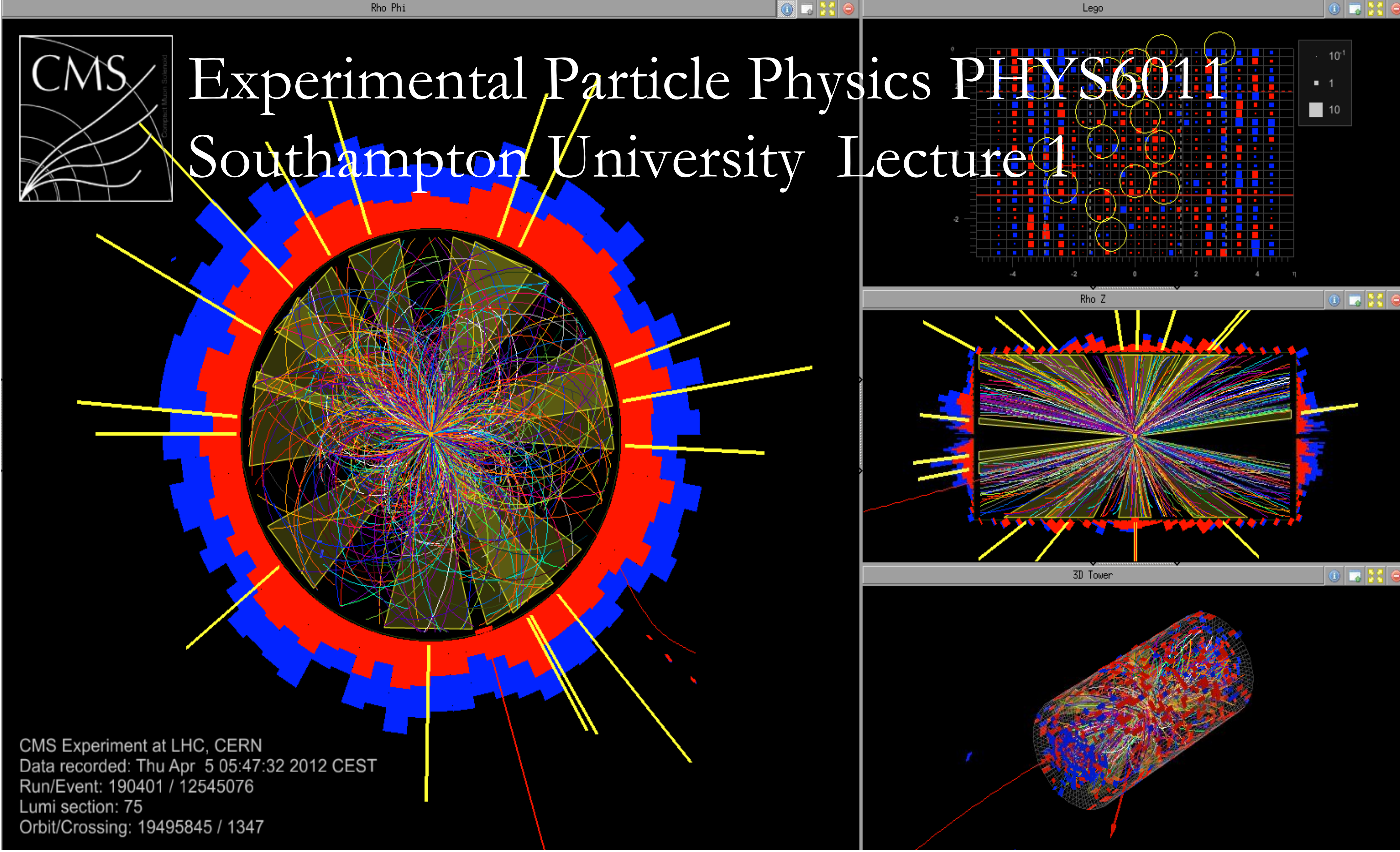
Experimental Particle Physics PHYS6011
Southampton University Lecture 1



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Administrative Points

- 5 lectures:
  - Monday 10am: 29th April (07/3019)
  - Friday 10am: 3rd and 10th May (07/3019)
  - Friday 11am: 3rd and 10th May (16/2025)
- Course Objectives, Lecture Notes, Problem examples:
  - http://www.phys.soton.ac.uk/module/PHYS6011/
  - http://hepwww.rl.ac.uk/fwilson/Southampton
- Resources:
  - K. Wille, "The Physics of Particle Accelerators"
  - D. Green, "The Physics of Particle Detectors"
  - K.Kleinknecht, "Detectors for Particle Radiation"
  - I.R. Kenyon, "Elementary Particle Physics" (chap 3).
  - Martin and Shaw, "Particle Physics"
  - Particle Data Group, http://pdg.lbl.gov

Syllabus – 5 lectures

1. Part 1 – Building a Particle Physics Experiment
    1. Accelerators and Sources
    2. Interactions with Matter
    3. Detectors
2. Part 2 – Putting it all together
    1. Searching for the Higgs – Part 1
    2. Searching for the Higgs and Supersymmetry (or what can you get for $10,000,000,000?)

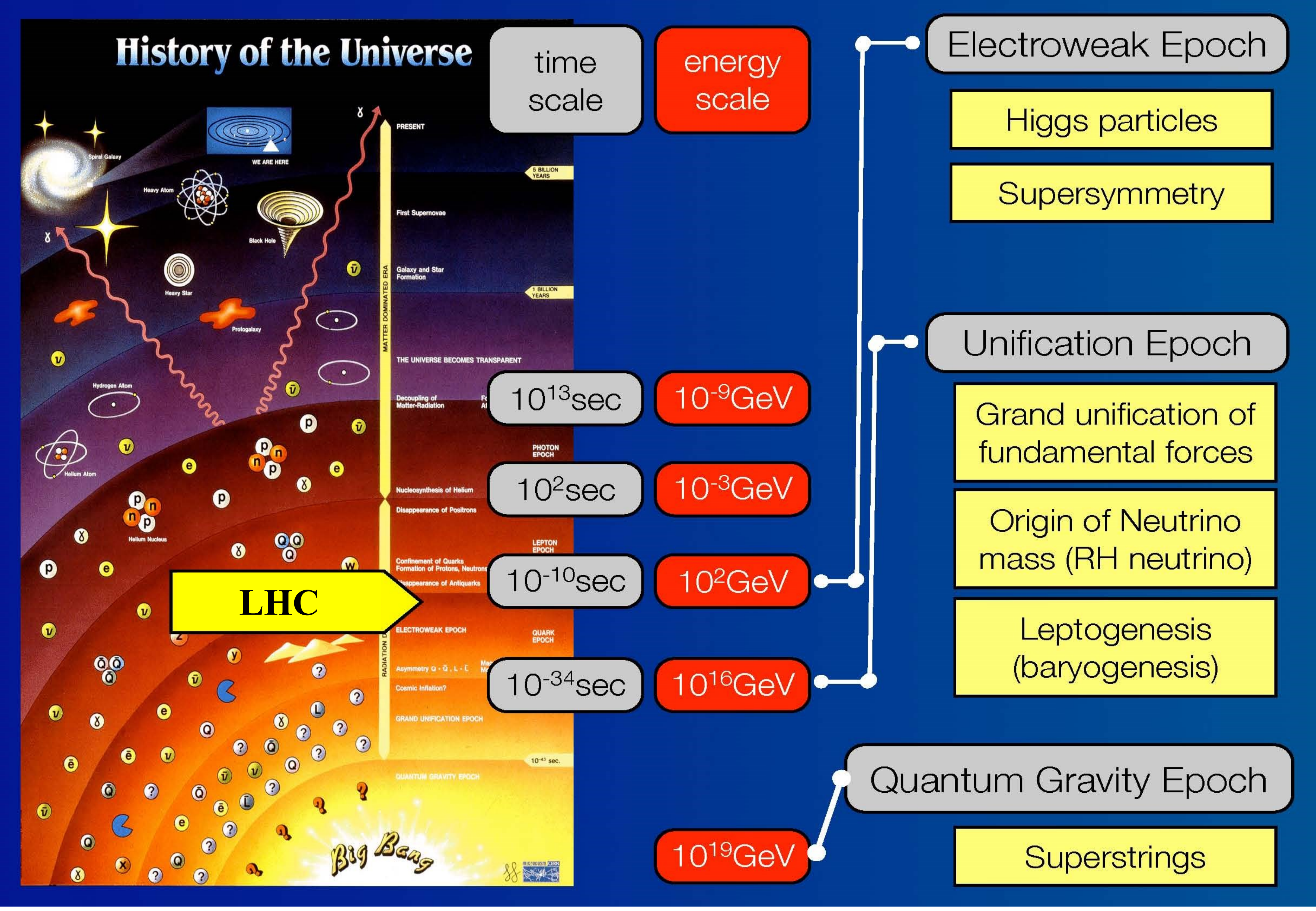
Natural Units

- Natural Units:
  - Energy - GeV
  - Mass – GeV/c^2
  - Momentum – GeV/c
  - Length and time – GeV^{-1}
- Use the units that are easiest.
- 1 eV = 1.602×10^{-19} J
- Boltzmann Constant = 8.619×10^{-5} eV/Kelvin

$$\hbar = c = 1$$

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

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


History of the Universe
PRESENT
WE ARE HERE
Spiral Galaxy
Heavy Atom
Black Hole
5 BILLION YEARS
First Supernovae
Heavy Star
Galaxy and Star Formation
1 BILLION YEARS
Protogalaxy
MATTER DOMINATED ERA
THE UNIVERSE BECOMES TRANSPARENT
Hydrogen Atom
Decoupling of Matter-Radiation
Helium Atom
PHOTON EPOCH
Nucleosynthesis of Helium
Helium Nucleus
Disappearance of Positrons
LEPTON EPOCH
Confinement of Quarks
Formation of Protons, Neutrons
Disappearance of Antiquarks
LHC
ELECTROWEAK EPOCH
QUARK EPOCH
RADIATION DOMINATED ERA
Cosmic Inflation?
GRAND UNIFICATION EPOCH
10-43 sec.
QUANTUM GRAVITY EPOCH
Big Bang
time scale
energy scale
10^13 sec
10^-9 GeV
10^2 sec
10^-3 GeV
10^-10 sec
10^2 GeV
10^-34 sec
10^16 GeV
10^19 GeV
Electroweak Epoch
Higgs particles
Supersymmetry
Unification Epoch
Grand unification of fundamental forces
Origin of Neutrino mass (RH neutrino)
Leptogenesis (baryogenesis)
Quantum Gravity Epoch
Superstrings

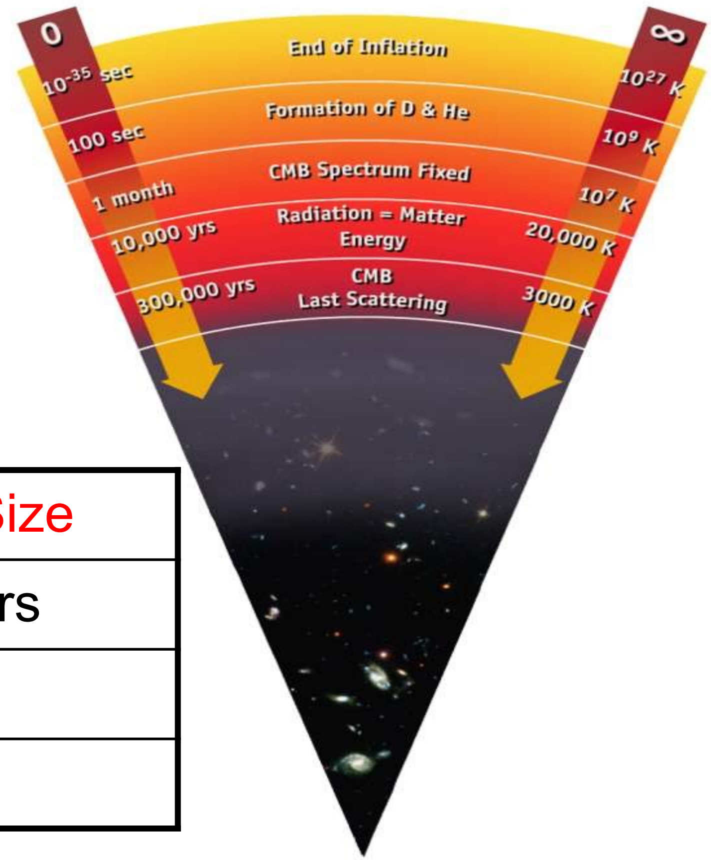
Universe energy

$$T_{univ}(K) = 1.5\times10^{12}\,t^{-2/3} \quad t<10^{11}\text{secs}$$

$$T_{univ}(K) = 2\times10^{10}\,t^{-1/2} \quad t>10^{11}\text{secs}$$

Boltzmann constant, $k = 8.619\times10^{-5}\,\text{eV K}^{-1}$

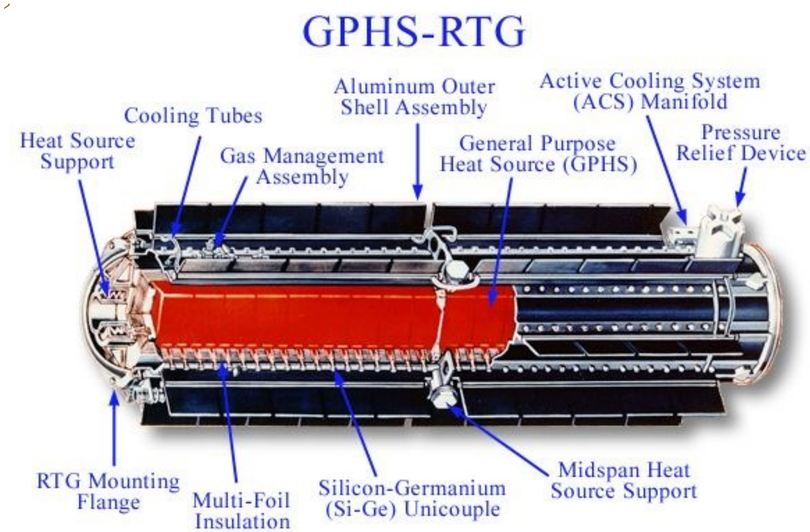
- Time, energy (temperature) and distance are related:
  - High momentum : Small distance : High temperature : Early Universe



Energy	Age (secs)	Temp. (K)	Observable Size
1 eV	10^{13}	10^{4}	10^{6} Light Years
1 MeV	1	10^{10}	10^{6} km
10 TeV	10^{-14}	10^{17}	10^{-2} mm

Natural Radioactivity

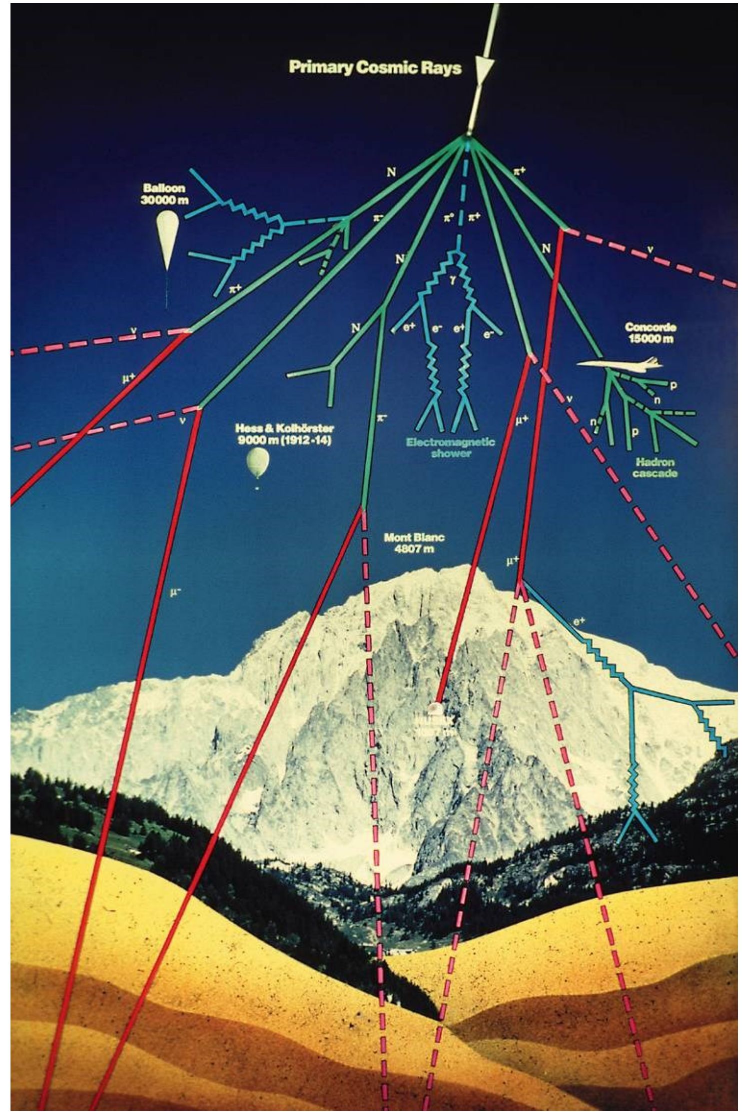
- First discovered in late 1800s (X-rays Becquerel 1896)
- Used as particle source in many significant experiments
  - Rutherford's 1906 experiment: elastic scattering α+N$\rightarrow$ α+N
  - Rutherford's 1917 experiment: inelastic scattering α+N$\rightarrow$ p+X
- Common radioisotopes include
  - ^{55}Fe: 6 keV γ, $\tau_{1/2}$ = 2.7 years (discovered?)
  - ^{90}Sr: 500 keV β, $\tau_{1/2}$ = 28.9 years (1790)
  - ^{241}Am: 5.5 MeV α, $\tau_{1/2}$ = 432 years (1944)
  - ^{210}Po: 5.41 MeV α, $\tau_{1/2}$ = 137 days (1898)
- Radioactivity of food
  - Bananas : 3500 pCi/Kg
  - Beer: 400 pCi/Kg
- Easy to control, predictable flux but low energy
- Still used for calibrations and tests



Cassini probe: http://saturn.jpl.nasa.gov/index.cfm

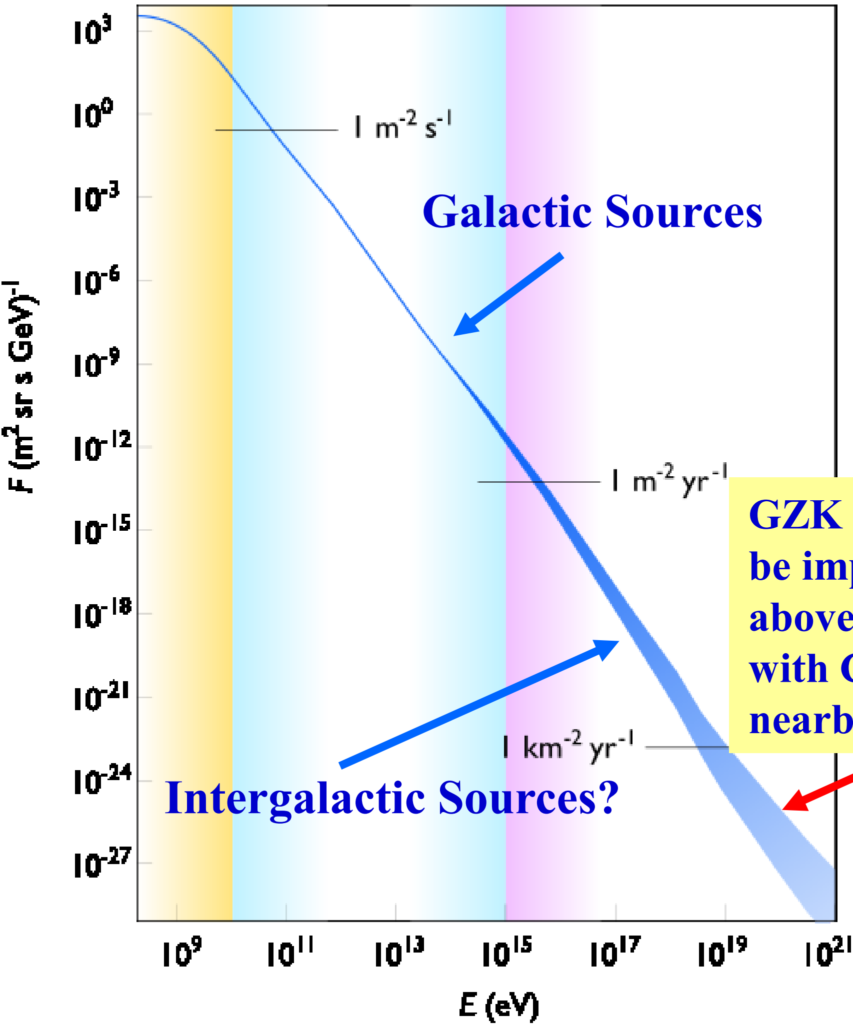
Cosmic Rays

- History
  - 1912: First discovered (Hess)
  - 1927: First seen in cloud chambers
  - 1962: First 10^{20} eV cosmic ray seen
- Low energy cosmic rays from Sun
  - Solar wind (mainly protons)
  - Neutrinos
- High energy particles from sun, galaxy and perhaps beyond
  - Primary: Astronomical sources.
  - Secondary: Interstellar Gas.
  - 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: 100-200 s^{-1} m^{-2}
- Highest energy ever seen ~10^{20}eV



Cosmic Rays

$$I_N(E) \approx 1.8 E^{-2.7} \frac{nucleons}{\text{cm}^2\text{s sr GeV}} \qquad E < 100\text{TeV}$$



GZK cutoff 10^{20} eV. Should be impossible to get energies above this due to interaction with CMB unless produced nearby => Black Holes?

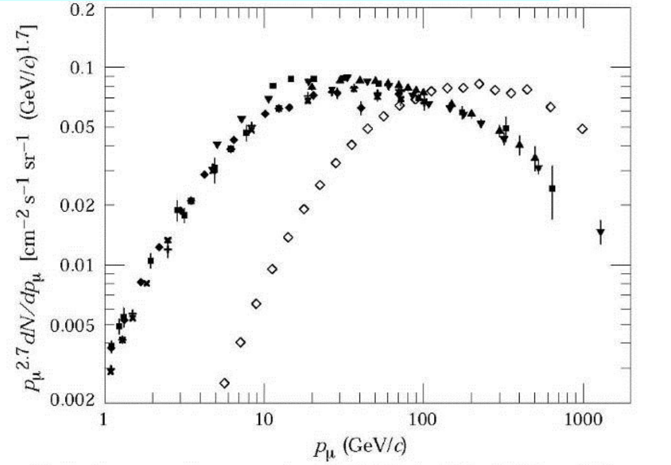
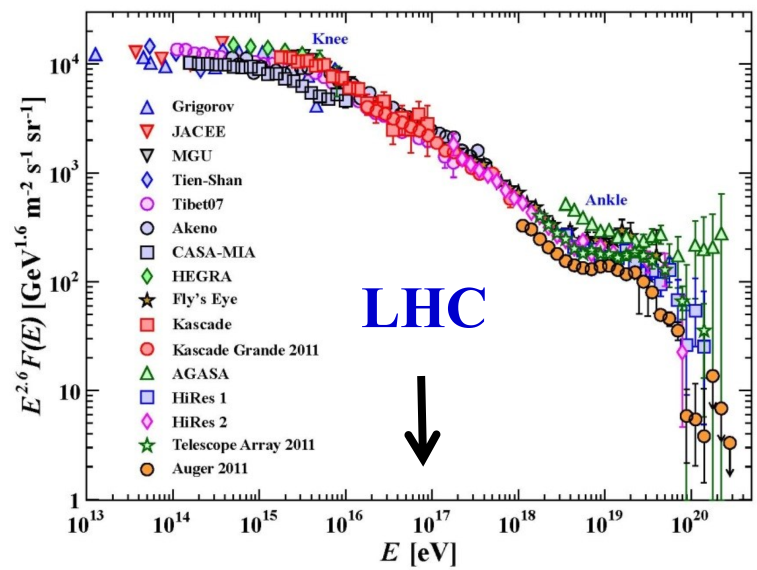


Figure 24.4: Spectrum of muons at $\theta = 0°$ (♦ [29], ■ [34], ▾ [35], ▲ [36], × and + [31], and $\theta = 75°$ ◊ [37]) .



Cosmic Ray Experiments

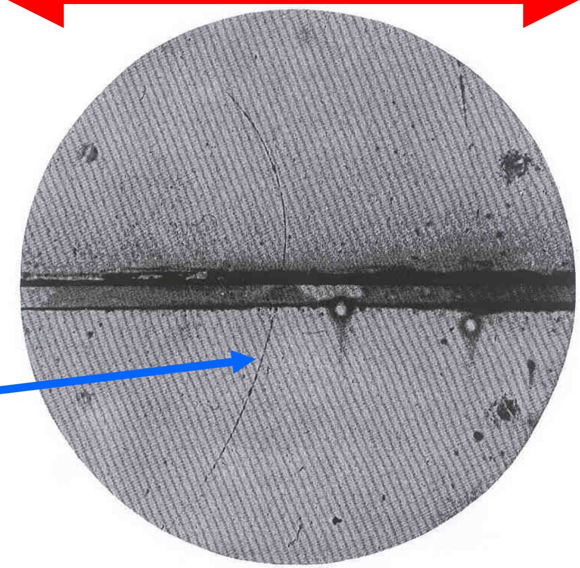
- Primary source for particle physics experiments for decades
- Detectors taken to altitude for larger flux/higher energy
- Positron (1932) and many other particles first observed

Modern experiments include:

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

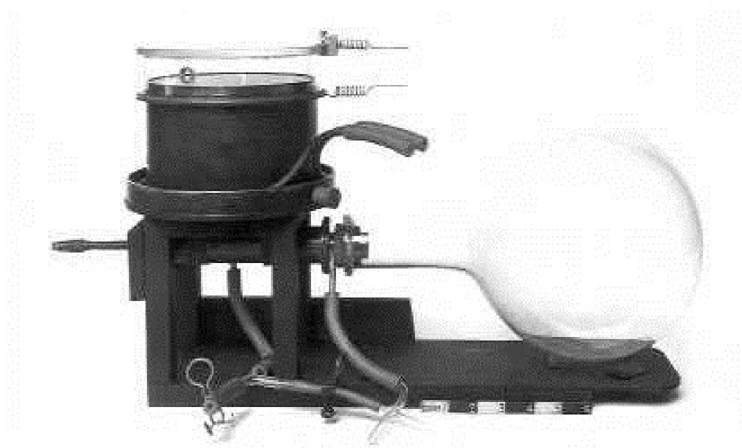
Still useful for calibration and testing

6cm



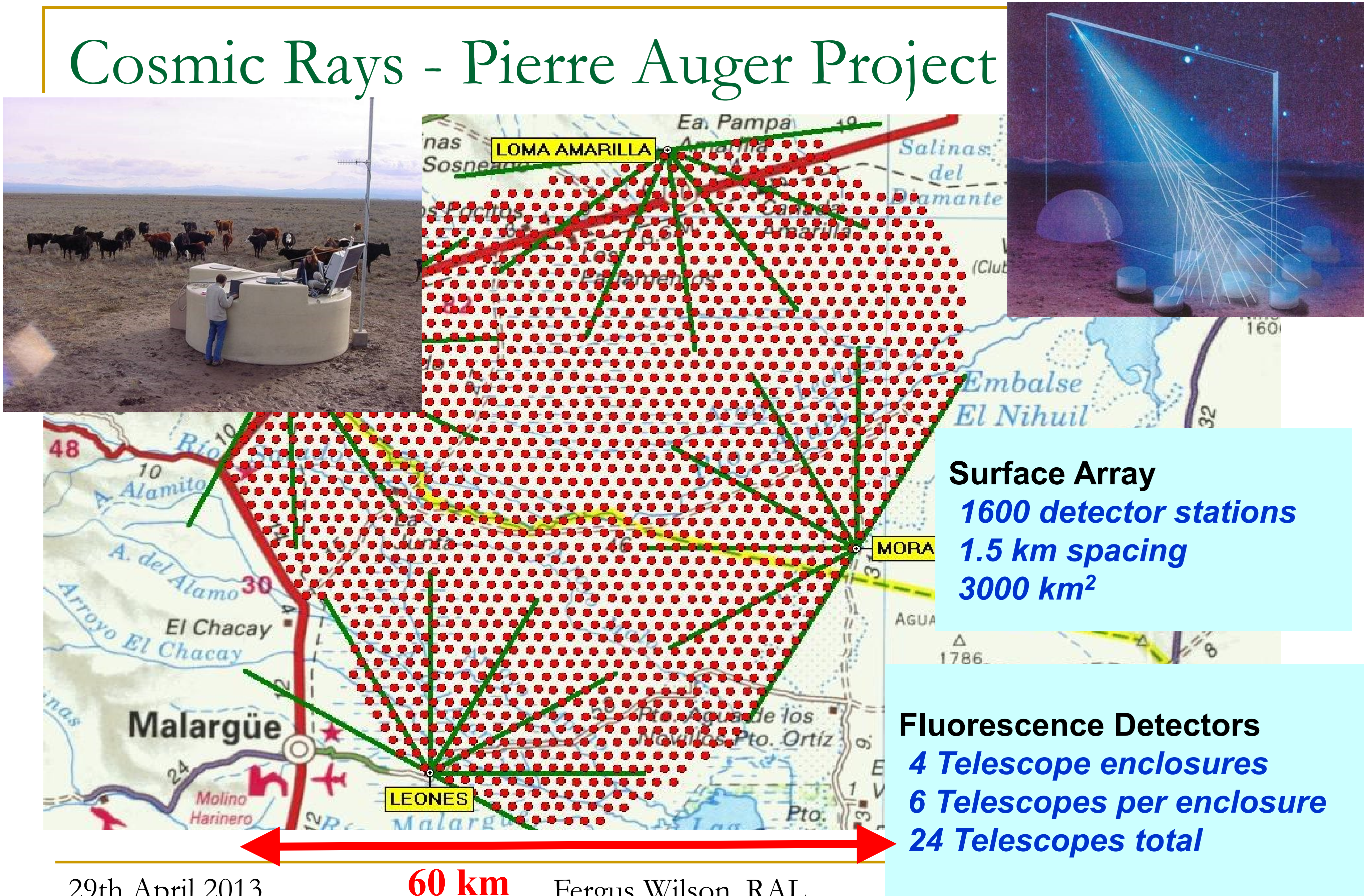
Which direction is the e^+ moving (up or down)?

Is the B-field in or out of the page?



1912 CTR Wilson Cloud Chamber

Cosmic Rays - Pierre Auger Project



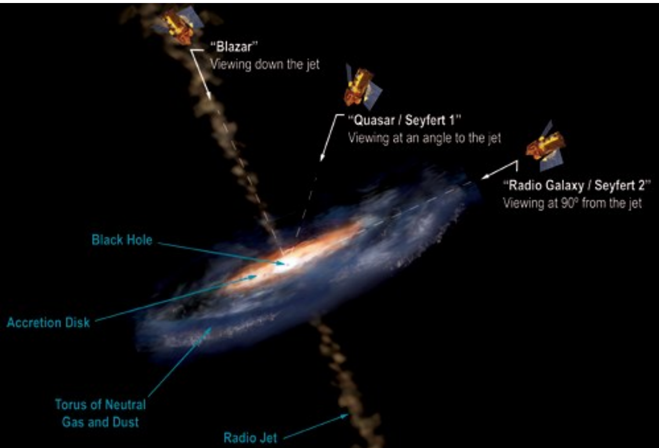
Surface Array

- *1600 detector stations*
- *1.5 km spacing*
- *3000 km²*

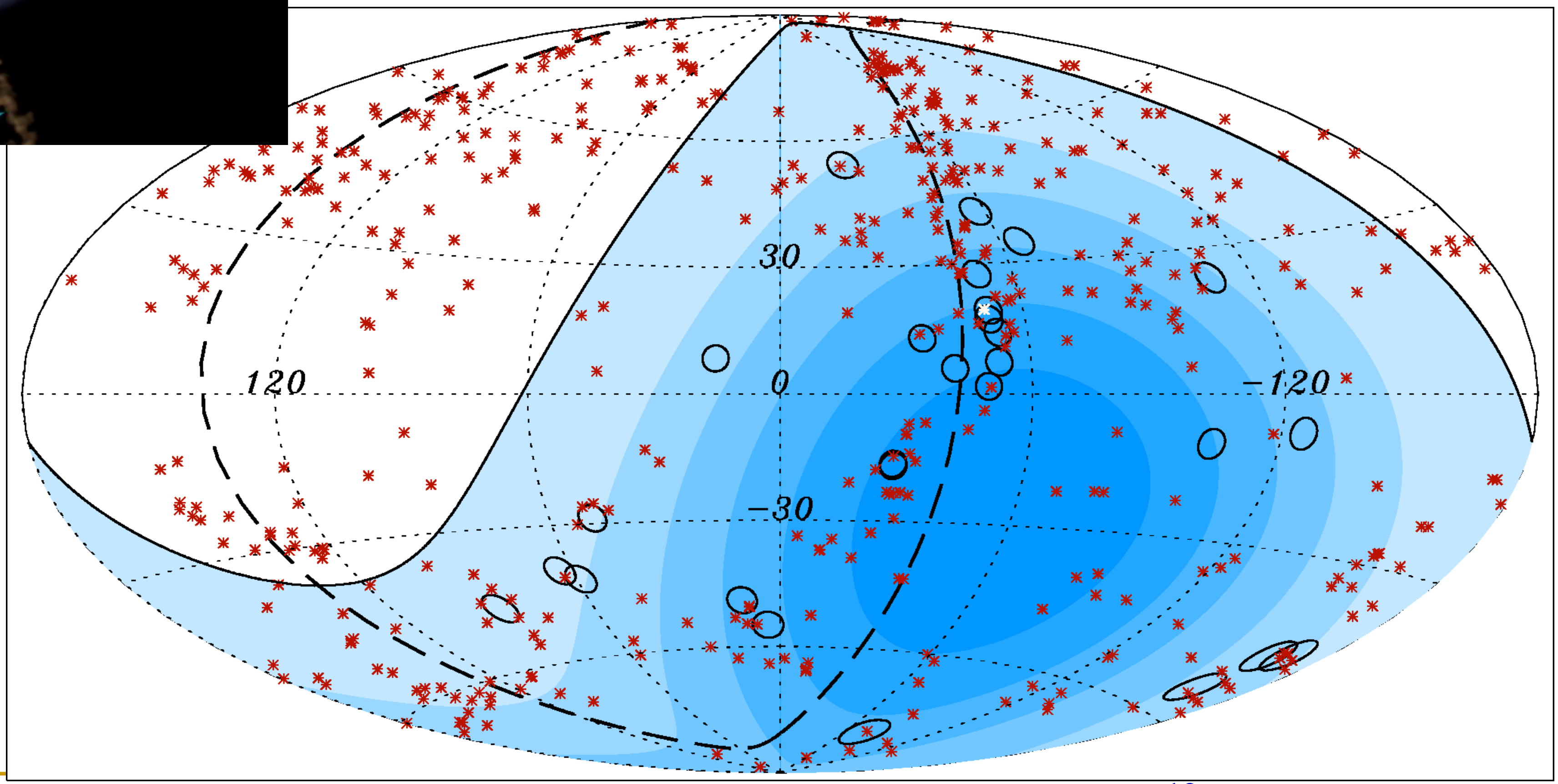
Fluorescence Detectors

- *4 Telescope enclosures*
- *6 Telescopes per enclosure*
- *24 Telescopes total*

Active Galactic Nuclei and cosmic rays

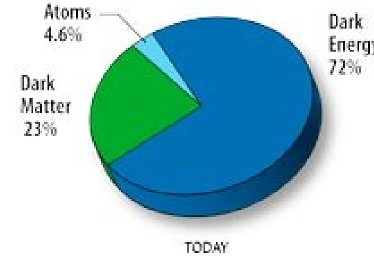


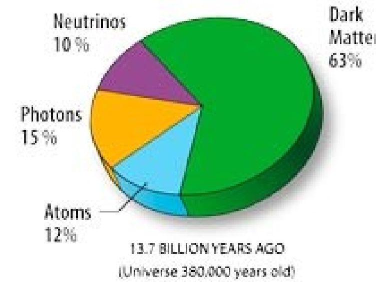
Highest energy cosmic rays seem to be associated with Active galactic nuclei but are they? www.auger.org



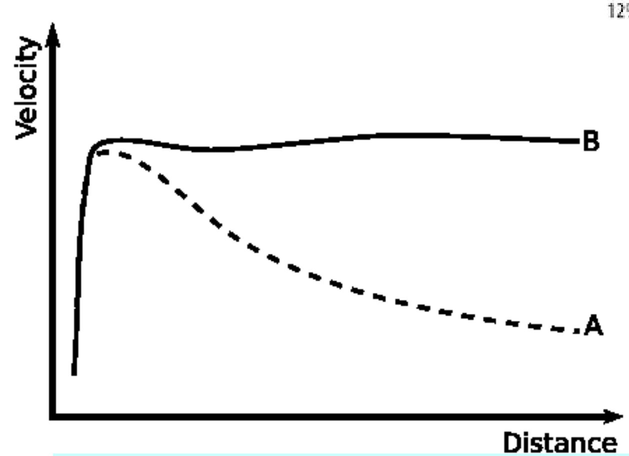
E>5.7x10^{19}GeV

Dark Energy and Dark Matter





- Most of the Universe is invisible.
- Dark Energy:
  - Exerts a negative pressure on the Universe
  - Increases the acceleration of the galaxies.
- Dark Matter:
  - Just like ordinary matter but not visible (does not give off light).
- 1: Baryonic Dark Matter
  - ~2% of the Universe
  - MACHOS, dwarf stars, etc…
- 2: Non-Baryonic Dark Matter
  - ~20% of the Universe
  - Hot (neutrinos) and Cold (WIMPS, axions, neutralinos).
  - Expected to be mostly Cold



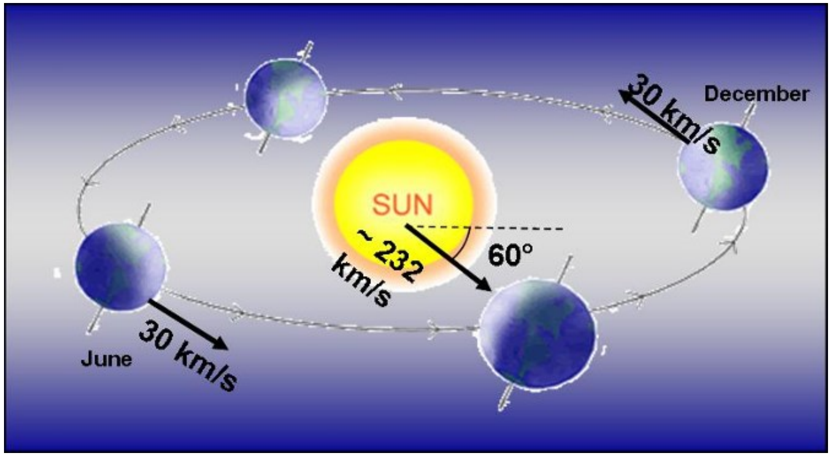
Observed

Predicted

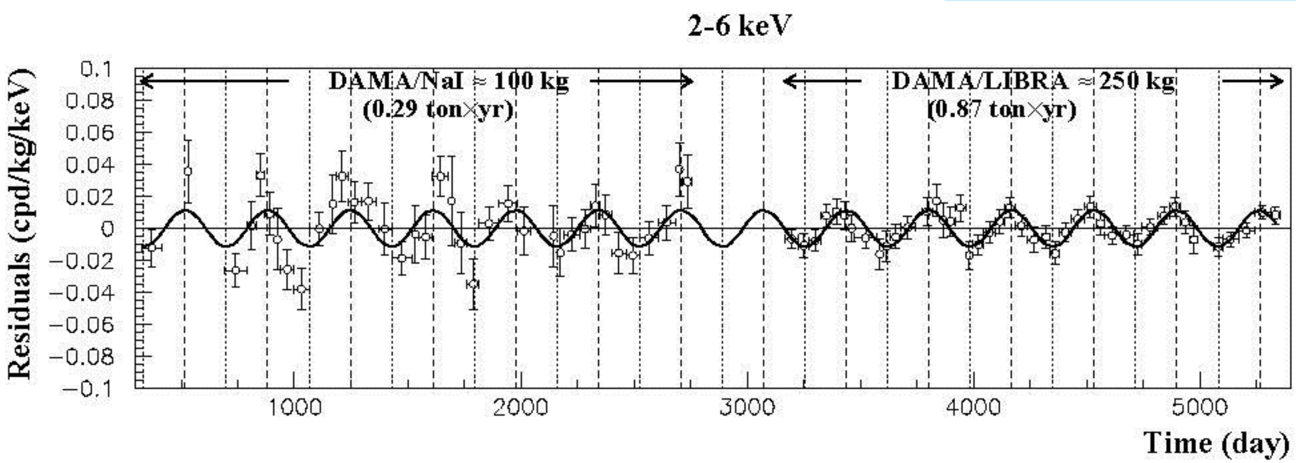
Rotation Velocity $v(r) = \sqrt{\dfrac{M(r)}{r}}$

Outside Galaxy $v(r) \propto \dfrac{1}{\sqrt{r}}$

Dark Matter – DAMA/LIBRA



1. **As the earth goes round the sun, its velocity relative to the galaxy changes by +/-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?**



http://arxiv.org/abs/1301.6243

Neutrinos – Nuclear Reactors and the Sun

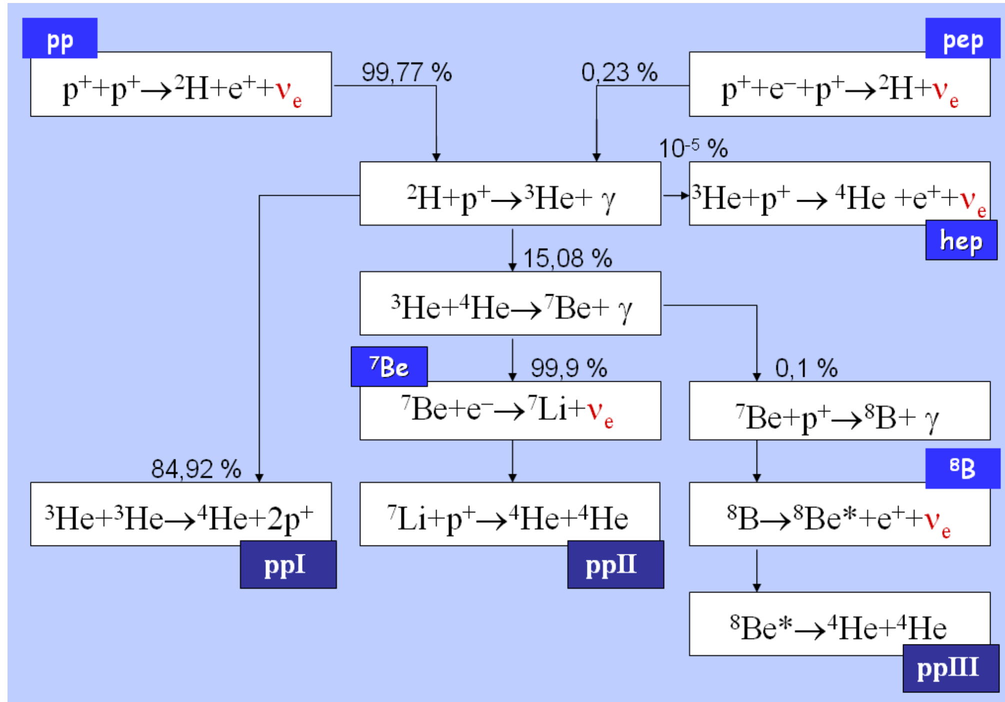
- Reactors – Nuclear Fission
- Sun – Nuclear Fusion
- But still weak interactions. Well understood.
- Huge fluxes of MeV neutrons and electron neutrinos.
- But low energy.
- First direct neutrino observation in 1955.

Neutrino density at Earth $\sim 5\times10^{6}\,cm^{-2}s^{-1}$

Mean free path d :

$$d \approx \frac{u}{\sigma\rho} = \frac{1.66\times10^{-27}\,\text{kg}}{\left(10^{-47}\,\text{m}^2\right)\left(\rho\,\text{kg/m}^3\right)}$$

$$\Rightarrow d_{\text{water}} = 18 \text{ light years}$$



Neutrino Oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle \qquad P_{\alpha\to\beta} = |<\nu_\beta | \upsilon_\alpha(t)>|^2$$

α = neutrino with definite flavour (e,μ,τ)

i = neutrino with definite mass (1,2,3)

$U_{\alpha i}$ = PMNS mixing matrix

$$P_{\nu_\alpha\to\nu_\beta} = \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km}\right)$$

$$\Delta m^2_{12} = \Delta m^2_{solar} = (8.0^{+0.6}_{-0.4})\times 10^{-5}\, eV^2$$

$$\theta_{12} = \theta_{solar} = (33.9^{+2.4}_{-2.2})^o$$

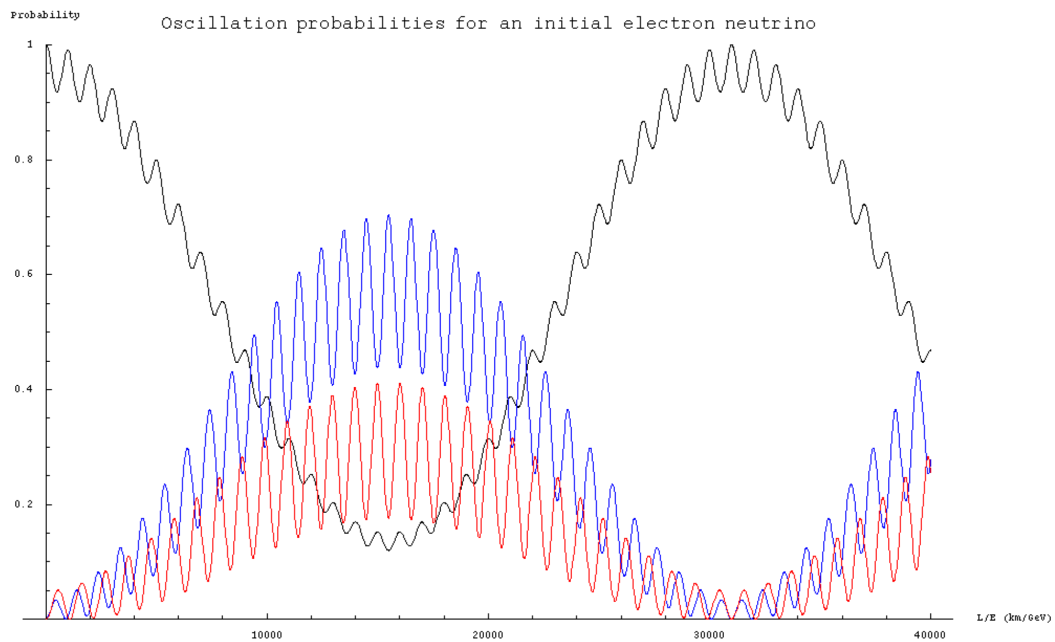
$$\Delta m^2_{23} = \Delta m^2_{atm} = (2.4^{+0.6}_{-0.5})\times 10^{-3}\, eV^2$$

$$\theta_{32} = \theta_{atm} = (45 \pm 7)^o$$

$$\theta_{13} = \sim (8 \pm 1)^o$$

$$\Delta m^2_{13} = 2.32\times 10^{-3}\, eV^2$$

- Neutrinos “Oscillate”:
  - Can change from one type to another.
  - Implies ν have mass.
  - Oscillation experiments can only measure difference in squared mass Δm^2

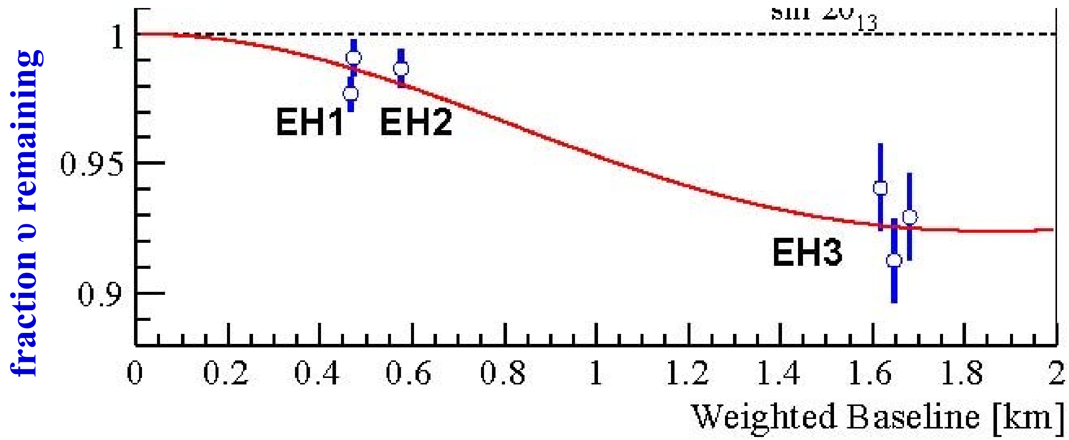


L/E (km/GeV)

Daya Bay (Oct 23rd 2012)

- 3 sets of detectors surrounded by 6 civilian nuclear reactors
- Look for number of electron anti-neutrinos surviving

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2_{13} L / E)$$



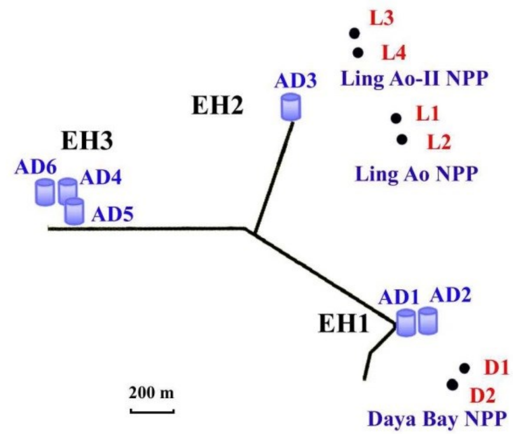
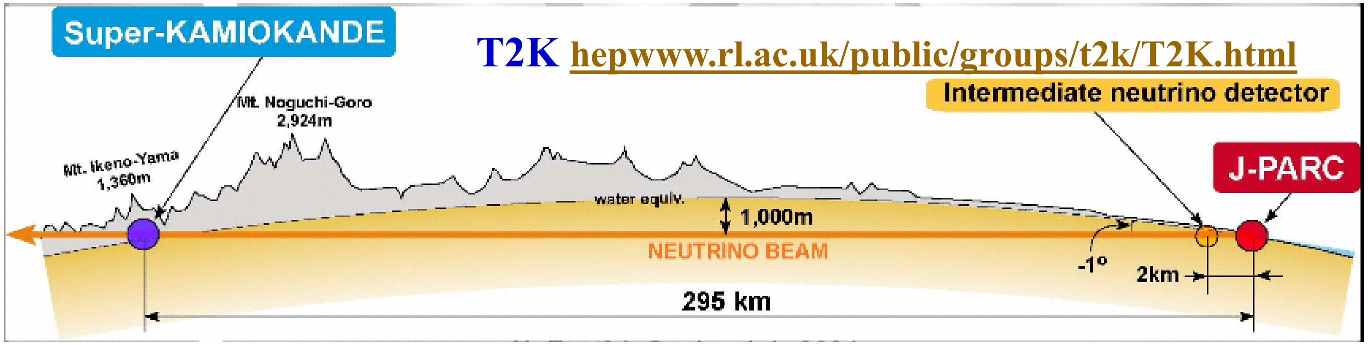


FIG. 1. Layout of the Daya Bay experiment. The dots represent reactors, labeled as D1, D2, L1, L2, L3 and L4. Six ADs, AD1–AD6, are installed in three EHs.

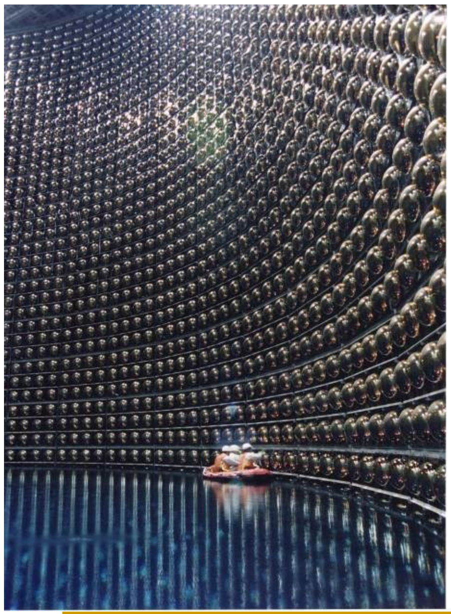
- Result: $\sin^2(2\theta_{13}) = 0.089 \pm 0.010(stat) \pm 0.005(syst)$
  - Implies value > 0

RENO (South Korea) has also reported results (3-Apr-2012)

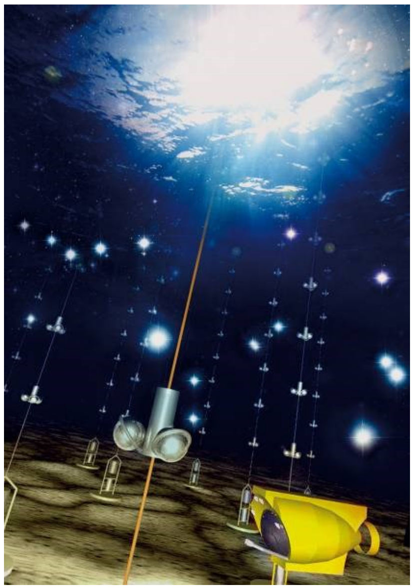
Some Neutrino Detectors – Present and Future



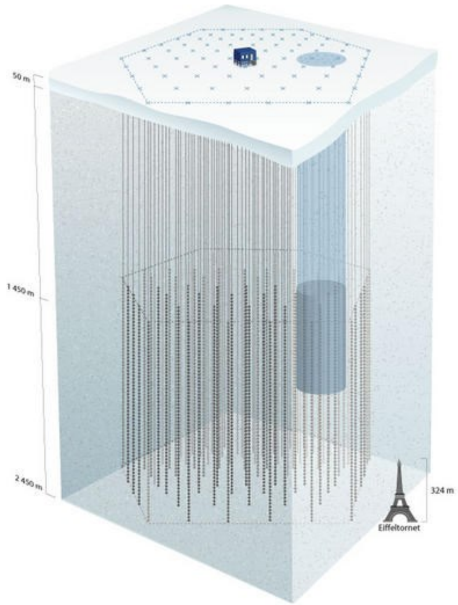
Super-Kamiokande
http://www-sk.icrr.u-tokyo.ac.jp/



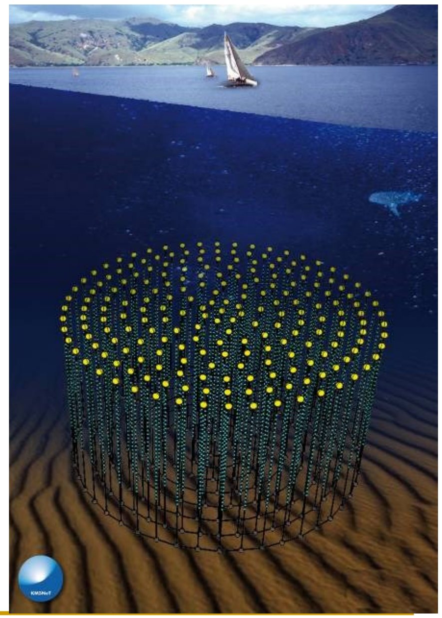
Antares
http://antares.in2p3.fr



Ice Cube
http://icecube.wisc.edu/



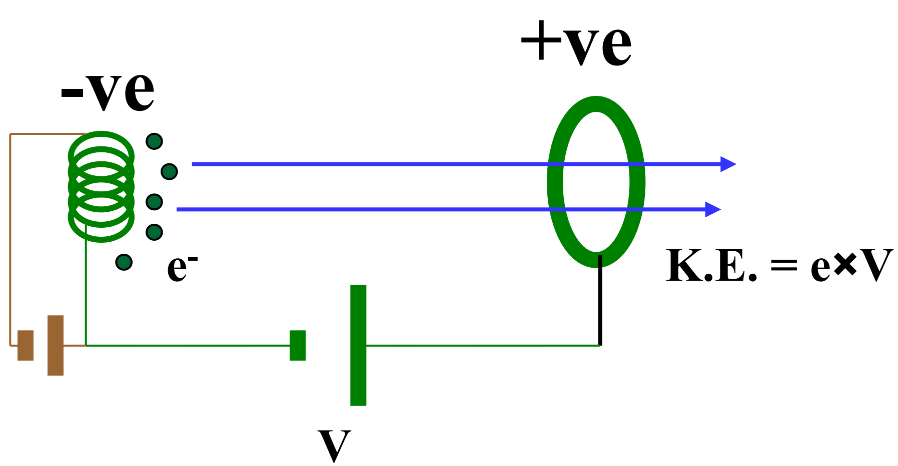
KM3NeT
http://www.km3net.org



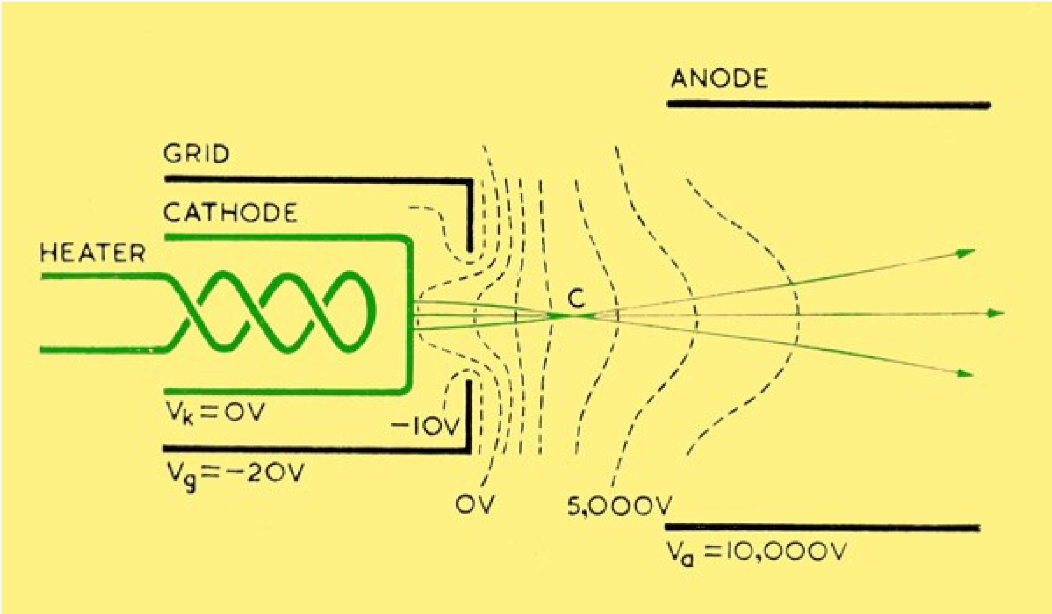
Particle Sources

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

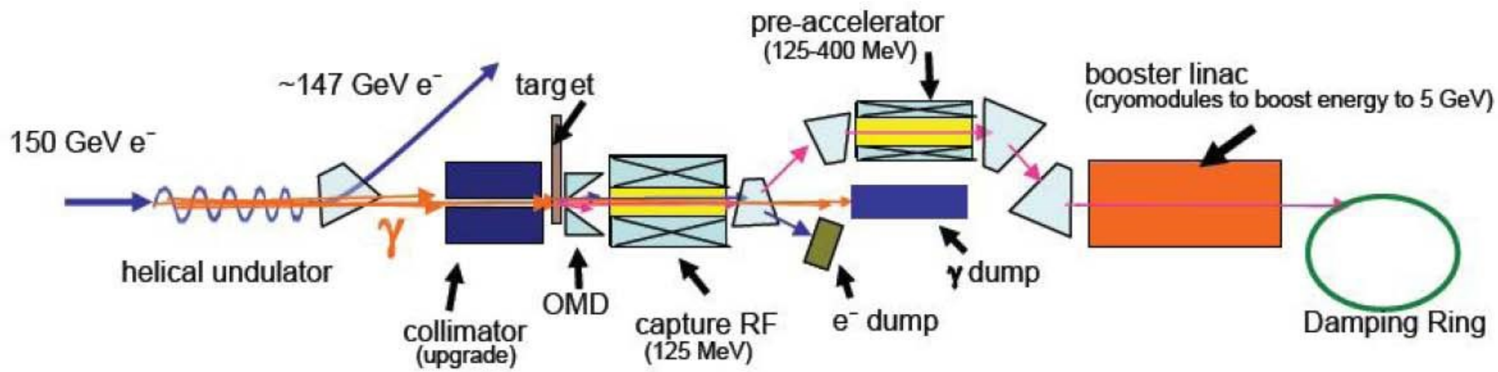


Creating Electrons



- Triode Gun
- Current: 1 A
- Voltage: 10 kV
- The grid is held at 50V below cathode (so no electrons escape).
- When triggered, grid voltage reduced to 0V. Electrons flow through grid.
- Pulse length: ~1ns

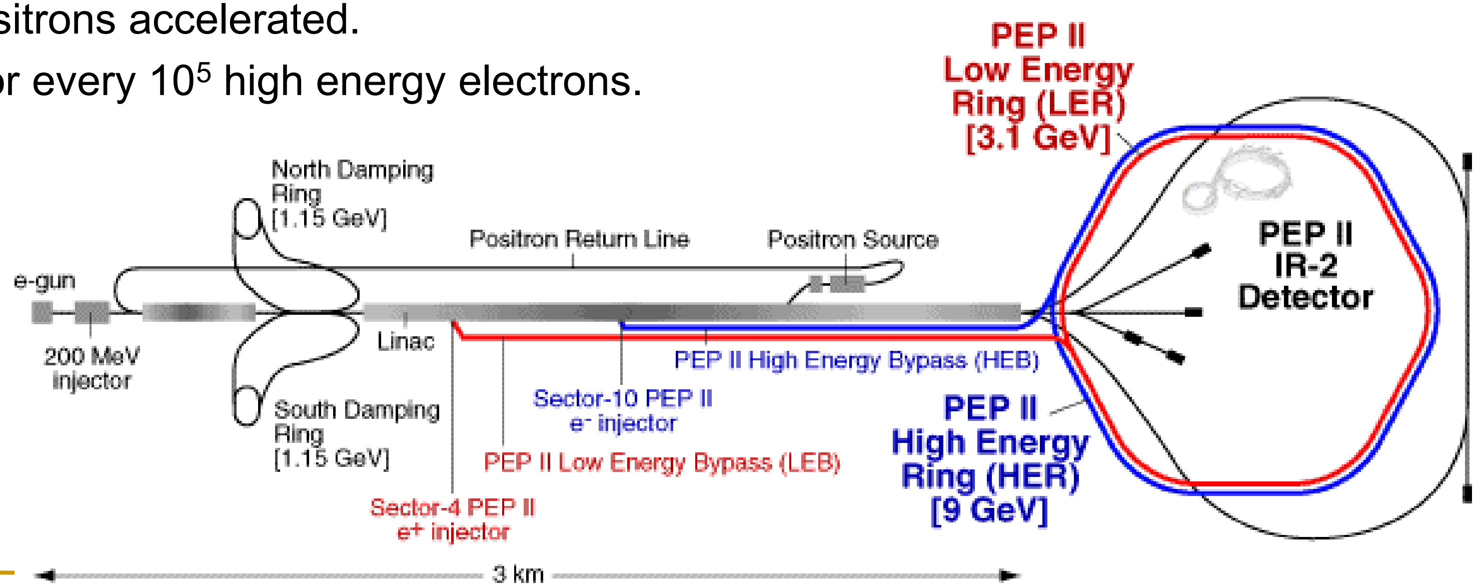
Creating Positrons



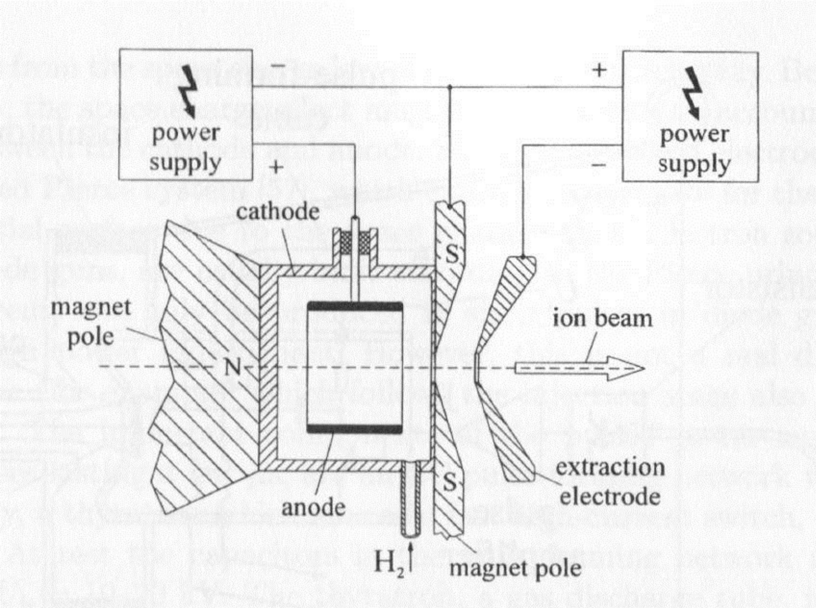
Example of how it will be done at the ILC (2030?)

- High energy e- emit photons in undulator.
- Photons hit target (tungsten)
- Positrons and electrons emitted by pair-production.
- Electrons removed, positrons accelerated.
- Inefficient: 1 positron for every 10^5 high energy electrons.

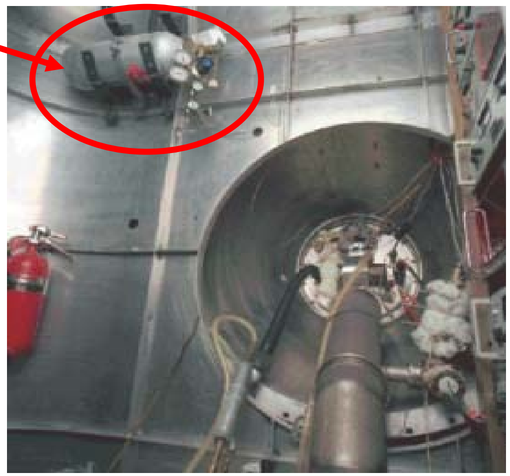
Example of how it is done at SLAC (2005)



Creating Protons – PIG (Penning Ion Gauge)



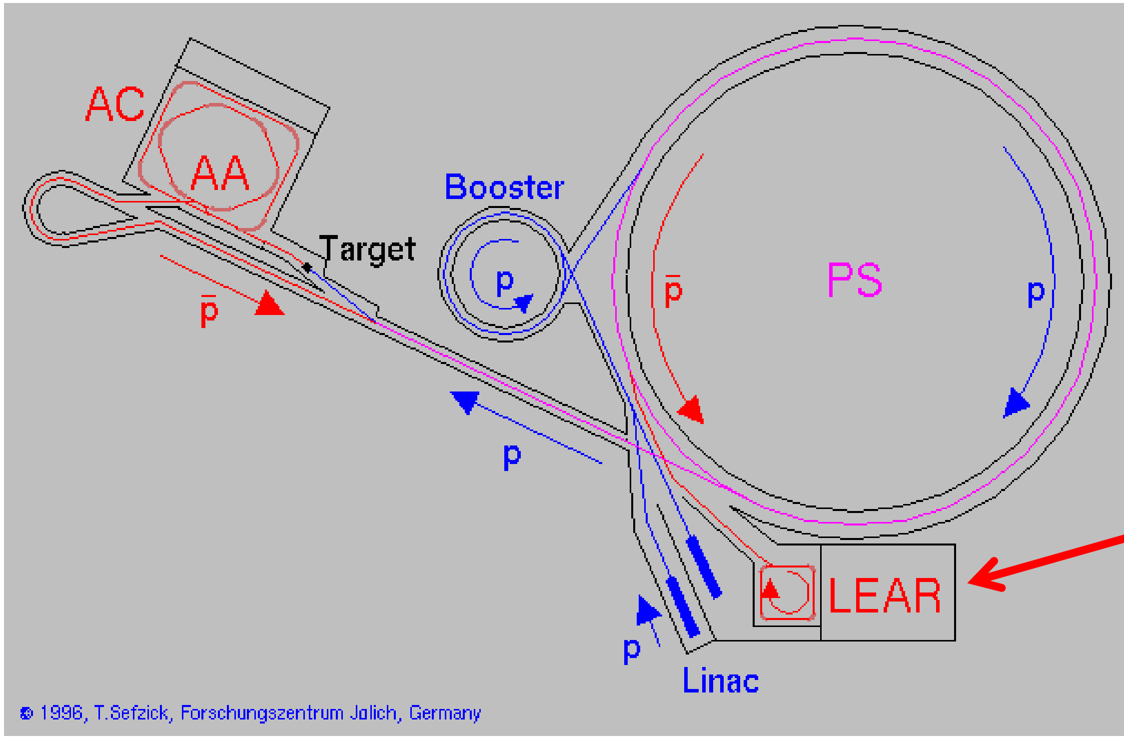
Hydrogen gas bottle

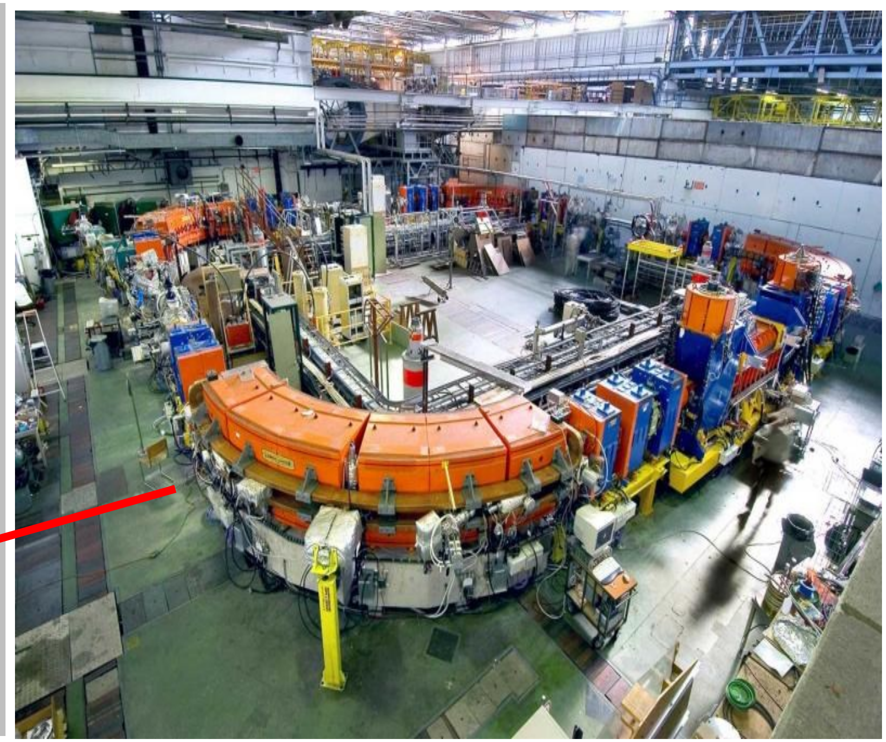


Tevatron

- Ion source (e.g. H_2) introduced as a gas and ionised.
- Magnetic field 0.01T perpendicular to E-field causes ions to spiral along B-field lines.
- Low pressure needed to keep mean-free path long (10^{-3} Torr).
- Modern methods are more complicated.
- http://www-bdnew.fnal.gov/tevatron/

Anti-Proton Production at CERN

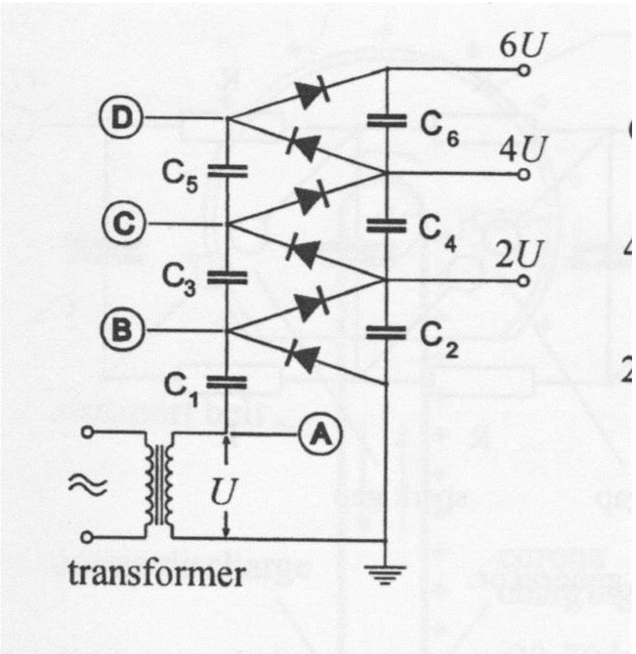




Protons are accelerated in a linear accelerator, booster, and proton synchroton (PS) up to 27 GeV. These protons hit a heavy target (Beryllium). In the interaction of the protons and the target nuclei many particle-antiparticle pairs are created out of the energy, in some cases proton-antiproton pairs. 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.

DC Accelerators – Cockcroft Walton

How it works



Cockcroft and Walton's Original Design (~1932)

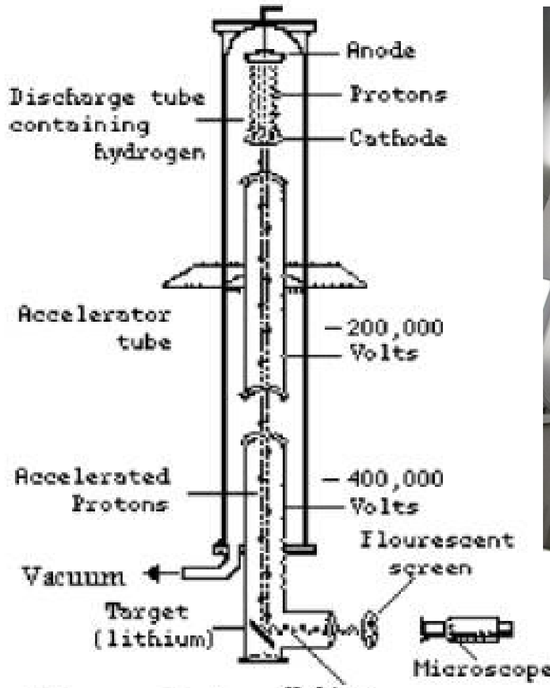
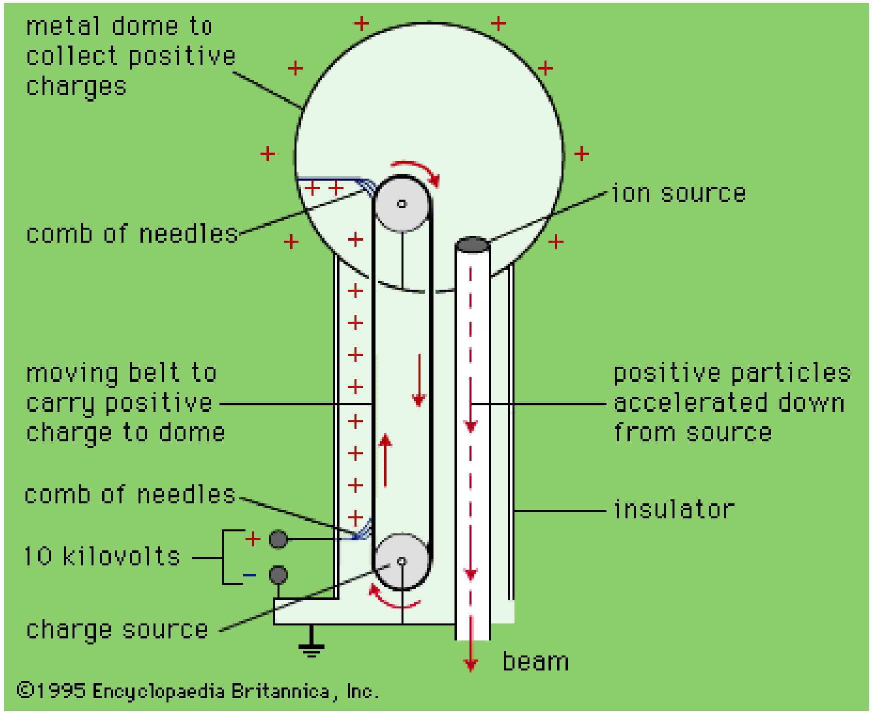


Figure 1.2

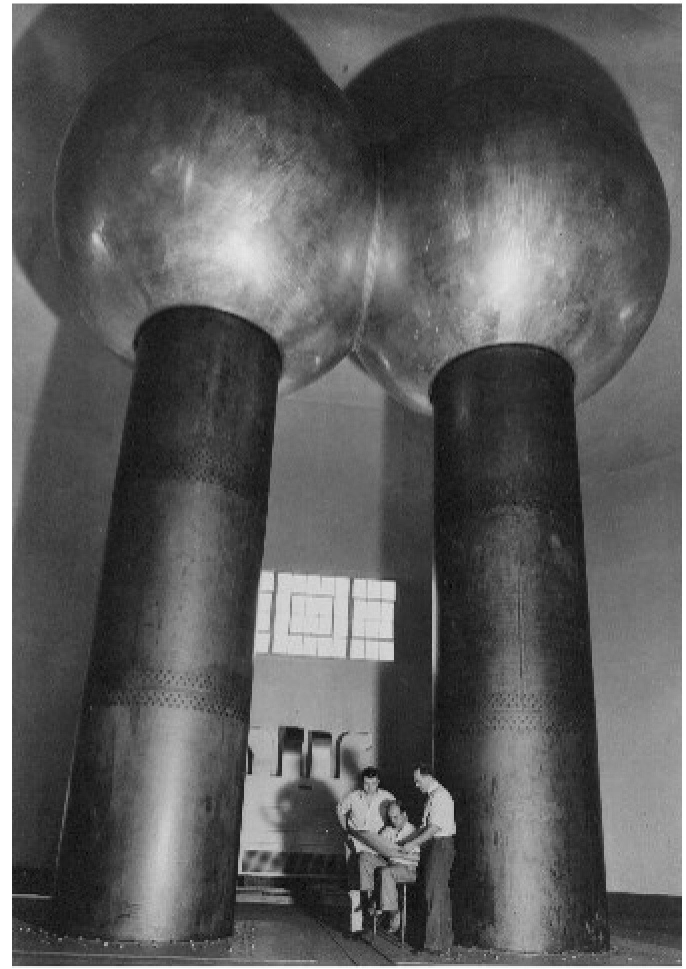
Fermilab's 750kV Cockroft-Walton

- DC accelerators quickly become impractical
- Air breaks down at ~1 MV/m

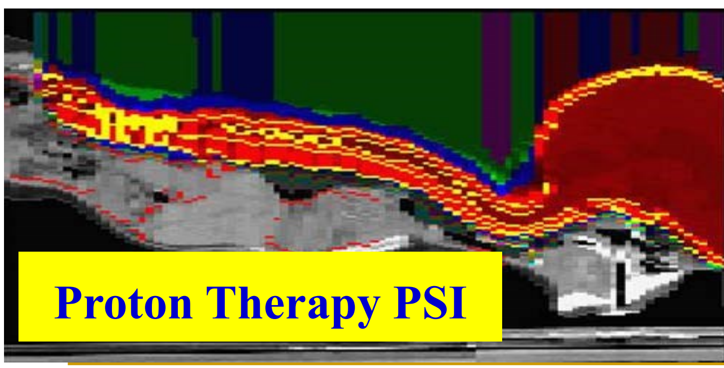
DC Accelerators – Van der Graff



Van de Graaf at MIT (25 MV)

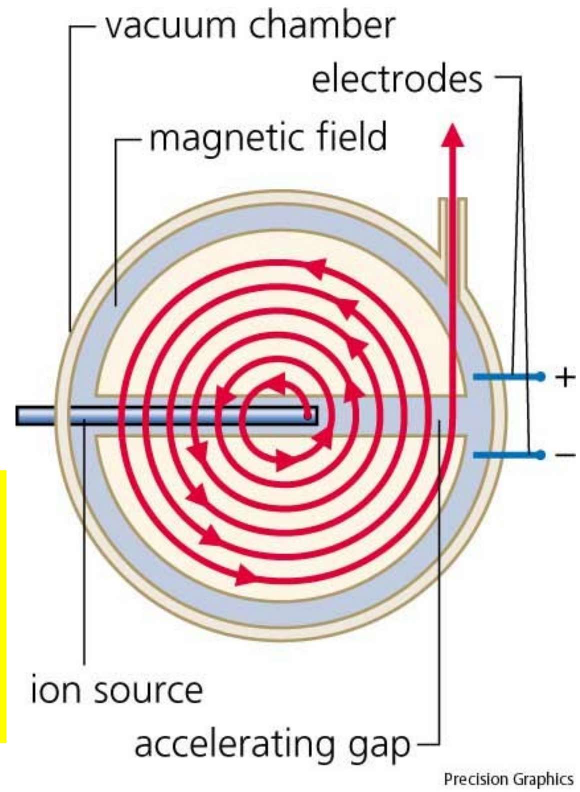


Cyclotrons



- Utilise motion in magnetic field:
  p (GeV/c) = 0.3 q B R
- Apply AC to two halves
- Lawrence achieved MeV particles with 28cm diameter
- Magnet size scales with momentum…

$$\omega = \frac{qB}{m}$$



- Still used for
  - Medical Therapy
  - Creating Radioisotopes
  - Nuclear Science

Cyclotrons - Variations

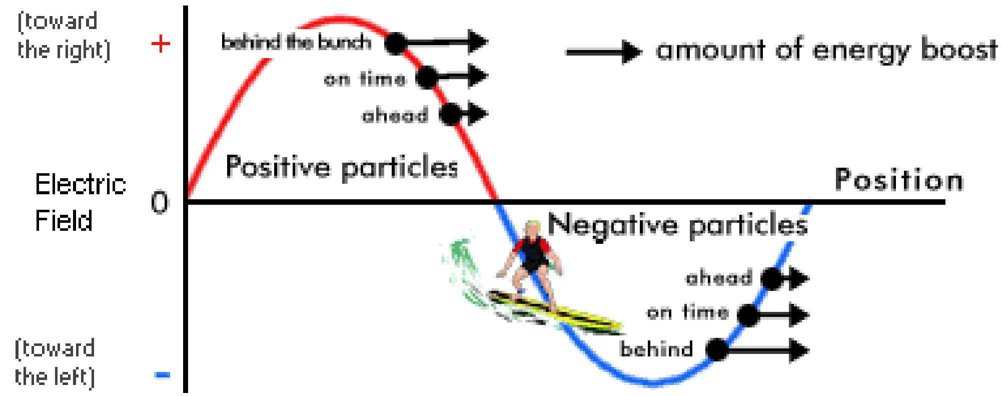
- Cyclotron limitations:
  - Energy limit is quite low: 25 MeV per charge
  - Non-relativistic velocity $v < 0.15c$
- Alternatives:
  - Syncro-cyclotron
    - Keep magnetic field constant but decrease RF frequency as energy increases to compensate for relativistic effects.
  - Iso-cyclotron
    - Keep RF frequency the same but increase the radial magnetic field so that cyclotron frequency remains the same:
    - Can reach ~600 MeV
  - Synchrotron
    - For very high energies. See later…

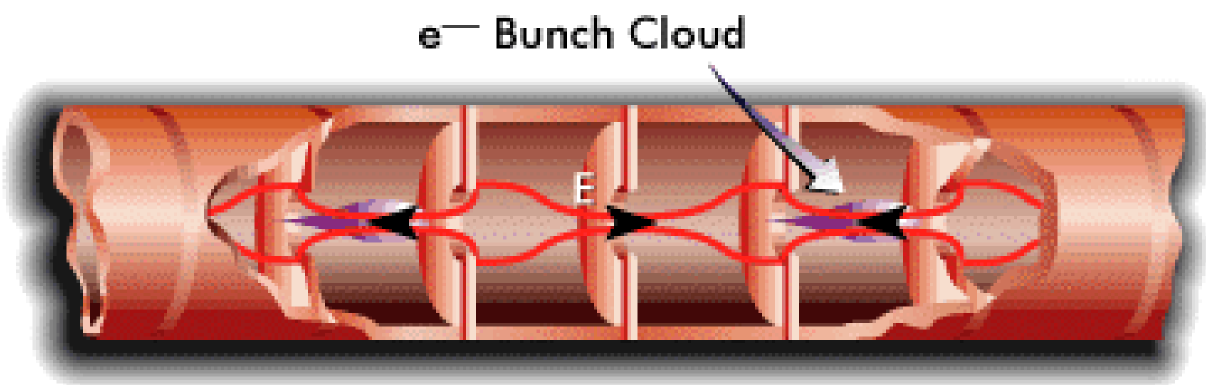
$$\omega = \frac{qB(r(E))}{m(E)} = const.$$

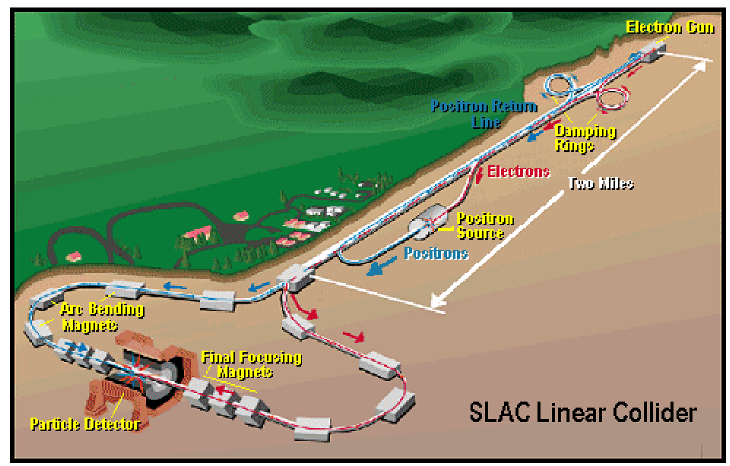
Linear Accelerators

For energies greater than few MeV:

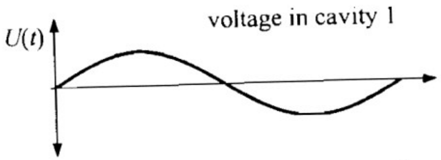
- Use multiple stages
- RF easier to generate and handle
- Bunches travel through resonant cavities
- Spacing and/or frequency changes with velocity
- Can achieve 10MV/m and higher
- 3km long Stanford Linac reached 45 GeV
- 30km Linear Collider would reach 250 GeV.

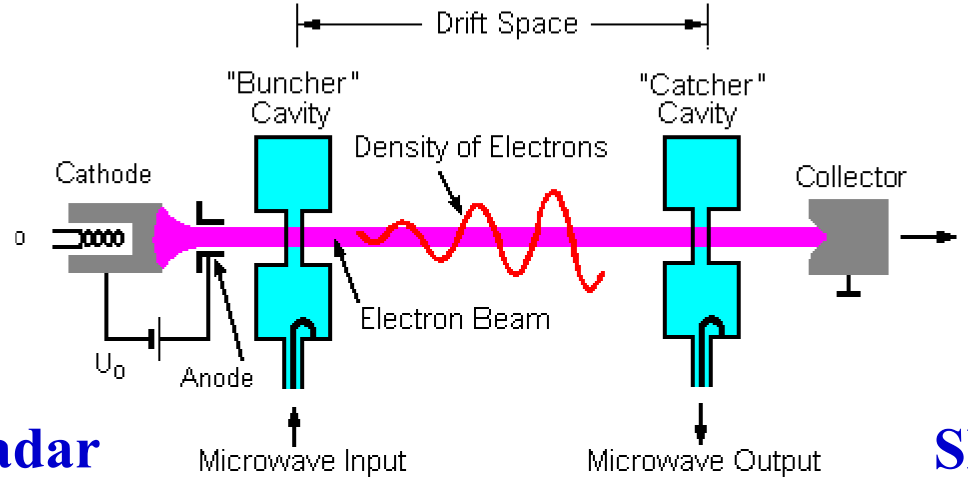


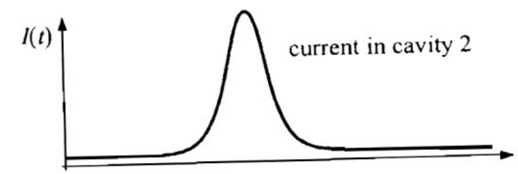




Superconducting Cavities & Klystron

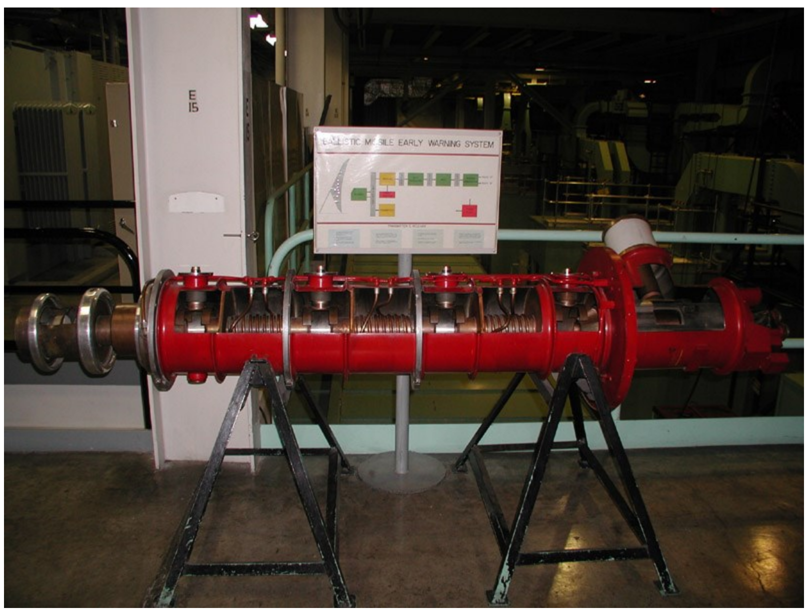


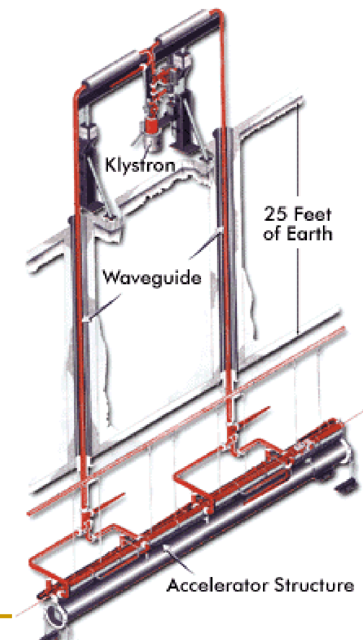


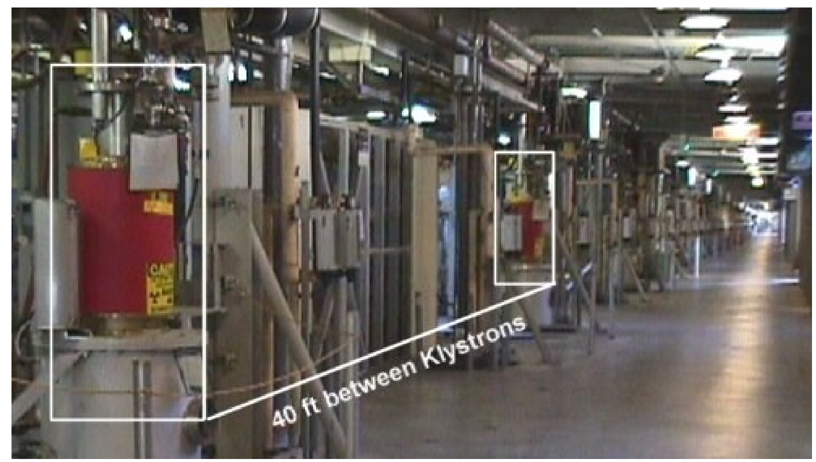


Early Warning Radar

SLAC Klystron Hall

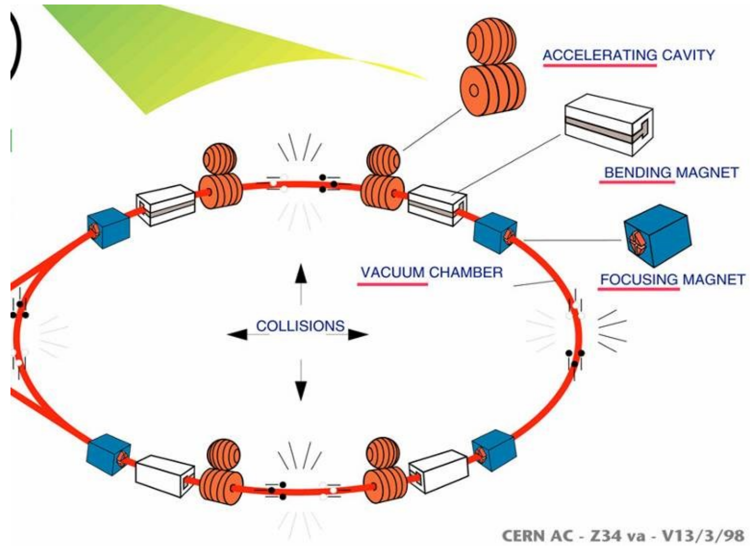






Synchrotrons

- *p (GeV/c) = 0.3 q B R*
- Cyclotron 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 (focusing)
  - sextuples (achromaticity)
  - 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 ~ 1/mass^4
  - (this comes from γ in the power loss equation)
- Electron losses much larger than proton
  - High energy electron machines have very large or infinite *R (i.e. linear).*
- Pulsed, intense X-ray source may be useful for some things....

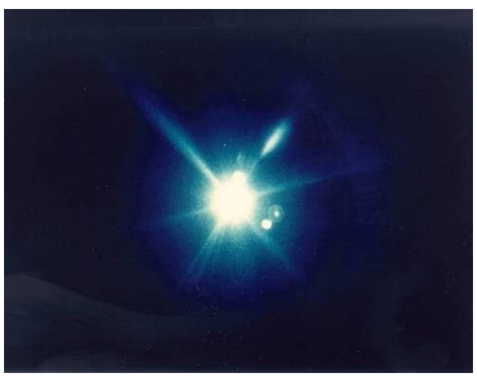
Power loss (Watts) $= \dfrac{1}{6\pi\varepsilon_0}\dfrac{e^2a^2}{c^3}\gamma^4 \quad a = \dfrac{\text{v}^2}{R} \quad \gamma = \dfrac{E}{m_o}$

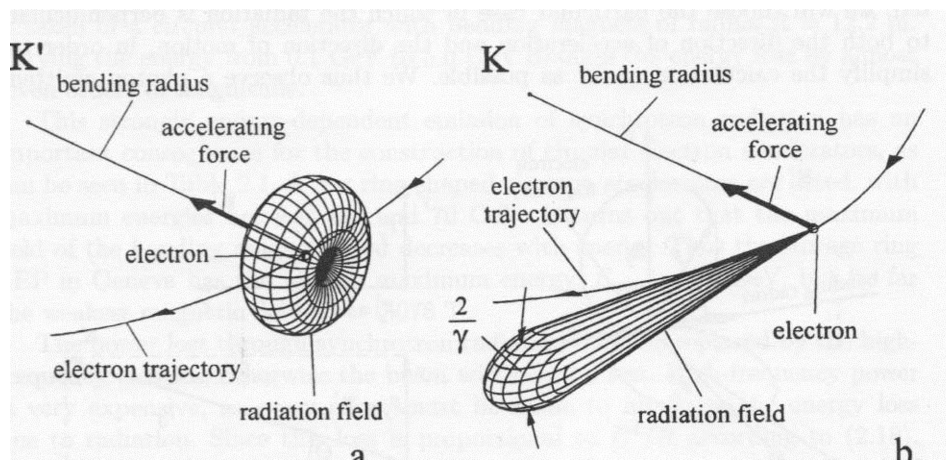
$\Rightarrow$ Electron Power Loss per turn $= \dfrac{8.85\times10^{-5}E^4}{R}$ MeV/turn

E in GeV, R in km.

$\Rightarrow$ Proton Power Loss per turn $= \dfrac{7.78\times10^{-3}E^4}{R}$ keV/turn

E in TeV, R in km.



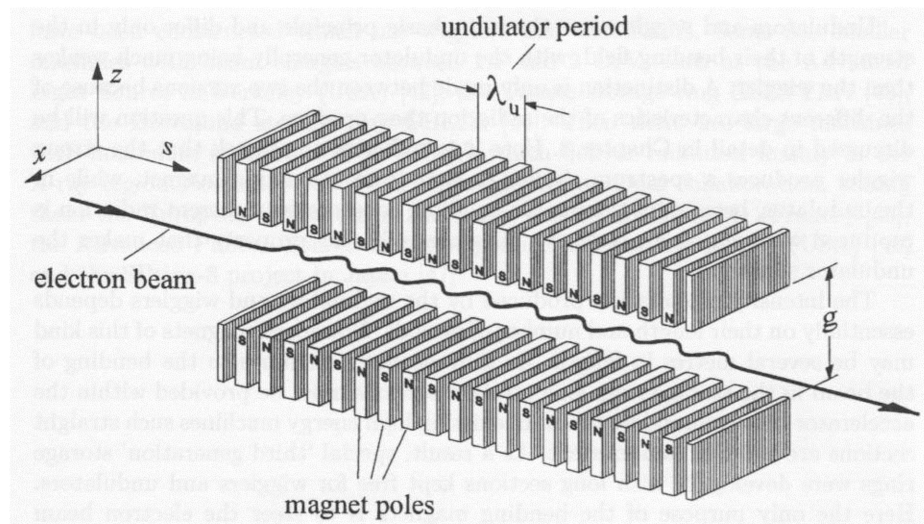


Real Synchrotrons

Grenoble, France

Bevatron, LBNL, USA (1954)

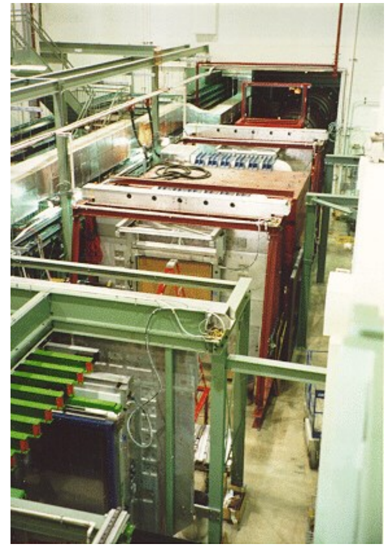
DIAMOND, RAL, UK



Fixed Target Experiments

Beam incident on stationary target

- Interaction products have large momentum in forward direction
- Large "wasted" energy ⇔ small $\sqrt{s}$
- Intense beams/large target ⇒ high rate
- Secondary beams can be made.

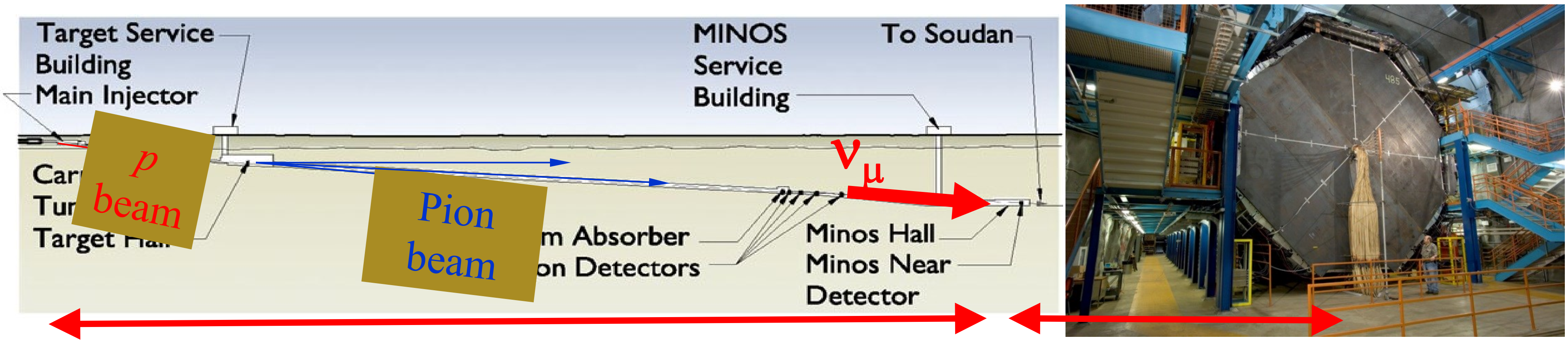


$$p_1 = (E_1, \bar{p}_1) \quad p_2 = (E_2, \bar{p}_2) \quad E^2 = p^2 + m_0^2$$

Centre of Mass energy squared $s = E_{cm}^2 = (p_1 + p_2)^2$

$$\Rightarrow E_{cm} = \left[\left(E_1 + E_2\right)^2 - \left(\bar{p}_1 + \bar{p}_2\right)^2 \right]^{1/2}$$

Fixed Target - Neutrino Beams

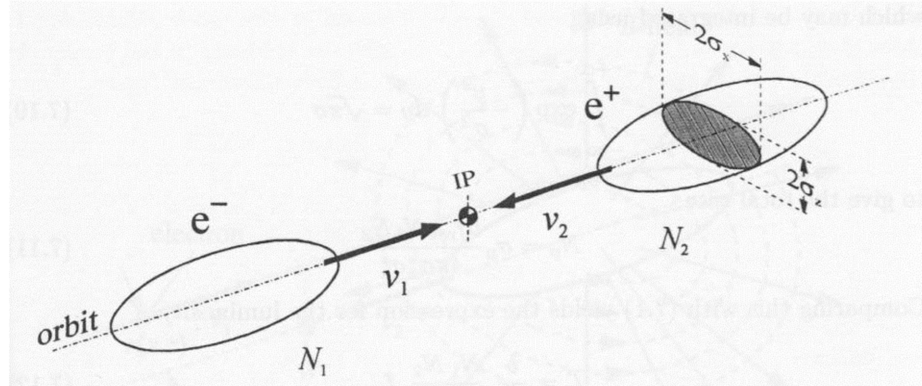


700 m

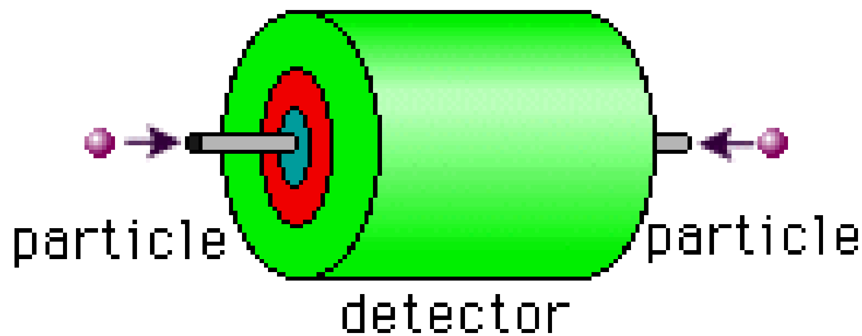
700 km

- Fermilab sends a ν_μ 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 ⇒ *Antiparticle accelerator for free!*
  - particle/antiparticle quantum numbers also cancel
- *Technically challenging*



Event Rate $R = L\sigma$

Current $I_i = n_i e f N_b$

$$\text{Luminosity} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y} = \frac{I_1 I_2}{4\pi f N_b e^2 f \sigma_x \sigma_y}$$

particles per bunch

frequency

bunch size

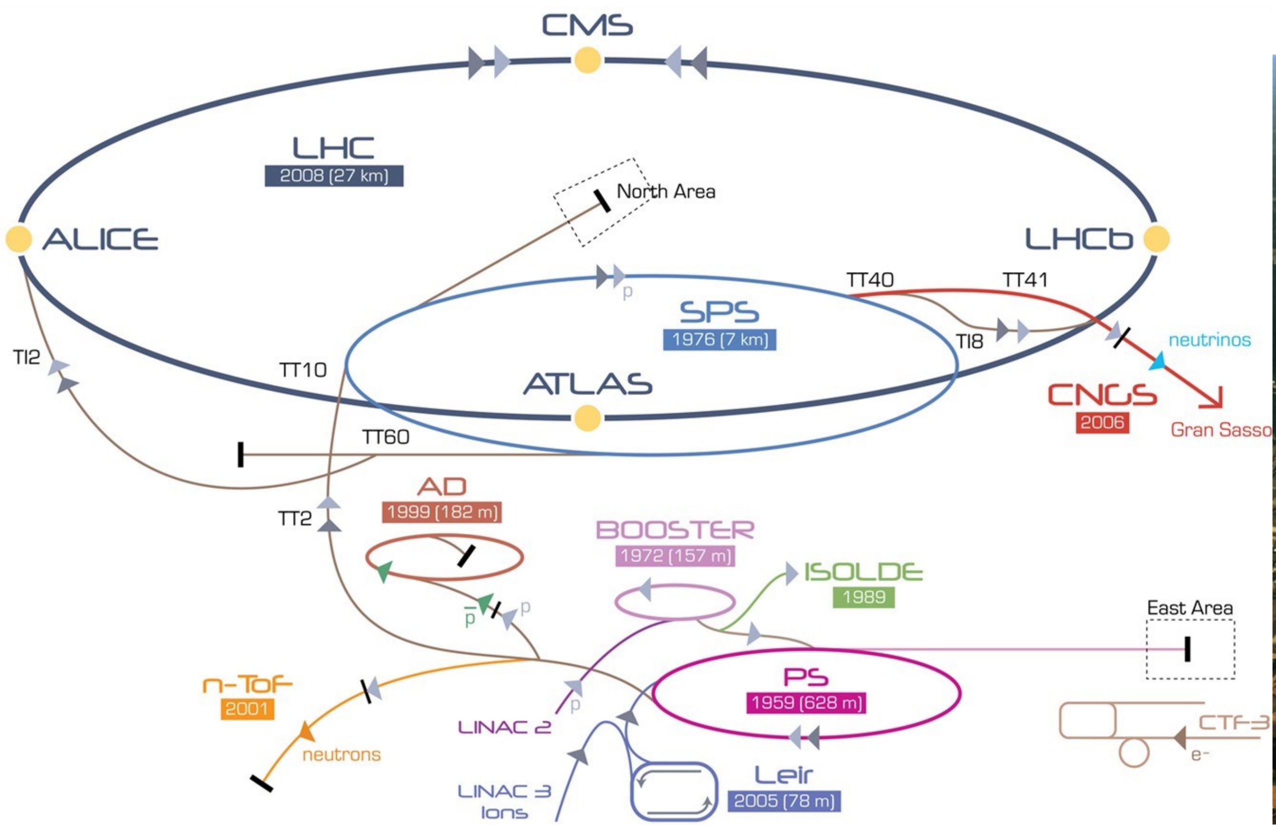
#bunches

Different Colliders

- *p anti-p*
  - energy frontier
  - difficult to interpret
  - limited by anti-p production
  - *SPS, Tevatron*
- *p p*
  - high luminosity
  - energy frontier
  - *LHC*
- *μ+ μ-*
  - 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*
- *ν ν*
  - Muon Collider !!!

Complexes

- Synchrotrons can’t accelerate particles from rest
- Designed for specific energy range, normally about factor of 10
- Accelerators are linked into complexes



Collider Parameters

	KEKB (KEK)	PEP-II (SLAC)	SuperB (Italy)	SuperKEKB (KEK)
Physics start date	1999	1999	TBD	2014 ?
Physics end date	—	2008	—	—
Maximum beam energy (GeV)	e^-: 8.33 (8.0 nominal) e^+: 3.64 (3.5 nominal)	e^-: 7–12 (9.0 nominal) e^+: 2.5–4 (3.1 nominal) (nominal E_{cm} = 10.5 GeV)	e^-: 4.2 e^+: 6.7	e^-: 7 e^+: 4
Luminosity (10^{30} cm^{-2}s^{-1})	21083	12069 (design: 3000)	1.0×10^6	8×10^5
Time between collisions (μs)	0.00590 or 0.00786	0.0042	0.0042	0.004

Full details at http://pdg.lbl.gov/

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)				LHC† (CERN)	
Physics start date	1992	1987	2001	2000	2004	2002	2009	2010
Physics end date	2007	—	—				—	
Particles collided	ep	$p\bar{p}$	pp (pol.)	Au Au	Cu Cu	d Au	pp	Pb Pb
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.25 34% pol	0.1 TeV/n	0.1 TeV/n	0.1 TeV/n	7.0 (3.5)	2.76 TeV/n (1.38 TeV/n)
Luminosity (10^{30} cm^{-2}s^{-1})	75	402	85 (pk) 55 (ave)	0.0040 (pk) 0.0020 (ave)	0.020 (pk) 0.0008 (ave)	0.27 (pk) 0.14 (ave)	1.0×10^4 (170)	1.0×10^{-3} (1.3×10^{-5})
Time between collisions (ns)	96	396	107	107	321	107	24.95 (49.90)	99.8 (1347)

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	2010	CERN	3.5 TeV
Collider	LHC	27km	2014	CERN	7.5 TeV

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

Next Time...

Charged particle interactions and detectors