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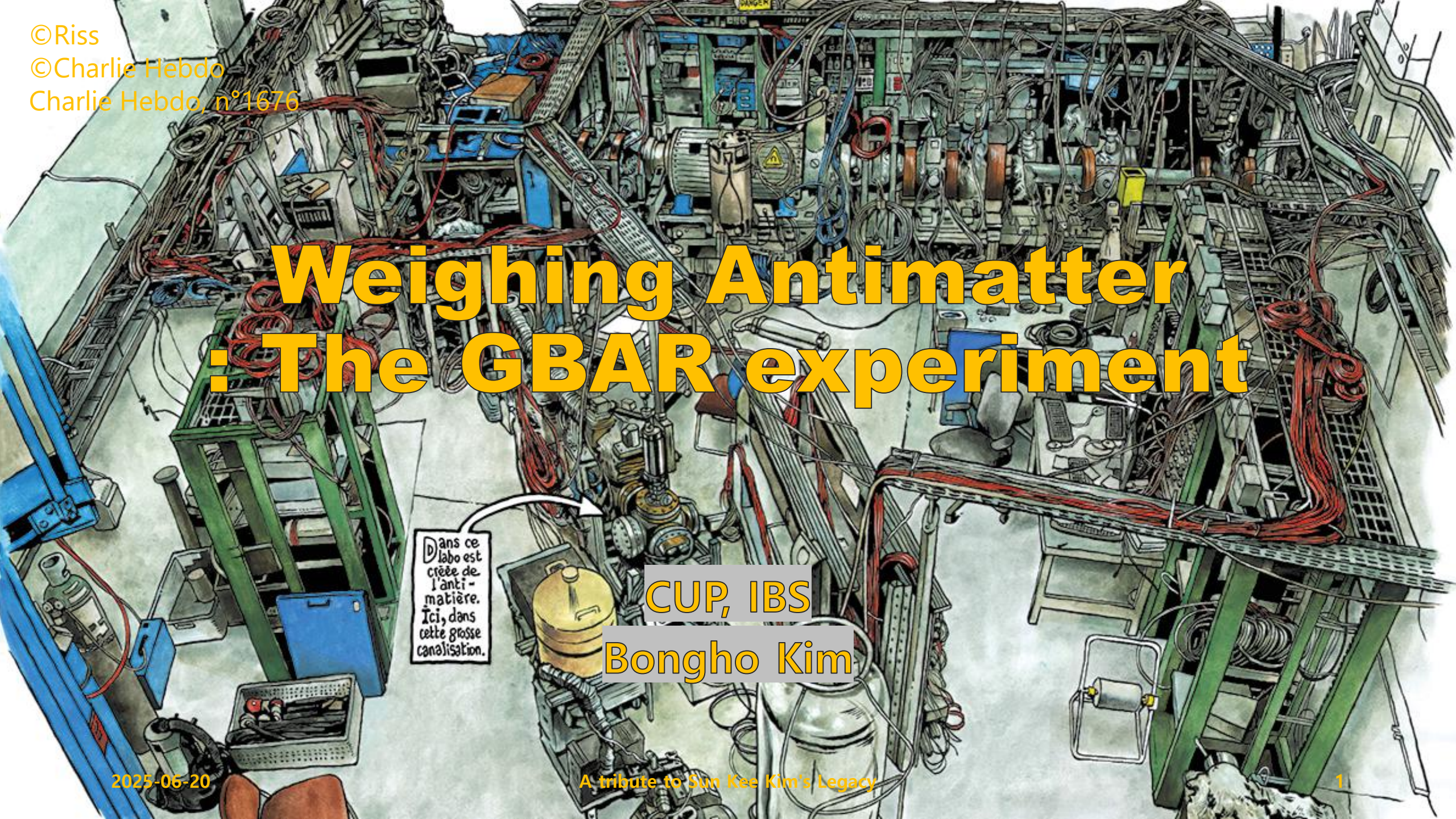
Charlie Hebdo, n°1676

Weighing Antimatter : The GBAR experiment



CUP, IBS
Bongho Kim

Weighing Antimatter : The GBAR experiment

CUP, IBS
Bongho Kim

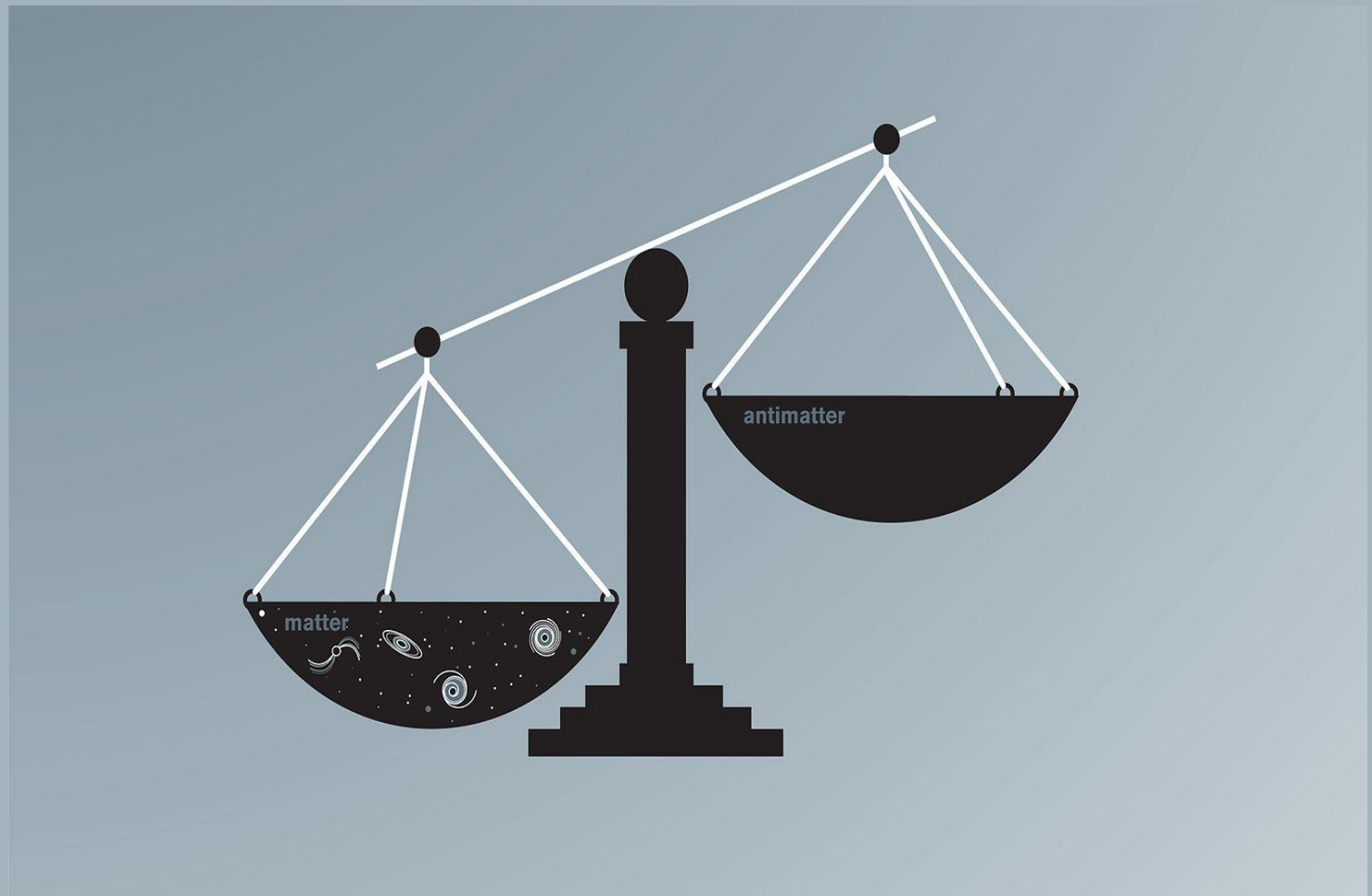
A tribute to Sun Kee Kim's Legacy

1. Motivation

- I never asked to Sunkee about the exact motivation to join the GBAR experiment.....
- So, I would say basic motivation + motivation which I think Sunkee would think about

Weighing Antimatter

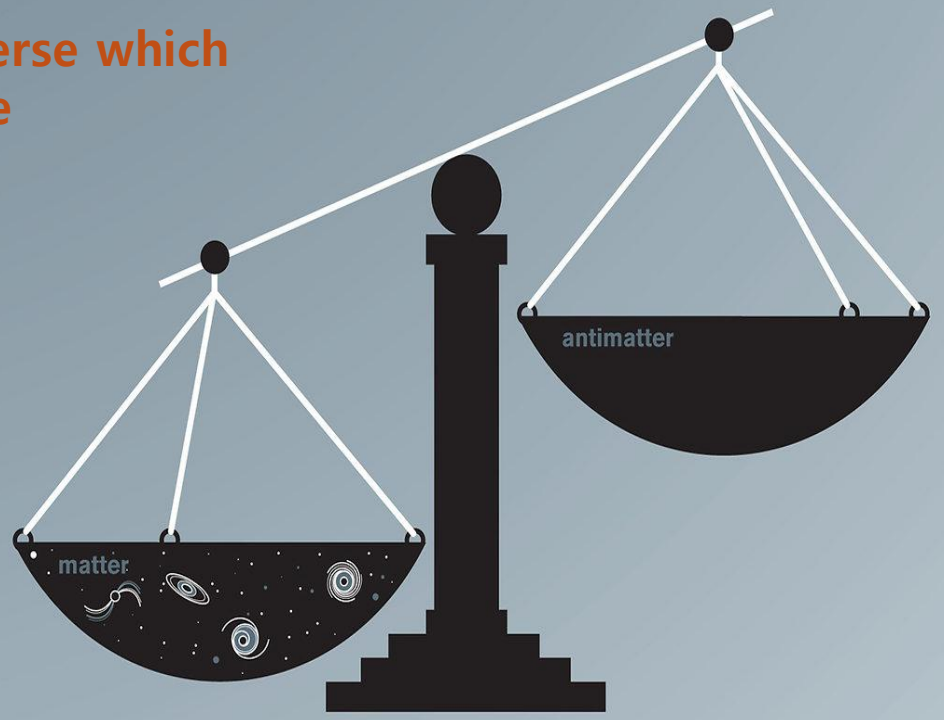
Weighing the antimatter of the universe has already been achieved — the pendulum has swung, hasn't it?



Weighing Antimatter

Weighing the antimatters of the universe has already been realized, and the pendulum has swung, isn't it?

- **This is the Mystery of Universe which is matter dominant universe**

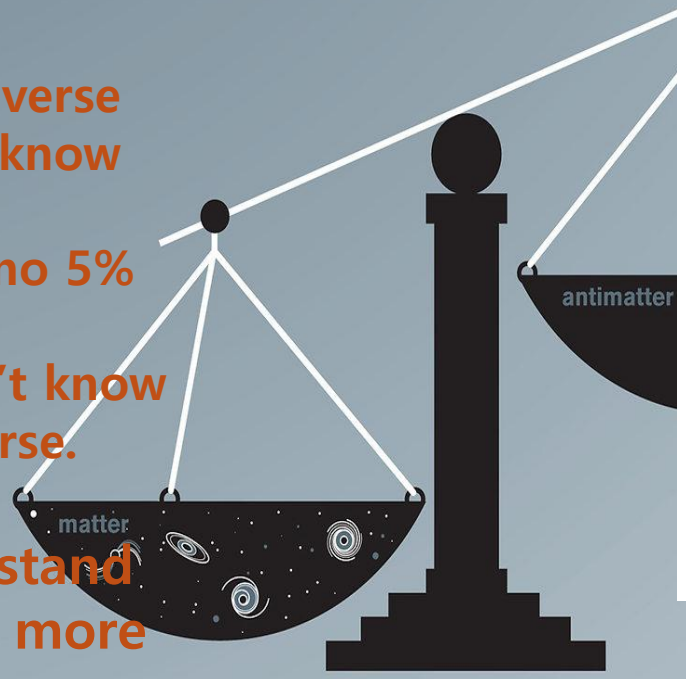


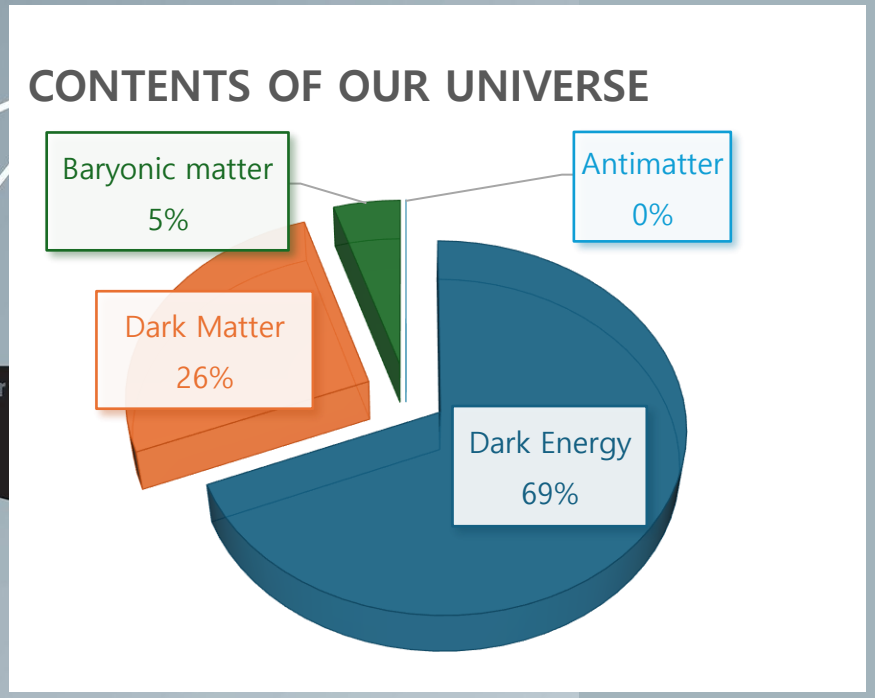
Weighing Antimatter

Weighing the antimatters of the universe has already been realized, and the pendulum has swung, isn't it?

- This is the Mystery of Universe which is matter dominant universe
- We talk about 5% of our universe contents although we don't know about 94%
- We don't know why there's no 5% antimatter
- So, I dare insist that we don't know well about 99% of our universe.

→ Let's give effort to understand the 5% expected antimatter more





Weighing Antimatter

Yes, we know the pendulum swung by $n_B \gg n_{\overline{B}}$

But what about the gravitational mass? $m_G =? \overline{m_G}$

Weighing Antimatter

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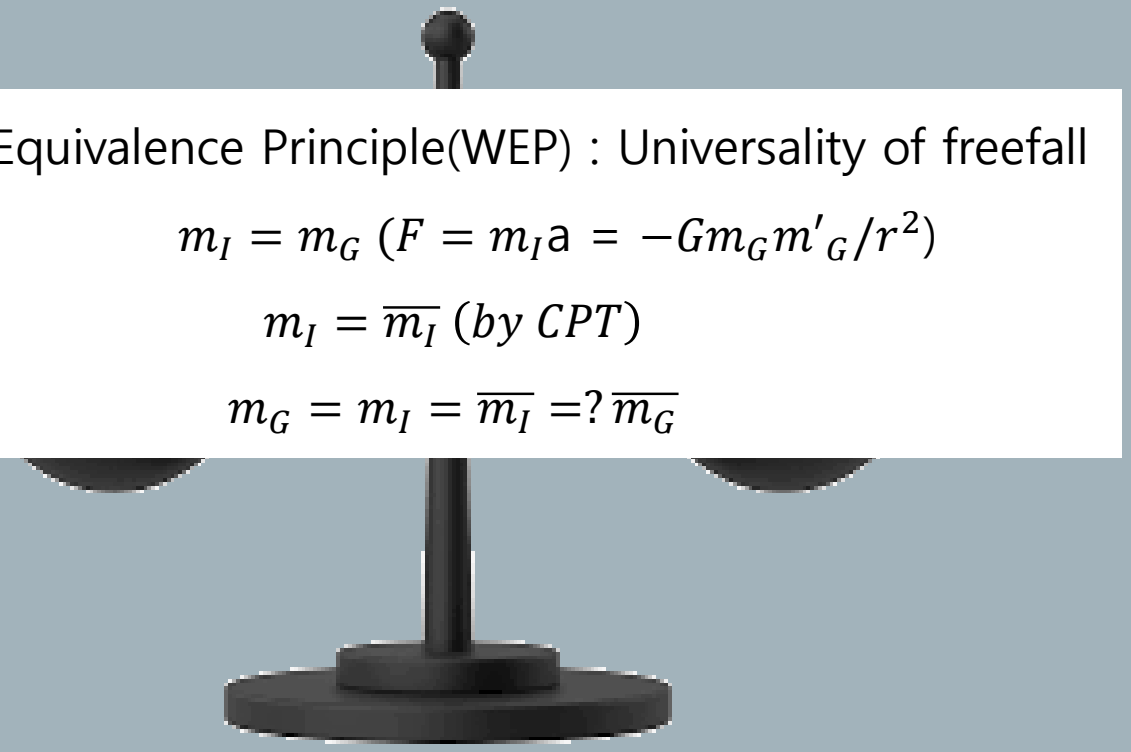

❖ Weak Equivalence Principle(WEP) : Universality of freefall

$$m_I = m_G \; (F = m_I \mathrm{a} = -G m_G m'_G / r^2)$$

$$m_I = \overline{m_I} \; (by \; CPT)$$

$$m_G = m_I = \overline{m_I} =? \overline{m_G}$$

Weighing Antimatter

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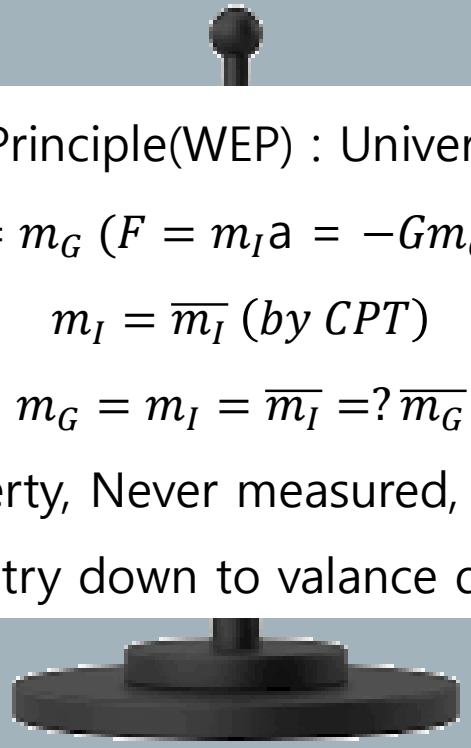

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$$m_G = m_I = \overline{m_I} =? \overline{m_G}$$

❖ Fundamental property, Never measured, Technology is feasible then why don't we try down to valance quark level?

Weighing Antimatter

Yes, we know the pendulum swung by $n_B \gg n_{\overline{B}}$

But what about the gravitational mass? $m_G =? \overline{m_G}$

Let's do.
Something Crazy but worth to try.

PS)

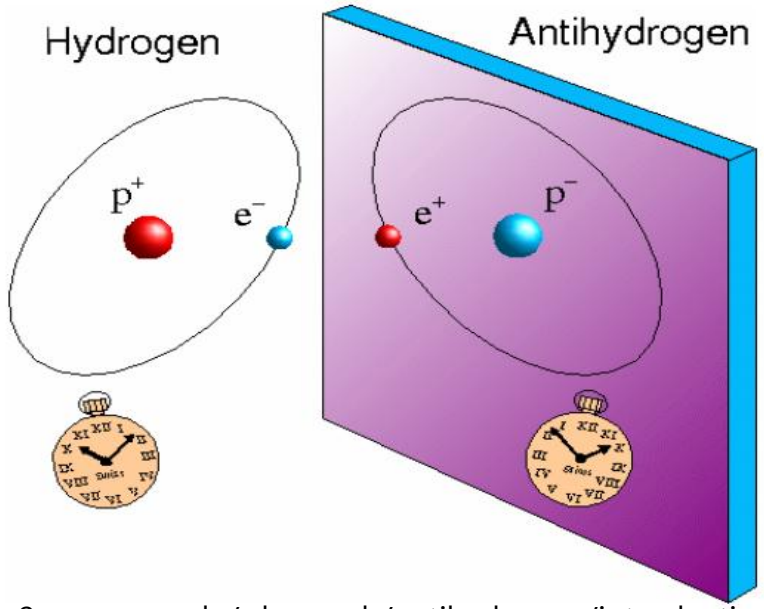
Of course, there are many more realistic and complex motivations when it comes to starting.

(when I personally think)

- Despite much effort, no candidate for dark matter has been found, and the long, tedious, and possibly goalless, race is expected ahead.
- With construction of RAON and requirement of domestic particle experiment, growing up more related exports and technology would be required.
- Or just to satisfy curiosity and for fun?

: I will ask Sunkee personally later ;-)

Antimatter (skip)



from
http://www2.mpq.mpg.de/~haensch/antihydrogen/introduction.html

Dirac equation (1928)

$$(i\hbar\gamma^{\mu}\partial_{\mu} - mc)\psi = 0$$

❖ **Antiparticle**

- Paul Dirac predicted the existence of antiparticle in1931 and positron was discovered in 1932
- Antiparticle as a counterpart of ordinary particle for charge conjugation (charge, magnetic moment)
- With CPT symmetry (transformation), other quantities (mass, lifetime) are expected to be same

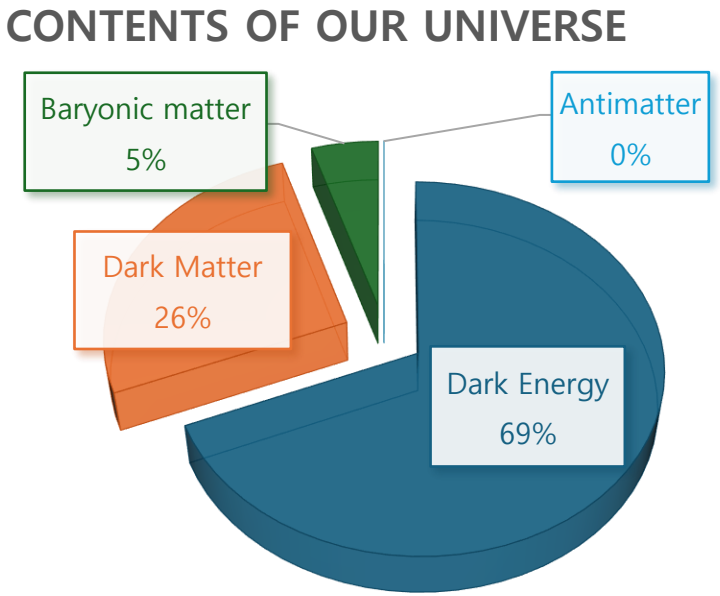
❖ **Matter and Antimatter asymmetry**

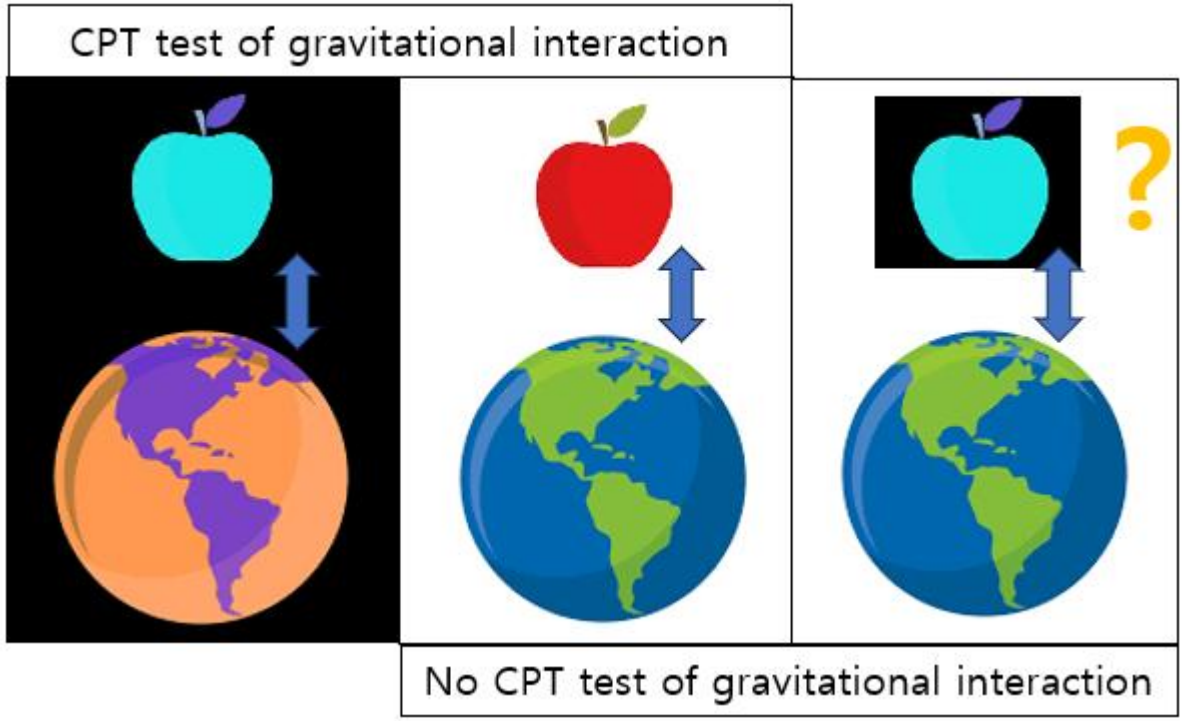
- Different with expectation based on CPT theorem and Standard Model, Matter domain (baryon asymmetry) in observable Hubble volume : $n_B \gg n_{\bar{B}}$

(baryon-to-photon ratio : $0.6e^{-9}$(observed) $\gg 10^{-18}$(expect))

- Model to understand : Baryogenesis, Leptogenesis, etc..

Antimatter : WEP (skip)





❖ Dark matter and Dark energy

- We do not understand 94% of the mass energy density

❖ For known 6% contents which is mainly baryonic matters and radiation, we don't know why there's almost no antimatter

❖ Check fundamental interaction between matter & antimatter

❖ Weak Equivalence Principle(WEP) : Universality of freefall

$$m_I = m_G \; (F = m_I \mathrm{a} = -G m_G m'_G / r^2)$$

$$m_I = \overline{m_I} \; (by \; CPT)$$

$$m_G = m_I = \overline{m_I} = ? \, \overline{m_G}$$

2. How it started

No new collaborator founded…

- Sunkee Kim, YoungKee Kim and Patrice Perez knew each other from AMY experiment
- When Patrice (spokesperson) met YoungKee Kim in 2014, she suggested to find new collaborators in Korea
- Patrice looked around China and Korea to find collaborator, but he couldn't meet Sunkee.
- But Sunkee mailed to Patrice later that he has interest and it started

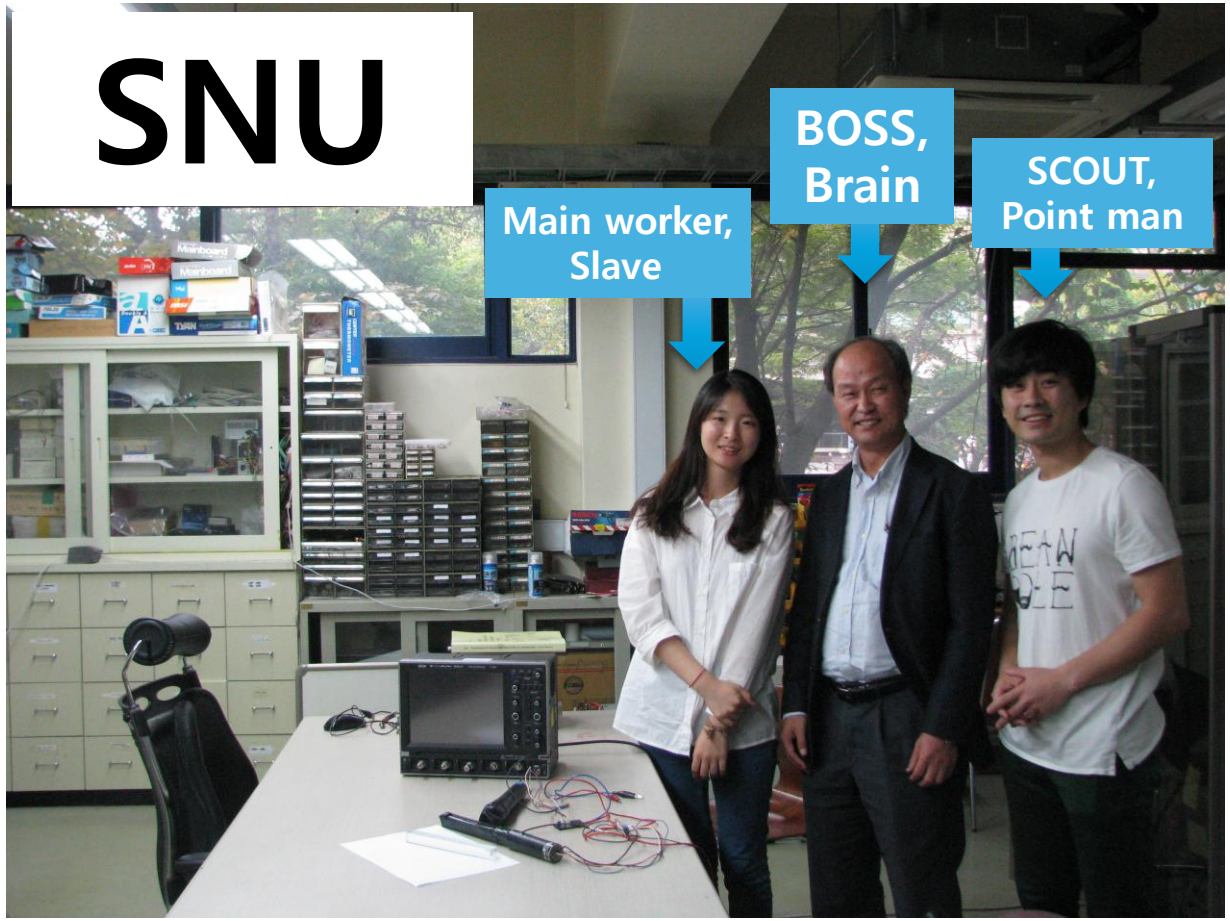
MISSING

GBAR collaboration

P.N.Lebedev Physical Institute of the Russian Academy of Science

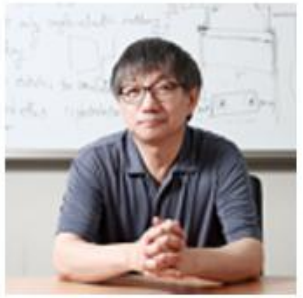
P. Adrich[1], P. Blumer[2], G. Caratsch[2], M. Chung[3], P. Cladé[4], P. Comini[5], P. Crivelli[2], O. Dalkarov[6], P. Debu[5], A. Douillet[4,7], D. Drapier[4], P. Froelich[8,20], N. Garroum[4,21], S. Guellati-Khelifa[4,9], J. Guyomard[4], P-A. Hervieux[10], L. Hilico[4,7], P. Indelicato[4], S. Jonsell[8], J-P. Karr[4,7], B. Kim[11], S. Kim[12], E-S. Kim[13], Y.J. Ko[11], T. Kosinski[1], N. Kuroda[14], B.M. Latacz[5,22], B. Lee[12], H. Lee[12], J. Lee[11], E. Lim[13], L. Liszkay[5], D. Lunney[15], G. Manfredi[10], B. Mansoulié[5], M. Matusiak[1], V. Nesvizhevsky[16], F. Nez[4], S. Niang[15,22], B. Ohayon[2], K. Park[11,12], N. Paul[4], P. Pérez[5], C. Regenfus[2], S. Reynaud[4], C. Roumegou[15], J-Y. Roussé[5], Y. Sacquin[5], G. Sadowski[5], J. Sarkisyan[2], M. Sato[14], F. Schmidt-Kaler[17], M. Staszczak[1], K. Szymczyk[1], T.A. Tanaka[14], B. Tuchming[5], B. Vallage[5], A. Voronin[6], D.P. van der Werf[18], D. Won[12], S. Wronka[1], Y. Yamazaki[19], K-H. Yoo[3], P. Yzombard[4]

(2015) Sunkee asked :
Do you have interest to measure gravitational acceleration of antimatter?



I said :
Yes, I have

Korean GBAR group organized in 2015
SNU + IBS +… UNIST +KU



IBS

KU

UNIST

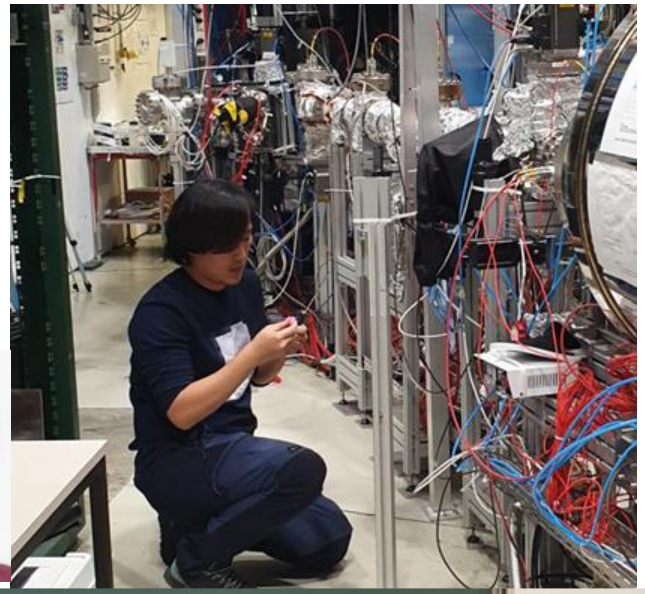
Korean GBAR collaboration

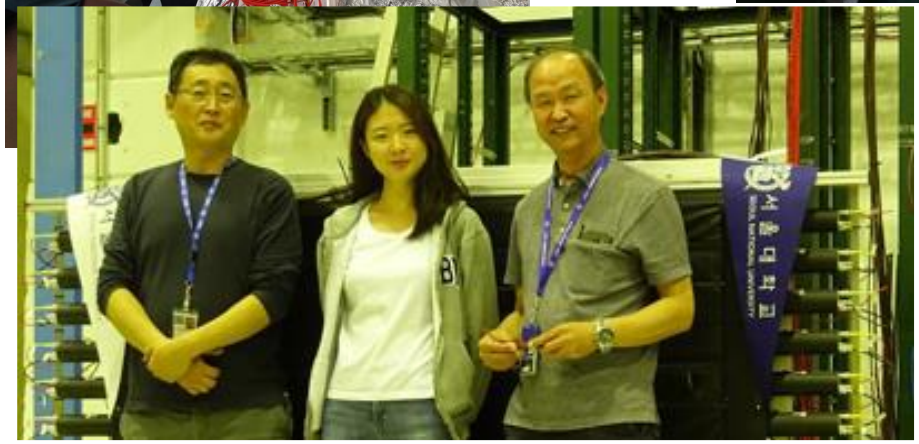
서울대학교 SEOUL NATIONAL UNIVERSITY

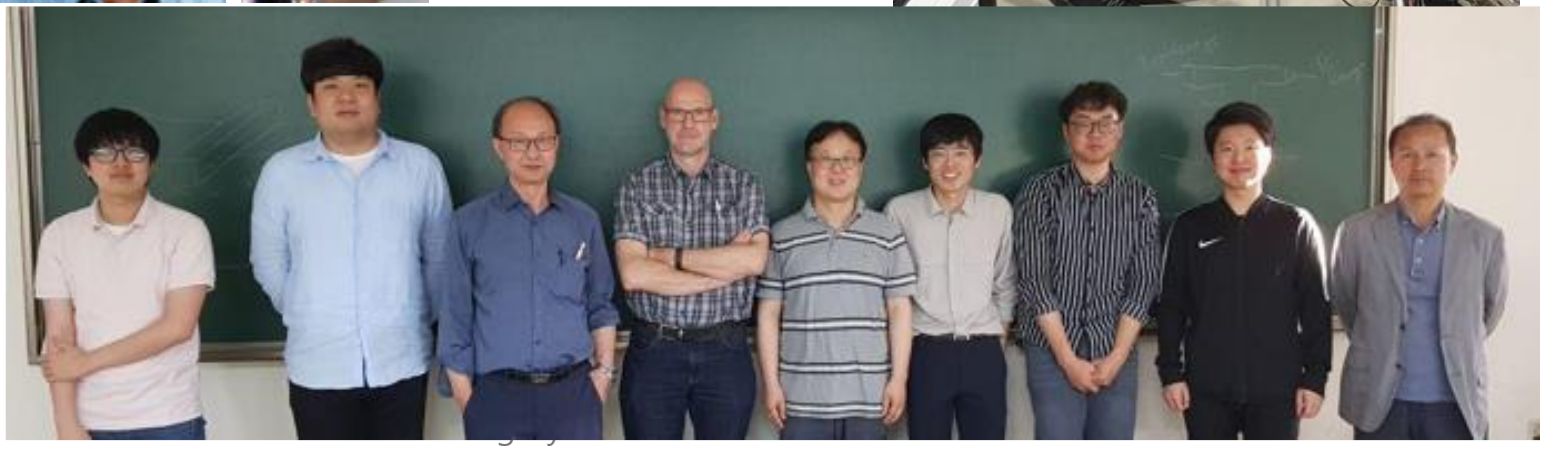
KOREA UNIVERSITY

ibs Institute for Basic Science

POSTECH POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY



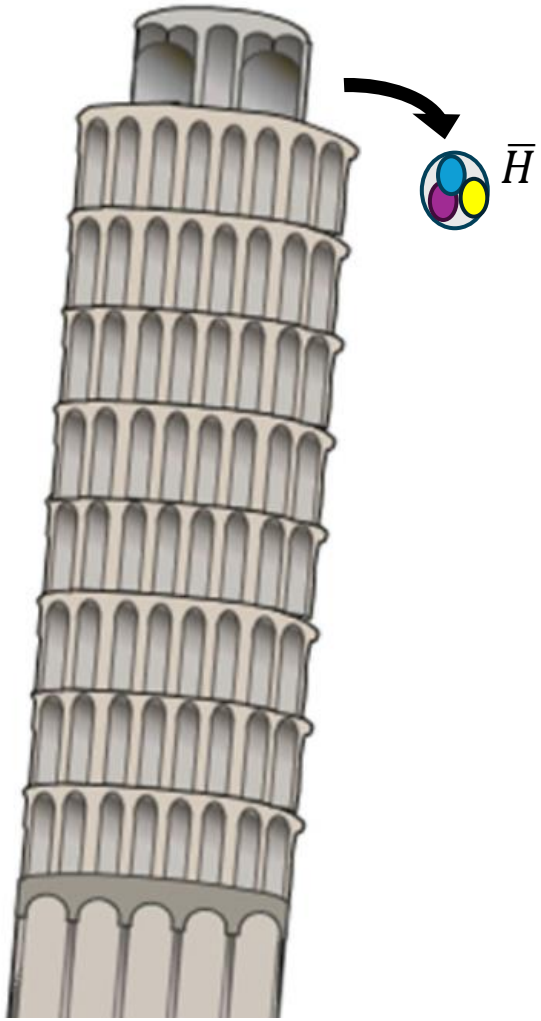




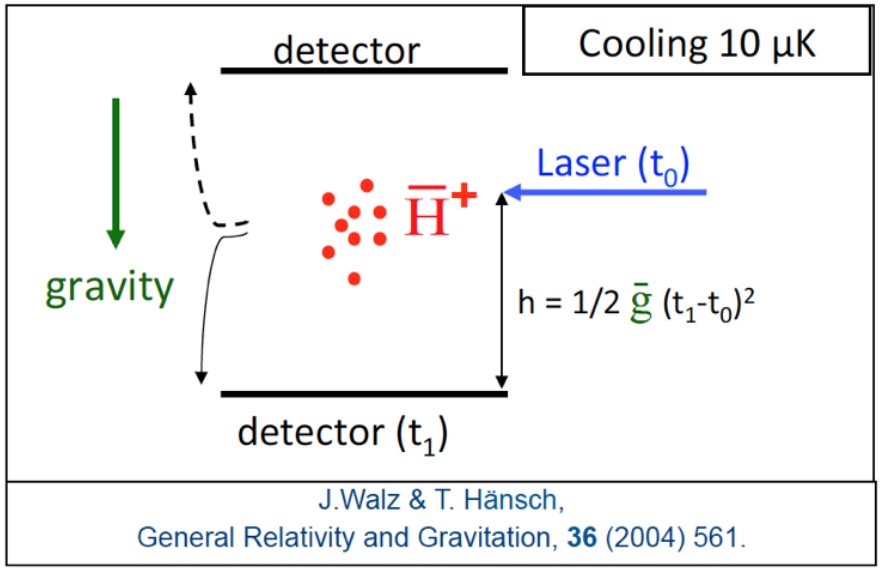
Resting Corner

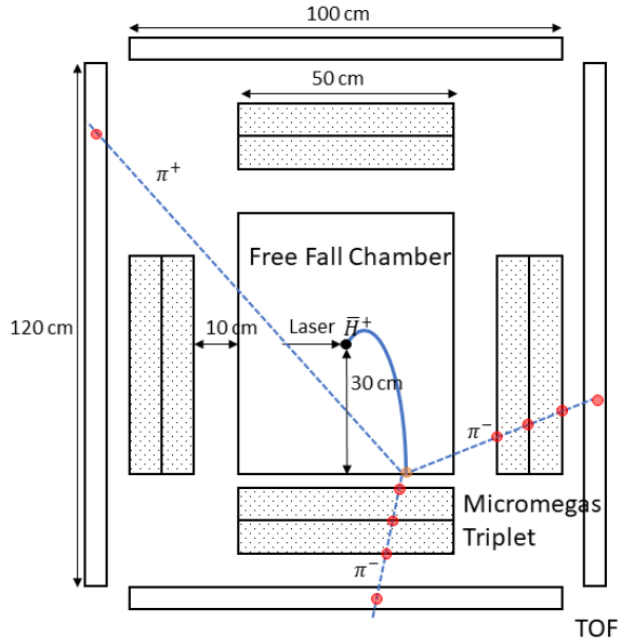
: Which means that the section is for explanation of the experiment

GBAR experiment



ⓒ Wikibooks / Theresa Knott





GBAR : Gravitational Behaviour of Antimatter at Rest

- Classical freefall test of antimatter using ultra-cold $\bar{H}$ (10uK)
- Time of flight (ΔT) measurement (Basic detection)

$$\bar{g} = \frac{2H}{\Delta T^2}$$

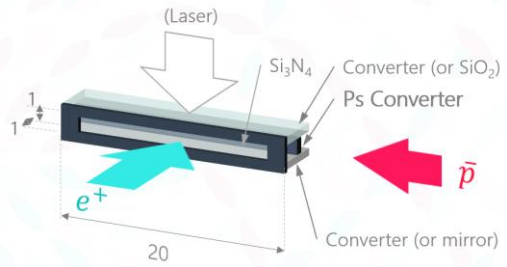
ex) H=10cm → ΔT = 143ms (for g)

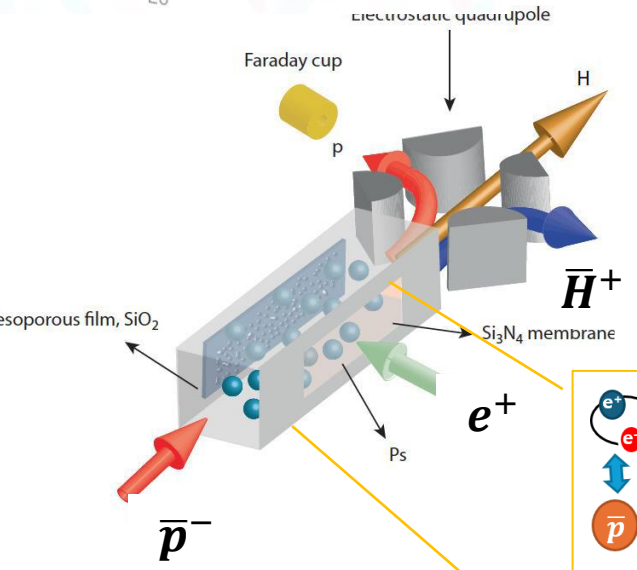
Velocity fluctuation	100m/s	3m/s	0.1m/s
Temperature	1K	1mK	1uK

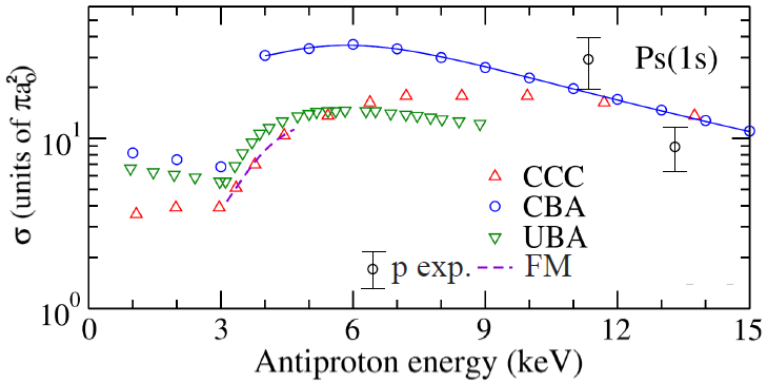
GBAR experiment

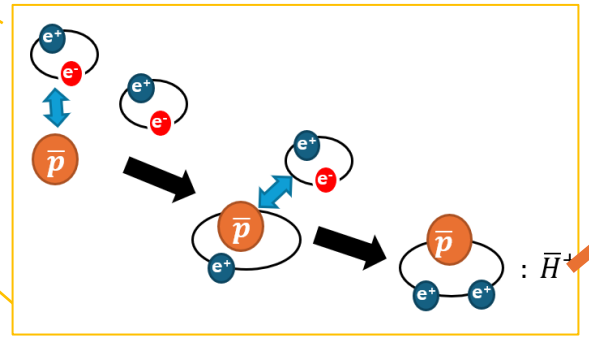
Phys.Rev.A 107 (2023) 5, 052813

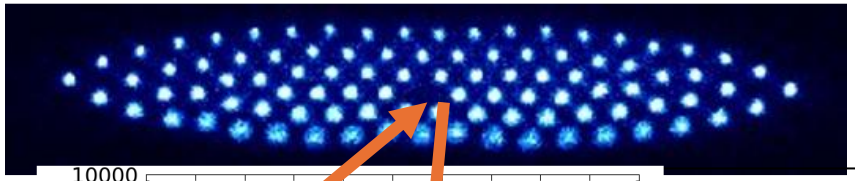
Proton exp. data: Phys. Rev. Lett. 78, 2728 (1997)

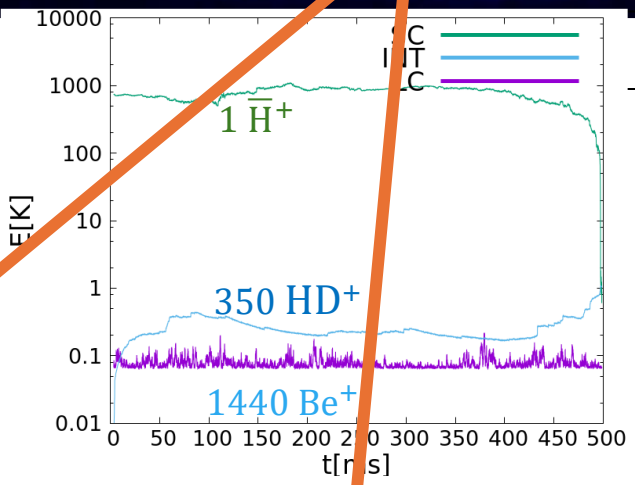






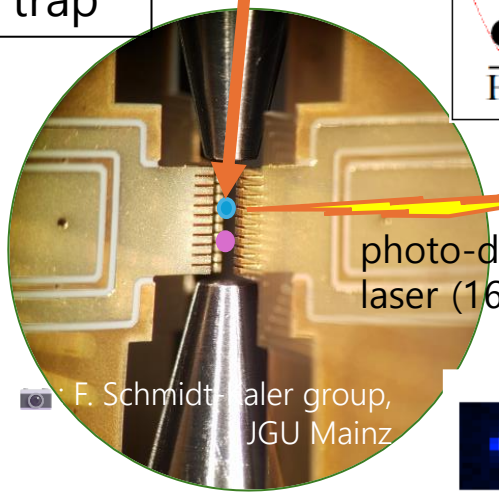






Capture trap

Precision trap



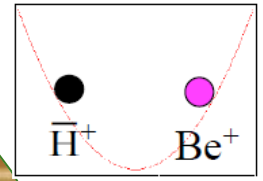
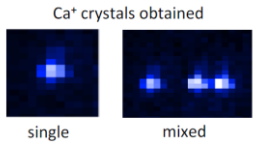


photo-detachment laser (1640nm)

F. Schmidt-Kaler group, JGU Mainz



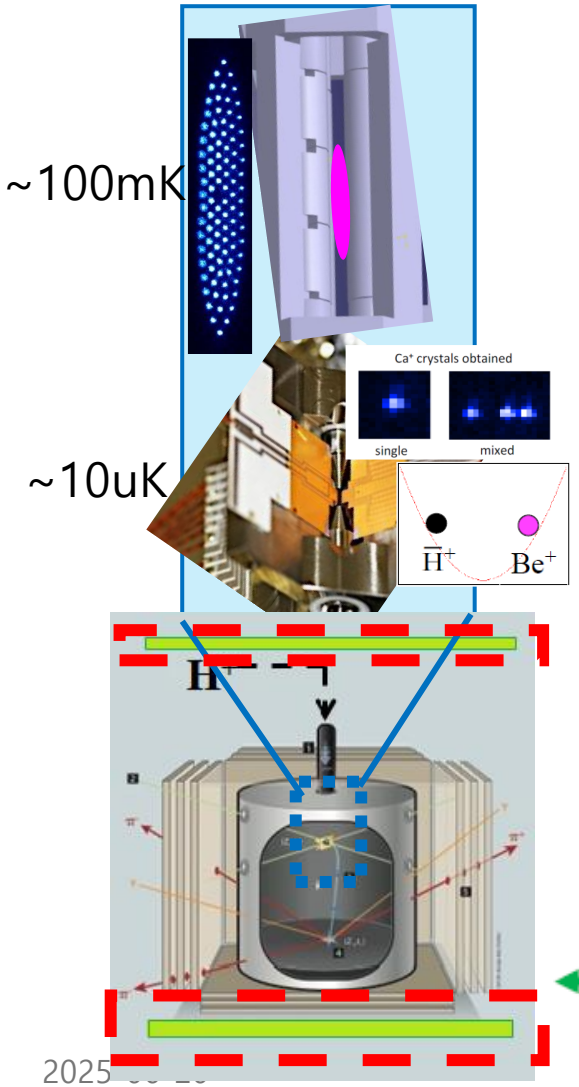
$\bar{p} + Ps \rightarrow \bar{H} + e^-$: 1st milestone

$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$: 2nd milestone

Cooling $\bar{H}^+$ and freefall : 3rd milestone

GBAR experiment (2022)

Experiment Scheme



3.5→0.1GeV/c

AD

5.3MeV

ELENA

now $1x10^7$

100keV ($0.5x10^7$ $\bar{p}$ /110s)

Anti-proton beam line

decelerator

$\overline{P}$ trap

10eV~10keV

4kV

Laser Ps*

$\rho_{Ps} = 10^{12} cm^{-3}$

$\overline{H}$

$\overline{p}$

$\overline{H}^+$ ion

$\sim 1\bar{H}^+/bunch$

Recycler #($\bar{p}$) x10 (?)

High field trap

buncher

Ne remoderator

BG trap

e^+ target

Linac

Positron beam line

10^{10} e^+/bunch

1MeV→3eV → 50eV

$3x10^8 e^+/s$

e^- 10MeV

Antiproton beam line
- High efficiency
- Good phase-space
- Possible accumulation

Positron beam line
- High intensity
- High accumulation rate
- Narrow spot at target

: KGBAR mainly

: participating

The way to make antiproton trap in Korea

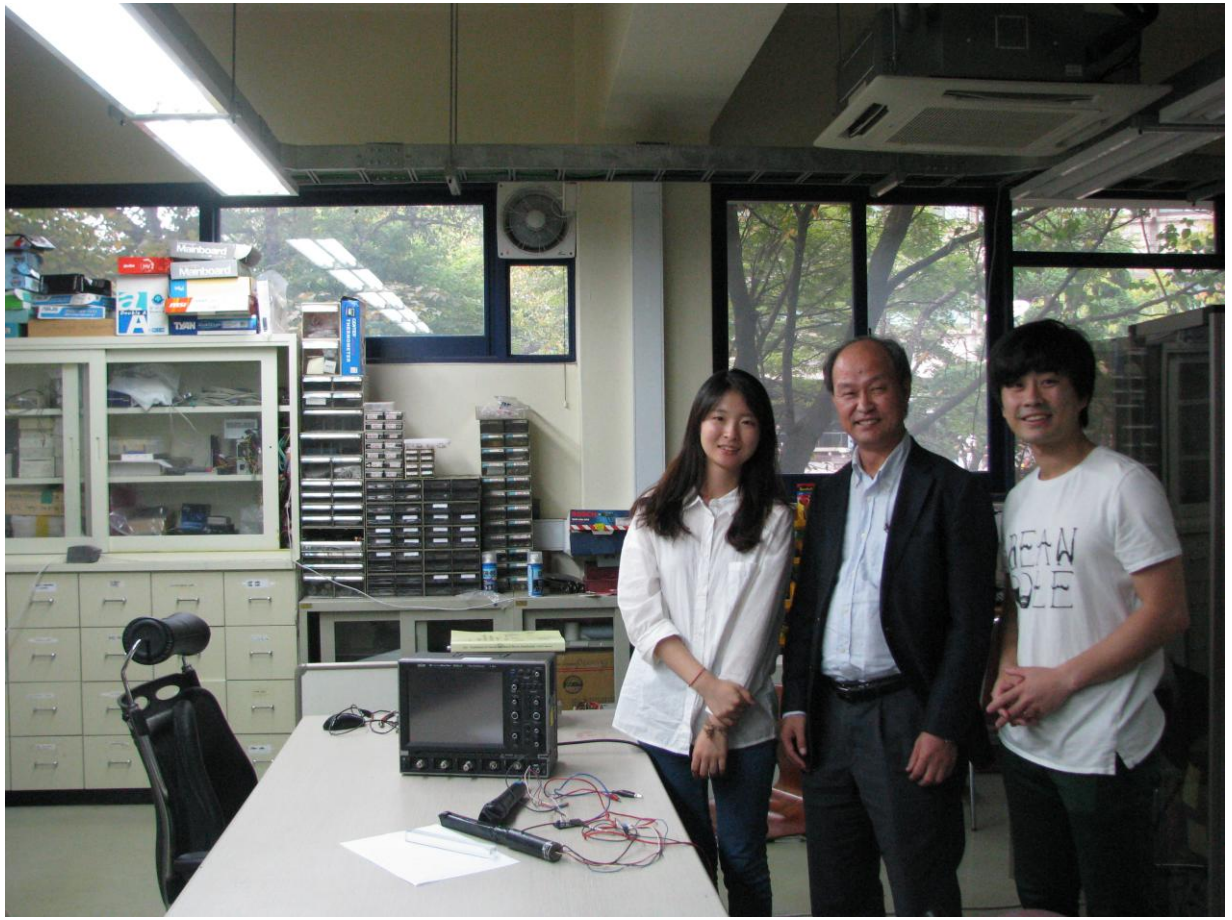
- Without accumulated technology and know-how
- Initiated by one person


Mini-workshop for antiproton trap

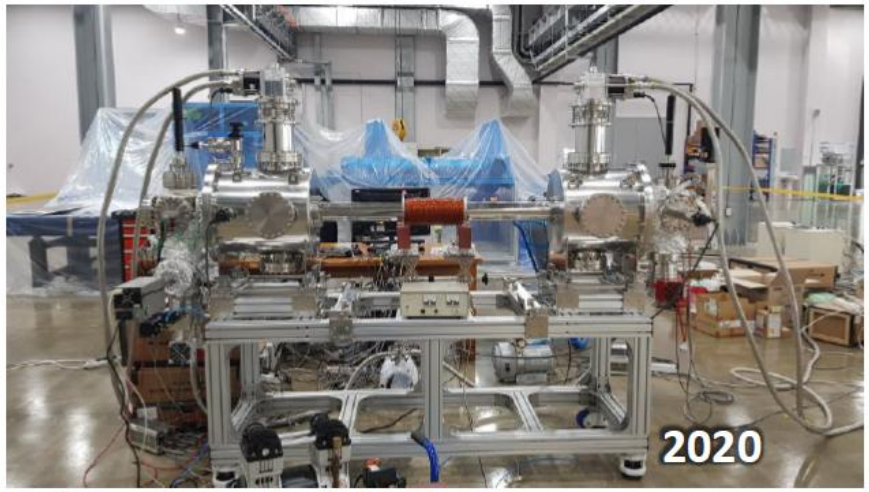
Mini-workshop for antiproton trap

1. Gathering exports
2. have a meeting, meeting and meeting… (drinking?)
3. Prepare manpower
4. Use Boss’s brain to make real design and decision

Do you have interest to measure gravitational acceleration of antimatter?



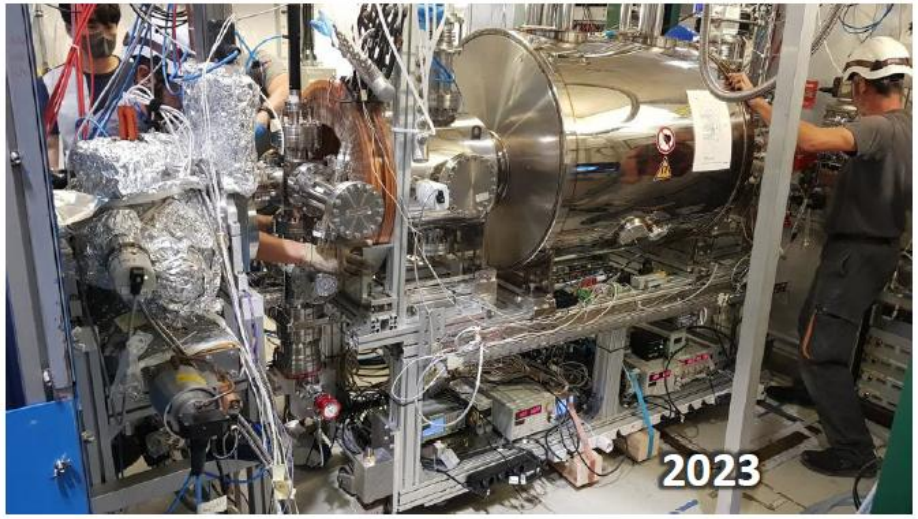
Yes.
From that time, I have trapped from 2015.



Korea University, Sejong

Delivery to CERN, basic tests

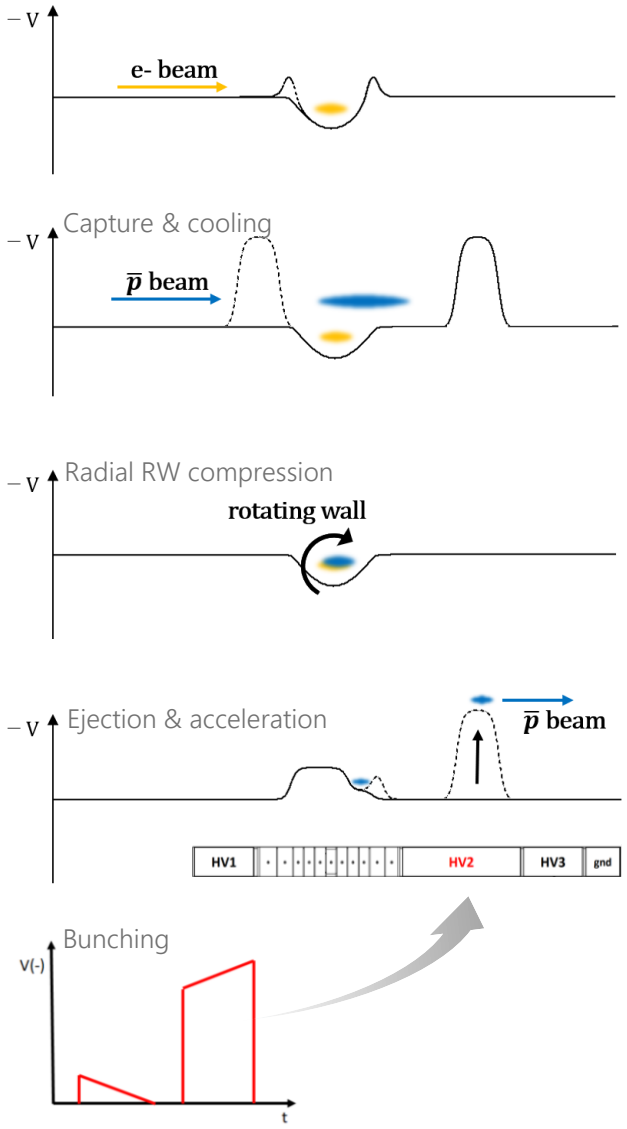
Putting it in the GBAR experimental zone (temporary location)
electron trapping, antiproton trapping tests



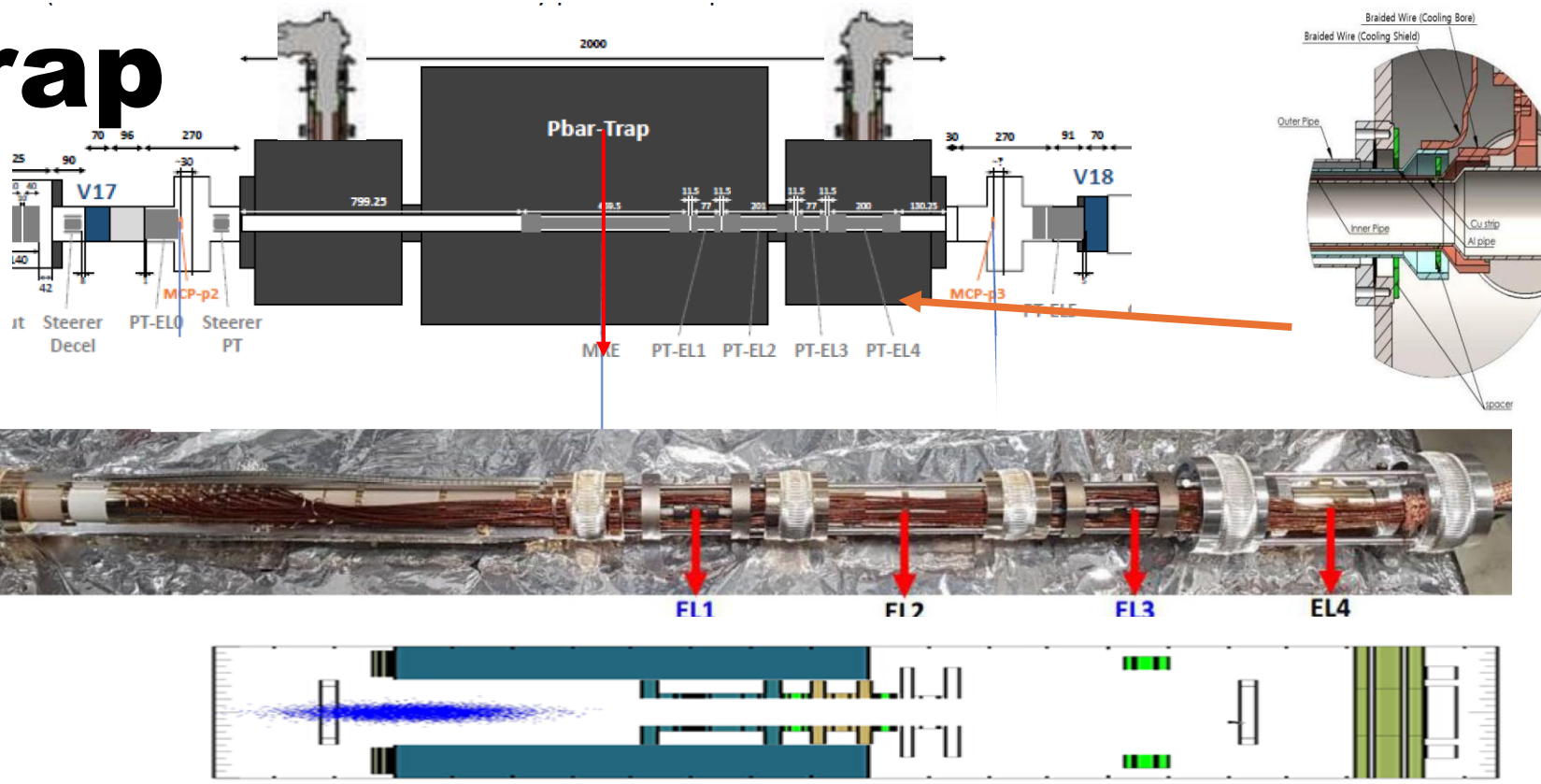
2023,
Connecting to the beamline,
Commissioning

2024,
Antihydrogen production

Antiproton trap



~ 20 s

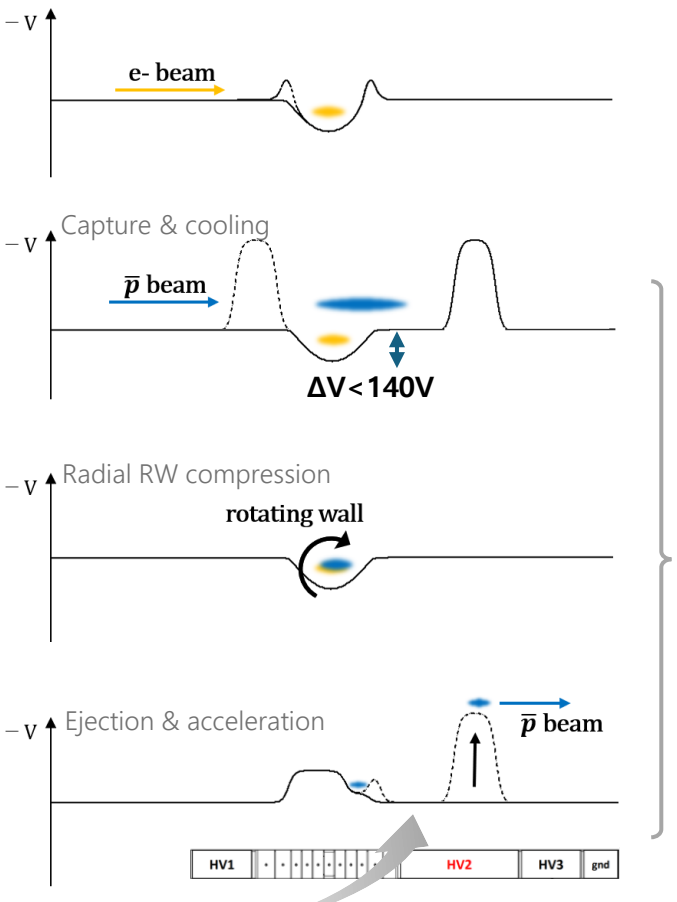


- Penning-Malmberg trap (5T; 7T max) for antiproton beam reprocessing
- Temperature at Multi-Ring-Electrode (MRE) is about
- Pressure at MRE is about 10^{-12}mbar
- PXI (sequence controller) + cRIO (FPGA + safety controller) system
- Function : Trapping, cooling (sympathetic cyclotron cooling), compression, acceleration, bunching and accumulation ➔ $\bar{p}$ reprocessing device

Antiproton trap

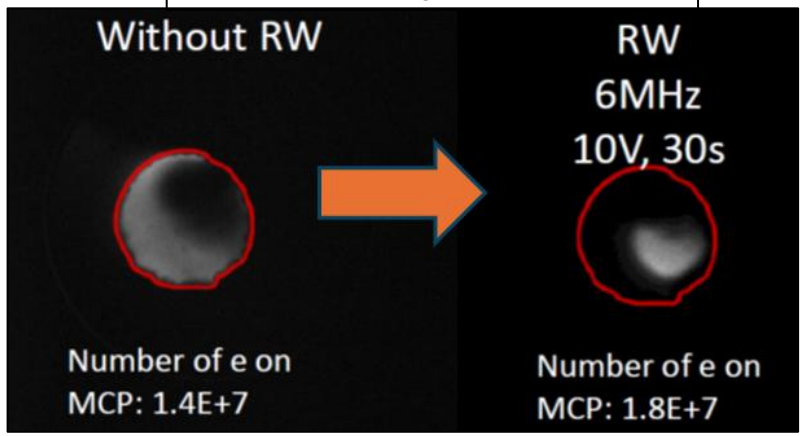
Preliminary

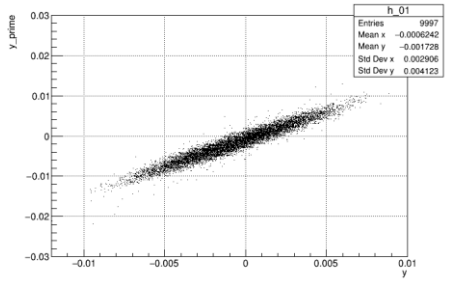
By B.C.Lee, K.H.Park, D.H.Won

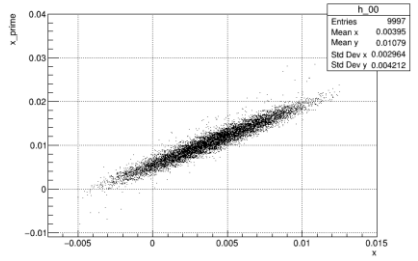


~ 20 s

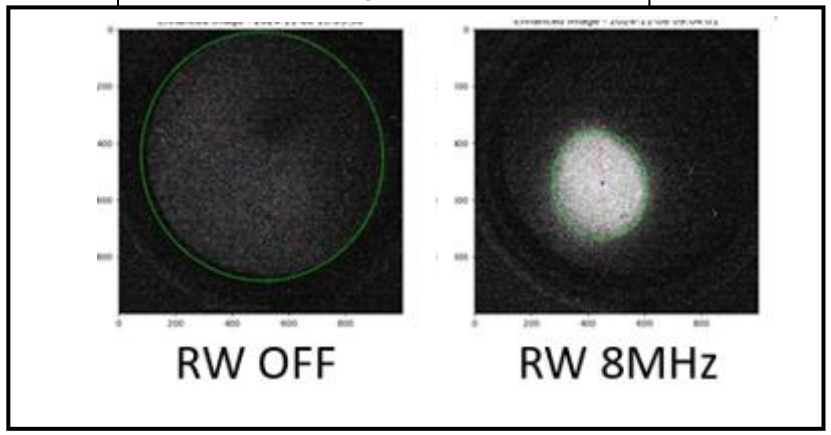
e- compression





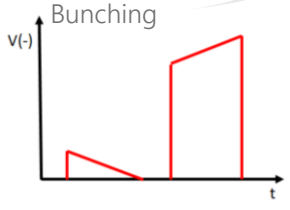


$\bar{p}$ compression



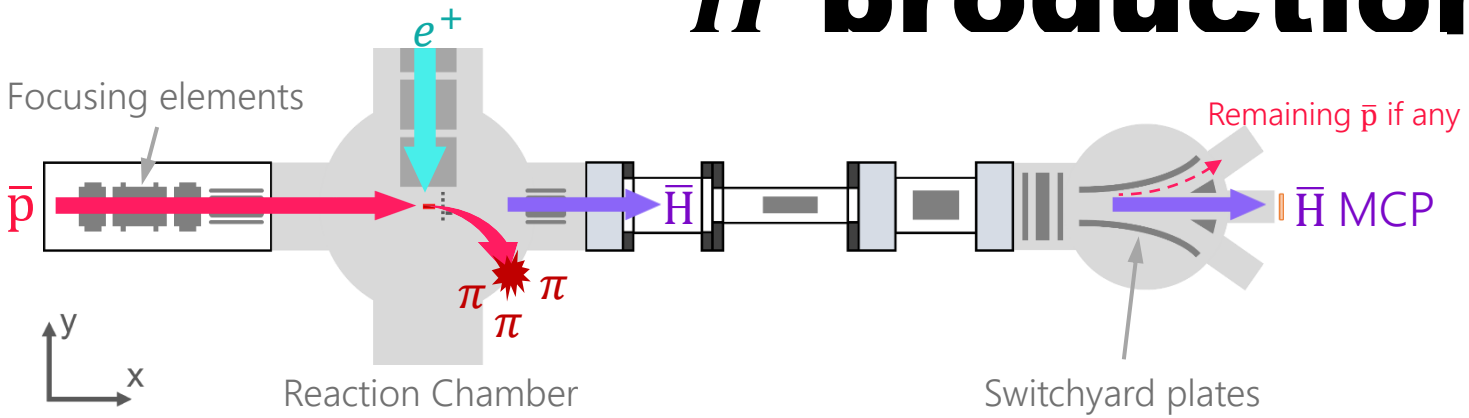
2024 comissioning

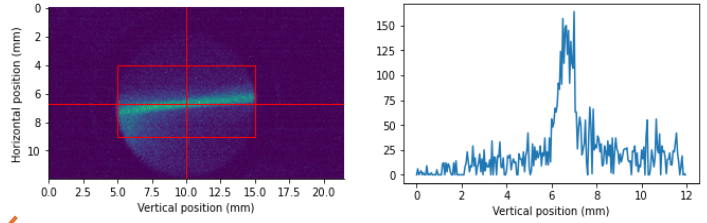
Beam Intensity	$(4.9 \pm 0.4) \times 10^6$
Extraction efficiency (/ELENA)	$(43 \pm 4)\%$
Beam size (σ_x)	2.71mm
Beam size (σ_y)	2.99mm
Bunch length (FWHM)	80ns



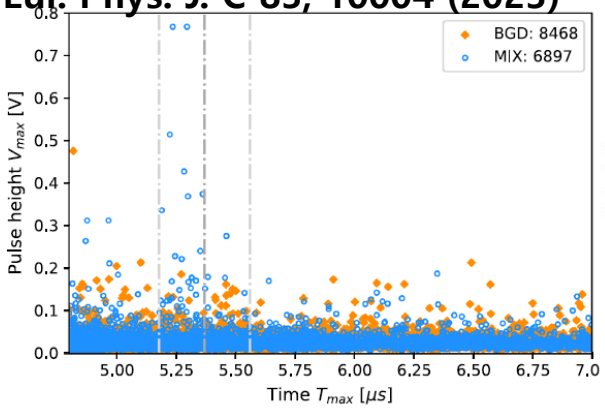
- e- accumulation & compression : enough accumulation(~10x #($\bar{p}$)) with possible compression
- Cooled $\bar{p}$ trapping : 55% of injection from ELENA (Temp measurement is planned), τ>10min
- $\bar{p}$ compression : Simulation based on extracted beam data expects the density is near designed value
- Re-accelerated $\bar{p}$ beam status : Success to pass through target cavity above 1x10^6 $\bar{p}$ /ELENA pulse

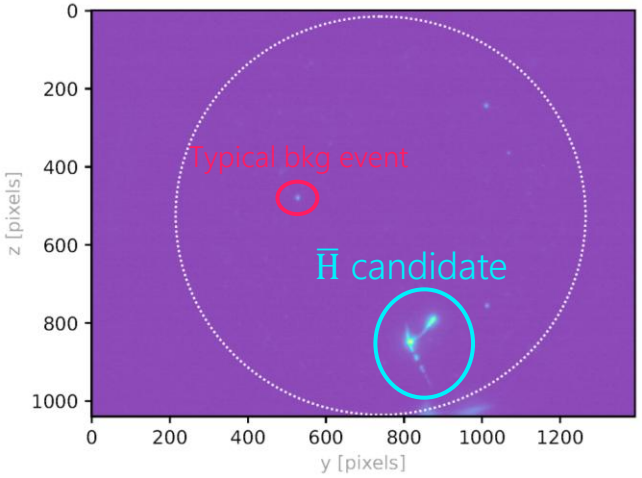
$\bar{H}$ production

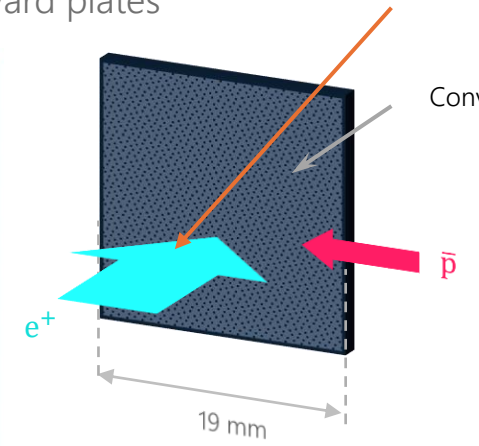




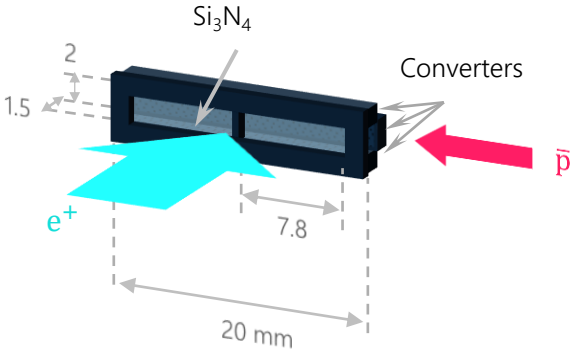
Eur. Phys. J. C 83, 10004 (2023)

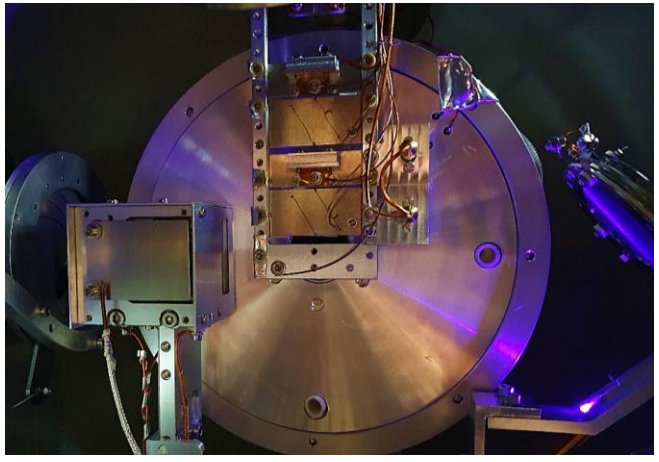






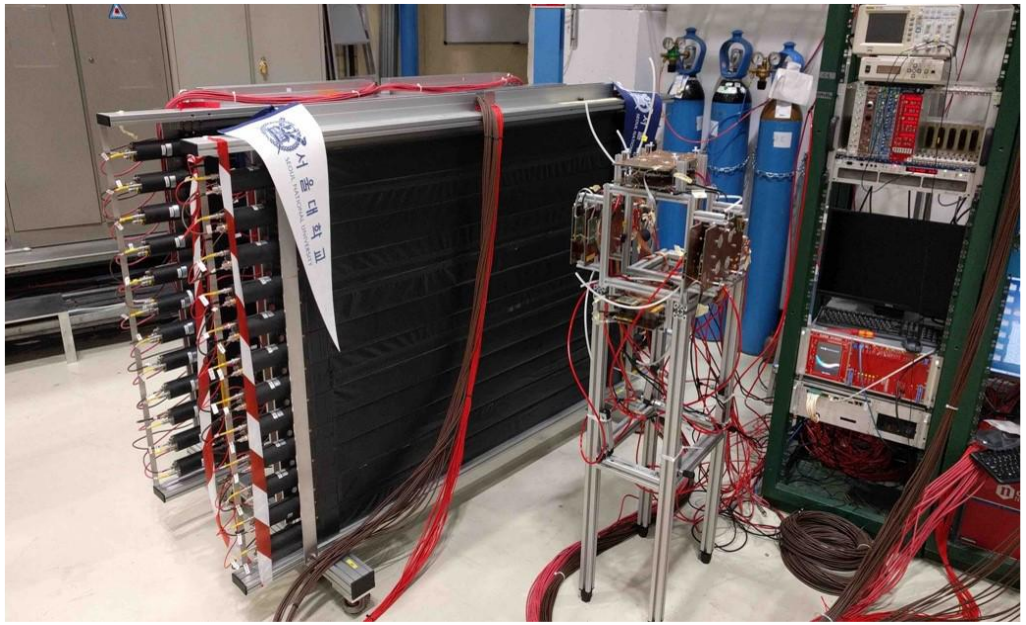
2022 2023

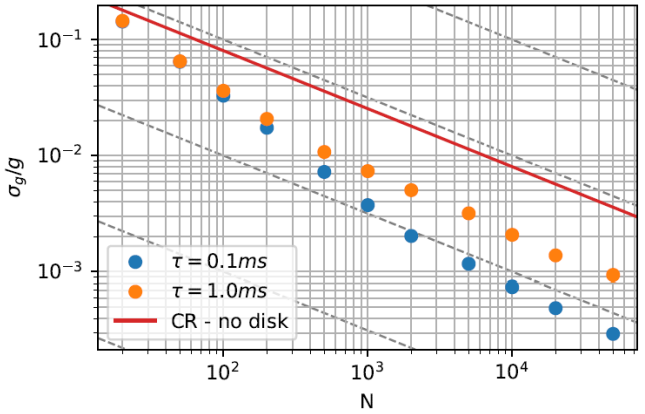




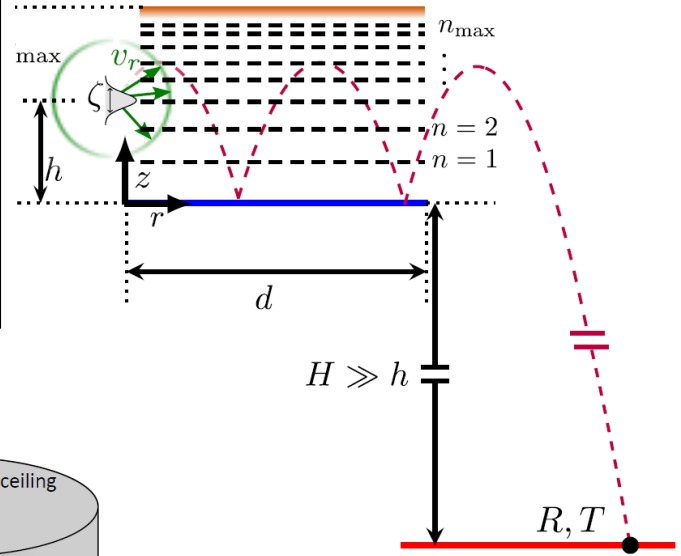
- Produced antihydrogen is detected above 3σ (which is **1st milestone**) at 2022
- production in flat target and then cavity target with antiproton trap
- (First) production of $\bar{H}$ by charge exchange between o-Ps and antiproton **beam**
- **Antihydrogen detection rate increased by 30 times (2023)** compared to 2022

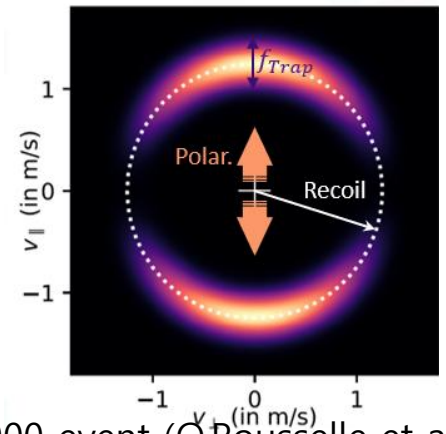
GBAR : Quantum reflection and levitation

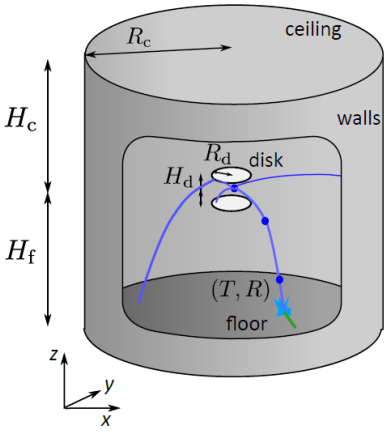


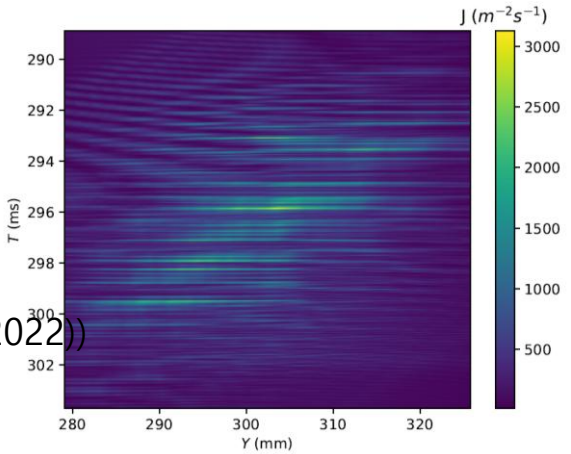


O. Rousselle et al, Phys. Rev. A **105**, 022821 (2022)









O. Rousselle *et al.*, Eur. Phys. J. D **76**, 209 (2022)

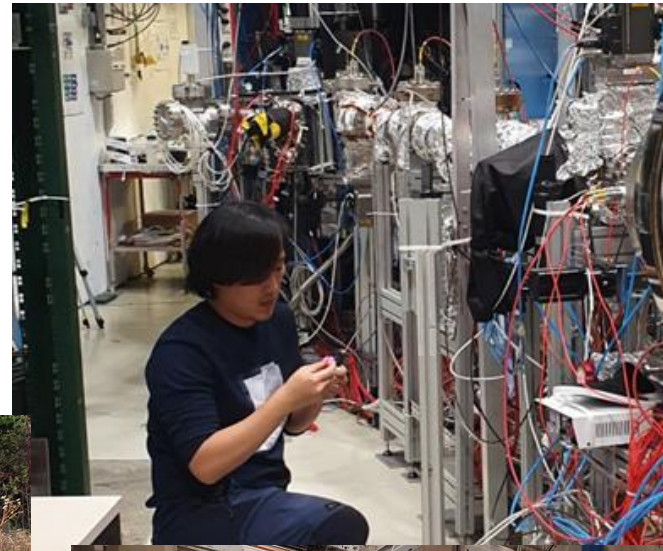
0. Tracker and TOF detector are prepared for secondary particle reconstruction and $\bar{g}$ with 1% for 1500# events

1. Polarization and Shaping with 0.1% uncertainty for 10,000 event (O.Rousselle et al, Eur. Phys. J. D **76**, 209 (2022))

2. Quantum bouncing by Casimir-Polder potential vs Gravitational potential 10^{-5} precision

(G. Dufour et al., Eur. Phys. J. C (2014) 74: 2731)

Many trial, failure and efforts for sure



Kee Kim's Legacy

Summary

- Trial to investigate the symmetry breaking mystery by fundamental research based on antimatter in the GBAR experiment.
- Sunkee has led the GBAR experiment especially for Korean GBAR.
- To reach the new technology from the beginning without basis, 5 years with good boss is necessary.
- By KGBAR, well-trained exports has been made, and we have world class technology for antimatter plasma trapping.
- Freefall test by ultra-cold antihydrogen has approached.

Thank you for audience and Sunkee


G
GBAR