Title: All Optical Quantum Information Processing?

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Abstract: Optical experiments led the way to quantum information with striking examples of Bell's inequality tests and entangled state synthesis. Early demonstrations of quantum communication proved that optics are important for quantum communication and more recent ideas about linear optic quantum computing raised hopes that this would also be true for computing. I will give an overview of the various elements that are required for optical QIP and the state-of-the-art characteristics. I will then specialize on sources of single photons and entangled photon pairs and show how they need to be adapted to the task at hand.

All Optical Quantum Information Processing?

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Ontario

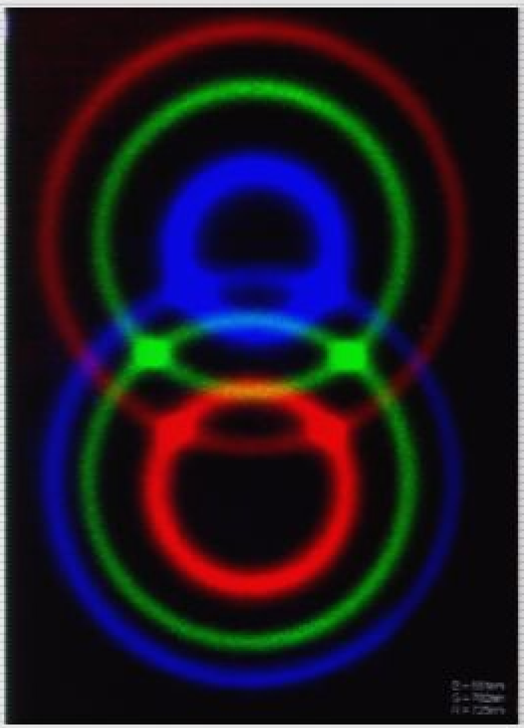
NSERC CRSNG

CIAR

Ontario Photonics Consortium

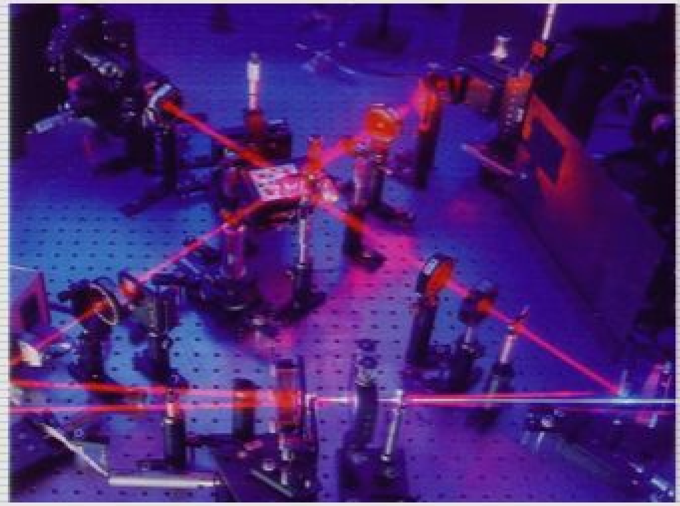
Contents

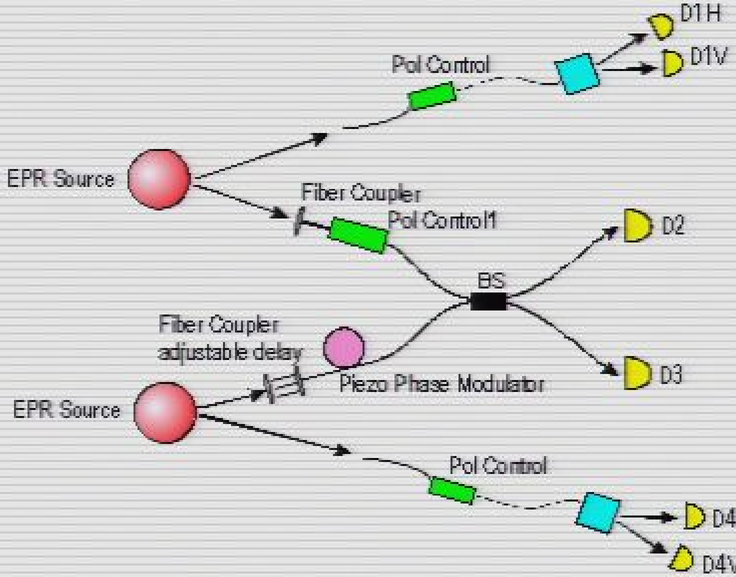
- Status of optical QIP
- Photon space
- Elements of optical QIP
  - Preparation (Sources)
  - Gates
  - Detection, QND
  - Storage
  - Errors
  - Integration
- Sources
  - Entangled pairs
  - Photonic crystal down-conversion



Optical Quantum Information Processing

- Quantum Key Distribution
- Teleportation
- Multipartite entangled states
  - 5-photon GHZ
- Repeaters
  - Entanglement Swapping
  - Purification
- Linear optics quantum computation
  - KLM like gates
  - 4-qubit cluster state





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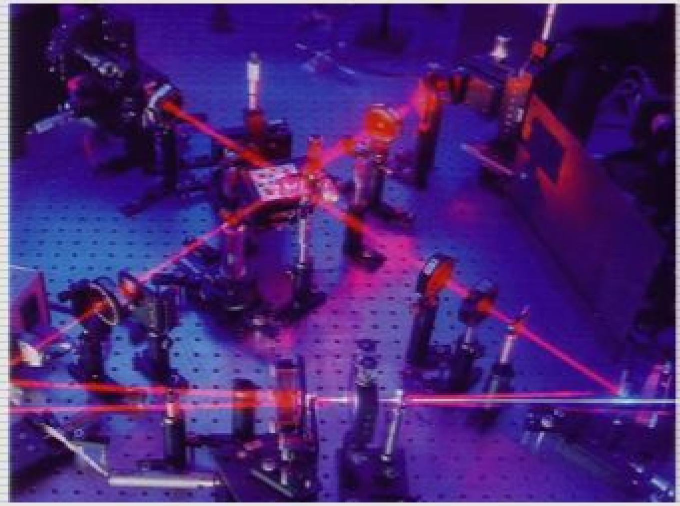

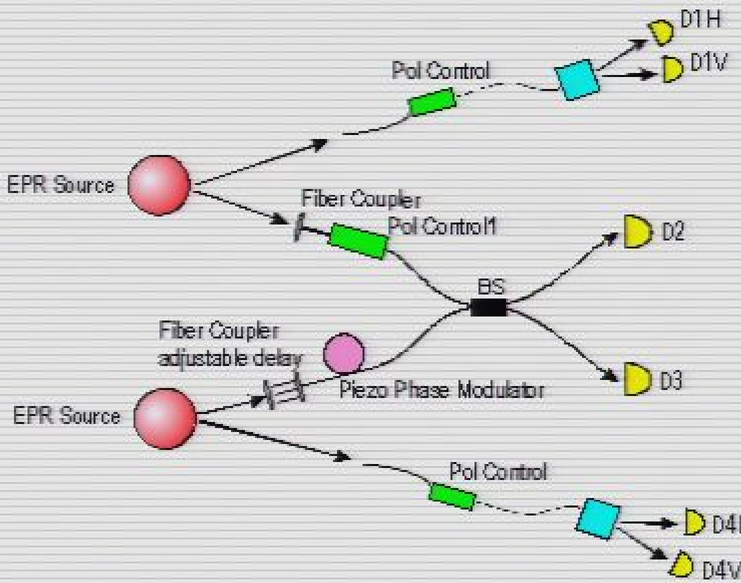

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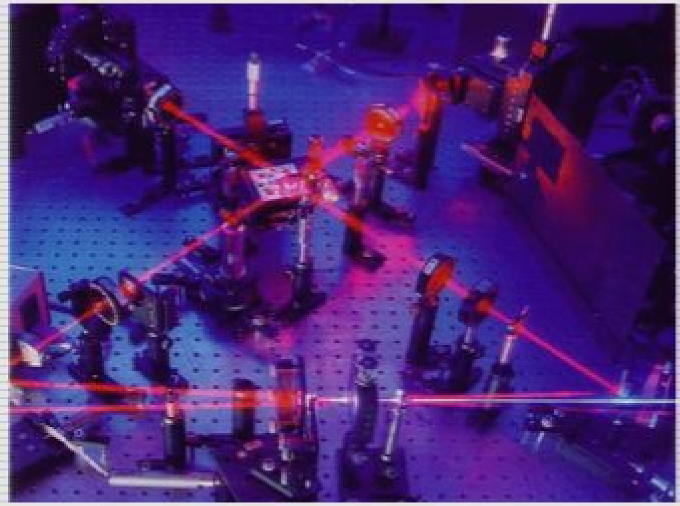
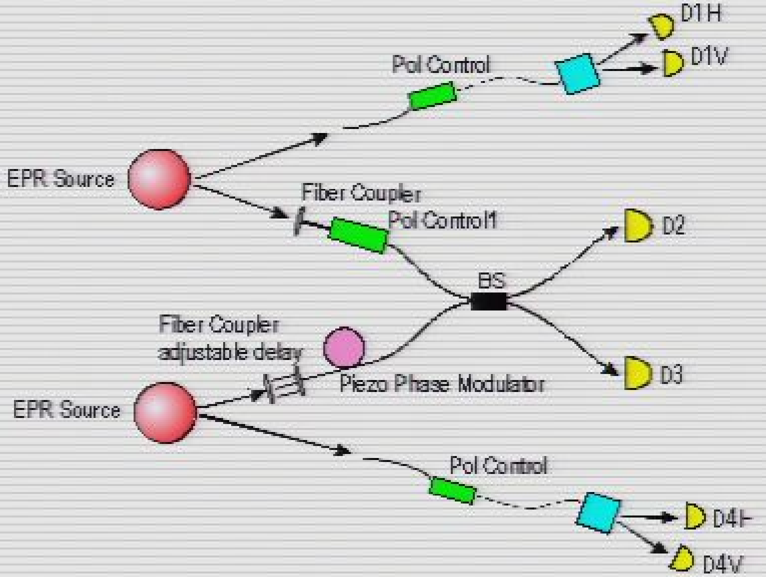




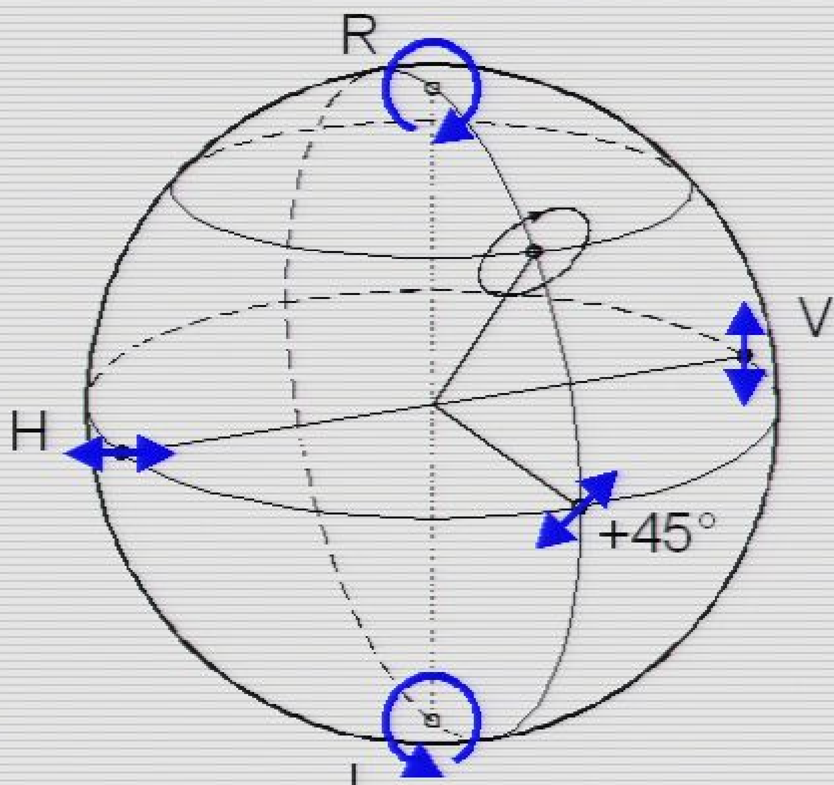
Photon space

Considerations

- Application
- Environment
- Scalability
  - need multiple bosonic modes
  - multiple excitations

Degrees of freedom

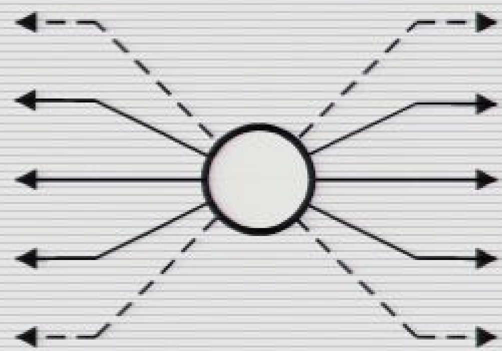
- Polarization
- Space
- Time
- Intensity



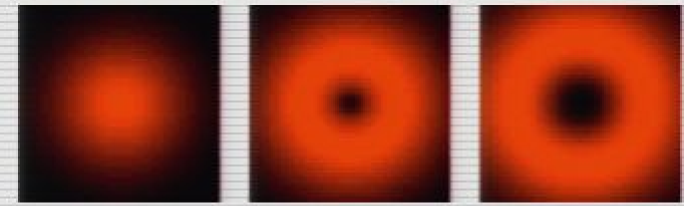
Spatial / momentum encoding

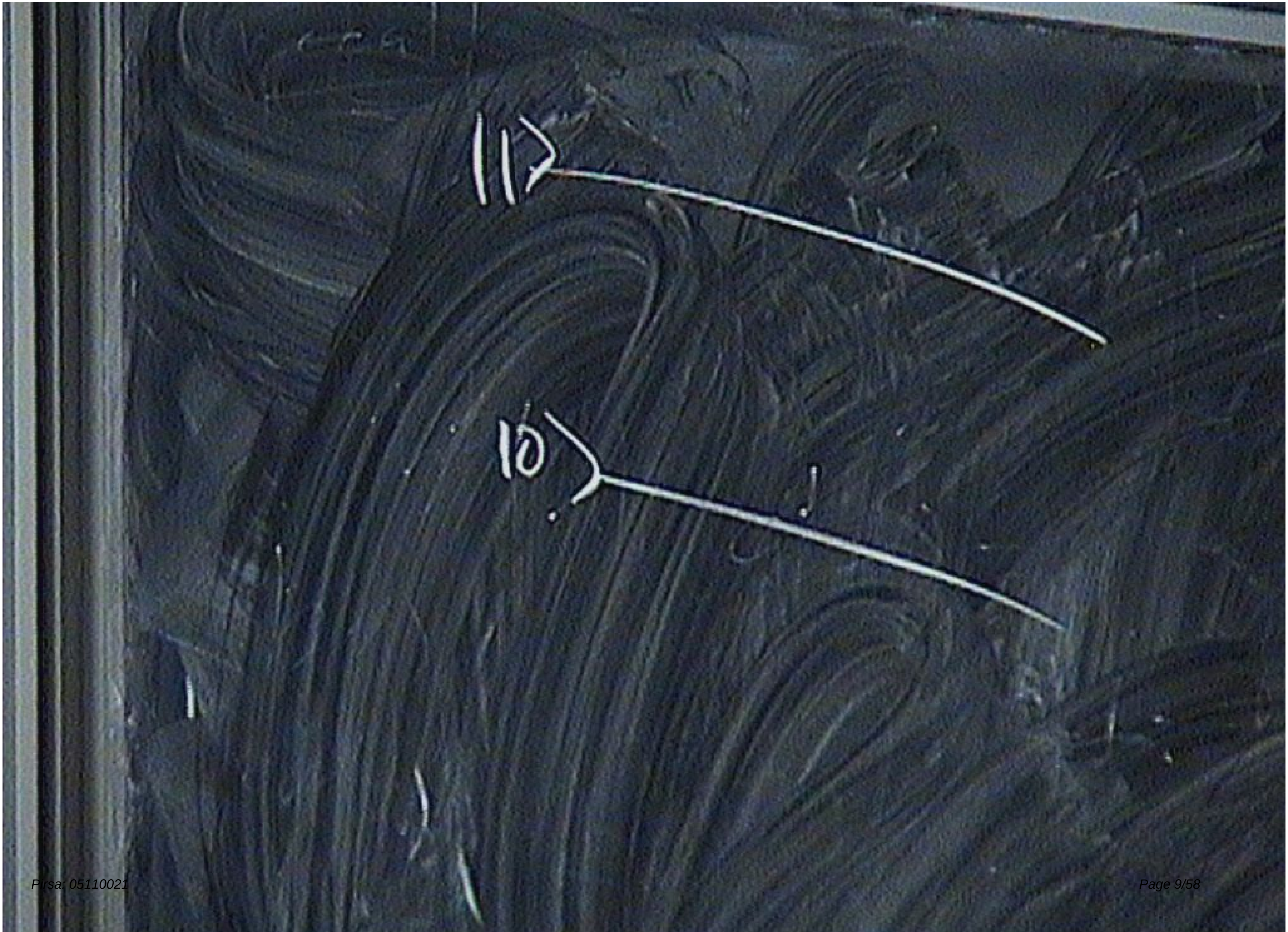
Various discretizations of continuous degree of freedom

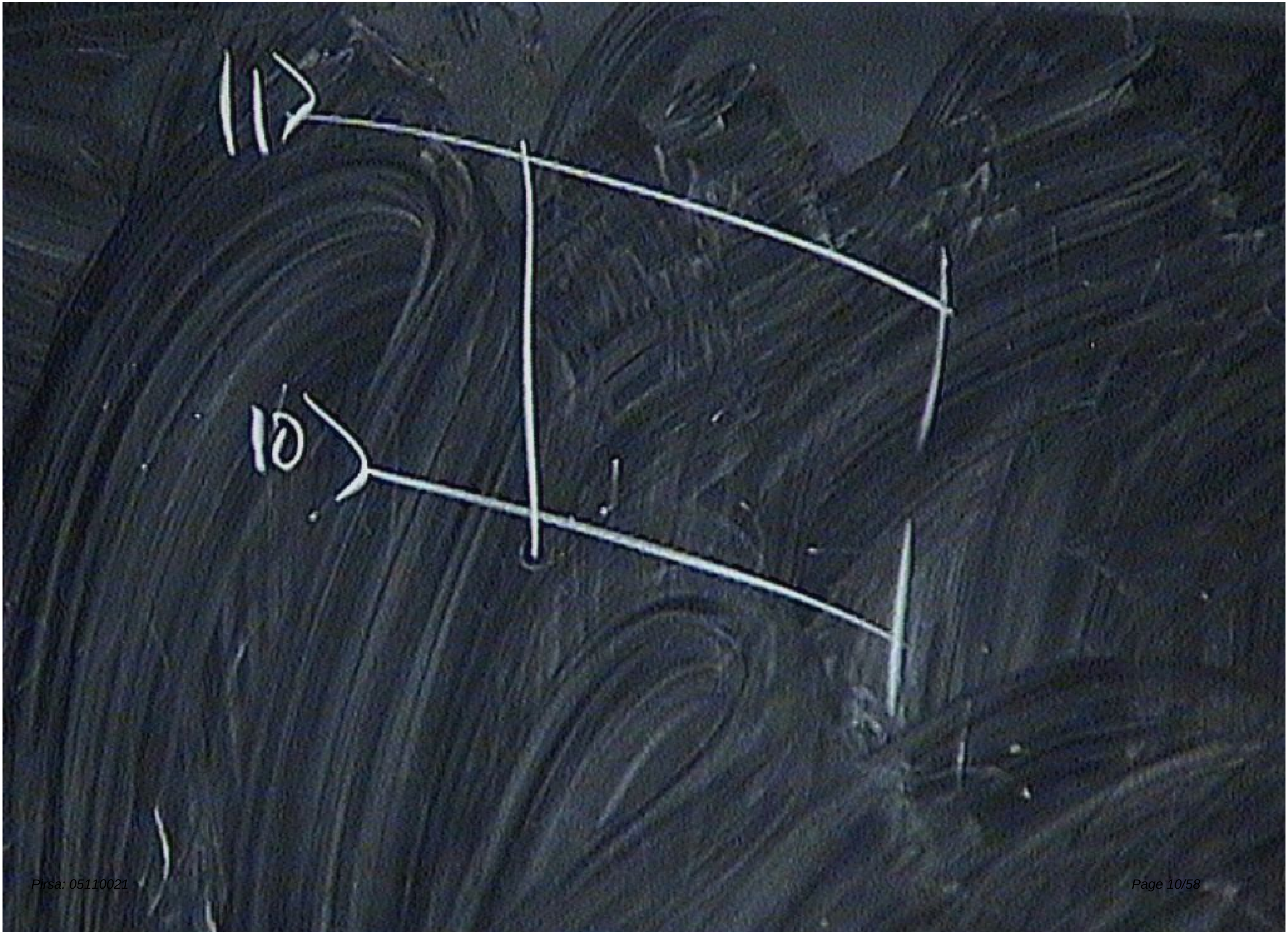
- Gaussian beams, rail encoding



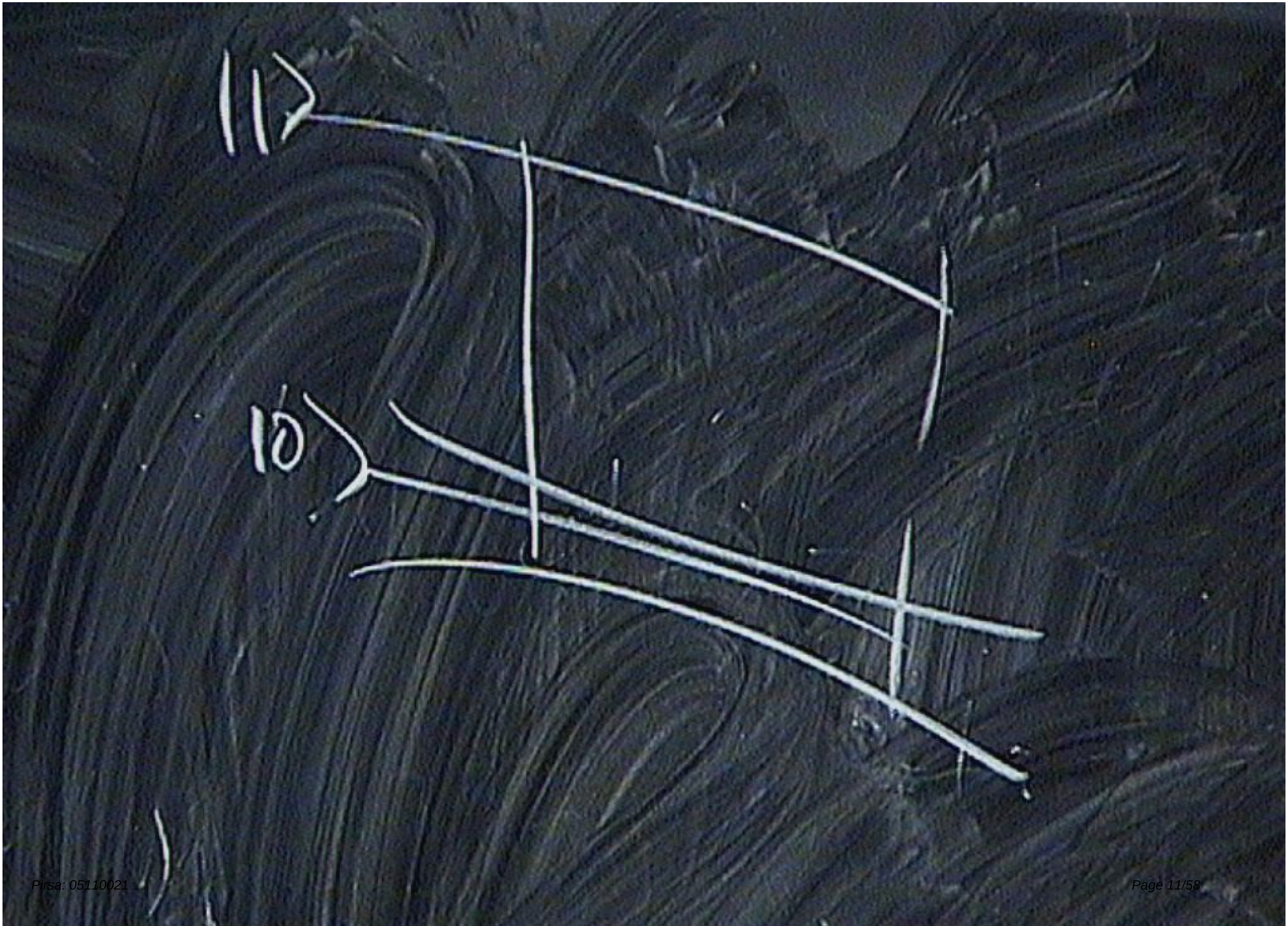
- "Pixels" / Directional encoding
  - Momentum correlated sources
  - Space correlated sources
- Wavefront encoding
  - Orbital angular momentum
  - Hermit-Gaussian modes




11
10



|1⟩
|0⟩


|1>
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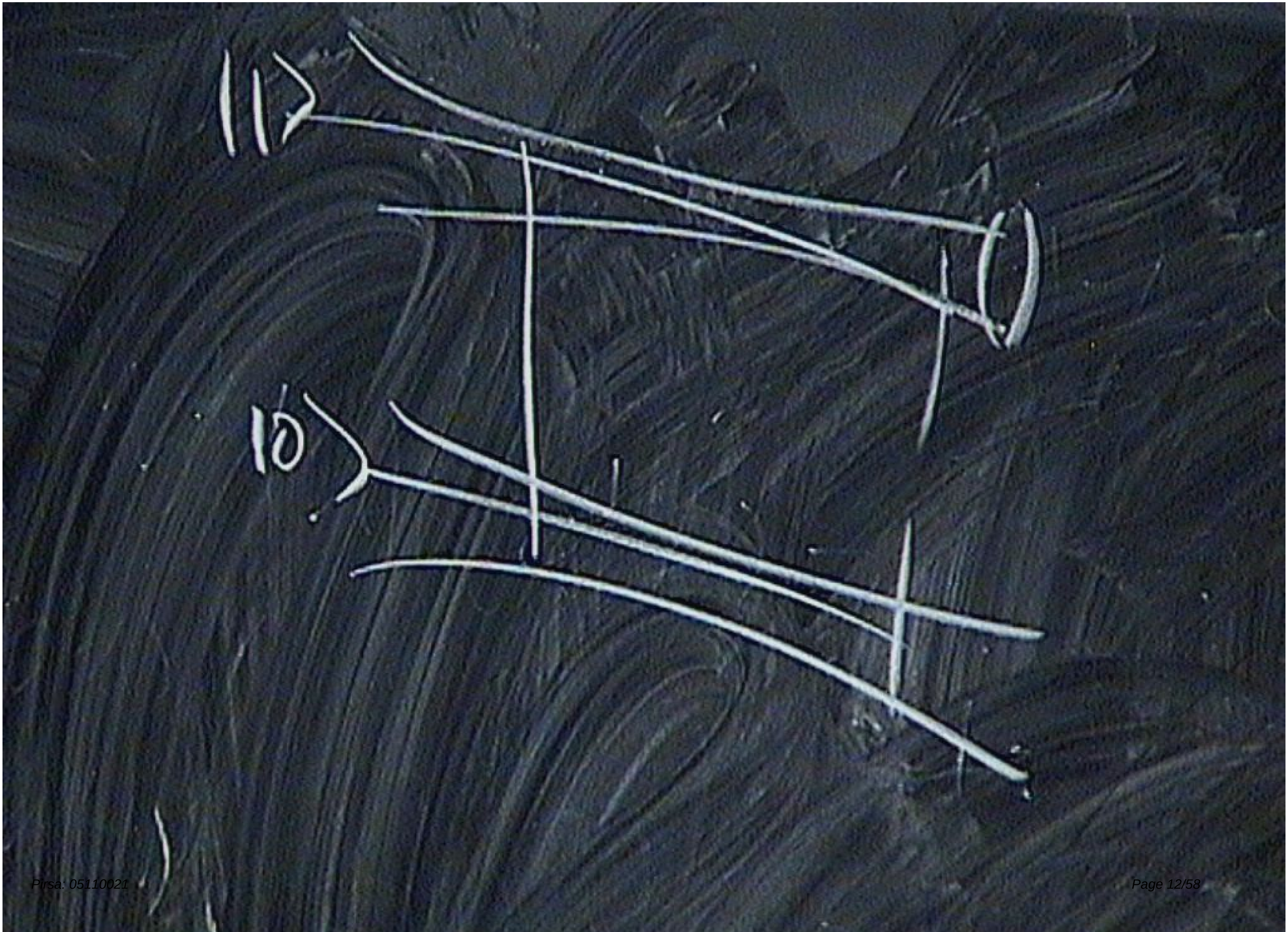
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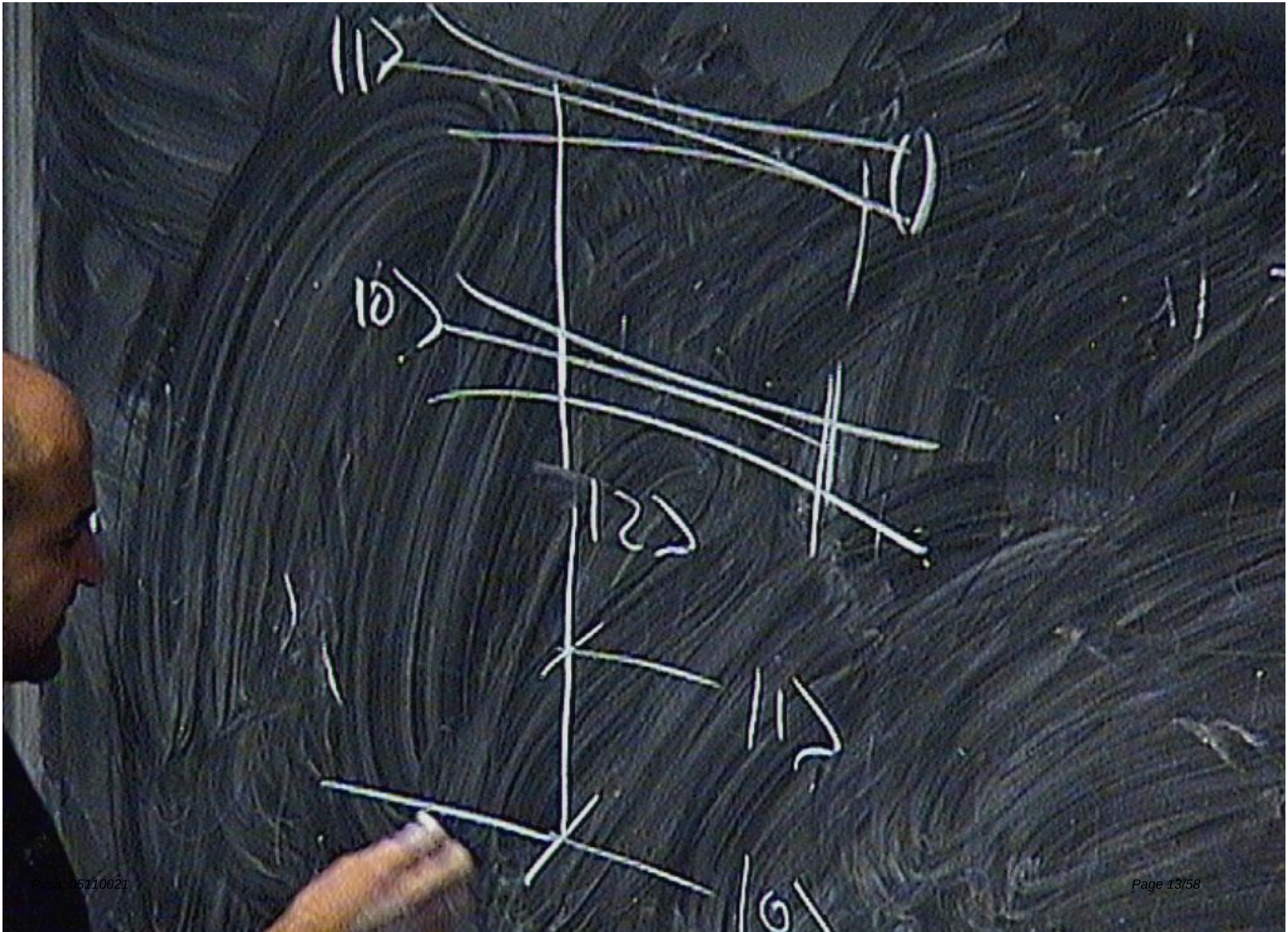
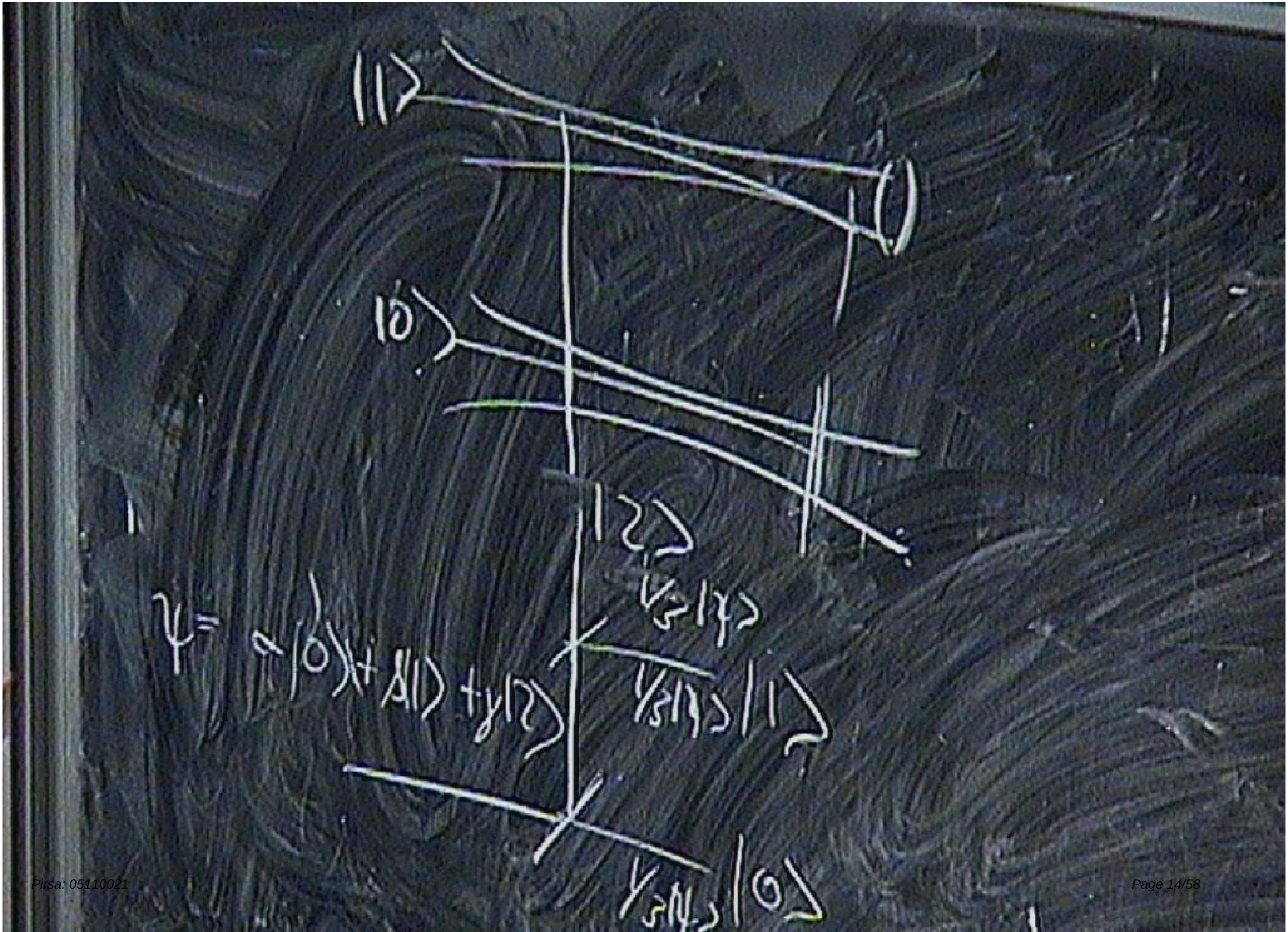
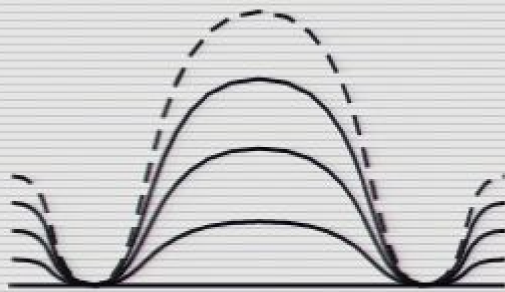
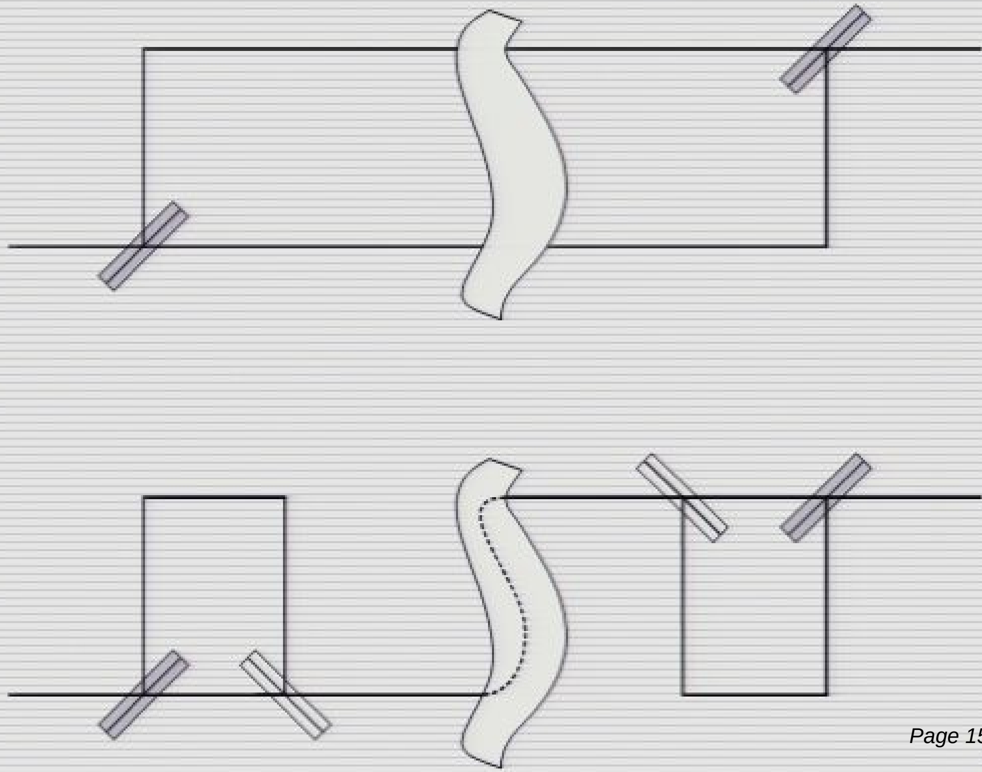

|1⟩
|0⟩
|2⟩
|1⟩
|0⟩


|1⟩
|0⟩
|2⟩
ψ = α|0⟩ + β|1⟩ + γ|2⟩

Temporal / frequency encoding

- Frequency encoding
- Franson interferometry
- Time-bin encoding (pulsed Franson)
- Differential phase shift keying





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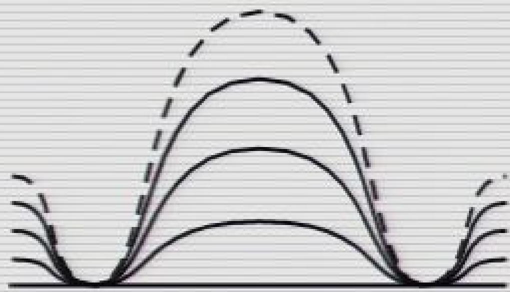

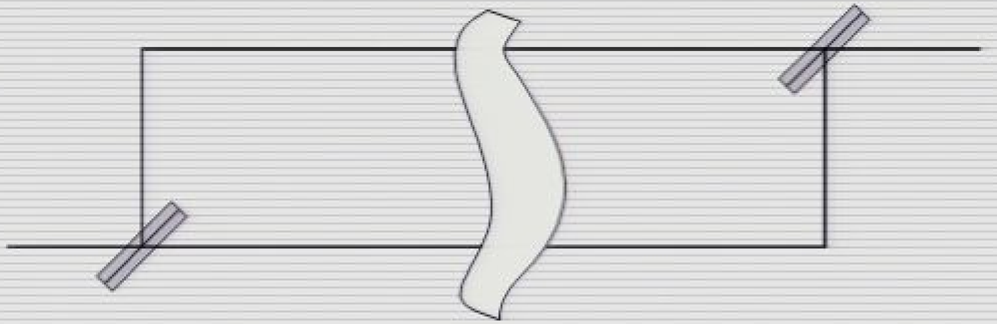

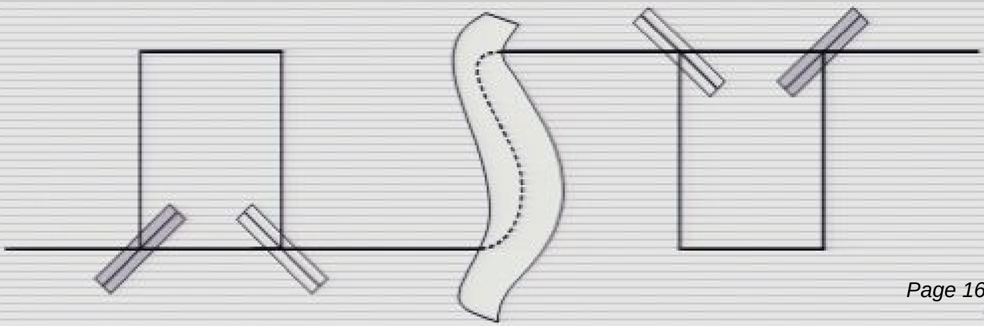

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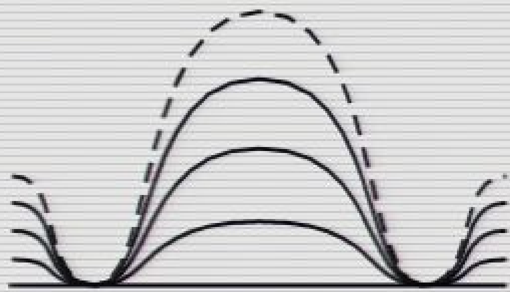
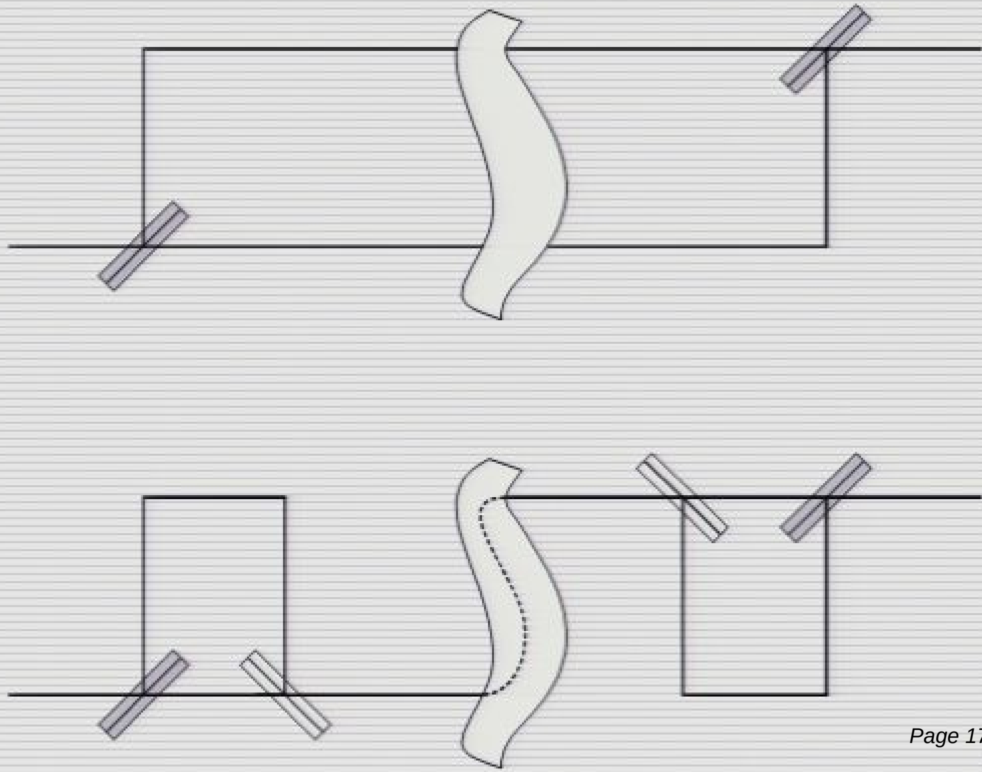
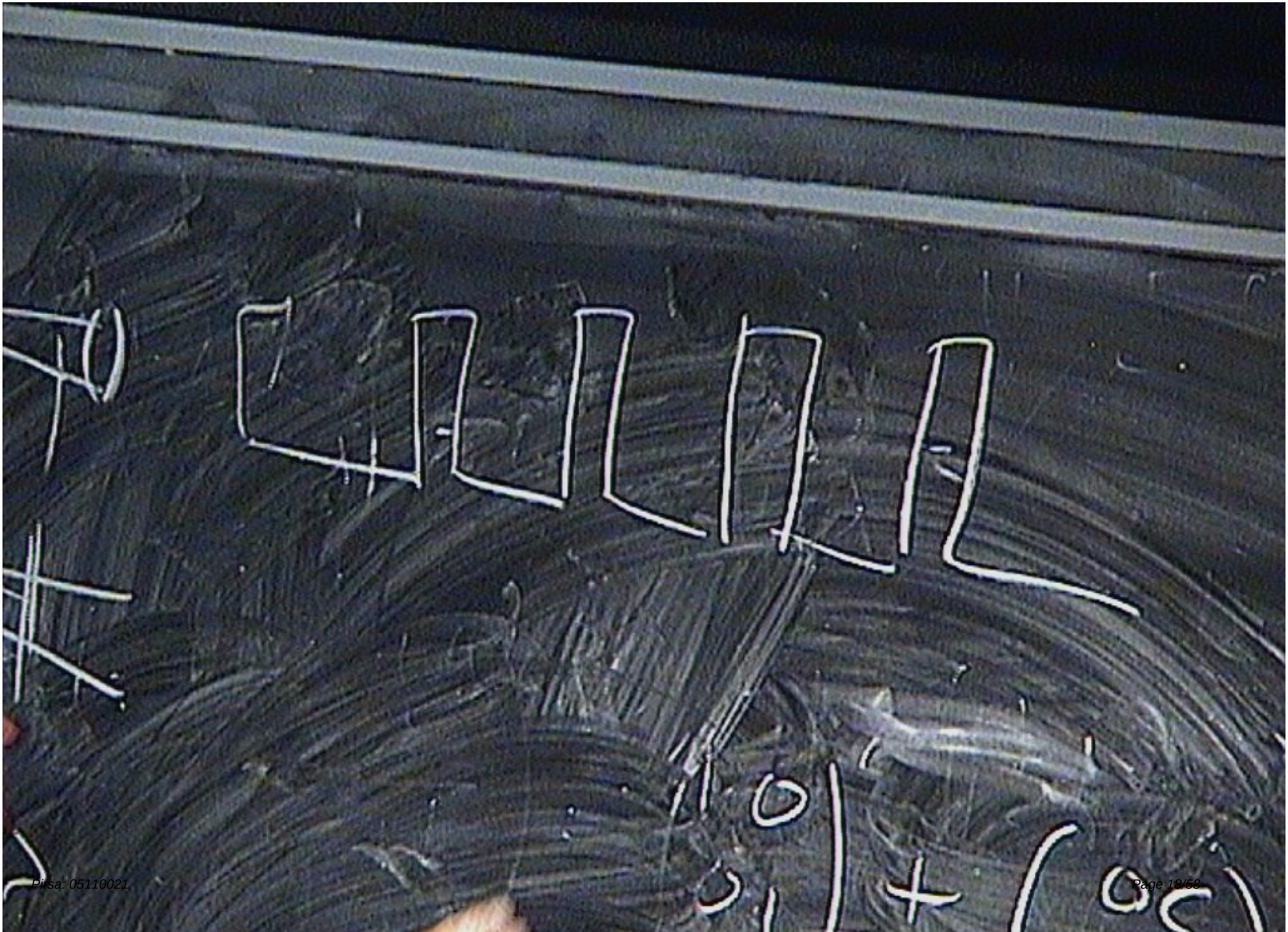
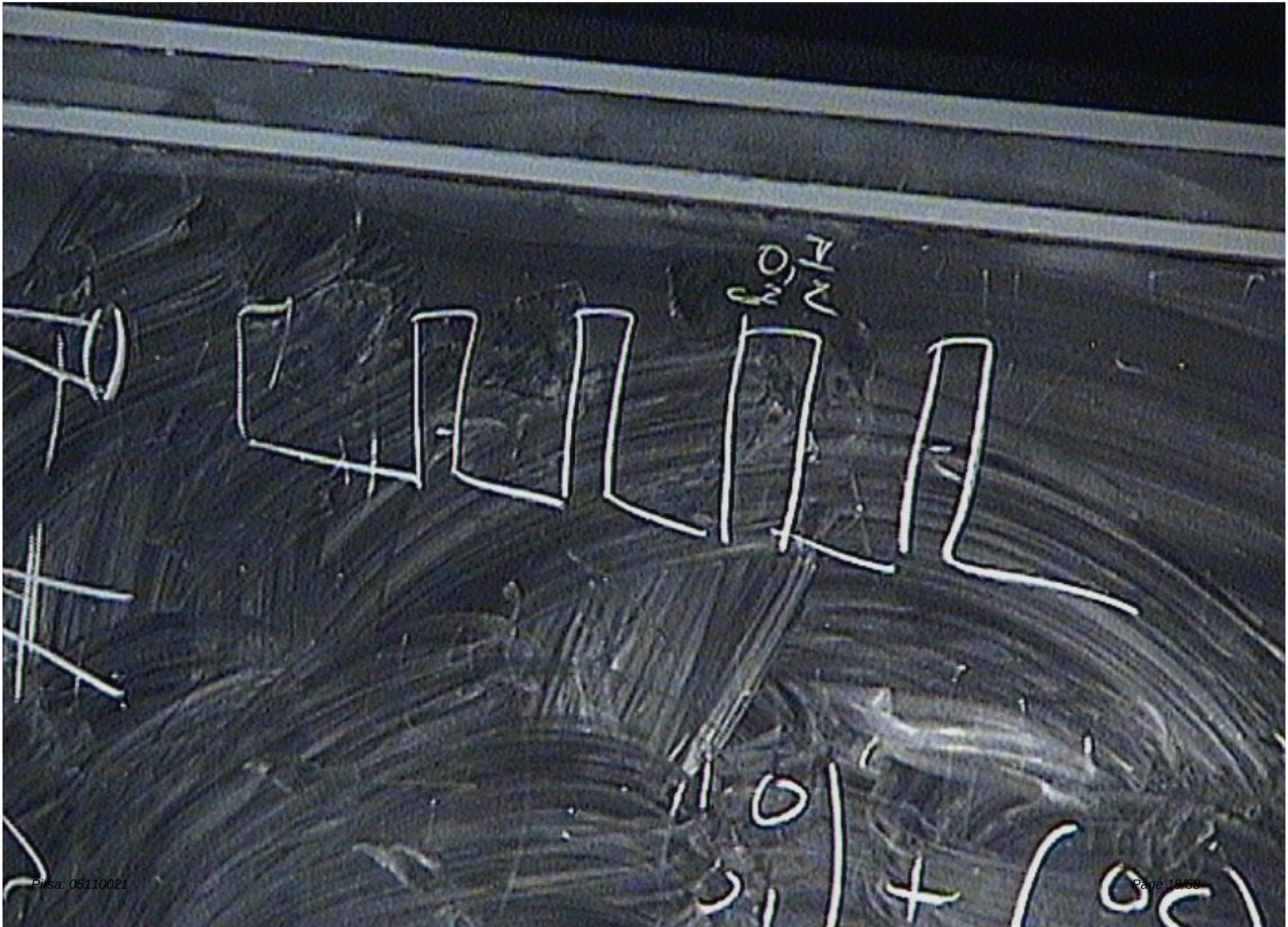
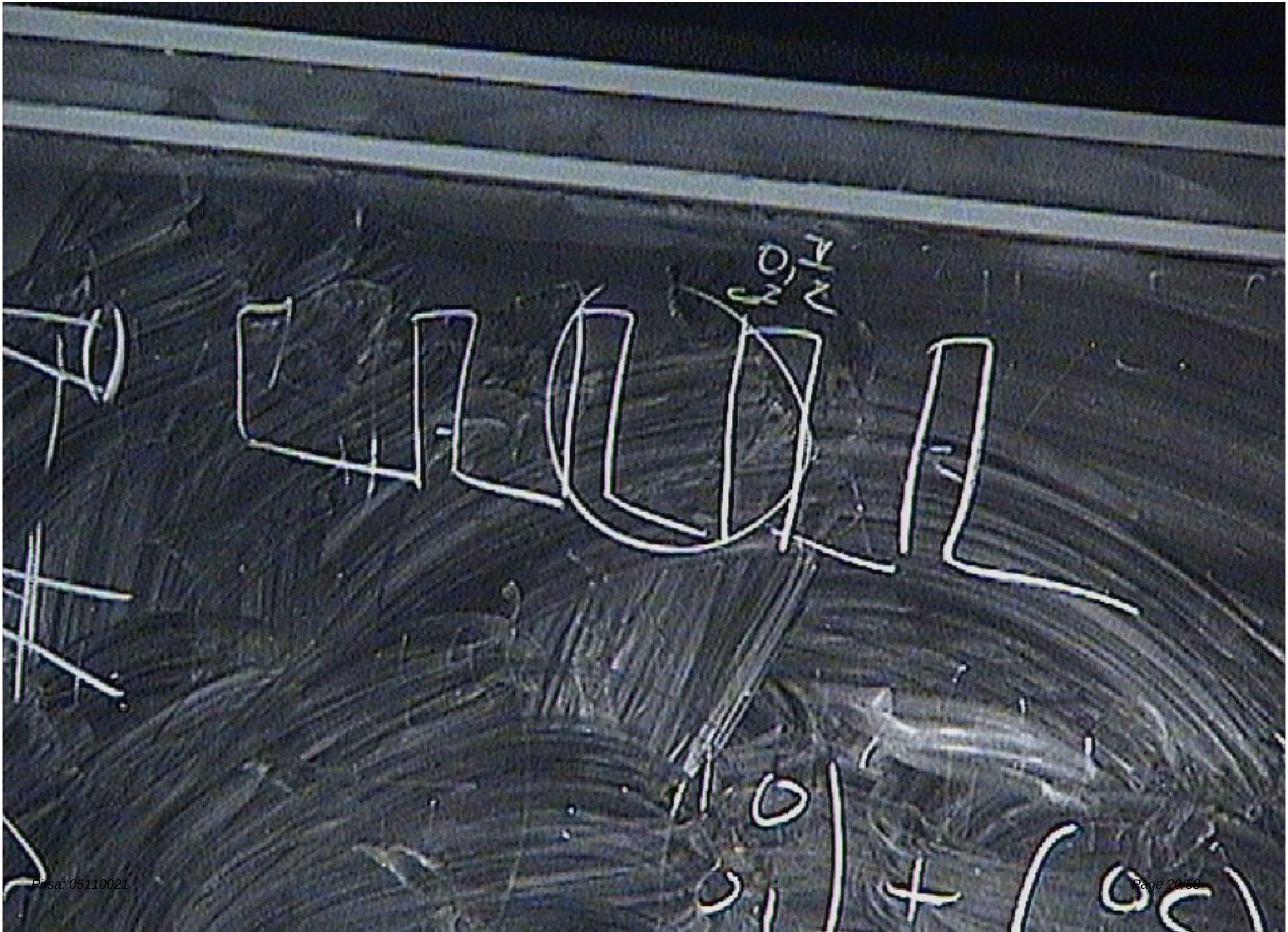






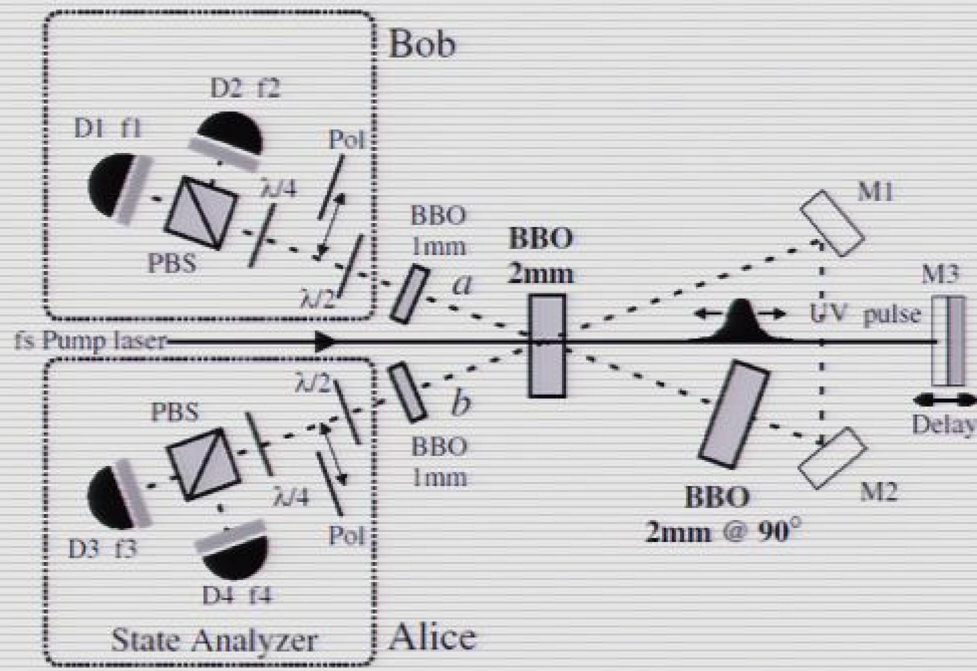




Photon number / quadrature encoding

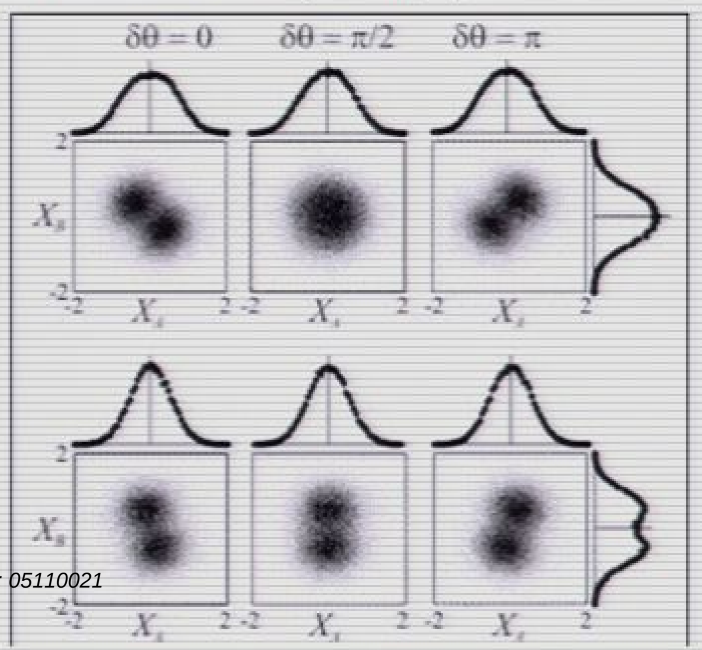
Fock states

- $|0\rangle, |1\rangle, |2\rangle$
- Direct detection



From D. Bouwmeester, UCSB

From A. Lvovsky, Calgary



Quadrature encoding (continuous variables)

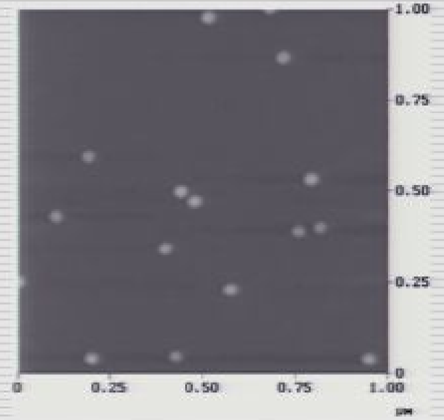
- Squeezed vacuum
- Bright squeezed states
- Homodyne detection

Elements of optical QIP

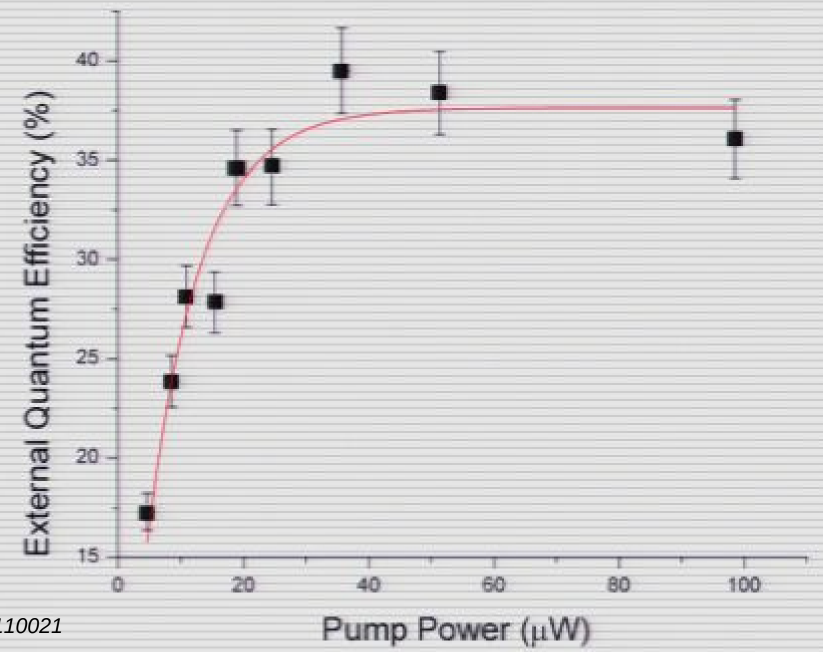
State preparation

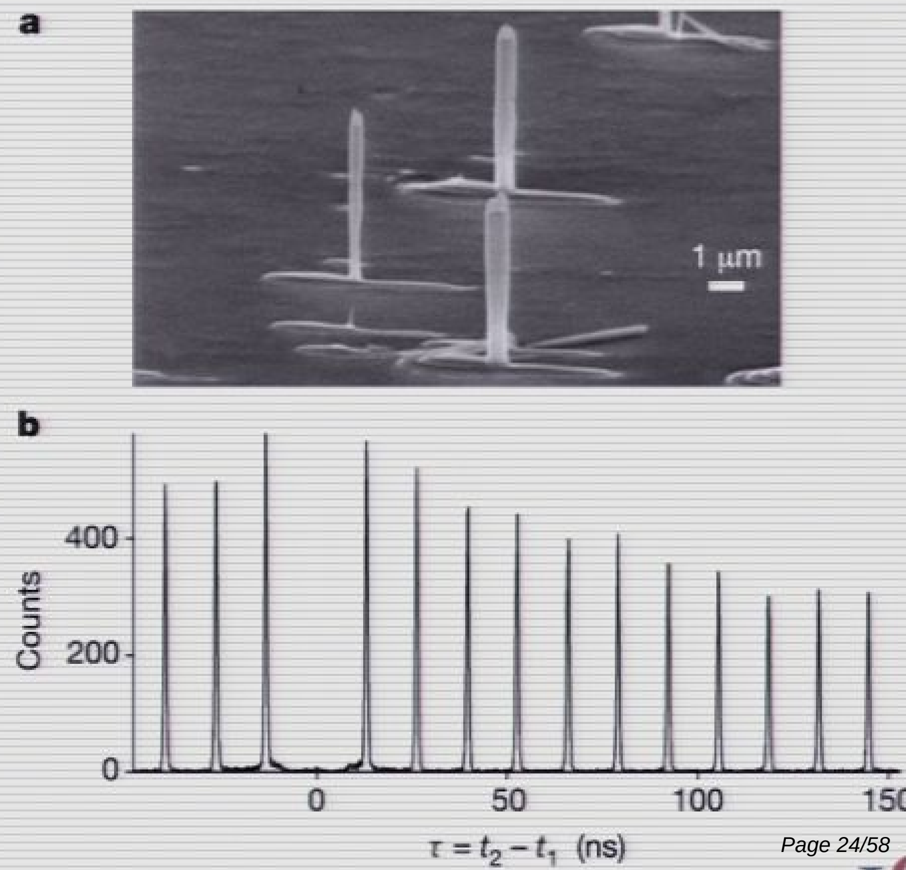
- Single photon sources
  - Quantum dot
  - Atom
  - Molecule
  - Triggered partner photon from pair
- Entangled state sources
  - Parametric down-conversion
  - Atom
  - Quantum dot
- Squeezed state sources
  - Optical parametric oscillator (down-converter)

Single photons from quantum dots

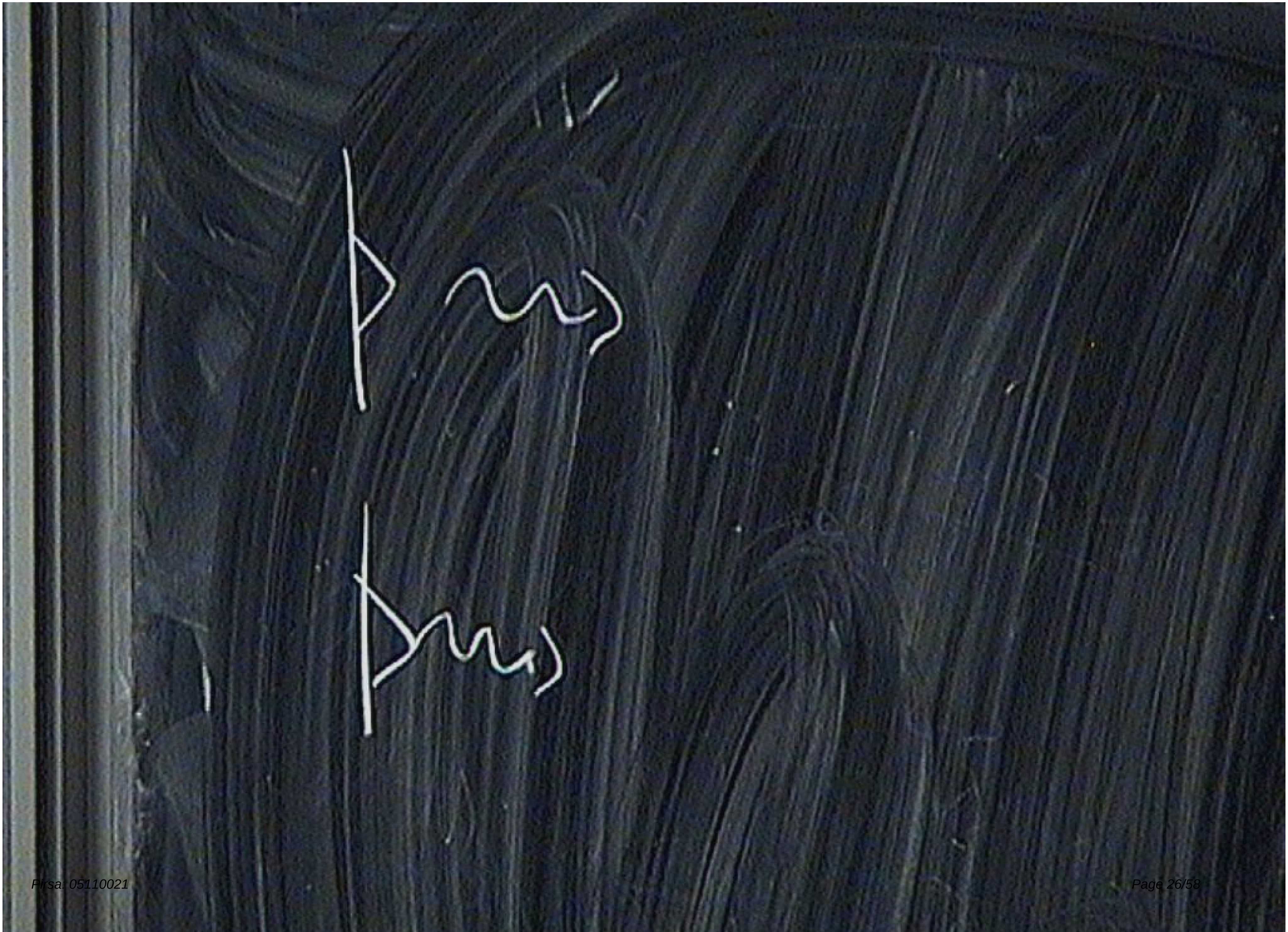


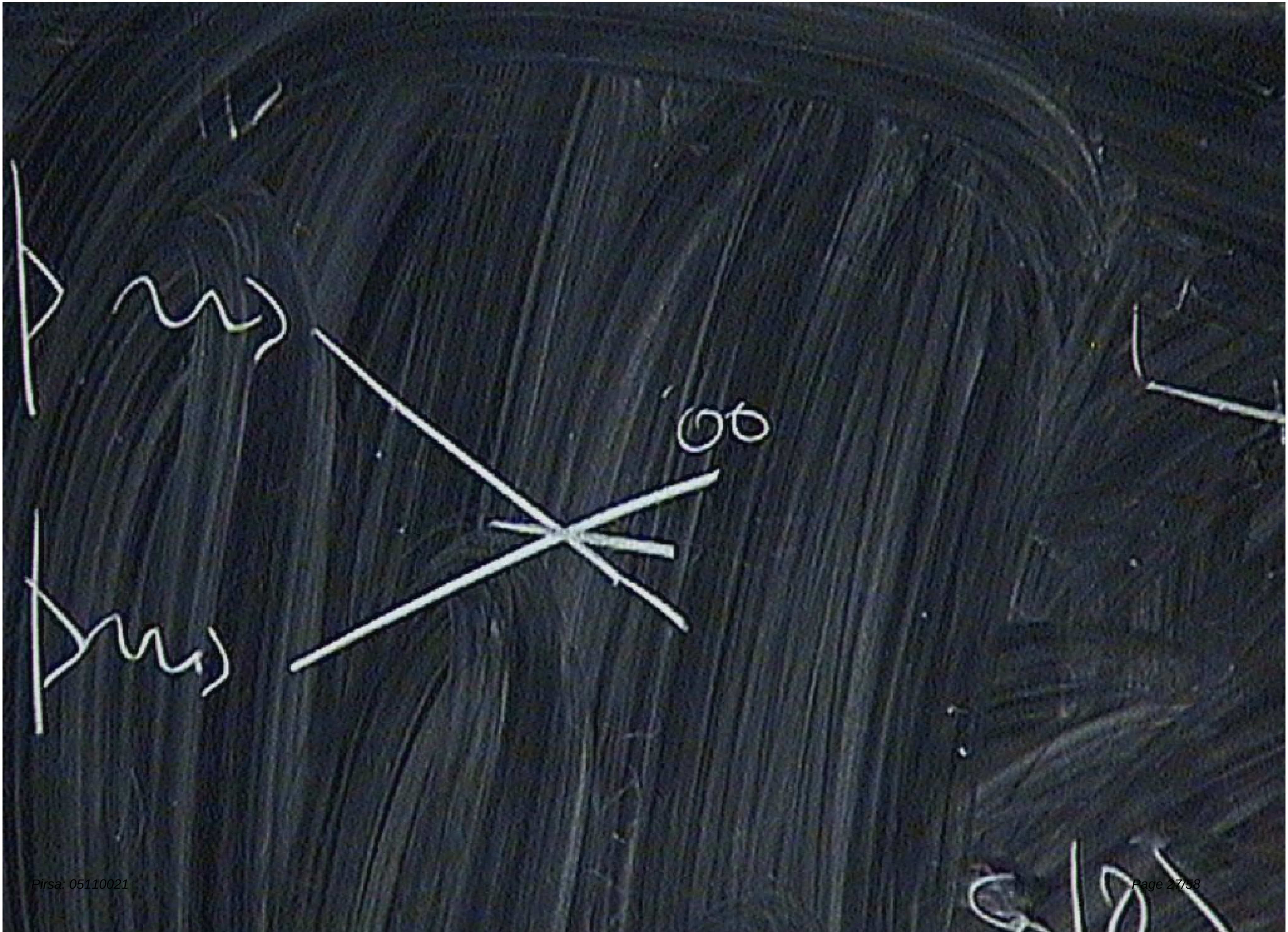
$$g^{(2)}(0)=0.01$$

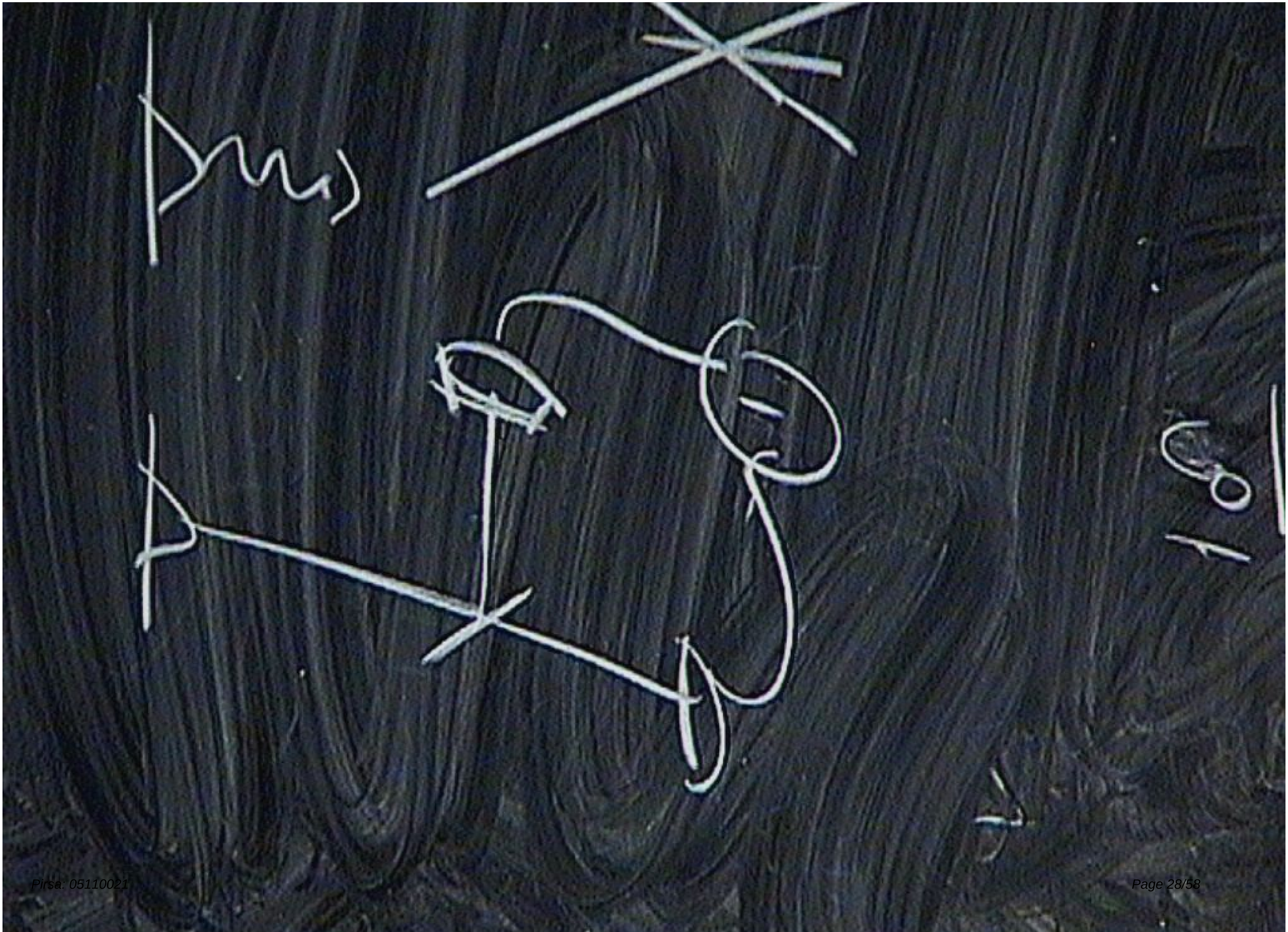


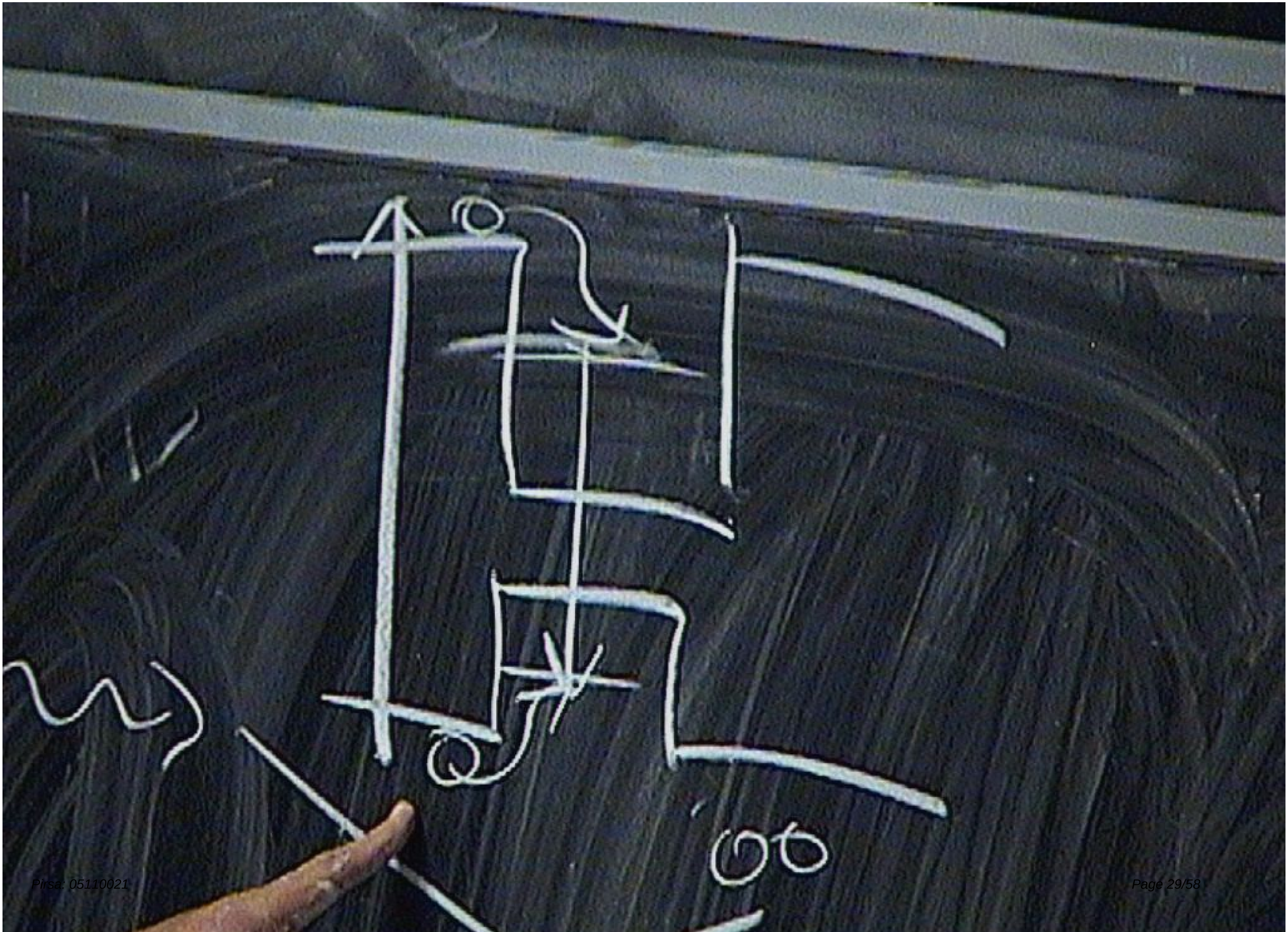


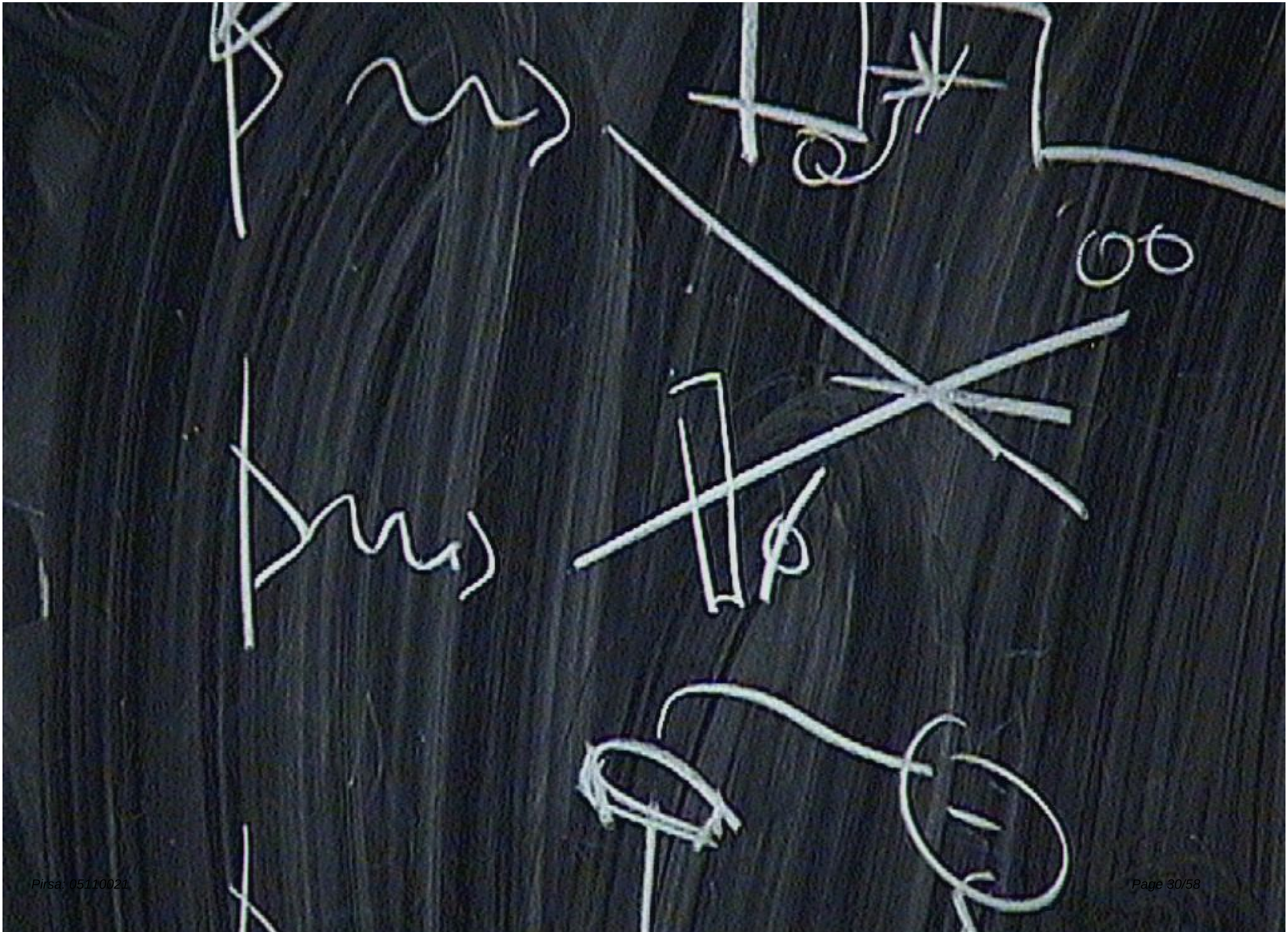
$$c_0|0\rangle + c_1|1\rangle + c_2|2\rangle$$





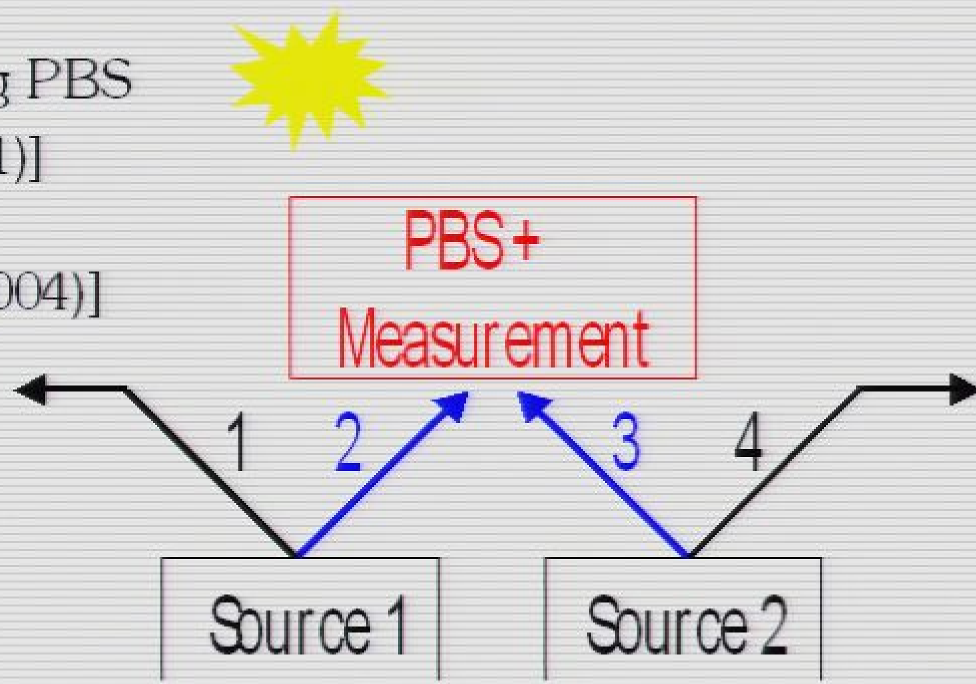






Preparation of higher entangled states

- GHZ family by parity check using PBS
  - 4 photons [PRL ***86***, 4435 (2001)]
  - 5 photons
    [Zhao et al., Nature ***430***, 54 (2004)]



- Cluster States
  similar to GHZ creation
  [P. Walther et al., Nature ***434***, 169 (2005)]
- Approximate W-states
  convert from GHZ by selective attenuation
  [P. Walther, K. Resch & AZ PRL ***94***, 240501 (2005)]

All of these need high pair generation rates for going to higher numbers

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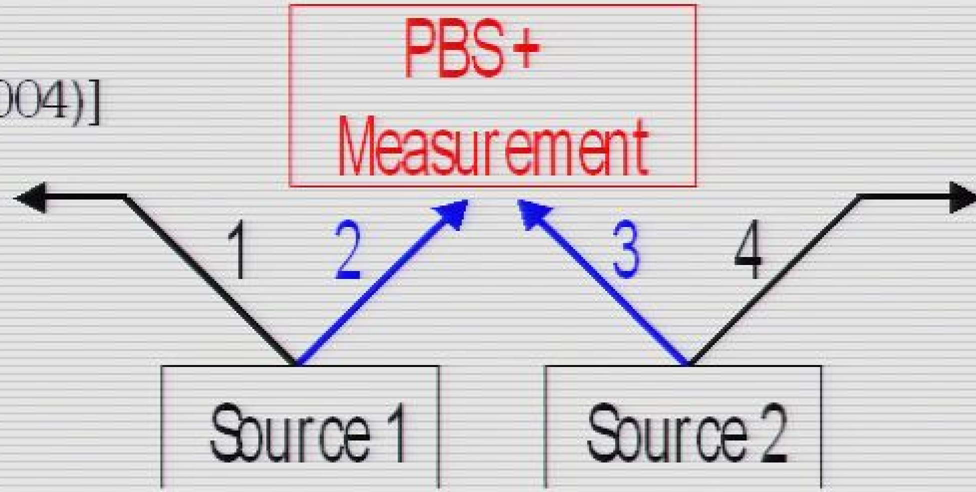

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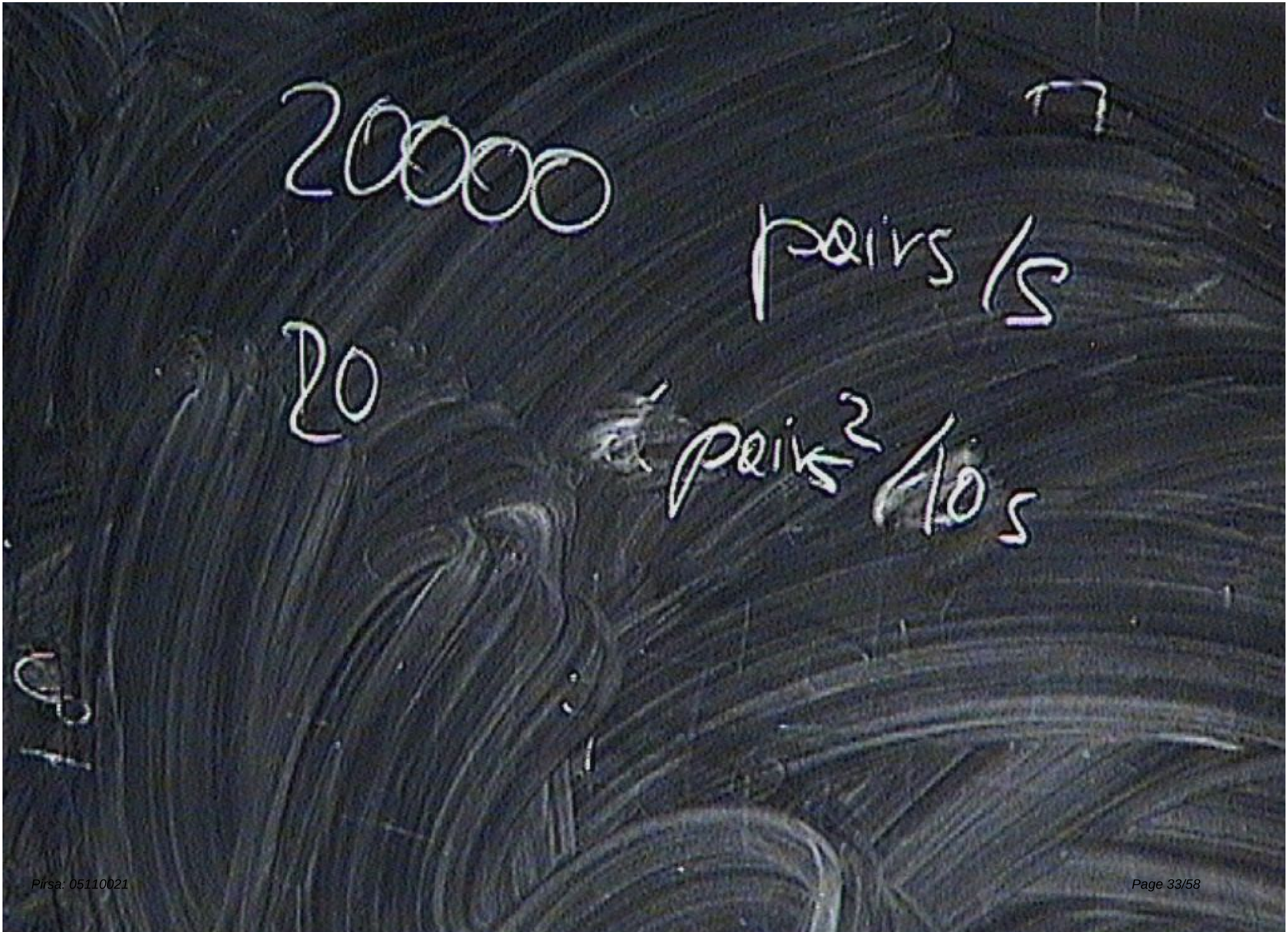
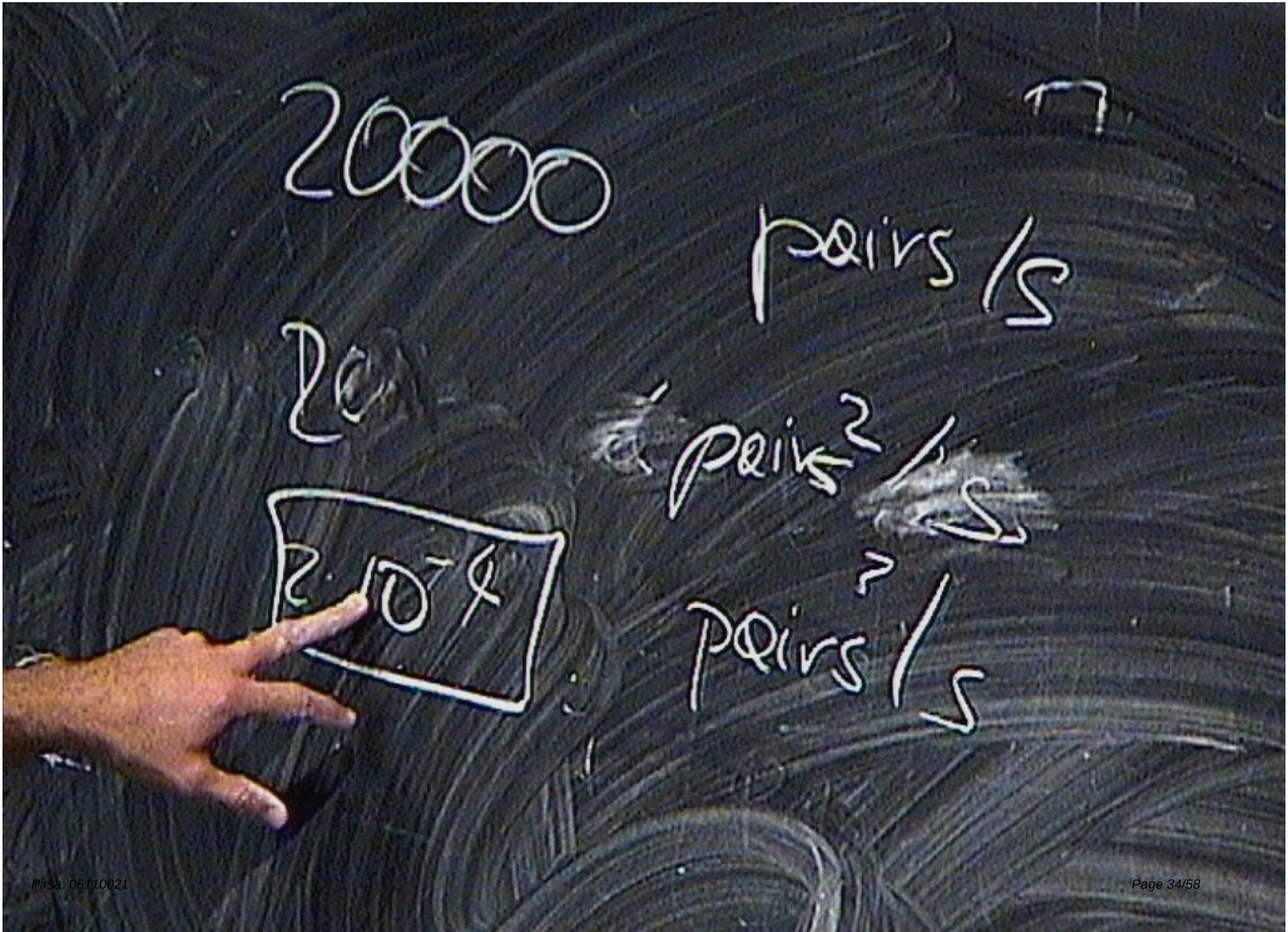
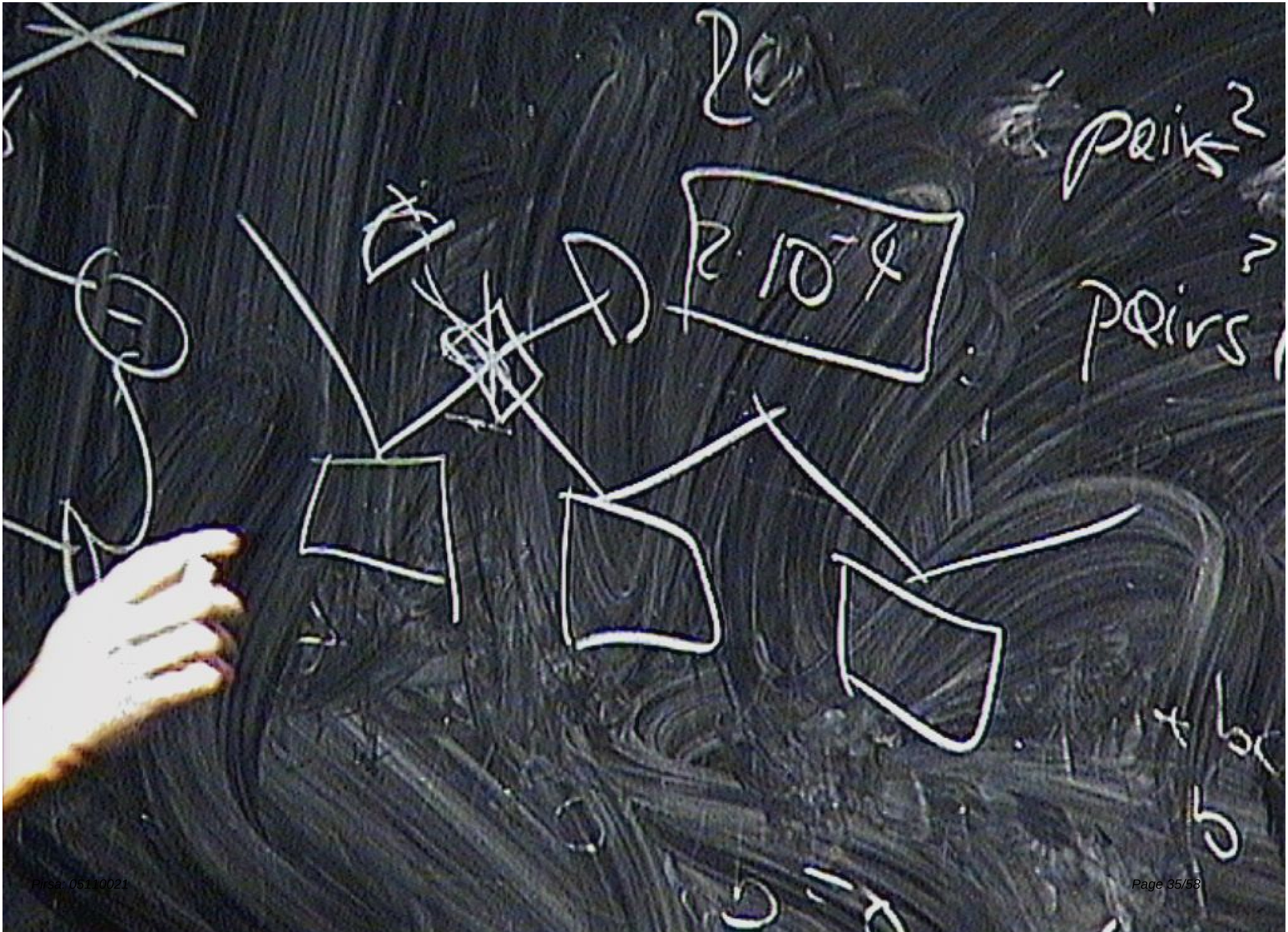
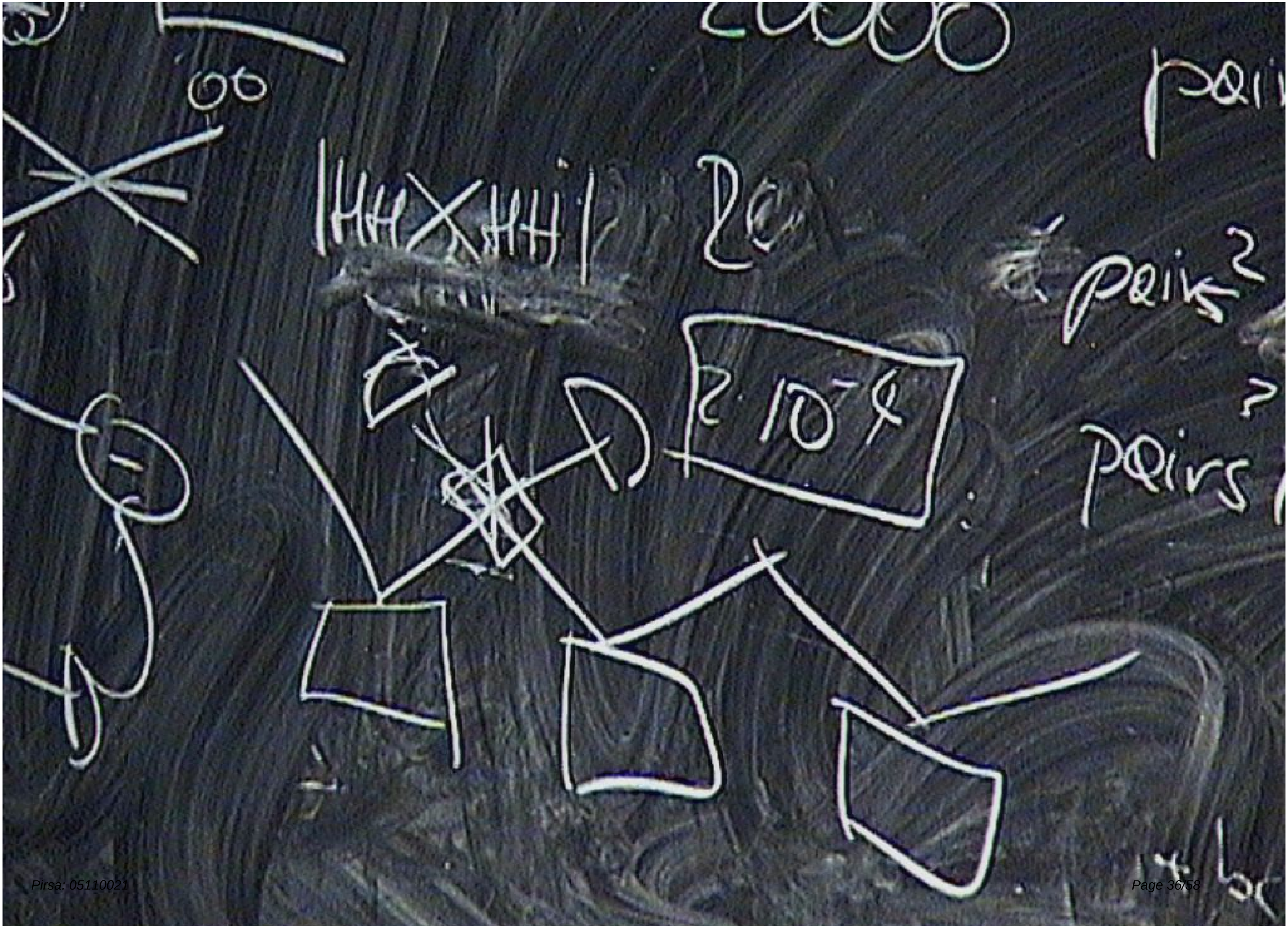
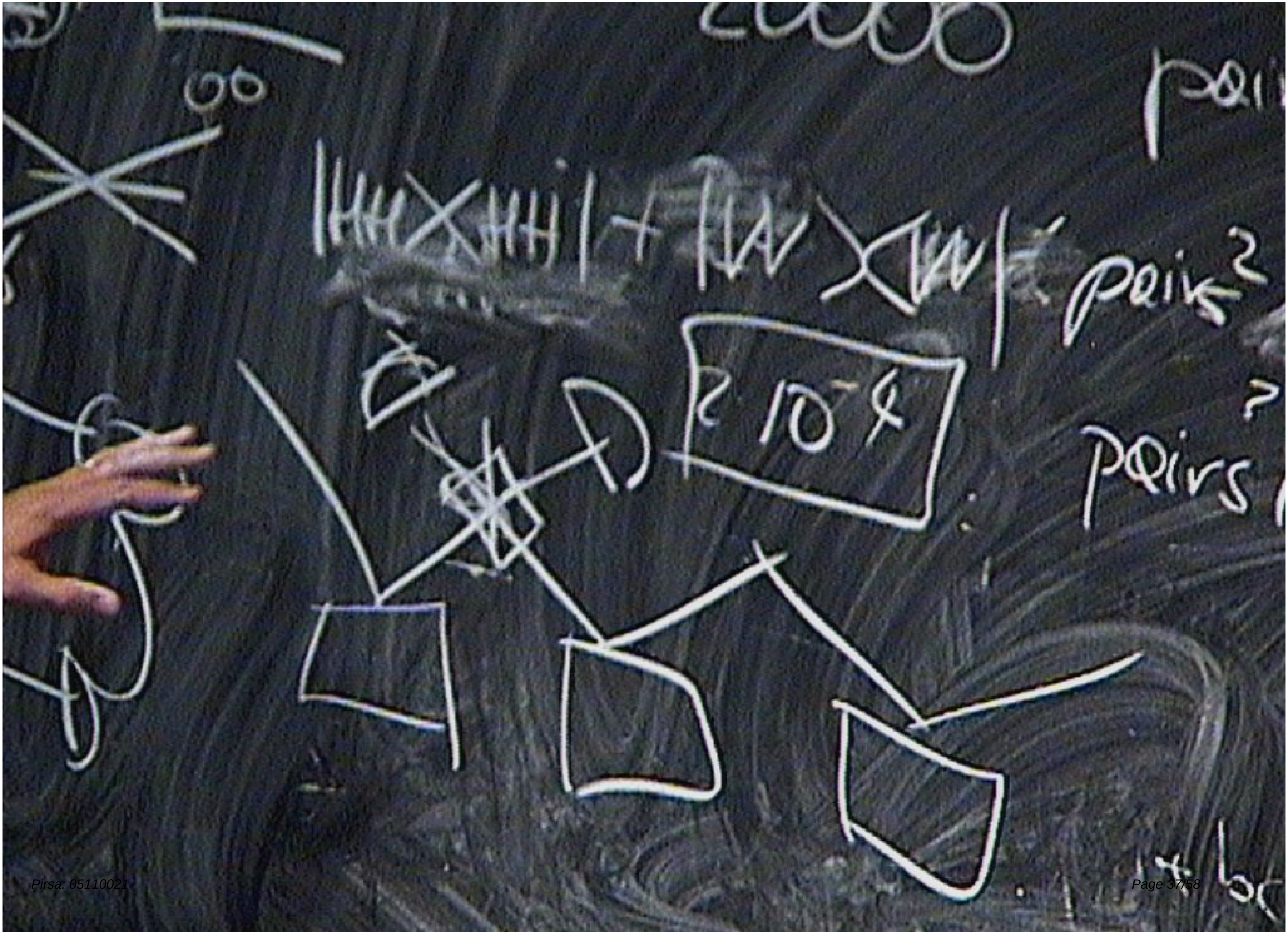

20000
pairs/s
20
pairs^2/10s


20000
pairs/s
20
pairs²/s
2·10⁻⁴
pairs²/s



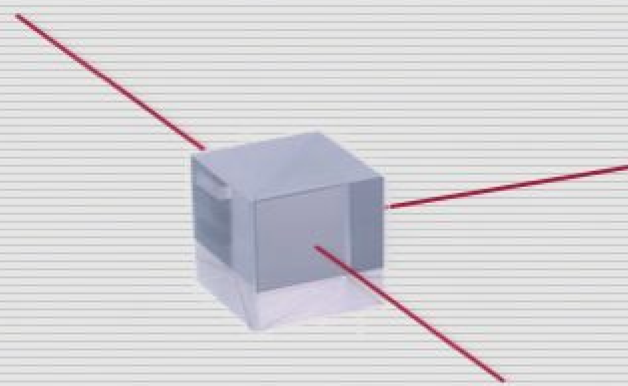

20000
pairs²
pairs
2·10^9

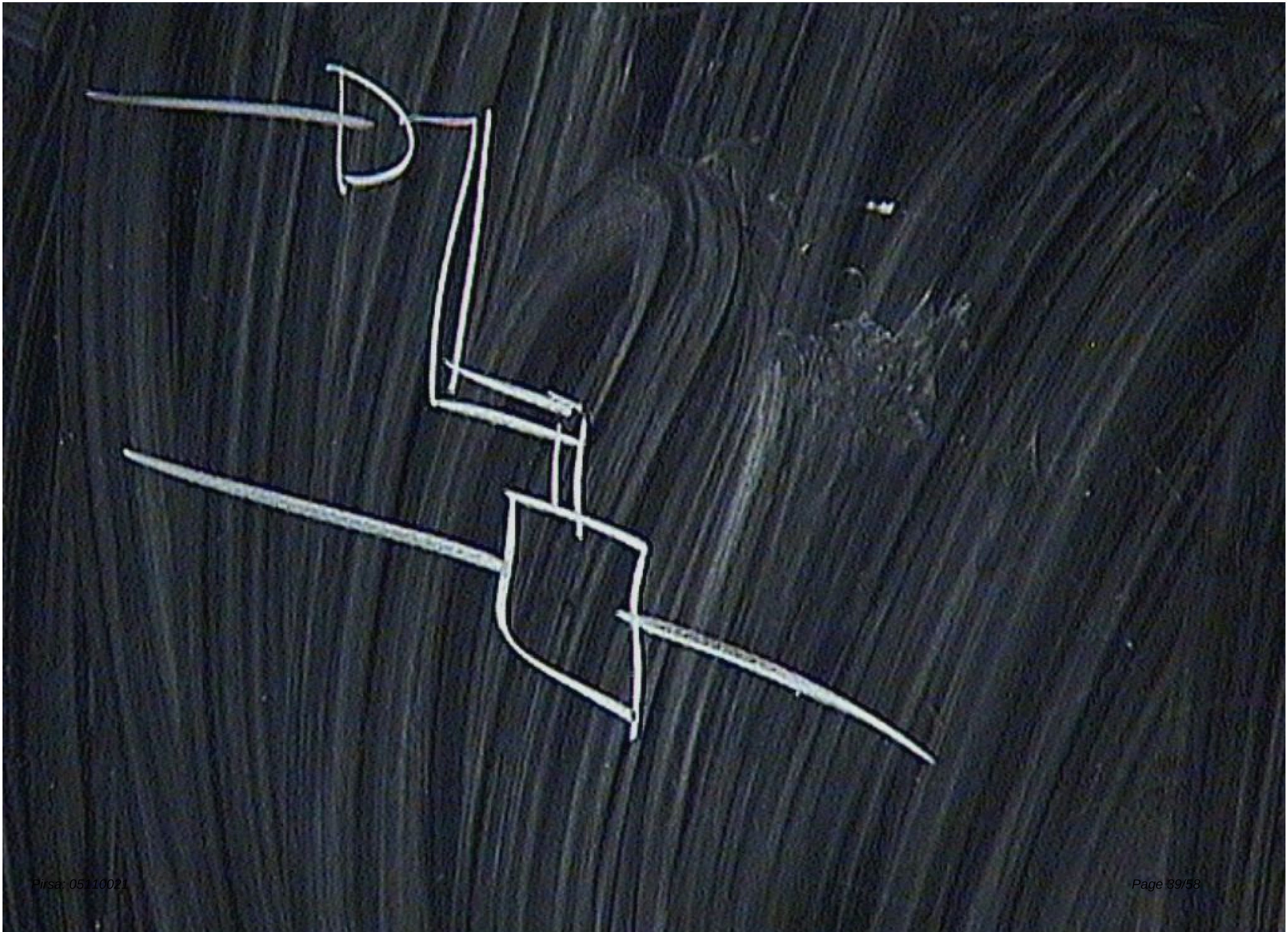

pairs²
pairs
10⁻⁴

Single qubit gates

- Easy and precise for static op
- Accuracy better than 99%
- Polarization: waveplates/retarders
- Dual rail: beamsplitters/interferometers

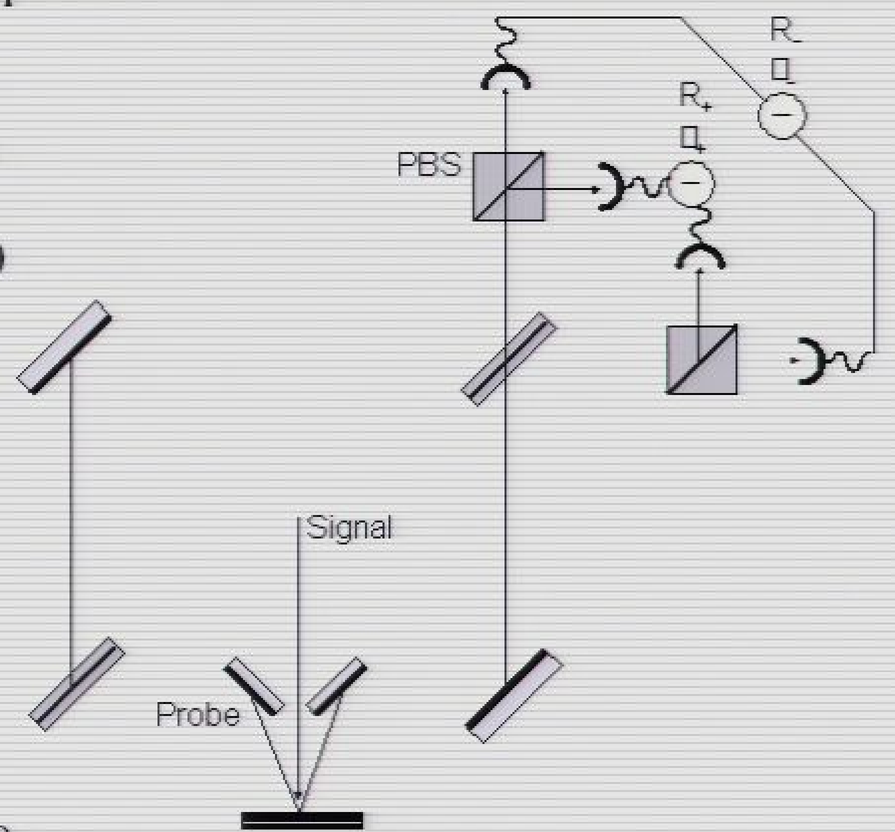
- Dynamic rotations via integrated modulators have 50% loss but up to 60 GHz operation
- Bulk modulators go up to 100 MHz with low loss but have significant static delay (feed-forward issue)





Deterministic two-qubit gates

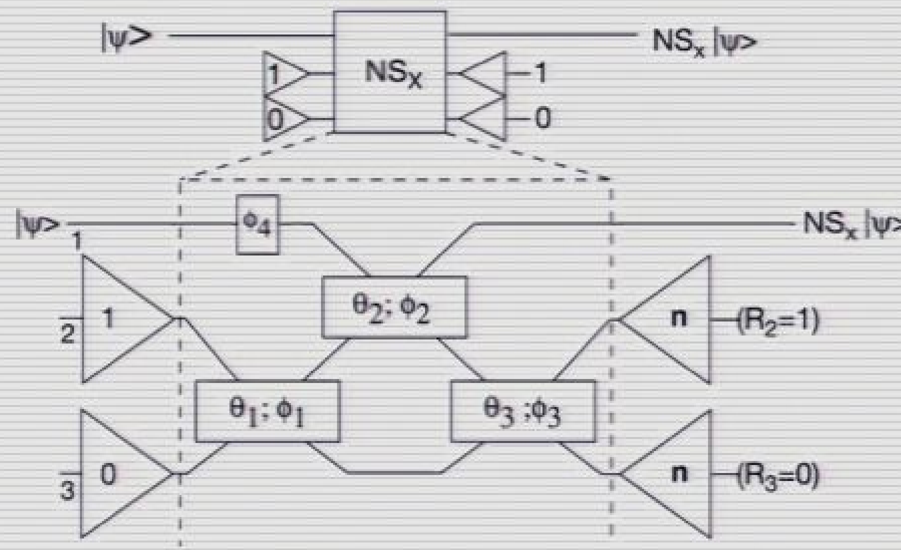
- No interaction between photons in vaccum
- Nonlinear optics provides interaction
  - Single photon level nonlinearity in cavities with single atom yielded 16° nonlinear phase shift [Turchette et al., PRL **75,** 4710 (1995)]
  - Optically pumped atomic vapors (EIT)
  - Waveguides in nonlinear optical materials
  - Strongly coupled semiconductor microcavities
- Weak nonlinearities
  - Munro, Nemoto & Spiller NJP **7,** 137 (2005): Couple two qubits to strong field to enhance effective nonlinearity
  - Franson, Jacobs & Pittman, quant-ph/0401133: extended weak nl + measurement



G. Weihs et al.,
Semi. Sci. Tech **18,** S386 (2003).

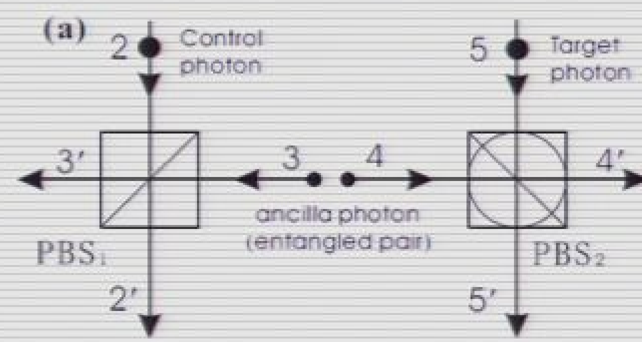
Probabilistic two qubit gates

- Original suggestion
  Knill, Laflamme, Milburn,
  Nature ***409***, 46 (2000)
  Nonlinear sign (π phase) gate



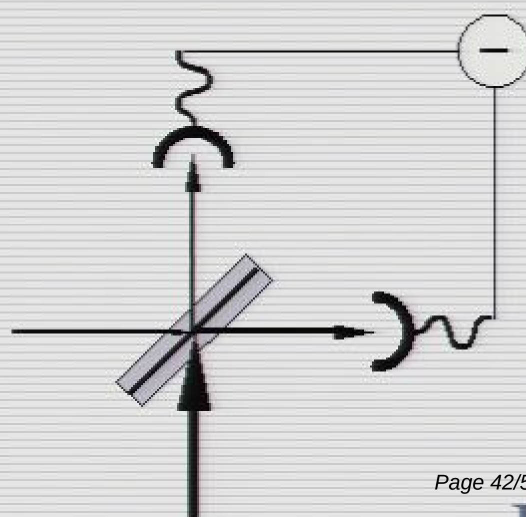
- Maximum success
  probability is 25%
  [Eisert, PRL ***25***, 040502 (2005)]

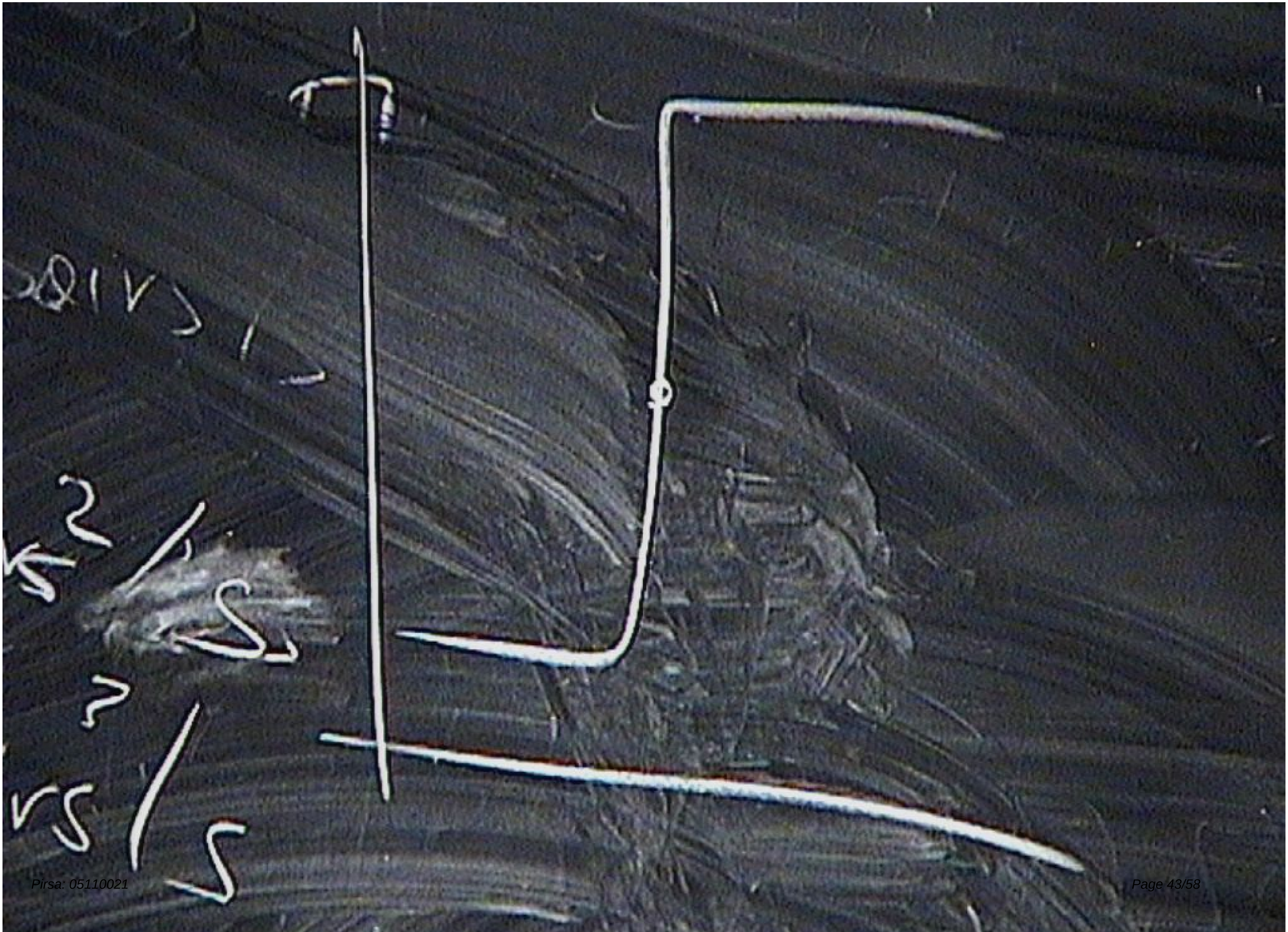
- Practical implementations
  use entangled ancillas
  [Pittman et al., PRA ***64***, 062311 (2001)]

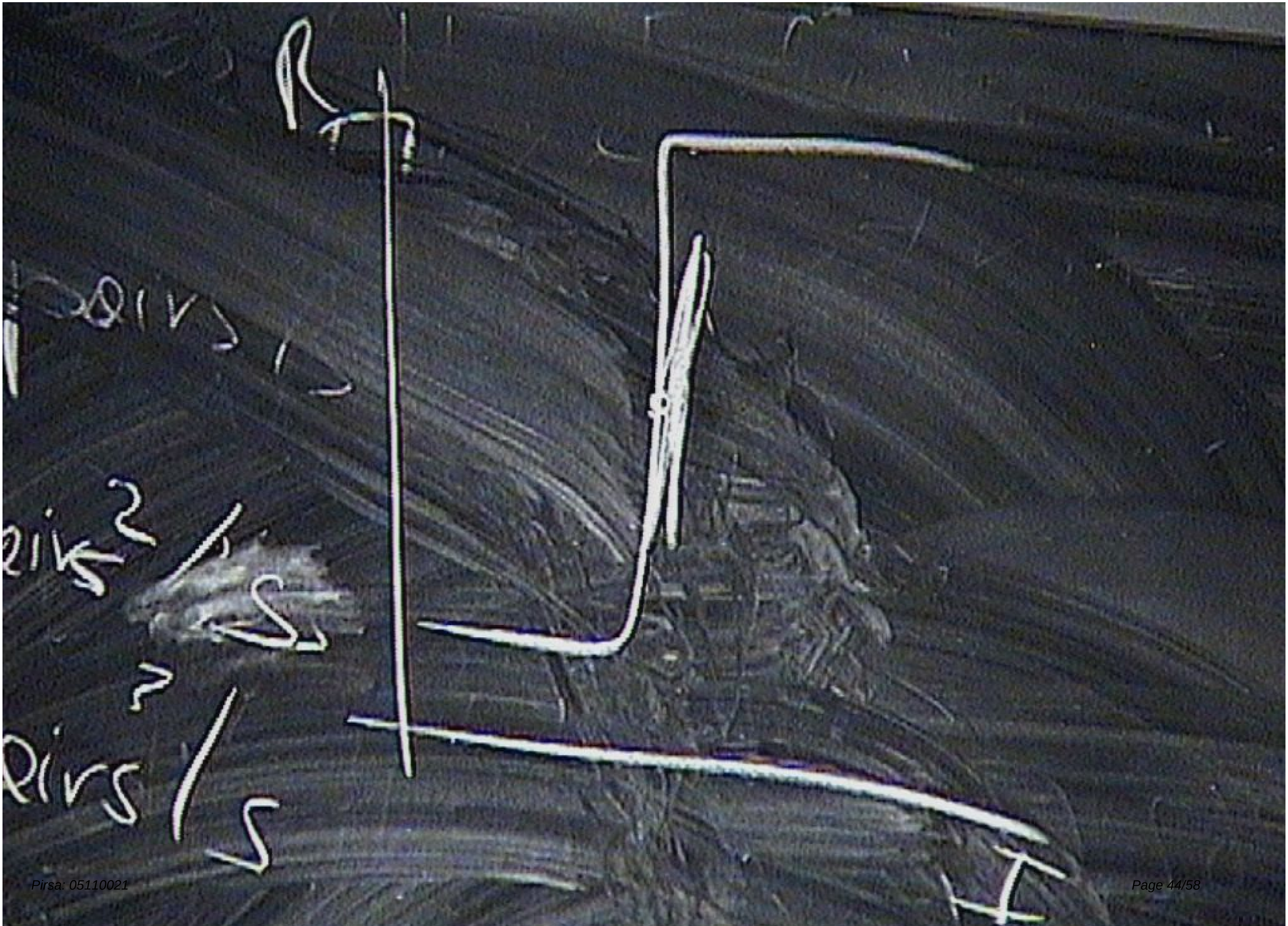


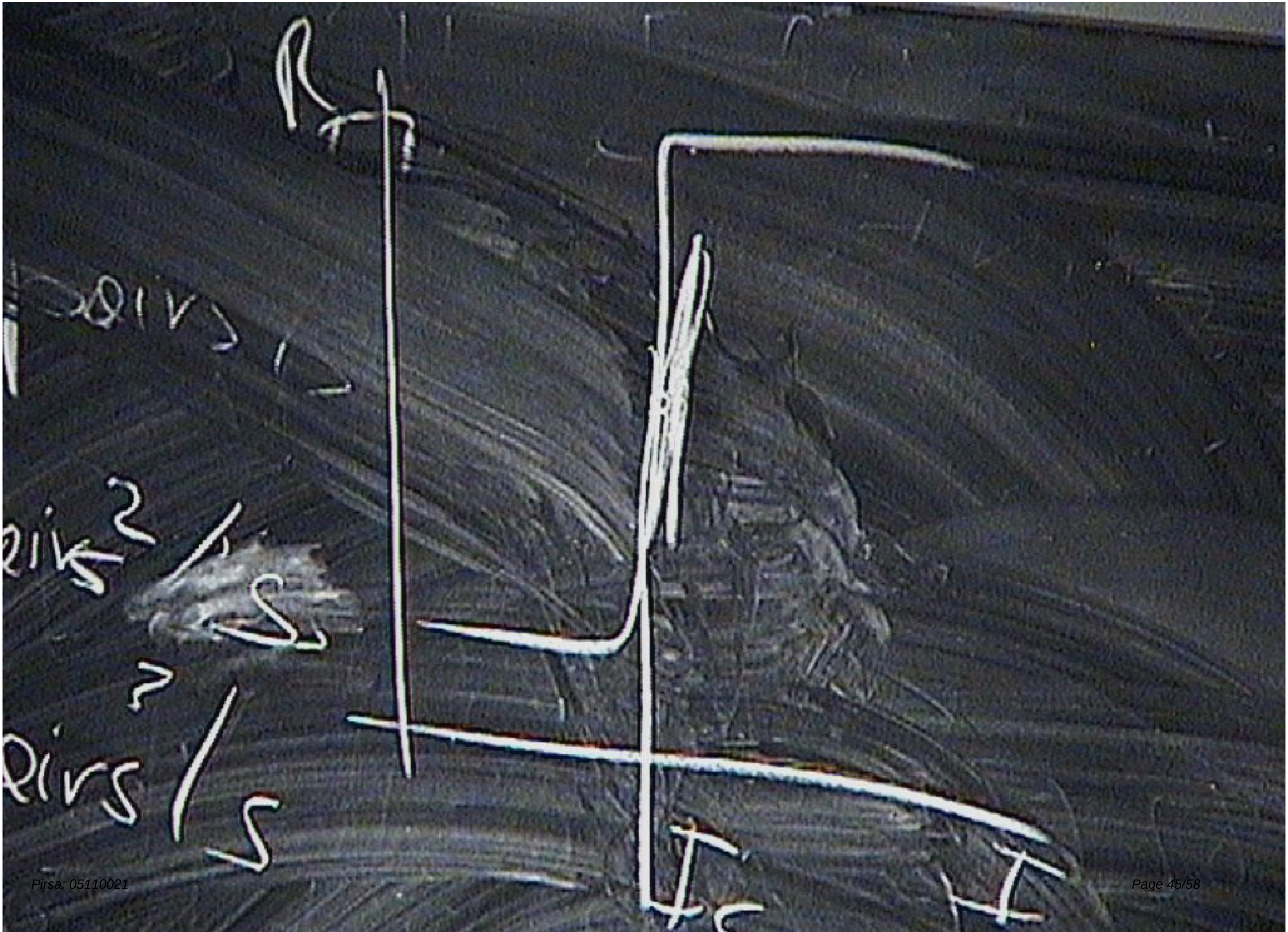
Detection / Measurement

- Single photon detectors
  - Photomulitpliers
    efficient for VIS / UV light with low dark count (few / second)
    very fast
  - Avalanche Photodiodes
    Si: efficient in VIS / NIR with low dark count (few/second)
    Ge: small efficiency in NIR, dark >10 kcps
    InGaAs: small efficiency in NIR, dark >10 kcps
    tradeoff between speed and efficiency
  - Solid State Photomulitpliers
    very efficient in VIS/NIR dark ~10 kcps
    slow
  - Superconducting transition edge sensors
    fairly efficient, very low dark, speed varies
- Homodyne detection
  - Very efficient, slow, needs local oscillator





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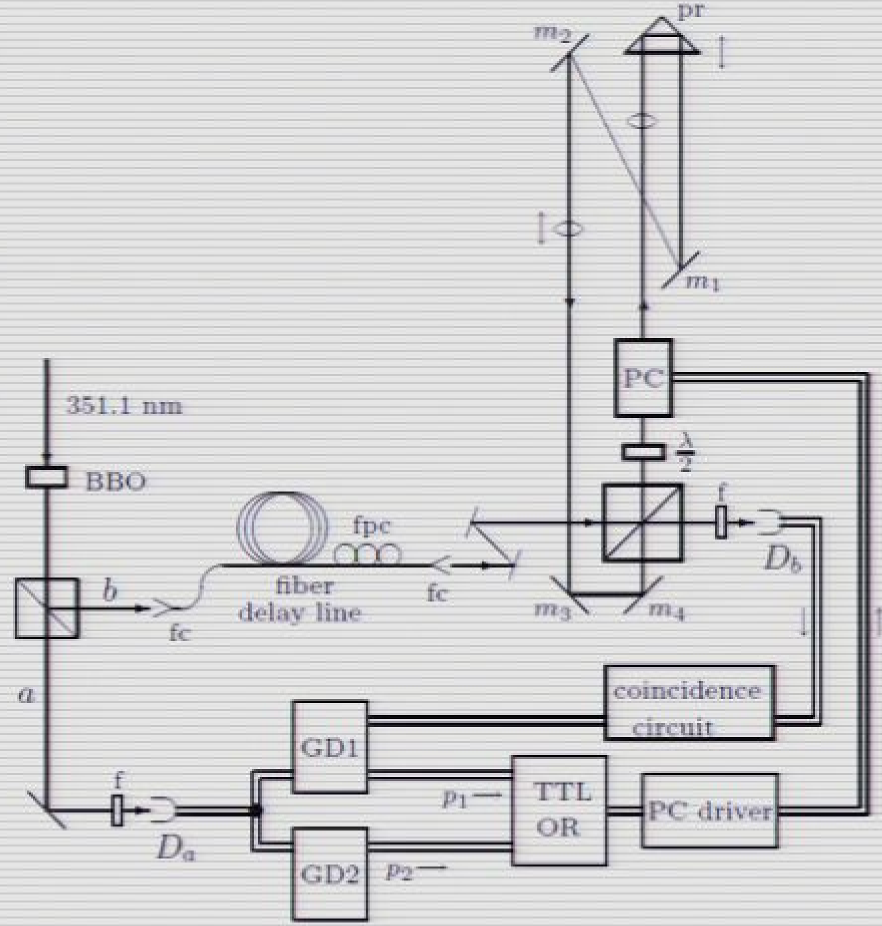
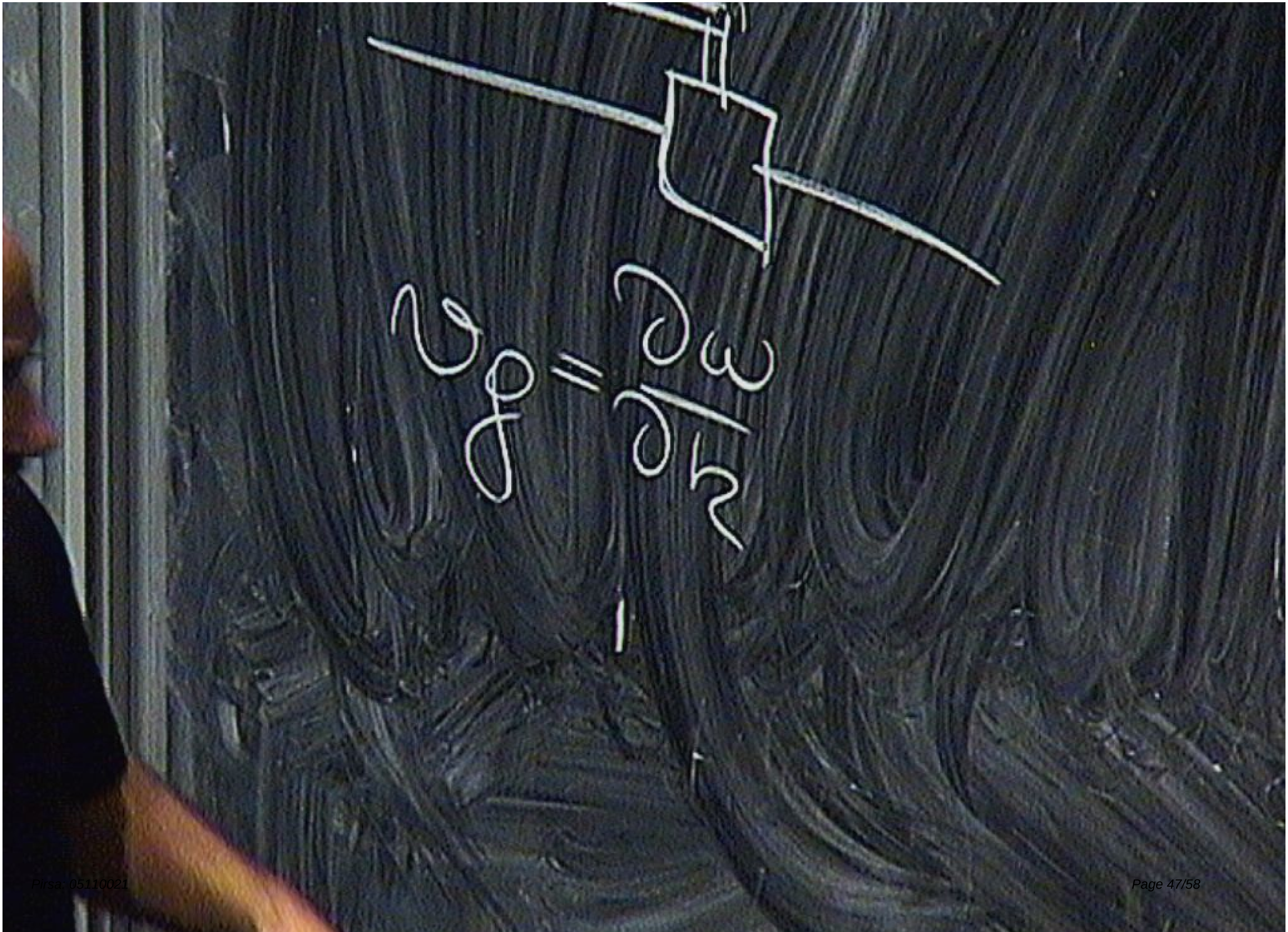
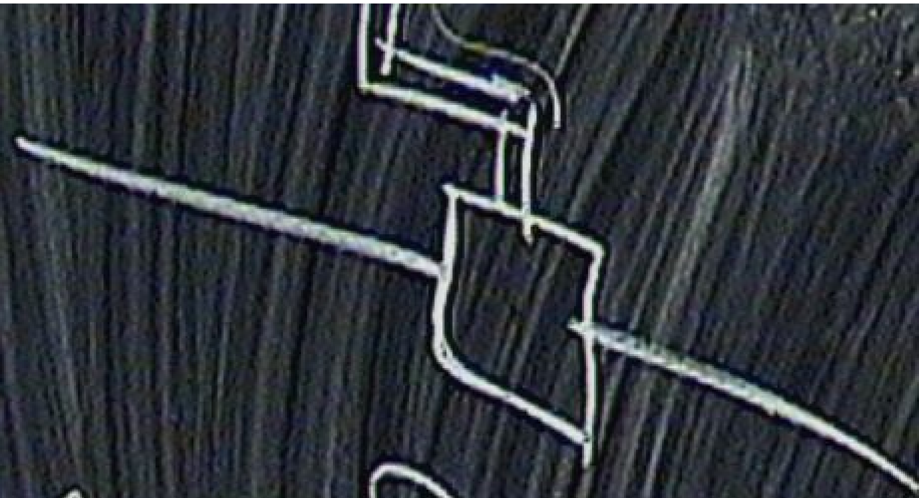
Storage

- Fiber loops
  - Telecom wavelengths are attenuated with 0.1 db/km ~ 1% / 1 μs
- EIT (slow light / dark state polaritons)
  - Control group velocity by coherence between atomic levels
- Photonic crystal waveguides
  - Coupled resonators produce small group velocity
- Interfaces
  - Atoms
  - Ions
  - Superconductors (for microwaves)



From: Pittman et al., PRA ***66***, 042303 (2002)


$v_g = \frac{\partial \omega}{\partial k}$



$$v_g = \frac{\partial \omega}{\partial k} \qquad v_p = \frac{\omega}{k}$$

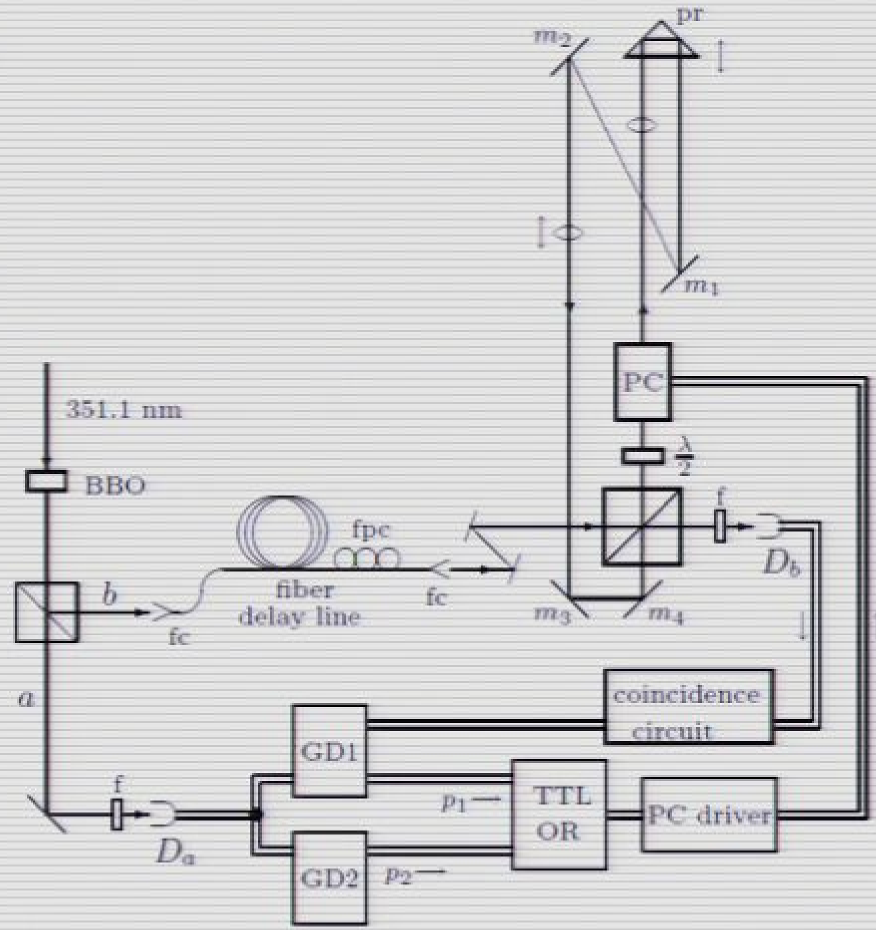
Errors

- Free space
  - Local (tabletop): only propagation phase errors, loss per element very small
  - Long distance: turbulence → phase errors, scattering → loss
  - Gates: interferometry with limited visibility
- Fibers
  - Random walk depolarization
  - Dephasing (low frequency)
  - Gates: lossy modulators, high visibilty interferometry
- Detector dark counts?
- Any realistic attempt at optical QIP must integrate sources, gates, and detection on an "optical chip"

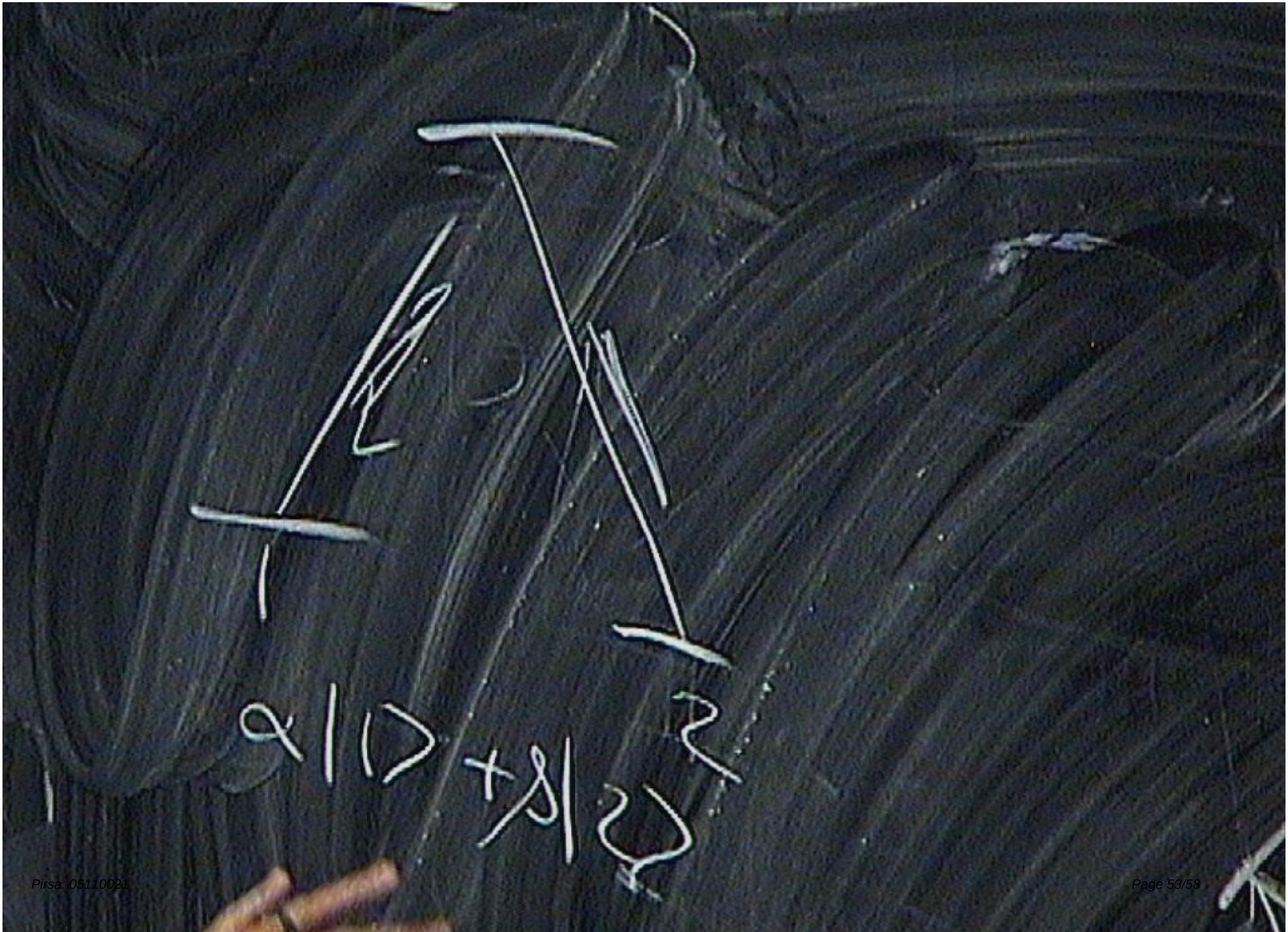
Sources of entangled photon pairs

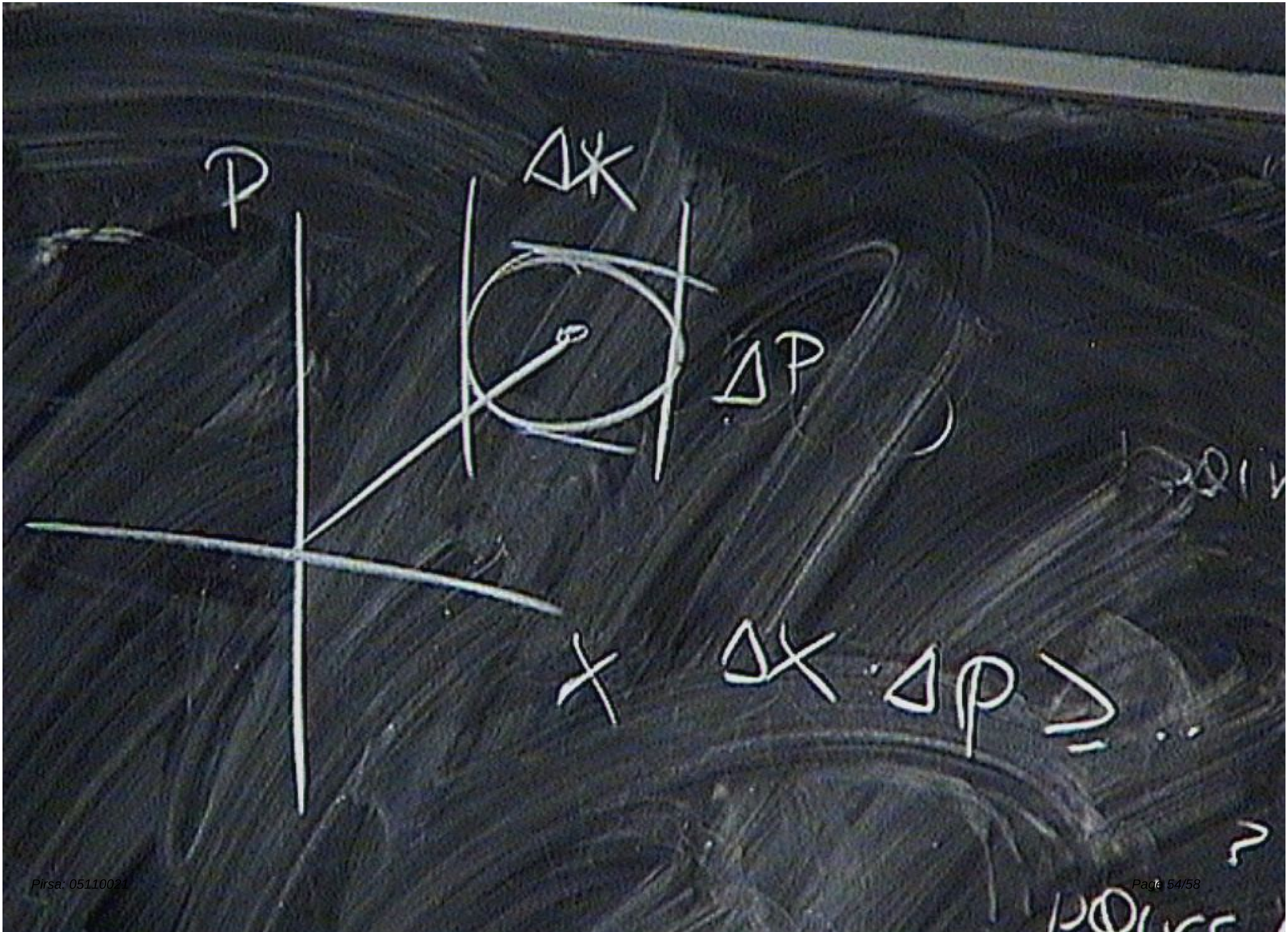
Storage

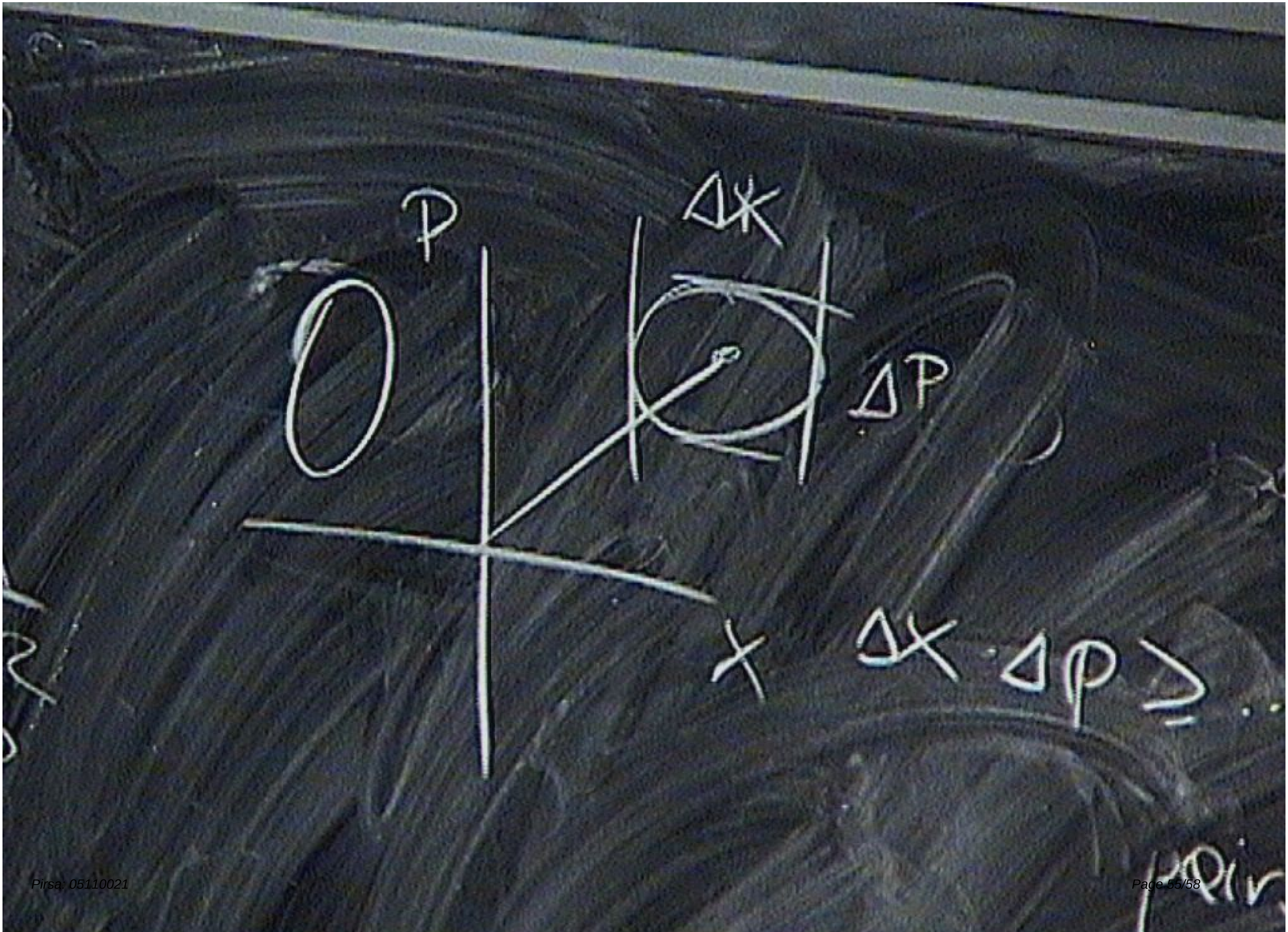
- Fiber loops
  - Telecom wavelengths are attenuated with 0.1 db/km ~ 1% / 1 μs
- EIT (slow light / dark state polaritons)
  - Control group velocity by coherence between atomic levels
- Photonic crystal waveguides
  - Coupled resonators produce small group velocity
- Interfaces
  - Atoms
  - Ions
  - Superconductors (for microwaves)



From: Pittman et al., PRA ***66,*** 042303 (2002)




P
Δx
Δp
x
Δx · Δp ≥ ...


p
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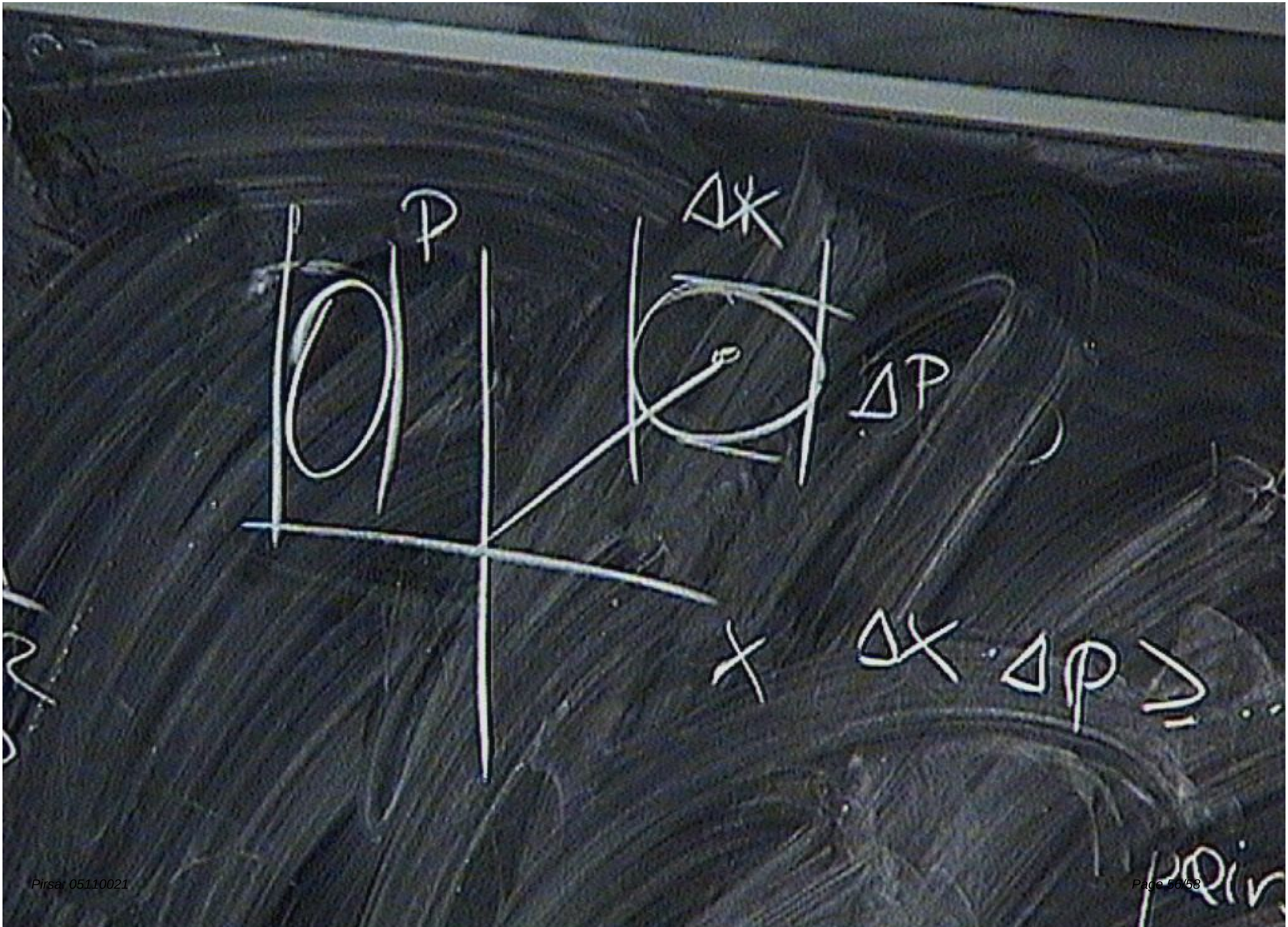
p
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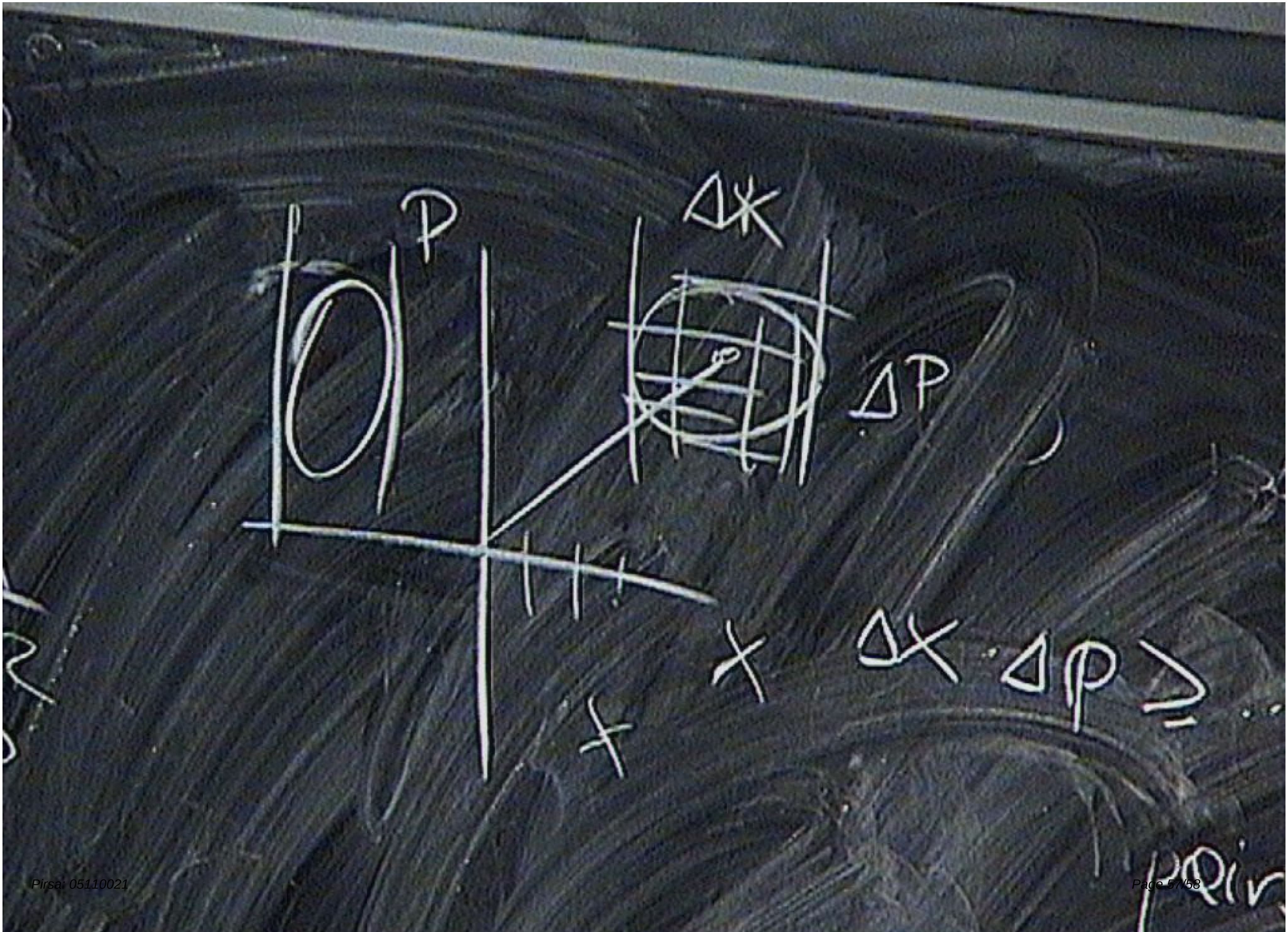
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