Large scale structure as a probe of gravitational slip

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Problems with ΛCDM

- Λ too small (~120 orders of magnitude)
- Λ too big (not zero)
- Coincidence problem ($\Omega_\Lambda \sim \Omega_m$ today)

Dynamical acceleration

- Dark energy
  - Scalar fields $\mathcal{L} = -\frac{R}{16\pi G} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi + V(\phi)$
  - Vector fields

$$\mathcal{L} = -\frac{R}{16\pi G} - \frac{1}{2}\nabla_\mu A_\nu \nabla^\mu A^\nu + \frac{1}{2}R_{\mu\nu}A^\mu A^\nu$$

Jimenez and Maroto PRD 78, 063005 (2008)

- Modified gravity…

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)

DGP gravity

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

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

How would we know?

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

In general relativity $\phi = \psi$

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

affect growth of structure

and the
integrated Sachs-Wolfe effect

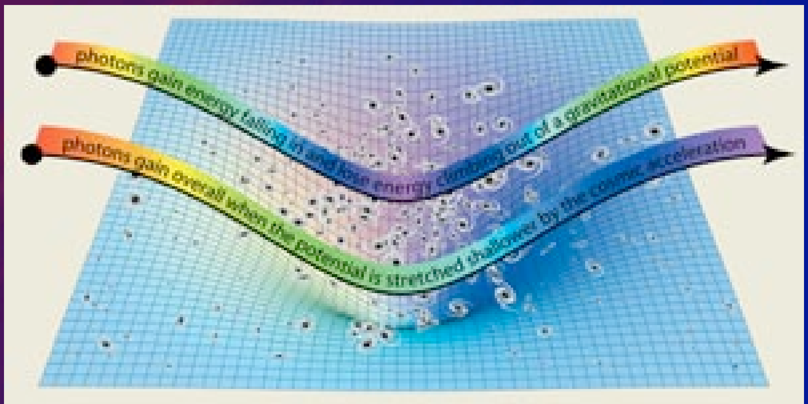

image taken from http://physicsworld.com/cws/article/print/19419/1/pwfea2_05-04

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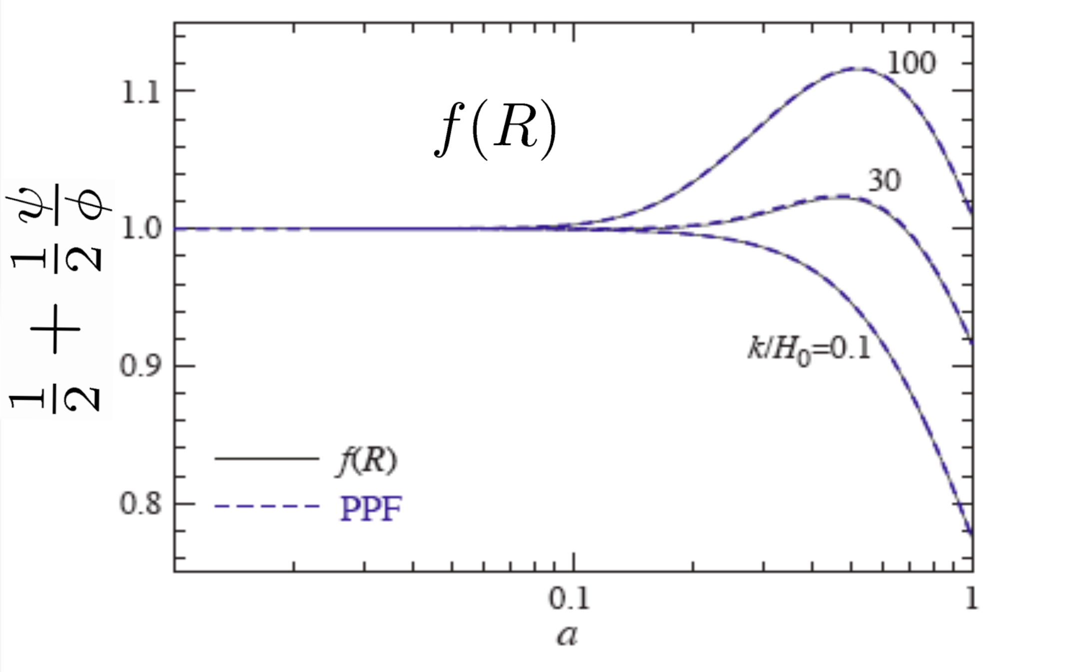
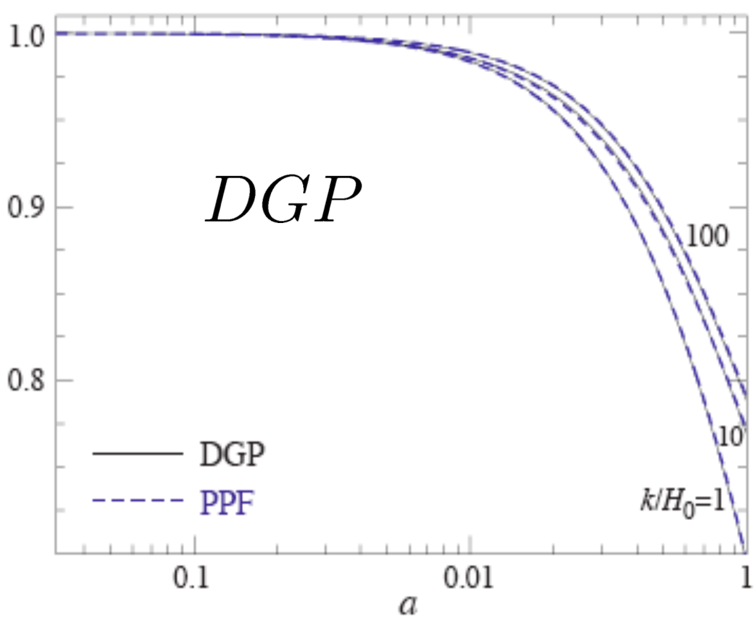
Hu and Sawicki, PRD **76**, 104043 (2007)





Our parametrization

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

$$\psi = (1+\varpi)\phi \qquad \varpi = \varpi_0 \frac{\Omega_\Lambda}{\Omega_m} a^3$$

$\varpi_0 > 0 \rightarrow |\psi| > |\phi| \rightarrow$ a given mass exerts more attraction relative to ΛCDM

$\varpi_0 < 0 \rightarrow |\psi| < |\phi|$

or $(\psi > 0, \phi < 0) \rightarrow$ suppressed growth or ***gravitational repulsion***???

Equations of Motion

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

$$\psi = \dot{\alpha} + \mathcal{H}\alpha \qquad \phi = \eta - \mathcal{H}\alpha$$

$$\begin{aligned} k^2\eta - \frac{1}{2}\mathcal{H}\dot{h} &= 4\pi G a^2 \delta T^0_0 \\ \ddot{h} + 2\mathcal{H}\dot{h} - 2k^2\eta &= -8\pi G a^2 \delta T^i_i \\ k^2\dot{\eta} &= 4\pi G a^2 (\bar{\rho} + \bar{p})\theta \end{aligned}$$

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

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

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

Caldwell *et al.*, PRD **76**, 023507 (2007)

Equations of Motion

zero-i Einstein equation:

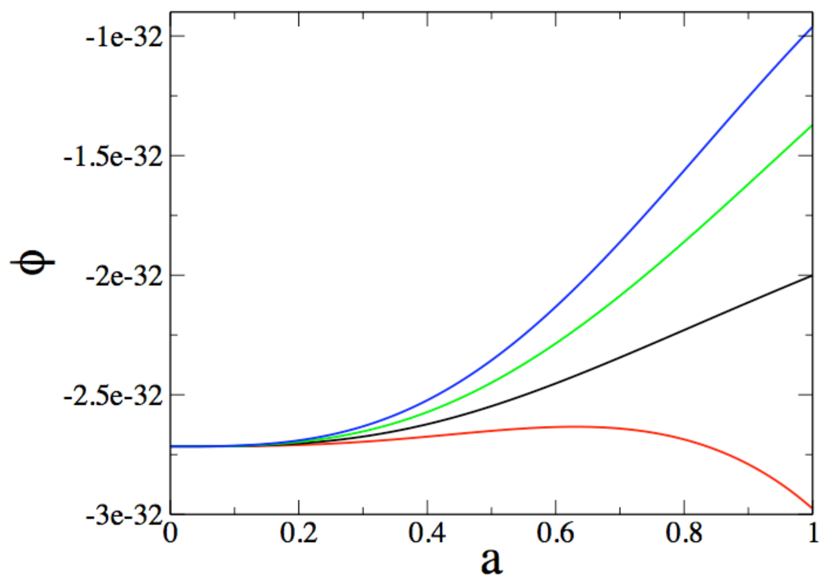
$$k^2\left(\dot{\phi}+\mathcal{H}\psi\right)=4\pi G a^2\bar{\rho}(1+w)\theta$$

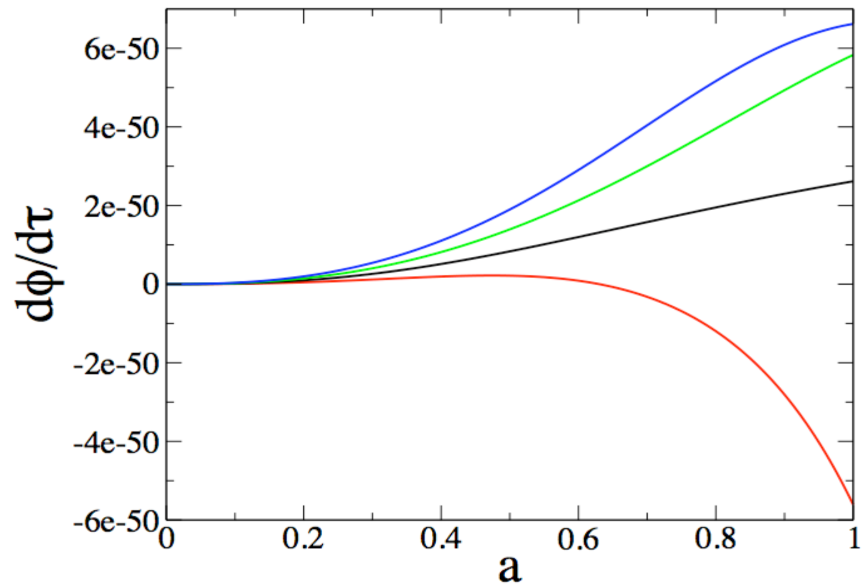
stress energy conservation:

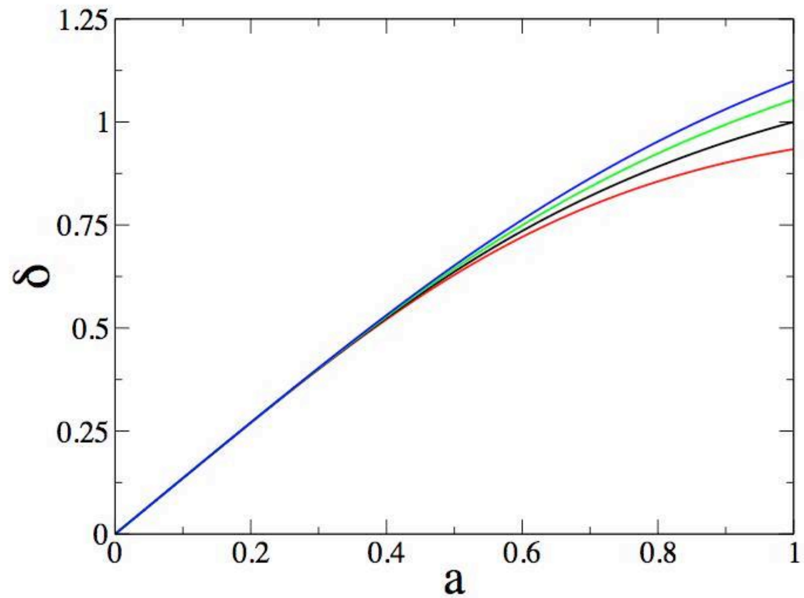
$$\dot{\theta}=-\mathcal{H}(1-3w)\theta-\frac{\dot{w}}{1+w}\theta+\frac{\delta P/\delta\rho}{1+w}k^2\delta-k^2\sigma+k^2\psi$$

$$\ddot{\phi}=-\dot{\phi}\mathcal{H}(3+\varpi)-\phi\mathcal{H}\dot{\varpi}-3\phi\mathcal{H}^2(1-\Omega_m)(1+\varpi)$$

$$\dot{\delta}=3\dot{\phi}-\left(\frac{k}{\mathcal{H}}\right)^2\frac{\dot{\phi}+\phi\mathcal{H}(1+\varpi)}{1.5\Omega_m}$$







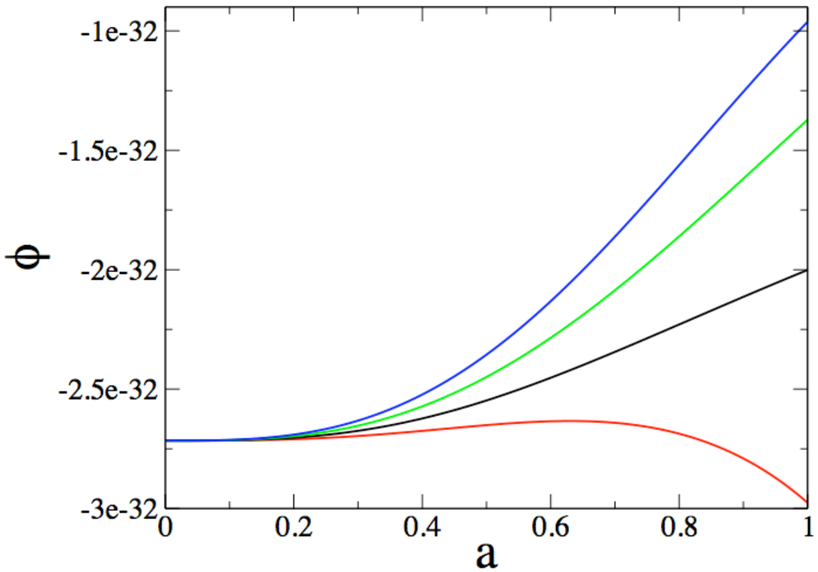
red: $\varpi_0 = -0.5$

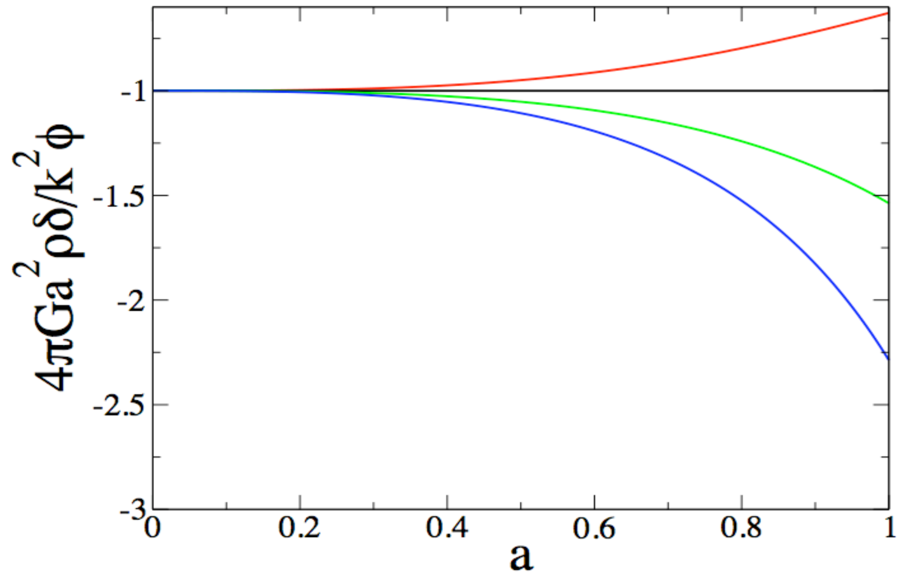
black: $\varpi_0 = 0.0$

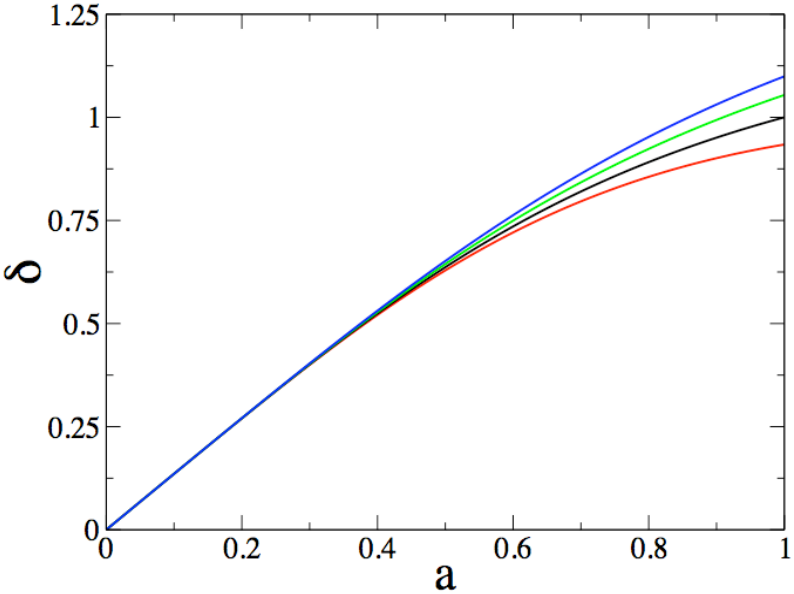
green: $\varpi_0 = 0.5$

blue: $\varpi_0 = 1.0$

recall: $\varpi_0 > 0$ means that the Newtonian potential is deeper than the longitudinal potential; $\varpi_0 < 0$ means that the Newtonian potential is shallower/"repulsive"







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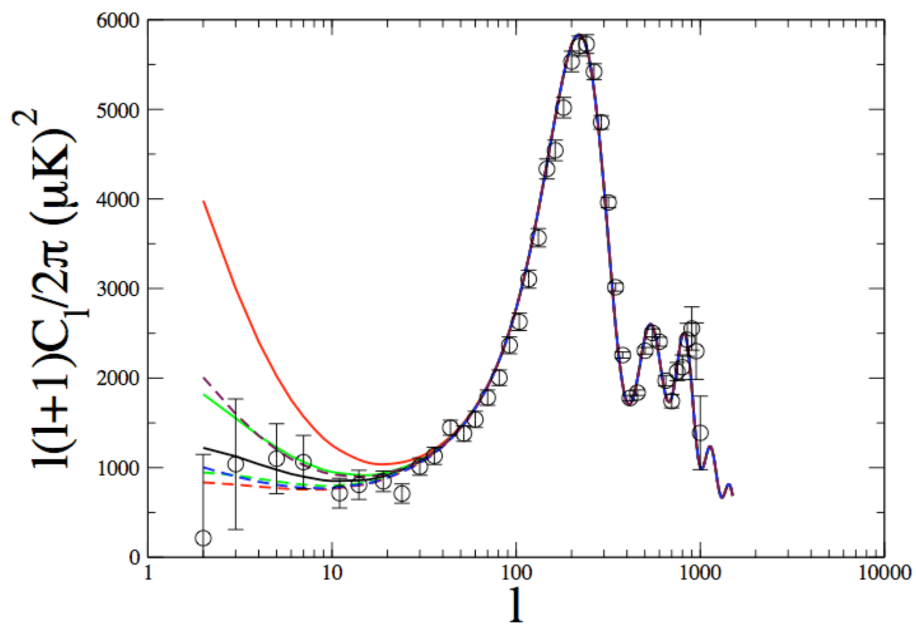
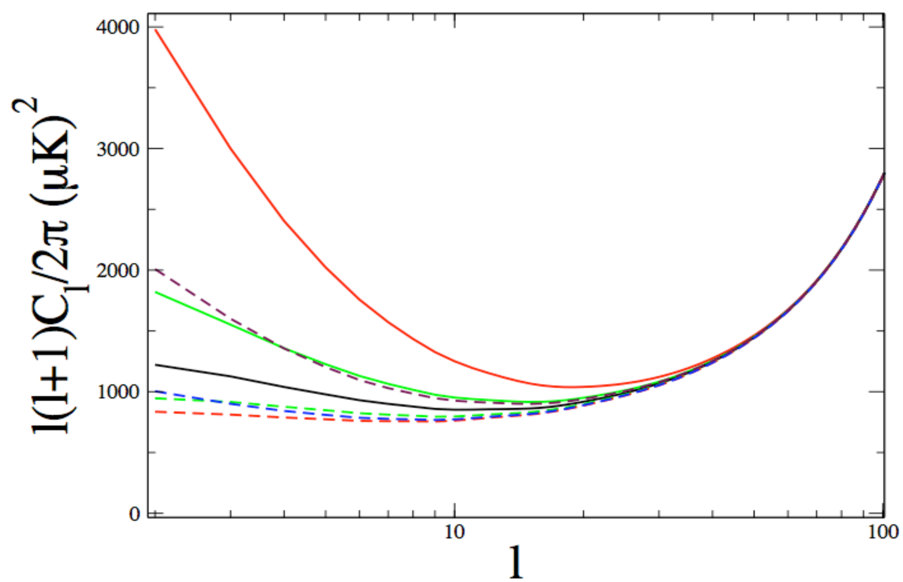
Effect on CMB

red: $\varpi_0 = -0.5$
green: $\varpi_0 = -0.2$
black: $\varpi_0 = 0.0$
green dash: $\varpi_0 = 0.2$
red dash: $\varpi_0 = 0.5$
blue dash: $\varpi_0 = 1.0$
brown dash: $\varpi_0 = 2.0$

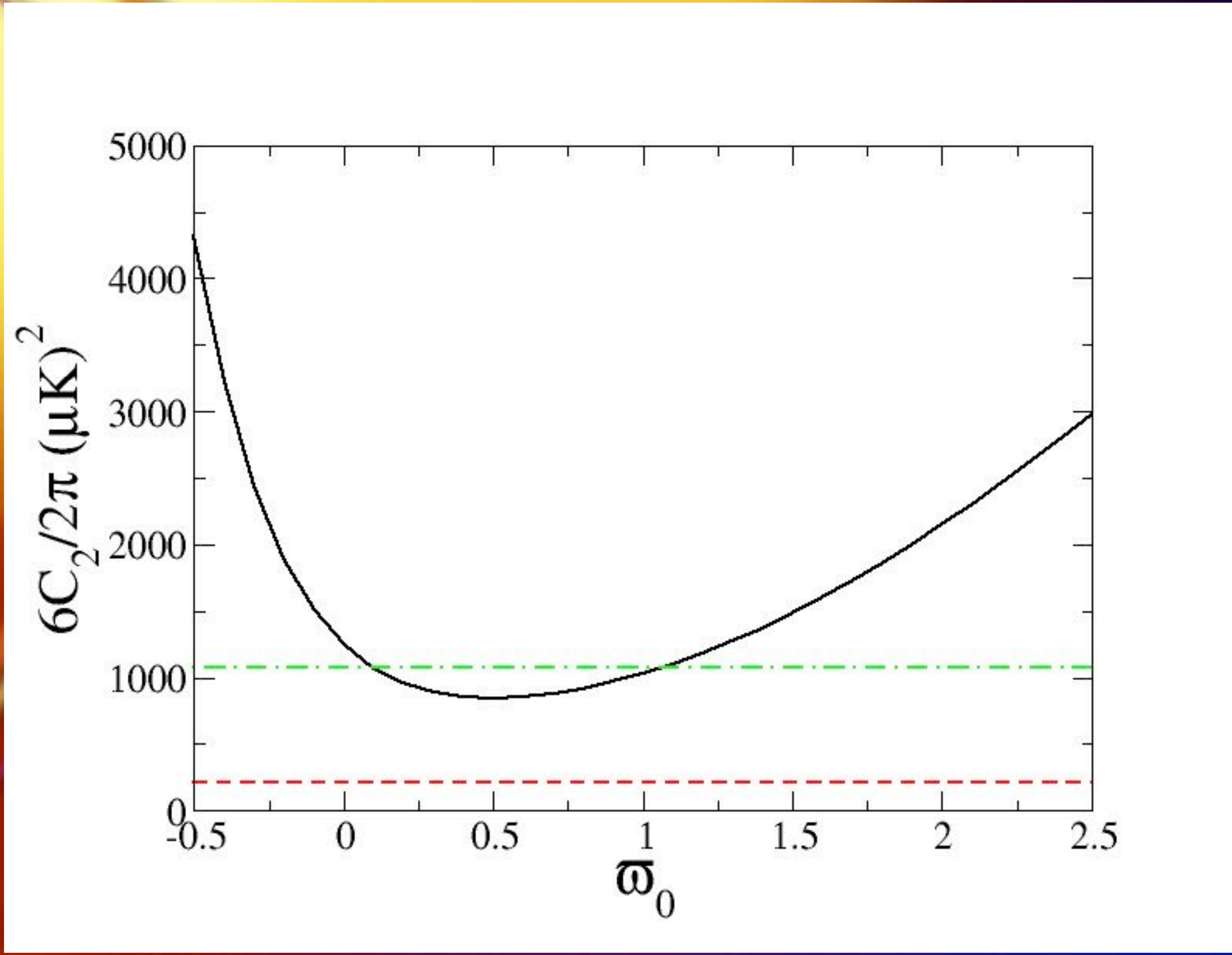
data: WMAP 5 year
Dunkley *et al*
arXiv:0803.0586

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





Effect on CMB



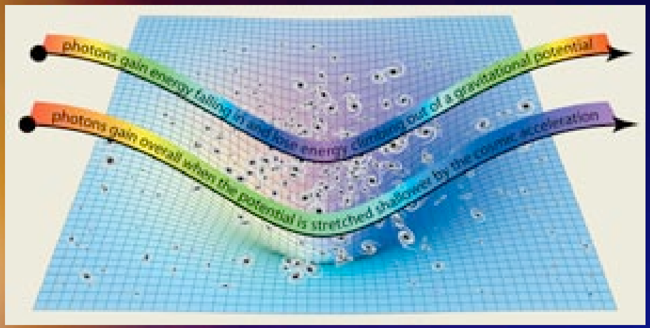
Effect on CMB

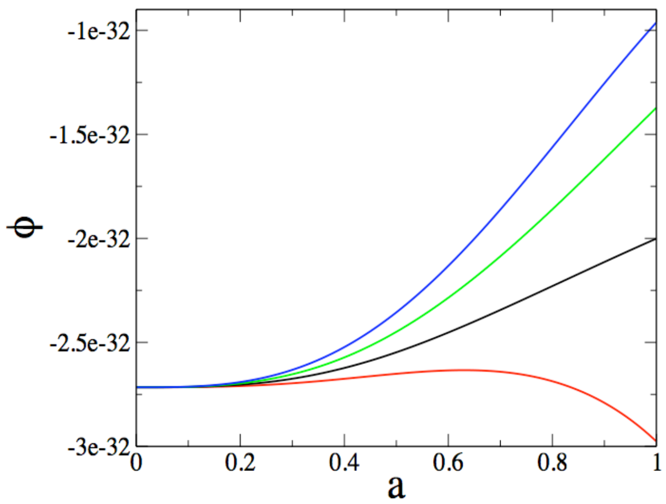
the integrated Sachs-Wolfe effect

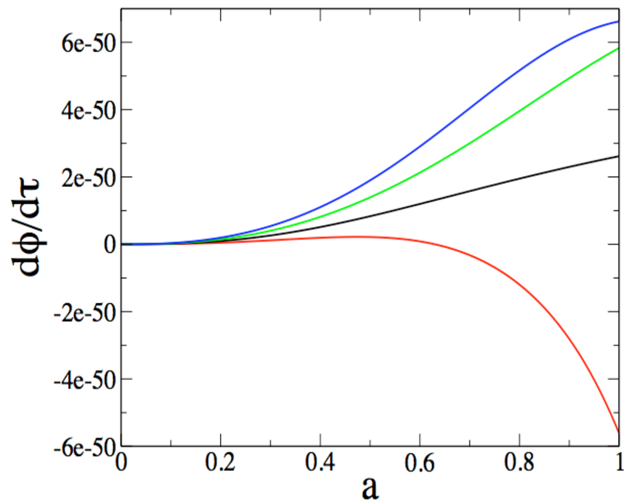
$$\int_0^{\tau_0} d\tau \exp[-\kappa](\dot\phi + \dot\psi) j_l[k(\tau_0 - \tau)]$$

$$\dot\phi + \dot\psi = \dot\phi(2 + \varpi) + \phi\dot\varpi$$

$$\dot\varpi = 3\mathcal{H}\varpi$$







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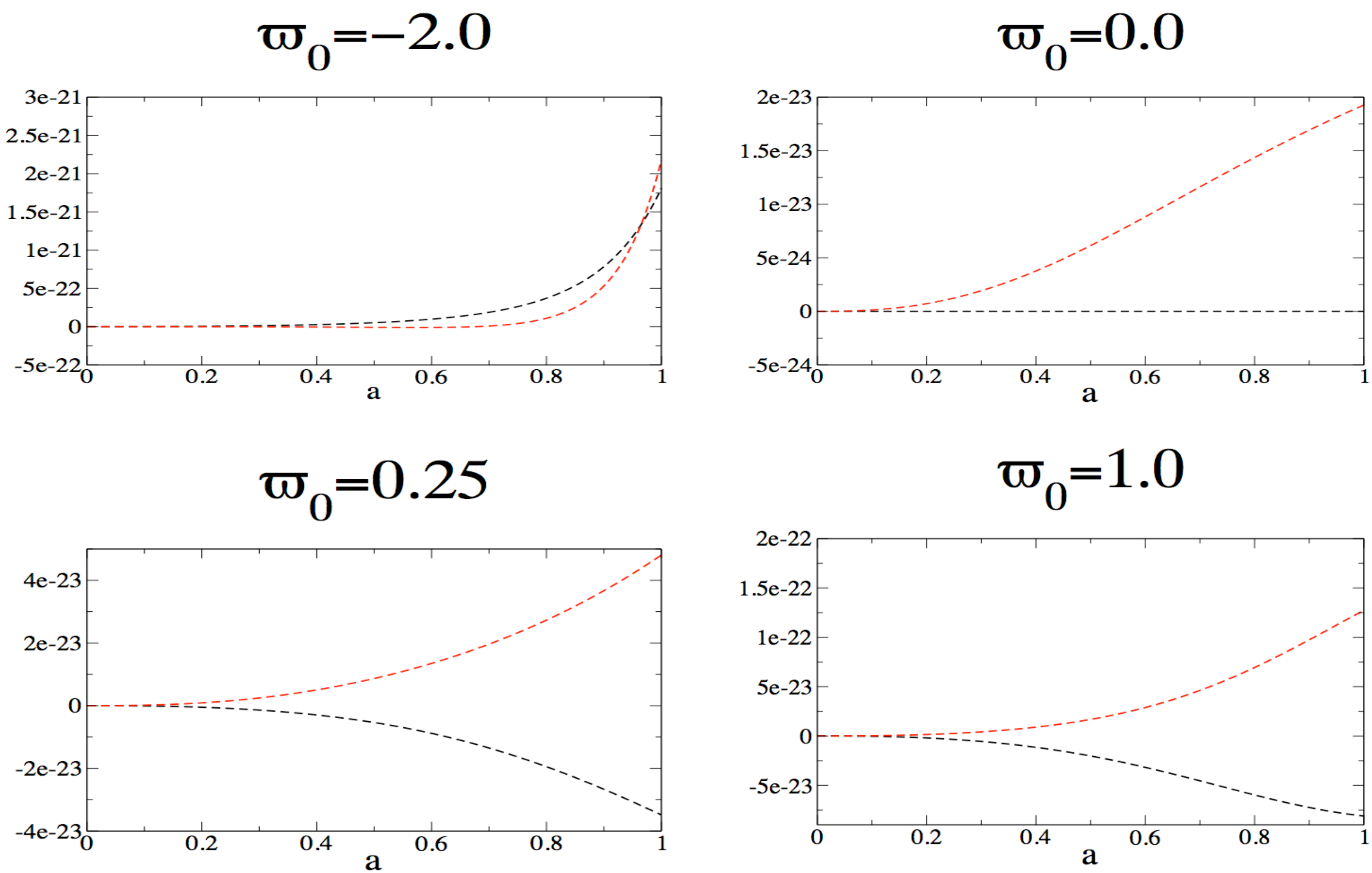
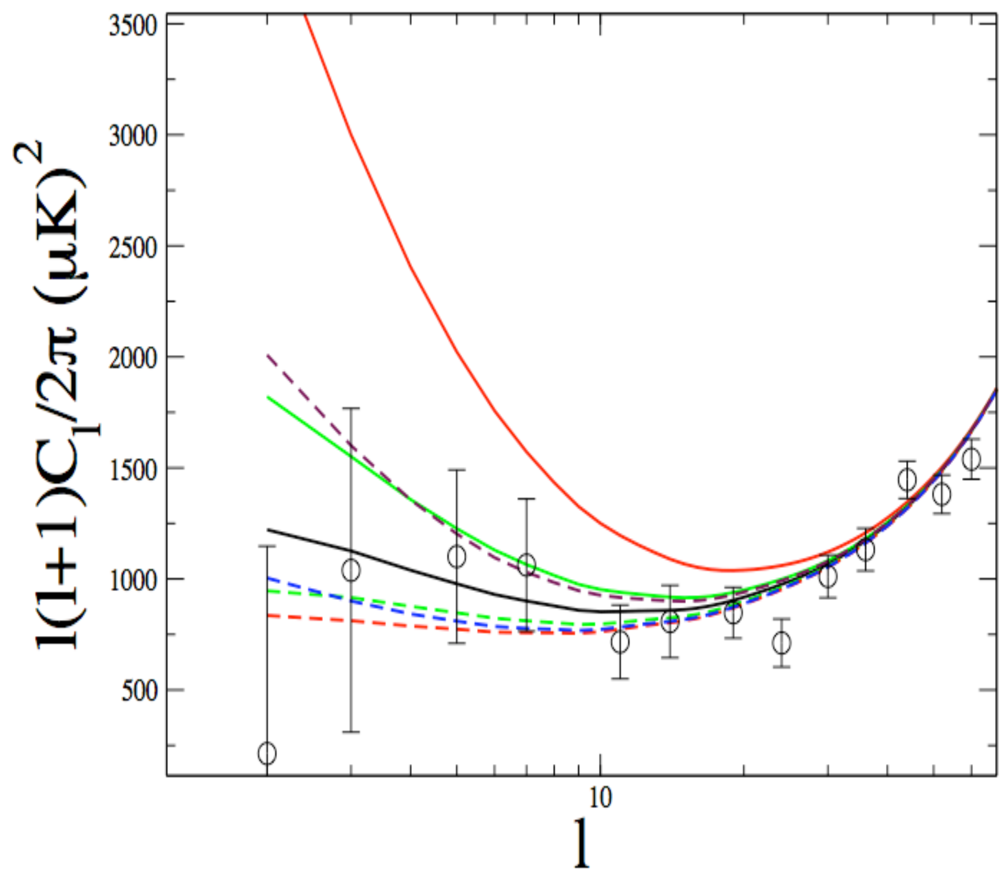


black: $\phi \dot{\varpi}$ red: $\dot{\phi}(2 + \varpi)$

Effect on CMB



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data: WMAP 5 year
Dunkley *et al*
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Effect on weak lensing

ΛCDM

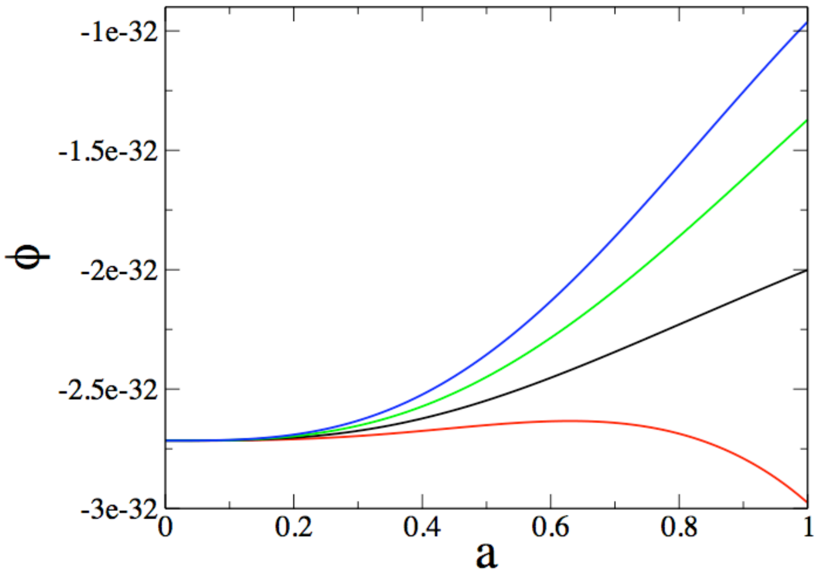
ϖCDM

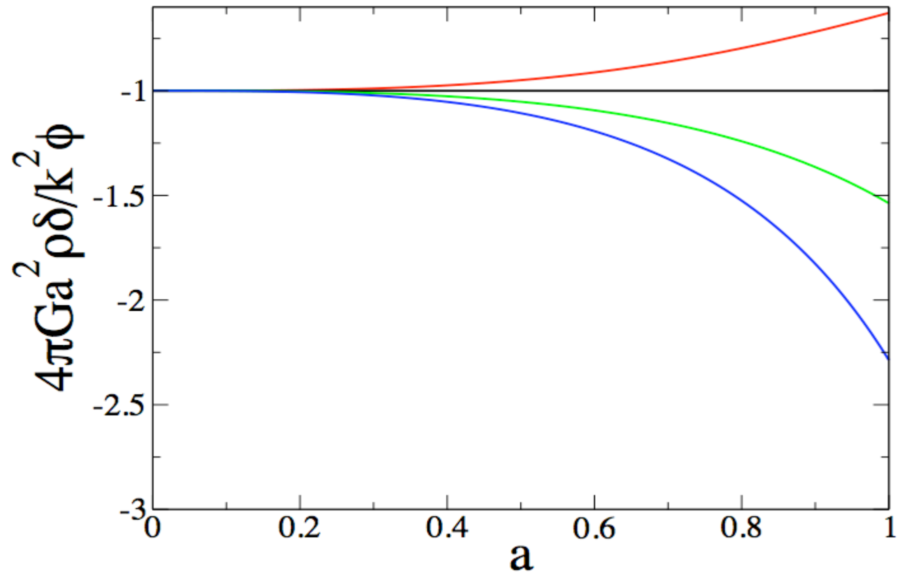
$$\phi + \psi = 2\phi \quad \rightarrow \quad \phi + \psi = (2 + \varpi)\phi$$

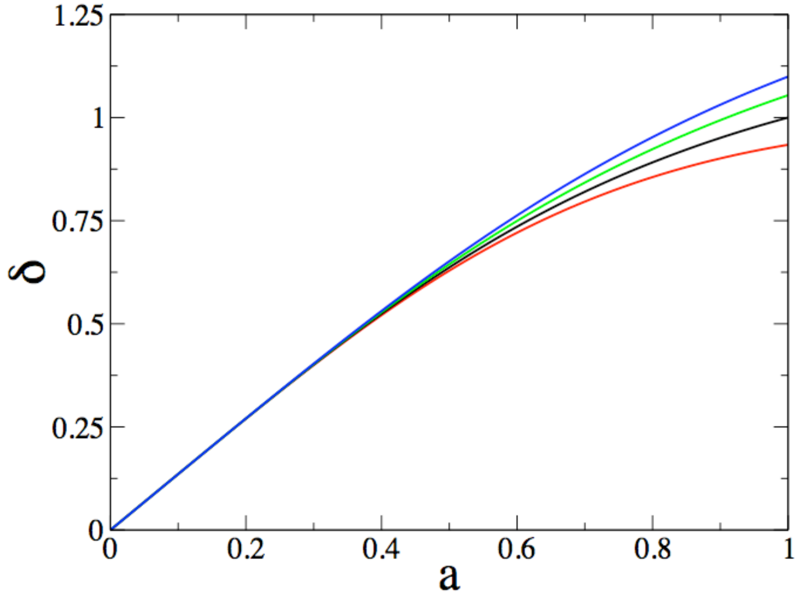
$$P_\phi = \left(\frac{4\pi G\bar{\rho}}{k^2}\right)^2 P_\delta \quad \rightarrow \quad P_\phi = A^2 P_\delta$$

pre-factor determined from Poisson equation

pre-factor (A) determined from equations of motion







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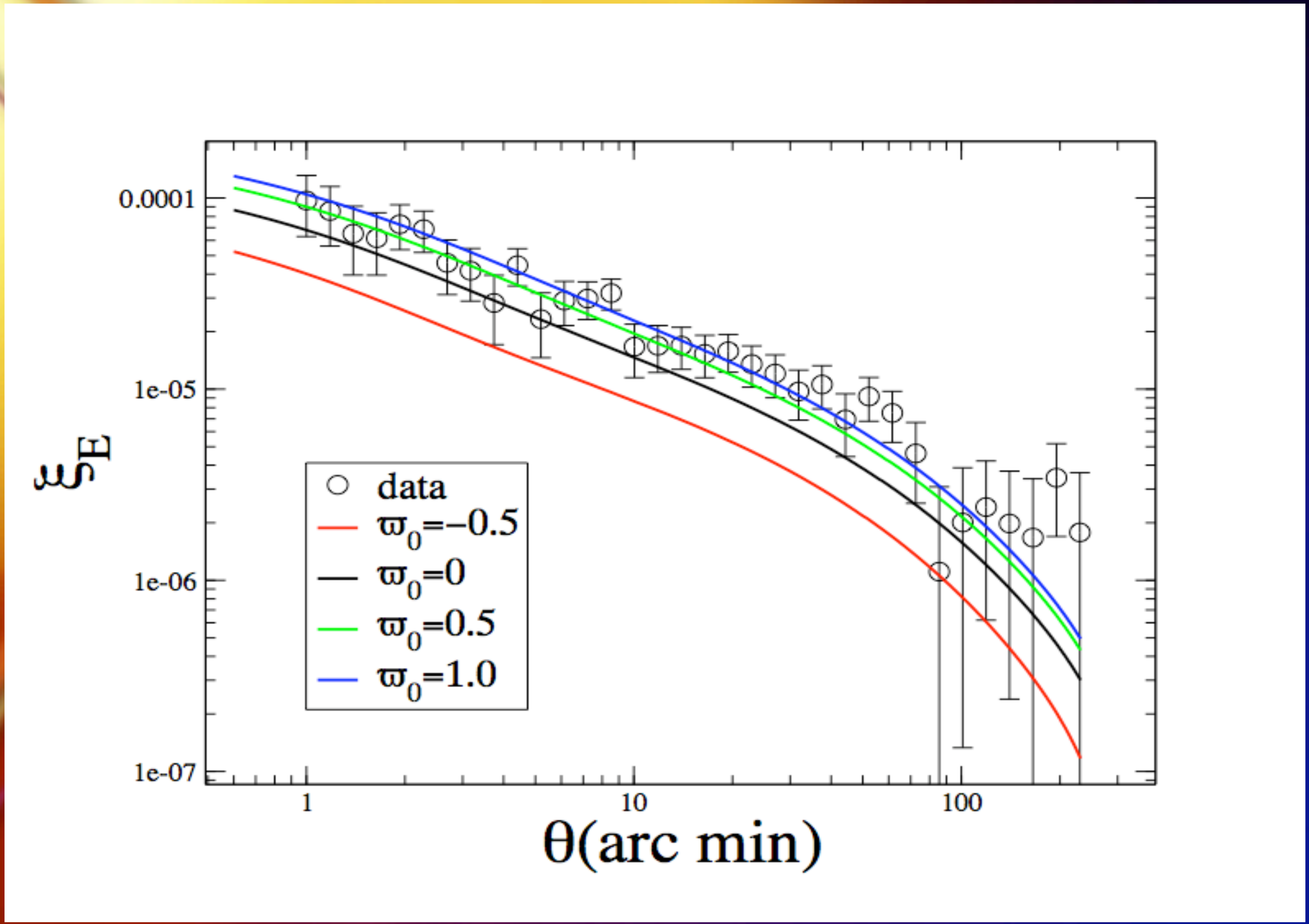
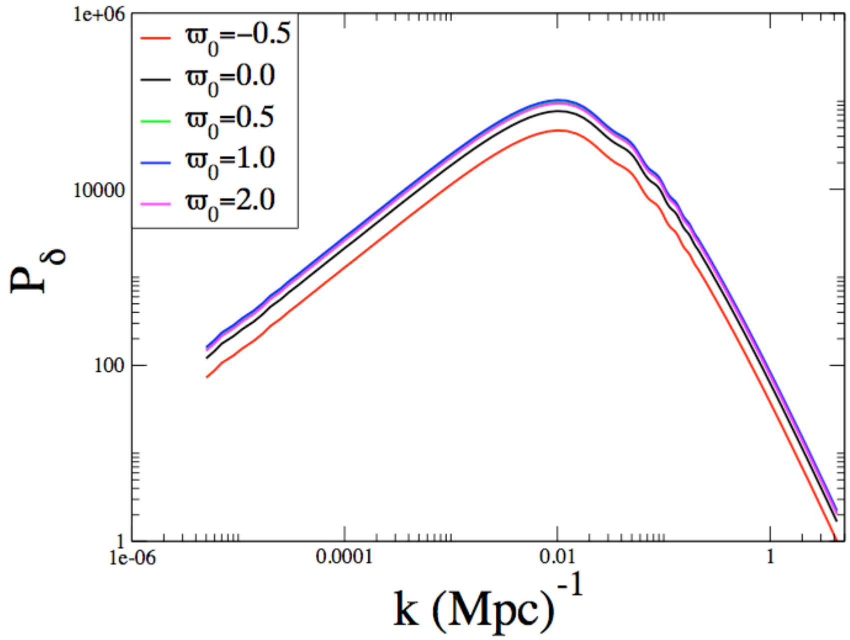
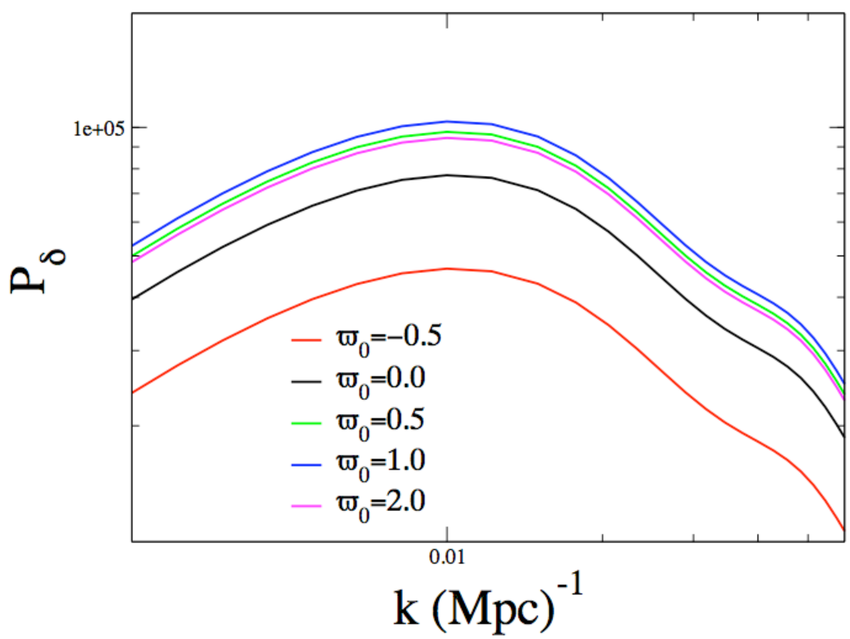


data taken from CFHTLS -- Fu *et al.*, arXiv:0712.0884

Effect on weak lensing

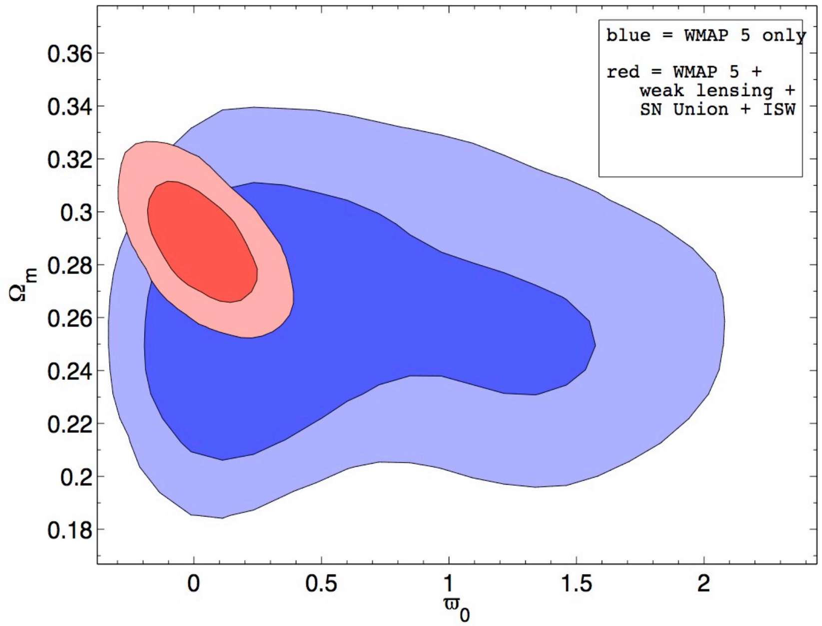
ϖ_0 and σ_8 are correlated



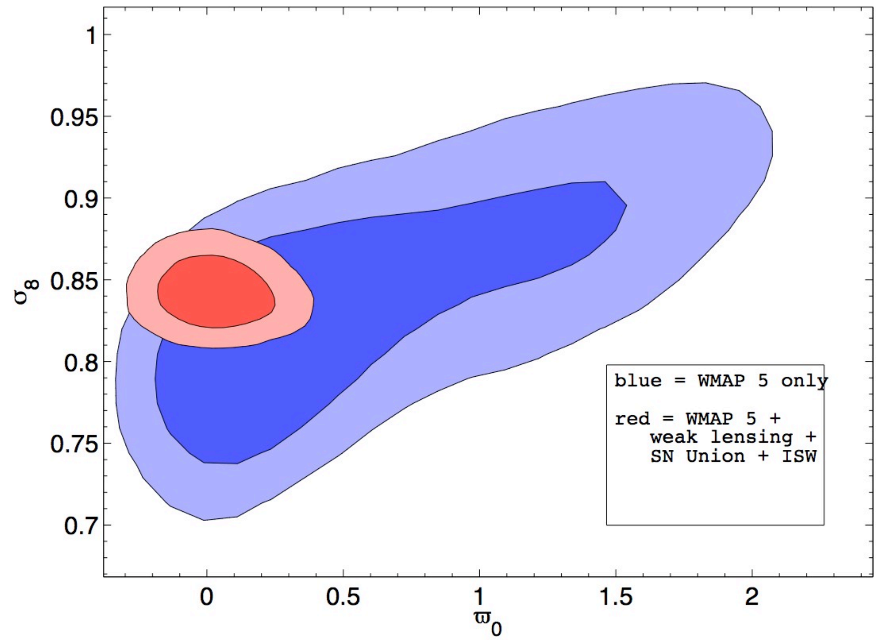


Markov chain analysis

marginalized constraint: $\varpi_0 = 0.03 \pm 0.14$



COSMOMC
Lewis and Bridle
PRD **66**, 103511
(2002)



data sets:

WMAP 5 - arXiv:0802.0586 (blue + red)

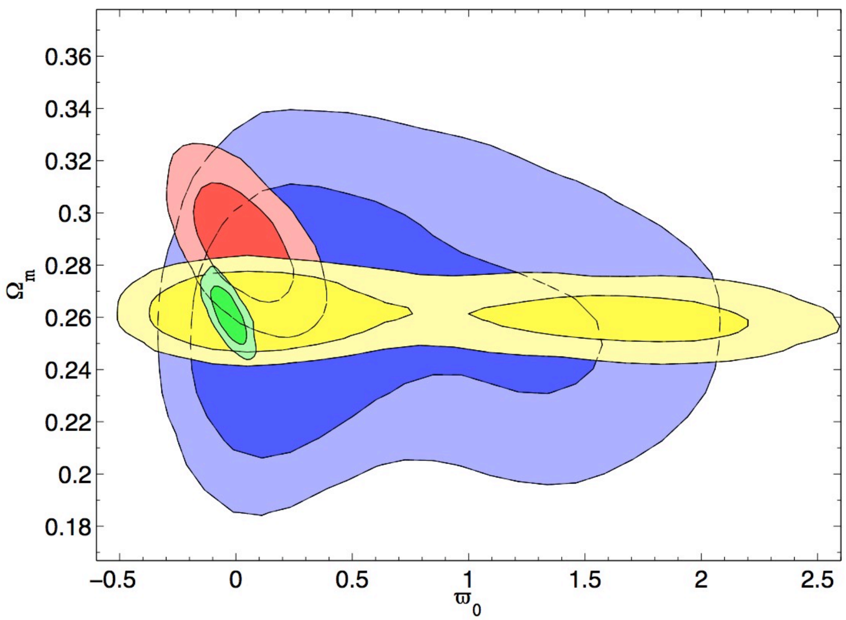
CFHTLS - arXiv:0810.5129 (red)

SN Union - arXiv:0804.4142 (red)

ISW - arXiv:0801.0642 (red)

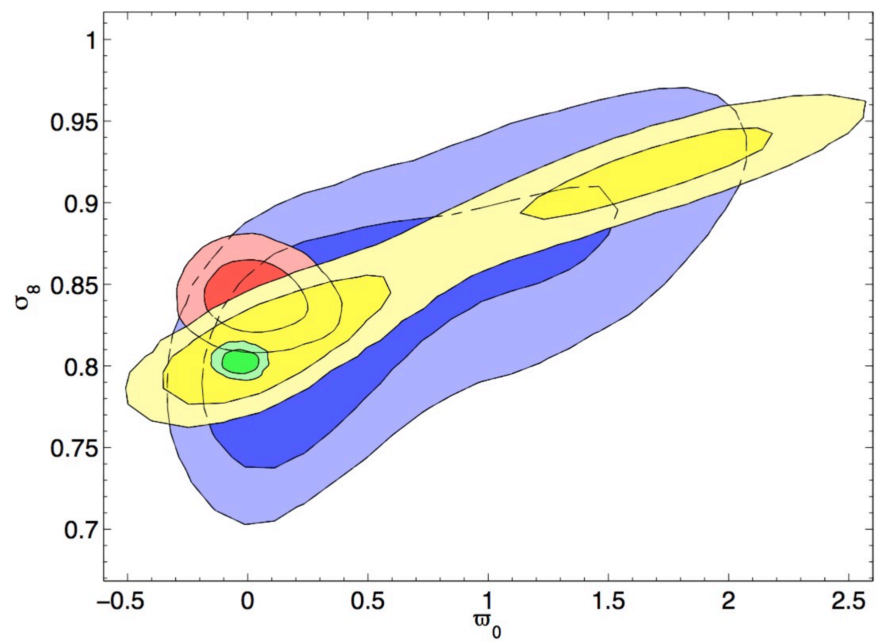
Future data sets

marginalized constraint: $\varpi_0 = -0.03 \pm 0.05$



Planck (yellow)
see recipe at
http://cosmocoffee.info/viewtopic.php?t=231

Planck+ DUNE (green)
astro-ph/0610062



Fiducial model:

$$\varpi_0 = 0.0$$
$$\Omega_m = 0.256$$
$$\sigma_8 = 0.796$$

Future data sets

	Planck only	Planck+DUNE	Fiducial
$\Omega_b h^2$	2.22e-2 ± 6e-4	2.25e-2 ± 2e-4	2.273e-2
$\Omega_{cdm} h^2$	1.09e-1 ± 6e-3	1.11e-1 ± 1e-3	1.099e-1
n_s	9.5e-1 ± 1e-2	9.58e-1 ± 4e-3	9.63e-1
τ	9e-2 ± 2e-2	8.6e-2 ± 5e-3	8.7e-2
h	7.1e+1 ± 3e-2	7.15e-1 ± 7e-3	7.19e-1
σ_8	8.4e-1 ± 5e-2	8.03e-1 ± 5e-3	7.96e-1
ϖ_0	6e-1 ± 6e-1	-3e-2 ± 5e-2	0.0

Conclusions

- ✦CMB alone cannot constrain modified gravity
- ✦Large scale structure can
- ✦Present data favors general relativity with a cosmological constant to ~ 10%