

Title: Large Scale Structure as a Probe of Gravitational Slip

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Abstract: Many modified gravity schemes predict a non-zero difference ('`gravitational slip\'') between the Newtonian and longitudinal perturbed metric potentials. Such a slip would affect the growth of large scale structure without altering the expansion history of the universe. We quantify the slip with a new parameter  $\varpi$ , show the effect of non-zero  $\varpi$  on the growth of cosmic overdensities, and constrain its value using CMB and weak lensing data.

# Large scale structure as a probe of gravitational slip

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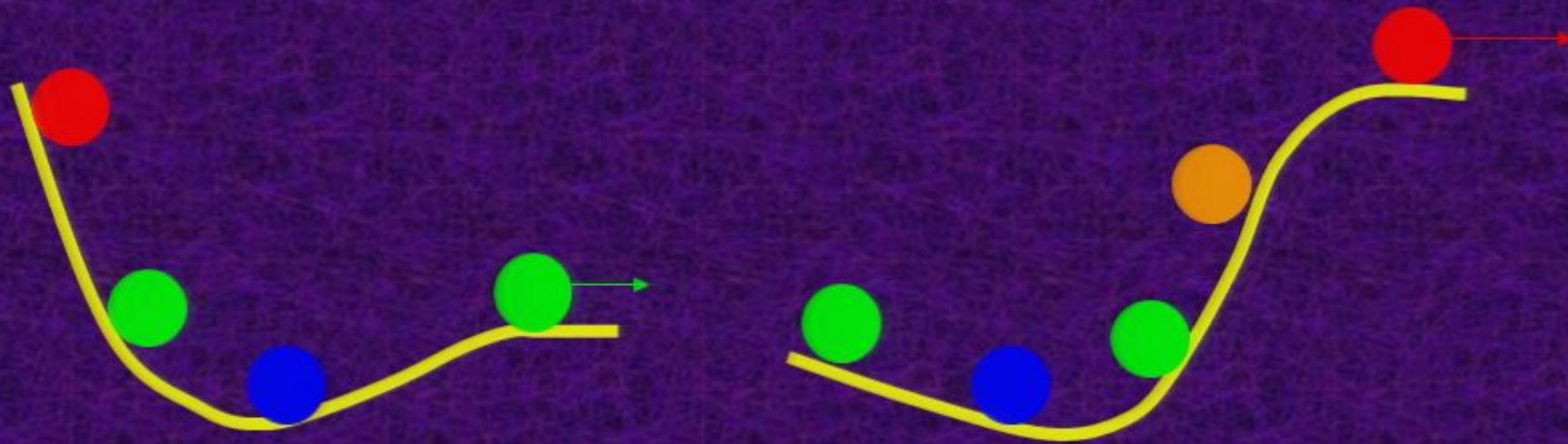
Alessandro Melchiorri - University of Rome

PRD 77, 103513 (2008) [arXiv:0802.1068]

# The potentials

$$ds^2 = a^2 \left[ - (1 + 2\psi) d\tau^2 + (1 - 2\phi) d\vec{x}^2 \right]$$

$$\ddot{\vec{x}} = -\vec{\nabla}\psi \quad \nabla^2\phi = -4\pi G a^2 \delta\rho$$



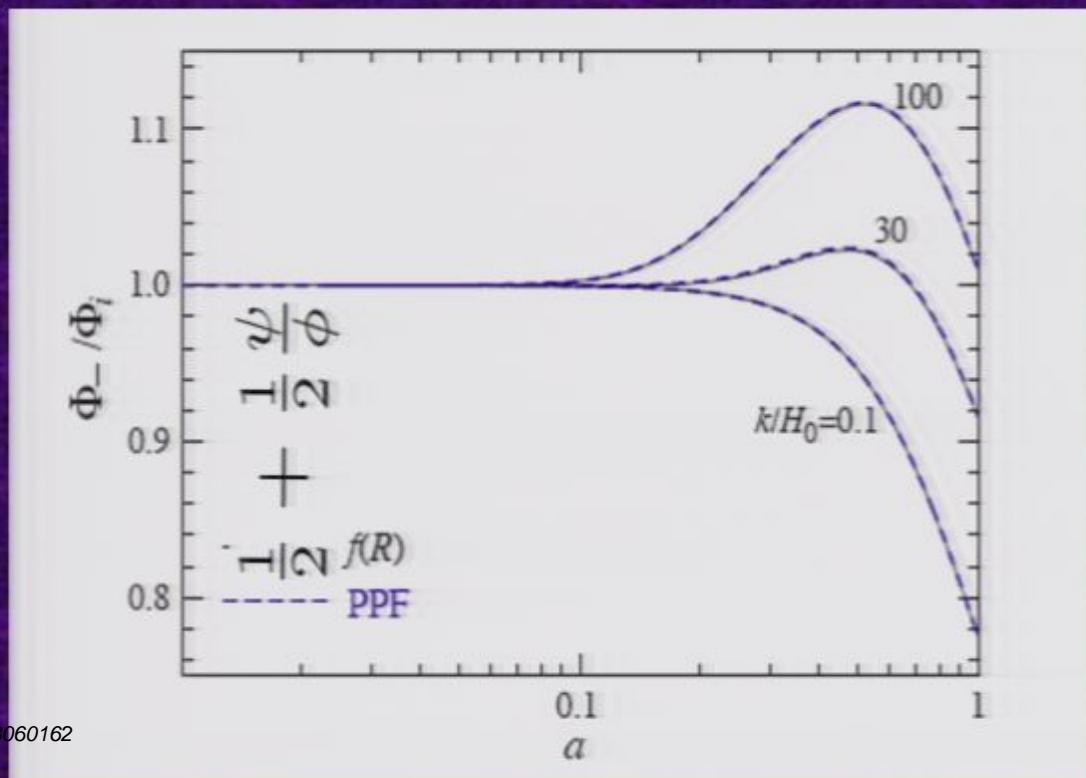
(Integrated Sachs-Wolfe Effect)

# Possible modified gravity theories

$f(R)$  gravity

$$\mathcal{L} = \frac{R}{16\pi G} + \text{generic function of } R$$

Carroll *et al.*, PRD 71, 063513 (2005)



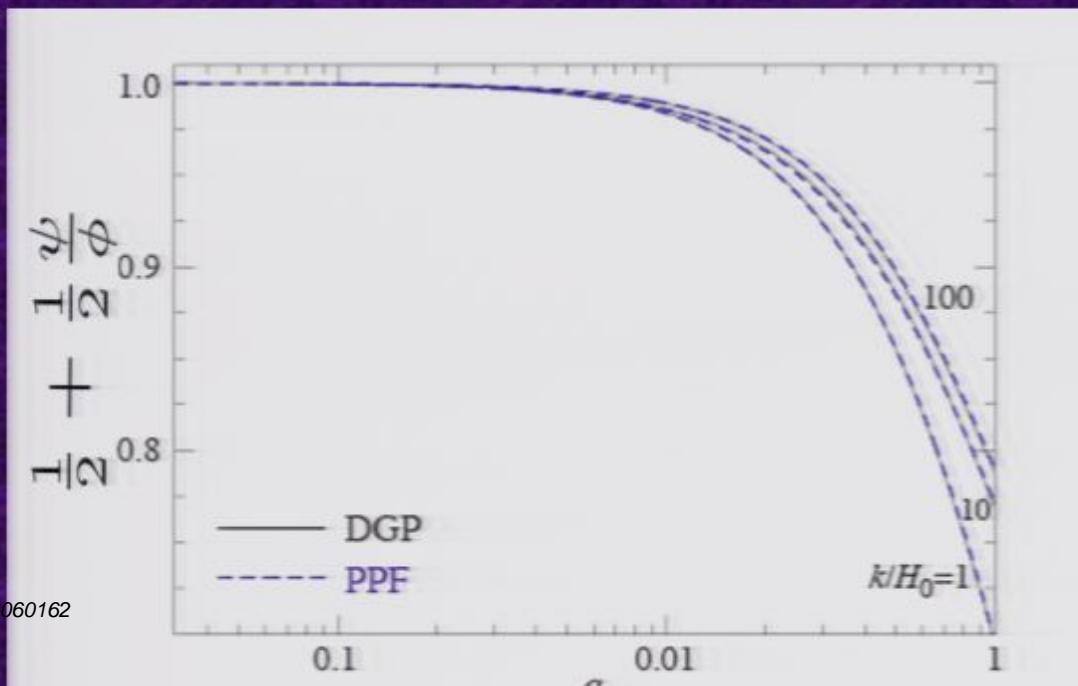
Hu and Sawicki  
PRD 76, 104043 (2007)

# Possible modified gravity theories

## DGP gravity

The universe is a (3+1) brane in a 5-D bulk.  
Gravity exists on the bulk.

Dvali, Gabadadze, and Poratti, Phys. Lett. B. **485** 208 (2000)  
A. Lue, Phys. Reports **423**, 1 (2006)



Hu and Sawicki  
PRD **76**, 104043 (2007)

# Parametrizations

Caldwell *et al.*, PRD **76**, 23507 (2007)

Daniel *et al.*, PRD **77**, 103513 (2008)

$$\psi = (1 + \varpi(z, \vec{x}))\phi$$

Bertschinger and Zukin, arXiv:0801.2431

$$\phi = \gamma(a)\psi + \dots$$

$$\gamma(a) = 1 + \beta a^s$$

Jain and Zhang, arXiv:0709.2375

$$k^2(\phi + \psi) = -8\pi G \delta \rho a^2 \rightarrow -8\pi G_{eff} \frac{1}{2} (1 + \frac{1}{\eta(z, \vec{x})}) \delta \rho a^2$$

Hu, arXiv:0801.2133

$$g(z, k) = \frac{\psi - \phi}{\phi + \psi}$$

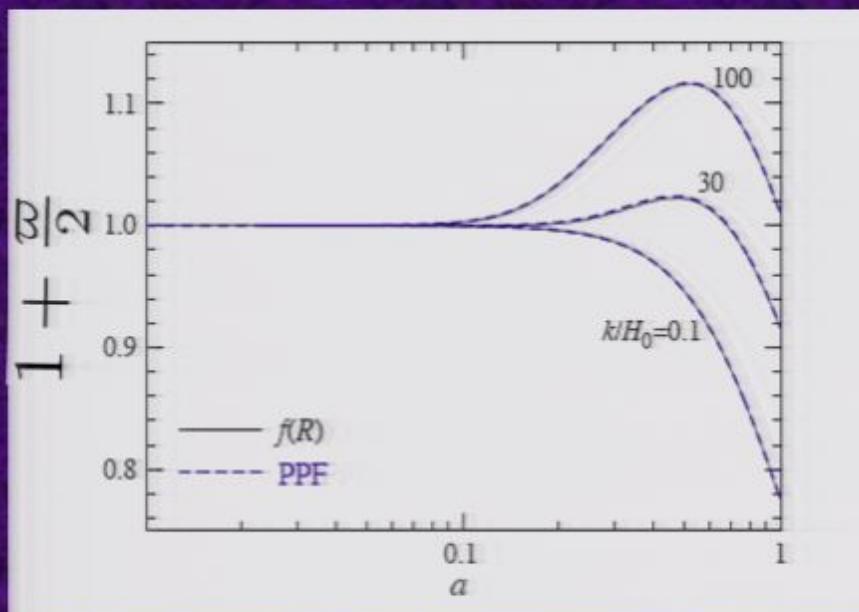
# What can we expect?

$$\begin{aligned} k^2 \phi &= -4\pi G \delta \rho & \frac{\phi - \psi}{\phi} &= -\frac{\delta p}{\delta \rho} \\ k^2(\phi - \psi) &= 4\pi G \delta p & \longrightarrow & \\ \end{aligned}$$

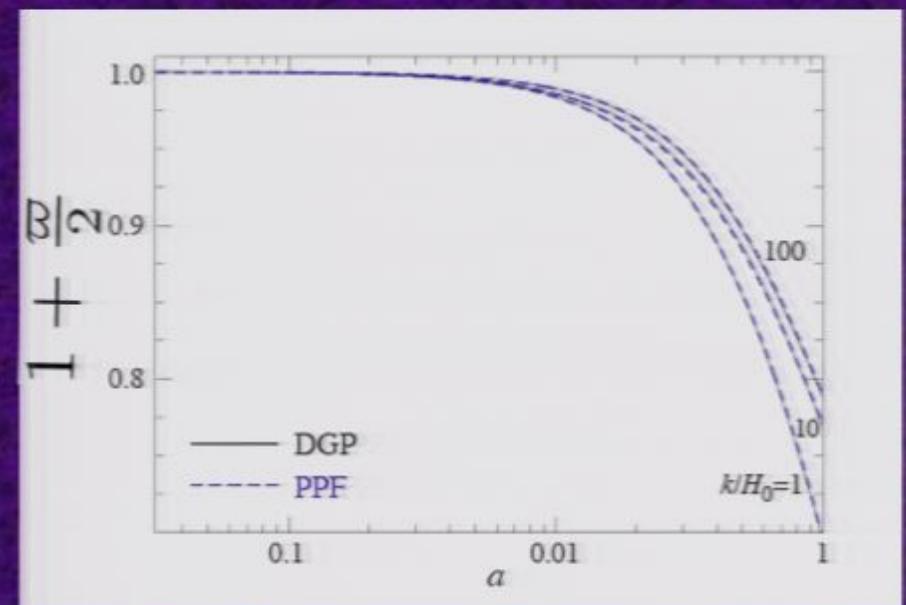
$\varpi \sim \pm 0.7$

Hu and Sawicki, PRD **76**, 104043 (2007)

$f(R)$



DGP



# Equations of motion

$$\varpi(z) = \varpi_0 \frac{\Omega_\Lambda}{\Omega_m} (1+z)^{-3} \quad \alpha \equiv \frac{1}{2k^2} (\dot{h} + 6\dot{\eta})$$

$$\psi = \dot{\alpha} + \frac{\dot{a}}{a} \alpha \quad \phi = \eta - \frac{\dot{a}}{a} \alpha$$

Unmodified CMBfast - Seljak and Zaldarriaga, ApJ **469**, 437 (1996)

$$k^2 \eta - \frac{1}{2} \frac{\dot{a}}{a} \dot{\eta} = -4\pi G a^2 \delta T_0^0$$

Ma and Bertschinger,  
ApJ **455**, 7 (1995)

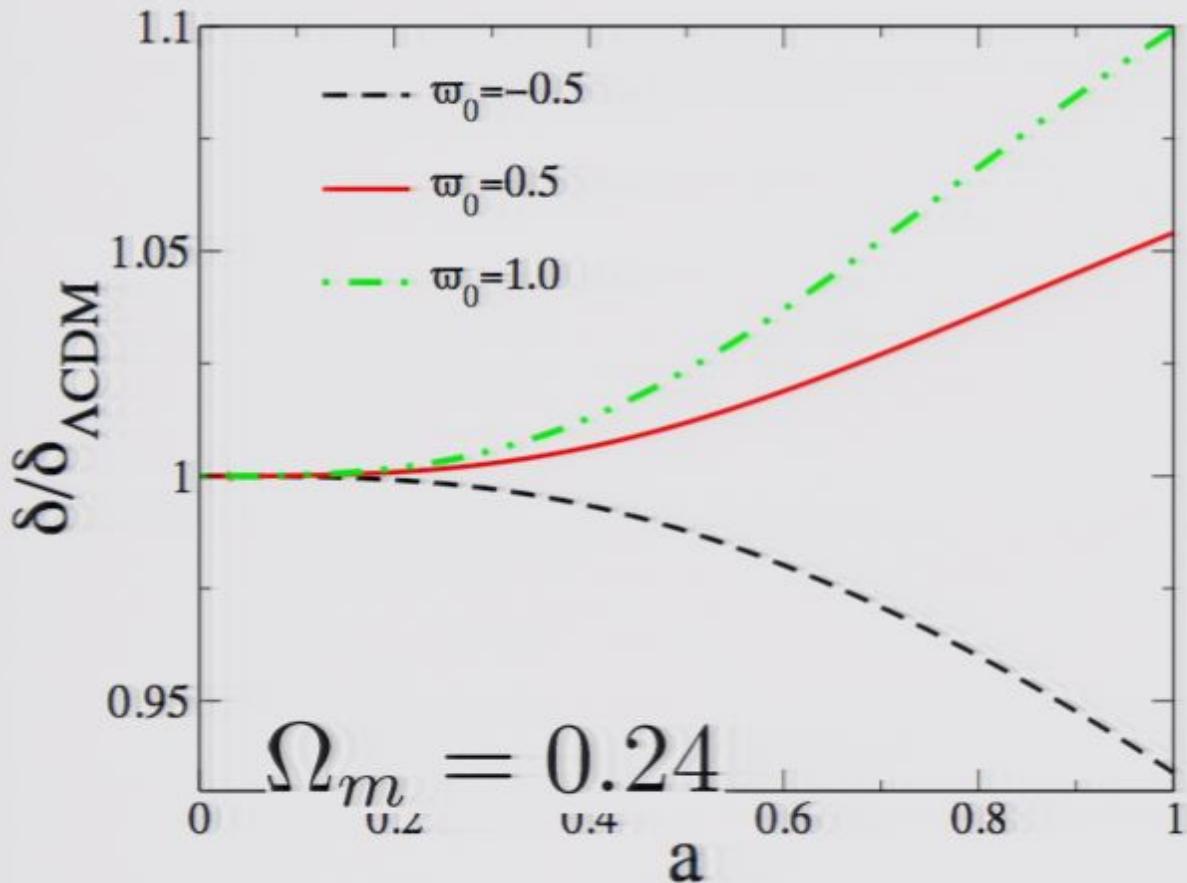
$$\dot{h} + 2 \frac{\dot{a}}{a} \dot{h} - 2k^2 \eta = -8\pi G a^2 \delta T_i^i$$

$$k^2 \dot{\eta} = -4\pi G a^2 (\bar{\rho} + \bar{p}) \theta$$

$$\dot{\alpha} = -2 \frac{\dot{a}}{a} \alpha + \eta - \frac{12\pi G a^2 (\bar{\rho} + \bar{p}) \sigma}{k^2}$$

$$\dot{\alpha} = -(2 + \varpi) \frac{\dot{a}}{a} \alpha + (1 + \varpi) \eta - \frac{12\pi G a^2 (\bar{\rho} + \bar{p}) \sigma}{k^2}$$

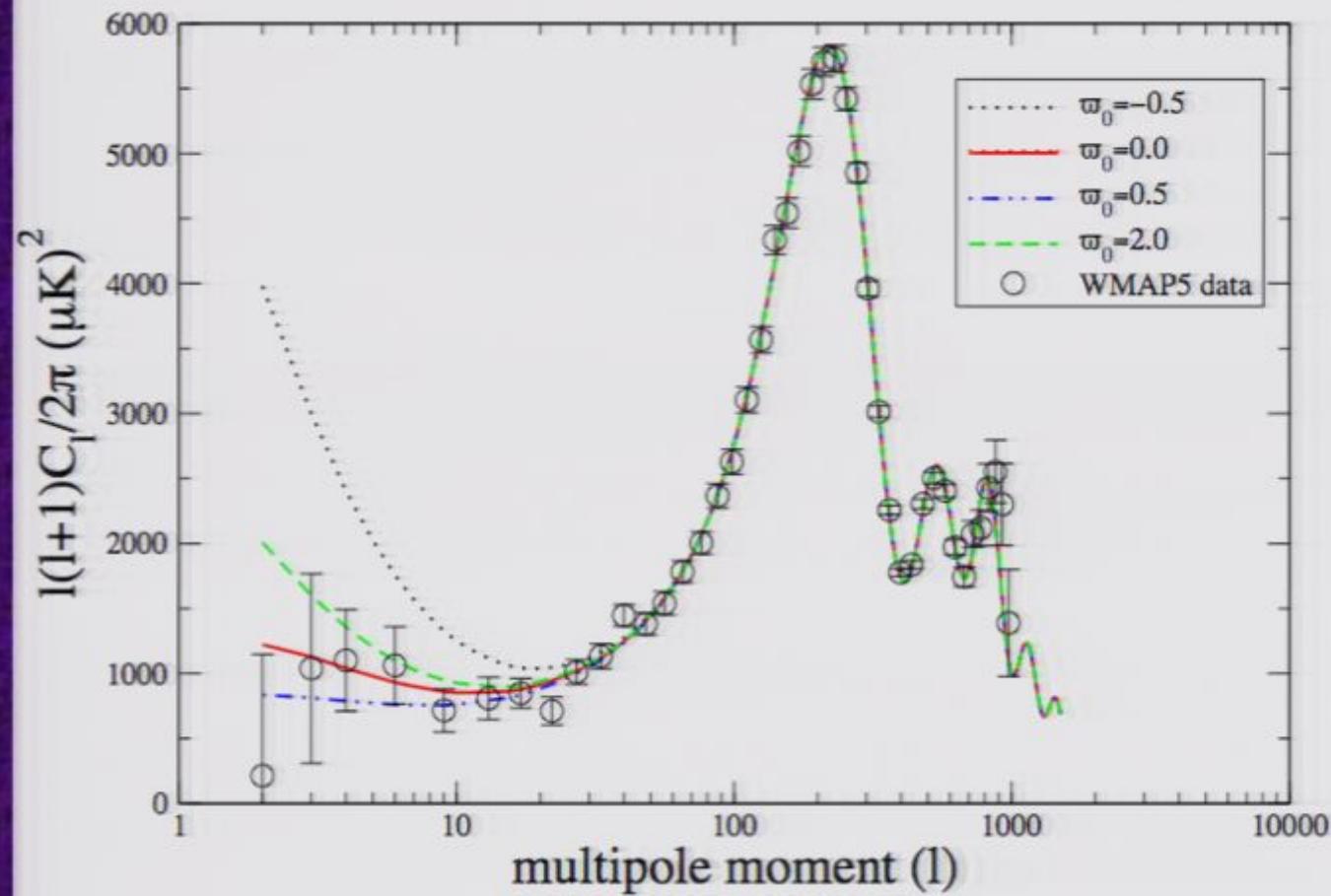
# Effects on structure growth



$$\ddot{\vec{x}} = -\vec{\nabla}\psi$$

$$\nabla^2\phi = -4\pi G a^2 \delta\rho$$

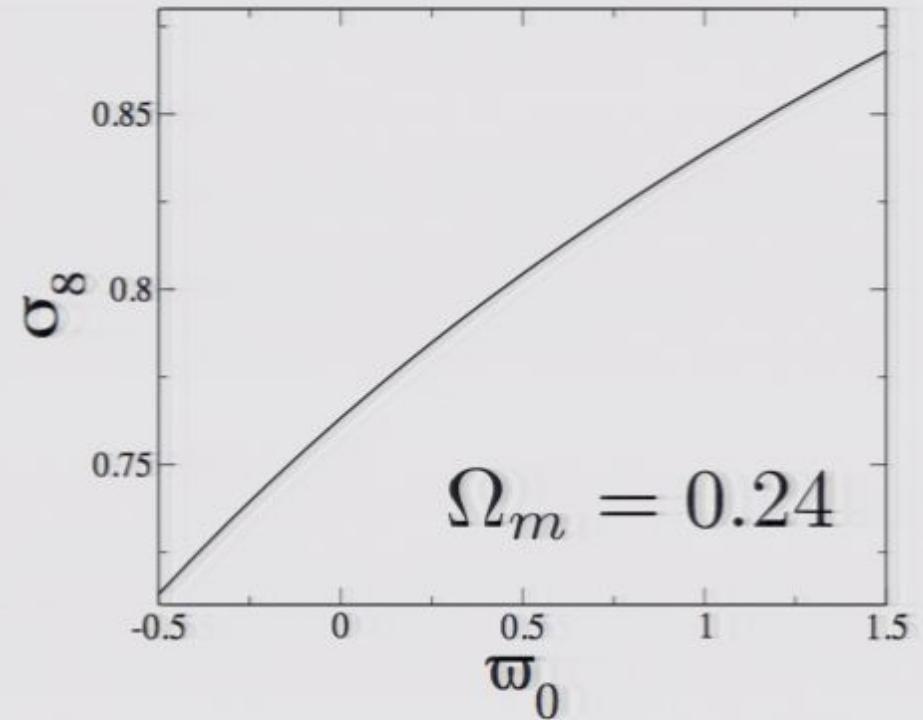
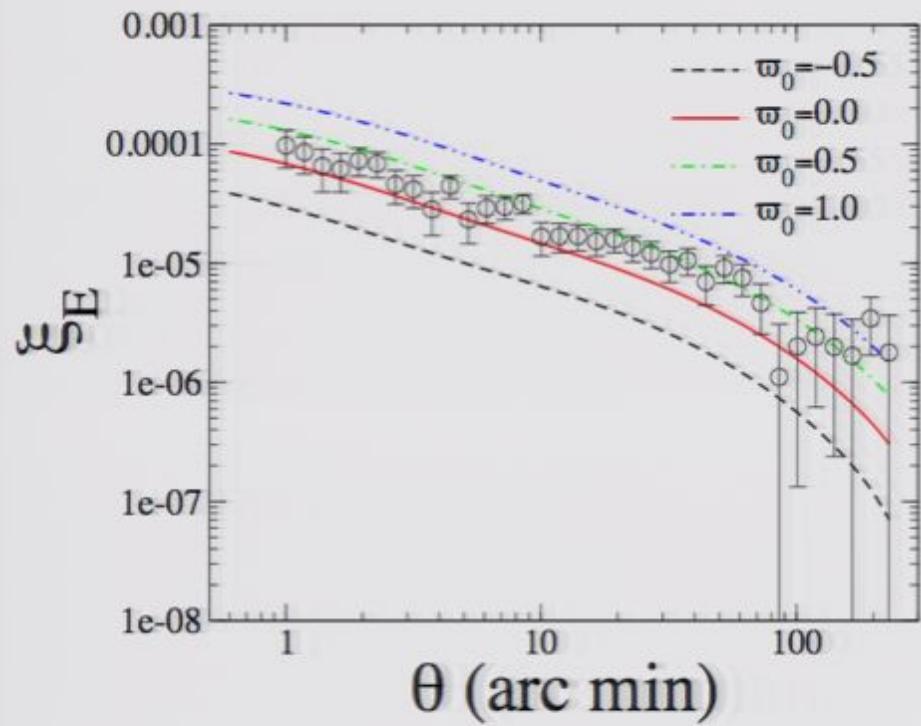
# Effects on CMB



Data from WMAP 5 year release

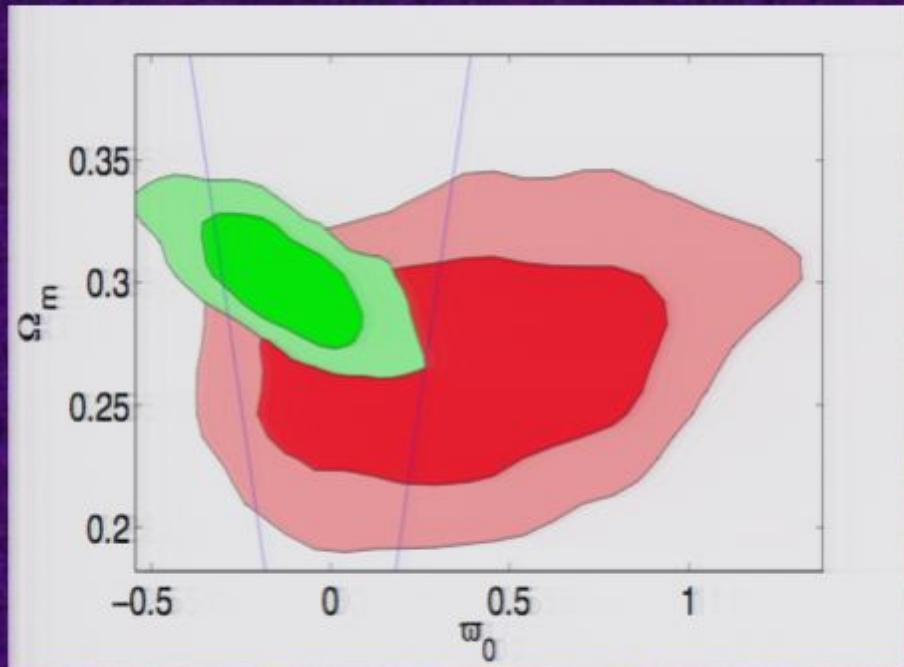
<http://lambda.gsfc.nasa.gov/>

# Effects on Weak Lensing



data from CFHT Legacy Survey  
Fu *et al.*, arXiv:0712.0884

# Likelihood contours



$$\varpi \sim \frac{\delta p}{\delta \rho} \rightarrow \varpi_0 \sim \pm \Omega_m$$

Red: just CMB

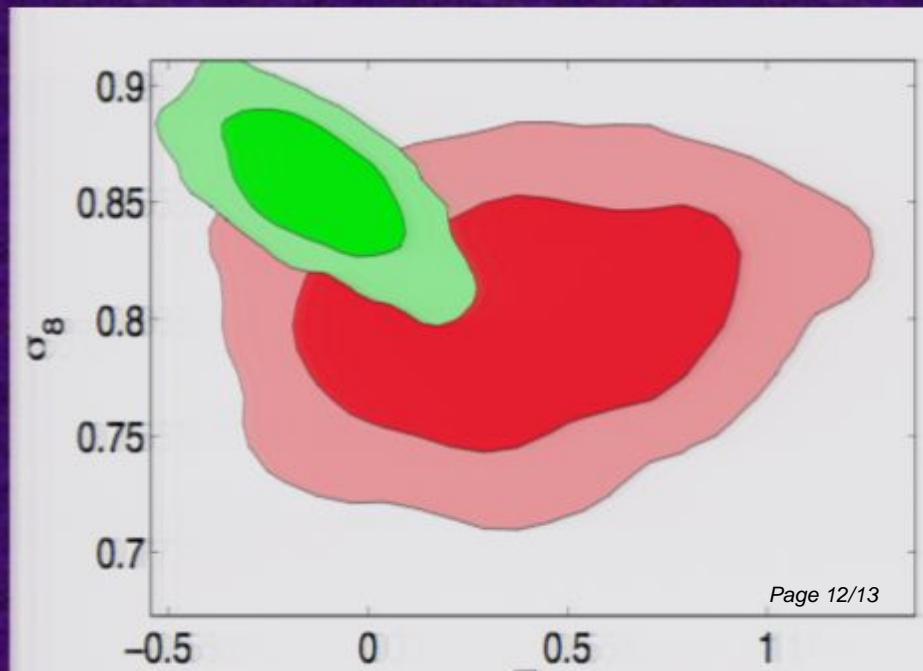
Green: lensing+CMB+SNe

Calculations run on CosmoMC

Lewis and Bridle

PRD 66 103511 (2002)

WL data from  
Fu *et al.*, arXiv:0712.0884  
WMAP data from  
<http://lambda.gsfc.nasa.gov>  
SN data from  
Wood *et al.*, arXiv:astro-ph/0701041



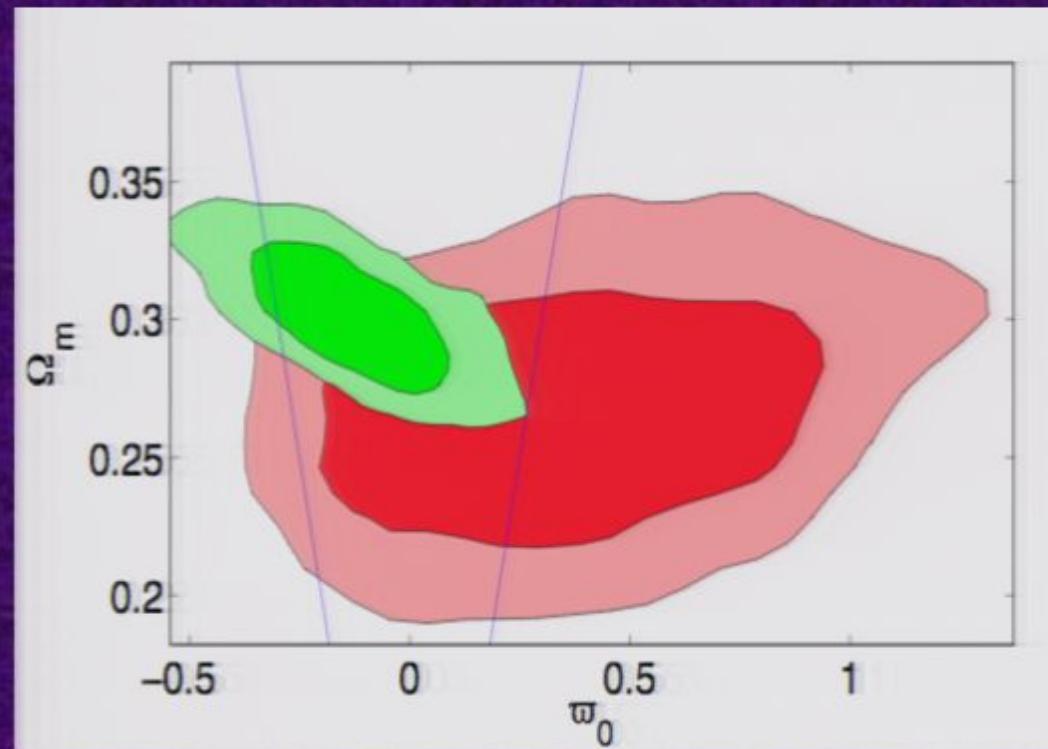
# Conclusions

Scale dependence?

$$\varpi(z, k) = \varpi_0 \frac{\Omega_\Lambda}{\Omega_m} (1 + z)^{-3} \exp[-k/\kappa]$$

Result unchanged to 5%  
for  $\kappa > 20 \text{ hMpc}^{-1}$   
( $\lambda_\kappa < 0.5 \text{ Mpc}$ )

Non-zero  $\varpi_0$  is possible,  
but it's degenerate with  
different values of  $\sigma_8$   
and  $\Omega_m$



Stronger conclusions depend on tighter constraints from  
weak lensing