First Observation of Antimatter Quantum Interference

Marco Giammarchi

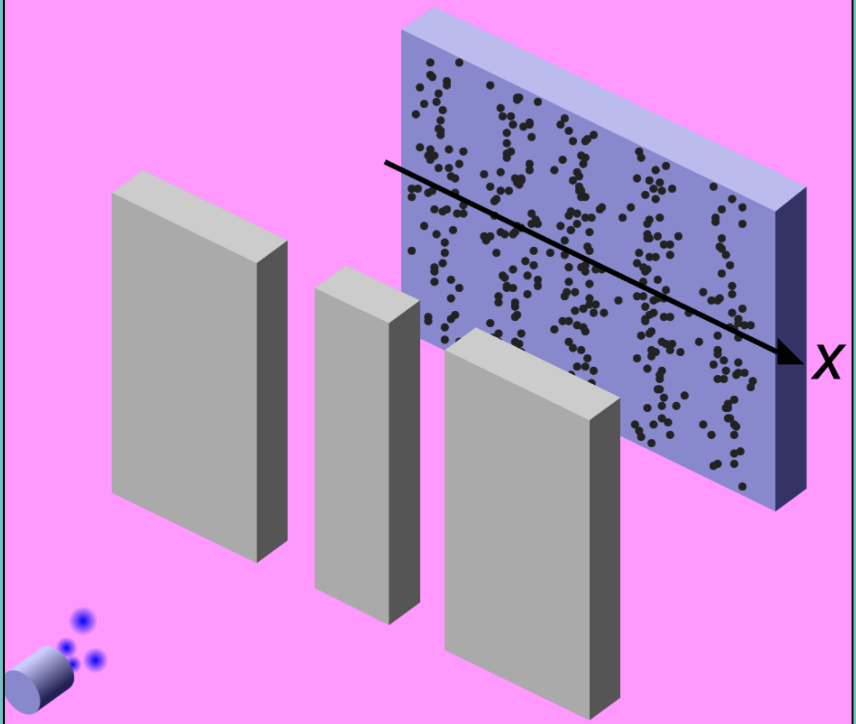
Istituto Nazionale di Fisica Nucleare – Sezione di Milano

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 (as of May 2019)

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, P. Scampoli
Science Advances 5 eaav7610 (2019) doi: 10.1126/sciadv.aav7610 → Antimatter wave interference

A. Ariga, S. Cialdi, G. Costantini, A. Ereditato, R. Ferragut, M. Giammarchi, M. Leone, G. Maero, L. Miramonti, C. Pistillo, M. Romè, S. Sala, P. Scampoli, V. Toso
Nuclear Instruments & Methods A 951 (2020) 163019. → The Quplas-0 apparatus

physicsworld TOP 10 BREAKTHROUGH 2019

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

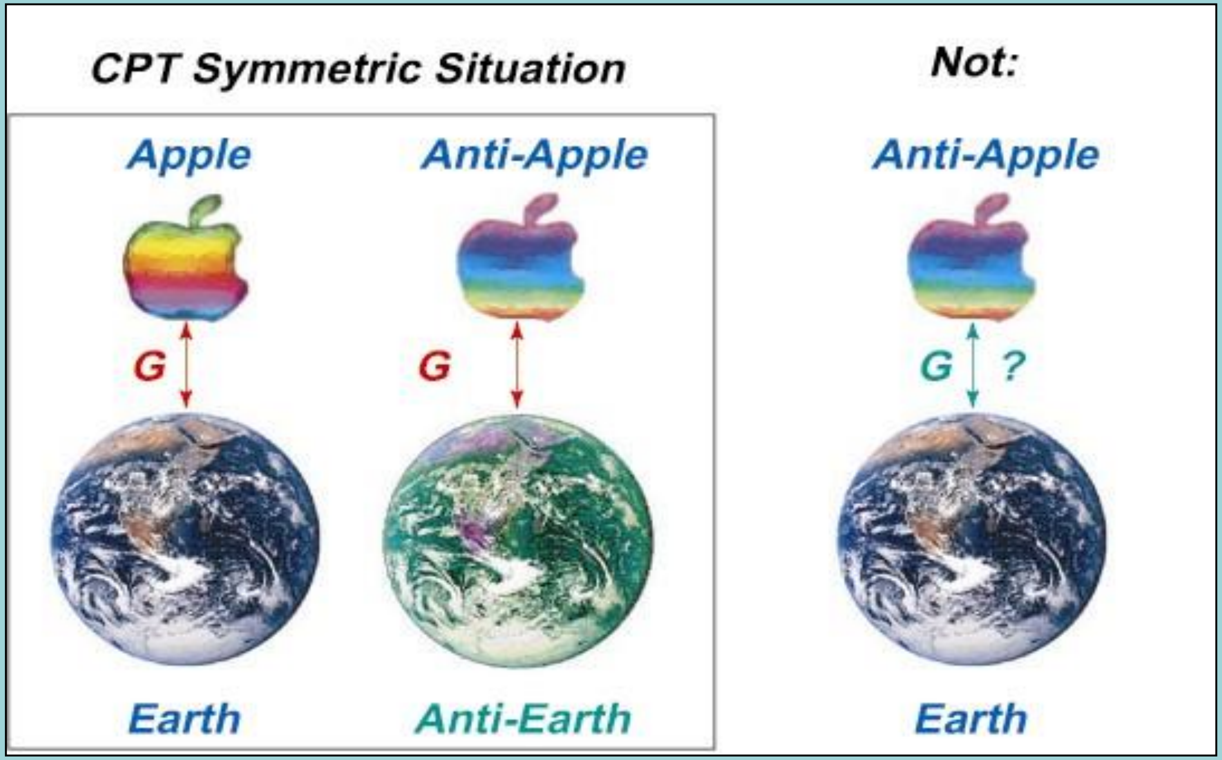
Gravity and the Particles (CPT)

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 → $m_I = \overline{m}_I$ ↛ $m_G = m_I = \overline{m}_I \; ? \; \overline{m}_G$

Which means that

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

Would not necessarily mean that CPT is broken

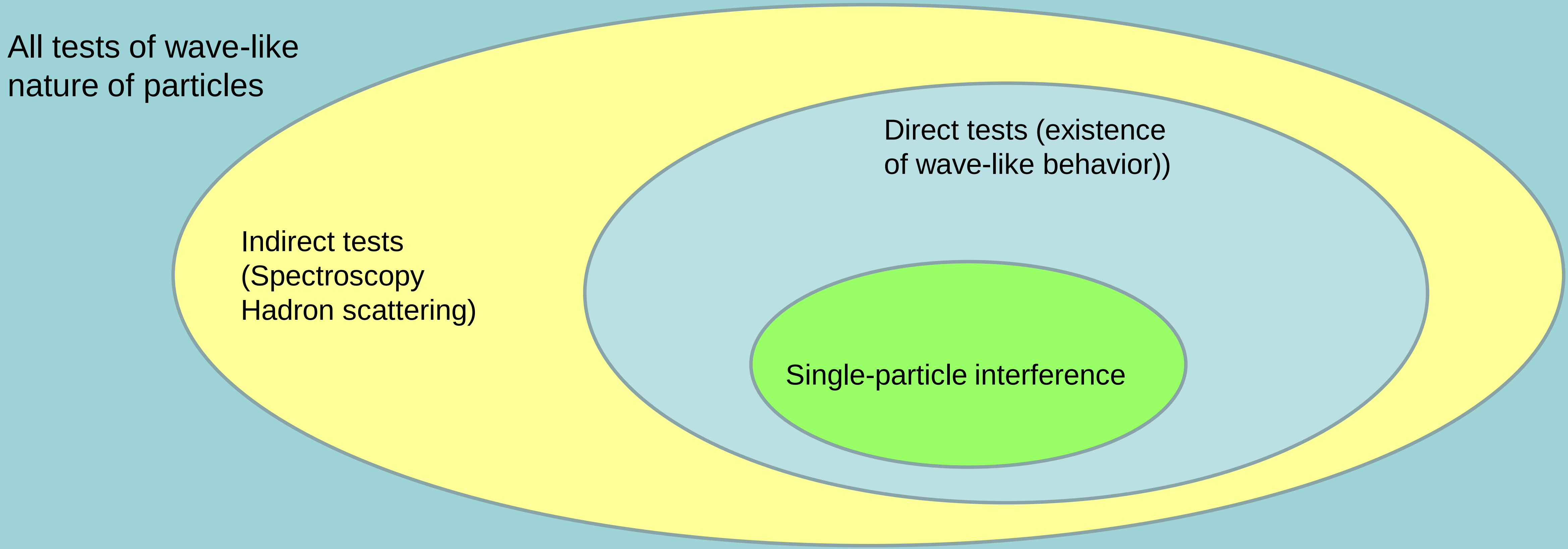
$$m_G \neq \overline{m}_G$$

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

Beginning of the (interferometry) story

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

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



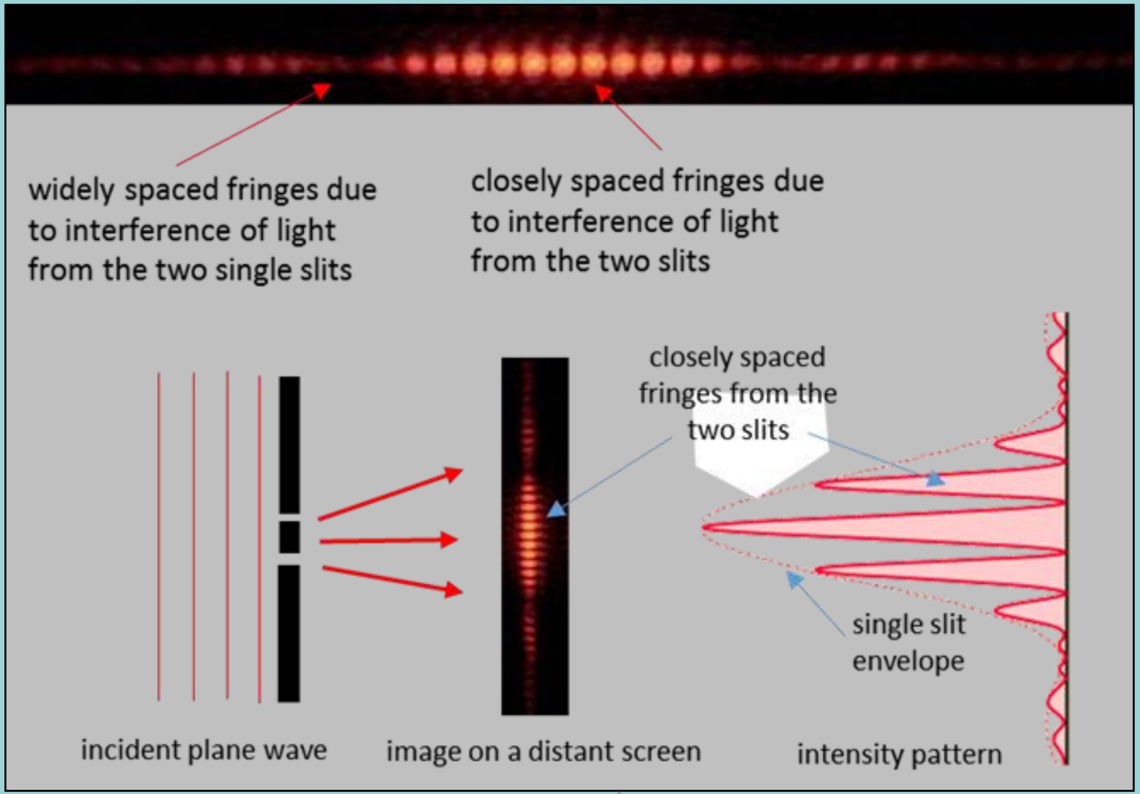
Direct tests of wave-like nature of particles :

- 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*.

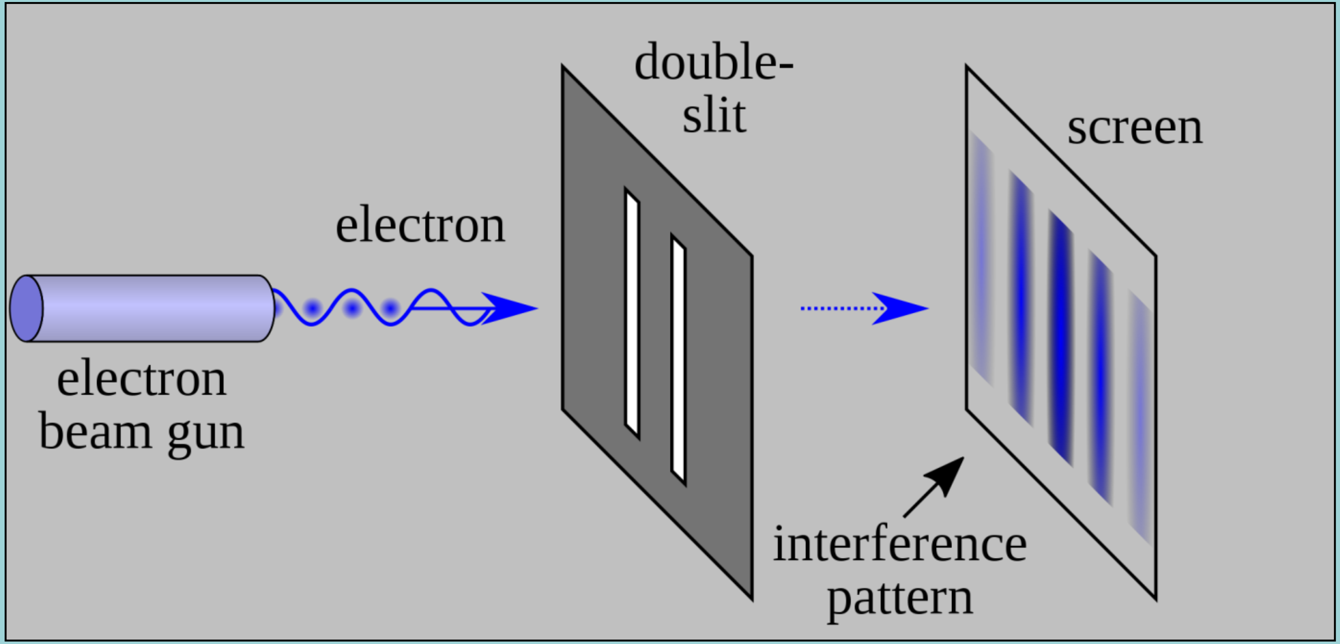
Single-particle interference

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



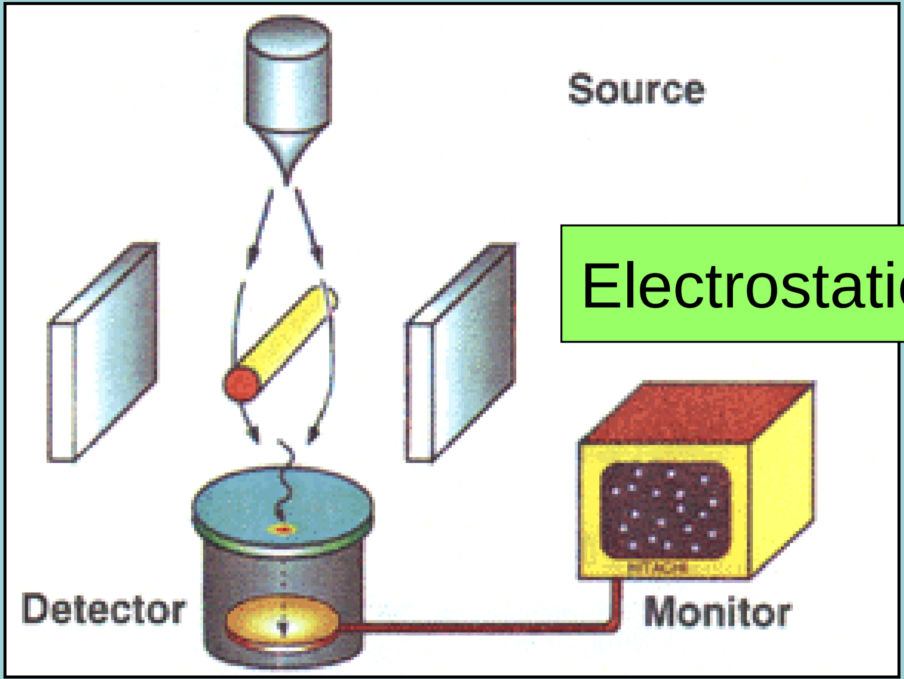
One single particle at a time ?

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



Electrostatic Biprism

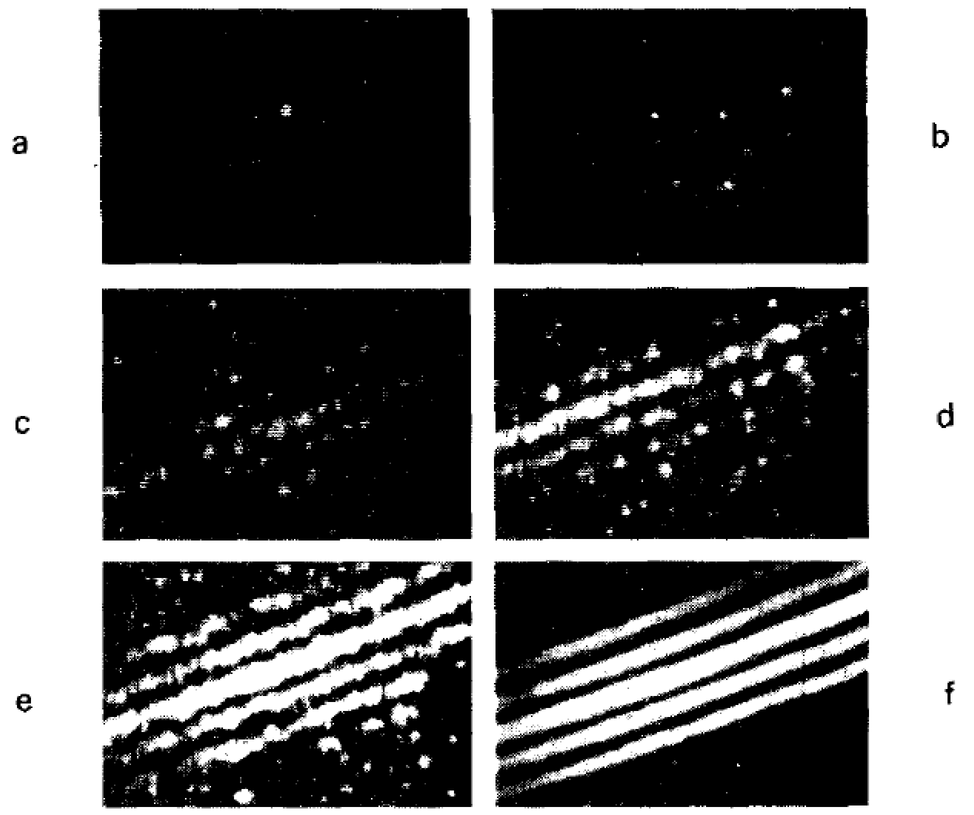
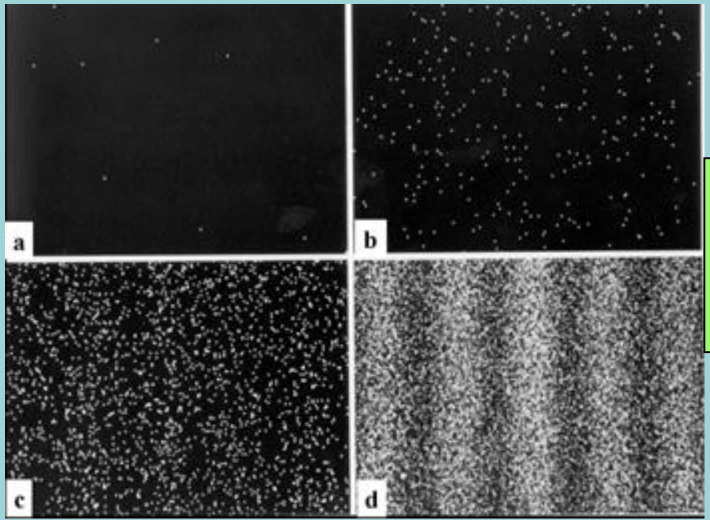


Fig. 1. (a–f) Electron interference fringe patterns filmed from a TV monitor at increasing current densities.

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



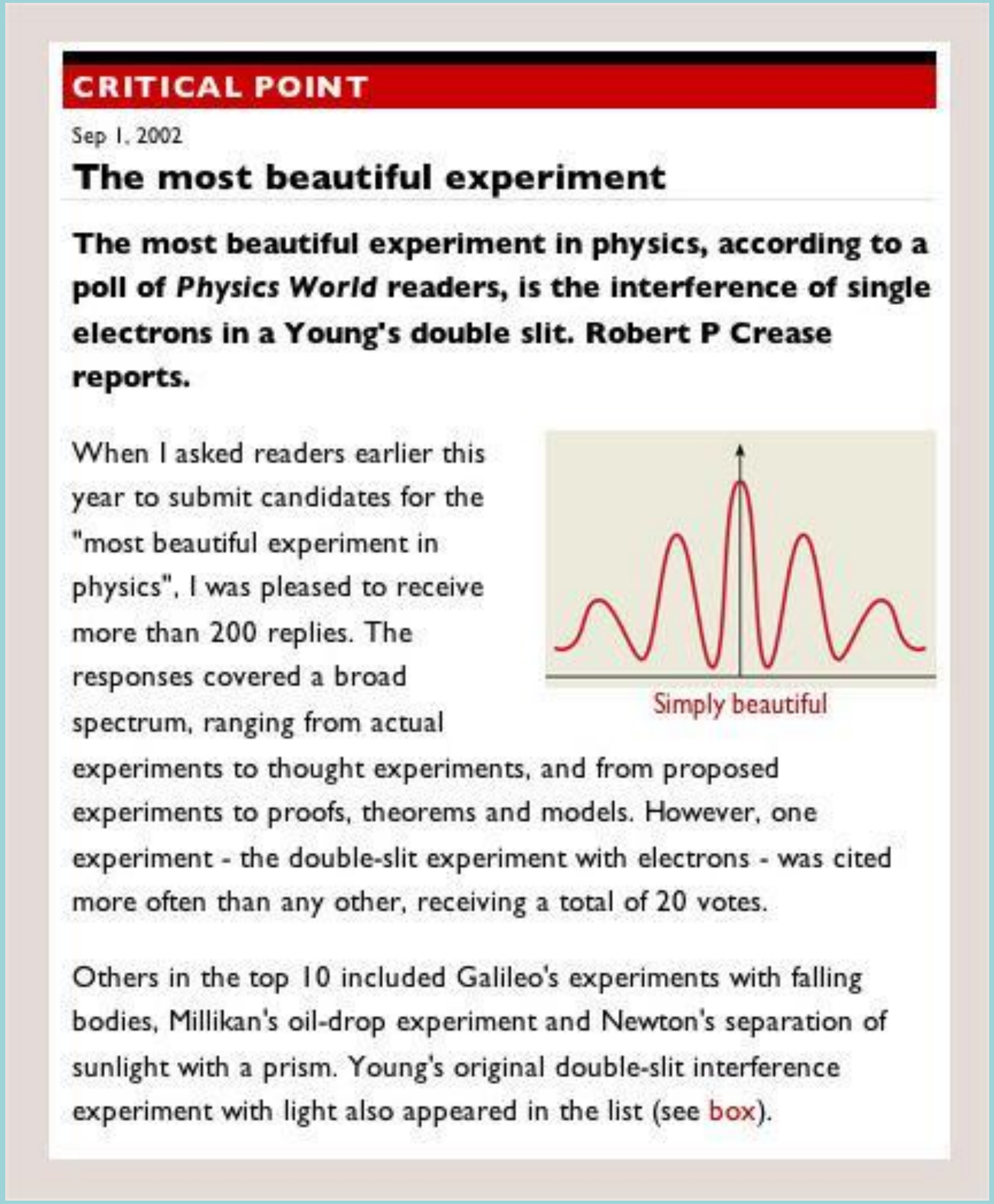
Different integration time: build-up! (the Tonomura et al. version)

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).

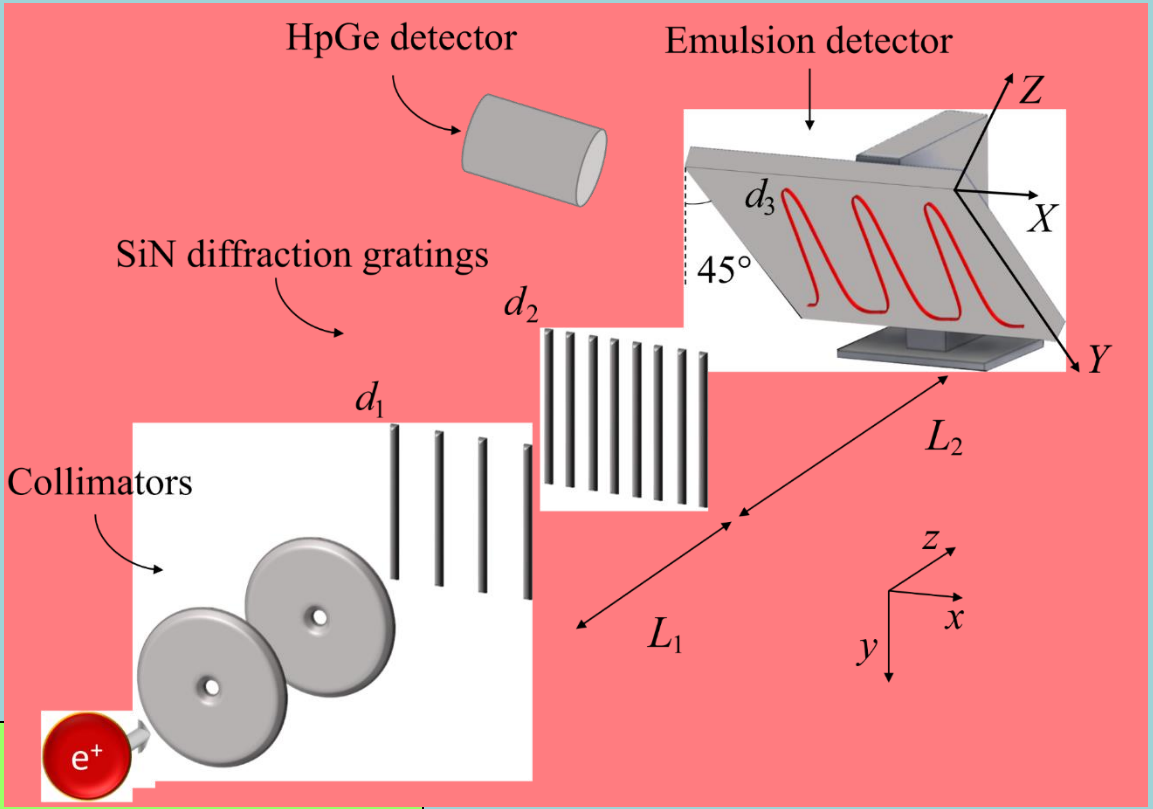
This experiment (QUPLAS-0)

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

Magnifying configuration for interferometry



QUPLAS-0:

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

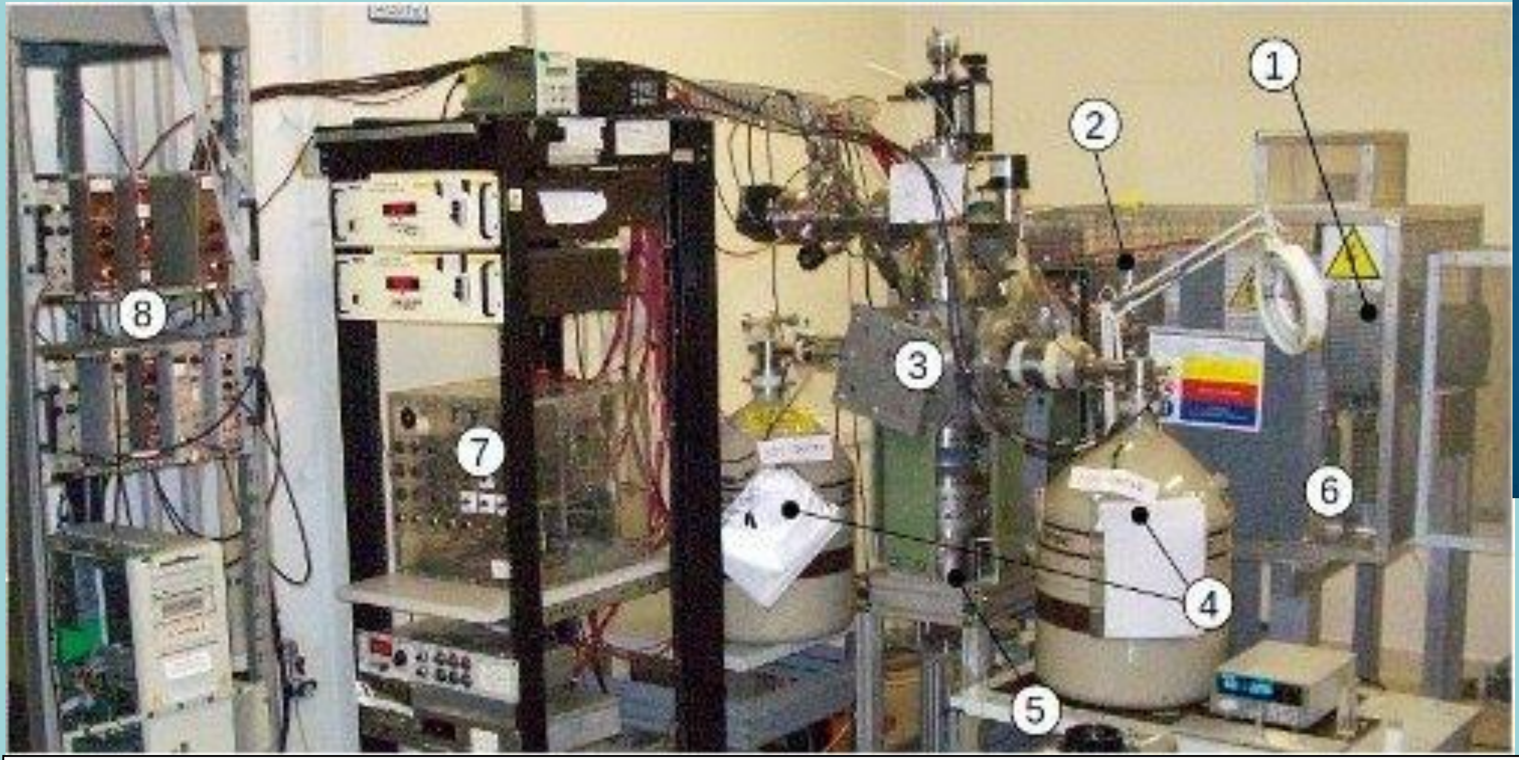
- The L-NESS positron beam in Como
- The Interferometer
- The nuclear emulsion detector

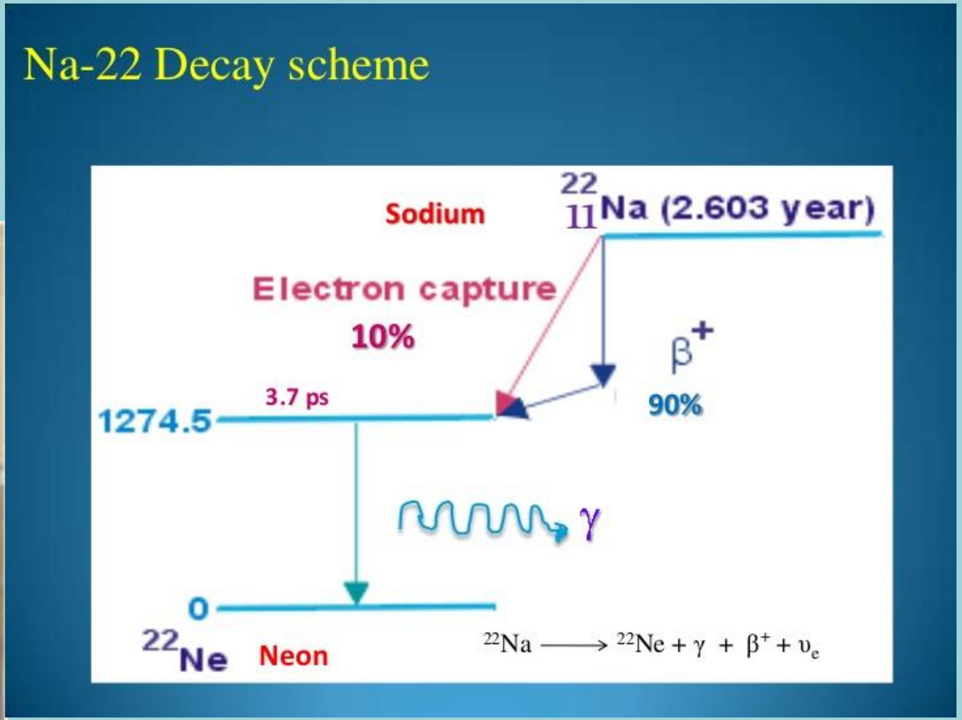
The Como continuous e+ beam

$$^{22}Na \rightarrow {}^{22}Ne + e^{+} + \nu_e + \gamma$$

The VEPAS Laboratory at the L-Ness Politecnico di Milano at Como (R. Ferragut).

WEBSITE:

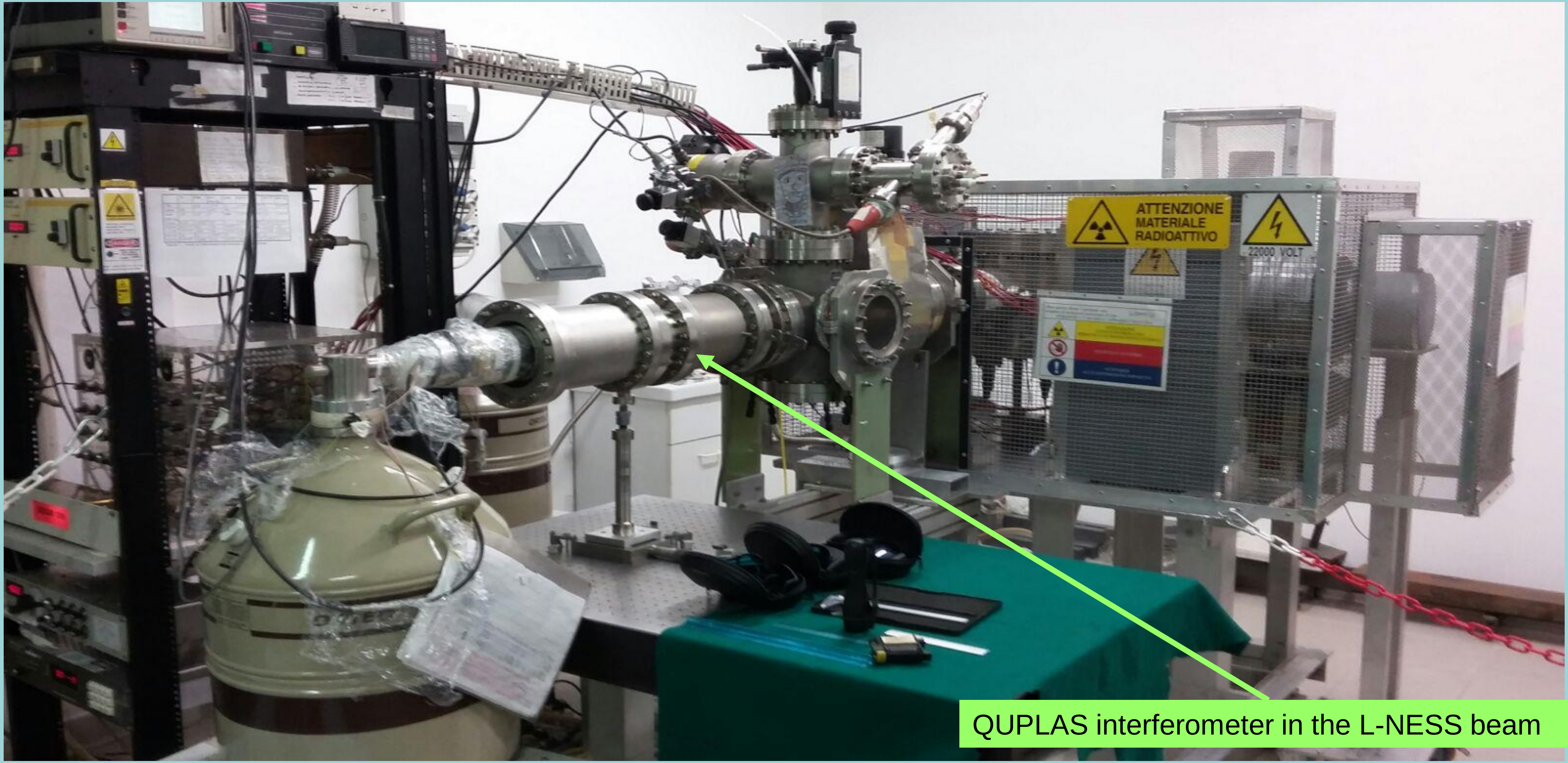




Intensity of the source: 50 mCi
Tungsten moderator → reduces E down to a few eV
Electrostatic transport → positron beam

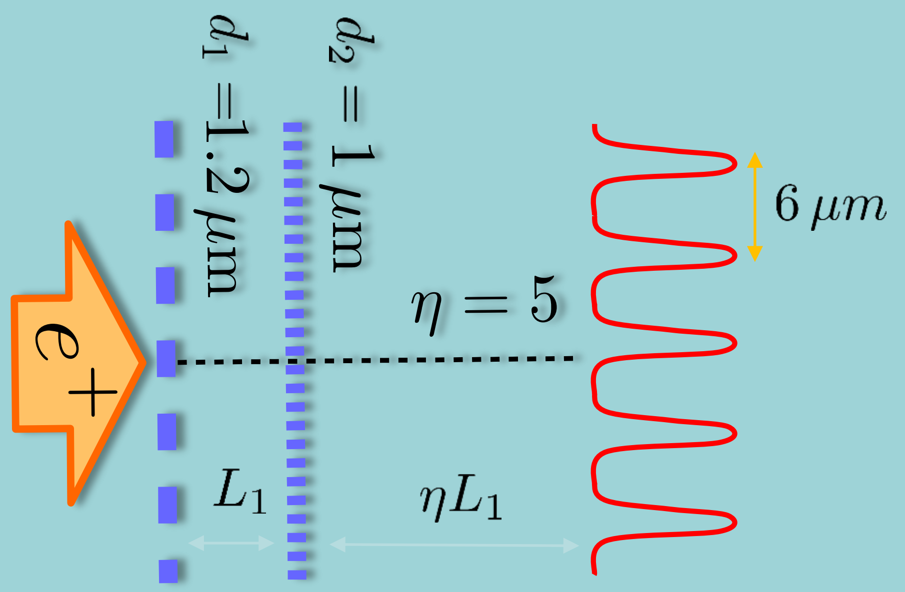
Slow positron beam. 1. Radioactive source; 2. Electrostatic optics; 3. Sample chamber; 4. HpGe detectors; 5. Cryostat; 6. High voltage protection cage; 7. Power suppliers; 8. Detector electronics.

The VEPAS Laboratory at the L-NESS Politecnico di Milano at Como



QUPLAS interferometer in the L-NESS beam

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 !

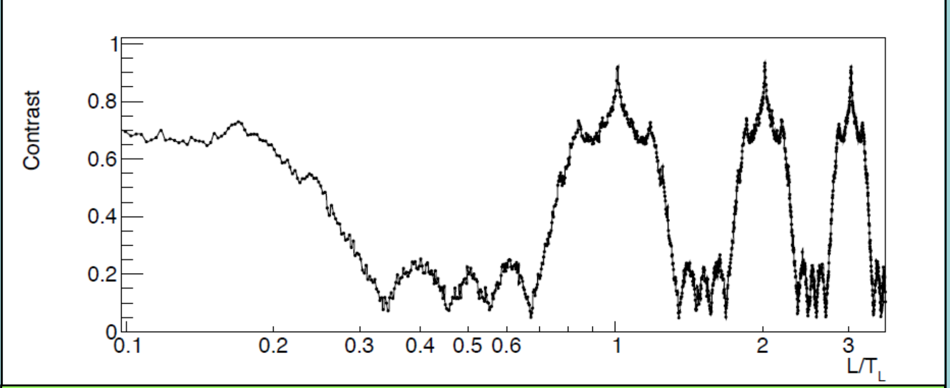
L_1 = 11.8 cm, L_2 = 59 cm

The de Broglie wavelength

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

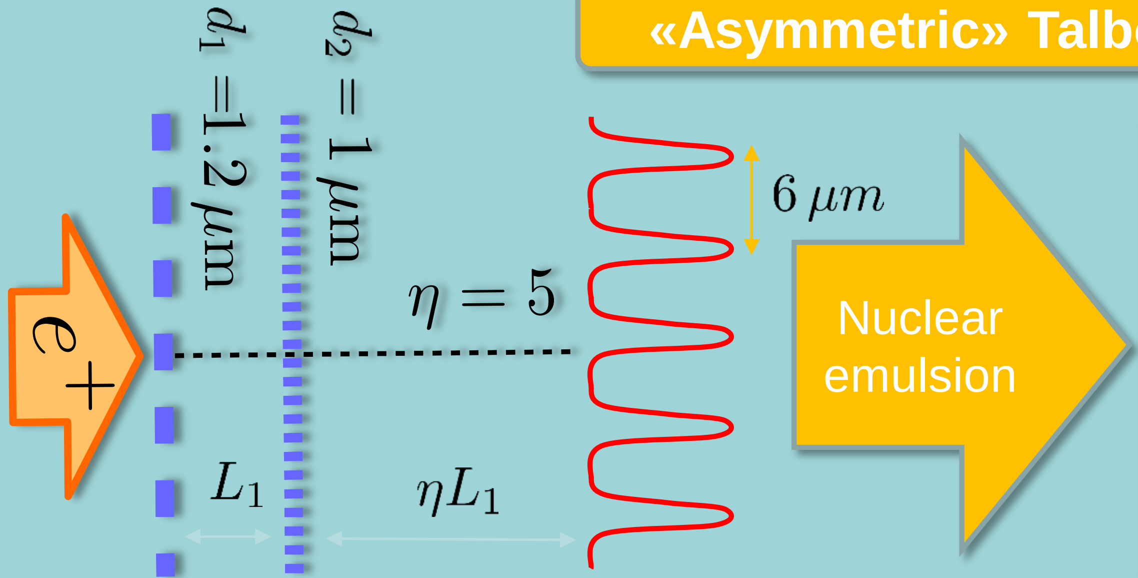
The Talbot length

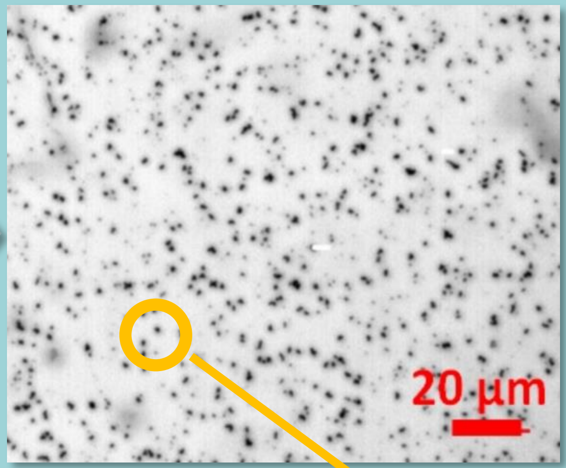
$$L_T = \frac{d^2}{\lambda} = 9{,}7\ cm$$



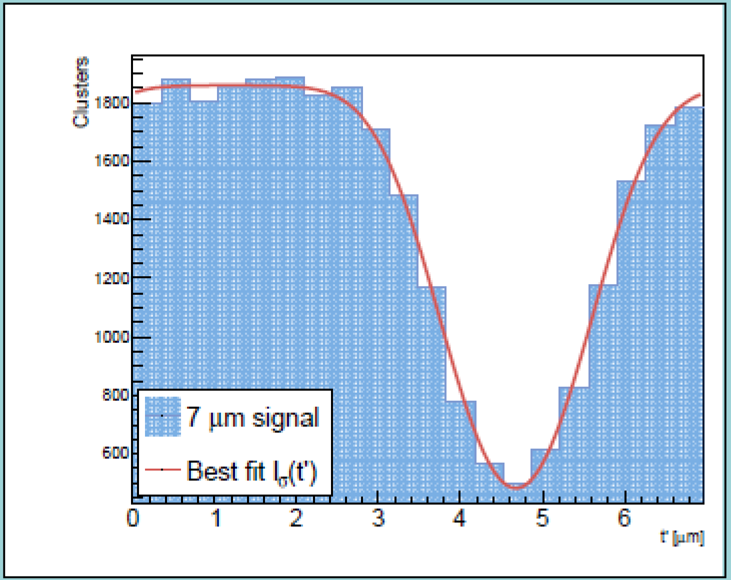
The Talbot «revival» principle

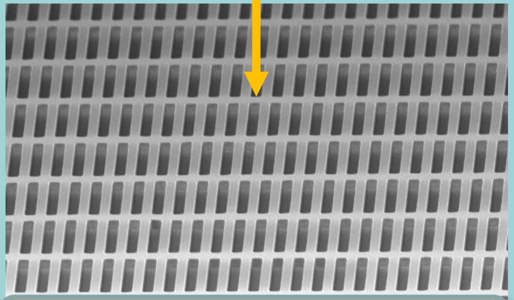
«Asymmetric» Talbot- Lau interferometer and the emulsion detector





Individual positrons



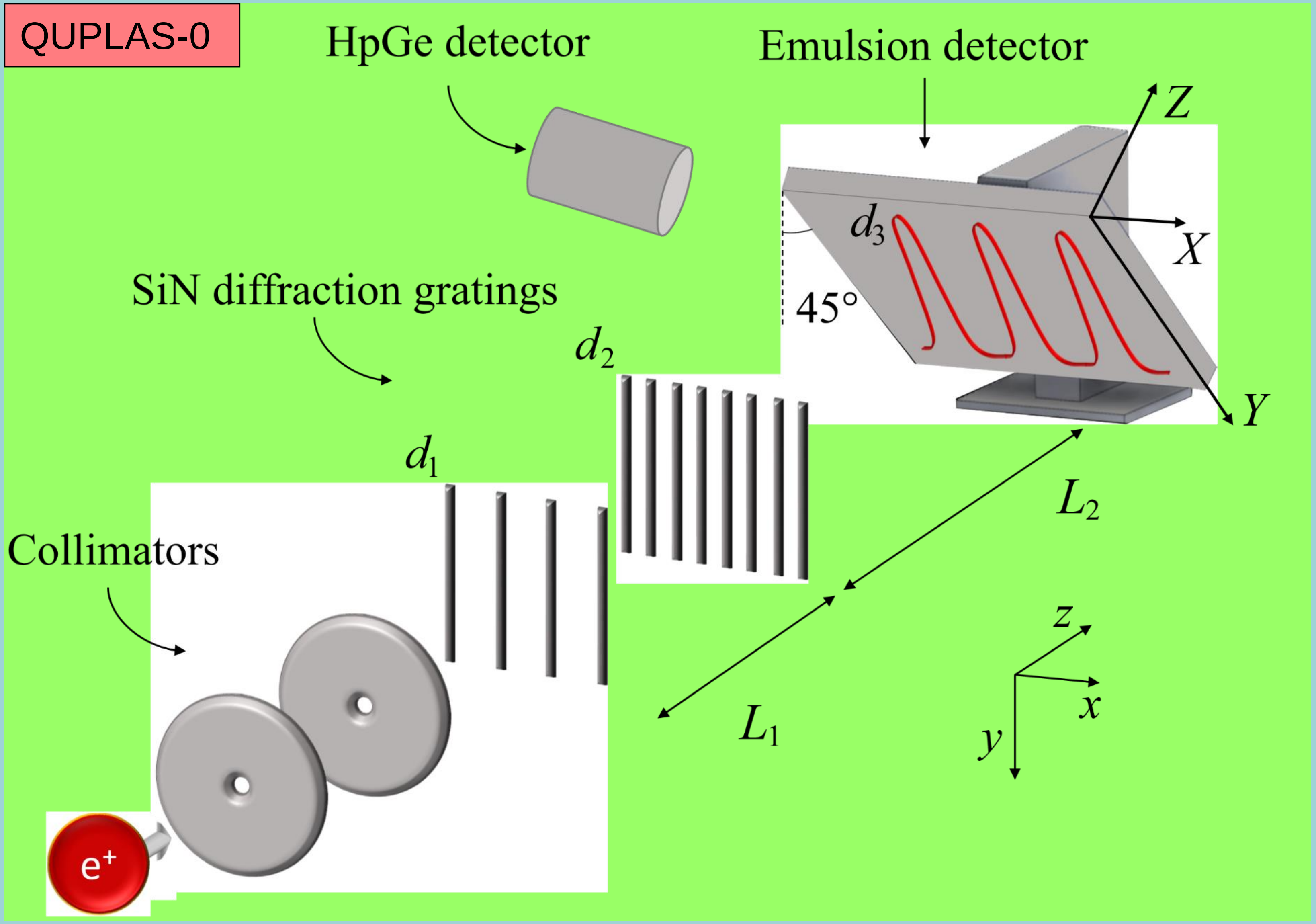


SiNx diffraction gratings

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
Journal of Instrumentation JINST 11 (2016) P06017

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

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

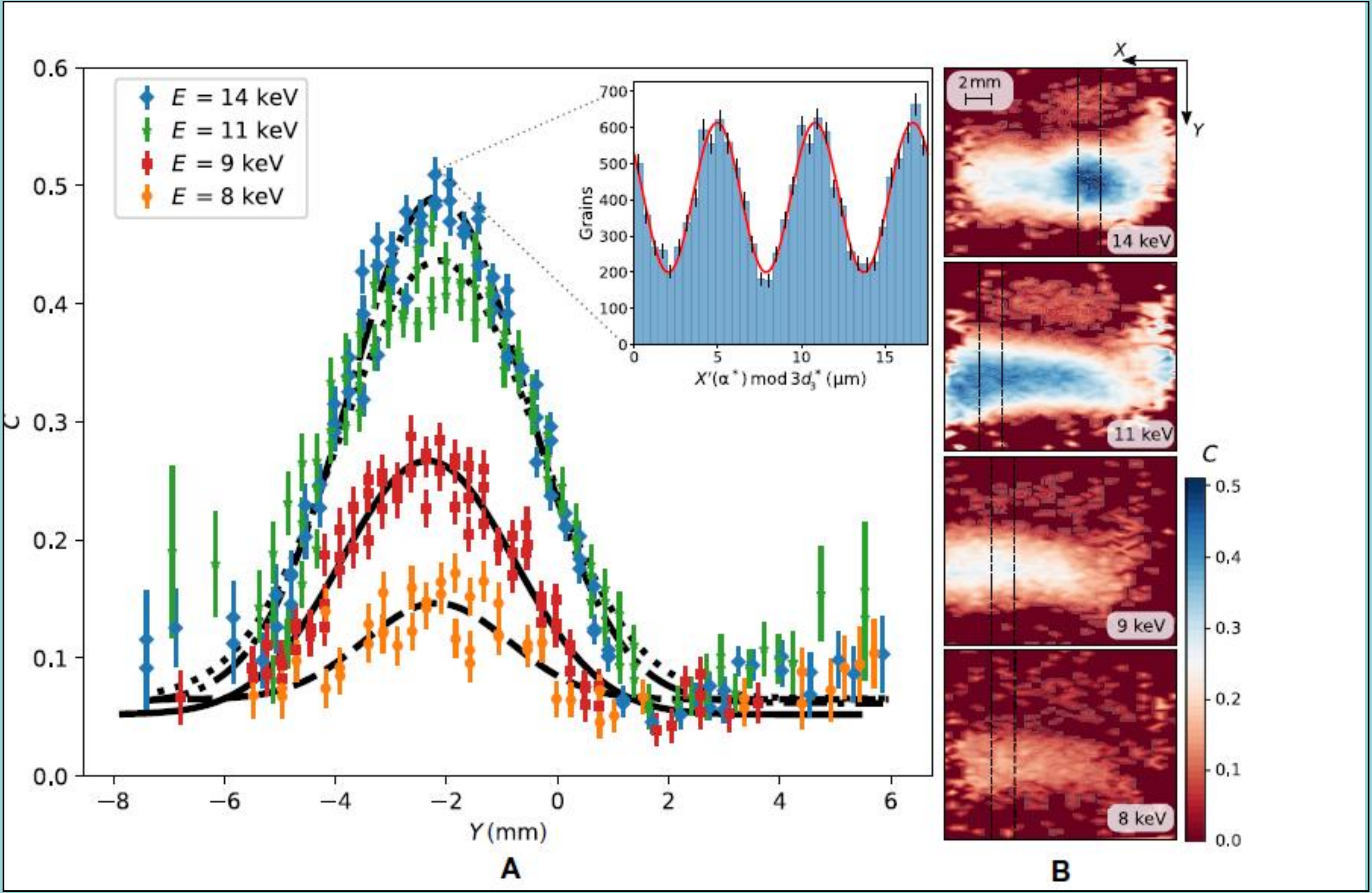

QUPLAS-0
HpGe detector
Emulsion detector
SiN diffraction gratings
Collimators
d_1
d_2
d_3
45°
L_1
L_2
X
Y
Z
x
y
z
e^+


ATTENZIONE
MATERIALE
RADIOATTIVO

The interferometric pattern at different positron energies

Data taking April-August 2018:

- Emulsion exposure
- Emulsion development
- Data analysis



Visibility at different energies

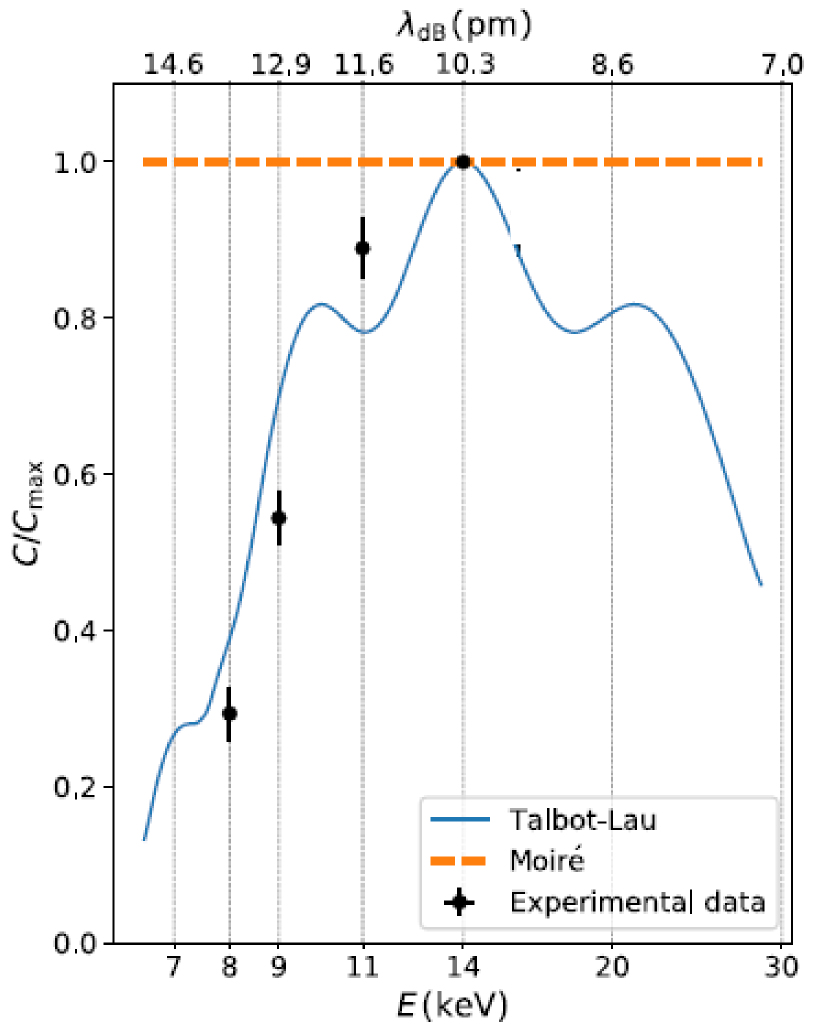


Fig. 5. Contrast as a function of energy. Measured contrast normalized to the resonance value, defined as $C/C_{max}(E)$. The 68% confidence interval uncertainties are obtained by standard error propagation. The solid line is the quantum-mechanical prediction, while the classical prediction is indicated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

Contrast of fringes as a function of energy (wavelength)

A classical (projective, moiré) effect would be achromatic

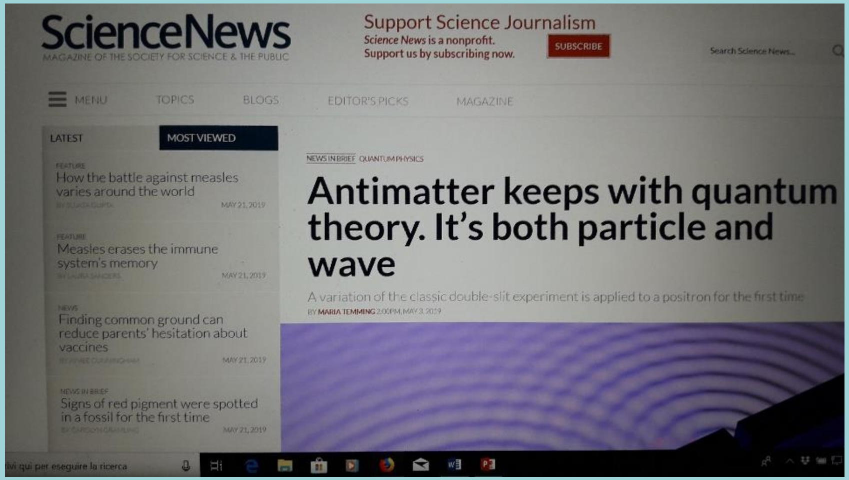
A quantum effect would be energy (wavelength) dependent (Talbot-Lau)

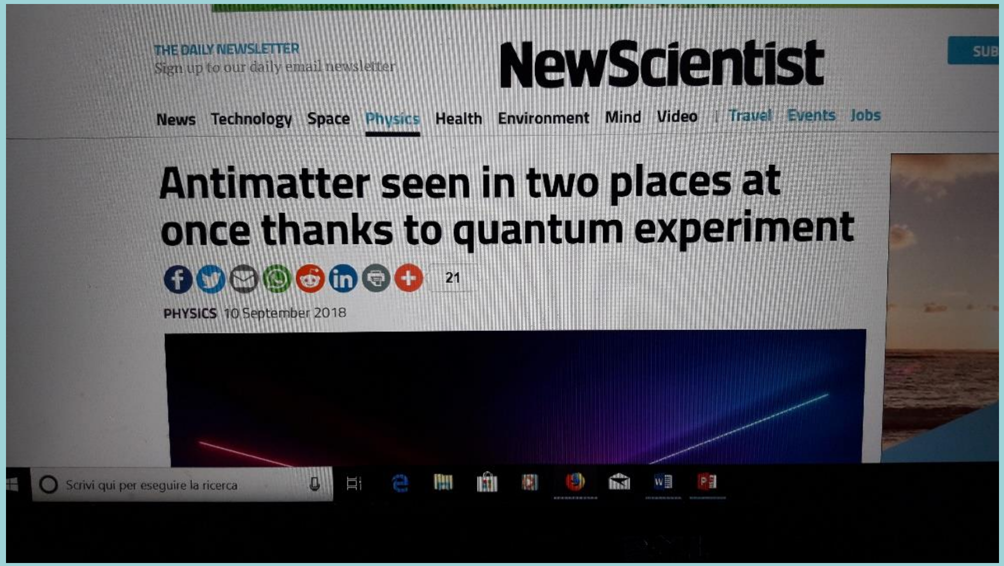
- Disagrees with (moiré) Classical Physics
- Agrees with Quantum Mechanics
- Single-particle Talbot-Lau Quantum interferometry!

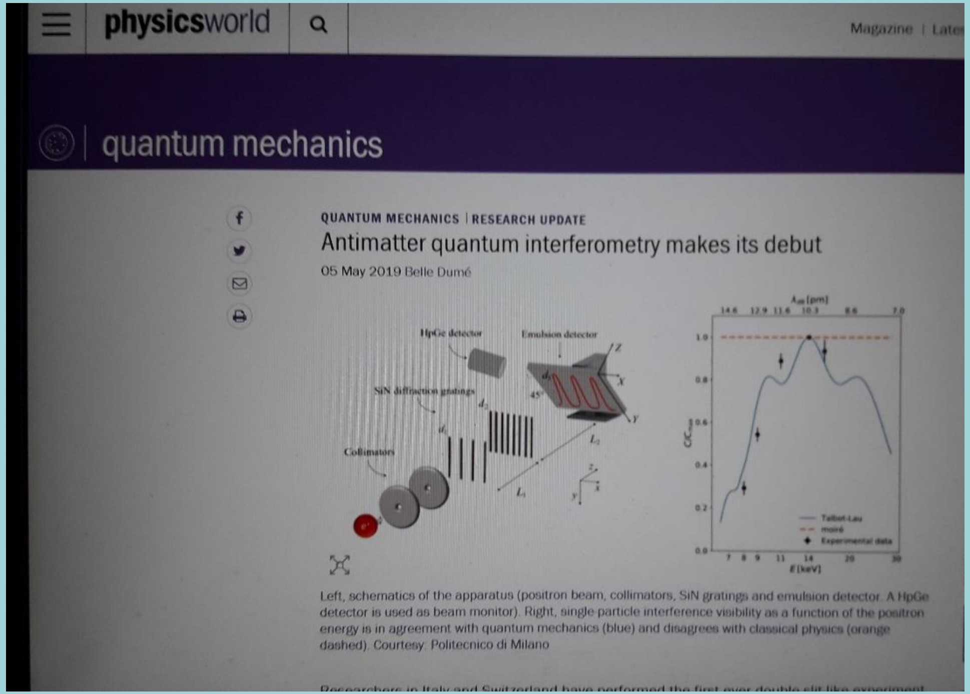
Preliminary on August 2018: https://arxiv.org/abs/1808.08901

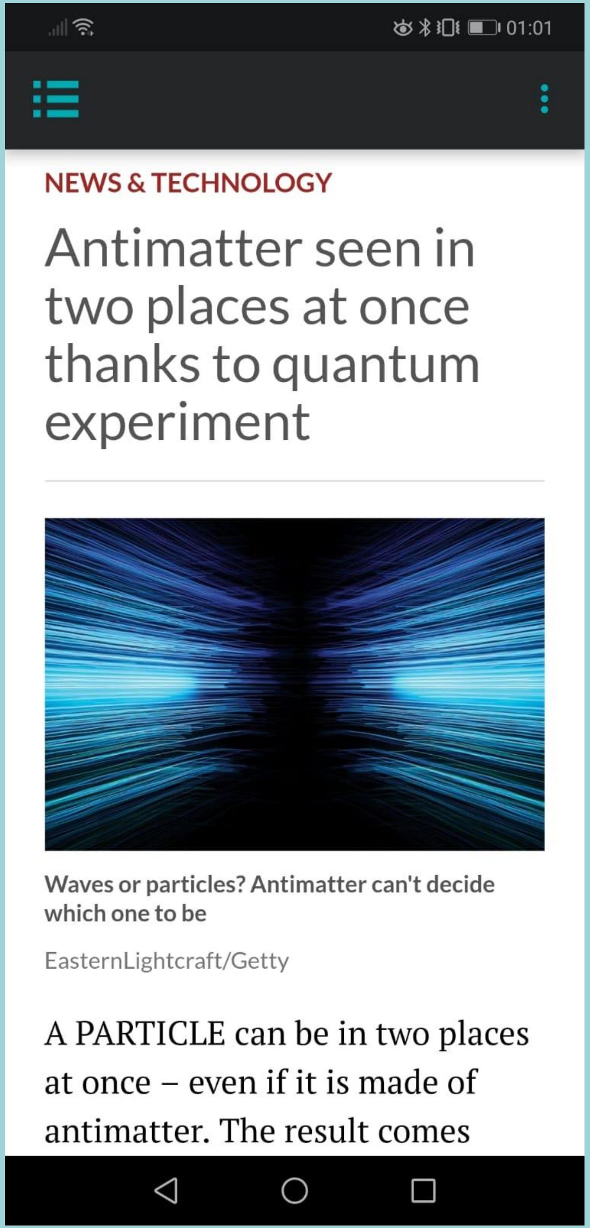
Published on Science Advances: 3.rd of May 2019

Media Slide





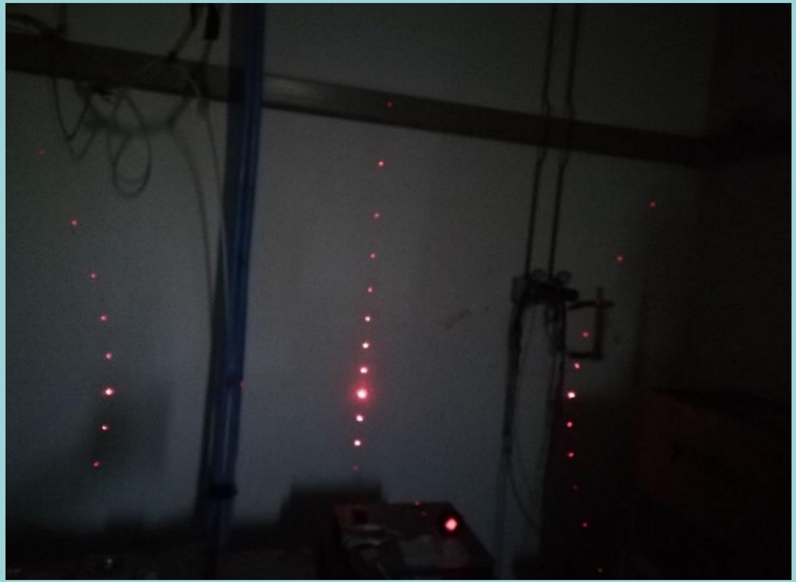


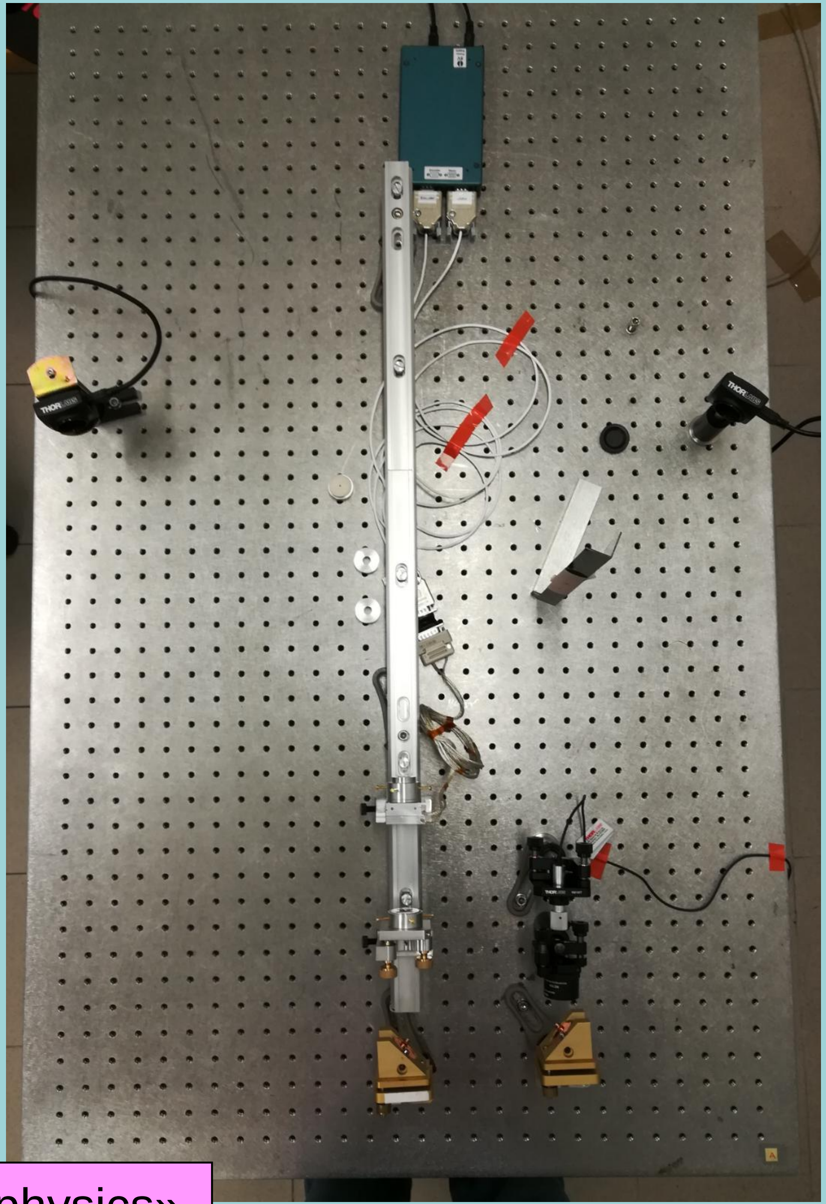


Funniest: demonstration that

QUANTUM MECHANICS DOMINATES THE UNIVERSE! (WoW)

Conclusion





By making use of

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

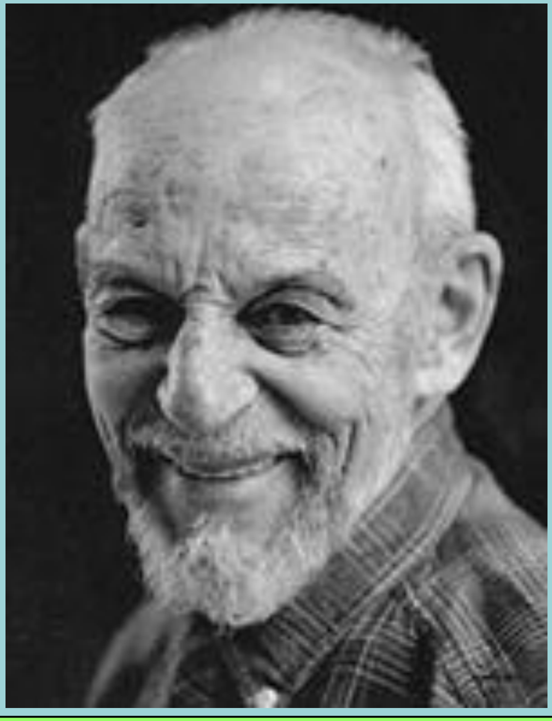
We have demonstrated:

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

Exaggeration: «The antimatter version of the most beautiful experiment in physics»

A personal dedication to the memory of

If I have seen further it is by standing on ye sholders of Giants (I. Newton)



Martin Deutsch (1917-2002)

Alfredo Dupasquier (1939-2015)

Thank you for your attention