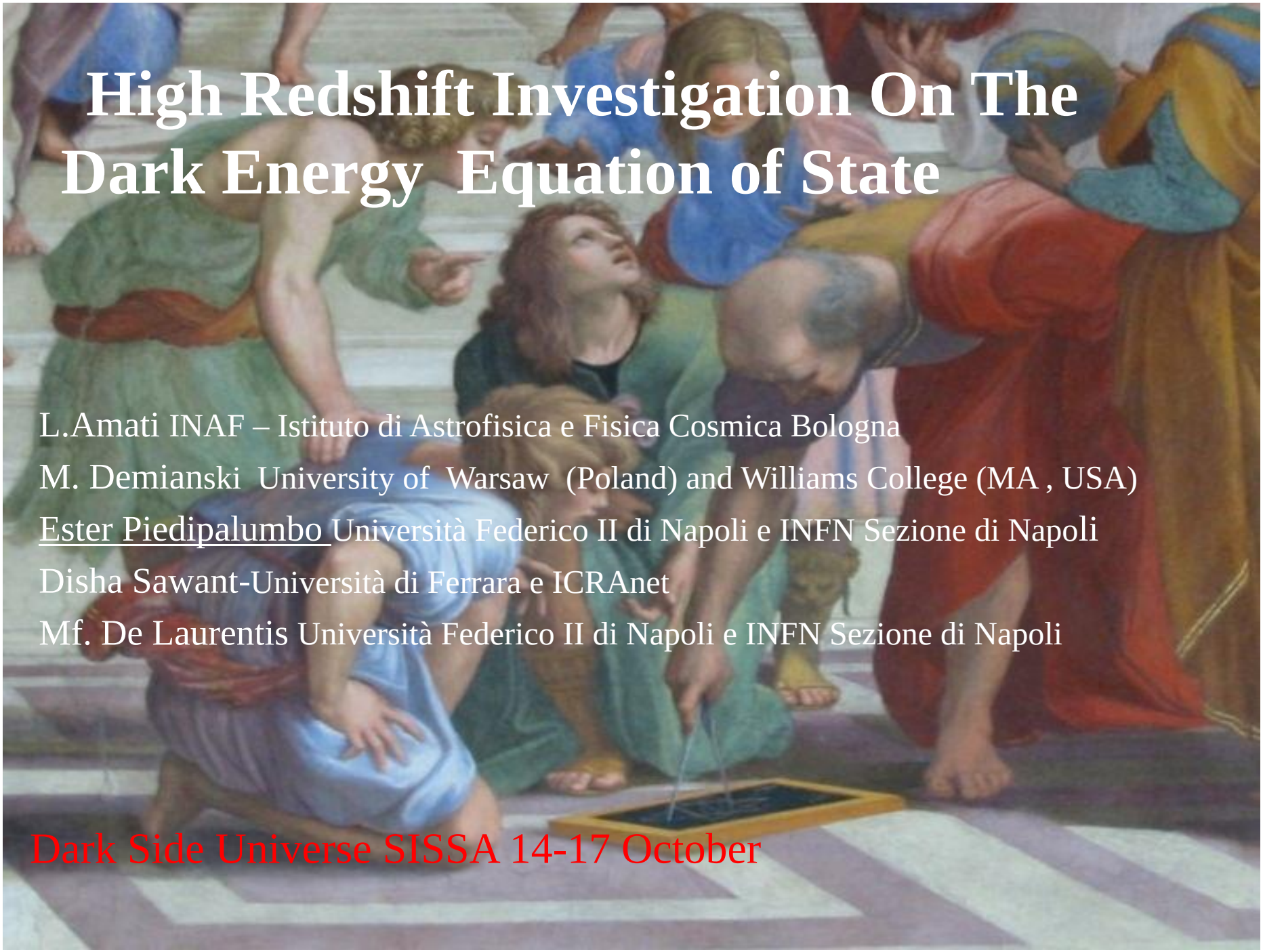

High Redshift Investigation On The Dark Energy Equation of State

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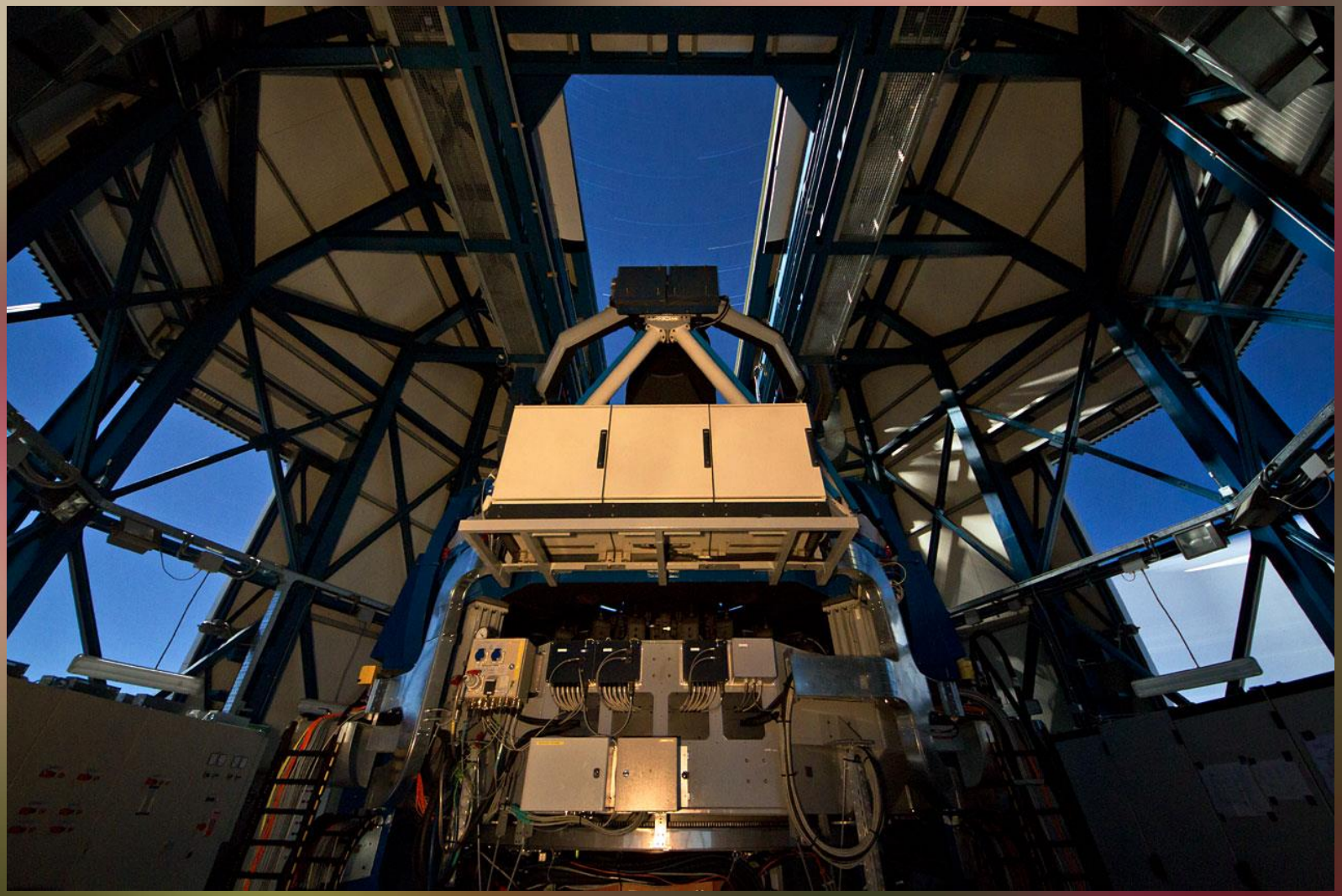
Dark Side Universe SISSA 14-17 October



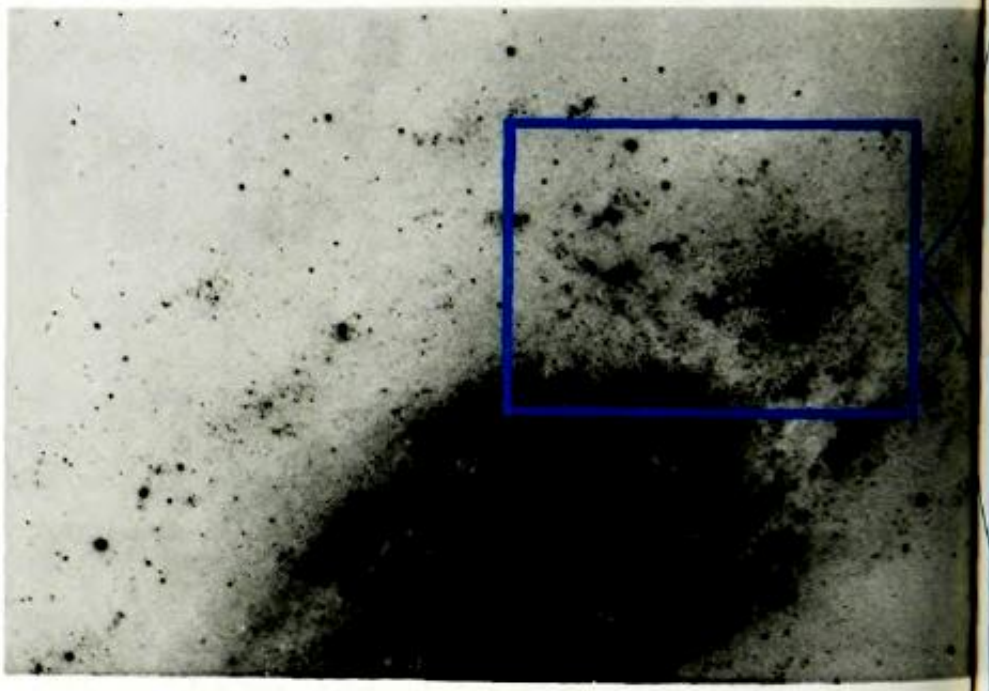
COSMOLOGY: A SEARCH FOR TWO NUMBERS

Precision measurements of the rate of expansion and the deceleration of the universe may soon provide a major test of cosmological models

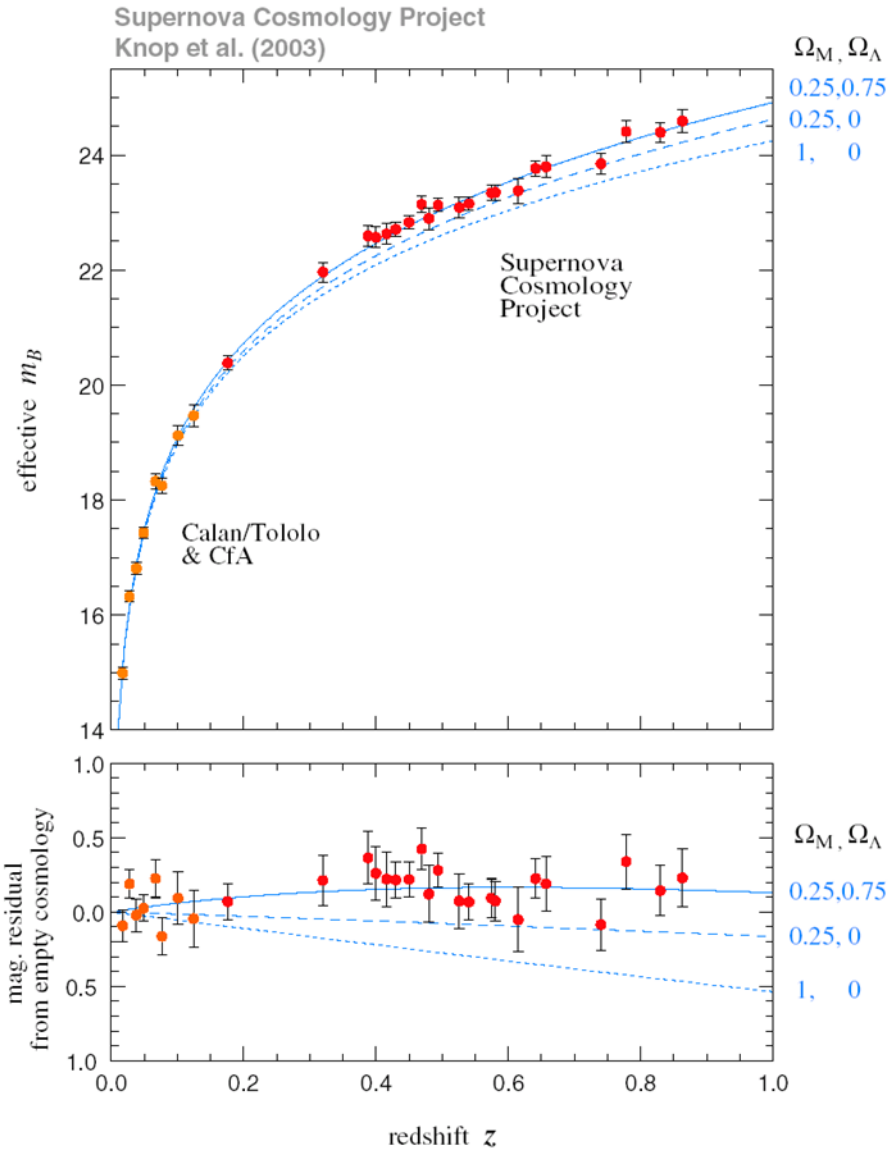
ALLAN R. SANDAGE

AS RECENTLY AS THE 1950's about all that observational cosmology had succeeded in establishing was that galaxies exist and the universe expands. But beginning in the 1960's a flood of new discoveries has enriched our picture of the universe and has begun to provide a basis on which to distinguish between competing cosmological models. There has been a 30-year effort, now drawing to a close, to get precise measurements of two parameters that will provide a crucial test for cosmological models. The two key numbers are the rate of expansion (the Hubble constant H_0) and the deceleration in the expansion (q_0). The hope is that current research, by determining the extragalactic distance scale for nearby galaxies and searching for exceedingly distant clusters where the redshift is large, will measure both of these numbers to a precision of 15%.

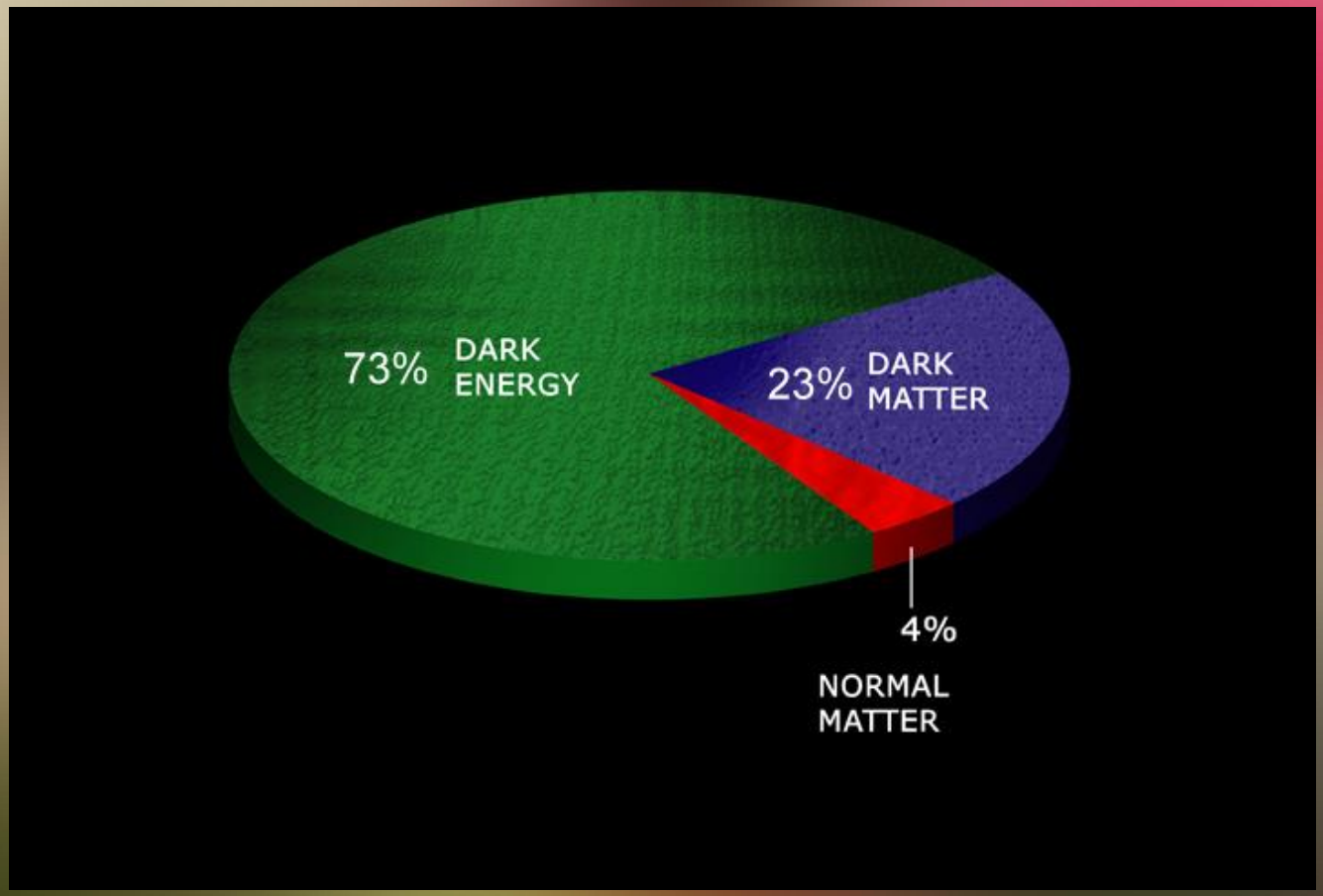
New discoveries of the 1960's, spurred by the sophistication of new instruments and ideas, include:



THREE CEPHEIDS in NGC2403 from blue plates taken 359 days apart with the 200-inch telescope. Periods are 46.460, 20.260 and 34.354 days for variables 5, 6 and 8. Magnitudes are 22.07 and 22.32 for variables 5 and 6 in the upper right and 22.02 for variable 8 in the lower right panel. —FIG. 1


Supernova Cosmology Project
Knop et al. (2003)
Ω_M, Ω_Λ
0.25,0.75
0.25, 0
1, 0
Supernova Cosmology Project
Calan/Tololo & CfA
effective m_B
24
22
20
18
16
14
mag. residual from empty cosmology
1.0
0.5
0.0
0.5
1.0
0.0
0.2
0.4
0.6
0.8
1.0
redshift z

The surprising portrait of the Universe



An ocean of theoretical scenarios

New High Quality Data
have confirmed the accelerated expansion

The **Cosmological Constant** remains consistent with a lot of data as a driving force of the acceleration.

Changing matter

An **Evolving Dark Energy** is also allowed by the data within General Relativity

Scalar Tensor extensions of General Relativity are consistent with the data which describe the expansion histories.

Changing gravity

High order--F(R)-- extensions of General Relativity are consistent with the full range of allowed expansion histories.

Scalar tensor and f(R) models need to satisfy local gravity constraints (MAINLY in strong gravity regime)

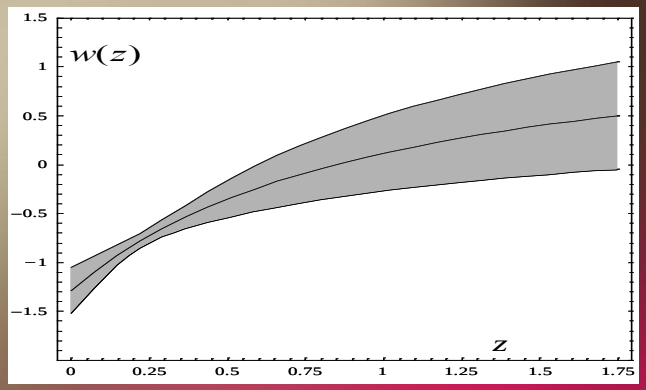
Key Questions

Is General Relativity the correct theory on cosmological scales?

What is the most probable form of w(z) and does w(z) evolve?

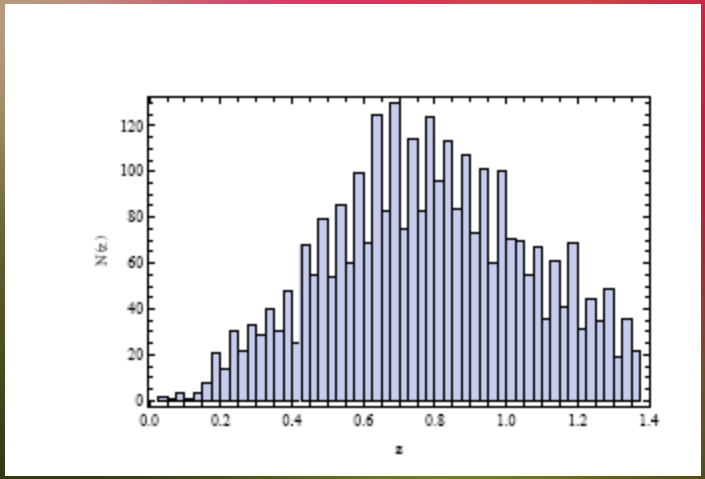
BUT…….to investigate w(z) is very complicated

Reconstructed EoS



EoS models and a huge degeneration

About 5600 SNe-Ia simulated assuming a CPL EoS



$$\sigma_\mu(z) = \sqrt{\sigma_{sys}^2 + (z/z_{max})^2 \sigma_m^2}$$

$$(z_{max}, \sigma_{sys}, \sigma_m) = (1.4, 0.15, 0.02)$$

A different approach: the cosmography

- Cosmography
  - is a promising approach to understand the acceleration of the Universe .
  - is based on the series expansion of the scale factor a(t) and related functions.
  - proceeds with minimal assumptions:
    - ❖ No particular form of the Friedmann equations is assumed.
    - ❖ The large-scale geometry is supposed to be well described by the Friedmann-Robertson-Walker (FRW) metric.
- Thus, it is largely model and setting independent.

Cosmographic approach - methodology

- Specify geometry

- Find general expressions for the measurable quantities

- Expand all quantities around t = t(present)

- Fit the observable quantities with the real data

- Extract values of the expansion parameters

$$H(t) = +\frac{1}{a}\frac{da}{dt}\,, \qquad \text{the Hubble parameter}$$

$$q(t) = -\frac{1}{a}\frac{d^2a}{dt^2}\frac{1}{H^2}\,, \qquad \text{the deceleration parameter}$$

$$j(t) = +\frac{1}{a}\frac{d^3a}{dt^3}\frac{1}{H^3}\,, \qquad \text{the jerk parameter}$$

$$s(t) = +\frac{1}{a}\frac{d^4a}{dt^4}\frac{1}{H^4}\,, \qquad \text{the snap parameter}$$

$$l(t) = +\frac{1}{a}\frac{d^5a}{dt^5}\frac{1}{H^5}\,, \qquad \text{the lerk parameter}$$

$$d_L(z) = \frac{cz}{H_0}\left(\mathcal{D}_{L0} + \mathcal{D}_{L1}z + \mathcal{D}_{L2}z^2 + \mathcal{D}_{L3}z^3 + \mathcal{D}_{L4}z^4 + \mathcal{O}(z^5)\right) ,$$

where

$$\mathcal{D}_{L0} = 1 ,$$

$$\mathcal{D}_{L1} = -\frac{1}{2}\left(-1 + q_0\right) ,$$

$$\mathcal{D}_{L2} = -\frac{1}{6}\left(1 - q_0 - 3q_0^2 + j_0\right) ,$$

$$\mathcal{D}_{L3} = \frac{1}{24}\left(2 - 2q_0 - 15q_0^2 - 15q_0^3 + 5j_0 + 10q_0 j_0 + s_0\right) ,$$

$$\mathcal{D}_{L4} = \frac{1}{120}\left(-6 + 6q_0 + 81q_0^2 + 165q_0^3 + 105q_0^4 - 110q_0 j_0 - 105q_0^2 j_0 - 15q_0 s_0 + \right.$$
$$\left. - 27j_0 + 10j^2 - 11s_0 - l_0\right) .$$

y-redshift

$$y = \frac{z}{1+z}$$

$$0 \leq z \leq \infty$$

$$0 \leq y \leq 1$$

Statistical procedure

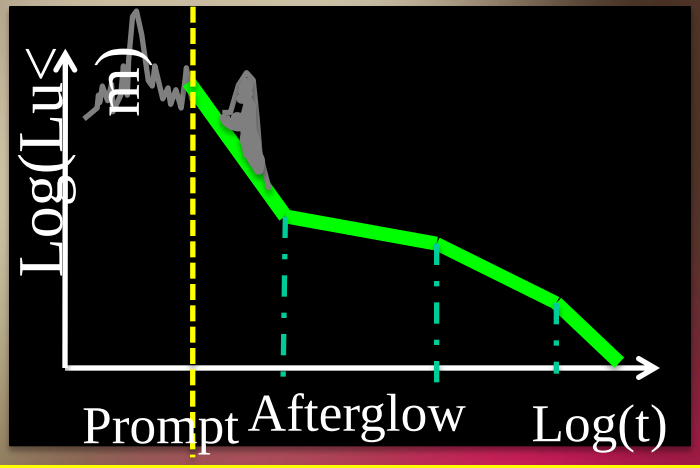
Markov Chain Monte Carlo method

- We use it to explore the probability distributions of our parameters:
  - Samples are extracted sequentially using a probabilistic algorithm.
  - Bayesian priors can be implemented and eventually provide tighter constraints.

Data sets:

- SNIa Union 2 $z < 1.55$
- Gamma Ray Bursts $z < 8.26$ (Amati relation 109 data+ 100 L_X-T_a correlation)
- Baryon Acoustic Oscillations
- CMB WMAP-7

The Ep,i – Eiso correlation: ***GRBs can be used as distance indicators !***

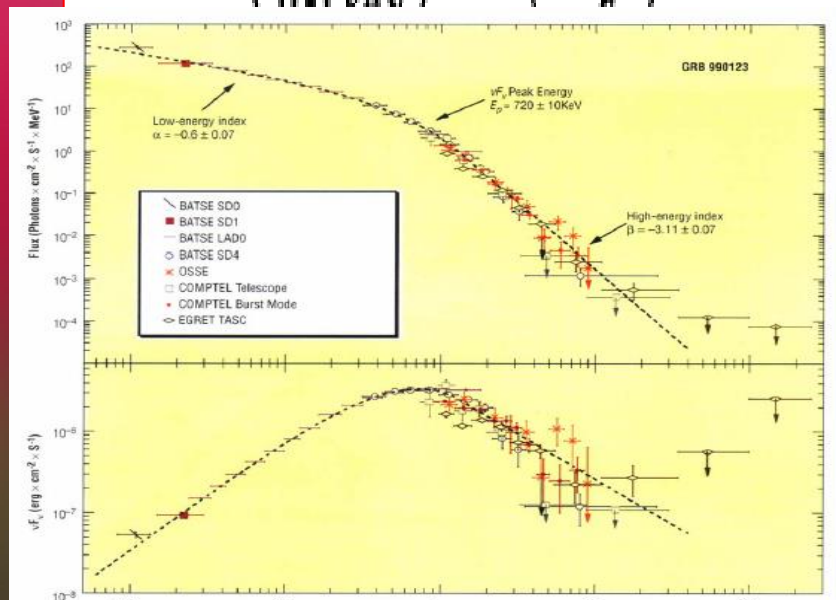


The robust correlation between the photon energy at which the photon spectrum peaks and the GRB radiated energy is at the base of the GRBs Hubble diagram

Spectra and energetics of GRBs

The spectrum of GRBs is nonthermal and can be empirically described by the so-called Band function, a broken power law characterized by the low-energy spectral index α and the high energy index β.

$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right),$$



$$\beta)E_0 \geq E$$

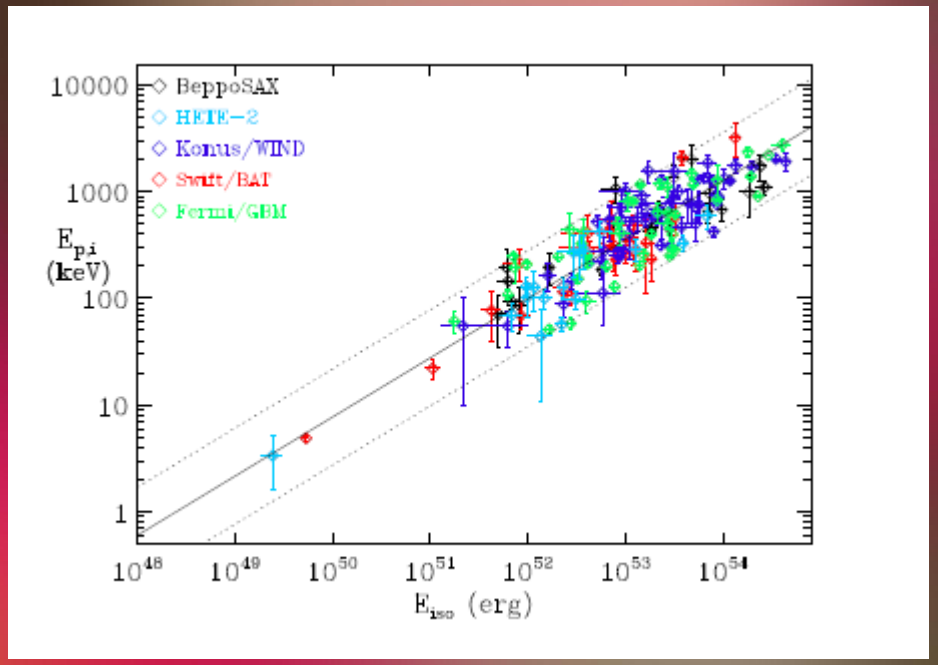
$$\left(\frac{E}{\overline{\nu}}\right)^{\beta},$$

$$\beta)E_0 \leq E$$

- E_0=break energy
- **$E_p = E_0 \times (2 + a)$ = peak energy of the nFn spectrum**

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \mathrm{erg}$$

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \mathrm{erg}$$



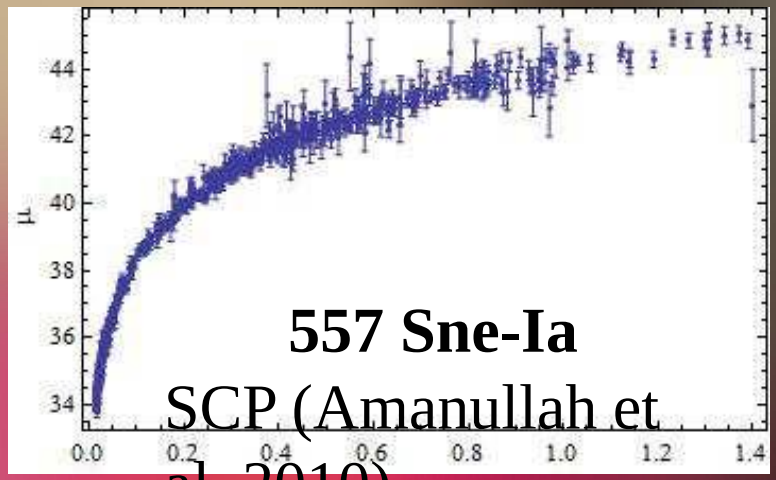
The Ep,i – Eiso correlation in long GRBs (as of the end of 2012). From L. Amati and M. Della Valle, 2013, International Journal of Modern Physics D,. 22, 1330028

Calibration with SNe-Ia

AMATI RELATION

$$\log\left(\frac{E_{iso}}{1\ erg}\right) = b + a\log\left[\frac{E_{peak}\ (1+z)}{300\ keV}\right]$$

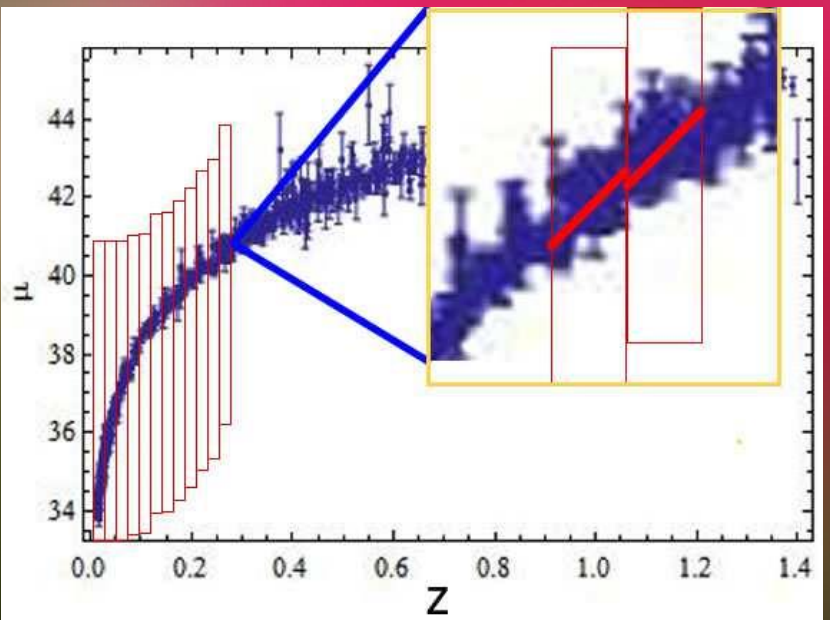
CALIBRATION PROCEDURE

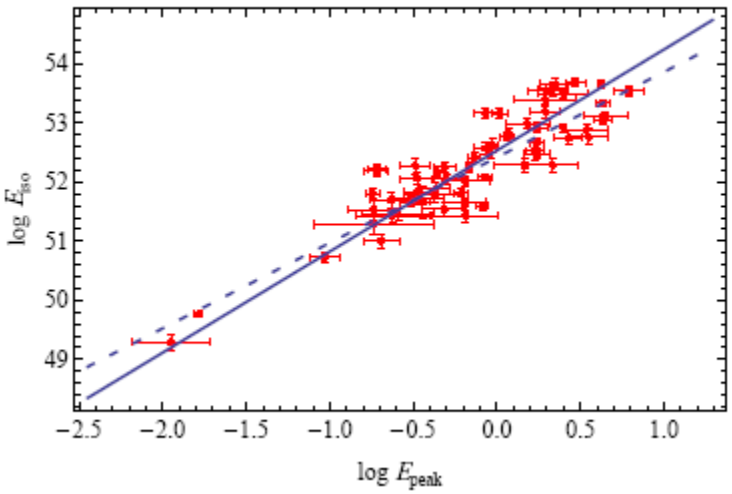


557 Sne-Ia

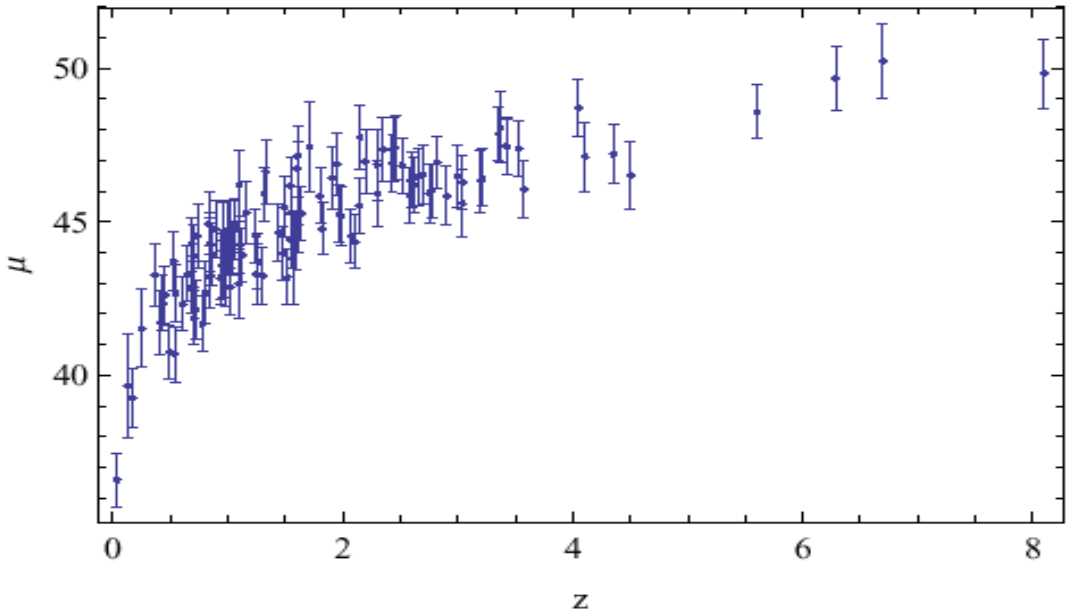
SCP (Amanullah et al. 2010)

We fit in each bin $\mu = \mu_0 + \alpha z$

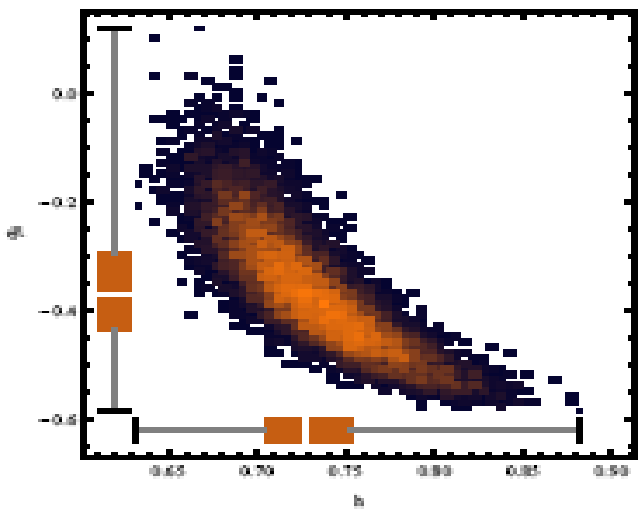


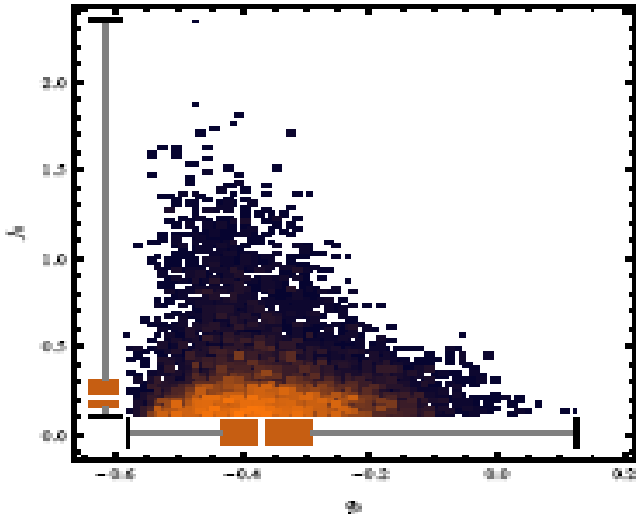


Best fit curves for the *E*p,i – *E*iso correlation relationn superimposed on the data. The solid and dashed lines refer to the results obtained with the maximum likelihood (*Reichart likelihood*) and weighted $\chi 2$ estimator respectively



Calibrated GRBs Hubble diagram made by fitting the Amati correlation

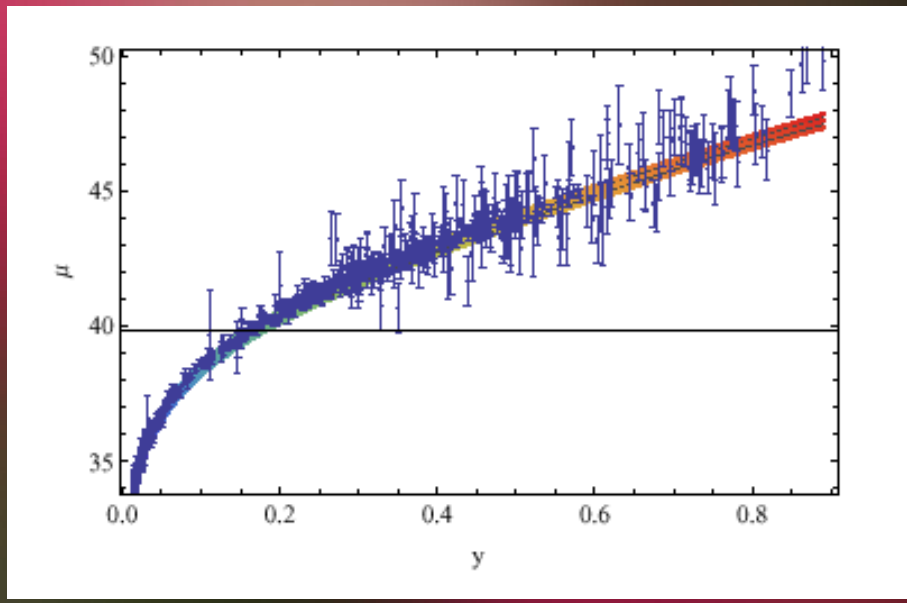




Confidence regions from Cosmography II

On the axes are plotted the box-and-whisker diagrams relatively to the different parameters: the bottom and top of the diagrams are the 25th and 75th percentile (the lower and upper quartiles, respectively), and the band near the middle of the box is the median

Cosmography II



Parameter	h	q_0	j_0	s_0	l_0
Best Fit	0.755	-0.462	0.134	0.696	-3.57
Mean	0.761	-0.471	0.258	0.164	-0.453
$2\ \sigma$	$(0.71, 0.81)$	$(-0.53, -0.40)$	$(0.105, 0.68)$	$(-0.996, 1.28)$	$(-8.23, 7.37)$

Cosmography I

Parameter	h	q_0	j_0	s_0	l_0
Best Fit	0.742	-0.406	0.86	29.767	-7.757
Mean	0.732	-0.359	0.28	20.33	1.044
$2\ \sigma$	$(0.67, 0.81)$	$(-0.53, -0.134)$	$(0.104, 0.95)$	$(-0.86, 29.72)$	$(-30.01, 29.95)$

Cosmography II

Parameter	h	q_0	j_0	s_0	l_0
Best Fit	0.74	-0.44	0.386	-0.719	3.82
Mean	0.713	-0.402	0.45	2.54	-24.1
$2\ \sigma$	$(0.68, 0.79)$	$(-0.50, -0.26)$	$(-0.73, 1.4)$	$(-1.3, 8.4)$	$(-72.0, 8.5)$

Cosmography III

M. Demianski, E. Piedipalumbo, C.rubano, P.Scudellaro,2012, MNRAS, 426, 1396-1415

Implications for dark energy

- the so-called Chevalier-Polarski Linder (CPL) model (Chevallier and Polarski 2001; Linder 2003).This parametrization assume a dark energy EOS given by

$$w(z) = w_0 + w_1 z (1+z)^{-1}$$

- a novel parametrization recently introduced in (Ma & Zhang 2011) to avoid the future divergency problem of the CPL parametrization, and to probe the dynamics of dark energy not only in the past evolution but also in the future evolution,

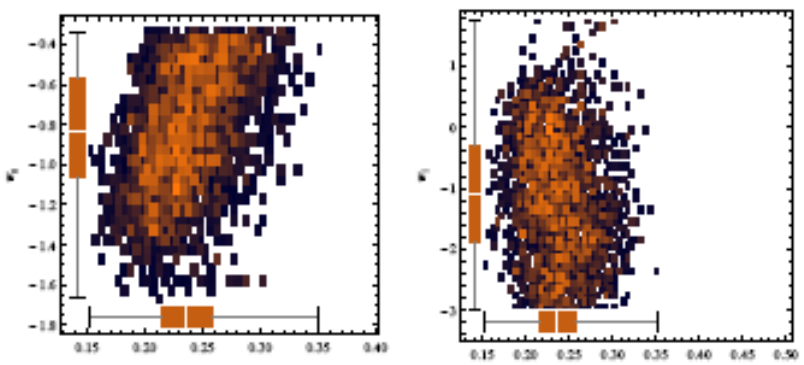
$$w(z) = w_0 + w_1 \left[\frac{\sin(z+1)}{z+1} - \sin(1) \right]$$

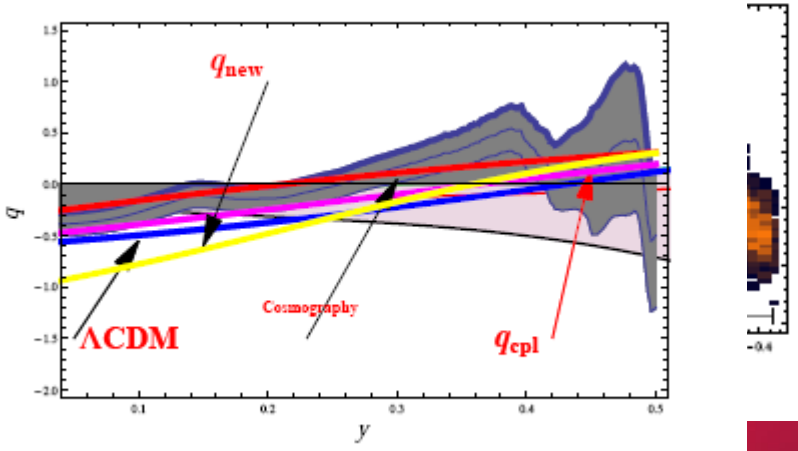
- an oscillating dark energy EOS recently discussed in (Lazkoz, Salzano and Sendra 2010)

$$w(z) = \frac{w_1 \left[1 - \cos(\delta \log(z+1))\right]}{\log(z+1)} + w_0 \,.$$

E. Piedipalumbo, E.Della Moglie, MF DE Laurentis, P.Scudellaro,2013, sub. to MNRAS

Implications for dark energy





Id	x_{bf}	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL
$w(z) = w_0 + w_1 z(1+z)^{-1}$					
Ω_M	0.225	0.238	0.237	(0.206, 0.272)	(0.183, 0.305)
h	0.732	0.714	0.713	(0.68, 0.745)	(0.659, 0.778)
w_0	-1.15	-0.832	-0.834	(-1.17, -0.476)	(-1.41, -0.36)
w_1	-0.99	-1.06	-1.05	(-2.2, 0.037)	(-2.8, 0.74)
$w_0 + w_1\left(\frac{\sin(z+1)}{z+1} - \sin(1)\right)$					
Ω_M	0.225	0.235	0.234	(0.205, 0.264)	(0.182, 0.294)
h	0.735	0.72	0.72	(0.69, 0.75)	(0.66, 0.78)
w_0	-1.01	-0.96	-1.0	(-1.23, -0.742)	(-1.43, -0.493)
w_1	0.14	0.88	0.82	(-0.27, 2.1)	(-1.18, 2.8)
$w(z) = \frac{w_1(1-\cos(\delta \log(z+1)))}{\log(z+1)} + w_0$					
Ω_M	0.15	0.154	0.153	(0.15, 0.21)	(0.13, 0.24)
h	0.7	0.73	0.73	(0.72, 0.75)	(0.7, 0.78)
w_0	-1.55	-1.54	-1.55	(-1.59, -1.48)	(-1.66, -1.45)
w_1	0.45	0.47	0.37	(0.07, 0.78)	(0.013, 1.9)
δ	0.76	0.66	0.62	(0.54, 0.8)	(0.5, 1.1)

Constraints from Cosmography

$$H(z)=H_0\sqrt{(1-\Omega_m)g(z)+\Omega_m(z+1)^3}\,,$$

$$H_d(z)=-(z+1)H(z)H'(z)\,,$$

$$H_{2d}(z)=-(1+z)H(z)H'_d(z)\,,$$

$$H_{3d}(z)=-(1+z)H(z)H'_{2d}(z)\,,$$

$$H_{4d}(z)=-(1+z)H(z)H'_{3d}(z)\,,$$

where $g(z)=\exp^{3\int_0^z \frac{w(x)+1}{x+1}\,dx}$, and $w(z)$ any para

$$\lim_{z->0} H_d(z)=-H_0\,(1+q_0)\,,$$

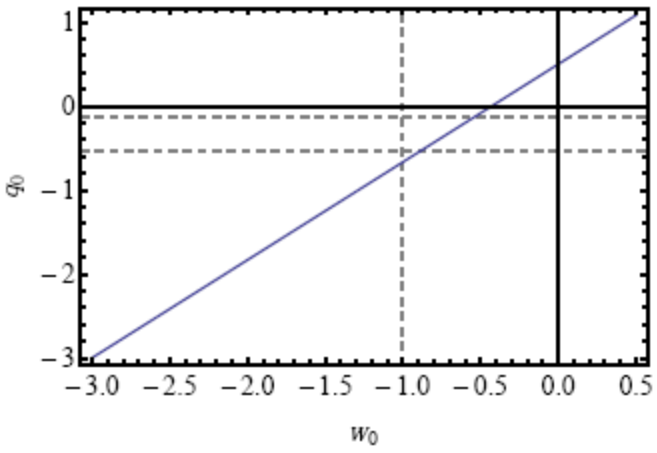
$$\lim_{z->0} H_{2d}(z)=H_0^3\,(j_0+3q_0+2)\,,$$

- The correspondence is:

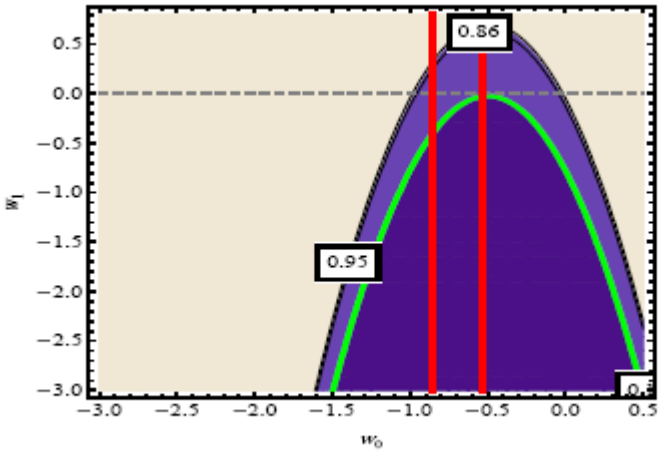
$$q_0=\frac{1}{2}+\frac{3}{2}(1-\Omega_m)w_0$$

$$j_0=1+\frac{3}{2}(1-\Omega_M)\,[3w_0(1+w_0)+w_1]$$

$$s_0=-\frac{7}{2}-\frac{33}{4}(1-\Omega_m)w_1-\frac{9}{4}(1-\Omega_M)\,[9+(7-\Omega_M)w_1]\,w_0$$
$$-\frac{9}{4}(1-\Omega_M)(16-3\Omega_M)w_0^2\frac{27}{4}(1-\Omega_M)(3-\Omega_M)w_0^3$$



Behaviour of q_0 as function of w_0 for $\Omega_m = 0.237$. The horizontal dashed lines correspond to the 2 σ range of confidence for q_0.

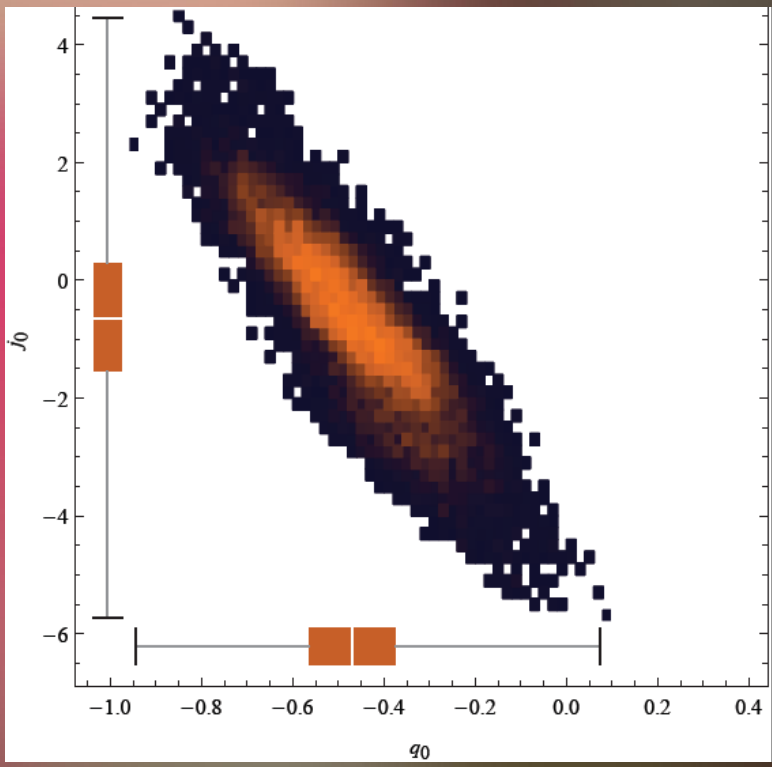


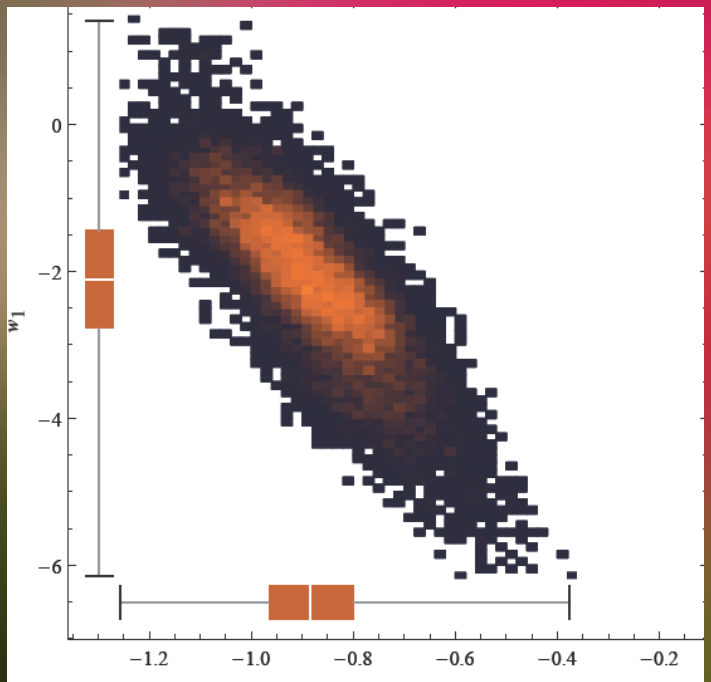
Contour plot of j_0 in the plane w_0- w_1 for a CPL EOS and $\Omega_m = 0.237$.

New results from cosmography

A new Gamma ray Bursts sample(Amati relation 162 data)

- Baryon Acoustic Oscillations
- CMB WMAP-7





L.Amati, M. Demianski E. Piedipalumbo,D. Sawant,, MF DE Laurentis, preliminary results…..work in progress

Stronger Constraints from Padè approximants

H. Padé
(1863-1953)
Student of Hermite
His thesis won
French Academy of
Sciences Prize

C. Hermite
(1822-1901)
Used Padé
approximants
to prove that e
is trancendental

But origins of subject go back to Cauchy, Jacobi, Frobenius.

Idea of PA: Given m, n

Rational function $R = P/Q$

$$\deg P \le m\,, \quad \deg Q \le n$$

Choose P, Q so that

$$(f - R)(z) = \mathcal{O}\left(z^l\right)\,,$$

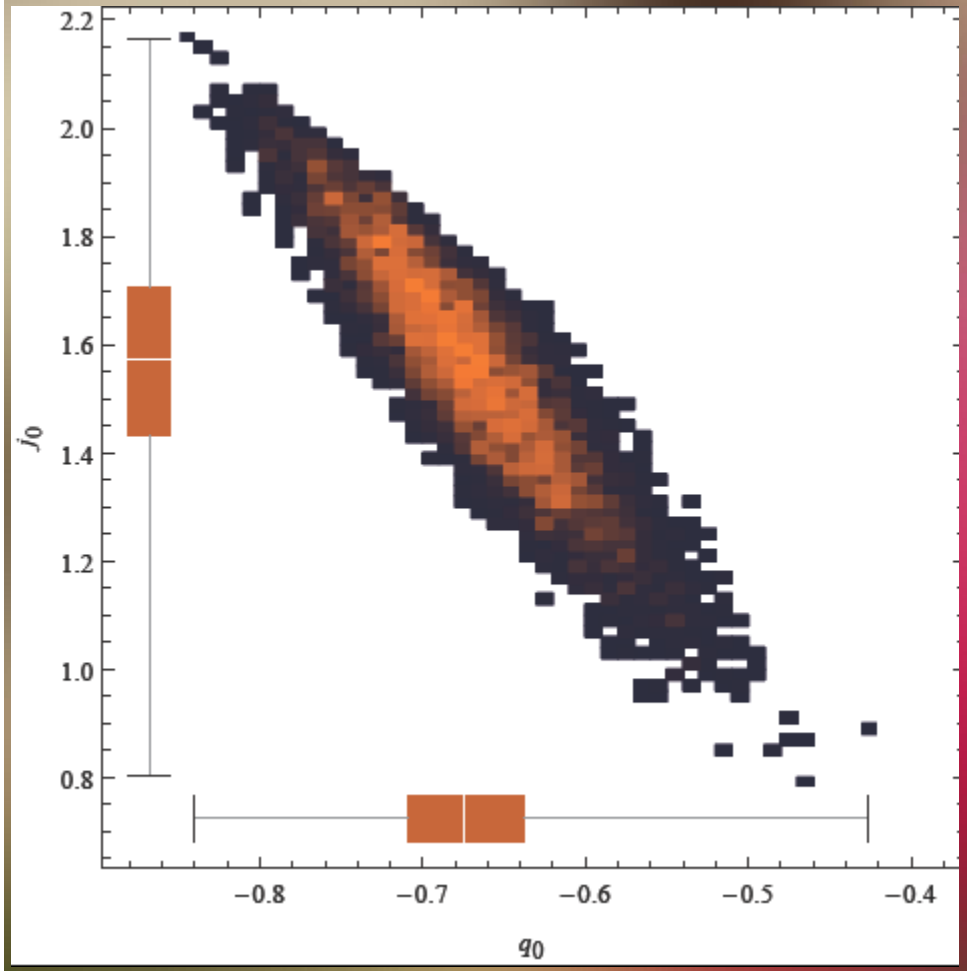
l as large as possible.

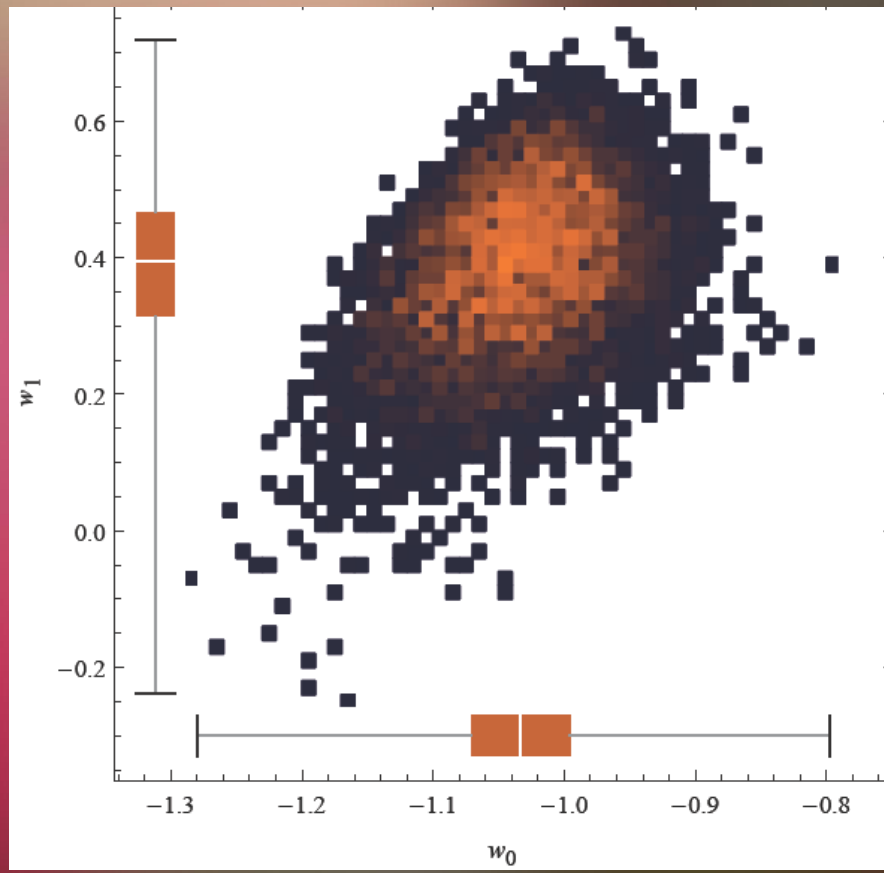
How large can we expect l to be?

P	has	$m+1$	parameters
Q	has	$n+1$	parameters
P/Q	has	-1	parameter
So total	of	$m+n+1$	parameters

Expect: $\left(f - \dfrac{P}{Q}\right)(z) = \mathcal{O}\left(z^{m+n+1}\right)$.

Stronger Constraints from Padè approximants





L.Amati, M. Demianski E. Piedipalumbo,D. Sawant,, MF DE Laurentis, preliminary results…..work in progress

Conclusions

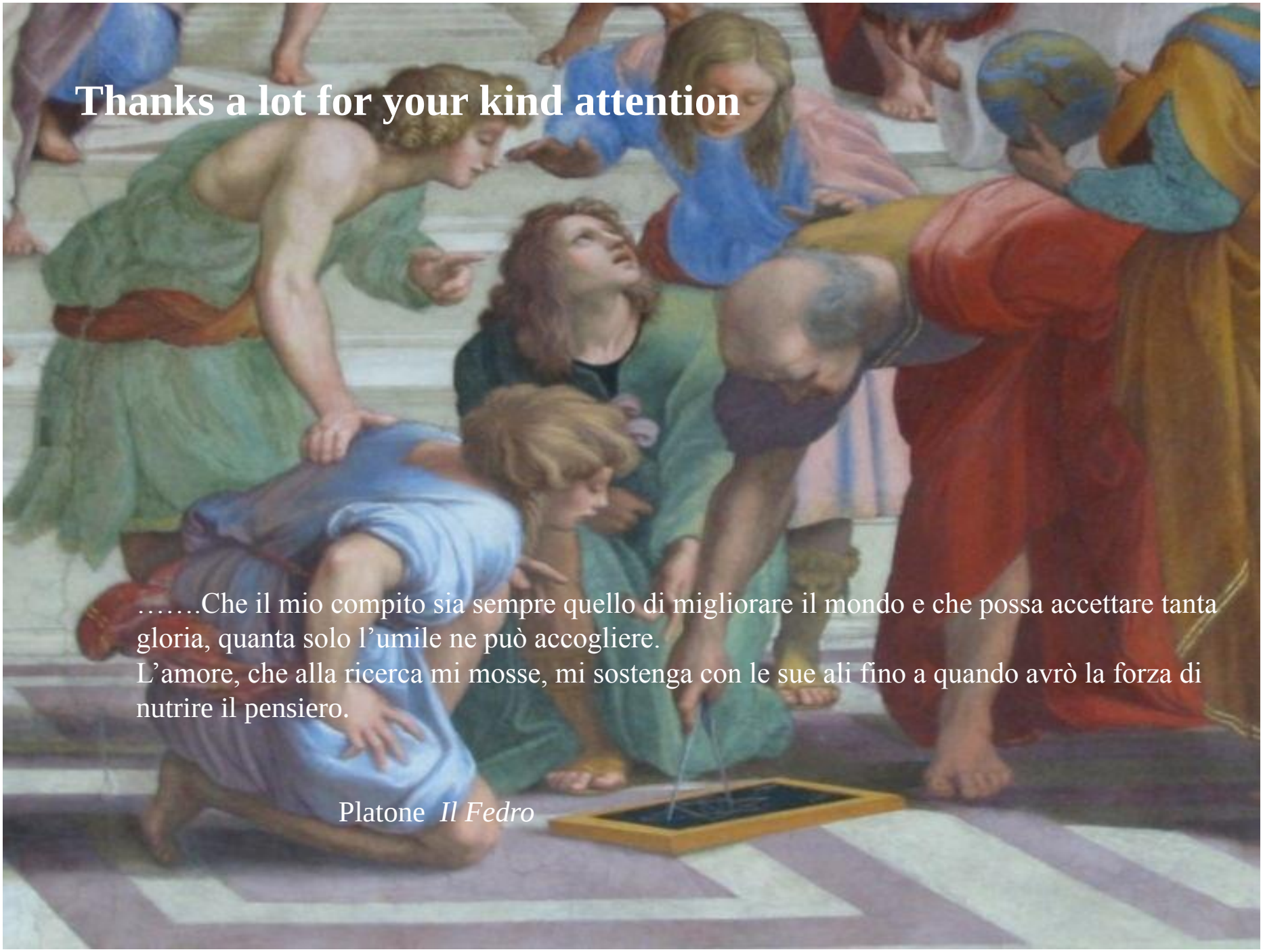
- The ΛCDM model is only marginally consistent with the data
- Dark energy equation of state evolve in time GRBs open up a new possibilities to constrain cosmological models
- GRbs Hd are important for the Cosmography And the investiigation on EOS

Conclusions (II)

- Cosmology is not finished……..and is not few numbers

Verum est totum

Thanks a lot for your kind attention



…….Che il mio compito sia sempre quello di migliorare il mondo e che possa accettare tanta gloria, quanta solo l'umile ne può accogliere.
L'amore, che alla ricerca mi mosse, mi sostenga con le sue ali fino a quando avrò la forza di nutrire il pensiero.

Platone *Il Fedro*