First Demonstration of Antimatter Quantum Interference

Marco Giammarchi

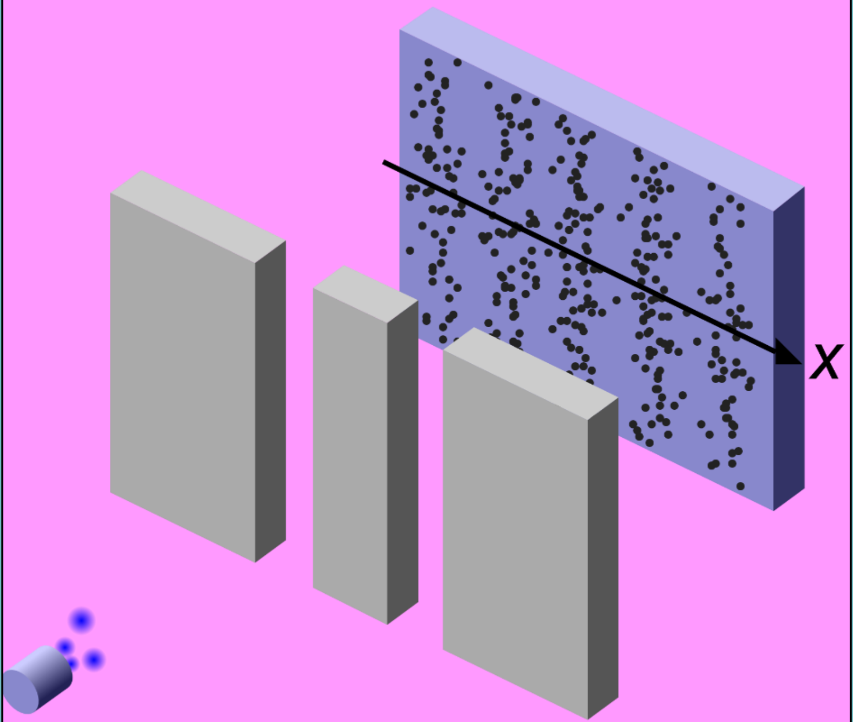
Istituto Nazionale di Fisica Nucleare – Sezione di Milano

On behalf of

Q U P L A S

QUantum interferometry and gravitation with Positrons and LASers

S. Sala, A. Ariga, A. Ereditato, R. Ferragut, M. Giammarchi, M. Leone, C. Pistillo, P. Scampoli
First Demonstration of Antimatter Wave Interference
Science Advances 5 eaav7610 (2019)



Single (anti)particles: ?

The QUPLAS Collaboration (at large)

Università degli Studi di Milano and Infn Milano

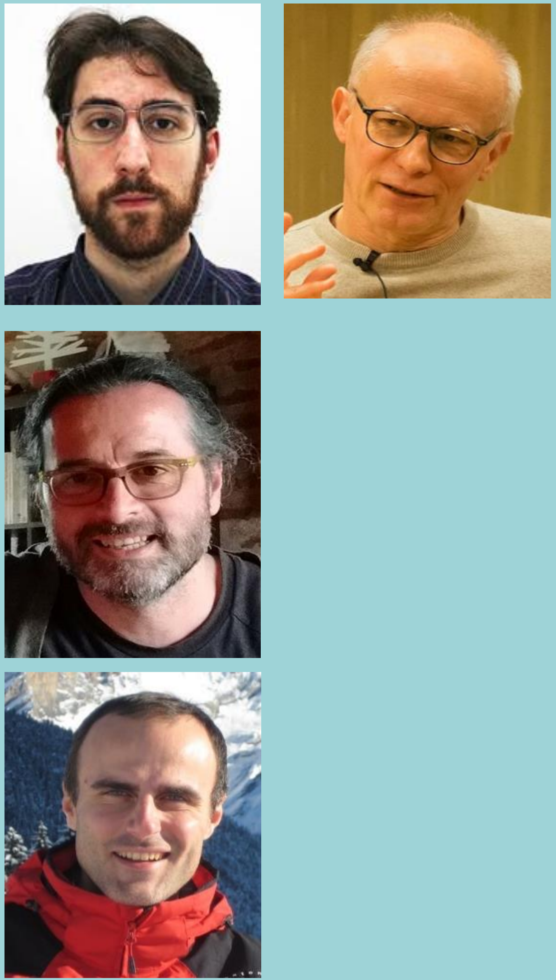
S. Castelli, S. Cialdi, M. Costantini, M. Giammarchi (spokesperson),
G. Maero, L. Miramonti, S. Olivares, M. Romé, S. Sala

L-NESS Laboratory of the Politecnico di Milano (at Como)

R. Ferragut, M. Leone, V. Toso

Albert Einstein Center – Laboratory for HEP – Bern University

A. Ariga, A. Ereditato, C. Pistillo, P. Scampoli



Home of the Experiment: L-NESS Laboratory of the Milano Politecnico in Como

https://sites.google.com/site/positronlaboratoryofcomovepas/

QUPLAS in a slide

- QUPLAS-0: Positron interferometry

S. Sala, F. Castelli, M. Giammarchi, S. Siccardi and S. Olivares, **J. Phys. B 48 (2015) 195002**	Concept of antimatter quantum interference
S. Sala, M. Giammarchi and S. Olivares, **Phys. Rev. A 94 (2016) 033625**	Magnifying configuration for interferometry
S. Aghion, A. Ariga, T. Ariga, M. Bollani, E. Dei Cas, A. Ereditato, C. Evans, R. Ferragut, M. Giammarchi, C. Pistillo, M. Romè, S. Sala and P. Scampoli **Journal of Instrumentation JINST 11 (2016) P06017**	Detector characterization down to 9 keV
S. Aghion, A. Ariga, M. Bollani A. Ereditato, R. Ferragut, M. Giammarchi, M. Lodari, C. Pistillo, S. Sala, P. Scampoli and M. Vladymyrov **Journal of Instrumentation JINST 13 (2018) P05013**	Detector characterization: reconstruction of fringe patterns (Engineering Run)
S. Sala, A. Ariga, A. Ereditato, R. Ferragut, M. Giammarchi, M. Leone, C. Pistillo and P. Scampoli **Science Advances 5 eaav7610 (2019) doi: 10.1126/sciadv.aav7610**	First observation of antimatter wave interference

- QUPLAS-I: Positronium Interferometry
- QUPLAS-II: Positronium Gravitation

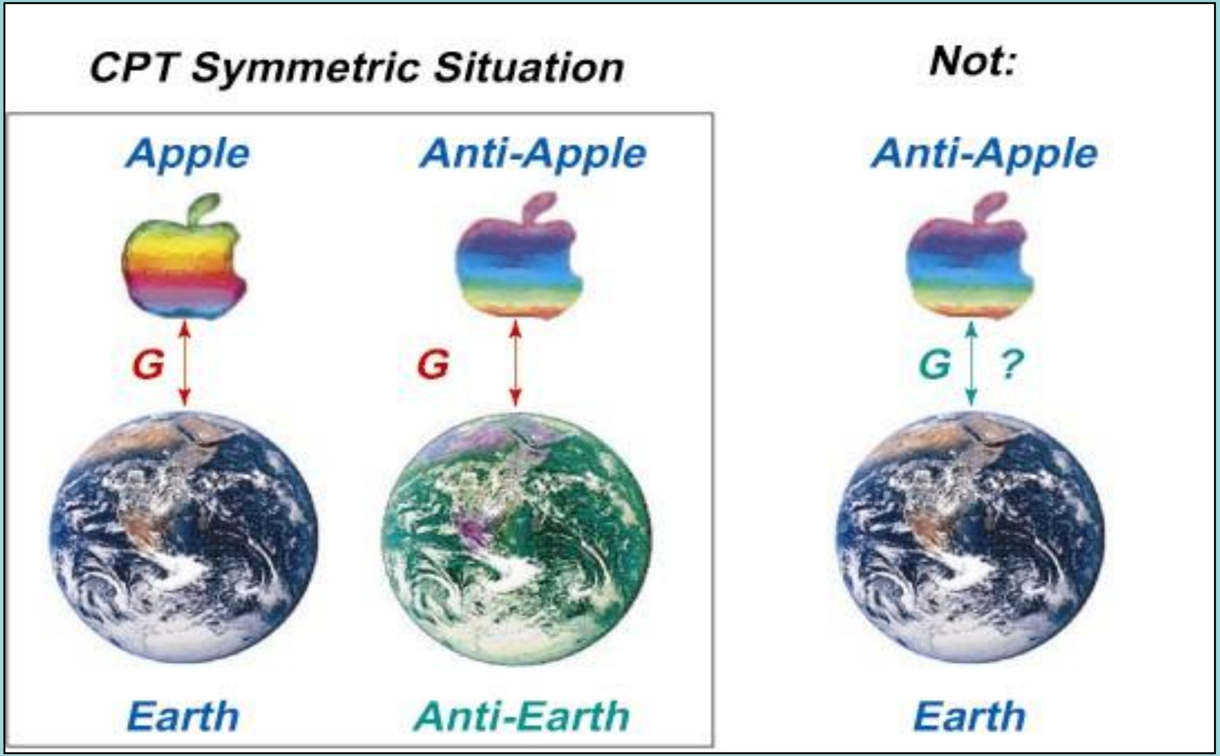
Gravity and the Particles (CPT)

Dynamical meaning

$$F = m_I\, a$$

The gravitational «charge»

$$F = -G\, m_G M_G / r^2$$



According to the WEP

$$m_I = m_G$$

CPT Theorem $\Rightarrow$ $m_I = \overline{m}_I$ $\not\Rightarrow$ $m_G = m_I = \overline{m}_I \,?\, \overline{m}_G$

Which means that

$$m_G \neq \overline{m}_G$$

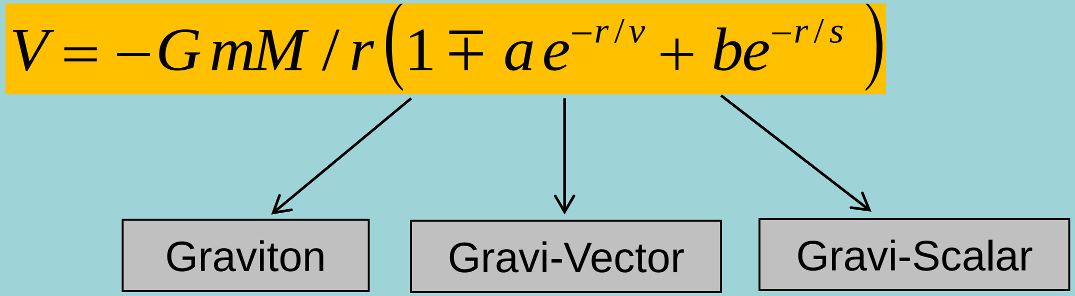
Would not necessarily mean that CPT is broken

$$m_G \neq \overline{m}_G$$

Means that either CPT or the WEP are broken at the particle level

Gravity and the Particles

In many Quantum Gravity models (in the classical static limit), one has :



$$V = -GmM/r\left(1 \mp a e^{-r/v} + b e^{-r/s}\right)$$

- The sign of the Gravi-Vector can be different between Matter and Antimatter
- Ranges and strength unknowns

From the Particle Physics point of view, it could be mediated by a tensor (spin-2) carrier, with the charge being mass-energy.

	Matter-Matter (e- e-)	**Antimatter-Matter (e+ e-)**	**Quantum Gravity**
Scalar	attractive	Attractive	gravi-scalar
Vector	repulsive	Attractive	gravi-vector
Tensor (Gravity)	attractive	Attractive	graviton
Tensor (Antigravity)	Attractive	Repulsive (CPT violating)	

QUPLAS in a slide

- QUPLAS-0: Positron interferometry

S. Sala, F. Castelli, M. Giammarchi, S. Siccardi and S. Olivares, **J. Phys. B 48 (2015) 195002**

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- QUPLAS-I: Positronium Interferometry
- QUPLAS-II: Positronium Gravitation

Concept of antimatter quantum interference

Magnifying configuration for interferometry

Detector characterization down to 9 keV

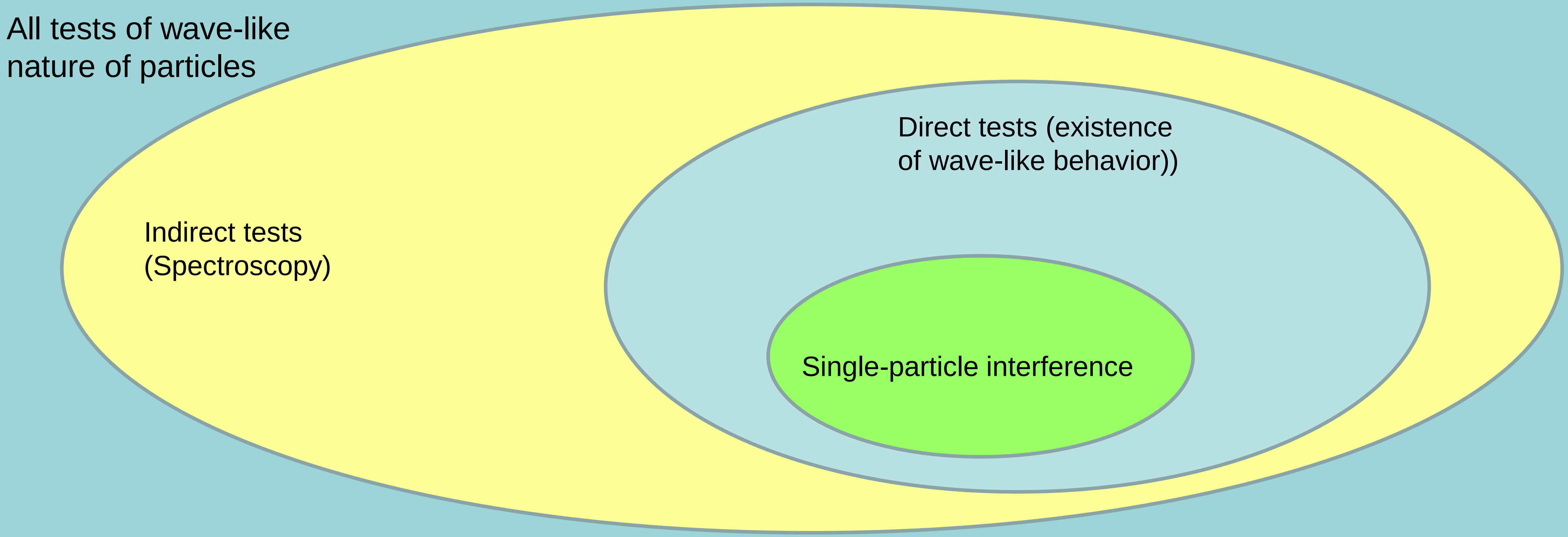
Detector characterization: reconstruction of fringe patterns (Engineering Run)

First observation of antimatter wave interference

Beginning of the (interferometry) story

1923: de Broglie hypothesis on the wave-like nature of the electron

$$\lambda = \frac{h}{p}$$



All tests of wave-like nature of particles

Indirect tests (Spectroscopy)

Direct tests (existence of wave-like behavior))

Single-particle interference

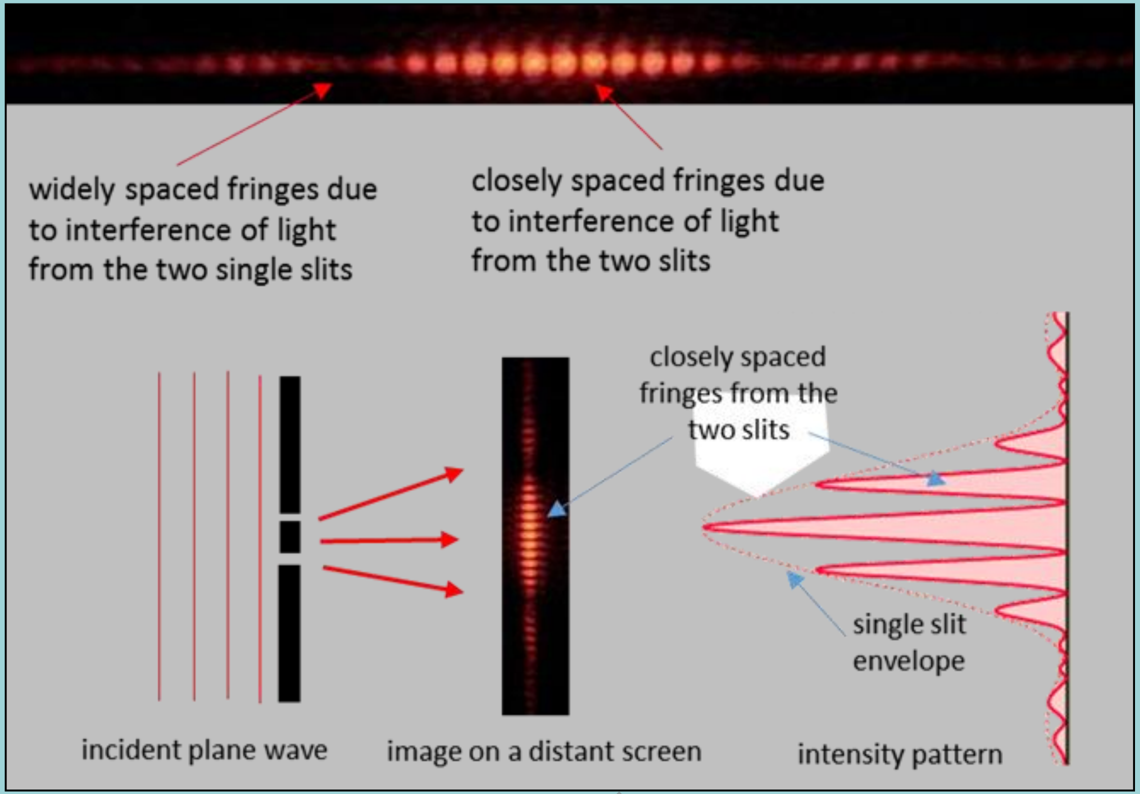
Direct tests of wave-like nature of particles :

- Electrons) C.J. Davisson, L.H. Germer, *Proc. Natl. Acad. Sci. 14 (1928) 317*.
- Electrons) G.P. Thomson, A. Reid, *Nature 119 (1927) 890*.
- Neutrons) A.V. Overhauser, R. Colella, *Phys. Rev. Lett. 33 (1974) 1237*. And a gravitatinally induced phase.
- Single electrons) P.G. Merli, G.G. Missiroli, G. Pozzi, *Am. J. Phys. 44 (1976) 306.*
- Positrons) I.J. Rosberg, A.H. Weiss, K.F. Canter, *Phys. Rev. Lett. 44 (1980) 1139*.
- Single Neutrons) A. Zeilinger, R. Gaehler, C.G. Shull, W. Treimer, W. Mampe, *Rev. Mod. Phys. 60 (1988) 106*.
- Potassium) J.F. Clauser, S. Li, *Phys. Rev. A 49 (1994) R2213*.
- Single C60) M. Arndt, O. Nairz, J. Vos-Andreae, C. Keller, G. van der Zouw, A. Zeilinger, *Nature 401 (1999) 680*.
- Single Positrons) S. Sala, A. Ariga, A. Ereditato, R. Ferragut, M. Giammarchi, M. Leone, C. Pistillo, P. Scampoli, *Science Adv. 5 (2019) eaav7610*.

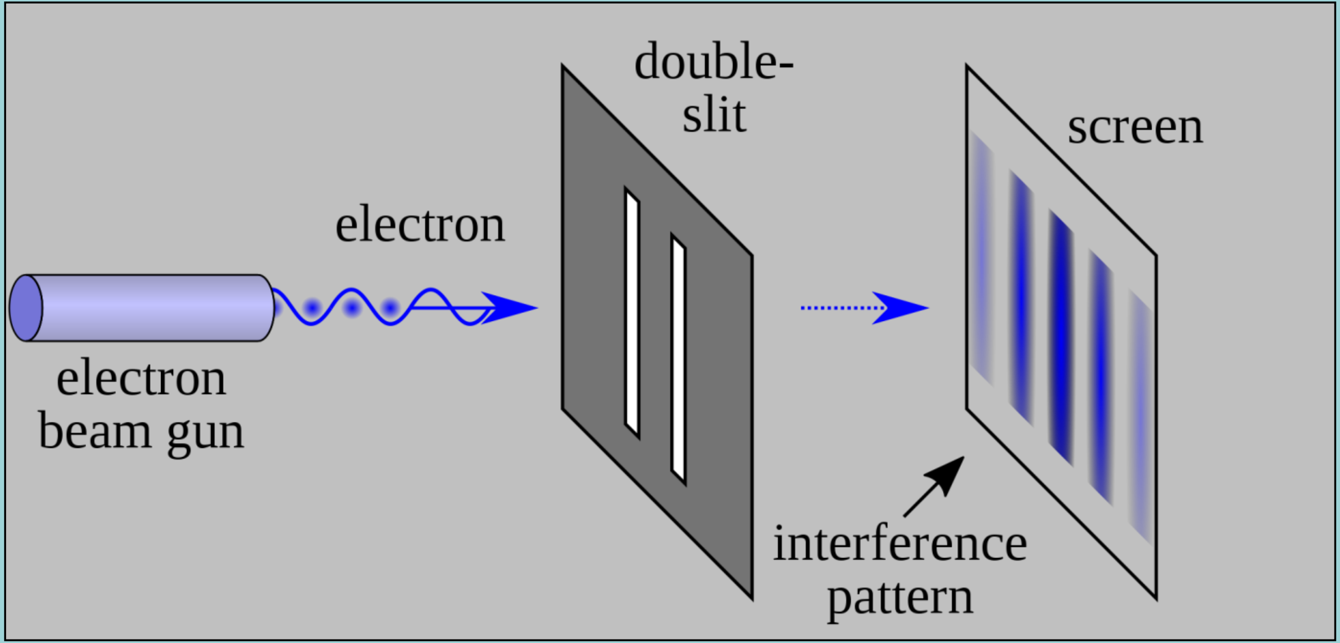
Single-particle interference

We choose to examine a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery.

(**R.P. Feyman**, Feynman Lectures)



«old good» optics



One single particle at a time ?

Single-electron interference

P.G. Merli, G.F. Missiroli, G. Pozzi

On the statistical aspect of electron interference phenomena

Am. J. of Physics 44 (1976) 306

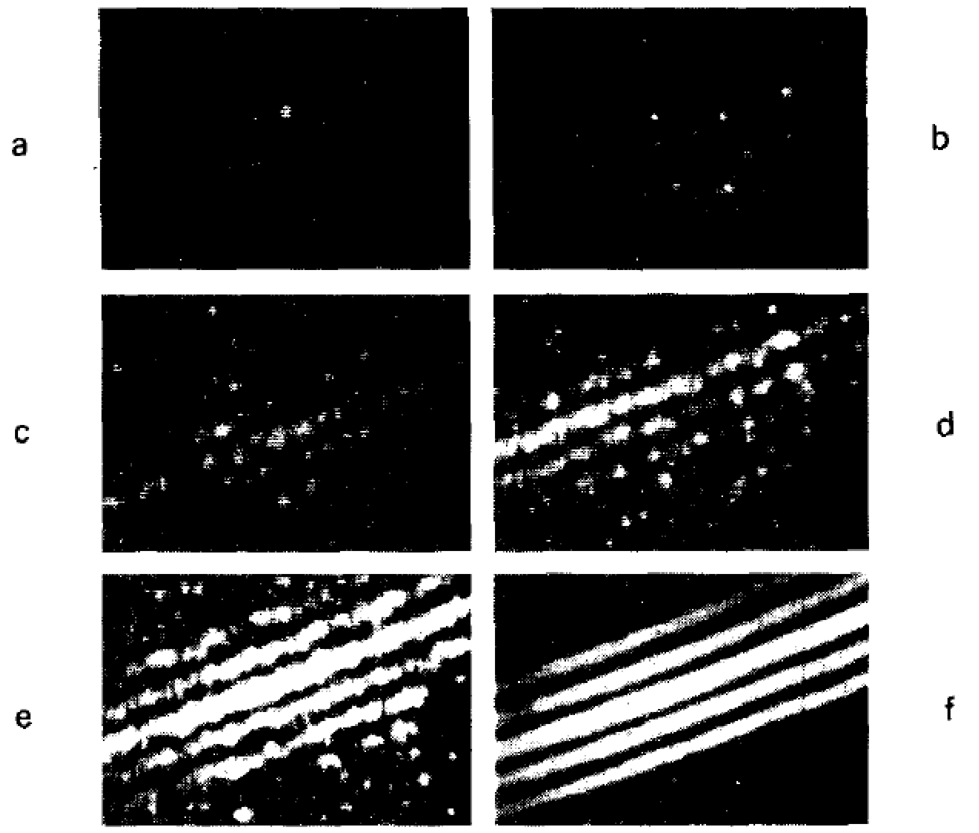
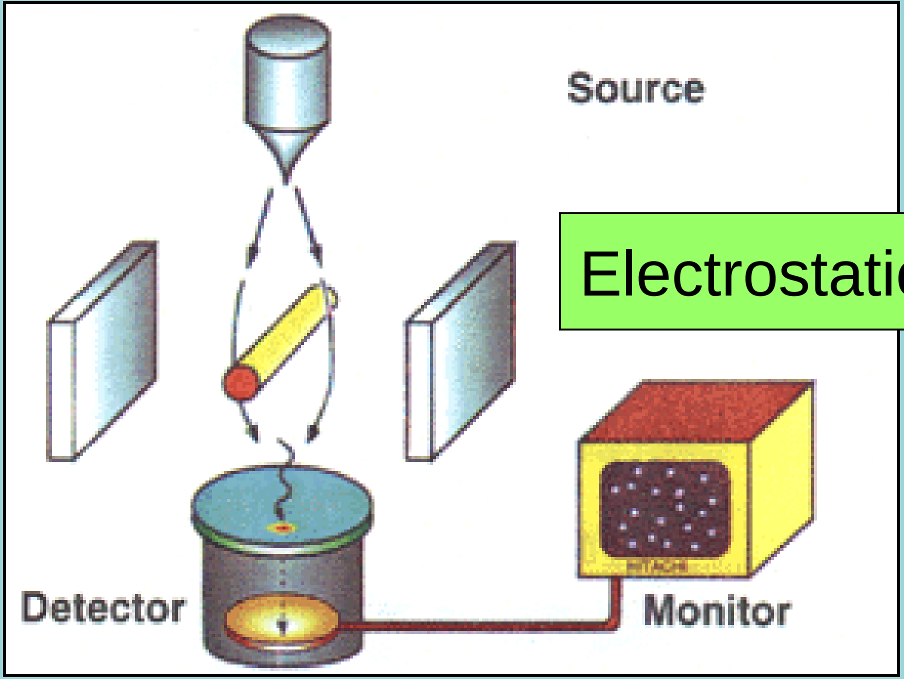


Fig. 1. (a–f) Electron interference fringe patterns filmed from a TV monitor at increasing current densities.

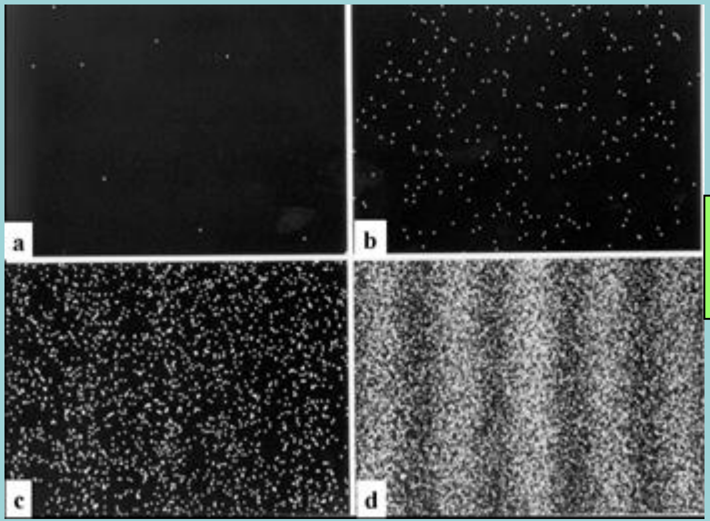


Electrostatic Biprism

Nicely reproduced by

A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki and H. Ezawa
Demonstration of single-electron buildup of an interference pattern
Am. J. of Physics 57 (1989) 2

Single particle interference conclusively demonstrated



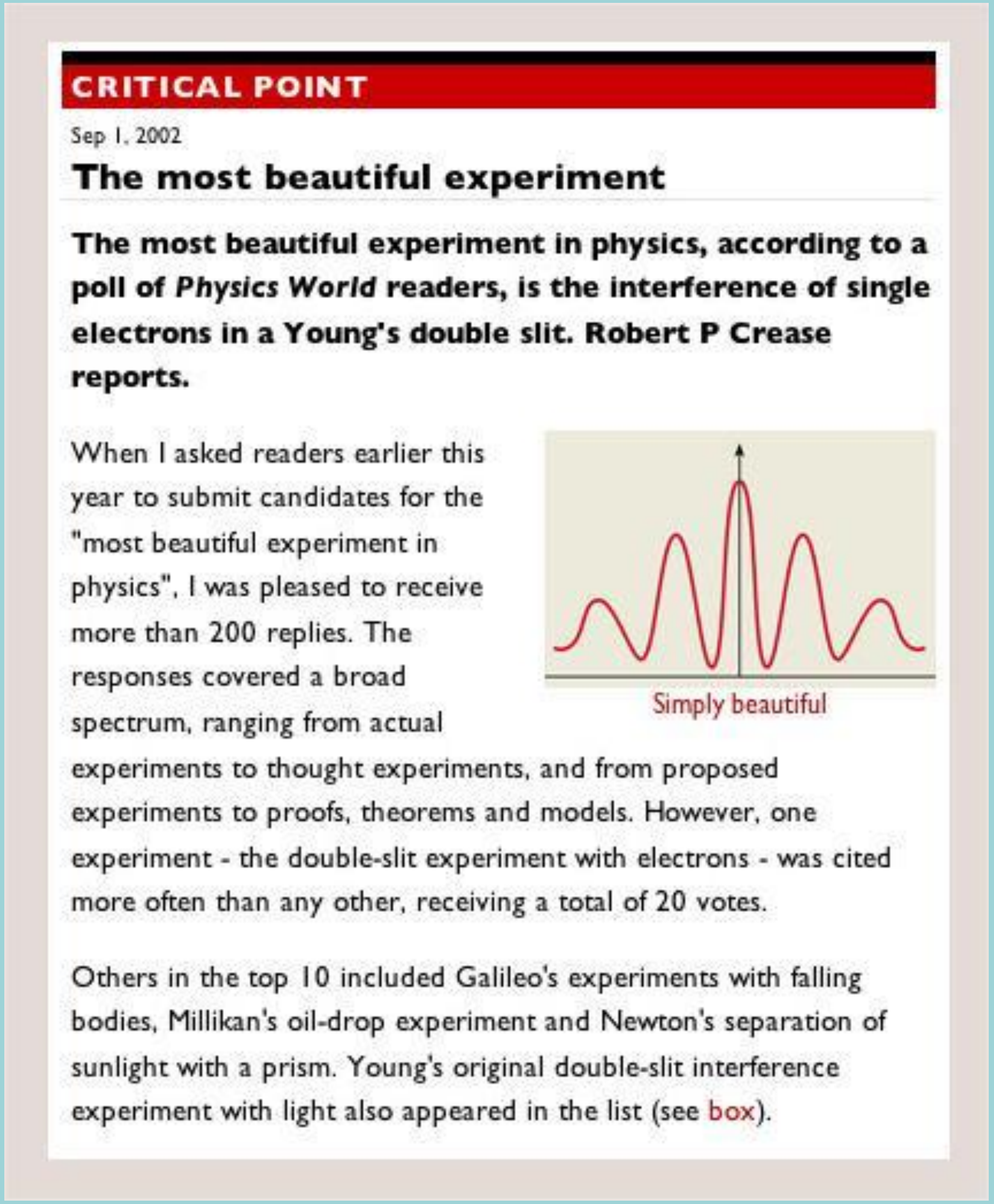
Different integration time: build-up!

What about anti-particles?

$$(i\gamma^{\mu}\partial_{\mu} - m)\,\psi = 0$$

1927 Dirac Equation
1932 Positron discovery

Diffractive effects for positrons observed in 1980:
I.J. Rosenberg, A.H. Weiss and K.F. Canter
Physical Review Letters 44 (1980) 17



CRITICAL POINT

Sep 1, 2002

The most beautiful experiment

The most beautiful experiment in physics, according to a poll of *Physics World* readers, is the interference of single electrons in a Young's double slit. Robert P Crease reports.

When I asked readers earlier this year to submit candidates for the "most beautiful experiment in physics", I was pleased to receive more than 200 replies. The responses covered a broad spectrum, ranging from actual experiments to thought experiments, and from proposed experiments to proofs, theorems and models. However, one experiment - the double-slit experiment with electrons - was cited more often than any other, receiving a total of 20 votes.

Simply beautiful

Others in the top 10 included Galileo's experiments with falling bodies, Millikan's oil-drop experiment and Newton's separation of sunlight with a prism. Young's original double-slit interference experiment with light also appeared in the list (see box).

This experiment (QUPLAS-0)

S. Sala, F. Castelli, M. Giammarchi, S. Siccardi and S. Olivares
J. Phys. B 48 (2015) 195002

S. Sala, M. Giammarchi and S. Olivares
Phys. Rev. A 94 (2016) 033625

Concept of antimatter quantum interference

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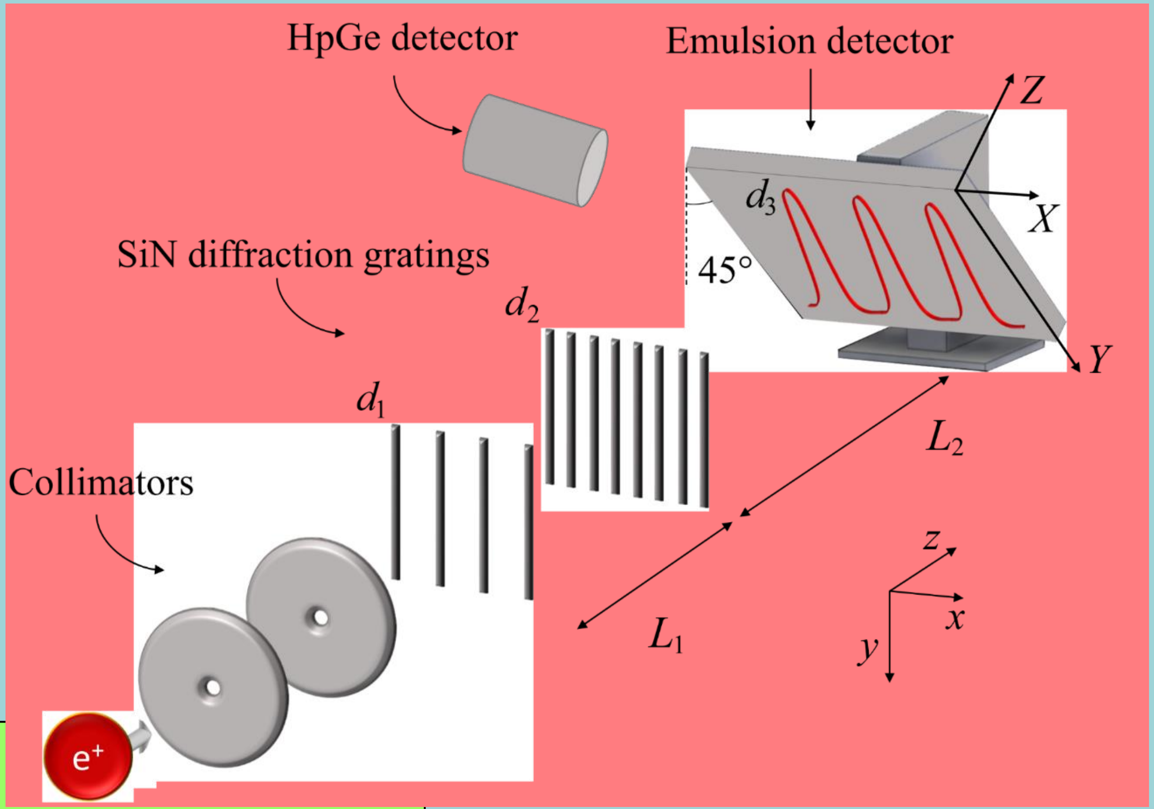
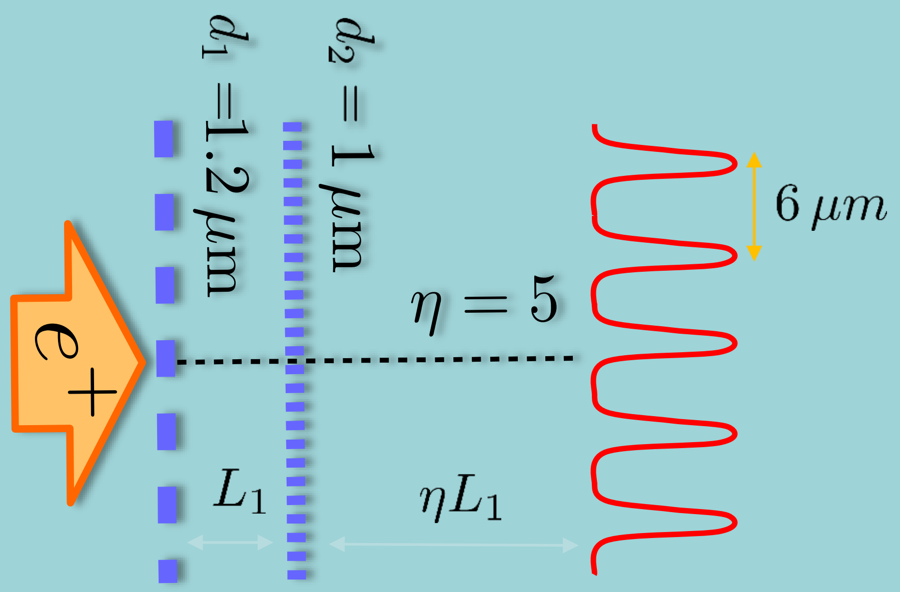


QUPLAS-0:

A (magnifying) Talbot-Lau interferometer operating on a 8-16 keV positron beam and coupled to an emulsion detector.

- The L-NESS positron beam in Como
- The Interferometer
- The nuclear emulsion detector

The «Asymmetric» Talbot-Lau Interferometer



Positron beam energy: from 8 few keV up to 14 keV

Reference value: 10 keV

Intensity: ~ 10^3 e^+/s

$$T = 14 \quad keV \qquad v = 7 \times 10^7 \quad m/s$$

Production time-scale : ~ ms

Transit time scale : 10^{-8} s

Incoherent fermion source

Single particle experiment !

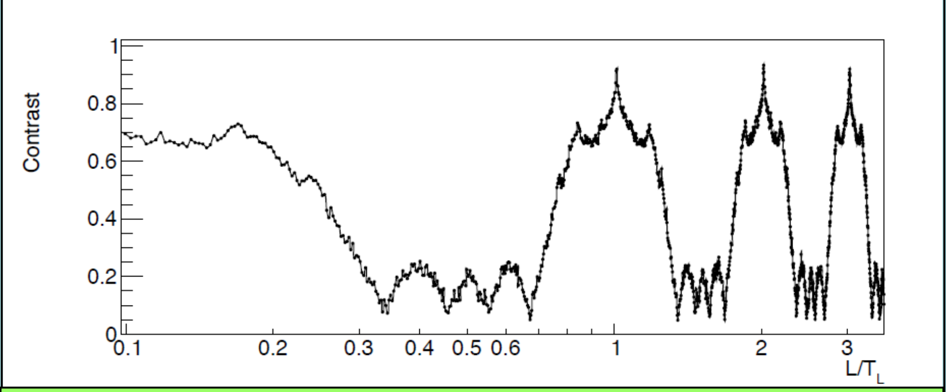
$L_1 = 11.8$ cm, $L_2 = 59$ cm

The de Broglie wavelength

$$\lambda = \frac{h}{mv} = 1.3 \times 10^{-11} \quad m$$

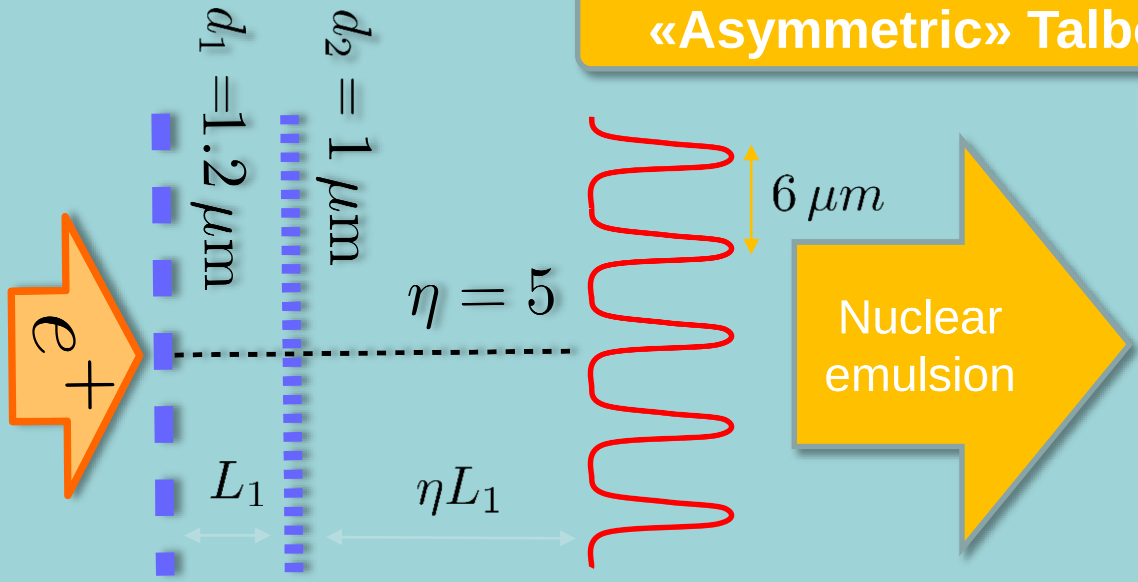
The Talbot length

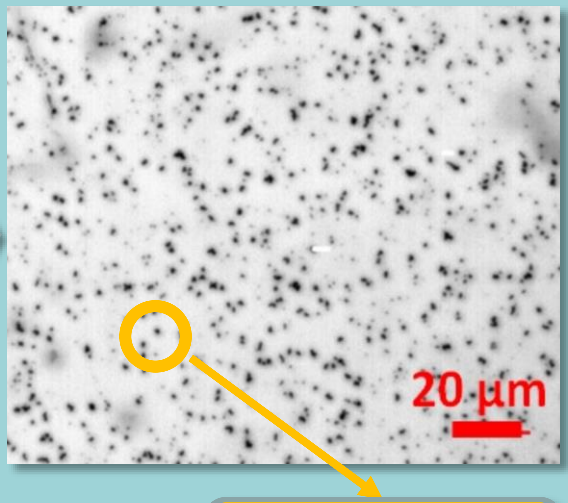
$$L_T = \frac{d^2}{\lambda} = 9{,}7\ cm$$



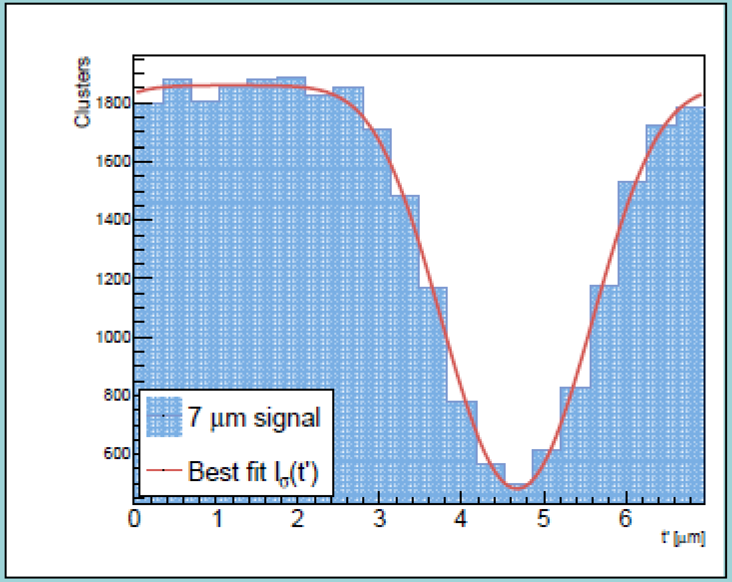
The Talbot «revival» principle

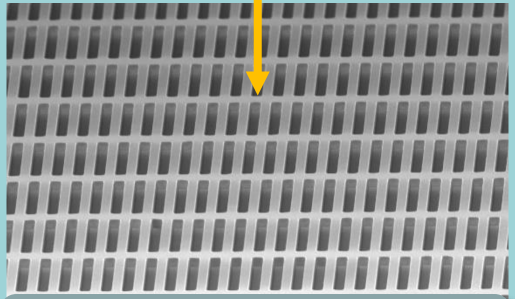
«Asymmetric» Talbot- Lau interferometer and the emulsion detector





Individual positrons





SiNx diffraction gratings

S. Aghion, A. Ariga, T. Ariga, M. Bollani, E. Dei Cas, A. Ereditato, C. Evans, R. Ferragut, M. Giammarchi, C. Pistillo, M. Romè, S. Sala and P. Scampoli
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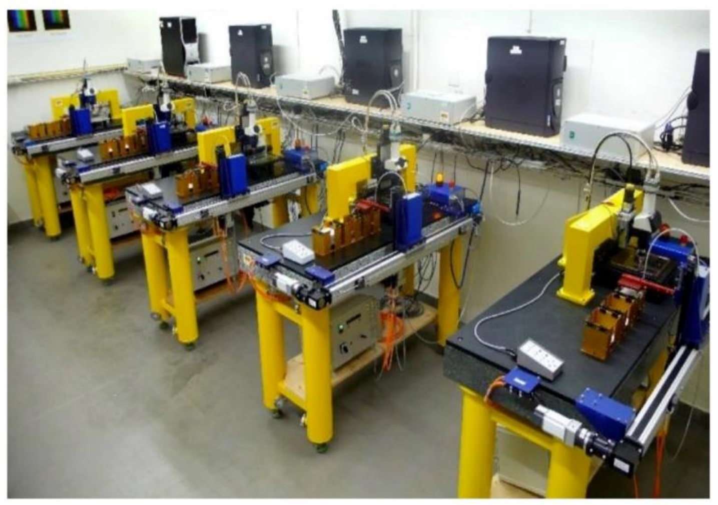
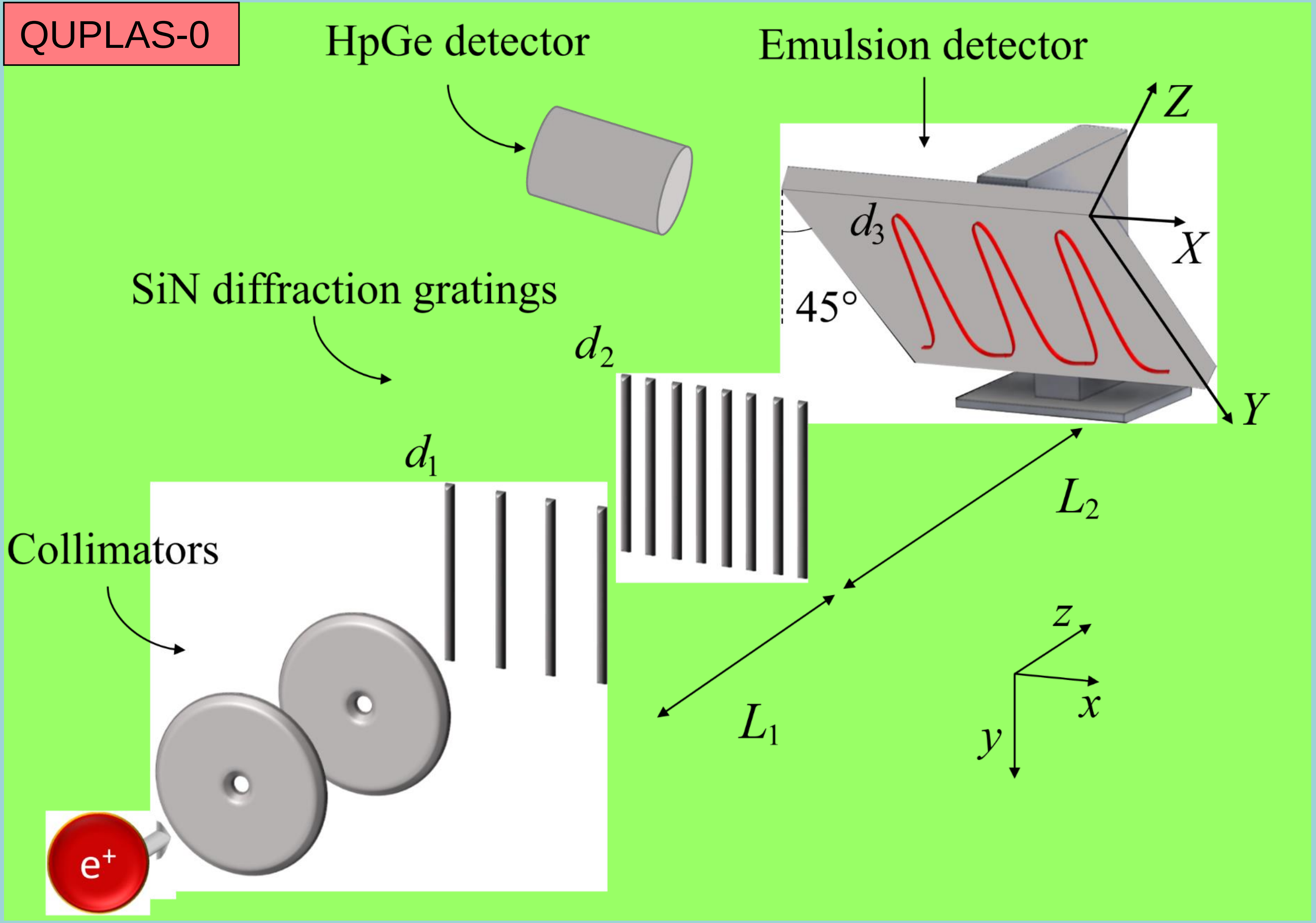


Emulsions taken in Como, transported, developed and analyzed at the Bern scanning facility. Configuration able to detect «keV» positrons in a 5 micron periodic pattern

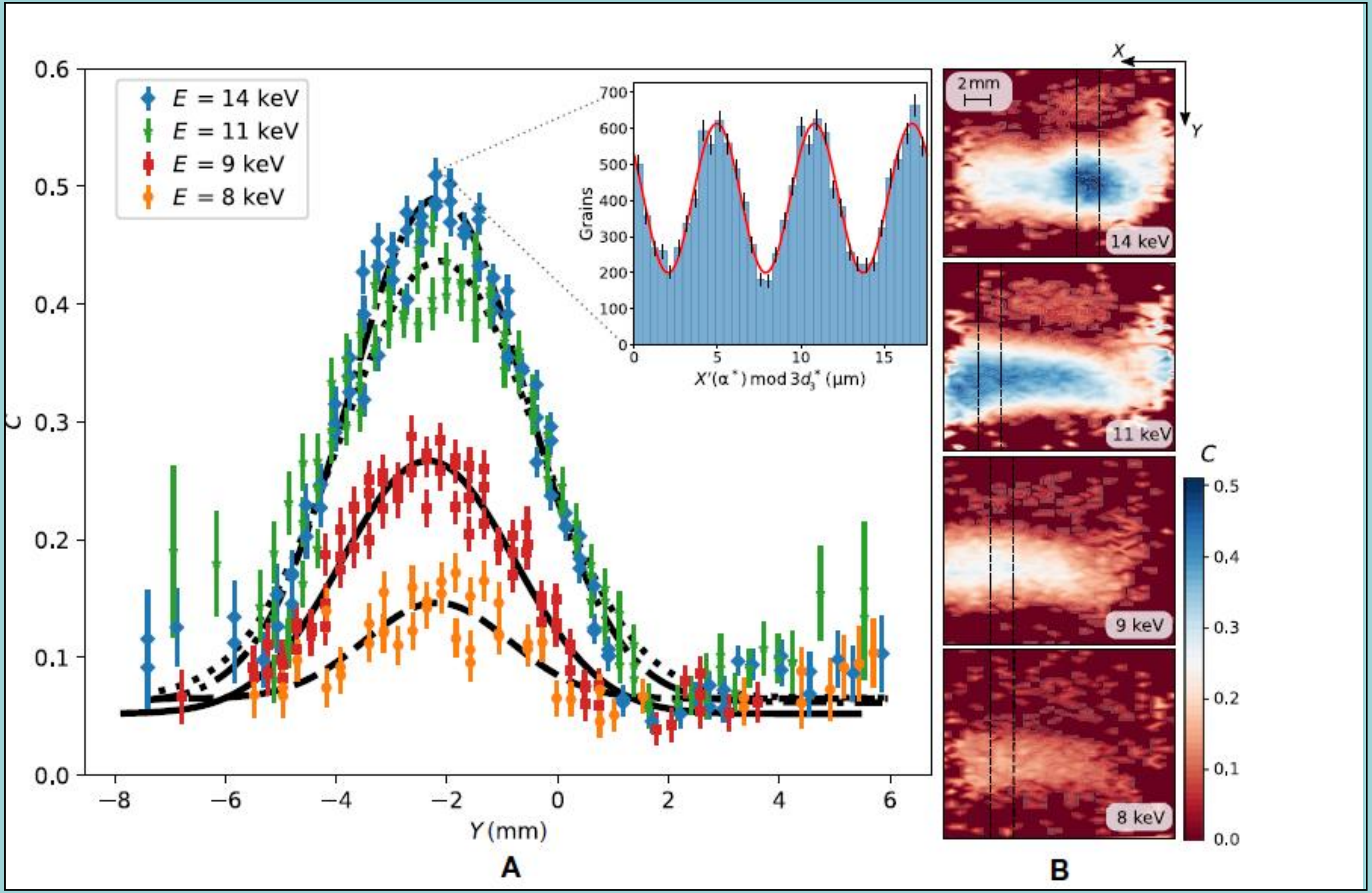
QUPLAS-0


HpGe detector
Emulsion detector
Z
X
Y
d_3
45°
SiN diffraction gratings
d_2
d_1
Collimators
L_2
L_1
z
x
y
e^+

The interferometric pattern at different positron energies

Data taking April-August 2018:

- Emulsion exposure
- Emulsion development
- Data analysis



Visibility at different energies

Contrast of fringes as a function of energy (wavelength)

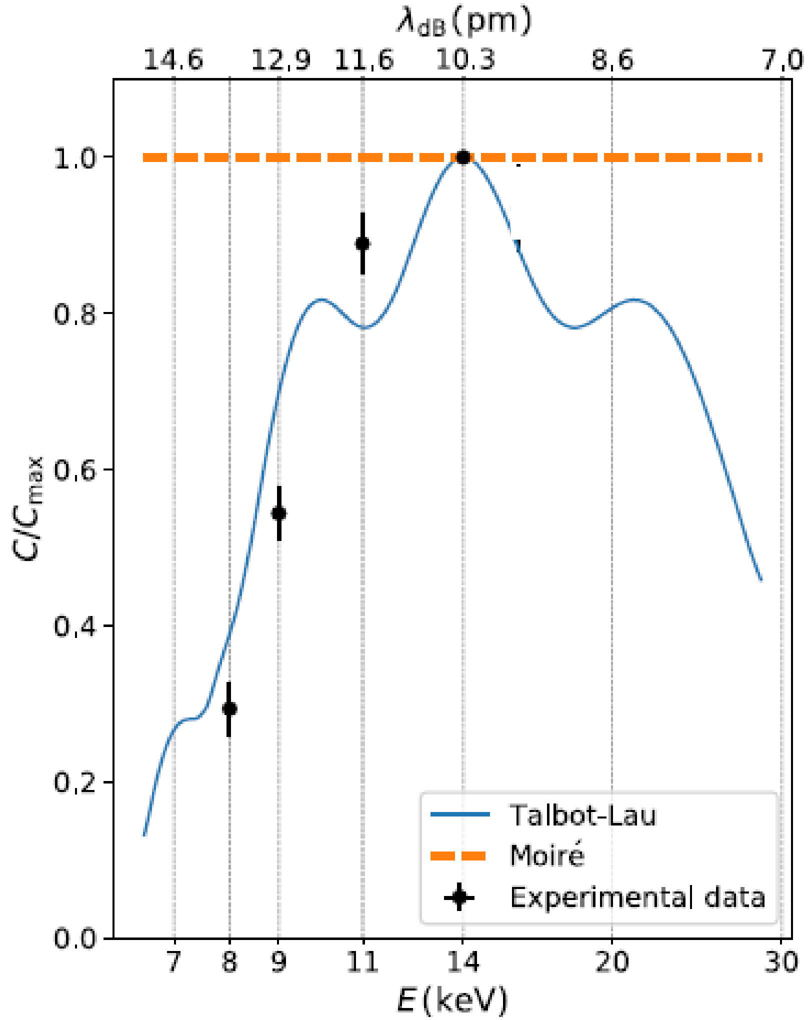


Fig. 5. Contrast as a function of energy. Measured contrast normalized to the resonance value, defined as $C/C_{max}(E)$. The 68% confidence interval uncertainties are obtained by standard error propagation. The solid line is the quantum-mechanical prediction, while the classical prediction is indicated by the dashed line.

A classical (projective, moiré) effect would be achromatic

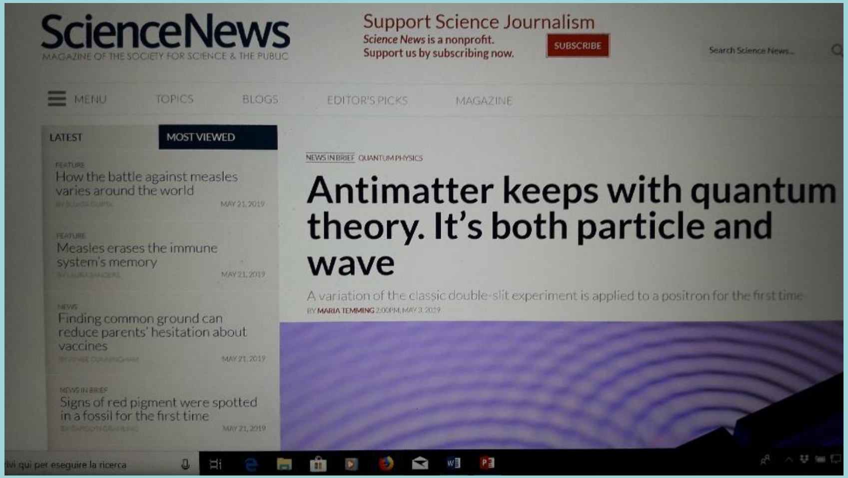
A quantum effect would be energy (wavelength) dependent (Talbot-Lau)

- Disagrees with (moiré) Classical Physics
- Agrees with Quantum Mechanics
- Single-particle Talbot-Lau Quantum interferometry!

Preliminary on August 2018: https://arxiv.org/abs/1808.08901

Published on Science Advances: 3.rd of May 2019

Media Slide



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MAY 21, 2019

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Measles erases the immune system's memory
MAY 21, 2019

NEWS
Finding common ground can reduce parents' hesitation about vaccines
MAY 21, 2019

NEWS IN BRIEF
Signs of red pigment were spotted in a fossil for the first time
MAY 21, 2019

NEWS IN BRIEF QUANTUM PHYSICS

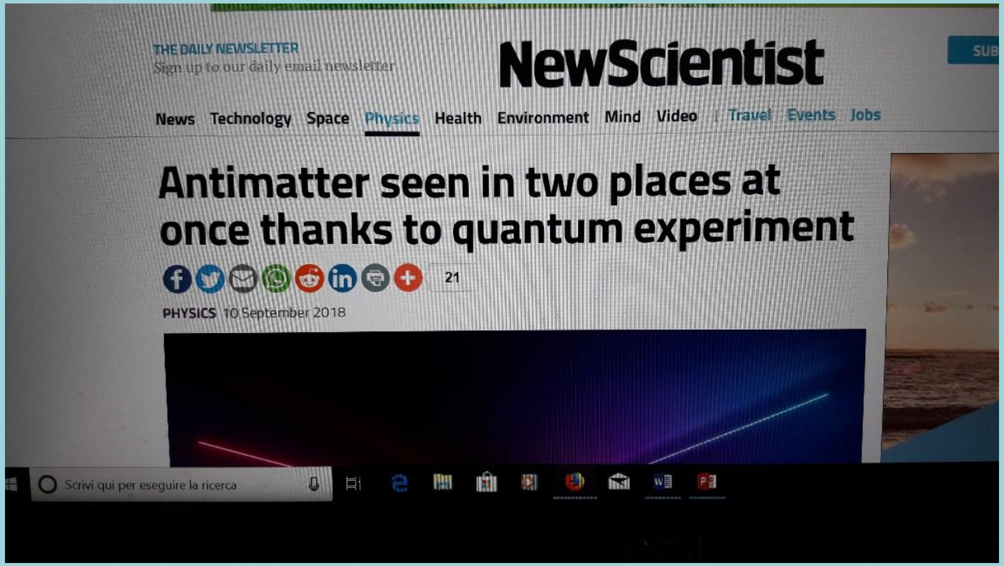
Antimatter keeps with quantum theory. It's both particle and wave

A variation of the classic double-slit experiment is applied to a positron for the first time

BY MARIA TEMMING 2:00PM, MAY 3, 2019

Funniest: demonstration that

QUANTUM MECHANICS DOMINATES THE UNIVERSE! (WoW)



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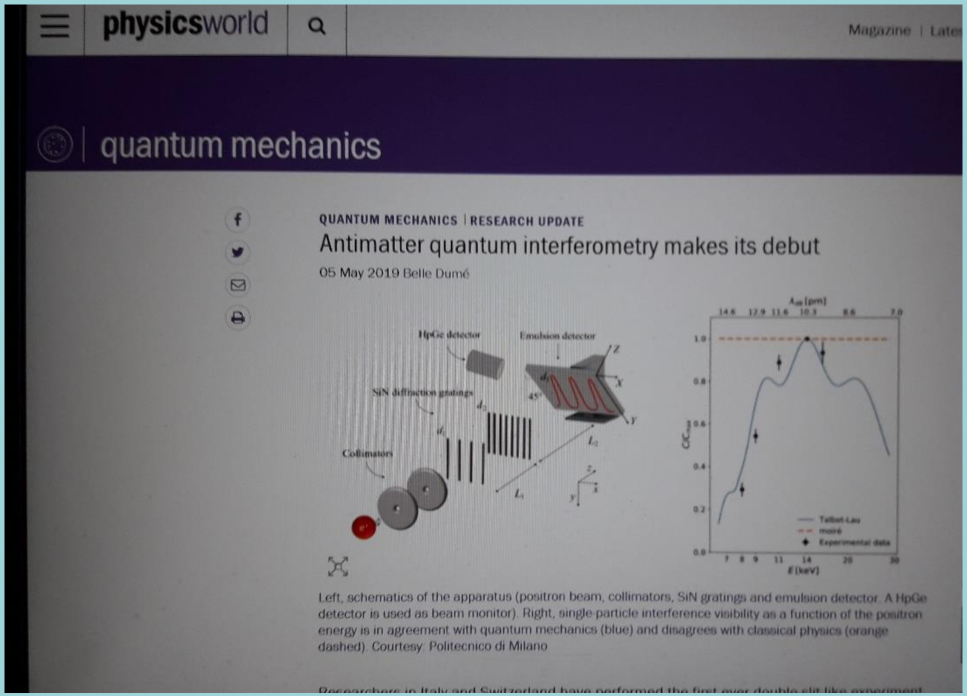
NewScientist

Antimatter seen in two places at once thanks to quantum experiment

PHYSICS 10 September 2018



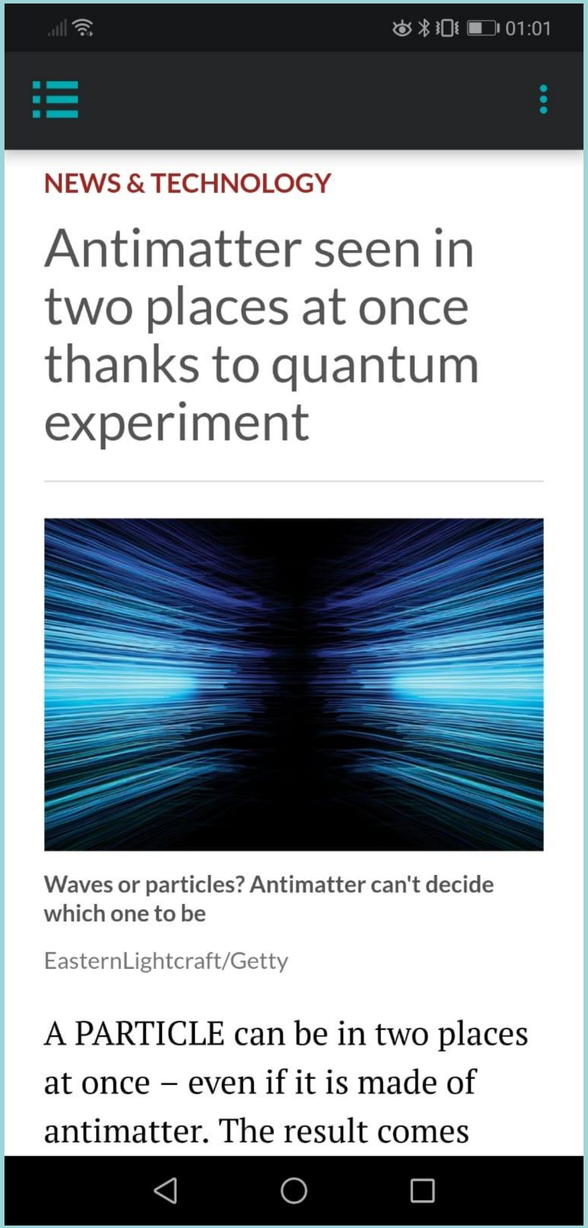
QUANTUM MECHANICS | RESEARCH UPDATE

Antimatter quantum interferometry makes its debut

05 May 2019 Belle Dumé

Left, schematics of the apparatus (positron beam, collimators, SiN gratings and emulsion detector. A HpGe detector is used as beam monitor). Right, single-particle interference visibility as a function of the positron energy is in agreement with quantum mechanics (blue) and disagrees with classical physics (orange dashed). Courtesy: Politecnico di Milano

Researchers in Italy and Switzerland have performed the first ever double-slit-like experiment



NEWS & TECHNOLOGY

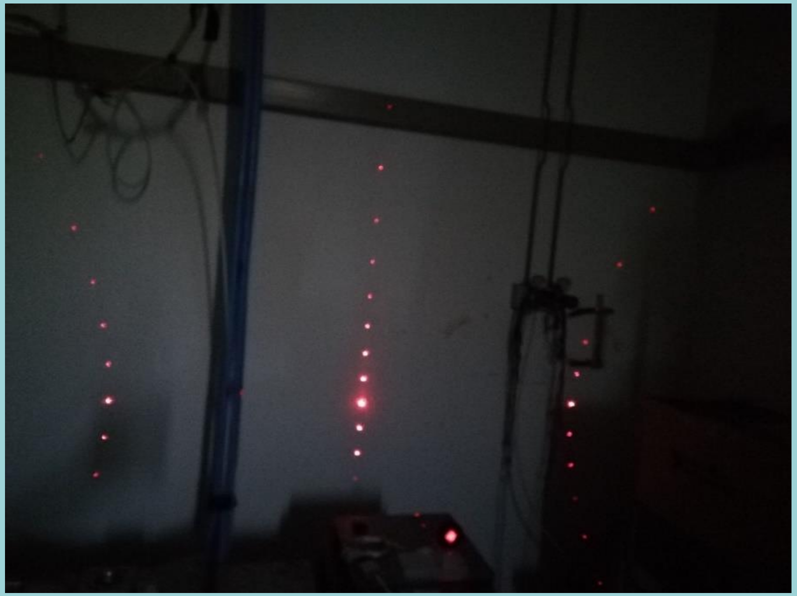
Antimatter seen in two places at once thanks to quantum experiment

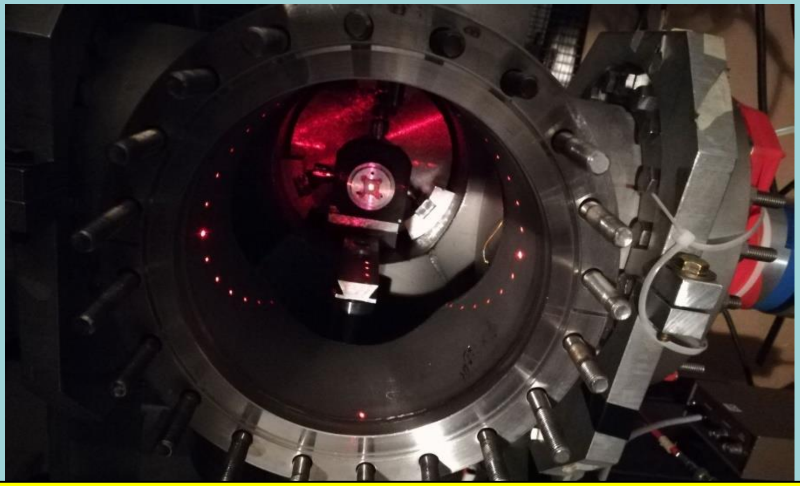
Waves or particles? Antimatter can't decide which one to be

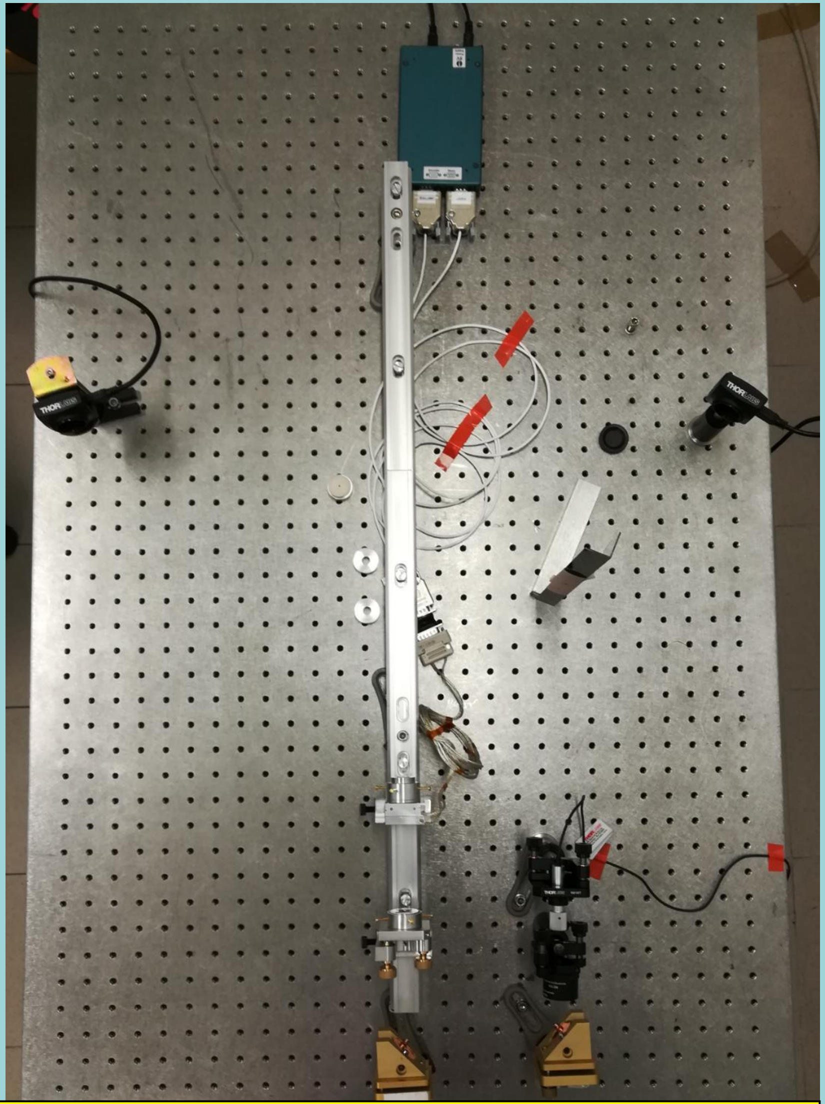
EasternLightcraft/Getty

A PARTICLE can be in two places at once – even if it is made of antimatter. The result comes

Conclusion







By making use of

- The (Como) positron beam
- The (Milano)interferometer
- The (Bern) nuclear detector

We have demonstrated:

Single Particle Interference for Antimatter (a single fundamental anti-fermion)

Thank you for your attention