Title: Photons and Quantum Gravity in Astrophysics

Date: Oct 22, 2012 04:30 PM

URL: http://pirsa.org/12100085

Abstract: Asymptotically safe inflation and CMB polarization
The presence of complex critical exponents in the scaling behavior of the Newton constant and Cosmological constant has dramatic consequences at the inflation scale. In particular an infinite number of unstable de-Sitter vacua emerges from an effective quantum gravitational action. In this framework, the possibility of detecting specific signaturesof a non-gaussian fixed point of the gravitational interactions in the CMB polarization spectrum will then be discussed.

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Cosmological
windows such as CMB polarization and 21cm redshift surveys to probe
Planck-scale physics

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Quantum
gravity and a chiral signature in gravity waves
I show how quantum gravity could lead to a chiral signature in the graviational wave background, proportional to the imaginary part of the Immirzi parameter. This would leave a distinctive imprint in the polarization of the cosmic microwave background. I will discuss how this isue is closely related to that of identifying the ground of base state for quantum gravity.

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A Possible Bound on Spectral
Dispersion from

Fermi-Detected
Gamma Ray Burst 090510A
Three photons spanning about 30 GeV arrived within about one millisecond from the Fermi-detected GRB 090510A at a redshift of about 0.9. Although conceivably a > 3Ã•Æ’ statistical fluctuation when taken at face value this photon bunch -- quite possibly a classic GRB pulse -- leads to a relatively tight bound on the ability of our universe to disperse high energy photons. Specifically given a generic dispersion relation where the time delay is proportional to the photon energy to the first power the limit on the dispersion strength is k1 < 1.61Ãƒâ€”10-5 sec Gpc-1 GeV-1. In the context of some theories of quantum gravity this conservative bound translates into an minimum energy scale greater than 525 m_Planck suggesting that spacetime is smooth at energies perhaps three orders of magnitude over the Planck mass.

Quantum Gravity in Astrophysics

quest for a falsifiable theory

Why Astrophysics?

- We only need to use Quantum Gravity in extreme conditions

Why Astrophysics?

- We only need to use Quantum Gravity in extreme conditions
- Astrophysics and Cosmology provide observable extremes that are impossible to achieve in the lab

1-Quantum nature of gravitational waves

- Nonquantum gravity!

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- Amplitude of inflationary GW's

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- Helicity of inflationary GW's

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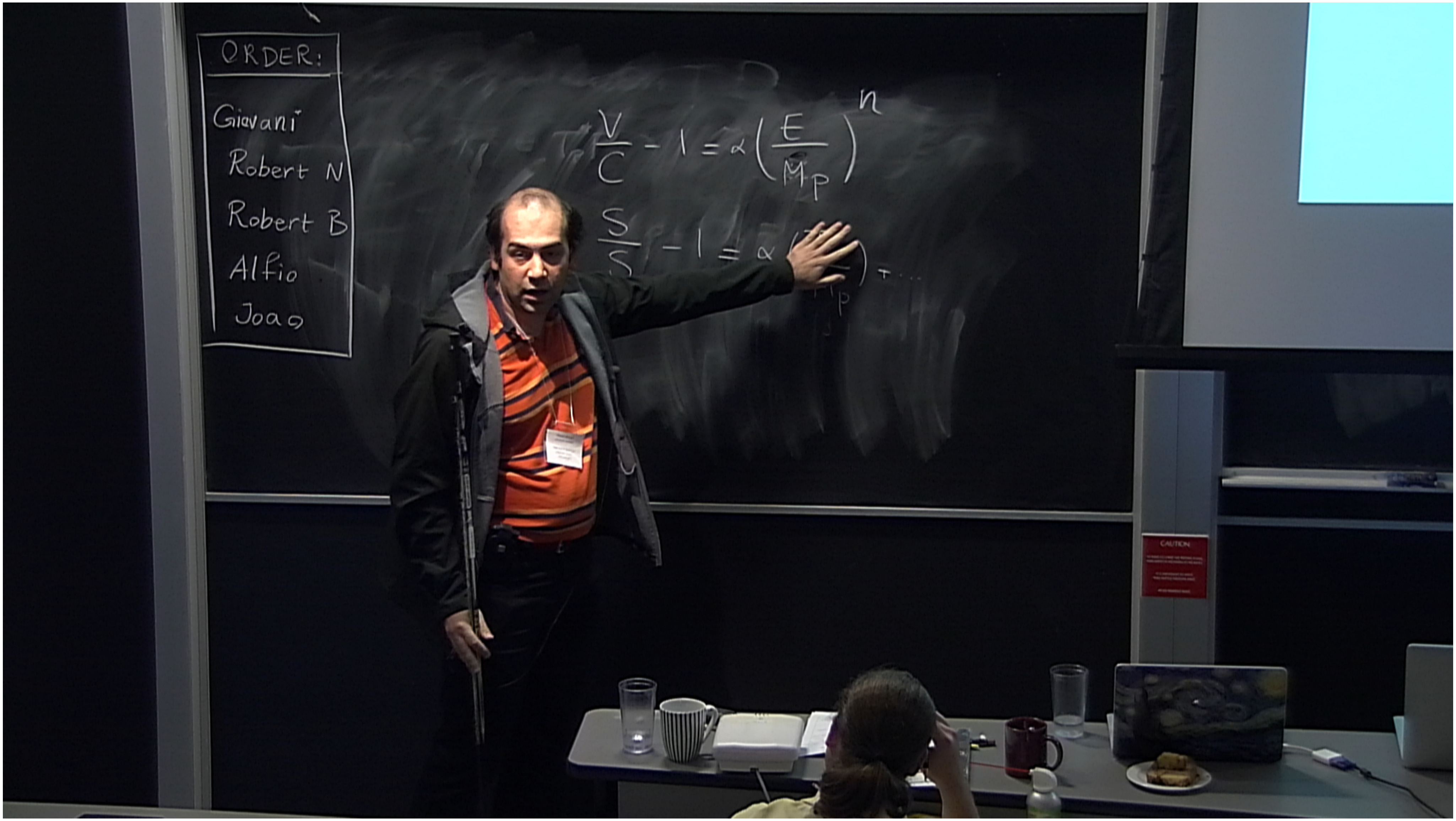
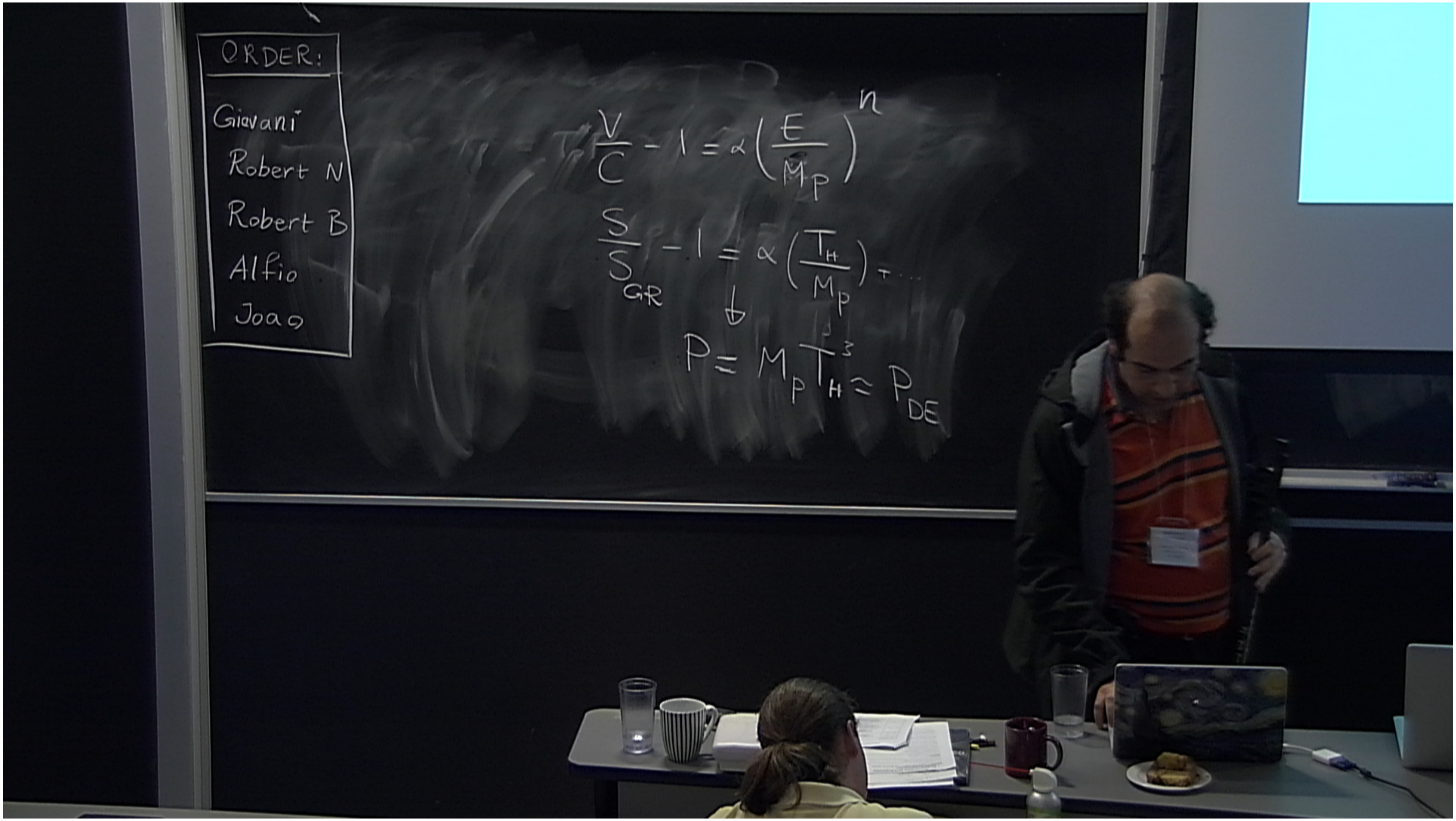

ORDER:
Giovani
Robert N
Robert B
Alfio
Joao
$\frac{V}{C} - 1 = \alpha \left(\frac{E}{M_p} \right)^n$


ORDER:
Giovani
Robert N
Robert B
Alfio
Joao
V/C - 1 = α(E/Mp)^n
S/SGR - 1 = α(TH/Mp) + ...
P = Mp TH^3 ≃ PDE

3-What does QG entail?

- Cosmic Strings (string theory)

3-What does QG entail?

- Cosmic Strings (string theory)
- Aether (Horava-Lifshitz gravity)
- Diffusion (causal sets, non-commutativity)

Implications of Planck-scale worldline fuzziness for quasar images and GRBs

Perimeter 22oct2012

Giovanni Amelino-Camelia
University of Rome "La Sapienza"

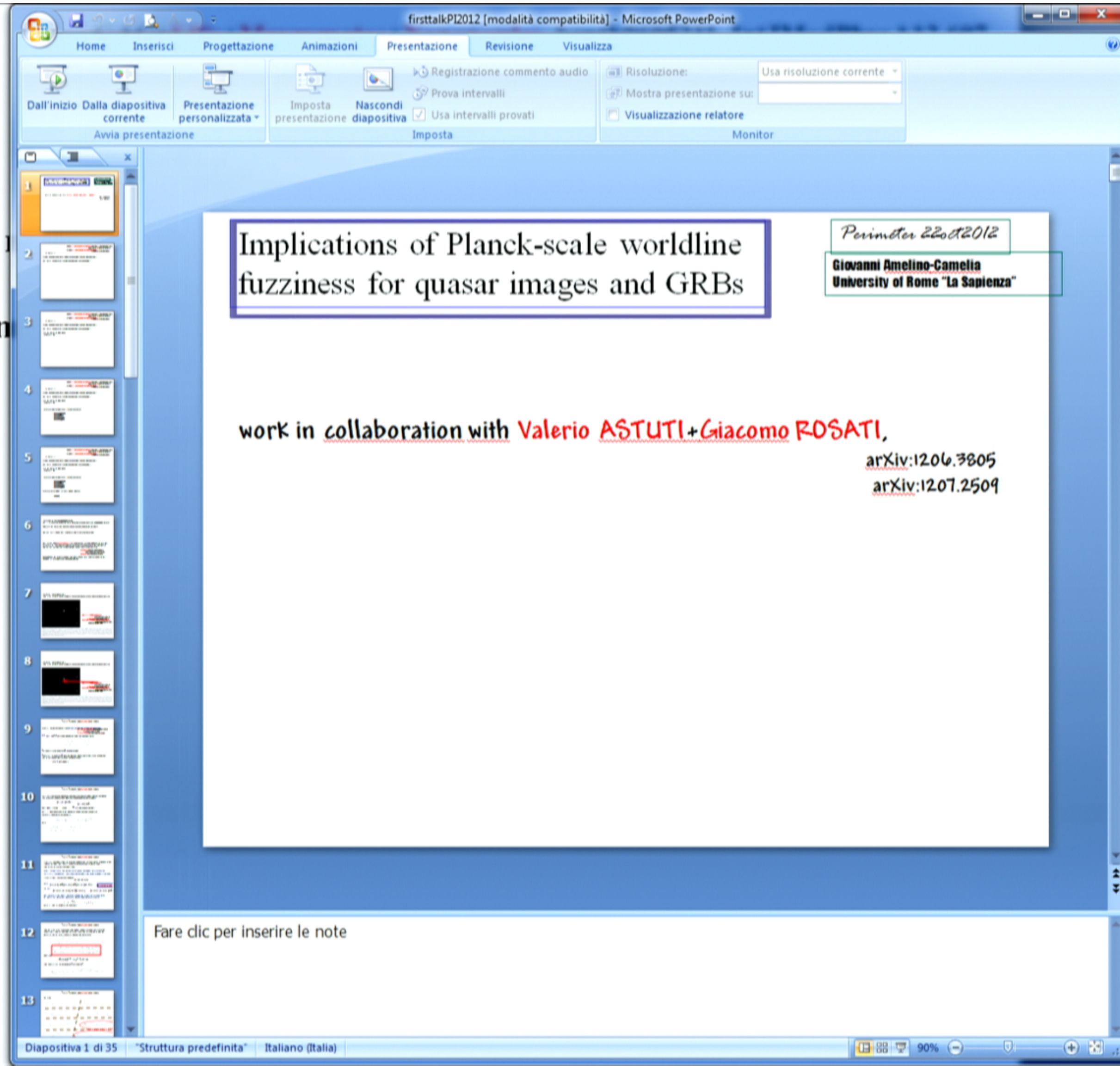
work in collaboration with Valerio ASTUTI+Giacomo ROSATI,

arXiv:1206.3805
arXiv:1207.2509

15 years!!!!!!

crude phenomenological r

but with abundant data n



GAC+Ellis+Mavromatos+Nanopoulos, hepth9605211, IntJModPhysA12,607
GAC, grqc9611016,PhysLettB392,283
GAC+Ellis+Mavromatos+Nanopoulos+Sarkar,
astroph9712103,Nature393,763

15 years!!!!!!

crude phenomenological model of in-vacuo dispersion proved useful...

but with abundant data more refined models will be needed....

are we going to need them?
probably not:

QG-relevant GRBS in first 13 months of Fermi

GRB080916C
GRB090510
GRB090902B
GRB090926A

QG-relevant GRBS in last 37 months of Fermi

NONE

in-vacuo dispersion plausible for QG

but a Planck-scale contribution to worldline fuzziness appears to be inevitable for QG

how can we formalize Planck-scale contribution to worldline fuzziness?

notice that it would play a significant role in the analysis of GRBs

our setup (GAC+ASTUTI+ROSATI, arXiv:1206.3805;arXiv:1207.2509)produces the first ever example of a quantum-spacetime picture predicting Planck-scale contributions to worldline fuzziness that grow along the way, as the particle propagates

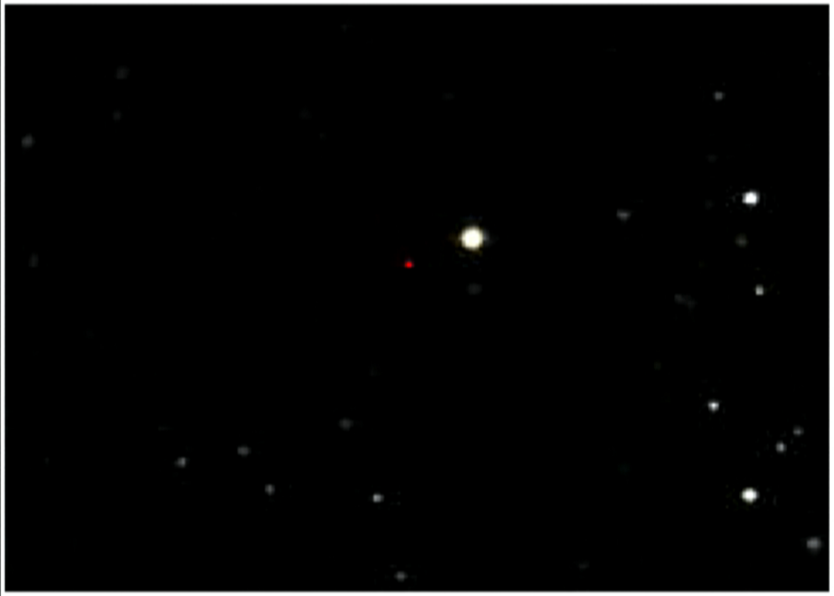
Ng+VanDam,ModPhysLettA9(1994)335

GAC, ModPhysLettA9(1994)3415

Lieu+Hillman,AstrophysJ585(2003)L77

dependence on propagation distance opens the way to an amplification of the sort needed in Quantum Gravity Phenomenology relevant for GRB analysis

and also relevant for searches of Planck-scale effects blurring images of distant quasars



Christiansen+Ng+VanDam, PhysRevLett96(2006)051301

Steinbring, AstrophysJ655(2007)714

Tamburini+Cuofano+DellaValle+Gilmozzi, AstronAstrophys533(2011)A71

GAC,Nature478(2011)466

Figure 1: Composite image created from the Sloan Digital Sky Survey and the UKIRT Infrared Deep Sky Survey. The quasar ULAS J1120+0641, at redshift of 7.1, appears as a faint red dot close to the center. Observations of quasars by ground telescopes must handle the effects of image blurring produced when light crosses the atmosphere. Even space telescopes would be affected by some image blurring, according to heuristic descriptions of gravity-induced foaminess of spacetime. Heuristics is however not providing reliable estimates of the magnitude and form of this novel blurring effect. For this we here seek the guidance of a form of spacetime noncommutativity inspired by rigorous results within 3D quantum gravity.

this sets the stage for addressing the most crucial long-standing issue for the study of the kappa-Minkowski (and other similar) noncommutative spacetime

$$[x_j, x_0] = i\ell x_j \qquad [x_j, x_k] = 0$$

what does it mean? [x,t]≠0? "t" is an evolution parameter!!!

well it does make sense on the kinematical Hilbert space of the covariant formulation of quantum mechanics

$$\hat{x}_0 = \hat{q}_0 \ , \qquad \hat{x}_1 = \hat{q}_1 e^{\ell \hat{\pi}_0}$$

with

$$[\hat{\pi}_0, \hat{q}_0] = i \ , \qquad [\hat{\pi}_0, \hat{q}_1] = 0$$
$$[\hat{\pi}_1, \hat{q}_0] = 0 \ , \qquad [\hat{\pi}_1, \hat{q}_1] = -i$$

"fuzzy1" kinematics: GAC+Astuti+Rosati,arXiv:1206.3805

and we also give a representation on our Hilbert space of the translation generators (which combine with the translation parameters to give the description of translation map between two observers)

$$P_\mu \triangleright [\hat{x}_1, \hat{x}_0] = i\ell P_\mu \triangleright \hat{x}_1$$

$$P_\mu \triangleright f(\hat{x})g(\hat{x}) = (P_\mu \triangleright f(\hat{x}))\, g(\hat{x}) + \left(e^{-\ell \delta^1_\mu P_0} \triangleright f(\hat{x})\right)(P_\mu \triangleright g(\hat{x}))$$

$$P_0 \triangleright f(\hat{x}_0, \hat{x}_1) \longleftrightarrow [\hat{\pi}_0, f(\hat{q}_0, \hat{q}_1 e^{\ell \hat{\pi}_0})]$$

$$P_1 \triangleright f(\hat{x}_0, \hat{x}_1) \longleftrightarrow e^{-\ell \hat{\pi}_0}[\hat{\pi}_1, f(\hat{q}_0, \hat{q}_1 e^{\ell \hat{\pi}_0})]$$

now take

$$Bob = [\mathbf{1} - i\varepsilon_\mu P^\mu]\, Alice$$

and specialize to the following "fuzzy points"

$$\Psi_{\overline{q}_0, \overline{q}_1}(\pi_\mu; \overline{\pi}_\mu, \sigma_\mu) = N e^{-\frac{(\pi_0 - \overline{\pi}_0)^2}{4\sigma_0^2} - \frac{(\pi_1 - \overline{\pi}_1)^2}{4\sigma_1^2}} e^{i\pi_0 \bar{q}_0 - i\pi_1 \bar{q}_1}$$

“fuzzy1” kinematics: GAC+Astuti+Rosati,arXiv:1206.3805

we find

$$\langle x_0 \rangle = \overline{q}_0$$

$$\langle \mathcal{T}_{a^\mu} \triangleright x_0 \rangle = \overline{q}_0 - a_0$$

$$\delta x_0 = \frac{1}{2\sigma_0}$$

$$\delta\left(\mathcal{T}_{a^\mu} \triangleright x_0\right) = \frac{1}{2\sigma_0}$$

$$\langle x_1 \rangle = \langle q_1 \rangle \left\langle e^{\ell \pi_0} \right\rangle = \overline{q}_1 e^{\ell \bar{\pi}_0} e^{-\frac{\ell^2 \sigma_0^2}{2}}$$

$$\langle \mathcal{T}_{a^\mu} \triangleright x_1 \rangle = \left(\overline{q}_1 - a_1\right) e^{\ell \overline{\pi}_0} e^{-\frac{\ell^2 \sigma_0^2}{2}}$$

$$\delta x_1 = e^{\ell \bar{\pi}_0} \left[\frac{1}{4\sigma_1^2} + \overline{q}_1^2 \left(1 - e^{-\ell^2 \sigma_0^2}\right)\right]^{1/2}$$

$$\delta(\mathcal{T}_{a^\mu} \triangleright x_1) = e^{\ell \overline{\pi}_0} \left[\frac{1}{4\sigma_1^2} + (\overline{q}_1 - a_1)^2 \left(1 - e^{-\ell^2 \sigma_0^2}\right)\right]^{1/2}.$$

relative locality in a quantum spacetime!!!

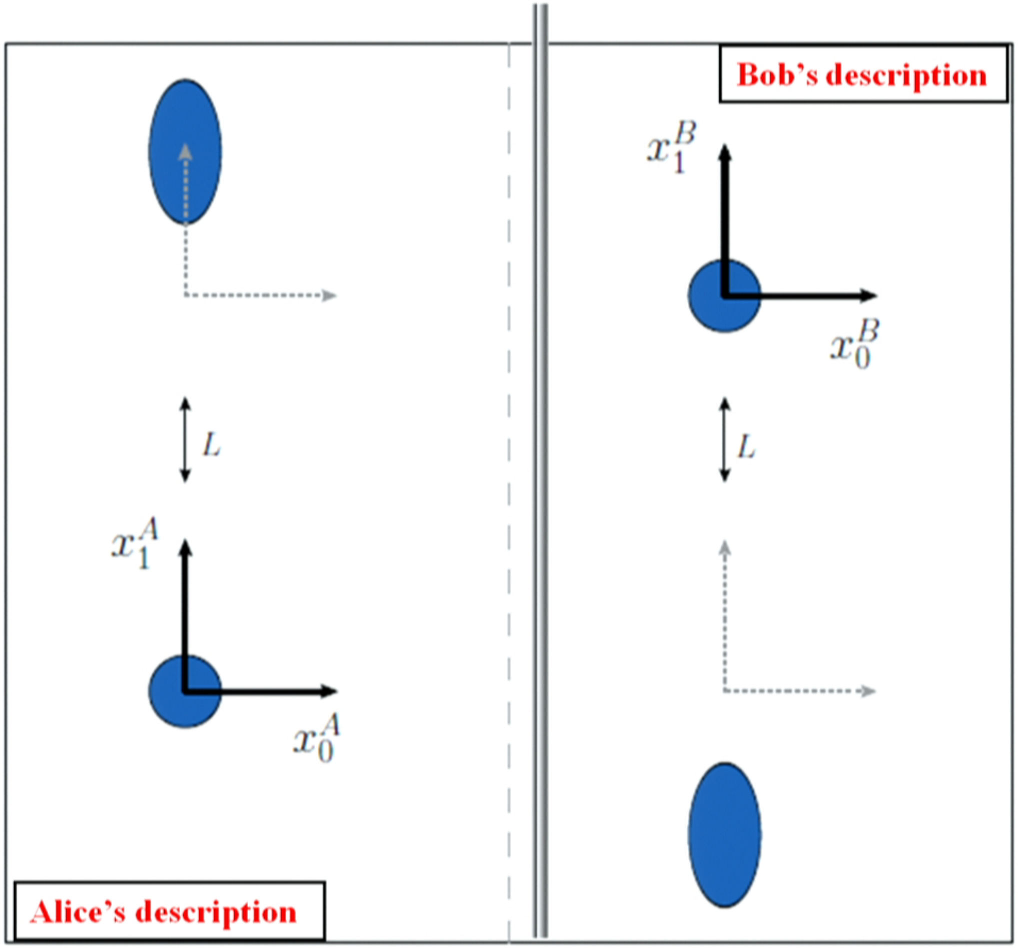


FIG. 1. We illustrate the features of relative locality we uncovered for the κ-Minkowski quantum spacetime by considering the case of two distant observers, Alice and Bob, in relative rest (with synchronized clocks). In figure we have only two points in κ-Minkowski, each described by a gaussian state in our Hilbert space. One of the points is at Alice (centered in the spacetime origin of Alice's coordinatization) while the other point is at Bob. The left panel reflects Alice's description of the two points, which in particular attributes to the distant point at Bob larger fuzziness than Bob observes (right panel). And in Alice's coordinatization the distant point is not exactly at Bob. Bob's description (right panel) of the two points is specular, in the appropriately relativistic fashion, to the one of Alice. The magnitude of effects shown would require the distance L to be much bigger than drawable. And for definiteness in figure we assumed $\bar{\sigma}_0 \simeq 2\sigma_0$ and $\sigma_1 \simeq \sigma_0$.

notice features of standard relative locality

[GAC+Freidel+KowalskiGlikman +Smolin,PRD84 (2011) 084010 but here for free theory as in GAC+Matassa+Mercati+Rosati, PRL106(2011) 071301]

<u>notice novel features of quantum-spacetime relative locality</u>

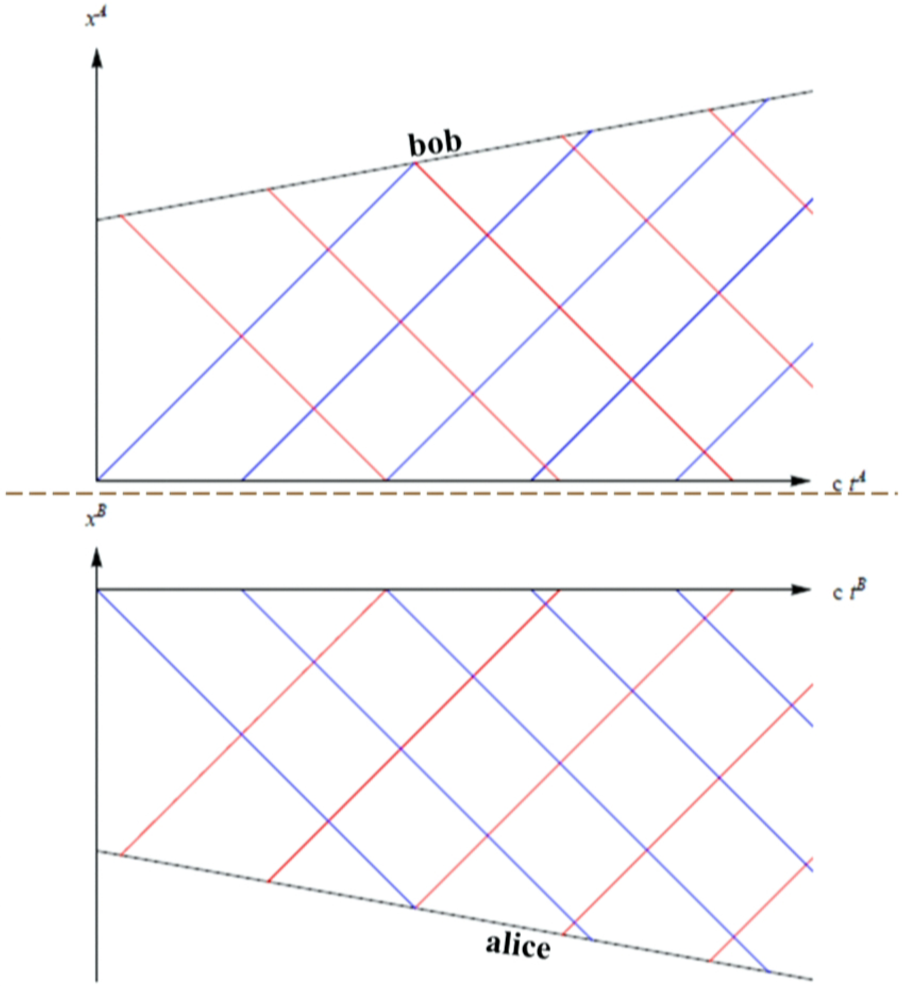
still a fully relativistic theory!
no preferred frame!

but not relativistic in the sense of the classical Poincare' symmetries

the relativistic symmetries of these theories are DSR-deformed

GAC, grqc0012051,IntJModPhysD11,35
,hepth0012238,PhysLettB510,255
Kowalski-Glikman, hep-th0102098,PhysLettA286,391
Magueijo+Smolin, hep-th0112090, PhysRevLett88, 190403

analogy with relative simultaneity....



Here Alice (coordinatization shown on top) and Bob (coordinatization shown in bottom) are evidently in relative motion with constant speed. Validity of ordinary special relativity is assumed. Alice and Bob have stipulated a procedure of clock synchronization and they have agreed to build emitters of blue photons. They also agreed to then emit such red blue photons in a regular sequence, with equal time spacing T.
We arranged the starting time of each sequence of emissions so that there would be two cases of a detection coinciding with an an emission. These coincidences of events are of course manifest in both coordinatizations (special relativity is absolutely local).
But relative simultaneity is directly or indirectly responsible for several features that would appear to be paradoxical to a Galilean observer (observer assuming absolute simultaneity). In particular, while they stipulated to build blue-photon emitters they detect red photons, and while the emissions are time-spaced by T the detections are separated by a time greater than T

"fuzzy2" dynamics: GAC+Astuti+Rosati,arXiv:1207.2509

let us now move on to the physical Hilbert space

$$\langle\psi|\phi\rangle_{\mathcal{H}_\ell} = \langle\psi|\delta\left(\mathcal{H}_\ell\right)\Theta(\pi_0)|\phi\rangle$$ Rovelli+Reisenberger,PhysRevD65(2002)125016

enforcing invariance under (suitably deformed) boost transformations one finds that the Hamiltonian constraint for free massless particles should be

$$\mathcal{H}_\ell = \left(\frac{2}{\ell}\right)^2 \sinh^2\left(\frac{\ell\pi_0}{2}\right) - e^{-\ell\pi_0}\pi_1^2 = 0$$

X and T are not good Dirac observables!!!

we can characterize localization by a suitably-deformed Newton-Wigner operator

$$\mathcal{A} = e^{\ell\pi_0}\left(q_1 - \mathcal{V}q_0 - \frac{1}{2}[q_0, \mathcal{V}]\right)$$

where $\mathcal{V}$ is short-hand for $\mathcal{V} \equiv (\partial\mathcal{H}_\ell/\partial\pi^0)^{-1}\partial\mathcal{H}_\ell/\partial\pi^1$

$\mathcal{A}$ **does commute with** $\mathcal{H}_\ell$

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one then finds that starting from

$$\langle \Psi_{0,0} | \mathcal{A} | \Psi_{0,0} \rangle_{\mathcal{H}_\ell} = 0$$

$$\delta \mathcal{A}^2_{[\ell]} = \left(\langle \Psi_{0,0} | \mathcal{A}^2 | \Psi_{0,0} \rangle_{\mathcal{H}_\ell} \right)_{[\ell]} \approx \frac{\ell \langle \pi_0 \rangle}{2\sigma^2}$$

it turns out that

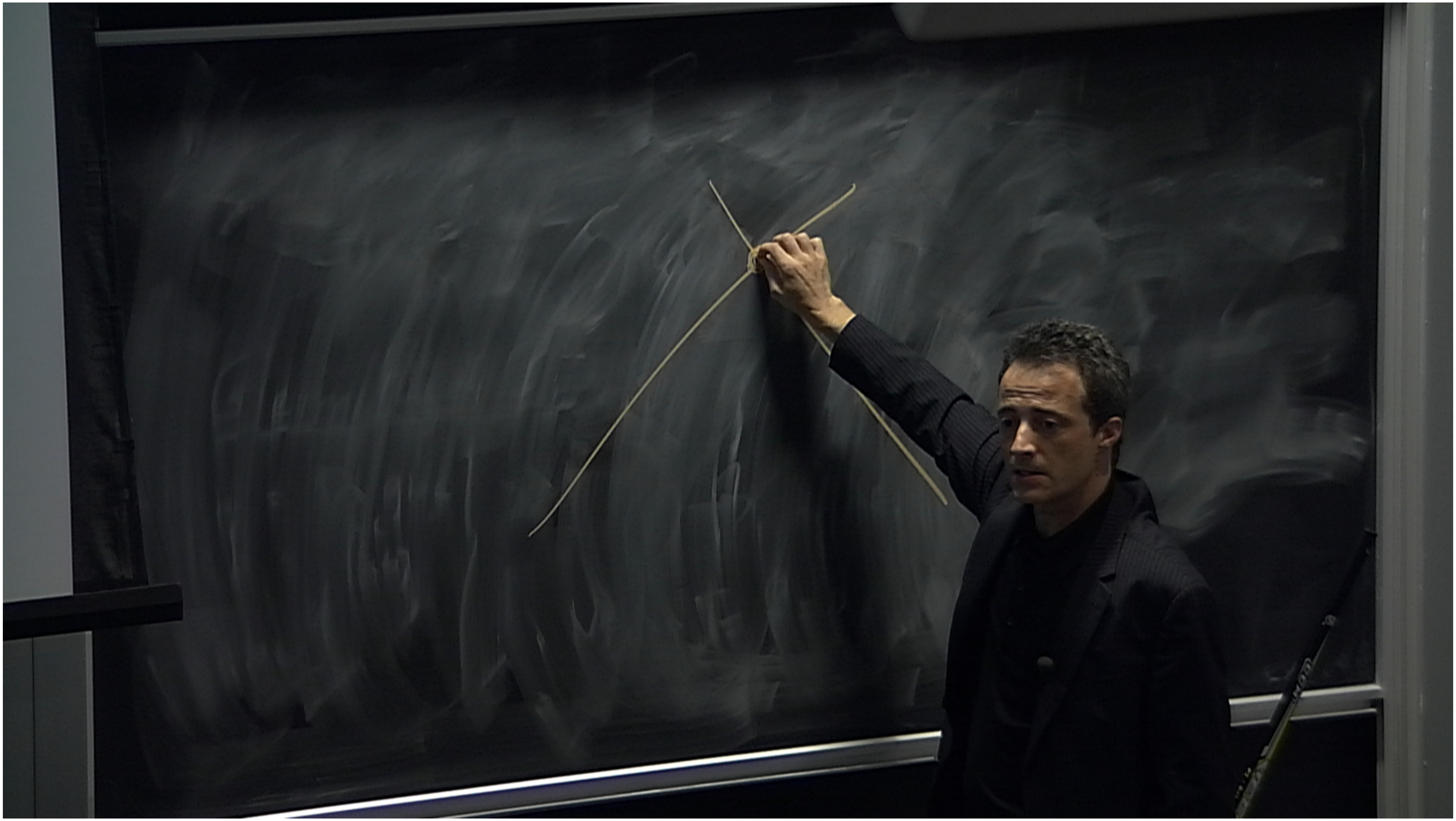
$$\langle \Psi_{a_0,a_1} | \mathcal{A} | \Psi_{a_0,a_1} \rangle_{\mathcal{H}} = 0$$

$$\delta \mathcal{A}^2_{[\ell]} = \left(\langle \Psi_{a^0,\langle \mathcal{V} \rangle a^0} | \mathcal{A}^2 | \Psi_{a^0,\langle \mathcal{V} \rangle a^0} \rangle_{\mathcal{H}_\ell} \right)_{[\ell]} \approx \left(\frac{\ell \langle \pi_0 \rangle}{2\sigma^2} + \ell^2 a_0^2 \sigma^2 \right)$$

$$\delta E^2 \simeq \sigma^2$$

interpretation:
our observer Alice, the observer on the worldline for whom the fuzziness of the intercept takes the minimum value, is the observer at the source (where the particle is produced), and then the intercept of the particle worldline with the origin of the reference frames of observers distant from Alice (where the particle could be detected) has bigger uncertainty

ν



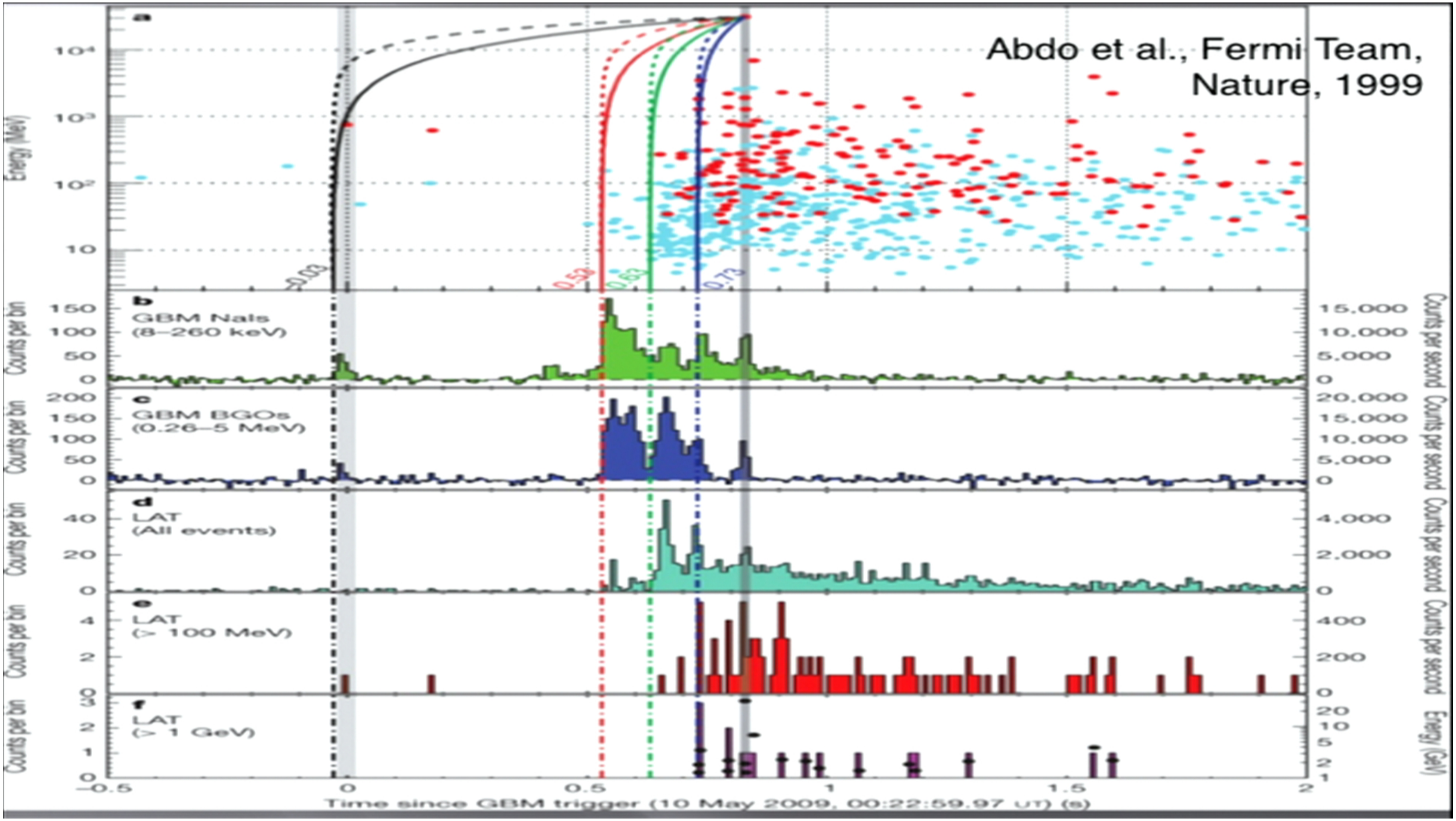
A POSSIBLE BOUND ON SPECTRAL DISPERSION FROM FERMI-DETECTED GAMMA RAY BURST 090510A

Robert J. Nemiroff
Michigan Tech

My Goal: Three numbers

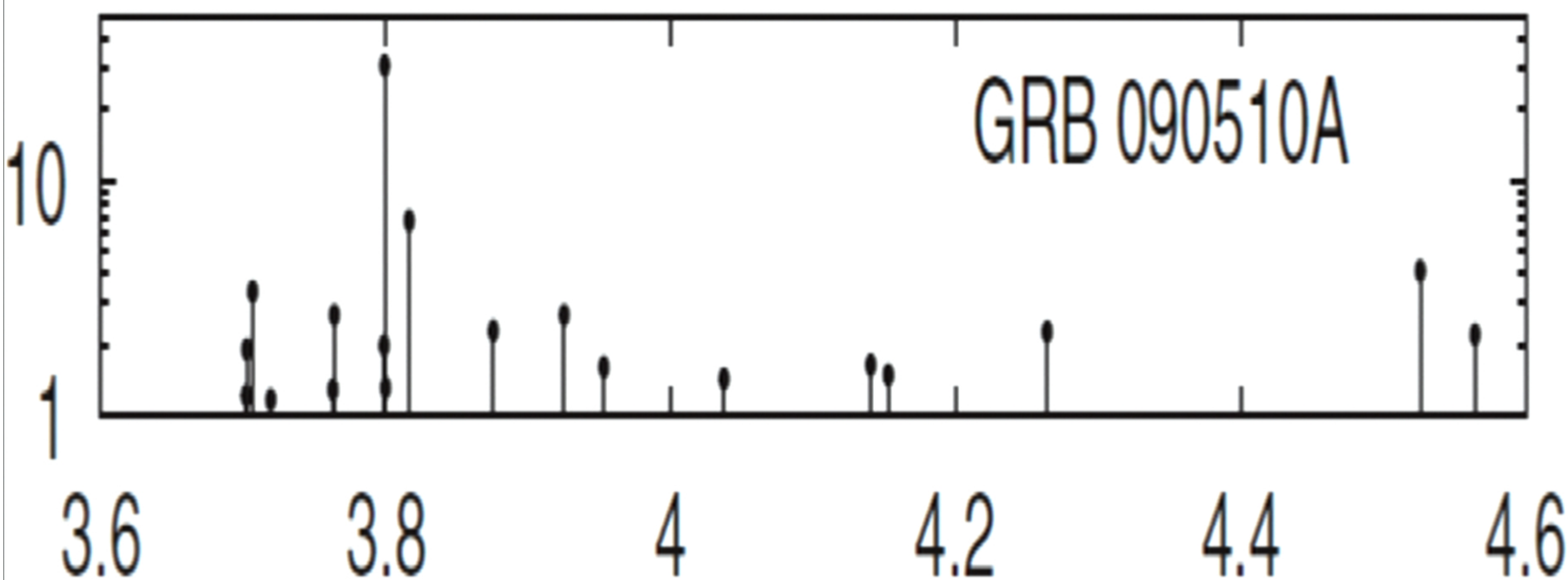
- Δt: minimize
- ΔE: maximize
- z: maximize

- For GRB 090510A
  - $\Delta E \sim 30$ GeV
  - $z \sim 0.9$
- A new possibility is
  - $\Delta t \sim 0.001$ seconds



Abdo et al., Fermi Team,
Nature, 1999
Energy (MeV)
GBM NaIs
(8–260 keV)
GBM BGOs
(0.26–5 MeV)
LAT
(All events)
LAT
(> 100 MeV)
LAT
(> 1 GeV)
Counts per bin
Counts per second
Energy (GeV)
Time since GBM trigger (10 May 2009, 00:22:59.97 UT) (s)

Consider only high energy photons



Were these 3 photons really isolated?

---- GRB 090510A ----Pass 7----

Time (s)	Energy (GeV)
-507.37014	1.93
-380.59269	1.15
3.7022335	1.22
3.7027825	1.91
3.7069414	3.37
3.7194310	1.17
3.7631084	1.29
3.7641773	2.68
3.7991902	1.98
3.7993189	30.86
3.8000964	1.31
3.8167293	6.75
3.8757667	2.29
3.9253115	2.67
3.9530931	1.60
4.0376598	1.44
4.1406114	1.64
4.1527832	1.49
4.2644487	2.28
4.5259632	4.12
4.5643419	2.22
5.1267243	1.06
5.2103540	1.68
5.9021644	2.08
6.1776803	1.53
6.4026321	2.78
6.6466461	3.69
7.8898184	1.25
12.265765	1.04
12.618712	1.73
26.082871	1.40
41.571826	1.22
50.966219	1.52
101.89744	1.41

You're basing this possibility on just three photons?

- Partly.
- "Why Most Published Research Findings Are False"
  - Ioannidis: doi:10.1371/journal.pmed.0020124
- Other < 0.001 s 2-photon pair "pulses"
  - Two other pairs included in PRL analysis
  - Three more pairs not included in PRL analysis
    - Two involve pairing between super and sub-GeV photons
- Pulse widths narrow as energy increases

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How was significance estimated?

- χ^2 to find flat arrival epochs
- Photon-photon correlation function to find chance that 5 photon pairs with $\Delta t < 1.069$ ms would be found among 11 photons spread uniformly over ~ 0.1745 seconds
- Statistical comparisons to 10^9 Monte Carlo runs
- Then assume 1.069 ms pairs drawn randomly from a classic Norris GRB pulse shape
  - Δt increased to 1.550 ms => "real pulse width"
  - Norris et al, ApJ, 2005, Nemiroff et al, MNRAS, 2012

How is this analysis different?

- Followed a fortuitous lead …
- Concentrated only on high energy photons
  - PRL paper: GeV+ photons only
  - Work in Progress: 100 MeV+ photons only
- Did not match up photons from different energy regimes
  - Same detector (unlike Abdo et al. Nature, 1999)
  - Same emission mechanism (worry of Wagner, last QG meeting, NORDITA, 2010)
- Better realized that $\Delta E \sim E_{max}$, not E_{max}/E_{min}

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What if the 30 GeV photon is unassociated with the short pulses?

- Statistical significance drops
- ΔE drops by factor of 10

- 30 GeV photon is still part of GRB 090510A
  - 30 GeV photons do occur in GRBs
  - Fermi team looked at this one photon very closely

Are there any precedents for such short duration GRB pulses?

Name	Δt (sec)	ΔE (MeV)	z	Ref.
GRB 790305	*0.0002 (rise)*	*1?*	*?*	*Bhat et al., Nature 1992*
GRB 820405	*0.012*	*~0.1*	*?*	*Mazets et al., AIP Conf., 1983*
GRB 841215	*0.005*	*~ 1.0*	*?*	*Laros et al, Nature, 1985*
GRB 910711	*0.008*	*~1.0*	*?*	*Bhat et al., Nature, 1992*
GRB 930229	*0.0002 (rise)*	*0.170*	*?*	*Schaefer, PRL, 1999*
GRB 021206	*< 0.0048*	*14*	*0.3 (pseudo)*	*Boggs et al., ApJ, 2006*
GRB 051221	*< 0.004*	*0.300*	*0.547*	*Martinez et al., JCAP, 2006*
Informal	*reports*	*of*	*many*	*others.*

Who cares if Δt ~ 0.001 s?

The 3 numbers (Δt, ΔE, z) are plugged into a generic "black box" dispersion equation:

$$\Delta t = k_n D_n E^{n-1} \Delta E,$$

k_n is then matched up with the dispersion predicted by a popular flavor of QG spacetime foam.

$$D_n = \frac{c}{H_o} \int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda}},$$

$$M_1 c^2 = (k_1 c)^{-1}$$

$$M_2 c^2 = (3 k_2 c/2)^{-1/2}$$

See, for example:
Amelino-Camelia et al., Nature, 1998;
Ellis et al, ApJ, 2000; Jacob & Piran, JCA, 2008
Amelino-Camelia & Smolin, PRD, 2009

General Results

Published: assuming the Δt's found are 30 GeV associated and not statistical flukes:

Limits on spacetime foam from a popular published flavor of linear QG:

$M_{QG}/M_{Planck} > 525$ (published, less cons. than I thought)

$M_{QG}/M_{Planck} > 653$ (mean)

$M_{QG}/M_{Planck} > 9750$ (liberal)

Strictest limits yet suggested on QG?

Have you told anybody?

PRL **108,** 231103 (2012) PHYSICAL REVIEW LETTERS week ending 8 JUNE 2012

Bounds on Spectral Dispersion from Fermi-Detected Gamma Ray Bursts

Robert J. Nemiroff, Ryan Connolly, Justin Holmes, and Alexander B. Kostinski
Department of Physics, Michigan Technological University, 1400 Townsend Drive, Houghton, Michigan 49931, USA
(Received 23 September 2011; revised manuscript received 27 March 2012; published 8 June 2012)

Data from four Fermi-detected gamma-ray bursts (GRBs) are used to set limits on spectral dispersion of electromagnetic radiation across the Universe. The analysis focuses on photons recorded above 1 GeV for Fermi-detected GRB 080916C, GRB 090510A, GRB 090902B, and GRB 090926A because these high-energy photons yield the tightest bounds on light dispersion. It is shown that significant photon bunches in GRB 090510A, possibly classic GRB pulses, are remarkably brief, an order of magnitude shorter in duration than any previously claimed temporal feature in this energy range. Although conceivably $a > 3\sigma$ fluctuation, when taken at face value, these pulses lead to an order of magnitude tightening of prior limits on photon dispersion. Bound of $\Delta c/c < 6.94 \times 10^{-21}$ is thus obtained. Given generic dispersion relations where the time delay is proportional to the photon energy to the first or second power, the most stringent limits on the dispersion strengths were $k_1 < 1.61 \times 10^{-5}$ sec Gpc^{-1} GeV^{-1} and $k_2 < 3.57 \times 10^{-7}$ sec Gpc^{-1} GeV^{-2}, respectively. Such limits constrain dispersive effects created, for example, by the spacetime foam of quantum gravity. In the context of quantum gravity, our bounds set M_1c^2 greater than 525 times the Planck mass, suggesting that spacetime is smooth at energies near and slightly above the Planck mass.

DOI: 10.1103/PhysRevLett.108.231103 PACS numbers: 98.70.Rz, 03.30.+p, 04.60.Pp, 14.70.Bh

Are there any Emergency Backup Photons?

- Pair with one $E < 1$ GeV photon: shortest Δt:
  - $\Delta t = 0.0000415$ sec
  - $\Delta E = 746$ MeV
  - by itself ~2.6 σ (preliminary)
- Pair with both $E < 1$ GeV photon: shortest Δt:
  - $\Delta t = 0.0000300$ sec
  - $\Delta E = 6.84$ MeV
  - by itself ~2.3 σ (preliminary)

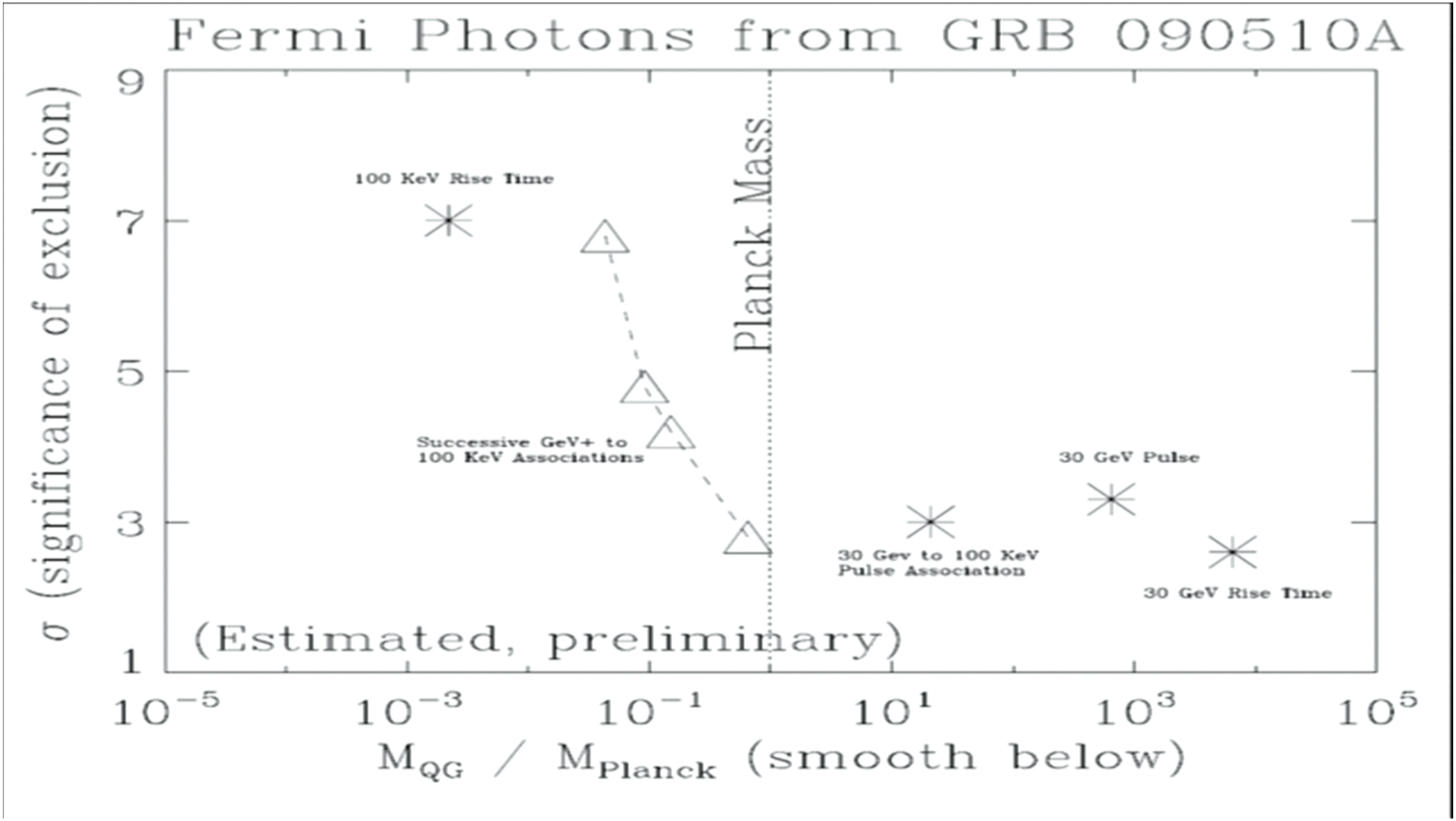
Limits from Emergency Backup Photons

Preliminary: Assuming these Δt's are not flukes:

Limits on spacetime foam from a popular published flavor of linear QG:

$M_{QG}/M_{Planck} > 595$ (first pair, mean)

$M_{QG}/M_{Planck} > 7.6$ (second pair, mean)

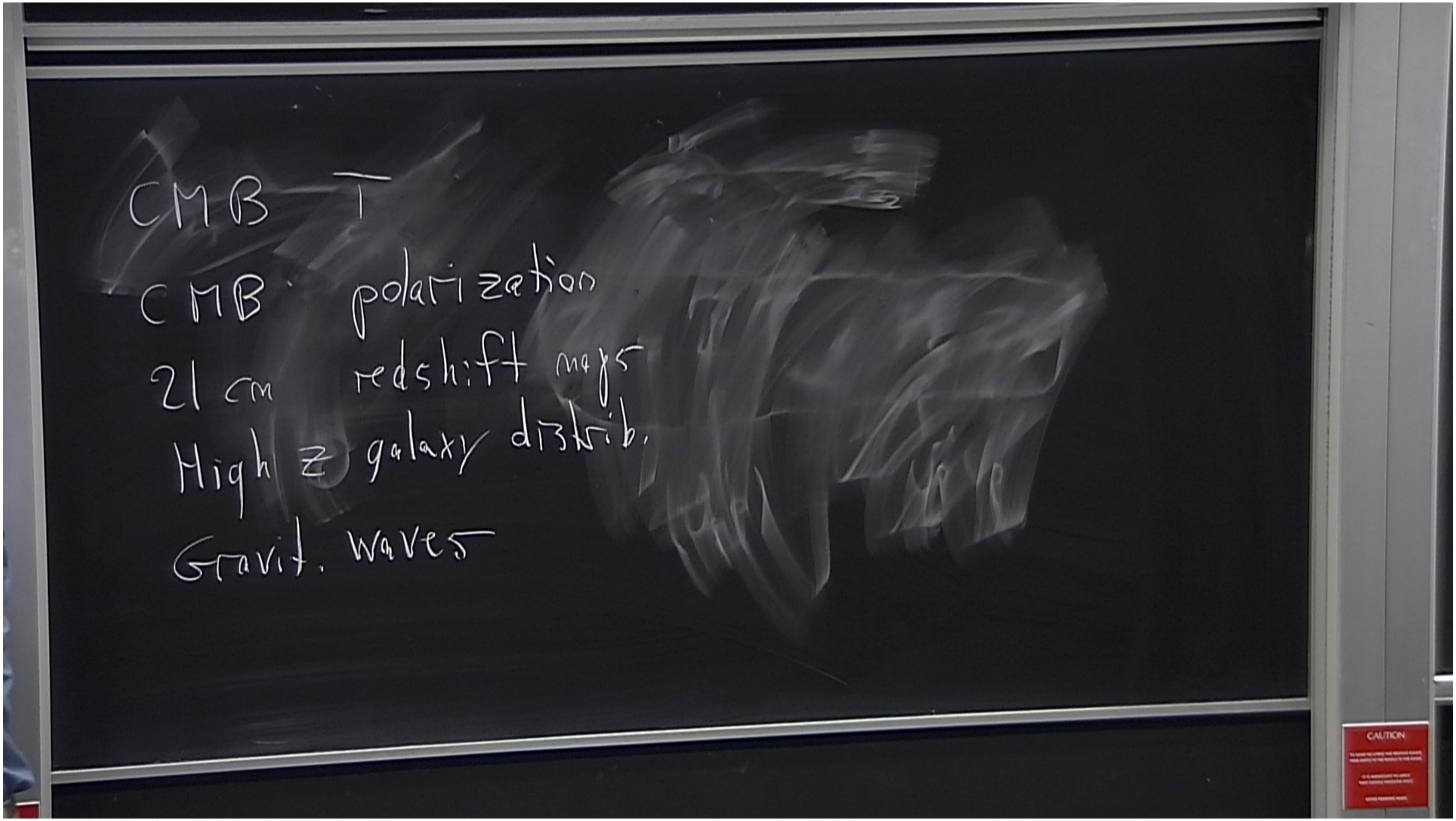

Fermi Photons from GRB 090510A
σ (significance of exclusion)
Planck Mass
100 KeV Rise Time
Successive GeV+ to
100 KeV Associations
30 GeV Pulse
30 Gev to 100 KeV
Pulse Association
30 GeV Rise Time
(Estimated, preliminary)
9
7
5
3
1
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
M_{QG} / M_{Planck} (smooth below)

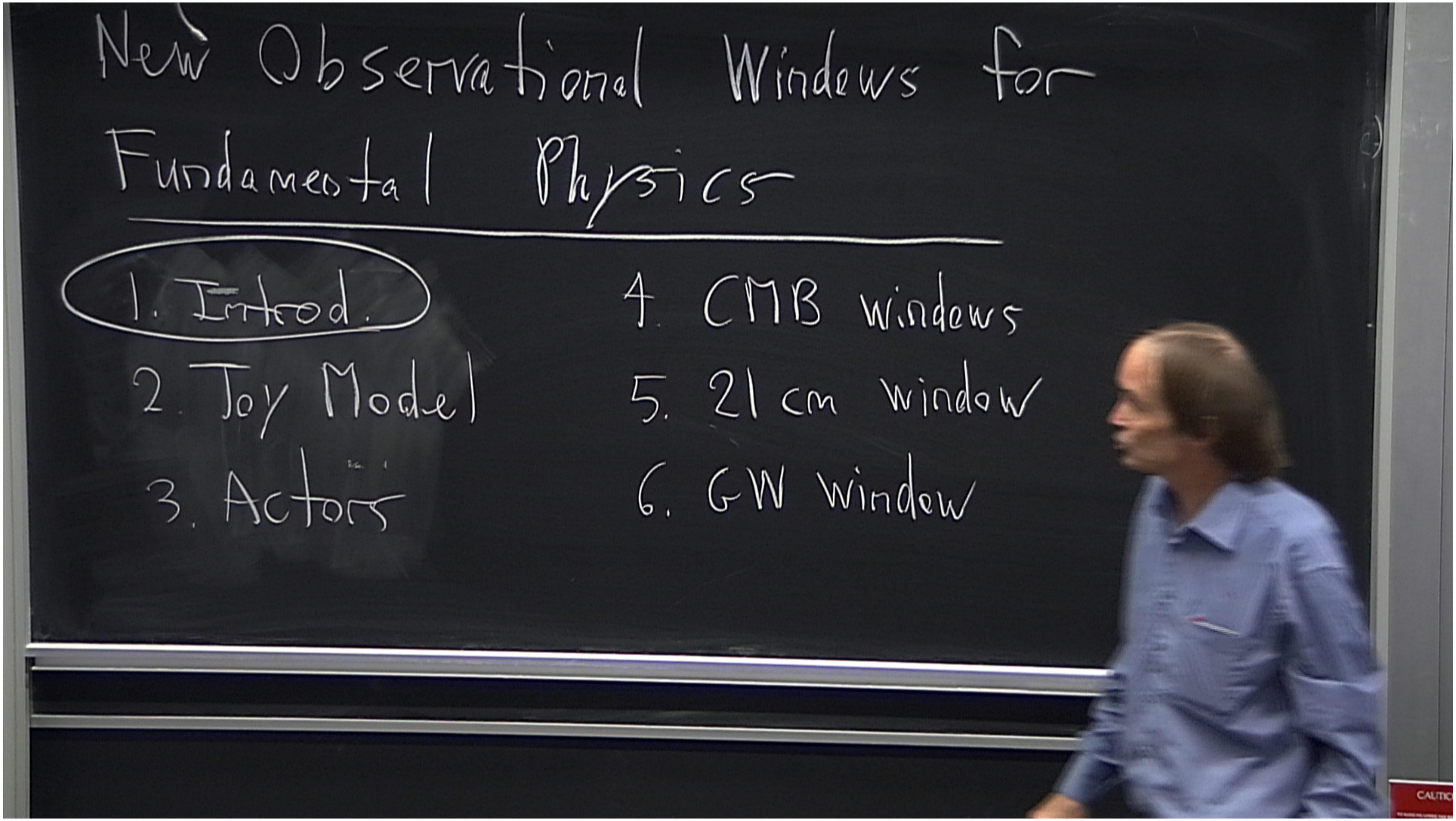
Is the Fermi GRB Team Skeptical?

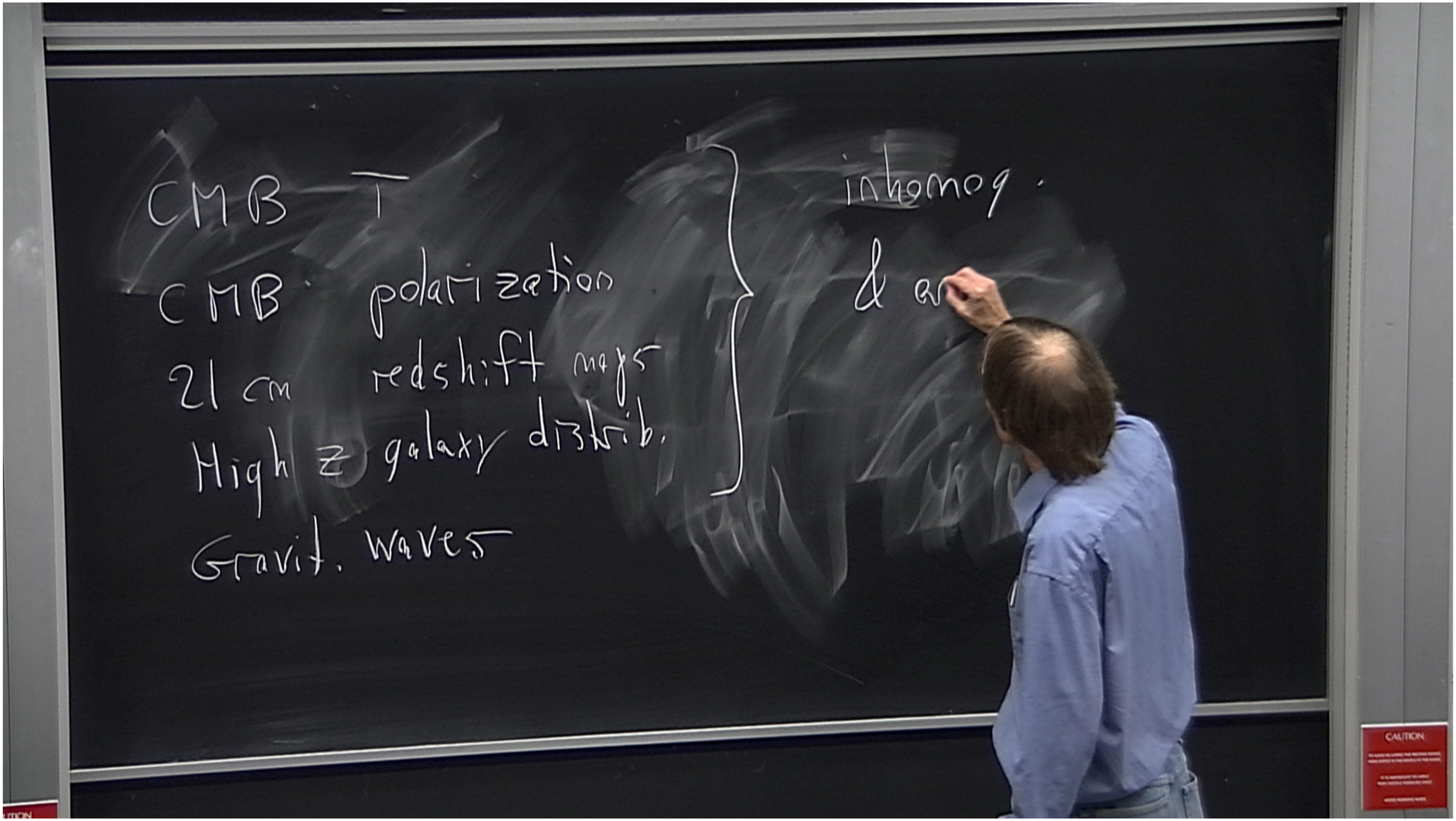
- “i think an argument against choosing your delt(t)s would be that the photon bunching analysis doesn't really preclude overlapping pulses.“ Jerry T. Bonnell (Fermi Team)
  - “Reverse dispersion unlikely” my reply
  - “Unlikely” as compared to 10^9 MC runs
- “It looks like an interesting and novel approach.” Vlasios Vasileiou (Fermi Team)
- “I like it, it's good.” Jay P. Norris (Fermi Team)

Acknowledgements

- J. Bonnell (Fermi Team: Data)
- A. Kostinski (Michigan Tech: Statistics)
- J. Norris (Fermi Team: Data)
- J. Scargle (Fermi Team: Background)
- K. Wood (Fermi Team: “That might be important!”comment)
- V. Trimble (1993 email)
- R. Connolly (MTU Undergrad: Detail work)


CMB T
CMB polarization
21 cm redshift maps
High z galaxy distrib.
Gravit. waves
CAUTION


New Observational Windows for
Fundamental Physics
1. Introd.
2. Toy Model
3. Actors
4. CMB windows
5. 21 cm window
6. GW window


CMB T
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21 cm redshift maps
High z galaxy distrib.
Gravit. waves
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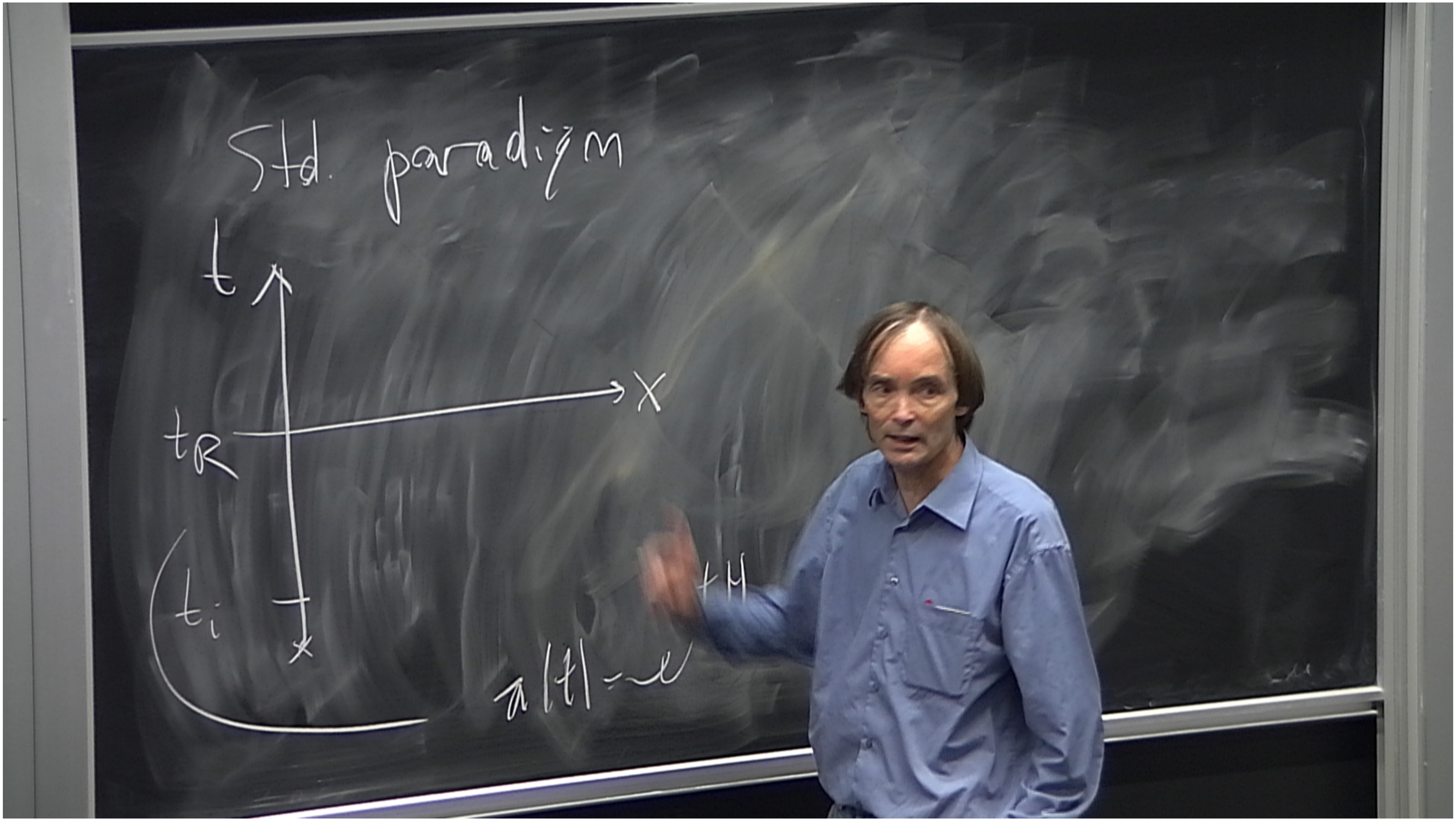
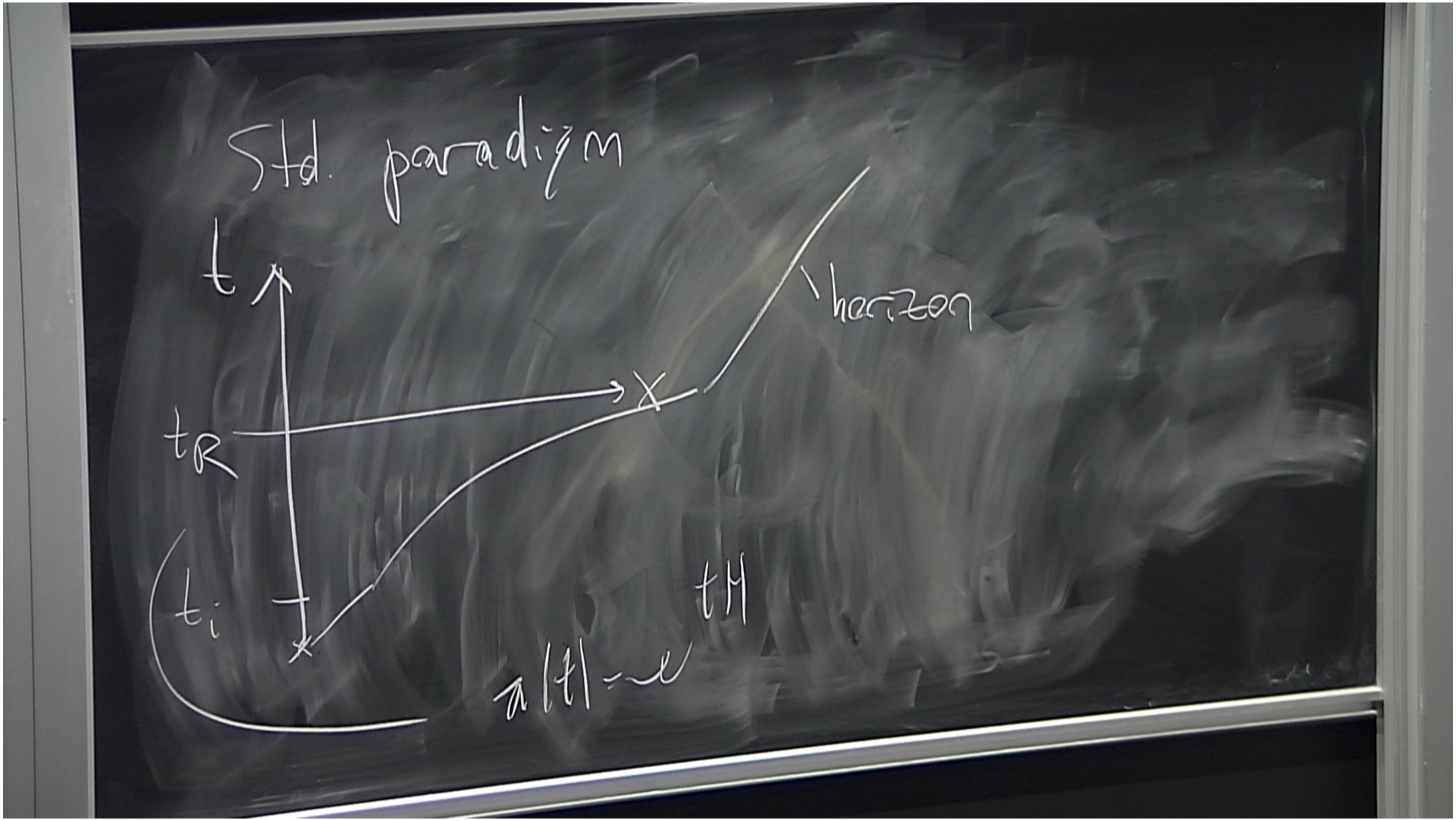
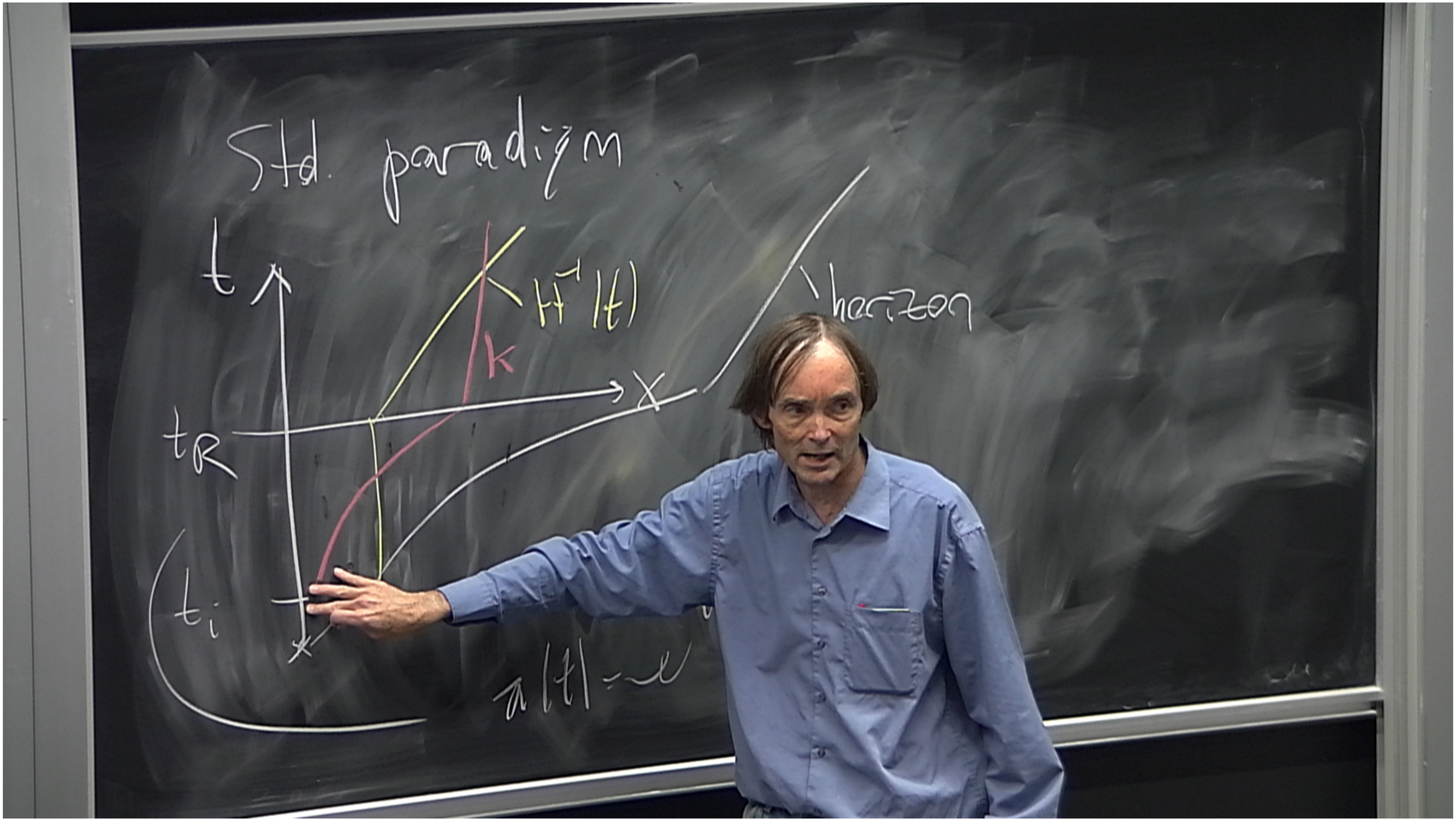
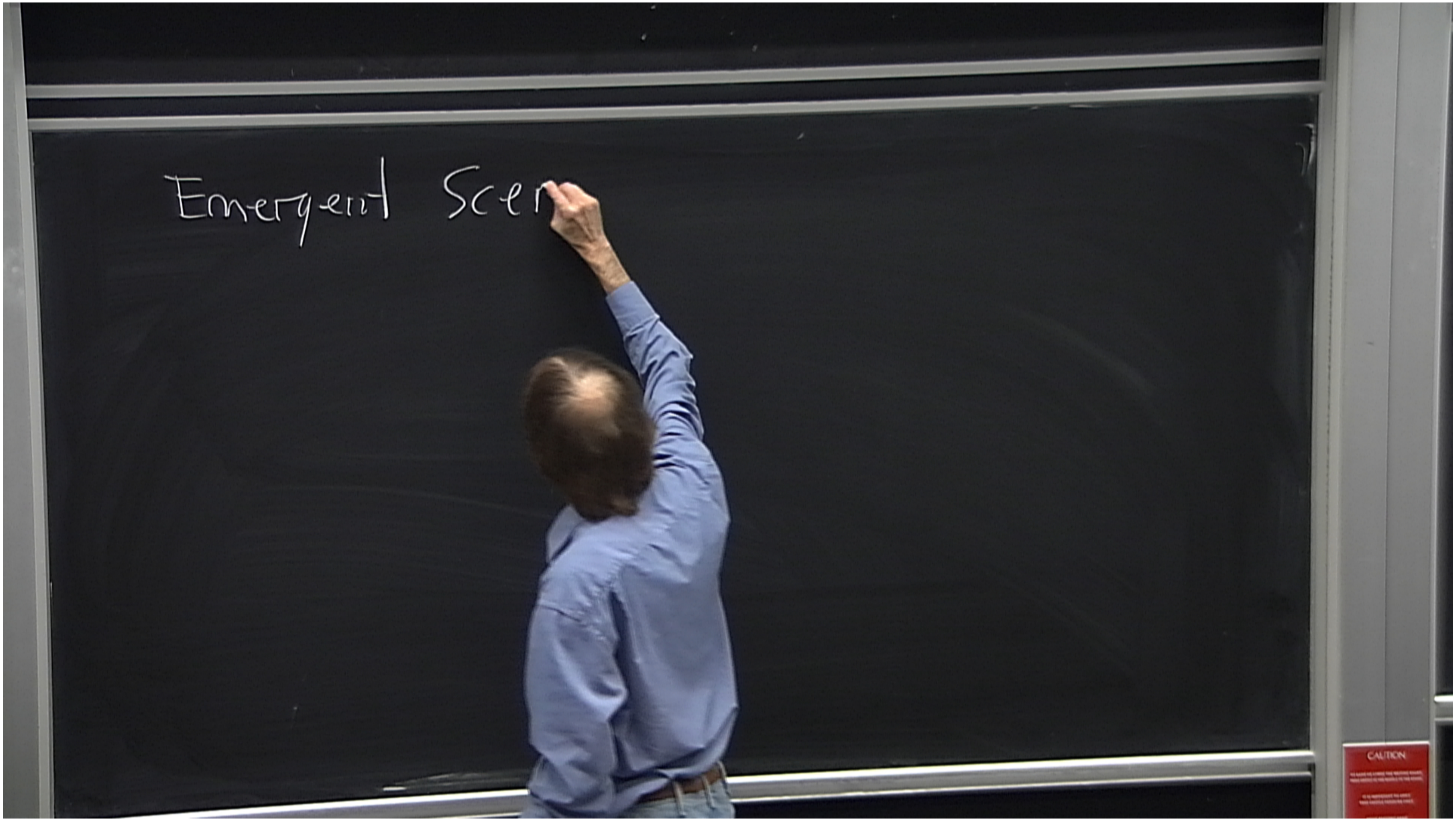
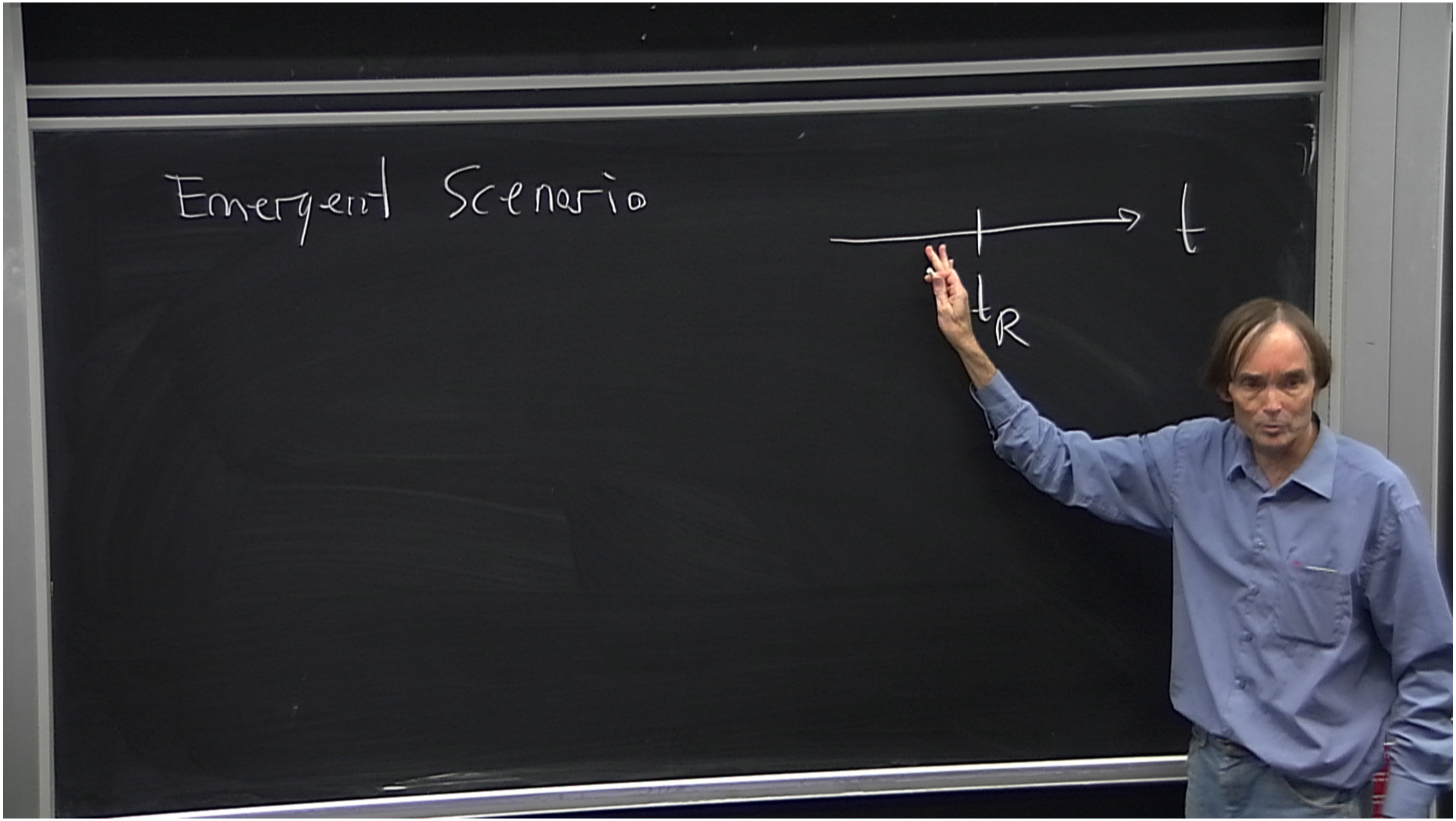
CAUTION

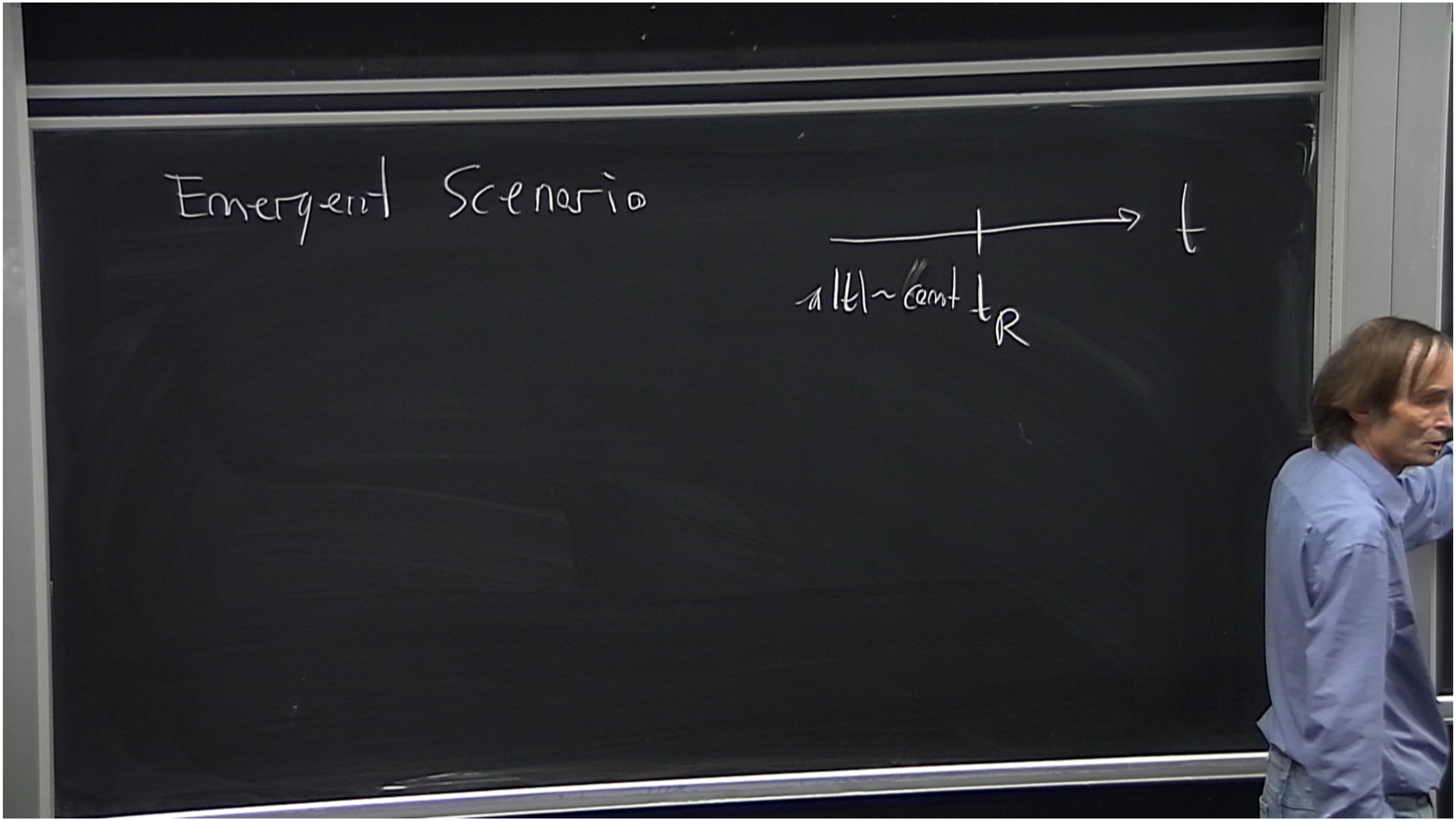

Std. paradigm
t
x
t_R
t_i

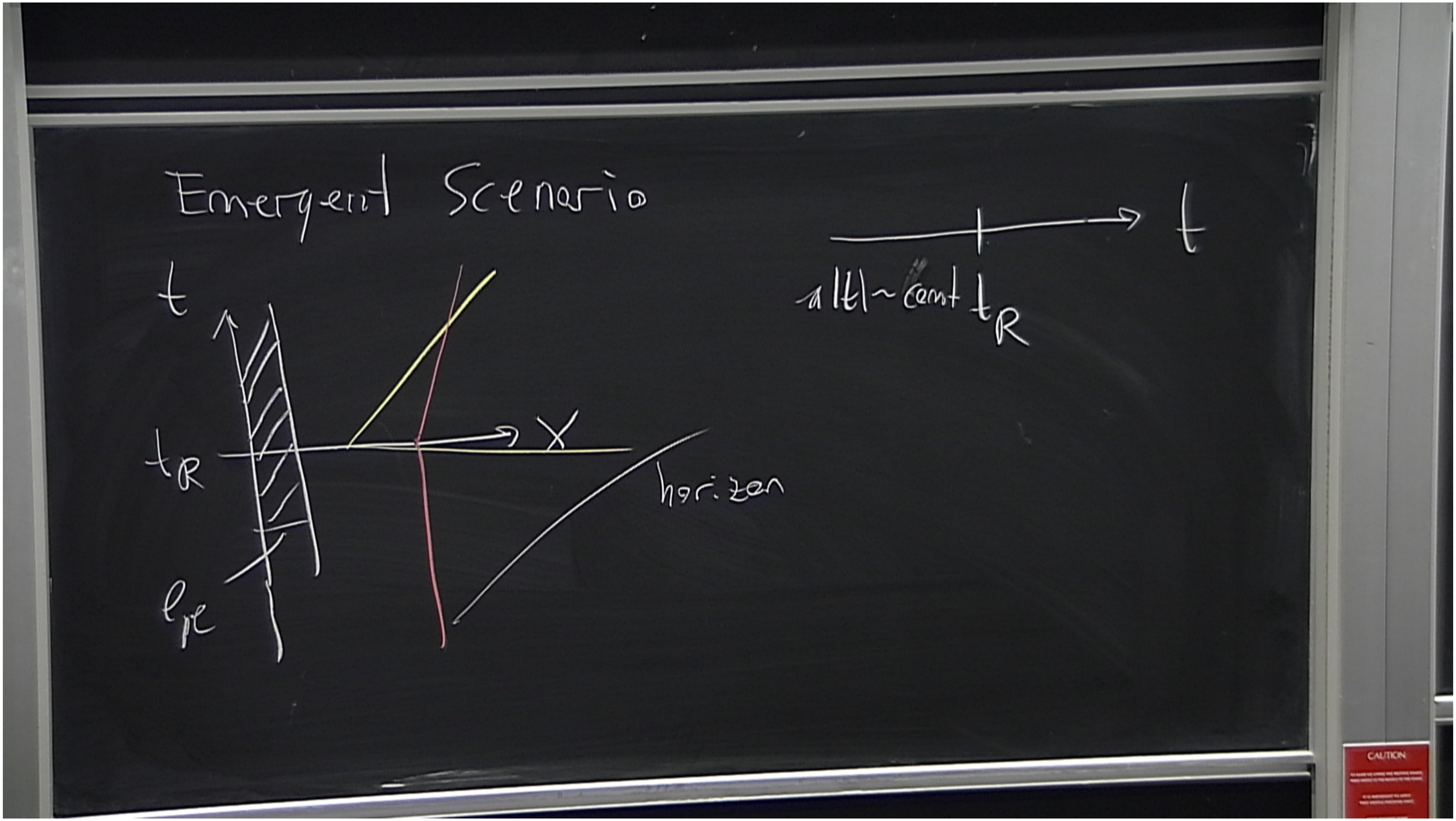

Std. paradigm
t
horizon
t_R
t_i
t_M
a(t) ~ e

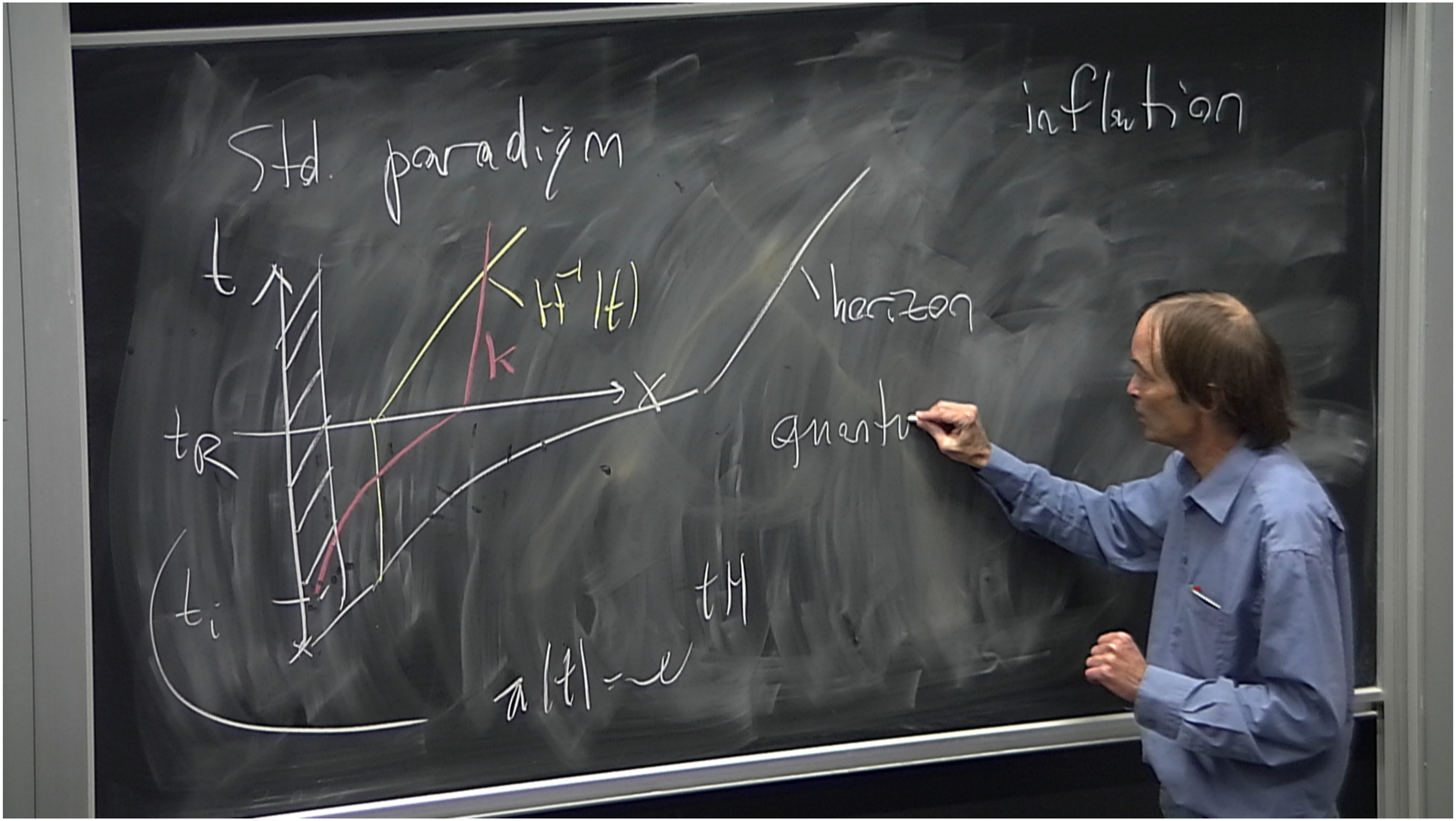

Std. paradigm
t
$H^{-1}(t)$
k
horizon
x
t_R
t_i
a(t) ~ e


Emergent Scen


Emergent Scenario
t
t_R


Emergent Scenario
a(t) ~ const
t_R
t


Emergent Scenario
t
t_R
x
horizon
ℓ_{pl}
$a(t) \sim$ const
t_R
t


Std. paradigm
inflation
horizon
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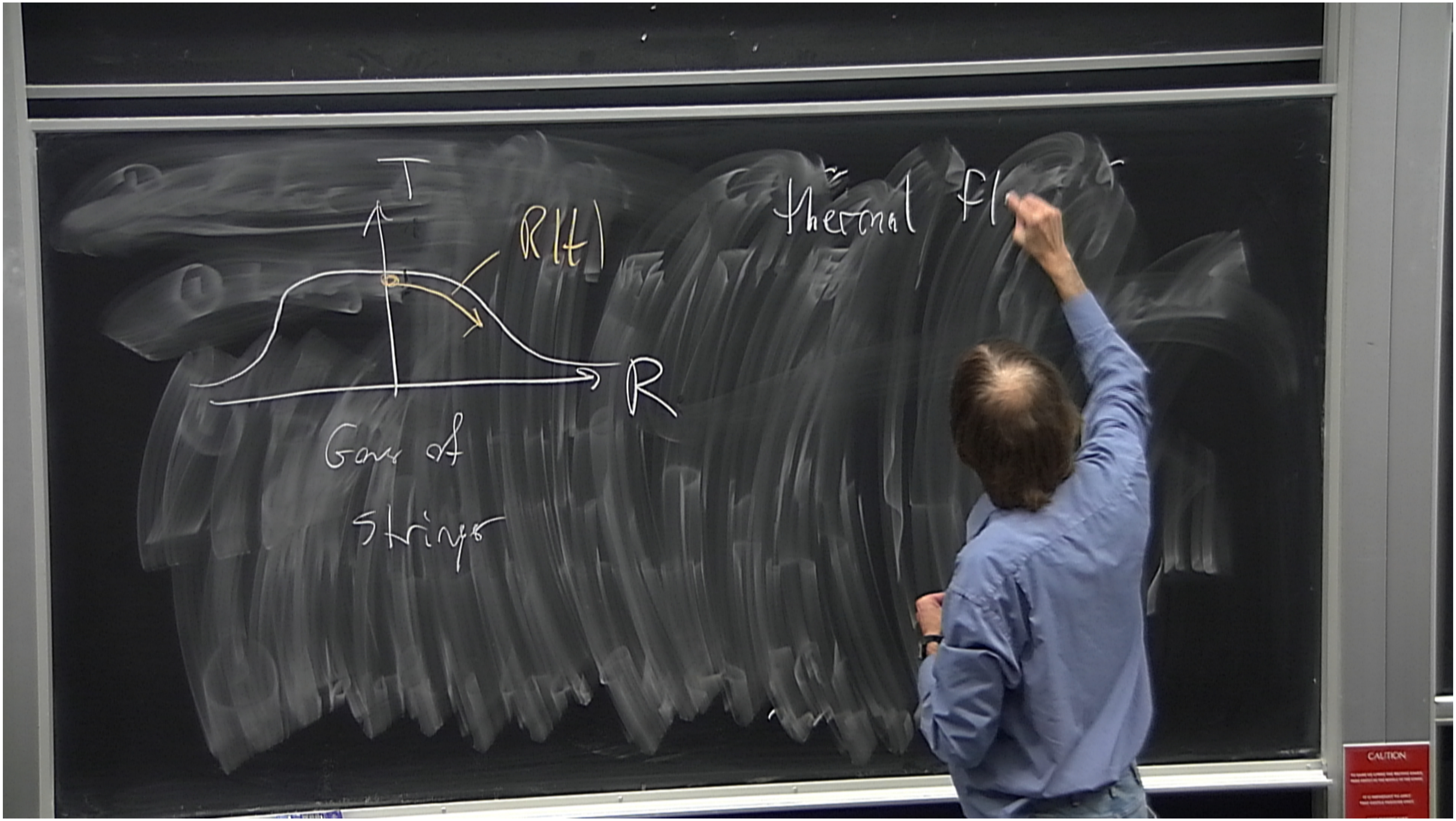
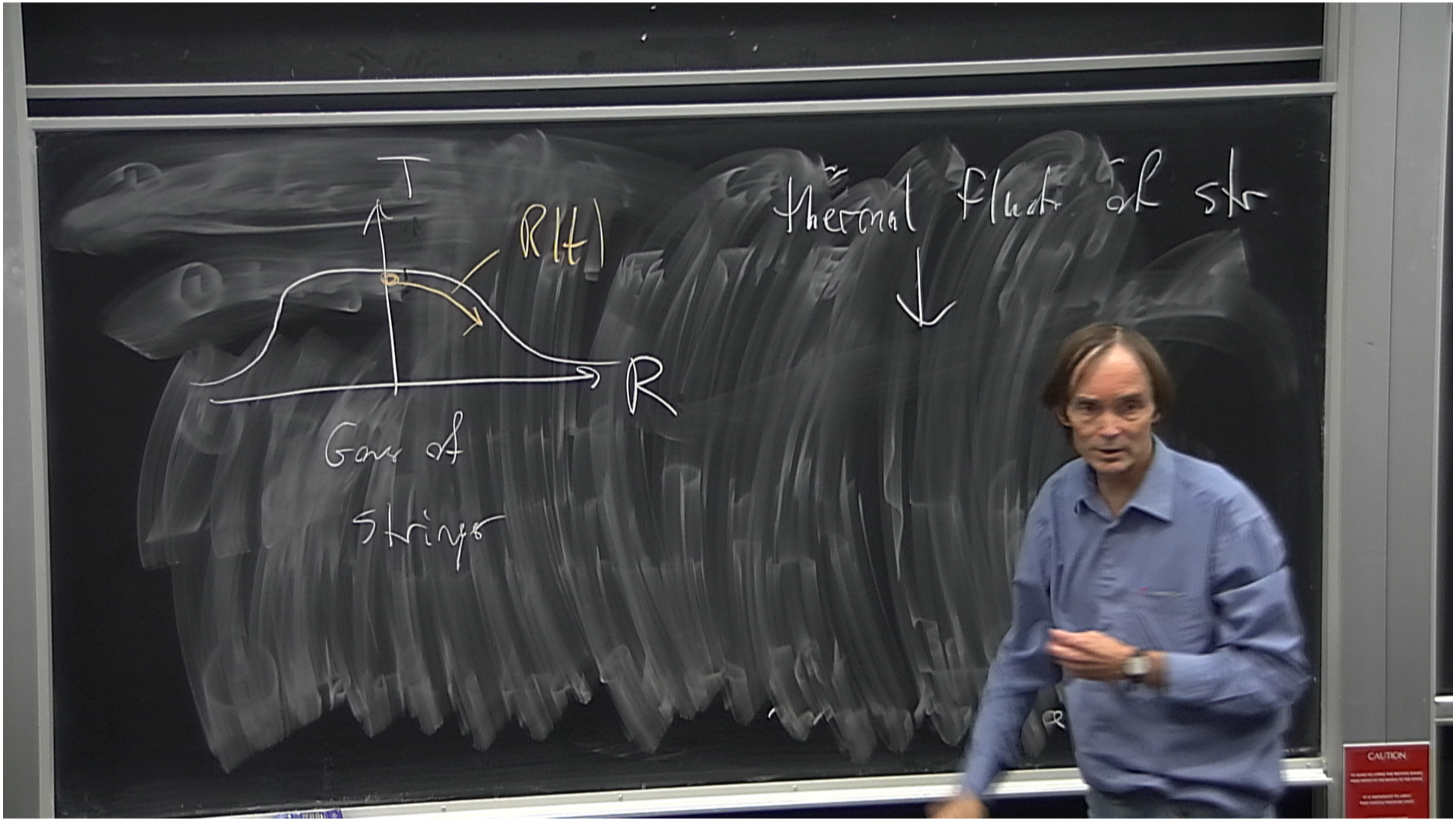
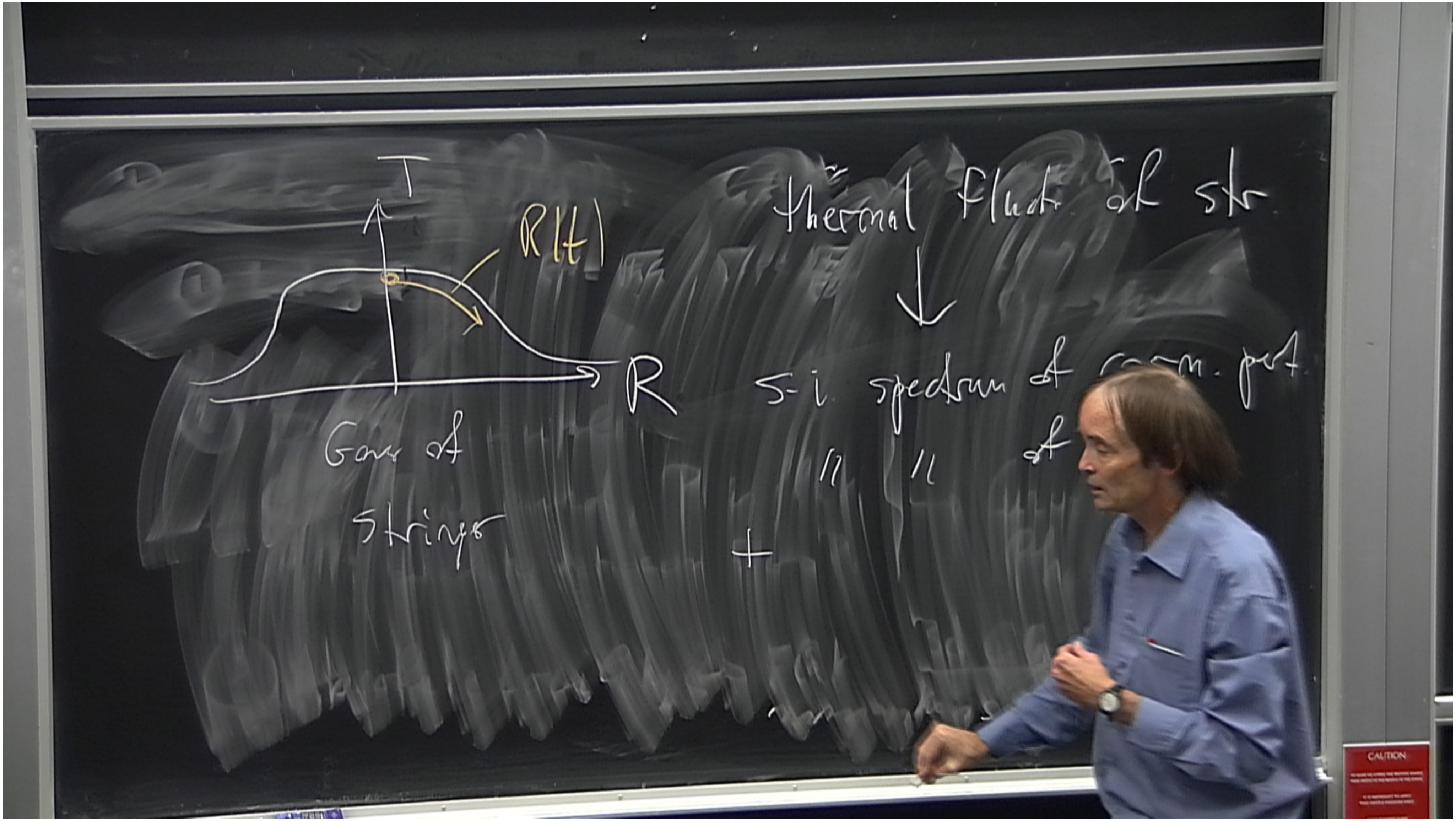
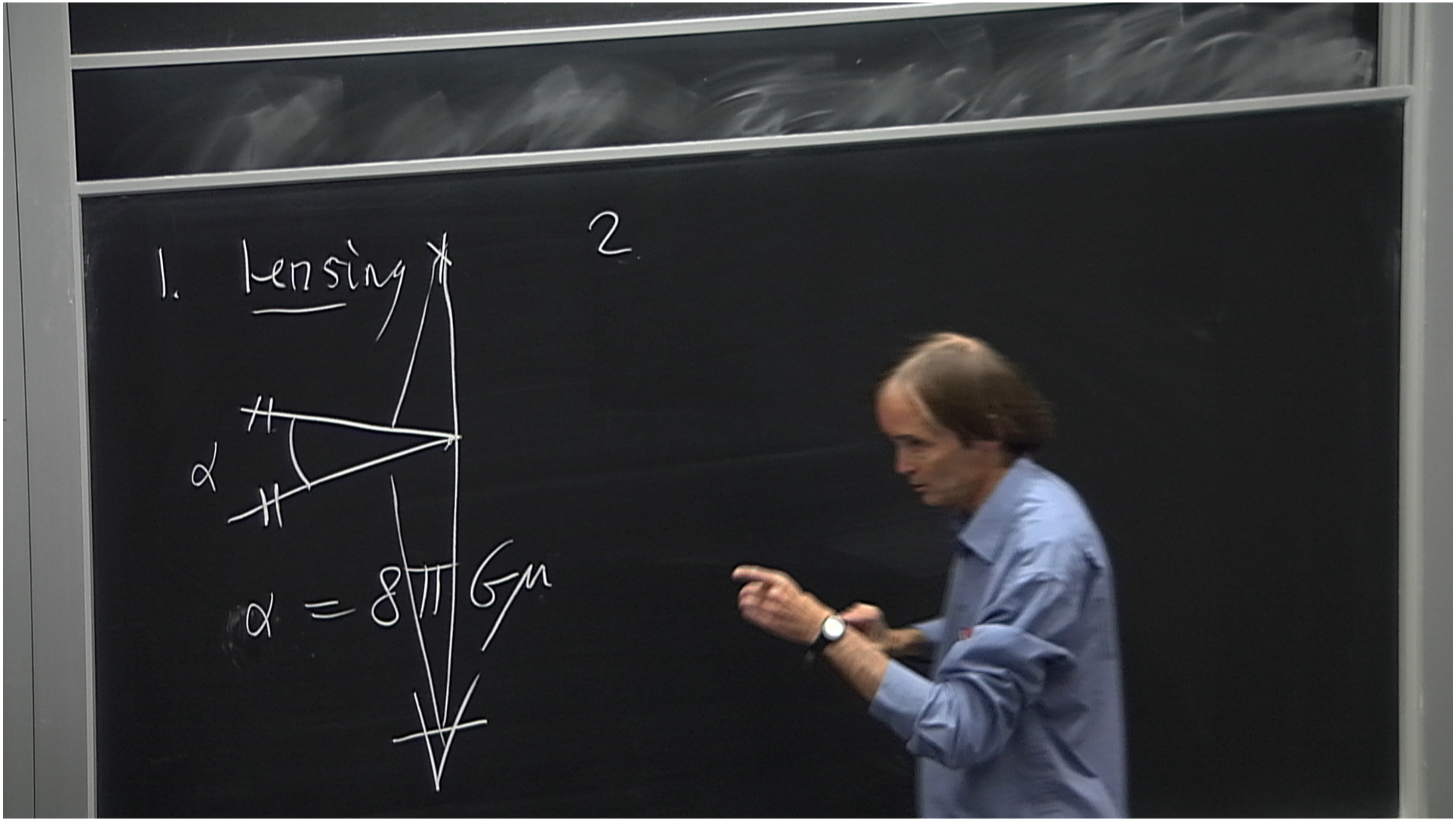
k
t
x
t_R
t_i
$H^{-1}(t)$
tM

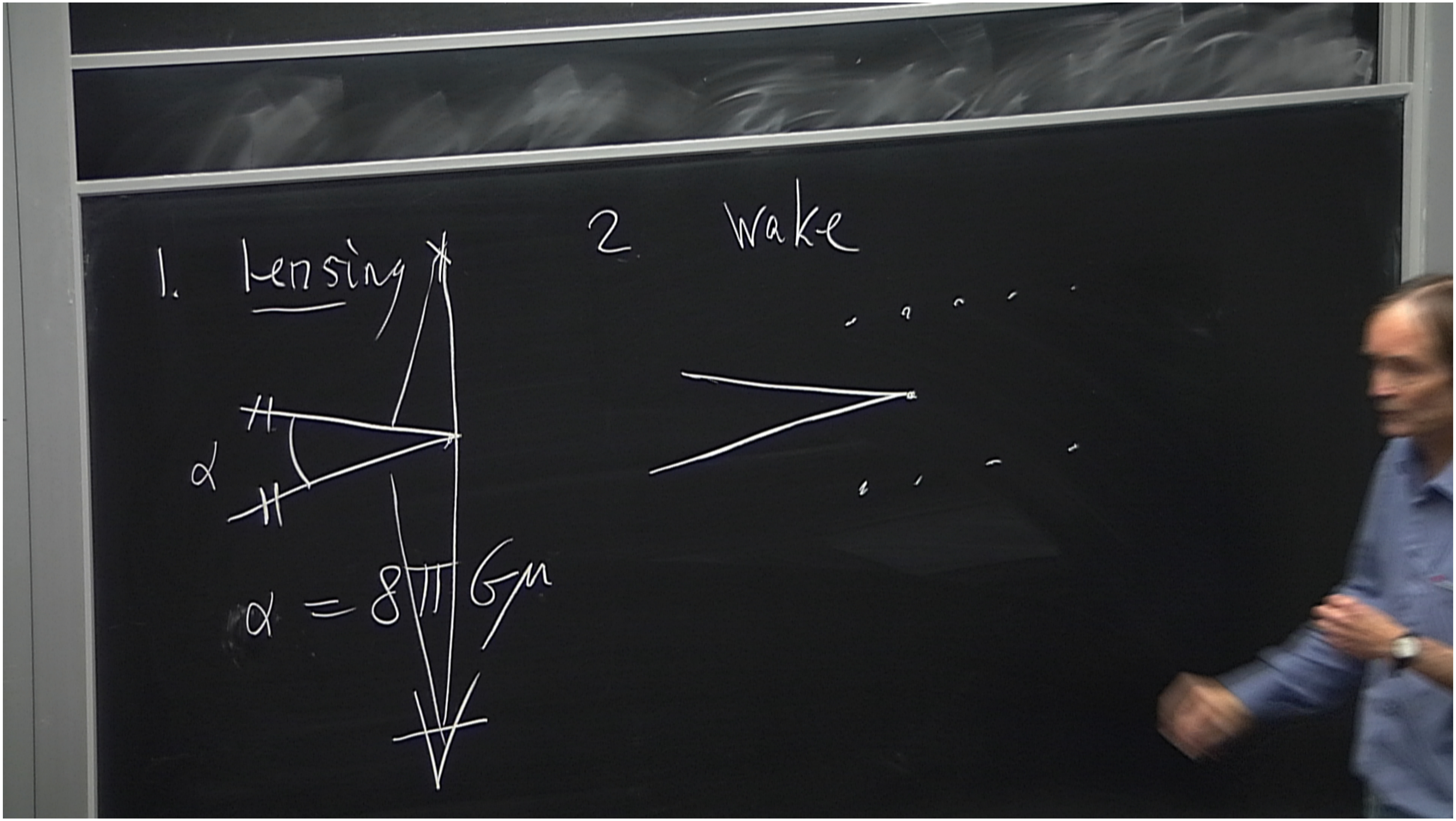

T
R(t)
R
Gas of
strings
thermal fl



T
R(t)
R
Gas of
strings
thermal fluct of str


T
R(t)
R
Gas of
strings
thermal fluct. of str
s-i. spectrum of


1. Lensing
2.
α
α = 8π Gμ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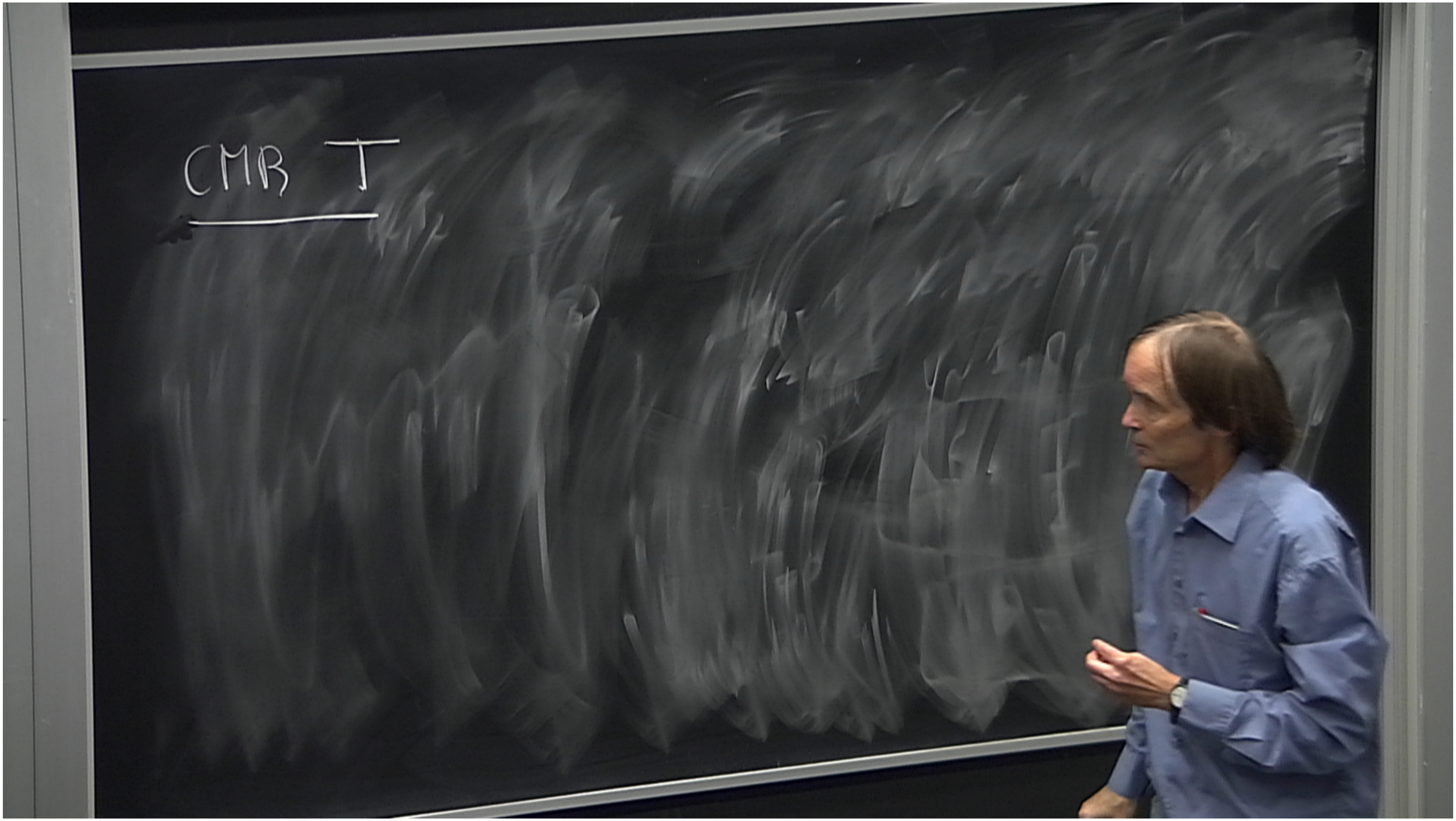
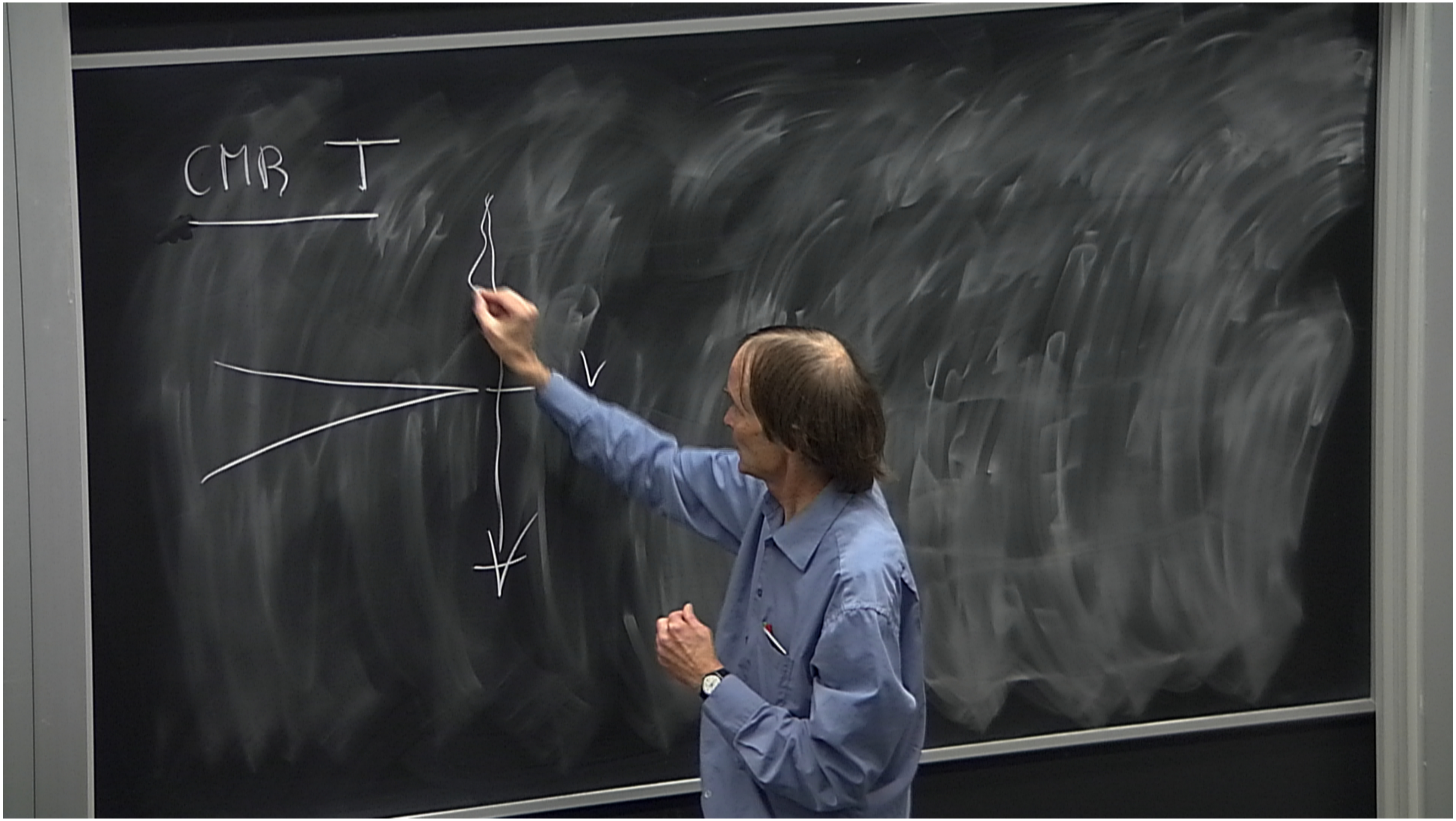
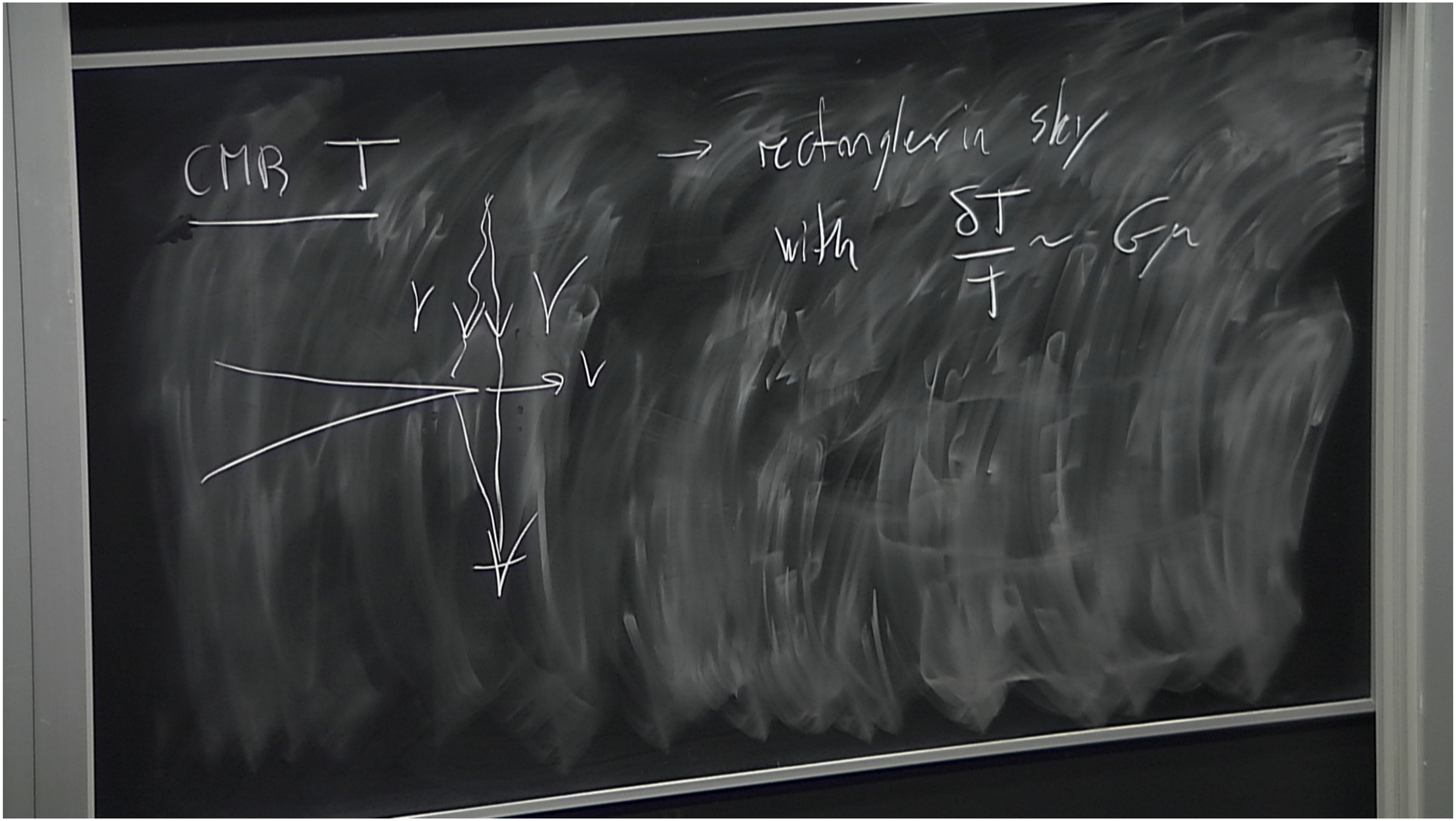
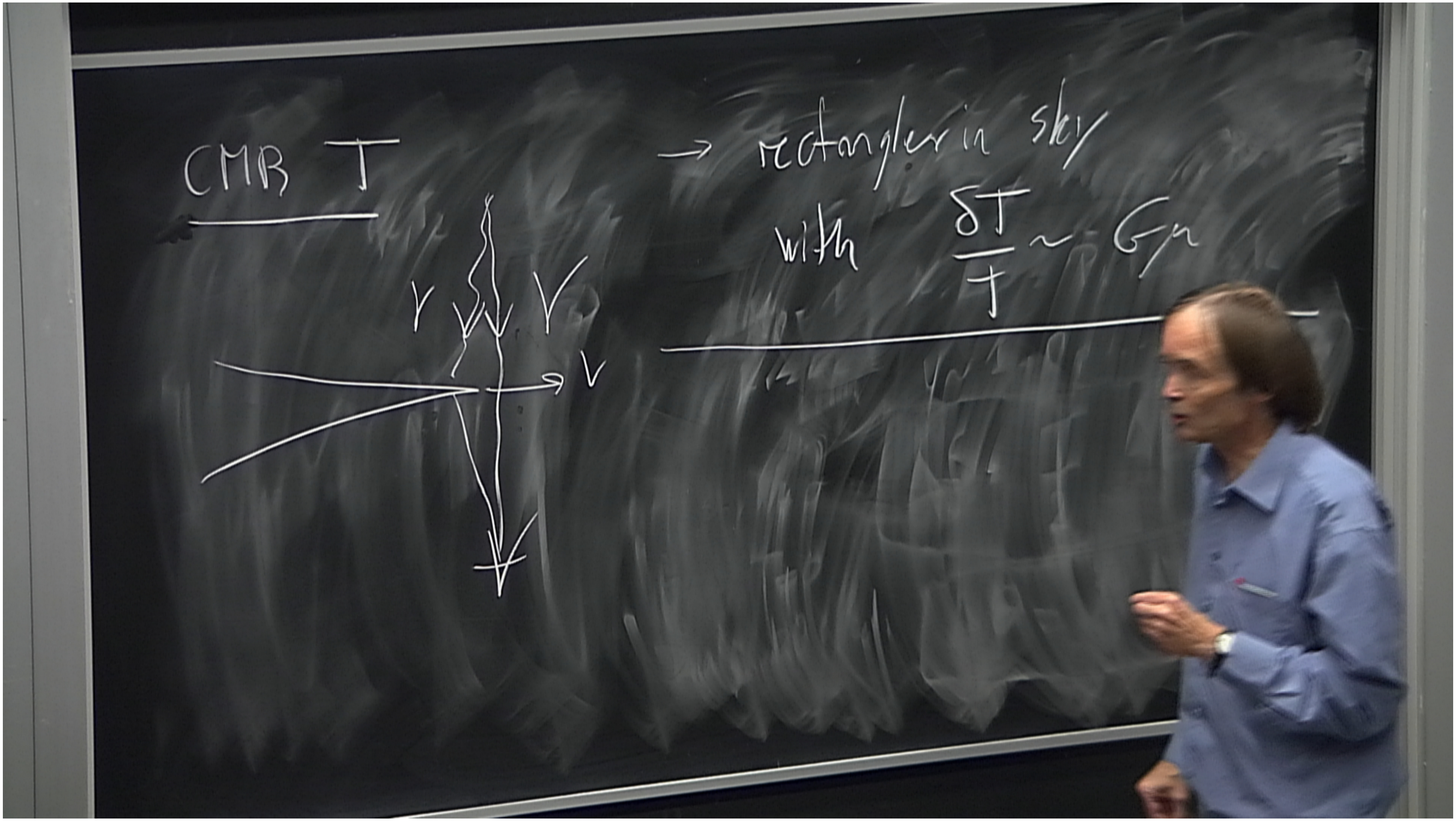
2 Wake
α
α = 8π Gμ


CMB T


CMB T


CMB T
→ rectangle in sky
with δT/T ~ Gμ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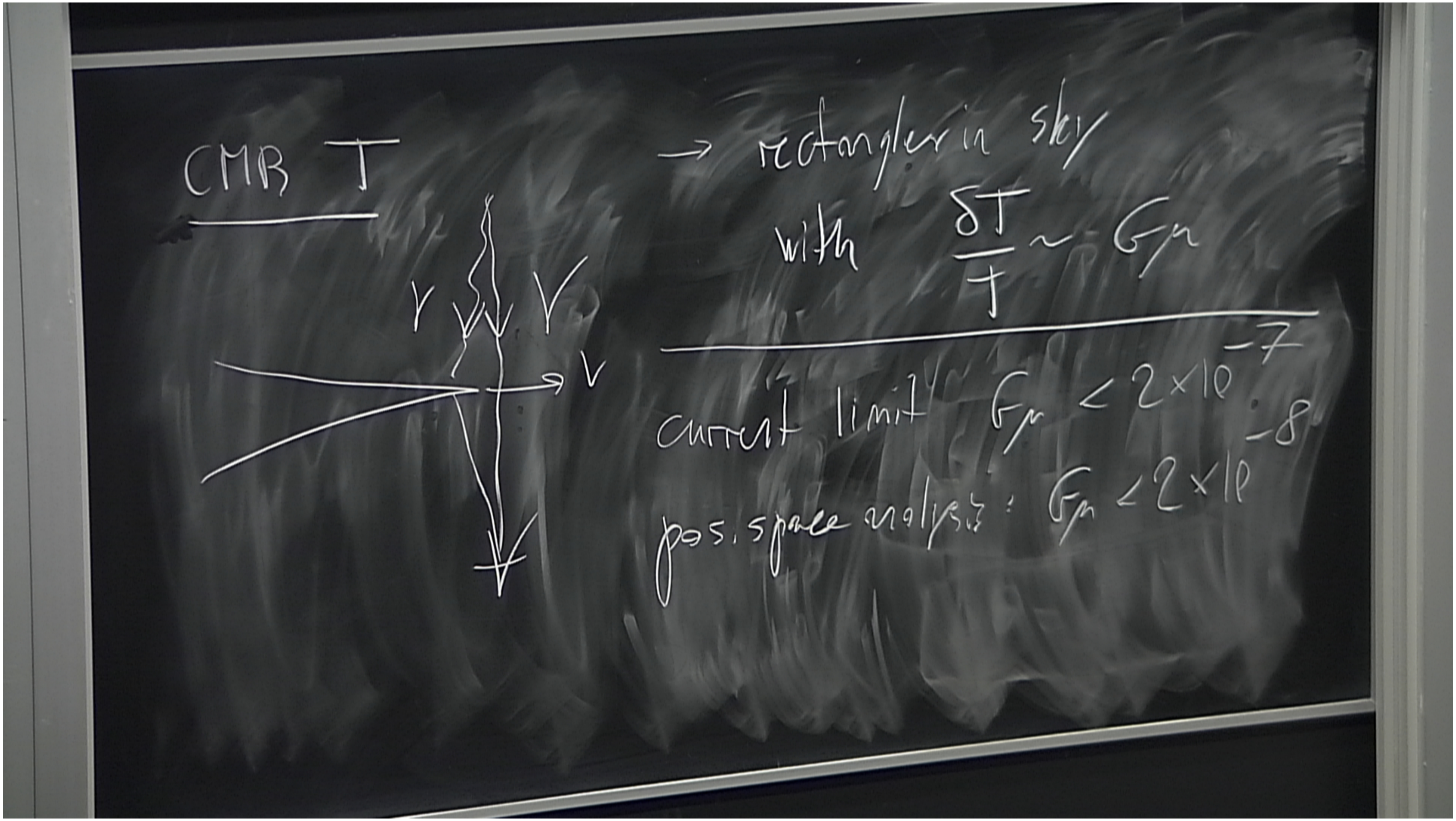
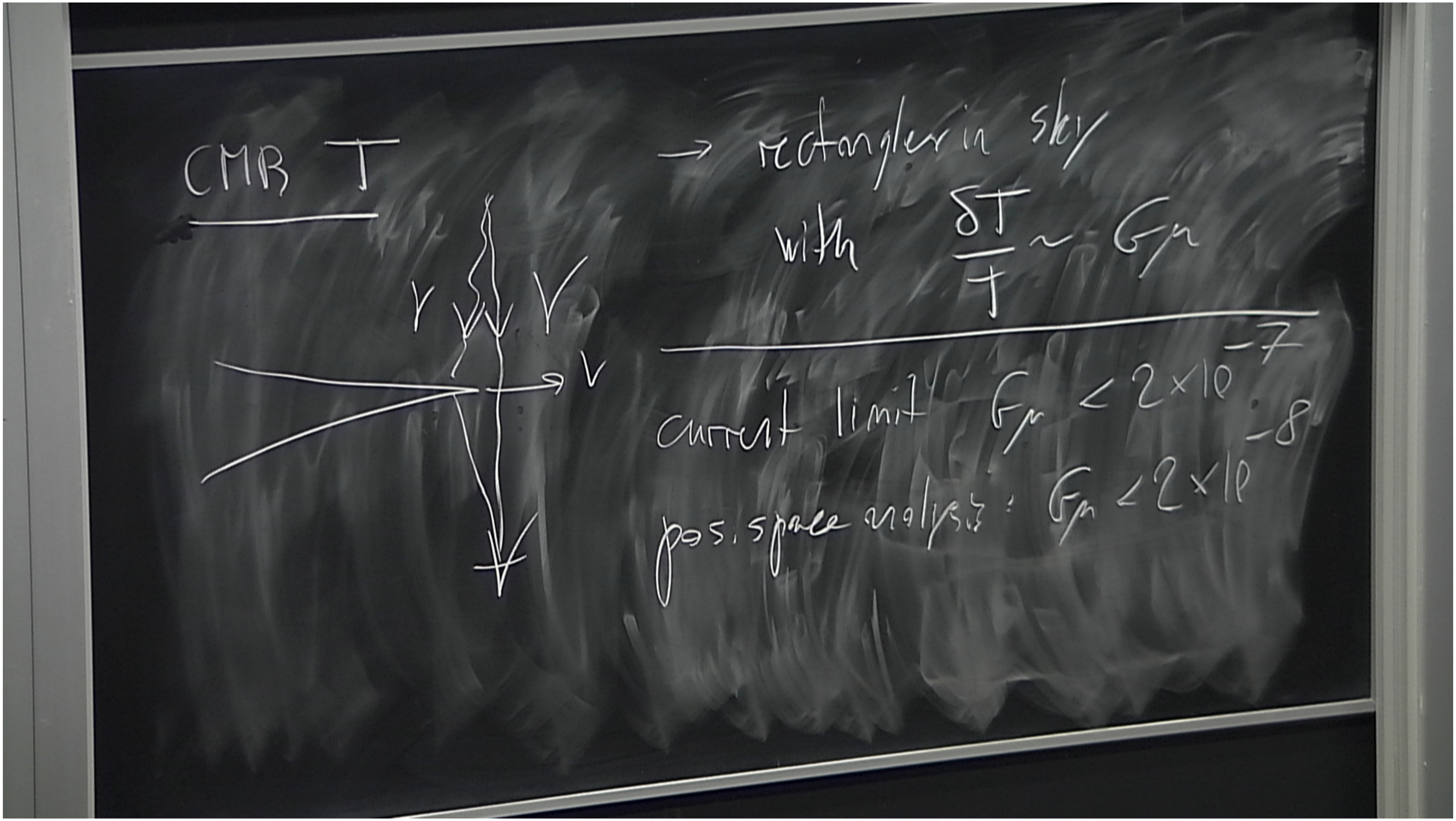

CMB T
→ rectangle in sky
with δT/T ~ Gμ
current limit: Gμ < 2×10^-7
pos. space analysis: Gμ < 2×10^-8


CMB T
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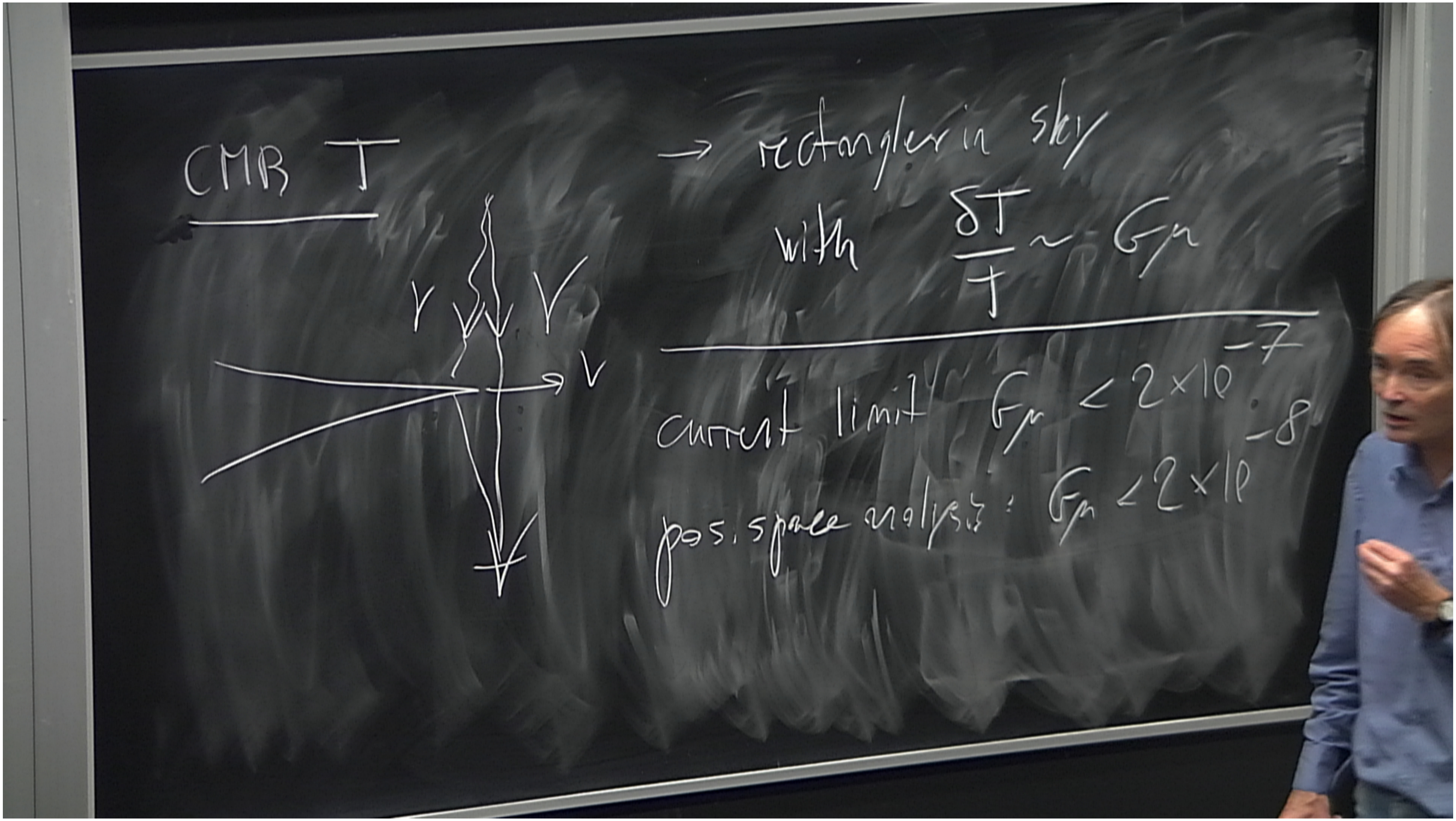
CMB T
→ rectangle in sky
with δT/T ~ Gμ
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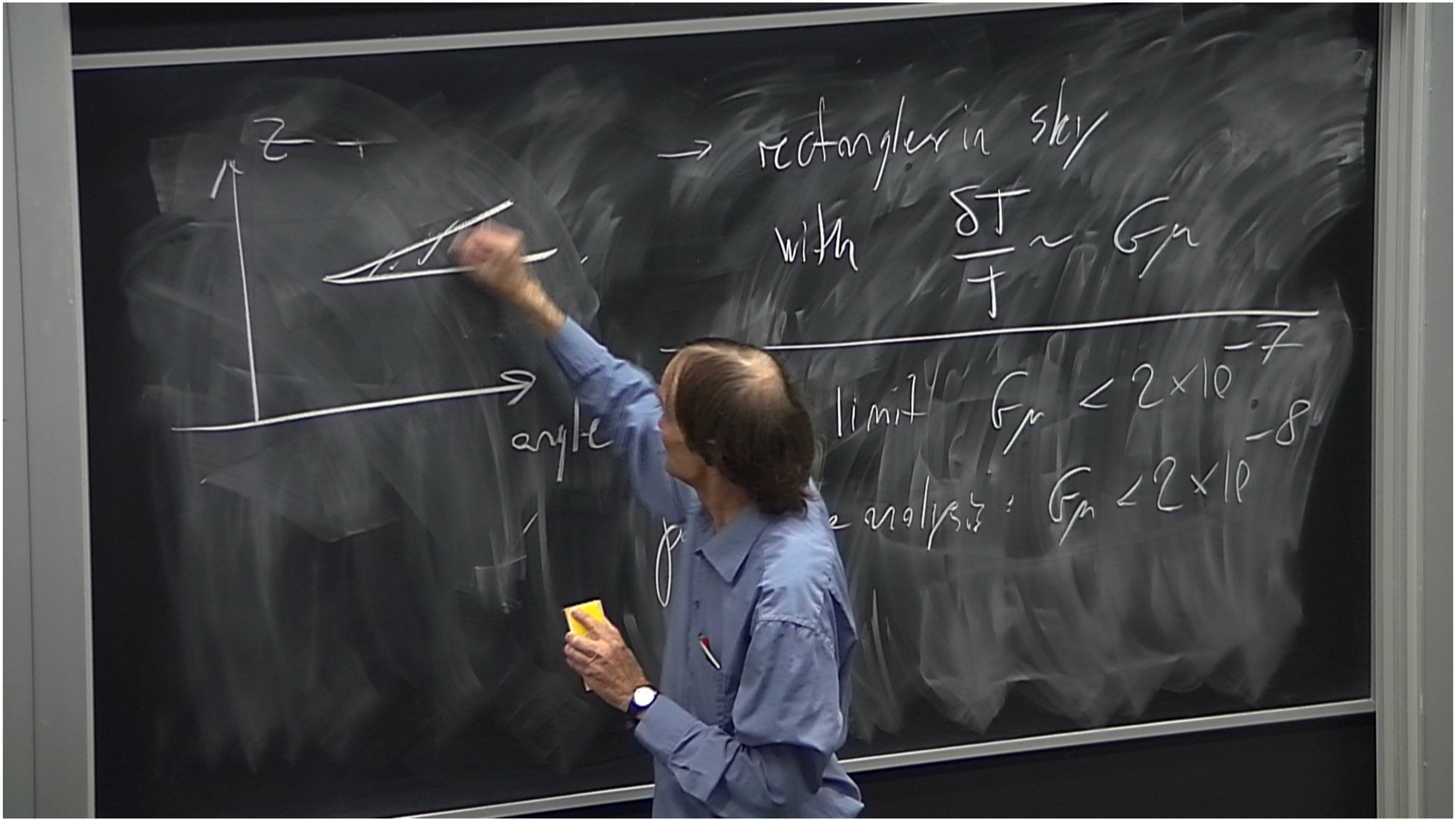
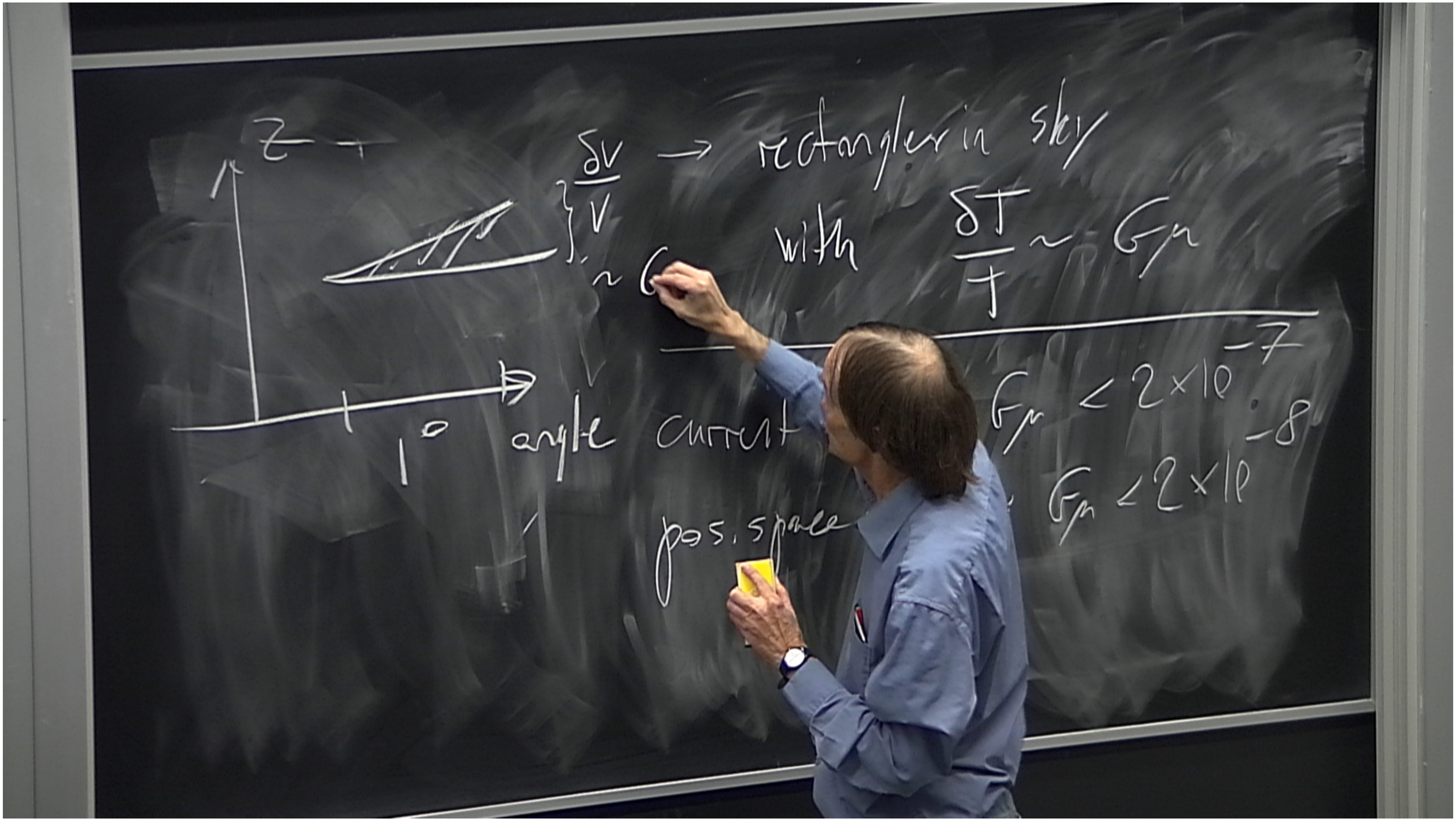
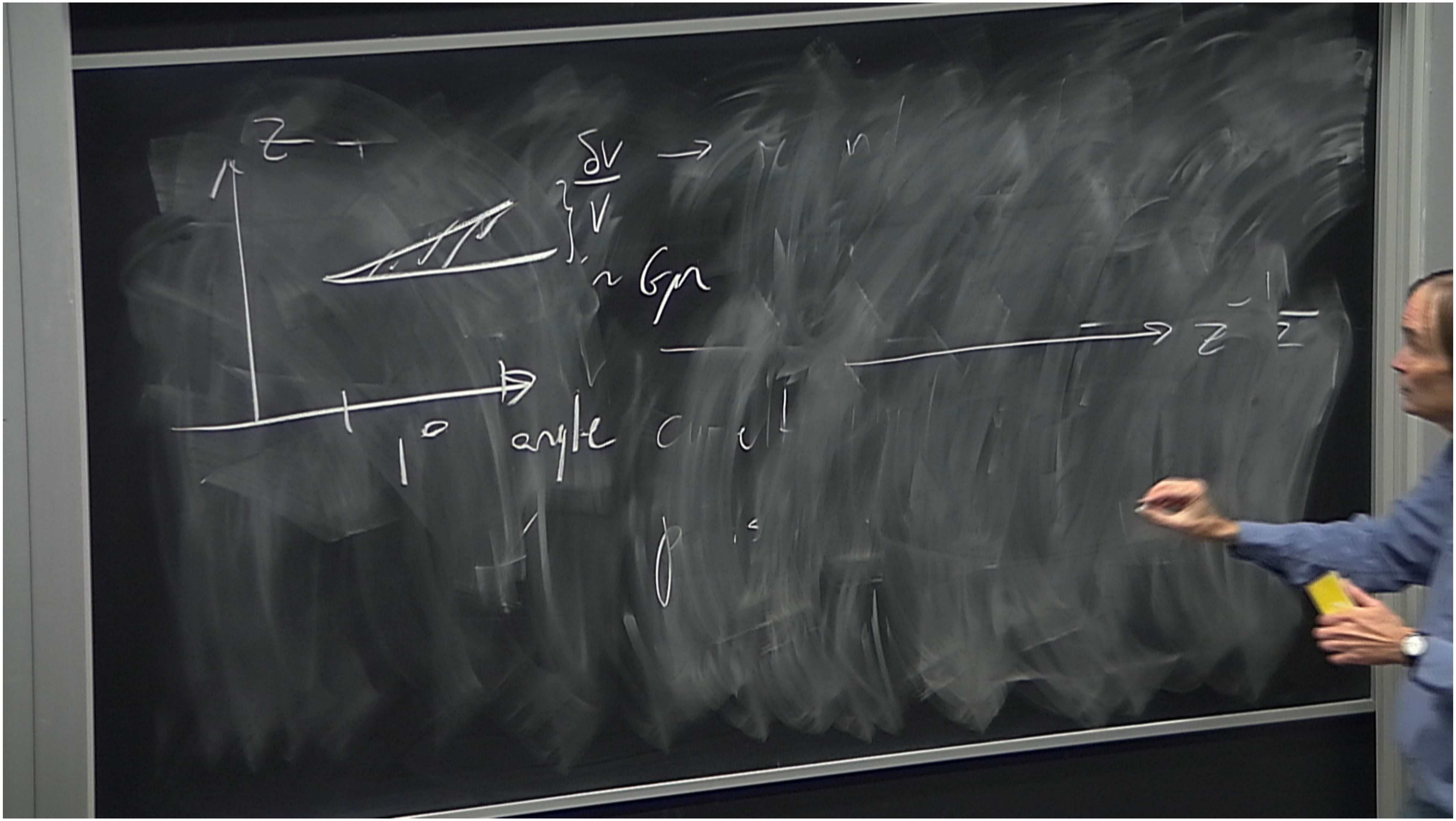


z
angle
→ rectangle in sky
with δT/T ~ Gμ
limit Gμ < 2×10⁻⁷
analysis: Gμ < 2×10⁻⁸

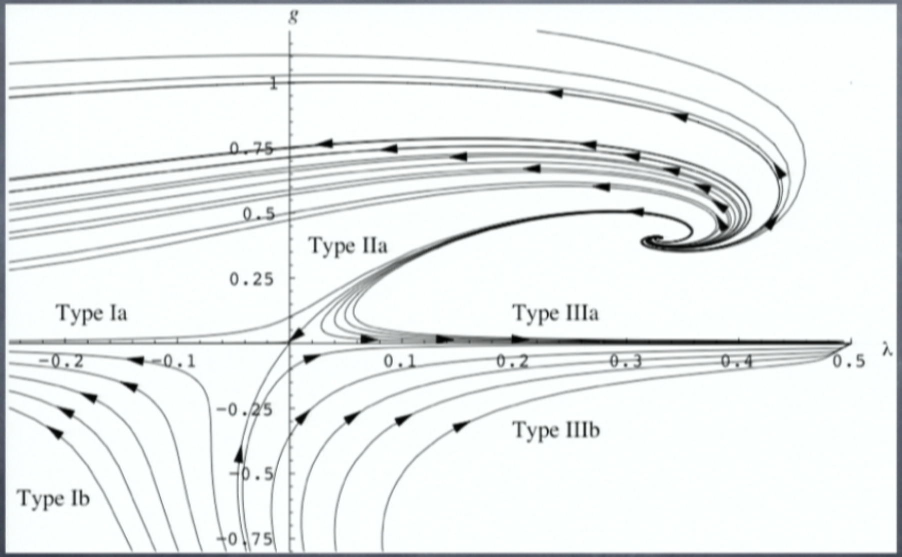

z
δv/v → rectangle in sky
~ G
with δT/T ~ Gμ
Gμ < 2×10^-7
Gμ < 2×10^-8
1°
angle
current
pos. space



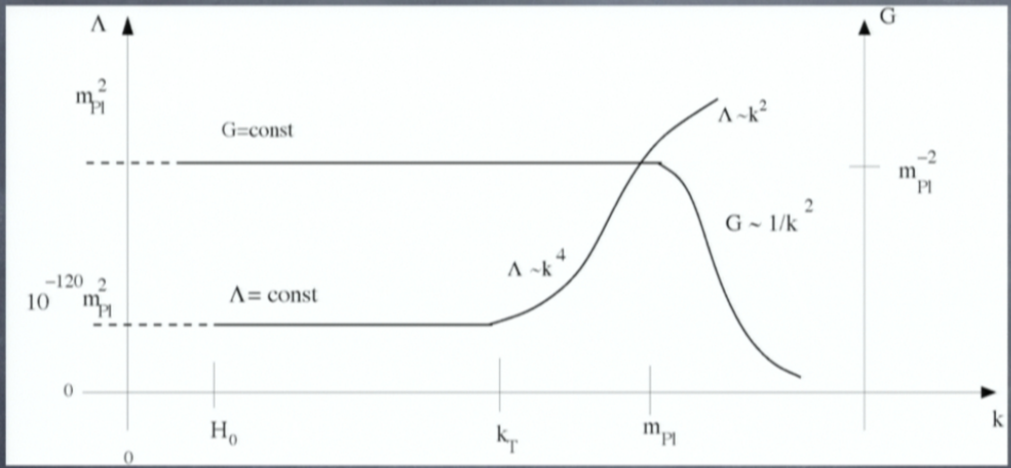
Z
δV
V
~ 6pn
1°
angle
Z


Asymptotically Safe
Inflation and CMB
Alfio Bonanno - INAF -

two attractive relevant directions with complex critical exponents



Complete cosmic history



AB & M Reuter, 2007, 2008

Asymptotically Safe Inflation (Weinberg 2010)

$$I_\Lambda[g] = -\int d^4x \sqrt{-\mathrm{Det}g}\Big[\Lambda^4 g_0(\Lambda) + \Lambda^2 g_1(\Lambda) R + g_{2a}(\Lambda) R^2$$
$$+ g_{2b}(\Lambda) R^{\mu\nu} R_{\mu\nu} + \Lambda^{-2} g_{3a}(\Lambda) R^3 + \Lambda^{-2} g_{3b}(\Lambda) R R^{\mu\nu} R_{\mu\nu} + \ldots\Big]$$

Consider a general truncation

Optimal cutoff: radiative corrections just beginning to be important and higher order terms just beginning to be less important

Objective: to obtain a dS solution which is unstable but lasts N>60 e-folds

Alternative strategy: use the field strength as a cutoff as in the “leading-log” model

RG-improve the standard QCG Lagrangian

$$\mathcal{L}_{\rm eff}^{\rm QCD} = \frac{\mathcal{F}}{2g^2_{\rm running}} \qquad g^2_{\rm running} = \frac{2g^2(\mu^2)}{1+\frac{1}{4}\,b\,g^2(\mu^2)\log\left(\frac{\mathcal{F}}{\mu^4}\right)}$$

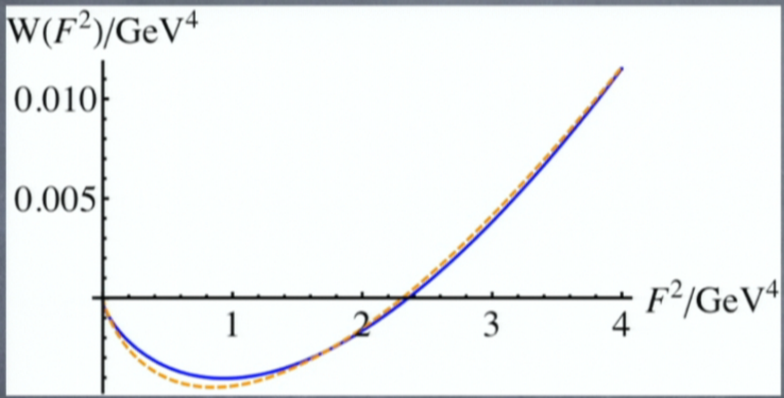
$$k^2 \propto \mathcal{F}^{1/2}$$

Alternative strategy: use the field strength as a cutoff as in the "leading-log" model

$$\mathcal{L}_{\rm eff}^{\rm QCD}(\mathcal{F}) = \frac{\mathcal{F}}{g^2}\left[1 + \frac{1}{4} b\, g^2 \log\left(\frac{\mathcal{F}}{\mu^4}\right)\right] = \frac{1}{8}\, b\, \mathcal{F} \log\left(\frac{\mathcal{F}}{{\rm e}\kappa^2}\right)$$

$$\mathcal{F} = -\frac{1}{2}(D_\mu A_\nu^a - D_\nu A_\mu^a)^2, \qquad \kappa^2 = \frac{\mu^4}{\rm e} \exp\left(-\frac{4}{bg^2}\right)$$

Alternative strategy: use the field strength as a cutoff as in the "leading-log" model



Eichhorn, Gies and Pawlowski, 2011

Apply the same approach in QG

Einstein-Hilbert truncation: $\mathcal{L}^{\mathrm{EH}} = \frac{1}{16\pi G}(R - 2\Lambda)$

Linearized flow around NGFP:

$$(\lambda, g)^{\mathbf{T}} = (\lambda_*, g_*)^{\mathbf{T}} + 2\{[\mathrm{Re}C\cos(\theta''t) + \mathrm{Im}C\sin(\theta''t)]\mathrm{Re}\,V$$
$$+[\mathrm{Re}C\cos(\theta''t) - \mathrm{Im}C\sin(\theta''t)]\mathrm{Im}\,V\}\,e^{-\theta' t}$$

$t = \ln(k/k_0)$ $\theta = \theta' \pm i\theta''$

Substitute this solution in the EH Lagrangian after identifying k with the field strength

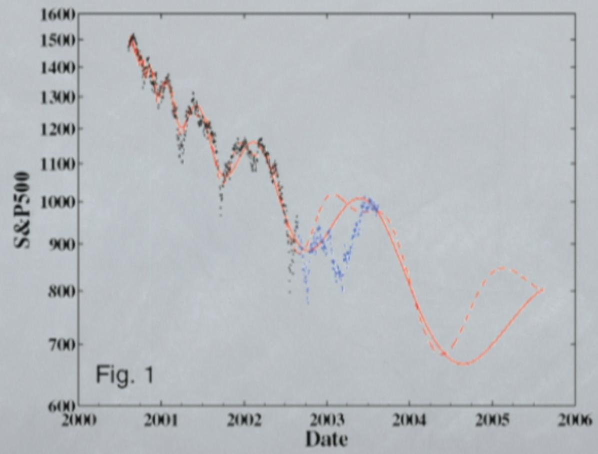
$$\mathcal{L}_{\rm eff}^{\rm QEG}(R) = R^2 + bR^2 \cos\left[\alpha \log\left(\frac{R}{\mu}\right)\right] \left(\frac{R}{\mu}\right)^{\beta}$$

$\alpha = \theta''/2,\ \beta = -\theta' < 0$

μ is a renormalization scale

$$2.1 < \theta' < 3.4, \qquad 3.1 < \theta'' < 4.3$$

Log-periodic oscillations



Stock market volatility...

$$\dot{H}^2 + 6^\beta b \cos\left[\alpha \ln\left(\frac{6(2H^2+\dot{H})}{\mu}\right)\right]\left(\frac{2H^2+\dot{H}}{\mu}\right)^\beta (2\beta H^4 + (4\alpha^2 - 6$$

$$-\beta(9+4\beta))H^2\dot{H} + (1+\beta)\dot{H}^2 + (\alpha - (1+\beta)(2+\beta))H\ddot{H})$$

$$= 2H(3H\dot{H} + \ddot{H}) + 6^\beta b\alpha \sin\left[\alpha \ln\left(\frac{6(2H^2+\dot{H})}{\mu}\right)\right]\left(\frac{2H^2+\dot{H}}{\mu}\right)^\beta$$

$$(2H^4 - (9+8\beta)H^2\dot{H} + \dot{H}^2 - (3+2\beta)H\ddot{H})$$

look for de Sitter solutions:

$$\bar{H} = \sqrt{\frac{\mu}{12}}\ \exp\left[\frac{1}{2\alpha}\left(\tan^{-1}\frac{\beta}{\alpha} + n\pi\right)\right], \quad n \in \mathbb{Z}$$

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Look for unstable solutions with growth time >>1/H so that inflation comes to an end after enough e-folds

- small perturbations: $H(t) = \bar{H} + \delta \exp(\xi \bar{H} t)$

$$\xi^2 + \xi \, 3 e^{\frac{n\pi}{2\alpha}} + A = 0$$

$$A = -\frac{4\alpha b(-1)^n\left(\alpha^2+\beta^2\right)e^{\frac{\beta \tan^{-1}\left(\frac{\beta}{\alpha}\right)+\pi(\beta+1)n}{\alpha}}}{\alpha b(-1)^n(\alpha^2+\beta^2-2)e^{\frac{\beta\left(\tan^{-1}\left(\frac{\beta}{\alpha}\right)+\pi n\right)}{\alpha}}-2\sqrt{\alpha^2+\beta^2}}$$

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The stability of the solutions does not depend on μ

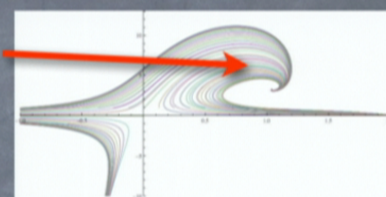
For negative values of n, A is always negative !

See Bonanno, 2012 PRD

Generation of primordial perturbations

AS cosmology: primordial perturbations arise essentially from QG fluctuations at the Planck scale

Look at the graviton propagator:



$$\langle h_{\mu\nu}(x) h_{\rho\sigma}(y) \rangle \propto \ln(x-y)^2$$

$$\tilde{G}(p) \propto 1/p^4, \quad p^2 \gg m_{Pl}^2$$

Contribution of the graviton spectrum is strongly suppressed at high momenta! -> very small power for tensor spectrum of primordial GW ...

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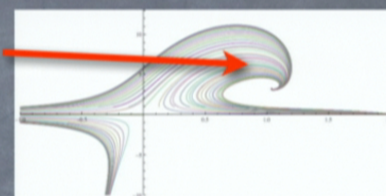

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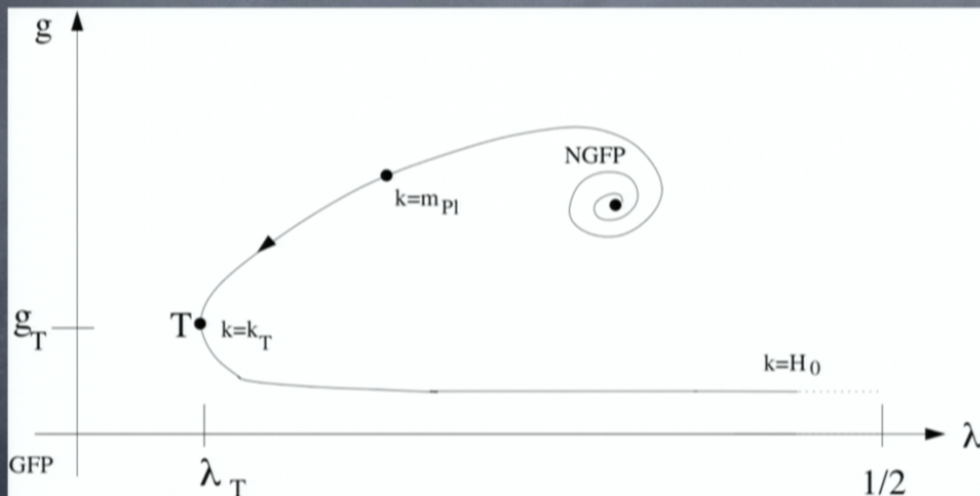
Conclusions

- An Effective Lagrangian for the Planck scale can be constructed
- de Sitter phase is unstable with the right number of e-folds with no fine tuning!
- Power spectrum of tensor perturbations at the Planck scale can be strongly suppressed

Cosmological consequences



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Could Quantum Gravity leave a chiral imprint in the Universe?

João Magueijo
2012
Imperial College, London

Based on:

* **PRL 101: 141101,2008** (Contaldi, JM, Smolin)
* **CQG 29 (2012) 052001 (Bethke, JM), PRD 84: 024014, 2011 (Bethke, JM),** PRL **106: 121302, 2011** (JM, Benincasa)
* **arXiv:1207.0637 (JM, Bethke)**

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* **CQG 29 (2012) 052001 (Bethke, JM), PRD 84: 024014, 2011 (Bethke, JM),** PRL **106: 121302, 2011** (JM, Benincasa)
* **arXiv:1207.0637 (JM, Bethke)**

Part I
The window of opportunity:

- Planck might not be as spectacular as hoped.
- We might just detect non-Gaussianities in the temperature maps.
- As for gravity waves…

The angular power spectrum:

- Usual meeting ground is the famous C_ℓ
- These are 2-point correlators: they apply to all possible pairs of T E B
- Even-parity ones: TT TE EE BB
- Odd-parity ones: TB EB

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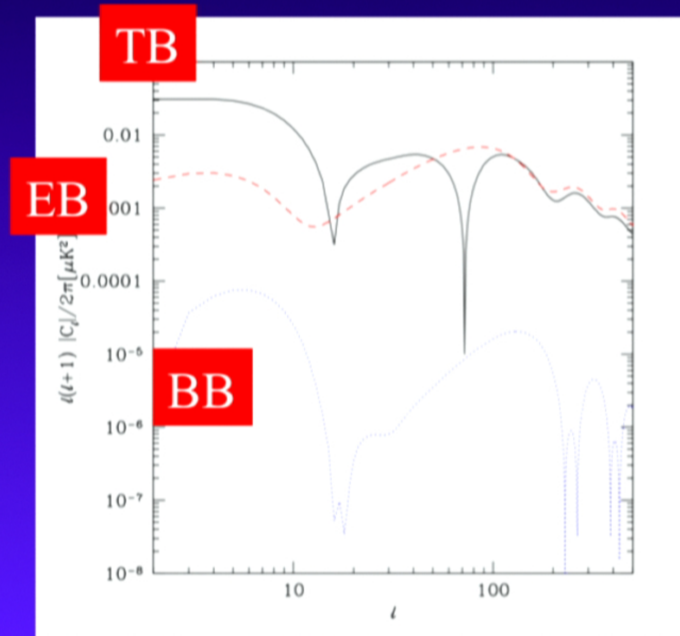
Even modest amount of L/R asymmetry in gravity waves and:

PRL101141101,2008 (Contaldi, JM, Smolin)



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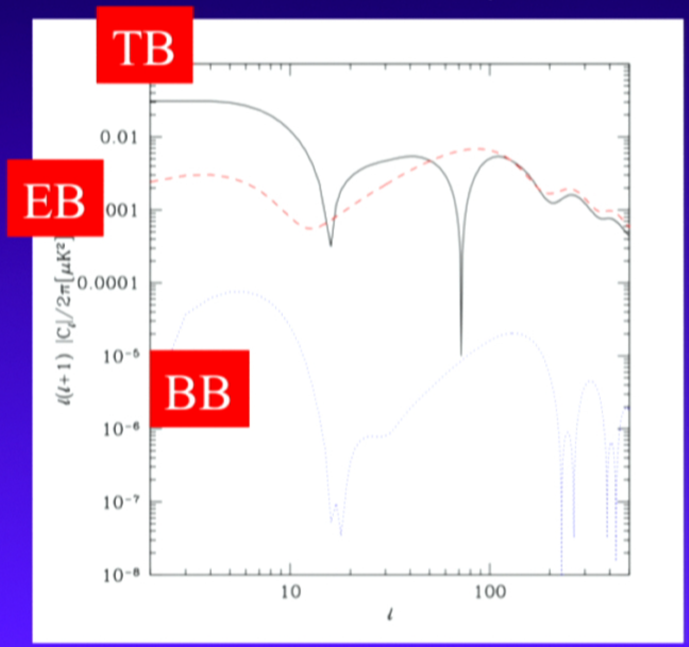

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Killing two pigeons with one stone

- Obviously it may be that there are no tensor modes (grav. wave): then of course we can't detect chirality via them!
- Obviously, it may be that there's no chirality, in which case TB=0
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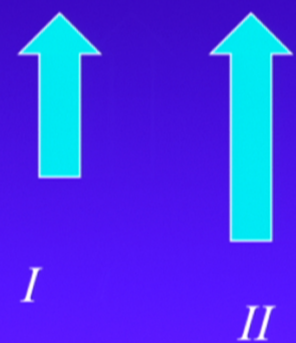
This is a general point for all theories, but…

- …here's the punch line for the calculation I'm about to present: TB>BB for

$$\frac{1}{800} < |Im\gamma| < 800$$

How tensor fluctuations are produced in a deSitter background:

$$v'' + \left(k^2 - \frac{2}{\eta^2}\right)v = 0$$



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- What is the vacuum? (Bunch-Davis?)
- Can we really second quantize metric fluctuations without full knowledge of quantum gravity?
- Is the calculation indifferent to the details of quantum gravity?

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YOU GUYS HAVE NOT HELPED MATTERS:

- A few years back there were some serious claims made regarding the value of the Kodama state.
- Controversy…
- Smoke screen

First must recover standard Cosmological Perturbation Theory in Ashtekar's formalism

- A character building exercise: But it's an important check!
- It exposes past "misunderstandings":
  - Helicity aligns with duality
  - The Kodama state can be used as the ground state of quantum gravity

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  - The Kodama state can be used as the ground state of quantum gravity

Not nice, but right… (8 instead of 2)

$$\delta e_{ij} = \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}} \sum_r \epsilon^r_{ij}(\mathbf{k})\tilde{\Psi}_e(\mathbf{k},\eta)e_{r+}(\mathbf{k}) + \epsilon^{r\star}_{ij}(\mathbf{k})\tilde{\Psi}^\star_e(\mathbf{k},\eta)e^\dagger_{r-}(\mathbf{k})$$

$$a_{ij} = \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}} \sum_r \epsilon^r_{ij}(\mathbf{k})\tilde{\Psi}^{r+}_a(\mathbf{k},\eta)a_{r+}(\mathbf{k}) + \epsilon^{r\star}_{ij}(\mathbf{k})\tilde{\Psi}^{r-\star}_a(\mathbf{k},\eta)a^\dagger_{r-}(\mathbf{k})$$

$$\tilde{\Psi}(\mathbf{k},\eta) = \Psi(k,\eta)e^{i\mathbf{k}\cdot\mathbf{x}}$$

$$\Psi(k,\eta) \sim e^{-ik\eta}$$

Duality and helicity don't align

	$r = +$ [R]	$r = -$ [L]
$p = +$ $[G]$	SD	ASD
$p = -$ $[\overline{G}]$	ASD	SD

A. Ashtekar, J. Math.Phys. 27, 824, 1986.

What's new in this version of QG? Quantization is different!!!

A sort of uncertainty relations between metric and connection

$$[\tilde{a}_{rp}(\mathbf{k}), \tilde{e}^{\dagger}_{sq}(\mathbf{k}')] = -i\gamma p \frac{l_P^2}{2} \delta_{rs} \delta_{p\bar{q}} \delta(\mathbf{k} - \mathbf{k}') ,$$

It begs the question: that being the case, what's the graviton made of?

The Hamiltonian reveals special graviton operators (for SD/ASD)

$$
\begin{aligned}
g_{r+}(\mathbf{k}) &= \tilde{a}_{r+}(\mathbf{k}) \\
g^{\dagger}_{r+}(\mathbf{k}) &= -\tilde{a}^{\dagger}_{r-}(\mathbf{k}) + 2kr\tilde{e}^{\dagger}_{r-}(\mathbf{k}) \\
g_{r-}(\mathbf{k}) &= -\tilde{a}_{r+}(\mathbf{k}) + 2kr\tilde{e}_{r+}(\mathbf{k}) \\
g^{\dagger}_{r-}(\mathbf{k}) &= \tilde{a}^{\dagger}_{r-}(\mathbf{k})
\end{aligned}
$$

(Much more intricate for general gamma, see: Bethke and JM PRD 84: 024014, 2011.)

They inherit a funny algebra:

- Something is wrong with half the modes:

$$[g_{rp}(\mathbf{k}), g^{\dagger}_{sq}(\mathbf{k}')] = -i\gamma l_P^2 (pr) k \delta_{rs} \delta_{pq} \delta(\mathbf{k} - \mathbf{k}')$$

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The inner product then implements the reality conditions:

With ansatz:

$$\langle \Phi_1 | \Phi_2 \rangle = \int dz d\bar{z} e^{\mu(z,\bar{z})} \bar{\Phi}_1(\bar{z}) \Phi_2(z)$$

We should require on all states:

$$\langle \Phi_1 | g^{\dagger}_{rp} | \Phi_2 \rangle = \overline{\langle \Phi_2 | g_{rp} | \Phi_1 \rangle}$$

With solution:

$$\mu(z, \bar{z}) = \int d\mathbf{k} \sum_{rp} \frac{pr}{ik\gamma l_P^2} z_{rp}(\mathbf{k}) \bar{z}_{rp}(\mathbf{k})$$

If you choose a non-chiral ordering you get chiral physical VEV

- This propagates into the vacuum two-point function, with similar chiral behaviour:

$$
\begin{aligned}
A_R^{ph}(\mathbf{k}) &= a_{R+}(\mathbf{k})e^{-ik\cdot x} = g_{R+}(\mathbf{k})e^{-ik\cdot x} \\
A_L^{ph}(\mathbf{k}) &= a_{L+}^\dagger(\mathbf{k})e^{ik\cdot x} = g_{L+}^\dagger(\mathbf{k})e^{ik\cdot x} \ ,
\end{aligned}
$$

$$
\begin{aligned}
\langle 0|A_R^{ph\dagger}(\mathbf{k})A_R^{ph}(\mathbf{k}')|0\rangle &= \langle 0|g_{R+}^\dagger(\mathbf{k})g_{R+}(\mathbf{k})|0\rangle = 0 \\
\langle 0|A_L^{ph\dagger}(\mathbf{k})A_L^{ph}(\mathbf{k}')|0\rangle &= \langle 0|g_{L-}(\mathbf{k})g_{L-}^\dagger(\mathbf{k})|0\rangle \neq 0
\end{aligned}
$$

- Eg: for the SD connection only the L graviton has vacuum fluctuations

Quantum gravity does correct the inflationary calculation

- Scale invariant tensor fluctuations are left outside the horizon, but they are chiral:

$$\frac{P_R - P_L}{P_R + P_L} = \frac{2i\gamma}{1-\gamma^2}$$

- The chirality depends on the Barbero-Immirzi parameter

The punch line:

- TB>BB for

$$\frac{1}{800} < |Im\gamma| < 800$$