

Watching Galaxies Fall:

structure formation in the universe as a
probe of gravity

David Parkinson
University of Queensland

Summary

- Introduction

- *Modified gravity - why change a good thing?*

- Theory of Structure formation

- *Motion of matter, galaxies as test particles*
 - *Motion of light, photons as test particles*

- Cosmological data

- *Redshift-Space distortions (WiggleZ, BOSS, 2dFLenS)*
 - *Weak gravitational lensing (CFHTLenS, KiDS, DES)*

- Beyond potentials - fifth forces

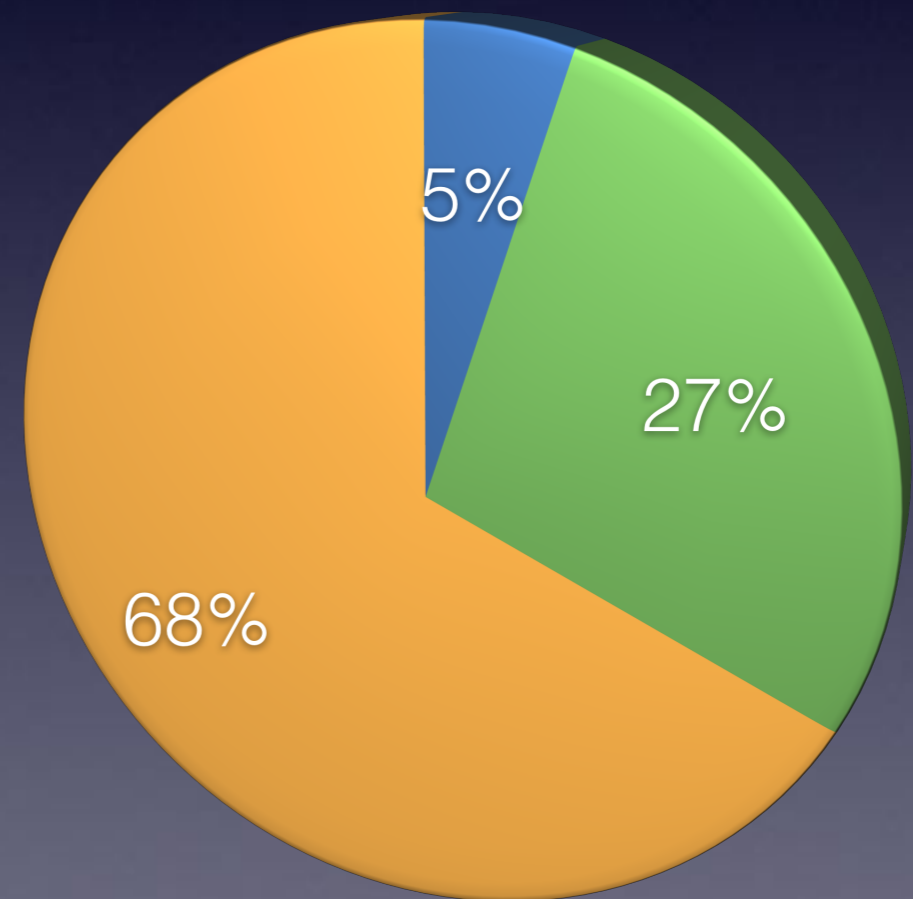
- *Deterministic and stochastic velocity bias*

- Conclusions

Testing gravity

- The expansion of the Universe is accelerating
- The simplest explanation of a cosmological constant is problematic
- Vacuum energy calculations imply cosmological constant is 10^{120} times larger than its measured value - too small
- Coincidence problem - why is density of matter ($1/a^3$) so close to density of dark energy (\sim constant) today?

● Baryons
● Dark Matter
● Dark Energy



Cosmological Constant Problem

- Why is the energy density of the vacuum so small?
- Alternatively we can ask, why does the vacuum energy gravitate so little?
 - “The effective Newton constant becomes very small at large length scales, so that sources with immense wavelengths and periods -- such as the vacuum energy-- produce minuscule curvature” (Arkani-Hamed, Dimopoulos, Dvali, Gabadadze)
 - Similar to the manner in which long wavelength excitations beyond the Debye sphere are screened by the effective photon mass in a plasma.

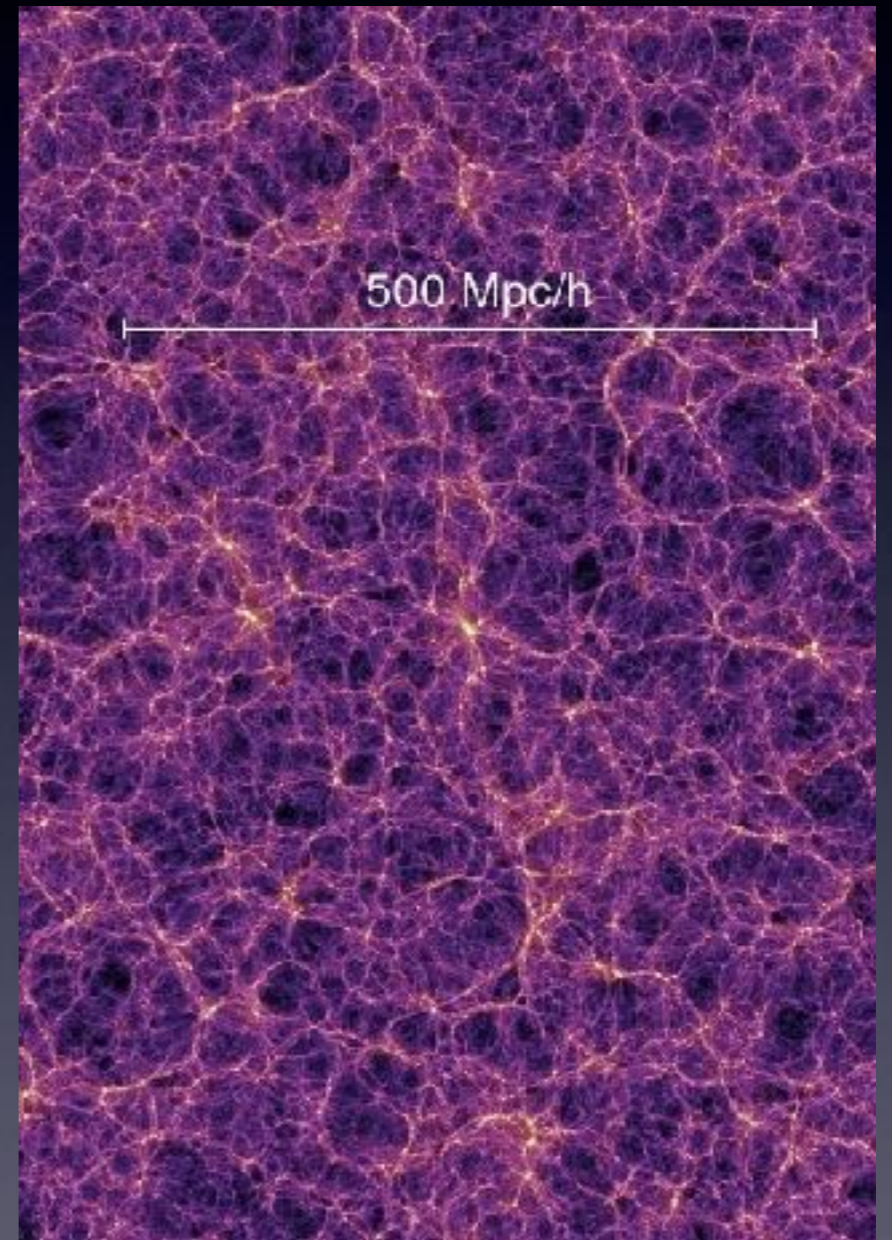
Modified Gravity

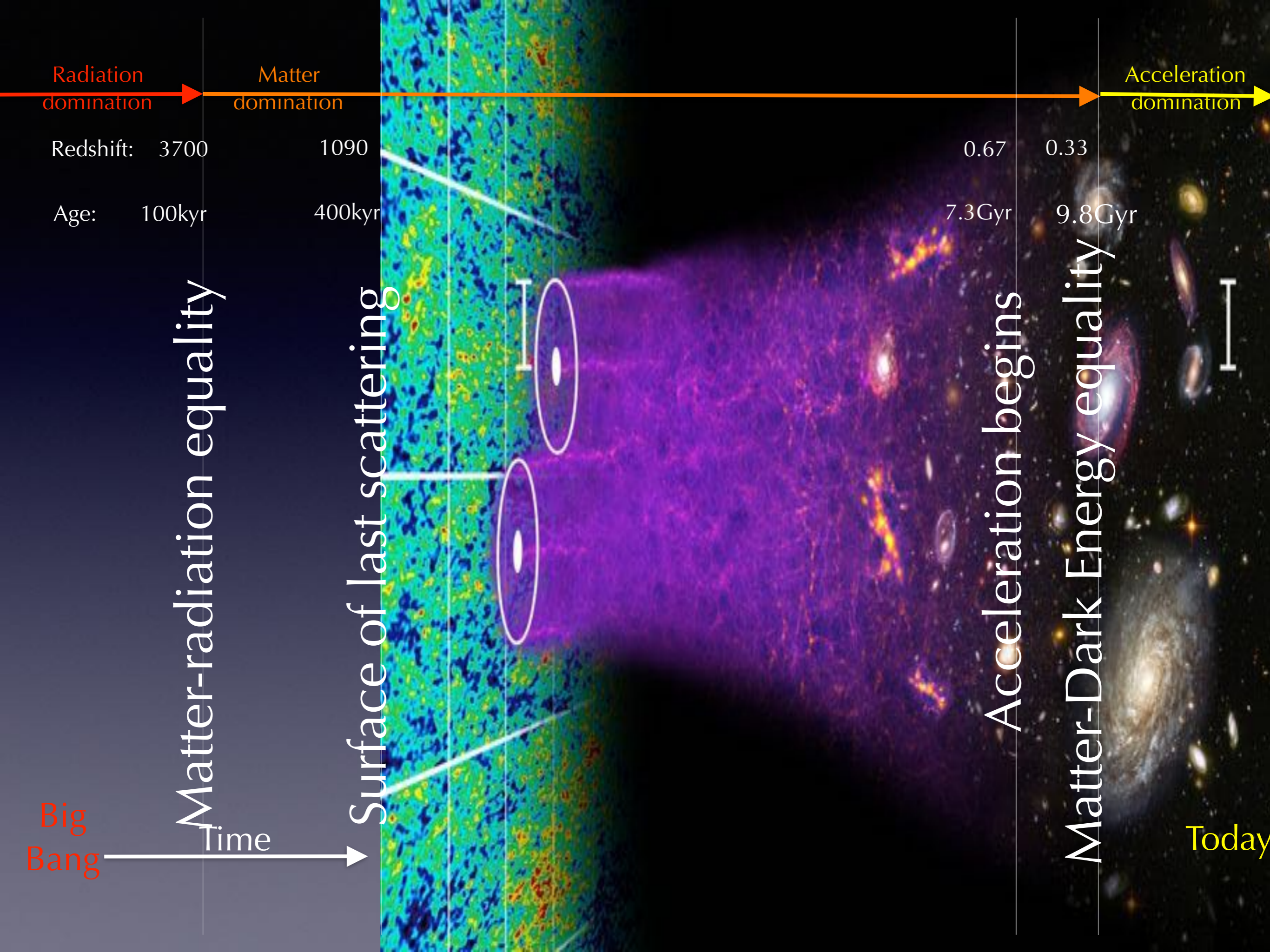
- Consider this as a change in the theory of gravity at large scales
- Can be either:
 - gravity gets weaker on large scales, owing to extra-dimension effects (Dvali-Gabadadze-Porrati model)
 - graviton has (induced) mass, meaning it does not propagate in the expected manner on large scales (massive gravity)
- Theories like this predict existence of extra degrees of freedom
 - The scalar degrees of freedom will affect the generation and propagation of gravitational instabilities

Theory of Structure Formation

Tracing structure

- Our observable universe is filled with structure, on all scales
- It's only visible through galaxies
 - The relation between distribution of galaxies and matter is given by the 'bias'
- Galaxies here are functioning as test particles
 - tracing out the gravitational field





Radiation
domination

Matter
domination

Acceleration
domination

Redshift: 3700

1090

0.67

0.33

Age: 100kyr

400kyr

7.3Gyr

9.8Gyr

Matter-radiation equality

Surface of last scattering

Acceleration begins

Matter-Dark Energy equality

Big
Bang

Time

Today

Post-recombination: Perturbation theory

- Metric:

$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)d\mathbf{x}^2$$

- The force equation for matter is

$$\frac{d\theta_m}{dt} = -2H\theta_m - \frac{\partial^2}{a^2}\Psi$$

- The perturbation equation is

$$\frac{d\delta_m}{dt} = -\theta_m - \dot{\Phi}$$

- From these we derive the growth equation

$$\ddot{\delta} = 2H\theta - \frac{k^2}{a^2}\Psi$$

Einstein Gravity

- Here the Newtonian potential Φ is given by the Poisson equation

$$-k^2 \Phi = 8\pi G \frac{a^2}{2} \left(\rho \delta + 3H(\rho + p) \frac{a^2}{k^2} \theta \right),$$

- If we assume no anisotropic stress, $\Phi = -\Psi$ and so we can complete the system (assuming matter domination, and sub-horizon scales)

$$\ddot{\delta} = -2H\dot{\delta} + 4\pi G\rho\delta$$

- In the completely matter dominated limit, $\delta \sim a$
- In the quasi-static limit, the growth of matter fluctuations can be written as

$$\frac{d \ln \delta}{d \ln a} \equiv f = -\frac{\theta_m}{H \delta_m}$$

Modified Gravities

- Single fluctuation generated by Newtonian potential Ψ

$$\delta_m(k) = T_{\Phi}^{\delta_m}(k) \Phi_*(k)$$

$$\theta_m(k) = T_{\Phi}^{\theta_m}(k) \Phi_*(k)$$

- transfer function $T(k)$: describes how initial metric fluctuation is reprocessed into a late-time configuration of the species
- Growth rate now has a more general form

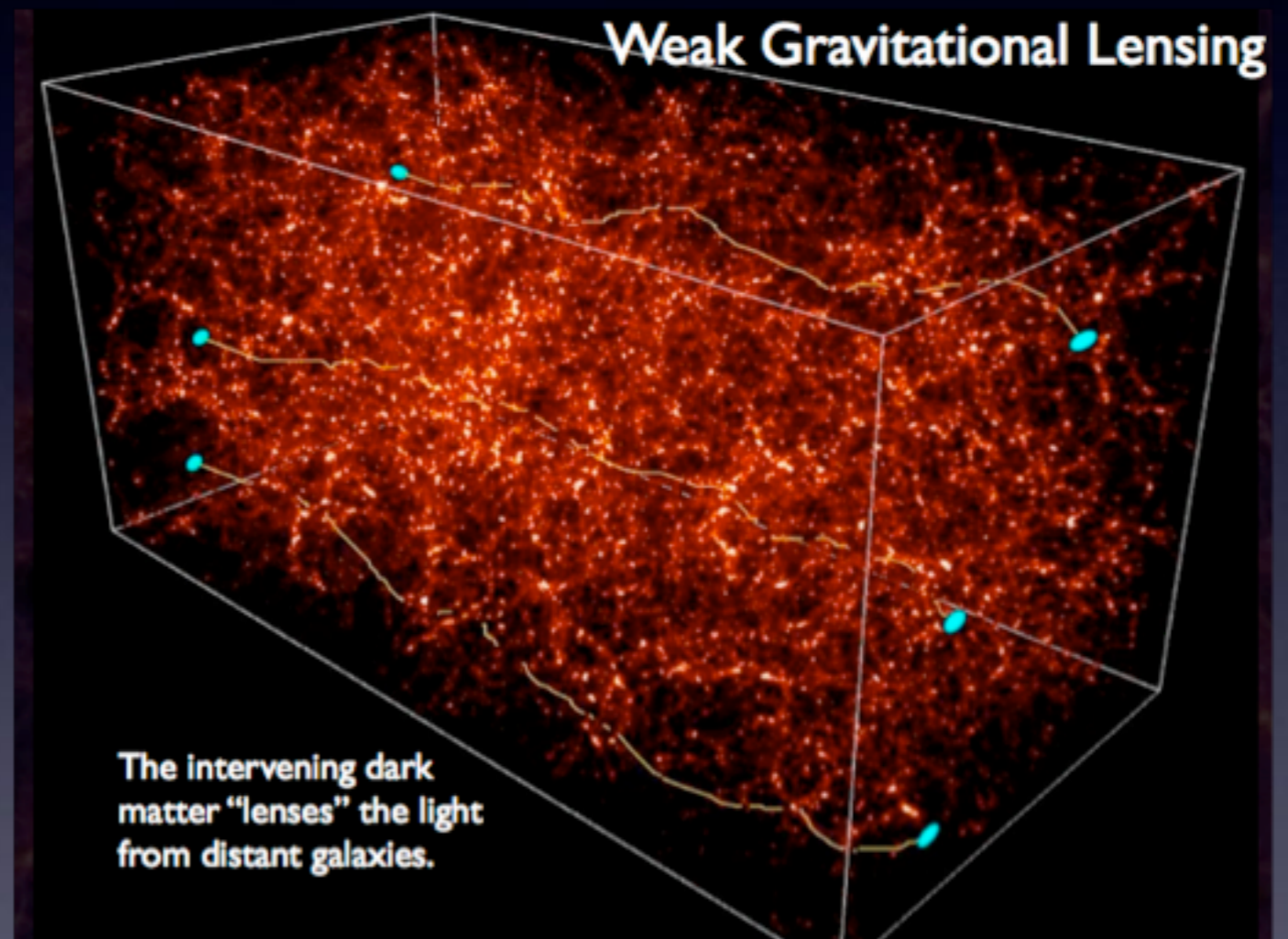
$$f_{\text{eff}}(k) \equiv -\frac{T_{\Phi}^{\theta_m}(k)}{T_{\Phi}^{\delta_m}(k)}$$

- Deterministic bias $\langle \delta_m \theta_m \rangle = -f_{\text{eff}} \langle \delta_m \delta_m \rangle$

$$\langle \theta_m \theta_m \rangle = f_{\text{eff}}^2 \langle \delta_m \delta_m \rangle.$$

Massless particle motion: gravitational lensing

- The motions of photons are also perturbed by the local gravitational potential
- This is manifested as gravitational lensing
- The ellipticities of galaxy shapes become correlated with the matter density, integrated over the whole photon trajectory



Lensing potential

- Null condition states

$$k^\mu k_\mu = 0$$

- Thin lens approximation gives

$$\frac{d^2 x^i}{d\lambda_s} + 2\mathcal{H} \frac{d\eta}{d\lambda_s} \frac{dx^i}{d\lambda_s} - (\Phi_{,x^i} - \Psi_{,x^i}) \left(\frac{d\eta}{d\lambda_s} \right)^2$$

- Finally we compute deflection equation

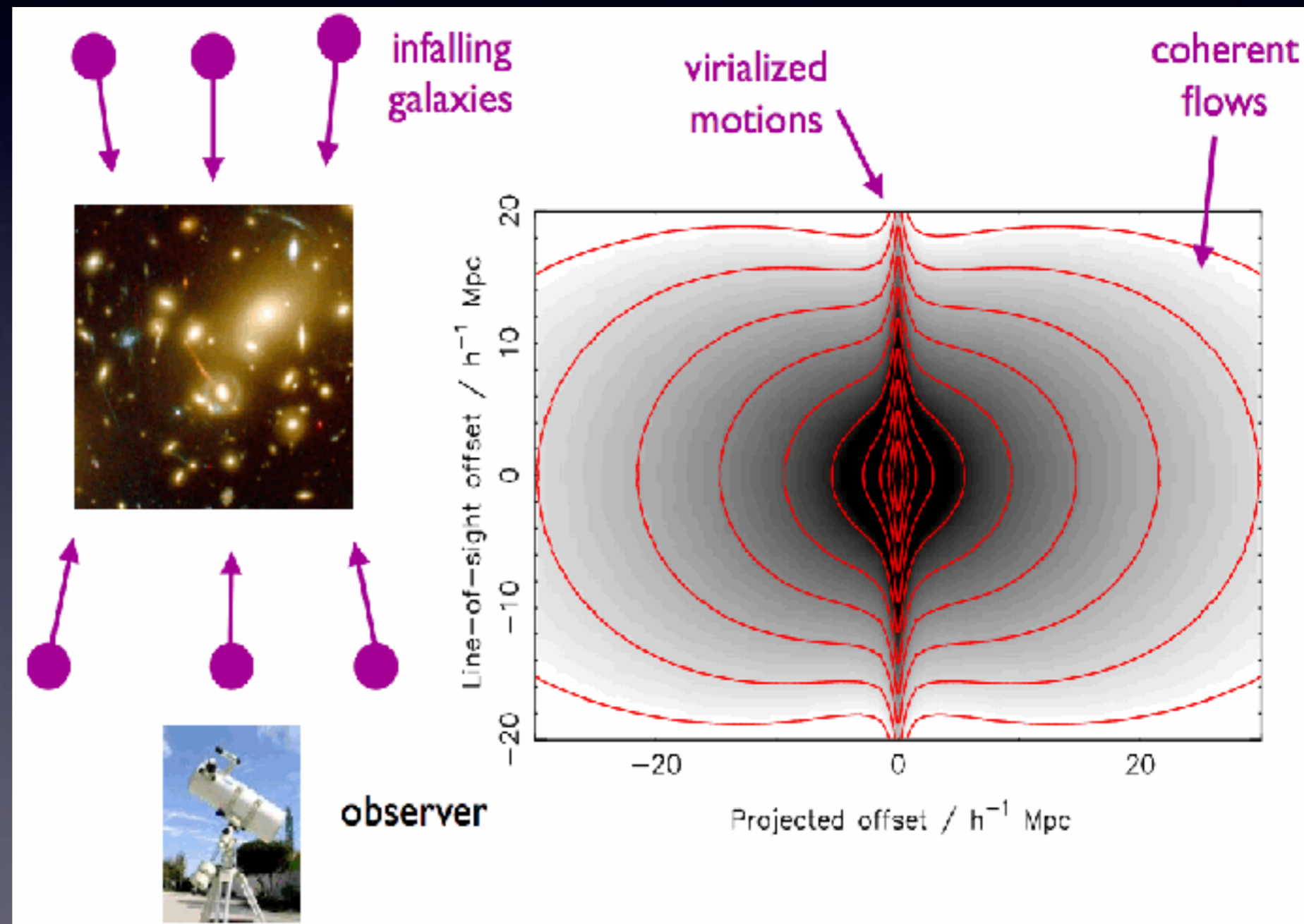
$$\frac{d^2 x^i}{dr^2} = \Phi_{,x^i} - \Psi_{,x^i}$$

- Difference between potentials is lensing potential, and deflection is sourced by spatial gradient of lensing potential

Cosmological Data

Redshift-space distortions

- The motions of galaxies are perturbed by the local gravitational field
- The Power spectrum/ correlation function in the line of sight is distorted relative to the transverse direction
- Assuming these motions are generated by matter perturbations, we can measure the growth of structure



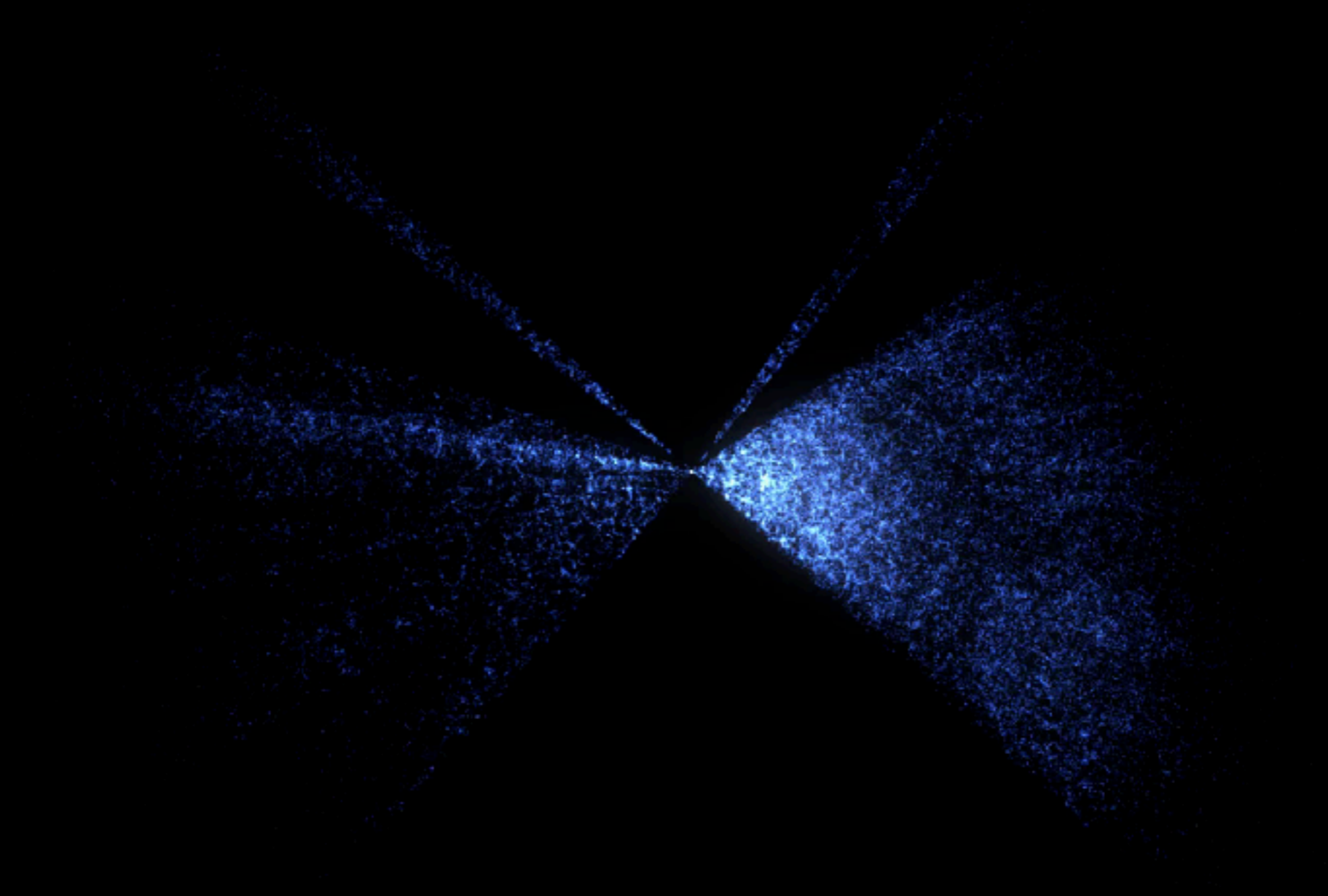
Multipole power spectra

- Density and velocity divergence have different angular dependence
- Use Power spectra decomposed into Legendre polynomials (Cole, Fisher and Weinberg 1994)

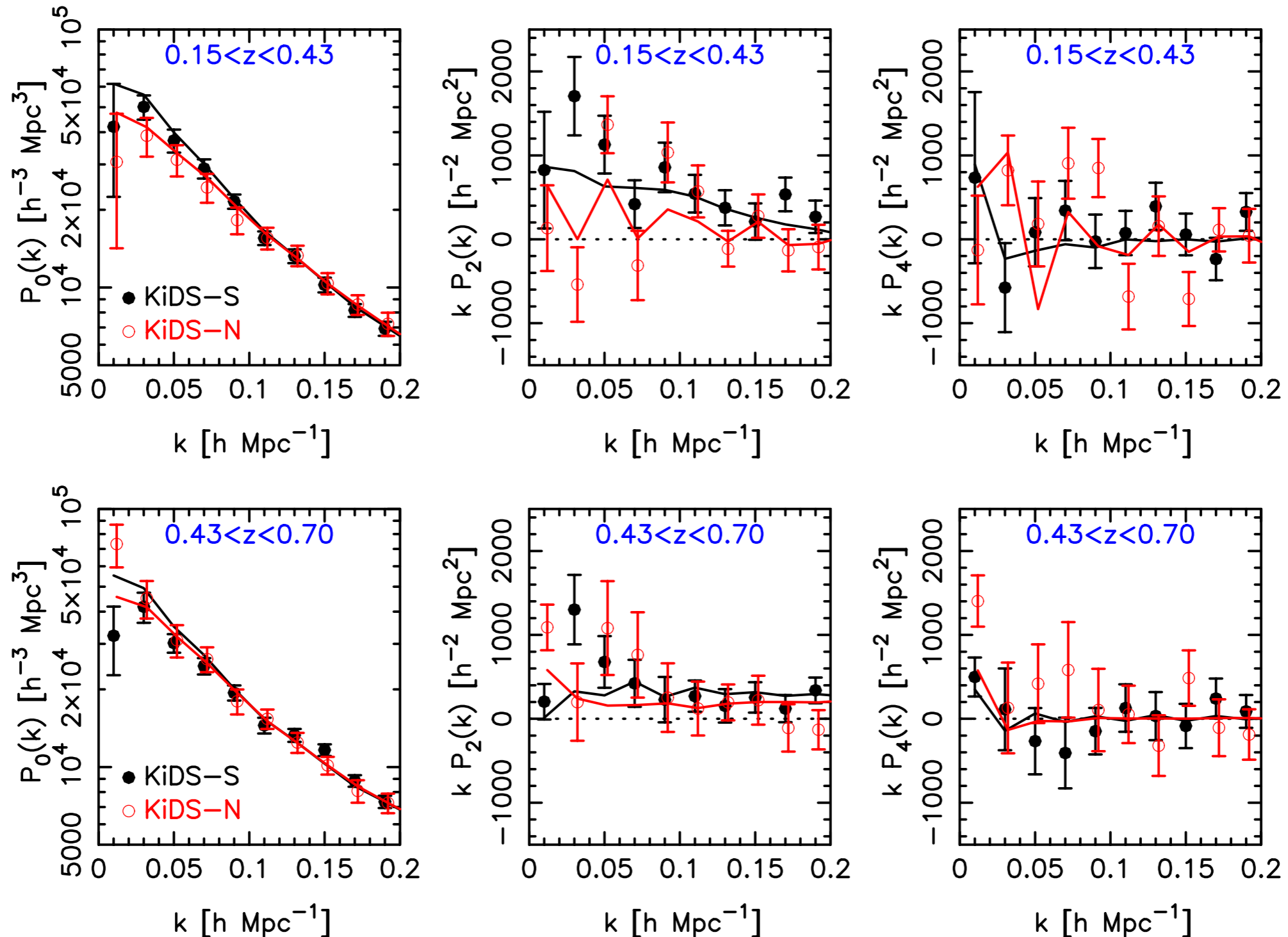
$$P(k, \mu) = \sum_{\ell=0}^{\infty} P_{\ell}(k) L_{\ell}(\mu)$$

- Orthogonality of the Legendre polynomials leads to the relation

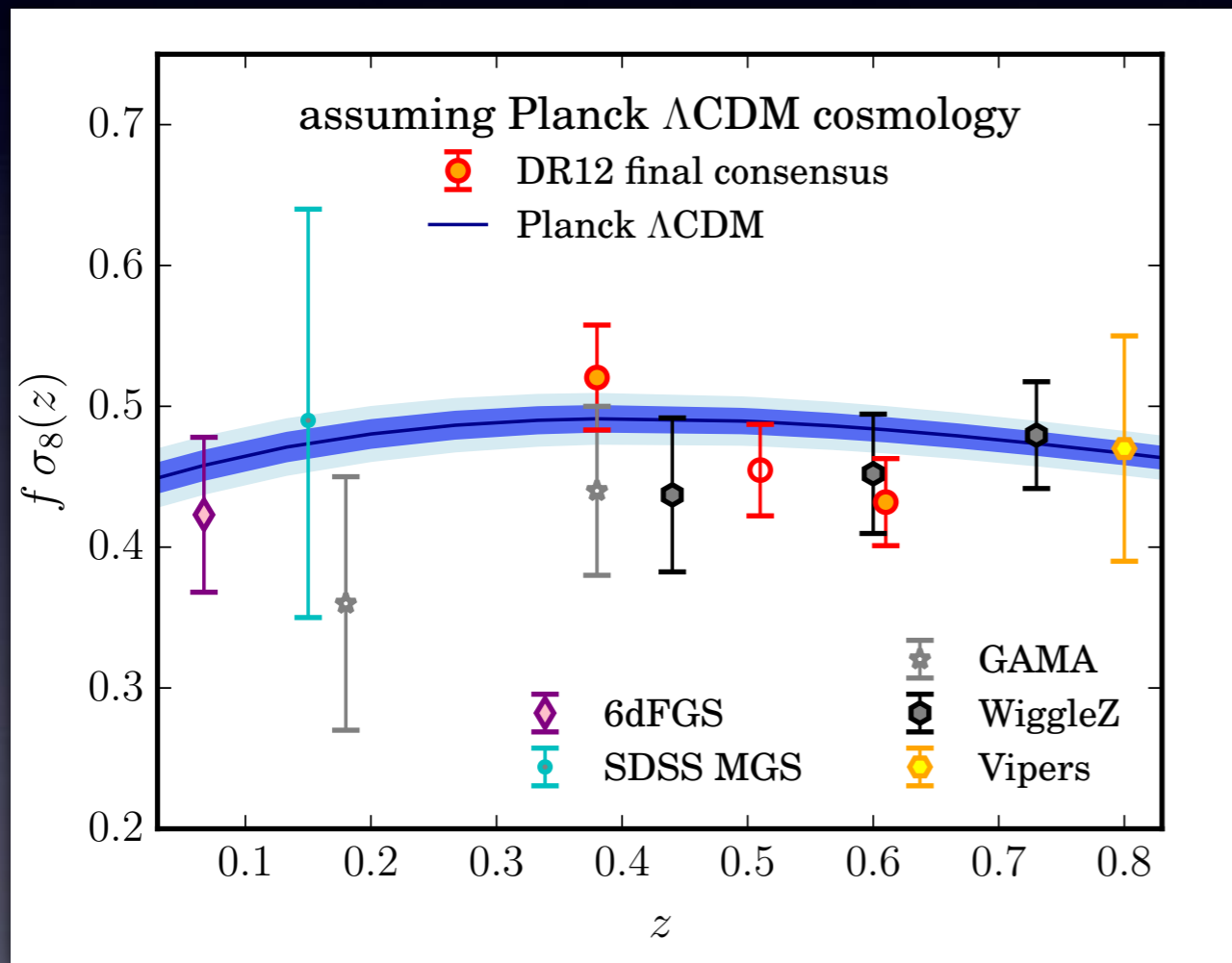
$$P_{\ell} = \frac{2\ell + 1}{2} \int_{-1}^{+1} d\mu P^s(k, \mu) L_{\ell}(\mu)$$



2dFlens - Results



Growth history



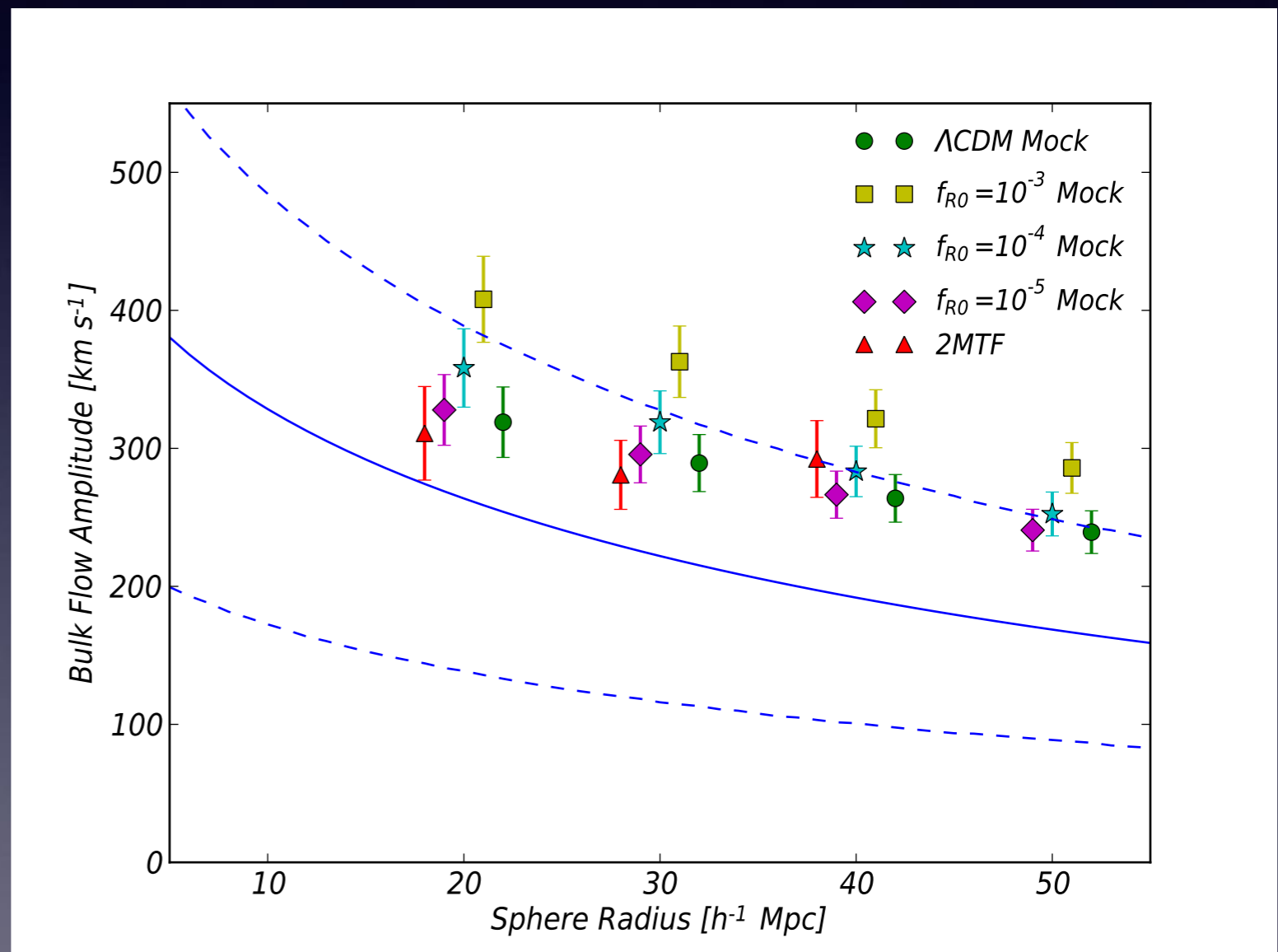
Alam et al 2016

- Growth rate (f) and amplitude of fluctuations (σ_8) sourced by both gravitational force and expansion rate
- Need to fit for both simultaneously, so some degeneracy with BAO signal

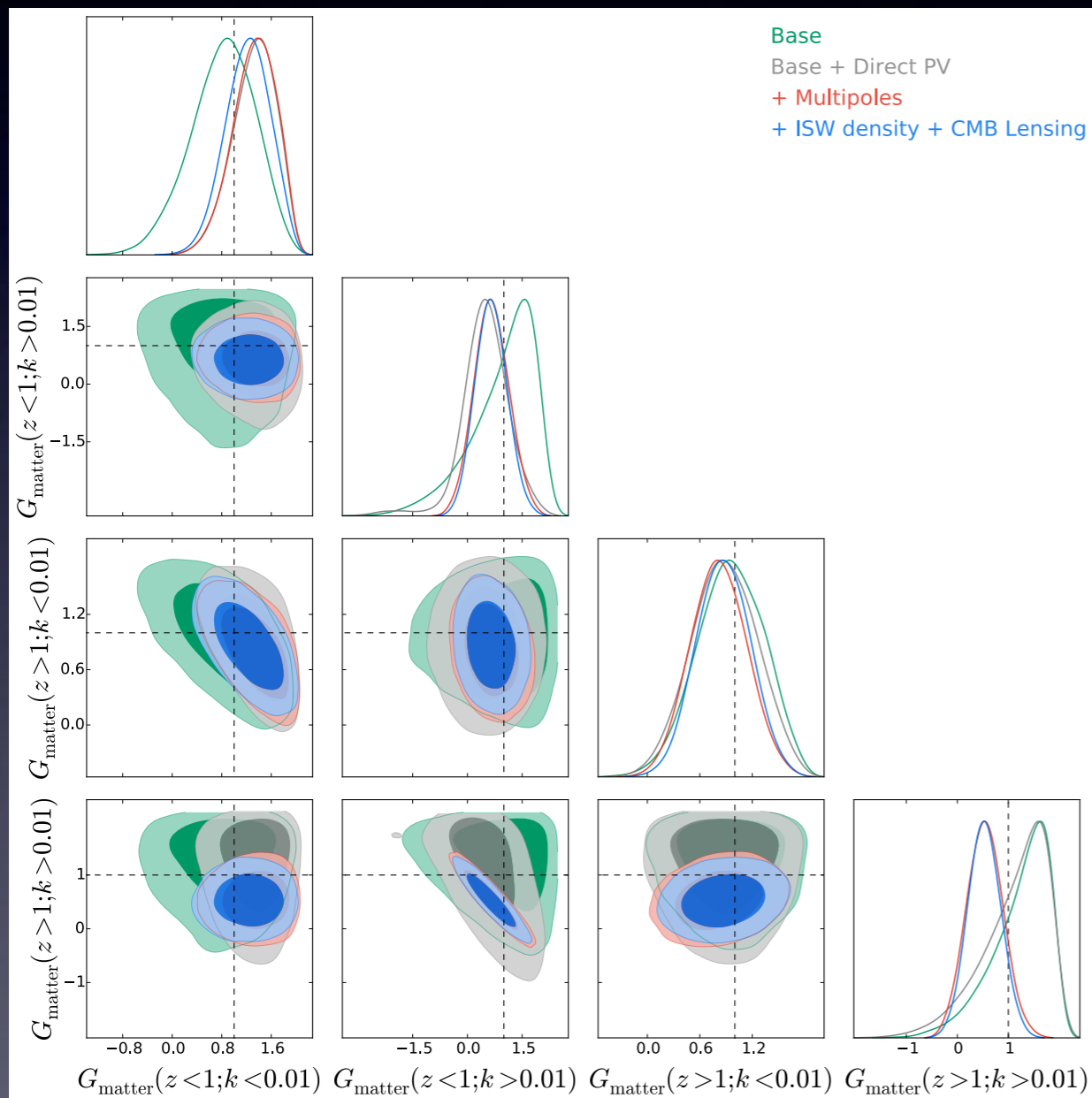
Peculiar velocities

- Data from the Two Micron All-Sky Survey (2MASS; Scrutskie et al. 2006) Tully-Fisher Survey (2MTF; Masters 2008) covers most of the sky, and uses 2018 galaxies to measure the bulk flow.
- Numerical simulation for the same sky, and select from the same redshift distribution
- $f(R)$ gravity predicts a larger bulk flow velocity than Λ CDM

$$z_{\text{observed}} \simeq z_{\text{cosmological}} + z_{\text{peculiar}}$$



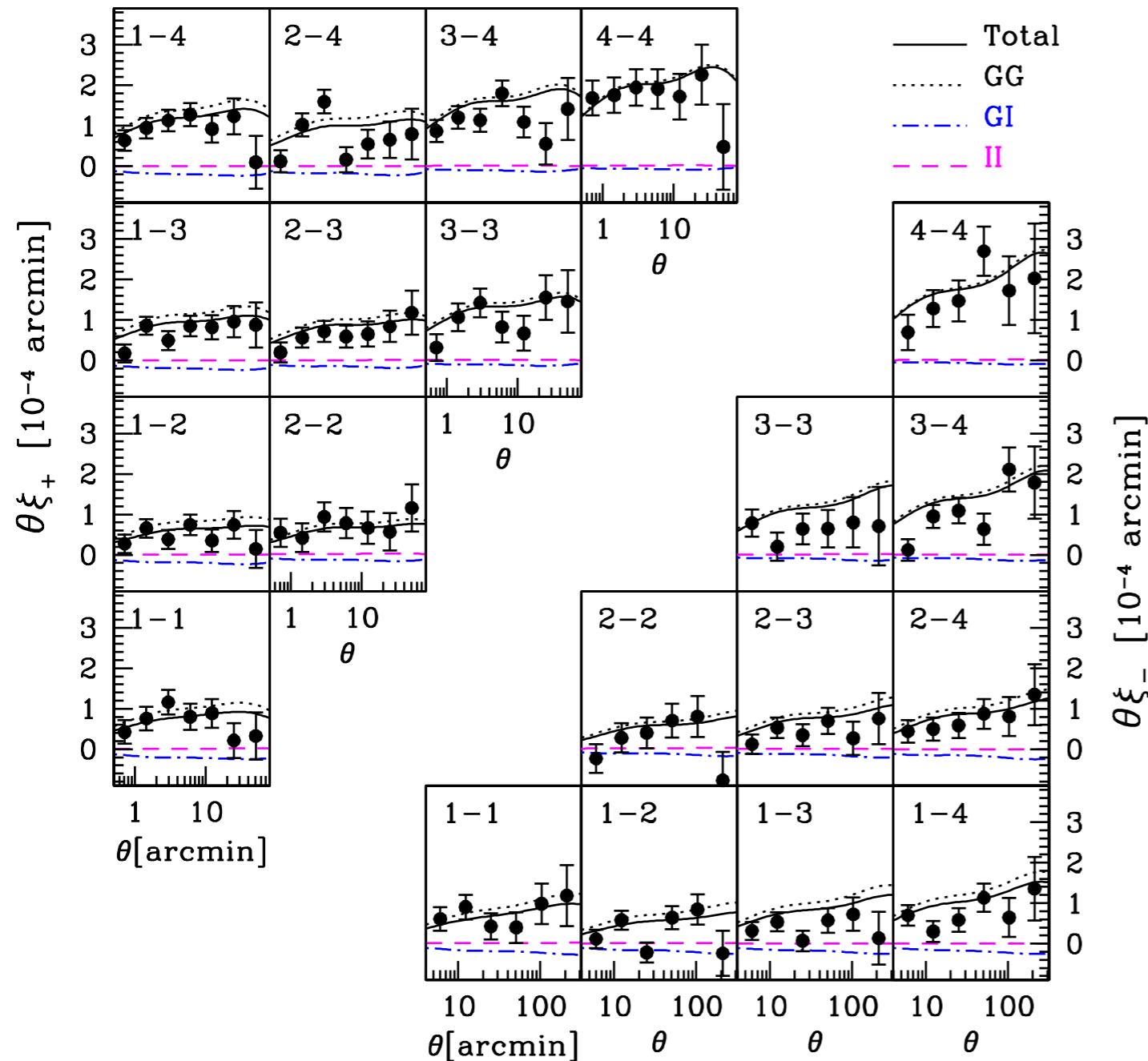
Peculiar velocity power spectra



- Can measure power spectra of velocities
- No galaxy bias
- Use to measure deviations from gravitational force law on different scales

Johnson, Blake, Dossett, Koda,
Parkinson, Joudaki, MNRAS 458
(2016), 2725-2744

Lensing Data



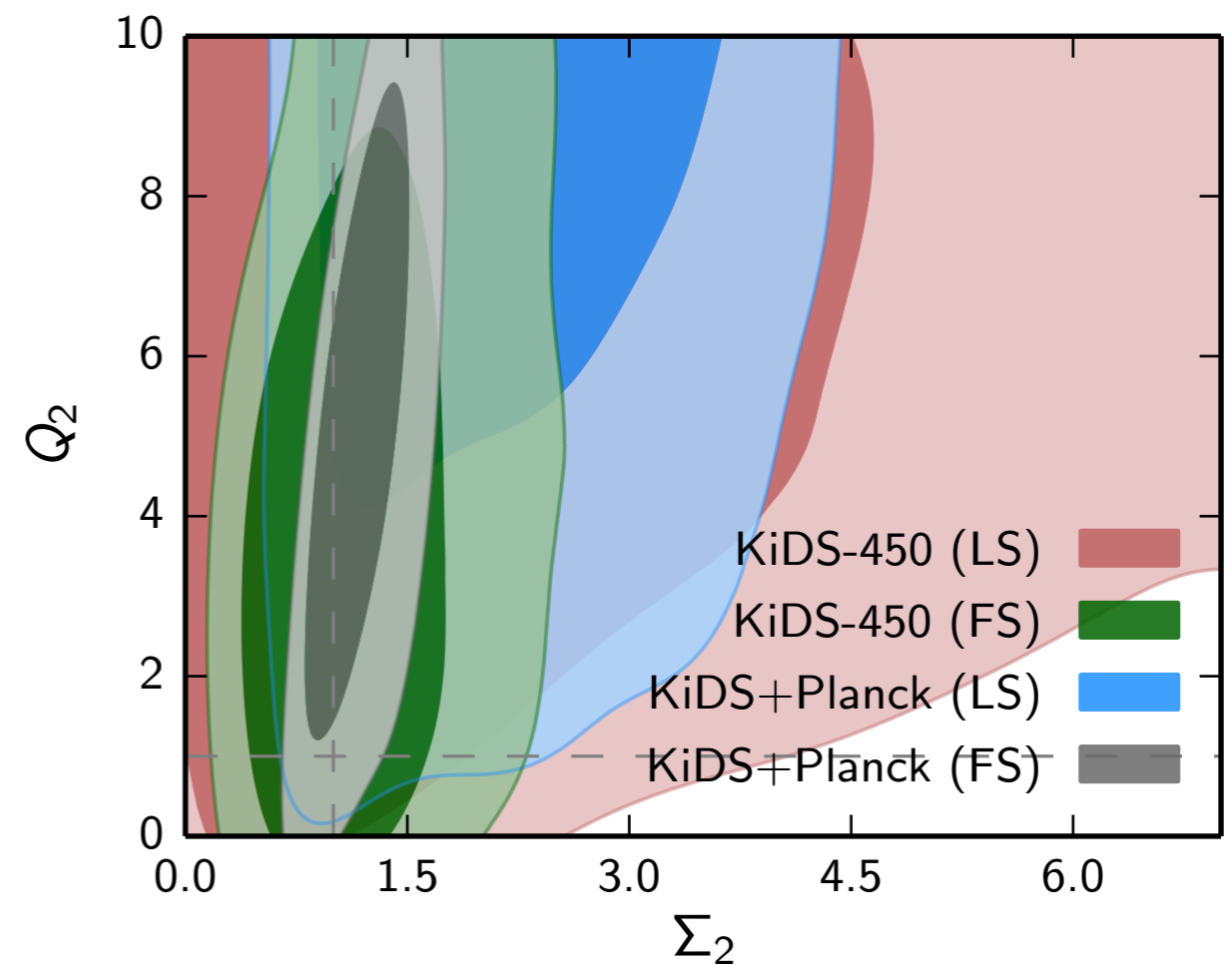
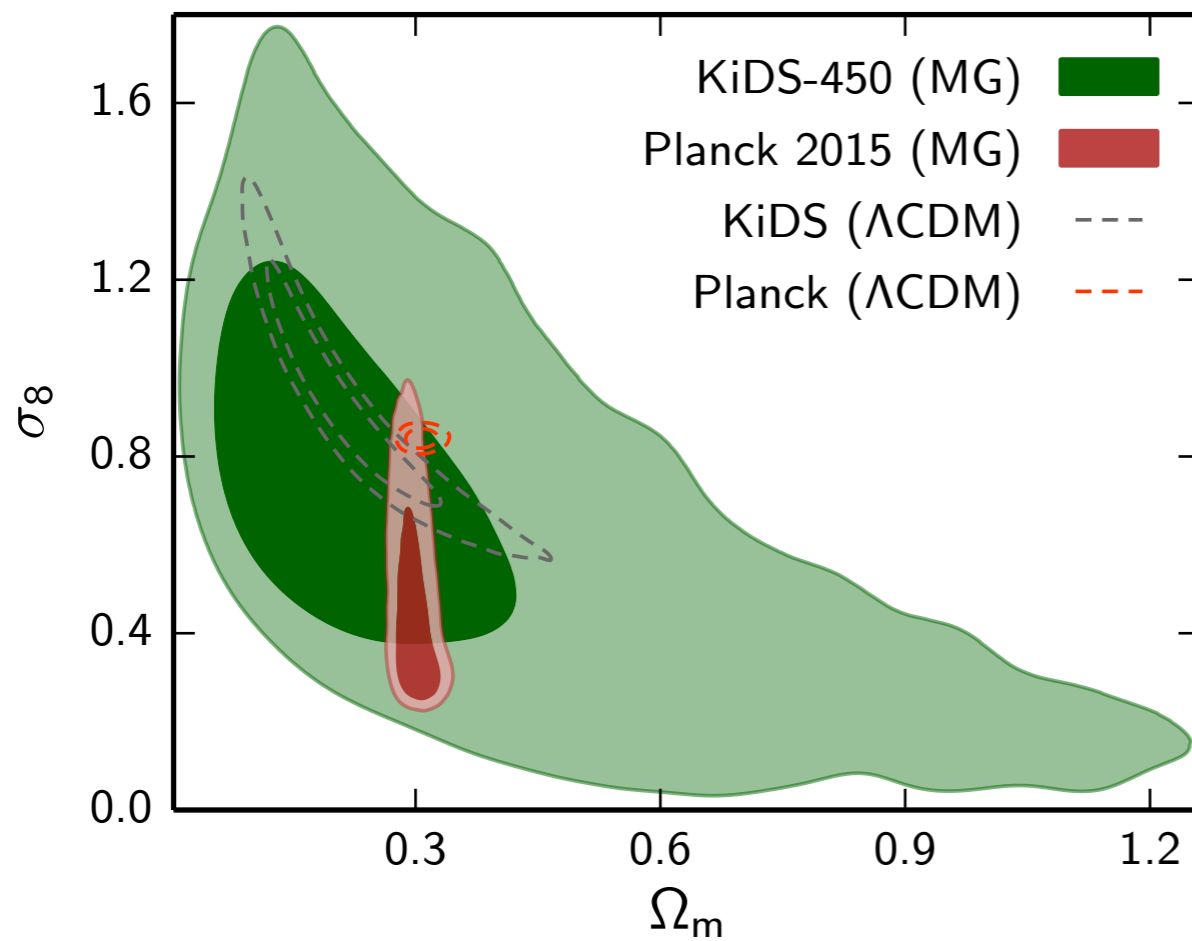
- Lensing convergence power spectra

$$P_{\kappa^{ij}}(\ell) = \int_0^{r_H} dr \frac{q_i(r)q_j(r)}{[f_{\kappa}(r)]^2} P_{\delta} \left(\frac{\ell}{f_{\kappa}(r)}, r \right)$$

- tomographic angular two-point shear correlation function

$$\xi_{\pm}^{ij}(\theta) = \frac{1}{2\pi} \int d\ell \ell P_{\kappa}^{ij}(\ell) J_{0,4}(\ell\theta)$$

Parameter constraints



Fifth forces

Fifth forces

- (With Seery and Burrage)

- Metric: $ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)d\mathbf{x}^2$

- The force equations for matter and radiation are

$$\frac{d\theta_m}{dt} = -2H\theta_m - \frac{\partial^2}{a^2}\Psi + F_{5r}$$

$$\frac{d\theta_r}{dt} = -H\theta_r - \frac{\partial^2}{a^2}\Psi - \frac{1}{4}\frac{\partial^2}{a^2}\delta_r + F_{5m}$$

- Perturbation equations

$$\frac{d\delta_m}{dt} = -\theta_m - 3\dot{\Phi} + j_{5m}$$

$$\frac{d\delta_r}{dt} = -\frac{4}{3}\theta_r - 4\dot{\Phi} + j_{5r}$$

Stochastic bias

- Several primordial perturbations:
 - fifth force mediated by scalar field (ϕ) that also has its own fluctuations

$$\delta_m(k) = T_{\Phi}^{\delta_m}(k)\Phi_*(k) + T_{\phi}^{\delta_m}(k)\delta\phi_*(k)$$

$$\theta_m(k) = T_{\Phi}^{\theta_m}(k)\Phi_*(k) + T_{\phi}^{\theta_m}(k)\delta\phi_*(k).$$

- Relation between growth and density has now changed

$$\theta_m = -f_{\text{eff}}\delta_m + \frac{W}{T_{\Phi}^{\delta_m}}$$

- Here W is a Wronskian-like function which measures the correlation of δ and θ

New correlation functions

- The correlation functions now satisfy

$$\begin{aligned}\langle\theta\delta\rangle_k &= \langle\delta\delta\rangle_k \left(-f_{eff}^\Phi(k) + \frac{f_{eff}^\Phi(k) - f_{eff}^\phi(k)}{1 + \rho(k)} \right) \\ \langle\theta\theta\rangle_k &= \langle\delta\theta\rangle_k \left(-f_{eff}^\Phi(k) + \frac{f_{eff}^\Phi(k) - f_{eff}^\phi(k)}{1 + \sigma(k)} \right) \\ &= \langle\delta\delta\rangle_k \left(-f_{eff}^{\Phi 2}(k) + \frac{f_{eff}^{\Phi 2}(k) - f_{eff}^{\phi 2}(k)}{1 + \rho(k)} \right)\end{aligned}$$

- If we measure $\langle\delta_m\delta_m\rangle$, $\langle\delta_m\theta_m\rangle$ and $\langle\theta_m\theta_m\rangle$, and do not see complete correlation between δ and θ , we have gone beyond f_{eff} as a test of modified gravity

Example: Galileons

- Galileons are scalar fields that are invariant under shifts in the field value

$$\pi \rightarrow \pi + c + b_\mu x^\mu$$

- Only 5 possible Lagrangians that give 2nd order equations of motion and are ghost free

$$\mathcal{L}_1 = M^3 \pi$$

$$\mathcal{L}_2 = (\nabla \pi)^2$$

$$\mathcal{L}_3 = (\square \pi)(\nabla \pi)^2 / M^3$$

$$\mathcal{L}_4 = (\nabla \pi)^2 [2(\square \pi)^2 - 2\pi_{;\mu\nu}\pi^{;\mu\nu} - R(\nabla \pi)^2 / 2] / M^6$$

$$\mathcal{L}_5 = (\nabla \pi)^2 [(\square \pi)^3 - 3(\square \pi)\pi_{;\mu\nu}\pi^{;\mu\nu} + 2\pi^\nu_{;\mu}\pi^\rho_{;\nu}\pi^\mu_{;\rho} - 6\pi_{;\mu}\pi^{;\mu\nu}\pi^{;\rho}G_{\nu\rho}] / M^9$$

Coupling to matter

- We expect a coupling of the Galileon field (for example) to matter

$$T_\phi = -\frac{1}{2\Lambda} \left(1 + \frac{\phi}{\Lambda}\right)^{-1} T_m$$

- The field starts small, and remains small during the evolution of the universe
- The perturbation of the field can grow, and will grow quickly at late times through the coupling to the matter perturbation
 - While the Galileon fluctuation will be smaller than the matter perturbation at matter-radiation decoupling, it can grow and become very large today.
- This is stochastic bias, where structures can form without presence of standard 'Newtonian' potential generated by the presence of matter

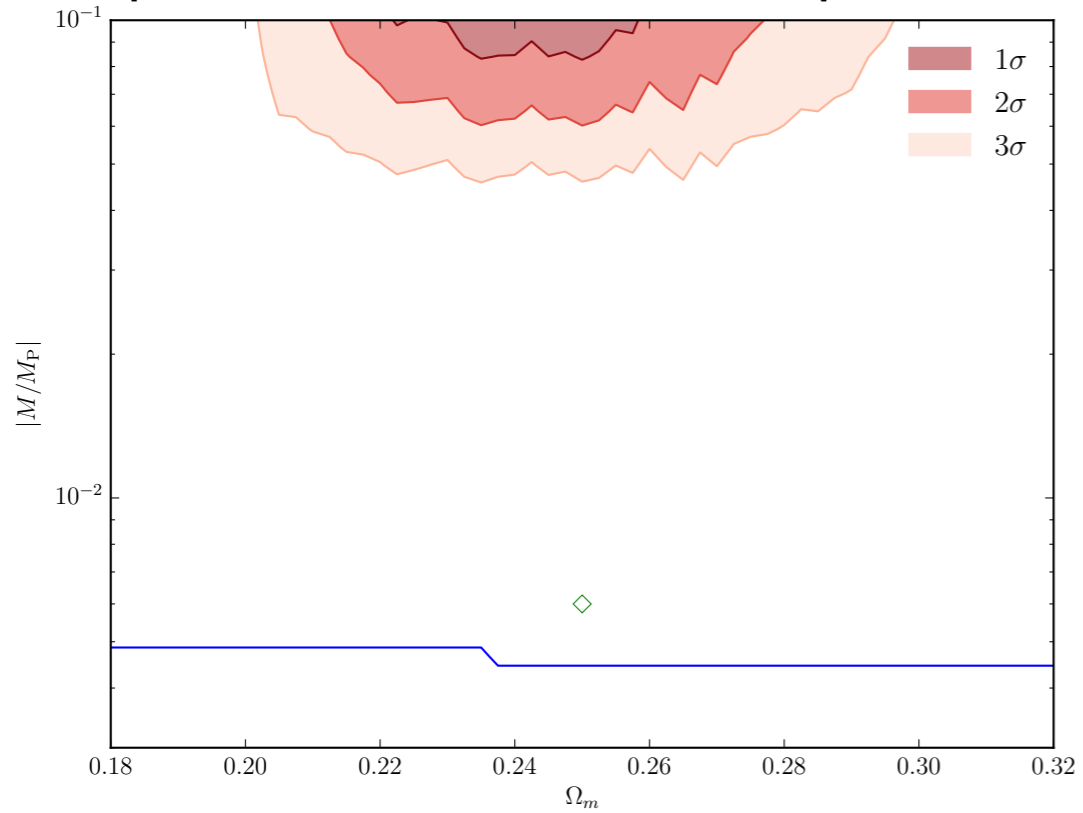
Screening mechanisms

- If the gravity is different, we can test it on lab or solar system system scales
 - e.g. fifth force effect, or scale-dependent G_{Newton}
- Three “screening mechanisms” save the theories

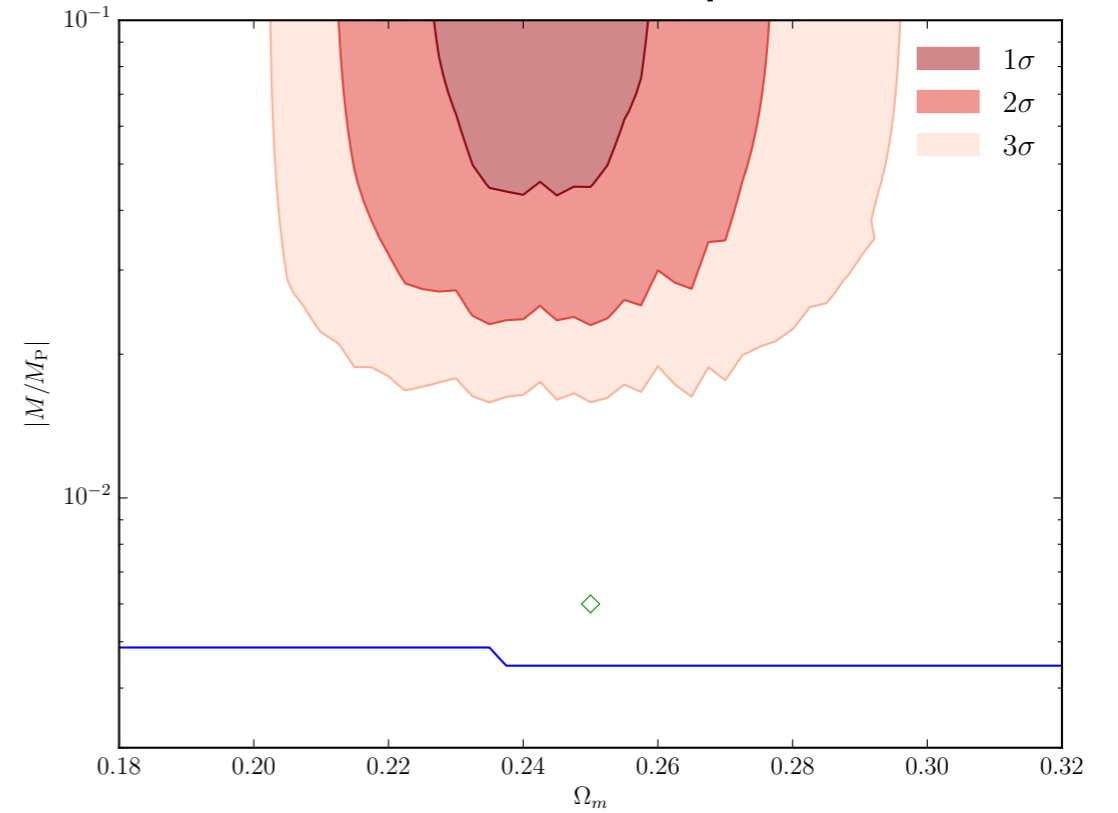
$$L \supset -\frac{1}{2}Z(\phi_0)(\partial\delta\phi)^2 - \frac{1}{2}m^2(\phi_0)\delta\phi^2 + (\beta(\phi)/m_P)\delta\phi\delta T$$

- **Vainshtein mechanism**: higher-order corrections (cubic and above) recover GR on scales smaller than Vainshtein radius (DGP, Galileon)
- **Chameleon mechanism**: mass of field large enough to suppress range of fifth force (f(R) theories)
- **Symmetron mechanism**: direct coupling to stress-energy tensor (T) is small

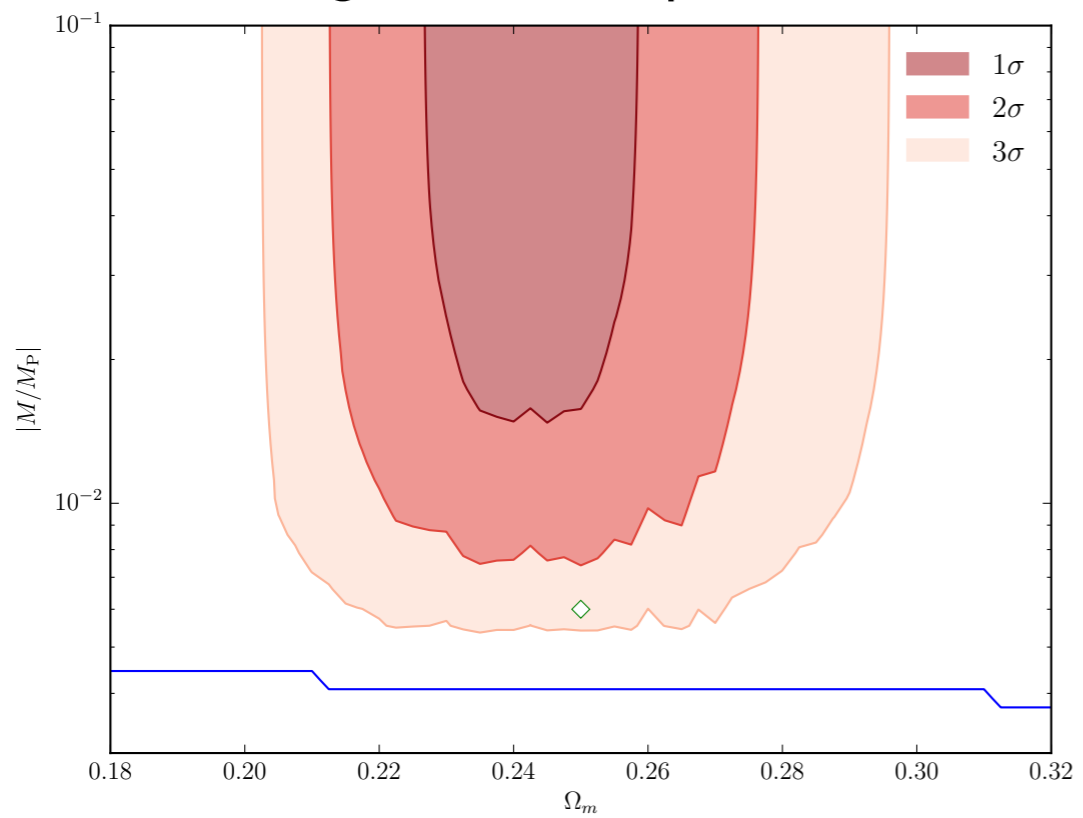
Equal Galileon and Newtonian potentials



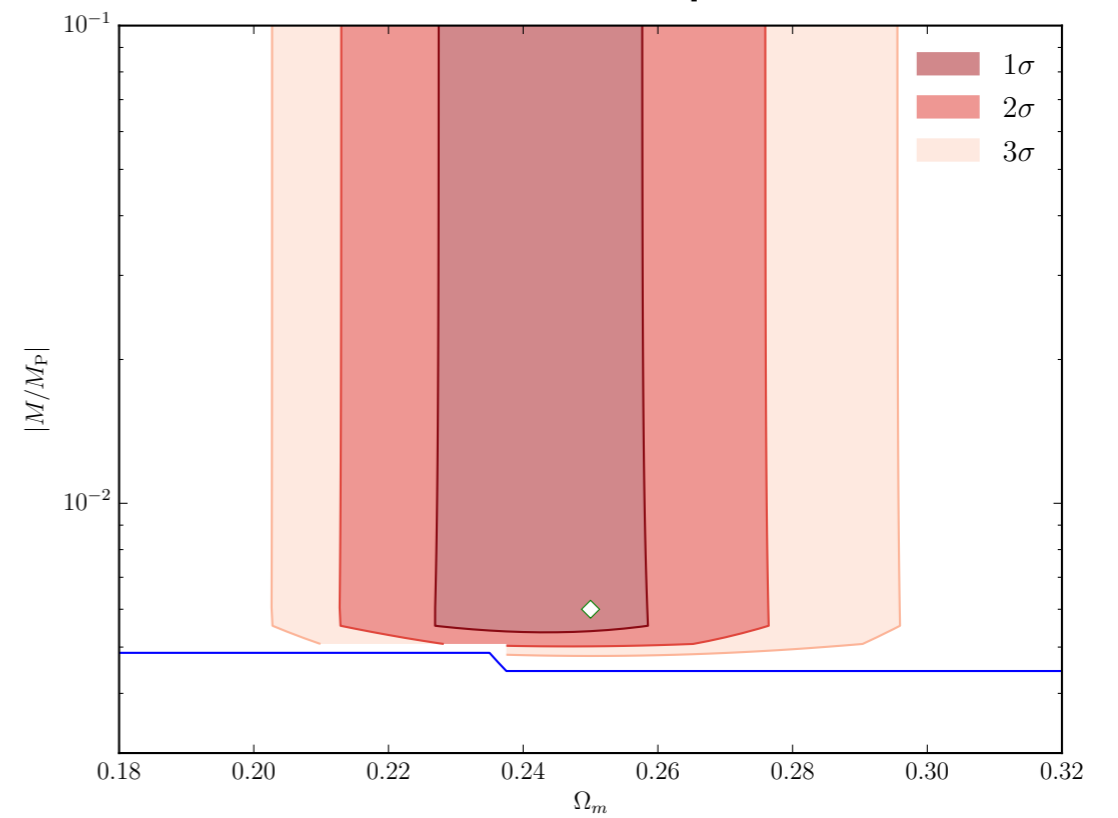
Relevant Galileon potentials



Marginal Galileon potentials



Irrelevant Galileon potentials



Lensing

- Fifth forces: cannot distinguish between strength of coupling and size of field fluctuations
- Need to measure size of metric fluctuations independently
- A conformal coupling induces no change in the lensing potential
 - Photons only feel Newtonian potential
- However, matter formation (that sources the lensing potential) still influenced by fifth forces
- Considering only Galileon actions up to L_3 (which we are), there is no anisotropic stress, so $\phi = -\psi$
- Cross-correlation of lensing with RSD will determine strength of stochastic bias

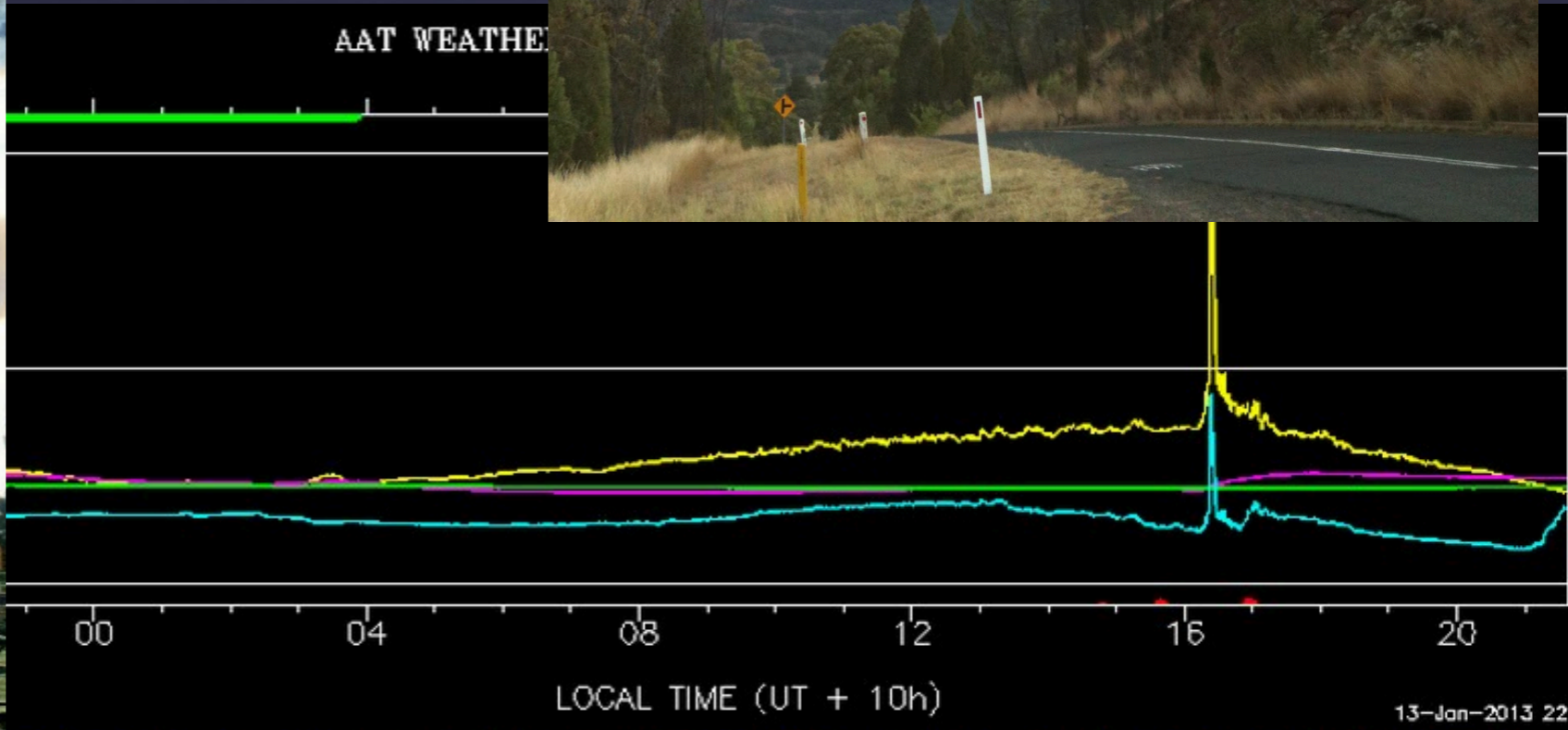
Conclusions

- Structure formation tests of gravity effectively measure force law on largest scales
- The growth rate f gives the correlation between density and velocity statistics of galaxies
- Lensing power spectrum gives correlation between induced ellipticity and density of matter
- If fifth forces become important at late times, the density and velocity (or velocity and lensing) perturbations may no longer be perfectly correlated
 - Galileons are an example of this behaviour, as the fluctuations in the field grow at late times and become a new source of structure formation, leading to *stochastic bias*
- Cross-correlation of lensing and RSD data will provide direct measurement of stochastic bias effect

Thank you

The AAT





outside air temperature cyan: outside dewpoint magenta: dome air temperature green: mirror temperature

2dFLens

- Spectroscopic survey, providing follow-up of lensing galaxies from KiDS survey

- **Swinburne:** Chris Blake (PI), Karl Glazebrook, Andrew Johnson, Shahab Joudaki, Felipe Marin
- **University of Queensland:** David Parkinson
- **Mount Stromlo, ANU:** Mike Childress, Chris Wolf
- **Edinburgh:** Catherine Heymans, Alexandra Amon
- **Bonn:** Thomas Erben, Hendrik Hildebrandt, Dominik Klaes
- Konrad Kuijken (Leiden)
- Chris Lidman (AAO)
- Greg Poole (U.Melbourne)

