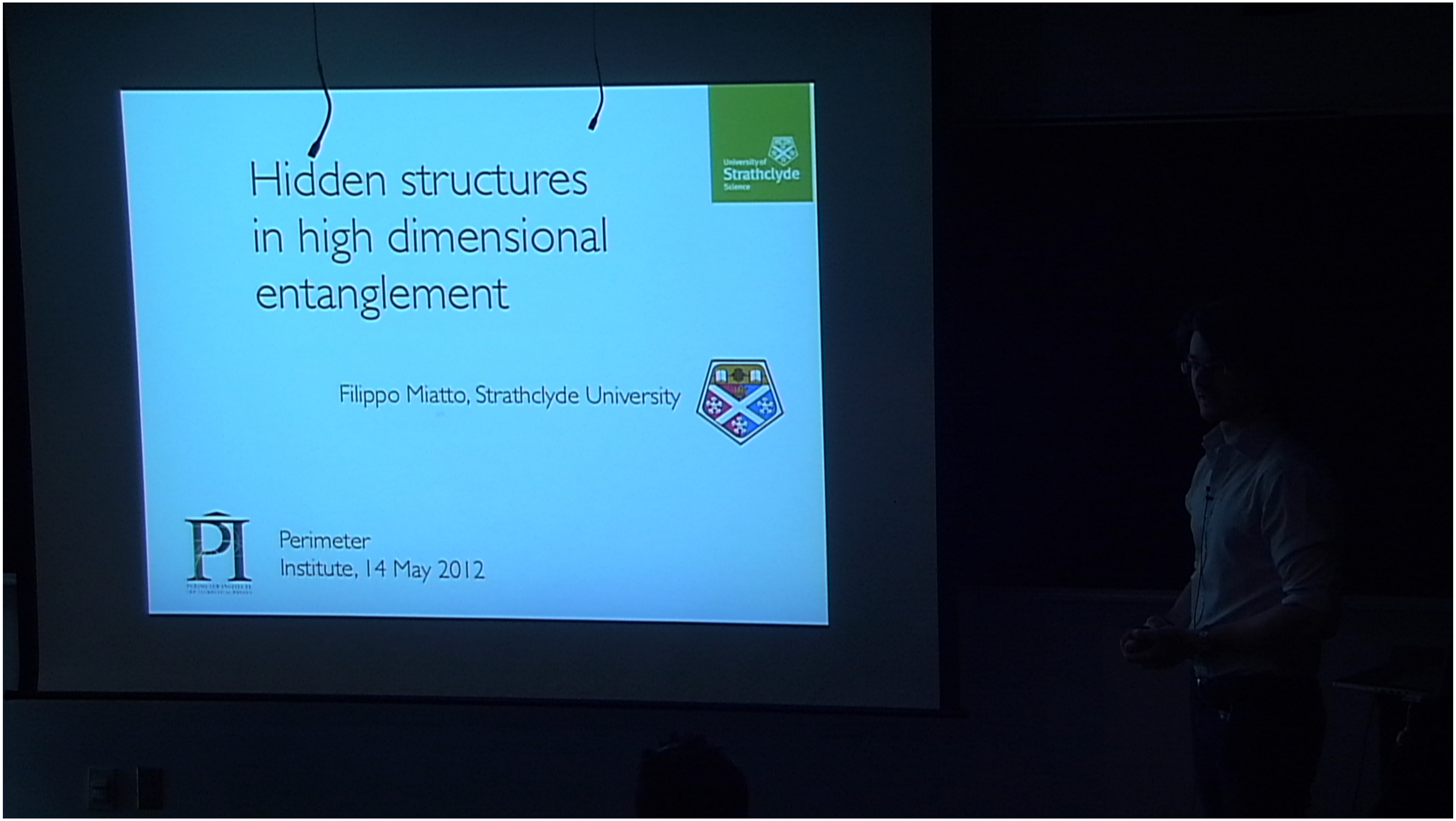
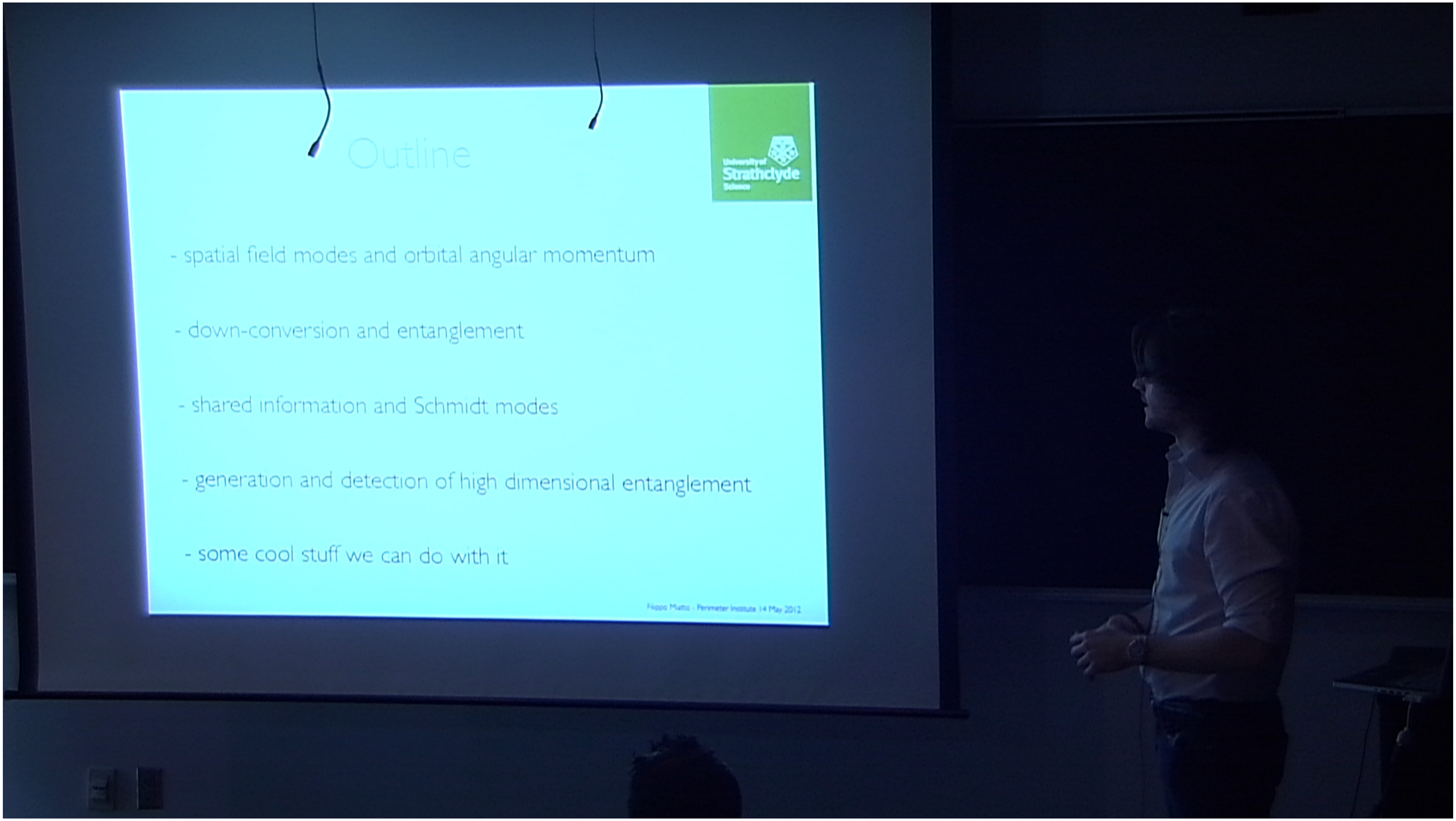
Title: Hidden Structures in High Dimensional Entanglement

Date: May 14, 2012 04:00 PM

URL: http://pirsa.org/12050064

Abstract: The minimal dimension of the Hilbert space that hosts states of an entangled pair of photons can be extremely high. The process of spontaneous parametric down-conversion (SPDC) is a possible way of producing highly entangled photon pairs, in both the spatial and temporal parts of the wave function. However, the most common approximations that are used in the analytical treatment of SPDC hinder the possibility of noticing further structures of the single joint modes. We used a more general formalism, showing that the entangled modes are still eigenfunctions of the orbital angular momentum, but the radial modes are far from the usual ones and they show novel interesting features that might be explained by introducing an additional quantum number. The problem of dealing with SPDC states has two faces: we need to know with enough confidence what state are created, and we need to know with enough confidence what states we are projecting on, upon measurement. We tried to approach both these problems together, and we showed that high dimensional entanglement shields the amount of information that can be stored in a photon from imperfect measurements. In my talk I will present both these aspects of high-dimensionally entangled states of photon pairs.


Hidden structures
in high dimensional
entanglement
Filippo Miatto, Strathclyde University
University of
Strathclyde
Science
Perimeter
Institute, 14 May 2012


Outline
University of Strathclyde Science
- spatial field modes and orbital angular momentum
- down-conversion and entanglement
- shared information and Schmidt modes
- generation and detection of high dimensional entanglement
- some cool stuff we can do with it
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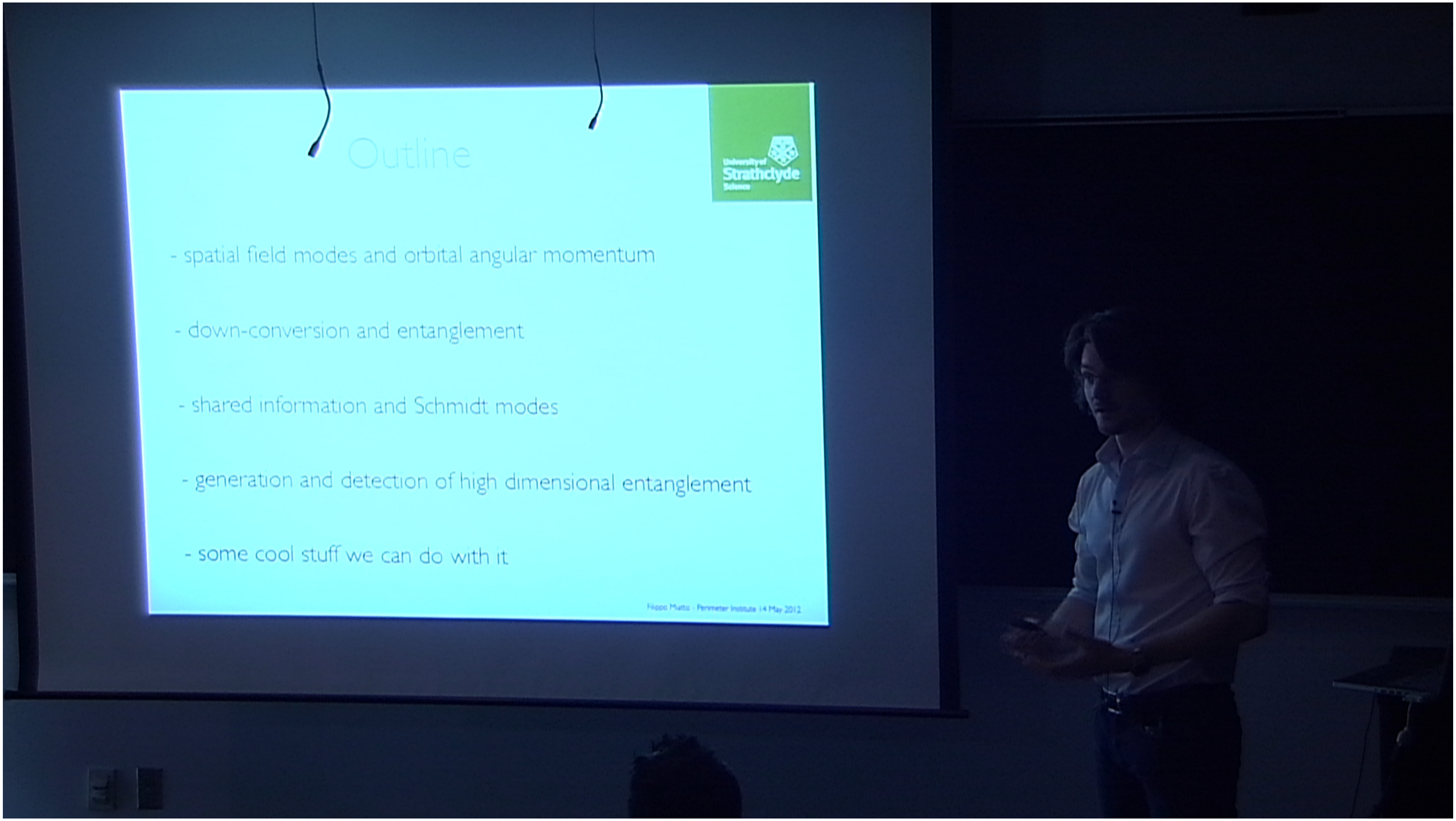
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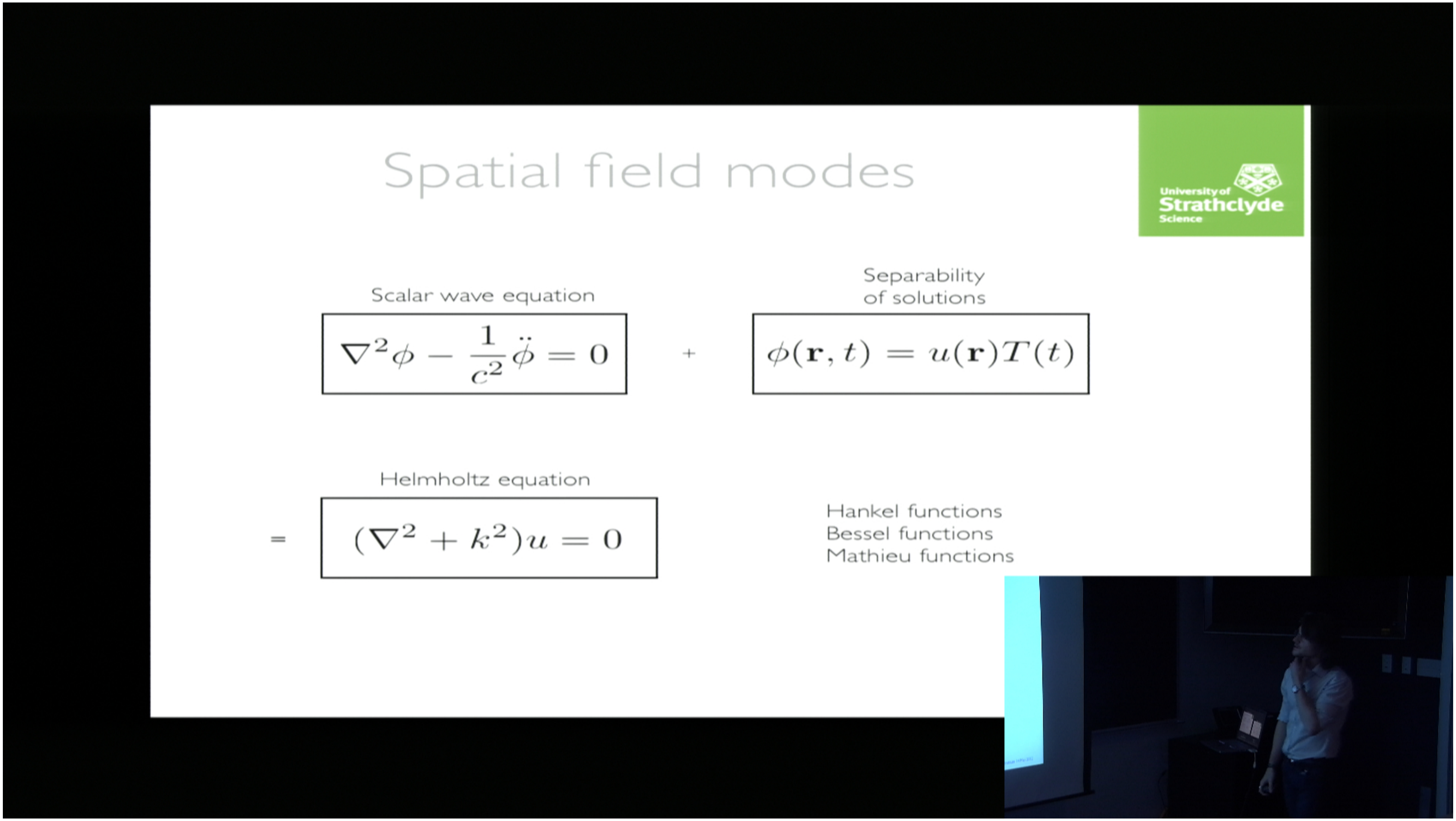
Spatial field modes
University of Strathclyde Science
Scalar wave equation
$\nabla^2\phi - \frac{1}{c^2}\ddot{\phi} = 0$
+
Separability of solutions
$\phi(\mathbf{r}, t) = u(\mathbf{r})T(t)$
=
Helmholtz equation
$(\nabla^2 + k^2)u = 0$
Hankel functions
Bessel functions
Mathieu functions

Spatial field modes

University of Strathclyde Science

Scalar wave equation

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Separability of solutions

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Helmholtz equation

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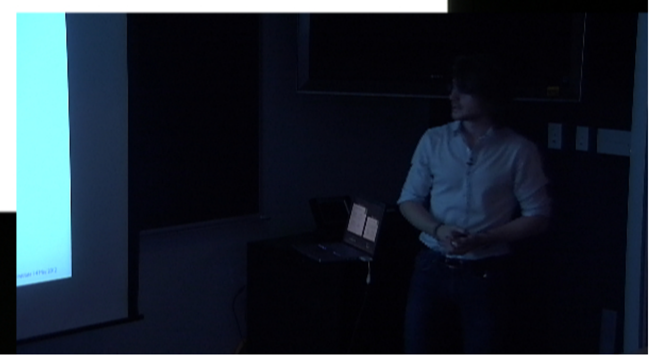

Spatial field modes

Scalar wave equation

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+

Separability of solutions

$$\phi(\mathbf{r}, t) = u(\mathbf{r})T(t)$$

Helmholtz equation

=

$$(\nabla^2 + k^2)u = 0$$

Hankel functions
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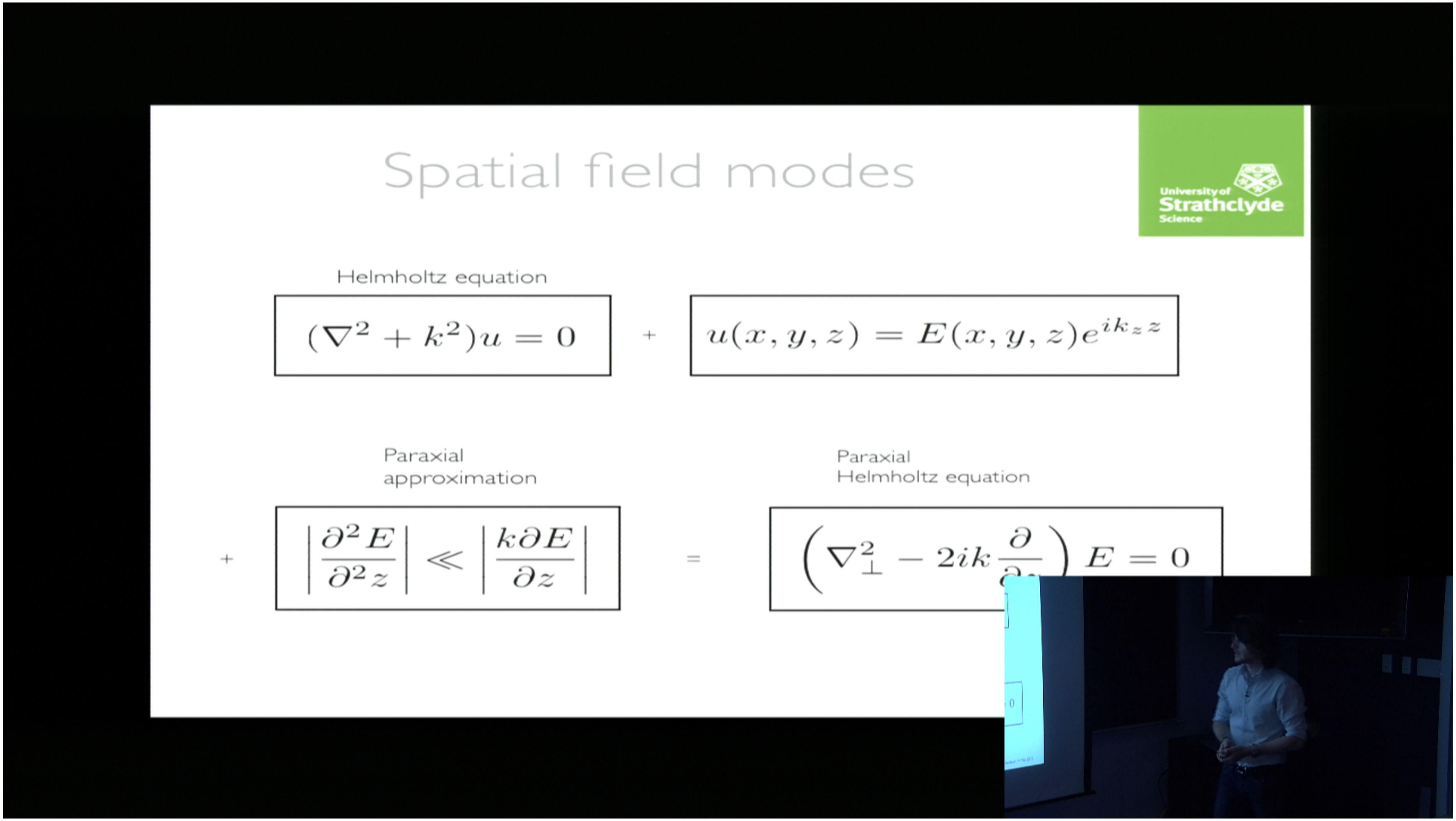

Spatial field modes
University of Strathclyde Science
Helmholtz equation
$(\nabla^2 + k^2)u = 0$
+
$u(x,y,z) = E(x,y,z)e^{ik_z z}$
Paraxial approximation
+
$\left|\frac{\partial^2 E}{\partial^2 z}\right| \ll \left|\frac{k\partial E}{\partial z}\right|$
=
Paraxial Helmholtz equation
$\left(\nabla_\perp^2 - 2ik\frac{\partial}{\partial z}\right)E = 0$

Spatial field modes

Helmholtz equation

$$(\nabla^2 + k^2)u = 0$$

+

$$u(x,y,z) = E(x,y,z)e^{ik_z z}$$

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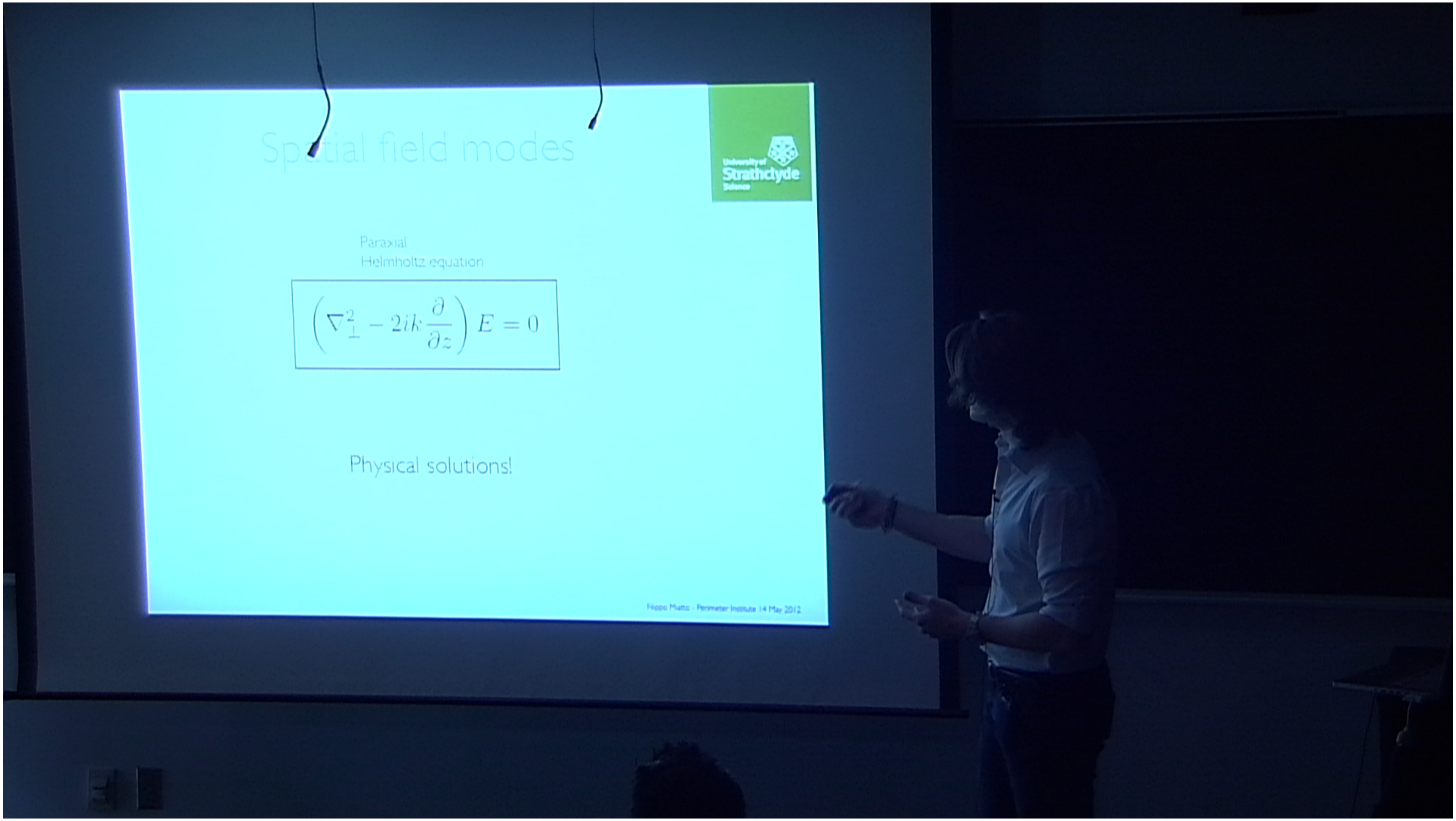
Spatial field modes
University of Strathclyde Science
Paraxial
Helmholtz equation
$$\left(\nabla_\perp^2 - 2ik\frac{\partial}{\partial z}\right)E = 0$$
Physical solutions!
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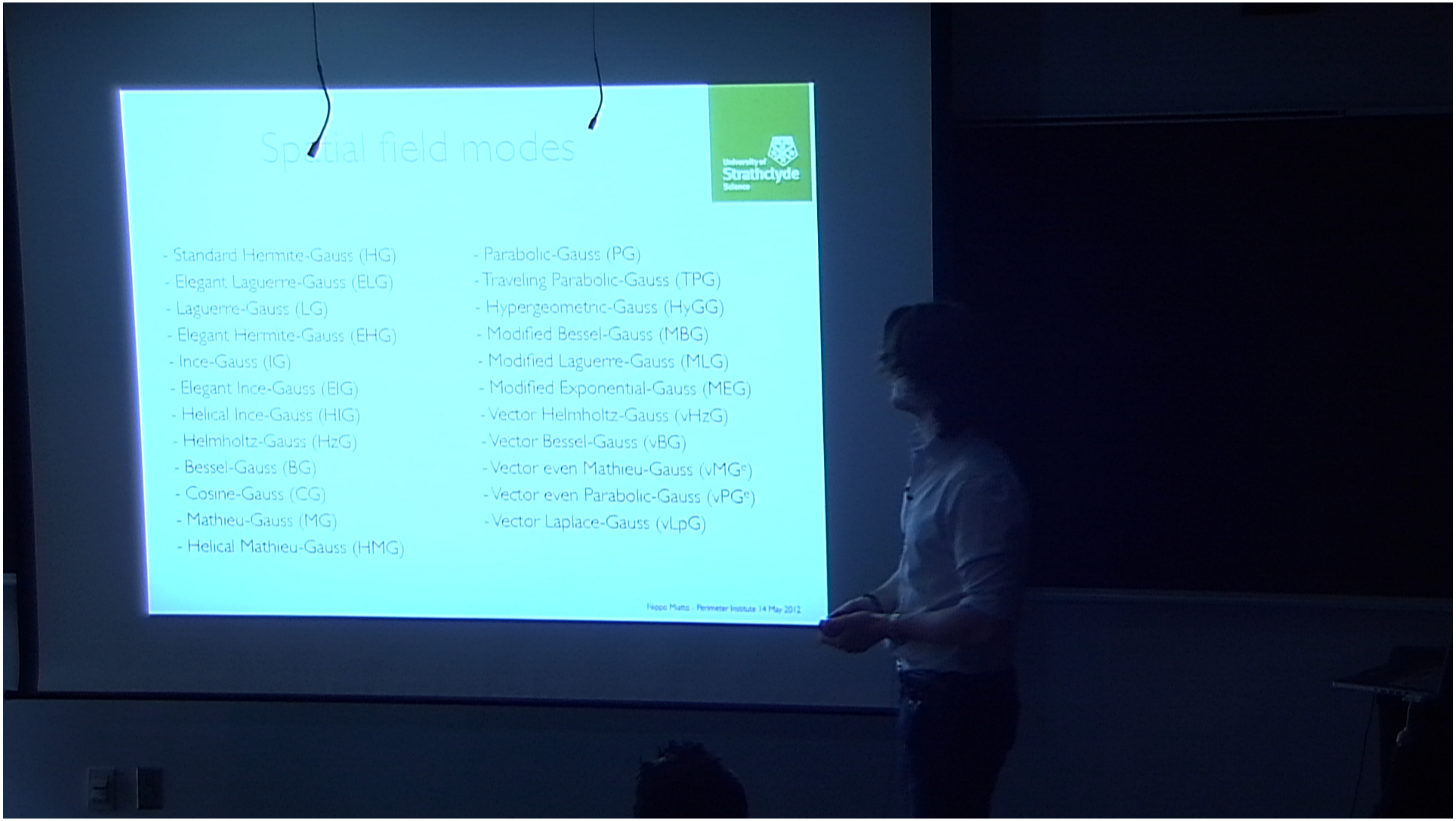
Spatial field modes
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Science
- Standard Hermite-Gauss (HG)
- Elegant Laguerre-Gauss (ELG)
- Laguerre-Gauss (LG)
- Elegant Hermite-Gauss (EHG)
- Ince-Gauss (IG)
- Elegant Ince-Gauss (EIG)
- Helical Ince-Gauss (HIG)
- Helmholtz-Gauss (HzG)
- Bessel-Gauss (BG)
- Cosine-Gauss (CG)
- Mathieu-Gauss (MG)
- Helical Mathieu-Gauss (HMG)
- Parabolic-Gauss (PG)
- Traveling Parabolic-Gauss (TPG)
- Hypergeometric-Gauss (HyGG)
- Modified Bessel-Gauss (MBG)
- Modified Laguerre-Gauss (MLG)
- Modified Exponential-Gauss (MEG)
- Vector Helmholtz-Gauss (vHzG)
- Vector Bessel-Gauss (vBG)
- Vector even Mathieu-Gauss (vMGe)
- Vector even Parabolic-Gauss (vPGe)
- Vector Laplace-Gauss (vLpG)
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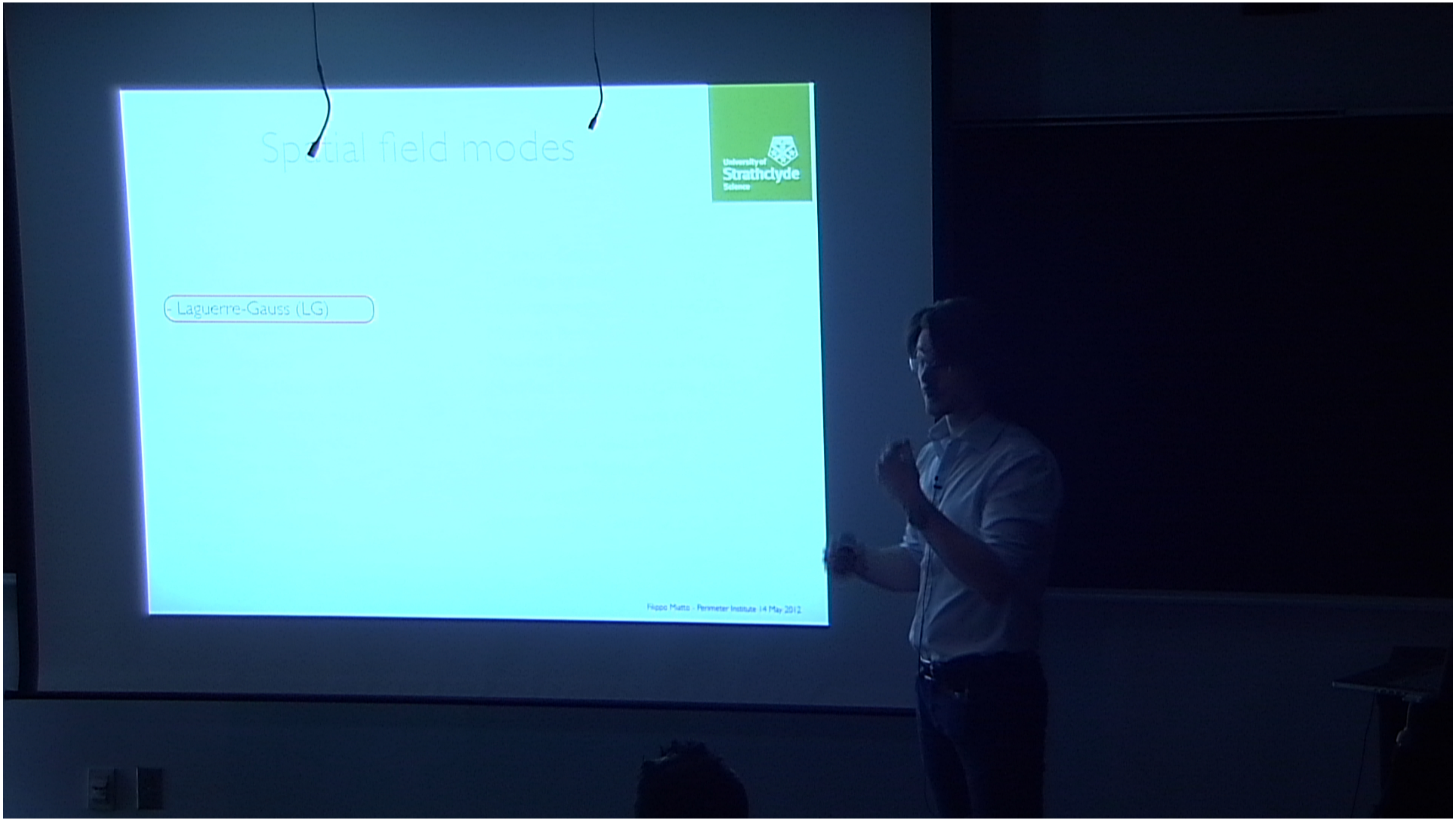
Spatial field modes
University of Strathclyde Science
- Laguerre-Gauss (LG)
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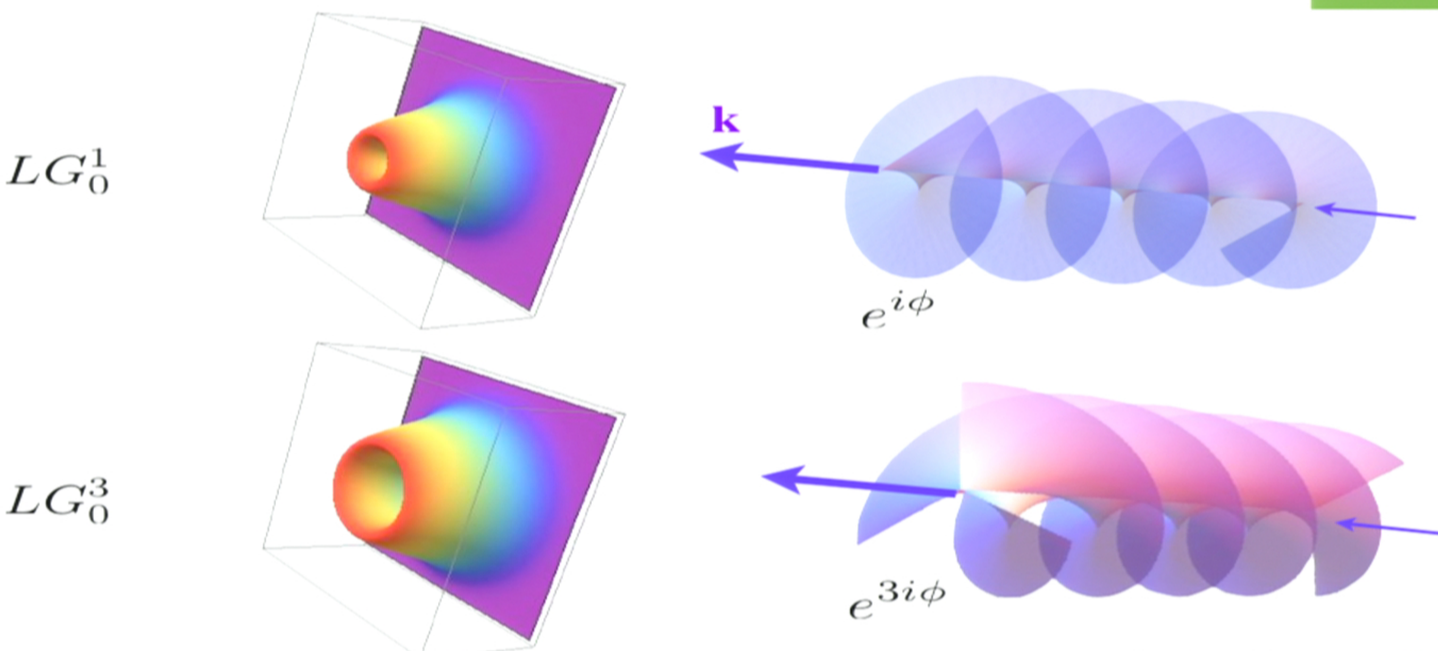
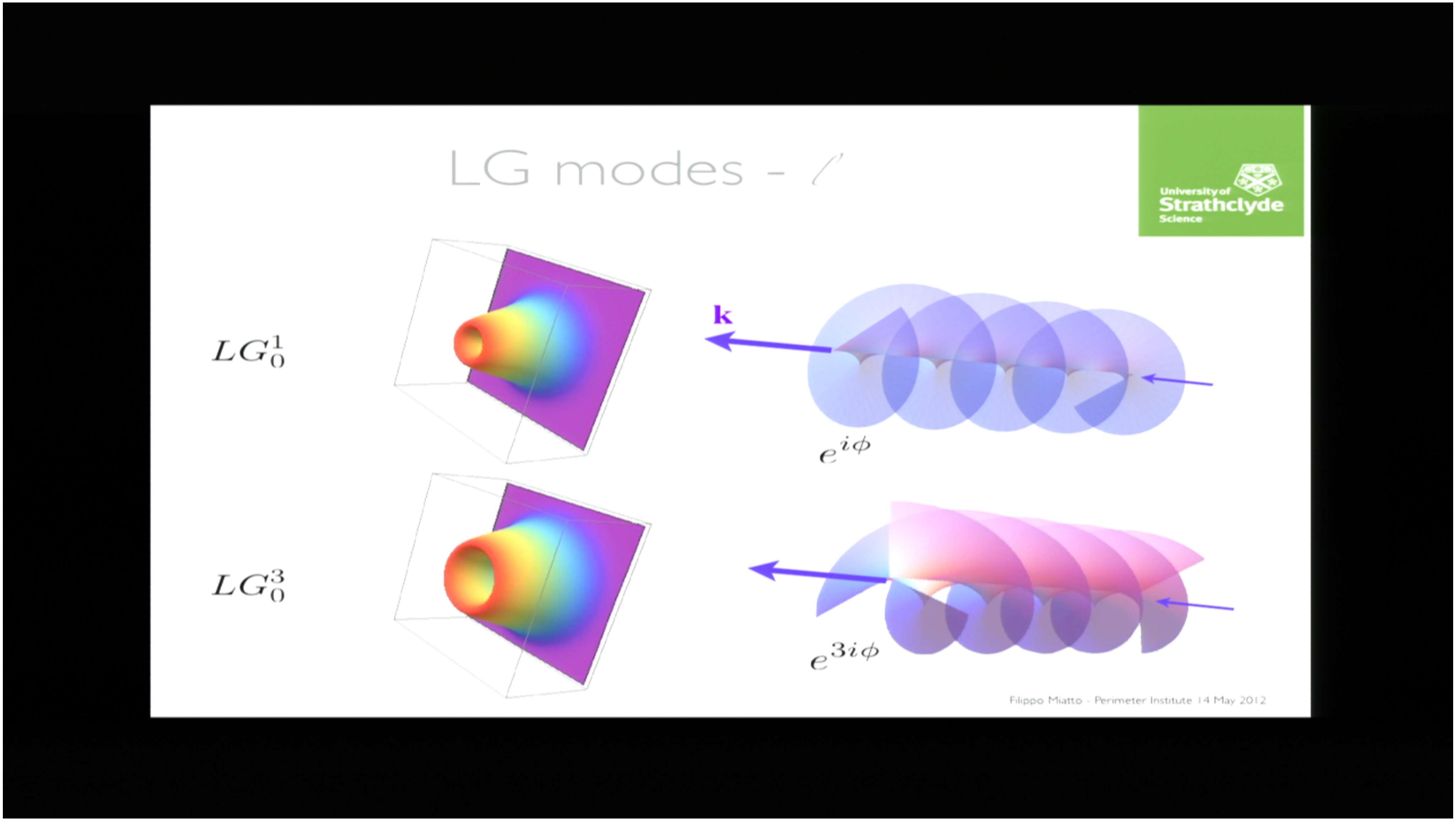
LG modes - ℓ





LG modes - ℓ
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LG_0^1
k
$e^{i\phi}$
LG_0^3
$e^{3i\phi}$
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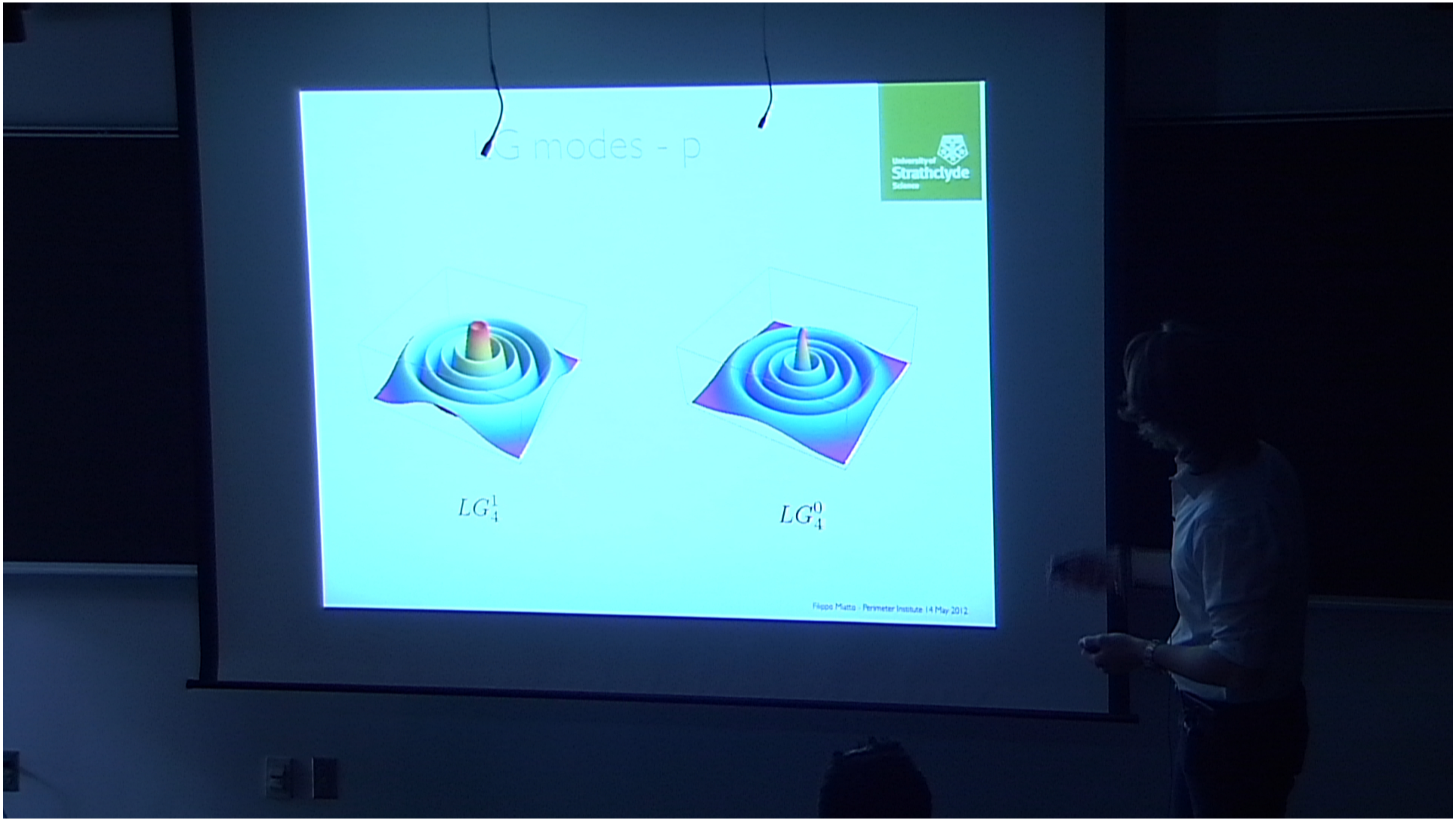
LG modes - p
University of Strathclyde Science
LG_4^1
LG_4^0
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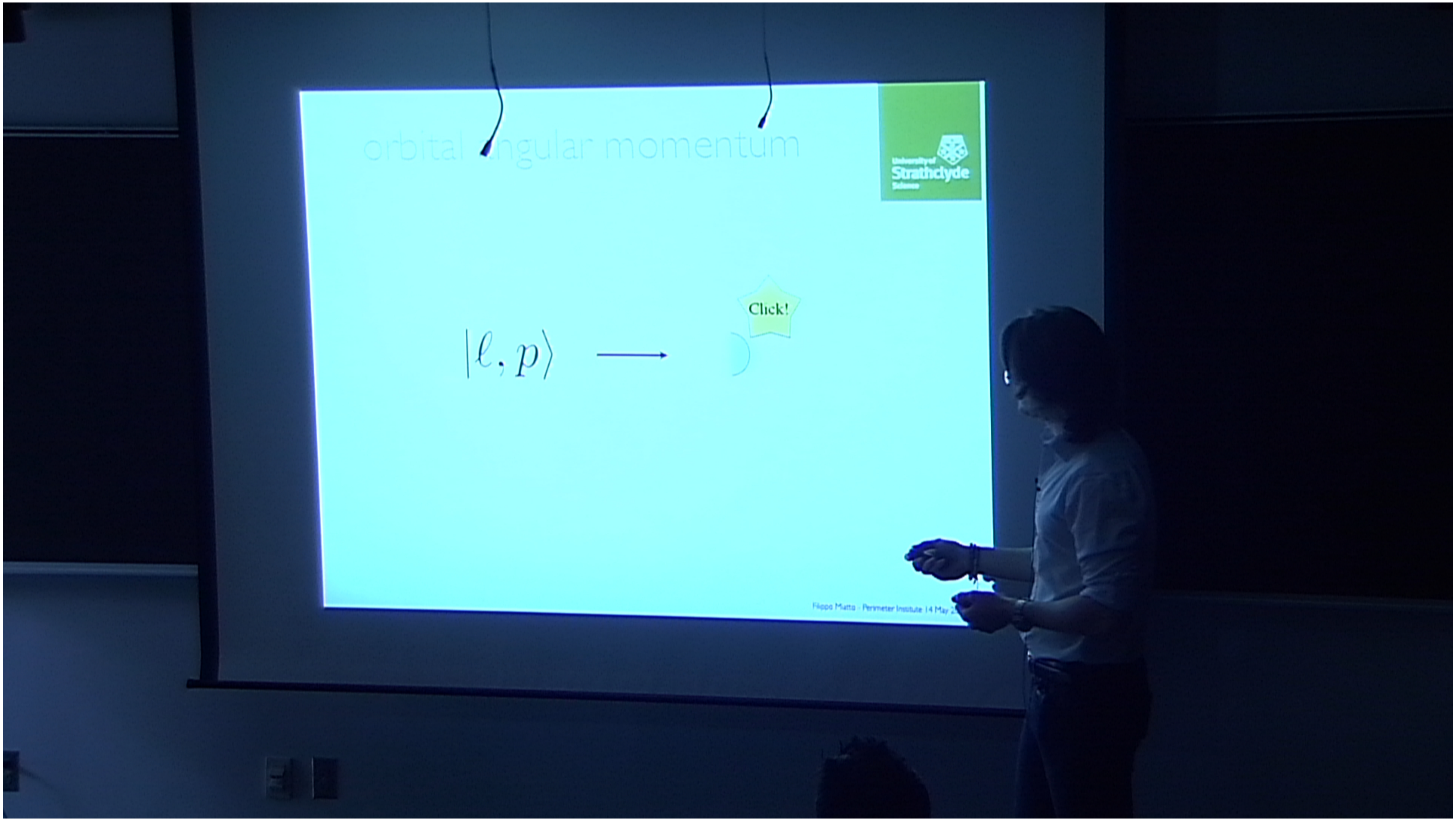
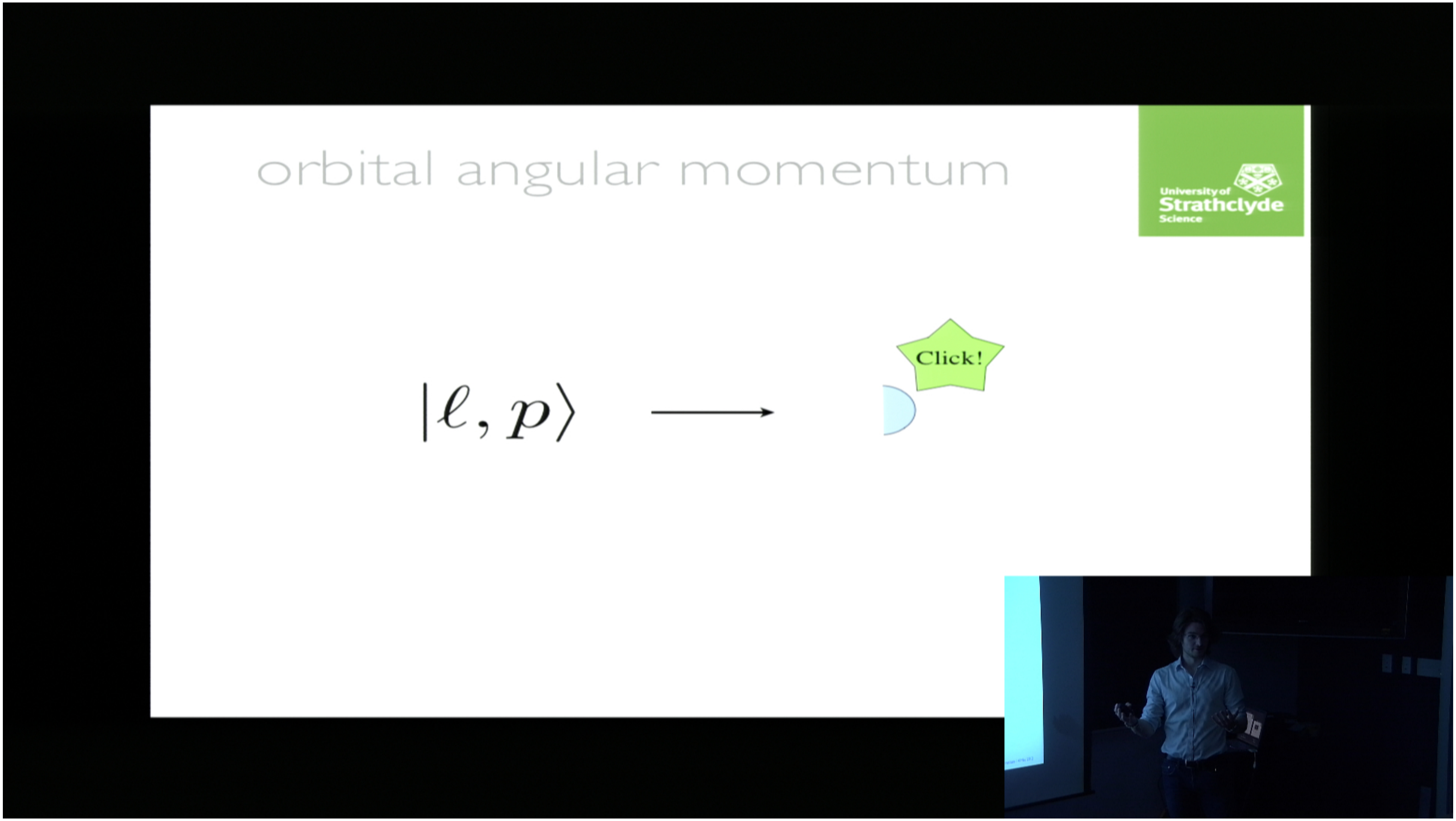

orbital angular momentum
University of Strathclyde Science
Click!
$|\ell, p\rangle$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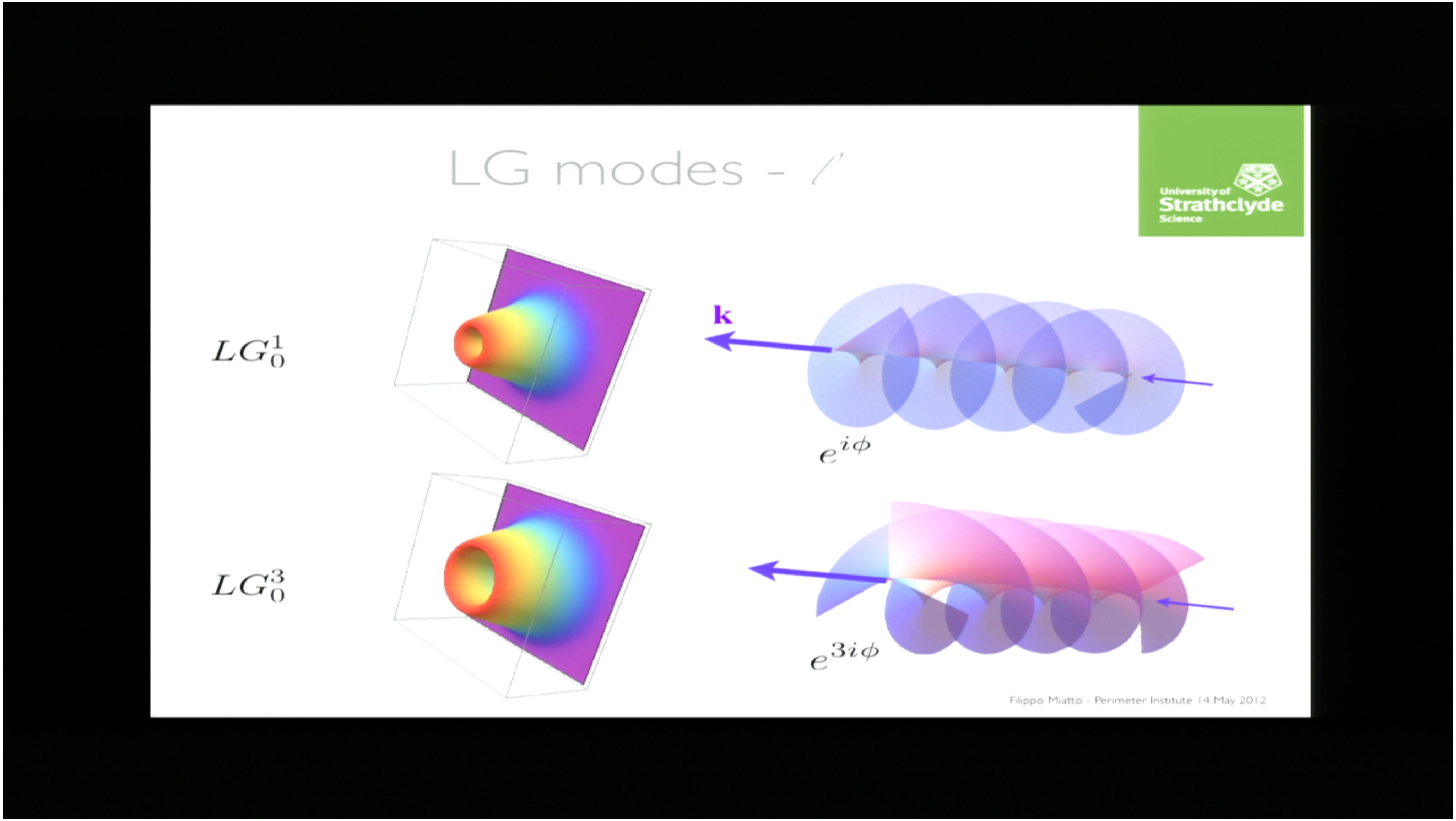
$|\ell, p\rangle$
Click!


LG modes - ℓ
University of Strathclyde Science
LG_0^1
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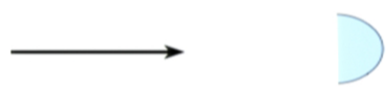
orbital angular momentum

University of Strathclyde Science

$$|\ell, p\rangle$$



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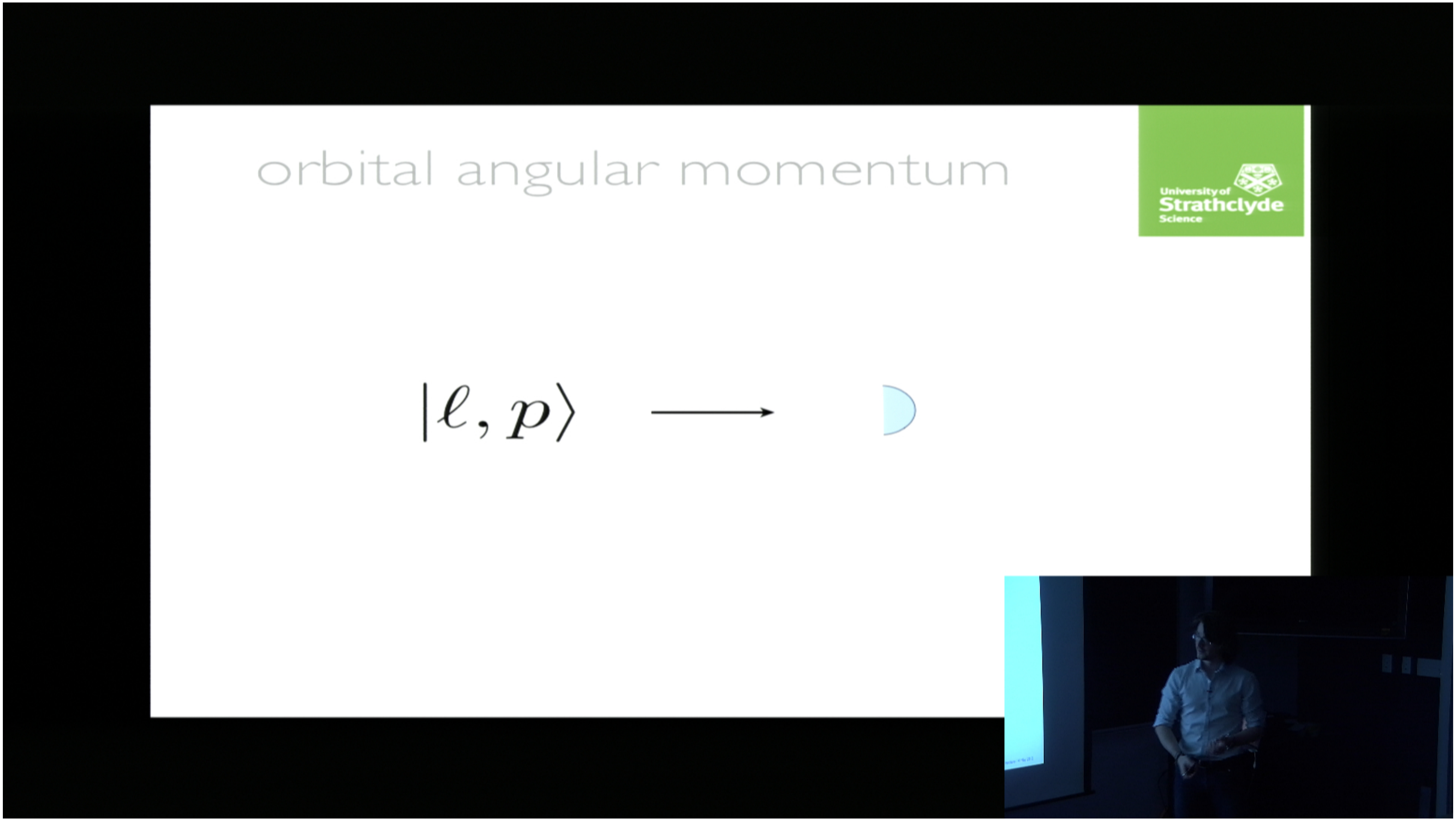
orbital angular momentum
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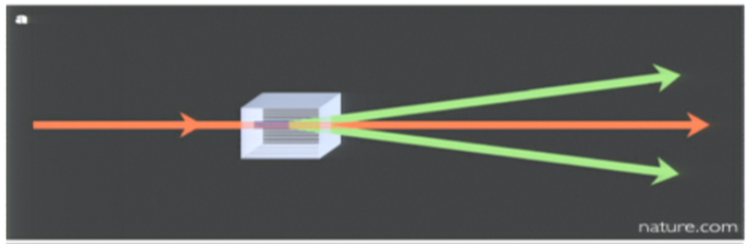
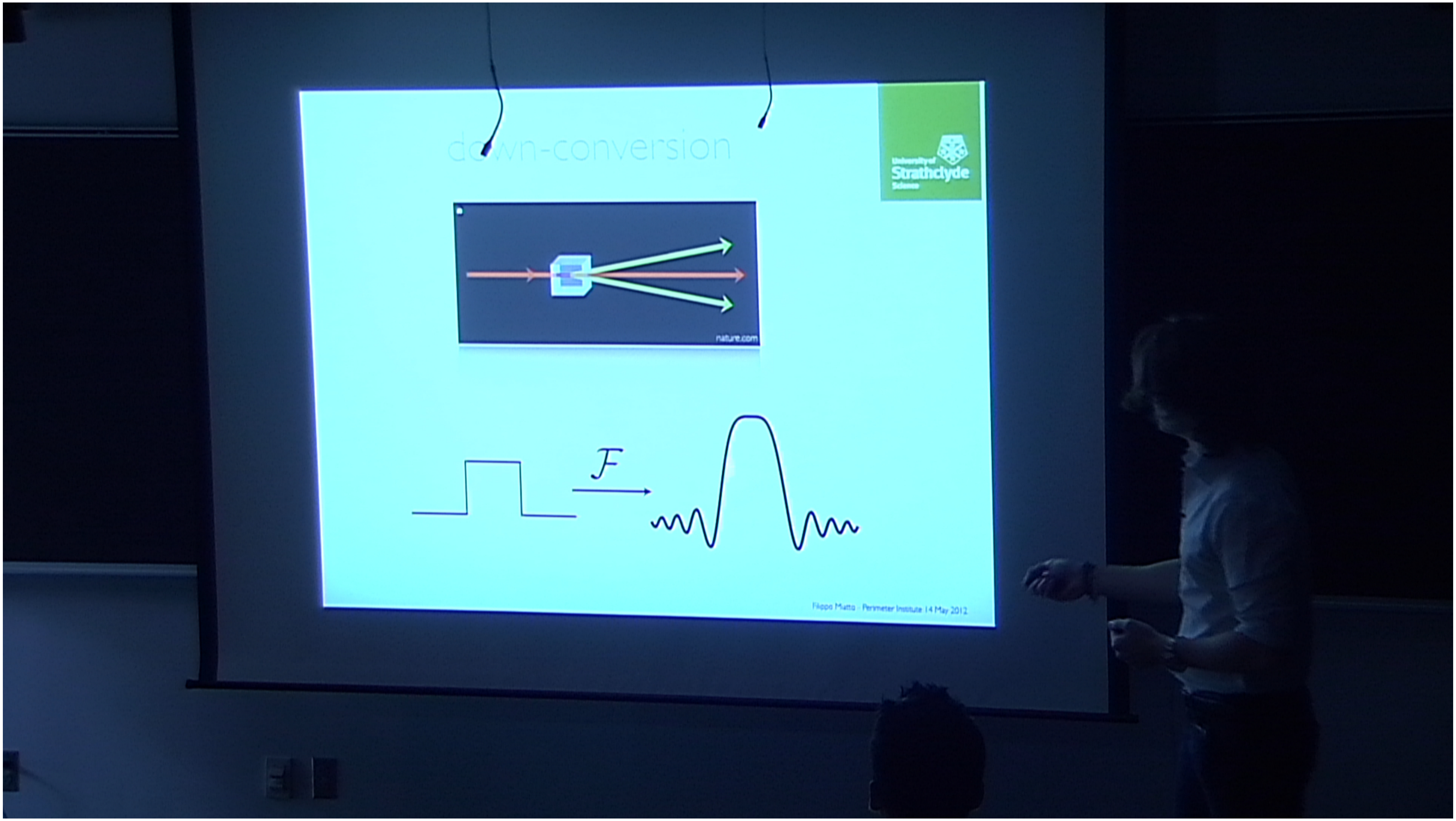
Strathclyde
Science
$|\ell, p\rangle$

down-conversion



Nonlinear susceptibility ⟶ nonlinear terms in hamiltonian ⟶ down-conversion


down-conversion
University of Strathclyde Science
nature.com
$\mathcal{F}$
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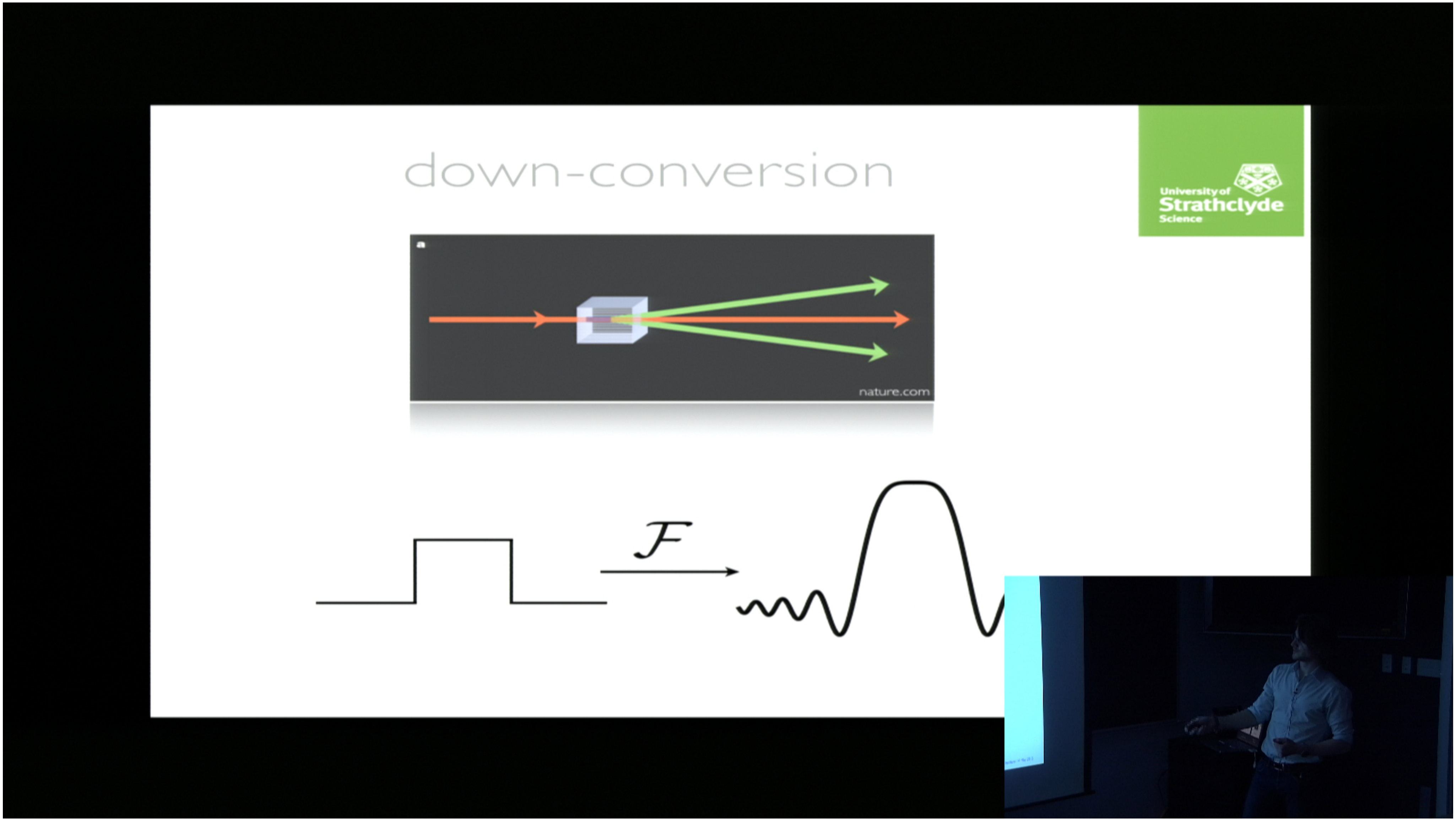
down-conversion



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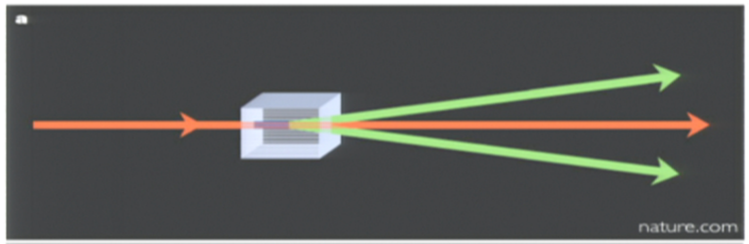

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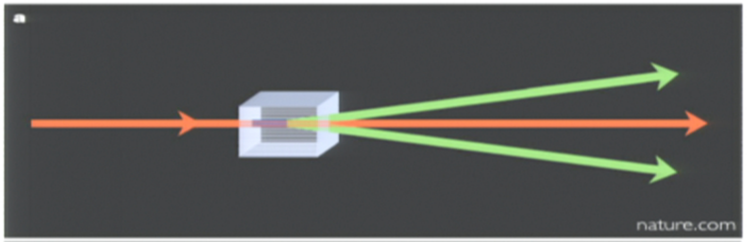

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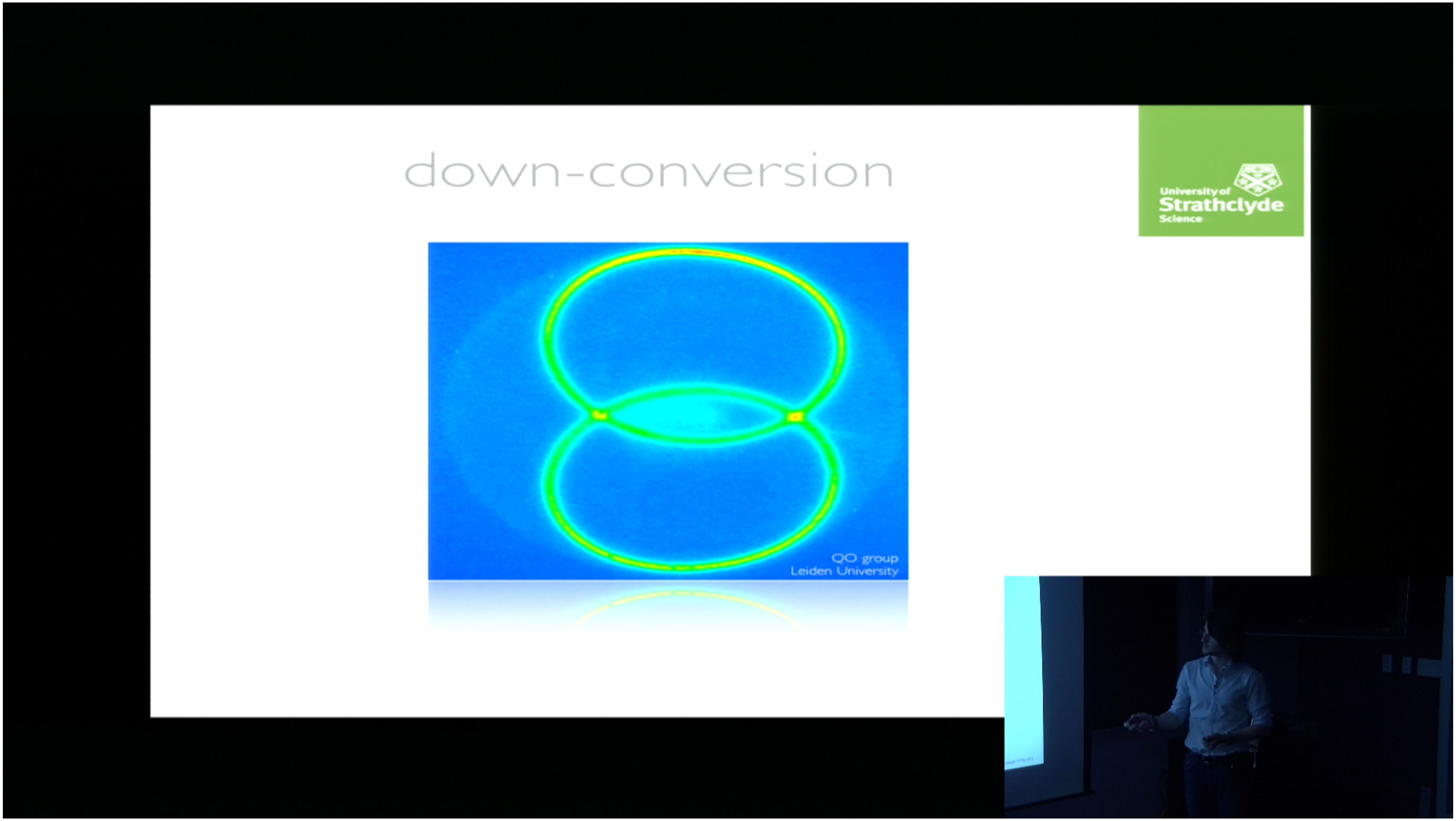
down-conversion
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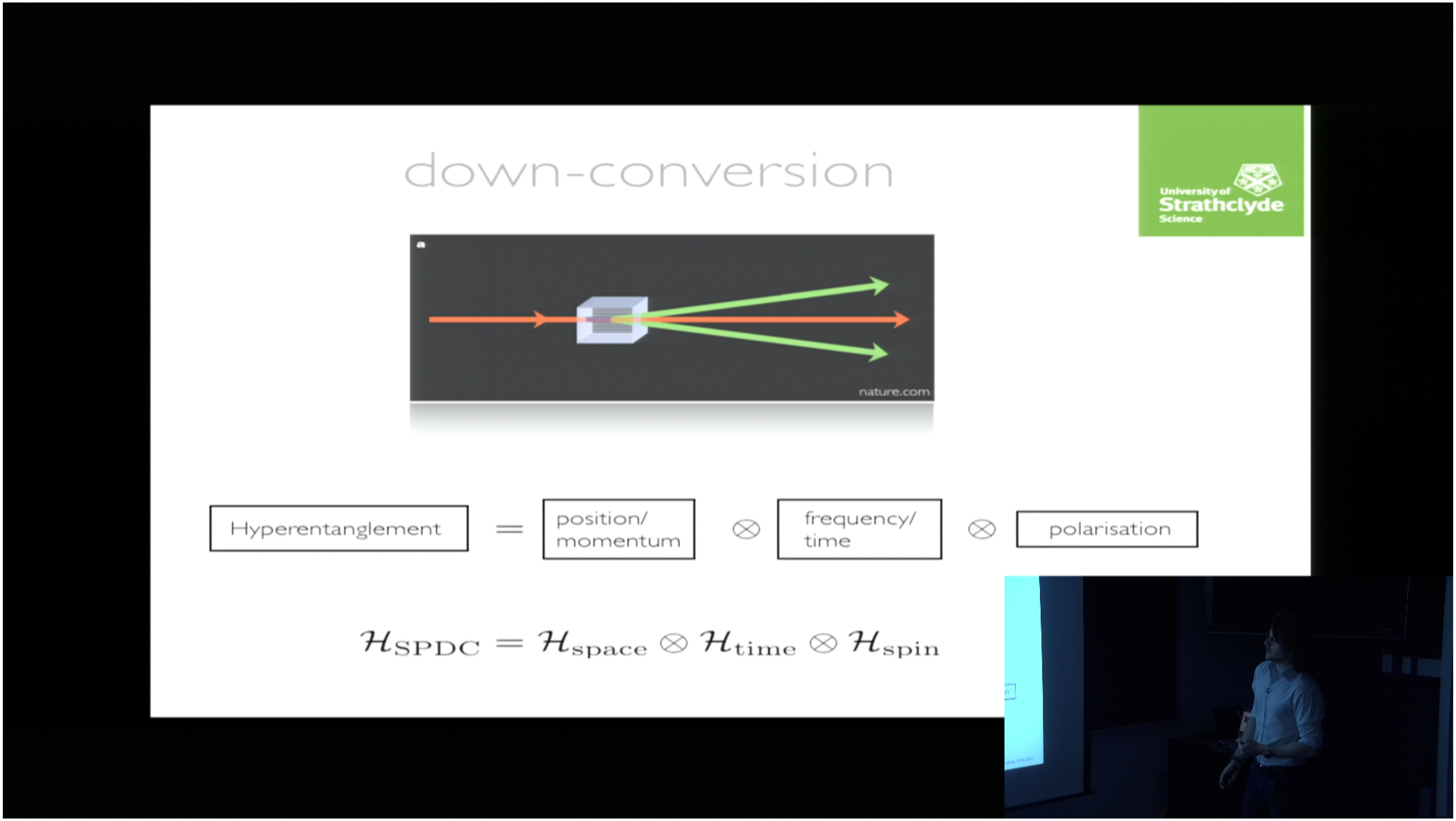
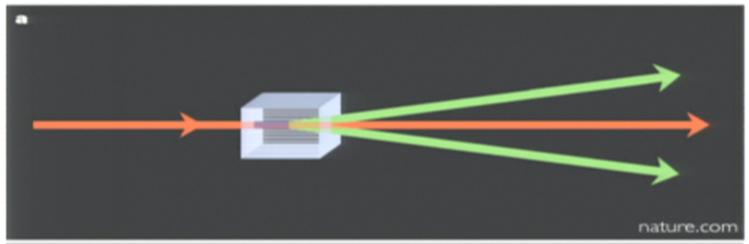
Strathclyde
Science
QO group
Leiden University


down-conversion
University of Strathclyde Science
nature.com
Hyperentanglement = position/ momentum ⊗ frequency/ time ⊗ polarisation
$\mathcal{H}_{\mathrm{SPDC}} = \mathcal{H}_{\mathrm{space}} \otimes \mathcal{H}_{\mathrm{time}} \otimes \mathcal{H}_{\mathrm{spin}}$

down-conversion

University of Strathclyde Science



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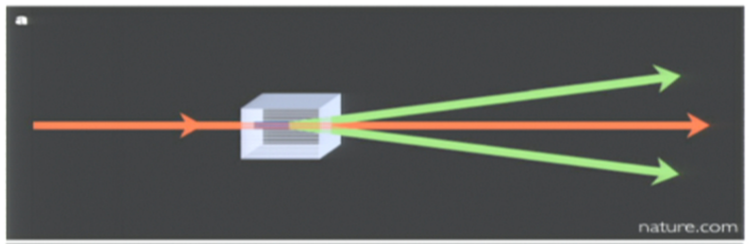
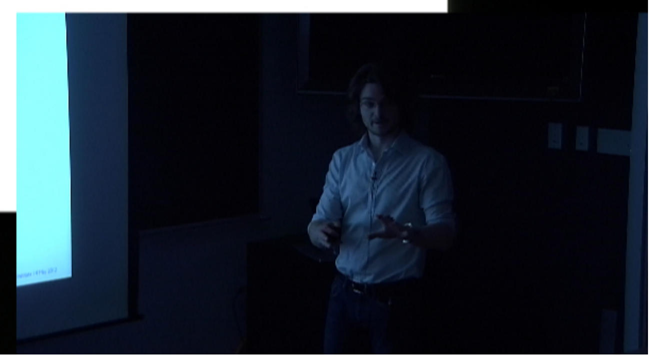
down-conversion



$$|\psi\rangle = \sum_{\ell,p} \sqrt{\lambda_{\ell,p}}|\ell,p\rangle \otimes |-\ell,p\rangle$$

$$K = \frac{1}{\sum_{\ell,p}\lambda_{\ell,p}^2} = 2^{H_2(\{\lambda\})}$$



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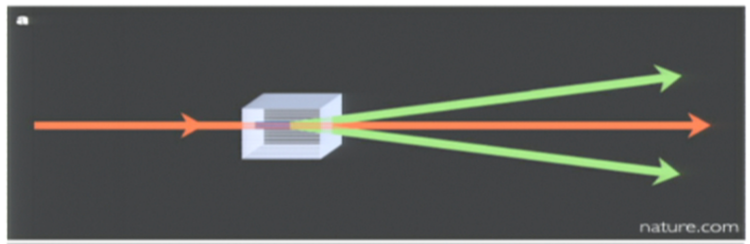

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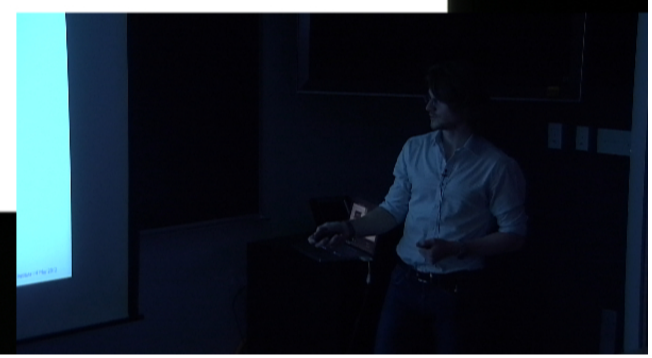
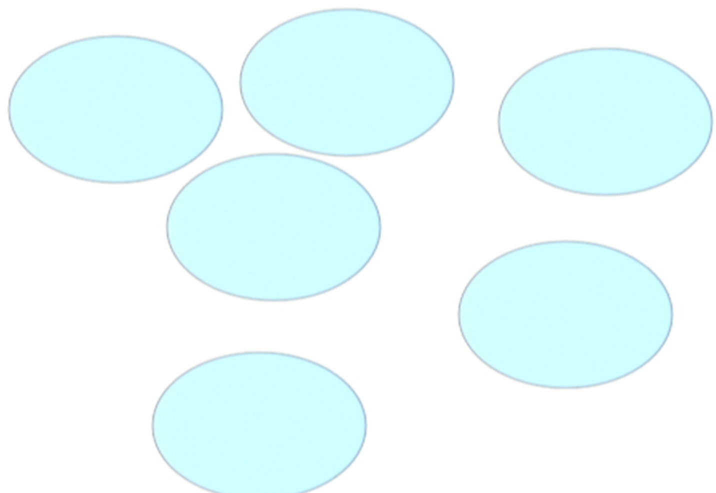


shared information



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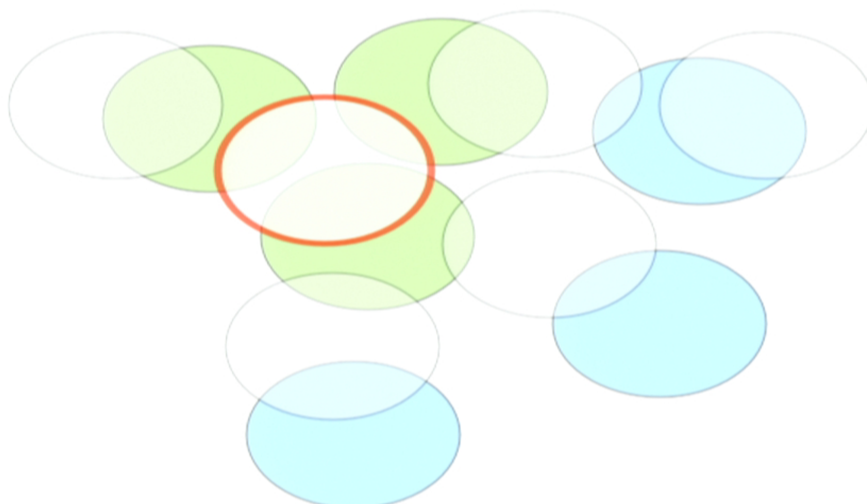
shared information



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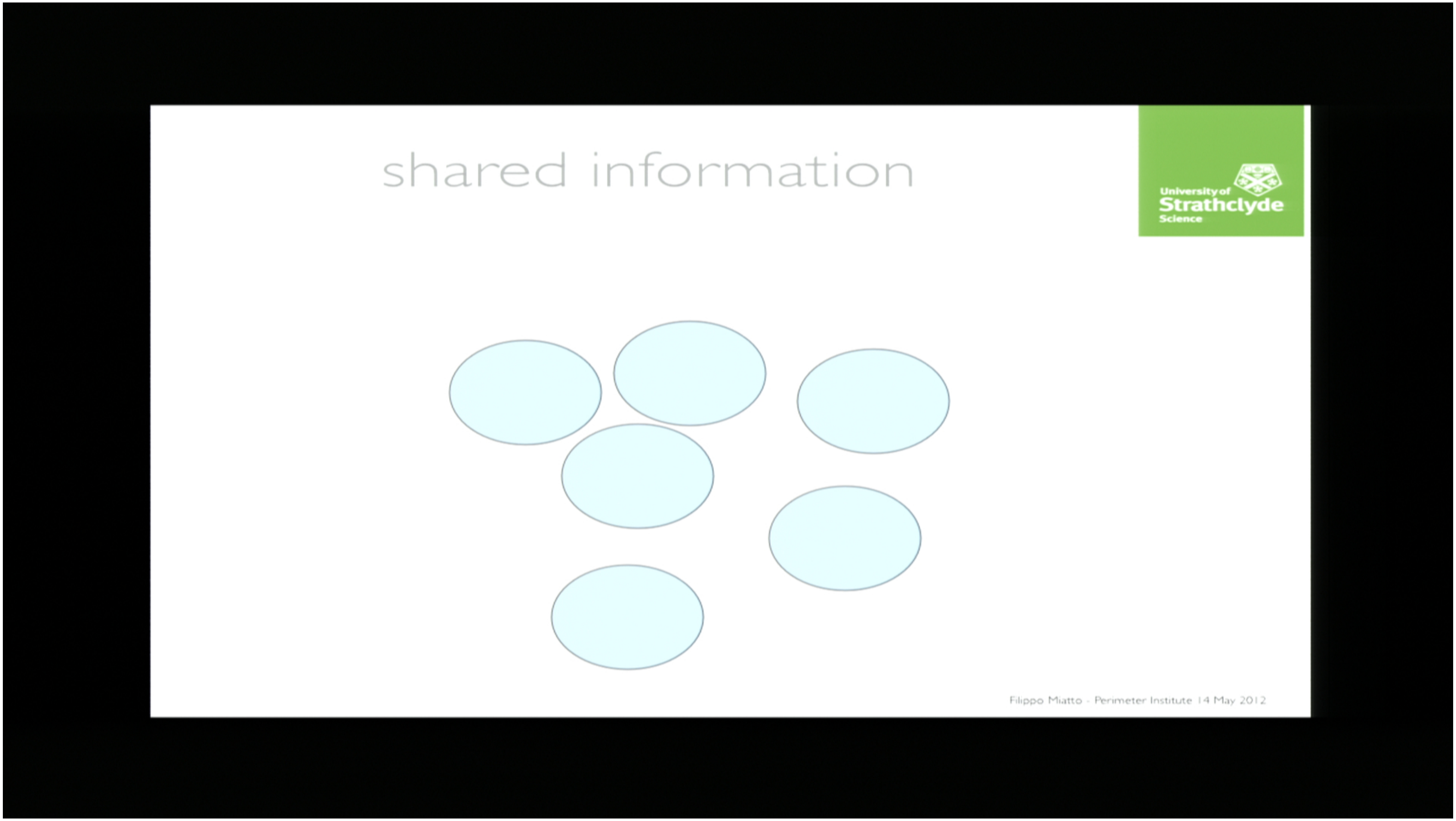
shared information
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Science
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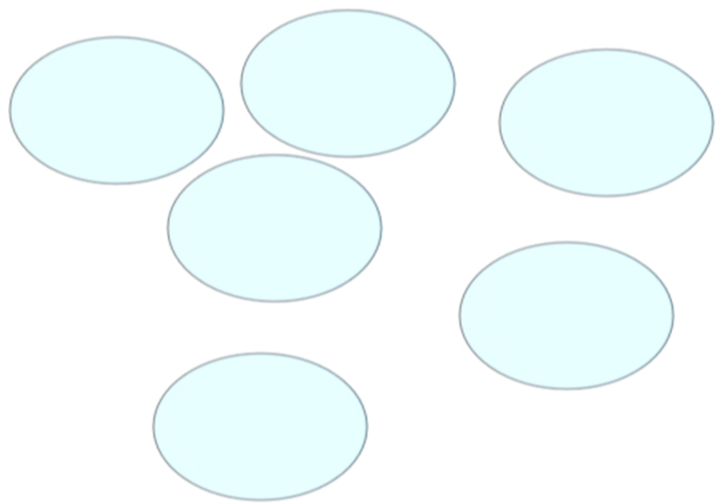
shared information



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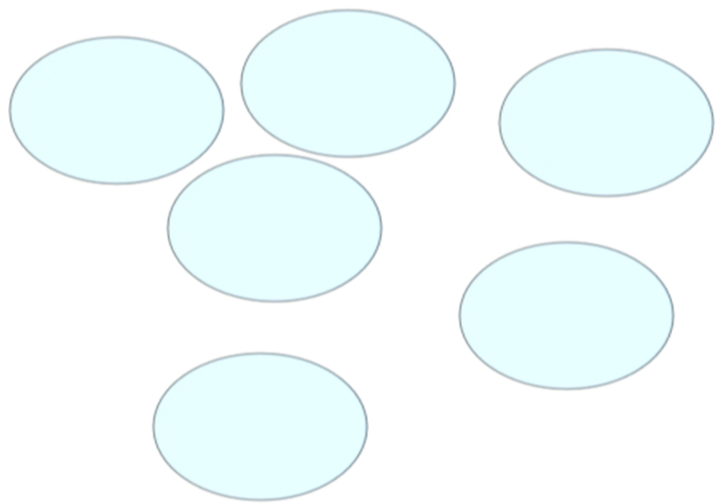

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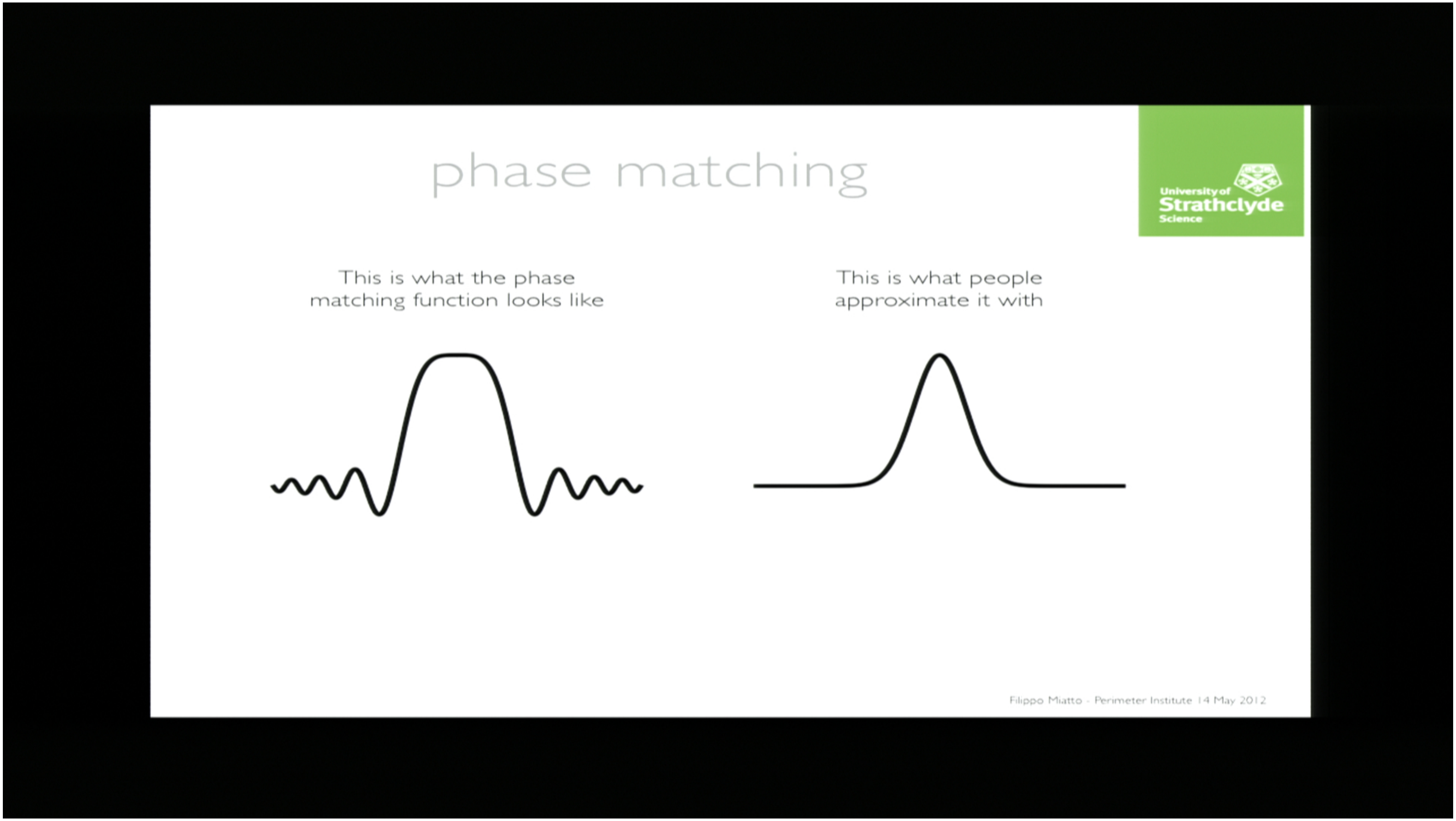
phase matching
University of Strathclyde Science
This is what the phase matching function looks like
This is what people approximate it with
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phase matching

University of Strathclyde Science

This is what the phase matching function looks like

$$K = ?$$

This is what people approximate it with

$$K = \frac{1}{4}\left(b\sigma + \frac{1}{b\sigma}\right)^2$$

phase matching

University of Strathclyde Science

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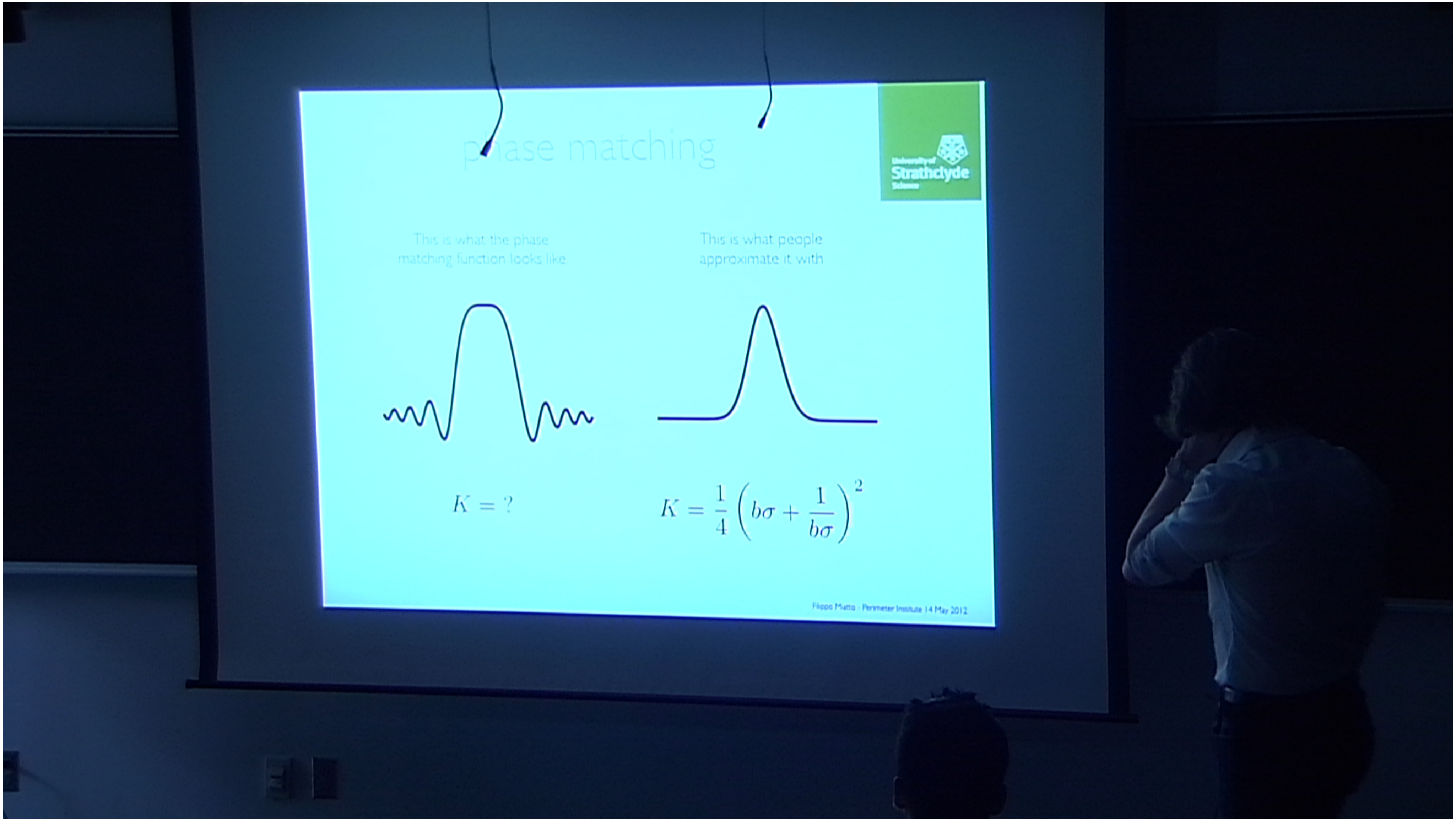
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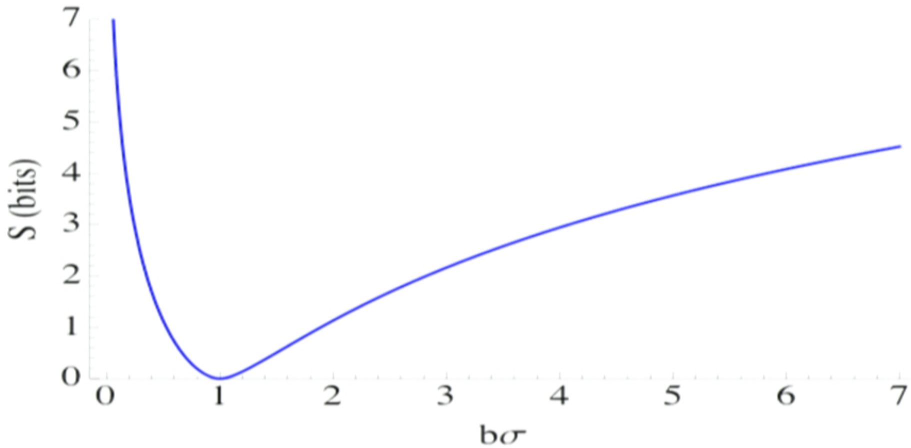
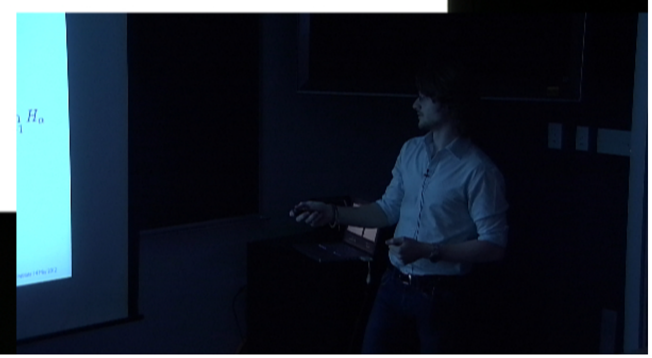
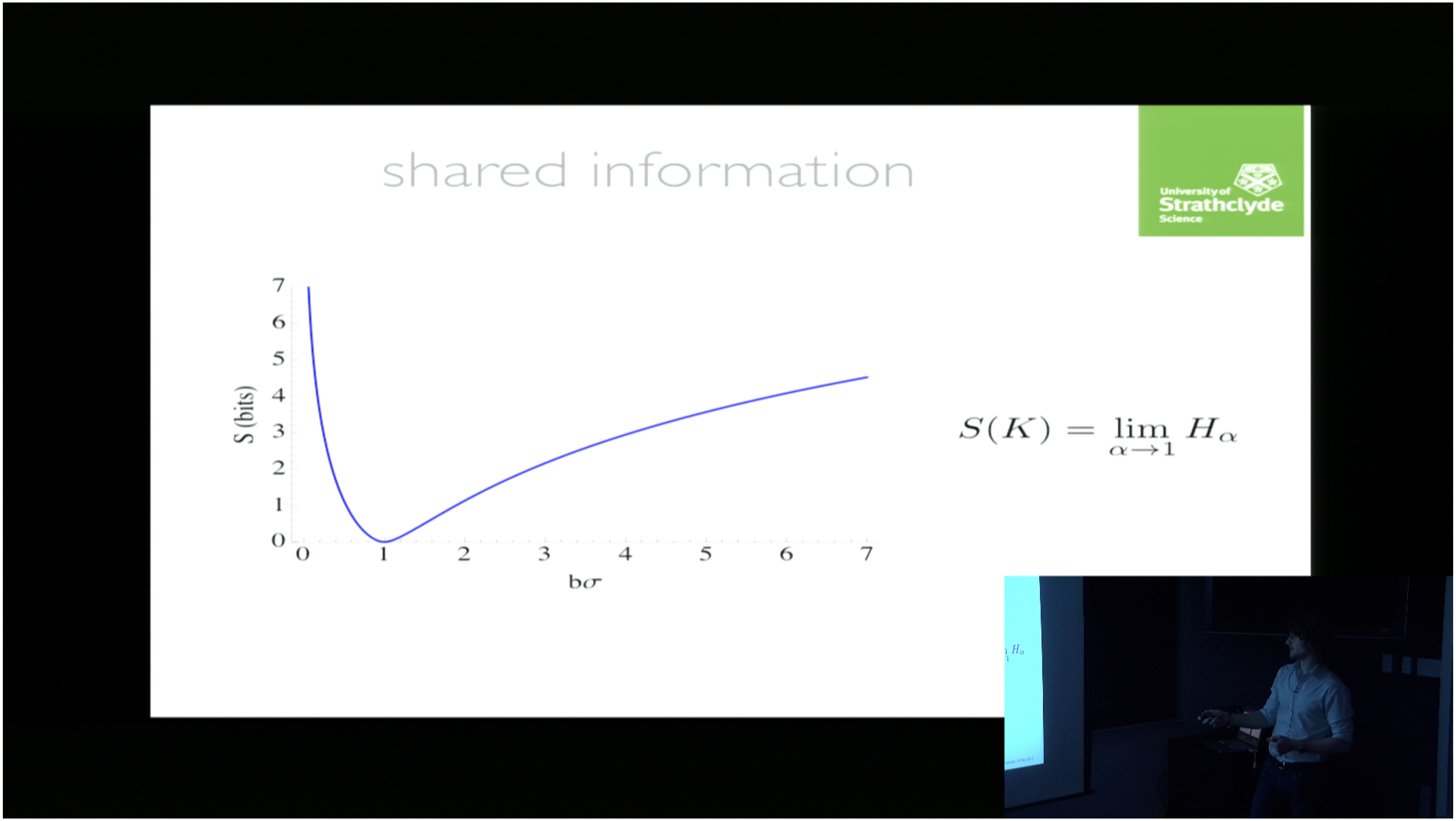
shared information



$$S(K) = \lim_{\alpha \to 1} H_\alpha$$




shared information
University of Strathclyde Science
S (bits)
bσ
0
1
2
3
4
5
6
7
$S(K) = \lim_{\alpha \to 1} H_\alpha$

non-ideal detection

- cross talk
- accidentals
- dark counts
- turbulence
- ...


non-ideal detection
University of Strathclyde Science
- cross talk
- accidentals
- dark counts
- turbulence
- ...

non-ideal detection

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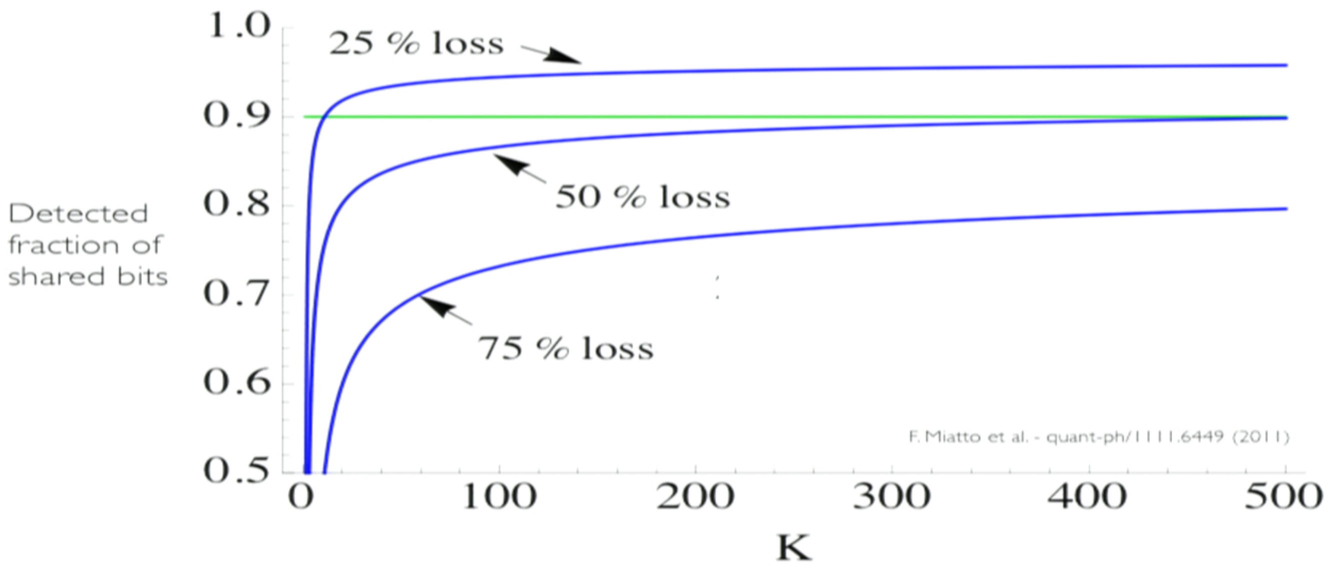

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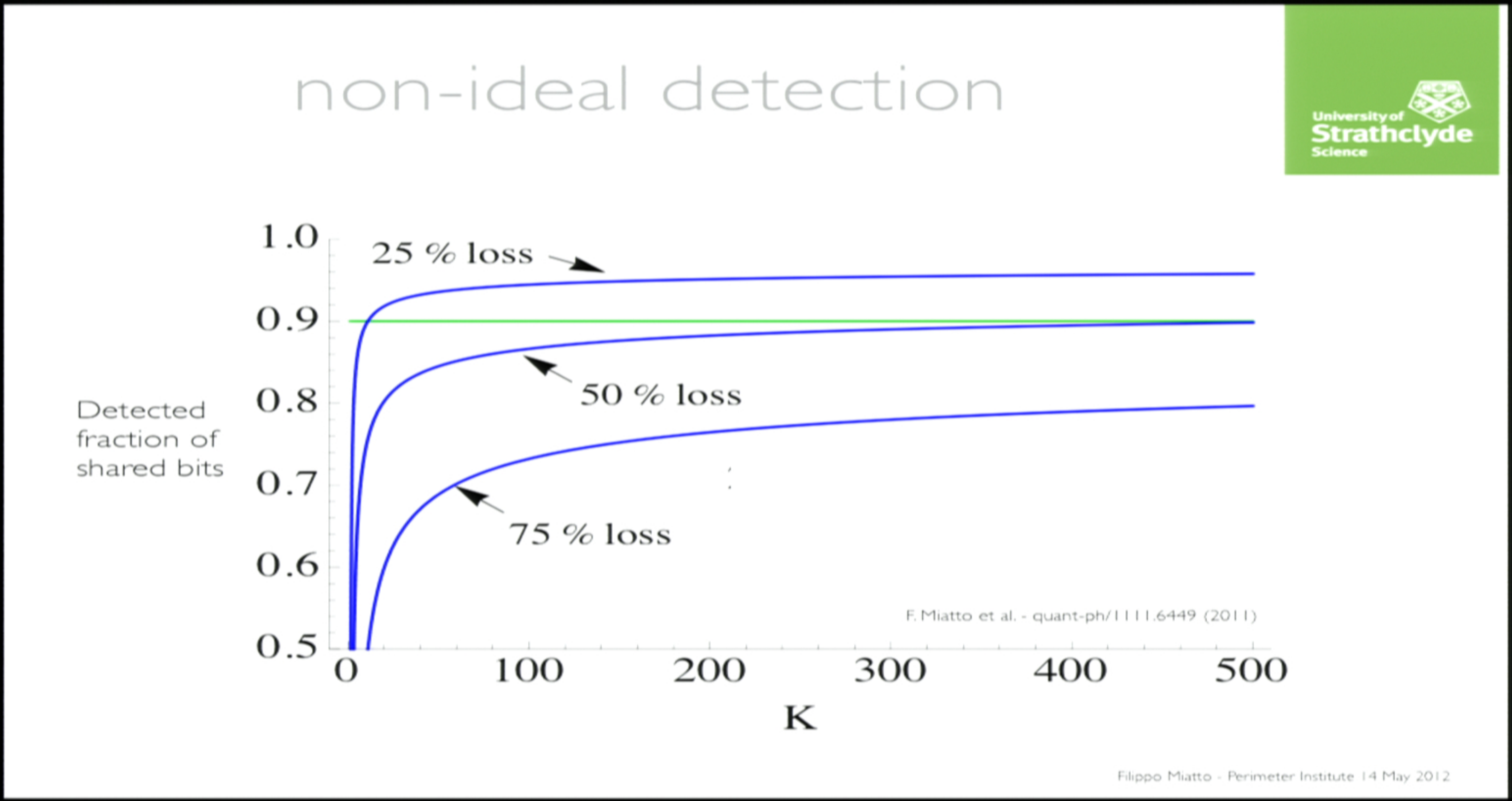
non-ideal detection
University of Strathclyde Science
1.0
0.9
0.8
0.7
0.6
0.5
Detected fraction of shared bits
25 % loss
50 % loss
75 % loss
0
100
200
300
400
500
K
F. Miatto et al. - quant-ph/1111.6449 (2011)
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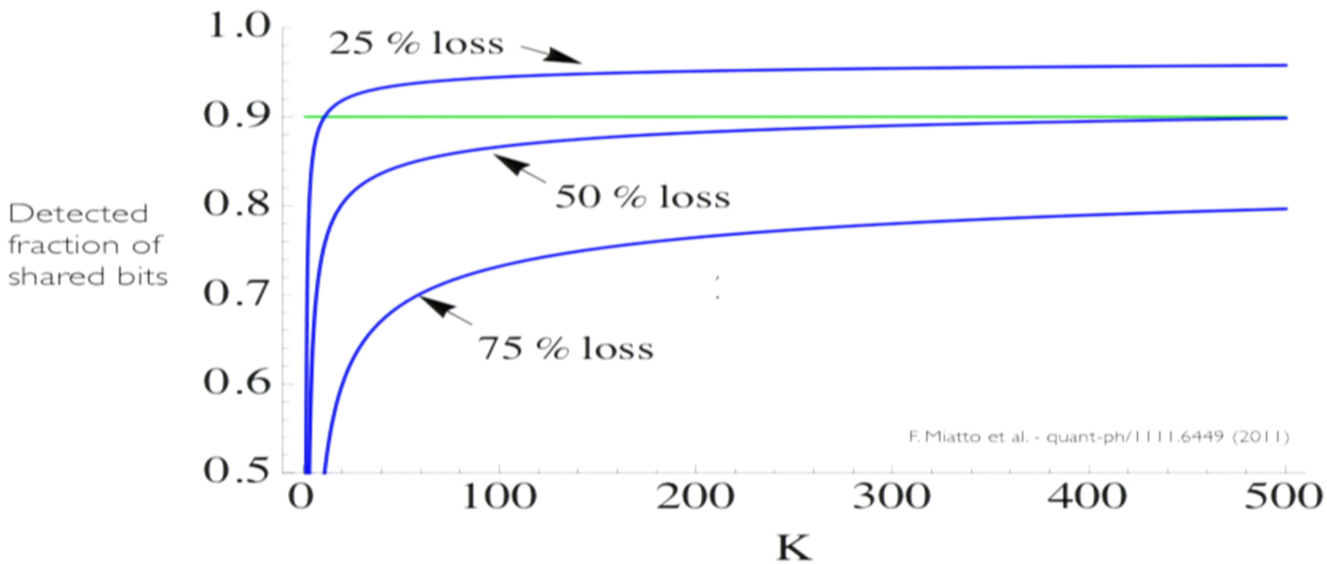
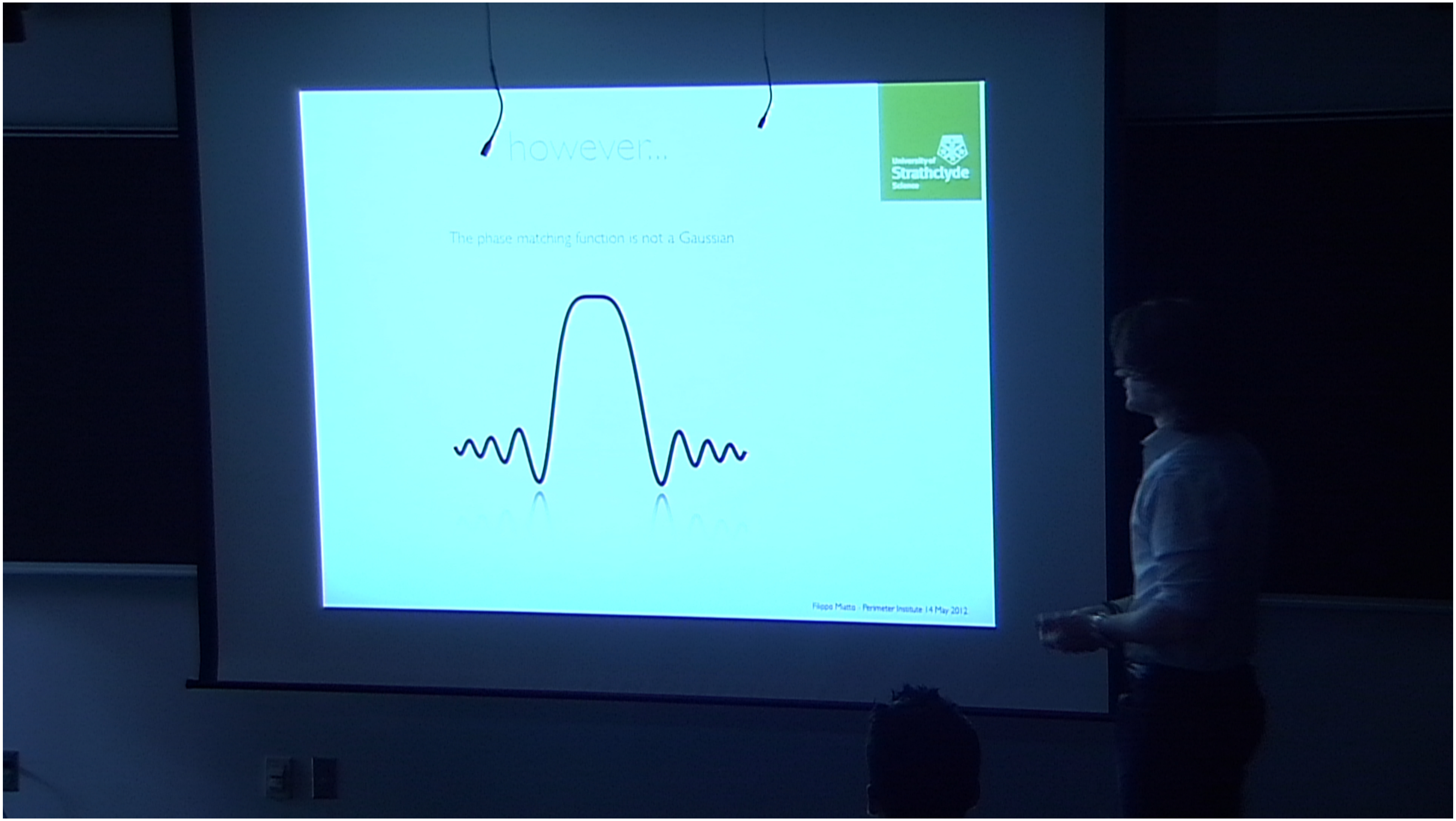
non-ideal detection




however...
University of
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The phase matching function is not a Gaussian
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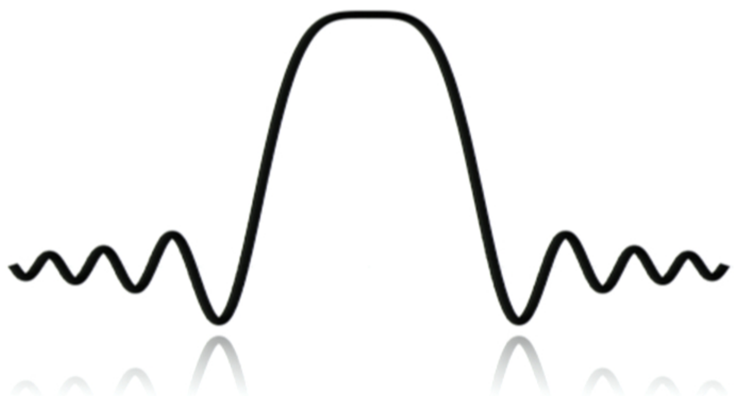
however...

The phase matching function is not a Gaussian



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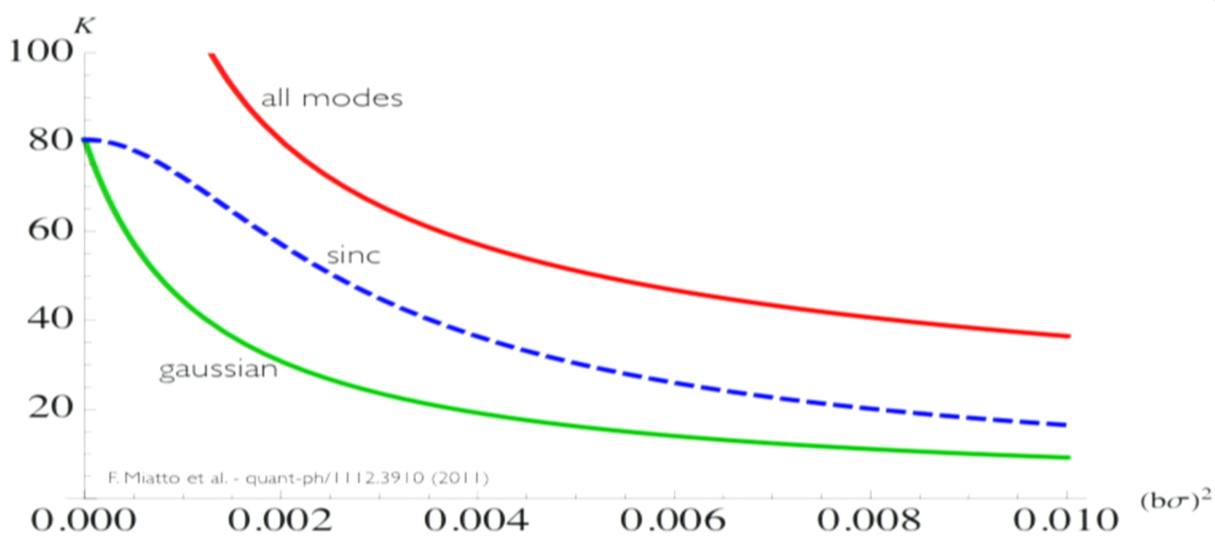
sinc phase matching (p = 0)



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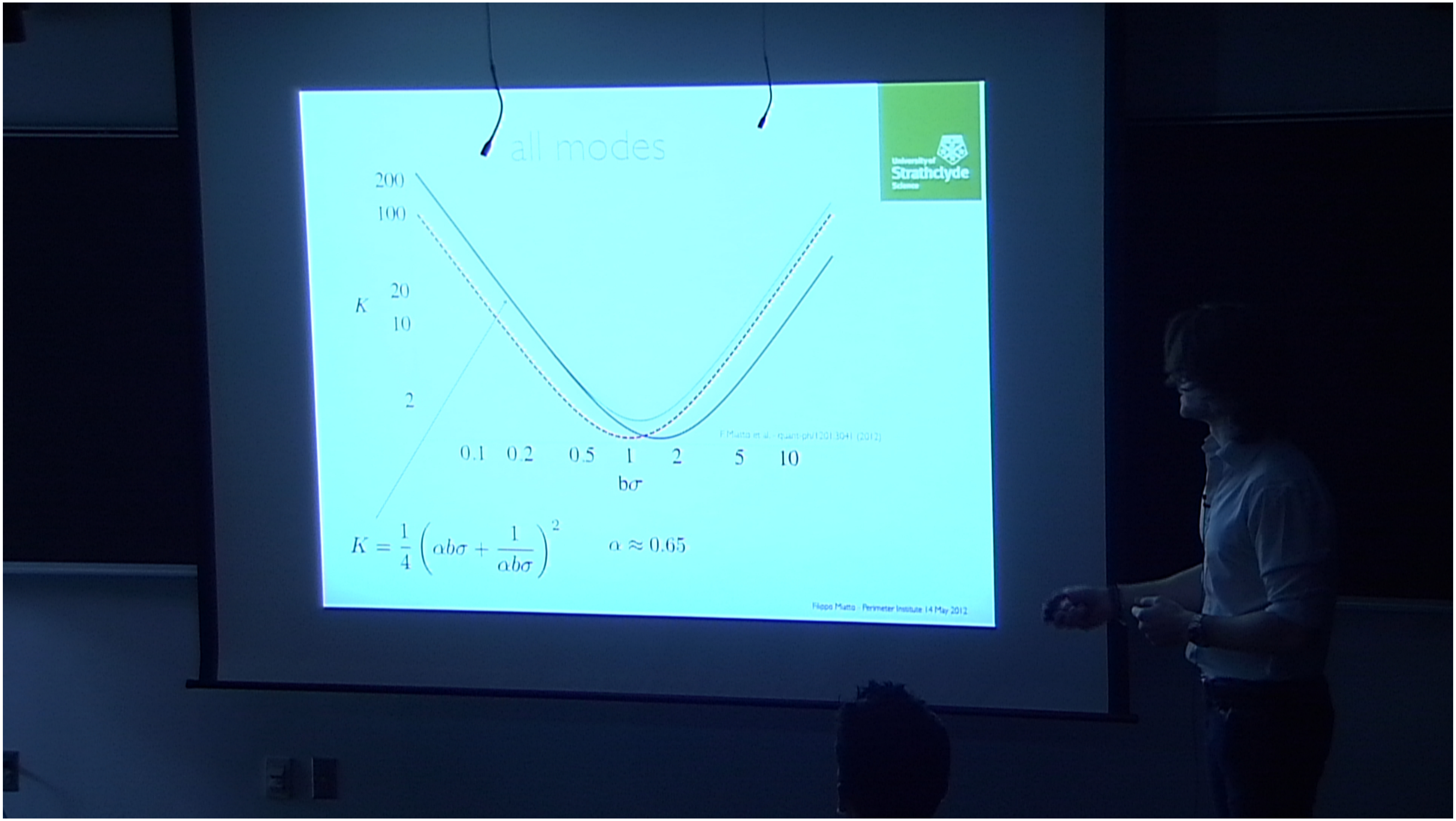
all modes
University of Strathclyde Science
200
100
20
10
2
K
0.1 0.2 0.5 1 2 5 10
bσ
$K = \frac{1}{4}\left(\alpha b\sigma + \frac{1}{\alpha b\sigma}\right)^2$
$\alpha \approx 0.65$
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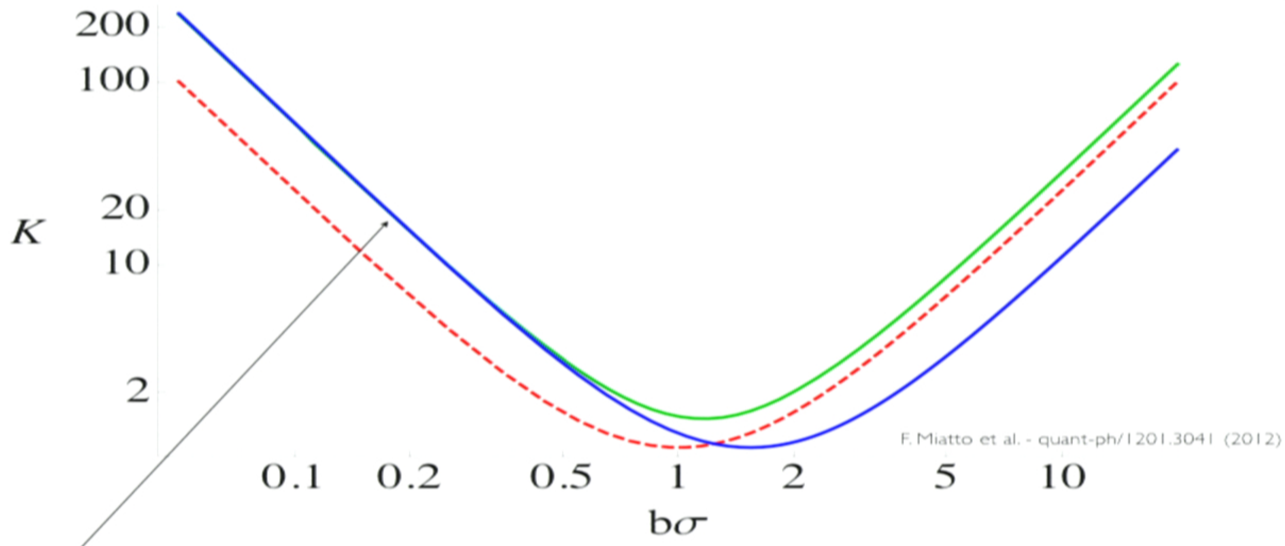
all modes



$$K = \frac{1}{4}\left(\alpha b\sigma + \frac{1}{\alpha b\sigma}\right)^2 \qquad \alpha \approx 0.65$$

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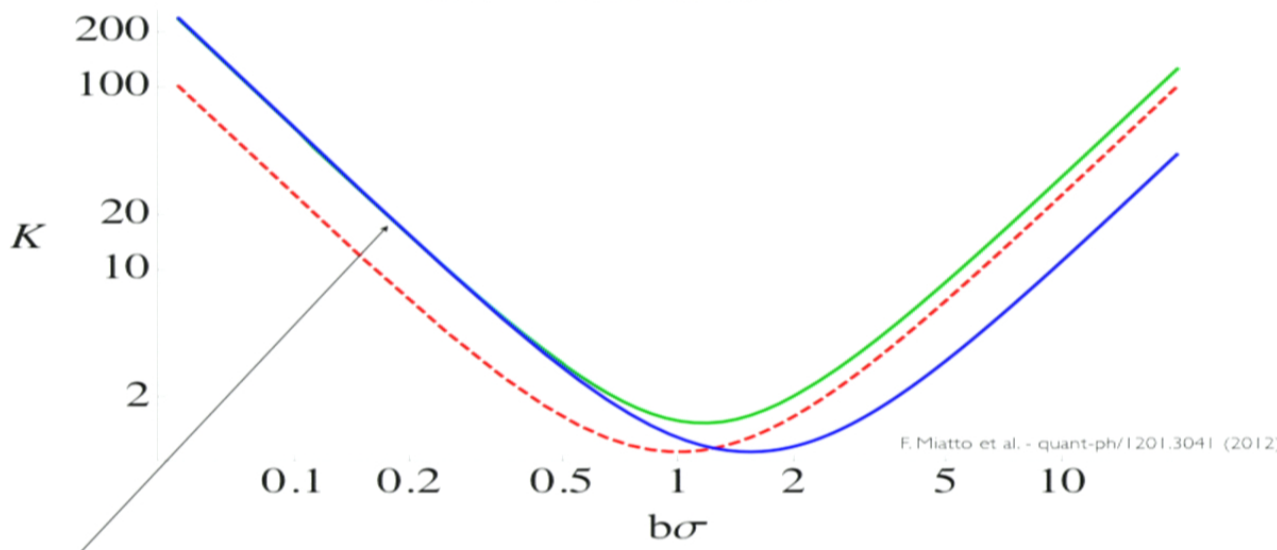
all modes



$$K = \frac{1}{4}\left(\alpha b\sigma + \frac{1}{\alpha b\sigma}\right)^2 \qquad \alpha \approx 0.65$$

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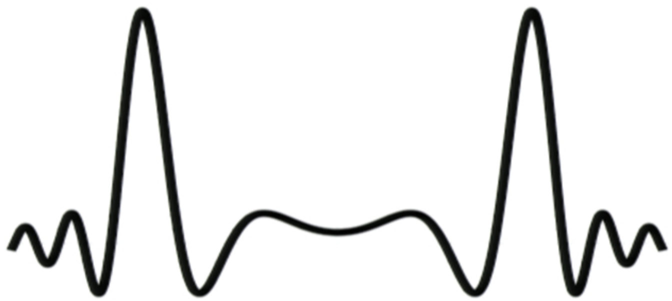
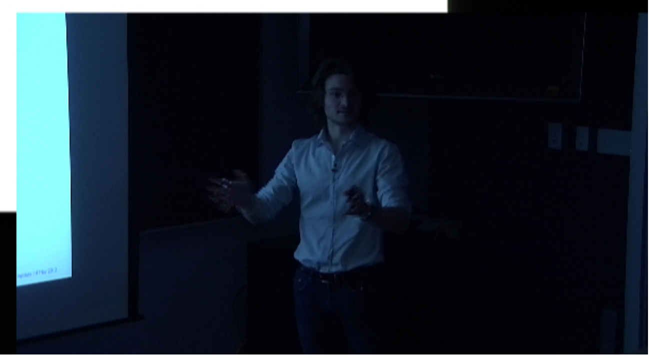
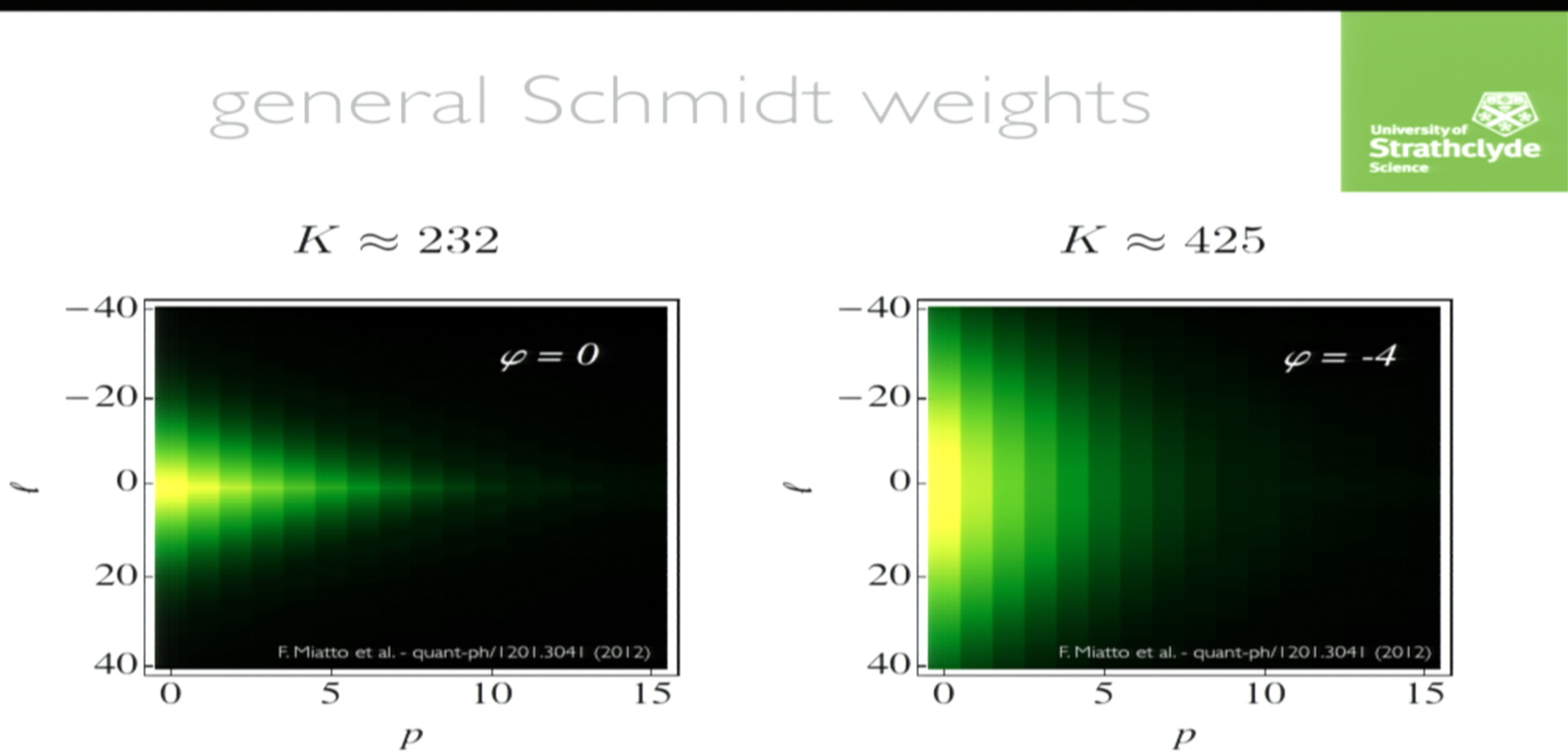
however...

The photons can be phase-mismatched





general Schmidt weights



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general Schmidt weights

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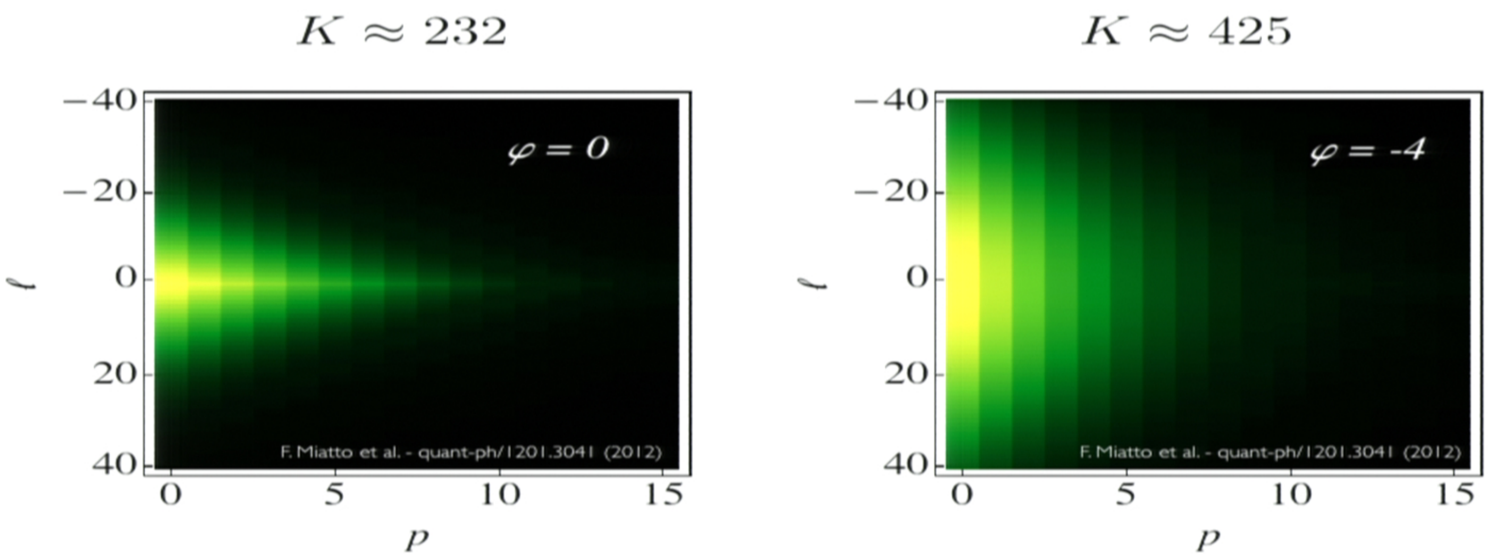

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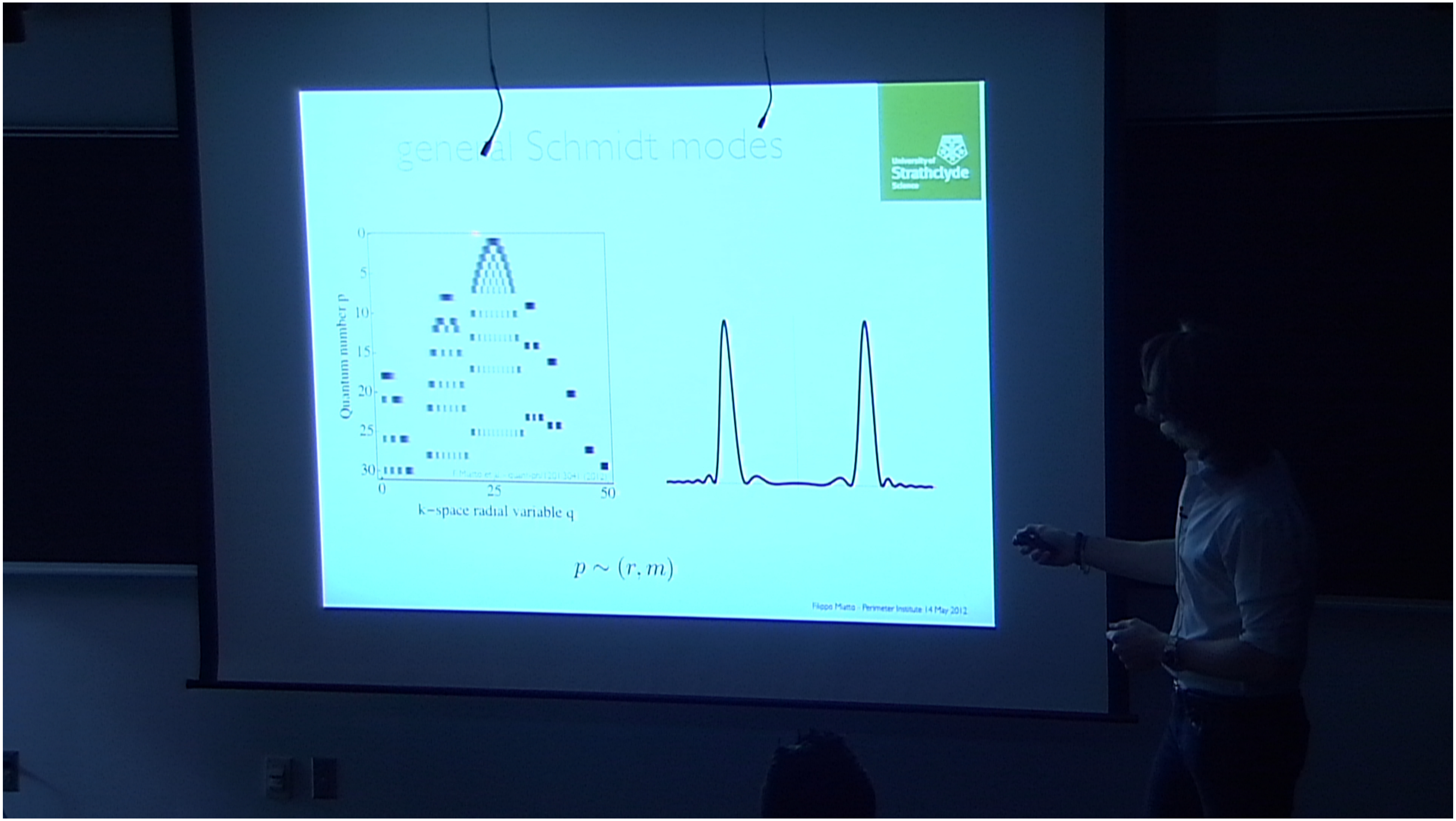
general Schmidt modes
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Quantum number p
k−space radial variable q
$p \sim (r, m)$
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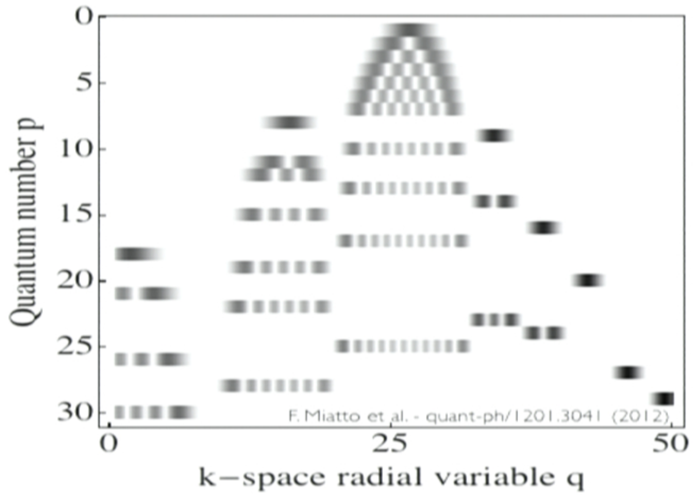
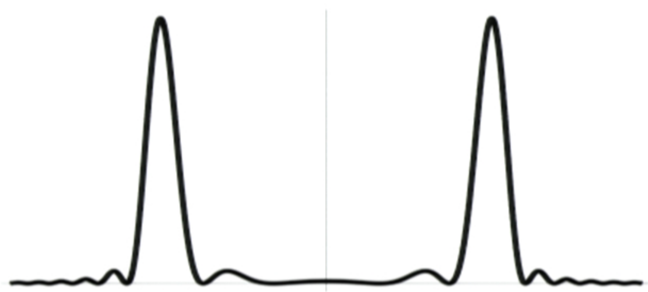
general Schmidt modes





$$p \sim (r, m)$$

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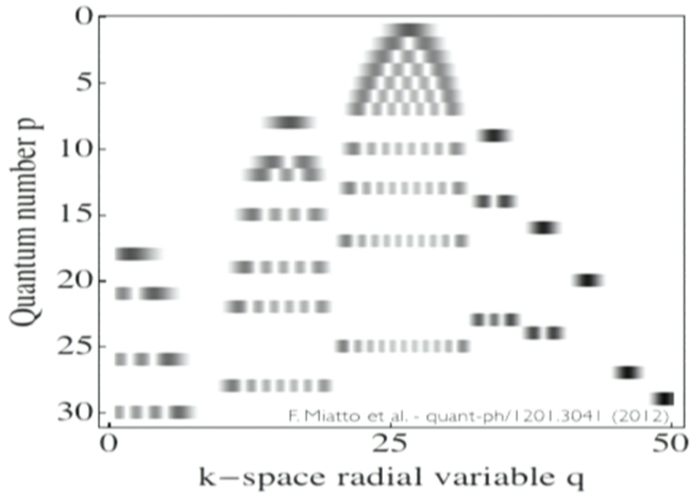
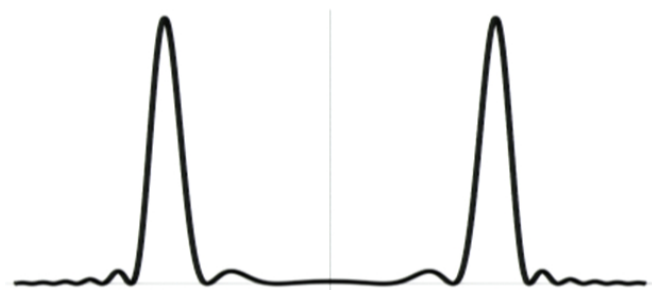
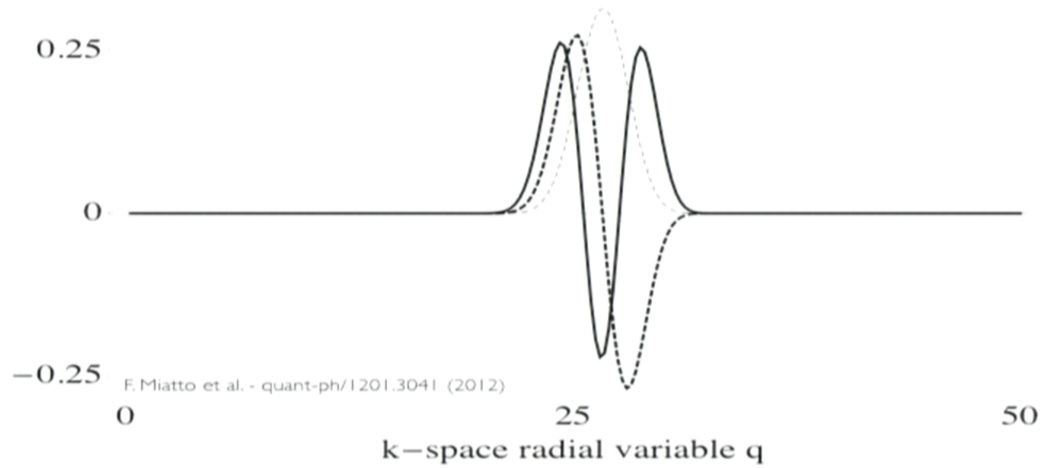
general Schmidt modes





$$p \sim (r, m)$$

general Schmidt modes



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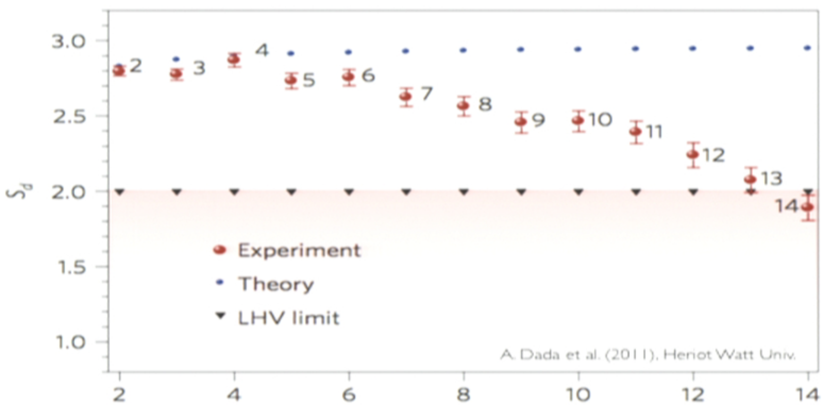
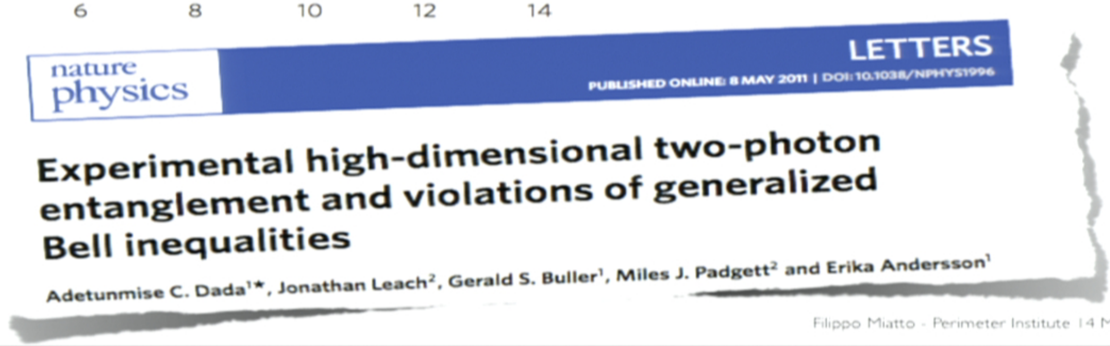
some cool stuff




nature physics
LETTERS
PUBLISHED ONLINE: 8 MAY 2011 | DOI: 10.1038/NPHYS1996

Experimental high-dimensional two-photon entanglement and violations of generalized Bell inequalities

Adetunmise C. Dada[1]*, Jonathan Leach[2], Gerald S. Buller[1], Miles J. Padgett[2] and Erika Andersson[1]

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IOP Publishing
J. Opt. 13 (2011) 064008 (8pp)
Journal of Optics
doi:10.1088/2040-8978/13/6/064008
High-dimensional entanglement with orbital-angular-momentum states of light
Bart-Jan Pors[1], Filippo Miatto[1,2,4], G W 't Hooft[1,3], E R Eliel[1] and J P Woerdman[1]
[1] Huygens Laboratory, Leiden University, PO Box 9504, 2300 RA Leiden, The Netherlands
[2] Dipartimento di Fisica 'Galileo Galilei', University of Padua, via Marzolo, 8, I-35131 Padova, Italy
[3] Philips Research Laboratories, 5656 AE, Eindhoven, The Netherlands
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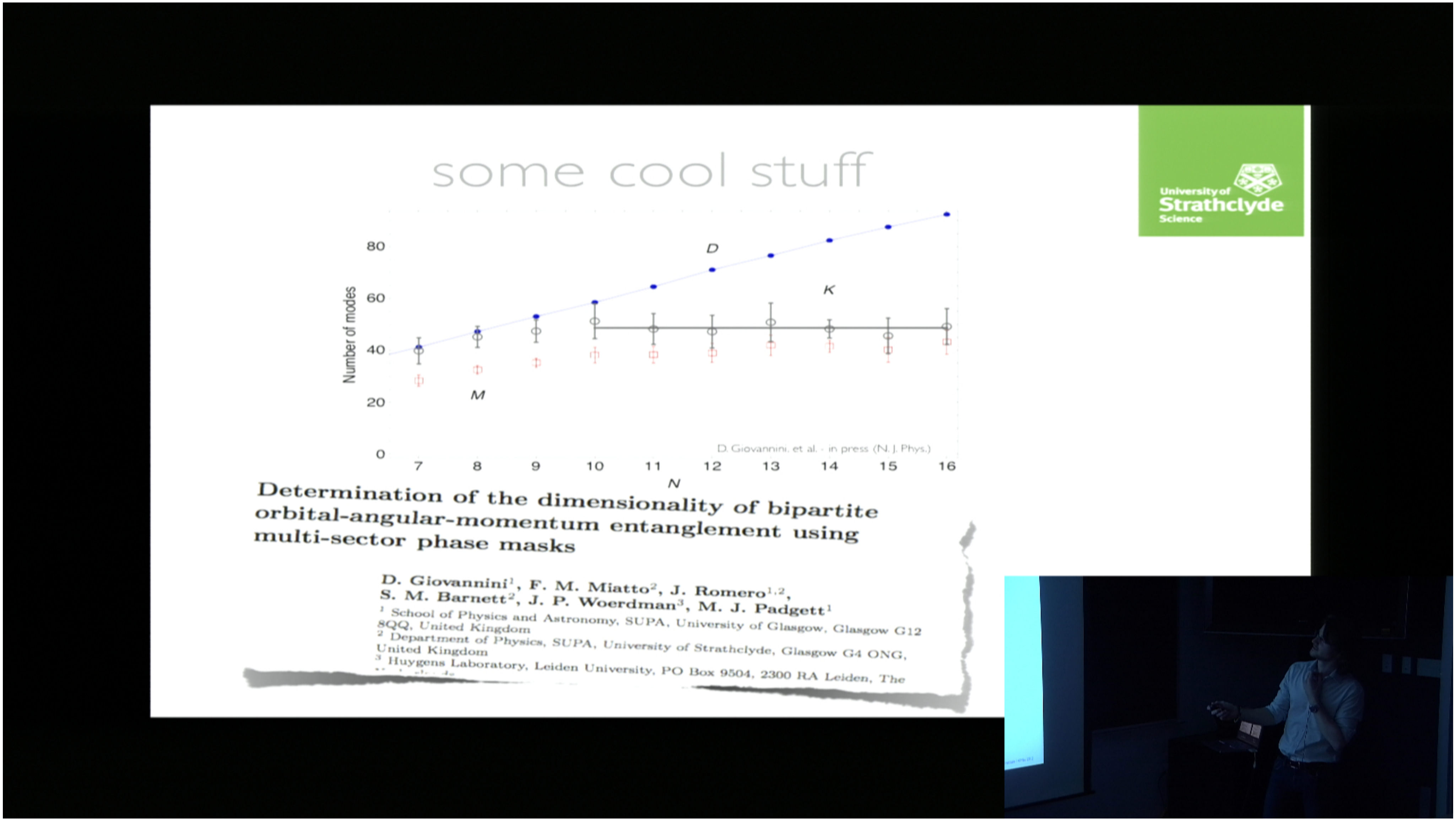
some cool stuff
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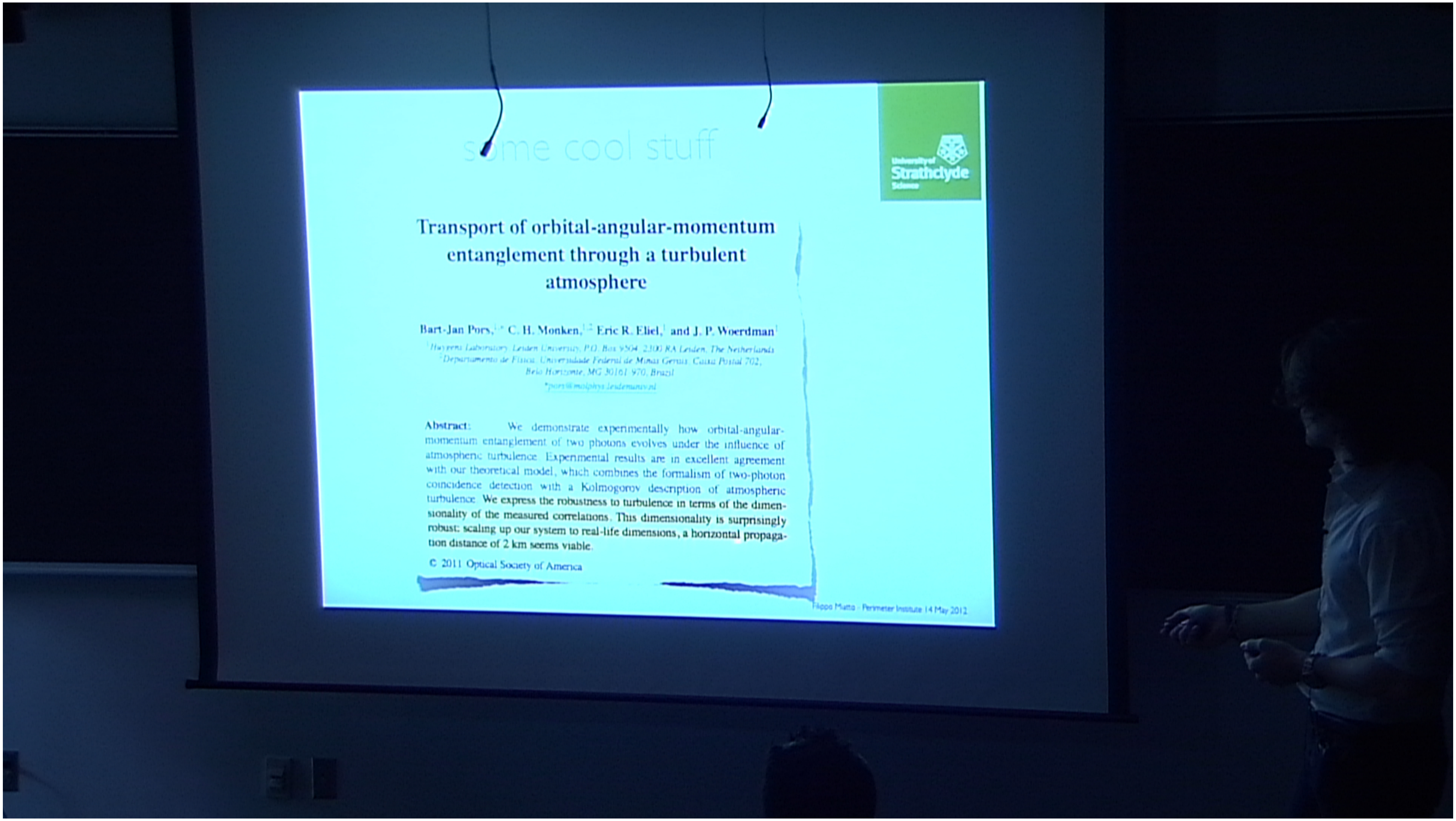
Number of modes
0
20
40
60
80
7
8
9
10
11
12
13
14
15
16
N
D
K
M
D. Giovannini, et al. - in press (N. J. Phys.)
Determination of the dimensionality of bipartite orbital-angular-momentum entanglement using multi-sector phase masks
D. Giovannini[1], F. M. Miatto[2], J. Romero[1,2], S. M. Barnett[2], J. P. Woerdman[3], M. J. Padgett[1]
[1] School of Physics and Astronomy, SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom
[2] Department of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, United Kingdom
[3] Huygens Laboratory, Leiden University, PO Box 9504, 2300 RA Leiden, The


some cool stuff
University of Strathclyde Science
Transport of orbital-angular-momentum entanglement through a turbulent atmosphere
Bart-Jan Pors, C. H. Monken, Eric R. Eliel, and J. P. Woerdman
Huygens Laboratory, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands
Departamento de Física, Universidade Federal de Minas Gerais, Caixa Postal 702, Belo Horizonte, MG 30161-970, Brazil
Abstract: We demonstrate experimentally how orbital-angular-momentum entanglement of two photons evolves under the influence of atmospheric turbulence. Experimental results are in excellent agreement with our theoretical model, which combines the formalism of two-photon coincidence detection with a Kolmogorov description of atmospheric turbulence. We express the robustness to turbulence in terms of the dimensionality of the measured correlations. This dimensionality is surprisingly robust: scaling up our system to real-life dimensions, a horizontal propagation distance of 2 km seems viable.
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Transport of orbital-angular-momentum entanglement through a turbulent atmosphere

Bart-Jan Pors,[1,*] **C. H. Monken,**[1,2] **Eric R. Eliel,**[1] **and J. P. Woerdman**[1]

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[2] *Departamento de Física, Universidade Federal de Minas Gerais, Caixa Postal 702, Belo Horizonte, MG 30161-970, Brazil*
**pors@molphys.leidenuniv.nl*

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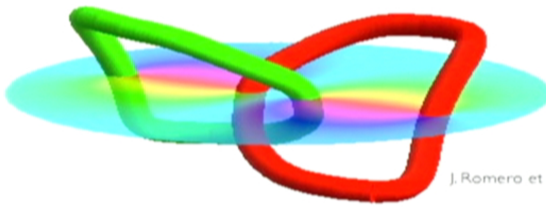


J. Romero et al. (2011), Glasgow Univ.

'RL 106, 100407 (2011) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2011

Entangled Optical Vortex Links

J. Romero,[1,2] J. Leach,[1] B. Jack,[1] M. R. Dennis,[3] S. Franke-Arnold,[1] S. M. Barnett,[2] and M. J. Padgett[1]

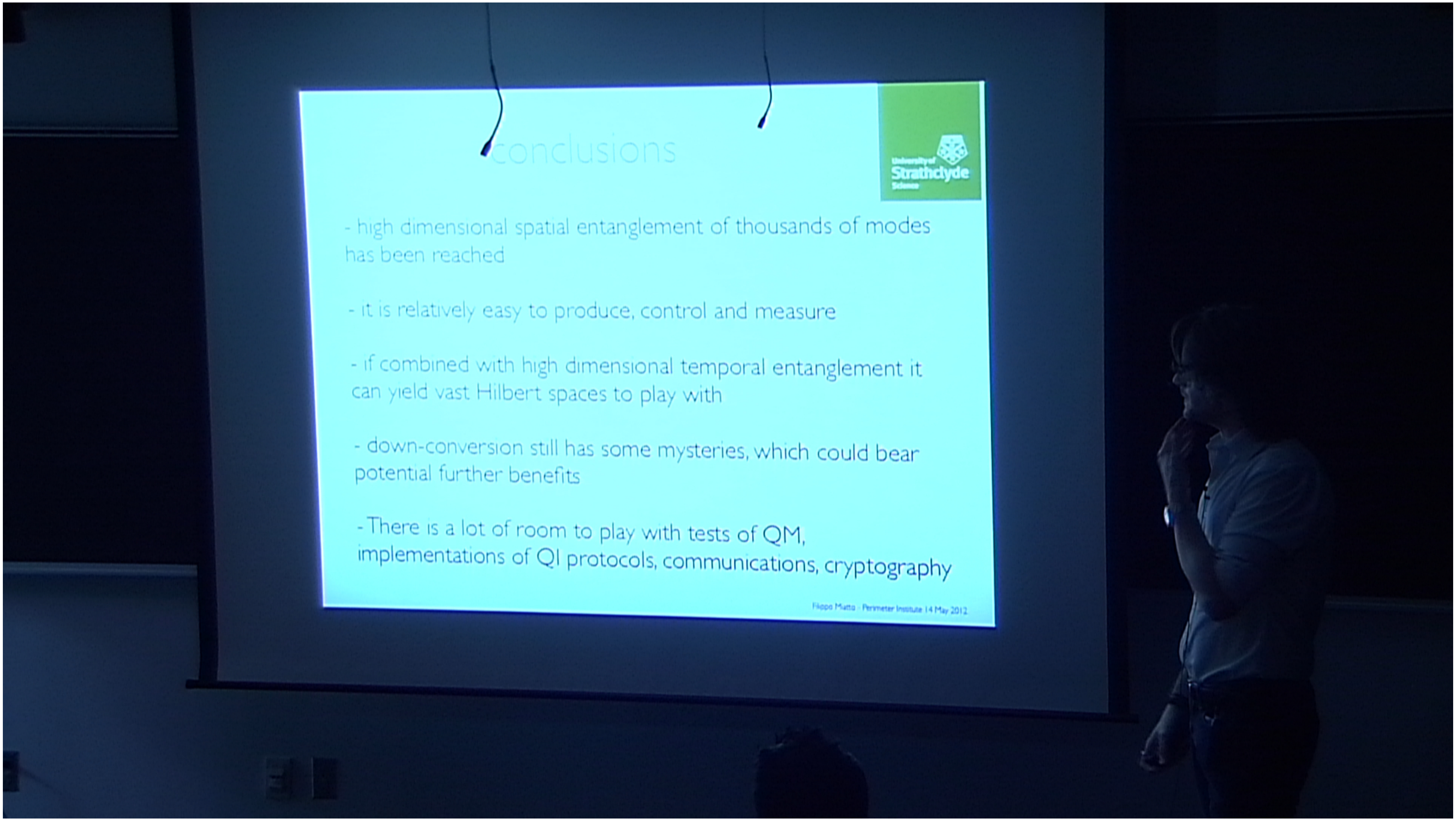
[1]*School of Physics and Astronomy, SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*

[2]*Department of Physics, SUPA, University of Strathclyde, Glasgow G4 ONG, United Kingdom*

[3]*H. H. Wills Physics Laboratory, University of Bristol, Bristol BS8 1TL, United Kingdom*

(Received 15 June 2010; revised manuscript received 9 November 2010; published 11 March 2011)

Optical vortices are lines of phase singularity which percolate through all optical fields. We report the entanglement of linked optical vortex loops in the light produced by spontaneous parametric down-conversion. As measured by using a Bell inequality, this entanglement between topological features extends over macroscopic and finite volumes. The entanglement of photons in complex three-dimensional topological states suggests the possibility of entanglement of similar features in other quantum systems describable by complex scalar functions, such as superconductors, superfluids, and Bose-Einstein condensates.


conclusions
Strathclyde
- high dimensional spatial entanglement of thousands of modes has been reached
- it is relatively easy to produce, control and measure
- if combined with high dimensional temporal entanglement it can yield vast Hilbert spaces to play with
- down-conversion still has some mysteries, which could bear potential further benefits
- There is a lot of room to play with tests of QM, implementations of QI protocols, communications, cryptography
Filippo Miatto - Perimeter Institute 14 May 2012

conclusions

University of Strathclyde Science

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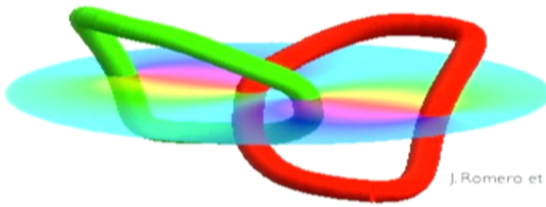

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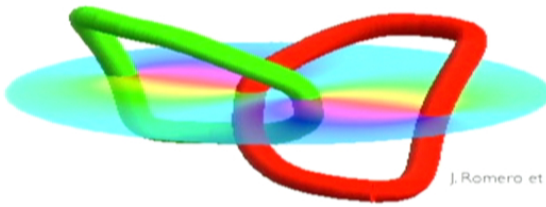

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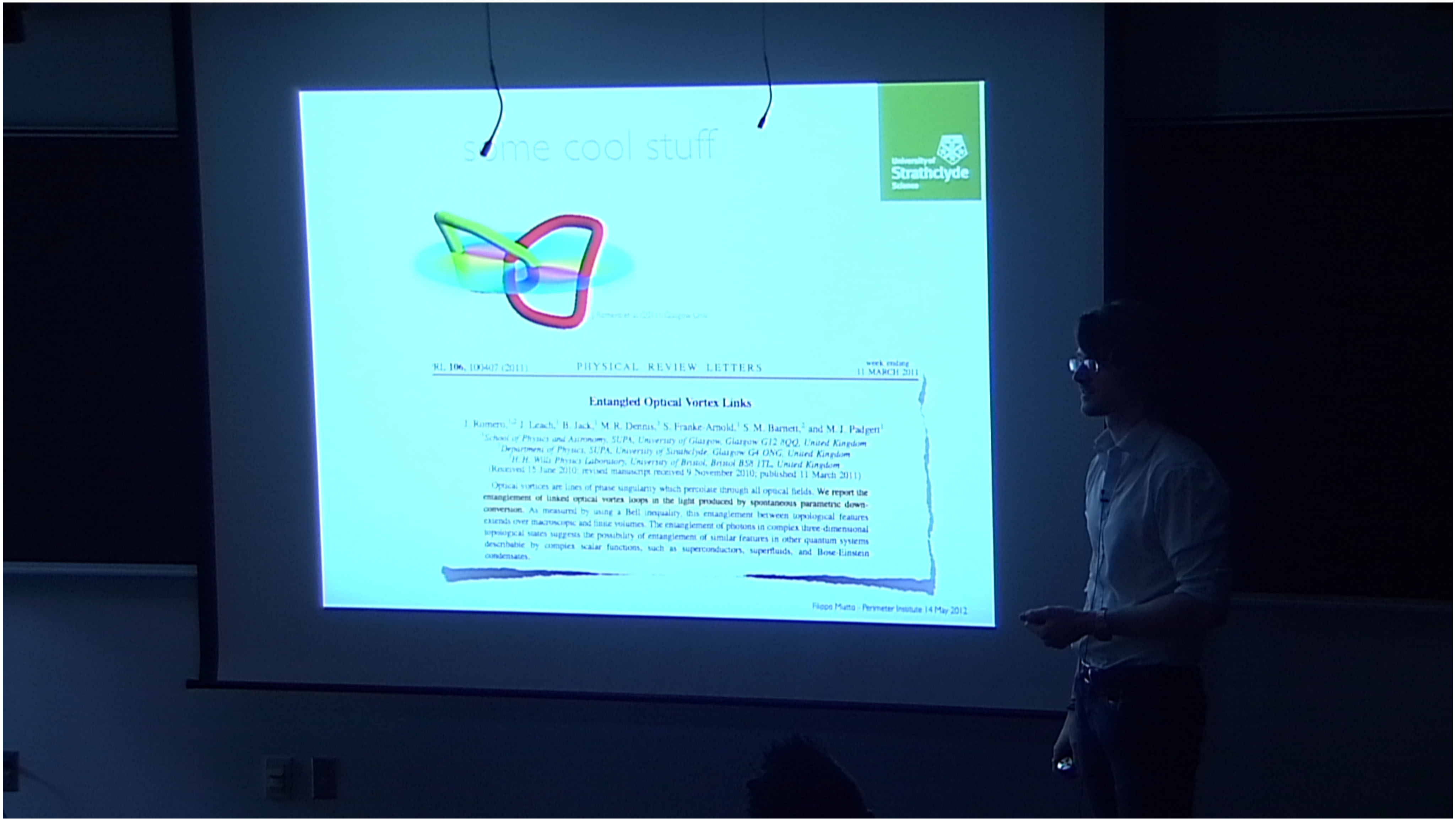
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PHYSICAL REVIEW LETTERS
week ending
11 MARCH 2011
Entangled Optical Vortex Links
Filippo Miatto - Perimeter Institute 14 May 2012


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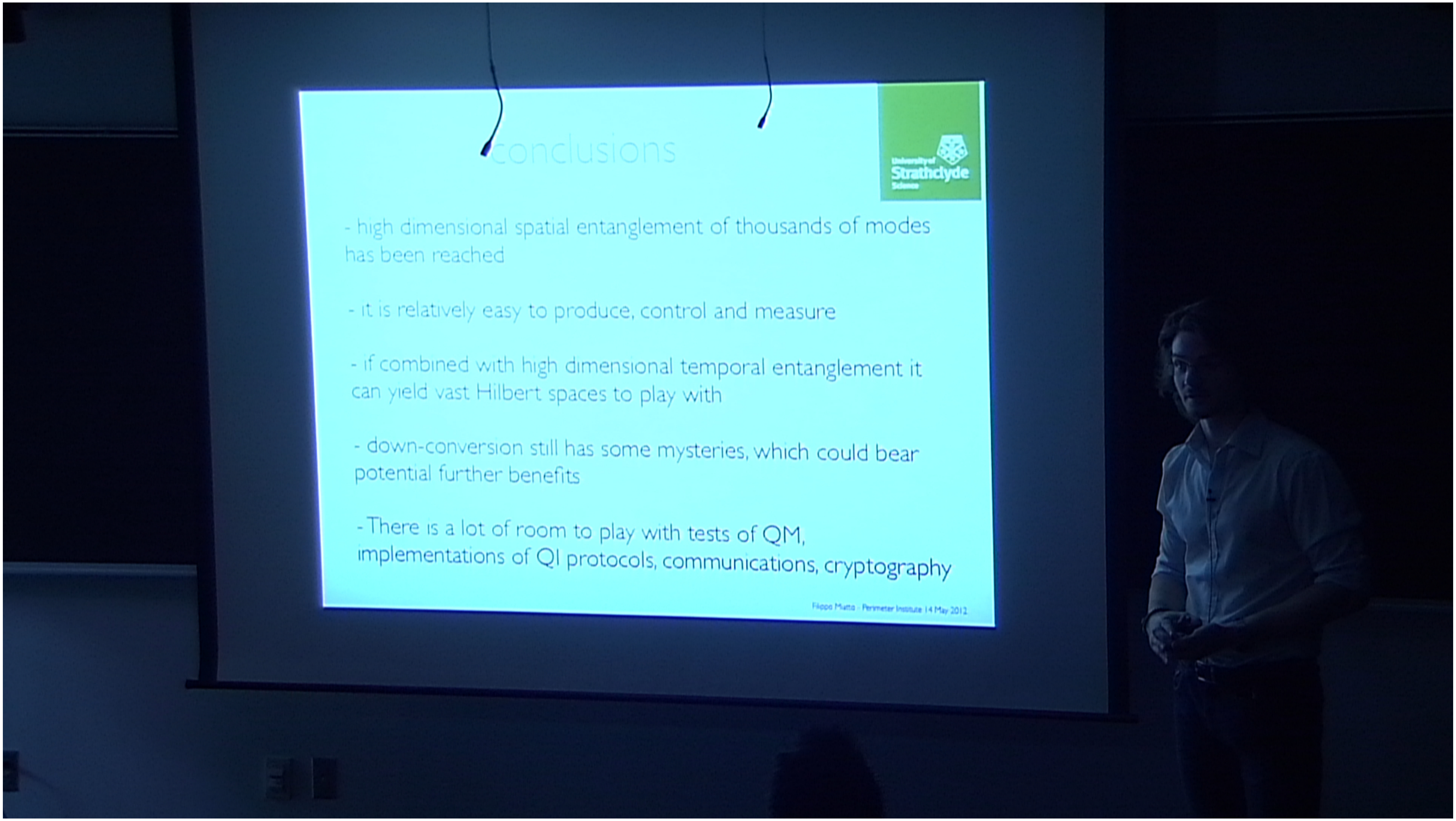
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University of Strathclyde Science
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