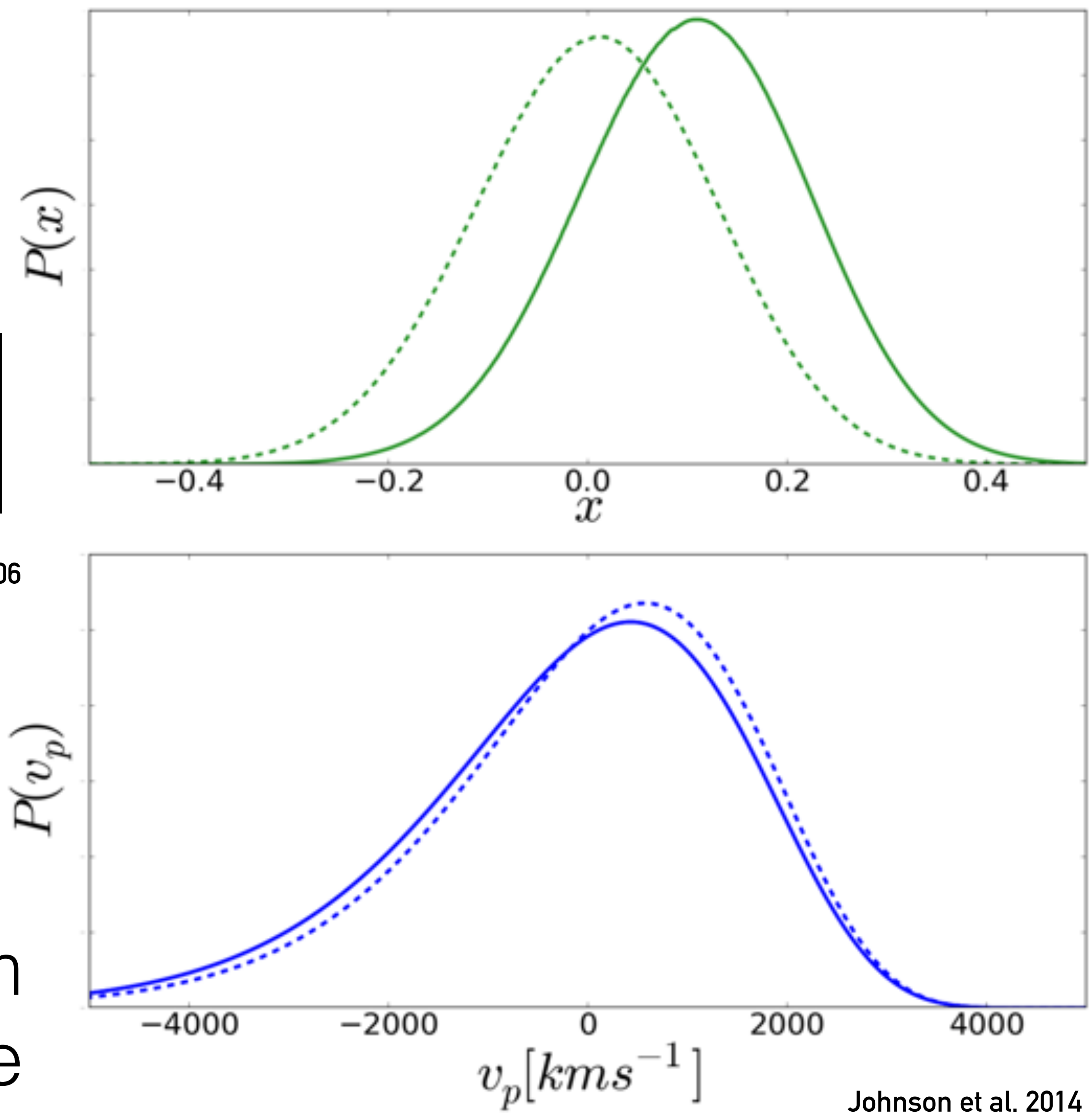
$$x = \frac{1}{\ln(10)} \frac{v_p}{c} \left[ 1 - \frac{(1+z)c}{H(z)\chi_z} \right]$$

Hui & Greene 2006

For:

$$x = \log_{10}\left(\frac{\chi_z}{\chi_H}\right)$$

measured from Fundamental Plane




Johnson et al. 2014

# Bonus Slide: Exact equations

$$\Sigma_{\mu\nu} = A_\mu A_\nu \int_0^{k_{\max}} \frac{k^n}{2\pi^2} P_{\text{matter}}(k) W_{\mu\nu}(k) dk + \text{error}$$

| | $A_\mu A_\nu$ | $n$ | $W(k)$ | error |
|---|---|---|---|---|
| $\delta_g \delta_g$ | $b^2 {\sigma_8}^2$ | 2 | $j_0(kr)$ | $\frac{1}{N_{\text{exp}_i}}$ |
| $\delta_g v_p$ | $f b {\sigma_8}^2$ | 1 | $aH(\hat{r} \cdot \hat{x_v})$ | 0 |
| $v_p v_p$ | $f^2 {\sigma_8}^2$ | 0 | $(aH)^2 \left[\frac{1}{3}\cos\alpha\,(j_0(kr) - 2j_2(kr)) + \frac{x_\delta x_v}{r^2} j_2(kr)\sin^2\alpha\right]$ | $\sigma^2_{\text{obs}} + \sigma^2_v$ |