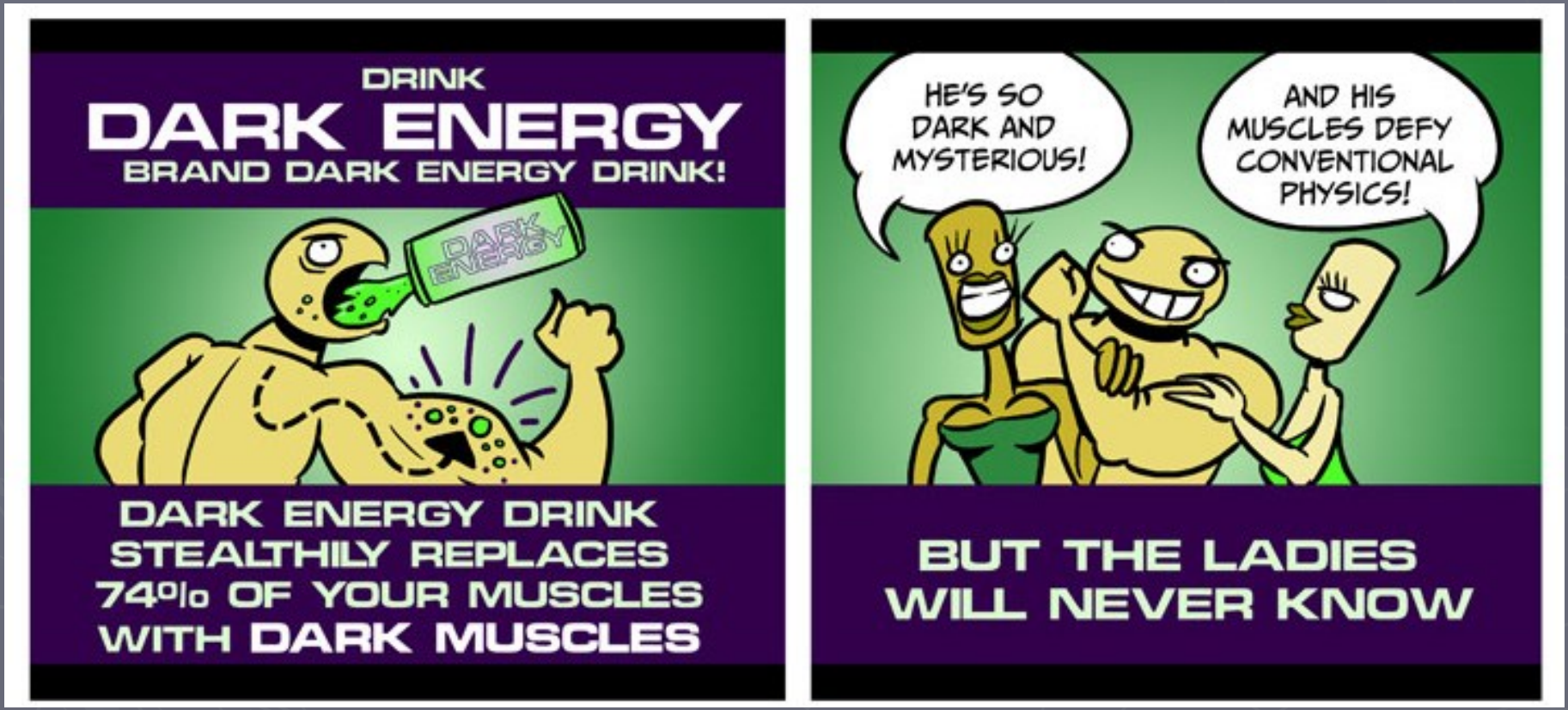
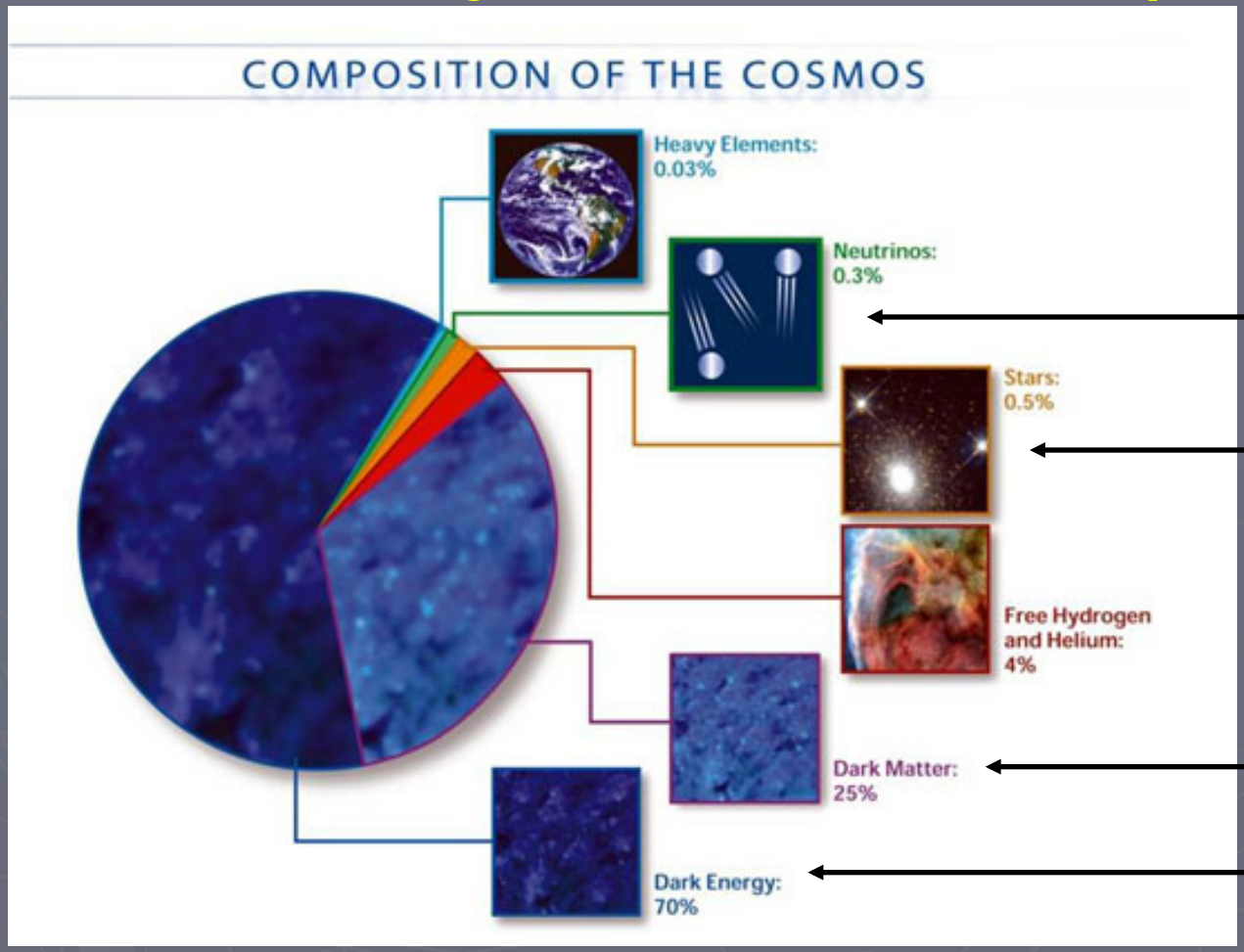
Dark Energy



Vincenzo Fabrizio Cardone

1st Sinergy LNF - OAR Workshop – Frascati 17/04/2014

The Dark Universe : a LNF/OAR Sinergy



Guetta, Longhin, Paoloni

Antonelli, Lops, Pedichini, Piconcelli, Porcelli

Antonelli, Menci

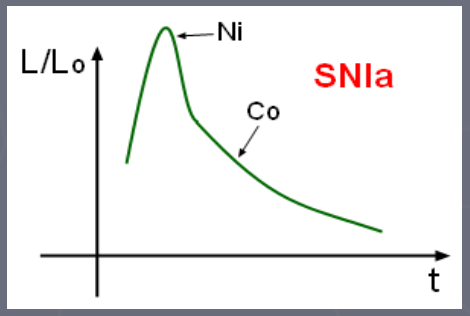
Cardone, Scaramella

1. Dominant component of the matter/energy budget
2. Not clustering on galactic scales
3. Speeding up the cosmic expansion

Why Dark Energy ? I. SNeIa Hubble Diagram

Tracing Distance to High - z

- Standard(izeable) candles up to z ~ 2



1. *Apparent peak mag m*
2. *Time duration from lc*
3. *Phillips law to get M*
4. *Distance modulus :*

$m - M = 25 + 5 \log D_L(z)$

- Probe the background cosmic expansion

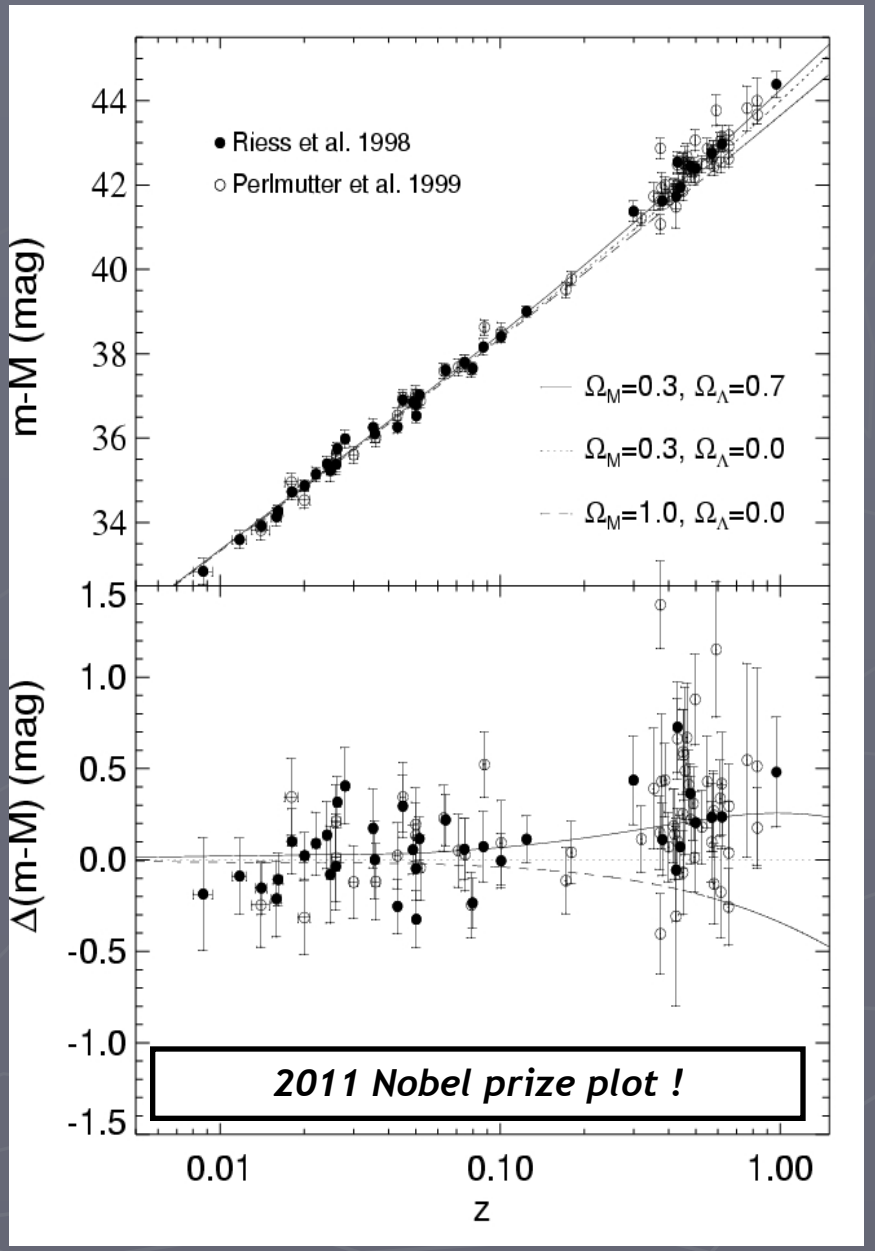
$$D_L(z) = \frac{c}{H_0}(1+z)\int_0^z \frac{1}{E(z')}dz'$$

$$E(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_{DE} f_{DE}(z)} = \sqrt{\Omega_M(1+z)^3 + \Omega_{DE}\Omega_M(1+z)^{3(1+w)}}$$

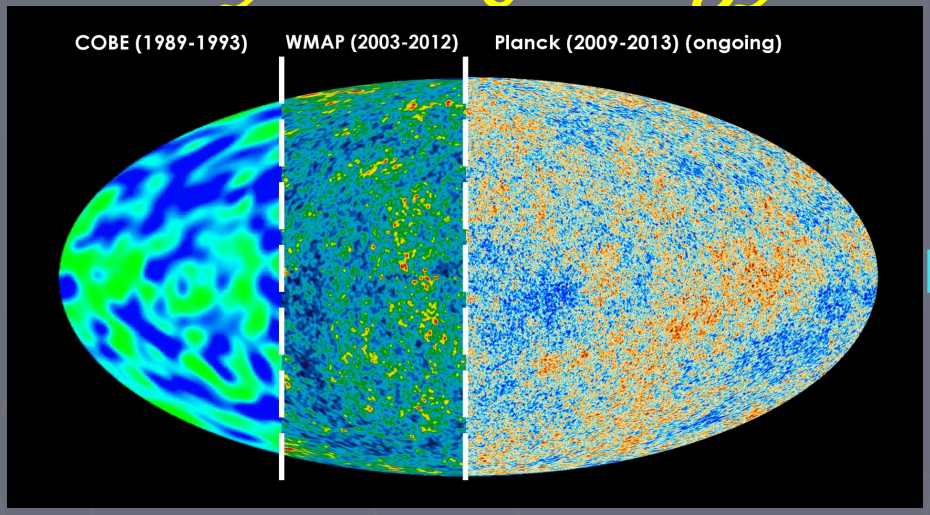
- First evidence of accelerated expansion

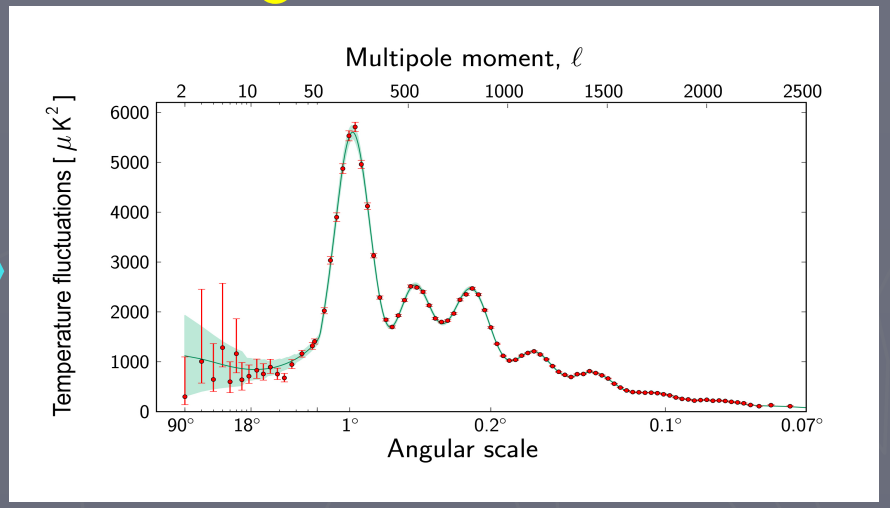
$$q_0 = \left(-\frac{1}{H^2}\frac{\ddot{a}}{a}\right)_{z=0} = \frac{1}{2}(1+3w)$$

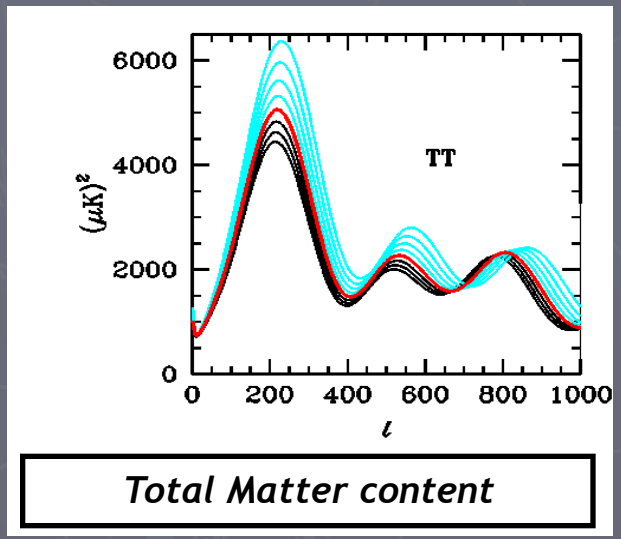
- More than 700 SNeIa today
- Expand the redshift range to z = 4 with E-ELT
- Systematics limited



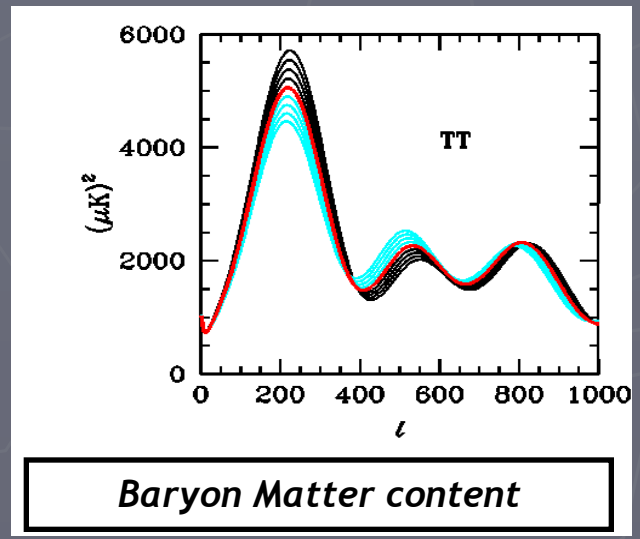
Why Dark Energy ? II. CMBR and Flatness



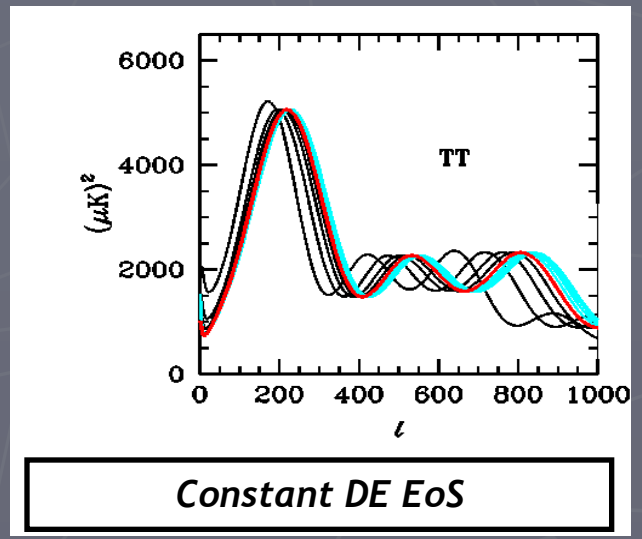




Total Matter content



Baryon Matter content



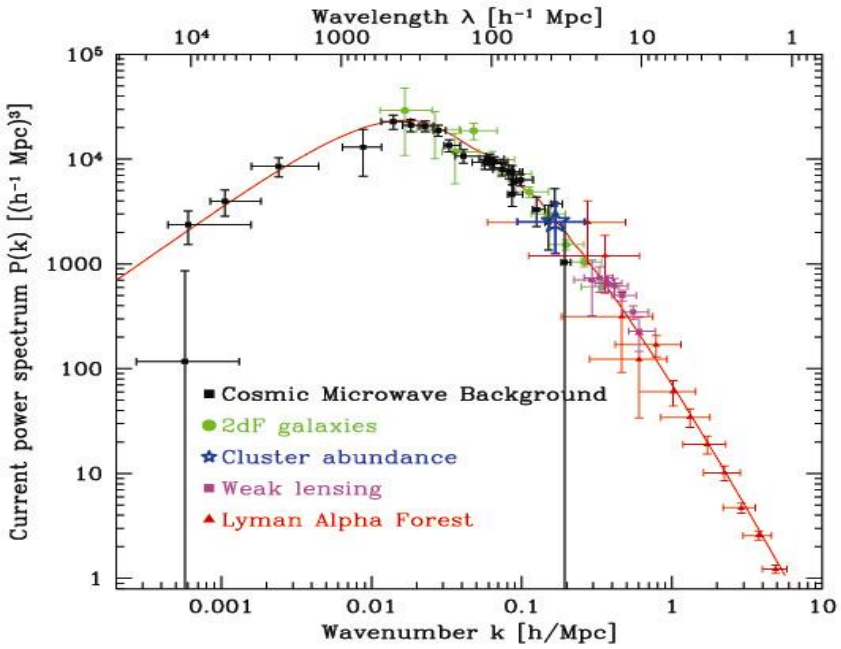
Constant DE EoS

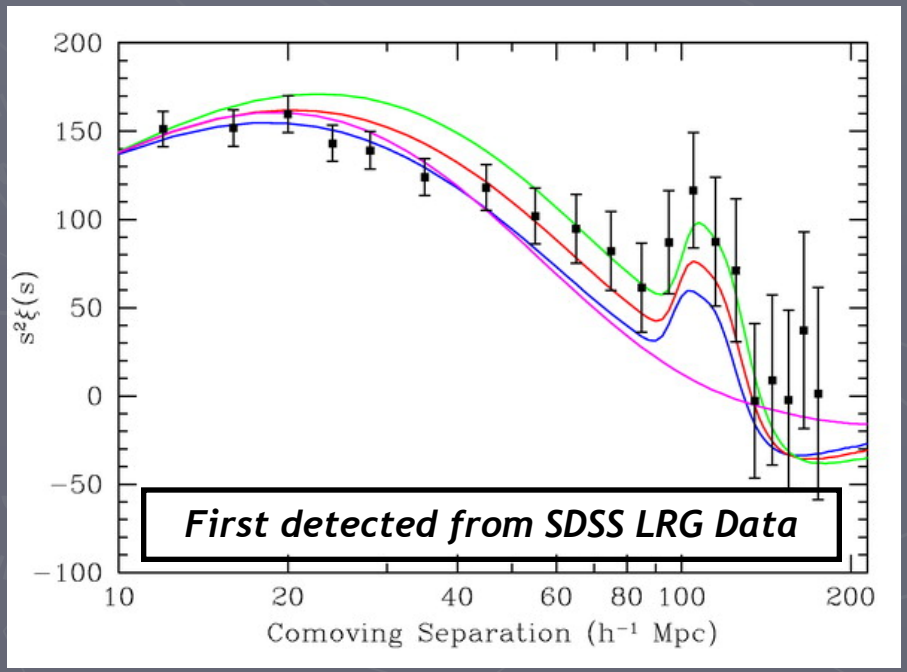
1. A map of the primordial density fluctuations and a success of hot Big Bang cosmology
2. Angular diameter distance to the last scattering surface : *flatness of the universe*
3. Spatially flat in subcritical matter content : *need for dark energy !*

Why Dark Energy ? III. BAOs from Surveys

Matter Power Spectrum

- Test background expansion …
- … and growth of structures
- Traced by different probes in particular :
- Spectroscopic galaxy survesy
- Weak lensing tomography
- Lyα forest data (on very large scales)

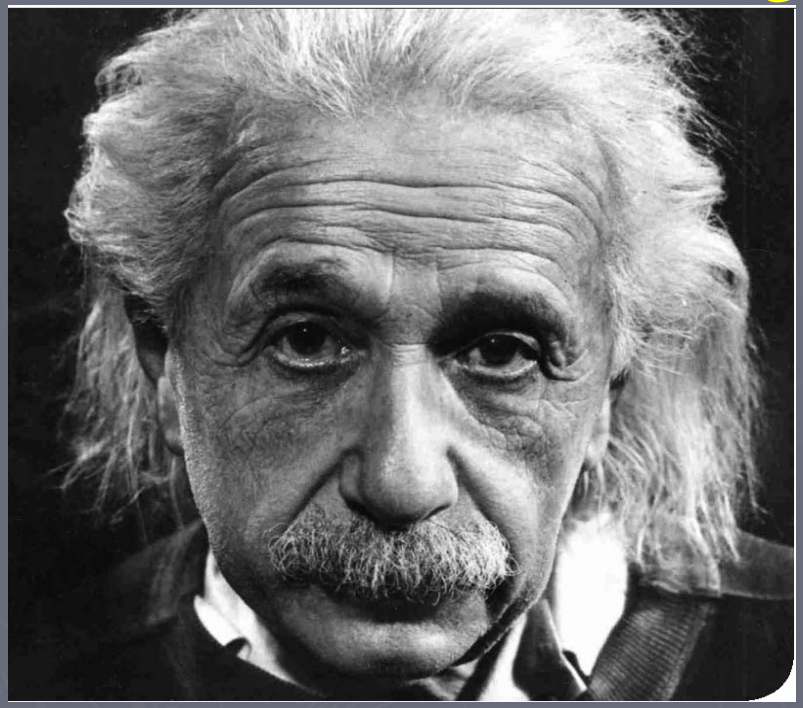




Baryonic Acoustic Oscillations

- Matter decoupling from radiation
- Overabundance at the sound horizon
- Observations vs theory : standard ruler !
- Peak in the CF and oscillations in the PS
- Measurement of both H(z) and $D_A(z)$!

What is Dark Energy ? Cosmological Constant



A Constant to Rule Them All

- Einstein "biggest blunder" (if he ever said it)
- Negative pressure to make the universe static
- Negative pressure to speed up expansion
- Constant EoS : $p = -\rho$, $w = -1$, $f_{DE}(z) = 1$
- Perfect fit to every possible data
- Concordance Cosmological Model ΛCDM
- No evidence for deviations from w = -1
- To be further tested with next to come data

Every Magic Comes with a Price !

- A constant introduced by hand : where it comes from ?
- Vacuum energy ? { $\Lambda \sim 10^{-48}$ GeV^4 from cosmology ; $\Lambda \sim (100$ GeV$)^4$ from QFT } ⟹ 120 orders of magnitude
- Ω_M same order as Ω_Λ : why now ?
- If Λ start dominates earlier, no structure formation (no LNF/OAR meeting too)

What is Dark Energy ? Quintessence

- Solve the "why now problem" : *add dynamics to the cosmological constant*
- Ingredients : *1. a self interacting scalar field; 2. an interaction potential*

From Theory to Data

Energy : $\rho_Q = \frac{1}{2}\dot{\phi}^2 + V(\phi)$

Pressure : $p_Q = \frac{1}{2}\dot{\phi}^2 - V(\phi)$

EoS : $w_Q = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$

Friedmann Equations :

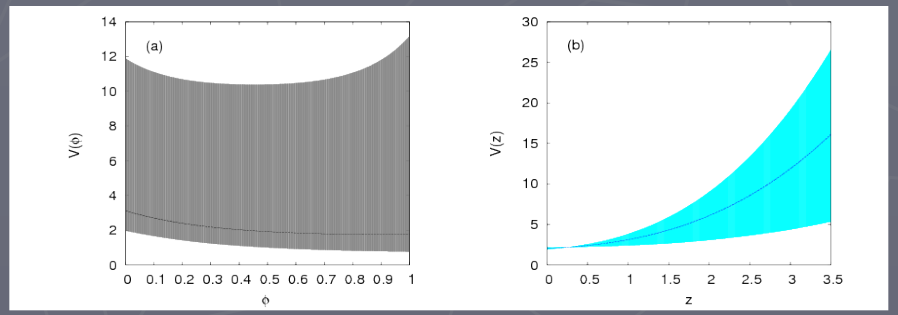
$H^2 = \frac{8\pi G}{3}(\rho_M + \rho_Q)$ $\quad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_M + \rho_Q + 3p_Q)$

From Data to Theory

- Non parametric reconstruction of (ρ_Q, w_Q)
- Invert the Friedmann equations

$$\dot{\phi}(z) = \sqrt{\rho_Q(z)[1 + w_Q(z)]/2}$$

$$V(z) = \rho_Q(z)[1 - w_Q(z)]/2$$



Every Magic Comes with a Price

- *What is the potential ? Exponential ? Power - law ? SUGRA - like ? (but see trackers !)*
- *Where the scalar field comes from ? Why it starts dominating now ?*
- *How to cross the phantom divide (w < -1) ? Non canonical kinetic term ? Double field ?*

What is Dark Energy ? Unified Dark Energy

- "Kill two birds with one stone" : *dark matter and dark energy from a single fluid*
- No "why now problem" : *they have always been the same quantity*
- Structure formation and growth : *critically depends on the sound speed c_s*

Adiabatic UDE : $p = p(\rho)$

Generalized Chaplygin gas :

$$p = -A/\rho^{\alpha} \quad (0 < \alpha \leq 1)$$

$$\rho = \Lambda\left[1 + (\Omega_M/\Omega_\Lambda)(1+z)^{3(\alpha+1)}\right]^{\frac{1}{\alpha+1}}$$

Sound speed : $c_s^2 = -\alpha w$; fit data for $|\alpha| < 10^{-5}$

Dark fluid :

$$p = -A + \alpha\rho$$

$$\rho = \Lambda\left[1 + (\Omega_M/\Omega_\Lambda)(1+z)^{3(\alpha+1)}\right]$$

Sound speed : $c_s^2 = -\alpha$; fit data for $|\alpha| < 10^{-7}$

Non Adiabatic UDE : $p \neq p(\rho)$

From Lagrangian :

$$p = L(\phi, X) \; ; \; X = \dot{\phi}^2/2$$

$$\rho = 2X\,dL(\phi, X)/dX - L(\phi, X)$$

Assumption :

$$L(\phi, X) = f(\phi)\,g(X) - V(\phi)$$

Sound speed : $c_s^2 = -p_{,X}/\rho_{,X}$ (non adiabatic)

$$c_s^2 = \frac{c_\infty}{1 + (1 - c_\infty)(\Omega_M/\Omega_\Lambda)\,\nu\, a^{-3}}$$

E(z) as in ΛCDM

⇒ Lagrangian

Every Magic Comes with a Price

- *Extreme fine tuning of the parameters typically reducing to ΛCDM*
- *Ad hoc Lagrangian (with non canonical kinetic term) to restore agreement with data*
- *A possible way out : two distinct interacting fluids (beware of fifth force !)*
- *A possible way out : dark energy interacting with neutrinos (which ? why ? how ?)*

What is Dark Energy ? A Misunderstanding !

- Einstein equations
  - $G_{mn} = k\,(T_{mn} + X_{mn})$: dark energy
  - $G_{mn} + H_{mn} = k\,T_{mn}$: modified gravity
- Generalizing GR
  - change the no. of dimensions : braneworld models
  - change the variable in the Lagrangian : f(T) models
  - change the order of the equations : f(R) and f(G) models
  - change the geometry terms : Galileon and vector models

A Textbook Example : f(R) theories

Einstein eqs :

$$f'(R)R_{\alpha\beta} - \frac{1}{2}f(R)g_{\alpha\beta} - f'(R)^{;\alpha\beta}(g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\beta}g_{\mu\nu}) = \tilde{T}^{M}_{\alpha\beta}$$

Friedmann eqs :

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\left[\rho_{curv} + \frac{1}{f'(R)}\rho_m\right] \qquad 2\,\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 = -(p_{curv} + p_m)$$

Effective EoS :

$$\rho_{curv} = \frac{1}{f'(R)}\left\{\frac{1}{2}[f(R) - Rf'(R)] - 3H\dot{R}f''(R)\right\} \qquad w_{curv} = -1 + \frac{\ddot{R}f''(R) + \dot{R}\left[\dot{R}f'''(R) - Hf''(R)\right]}{[f(R) - Rf'(R)]/2 - 3H\dot{R}f''(R)}$$

1. cosmic speed up ; 2. fit the data ; 3. fourth order eqs ; 4. match any DE expansion

DE or MG ? Looking for an Answer !

Dark Energy

- Cosmic speed up from new source
- Excellent fit to the data
- Second order linear eqs
- Hubble rate in agreement with data
- No deviations from GR on SS scales

f(R) Gravity

- Cosmic speed up from geometry
- Excellent fit to the data
- Fourth order nonlinear eqs
- Hubble rate in agreement with data
- No deviations from GR on SS scales

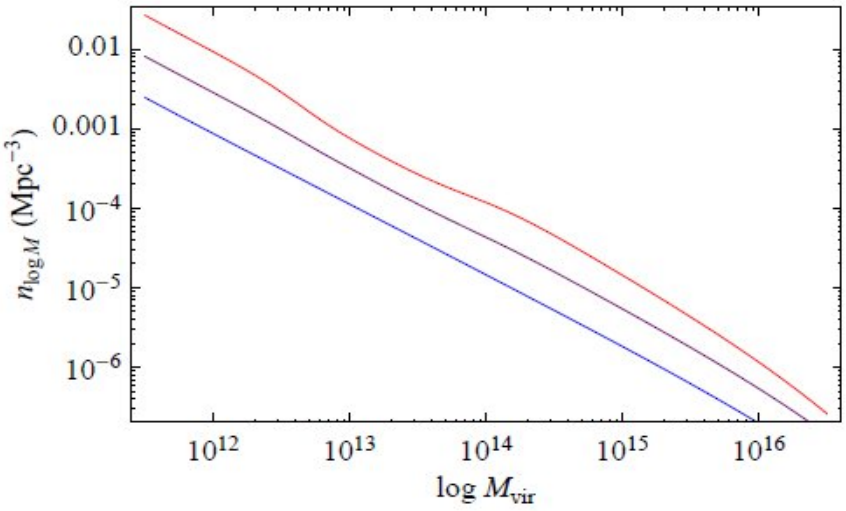
- Linearly perturbed metric : $ds^2 = a^2 [(1 + 2\,\Phi)\, dt^2 - (1 - 2\,\Psi)\,(dx^2 + dy^2 + dz^2)]$
- Dark energy models : $\Phi = \Phi(z, k)$; $\Psi = \Psi(z, k)$; $\Phi(z, k) = -\Psi(z, k)$; $G = G_N$
- Fourth order gravity : $\Phi = \Phi(z, k)$; $\Psi = \Psi(z, k)$; $\Phi(z, k) \neq -\Psi(z, k)$; $G = G(k, z)$

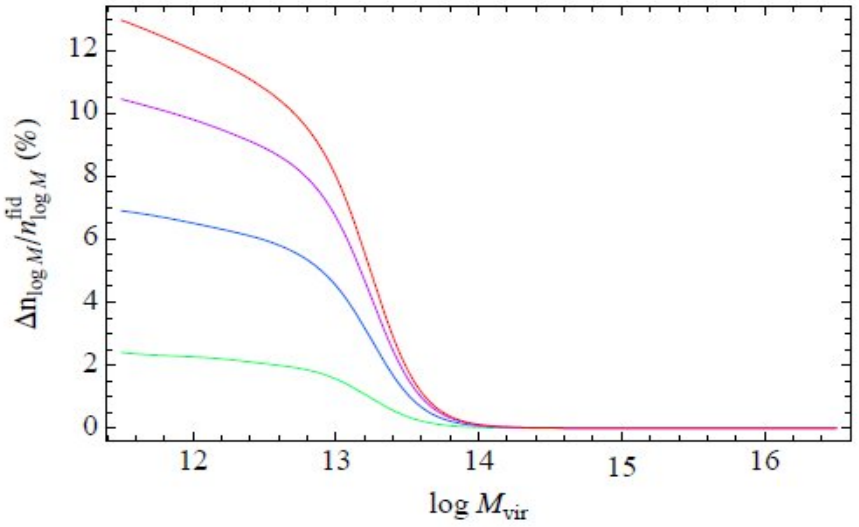
Probing the Growth of Structures

- Galaxy power spectrum : $P_{gal}(k, z) = b^2(z)\, P_{mat}(k, z) \sim b^2(z)\, \Psi^2(k, z)$
- Weak lensing power spectrum : $P_{lens}(k, z) \sim [\Phi(k, z) + \Psi(k, z)]^2$
- Galaxy peculiar velocities : $P_{pv}(k, z) \sim [d\Psi(k, z)/dz] / [b^2(z)\, \Psi(k, z)]$
- A single mission for three probes : Euclid (see next talk by Scaramella) !

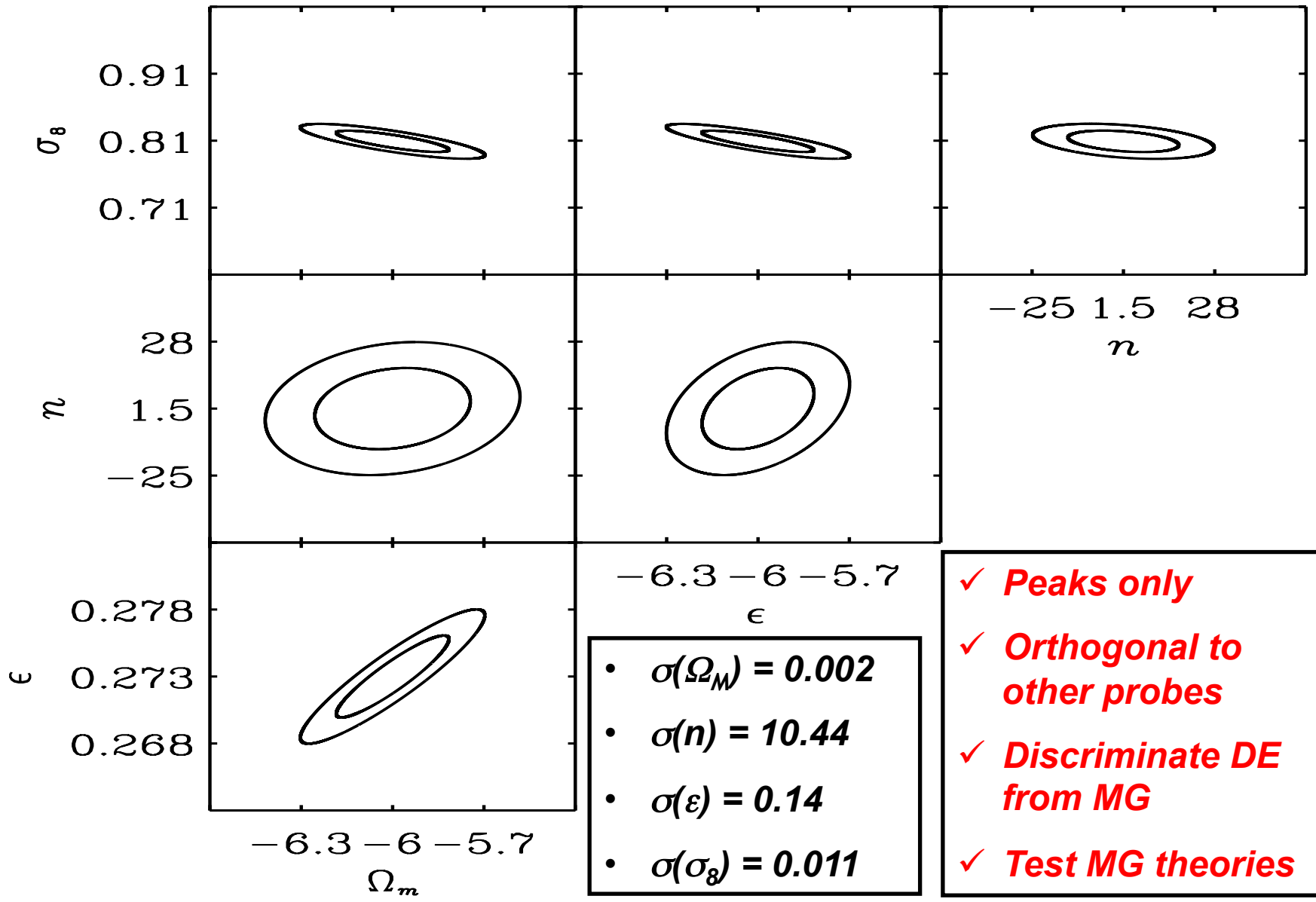
DE or MG ? Mass Function and WL Peaks

- Theoretical mass function : $$\mathcal{N}(\ln M_{vir}) = \frac{\rho_M(z=0)}{M_{vir}} \frac{d\ln\nu}{d\ln M_{vir}} \nu\varphi(\nu)$$
- Variance of perturbations :
$$\sigma^2[R(M_{vir})] = \frac{1}{(2\pi)^3}\int P_\delta(k)|W(kR)|^2 d^3k$$
$$\sigma(M_{vir}) = \frac{\sigma_{FoG}(M_{vir}) + (M_{vir}/M_{th})^\alpha \sigma_{GR}(M_{vir})}{1+(M/M_{th})^\alpha}$$
- Matter power spectrum : $$P_\delta(k,z) = \mathcal{A}k^{n_{PS}}T^2(k)D^2(k,z)$$
- Growth factor : $$\ddot{\delta} + 2H\dot{\delta} - 4\pi\mathcal{G}_{eff}(a,k)\rho_M\delta = 0$$
$$\mathcal{G}_{eff}(a,k) = \frac{G}{f'(R)}\frac{1+4(k^2/a^2)[f''(R)/f'(R)]}{1+3(k^2/a^2)[f''(R)/f'(R)]}$$





DE or MG ? Forecast for Euclid



- $\sigma(\Omega_M) = 0.002$
- $\sigma(n) = 10.44$
- $\sigma(\varepsilon) = 0.14$
- $\sigma(\sigma_8) = 0.011$

- ✓ ***Peaks only***
- ✓ ***Orthogonal to other probes***
- ✓ ***Discriminate DE from MG***
- ✓ ***Test MG theories***

Dark Energy : Yesterday, Today and Tomorrow

Dark Energy Yesterday : Something Weird is Out There

- SNeIa Hubble diagram first evidence for accelerated expansion
- CMBR definitive evidence for flat universe with subcritical matter content
- Need for something driving cosmic speed up and filling the gap
- A dominant fluid with negative pressure and not clustering on small scales

Dark Energy Today : Too Many Candidates for Something

- Refined data (SNeIa, CMBR) and new tracers (BAOs) : same conclusion
- Cosmological constant : a perfect fit to the data but the wrongest model !
- Solving the ΛCDM problems : quintessence and interacting DE/DM models
- A change of perspective : no dark energy but modified gravity

Dark Energy Tomorrow : Discriminating DE from MG

- Going beyond the background expansion : test the growth of structure
- A change of probes : spectroscopic surveys and weak lensing tomography
- Beware of confirmation bias : not look for consistency but for discrepancy !