Cosmology codes on Mathematica

...or cosmology comes to the 21st century

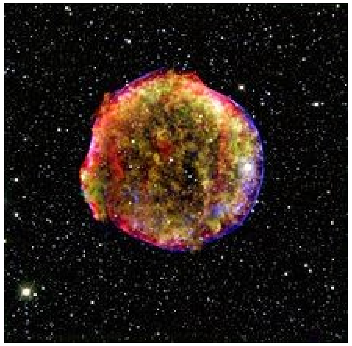
Savvas Nesseris

Juan Garcia-Bellido

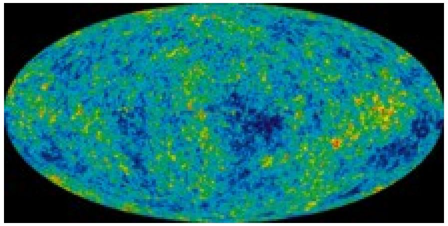
IFT/University of Madrid, Madrid, Spain

Data used in the code

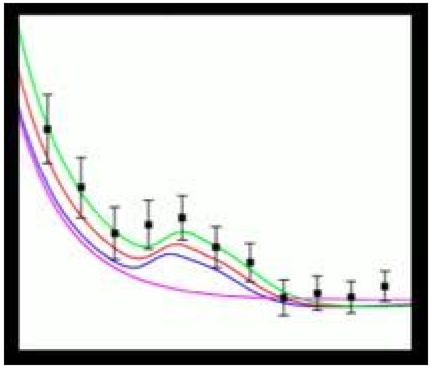
SnIa



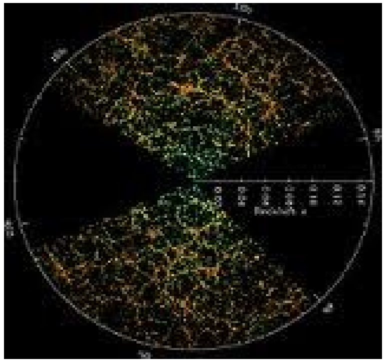
CMB



BAO



Growth-rate



Data used in the code

1) 580 SnIa points from Union 2.1

- SnIa data are given in terms of the distance modulus:

$$\mu_{obs}(z_i) \equiv m_{obs}(z_i) - M$$

- DE is described by w(z)

$w(z) \equiv \frac{P}{\rho}$

$$w(z) = -1 + \frac{1}{3}(1+z)\frac{d\ln(\delta H(z)^2)}{d\ln z}$$

$$\delta H(z)^2 = H(z)^2/H_0^2 - \Omega_{0\rm m}(1+z)^3$$

- Theoretical prediction:

(For FRW // Both flat & non-flat Univ. are supported)

$$D_L(z) = (1+z)\int_0^z dz' \frac{H_0}{H(z';\Omega_{0\rm m}, w_0, w_1)}$$

$$\mu_{th}(z_i) \equiv m_{th}(z_i) - M = 5log_{10}(D_L(z)) + \mu_0$$

$$\mu_0 = 42.38 - 5log_{10}h$$

- Minimize to find the best fit parameters:

$$\chi^2_{SnIa}(\Omega_{0\rm m}, w_0, w_1) = \sum_{i=1}^{N} \frac{(\mu_{obs}(z_i) - \mu_{th}(z_i))^2}{\sigma^2_{\mu\ i}}$$

Data used in the code

2) The BAO data:

	6dF	SDSS		WiggleZ		
z	0.106	0.2	0.35	0.44	0.6	0.73
d_z	0.336	0.1905	0.1097	0.0916	0.0726	0.0592
Δd_z	0.015	0.0061	0.0036	0.0071	0.0034	0.0032

$$C_{ij}^{-1} = \begin{pmatrix} 4444 & 0. & 0. & 0. & 0. & 0. \\ 0. & 30318 & -17312 & 0. & 0. & 0. \\ 0. & -17312 & 87046 & 0. & 0. & 0. \\ 0. & 0. & 0. & 23857 & -22747 & 10586 \\ 0. & 0. & 0. & -22747 & 128729 & -59907 \\ 0. & 0. & 0. & 10586 & -59907 & 125536 \end{pmatrix}$$

$$d_z(z) = \frac{l_{BAO}(z_{drag})}{D_V(z)}$$ **where** $$D_V(z) = \left((1+z)^2 D_A(z)^2 \frac{c\,z}{H(z)}\right)^{1/3}$$

See Nesseris, Garcia-Bellido 1205.0364 for Refs.

3) The growth rate data in terms of fσ8:

$$f\sigma8(z) \equiv f(z)\cdot\sigma_8(z)$$

$$f(a) = \frac{d\ln\delta_m}{d\ln a}$$

$$\sigma_8(z) = \sigma_8(z=0)\frac{\delta_m(z)}{\delta_m(z=0)}$$

$$\delta_m \equiv \frac{\delta\rho_m}{\rho_m} \longrightarrow \ddot{\delta} + 2H\dot{\delta} = 4\pi G_N \rho_m \delta\rho_m$$

Models with G_N=>Geff(a,k) are also supported!

z	$f\sigma8_{obs}$
0.17	0.510 ± 0.060
0.35	0.440 ± 0.050
0.77	0.490 ± 0.180
0.25	0.351 ± 0.058
0.37	0.460 ± 0.038
0.22	0.420 ± 0.070
0.41	0.450 ± 0.040
0.60	0.430 ± 0.040
0.78	0.380 ± 0.040
0.30	0.407 ± 0.055
0.40	0.419 ± 0.041
0.50	0.427 ± 0.043
0.60	0.433 ± 0.067
0.57	0.451 ± 0.025

Data used in the code

4) The CMB shift parameters

$$R \equiv \sqrt{\Omega_m H_0^2}\, r(z_*)/c,$$
$$l_a \equiv \pi r(z_*)/r_s(z_*),$$
$$\omega_b \equiv \Omega_b h^2$$

Comoving distance

$$r(z) = cH_0^{-1}\, |\Omega_k|^{-1/2} \mathrm{sinn}[|\Omega_k|^{1/2}\, \Gamma(z)]$$
$$\Gamma(z) = \int_0^z \frac{dz'}{E(z')}, \qquad E(z) = H(z)/H_0$$

Horizon scale

$$r_s(z) = \int_0^t \frac{c_s\, dt'}{a} = cH_0^{-1} \int_z^\infty dz'\, \frac{c_s}{E(z')},$$
$$= cH_0^{-1} \int_0^a \frac{da'}{\sqrt{3(1+\overline{R_b}\, a')\, a'^4 E^2(z')}},$$

Wang, 1304.4514

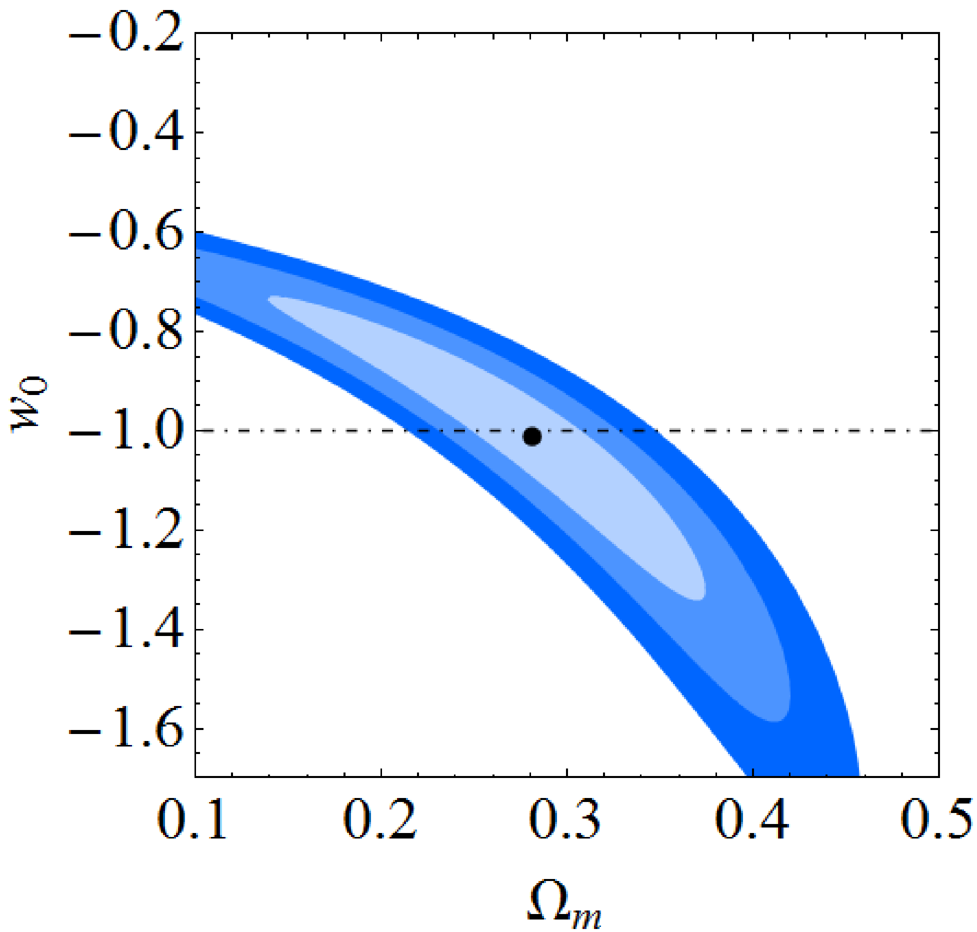
$$\langle l_a \rangle = 301.57, \sigma(l_a) = 0.18$$
$$\langle R \rangle = 1.7407, \sigma(R) = 0.0094$$
$$\langle \omega_b \rangle = 0.02228, \sigma(\omega_b) = 0.00030$$

$$\begin{pmatrix} 1.0000 & 0.5250 & -0.4235 \\ 0.5250 & 1.0000 & -0.6925 \\ -0.4235 & -0.6925 & 1.0000 \end{pmatrix}$$

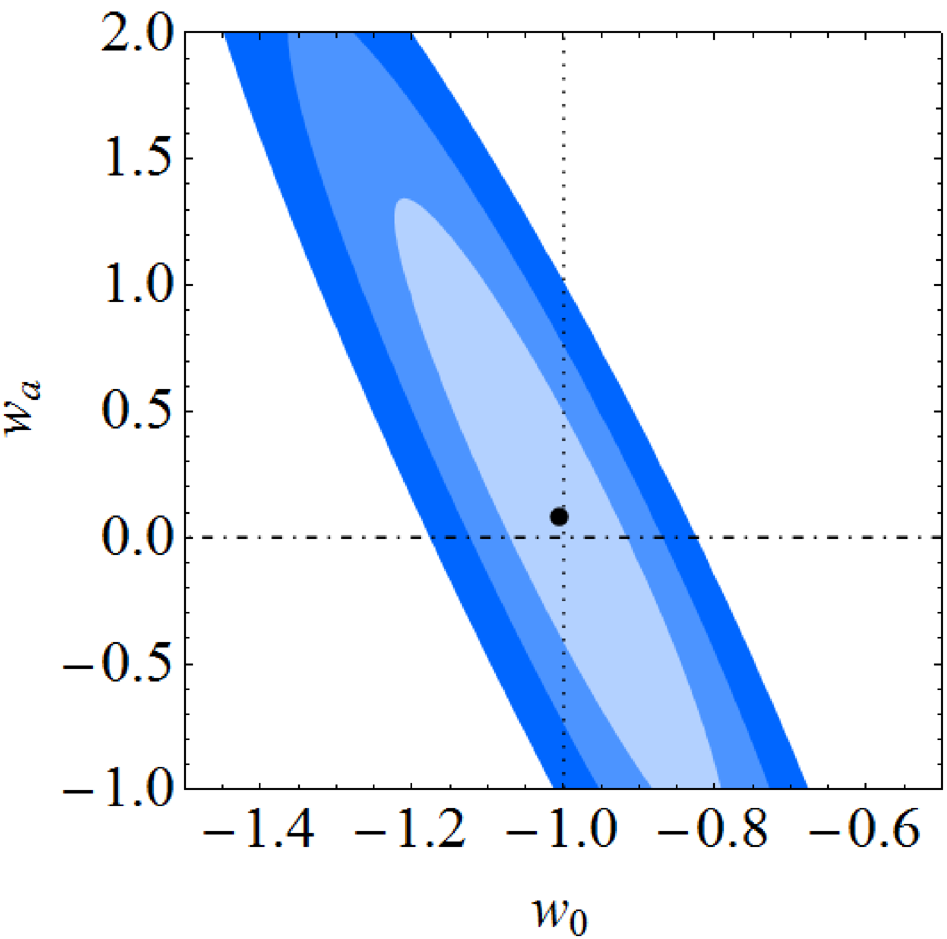
Normalized cov. matrix

Example plots

1) SnIa, Ωm vs w



2) SnIa, w0 vs w1



Plots + best-fits + errors in ~5 mins!!!!

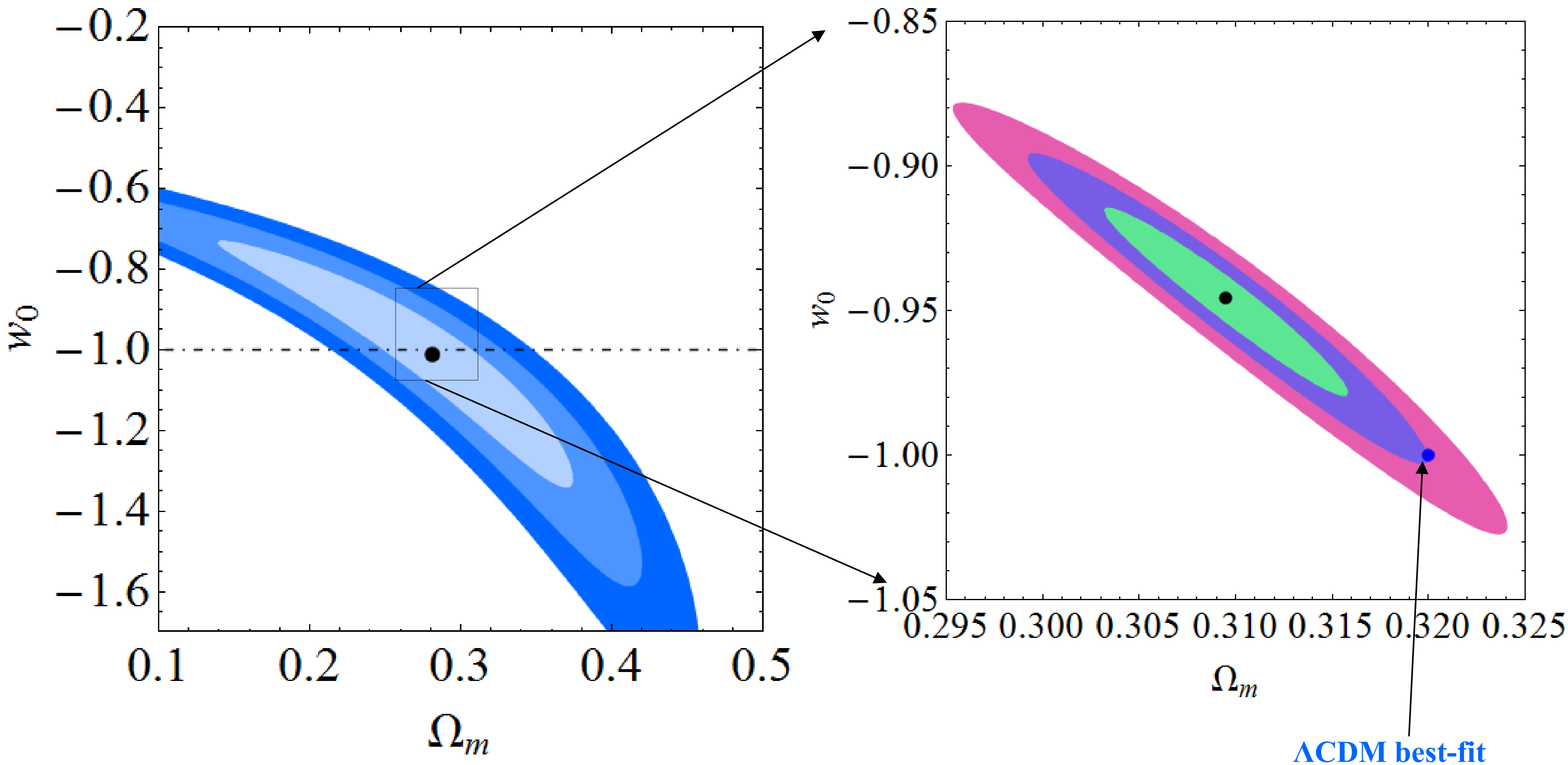
Errors and covariances come from Fisher-matrix approach. MCMC code under construction!

Example plots

1) SnIa, Ω_m vs w

3) All data (Planck etc), Ω_m vs w

(notice the improvement!)



Plots + best-fits + errors in ~5 mins!!!!

Marginalized plots coming in the next version!

Advantages of the code

1) Runs in Mathematica, no need to compile for different environments, no need to worry for compilers etc. License for Mathematica already available in most places.

2) Very easy to upgrade to other/better data, also easy to add new data (just add the chi^2!)

3) Easy to add new models, change assumptions, by modifying a few lines of code. No need to recompile and install!

4) Makes nice plots quite easily, with zero effort.

5) Very fast, no difference with native C/C++ code. Really!!!

6) Full MCMC code and likelihood sampler under construction!!!

7) Various versions of the code have been used in several publications over the years:

Nesseris et al 1309.1055, 1308.6142, 1302.6051, 1203.6760, 1010.0407, 0910.3949, 0908.2636, 0712.1232, astro-ph/0602053, astro-ph/0401556

Downloads

Available at:

www.uam.es/savvas.nesseris

Savvas Nesseris Home Research Gallery Education

In this part I will try to explain several key issues in data analysis and statistics with the use of explicit examples and numerical codes. Most of the following material is intended for master and fledgling PhD students who want to understand the basics of data analysis with a focus on cosmology and want to enter the world of research. However, some of the examples might be a bit more advanced...

Prerequisites:
1) Study Chapter 15 of Numerical Recipes regarding data-fitting, minimization, MCMC, statistics etc **[1]**, see also **[2]**.
2) Download the Mathematica codes found below and that illustrate several key issues, like minimization and basic statistical analysis, contours, MCMC, Fourier analysis, parallelization (CPU/GPU) etc.
3) Get CAMB from **here** and follow the instructions in the **Readme** to compile and install it. Gfortran 4.5+ is highly recommended.
4) Run the codes and try to understand what's going on and most importantly *why*.

Numerical codes: (right-click on "Download" and hit "Save as")
1) Statistical Significance and Sigmas. **Download**.
2) Stuff about covariance matrices. **Download**.
3) Data fitting, contours, error bars etc. **Download**.
4) Markov Chain Monte Carlo (MCMC). **Download**.
5) Bootstrap Monte Carlo. **Download**.
6) The Jack-knife **[3]**. **Download**.
7) Genetic Algorithms **[4]**. **Download**.
8) A Mathematica Interface for CosmoMC, go **here**.
9a) Fitting the SnIa data (standard) **[5]** **Download**.
9b) Fitting the SnIa data (**ultra-fast**) **[5]** **Download**.
10) Joint SnIa, CMB, BAO and growth-rate likelihood! (**ultra-fast**) **Download**.
11) Parallelization CPU/GPU (coming soon).
12) The CMB power spectrum and the cosmological parameters; the correlation function (no RSD) **Download**.

Also, have a look at some other cool stuff...

To-do list...

1) Extensions planned in the near future:

i) Finish the MCMC sampler (right now at 95%).

ii) Do thorough tests on the code.

iii) Full Planck likelihood (hopefully next month), full test against CMB shift params.

iv) Newer SnIa, BAO, growth rate data as they become available.

2) Other stuff:

i) Add more data relevant to DES.

ii) Test on different platforms.