Review on
Proposed antimatter gravity measurement with an antihydrogen beam

A. Kellerbauer, Nuclear Instruments and Methods in Physics Research B 266(2008)

Aram lee

1. Motivation
2. AEGIS experiments
    a. Aims
    b. Methods
3. Conclusion

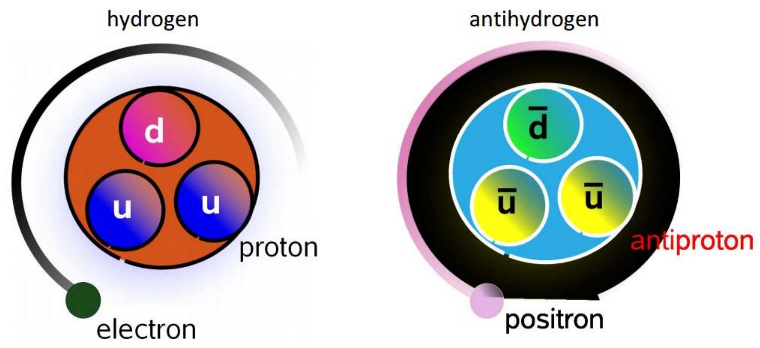
1. Motivation

1. Motivation

about antimatter

- Modern physics
  - General relativity – Weak Equivalence Principle
  - Quantum mechanics – CPT symmetry (matter-antimatter symmetry)

- Antimatter : a material composed of anti-particles



1928, prediction of antimatter (Dirac)
1932, discovery of positron in cosmic rays (Anderson)
1955, antiproton discovery (Segre')
1956, antineutron discovery (Cork)
1995, creation of high-energy antihydrogen (CERN)
2002, creation of 10K antihydrogen (ATHENA, ATRAP)
2011, antihydrogen confinement (ALPHA)

Marco G., AEGIS at CERN : measuring Antihydrogen fall, INFN, Posmol(2011)

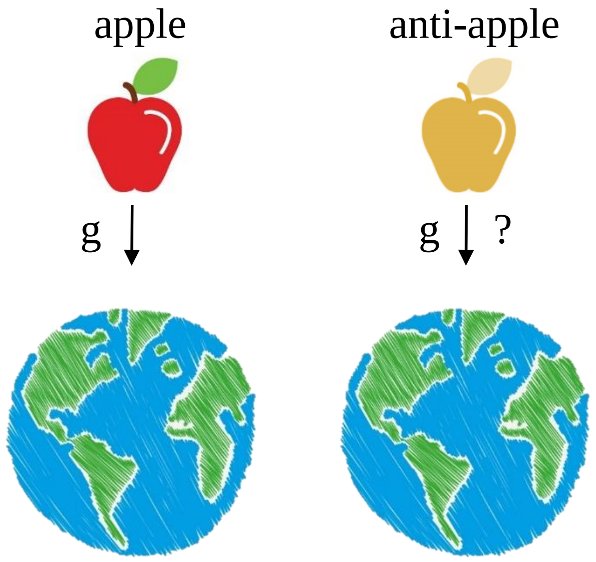
1. Motivation

Weak equivalence principle(WEP), in the general relativity

> " In a uniform gravitational field,
> all objects fall with the same acceleration,
> regardless of their composition."

WEP is tested with matter to high accuracy : $\sim 10^{-16}$ (2016)

But the behavior of anti-matter in a gravitational field
has never been tested experimentally.



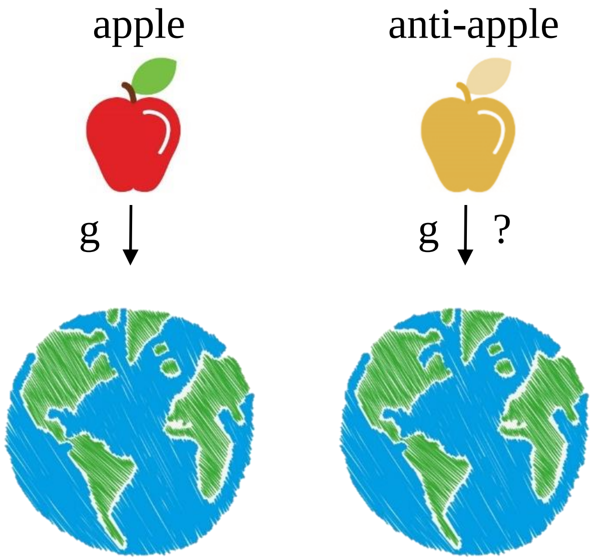
$$m_g \overset{?}{=} \overline{m_g}$$

1. Motivation

Weak equivalence principle(WEP), in the general relativity

Gravity is the only force not described by a quantum field theory.

According to a hypothetical quantum theory of gravity,
gravity could have with a tensor, vector, and scalar component.
A vector component might lead a repulsive force.
That constitute a violation of the WEP.



Anti-gravity can be a possible solution for cosmological problem.
But still a number of arguments against.

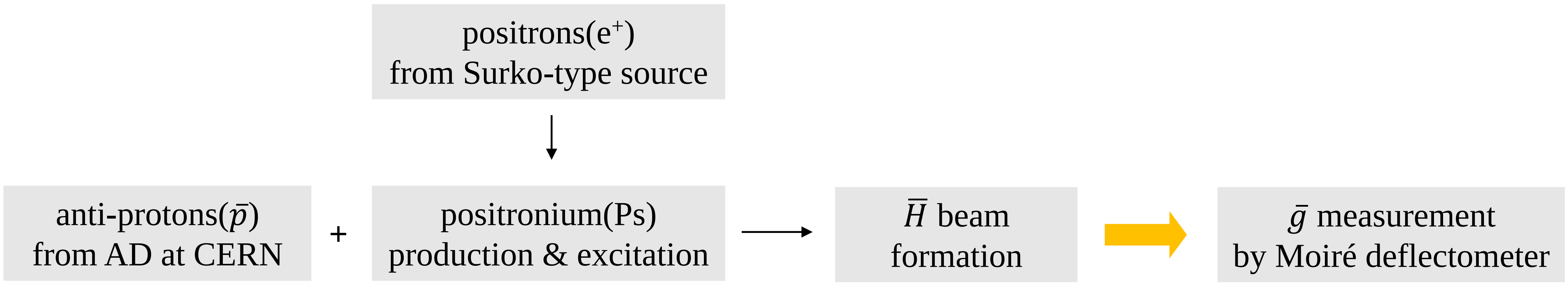
In order to repair contradictions and to incorporate gravity into the Standard model,
observing the behavior of antimatter in gravitational field is necessary.

1. Motivation
2. AEGIS experiments
   a. Aims
   b. Methods

2. AEGIS experiments – Aims

the AEGIS(Antimatter **E**xperiment : **G**ravity, **I**nterferometry, **S**pectroscopy**) experiments**

: the direct measurement of the Earth's local gravitational acceleration $\bar{g}$ on $\bar{H}$ with 1% precision



2. AEGIS experiments – Aims

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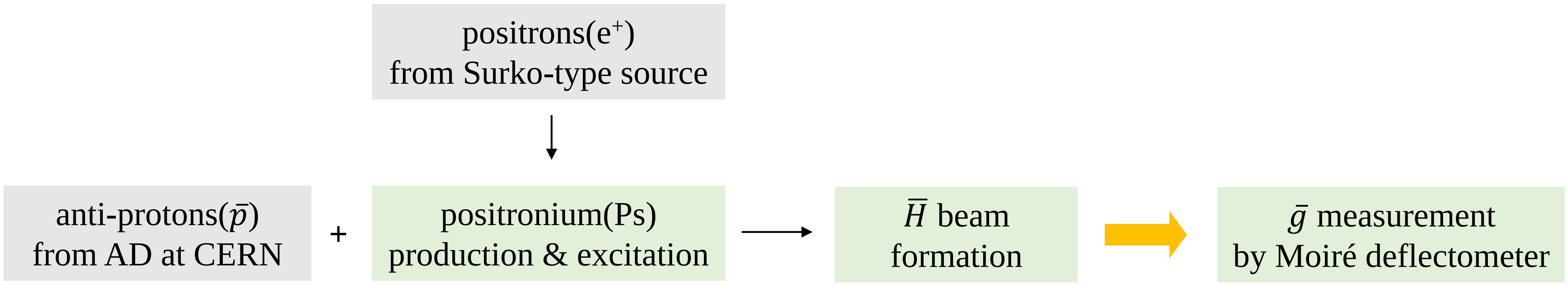
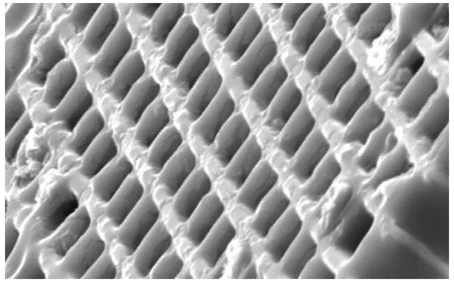


2. AEGIS experiments – Methods

① Ps production and excitation

A sizable fraction of Ps diffuses out of the nanoporous material film.

e^+
(100eV ~ few keV)



nanoporous materials

slowed to few eV
captured by e^-
and form Ps

diffuse

ortho-Ps

ortho-Ps : 140ns
para-Ps : 125ps

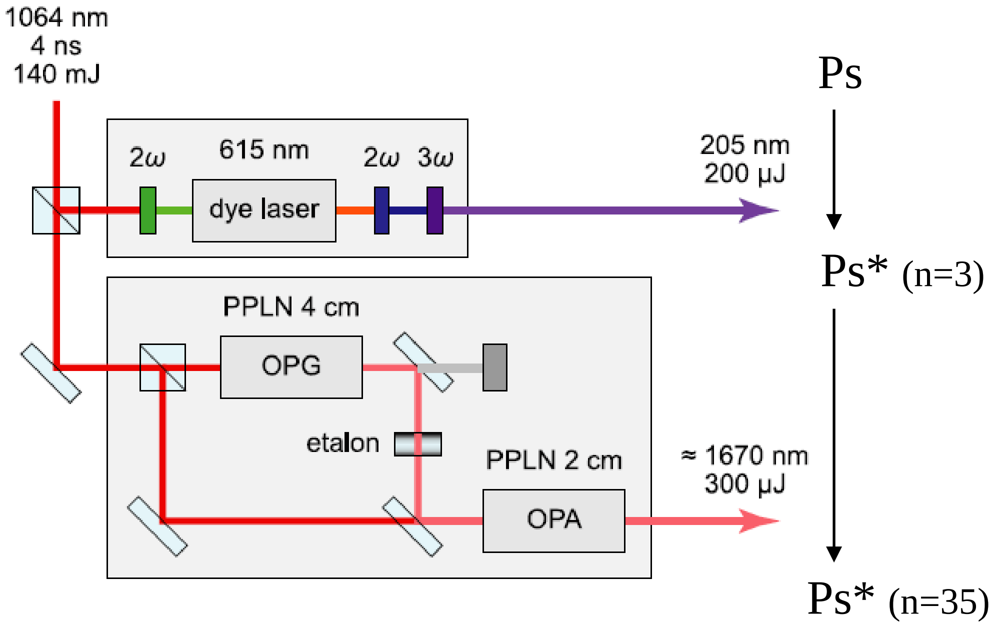
The yield depend on the target material, temperature and the implantation depth.
(~30% in silicon-based polymer materials cooled to 50K)

2. AEGIS experiments – Methods

① Ps production and excitation

The cross-section of the $\overline{H}$ formation reaction : $\sigma \approx a_0 n^4$ → excitation of Ps is needed

The Ps excited to a Rydberg state
with principal quantum number n=30…40
by two pulsed-laser systems.



2. AEGIS experiments – Methods

② $\bar{H}$ beam formation

The charge exchange reaction

$$Ps^{*} + \bar{p} \rightarrow \bar{H}^{*} + e^{-}$$

(* denotes a highly excited Rydberg state.)

- large cross-section ($\approx 10^{7}\text{Å}^{2}\ for\ n = 35$)
- narrow and well-defined band of $\bar{H}^{*}$
- determination of velocity distribution of $\bar{H}^{*}$ by $\bar{p}$ temperature ($\sim 25 - 80 m/s$)

2. AEGIS experiments – Methods

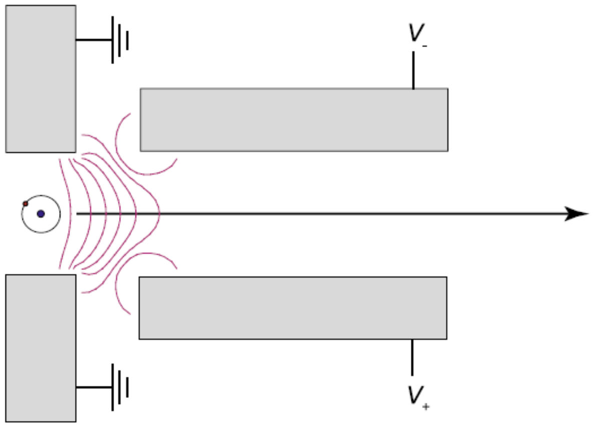
② $\bar{H}$ beam formation

Stark acceleration

Atoms are accelerated or decelerated (experienced the force) by electric field gradient.
Rydberg atoms which have large dipole moment are amenable.
they are accelerated into a beam by inhomogeneous electric field.

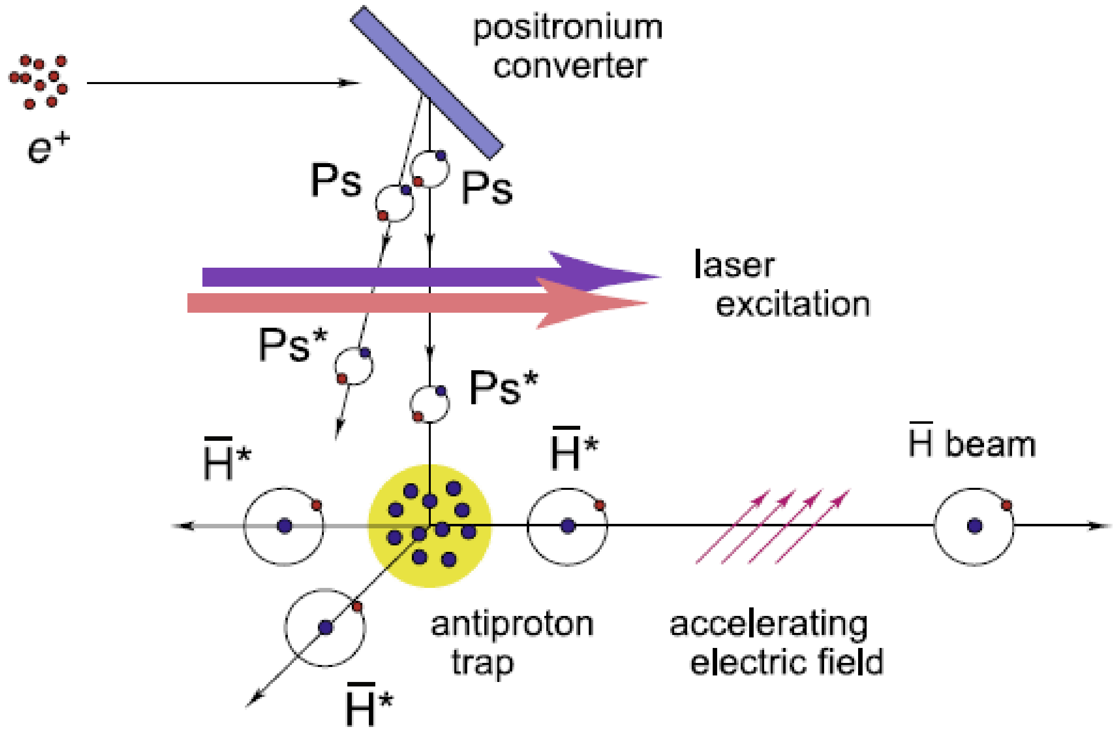
$$\vec{F} = -\frac{2}{3} e a_0 n(n-1) \nabla \vec{E}$$

$25 - 80(m/s)$



$400(m/s)$

2. AEGIS experiments – Methods



< Principle sketch until now >

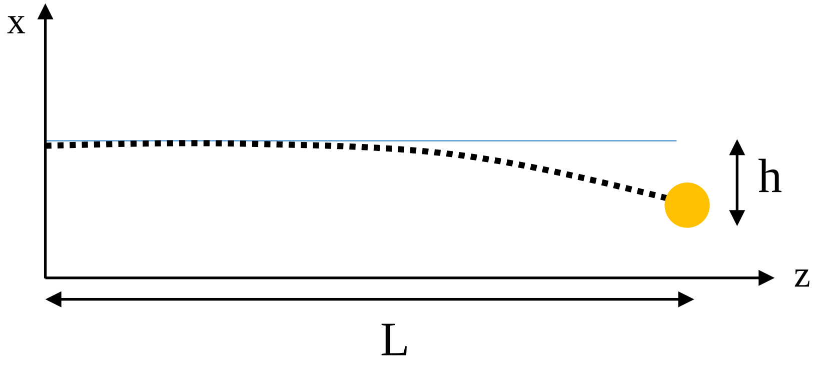
1. e^+ capture
2. $\bar{p}$ production
3. Ps formation
4. Ps excitation
5. $\bar{H}$ production
6. $\bar{H}$ beam formation

Note : $\bar{p}$ trap before acceleration

2. AEGIS experiments – Methods

③ Gravity measurement

Free-fall of $\overline{H}$ cannot be detected in usual way



$$h = \frac{1}{2}gT^2 = \frac{1}{2}g\left(\frac{L}{v_z}\right)^2$$

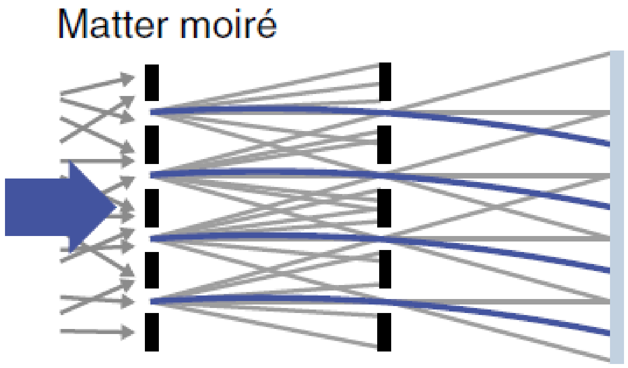
T : *time of flight*

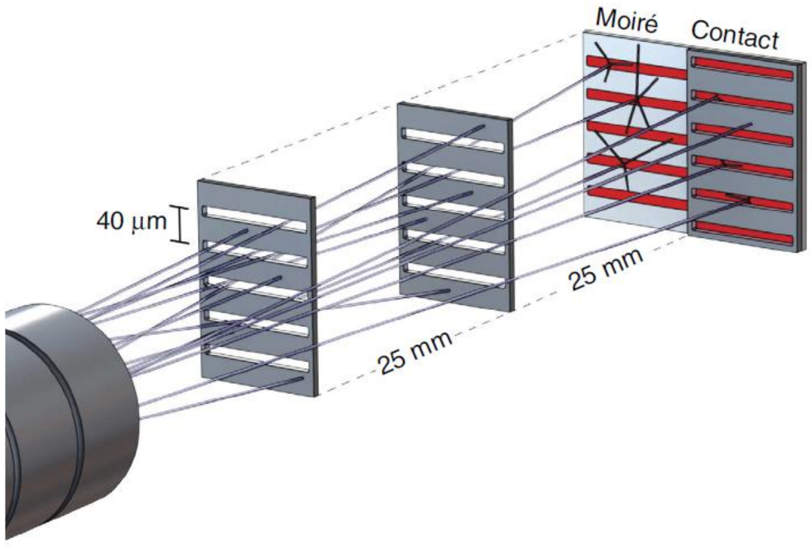
$h \sim 20\mu m,\ where\ L \sim 1m,\ v_x \sim 500m/s$
much larger than beam radial size after 1m flight (~ cm)

2. AEGIS experiments – Methods

③ Gravity measurement

Free-fall detection by Moiré deflectometer





S. Aghion, A moiré deflectometer for antimatter, nature communications(2014)

2. AEGIS experiments – Methods

③ Gravity measurement

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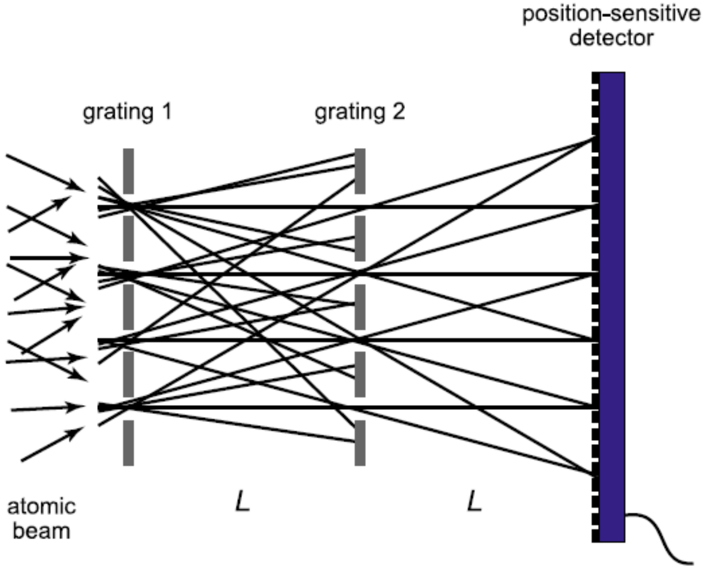
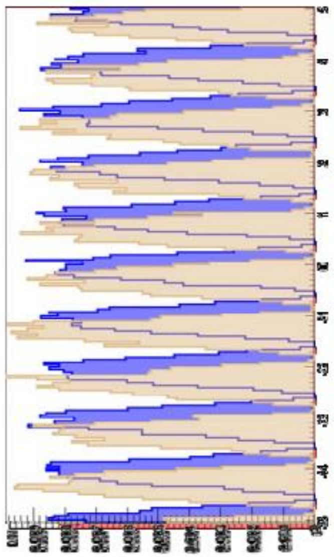




Grating transparency ~ 30%

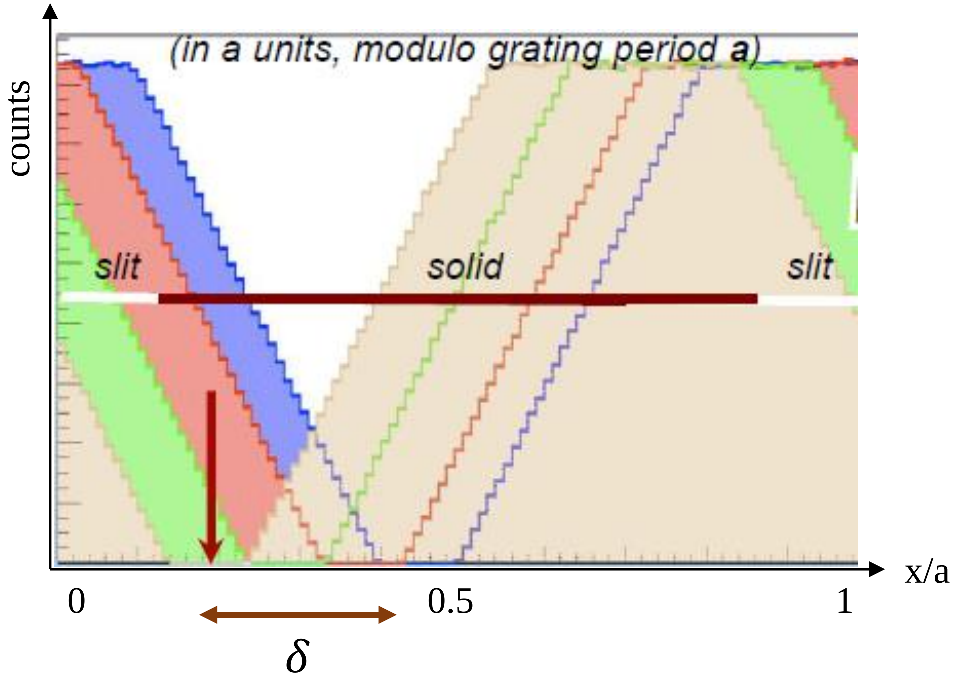
a : the grating period ($\sim 80\mu m$)
d : the gap in gratings
L : the length between gratings($\sim 40cm$)

It is NOT a quantum deflectometer.
No diffraction occurs.

$$\frac{d^2}{L} \gg \lambda_{dB}$$

③ Gravity measurement

Free-fall detection by Moiré deflectometer



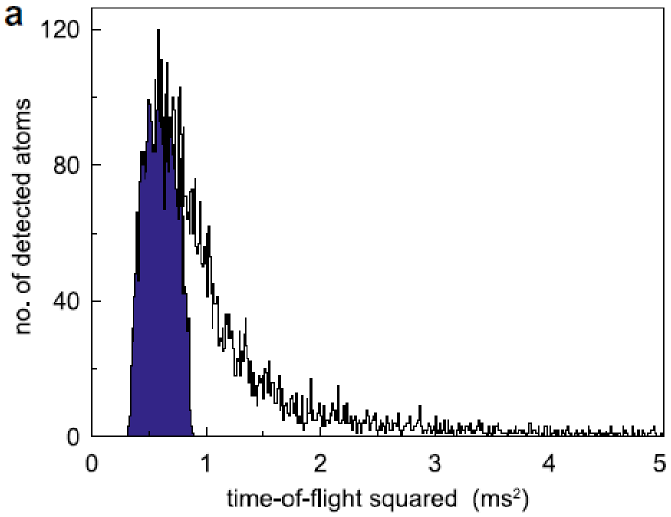
$$\delta = 2 * \left(\frac{1}{2} g T^2\right) / a = \frac{g T^2}{a}$$

2. AEGIS experiments – Methods

③ Gravity measurement

Extraction of g value from observables(T, δ) – illustrated by Monte-carlo simulations

First, record vertical position for each event as a function of T(or v)



And bin these events in symmetric classes of T^2

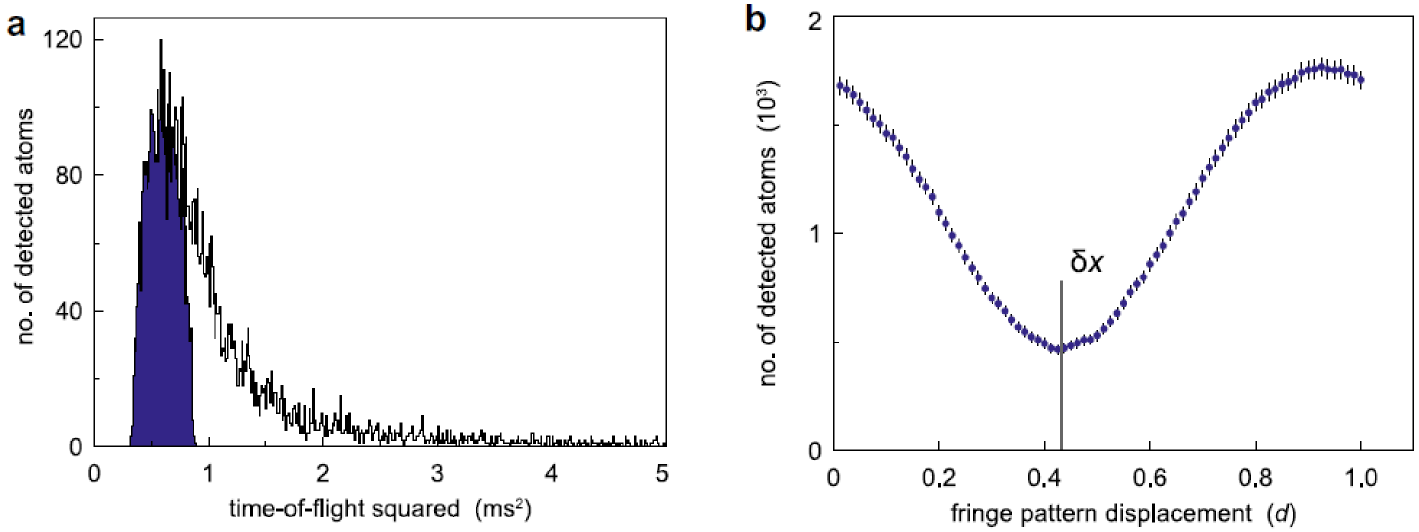
$v_{beam} = 600 - 550 - 500 - \cdots - 200\ m/s$

2. AEGIS experiments – Methods

③ Gravity measurement

Extraction of g value from observables(T, δ) – illustrated by Monte-carlo simulations

Next, extract δx of the fringe pattern for each of the count classes



2. AEGIS experiments – Methods

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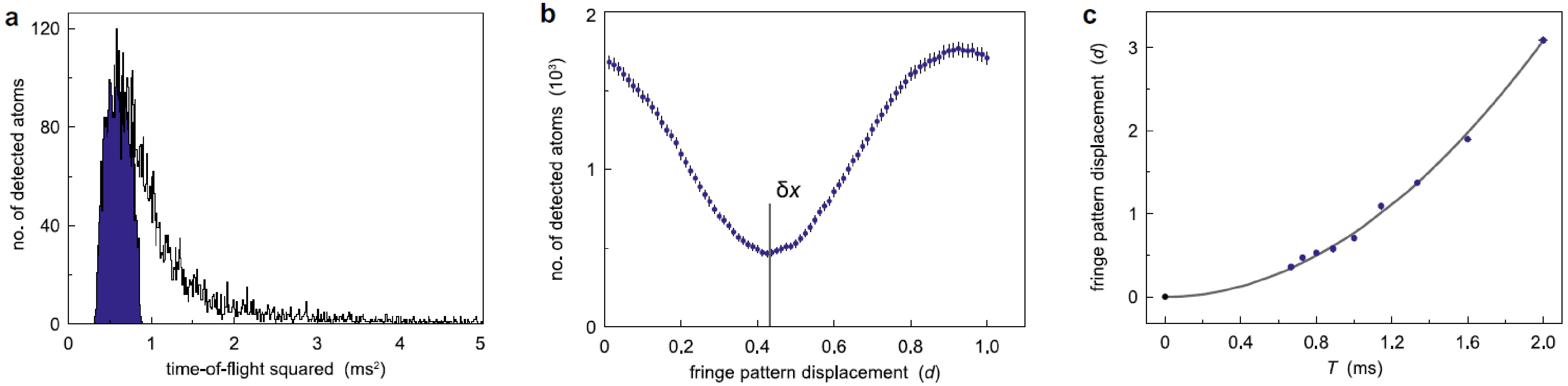
Finally, plot δx against the mean time of flight $\sqrt{< T^2 >}$



2. AEGIS experiments – Methods

③ Gravity measurement

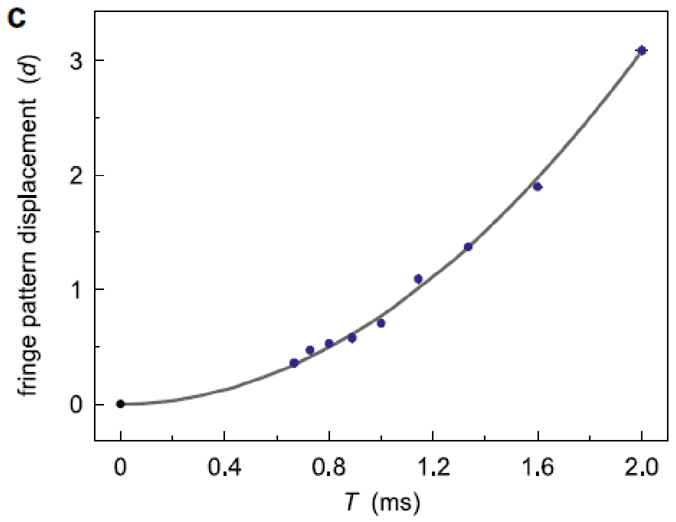
Extraction of g value from observables(T, δ) – illustrated by Monte-carlo simulations

Finally, plot δx against the mean time of flight $\sqrt{< T^2 >}$

the coefficient of a quadratic fit to that yields $\bar{g}$

$$\delta x = \delta * a = gT^2$$

(1% relative precision, about 10^5 $\bar{H}$ atoms at 100mK)



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3. Conclusion

- **AEGIS** = ATHENA ATRAP (at the AD) + Charge exchange production of $\overline{H}$, Stark acceleration, The Moiré deflectometer

- Obtaining $\overline{H}$ atoms at 100mK is an essential part,
  since the precision of gravity measurement is mainly limited by the $\overline{H}$ temperature.

- If even colder $\overline{H}$ ensembles can be attained, gravity measurements with even higher precision as well as competitive CPT tests through spectroscopy.