UNIVERSIDAD DE CÓRDOBA

Bayesian estimation of cosmological parameters with CosmoMC & MontePython

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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?

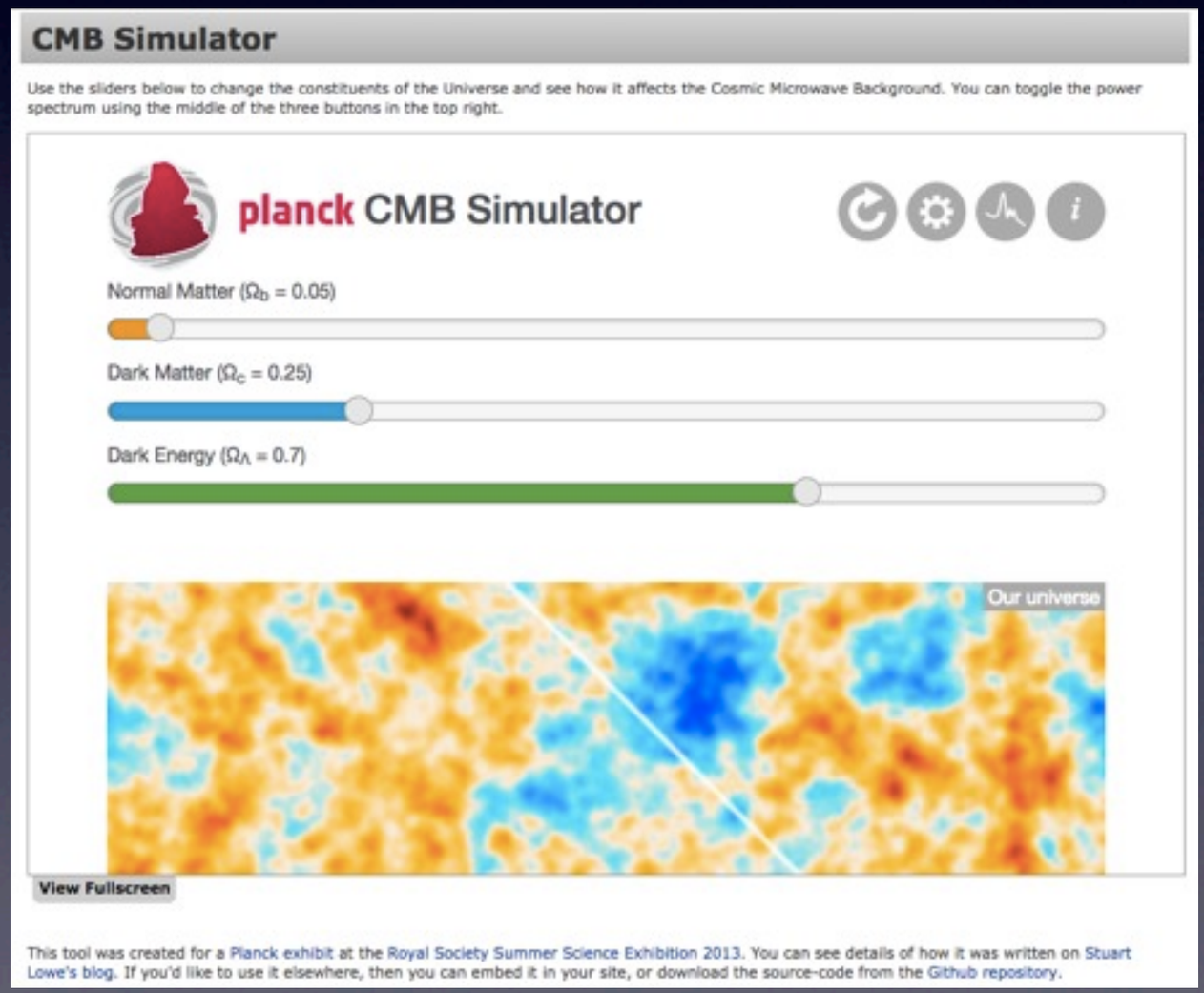
- The resulting constraints on each parameter will depend on these two ingredients:
  the DATA you input (each experiment targets a different cosmological probe)
  the MODEL studied (each model contains a different number of free parameters)

- 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*

- Furthermore, the constraints from two different datasets might appear to be inconsistent ("in tension", i.e. not overlap) in one model but not in another model

Cosmological parameter estimation

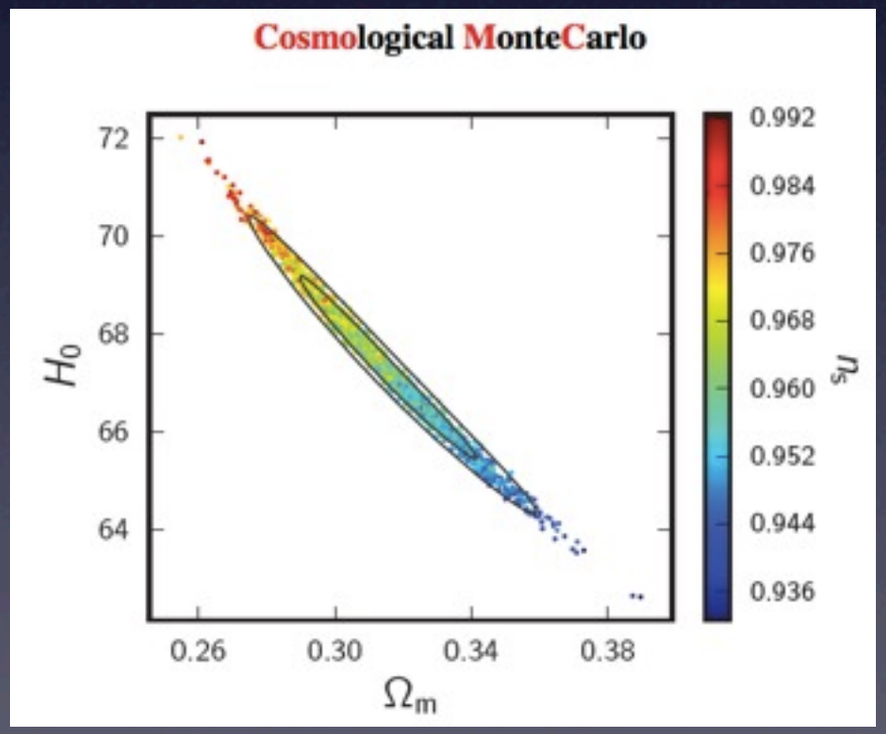
You can estimate parameters by eye (not recommended)...



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)

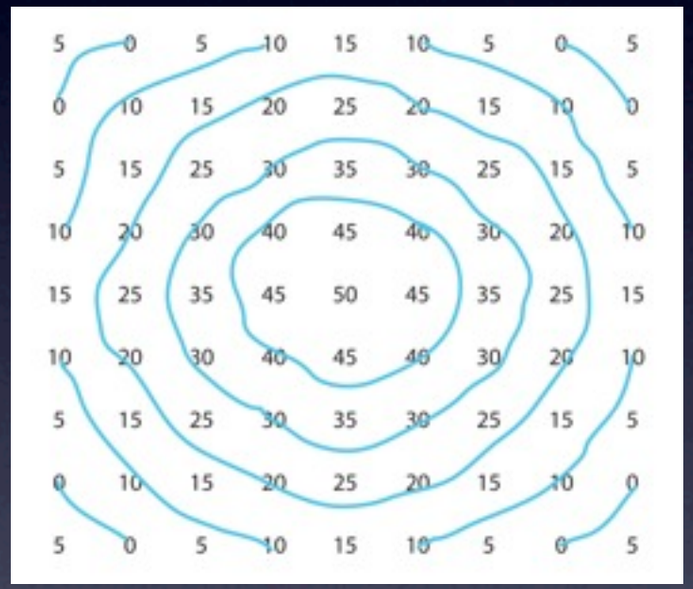
MCMC: How-To?

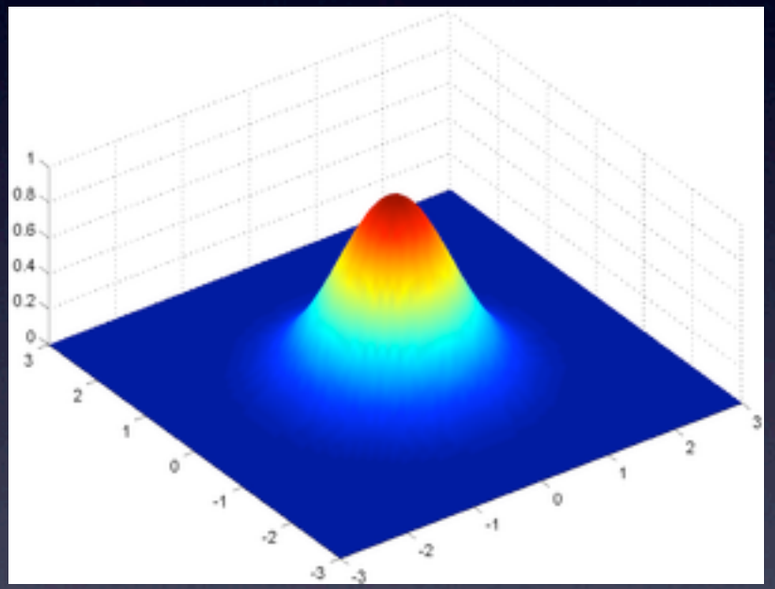
Breaking the code into individual tasks

- 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)

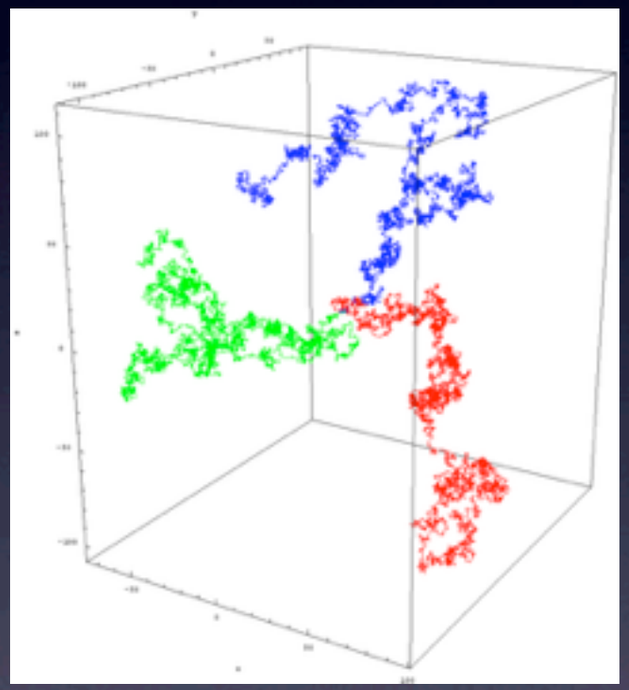


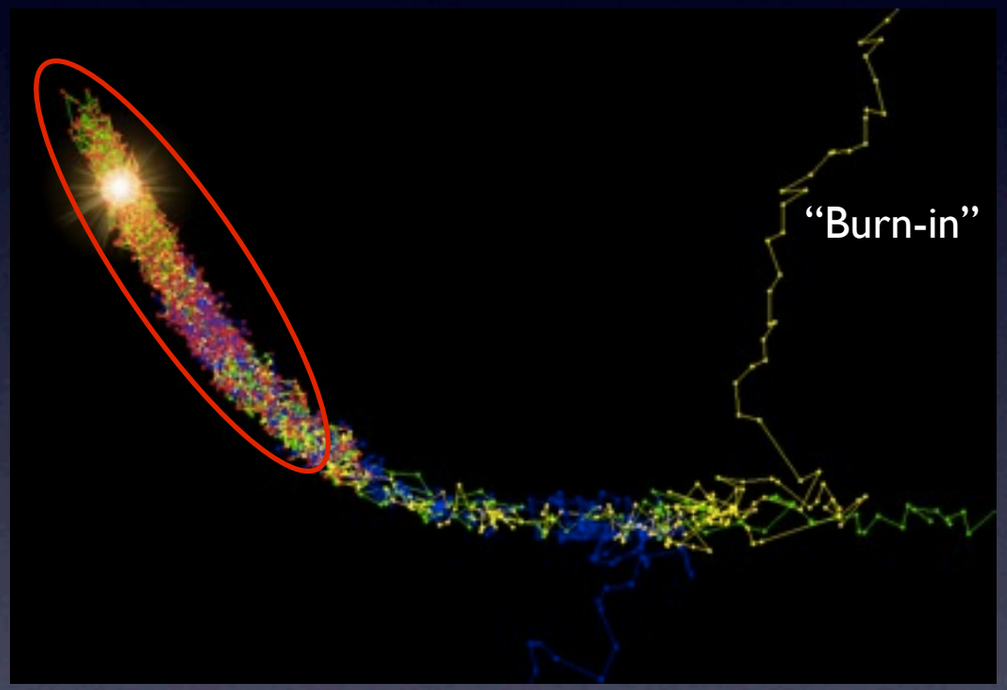


- Number of (potentially) visited points: N^d (grows exponentially with *d*).
  N depends on how fine the spatial discretization (resolution) you want it to be.
  Usually one computes the distribution in all the points (even away from the peak).

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.
  (M initial conditions)

- 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 —

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

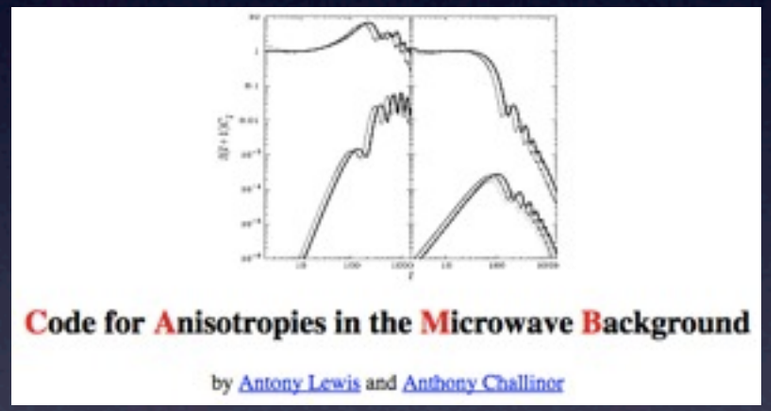
$$\dot{\theta} = -\frac{\dot{a}}{a}(1-3w)\theta-\frac{\dot{w}}{1+w}\theta+\frac{\delta P/\delta\rho}{1+w}k^2\delta-k^2\sigma\,,$$

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

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

H_0, Ω_b, Ω_m, n_s, τ, A_s

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

In general, if the data is a vector of values:

$$\chi^2 = \left(\vec{T} - \vec{D}\right) C^{-1} \left(\vec{T} - \vec{D}\right)$$

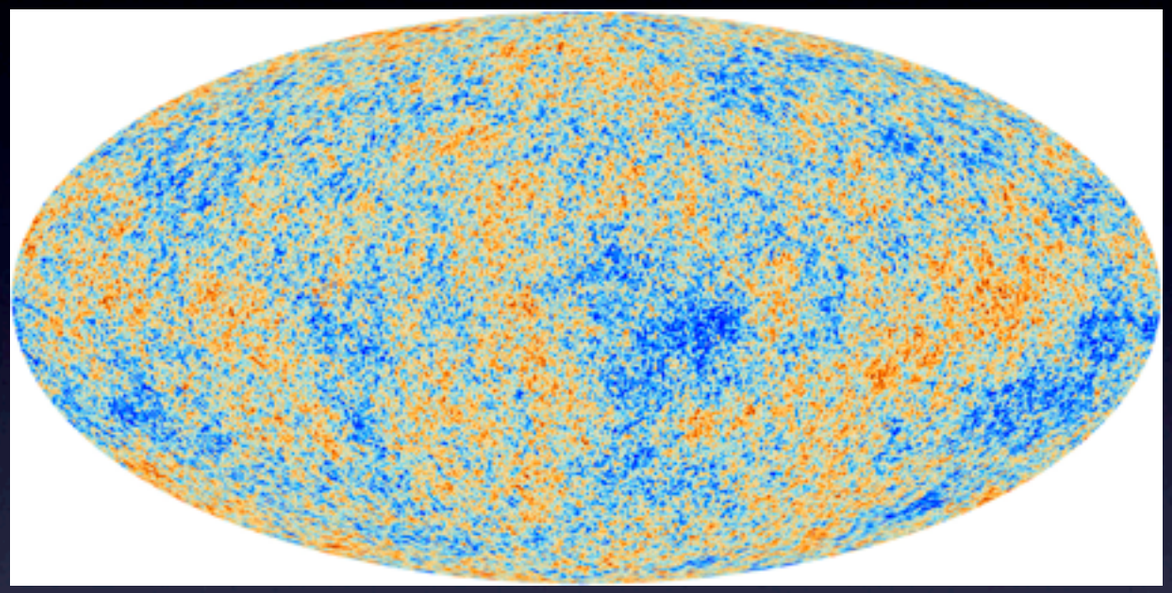
C is the data (not parameter!) covariance matrix

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)

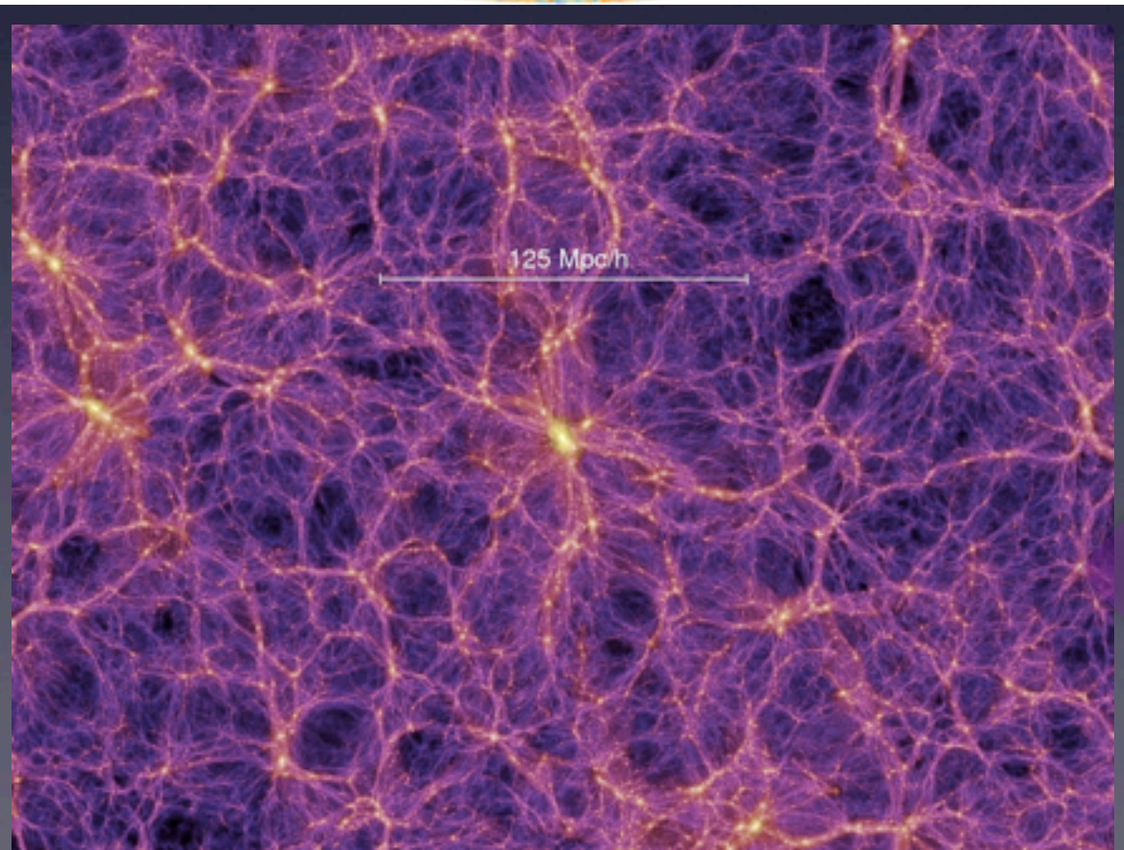
WARNING: If "value" is NOT a MCMC parameter, it might depend on the (cosmological) model!

Cosmological probes
(and most commonly used *observables*)

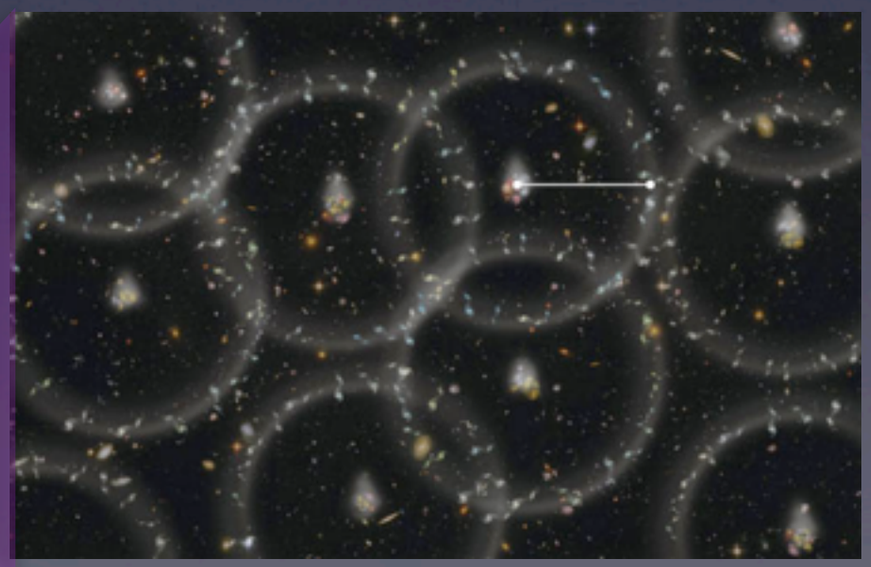


CMB

SNe

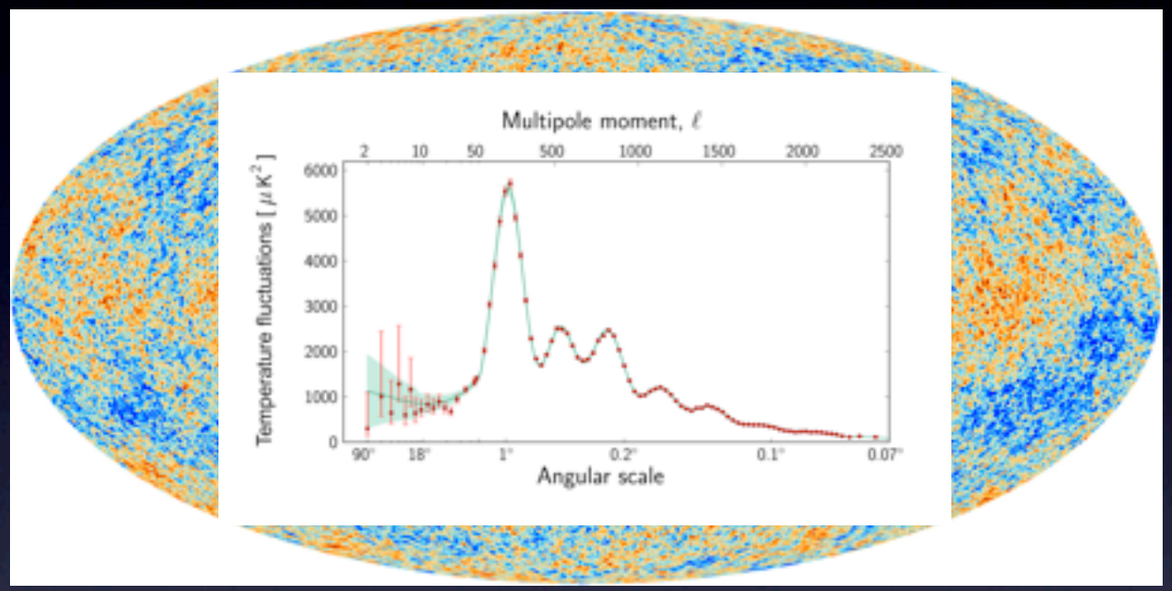


LSS

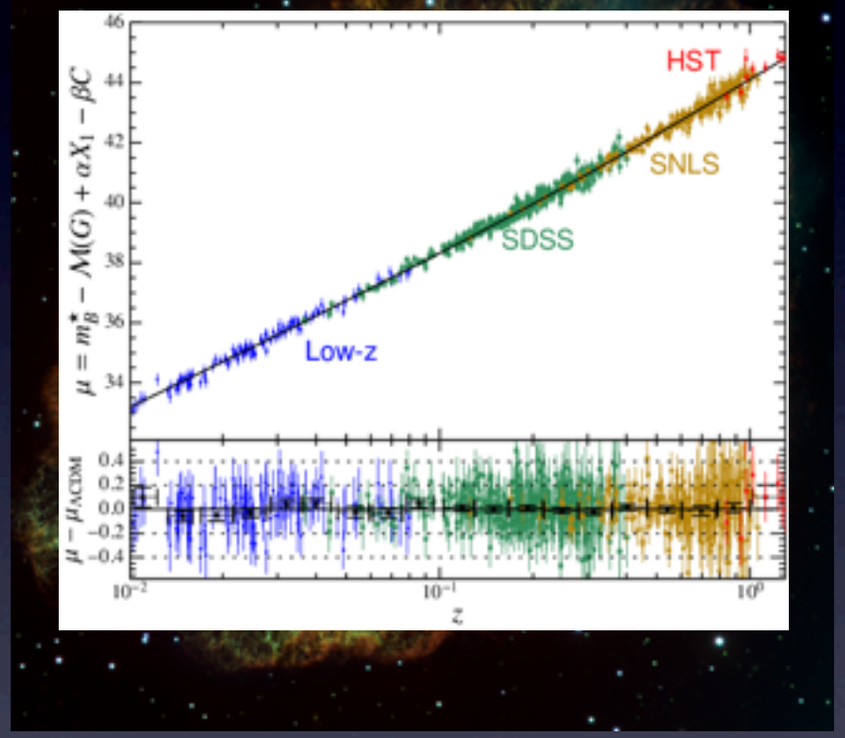


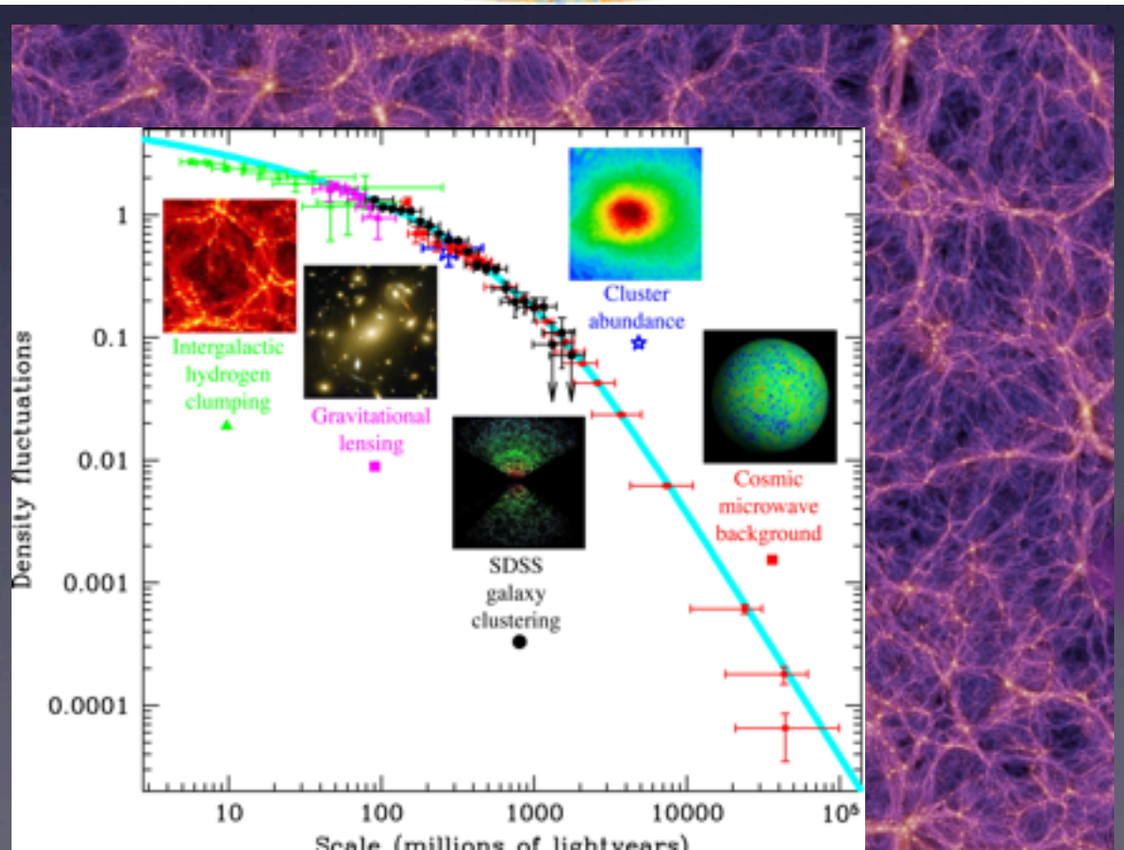
Cosmological probes
(and most commonly used *observables*)

CMB

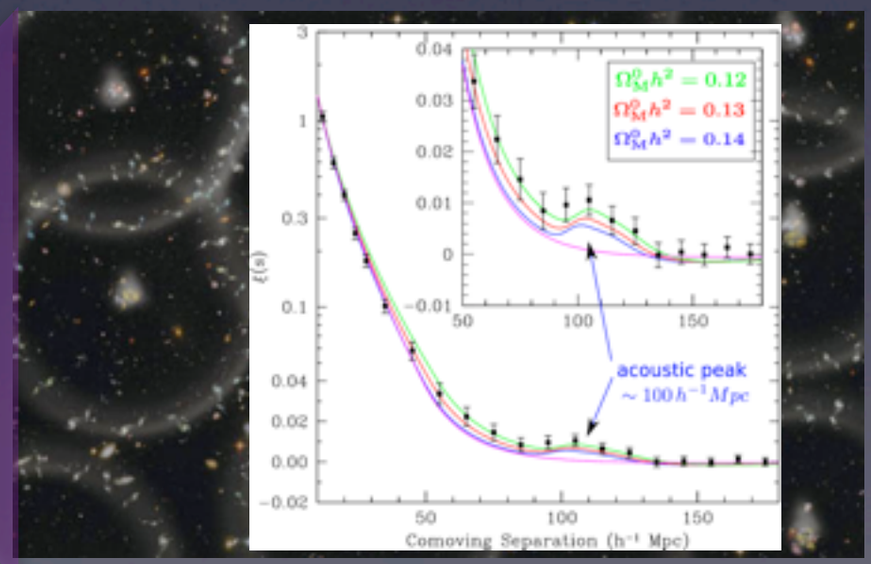


SNe

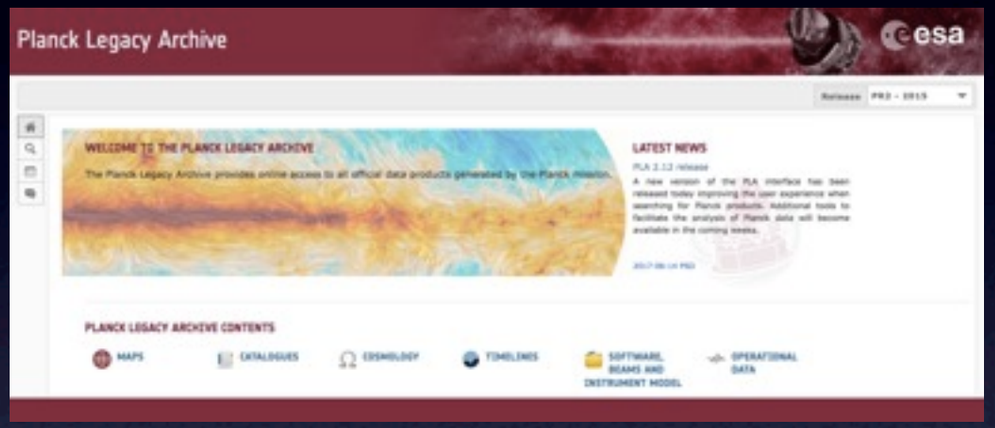




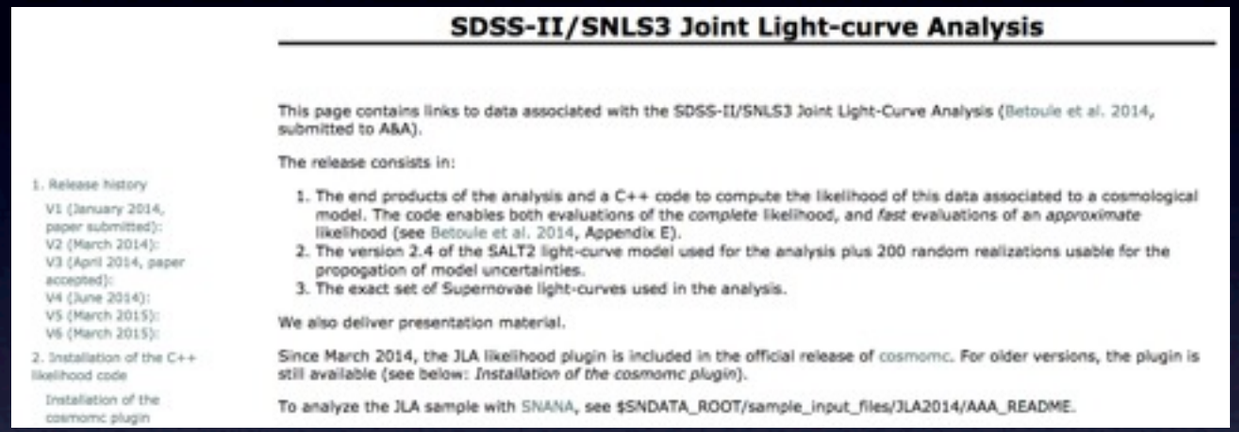
LSS



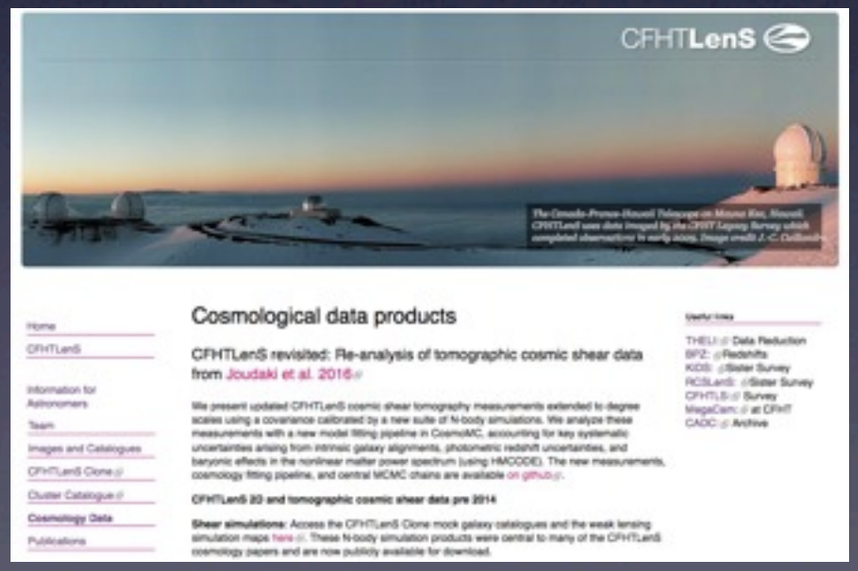
Step 3: Evaluate the likelihood(s)



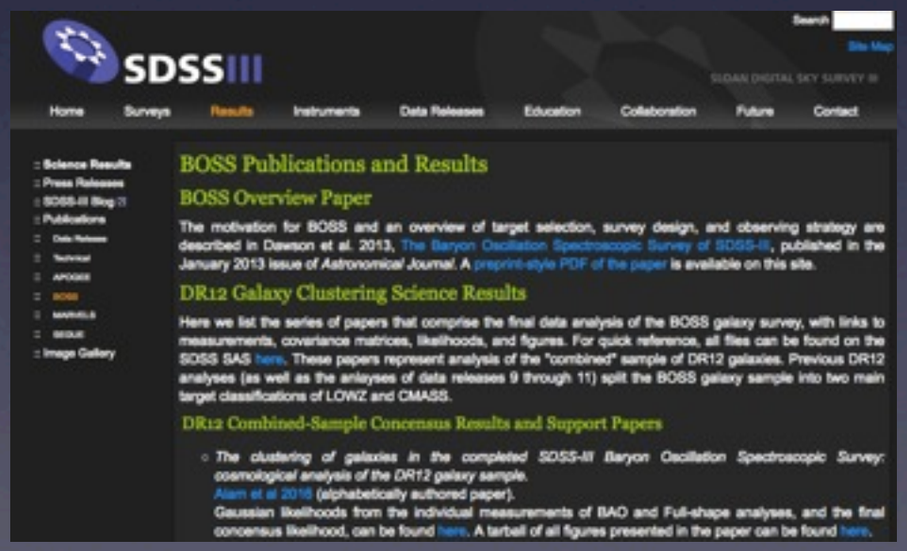
http://pla.esac.esa.int/pla/#home



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

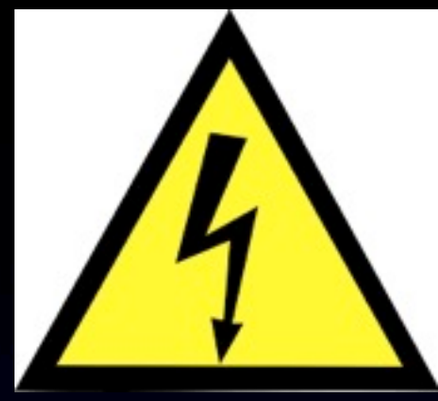
```
AJCuestaMacBookAir:CosmoMC ajcuesta$ ls batch2/
BAO.ini                       WLHeymans.ini                 lowTEB.ini
BAODR11.ini                   WLonly.ini                    lowl.ini
BAO_RSD.ini                   WLonlyHeymans.ini             lowl_old.ini
BK14                          WMAP.ini                      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

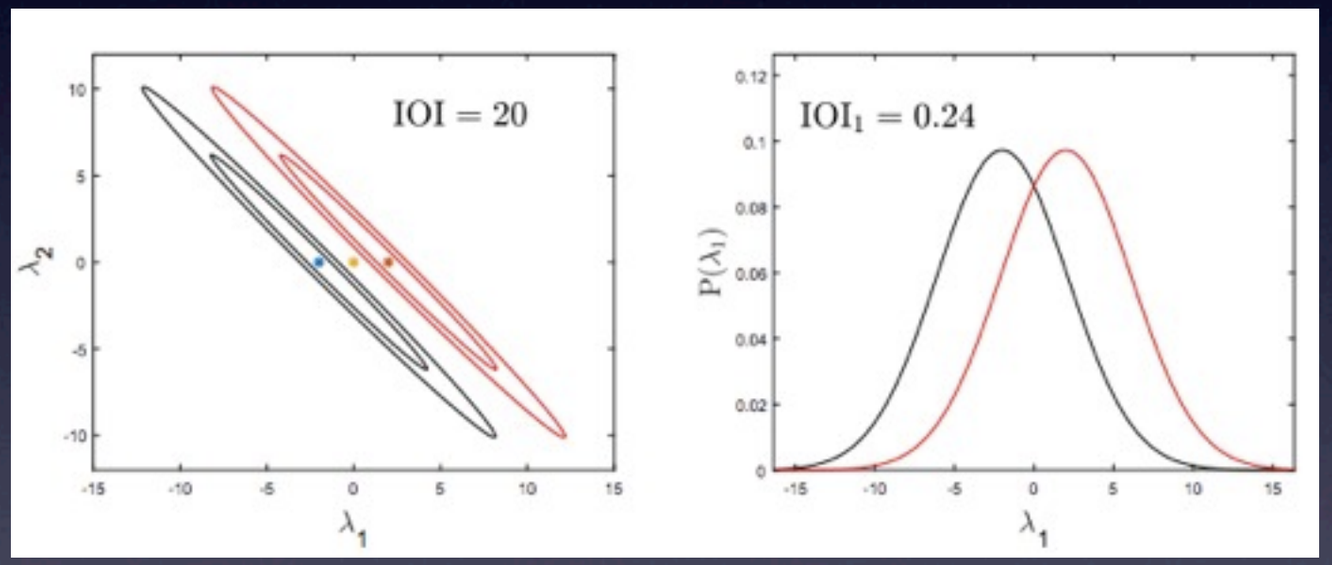
CMB from Planck (TT, TE, EE) and others, BAO (eg. BOSS), SNe (JLA), matter power spectrum, Hubble constant, Bicep/Keck CMB B-modes, Euclid/DESI mock likelihoods (for forecasts),....

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)



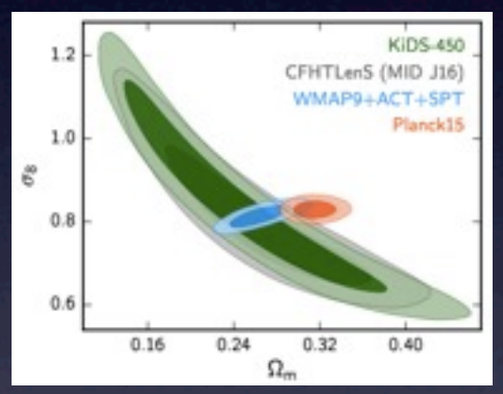
arXiv:1705.05303

- 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

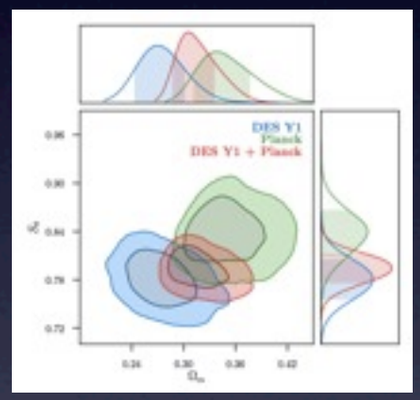
try to be minimalistic!

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)

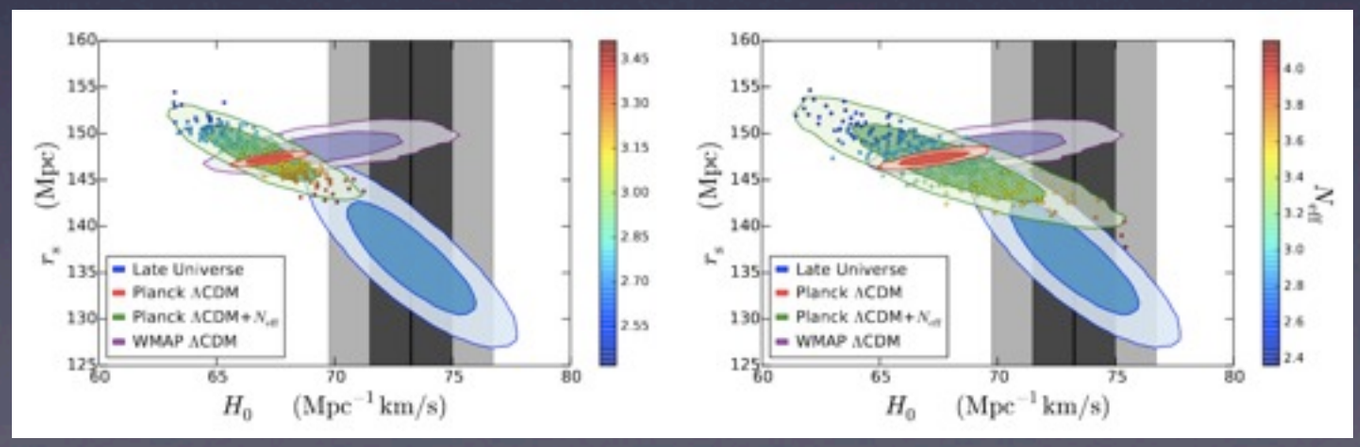


KIDS-450, arXiv: 1606.05338



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 ?)

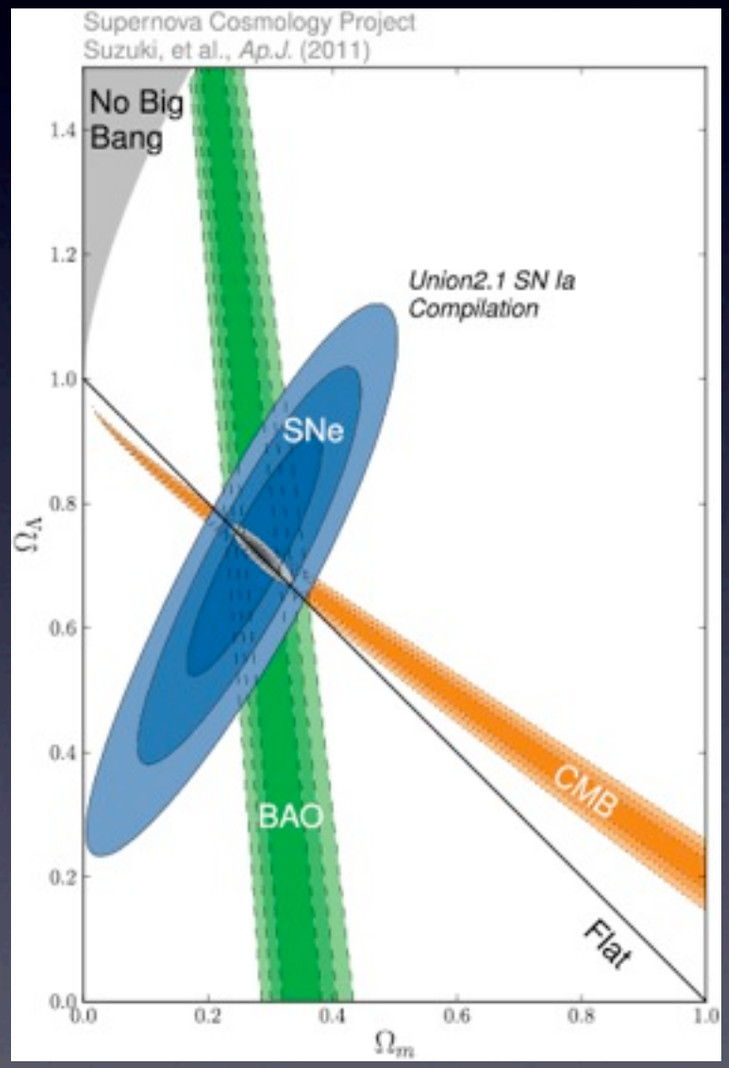
Step 4: Decide whether to accept the point & Write to file

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

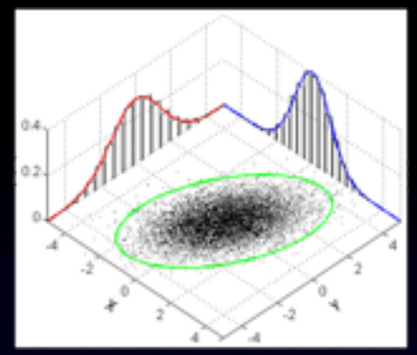
- For a *fixed* model, different datasets will allow different regions of the parameter space. If we combine all datasets, the allowed region will be the *intersection* of the individual allowed regions

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

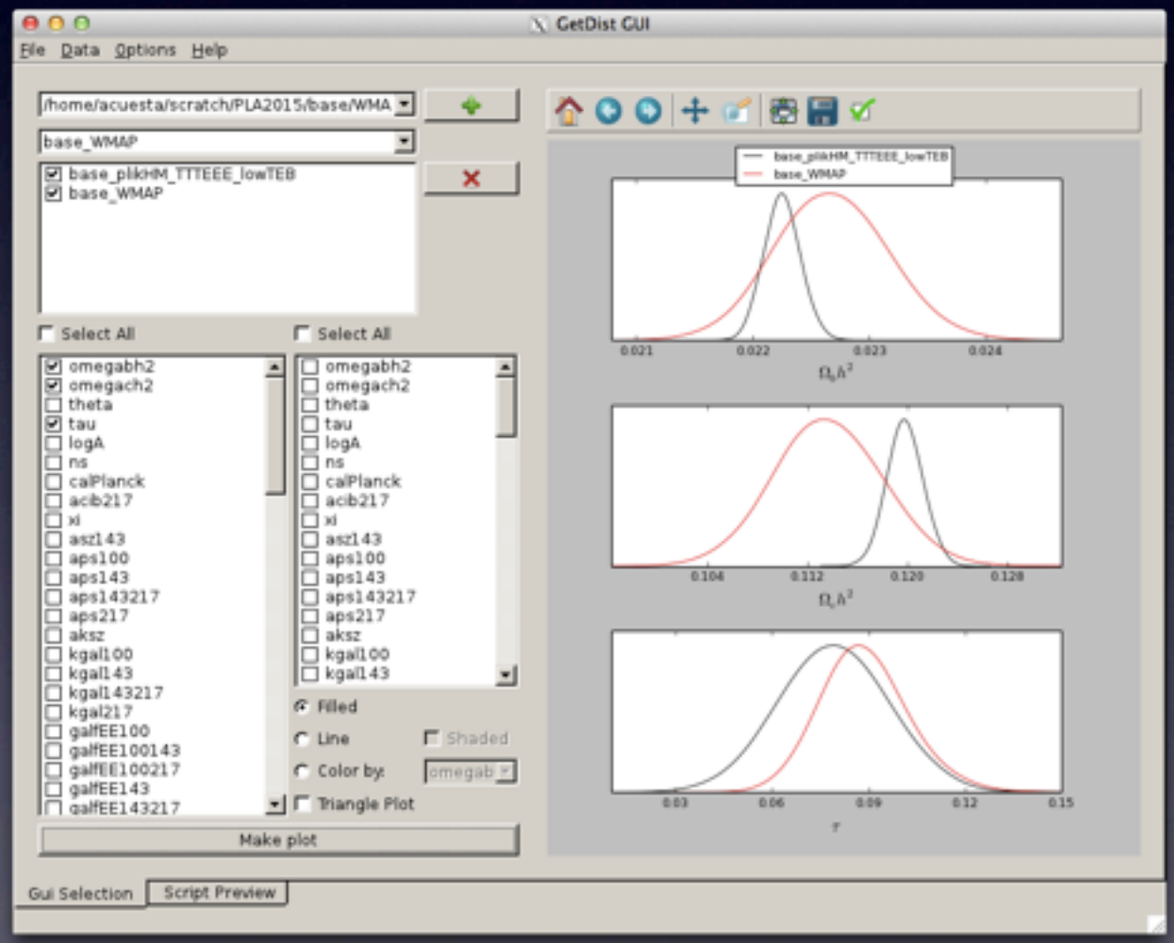
- Depending on this comparison, it will move to the new point or otherwise, it will count the previous point twice (the *multiplicity* of the point will be >1)



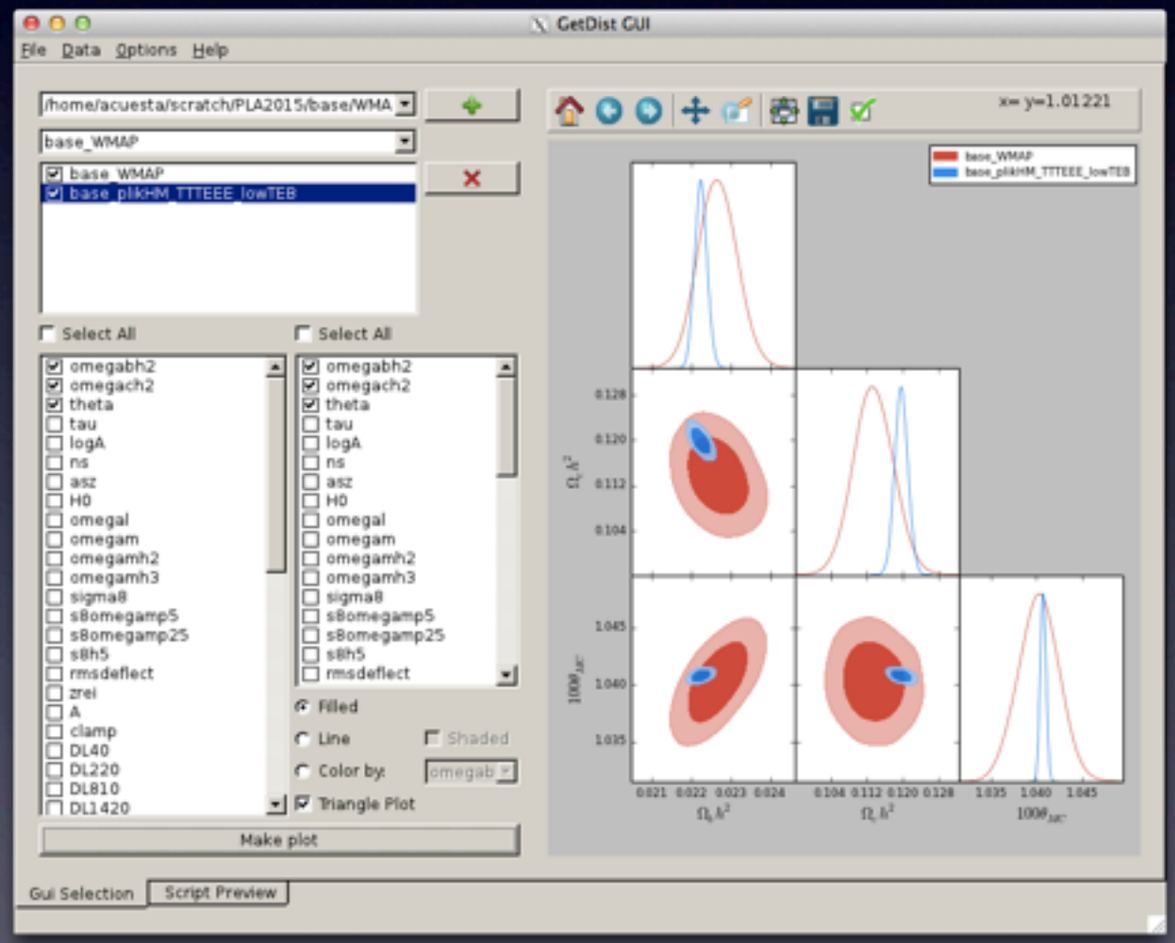
Step 5: Analysis of the results



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

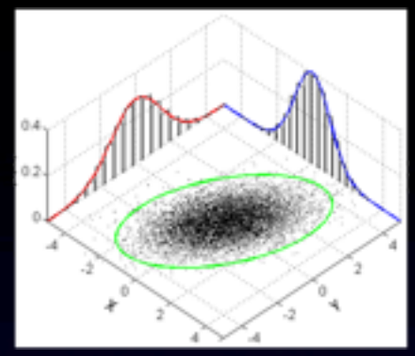


1D Plot
(mean values and standard deviations)



2D Plot
(correlations, degeneracy directions)

Step 5: Analysis of the results



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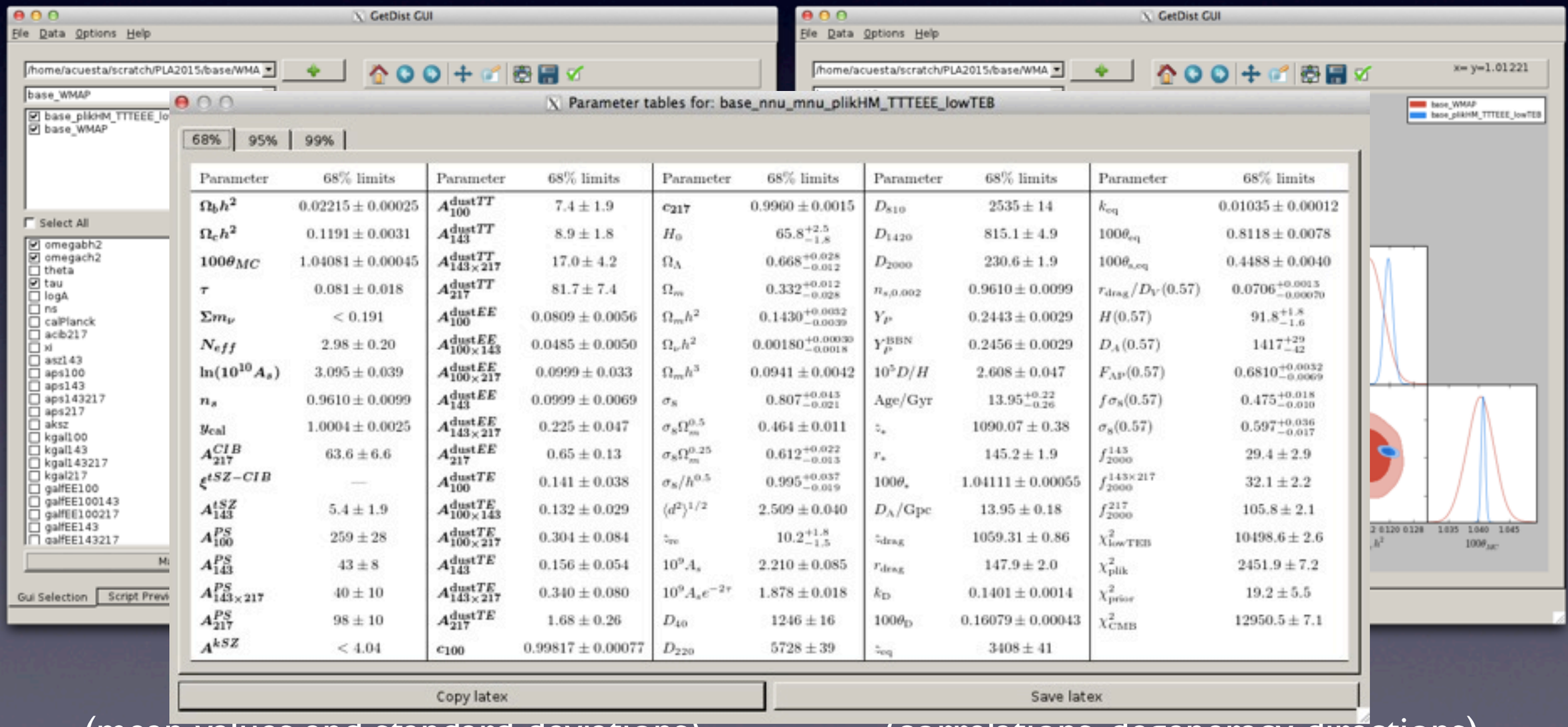
This requires *marginalization*: integrate the *d*-dim PDF over all other parameters



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		

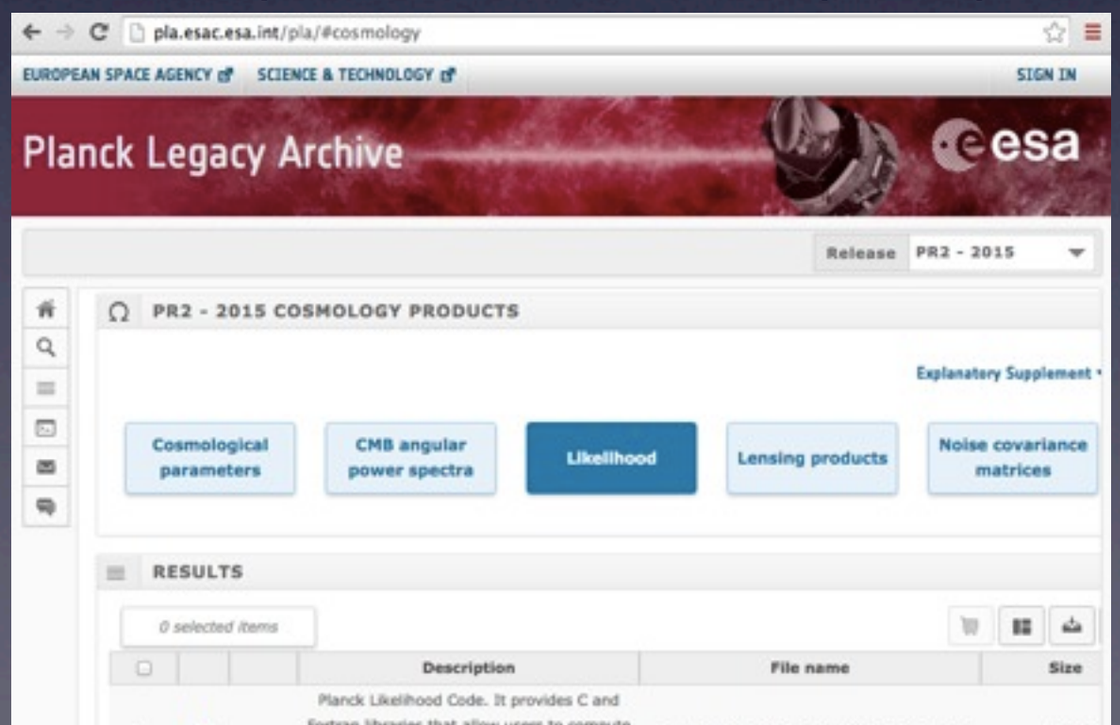
(mean values and standard deviations)

(correlations, degeneracy directions)

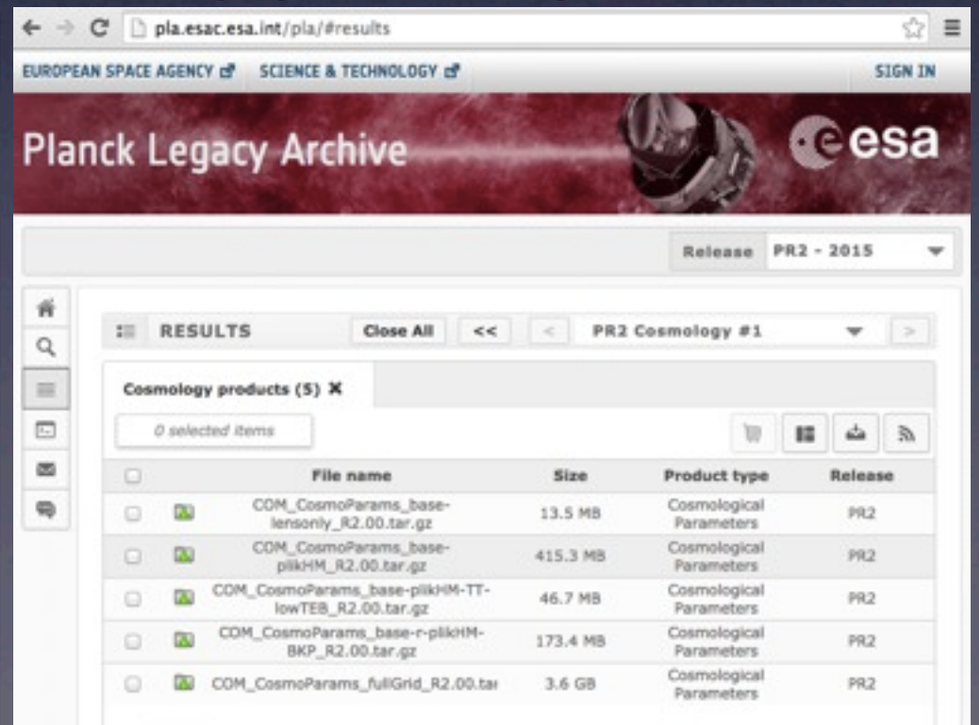
Planck's public chains

- 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
```

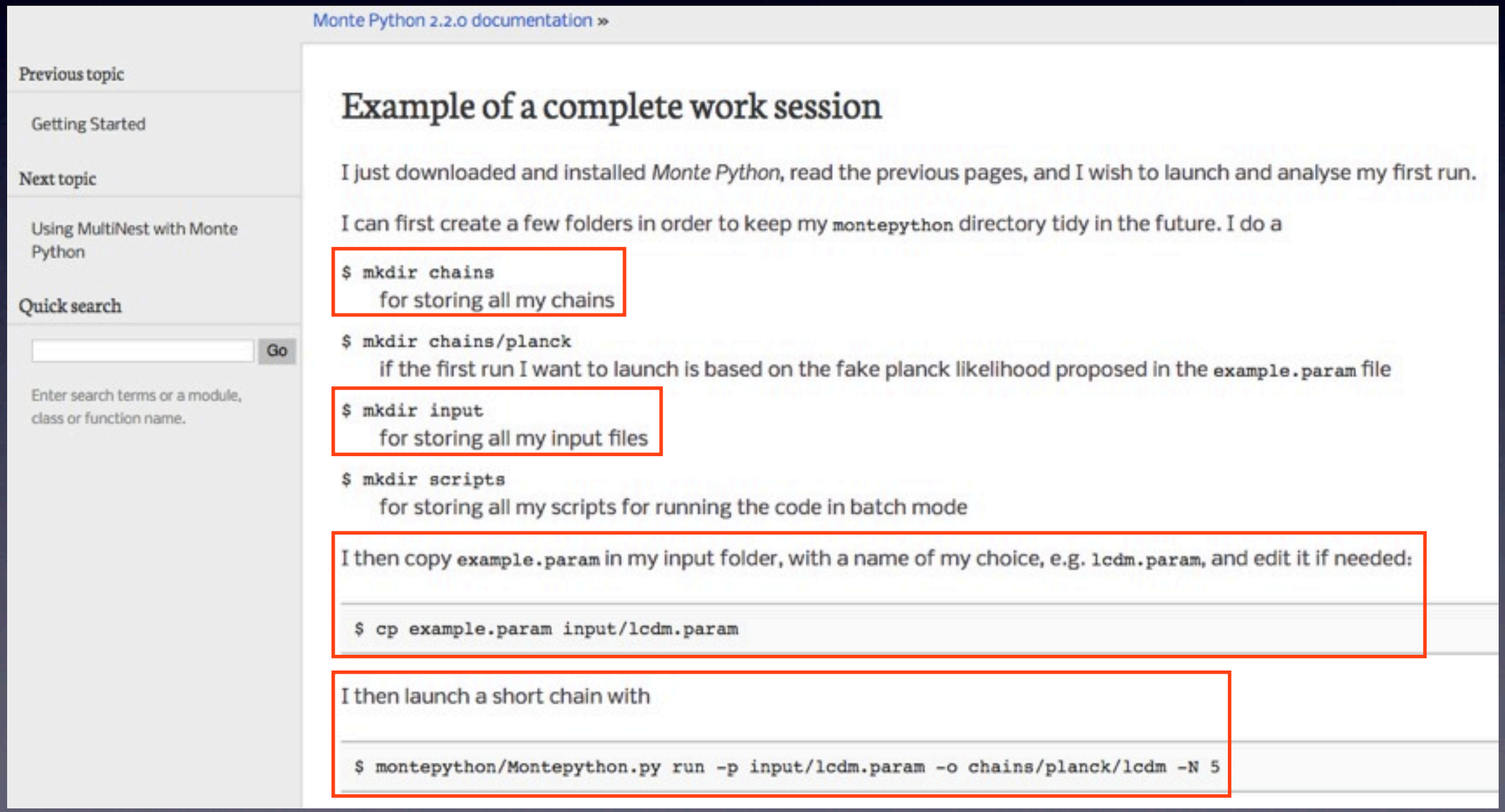
(from Miguel Zumalacarregui's notes)

- 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)

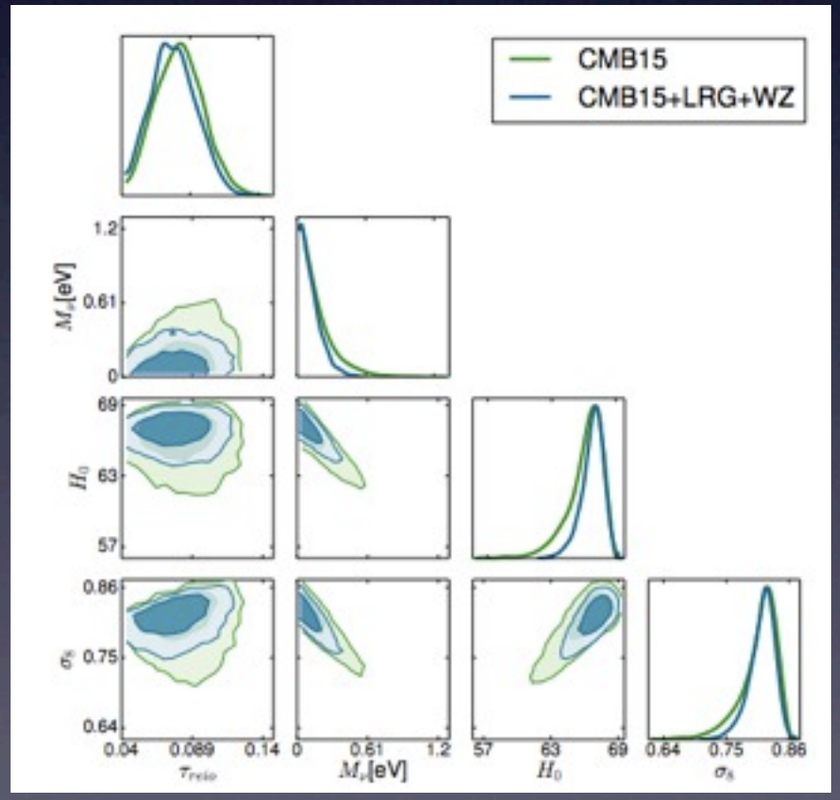
Plotting your results with MontePython info

- 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',...]

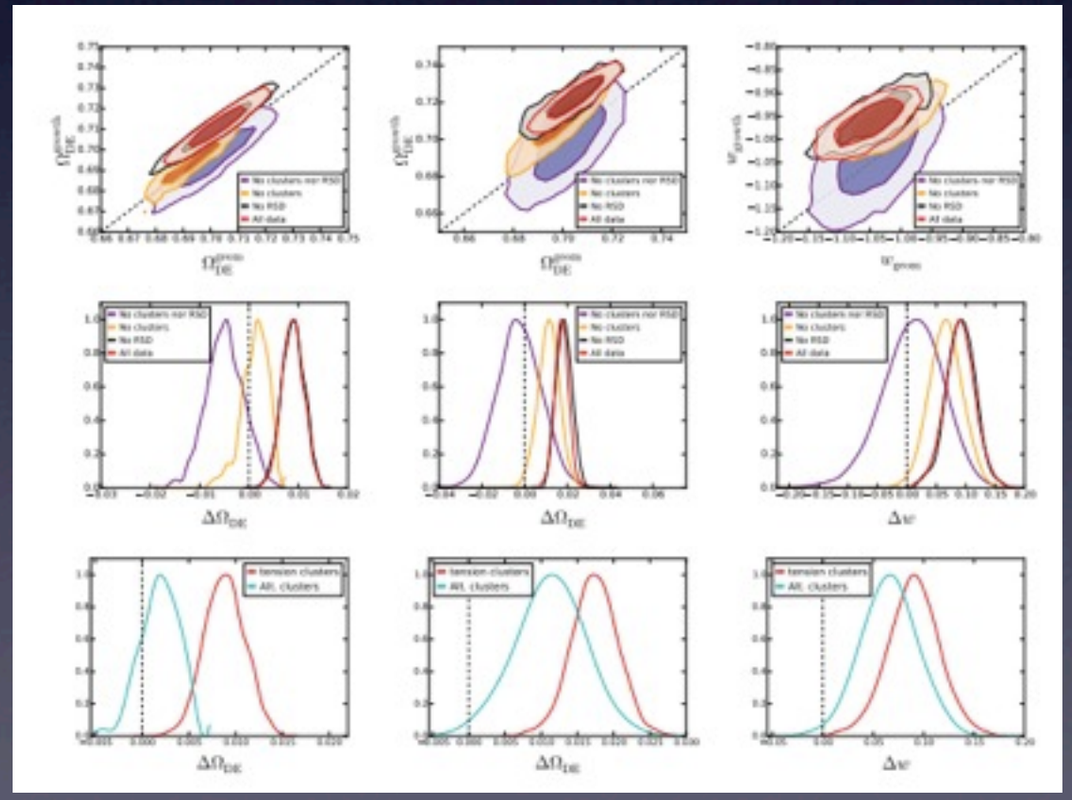
Plotting your results with MontePython info

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
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 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
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 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
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 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)

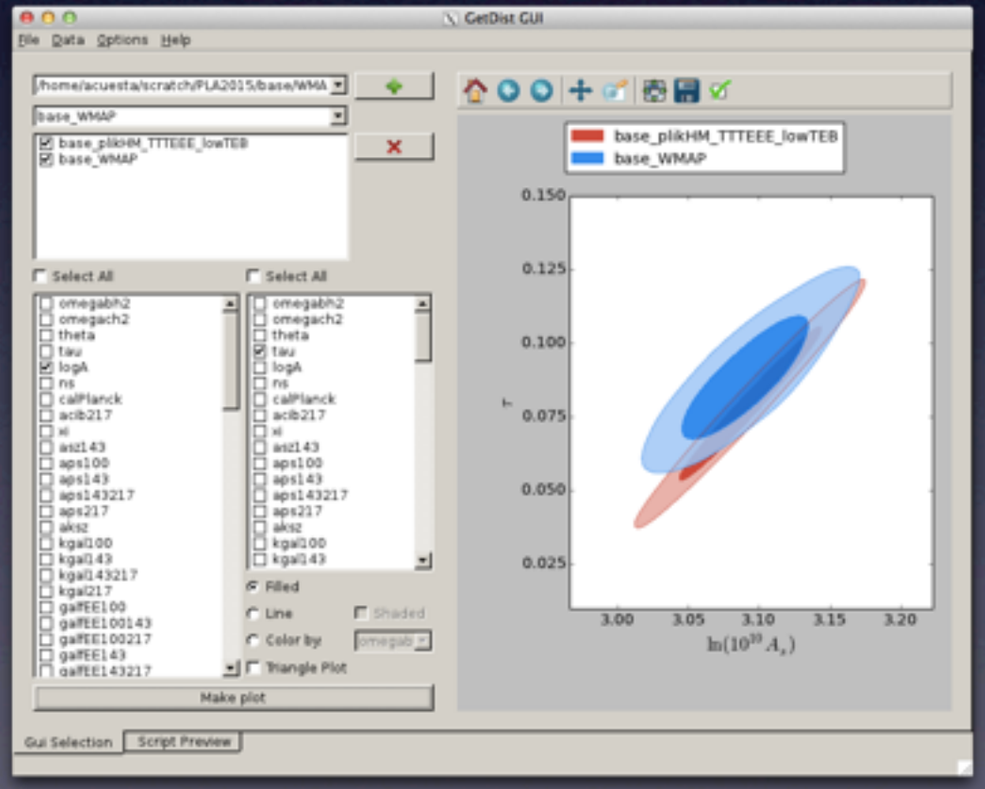
MCMC Convergence status

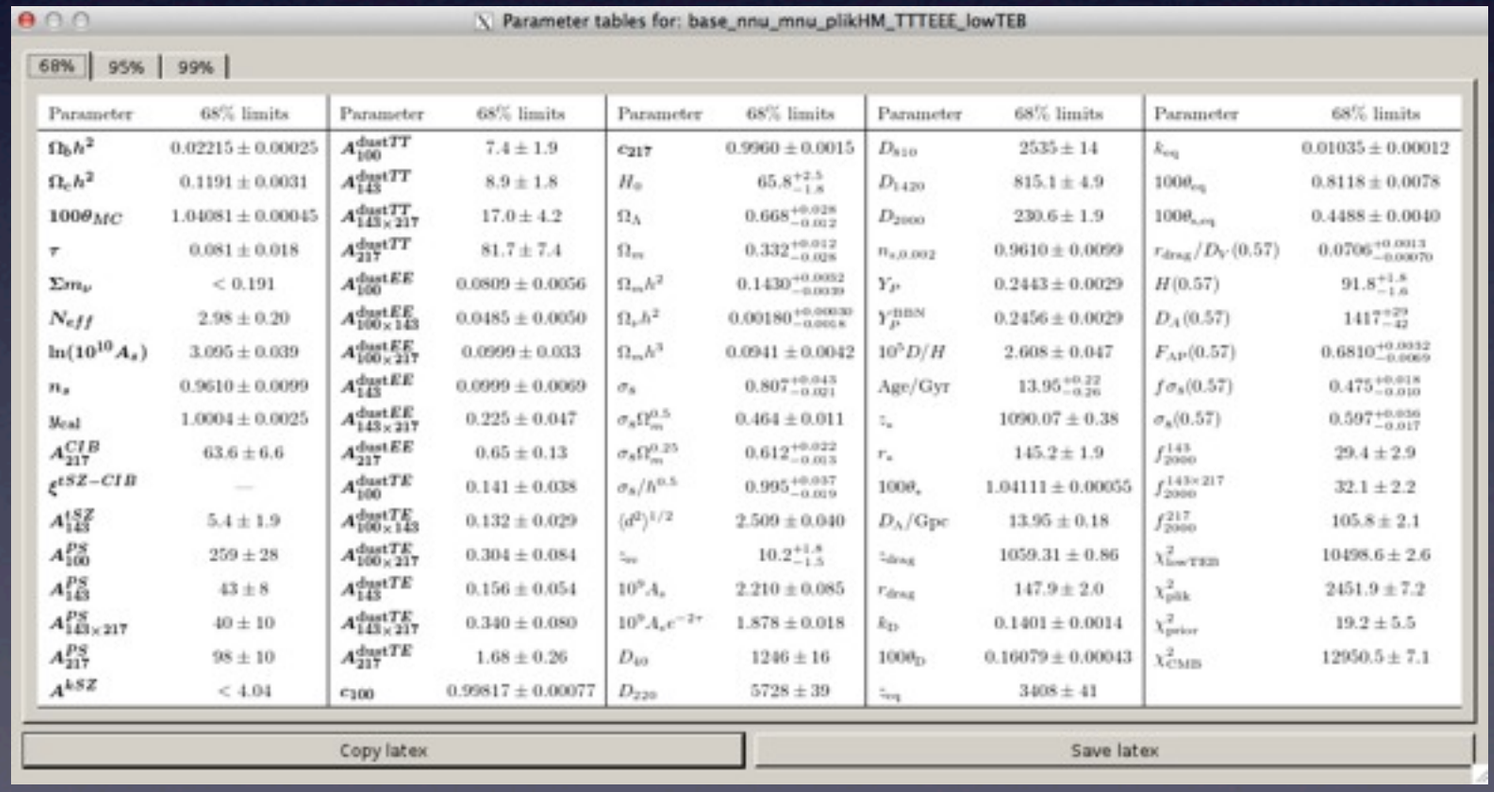
number of parameters (cosmo+nuisance+der)

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

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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

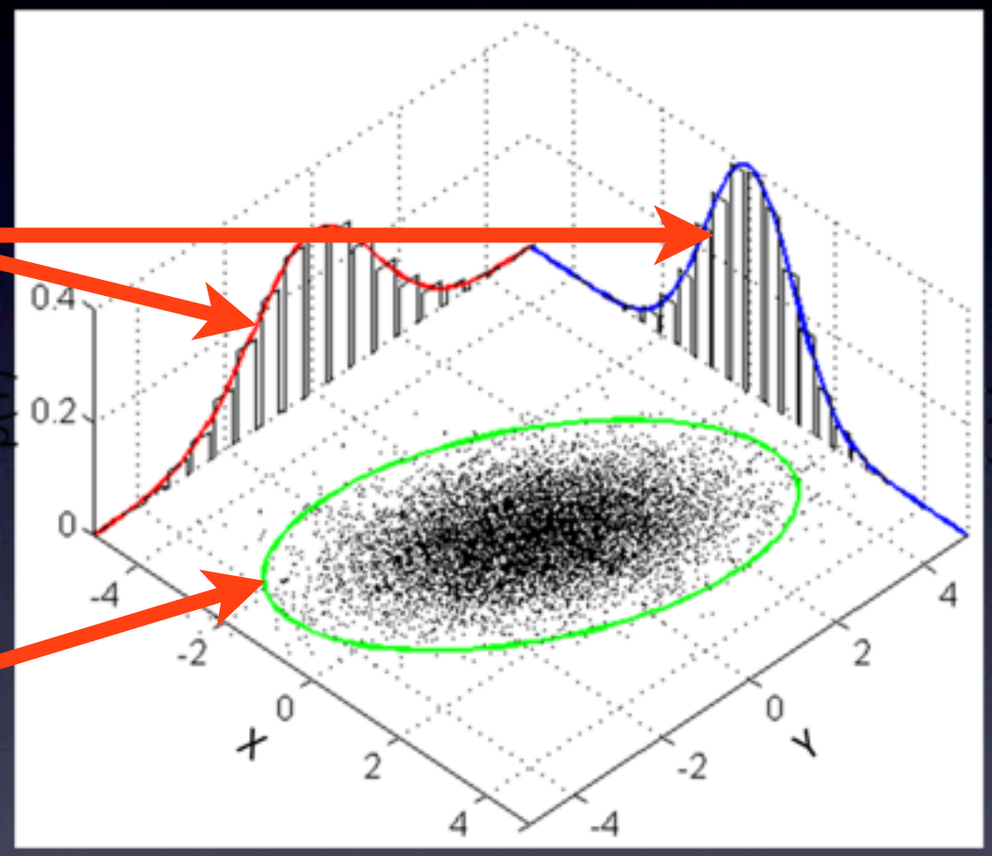
```
omegabh2        \Omega_b h^2      #physical baryon density
omegach2        \Omega_c h^2      #physical CDM matter density
theta           100\theta_{MC} #100 times the ratio of the angular diameter distance to the LSS sound horizon
tau             \tau
omegak          \Omega_K
mnu             \Sigma 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 much 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`