Overview:

1. Introduction and overview
2. Antimatter at high energies (SppS, LEP, Fermilab)
3. Meson spectroscopy (antimatter as QCD probe)

4. Astroparticle physics and cosmology
5. CP and CPT violation tests
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7. Precision tests with Antihydrogen: gravity
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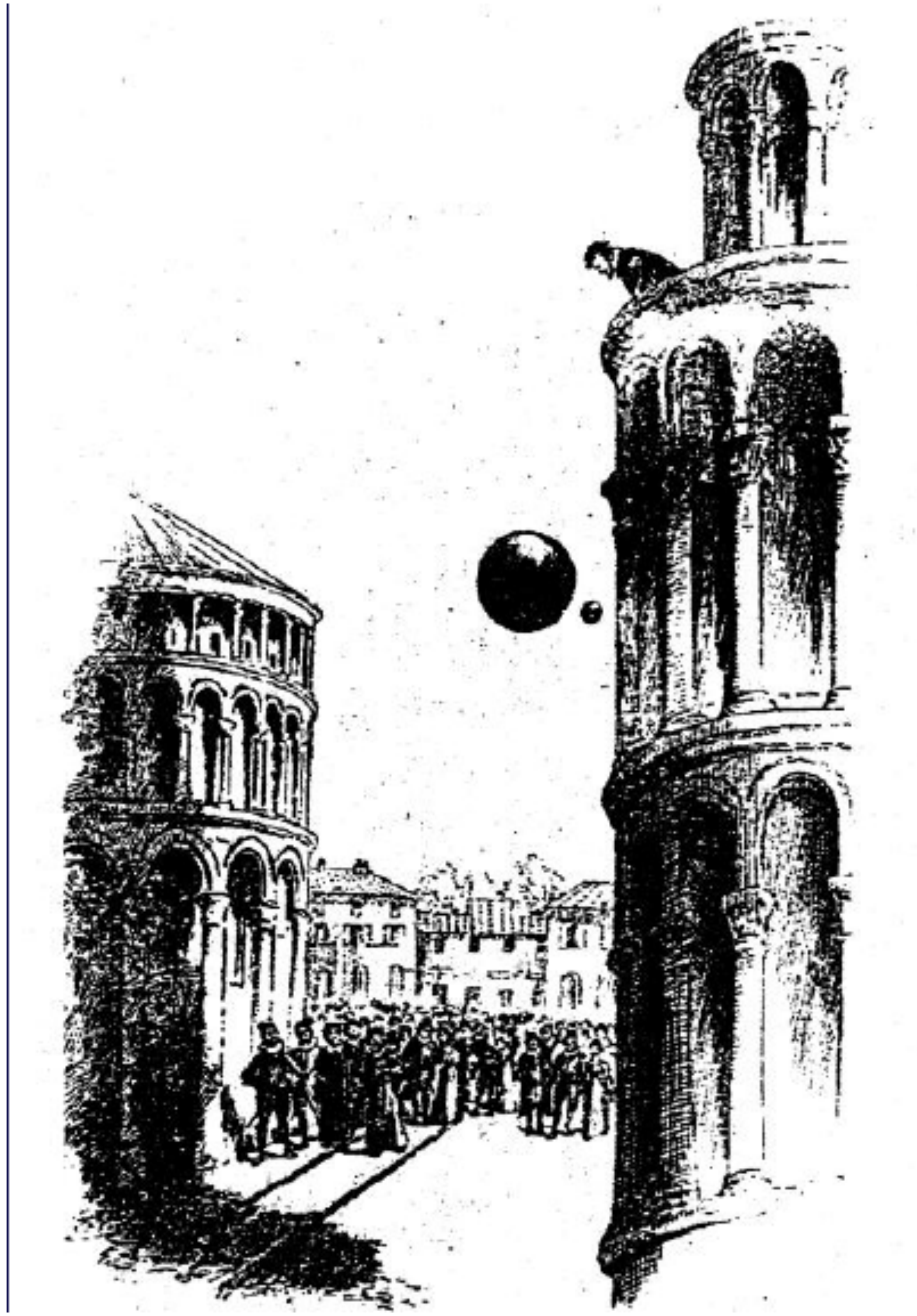
1589



2012


BROOKLYN SUPERHERO SUPPLY CO.
ITEM NO. 004450
MADE IN U.S.A.
GRAVITY
ONE GALLON
WARNING: CONTAINS GRAVITONS.
TO BE USED ONLY IN GRAVITY MANIPULATION EXPERIMENTS.
BROOKLYN SUPERHERO SUPPLY CO.
ANTIMATTER
IN A RECYCLABLE STEEL CAN
CHINASHOP
www.CHINASHOPMAG.com

Motivation

- General relativity is a classical (non quantum) theory;
- EEP violations may appear in some quantum theory
- New quantum scalar and vector fields are allowed in some models (Kaluza Klein ….)

Einstein field: tensor graviton (Spin 2, "Newtonian")

\+ Gravi-vector (spin 1)

\+ Gravi-scalar (spin 0)

- These fields may mediate interactions violating the equivalence principle

Discussion and experimental constraints — *M, Nieto and T. Goldman, Phys. Rep. 205 (1991) 221*

Motivation for antigravity in General Relativity — *G. Chardin, Hyperfine Interactions 109 (1997) 83*

Scalar: "charge" of particle equal to "charge of antiparticle" : attractive force

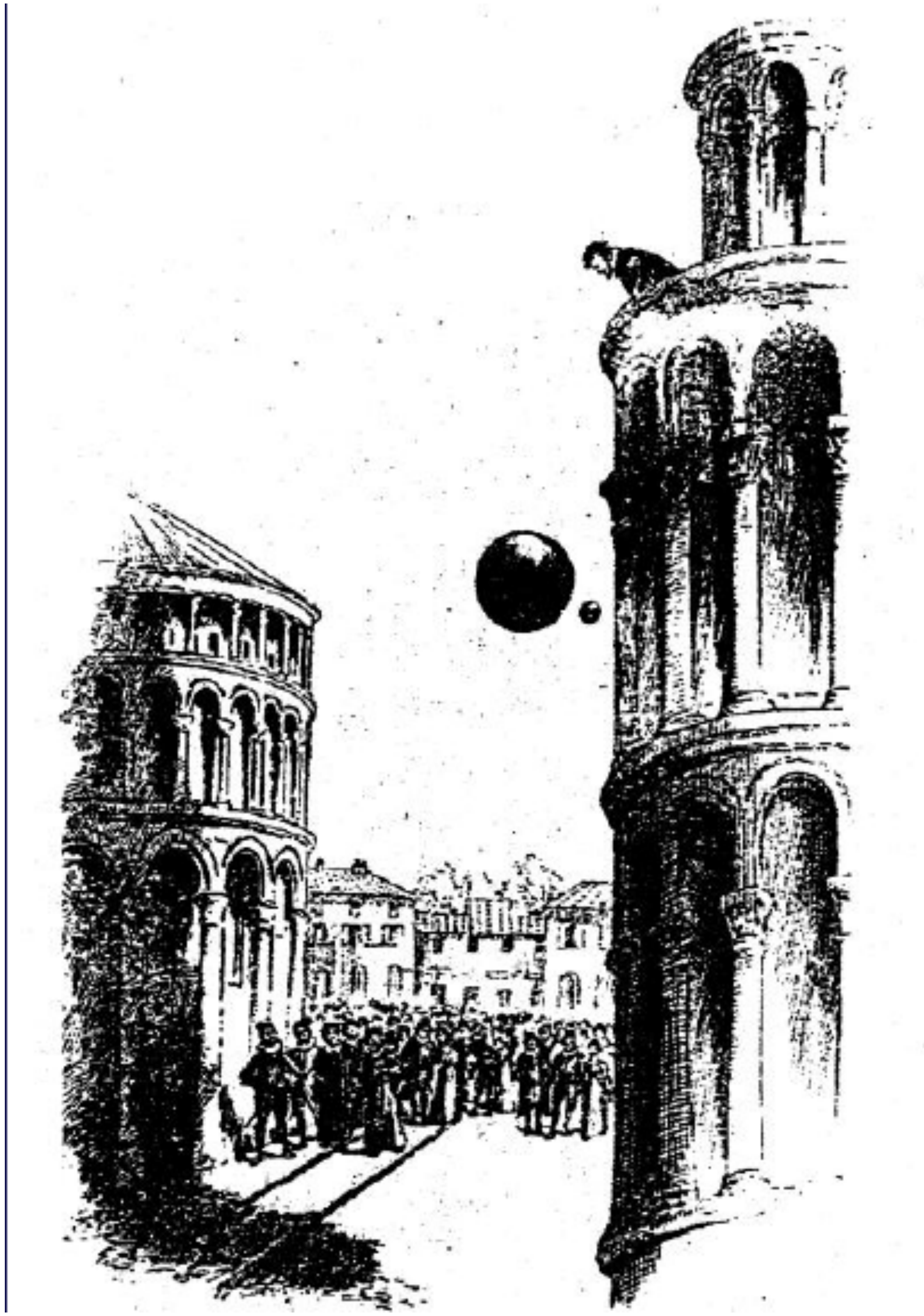
Vector: "charge" of particle opposite to "charge of antiparticle": repulsive/attractive force

$$V = -\frac{G_\infty}{r} m_1 m_2 \left(1 \mp a\, e^{-r/v} + b\, e^{-r/s} \right)$$

Phys. Rev. D 33 (2475) (1986)

Cancellation effects in matter experiment if $a \approx b$ and $v \approx s$

AE$\bar{g}$IS: Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy



Tests of gravity require very cold trapped $\bar{H}$ or a pulsed cold beam of $\bar{H}$

G ~ 100nV/m on $\bar{p}$

Experimental goal: g measurement with 1% accuracy on antihydrogen

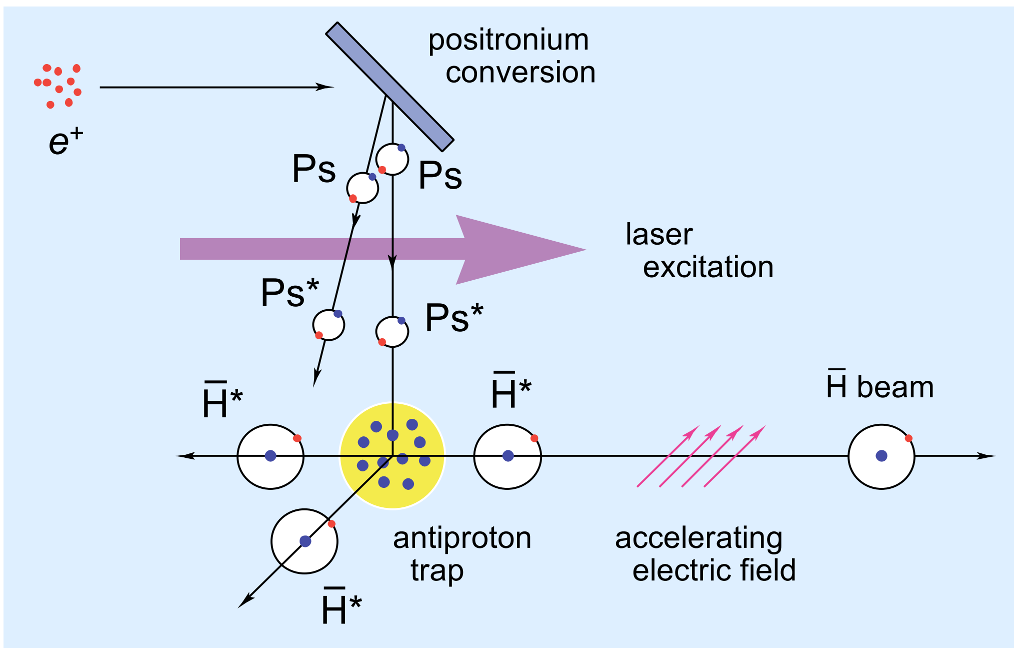
(first direct measurement on antimatter)

a) production of a pulsed cold beam of antihydrogen (T~0.1K)

b) measurement of the beam deflection with a Moiré deflectometer

Schematic: i) antihydrogen formation

- Charge exchange reaction:



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

Works well at temperatures from 0–10 K

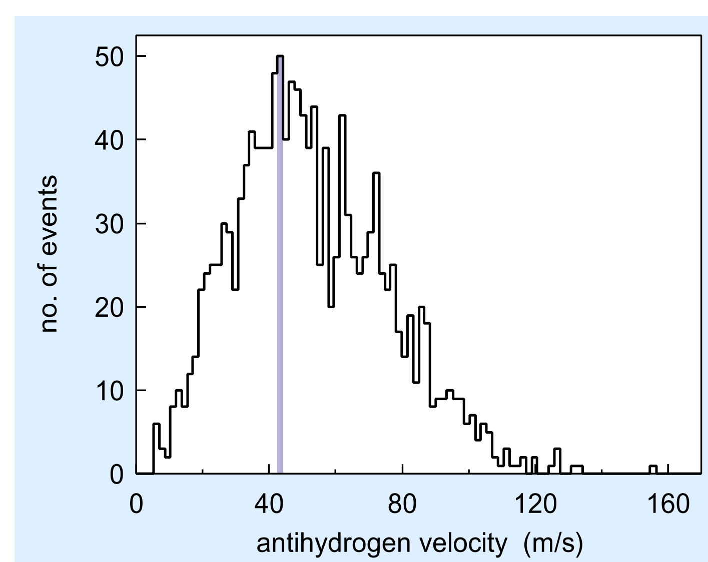
- Principle demonstrated by ATRAP (Cs* → Ps* → $\bar{H}$*)
  [C. H. Storry *et al.*, Phys. Rev. Lett. **93** (2004) 263401]

- Advantages:

– Large cross-section $\sigma = a_0 n^4$

– Narrow and well-defined $\bar{H}$ *n*-state distribution

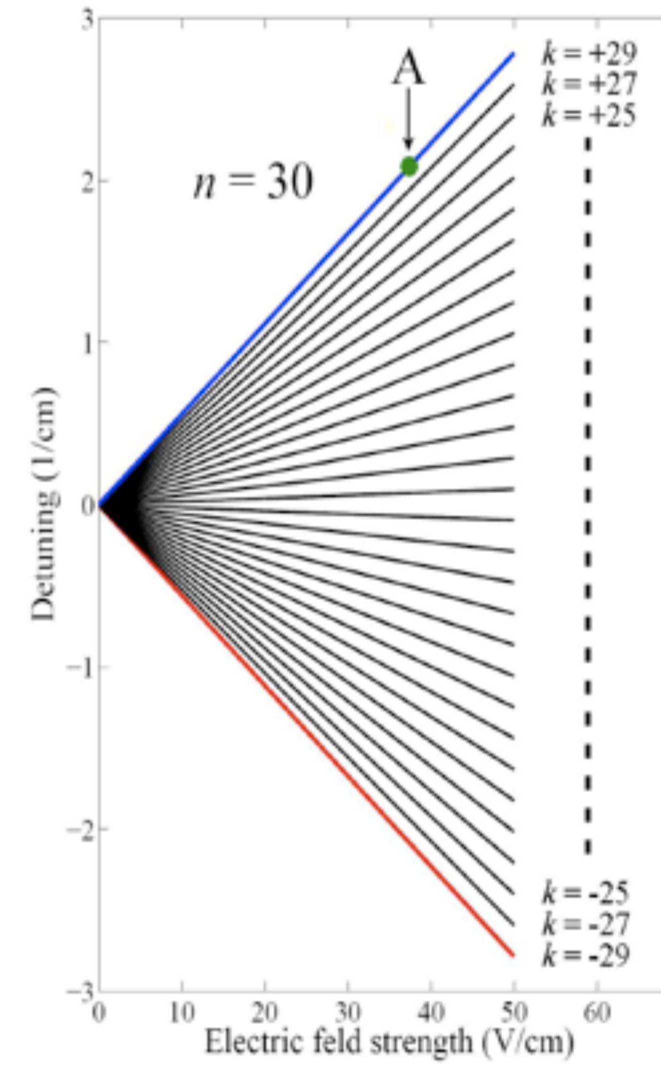
– $\bar{H}$ production from $\bar{p}$ at rest → ultracold $\bar{H}$



At T(p) = 100mK, n(Ps) = 35
⇒ v(H) ≈ 45 m/s
T(H) ≈ 120mK

Schematic: ii) beam formation

- Neutral atoms are not sensitive to static electric and magnetic fields
- Electric field gradients exert force on electric dipoles:

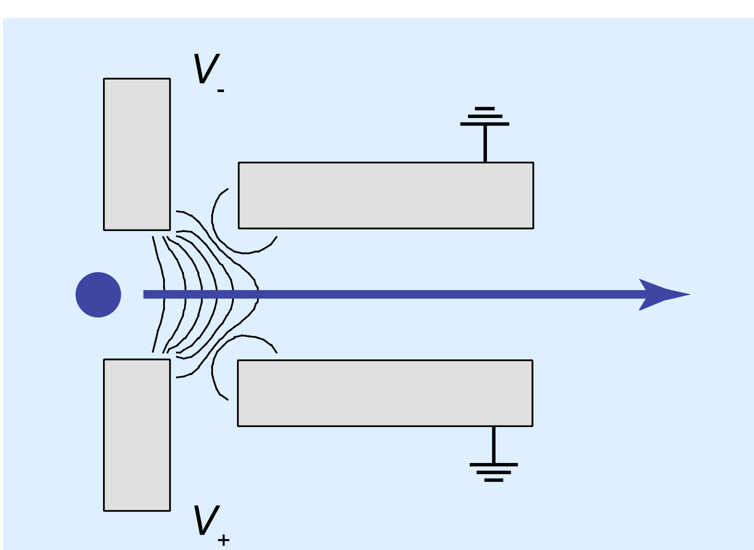


$$E = -\frac{1}{2n^2} + \frac{3}{2}nkF$$

$$Force = -\frac{3}{2}nk\vec{\nabla}F$$

⇒Rydberg atoms are very sensitive to inhomogeneous electric fields

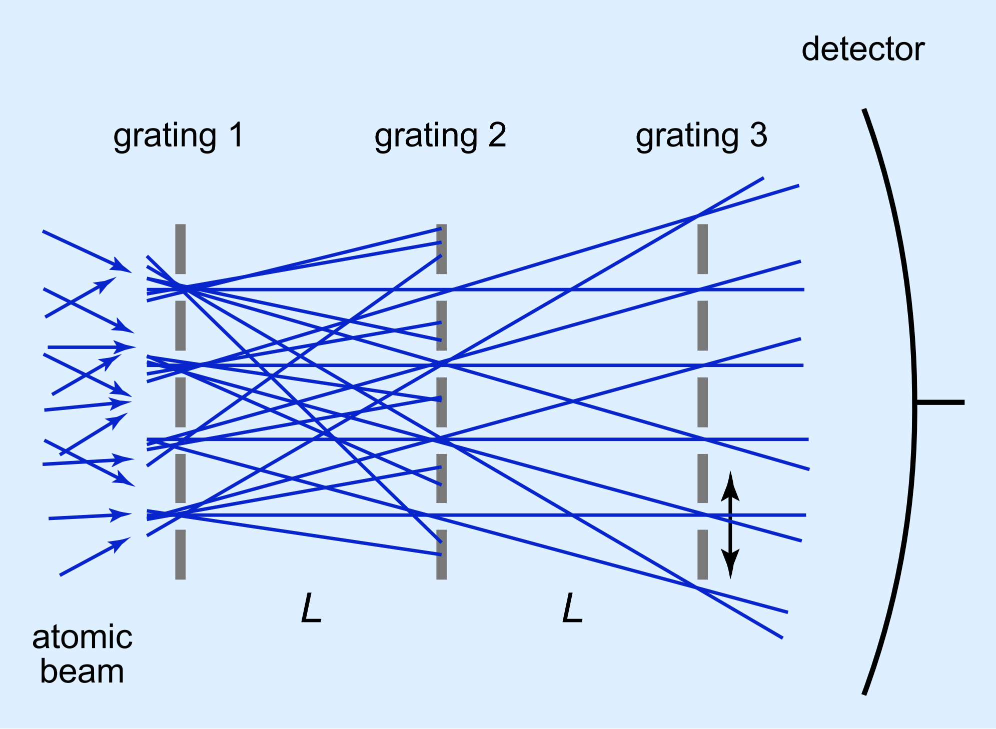
- Stark deceleration of hydrogen demonstrated
  [E. Vliegen & F. Merkt, J. Phys. B **39** (2006) L241 - ETH Physical Chemistry]



- n = 22,23,24
- Accelerations of up to 2×10^8 m/s^2 achieved
- Hydrogen beam at 700 m/s can be stopped in 5 μs over only 1.8 mm

Schematic: iii) trajectory measurement

- Classical counterpart of the Mach-Zehnder interferometer
- Decoherence effects reduced
- "Self-focusing" effect – beam collimation uncritical



Fringe phase <u>and</u> phase shift identical to Mach-Zehnder interferometer!

- Replace the third grating and detector by position-sensitive detector

  ⇒ Transmission increases by ~ factor 3

- Has been successfully used for a gravity measurement with ordinary matter, $\sigma(g)/g = 2\times10^{-4}$

  [M. K. Oberthaler *et al.*, Phys. Rev. A **54** (1996) 3165]

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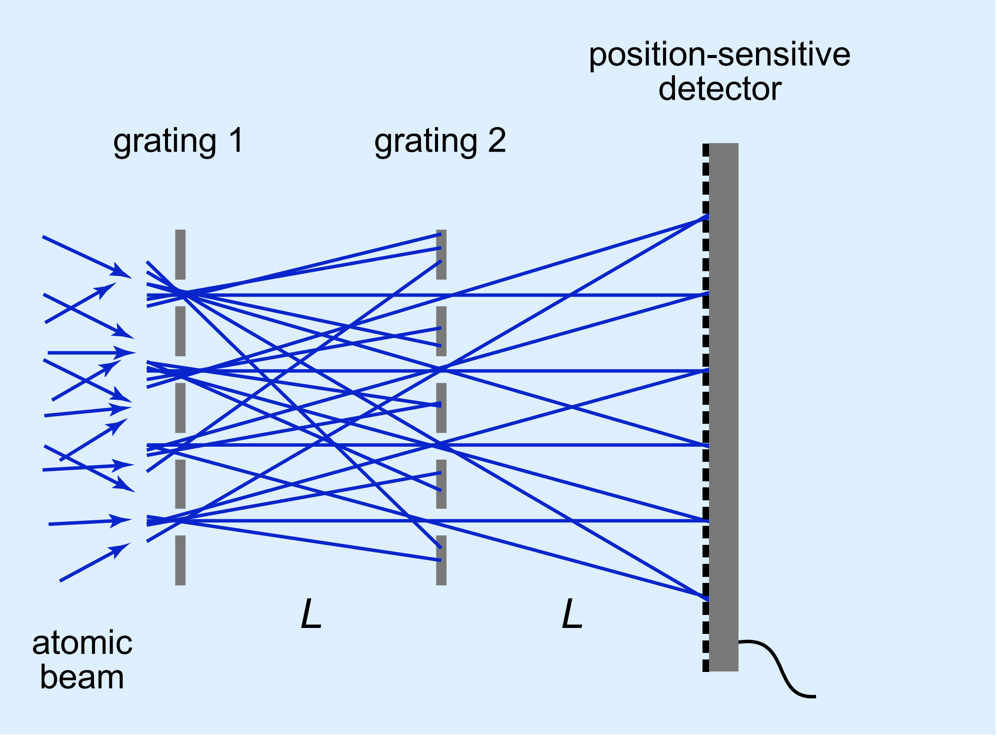

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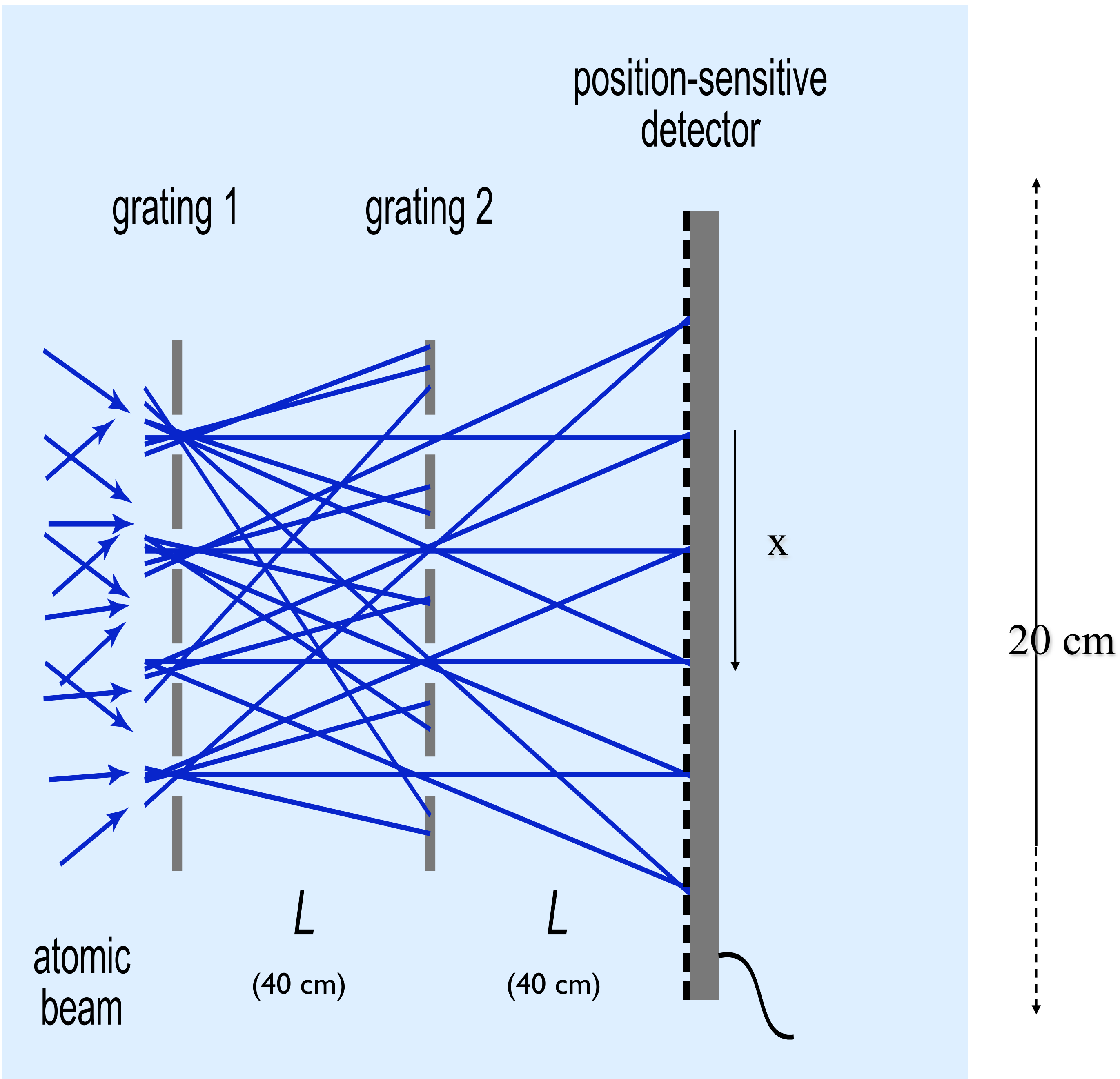
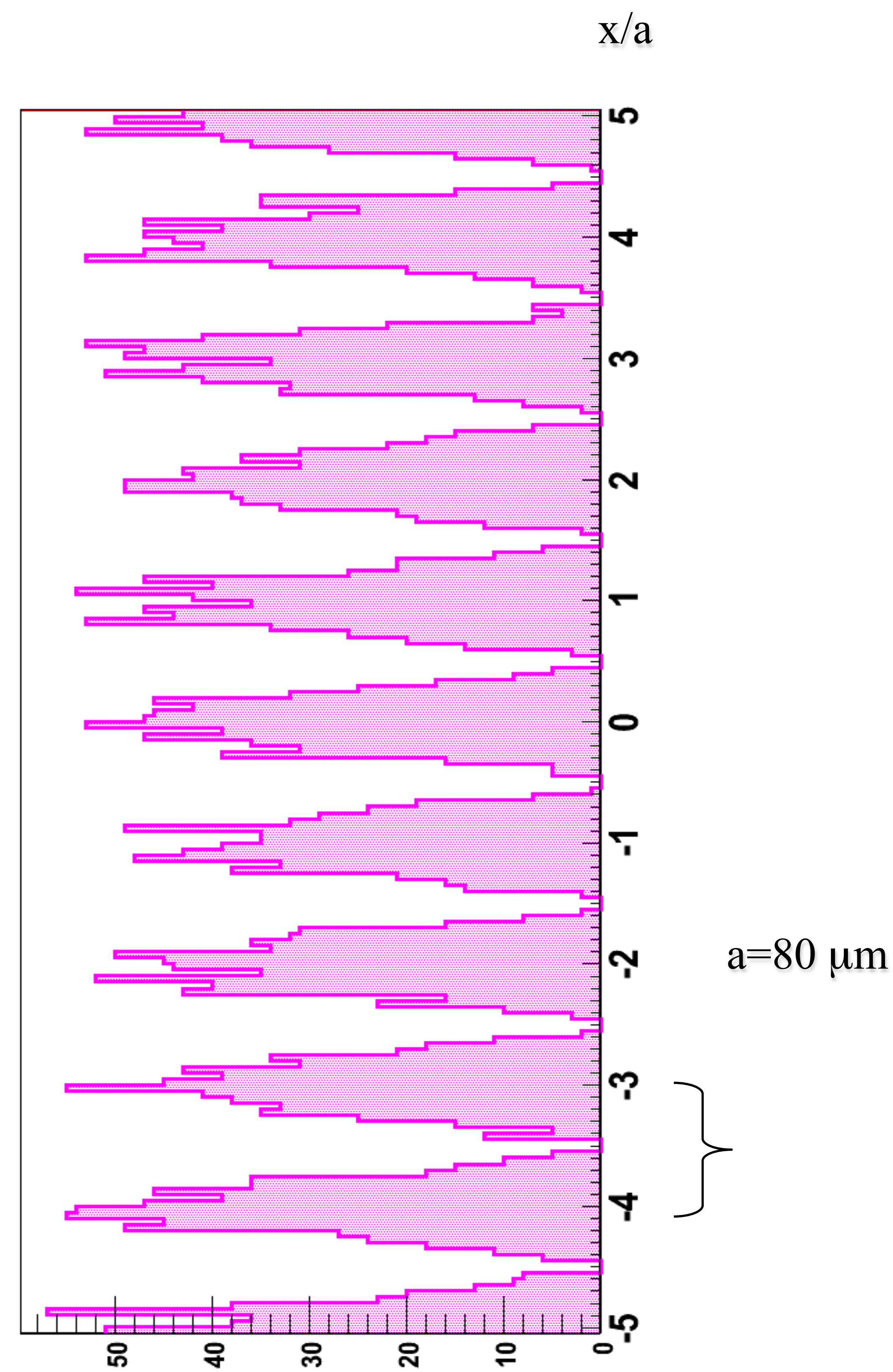
Moiré deflectometer: principle of operation

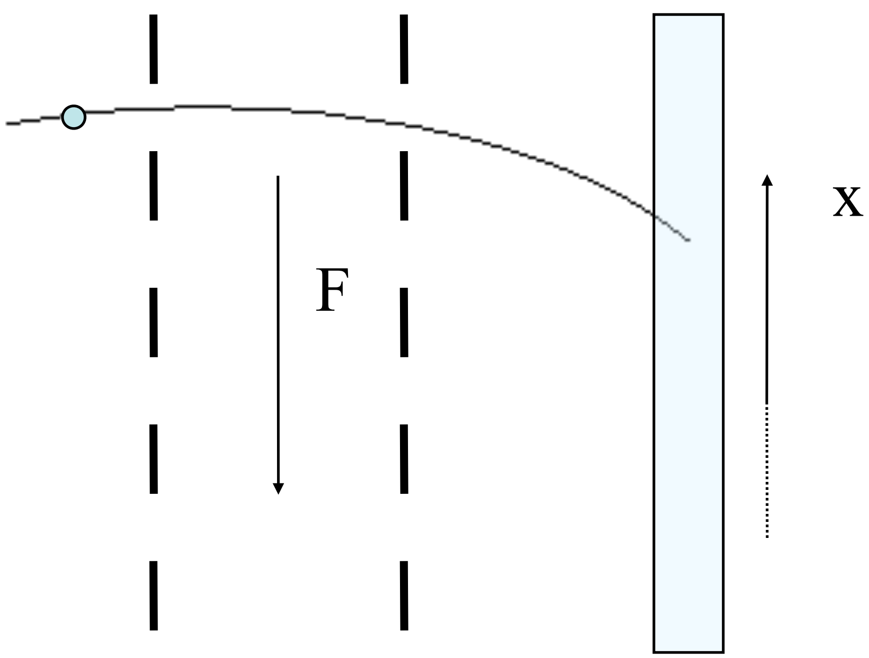
1) No gravity, very high statistics

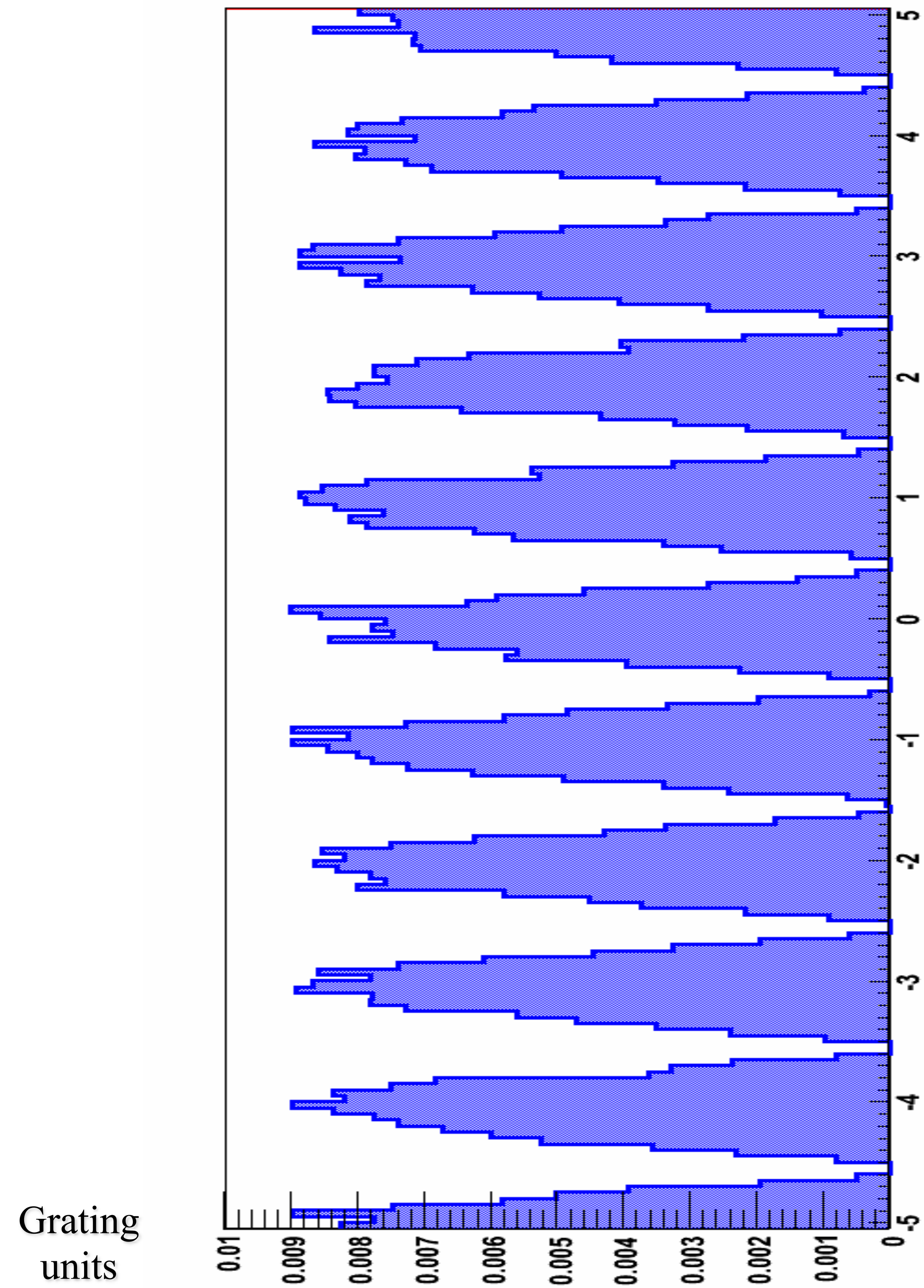




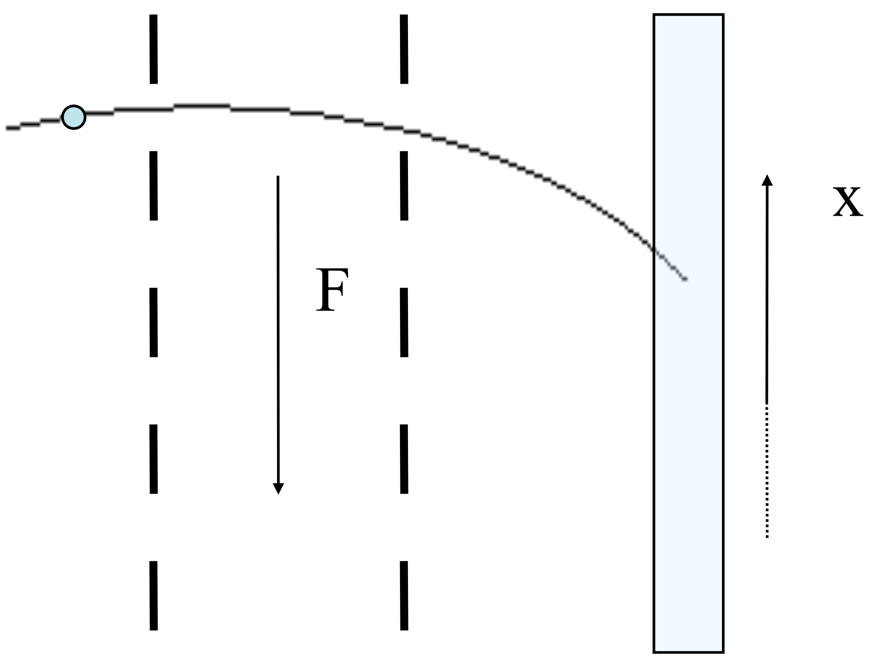
$V_h = 600$ m/s

With gravity

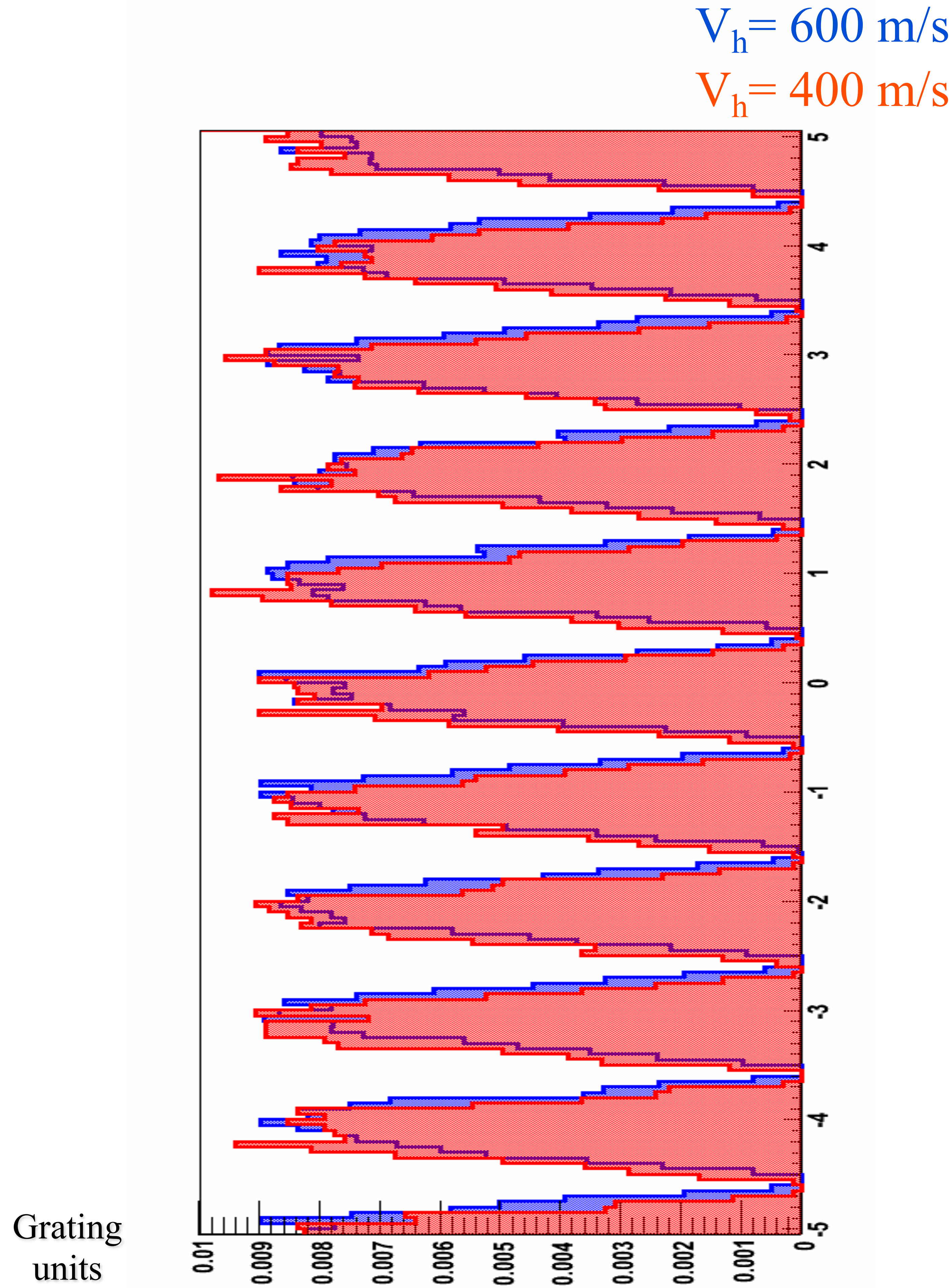




With gravity



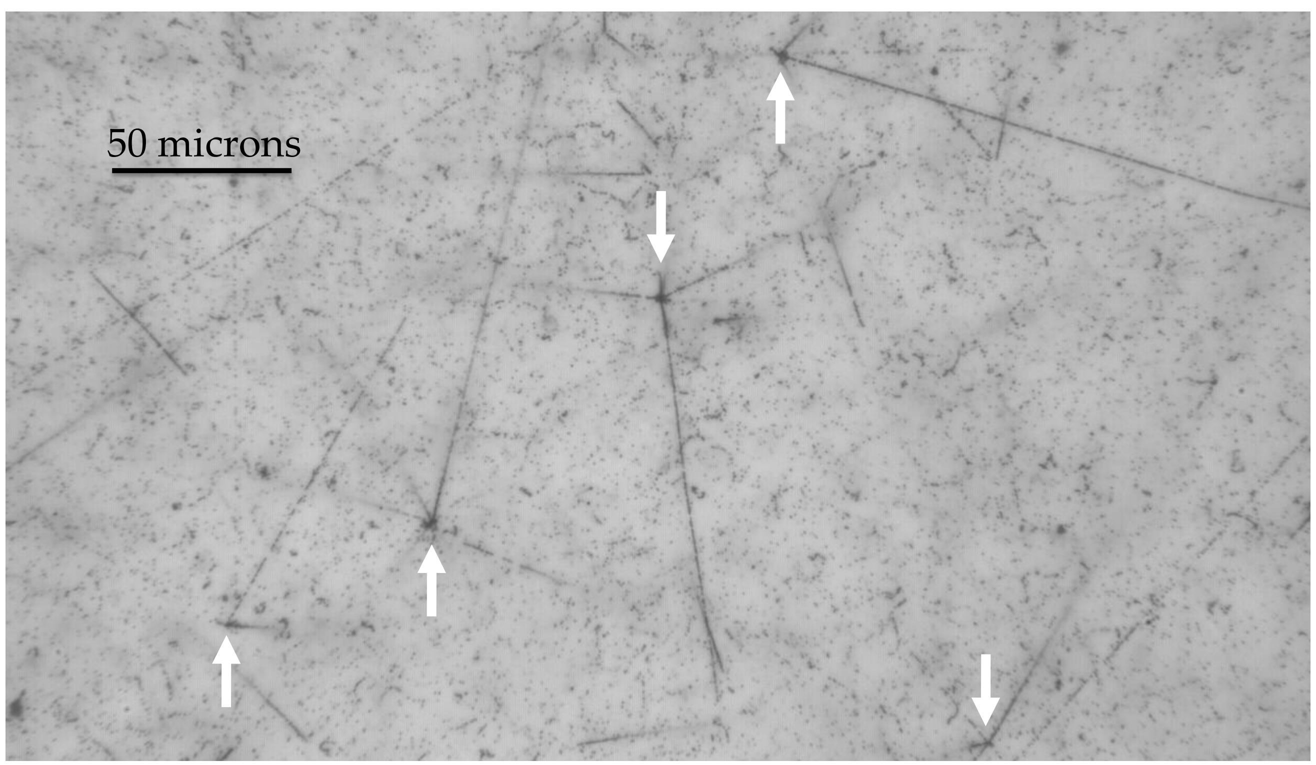
slight shift (~10 μm)



measure impact point to (≤10 μm)

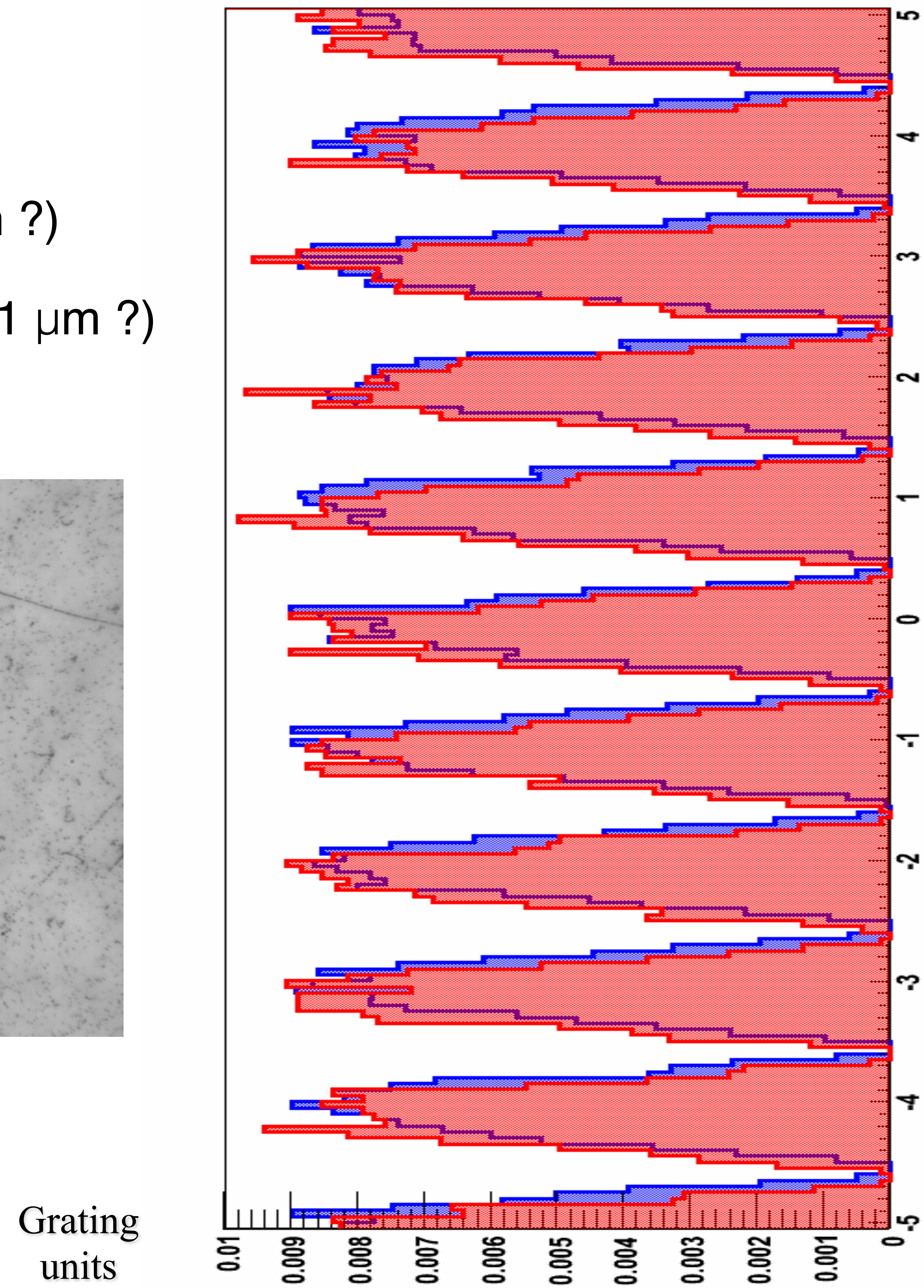
solution 1: Si strip detectors (~10 μm ?)

solution 2: photographic emulsion (≤1 μm ?)



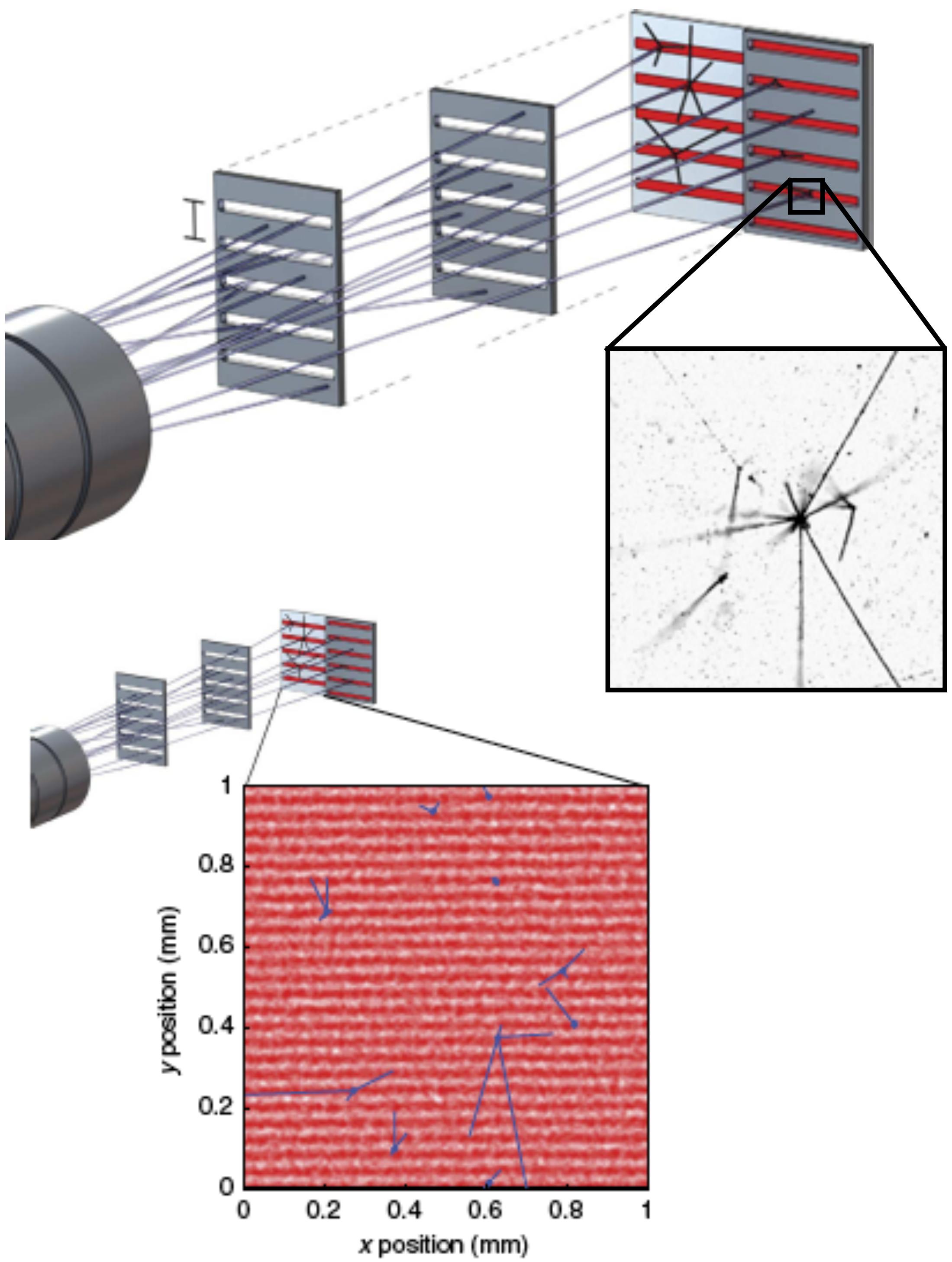
V_h= 600 m/s

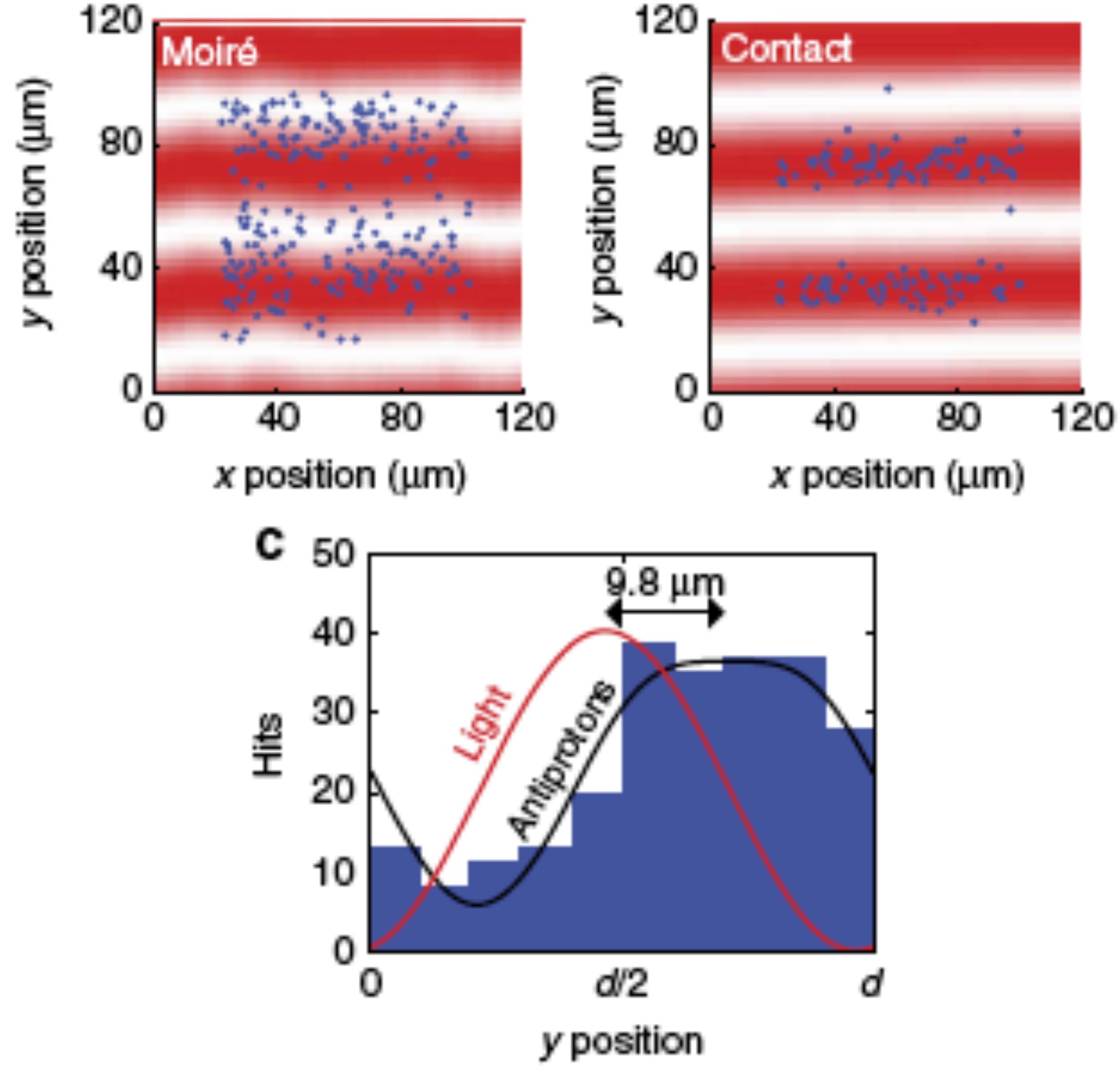
V_h= 400 m/s

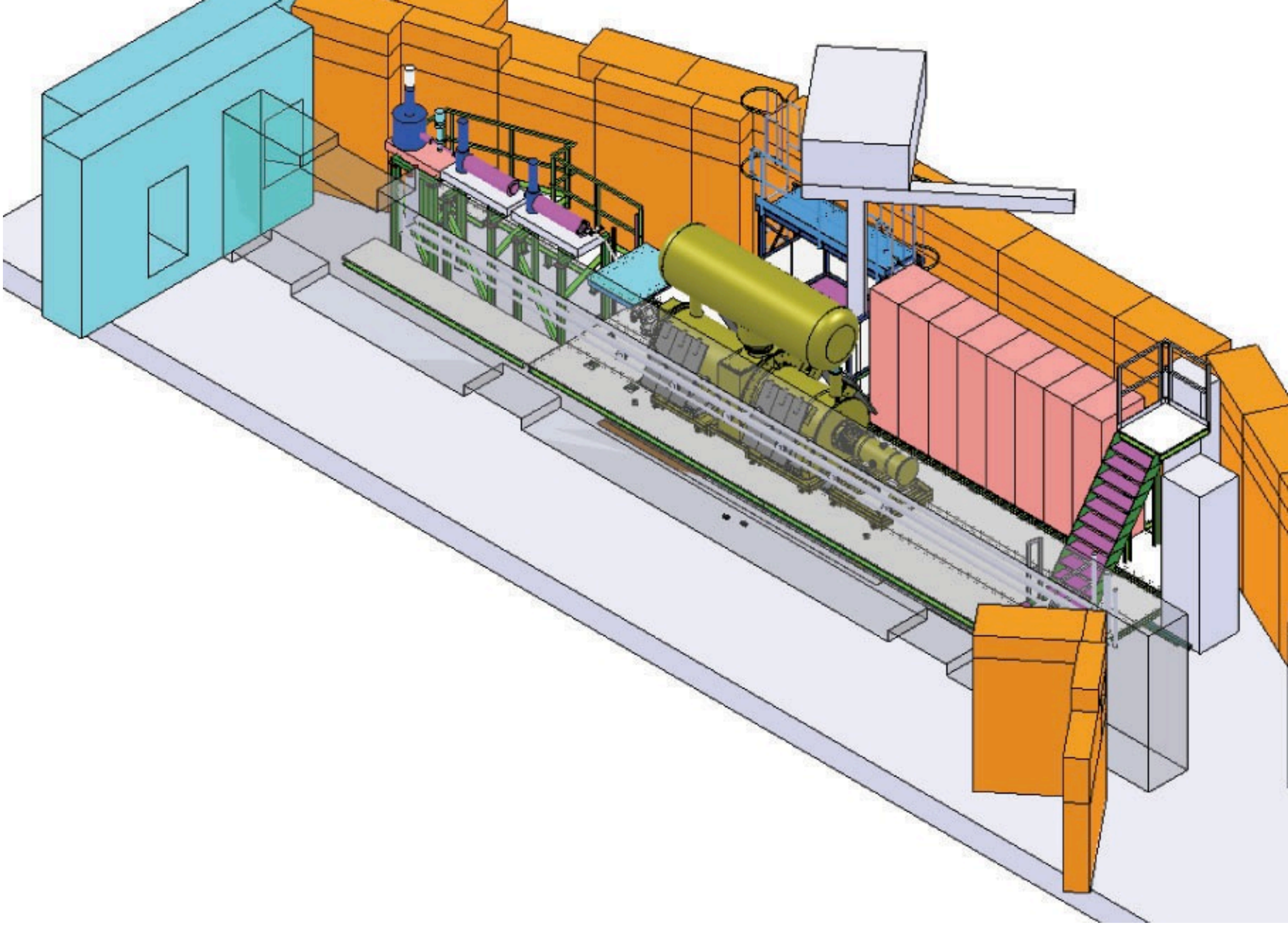


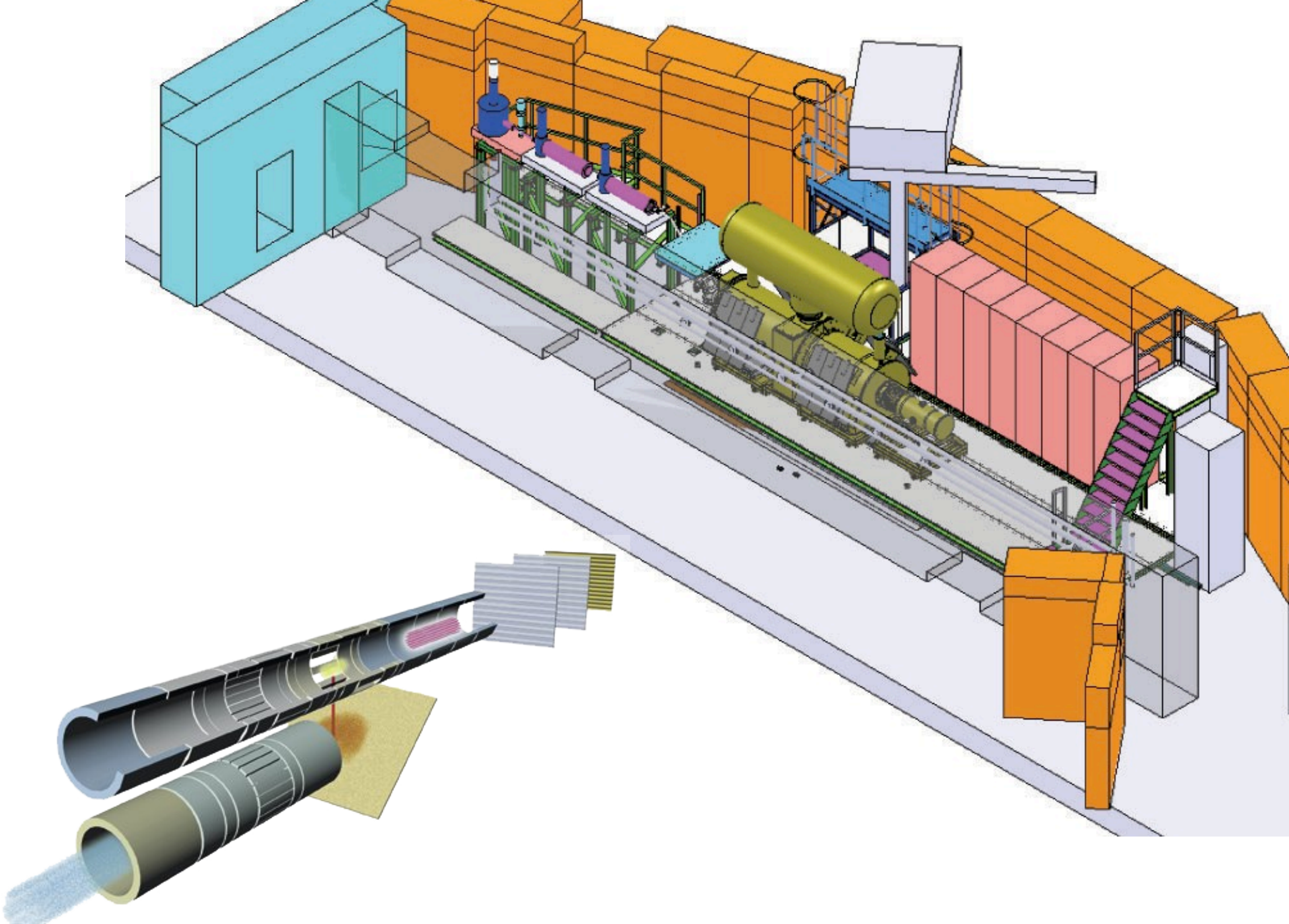
Will this work? Yes!

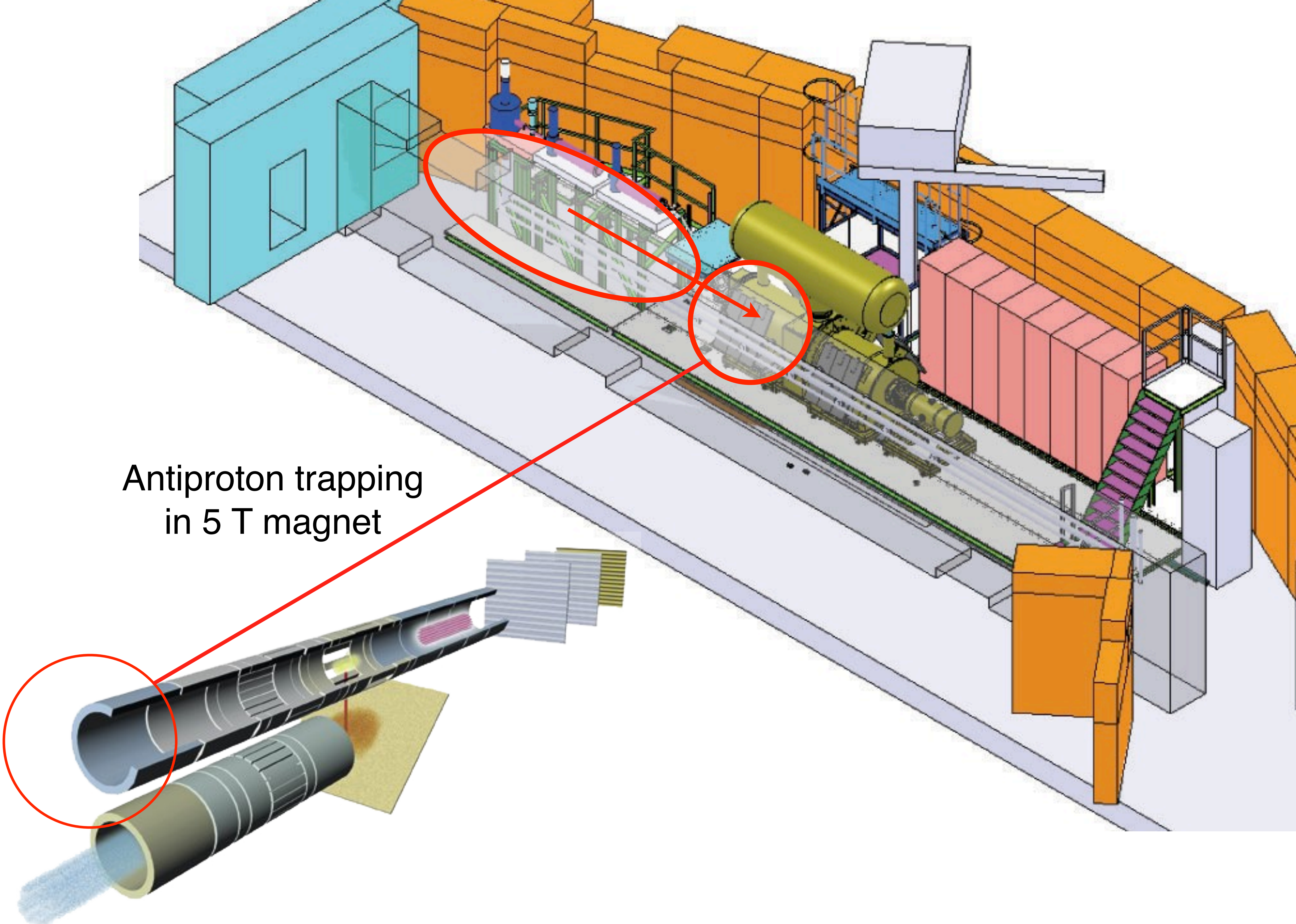
Nature Communications 5 (2014) 4538

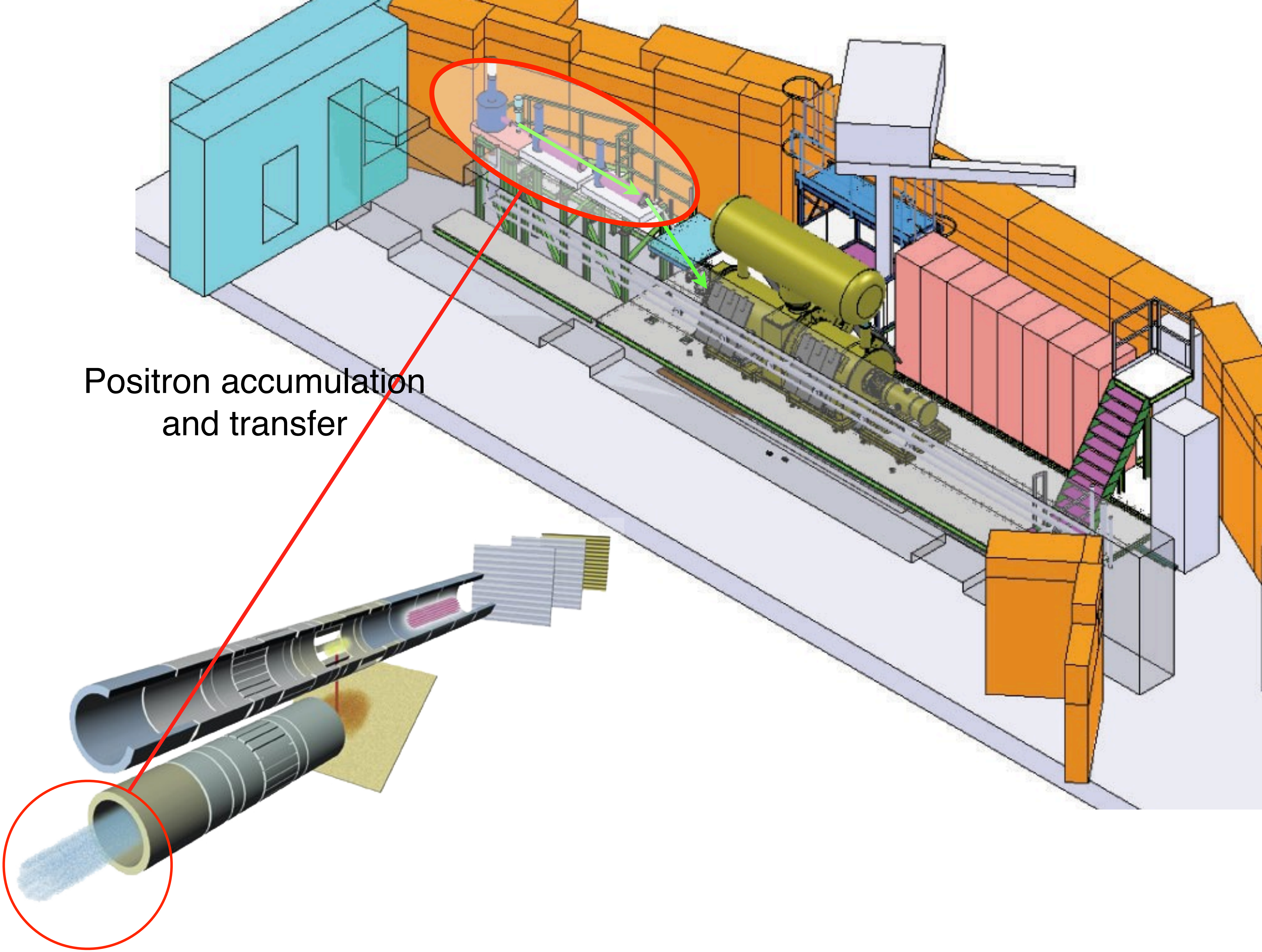


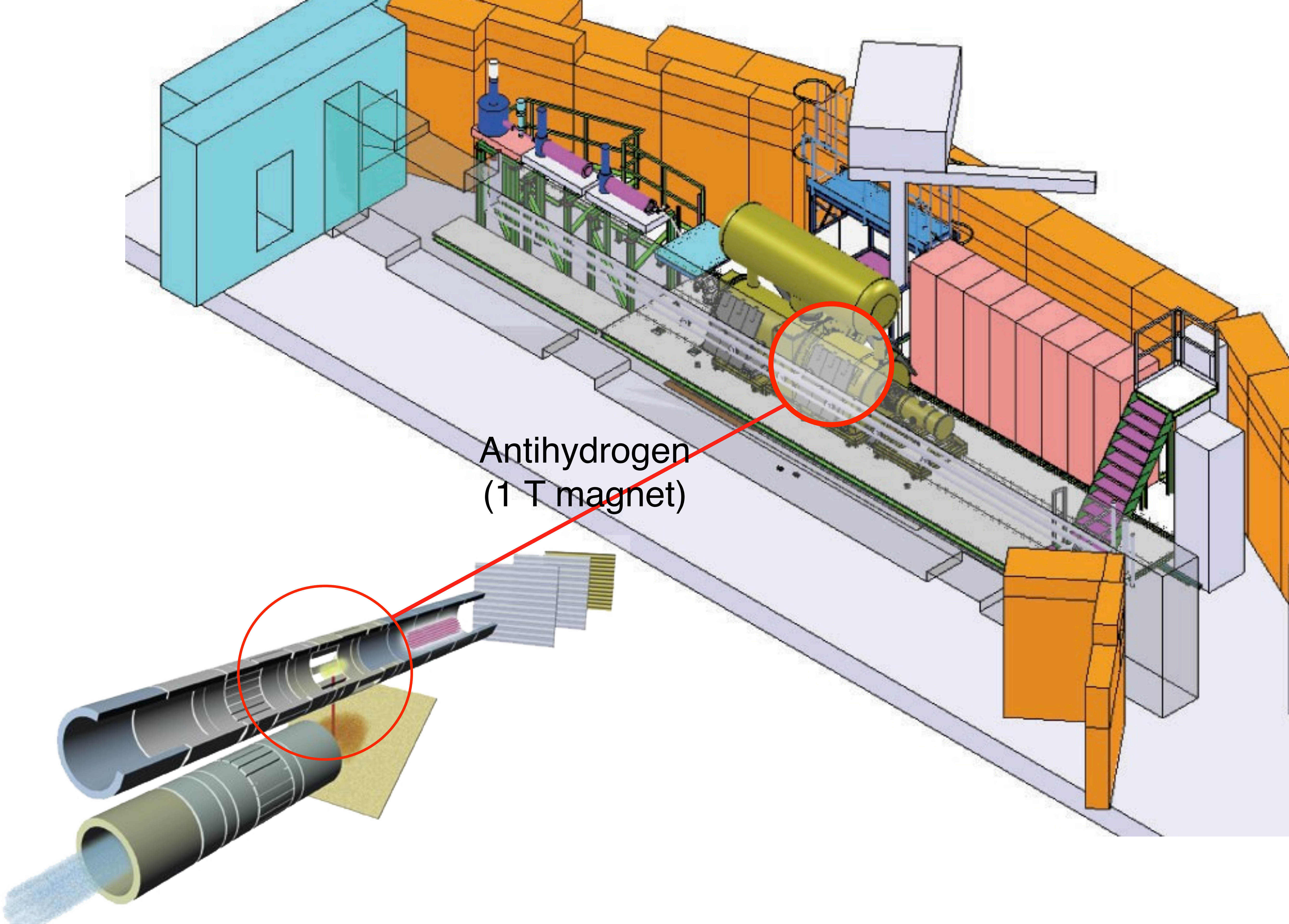


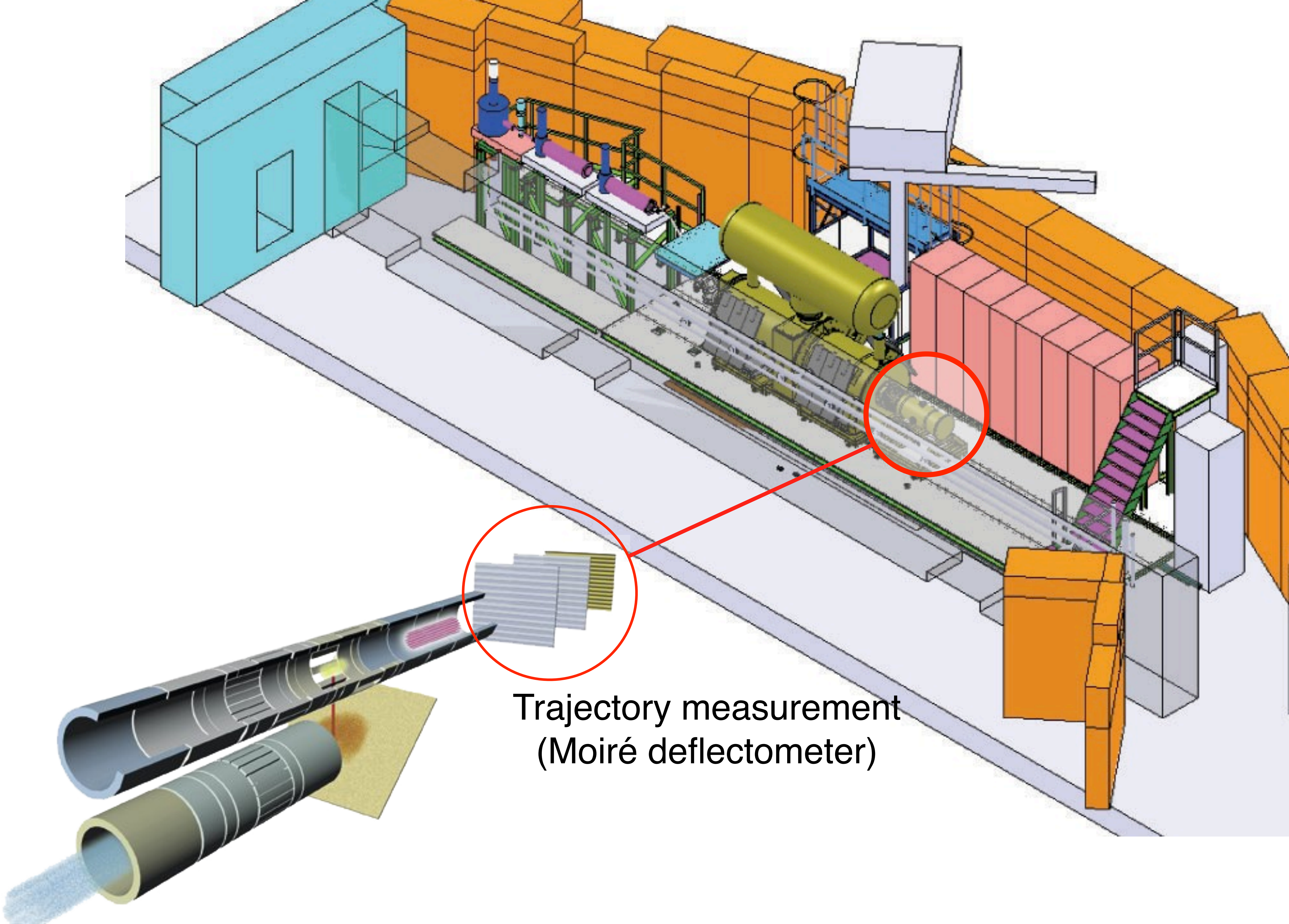




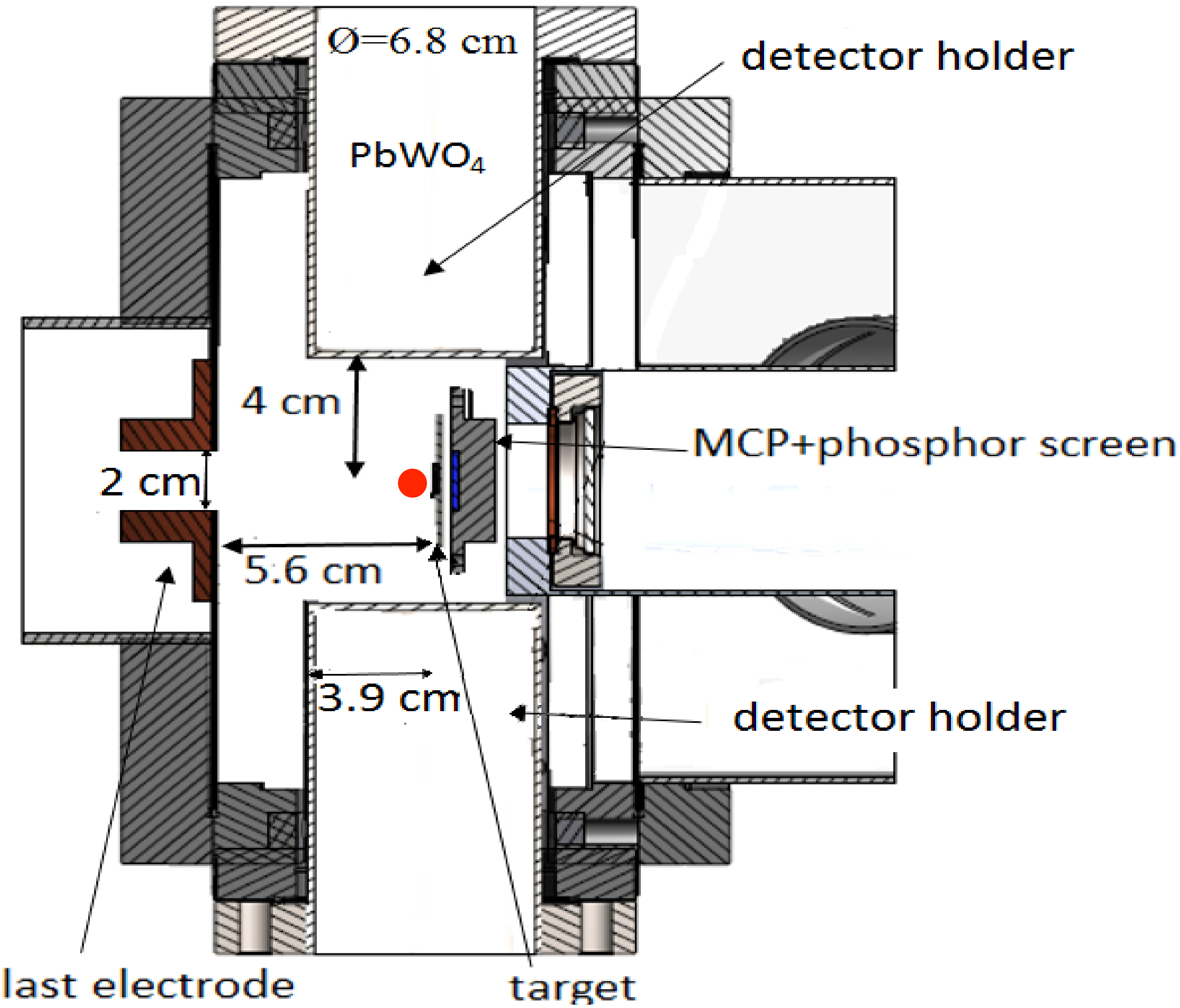

Antiproton trapping
in 5 T magnet


Positron accumulation
and transfer

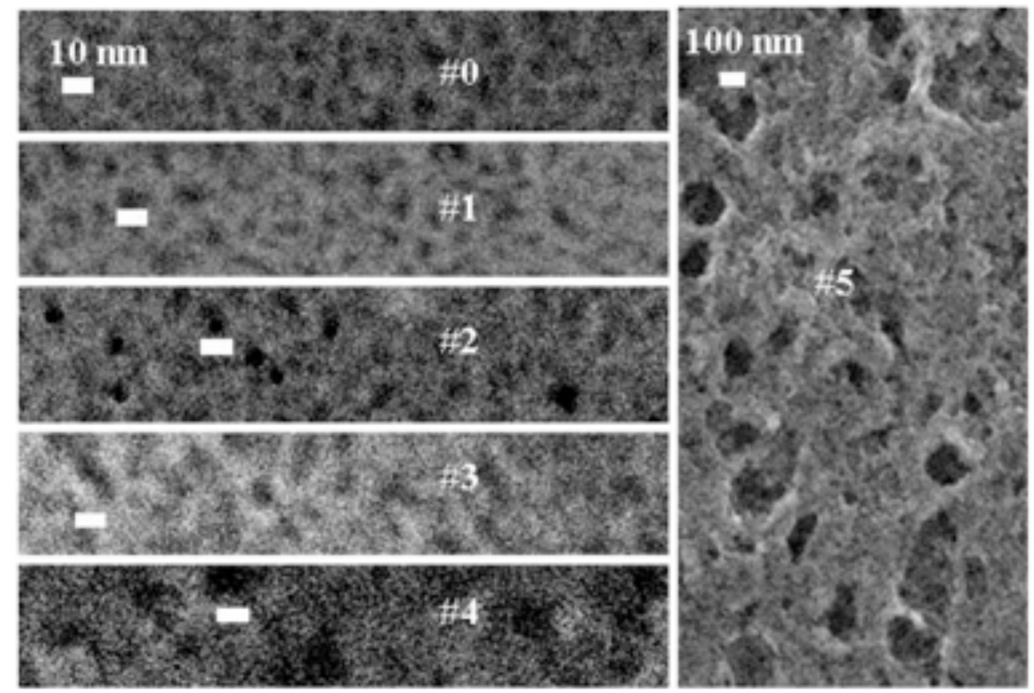

Antihydrogen
(1 T magnet)

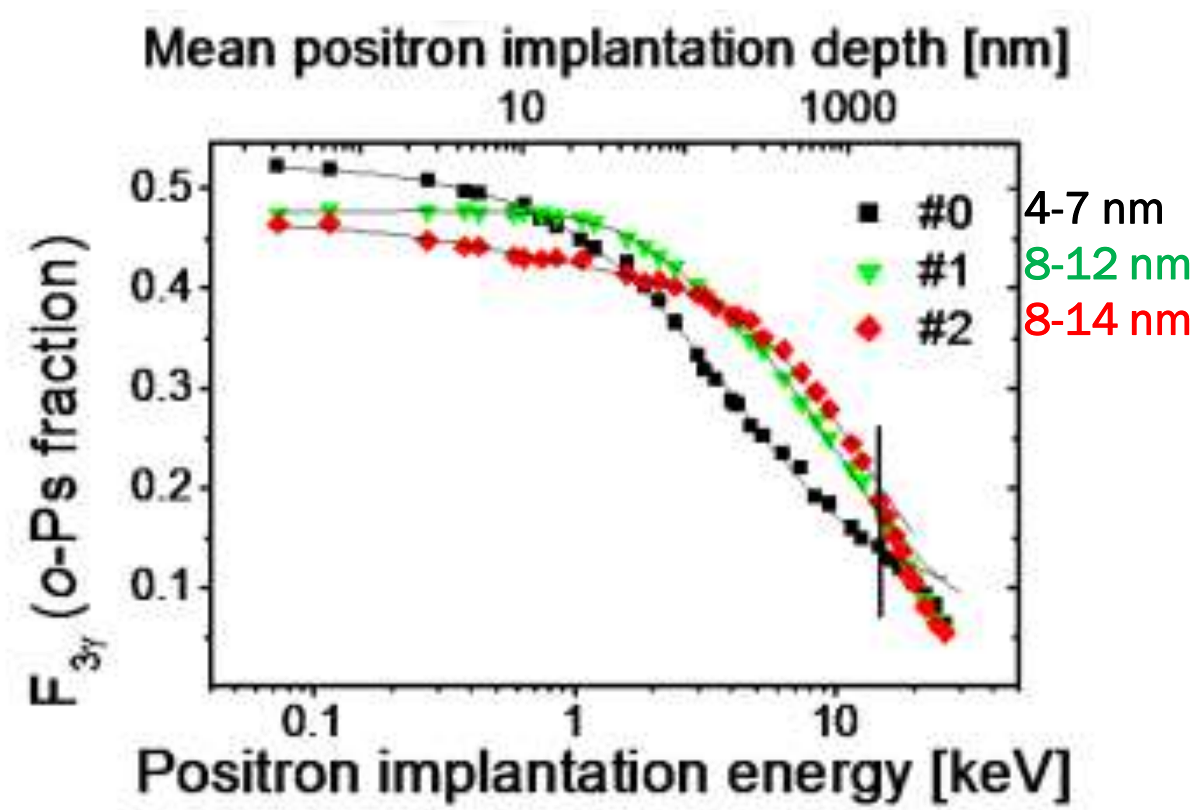

Trajectory measurement
(Moiré deflectometer)

Positronium formation:



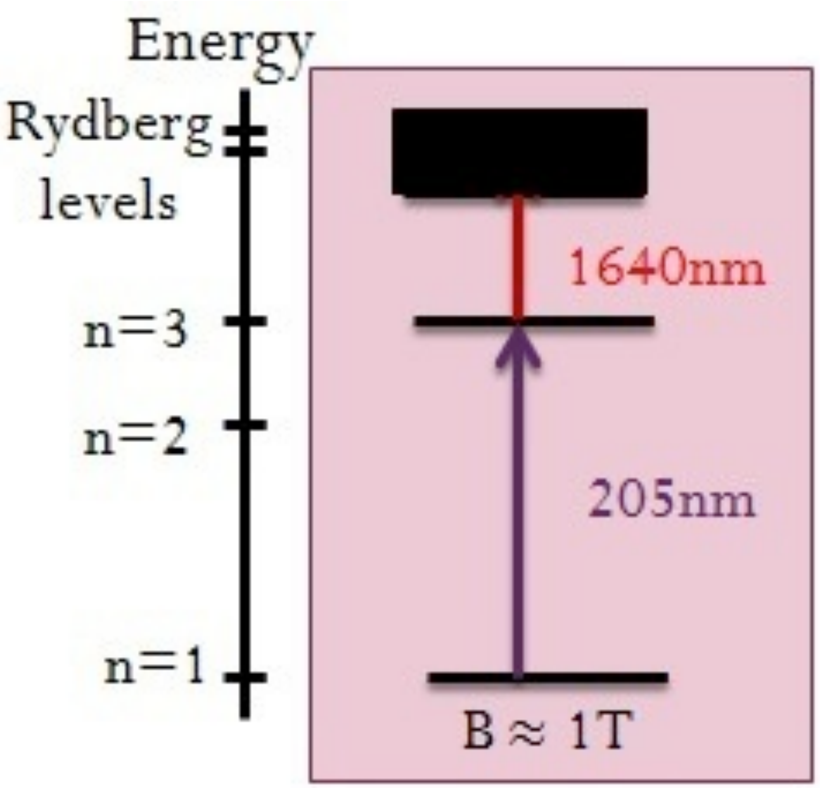
Silica-based nano-porous target (SEM image)

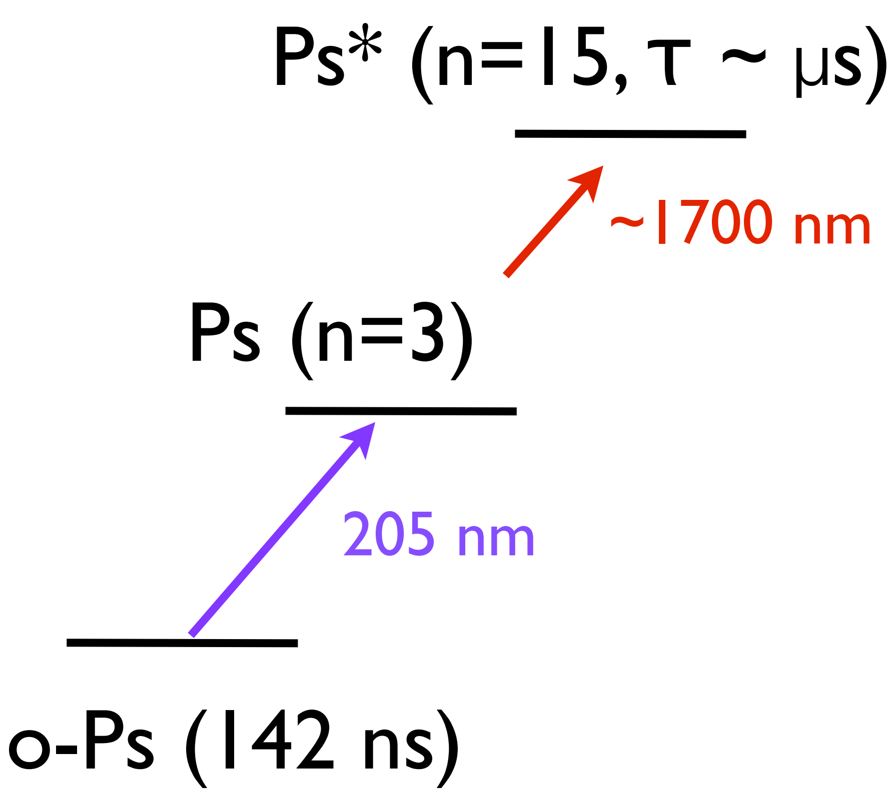


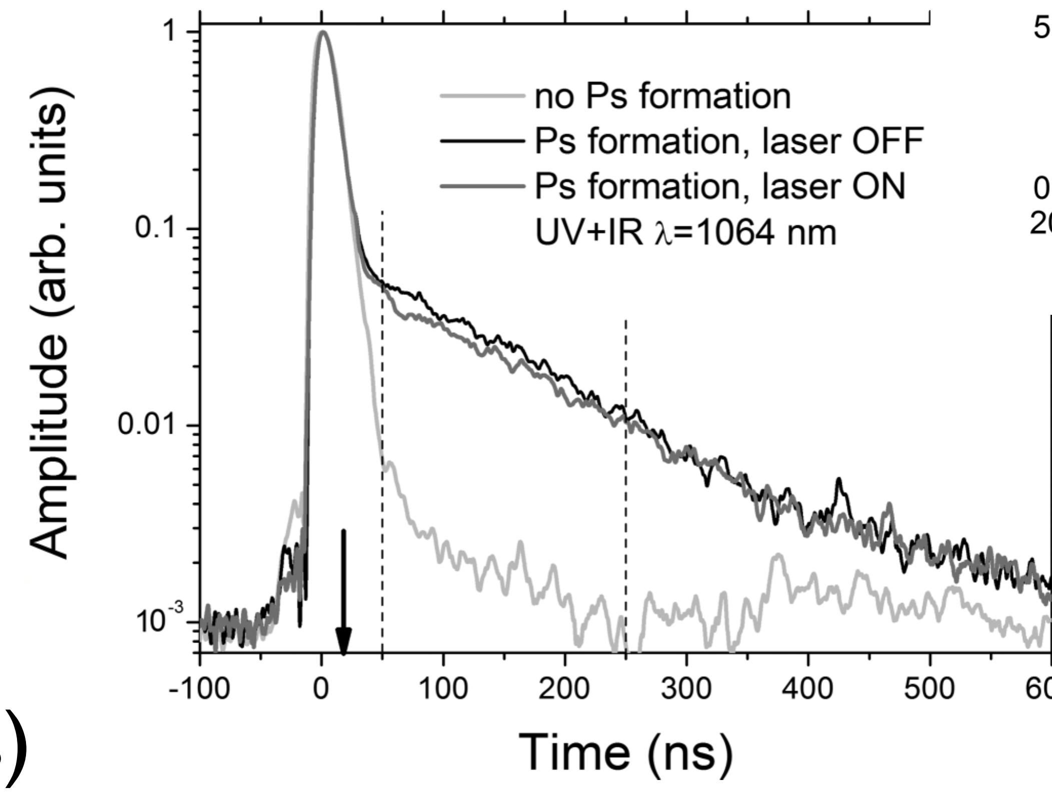


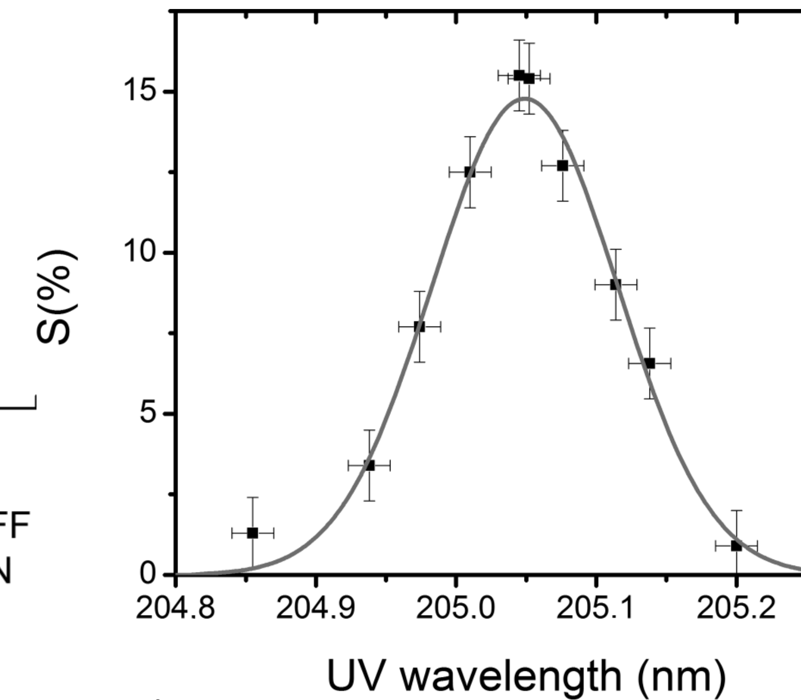
S. Mariazzi et al., *Phys. Rev. B* 81 235418 (2010)

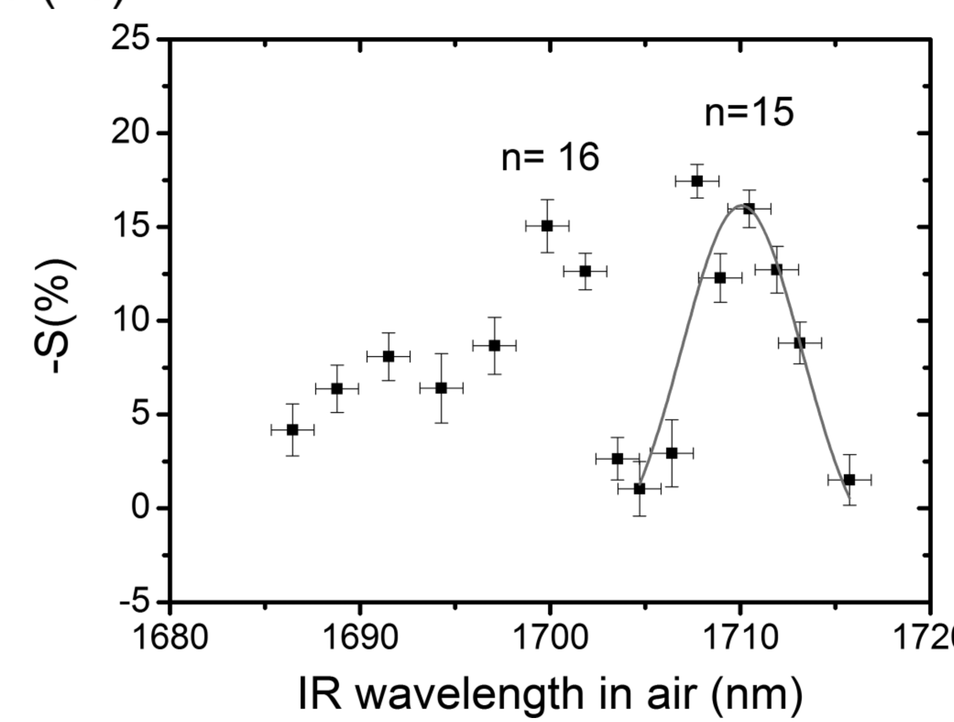
Positronium laser excitation:











Timeline:

2012: AEGIS assembly, tests with antiprotons

2013: no antiprotons! tests with electrons, positrons

2014: antiprotons are back (but only briefly!)!
Ps spectroscopy, tests with antiprotons, protons

2015: $\bar{H}$ production!?

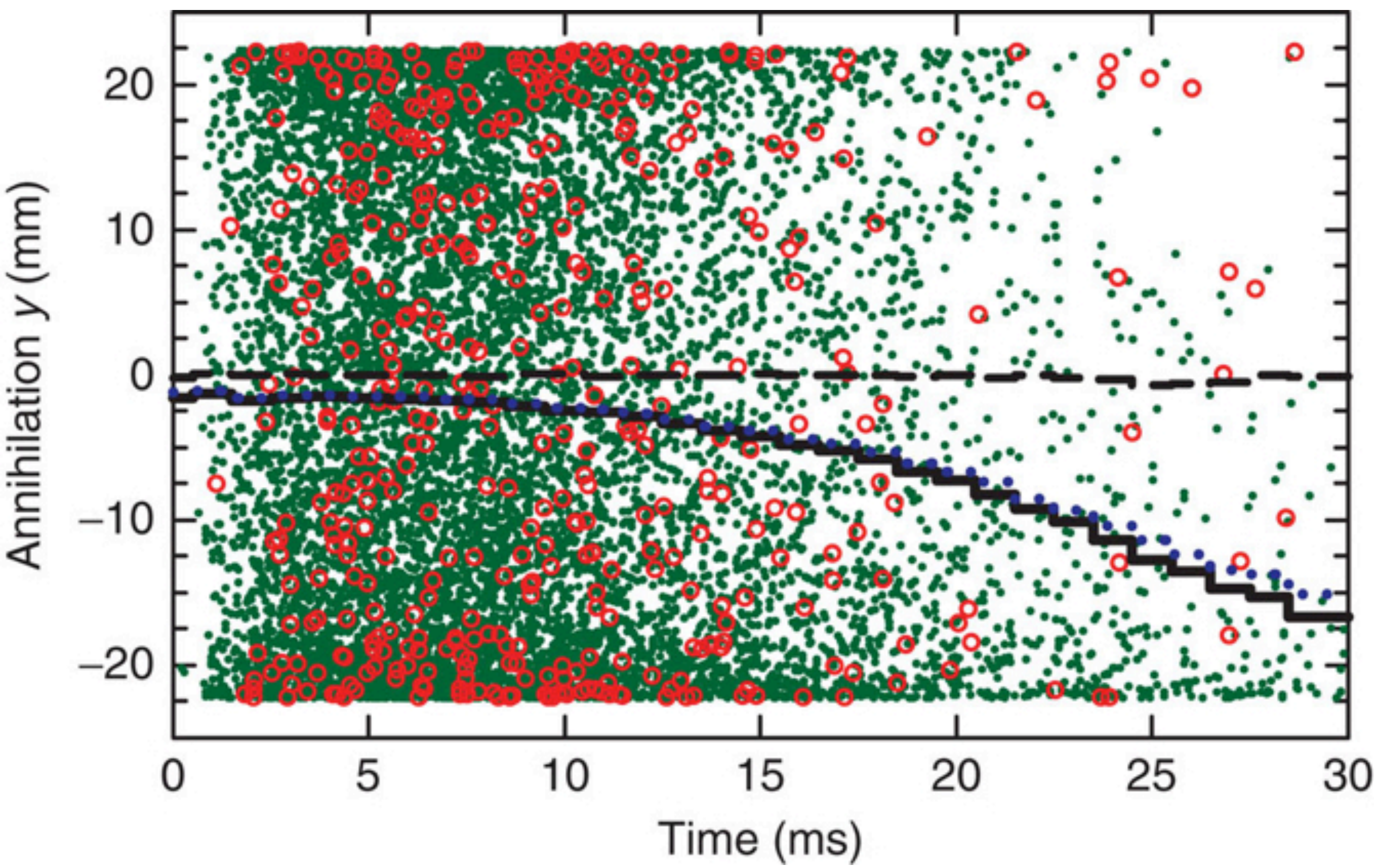
2016: $\bar{H}$ beam?! gravity measurement & $\bar{H}$ spectroscopy ???

2017: ELENA starts up: GBAR enters the game

(meanwhile, of course, ALPHA, ATRAP, ASACUSA are very active....)

ALPHA

When the $\overline{H}$ trap is opened, do the atoms fall up or down? in 10 ms, y = 0.5 mm



T~ 0.5K: v ~ 250 m/s

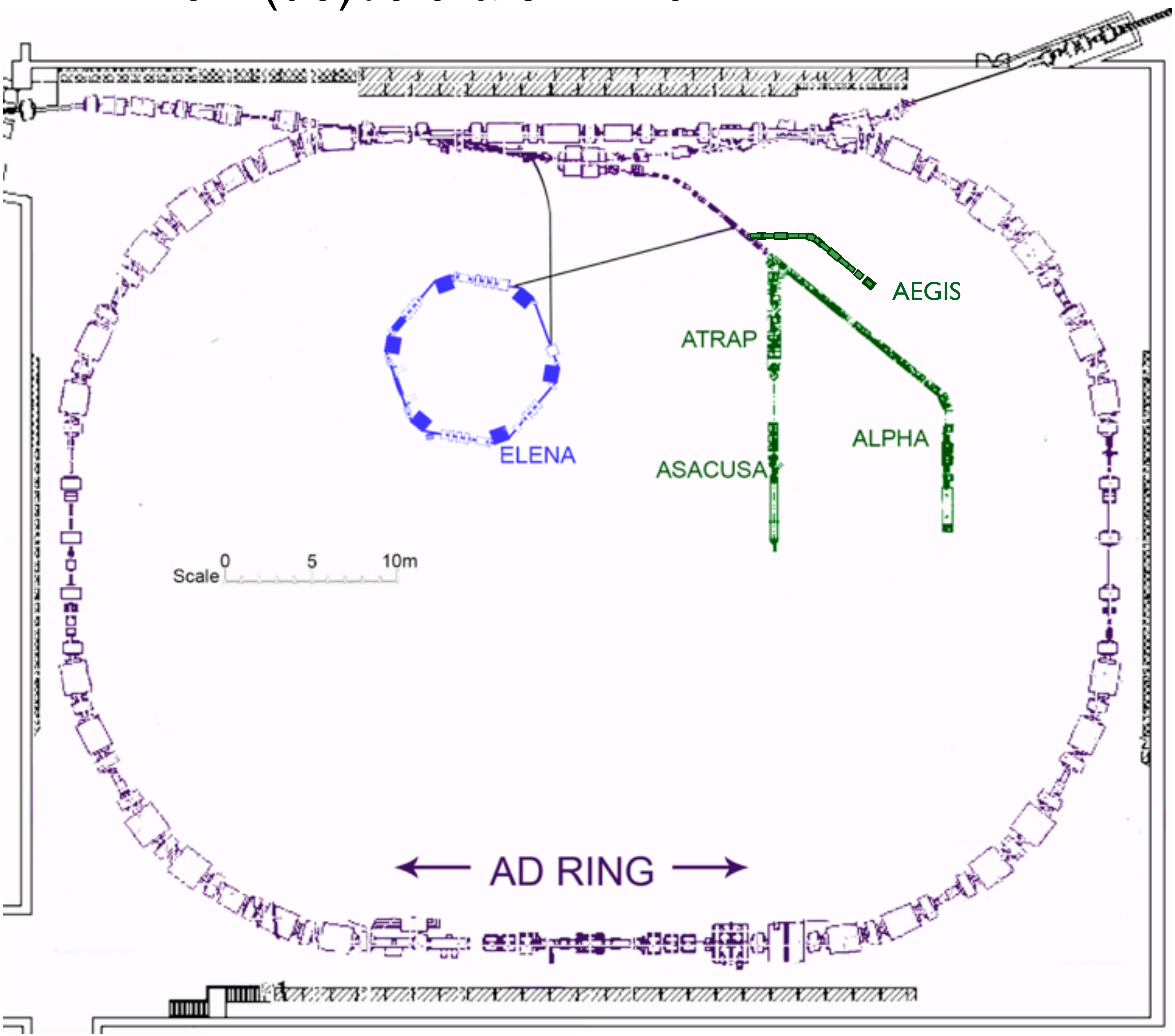
h ~ 500 m

T~ 1 mK: v ~ 5 m/s

h ~ 1 m

http://www.nature.com/ncomms/journal/v4/n4/full/ncomms2787.html

new (de)celerator in 2017: ELENA



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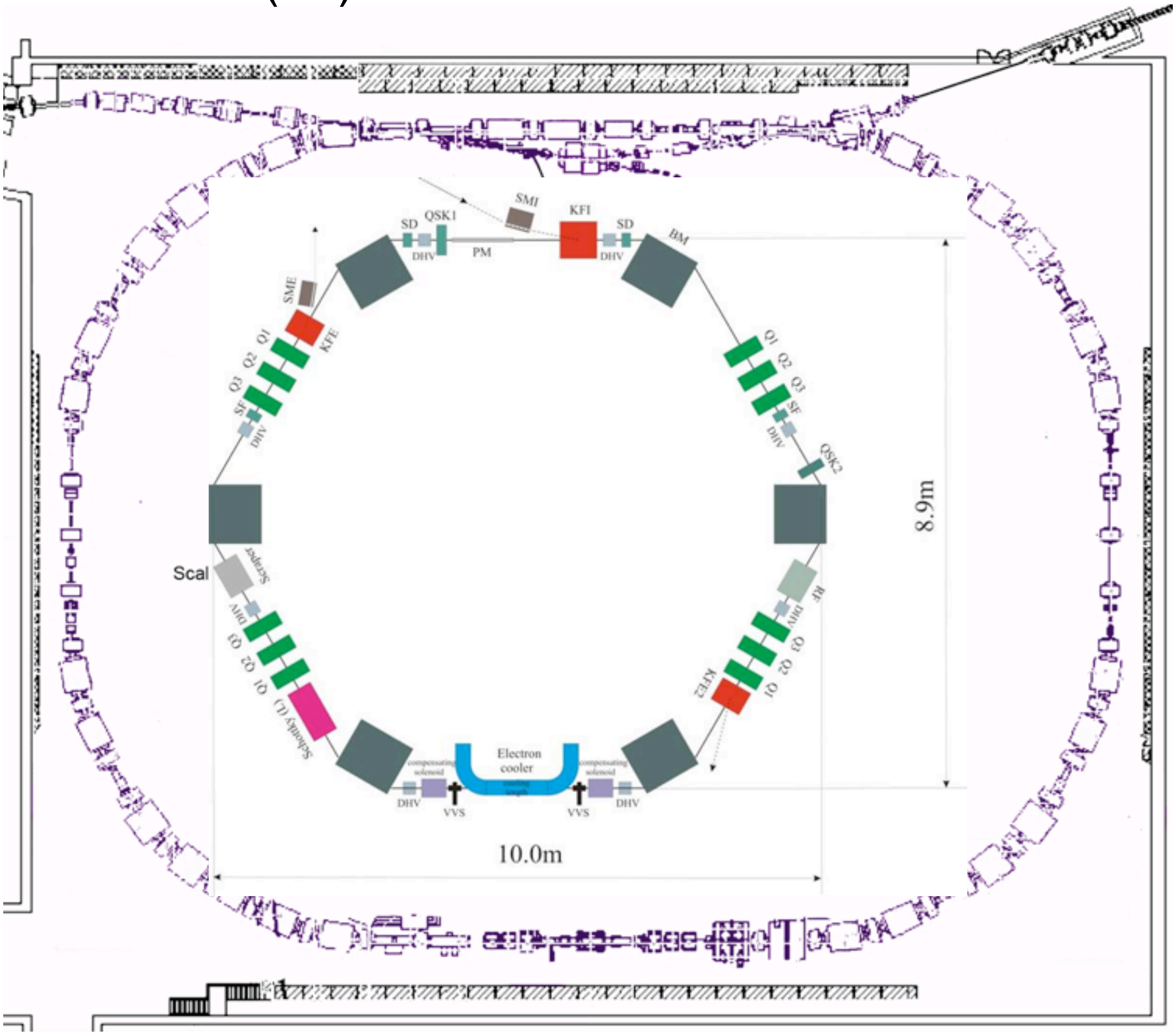

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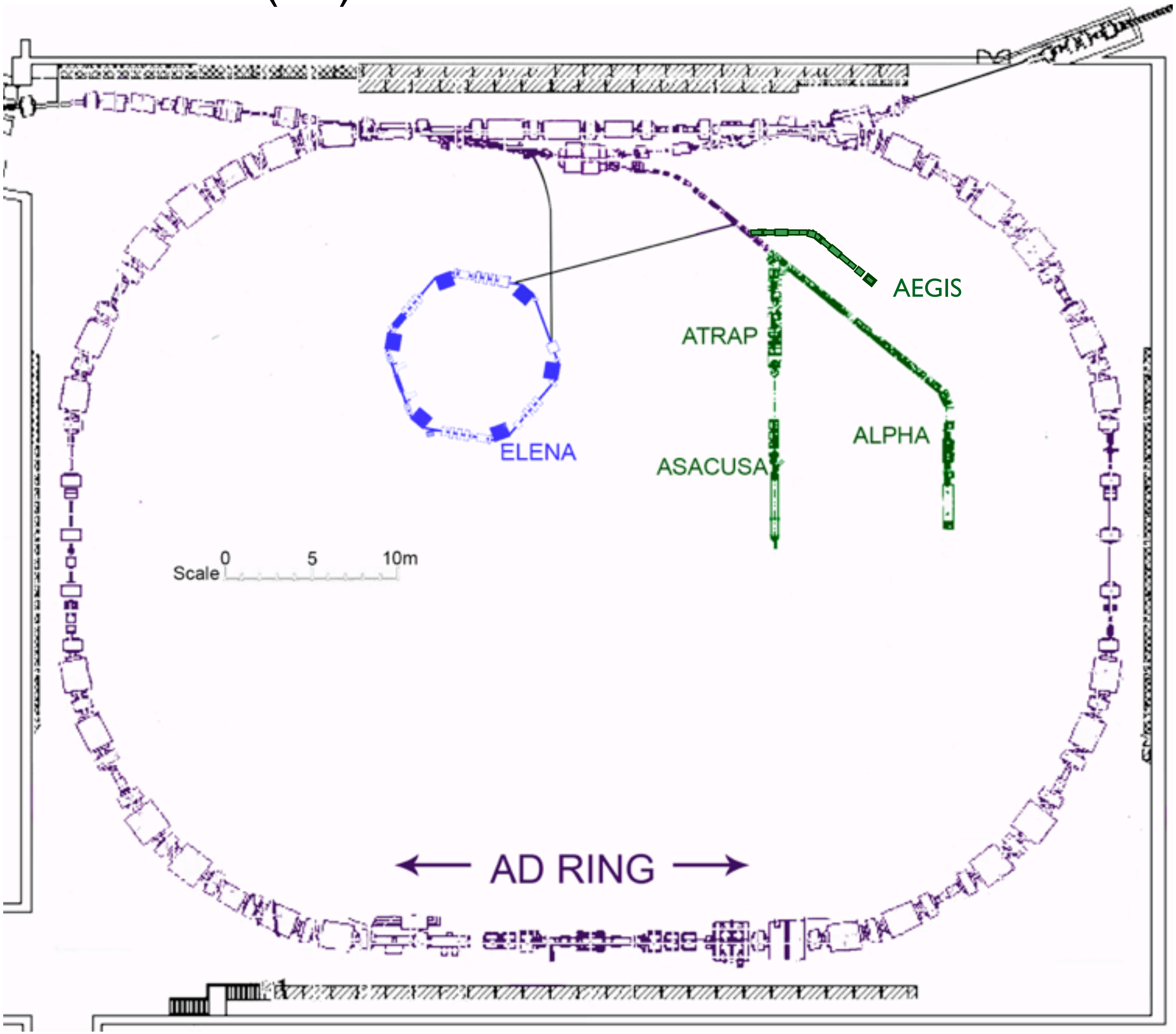
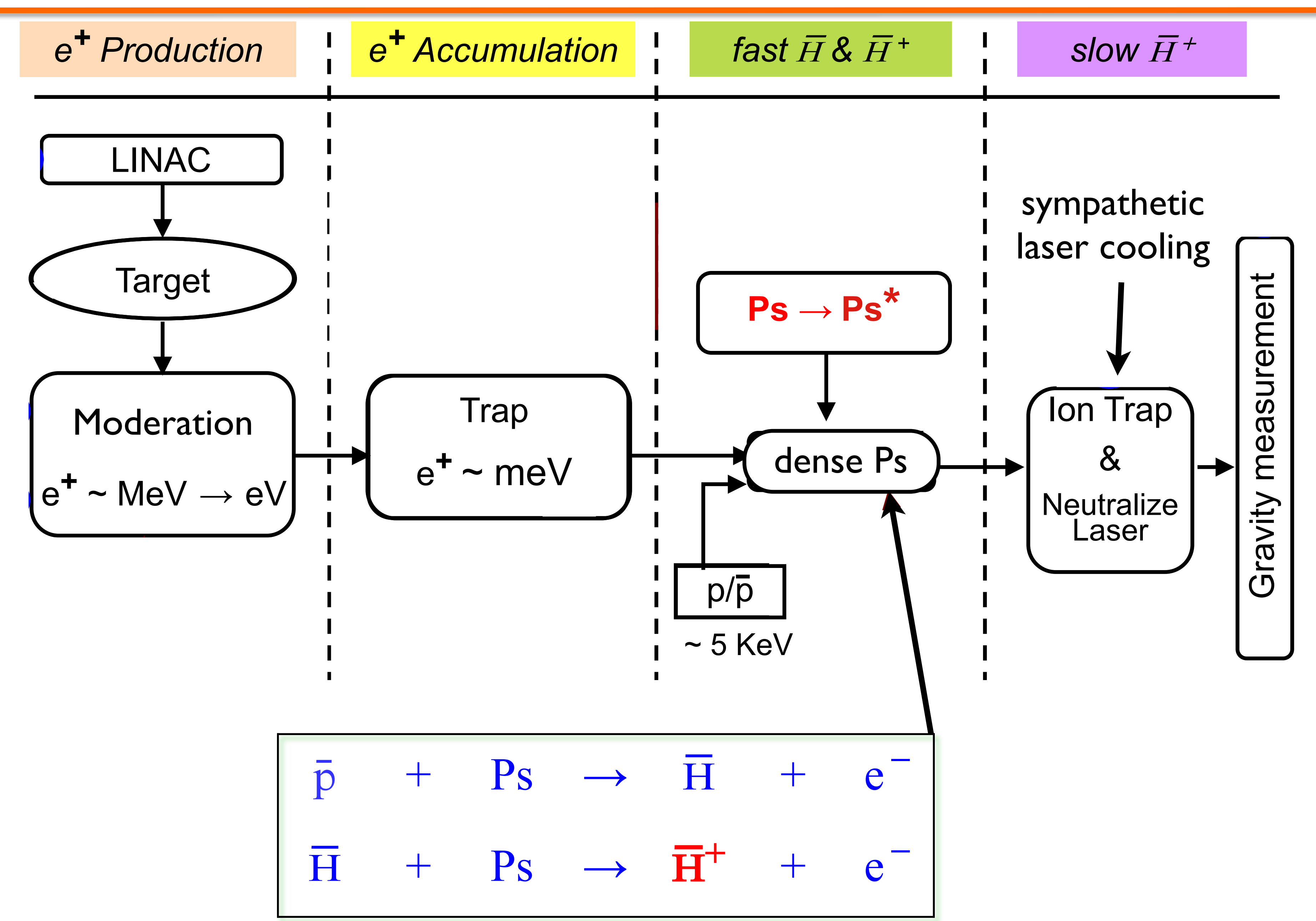


new experiments in 2017: GBAR

Synoptic Scheme

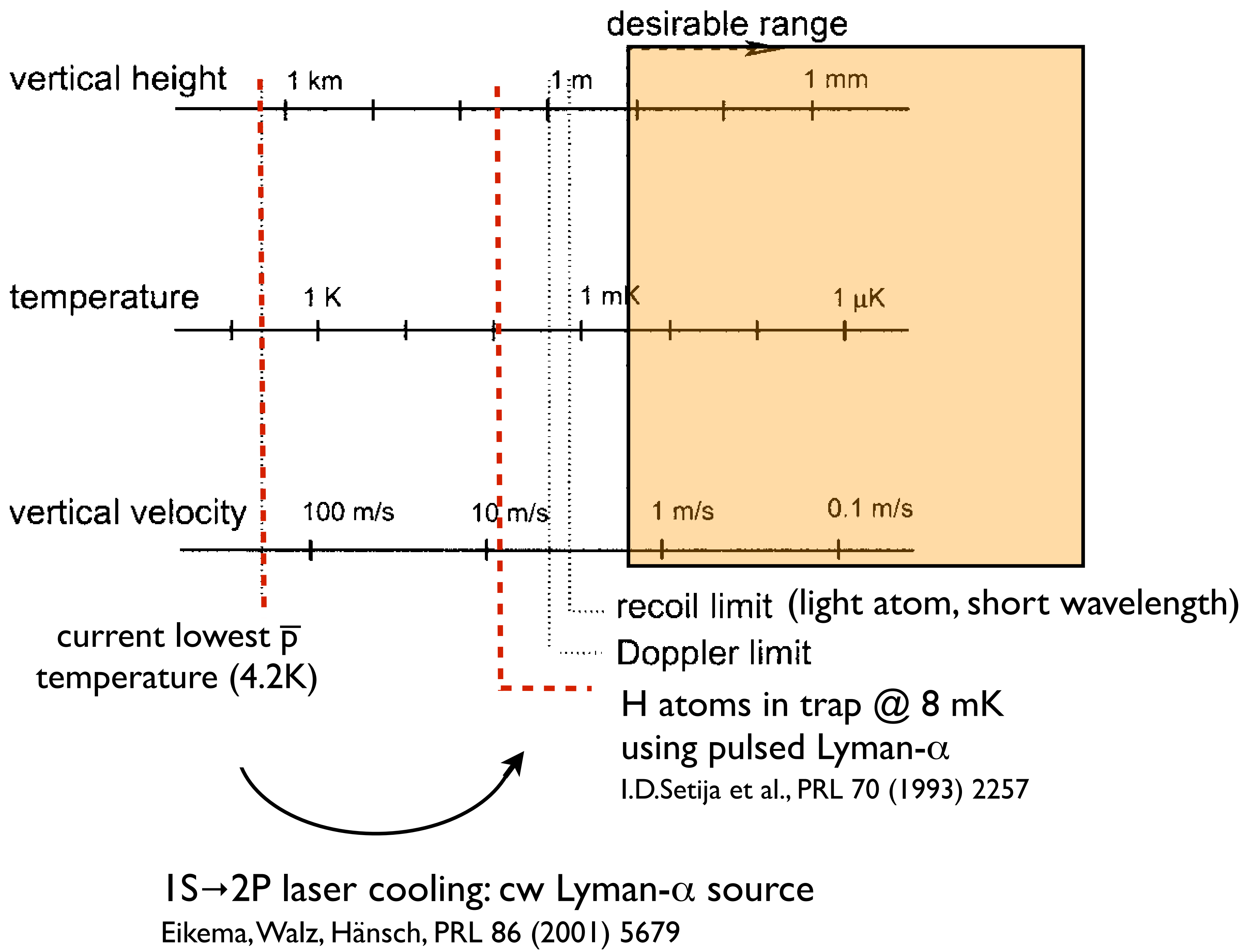


- Produce ion $\bar{H}^+$
- Capture ion $\bar{H}^+$
- Sympathetic cooling 20 μK
- Photodetachment of e^+
- Time of flight

\# antiprotons: x100

\# positrons: x1000

Precision requires "Ultra-cold" (~1 μK) Antihydrogen



sympathetic cooling to the rescue

GBAR

cooling of $\bar{H}^+$

J. Walz and T. Hänsch, Gen. Rel. and Grav. 36 (2004) 561

AEGIS

sympathetic cooling to the rescue

GBAR

cooling of $\bar{H}^+$

J.Walz and T. Hänsch, Gen. Rel. and Grav. 36 (2004) 561

formation of $\bar{H}^+$ (binding energy = 0.754 eV)

how? perhaps through $Ps(2p)+\bar{H}(1s) \rightarrow \bar{H}^+ + e^-$

Roy & Sinha, EPJD 47 (2008) 327

sympathetic cooling of $\bar{H}^+$

e.g. $In^+ \rightarrow 20\ \mu K$

photodetachment at ~6083 cm^{-1}

gravity measurement via TOF

AEGIS

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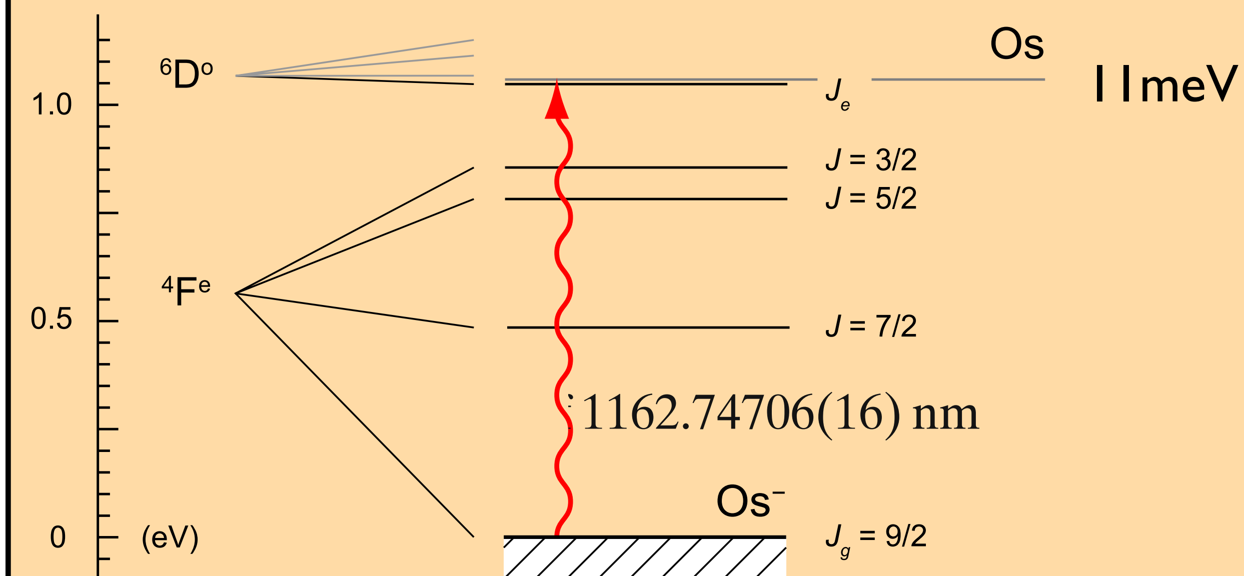
cooling of $\bar{p}$

Warring et al, PRL 102 (2009) 043001

Fischer et al, PRL 104 (2010) 073004



very weak cooling

→ best to start at ~ 4K and cool to Doppler limit ($T_D \approx 0.24\ \mu K$)

sympathetic cooling to the rescue

GBAR

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Warring et al, PRL 102 (2009) 043001
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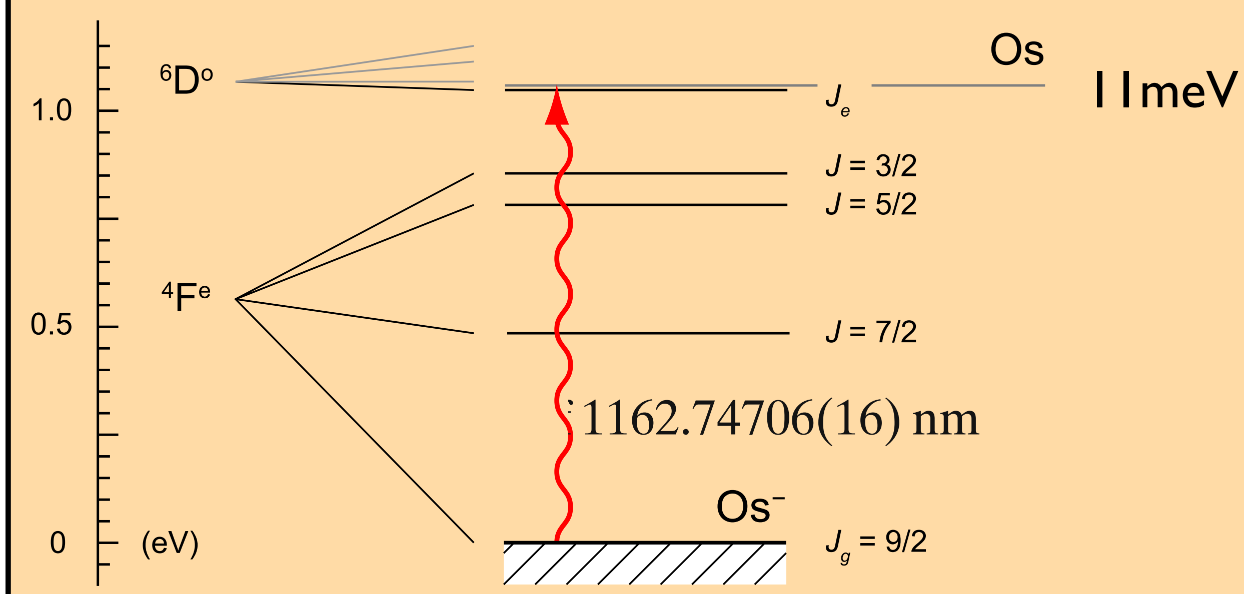
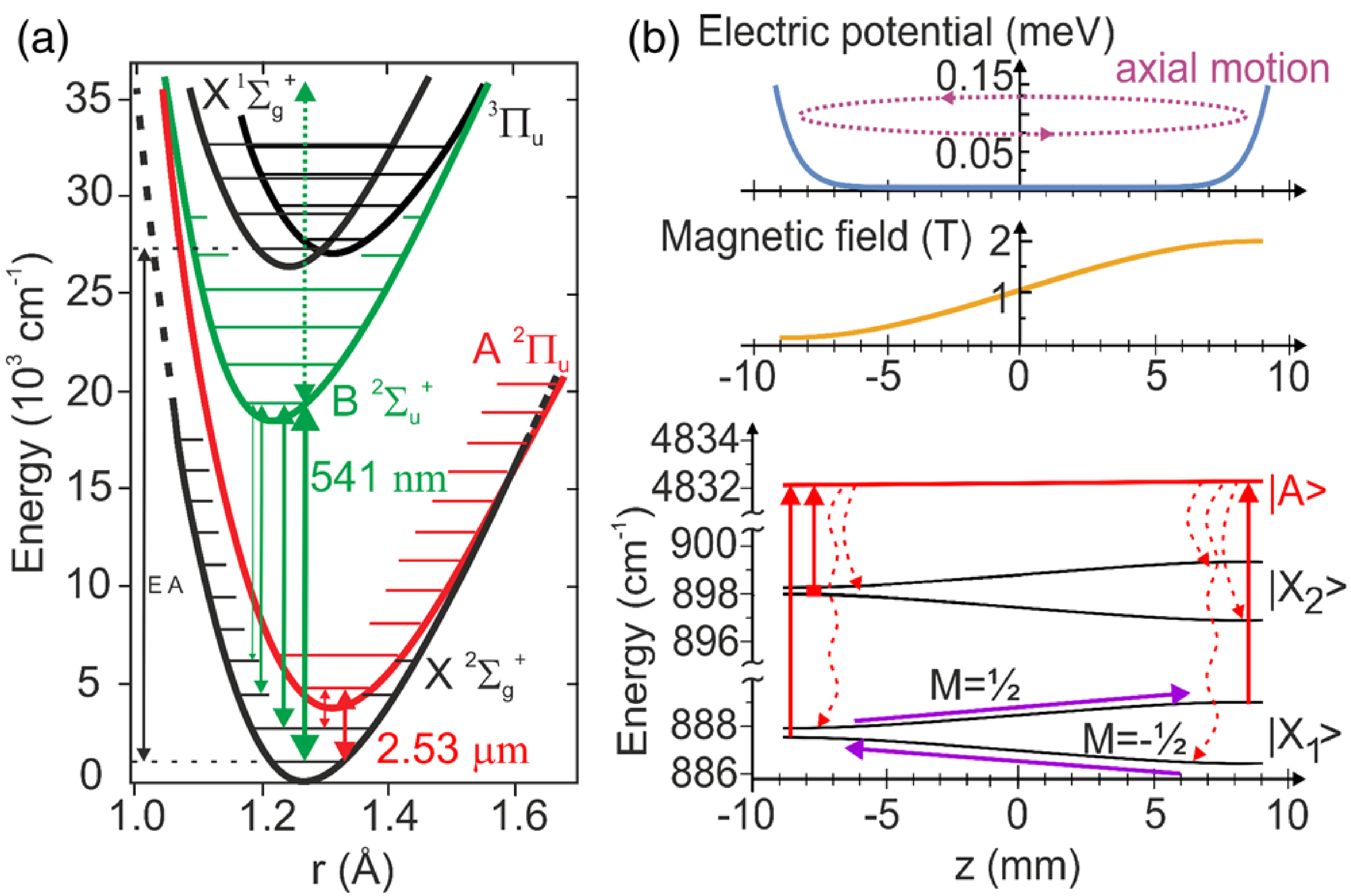


very weak cooling
→ best to start at ~ 4K and cool to Doppler limit ($T_D \approx 0.24\ \mu K$)

should allow reaching same precision on **g** as with atoms (10^{-6} or better)

sympathetic cooling to the rescue

C_2^-



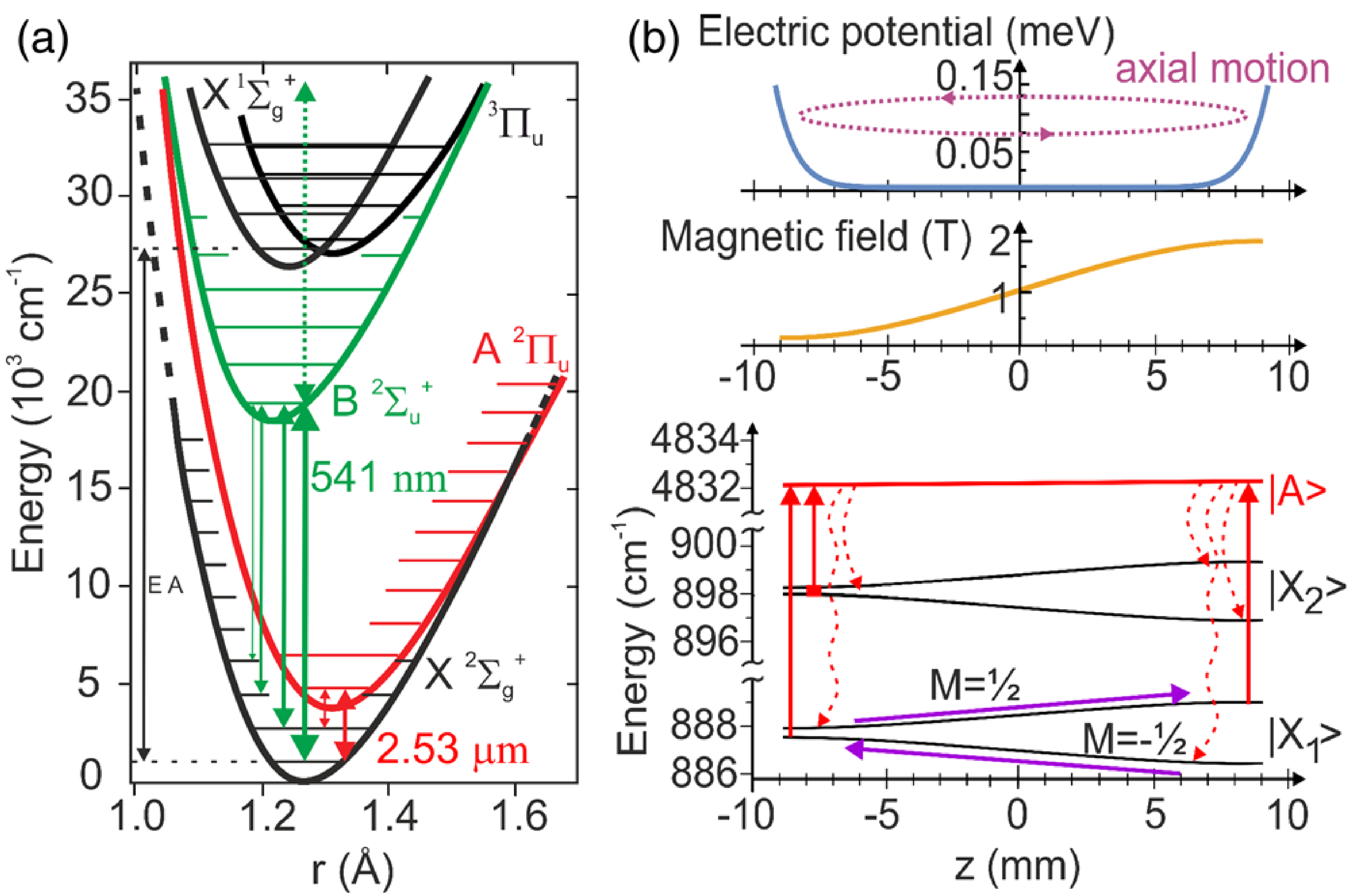
P. Yzombard et al., PRL 114, 213001 (2015)

~ mK reachable, and offers a path towards µK

sympathetic cooling to the rescue

cooling of p̄: use other anions, such as anionic molecules

C_2^-



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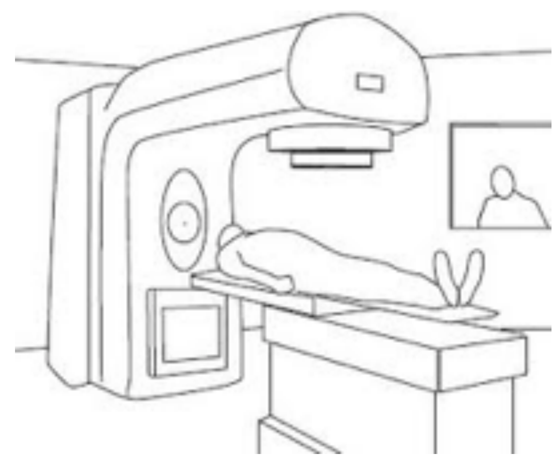
(aka: can it make me rich?)

Applications:

1. Positron emission tomography

2. Radiotherapy



3. Fuel

4. Other ideas

Applications:

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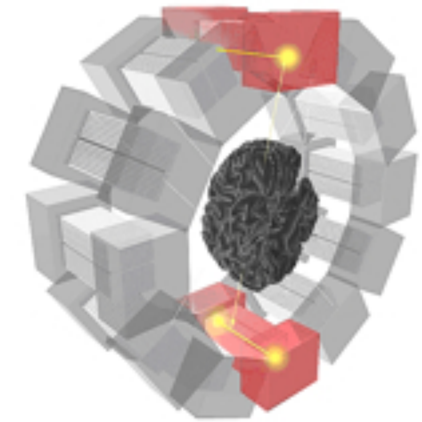
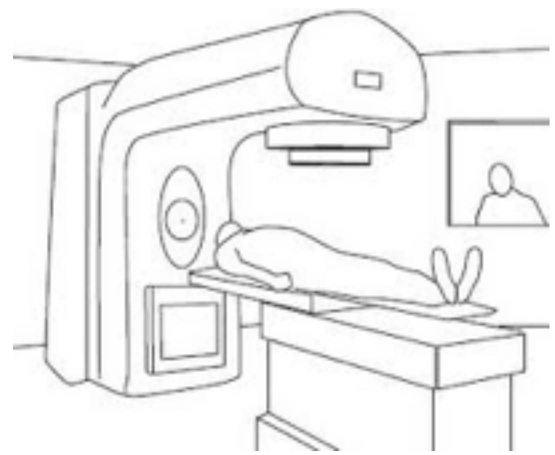
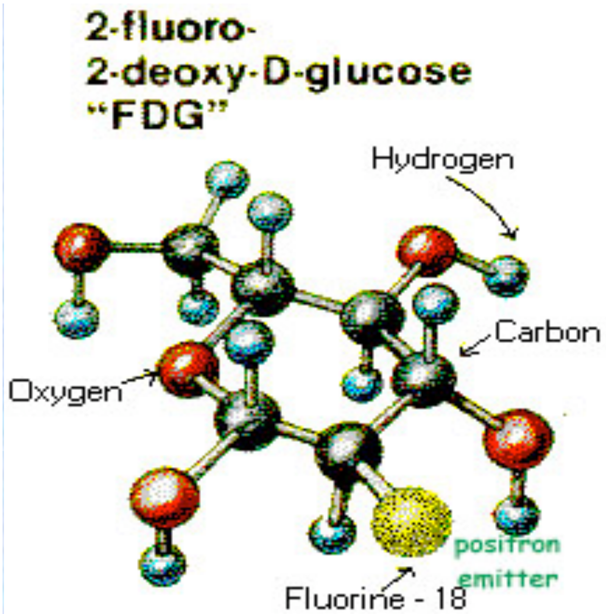


2. Radiotherapy



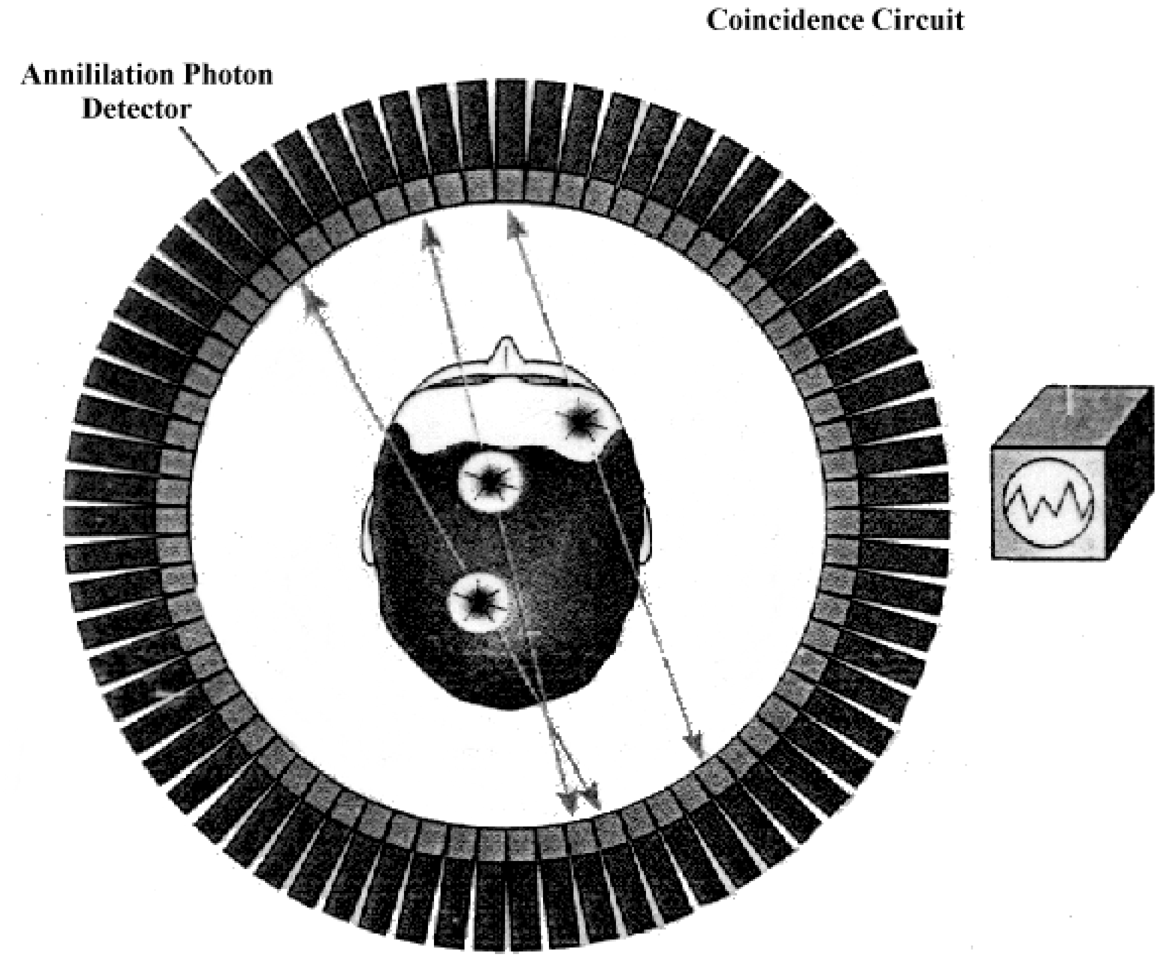
3. Fuel

4. Other ideas



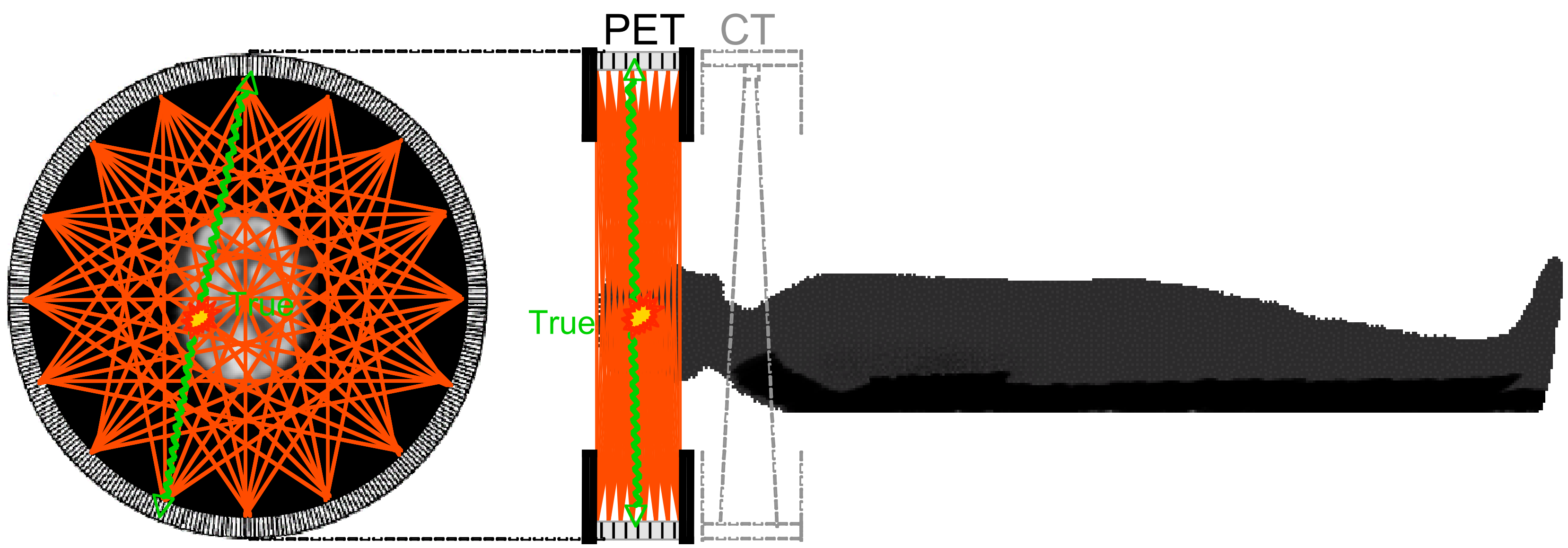
Insert e^+ emitting isotopes (C-11, N-13, O-15, F-18) into physiologically relevant molecules (O_2, glucose, enzymes) and inject into patient.

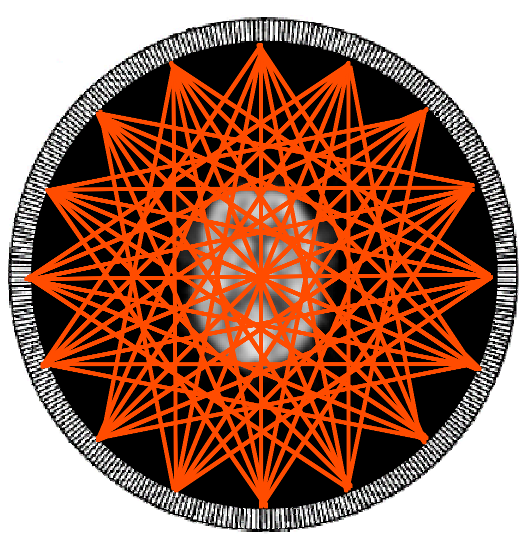
(Lifetimes ~ few to 100 minutes)

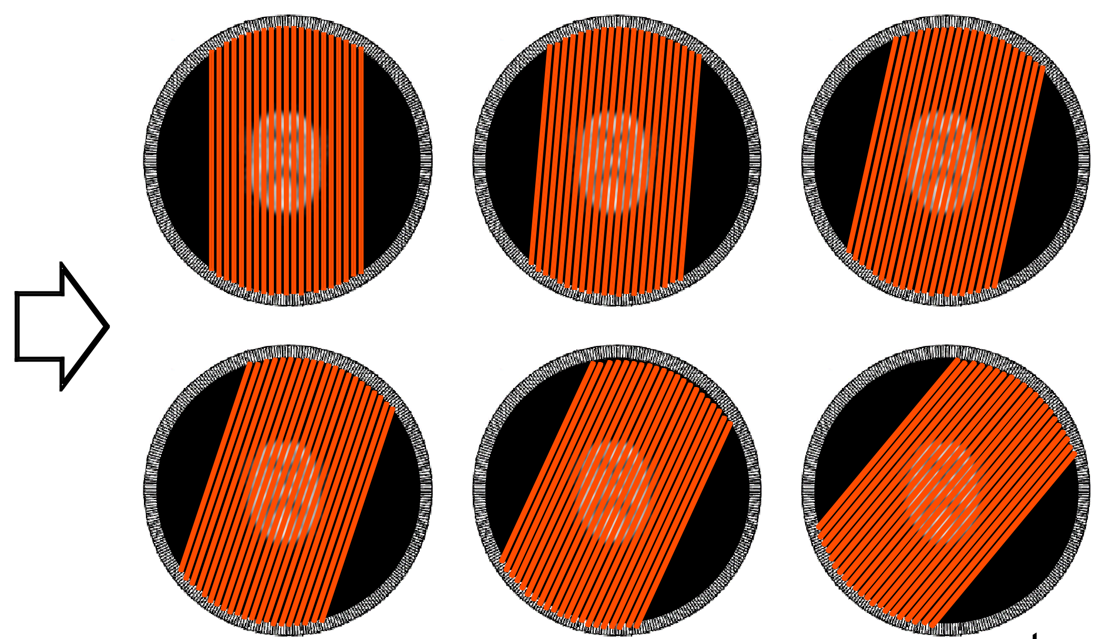


Multiple radiation detectors arranged around the subject's head are connected by coincidence circuits.

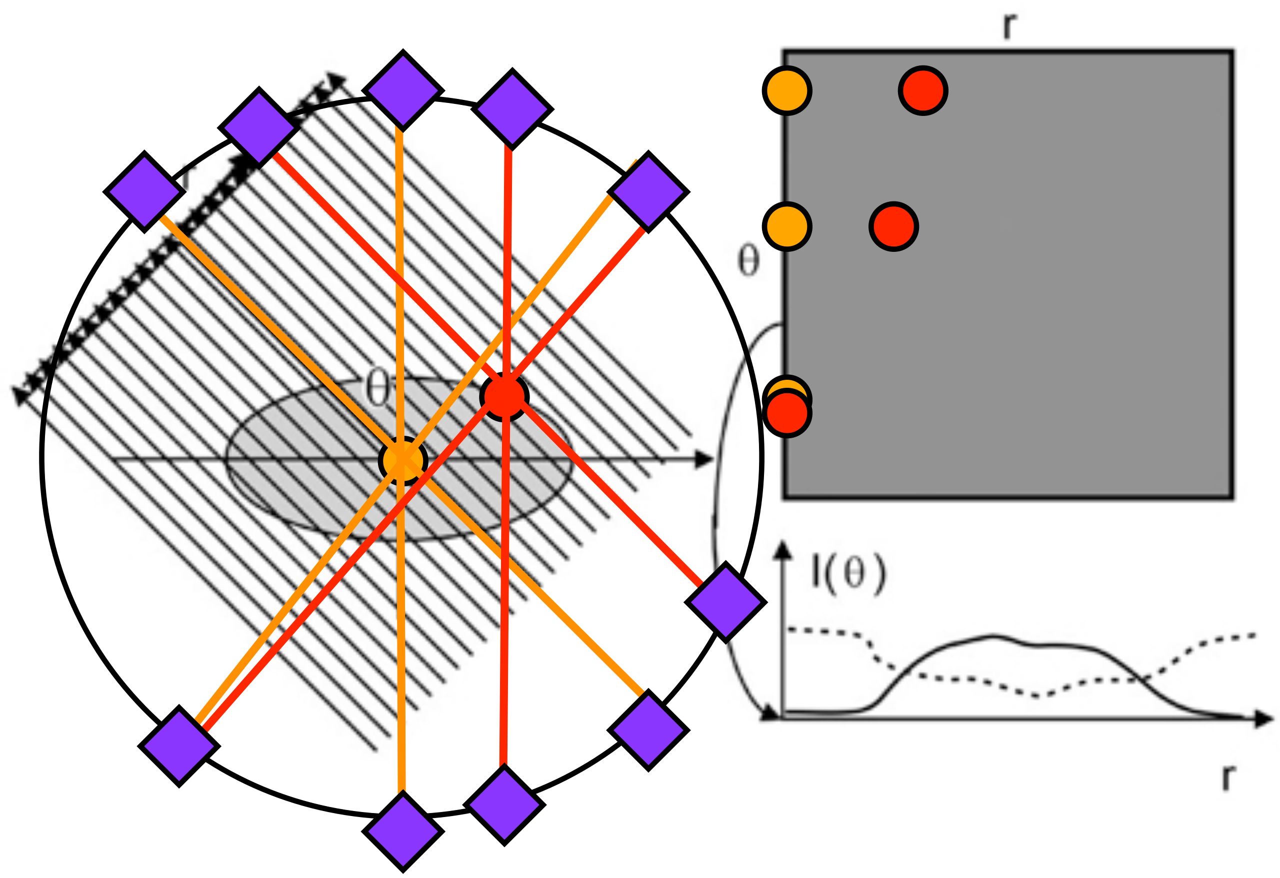
Reconstruct place of positron annihilation with crystal calorimeter


PET
CT
True
True

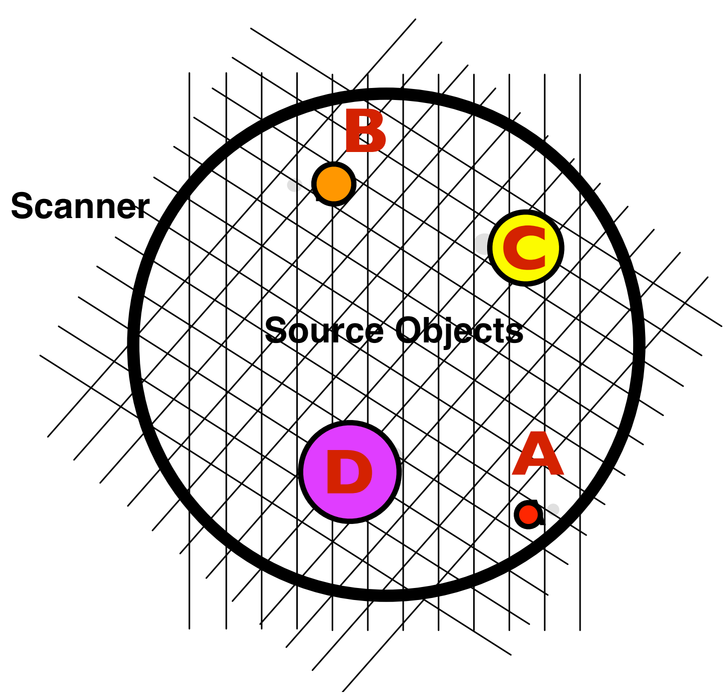


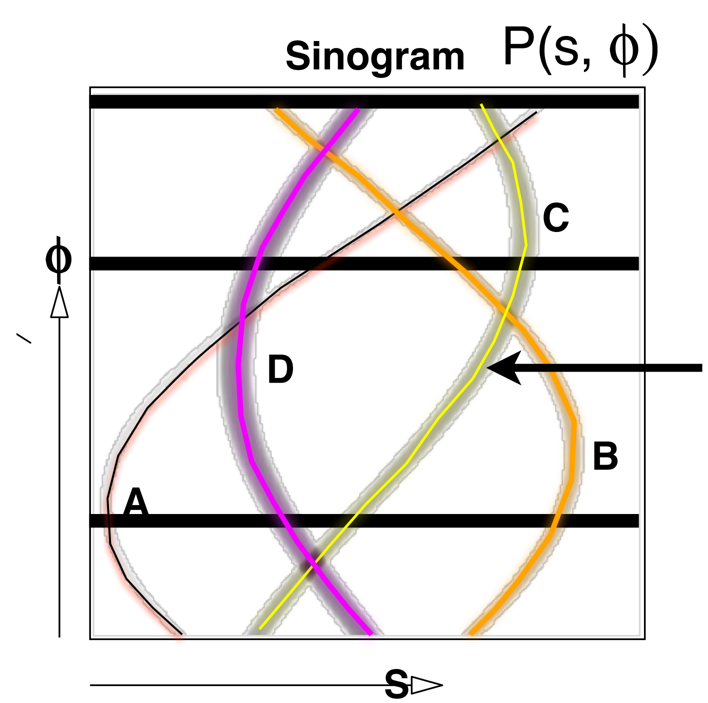

etc…

Data representation: sinograms

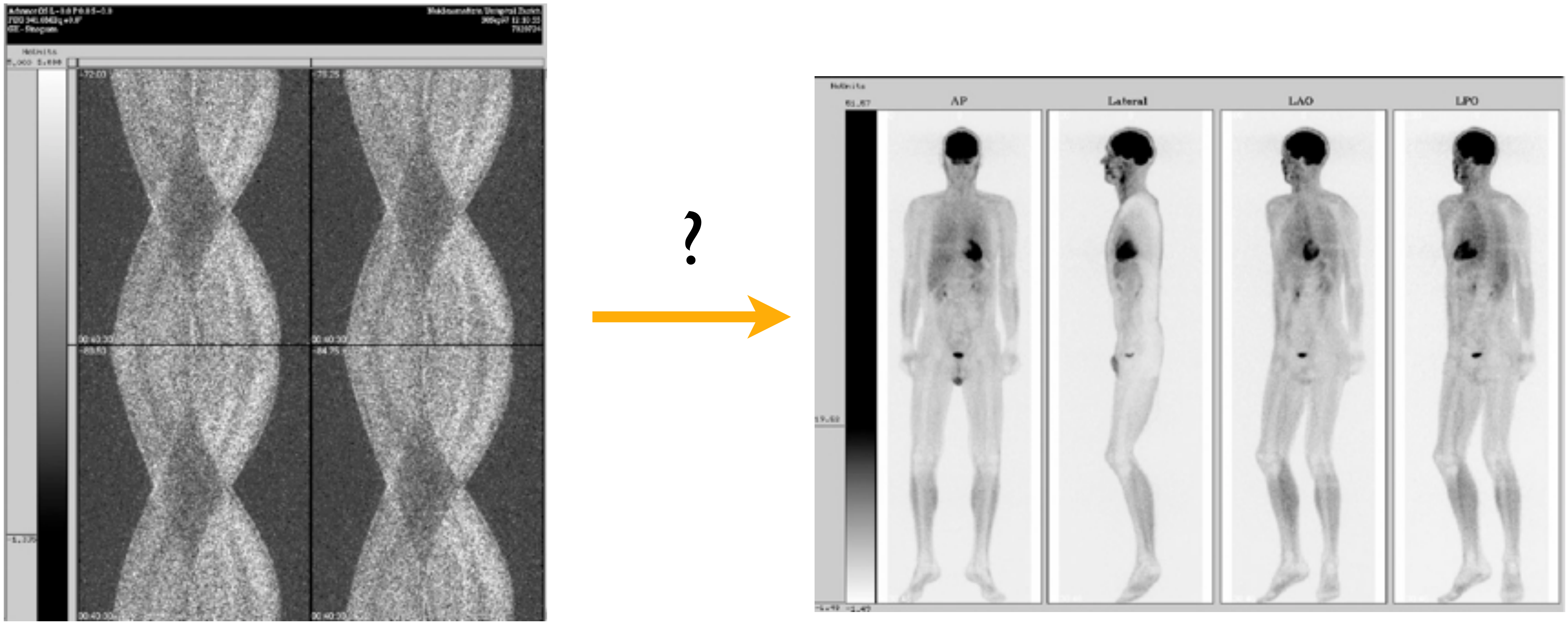


The number of events detected along a line is proportional to the integral of activity along that line





Intensity =
Line integral through tracer distribution for a particular (s, phi)



http://research.nokia.com/files/tomoRGI.pdf

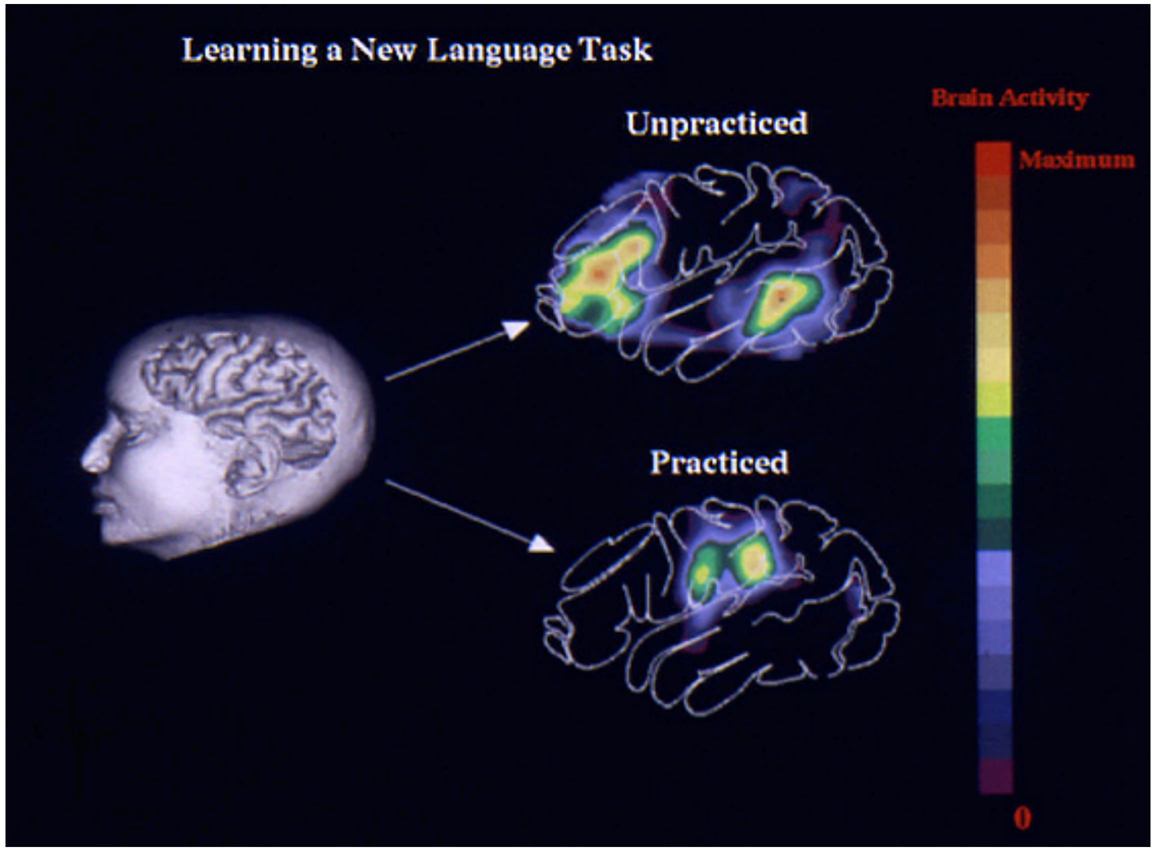
- Filtered back-projection

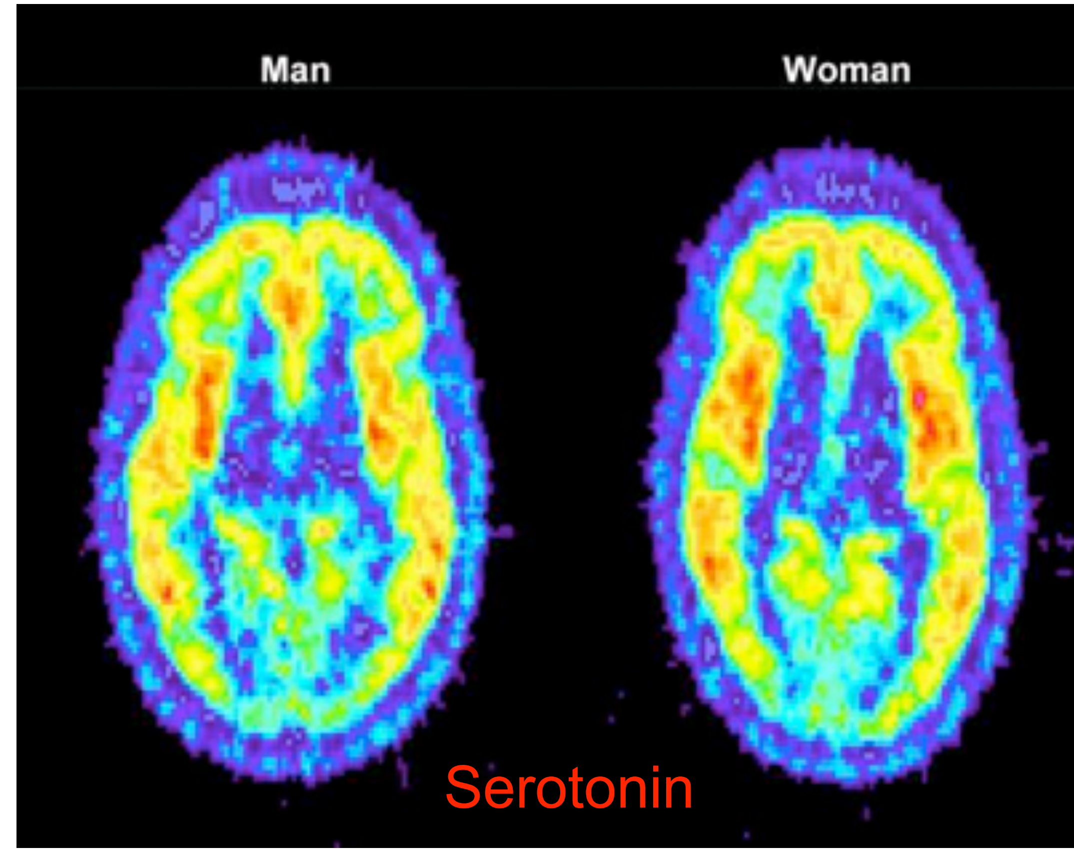
  fast, cheap, inaccurate

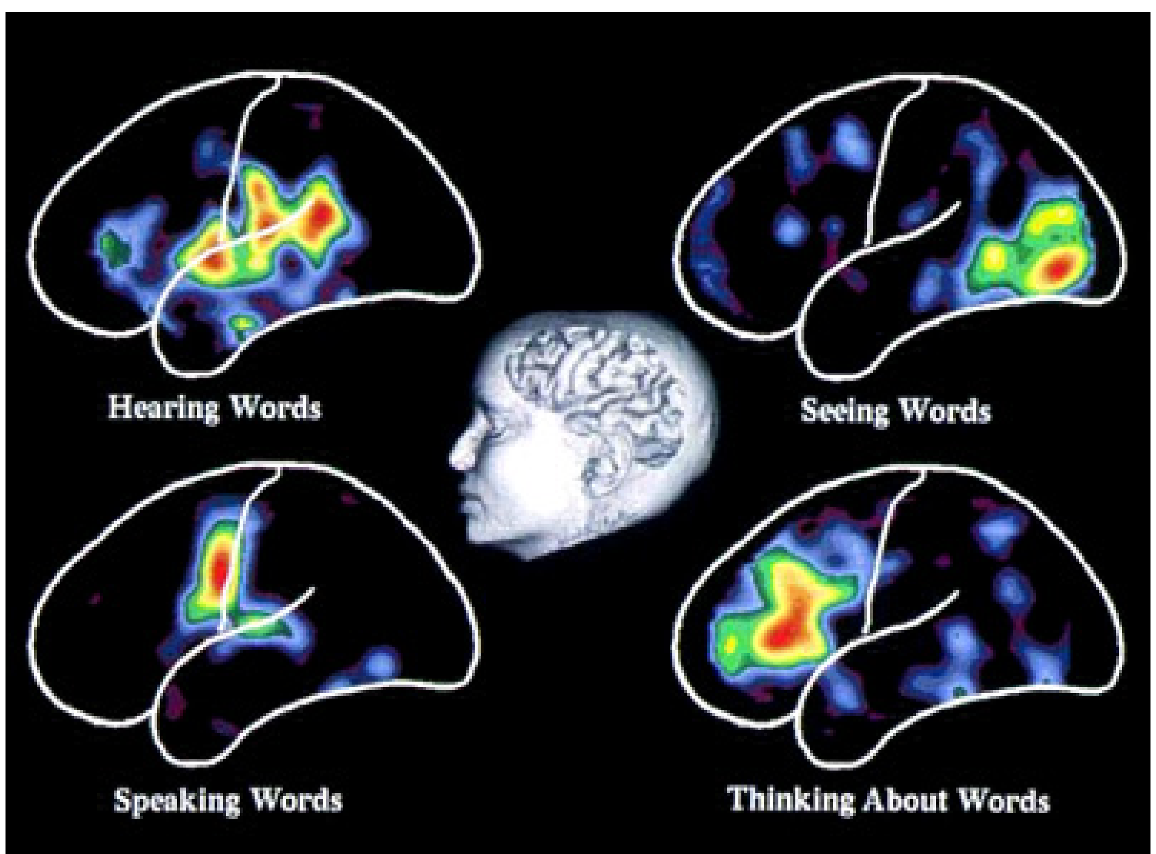
- Expectation maximization (iterative procedure)

  slow, expensive, accurate

Good for mapping metabolism, neurotransmitters and physiological changes







Serotonin receptors

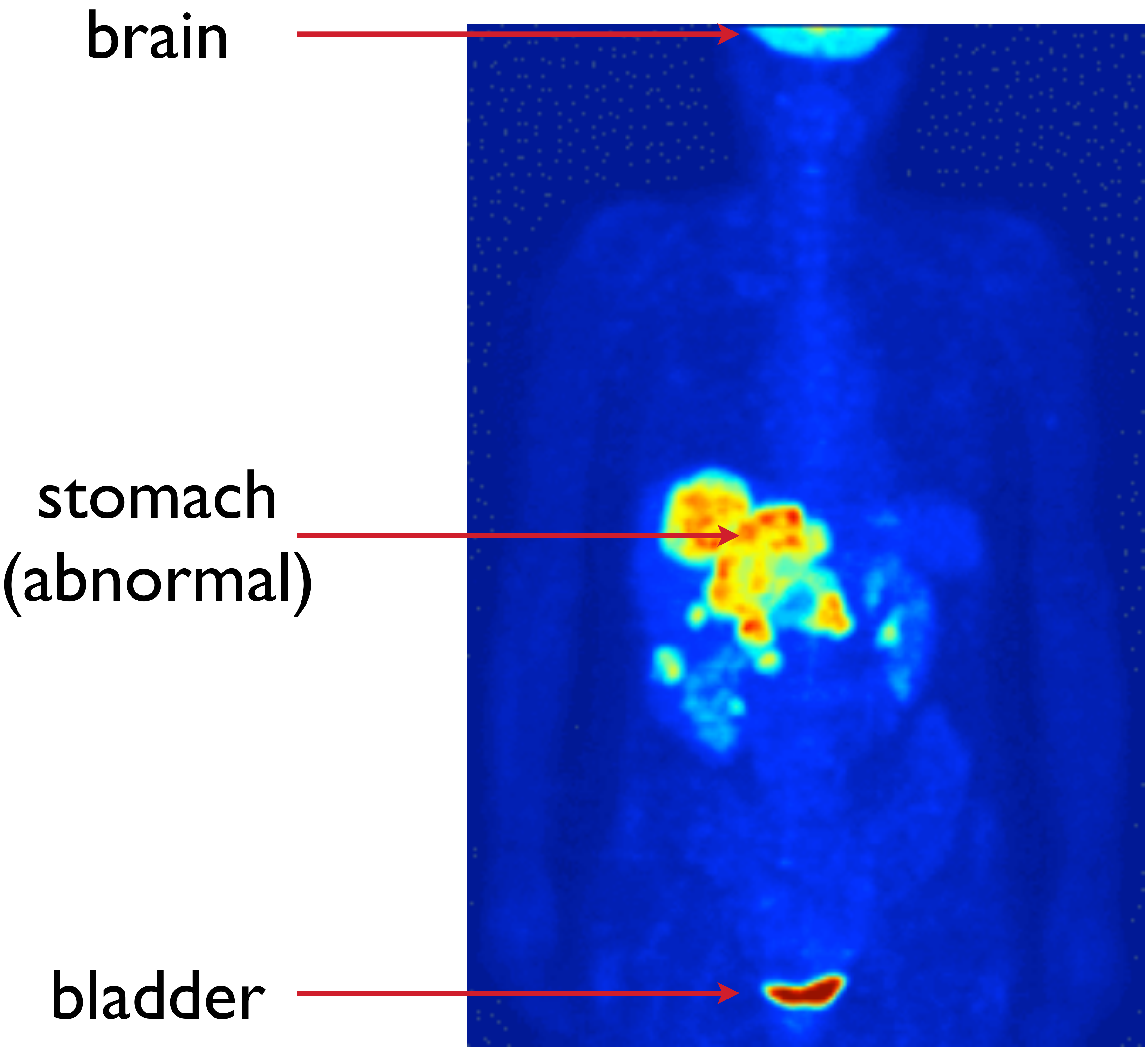
Dopamine receptors

Glucose

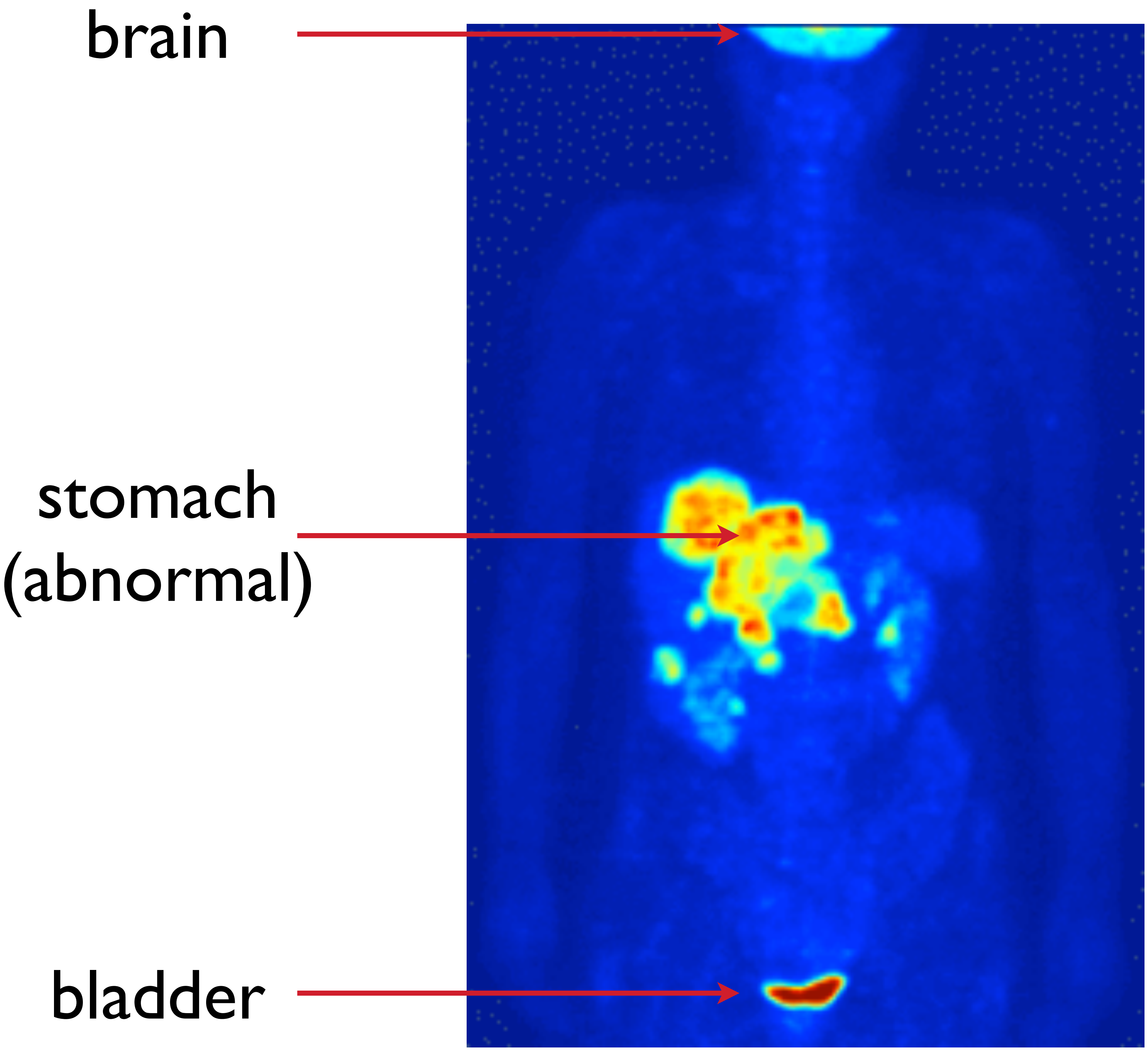
Amyloid-binding molecules

Opioid receptors

Pharmacological tests



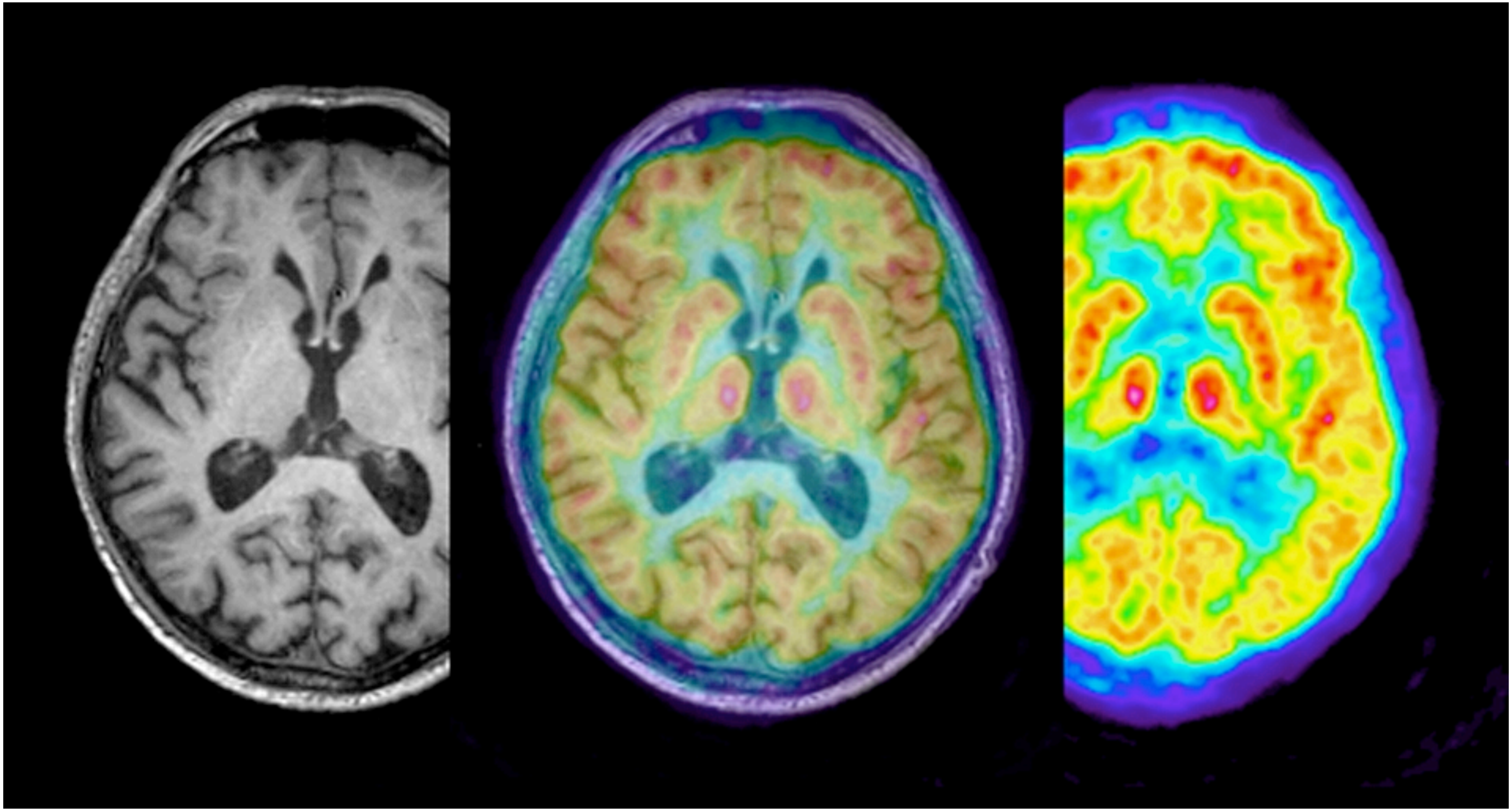
Maximum Intensity Projection of a ^{18}F-FDG whole body PET acquisition



develop faster, more compact calorimeter crystals, faster electronics, faster triggers, worry about deadtime, pile-up...

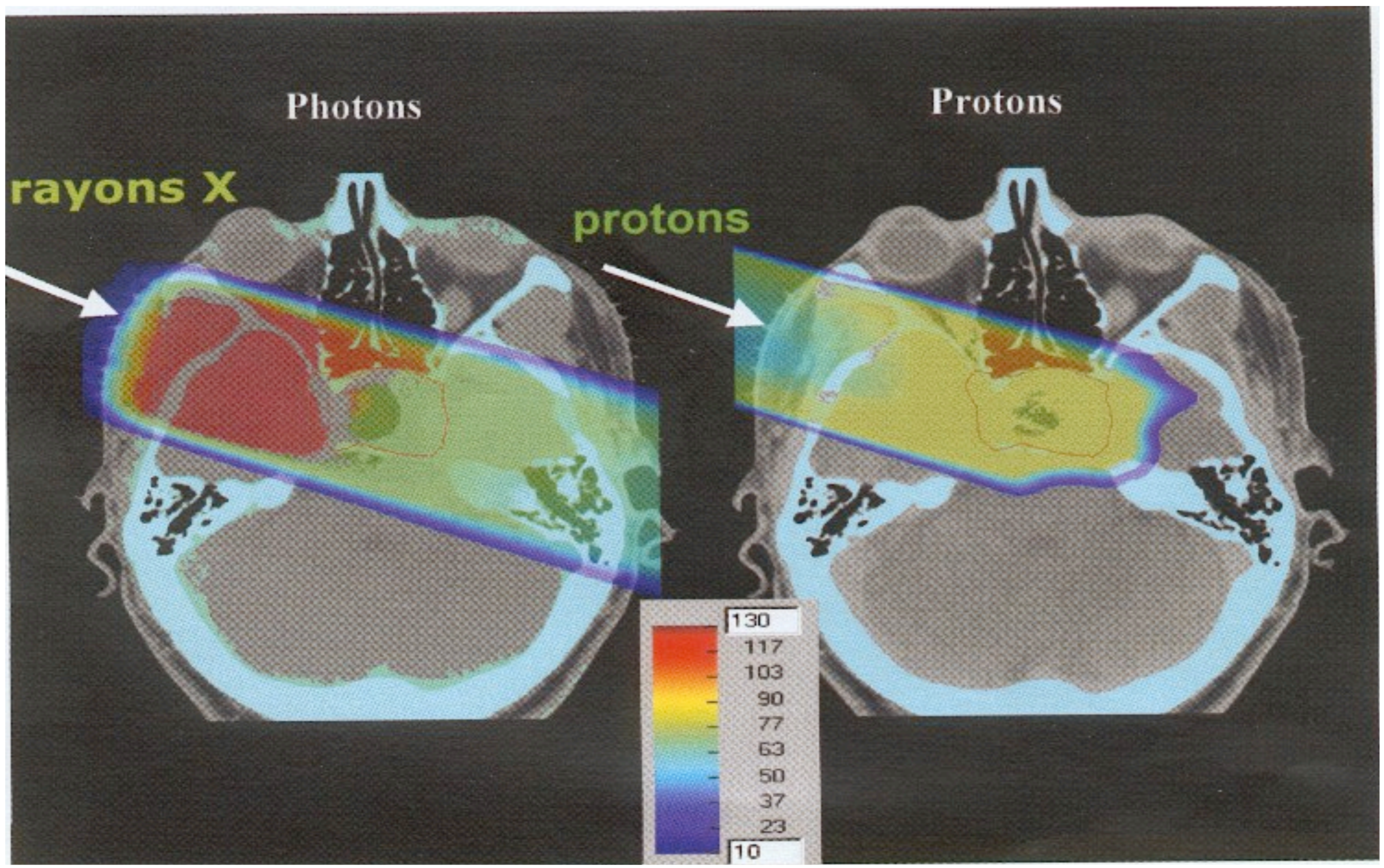
CLIC, ILC detector developments!

Maximum Intensity Projection of a ^{18}F-FDG whole body PET acquisition

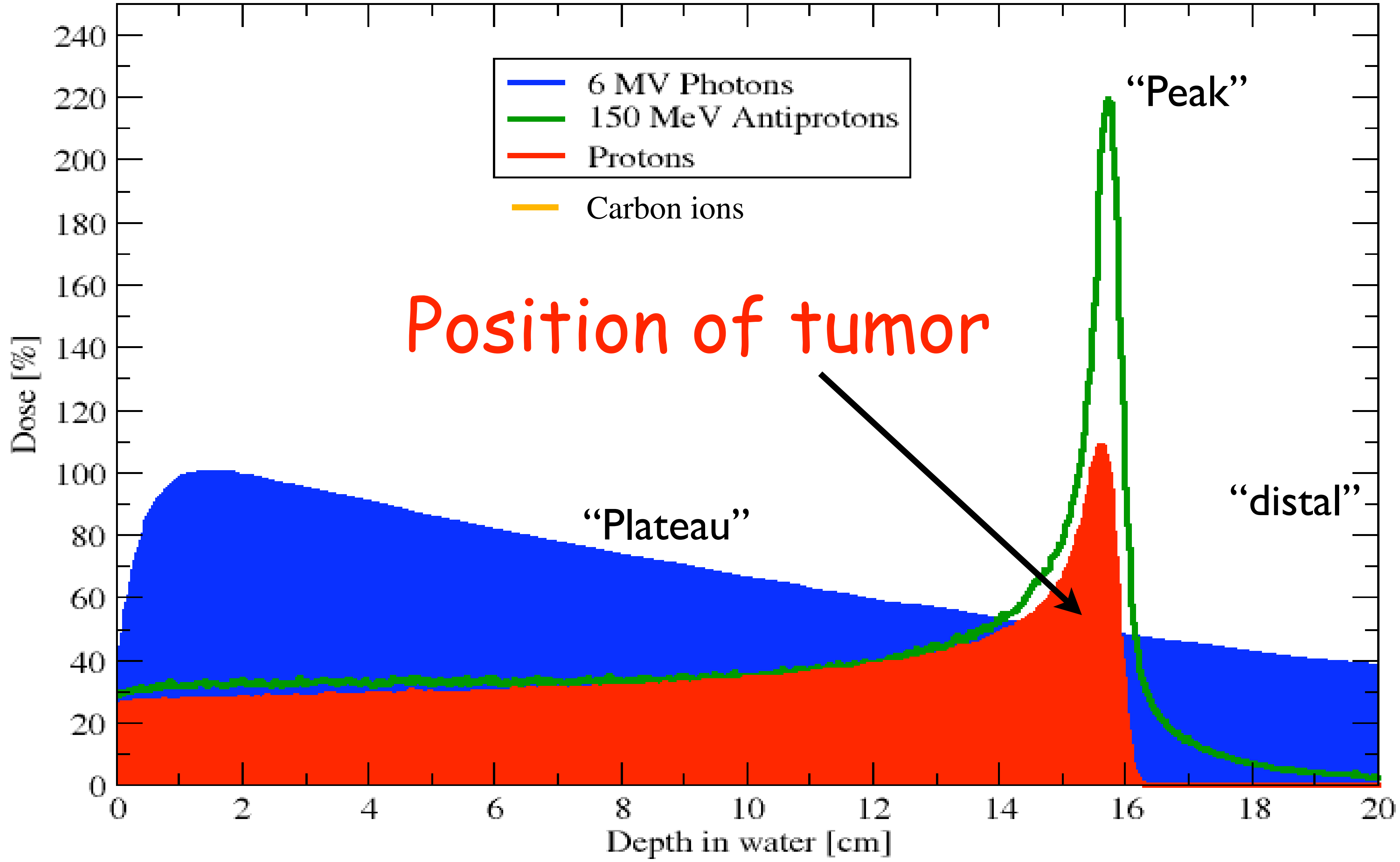


MRI Combined PET

Radiotherapy



Monte Carlo simulations



MCNPX

FLUKA

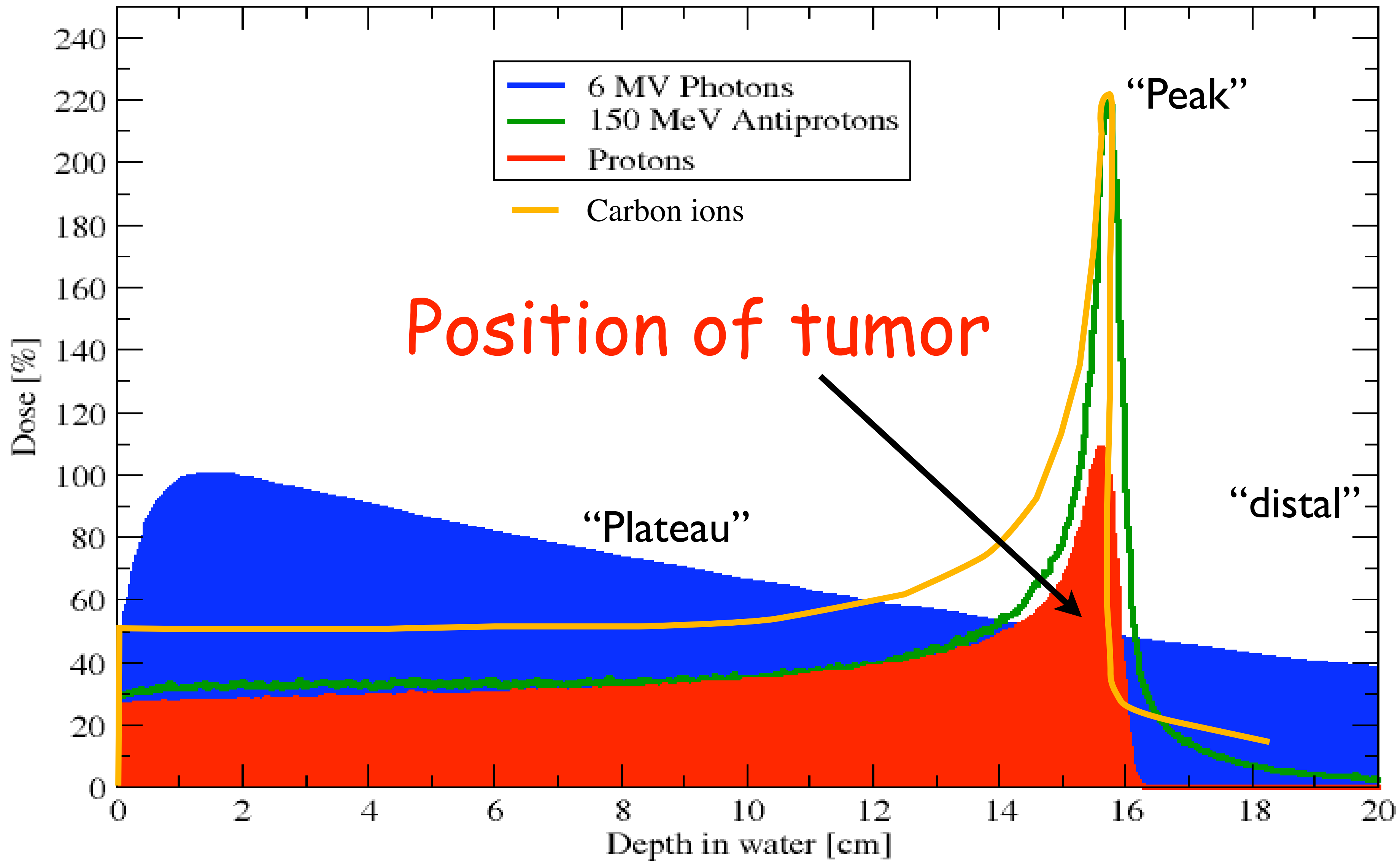
GEANT

SHIELD HIT

.

.

Monte Carlo simulations



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SHIELD HIT

.

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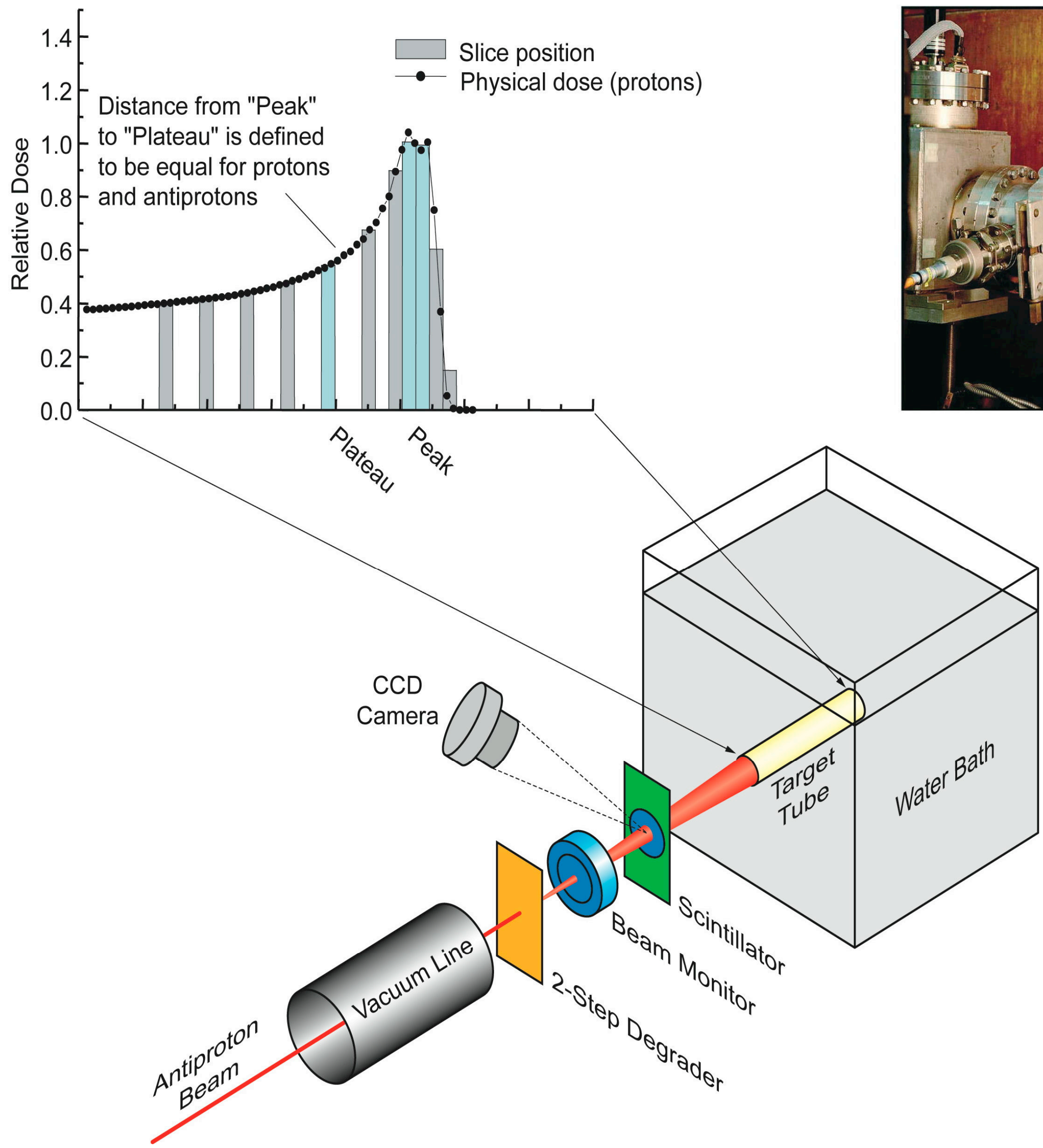
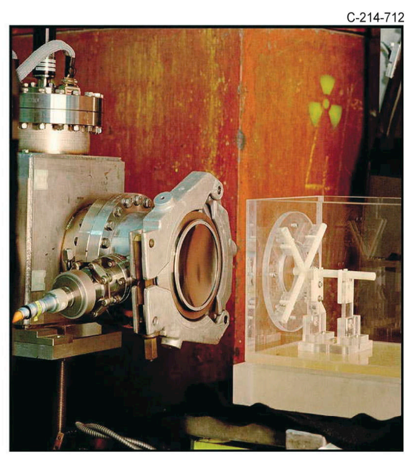
The AD-4 Experiment at CERN





Number of Surviving cells

INGREDIENTS:

- **V-79 Chinese Hamster cells embedded in gelatin**
- **Antiproton beam from AD (126 MeV)**

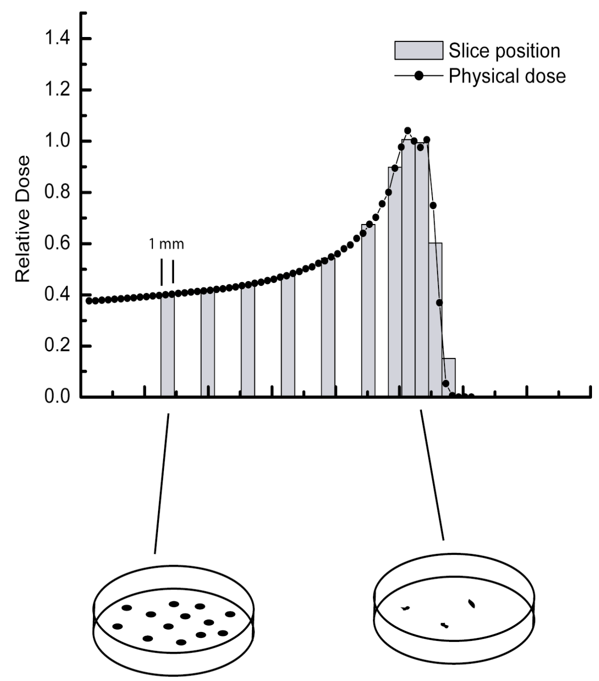
METHOD:

- **Irradiate cells with dose levels to give survival in the peak is between 0 and 90 %**
- **Slice samples, dissolve gel, incubate cells, and look for number of colonies**

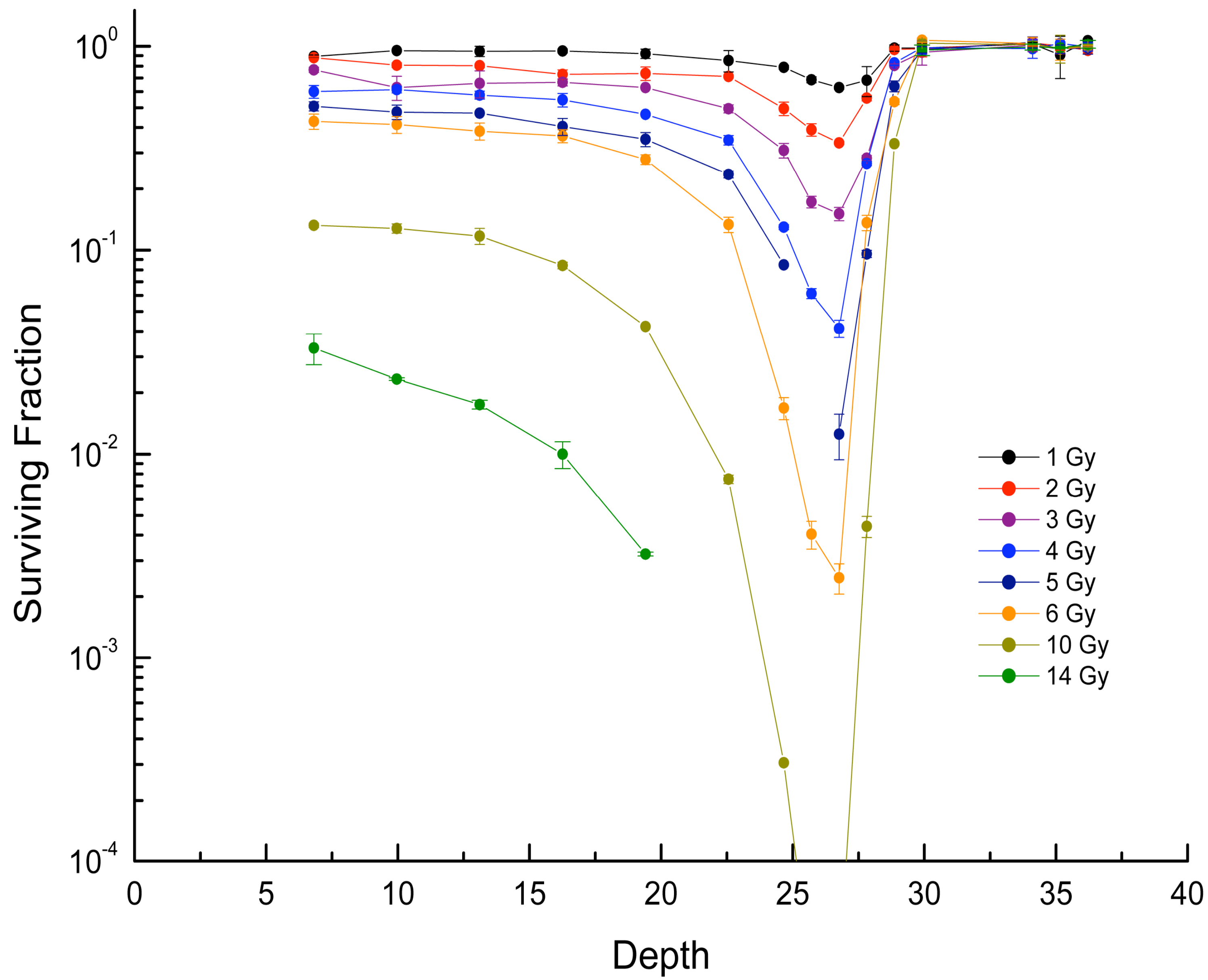
ANALYSIS:

- **Study cell survival in peak (tumor) and plateau (skin) and compare the results to protons (and carbon ions)**

Biological Analysis Method

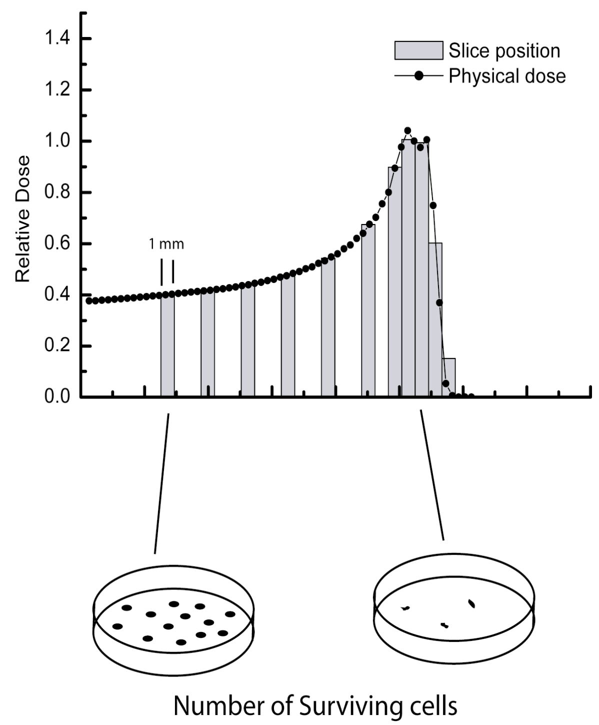


- Irradiate sample tube with living cells suspended in gel.
- Slice sample tube in ≤1 mm slices and determine survival fraction for each slice.
- Repeat for varying (peak) doses.



Example: Protons at TRIUMF

Biological Analysis Method



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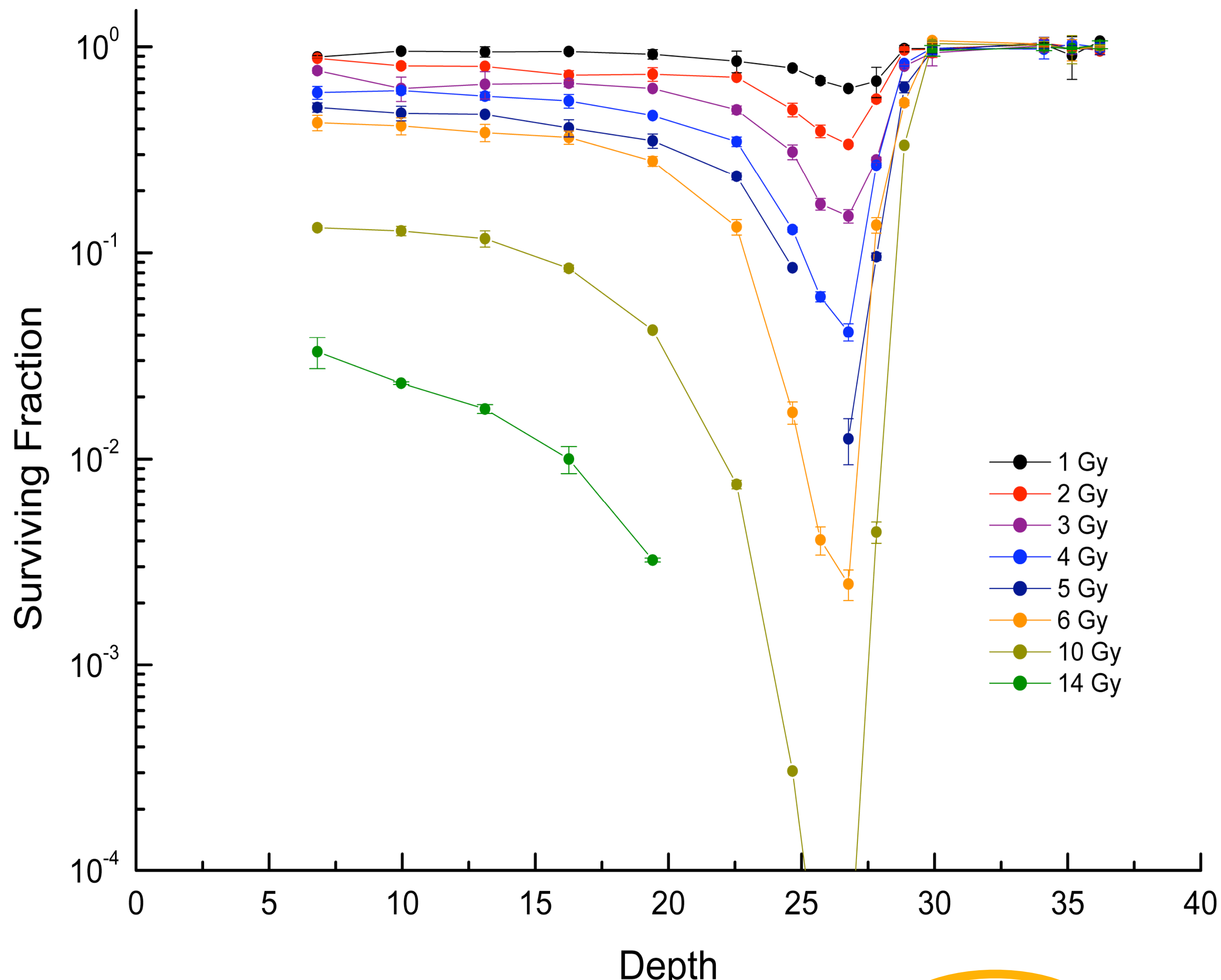

Example: Protons at TRIUMF

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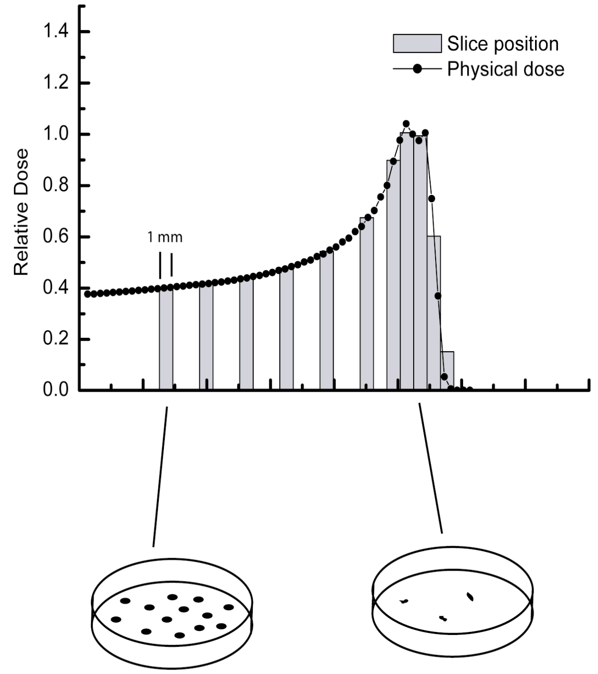

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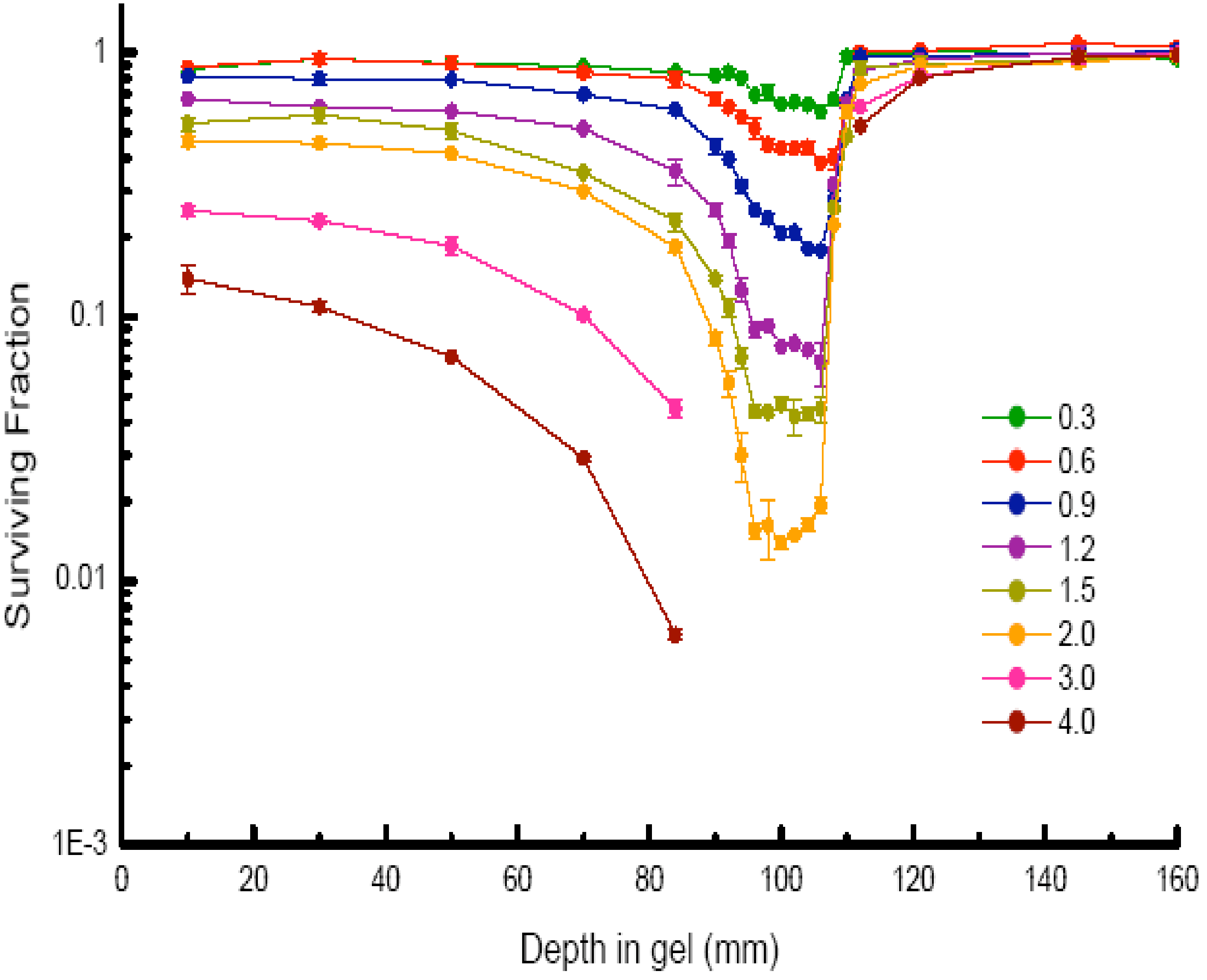
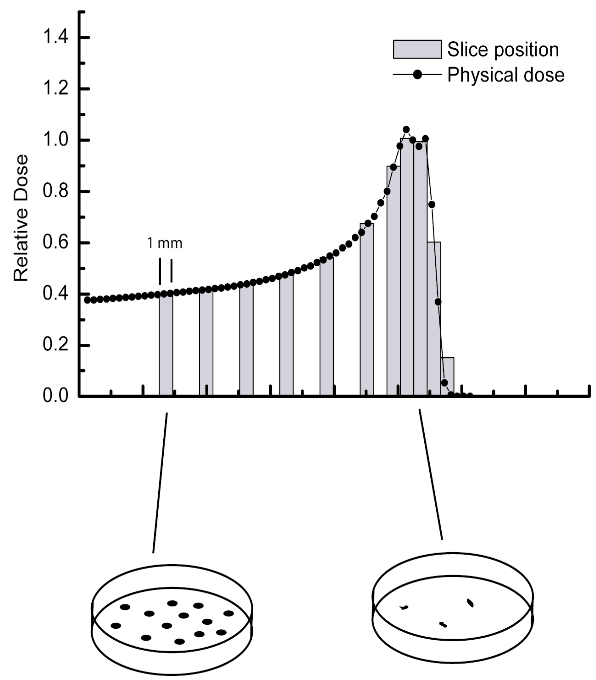


Example: SOBP of Carbon Ions at GSI

Biological Analysis Method



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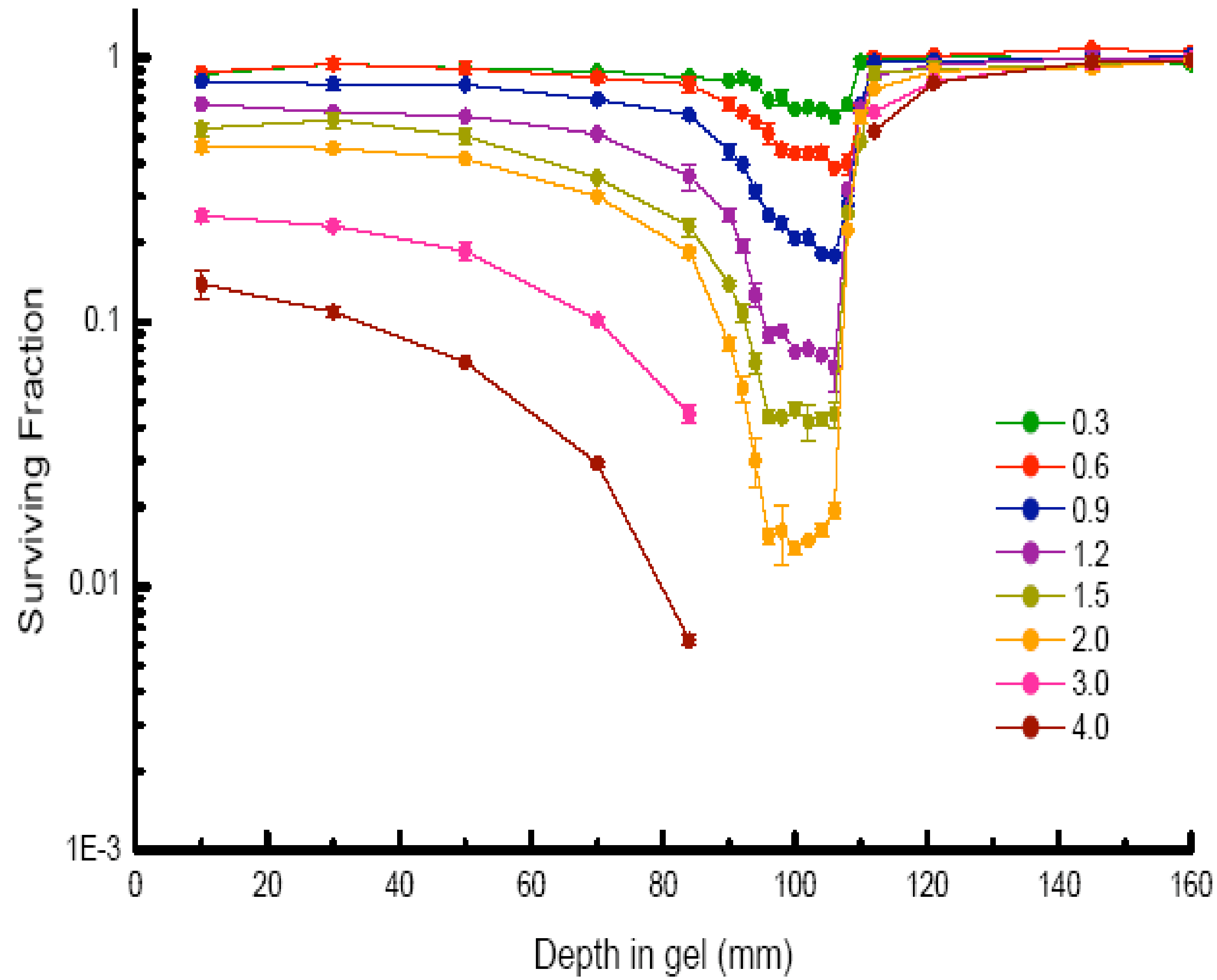
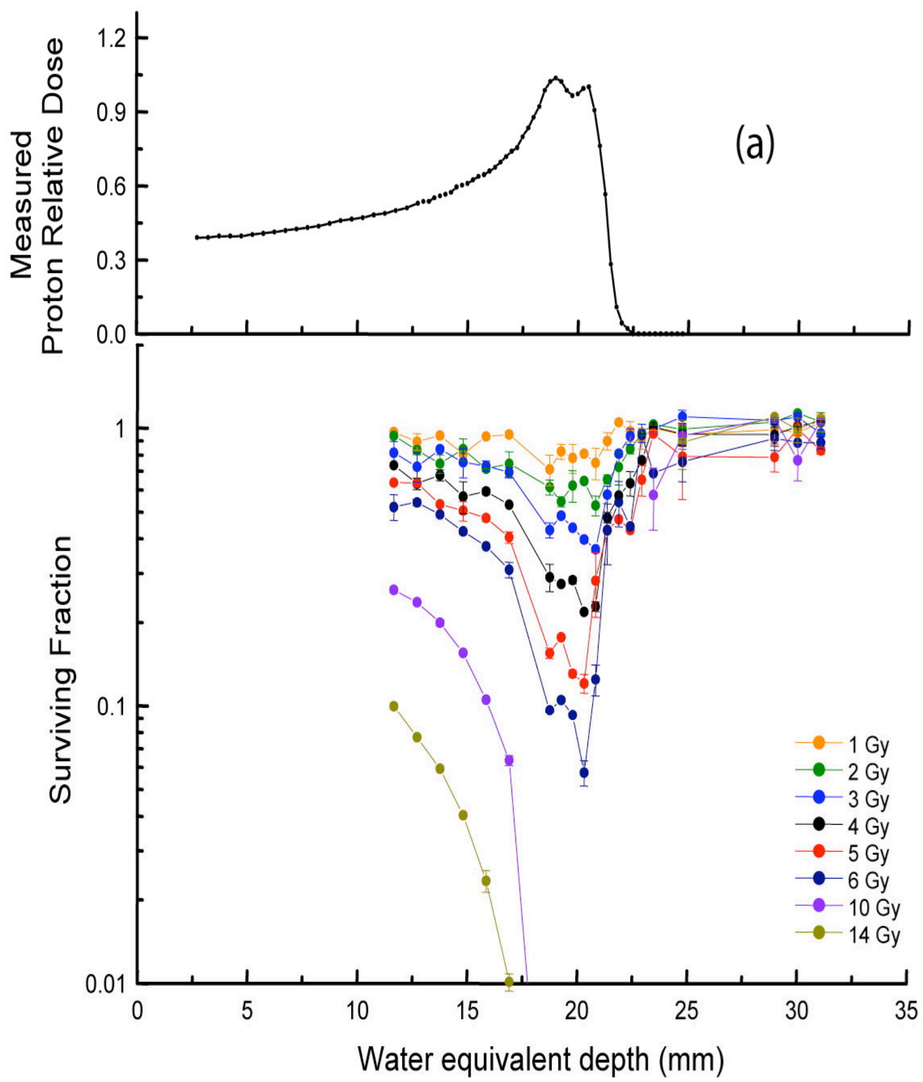


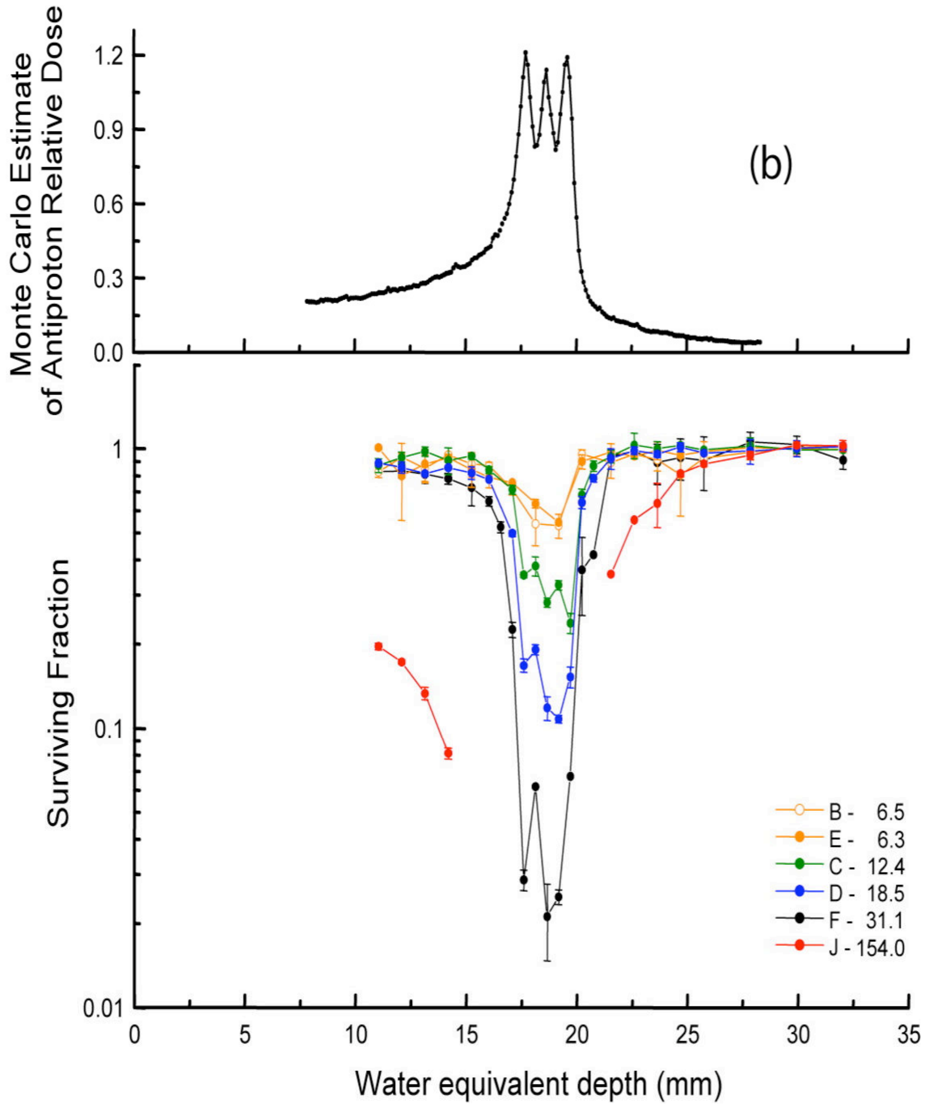
Example: SOBP of Carbon Ions at GSI

Antiproton – Proton Comparison

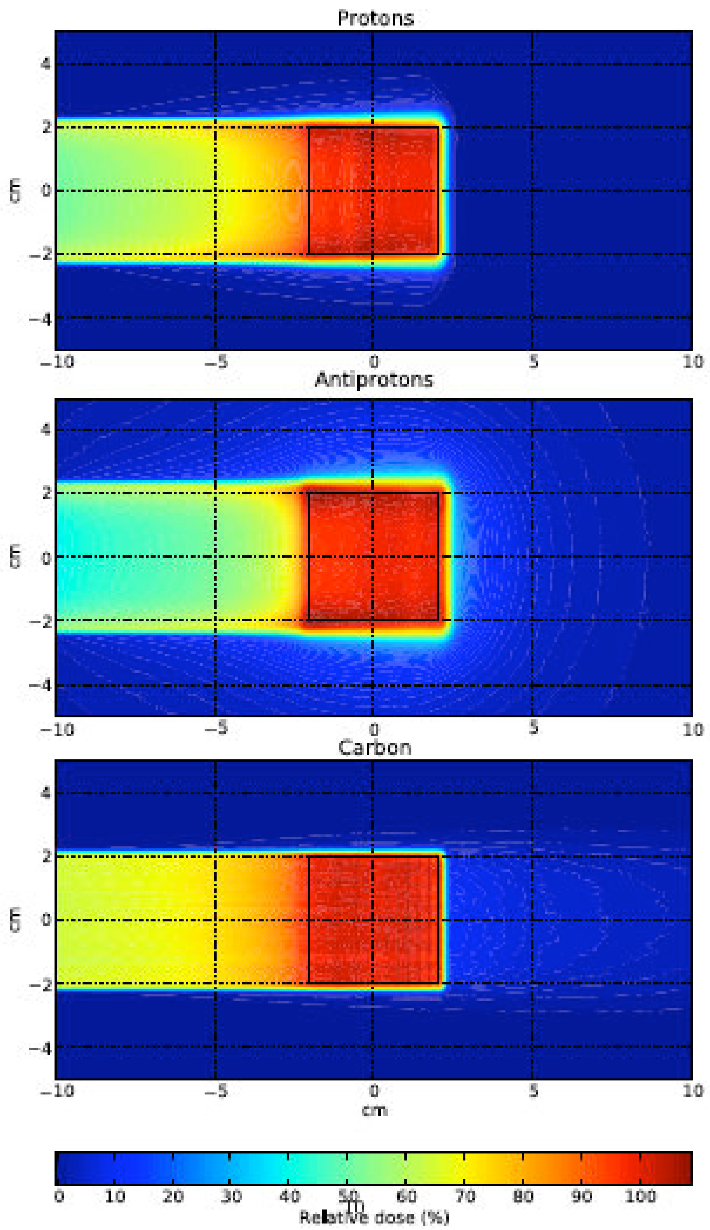
Protons



Antiprotons



Potential Clinical Advantages?



Each Particle Type shows distinct features

- Protons are well known and easy to plan (RBE = 1) which is the reason they are most widely adopted.
- Antiprotons have lowest entrance dose for the price of an extended isotropic low dose halo.
- Carbon ions have sharpest lateral penumbra but comparatively higher entrance dose than even protons (no RBE included here), but show forward directed tail due to in beam fragmentation.

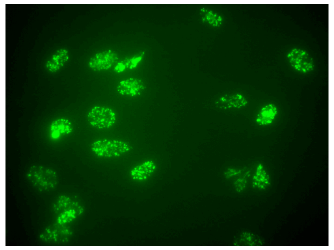
Detailed dose plans (including RBE) will need to be developed to assess applicability of particle types for different tumor types and locations!

DNA Damage Assays

There is more to biology than just clonogenics
– especially outside the targeted area:

- Immediately after attack on DNA proteins are recruited to the site
- This event signals cell cycle arrest to allow repair
- If damage is too extensive to repair programmed cell death (apoptosis) is induced
- Cells also deficient of cell cycle check point proteins may enter mitosis (cancer cells are often deficient in repair proteins and continue dividing)

γ-H2AX: Phosphorylation of H2AX in the presence of Double Strand Breaks

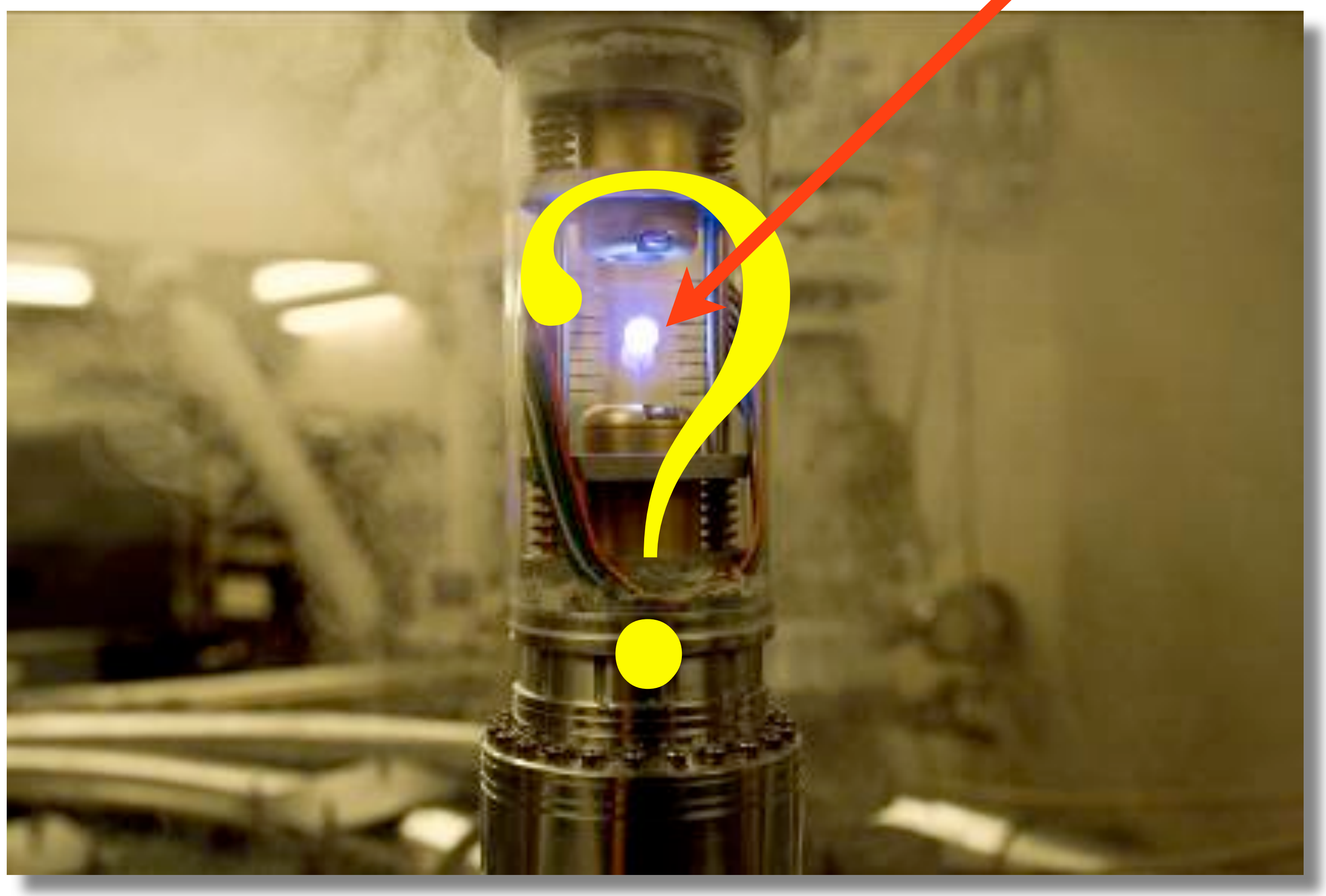


Micronuclei: Fluorescent detection of micronuclei (parts of whole chromosomes) formed due to DNA damage indicating potential of tumorigenesis

γ-H2AX and Micronucleus assays are typically used to study immediate and long term DNA damage respectively

Fuel and energy

MOT!

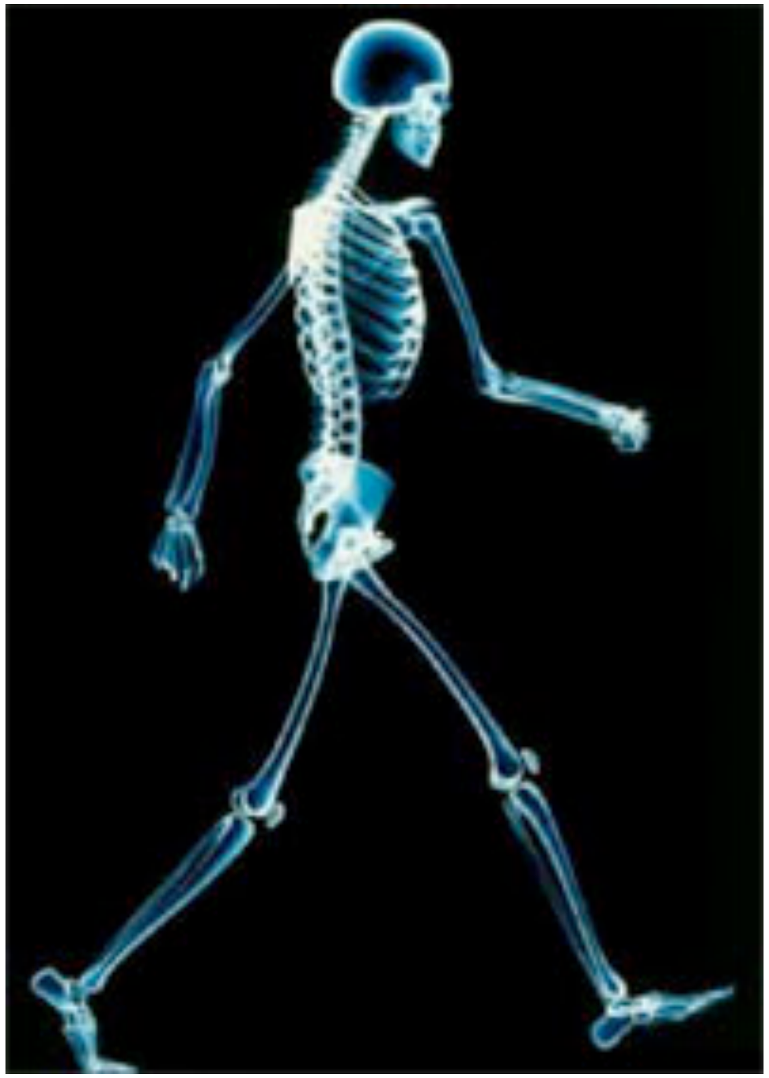


Antimatter in a trap
(in the film *Angels and Demons*)

Fuel and energy

MOT!

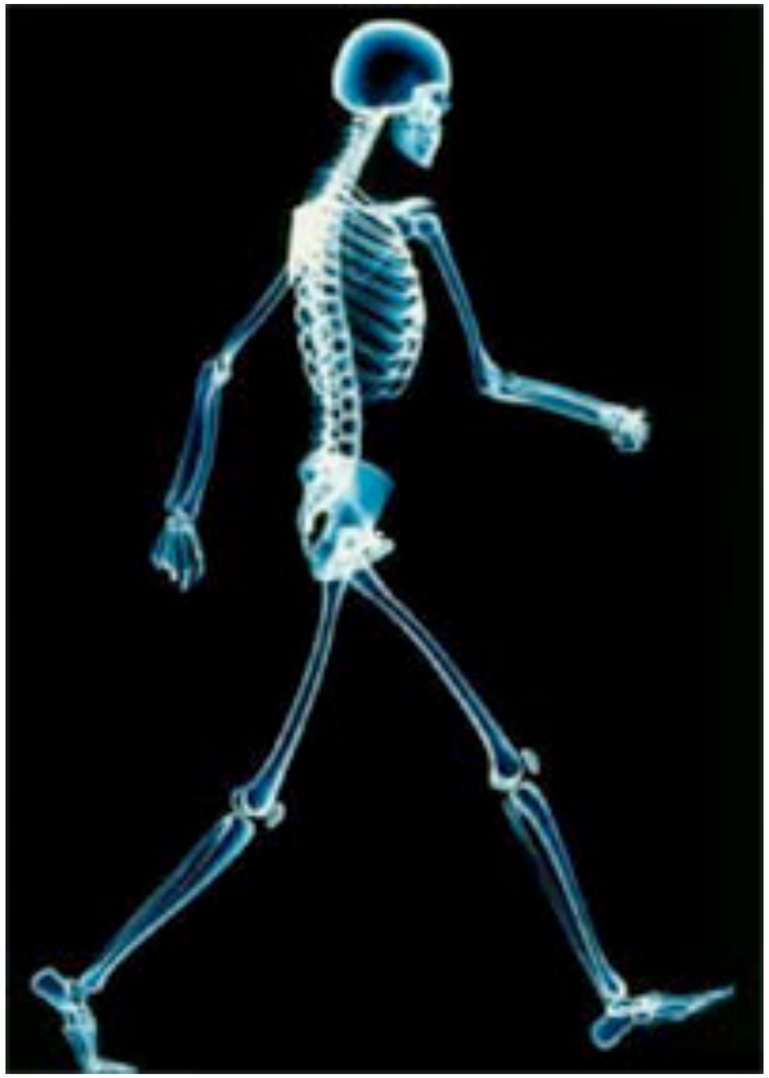
You are an antimatter factory



Your body produces antimatter:

The body of an 80 kg individual produces 180 positrons per hour! These come from the disintegration of potassium-40, a natural isotope which is absorbed by drinking water, eating (bananas!) and breathing.

You are an antimatter factory



Your body produces antimatter:

The body of an 80 kg individual produces 180 positrons per hour! These come from the disintegration of potassium-40, a natural isotope which is absorbed by drinking water, eating (bananas!) and breathing.

maybe we can do better...

...but not a lot better:

CERN produces $3x10^7 \bar{p}$/cycle ~ $10^{15} \bar{p}$/yr

20 kt TNT = $8.4 \cdot 10^{13}$ J
0.5 g antimatter
+ 0.5 g matter

0.5 g antimatter = $4.5 \cdot 10^{13}$ J

Total energy needed (efficiency $=10^{-9}$) : $4.5 \cdot 10^{22}$ J

Electricity discount price CERN
[1 kWh = $3.6 \cdot 10^6$ J = 0.1 €]

Price ~ 1,000,000,000,000,000 €

Delivery time ~ 1 000 000 000 years

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....so, can (rare, expensive and difficult-to-produce) antimatter be used for anything useful?

The usefulness of antimatter

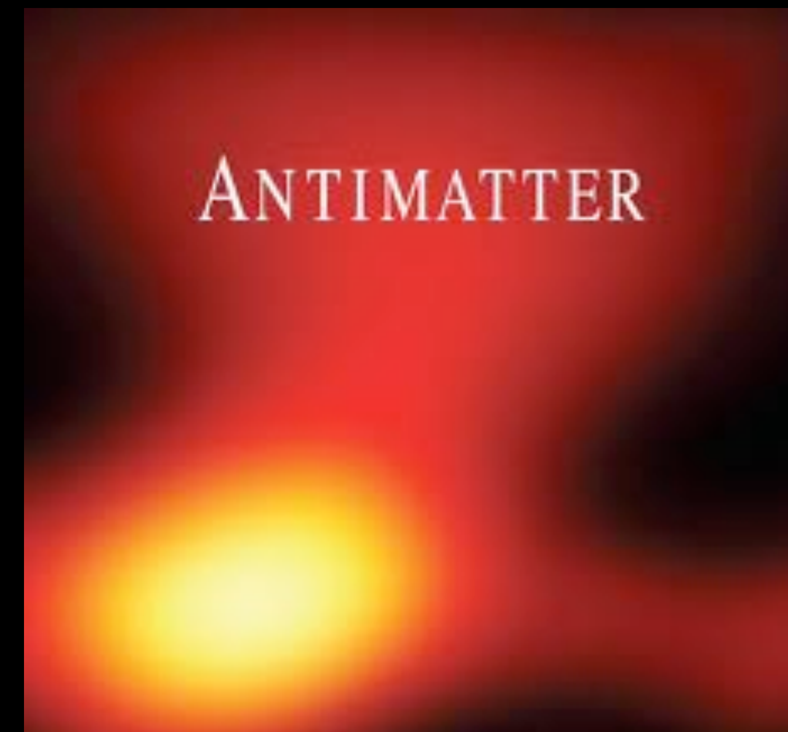
„Anti-Protonic Assumption"
Salvador Dali, 1956

The usefulness of antimatter

„Anti-Protonic Assumption“
Salvador Dali, 1956

...it’s certainly an inspiration for the imagination of artists...

The artistic value of antimatter



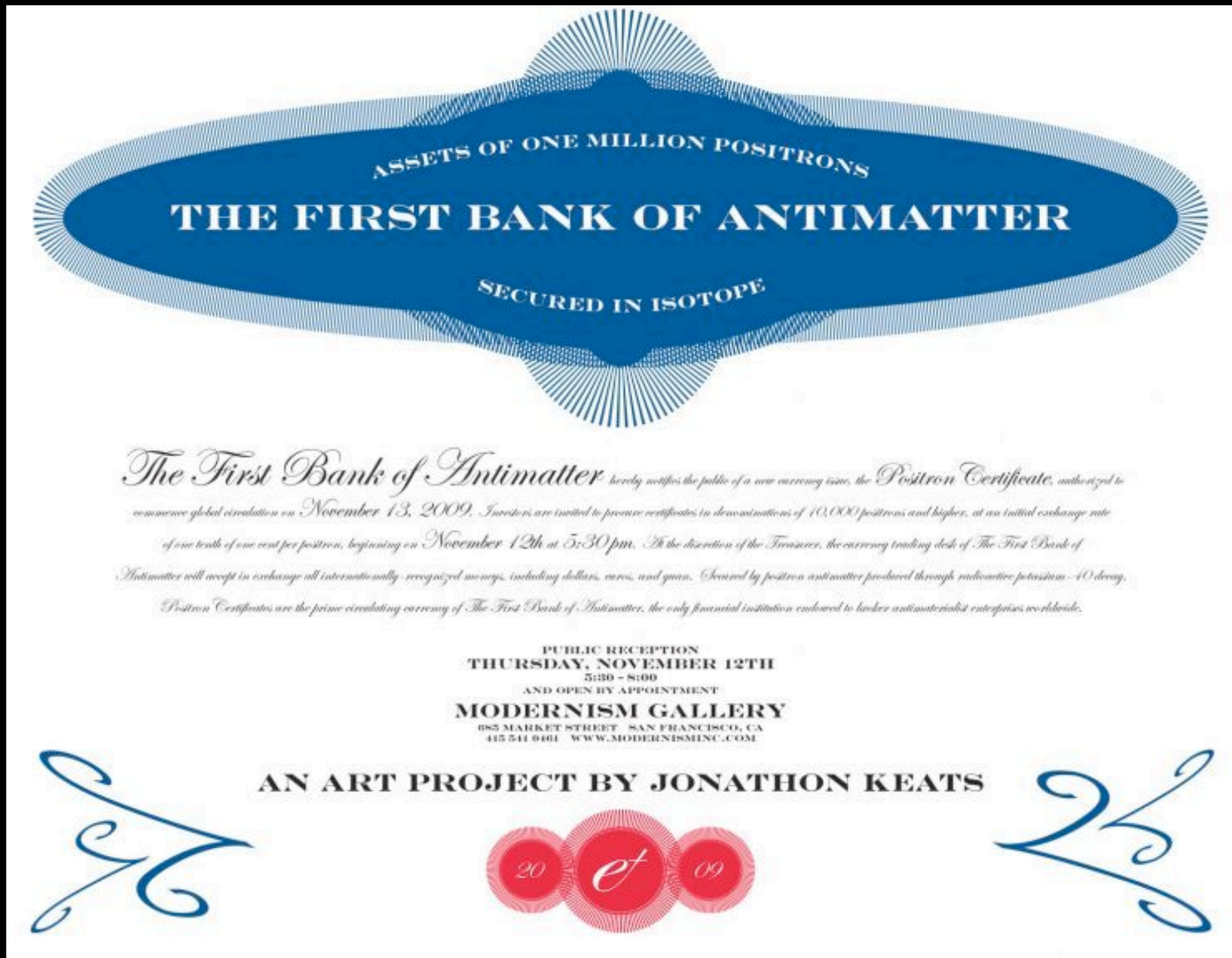
The monetary value of antimatter

Gold:
(50 kCHF/kg)

Antimatter (positrons):
(50 kCHF/GBq)

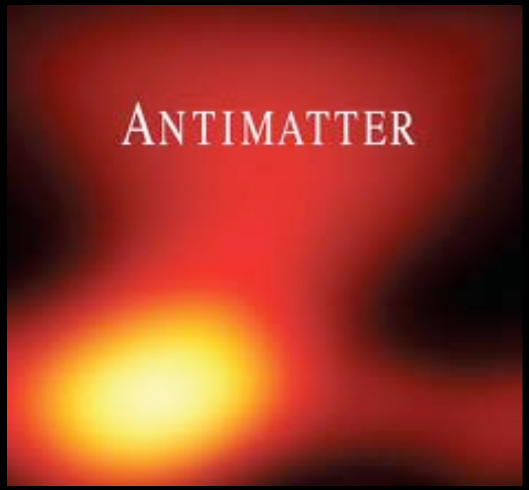
(1.5 GBq ^{22}Na source will produce about
$10^{17} e^{+} \sim 10^{-10}$ g)

The monetary value of antimatter



Two final questions:

- what does antimatter *sound* like?



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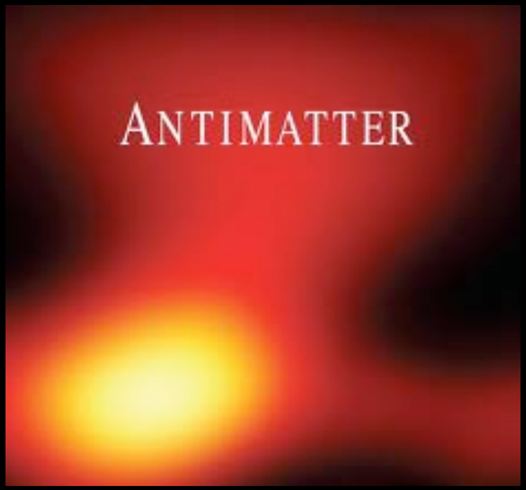

Leaving Eden is the fourth album by the UK band Antimatter.

- what does antimatter *look* like?