Title: Turbulence in the universe

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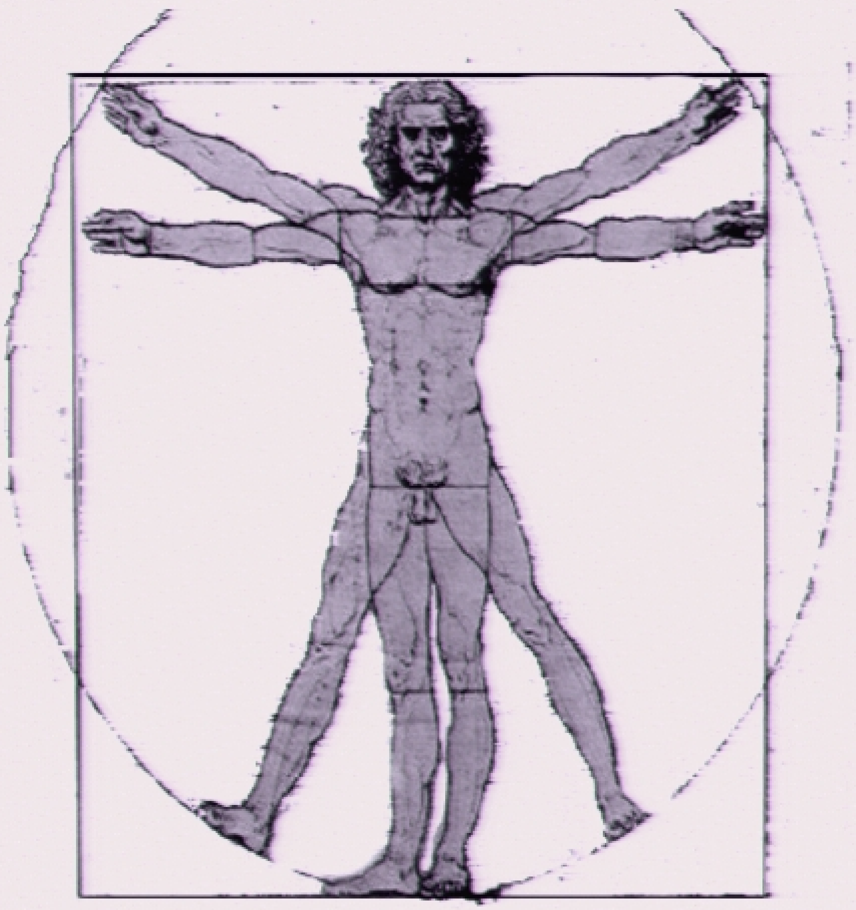
Abstract:

Turbulence in the Universe: an outsider's view

Maya Paczuski

Leonardo's sketches – symmetries of nature and the forces of fashion



“The last great unsolved problem in classical physics”

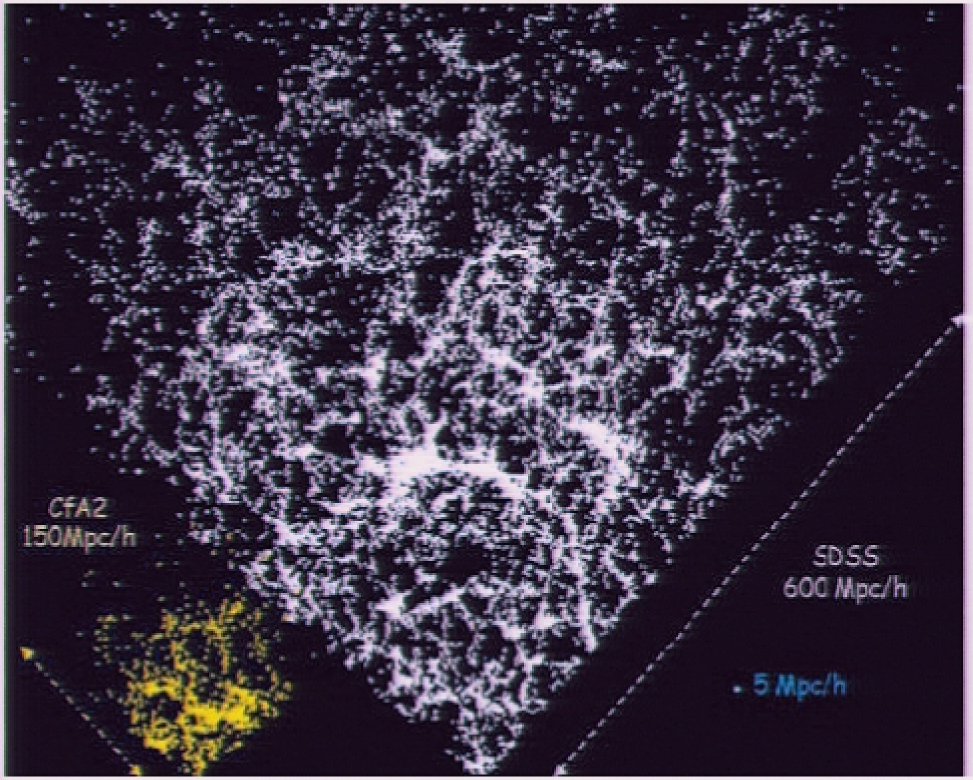
- When I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics , and the other is the turbulent motion of fluids. And about the former I am rather optimistic.

Supernovas

Gazing up at a starlit sky gives an impression of majestic calm in the Universe. But the reality is entirely different. Exploding *supernovas*, irresistible black holes, and throbbing *pulsars* all wreak celestial havoc.

These phenomena are extreme in their violence and the energy they release. They emit gamma rays - electromagnetic waves - 100,000 times more powerful than any visible light. But these cosmic cataclysms and collisions are essential in forming the elements of the Universe.

Large scale structure of Luminous Matter in the Universe

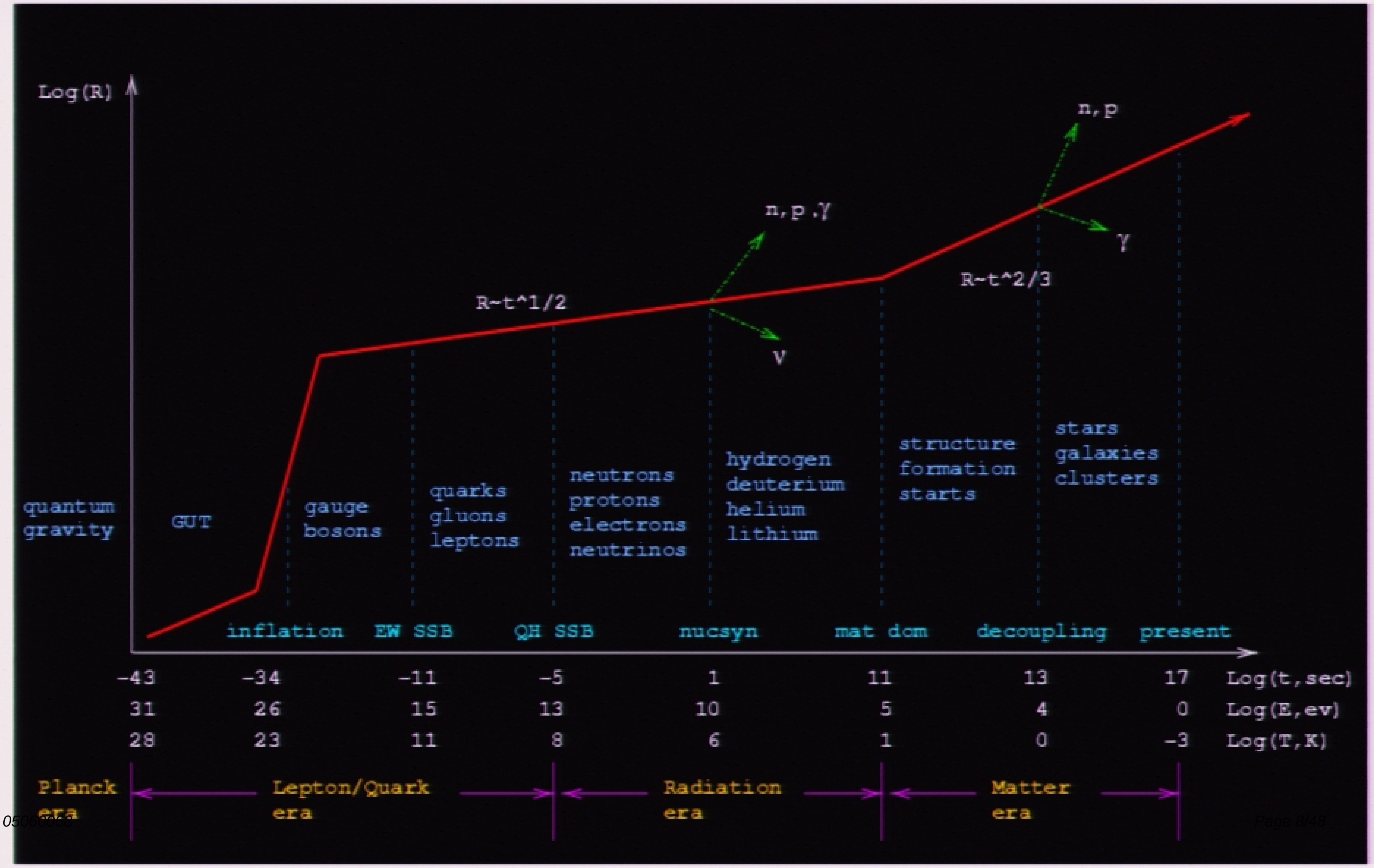


Courtois, Paturel, Sousbie, & Labini (2004)

It is striking to see that the very local view of the local universe with bubbles, chains and walls can still be seen at a scale 10 times larger. One cannot guess the intrinsic scale of the structures by looking at these maps. We can really begin to speak about hierarchy in the large-scale structures, another word for scale invariance. Studies of the statistical properties of such distributions are ongoing and we will present them soon. For the moment, it is for instance clear that a galaxy correlation-length of 15Mpc could hardly be a meaningful statistical indicator tracing the galaxy clustering properties in the Local Universe.

Turbulence at all scales!

A brief history



Fundamental Mechanisms

Why did the big bang lead to increasing complexity in our universe, rather than exploding into a simple gas-like fragmented substance, as explosions usually do, or imploding into a plain solid or black hole?

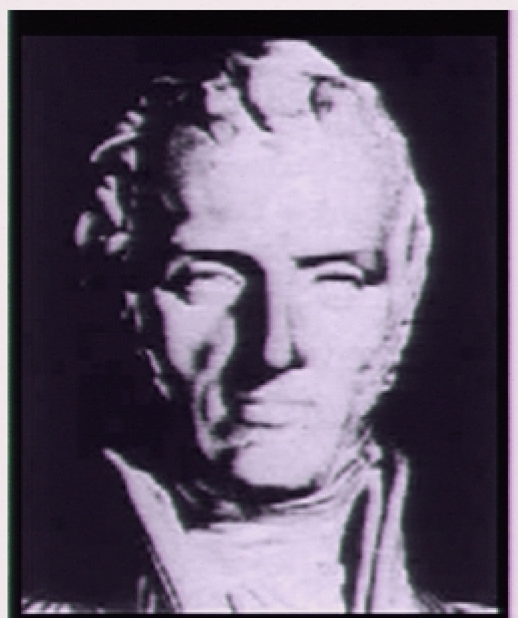
Some intricately balanced feature of the initial state may have existed that allowed this to happen.

Another possibility is that the laws of physics change (or self-organize) over the history of the universe.

Common thread -- TURBULENCE

Navier Stokes Equation (incompressible)

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{\nabla P}{\rho} + \nu \nabla^2 \mathbf{u} + \frac{\mathcal{F}}{\rho},$$



The Reynolds number

$$Re = \frac{v_s L}{\nu} \; .$$

The Reynolds number is the ratio of inertial forces to viscous forces and is used for determining whether a flow will be laminar or turbulent. Laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion, while turbulent flow, on the other hand, occurs at high Reynolds numbers and is dominated by inertial forces, producing random eddies, vortices and other flow fluctuations

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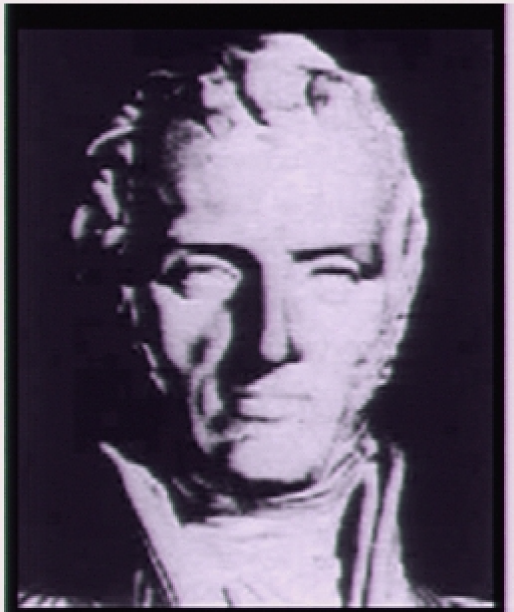

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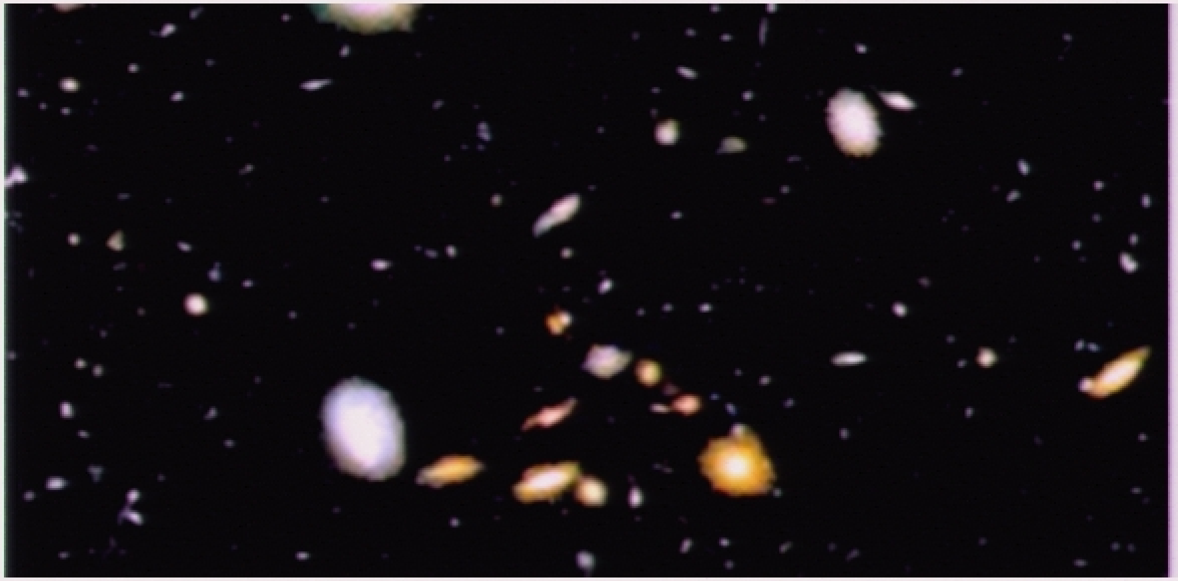
The universe appearing in a reactor near you!

- Nuclear fusion reactors could be used to study what the universe was like just after the big bang. So claims a physicist who noticed that the plasma created inside these reactors is distributed in a strikingly similar way to galaxies in today's universe. Nils Basse of the Massachusetts Institute of Technology does not normally concern himself with events in the early universe. But when he chanced upon the Sloan Digital Sky Survey (SDSS)- which is mapping a quarter of the sky in detail- he noticed something uncanny. The mathematical equation governing the distribution of voids and galaxies looks remarkably like the one describing the millimetre-sized knots and clots of plasma in the Wendelstein 7-AS "stellarator" fusion reactor in Garching, Germany (Physics Letters A, vol 340, p 456).
- Basse argues that the distribution of galaxies today could be the result of variations in the density of plasma after the big bang. "I think it all comes from turbulence in the very early universe," he says. "[The galaxy distribution today] is just a blow-up of what was going on at that point." This suggests that stellarator reactors could serve as models of the early universe.
- But cosmologist Daniel Eisenstein of the University of Arizona in Tucson, who works on the SDSS project, disagrees. He points out that the kind of plasma that Basse describes existed only for the first millisecond after the big bang, and that epoch ended too soon to influence the large scale structure of today's universe. Eisenstein calculates that the largest structure that could have arisen because of any such primordial density variations would only stretch a few light years across today.
- Eisenstein also says that Basse's claim is difficult to reconcile with the results of the Wilkinson Microwave Anisotropy Probe (WMAP), which has mapped the distribution of the oldest light in the universe dating back to some 380,000 years after the big bang. This "baby picture" of the cosmos yields markedly different density fluctuations to the SDSS map. "I don't see any way to get turbulence into this mix without throwing out all the [WMAP] data," Eisenstein says. "And that's very powerful data."

A cosmological scenario (Bak & MP (2004))

- Almost perfect uniformity of CMB suggest universe was in equilibrium at decoupling, about 300,000 years after the Big Bang
- On the other hand, luminous matter is strongly clustered and intermittent with correlations up to (maybe) 300Mpc
- In fact intensive luminous matter may have existed already ½ billion years after the Big Bang

Frenzied Star Formation in the Early Universe



(Lanzetta et al (2002))

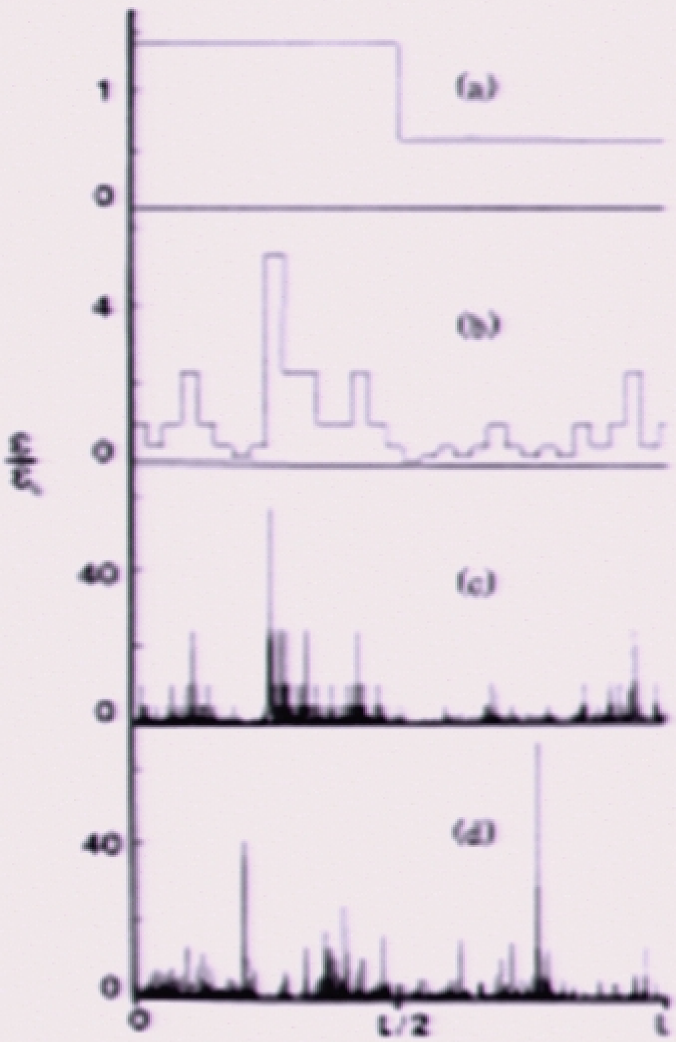
WMAP high optical depth for reionization

Recent observations have significantly advanced our understanding of the reionization of the universe. Estimates of the Thomson optical depth from the *Wilkinson Microwave Anisotropy Probe (WMAP)* suggest that the reionization epoch began at redshifts 14 . *z* . 20 (Bennett et al. 2003; Spergel et al. 2003) and Gunn-Peterson troughs in distant quasars indicate that reionization ended at *z* 6 (Becker et al. 2001; Fan et al. 2002). However, the known population of quasars cannot produce sufficient ionizing radiation (Fan et al. 2001), so star-forming galaxies are most likely the dominant source of ionizing photons at redshifts $z > 7$, a view supported by theoretical studies of reionization (e.g., Tinsley 1973; Sokasian et al. 2003a). The direct detection of these objects lies at the next frontier in the study of the evolution of the early universe.

Intermittency at high Re

- Velocity gradients are small almost everywhere – those regions appear in equilibrium (very small temperature fluctuations)
- Dissipation at small scales ~ $(Re)^{-3/4}$ in sparse, filamentary regions with huge gradients
- Dissipation field is “on-off”

models of intermittency



(Meneveau and Sreenivasan (1987))

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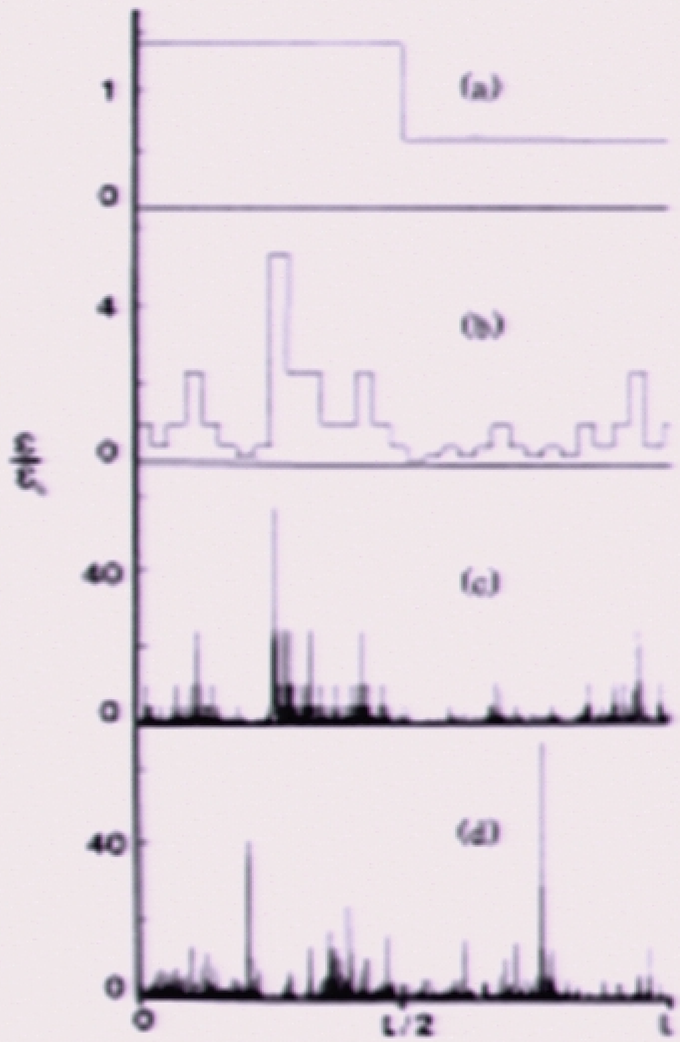


(Meneveau and Sreenivasan (1987))

At decoupling

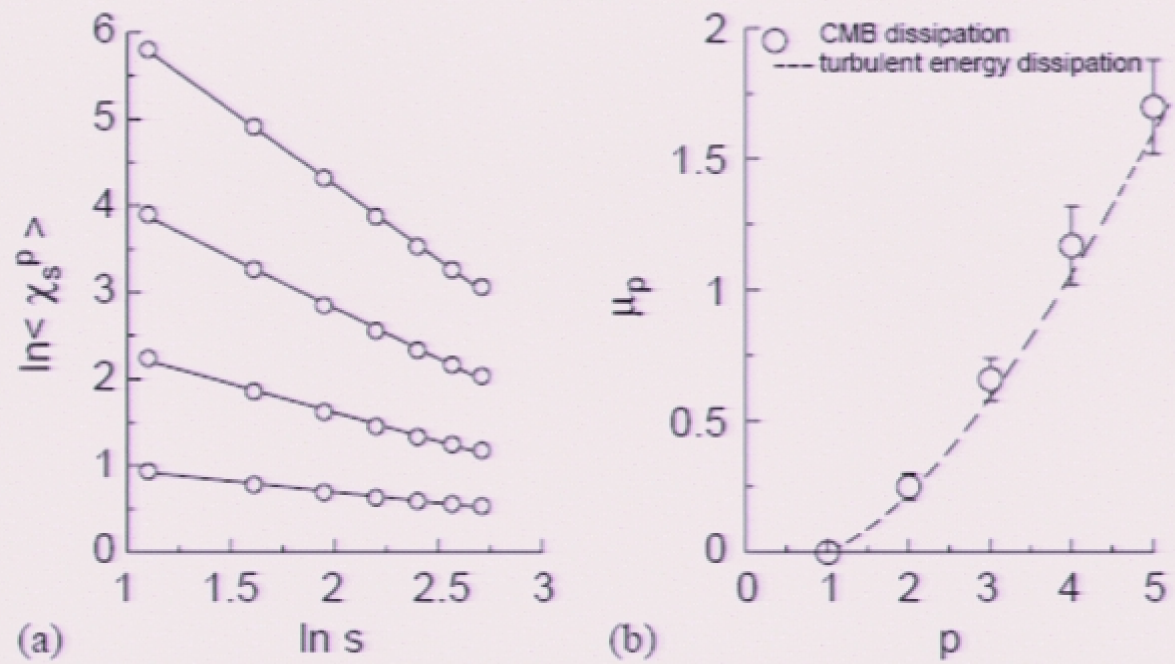
- In the "equilibrium" background sea, plasma condenses into hydrogen, releasing almost uniform radiation
- The sparse, filamentary bursts pass through unaffected since their higher temperature prevents condensation
- Luminous matter has evolved from these bursts already present at T_c

COBE data supports the Bak–Paczuski cosmological scenario

A. Bershadskii

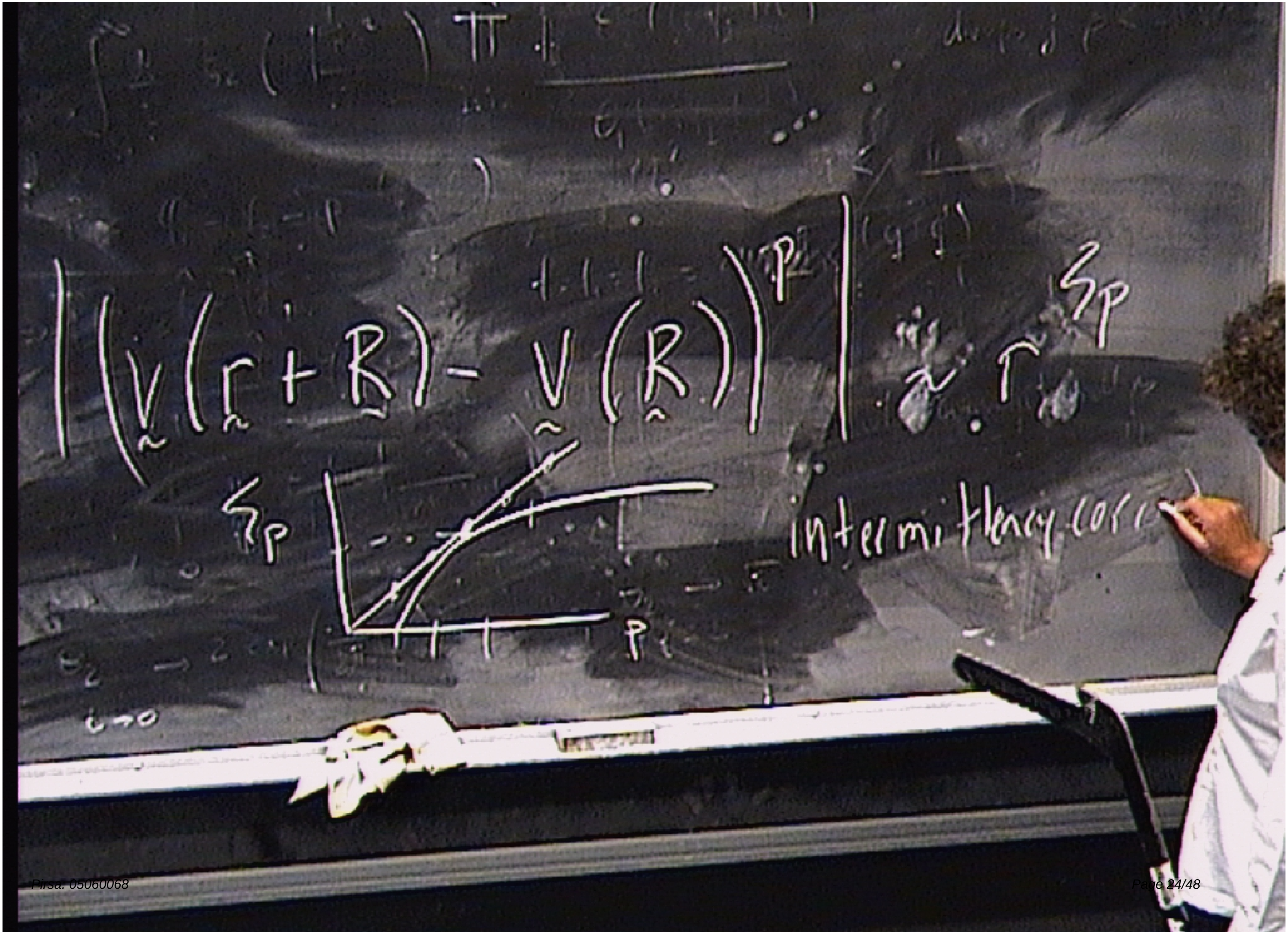
$$\chi_r = \frac{\int_{v_r} (\nabla T)^2 \, \mathrm{d}v}{v_r}$$

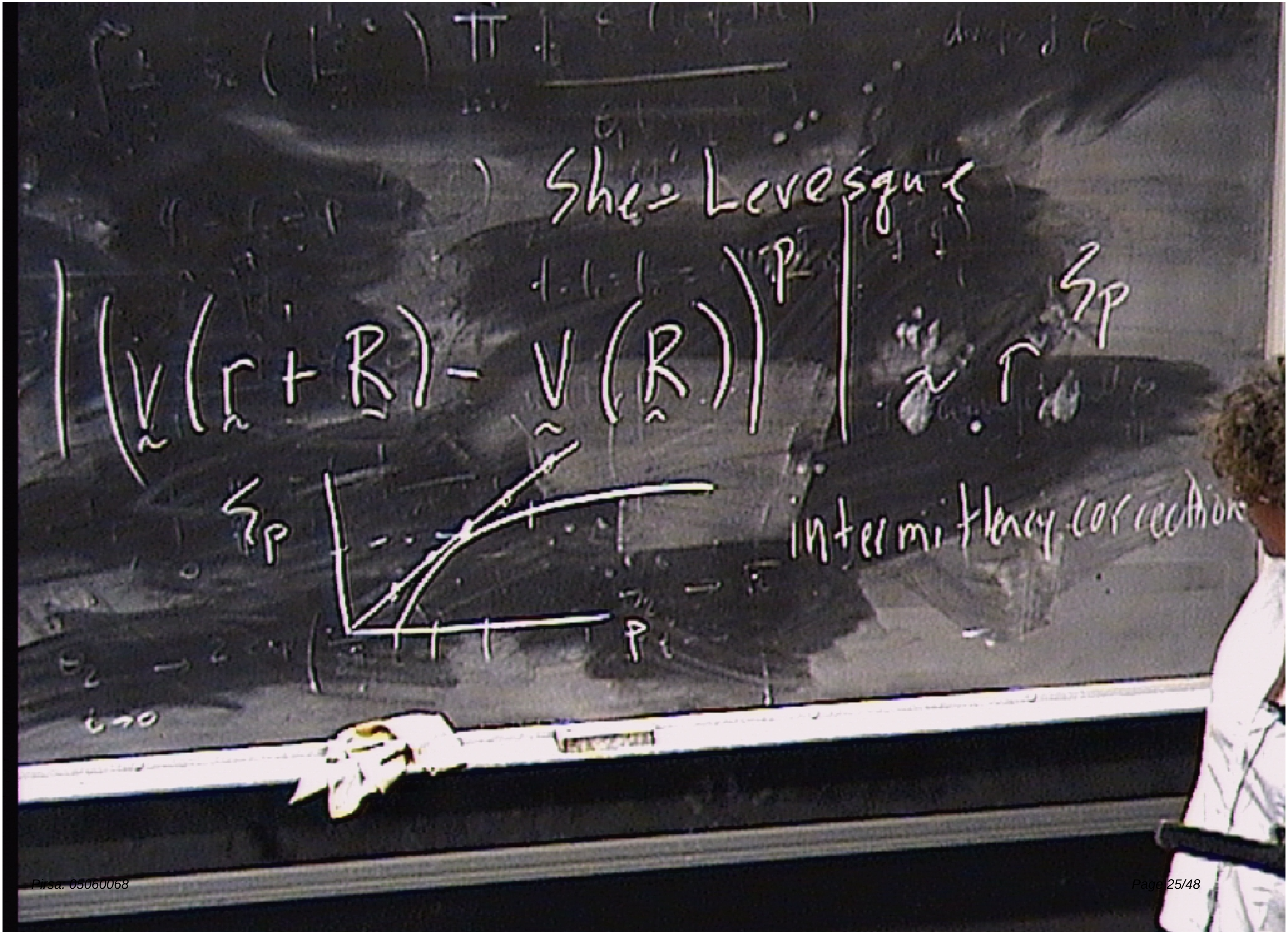
$$\langle \chi_s^p \rangle \sim s^{-\mu_p}$$



Comparison of cmb data with log-Poisson statistics of turbulence

$$\Delta T_r = |T(\mathrm{x}+\mathrm{r}) - T(\mathrm{x})|$$


|(v(r+R) - v(R))^p| ~ r^ζp
ζp
p
intermittency corr


She-Levesque
|(v(r+R) − v(R))^p| ∝ r^ζp
ζp
p
intermittency correction

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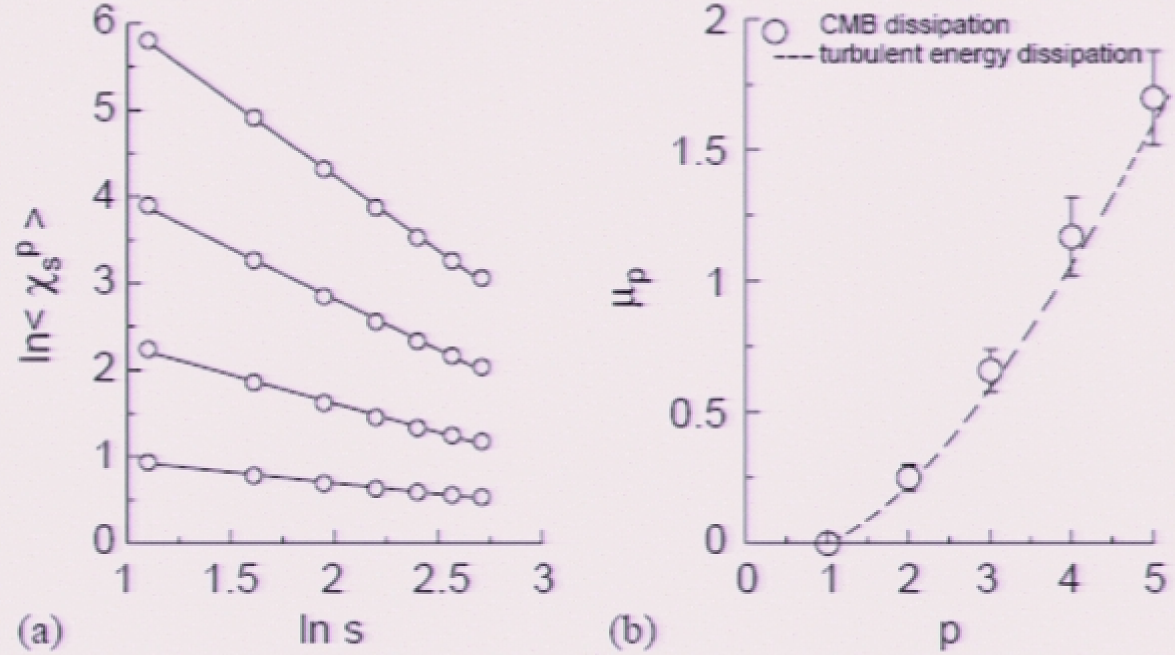

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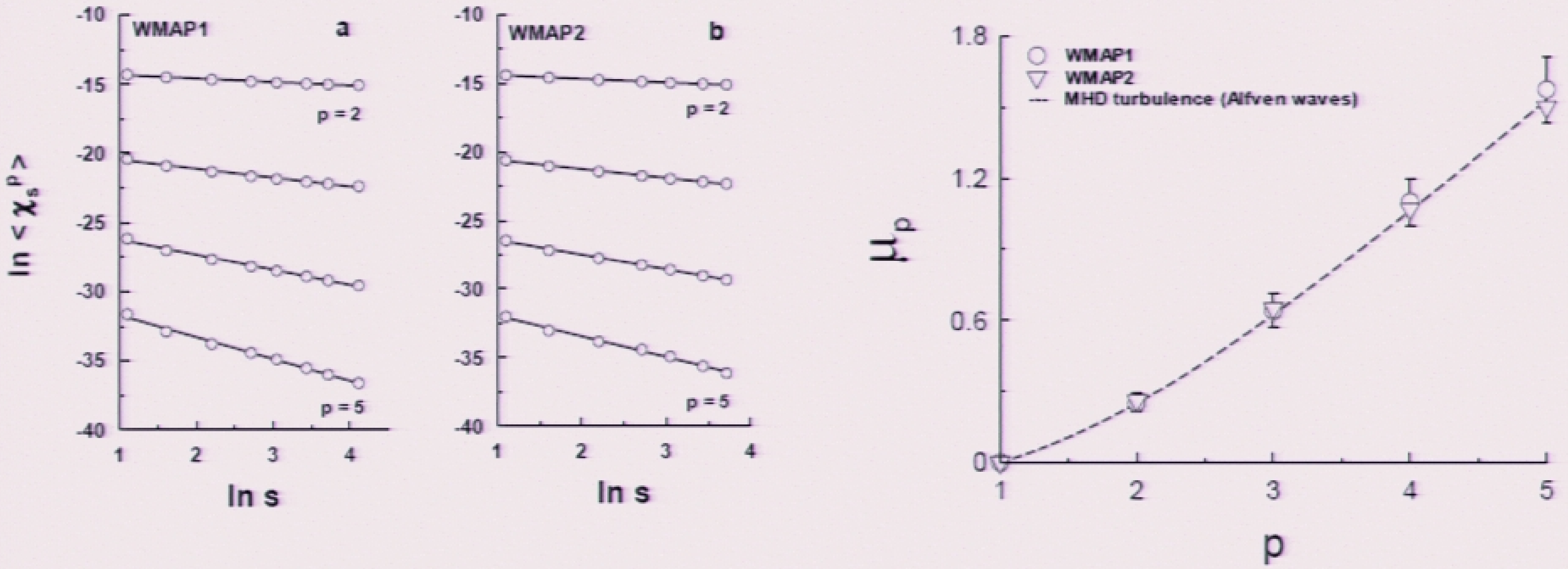
Results for WMAP



Bershadskii and Sreenivasan (2004)

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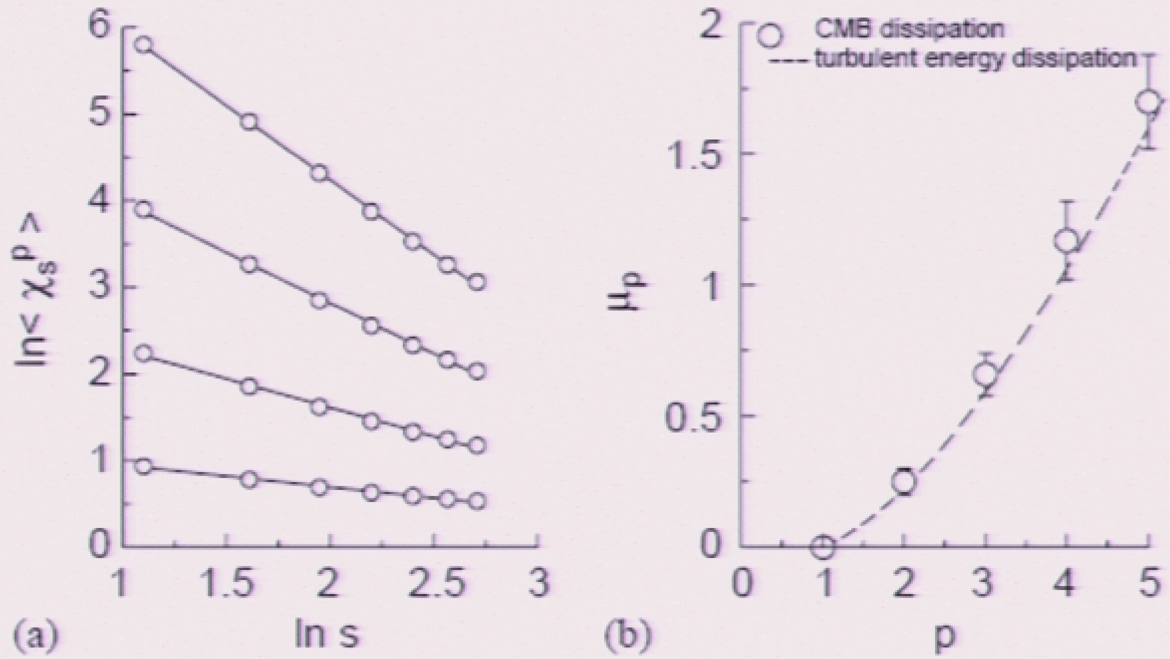

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Chiang and Naselsky tests of ESS: soft pixel method without any cuts

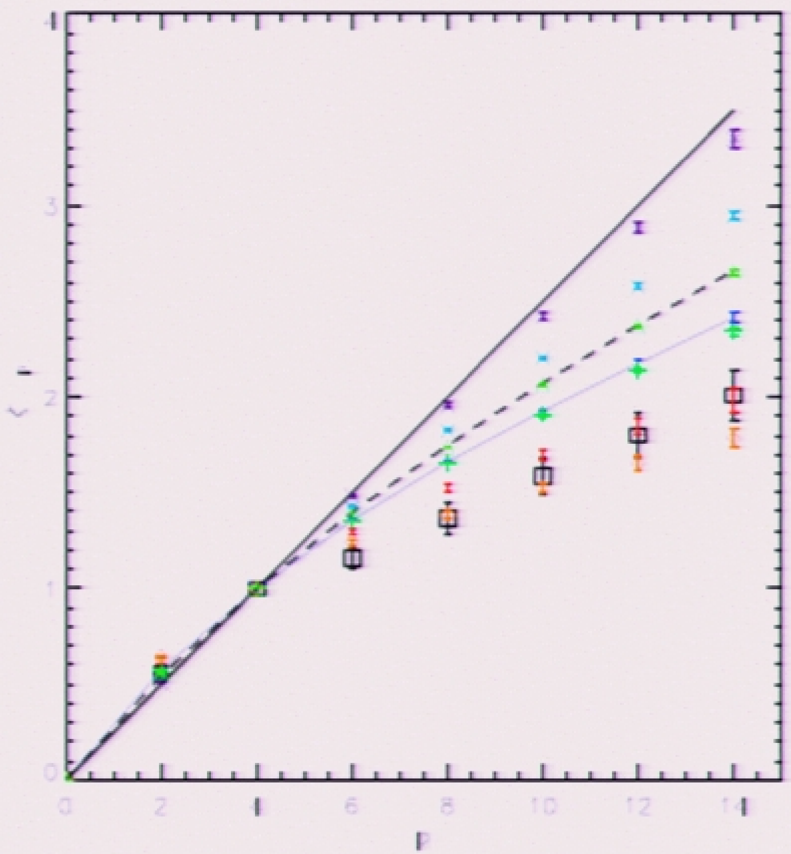


Figure 7. The power spectra of simulated maps and the ζ_p plots. From top to bottom: the ***purple star sign*** is from a simulation with $C_\ell = \ell^{-4}$, the ***light blue cross sign*** is from a simulation with the best-fit ΛCDM power spectrum with random phases, the ***light green triangle sign*** is from the ΛCDM map plus white noise with $C_\ell = 5 \times 10^{-7}$, the ***blue line*** is from a simulation of white noise with constant $C_\ell = 10^{-7}$, whereas the ***green plus sign*** is white noise with constant $C_\ell = 10^{-4}$, ***the red point*** is from a simulation with power spectrum $C_\ell = 10^{-8}\ell^2$, ***the orange diamond sign*** is from a simulation with power spectrum $C_\ell = 10^{-18}\ell^6$. The ***black square sign*** is the WFM (as in Fig.8) as a reference. The dash line is the theoretical curve for the Alfven wave dominated model. Notice that the noise-added ΛCDM map fit the theoretical curve.

Forest Fire Model: An "Ising" Model of Turbulence (Bak, Chen, Tang (1990))

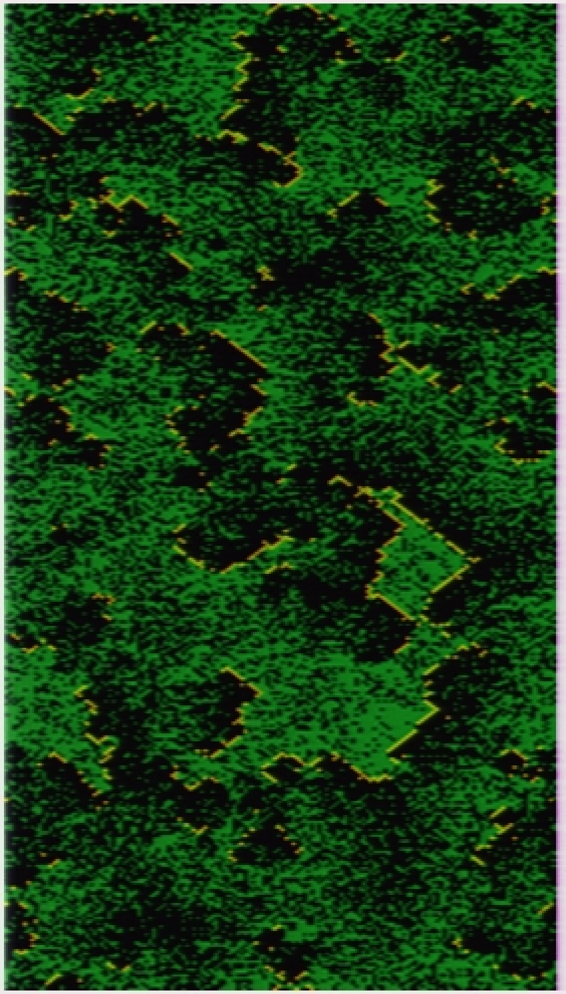
AT EACH TIME STEP

- Fires ignite neighboring trees and burn down, leaving an empty site
- Trees grow randomly on empty sites at rate p

CORRELATED STEADY STATE WITH FIRES WHEN

$$1 < l < \xi \ll L$$

$$\xi = (0.77p)^{-2/3}$$

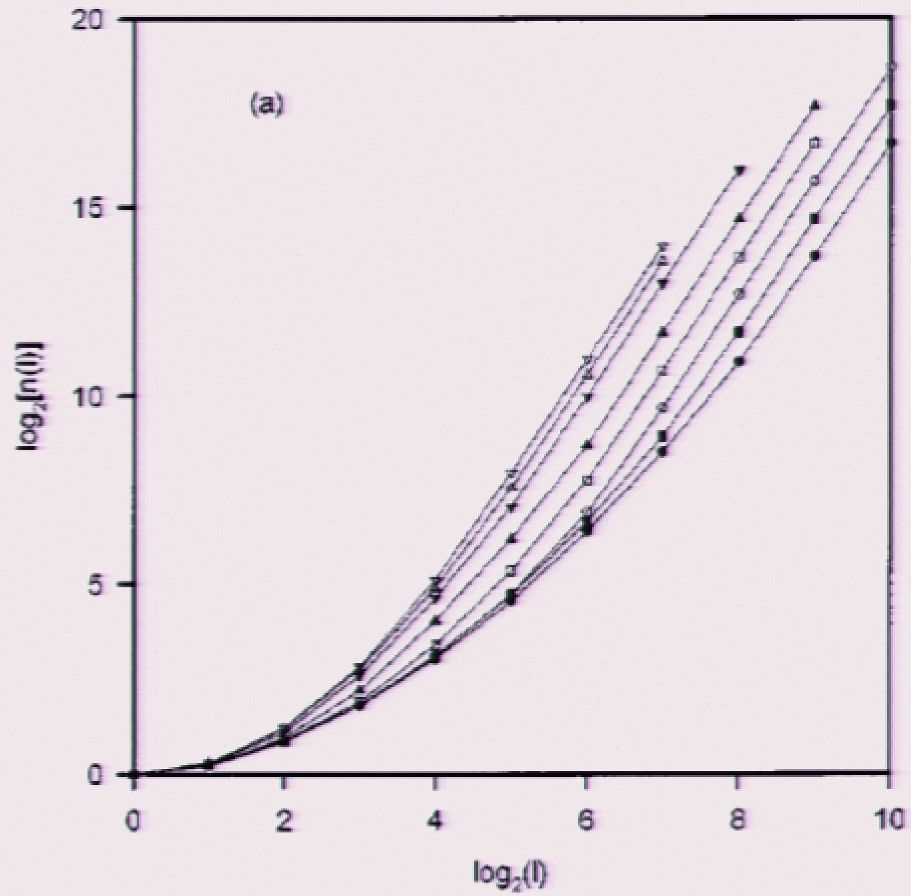


Geometry of dissipation pattern is neither uniform nor fractal in three dimensions

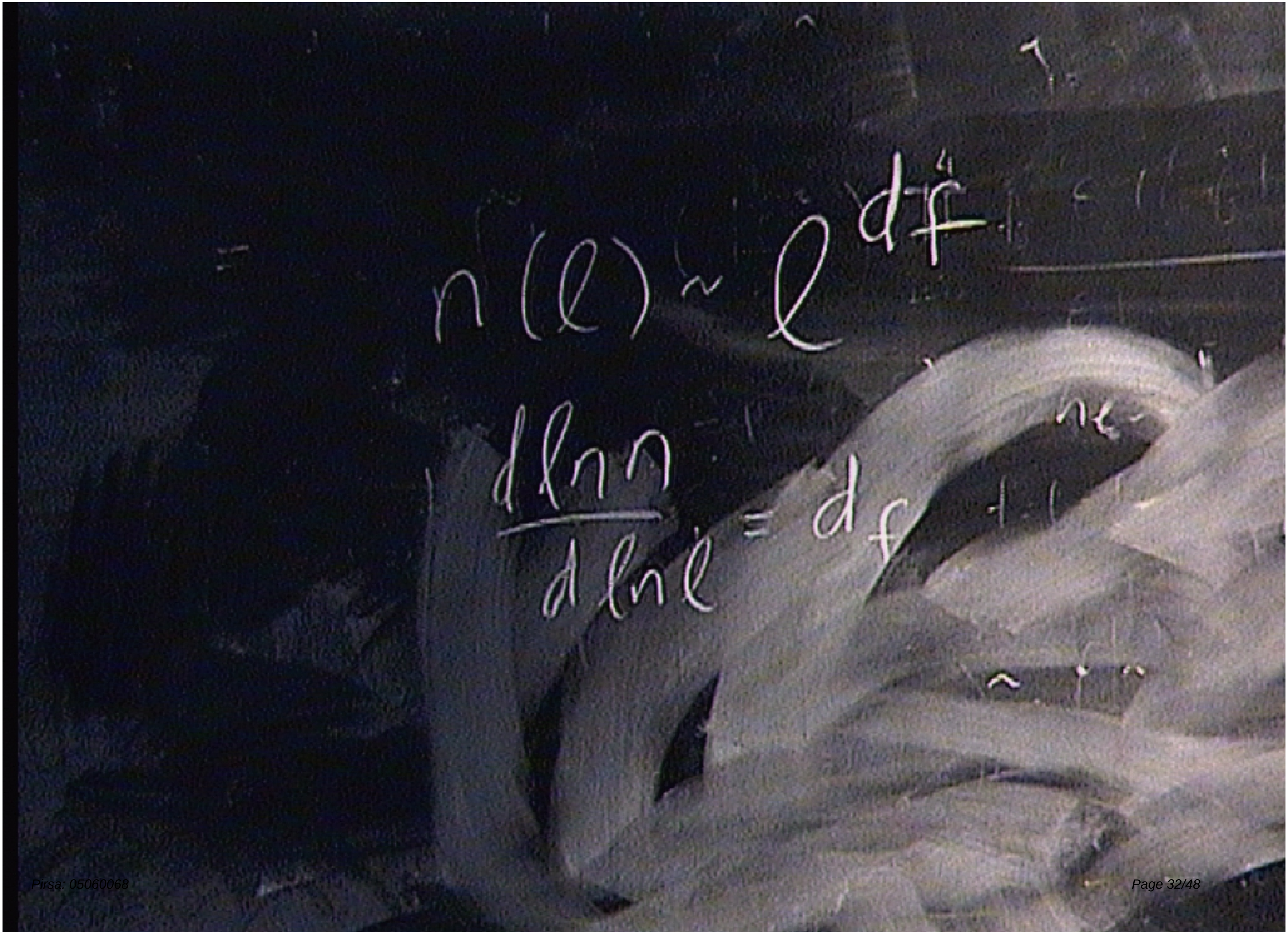
n(l) is the average number of fires within boxes of length *l* that contain fires

$$\ln(n) \sim \left(\frac{3}{2} \frac{\ln(l/l_0)}{\ln(\xi/l_0)} \right) \ln(l/l_0).$$

For lengths smaller than the correlation length



(Chen & Bak (2000))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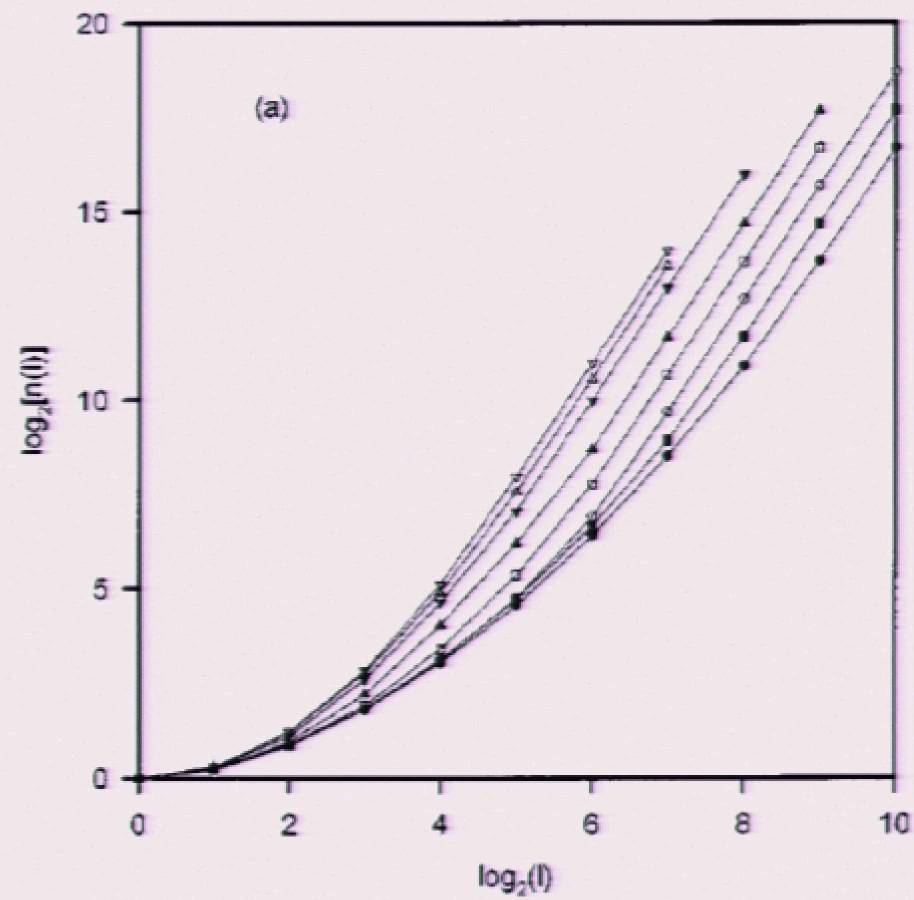


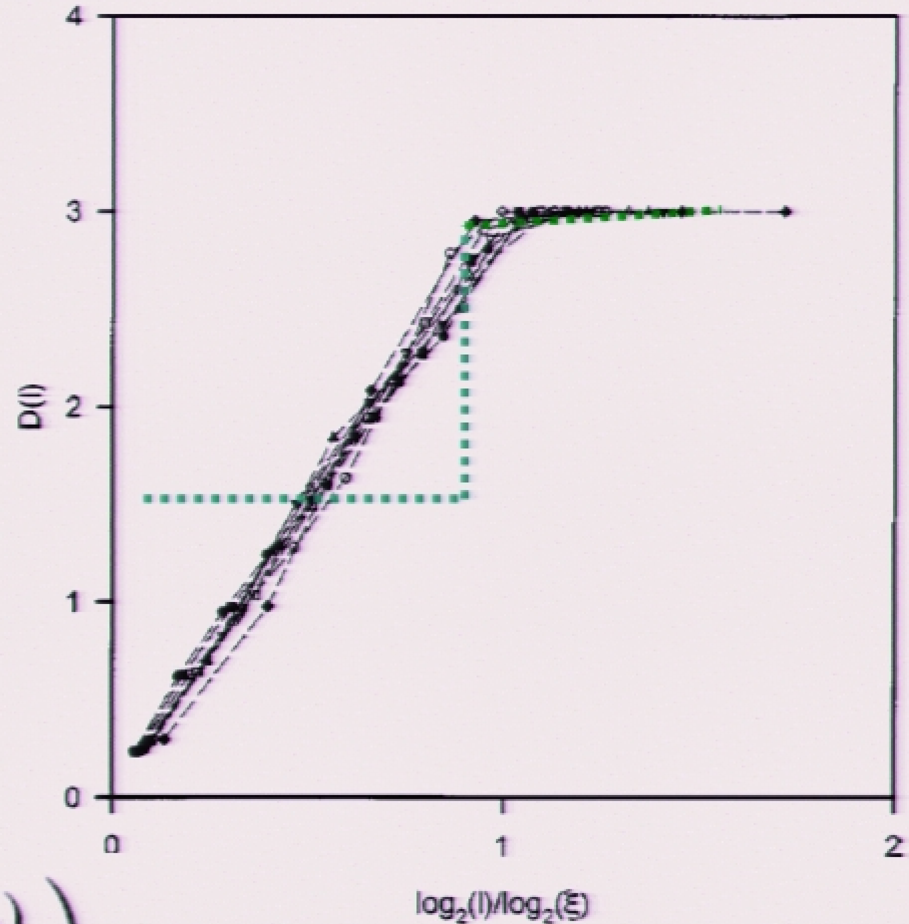
(Chen & Bak (2000))

Length dependent fractal dimension (Chen & Bak (2000))

$10^{-4}<p<10^{-2}$,

L= 128 to 1024

- At small scales point like with D=0
- At larger scales, string like with D=1
- Even larger, sheets with D=2…



$$D(l) = \frac{d\log(n)}{d\log(l)} \sim 3\left(\frac{\log(l/l_0)}{\log(\xi/l_0)}\right).$$

Scale covariance rather than scale invariance

Dissipation is invariant under a transformation that leaves the smallest scale unchanged

$$l \rightarrow l^{\gamma},\ \xi \rightarrow \xi^{\gamma},\ \text{and}\ n(l) \rightarrow n(l)^{\gamma}$$

NOT usual scale dilation

$$\mathbf{u} \rightarrow \lambda \mathbf{u},\ \ \mathbf{x} \rightarrow \lambda^{h} \mathbf{x}.$$

e.g. Galilean vs. Lorentz invariance

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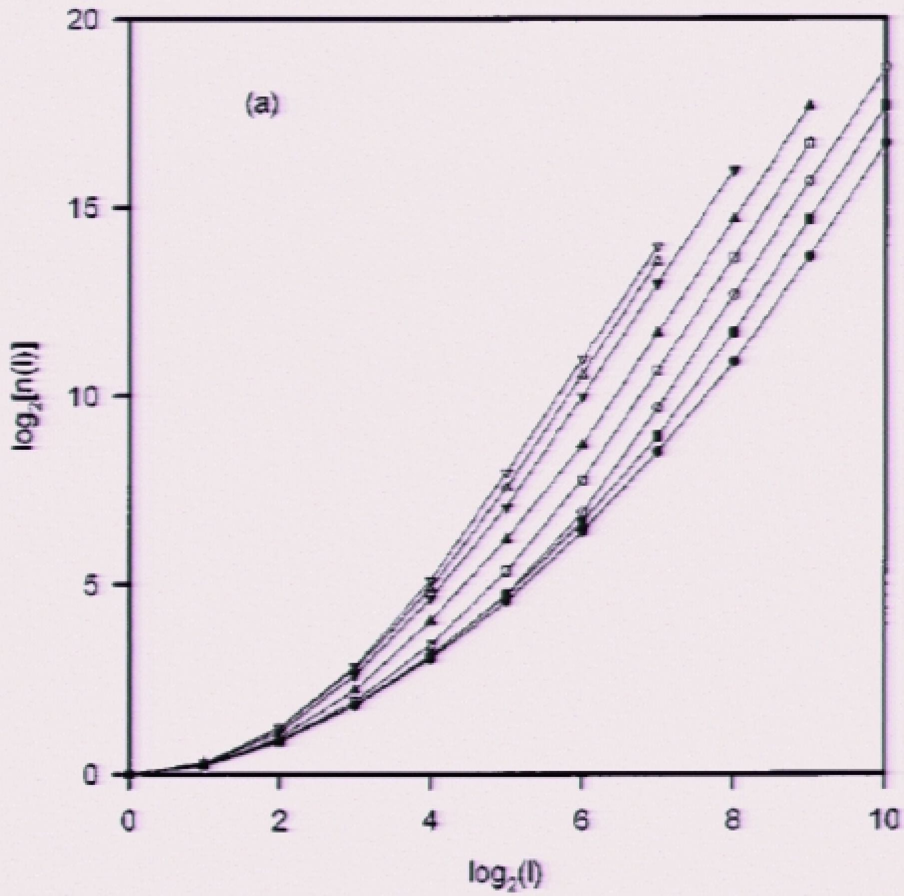

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A theoretical understanding

VOLUME 73, NUMBER 7 PHYSICAL REVIEW LETTERS 15 AUGUST 1994

Intermittency in Fully Developed Turbulence: Log-Poisson Statistics and Generalized Scale Covariance

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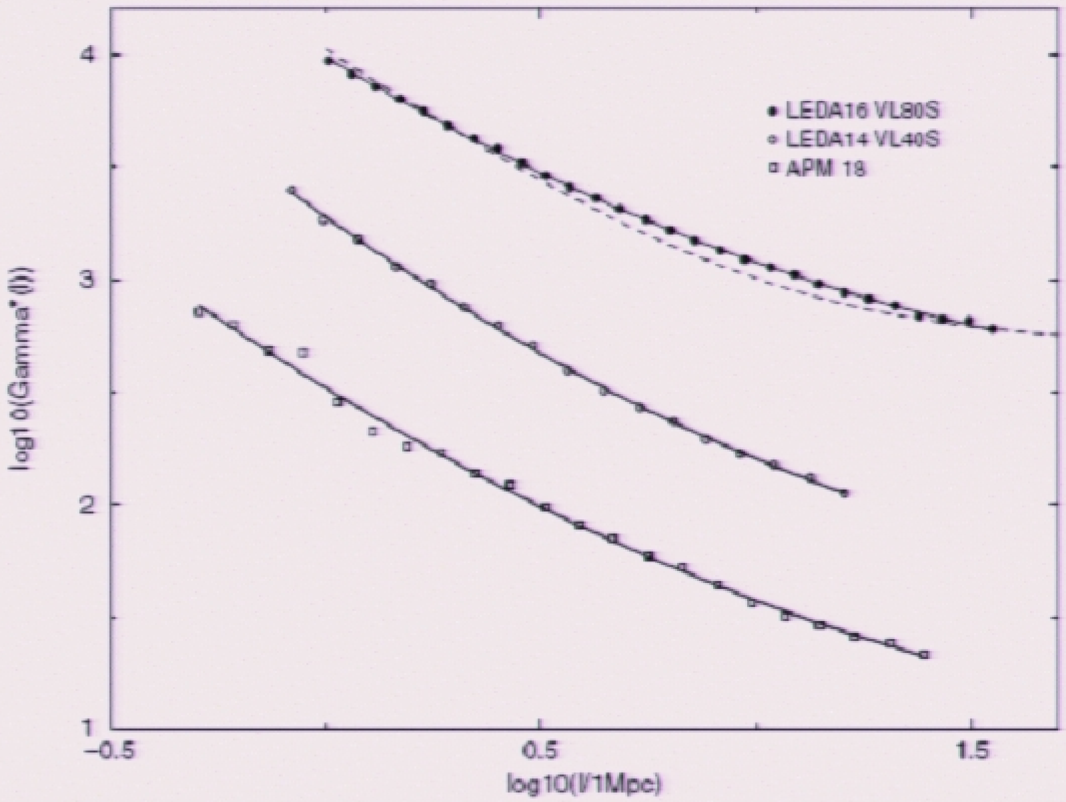
Centre National de la Recherche Scientifique, UPR 182, Commissariat à l'Energie Atomique, Direction des Sciences de la Matiere, Departement d'Astrophysique, Physique de Particules, Physique Nucleaire et d'Instrumentation Associee, Service d'Astrophysique, Centre d'Etudes de Saclay, F-91191 Gif sur Yvette, France, and Centre National de la Recherche Scientifique, URA 285, Observatoire Midi Pyrénées, 14 avenue Belin, F-31400 Toulouse, France
(Received 3 March 1994)

Some properties of a model of intermittency in fully developed turbulence due to She and Lévêque [Phys. Rev. Lett. **72**, 336 (1994)] are explored. The probability functions solution of the model is shown to be simply related to the log-Poisson statistics of local nondimensional energy dissipation. It is also shown that the intermittency obtained by She and Lévêque can be interpreted as the consequence of the scale covariance of the energy dissipation. Based on these observations, a new picture of turbulence is presented, in which scale covariance plays a central role.

Analysis of Galaxy Maps



$$\log[\Gamma^*(l)] \sim \left[\frac{3}{2} \left(\frac{\log(l/l_0)}{\log(\xi/l_0)} \right) - 3 \right] \log(l/l_0).$$

scale covariant

$$\Gamma^*(l) \sim \langle n \rangle [1 + g(l)], \quad g(l) = (r_0/l)^\gamma$$

scale invariant

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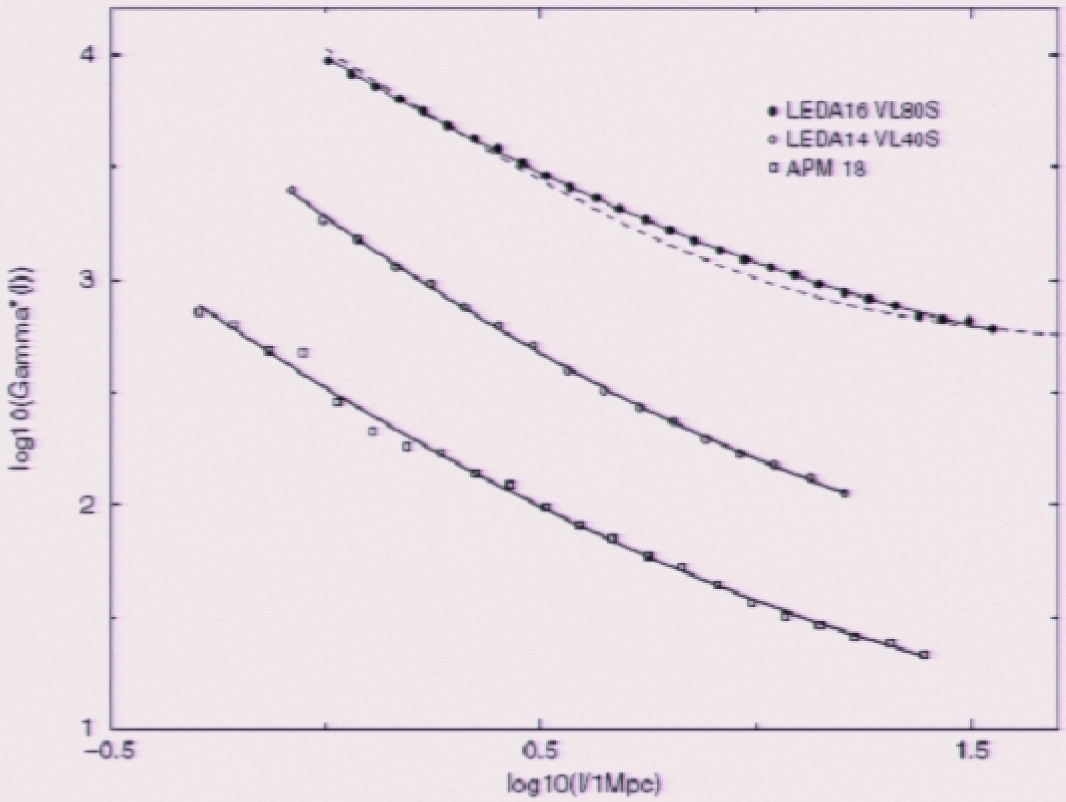

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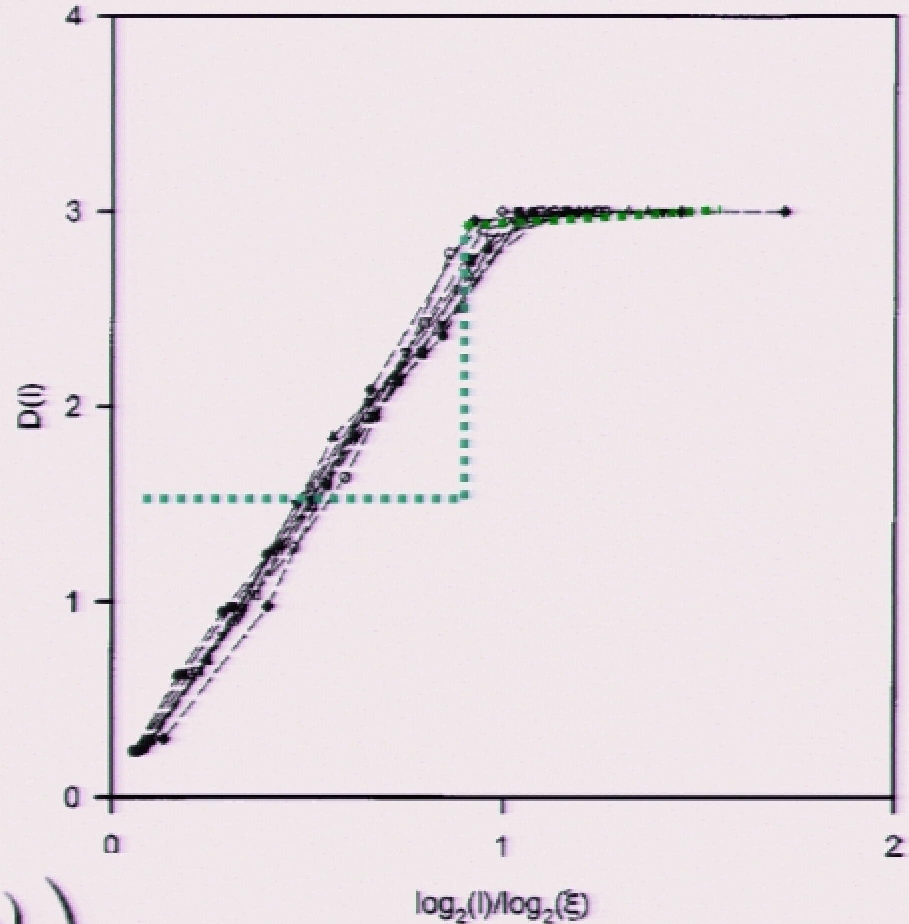

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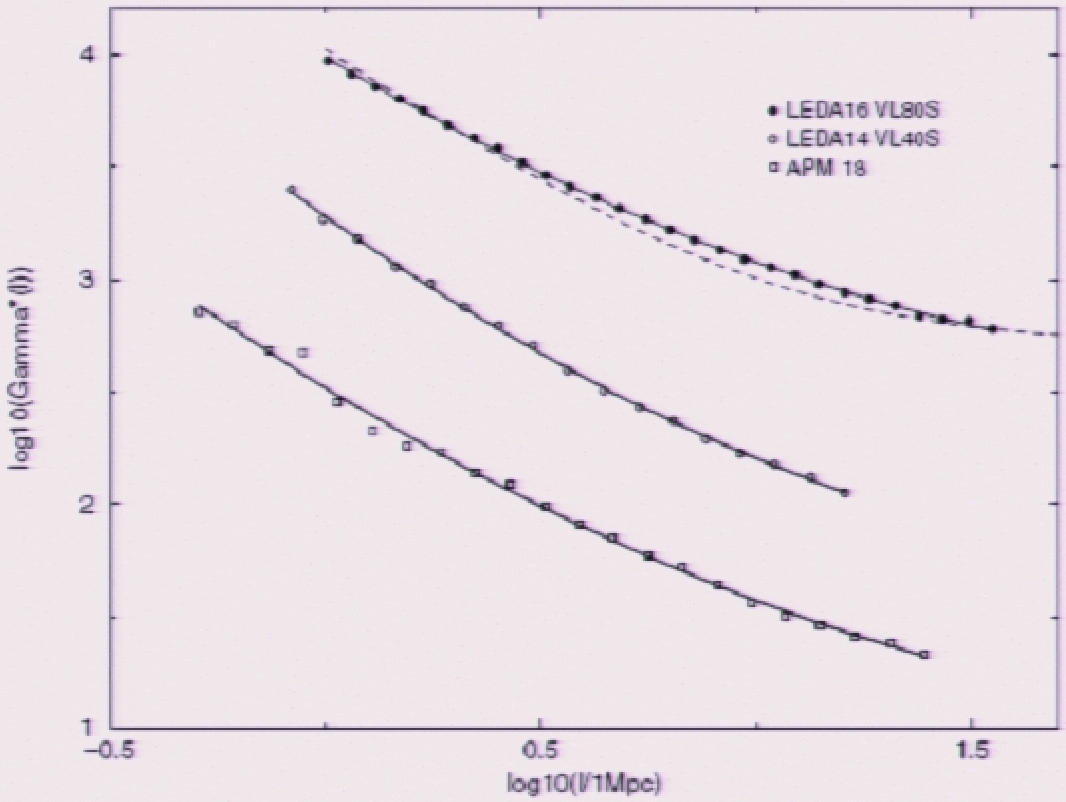

$$\log[\Gamma^*(l)] \sim \left\lfloor \frac{3}{2}\left(\frac{\log(l/l_0)}{\log(\xi/l_0)}\right) - 3 \right\rfloor \log(l/l_0).$$ scale covariant

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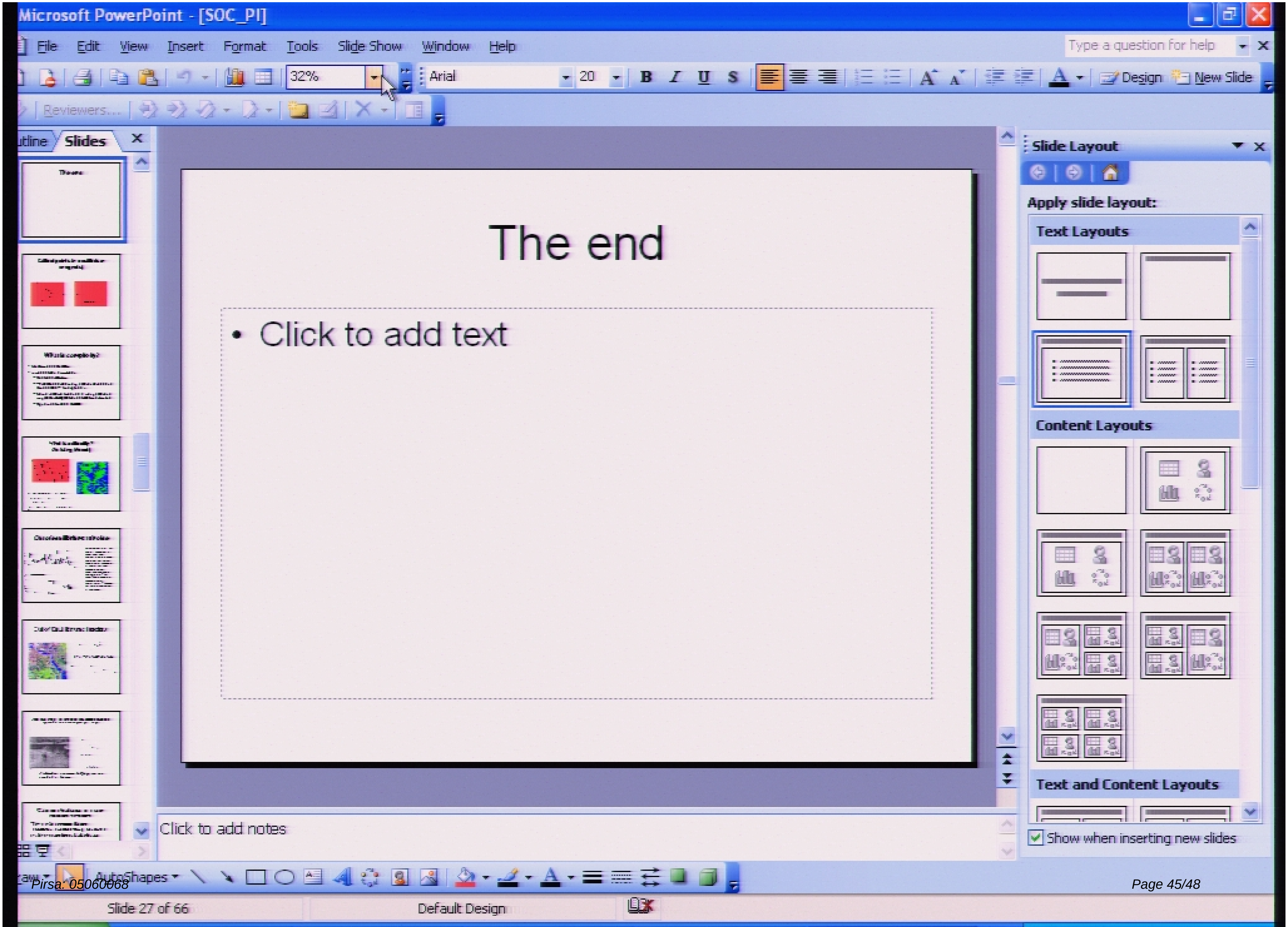
The end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Apply slide layout:
Text Layouts
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AutoShapes
Slide 27 of 66
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Small-scale microwave background anisotropies arising from tangled primordial magnetic fields

Kandaswamy Subramanian[1★] and John D. Barrow[2]

[1]*Inter University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411 007, India*

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ABSTRACT

An inhomogeneous cosmological magnetic field creates vortical perturbations that survive damping on much smaller scales than compressional modes. This ensures that there is no s cut-off in anisotropy on arcminute scales. As we had pointed out earlier, tangled magı fields, if they exist, will then be a potentially important contributor to small-angular-s cosmic microwave background radiation anisotropies. Several ongoing and new experim are expected to probe the very small angular scales, corresponding to multipoles with $l > 1$ In view of this observational focus, we revisit the predicted signals arising from primo tangled magnetic fields, for different spectra and different cosmological parameters. We identify a new regime, where the photon mean-free path exceeds the scale of the perturba which dominates the predicted signal at very high l. A scale-invariant spectrum of tan fields which redshifts to a present value $B_0 = 3 \times 10^{-9}$ G produces temperature anisotrc at the 10-μK level between $l \sim 1000$ and 3000. Larger signals result if the universe is lam dominated, if the baryon density is larger, or if the spectral index of magnetic tangles is ste $n > -3$. The signal will also have non-Gaussian statistics. We predict the distinctive form o increased power expected in the microwave background at high l in the presence of signifi

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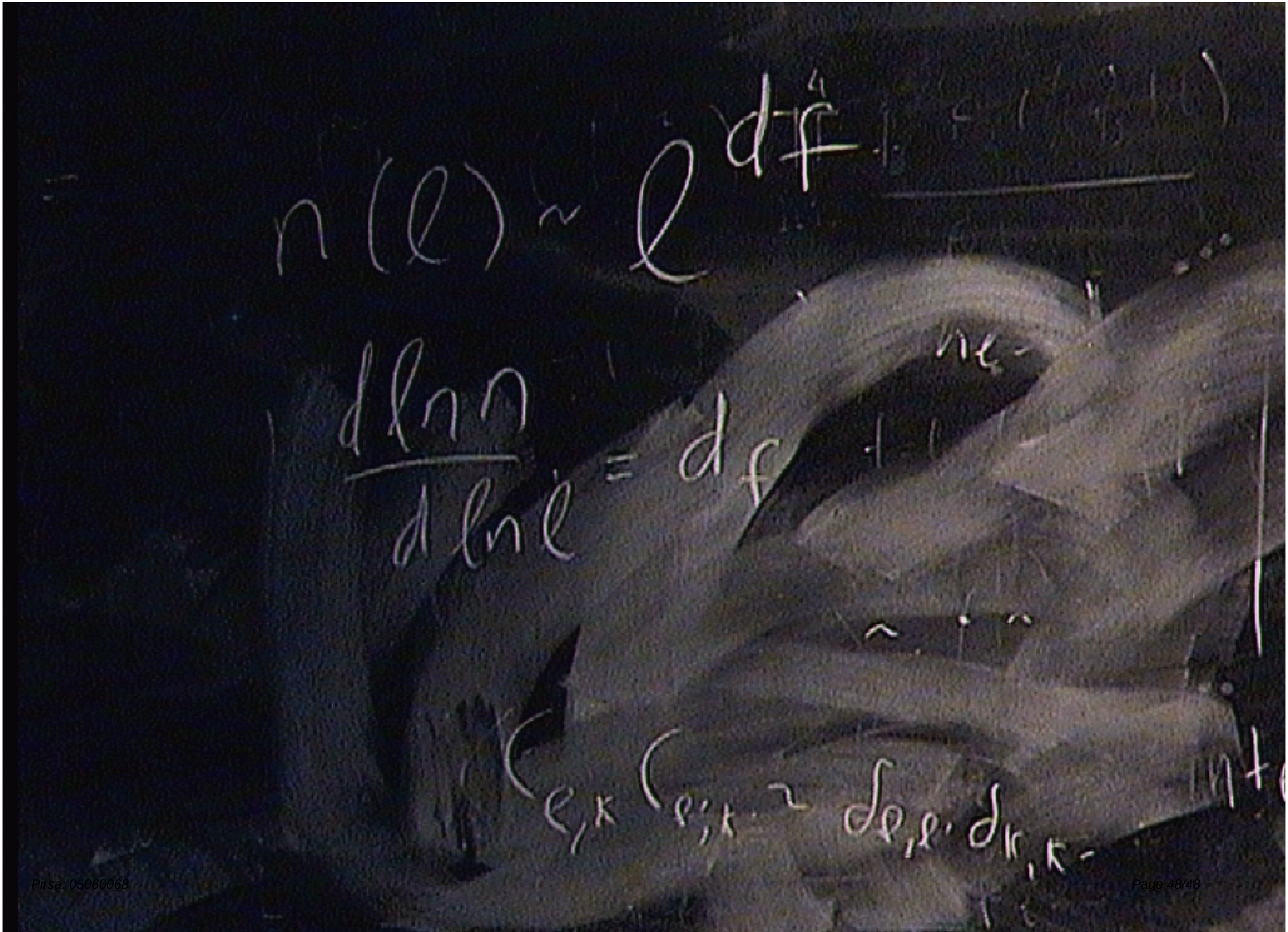
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