“Exotic” models

or

What may (or may not) be part of the future of CMB analysis

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A stupid definition

By "exotic", we do not mean

- Something so crazy that nobody (including the people who promoted it) believe in it

- Something so complicated that nobody (possibly including the people who promoted it) has a good understanding of it

- Something so new that nobody (apart from the people who promoted it) has ever heard about

No, by "exotic", we mean something that is not (yet) implemented in CMBFAST and CAMB

What could leave some imprint on CMB and other cosmological data

- **Dark energy properties ($w(z)$)**
- **Dark matter properties (m, $\sigma_{\mathrm{DM-X}}$, weirder Dark Matter)**
- **Extra dimensions**
- **Fundamental constants (α, G)**
- **Magnetic fields**
- **Neutrinos properties (m, N_ν, μ)**
- **Stuff about inflation (non Gaussianity, running spectral index, isocurvature modes...)**
- **Topological defects**
- **Topology**
- **Transplanckian physics**

Fundamental constants

- **Varying α is relatively straightforward and has a clear observational motivation**

- **Varying G (e.g. scalar tensor theories) is more involved:**

  - **For minimally coupled quintessence, correct parametrization is not $w(z)$ but $V(\phi) = \Lambda^{4+\alpha}/\phi^\alpha$**

  - **Λ determines Ω_Q, α determines w_Q, but no exact solution for $V(z)$**

  - **$\Lambda(\Omega_Q)$ is not known a priori and has to be found numerically**

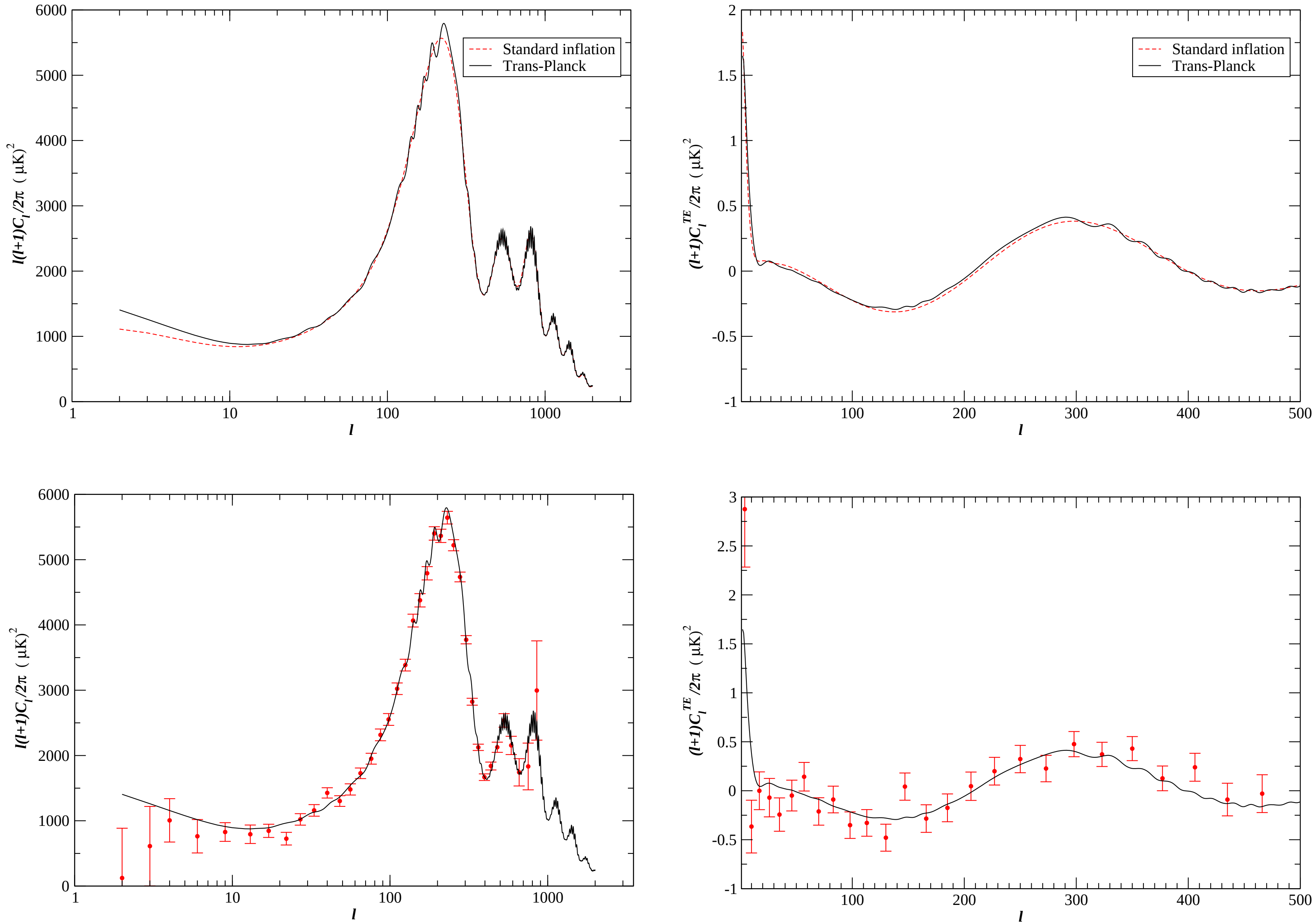
  - **For scalar tensor theories, $G = G(\phi(z))$ is an effective constant depending on G_b, the bare Newton constant**

  - **As for $\Lambda(\Omega_Q)$, $G^0_{\text{eff}}(G_b)$ has to be found numerically**

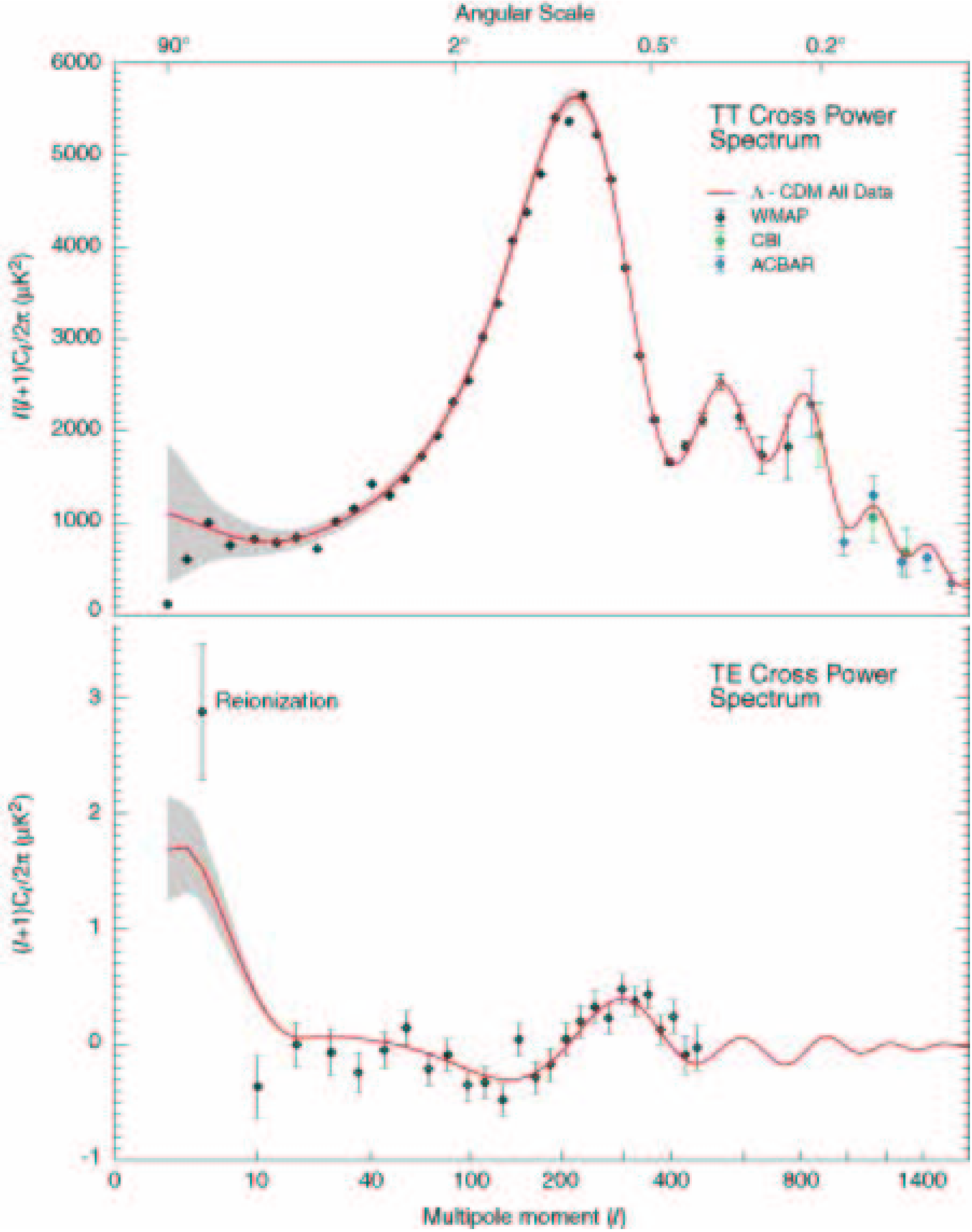
  - **On the data analysis side, $G = G(z)$ implies that SN are no longer standard candles, but their luminosity depends in some way on $M_{\text{Ch}}(G(z))$ and one has to check that all constraints on these scenarios are passed**

Transplanckian physics

- **Idea is to modify initial quantum state of fluctuations during inflation**
- **Usually, initial conditions for the quantum state are taken in the asymptotic limit** $k/a \gg H$
- **But this corresponds to a situation where the wavelength is smaller than the Planck length**
- **Possible modification of the usual ansatz for the initial state translates into a modification of the initial power spectrum**
- $$P_{\mathcal{R}} = P_{\mathcal{R}}^{\rm inf} \left(1 + \varepsilon \cos(\log(k/k_*) + \varphi)\right)$$
- $\rightarrow$ **High frequency wiggles in the** C_ℓ **spectrum**



Standard inflation
Trans-Planck
$l(l+1)C_l/2\pi$ (μK)^2
$(l+1)C_l^{TE}/2\pi$ (μK)^2
l
0
1000
2000
3000
4000
5000
6000
1
10
100
1000
-1
-0.5
0
0.5
1
1.5
2
2.5
3
100
200
300
400
500



Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
l(l+1)C_l/2π (μK²)
3
2
1
0
-1
Reionization
TE Cross Power Spectrum
(l+1)C_l/2π (μK²)
0
10
40
100
200
400
800
1400
Multipole moment (l)

Active seeds

- **Just add an extra term in the matter perturbed stress-energy tensor, corresponding to an extra component**

- **Extra term may correspond to anything (topological defects, magnetic fields, extra dimensions...), and evolve more or less independently of the rest of the matter**

- **Dynamics of extra term sufficiently complicated to produce both scalar, vector and tensor modes**

- **Vector-to-scalar and tensor-to-scalar ratios can be computed (difficult !)** $\rightarrow C_\ell^{BB}/C_\ell^{TT}$

- **Possible non Gaussian signatures (defects and magnetic fields)**

Topological defects / Magnetic fields

- $$T^S_{\mu\nu} = \begin{pmatrix} a^2\rho^2 & a^2(\partial_i v + \bar{v}_i) \\ a^2(\partial_i v + \bar{v}_i) & \begin{array}{l} a^2 P\delta_{ij} + a^2\left(\partial_{ij} - \frac{1}{3}\Delta\delta_{ij}\right)\Pi \\ +a^2\frac{1}{2}(\partial_i\bar{\Pi}_j + \partial_j\bar{\Pi}_j) + a^2\bar{\bar{\Pi}}_{ij} \end{array} \end{pmatrix}$$

- **On large scales,** $\partial_i v \propto \bar{v}_i$ **and** $\partial_{ij}\Pi \propto \partial_i\bar{\Pi}_j \propto \bar{\bar{\Pi}}_{ij}$

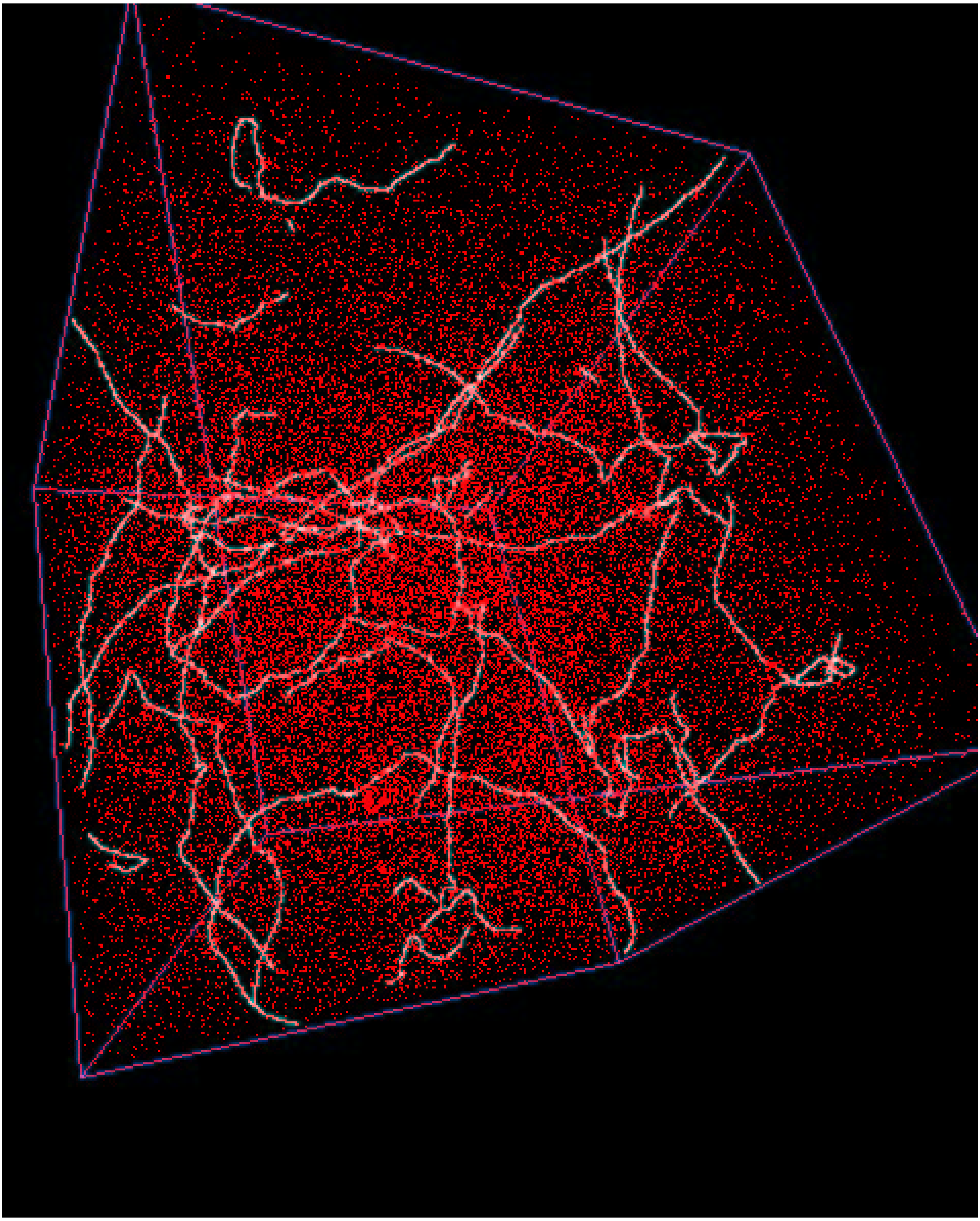
- **Scalar modes dominated by** ρ**, vector components dominated by** $\bar{v}_i$

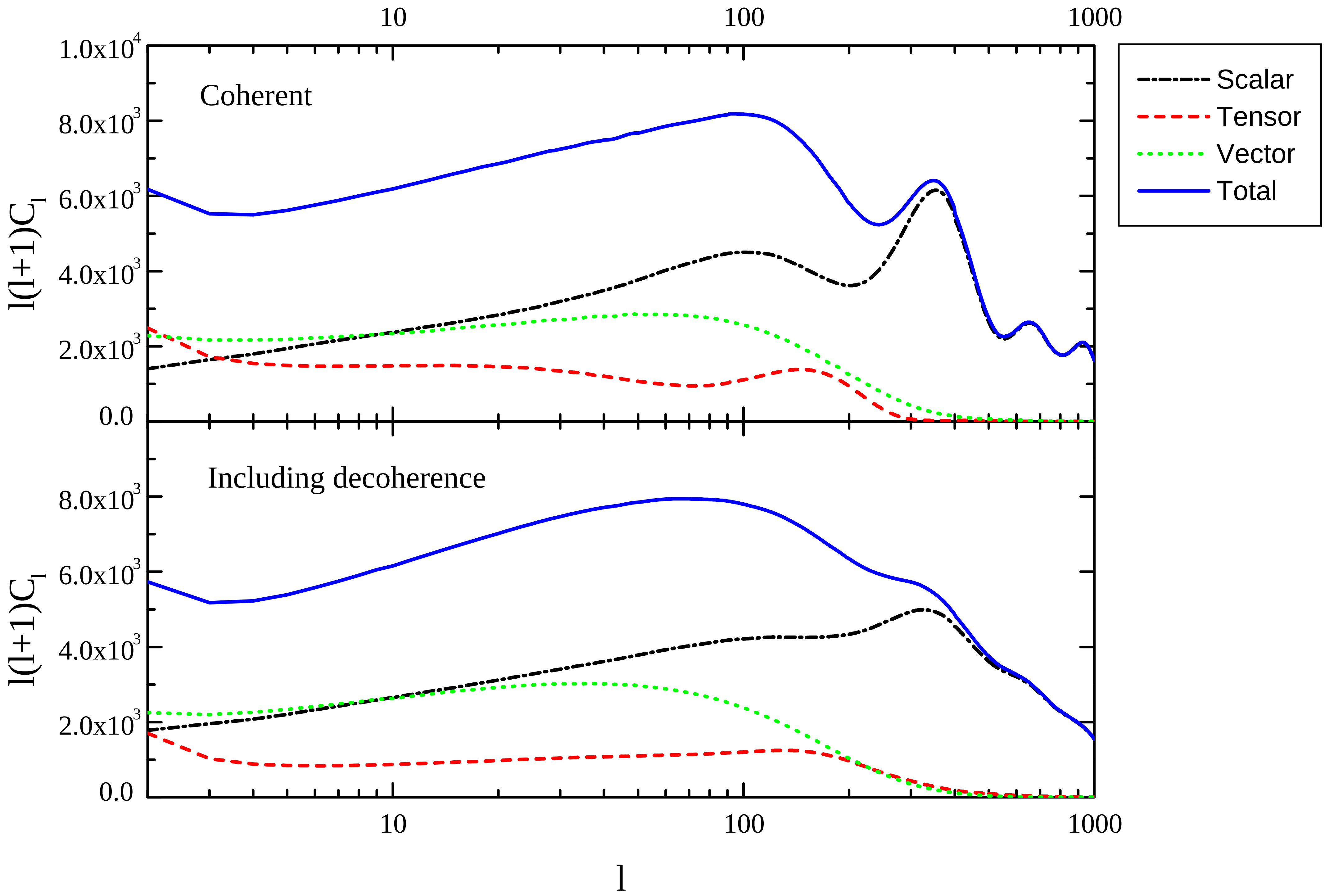
- **Tensor / Vector / Scalar** C_ℓ **follow the ratio** $k^2\Pi : kv : \rho$

- **Ratios are very model dependent and very often hard to compute**

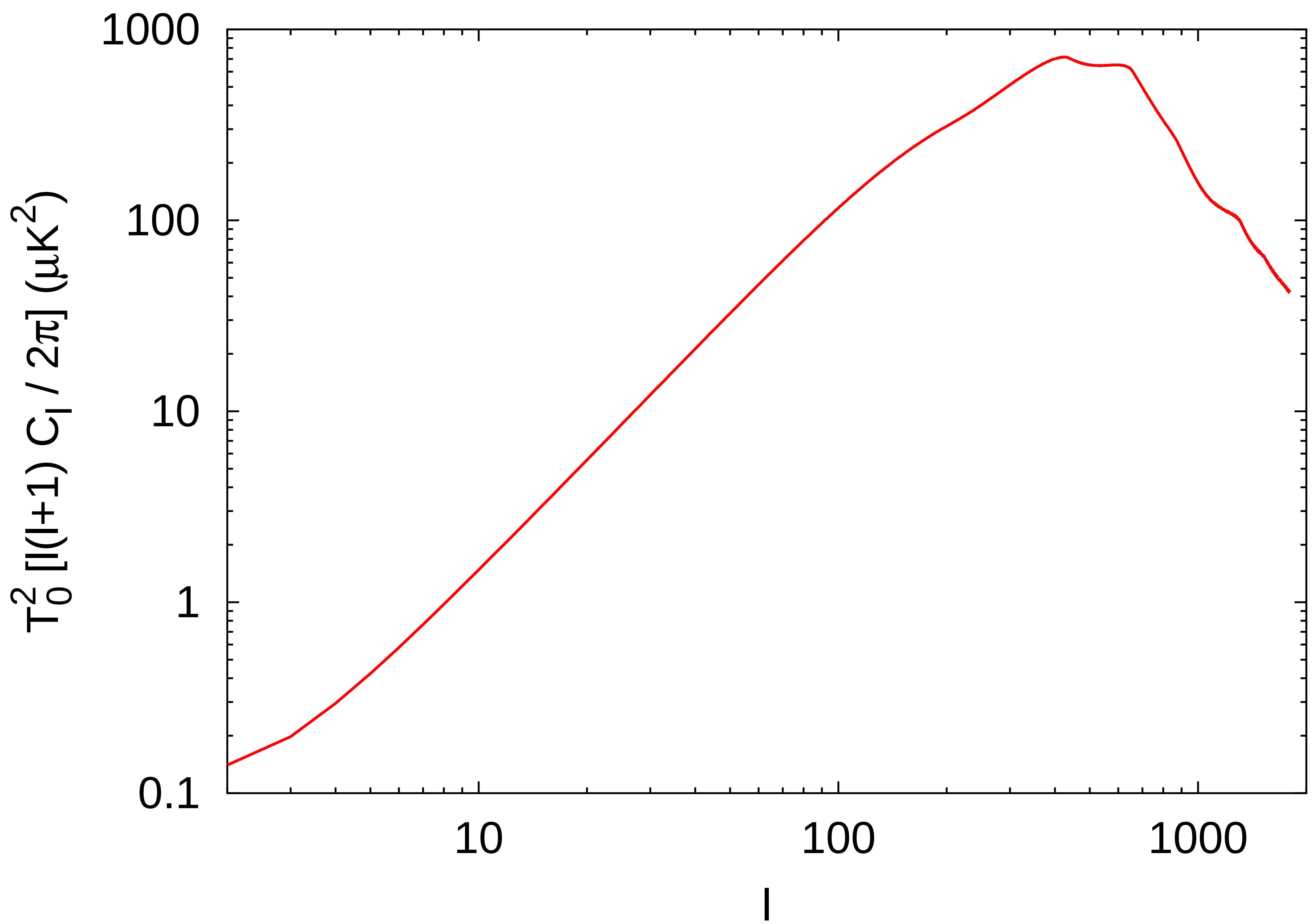
- **What one has to compute is:**
  - **Several realizations of the sources**
  - $C_{mu\nu\rho\sigma}(k,\eta,\eta') = \langle T_{\mu\nu}(k,\eta)T_{\rho\sigma}(k,\eta')\rangle$
  - **Diagonalize this huge matrix**
  - **Plug the (numerous) correlators into the Poisson equation**

- **Non linear effects in stress energy tensor destroy Doppler peak pattern**





10
100
1000
1.0x10^4
8.0x10^3
6.0x10^3
4.0x10^3
2.0x10^3
0.0
Coherent
l(l+1)C_l
Scalar
Tensor
Vector
Total
Including decoherence
8.0x10^3
6.0x10^3
4.0x10^3
2.0x10^3
0.0
l(l+1)C_l
10
100
1000
l



T_0^2 [l(l+1) C_l / 2π] (μK^2)
1000
100
10
1
0.1
10
100
1000
l

Extra dimensions

- **At 4D, in presence of matter, metric had 6 degrees of freedom (2 scalar, 2 vector, 2 tensor)**

- **At 5D, 5 degrees of freedom for the metric (gravitons), plus one degree of freedom for the brane position = 6 degrees of freedom**

- **A 5D graviton can source scalar, vecor or tensor modes on the brane depending on the projection of its spin on the brane**

- **If brane position does not dominate over bulk gravitons, and brane perturbation do not dominate over bulk perturbation, possible large B modes**

- **Solving bulk perturbations is in general very difficult because one has nolonger ODE's but PDE's, and because one has to specify boundary conditions**

- **In addition, background equations are modified at early times**

Topology

- **Tile spacelike sections with a *fundamental polyhedron* (e.g. a cube), under the action of a fixed-point free isometry *holonomy group***

- **No simple theoretical framework, goes against inflation philosophy**

- **Necessitates to introduces a new scale (at least when $\Omega = 1$), unless it has to do with Λ**

- **Produces correlations on pairs of circles both in temperature and polarization maps because of periodic boundary conditions**

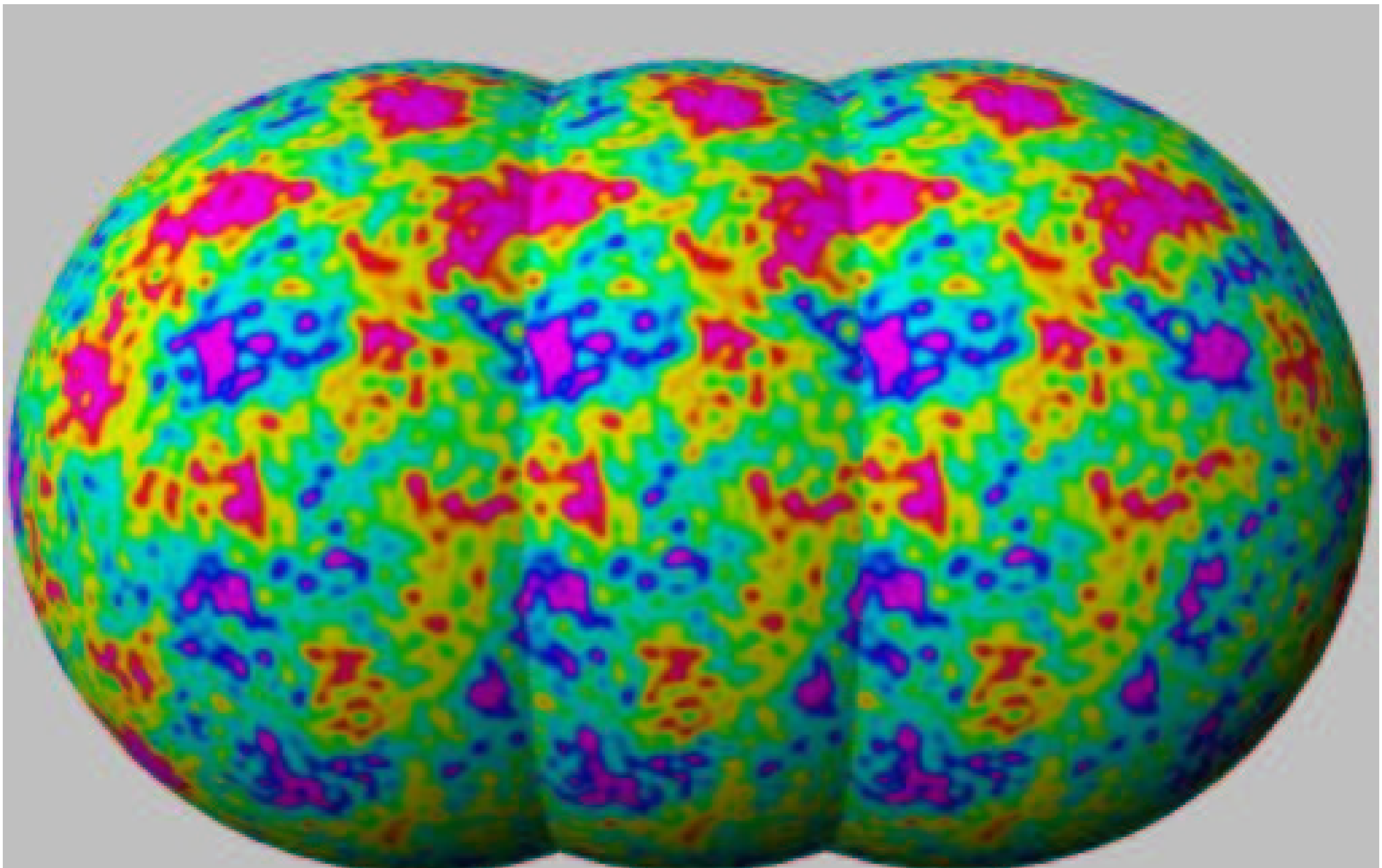
- **Also produces large scale anisotropy because of preferred direction in smallest wavemodes**

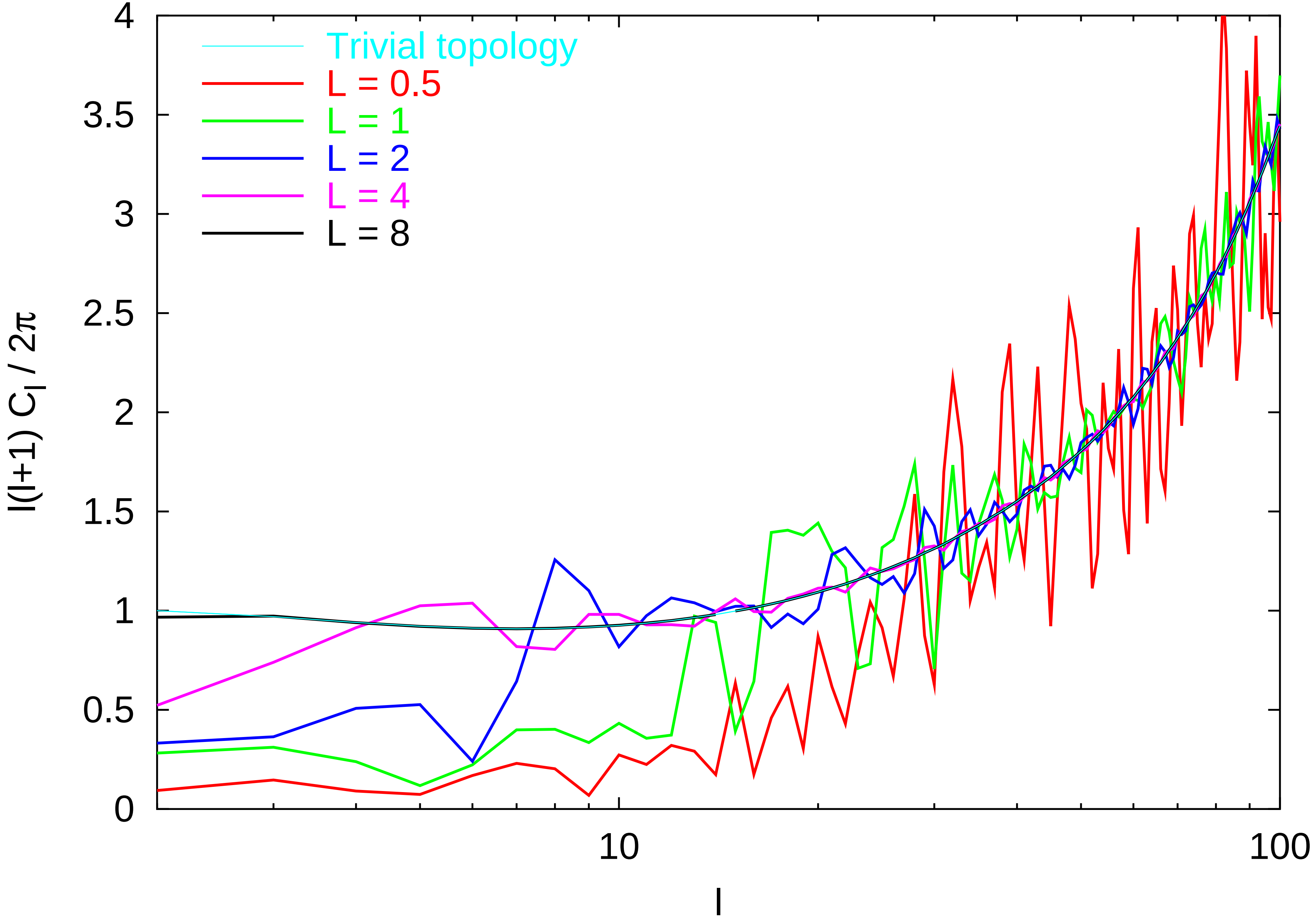
Topology

- **Technically simple:**

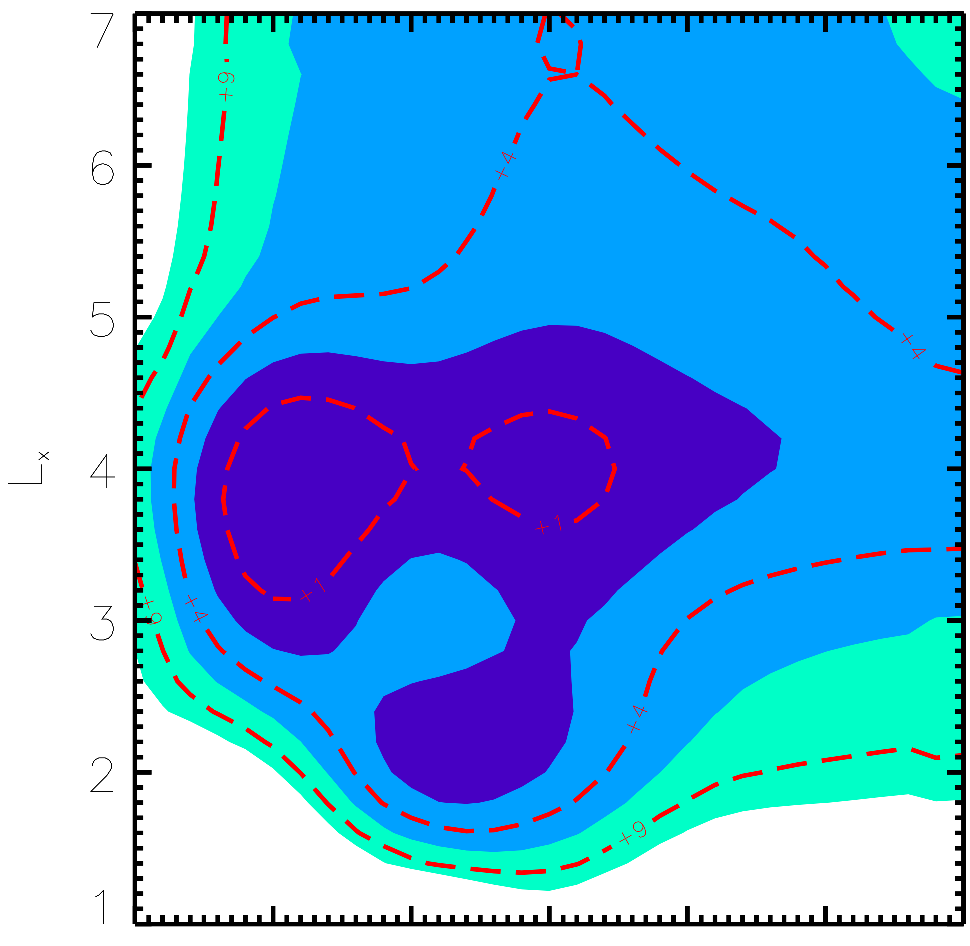
$$C_\ell = \int \Theta_\ell^2(k) P(k) k^2 \mathrm{d}k \longrightarrow \langle a_{\ell m} a^*_{\ell' m'} \rangle = \sum_{\mathbf{k}} \xi^{\mathbf{k}}_{\ell m} \xi^{\mathbf{k}}_{\ell' m'} \Theta_\ell(k) \Theta_{\ell'}(k) P(k)$$

- **Computationally challenging:**
  - **For a single realization:** $t_r \propto V \ell_{\rm max}^5$
  - **For the simplest case (cubic torus with a specific orientation),** $t_r \sim$ **a few 100 hours on a single 2GHz CPU for** $\ell_{\rm max} = 250$ **and** V **which reproduces WMAP low** ℓ **cutoff**
  - **For the full correlation matrix:** $t_c \propto V \ell_{\rm max}^7$
  - **For the simplest case (cubic torus with a specific orientation),** $t_c \sim$ **a few 100 hours on a single 2GHz CPU for** $\ell_{\rm max} = 60$ **and** V **which reproduces WMAP low** ℓ **cutoff**

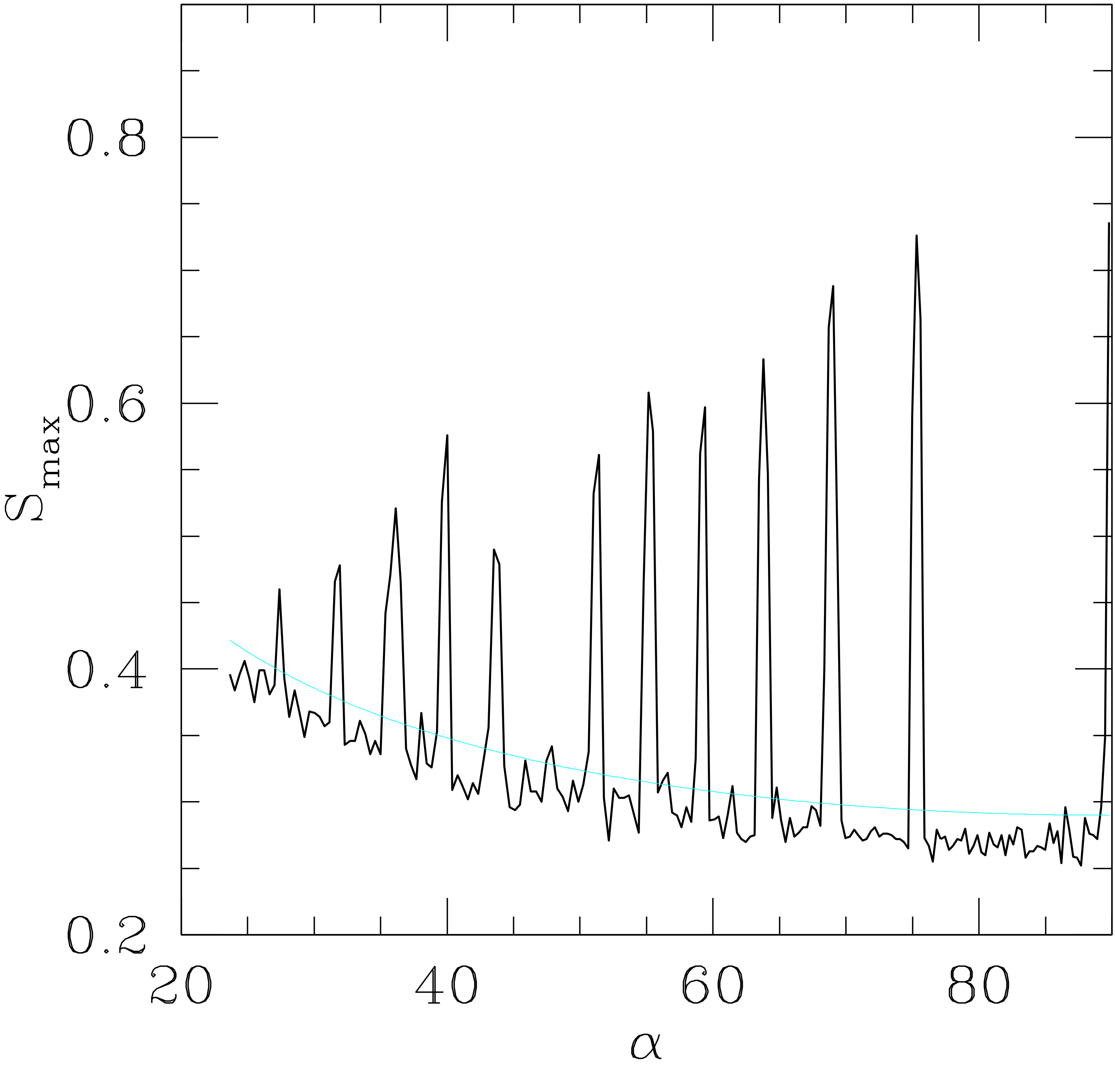




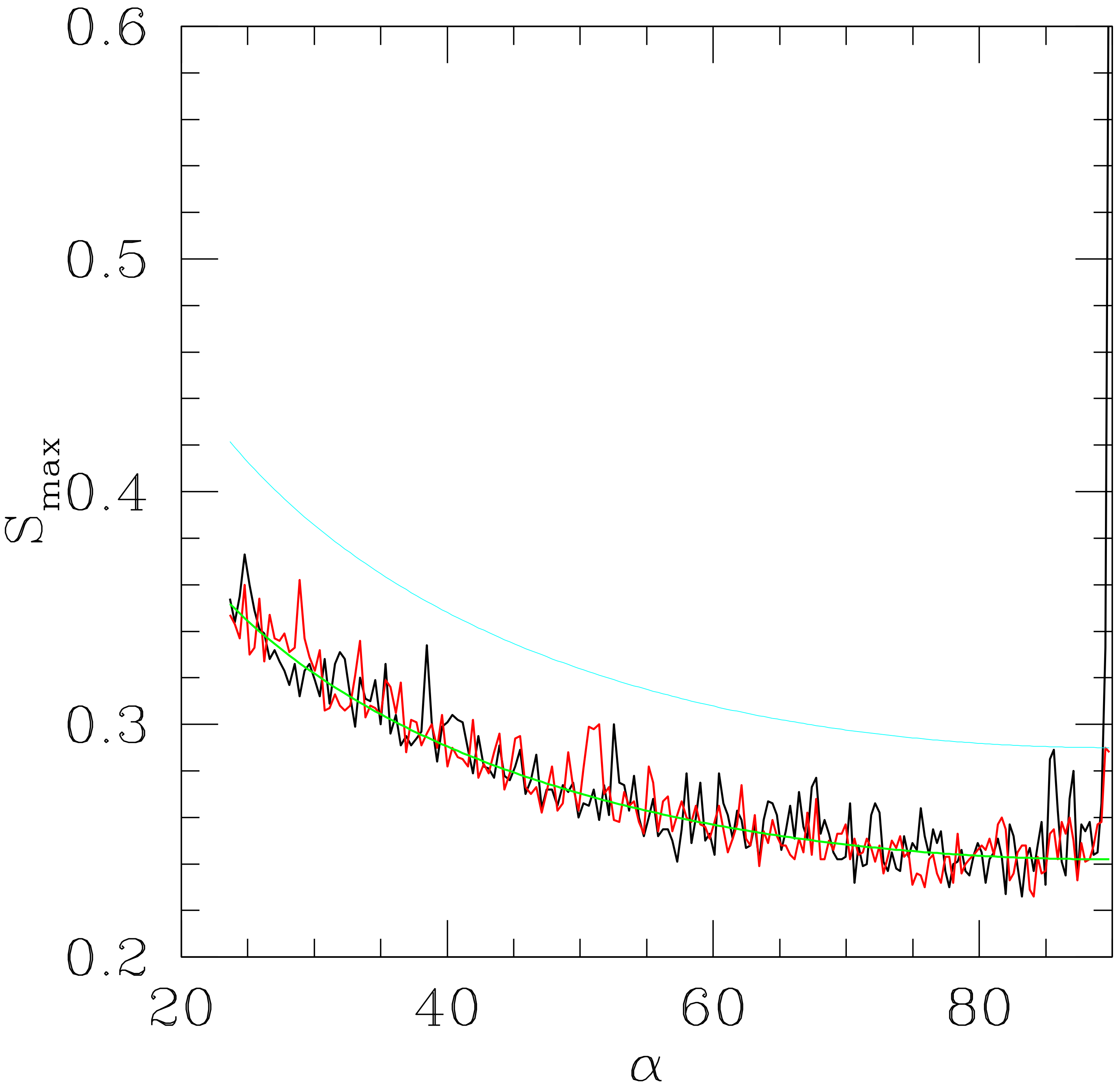
Trivial topology
L = 0.5
L = 1
L = 2
L = 4
L = 8
l(l+1) C_l / 2π
l
0
0.5
1
1.5
2
2.5
3
3.5
4
10
100



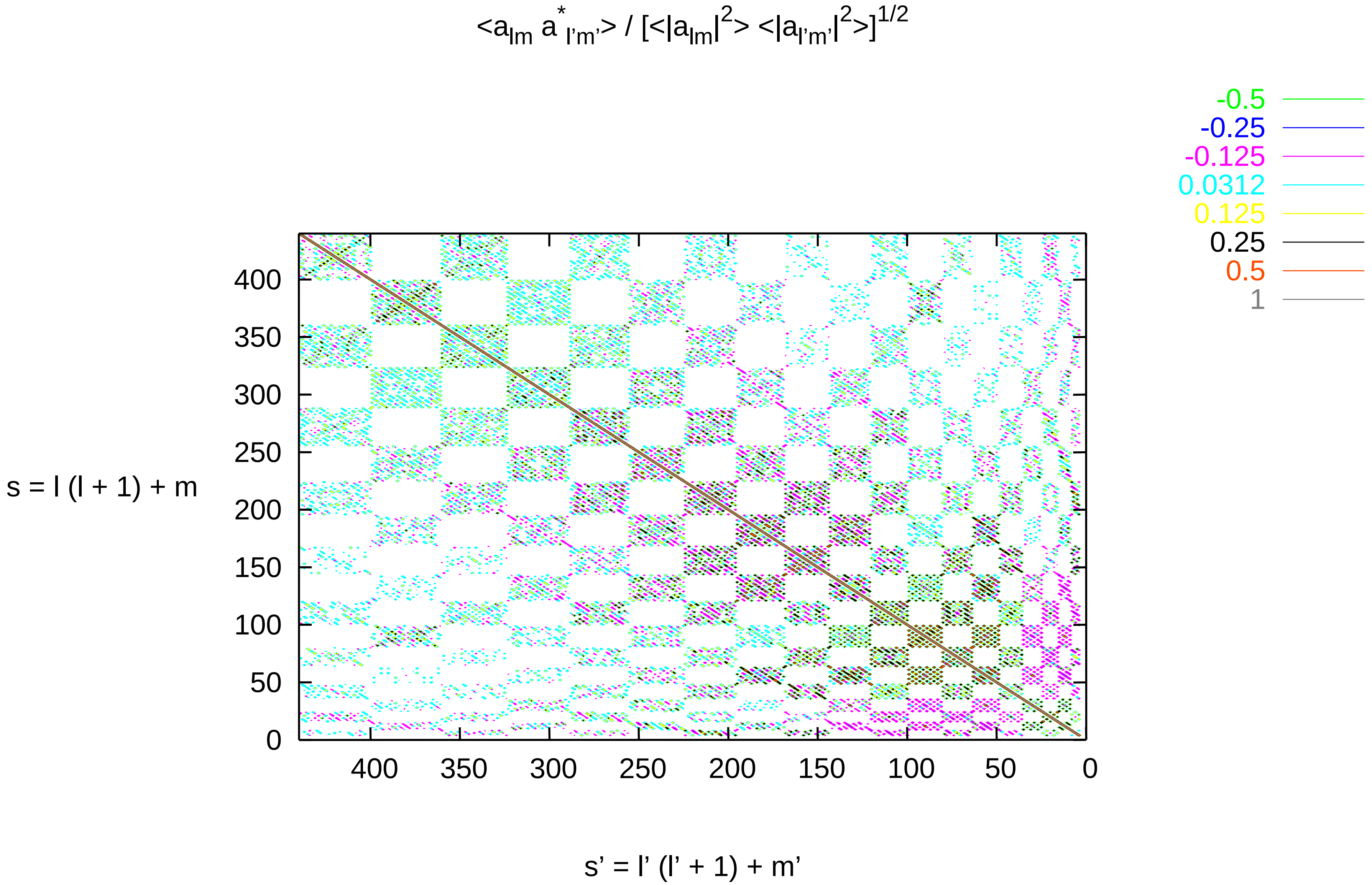
L_x
L_z
1
2
3
4
5
6
7
+1
+4
+9

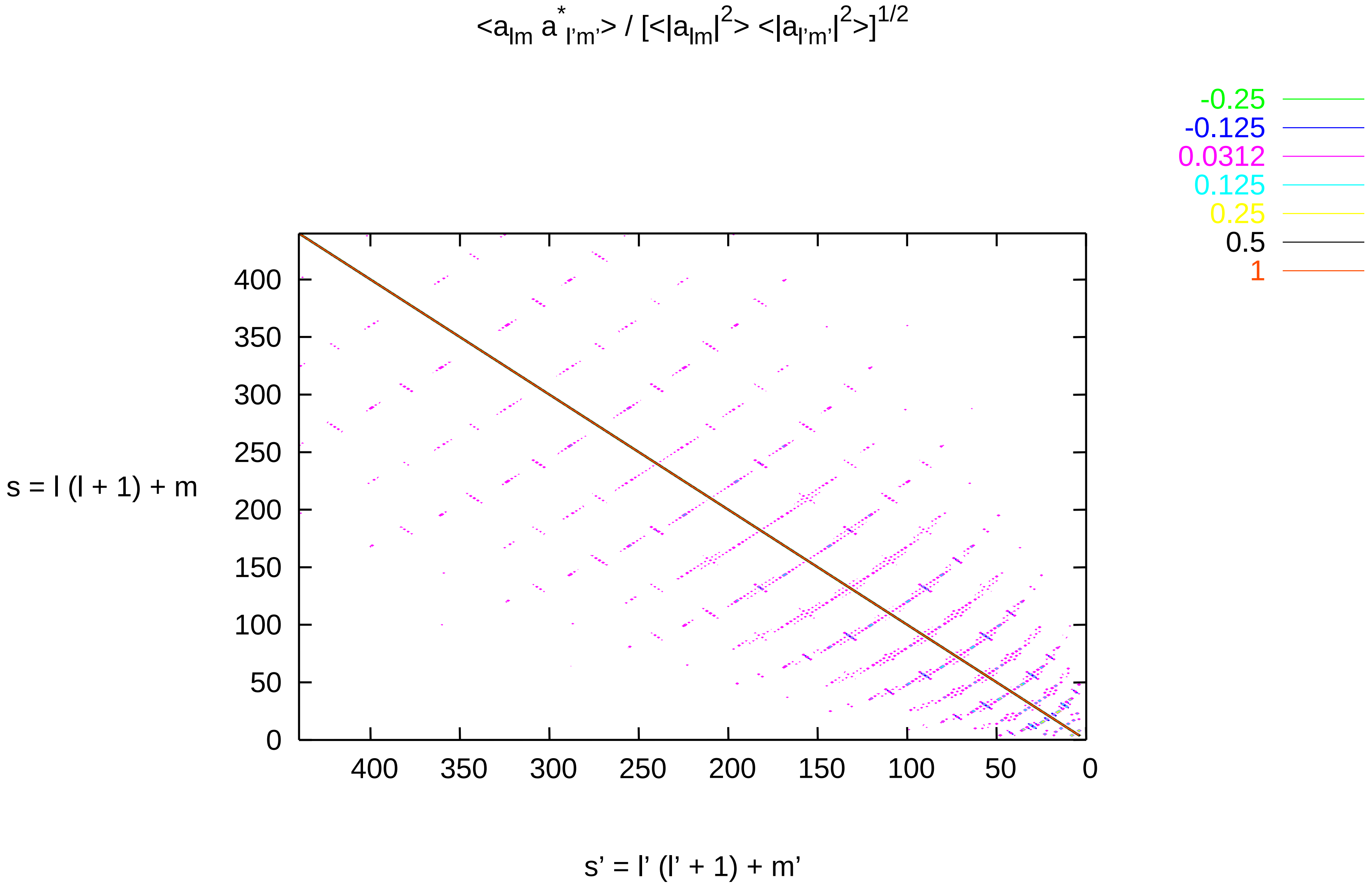


0.2
0.4
0.6
0.8
S_{max}
20
40
60
80
α

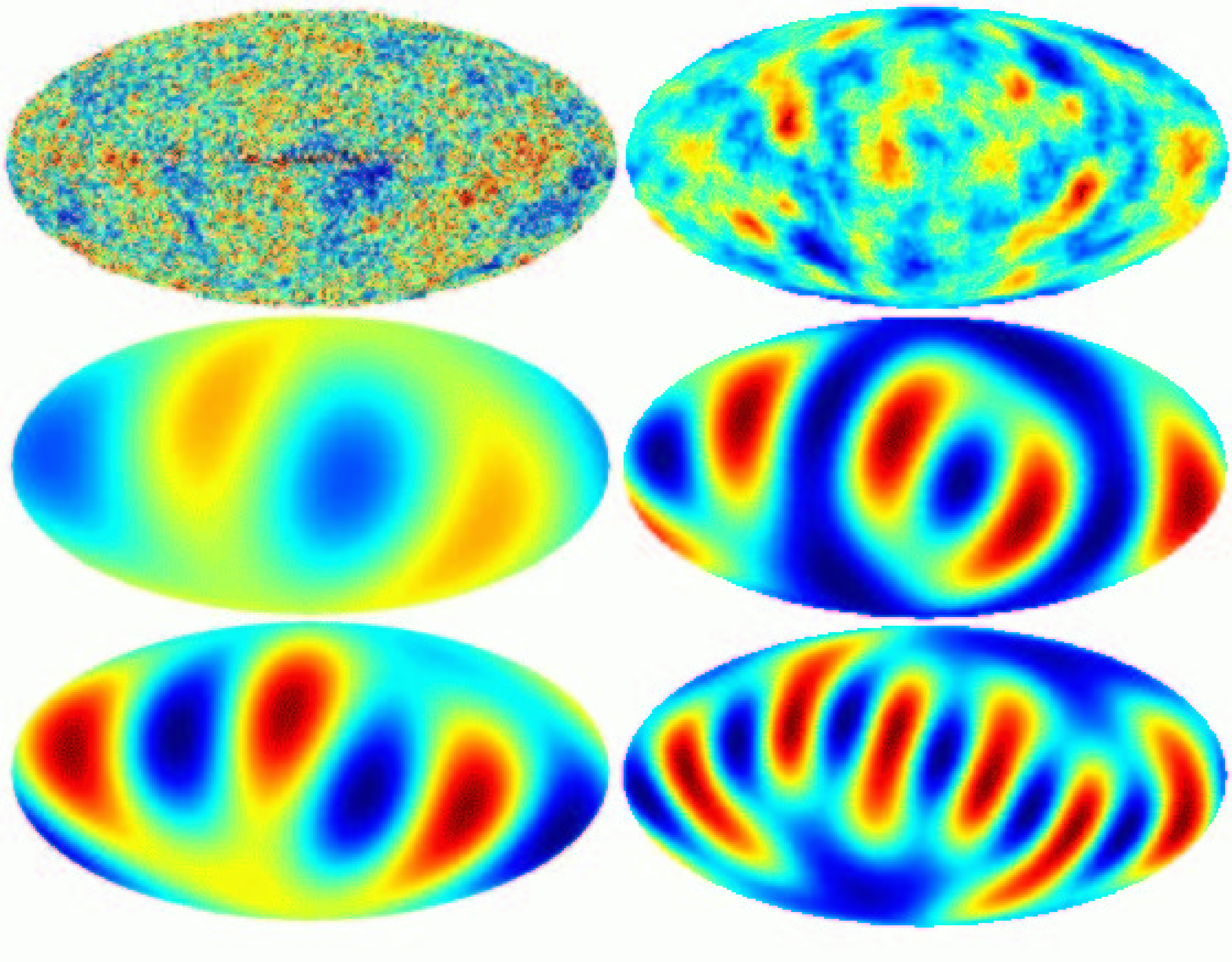


0.6
0.5
0.4
0.3
0.2
20
40
60
80
S_{max}
α


$<a_{lm}\, a^*_{l'm'}> / [<|a_{lm}|^2> <|a_{l'm'}|^2>]^{1/2}$
-0.5
-0.25
-0.125
0.0312
0.125
0.25
0.5
1
s = l (l + 1) + m
s' = l' (l' + 1) + m'
0
50
100
150
200
250
300
350
400



<a_lm a*_l'm'> / [<|a_lm|^2> <|a_l'm'|^2>]^1/2
-0.25
-0.125
0.0312
0.125
0.25
0.5
1
s = l (l + 1) + m
400
350
300
250
200
150
100
50
0
s' = l' (l' + 1) + m'



Conclusion

"Science begins as heresy,
advances as orthodoxy
and ends as superstition" (anonymous)

- Some of the formerly exotic stuff have now become fairly common (quintessence, isocurvature modes)
- It is difficult to predict what the next step could be (topology was unlikely to raise so much attention)
- Still a lot of things to do for those who do not want to follow orthodoxy