Title: Quantum Field Theory for Cosmology - Lecture 1

Date: Jan 12, 2010 04:00 PM

URL: http://pirsa.org/10010071

Abstract: This course begins with a thorough introduction to quantum field theory. Unlike the usual quantum field theory courses which aim at applications to particle physics, this course then focuses on those quantum field theoretic techniques that are important in the presence of gravity. In particular, this course introduces the properties of quantum fluctuations of fields and how they are affected by curvature and by gravitational horizons. We will cover the highly successful inflationary explanation of the fluctuation spectrum of the cosmic microwave background - and therefore the modern understanding of the quantum origin of all inhomogeneities in the universe (see these amazing visualizations from the data of the Sloan Digital Sky Survey. They display the inhomogeneous distribution of galaxies several billion light years into the universe: Sloan Digital Sky Survey).

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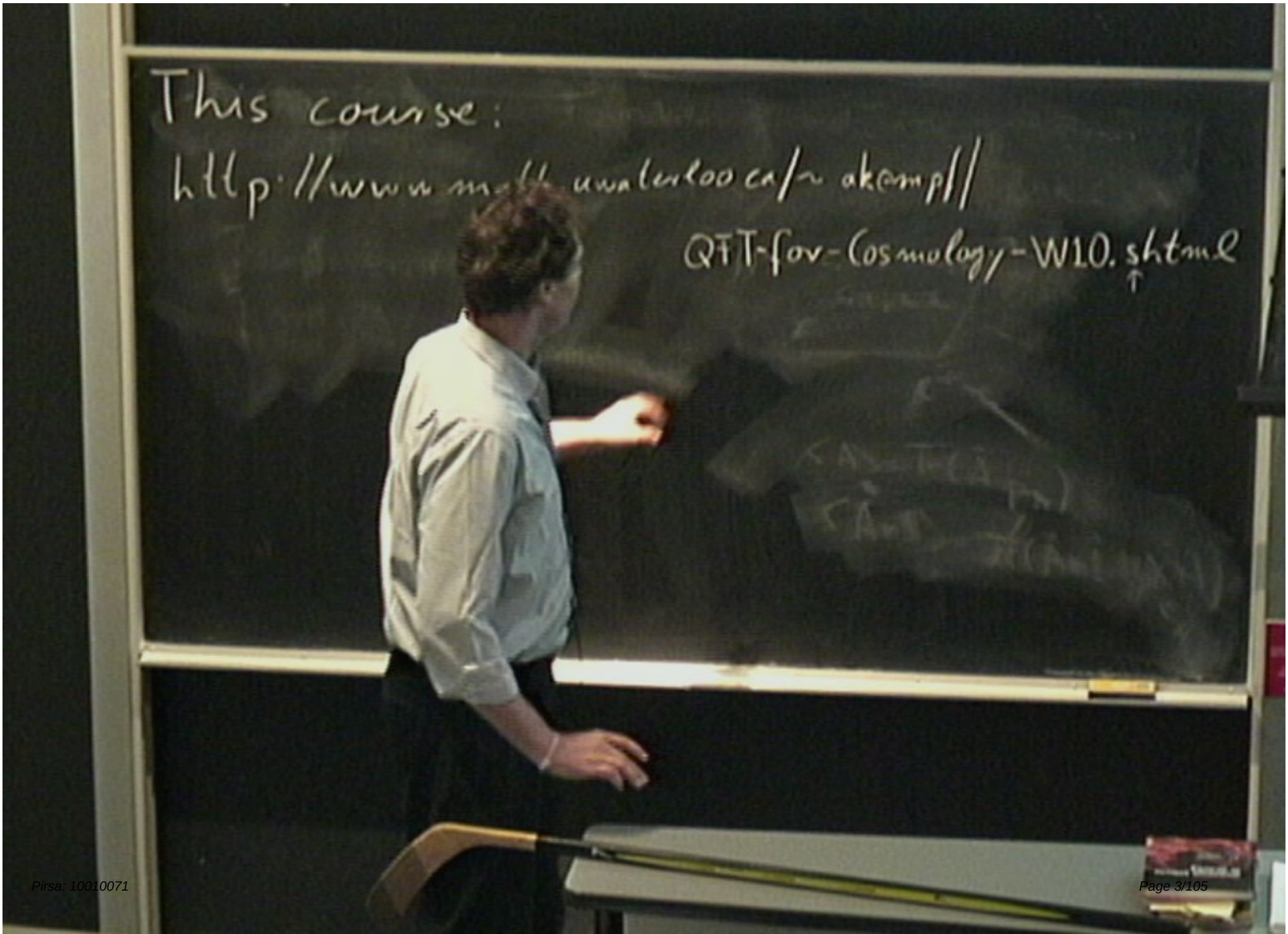
Quantum Field Theory for Cosmology

AMATH872 / PHYS785

Winter 2010

Instructor:	A. Kempf, (MC6071, ext. 35462)
Prerequisite:	AMATH 673, PHYS702 or consent of instructor. Some knowledge of General Relativity.
Time:	Tuesdays 4-5:20pm + Thursdays 5-6:20pm
Venue:	Perimeter Institute's Bob room Video-linked to: * Univ. of Waterloo, Room MC6091 * Univ. of Guelph, Rozanski Room 106 * possibly other venues upon request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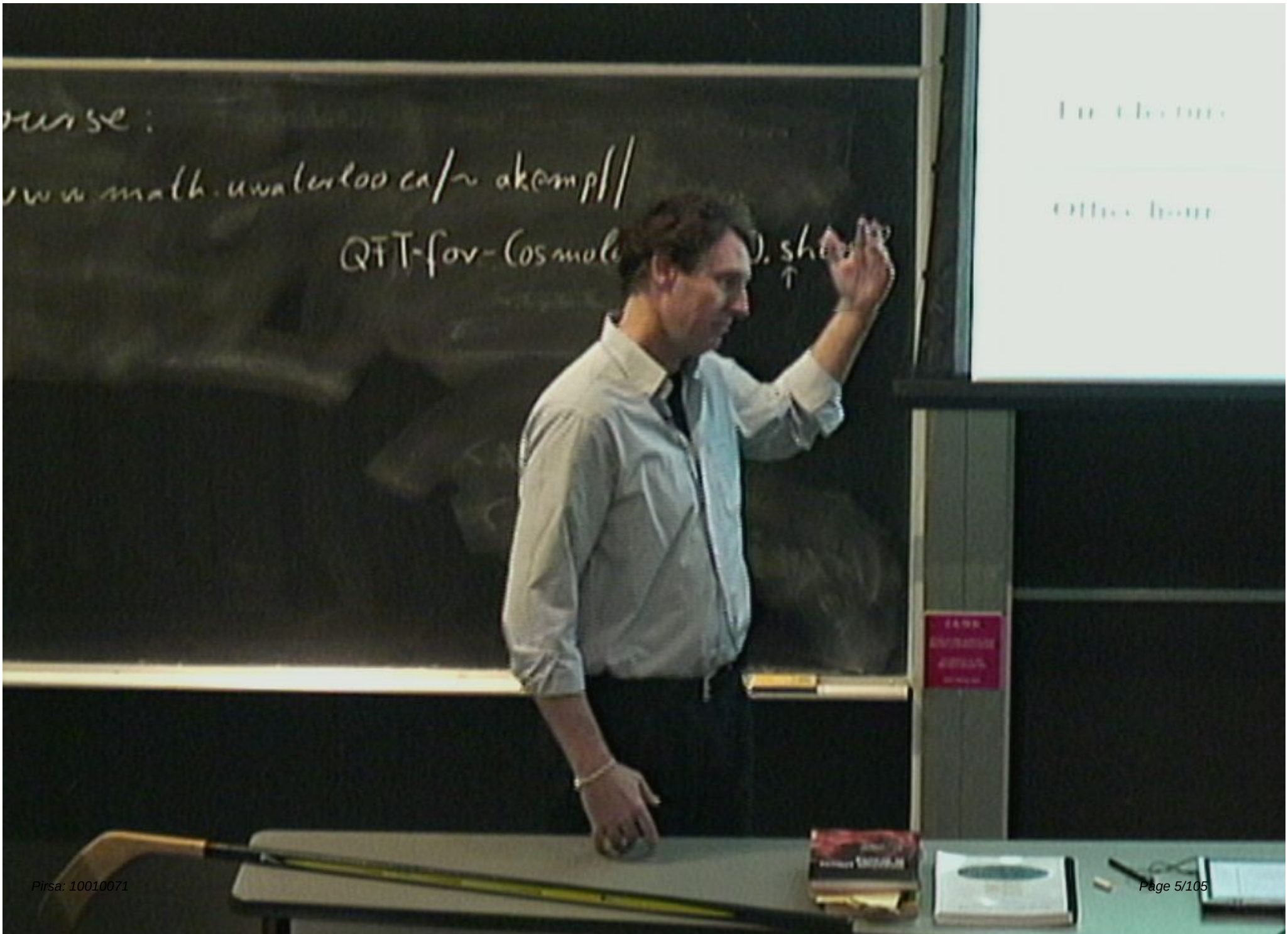
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First lecture:	**Tuesday, January 12, 2010, Bob room, PI, 4-5:20pm**
Office hours:	by arrangement

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| Achim Kempf | Department of Applied Mathematics | University... http://www.math.uwaterloo.ca/~akempf/QFT-for-Cosmol

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Outline:

- From first to second quantization.

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- From first to second quantization.
- Introduction to scalar quantum field theory.

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Outline:

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Outline:

- From first to second quantization.
- Introduction to scalar quantum field theory.
- The Unruh effect.
- Canonical quantization in curved space-times.
- Path integral quantization of fields
- Quantum fluctuations of scalar fields and of the metric.
- Applications: Inflationary cosmology and the origin of structure.
- (Time permitting:) Effective action and gravitational backreaction

---

Lecture notes:

Detailed lecture notes will be made freely available here, usually a few days before each lecture.

In the meantime, here are the lecture notes of the previous teaching of this course, in W08:

Lecture notes of W08: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

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Additional Literature:

- We will often follow this text:

  V. Mukhanov, Sergei Winitzki, Introduction to Quantum Effects in Gravity, Cambridge University Press, June 2007

Note that this text includes problems with solutions

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  - A. R. Liddle, D. H. Lyth, *Cosmological Inflation and Large-Scale Structure*, CUP, 2000.
  - T. Jacobson, *Introduction to Quantum Fields in Curved Spacetime and the Hawking Effect*, freely available at http://arxiv.org/abs/gr-qc/0308048
  - L.H. Ford, *Quantum Field Theory in Curved Spacetime*, freely available at http://arxiv.org/abs/gr-qc/9707062

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Essay topics:

- *Planck scale effects in inflationary cosmology*
  Literature suggestions: Brandenberger et al., Kempf et al., Greene et al, see also Brian Greene's talk online.

- *Sonic analog of black holes and Hawking radiation*
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What is expected in an essay:

Show that you have understood and critically reflected upon the material by making it your own. You make it your own by coming up with an original way for presenting the material that you are bringing together. Try to give it your

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a way that is hard to improve. In this case, you can make it your own by filling in steps in trhe calculation that the author omitted (and point out that you do so). That obviously proves that you understood that calculation. No original research is expected but try to become sufficiently familiar with the topic that you can make educated speculations about what interesting things could be done in this area. Feel free to mention what comes to mind. Show creativity. In research, just asking the right questions is often the key to breakthroughs.

Essay format:

- Length: 15-20 pages, pdf format
- Format: title+abstract page / introduction / main parts / summary (or conclusions) / bibliography
- It is very important that you refer to your sources explicitly, i.e. the bibliography is very important. List items in the sequence in which you are referring to them in the text.

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Relationship to other courses:

This course is one in a group of four related graduate courses whose curricula have been coordinated so as to optimally complement another:

- AMATH875/PHYS786, *General Relativity for Cosmology*, taught F07, F09 etc., see GR for Cosmology.
- PHYS784/AMATH874, *Advanced Techniques in General Relativity and Applications to Black Holes*, taught W08, W10 etc.
- AMATH872/PHYS785, *Introduction to Quantum Field Theory for Cosmology*, (this course) taught W08, W10 etc.
- PHYS703,AMATH873, *Quantum Field Theory* (for high energy physics), taught

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Grades:

The final will count 40%, the essay 60%.

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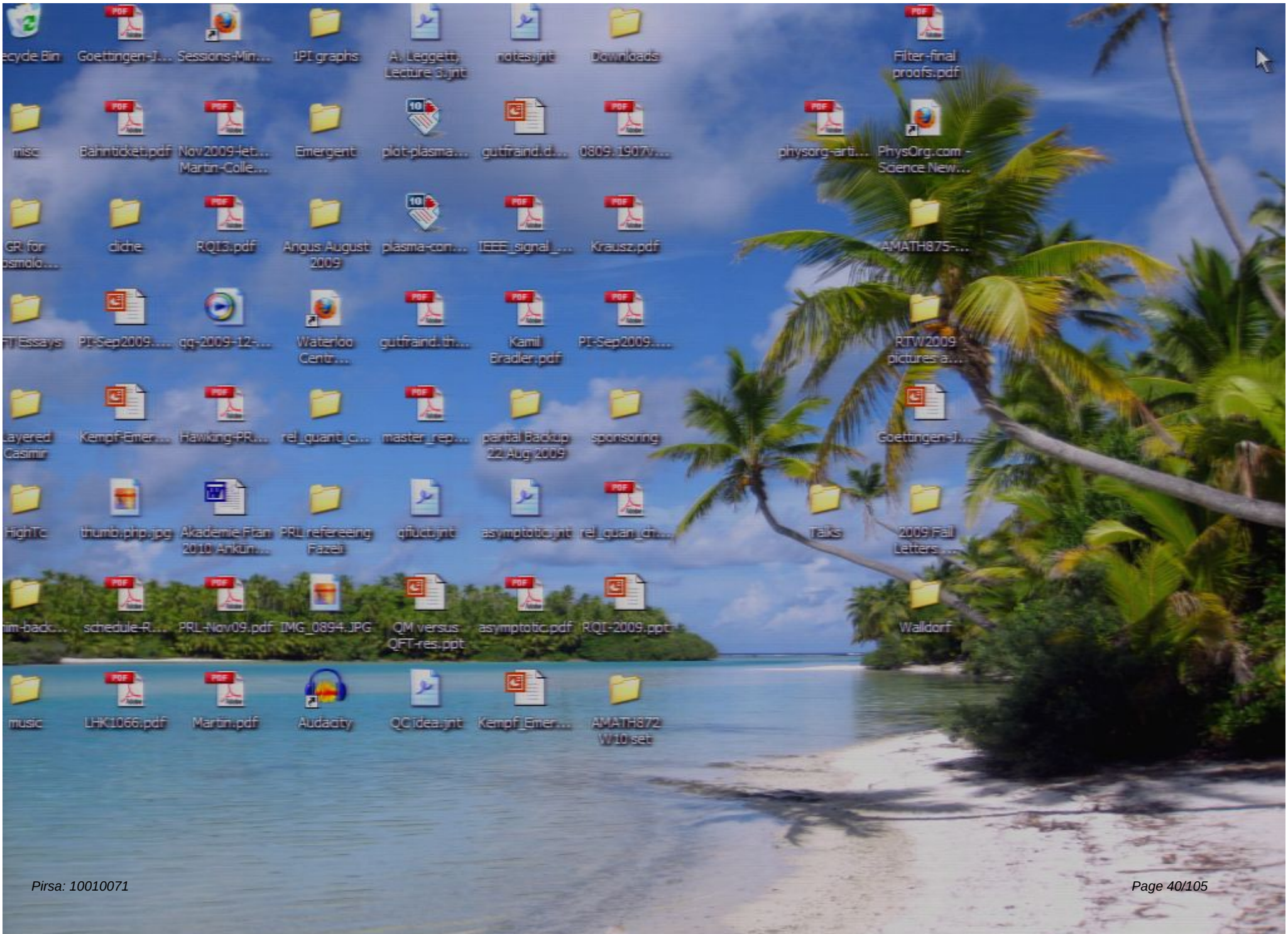
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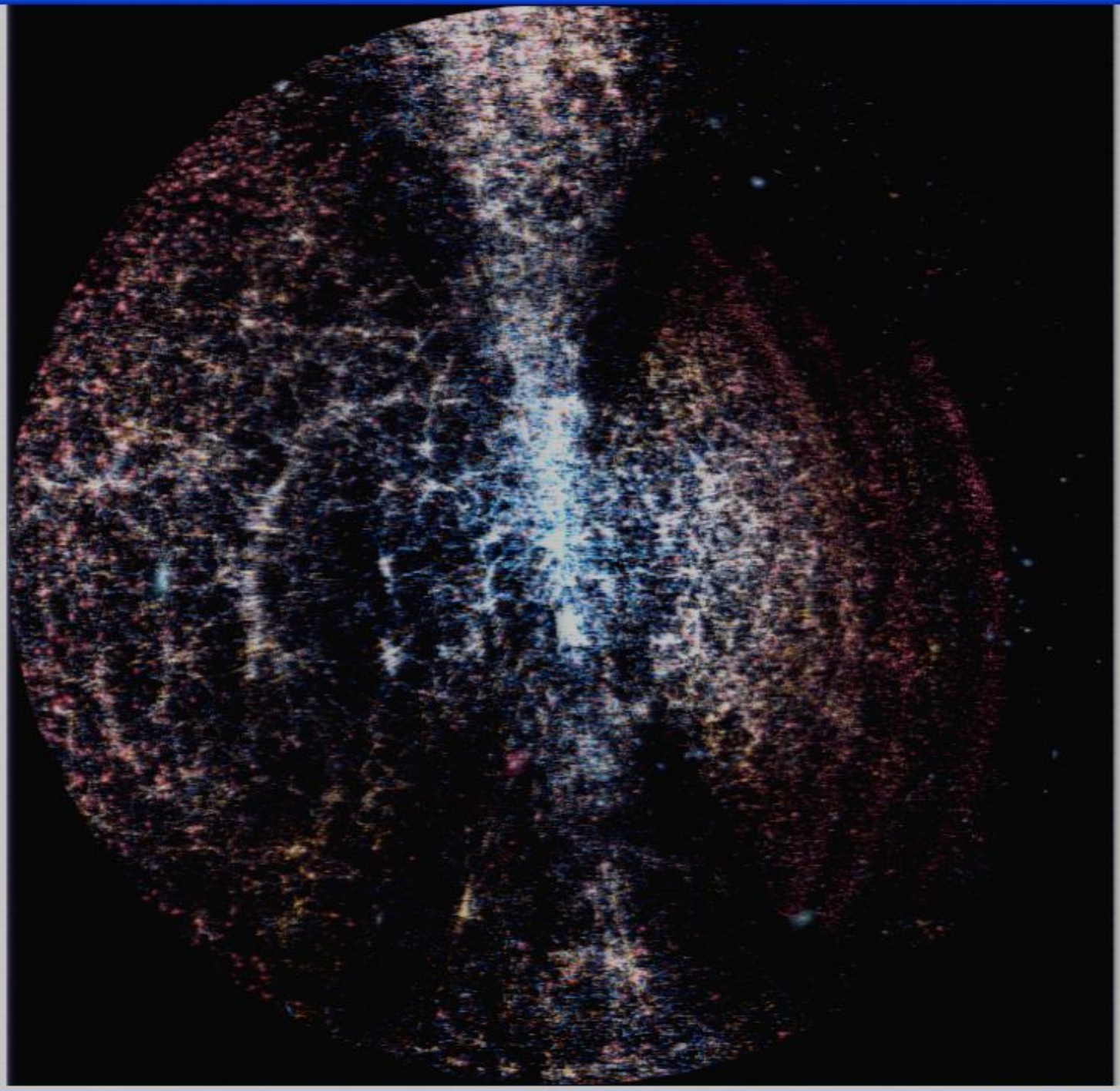

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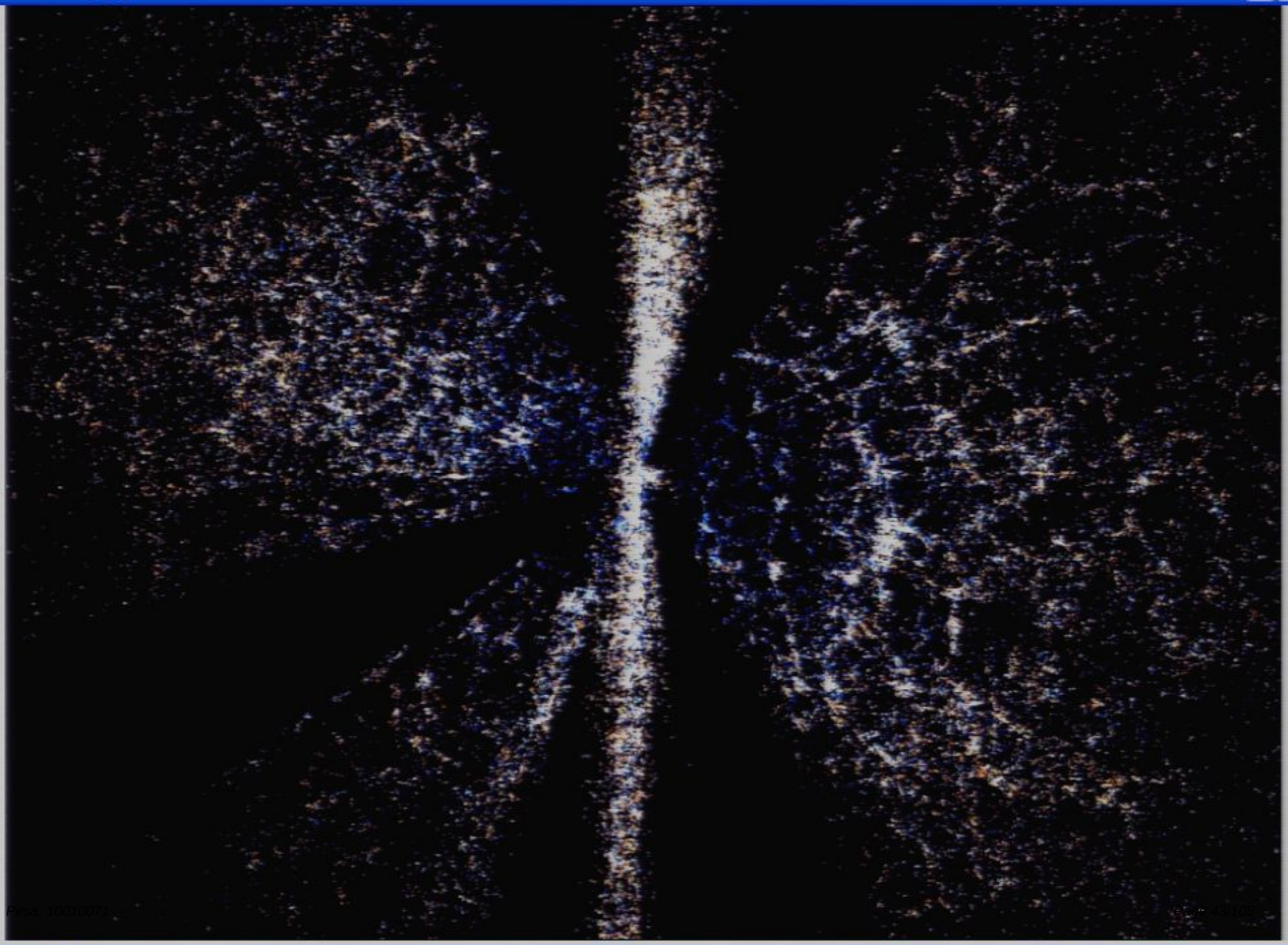

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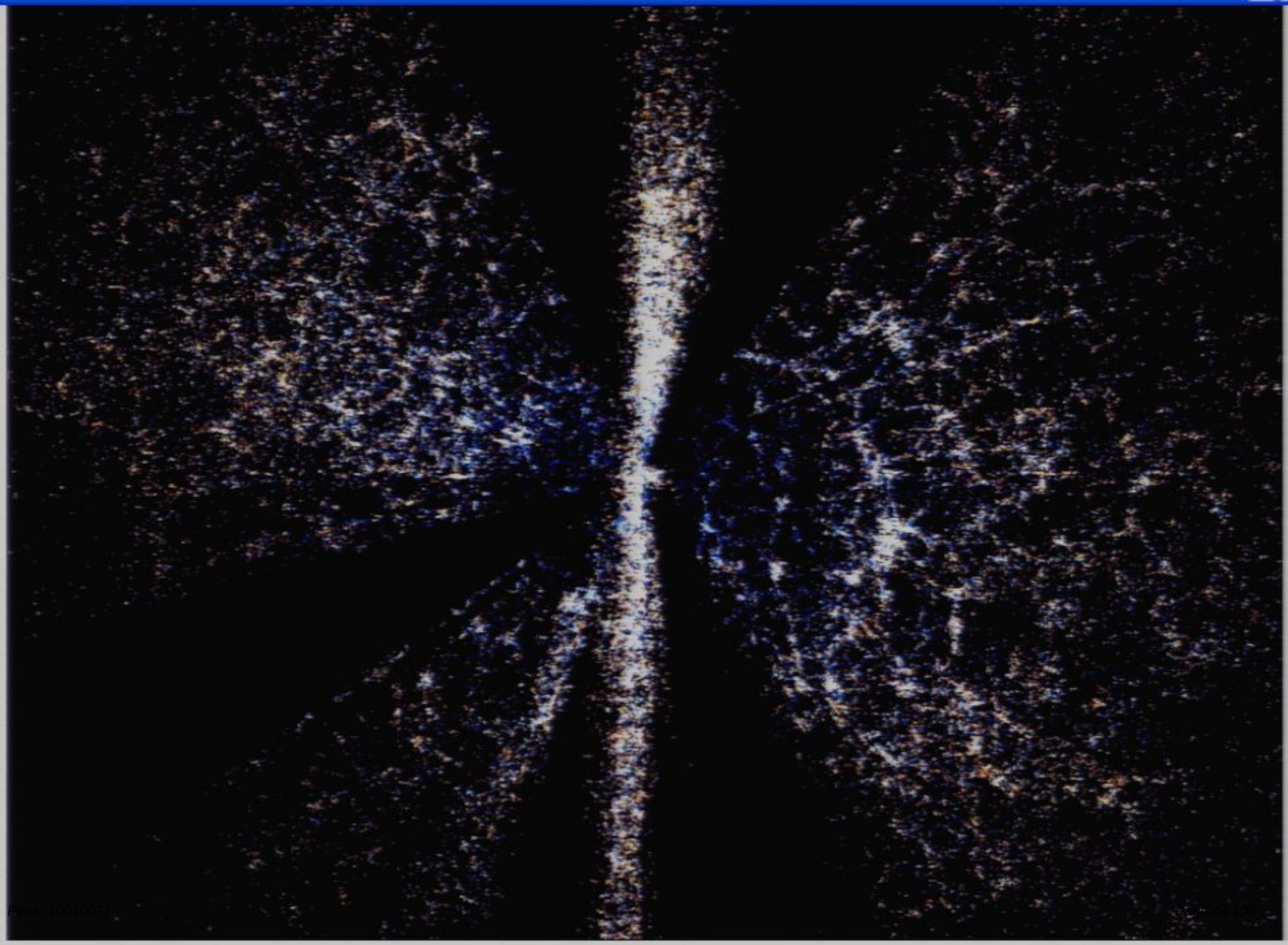

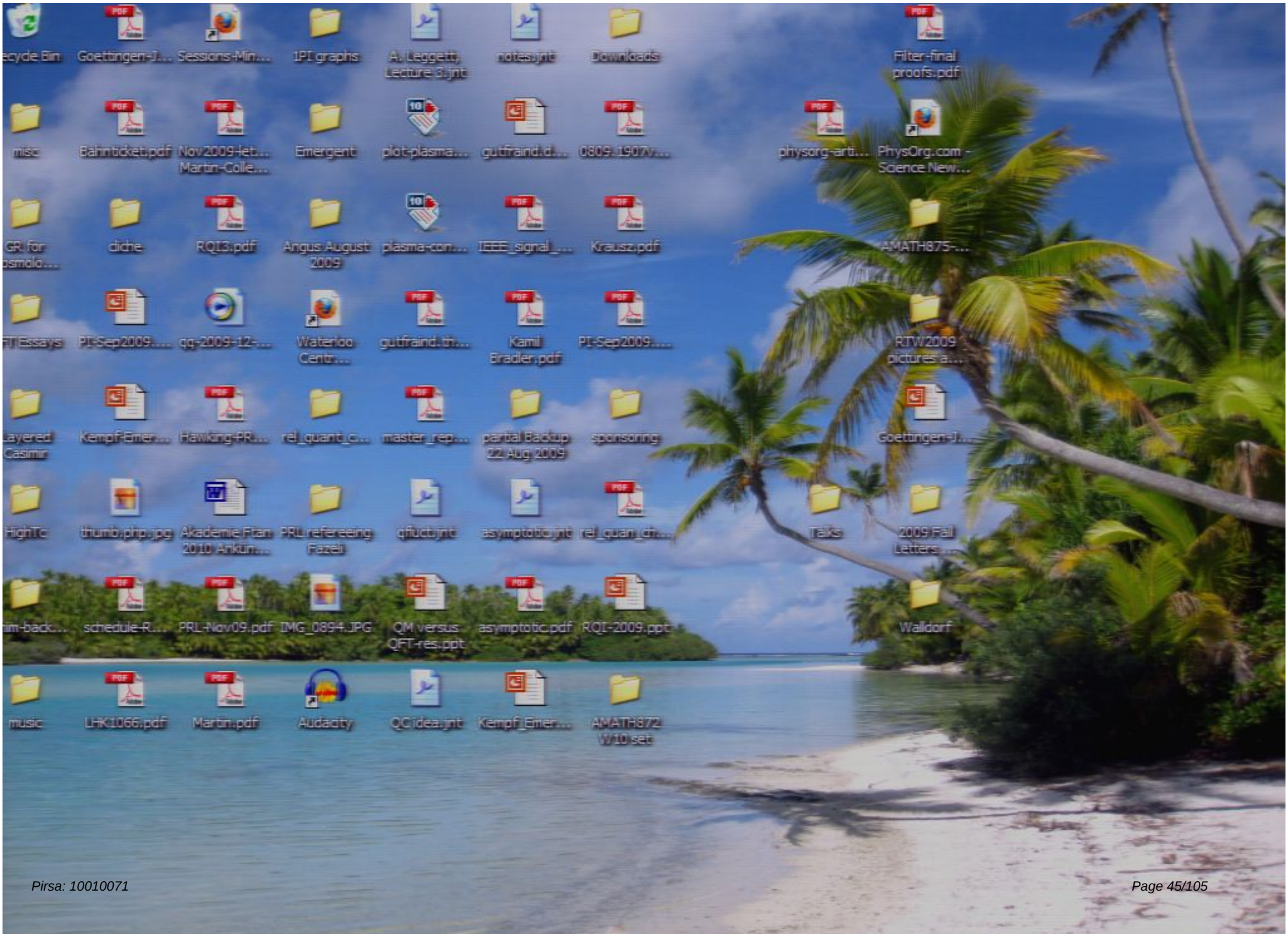
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QFT for Cosmology, Achim Kempf, Winter 10, Lecture 1

Note Title 1/9/2006

Historical background:

- ≈ 1900:

Classical mechanics became experimentally untenable:

- Black body radiation ← ("Ultraviolet catastrophe")
- Photoelectric effect ← (Ionization depends on color, not intensity)
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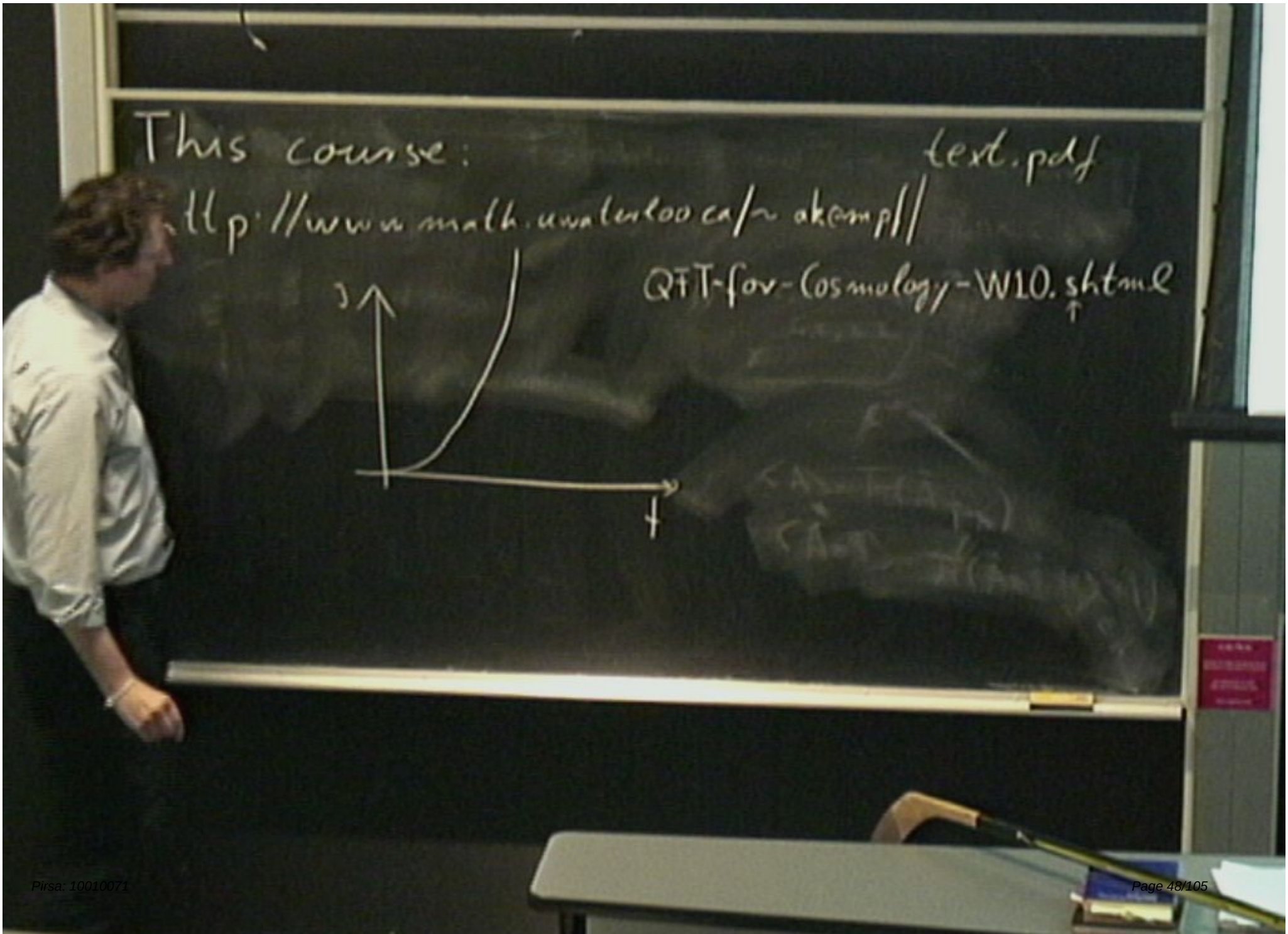
Heisenberg discovers nonrelativistic quantum mechanics (QM):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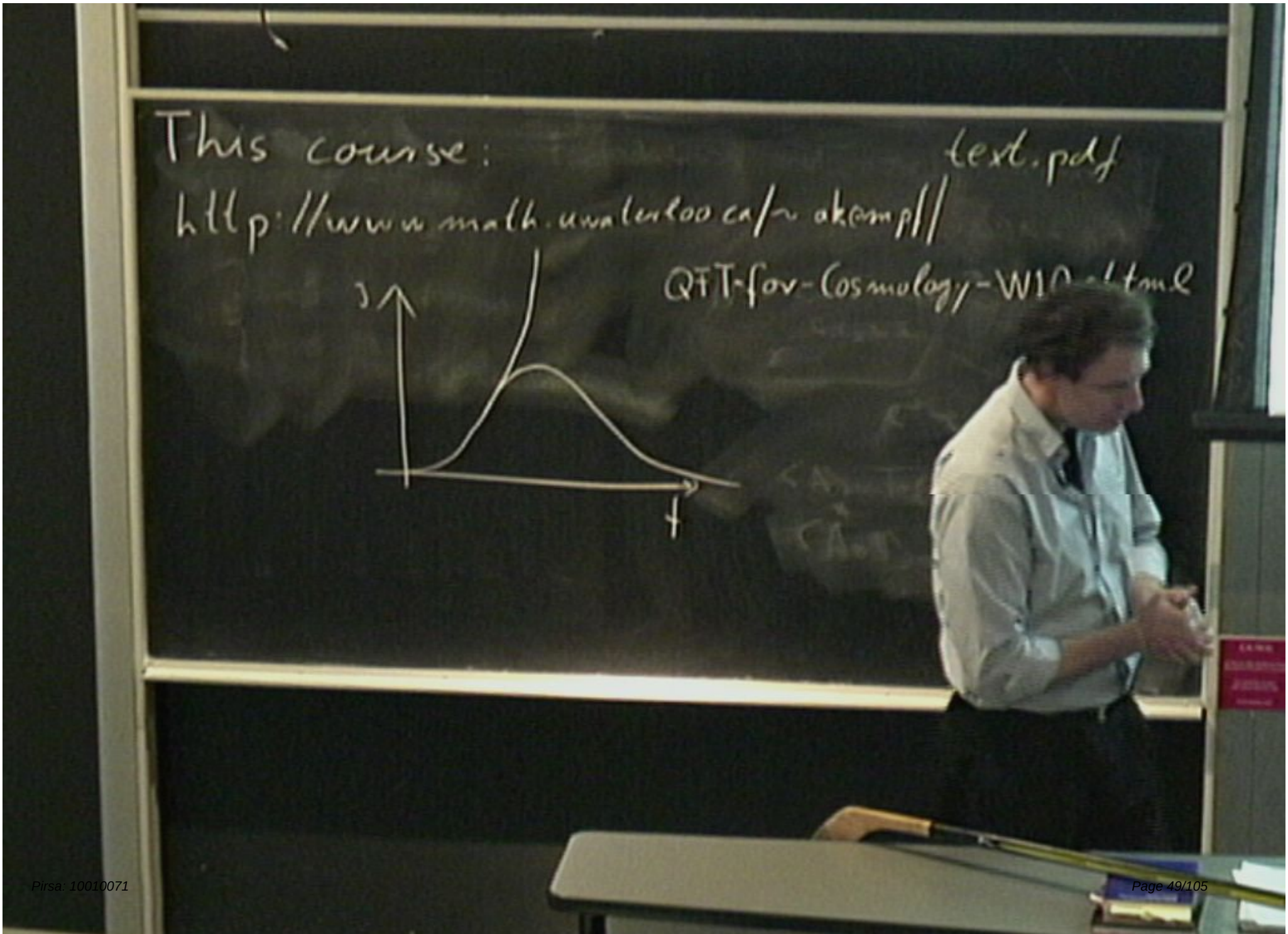
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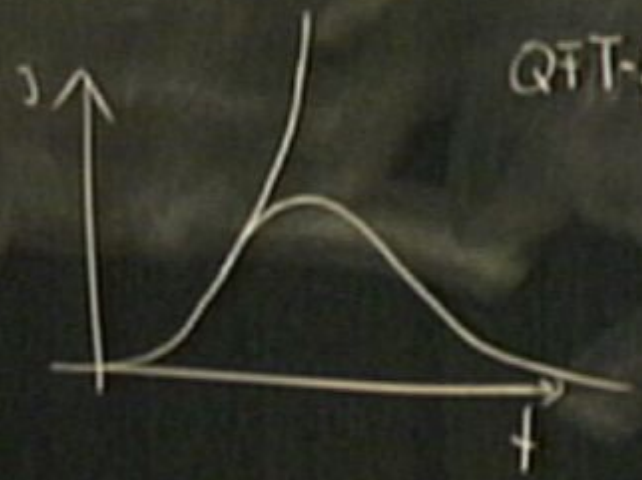


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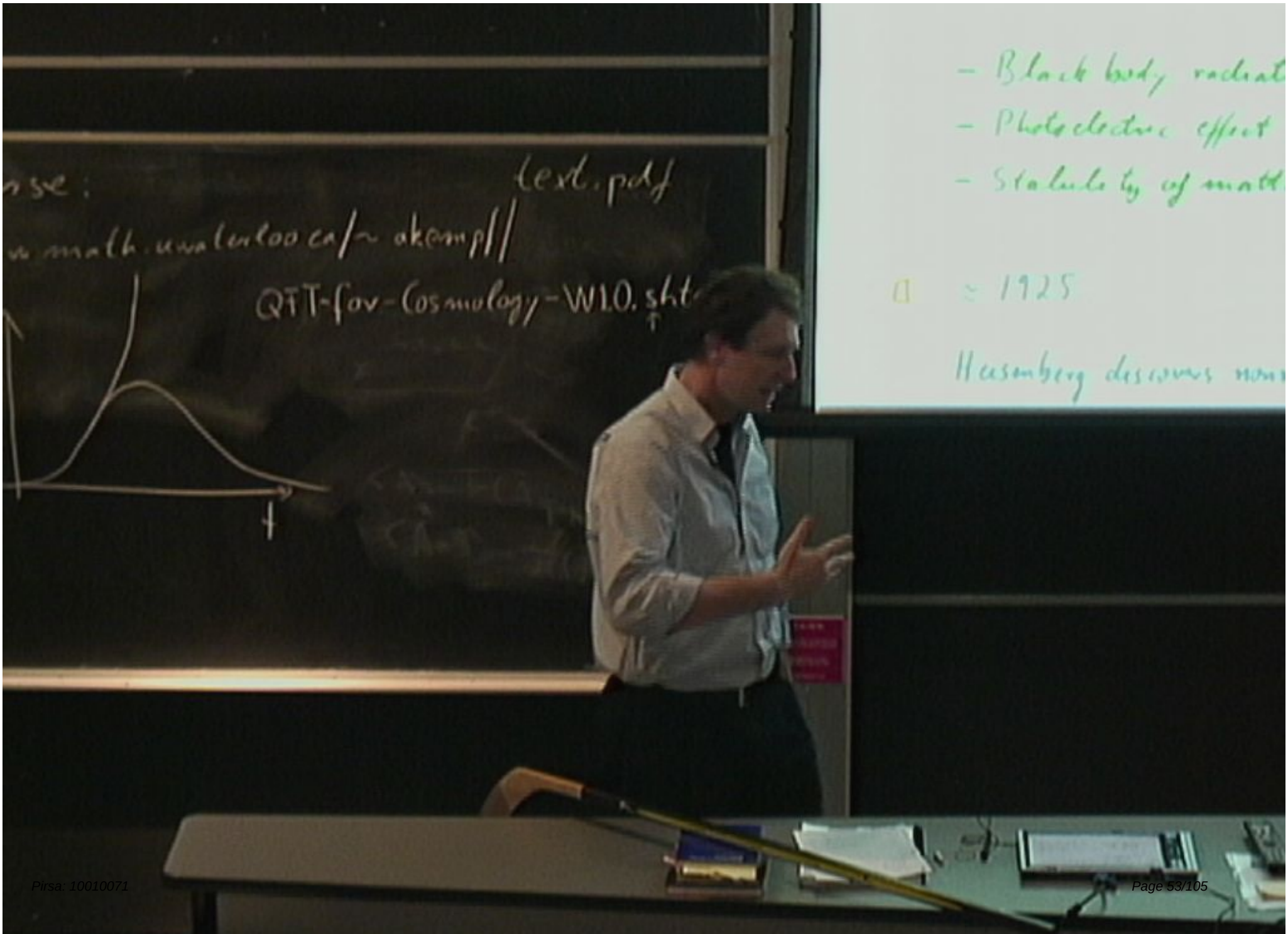
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$$m\ddot{\hat{x}} = -K\hat{x} \qquad \text{(harm. oscillator)}$$

- but we have noncommutativity:

$$[\hat{x}, \underbrace{m\dot{\hat{x}}}_{=\hat{p}}] = i\hbar \qquad \text{"canonical commutation relation"}$$

- Remark:

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$$\Delta x_i \Delta p_j \geq \frac{\hbar}{2} \delta_{ij}$$

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- **But:** Nonrelativistic quantum mechanics, i.e.,

$$[\hat{x}_i, \hat{p}_j] = i\hbar\delta_{ij} \quad \text{and} \quad i\hbar \frac{d}{dt} \hat{f}(\hat{x},\hat{p}) = [\hat{f}(\hat{x},\hat{p}), \hat{H}]$$

soon became unsatisfactory.

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$\Rightarrow$ The effects of special relativity were soon spectroscopically measurable.

$\Rightarrow$ measurable contradiction to QM!

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⇒ measurable contradiction to QM:

- Attempts to find a covariant generalization of the Schrödinger equation led to:
  - "Dirac Equation"
  - "Klein Gordon Equation" (see later)
- They had some success, but suffer serious problems too:
  - Energy not bounded from below ⇒ "instability"
  - Unitarity of time evolution unclear
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  - Also: It remained unclear how particle creation and annihilation processes could be calculated.
- Thus, a new idea was needed!

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The idea of 2nd quantization: (Heisenberg and others, 1930s)

Observation:

In QM, all is subject to quantum fluctuations and therefore to uncertainty – except for the wave function $\Psi(x,t)$:

Namely:

As in classical theories, if the wave function's initial conditions are known, then the equation of motion (say the Schrödinger, Klein Gordon or Dirac equation) determines the evolution of $\Psi(x,t)$

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Similar to $\hat{p}_i = \dot{\hat{x}}_i$ (in suitable units)

introduce a "momentum wave function":

$$\hat{\pi}(x,t) = \dot{\hat{\Psi}}(x,t)$$

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Problems with energy positivity, unitarity etc can be solved.

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→ $\hat{\varphi}(x,t)$ and $\hat{\pi}(x,t)$ can no longer be number-valued.

→ For each x and t the "value"

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→ $\hat{\varphi}(x,t)$ and $\hat{\pi}(x,t)$ can no longer be number-valued.

→ For each x and t the "value"

$$\hat{\varphi}(x,t)$$

is an operator on a Hilbert space!

Notice: (Recall: The eqns of motion stay the same also in 1st quantization)

The equations of motion (Schrödinger, Klein Gordon or Dirac equation) stay the same only now with $\hat{\varphi}, \hat{\pi}$ noncommutative.

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we'll need to discuss that

$$\Delta\Psi(x,t)\,\Delta\Pi(x',t) \geq \frac{\hbar}{2}\,\delta^3(x-x')$$

$x = (x_1, x_2, x_3)$

$\Rightarrow$ The "wave function" is now subject to quantum fluctuations and uncertainty!

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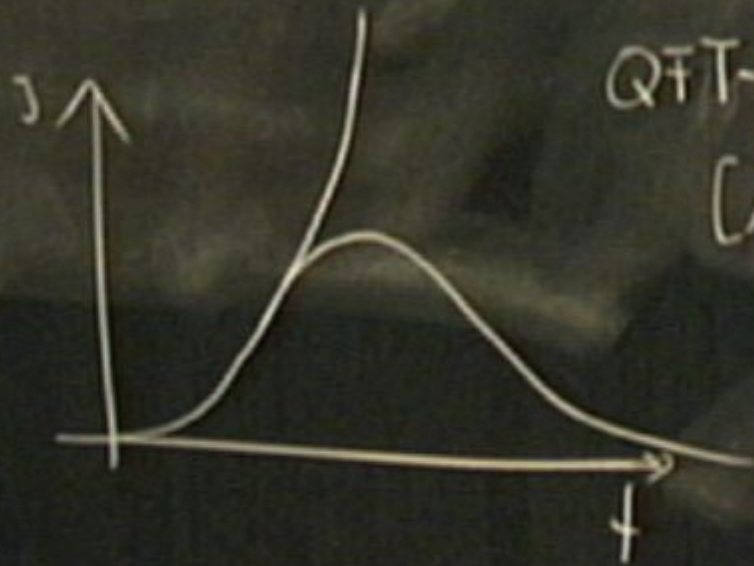
This course:

text.pdf

http://www.math.uwaterloo.ca/~akempf/

QFT-for-Cosmology-W10.shtml



$$[\hat{A},\hat{B}] \neq 0$$

$$\Downarrow$$

$$\Delta A \, \Delta B \geq \frac{1}{2} \left| \langle [\hat{A},B] \rangle \right|$$

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Similar to $\hat{p}_i = \hat{x}_i$ (in suitable units)

introduce a "momentum wave function":

$$\hat{\pi}(x,t) = \dot{\hat{\psi}}(x,t)$$

Then, similar to $[\hat{x}_i, \hat{p}_j] = i\hbar\delta_{ij}$, require:

$$[\hat{\psi}(x,t), \hat{\pi}(x',t)] = i\hbar\,\delta(x-x')$$

- Success!

Problems with energy positivity, unitarity etc can be solved.

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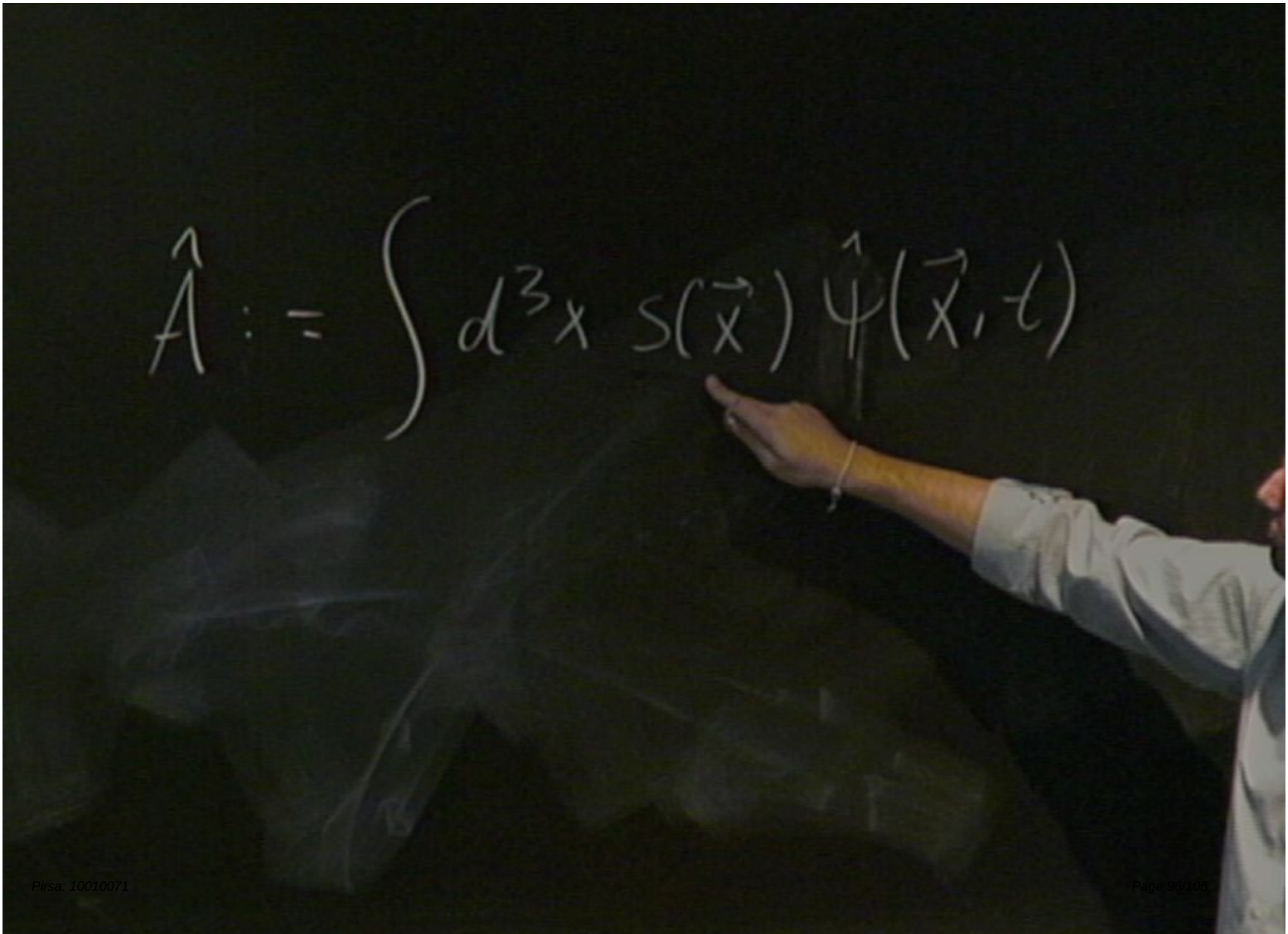
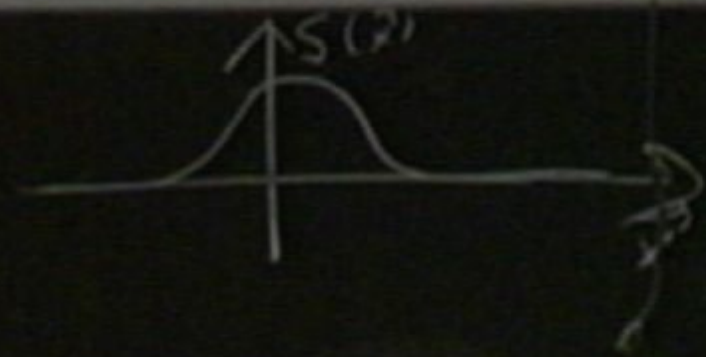

$\hat{A} := \int d^3x \, s(\vec{x}) \, \hat{\varphi}(\vec{x}, t)$



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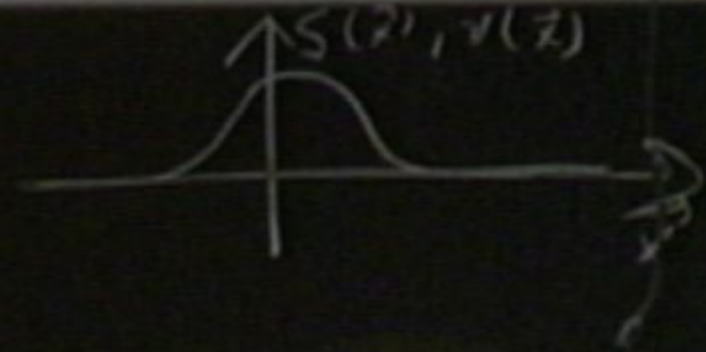

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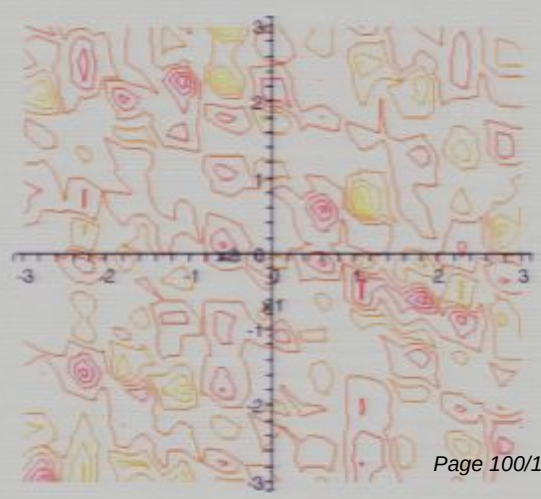

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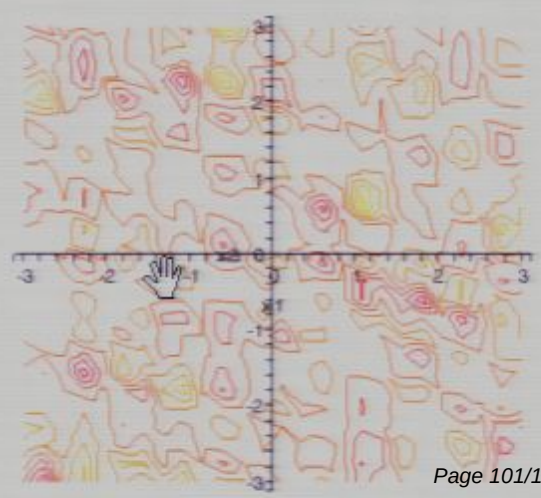

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Aim of this course:

- Introduce 2nd quantization, i.e. "Quantum field theory"
- Study field fluctuations in presence of horizons and gravity.
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Quantum fluctuations became amplified and stretched to large scales during an early period of

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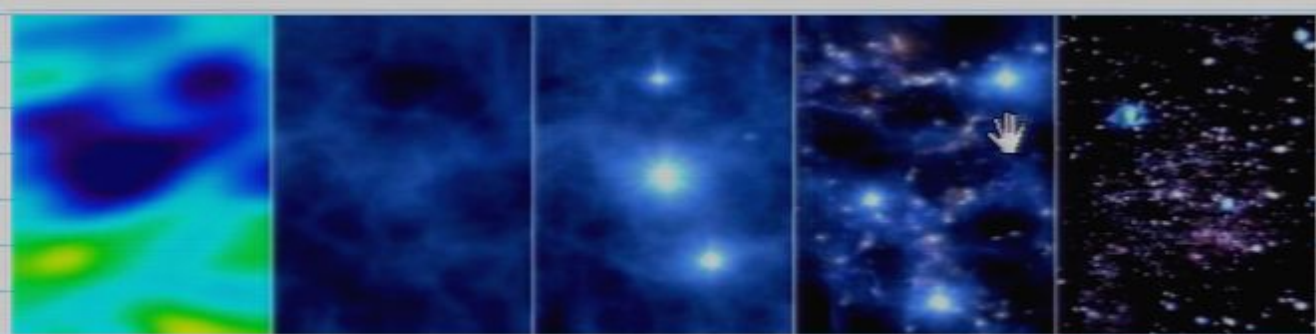
"Inflationary Scenario": (≈1980)

Quantum fluctuations became amplified and stretched to large scales during an early period of near-exponential so-called "inflationary" expansion, leaving an imprint in primordial hydrogen gas.



Our target