Probing Models of Cosmic Acceleration

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Excellence Cluster Universe

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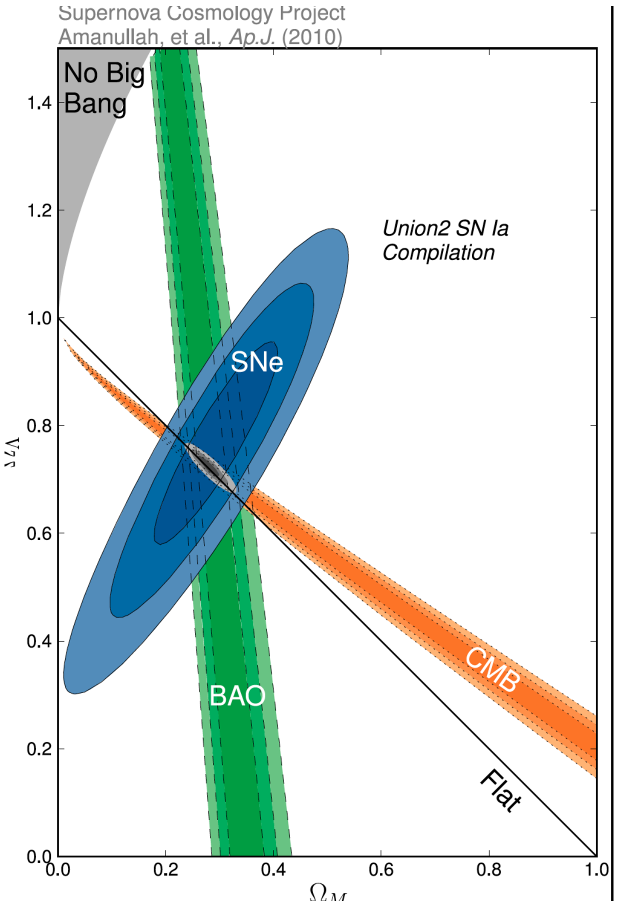
Universe

How much vacuum energy?

- **Energy densities in the Universe:**
  - **Radiation (from CMB temperature):** $\Omega_r \approx 5\times10^{-5}$
  - **combine SNe & CMB:**
    - **matter:** $\Omega_m \approx 0.28$ **(baryons: ≈ 0.04; [BBN/CMB]**
    - **cosmological constant:** $\Omega_\Lambda \approx 0.72$ **(space is close to flat)**

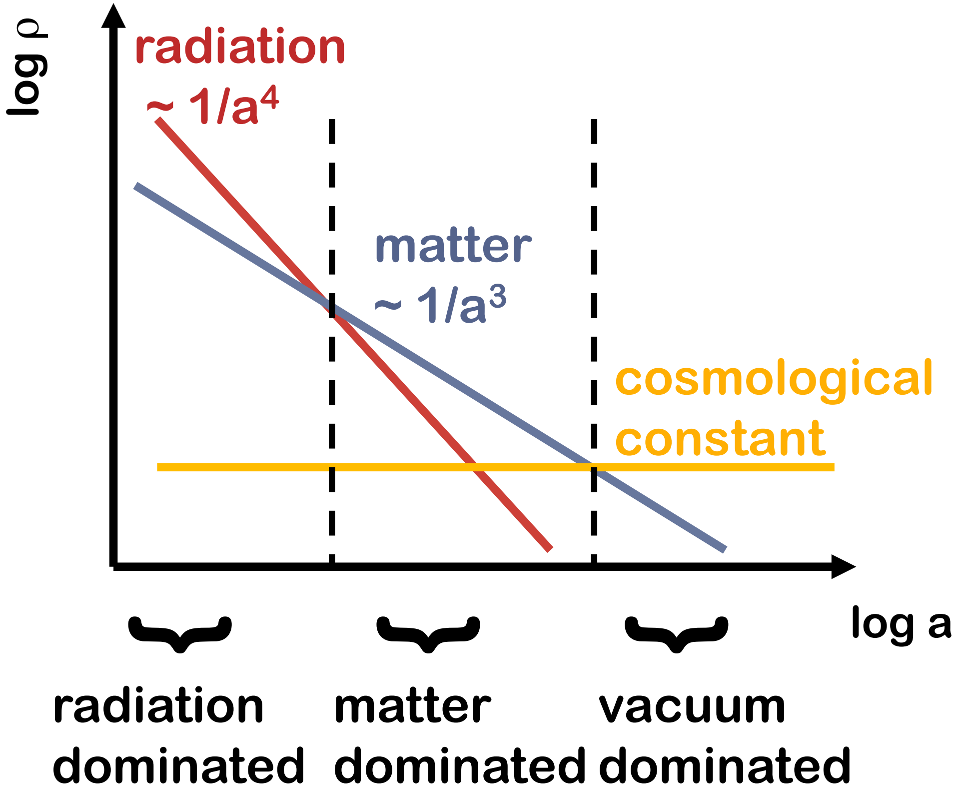
Union II analysis



Cosmological Constant in GR

- Most general form of Einstein's equations of gravity contains cosmological constant
- "density" Ω_Λ in cosmological constant stays constant
- cosmological constant $\rightarrow$ accelerated expansion

What is the problem with the cosmological constant Λ?



- "Expected" value from Planck scale: $\rho_\Lambda \approx 10^{78}$ (GeV)^4
- Measured value $\rho_\Lambda \approx 10^{-45}$ (GeV)^4
- Why is $\Lambda <<$ (TeV)^4 ?
- Why $\Omega_\Lambda \approx \Omega_m$?

cosmological constant ≅ vacuum energy (Zel'dovich)

If not Λ, what else?

- dynamical dark energy
  - general fluid
  - scalar field (Quintessence, k-essence, ...)
  - elastic (formerly known as solid) dark energy
- modifications of General Relativity on large scales
  - Extra dimensions and brane worlds (DGP)
  - f(R)
  - more exotic modifications: $f(R, R_{\mu\nu}R^{\mu\nu}, R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma})$
- apparent effect; "backreaction" from small scale inhomogeneities

Dark Energy

simple fluid: $p = w\rho$

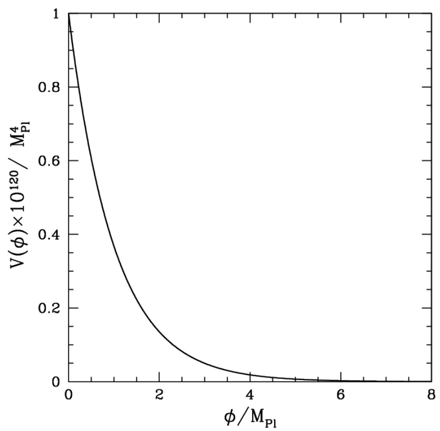
Deceleration parameter (flat Universe, only DE):

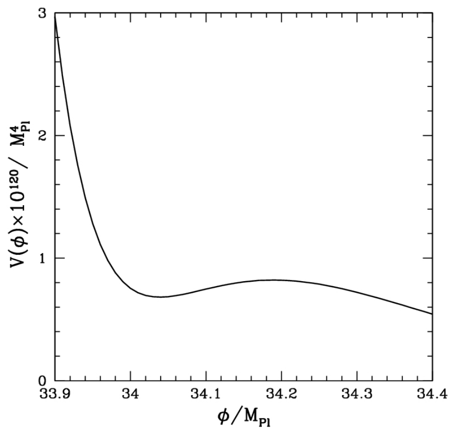
$$q_0 = -\frac{\ddot{a}_0}{H_0^2} = \frac{1+3w}{2}$$

Hence accelerated expansion for w<-1/3 !

Cosmological constant: w=-1

Quintessence





$$\Omega_\Lambda = 0.7 \quad \rightarrow \rho_\Lambda \approx 10^{-48}\ \mathrm{eV} = 10^{-121}\ M_{\mathrm{pl}}^4$$

Dynamical dark energy

Equation of state of scalar field:

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

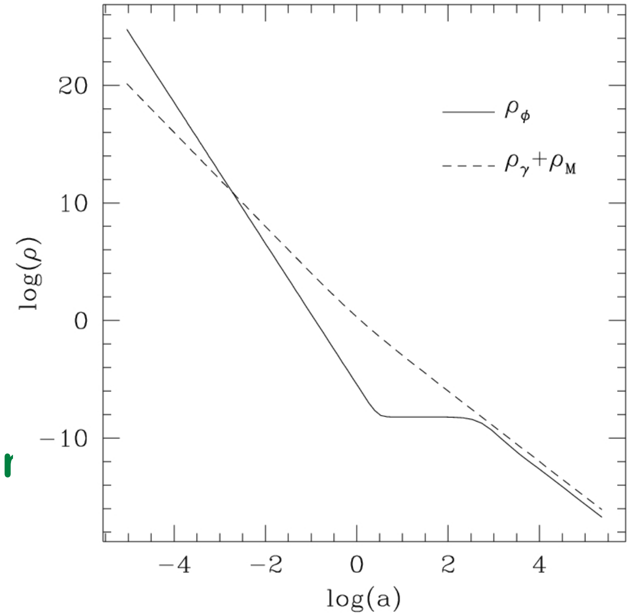
Quintessence

1st try (Wetterich, Ratra and Peebles 1988, Ferreira and Joyce 1998):

$$V(\phi) = e^{-\lambda\phi/M_{\rm pl}}$$

attractor, hence ***NO FINE TUNING*** required !

but: attractor in regime: $\Omega_{de} < \Omega_{r}$

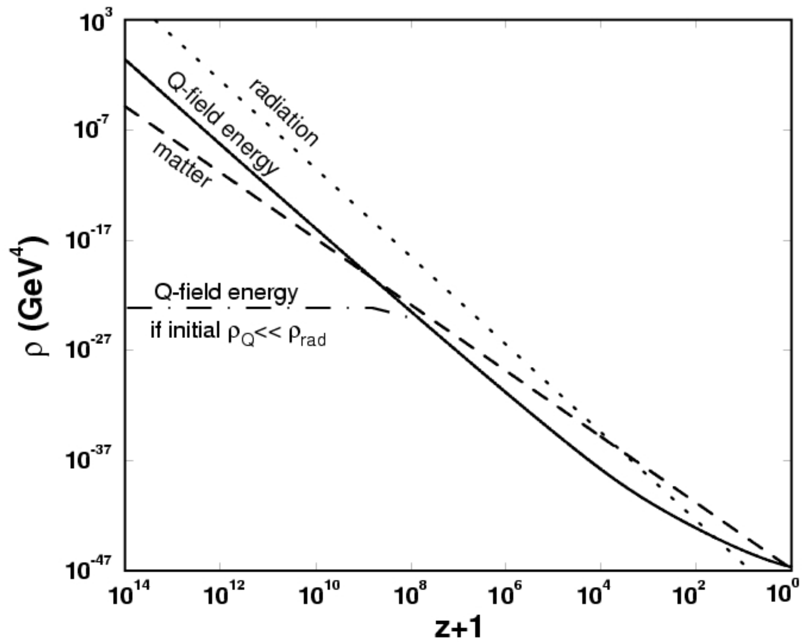


Ferreira & Joyce 1998

2nd try (Steinhardt, Caldwell et al. 1998):

$$V(\phi) = M^4 e^{-M_{\rm pl}/\phi} \quad ; \quad V(\phi) = M^{4+\alpha}/\phi^\alpha$$

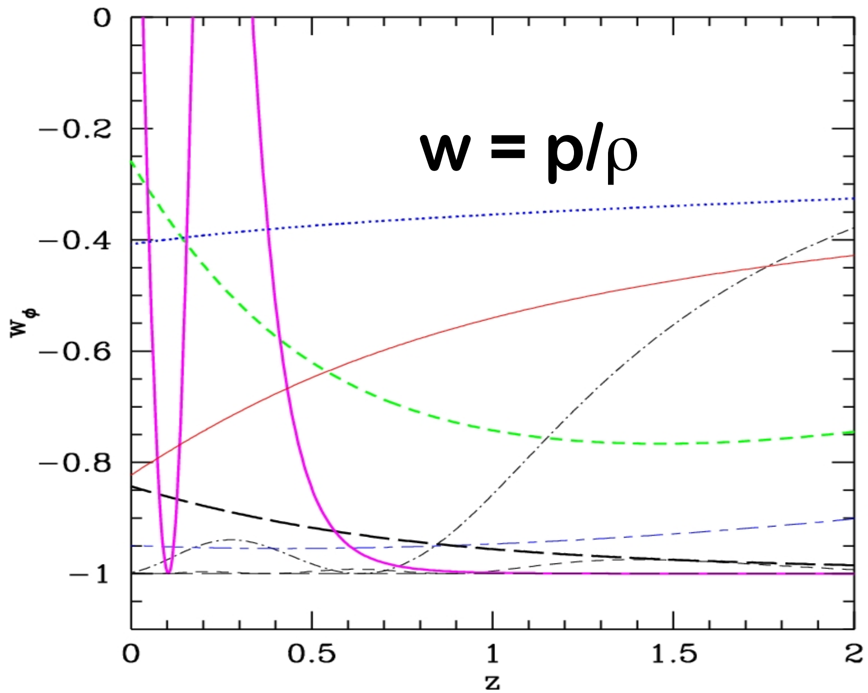
tracker solution !



Zlatev et al. 1998

Different Quintessence Models

scalar field dark energy models (quintessence)



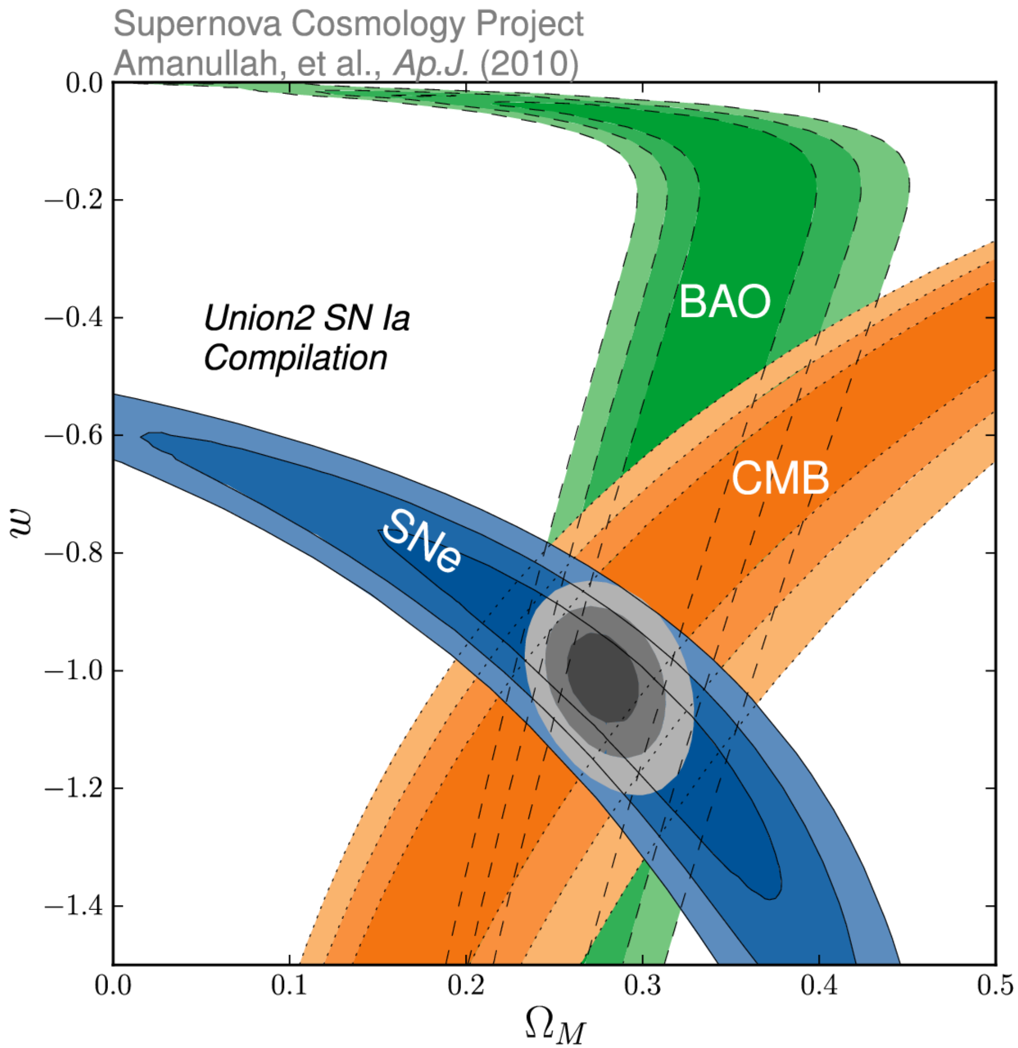
All models ad hoc

Parameterization:

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

$= w_0 + w_a z/(1+z)$

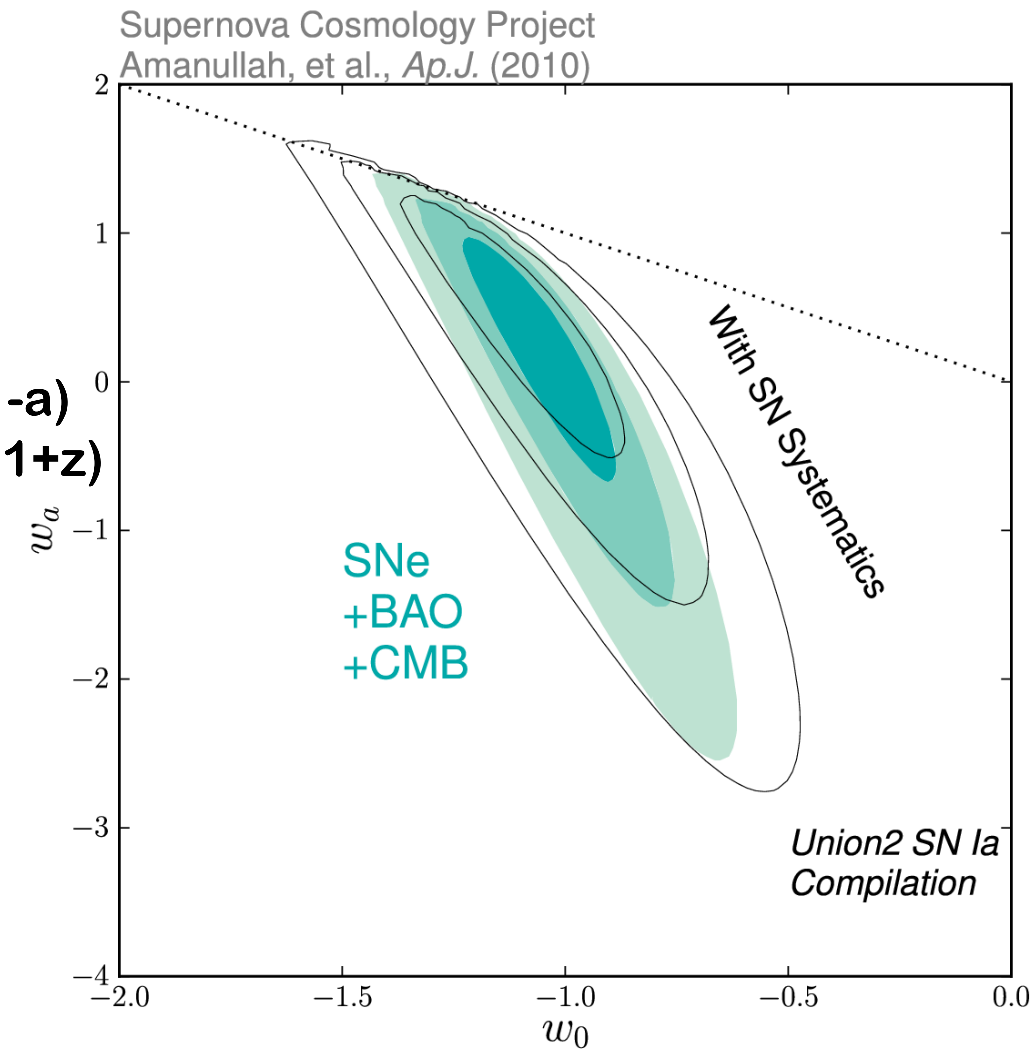
Constraints on w from Union II



w = -0.997±0.051

Constraints on evolution of w

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



Modified Gravity as source of cosmic acceleration

$$S_{EH}=\int_M \sqrt{-g}\,d^4x\left[\frac{R}{16\pi G}+L_m+L_{de}\right]$$

$$R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R=8\pi G(T_{\mu\nu}+T_{\mu\nu}^{(de)})$$

$$S_{MG}=\int_M \sqrt{-g}\,d^4x\left[\frac{R+f(R)}{16\pi G}+L_m\right]$$

$$R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R+M_{\mu\nu}[g,\partial g,\partial\partial g]=8\pi G T_{\mu\nu}$$

New particle: Scaleron; tiny mass evolves with time
COUPLED TO ALL MATTER!

$$M^2=\frac{1}{3\bar{f}_{RR}}.$$

m -> ∞: std. gravity

Geometric Degeneracy

- **Arbitrary dark energy model with suitable chosen equation of state w (a) can mimic expansion history of any modified gravity model**

Example: Dvali, Gabadadze, Porrati (2000)

modified Friedmann eqn. $$H^2 - \frac{H^\alpha}{r_c^{2-\alpha}} = \frac{8\pi G\rho}{3}$$

$$r_c = \frac{1}{H_0(1-\Omega_m)^{\frac{1}{2-\alpha}}}$$

Growth of structures in modified gravity

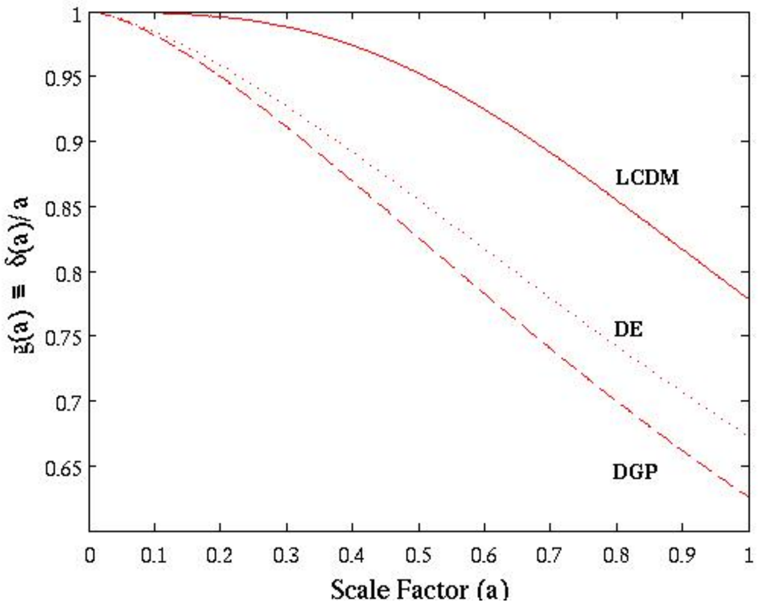
$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G(1 + \frac{1}{3\beta})\rho_m \delta$$

δ : overdensity

modified gravity

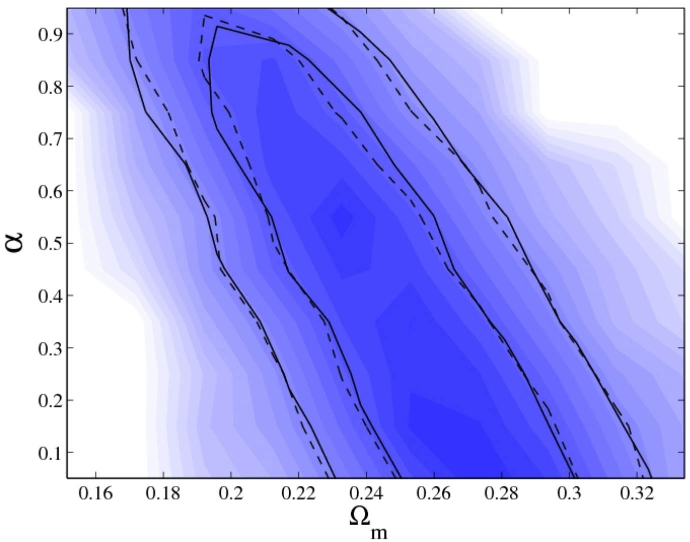
From large scale structure point of view
G is varying in time on large scales

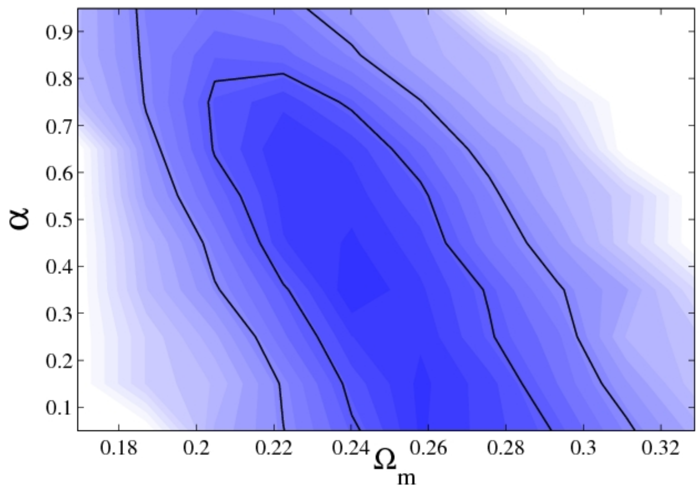
The Growth Factor



- Growth can break degeneracy between mDGP and dark energy
- Possible growth probes
  - weak lensing
  - galaxy cluster counts
  - redshift space distortions

Combined Constraints CFHTLS+SNe+BAO





all angular scales
α <0.86 (95% C.L.)

α <0.91 (95% C.L.)
DGP marginally ruled out

Thomas, Abdalla, Weller 08

New CFHT results: Heymans talk on Friday

The Story of Two Potentials

- Large Scale Structure related to perturbations in the metric:

$$ds^2 = a^2[(1+2\phi)dt^2 - (1-2\psi)(dx^2 + dy^2 + dz^2)]$$

- Poisson Equation

$$k^2\phi = -4\pi G a^2 Q(k,a)\rho_m \delta_m$$

std. gravity
Q=1

- Anisotropic Stress

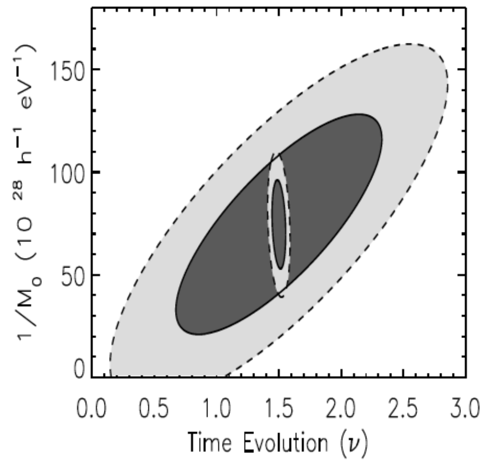
$$\eta(k,a) = \frac{\phi - \psi}{\psi}$$

std. gravity
η =0

Amendola, Kunz and Sapone, 2007

Potentials, Growth and Modified Gravity

Euclid



$$\psi = \left(1 + \frac{2\bar{K}^2}{3+2\bar{K}^2}\right)\phi,$$

$$k^2\phi = -4\pi G\left(\frac{3+2\bar{K}^2}{3+3\bar{K}^2}\right)a^2\rho_{\rm m}\delta_{\rm m},$$

tight: including non-linear scales

$$\ddot{\delta}_{\rm m} + 2H\dot{\delta}_{\rm m} - 4\pi G\left(\frac{3+4\bar{K}^2}{3+3\bar{K}^2}\right)\rho_{\rm m}\delta_{\rm m} = 0,$$

as useful parameterization:

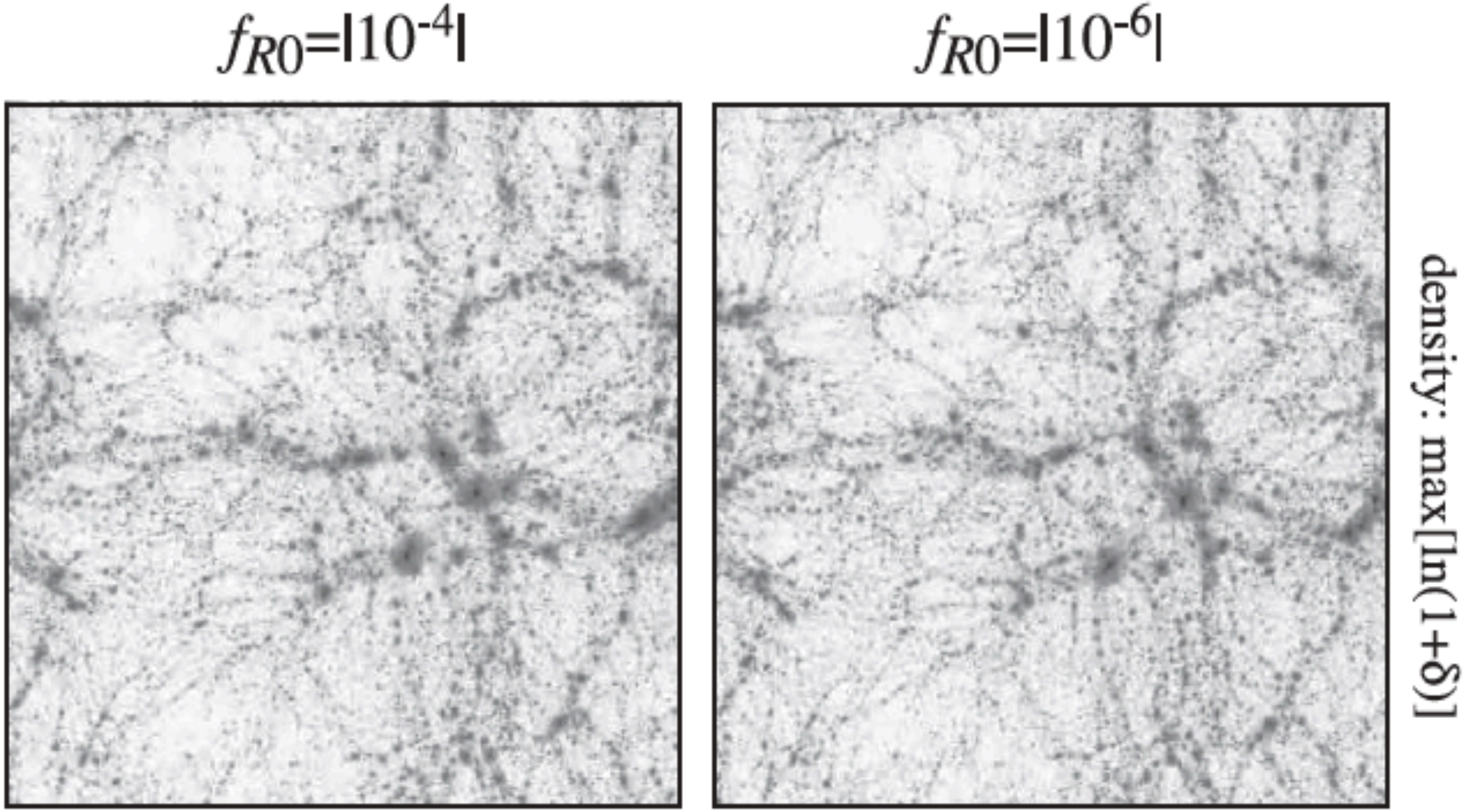
with K=k/(aM(a))

Appleby, Thomas, Weller 2011

$$M^2 = M_0^2\left(\frac{a^{-3}+4a_*^{-3}}{1+4a_*^{-3}}\right)^{2\nu},$$

f(R) in the Non-Linear Regime

$$f(R) = -16\pi G\rho_\Lambda - f_{R0}\frac{\bar{R}_0^2}{R}$$



Oyaziu et al. 2008 **see also Beynon talk Thursday afternoon, COS4**

What can we measure ?

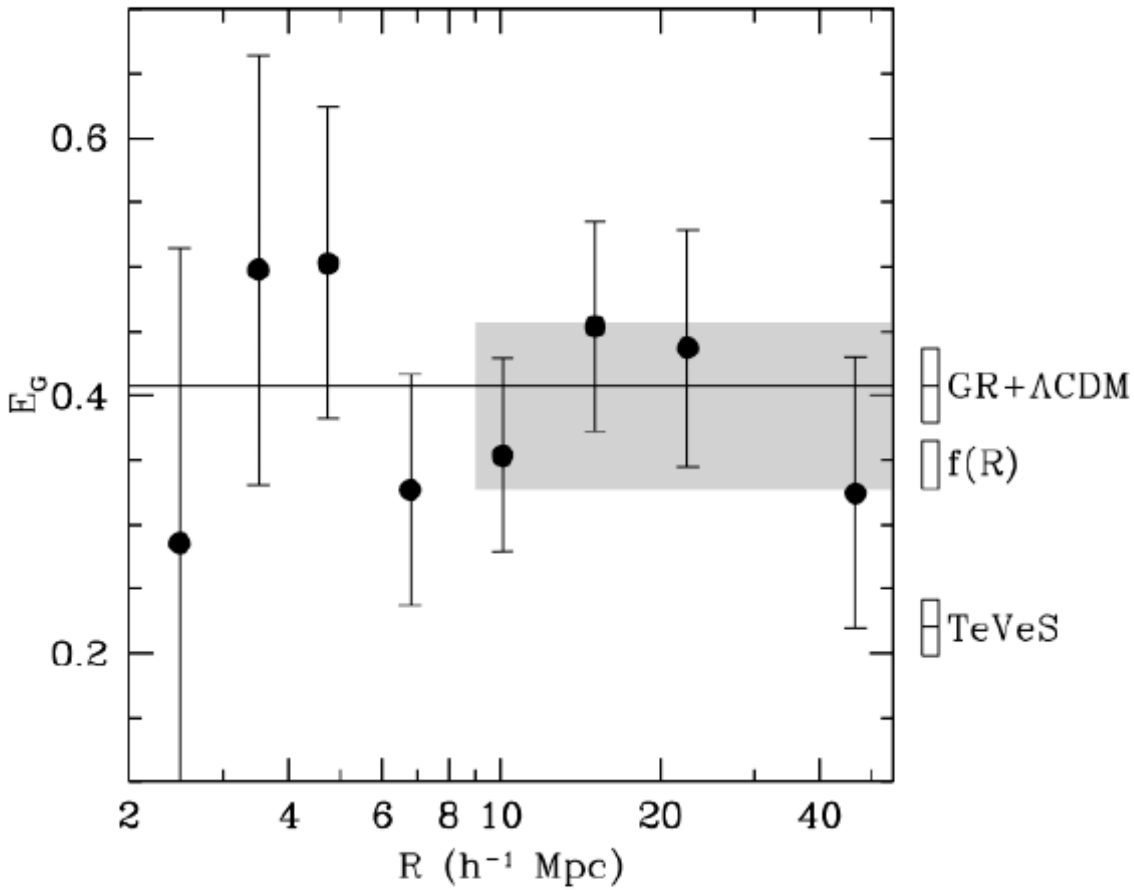
- galaxy correlations:
  $P_{gal}(k,z) \sim (1+\beta\mu^2)b^2\delta^2(k,z)$
  $\beta = \delta`/\delta b$

- Correlation of galaxy ellipticities (weak lensing):
  $P_{ellipt}(k,z) \sim (\Phi+\psi)^2$

- Correlation of galaxy velocities:
  $P_z \sim (1+\beta\mu^2)P_r$

- Three combinations can be measured for 5 quantities (velocity, bias, density perturbation, 2 potentials) and two theoretical relations are available: Poisson eqn. and Anisotropic stress: At linear order we can test gravity models
- see Fergus Simpson talk in afternoon (COS4)

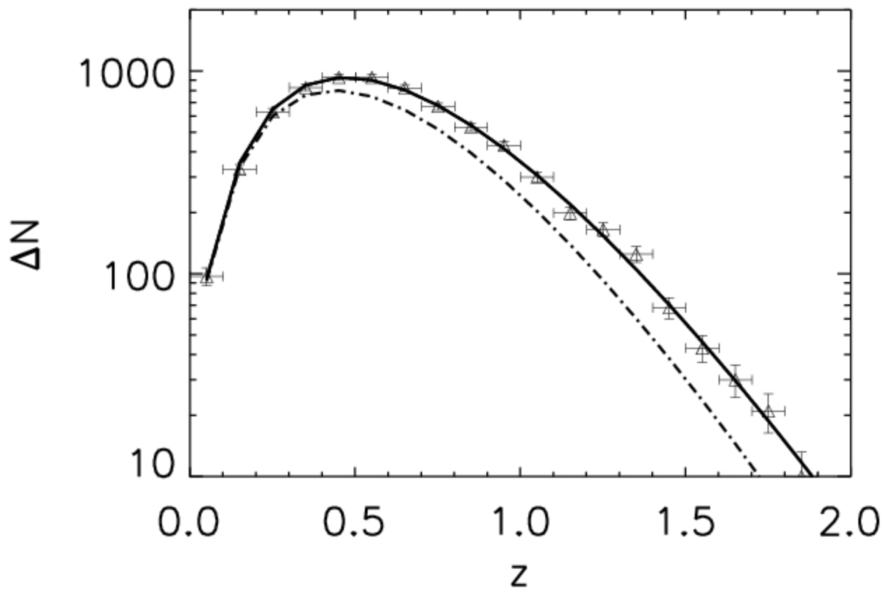
Combined Probes of Modified Gravity



Galaxy-Galaxy lensing, galaxy clustering and galaxy velocities
Reynes et al. 2010

Cluster Counts in Modified Gravity Model

- MG number counts for σ_8 = 0.75, n=1, $M_{lim}=1.7\times10^{14}h^{-1}M_\odot$
- mock data assuming Poisson errors
- mimic DE model



significant difference between mimic DE and MG

Constraints on Scaleron (f(R)) gravity

Parameters	$f(R)$		$f(R)$ (with gISW)		$f(R)$ (with E_G)	
$100\Omega_b h^2$	2.223 ± 0.053	2.206	2.225 ± 0.054	2.253	2.224 ± 0.054	2.206
$\Omega_c h^2$	0.1123 ± 0.0036	0.1109	0.1117 ± 0.0036	0.1133	0.1125 ± 0.0036	0.1131
θ	1.0403 ± 0.0027	1.0392	1.0403 ± 0.0027	1.0416	1.0403 ± 0.0027	1.0394
τ	0.083 ± 0.016	0.082	0.084 ± 0.016	0.090	0.083 ± 0.016	0.083
n_s	0.954 ± 0.012	0.950	0.954 ± 0.012	0.965	0.954 ± 0.013	0.952
$\ln[10^{10} A_s]$	3.212 ± 0.040	3.215	3.209 ± 0.039	3.200	3.213 ± 0.039	3.221
$100B_0$	< 315	28	< 43.2	0.0	< 319	30
Ω_m	0.272 ± 0.016	0.268	0.269 ± 0.016	0.272	0.273 ± 0.016	0.279
H_0	70.4 ± 1.4	70.4	70.7 ± 1.3	70.7	70.3 ± 1.3	69.6
$10^3\|f_{R0}\|$	< 350	46	< 69.4	0.0	< 353	51
$-2\Delta \ln L$	-1.104		1.506		-0.696	

TABLE III: Same as Tab. I, but for $f(R)$ gravity. $-2\Delta \ln L$ is quoted with respect to the corresponding maximum likelihood flat ΛCDM model. Limits on B_0 and $|f_{R0}|$ indicate the one-sided 1D marginalized upper 95% C.L. Note that as $B_0 \to 0$ reproduces ΛCDM predictions, the slightly poorer fits of $f(R)$ gravity should be attributed to sampling error in the MCMC runs.

SNe, BAO, Hubble
CMB, WL, galaxy flows
galaxy-galaxy lensing
Cluster counts
of MaxBCG clusters and groups: three mass bins and two redshift bins

Parameters	$f(R)$ (with CA)		$f(R)$ (with E_G&CA)		$f(R)$ (all)	
$100\Omega_b h^2$	2.209 ± 0.054	2.204	2.213 ± 0.054	2.235	2.216 ± 0.054	2.210
$\Omega_c h^2$	0.1064 ± 0.0032	0.1112	0.1073 ± 0.0029	0.1108	0.1076 ± 0.0028	0.1104
θ	1.0390 ± 0.0027	1.0398	1.0392 ± 0.0027	1.0413	1.0394 ± 0.0027	1.0398
τ	0.077 ± 0.016	0.080	0.077 ± 0.015	0.084	0.079 ± 0.015	0.075
n_s	0.953 ± 0.012	0.951	0.954 ± 0.012	0.956	0.954 ± 0.012	0.951
$\ln[10^{10} A_s]$	[illegible]	3.209	3.179 ± 0.037	3.203	3.182 ± 0.0037	3.193
$100B_0$	< 0.333	0.000	< 0.152	0.000	< 0.112	0.001
Ω_m	0.247 ± 0.014	0.268	0.251 ± 0.012	0.261	0.252 ± 0.012	0.264
H_0	[illegible]	70.5	71.9 ± 1.3	71.4	71.9 ± 1.2	70.8
$10^3\|f_{R0}\|$	< 0.484	0.001	< 0.263	0.000	< 0.194	0.002
$-2\Delta \ln L$	0.802		0.264		0.926	

TABLE IV: Same as Tab. II, but for $f(R)$ gravity. See also Tab. III.

Lombriser, Slosar, Seljak & Hu 2010

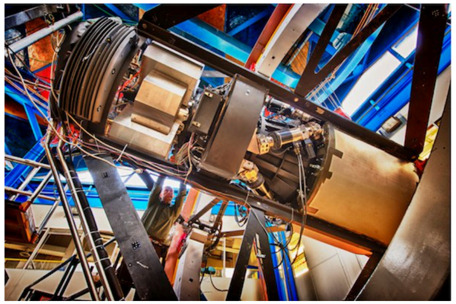
$B_0 \sim m^{-1}$ mass of additional scalar degree of freedom of gravity

Uses SDSS maxBCG catalog

Conclusions

- Current constraints are homing in on cosmological constant (at the 5-10% level)
- Currently only weak constraints on the evolution of the equation of state
- Constraints on modification of gravity are not very strong

Outlook



- Next Generation Dark Energy Probes (like DES, PanStarrs) will push constraint on w below 2% and begin to constrain evolution in w
  (Nichol, Mohr and Farrow talk, Friday afternoon)
- Euclid (2019) will allow to differentiate different cosmic acceleration scenarios and dark energy models (evolution in w, different growth)(see Tom Kitching talk, Friday morning)