How isotropic is the Universe?

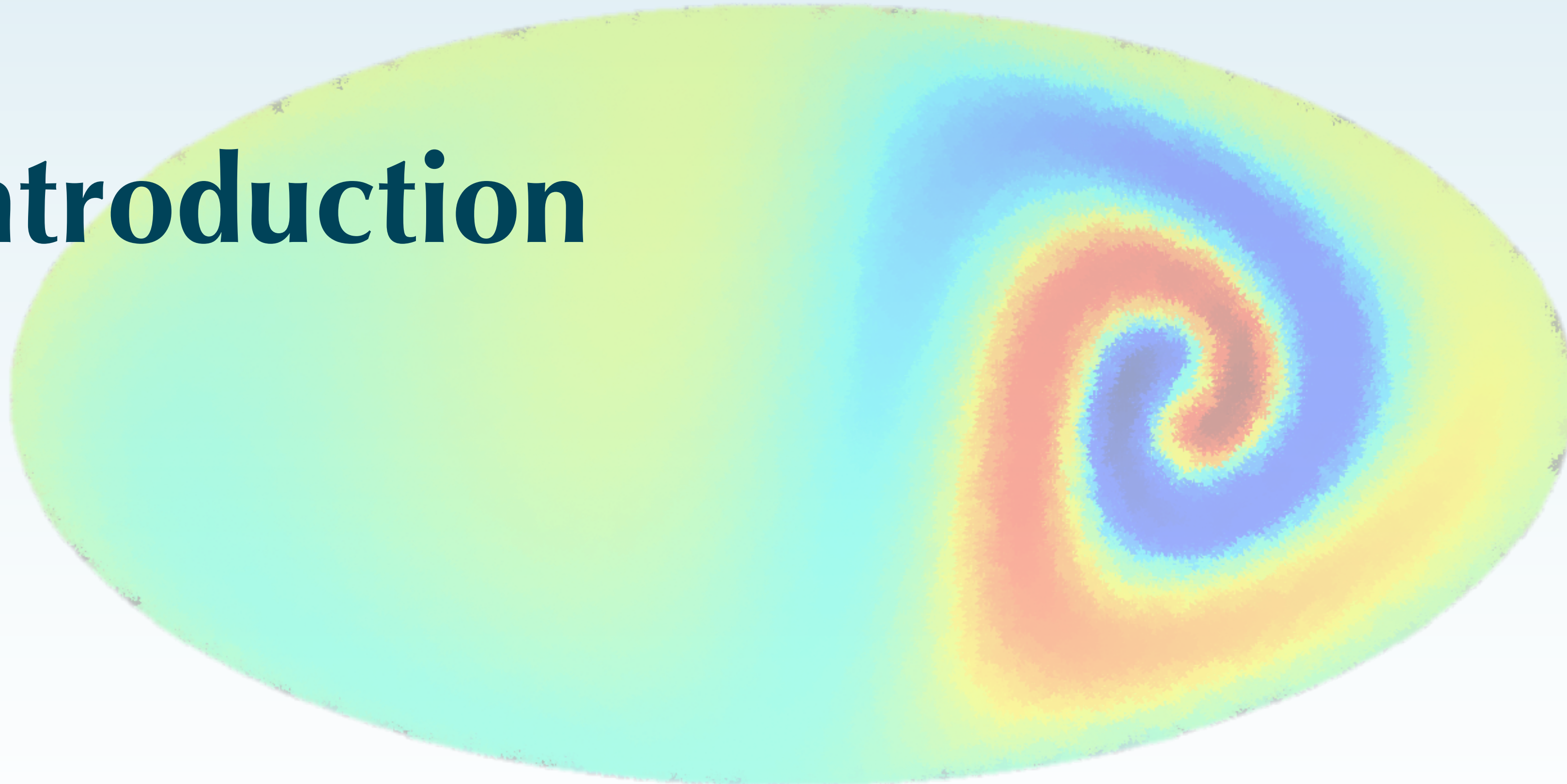
Phys. Rev. Lett. 117, 131302 (2016), arXiv: 1605.07178
MNRAS 462, 1802 (2016), arXiv: 1604.01024

Daniela Saadeh
with S. M. Feeney, A. Pontzen, H. V. Peiris, J. D. McEwen

Outline

- Introduction
  - Testing the isotropy of the Universe
- Method
  - Modelling anisotropy
  - Looking for anisotropy in the CMB
- Results
- Conclusions

Introduction



- The problem

The problem

The Standard Model of Cosmology relies on the fundamental assumption that the large-scale Universe is

isotropic + **homogeneous**

The University of Nottingham UCL

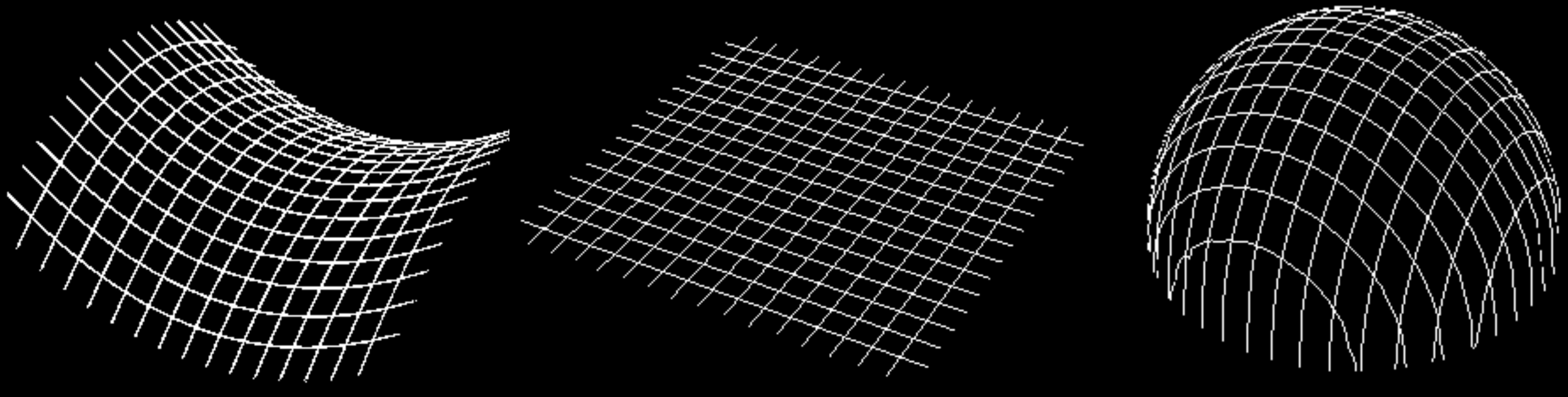
The problem

The Standard Model of Cosmology relies on the fundamental assumption that the large-scale Universe is

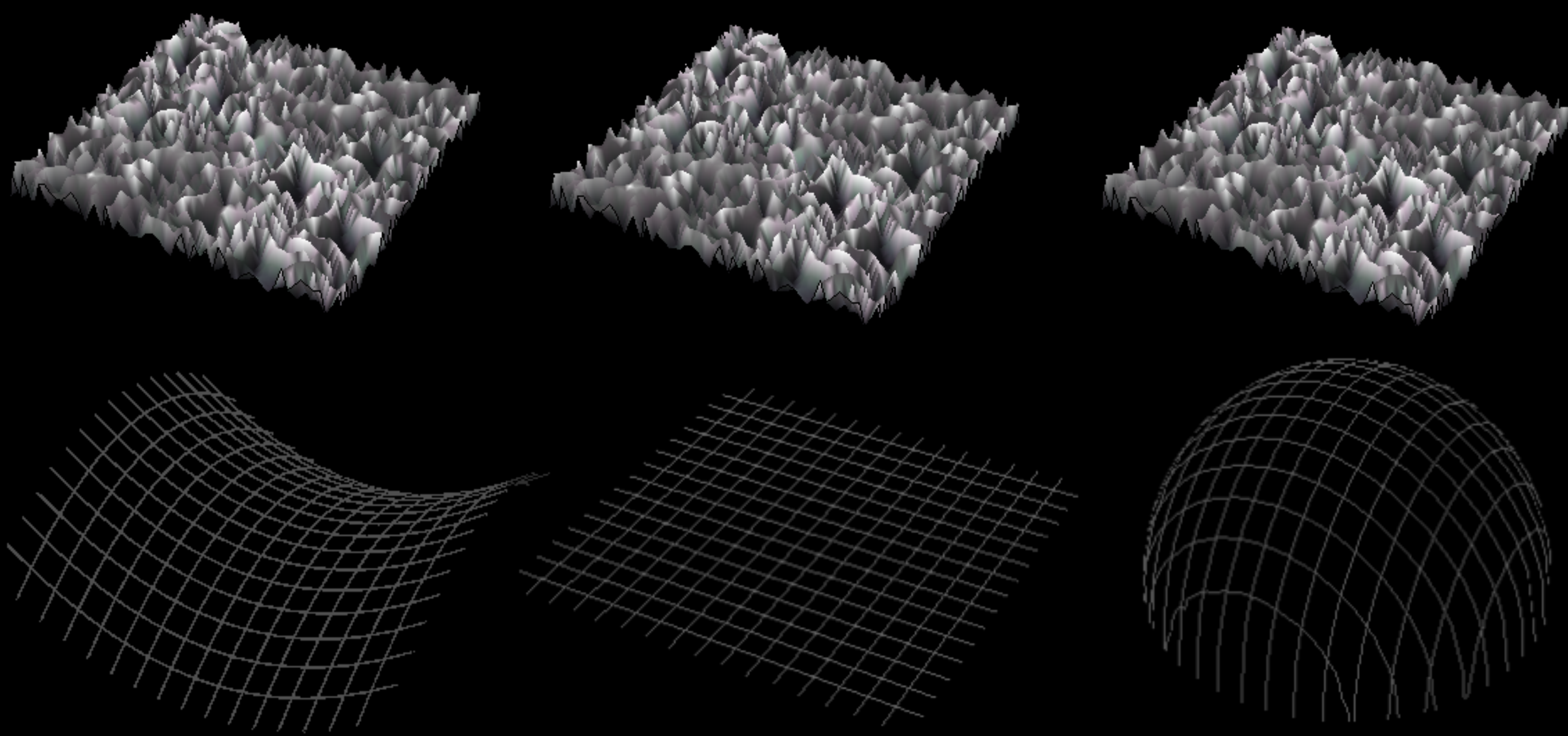
isotropic + **homogeneous**

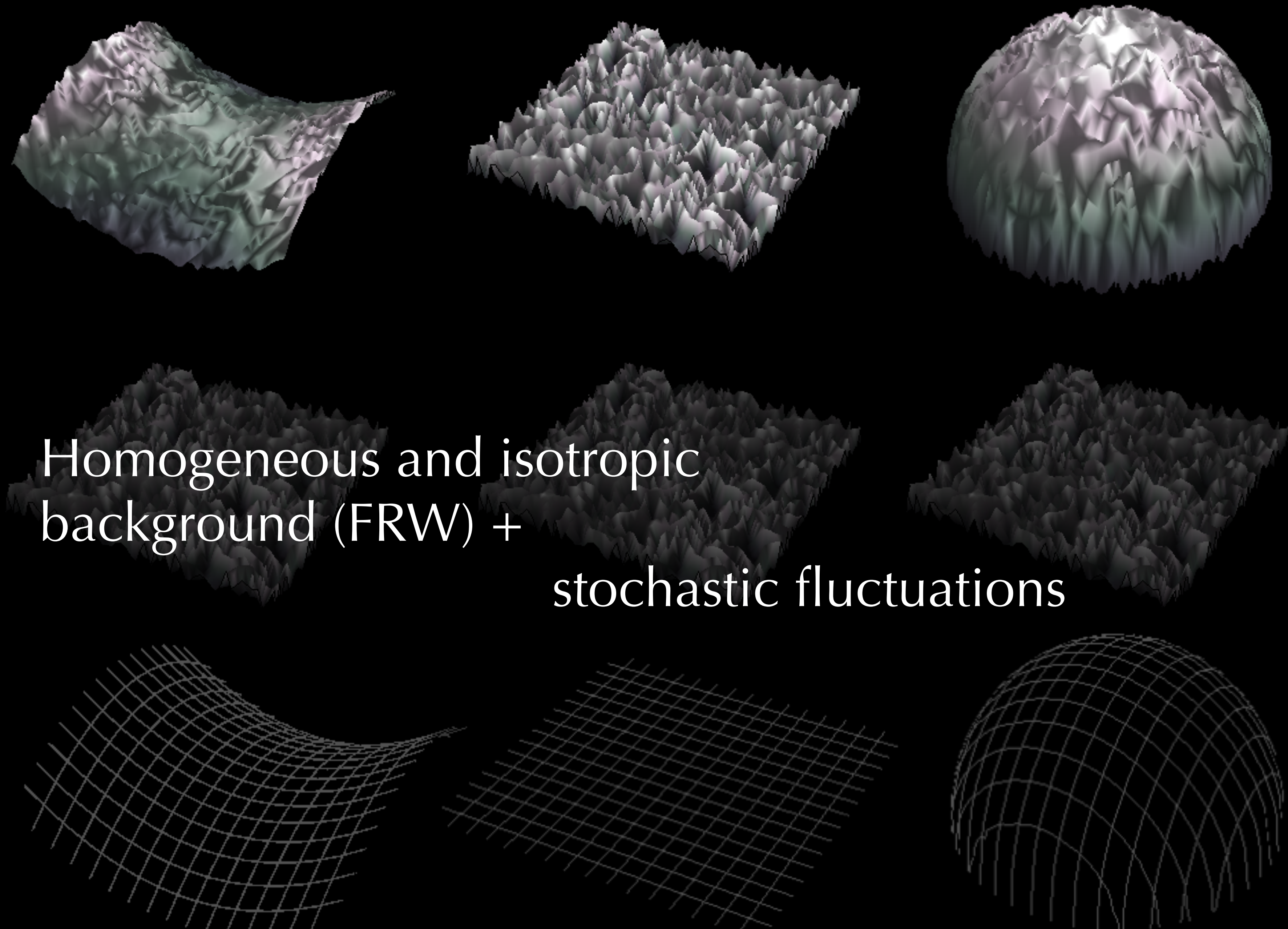
= FRW background metric

Homogeneous and isotropic background (FRW)



Stochastic fluctuations





Homogeneous and isotropic
background (FRW) +
stochastic fluctuations

The problem

The Standard Model of Cosmology relies on the fundamental assumption that the large-scale Universe is

isotropic … ogeneous

Assumptions must be tested

We want to **test** the **isotropy** of the Universe with the **CMB**

The problem

The Standard Model of Cosmology relies on the fundamental assumption that the large-scale Universe is

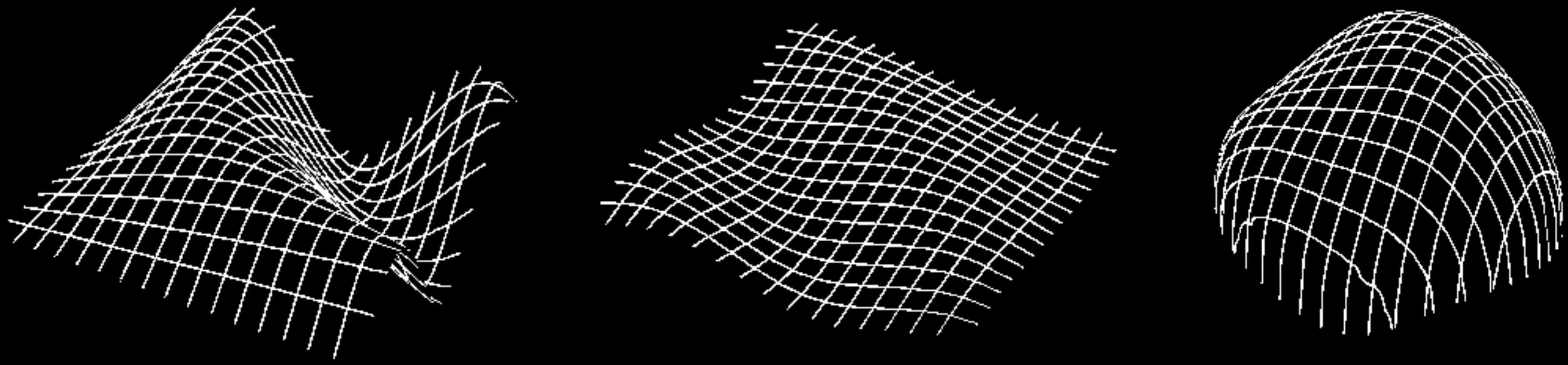
~~**isotropic**~~ + **homogeneous**

The problem

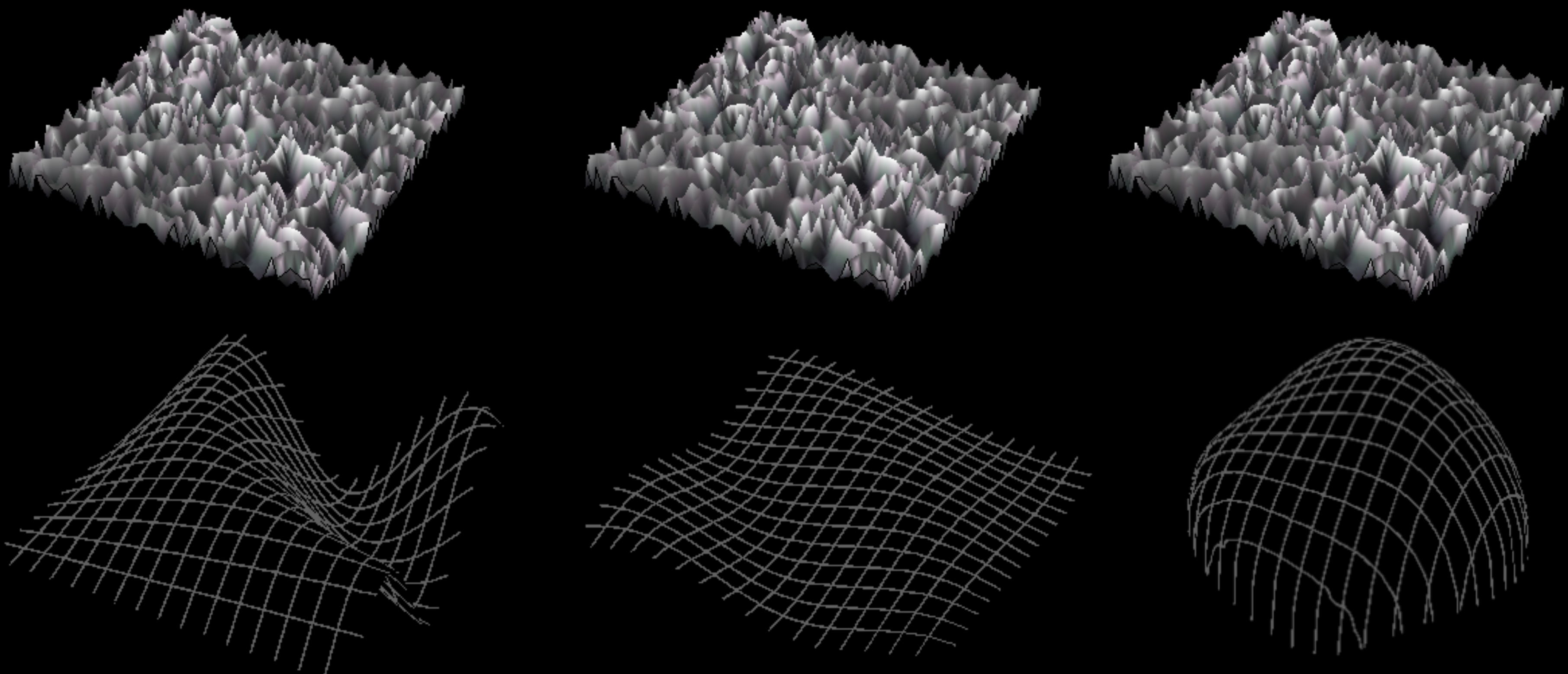
= Bianchi models

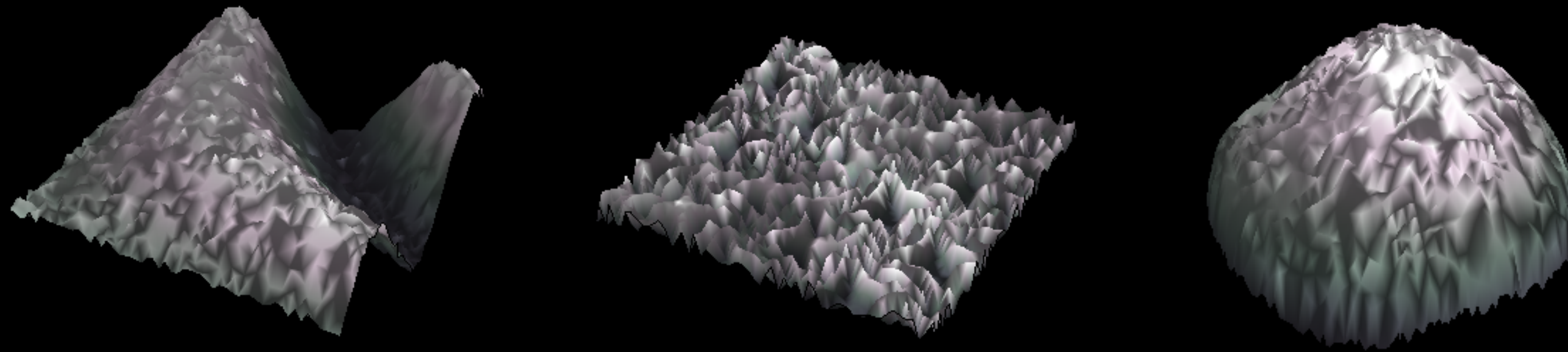
~~isotropic~~ + homogeneous

Homogeneous and **an**isotropic background (Bianchi model)



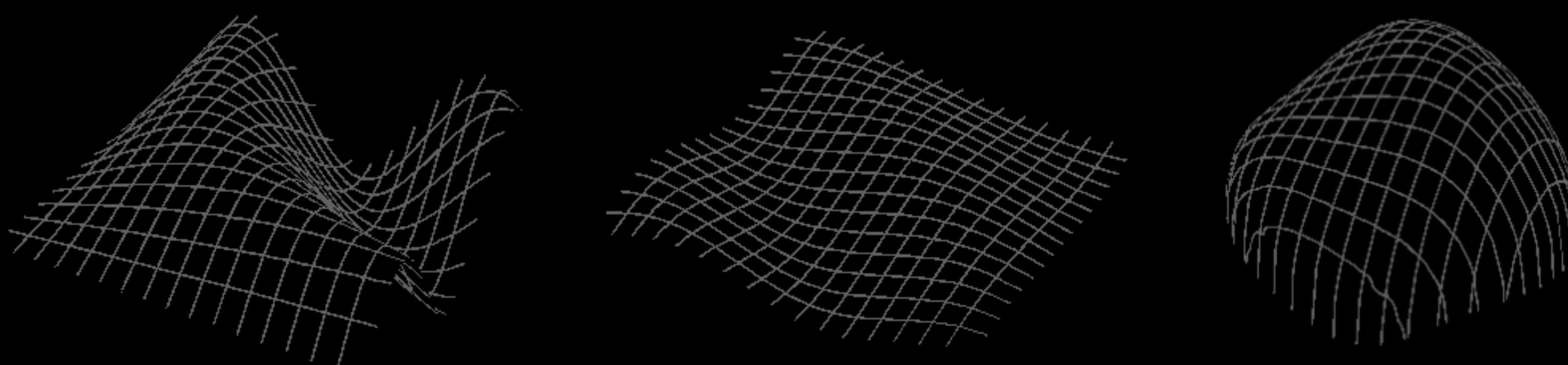
Stochastic fluctuations



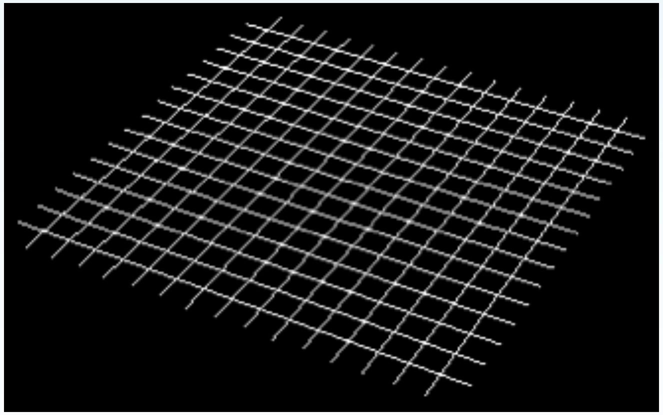


Homogeneous and **anisotropic** background
(Bianchi model) +

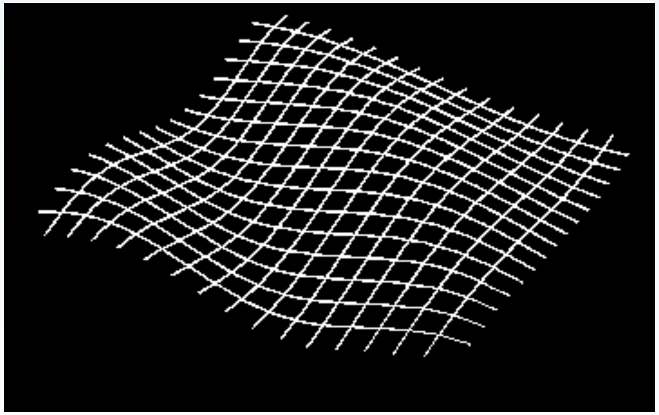
stochastic fluctuations



Testing isotropy



VS

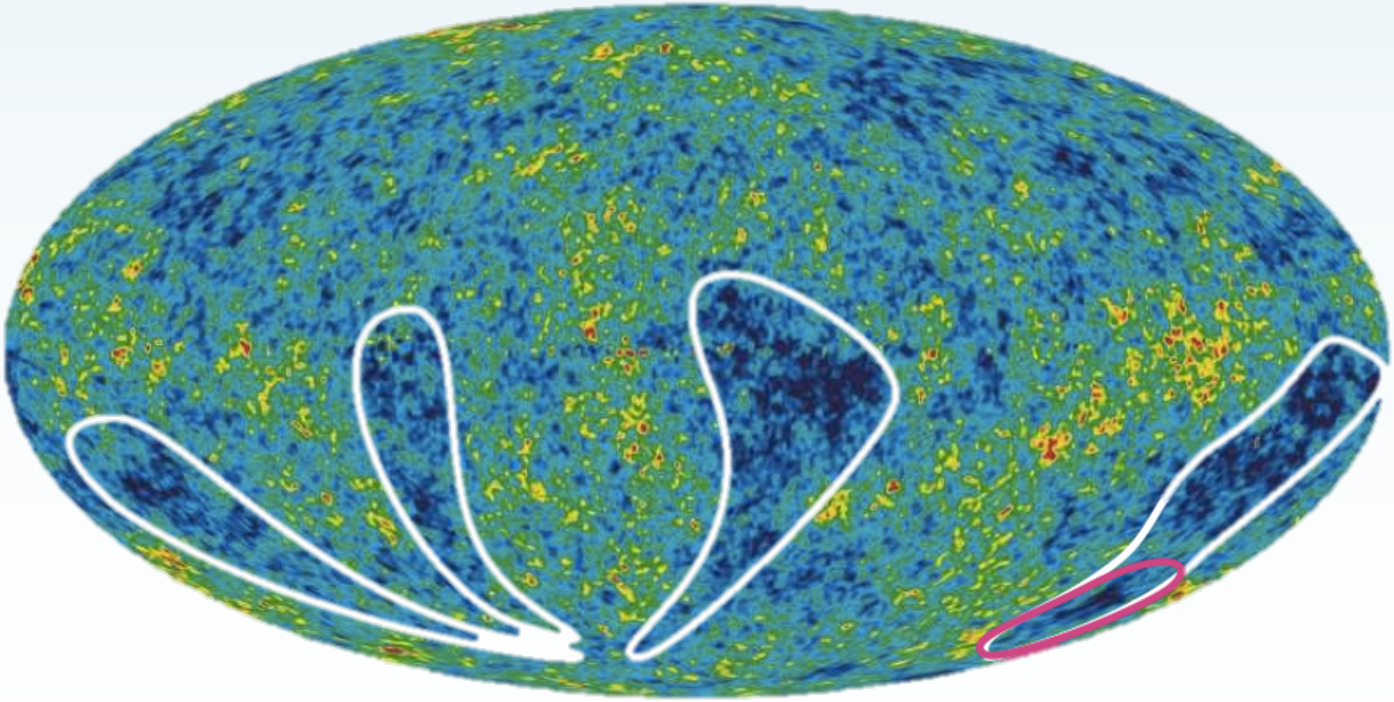


Which one is a better fit to the data?

Quick historical review

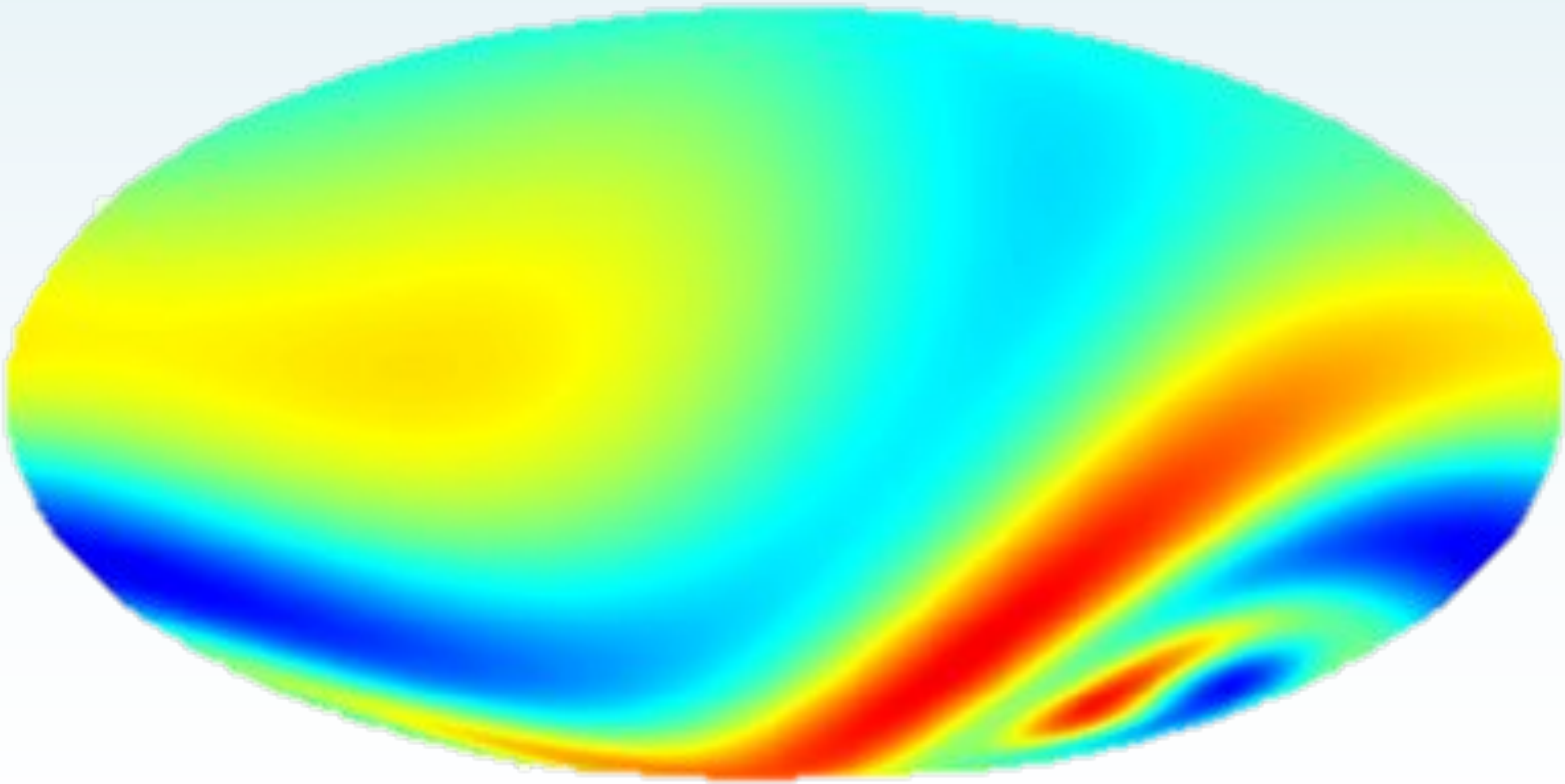
How did we get here?

Large scale anomalies?



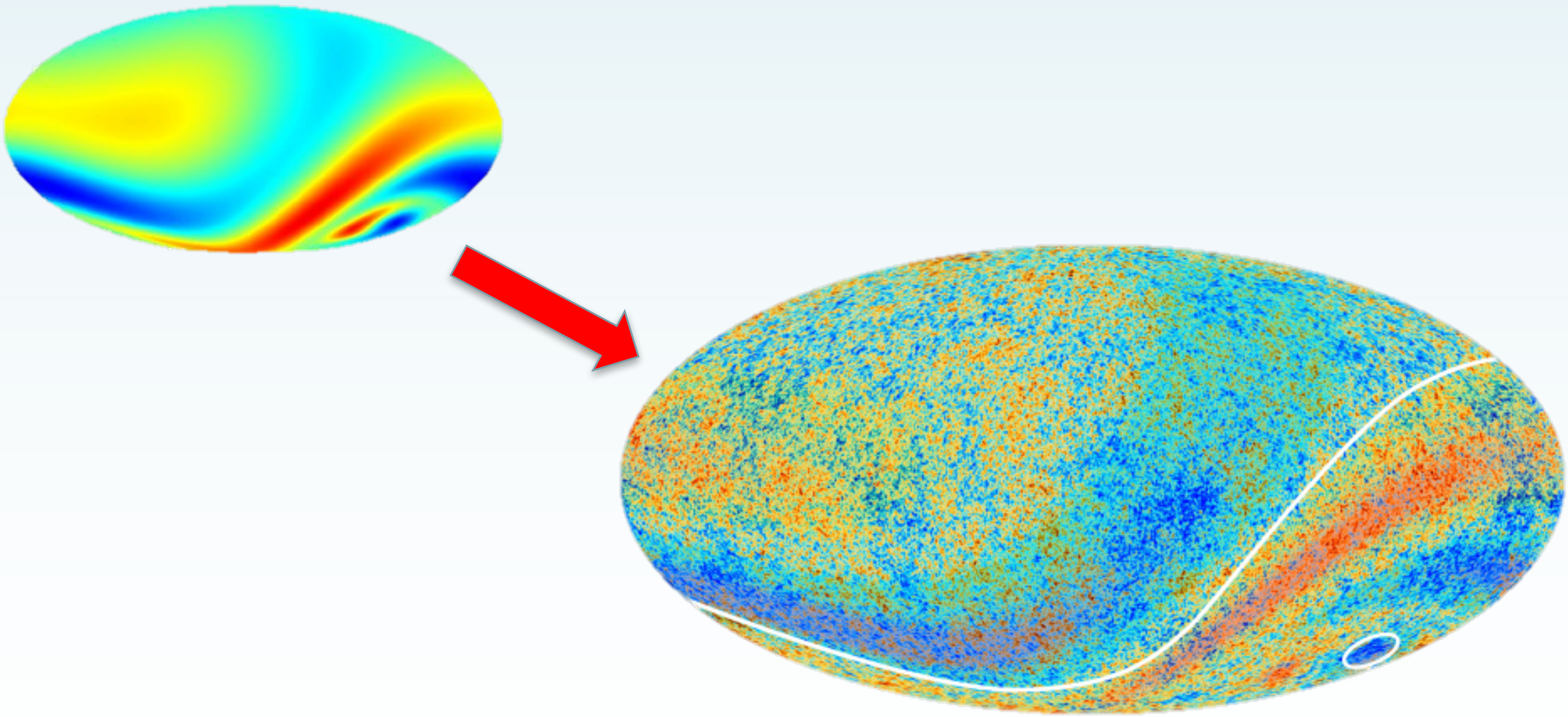
WMAP collaborations, 7-year data

Evidence of a Bianchi signal?



Jaffe, T. R., Hervik, S., Banday, A. J., Górski, K. M., 2006, ApJ, 644, 701

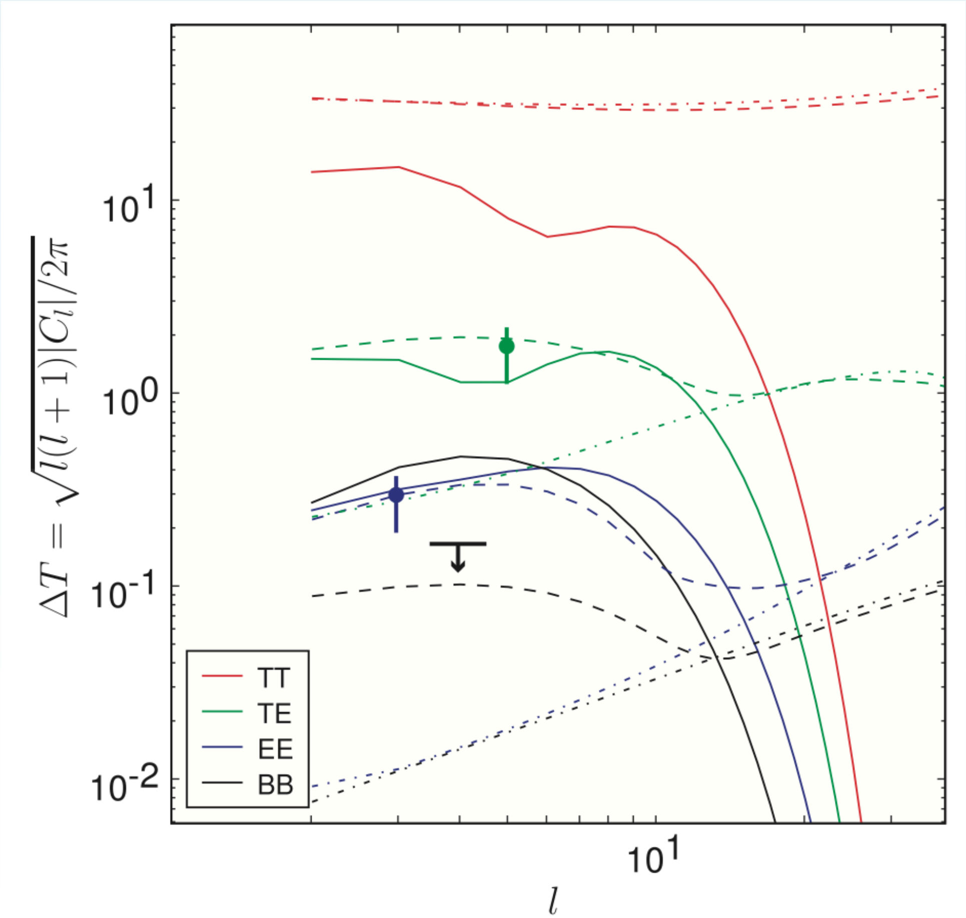
Evidence of a Bianchi signal?



Jaffe, T. R., Hervik, S., Banday, A. J., Górski, K. M., 2006, ApJ, 644, 701

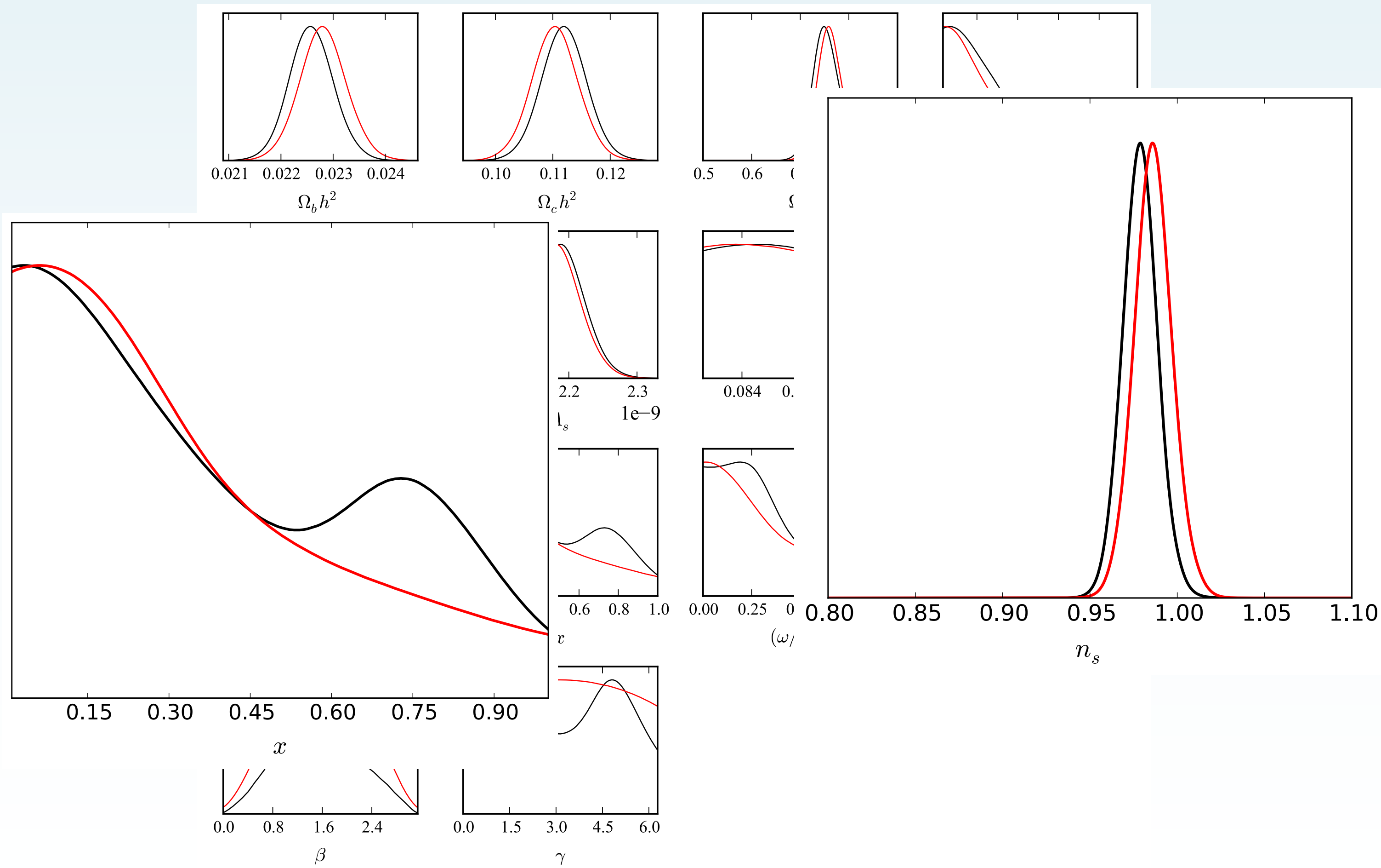
ESA and the Planck Collaboration

Too much B-mode polarization!



Pontzen, A., Challinor, A., MNRAS 380 (2007) 1387-1398

Statistical searches for Bianchi models



McEwen *et al.*, MNRAS, 436(4):3680-3694, 2013

Several things still *missing*…

- **3** out of **5** degrees of freedom **untested** for

  → anisotropy can still sit there unseen!

- Constraints from **polarization** not used

  → but they are very stringent!

- **small scales** not exploited

  → constraining power lost!

Several things still *missing*…

- **3** out of **5** degrees of freedom

  → anisot…

- Constrai…

  → … stringent!

- **sn**… …xploited

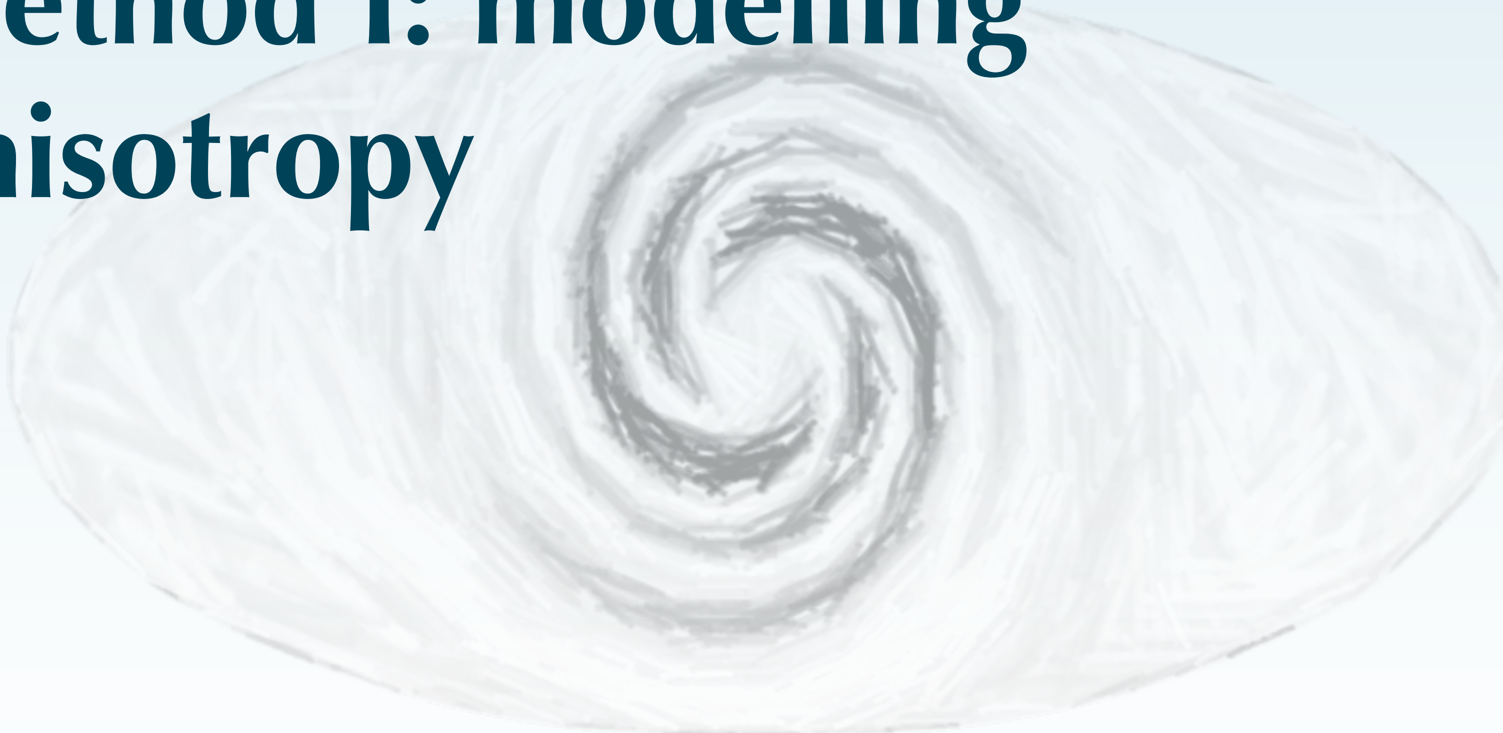
  → constraining power lost!

Not enough to test isotropy

Method

- how we model anisotropy
- how we search for it

Method I: modelling anisotropy



- Which Bianchi models?
- What kind of anisotropy?

Bianchi models

- Bianchi models cover *all the possible ways* for a 3-space of being *homogeneous*

- Testing for types

$$I,\ VII_0,\ V,\ VII_h,\ IX$$

is sufficient to test for *all the Bianchi models that are close to isotropy*

Which Bianchi models?

Flat: Bianchi I and VII_0

Open: Bianchi V and VII_h

Closed: Bianchi IX

Which Bianchi models?

Flat: Bianchi I and VII_0

Open: Bianchi V and VII_h

~~Closed: Bianchi IX~~

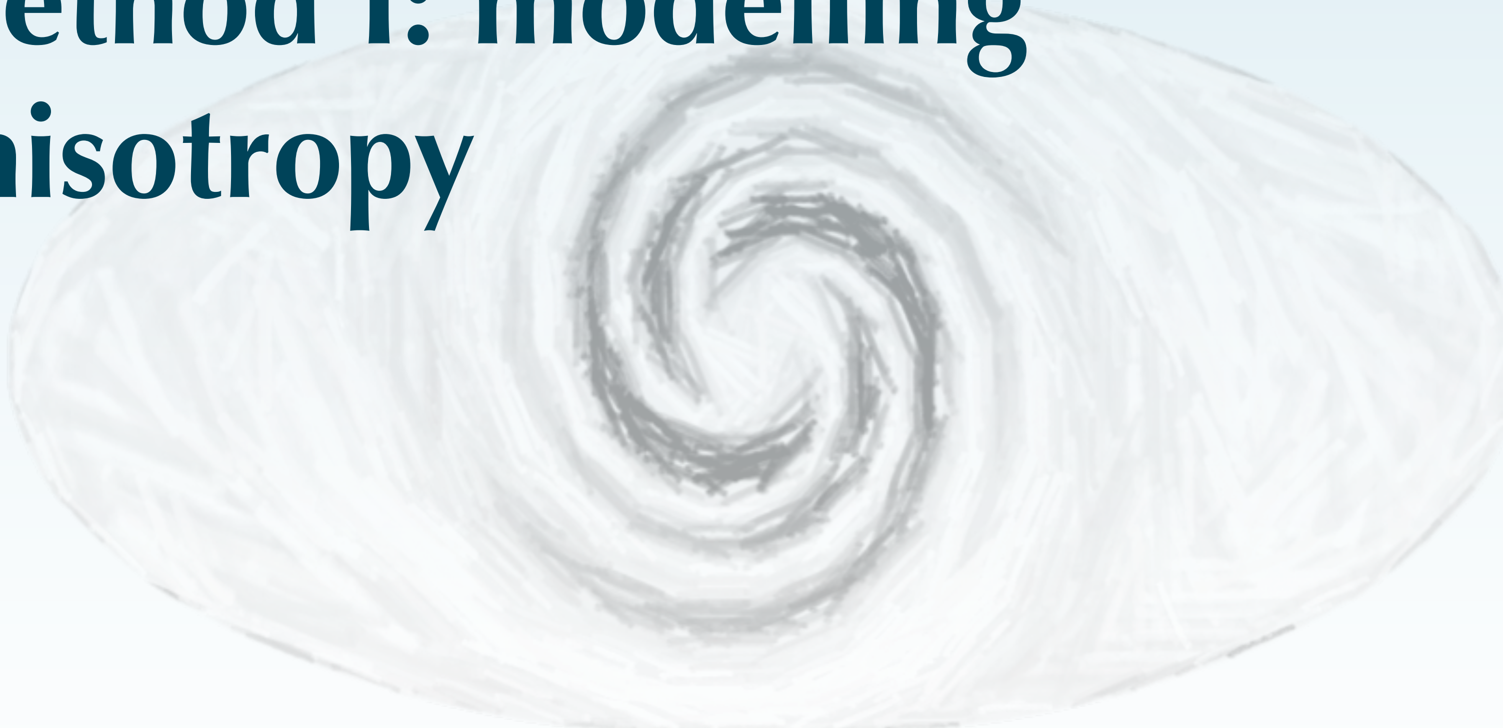
Only an additional quadrupole

= not much constraining information available

The goal

- We test for the **most general** departure from isotropy in the CMB
  - that keeps homogeneity
  - that keeps anisotropy small: must be consistent with observations!
  - that deals with a flat or open Universe

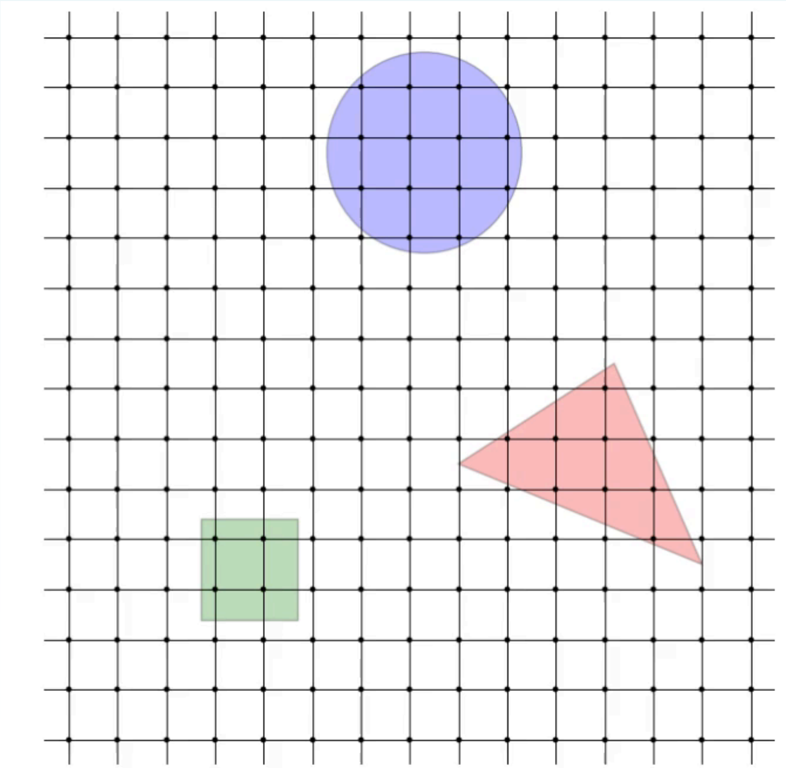
Method I: modelling anisotropy



- Which Bianchi models?
- What kind of anisotropy?

Implementing anisotropy

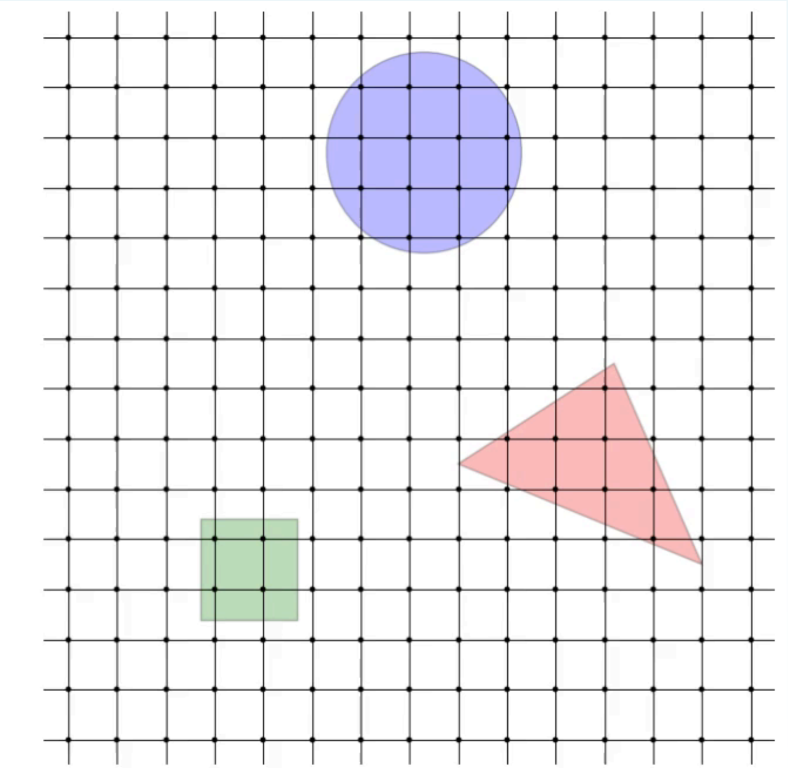
What does it mean to be anisotropic?



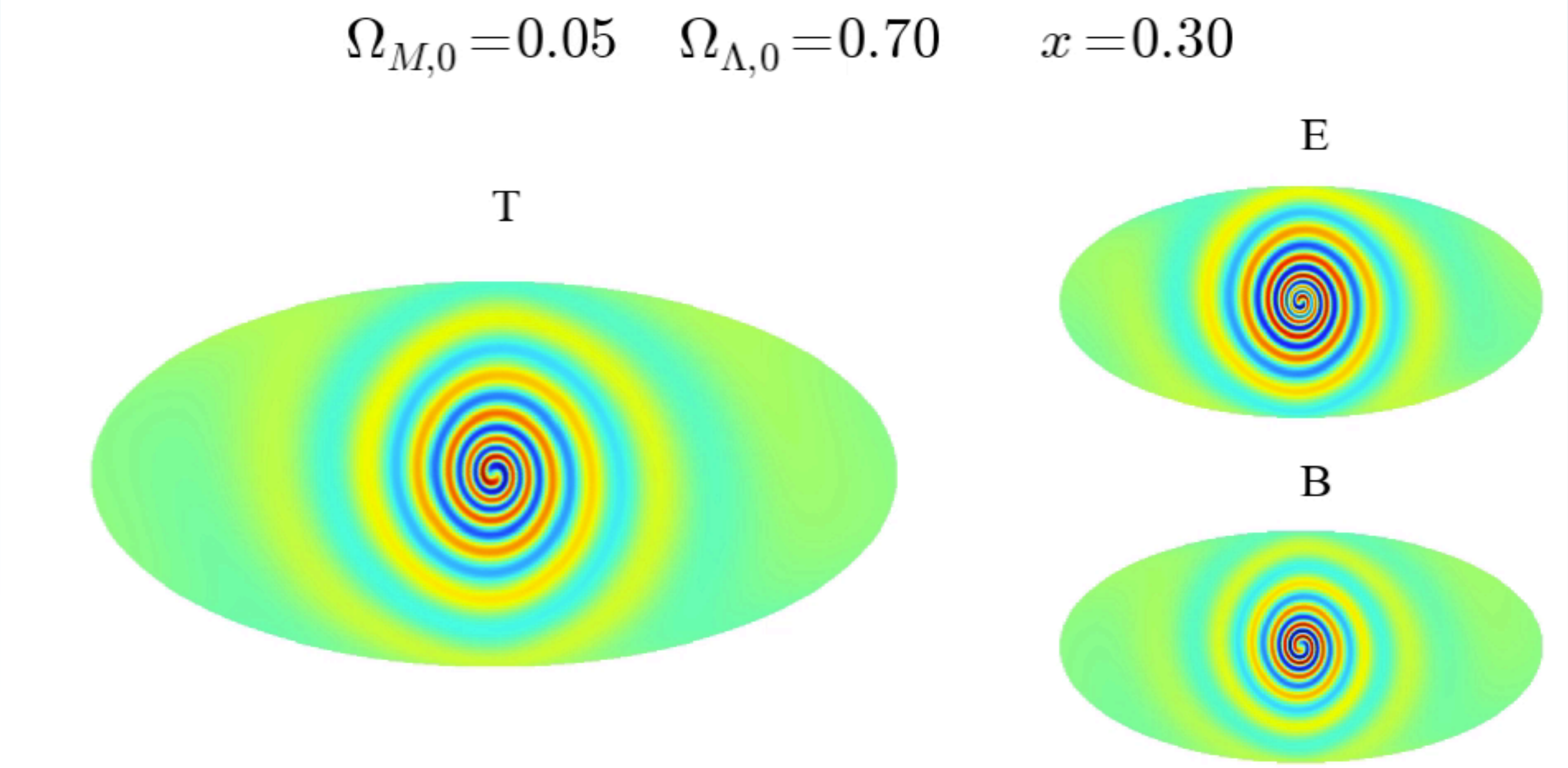
Implementing anisotropy

What does it mean to be anisotropic?

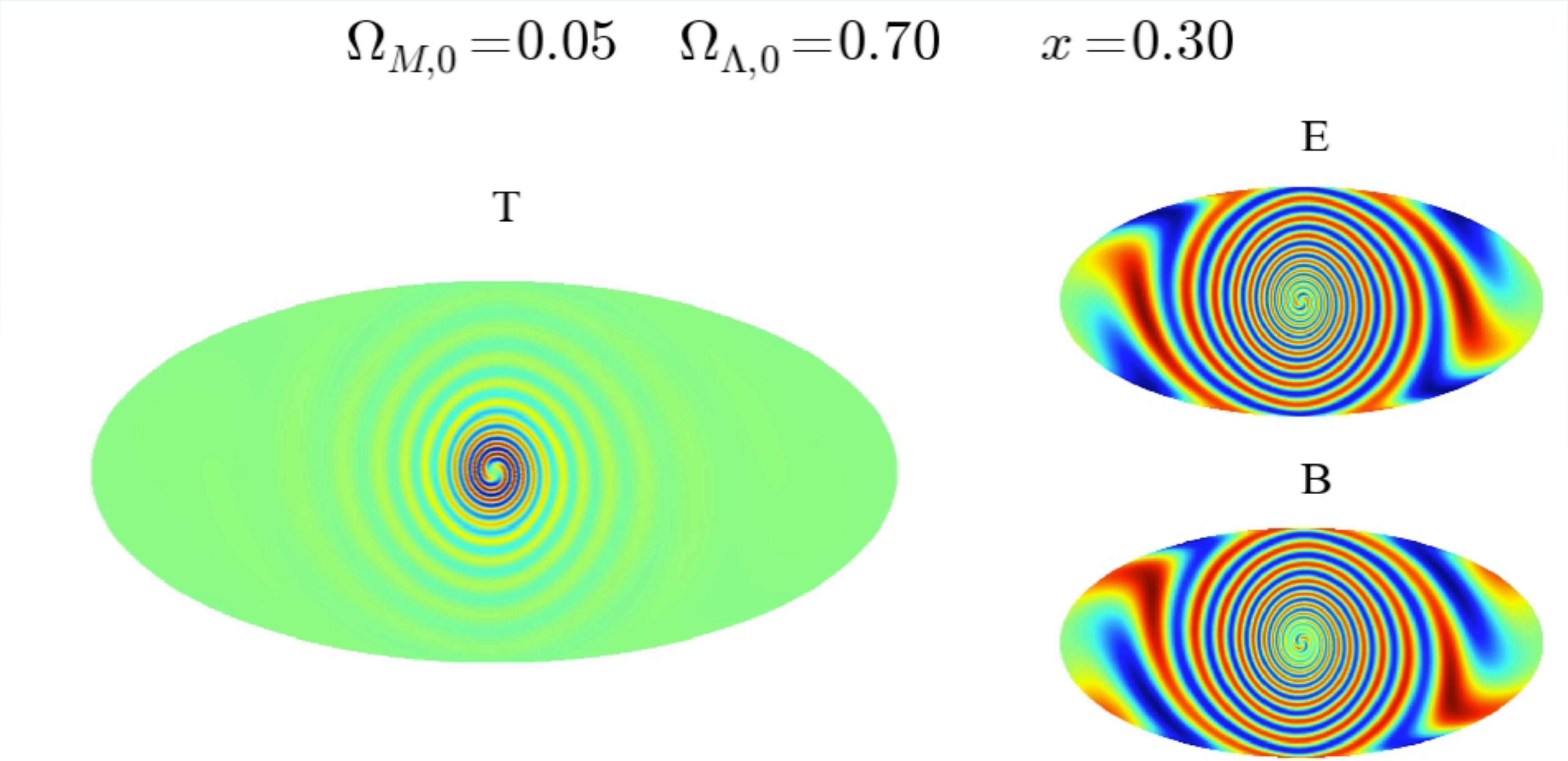
... more than this!



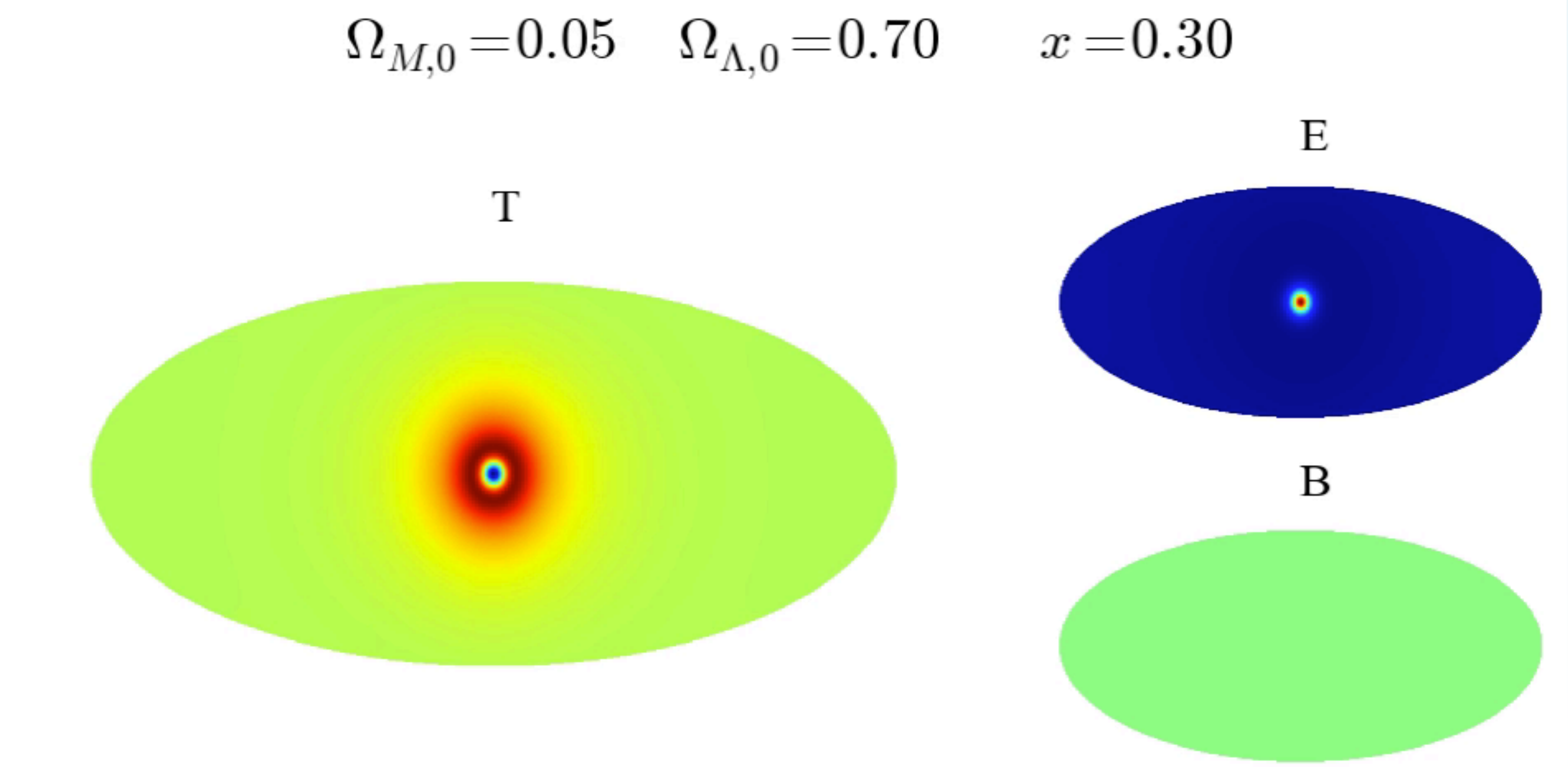
The d.o.f. of anisotropy: vector modes



The d.o.f. of anisotropy: tensor modes

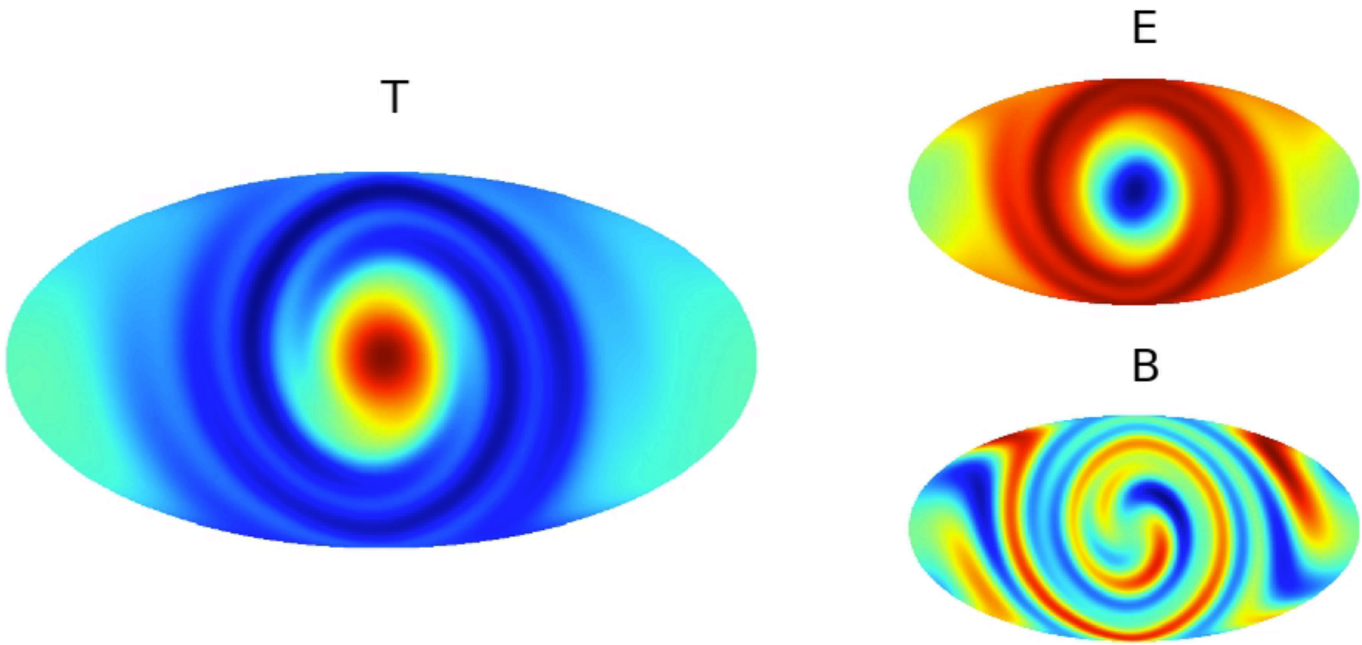


The d.o.f. of anisotropy: scalar modes



The full freedom!

$(\frac{\sigma_S}{H})_0 = -1.0 \times 10^{-8}$ $(\frac{\sigma_V}{H})_0 = 1.0 \times 10^{-9}$ $(\frac{\sigma_T^{(reg)}}{H})_0 = 1.0 \times 10^{-6}$ $(\frac{\sigma_T^{(irr)}}{H})_0 = 1.0 \times 10^{-7}$ $\gamma_{VT} = 0$



Saadeh, Feeney, Pontzen, Peiris, McEwen, Phys. Rev. Lett. 117, 131302 (2016)

Implementing anisotropy

ABSolve (***Anisotropic Boltzmann Solver***)

Bianchi code developed for our analysis:

- temperature and polarization maps (and C_l's)
- all open/flat Bianchi models close to FRW
- all the shear degrees of freedom
- stable across a vast range of parameters

Saadeh, Feeney, Pontzen, Peiris, McEwen, *MNRAS* 462, 1802 (2016)

Implementing anisotropy (cc′ed)

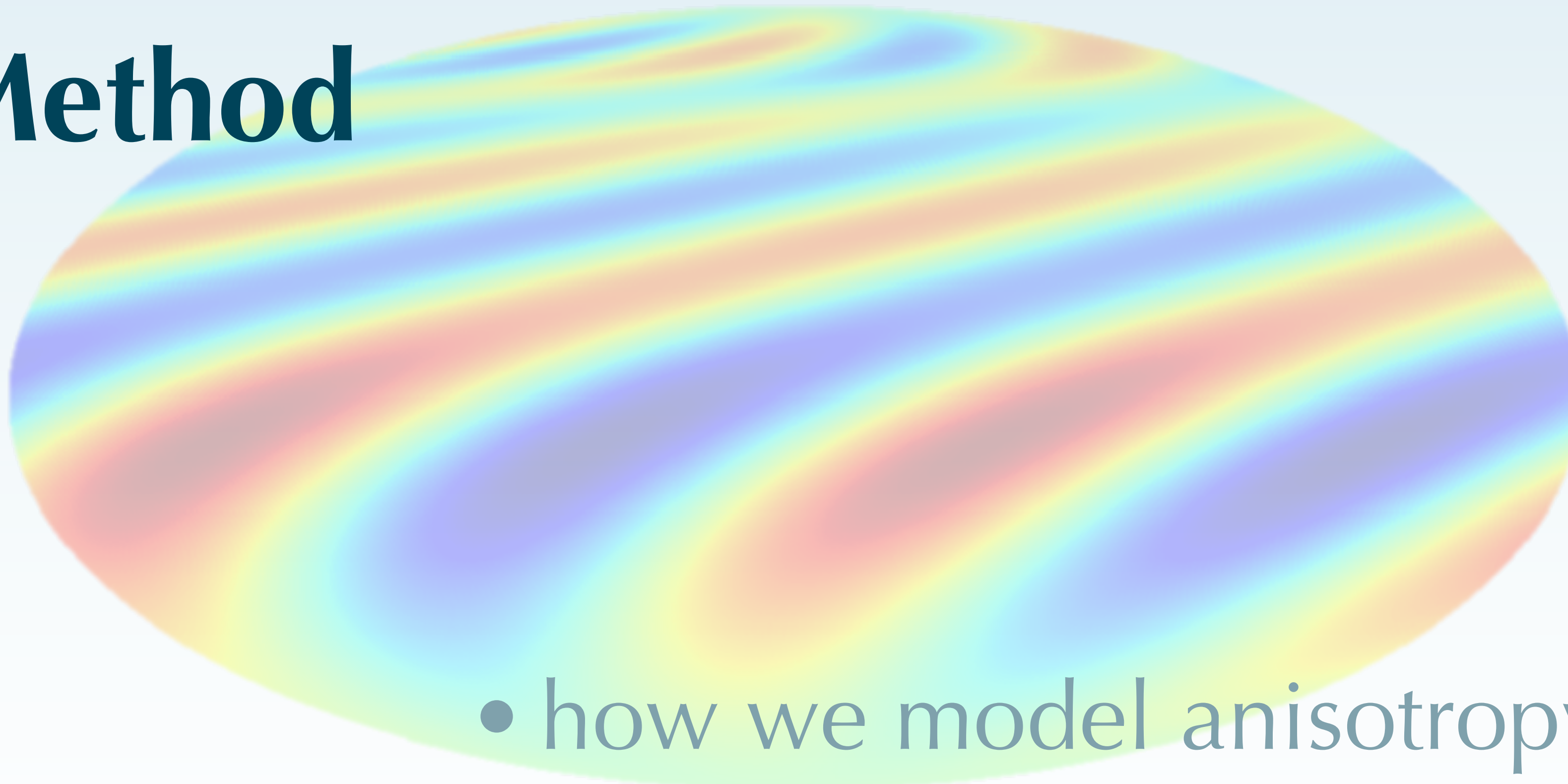
ABSolve (***Anisotropic Boltzmann Solver***)

Bianchi code developed for our analysis (cc′ed):

- written in Python and Cython
- ~1 s typical run time
  (varies a lot across parameter space)

Saadeh, Feeney, Pontzen, Peiris, McEwen, *MNRAS* 462, 1802 (2016)

Method



- how we model anisotropy
- how we search for it

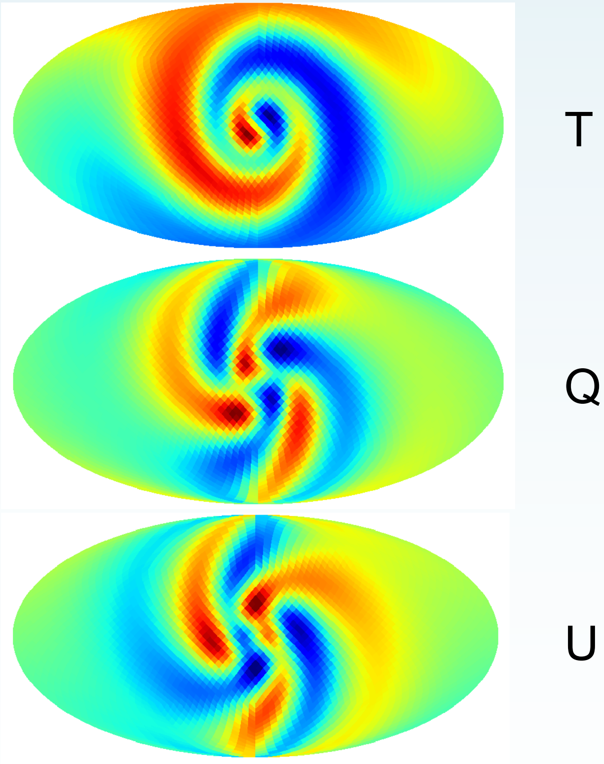
Method II: searching for anisotropy

- the datasets
- the statistical analysis
- the importance of the small scales

The datasets

Temperature and polarization have complementary constraining power!

Planck data: temperature and low-*l* polarization

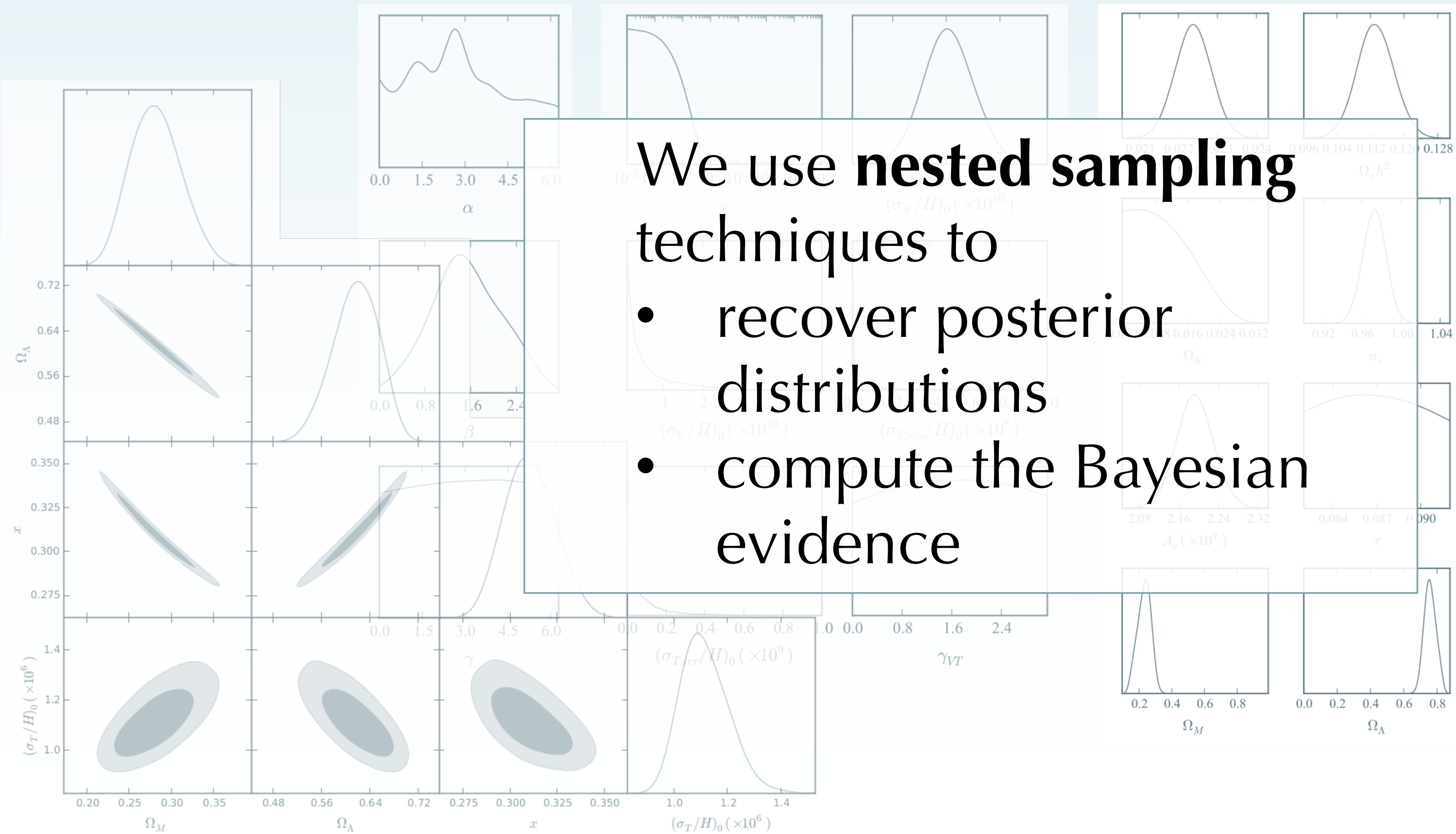


$$+\,C_\ell^{TT}$$

Method II: searching for anisotropy

- the datasets
- the statistical analysis
- the importance of the small scales

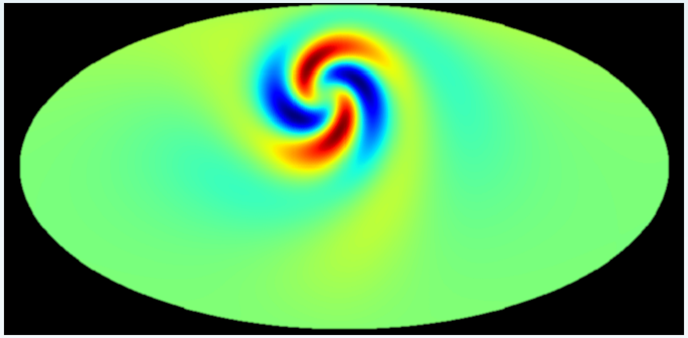
Statistical analysis



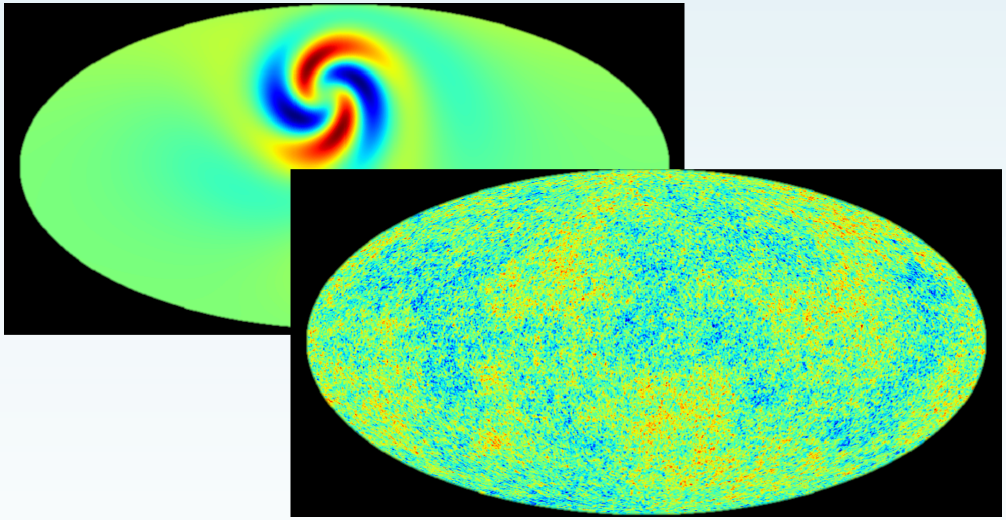
We use **nested sampling** techniques to

- recover posterior distributions
- compute the Bayesian evidence

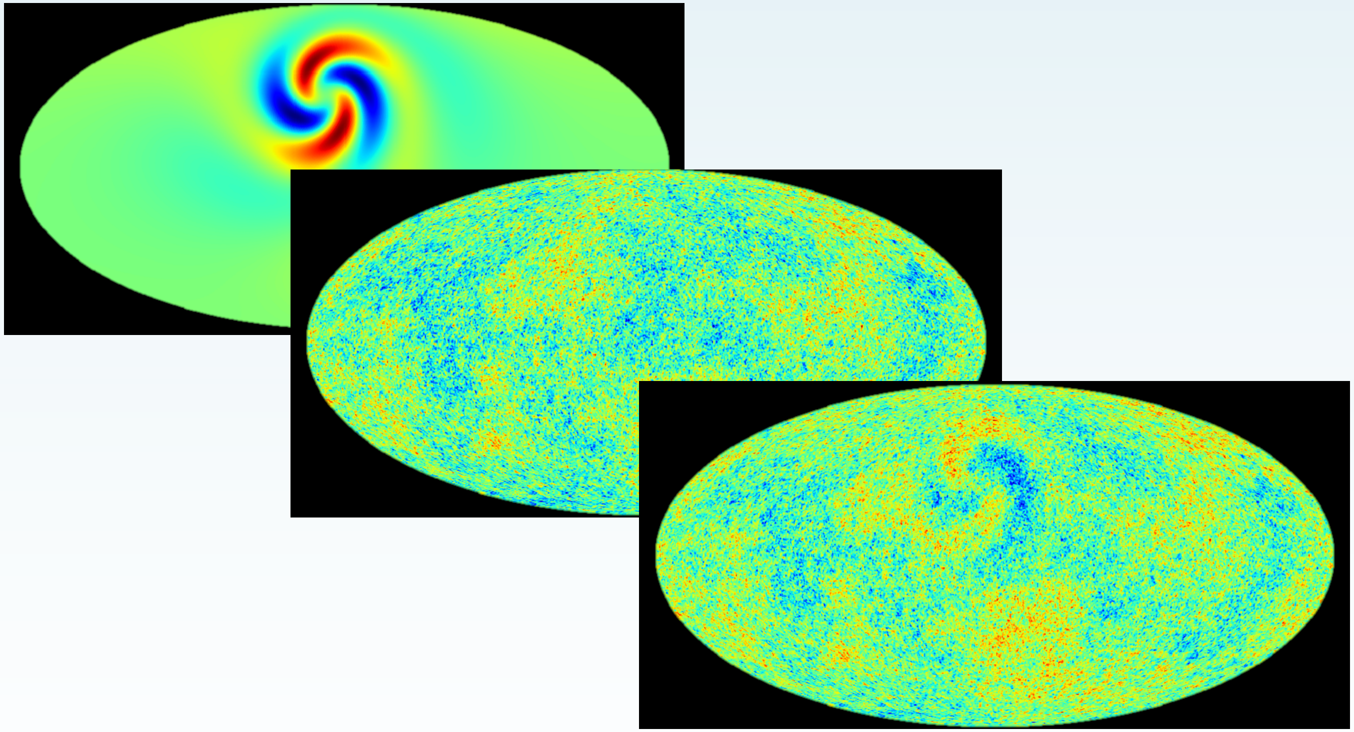
Statistical analysis



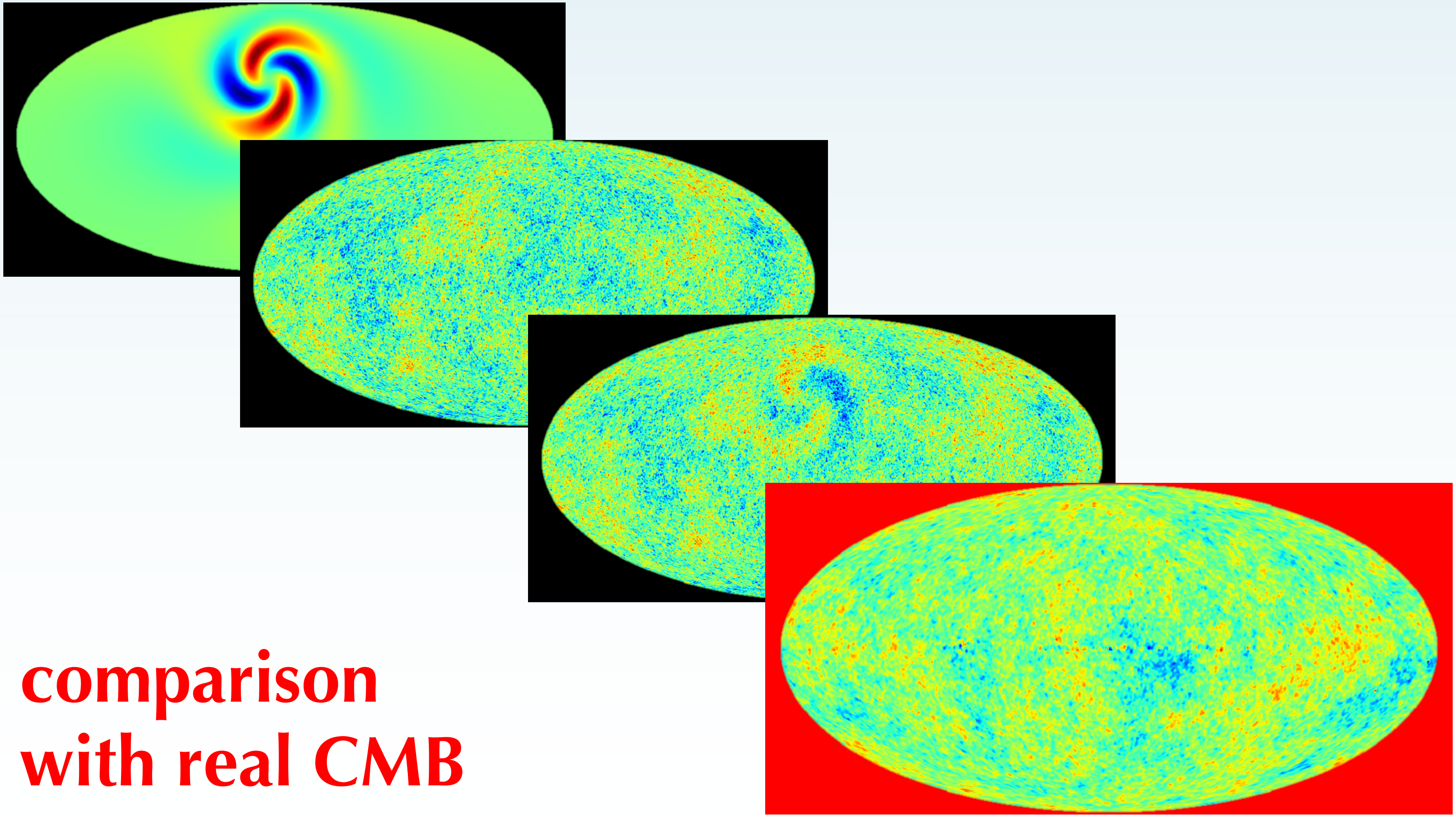
Statistical analysis



Statistical analysis



Statistical analysis



comparison with real CMB

Method II: searching for anisotropy

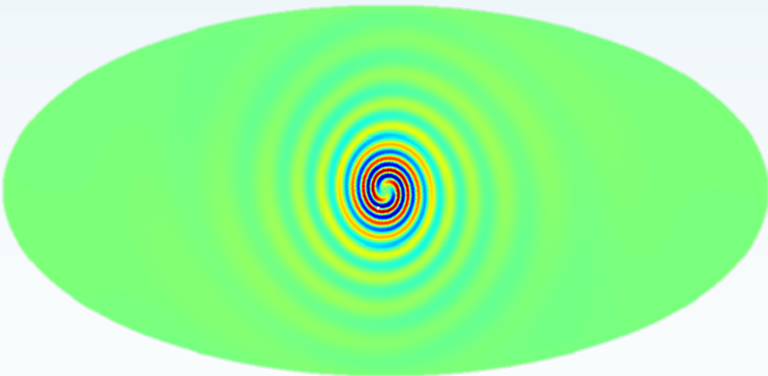
- the datasets
- the statistical analysis
- the importance of the small scales

The small scales

Despite Bianchi models mostly affecting the large scales, the small scales are important!

truncated at
l=32

(older method)



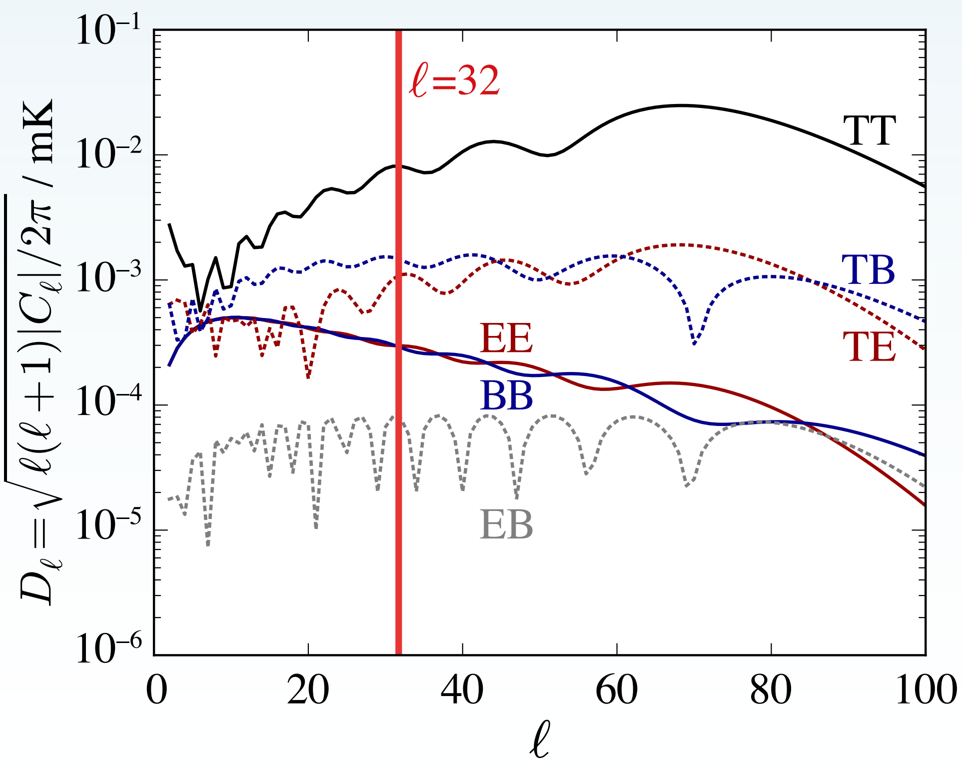
truncated at
l=200

(correctly characterised)

Saadeh, Feeney, Pontzen, Peiris, McEwen, *MNRAS* 462, 1802 (2016)

The small scales

Despite Bianchi models mostly affecting the large scales, the small scales are important!



Saadeh, Feeney, Pontzen, Peiris, McEwen, *MNRAS* 462, 1802 (2016)

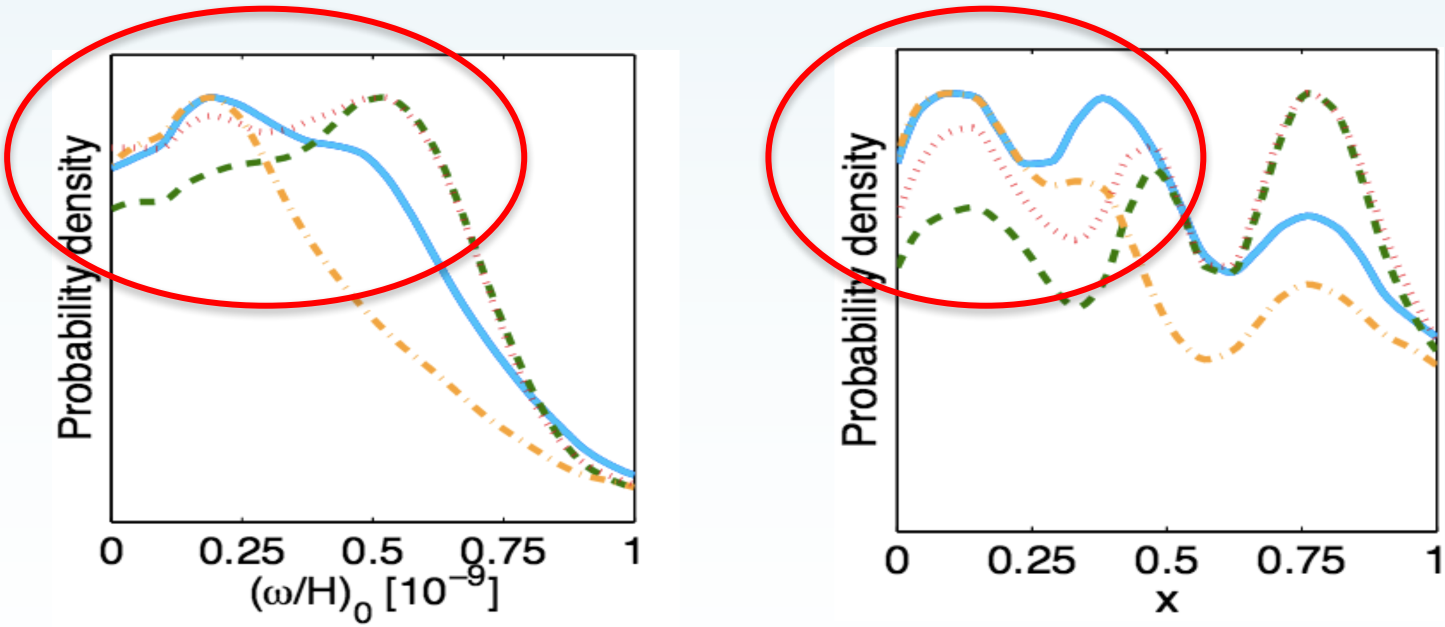
The small scales

truncated at
l=32

If the small scales are wiped out, some Bianchi models will *look* like pure ΛCDM…

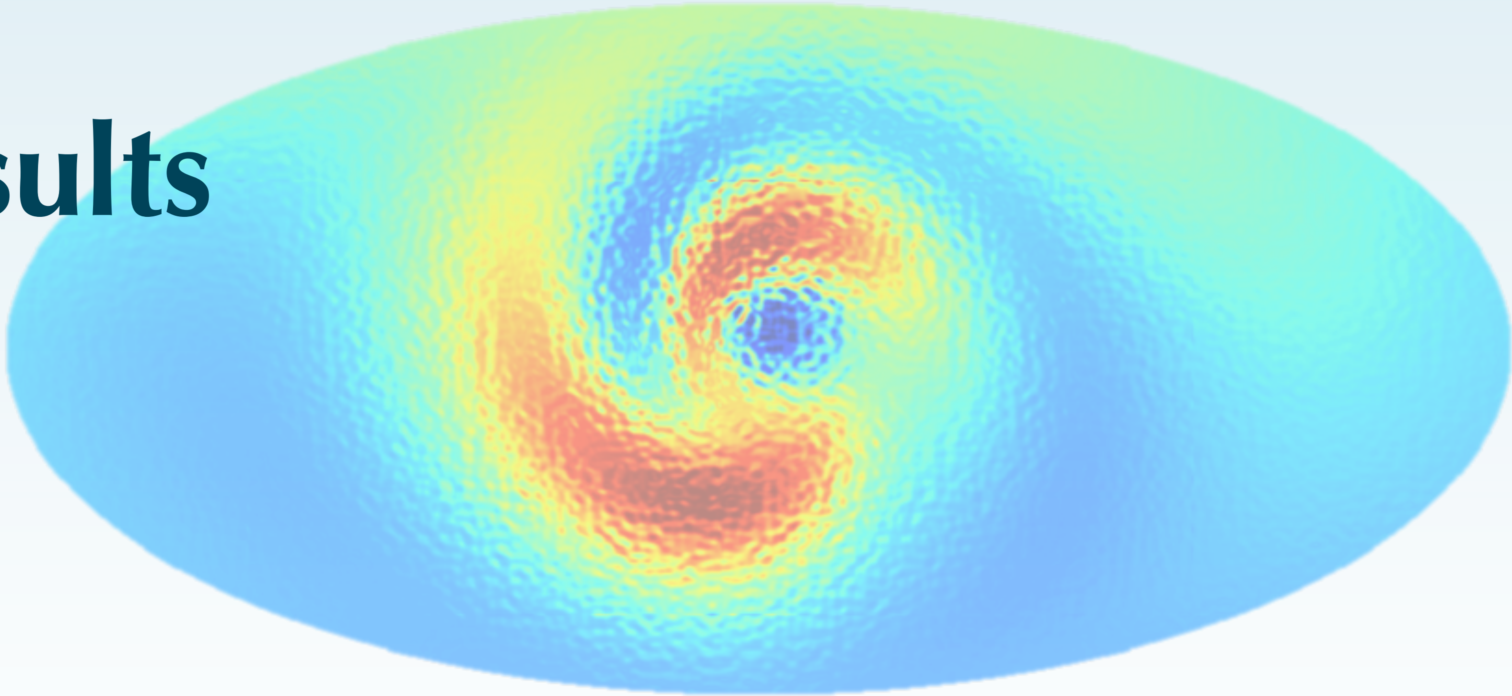
The small scales

… and will be favoured if the statistical analysis disfavours Bianchi models!



Planck 2015 results. XVIII. Background geometry & topology

Results



- With and without polarization
- Isotropy or anisotropy?

Results – with and without polarization

To assess the **impact of** including **polarization** data in our analysis, we first apply our search to Bianchi vector modes alone

$\longrightarrow$ comparison with previous work available

Saadeh, Feeney, Pontzen, Peiris, McEwen, Phys. Rev. Lett. 117, 131302 (2016)

The University of Nottingham UCL

Results – with and without polarization

95% confidence level on vorticity parameter:

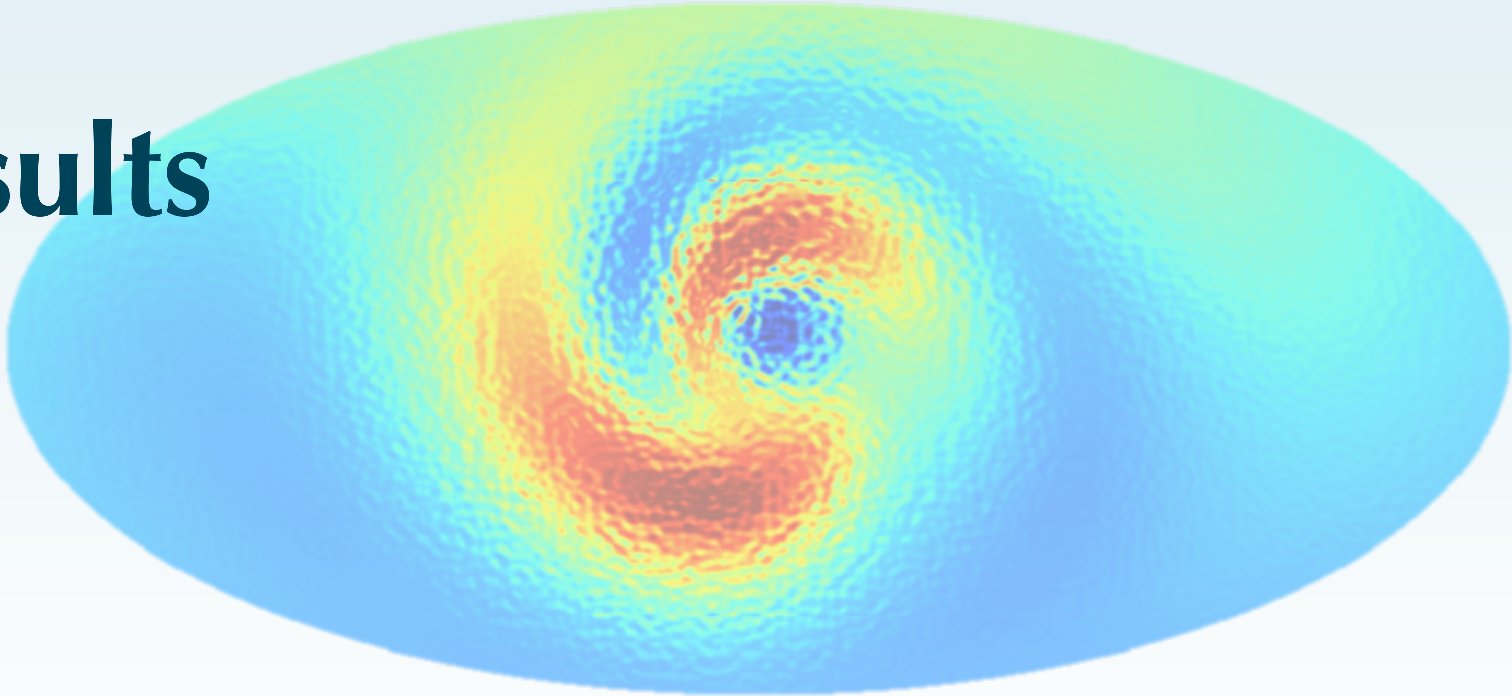
This analysis	Planck 2015
$< 5.2 \times 10^{-11}$	$< 7.6 \times 10^{-10}$

An order of magnitude improvement!

Saadeh, Feeney, Pontzen, Peiris, McEwen, Phys. Rev. Lett. 117, 131302 (2016)

Planck 2015 results. XVIII. Background geometry & topology

Results



- With and without polarization
- Isotropy or anisotropy?

Results – Constraints on anisotropy

- Bianchi types VII$_h$, VII$_0$, V, I
- All degrees of freedom of anisotropic expansion
- Joint analysis of *Planck* temperature and polarization

$$-6.7 \times 10^{-11} < (\sigma_S/H)_0 < 9.6 \times 10^{-11}$$
$$(\sigma_V/H)_0 < 4.7 \times 10^{-11}$$
$$(\sigma_{T,\mathrm{reg}}/H)_0 < 1.0 \times 10^{-6}$$
$$(\sigma_{T,\mathrm{irr}}/H)_0 < 3.4 \times 10^{-10}$$

Saadeh, Feeney, Pontzen, Peiris, McEwen, Phys. Rev. Lett. 117, 131302 (2016)

Results – Constraints on anisotropy

- Bianchi types VII_h, VII_0, V, I
- All degrees of freedom of anisotropic expansion
- Joint analysis of *Planck* temperature and polarization

$$-6.7 \times 10^{-11} < (\sigma_S/H)_0 < 9.6 \times 10^{-11}$$
$$(\sigma_V/H)_0 < 4.7 \times 10^{-11}$$
$$(\sigma_{T,\mathrm{reg}}/H)_0 < 1.0 \times 10^{-6}$$
$$(\sigma_{T,\mathrm{irr}}/H)_0 < 3.4 \times 10^{-10}$$

Saadeh, Feeney, Pontzen, Peiris, McEwen, Phys. Rev. Lett. 117, 131302 (2016)

Results – model comparison

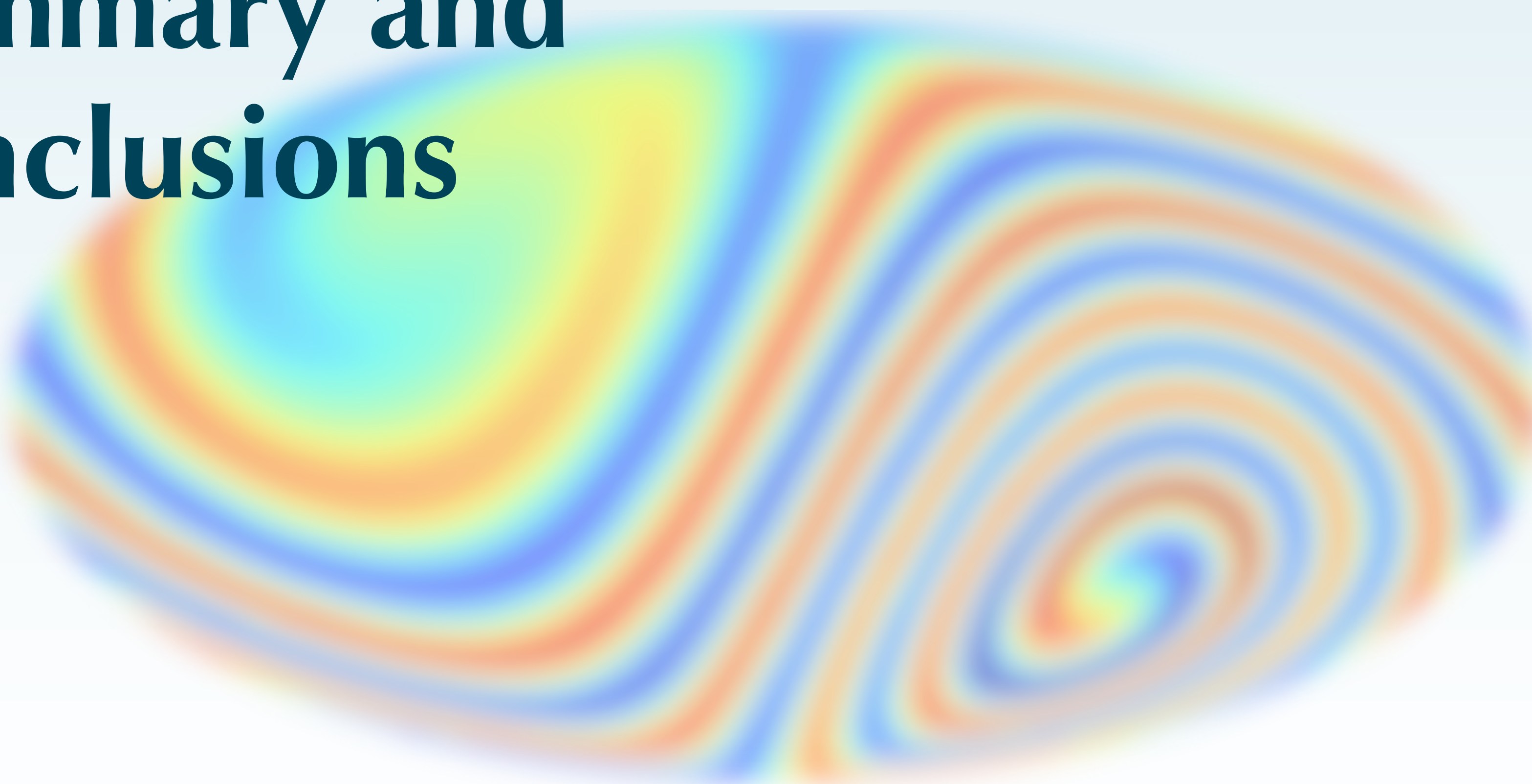
Bianchi vs ΛCDM, log-Bayes factor:

-11.7 ± 0.3

Anisotropic expansion of the Universe disfavoured with odds **121,000 : 1** against!

Saadeh, Feeney, Pontzen, Peiris, McEwen, Phys. Rev. Lett. 117, 131302 (2016)

Summary and conclusions



- Take-home message

Summary

- Large-scale **isotropy** is a **foundational assumption** of the standard model of cosmology
- We put this assumption to the **test**, using data from the **cosmic microwave background**

Summary

For the first time, we included

- all the **open/flat Bianchi types** close to isotropy
- **all** the anisotropy **degrees of freedom**
- **polarization** data
- the **small scales**

Conclusions

- **We find strong evidence against anisotropy**

	Scalars	Vectors	Tensors (reg)	Tensors (irr)
95% CL	$> -6.7 \times 10^{-11}$ $< 9.6 \times 10^{-11}$	$< 4.7 \times 10^{-11}$	$< 1.0 \times 10^{-6}$	$< 3.4 \times 10^{-10}$

Log-Bayes factor	-11.7 ± 0.3

Thank you for your attention!