

# 超低速反陽子ビームを用いた 原子衝突実験

Hirooyuki A. TORII 鳥居 寛之



東京大学大学院総合文化研究科



ASACUSA collaboration (CERN)

永田祐吾、豊田寛、今尾浩士、黒田直史、V. L. Varentsov、山崎泰規

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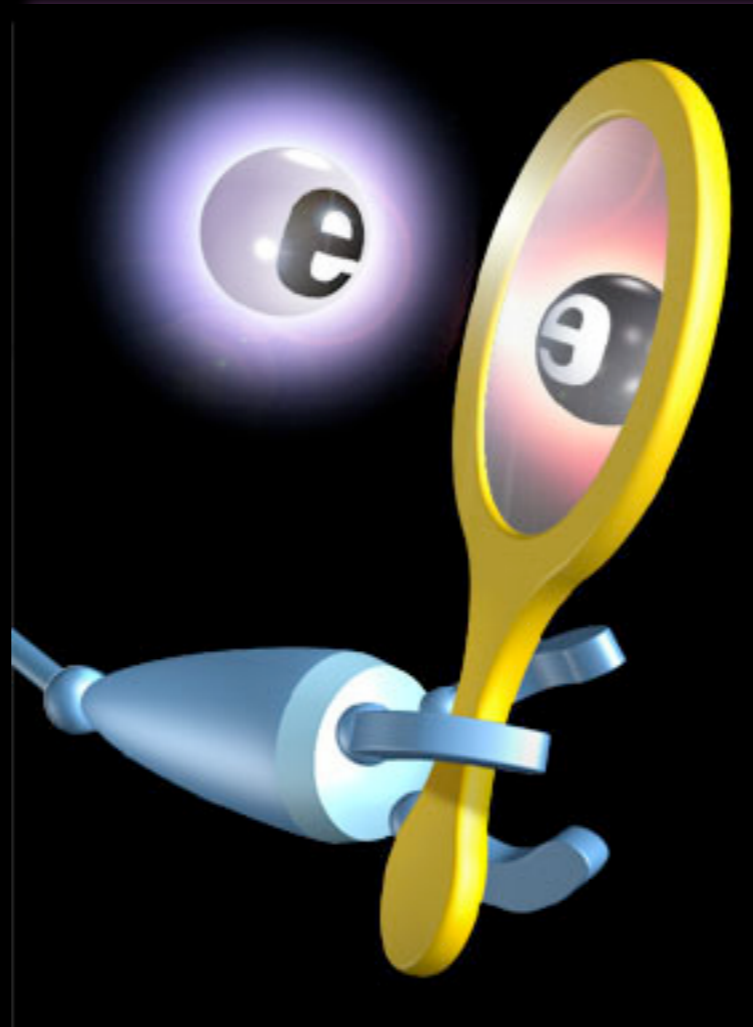
東京大学大学院総合文化研究科



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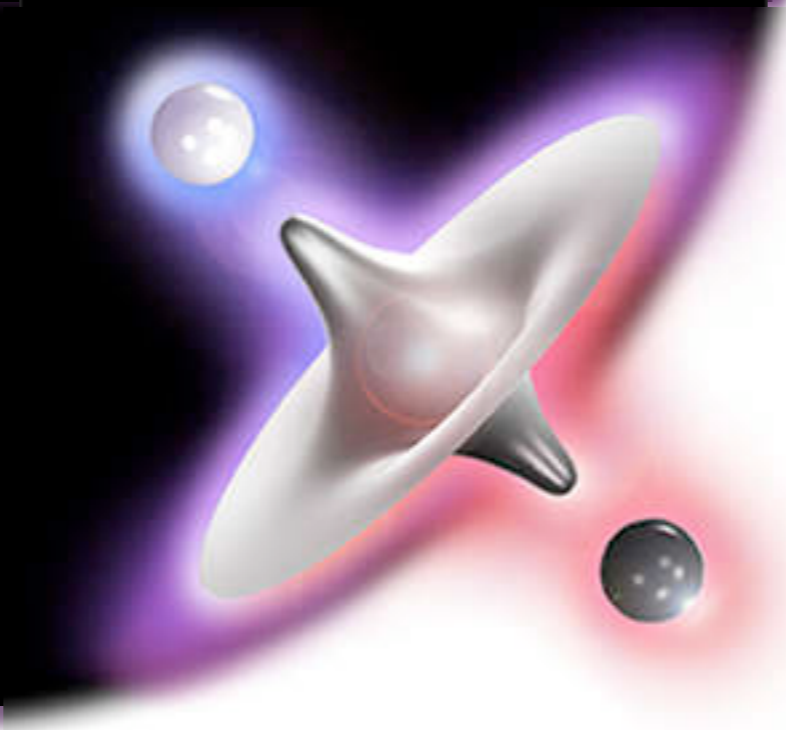
永田祐吾、豊田寛、今尾浩士、黒田直史、V. L. Varentsov、山崎泰規

物質の世界

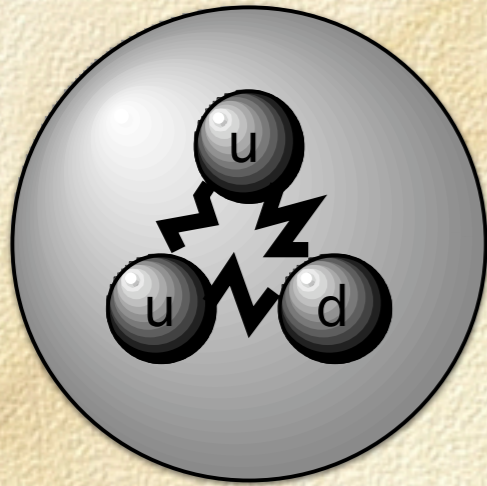


**C** 対称性  
**P** 対称性  
**T** 対称性  
**CP** 対称性  
**CPT** 対称性

反物質の世界

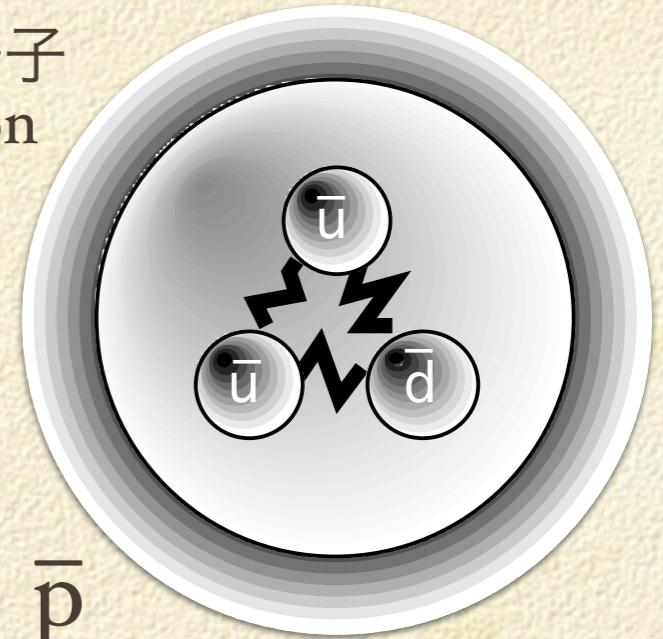


陽子  
proton



p

反陽子  
antiproton



p̄

# 粒子 / 反粒子

**Why No Antimatter?**

物質                      反物質

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

$e^-$



電子 electron

$e^+$



陽電子 positron

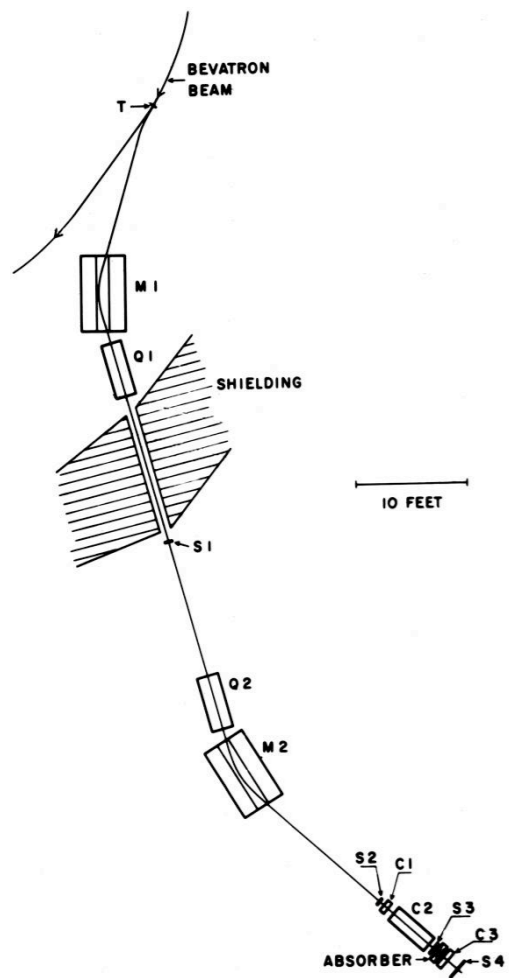
**Paul Dirac**  
(相對論的量子力学)

# Discovery of Antiproton

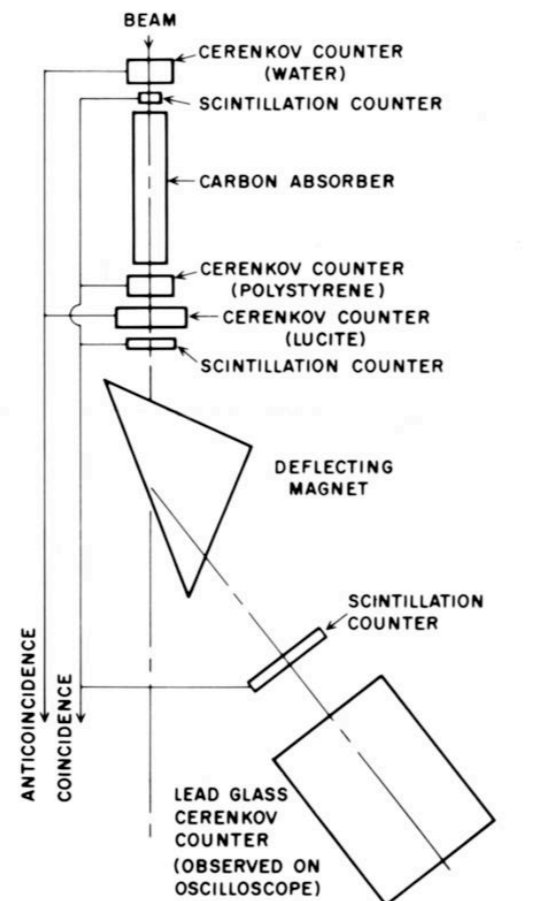
1955; E. Segré & O. Chamberlain

Lawrence-Berkeley Lab., Bevatron

# 反陽子の発見



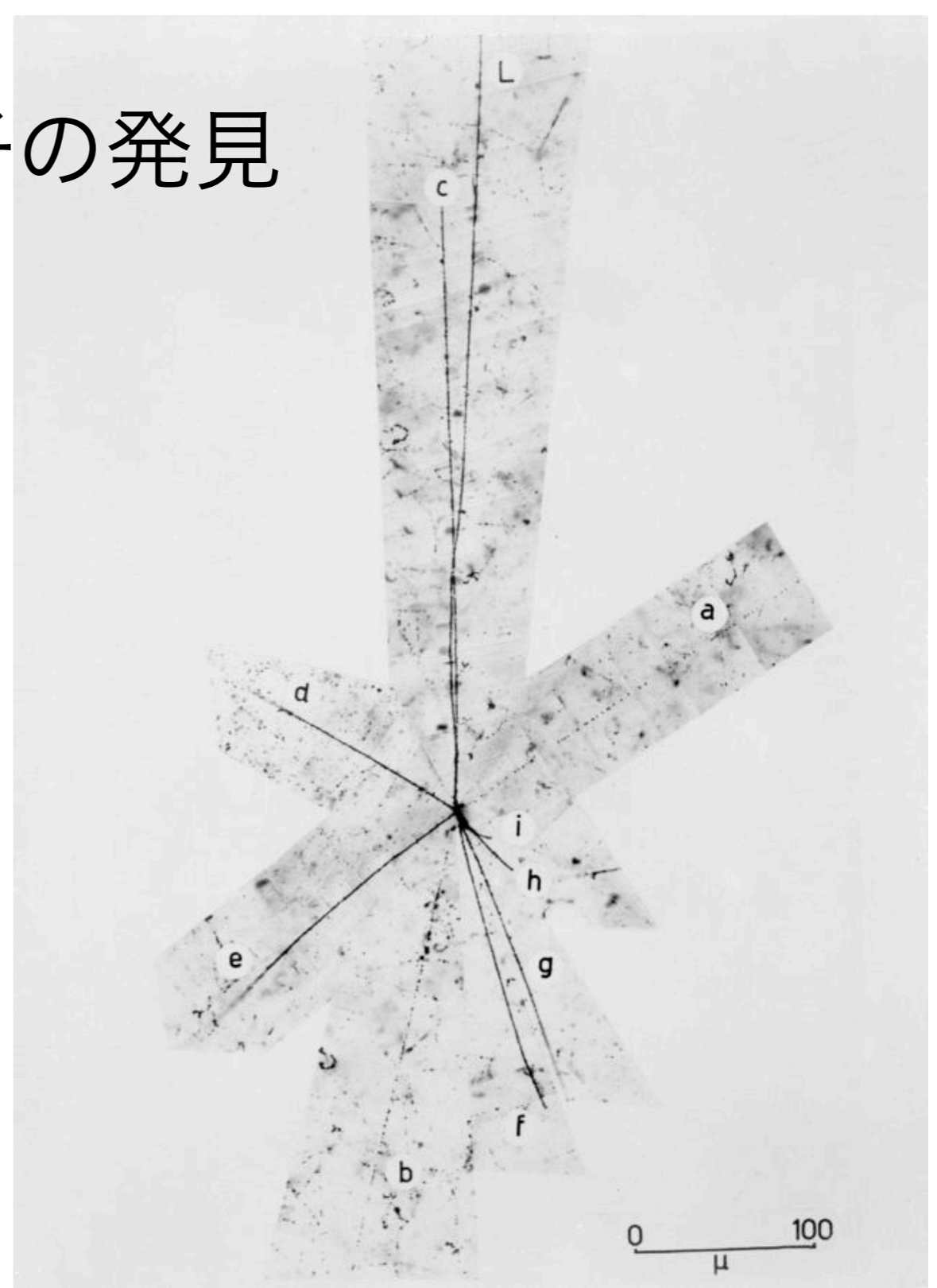
XBD 9606-02963



XBD 9606-02964

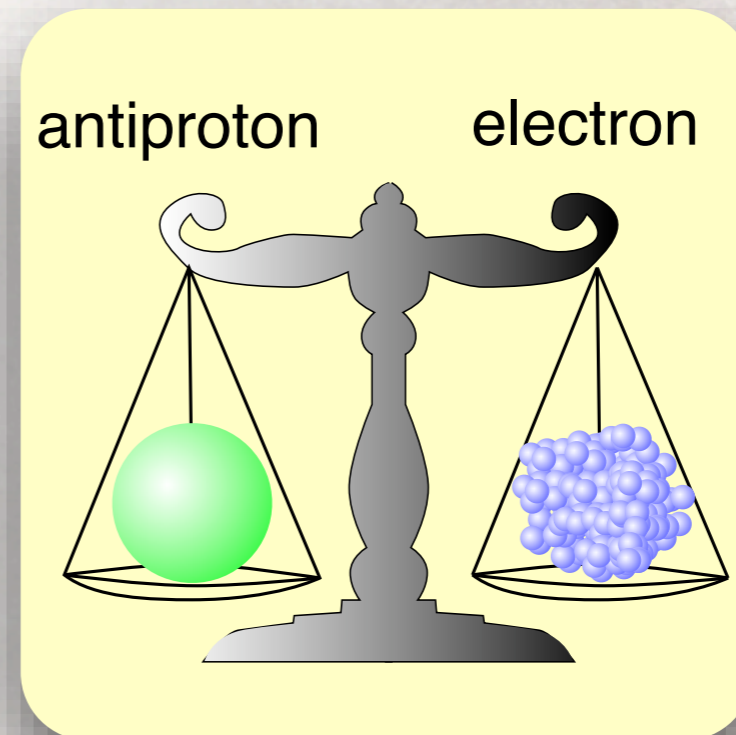
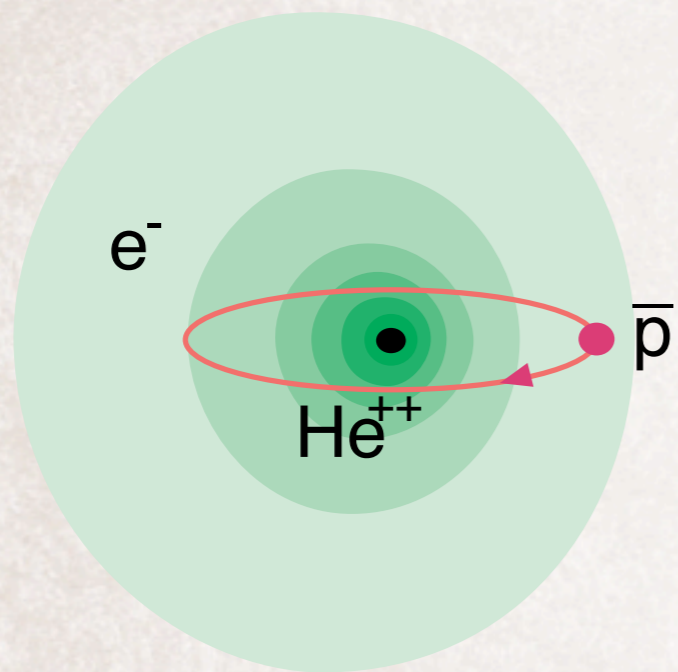
Anti-proton detector used successfully in 1955 by Segre's group. M indicates bending magnets, Q indicates focusing quadrupole magnets, S indicates scintillation counters and C indicates Cerenkov counters to eliminate false counts

Anti-proton detector, used by Lofgren's group, analyzed the beam from Segre's magnets. The small Cerenkov counters distinguished the anti-proton from a meson, the large one registered the annihilation of an anti-proton with a proton.

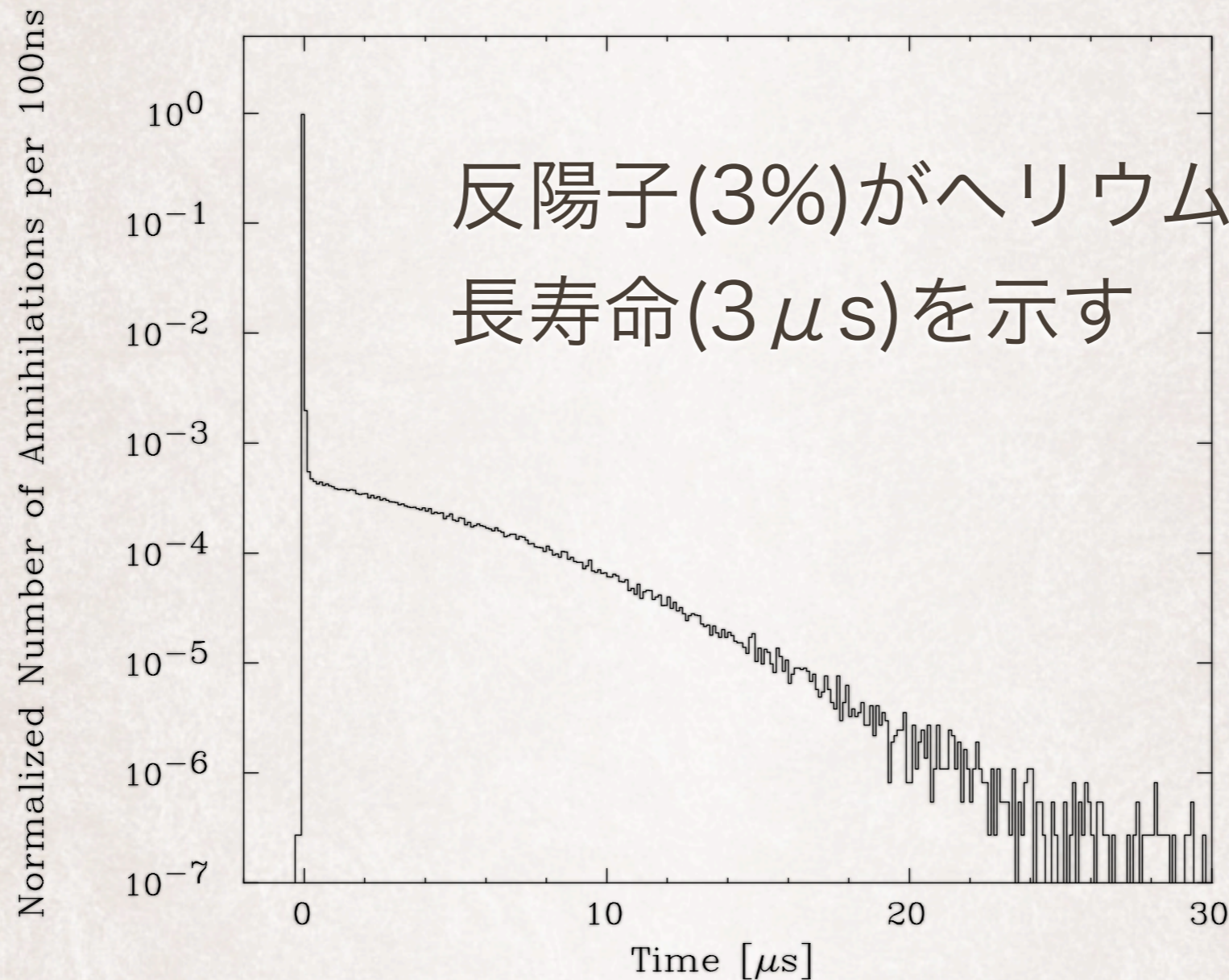


First annihilation star "Faustina" of an anti-proton found in film exposed by the Segre group, 1955. Segre's group pressed forward with the scanning of emulsion stacks in collaboration with a group under Edoardo Amaldi in Rome. The Rome team found the first annihilation star, whose visible energy (the combined energy of all ionizing fragments) amounted to above 826 MeV, an amount deemed appropriate for an explosion initiated by an antiproton. (The preceding information was excerpted from the text of the Fall 1981 issue of LBL Newsmagazine.)

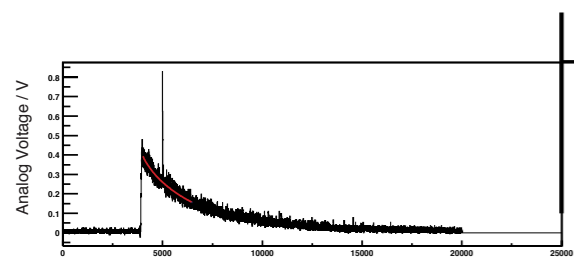
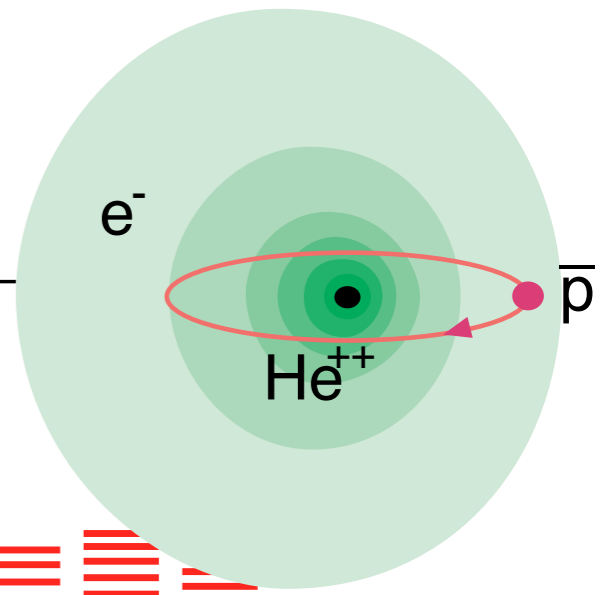
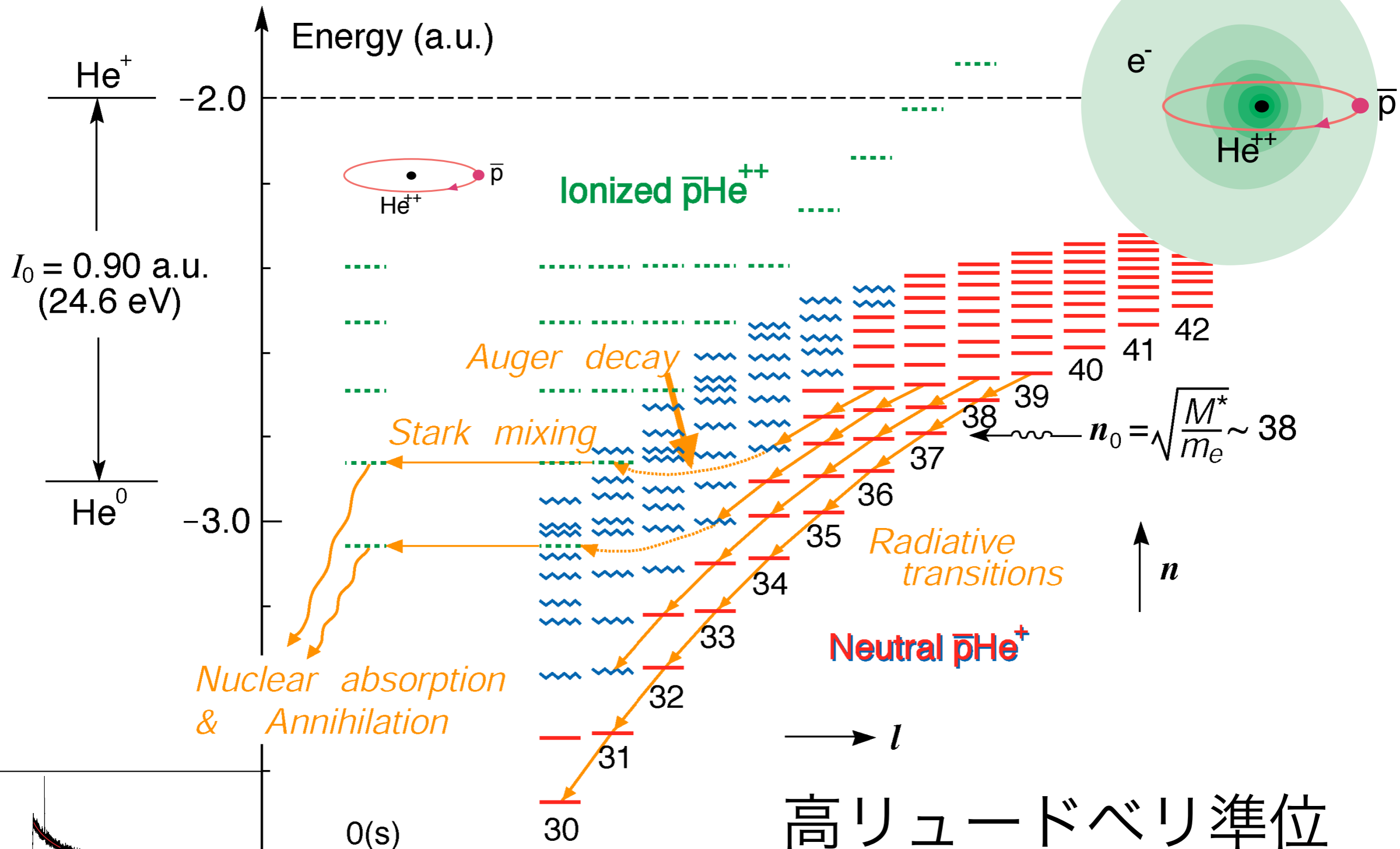
# 反陽子へリウム原子の精密分光



# Delayed Annihilation Time Spectrum of Antiprotons

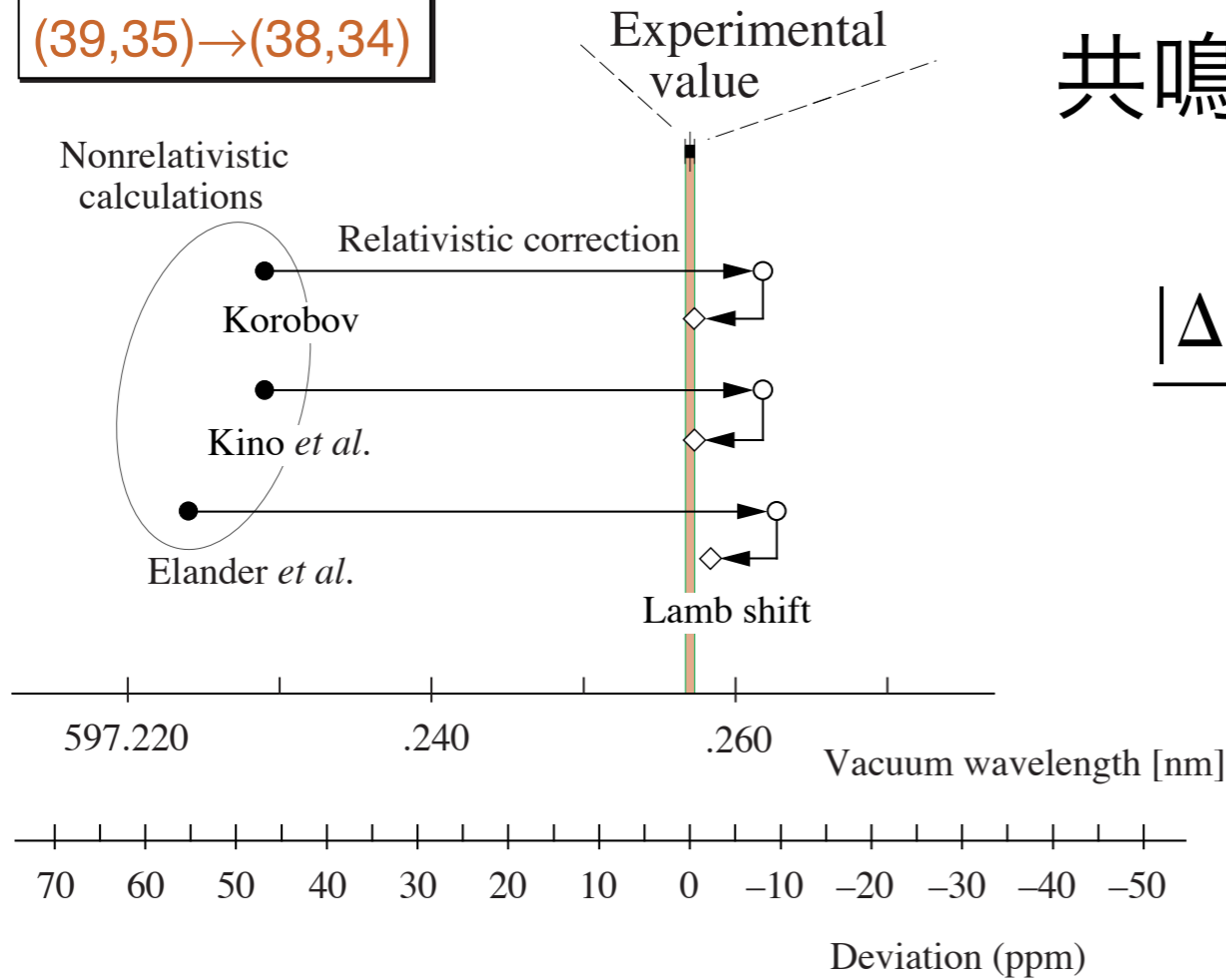


はじめはハイパー核の研究中に  $K^-$  中間子の  
長寿命として観測。次いで  $\pi^-$  でも確認。





(39,35)→(38,34)



# 共鳴周波数の理論計算との比較

$$\frac{|\Delta E_{\text{th}} - \Delta E_{\text{expt}}|}{\Delta E} = \frac{|\lambda_{\text{th}} - \lambda_0|}{\lambda_0} < 2 \times 10^{-6}$$

ppm で一致

# 反陽子の質量を精密に決定

## ● 反陽子ヘリウム原子

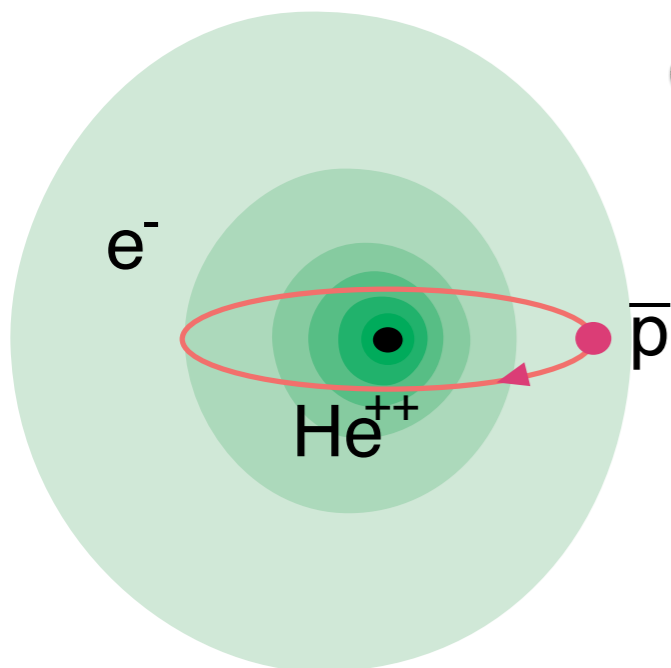
### ● クーロン三体系；高リュードベリ準位

● 電子（原子単位で質量 = 1 a.u.）

● 重粒子（原子質量単位 u (a.m.u.)）

● 反陽子（陽子と比較；CPT対称性）

● ヘリウム原子核（対陽子質量比は既知）





● 反陽子の質量の精密測定研究

● 2006年：精度  $2 \times 10^{-9}$  (パルス増幅、光コム)

● 陽子と電子の質量比の決定へ

● 2006年：精度  $3 \times 10^{-9}$

CODATA  
との比較

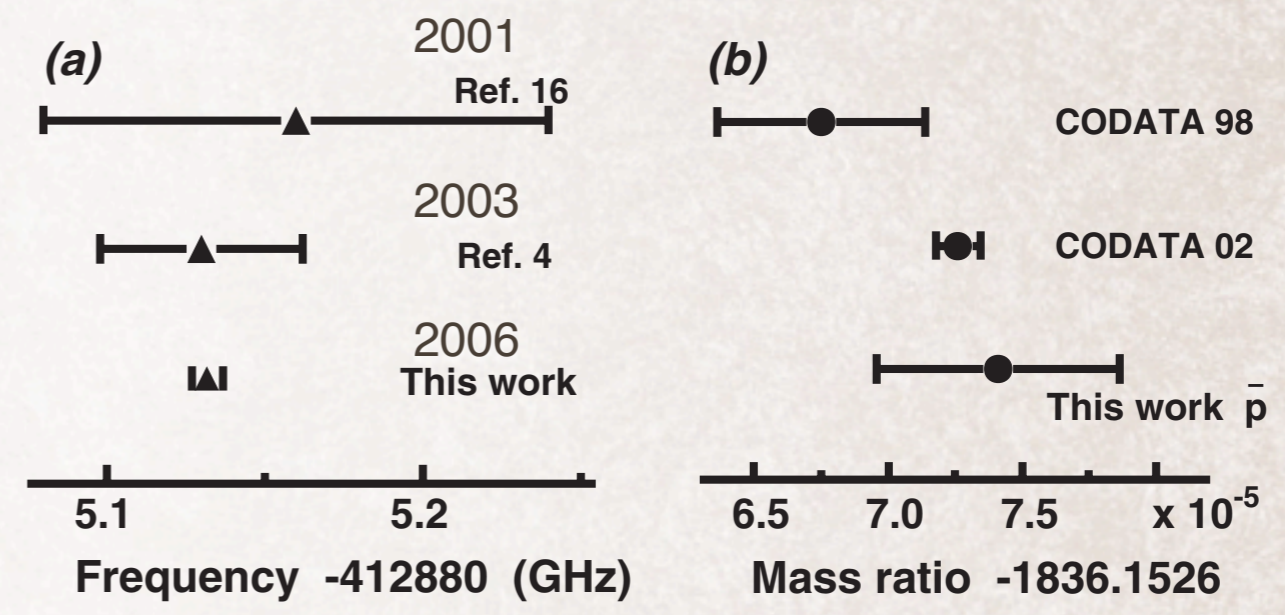
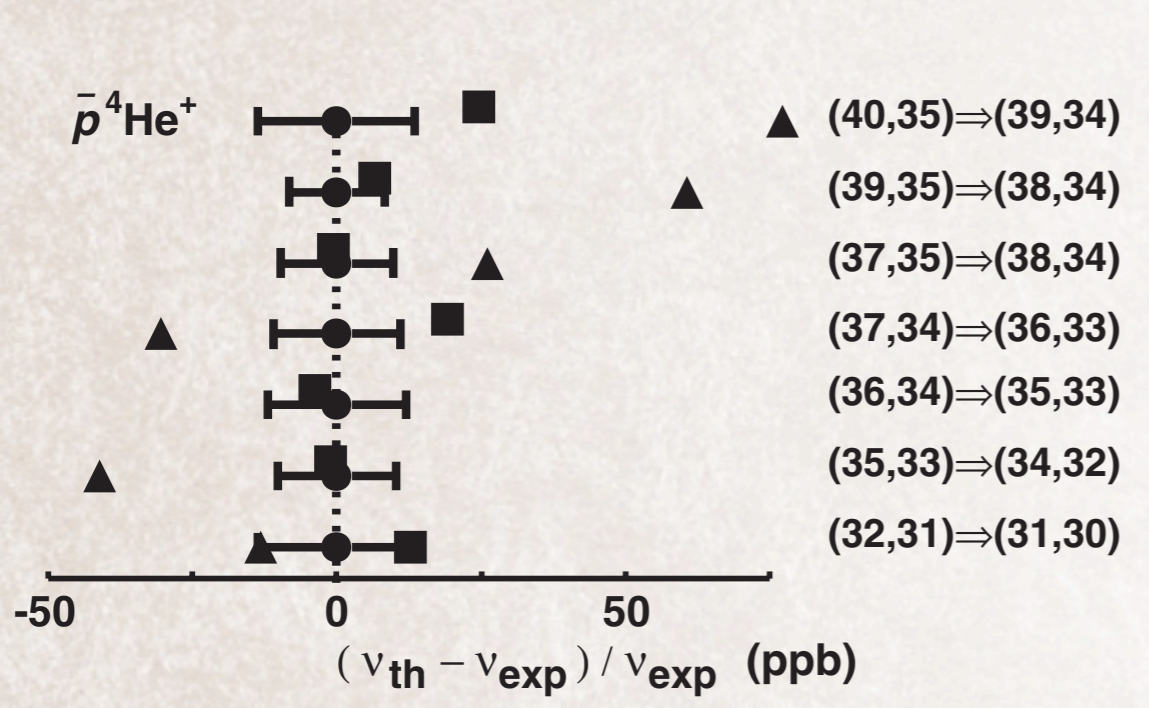
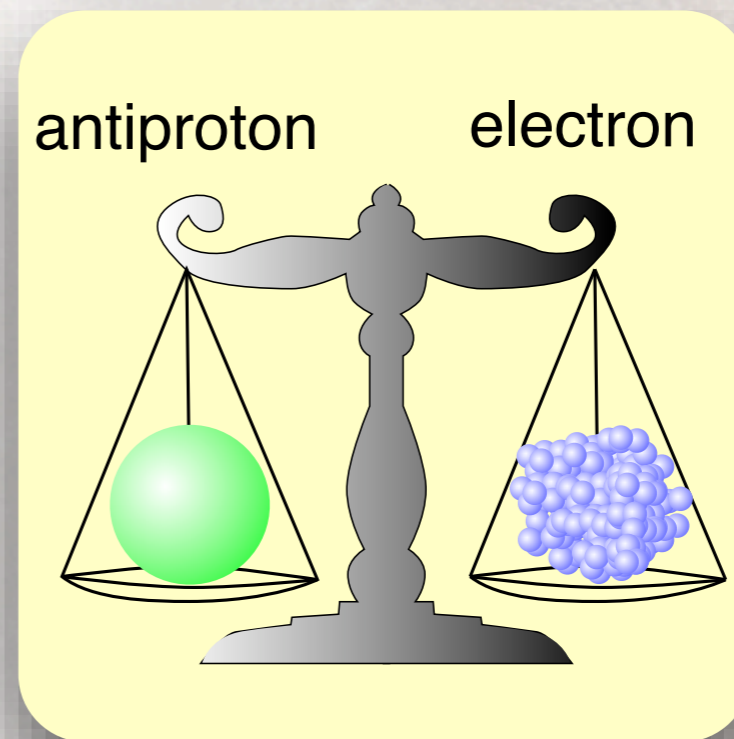
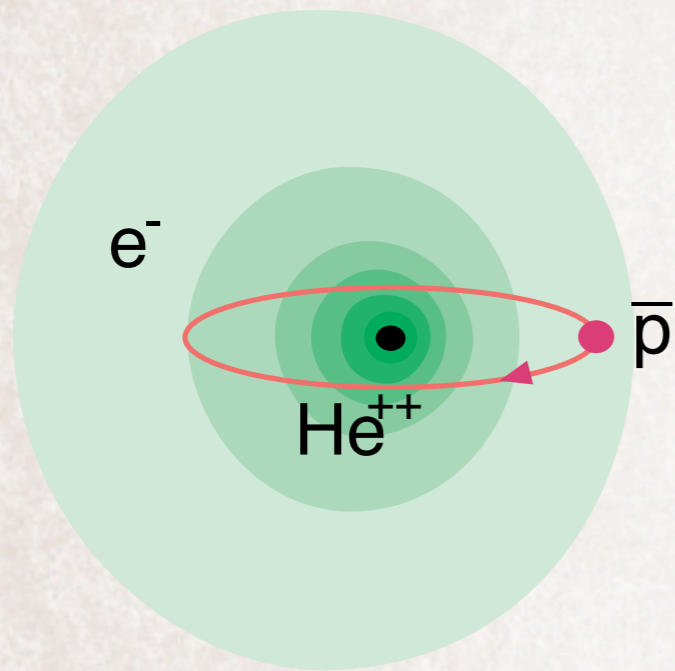
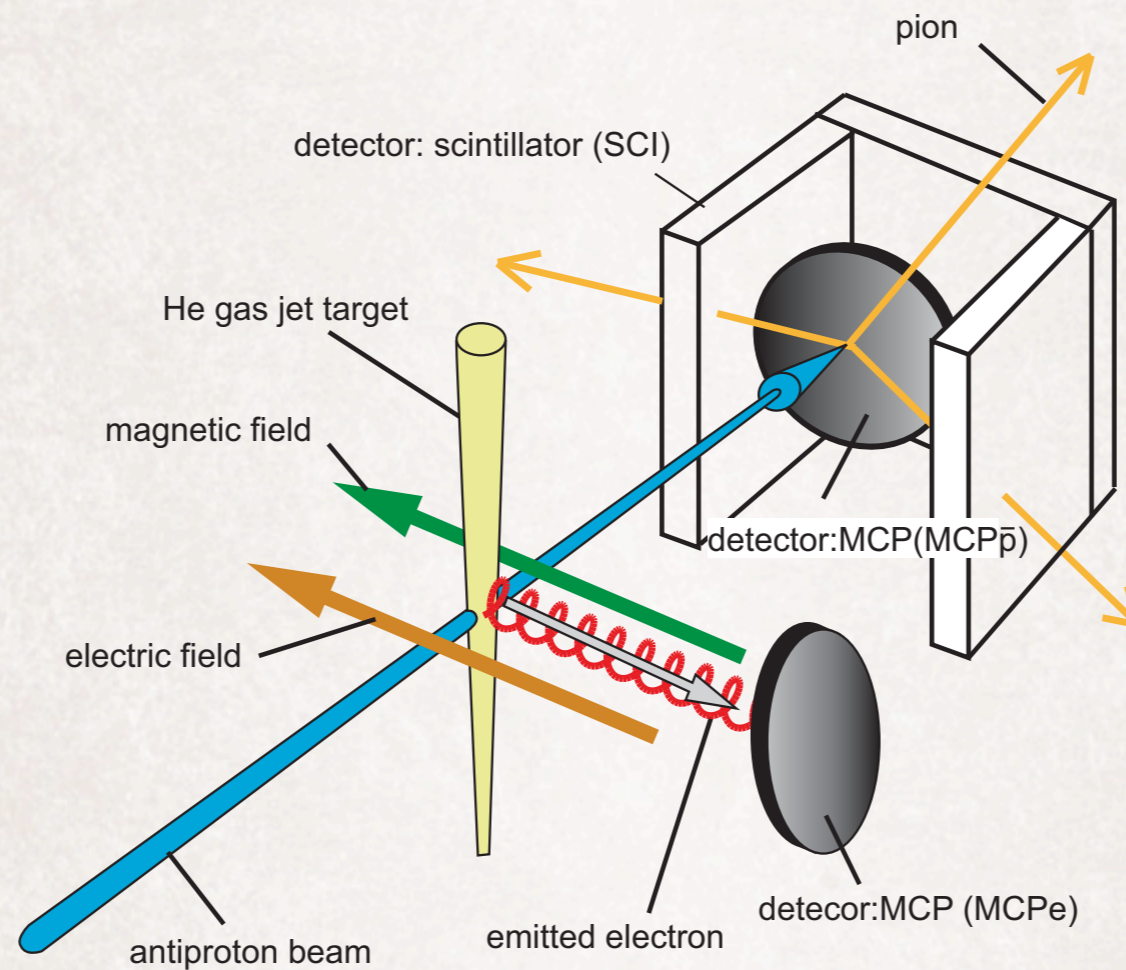


FIG. 6. (a) Frequency of the  $\bar{p}^4\text{He}^+$  transition (37, 35)  $\rightarrow$  (38, 34) measured in this and previous [4,16] experiments. (b) Proton-to-electron [7] and antiproton-to-electron mass ratios.

- 反陽子ヘリウム原子の精密レーザー分光による反陽子の質量の精密測定研究
- 反陽子ヘリウム原子のマイクロ波分光による反陽子の磁気モーメントの測定研究



# 超低速反陽子ビームの生成と 原子衝突実験



# Collision Dynamics

低エネルギー反陽子ビーム

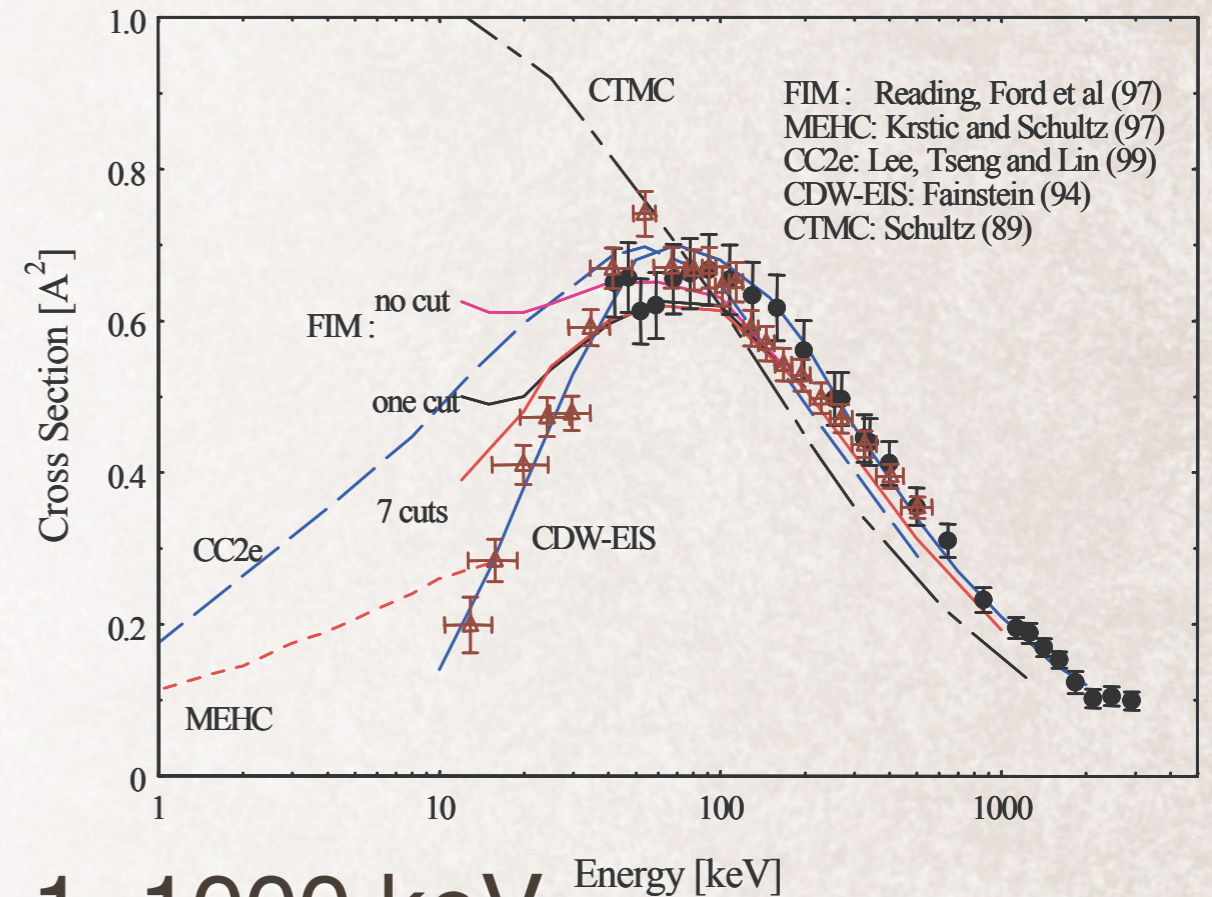
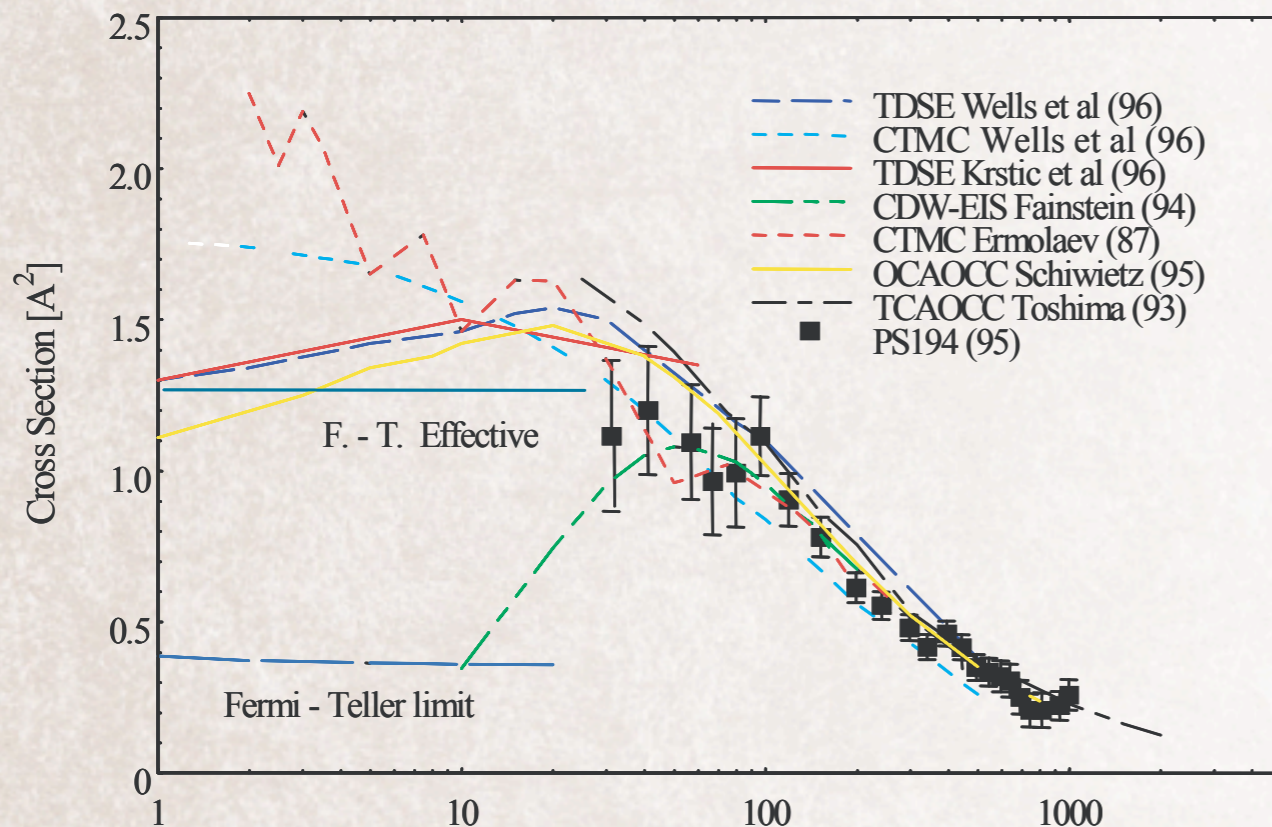
重い電子

— 原子衝突過程の優れたプローブ

負電荷の陽子

ionization cross section for atomic  $\bar{p} - D$

single ionization cross sect. for  $\bar{p} - He$

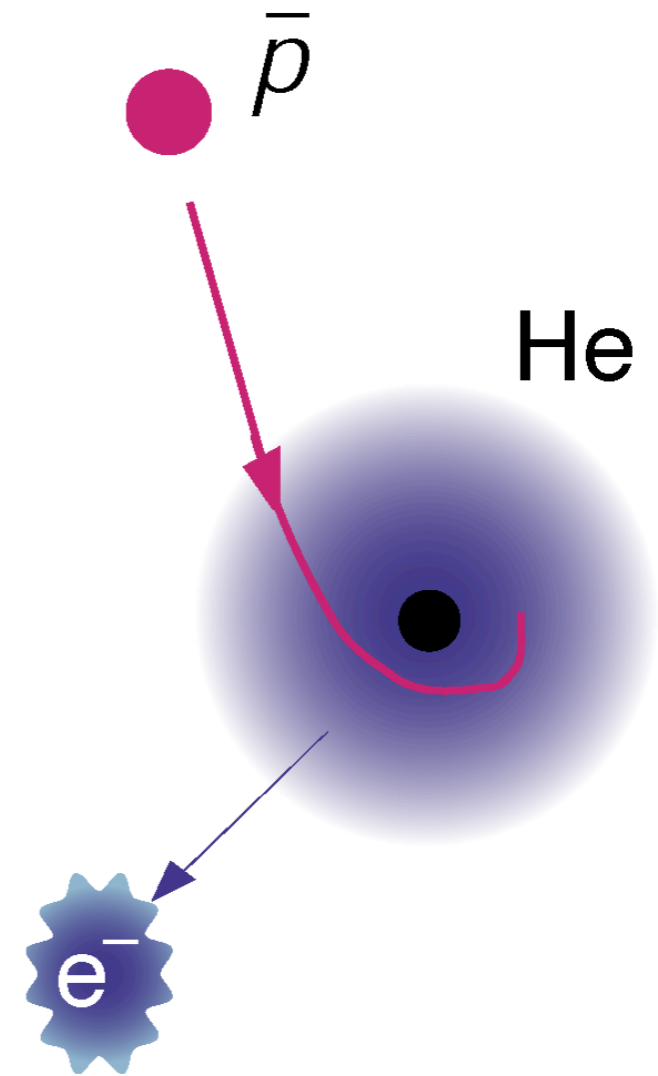
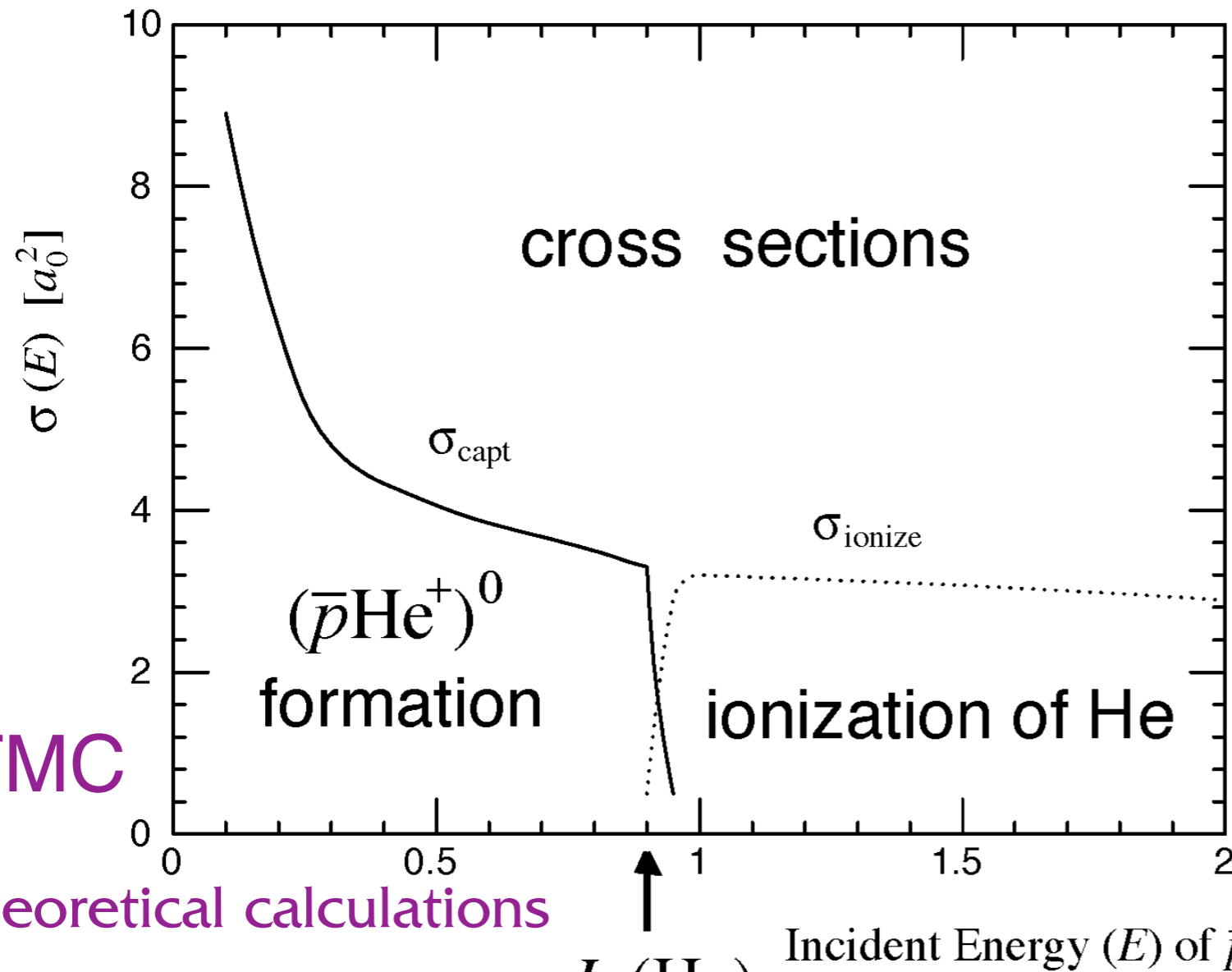


ionization : 1–1000 keV



原子物理の単純な系でも衝突過程はまだ理解が足りない！

$\bar{p} + \text{He}$



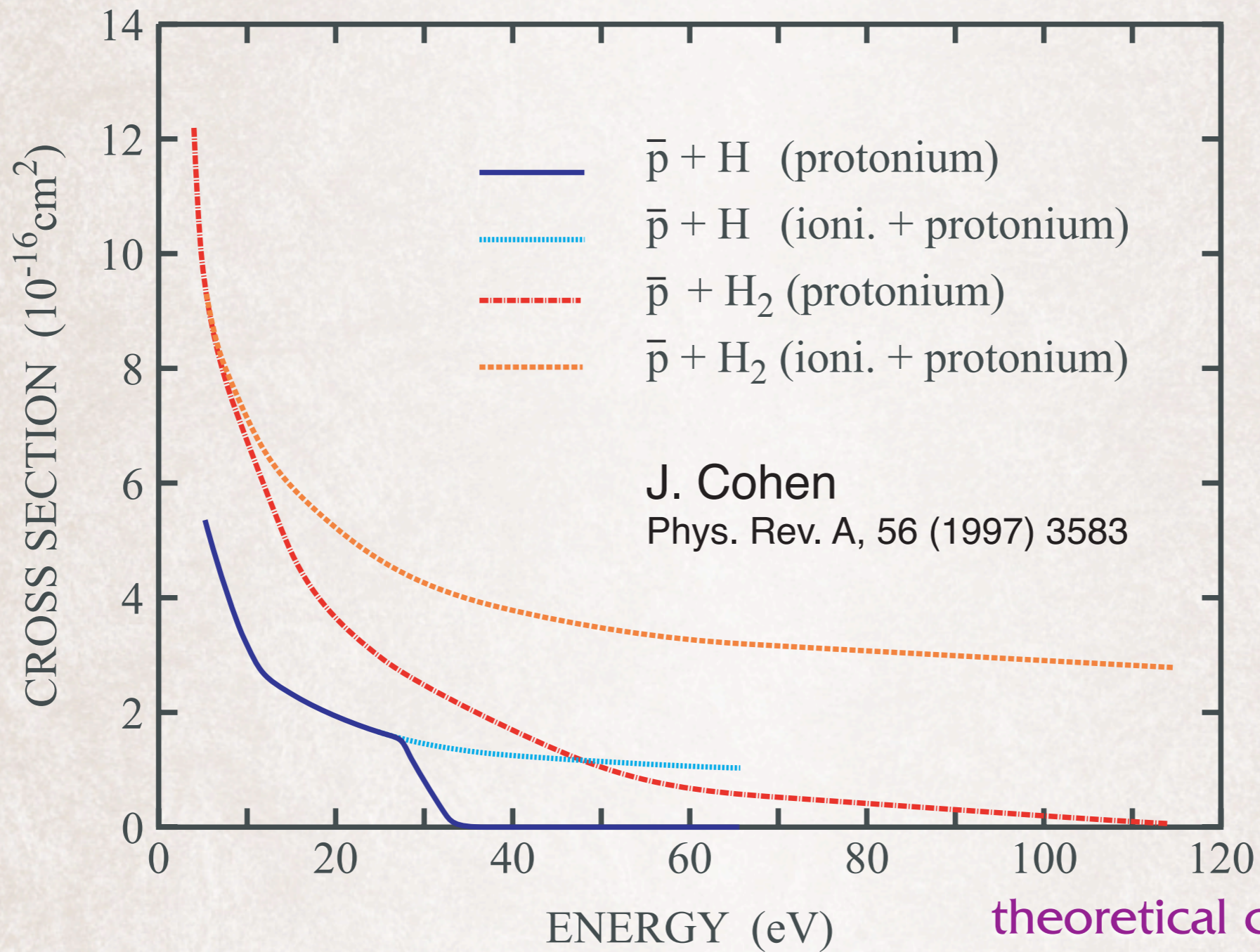
CTMC

theoretical calculations

atomic formation : 1–100 eV

# Exotic Atom Formation

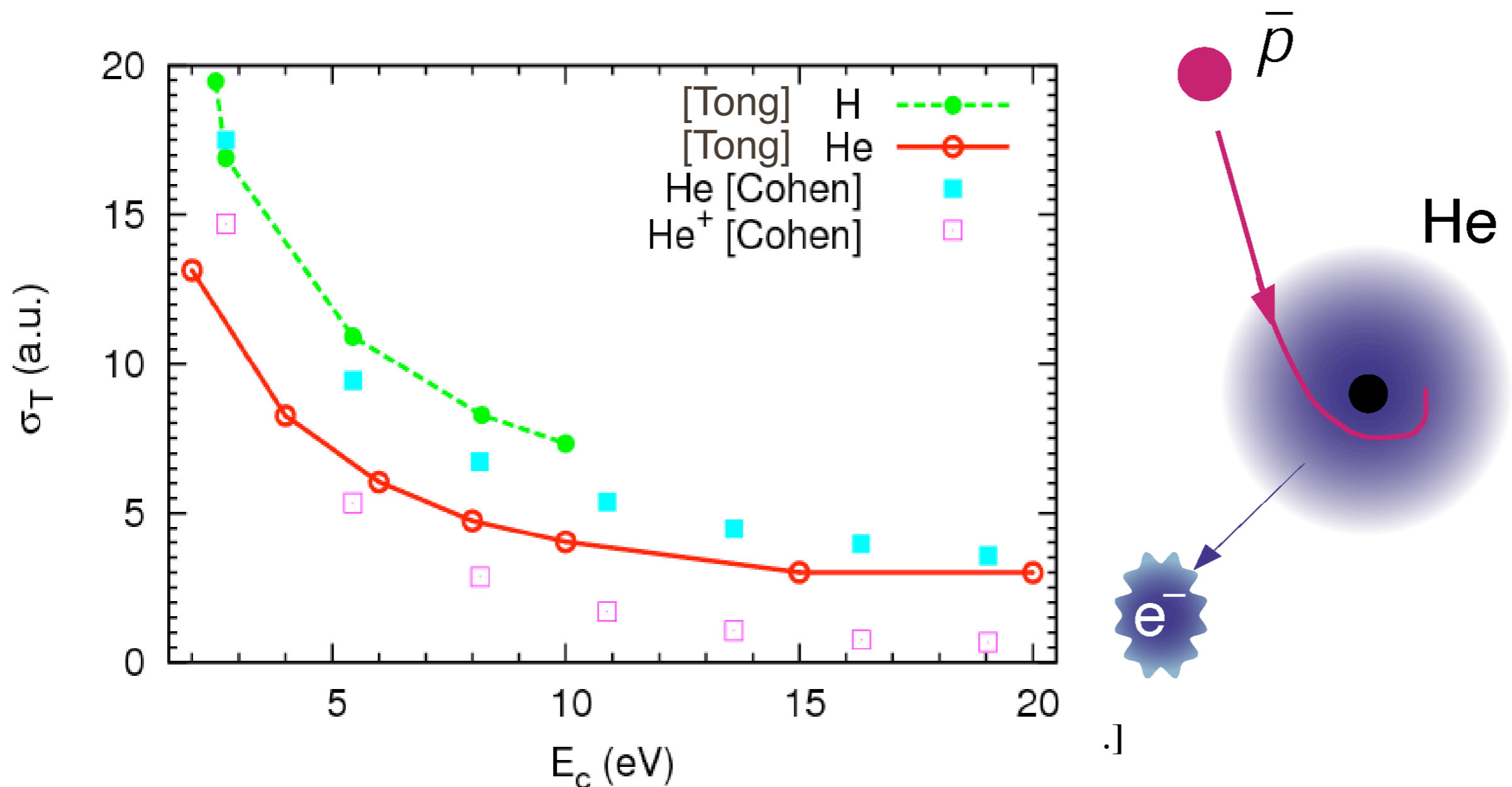
capture + ioniz. cross. sect. for  $\bar{p} + \text{H} / \text{H}_2$



atomic formation : 1–100 eV

# $\bar{p} + \text{He}$

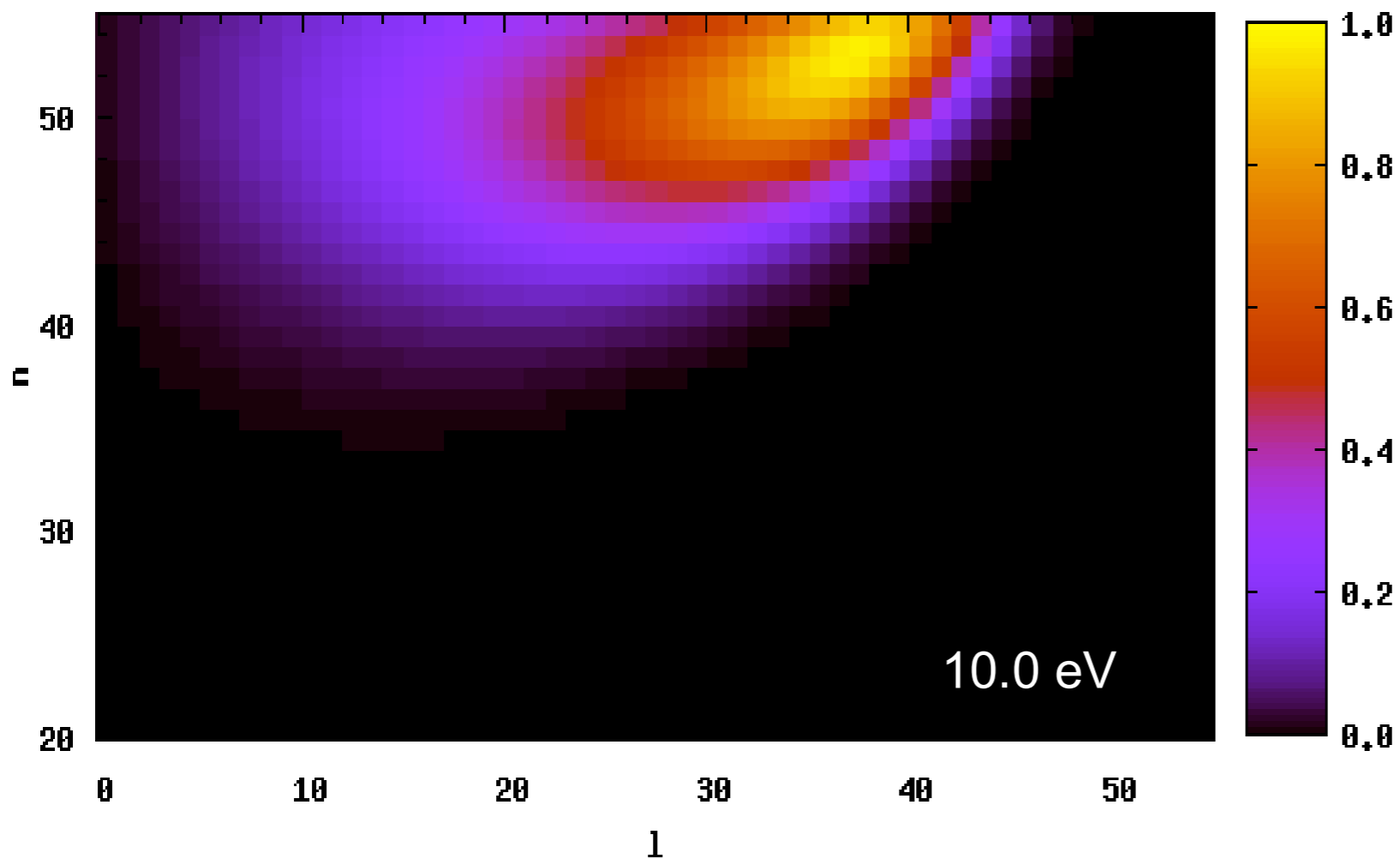
Cohen, Sakimoto, Tong, ...



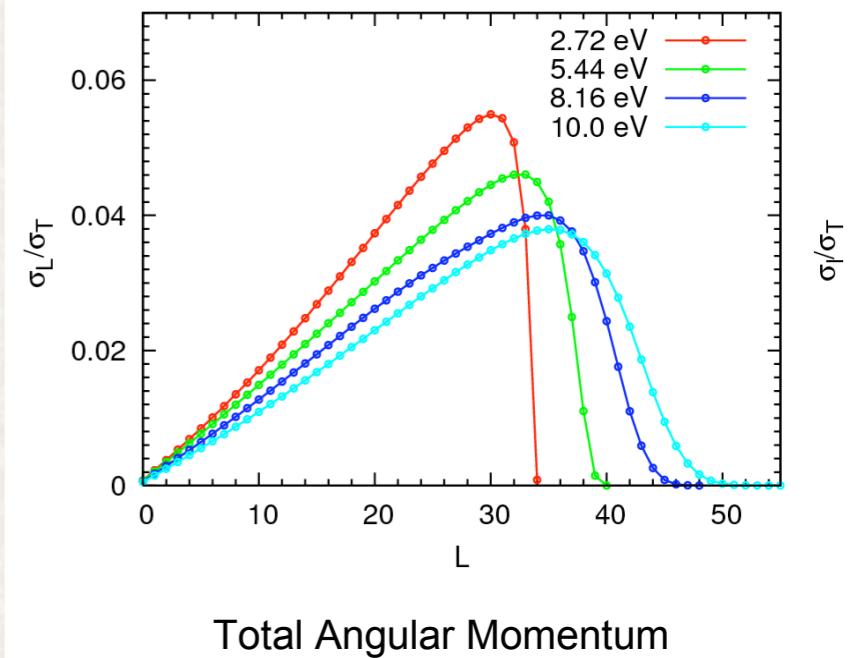
atomic formation : 1–100 eV



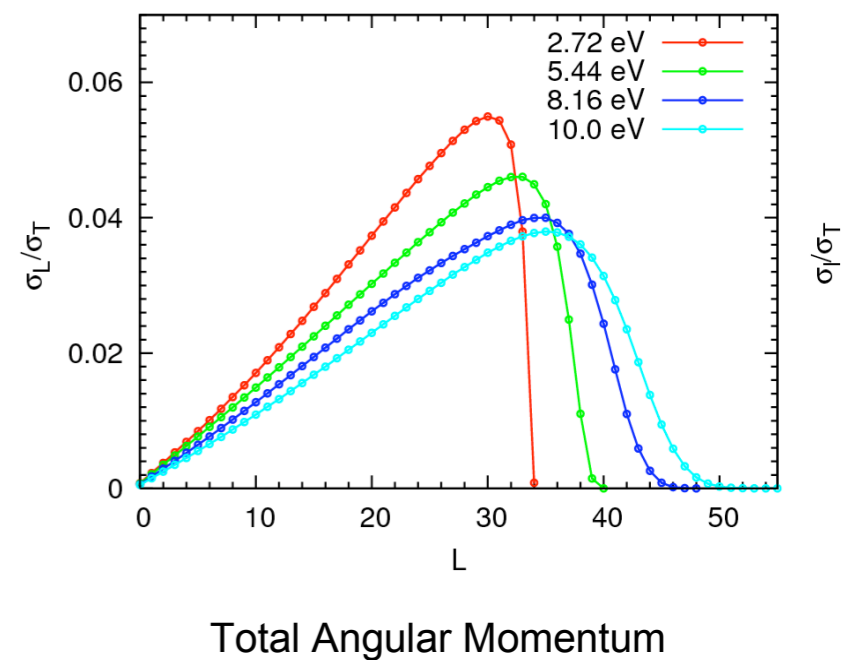
$$\sigma_{nl} = \sum_L \sigma_{nl}^L$$



$$\sigma_L = \sum_{nl} \sigma_{nl}^L$$



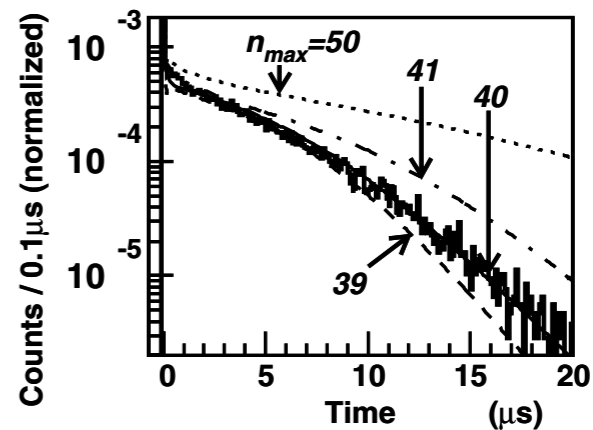
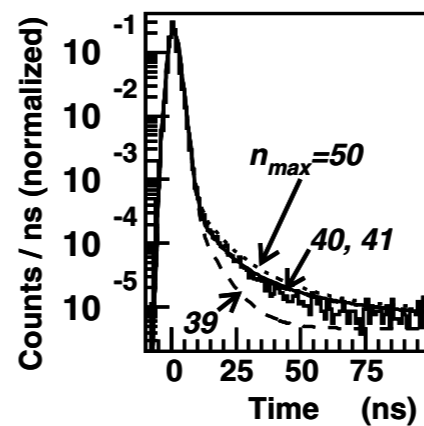
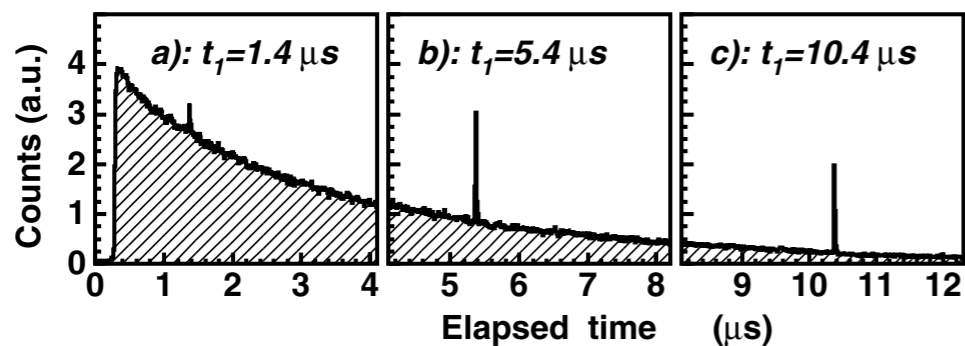
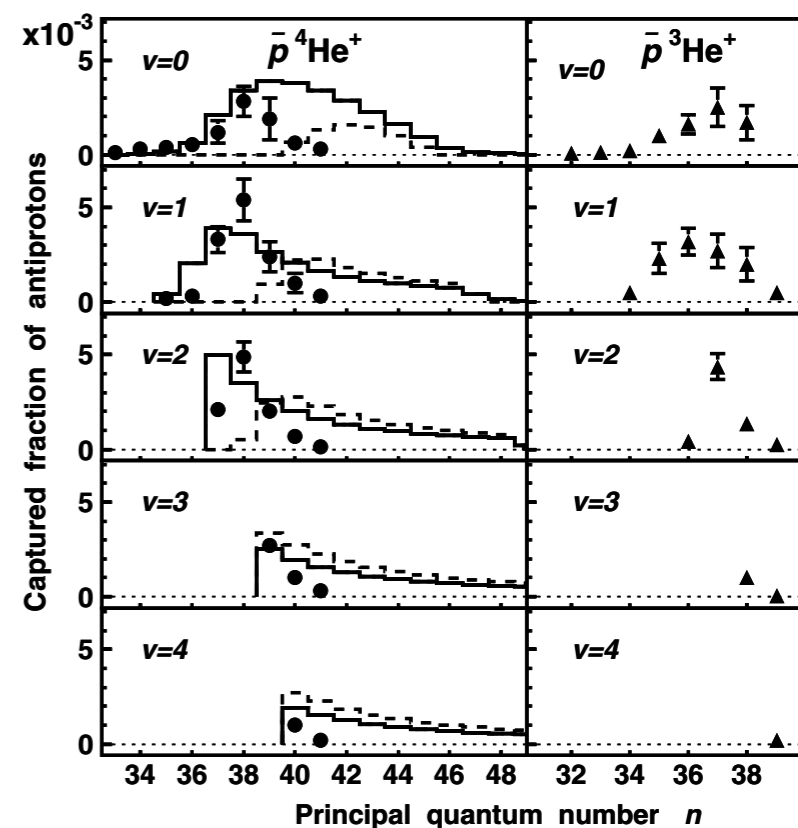
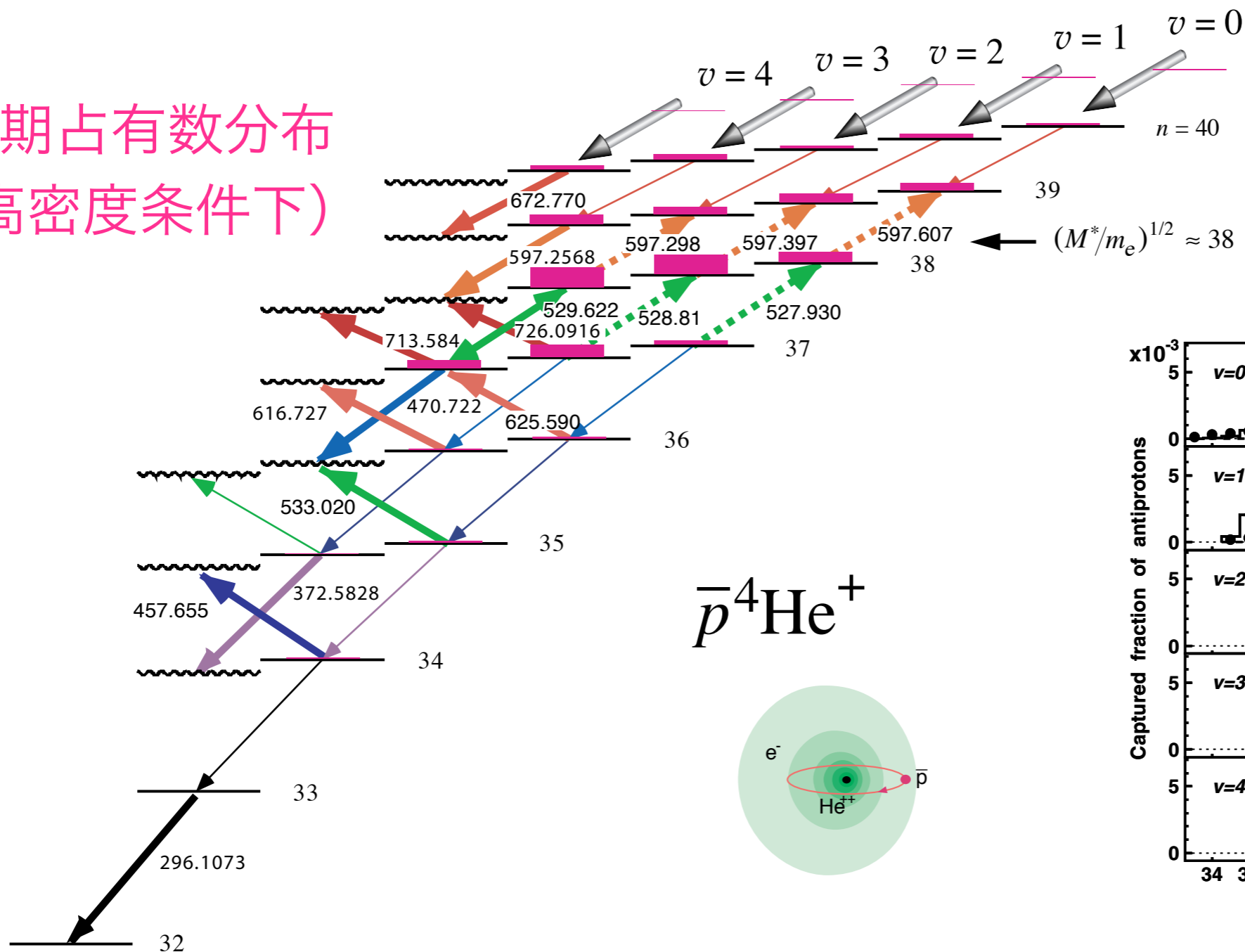
$$\sigma_L = \sum_{nl} \sigma_{nl}^L$$



X.-M. Tong et al.

$l = 32 \quad 33 \quad 34 \quad 35 \quad 36 \quad 37 \quad 38 \quad 39$

初期占有数分布  
(高密度条件下)





## ASACUSA

Atomic Spectroscopy  
And Collisions  
Using Slow Antiprotons

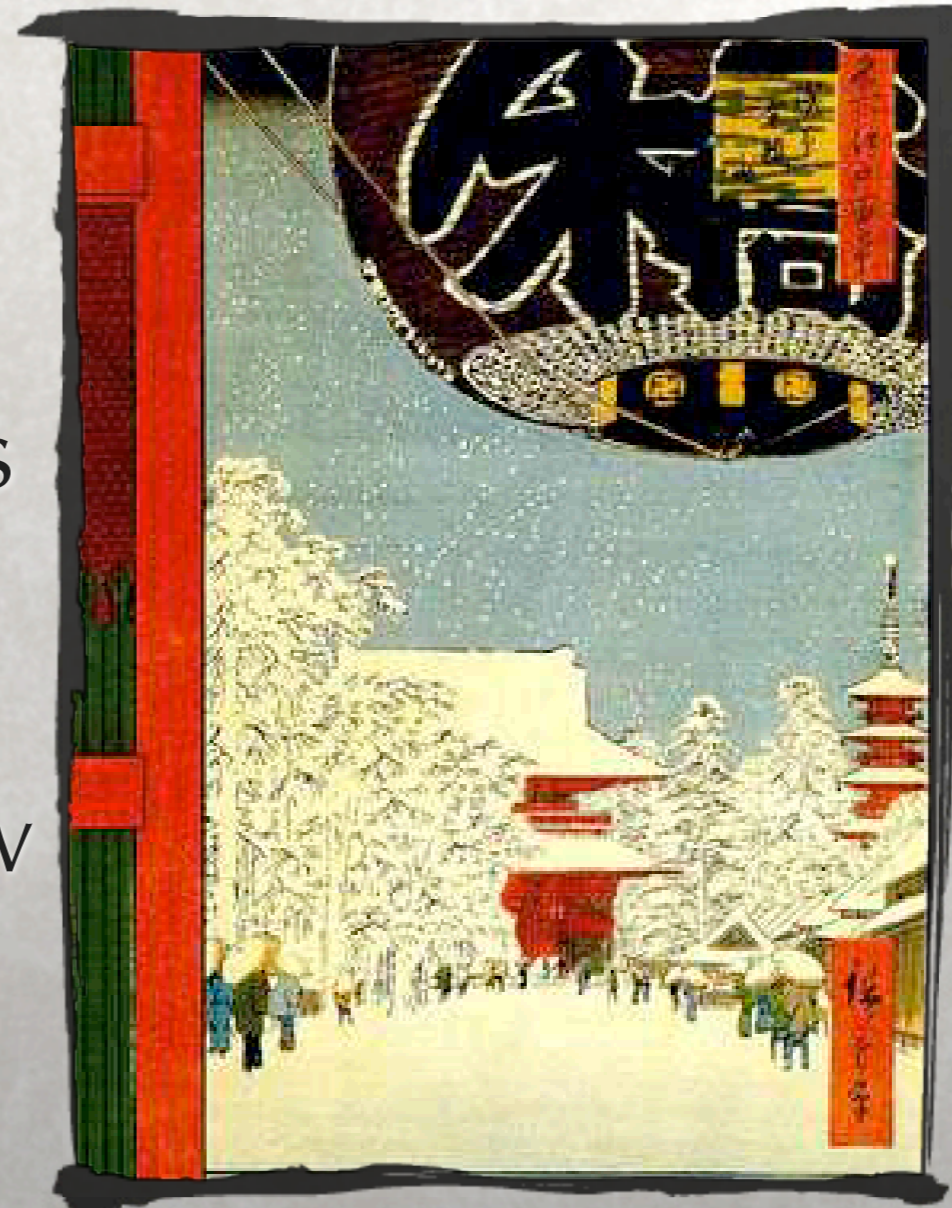


## MUSASHI

Monoenergetic UltraSlow  
Antiproton Source  
for High-precision  
Investigations

武蔵

浅草



*Asakusa, Tokyo*

# 反物質の世界

**CPT 対称性**

高エネルギー  
(素粒子)  
から  
低エネルギー  
(原子)  
への挑戦



物質の真実

# 反陽子の生成

$$E = mc^2$$

エネルギーと質量は等価

エネルギー・運動量保存

バリオン(重粒子)数保存

# 反陽子の生成

$$E = mc^2$$

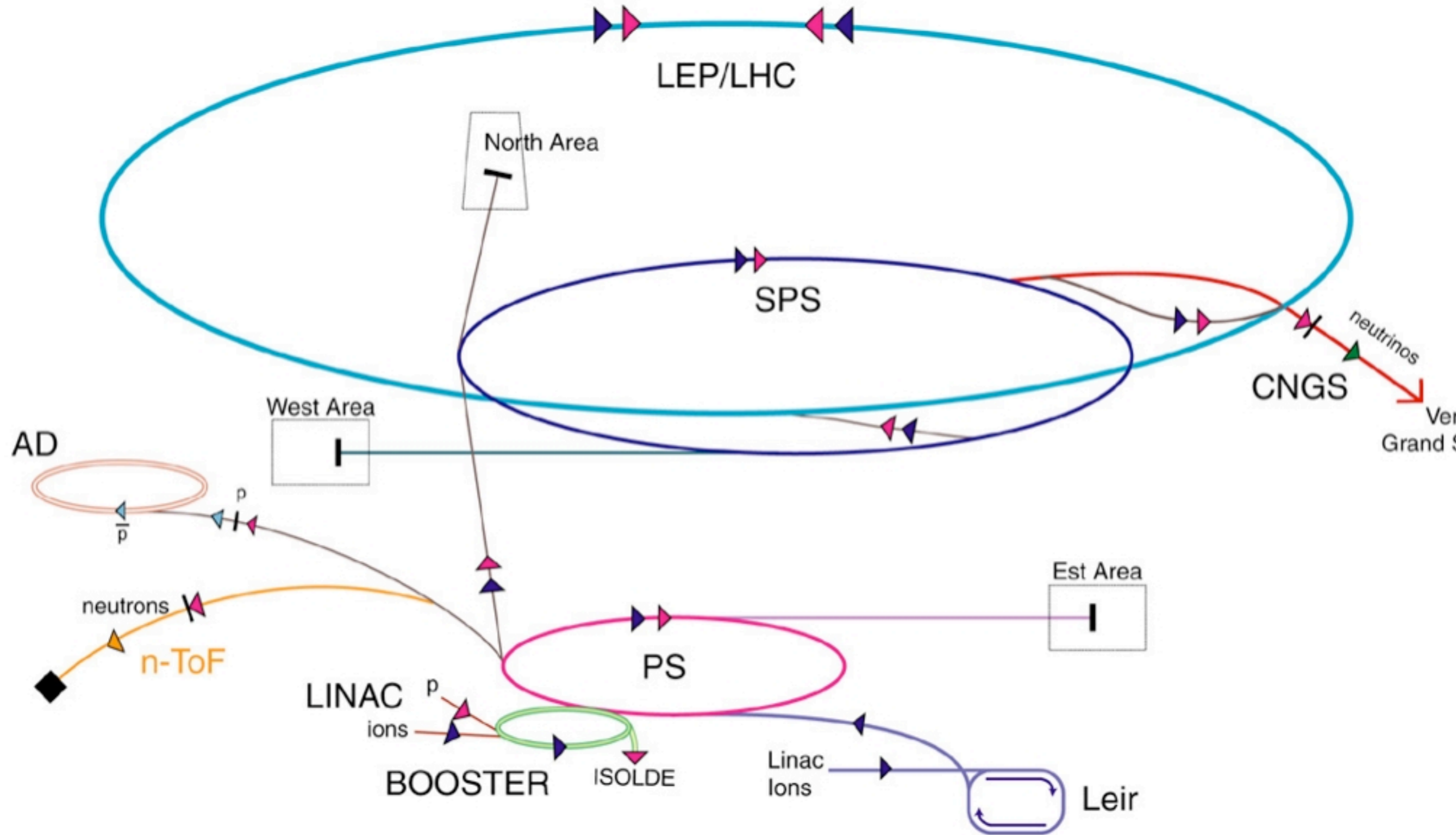
エネルギーと質量は等価



エネルギー・運動量保存

バリオン(重粒子)数保存

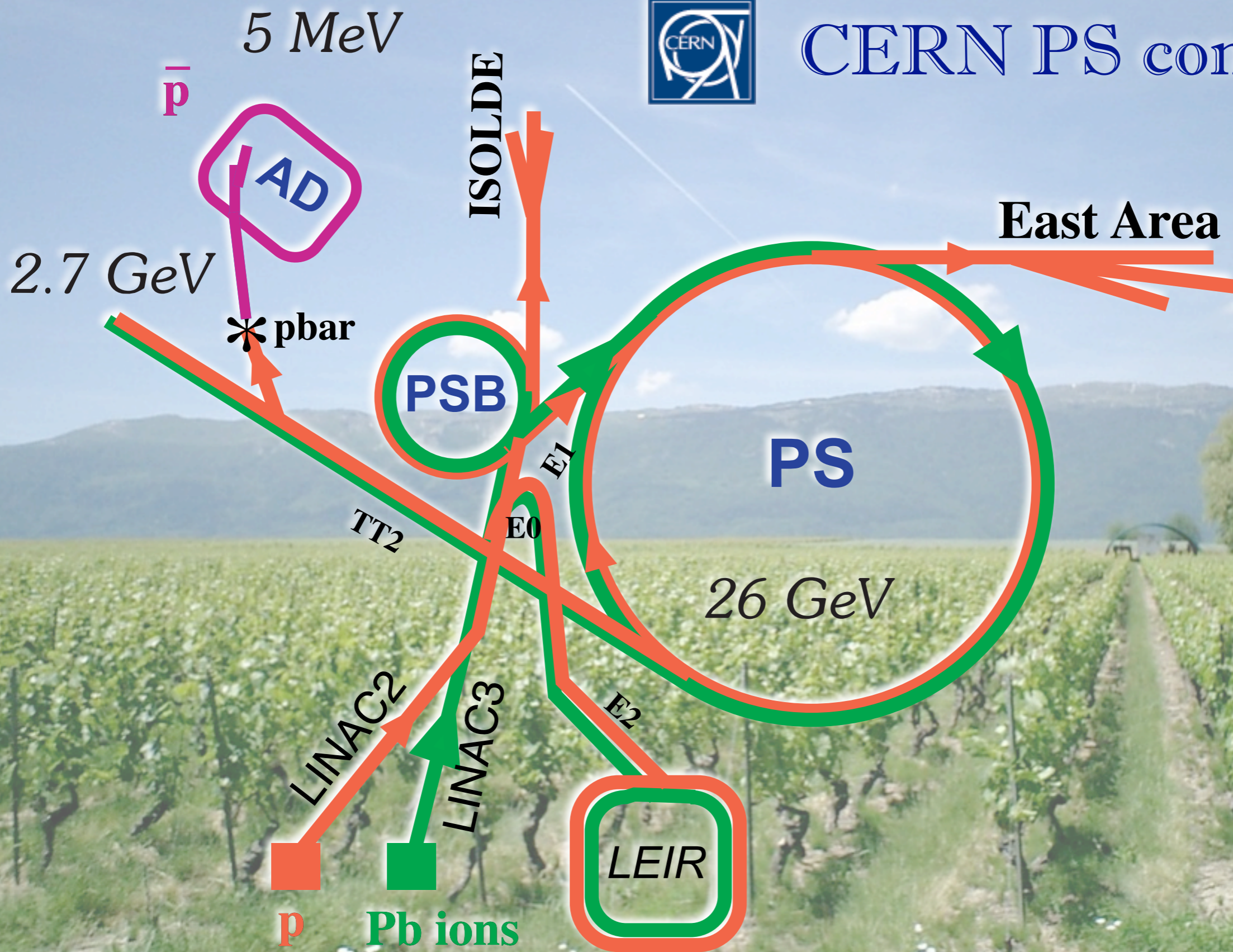
# Accelerator chain of CERN (operating or approved projects)



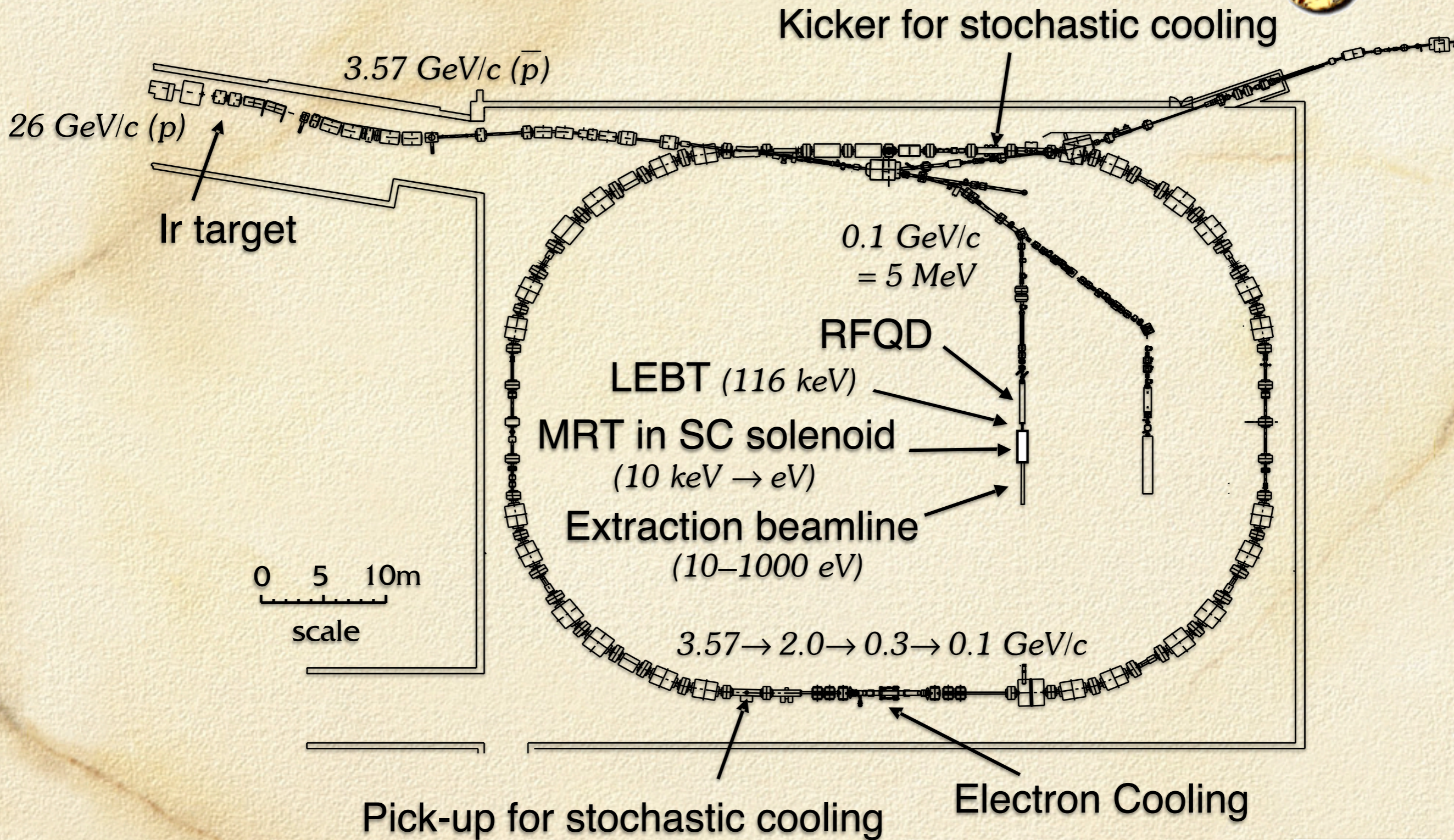
- |              |                                |                              |                                 |
|--------------|--------------------------------|------------------------------|---------------------------------|
| ▶ p (proton) | ▶ $\bar{p}$ (antiproton)       | AD Antiproton Decelerator    | LHC Large Hadron Collider       |
| ▶ ion        | ↔ proton/antiproton conversion | PS Proton Synchrotron        | n-ToF Neutrons Time of Flight   |
| ▶ neutrons   | ▶ neutrinos                    | SPS Super Proton Synchrotron | CNGS Cern Neutrinos Grand Sasso |



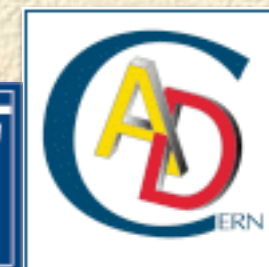
# CERN PS complex

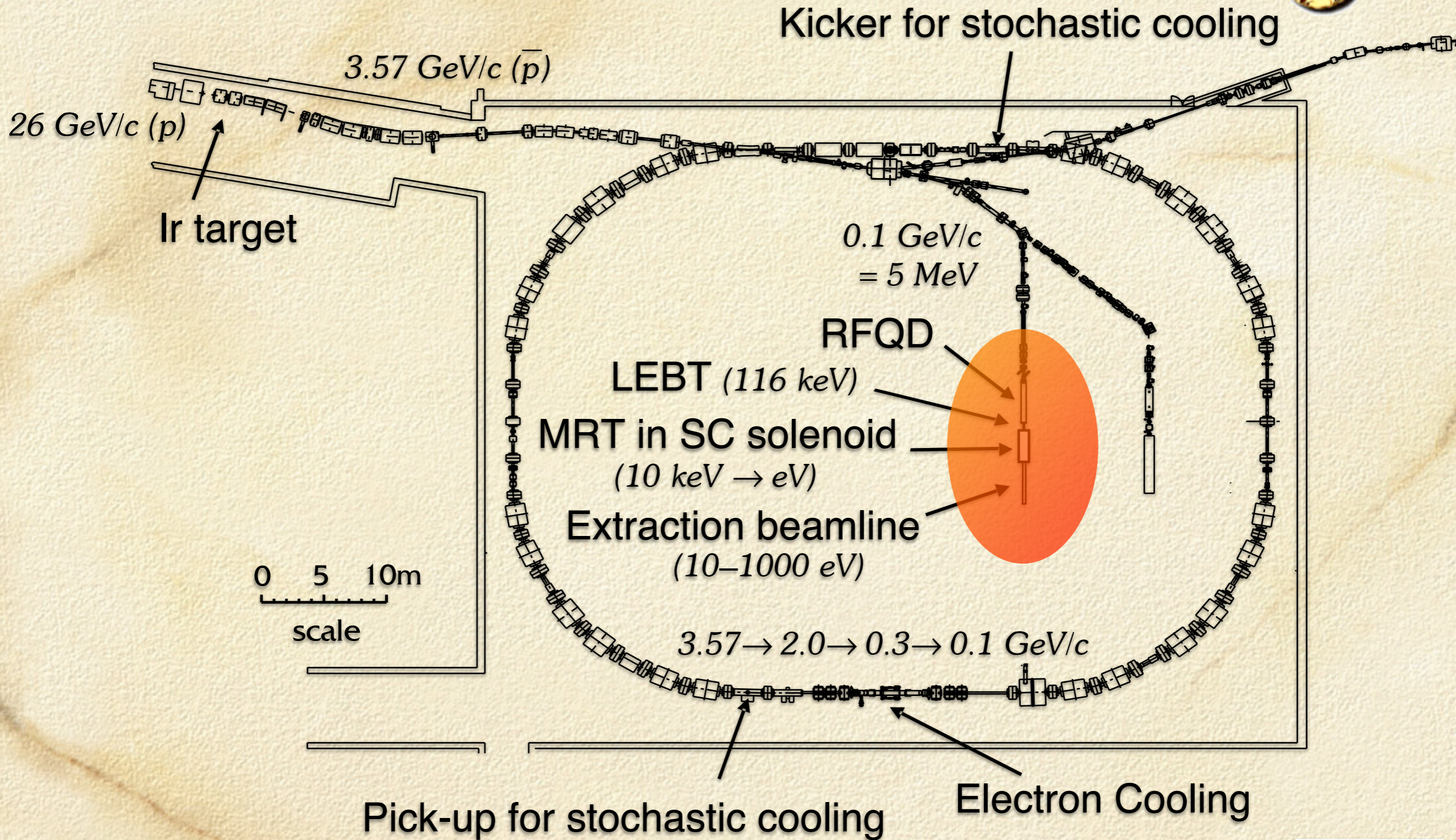




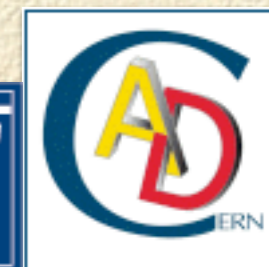


**CERN AD ring**  
Antiproton Decelerator





**CERN AD ring**  
Antiproton Decelerator



# Cooling scheme

5.3 MeV antiproton from AD

↓  
RFQD (Radio-Frequency  
Quadrupole Decelerator)

~ 100 keV antiproton

↓  
thin degrader foils

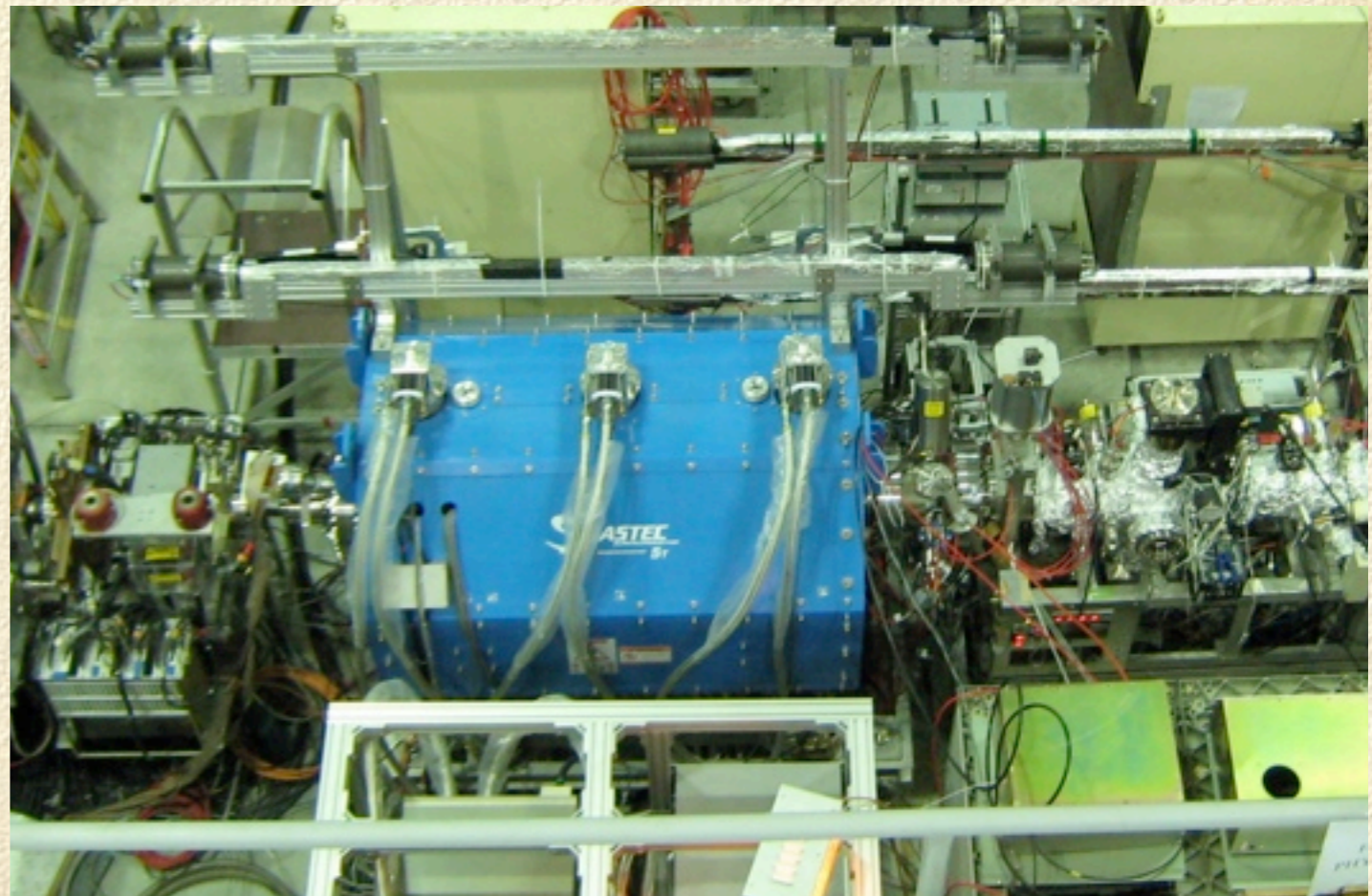
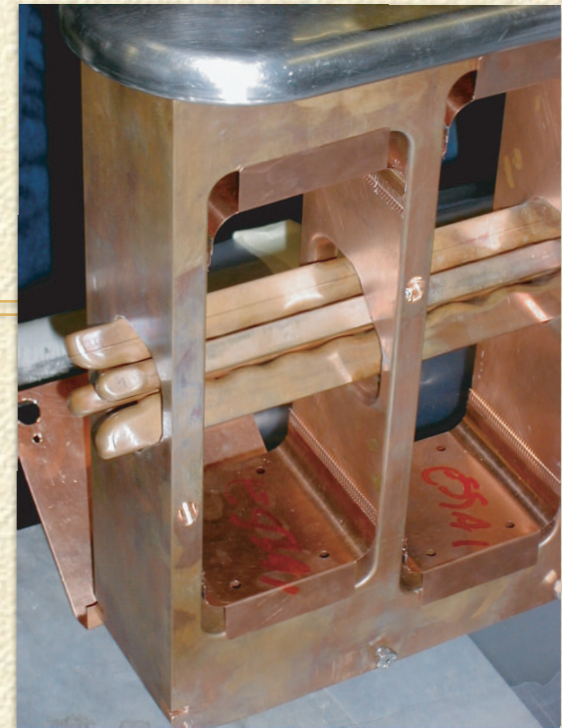
< 10 keV antiproton

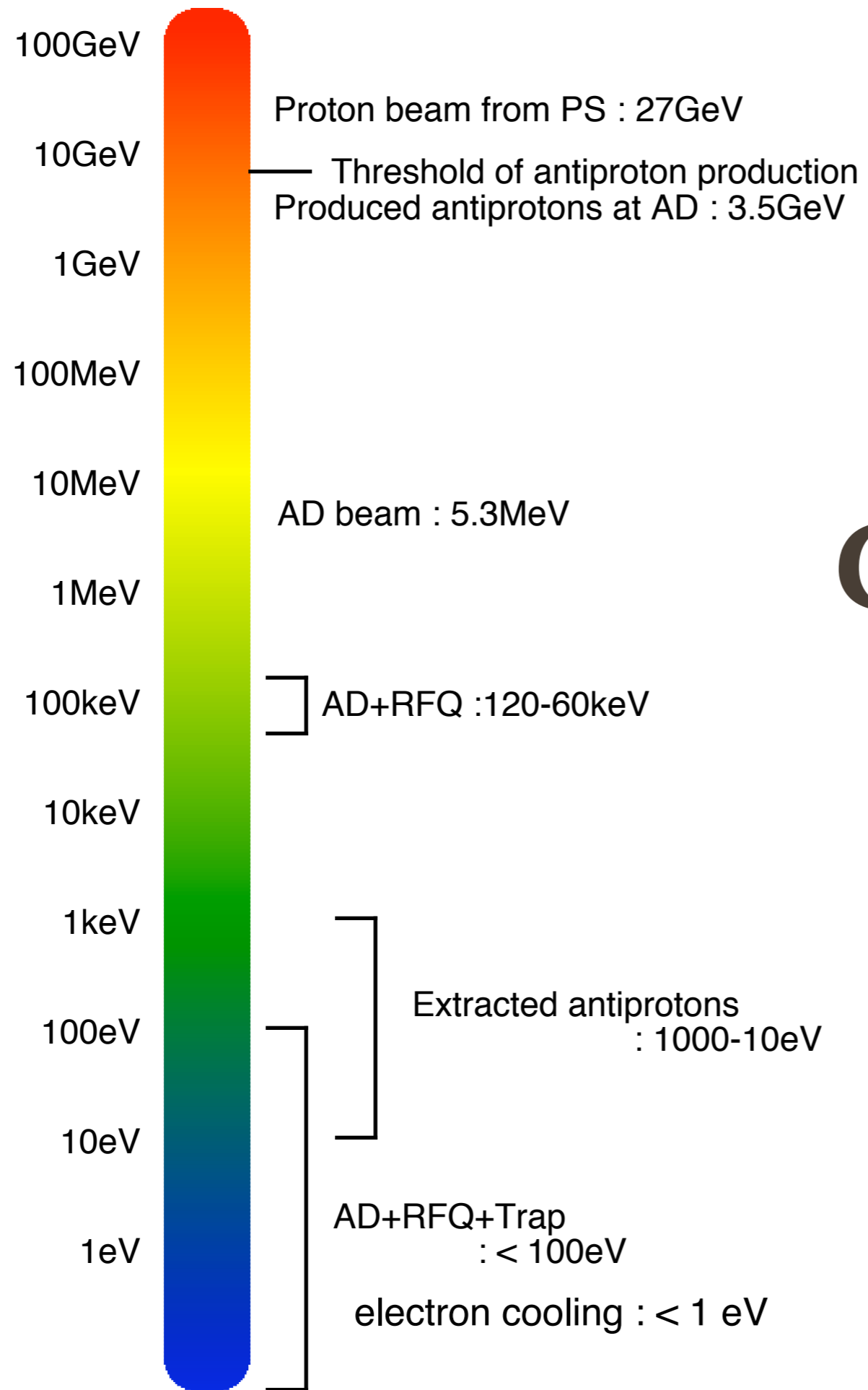
↓  
MRT (Trap)  
electron cooling

sub-eV antiproton

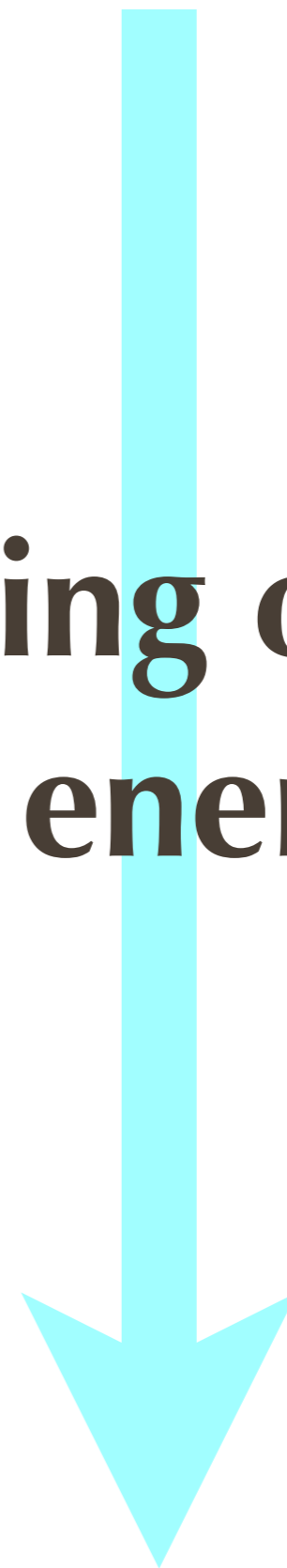
↓  
beamline

extraction of 10–1000 eV (... 20 keV) antiproton beam

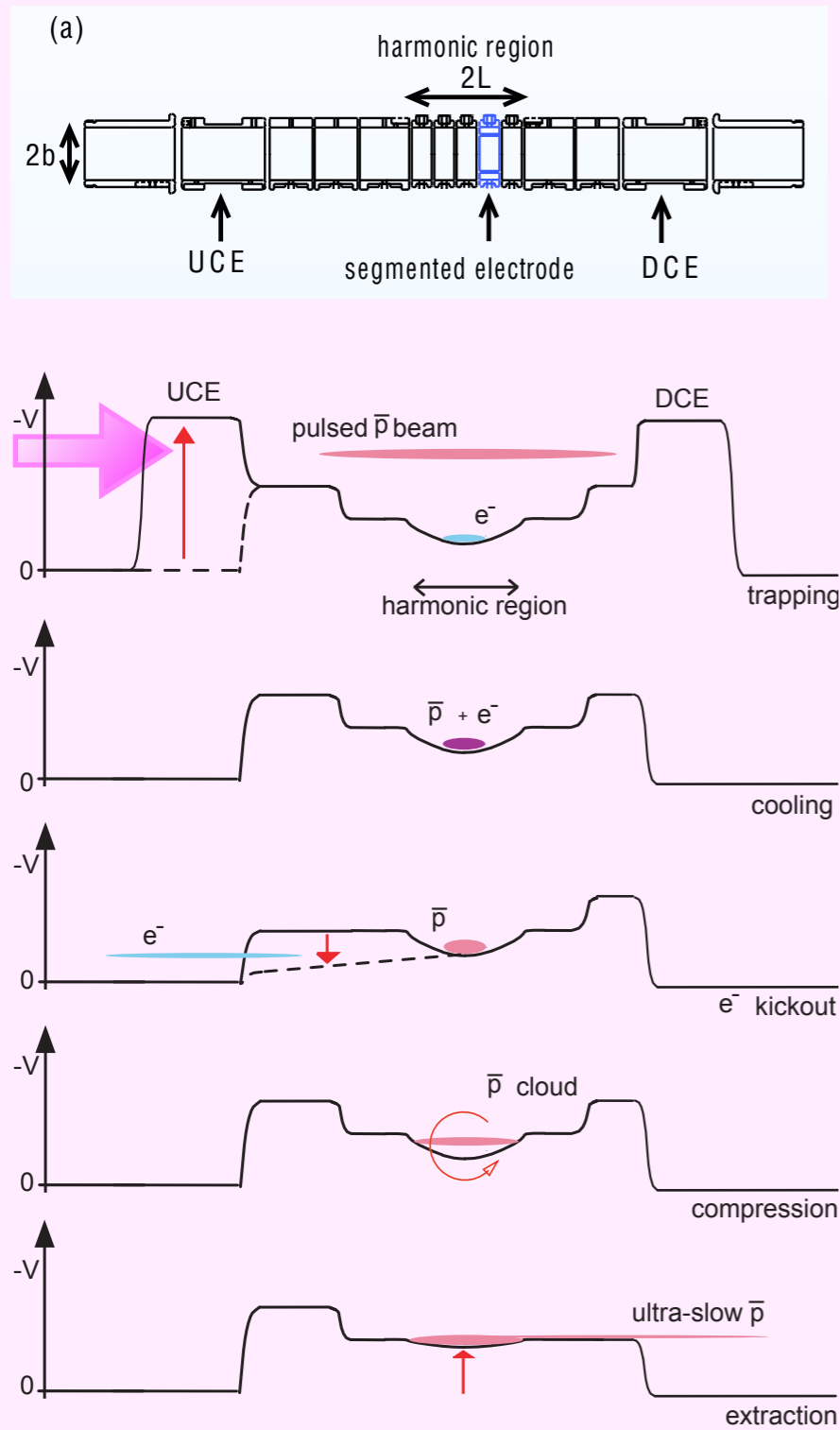


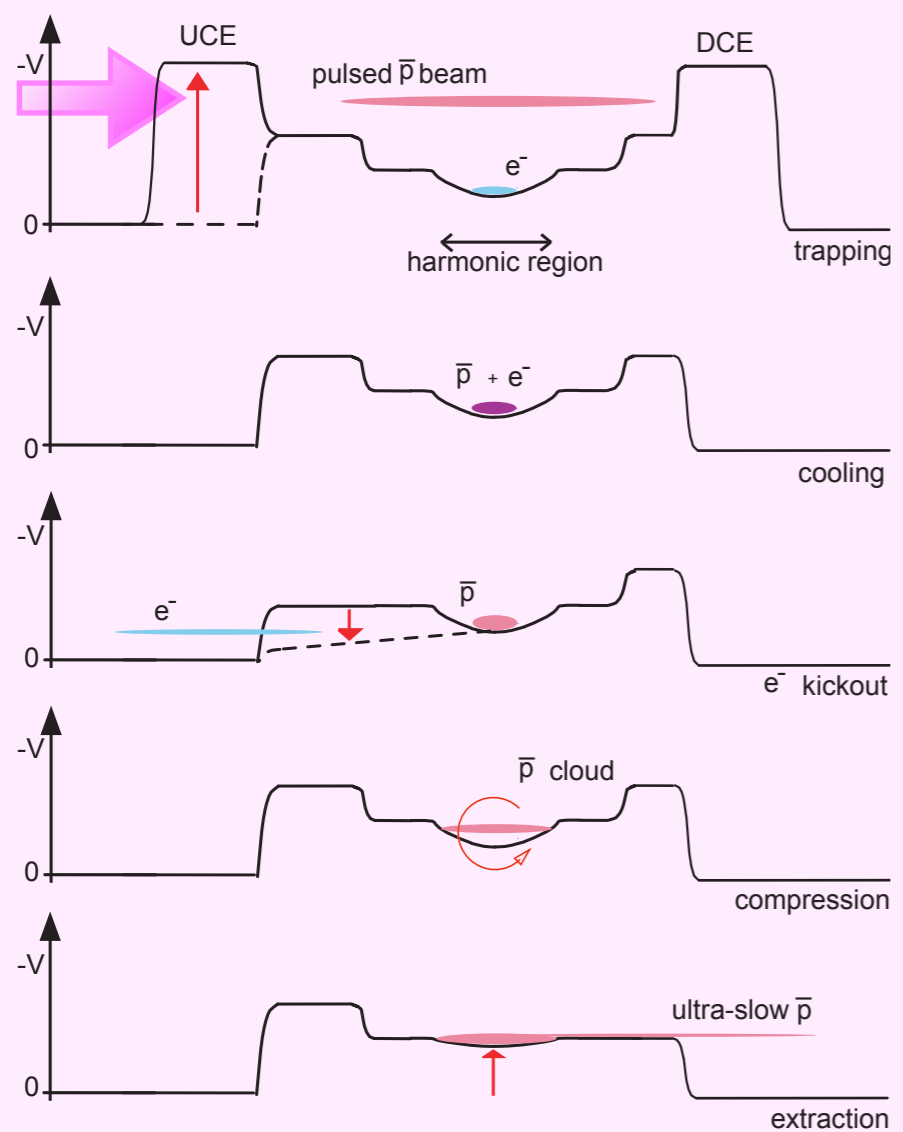
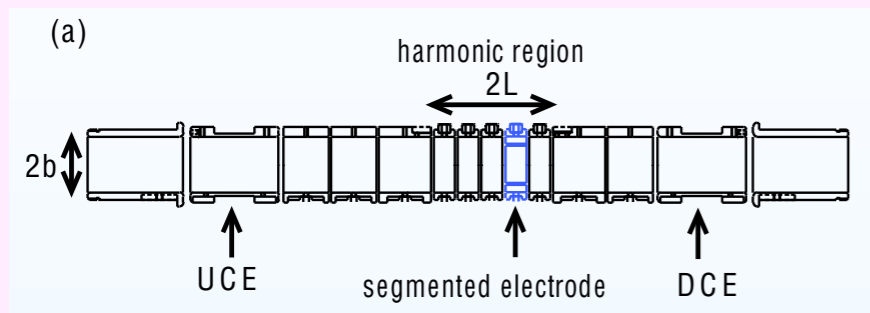


**Cooling of  $10^{-11}$   
in energy !**



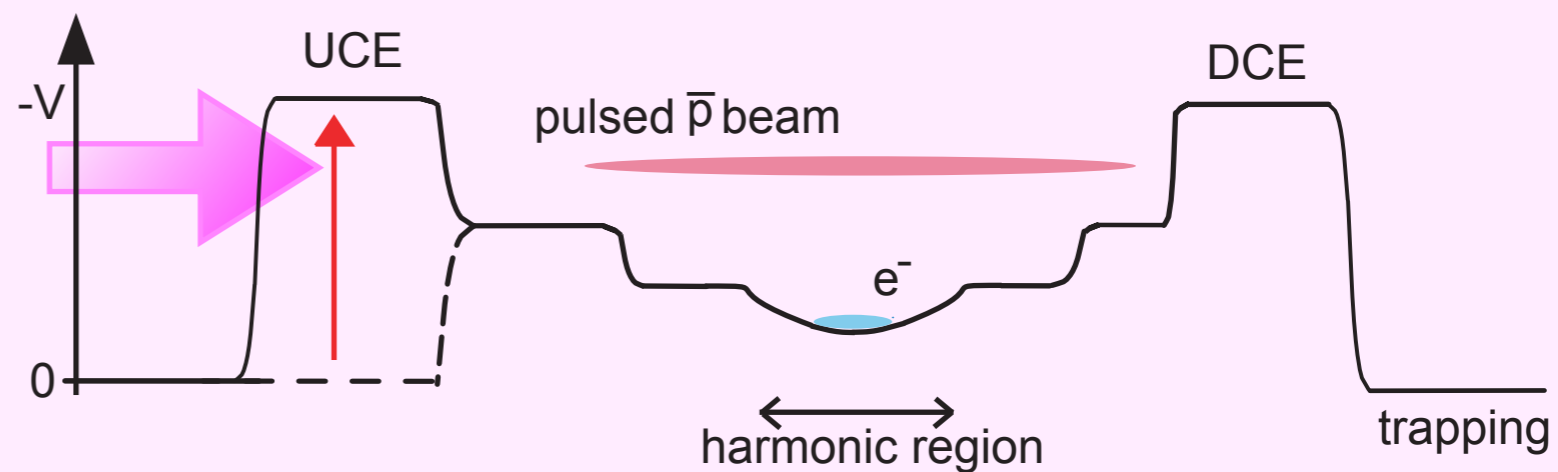
# Confinement and Cooling

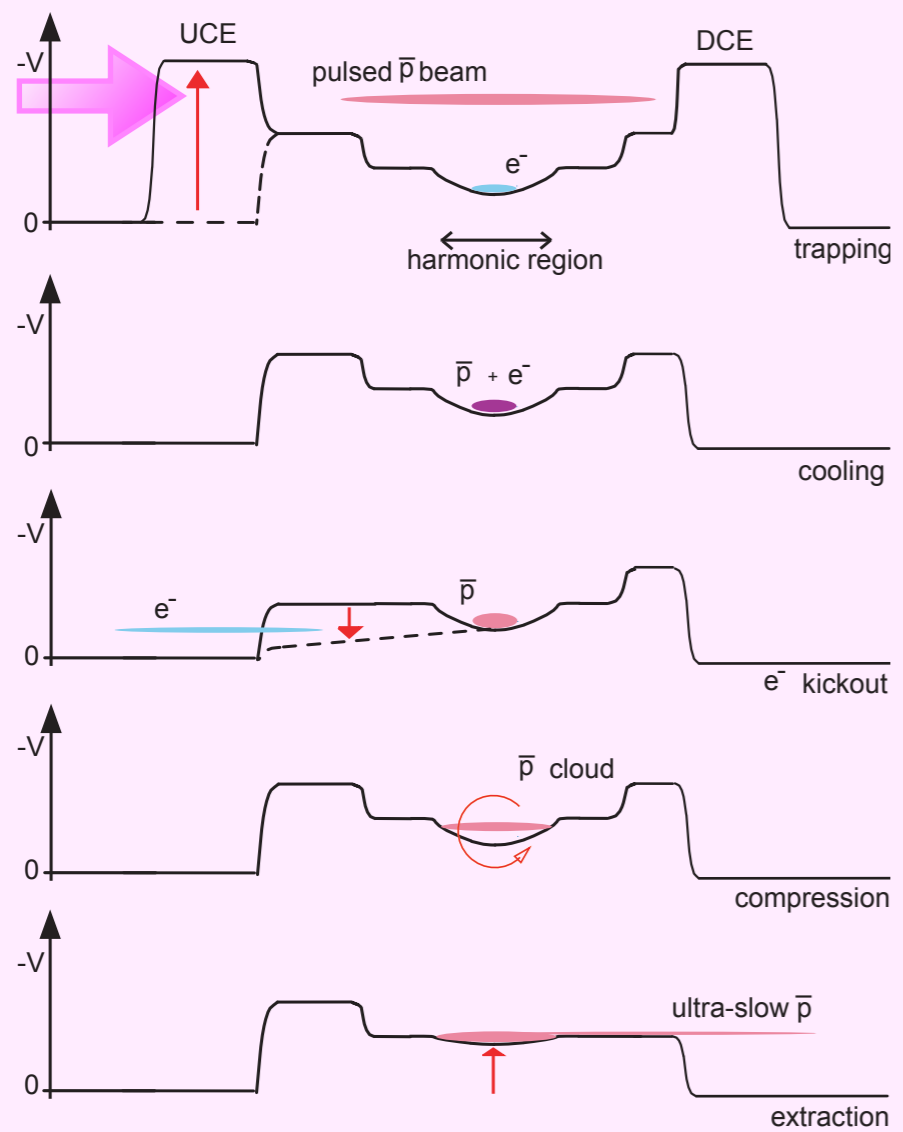
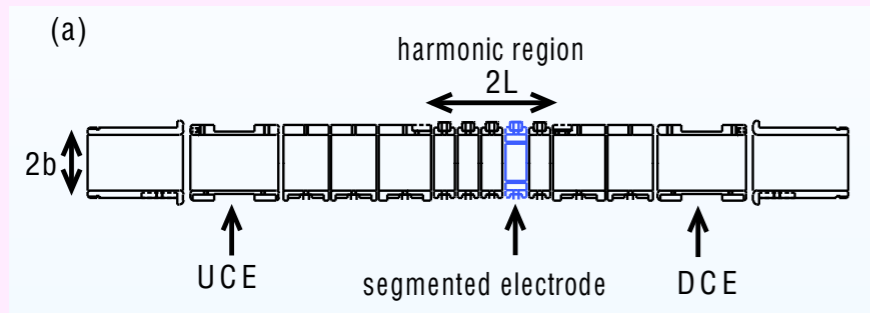




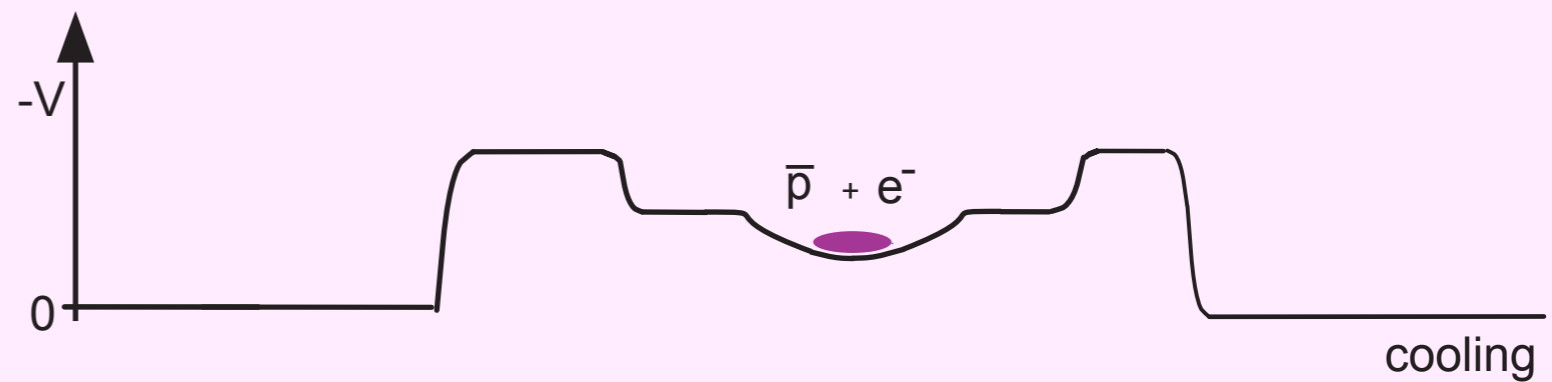
# Capture

ca. 200 ns

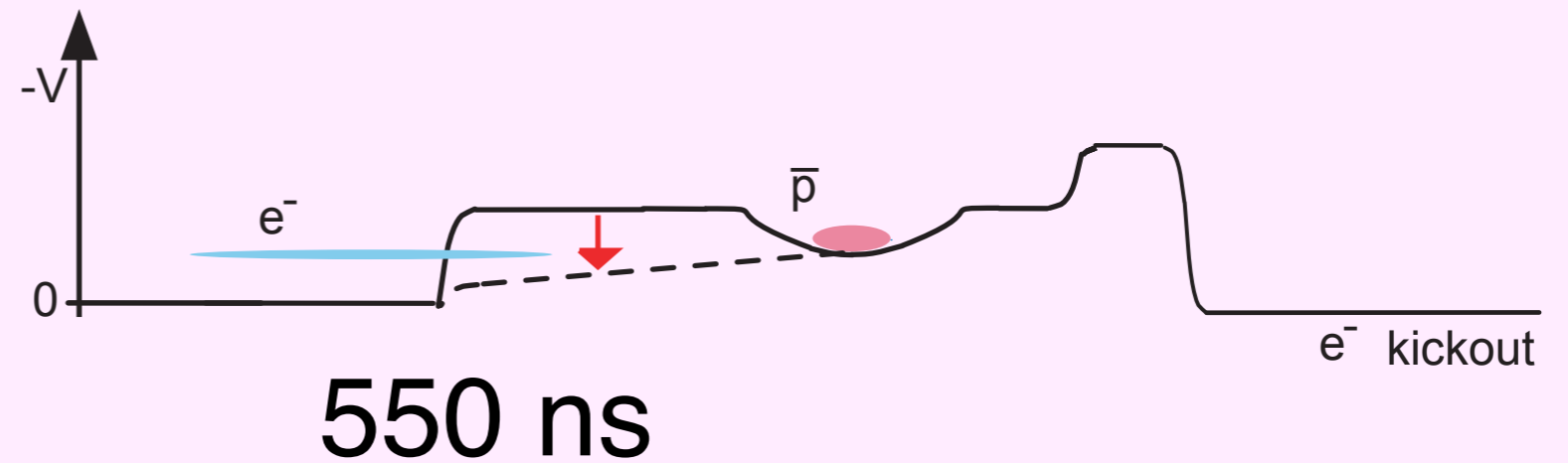
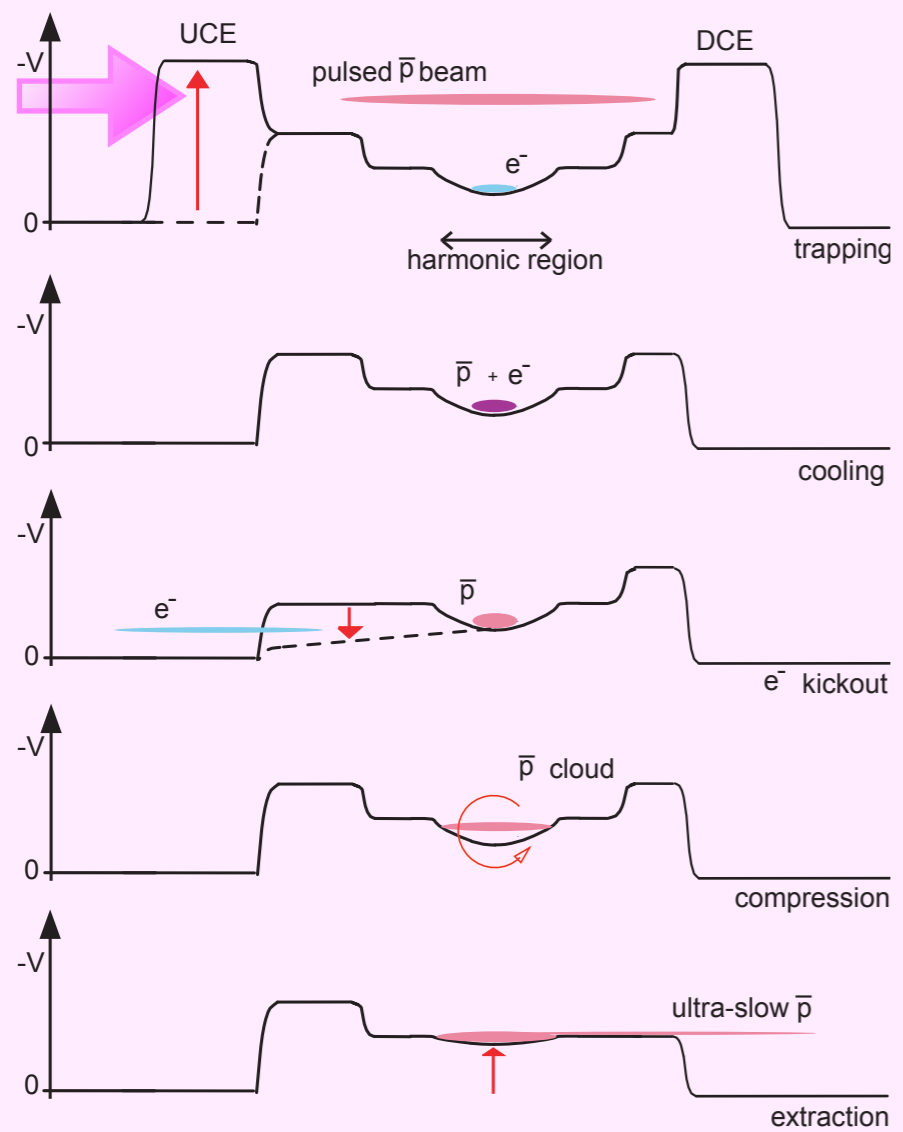
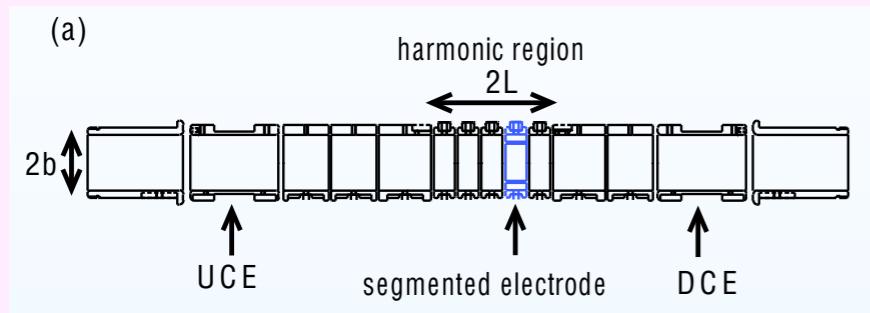




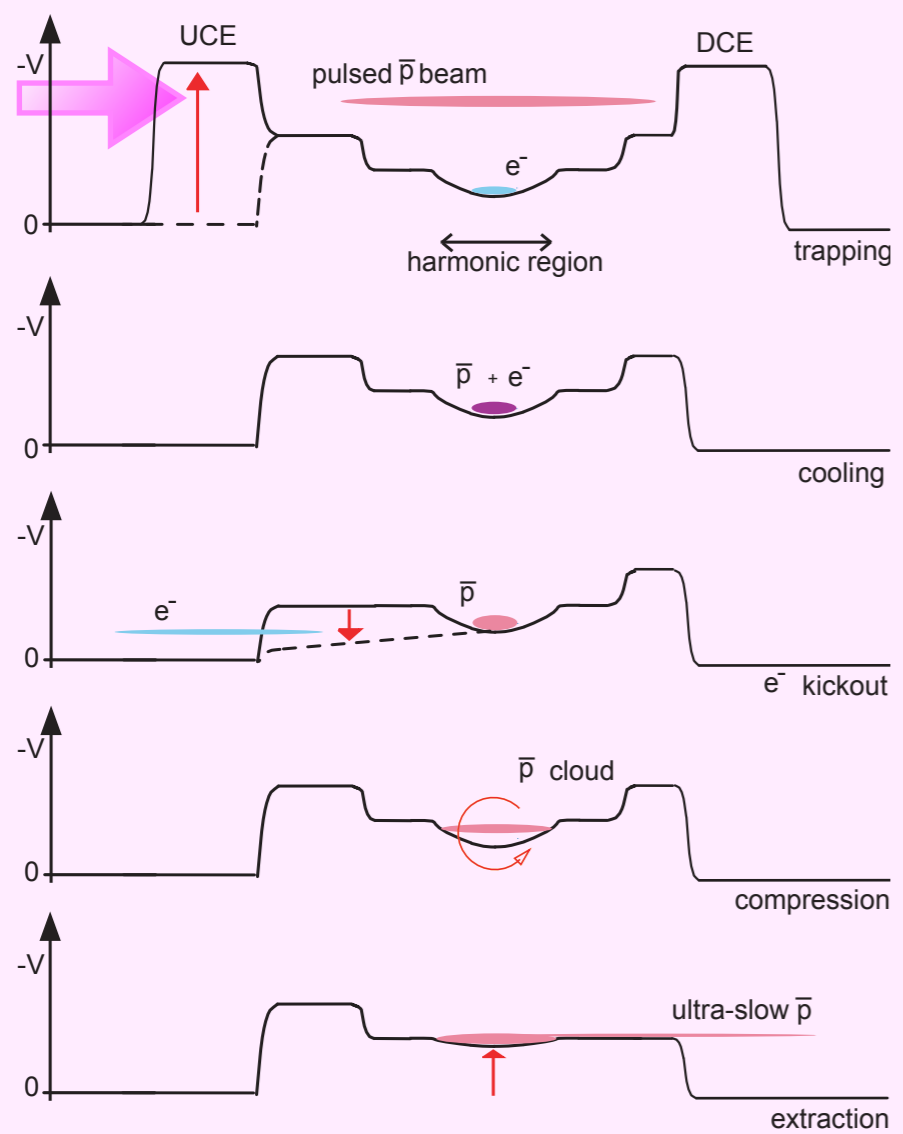
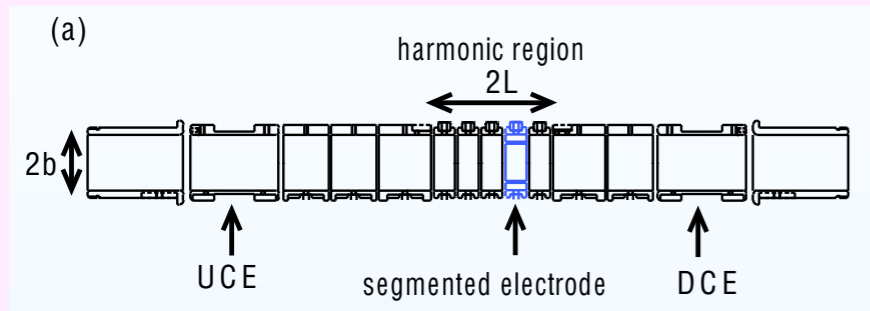
# Cooling



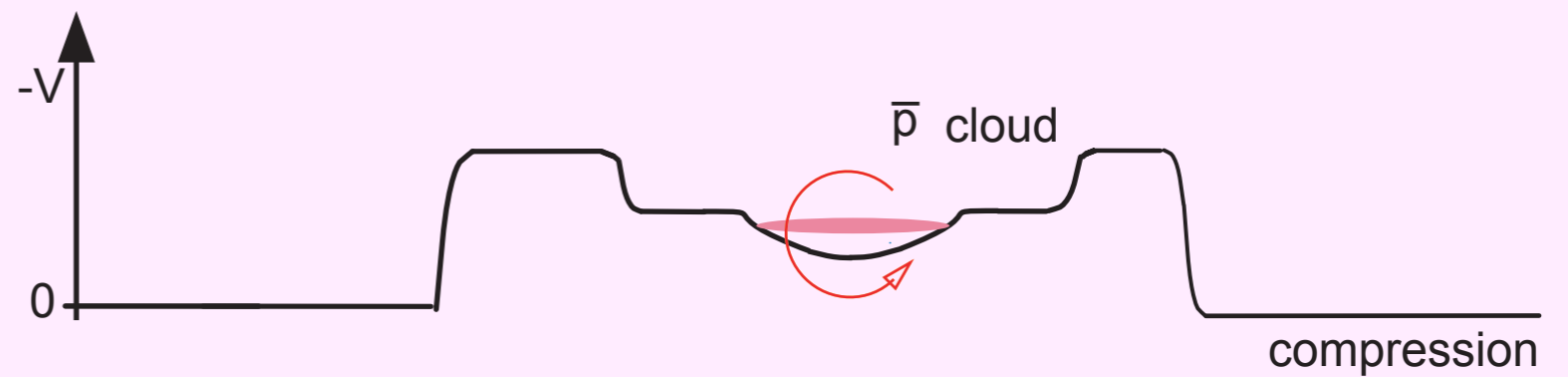
# Electron ejection

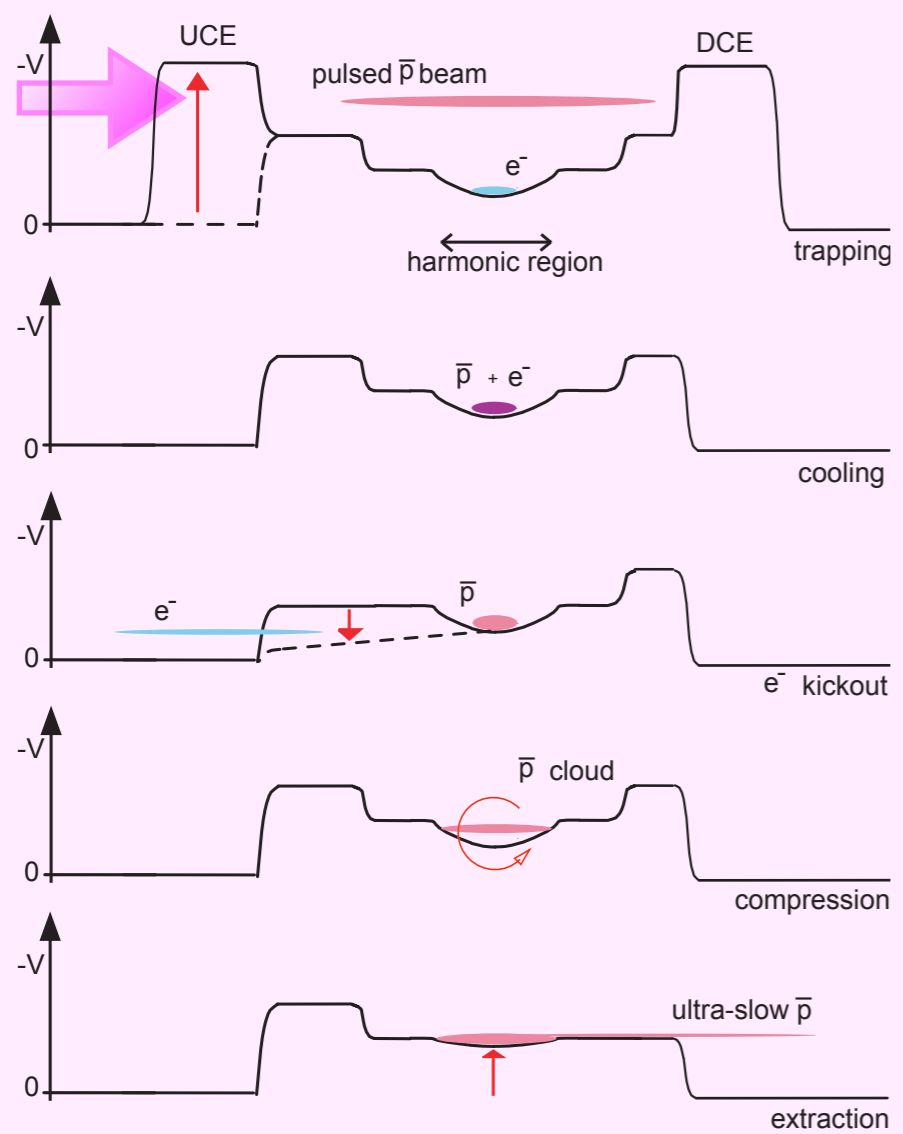
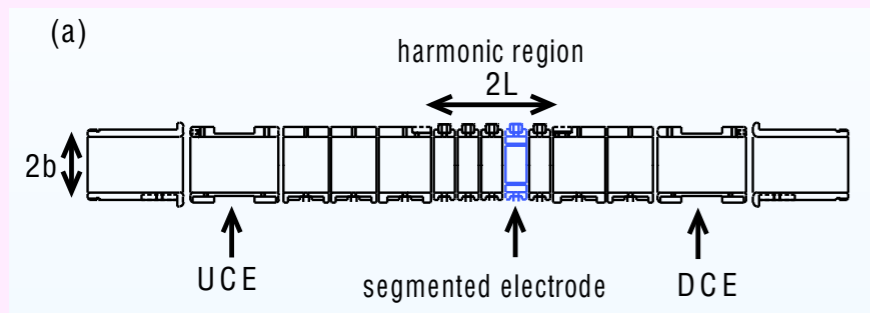




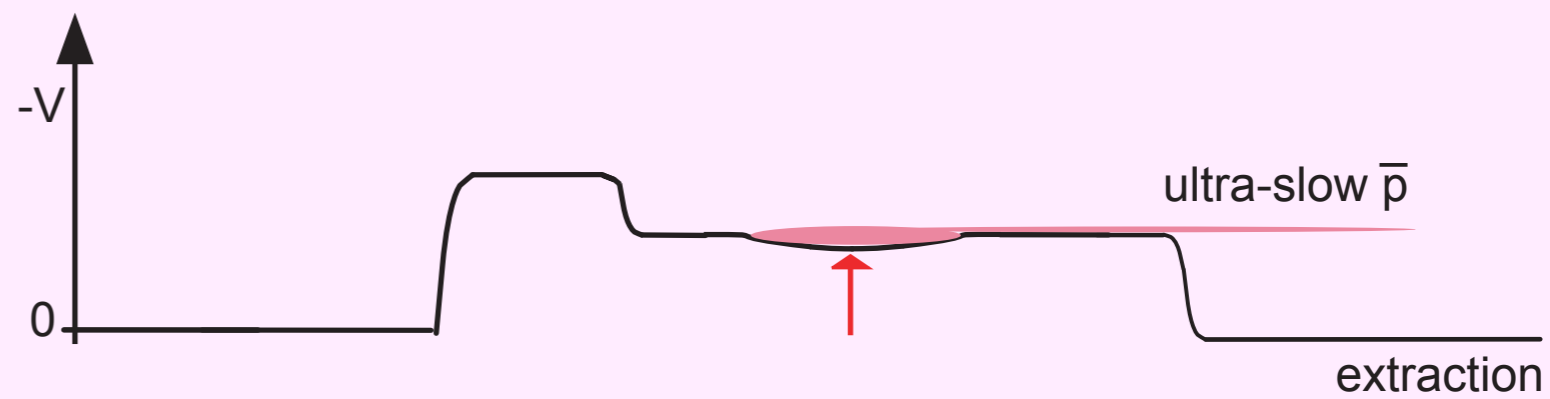


# Compression





# Extraction

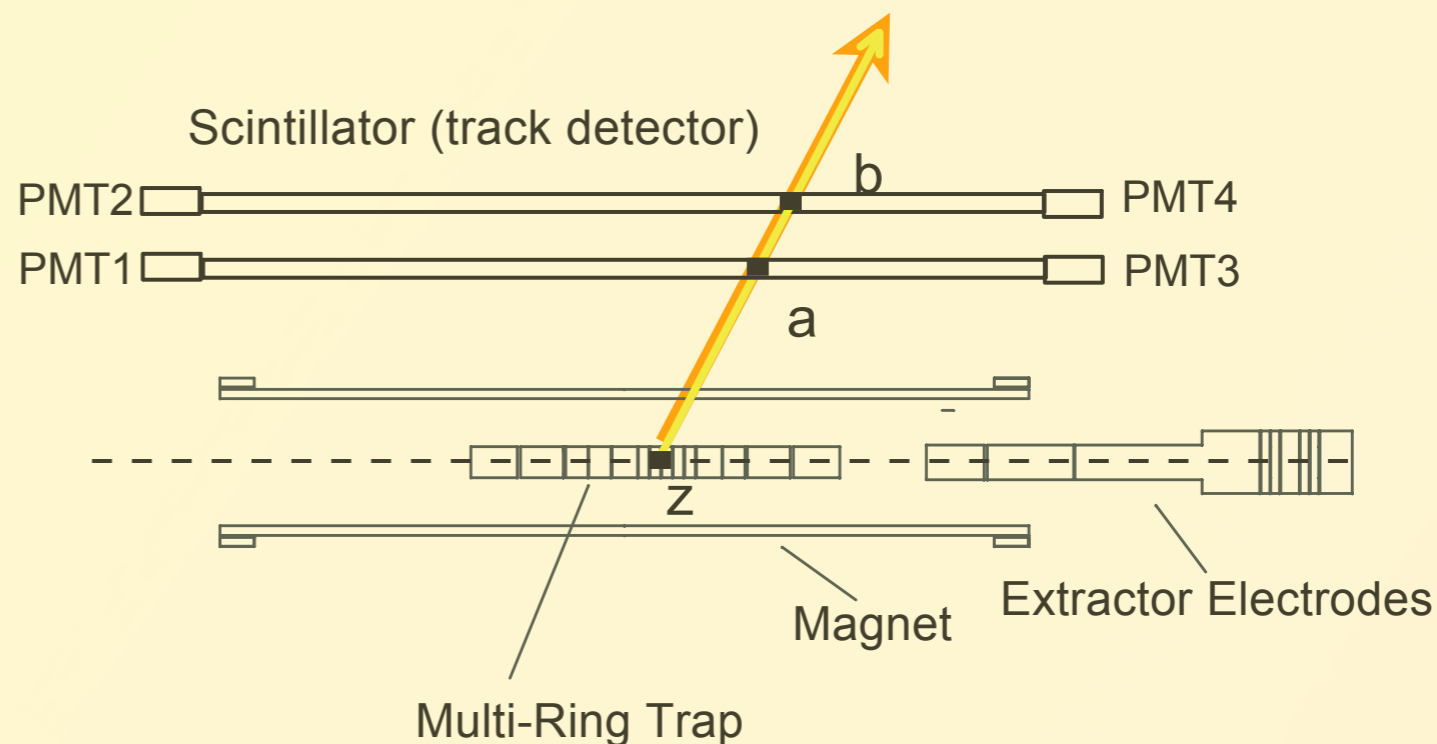


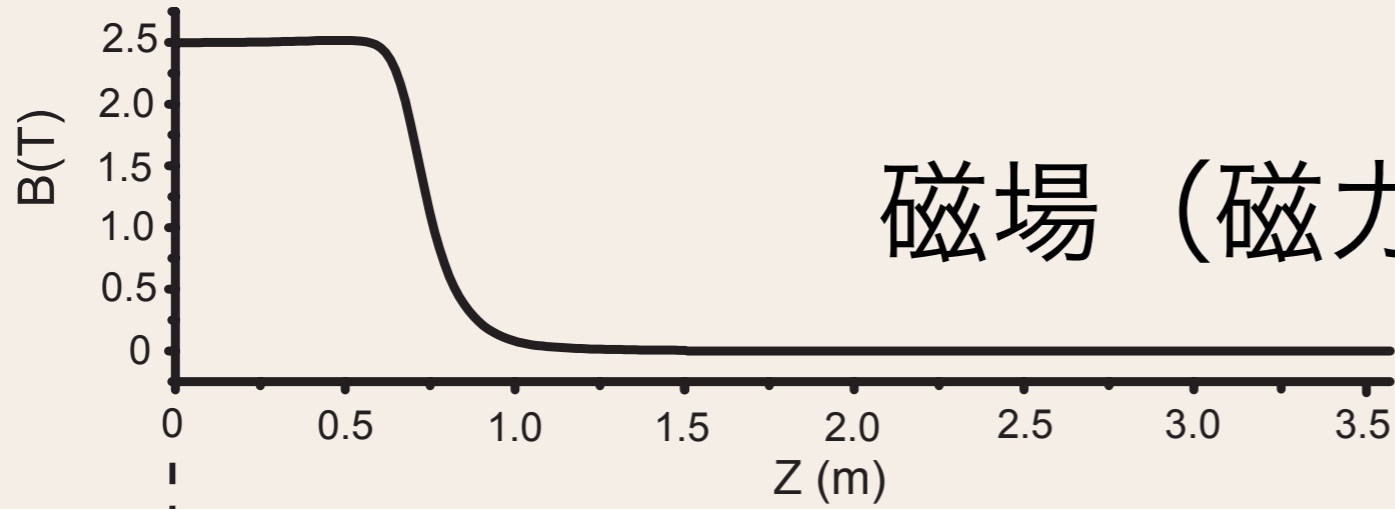
# 反陽子のトラップと蓄積

- 1 AD shot あたり  
120万個の反陽子を真空中( $10^{-10}$  Pa) にトラップ
- 数 shot の蓄積により最大 1000 万個 !!!

## トラック検出器

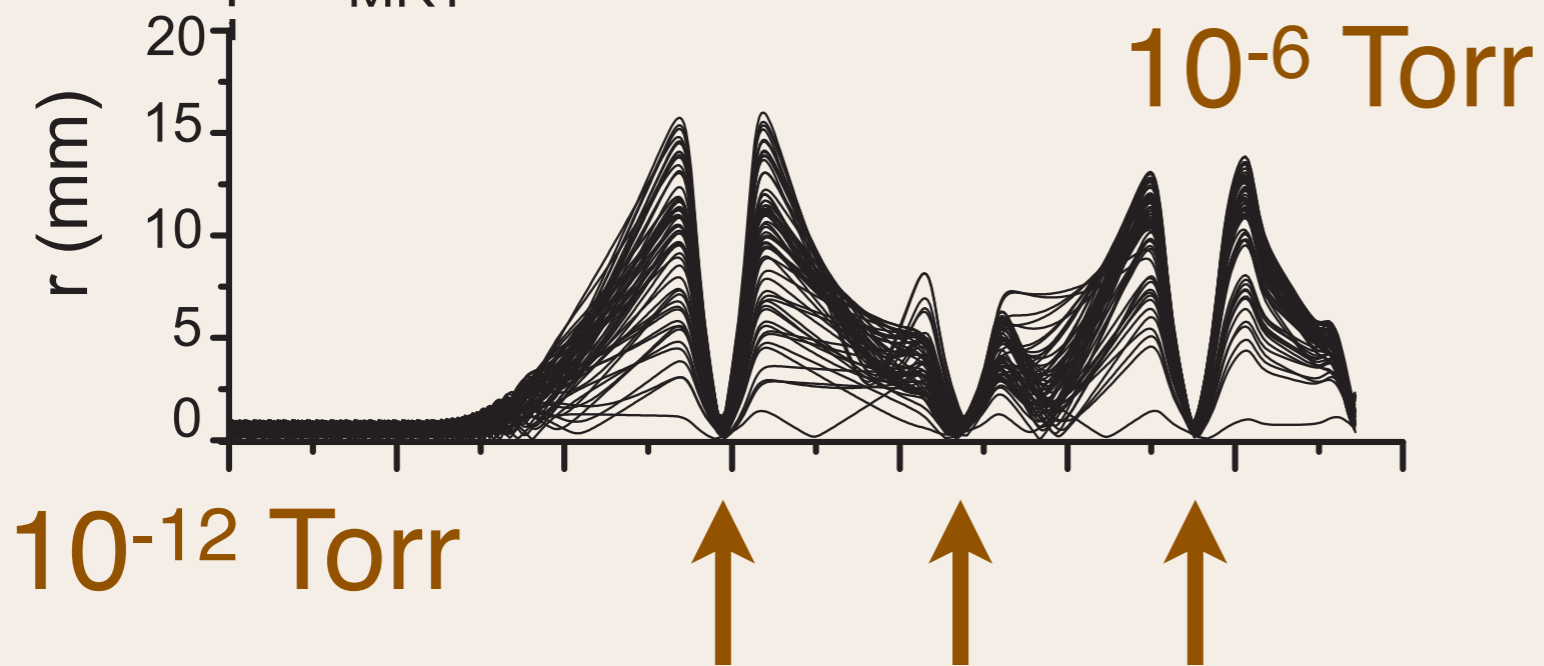
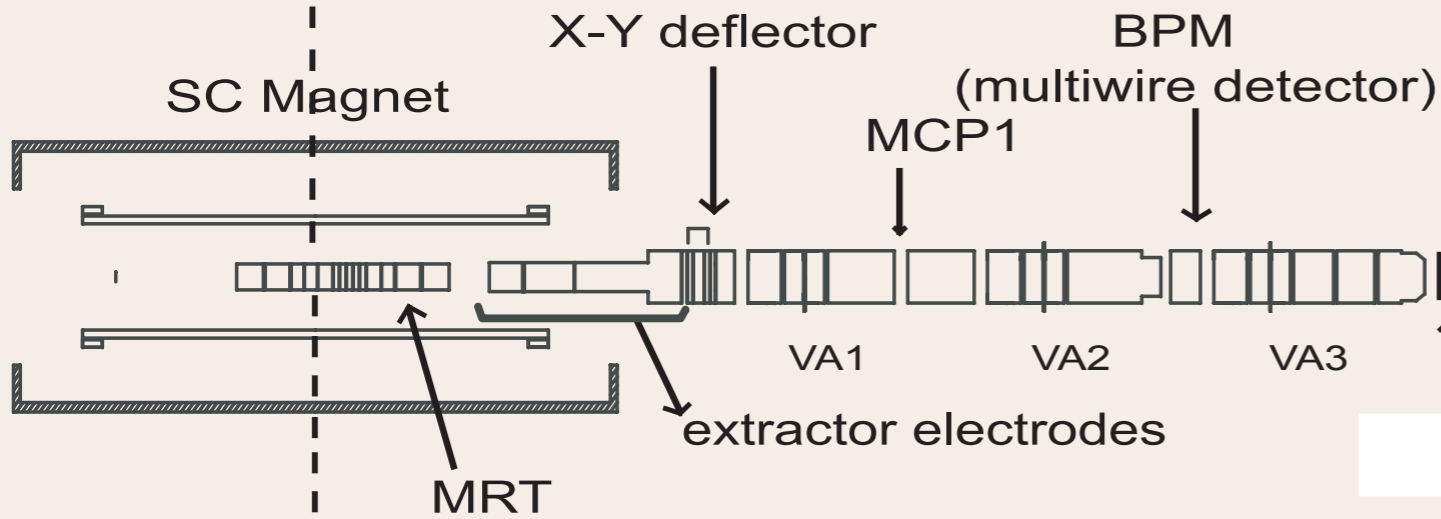
反陽子消滅位置は  
トラック検出器で  
 $\pi^\pm$  の飛跡を辿る。



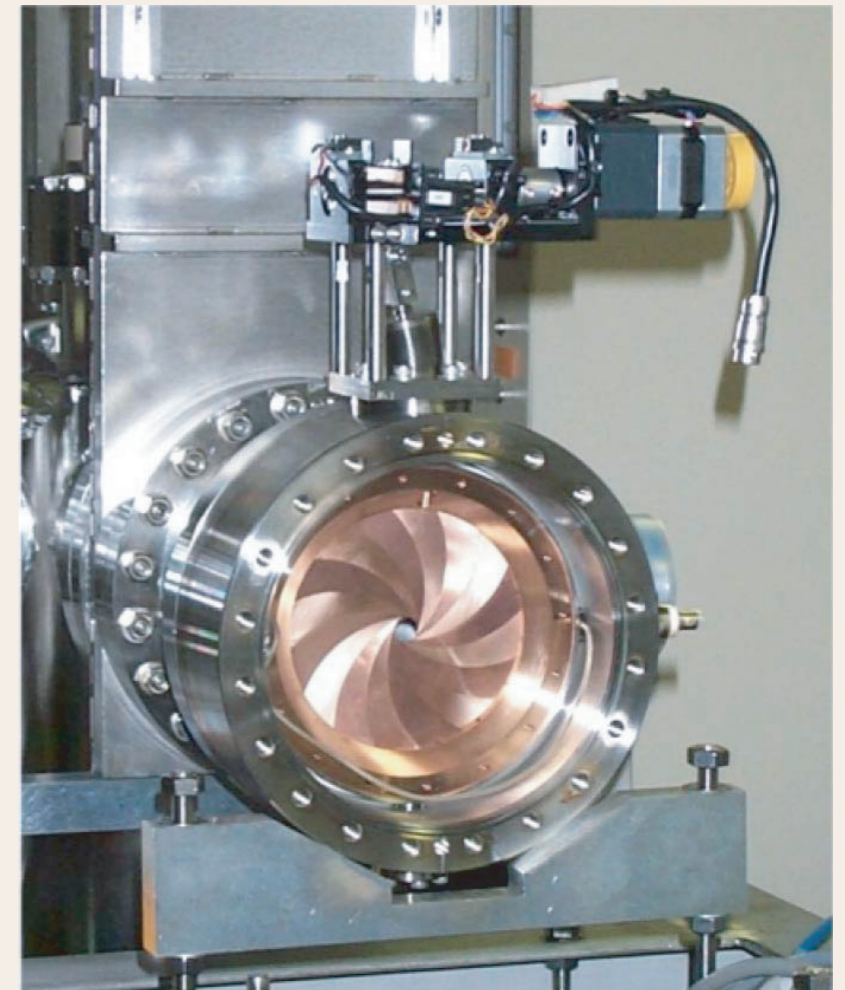


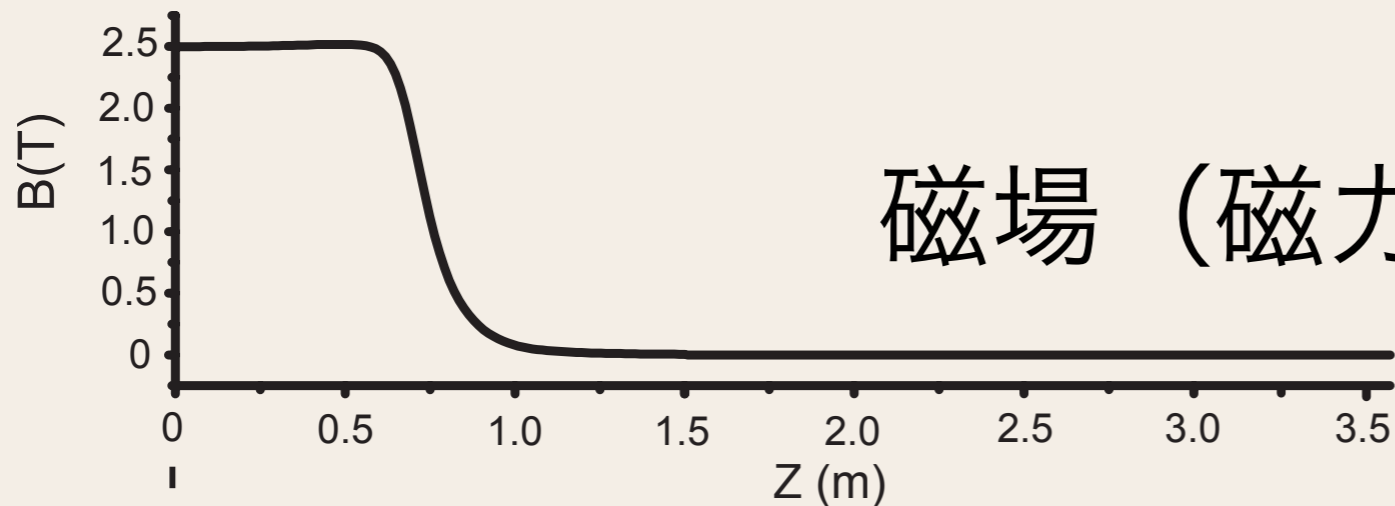
引出しビームライン

差動排気6桁!



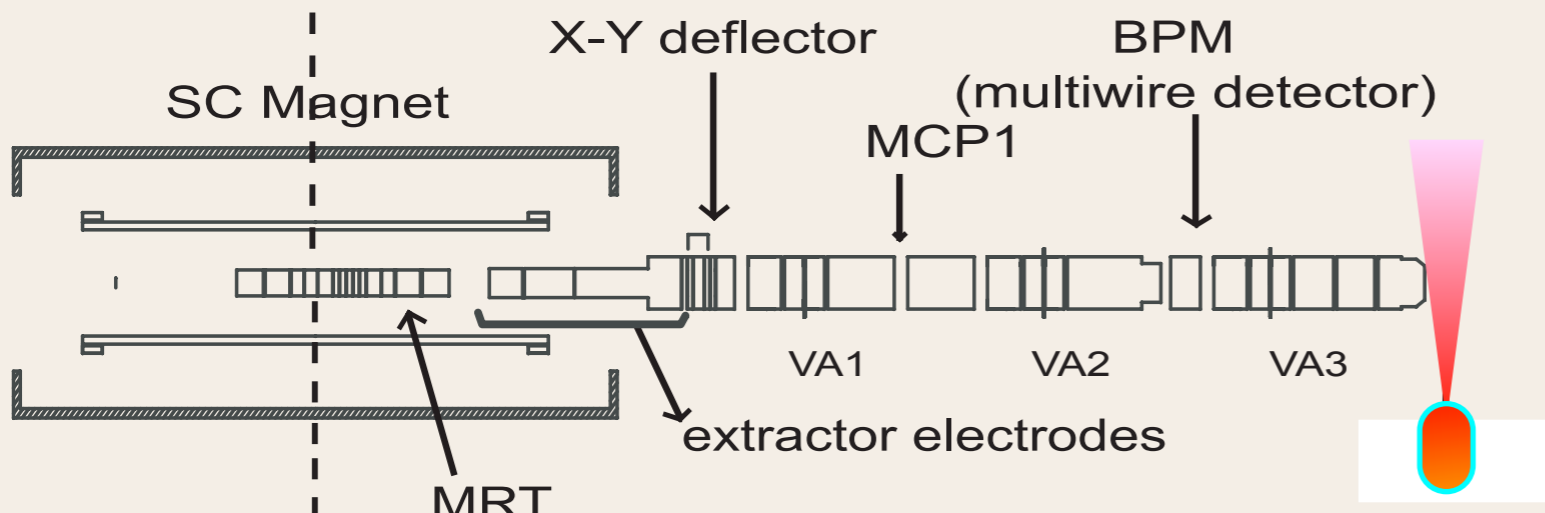
$10^{-12}$  Torr



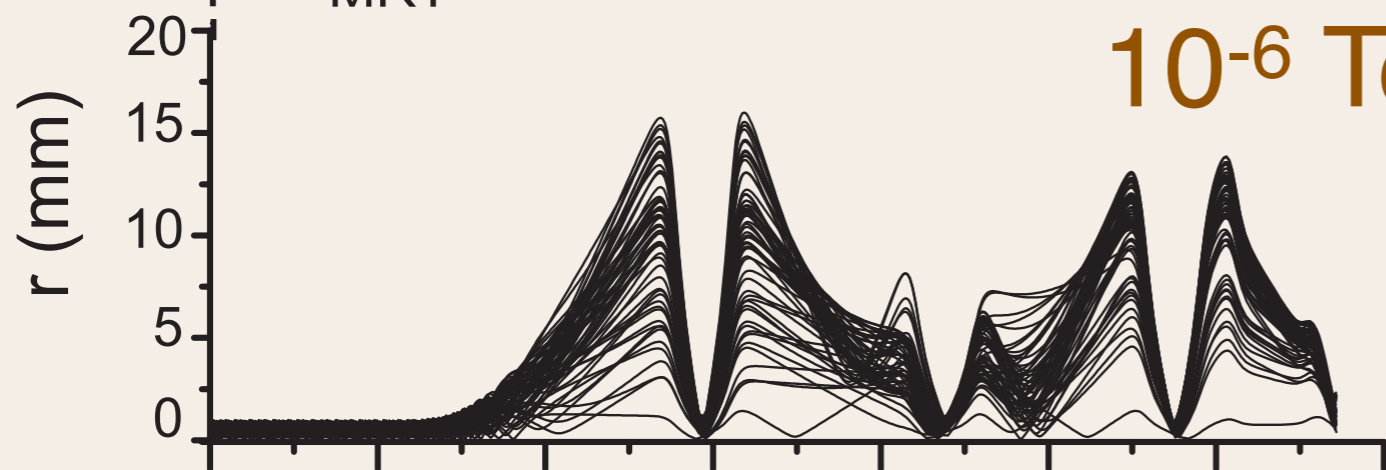


引出しビームライン

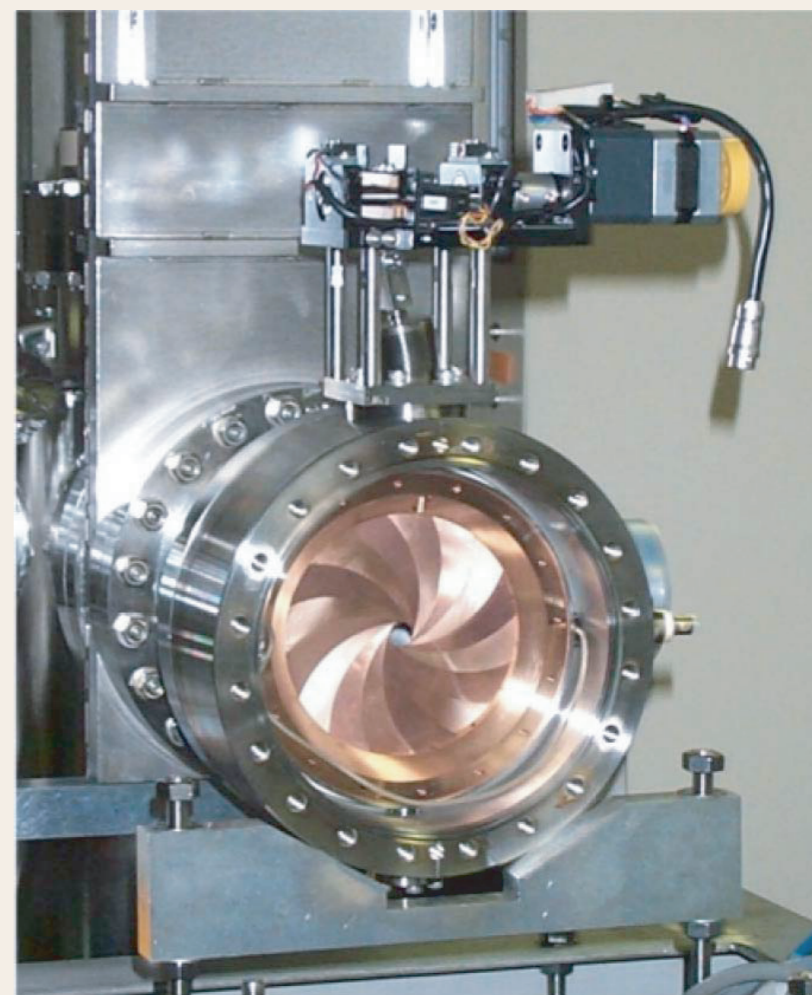
差動排気6桁!



$10^{-6}$  Torr

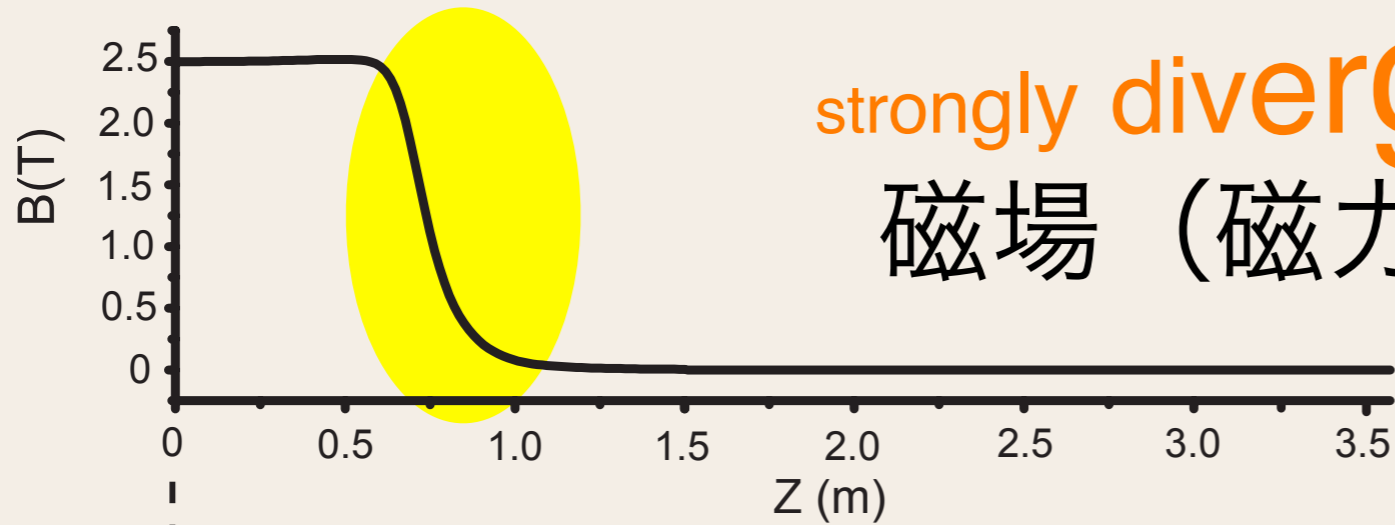


$10^{-12}$  Torr



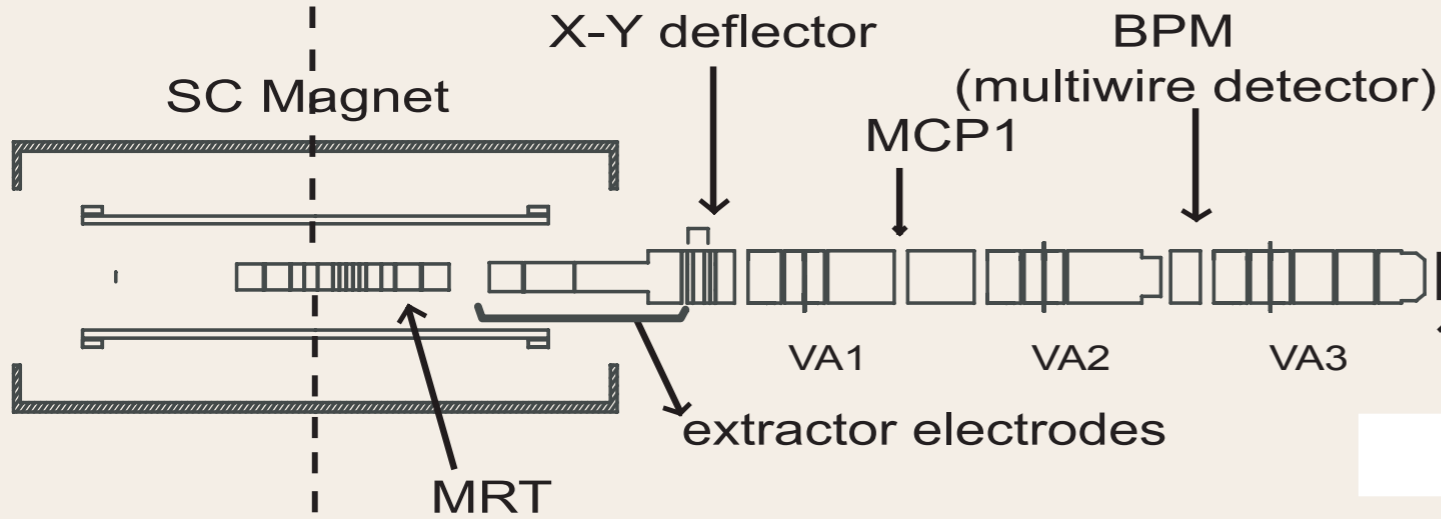
# strongly diverging

## 磁場 (磁力線)

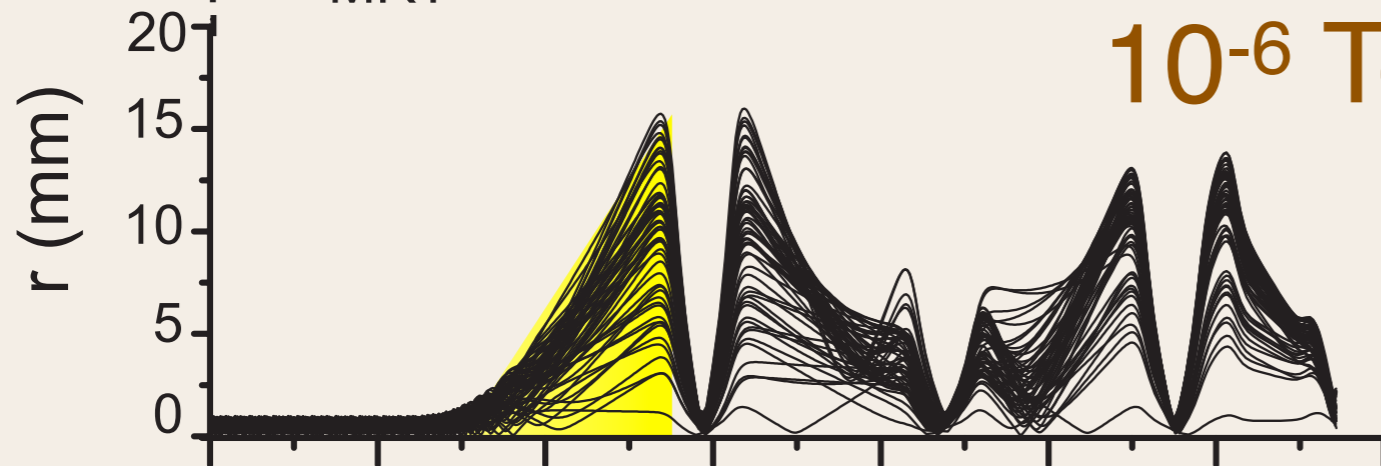


### 引出しビームライン

### 差動排気6桁!



### Einzel レンズで 電氣的にビーム フォーカス

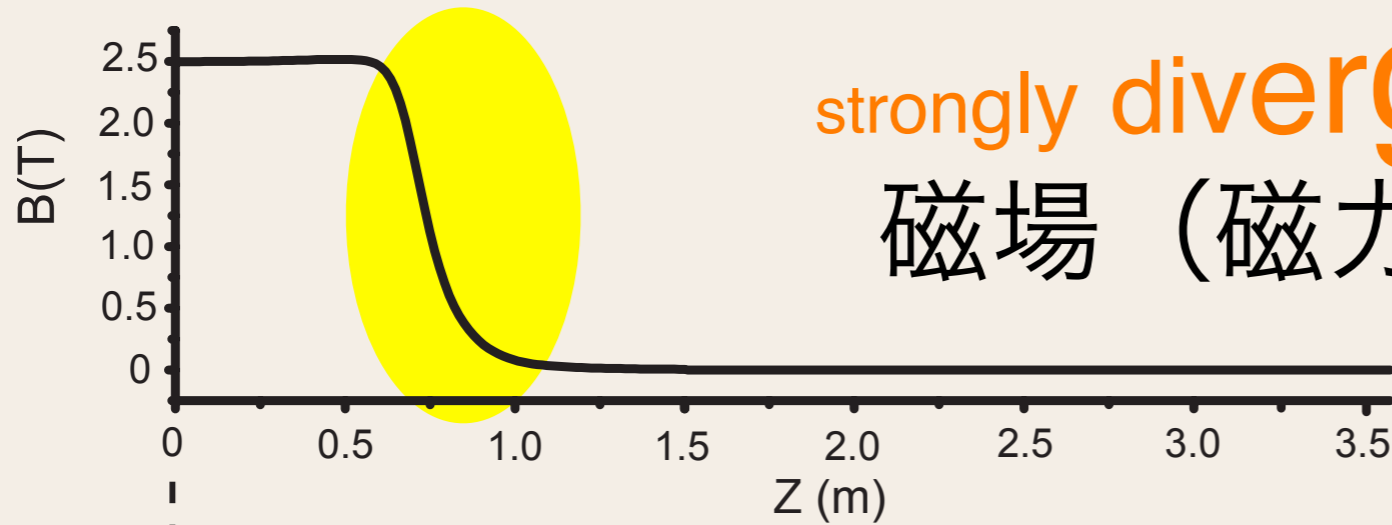


$10^{-6}$  Torr

$10^{-12}$  Torr

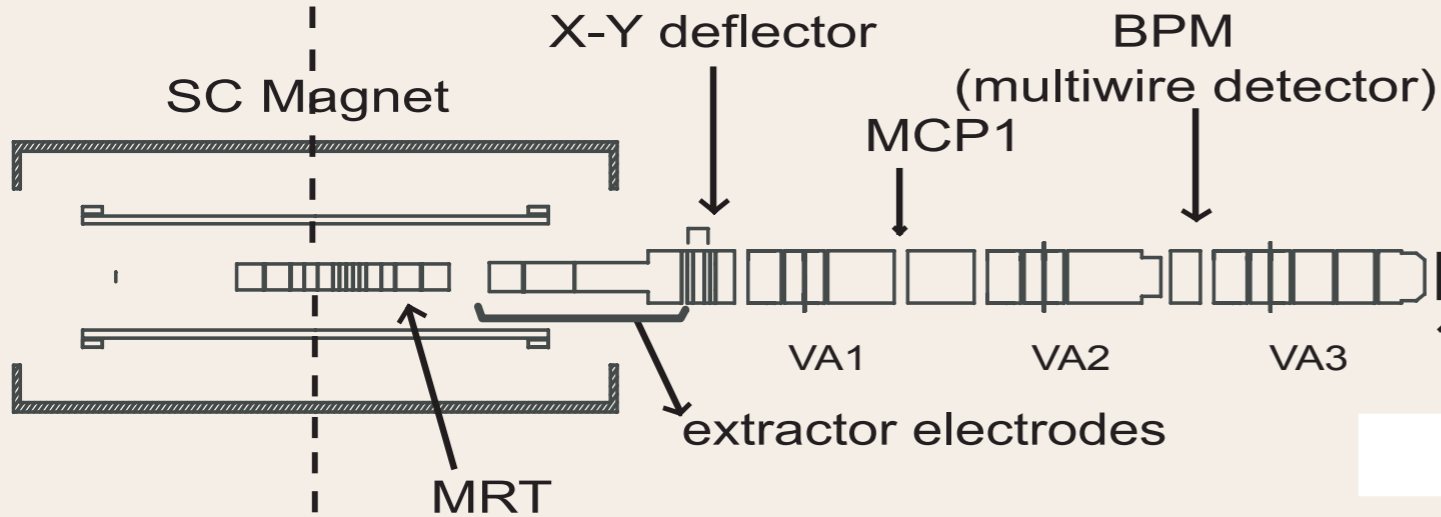
# strongly diverging

## 磁場 (磁力線)

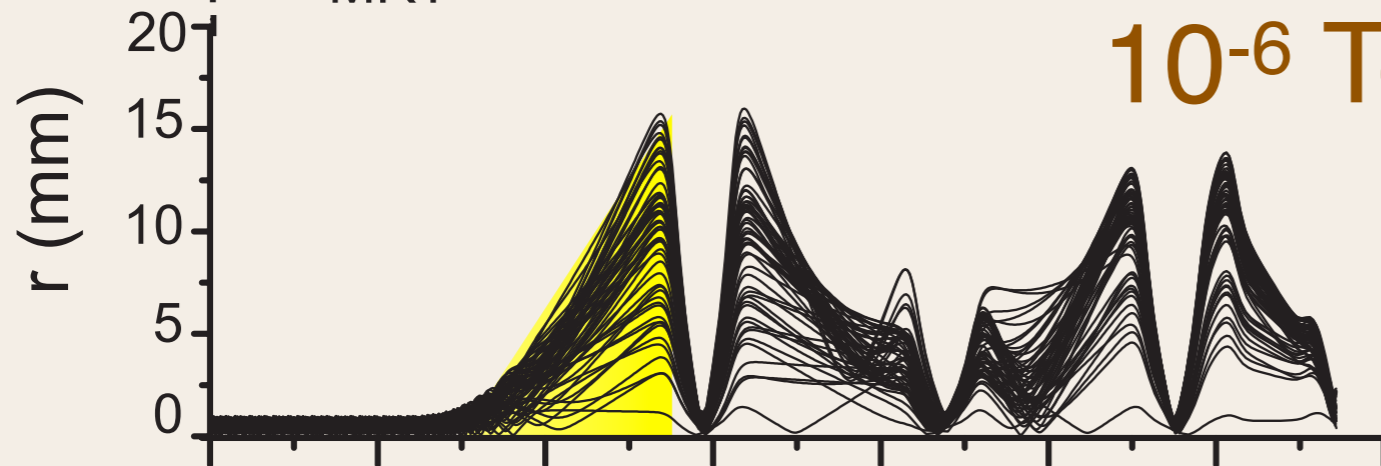


### 引出しビームライン

### 差動排気6桁!

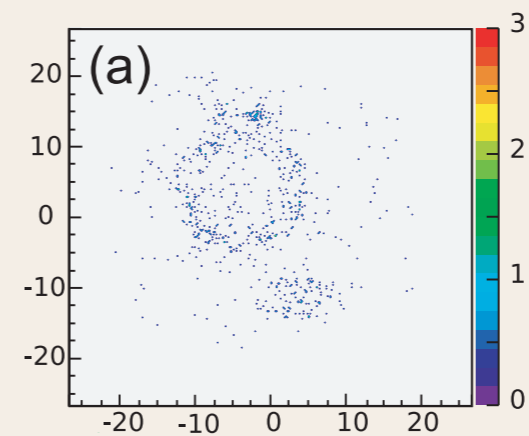
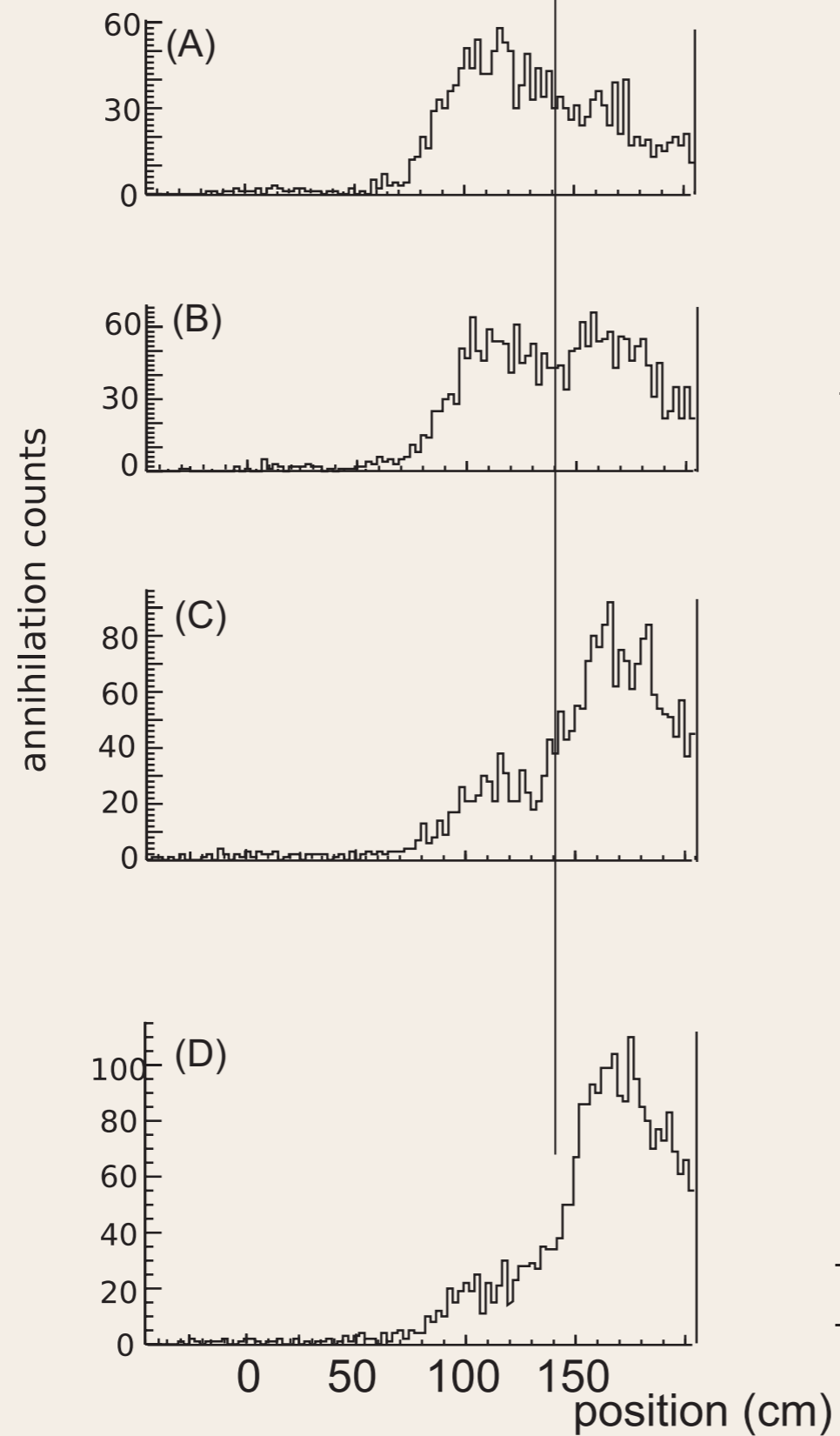
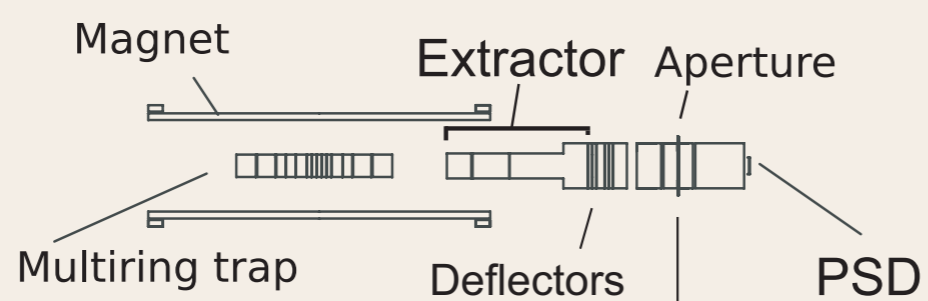


### Einzel レンズで 電氣的にビーム フォーカス

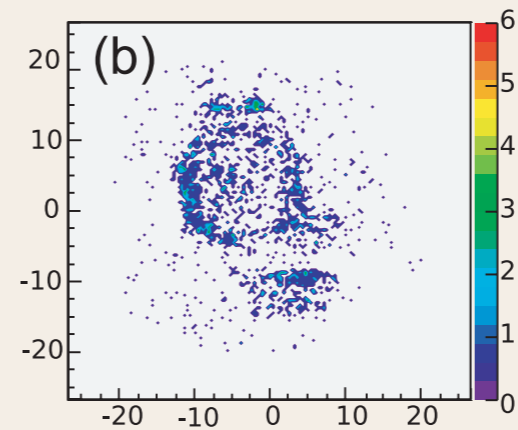


$10^{-6}$  Torr

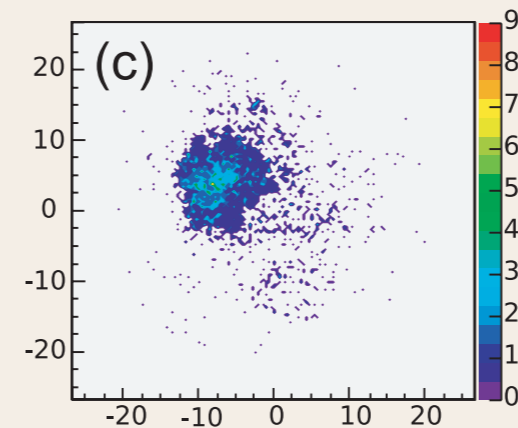
$10^{-12}$  Torr  
**2 mm  $\varnothing$**



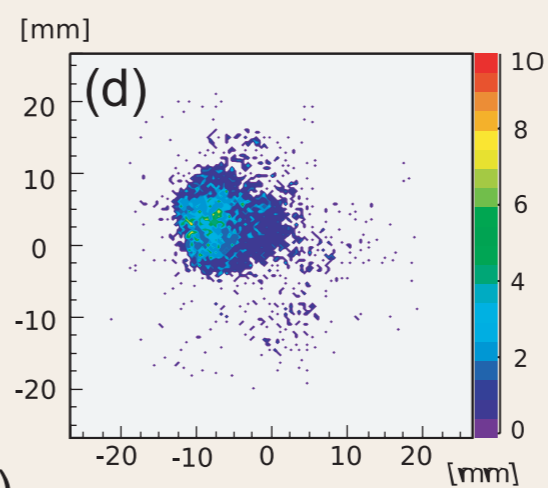
0 s



60 s



120 s



0.5 mm diam.

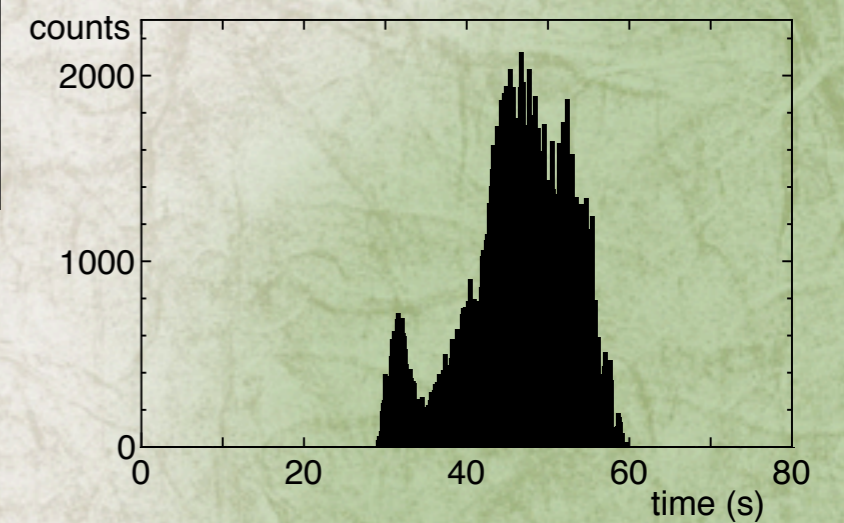
200 s



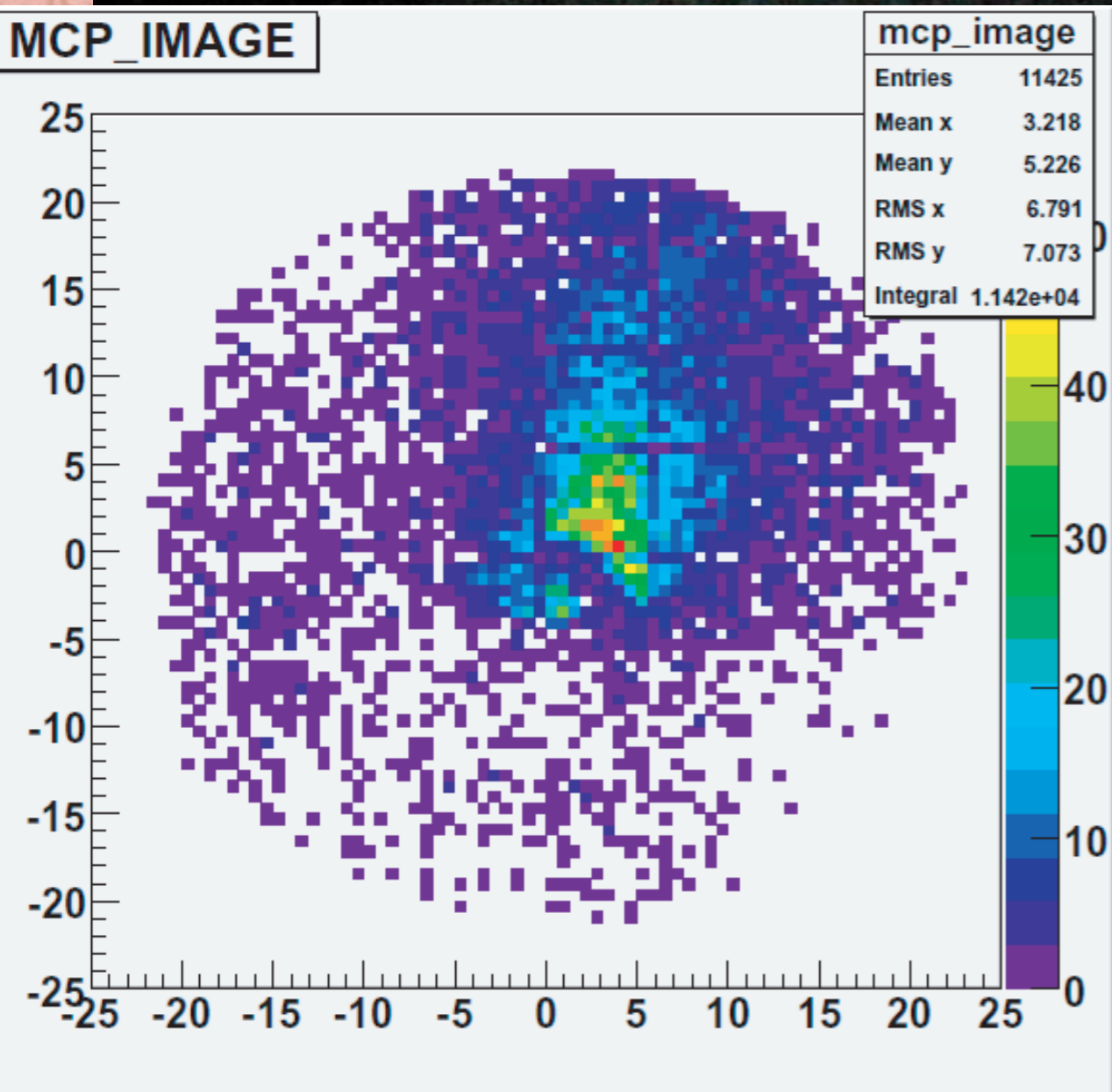
# 超低速反陽子ビーム



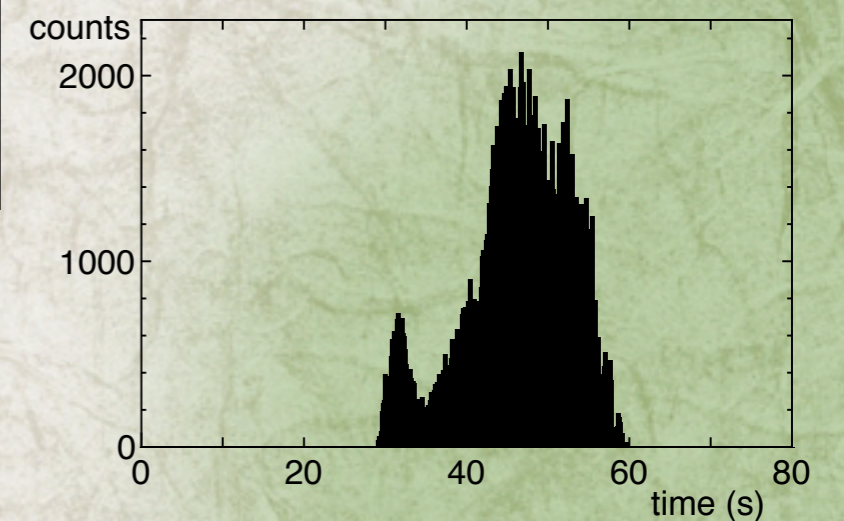
MicroChannel Plate (MCP) + 蛍光膜で観測



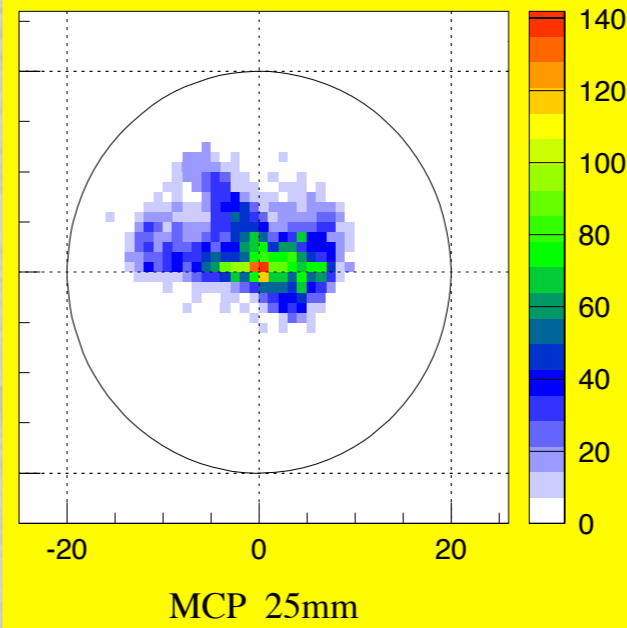
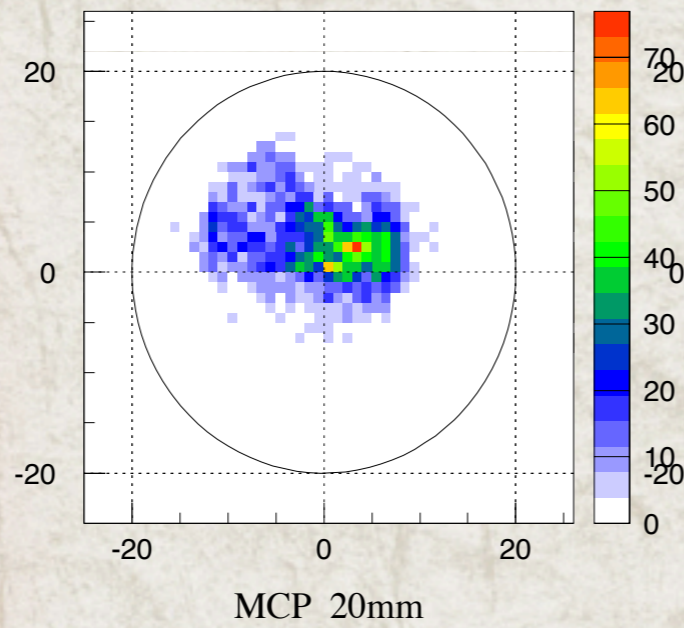
# 超低速反陽子ビーム



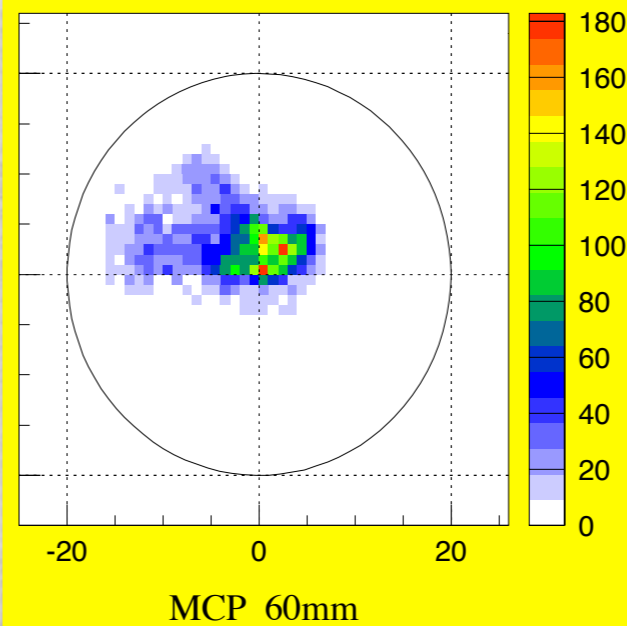
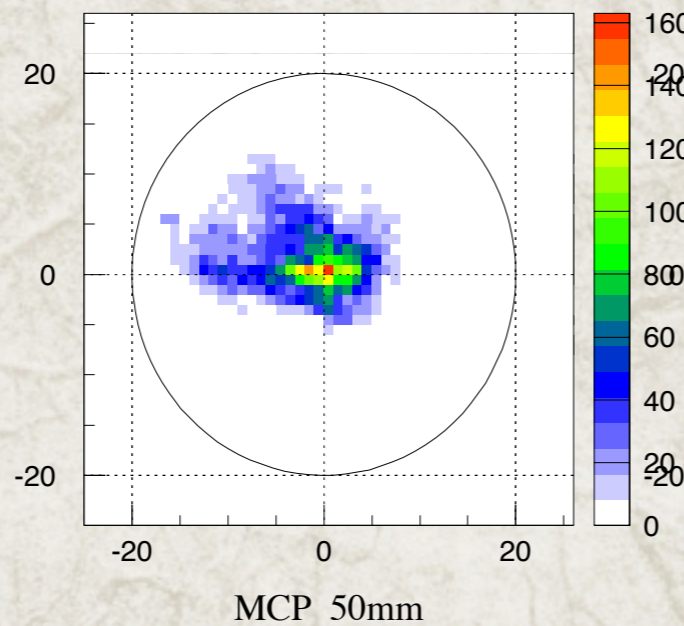
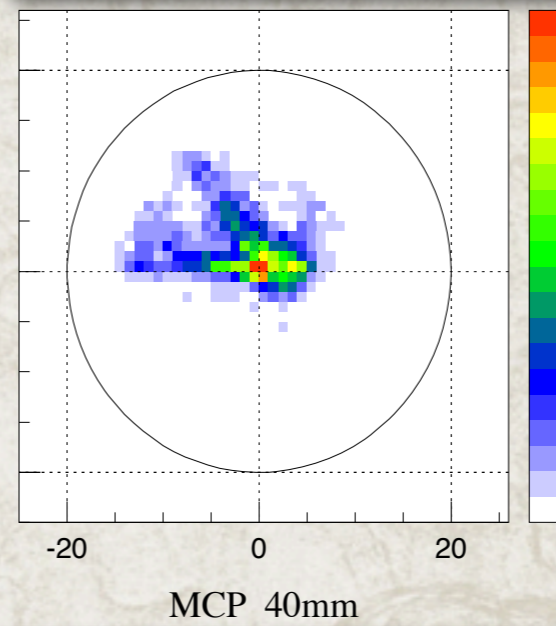
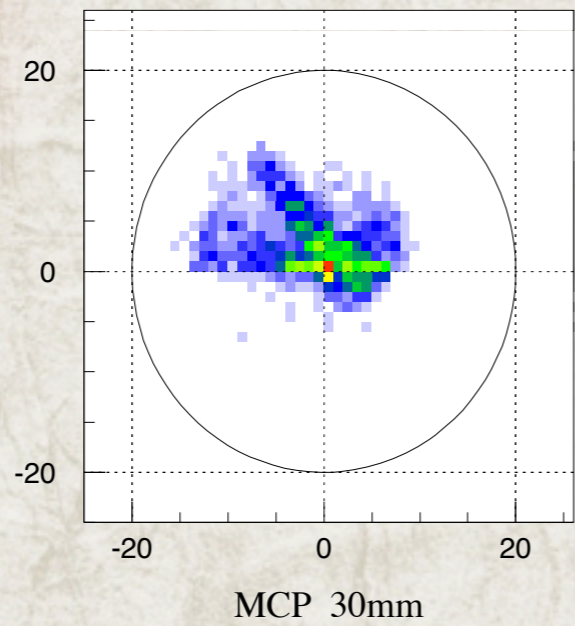
MicroChannel Plate (MCP) + 蛍光膜で観測



# Beam Profile @ 250 eV

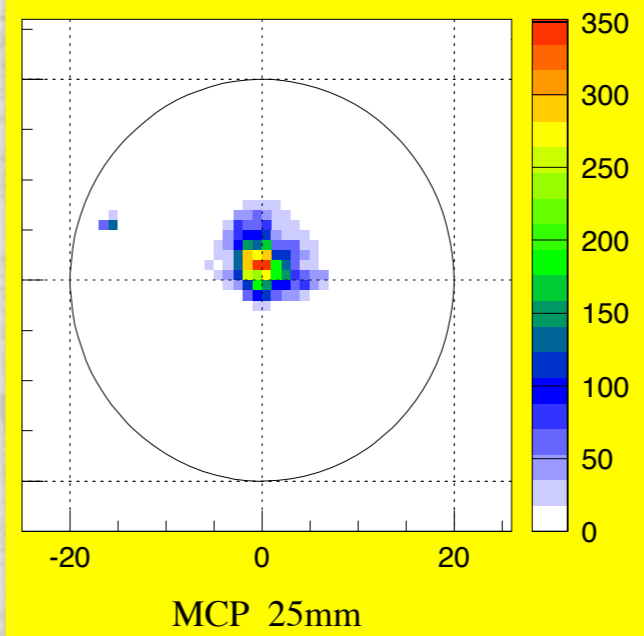
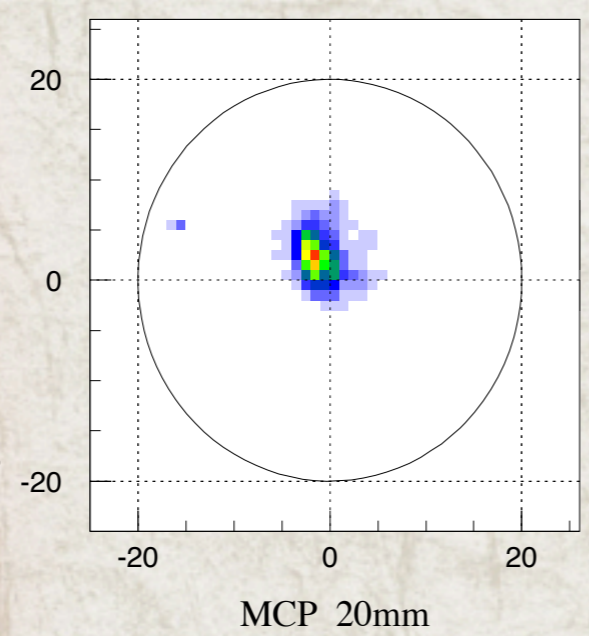


target  
position

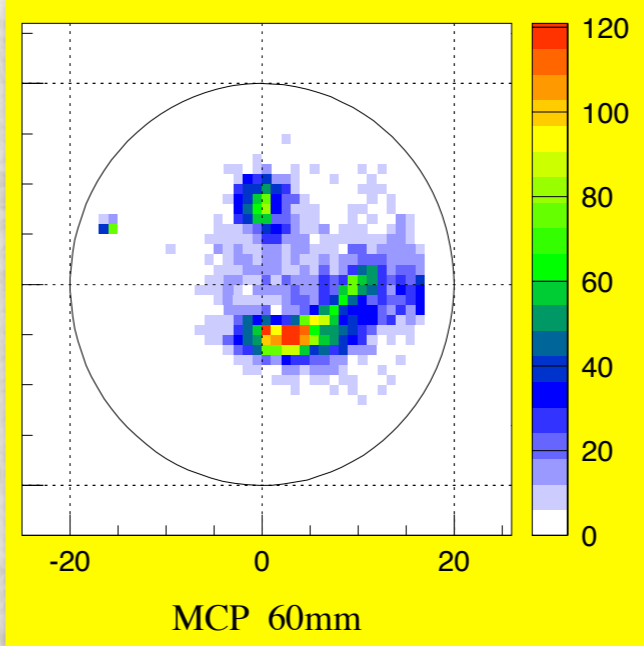
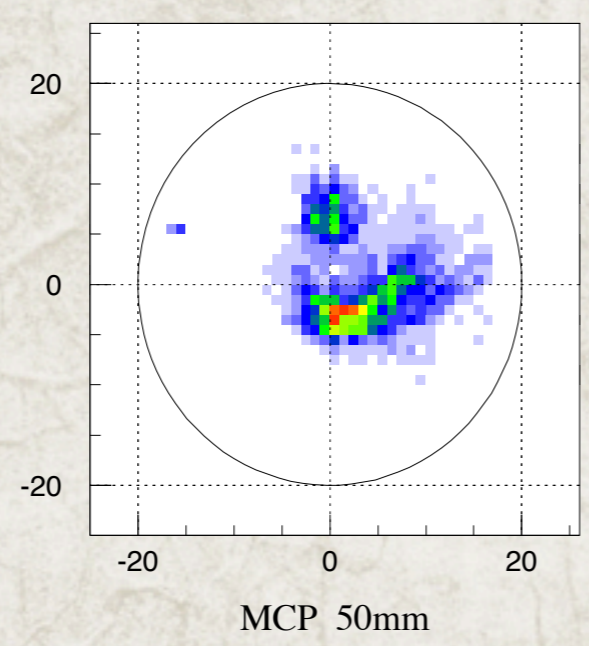
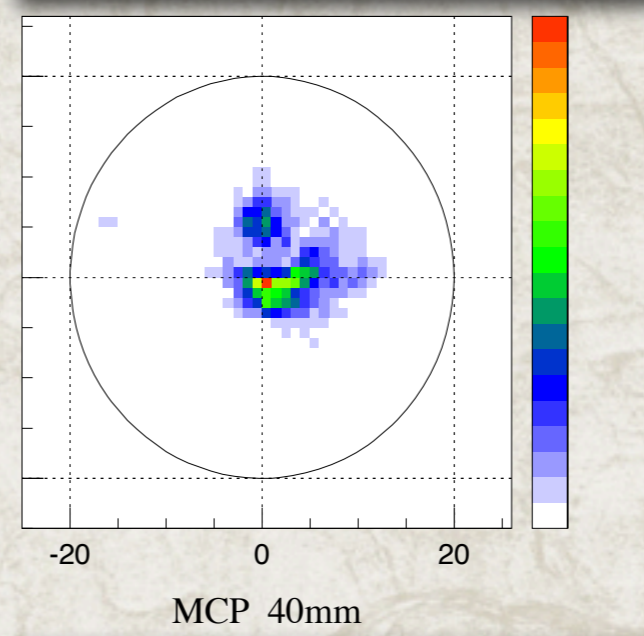
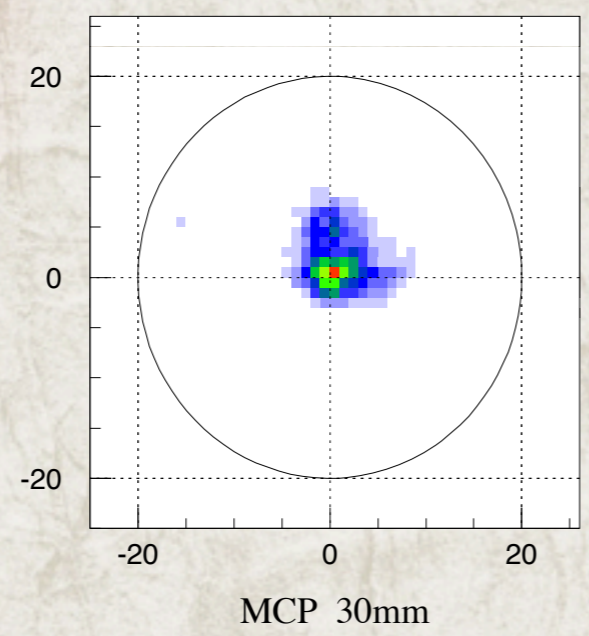


MCP  
position

# Beam Profile @ 27.5 eV



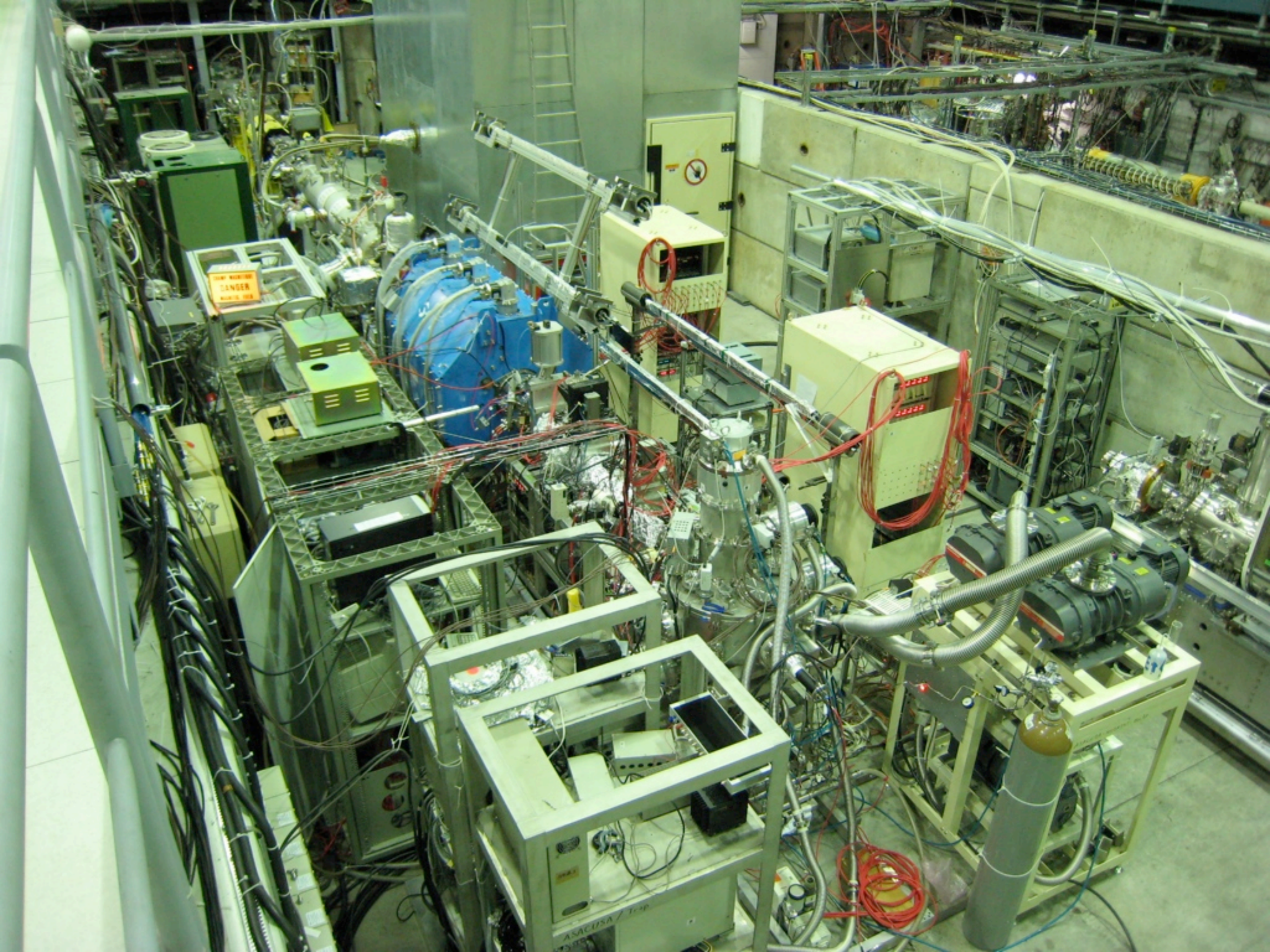
target position

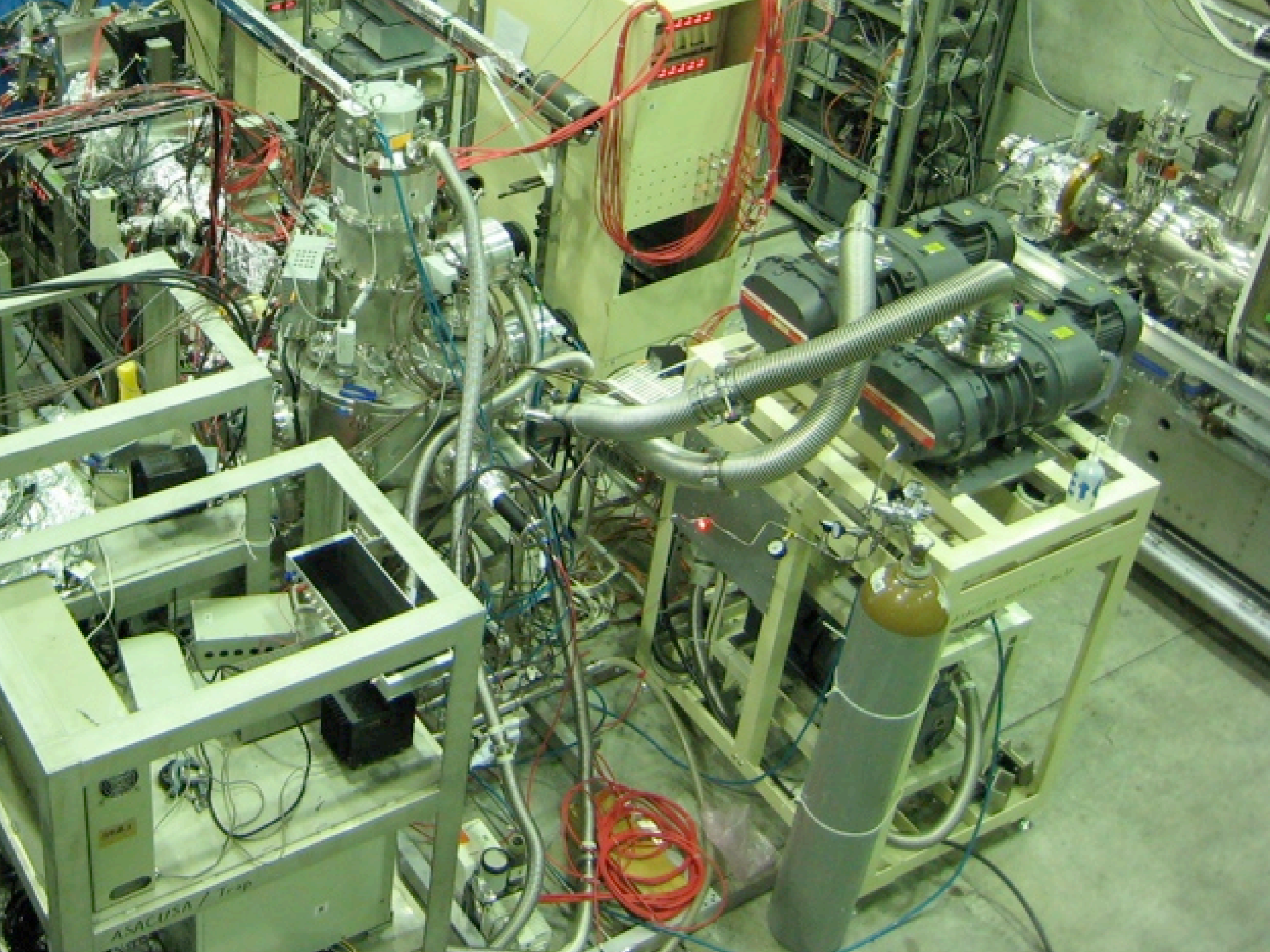


MCP position

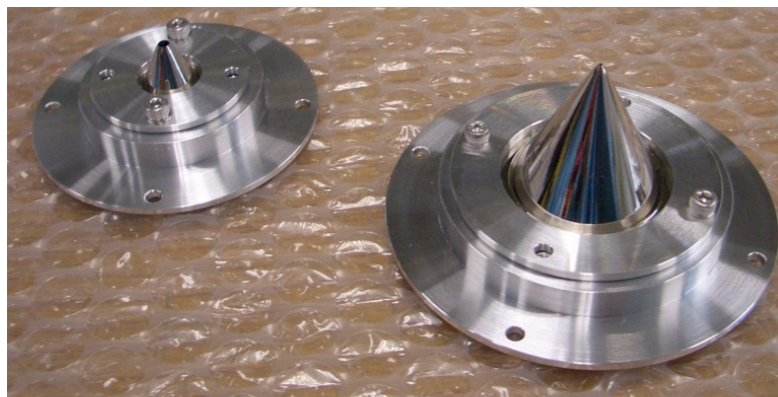
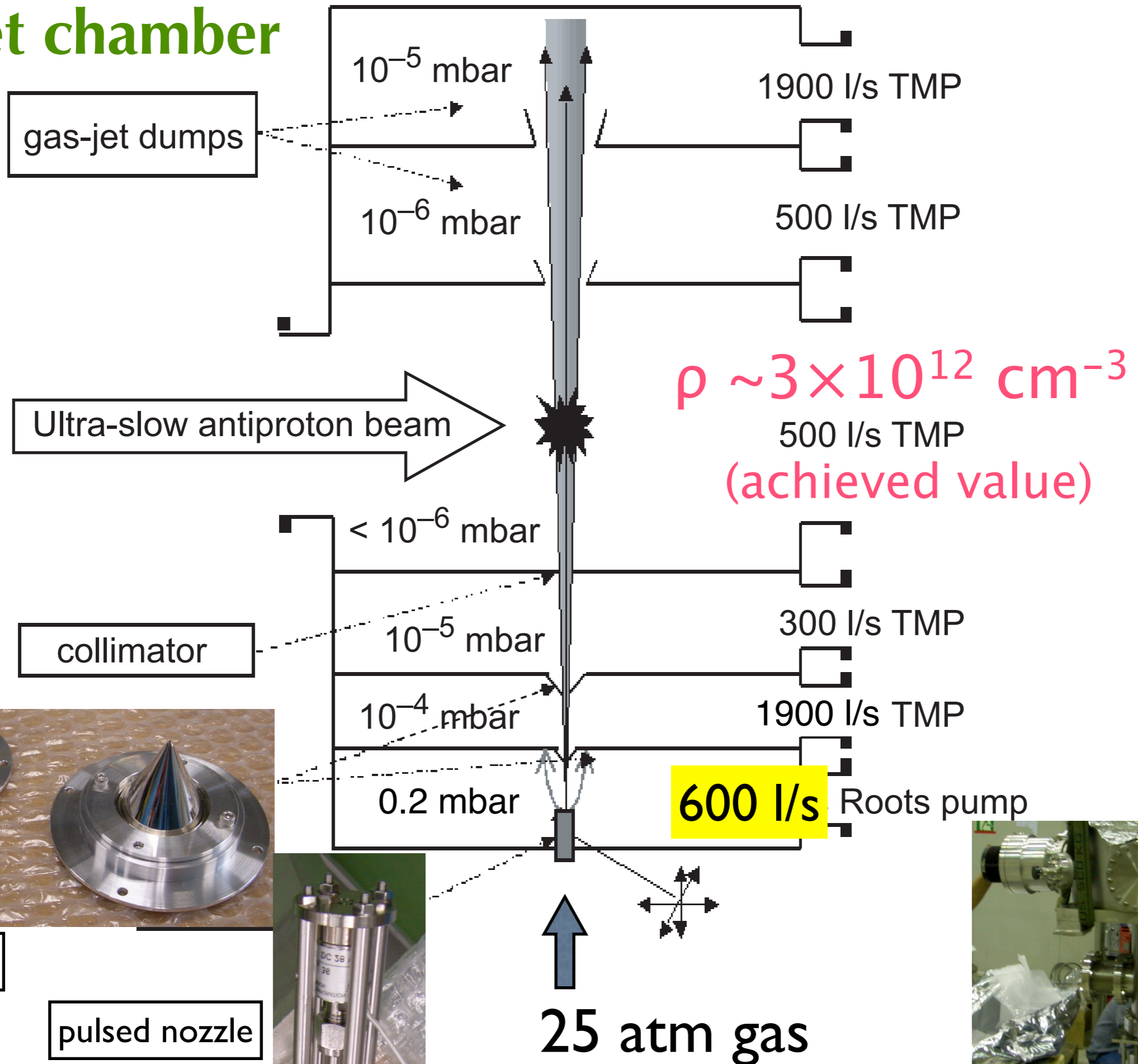
# 超低速反陽子ビーム

- 10 – 1000 eV の単一エネルギービーム
- 再加速も可能 (upto 30 keV)
- 30~70万個の反陽子
- 10~30秒間の連続ビーム引き出し
- 2  $\mu$ s のパルス引き出しも可能



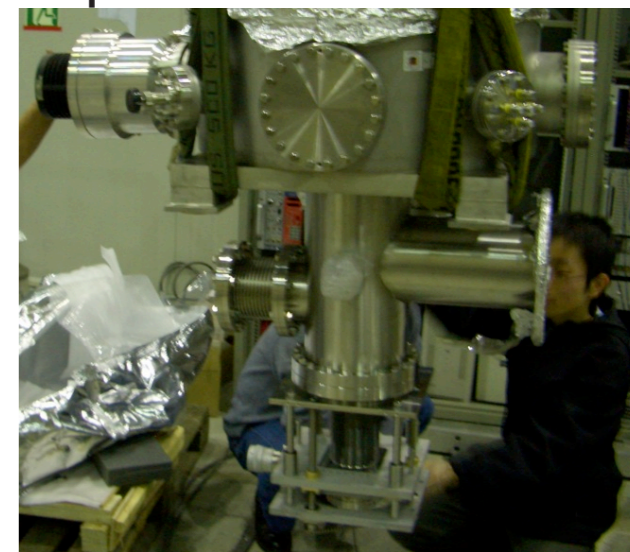
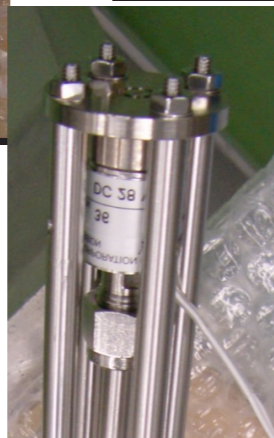


# Gas-jet chamber



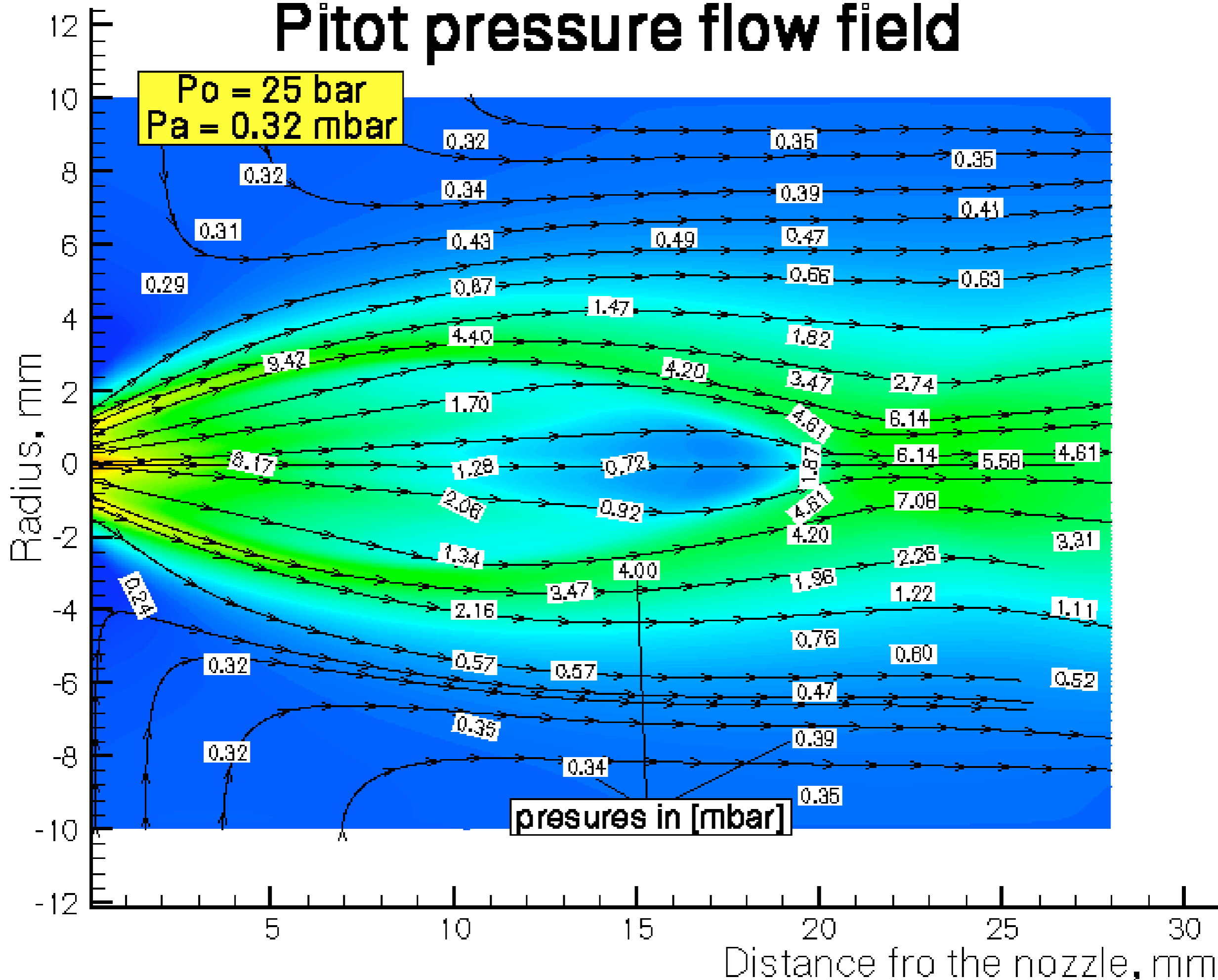
skimmers

pulsed nozzle

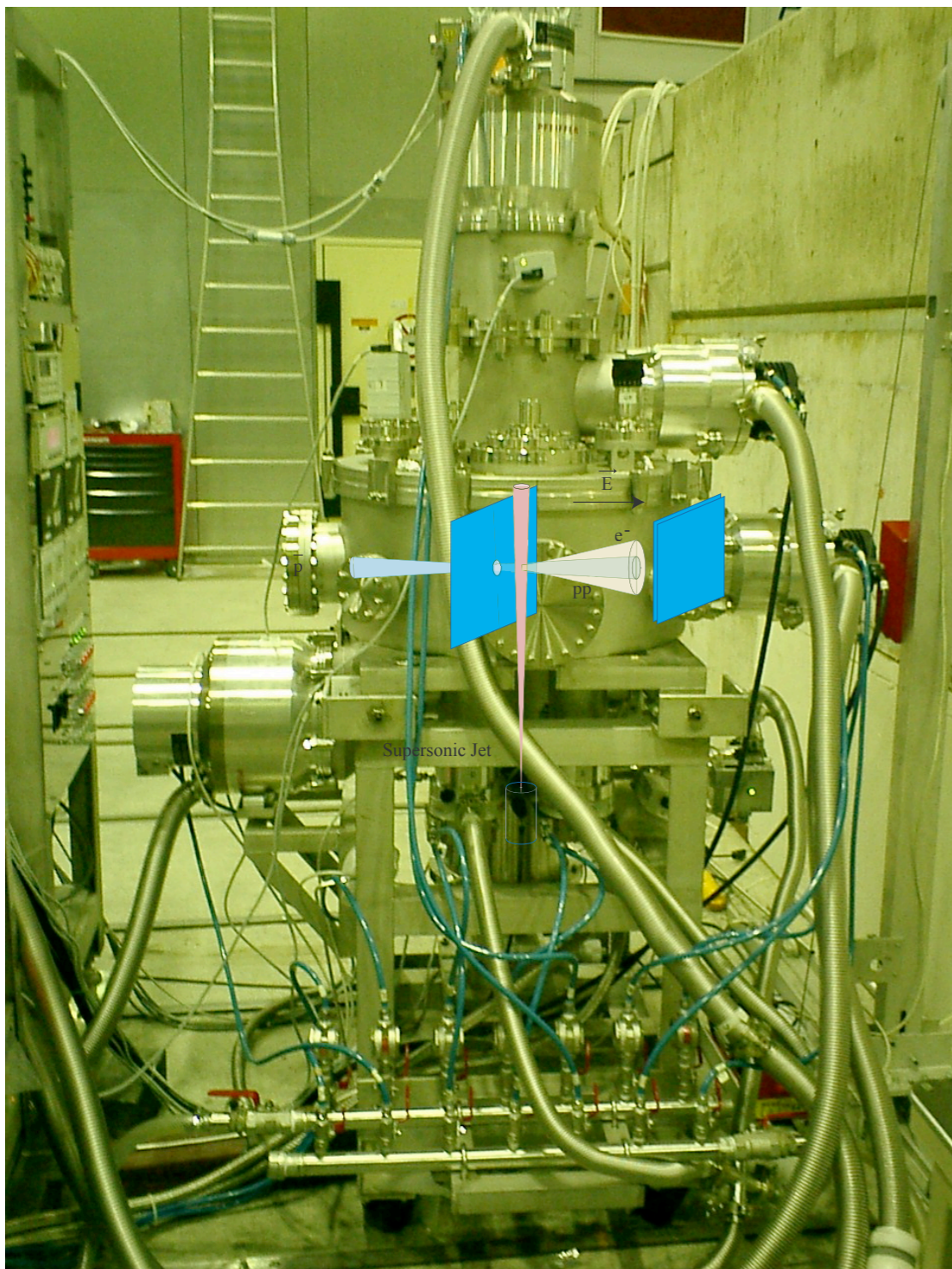




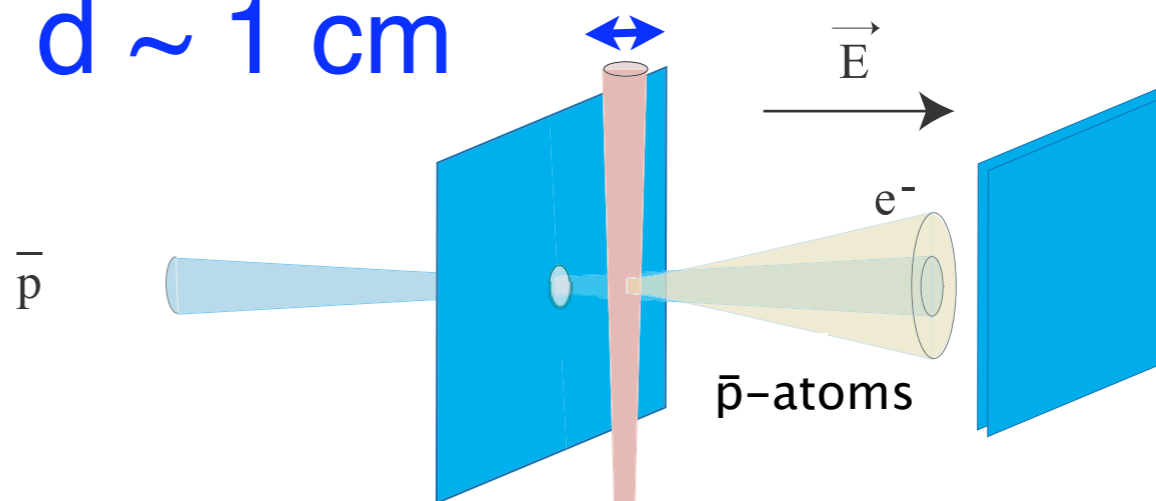
# Pitot pressure flow field



# Gas-jet target



$d \sim 1 \text{ cm}$



Supersonic Jet

RT (300 K)  
25 atm



$$\rho \sim 3 \times 10^{12} \text{ cm}^{-3}$$

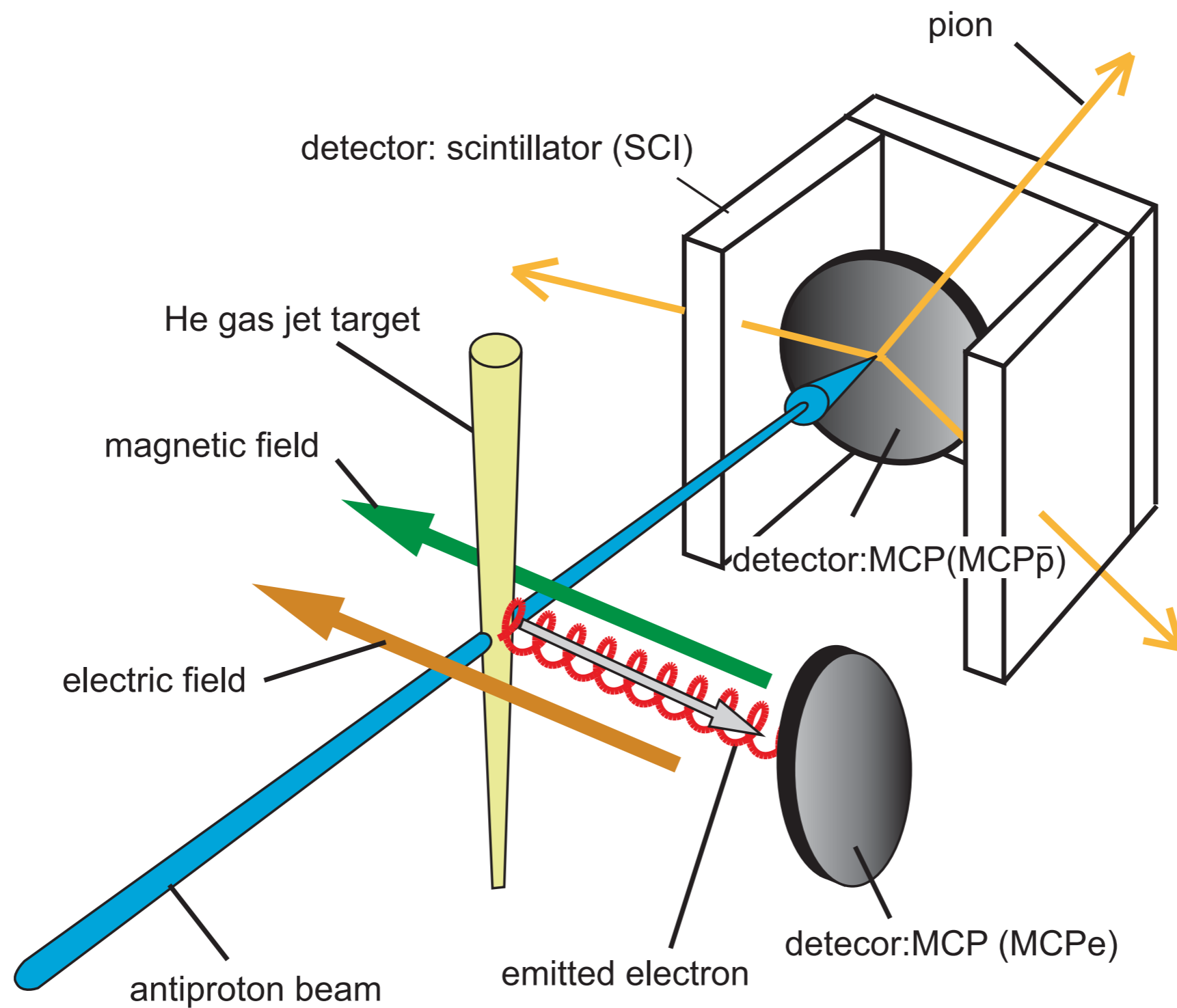
$$\rho \sigma d = 0.03\%$$

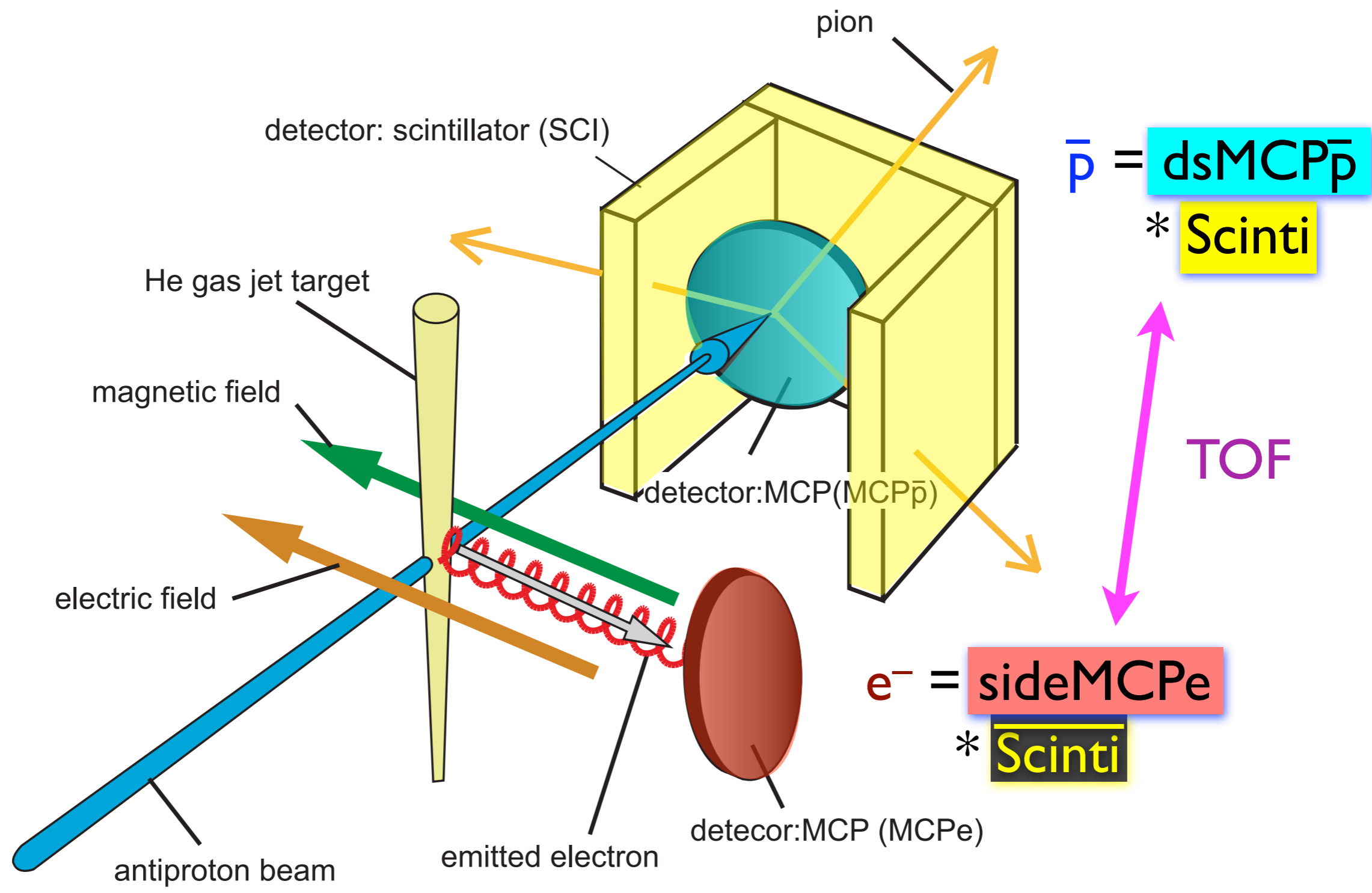
$$\text{@ } \sigma = \text{~~10}^{-16} \text{ cm}^2~~$$

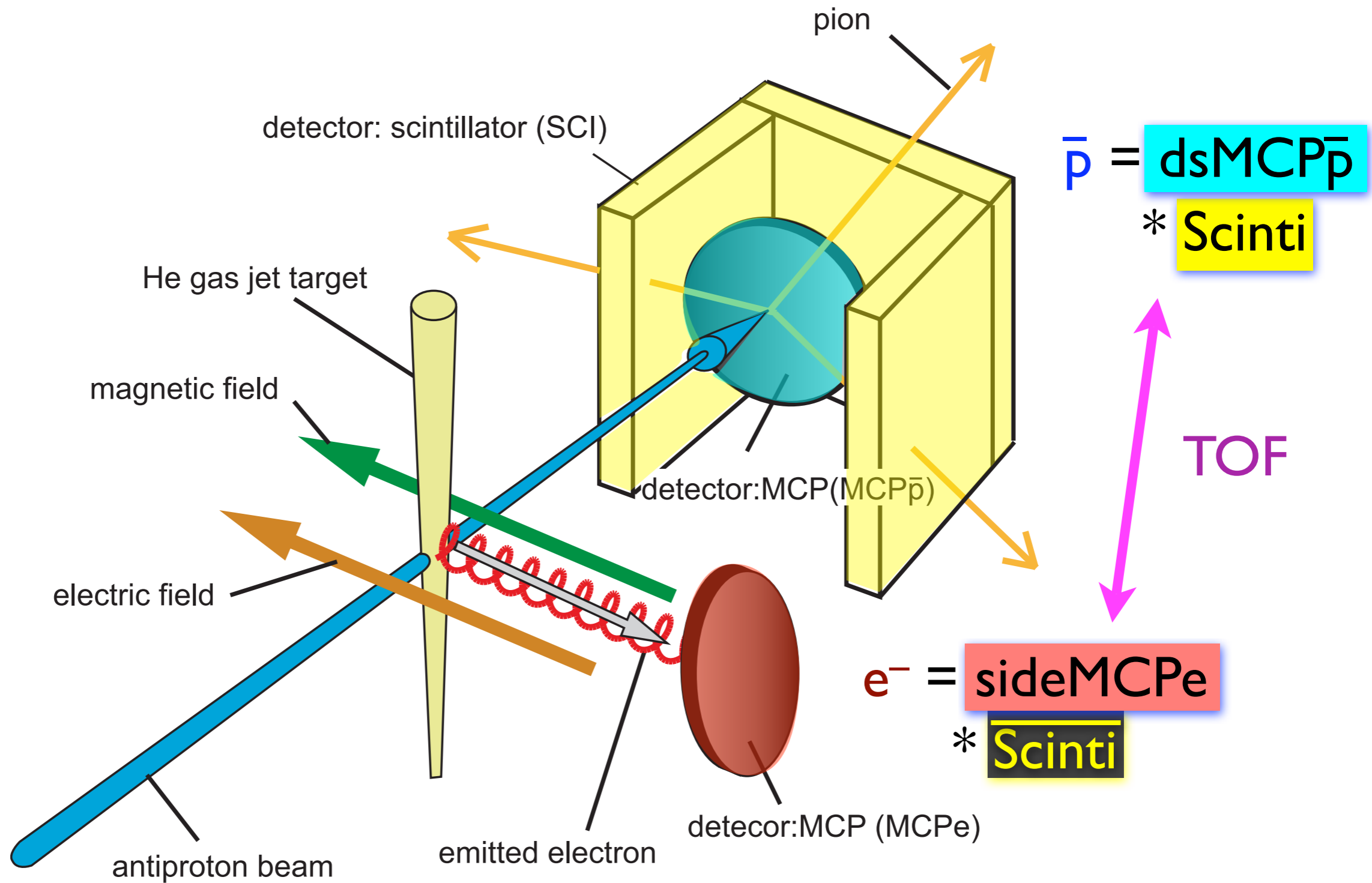
a few  $\times 10^{-17} \text{ cm}^2$

~~$$10^5 \bar{p} \Rightarrow 30 \bar{p} \text{ atoms}$$~~

$$3 \times 10^5 \bar{p} \Rightarrow 10 \bar{p}\text{-atoms}$$





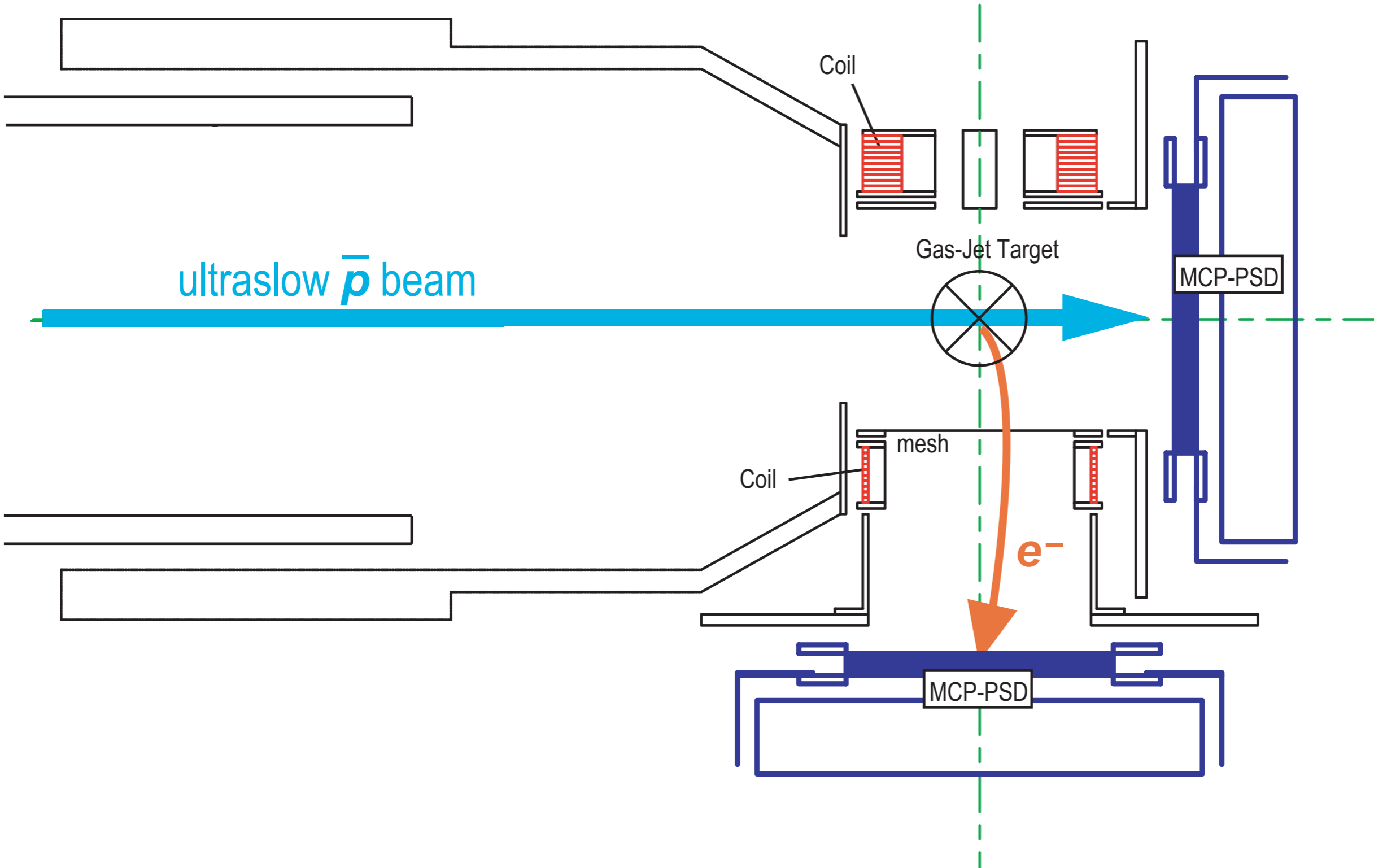


生成する反陽子原子はガスジェットで偏向する！

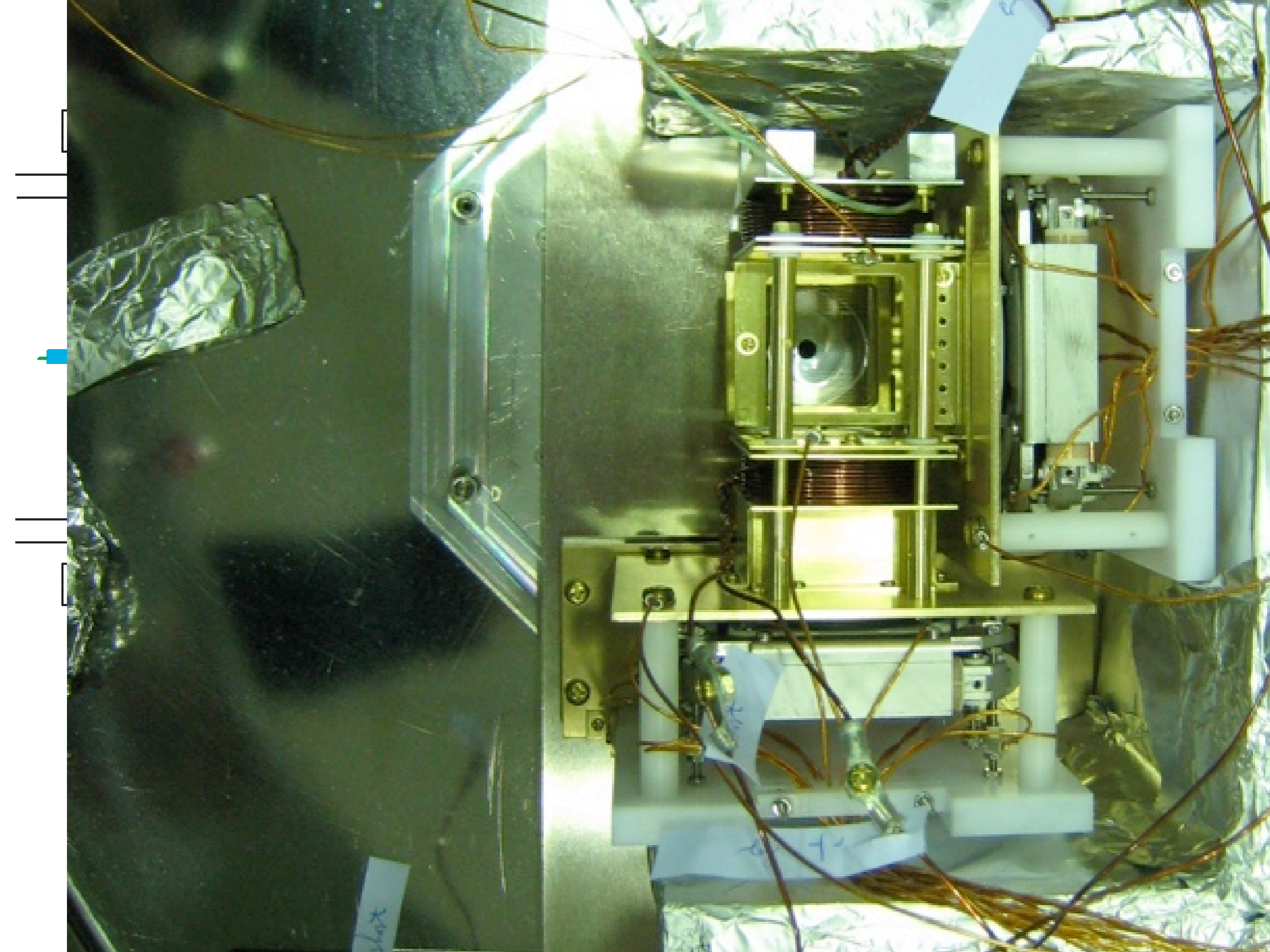
(速度 :  $1 \mu\text{s} / 1 \text{cm}$ )

(a few mm : 運動量保存)

# Detectors

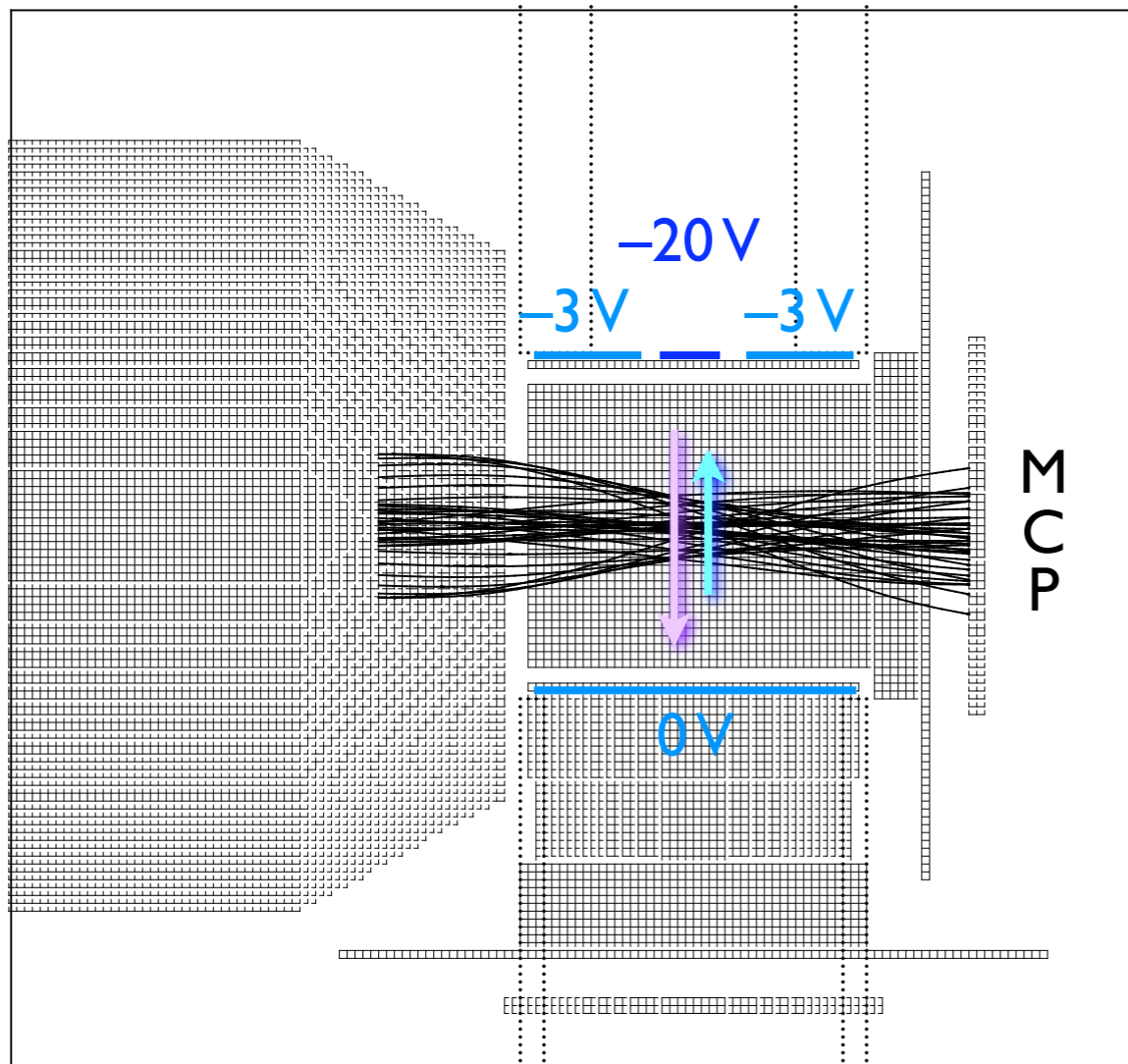


Scintillator

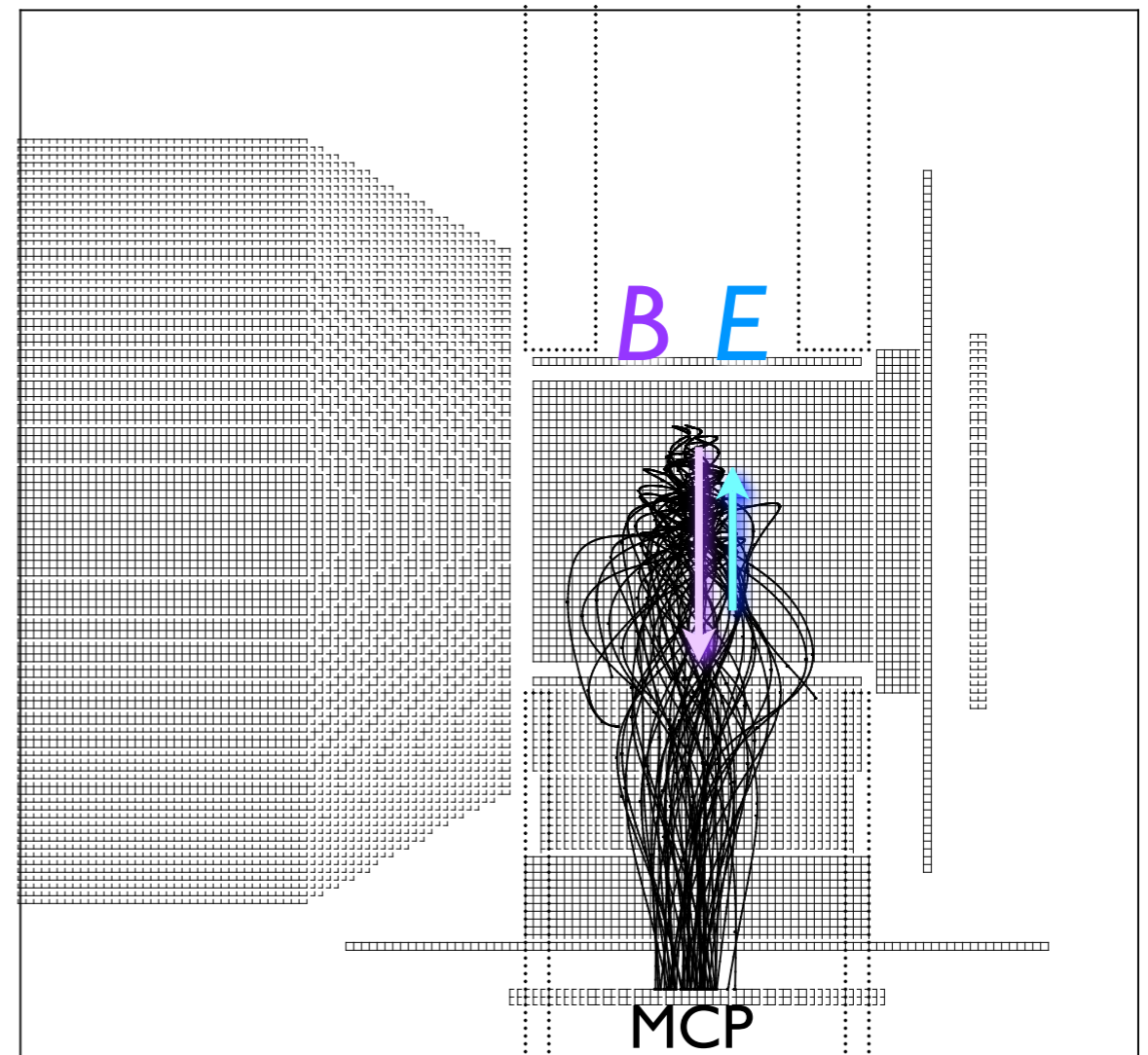


# 検出器系

- 弱磁場 & 弱電場により電子を横方向に引き込む
- 反陽子の軌道への影響は十分小さくできる
- 反陽子と電子を前方および横の MCP で分けて検出



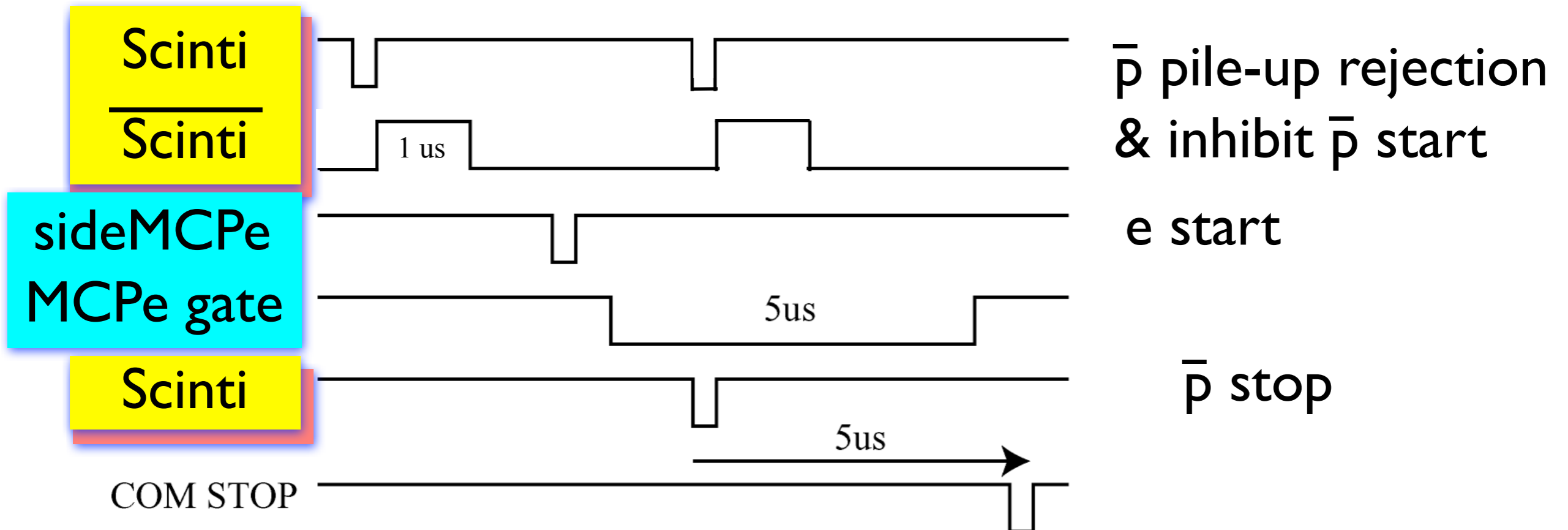
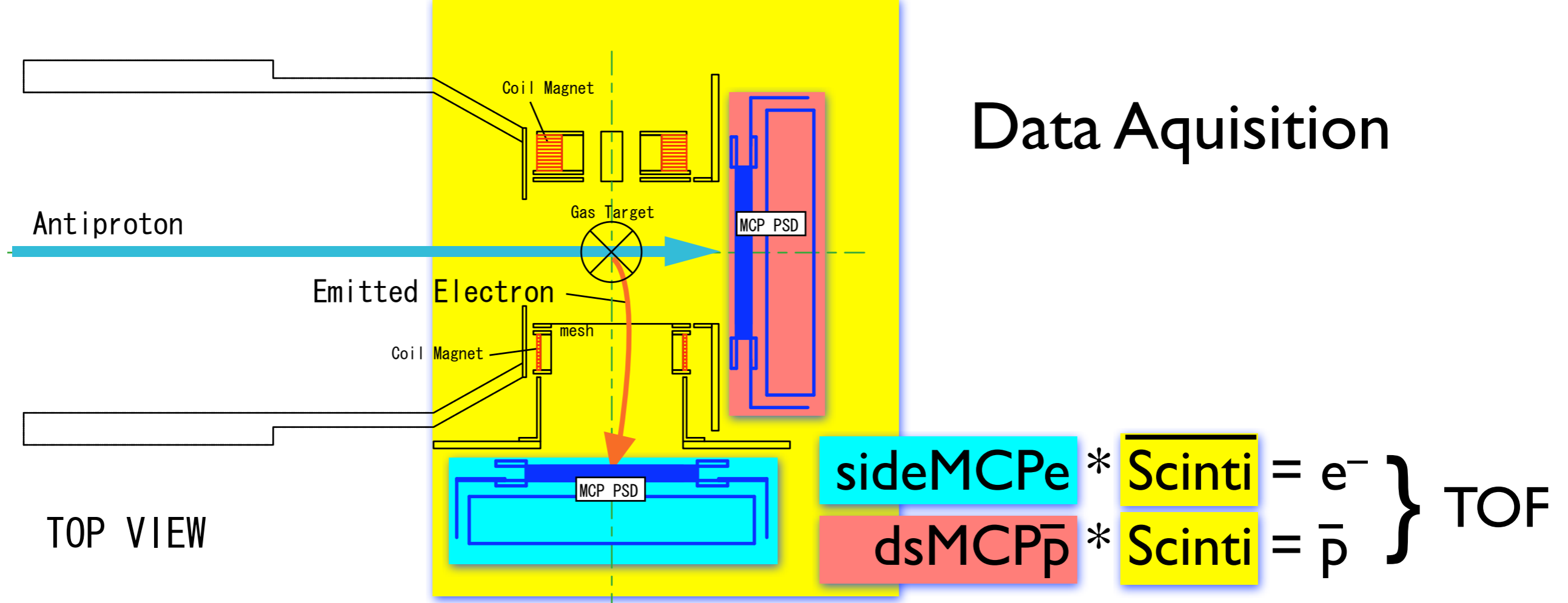
反陽子 (30 eV)

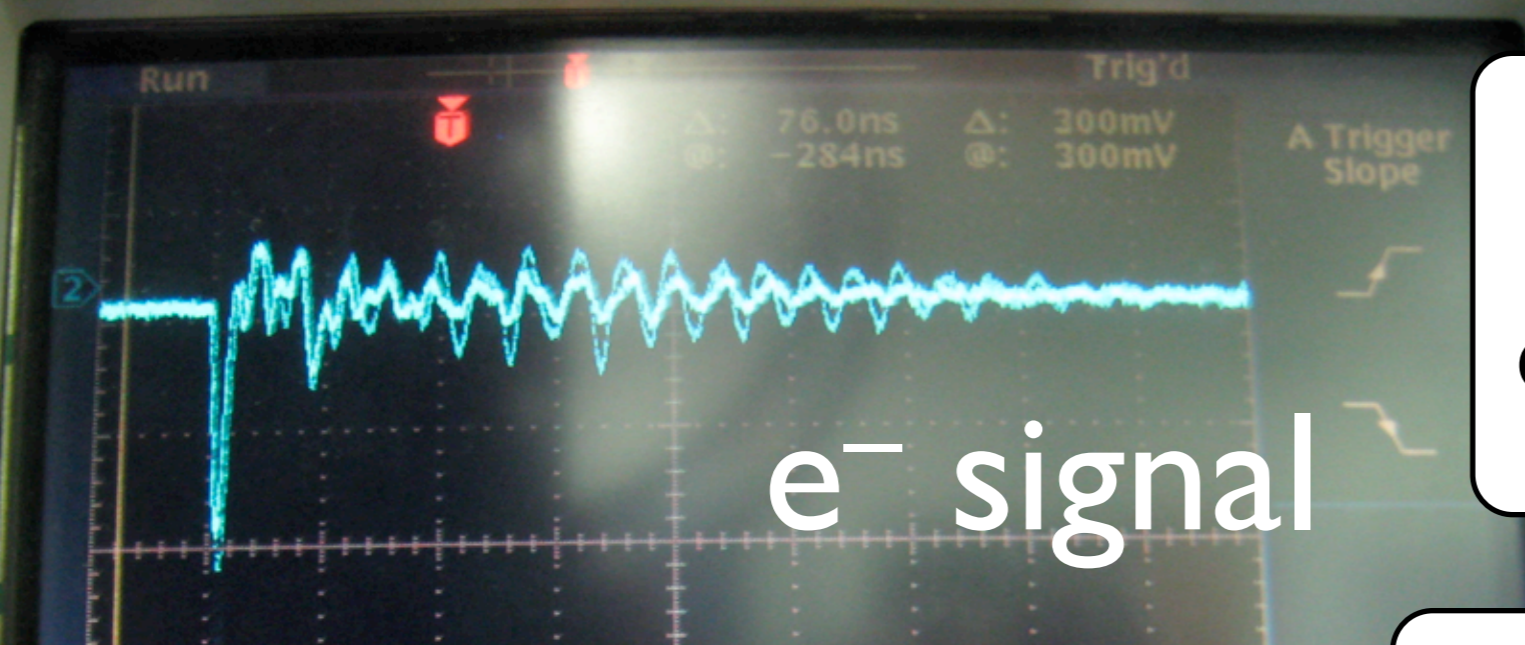


電子 (5 eV)

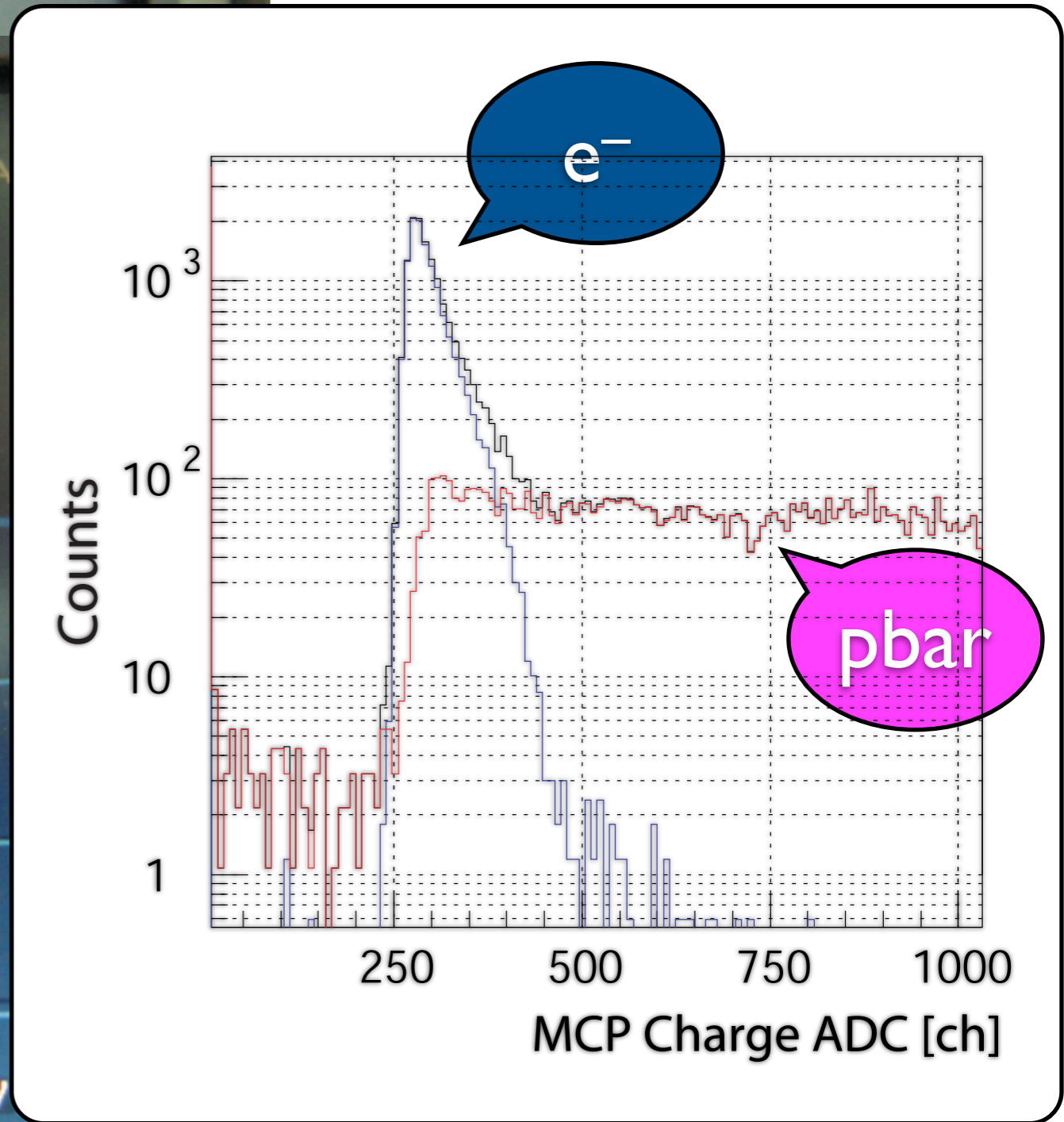
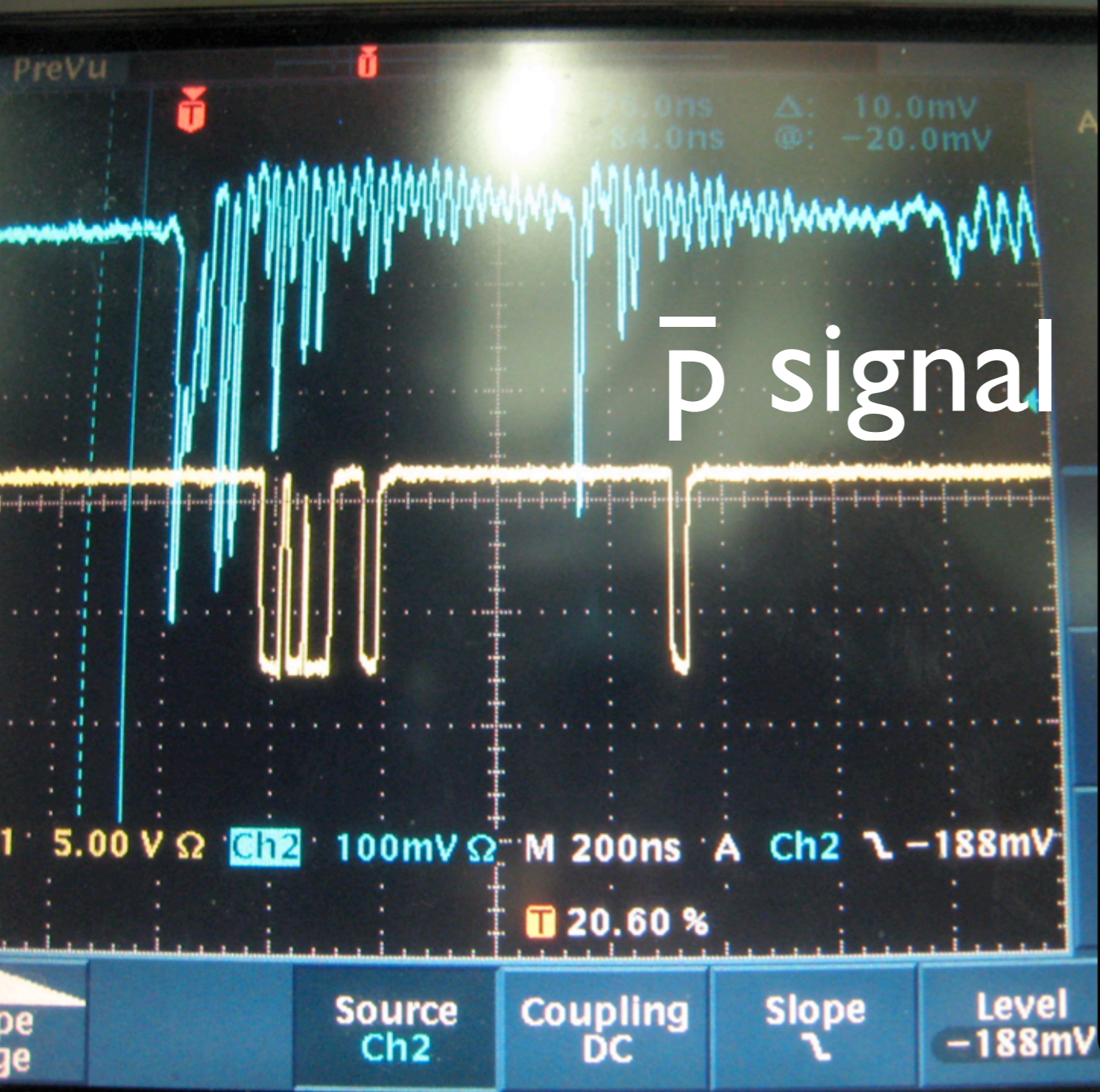


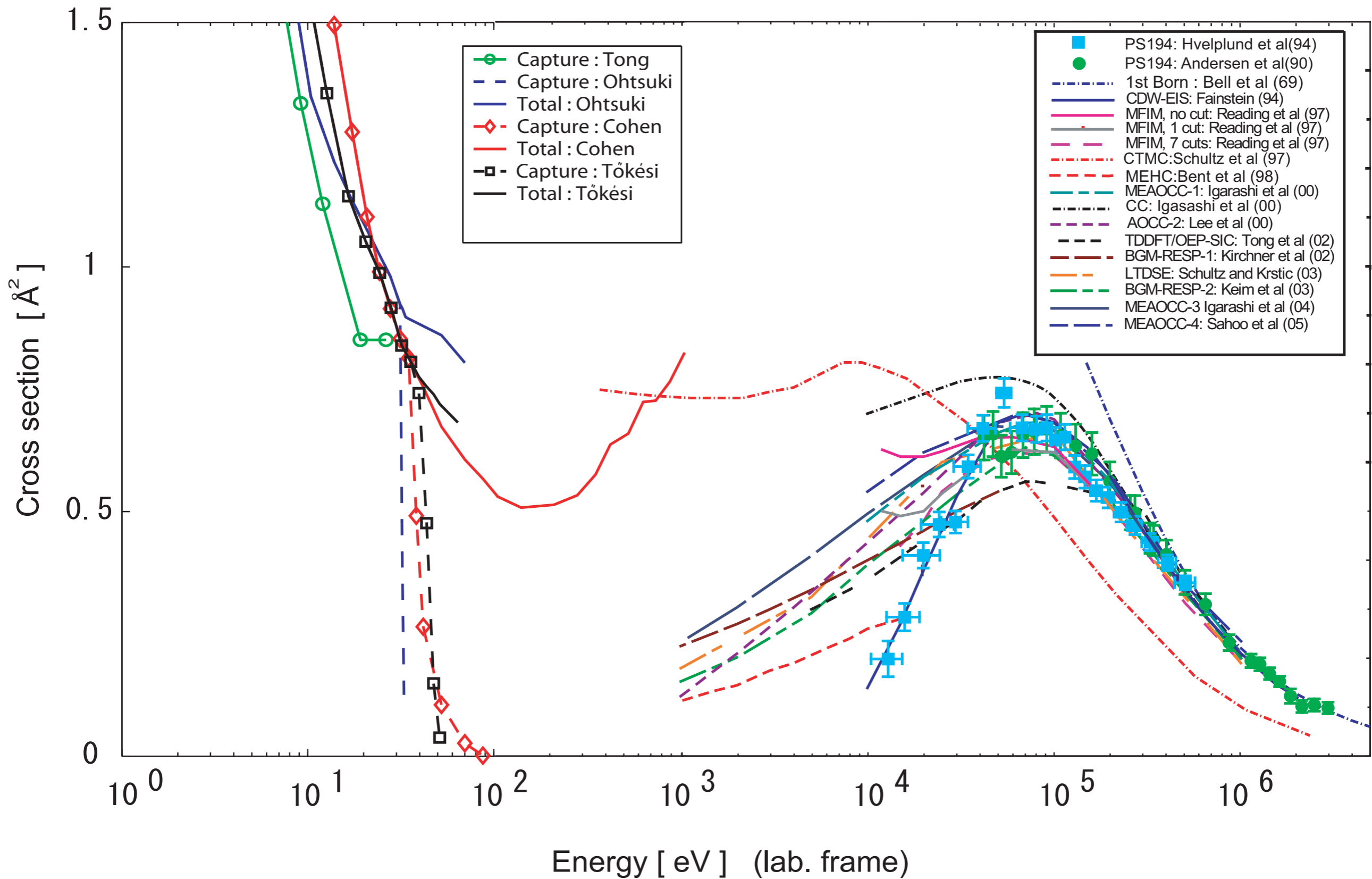
# Data Acquisition

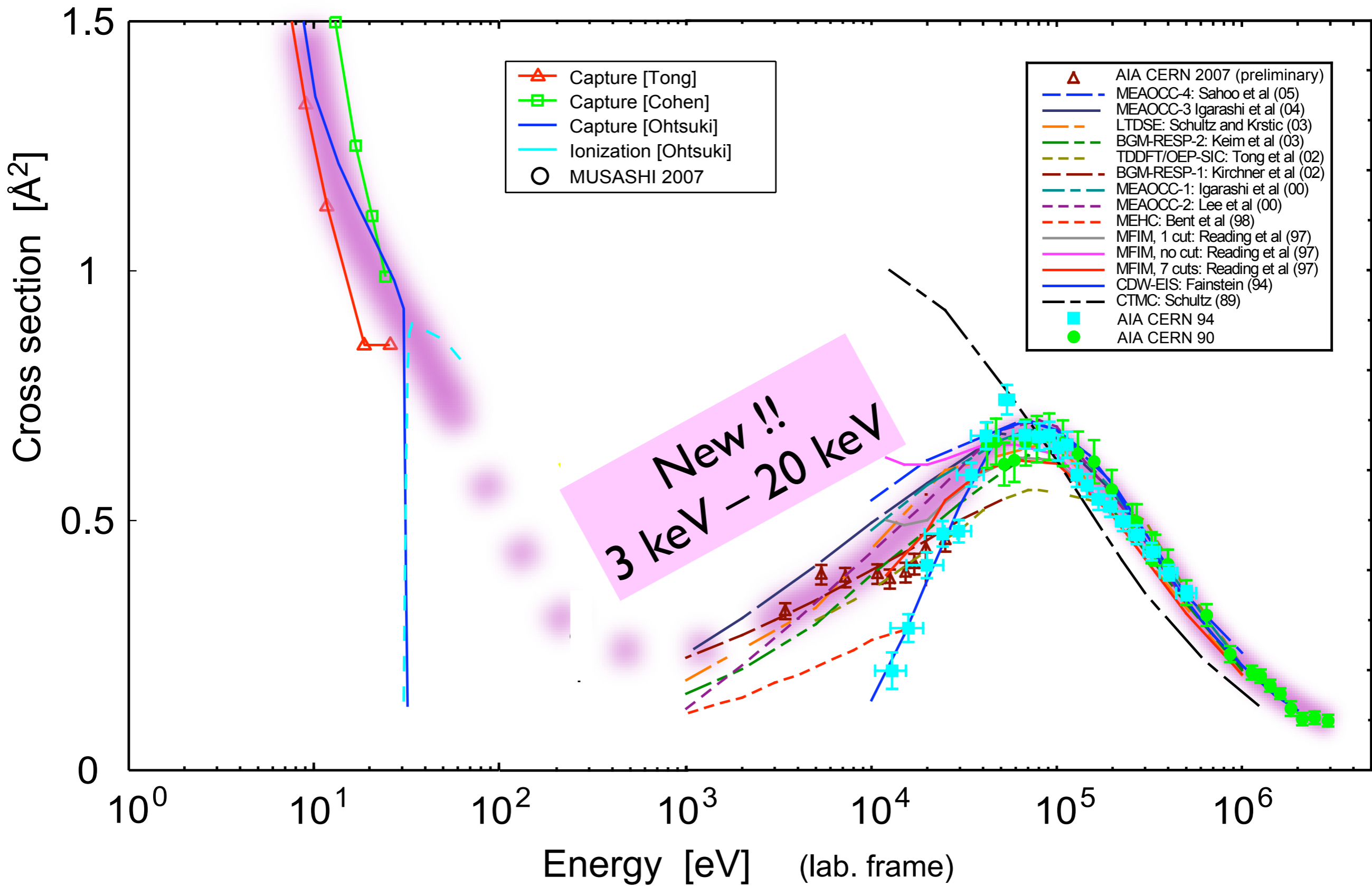


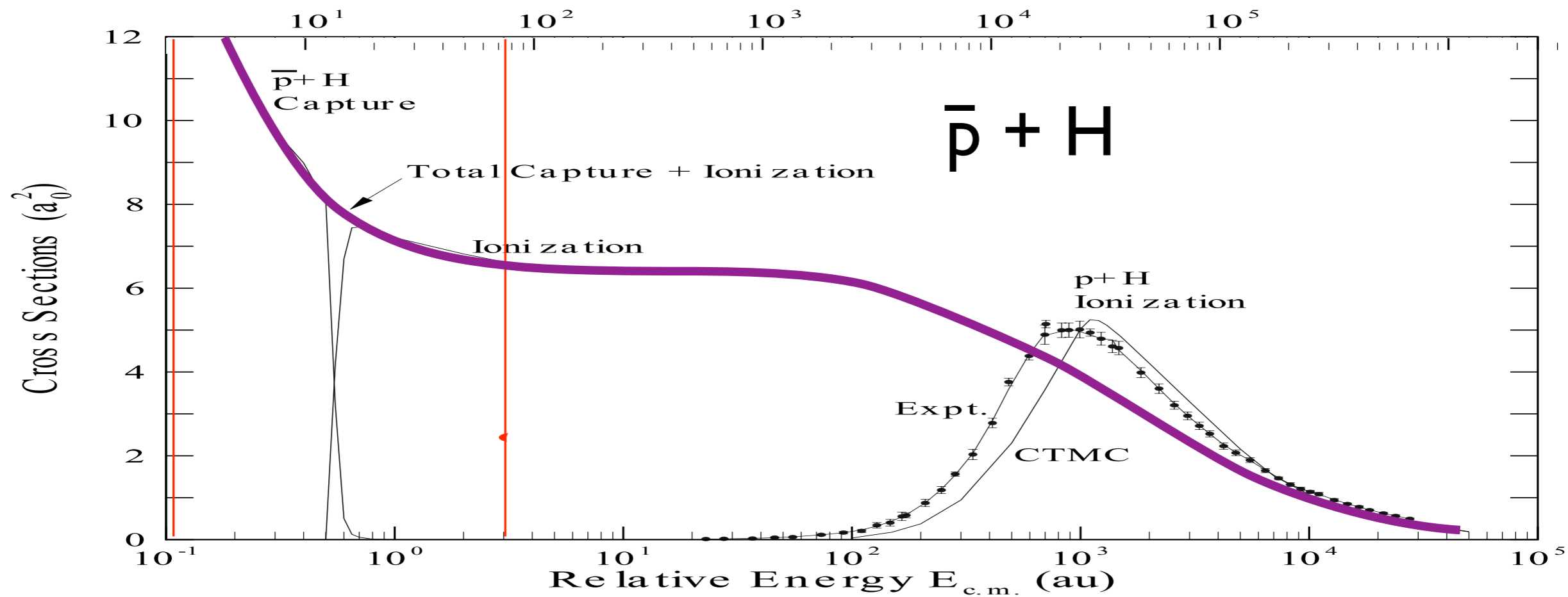
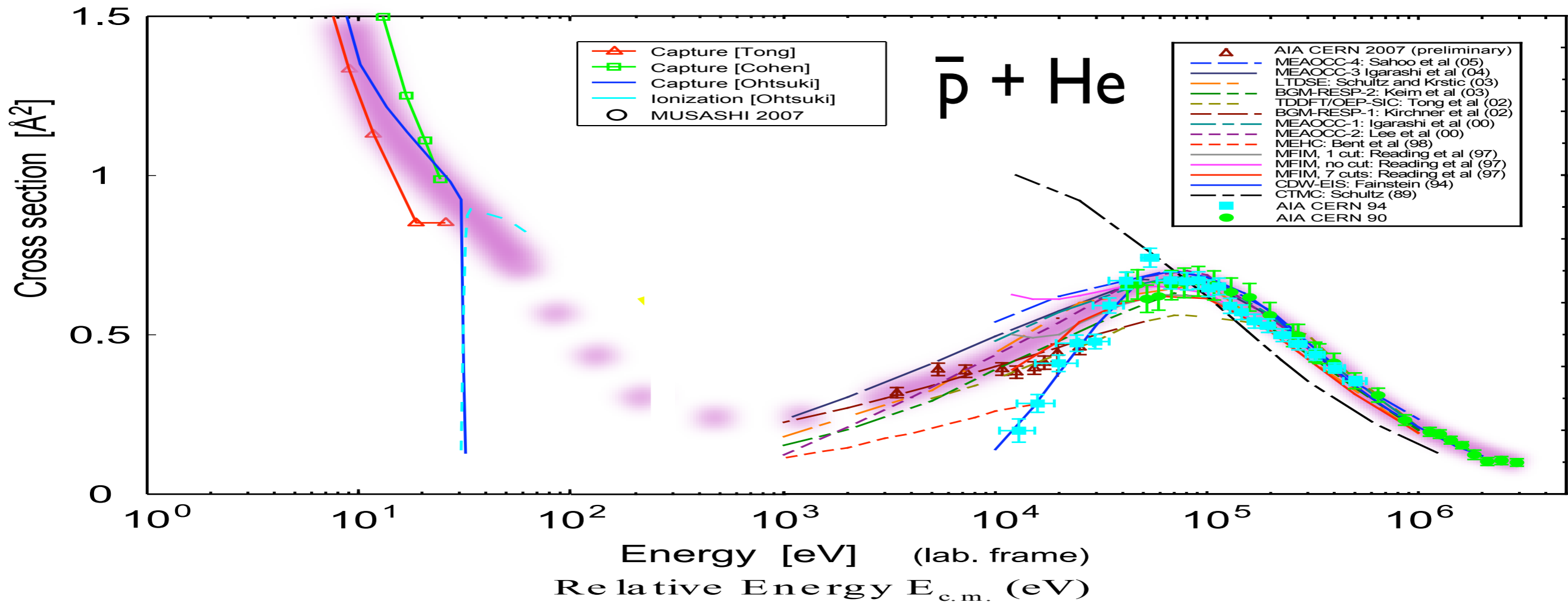


MCP signals  
 electrons & antiprotons









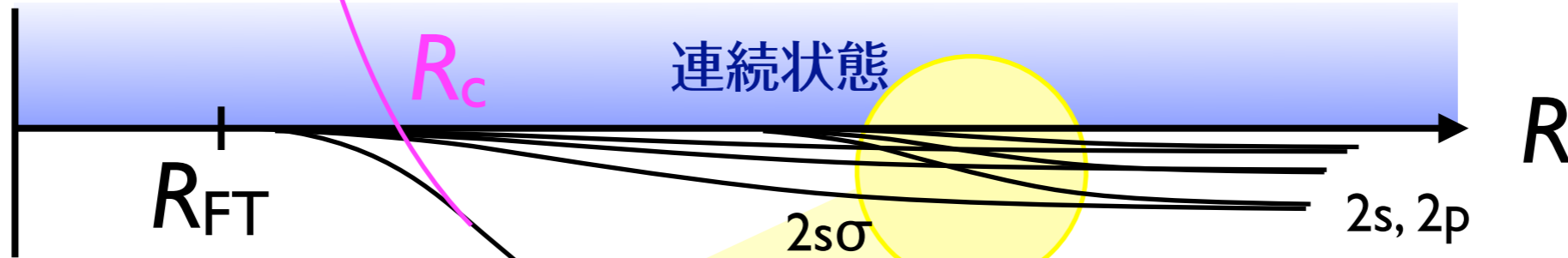
$Pn (\bar{p}p) + e^-$

$$\sigma = \pi R_c^2 ?? > \pi R_{FT}^2$$

透熱ポテンシャル曲線

$R_c$

連続状態



$R_{FT}$

(0.639 au)

$2s\sigma$

$2s, 2p$

$R$

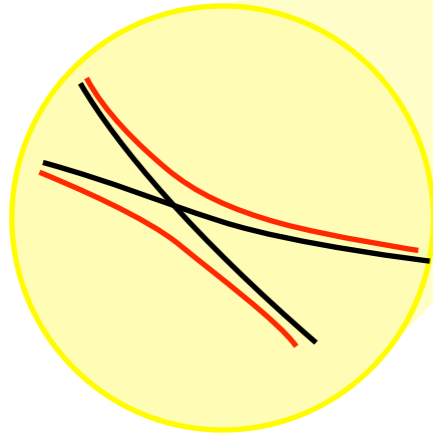
$(Z=0) + e^-$

断熱ポテンシャル曲線

$\bar{p} + H$

$1s\sigma$

$1s$



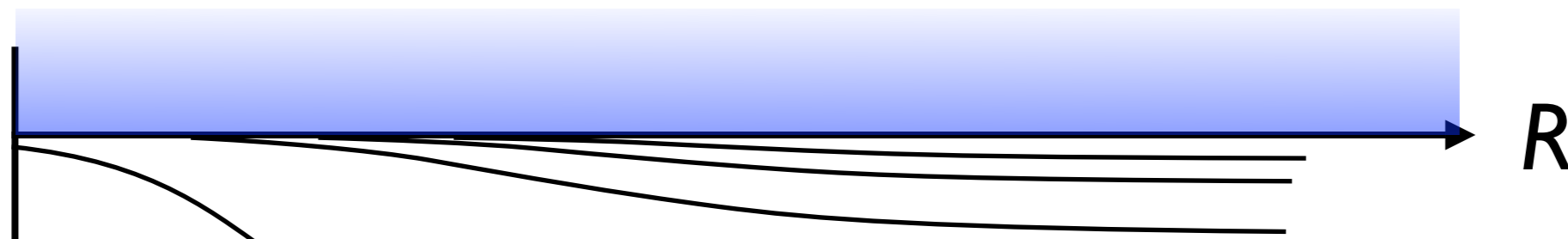
ポテンシャル交叉

Born-Oppenheimer 近似 ??

-0.7 eV

$H^-$

$R=0$



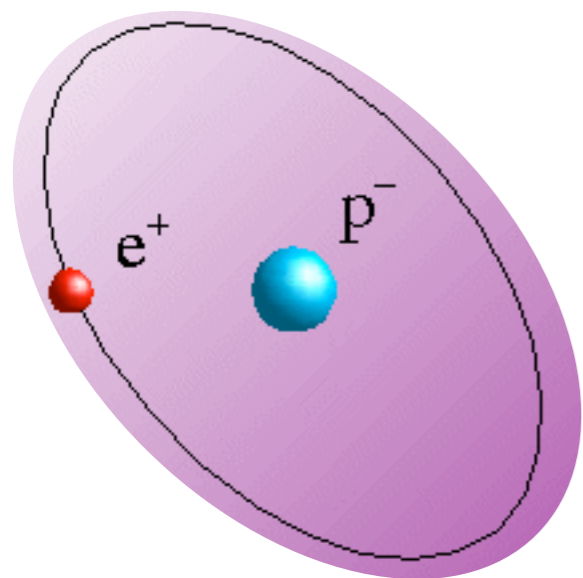
$R$

$\bar{p} + He$

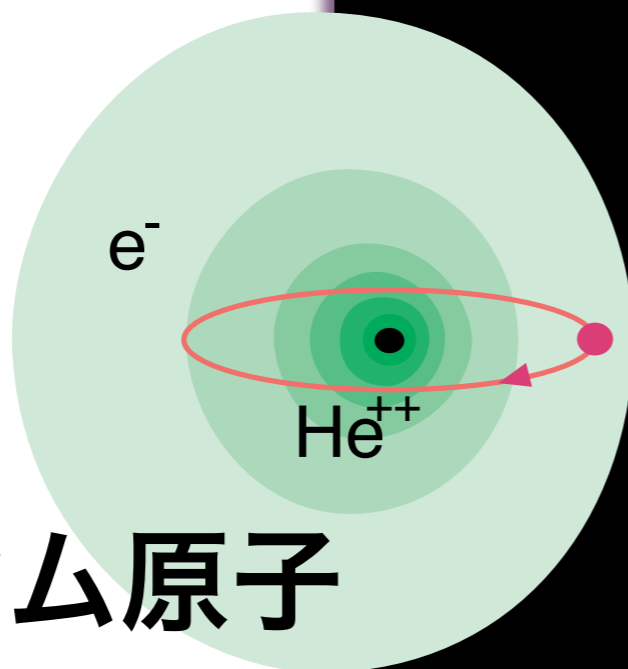
$\sigma = 0$  at adiabatic passage limit

# 反物質の世界

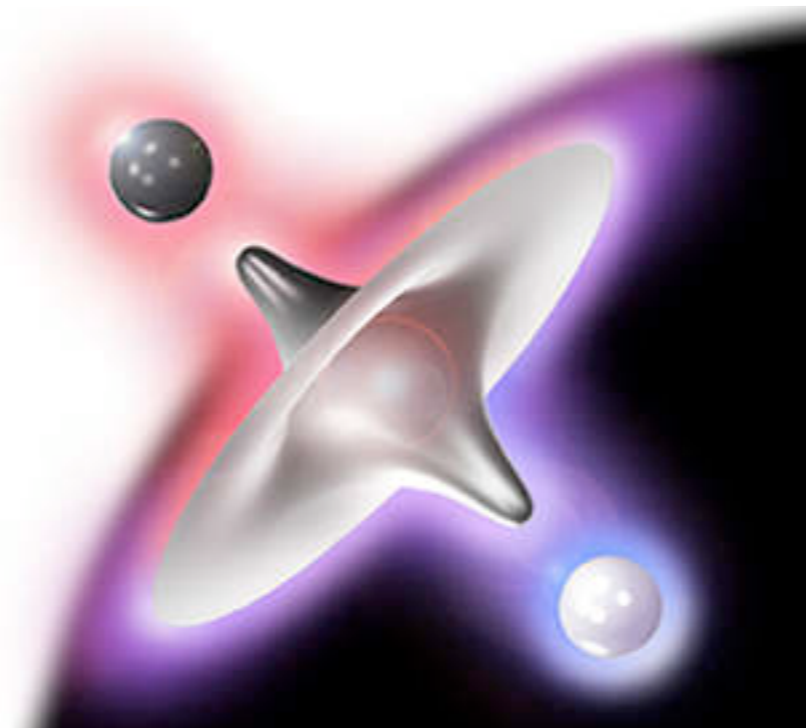
## 反水素原子



## 半物質



## 反陽子ヘリウム原子



物質の世界

# 反水素原子



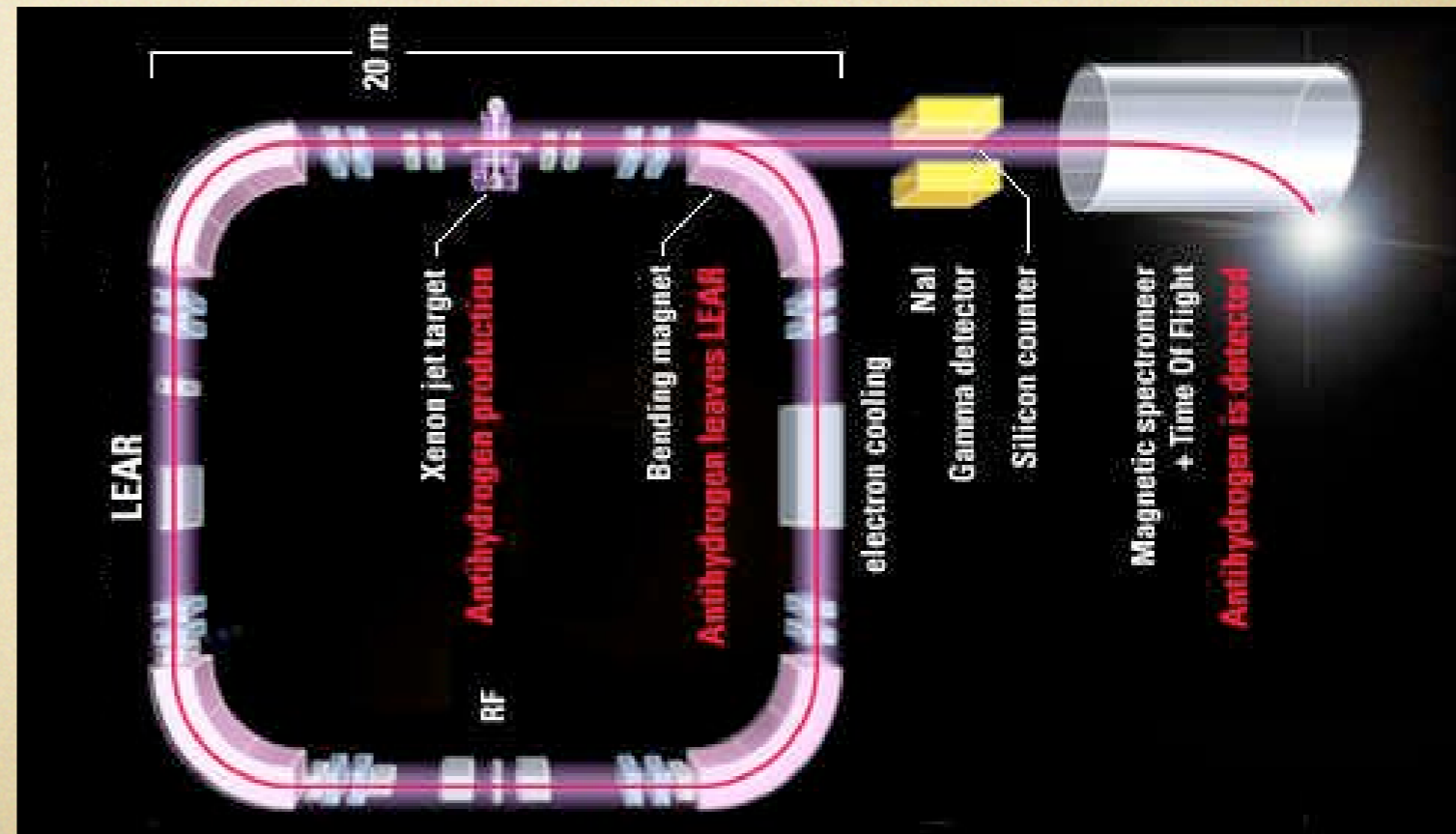
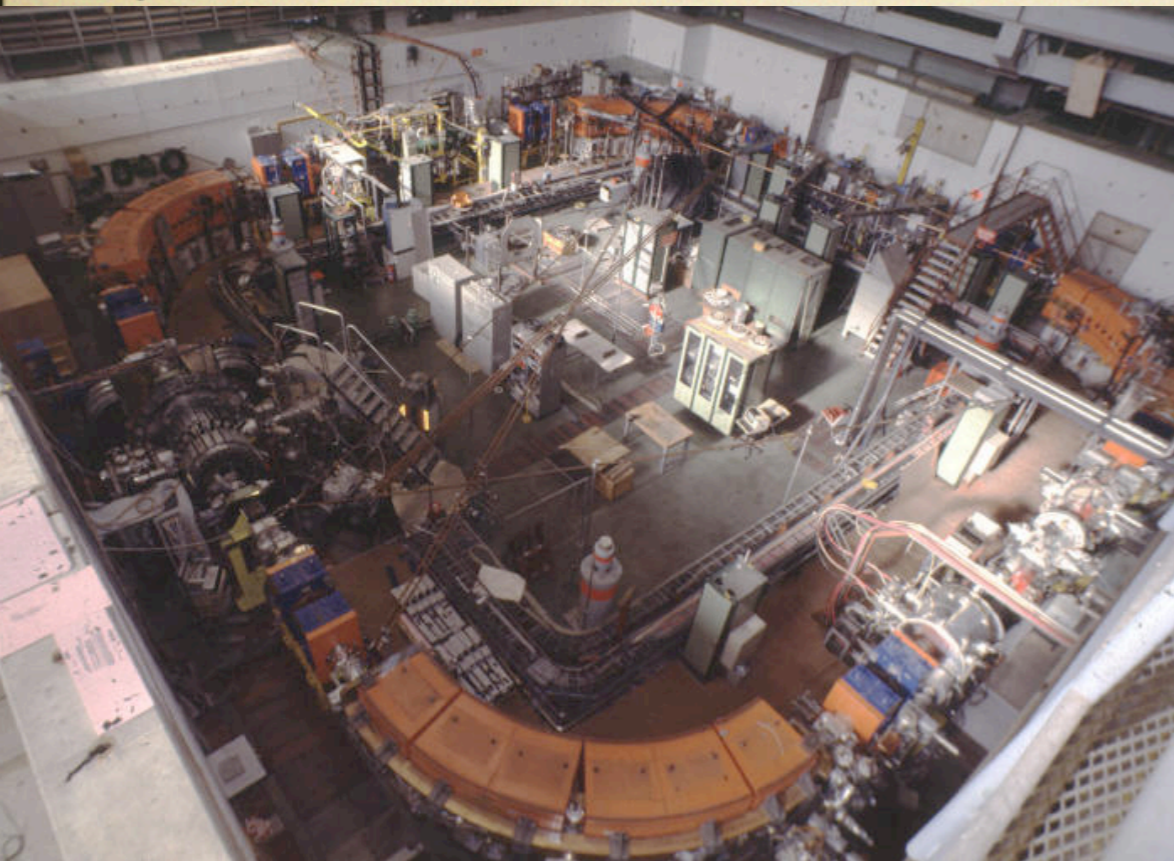
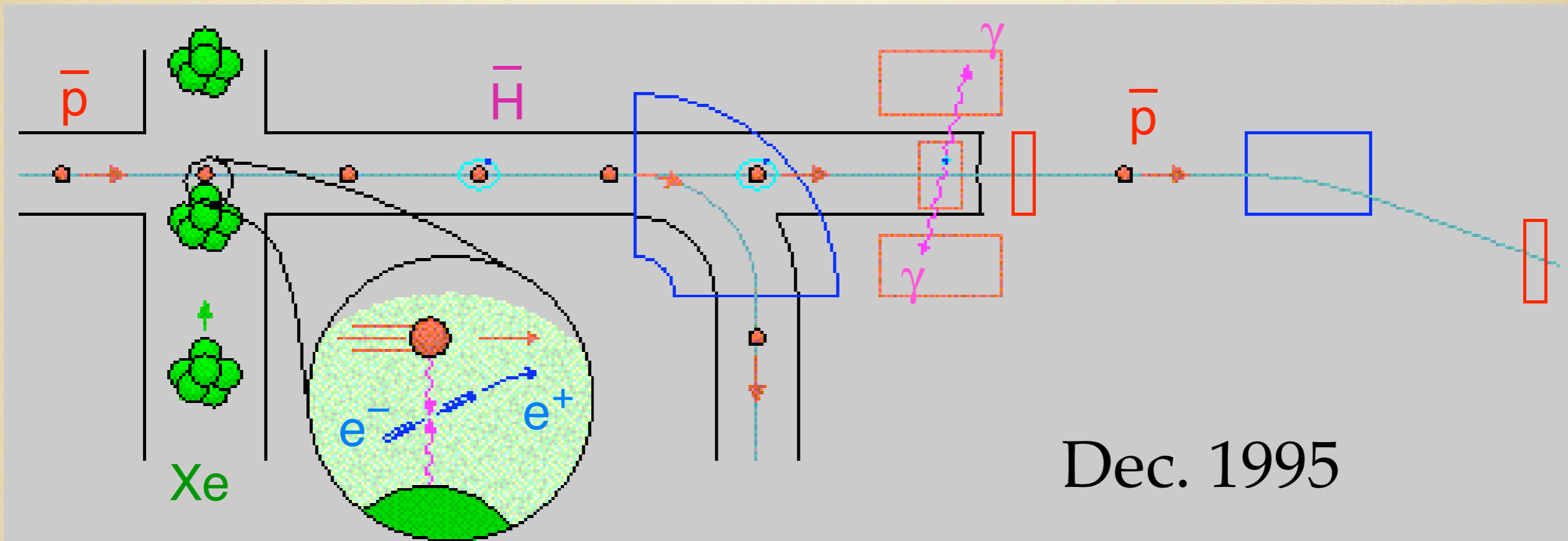
原子番号 -1

最も単純な反物質





# Antihydrogen Production in Flight (PS210 experiment at LEAR)





# PRESS RELEASE

Laboratoire Européen pour la Physique des Particules  
European Laboratory for Particle Physics  
Europäisches Laboratorium für Teilchenphysik  
Laboratorio europeo per la fisica delle particelle

## FIRST ATOMS OF ANTIMATTER PRODUCED AT CERN

In September 1995, Prof. Walter Oelert and an international team of scientists from the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany, succeeded for the first time in producing antiprotons, the antimatter counterpart of protons.

Mitteldeutsche Zeitung 6/01/96

### Herstellung von Antimaterie

# Die Enterprise bleibt Fiktion

Physiker dämpft Euphorie nach bahnbrechender Entdeckung

Von unserem Redakteur  
LOTHAR VAHAR-MATIAR

Jülich/Halle/MZ. Wenn's eng wird, Klingonen-Flotten aus allen Röhren lasern oder galaktische Staubsauger die Enterprise im Gamma-Quadranten verschwinden lassen, wird Captain Kirk bald zu einem beliebigen Mann. Denn die Entdeckung der Antimaterie wird zwei Monate

unumstritten. Dennoch kann Walter Oelert über die Enterprise-Geschichten nur müde lächeln: "Science Fiction ist etwas für Träumer. Und die Fans werden auch nach meiner Entdeckung weiter träumen müssen." Träumen von einer praktischen Nutzung der Antimaterie.

„Der Weltraum, unendliche Welten...“ Weit entfernt vom Raumschiff à la Enterprise mit „Materie-Antir



10 января 1996 года  
**Потусторонний мир, возможно, реален —**  
на такую мысль наводит сенсационное открытие европейских ученых

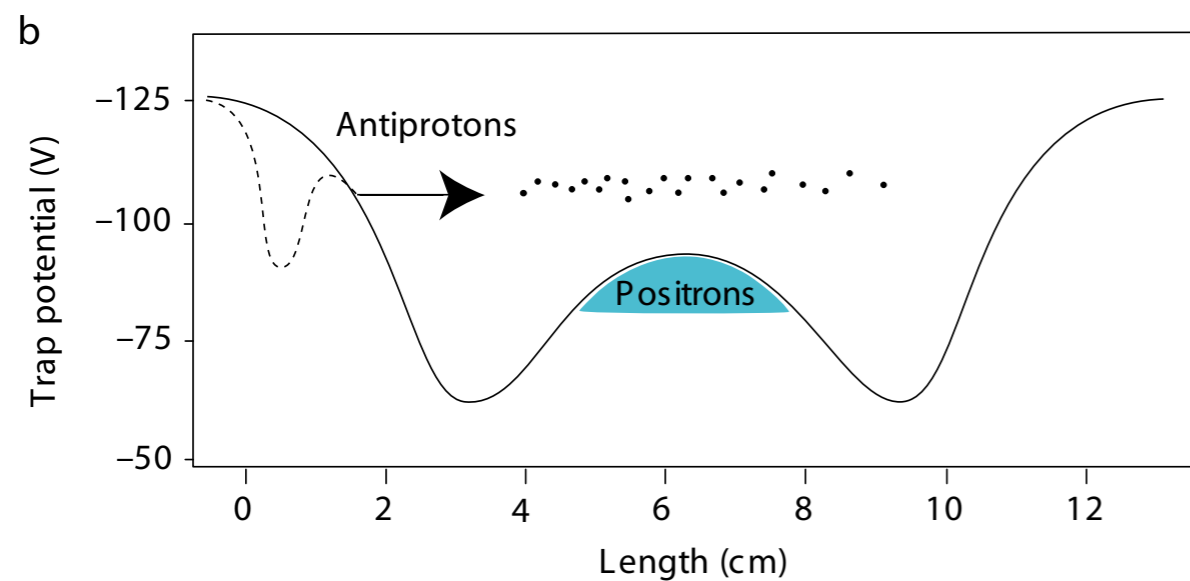
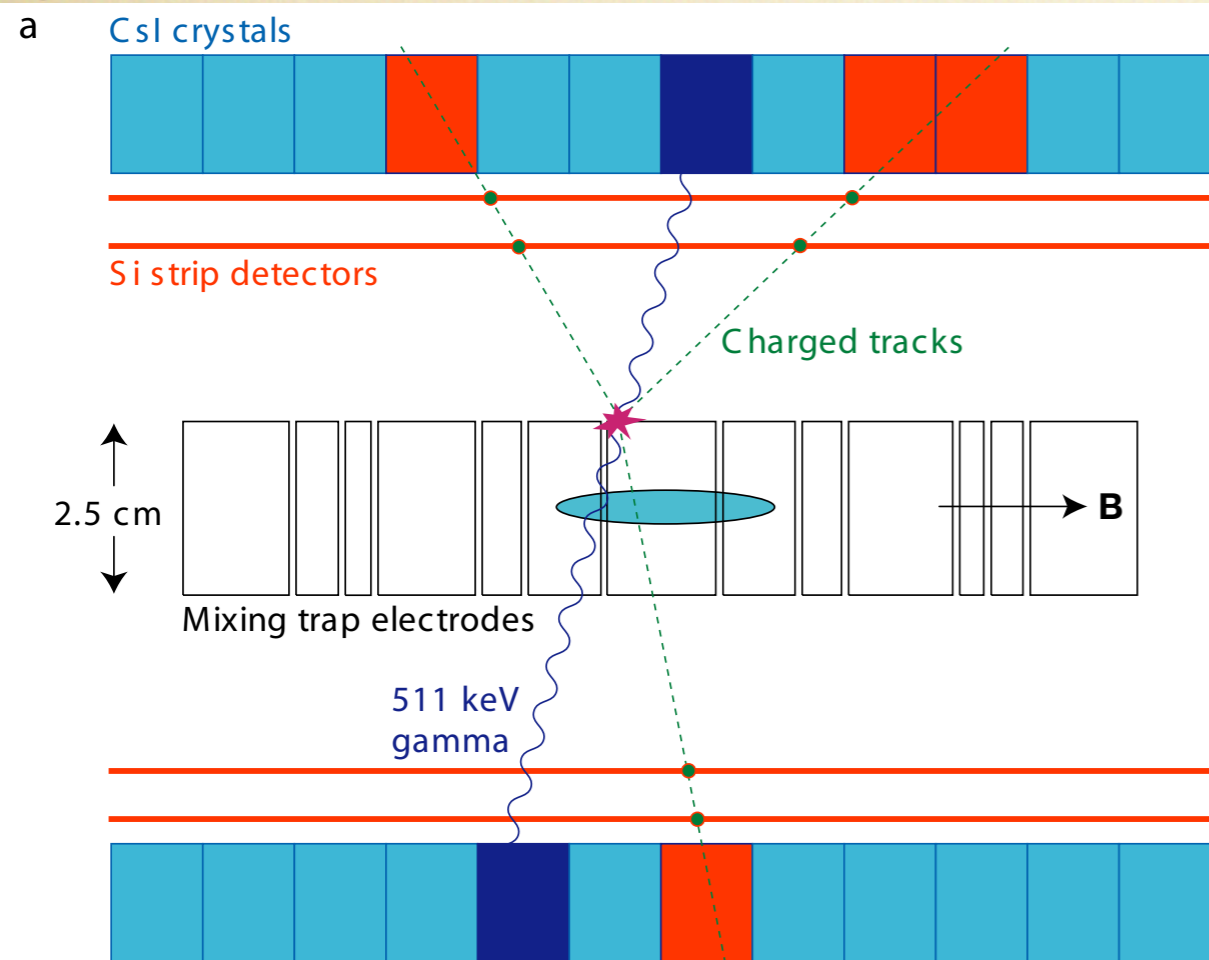
ТРОВ. «Известия»  
Франс Пресс, ученые крупнейшей в Европе лаборатории физики твердых частиц, утверждают, что им впервые удалось создать антиматерию; это открывает дорогу к созданию в атомной энергии.

# SCIENCE

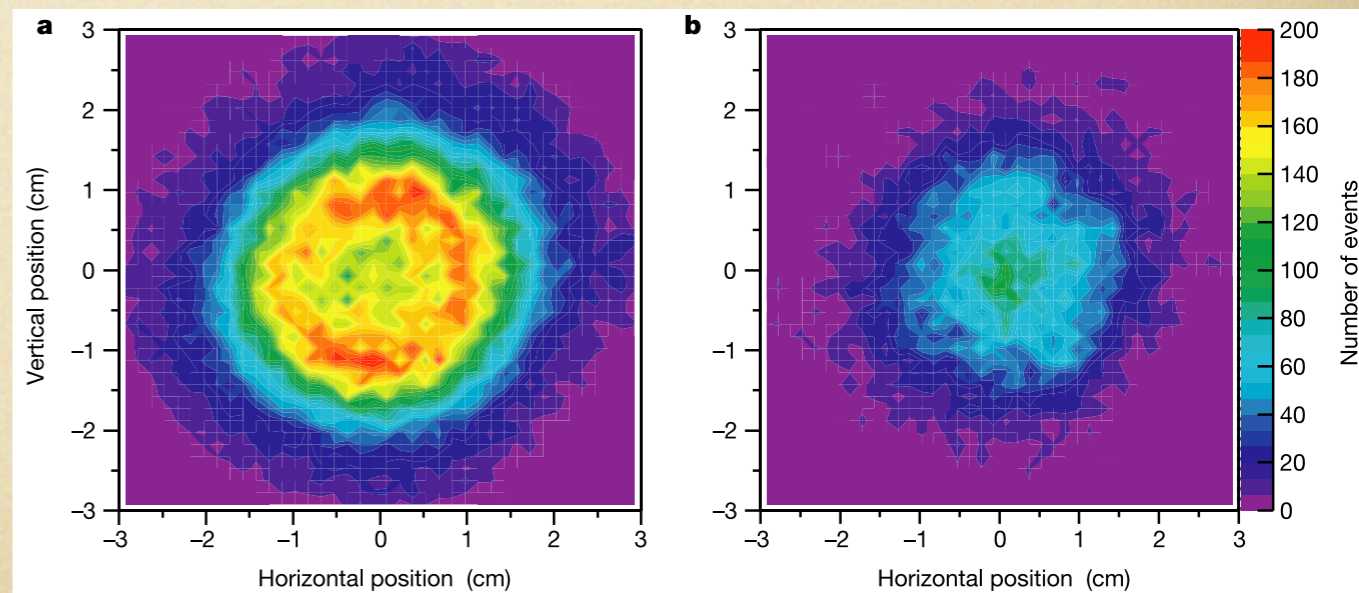
TO VIMA  
14/01/96  
ΚΥΡΙΑΚΗ 14 ΙΑΝΟΥΑΡΙΟΥ 1996  
ΑΝΑΚΑΛΥΨΕΙΣ  
"Window to the antiworld"  
**Παράθυρο στον αντισκόκο**  
Τι σημαίνει η δημιουργία αντισκόκου στο Ευρωπαϊκό Ε-



# 冷たい反水素原子の生成 (2002, ATHENA collab.)



- CPT 対称性テスト
- 1S-2S 分光
- GS-HFS  
基底状態超微細構造
- 重力実験 (WEP)



# Production of Cold Antihydrogen

# ATRAP

PHYSICAL REVIEW LETTERS

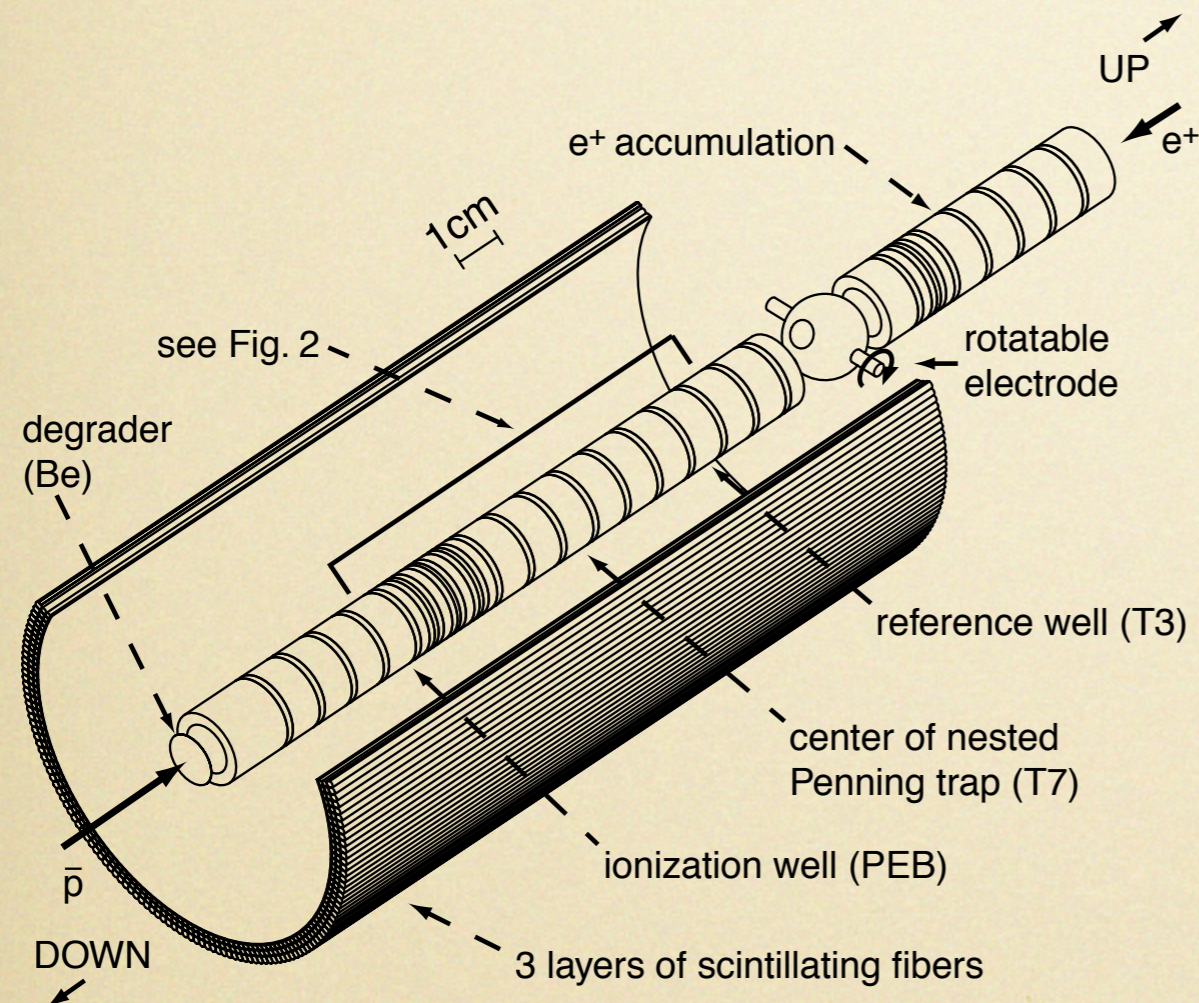


FIG. 1. Overview of the trap and detectors. Antiprotons are loaded from below (left), into the trap electrodes below the rotatable electrode. Positrons are simultaneously loaded from above (right) into the electrodes above the rotatable electrode.  $\bar{H}$  formation is observed within the lower region detailed in the next figure.

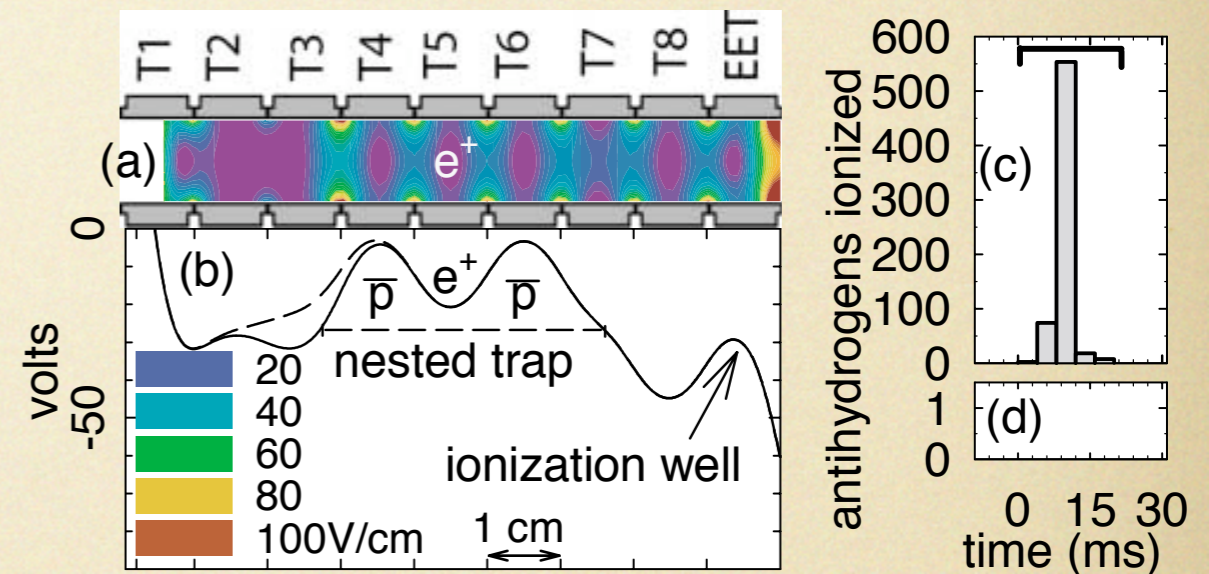
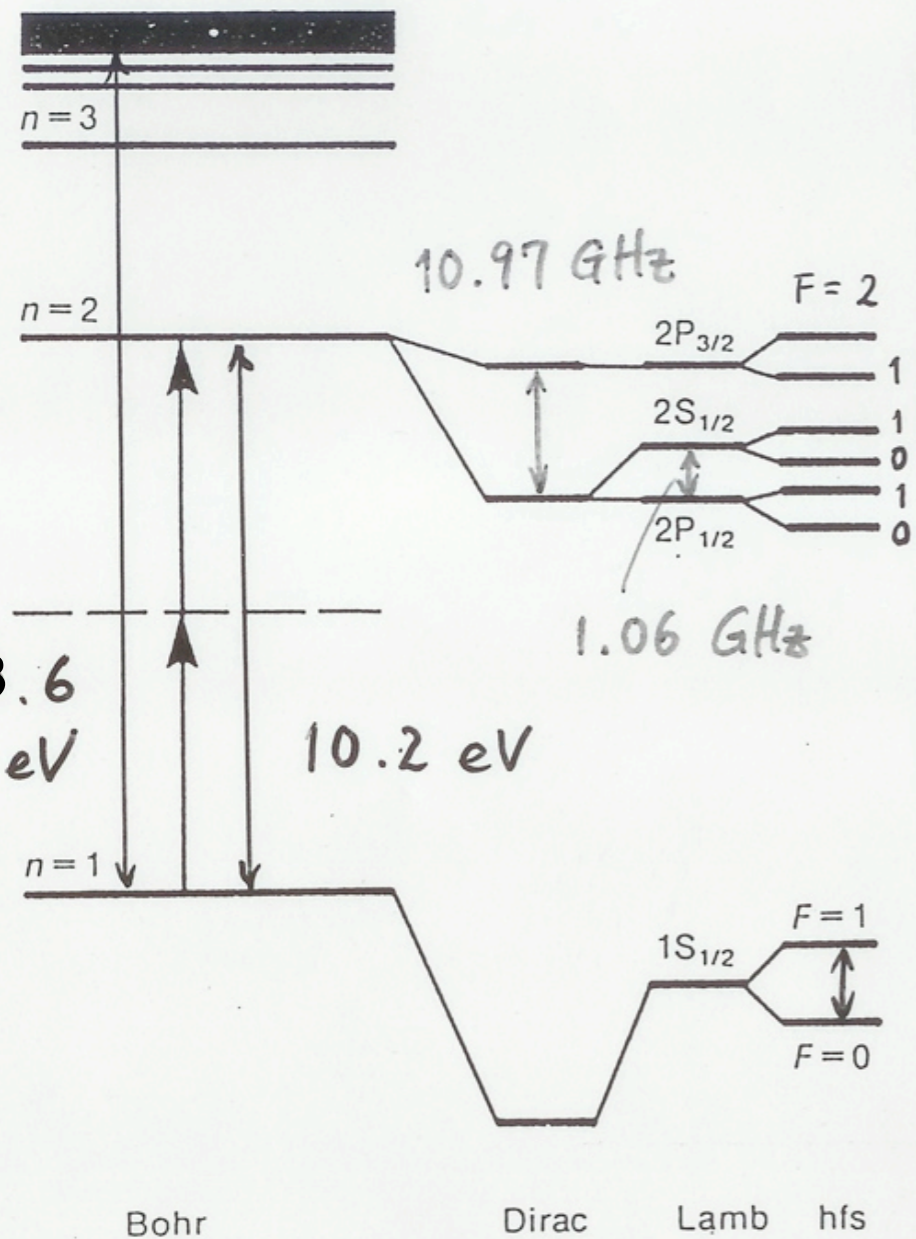


FIG. 2 (color). (a) Electrodes for the nested Penning trap. Inside is a representation of the magnitude of the electric field that strips  $\bar{H}$  atoms. (b) Potential on axis for positron cooling of antiprotons (solid line) during which  $\bar{H}$  formation takes place, with the (dashed line) modification used to launch  $\bar{H}$  into the well. (c) Antiprotons from  $\bar{H}$  ionization are released from the ionization well during a 20 ms time window. (d) No  $\bar{H}$  are counted when no  $\bar{H}$  are in the nested Penning trap.

水素原子  
氢原子

HYDROGEN



$$\frac{97492}{\text{cm}^{-1}}$$

$$\frac{82259.279}{\text{cm}^{-1}}$$

$$\frac{82258.949}{\text{cm}^{-1}}$$

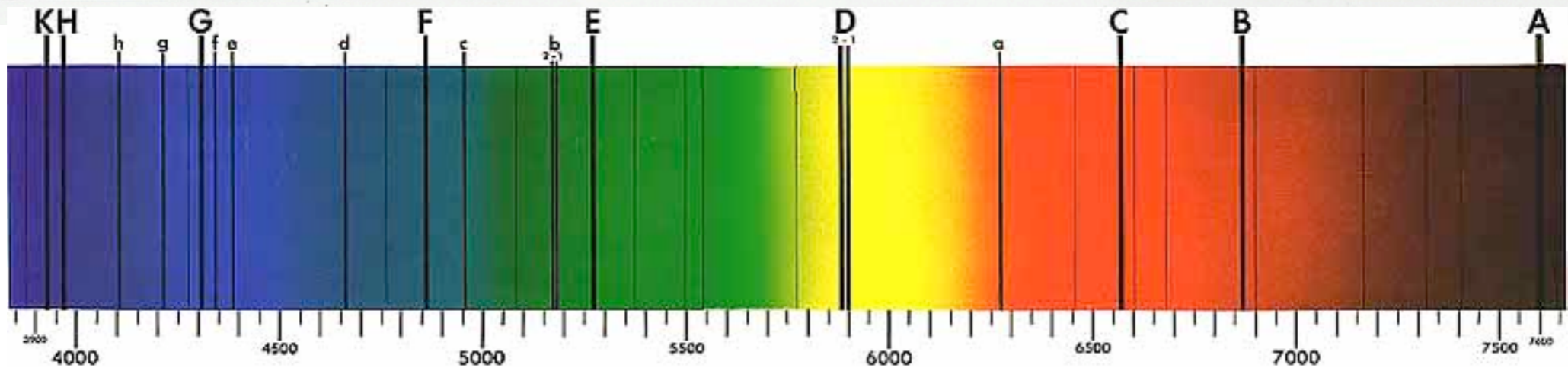
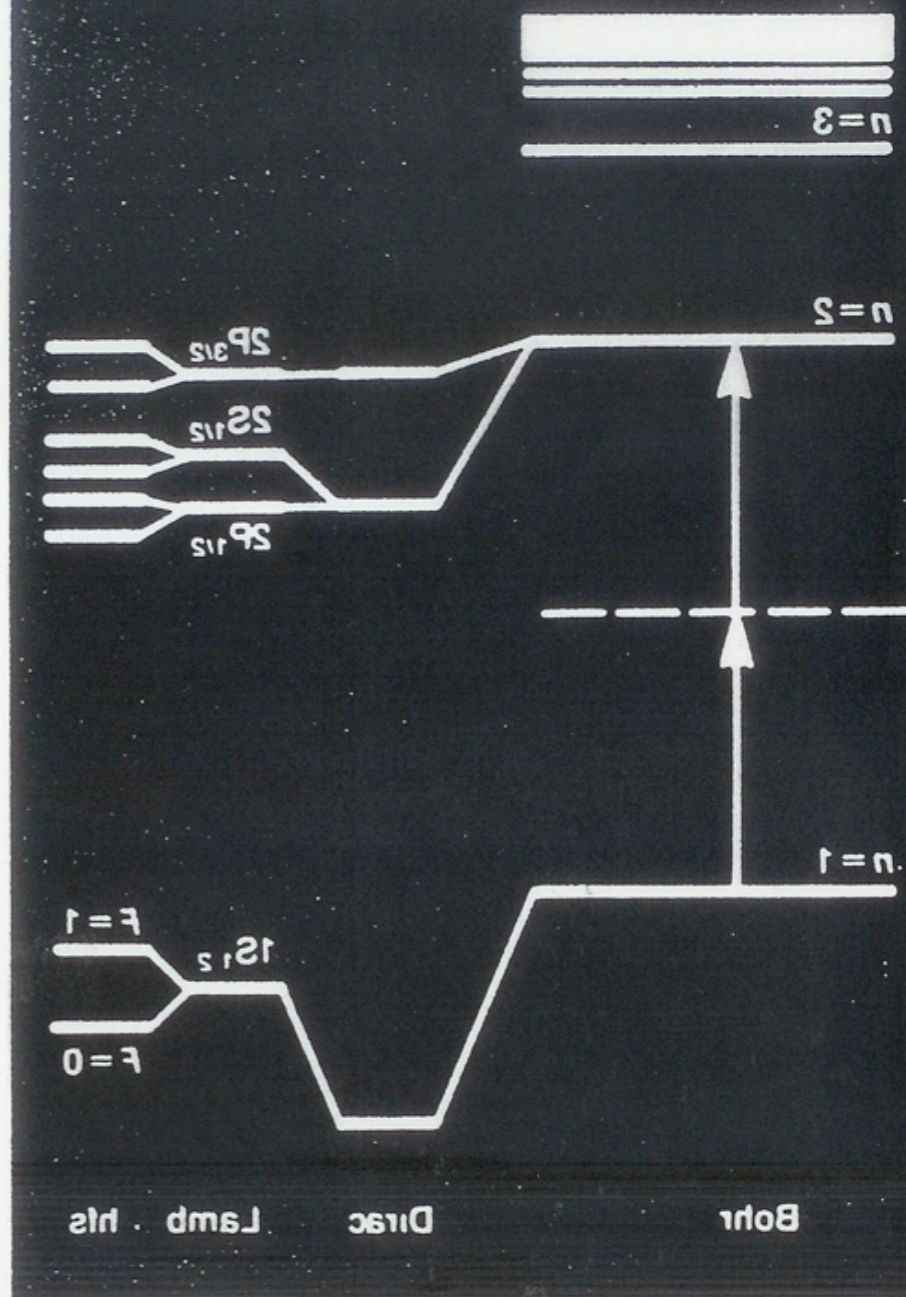
$$\frac{82258.913}{\text{cm}^{-1}}$$

$\updownarrow$  24 MHz  
 $\updownarrow$  178 MHz  
 $\updownarrow$  59 MHz

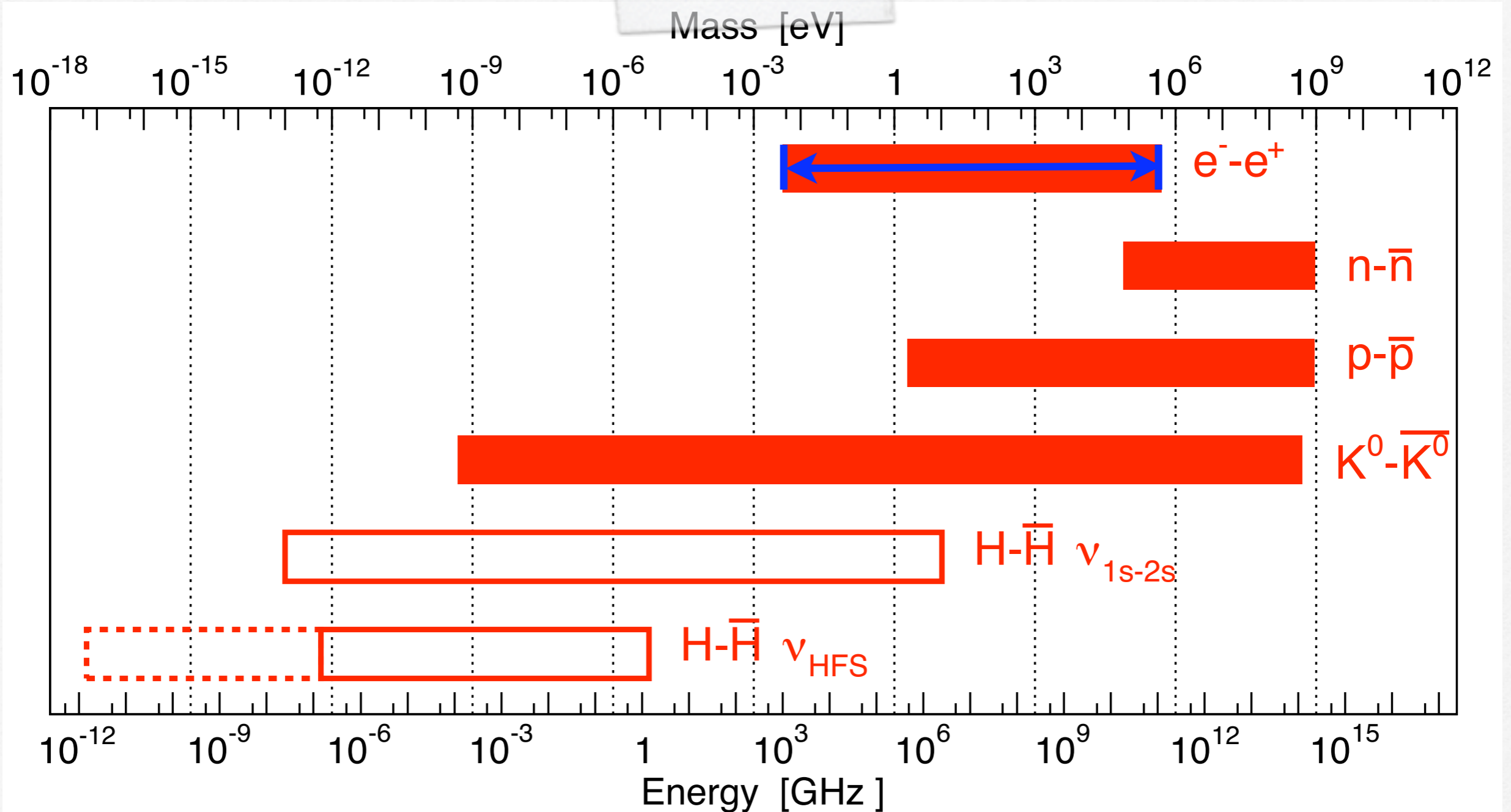
1.42 GHz

0.000

АНТИДРОГЕН



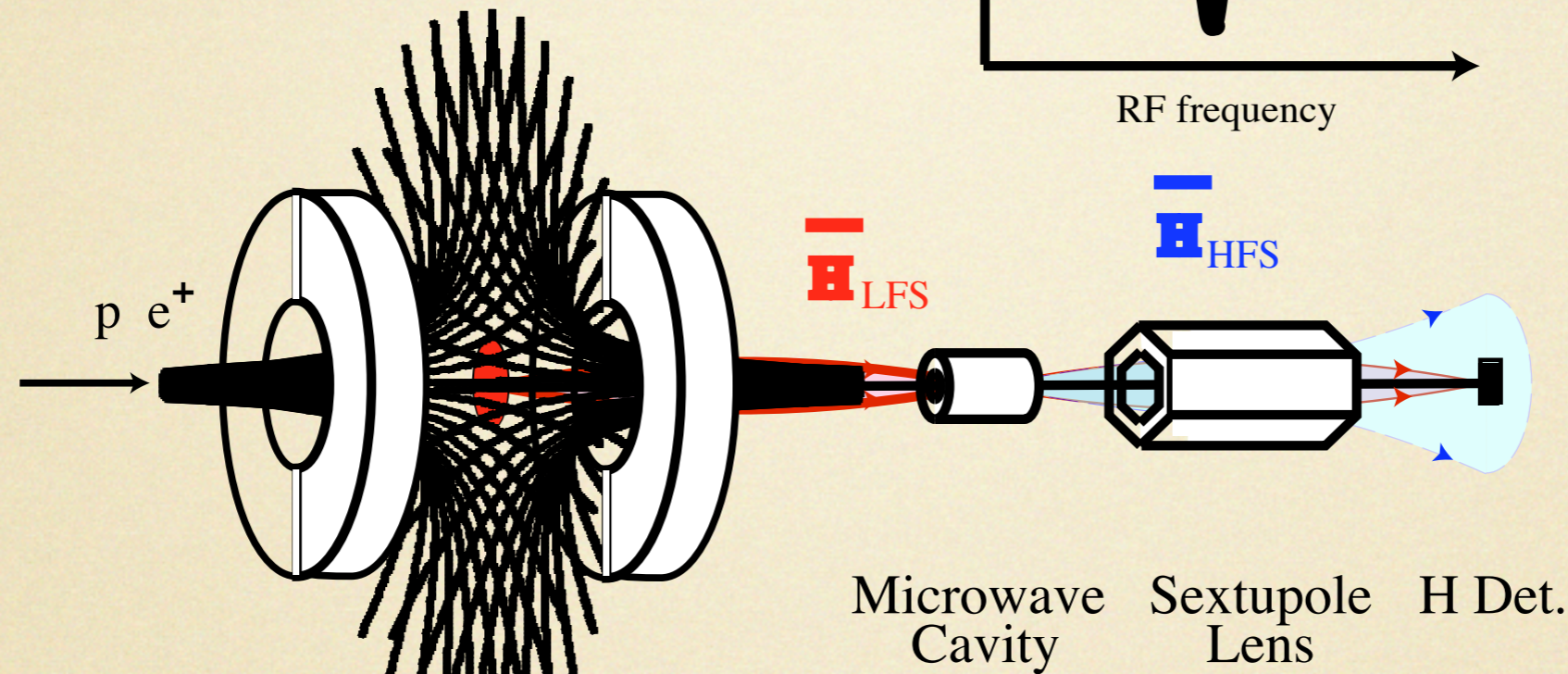
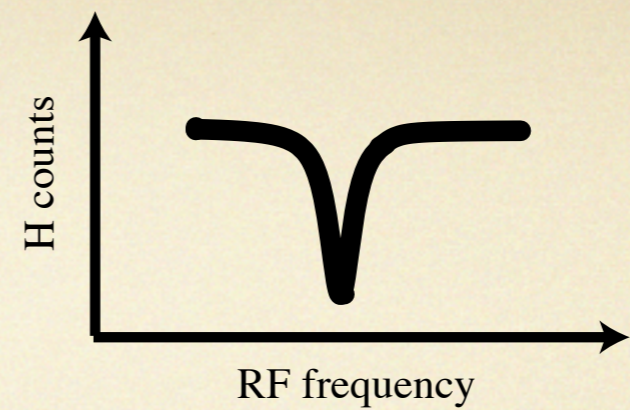
# Mass/energy CPT limits



$$\frac{\text{absolute precision (left edge)}}{\text{measured quantity (right edge)}} = \text{relative precision (length)}$$

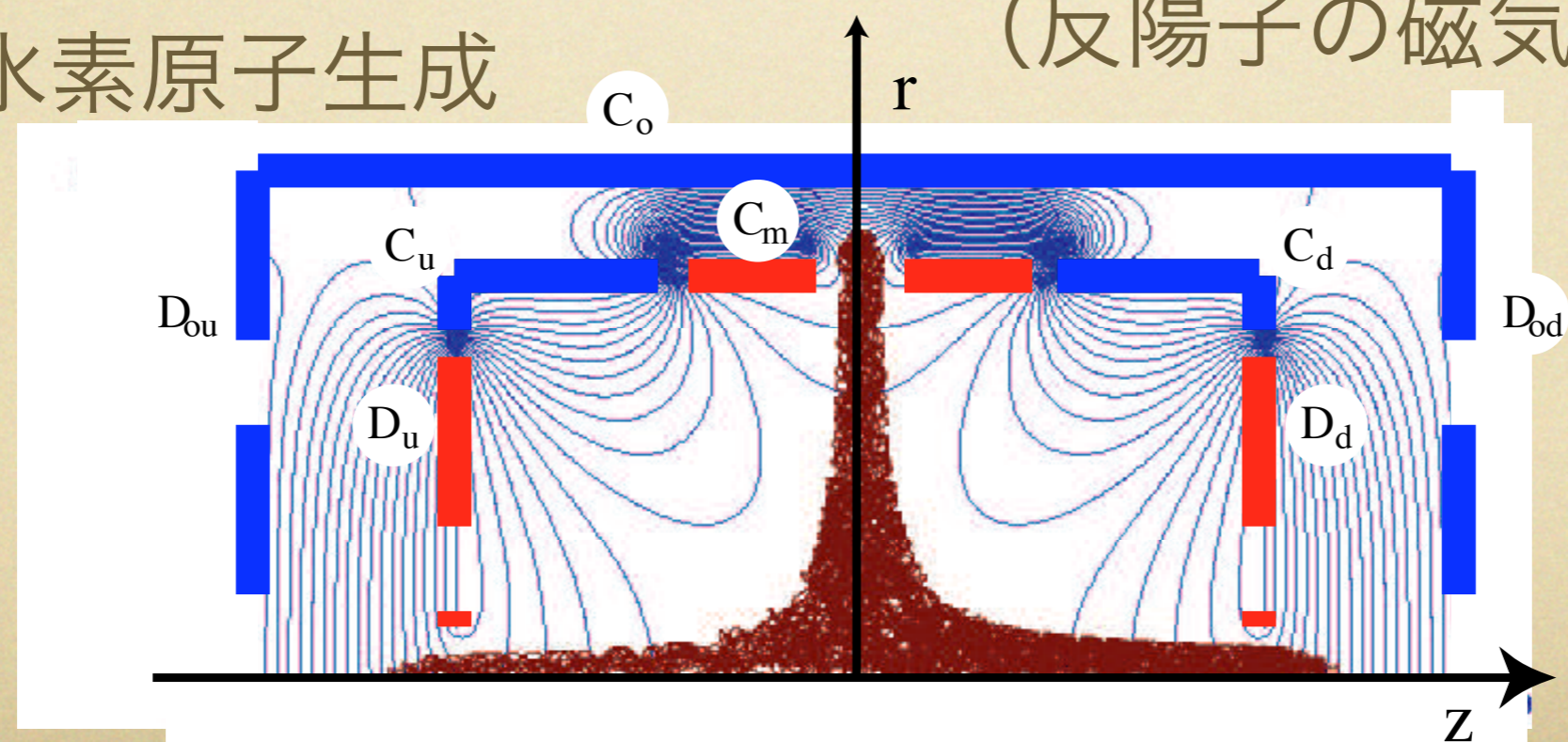


# ASACUSA Cusp Trap

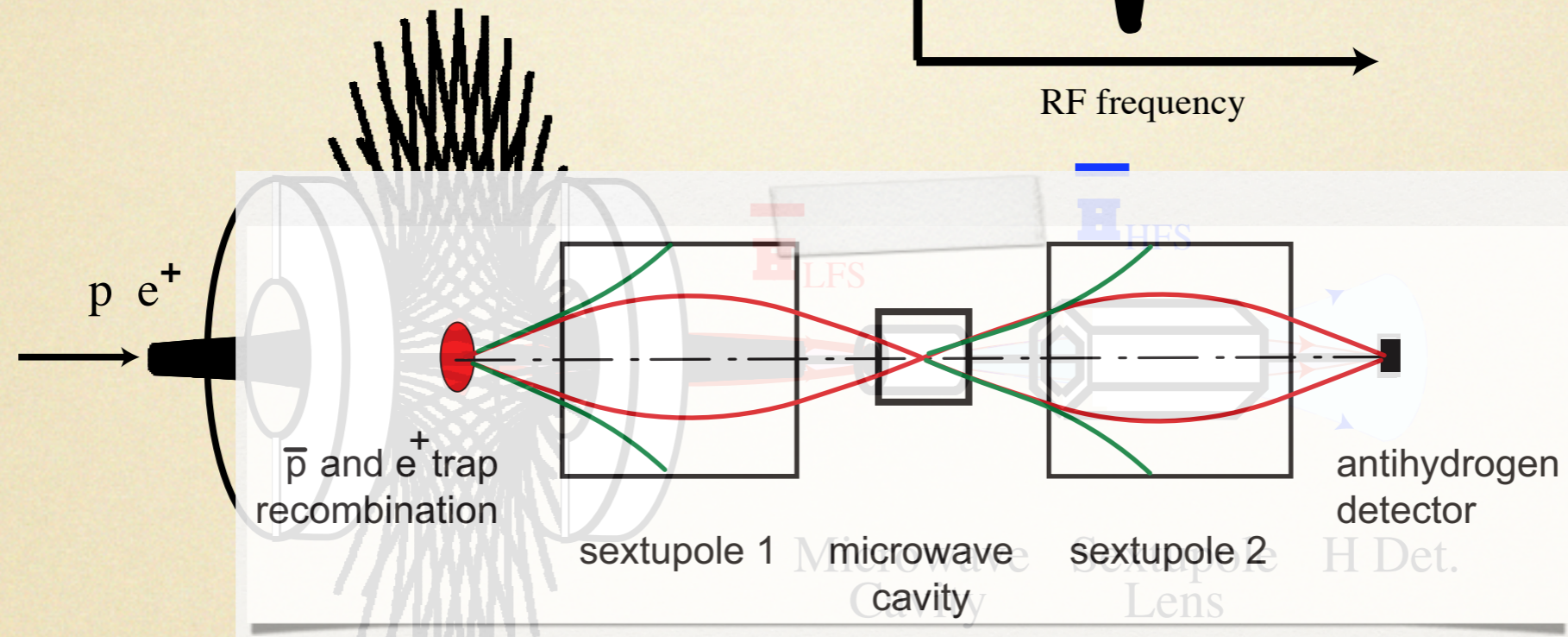
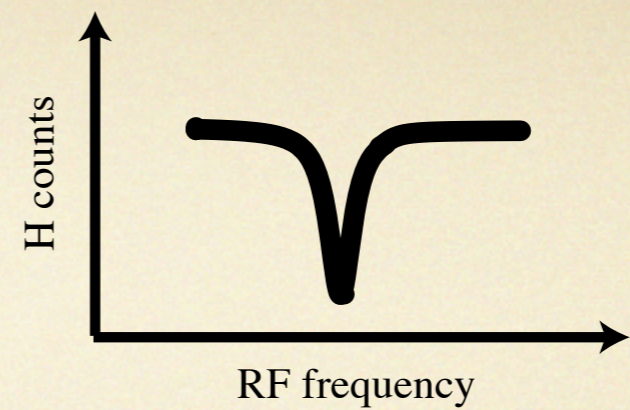


カスプトラップによる  
反水素原子生成

基底状態超微細構造  
(反陽子の磁気モーメント)

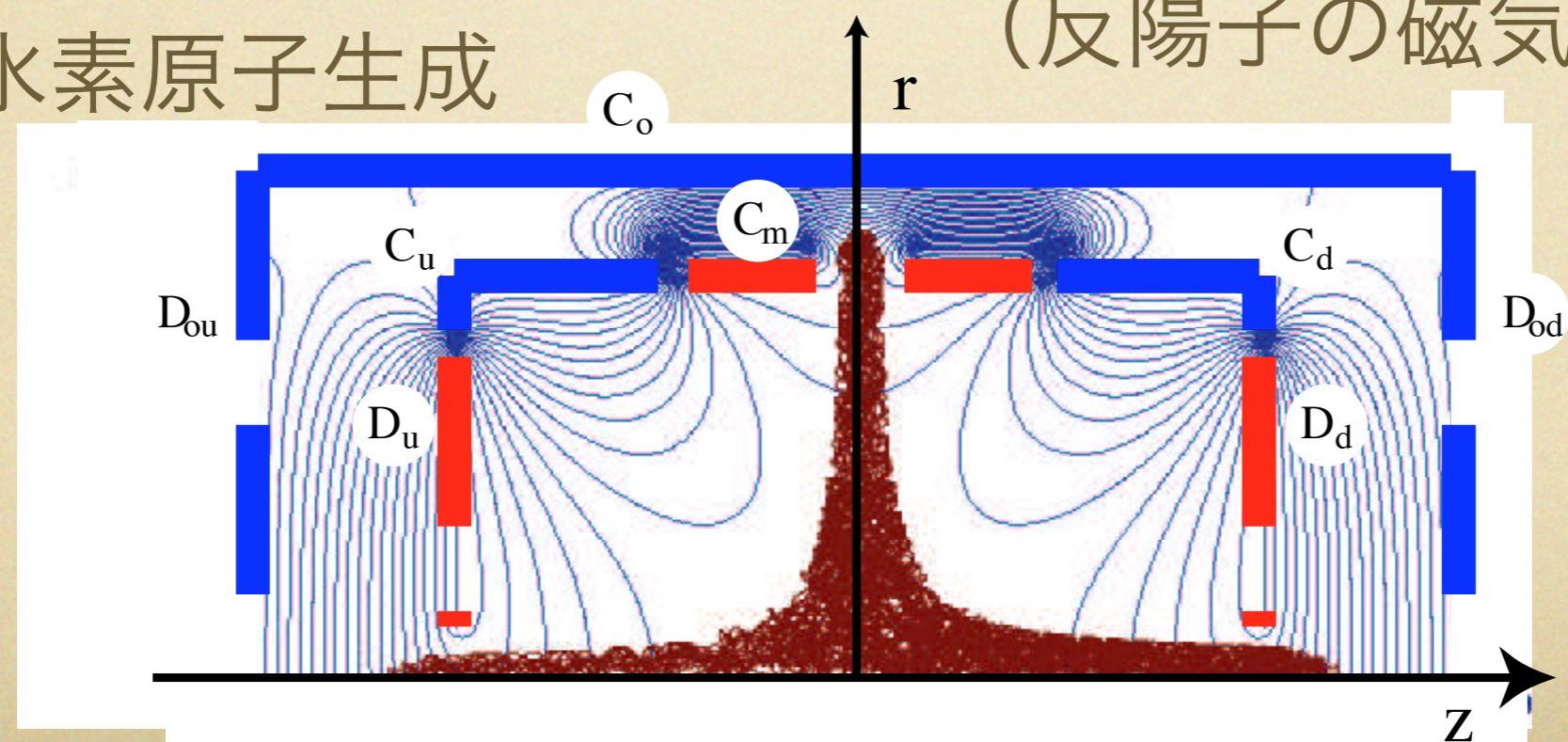


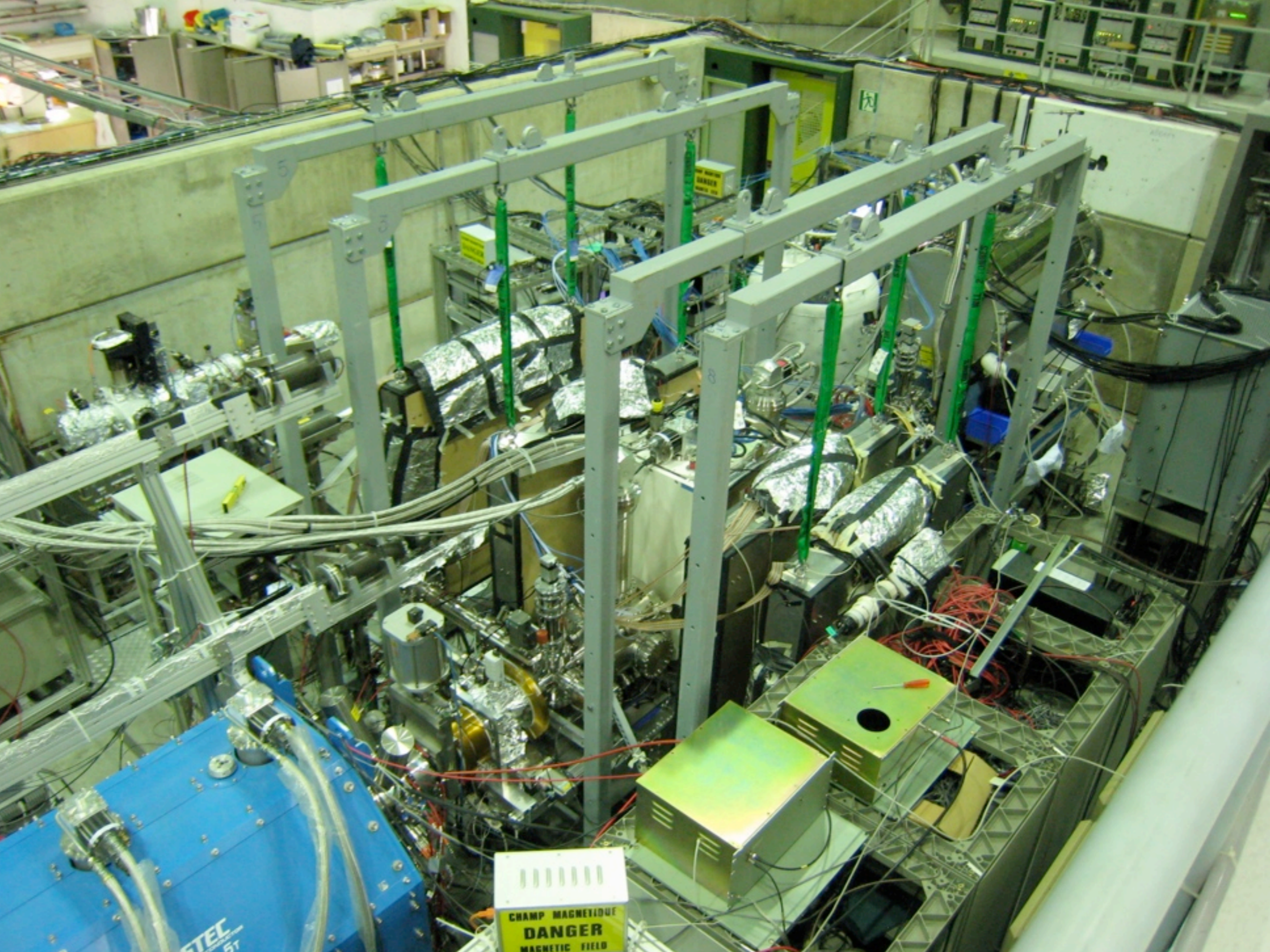
# ASACUSA Cusp Trap



カスプトラップによる  
反水素原子生成

基底状態超微細構造  
(反陽子の磁気モーメント)





CHAMP MAGNETIQUE  
**DANGER**  
MAGNETIC FIELD

FTEC  
5T

# CPT-Symmetric Situation

Apple



Earth

Anti-Apple



Anti-Earth

# Not

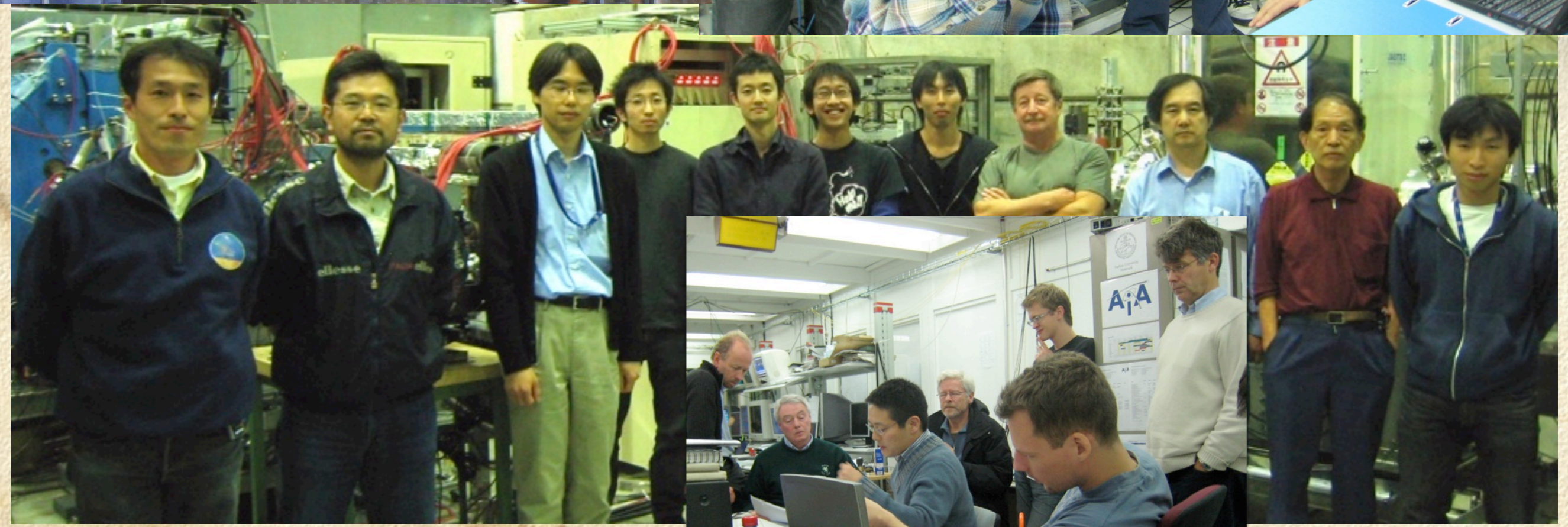
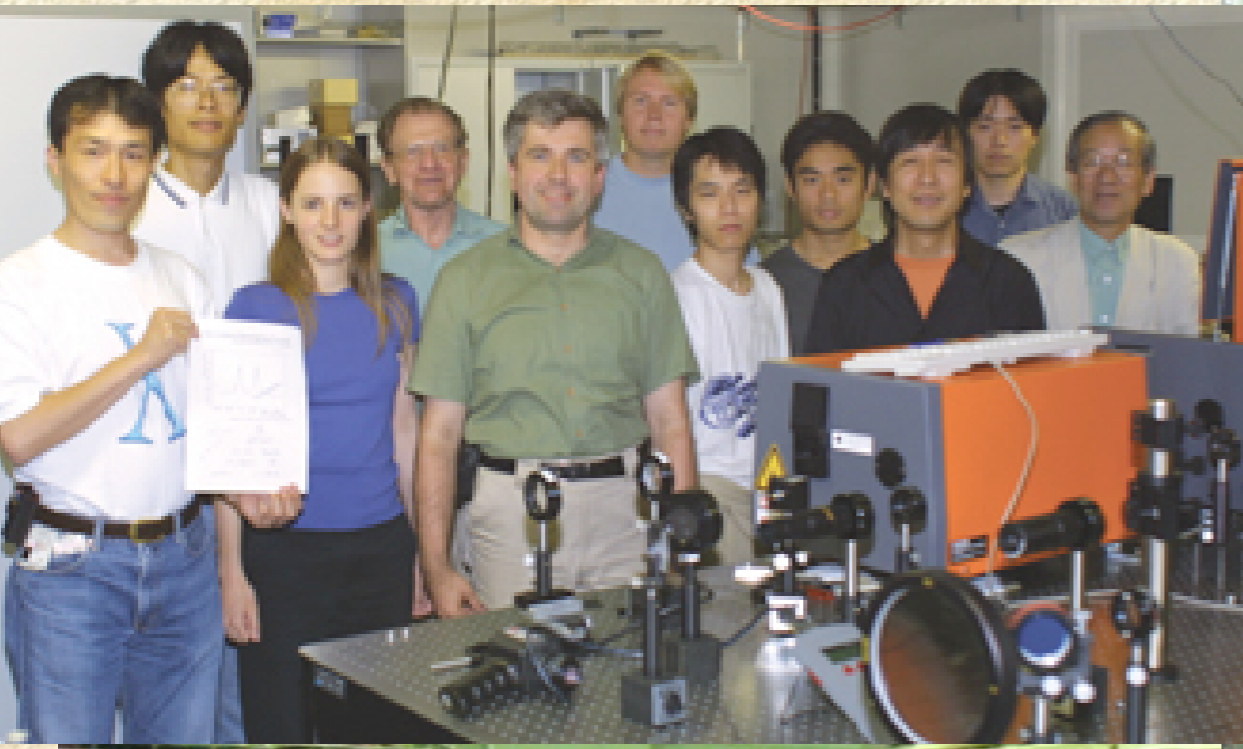
Anti-Apple



Earth

東大院総合・理研 山崎研  
東大理 早野研, Wien SMI,  
Aarhus Univ., Brescia Univ.

# ASACUSA collaboration



# 反物質科学

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- 原子物理学の新たな分野の開拓
- 様々な物理分野の知識が必要な境界分野
  - 原子衝突、原子核、素粒子、高エネルギー加速器物理、レーザー、プラズマ物理
- 中規模の人数による国際的共同研究
  - CERN では「小さい」規模の研究
- Unique experiments, Dream for the future

