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# Experimental Particle Physics

## PHYS6011

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# Administrative Points

- 5 lectures:
  - 13<sup>th</sup>, 20<sup>th</sup>, 22<sup>nd</sup> February 2007
  - 1<sup>st</sup> and 8<sup>th</sup> May 2007
- Course Objectives, Lecture Notes, Problem examples:
  - <http://www.slac.stanford.edu/~fwilson/south/>
- Resources:
  - D. Green, “The Physics of Particle Detectors”
  - K. Kleinknecht, “Detectors for Particle Radiation”
  - I.R. Kenyon, “Elementary Particle Physics” (chap 3).
  - Particle Data Group, <http://pdg.lbl.gov>

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# Syllabus

1. Accelerators and Sources
2. Interactions with Matter
3. Detectors
4. A modern particle physics experiment
5. How analysis is performed.

# Introduction

- Time, energy (temperature) and distance are related:

- High momentum  $\Leftrightarrow$   
Small distance  $\Leftrightarrow$   
High temperature  $\Leftrightarrow$   
Early Universe

- Natural Units:

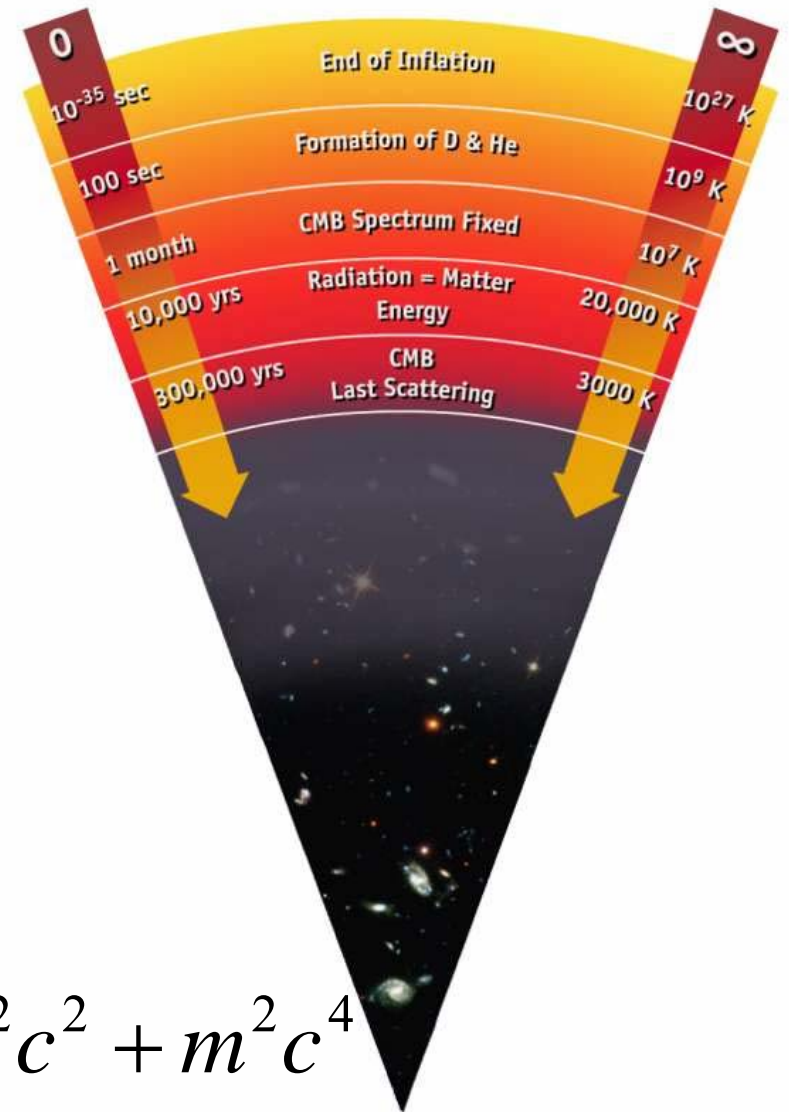
- Energy - GeV
- Mass - GeV/c<sup>2</sup>
- Momentum - GeV/c
- Length and time - GeV<sup>-1</sup>

- Use the units that are easiest.

$$h = c = 1$$

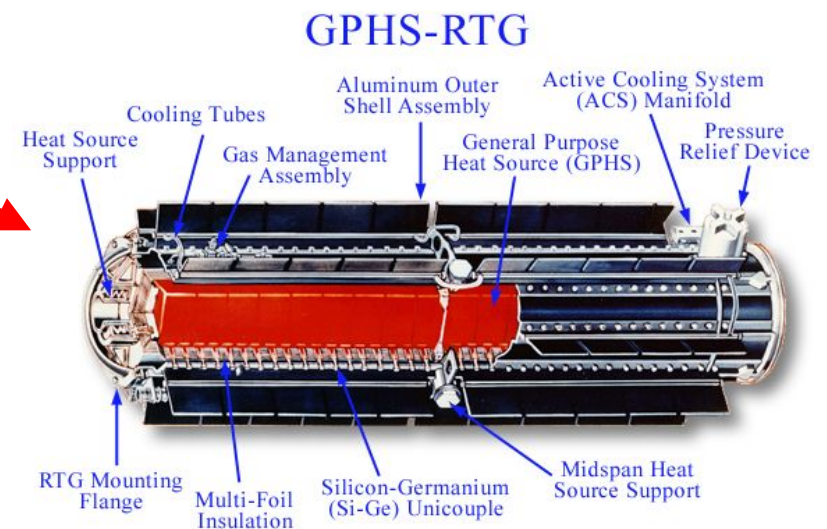
$$E^2 = p^2 c^2 + m^2 c^4$$

$$\Rightarrow E^2 = p^2 + m^2$$



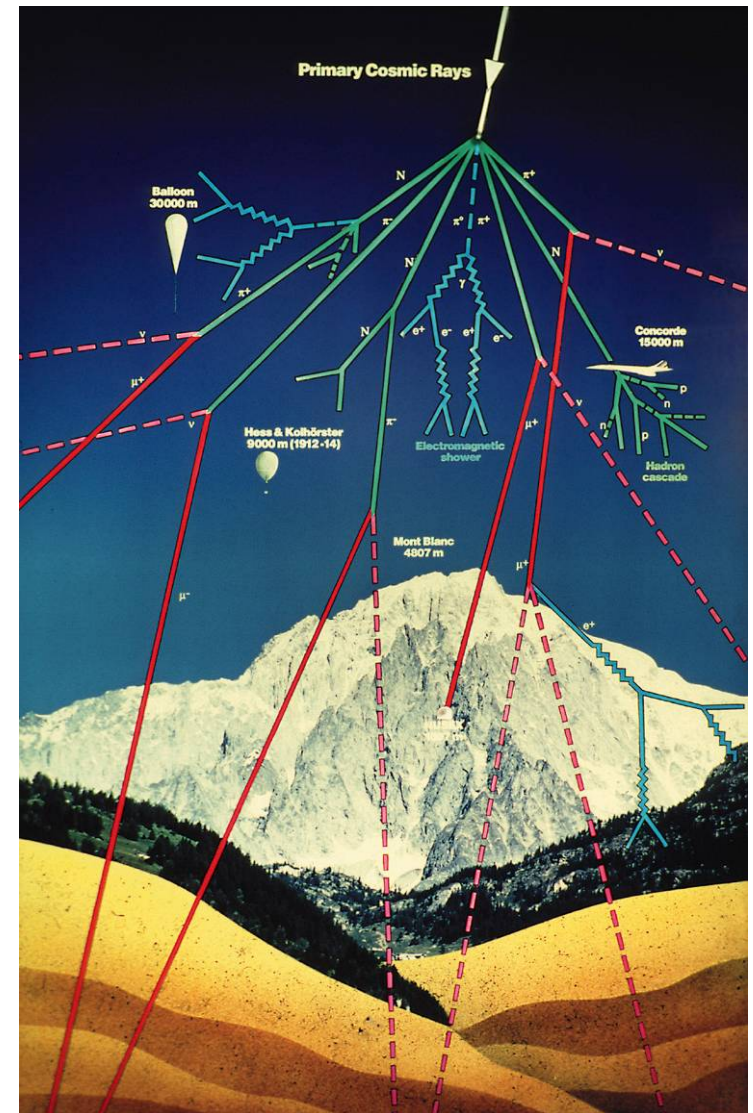
# Natural Radioactivity

- First discovered in late 1800s
- Used as particle source in many significant experiments
  - Rutherford's 1906 experiment: elastic scattering  $\alpha + N \rightarrow \alpha + N$
  - Rutherford's 1917 experiment: inelastic scattering  $\alpha + N \rightarrow p + X$
- Common radioisotopes include
  - $^{55}\text{Fe}$ : 6 keV  $\gamma$ ,  $\tau_{1/2} = 2.7$  years
  - $^{90}\text{Sr}$ : 500 keV  $\beta$ ,  $\tau_{1/2} = 28.9$  years
  - $^{241}\text{Am}$ : 5.5 MeV  $\alpha$ ,  $\tau_{1/2} = 432$  years
  - $^{210}\text{Po}$ : 5.41 MeV  $\alpha$ ,  $\tau_{1/2} = 137$  days
- Easy to control, predictable flux but low energy
- Still used for calibrations and tests



# Cosmic Rays

- History
  - ❑ 1912: First discovered
  - ❑ 1927: First seen in cloud chambers
  - ❑ 1962: First 1020 eV cosmic ray seen
- Low energy cosmic rays from Sun
  - ❑ Solar wind (mainly protons)
  - ❑ Neutrinos
- High energy particles from sun, galaxy and perhaps beyond
  - ❑ Neutrinos pass through atmosphere and earth
  - ❑ Low energy charged particles trapped in Van Allen Belt
  - ❑ High energy particles interact in atmosphere.
  - ❑ Flux at ground level mainly muons:  $100\text{-}200\text{ s}^{-1}\text{ m}^{-2}$
- Highest energy ever seen  $\sim 10^{20}\text{eV}$ 
  - ❑ GZK cutoff



# Cosmic rays

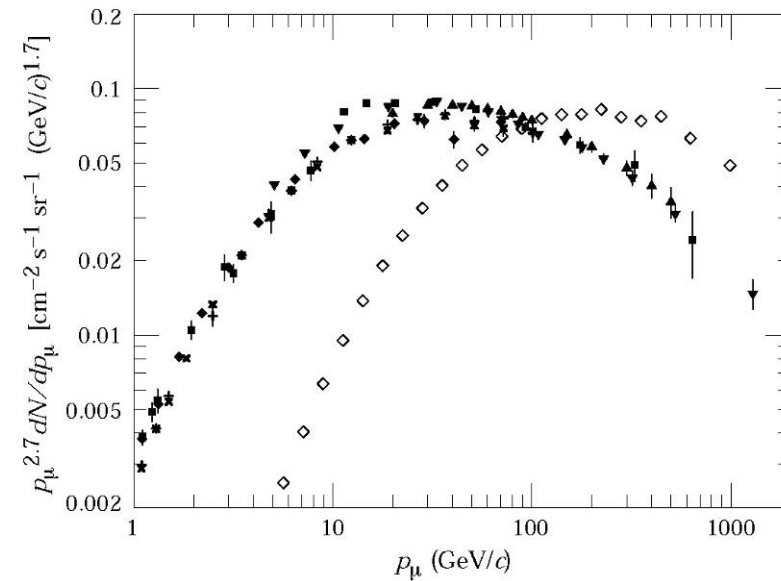
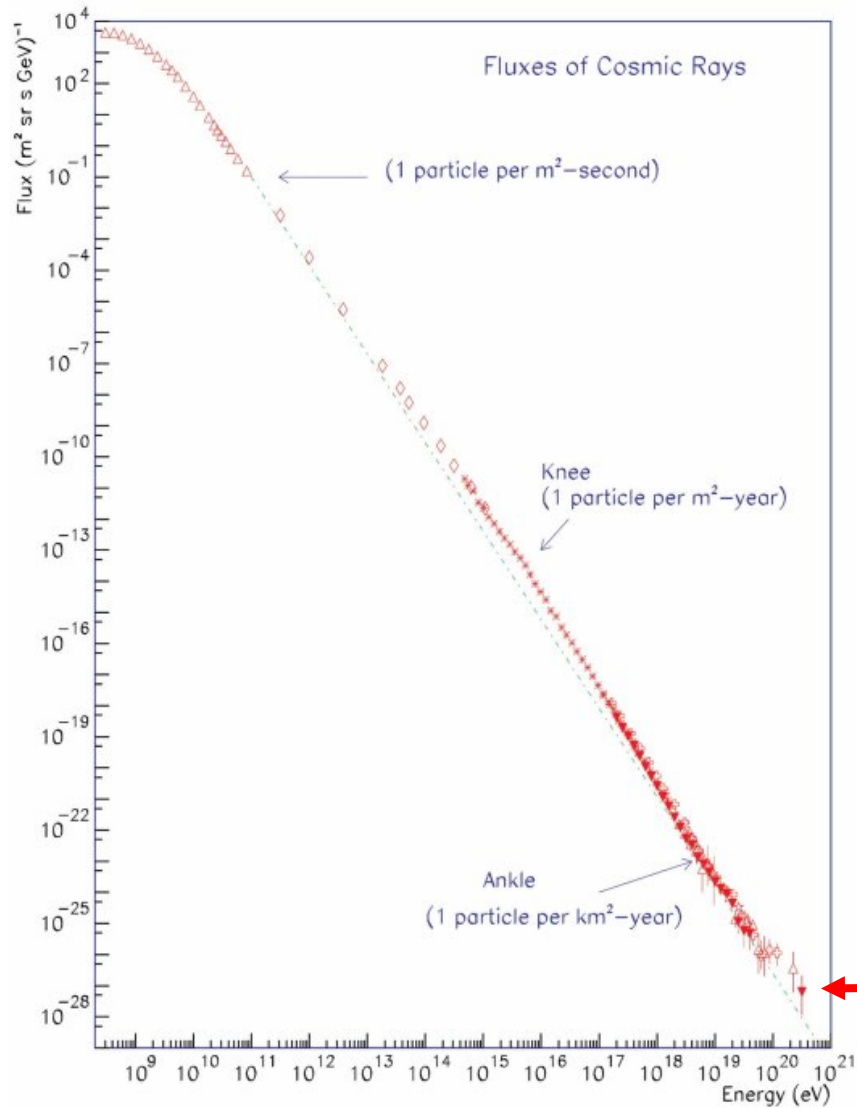
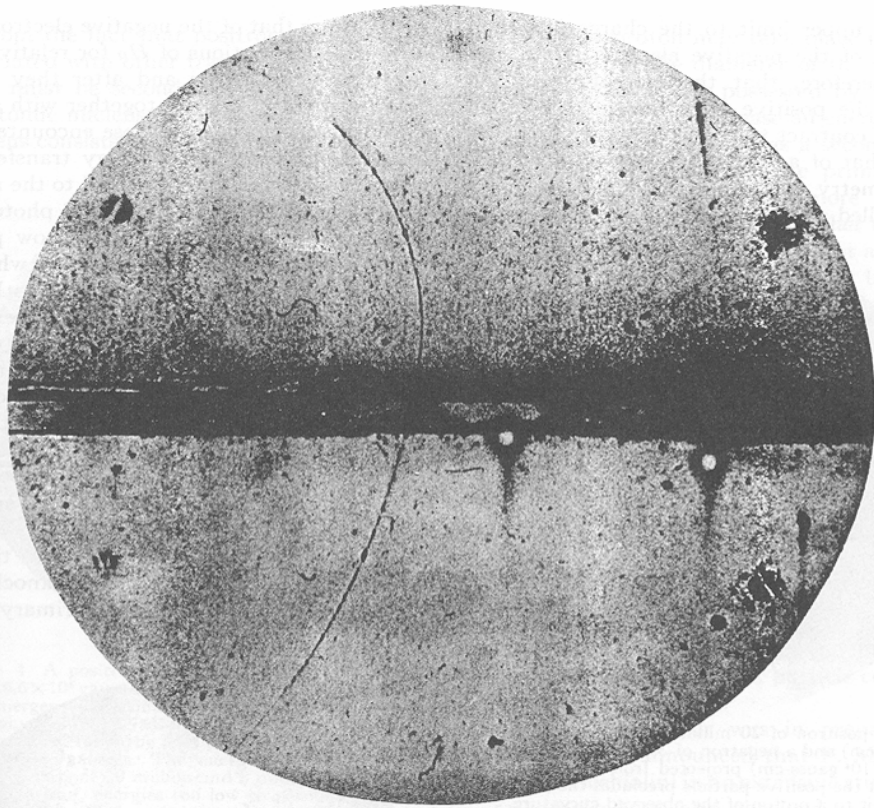


Figure 24.4: Spectrum of muons at  $\theta = 0^\circ$  ( $\blacklozenge$  [29],  $\blacksquare$  [34],  $\blacktriangledown$  [35],  $\blacktriangle$  [36],  $\times$  and  $+$  [31], and  $\theta = 75^\circ$   $\diamond$  [37]).



# Cosmic Ray Experiments

- Primary source for particle physics experiments for decades
- Detectors taken to altitude for larger flux/higher energy
- Positron and many other particles first observed



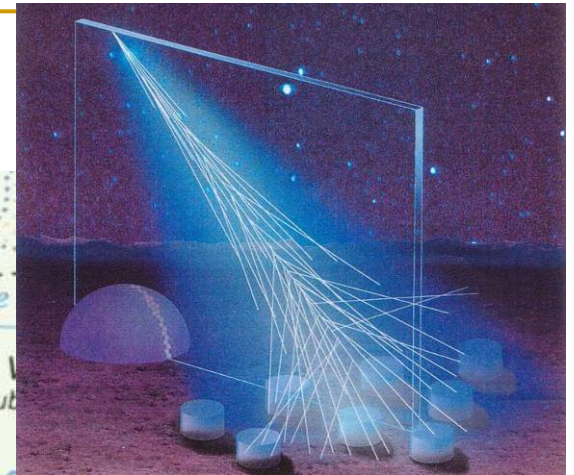
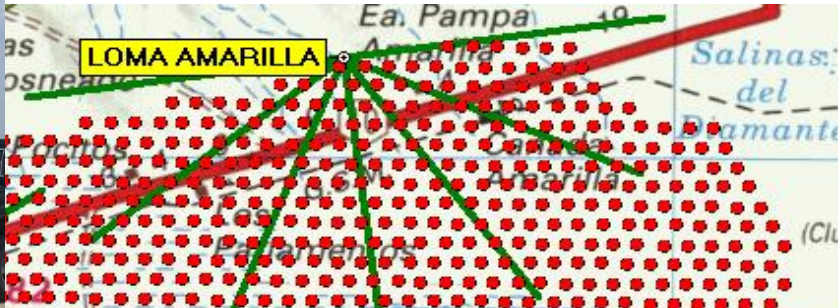
Modern experiments include:

- Particle astrophysics
  - Space, atmosphere, surface, underground
- Neutrino
  - Solar, atmospheric
- “Dark Matter” searches

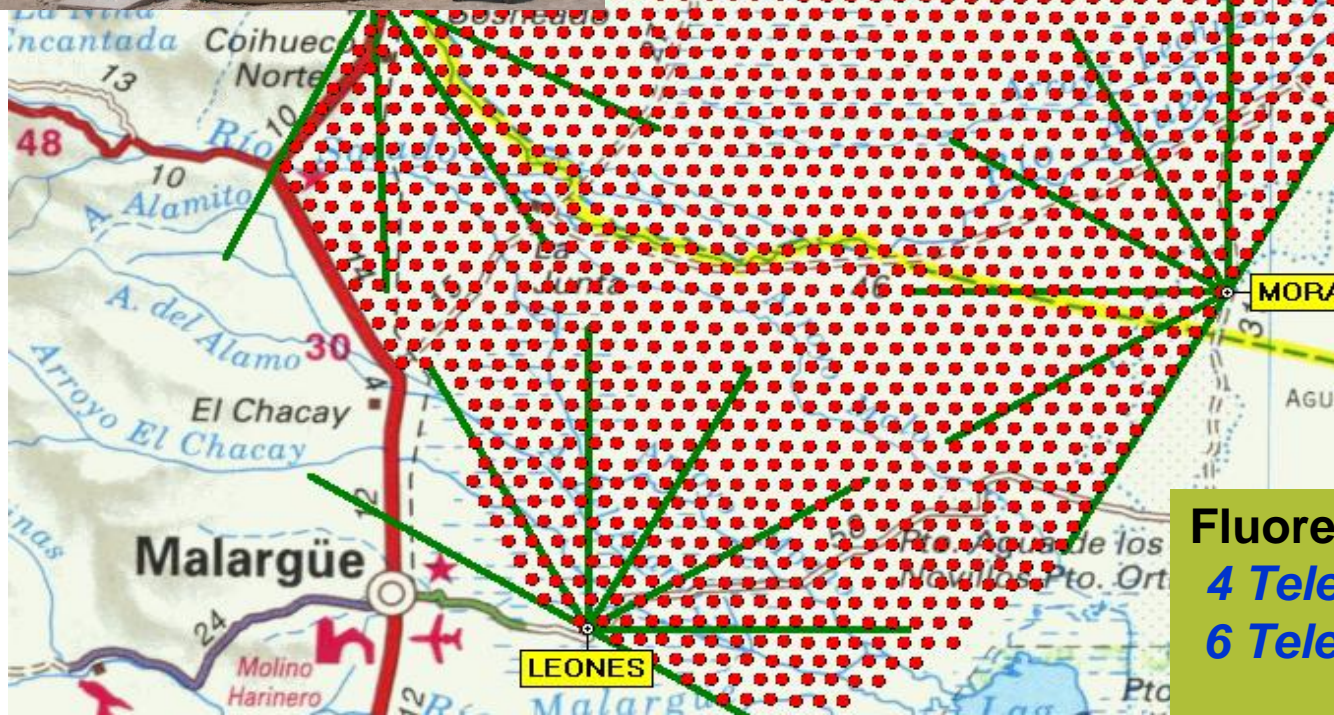
Still useful for calibration and testing



# Cosmic rays - Pierre Auger Project



**Surface Array**  
*1600 detector stations*  
*1.5 km spacing*  
*3000 km<sup>2</sup>*

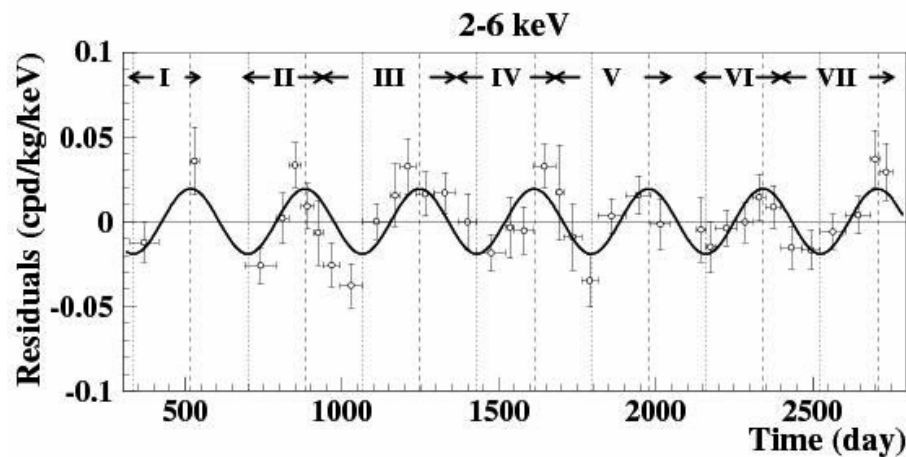
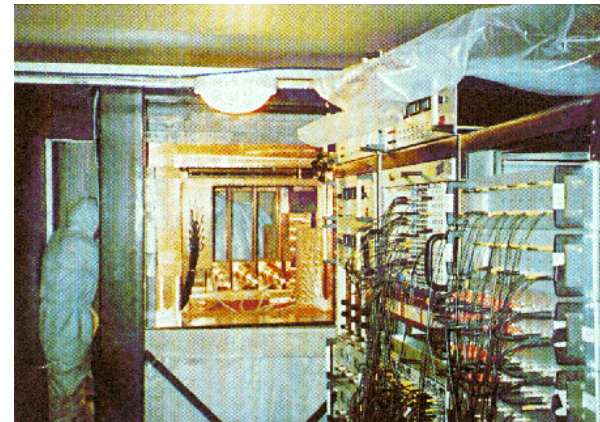
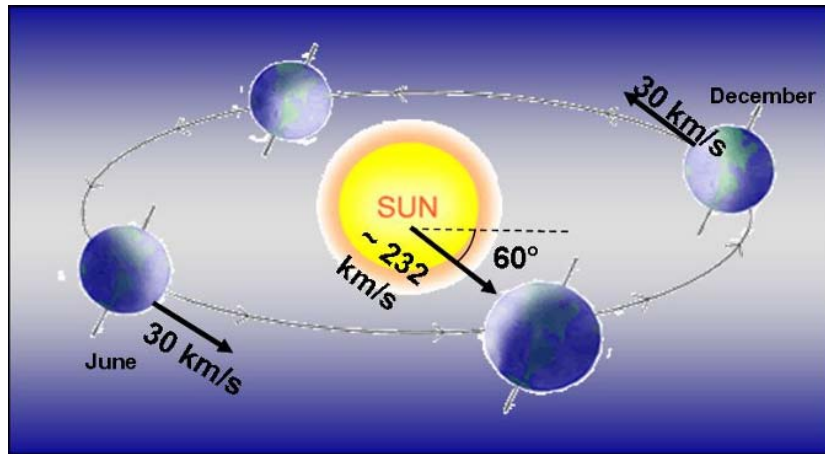


**Fluorescence Detectors**  
*4 Telescope enclosures*  
*6 Telescopes per enclosure*  
*24 Telescopes total*



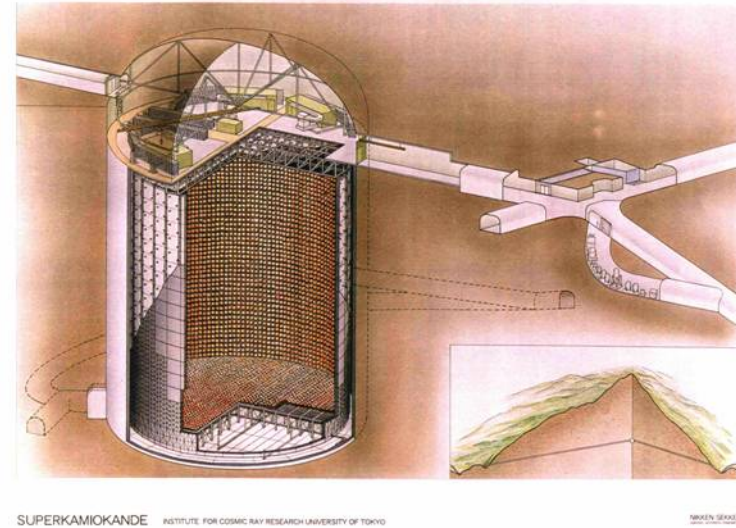
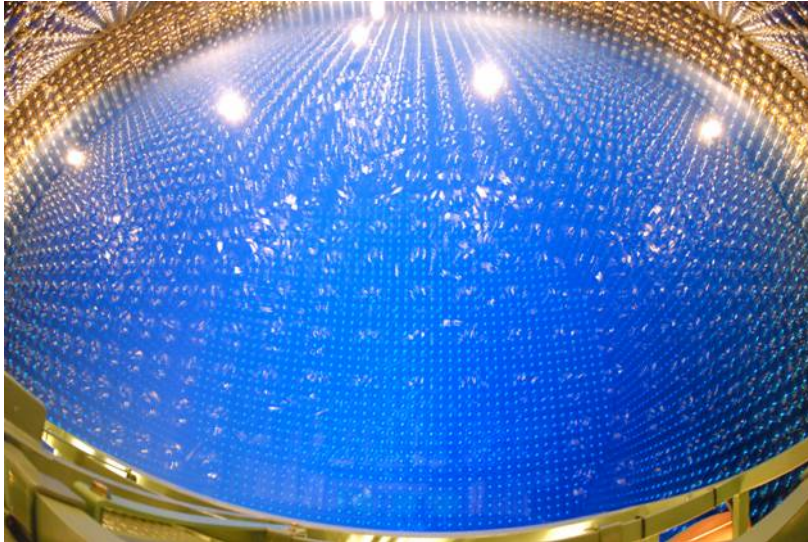
# Dark Matter - DAMA

<http://people.roma2.infn.it/~dama>



1. As the earth goes round the sun, its velocity relative to the galaxy changes by  $\pm 30$  km
2. Look for nuclear recoil in NaI as nucleus interacts with “dark matter” particle.
3. Expect to see a change in the rate of interactions every six months
4. But is there really a pattern? and is it really dark matter?

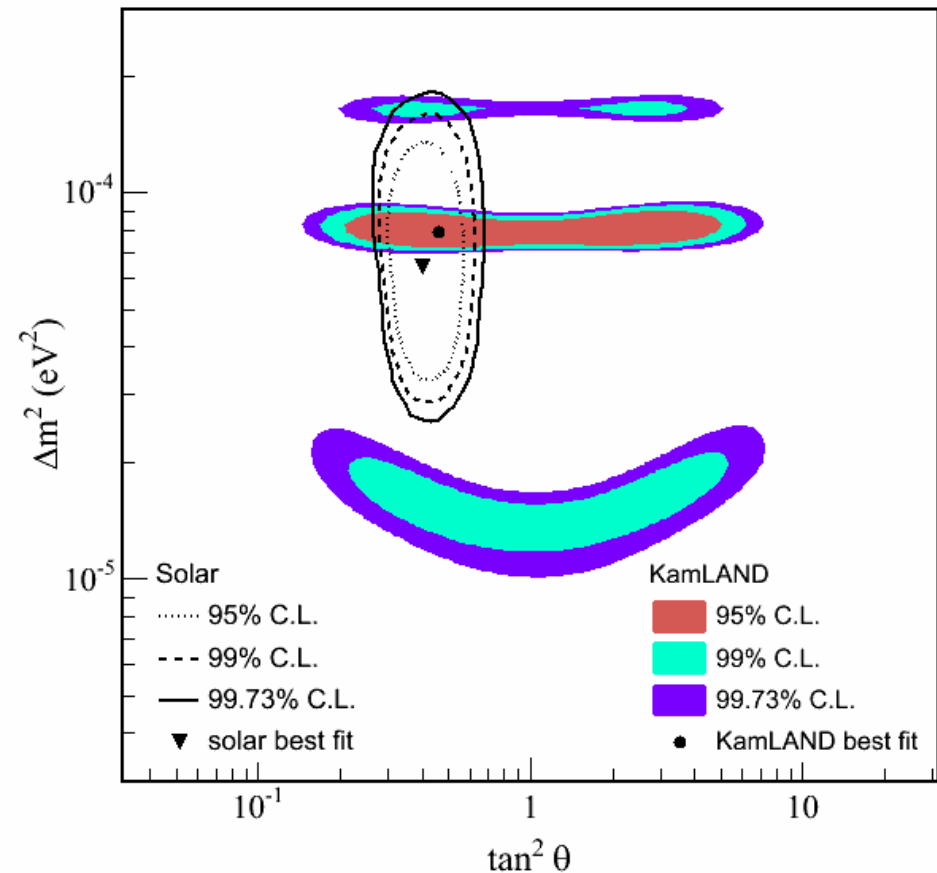
# Solar Neutrino – Super-Kamiokande



Kamioka Observatory,  
ICRR(Institute for Cosmic Ray Research),  
The University of Tokyo

# Reactor Experiments

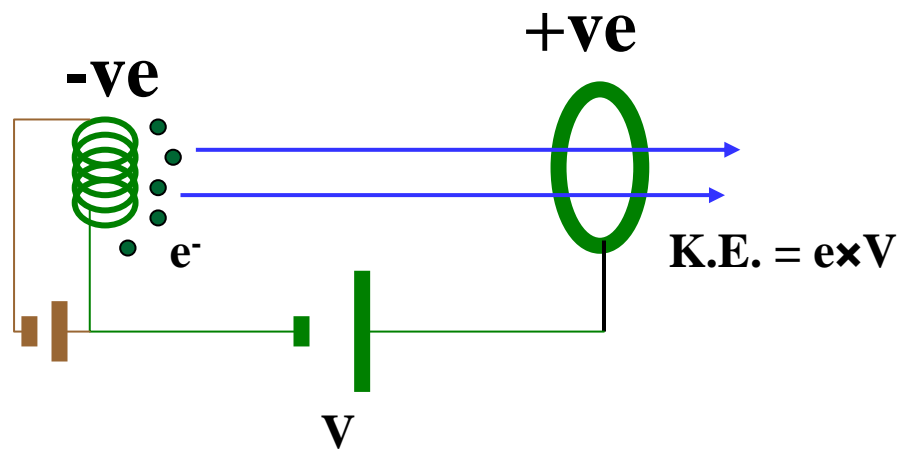
- Huge fluxes of MeV neutrons and electron neutrinos
- First direct neutrino observation
- New results on neutrino oscillations



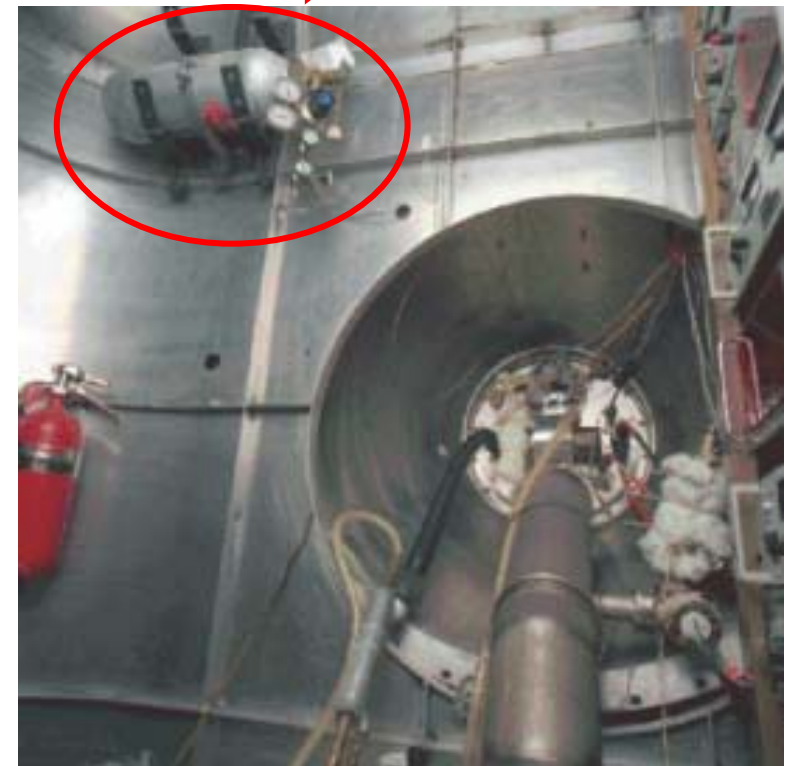
# Particle Sources

Want intense monochromatic beams on demand:

1. Make some particles
  - Electrons: metal + few eV of thermal energy
  - Protons/nuclei: completely ionise gas
2. Accelerate them in the lab



Hydrogen gas bottle





# DC Accelerators

## Cockcroft and Walton's Original Design

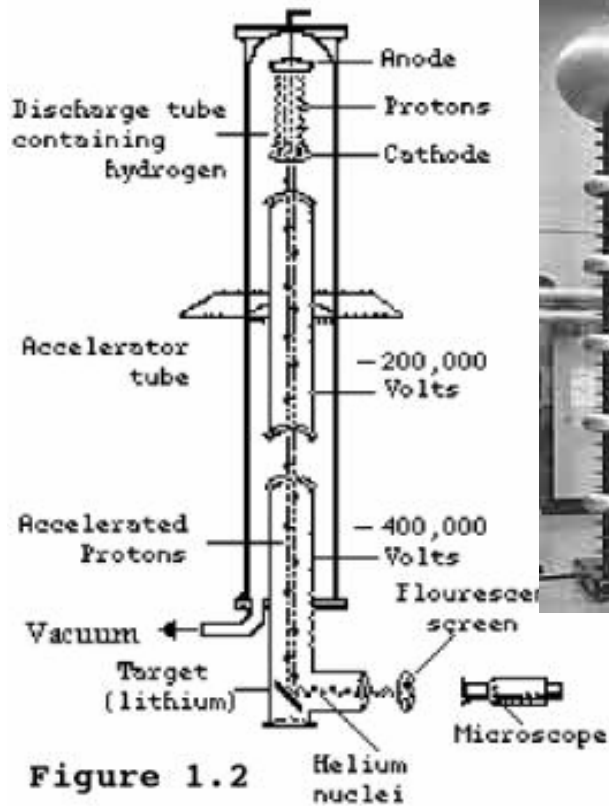
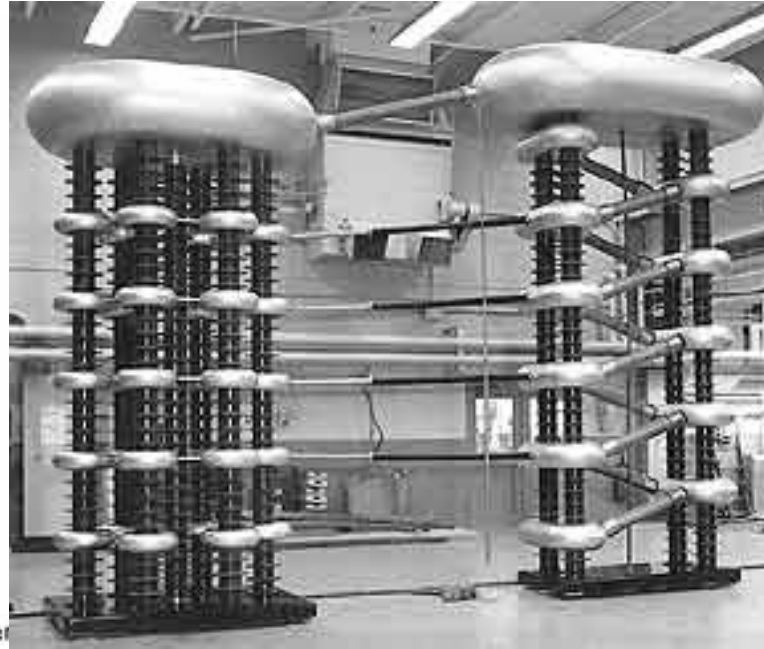


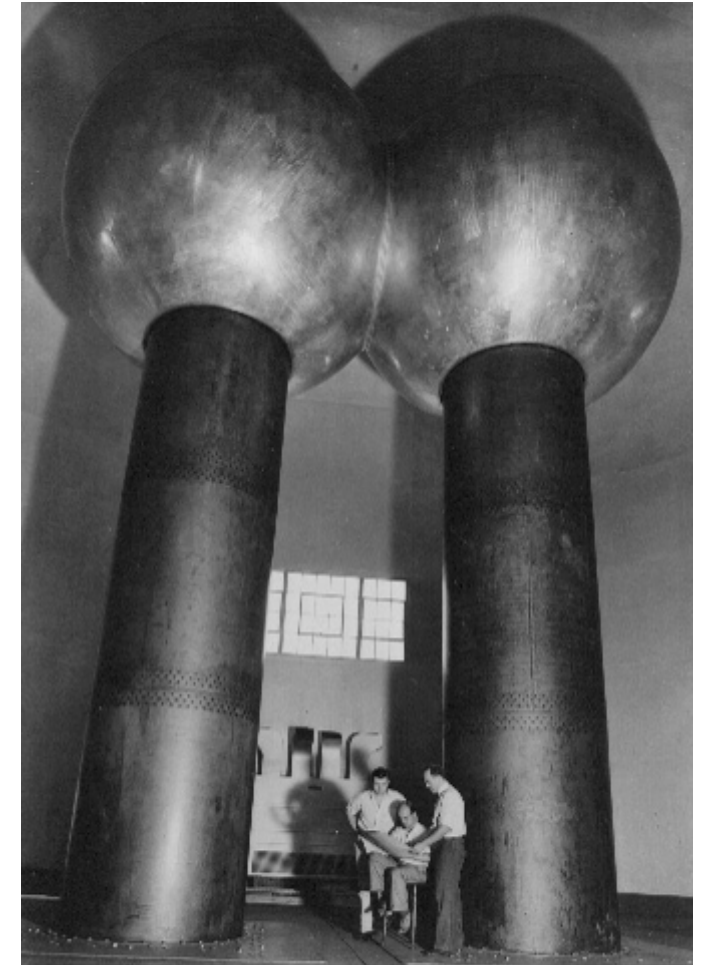
Figure 1.2

- DC accelerators quickly become impractical
- Air breaks down at  $\sim 1$  MV/m

## Fermilab's 750kV Cockcroft-Walton



## Van de Graaff at MIT





# Cyclotrons

Berkeley

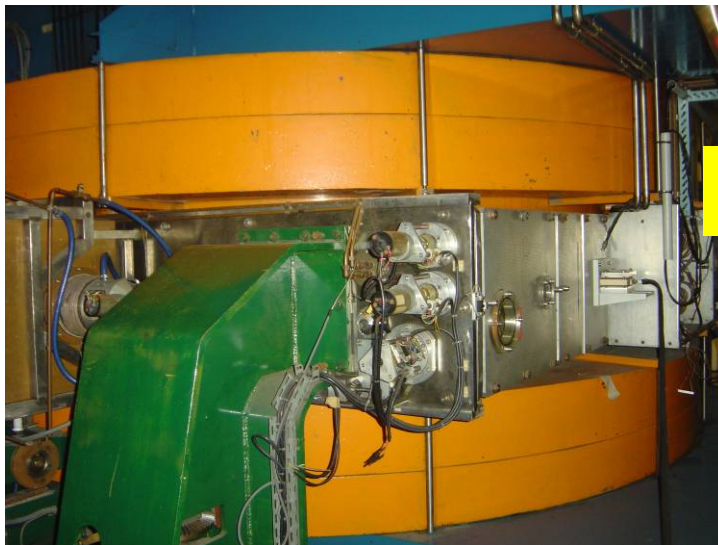


Berkeley

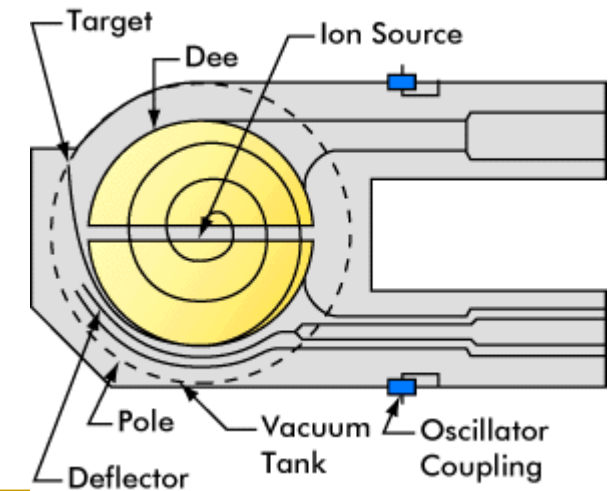


- Utilise motion in magnetic field:  $p = k q B R$
- Apply AC to two halves
- Lawrence achieved MeV particles with 28cm diameter
- Magnet size scales with momentum...

Orsay



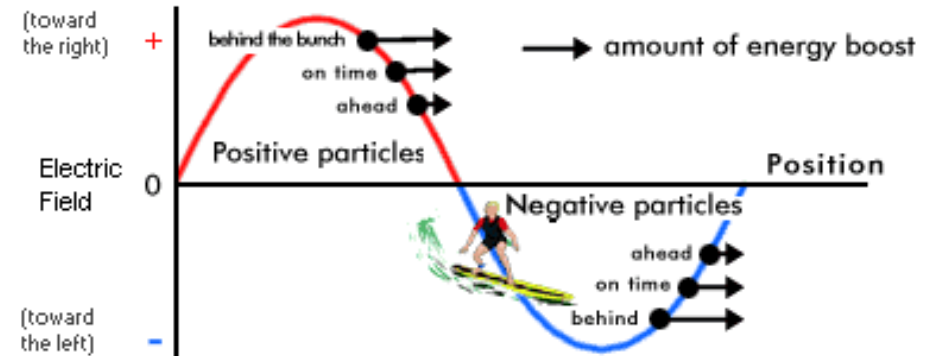
for medical purposes



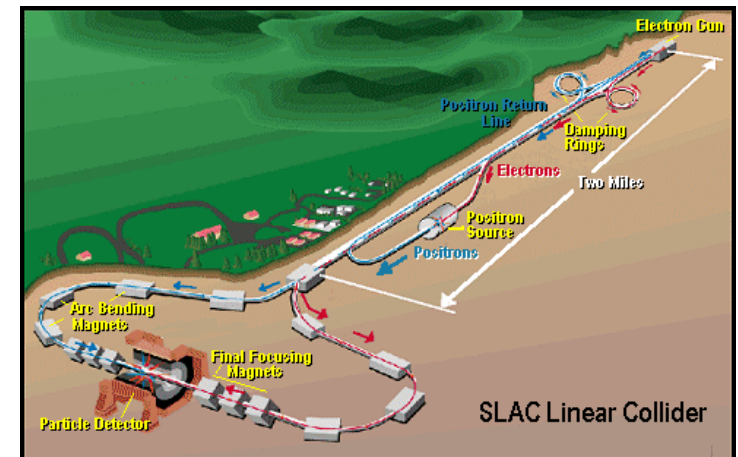
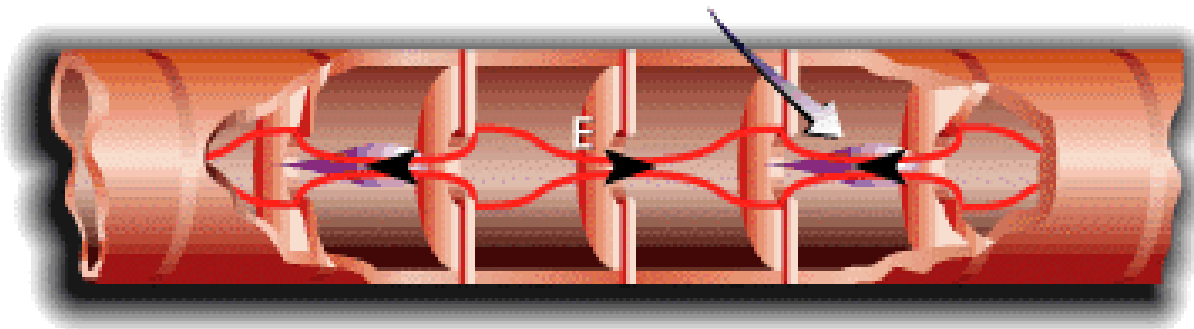
# Linear Accelerators

For energies greater than few MeV:

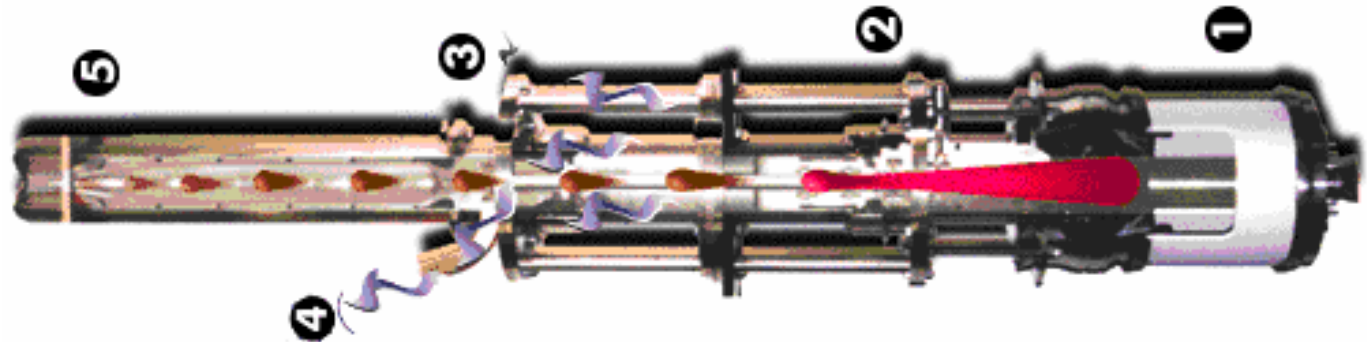
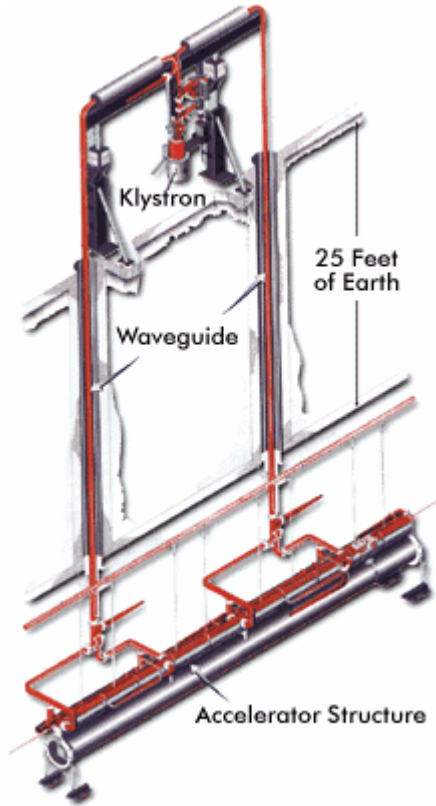
- use multiple stages
- RF easier to generate and handle
- Bunches travel through resonant cavities
- Spacing and/or frequency changes with velocity
- Can achieve 10MV/m and higher
- 3km long Stanford Linac reached 45 GeV



$e^-$  Bunch Cloud

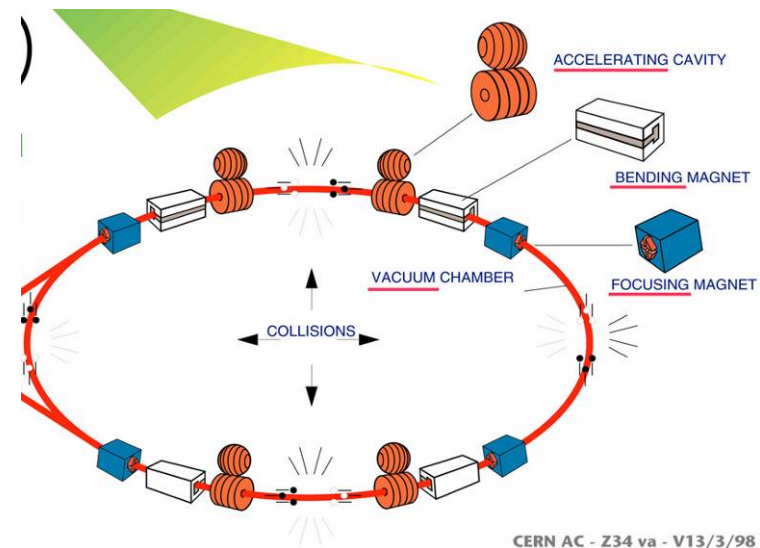


# Superconducting Cavities & Klystron



# Synchrotrons

- $p = k q B R$
- Cyclotron (see page 15) has constant  $B$ , increasing  $R$
- Increase  $B$  keeping  $R$  constant:
  - ❑ variable current electromagnets
  - ❑ particles can travel in small diameter vacuum pipe
  - ❑ single cavity can accelerate particles each turn
  - ❑ efficient use of space and equipment
- Discrete components in ring
  - ❑ cavities
  - ❑ dipoles (bending)
  - ❑ quadrupoles etc. (focusing)
  - ❑ diagnostics
  - ❑ control



$$mv^2 = Bqv$$

$$\omega = \frac{v}{r} = \frac{Bq}{m}$$

$$f = \frac{Bq}{2m\pi} \frac{m_0}{m_0 + T}$$



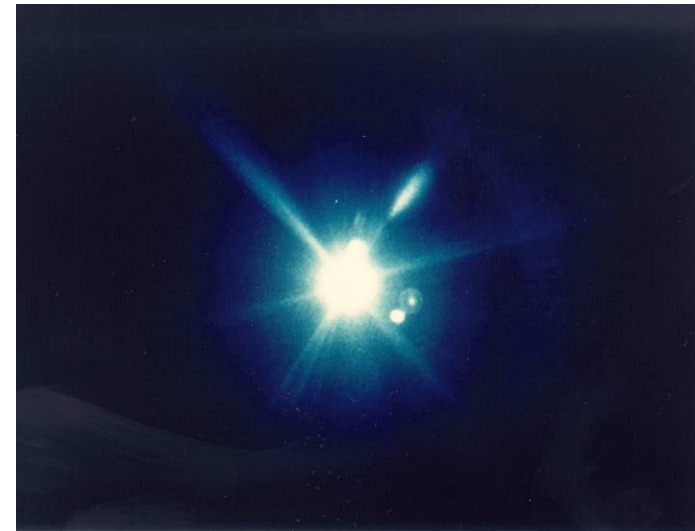
# Synchrotron Radiation

- Accelerated charges radiate
- Average power loss per particle:
- Quantum process → spread in energy
- For a given energy  $\sim 1/\text{mass}^4$ 
  - (this comes from  $\gamma$  in the Power loss equation)
- Electron losses  $10^{13}$  times proton
  - High energy electron machines have very large or infinite  $R$
- Pulsed, intense X-ray source may be useful for some things....

$$\text{Power loss} = \frac{1}{6\pi\epsilon_0} \frac{e^2 a^2}{c^3} \gamma^4 \quad a = \frac{v^2}{R}$$

$$\text{Power Loss per turn} = 8.85 \times 10^{-5} E^4 / R \text{ MeV/turn}$$

E in GeV, R in km.



# Real Synchrotrons



**Bevatron, LBNL, USA**

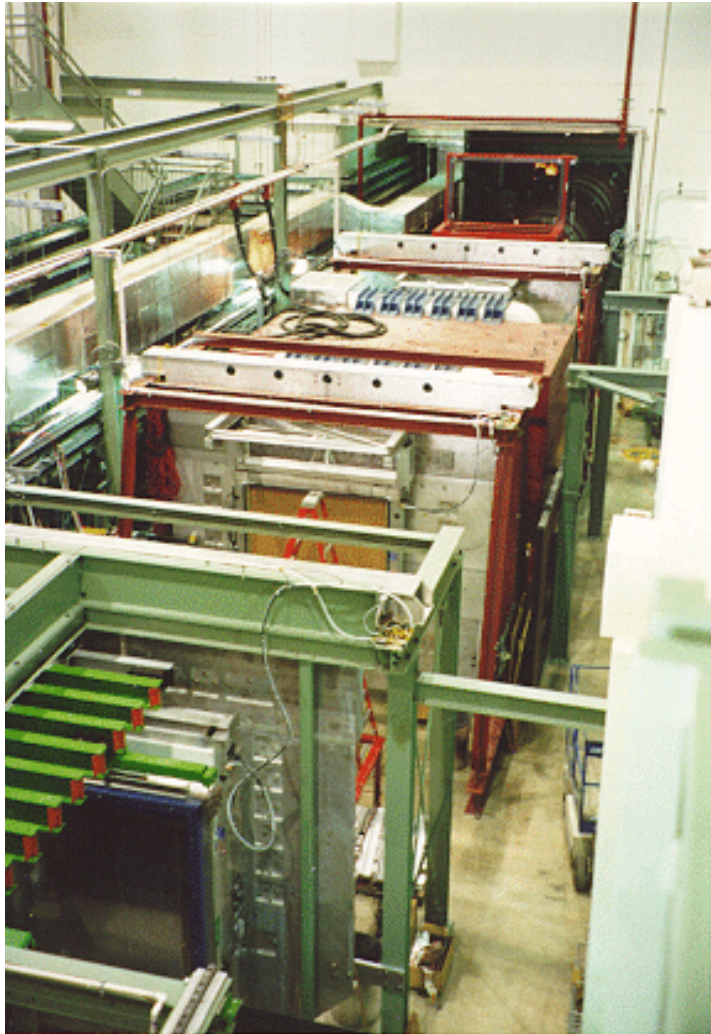
**Grenoble, France**



**DIAMOND, RAL, UK**



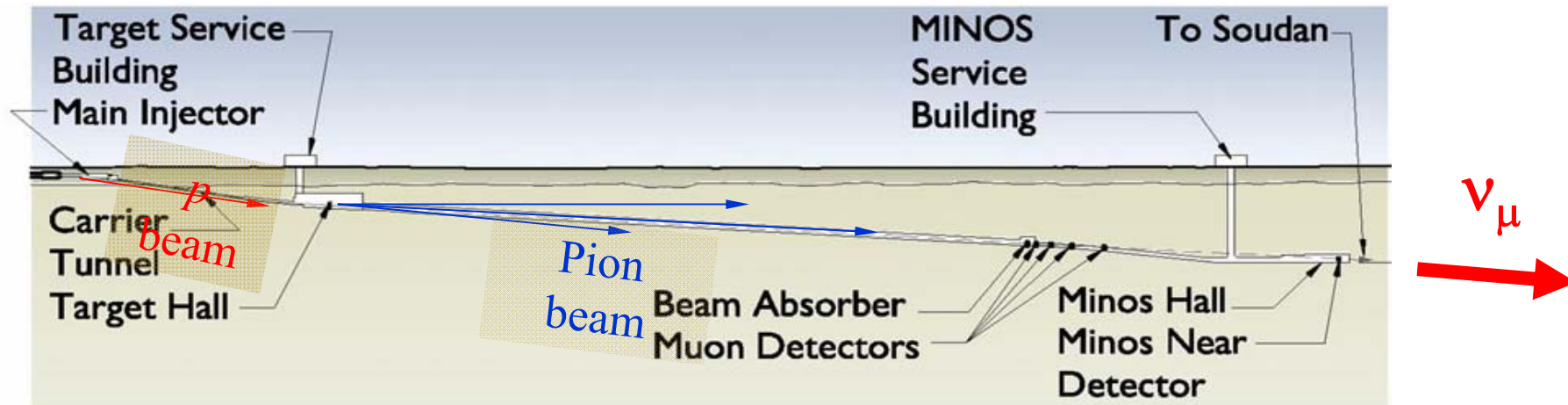
# Fixed Target Experiments



Beam incident on stationary target

- Interaction products have large momentum in forward direction
- Large “wasted” energy  $\Leftrightarrow$  small  $\sqrt{s}$
- Intense beams/large target  $\Rightarrow$  high rate
- Secondary beams can be made

# Neutrino Beams



- Fermilab sends a muon-neutrino beam to Minnesota
- Looking for oscillations
- Detector at bottom of mine shaft



# Colliders

- Incoming momenta cancel
- $\sqrt{s} = 2E_{beam}$
- Same magnetic field deflects opposite charges in opposite directions  $\Rightarrow$   
*Antiparticle accelerator for free!*
  - particle/antiparticle quantum numbers also cancel
- *Technically challenging*

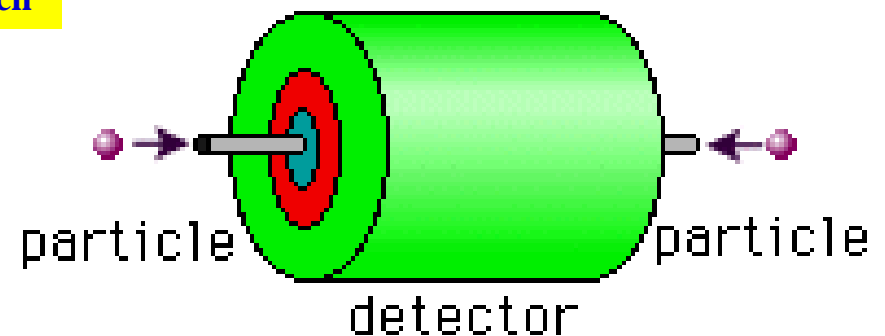
$$\text{Event Rate } R = L\sigma$$

$$\text{Luminosity} = f \frac{n_1 n_2}{4\pi\sigma_x \sigma_y}$$

frequency

bunch size

particles per bunch

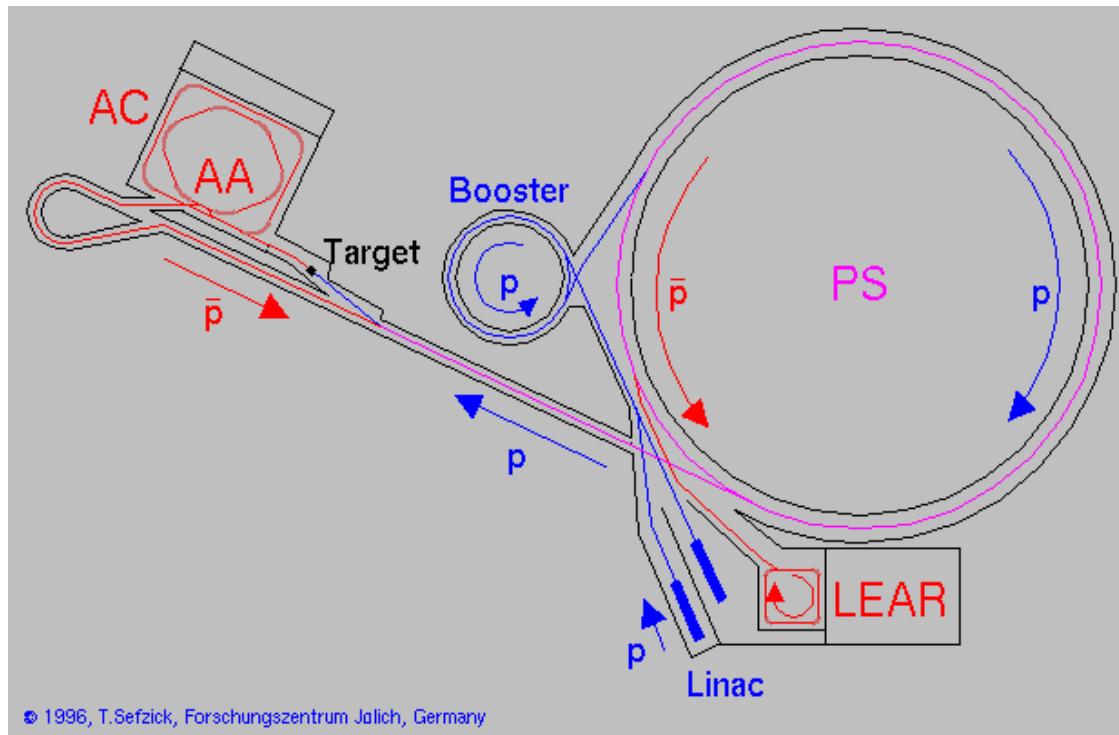


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# Antiparticle Production

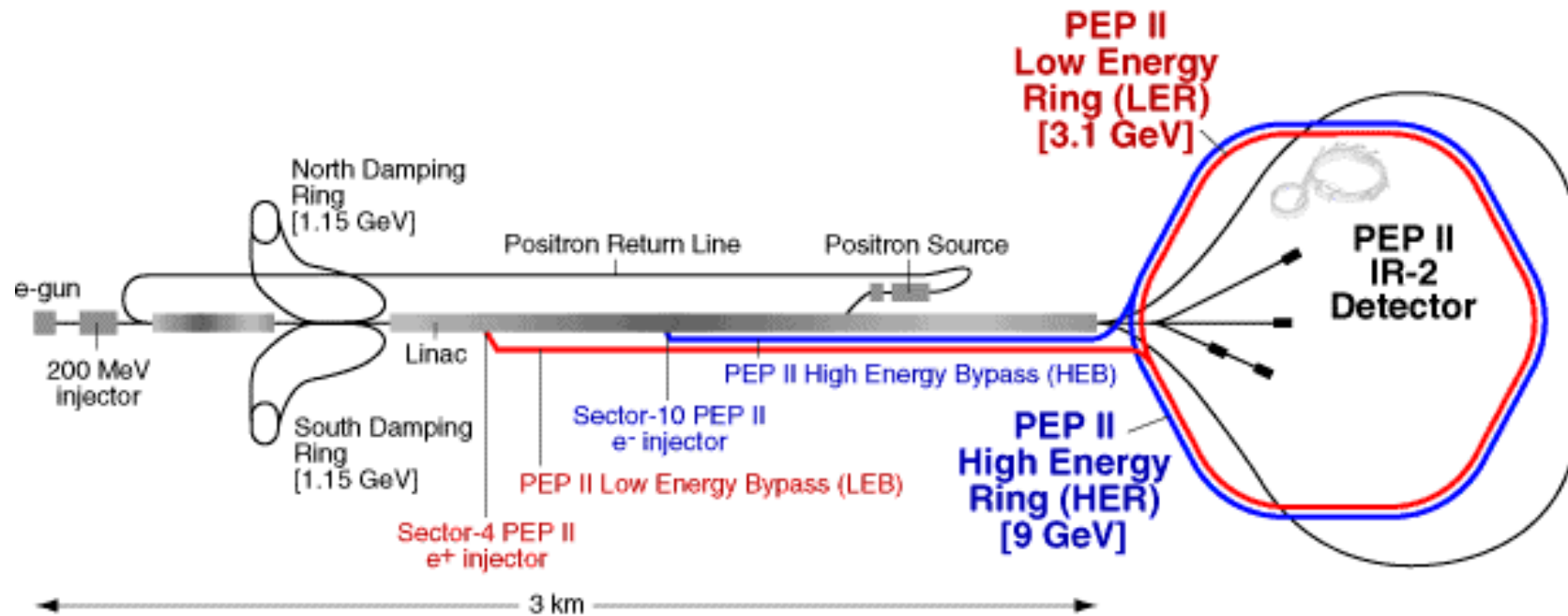
1. Positrons and antiprotons produced in fixed target collisions
  - typical efficiency  $10^5$  protons per antiproton
2. Large phase space (different momenta) – must be “cooled”
  - synchrotron radiation damps electrons
  - antiproton cooling techniques won Nobel Prize for van der Meer in the 1984.
3. Decelerated and accumulated in storage rings

# Anti-Proton Production at CERN



Protons are accelerated in a linear accelerator, booster, and proton synchrotron (PS) up to 27 GeV. These protons hit a heavy target (Beryllium). In the interaction of the protons and the target nuclei many particle-antiparticle pairs are created out of the energy, in some cases proton-antiproton pairs. Some of the antiprotons are caught in the antiproton cooler (AC) and stored in the antiproton accumulator (AA). From there they are transferred to the low energy antiproton ring (LEAR) where experiments take place.

# Positron Production (PEP II at SLAC)



- **Positrons are produced by diverting some of the electrons from the accelerator and colliding them with a large piece of tungsten. This collision produces large numbers of electron-positron pairs. The positrons are collected and sent back along a separate line to the start of the linac.**



# Different Colliders

## ■ $p$ anti- $p$

- energy frontier
- difficult to interpret
- limited by anti- $p$  production
- *SPS, Tevatron*

## ■ $p p$

- high luminosity
- energy frontier
- *LHC*

## ■ $\mu^+ \mu^-$

- some plans exist

## ■ $e^+ e^-$

- relatively easy analysis
- high energies difficult
- *LEP, PEP, ILC...*

## ■ $e p$

- proton structure
- *HERA*

## ■ ion ion

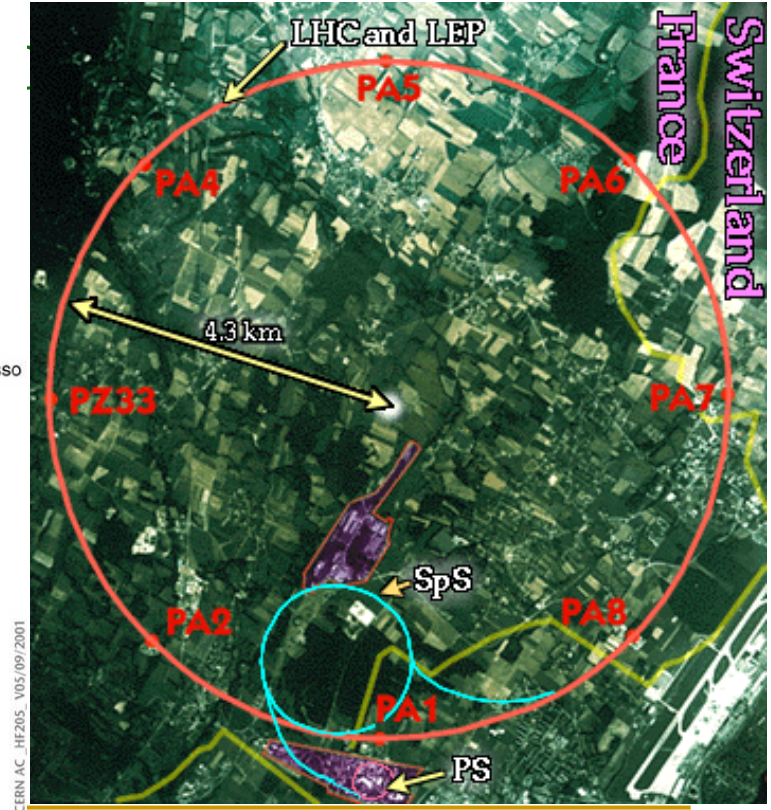
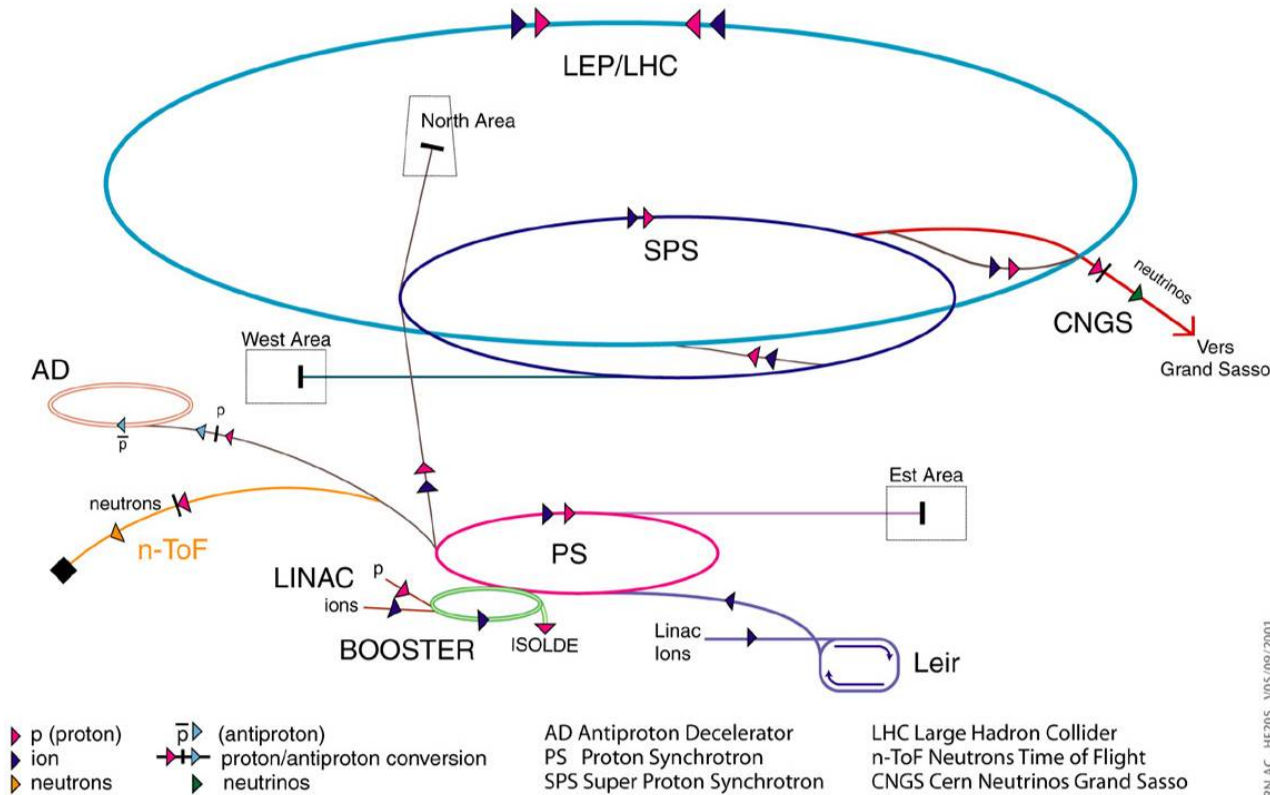
- quark gluon plasma
- *RHIC, LHC*

## ■ $\nu \nu$

- !!!

# Complexes

- Synchrotrons can't accelerate particles from rest
- Designed for specific energy range, normally about factor of 10



# Collider Parameters

	CESR (Cornell)	CESR-C (Cornell)	KEKB (KEK)	PEP-II (SLAC)	LEP (CERN)
Physics start date	1979	2002	1999	1999	1989
Physics end date	2002	—	—	—	2000
Maximum beam energy (GeV)	6	6	$e^- \times e^+ : 8 \times 3.5$	$e^- : 7-12$ (9.0 nominal) $e^+ : 2.5-4$ (3.1 " ) (nominal $E_{\text{cm}} = 10.5$ GeV)	101 in 1999 (105=max. foreseen)
Luminosity ( $10^{30} \text{ cm}^{-2}\text{s}^{-1}$ )	1280 at 5.3 GeV/beam	35 at 1.9 GeV/beam	11305	6777	24 at $Z^0$ 100 at $> 90$ GeV
Time between collisions ( $\mu\text{s}$ )	0.014 to 0.22	0.014 to 0.22	0.008	0.0042	22

**Full details at [pdg.lbl.gov](http://pdg.lbl.gov)**

	HERA (DESY)	TEVATRON (Fermilab)	RHIC (Brookhaven)			LHC (CERN)	
Physics start date	1992	1987	2000			2007	2008
Physics end date	—	—	—			—	
Particles collided	$ep$	$p\bar{p}$	$pp$ (pol.)	Au Au	d Au	$pp$	Pb Pb
Maximum beam energy (TeV)	$e$ : 0.030 $p$ : 0.92	0.980	0.1 40% pol	0.1 TeV/u	0.1 TeV/u	7.0	2.76 TeV/u
Luminosity ( $10^{30} \text{ cm}^{-2}\text{s}^{-1}$ )	75	50	6	0.0004	0.07	$1.0 \times 10^4$	0.001
Time between collisions ( $\mu\text{s}$ )	0.096	0.396	0.213			0.025	0.100

## Some notable accelerators

Type	Name	Size	Start Year	Place	Energy
Cockcroft-Walton		3m	1932	Cambridge	0.7MeV
Cyclotron	9"	9"	1931	Brookhaven	1.0 MeV
Cyclotron	184"	184"	1942	Brookhaven	100 MeV
Synchrotron	Cosmotron	72m	1953	Brookhaven	3.3 GeV
Synchrotron	AGS	72m	1960	Brookhaven	33 GeV
Collider	LEP	27km	1995	CERN	104 GeV
Collider	LHC	27km	2007?	CERN	7 TeV

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# Summary of Lecture I

- Admin
- Particle Sources
  - Natural Radiation
  - Cosmic Rays
  - Reactors
  - Accelerators
- Accelerators
  - Cockcroft Walton
  - Van der Graaf
  - Cyclotron
  - Synchrotron
  - Linear Accelerator
- Antiparticle Production
- Collider Parameters

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Next Time...

*Charged particle interactions and detectors*