Why is Fundamental Research Important ?

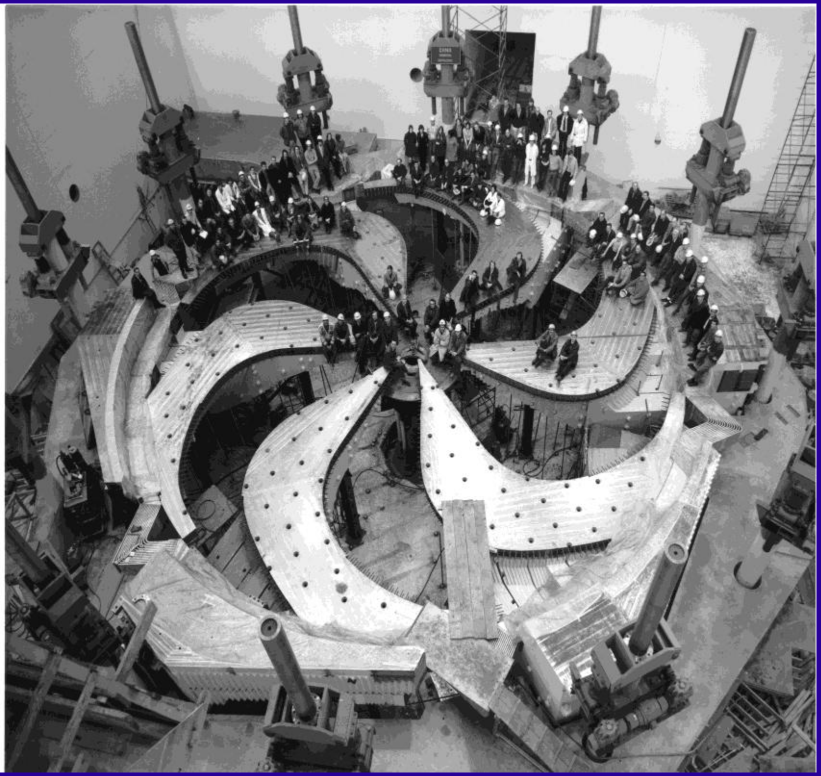
Stanley Yen
TRIUMF

TRIUMF and other physics labs around the world address fundamental questions like:

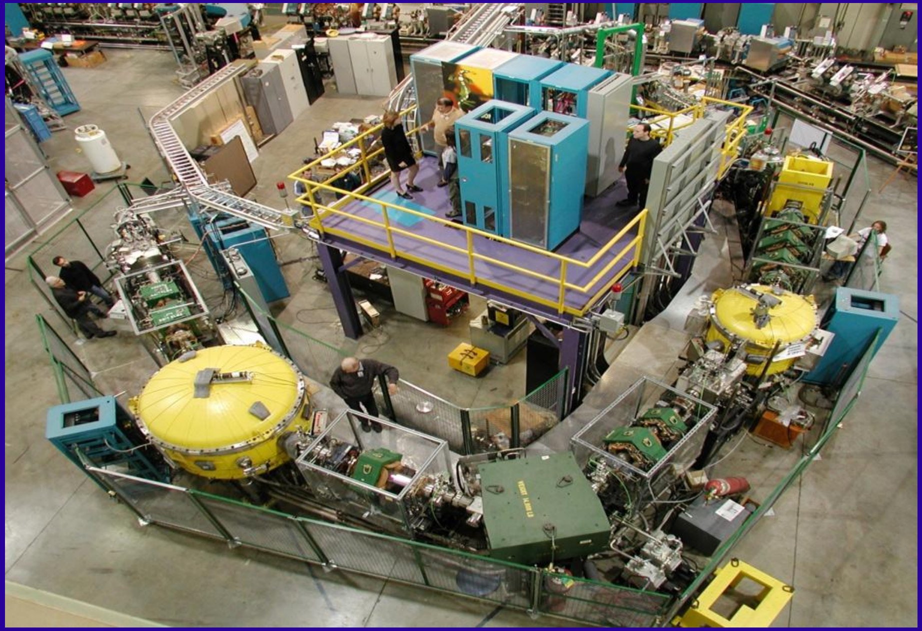
- Where do the chemical elements come from?
- What are the nuclear processes that produce energy in stars, supernovae and other violent cosmic events?
- What are dark matter and dark energy?
- What is the origin of mass?
- Are there extra dimensions?
- the nature of neutrinos?
- the quark structure of protons and neutrons?
- the cosmological history and destiny of the universe?

Intellectual stimulating research...

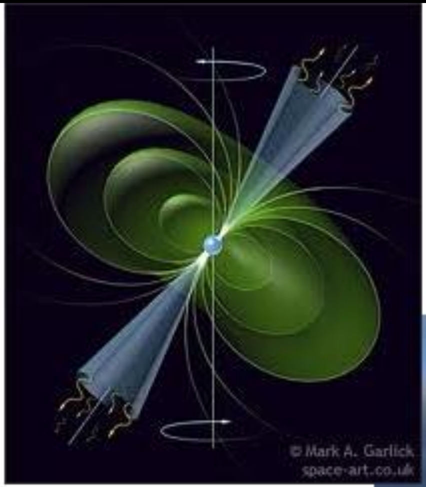
... that require large, expensive facilities



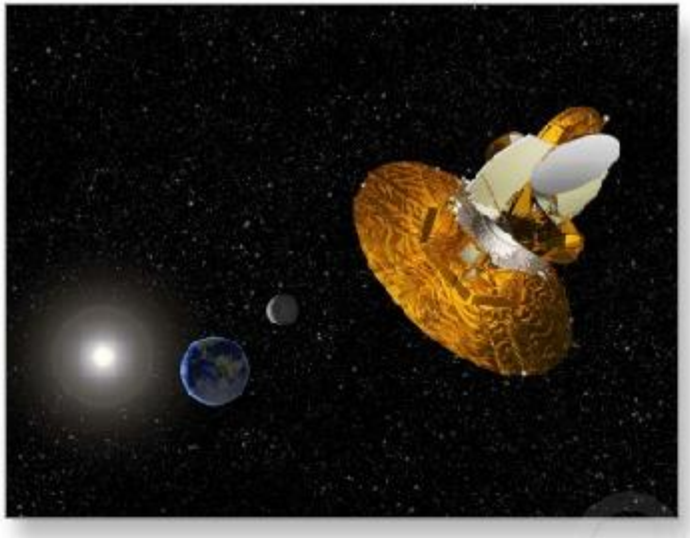
TRIUMF-ISAC
nuclear astrophysics

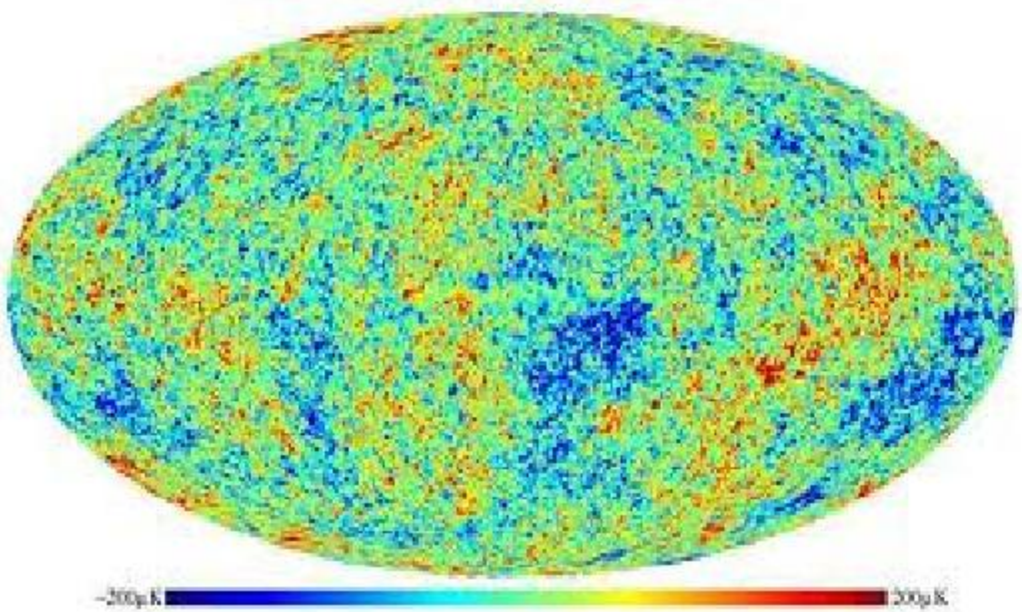


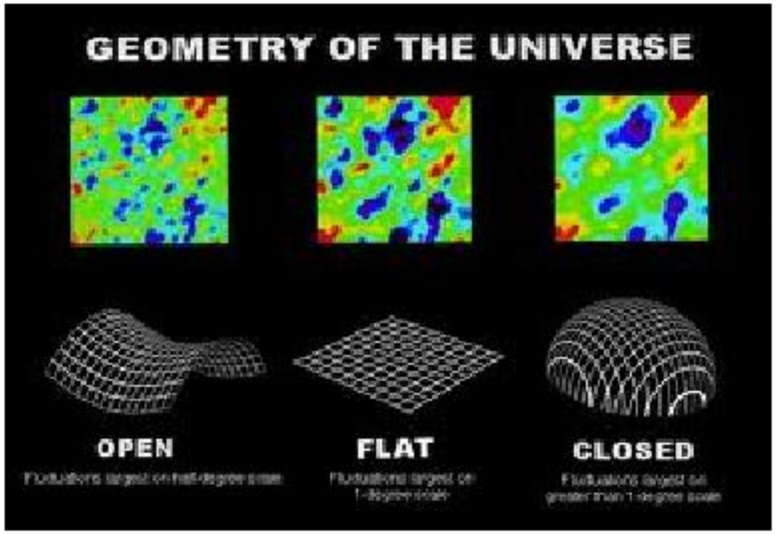
Cosmic microwave background



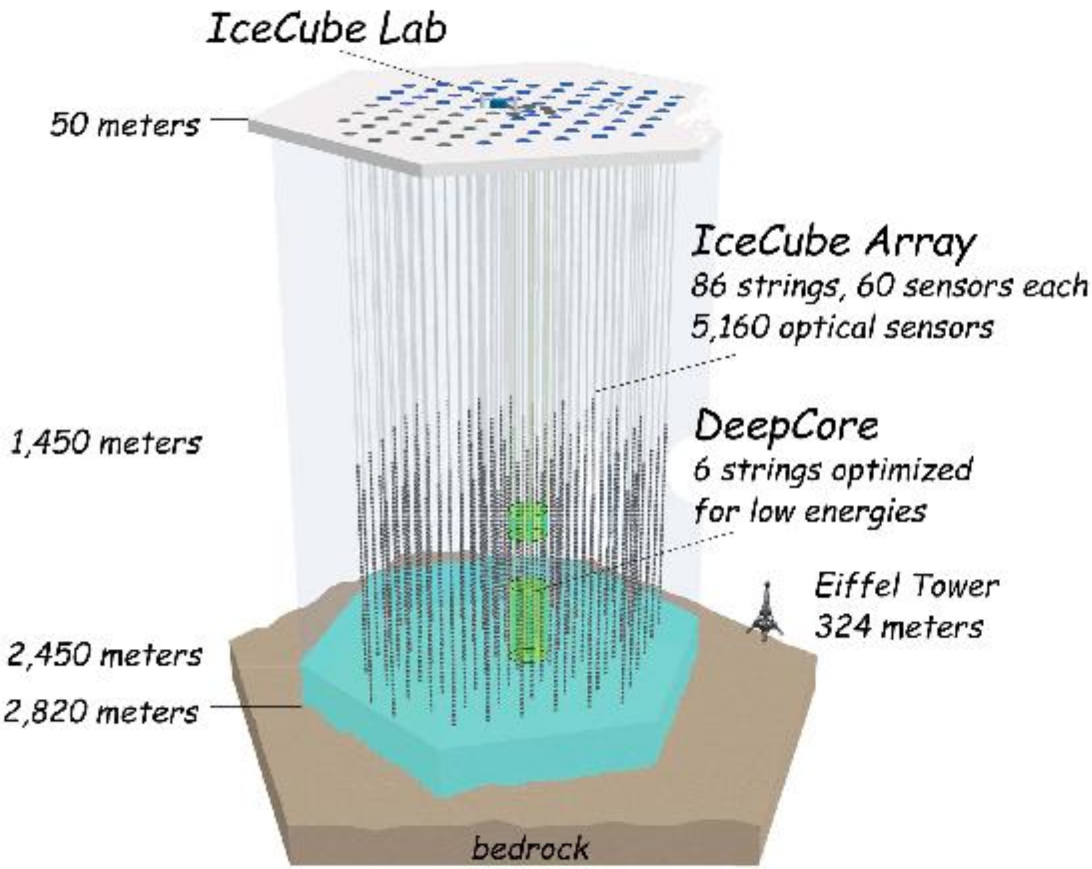
Pulsars



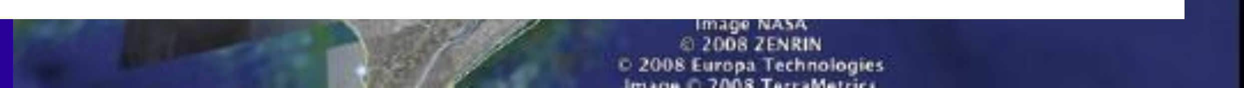


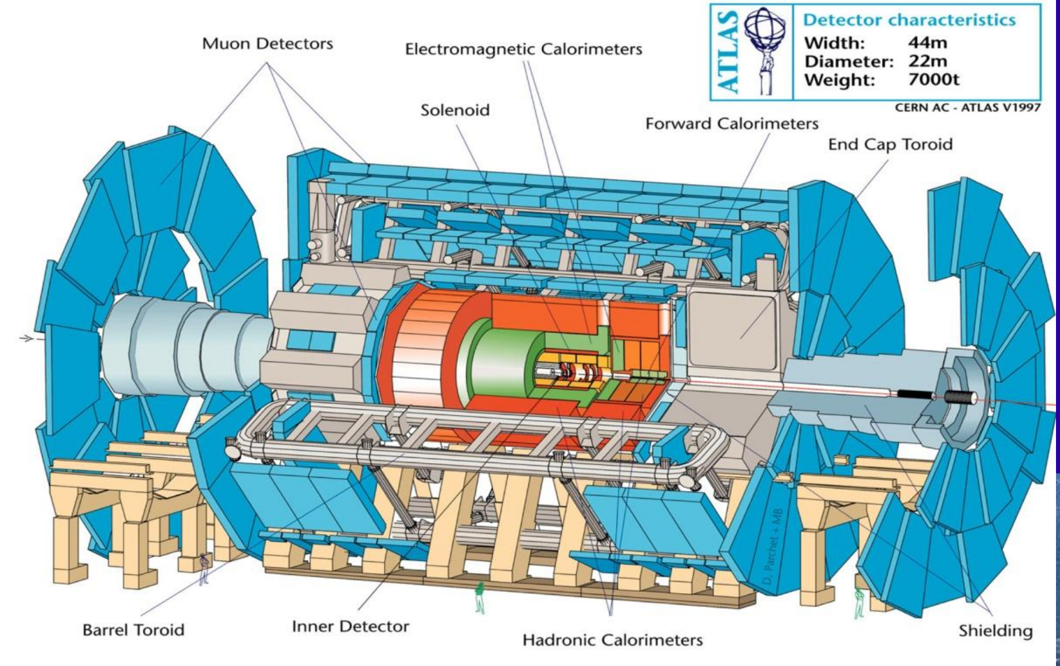


neutrino detectors in deep underground laboratories



Sudbury Neutrino Observatory





Large Hadron Collider
ATLAS detector
origin of mass, extra dimensions, supersymmetry

“But what practical use does it have?”

the public asks

“What are we going to use dark matter
or neutrinos or the Higgs boson for ?”.

Why spend big $$$ on answering such questions of minimal relevance to the real problems the world is facing?


The Sydney Morning Herald

EXTENT OF CRISIS REVEALED

20,000 die each day

The answer in a nutshell:

You never know what's going to be useful until you understand it.

Fundamental research provides a foundation of principles on which future practical applications will be based. No foundation-building today means no future applications.

I will illustrate, using several examples from the history of science, how answering seemingly useless questions ended up providing immensely important applications, in ways that the investigators themselves could not have imagined.

c 1674 van Leeuwenhoek's microscopes

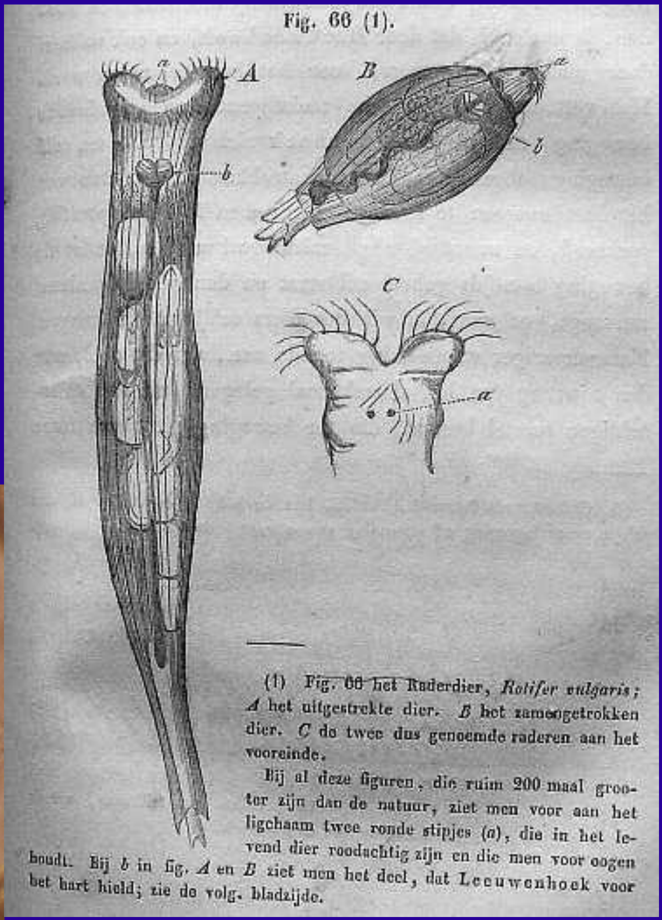


Fig. 66 (1).

(1) Fig. 66 het Raderdier, *Rotifer vulgaris*; *A* het uitgestrekte dier. *B* het zamengetrokken dier. *C* de twee dus genoemde raderen aan het vooreinde.

Bij al deze figuren, die ruim 200 maal grooter zijn dan de natuur, ziet men voor aan het ligchaam twee ronde stipjes (*a*), die in het levend dier roodachtig zijn en die men voor oogen houdt. Bij *b* in fig. *A* en *B* ziet men het deel, dat Leeuwenhoek voor het hart hield; zie de volg. bladzijde.

In hindsight, the importance of the microscope to medical science is obvious.

But in 1674, if asked “What is the best investment you can make to improve the quality of health care?”, who would have had the foresight to say “Pay van Leeuwenhoek to grind more glass lenses?”

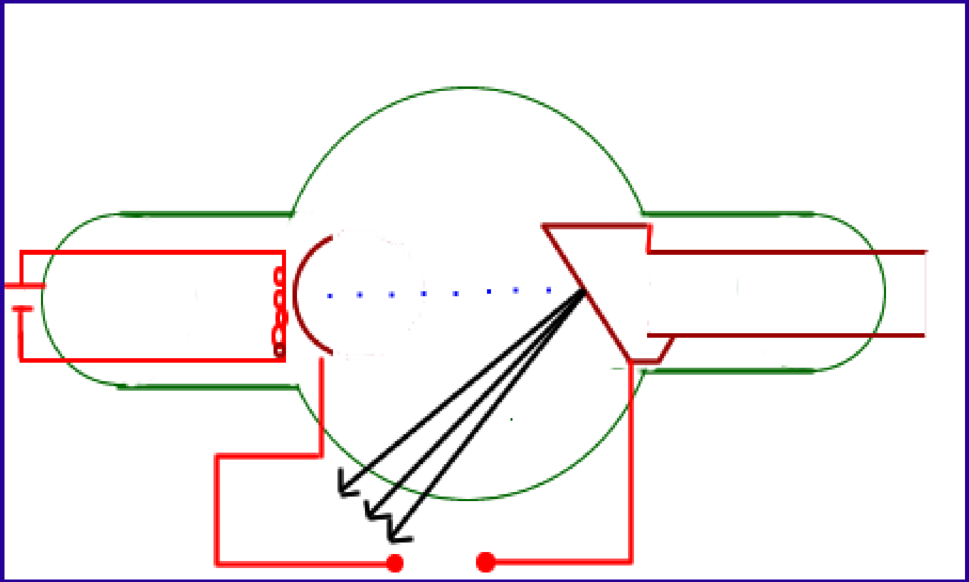
c. 1880 Cathode Rays – electrical discharges in vacuum tubes

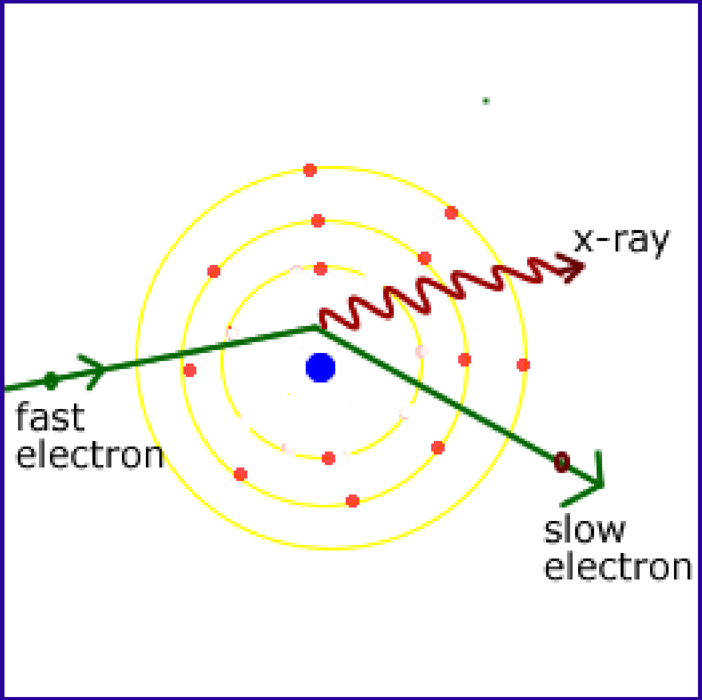
- alternating regions of dark and light, depending on pressure, voltage, gas
- particles or rays? massive or not?

- “much ado about nothing” - who cares why there are coloured bands in the tube?

1895 – Rontgen discovers X-rays

X-rays produced when high energy electrons are deflected (decelerated) by the atomic nucleus of the metal target at the anode





Cathode ray tubes

→ discovery of electrons
→ electronics industry
→ radio, television,
computers
Ubiquitous in modern world!

In hindsight, the importance of X-rays in medicine is obvious. The importance of electronics is obvious.

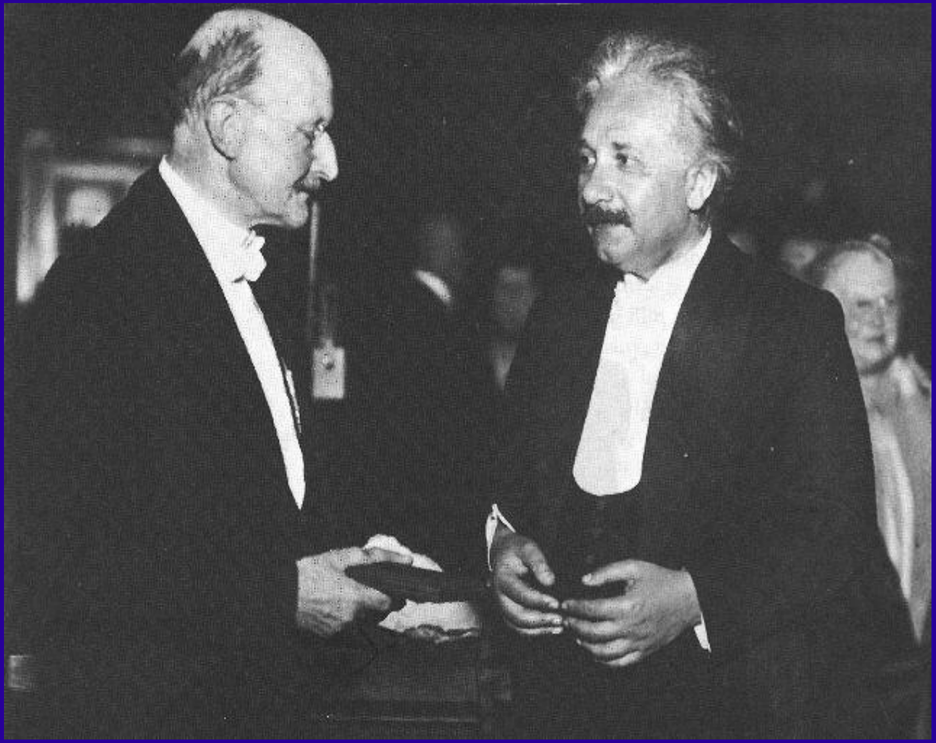
But in 1880, if asked “What is the best investment for improving the quality of health care?”,
or “What is the best investment for improving communications?”
who would have had the foresight to say
“Study electrical discharges in vacuum tubes?”

c. 1910 Quantum mechanics

Why doesn't the orbiting electron radiate energy and fall into the atomic nucleus?

Quantum Mechanics: only certain energy states are permitted, and an electron cannot drop lower than the lowest state

At very small scales (atoms and smaller), Newtonian mechanics and classical electro-magnetism don't work – we need a brand new theory, namely **Quantum Mechanics.**



Planck, Einstein

Light energy quantized in energy packets

$E = h f$

DeBroglie:

Wave-particle duality – particles behave like waves

Wavelength of a particle

$\lambda = h / p$

Heisenberg:

Uncertainty principle

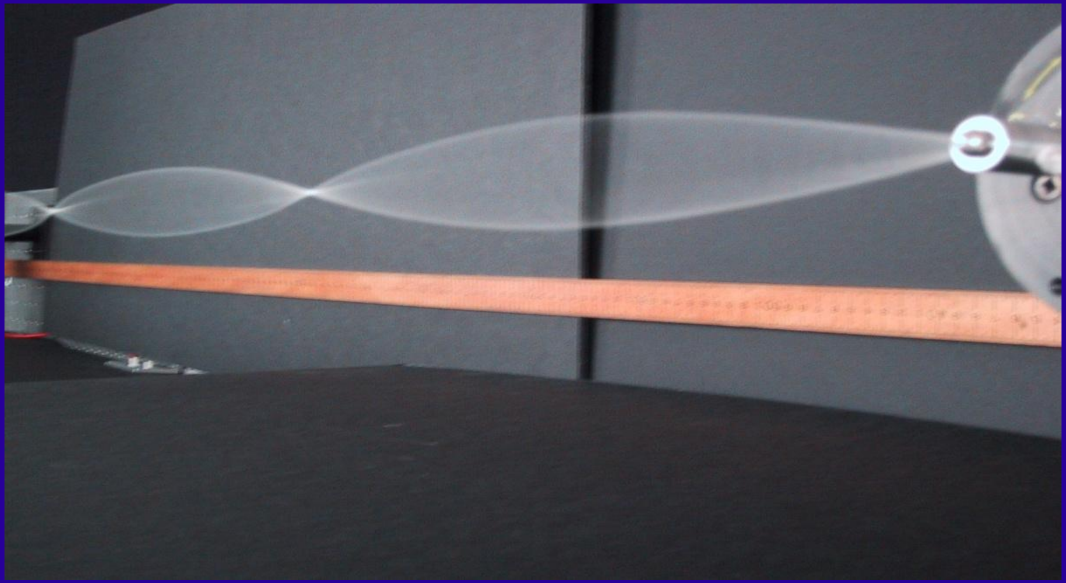
$\Delta p \, \Delta x \geq h/2\pi$

$\Delta E \, \Delta t \geq h/2\pi$

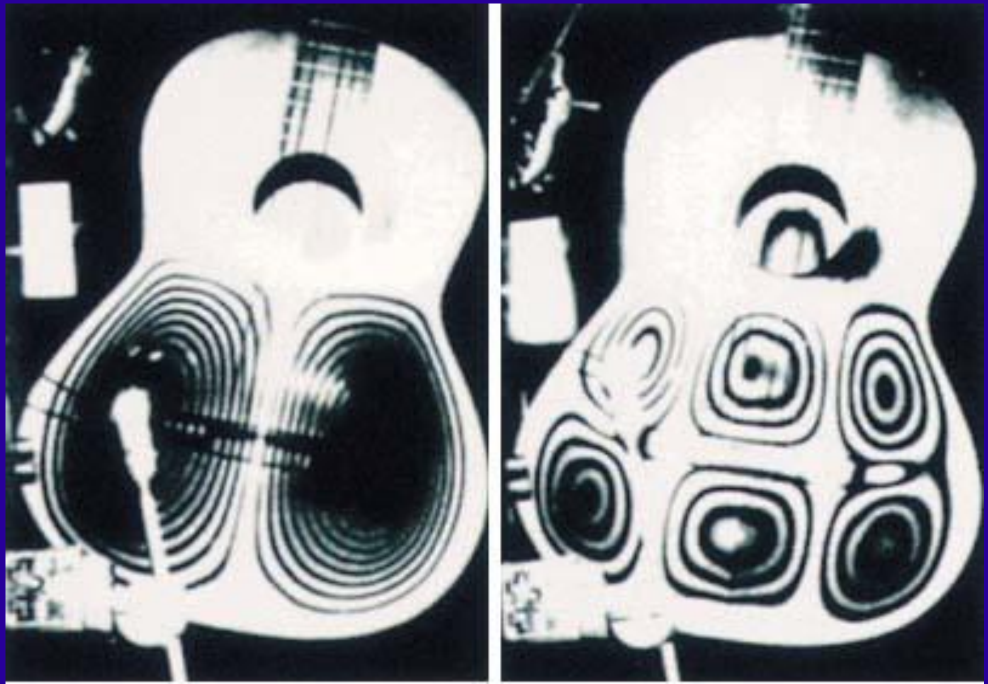
Schrodinger:
Wave equation that describes quantum mechanical waves. Fundamental to quantum chemistry and physics.

$$-\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r})+V(\mathbf{r})\psi(\mathbf{r}) = E\,\psi(\mathbf{r})$$

Just like solving the relevant wave equations give the vibration modes of:

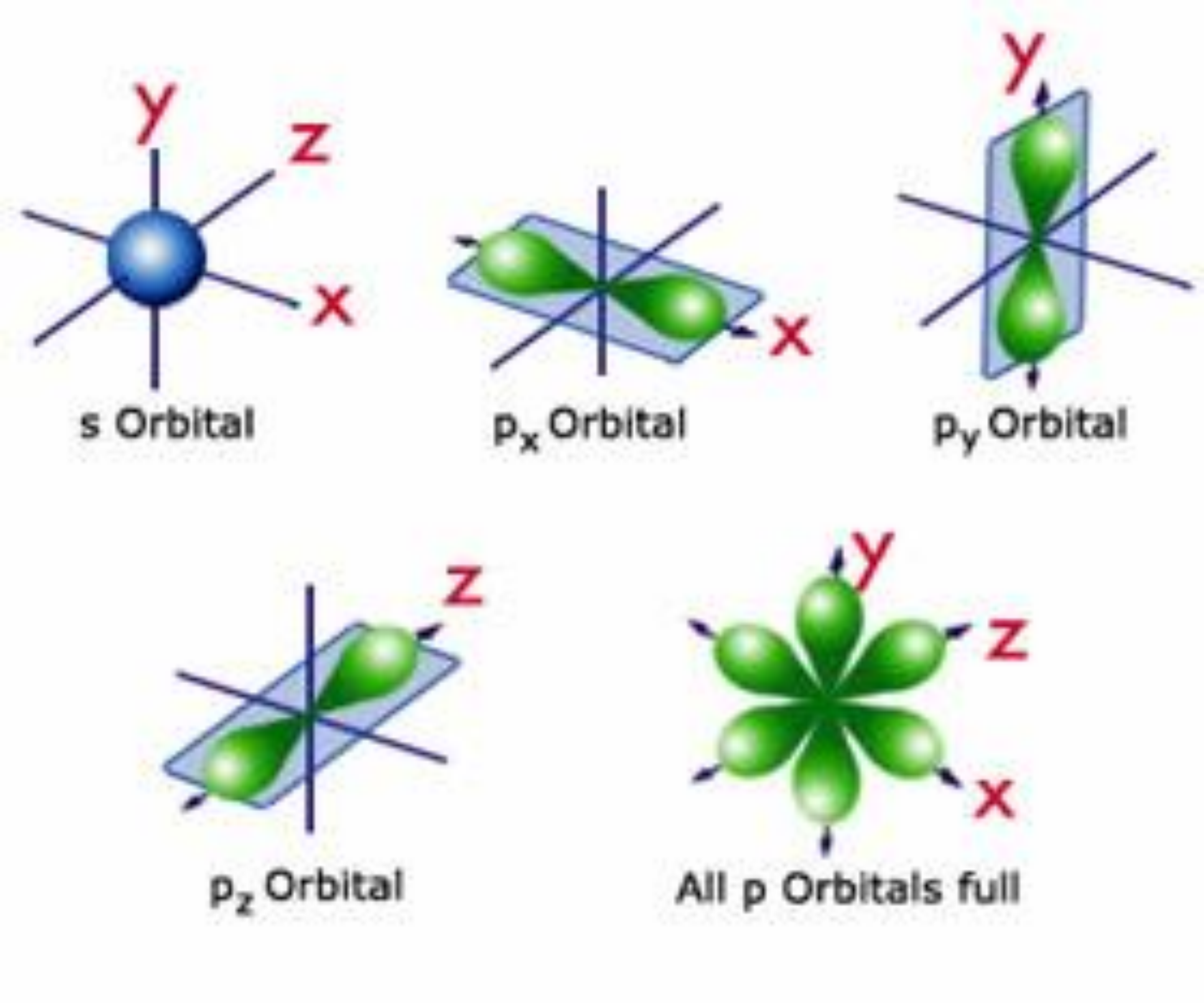


waves on a string

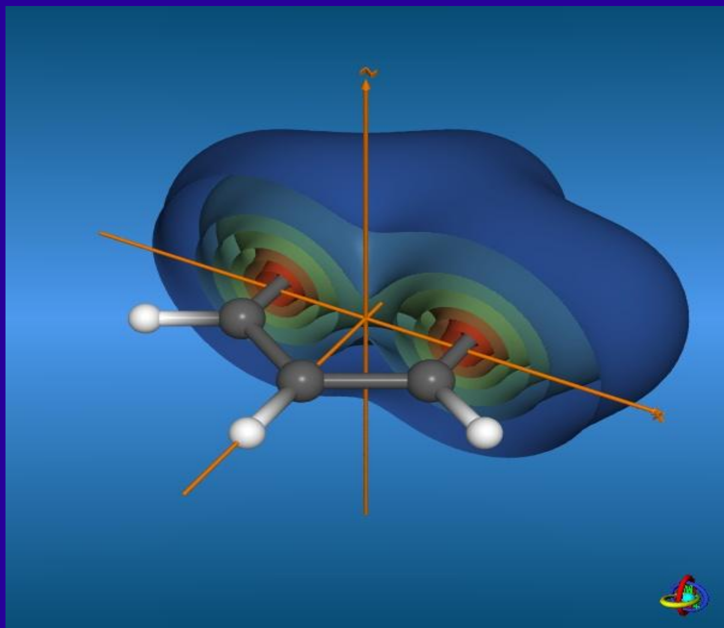


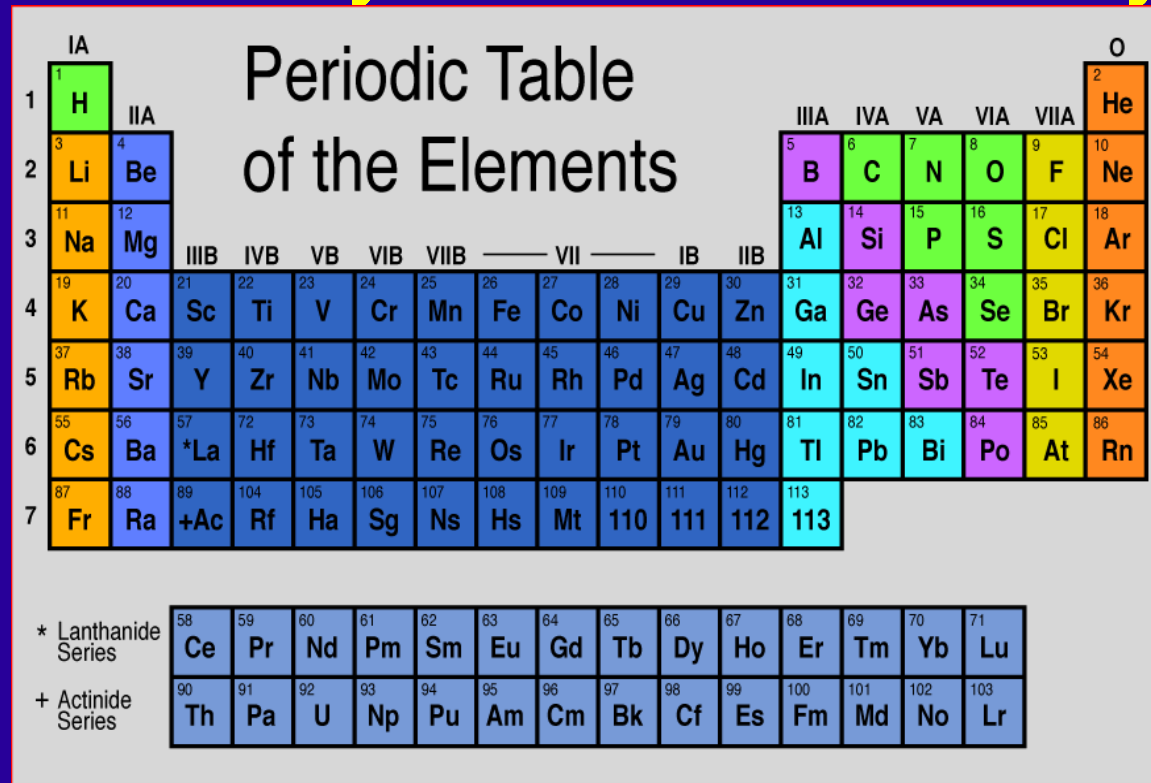
a guitar box

solving the Schrodinger wave equation gives the vibration modes of the quantum mechanical waves describing electrons in an atom



This allows us to understand key features of chemistry:



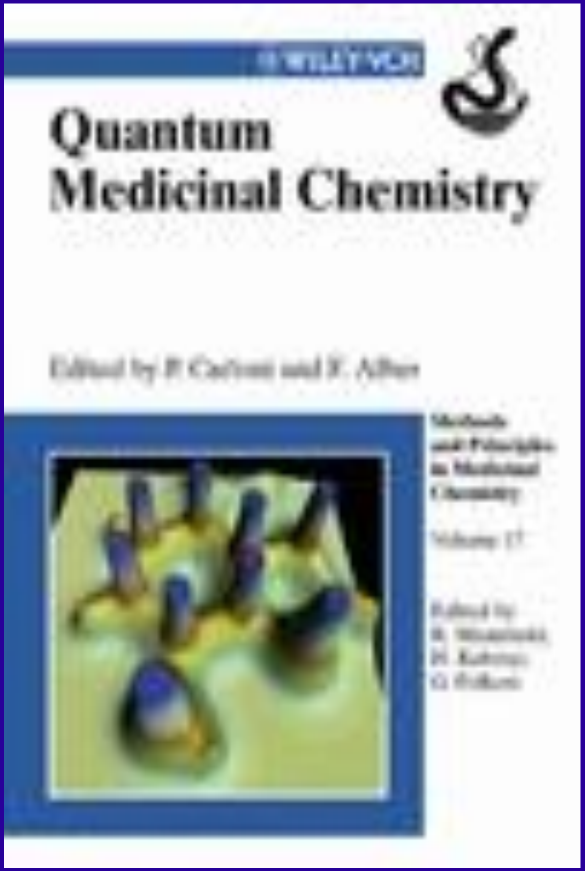


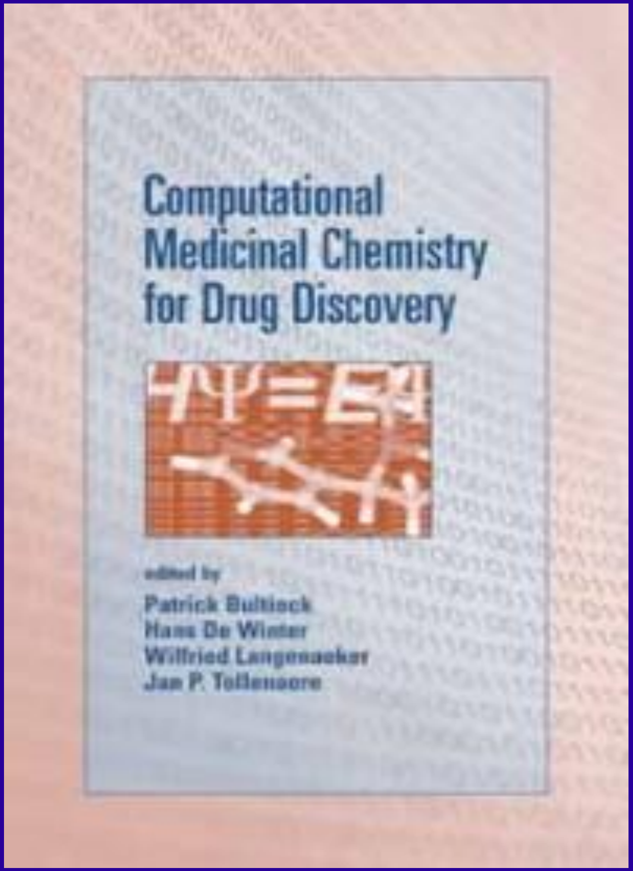
molecular binding
shapes of molecules

chemistry = Schrodinger's Eq. + Coulomb potential

Quantum mechanics changed chemistry from being descriptive to being predictive - one can now calculate from first principles the chemical properties of molecules and how they react with each other.

quantum chemistry – using computers to calculate the properties of chemical compounds – a way to theoretically develop new pharmaceuticals

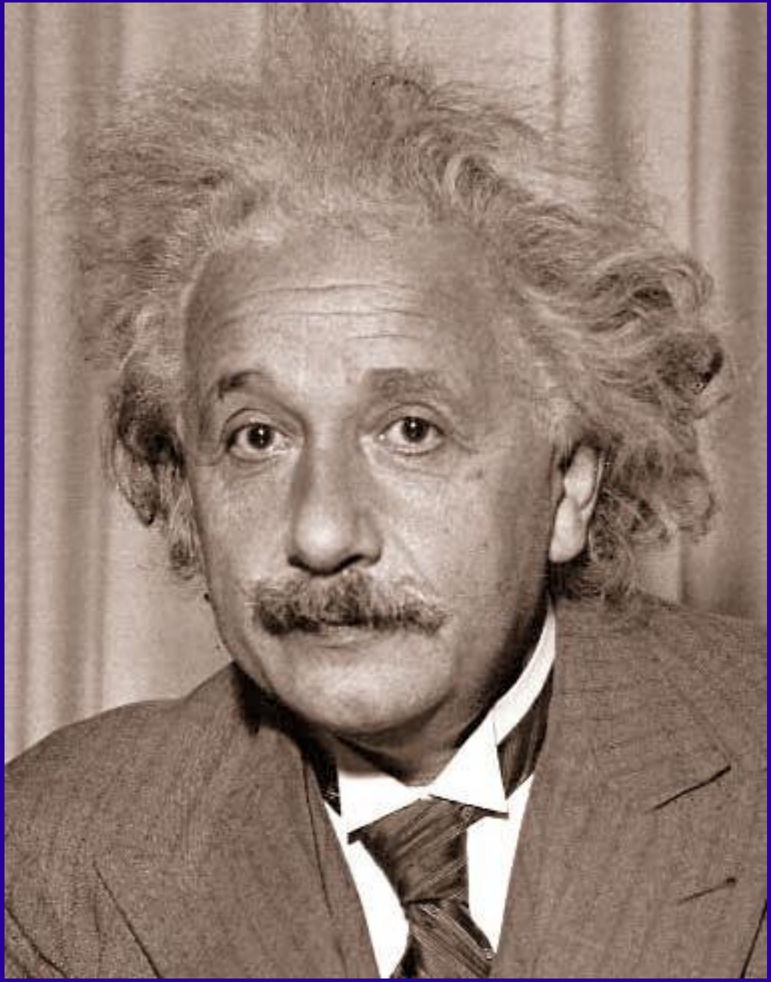




In hindsight, it is obvious how important quantum theory has been to our understanding of chemistry and its applications,

but in 1920, if asked “How can we improve the design of new drugs?”, who would have had the foresight to say “understand why the electron doesn't fall into the atomic nucleus”.

1905 – Einstein's Special Relativity – describes objects going near the speed of light



Startling predictions:

- nothing exceeds speed of light
- moving clocks run slow
- length contracts
- mass increases

all verified by experiment

But does it have any practical application?

Quantum mechanics describes very small objects

Special Relativity describes objects near the speed of light

What about small objects going near the speed of light?
We need to combine QM and SR together in a consistent theory.

Dirac's equation does this

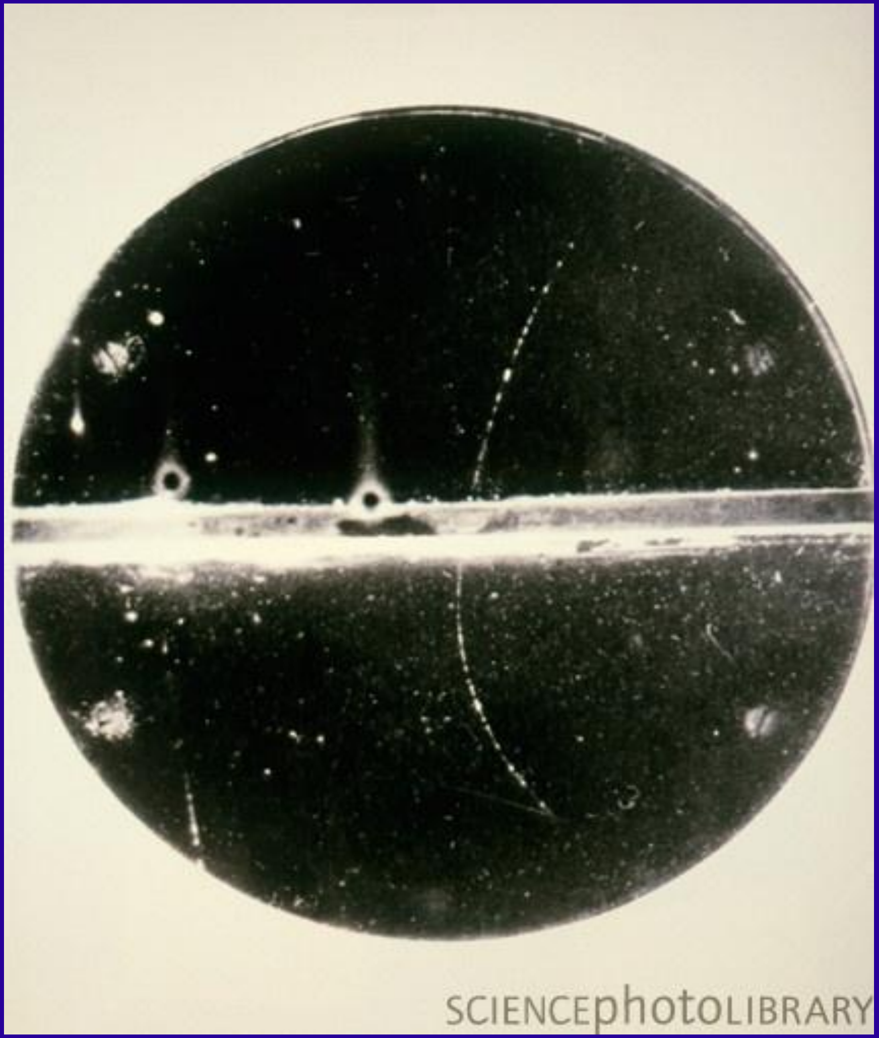
$$\left(i\hbar\gamma^{\mu}\frac{\partial}{\partial x^{\mu}} - mc\right)\Psi(x^{\mu}) = 0$$

Dirac's equation has TWO mathematical solutions:

- one solution describes a negative electron
- the second solution describes a positive electron

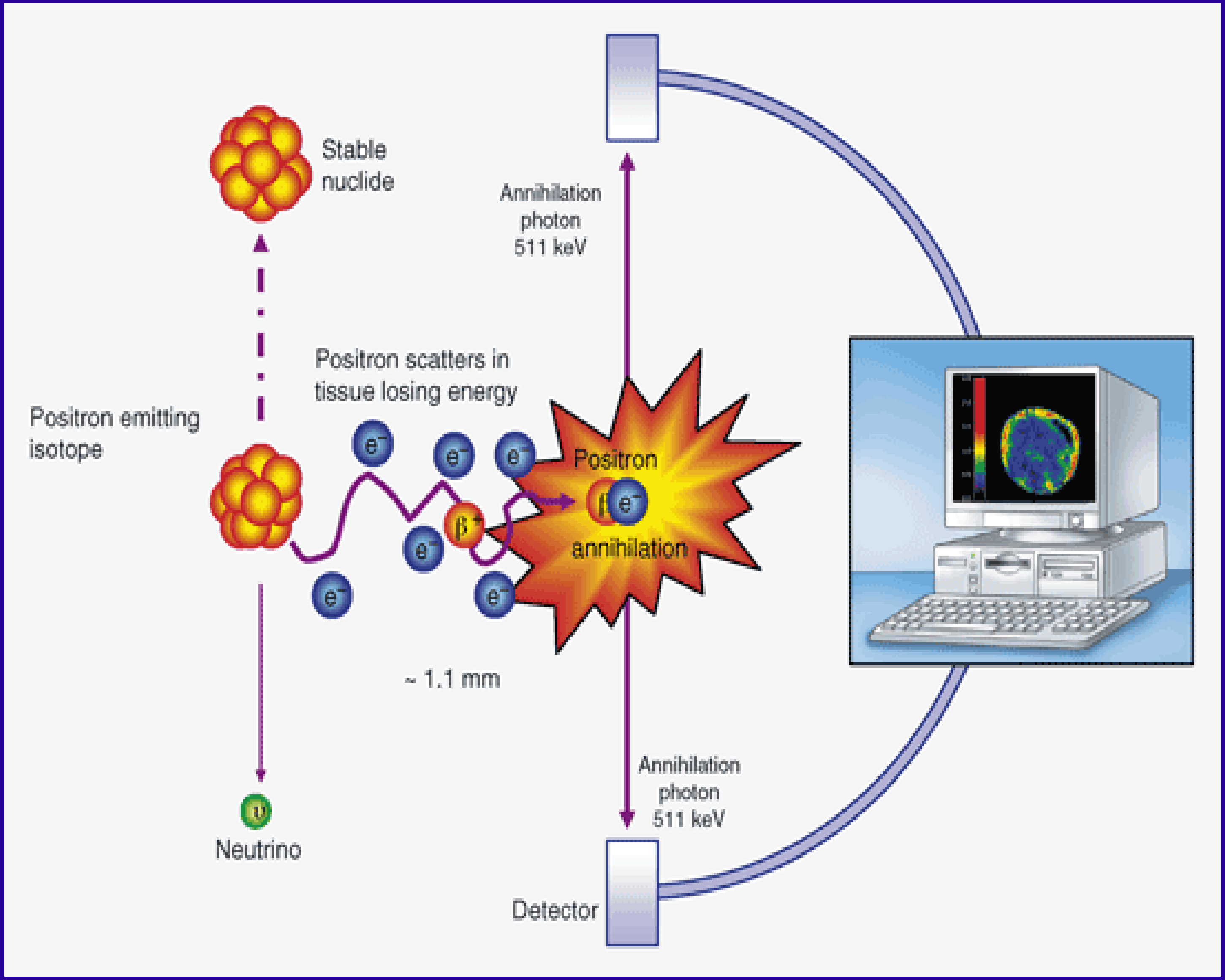
Is this just a spurious bit of math, or does it correspond to reality?

1933: Carl Anderson discovers the positron in cosmic rays

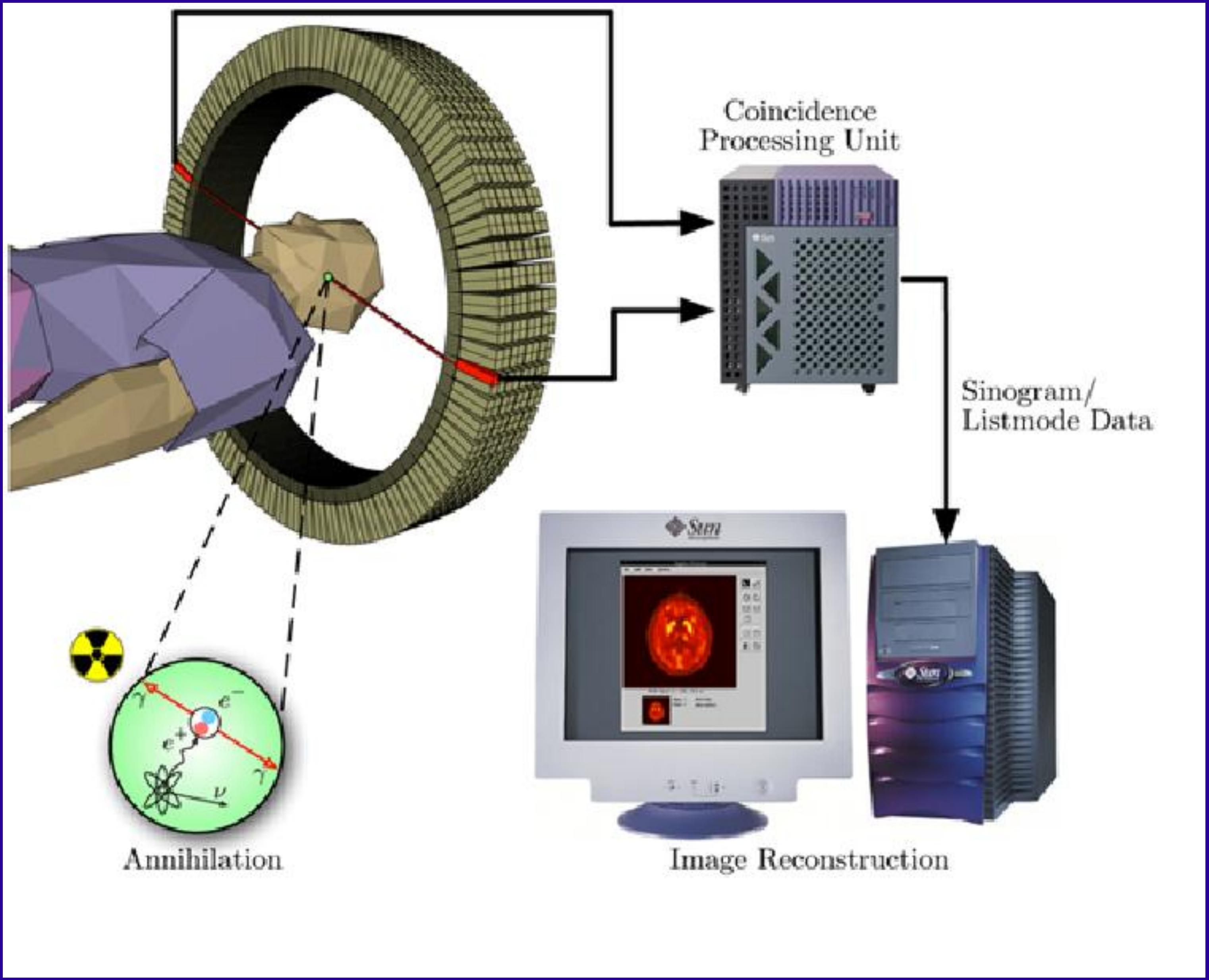


e^+ = positron (positive electron) – the antimatter version of the electron

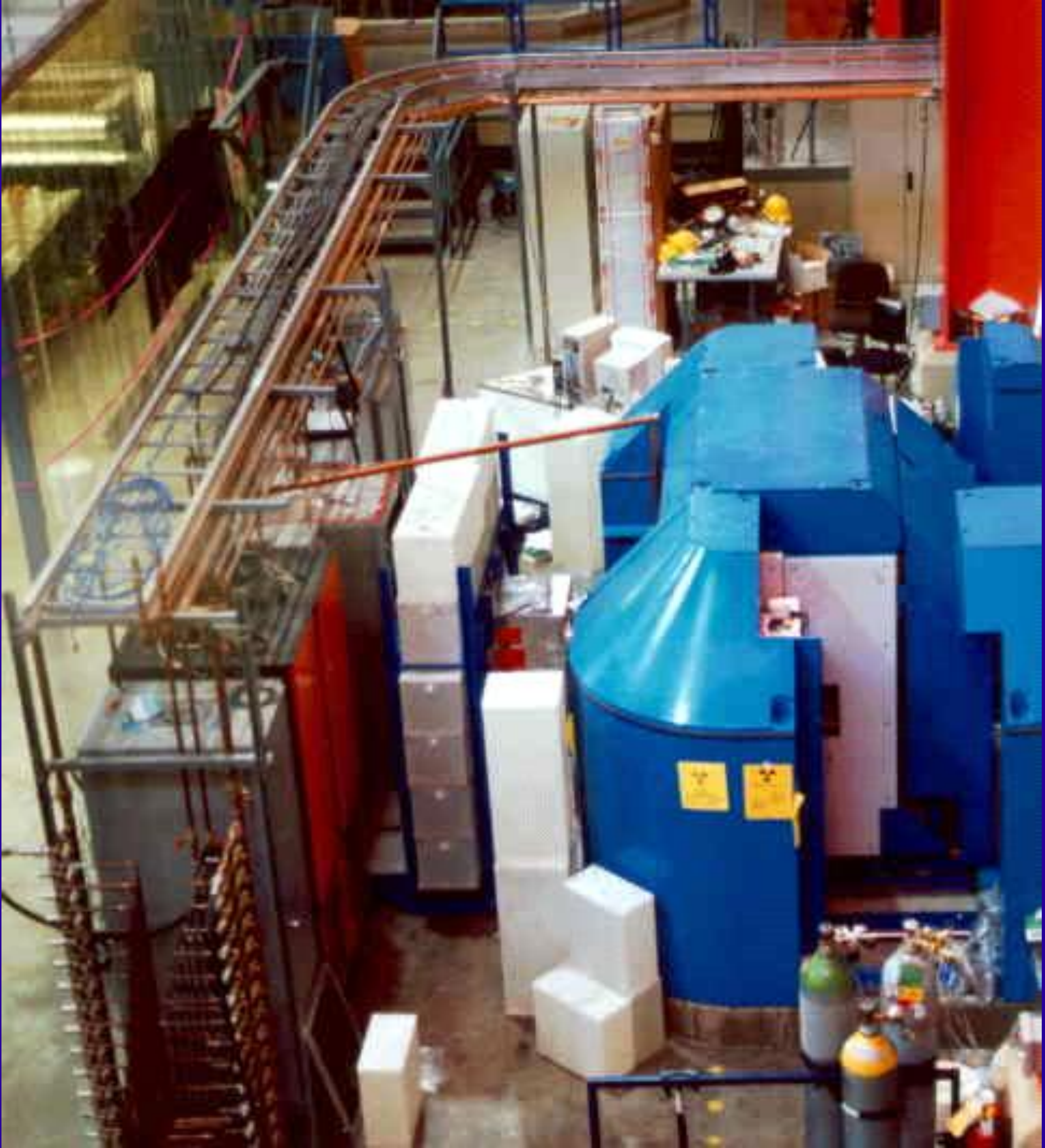
1950's cyclotrons produce nuclear isotopes that decay by emitting positrons



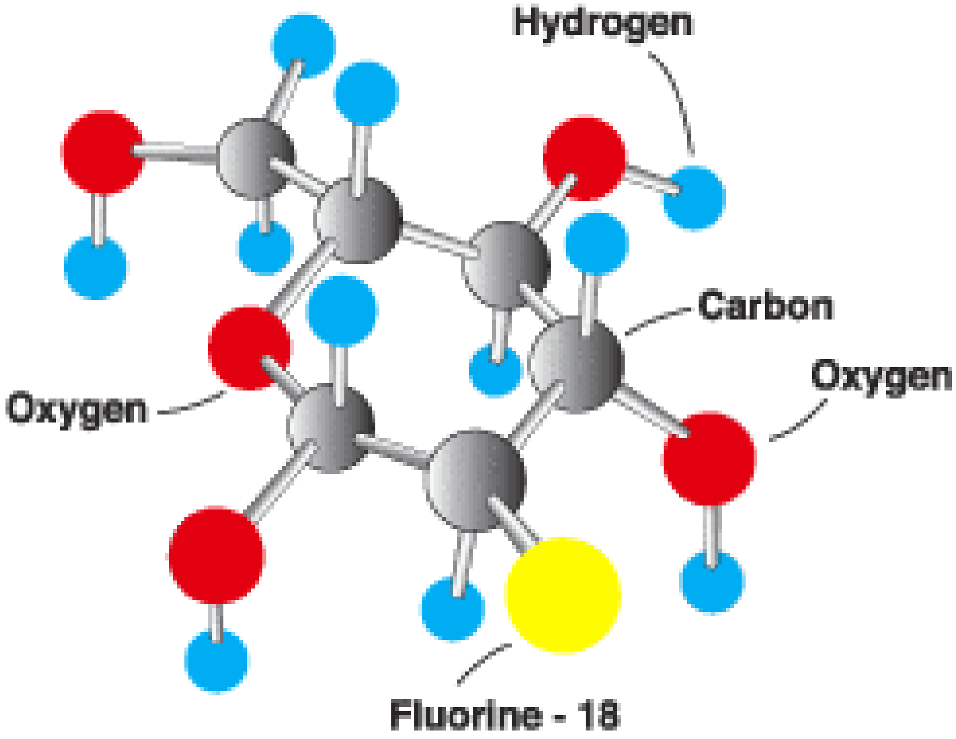
1970's Idea of medical imaging using positrons



From nucmed.wikispaces.com

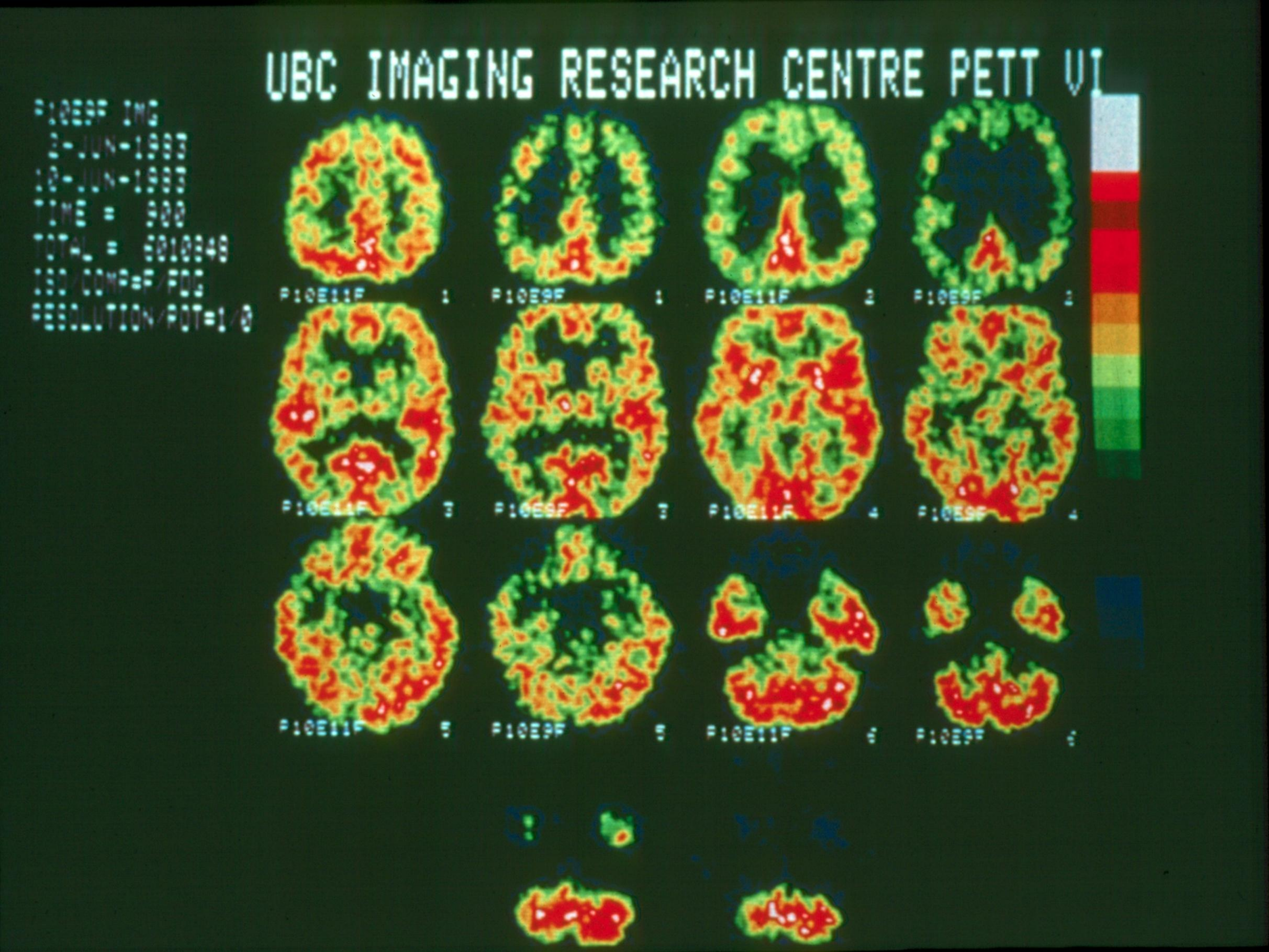


TR13 cyclotron at TRIUMF produces positron emitting nuclei carbon-11 and fluorine-18



FGD Fluoro-deoxyglucose

A glucose molecule with a radioactive Fluorine-18 atom attached.


UBC IMAGING RESEARCH CENTRE PETT VI
P10E9F IMG
2-JUN-1983
10-JUN-1983
TIME = 900
TOTAL = 6010848
ISO/COMP=F/FDG
RESOLUTION/ROT=1/0
P10E11F 1
P10E9F 1
P10E11F 2
P10E9F 2
P10E11F 3
P10E9F 3
P10E11F 4
P10E9F 4
P10E11F 5
P10E9F 5
P10E11F 6
P10E9F 6

combined PET-CT image of metastatic breast cancer, taken with TRIUMF-produced FGD at BC Cancer Agency

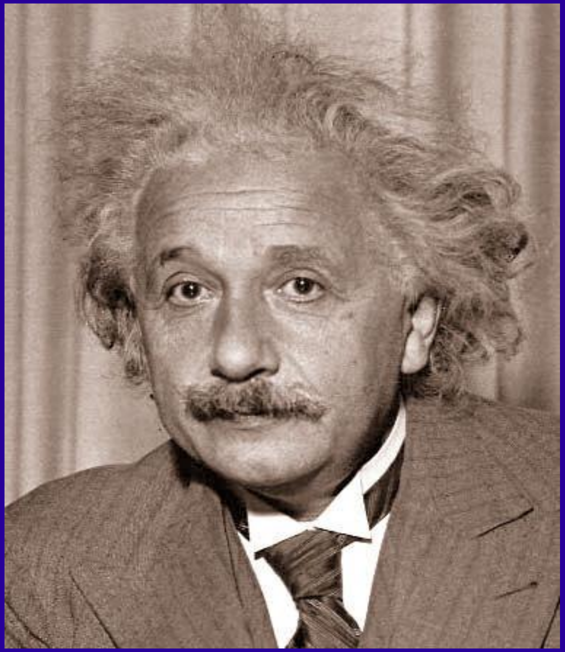
PET (Positron Emission Tomography) is the premier tool for imaging function of the brain and detection of cancer.

It arose from Dirac's desire to unify quantum mechanics with special relativity.

Antimatter went from a mathematical idea to a rare cosmic ray particle, to something that we today produce by the vial-full (if not quite bucket-full).

In 1930, if you had asked anyone, “How can we find a way to take images of the brain's function and check for spread of metastatic cancer”, nobody would have had the foresight to say “unify quantum mechanics with special relativity”.

c. 1915 General Relativity – the warping of space and time

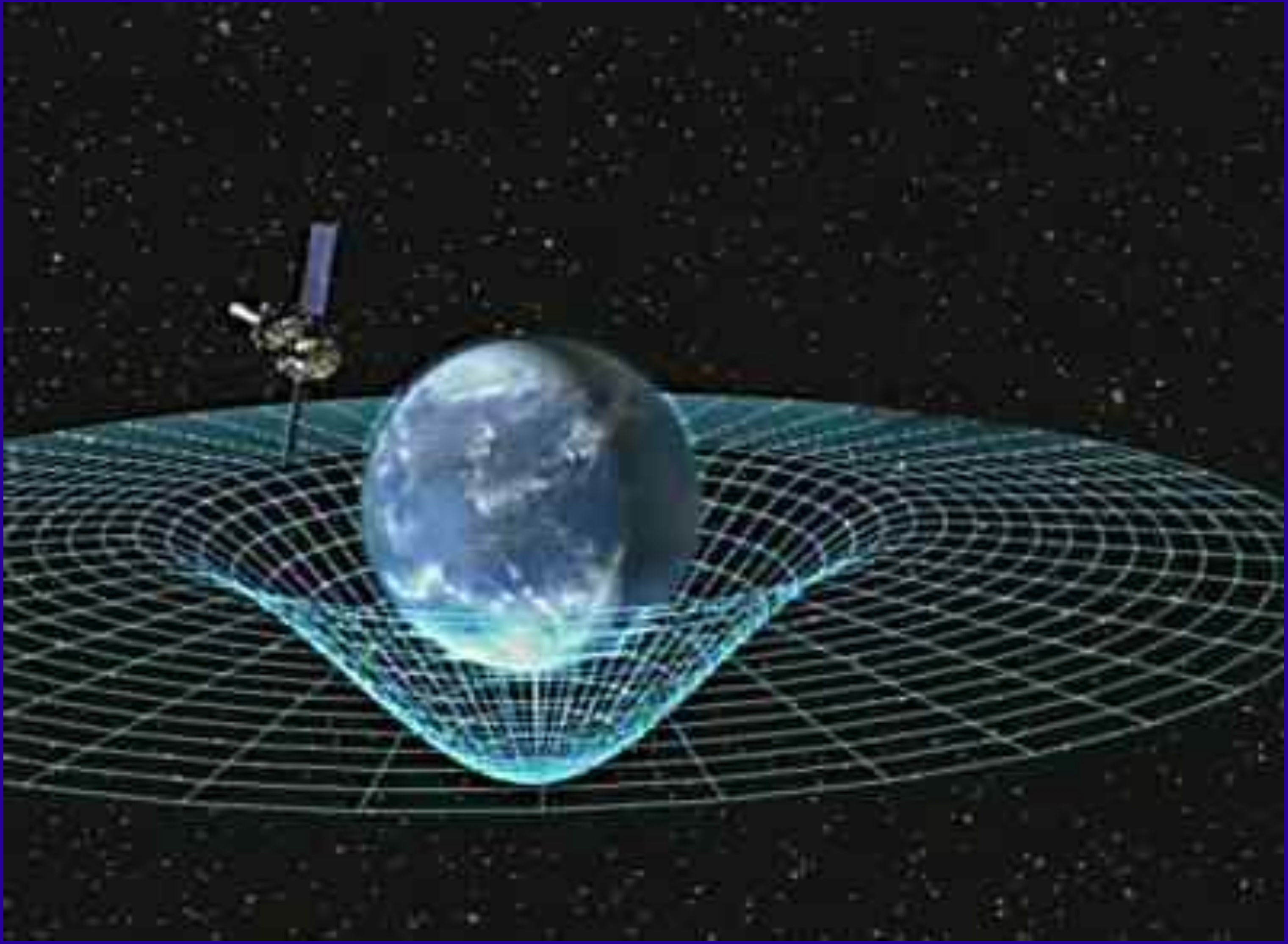


- special relativity relates to objects moving at uniform velocity wrt to one another

- Einstein wanted to generalize this to objects accelerating wrt to one another

- the fact that gravity causes bodies to accelerate means that general relativity is intimately related to the question of what gravity is

Einstein's idea: gravity is due to the warping of space and time around a massive object



Startling predictions:

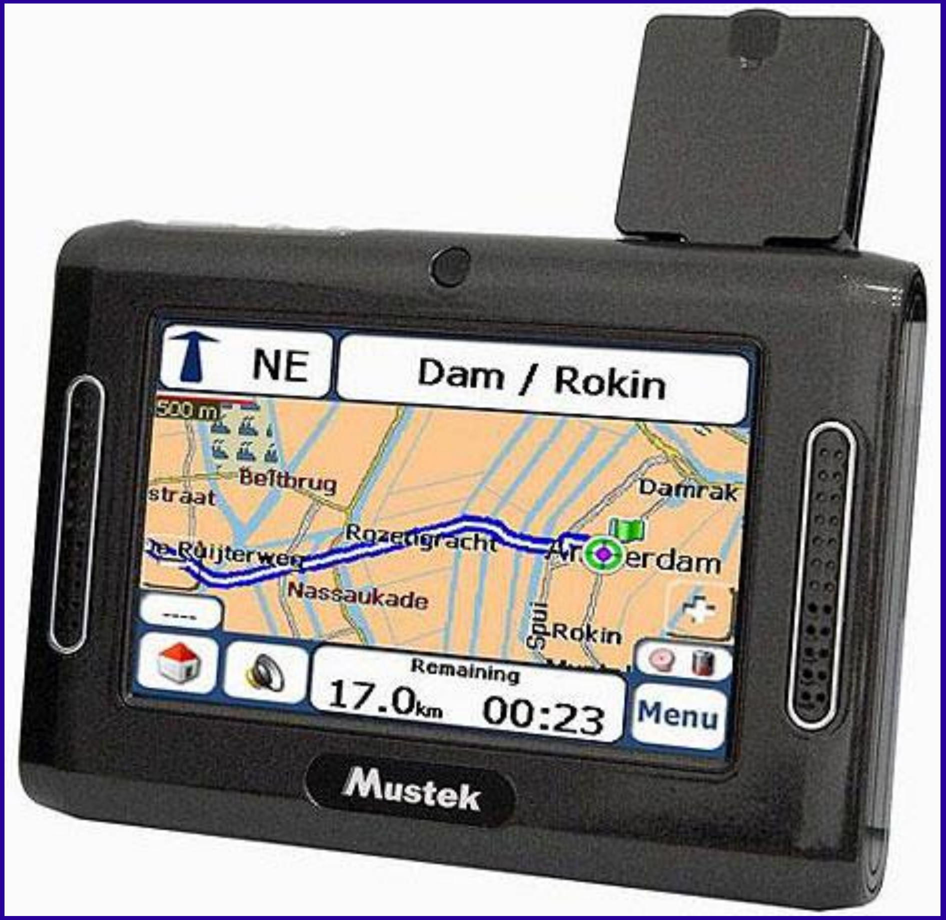
- light rays travelling near the sun would be bent
  verified by deflection of stars during a solar eclipse

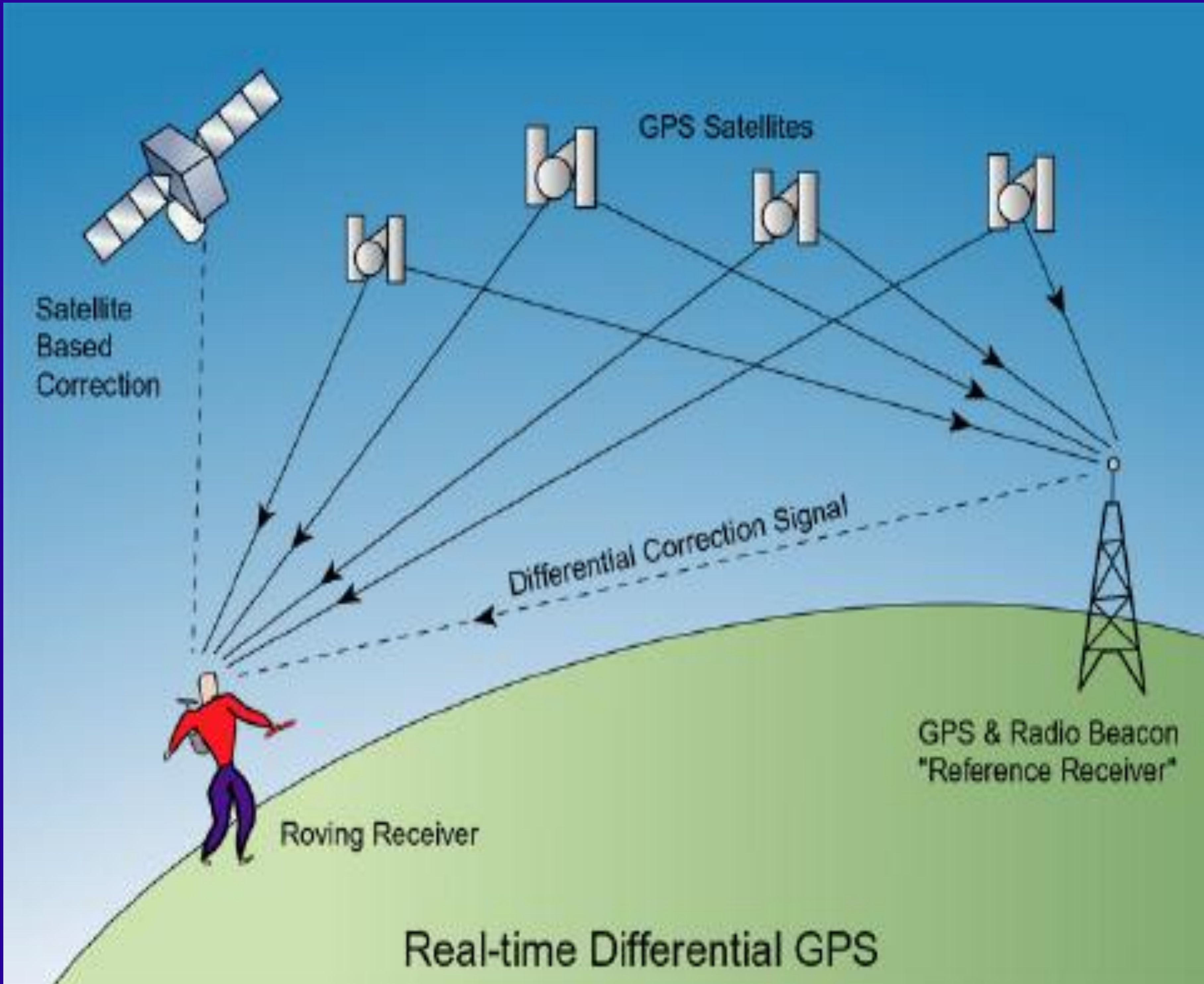
- delays in radio waves coming from distant planets because space is curved, not flat
  verified by delays in radar echos bounced off Venus

- shift in the perihelion of Mercury's orbit
  Einstein's prediction matches observation, Newtonian mechanics does not

- clocks in a gravitational field would run slow

These are tiny, tiny effects for people living on the surface of the Earth. Does it have any relevance for everyday life?




GPS Satellites
Satellite
Based
Correction
Differential Correction Signal
GPS & Radio Beacon
"Reference Receiver"
Roving Receiver
Real-time Differential GPS

The GPS system depends on accurate timing signals received from satellites in orbit – 0.02 microsecond (20 nanosecond) precision required.

Special relativity effect because the satellites are in motion. (satellite clocks lose 7 microseconds/day relative to ground)

General relativity effect because the surface of the Earth is in a gravitational potential (satellite clock advances 45 microsec/day relative to ground).

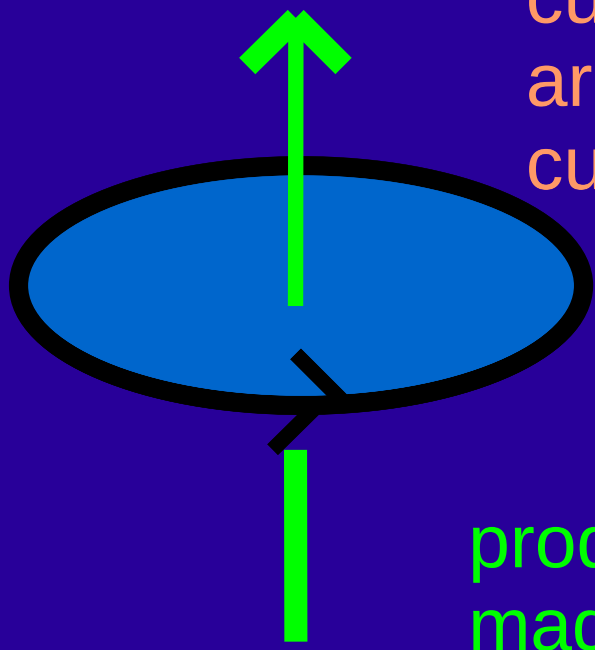
Net effect of 38 microsec per day due to relativity!

It is essential to account for both effects for the GPS system to function properly.

In 1915, if you had asked anyone what are the essential steps in improving the accuracy of navigation on earth, could anyone have had the foresight to say “understand how gravity affects the geometry of space and time?”.

SPINNING SUBATOMIC PARTICLES

c. 1926 Goudschmidt and Uhlenbeck discover that electrons are spinning, from the fine structure in the spectral lines of hydrogen



current loop
area A
current I

$\equiv$

produces
magnetic dipole
moment

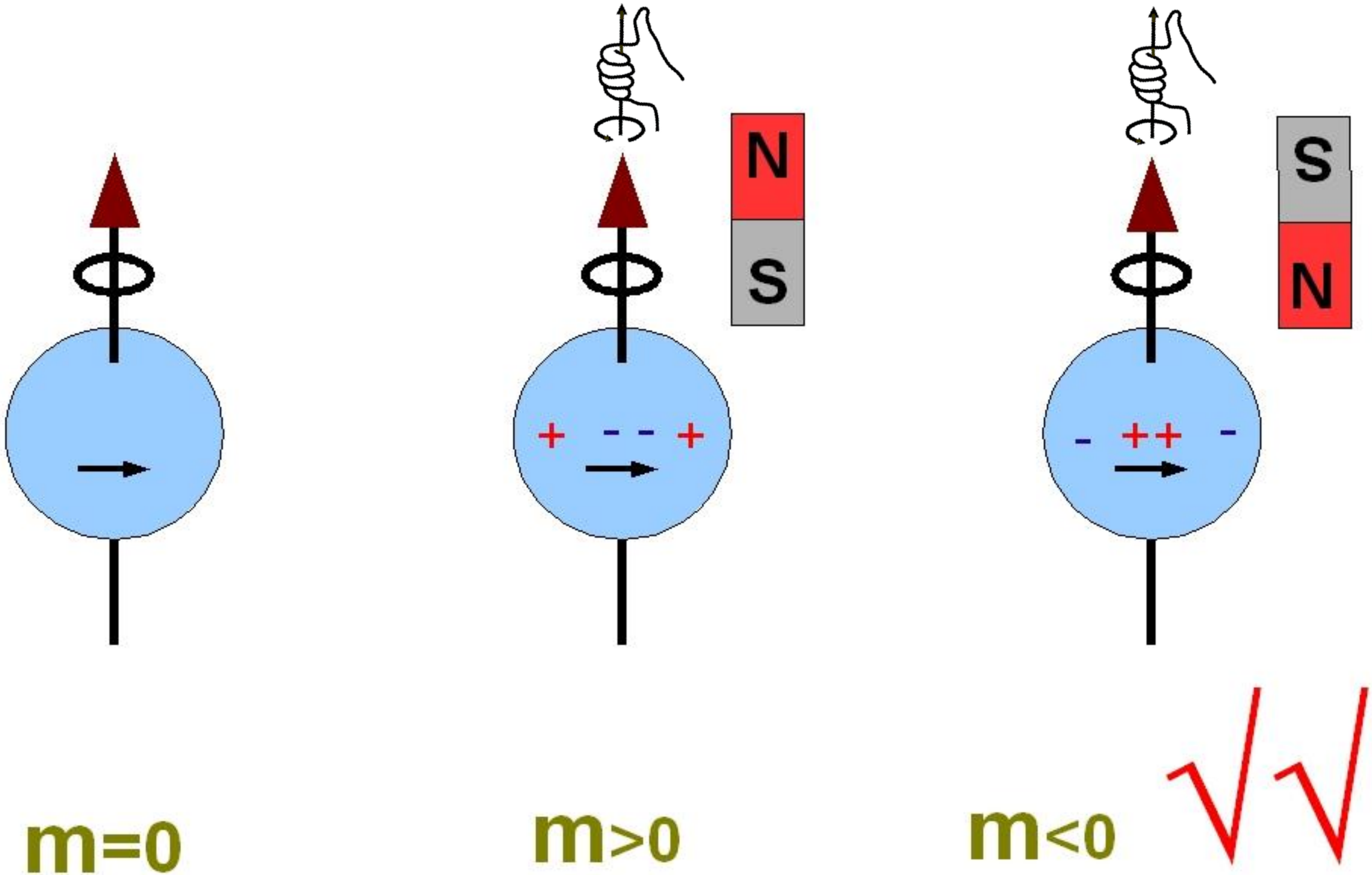
$m = I \cdot A$

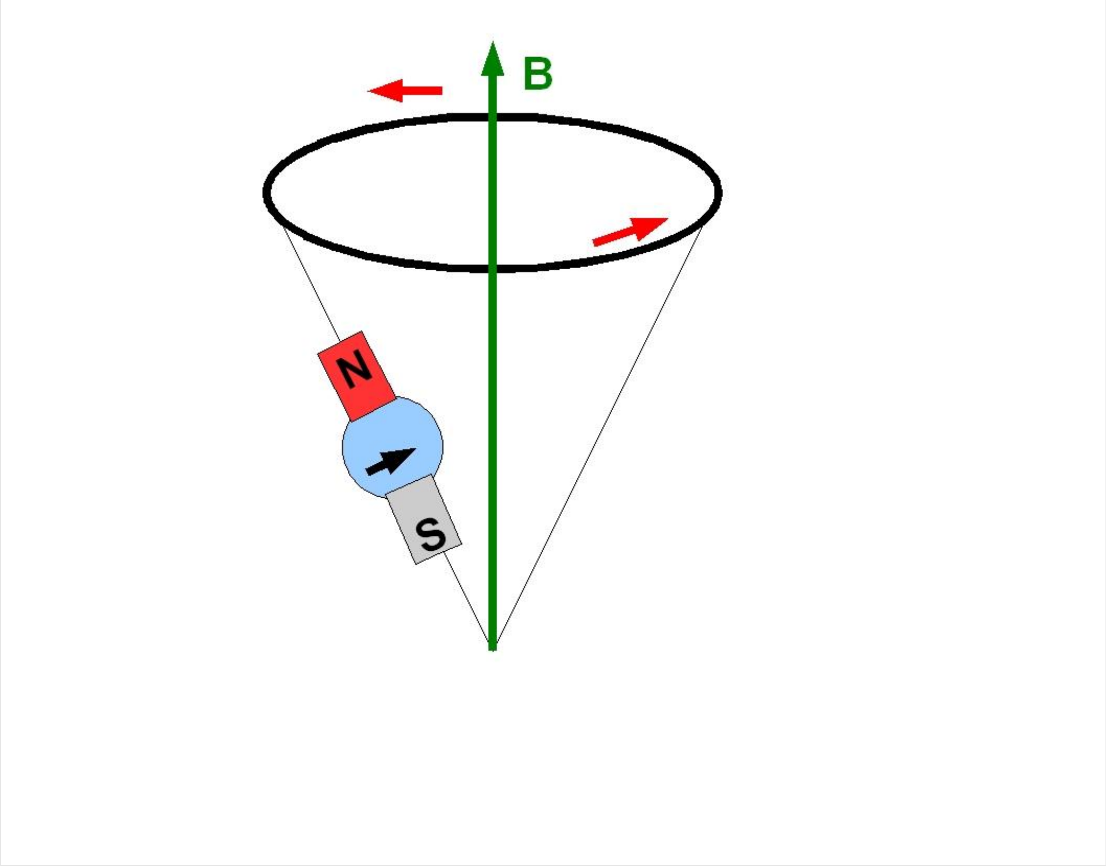
In fact, electron, protons and neutrons all have spin, and act like tiny little bar magnets

measuring the magnetic dipole moment **m**
(“the strength of the bar magnet”)
tells us about the distribution of the circulating charge inside the proton and neutron

An ambition of nuclear physicists in the 1940's.

Three Models of the Neutron



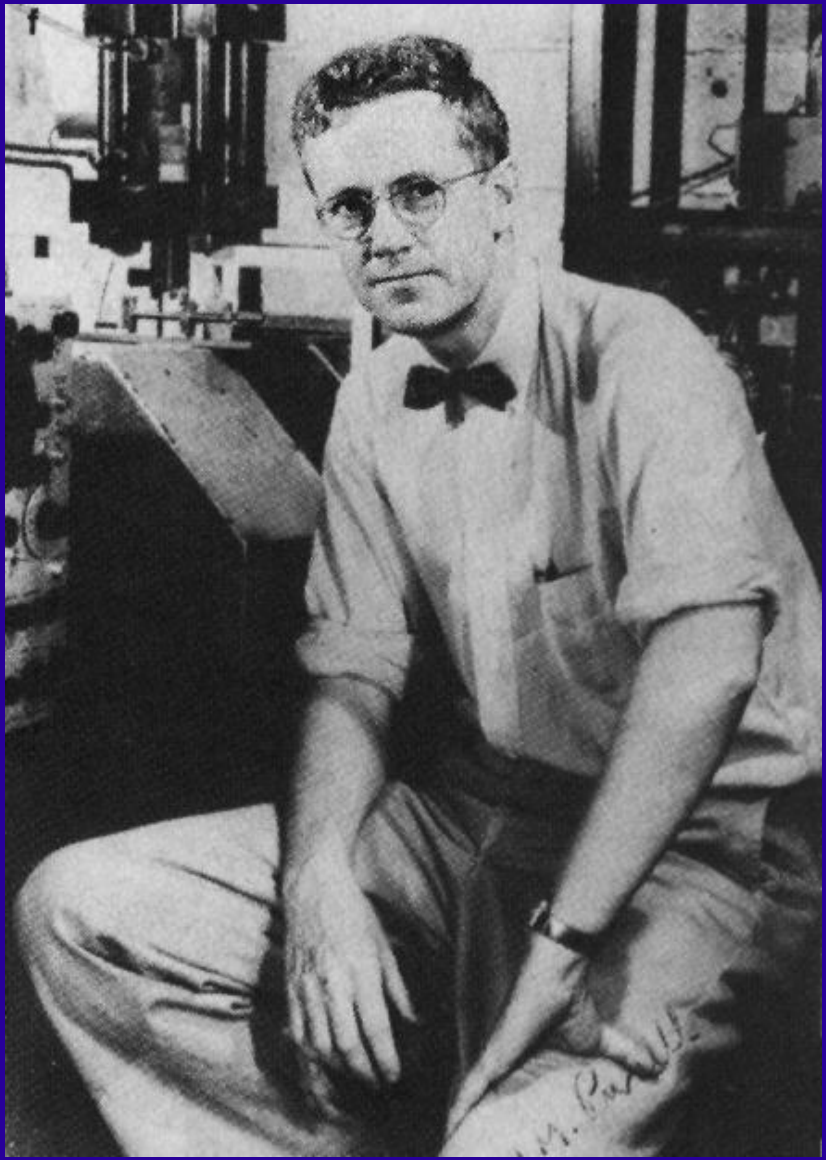


In an external magnetic field B, the magnetic dipole **m** precesses like a top, with Larmor frequency

$$f \sim \mathbf{m}.B$$

So measuring the precession frequency f in a known magnetic field B allows us to deduce **m**...

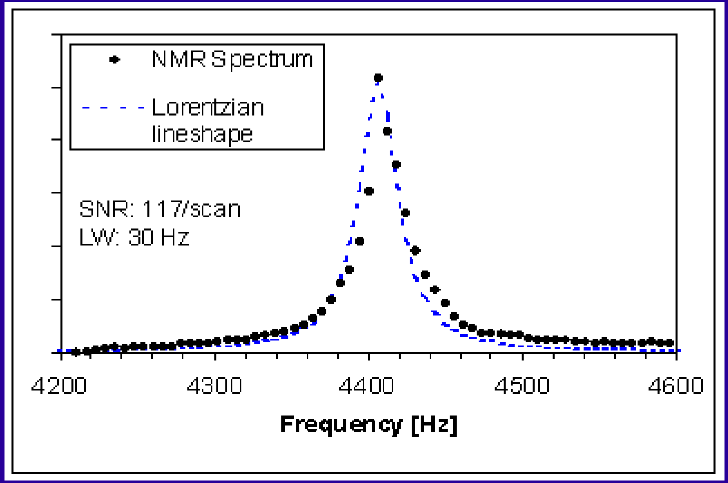
c. 1946 Ed Purcell & colleagues at Harvard try to measure the magnetic dipole moment of the proton



Where do we find protons?

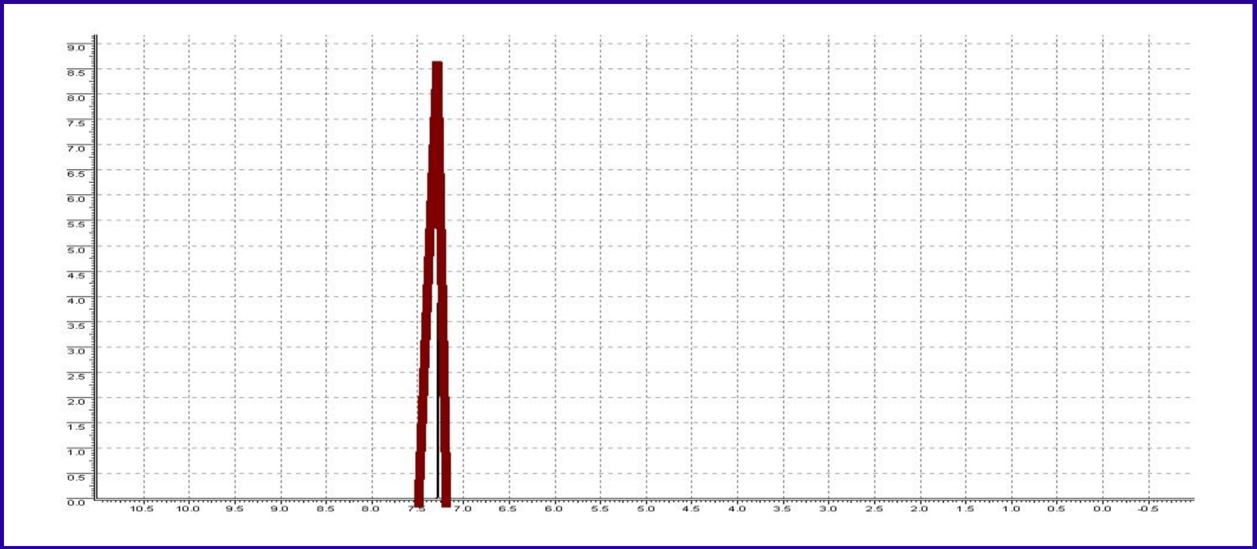
Water, alcohol, benzene

Let's try them ...

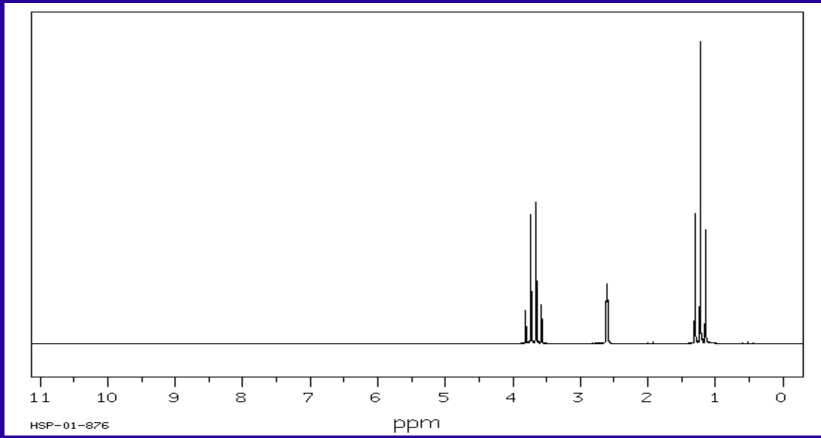


NMR Spectrum
Lorentzian lineshape
SNR: 117/scan
LW: 30 Hz
4200
4300
4400
4500
4600
Frequency [Hz]

benzene



GLEN MAVIS
BLENDED
SCOTCH WHISKY
PRODUCT OF SCOTLAND



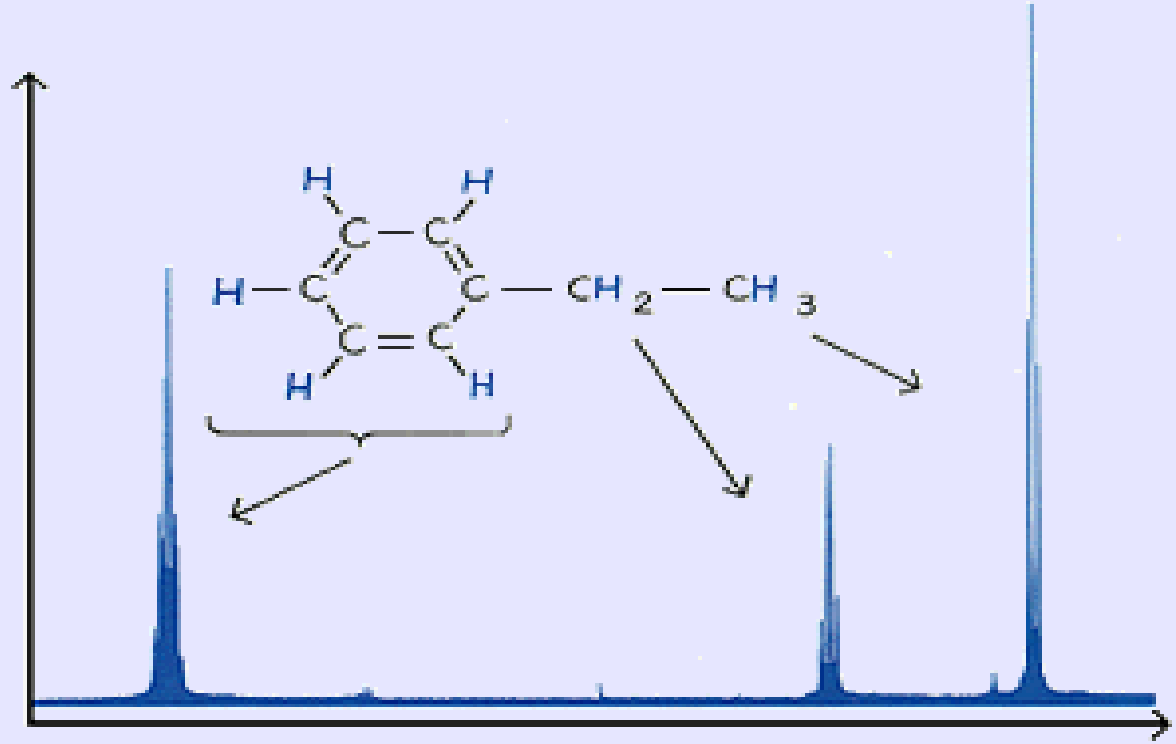
11
10
9
8
7
6
5
4
3
2
1
0
ppm
HSP-01-876

The precession frequency depends on the chemical environment of the proton.

Measurement of the magnetic dipole moment of the proton spoiled by the &@#%!! "**chemical shifts**" of the precession frequency.

Bad news for the nuclear physicist wanting to learn about the structure of the proton.

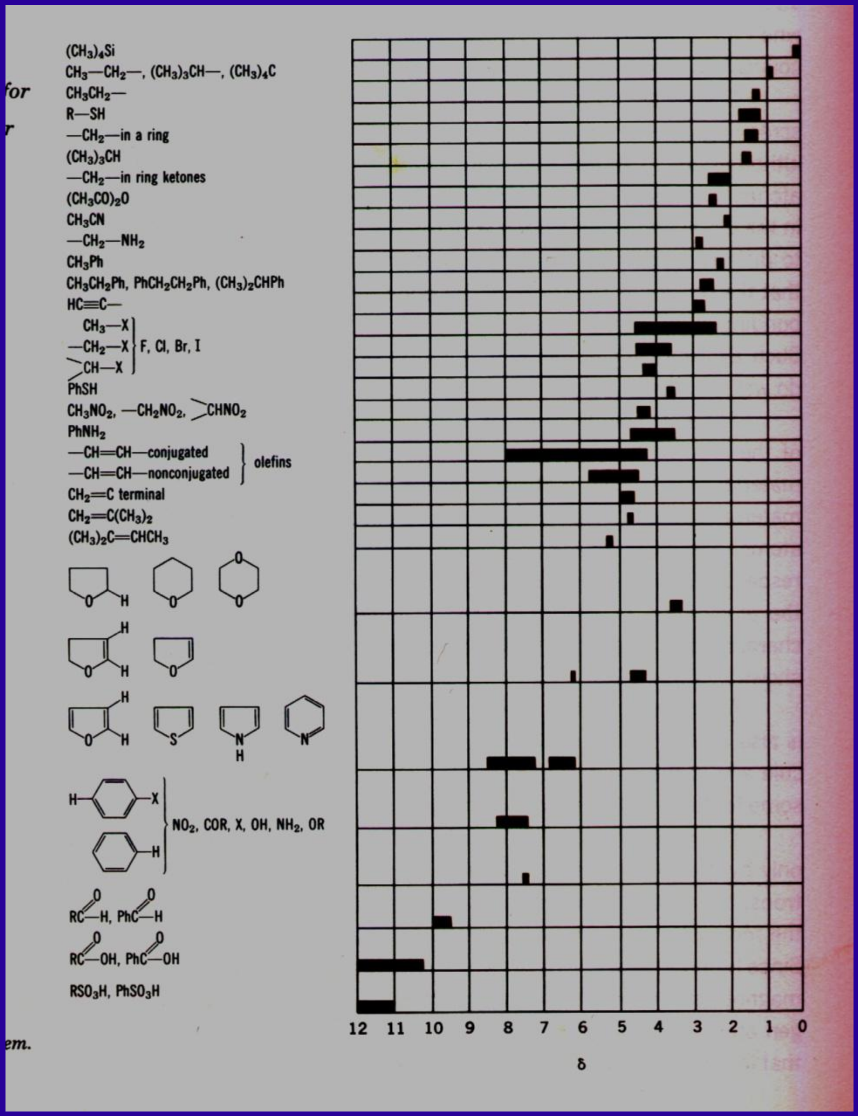
The electrical currents of the orbital electrons in the molecule make local magnetic fields that change the magnetic environment of the protons. Thus protons sitting at different locations in the molecules precess at different frequencies.



A proton NMR spectrum of a solution containing a simple organic compound, ethyl benzene. Each group of signals corresponds to protons in a different part of the molecule.

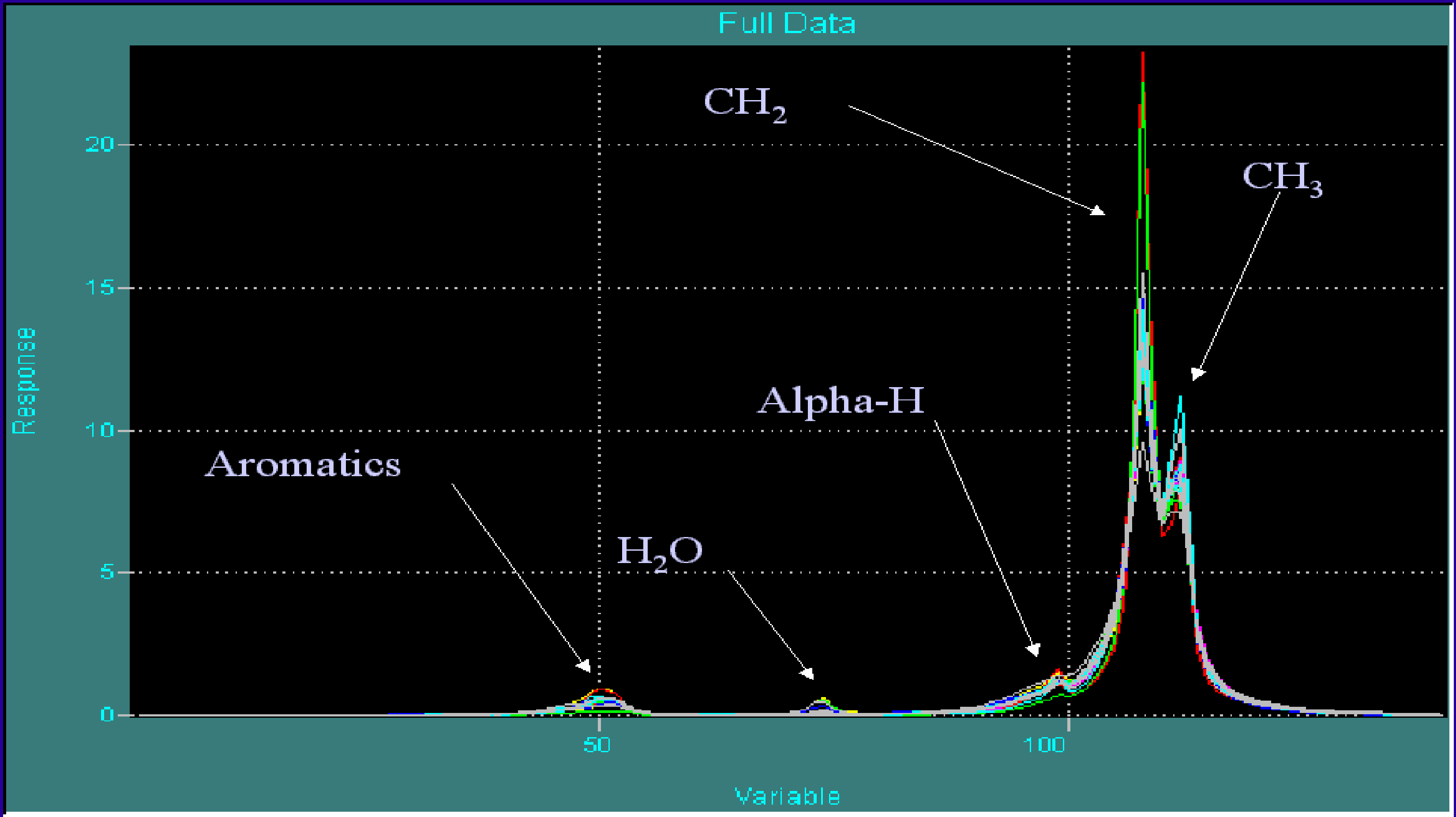
“One man's poison is another man's food”

so the nuclear physicist's bane
becomes the organic chemist's boon !



← atlas of chemical shifts for known chemical structures

Nuclear magnetic resonance (NMR) is now a standard tool for organic chemists to identify the structure of unknown compounds. Measure the “chemical shift” of the sample and compare it with the atlas to identify the functional groups in the sample.

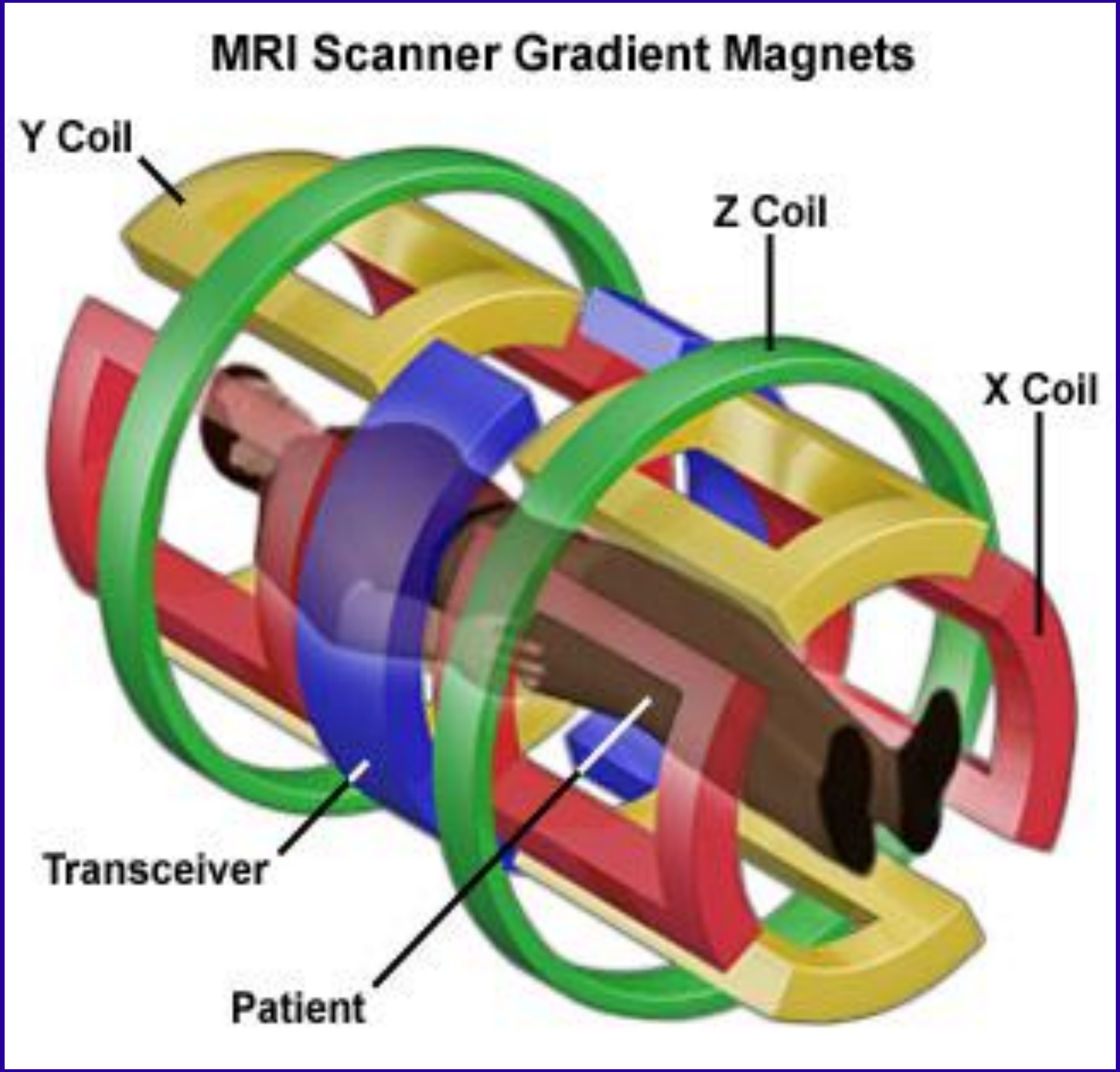


Spectral Variability Observed in Crude Oil Samples

The magnetic dipole moment of spinning protons is used in the medical imaging technique of **Magnetic Resonance Imaging (MRI).**

X-rays and CT scanners measure electron density, so good for imaging bone structures.

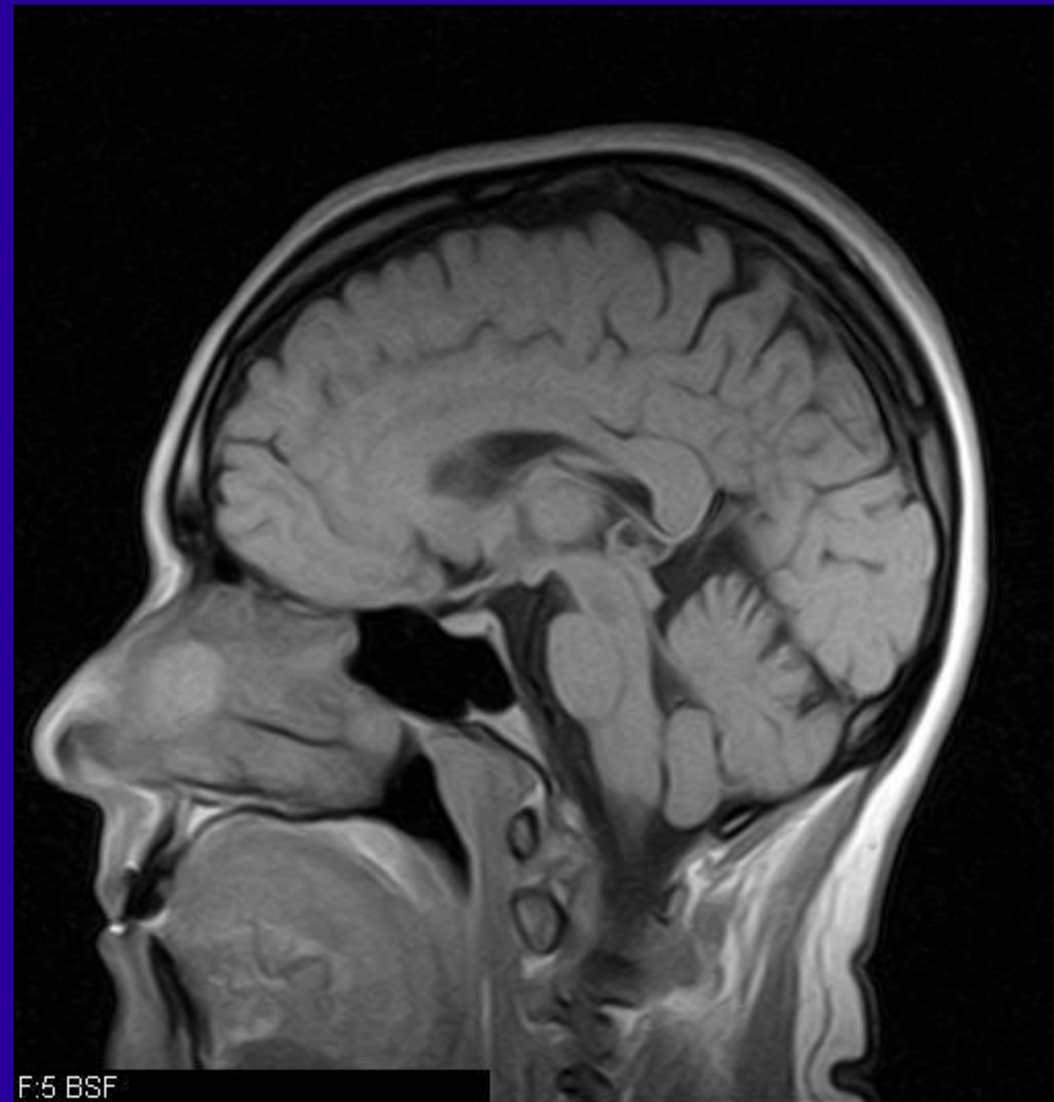
MRI detects protons (water and fat) and is good for imaging soft tissues.



- gradient coils provide a non-uniform magnetic field, so each point in the body feels a different B-field and precess at a different frequency

- measuring signal strength versus frequency tells the density of protons at that particular location


GE MEDICAL SYSTEMS
GENESIS_SIGNA GEMSLXMR
Ex 6151
Se: 103
Im: 11
O Ax S 31.2
DFOV 20.8cm
AIR
Monash Medical Centre
BRAIN A
F 103Y/Jan 01 1900
Nov 19 2003
04:28:27 PM
Mag = 1.11
FL:
ROT:
ET:15
R
I
P
L
S
A
TR:4020
TE:82.0/Ef
EC: 1/1 20.8kHz
8HRBRAIN/IIC
FOV:23x17.25
5.0thk/2.0sp
19/00:52
320X224/1.00 NEX
FCs/St:I/YB/TRF
PSL


F:5 BSF

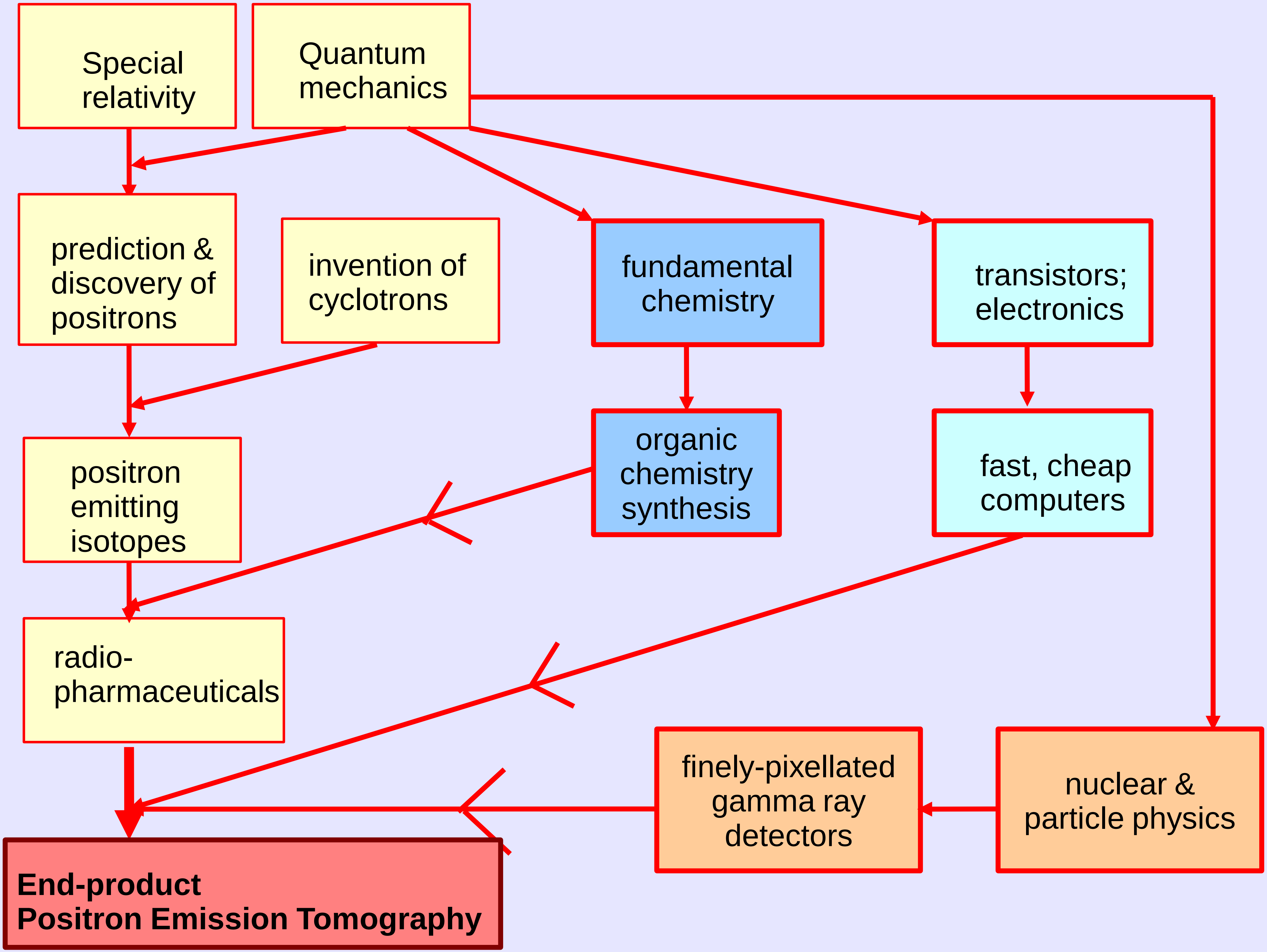
NMR is one of the principal tools of the organic chemist
MRI is the premier imaging modality for soft tissue.

Who could have anticipated that such practical applications could arise from the desire to measure the magnetism from spinning protons?

We see from these examples how fundamental research can reveal new foundational principles from which new applications can arise.

e.g. without Einstein's work on relativity, the GPS satellites would have been launched, and the whole system would not work, and nobody would understand why not.

Let's examine the different aspects of fundamental research that have contributed to Positron Emission Tomography:



Special relativity
Quantum mechanics
prediction & discovery of positrons
invention of cyclotrons
fundamental chemistry
transistors; electronics
positron emitting isotopes
organic chemistry synthesis
fast, cheap computers
radio-pharmaceuticals
finely-pixellated gamma ray detectors
nuclear & particle physics
End-product
Positron Emission Tomography

It is impossible to predict which fundamental principles will end up being useful, because end-applications typically depend on the confluence of multiple advances in several different fields.

Experts might be able to predict one advance in one field, but nobody can predict how advances in different fields will meld together to make the final end-product.

“useless questions” (Why are there coloured bands in a vacuum tube? Why doesn't the electron fall into the atomic nucleus? What happens when a small object goes near the speed of light?”)

↓

New foundational principles (quantum mechanics, special relativity, general relativity, nuclear magnetism)

↓

Today's practical applications (X-rays, electronics, lasers, GPS, PET scans, MRI)

so, funding agencies beware:

The focus on industrial partnerships and applied research is well and good, but the really big advances will come from fundamental research, from a confluence of different directions that neither you nor anyone else can anticipate.

Fundamental science provides a foundation on which future practical applications will be based. No foundation-building today means no future applications.

Summary

I have given examples of curiosity-driven research that had no apparent practical applications

- Leeuwenhoek's microscopes
- electrical discharges in vacuum tubes
- why doesn't the electron fall into the nucleus?
- unifying relativity and quantum mechanics
- warping of space and time by gravity
- the magnetism of spinning protons

and shown how they have given rise to important applications that no one could have anticipated.