SNS, April 18, 2002

Dark Energy

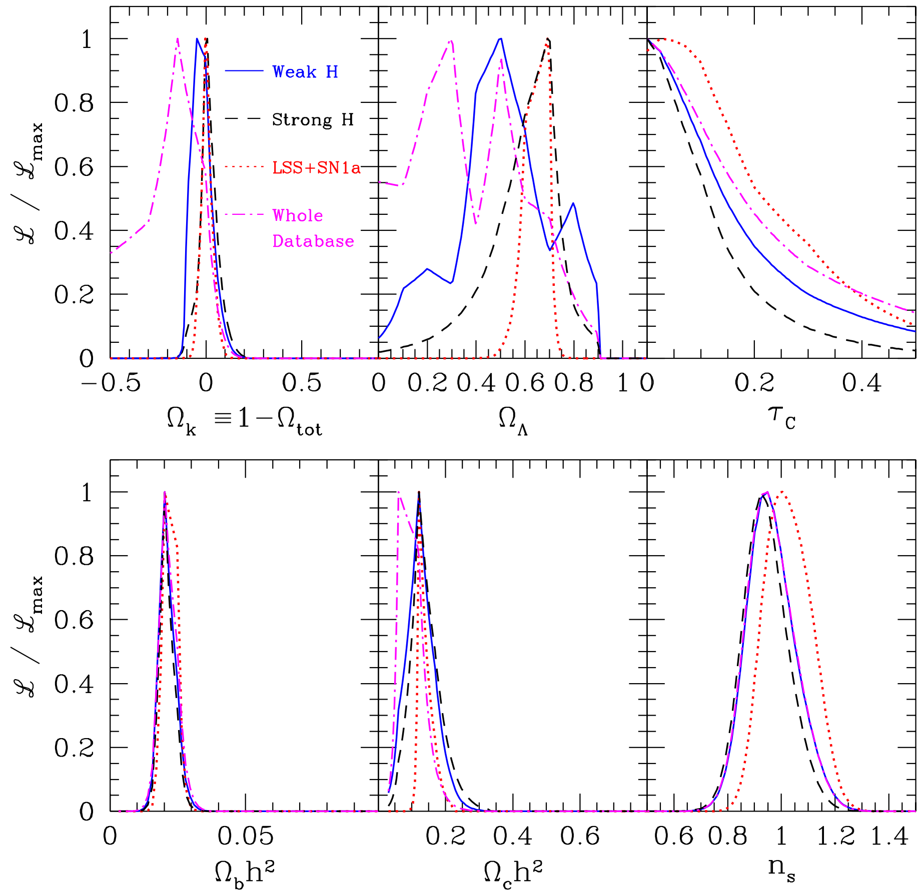
The first surprise in the era of precision cosmology?

Carlo Baccigalupi

SISSA/ISAS, bacci@sissa.it

Cosmic Microwave Background

From BOOMERanG 98, Netterfield et al. astro-ph/0104460



Weak H: $0.45 < h < 0.90$,

Strong H: $h = 0.71 \pm 0.08$,

LSS+SNIa: cluster abundance+SN data,

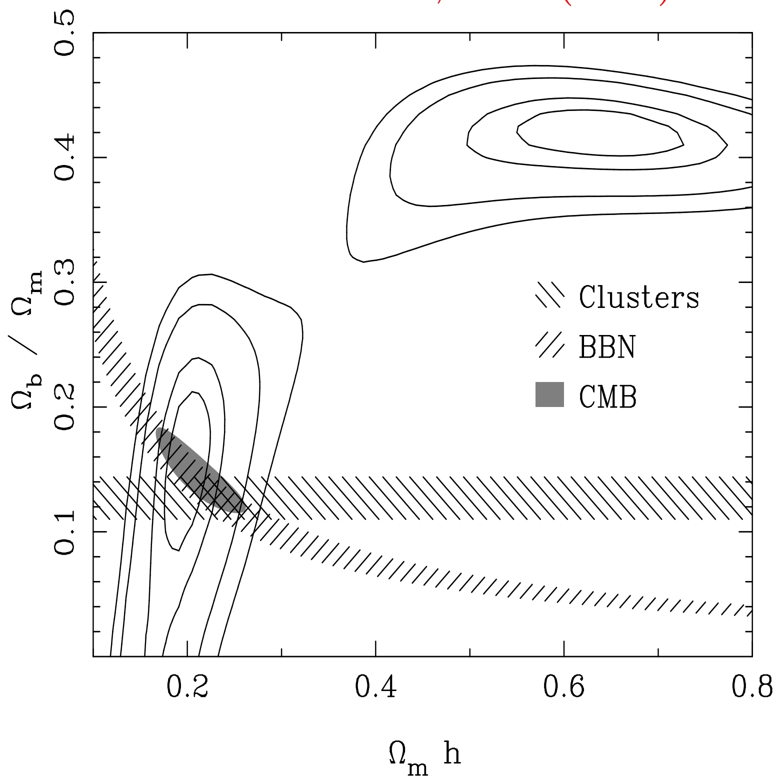
No gravitational waves, other parameters fixed.

Large Scale Structure

In favour of $\Omega_m \simeq 0.3$

Measure galaxies in 3D, assume a bias, compute Fourier transform, compare with models

Fig.6 of Percival et al. MNRAS 327, 1297 (2001):



Large Scale Structure favours a low matter Universe

First CMB acoustic peak indication a flat Universe

$\Downarrow$

Evidence for dark energy (Efstathiou et al. MNRAS 330, 29, (2002))

Vacuum energy, a mystery for physics

The Planck mass is 10^{19}GeV...

We infer unification for physics at the Planck scale... so if there exist some fundamental vacuum energy density Λ we would expect

$$\Lambda \sim (10^{19}\mathrm{GeV})^4 \; .$$

Instead, the one that is arising from data is at the level of the critical energy density today

$$\Lambda \simeq 10^{-49} h^2 \mathrm{GeV}^4 \; .$$

?

? ?

? ?

? ?

We WANT to know:

- Existence: Why vacuum energy does (not) exist?

  Light from distant objects indicates that vacuum energy is playing a cosmological role. If so we have two other tremendous questions:

- Fine-tuning: What made it so small at the beginning with respect to the Planck scale?

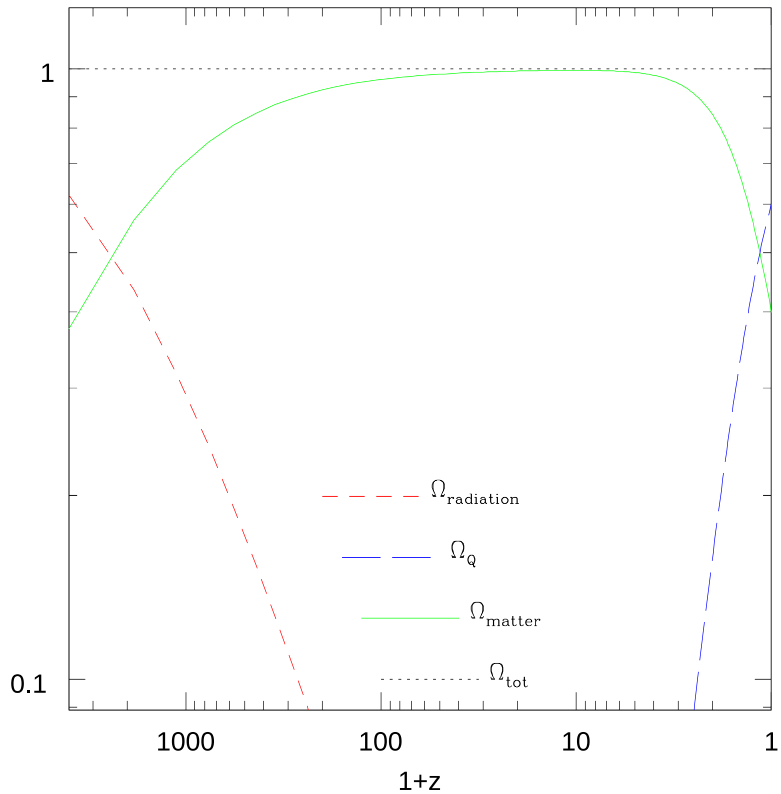
- Coincidence: Why are you dominating cosmic expansion right now?

Dark Energy candidates

up to now

- **Trans-Planckian**: energy stored in perturbation modes beyond the Planck scale (Mersini, Bastero-Gil & Kanti, Phys.Rev. D64 043508, 2001)
- **Spacetime microstructure**: self-adjusting, vacuum energy absorbing spacetime (Padmanabhan, gr-qc/0204020)
- **Matter → Energy Transformation**: Dark Matter converts to Dark Energy at low redshifts (Basset, Kunz, Silk, Ungarelli, astro-ph/0203383)
- **Brane worlds**: brane tension (Sahni & Shtanov astro-ph/0202346), cyclic-ekpyrotic cosmic vacuum generator (Steinhardt & Turok hep-th/0111098)
- **Quintessence**: tracking scalar fields (Steinhardt, Wang & Zlatev, Phys.Rev. D59 123504, 1999)
- **Brans-Dicke field**: non-minimal coupling to Gravity (Perrotta, Baccigalupi, Matarrese, Phys.Rev. D61 023507, 2000)

Quintessence



Quintessence is a dynamical entity,

usually described as a self-interacting scalar field,

possibly connected with very high energy physics theories,

obeying a potential $V(\phi)$ becoming dominanting at low redshifts

and mimicking a cosmological constant.

Basic Equations

Background evolution:

$$\mathcal{H}^2 = \frac{8\pi G}{3}\left(a^2\rho_{fluid} + \frac{1}{2}\dot{\phi}^2 + a^2 V\right)$$

$$+$$

$$\ddot{\phi} + 2\mathcal{H}\dot{\phi} + a^2 V_\phi = 0 \ ,$$

where $\mathcal{H} = \dot{a}/a$ is the conformal time expansion rate.

Perturbations:

$$\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$$

$$+$$

$$\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + \left(k^2 + a^2 V_{\phi\phi}\right)\delta\phi + \frac{1}{2}\dot{\phi}\dot{h} = 0 \quad \text{(synchronous gauge)} \ .$$

Tracking Solutions

Ratra & Peebles 1988, Wetterich 1988, Liddle & Scherrer 1999, Ferreira & Joyce 1998,

Steinhardt, Wang & Zlatev 1999, Uzan 1999, Chiba 1999, Baccigalupi, Matarrese, Perrotta 2000

A scalar field ϕ, dynamically driven by a potential $V(\phi)$ is the simplest generalisation of a Cosmological Constant.

In a cosmological context, for interesting potential forms (inverse power law, exponential, ...), the following trajectories are attractors:

$$\frac{p_\phi}{\rho_\phi} = w_\phi \simeq constant \Leftrightarrow \rho_\phi \simeq (1+z)^{3(1+w_\phi)}$$

Exponential potential: ϕ scales as the dominant component.

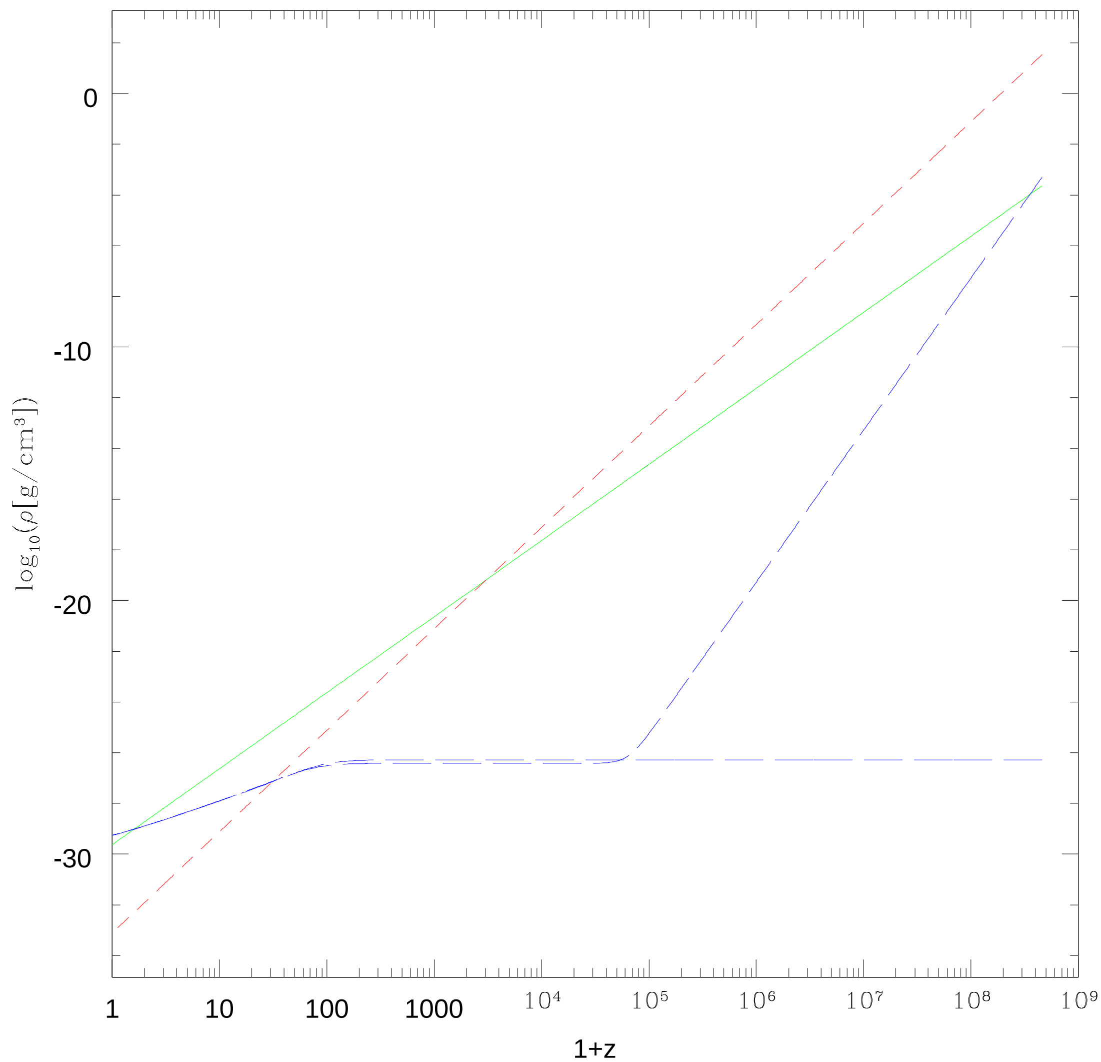
Inverse power law potential: w_ϕ depends on the exponent as

$$V(\phi) \propto \phi^{-\alpha} \ , \ w_Q = -\frac{2}{\alpha+2} \ \text{(tracking solutions)} \ .$$

Cosmological consequence

Avoidance of Fine-Tuning: a required field energy density at present can be reached starting from an initial one which was tens of order of magnitude larger.

Avoidance of Fine-Tuning: Tracking Solutions



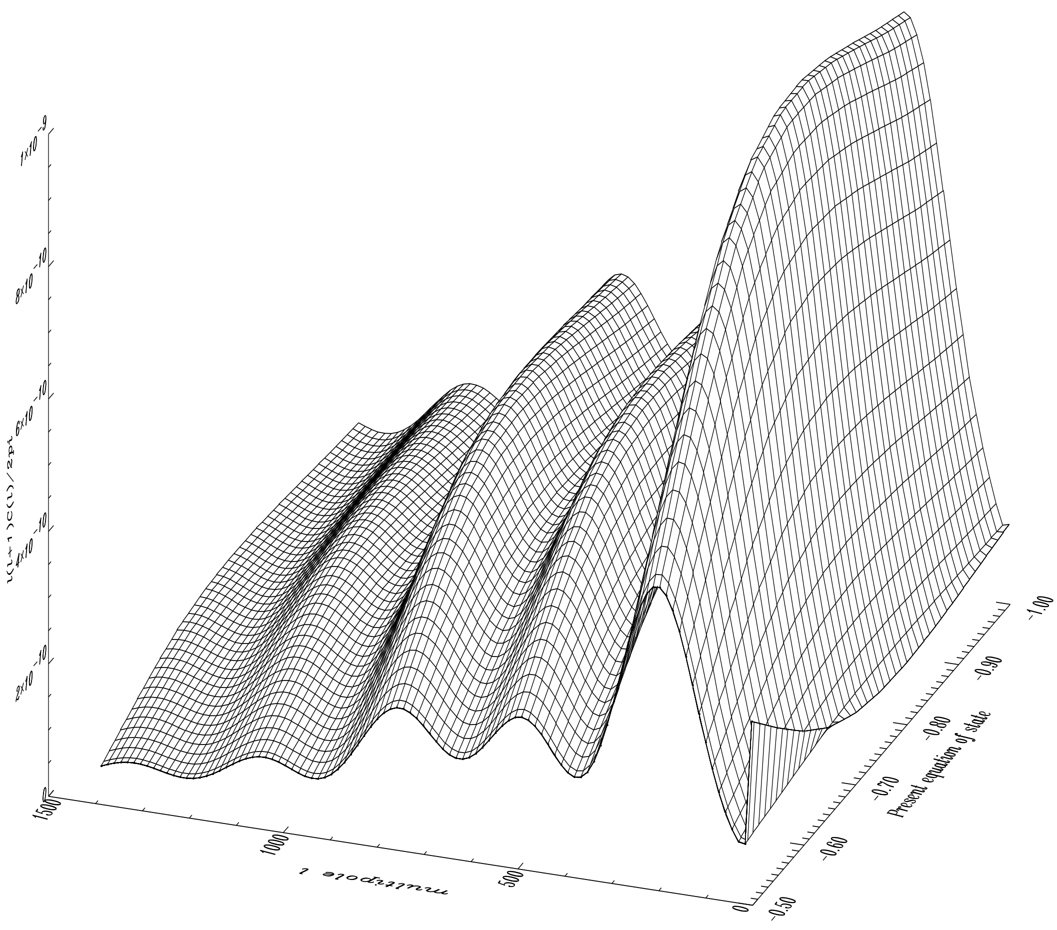
$$V_\phi \sim \phi^{-\alpha} \quad , \quad \alpha > 0$$

$$\rho_\phi \sim (1+z)^\epsilon \quad , \quad \epsilon = \frac{3\alpha}{\alpha+2}$$

$$w_\phi = -\frac{2}{\alpha+2}$$

$$w_{\phi 0} \neq w_\phi$$

Effects on the CMB



We can see the difference between Q and Λ at low redshift; this affects two well-known CMB features:

- Projection
- Integrated Sachs-Wolfe

Effects on the CMB

Projection:

$$\theta_H = \frac{\lambda_{H,dec}}{d_{dec}} \ ,$$

$$d_{dec} \propto \int_0^{zdec} \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\phi(1+z)^{3(1+w_\phi)} + \Omega_K(1+z)^2 + \Omega_{rad}(1+z)^4}}$$

Integrated Sachs-Wolfe: from Bardeen (1980)

$$\Phi(z) - \frac{2}{3}\frac{1}{1+w(z)}\Psi(z) = constant \ ,$$

so that a time variation cosmic equation of state w induces a variation into the gravitational potentials, impressing extra power at $l \lesssim 10$, breaking cosmic variance degeneracy with the Cosmological Constant for $w_\phi \gtrsim -0.6$.

Quintessence fluctuations

Ferreira & Joyce 1998, Hu 1998, Perrotta & Baccigalupi 1999,

Ma et al. 1999, Brax et al. 2000, Bean 2001, Perrotta & Baccigalupi 2002

There is not a theory for the origin of dark energy in the early Universe. Initial conditions should be thought as general as possible.

$$\ddot{\delta\phi} + 2\mathcal{H}\dot{\delta\phi} + (k^2 + a^2 V_{\phi\phi})\delta\phi =$$

$$= (\dot{\Psi} - 3\dot{\Phi})\dot{\phi} - 2a^2 V_{\phi}\Psi \quad , \quad \text{(Newtonian gauge)} \ .$$

The gravitational potentials drag Quintessence fluctuations.

As an example, in minimally coupled theories, in Newtonian gauge, early in the radiation dominated era, the following growing modes are found (Perrotta & Baccigalupi 1999):

$$\delta\phi \propto \tau^2 \quad \text{(adiabatic)}$$

$$\delta\phi \propto \tau^3 \quad \text{(isocurvature, CDM)}$$

Extended Quintessence

Carlo Baccigalupi *, Sabino Matarrese †, Francesca Perrotta ‡

References:

F. Perrotta, C. Baccigalupi, S. Materrese, astro-ph/9906066, Phys.Rev. D61 (2000) 023507

C. Baccigalupi, S. Matarrese, F. Perrotta, astro-ph/0005543, Phys.Rev. D62 (2000) 123510

F. Perrotta, C. Baccigalupi astro-ph/0201335, Phys.Rev. in press (2002)

*bacci@sissa.it

†matarrese@pd.infn.it

‡perrotta@sissa.it

Extended Quintessence

Main features:

- A Quintessential scalar field ϕ provides the universe acceleration today through its potential V
- The field is non-minimally coupled to the Ricci scalar:

$$\frac{1}{8\pi G}R \rightarrow \frac{1}{2}F(\phi) \cdot R$$

The name "extended" is in honour and analogy to the extended inflation models (La & Steinhardt 1989).

Why non-minimal coupling?

Riazuelo & Uzan astro-ph/0107386 2001, Chiba Phys.Rev.D64 103503 2001

Chen et al. Phys.Rev.D63 123504 2001, Esposito-Farese & Polarski Phys.Rev.D63 063504 2001

Baccigalupi et al. Phys.Rev.D62 123510 2000, Faraoni Phys.Rev.D62 023504 2000

- Idea of Dark Energy arising from Gravity, as the Brans-Dicke field
- Suggestions from fundamental theories (strings, branes, dilaton fields, ...)
- Data hints: BBN
- Data hints: minimally coupled Q requires

$$\frac{dH^2}{dz} \geq 3\Omega_{matter} H_0^2 (1+z)^2 \ ,$$

argument from Sahni & Starobinsky Int.J.Mod.Phys.2000.

Scalar-Tensor cosmology

Lagrangian:

$$\mathcal{L} = \frac{1}{2}F(\phi)R - \frac{1}{2}\phi^{;\mu}\phi_{;\mu} - V(\phi) + \mathcal{L}_{fluid} \ .$$

Cosmological equations:

$$\mathcal{H}^2 = \frac{1}{3F}\left(a^2\rho_{fluid} + \frac{1}{2}\dot{\phi}^2 + a^2V - 3\mathcal{H}\dot{F}\right) \ ,$$

Klein-Gordon:

$$\ddot{\phi} + 2\mathcal{H}\dot{\phi} = -\frac{1}{2}\left(-a^2F_{\phi}R + 2a^2V_{\phi}\right) \ ,$$

Models:

$$F(\phi) = \xi\phi^2 \ \ \text{(Induced Gravity)}$$

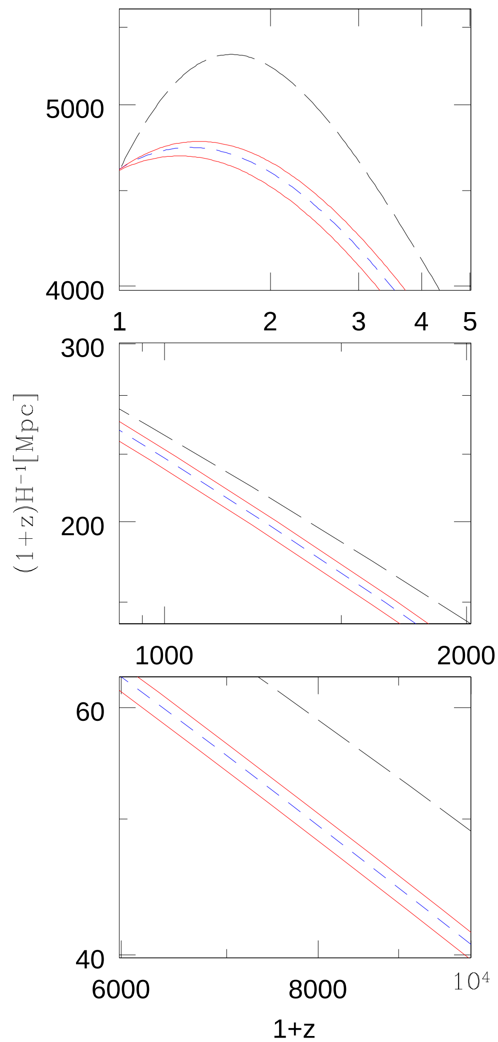
$$F(\phi) = \frac{1}{8\pi G} + \xi(\phi^2 - \phi_0^2) \ \ (\mathrm{Non-Minimal\ Coupling}) \ ,$$

...

where at the present $F(\phi_0) = 1/8\pi G$ to reproduce our gravity.

But $F(\phi)$ is defined as an external function in our code...

The motion of Gravity



$$\mathcal{H} \propto \sqrt{G} \propto \frac{1}{\sqrt{F}}$$

$$\text{early times}: \ \mathrm{F}(\phi) = \frac{1}{8\pi\mathrm{G}} - \xi\phi_0^2 \ , \quad \text{now}: \mathrm{F}(\phi) = \frac{1}{8\pi\mathrm{G}} \ ,$$

$(\mathrm{NMC}, \xi = 1.5 \cdot 10^{-2}, \phi_0 \simeq 0.3 \cdot M_{Planck}, \Omega_\phi = 70\%, w_0 \simeq -0.6,, V \propto \phi^{-\alpha}, \ldots)$

in typical cases, $\Delta F/F \simeq 5 \cdot 10^{-2}$

Experimental constraints

Couplings between R and scalar fields in the Lagrangian are constrained by Solar System Experiments (SSE):

$$\text{time variation of G}: \left|\frac{\mathrm{G}_t}{\mathrm{G}}\right| = \left|\frac{\mathrm{F}_t}{\mathrm{F}}\right| \leq 10^{-11} \text{ per year},$$

$$\text{deflection of light}: \omega_{\mathrm{JBD}} = \frac{\mathrm{F}}{\mathrm{F}_\phi^2} \geq 2500 \ .$$

Predictions for BBN

Chen, Scherrer & Steigman (astro-ph/0011531, Phys.Rev. D63 (2001) 123504) computed the EQ predictions on BBN:

$$\mathcal{H} \propto \sqrt{G} \propto \frac{1}{\sqrt{F}} \Rightarrow \frac{\delta \mathcal{H}}{\mathcal{H}} \simeq -\frac{1}{2}\frac{\delta F}{F} \ .$$

This predicts a variation in primordial helium abundance and a number of extra neutrinos:

$$\Delta Y_P \simeq \frac{\delta \mathcal{H}}{\mathcal{H}} \ , \ \ \Delta N_\nu \simeq \frac{43}{7}\frac{\delta \mathcal{H}}{\mathcal{H}} \ .$$

BBN predicts primordial helium abundance $Y_P = 0.248 \pm 0.001$. By considering potential index $5 \leq \alpha \leq 15$, it could be reconciled with measures from Olive & Steigman (1995, $Y_P = 0.234 \pm 0.003$) and from Izotov & Thuan (1998, $Y_P = 0.244 \pm 0.002$).

Scalar-Tensor cosmological linear perturbations

Equations for metric perturbations do not change in form.

In synchronous gauge, Fourier space and scalar realm you have

$$k^2\eta - \frac{1}{2}\mathcal{H}\dot{h} = -\frac{a^2\delta\rho}{2} \ ,$$

$$k^2\dot{\eta} = \frac{a^2(p+\rho)\theta}{2} \ ,$$

$$\ddot{h} + 2\mathcal{H}\dot{h} - 2k^2\eta = -3a^2\delta p \ ,$$

$$\ddot{h} + 6\ddot{\eta} + 2\mathcal{H}(\dot{h} + 6\dot{\eta}) - 2k^2\eta = -3a^2(p+\rho)\sigma \ ,$$

where

h,η : metric trace and traceless perturbation,

$\delta\rho$,δp : total density and pressure perturbation,

θ,σ : total velocity and shear perturbation,

$8\pi G$ disappeared, but...

Linear fluid perturbations are modified (Hwang CQG90, ApJ91, PRD96):

$$\delta\rho = \frac{1}{F}[\delta\rho_{fluid} + \frac{\dot{\phi}\delta\dot{\phi}}{a^2} + \frac{1}{2}(-F_\phi R + 2V_{,\phi})\delta\phi - 3\frac{\mathcal{H}\delta\dot{F}}{a^2} -$$
$$-(\frac{\rho+3p}{2} + \frac{k^2}{a^2})\delta F + \frac{\dot{F}\dot{h}}{6a^2}] \ ,$$
$$\delta p = \frac{1}{F}[\delta p_{fluid} + \frac{\dot{\phi}\delta\dot{\phi}}{a^2} + \frac{1}{2}(F_\phi R - 2V_{,\phi})\delta\phi + \frac{\delta\ddot{F}}{a^2} + \frac{\mathcal{H}\delta\dot{F}}{a^2} +$$
$$+(\frac{p-\rho}{2} + \frac{2k^2}{3a^2})\delta F - \frac{1}{9}\frac{\dot{F}\dot{h}}{a^2}] \ ,$$
$$(p+\rho)\theta = \frac{(p_{fluid}+\rho_{fluid})\theta_{fluid}}{F} - \frac{k^2}{a^2}\left(\frac{-\dot{\phi}\delta\phi - \delta\dot{F} + \mathcal{H}\delta F}{F}\right) \ ,$$
$$(p+\rho)\sigma = \frac{(p_{fluid}+\rho_{fluid})\sigma_{fluid}}{F} + \frac{2k^2}{3a^2F}\left[\delta F + 3\frac{\dot{F}}{k^2}\left(\dot{\eta} + \frac{\dot{h}}{6}\right)\right] \ ,$$
$$\delta\ddot{\phi} + 3\mathcal{H}\delta\dot{\phi} + \left[k^2 + a^2\left(\frac{-F_\phi R + 2V_{,\phi}}{2}\right)_{,\phi}\right]\delta\phi = \frac{\dot{\phi}\dot{h}}{6} + \frac{a^2}{2}F_\phi \delta R \ ,$$

with the Ricci scalar variation:

$$\delta R = \frac{1}{3a^2}\left(\ddot{h} - 3\mathcal{H}\dot{h} + 2k^2\eta\right) \ ,$$

Assume initially Gaussian (nearly) adiabatic scale-invariant spectra (see e.g. Perrotta & Baccigalupi PRD 1999) and integrate everything to obtain the EQ-effects...

Tracking Extended Quintessence

Baccigalupi, Matarrese & Perrotta astro-ph/0005543, Phys.Rev. D62 (2000) 123510

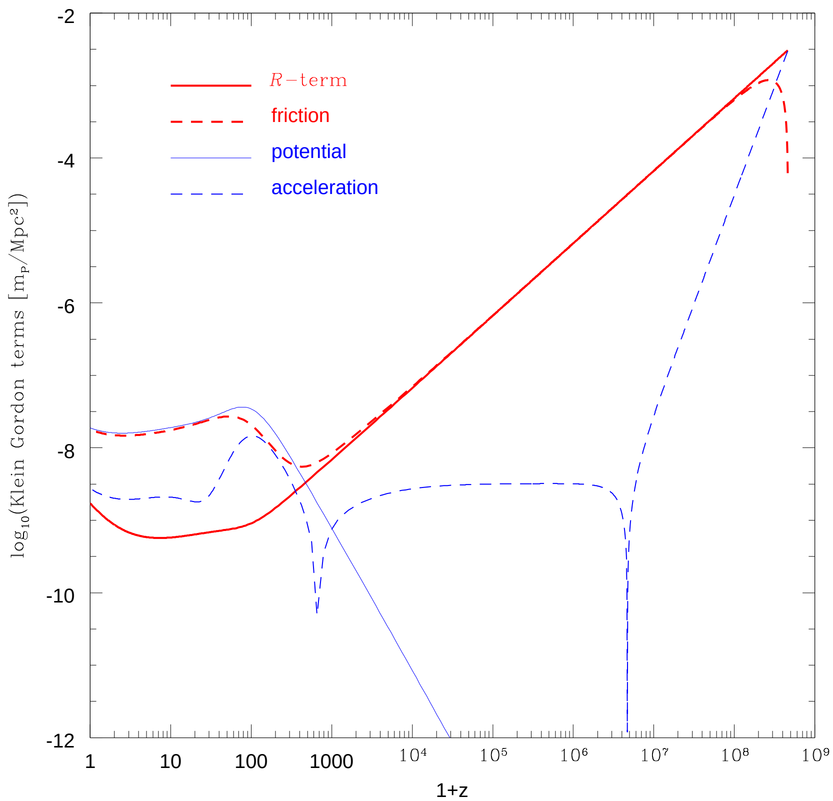
- Extended Quintessence admit tracking solutions.
- They differ from ordinary one because of R.

$$R = \frac{6}{a^2}(\dot{\mathcal{H}} + \mathcal{H}^2) =$$

$$= -\frac{1}{F}\left[-\rho_{fluid} + 3p_{fluid} + \frac{\dot{\phi}^2}{a^2} - 4V + 3\left(\frac{\ddot{F}}{a^2} + 2\frac{\mathcal{H}\dot{F}}{a^2}\right)\right] \ .$$

In the RDE $a \propto \tau$, but ρ_{matter} survives in R, that diverges with $a \to 0$ as $1/a^3$!

R-boost



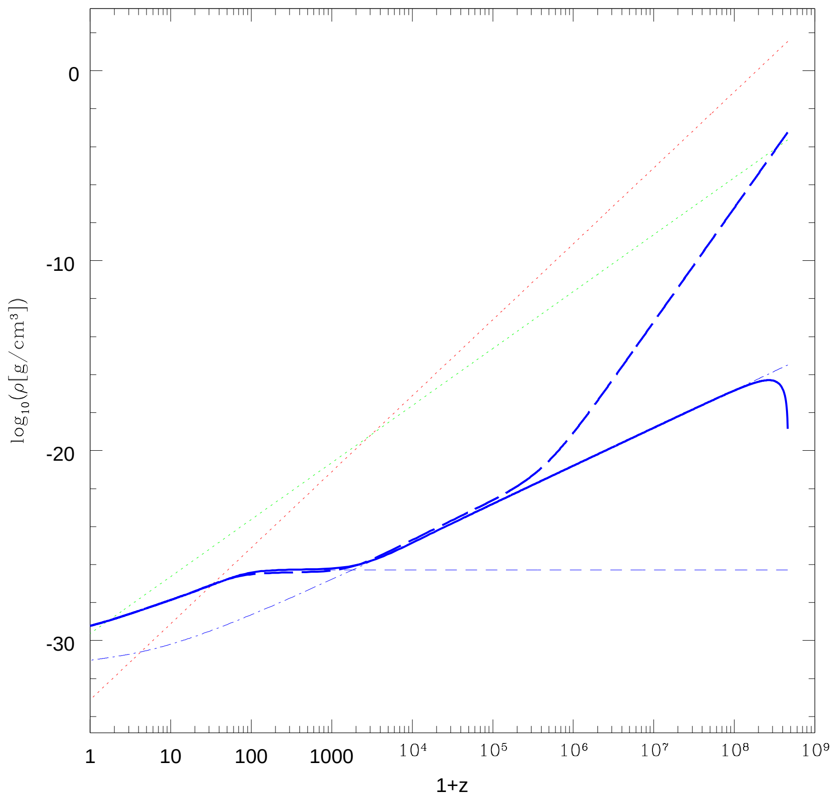
The Klein Gordon equation

$$\ddot{\phi} + 2\mathcal{H}\dot{\phi} = -\frac{1}{2}\left(-a^2 F_\phi R + 2a^2 V_\phi\right) \ ,$$

shrinks to

$$2\mathcal{H}\dot{\phi} \simeq \frac{a^2 R}{2} F_\phi \ .$$

R-boost



with

$$F(\phi) = \frac{1}{8\pi G} + \xi(\phi^2 - \phi_0^2) \ ,$$

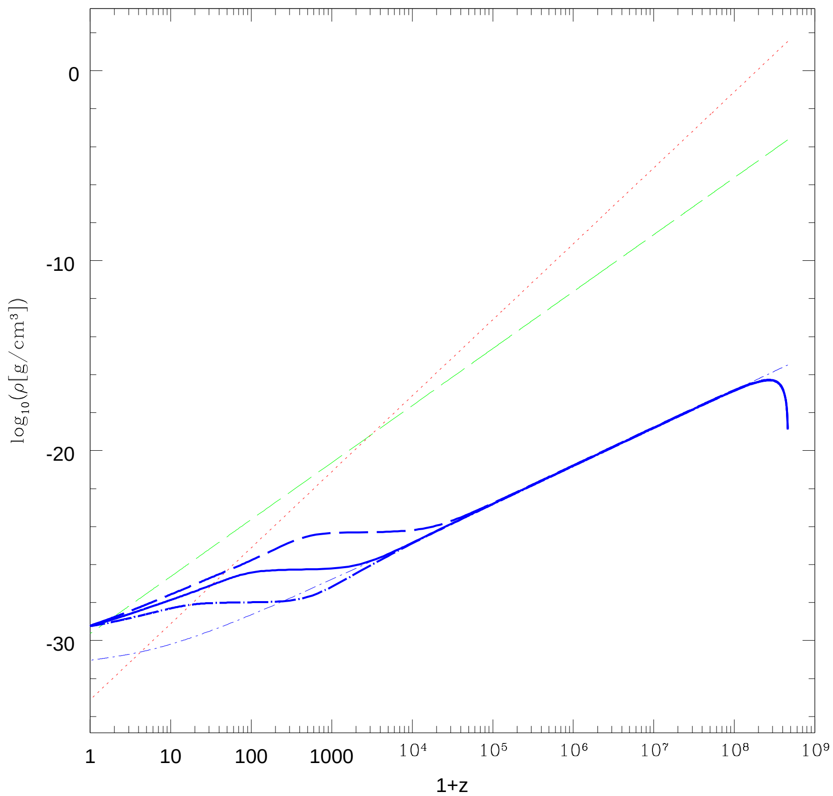
the approximate solution is easily found:

$$\phi = \phi_{beg} \exp\left[\mathcal{C}(\tau - \tau_{beg})\right] \ , \ \mathcal{C} = \frac{3H_0^2\Omega_{matter}}{2\sqrt{8\pi G\rho_{r0}/3}}\xi \ .$$

$\mathcal{C} \simeq 10^{-4}$ Mpc^{-1} with

$\Omega_\phi = 70\%$, $\xi = 1.5 \cdot 10^{-2}$, $H_0 = 70$ km/sec/Mpc.

R-boost



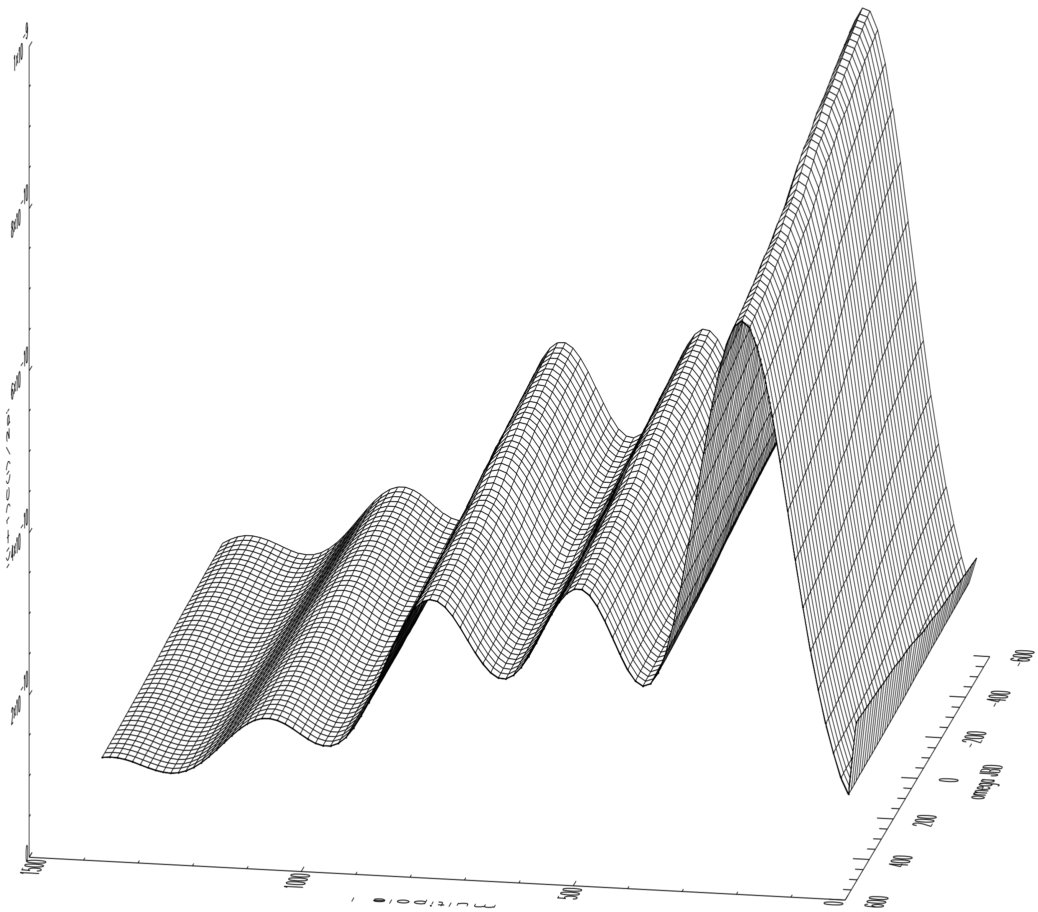
The Quintessence R-boost energy density goes like

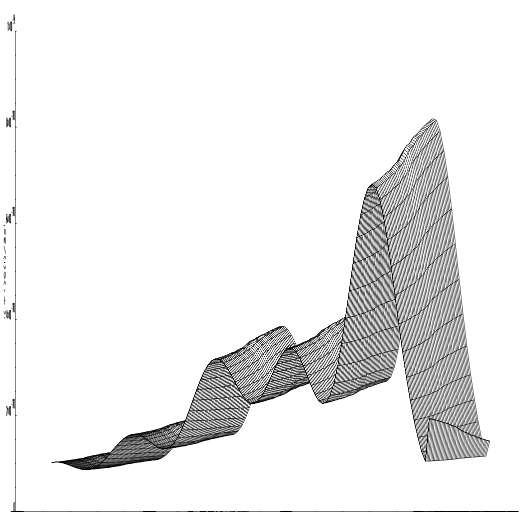
$$\rho_\phi = \frac{\dot{\phi}^2}{2a^2} + V(\phi) \simeq \frac{\dot{\phi}^2}{2a^2} \simeq \frac{\phi_{beg}^2 \mathcal{C}^2}{2a^2} \propto (1+z)^2 \ .$$

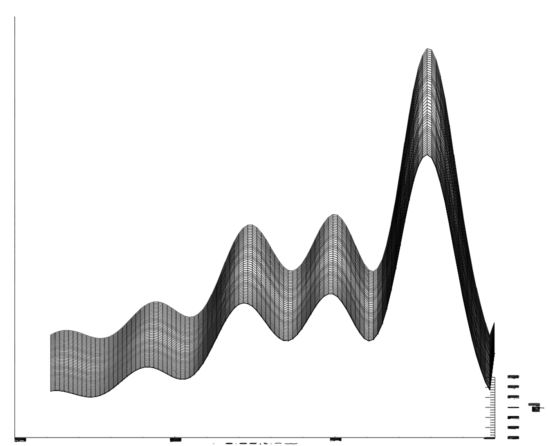
For $V(\phi) \propto \phi^{-\alpha}$, the R-boost ends when the potential becomes comparable to the kinetic energy:

$$1 + z \simeq \sqrt{\frac{6\Omega_\phi H_0^2 \phi_0^\alpha}{8\pi G \mathcal{C}^2 \phi_{beg}^{2+\alpha}}} \ .$$

Changing Gravity changing CMB







Integrated Sachs-Wolfe

$$\Psi \propto G \propto \frac{1}{F} \ .$$

Going from decoupling to now:

ξ positive makes Ψ decreasing,

ξ negative makes Ψ increasing:

$$\delta\Psi = \Psi\left(\frac{F_0}{F_{dec}} - 1\right) = \Psi \cdot 8\pi G \xi \phi_0^2 \ \ , \ \ (\delta T/T)_{ISW} \simeq 2\delta\Psi \ .$$

The more the Gravitational potential decreases, the stronger is the ISW power at $\ell \leq 10$ ($\delta T/T \simeq \Psi/3$).

$$\Downarrow$$

$$\frac{\delta C_{\ell\leq 10}}{C_{\ell\leq 10}} = \frac{C^{EQ}_{\ell\leq 10} - C^{Q}_{\ell\leq 10}}{C^{Q}_{\ell\leq 10}} \simeq \frac{[\delta T/T + (\delta T/T)_{ISW}]^2 - (\delta T/T)^2}{(\delta T/T)^2} \simeq$$

$$12 \cdot \left(1 - \frac{F_{dec}}{F_0}\right) \simeq 12 \cdot \left(1 - \frac{G}{G_{dec}}\right) \simeq 96\pi G \xi \phi_0^2 \ .$$

Acoustic peaks shift

$$\ell_{peaks} \propto \frac{\tau_0 - \tau_{dec}}{\tau_{dec}} \quad , \quad \tau = \int_0^a \frac{da}{a\dot{a}}$$

Variation from NMC enters in $\dot{a} \propto \mathcal{H} \propto \sqrt{G} \propto 1/\sqrt{F}$:

$$\delta\tau = \int_0^a \frac{da}{a\dot{a}[1 - (1/2)\delta F/F]} - \tau \simeq \frac{1}{2}\int_0^a \frac{da}{a\dot{a}}\frac{\delta F}{F} \ ,$$

$$\frac{\delta F}{F} = \frac{F(a) - F_0}{F_0} \ .$$

In most cases δF remains constant for 75% of the total conformal time, and shrinks to zero at the present:

$$\delta\tau_{dec} \simeq \tau_{dec} \cdot \frac{1}{2}\left(\frac{F_{dec}}{F_0} - 1\right) \quad , \quad \delta\tau_0 \simeq 75\% \cdot \tau_0 \cdot \frac{1}{2}\left(\frac{F_{dec}}{F_0} - 1\right) \ .$$

$$\Downarrow$$

$$\frac{\delta l_{peaks}}{l_{peaks}} = \frac{l_{peaks}^{EQ} - l_{peaks}^{Q}}{l_{peaks}^{Q}} \simeq -\frac{1}{8}\left(\frac{F_{dec}}{F_0} - 1\right) \simeq \left(\frac{G}{G_{dec}} - 1\right) \simeq \pi\xi G\phi_0^2 \ .$$

$$DE = DM \cdot c^2$$

Dark Energy and Matter

Are they related? Can we expect Dark Energy in dark haloes?

Some works on this:

Dark energy effective sound speed, Hu ApJ 506, 485 (1998)

Mass power spectrum, Ma, Caldwell, Bode, Wang ApJ 521 (1999) L1

EQ geometrical effects, Baccigalupi, Matarrese, Perrotta Phys.Rev. D62 (2000) 123510

Spherical collapse with dark energy, Lokas & Hoffman, MNRAS submitted, astro-ph/0108283

Dark Energy clustering, Perrotta & Baccigalupi Phys.Rev.D in press 2002, astro-ph/0201335

Extended Quintessence

Dark energy stress-energy tensor

$$\mathcal{L}_{grav} = \frac{1}{2} F R \ \ , \ \ F = \frac{1}{\kappa} + \mathcal{F}(\phi)$$

$$T_{\mu\nu}[\phi] = T_{\mu\nu}[\phi]^{mc} + T_{\mu\nu}[\phi]^{nmc} + T_{\mu\nu}[\phi]^{grav} =$$

$$= \nabla_\mu \phi \nabla_\nu \phi - \frac{1}{2} g_{\mu\nu} \nabla^\lambda \phi \nabla_\lambda \phi - V g_{\mu\nu} + + \nabla_\mu \nabla_\nu \mathcal{F} - g_{\mu\nu} \Box \mathcal{F} - \mathcal{F} G_{\mu\nu} \ .$$

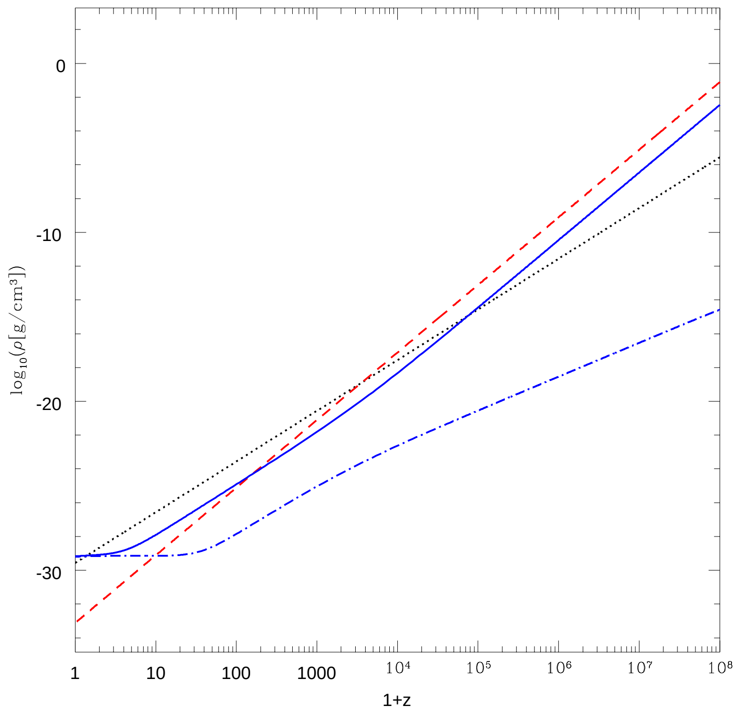
$$\delta T_{\mu\nu}[\phi] = \delta T_{\mu\nu}[\phi]^{mc} + \delta T_{\mu\nu}[\phi]^{nmc} + \delta T_{\mu\nu}[\phi]^{grav}$$

$$\delta T_{\mu\nu}[\phi]^{grav} = -\delta \mathcal{F} \, G_{\mu\nu} - \mathcal{F} \delta G_{\mu\nu}$$

Dark energy is fed by $G_{\mu\nu}$, which includes contributions from all the cosmological components. Even if the coupling is small, the product $\mathcal{F} G_{\mu\nu}$ can dominate on the other terms and drag the dark energy dynamics, both in background evolution and perturbations.

Gravitational Dragging

Background evolution



$$\rho_\phi = -T^0_0 = \rho_\phi^{mc} + \rho_\phi^{nmc} + \rho_\phi^{grav}$$

$$\rho_\phi^{grav} = \mathcal{F} G^0_0 = -\kappa \mathcal{F} \rho$$

In the gravitational dragging regime, dark energy scales as the dominant component.

Gravitational Dragging

Perturbations

Dark energy density contrast:

$$\frac{\delta\rho_\phi}{\rho_\phi} \equiv \delta_\phi = \delta_\phi^{mc} + \delta_\phi^{nmc} + \delta_\phi^{grav} \ ,$$

$$\delta_\phi^{grav} = \frac{-6\delta F\mathcal{H}^2 - 2a^2(1/\kappa - F)\delta G_0^0}{\omega\dot{\phi}^2 + 2a^2V + RF - f/\kappa - 6\mathcal{H}\dot{F} - 2a^2(1/\kappa - F)G_0^0} \ .$$

Dark energy effective sound speed (Hu 1998):

$$c_{eff\,\phi}^2 = \frac{\delta p_\phi + c_{s\,\phi}^2\, 3\mathcal{H}h_\phi(v_\phi - B)/k}{\delta\rho_\phi + 3\mathcal{H}h_\phi(v_\phi - B)/k} \ .$$

In the Gravitational Dragging Regime, matter dominated era,

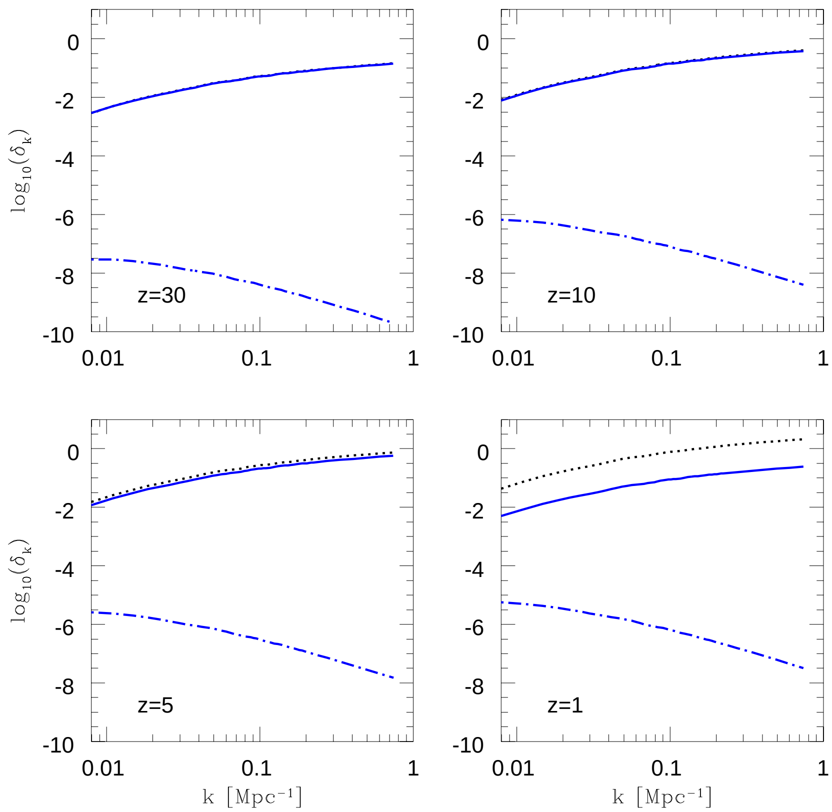
$$\delta_\phi \simeq \frac{\delta G_0^0}{G_0^0} = \frac{\delta\rho_m}{\rho_m} \ ,$$

$$c_{eff\,\phi}^2 \simeq \frac{\delta p_\phi}{\delta\rho_\phi} \simeq \frac{\delta G_i^i}{\delta G_0^0} = \frac{\delta p_m}{\rho_m} \ll 1$$

Dark Energy Clustering

Perrotta & Baccigalupi, Phys.Rev.D 2002, astro-ph/0201335

redshift behavior of $\delta_k^2 = 4\pi k^3 \delta^2 \equiv k-$mode fluctuation power



$$\delta_\phi \simeq \delta_m \quad , \quad c_{eff\,\phi} \ll 1$$

Extended Quintessence: Summary

- Extended Quintessence admits tracking solutions
- The Ricci scalar causes an initial enhancement of the field dynamics, the R-boost
- Gravitational dragging: the energy density scales as the dominant component
- Gravitational dragging: dark energy perturbations track the matter ones up to non-lineariry $\Rightarrow$ it does large scale structure (!)
- CMB: corrections at the 10% order with respect to ordinary Quintessence, detectable by satellite missions
- ISW: $\delta C_\ell / C_\ell \simeq 12(1 - G/G_{dec})$
- Acoustic peaks shift: $\delta\ell/\ell \simeq (1 - G/G_{dec})/8$

Quintessence & CMB

Carlo Baccigalupi [§] ,Amedeo Balbi [**], Sabino Matarrese [††],

Francesca Perrotta [‡‡], Nicola Vittorio [§§]

References:

F. Perrotta & C. Baccigalupi, astro-ph/9811156, Phys.Rev. D59 (1999) 123508

A. Balbi, C. Baccigalupi, S. Matarrese, F. Perrotta, N. Vittorio, astro-ph/0009432, Ap.J.L. (2001), L89

C. Baccigalupi, A. Balbi, S. Matarrese, F. Perrotta, N. Vittorio, astro-ph/0109097, Phys.Rev. D65 (2002) 063520

[§]bacci@sissa.it

[**]balbi@roma2.infn.it

[††]matarrese@pd.infn.it

[‡‡]perrotta@sissa.it

[§§]vittorio@roma2.infn.it

Quintessence and CMB

Constraints from CMB: generalities

Advantages:

perturbations in linear regime, well understood geometrical features of high amplitude, well above the sensitivity of MAP and PLANCK:

$$w_\phi \uparrow_{-1}^{-0.6} \ , \ l_{peaks} \downarrow_{200}^{220} \ , \ \mathrm{ISW} \uparrow_{\Lambda}^{2\Lambda} \ .$$

Disadvantages:

CMB degeneracy (Efstathiou, astro-ph/0109151, 2001); in particular, acoustic peaks projection from dark energy is degenerate with a positive spatial curvature.

Quintessence and CMB

Simulated CMB spectra

Hubble constant fixed, no spatial curvature:

$$h = 0.65 \ , \ \Omega_K = 0 \ ,$$

Cosmological abundances:

$$0.16 \leq \Omega_b h^2 \leq 0.40 \ (\text{step } 0.02) \ , \ \Omega_{CDM} = 1 - \Omega_\phi$$

$$0.40 \leq \Omega_\phi \leq 0.80 \ (\text{step } 0.02)$$

Quintessence equation of state:

$$-0.96 \leq w_Q \leq -0.6 \ (\text{step } 0.03) \ , \ w_Q = -1$$

Cosmological perturbations:

$$0.90 \leq n_S \leq 1.10 \ (\text{step } 0.02) \ , \ 0 \leq R \leq 0.5 \ (\text{step } 0.05) \ , \ n_T = -R/6.8 \ .$$

We assume Gaussian, purely adiabatic initial conditions for fluctuations in all components, including dark energy.

Quintessence and CMB

Database and analysis

We use public data from

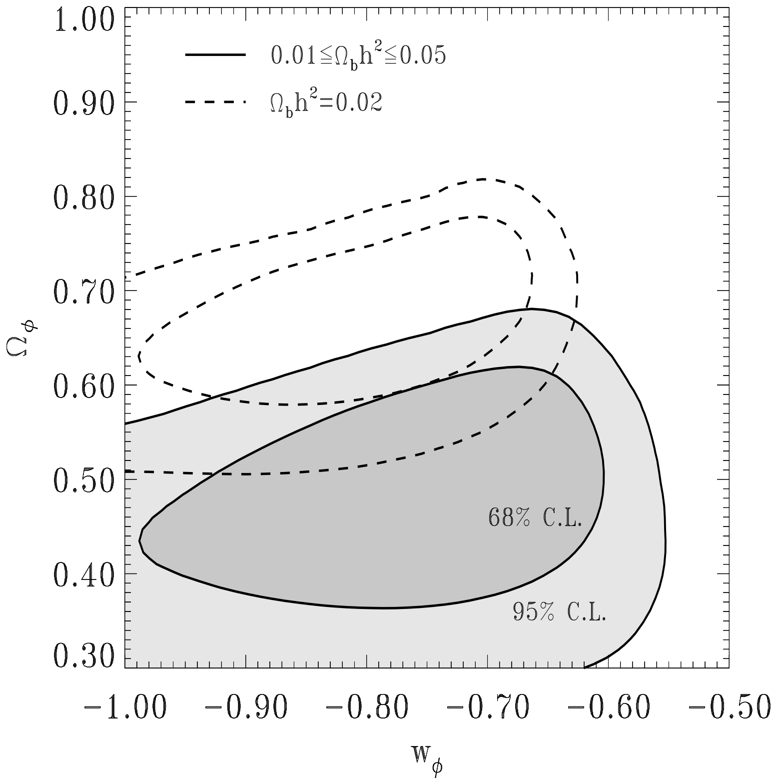
- BOOMERanG 19 points, $76 \leq l \leq 1025$, Netterfield et al. (2001), astro-ph/0104460
- MAXIMA 13 points, $36 \leq l \leq 1235$, Lee et al. (2001), astro-ph/0104459
- DASI 9 points, $104 \leq l \leq 864$, Halverson et al. (2001), astro-ph/0104489
- COBE/DMR 24 points, $2 \leq l \leq 25$, Bennet et al. (1996)

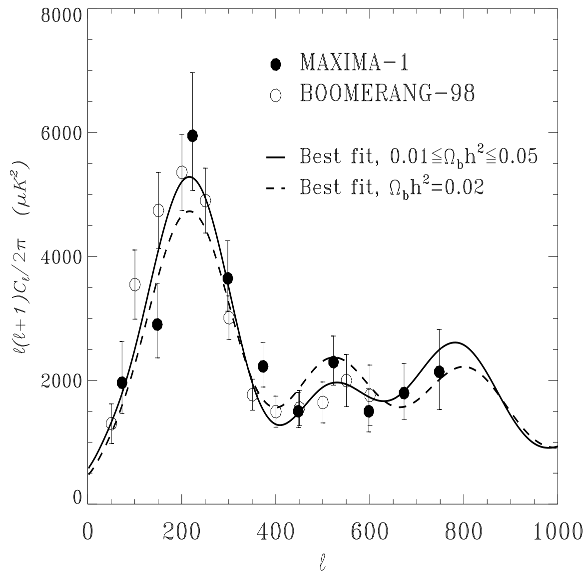
A Gaussian likelihood shape $\mathcal{L} \propto e^{-\chi^2/2}$ is assumed by default; where available, offset log-normal correction terms (Bond, Jaffe & Knox 2000) were taken into account.

Calibration uncertainty, $20\%, 8\%, 8\%$ for BOOMERanG, MAXIMA, DASI, respectively, is considered; correlation between data points is neglected.

Quintessence and CMB

Balbi et al., ApJL 547 (2001) L89, astro-ph/0009432



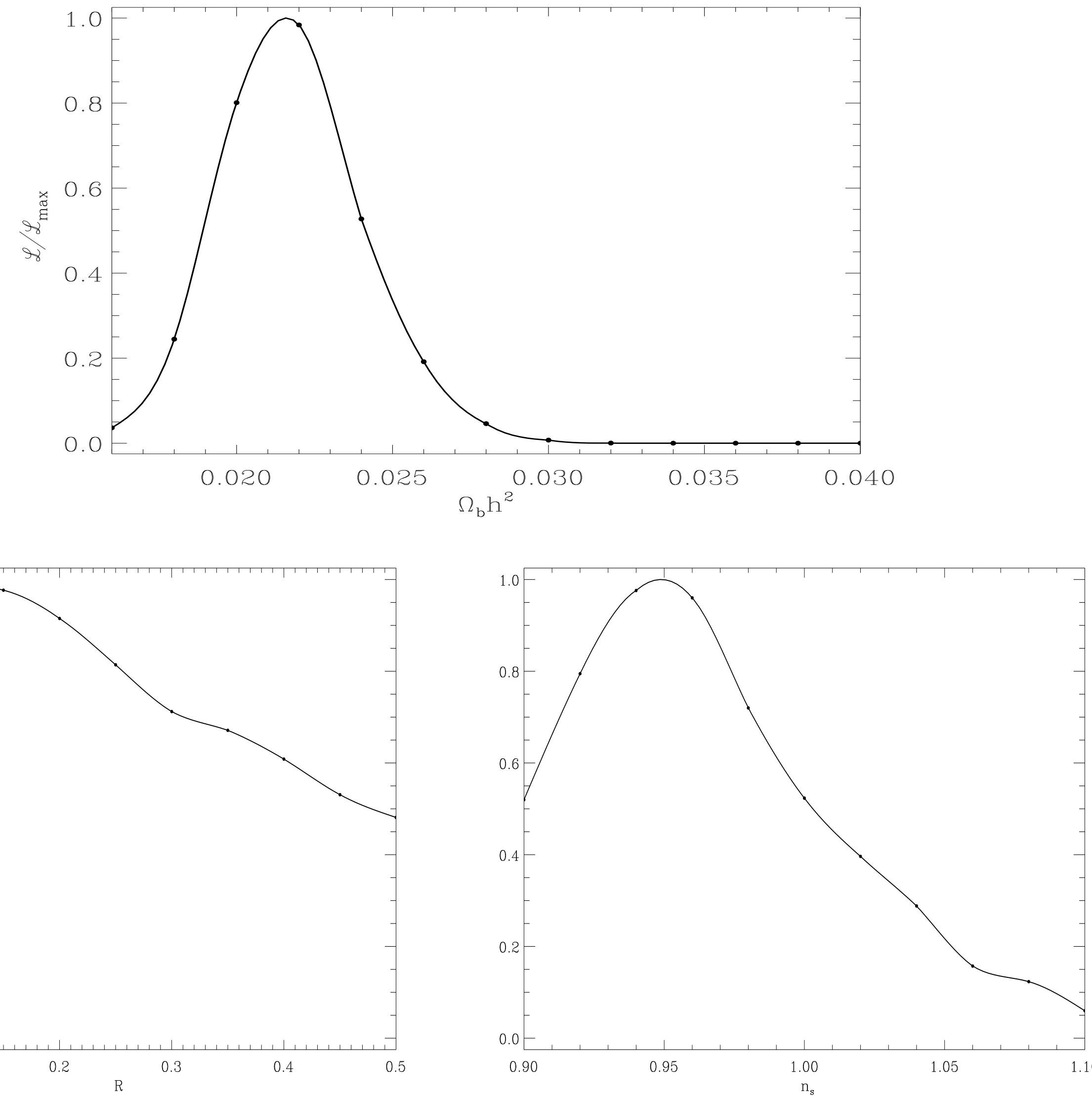


Early data from BOOMERanG, MAXIMA, COBE/DMR

$\Omega_K = 0,\ h = 0.65,\ 0.20 \leq \Omega_b h^2 \leq 0.40,\ 0.40 \leq \Omega_\phi \leq 0.80,\ -1 \leq w_\phi \leq -0.60, n_S = 1, R = 0$

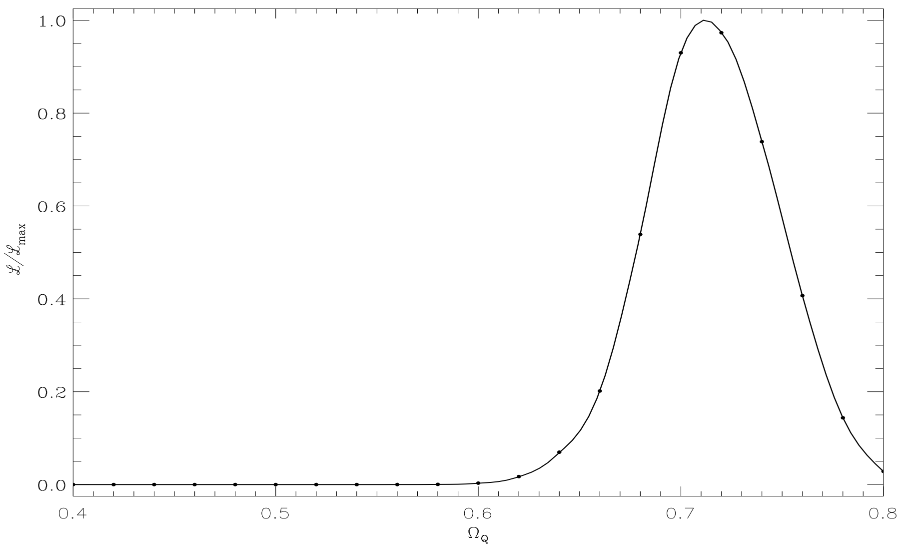
Quintessence and CMB

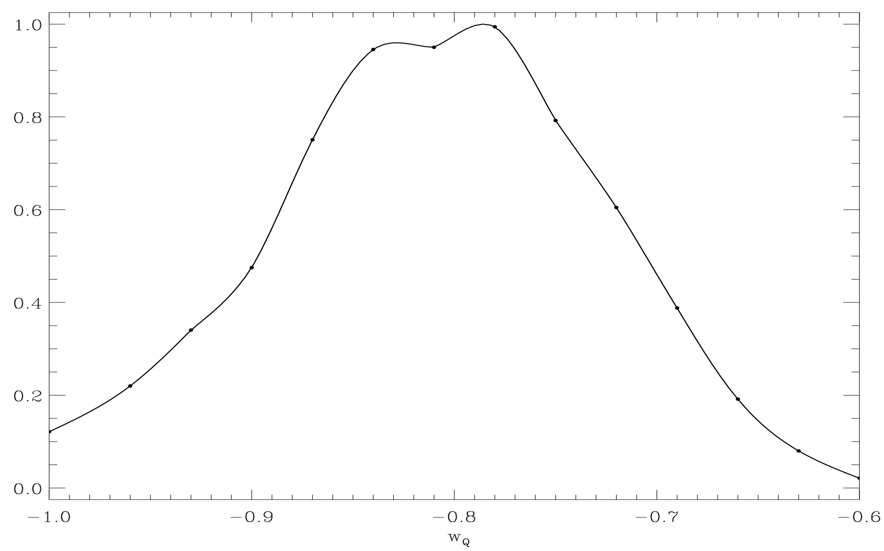
Present results for $\Omega_b h^2$, n_S, R



Quintessence and CMB

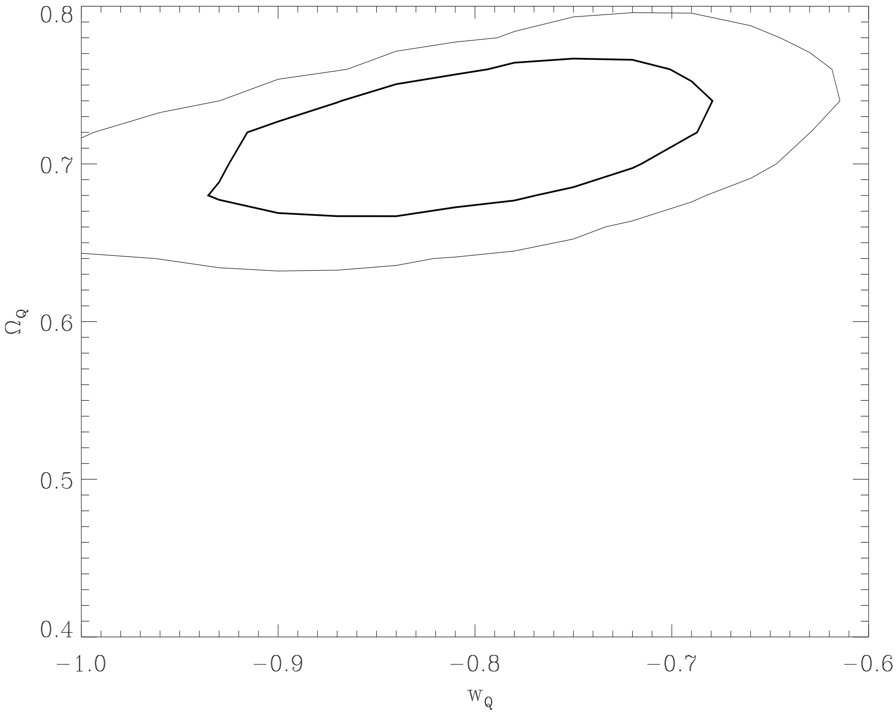
Present results for Ω_Q, w_Q

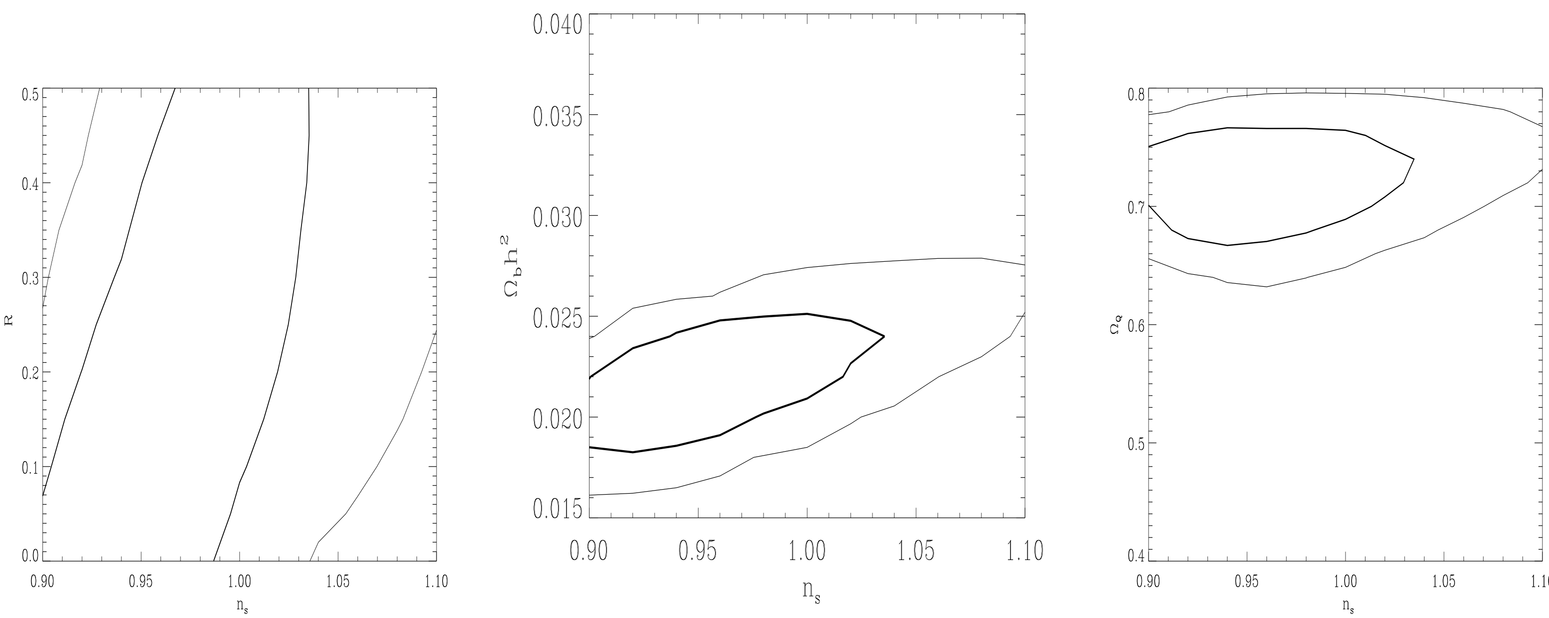




Quintessence and CMB

Present results





Quintessence and CMB

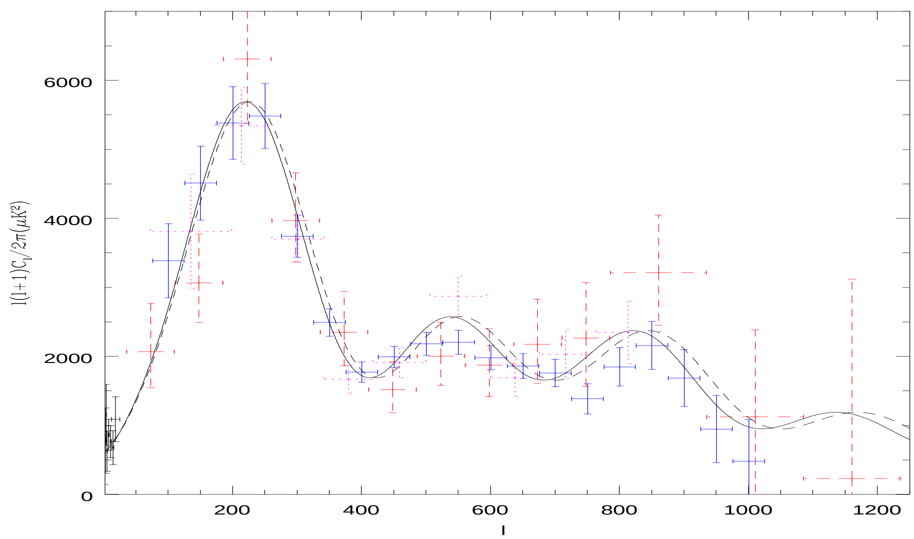
Is there a projection effect on the CMB sky?

BOOMERanG: $\Omega_{tot} = 1.02^{+0.06}_{-0.05}$, $\Omega_{tot} = 1.04 \pm 0.05$

MAXIMA: $\Omega_{tot} = 0.90^{+0.18}_{-0.16}$

DASI: $\Omega_{tot} = 1.04 \pm 0.06$

Combined data (+ our priors) give indication of a shift of acoustic peaks toward larger angular scales, with respect to an ordinary ΛCDM Universe.



Quintessence and CMB

Conclusions up to now

• In flat cosmologies, H_0 fixed, low GWs, CMB shows a mild preference for a time varying dark energy:

$$0.6 \lesssim \Omega_\phi \lesssim 0.8 \ , \ -1 \lesssim w_\phi \lesssim \ -0.6 \quad (2\sigma)$$

$$\Omega_\phi = -0.71^{+0.05}_{-0.04} \ \ , \ \ w_\phi = -0.82^{+0.14}_{-0.11} \quad (1\sigma)$$

• Inverse power law potentials $V(\phi) \propto \phi^{-\alpha}$ are connstrained as

$$\alpha = 0.8^{+0.6}_{-0.5} \quad (1\sigma)$$

• CMB is a basic observable for constraining dark energy. If experiments should keep indicating a positive spatial curvature, that can be read as an evidence in favour of dynamical cosmological vacuum energy in a flat background.

• Keep constraints updated with forthcoming CMB data, include independent, possibly geometrical, observables (SNa).

Dark energy up to now

- **Dark Energy evidence: robust; hints from independent cosmological observations**
- **Cosmological Constant difficulties justify, if not require, the search for different explanations**
- **Candidates: trans-Planckian, brane-worlds, matter energy transition, scalar fields...**
- **Scalar fields admit trajectories with nearly a constant equation of state at relevant redshifts**
- **At least the measure of the dark energy equation of state is achievable in the precision cosmology era**
- **Relation with dark matter: unknown, if any; both of them participate to large scale structure formation**
- **Cosmology is highlighting the role of vacuum, an unsolved issue in Physics. Surely more surprises and maybe great discoveries to come...**