Disentangling late-time cosmology effects from early cosmology in the CMB

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With Karim Benabed and Simon Prunet

Based on *1210.7183* and *1308.xxxx*$\pm$*0001.xxxx*

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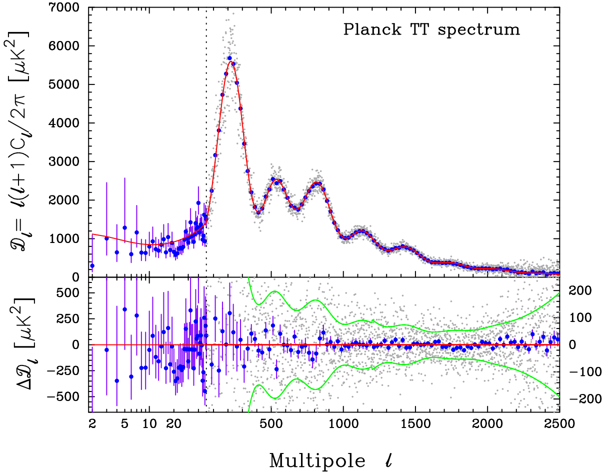
Outline

1. Problematic: Observing the Early Universe
2. Agnostic constraints on early parameters
   - Designing the agnostic study
   - Results
3. Constraining late homogeneous parameters
   - Homogeneous and perturbed probes
   - Procedure
   - Preliminary Results
4. Conclusion

Observing the early universe



Standard Model

Flat geometry

A_s

n_s

$\omega_{\rm b}$

$\omega_{\rm cdm}$

Ω_Λ

$\tau_{\rm reio}$

Tensions in Planck

"Anomalies"

Warning: on the significance of anomalies. . .

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But if we agree to go on:

- Anomalous lensing amplitude from Planck Temperature alone (CMB is being lensed too much)
- Tension with **local** Hubble rate measurement

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Suggestion

Could this come from (possibly incorrect) assumptions about the late time universe, **contaminating** our knowledge ?

Original idea by Vonlanthen, Rasanen, Durrer, 1003.0810

Observing the early universe

Trying to disentangle the signals

Early cosmology

- Inflation gives you an initial spectrum of perturbation $P(k) = \mathbf{A_s} \left(\frac{k}{k_0}\right)^{\mathbf{n_s}-1}$
- Initial amounts of baryons, CDM

Late cosmology

- Structures form, over-densities collapse: **non-linear**
- Universe present-day acceleration Ω_Λ: inhomogeneous universe ? cosmological constant ? Varying dark energy ? Something funnier ? **unknown, Ockham's razor at best**
- Reionization τ_{reio}: at one or several redshift ? With which shape ? **phenomenological description only**

Observing the early universe

Questions

Cosmic Microwave Background

- Do assumptions on the late time universe impact our knowledge of the early universe ?

Observing the early universe

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- And if yes, **what can we do with it ?**

Observing the early universe

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Agnostic approach

I don't know which model for the late evolution is true, if any.

What is left to me ?

Contamination in detail

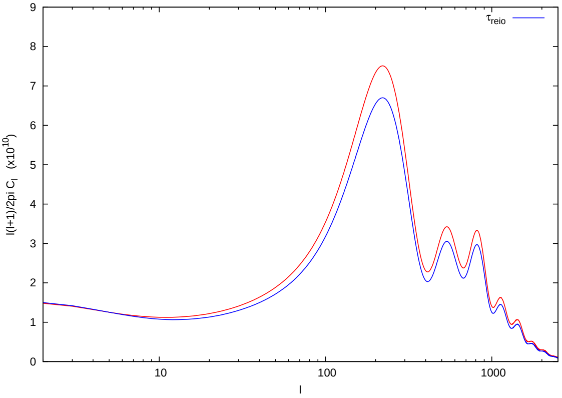
Contamination coming from...

- Reionization (phenomenological description)
- Dark Energy (no consensus besides Ockham's razor)
- Lensing from Large Scale Structures

Contamination in detail

Contamination

- Reionization
- Dark Energy
- Lensing LSS



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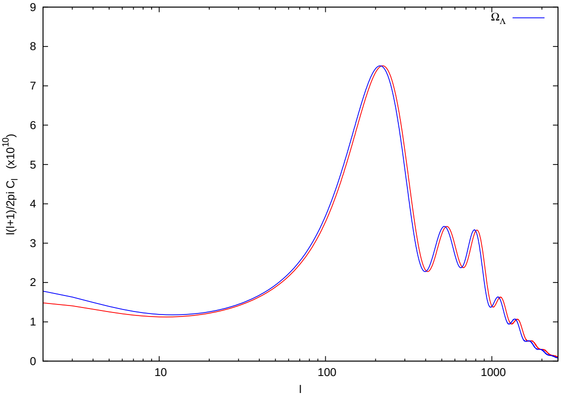

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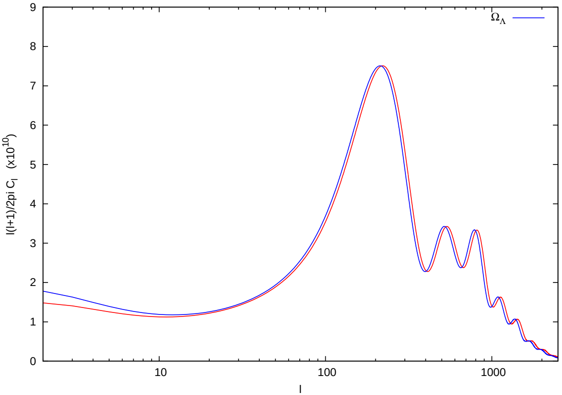

Questions

How do we get rid of this contamination ? *i.e.* how do we **forget** about this information ? Is it important ?

Solution: Combining parameters and trimming data

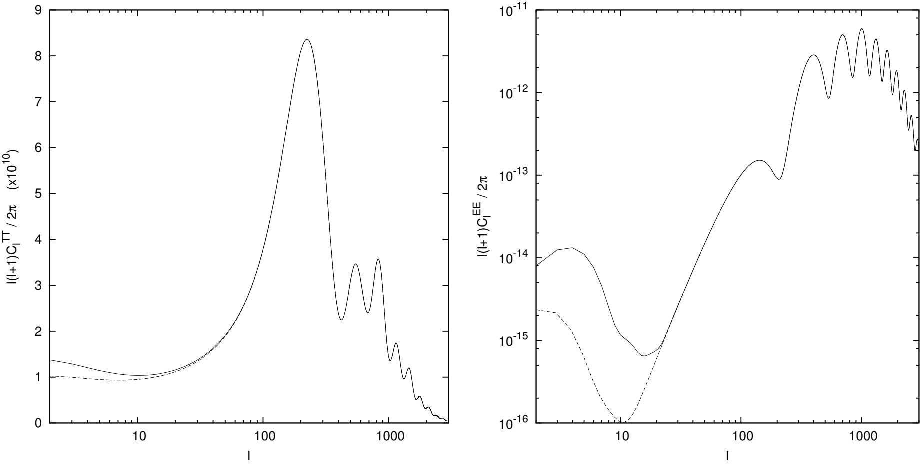

Figure: 2 ΛCDM Models with different late time evolution, rescaled and shifted

Combining parameters

Shift and Scaling

- $C_\ell \to C_{\beta\ell}$ Ω_Λ, controlling $d_A^{\rm rec}$
- $C_\ell \to \alpha C_\ell$ $\tau_{\rm reio}$, appearing in the combination $A_s e^{-2\tau}$

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Marginalizing: Lensing contaminates also ! (sorry SPT. . .)

Starting from lensing potential predicted from ΛCDM model, one can add

an arbitrary

- amplitude A_{lp}
- tilt (running of the amplitude) n_{lp}
- running of the tilt rn_{lp}
- . . .

and marginalize over it.

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and marginalize over it. **In practice,** A_{lp} **and** n_{lp} **are sufficient.**

Running Strategy

Cosmological parameters

$\{A_s e^{-2\tau}, \mathbf{n_s}, \omega_\mathbf{b}, \omega_\mathbf{c}, d_A^{\rm rec}, A_{lp}, n_{lp}\}$, for $\ell \gg 40$

Use your favorite Monte Carlo code: **CosmoMC** or **Monte Python**

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Testing starting ℓ dependancy

- From $\ell = 2$ to $\ell = 50$: big changes
- From $\ell = 50$ to $\ell = 100$: smaller

Results for WMAP-7 + SPT

	$100\,\omega_b$	ω_{cdm}	n_s	d_A^{rec}(Mpc)	$10^9 e^{-2\tau} A_s$	A_{lp}	n_{lp}
			ΛCDM				
	$2.241^{+0.043}_{-0.044}$	$0.1114^{+0.0048}_{-0.0048}$	$0.960^{+0.011}_{-0.011}$	$12.93^{+0.11}_{-0.12}$	$2.069^{+0.085}_{-0.092}$		
			same lensing potential as in ΛCDM				
$\ell \geq 40$	$2.204^{+0.048}_{-0.047}$	$0.1160^{+0.0056}_{-0.0059}$	$0.946^{+0.014}_{-0.014}$	$12.85^{+0.13}_{-0.13}$	$2.20^{+0.12}_{-0.13}$		
$\ell \geq 60$	$2.203^{+0.050}_{-0.053}$	$0.1163^{+0.0063}_{-0.0065}$	$0.945^{+0.016}_{-0.016}$	$12.84^{+0.14}_{-0.14}$	$2.20^{+0.13}_{-0.15}$		
$\ell \geq 80$	$2.190^{+0.053}_{-0.057}$	$0.1180^{+0.0067}_{-0.0073}$	$0.940^{+0.019}_{-0.018}$	$12.81^{+0.15}_{-0.15}$	$2.26^{+0.15}_{-0.18}$		
$\ell \geq 100$	$2.184^{+0.054}_{-0.056}$	$0.1187^{+0.0067}_{-0.0079}$	$0.935^{+0.020}_{-0.019}$	$12.80^{+0.16}_{-0.15}$	$2.29^{+0.16}_{-0.20}$		
			marginalization over lensing potential amplitude				
$\ell \geq 100$	$2.159^{+0.060}_{-0.064}$	$0.1227^{+0.0083}_{-0.0088}$	$0.926^{+0.022}_{-0.022}$	$12.73^{+0.18}_{-0.17}$	$2.39^{+0.20}_{-0.23}$	$0.88^{+0.12}_{-0.13}$	
			marginalization over lensing potential amplitude and tilt				
$\ell \geq 100$	$2.160^{+0.064}_{-0.068}$	$0.1222^{+0.0088}_{-0.0094}$	$0.927^{+0.024}_{-0.024}$	$12.74^{+0.18}_{-0.18}$	$2.38^{+0.20}_{-0.25}$	$0.78^{+0.20}_{-0.15}$	$-0.16^{+0.55}_{-0.33}$

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Update with Planck Results **(only high-l Planck data)**

Did we gain something, agnostically speaking ?

	$100\omega_b$	ω_c	n_s	A_{lp}	n_{lp}
WMAP-7	2.16 ± 0.07	0.122 ± 0.009	0.927 ± 0.024	0.78 ± 0.18	-0.16 ± 0.4
Planck Agn	2.24 ± 0.04	0.116 ± 0.004	0.966 ± 0.016	0.81 ± 0.25	-0.8 ± 0.5
Planck A_l	2.24 ± 0.04	0.118 ± 0.003	0.966 ± 0.009	1.28 ± 0.14	/
Planck std	2.21 ± 0.03	0.120 ± 0.003	0.962 ± 0.009	/	/

Table: update for agnostic constraints from wmap/Planck.

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Not so much... But: **no lensing amplitude issue!**
Moreover, values slightly shifted for
d_A^{rec} (angular diameter distance at decoupling), and
r_s (comoving sound horizon at baryon drag, derived)

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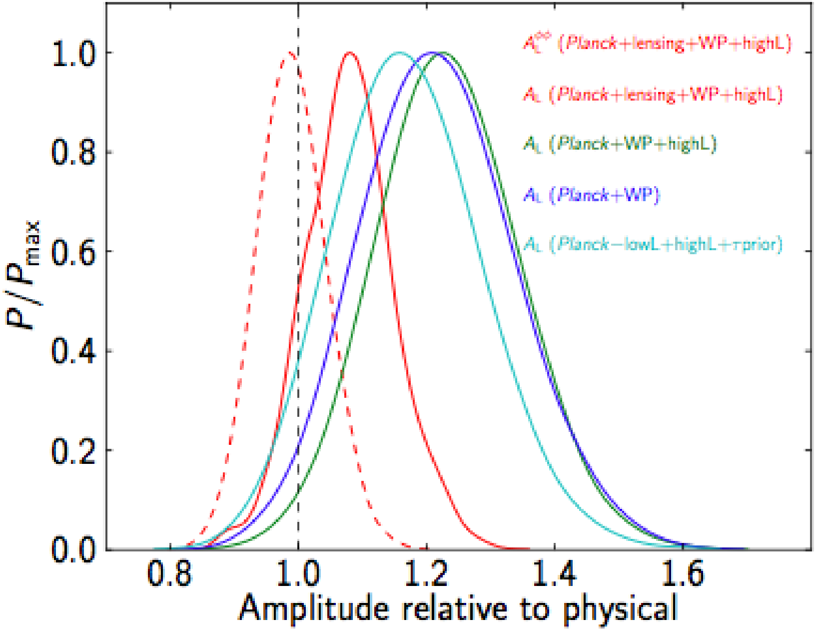
Keep in mind that the data for polarization is missing,
so this picture will change a lot next year


$A_L^{\phi\phi}$ (Planck+lensing+WP+highL)
A_L (Planck+lensing+WP+highL)
A_L (Planck+WP+highL)
A_L (Planck+WP)
A_L (Planck−lowL+highL+τprior)
P/P_{max}
1.0
0.8
0.6
0.4
0.2
0.0
0.8
1.0
1.2
1.4
1.6
Amplitude relative to physical

Conclusion on early agnostic

Ok, so what ?

- CMB alone, without contamination still gives robust prediction, free of assumptions
- Planck improved from WMAP, but not dramatically
- **No evidence for anomalous lensing amplitude**

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What's next ?

Now we can use these clean values to test a late-time model !

Observing the late universe

Homogeneous Quantities

- H_0 local measurements
- SN luminosity distance
- Quasar time-delay
- Baryon Acoustic Oscillations
- CMB: H_0 and Ω_Λ

Perturbed Probes

- galaxy redshift surveys
- weak lensing
- cluster count
- ly-α forest

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Do we understand enough non-linear PT ?

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H_0 local effects

Paper by Marra, Amendola, Sawicki, Valkenburg (1303.3121): this is not enough to make it agree with Planck

Question

Do we understand enough non-linear PT ? . . .

Going for it !

Choosing a model for the late homogeneous universe

And be simple: ΛCDM !

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All **this** for **that** ?

Going for it !

Choosing a model for the late homogeneous universe

And be simple: ΛCDM !

All **this** for **that** ?

Well, now we have a model independant knowledge of the early universe, let's see at least how good old ΛCDM fares in the late one !

At least to describe the homogeneous evolution

Late homogeneous cosmology

What are the problems there ?

$$H_0^{\mathrm{Planck}} = 67.40 \pm 1.4 \mathrm{km\ s}^{-1}\ \mathrm{Mpc}^{-1}$$
$$H_0^{\mathrm{HST}} = 73.8 \pm 2.4 \mathrm{km\ s}^{-1}\ \mathrm{Mpc}^{-1}$$

Bad agreement with HST

Good agreement with BAO

Important

To combine experiments, they must agree with each other, otherwise the new physics might be an artifact.

How does the agnostic knowledge change this picture ?

Late homogeneous cosmology

Strategy

- Agnostic analysis of early cosmology with Planck (fixed n_s, ω_b)
- Assuming flat ΛCDM, homogeneous cosmology: $\{H_0, \Omega_\Lambda\}$

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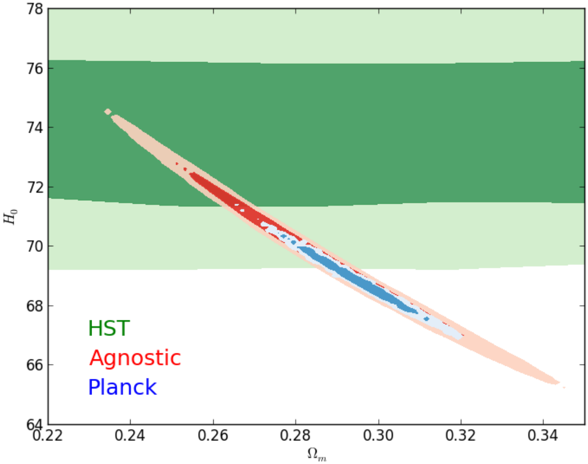
- Assuming flat ΛCDM, homogeneous cosmology: $\{H_0, \Omega_\Lambda\}$
- Use the agnostic information on $d_A^{\rm rec}$, $\omega_{\rm cdm}$ to extract information from CMB: **parameters are considered measured, not varied**
- Use the agnostic information on r_s, $d_A^{\rm rec}$ to analyze other experiments (BAO, SN, time delay): **measured as well**

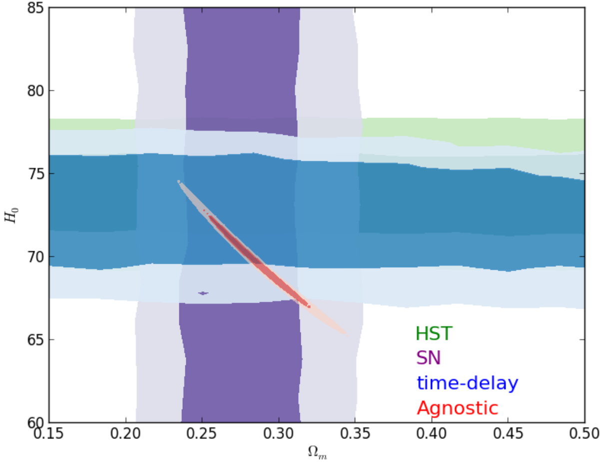
Late homogeneous cosmology

HST is back in the game !



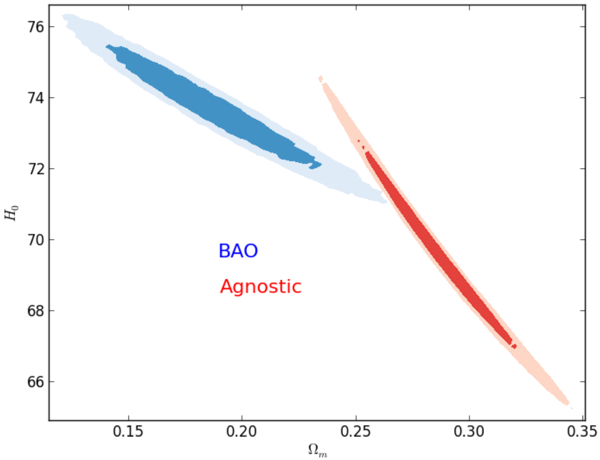
Late homogeneous cosmology

Is everything all right ?



Late homogeneous cosmology

Come on, BAO...



Late homogeneous cosmology

Summary

Results for ΛCDM

- Agnostic-Planck agrees with HST, SN, and time-delay
- Discrepancies between BAO and CMB instead ($\simeq 2\sigma$)
- Note how the BAO analysis was affected by the agnostic shift of paradigm: **proof of the importance of the contamination !**

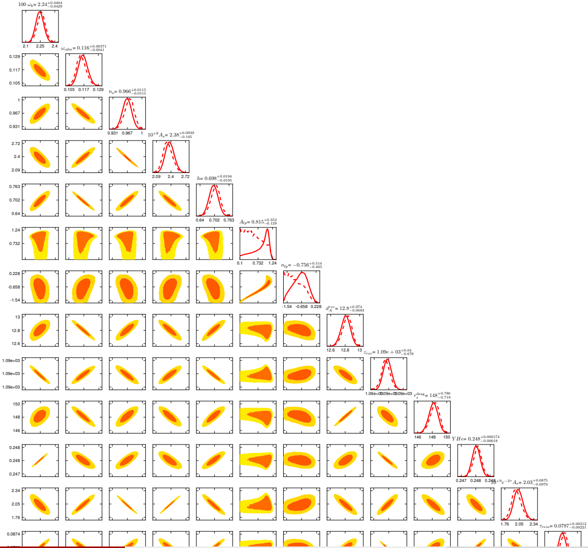
Outlook

Summary

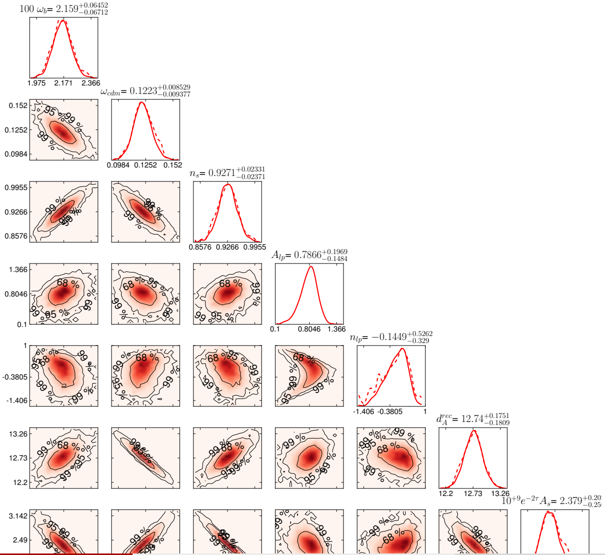
- It is possible to extract agnostic (*i.e.* **model independant**) constraints on early cosmology parameters
- They can be used to robustly constrain a late-time universe model
- For ΛCDM, it changes the picture of agreement-disagreement around (a lot. . .), suggesting **caution** when searching for new physics. . .
- With this formalism, we can also play the game of adding $N_{\rm eff}$, $\sum m_\nu$, varying dark energy, etc. . . with a bit more confidence
- Stay tuned in the coming month(s), depending on your remarks/comments !

Backup

Triangle plot for Planck Agnostic



Triangle plot for WMAP-7 SPT Agnostic



Python Power

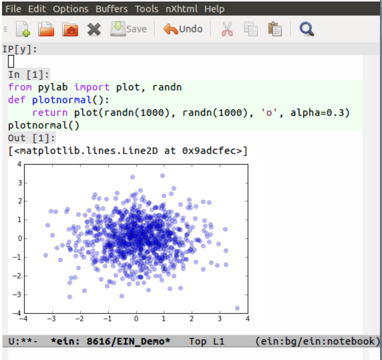
Python is A Good Thing^{TM}

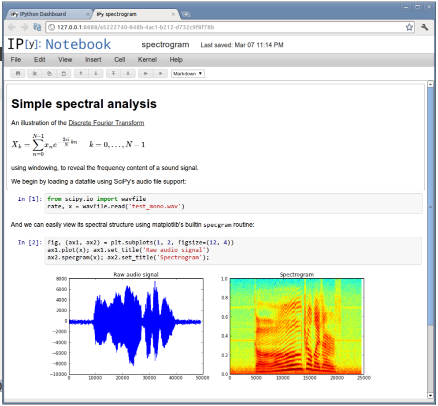
- No compilation (installs everywhere, fast to develop)
- Dynamic **and** strong typing (flexible and avoids mistake)
- Clear syntax, one way to do it: you can read your code one year after having written it !
- Object Oriented Programming
- Can work like Matlab/Mathematica (pylab mode)
- Simple C computation of problematic parts if speed is needed.
- **Incredible flexibility: test out your ideas in seconds !**

Python Power

Some examples

- Hello World program ? `print('Hello World !')`
- Loading a file to an array ? `numpy.loadtxt('file.dat','float')`





Monte Python, a Monte Carlo Markov Chain code in Python

Goal and Principles

- Likelihood formula given by an experiment
- Given a theoretical model, how likely it is that these data points are observed ?
- Integrating the likelihood via a random walk (shape being unknown), giving regions of parameters space

Monte Python

Sampling Algorithm

- Metropolis-Hastings algorithm
- Cholesky transform (Lewis astro-ph arXiv:1304.4473)

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Metropolis-Hastings

Proposal matrix to pick a new point: all parameters are varied simultaneously. The proposal matrix should be close to the posterior covariance matrix.

Monte Python

Sampling Algorithm

- Metropolis-Hastings algorithm
- Cholesky transform (Lewis astro-ph arXiv:1304.4473)

Cholesky

Decomposes the covariance matrix into the product of a triangular matrix and its hermitian conjugate
separates fast and slow parameters

$$\begin{pmatrix} S \\ S \\ F \\ F \\ F \end{pmatrix}_{\text{new}} = \begin{pmatrix} . & 0 & 0 & 0 & 0 \\ . & . & 0 & 0 & 0 \\ . & . & . & 0 & 0 \\ . & . & . & . & 0 \\ . & . & . & . & . \end{pmatrix} \begin{pmatrix} S \\ S \\ F \\ F \\ F \end{pmatrix}_{\text{old}} \tag{1}$$

Monte Python

Advantages

- Modularity (can accomodate Class, or any other cosmological code, properly wrapped)
- Memory Keeping and Safe Keeping
- No need to edit the code to add new parameters - as long as the cosmological code understands it, you can vary it !
- Covariances matrices
- Plotting is easy since 1 folder / 1 run

Likelihood Classes

- Many likelihoods follow the same syntax: using a .newdat format
- Implementing a new likelihood newdat in MontePython is creating two files: `new.py`, `new.data` in `likelihoods/new` folder, with 3 lines in total !

Monte Python Power

Github and Documentation

- Whole code (all versions !) is available on Github for everyone (clone it, implement something, send a pull-request), will try a clean master branch scheme, and release branches.
- You can always download whichever version you want, go back to an old one
- Extensively documented with Sphinx (semi-auto-documentation) available online and on pdf format.