The Reason for Beam Cooling:
Some of the Physics that Cooling Allows

Eagle Ridge, Galena, Il. USA
September 18 - 23, 2005

obvious:

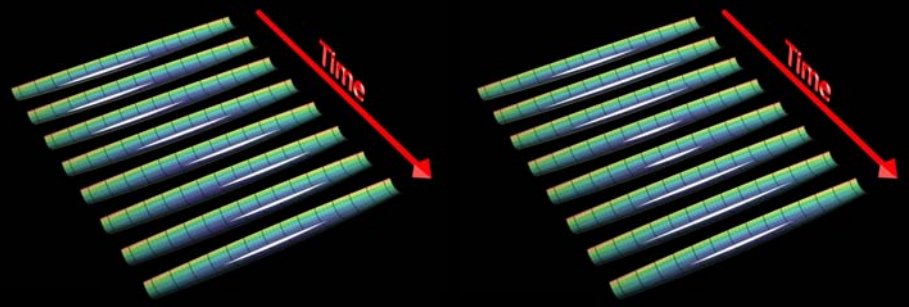
cooling and control of cooling
is the essential reason for our
existence,

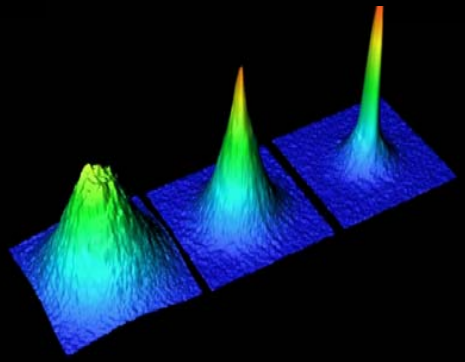
gives us the opportunity
to do and talk about

physics that cooling allows

Dipole oscillations of a one-dimensional Bose-Einstein condensate

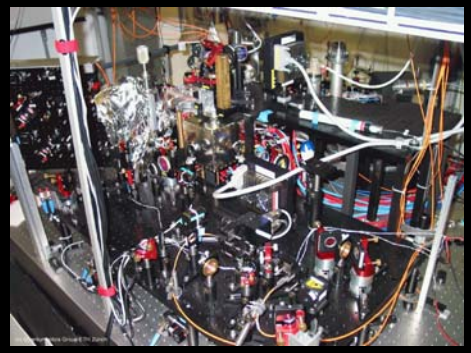
Breathing





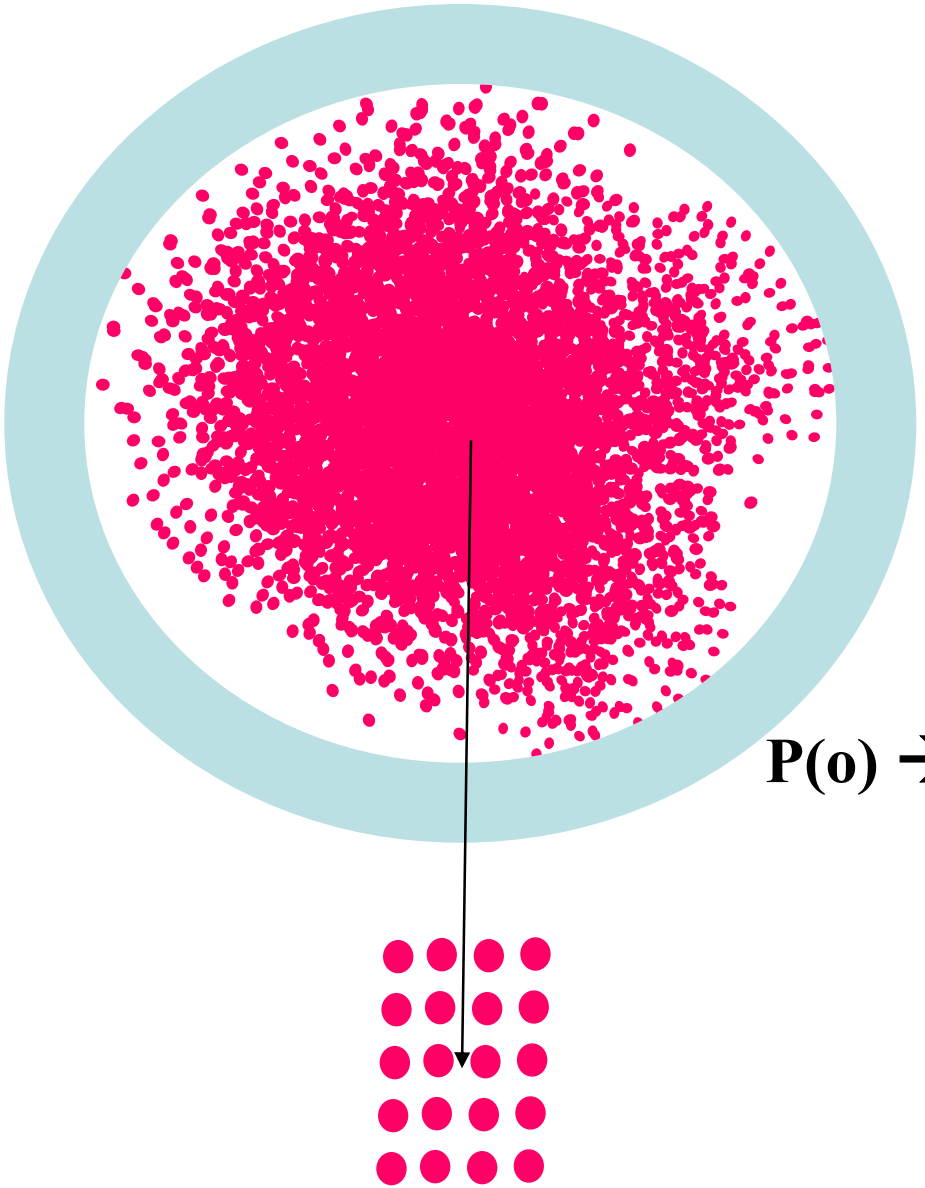
Bose-Einstein condensate: momentum distribution of ultracold bosonic atoms

generate laser light for atom cooling, trapping and manipulation

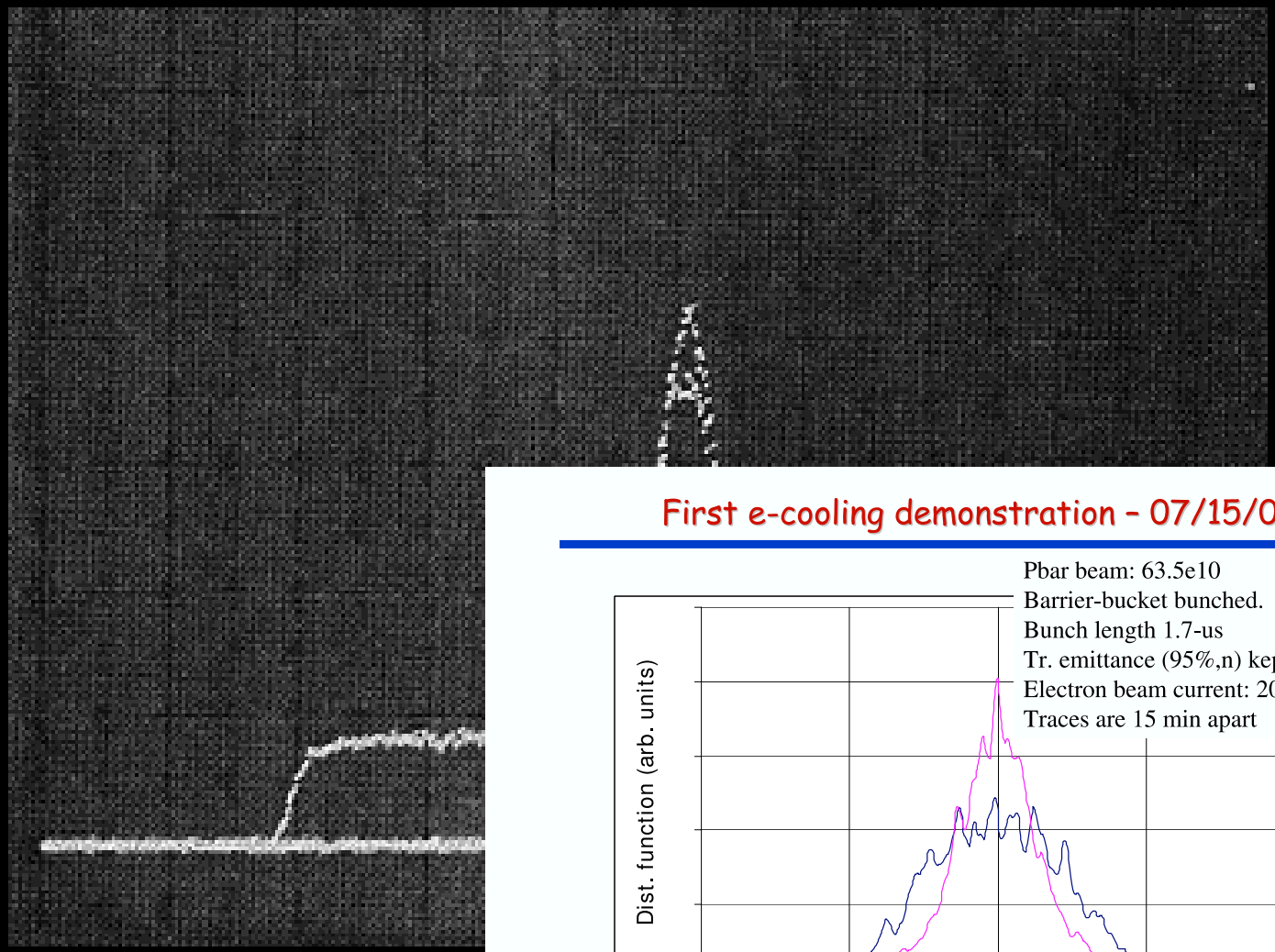


Vacuum chamber surrounded by optical elements and magnetic coils

D.M. Harber et al, Phys. Rev. A to be published

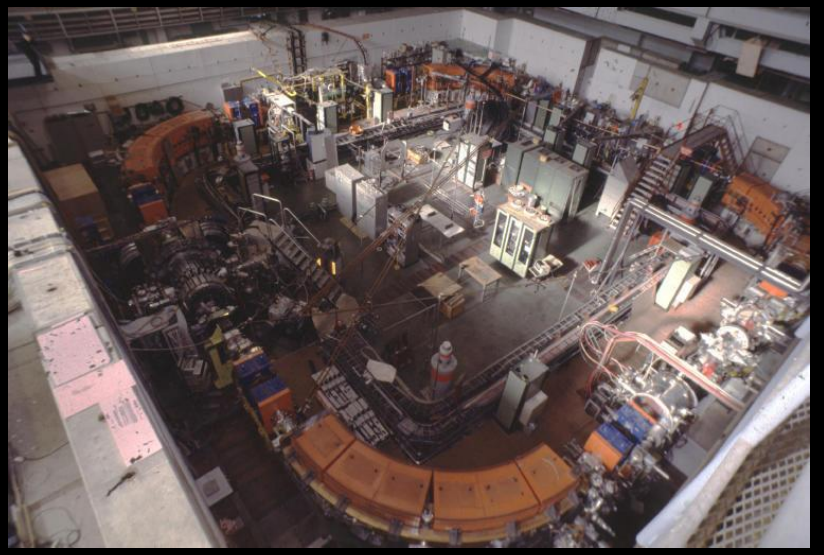


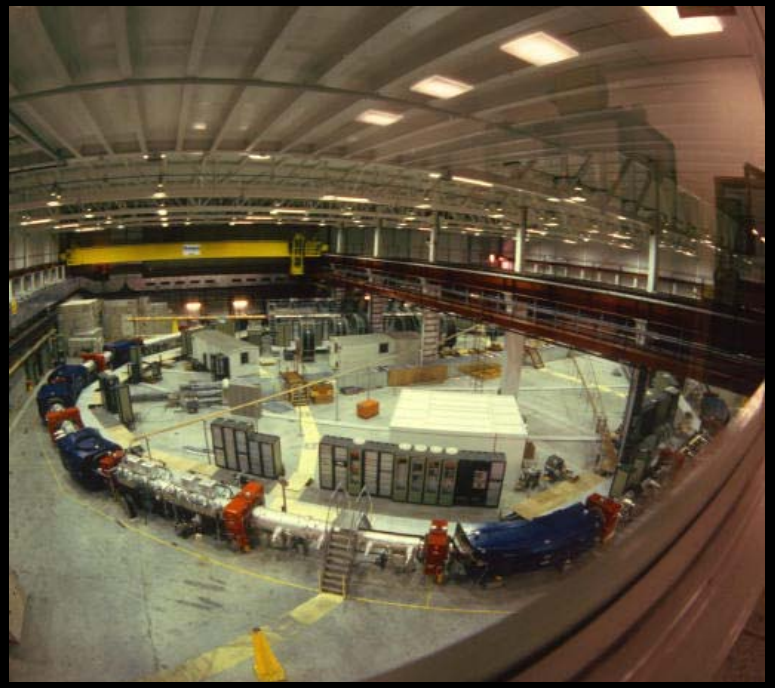
P(o) → x, x`, y, y` → ε

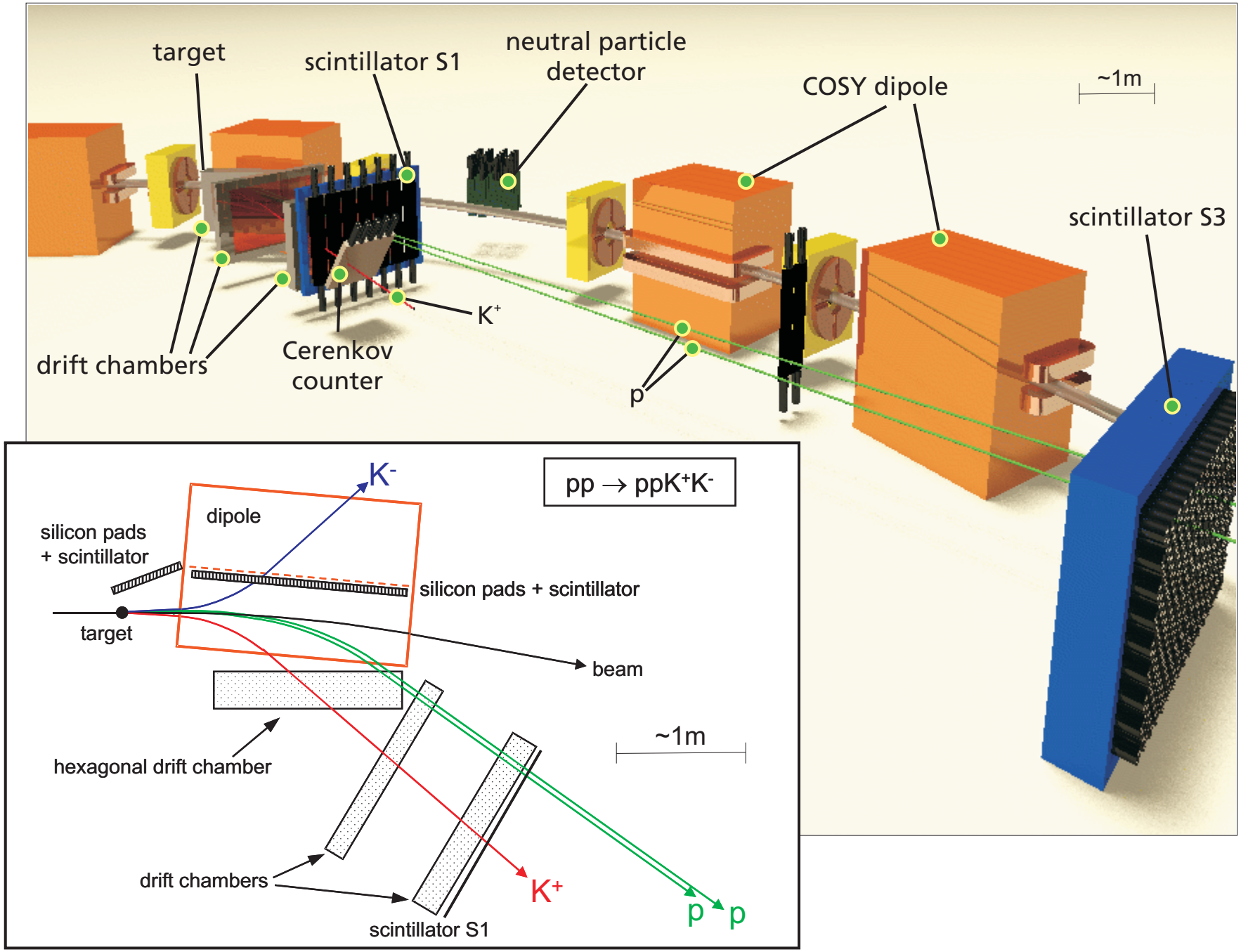


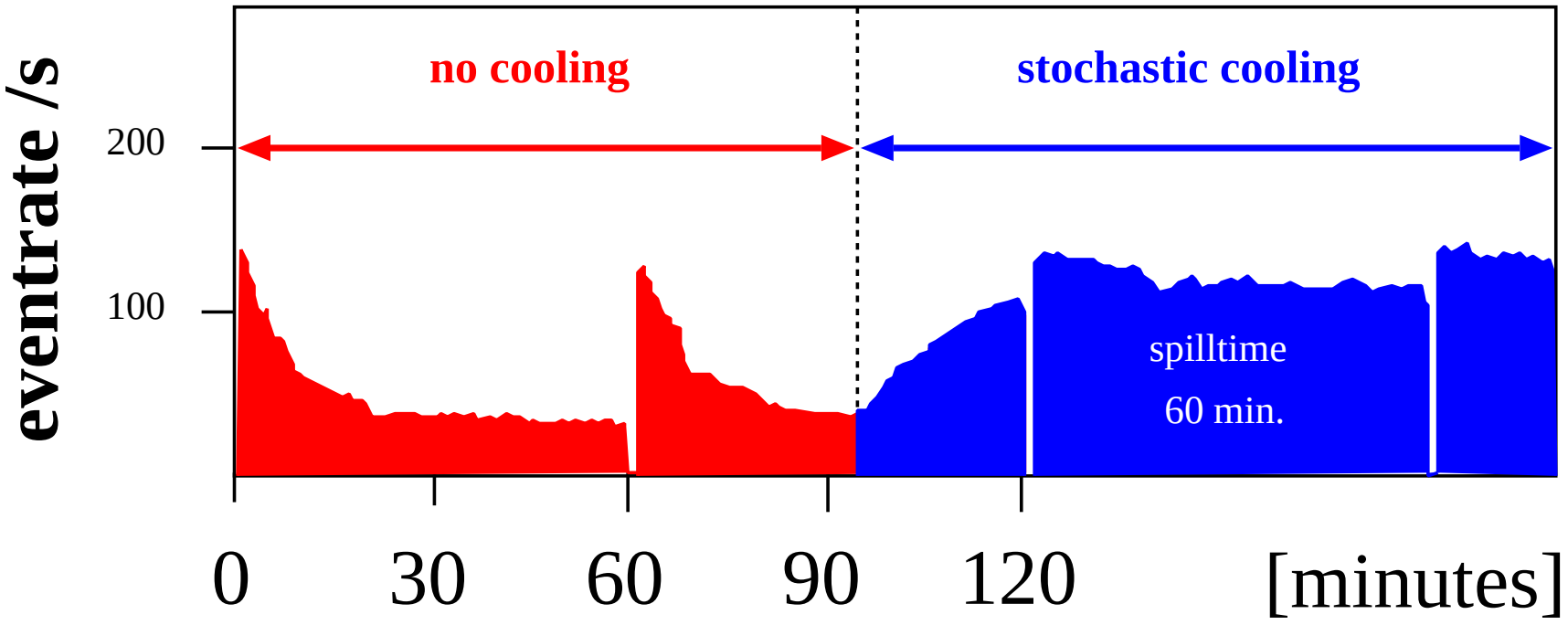
First e-cooling demonstration – 07/15/05

Pbar beam: 63.5e10
Barrier-bucket bunched.
Bunch length 1.7-us
Tr. emittance (95%,n) kept at 4-pi mm-mrad
Electron beam current: 200 mA
Traces are 15 min apart

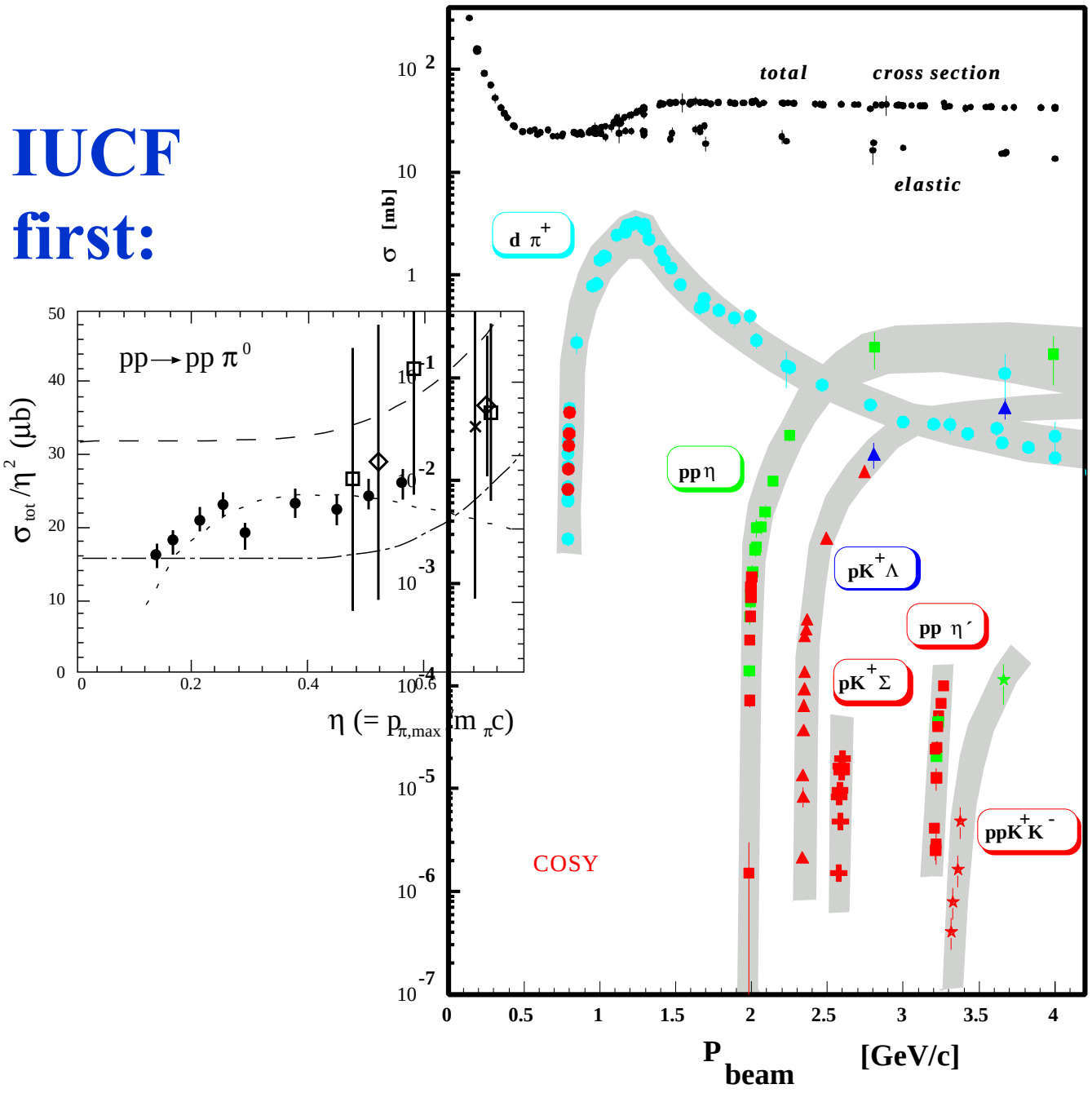


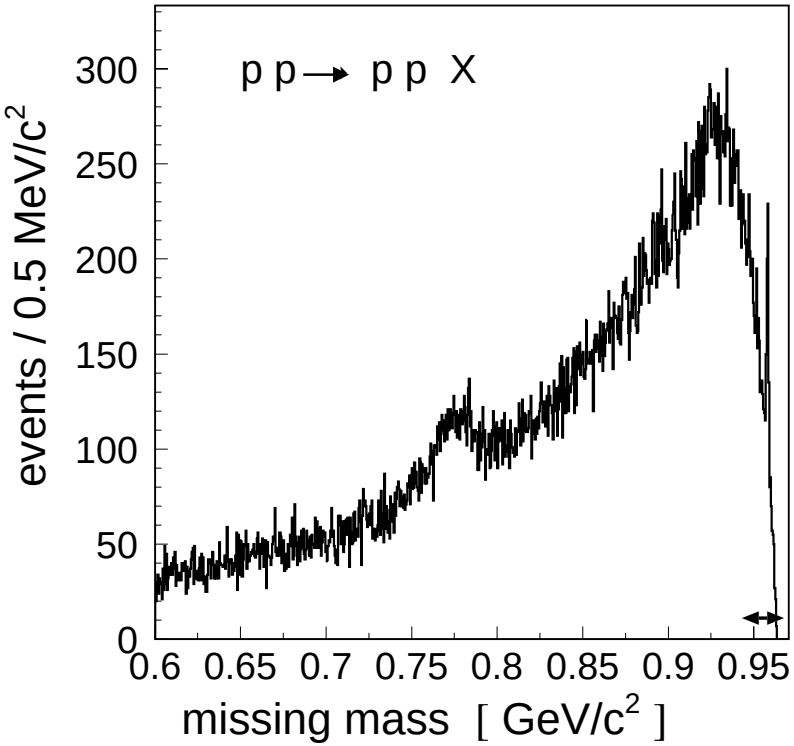


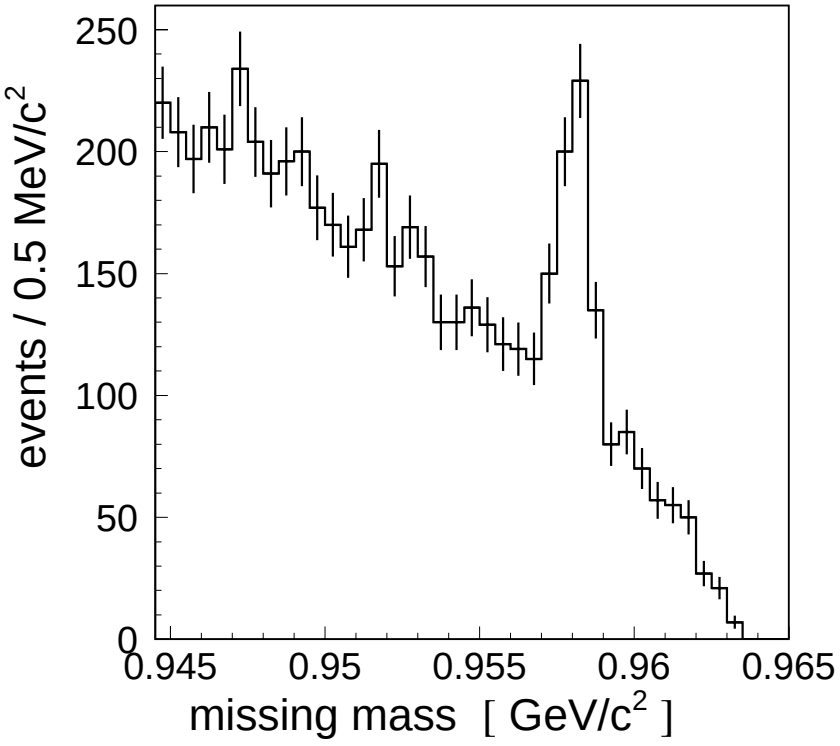

target
scintillator S1
neutral particle detector
COSY dipole
~1m
scintillator S3
K+
drift chambers
Cerenkov counter
p
pp → ppK+K-
K-
dipole
silicon pads + scintillator
silicon pads + scintillator
target
beam
~1m
hexagonal drift chamber
drift chambers
K+
p
p
scintillator S1

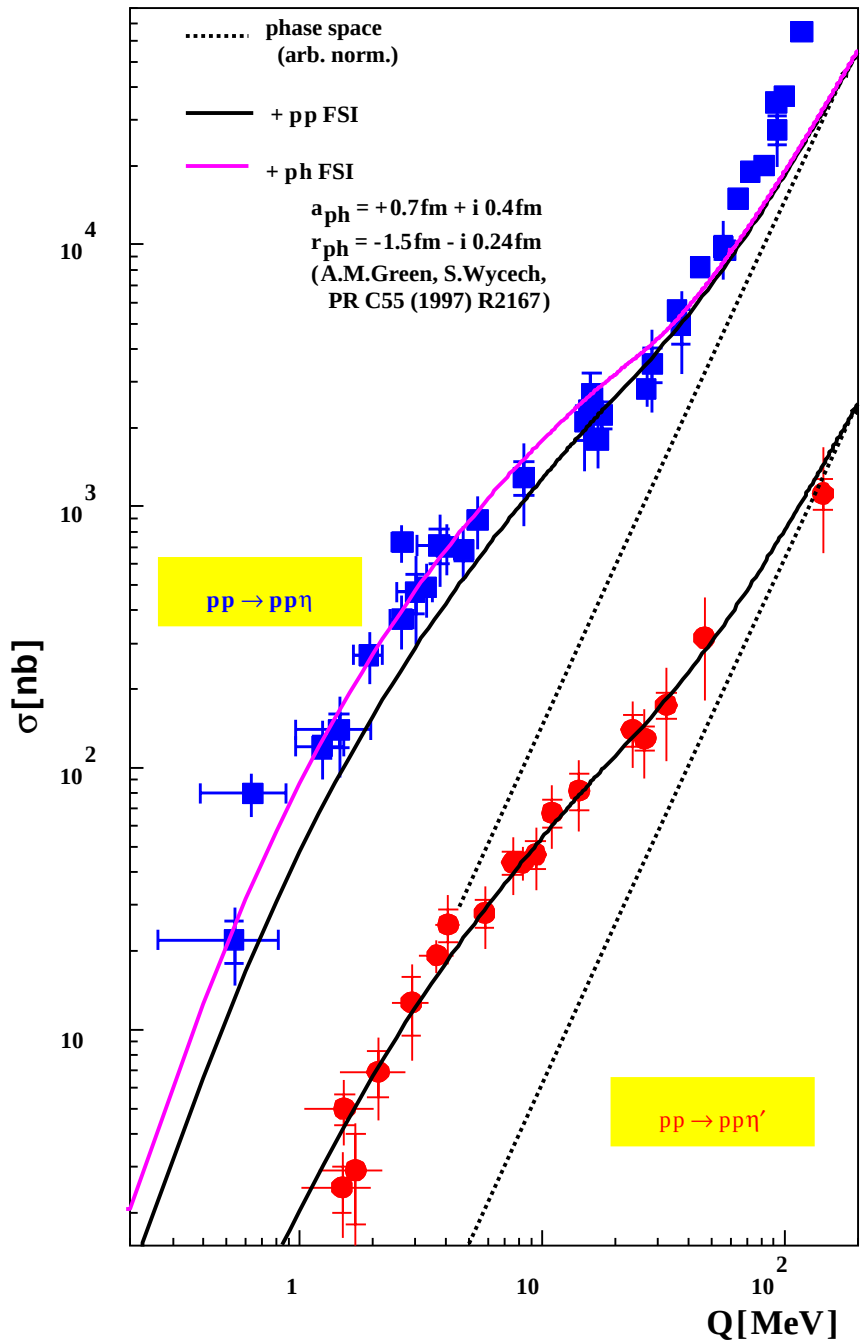

eventrate /s
200
100
no cooling
stochastic cooling
spilltime
60 min.
0
30
60
90
120
[minutes]

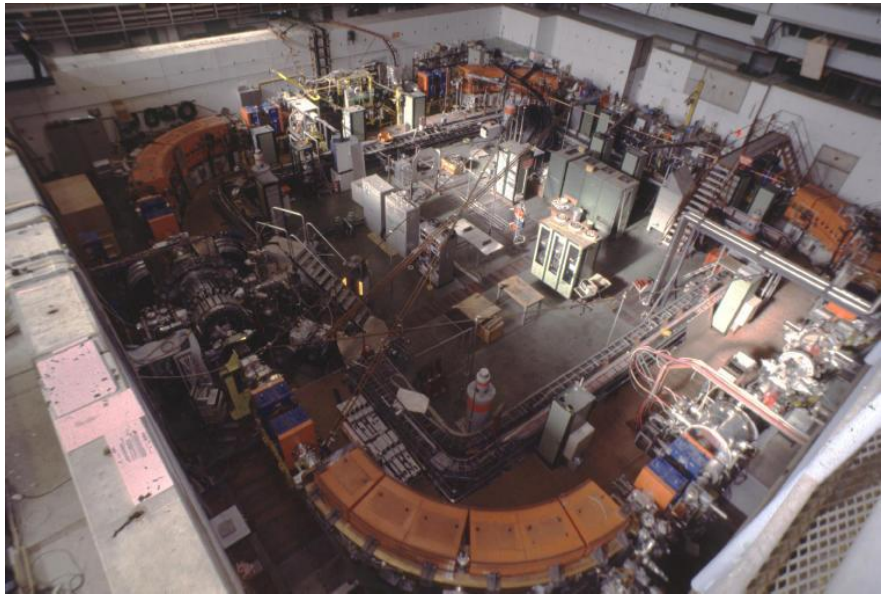
IUCF first:

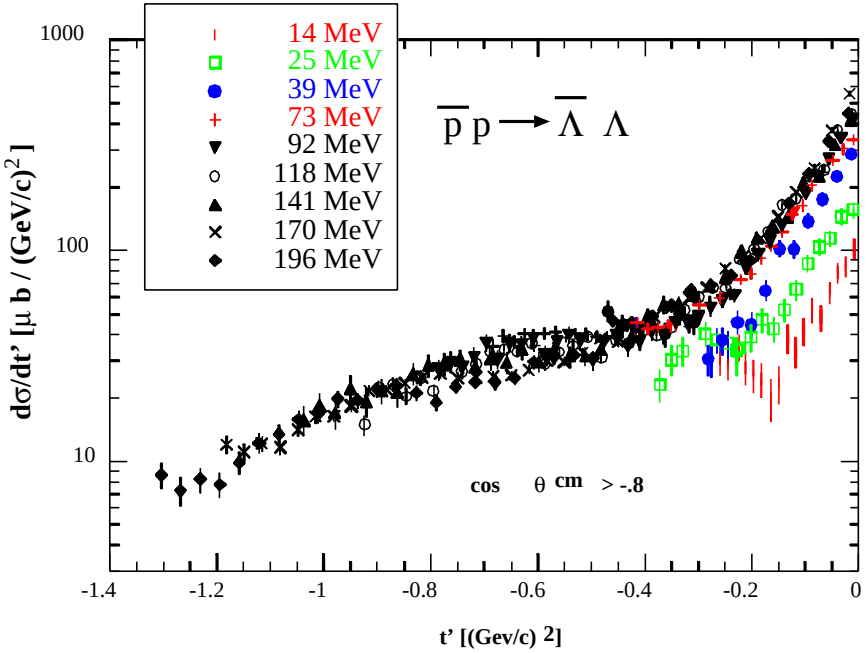

total cross section
elastic
σ [mb]
d π+
pp η
pK+Λ
pp η´
pK+Σ
ppK+K-
COSY
P beam [GeV/c]
pp → pp π0
σtot/η2 (μb)
η (= pπ,max/mπc)

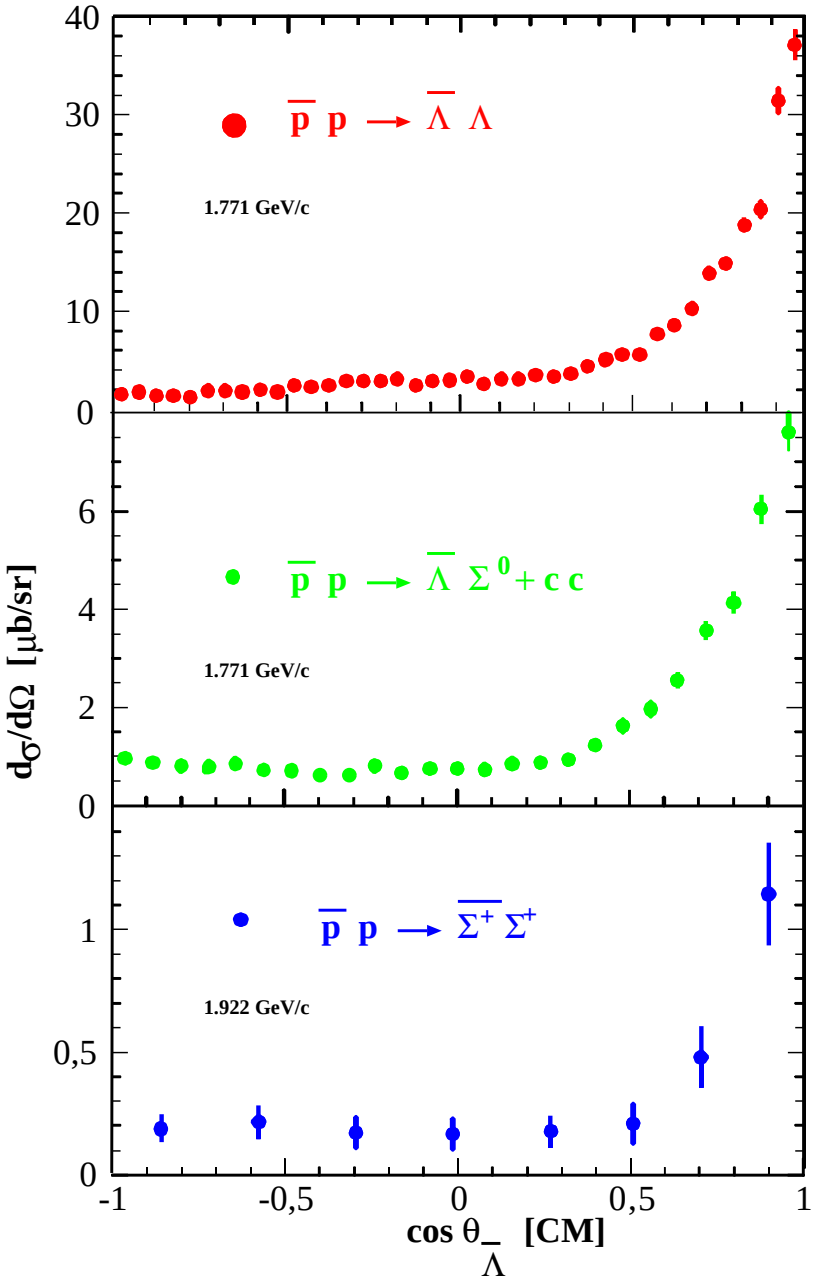

p p → p p X
events / 0.5 MeV/c^2
missing mass [GeV/c^2]
0
50
100
150
200
250
300
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95

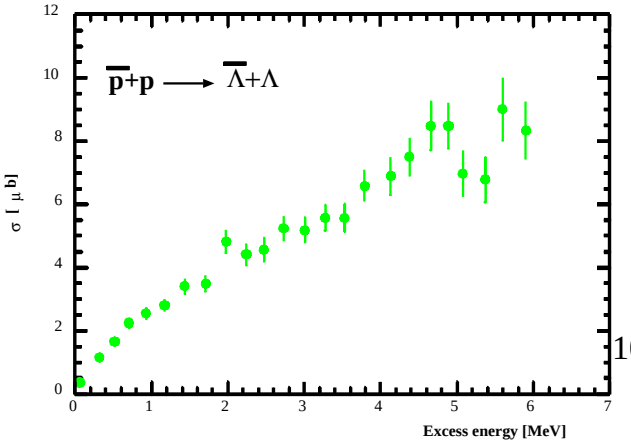

events / 0.5 MeV/c^2
missing mass [GeV/c^2]
0
50
100
150
200
250
0.945
0.95
0.955
0.96
0.965

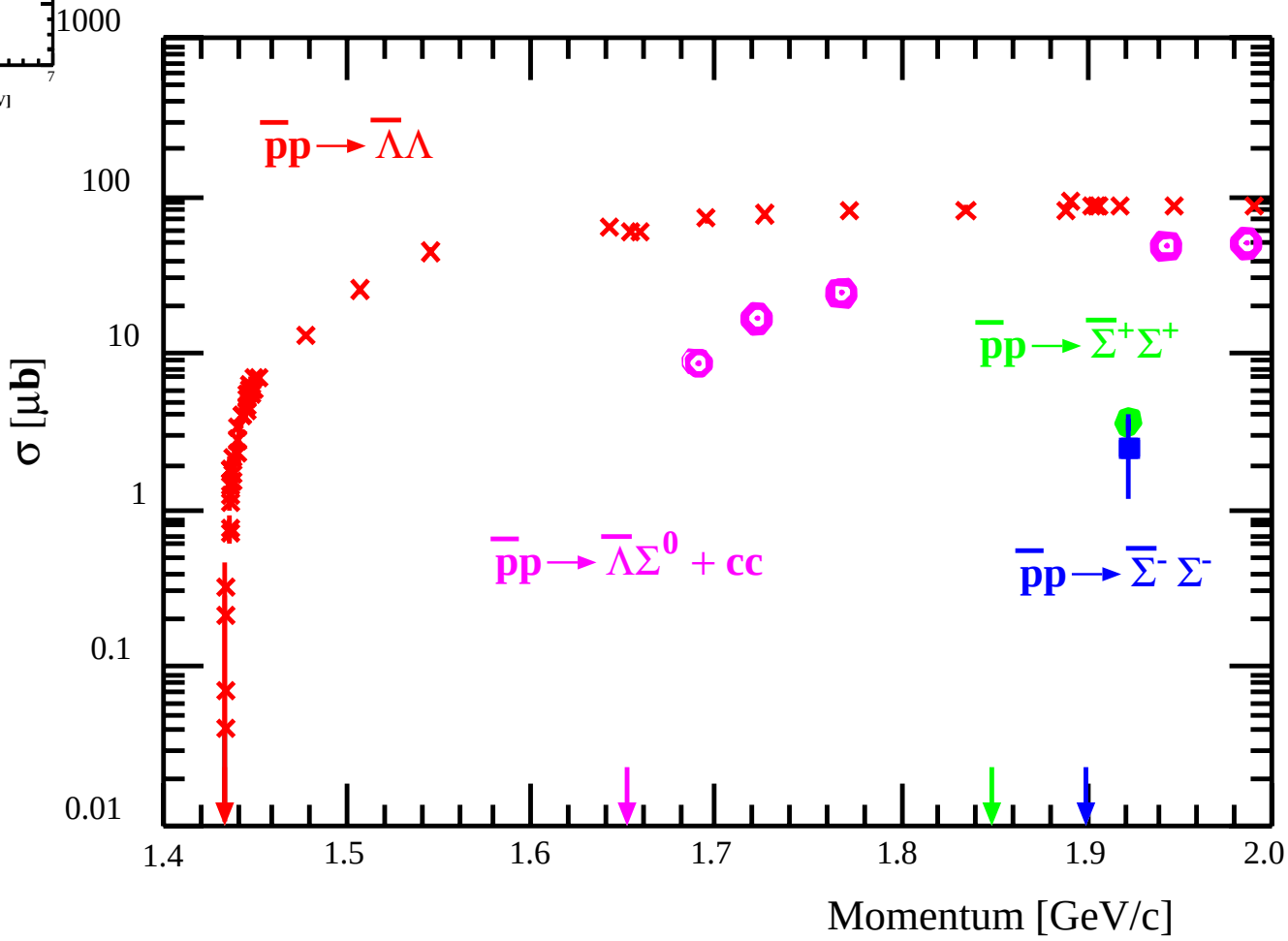

phase space
(arb. norm.)
+ pp FSI
+ ph FSI
a_{ph} = +0.7fm + i 0.4fm
r_{ph} = -1.5fm - i 0.24fm
(A.M.Green, S.Wycech,
PR C55 (1997) R2167)
pp → ppη
pp → ppη′
σ[nb]
Q[MeV]
10
10^2
10^3
10^4
1
10
10^2

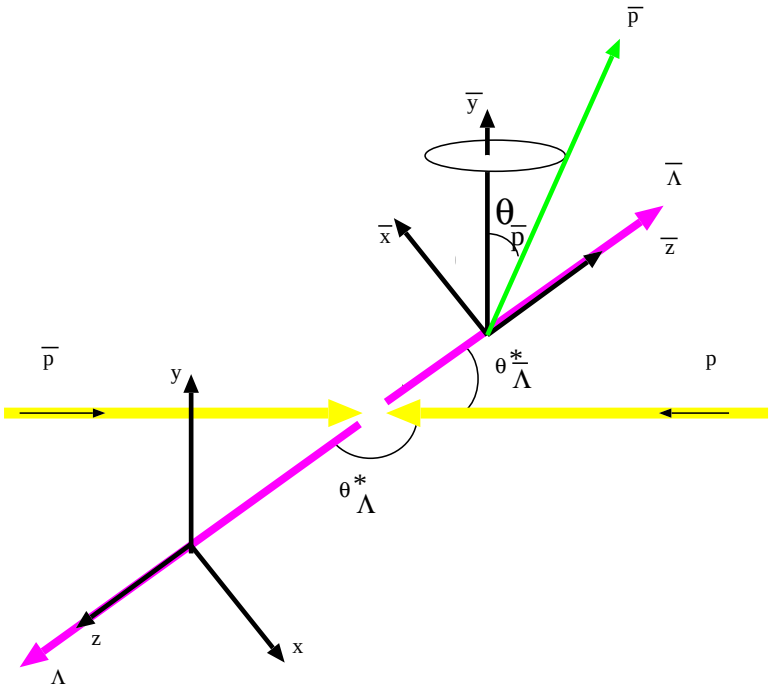


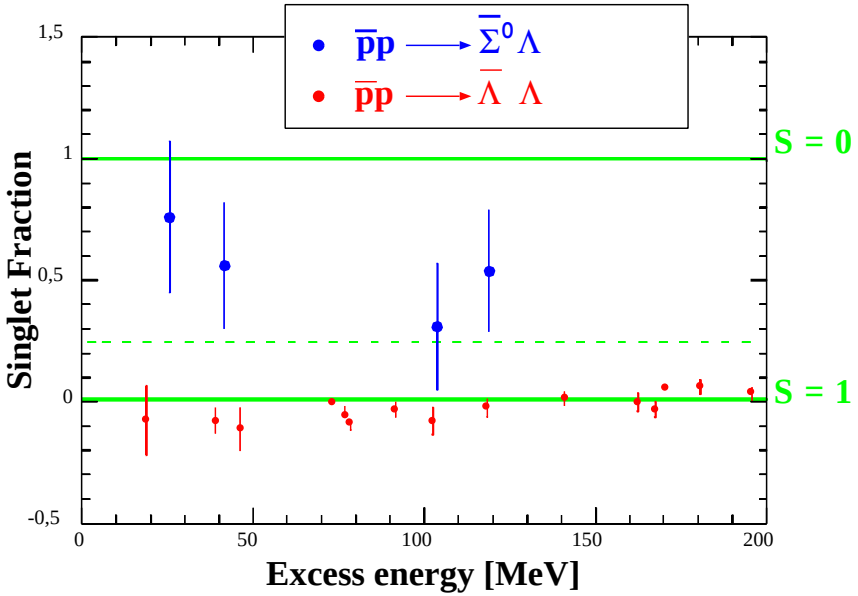

14 MeV
25 MeV
39 MeV
73 MeV
92 MeV
118 MeV
141 MeV
170 MeV
196 MeV
p̄ p → Λ̄ Λ
cos θ cm > -.8
dσ/dt' [μ b / (GeV/c)2]
t' [(Gev/c) 2]

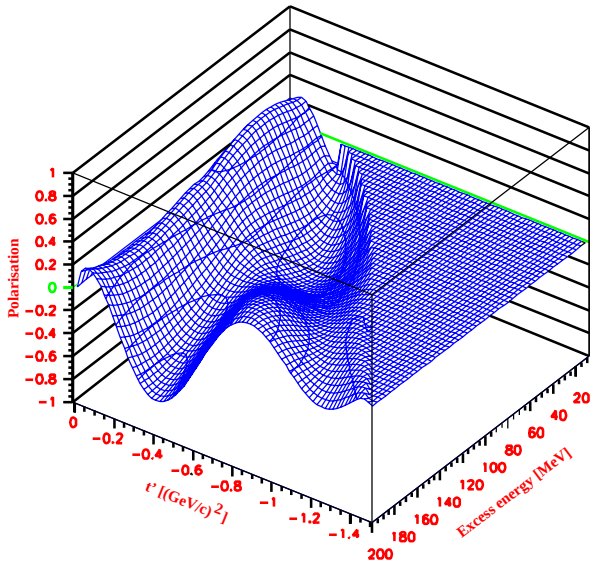

p̄ p → Λ̄ Λ
1.771 GeV/c
p̄ p → Λ̄ Σ0 + c c
1.771 GeV/c
p̄ p → Σ̄+ Σ+
1.922 GeV/c
dσ/dΩ [μb/sr]
cos θ Λ̄ [CM]


$\bar{p}+p \rightarrow \bar{\Lambda}+\Lambda$
σ [μ b]
Excess energy [MeV]

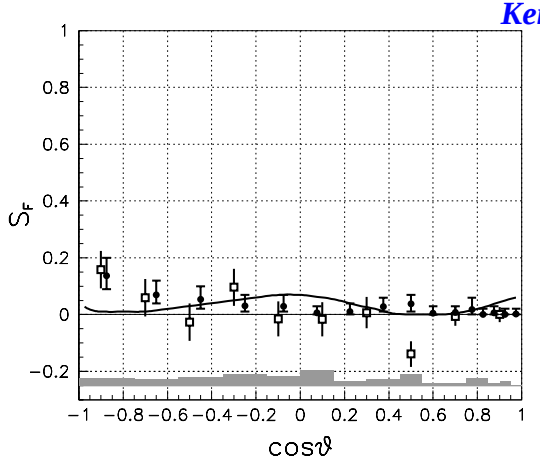

$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$
$\bar{p}p \rightarrow \bar{\Sigma}^{+}\Sigma^{+}$
$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^{0} + cc$
$\bar{p}p \rightarrow \bar{\Sigma}^{-}\Sigma^{-}$
σ [μb]
Momentum [GeV/c]


p̄
ȳ
Λ̄
θ p̄
x̄
z̄
p̄
y
θ* Λ
p
θ* Λ
z
x
Λ


p̄p → Σ̄0 Λ
p̄p → Λ̄ Λ
S = 0
S = 1
Singlet Fraction
Excess energy [MeV]
1,5
1
0,5
0
-0,5
0
50
100
150
200


Polarisation
t' [(GeV/c)²]
Excess energy [MeV]

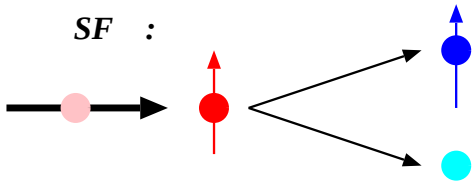
Kent D. Paschke
CMU

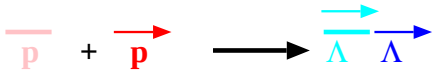


MEX

QG: SF= const. = 0

SF :

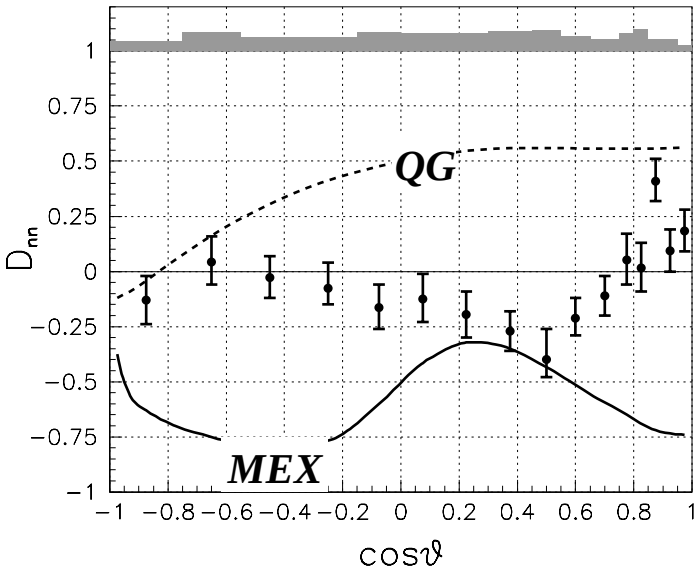


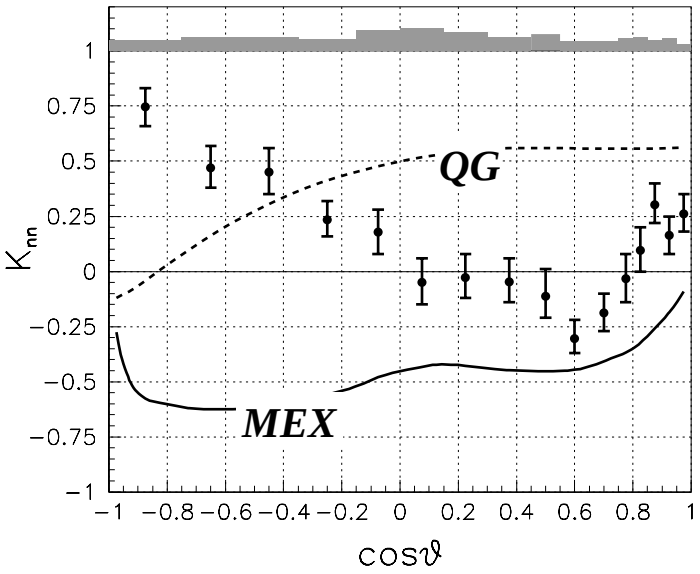


SF = 0

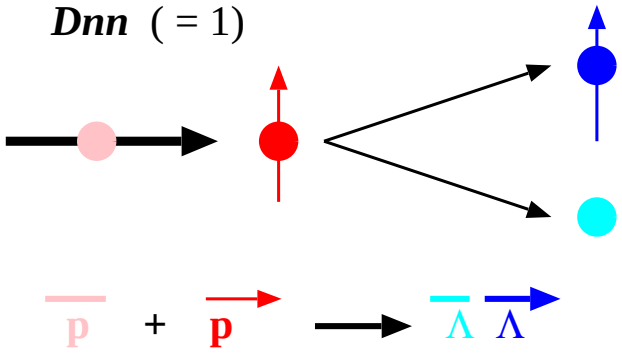
SF = 1

Kent D. Paschke
CMU

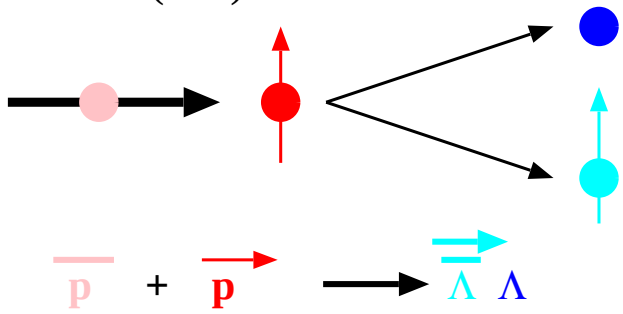




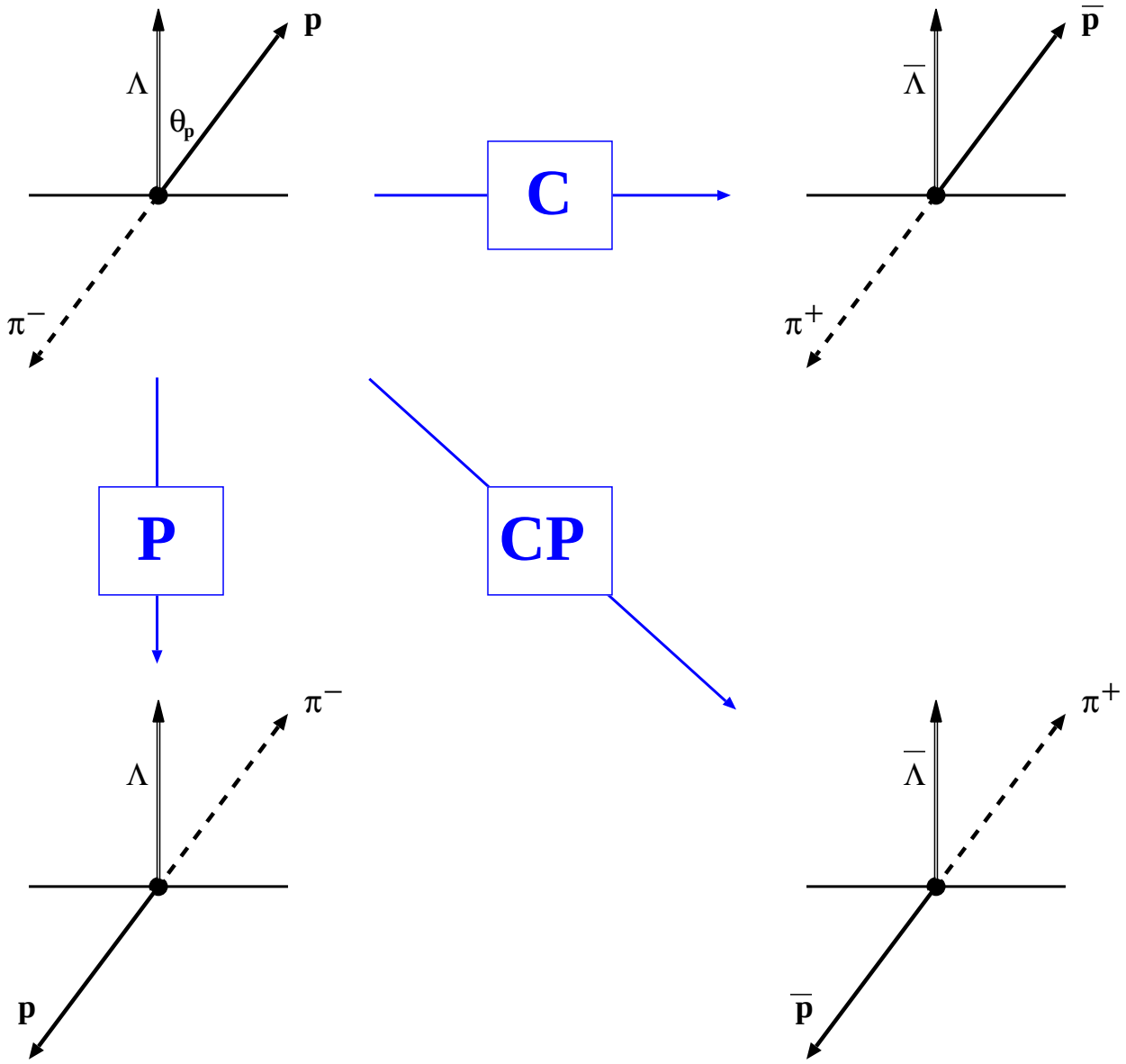
Dnn (= 1)

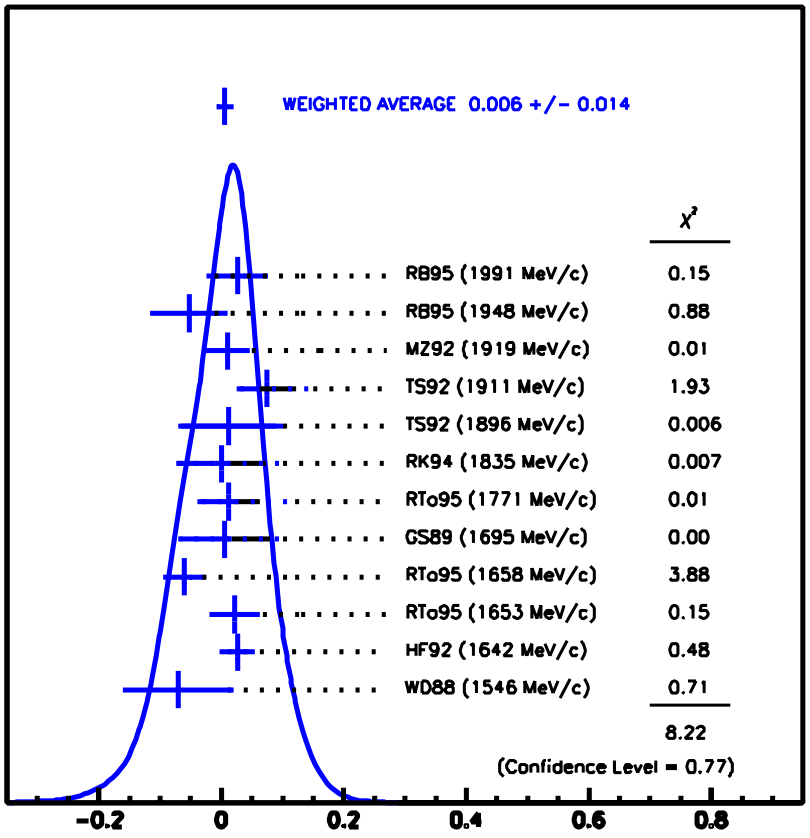


Knn (= 1)



MEX --> tensor interaction --> spin flip --> Dnn and Knn negativ
QG --> minor tensor interaction --> smaller and positive Dnn and Knn


p
Λ
θp
π−
C
p̄
Λ̄
π+
P
CP
π−
Λ
p
π+
Λ̄
p̄

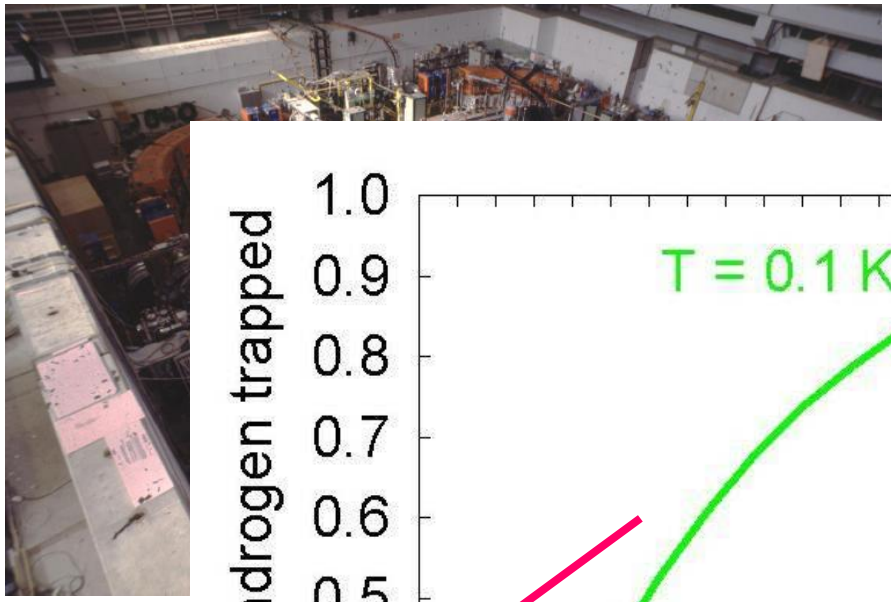


direct CP violation test:

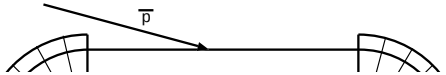
$I(\theta_y) = I_0 (1 + \alpha P \cos\theta_y)$ $\qquad$ $\overline{I}(\overline{\theta}_y) = \overline{I}_0 (1 + \overline{\alpha}\, \overline{P} \cos\overline{\theta}_y)$

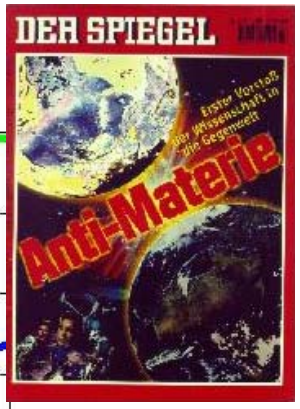
$\mathbf{P} = \overline{\mathbf{P}}$

$$A = (\alpha + \overline{\alpha}) / (\alpha - \overline{\alpha}) = 0.006 \pm 0.014$$

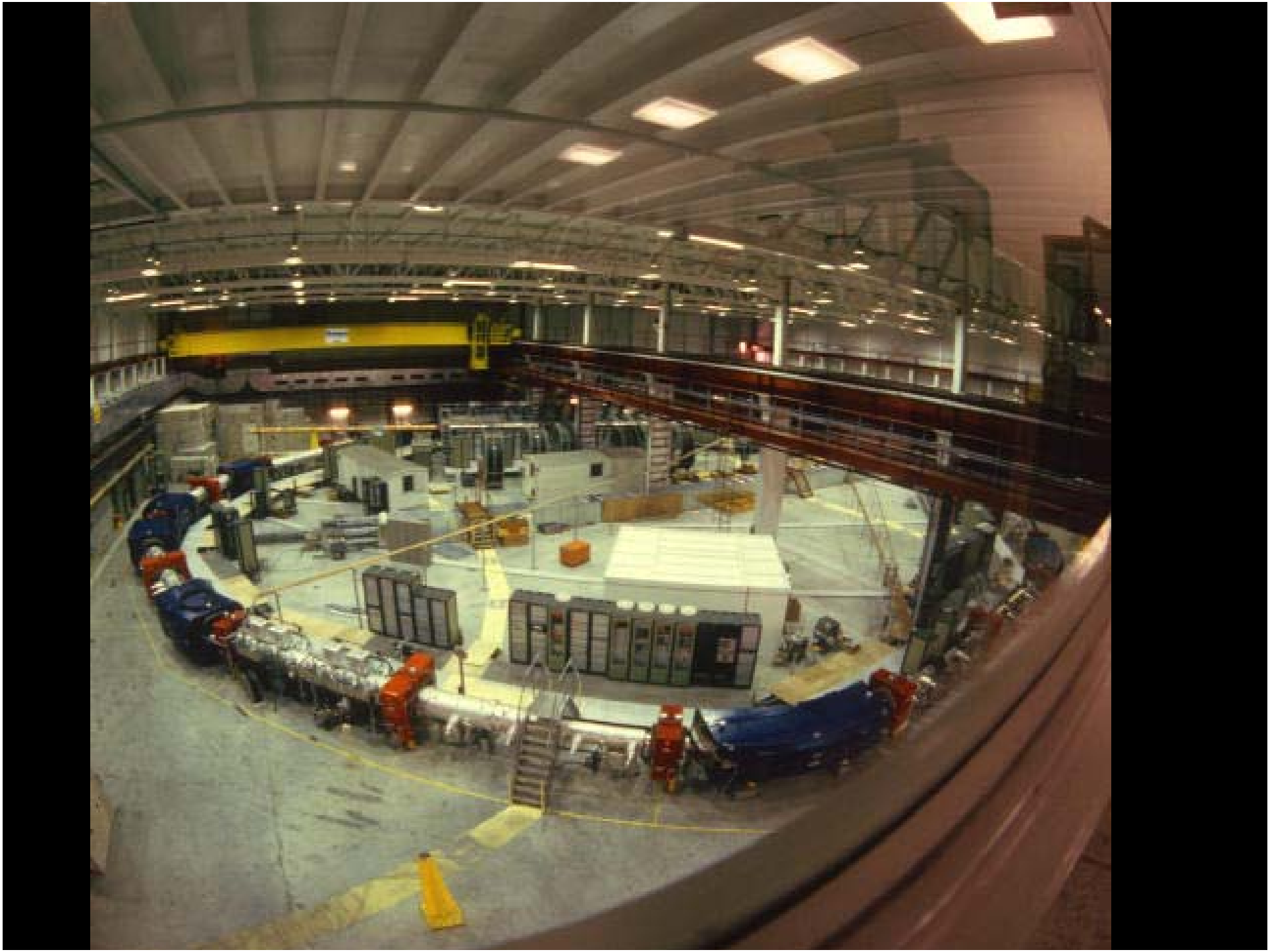


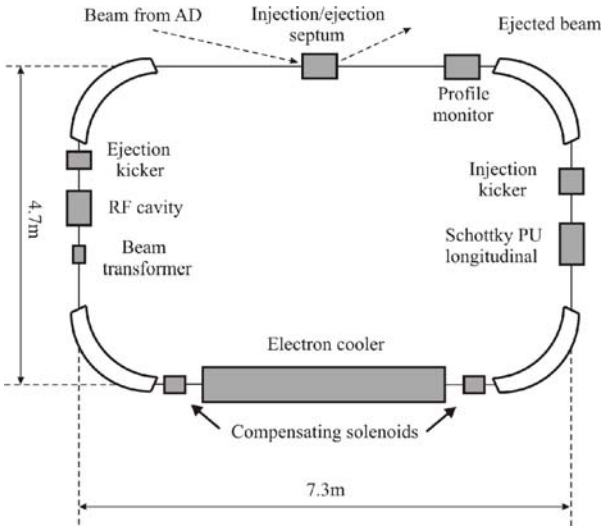
first $\bar{H}$ - production and - detection at LEAR



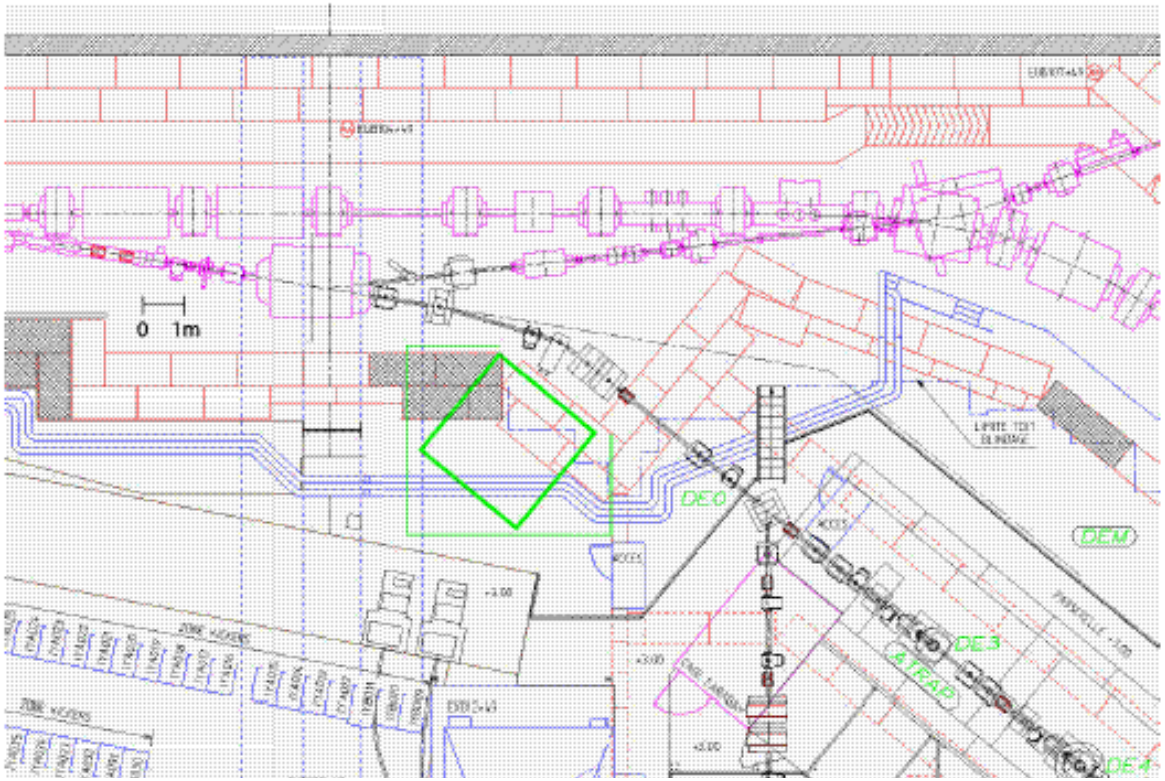


H. Herr, D. Möhl, A. Winnacker (1982)





see talk by
Pavel Belochitskii



Motivation
to make and study Cold Antihydrogen

- CPT invariance
  high precision
  spectroscopy

- gravitation
  matter - antimatter

CPT invariance
fundamental feature
of local relativistic
quantum field theories

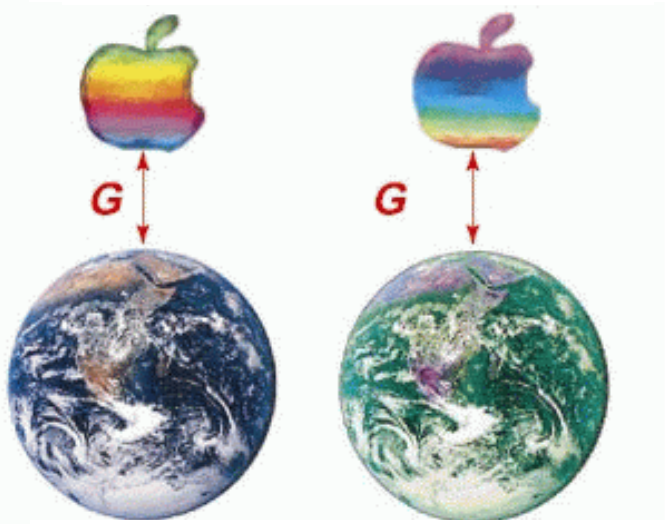
gravitational force
between matter and antimatter
is essentially unknown
even in the sign

Standard model of physics

G – fairly well understood

apple

anti-apple



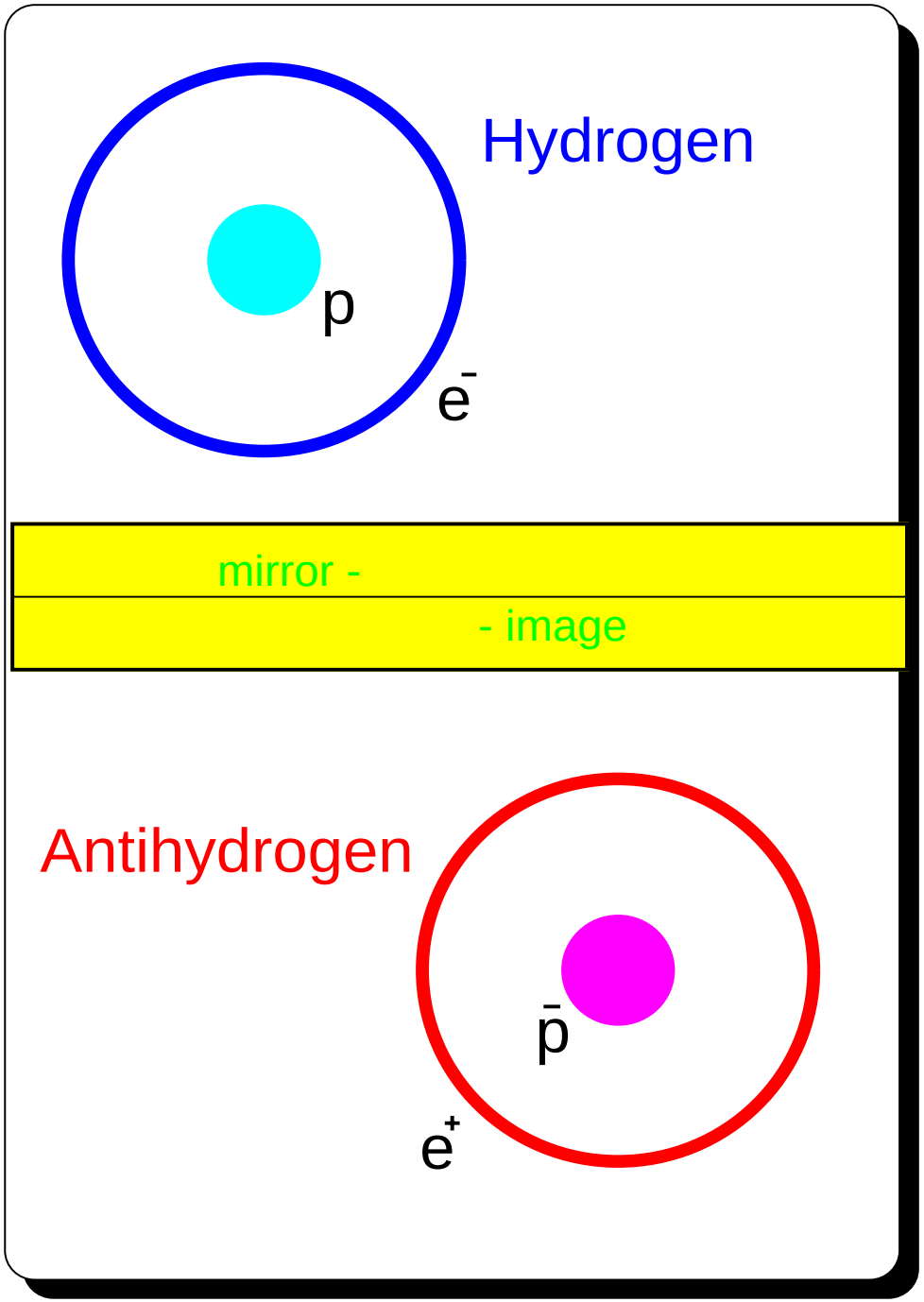
earth

anti-earth

G – experimentally not known, not studied

anti-apple

earth


Hydrogen
p
e-
mirror -
- image
Antihydrogen
p̄
e+

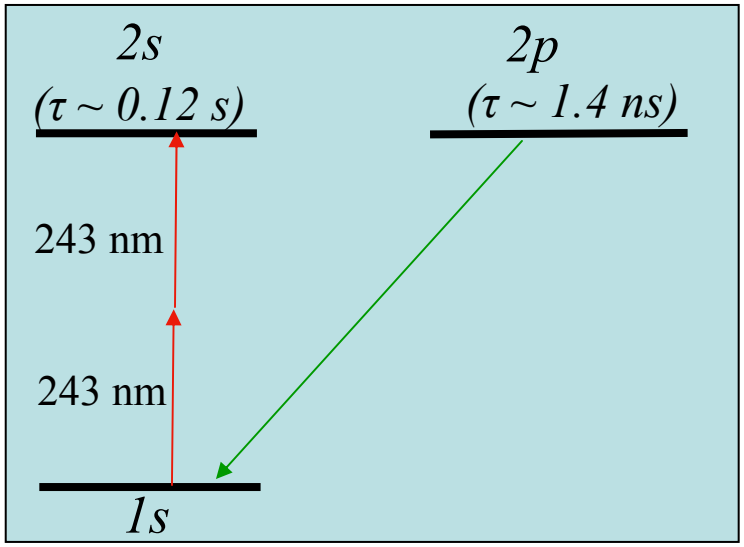
hydrogen 1s – 2s spectroscopy

cold (5-7 K) H atomic beam

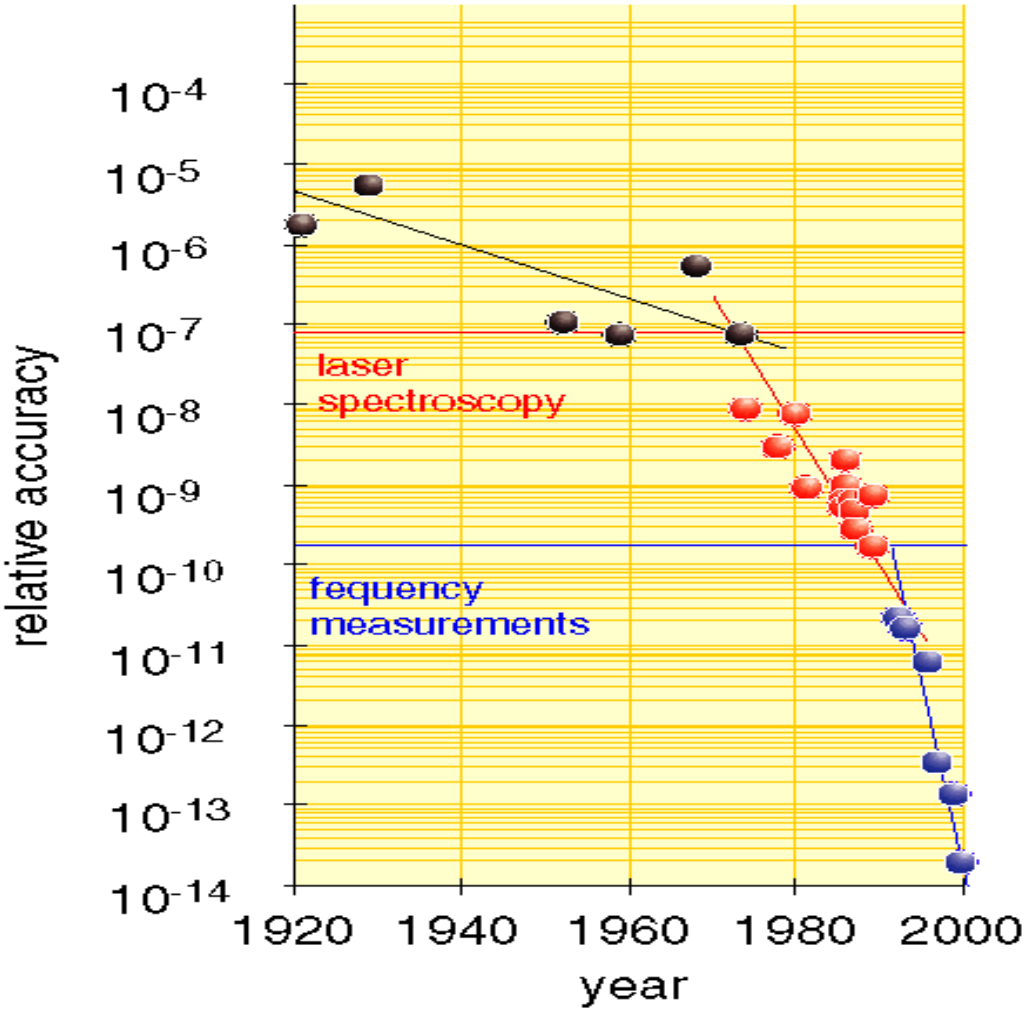
two photon excitation

velocity measurement
→ correct 2. order doppler shift

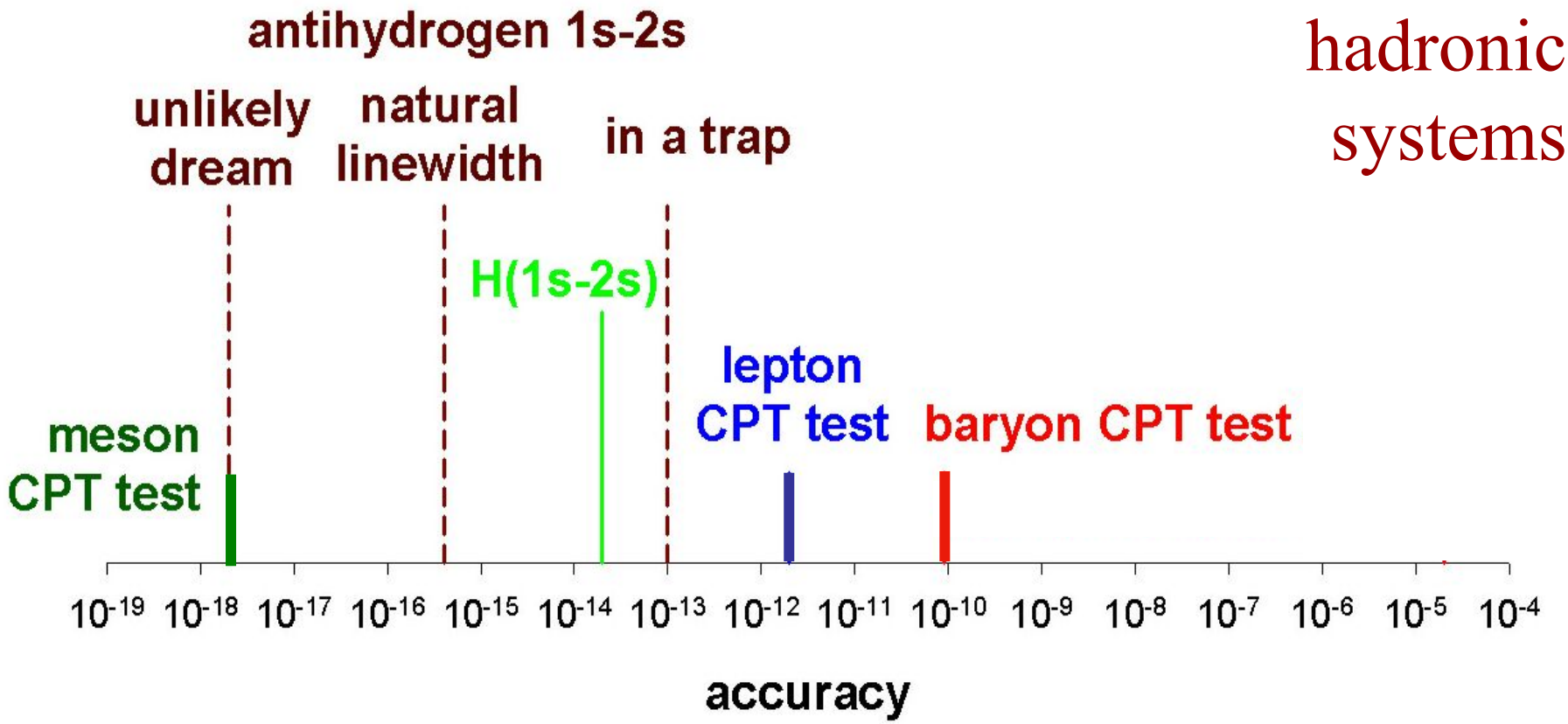
laser photon density variation
→ correct stark shift



M. Fischer et al., eprint physics/0311128



Status of CPT invariance in leptonic and hadronic systems

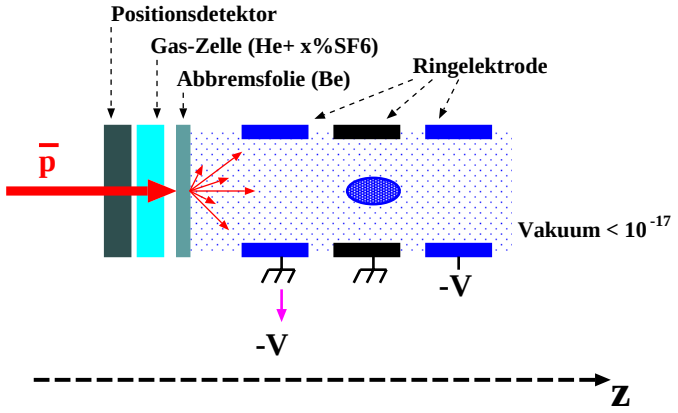


$$\frac{R_\infty[\bar{H}]}{R_\infty[H]} = \frac{m[e^+]}{m[e^-]}\left(\frac{q[e^+]}{q[e^-]}\right)^2\left(\frac{q[\bar{p}]}{q[p]}\right)^2\frac{1+m[e^+]/M[\bar{p}]}{1+m[e^-]/M[p]}$$

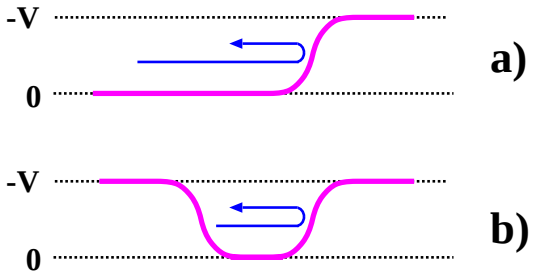
different CPT tests:

particle – antiparticle systems	CPT test accuracy	measurement accuracy	free gift
$K_0 \overline{K}_0$	2×10^{-18}	2×10^{-3}	10^{15}
$e^+ e^-$	2×10^{-12}	2×10^{-9}	10^{3}
$p \overline{p}$	9×10^{-11}	9×10^{-11}	1

Teilchen Falle
(Harvard)



$$\Phi_z = \left[\frac{\Phi_0}{2d^2}\right] z^2$$



Wirkungsgrad des Einfanges:

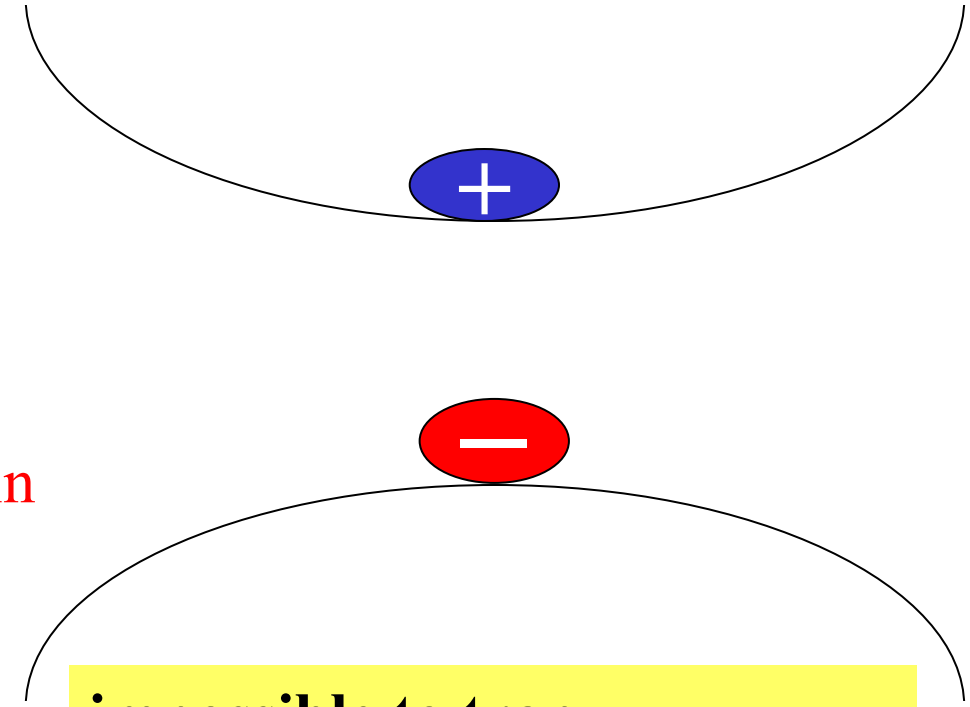
5×10^{-4} at V = - 4 kV

project:

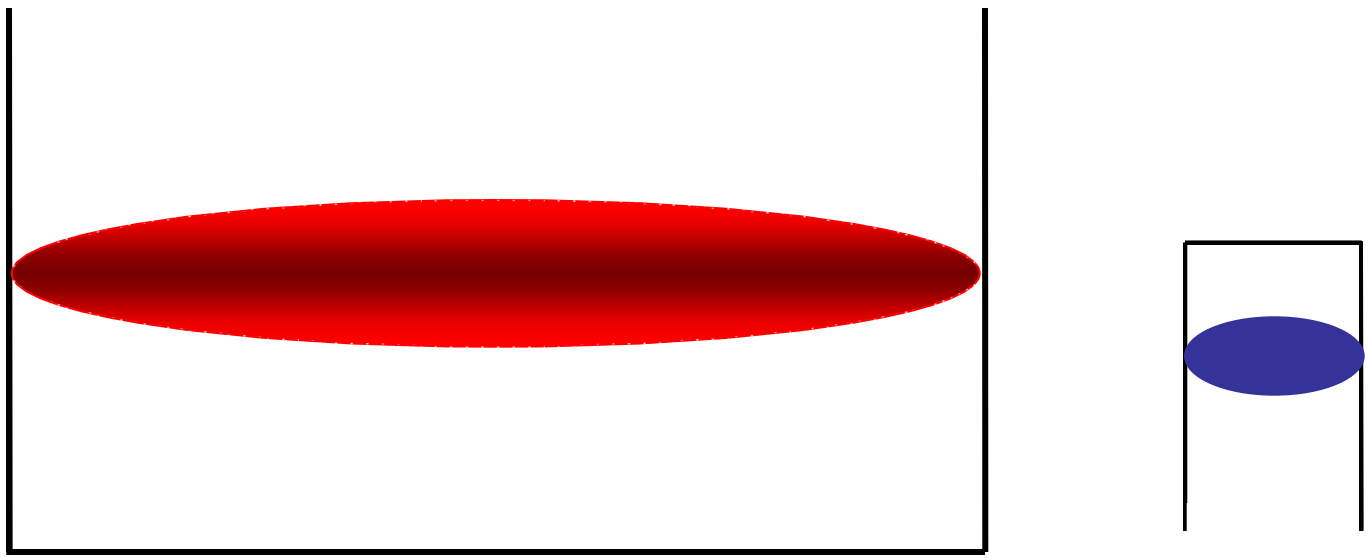
make cold particles of opposite charge to interact

potential valley
for + charge

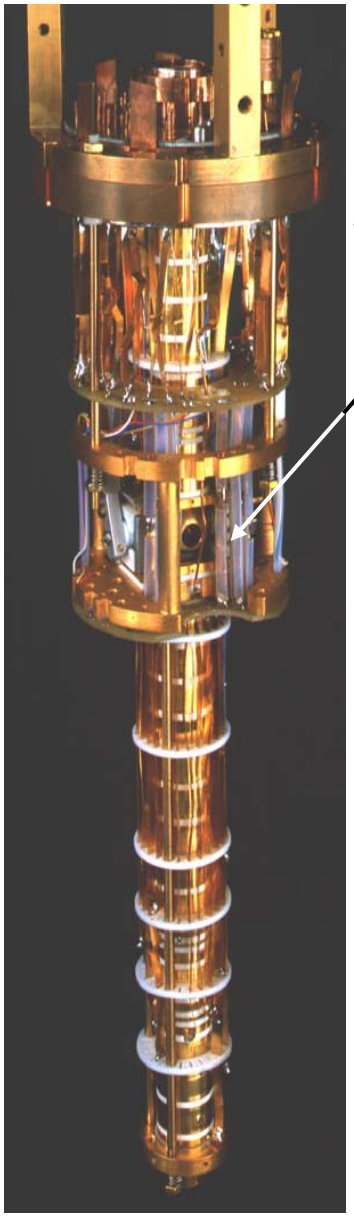
potential mountain
for – charge

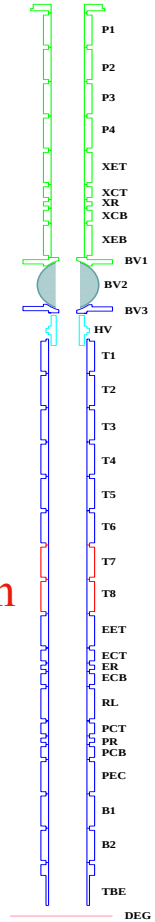


impossible to trap
positive und negative charge
within the same Penning-trap



ATRAP-I





e^+ trap

ball valve

$\bar{p}$ trap

$\bar{H}$ production area

e^+

e^+ trap

rotating electrode

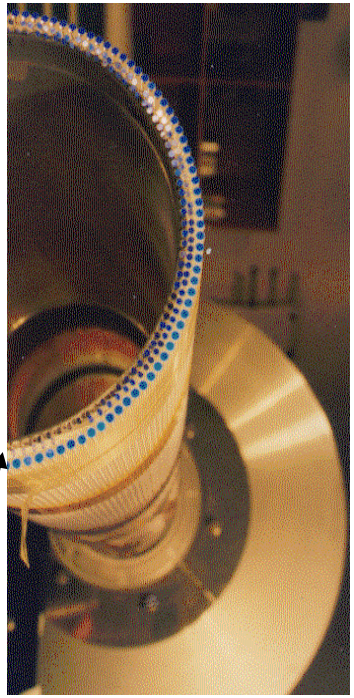
$\bar{p}$ trap

BGO

degrader (Be)

$\bar{p}$

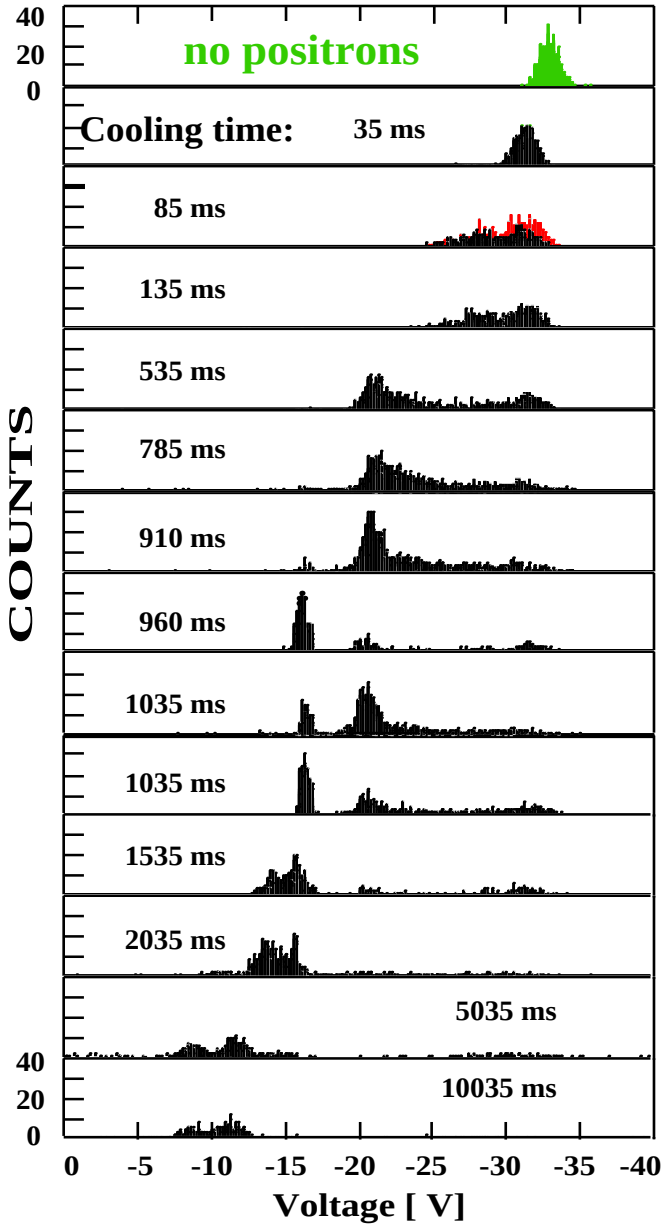
scintillating fibres

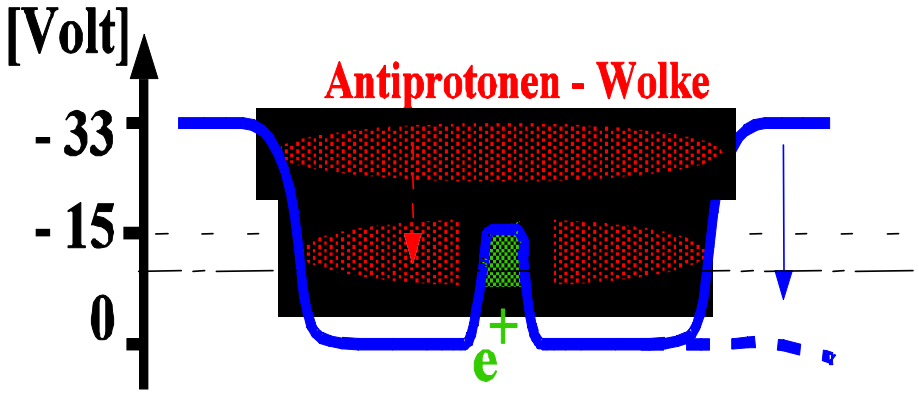


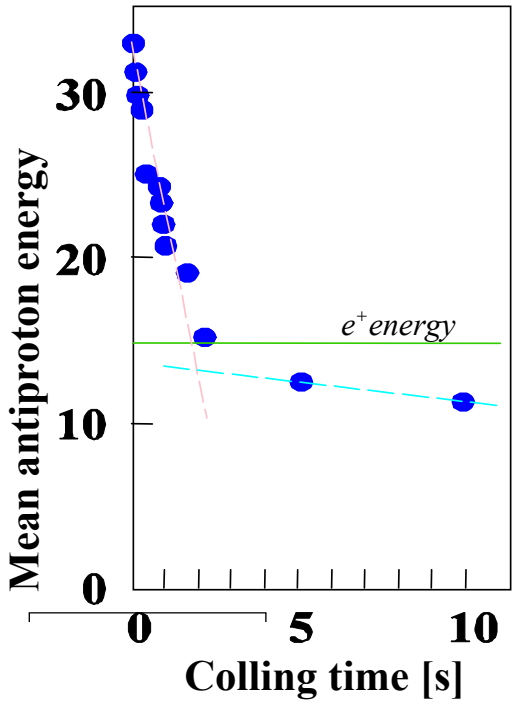
5 cm

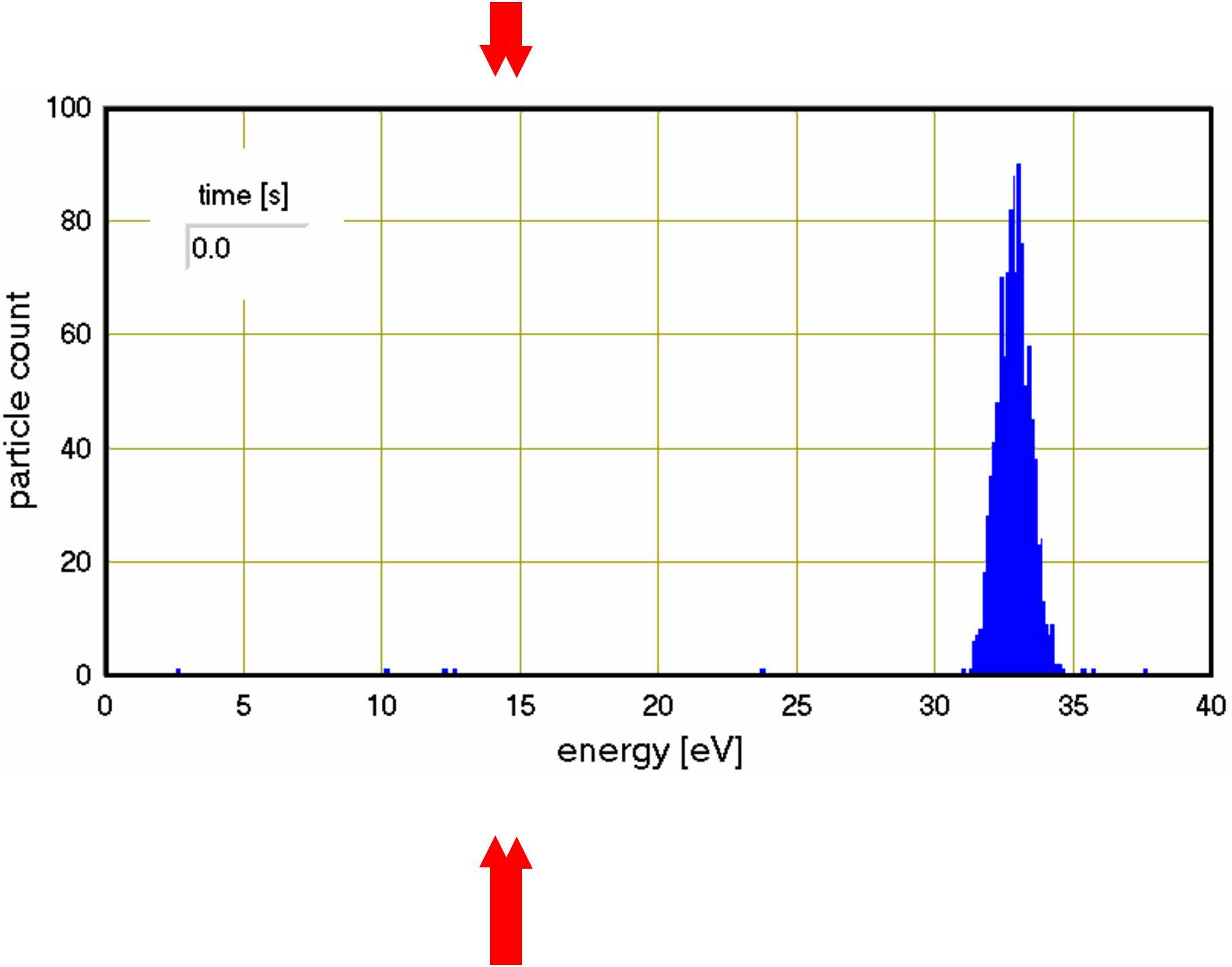
Positron Cooling of Antiprotons

with ~ 1.9 * 10 ^{5} e $^{+}$ @ - 15 Volt








time [s]
0.0
particle count
energy [eV]
0
20
40
60
80
100
0
5
10
15
20
25
30
35
40

the way to high precision $\overline{H}^0$ spectroscopy

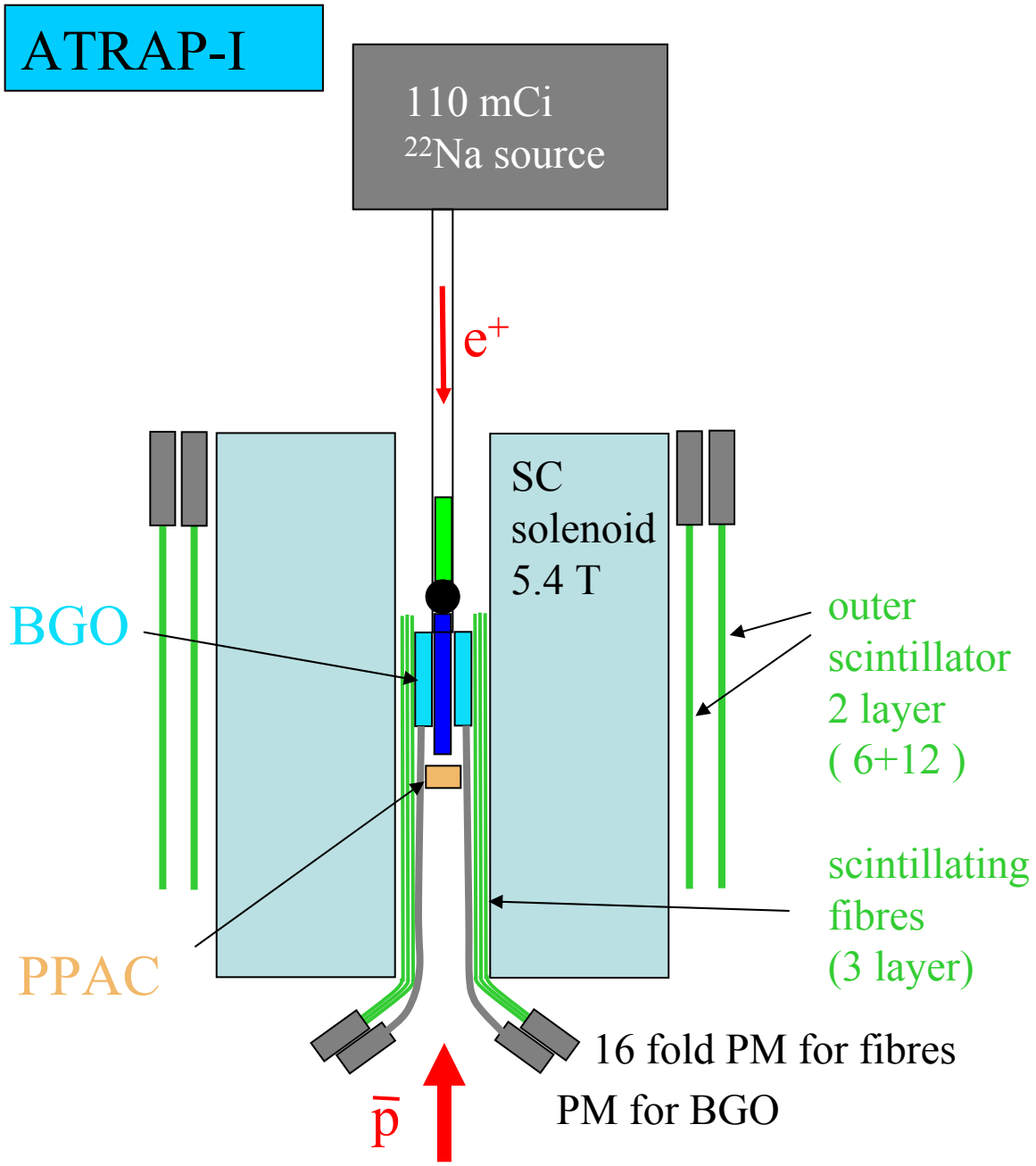
ATRAP-I

- cold trapped positrons ✓
- cold trapped antiprotons ✓
- overlap of $\overline{p}$ and e^+ ✓
- combine $\overline{p}$ and e^+ for production of $\overline{H}^0$ ✓
- maximize production rates
- produce ‘cold‘ $\overline{H}^0$

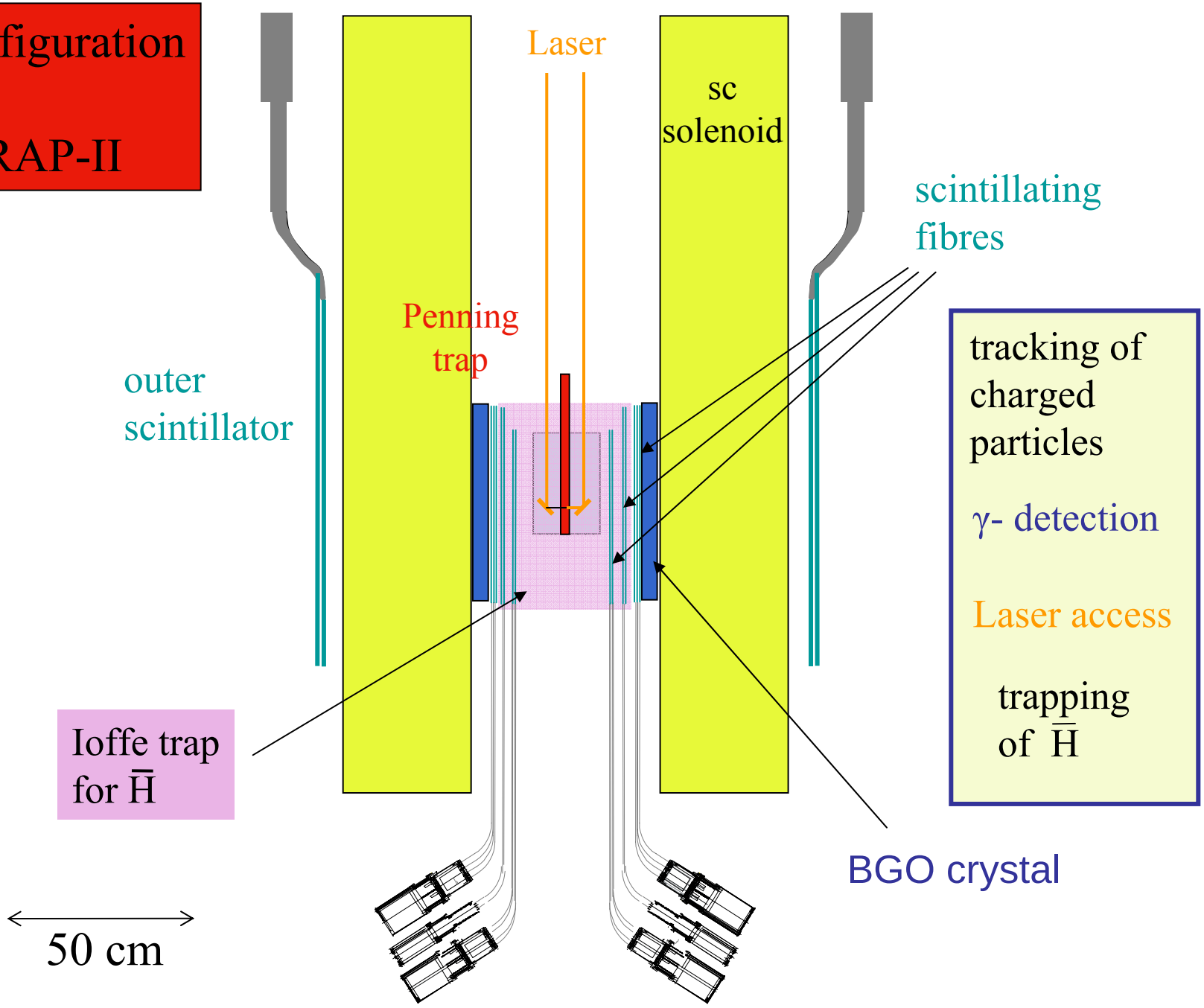
  study trapping mechanisms
- ground state $\overline{H}^0$!

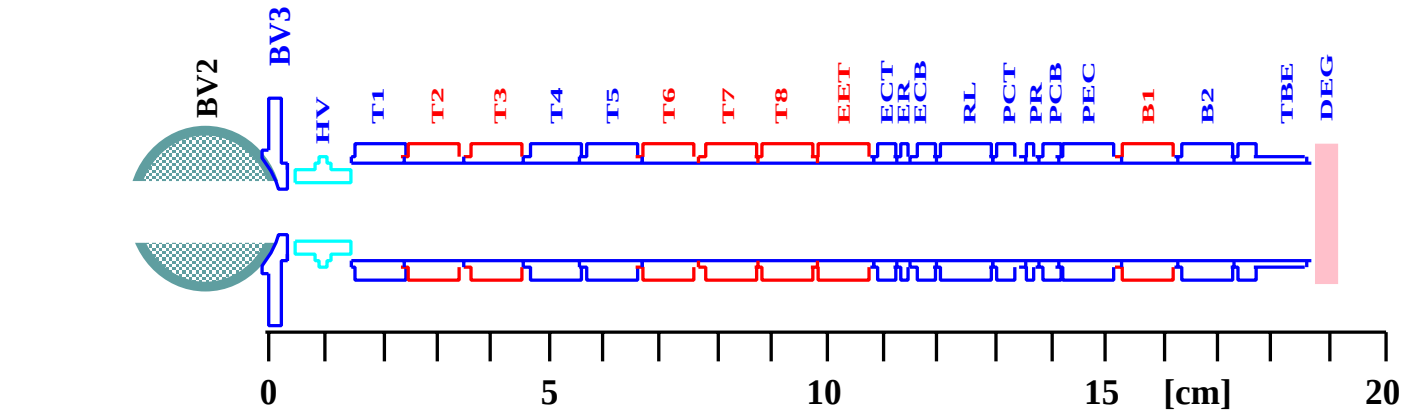
ATRAP-II

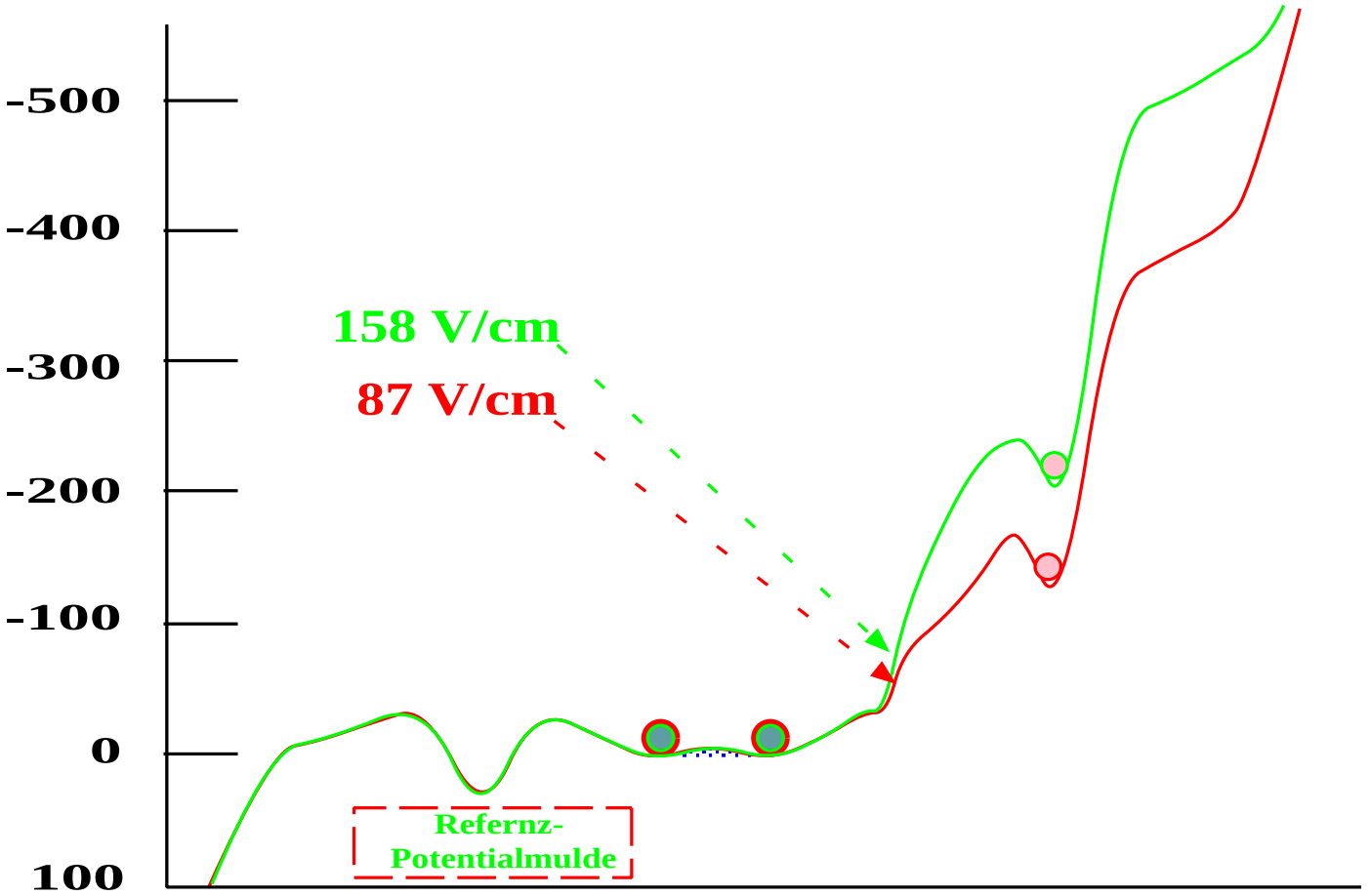
- trap neutral $\overline{H}^0$
- laser cooling
- 1s-2s spectroscopy
- gravitational questions

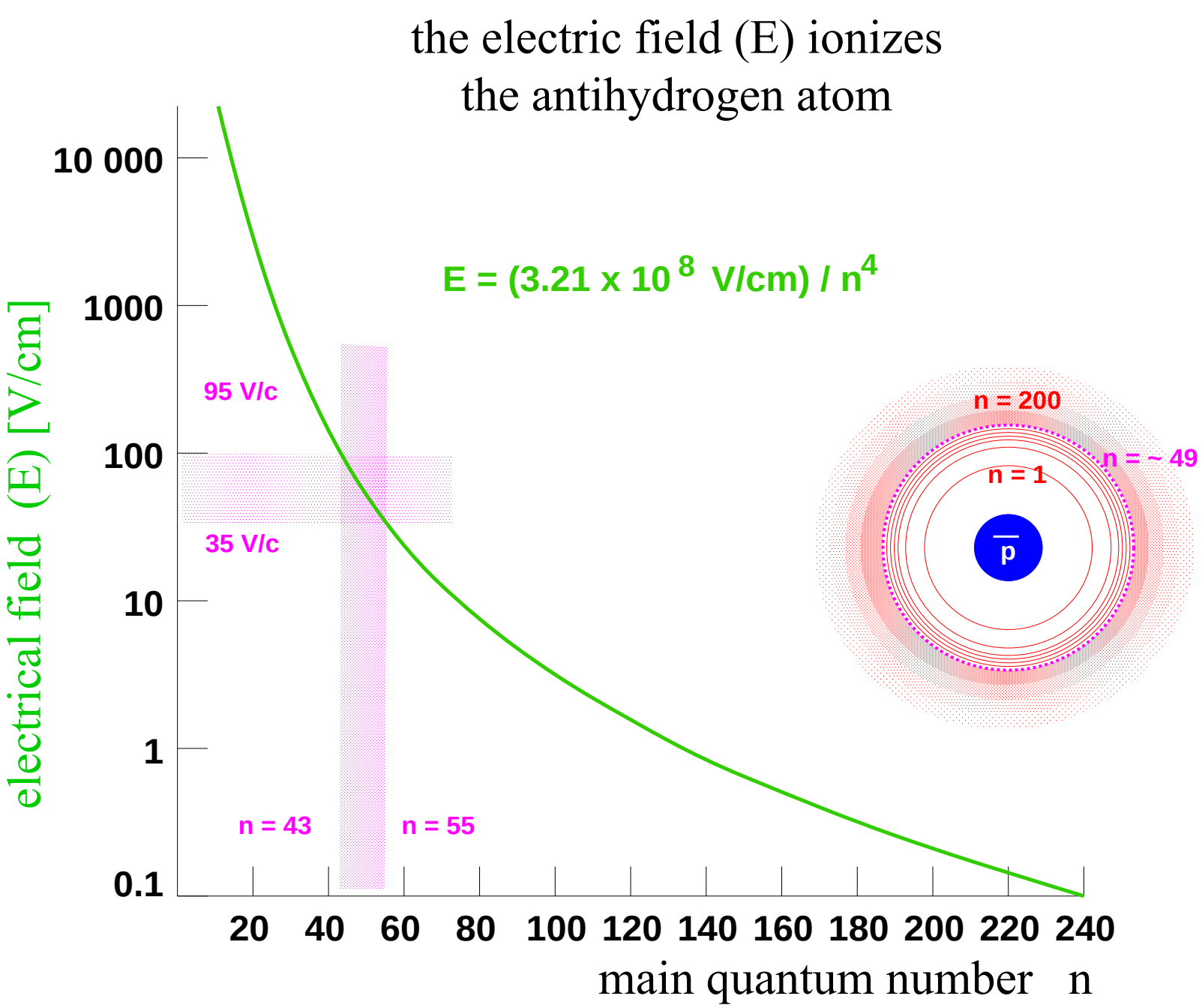

ATRAP-I
110 mCi
22Na source
e+
SC
solenoid
5.4 T
BGO
outer
scintillator
2 layer
(6+12)
scintillating
fibres
(3 layer)
PPAC
16 fold PM for fibres
PM for BGO
p̄

Configuration of ATRAP-II



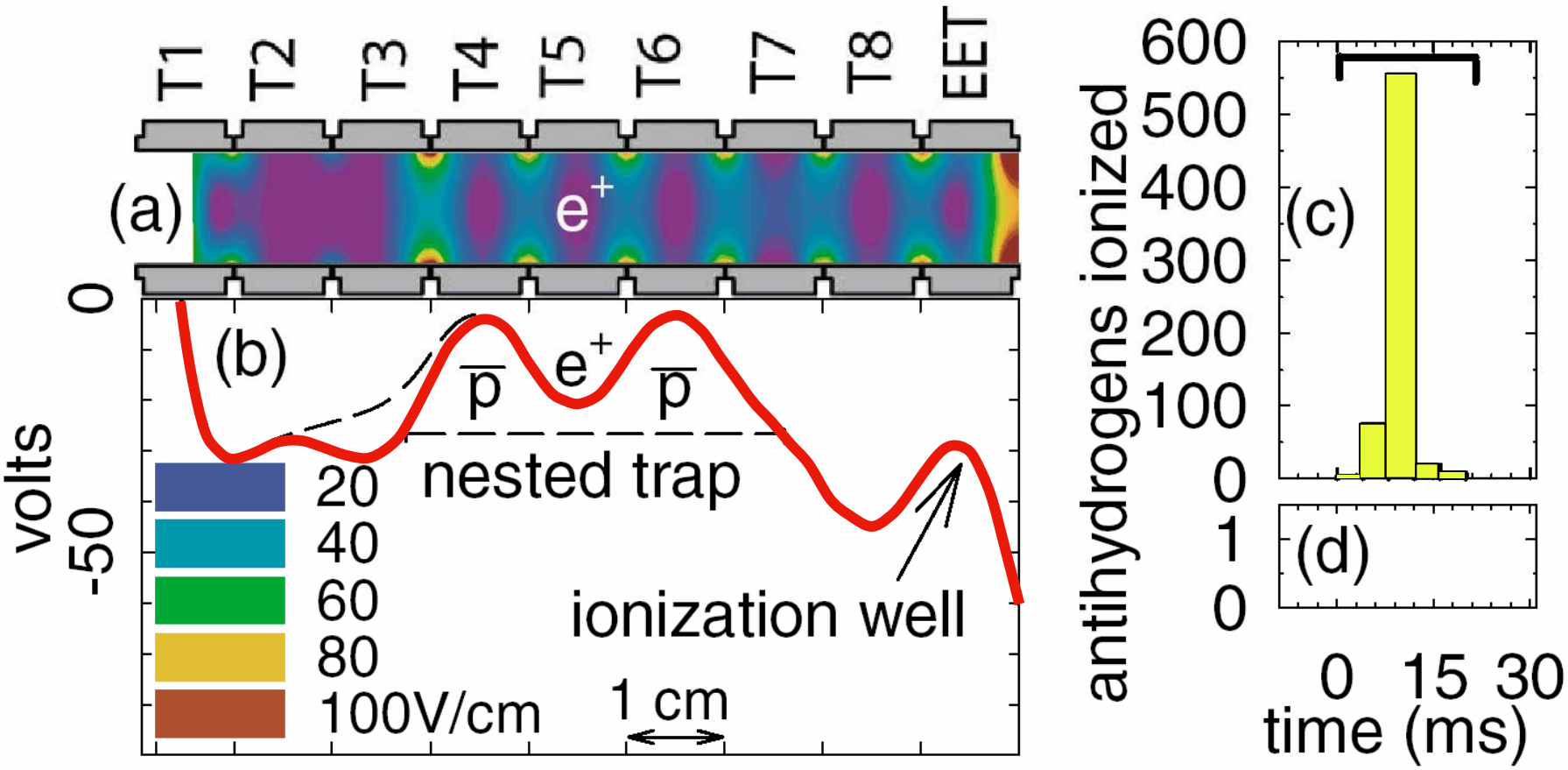

BV2
BV3
HV
T1
T2
T3
T4
T5
T6
T7
T8
EET
ECT
ER
ECB
RL
PCT
PR
PCB
PEC
B1
B2
TBE
DEG
0
5
10
15
[cm]
20


-500
-400
-300
-200
-100
0
100
158 V/cm
87 V/cm
Referenz-
Potentialmulde

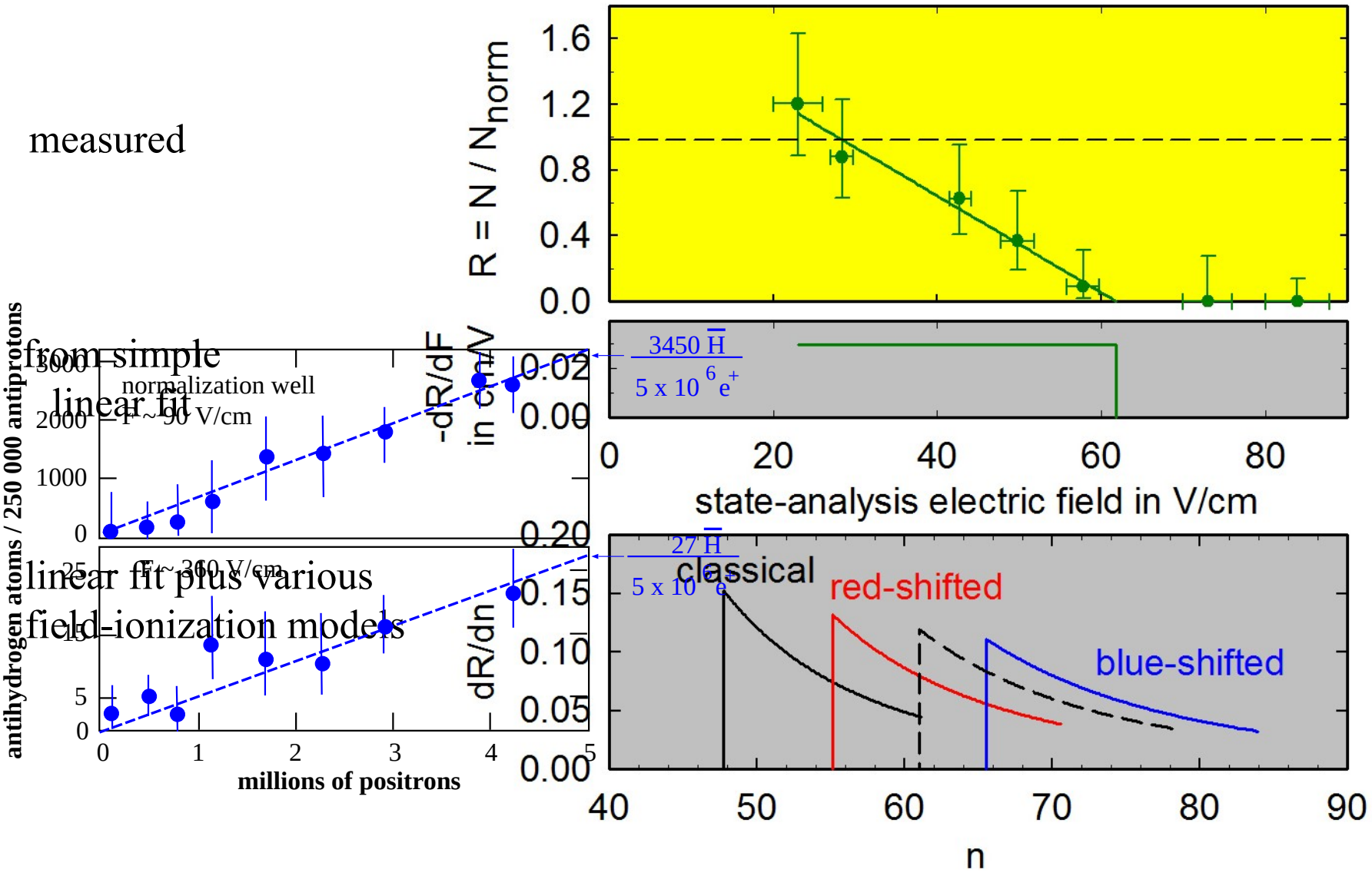

the electric field (E) ionizes
the antihydrogen atom
E = (3.21 x 10 8 V/cm) / n4
electrical field (E) [V/cm]
10 000
1000
100
10
1
0.1
95 V/c
35 V/c
n = 43
n = 55
n = 200
n = ~ 49
n = 1
p
20 40 60 80 100 120 140 160 180 200 220 240
main quantum number n

$\overline{H}$ production and detection

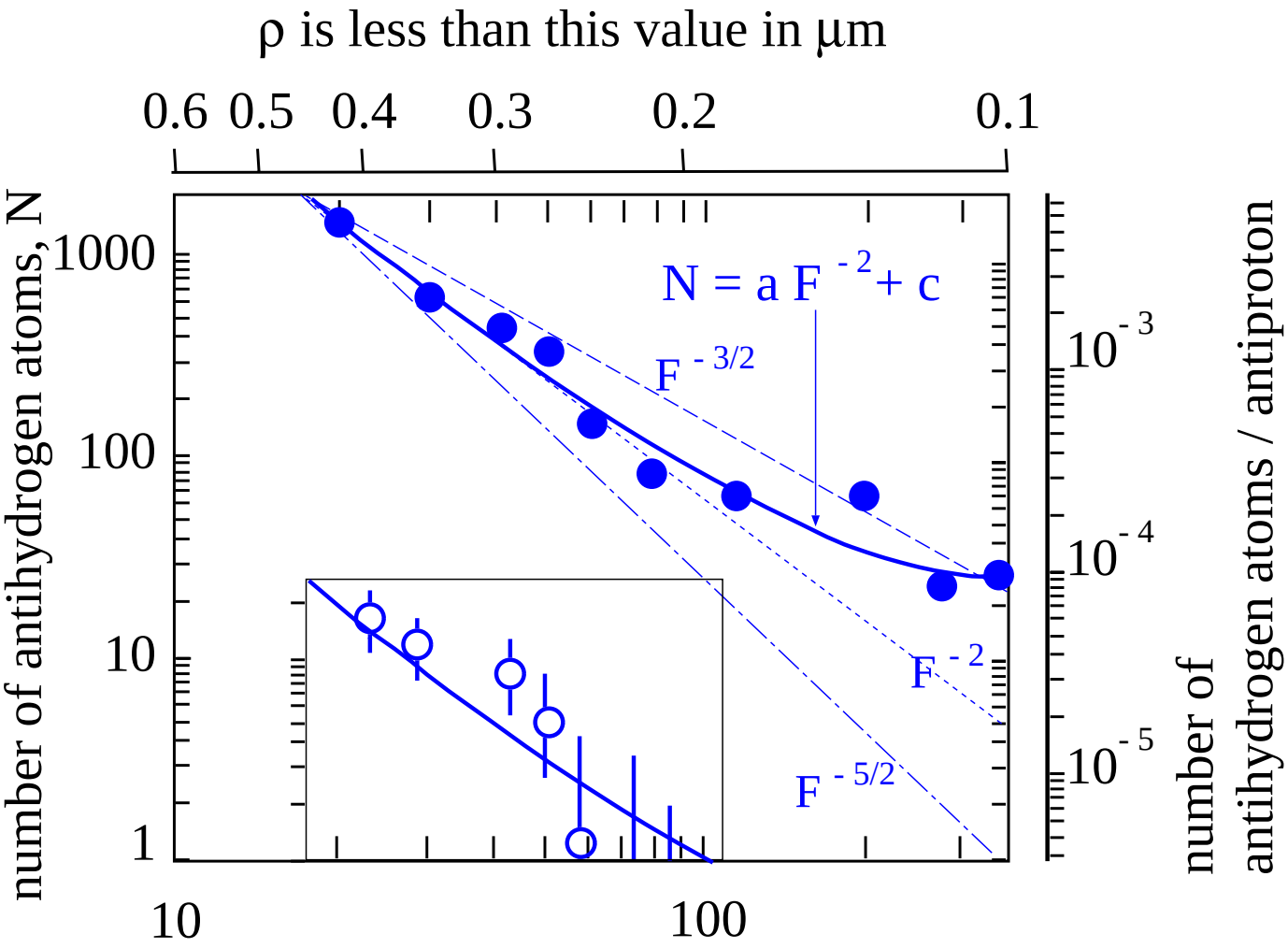
(Phys. Rev. Lett. 89 (2002) 233401 , 213401)



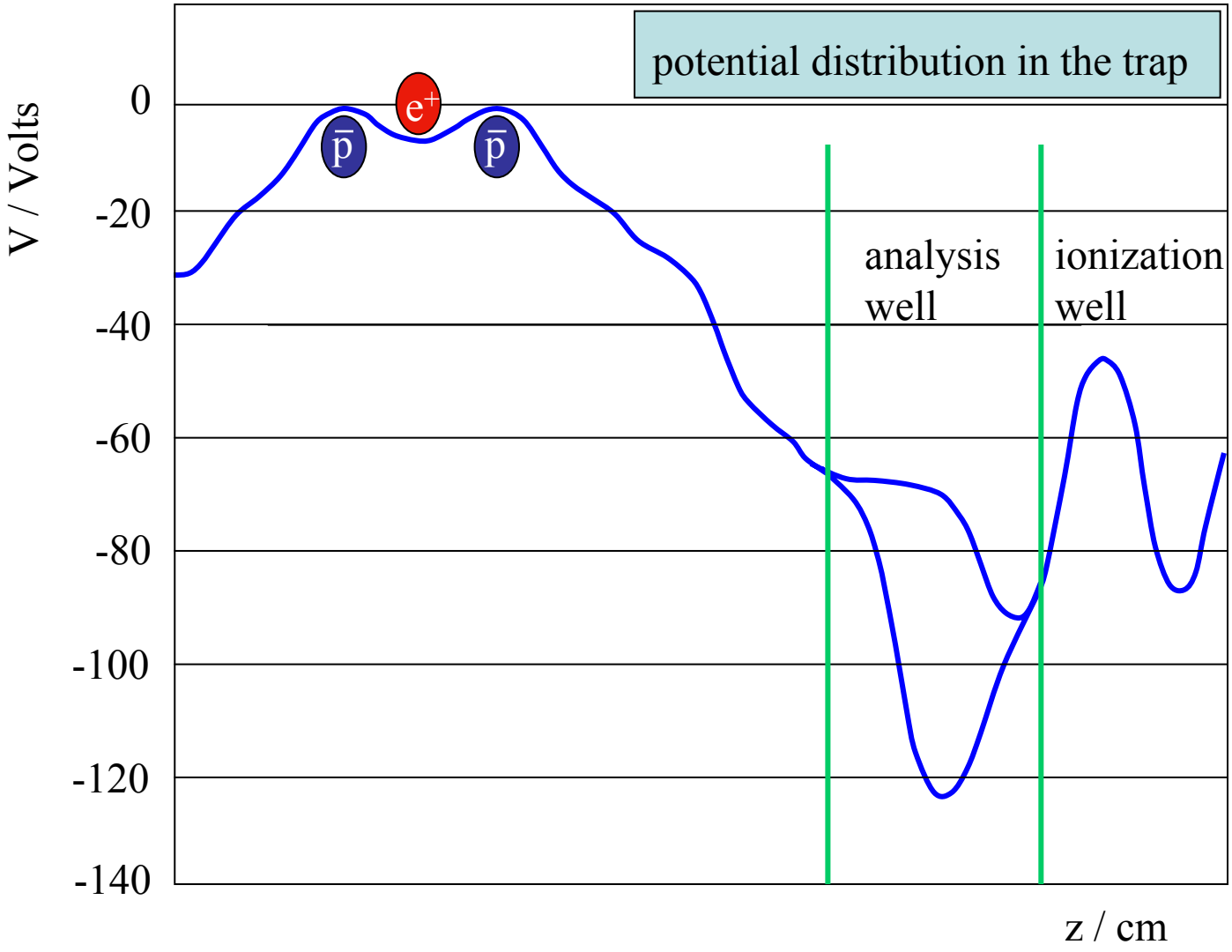
n – state distribution



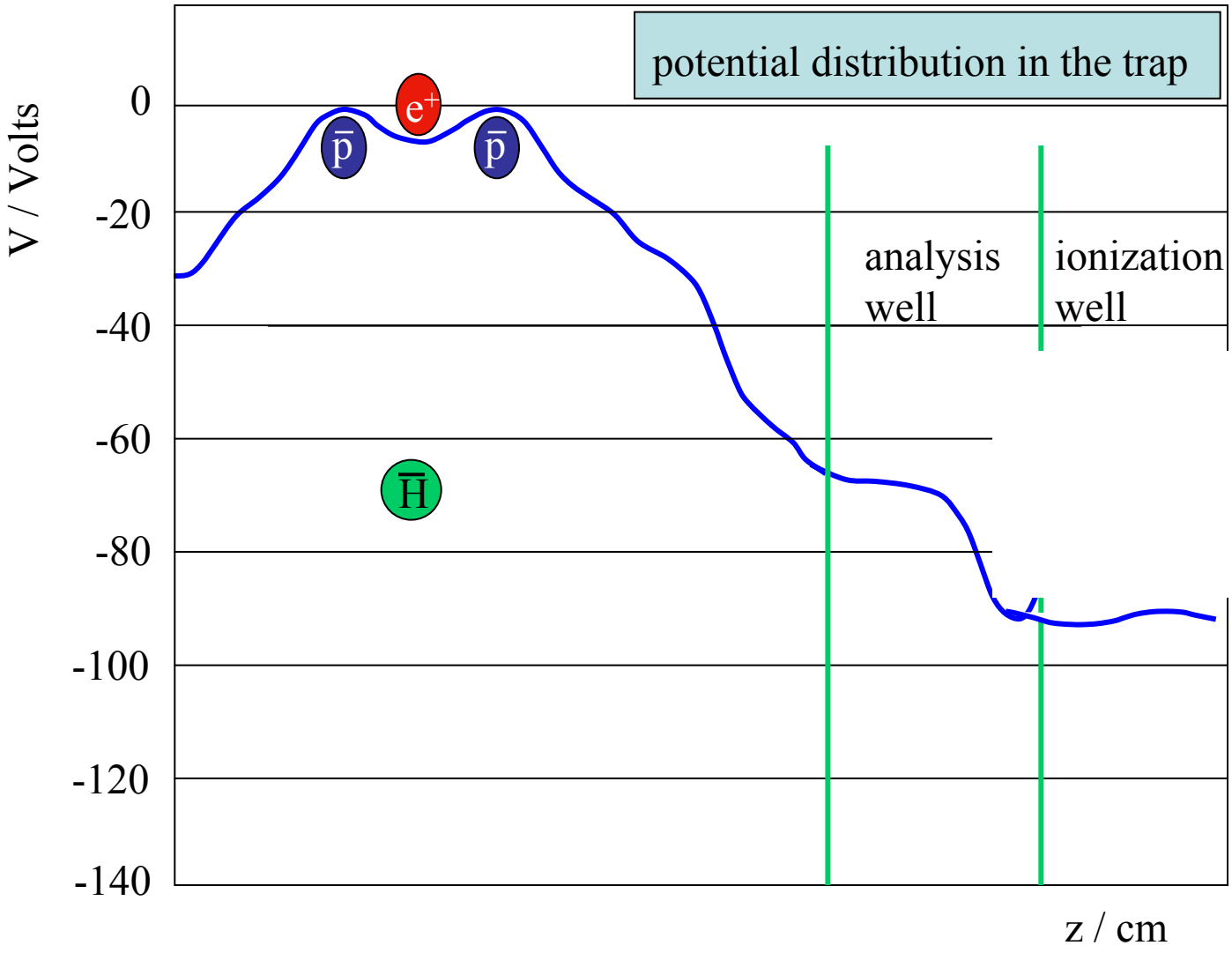
more deeply bound states

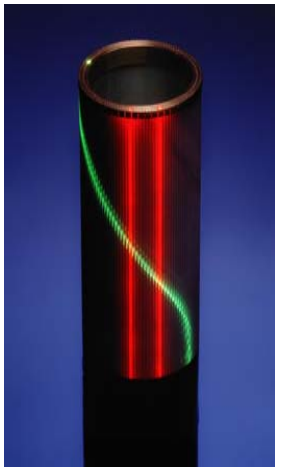


velocity measurement

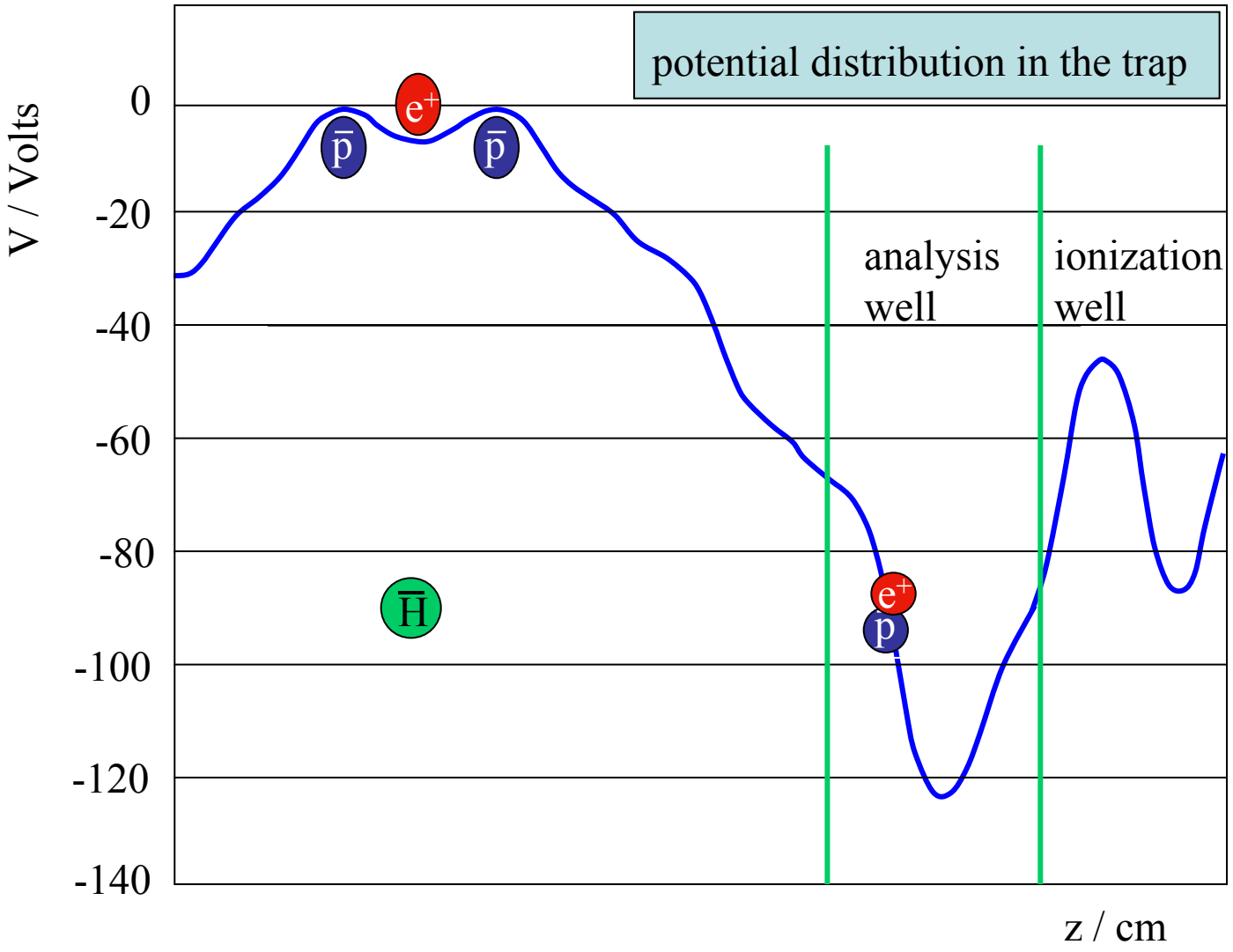


velocity measurement



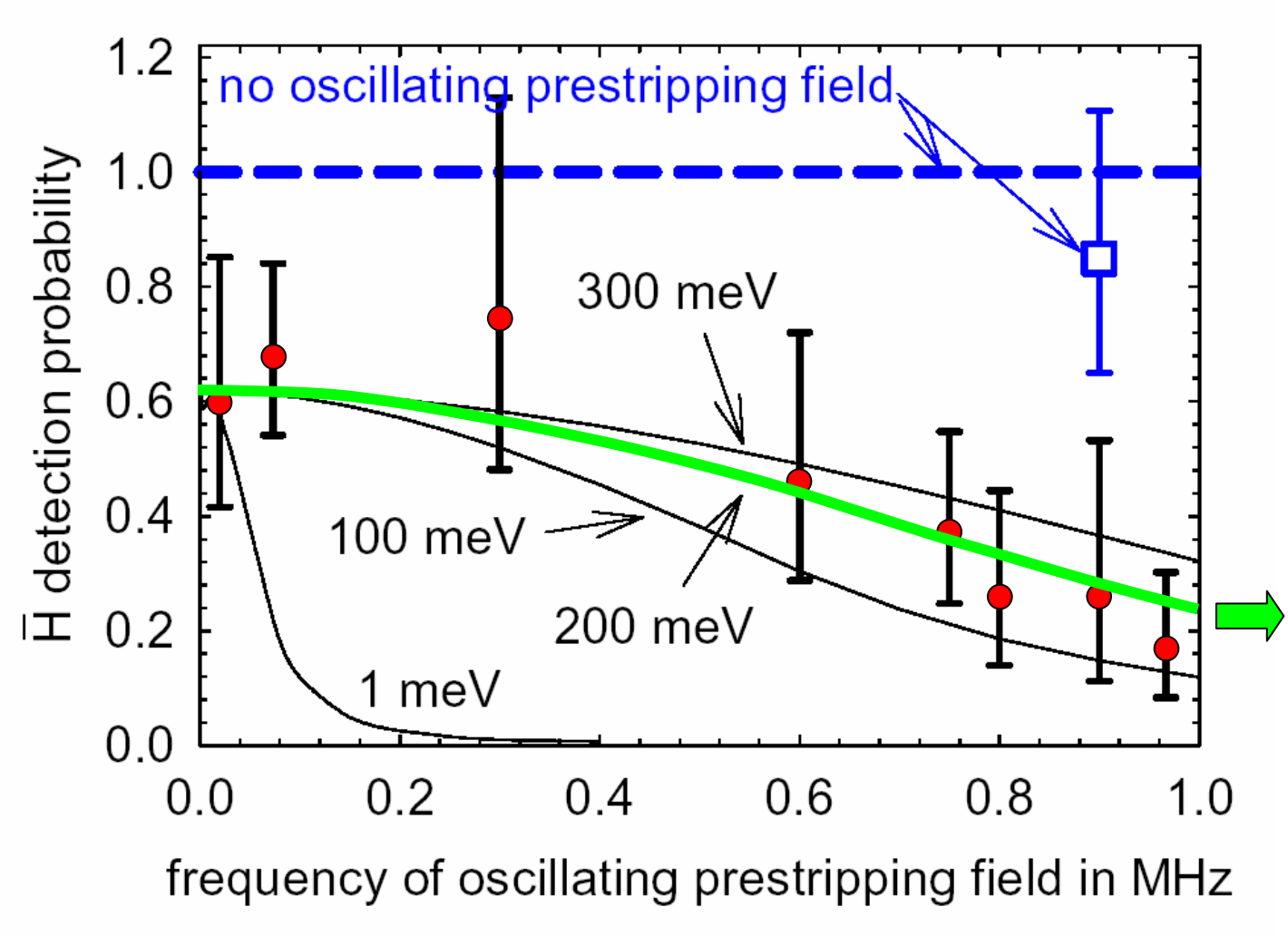


velocity measurement



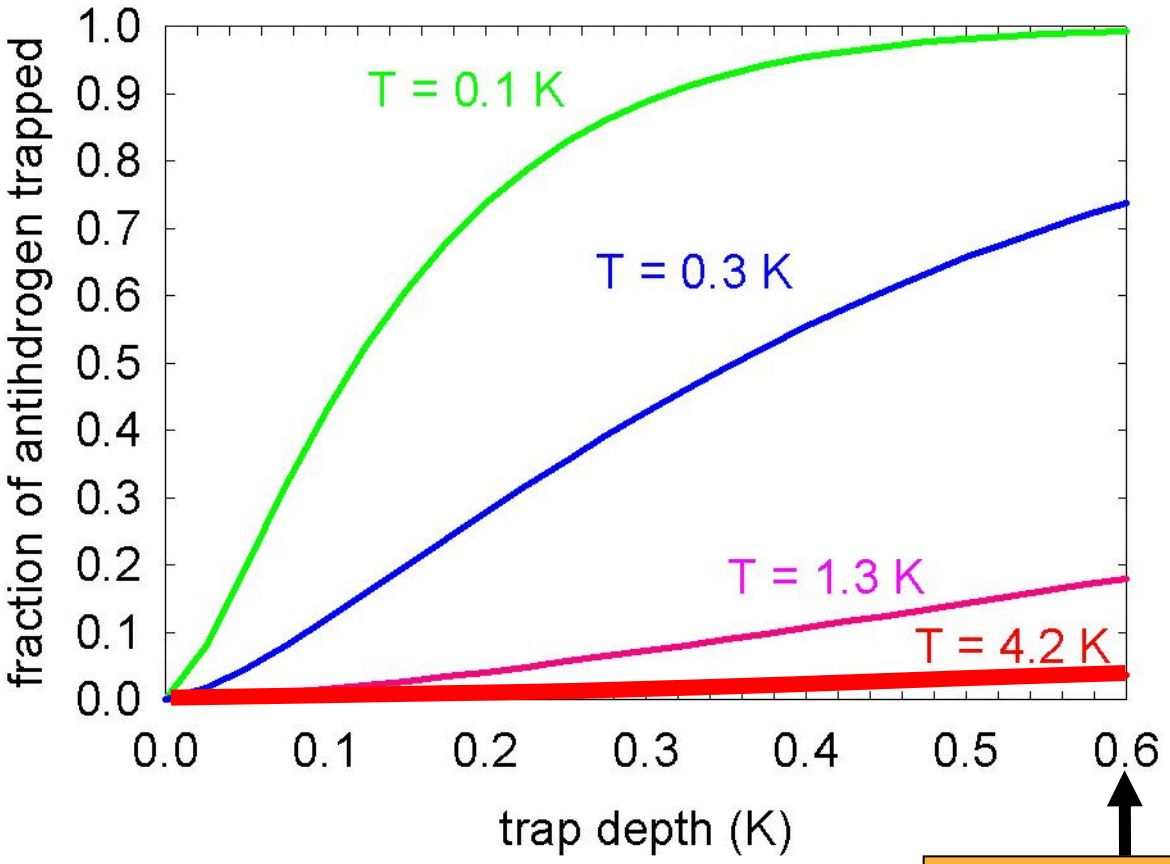
velocity measurement

accepted for publication PRL



$\bar{H}$ are hotter than expected

$\overline{H}$ trapping efficiency | **< 5 %** (4.2 K , ΔB=1T)



ΔB ~ 1T

magnetic quadrupol trap (Ioffe trap)

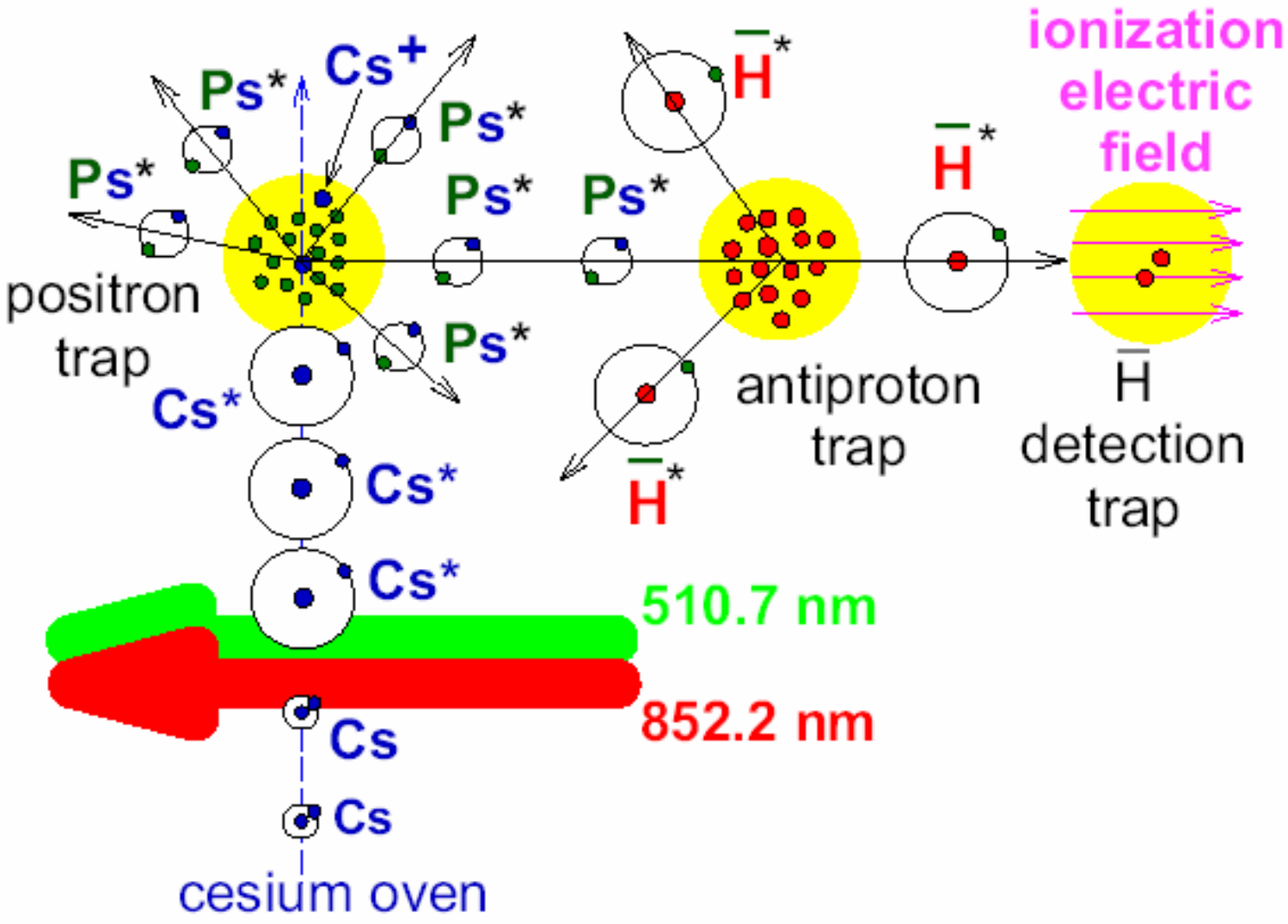
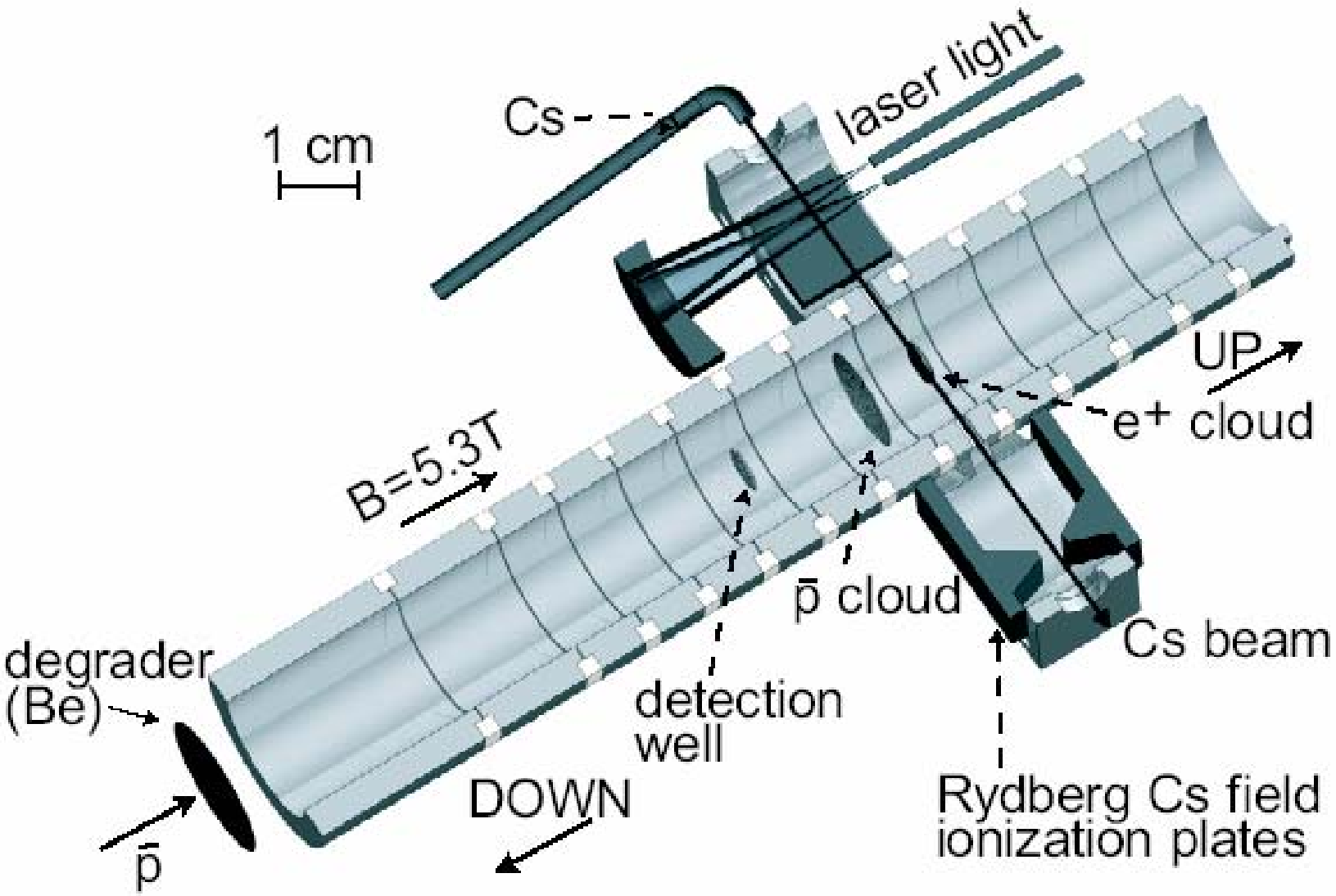
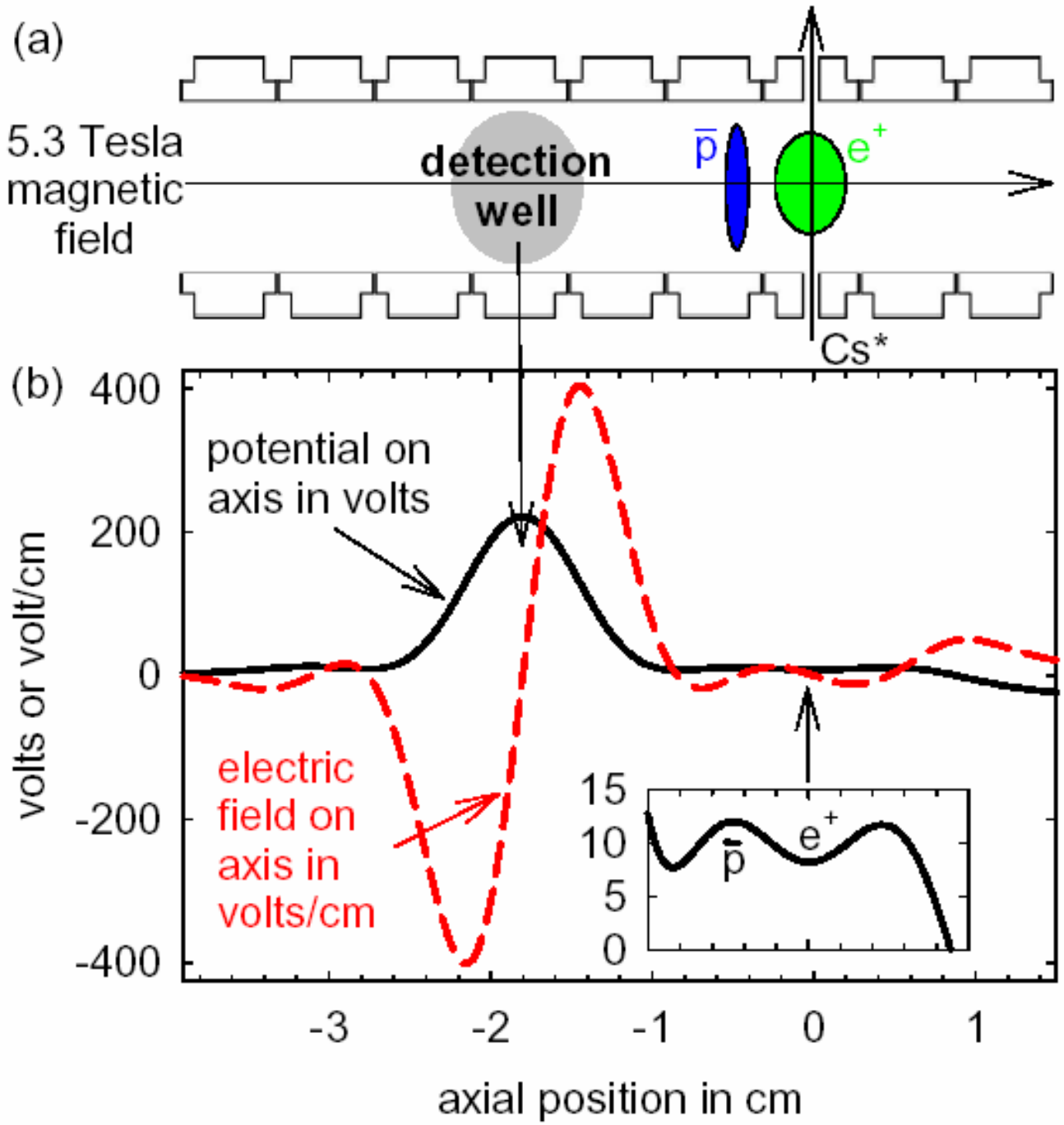
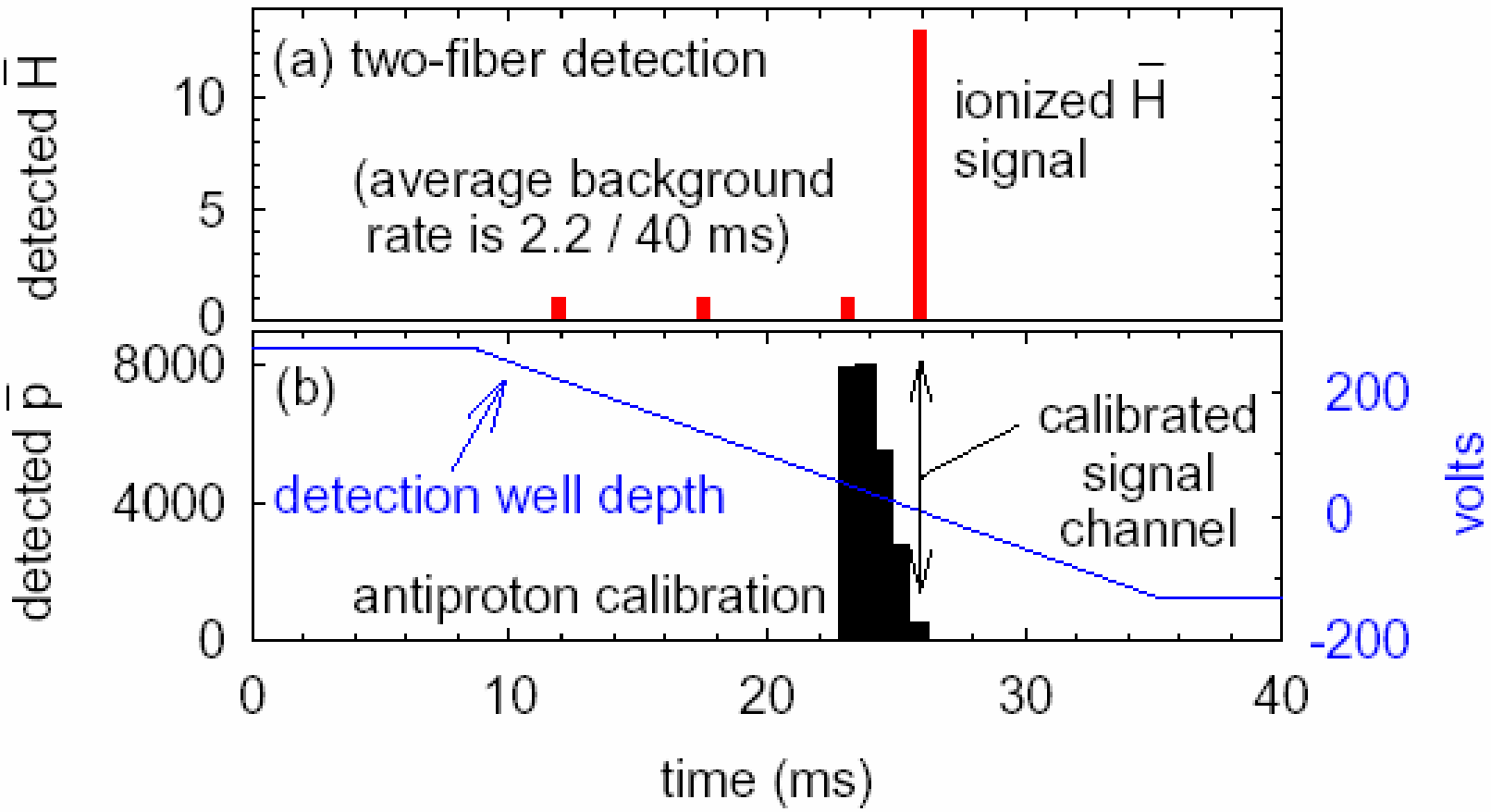
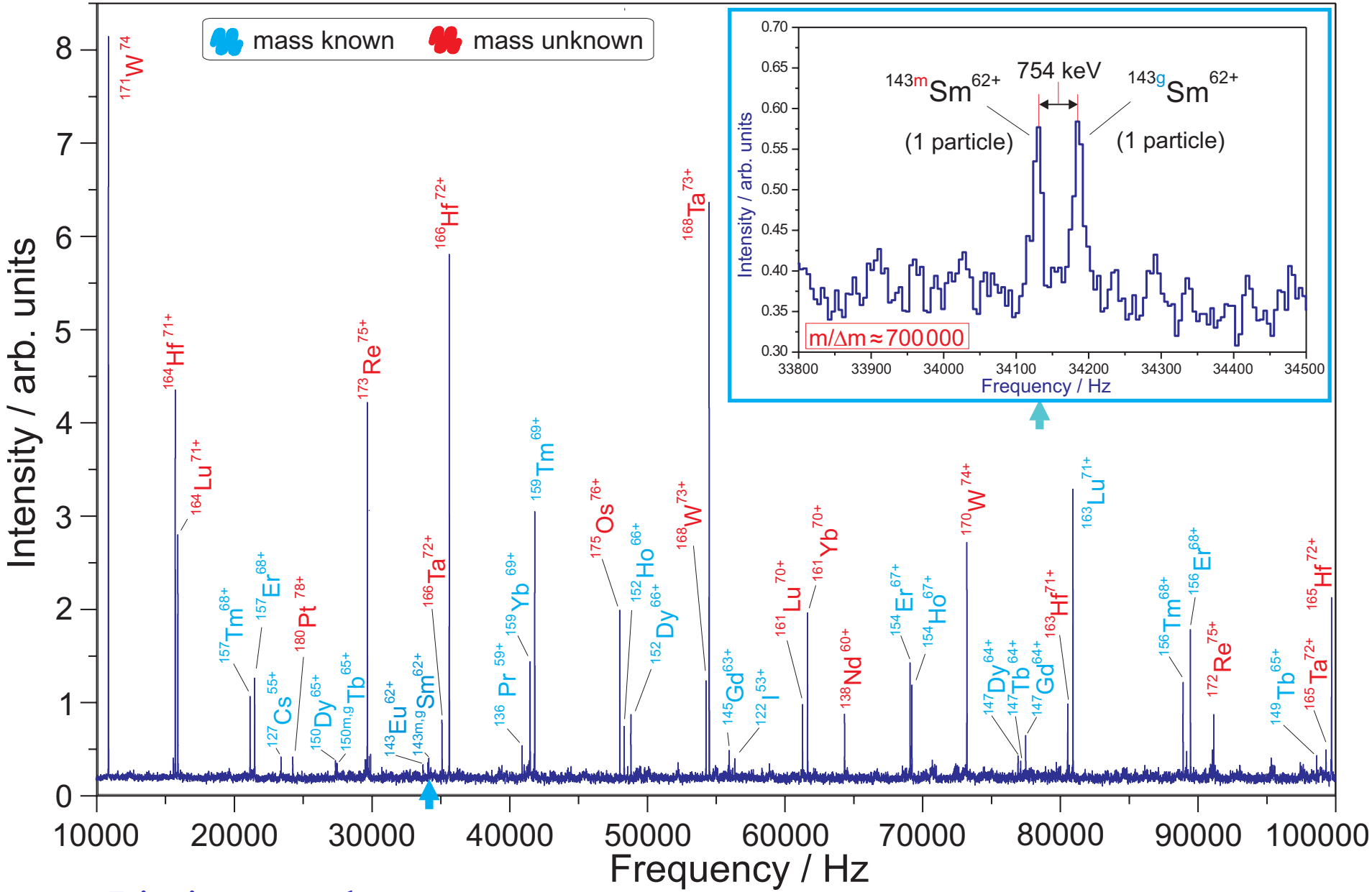


FIG. 1: Schematic of laser-controlled $\overline{\mathrm{H}}$ production.

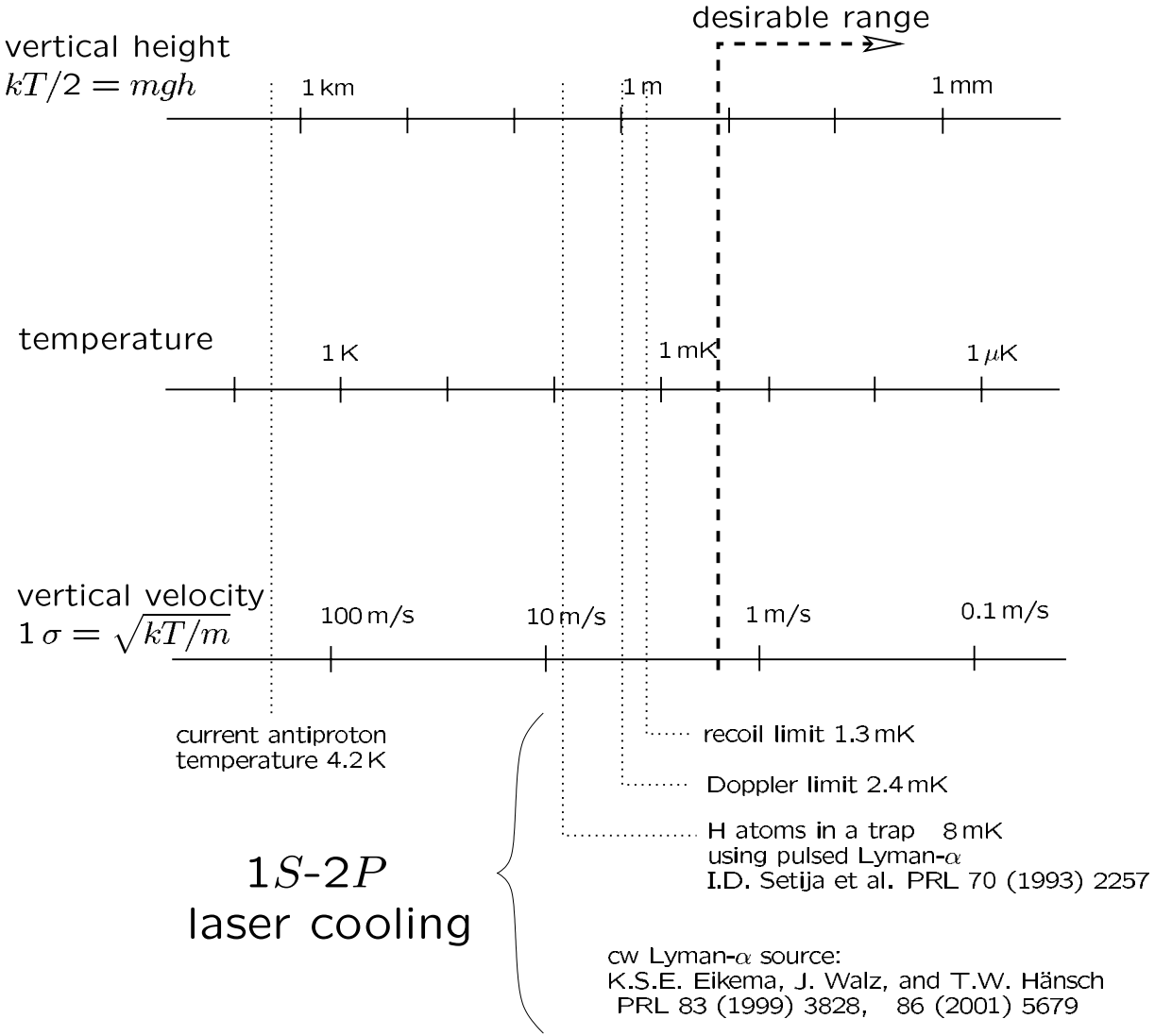

1 cm
Cs
laser light
UP
e+ cloud
B=5.3T
p̄ cloud
Cs beam
degrader
(Be)
detection
well
DOWN
Rydberg Cs field
ionization plates
p̄


(a)
5.3 Tesla
magnetic
field
detection
well
$\bar{p}$
e^+
Cs*
(b)
400
200
0
-200
-400
volts or volt/cm
potential on
axis in volts
electric
field on
axis in
volts/cm
15
10
5
0
$\bar{p}$
e^+
-3
-2
-1
0
1
axial position in cm


(a) two-fiber detection
(average background
rate is 2.2 / 40 ms)
ionized H̄
signal
detected H̄
10
5
0
(b)
detection well depth
antiproton calibration
calibrated
signal
channel
detected p̄
8000
4000
0
200
0
-200
volts
0
10
20
30
40
time (ms)



Litvinov et al.


desirable range
vertical height
$kT/2 = mgh$
1 km
1 m
1 mm
temperature
1 K
1 mK
1 μK
vertical velocity
$1\,\sigma = \sqrt{kT/m}$
100 m/s
10 m/s
1 m/s
0.1 m/s
current antiproton
temperature 4.2 K
recoil limit 1.3 mK
Doppler limit 2.4 mK
H atoms in a trap 8 mK
using pulsed Lyman-α
I.D. Setija et al. PRL 70 (1993) 2257
$1S$-$2P$
laser cooling
cw Lyman-α source:
K.S.E. Eikema, J. Walz, and T.W. Hänsch
PRL 83 (1999) 3828, 86 (2001) 5679


(c) 2001 Fabio Consani