Bianchi VII$_h$ cosmologies and *Planck*

XXVI. Background geometry and topology of the Universe

Planck Collaboration

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Outline

1. Topology
2. Bianchi VII_h cosmologies
3. Bayesian analysis
4. *Planck* results

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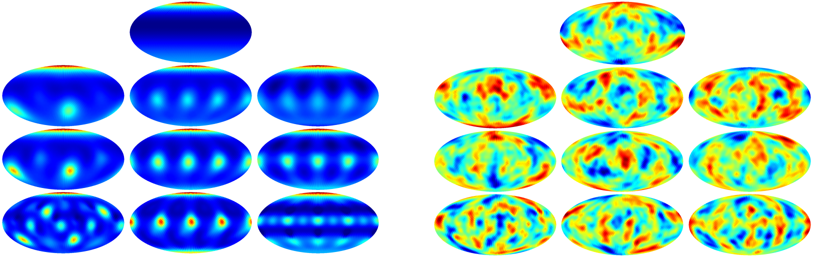
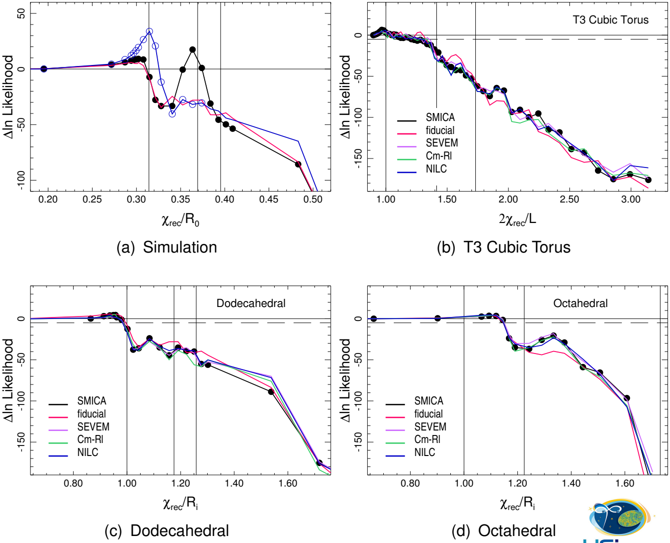
Topology



(a) Correlations (b) Simulations

Topology



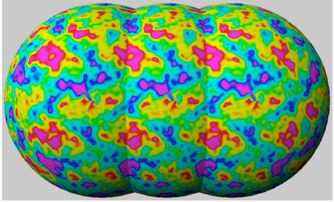
(a) Simulation

(b) T3 Cubic Torus

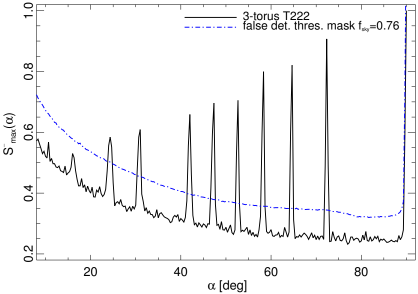
(c) Dodecahedral

(d) Octahedral

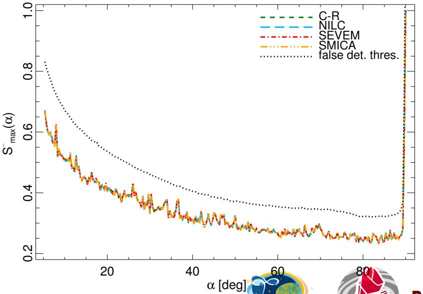
Topology



(a) Back-to-back circles



(b) Simulation

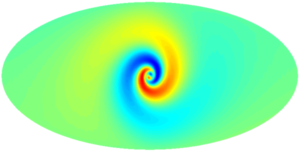


(c) *Planck* data

Outline

Bianchi VII_h cosmologies

- Relax assumptions about the global structure of spacetime by allowing anisotropy about each point in the Universe.
- Yields more general solutions to Einstein's field equations $\rightarrow$ Bianchi cosmologies.
- For small anisotropy, as already demanded by current observations, linear perturbation about the standard FRW model may be applied.
- Induces a characteristic subdominant, deterministic signature in the CMB, which is embedded in the usual stochastic anisotropies.
- First examined by Collins & Hawking (1973) and Barrow *et al.* (1985), however dark energy not included.
- Focus on Bianchi VII_h using solutions derived by Anthony Lasenby that do incorporate dark energy (also derived independently by Jaffe *et al.* 2006).



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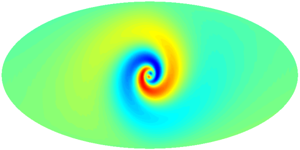
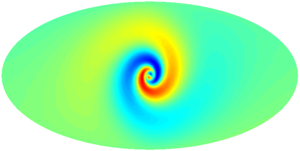


Bianchi VII$_h$ cosmologies

- Bianchi VII$_h$ models describe a universe with overall rotation, with angular velocity ω, and a three-dimensional rate of shear, specified by the antisymmetric tensor σ_{ij}. Throughout we assume equality of shear modes $\sigma = \sigma_{12} = \sigma_{13}$ (cf. Jaffe *et al.* 2005).
- The amplitude of induced CMB temperature fluctuations may be characterised by the dimensionless vorticity $(\omega/H)_0$, which influences the amplitude of the induced temperature contribution only and not its morphology.
- The model has a free parameter, denoted x, describing the comoving length-scale over which the principal axes of shear and rotation change orientation.
- The orientation and handedness of the coordinate system is also free.
- Bianchi VII$_h$ models may be described by the parameter vector:

$$\Theta_{\mathrm{B}} = (\Omega_{\mathrm{m}}, \Omega_\Lambda, x, (\omega/H)_0, \alpha, \beta, \gamma) .$$



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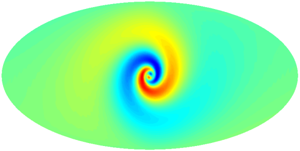

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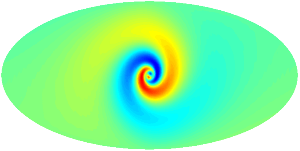

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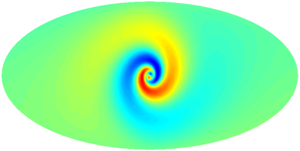

Bianchi VII_h cosmologies

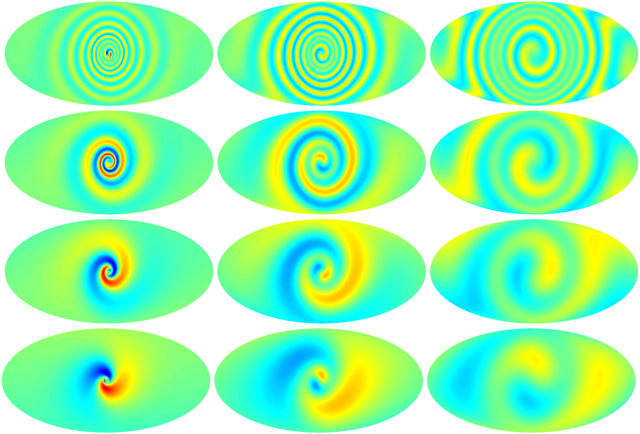

Figure: Simulated deterministic CMB temperature contributions in Bianchi VII_h cosmologies for varying x and $\Omega_{\rm total}$ (left-to-right $\Omega_{\rm total} \in \{0.10, 0.30, 0.95\}$; top-to-bottom $x \in \{0.1, 0.3, 0.7, 1.5\}$).

Outline

Bayesian analysis of Bianchi VII_h cosmologies

- Perform the Bayesian analysis described by

  JDM, Thibaut Josset, Stephen Feeney, Hiranya Peiris, Anthony Lasenby (2013)
  http://arxiv.org/abs/arXiv:1303.3409

  and applied to WMAP previously.

- Posterior distribution of the parameters Θ of model of interest M given data $\boldsymbol{d}$, as

$$\mathrm{P}(\Theta \,|\, \boldsymbol{d}, M) \propto \mathrm{P}(\boldsymbol{d} \,|\, \Theta, M)\, \mathrm{P}(\Theta \,|\, M)\,.$$

- Consider open and flat cosmologies with cosmological parameters:
  $\Theta_{\mathrm{C}} = (A_s,\ n_s,\ \tau,\ \Omega_{\mathrm{b}}h^2,\ \Omega_{\mathrm{c}}h^2,\ \Omega_\Lambda,\ \Omega_k)$.
- Recall Bianchi parameters:
  $\Theta_{\mathrm{B}} = (\Omega_{\mathrm{m}},\ \Omega_\Lambda,\ x,\ (\omega/H)_0,\ \alpha, \beta, \gamma)$.
- Likelihood is given by

$$\mathrm{P}(\boldsymbol{d} \,|\, \Theta_{\mathrm{B}}, \Theta_{\mathrm{C}}) \propto \frac{1}{\sqrt{|\mathbf{X}(\Theta_{\mathrm{C}})|}} \mathrm{e}^{\left[-\chi^2(\Theta_{\mathrm{C}},\Theta_{\mathrm{B}})/2\right]}\,,$$

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Bayesian analysis of Bianchi VII_h cosmologies

- Bianchi VII_h templates can be computed accurately and rotated efficiently in harmonic space $\rightarrow$ consider harmonic space representation, where $\boldsymbol{d} = \{d_{\ell m}\}$ and $\boldsymbol{b}(\Theta_\text{B}) = \{b_{\ell m}(\Theta_\text{B})\}$.
- Partial-sky analysis that handles in harmonic space a mask applied in pixel space.
- Add masking noise in order to marginalise the pixel values of the data contained in the masked region, with variance for pixel i given by

$$\sigma_m^2(\omega_i) = \begin{cases} \Sigma_m^2, & \omega_i \in \mathbb{M} \\ 0, & \omega_i \in \mathbb{S}^2 \backslash \mathbb{M} \end{cases},$$

  where Σ_m^2 is a constant masking noise variance.
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$$\boxed{\mathbf{X}(\Theta_\text{C}) = \mathbf{C}(\Theta_\text{C}) + \mathbf{M}},$$

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Bayesian analysis of Bianchi VII_h cosmologies

- Compute the Bayesian evidence to determine preferred model:

$$E = \mathrm{P}(\boldsymbol{d} \mid M) = \int \mathrm{d}\Theta \, \mathrm{P}(\boldsymbol{d} \mid \Theta, M) \, \mathrm{P}(\Theta \mid M) \ .$$

- Use MultiNest to compute the posteriors and evidences via nested sampling (Feroz & Hobson 2008, Feroz *et al.* 2009).
- Consider two models:
  - Flat-decoupled-Bianchi model: Θ_{C} and Θ_{B} fitted simultaneously but decoupled $\rightarrow$ phenomenological
  - Open-coupled-Bianchi model: Θ_{C} and Θ_{B} fitted simultaneously and coupled $\rightarrow$ physical

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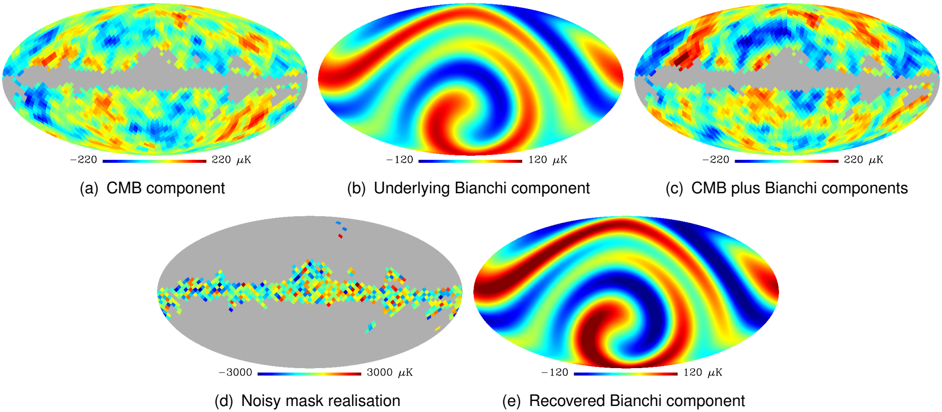
Validation with simulations



(a) CMB component

(b) Underlying Bianchi component

(c) CMB plus Bianchi components

(d) Noisy mask realisation

(e) Recovered Bianchi component

Figure: Partial-sky simulation with embedded Bianchi VII_h component at $\ell_{\max} = 32$.

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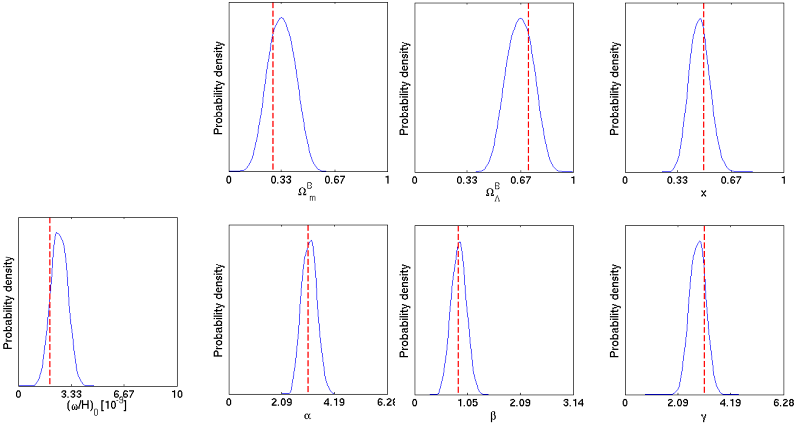

Figure: Marginalised posterior distributions recovered from partial-sky simulation at $\ell_{\max} = 32$.

Outline

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Planck results: flat-decoupled-Bianchi model

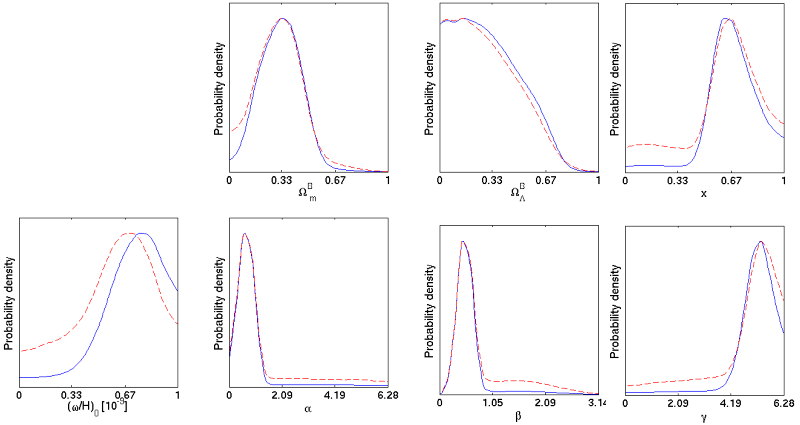

Figure: Posterior distributions of Bianchi parameters recovered for the phenomenological flat-decoupled-Bianchi model from *Planck* `SMICA` (solid curves) and `SEVEM` (dashed curves) data.

Planck results: flat-decoupled-Bianchi model

Table: Bayes factor relative to equivalent ΛCDM model (positive favours Bianchi model).

Model	$\Delta \ln E$	
	SMICA	SEVEM
Flat-decoupled-Bianchi (left-handed)	2.8 ± 0.1	1.5 ± 0.1
Flat-decoupled-Bianchi (right-handed)	0.5 ± 0.1	0.5 ± 0.1

- On the Jeffreys (1961) scale, evidence for the inclusion of a Bianchi VII_h component would be termed strong (significant) for SMICA (SEVEM) component-separated data.
- A log-Bayes factor of 2.8 corresponds to an odds ratio of approximately 1 in 16.
- *Planck* data favour the inclusion of a phenomenological Bianchi VII_h component.
- Best-fit Bianchi VII_h template is similar to that first found in WMAP data by Jaffe *et al.* 2005.

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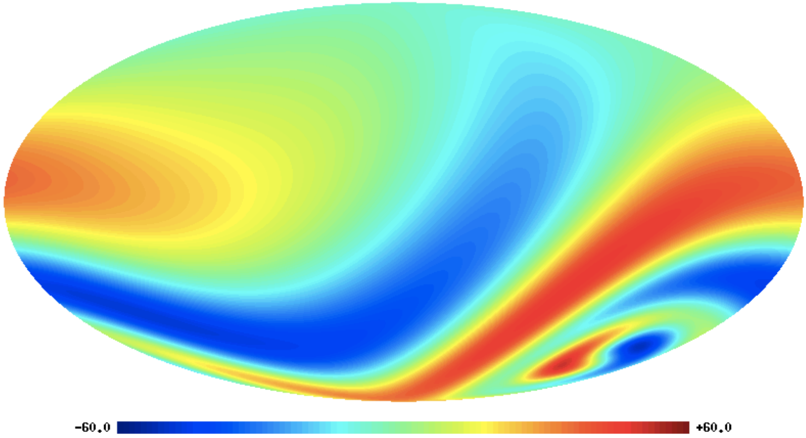

Figure: Best-fit template of flat-decoupled-Bianchi VII_h model found in *Planck* SMICA component-separated data.

Planck results: flat-decoupled-Bianchi model

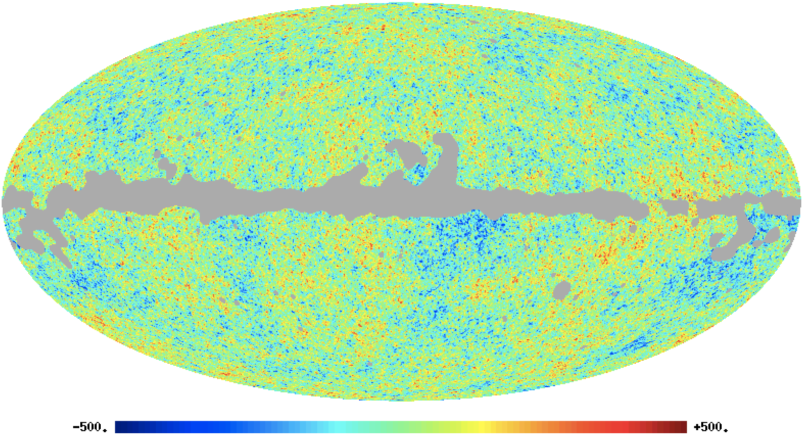

Figure: *Planck* SMICA component-separated data.

Planck results: flat-decoupled-Bianchi model

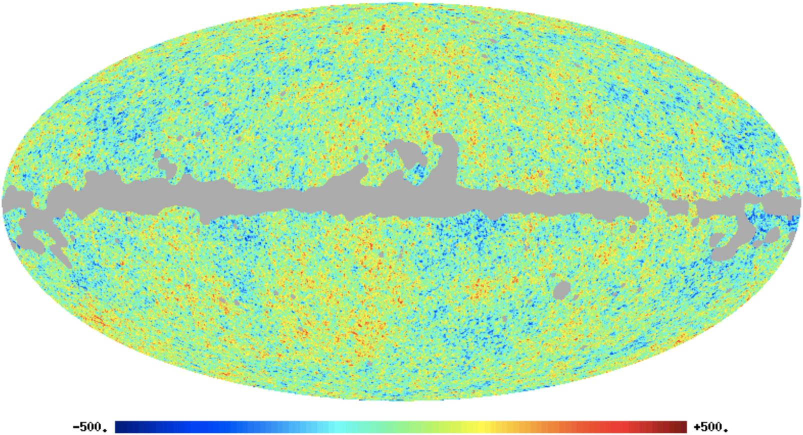

Figure: *Planck* SMICA component-separated data minus best-fit template of flat-decoupled-Bianchi VII$_h$ model.

Planck results: flat-decoupled-Bianchi model

- **BUT** the flat-Bianchi-decoupled model is phenomenological and **not physical!**

Table: Parameters recovered for flat-decoupled-Bianchi model.

Bianchi Parameter	SMICA MAP	SMICA Mean	SEVEM MAP	SEVEM Mean
Ω_{m}^{B}	0.38	0.32 ± 0.12	0.35	0.31 ± 0.15
Ω_{Λ}^{B}	0.20	0.31 ± 0.20	0.22	0.30 ± 0.20
x	0.63	0.67 ± 0.16	0.66	0.62 ± 0.23
$(\omega/H)_0$	8.8×10^{-10}	$(7.1 \pm 1.9) \times 10^{-10}$	9.4×10^{-10}	$(5.9 \pm 2.4) \times 10^{-10}$
α	38.8°	$51.3^\circ \pm 47.9^\circ$	40.5°	$77.4^\circ \pm 80.3^\circ$
β	28.2°	$33.7^\circ \pm 19.7^\circ$	28.4°	$45.6^\circ \pm 32.7^\circ$
γ	309.2°	$292.2^\circ \pm 51.9^\circ$	317.0°	$271.5^\circ \pm 80.7^\circ$

Planck results: open-coupled-Bianchi model

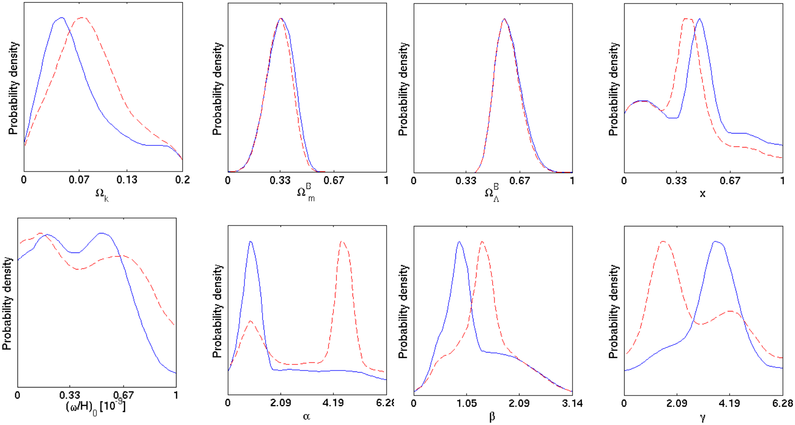

Figure: Posterior distributions of Bianchi parameters recovered for the physical open-coupled-Bianchi model from *Planck* SMICA (solid curves) and SEVEM (dashed curves) data.

Planck results: open-coupled-Bianchi model

Table: Bayes factor relative to equivalent ΛCDM model (positive favours Bianchi model).

Model	$\Delta \ln E$	
	SMICA	SEVEM
Open-coupled-Bianchi (left-handed)	0.0 ± 0.1	0.0 ± 0.1
Open-coupled-Bianchi (right-handed)	-0.4 ± 0.1	-0.4 ± 0.1

- In the physical setting where the standard cosmological and Bianchi parameters are coupled, *Planck* data do not favour the inclusion of a Bianchi VII_h component.
- We find no evidence for Bianchi VII_h cosmologies and constrain the vorticity of such models to $(\omega/H)_0 < 8.1 \times 10^{-10}$ (95% confidence level).

Summary

- Perform a Bayesian analysis of partial-sky Planck data for evidence of Bianchi VII$_h$ cosmologies.
- Planck data support the inclusion of a phenomenological Bianchi template. . .
- **BUT** this model is non-physical and the recovered cosmological parameters are inconsistent with standard constraints!
- In the physical model where the cosmological and Bianchi parameters are coupled, ***Planck* data do not favour the inclusion of a Bianchi VII$_h$ component**.
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The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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