UNIVERSIDAD DE CÓRDOBA

Bayesian estimation of cosmological parameters with CosmoMC & MontePython

Antonio J. Cuesta
Universidad de Córdoba, Spain

Cosmology School in the Canary Islands, Fuerteventura 18/09/2017

Outline
(keeping it simple...)

- Motivation & Initial remarks
- Generic steps when running MCMC's
- Introduction to MontePython
- Introduction to CosmoMC

Introduction & Motivation

What is all this about?

- Cosmological models have parameters (matter density Ω_m, Hubble constant H_0, ...)
  For example, ΛCDM = { $\Omega_b h^2$, $\Omega_c h^2$, H_0 (or θ_s) , A_s (or $\ln 10^{10} A_s$), n_s , τ_{reio} }
- We want to know the value and the error of those parameters (mean and rms).
- Ideally, we want the full probability distribution function (pdf) for each parameter, and even the full joint distribution for all the parameters together $P(\theta_1,\theta_2,\theta_3,...)$
- The limits on the possible values of those parameters (1sigma=68.3% confidence, 2sigma=95.4%, 3sigma=99.7%...) can be obtained in a Bayesian way, in which the prior knowledge of the parameters will play an important role $P(\theta|\mathbf{x})=P(\theta)\mathscr{L}(\mathbf{x}|\theta)$

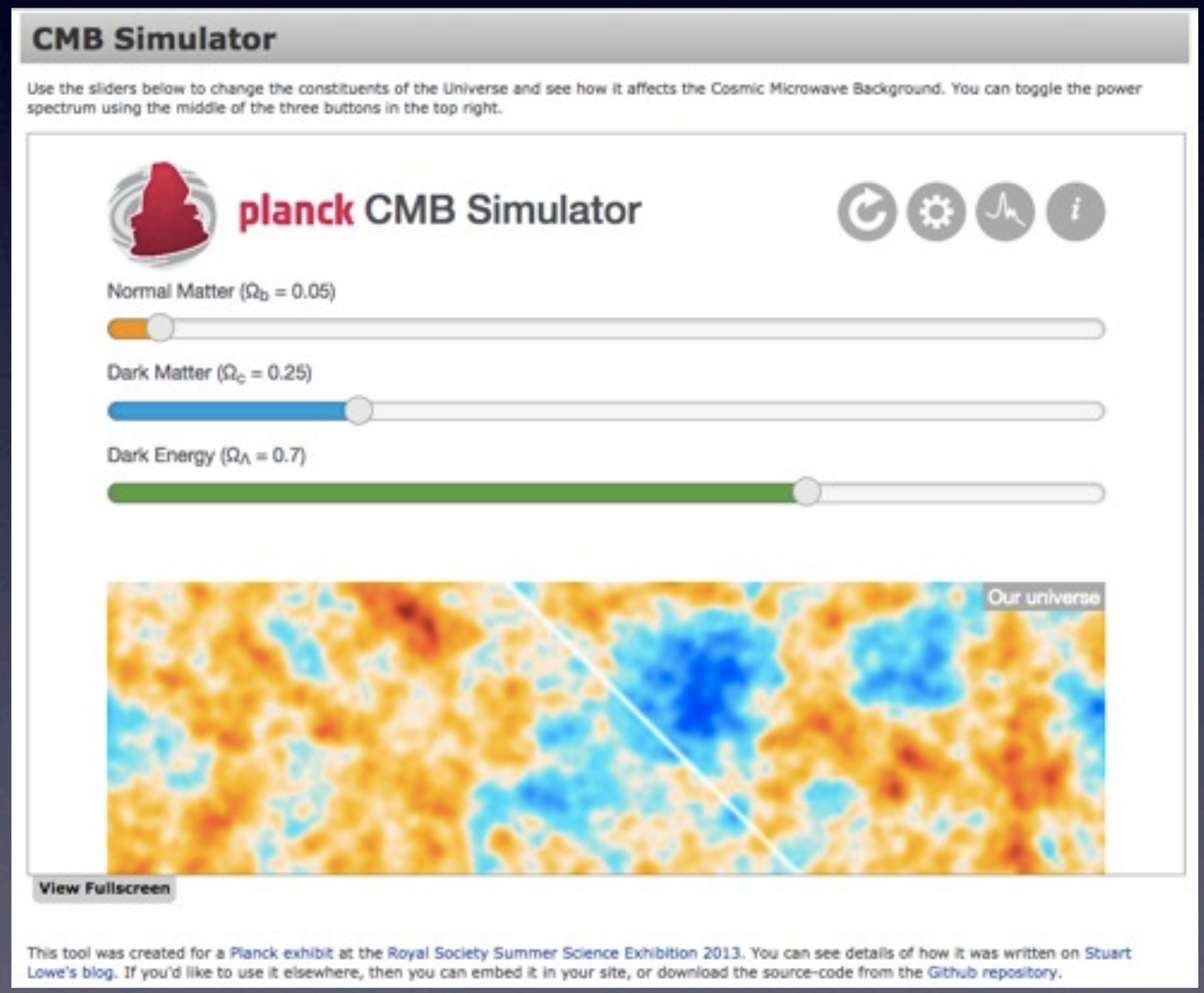
What is all this about?

- The resulting constraints on each parameter will depend on these two ingredients:
  the DATA you input (each experiment targets a different cosmological probe)
  the MODEL studied (each model contains a different number of free parameters)

- In general, a model with *more* free parameters will usually provide *weaker* constraints, but also provides a better fit: more parameters can accommodate more features, (hence returning a lower χ^2) although not necessarily will improve the *bayesian evidence*

Cosmological parameter estimation

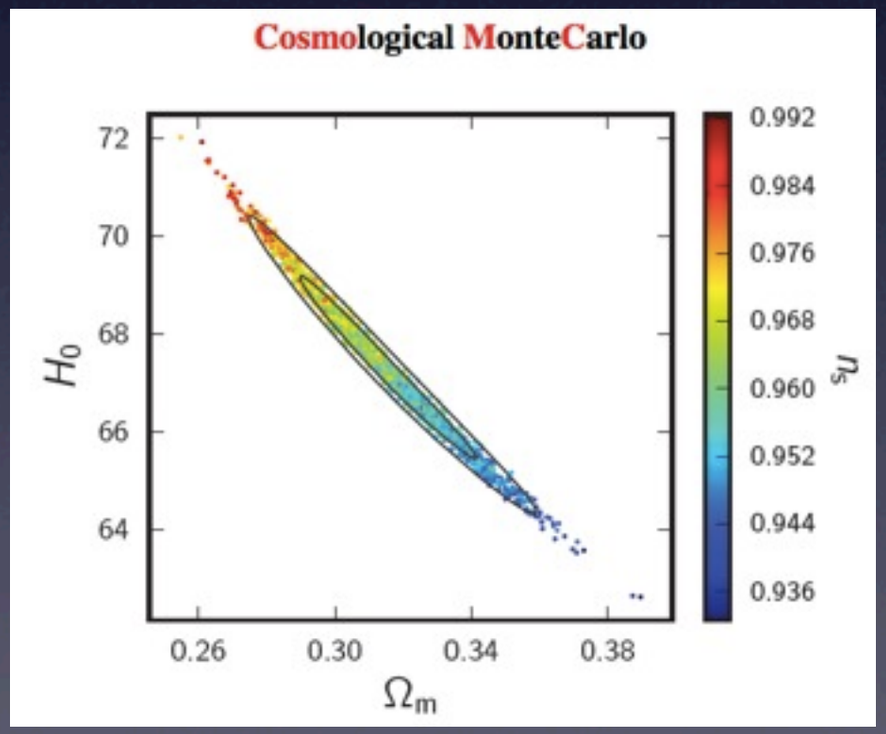
You can estimate parameters by eye (not recommended)...



http://planck.cf.ac.uk/cmb-sim

Cosmological parameter estimation

Or we can estimate parameters *quantitatively*
In cosmology there are two major codes for this:
CosmoMC and MontePython (& Cosmosis, PICO,...)



Monte Python

The Monte Carlo code for CLASS in Python

http://cosmologist.info/cosmomc/

http://baudren.github.io/montepython.html

Why CosmoMC?

- It has been used in many papers!
  (2000+ citations to Lewis & Bridle 2002)
- Usually new data (likelihood codes)
  are typically available first in CosmoMC
- It has a GUI to analyze the chains!!
  (but you can use it for MontePython chains too)
- Its Boltzmann solver, CAMB (based on CMBFAST)
  has been extensively used for a long time
- Lots of tools to run this code in a cluster
  Capabilities to run batches of models, MPI/OpenMP parallelization

Why MontePython?

- It is very easy to get started!
  (we'll see that in the afternoon hands-on session)
- It is written in Python:
  the code is easy to read and easy to modify
- Its Boltzmann solver (the code to compute the evolution of perturbations) is CLASS: (or hi-class)
  a direct transcript of the equations in astro-ph/9506072 (Ma & Bertschinger 1995)
  very well commented, so less pain to implement new physics (if not already built-in)
- It is completely agnostic about cosmology:
  if you define a new parameter in CLASS, you don't need to modify MontePython

Running Markov Chain Monte Carlo (MCMC)

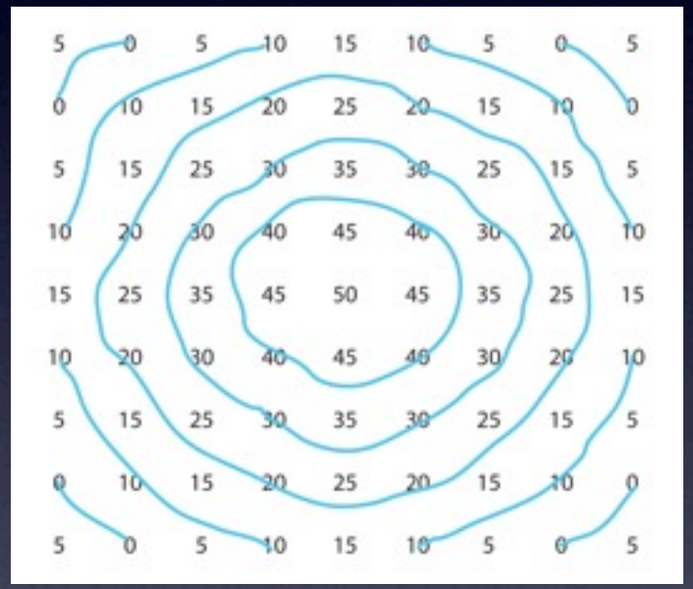
MCMC: How-To?

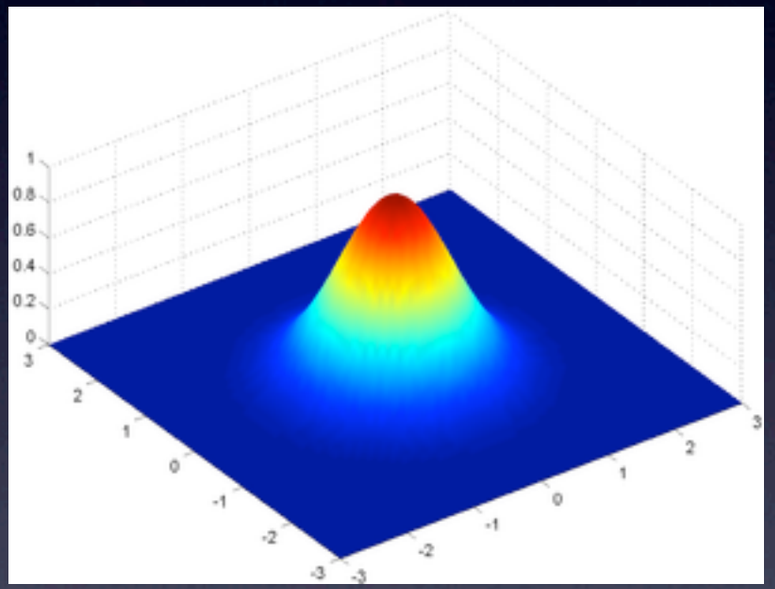
Breaking the code into individual tasks

- Step 1: Choose a point in the parameter space (*walk* the parameter space)
- Step 2: Solve the Boltzmann equations for those values of the parameters which are translated into the observables P(k), D(z), C_ℓ ...
- Step 3: Evaluate the likelihood of this point for each dataset (CMB, BAO, SNe...) by comparing observables with the measurements (evaluation of χ^2)
- Step 4: Compute the total likelihood, and Accept the point if the likelihood is larger (-lnlike smaller), or reject it otherwise, then move to another point (step1)
- Step 5: After you have RUN the chains (i.e. after getting enough points to sample the posterior distribution) the final step is to do an ANALYSIS of the results

Step 1: walk a parameter space (low-*d* case)

- If the number of dimensions d is small (1D or 2D), then a grid (discretized) would suffice, but this is not true in cosmology (even ΛCDM has already 6 parameters)

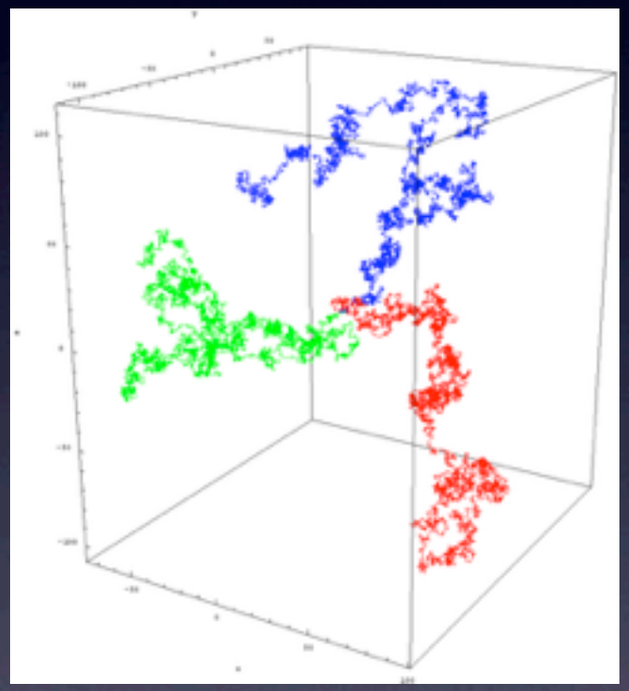


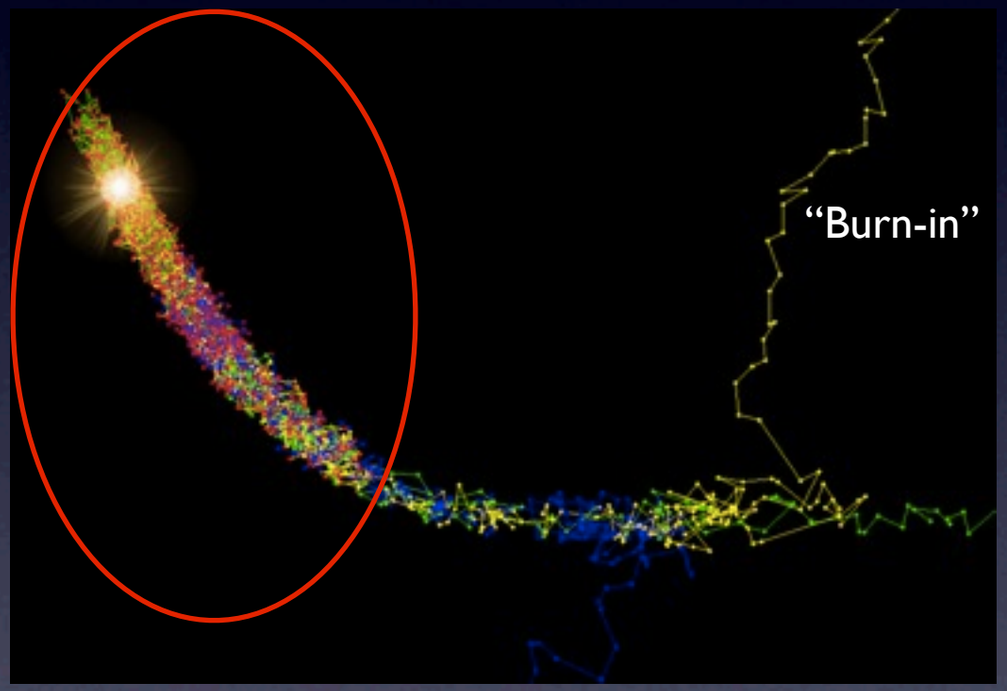


- Number of (potentially) visited points: N^d (grows exponentially with *d*).
  N depends on how fine the spatial discretization (resolution) you want it to be.
  Usually one computes the distribution in all the points (even away from the peak).

Step I: walk a parameter space (high-*d* case)

- If the number of dimensions is large, it is not feasible nor efficient to do a grid





unimodal distribution → different initial conditions will converge to the same region

- It is better to do a *random walk*, in which there is some kind of "dragging force" towards the high likelihood region plus a thermal bath to move around the peak (the goal is not to find the maximum -- it is to sample points from the distribution)

The Metropolis-Hastings algorithm

This is exactly what the Metropolis-Hastings algorithm does:

If you are at location x, pick a location y (within some search radius from x):

- If P(y) > P(x), jump there, and store y in the list of visited points
- If P(y) < P(x), then pick a uniform random number r between 0 and 1:
  - If r < P(y)/P(x), jump there, and store y to the list of visited points
  - If r > P(y)/P(x), do not jump there, and store x (again) to the list of visited points

Cycle over this loop until you get enough points (~10^5), or better, until a *convergence criterion* is achieved (see next slide)

Remember: In general x and y will be *d*-dimensional vectors, with as many components as parameters you want to determine

When MCMC is considered "converged"?

- The most common criterion is the R diagnostic by Gelman & Rubin (1992).
  This diagnostic is defined for each parameter, so we focus on a single parameter θ.
- Suppose all chains have length *N* (each chain has *N* steps) and we have run *M* chains.
- Each chain "*m*" will return a different mean μ_m and variance σ^2_m for the parameter θ.
- The variance of the means μ_m (times *N*) is called the variance "between chains" *B*.
- The mean of the variances σ^2_m is called the variance "within chains" *W*.
- The R parameter is then defined as (see Brooks & Gelman 2007 for exact formulae):

$$\hat{R} = \sqrt{1 + (1/N)(B/W)}$$

So when all chains return roughly the same μ_m & σ_m if the Central Limit Theorem applies (so $B \simeq W$) we have that *R-1* goes to zero as *N* goes to ∞

Typically, a *R-1* value of <0.03 (ideally <0.01) for all parameters is considered good enough

Step 2: Solve the Boltzmann equations

(already covered in the previous sessions...)

- CAMB and CLASS are written to solve efficiently the evolution of each component (baryons, neutrinos, photons, dark matter, dark energy, metric...)

Synchronous gauge —

$$\dot{\delta} = -(1+w)\left(\theta+\frac{\dot{h}}{2}\right)-3\frac{\dot{a}}{a}\left(\frac{\delta P}{\delta\rho}-w\right)\delta\,,$$

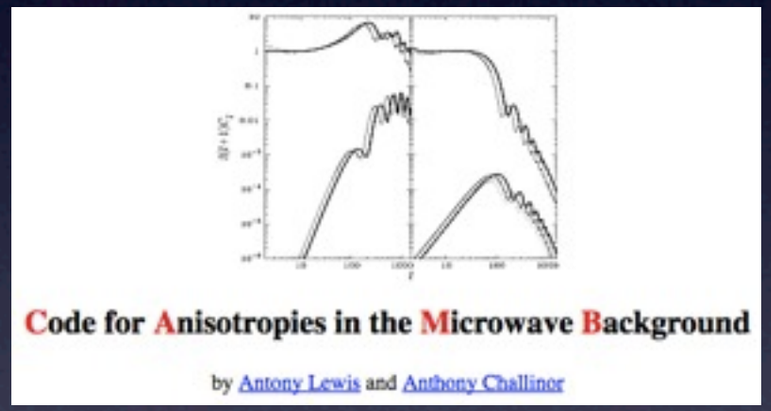
$$\dot{\theta} = -\frac{\dot{a}}{a}(1-3w)\theta-\frac{\dot{w}}{1+w}\theta+\frac{\delta P/\delta\rho}{1+w}k^2\delta-k^2\sigma\,,$$

Conformal Newtonian gauge —

$$\dot{\delta} = -(1+w)\left(\theta-3\dot{\phi}\right)-3\frac{\dot{a}}{a}\left(\frac{\delta P}{\delta\rho}-w\right)\delta\,,$$

$$\dot{\theta} = -\frac{\dot{a}}{a}(1-3w)\theta-\frac{\dot{w}}{1+w}\theta+\frac{\delta P/\delta\rho}{1+w}k^2\delta-k^2\sigma+k^2\psi\,.$$

and many others...



http://camb.info/

http://www.hiclass-code.net/

http://class-code.net/

- This is the part of the code you do not have to worry about (UNLESS you want to constrain non-standard cosmologies, which YOU will have to implement)

Step 3: Evaluate the likelihood(s)

parameter values at this MCMC step

Likelihood code

likelihood value or chi-squared value

$$\vec{x} \xrightarrow{\mathscr{L}} \chi^2$$

H_0 Ω_b Ω_m n_s τ A_s

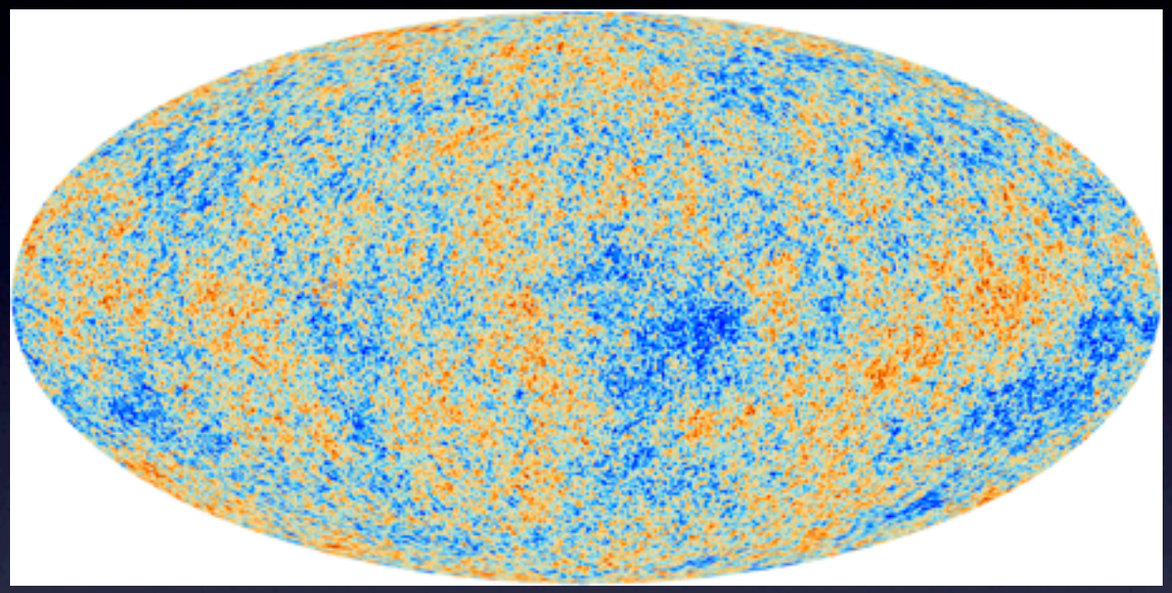
$$\chi^2 = \left(\frac{\text{theory value} - \text{measured value}}{\text{measured error}} \right)^2$$

CosmoMC and MontePython will report -ln (likelihood) = $\chi^2/2$ (Gaussian case, Wick's Theorem)

Here "value" can be a MCMC parameter (e.g. H_0) or a function of them (an observable, like P(k) or σ_8)

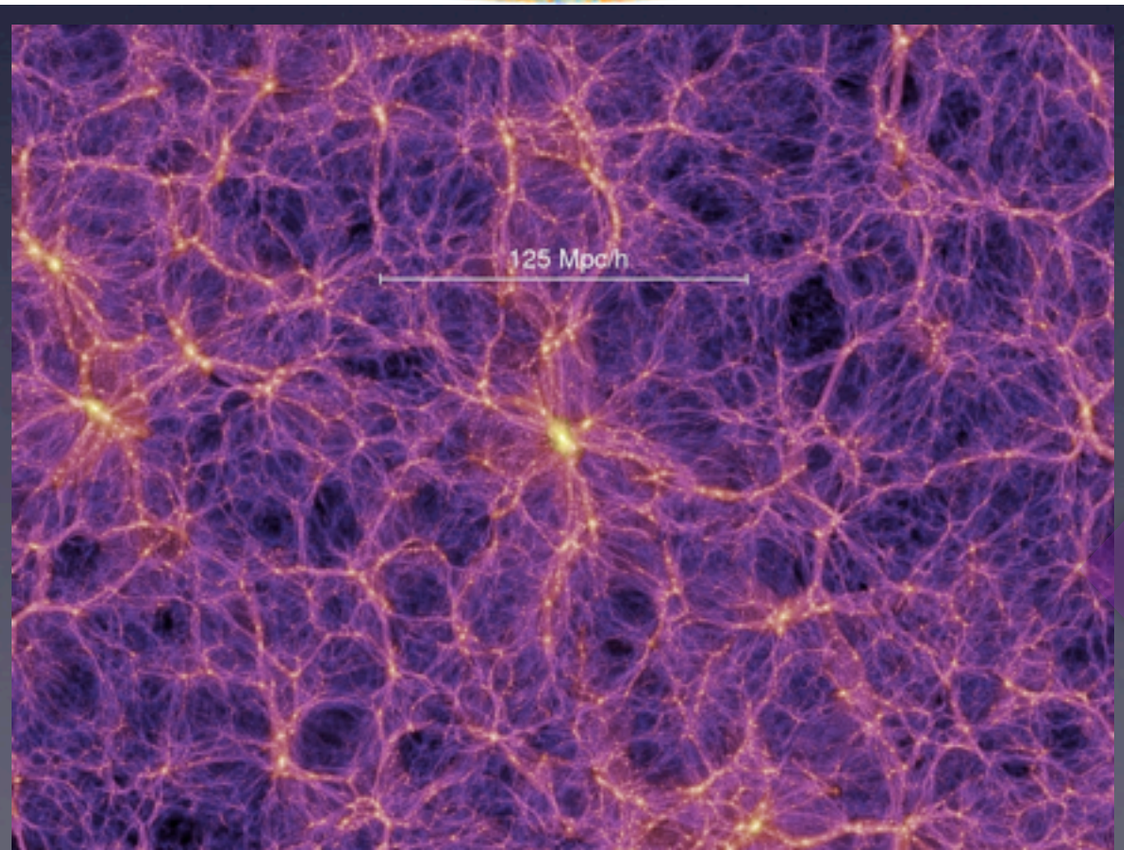
WARNING: If "value" is NOT a MCMC parameter, it might depend on the (cosmological) model!

Cosmological probes
(and most commonly used *observables*)

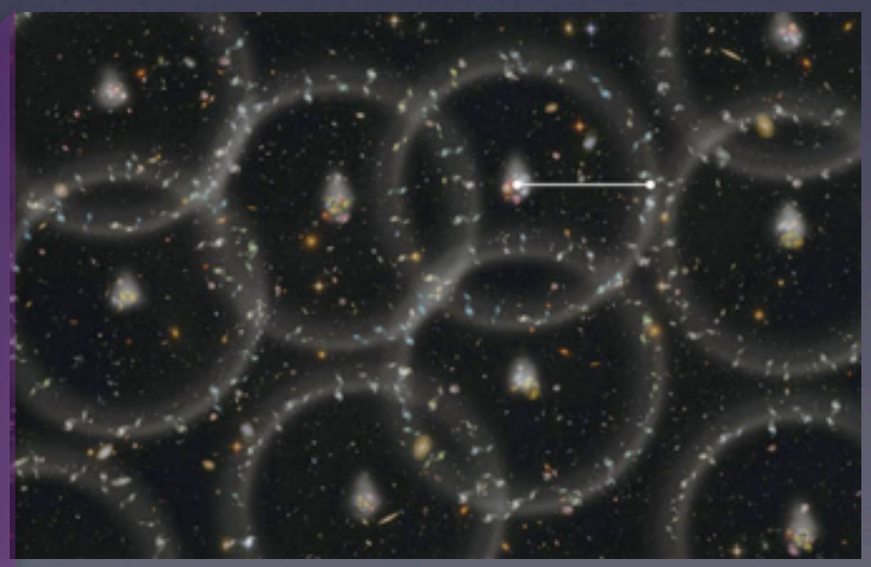


CMB

SNe

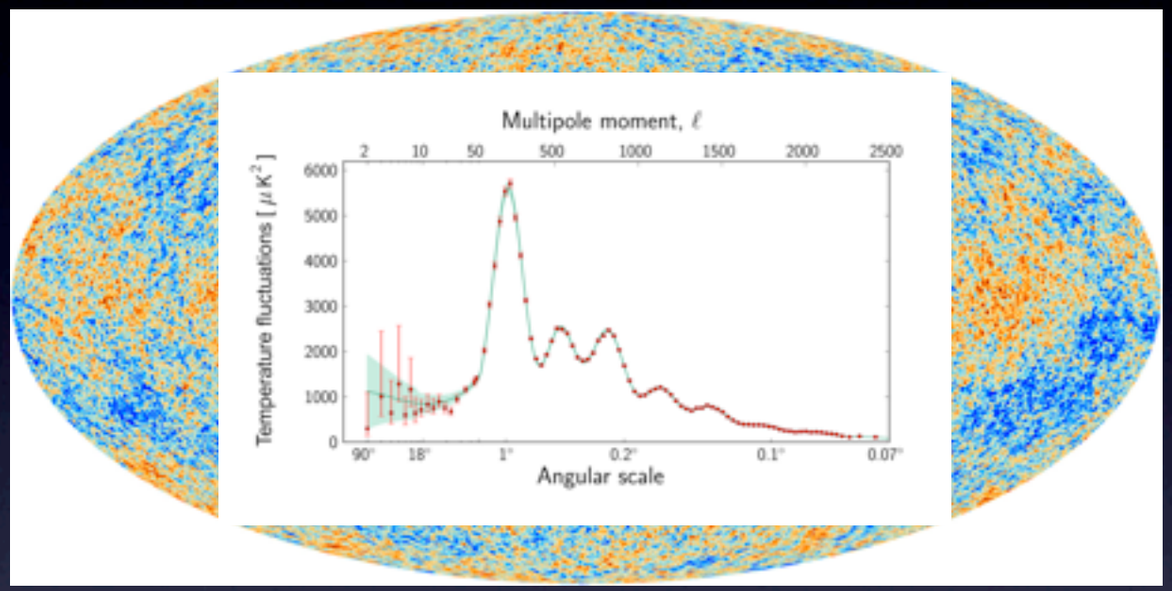


LSS

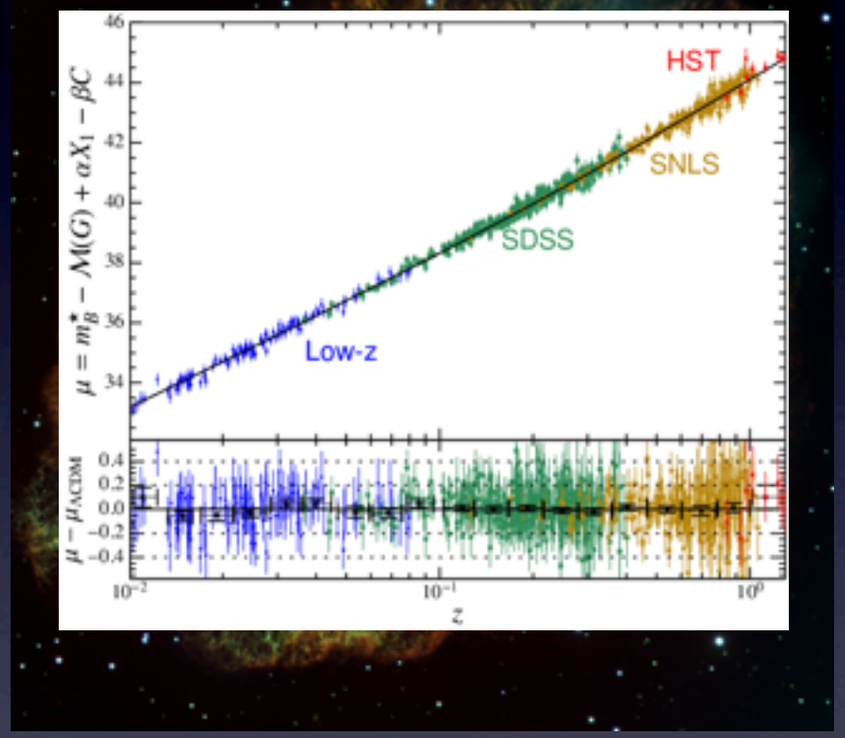


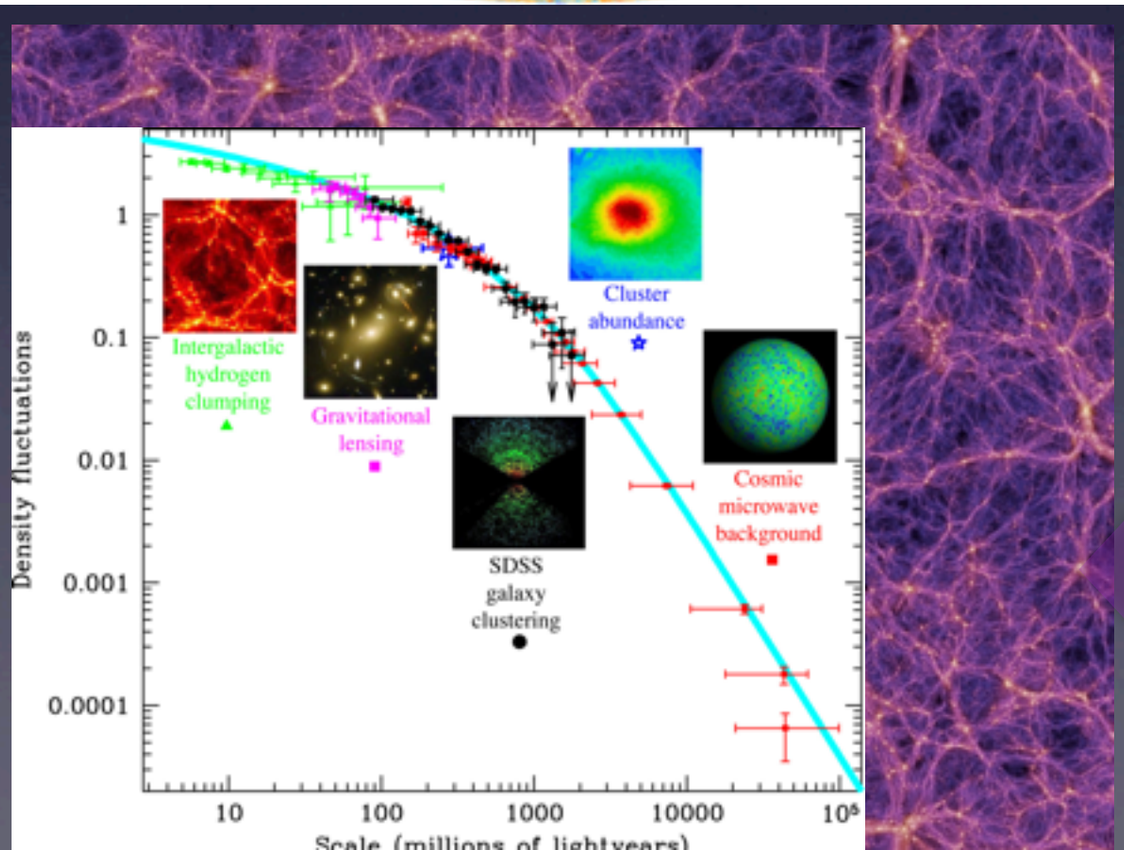
Cosmological probes
(and most commonly used *observables*)

CMB

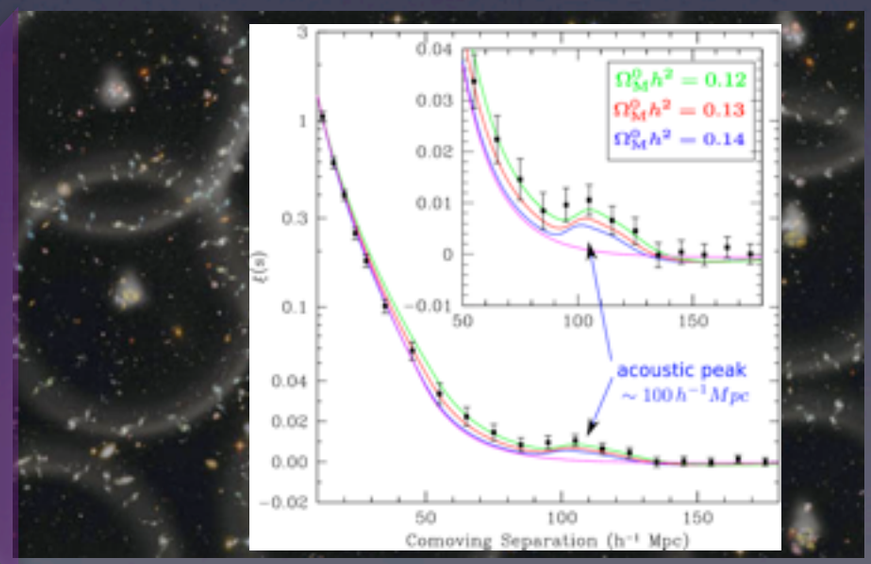


SNe

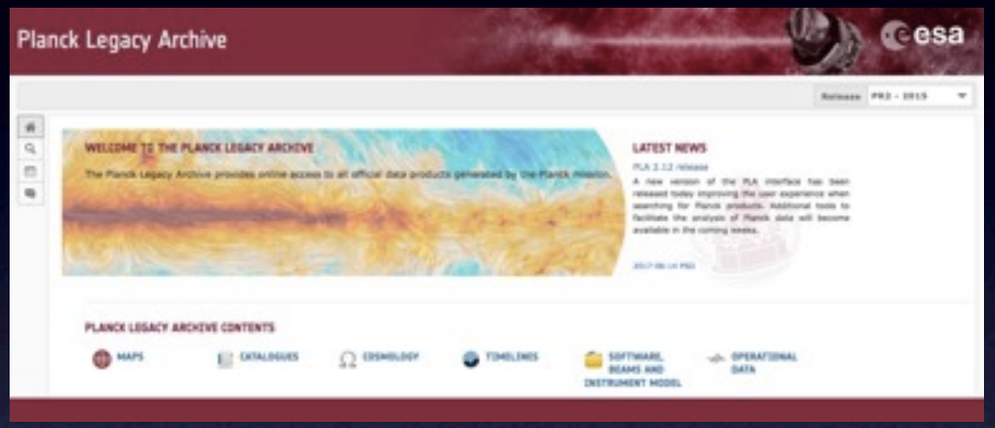




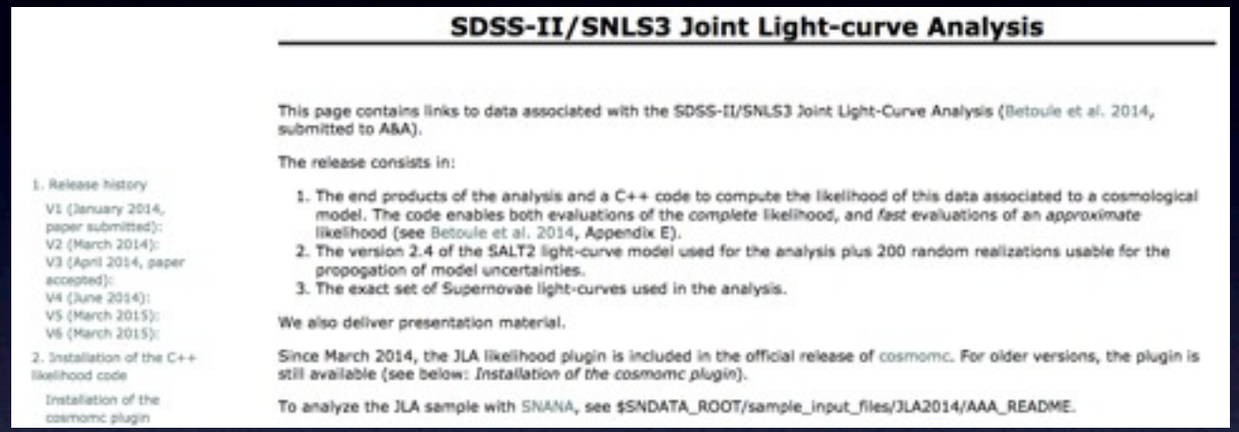
LSS



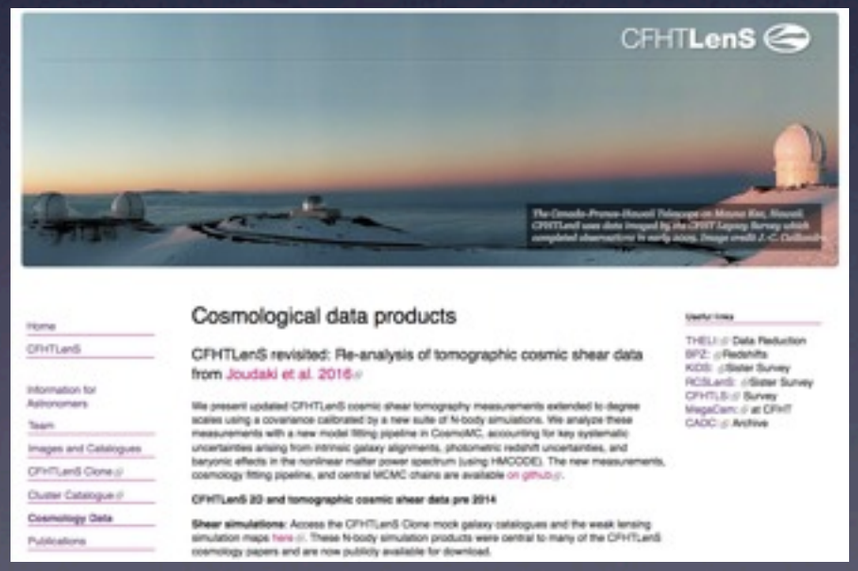
Step 3: Evaluate the likelihood(s)



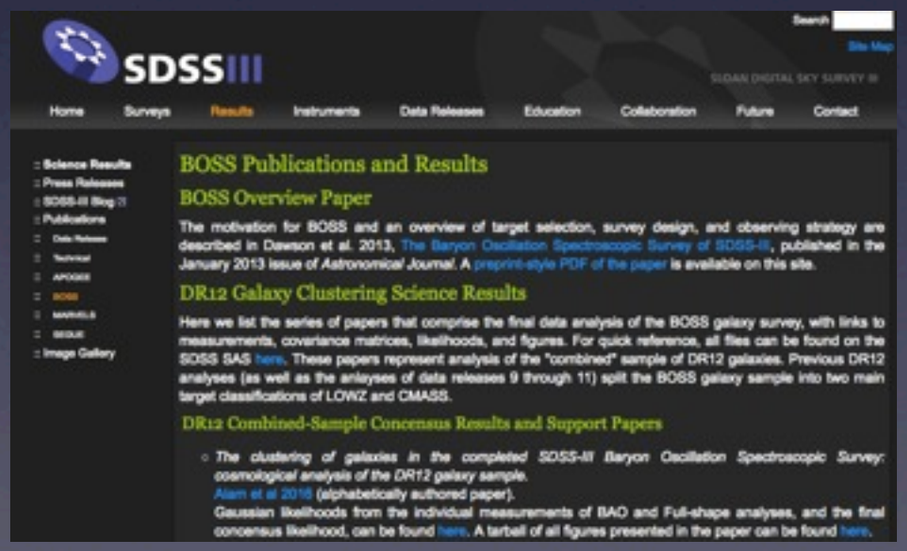
http://pla.esac.esa.int/pla/#home



http://supernovae.in2p3.fr/sdss_snls_jla/ReadMe.html



http://www.cfhtlens.org/astronomers/cosmological-data-products



http://www.sdss3.org/science/boss_publications.php

Built-in likelihoods

in CosmoMC & MontePython

Lots of likelihoods to choose from!

(you can also write your own, if you have the data)

```
AJCuestaMacBookAir:~ ajcuesta$ ls ~/montepython_public/montepython/likelihoods/
BK14                          bao_boss                      fake_planck_bluebook
BK14priors                    bao_boss_aniso                gunn_peterson
CFHTLens                      bao_boss_aniso_gauss_approx   hst
CFHTLens_correlation          bao_known_rs                  hst_riess
JLA                           bicep                         igm_temperature
JLA_simple                    bicep2                        lowlike
Planck_SZ                     boomerang                     polarbear
Planck_actspt                 cbi                           quad
Planck_highl                  clik_fake_planck              sdss_lrgDR4
Planck_highl_TTTEEE           clik_wmap_full                sn
Planck_highl_lite             clik_wmap_lowl                spt
Planck_lensing                cmb_baryon                    spt_2500
Planck_lowl                   cosmic_clocks_BC03            test_gaussian
WiggleZ                       cosmic_clocks_BC03_all        test_nuisance1
WiggleZ_bao                   cosmic_clocks_MaStro          test_nuisance2
__init__.py                   da_rec                        timedelay
__init__.pyc                  euclid_lensing                wmap
acbar                         euclid_pk                     wmap_9yr
bao                           fake_desi
```

MontePython likelihoods

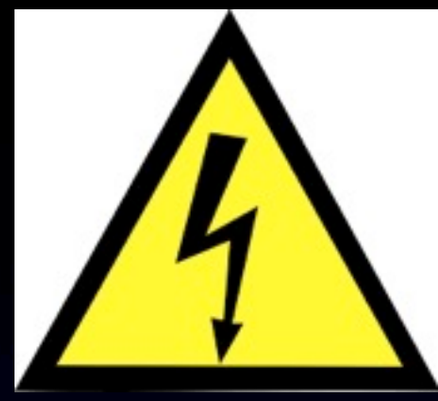
```
AJCuestaMacBookAir:CosmoMC ajcuesta$ ls batch2/
BAO.ini                       WLHeymans.ini                 lowTEB.ini
BAODR11.ini                   WLonly.ini                    lowl.ini
BAO_RSD.ini                   WLonlyHeymans.ini             lowl_old.ini
BK14                          WMAP.ini                      outputs
BK14.ini                      WMAPTEB.ini                   params_CMB_defaults.ini
BK14_README.txt               WMAP_lowl.ini                 pico.ini
BK14only.ini                  WMAP_tauprior.ini             planck_calibration.ini
BKPlanck                      WiggleZ_MPK.ini               plik_dx11dr2_DS_v18_EE.ini
BKPlanck.ini                  abundances.ini                plik_dx11dr2_DS_v18_TE.ini
BKPlanck_README.txt           accuracy.ini                  plik_dx11dr2_DS_v18_TT.ini
BKPlanckonly.ini              common.ini                    plik_dx11dr2_DS_v18_TTTEEE.ini
HST.ini                       fix_params.ini                plik_dx11dr2_HM_v18_EE.ini
HST_Freeman12.ini             getdist_background.ini        plik_dx11dr2_HM_v18_TE.ini
HST_GPE70p6.ini               getdist_base.ini              plik_dx11dr2_HM_v18_TT.ini
HST_GPE72p5.ini               getdist_common.ini            plik_dx11dr2_HM_v18_TTTEEE.ini
HST_high.ini                  importance_sampling.ini       plik_lite_TT.ini
JLA.ini                       lensing.ini                   plik_lite_TTTEEE.ini
JLA_marge.ini                 lensing_aggressive.ini        plik_v18_priors.ini
MPK.ini                       lensonly.ini                  reion_tau.ini
SZ_plus_CMB.ini               likelihood.ini                zre_prior.ini
SZ_plus_priors.ini            lowEB.ini
WL.ini                        lowLike.ini
```

CosmoMC likelihoods

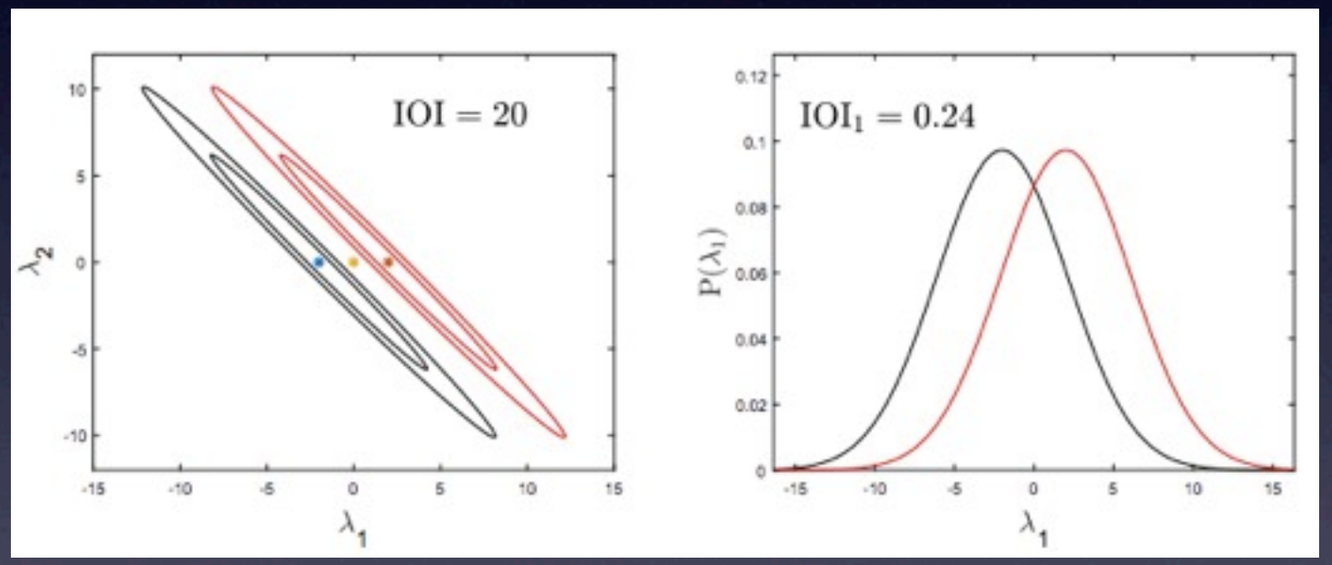
CMB from Planck (TT, TE, EE) and others, BAO (eg. BOSS), SNe (JLA), matter power spectrum, Hubble constant, Bicep/Keck CMB B-modes, Euclid/DESI mock likelihoods (for forecasts),....

Tensions!

why not use everything?



- When combining different datasets, one should always keep in mind that some pair of datasets can produce constraints that do not overlap in the *d*-dimensional parameter space (they might overlap in lower-dimensional plots)



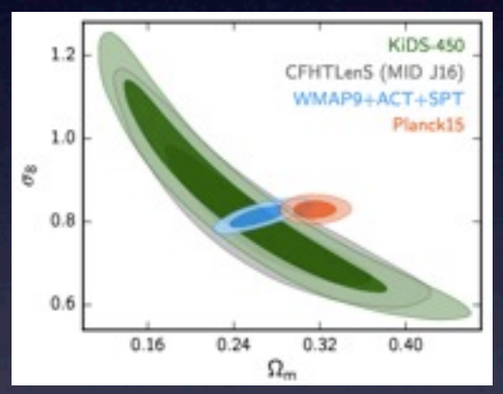
arXiv:1705.05303

- This can lead to multi-modal posteriors, (potentially) spurious constraints (e.g. claims of non-zero neutrino masses, dynamical dark energy, couplings in the dark sector,...) and to probably too many astro-ph.CO postings every day

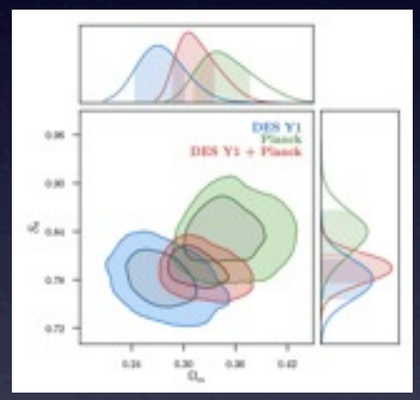
try to be minimalistic!

Tensions!

- Well-known examples of dataset tensions are:
  - The Large-Scale Structure (LSS) measurements of matter fluctuation amplitude σ_8 via weak lensing and those derived from the Cosmic Microwave Background (CMB)

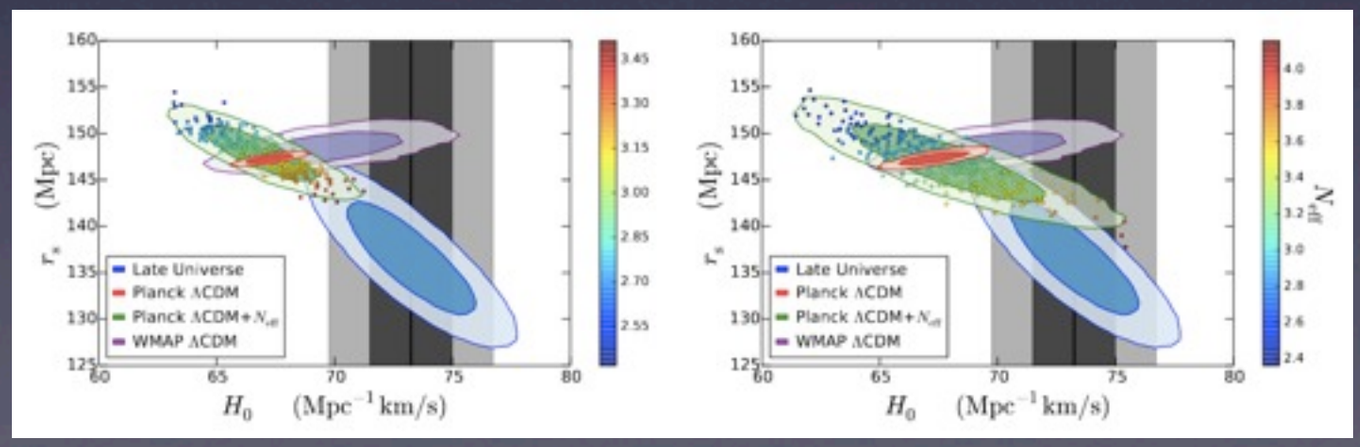


KIDS-450, arXiv: 1606.05338



DES Y1, arXiv: 1708.01530

  - The local measurement of H_0 and its extrapolation from CMB assuming ΛCDM



Bernal et al. arXiv:1607.05617

- Did we under-estimate uncertainties? Is ΛCDM wrong? Is GR/FLRW wrong? Is Planck wrong? (need for massive neutrinos / dark radiation / non-Λ dark energy / other extensions ?)

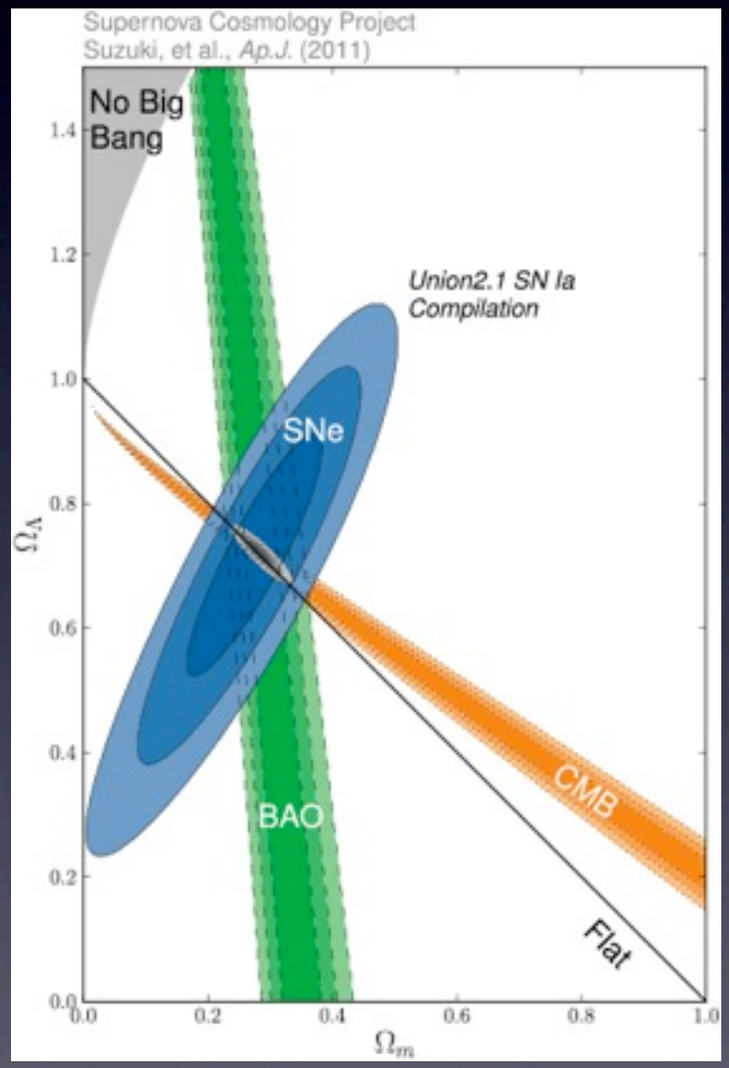
Step 4: Decide whether to accept the point & Write to file

- Assuming all datasets are independent, the total likelihood is the *product* of the individual likelihoods, so the -log(likelihoods) are *added*

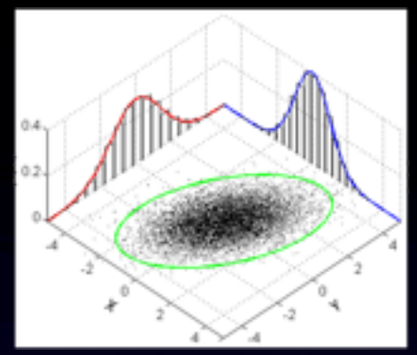
- For a *fixed* model, different datasets will allow different regions of the parameter space. If we combine all datasets, the allowed region will be the *intersection* of the individual allowed regions

- Following the Metropolis-Hastings algorithm, we compare the total likelihood at the new point with the likelihood at the previous point.

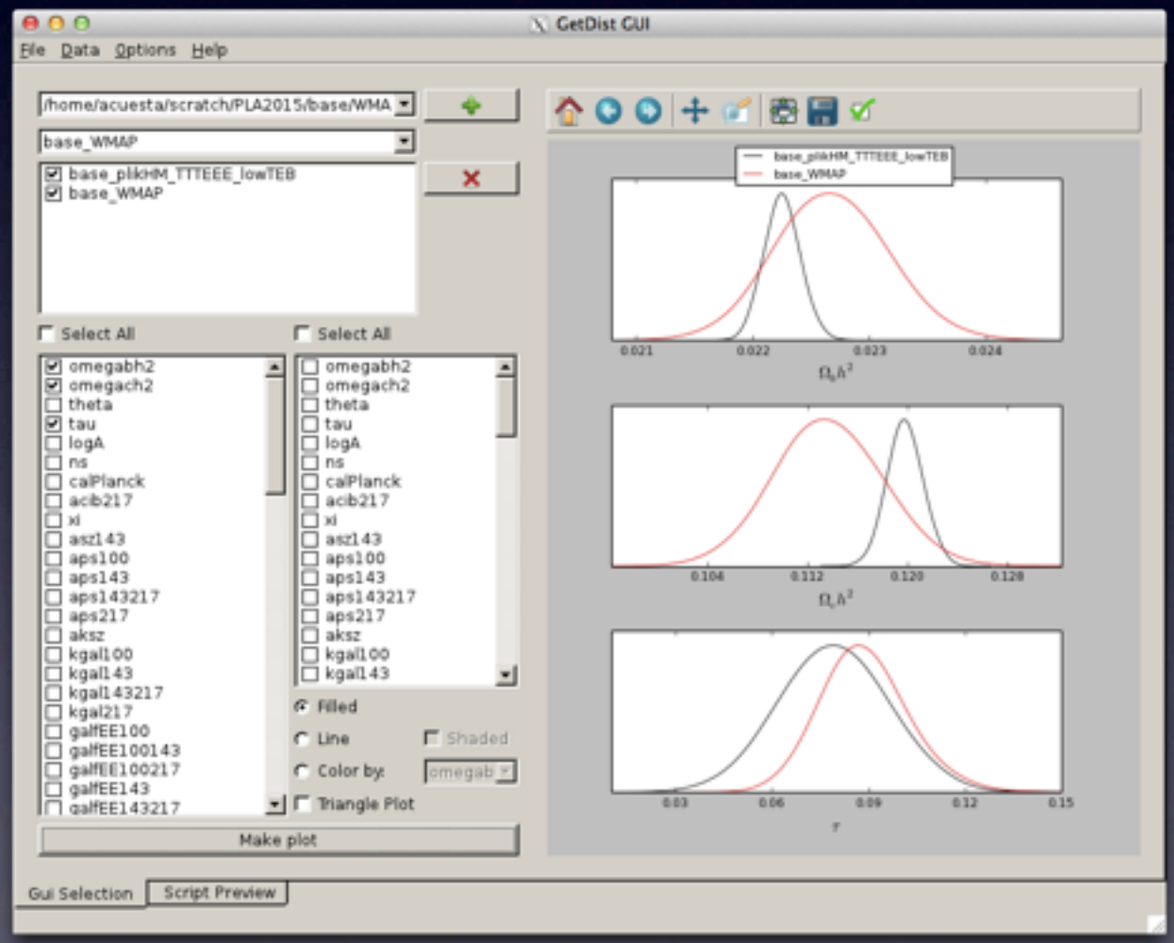
- Depending on this comparison, it will move to the new point or otherwise, it will count the previous point twice (the *multiplicity* of the point will be >1)



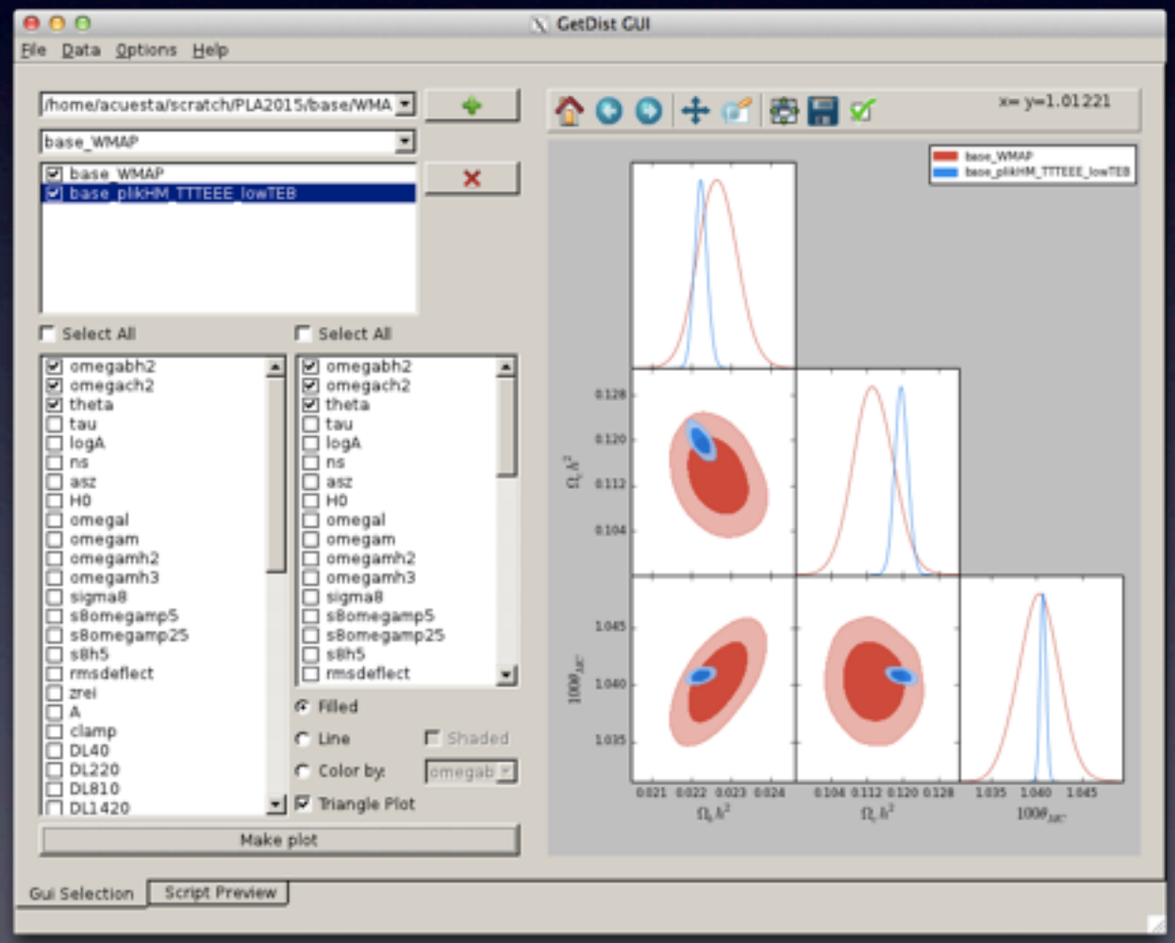
Step 5: Analysis of the results



Once the chains have converged, we can make different types of summary figures or tables to convey the resulting information
This requires *marginalization*: integrate the *d*-dim PDF over all other parameters

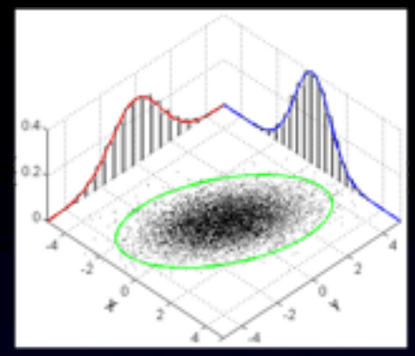


1D Plot
(mean values and standard deviations)

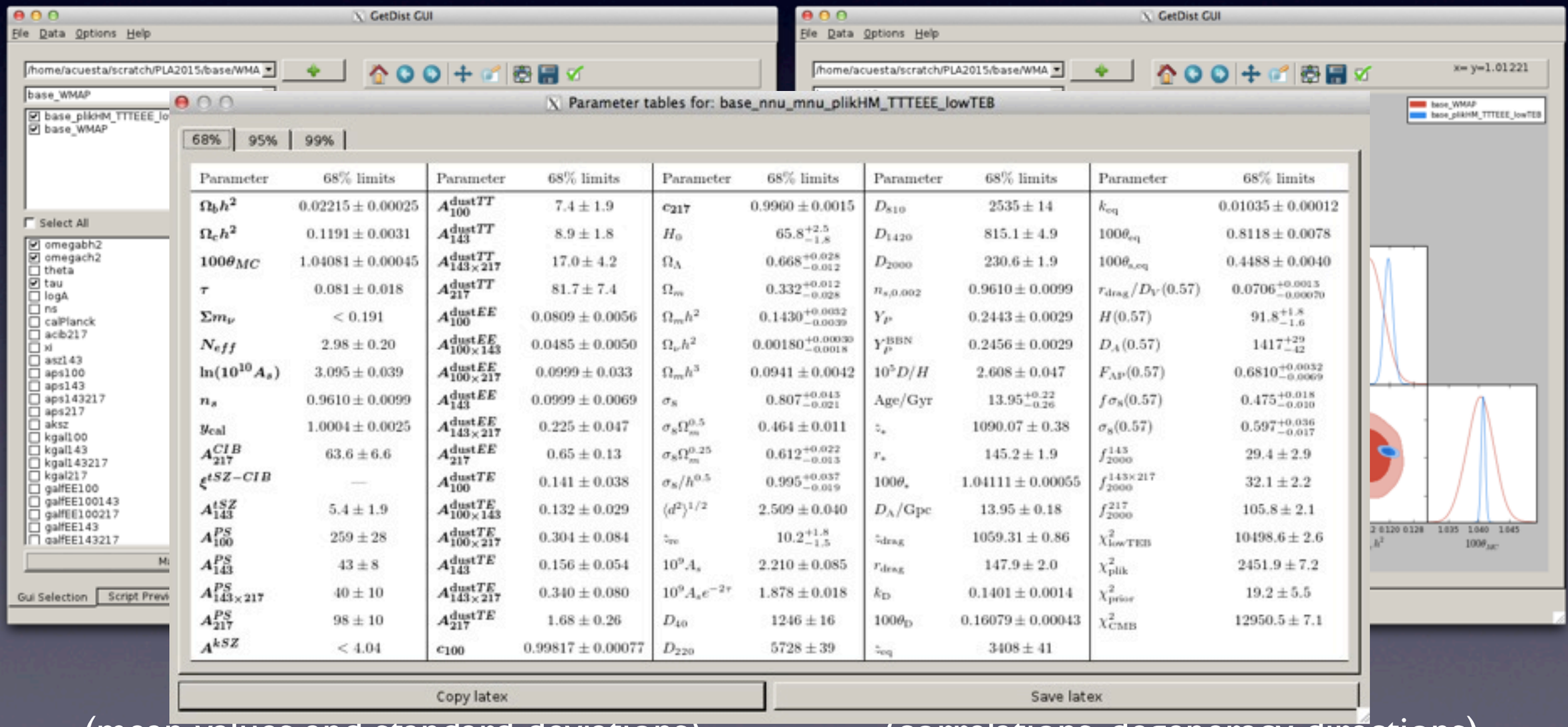


2D Plot
(correlations, degeneracy directions)

Step 5: Analysis of the results



Once the chains have converged, we can make different types of summary figures or tables to convey the resulting information
This requires *marginalization*: integrate the *d*-dim PDF over all other parameters



Parameter	68% limits	Parameter	68% limits	Parameter	68% limits	Parameter	68% limits	Parameter	68% limits
$\Omega_b h^2$	0.02215 ± 0.00025	$A_{100}^{\rm dust TT}$	7.4 ± 1.9	c_{217}	0.9960 ± 0.0015	D_{810}	2535 ± 14	$k_{\rm eq}$	0.01035 ± 0.00012
$\Omega_c h^2$	0.1191 ± 0.0031	$A_{143}^{\rm dust TT}$	8.9 ± 1.8	H_0	$65.8^{+2.5}_{-1.8}$	D_{1420}	815.1 ± 4.9	$100\theta_{\rm eq}$	0.8118 ± 0.0078
$100\theta_{MC}$	1.04081 ± 0.00045	$A_{143\times217}^{\rm dust TT}$	17.0 ± 4.2	Ω_Λ	$0.668^{+0.028}_{-0.032}$	D_{2000}	230.6 ± 1.9	$100\theta_{\rm s,eq}$	0.4488 ± 0.0040
τ	0.081 ± 0.018	$A_{217}^{\rm dust TT}$	81.7 ± 7.4	Ω_m	$0.332^{+0.032}_{-0.028}$	$n_{s,0.002}$	0.9610 ± 0.0099	$r_{\rm drag}/D_V(0.57)$	$0.0706^{+0.0013}_{-0.00070}$
Σm_ν	< 0.191	$A_{100}^{\rm dust EE}$	0.0809 ± 0.0056	$\Omega_m h^2$	$0.1430^{+0.0032}_{-0.0039}$	Y_p	0.2443 ± 0.0029	$H(0.57)$	$91.8^{+1.8}_{-1.6}$
N_{eff}	2.98 ± 0.20	$A_{100\times143}^{\rm dust EE}$	0.0485 ± 0.0050	$\Omega_\nu h^2$	$0.00180^{+0.00030}_{-0.0018}$	$Y_p^{\rm BBN}$	0.2456 ± 0.0029	$D_A(0.57)$	1417^{+29}_{-42}
$\ln(10^{10}A_s)$	3.095 ± 0.039	$A_{100\times217}^{\rm dust EE}$	0.0999 ± 0.033	$\Omega_m h^3$	0.0941 ± 0.0042	$10^3 D/H$	2.608 ± 0.047	$F_{\rm AP}(0.57)$	$0.6810^{+0.0032}_{-0.0069}$
n_s	0.9610 ± 0.0099	$A_{143}^{\rm dust EE}$	0.0999 ± 0.0069	σ_8	$0.807^{+0.043}_{-0.021}$	Age/Gyr	$13.95^{+0.22}_{-0.26}$	$f\sigma_8(0.57)$	$0.475^{+0.018}_{-0.010}$
$y_{\rm cal}$	1.0004 ± 0.0025	$A_{143\times217}^{\rm dust EE}$	0.225 ± 0.047	$\sigma_8\Omega_m^{0.5}$	0.464 ± 0.011	z_*	1090.07 ± 0.38	$\sigma_8(0.57)$	$0.597^{+0.036}_{-0.017}$
A_{217}^{CIB}	63.6 ± 6.6	$A_{217}^{\rm dust EE}$	0.65 ± 0.13	$\sigma_8\Omega_m^{0.25}$	$0.612^{+0.022}_{-0.013}$	r_*	145.2 ± 1.9	f_{2000}^{143}	29.4 ± 2.9
$\xi^{tSZ-CIB}$	—	$A_{100}^{\rm dust TE}$	0.141 ± 0.038	$\sigma_8/h^{0.5}$	$0.995^{+0.037}_{-0.019}$	$100\theta_*$	1.04111 ± 0.00055	$f_{2000}^{143\times217}$	32.1 ± 2.2
A_{143}^{tSZ}	5.4 ± 1.9	$A_{100\times143}^{\rm dust TE}$	0.132 ± 0.029	$\langle d^2\rangle^{1/2}$	2.509 ± 0.040	D_A/Gpc	13.95 ± 0.18	f_{2000}^{217}	105.8 ± 2.1
A_{100}^{PS}	259 ± 28	$A_{100\times217}^{\rm dust TE}$	0.304 ± 0.084	$z_{\rm re}$	$10.2^{+1.8}_{-1.5}$	$z_{\rm drag}$	1059.31 ± 0.86	$\chi^2_{\rm lowTEB}$	10498.6 ± 2.6
A_{143}^{PS}	43 ± 8	$A_{143}^{\rm dust TE}$	0.156 ± 0.054	$10^9 A_s$	2.210 ± 0.085	$r_{\rm drag}$	147.9 ± 2.0	$\chi^2_{\rm plik}$	2451.9 ± 7.2
$A_{143\times217}^{PS}$	40 ± 10	$A_{143\times217}^{\rm dust TE}$	0.340 ± 0.080	$10^9 A_s e^{-2\tau}$	1.878 ± 0.018	$k_{\rm D}$	0.1401 ± 0.0014	$\chi^2_{\rm prior}$	19.2 ± 5.5
A_{217}^{PS}	98 ± 10	$A_{217}^{\rm dust TE}$	1.68 ± 0.26	D_{40}	1246 ± 16	$100\theta_{\rm D}$	0.16079 ± 0.00043	$\chi^2_{\rm CMB}$	12950.5 ± 7.1
A^{kSZ}	< 4.04	c_{100}	0.99817 ± 0.00077	D_{220}	5728 ± 39	$z_{\rm eq}$	3408 ± 41		

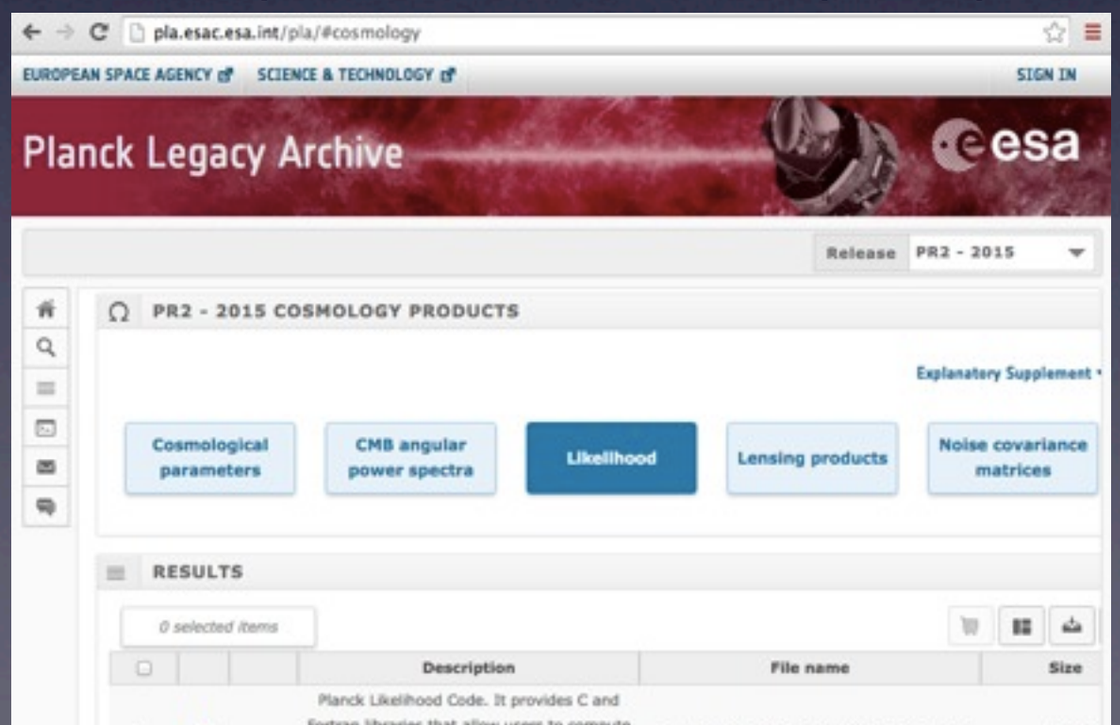
(mean values and standard deviations)

(correlations, degeneracy directions)

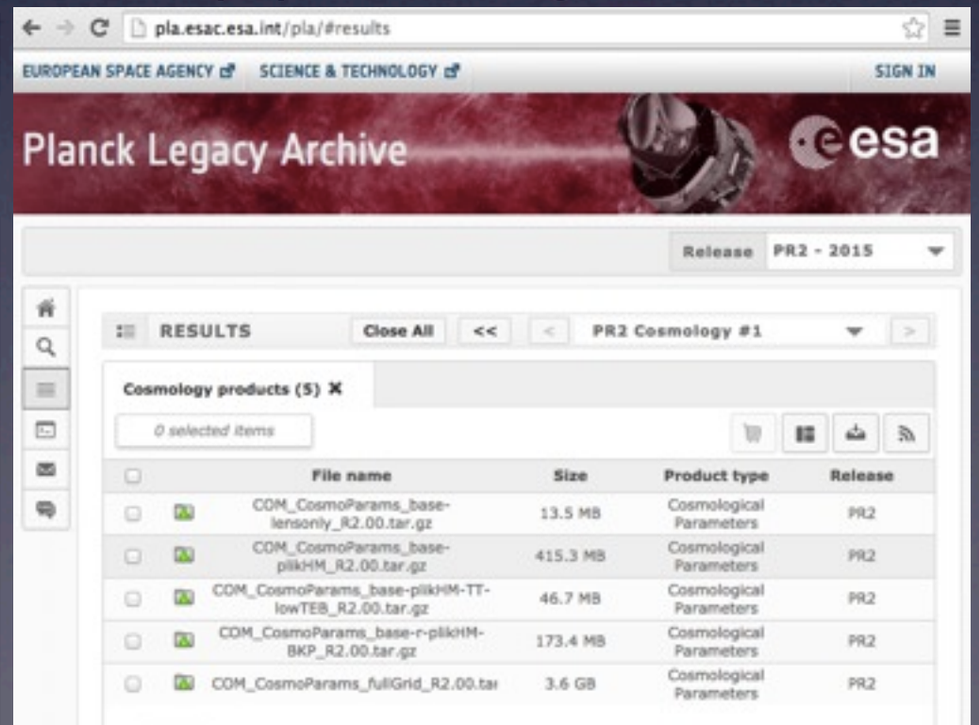
Planck's public chains

- Planck released their full analysis (done with CosmoMC) for a comprehensive combination of cosmological models and datasets
- They can be downloaded at `http://pla.esac.esa.int/pla` (Go to "Cosmology" and then click on "Cosmological parameters)
- The full grid shown in Planck 2015 Paper XIII can be found in the file `COM_CosmoParams_base-plikHM_R2.00.tar.gz` (3.6GB)
- More information can be found at the ESA/Planck wiki: http://wiki.cosmos.esa.int/planckpla2015/index.php/Cosmological_Parameters

Likelihood Code



Grid of chains



Introduction to MontePython

The CLASSY interface: CLASS Python wrapper

- Since MontePython and CLASS are written in different languages (Python and C) MontePython needs a wrapper to communicate with CLASS at each MCMC step (there is also a pycamb interface to CAMB)

- Much like Montepython does to run, this wrapper can also be used stand-alone:

Terminal: write your_parameter_file.ini

```
h = 0.6774
omega_b = 0.02230
Omega_cdm = 0.2603
Omega_fld = 0
Omega_smg = 0 #GR in hi_class
background_verbose = 1 #info
output = tCl,mPk #what to compute
write background = y
root = output/your_model_ #future files
```

Python: write a dictionary

```
params = {
    "h": 0.6774,
    "omega_b": 0.02230,
    "Omega_cdm": 0.2603,
    "Omega_fld" : 0,
    "Omega_smg" : 0, #GR in hi_class
    "background_verbose" : 1, #info
    "output" : "tCl,mPk" #observables
}
```

Terminal:

From the to the base directory run

```
./class your_parameter_file.ini
```

(plus an optional .pre precision file)

Your output will be ready in the root address.

Python:

```
from classy import Class
cosmos = Class() #create universe
cosmos.set(params) #feed params to cosmos
cosmos.compute() #duh...
...        #play with the output
cosmo.struct_cleanup() #free memory
cosmo.empty() #start over
```

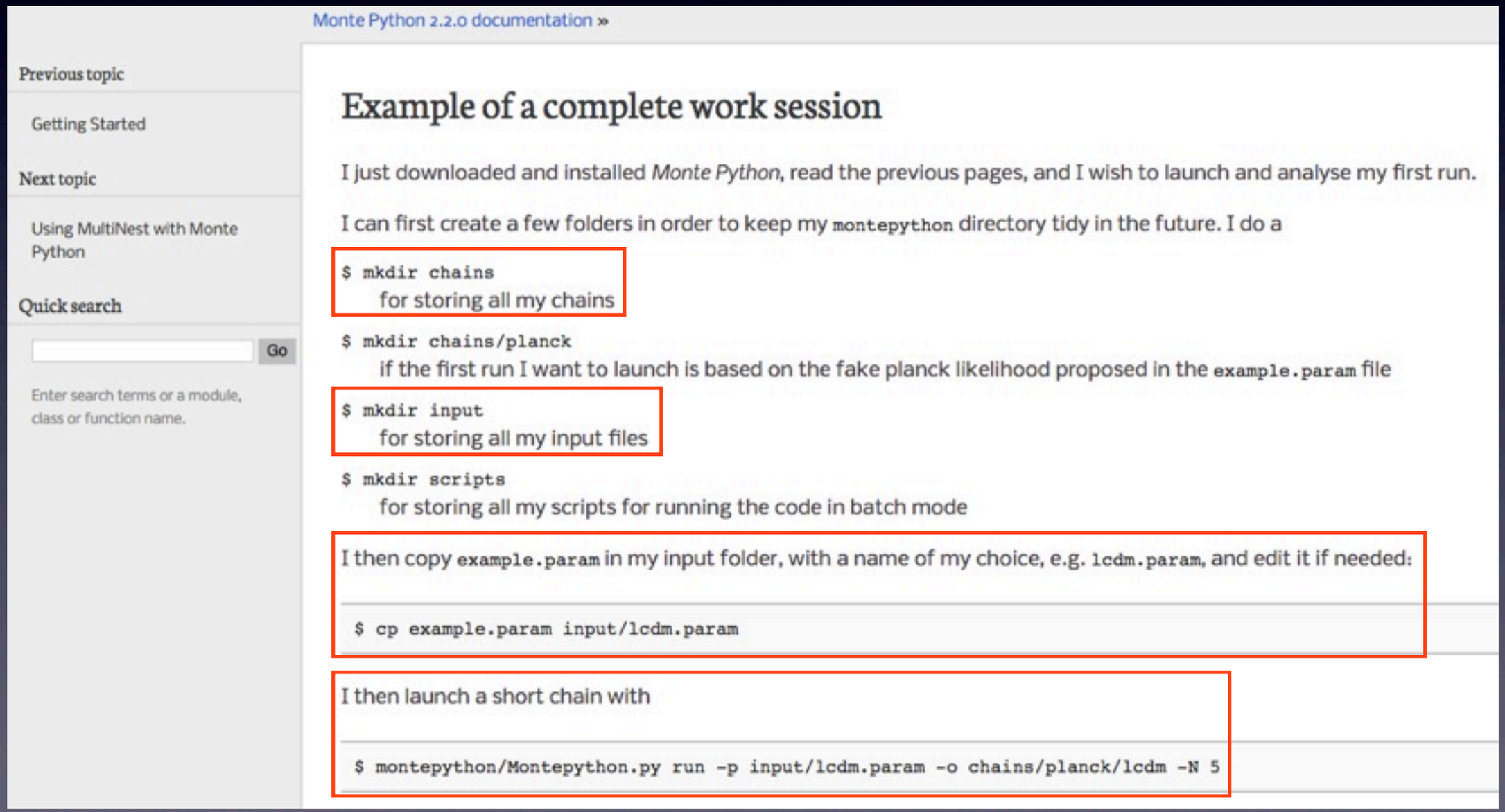
(from Miguel Zumalacarregui's notes)

- To check if your installation works, open a python terminal and type: `import classy`

- More details can be found at: https://github.com/lesgourg/class_public/wiki/Python-wrapper

Running Montepython

The procedure is well described in the official documentation website:
http://monte-python.readthedocs.io/en/latest/example.html



Monte Python 2.2.0 documentation »

Previous topic

Getting Started

Next topic

Using MultiNest with Monte Python

Quick search

Go

Enter search terms or a module, class or function name.

Example of a complete work session

I just downloaded and installed *Monte Python*, read the previous pages, and I wish to launch and analyse my first run.

I can first create a few folders in order to keep my `montepython` directory tidy in the future. I do a

```
$ mkdir chains
```
for storing all my chains

```
$ mkdir chains/planck
```
if the first run I want to launch is based on the fake planck likelihood proposed in the `example.param` file

```
$ mkdir input
```
for storing all my input files

```
$ mkdir scripts
```
for storing all my scripts for running the code in batch mode

I then copy `example.param` in my input folder, with a name of my choice, e.g. `lcdm.param`, and edit it if needed:

```
$ cp example.param input/lcdm.param
```

I then launch a short chain with

```
$ montepython/Montepython.py run -p input/lcdm.param -o chains/planck/lcdm -N 5
```

MontePython input file

The input file is where we specify:

- the experiments (cosmological datasets) we want to use (in folder montepython/likelihoods)
- the values of the parameters that we want fixed ("cosmo_arguments")
- the parameters we want to measure ("cosmo")
- the parameters required to be marginalized by some likelihoods ("nuisance")
- the extra parameters we want to be computed and written to file ("derived")
- other defaults like number of steps (override if specified), etc.

```
data.experiments = ['experiment1', 'experiment2', ...]

data.parameters['cosmo_name']       = [mean, min, max, sigma, scale, 'cosmo']
...

data.parameters['nuisance_name']    = [mean, min, max, sigma, scale, 'nuisance']
...

data.parameters['cosmo_name']       = [mean, min, max, sigma, scale, 'derived']
...

data.cosmo_arguments['cosmo_name']            = value

data.N = 10
data.write_step = 5
```

Running chains with MontePython run

- Each instance of `MontePython run` will run only one chain, unless you run the command with MPI (requires the python module mpi4py)
- You can specify: an input file, an output folder, the number of steps (the code will not stop at convergence), the best fit point and a proposal covariance matrix (these two are needed for faster convergence, but you will have these files only if you did a previous shorter run or a similar run)
- You can also specify a step size (default -f 2.4, target should be ~20% to 25% acceptance rate), sampling method (e.g.MultiNest), and not use fast/slow sampling
- You can update the proposal covariance matrix every 500 steps with the option `--update 500` (it will use *all* chains to recompute it, even without MPI)
- Example: if you want to run 4 chains with 10^5 points each:

```
for n $(seq 1 4); do python montepython/Montepython run \
                  -o output_directory -N 100000 [other_options]; done
```

The first run creates a log.param file in the output folder, so that if you (mistakenly) try to run a chain in that folder with a different input file, the old configuration overrides the input file (prevents mix-ups)

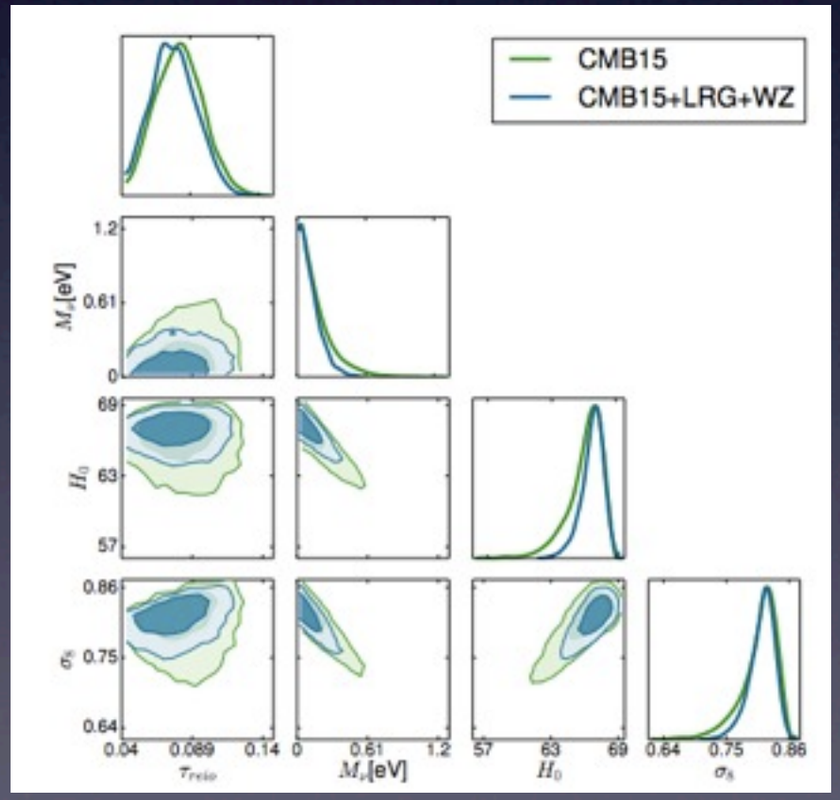
Plotting your results with MontePython info

- Customize your plots!! (use the **--extra** option if you have saved these options into a file)
  - Lots of layout options: font size, legend style, line width, no-mean, ...
  - Change the number of bins for credible intervals (less bins = less resolution)
  - Do Gaussian smoothing or increase interpolation (for smoother plots)
  - To do operations with the parameters:
    info.redefine = {'new_param':'5*old_param+10'}
  - To rename a parameter in the output plots:
    info.to_change={'old_name':'new_name'}
  - To plot and compute credible intervals for only some specific parameters:
    info.to_plot=['new_param','new_name','old_param2',...]

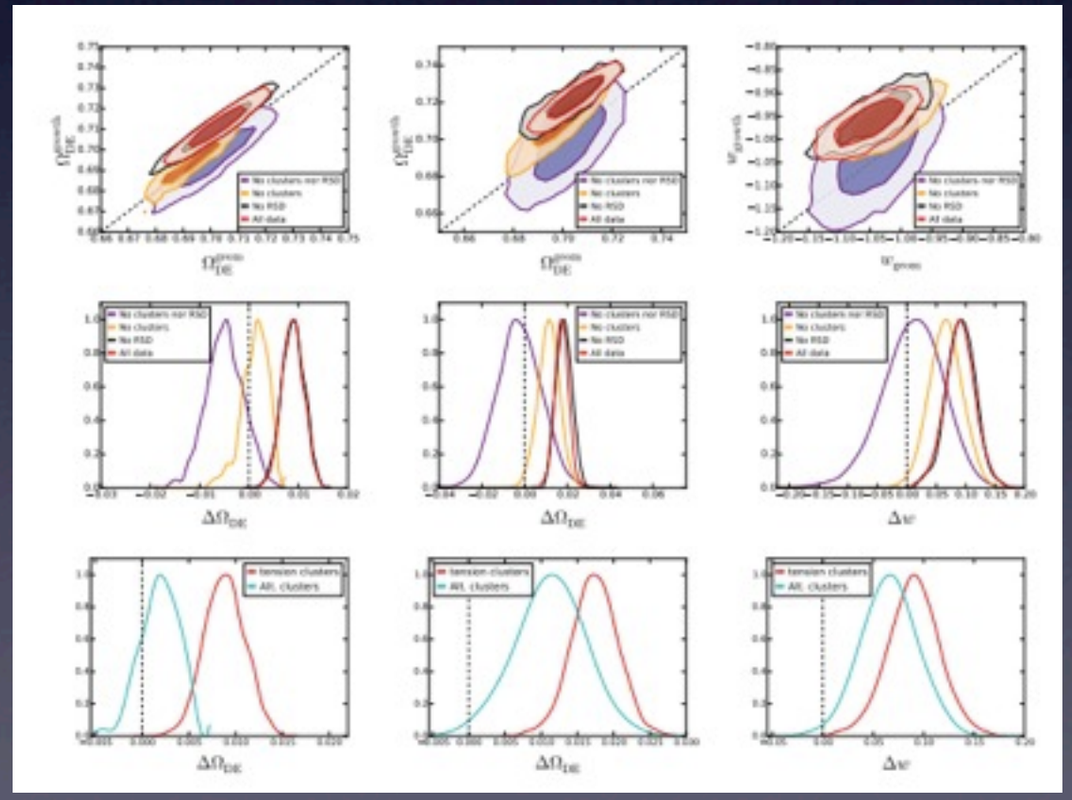
Plotting your results with MontePython info

To compare the constraints on two different models from a fixed dataset
(or on a single cosmological model from two different datasets)

```
python montepython/MontePython.py info experiment_1/ experiment_2/ ...
```



arXiv:1511.05983



arXiv:1511.03049

Creating tables from MontePython info

You can also use the output *tex files to compile *LaTeX* tables, including:

- All the parameters (‘cosmo’, ‘derived’, ‘nuisance’,...) especified in `to_plot`
- Their best-fit values and their mean values
- Their 1-sigma and 2-sigma credible intervals (sigma and 95%)
- Other info like the maximum likelihood found and minimum value of χ^2

Param	best-fit	mean$\pm\sigma$	95% lower	95% upper
Ω_k	0.1984	$0.1619^{+0.26}_{-0.14}$	−0.2234	0.4994
Ω_m	0.2115	$0.2315^{+0.072}_{-0.1}$	0.07255	0.4076
Ω_Λ	0.59	$0.6065^{+0.098}_{-0.16}$	0.3697	0.8639

$-\ln\mathcal{L}_{\min} = 341.105$, minimum $\chi^2 = 682.2$

HELP!!!

- MontePython is well documented:
  http://monte-python.readthedocs.io/en/latest/
- Quick access to all the options in each mode:
  - The options to run chains are:
    `python montepython/MontePython.py run --help`
  - The options to plot and analyze chains are:
    `python montepython/MontePython.py info --help`

Introduction to CosmoMC

Running CosmoMC

- Running a set of *N* chains is as simple as executing the compiled code `./cosmomc` with an input file `params.ini` in the command line (but you need to compile it first! Needs Intel Fortran 14 or GCC 6)

- CosmoMC also offers a simple way to generate job scripts and submit them to run the code in a computing cluster (e.g. Torque, MOAB, SLURM)

```
python python/runMPI.py --nodes 1 --chainsPerNode 8 --coresPerNode 16 --mem_per_node 40000
 --walltime 480:00:00 --job_template job_script_hipatia  --program ./cosmomc --queue batch ow0wacdmbaosn.ini
```

- When running in a cluster, each chain will be parallelized (using OpenMP) over a number of processors equal to `coresPerNode` over `chainsPerNode` The communication between chains will be done via MPI communication

CosmoMC input file

The input file for CosmoMC is named `params.ini` where we can set up:

```
#Folder where files (chains, checkpoints, etc.) are stored
root_dir = chains/

#Root name for files produced
file_root=planck15dr12
```

Output folder and chain file names

```
#action= 0 runs chains, 1 importance samples, 2 minimizes
#use action=4 just to quickly test likelihoods
action = 0
```

Execution mode (0=run chains)

```
#general settings
#Bicep-Keck-Planck, varying cosmological parameters
#DEFAULT(batch2/BKPlanck.ini)

#Planck 2015, default just include native likelihoods (others require clik)
DEFAULT(batch2/plik_dx11dr2_HM_v18_TTTEEE.ini)
DEFAULT(batch2/lowTEB.ini)
#DEFAULT(batch2/lowl.ini)
#DEFAULT(batch2/lensing.ini)

#Other Likelihoods
#DEFAULT(batch2/BAOnew.ini)
#DEFAULT(batch2/WiggleZ_MPK.ini)
#DEFAULT(batch2/MPK.ini)
#DEFAULT(batch2/WL.ini)
```

Planck2015 highL temperature+polarization
Planck2015 lowL temperature+polarization
Planck2015 lowL temperature only
Planck2015 CMB lensing

BAO from BOSS+MGS+6dF(+WiggleZ)
WiggleZ galaxy power spectrum
SDSS galaxy power spectrum
CFHTLens weak lensing
Also, SNe from JLA, etc.

Likelihoods (datasets) you want to include (each one is in turn a settings file)

```
#to vary parameters set param[name]= center, min, max, start width, propose width
#param[mnu] = 0 0 0 0 0
```

```
param[omegak] = 0 -0.1 0.1 0.005 0.005
param[w] = -1 -3 1 0.05 0.05
param[wa] = 0 -3 3 0.3 0.3
```

Model parameters: Values for fixed ones and ranges for those to be measured

```
prior[omegabh2] = 0.0223 0.0009
```

Easily implement Gaussian priors

GetDist: Analysis of CosmoMC chains

CosmoMC's traditional (text-only) analysis tool is GetDist. Besides outputting info to the screen, it creates files with parameter bounds (margestats), covariance matrices, and python scripts to generate plots with matplotlib (in the `plot_data` folder)
The analysis settings can be modified in the `distparams.ini` file

```
[acuesta@nova0 cosmomc2015jul]$ ./getdist distparams.ini chains/lcdmbaosn
 skipped unused params: omegak mnu nnu yhe Alens nrun r r02
 reading chains/lcdmbaosn_1.txt
 reading chains/lcdmbaosn_2.txt
 reading chains/lcdmbaosn_3.txt
 reading chains/lcdmbaosn_4.txt
 reading chains/lcdmbaosn_5.txt
 reading chains/lcdmbaosn_6.txt
 reading chains/lcdmbaosn_7.txt
 reading chains/lcdmbaosn_8.txt
 Number of chains used =            8
 var(mean)/mean(var), remaining chains, worst e-value: R-1 =       0.00666
 RL: Thin for Markov:          30
 RL: Thin for indep samples:   31
 RL: Estimated burn in steps: 120 (50 rows)
 mean input multiplicity =    2.39603247549020
 using        65280  rows, processing          92  parameters
 Approx indep samples:          5046
 Best fit sample -log(Like) =    6822.39800000000
 mean(-Ln(like)) =    6835.30173439549
 -Ln(mean like)  =    6830.18592659466
 Warning: sharp edge in parameter chi2_JLA - check limits[chi2_JLA] or limits86
 Warning: sharp edge in parameter chi2_6DF - check limits[chi2_6DF] or limits87
```

Syntax: ./getdist distparams.ini chains/root

parameters defined in distparams.ini but not in the chains

number of chains read (check that these are all your chains)

MCMC Convergence status

number of parameters (cosmo+nuisance+der)

warnings about non-converged parameters

GetDist: Analysis of CosmoMC chains

```
Marginalized limits: 0.68; 0.95; 0.99

parameter       mean            sddev           lower1          upper1          limit1 lower2          upper2          limit2 lower3          upper3          limit3
omegabh2        0.2227594E-01   0.1409804E-03   0.2213470E-01   0.2241652E-01   two    0.2200101E-01   0.2255144E-01   two    0.2191544E-01   0.2264190E-01   two     \Omega_b h^2
omegach2        0.1192956E+00   0.1068506E-02   0.1182545E+00   0.1203491E+00   two    0.1171635E+00   0.1213484E+00   two    0.1164438E+00   0.1221176E+00   two     \Omega_c h^2
theta           0.1040831E+01   0.2995374E-03   0.1040534E+01   0.1041130E+01   two    0.1040247E+01   0.1041420E+01   two    0.1040057E+01   0.1041614E+01   two     100\theta_{MC}
tau             0.8200741E-01   0.1643758E-01   0.6557802E-01   0.9862151E-01   two    0.4956239E-01   0.1138723E+00   two    0.4020595E-01   0.1240224E+00   two     \tau
logA            0.3097935E+01   0.3246072E-01   0.3065291E+01   0.3130707E+01   two    0.3034228E+01   0.3160888E+01   two    0.3013767E+01   0.3180444E+01   two     {\rm{ln}}(10^{10} A_s)
ns              0.9658500E+00   0.4063676E-02   0.9618321E+00   0.9698272E+00   two    0.9579955E+00   0.9740912E+00   two    0.9555469E+00   0.9768459E+00   two     n_s
calPlanck       0.1000465E+01   0.2516048E-02   0.9979804E+00   0.1002947E+01   two    0.9954956E+00   0.1005439E+01   two    0.9939398E+00   0.1007128E+01   two     y_{\rm cal}
acib217         0.6359261E+02   0.6577819E+01   0.5697960E+02   0.7011801E+02   two    0.5088221E+02   0.7649609E+02   two    0.4702681E+02   0.8075525E+02   two     A^{CIB}_{217}
xi              0.5220534E+00   0.2840235E+00   0.0000000E+00   0.1000000E+01   none   0.0000000E+00   0.1000000E+01   none   0.0000000E+00   0.1000000E+01   none    \xi^{tSZ-CIB}
asz143          0.5399273E+01   0.1871846E+01   0.3556131E+01   0.7442447E+01   two    0.1661532E+01   0.8952850E+01   two    0.7504497E+00   0.9658879E+01   two     A^{tSZ}_{143}
aps100          0.2590954E+03   0.2746669E+02   0.2316349E+03   0.2864320E+03   two    0.2053967E+03   0.3134392E+03   two    0.1890985E+03   0.3311659E+03   two     A^{PS}_{100}
aps143          0.4325286E+02   0.7687977E+01   0.3552913E+02   0.5095578E+02   two    0.2797599E+02   0.5791646E+02   two    0.2349064E+02   0.6198630E+02   two     A^{PS}_{143}
aps143217       0.4026165E+02   0.9948208E+01   0.3006222E+02   0.5063956E+02   two    0.2158706E+02   0.5957445E+02   two    0.1655117E+02   0.6414078E+02   two     A^{PS}_{143\times217}
aps217          0.9815534E+02   0.1100181E+02   0.8722243E+02   0.1092326E+03   two    0.7626975E+02   0.1192058E+03   two    0.6946944E+02   0.1255847E+03   two     A^{PS}_{217}
aksz            0.3160785E+01   0.2332050E+01   0.0000000E+00   0.4034485E+01   >      0.0000000E+00   0.7749367E+01   >      0.0000000E+00   0.1000000E+02   none    A^{kSZ}

[acuesta@nova0 cosmomc2015jul]$ ./getdist distparams.ini chains/lcdmbaosn
 skipped unused params: omegak mnu nnu yhe Alens nrun r r02
 reading chains/lcdmbaosn_1.txt
 reading chains/lcdmbaosn_2.txt
 reading chains/lcdmbaosn_3.txt
 reading chains/lcdmbaosn_4.txt
 reading chains/lcdmbaosn_5.txt
 reading chains/lcdmbaosn_6.txt
 reading chains/lcdmbaosn_7.txt
 reading chains/lcdmbaosn_8.txt
 Number of chains used =                8
 var(mean)/mean(var), remaining chains, worst e-value: R-1 =       0.00666
 RL: Thin for Markov:          30
 RL: Thin for indep samples:   31
 RL: Estimated burn in steps: 120 (50 rows)
 mean input multiplicity =     2.39603247549020
 using         65280  rows, processing           92  parameters
 Approx indep samples:          5046
 Best fit sample -log(Like) =    6822.39800000000
 mean(-Ln(like)) =    6835.30173439549
 -Ln(mean like)  =    6830.18592659466
 Warning: sharp edge in parameter chi2_JLA - check limits[chi2_JLA] or limits86
 Warning: sharp edge in parameter chi2_6DF - check limits[chi2_6DF] or limits87
```

Syntax: ./getdist distparams.ini chains/root

parameters defined in distparams.ini but not in the chains

number of chains read (check that these are all your chains)

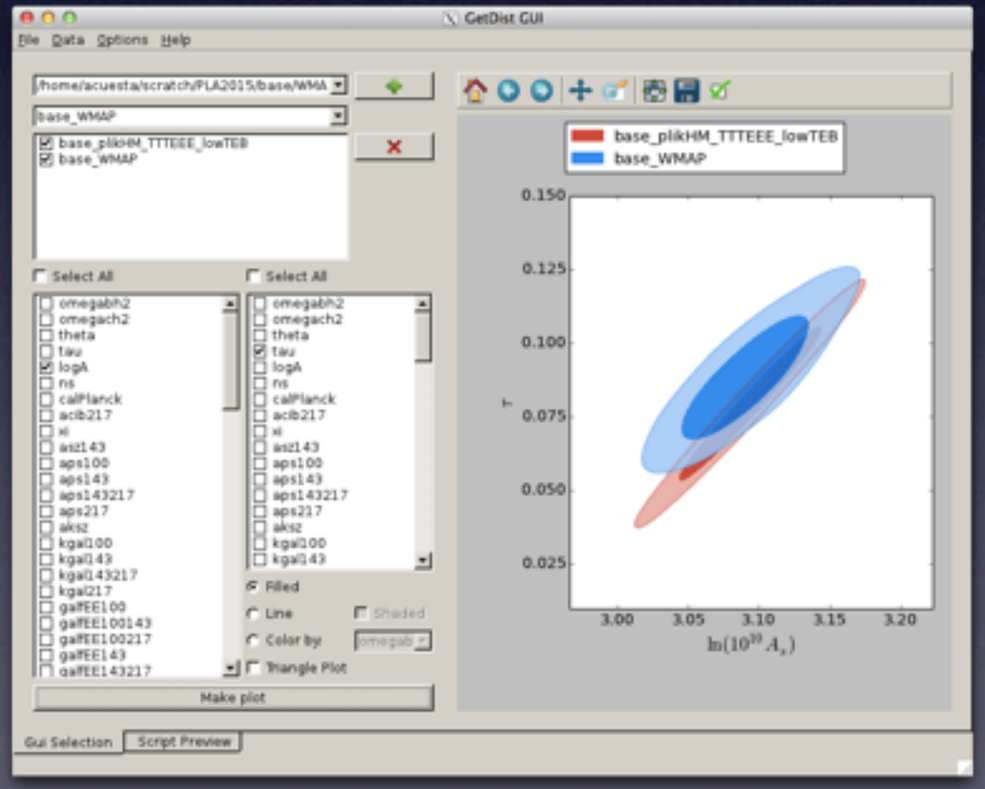
MCMC Convergence status

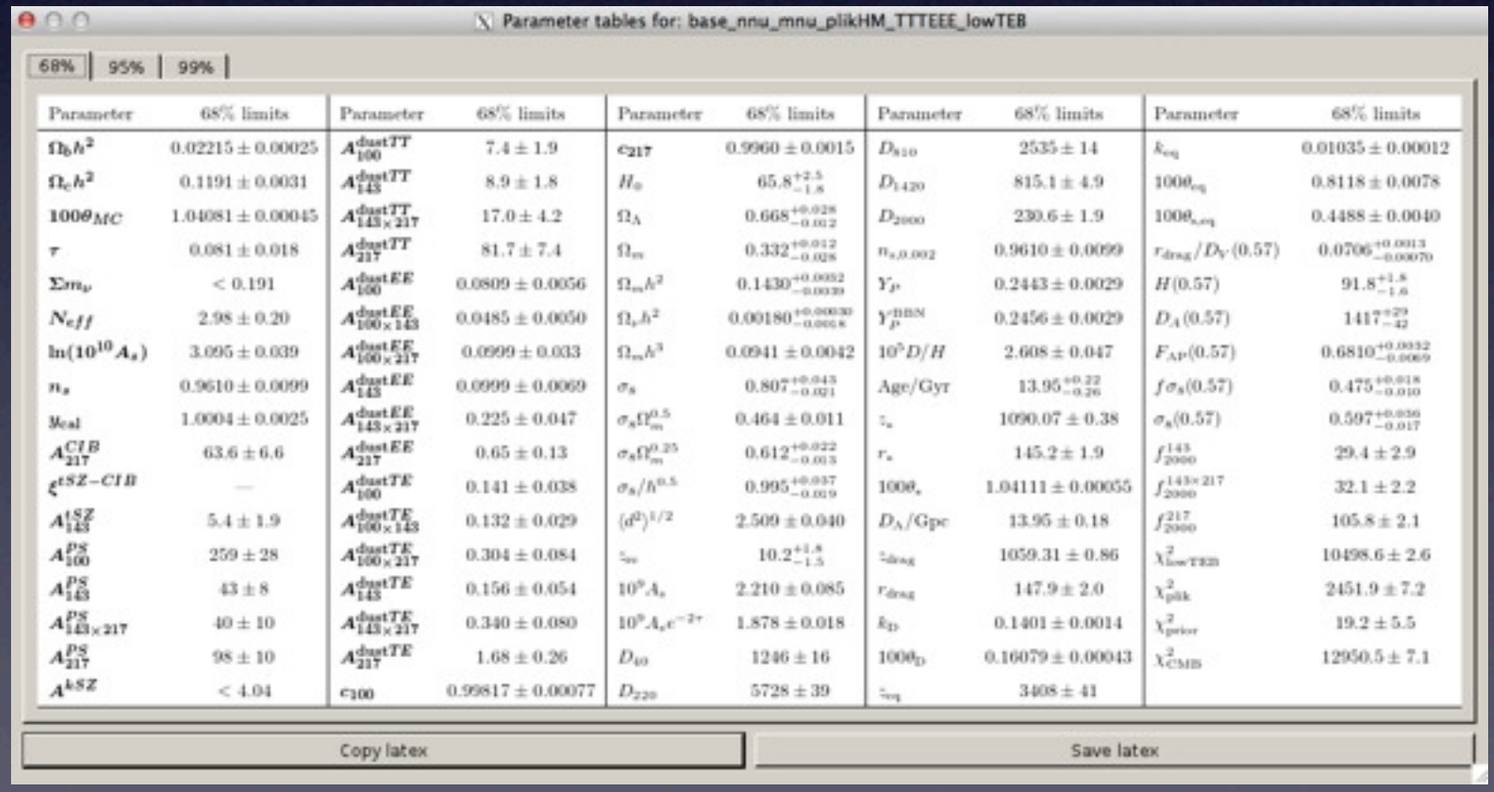
number of parameters (cosmo+nuisance+der)

warnings about non-converged parameters

GetDist GUI: MCMC graphical analysis

- Getdist's graphical interface allows the interactive analysis of CosmoMC but also MontePython chains, making it easy to visually inspect the results
- It has an option to create tables with parameter bounds and export to LaTeX





More examples are shown at http://getdist.readthedocs.org/en/latest/plot_gallery.html

HELP!!!

- CosmoMC has a complete README website:
  http://cosmologist.info/cosmomc/readme.html
- It contains individual pages for many topics:
  Planck likelihood, Python modules, GetDist GUI, running grids of models/datasets,...
- See also the CosmoCoffee forum:
  http://cosmocoffee.info/

Thank you

ajcuesta@uco.es

Supplementary slides

Structure of a chain file

- A chain file is just a text file, you can open it with any editor or manipulate it through any python script (or the way that is most convenient for you)

- Each row is a MCMC step. Each column is each one of the parameters in this order: cosmological, nuisance, and derived. Check the `*.paramnames` file to find out the ordering

- The first two columns are the multiplicity (or number of steps spent in that point) and the -log(likelihood), or "loglike", which is just 0.5 times the total χ^2 value.

mult & loglike

LCDM parameters

1MCMC step

```
   0.1000000E+01   0.7588278E+04   0.2217817E-01   0.1210163E+00   0.1040737E+01   0.9666908E-01   0.3097606E+01   0.9647925E+00   0.1001027E+01   0.1340781E+00   0.3073899E+01   0.5418683E+02   0.1625850E+00   0.2454537E+01   0.2706384E+03   0.4089315E+02   0.2765166E+02   0.1165507E+03   0.9301511E+00   0.4311650E+01   0.8043642E+01   0.2329630E+02   0.7097032E+02   0.6636701E-01   0.7642297E-01   0.1240745E+00   0.1117157E+00   0.3490495E+00   0.5606420E+00   0.1334311E+00   0.1757612E+00   0.3807932E+00   0.2035620E+00   0.6760326E+00   0.1314555E+01   0.9986082E+00   0.9941414E+00   0.6677979E+02   0.6774565E+00   0.3225435E+00   0.1438396E+00   0.6451439E-03   0.9605576E-01   0.8370669E+00   0.4753947E+00   0.6308226E+00   0.1024325E+01   0.2523461E+01   0.1168060E+02   0.2214488E+01   0.1825188E+01   0.1206639E+04   0.5520434E+04   0.2454898E+04   0.7891323E+03   0.2233522E+03   0.9647925E+00   0.2453066E+00   0.2466328E+00   0.2627639E+01   0.1382655E+02   0.1090254E+04   0.1443158E+03   0.1040935E+01   0.1386405E+02   0.1059551E+04   0.1470385E+03   0.1407766E+00   0.1609642E+00   0.3421912E+04   0.1044400E-01   0.8091325E+00   0.4473433E+00   0.1147113E+00   0.7956448E+02   0.1001239E+04   0.3507600E+00   0.7098143E-01   0.9268106E+02   0.1398548E+04   0.6788087E+00   0.4943056E+00   0.7053466E+00   0.4894761E+00   0.6200091E+00   0.3953857E+04   0.1049665E+05   0.6969622E+03   0.2200932E+00   0.5372448E+00   0.7533748E+01   0.7409717E+00   0.2005706E+02   0.1445050E+05   0.9032058E+01
   0.2000000E+01   0.7432273E+04   0.2205772E-01   0.1223525E+00   0.1040409E+01   0.9243788E-01   0.3091427E+01   0.9585111E+00   0.9999859E+00   0.1381403E+00   0.3085730E+01   0.6719501E+02   0.1607488E-01   0.2326024E+00   0.3234647E+03   0.4471673E+02   0.1465753E+02   0.8721921E+02   0.5519028E+01   0.4040853E+01   0.8603040E+01   0.2843156E+02   0.8216804E+02   0.6988734E-01   0.8529992E-01   0.1473713E+00   0.1212628E+00   0.4138422E+00   0.5325758E+00   0.2066227E+00   0.2024037E+00   0.3101160E+00   0.2384299E+00   0.6598682E+00   0.1248762E+01   0.9968187E+00   0.9981910E+00   0.6611572E+02   0.6681633E+00   0.3318367E+00   0.1450554E+00   0.6451439E-03   0.9590442E-01   0.8370717E+00   0.4821974E+00   0.6353218E+00   0.1029462E+01   0.2543836E+01   0.1138763E+02   0.2200845E+01   0.1829359E+01   0.1218436E+04   0.5524315E+04   0.2451456E+04   0.7855802E+03   0.2219278E+03   0.9585111E+00   0.2452473E+00   0.2465732E+00   0.2650759E+01   0.1385349E+02   0.1090526E+04   0.1440652E+03   0.1040627E+01   0.1384408E+02   0.1059361E+04   0.1468229E+03   0.1409091E+00   0.1610448E+00   0.3450975E+04   0.1053267E-01   0.8034780E+00   0.4444658E+00   0.1137244E+00   0.7910790E+02   0.1009162E+04   0.3515068E+00   0.7049756E-01   0.9239276E+02   0.1407670E+04   0.6811109E+00   0.4986407E+00   0.7037144E+00   0.4916913E+00   0.6178100E+00   0.3612763E+04   0.1049756E+05   0.6964181E+03   0.4869998E+00   0.1972903E+00   0.1102911E+02   0.1891800E+01   0.4420137E+02   0.1411032E+05   0.1360520E+02
   0.4000000E+01   0.7284871E+04   0.2198426E-01   0.1221917E+00   0.1040366E+01   0.1098112E+00   0.3125897E+01   0.9607862E+00   0.1000165E+01   0.1525372E+00   0.3207994E+01   0.8596888E+02   0.1055351E+00   0.3467409E+01   0.2893997E+03   0.4493034E+02   0.2553329E+02   0.7202911E+02   0.6357391E+01   0.1250935E+02   0.8057744E+01   0.2133231E+02   0.6452248E+02   0.6871896E-01   0.7897106E-01   0.1537515E+00   0.1198039E+00   0.4199892E+00   0.5379834E+00   0.1532049E+00   0.1571962E+00   0.4808829E+00   0.2579597E+00   0.7759683E+00   0.1462243E+01   0.9989428E+00   0.9984782E+00   0.6609619E+02   0.6685035E+00   0.3314965E+00   0.1448211E+00   0.6451439E-03   0.9572121E-01   0.8520634E+00   0.4905817E+00   0.6465344E+00   0.1048054E+01   0.2582354E+01   0.1288300E+02   0.2278031E+01   0.1828854E+01   0.1221446E+04   0.5509919E+04   0.2451231E+04   0.7856986E+03   0.2223143E+03   0.9607862E+00   0.2452129E+00   0.2465387E+00   0.2665088E+01   0.1386161E+02   0.1090606E+04   0.1441621E+03   0.1040593E+01   0.1385383E+02   0.1059208E+04   0.1469439E+03   0.1407185E+00   0.1611494E+00   0.3445374E+04   0.1051558E-01   0.8042171E+00   0.4449052E+00   0.1137728E+00   0.7907232E+02   0.1009537E+04   0.3514796E+00   0.7052297E-01   0.9234238E+02   0.1408265E+04   0.6810272E+00   0.5074146E+00   0.7163785E+00   0.5004196E+00   0.6289566E+00   0.3312784E+04   0.1050069E+05   0.7015079E+03   0.4721827E+00   0.2234986E+00   0.1081429E+02   0.1822413E+01   0.4143067E+02   0.1381347E+05   0.1333238E+02
```

List of CosmoMC's valid parameter names

You can see a complete list in the file paramnames/params_CMB.paramnames and also in Planck's documentation http://wiki.cosmos.esa.int/planckpla2015/images/b/b9/Parameter_tag_definitions_2015.pdf

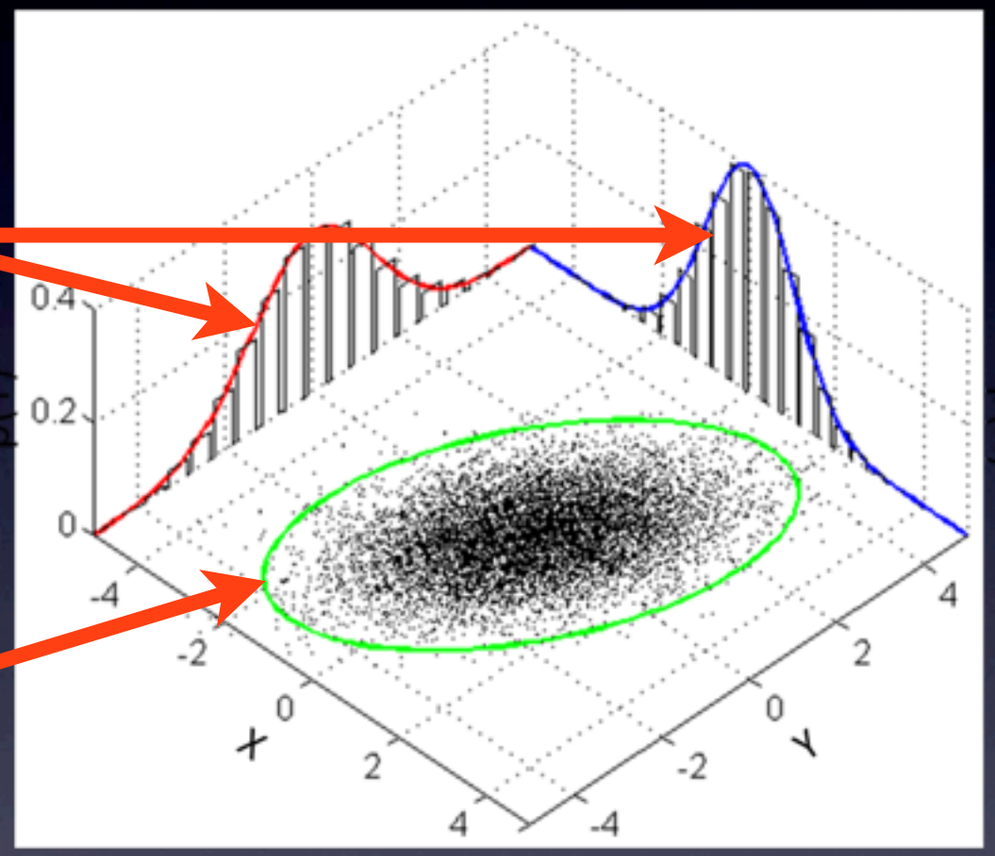
```
omegabh2        \Omega_b h^2      #physical baryon density
omegach2        \Omega_c h^2      #physical CDM matter density
theta           100\theta_{MC} #100 times the ratio of the angular diameter distance to the LSS sound horizon
tau             \tau
omegak          \Omega_K
mnu             \Sigma m_\nu    #sum of physical masses of standard neutrinos
meffsterile     m_{\nu,{\rm{sterile}}}^{\rm{eff}}  #effective mass of sterile neutrino, \approx omeganuh2*94
w               w                 #equation of state parameter for scalar field dark energy today
wa              w_a       #w_a variation
nnu             N_{eff}   #effective number of neutrinos (only clearly defined for massless)
H0*             H_0               #hubble parameter is H0 km/s/Mpc
omegal*         \Omega_\Lambda
omegam*         \Omega_m
```

Parameter Covariance Matrix

- Choosing a good covariance matrix is important because it HELPS the chain to converge faster

- It gives you the optimal sampling step size in each direction of the parameter space (diagonal elements of the matrix)

- But also, if the parameters are correlated, it also gives the direction where to move when we change one of the parameters (off-diagonal elements)



$$C_{ij} = \begin{pmatrix} \sigma_{\theta_1\theta_1} & \sigma_{\theta_1\theta_2} \\ \sigma_{\theta_1\theta_2} & \sigma_{\theta_2\theta_2} \end{pmatrix} \qquad R_{ij} = \frac{C_{ij}}{\sigma_{\theta_i}\sigma_{\theta_j}} = \begin{pmatrix} 1 & \rho_{\theta_1\theta_2} \\ \rho_{\theta_1\theta_2} & 1 \end{pmatrix}$$

Covariance matrix

Correlation matrix

$$\sigma_{\theta_i\theta_i} = \sigma^2_{\theta_i}$$

Modifying a (simple) CosmoMC likelihood

- Let's make a copy of this likelihood to `batch2/HSTnew.ini` because we want to use the new 2.4% determination of H_0 by Riess et al. 2016 http://arxiv.org/abs/1604.01424

```
# Riess et al (2011) value of H0 = 73.8 +/- 2.4 km/s/Mpc
# Riess et al: 1103.2976
Hubble_zeff = 0.04
Hubble_angconversion = 11425.8
#angconversion converts inverse of the angular diameter distance at z = zeff to H0
#for the fiducial cosmology (omega_k = 0, omega_lambda = 0.7, w = -1)
#likelihood is in terms of inverse of the angular diameter distance, so includes the tiny cosmological
#dependence of the measurement (primarily on w) correctly.
Hubble_H0 = 73.8
Hubble_H0_err = 2.4
Hubble_name = HST
use_HST=T
```

73.24

1.74

HSTnew

$$P(H_0) \propto e^{-0.5\left(\frac{H_0-73.24}{1.74}\right)^2}$$

- Now you can `INCLUDE` in your parameter file this new likelihood `batch2/HSTnew.ini`