Cosmological constraints: the Hubble constant

Wilmar Alberto Cardona Castro

September 22, 2016

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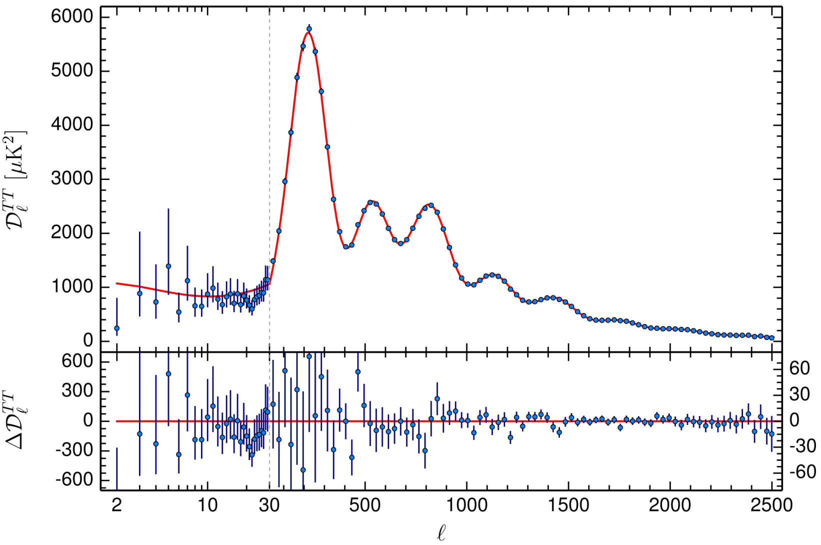
The concordance model of cosmology

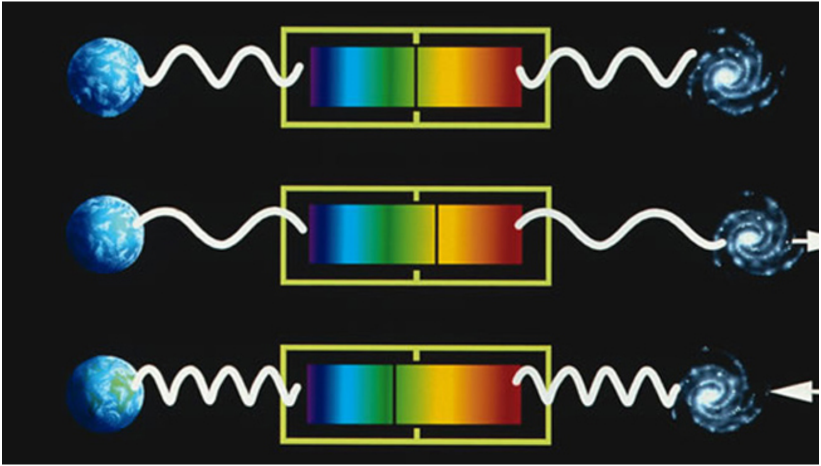
A good phenomenological description of the Universe



The concordance model of cosmology

Two important observational facts from the past century

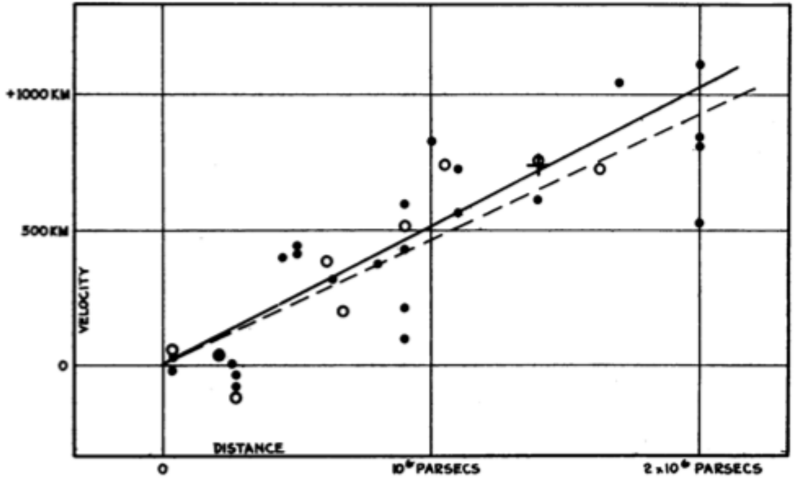
The Universe is expanding (1929)



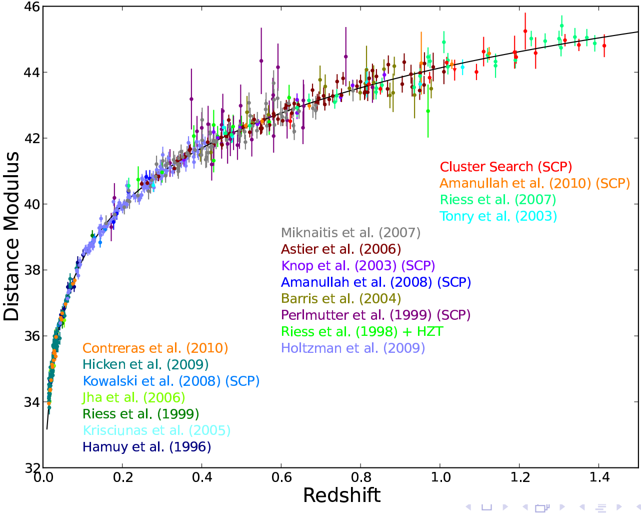
The concordance model of cosmology

Two important observational facts from the past century

The Universe is expanding (1929): $v \propto D = a(t)d$



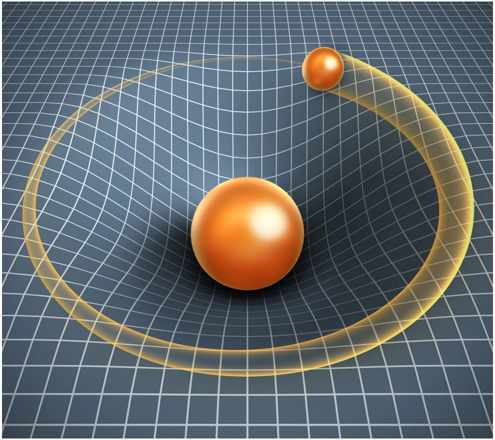
The Universe is speeding up: $\ddot{a}(t) > 0$



The concordance model of cosmology

Gravity

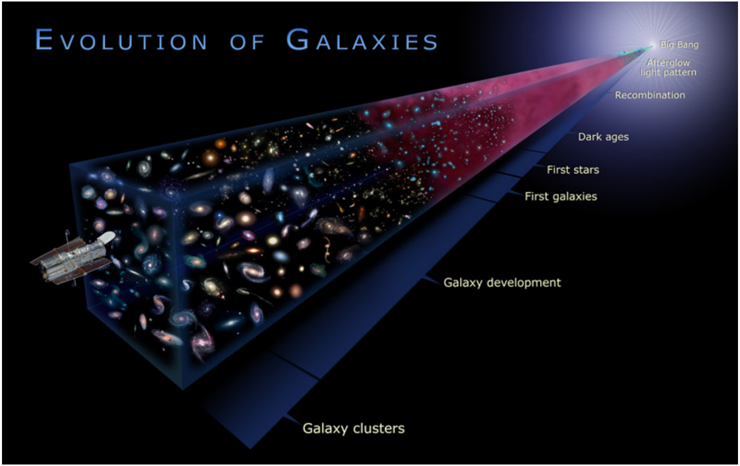
General Relativity: (geometry) $G_{\mu\nu} \propto T_{\mu\nu}$ (energy)



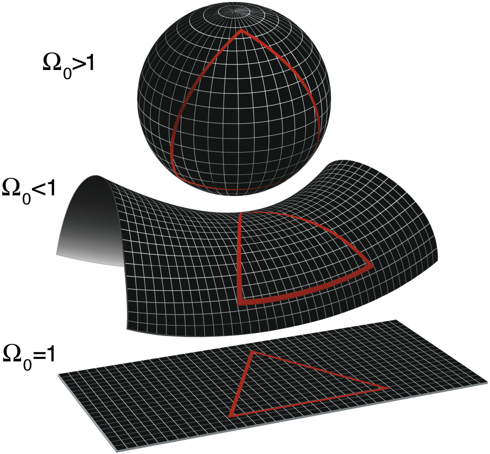
The concordance model of cosmology

Gravity

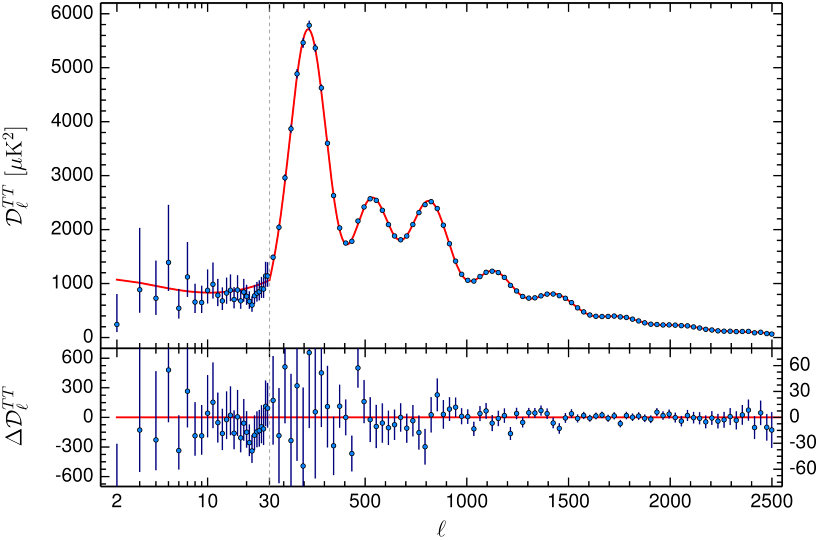
Matter collapses



Possible geometries in the standard model



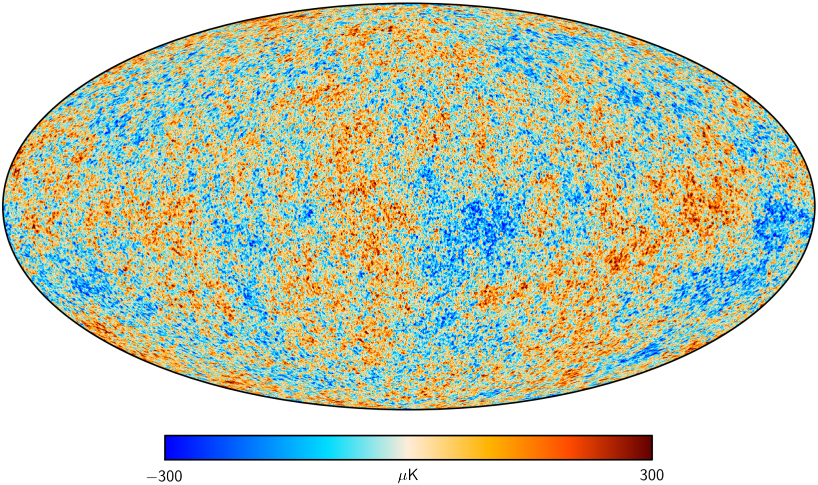
Planck constrains $|\Omega_K| < 0.005$



The concordance model of cosmology

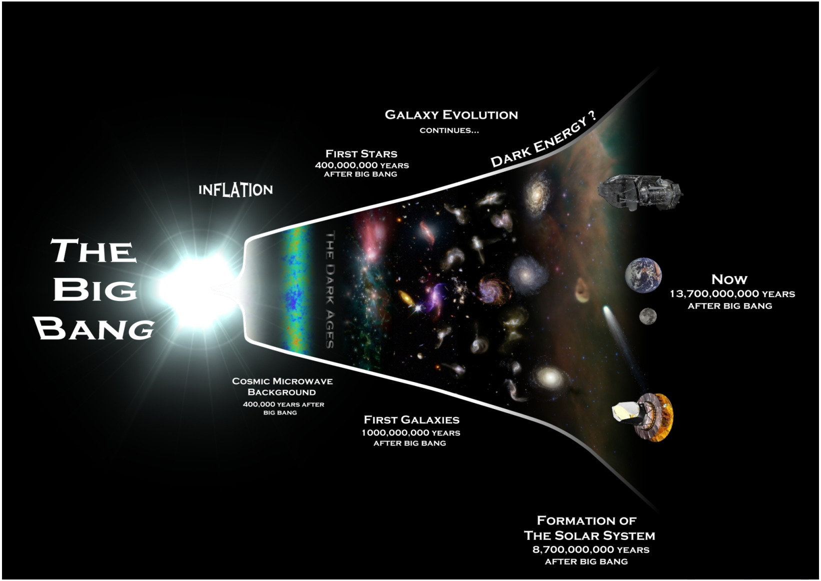
Flatness and isotropy

CMB is very isotropic: $\Delta T << \bar{T} = 2.7\mathrm{K}$



The concordance model of cosmology

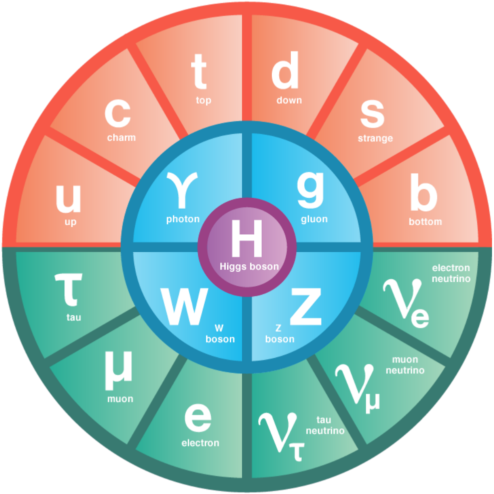
Visible matter

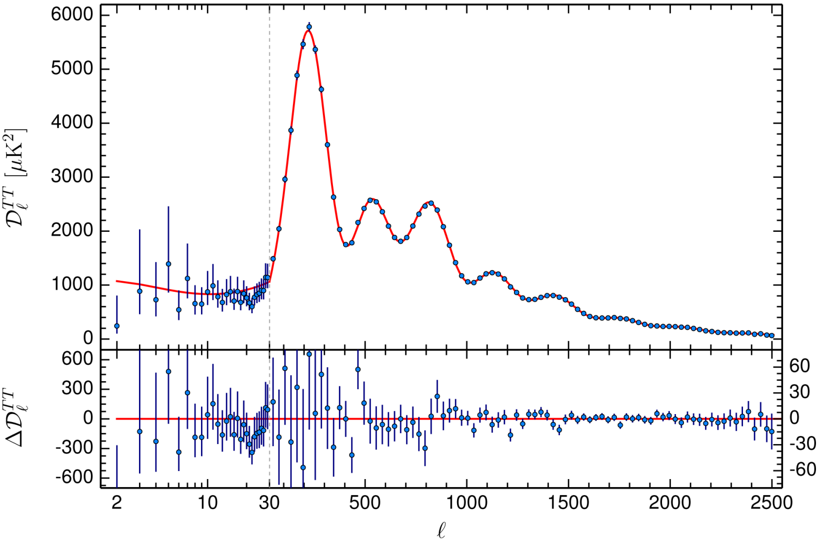


The concordance model of cosmology

Visible matter

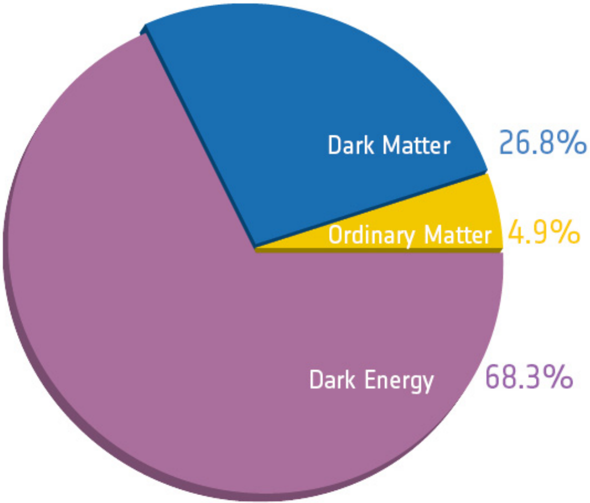
$\sum m_\nu$?





6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

ν are the only known DM candidates



Since DE dominates now, its pressure must be negative

- Flatness ($|\Omega_K| < 0.005$) ?

The concordance model of cosmology

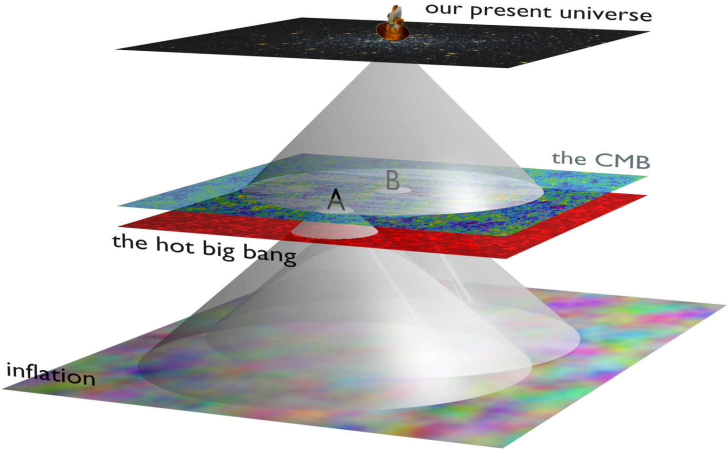
A few shortcomings

- Flatness ($|\Omega_K| < 0.005$) ?
- Horizon

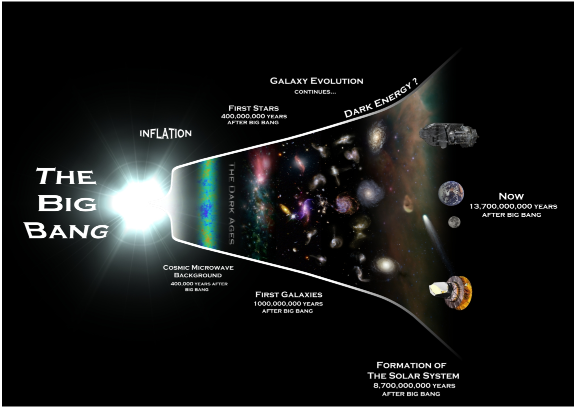
The concordance model of cosmology
A few shortcomings

- Flatness ($|\Omega_K| < 0.005$) ?
- Horizon
- What is the origin of the density perturbations $\delta\rho_i/\rho_i$ we observe today: (e.g., CMB anisotropies, galaxies) ?

The potential energy of an evolving scalar field would have dominated the energy content in the very early universe, so that its pressure was negative and $\ddot{a}(t) > 0$



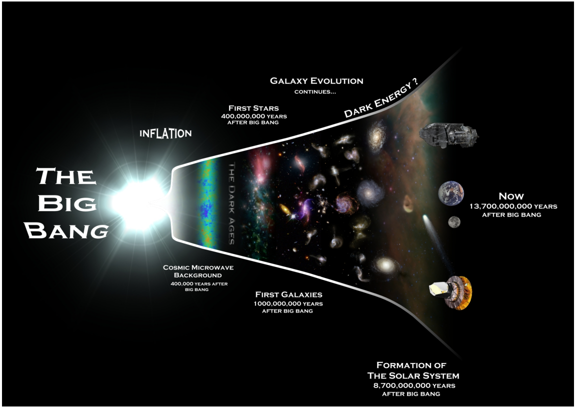
Quantum fluctuations of the scalar field would have seeded the density perturbations we see today: CMB anisotropies and LSS



The concordance model of cosmology

ΛCDM phenomenologically successful, but...

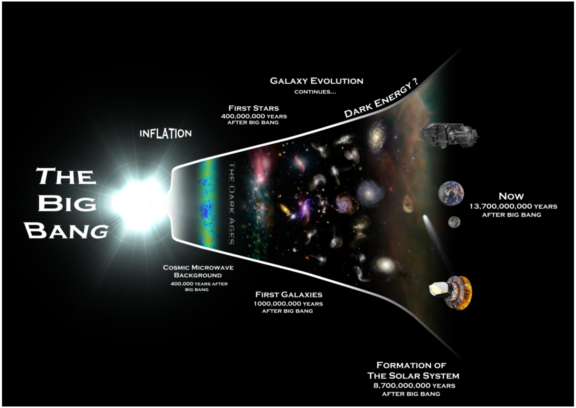
What is DM ? and $\sum m_\nu$?



The concordance model of cosmology

ΛCDM phenomenologically successful, but...

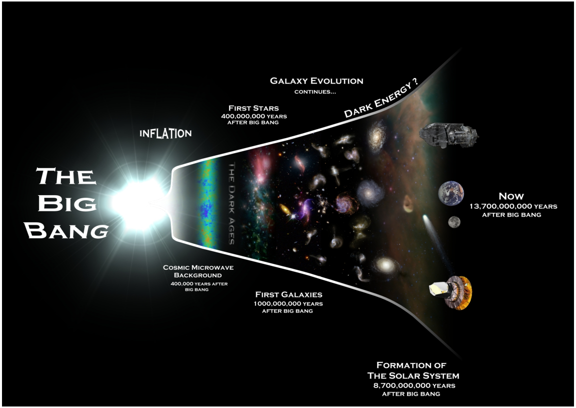
What is driving the accelerating expansion of the Universe ? DE ? Modified gravity ?



The concordance model of cosmology

ΛCDM phenomenologically successful, but...

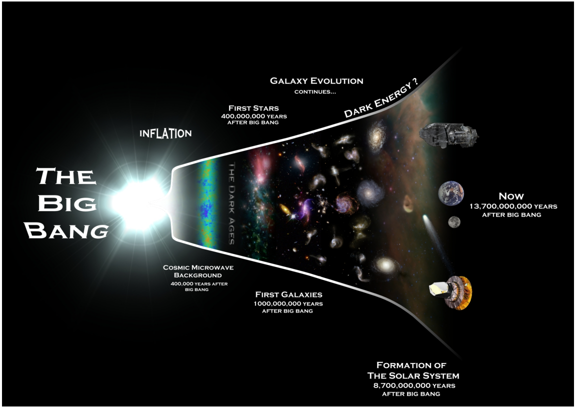
What mechanism produced inflation ?



The concordance model of cosmology

ΛCDM phenomenologically successful, but...

To what extent are valid the assumptions of the standard model
?



This thesis

- Constraints on Anisotropic Dark Energy: Dark Eenrgy vs Modified Gravity

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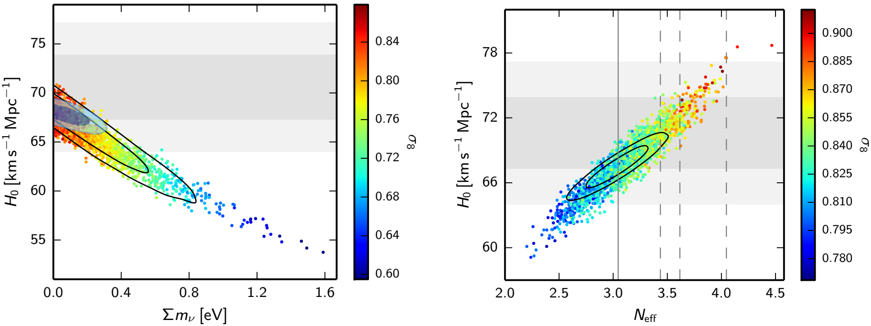
- Constraints on Anisotropic Dark Energy: Dark Eenrgy vs Modified Gravity
- Importance of lensing convergence for constraints of $\sum m_\nu$ with upcoming galaxy surveys
- A test of statistical isotropy with Planck data
- Measurement of the Hubble constant without rejecting data

Measuring the Hubble constant

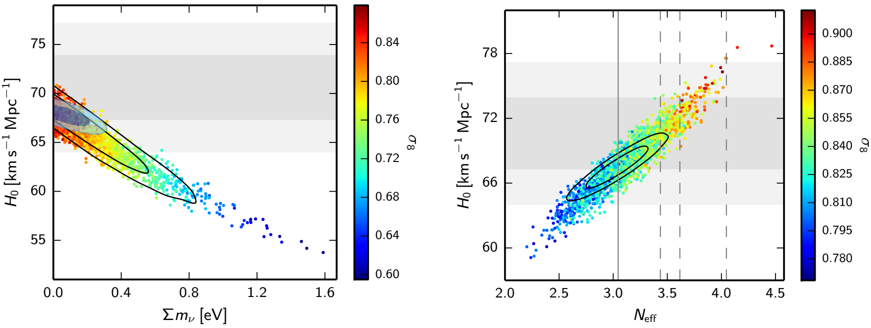
Why do we care about a local measurement of H_0?



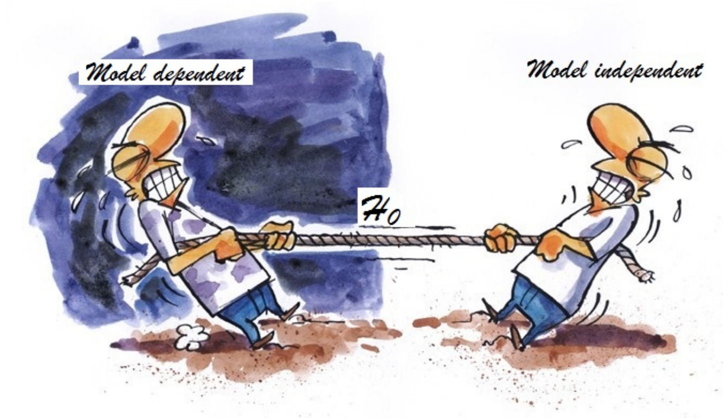
Crucial for understanding the standard model of cosmology (i.e., it sets cosmological scales, tackle cosmological parameters and break degeneracies)

Measuring the Hubble constant

Why do we care about a local measurement of H_0?



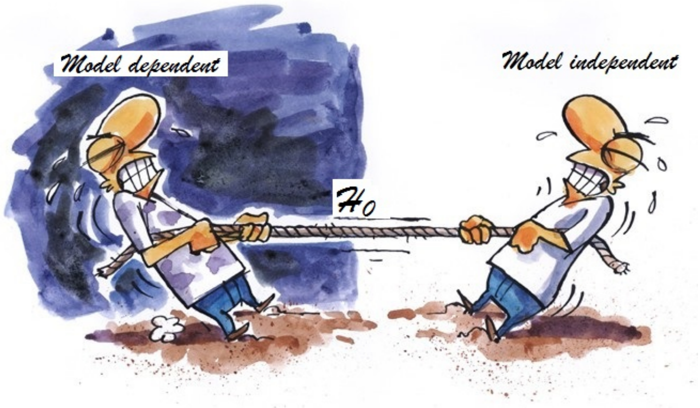
Inferred determinations are model dependent (e.g., properties of neutrinos, theory of gravity, nature of dark energy) and might be affected by assumed prior probability distributions



There is a 3.4σ tension between direct and inferred determinations of H_0

Measuring the Hubble constant

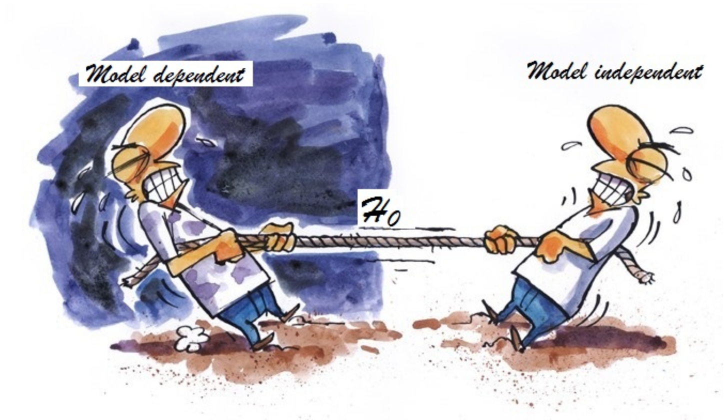
Why do we care about a local measurement of H_0?



New physics (e.g., modifying assumptions in the concordance model), contributions of the local gravitational potential, unaccounted second-order corrections to the background distance-redshift relation ?

Measuring the Hubble constant

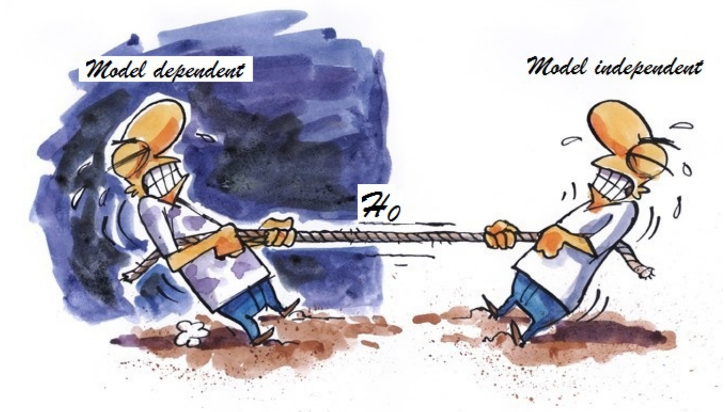
Why do we care about a local measurement of H_0?



Issues with statistical analysis (e.g., outlier rejection algorithms, anchors choice, period cut-off and assumptions in the Leavitt law, unaccounted systematics) ?

Measuring the Hubble constant

Why do we care about a local measurement of H_0?



Need to confirm 3.4σ tension and prove it robust against different statistical approaches.

Measuring the Hubble constant

How do we measure H_0?

- Estimate distances through luminosity distance

$$d_L \equiv \left(\frac{L}{4\pi l}\right)^{1/2}$$

- Define logarithmic measures of the luminosity

$$l = 10^{-2m/5} \times 2.52 \times 10^{-5}\,\mathrm{erg/cm^2\,s}$$

Measuring the Hubble constant

How do we measure H_0?

- Define logarithmic measures of the luminosity

$$L = 10^{-2M/5} \times 3.02 \times 10^{35}\,\mathrm{erg/s}.$$

- Express luminosity distance through the distance modulus

$$\mu_0 \equiv m - M = 5\log_{10}\left(\frac{d_L}{1\mathrm{Mpc}}\right) + 25$$

- Assuming flat FLRW metric one can compute luminosity distance

$$d_L(z) = (1+z)c \int_0^z \frac{dz'}{H(z')}$$

Measuring the Hubble constant

How do we measure H_0?

- For relatively small redshift one has

$$d_L(z) \equiv \frac{cz}{H_0}(1+\delta(z))$$

- Recalling

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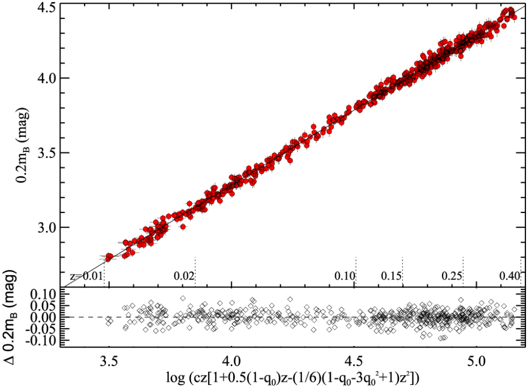
Measuring the Hubble constant

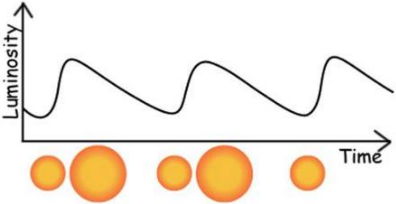
How do we measure H_0?



- Determine constant a_X with Supernova type Ia $(\mathrm{SNe\,Ia})$

$$5\log_{10}(cz(1+\delta(z))) - m_X = 5\log_{10} H_0 - M_X - 25 \equiv 5a_X$$

- Use now simultaneously $\mathrm{SNe\,Ia}$ and Cepheid stars



Measuring the Hubble constant

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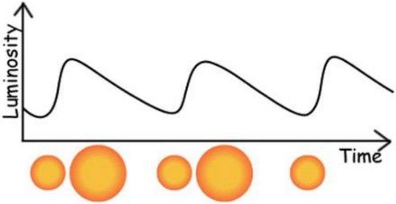

- $\mathrm{SNe\,Ia}$ apparent magnitudes

$$m_X^{\mathrm{SNe\,Ia}} = 5\log_{10} H_0 + \mu_0 - 5a_X - 25$$

Measuring the Hubble constant

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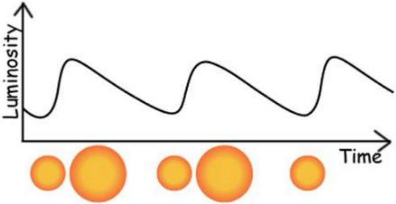
- Use now simultaneously $\mathrm{SNe\,Ia}$ and Cepheid stars



- $\mathrm{SNe\,Ia}$ apparent magnitudes

$$m_X^{\mathrm{SNe\,Ia}} = 5\log_{10} H_0 + \mu_0 - 5a_X - 25$$

- Cepheid variables apparent magnitudes

$$m_{Y,i,j}^{\mathrm{Cepheid}} = \mu_{0,i} + M_Y^{\mathrm{Cepheid}} + b_Y(\log P_{i,j} - 1) + Z_Y \Delta \log[O/H]_{i,j}$$

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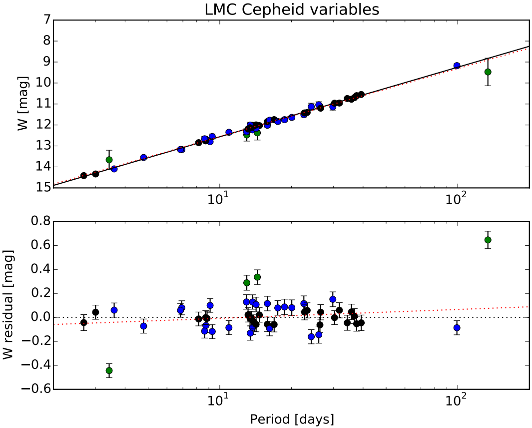
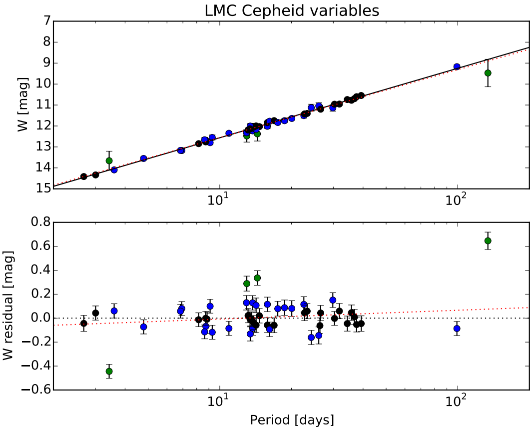
- Galaxies hosting both $\mathrm{SNe\,Ia}$ and Cepheid stars
- A few anchor distances: μ_0^{LMC}, μ_0^{NGC4258}, μ_0^{M31}, MW Cepheid stars parallaxes

Measuring the Hubble constant

How do we measure H_0?



- Need to determine the best fitting parameters in the relations above, but data sets include outliers...



- Outlier rejection algorithm or a Bayesian treatment ?

- Usually assumed data points drawn from a Gaussian PDF

$$P_G(D_i|\vec{w}) = \tilde{N}_i \, \frac{\exp(-\chi_i^2(\vec{w})/2)}{\sqrt{2\pi}}$$

Measuring the Hubble constant

How do we measure H_0?

- Usually assumed data points drawn from a Gaussian PDF

$$P_G(D_i|\vec{w}) = \tilde{N}_i \, \frac{\exp(-\chi_i^2(\vec{w})/2)}{\sqrt{2\pi}}$$

- Drop this and assume error bars can be underestimated: introduce hyper-parameters for each datum $\sigma_i \to \sigma_i/\sqrt{\alpha_i}$

Measuring the Hubble constant

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- Starting from usual Gaussian PDF with usual χ^2, but allow error bars to become greater and take into account every possible value for the rescaling (marginalise over HPs)

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$$P_G(D_i|\vec{w}) = \tilde{N}_i \, \frac{\exp(-\chi_i^2(\vec{w})/2)}{\sqrt{2\pi}}$$

- Drop this and assume error bars can be underestimated: introduce hyper-parameters for each datum $\sigma_i \to \sigma_i/\sqrt{\alpha_i}$
- Starting from usual Gaussian PDF with usual χ^2, but allow error bars to become greater and take into account every possible value for the rescaling (marginalise over HPs)
- End up with a new PDF: a Gaussian HP PDF

$$P(D_i|\vec{w}\,) = \tilde{N}_i \left(\frac{\mathrm{Erf}\left(\frac{\chi_i(\vec{w})}{\sqrt{2}}\right) - \sqrt{\frac{2}{\pi}}\chi_i(\vec{w}) \exp(-\chi_i^2(\vec{w})/2)}{\chi_i^3(\vec{w})} \right)$$

- Maximise likelihood and compute effective HPs for each datum (given the best fitting parameters)

$$
\begin{aligned}
\alpha_i^{\rm eff} &= 1, \quad \text{if} \quad \chi_i^2 \leq 1 \\
\alpha_i^{\rm eff} &= \frac{1}{\chi_i^2}, \quad \text{if} \quad \chi_i^2 > 1.
\end{aligned}
$$

- Maximise likelihood and compute effective HPs for each datum (given the best fitting parameters)

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- Asses compatibility of data sets through normalised weights

$$||\alpha^j|| \equiv \frac{\sum_{i=1}^{K_j} \alpha_{i,j}}{K_j},$$

- The R11 data set: 8 galaxies simultaneously hosting $\mathrm{SNe\,Ia}$ and Cepheid stars, three anchor distances (μ_0^{LMC}, μ_0^{NGC4258}, 13 MW Cepheid stars parallaxes)

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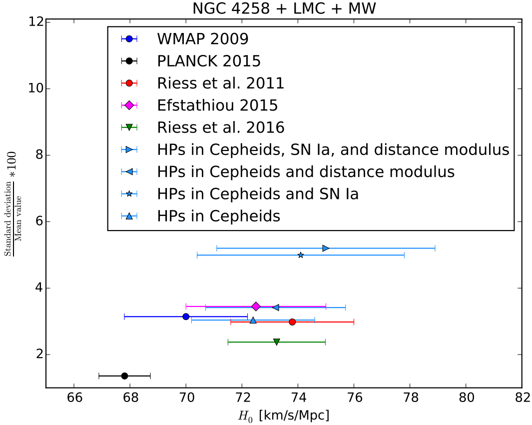
- The R16 data set: 19 galaxies simultaneously hosting $\mathrm{SNe\,Ia}$ and Cepheid stars, four anchor distances (μ_0^{LMC}, μ_0^{NGC4258}, μ_0^{M31}, 15 MW Cepheid stars parallaxes)

Consistency of period-luminosity relation				
Fit	Galaxy	M_W	b_W	σ_{int}
c	LMC	−5.93 (0.07)	−3.31 (0.05)	0.06
e	MW	−5.88 (0.07)	−3.30 (0.26)	0.02
f	NGC4258	−6.12 (0.15)	−3.02 (0.17)	0.12

- Find no reasons to exclude data sets: period-luminosity relation compatible with direct distance determinations

Measuring the Hubble constant

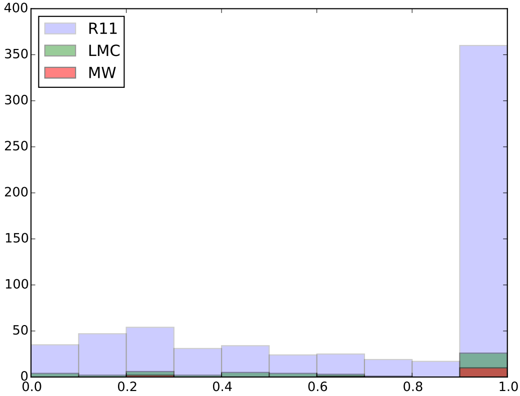
Results: the R11 data set



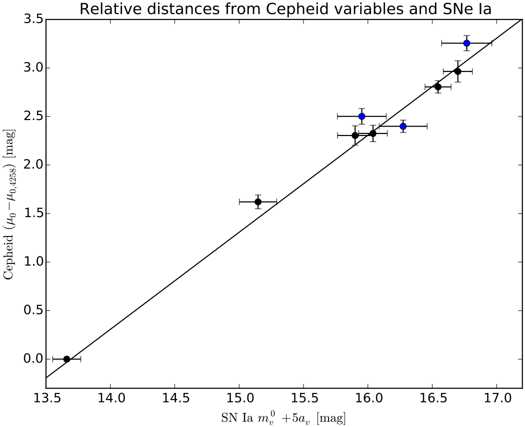
- Precision of H_0 depends on which data are included with HPs

Measuring the Hubble constant

Results: the R11 data set



- Down-weighted fraction in Cepheid sample



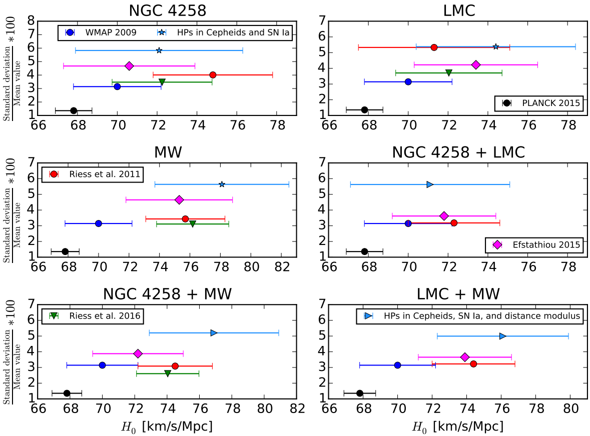
- Inconsistencies in SNe Ia data

- Baseline result for the R11 data set

$$H_0 = 75.0 \pm 3.9\,\mathrm{km/s/Mpc}$$

Measuring the Hubble constant

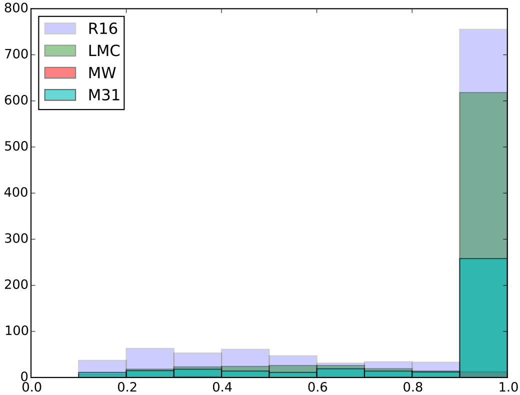
Results: the R11 data set



- Anchor choice and comparison with previous results

Measuring the Hubble constant

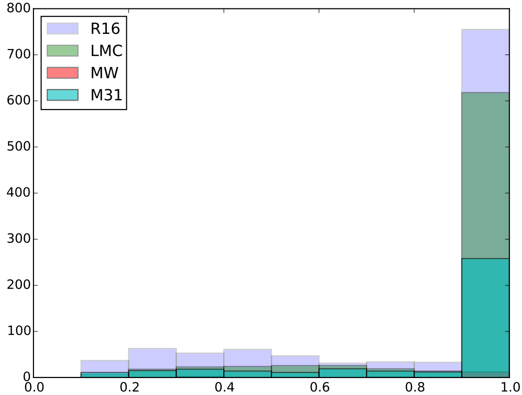
Results: the R16 data set



- No outliers released in the Cepheid sample, however...

Measuring the Hubble constant

Results: the R16 data set



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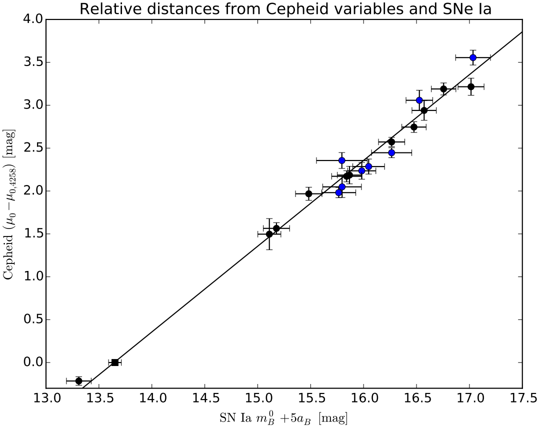
Measuring the Hubble constant

Results: the R16 data set



- Inconsistencies in SNe Ia data

- Consider variants of baseline analysis (e.g., period cut-off, metallicity dependence, reddening law) and compute systematic error due to these changes

$$\sigma_{\rm syst} = 0.20 \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

- Consider variants of baseline analysis (e.g., period cut-off, metallicity dependence, reddening law) and compute systematic error due to these changes

$$\sigma_{\rm syst} = 0.20 \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

- Baseline result for the R11 data set

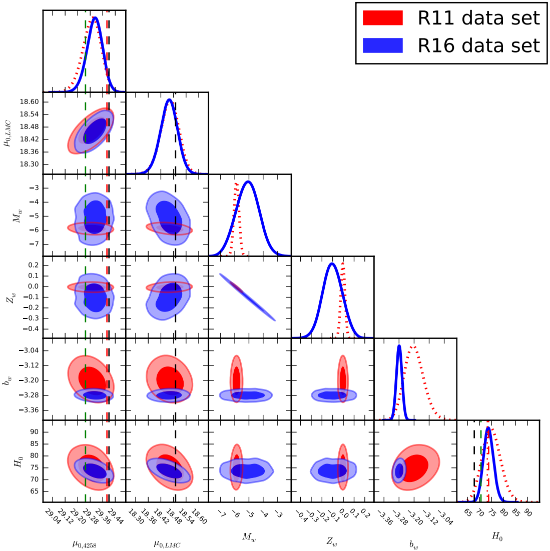
$$H_0 = 73.75 \pm 2.11\,\mathrm{km\,s^{-1}\,Mpc^{-1}},$$

Consistency of different kinds of data			
Data set	$\|\|\alpha^{\mathrm{Cepheid}}\|\|$	$\|\|\alpha^{\mathrm{SNe\,Ia}}\|\|$	$\|\|\alpha^{\mathrm{Anchors}}\|\|$
R11	0.72	0.74	0.86
R16	0.86	0.78	0.92

- Improvement of compatibility of different kinds of data

Measuring the Hubble constant

Results: the R16 data set



Measuring the Hubble constant

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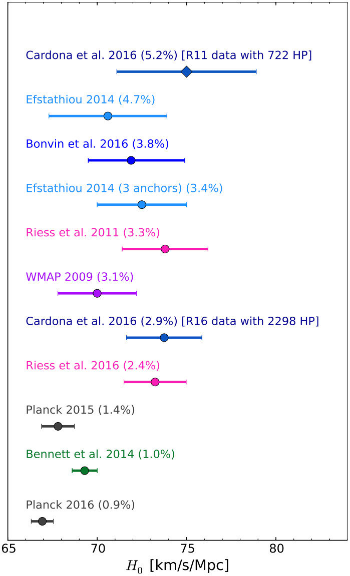

Conclusions

- Developed a method to search for deviations of statistical isotropy: CMB data from Planck is consistent with the Cosmological principle.

Conclusions

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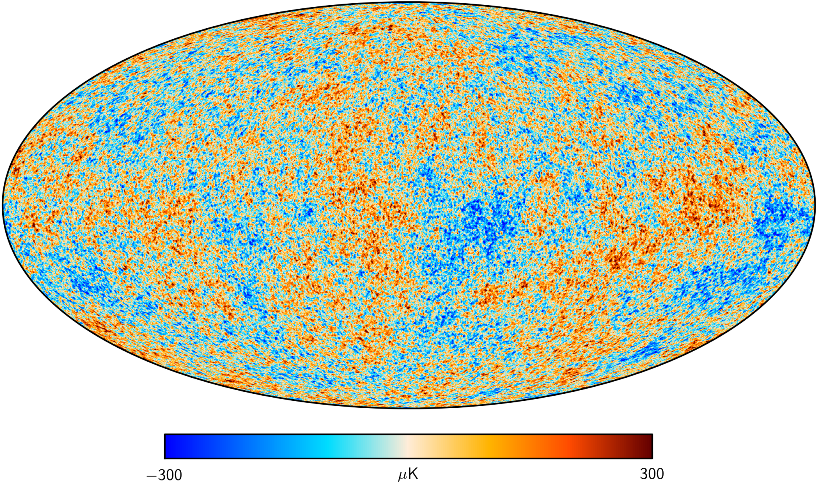
- Data is consistent with zero dark energy anisotropic stress
- Lensing convergence must be included in analyses of upcoming galaxy surveys
- Developed a method to measure the Hubble constant and asses consistency of data sets. Confirmed tension CMB and local measurements might suggest new physics or unaccounted systematics in CMB data

Project 1: testing a fundamental assumption of the standard model of cosmology

CMB anisotropies



Project 1: testing a fundamental assumption of the standard model of cosmology

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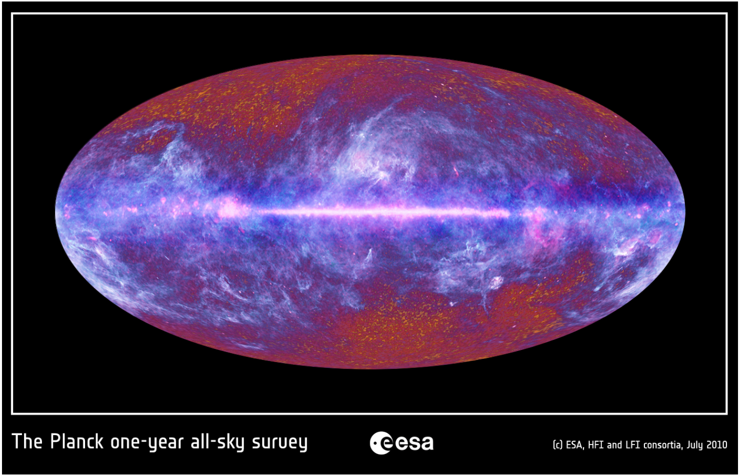

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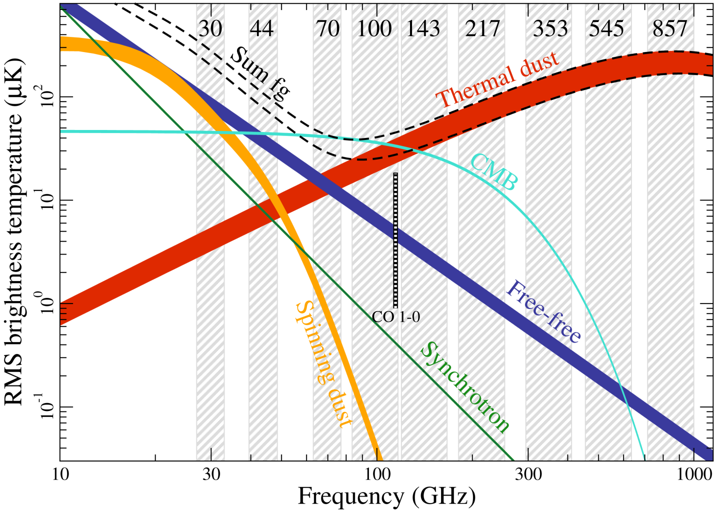

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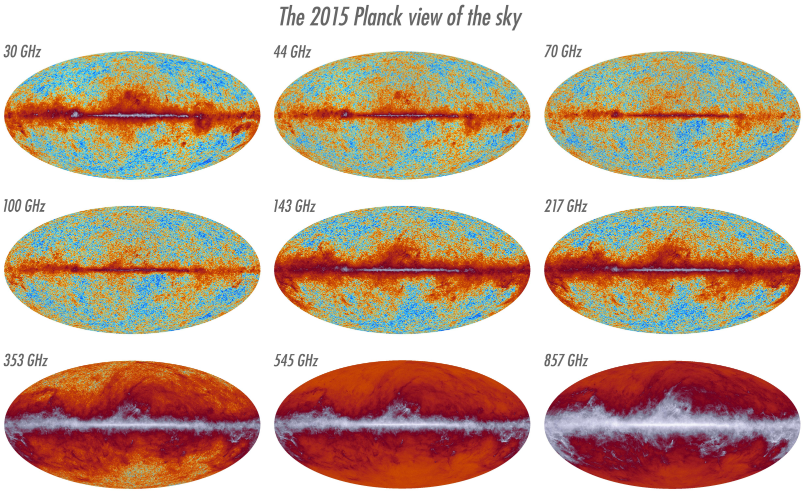

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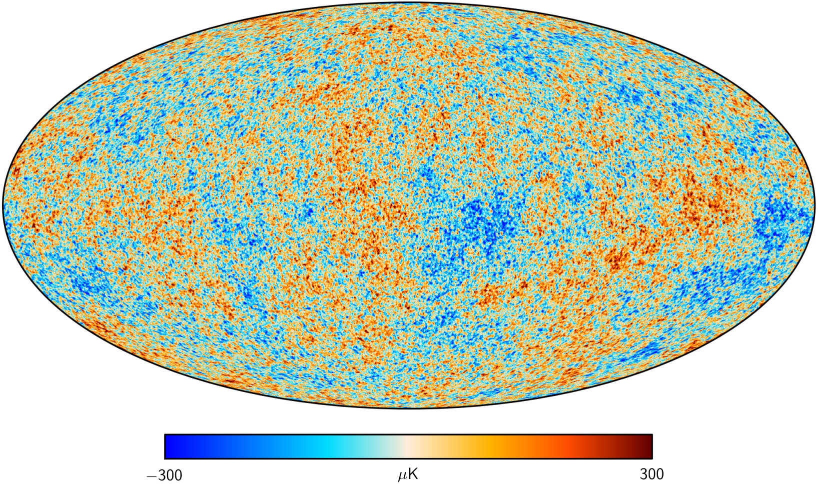

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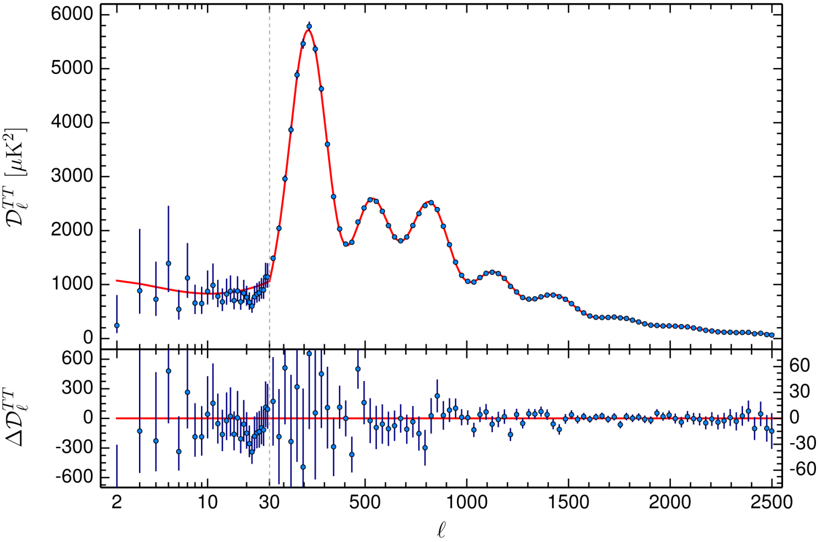
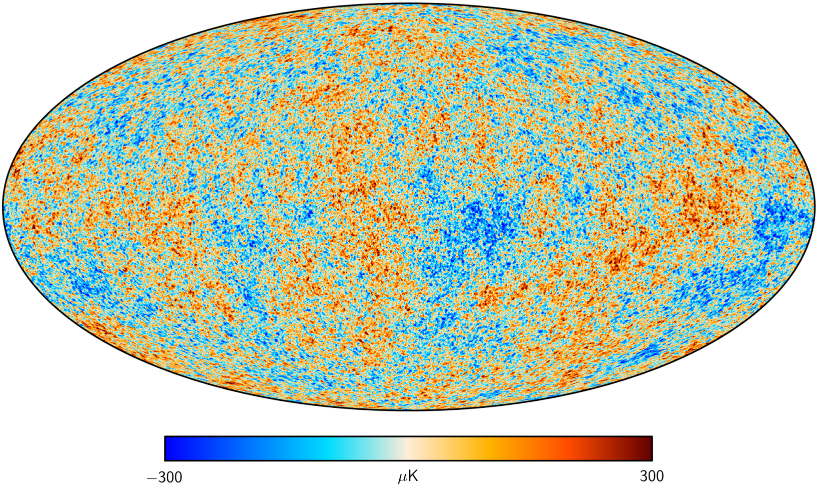


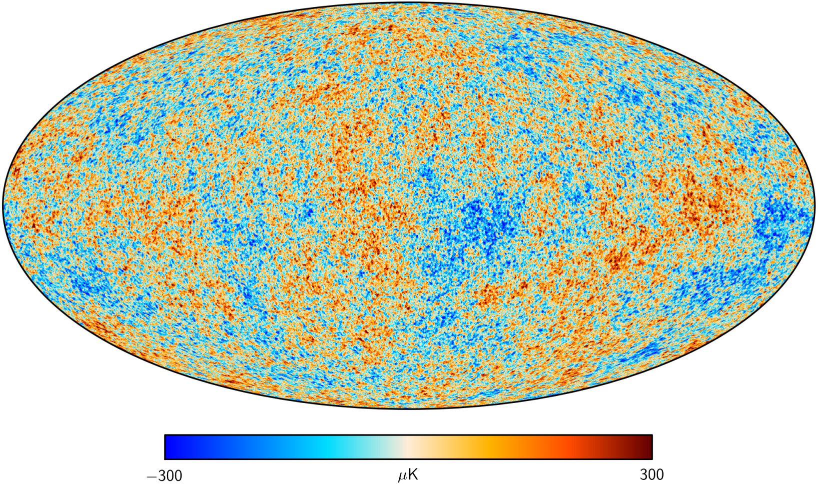
Statistical isotropy is fundamental in the concordance model



Project 1: testing statistical isotropy with Planck data

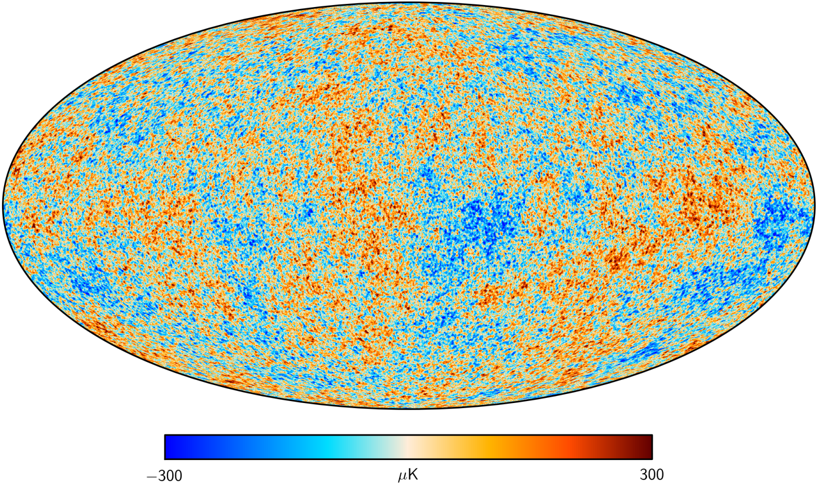
VSK method

Statistical properties of CMB allow to test assumptions



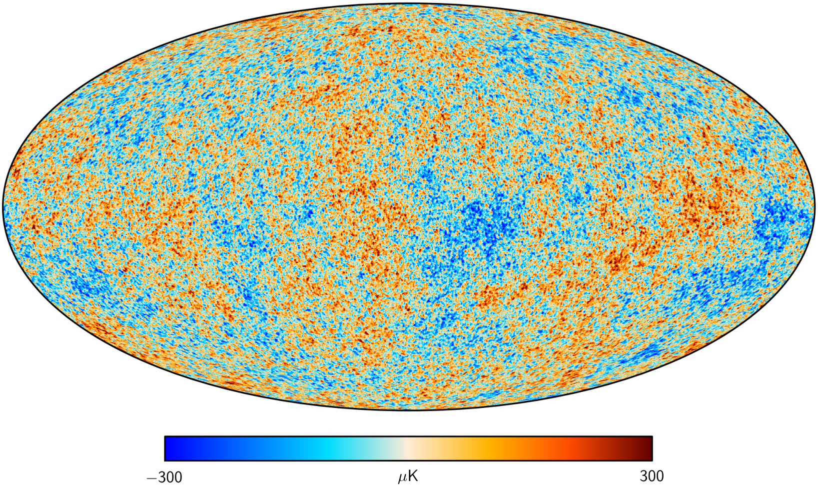
Project 1: testing statistical isotropy with Planck data
VSK method

CMB anisotropies... isotropic and Gaussian distributed ?



Project 1: testing statistical isotropy with Planck data
VSK method

Anomalies have been found by WMAP, Planck and other groups



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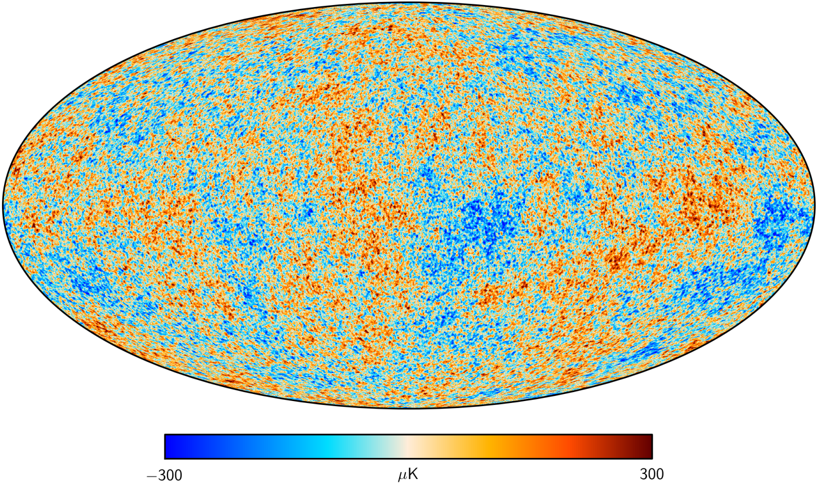
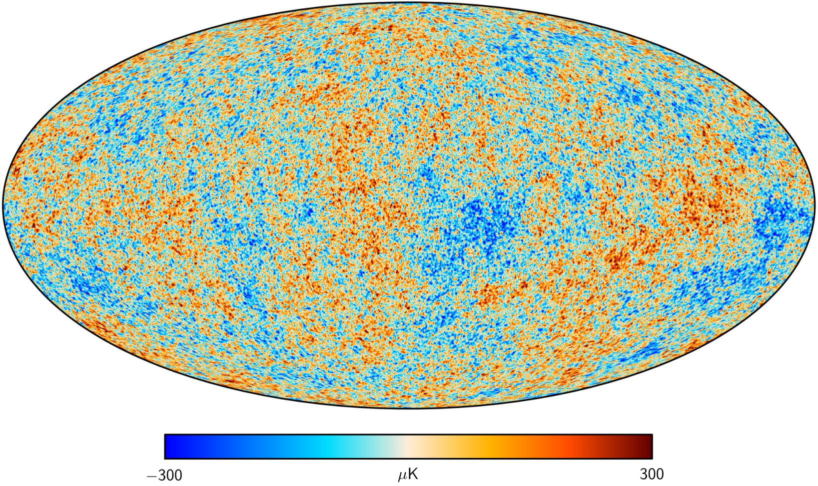
VSK method

Unaccounted systematics, non-subtracted foreground contamination, cosmological origin ?



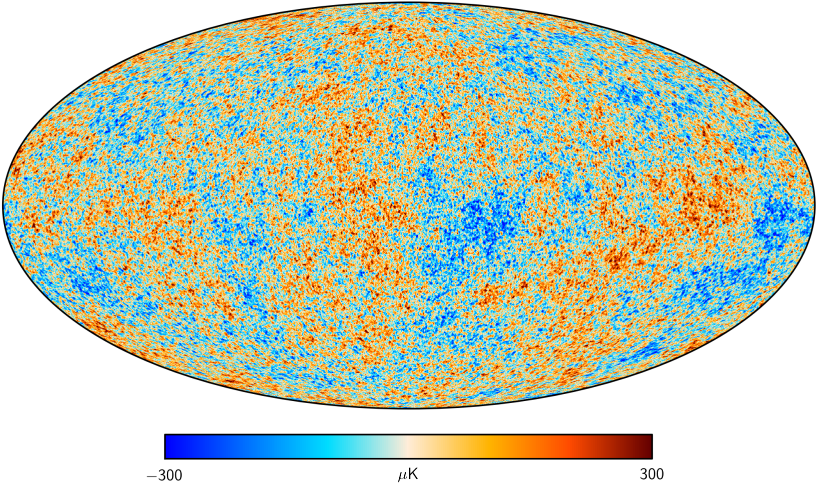
Project 1: testing statistical isotropy with Planck data
VSK method

WMAP and Planck are two independent experiments...
unaccounted systematics seems unlikely



Project 1: testing statistical isotropy with Planck data
VSK method

Then, anomalies due to unresolved foreground or cosmological origin ?



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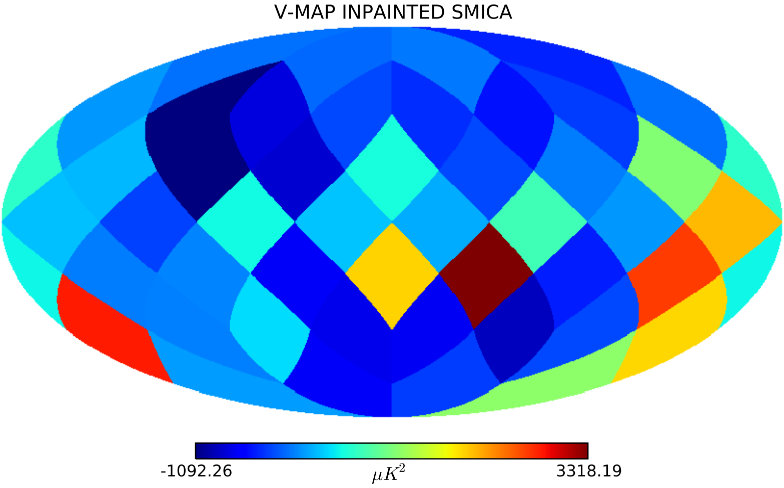

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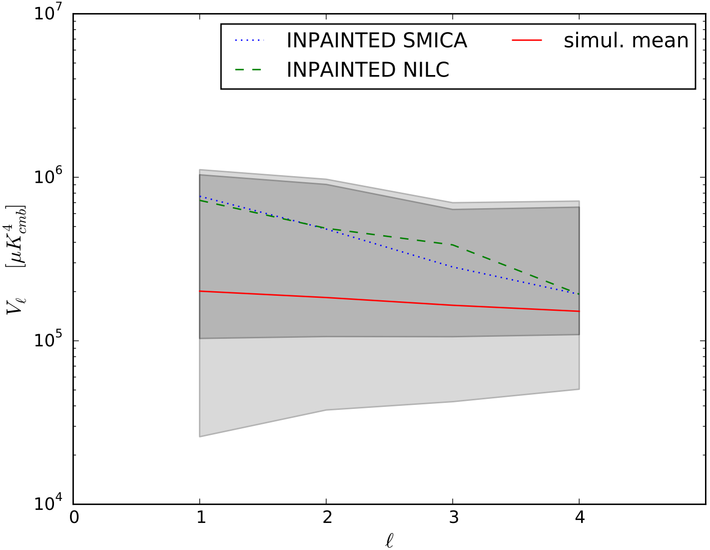

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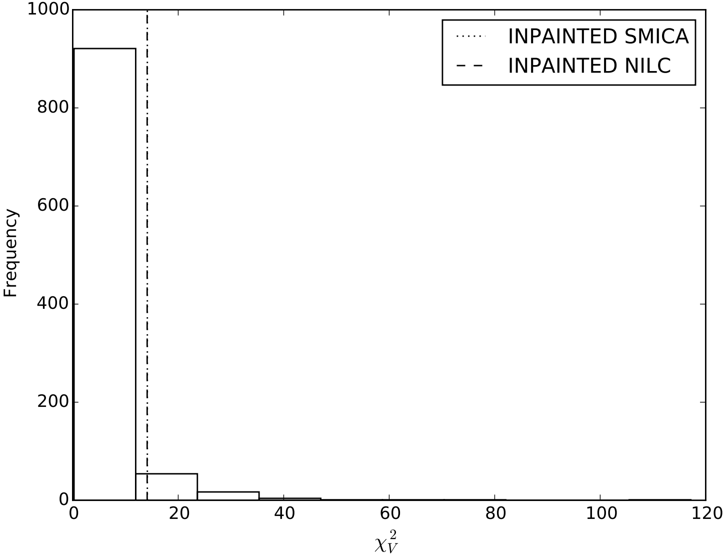

Lower-tail probability for the V, S, K estimators, for the $N_{side} = 2048$ inpainted SMICA and NILC.

	Probability		
CMB estimate	V	S	K
	$N'_{side} = 2$		
SMICA	0.939	0.388	0.096
NILC	0.939	0.022	1
	$N'_{side} = 4$		
SMICA	0.969	0.727	0.521
NILC	0.943	0.761	1
	$N'_{side} = 8$		
SMICA	1	0.551	0.581
NILC	0.964	0.474	1

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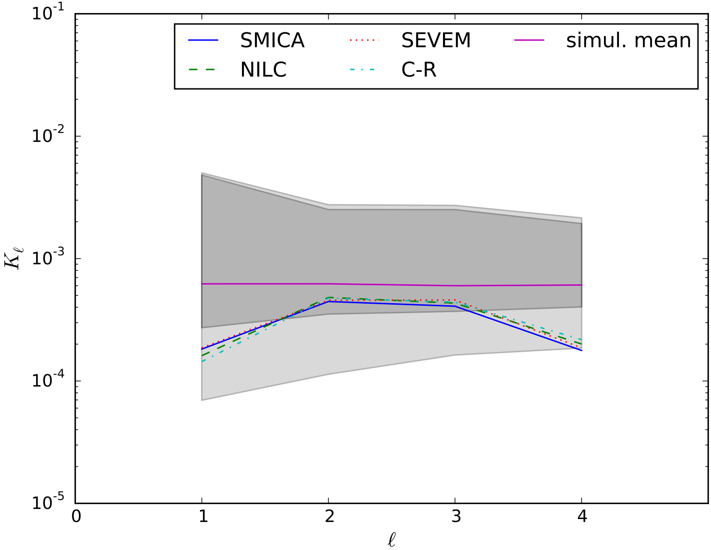
VSK method



SMICA CMB estimate using the U73 mask.

	Probability		
N'_{side}	V	S	K
	$N_{side} = 2048$		
2	0.004	0.024	0.367
4	0.893	0.407	0.340
8	0.695	0.116	0.406
	$N_{side} = 1024$		
2	0.556	0.022	0.281
4	0.873	0.446	0.229
8	0.782	0.117	0.264
16	0.442	0.084	0.153

SMICA CMB estimate using the U73 mask.

	Probability		
N'_{side}	V	S	K
	$N_{side} = 512$		
2	0.711	0.027	0.229
4	0.898	0.485	0.240
8	0.794	0.103	0.140
16	0.311	0.200	0.146
	$N_{side} = 256$		
2	0.040	0.123	0.225
4	0.996	0.480	0.404
8	1.0	0.235	0.104
16	1.0	0.584	0.459

SMICA CMB estimate using different masks.

	Probability		
N'_{side}	V	S	K
	U73 ($f_{sky} = 73\%$)		
2	0.004	0.024	0.367
4	0.893	0.407	0.340
8	0.695	0.116	0.406
	VALMASK ($f_{sky} = 89\%$)		
2	0.004	0.022	0.357
4	0.895	0.371	0.343
8	0.7	0.099	0.385
	INP_MASK ($f_{sky} = 97\%$)		
2	0.003	0.016	0.382
4	0.897	0.367	0.374
8	0.685	0.099	0.428

Project 2: constraints on anisotropic dark energy

Why do we care about anisotropic dark energy ?

- No clear explanation for the accelerating expansion of the universe

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- A general fluid can be characterised by equation of state, sound speed, and anisotropic stress
- Literature has focused on the background evolution, but what about DE perturbations ?
- Anisotropic stress is a key feature: it allows to distinguish standard DE model ($\Pi_{\rm de} = 0$) from modified gravity models ($\Pi_{\rm de} \neq 0$)

Project 2: constraints on anisotropic dark energy

How do we constrain anisotropic stress ?

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How do we constrain anisotropic stress ?

- Adopt a phenomenological approach: a DE model including a range of approaches (e.g.,)
- Find approximate solutions for DE perturbations
- Implement the model in CAMB and do MCMC with COSMOMC
- Data from Planck, BAO, supernovae, but exclude $P(k)$ and H_0

- The effect of anisotropic stress on CMB angular power spectrum and on the matter power spectrum

Project 2: constraints on anisotropic dark energy

Results

- The effect of anisotropic stress on CMB angular power spectrum and on the matter power spectrum
- Constrains do not show evidence of non-zero anisotropic stress.

Project 2: constraints on anisotropic dark energy

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Project 3: upcoming galaxy surveys, the lensing convergence and the neutrino mass

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- Underlying physics in the standard model of cosmology remains unknown

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- Neutrinos are massive, but their absolute scale remains unconstrained

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- Upcoming surveys will probe distances comparable to the Hubble horizon: relativistic effects must be consistently included in the analysis

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Galaxy number counts angular power spectrum $C_\ell(z, z')$

- $P(k, z)$ is not an observable. $C_\ell(z, z')$ is an observable

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- Assume statistical isotropy and compute angular power spectrum
- In practice, divide the catalogue in red-shift bins

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- Conservative treatment of non-linearities
- Include shot-noise (galaxy distribution is not a continuous field)
- Number counts alone
- Number counts and use CMB information from Planck

- Triangle plot including CMB information

Project 3: upcoming galaxy surveys, the lensing convergence and the neutrino mass

Results

- Triangle plot including CMB information
- Table showing biased parameters: spurious detection of neutrino mass

Project 3: upcoming galaxy surveys, the lensing convergence and the neutrino mass

Results

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- Plot showing auto- and cross-correlations, equation showing dominant contribution

Project 3: upcoming galaxy surveys, the lensing convergence and the neutrino mass

Results

- Triangle plot including CMB information
- Table showing biased parameters: spurious detection of neutrino mass
- Plot showing auto- and cross-correlations, equation showing dominant contribution
- Lensing convergence must be included in the analysis of upcoming galaxy surveys, with appropriate magnification bias