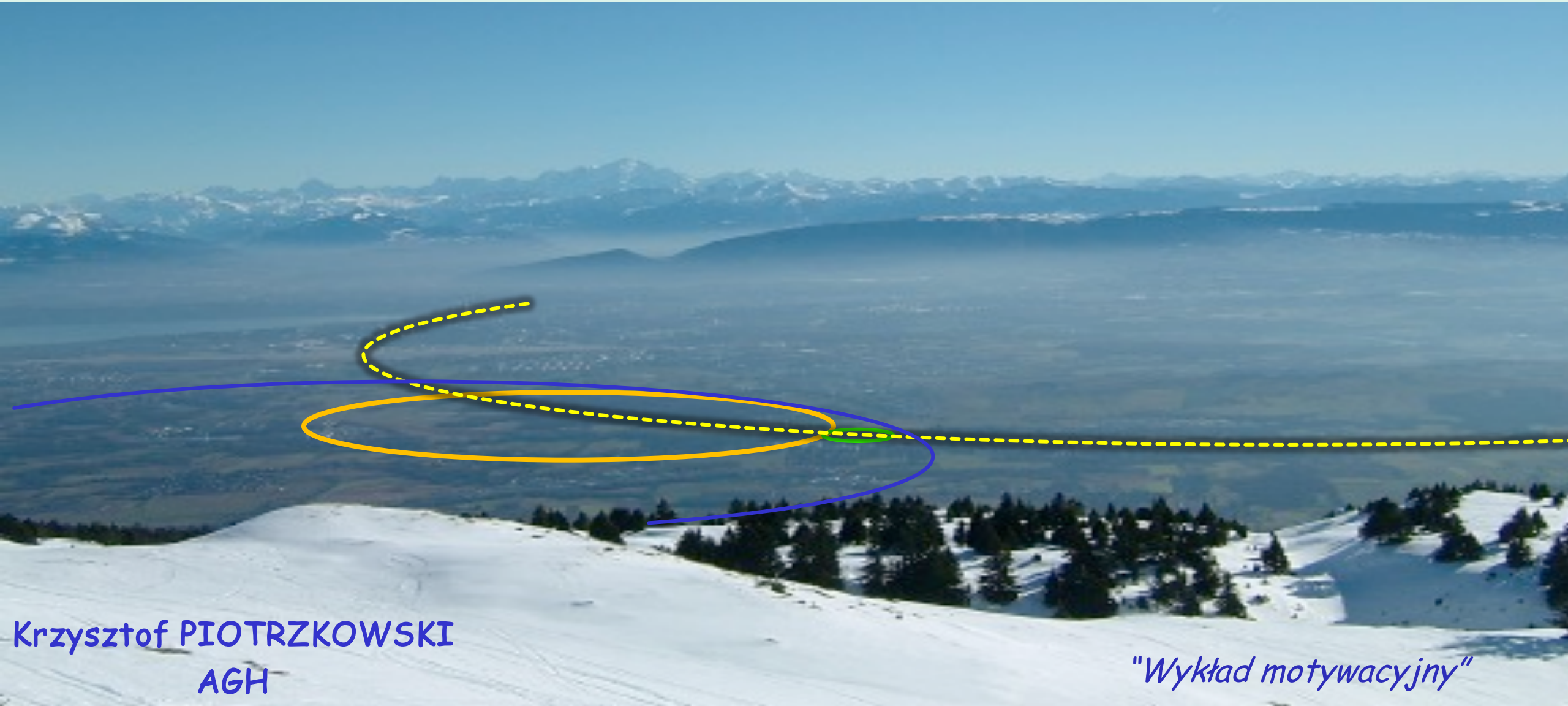
Nowoczesne detektory cząstek: od LHC do medycyny



Krzysztof PIOTRZKOWSKI
AGH

"Wykład motywacyjny"

“A picture is worth a [many] thousand words” (1911)

1932, cosmic rays in a Wilson chamber immersed in magnetic field of 1.5 T

Discovery of anti-matter!

One picture by Anderson ⇒ Nobel Prize in 1936

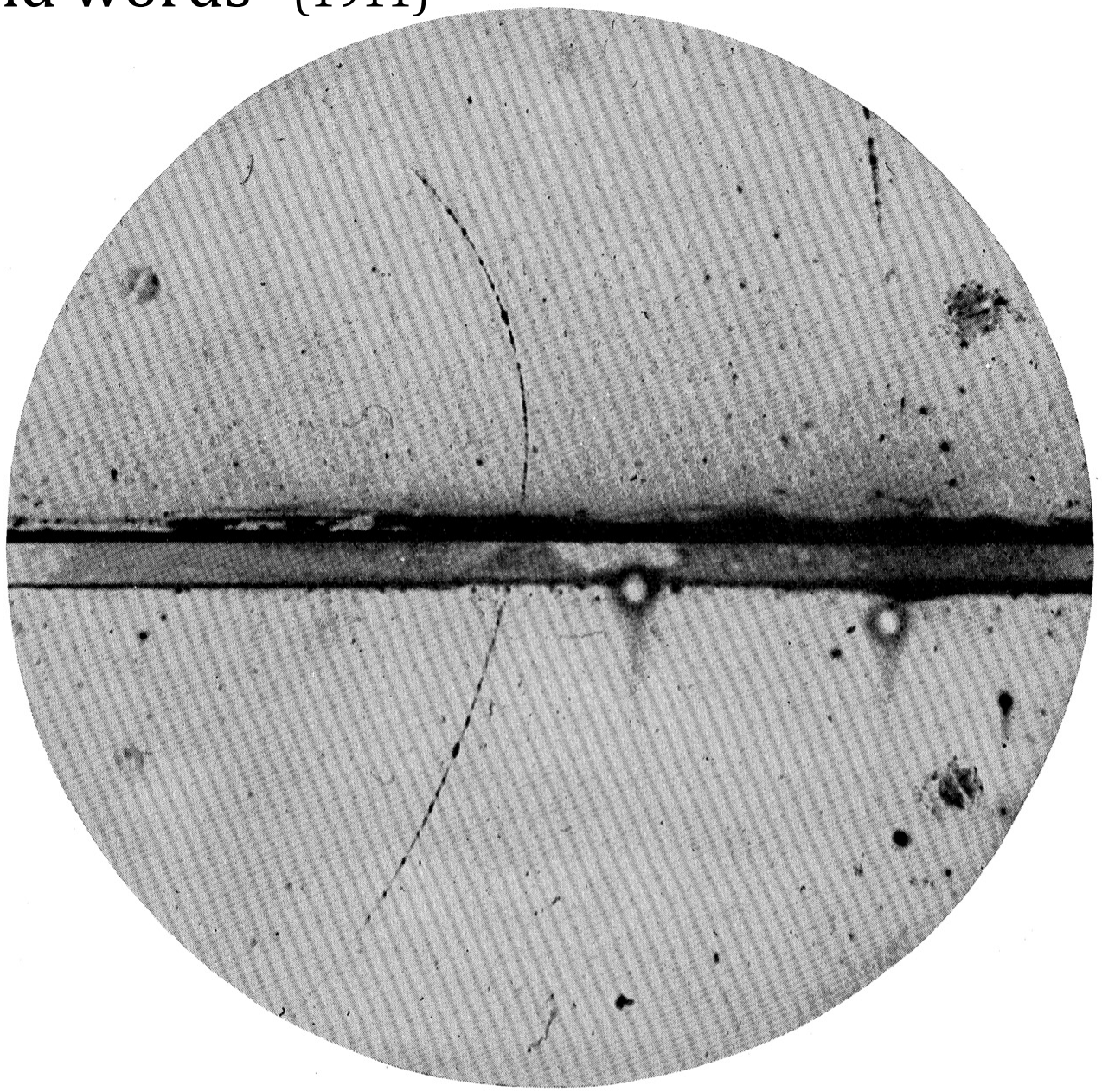
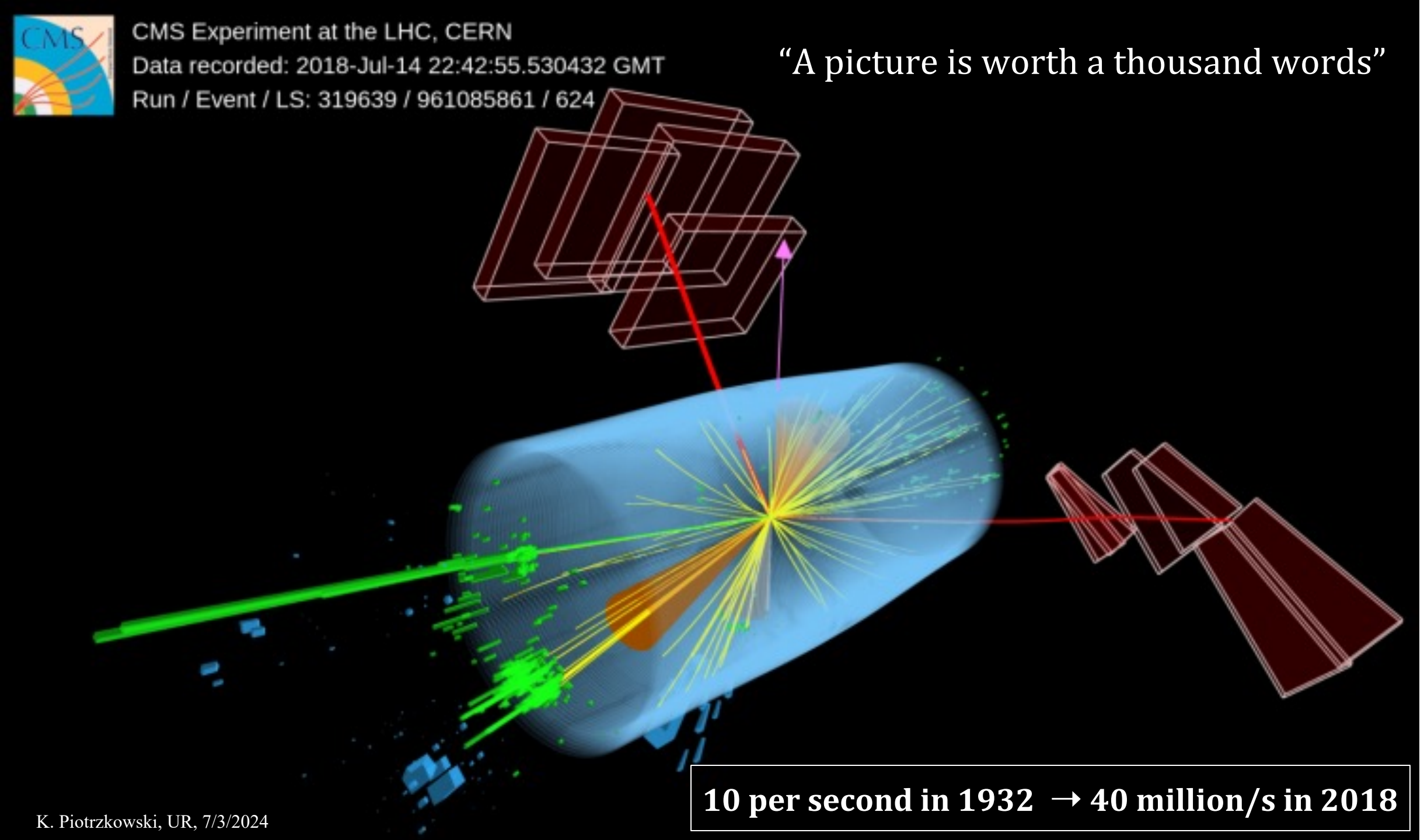


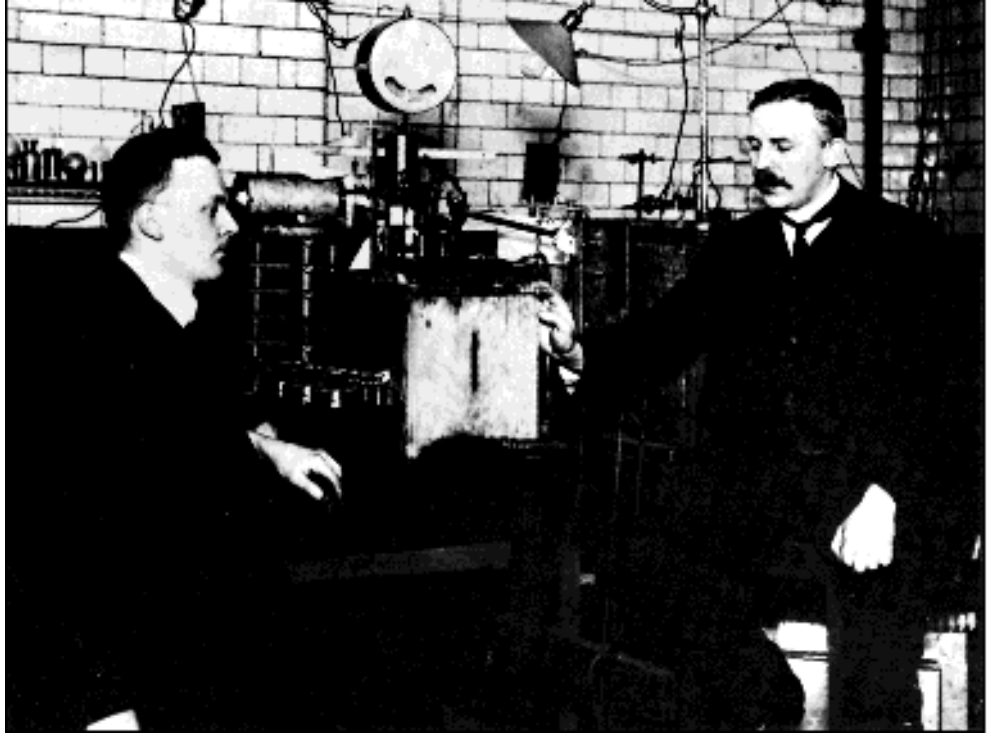
FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

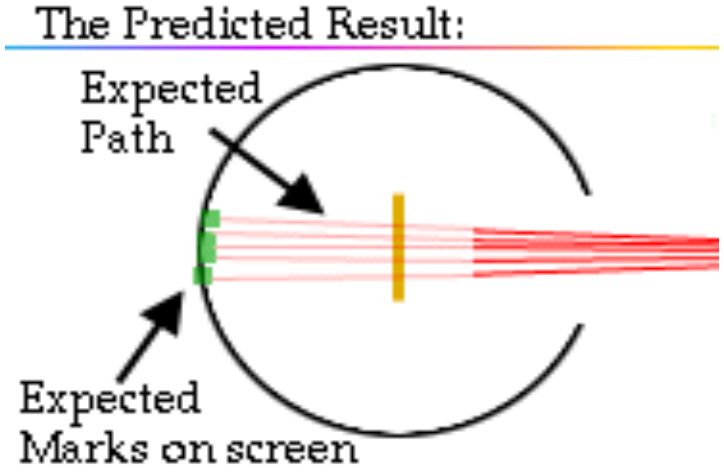


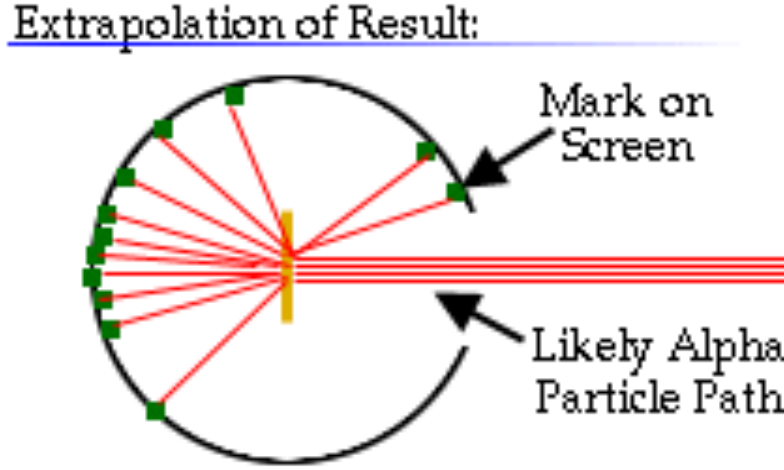
"A picture is worth a thousand words"

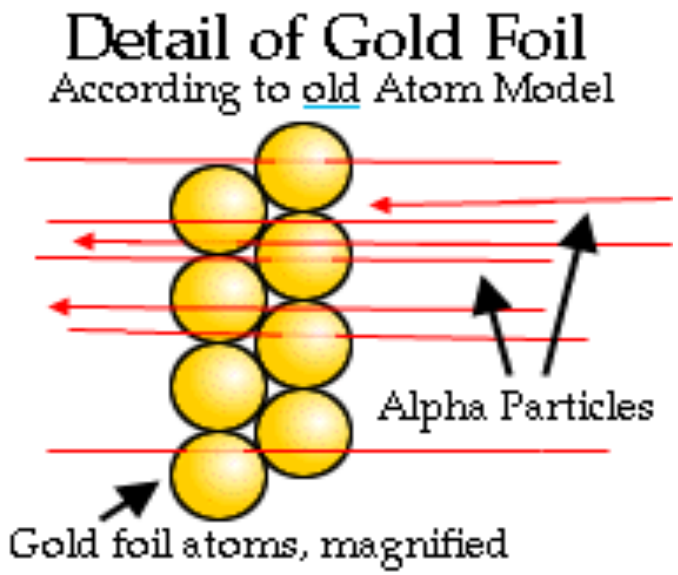
10 per second in 1932 → 40 million/s in 2018

When it all began…
(1908-13)



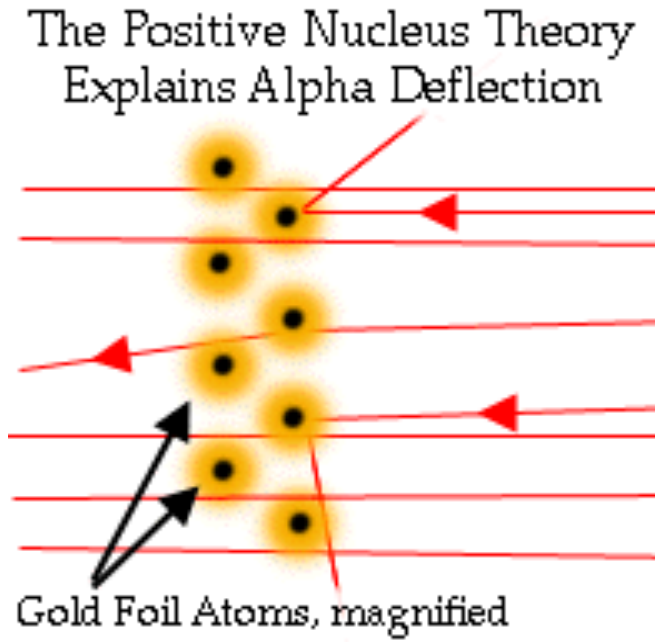






If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the atomic *fact*, or whatever you wish to call it) that *all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.*

http://www.feynmanlectures.info



Rutherford-Bohr atom model vs. *Balmer series*

Hydrogen emission lines (Ångström)

$$\lambda = B\left(\frac{m^2}{m^2 - n^2}\right) = B\left(\frac{m^2}{m^2 - 2^2}\right)$$

Where

- λ is the wavelength.
- B is a constant with the value of $3.645\,0682 \times 10^{-7}$ m or 364.506 82 nm.
- m is the initial state
- n is an integer such that $m > n \geq 2$.

This was final inspiration for proposing by N. Bohr first quantum model of atom

Experiments in particle physics... simply follow Rutherford's

Conceptually very simple:

Initial state $_{(t=-\infty)}$ ➔ **INTERACTIONS** ➔ Final state $_{(t=\infty)}$

Prepared Detected

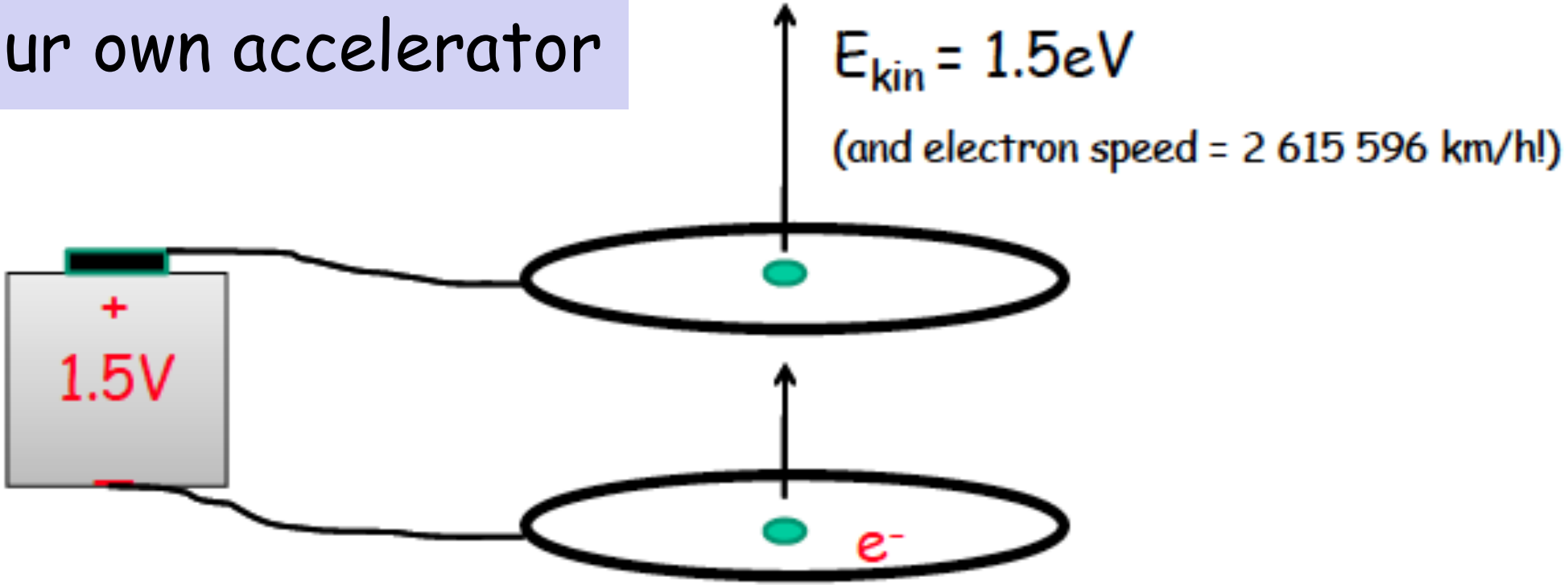
Various two-particle reactions (as *pp* or e^+e^-) are studied:

in general $1 + 1 \rightarrow N$, and $1 + 1 \rightarrow 1 \Rightarrow$ *resonance* production

SPECIAL (Rutherford) concepts: cross-section

and scattering of plane waves (for fixed momenta)

Build your own accelerator



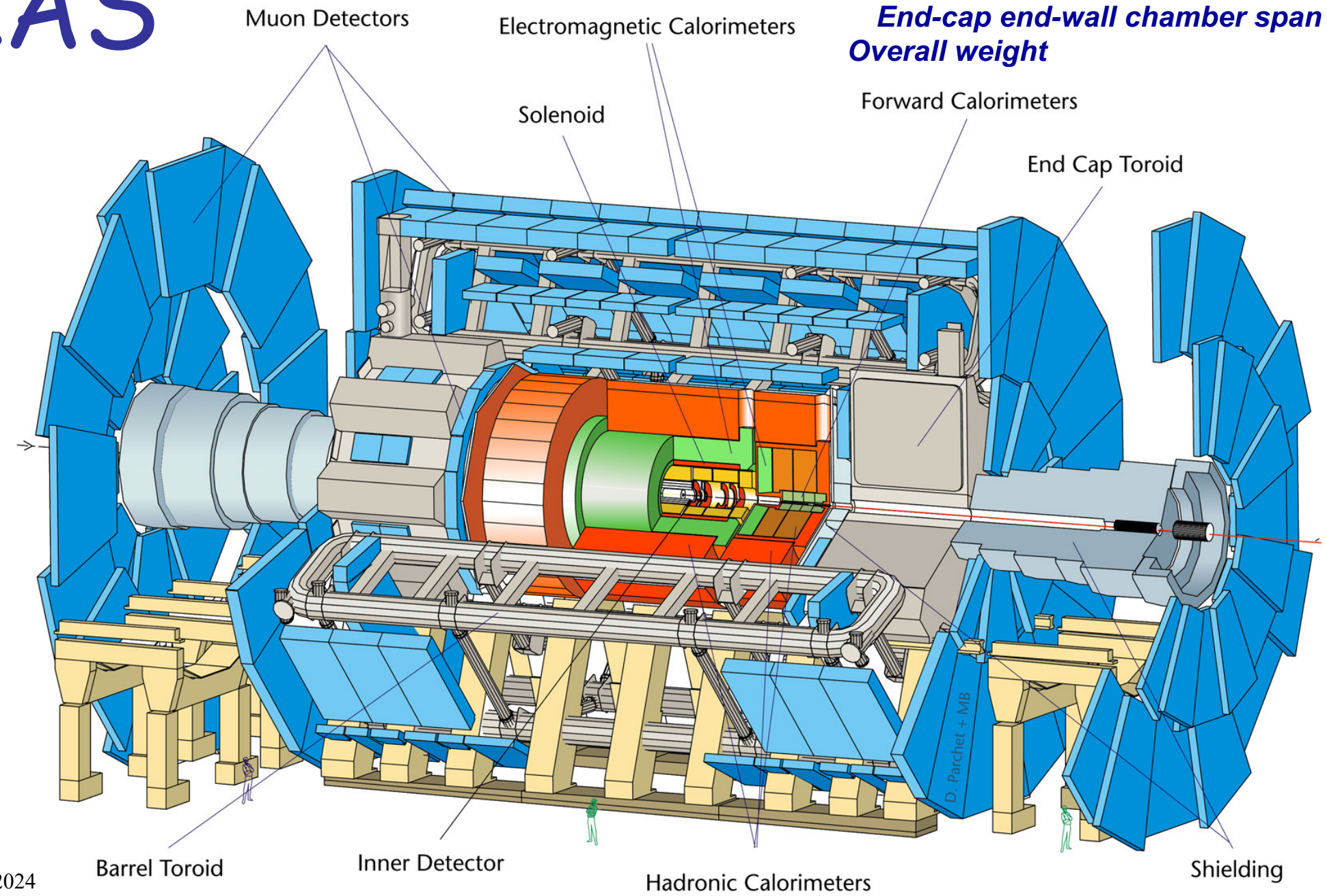
$E = mc^2 \rightarrow$ Energy in eV and mass in eV/c^2
(momentum in eV/c)

$e^+e^- \rightarrow \gamma\gamma$

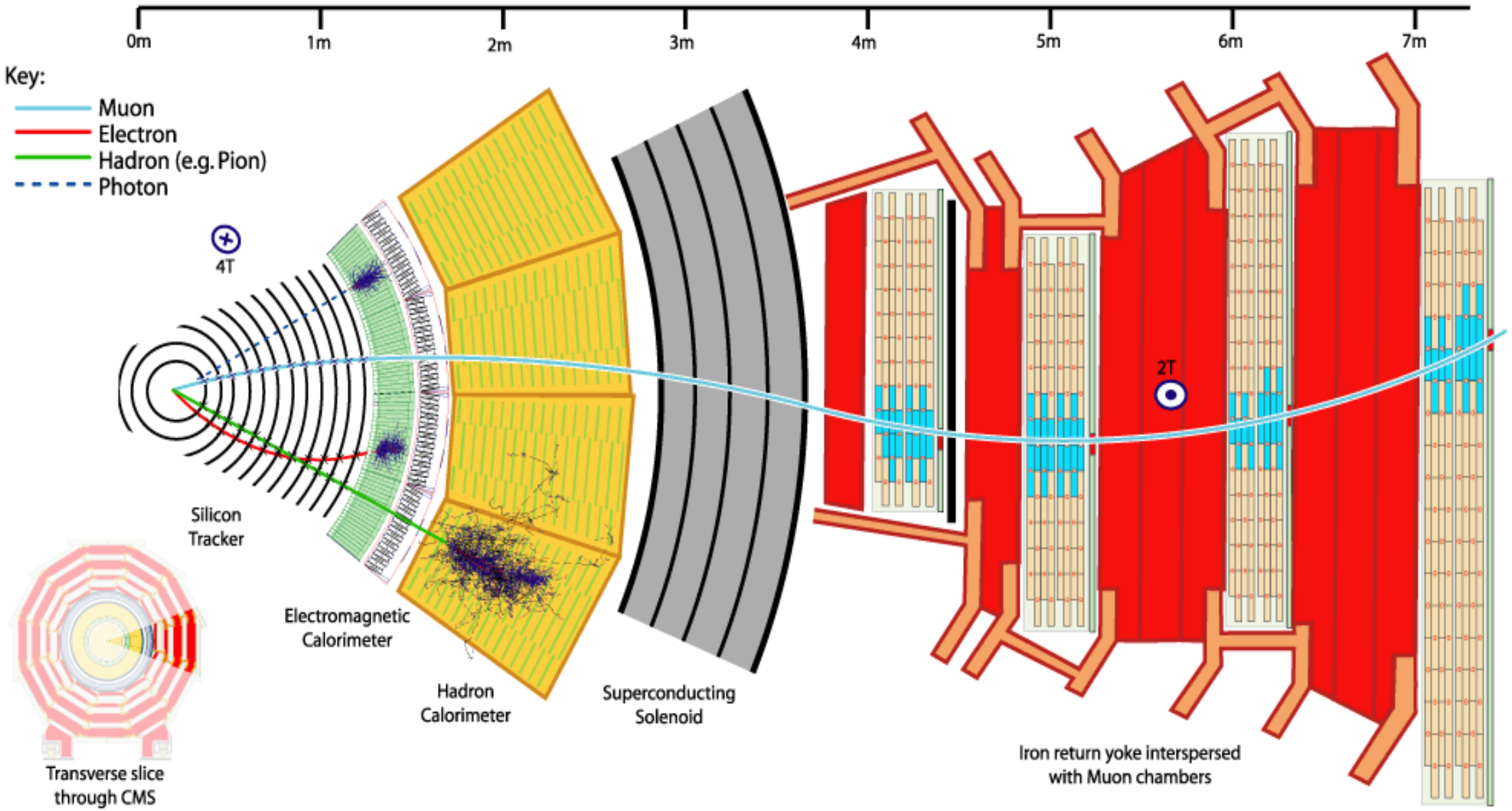
Proton mass = 938 MeV/c^2 (= 1.67×10^{-27} kg)
Electron mass = 511 keV/c^2 (= 9.11×10^{-31} kg)

ATLAS

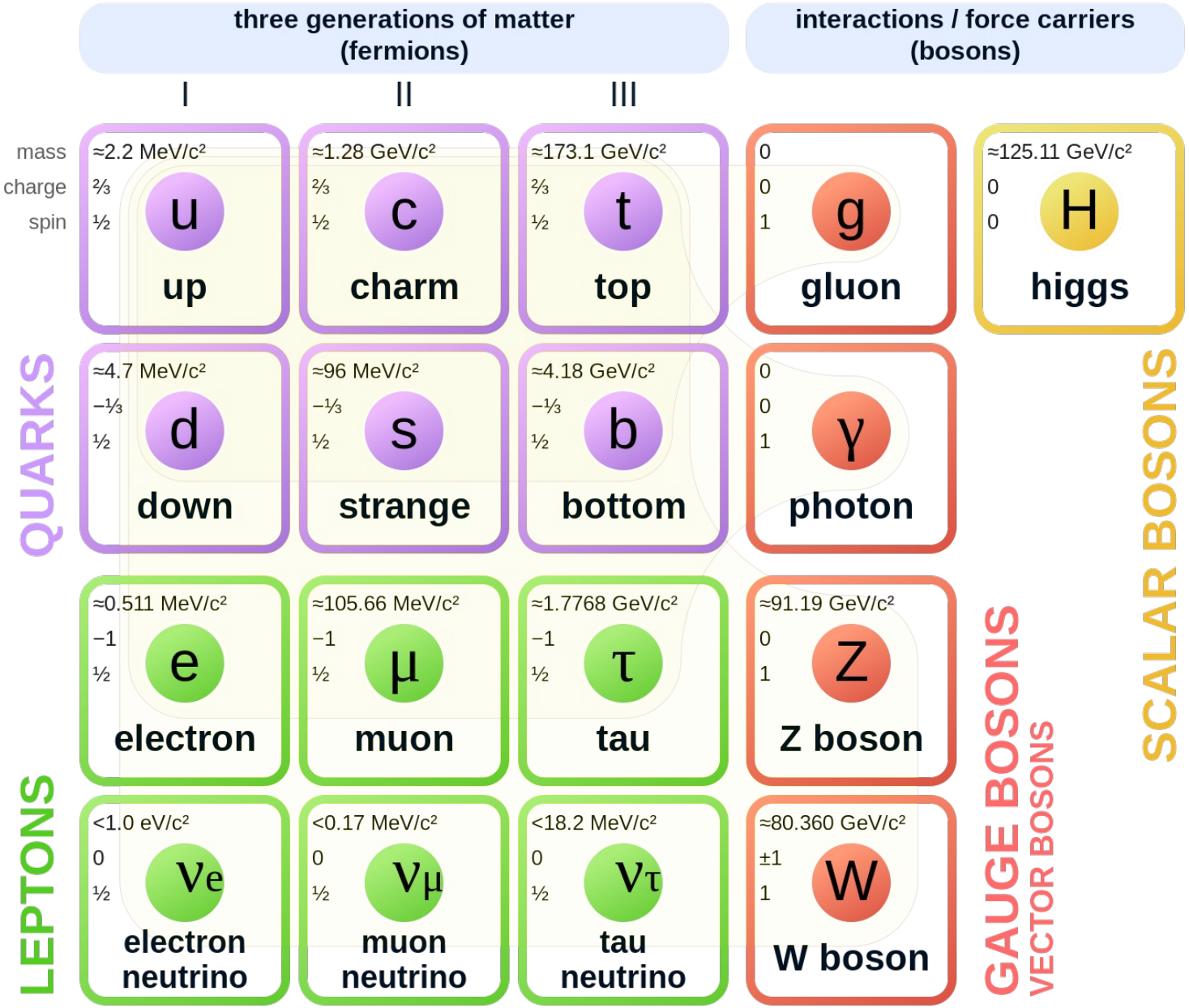
Diameter	***25 m***
Barrel toroid length	***26 m***
End-cap end-wall chamber span	***46 m***
Overall weight	***7000 Tons***



CMS *aka* Compact(!) Muon Spectrometer



Standard Model of Elementary Particles



Is Particle Physics completely explained by Standard Model, as chemistry was by Quantum Theory?

Not quite…

Many questions left unanswered:

- Why 3 families?
- Why such type of symmetries?
- Where is gravity?
- **Why such mass patterns?**

Mass patterns

Two fascinating numerical hints?

1. $m_H \simeq \sqrt{(m_{top} * m_Z)}$ - it combines spin = 0, 1/2 and 1 particles!

2. *Koide* charged lepton mass relation (back from 1981!)

$$Q = \frac{m_e + m_\mu + m_\tau}{\left(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau} \right)^2} = 0.666661(7) \approx \frac{2}{3}$$

Motivation 1: if **you** find explanation (remember Balmer vs. Bohr?), can calmly wait for phone from Stockholm…

1st Nobel prize

Use of photographic paper as detector
→ Detection of photons / x-rays

W. C. Röntgen, 1895 ()
Discovery of the ‘X-Strahlen’

Photographic paper/film

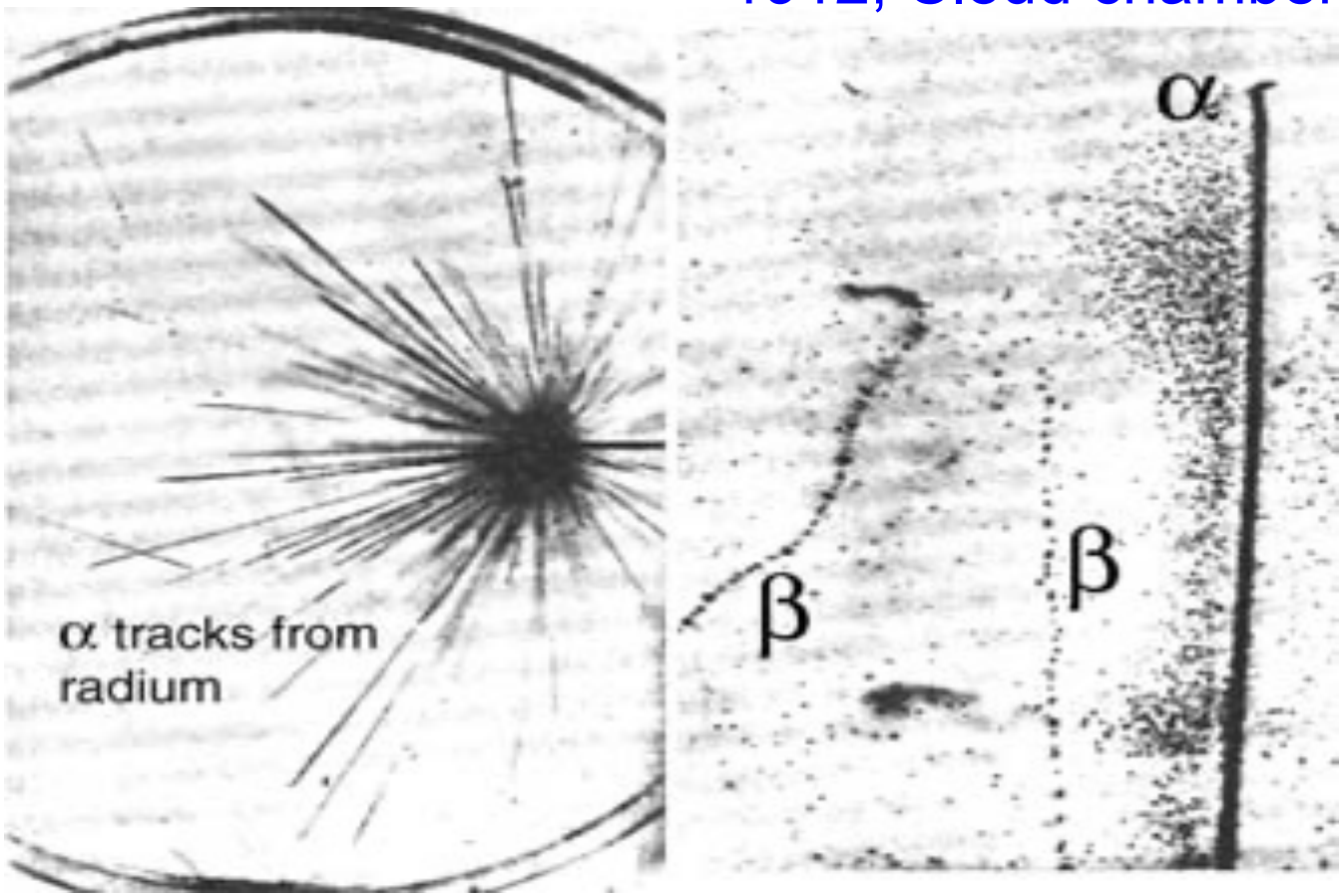
e.g. AgBr / AgCl

AgBr + ‘energy’
→ metallic Ag (blackening)

+ Very good spatial resolution
+ Good dynamic range
- No online recording
- No time resolution

... and (many) more ...

C. T. R. Wilson,
1912, Cloud chamber

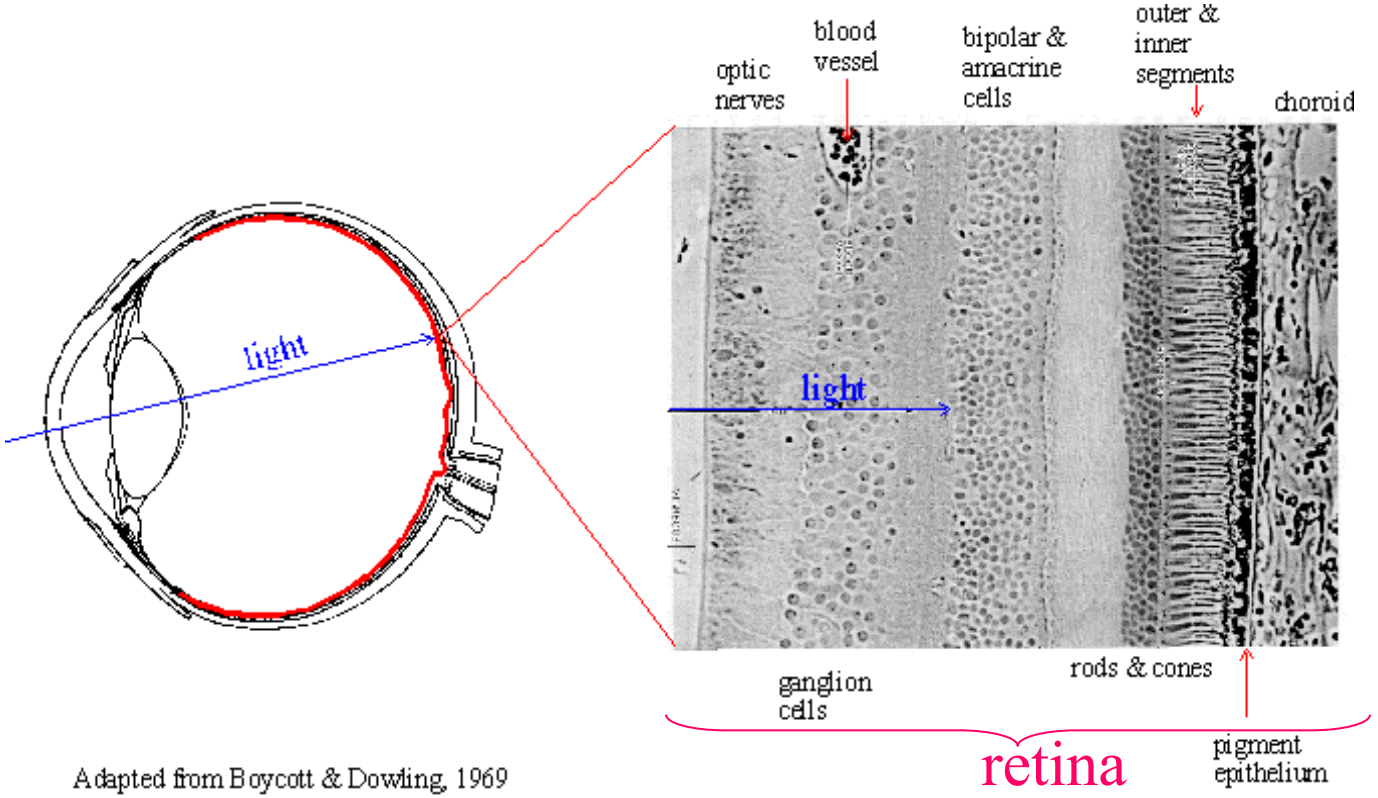


First tracking detector

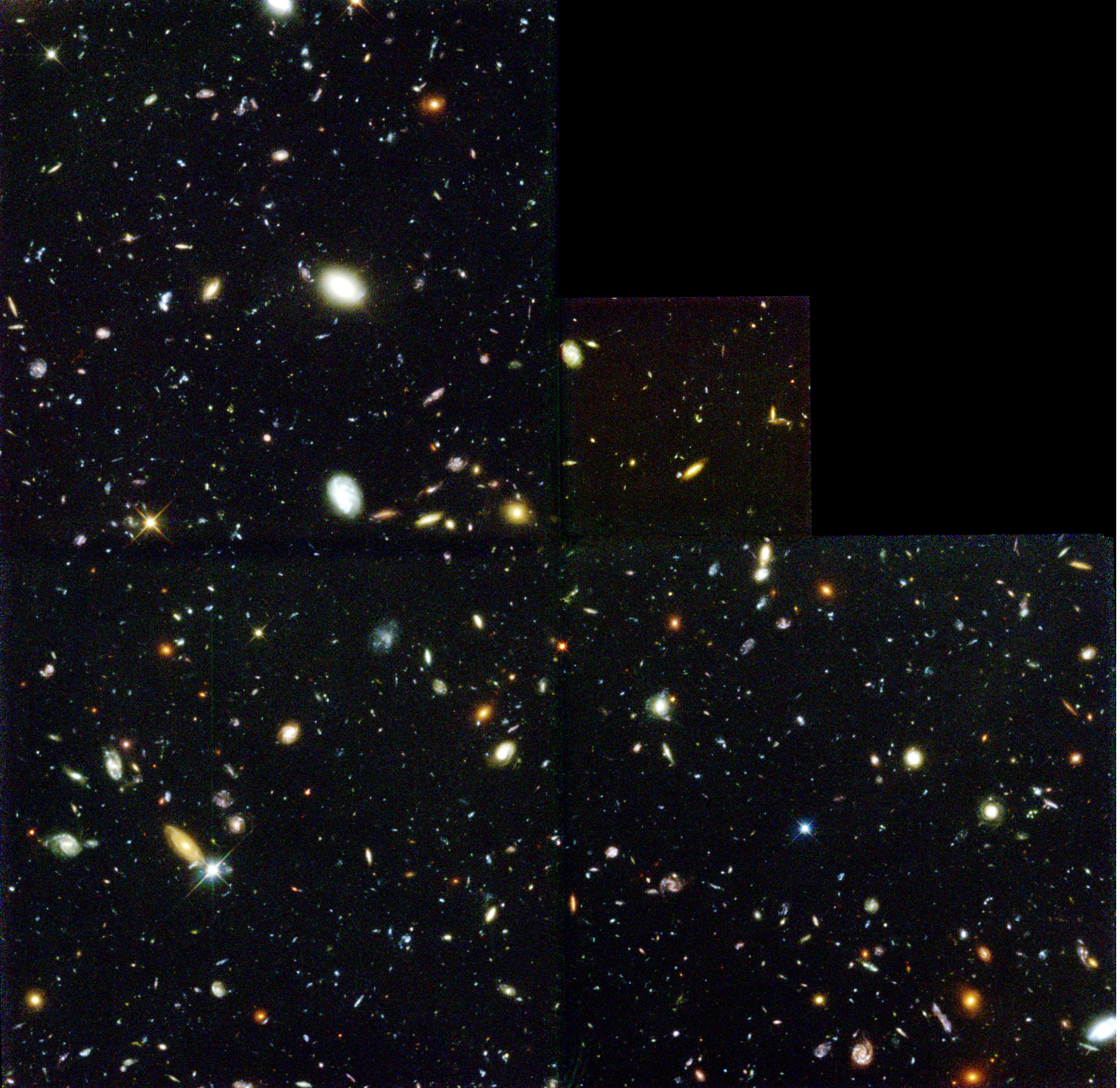
The general procedure was to allow water to evaporate in an enclosed container to the point of saturation and then lower the pressure, producing a super-saturated volume of air. Then the passage of a charged particle would condense the vapor into tiny droplets, producing a visible trail marking the particle's path.

“The oldest particle detector” (built many billion times)

- High sensitivity to photons
- Good spatial resolution
- Very large dynamic range (1:10^{14}) + automatic threshold adaptation
- Energy (wavelength) discrimination
- Modest speed; Data taking rate ~ 10Hz (incl. processing)



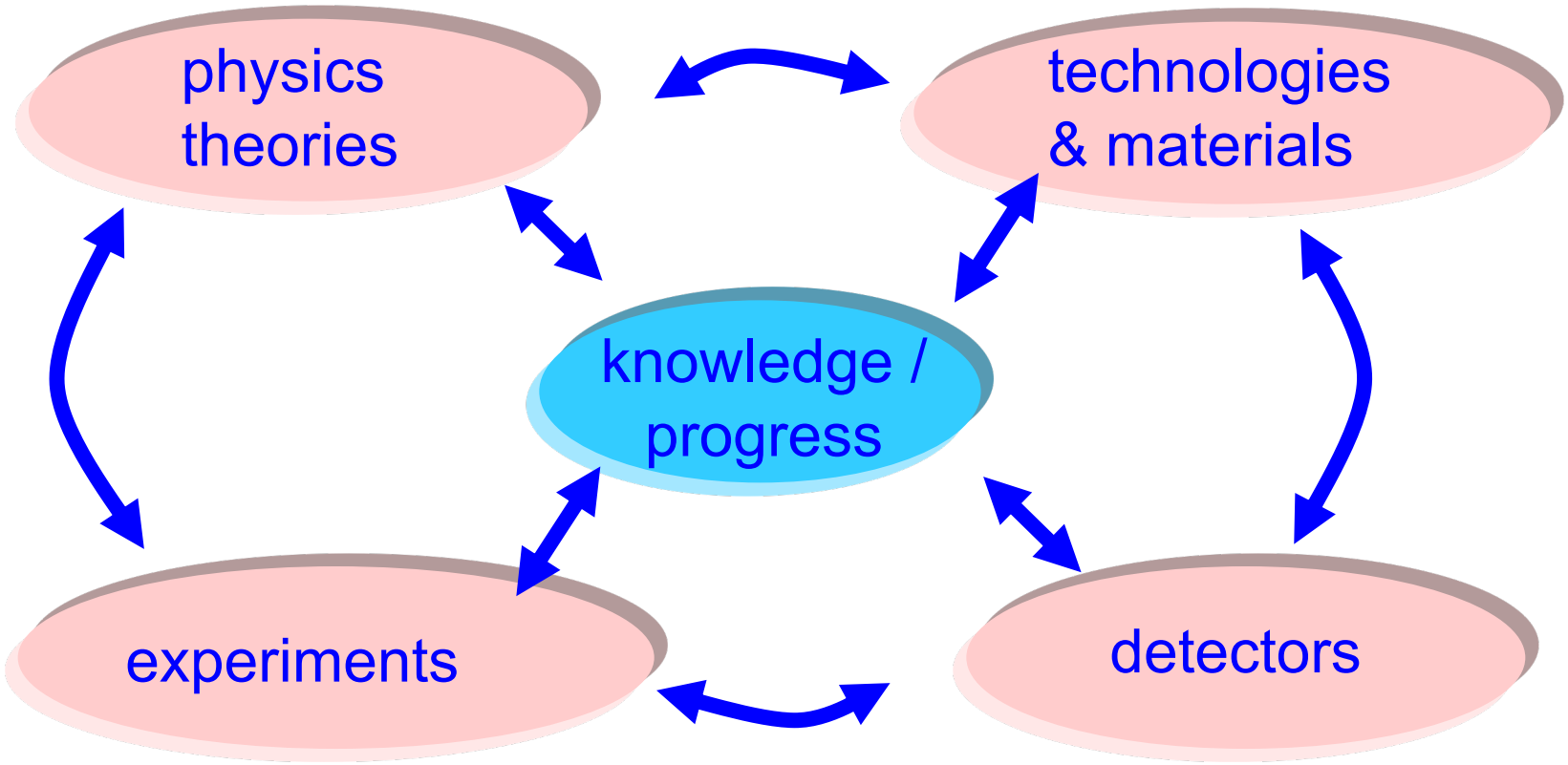
Adapted from Boycott & Dowling, 1969



Modern "instrumented eye" *aka* Hubble Deep Field image…

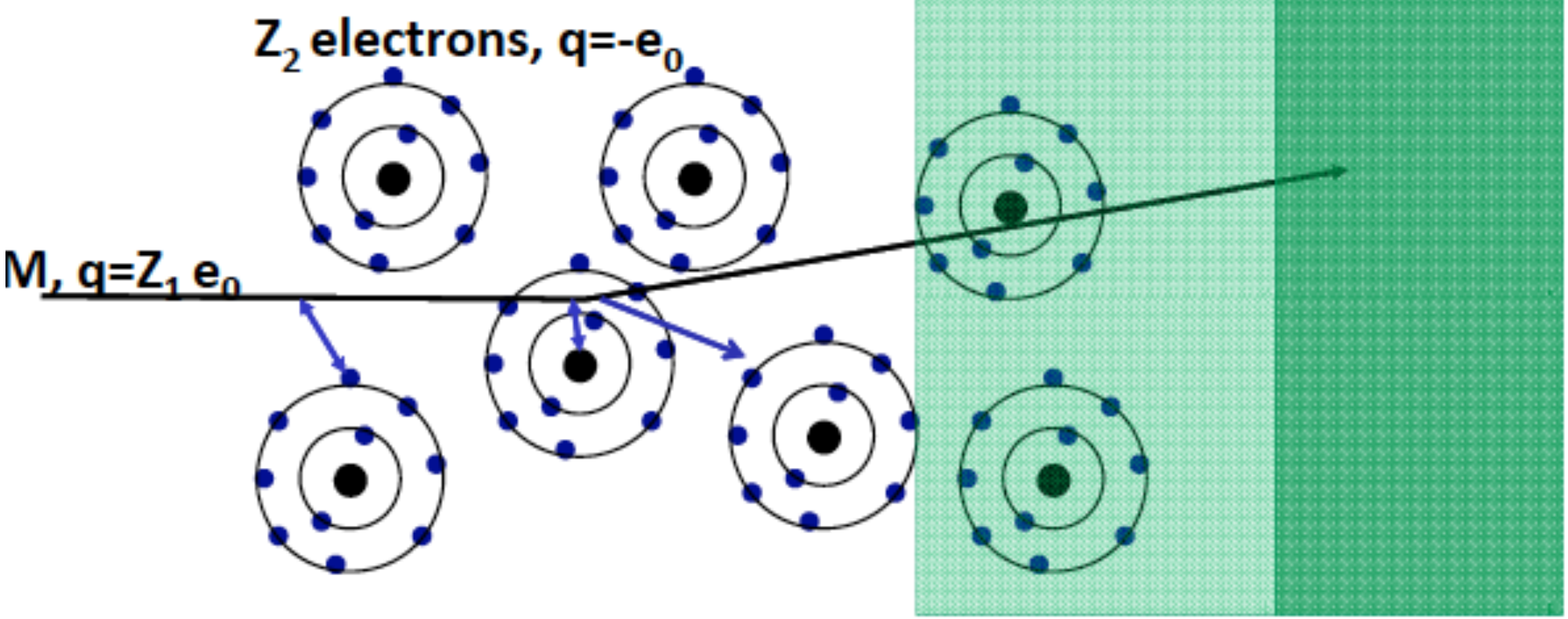
almost all objects here are (very distant) galaxies!

« Progress cycle »



Motivation 2

Developing novel particle detectors/technology is key aspect of cutting-edge (experimental) science !



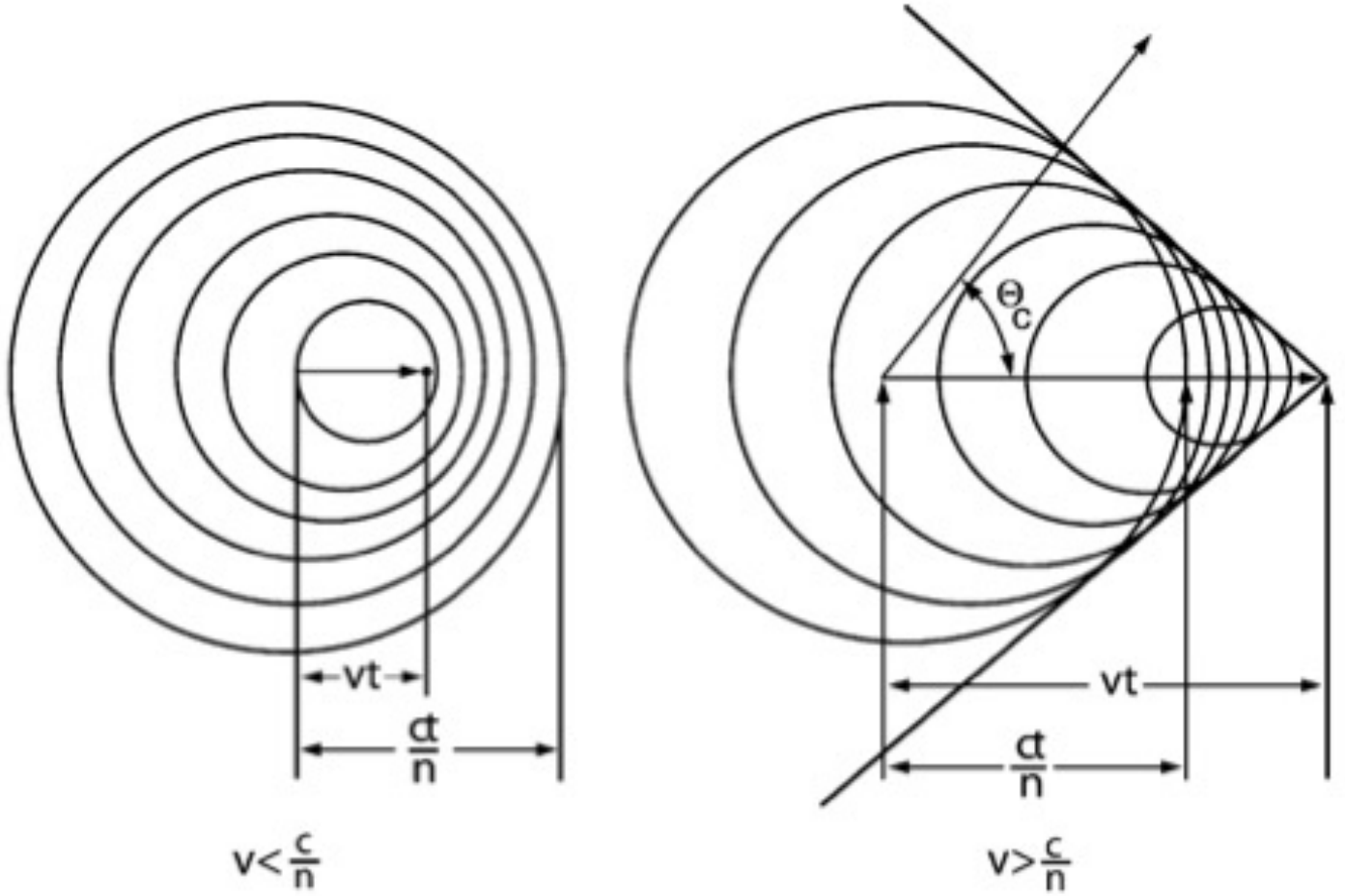
Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

??

Cherenkov effect vs. Huygens(-Fresnel) principle



$\beta > 1/n$

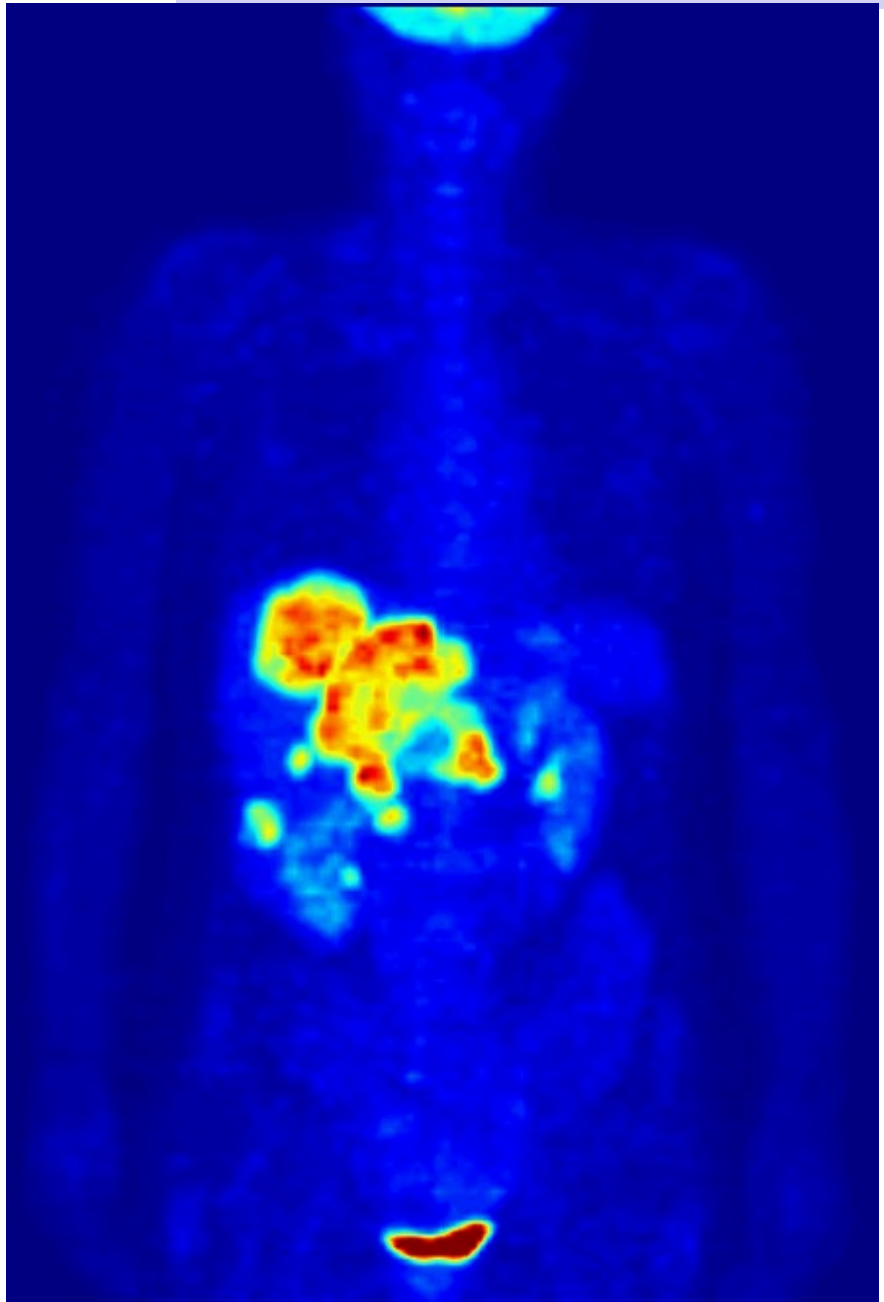
(*Left*) A particle is travelling at a speed lower than the speed of light in the medium.
(*Right*) A particle is travelling at a speed greater than the speed of light in the medium

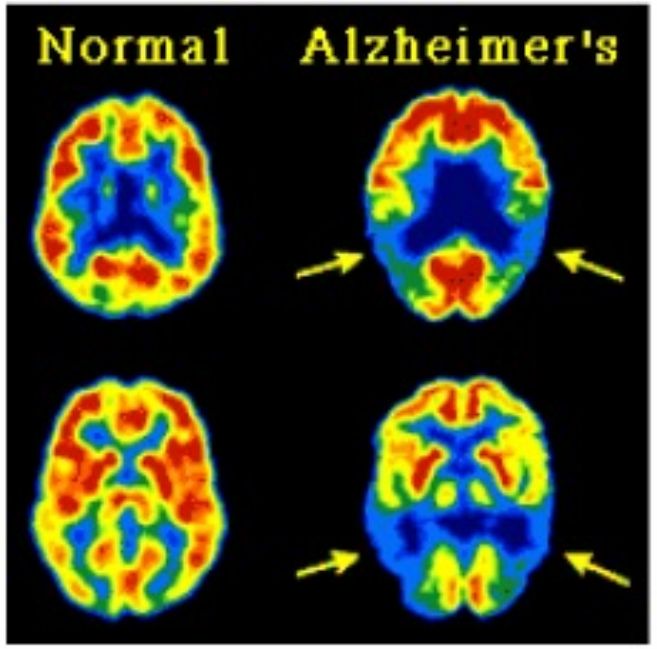
Cherenkov effect in nuclear power plants

$\beta > 1/n(H_2O) \simeq \frac{3}{4}$

$E_{min} = 0.77$ MeV

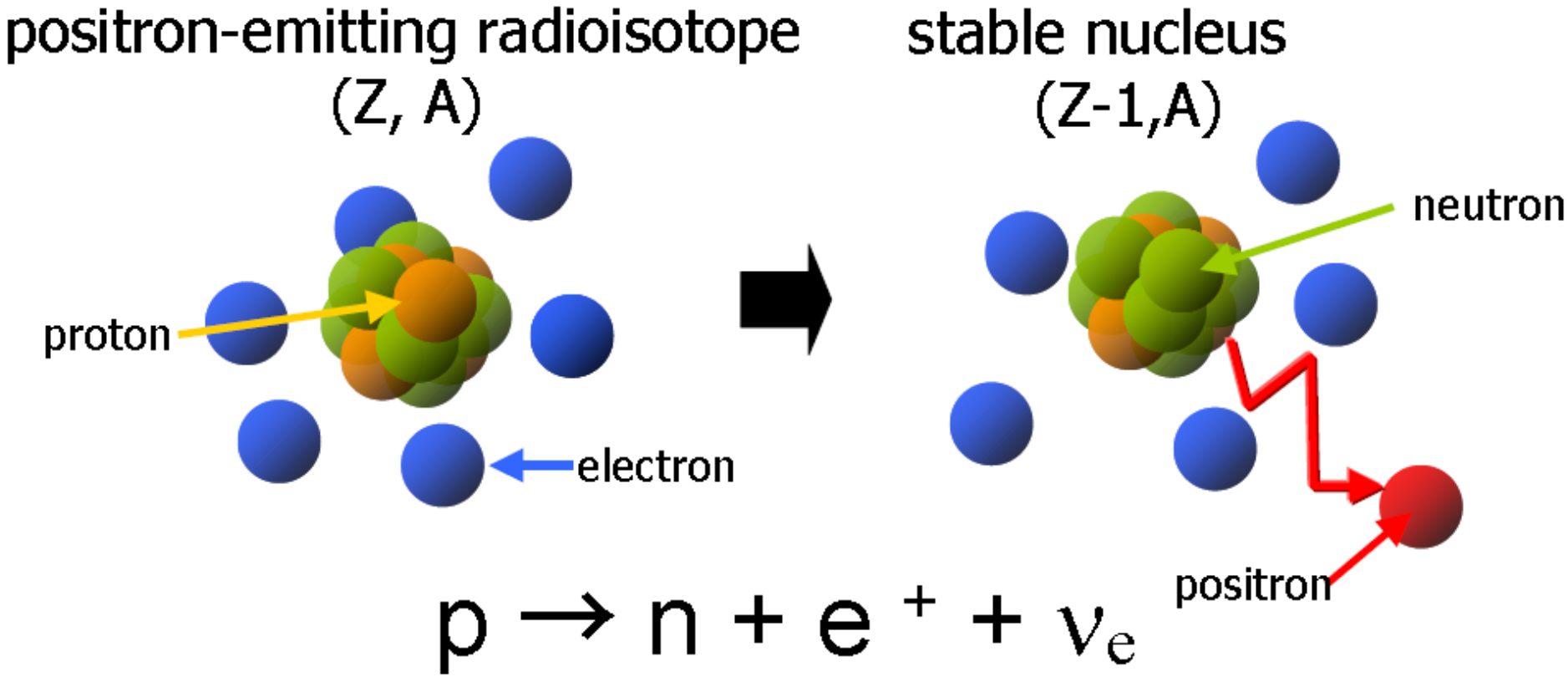
PET: Positron Emission Tomography





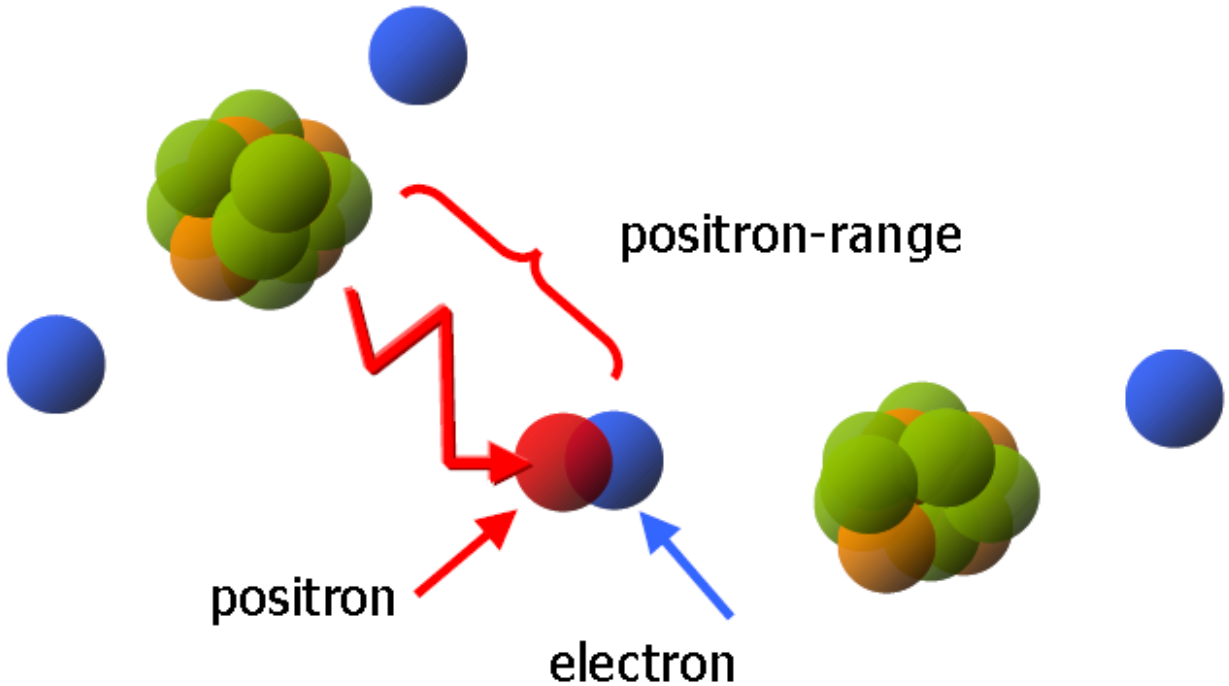
How does it work ?

Positron Emission



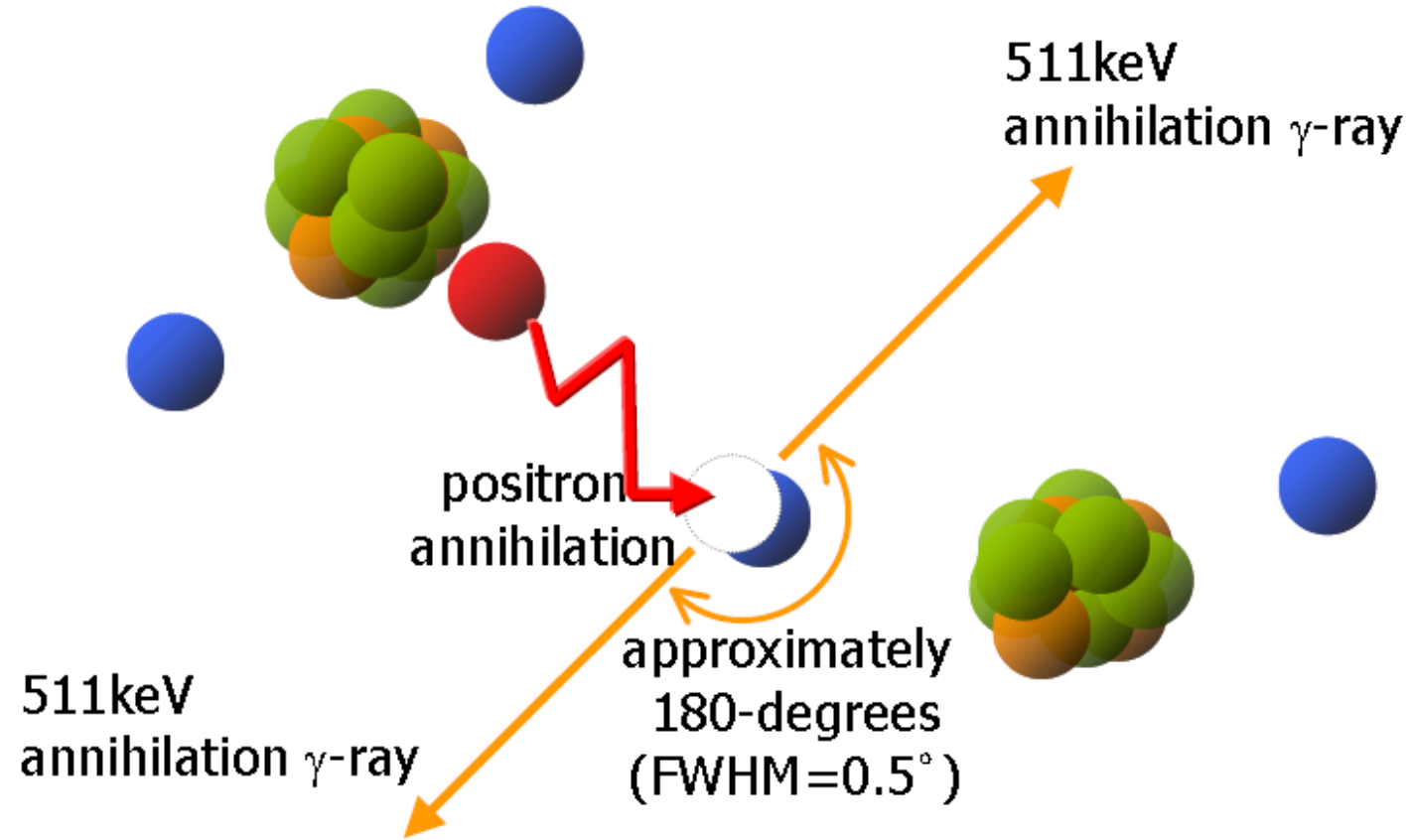
A positron(e^+) and a neutrino(ν_e) are emitted from a nucleus by the β^+ decay.

Positron-Range



A positron travels a short distance and is annihilated with an electron in a substance. The positron-range depends on the positron energy.

Positron Annihilation



When a positron is combined with an electron, they are annihilated and produce two 511-keV γ-rays which are emitted in the direction of 180-degrees to each other.

Motivation 3

Modern particle detectors play major roles in many areas of applied science, as in medical diagnostics!

Newest example – **3D PET scans** thanks to ultra-fast detectors of **511 keV** photons, and using Time-of-Flight information:

Interested to join the effort?

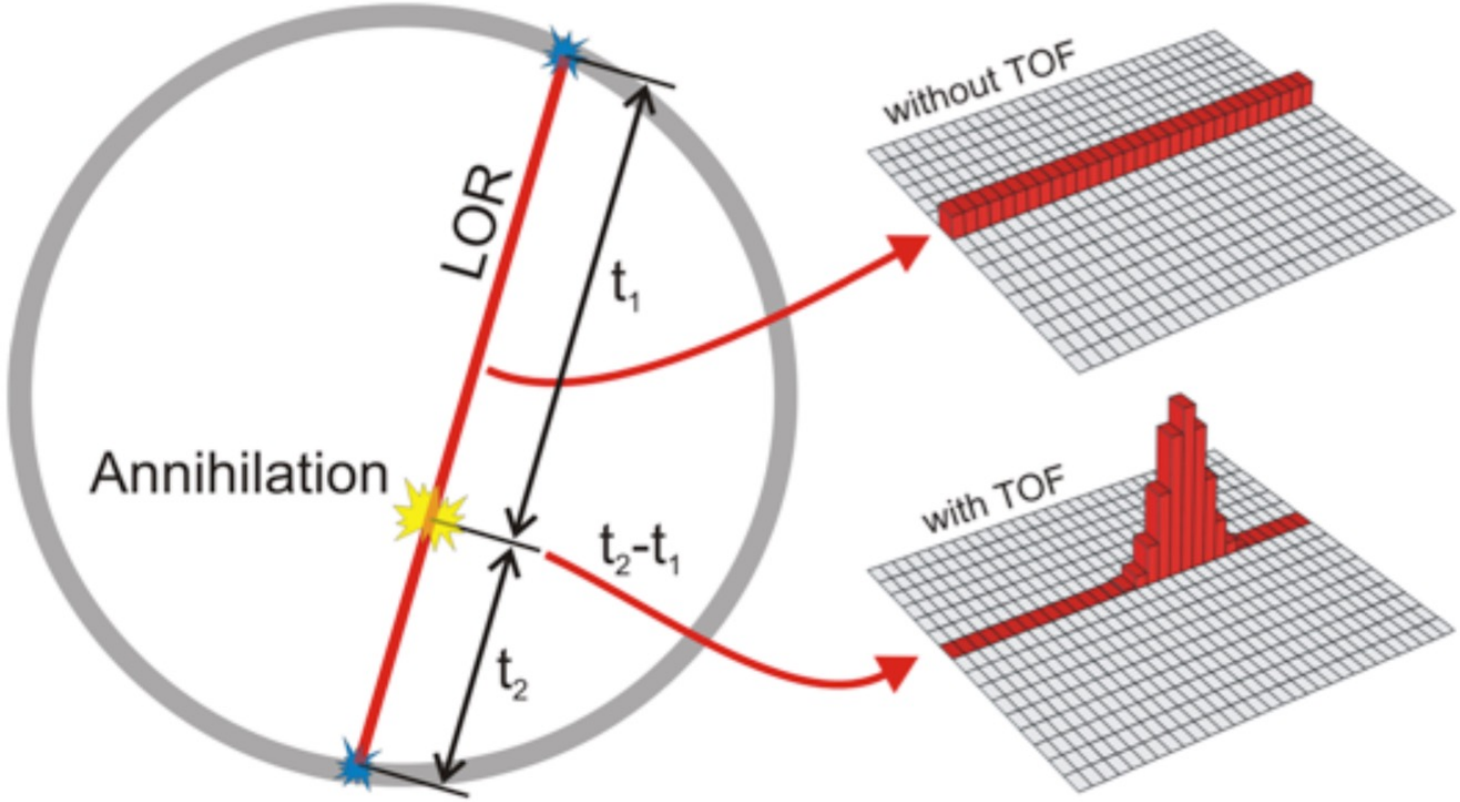
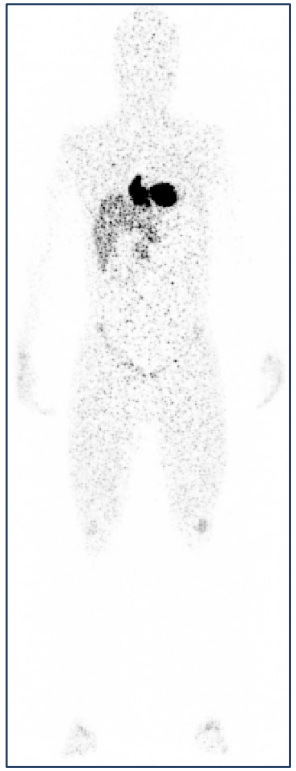


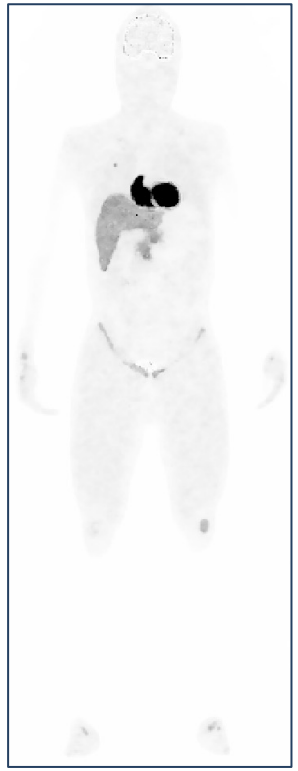
FIGURE 2:
The principle of the ToF Positron Emission Tomography (PET) – the position x of positron-electron annihilation, along the so-called line-of-response (LOR), is calculated from the time difference of detection of two 511 keV gammas. Hence, $x = (t_2 - t_1)/(2c)$, where c is the speed of light in vacuum. Therefore, a 10 ps time resolution for detection of each γ corresponds to about 2 mm resolution of the annihilation position x.

Better Image

- **> 15-fold improvement in SNR**
  - Reconstruct at higher spatial resolution
  - Detect smaller lesions
  - Detect low-grade disease
  - Better statistics for kinetic modeling



Non TOF PET



10ps TOFPET

Adapted from S. Cherry, UC Davis

Faster Image

10ps TOFPET

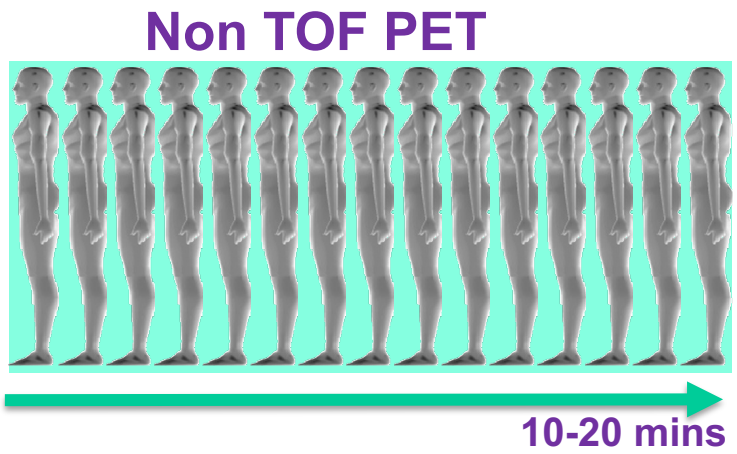
5 seconds/bed position

– Image in a single breath-hold

– Reduce respiratory/cardiac/bolus motion

– Higher resolution

– Kinetic imaging with high temporal resolution



Adapted from S. Cherry, UC Davis

Image Longer

- **200-fold greater dynamic range**

  can image for seven more half lives

- ^{11}C

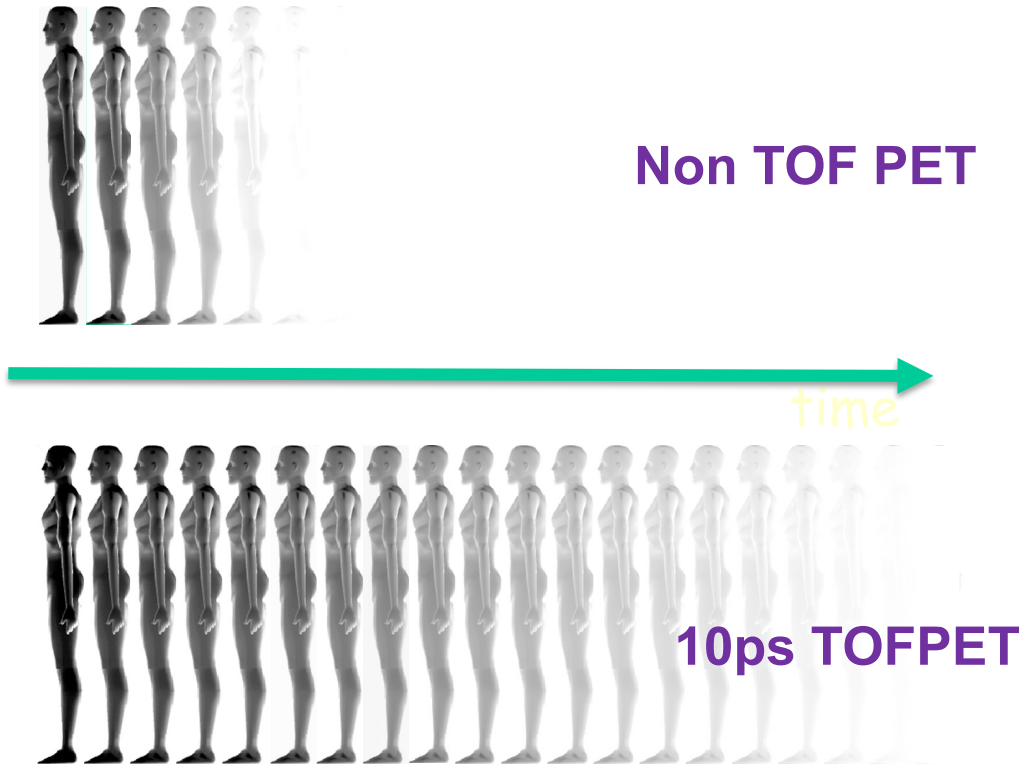
  Up to 4 hours

- ^{18}F

  Up to 20 hours

- ^{89}Zr

  Over 30 days



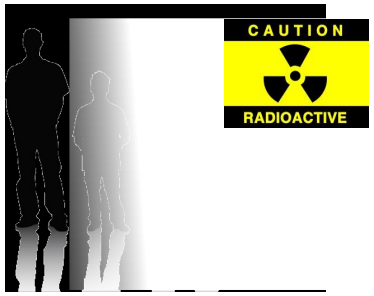
Adapted from S. Cherry, UC Davis

Total Body PET

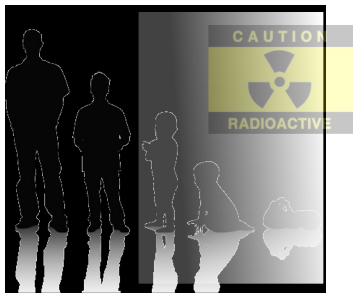
Courtesy of S. Cherry, UC Davis

Image Gently (Low Dose)

- **200-fold reduction in dose**
  - Whole-body PET at ~0.03 mSv
  - Annual natural background is ~2.4 mSv
  - Return flight (SFO-FRA) is ~0.11 mSv
  - PET can be used with minimal risk – new populations



Non TOF PET

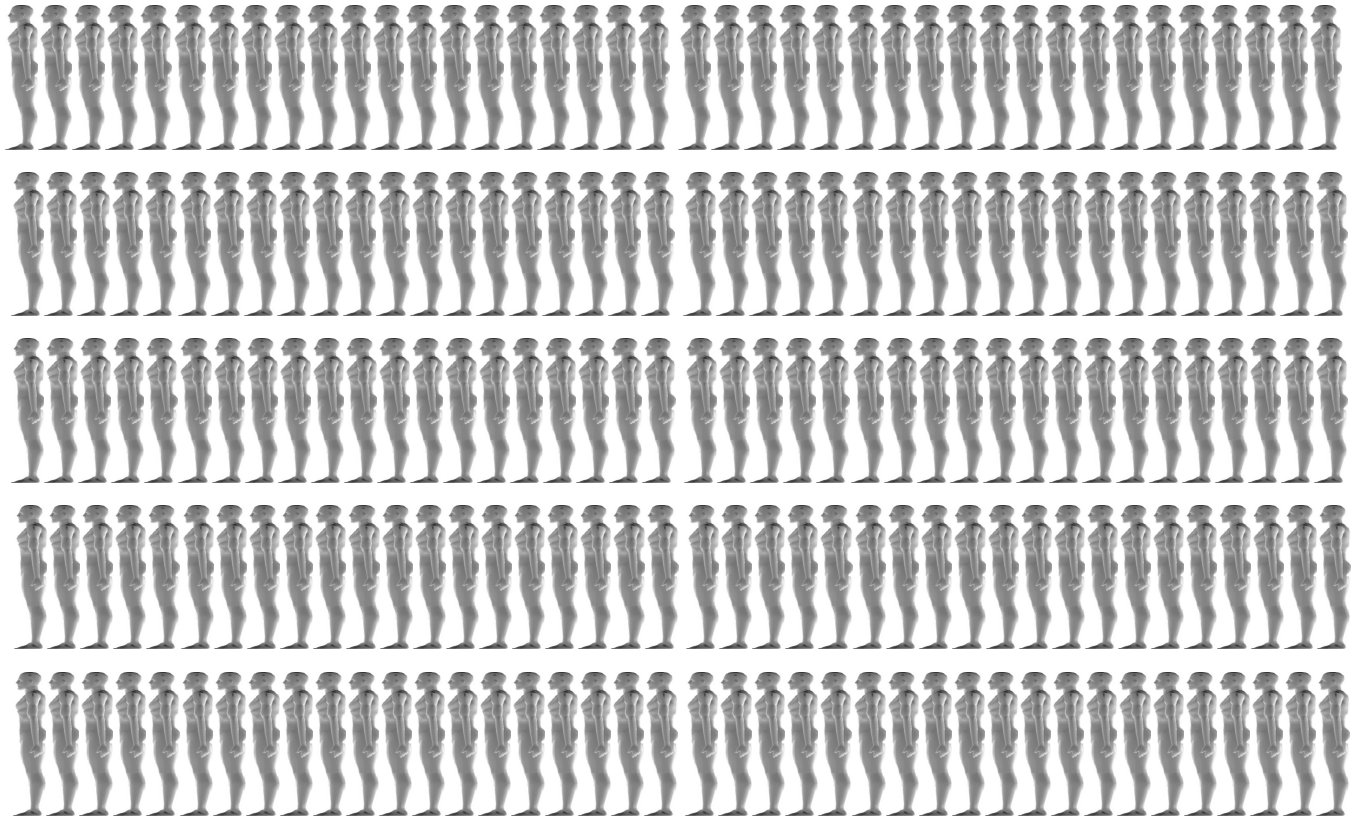


10ps TOFPET

Adapted from S. Cherry, UC Davis

Image More Often

Non TOF PET

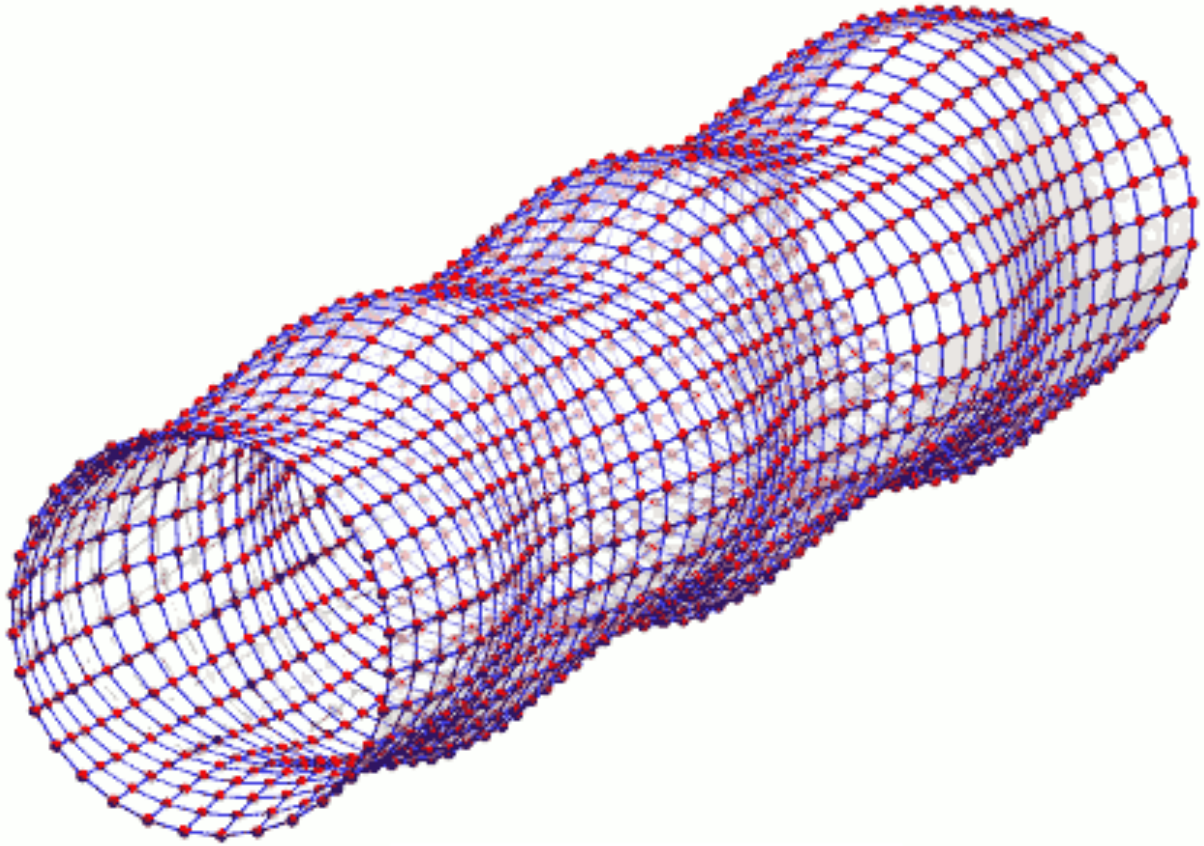


10ps TOFPET

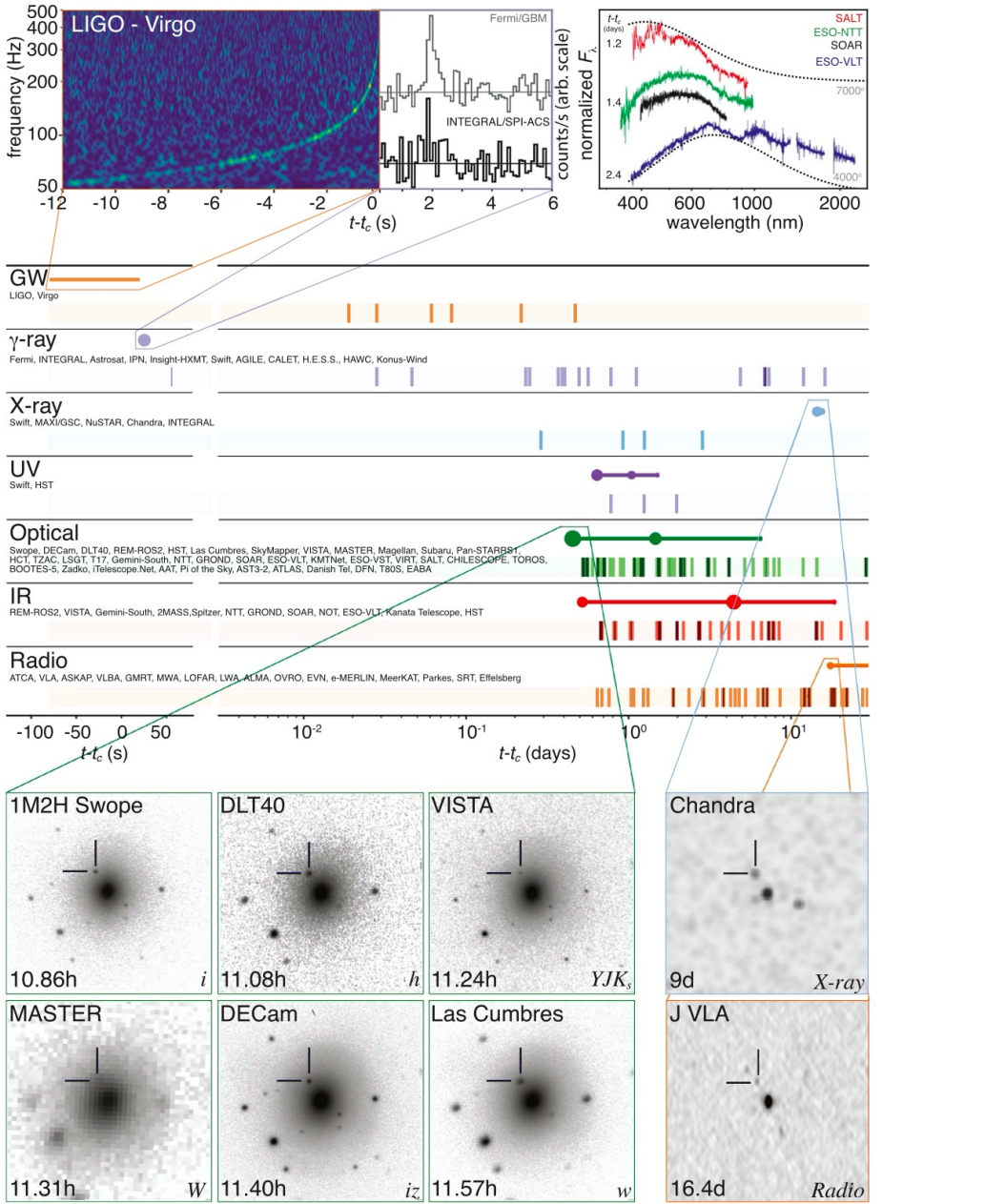
Adapted from S. Cherry, UC Davis

Dwa dodatkowe obrazki

Ultimate challenge: Detection of gravitational waves



The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20



El Descendimiento, by Rogier van der Weyden, from Prado

Ultimate “better-than-eye” camera with resolution of **14,000** megapixels...

Dziękuję za uwagę!