Cosmic Anomalies: A Skeptical Evaluation

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Two and a half Facts

Peter Scheuer (1963): “There are only two & a half facts in cosmology:

1) The sky is dark at night.
2) The galaxies are receding from each other as expected in a uniform expansion.
3) The contents of the Universe have probably changed as the Universe grows older.”

COSMOLOGY: A SEARCH FOR TWO NUMBERS

Precision measurements of the rate of expansion and the deceleration of the universe may soon provide a major test of cosmological models

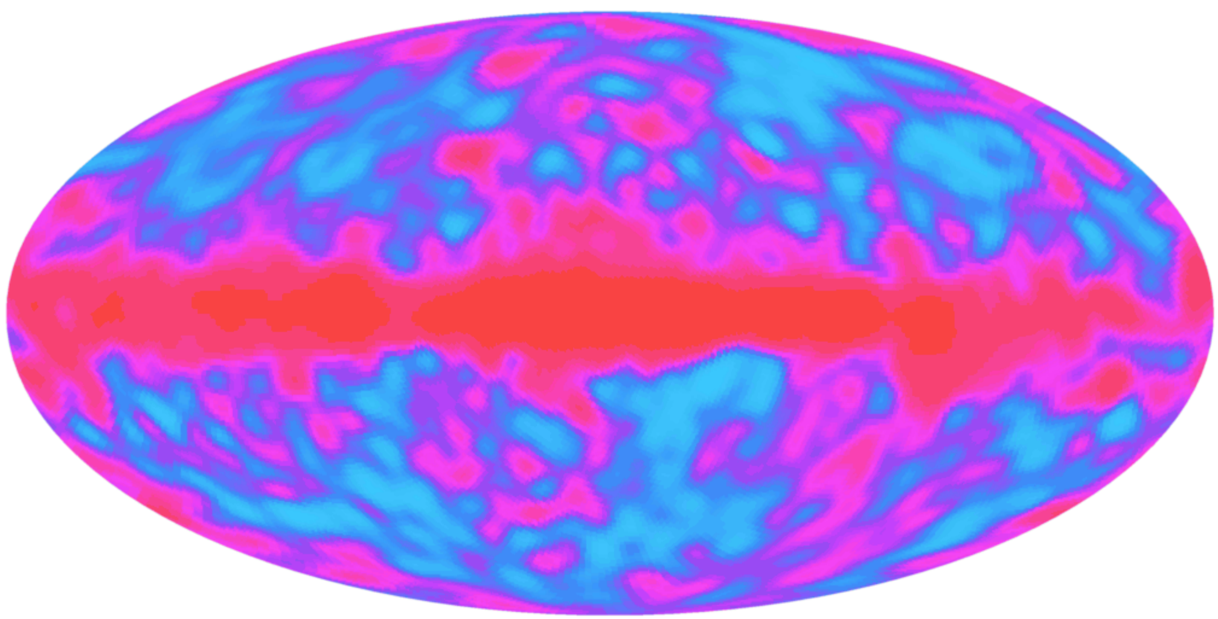
- Sandage, Feb 1970, Physics Today
- H_o = 49 to 130 km/sec/Mpc
  – Not yet hard over on 50
- $q_o = 1.2 \pm 0.4$
  – Notes not close to -1 for SS
  – Also not close to true -0.5 to -0.6

A Big Media Splash in 1992:

THE TIMES

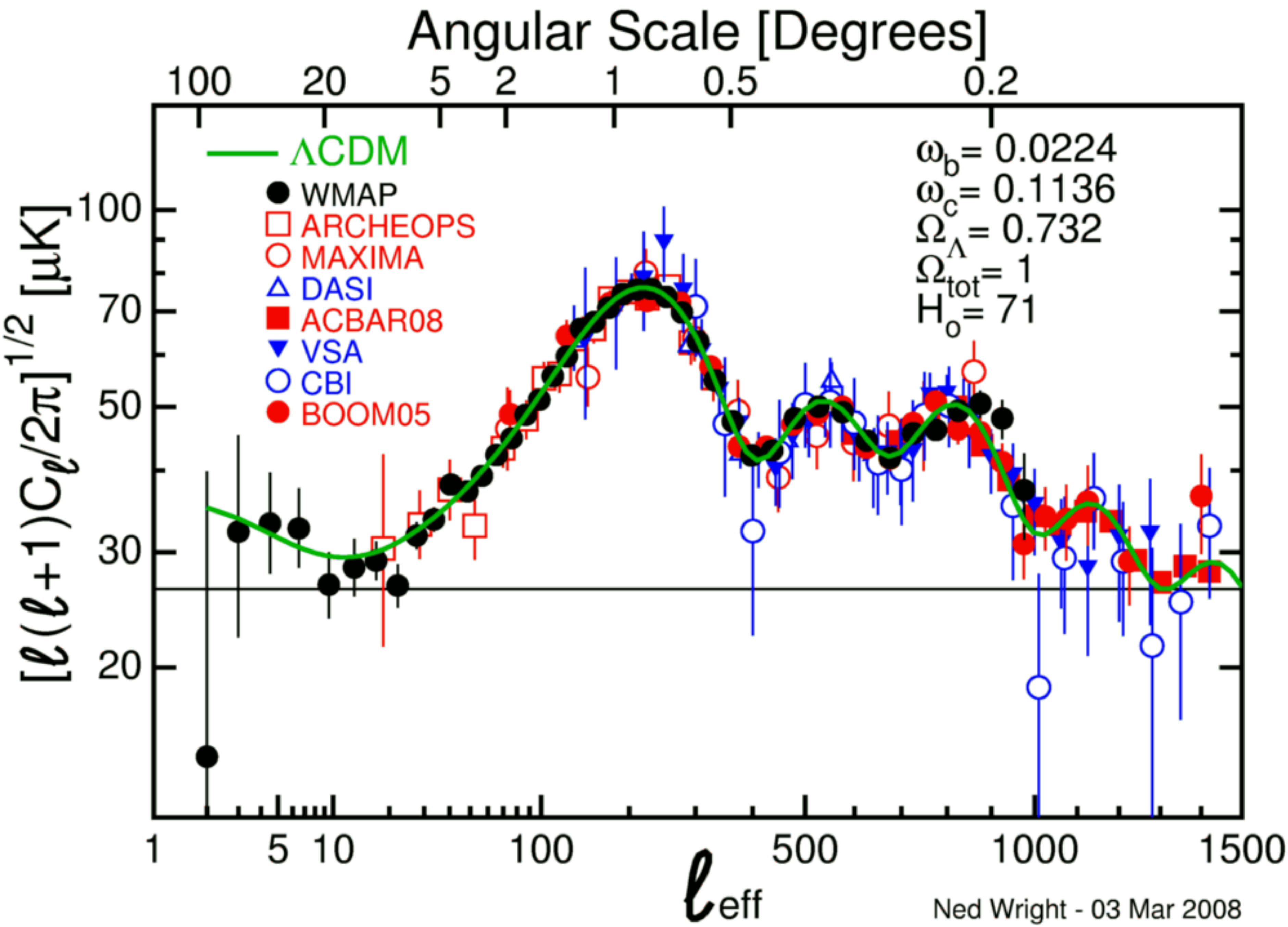
25 April 1992

Prof. Stephen Hawking of Cambridge University, not usually noted for overstatement, said: “It is the discovery of the century, if not of all time.”



Harlow Shapley

- “A hypothesis or theory is clear, decisive, and positive, but it is believed by no one but the man who created it.
- Experimental findings, on the other hand, are messy, inexact things, which are believed by everyone except the man who did the work.”



Angular Scale [Degrees]
100
20
5
2
1
0.5
0.2
ΛCDM
WMAP
ARCHEOPS
MAXIMA
DASI
ACBAR08
VSA
CBI
BOOM05
ω_b= 0.0224
ω_c= 0.1136
Ω_Λ= 0.732
Ω_{tot}= 1
H_o= 71
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ [μK]
100
70
50
30
20
1
5
10
100
500
1000
1500
ℓ_{eff}
Ned Wright - 03 Mar 2008

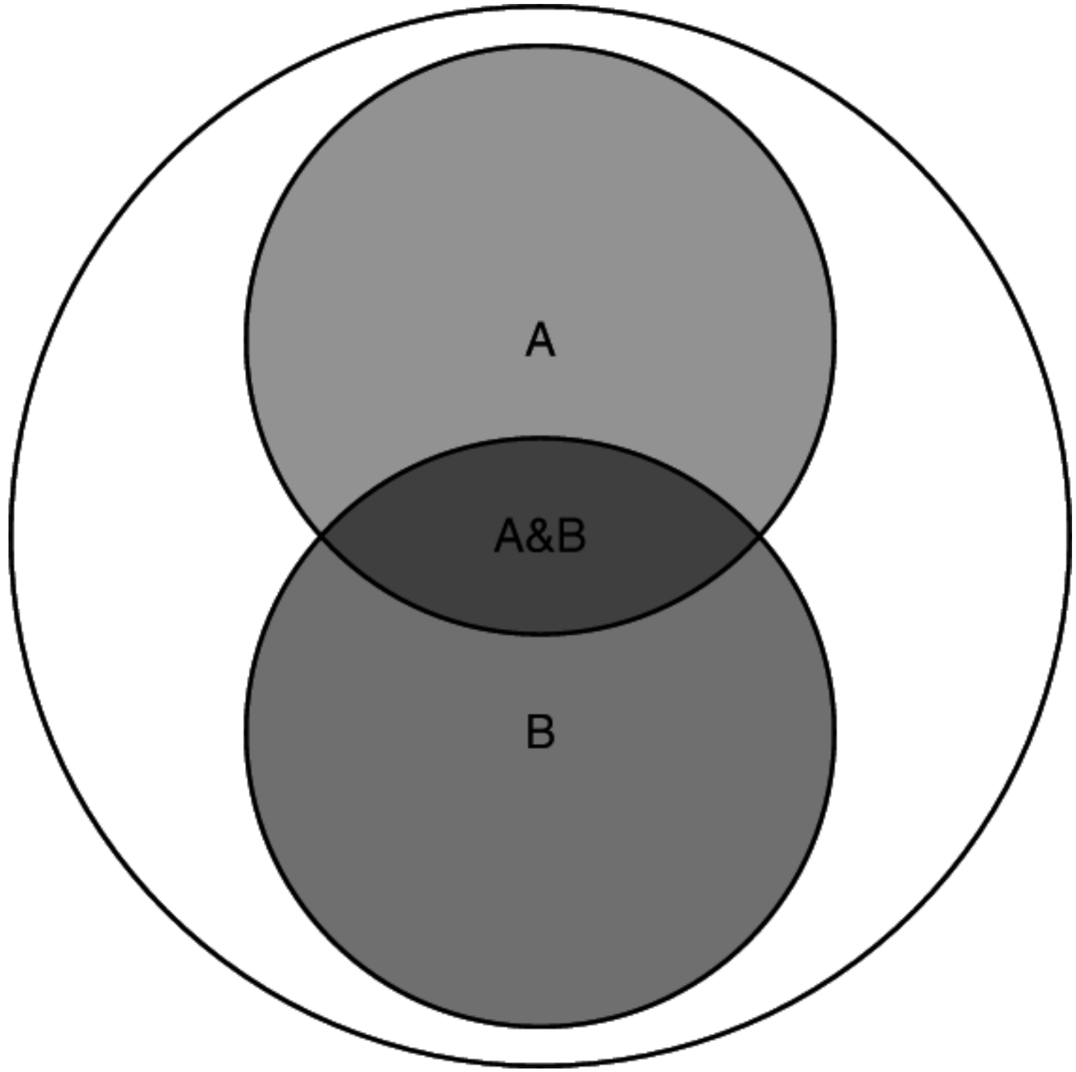
Bayesian?

- Who was Bayes?

- Thomas Bayes, 1702-1761, a Presbyterian minister. Bayes was elected a Fellow of the Royal Society in 1742 despite the fact that at that time he had no published works on mathematics, indeed none were published in his lifetime under his own name. Bayes set out his theory of probability in Essay towards solving a problem in the doctrine of chances published in the Philosophical Transactions of the Royal Society of London in 1764. The paper was sent to the Royal Society by Richard Price, a friend of Bayes', who wrote: *I now send you an essay which I have found among the papers of our deceased friend Mr Bayes, and which, in my opinion, has great merit...*

Bayes' Theorem

- Prob of A&B = (Prob of A) times (Prob of B given A)
- P(A&B) = P(A)P(B|A) = P(B)P(A|B)



Bayesian Statistics

In Bayesian statistics, we restate Bayes' theorem as:

$$P(M|D) = \frac{P(D|M)P(M)}{P(D)}$$

where: $P(M|D)$ is the probability of the *model* given the data
$P(M)$ is the *a priori* probability of the model, and this is what causes all the arguments,
$P(D)$, the probability of the data, is effectively constant, since we have the data in hand, and
$P(D|M)$, the probability of the data given the model is also known as the *LIKELIHOOD*.

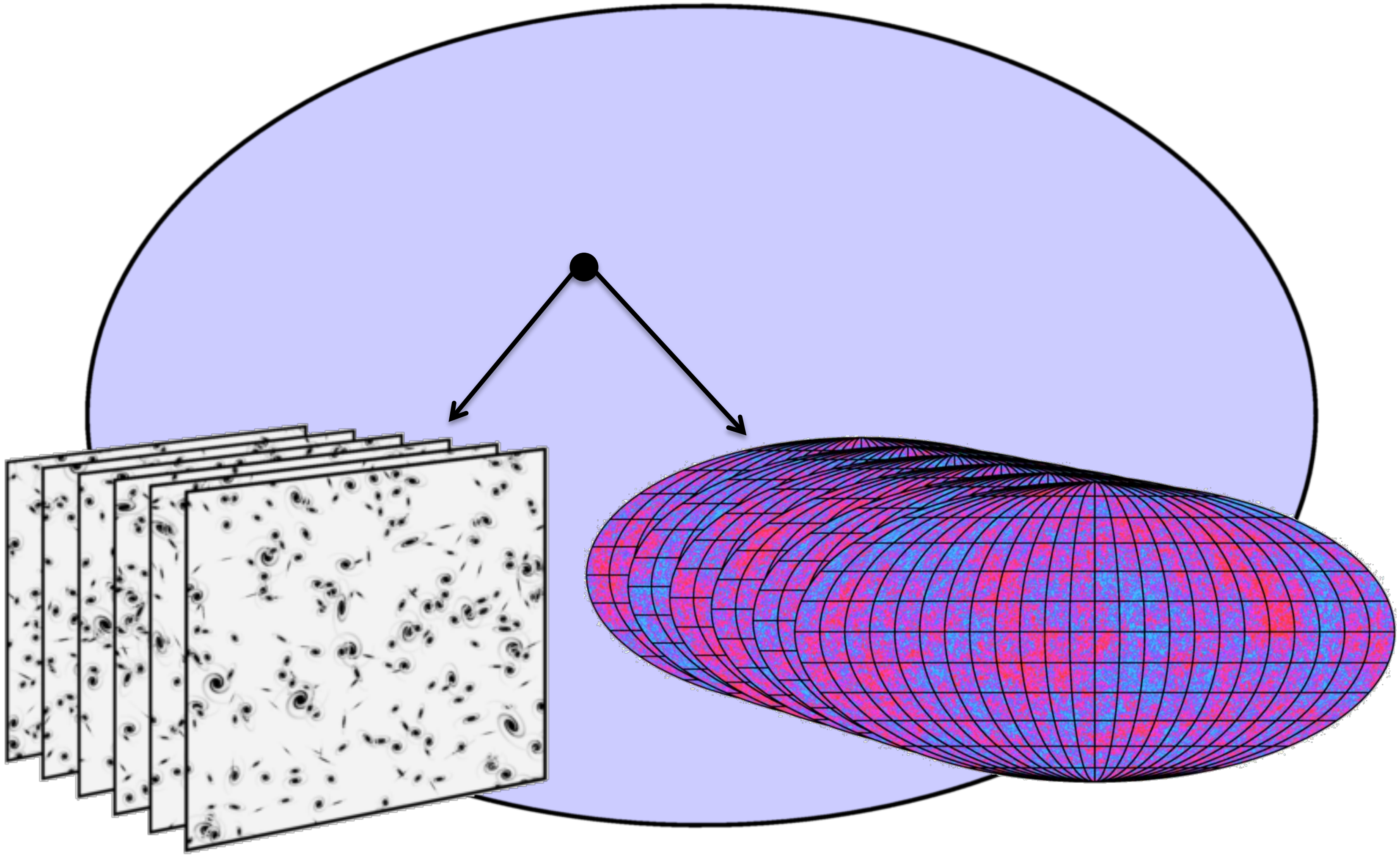
Ockham's Razor

Ockham chooses a razor

Why Ockham & Bayes

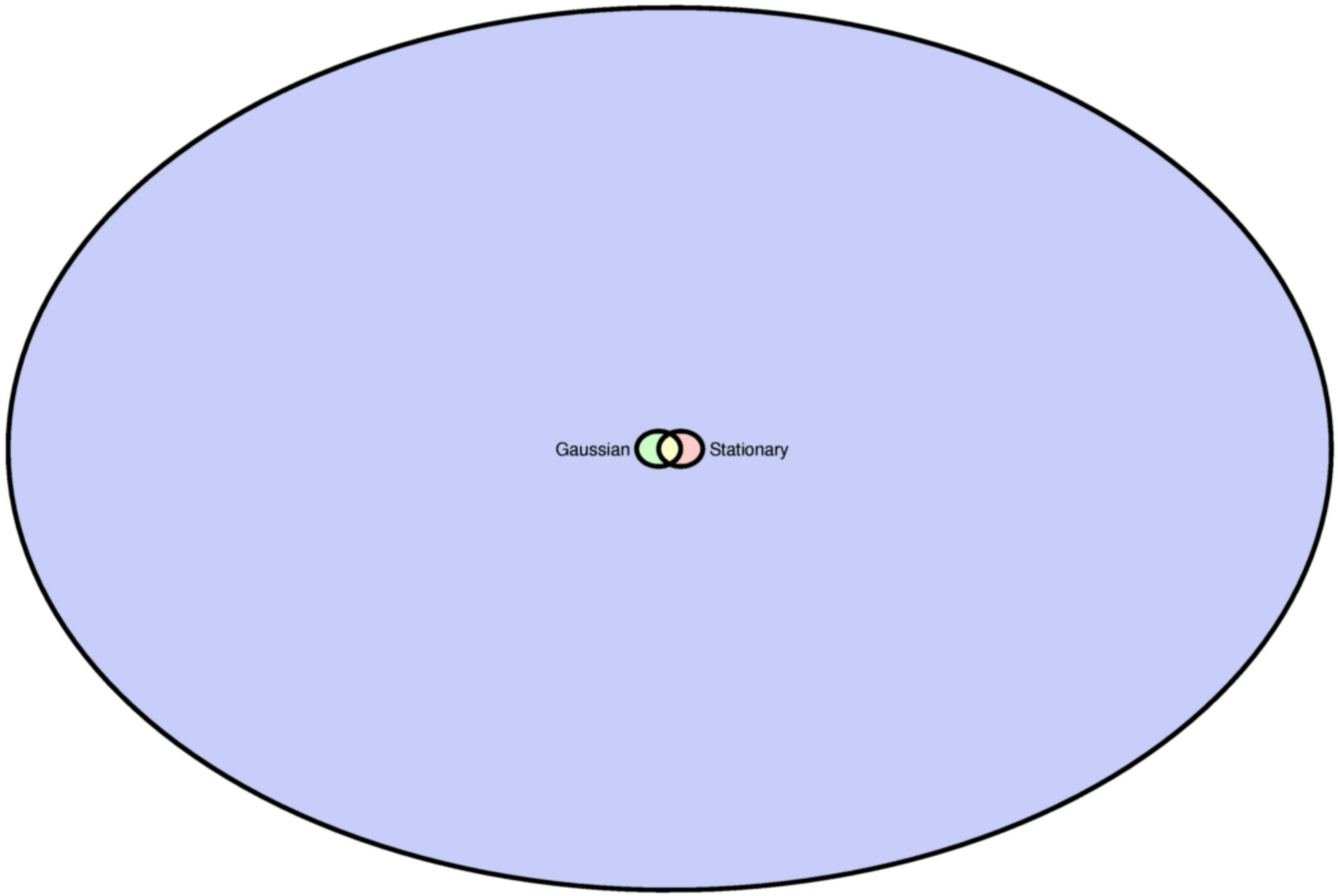
- A more complicated model exists in a bigger space.
- Since the prior p(M) is normalized in this bigger space, the value of the prior will be lower for the more complicated model.
- Then the posterior probability will also be lower UNLESS the likelihood gets a lot bigger.

Set of All Random Processes



- A cosmological model is a prescription for generating an ensemble of Universes. Each element of the ensemble describes a different realization of a random process.

Small Subsets of All Models



- Gaussian and/or stationary random processes

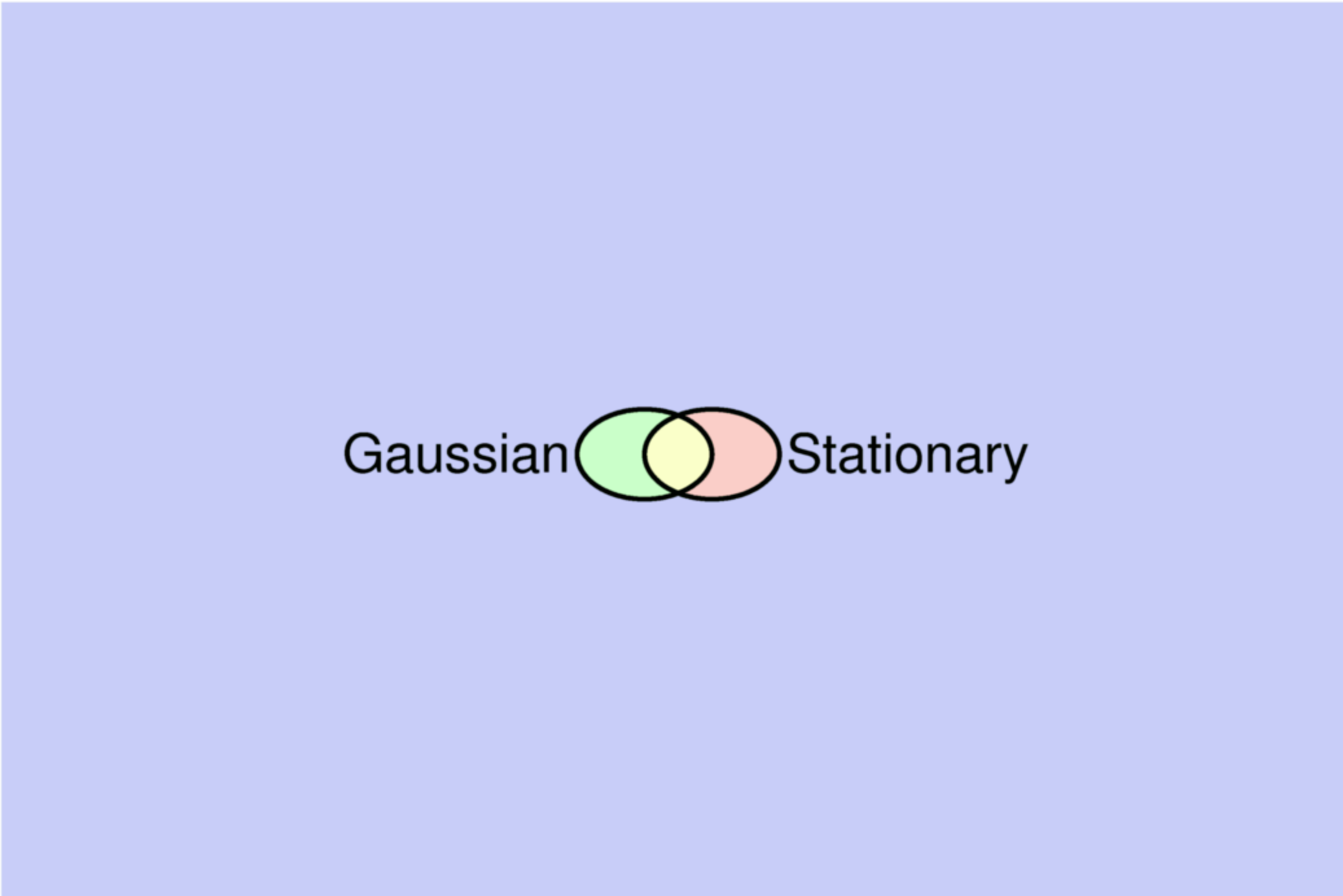
Gaussian models

- The one point distribution function is Gaussian for all locations.
- The two point distribution function is Gaussian.
- The three point distribution function is Gaussian.
- […]

Stationary Models

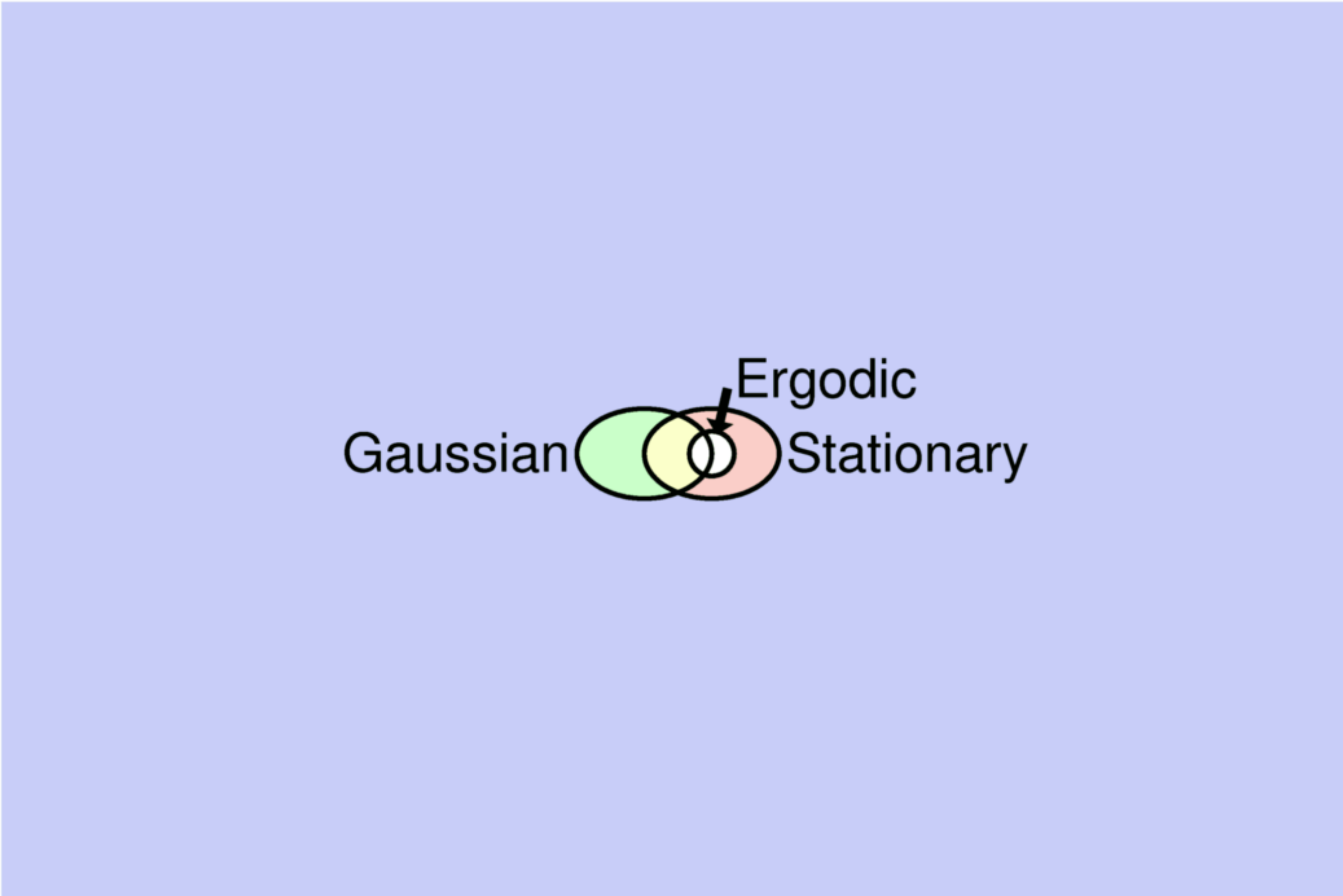
- The one point distribution function is independent of the location.
- The two point distribution function depends only on the (vector) separation.
- ISOTROPIC models: the distribution functions are invariant when the set of points is rotated.
- Stationary & isotropic models satisfy the Cosmological Principle.

Zoom into Center



- Gaussian & Stationary = Ergodic?

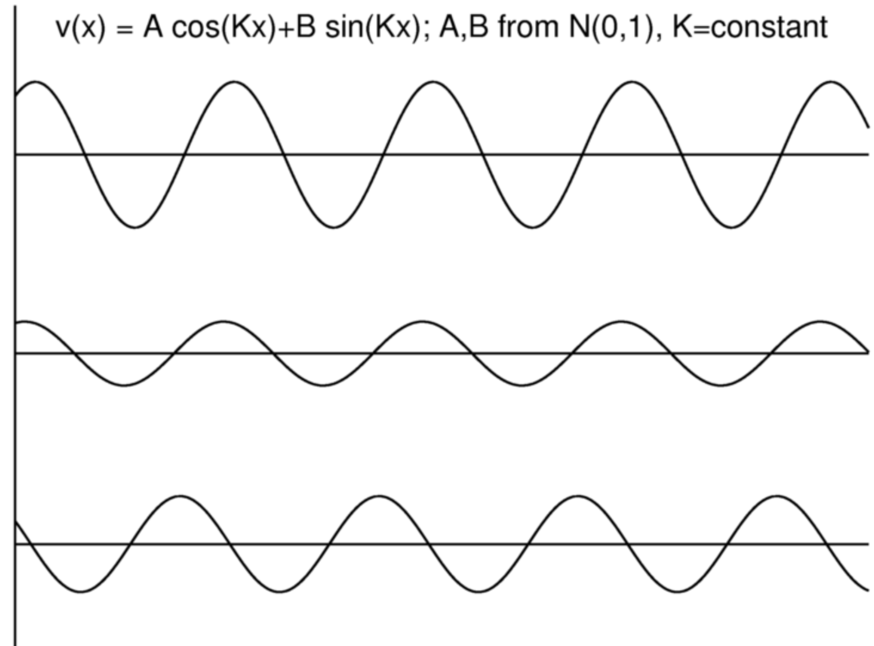
Gaussian & Stationary ≠ Ergodic



- There are gaussian & stationary but not ergodic processes.

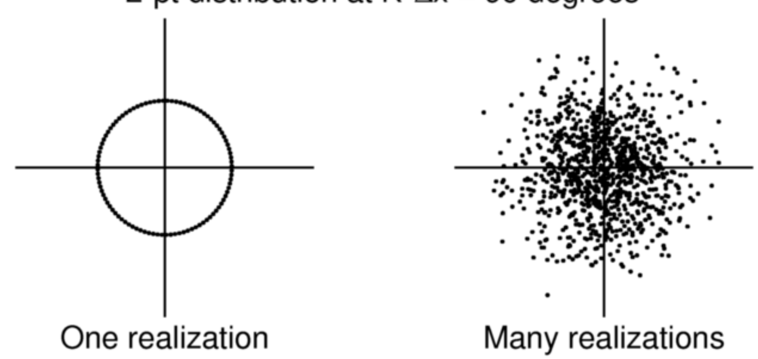
Gaussian, stationary, not ergodic

- A random process with a sine wave having Gaussian in-phase and quadrature amplitudes.
- For a single realization the 2-pt pdf traces out a circle, but the ensemble 2-pt pdf is a filled 2-D Gaussian.



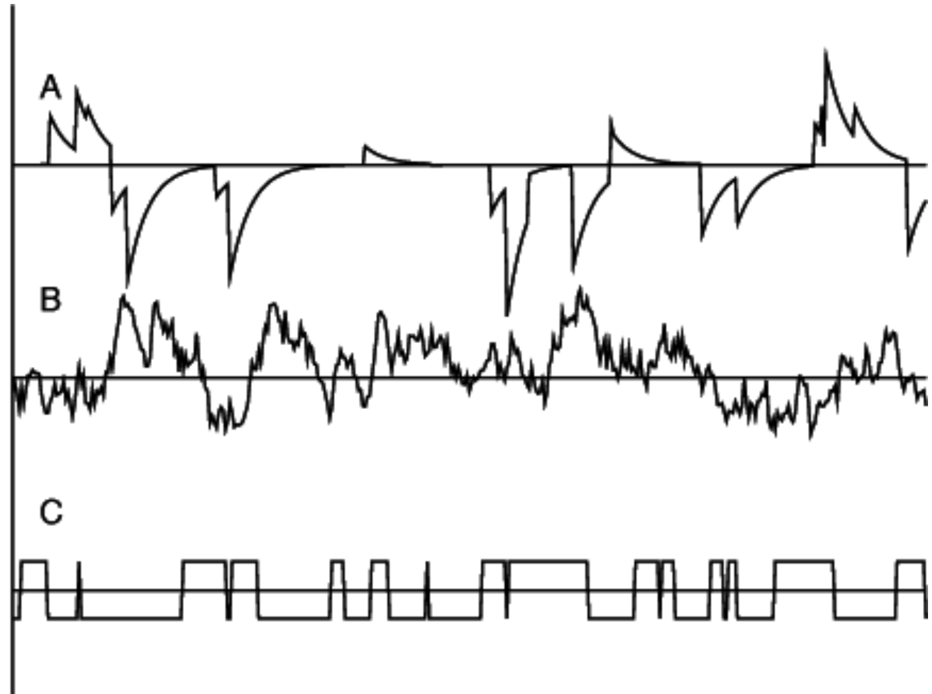
A Gaussian, stationary but not ergodic random process

2-pt distribution at $K^*\Delta x$ = 90 degrees



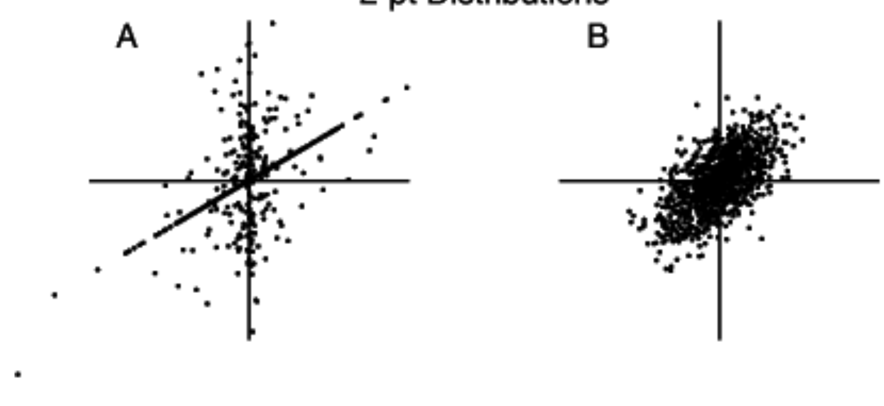
Ergodic but not Gaussian

- 3 processes with the same power spectrum.
- A & C are not Gaussian but B is.
- All three are ergodic.



Three random processes with the same power spectrum

2-pt Distributions

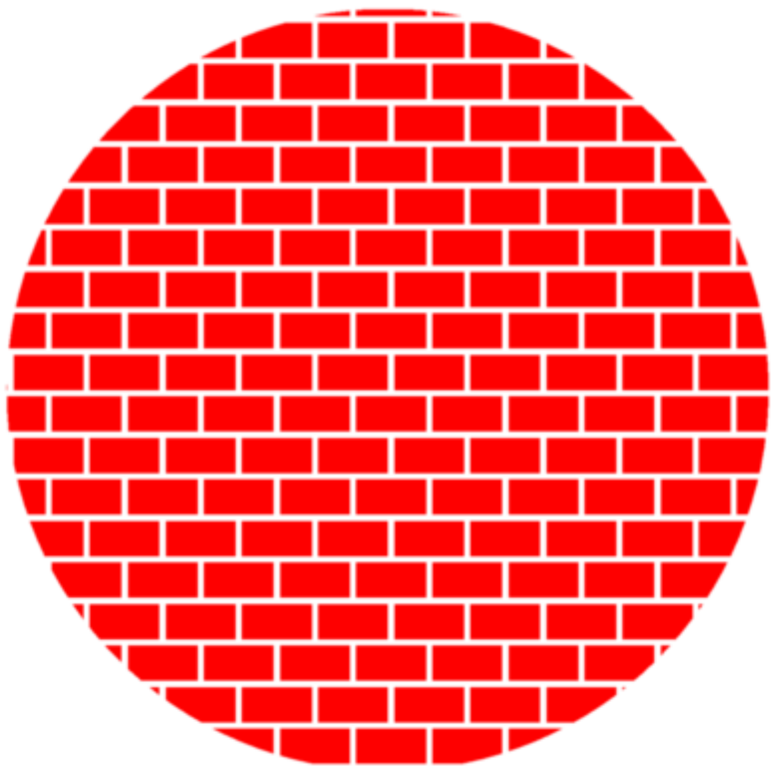


CMB: Ergodicity is Irrelevant

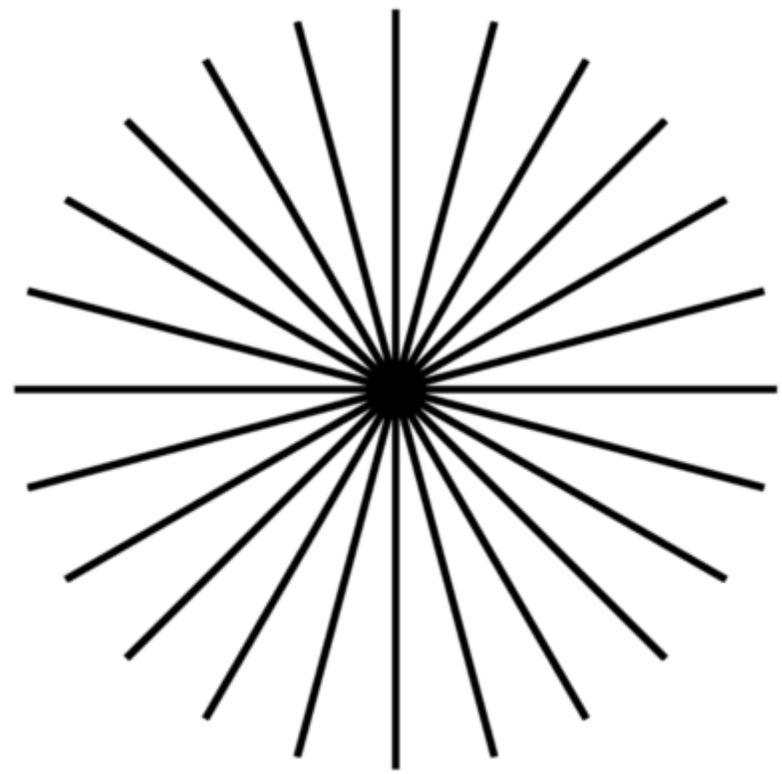
- We only observe 4π steradians, so we can never determine the ensemble distribution, even in principle.
- This is the [in]famous Cosmic Variance.
- The underlying 3D spatial model can be ergodic, and usually is, but of course we still can’t measure out to infinity, being limited by the horizon radius.

The Cosmological Principle

- The Universe is homogeneous and isotropic



Not isotropic



Not homogeneous

Random Processes vs. The Cosmological Principle

- Homogeneous is equivalent to a stationary random process.
- Isotropic means that:
  - The two point distribution depends only on the magnitude of the separation.
  - The three point distribution depends only on the three side lengths of the triangle formed by the points.
  - For a non-homogeneous but isotropic model one of the points has to be the origin.

Very Restrictive

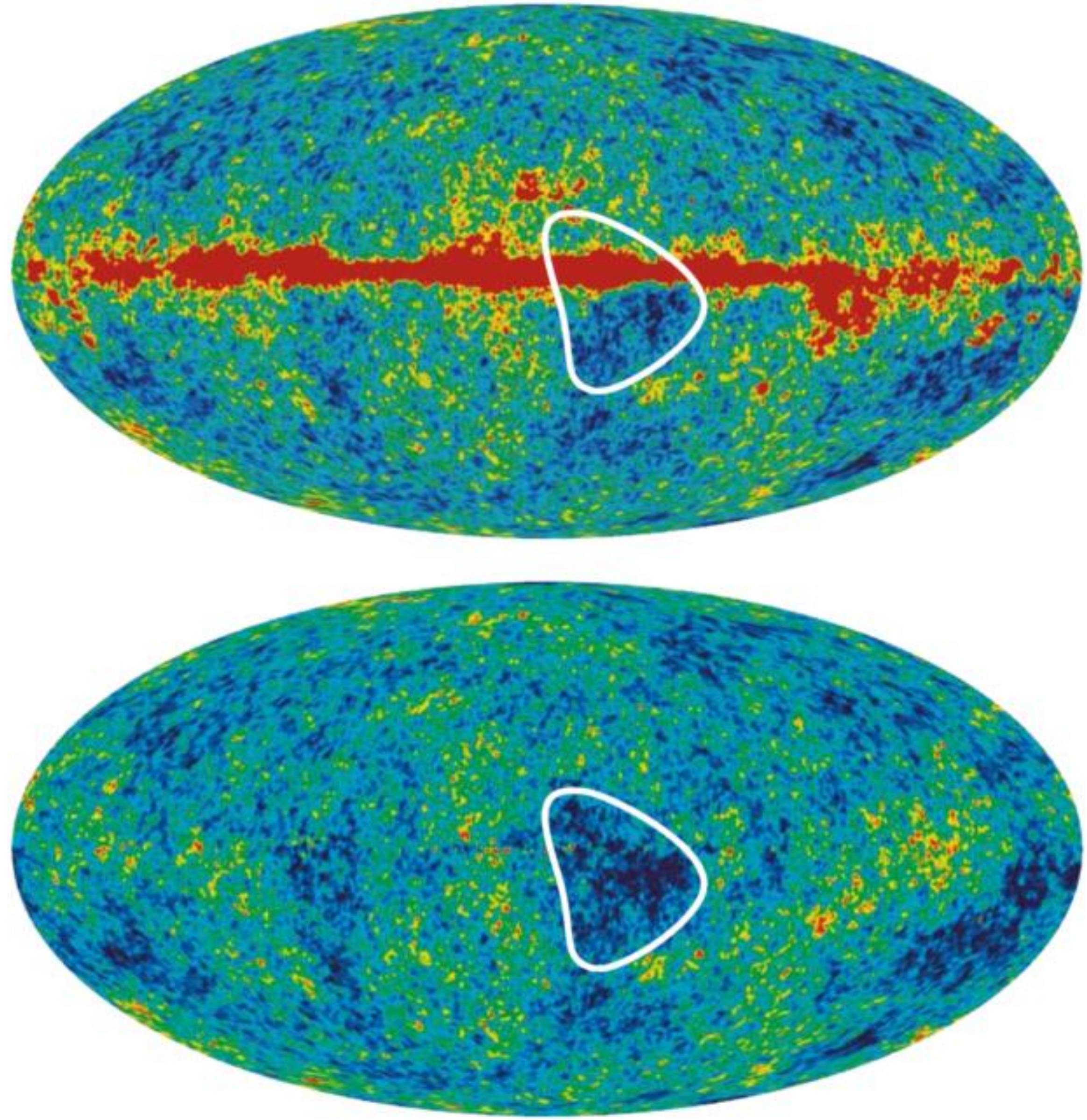
- The Cosmological Principle is very restrictive.
- The possible departures are very numerous – at least a 1000-fold – and involve at least a few extra parameters.
- Even a 3σ effect is not quite a 100:1 likelihood ratio.
- So a proposed departure from the cosmological principle must have extreme statistical significance before meriting serious consideration.

Large Scale Effects

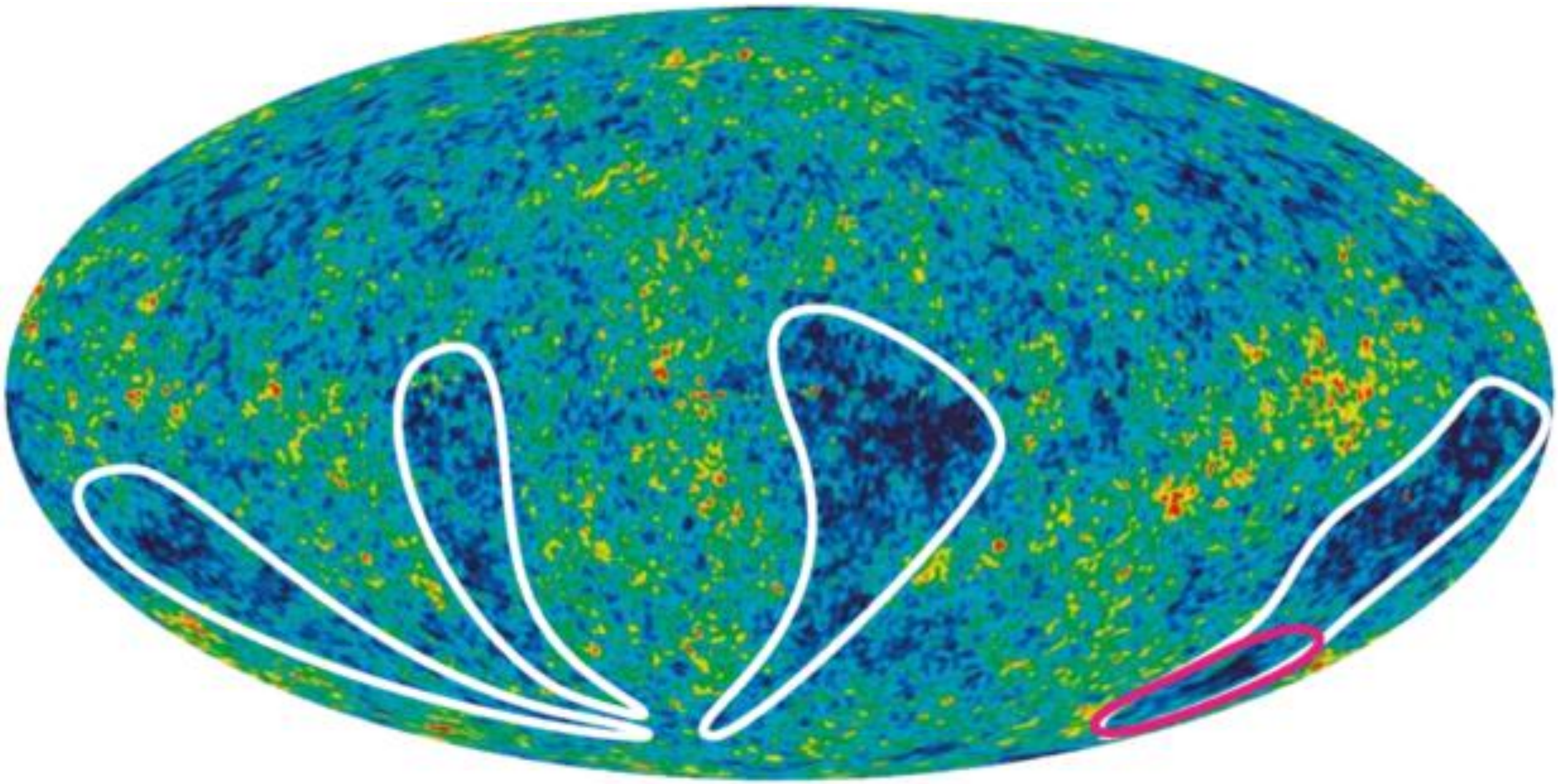
- The CMB quadrupole is low compared to ΛCDM.
- The octupole and quadrupole appear to be aligned.
- There is the infamous “dark spot”.

Look at the (W)MAP

- Fig 1 of Bennett etal, arXiv: 1001:4758
- This huge dark spot at the GC is not “the” dark spot.



Cold Fingers of God



- The red line outlines “the” dark spot.
- Better called the “dark fingernail” of God

Non-Gaussian Models

- There are a lot of non-gaussian models.
- The *a priori* probability of any one of them is tiny, so there has to be huge increase in the likelihood before they are worth considering.
- In many cases non-Gaussian models are just plain scary, not just unlikely.

Non-Gaussian model = non-dog animal

- Paraphrase of remark by Shandarin

But this is a false dichotomy

The Infamous “Dark Spot”

- Proposed by Cruz et al., astro-ph/0405341, “Detection of a non-Gaussian Spot in WMAP”
  - Of course it is nonsense to talk about “a non-Gaussian spot”: one has to prove that the underlying random process is non-Gaussian. If I choose a value from N(0,1), say 1.37, then the observed pdf is $\delta(T-1.37)$ which is non-Gaussian but the underlying process is Gaussian.

Large Search Space

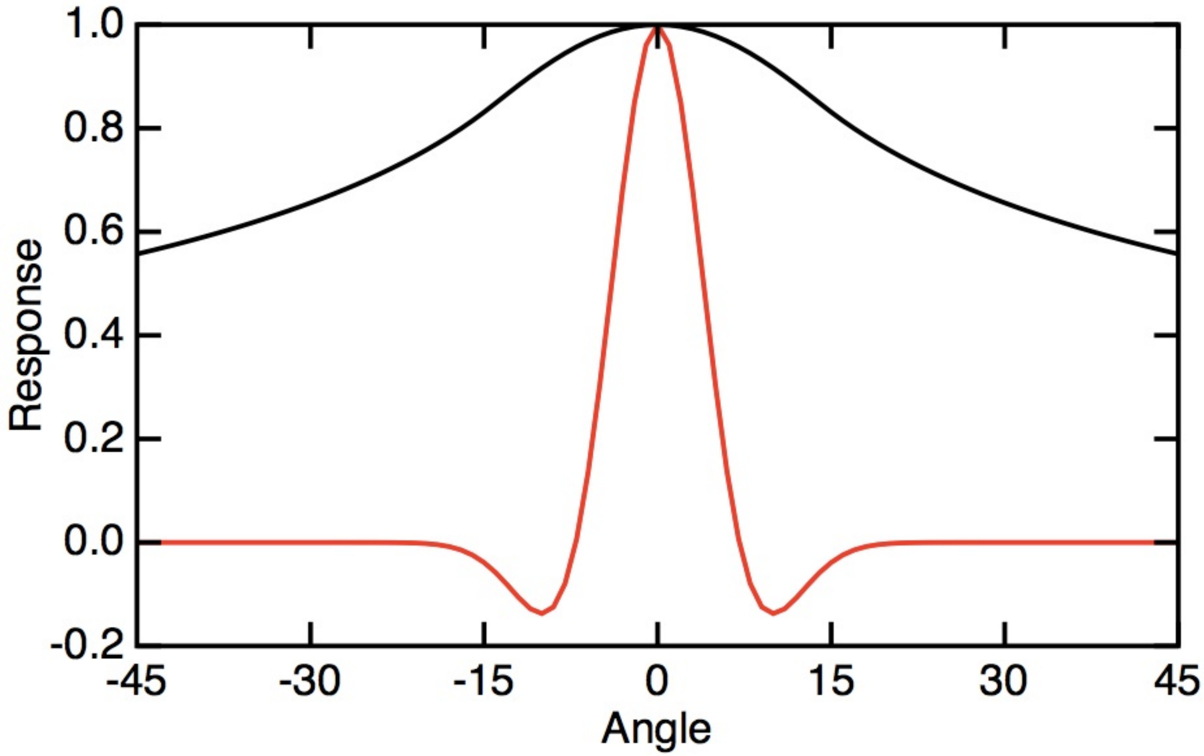
- 15 different spherical Mexican hat wavelet sizes were used.
- For each size, the whole sky was searched for outliers.
  - A fair ROM for the number of cases searched has to be > 10^5.
- Claim that (l,b) = (209,-57) is a 4.7σ cold spot with a 5^o scale (8.75^o FWHM).
- But $\exp(-\frac{1}{2}\times 4.7^2)$ is > 10^{-5}, so where's the beef?

Laura Mersini-Houghton

- Claimed the “dark spot” as evidence of a tunnel into another Universe in 24 Nov 2007 New Scientist:
  - "It is the unmistakable imprint of another universe beyond the edge of our own," says Laura Mersini-Houghton of the University of North Carolina at Chapel Hill.
- *And therefore the string theory landscape is correct!*
- A better question: if the dark spot is NOT significant, does that disprove string theory?

Dark Spot: A Supervoid?

- Szapudi et al., http://arxiv.org/abs/1405.1566
- R=220 Mpc at z=0.2, 14% density deficit
- This void is probably real.
- But the resulting cool spot in CMB is too large in radius, and would be filtered away by the spherical Mexican hat wavelet filter used by Cruz et al.



Kashlinsky's "Dark Flow"

- Again proof of the string theory landscape according to Laura Mersini-Houghton, again quoted in the *New Scientist*.
- Based on a cosmic variance magnifying filter.
- Kashlinsky's response to David Spergel's technical criticism was to threaten a lawsuit.

Kinematic SZ Effect

- Took dT through a mask isolating galaxy clusters with mean optical depth $<\tau>\approx 0.01$.
- The kinematic SZ effect gives the radial velocity of a cluster relative to the CMB frame: $v/c = -(dT/T)/\tau$
- Dipole fit to these dT's gives the "dark flow": $v/c = (dT/T)_{dipole}/<\tau>$.

Filtering out the CMB

- Sky variance is the sum of detector noise *n* and a cosmic term *C*.
- A Weiner filter to minimize the cosmic term should be:

$$f_\ell = \frac{n_\ell}{C_\ell^{model} + n_\ell}$$

- Instead, Kashlinsky used:

$$f_\ell = \frac{C_\ell^{obs} - C_\ell^{model}}{C_\ell^{obs}}$$

Magnified Quadrupole

- Since the radiometer noise is much less than the cosmic term then the correct Weiner filter would have $f_2 = 0.01$ & reduce the quadrupole.
- But since the observed quadrupole is 6x less than the model, Kashlinsky's filter gives $f_2 = -5$ & increases the quadrupole by a large factor.
- Sampling of this enhanced quadrupole through the random mask produced by the galaxy clusters gives the dipole Kashlinsky claims is a "dark flow".

Anisotropic Anisotropy

- Hemispheric or dipole, or dipole +quadrupole modulation of the anisotropy: see Spergel etal, astro-ph:0603449v1
- We considered an isotropic anisotropy multiplied by a slowly varying function f:

$$\tilde{T}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}}) \left[1 + f(\hat{\mathbf{n}})\right]$$

$$f(\hat{\mathbf{n}}) = \sum_{\ell=1}^{\ell_{max}} \sum_{\ell=-m}^{m} f_{\ell m} Y_{\ell m}(\hat{\mathbf{n}}))$$

Anisotropic Anisotropy: II

- Results:

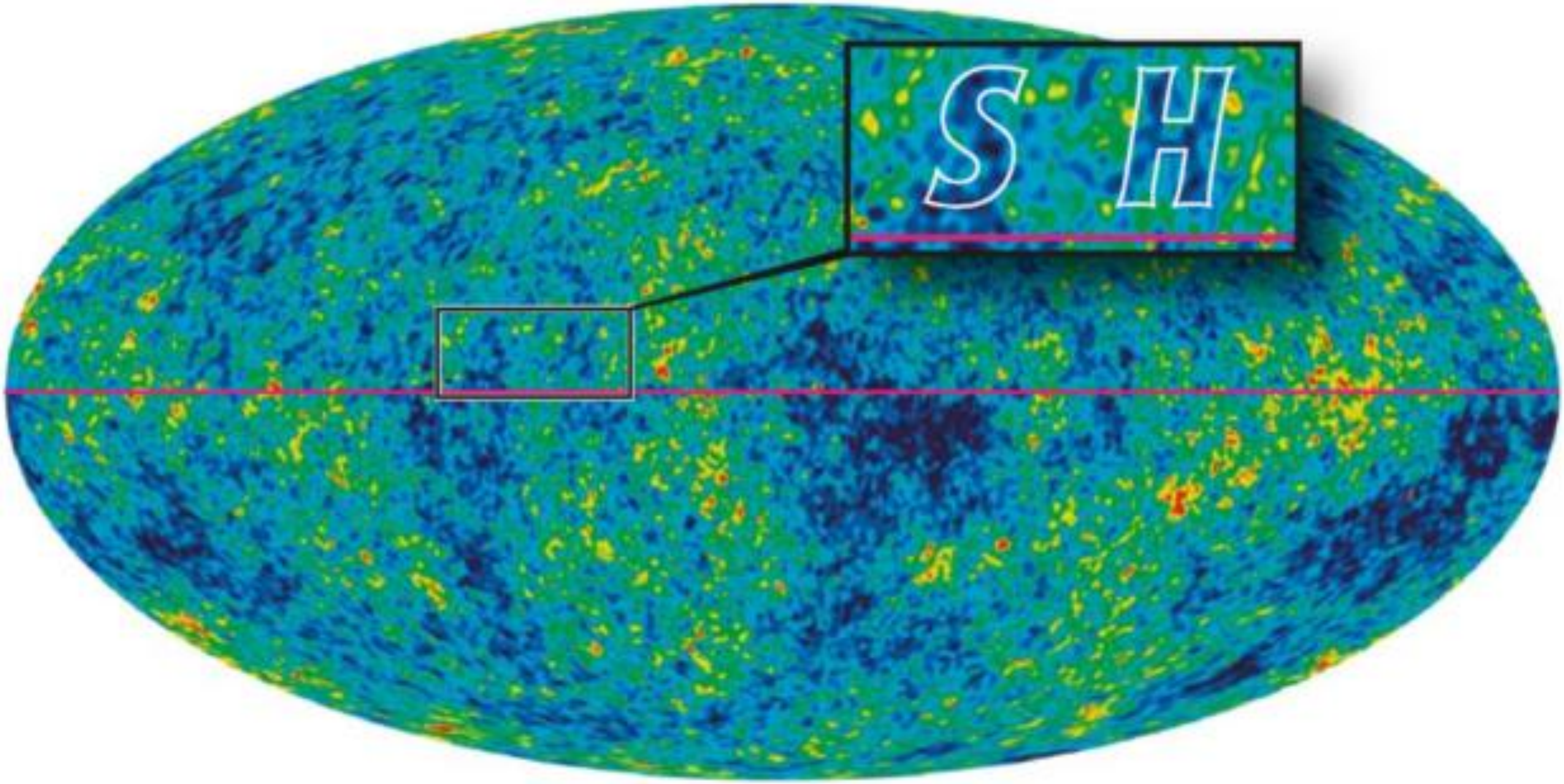
Whereas mild deviations from 0 are observed, the change in ln L when compared to the case where $f = 0$ and only C_ℓs are varied is Δ ln L = -1.7 for $\ell_{max} = 1$ (*i.e.* , 3 extra parameters) and Δ ln L = -3.98 for $\ell_{max} = 2$ (*i.e.* , 8 extra parameters.)

- So $\Delta\chi^2 = 3.4$ for 3 new parameters, and $\Delta\chi^2 = 8$ for 8 new parameters. There was nothing significant in the 3 year data.
- But the referee made us take this out!
- Dozens of papers on this effect in the 3 yr, 5 yr and 7 yr data have been posted and they are all insignifcant.

Finally: Weird but true!

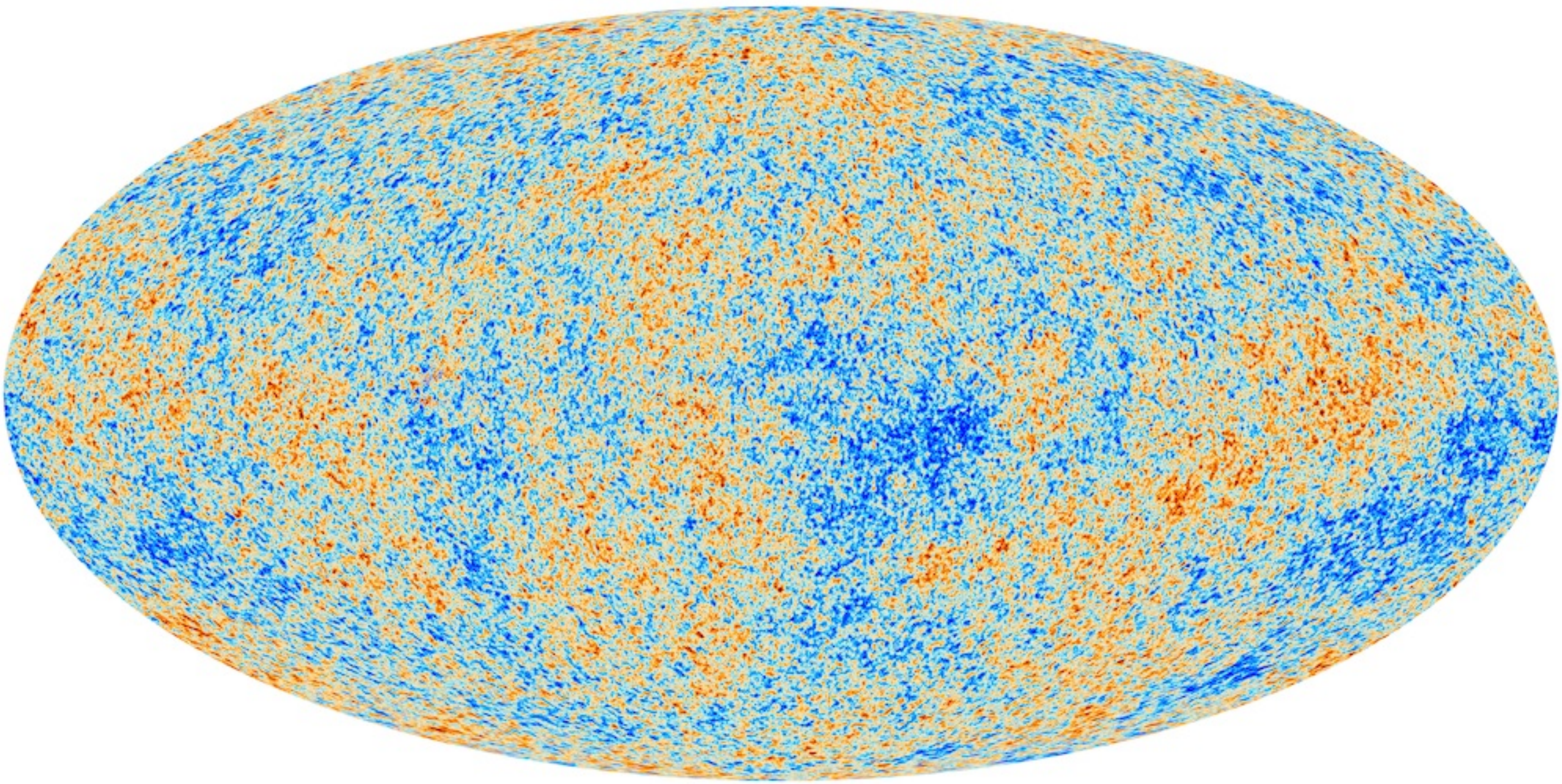
- Explain these constants:
  - The vacuum energy density is 3349(67) eV/cm^3 [Planck+WP+highL+BAO]
    - 2%! (assuming a flat Universe)
    - It's not 10^{93} gm/cc or 0
    - $\hbar c$ is 0.00002 eV-cm, so this is 3×10^{-11} eV^4. Don't tell me 10^{-4} or even (10 meV)^4
  - The CDM:baryon ratio is 5.33(6):1 (1%)
  - The baryon:photon ratio is $6.14(3)\times10^{-10}$ (½%)
  - The CDM:photon ratio is $5.43(5)\times10^{-33}$ grams/photon (1%)

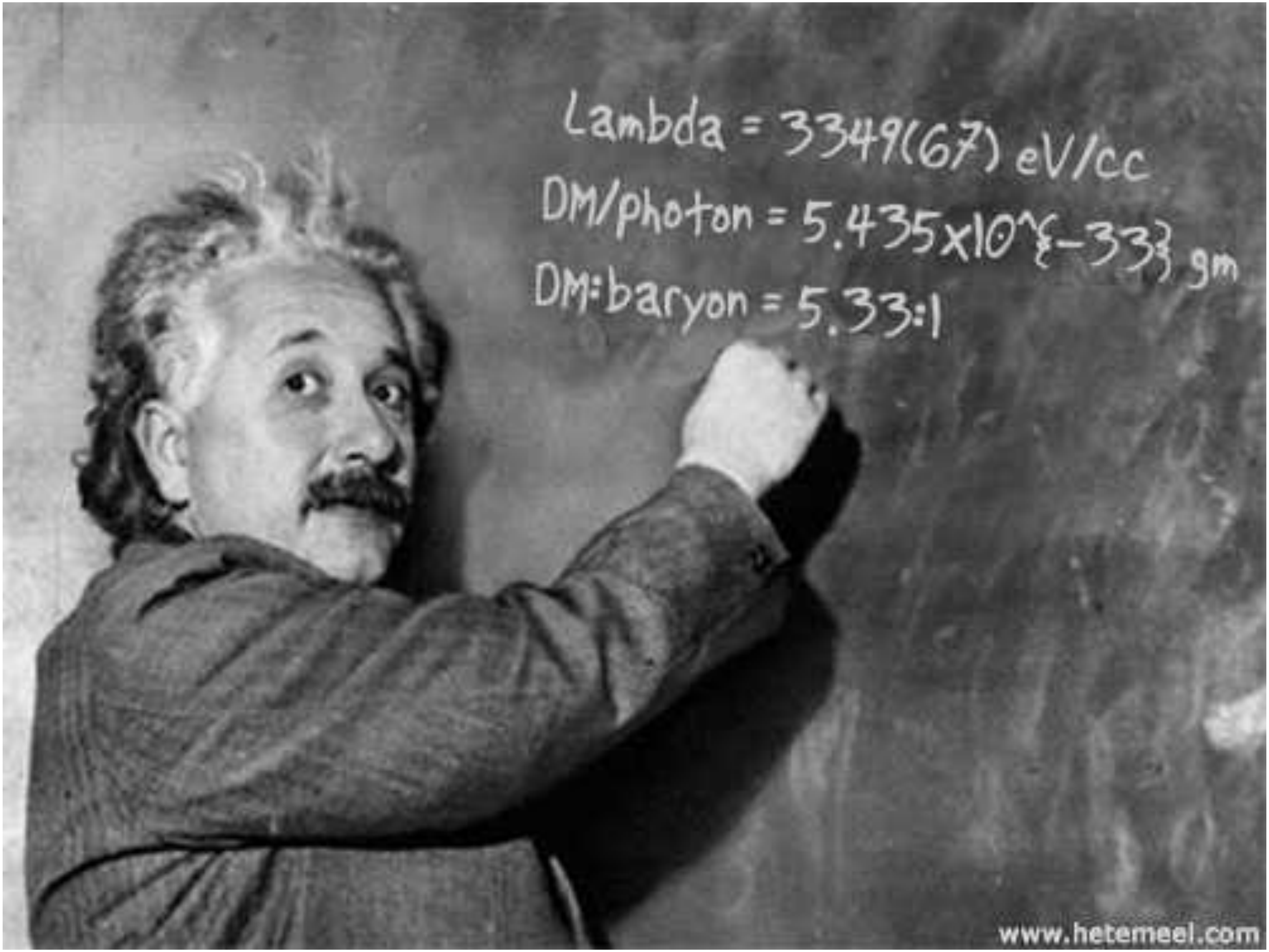
CONCLUSION



- A frequent referee requests: if it’s not weirder than Stephen Hawking’s initials on the sky, do not submit!

Not so obvious in Planck map




Lambda = 3349(67) eV/cc
DM/photon = 5.435x10^{-33} gm
DM:baryon = 5.33:1
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