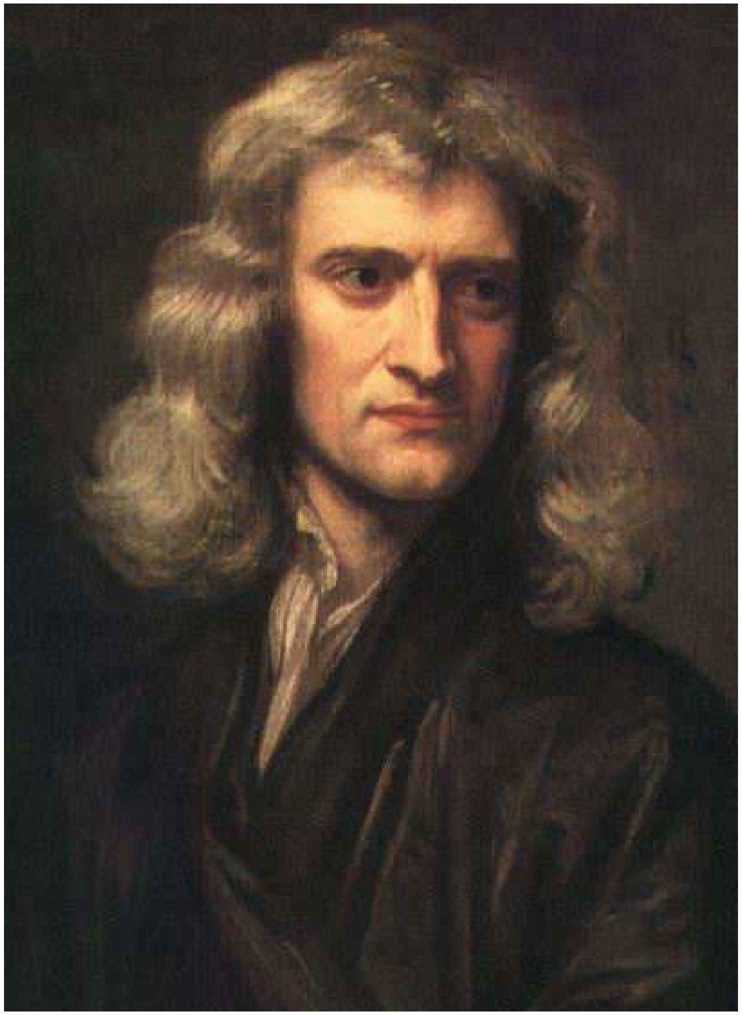
The Physics of *Cosmic Rays*

QuarkNet

summer workshop

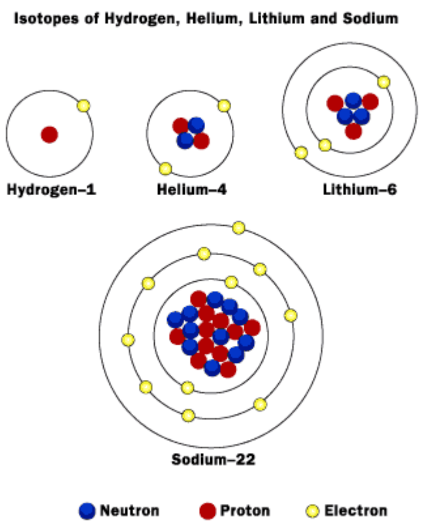
July 23-27, 2012

"Recent" History



- Most natural phenomena can be explained by a small number of simple rules.
- You can determine what these rules are by *observation* and by doing *experiments*.
- This is how science has progressed since the 1700's.

More Recent History



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- Nils Bohr described atomic structure using early concepts of Quantum Mechanics
- Albert Einstein extends the laws of classical mechanics to describe velocities that approach the speed of light.

All matter should obey the laws of quantum mechanics and special relativity.

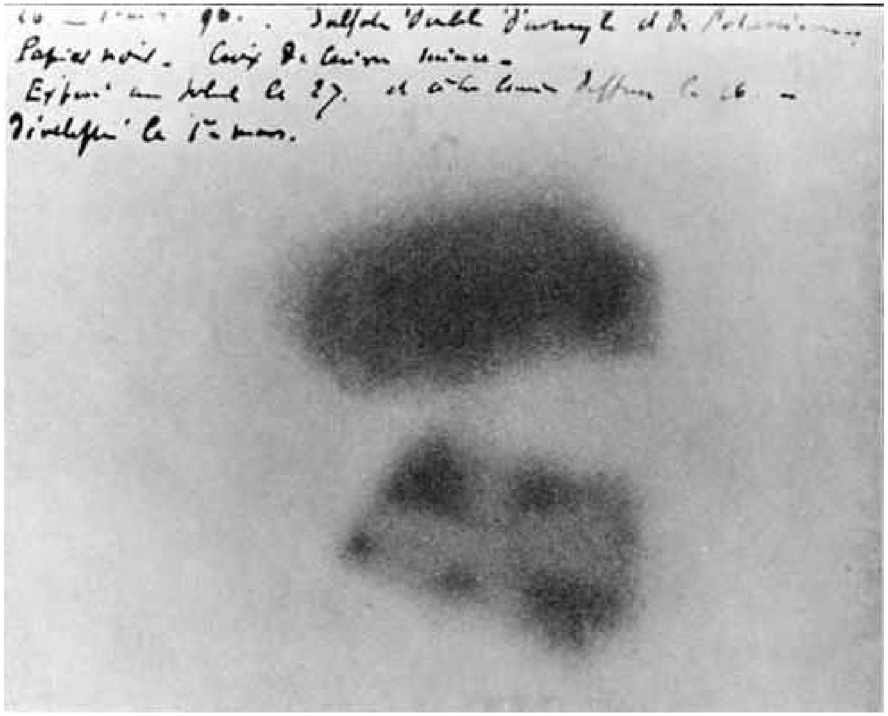
The Birth of Particle Physics

- In 1896, Thompson showed that electrons were particles, not a fluid.
- In 1905, Einstein argued that photons behave like particles.
- In 1907, Rutherford showed that the mass of an atom was concentrated in a nucleus.

Particles that should obey the laws of quantum mechanics and relativity.

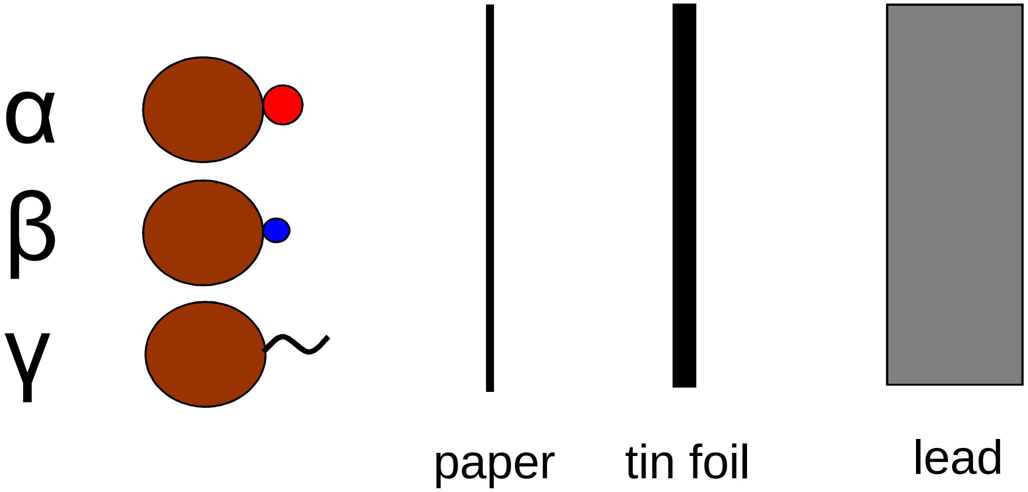
Something Totally New

- In 1896, Becquerel discovers “uranium rays”:



Something Totally New

- Rutherford classifies types of radiation:

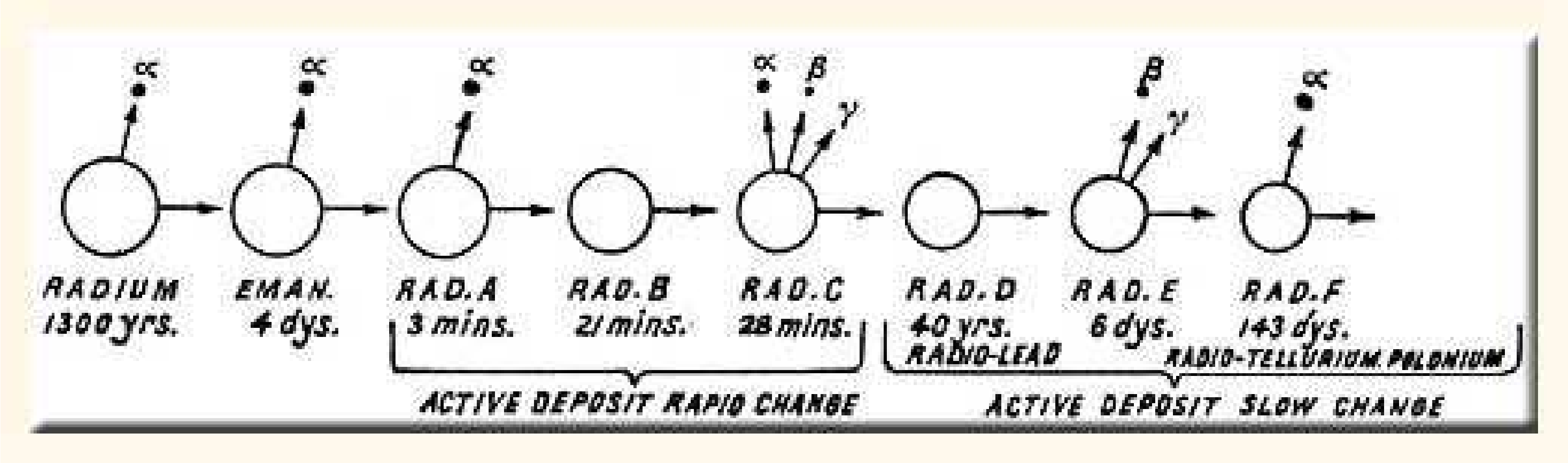


α
β
γ

paper
tin foil
lead

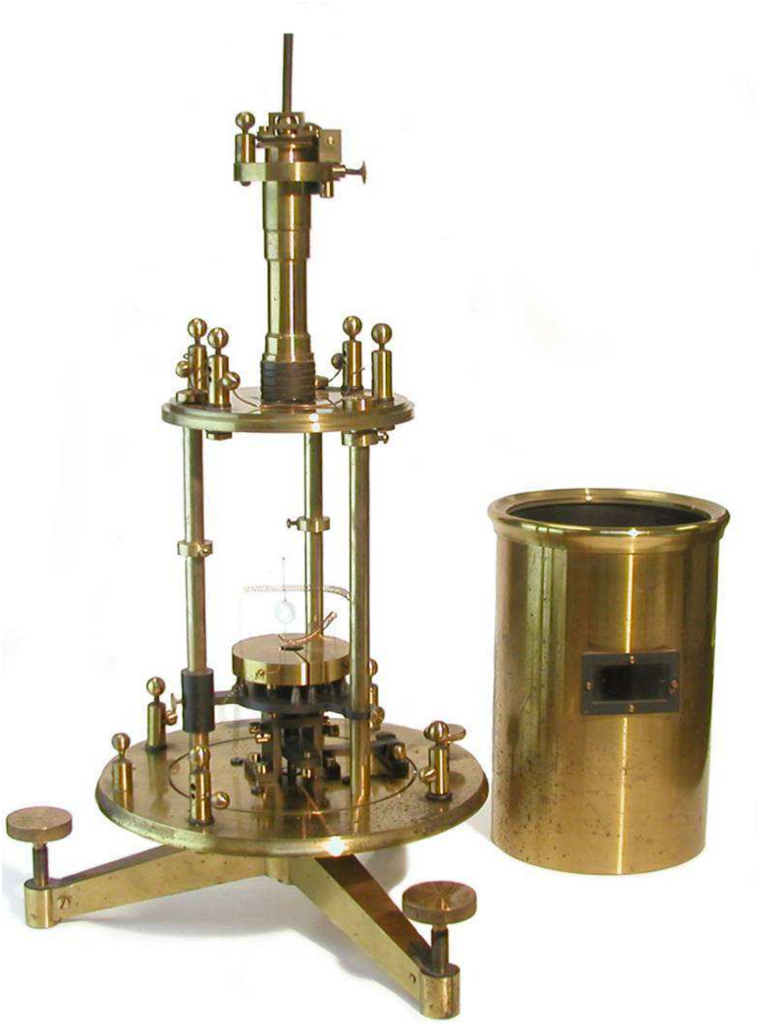
Something Totally New

- Marie Curie determines that radioactivity has nothing to do with chemistry...
- Nobel prizes in 1903 *and* 1911!



Discoveries of Cosmic Rays

- Viktor Hess studied the "electrification of air" using electrometers.
- Ionization from radioactive decay would deposit charge on the electrometer.
- But no matter how well they were made, they "leaked".
- Leakage rate was the same in the middle of a lake, but lower in a cave...



Discoveries of Cosmic Rays

In 1912 Viktor Hess carried three electrometers to an altitude of 5300 meters in a balloon flight:

- Ionization rate decreased up to ~700 m
- Above 700 m then it increased with altitude. At 5300 m the **ionization rate 4 × rate at ground level**
- "The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."

Open Questions

- Same intensity at night
  ➔ not from the sun!
- Were they charged like beta rays or uncharged like gamma rays?
- Do they come down or go up? How do you know for sure?
- Electrometers can’t easily answer these questions...

The New York Times

VOL. LXXXII....No. 27,370. December 31,1932

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

Correlation with Earth’s Magnetic Field

A. H. COMPTON AND R. N. TURNER

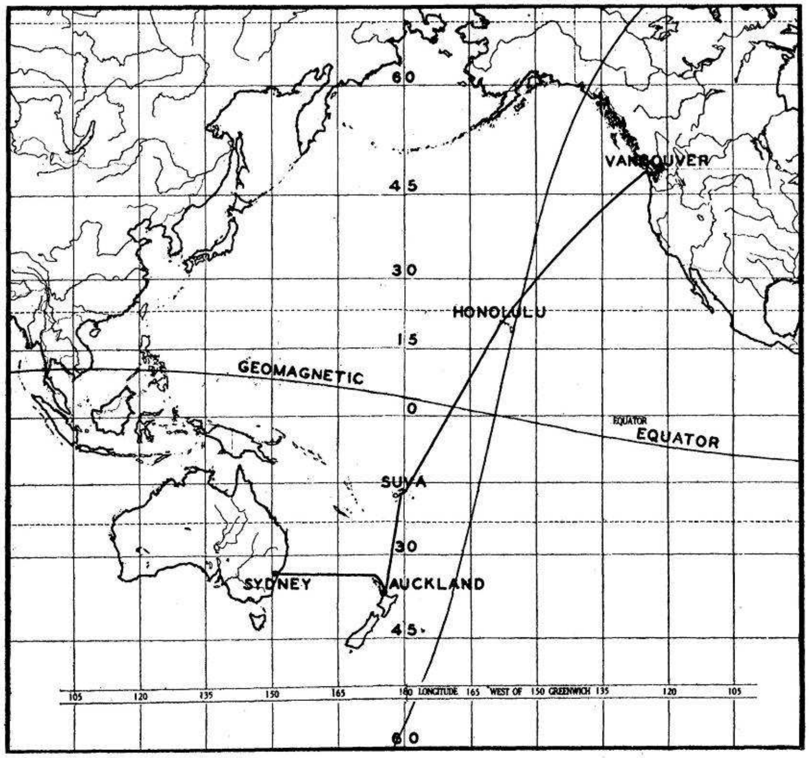


FIG. 1. Route of R. M. S. Aorangi.

A. H. COMPTON AND R. N. TURNER

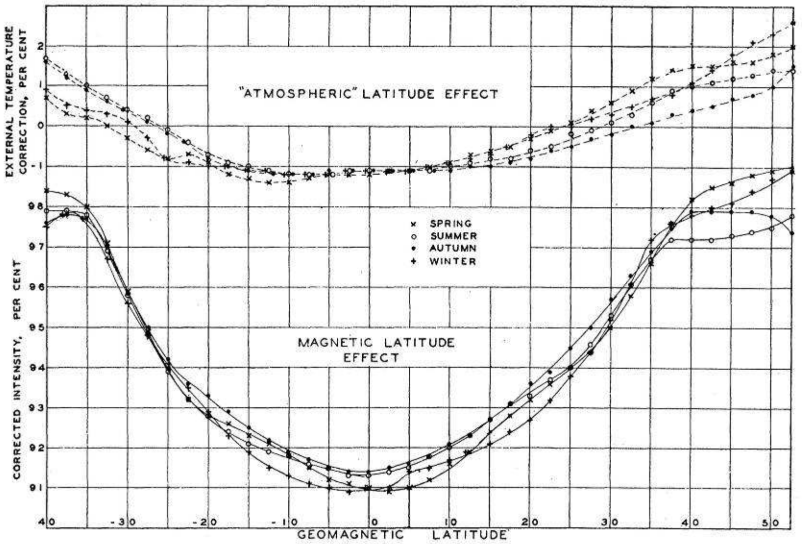


FIG. 10. Magnetic (solid lines) and atmospheric (broken lines) latitude effect for the four seasons. Sum of these two effects gives observed total effect of Fig. 7.

Compton argued strongly against the suggestion that they were photons!

Particle Detectors

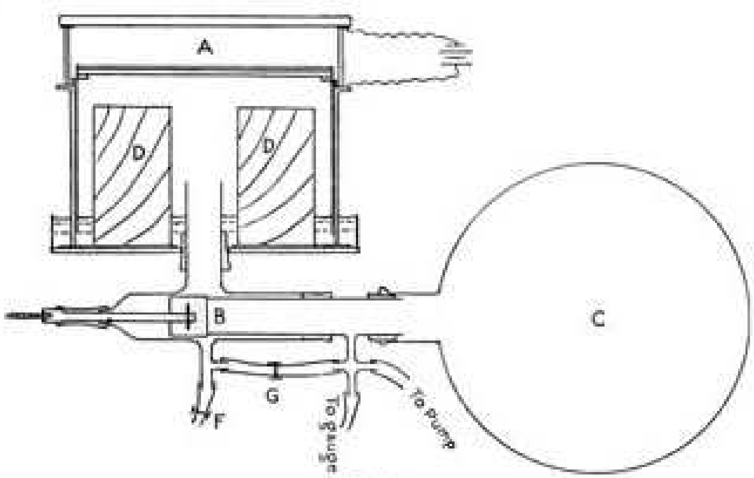


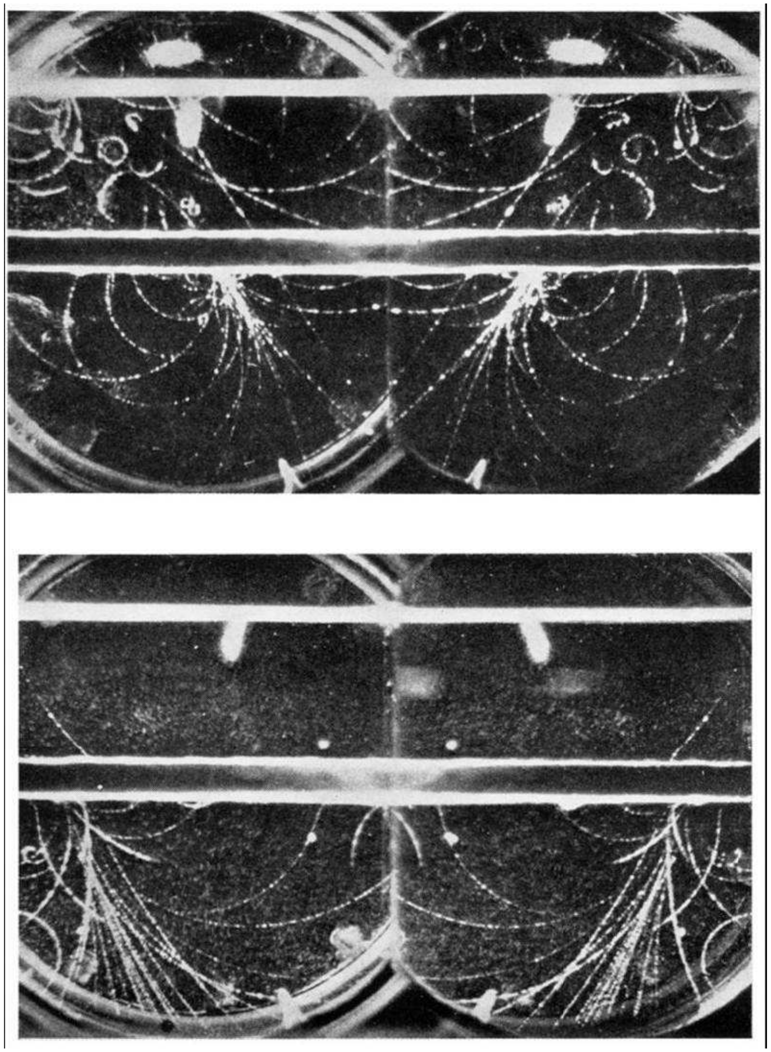
Fig. 1.

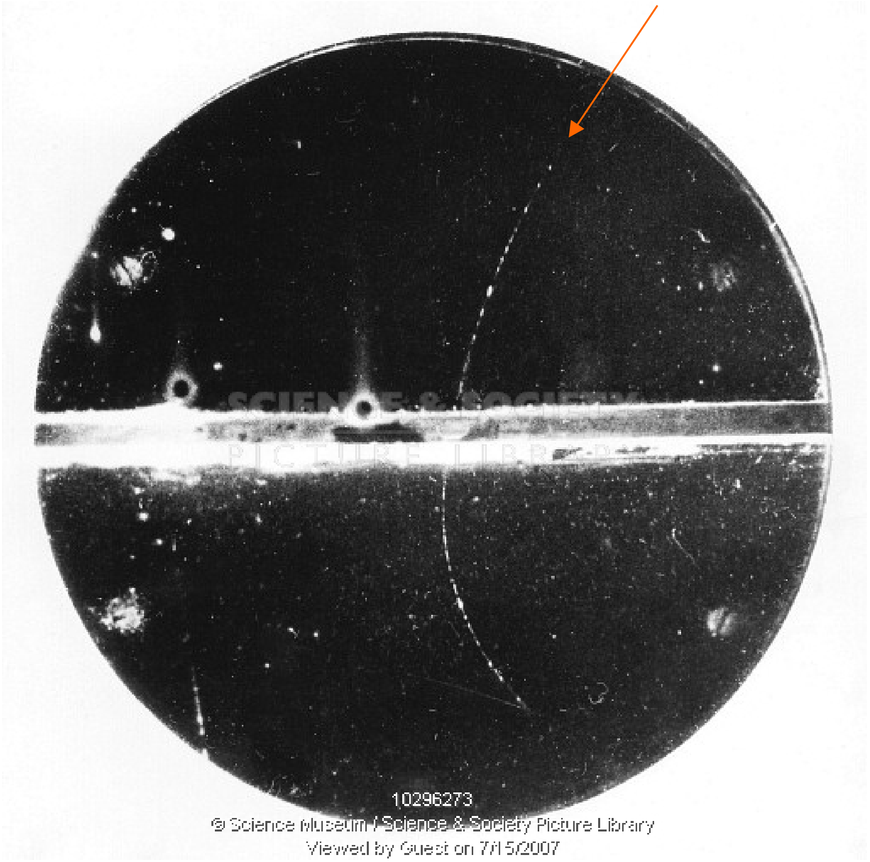
A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.

In 1911, Wilson developed the “expansion cloud chamber” which used saturated water vapor.

In the classroom, we would normally use a “diffusion cloud chamber” using saturated alcohol vapor.

Images of Cosmic Rays





Anderson discovers the "positive electron" in 1933.

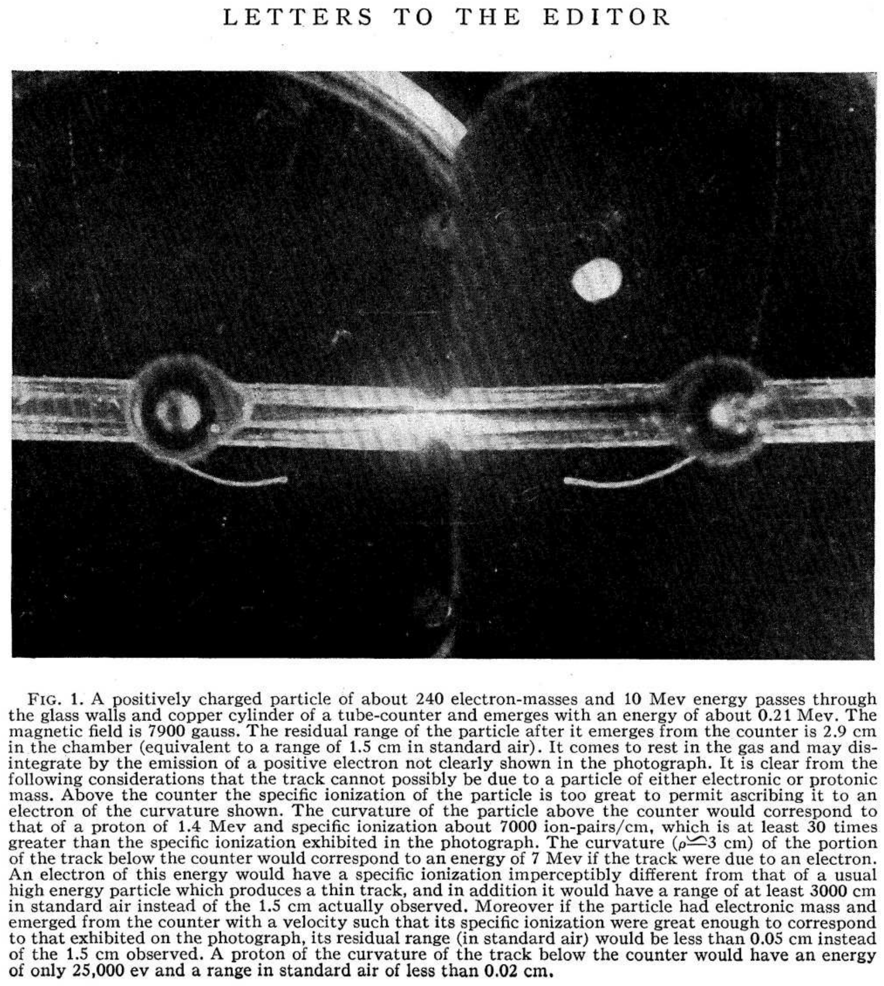
➔ Anti-matter!

Discovery of other particles

Anderson and Neddermayer got very good at measuring energy and mass. By triggering a camera using two Geiger counters they obtained this picture, published in 1938:

- Curved too much to be a proton.
- Traveled too far to be an electron.
- It must have intermediate mass...

$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$



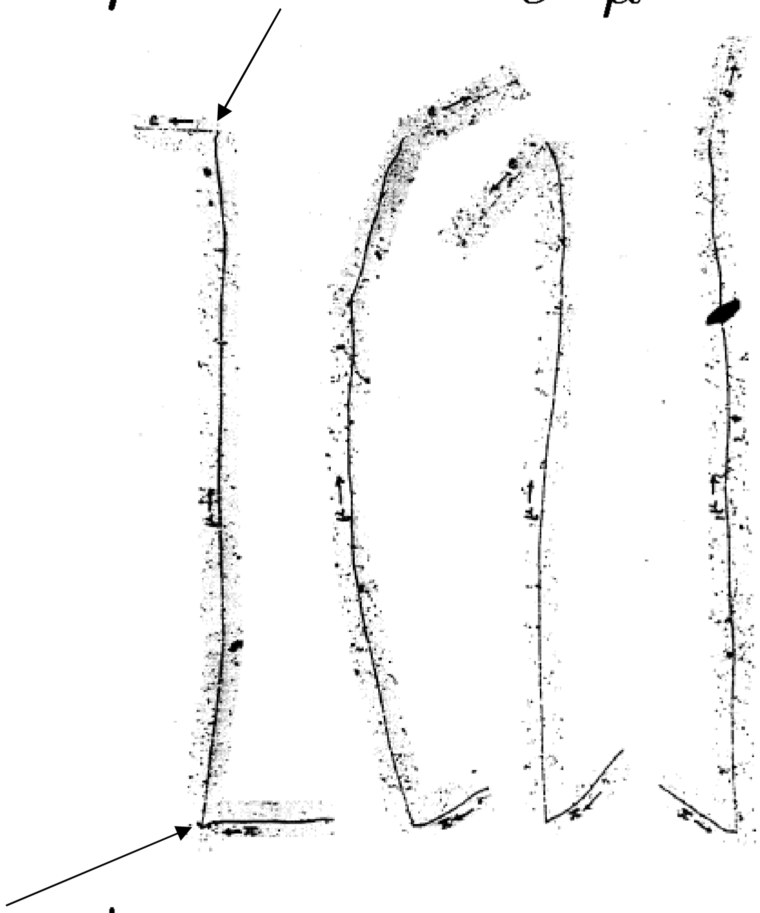
LETTERS TO THE EDITOR

FIG. 1. A positively charged particle of about 240 electron-masses and 10 Mev energy passes through the glass walls and copper cylinder of a tube-counter and emerges with an energy of about 0.21 Mev. The magnetic field is 7900 gauss. The residual range of the particle after it emerges from the counter is 2.9 cm in the chamber (equivalent to a range of 1.5 cm in standard air). It comes to rest in the gas and may disintegrate by the emission of a positive electron not clearly shown in the photograph. It is clear from the following considerations that the track cannot possibly be due to a particle of either electronic or protonic mass. Above the counter the specific ionization of the particle is too great to permit ascribing it to an electron of the curvature shown. The curvature of the particle above the counter would correspond to that of a proton of 1.4 Mev and specific ionization about 7000 ion-pairs/cm, which is at least 30 times greater than the specific ionization exhibited in the photograph. The curvature ($\rho \backsimeq 3$ cm) of the portion of the track below the counter would correspond to an energy of 7 Mev if the track were due to an electron. An electron of this energy would have a specific ionization imperceptibly different from that of a usual high energy particle which produces a thin track, and in addition it would have a range of at least 3000 cm in standard air instead of the 1.5 cm actually observed. Moreover if the particle had electronic mass and emerged from the counter with a velocity such that its specific ionization were great enough to correspond to that exhibited on the photograph, its residual range (in standard air) would be less than 0.05 cm instead of the 1.5 cm observed. A proton of the curvature of the track below the counter would have an energy of only 25,000 ev and a range in standard air of less than 0.02 cm.

Charged Pions and Kaons

- Charged particles also expose stacks of photographic emulsion
- The pion had been predicted to explain strong nuclear forces
- Not a muon: pions interacted with nuclei
- Another strange particle was observed with about ½ the mass of the proton
- Strangely, they were always produced in pairs and also interacted with nuclei

$$\mu^+ \longrightarrow e^+\nu_e\overline{\nu}_\mu$$

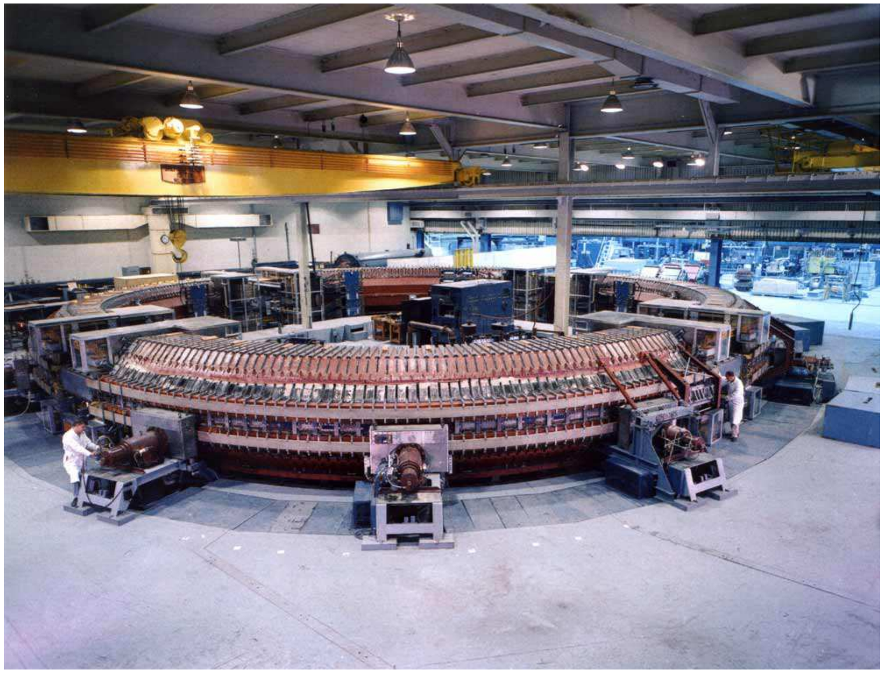


$$\pi^+ \longrightarrow \mu^+\nu_\mu$$

The Known Particles in 1950

symbol	particle	mass
p	proton	938 MeV$/c^2$
n	neutron	940 MeV$/c^2$
$\pi^\pm$	pion	140 MeV$/c^2$
$V^0, V^\pm$	???	???
$e^\pm$	electron	0.511 MeV$/c^2$
$\mu^\pm$	muon	106 MeV$/c^2$
ν	neutrino	0?
γ	photon	0

New Accelerators: Synchrotrons



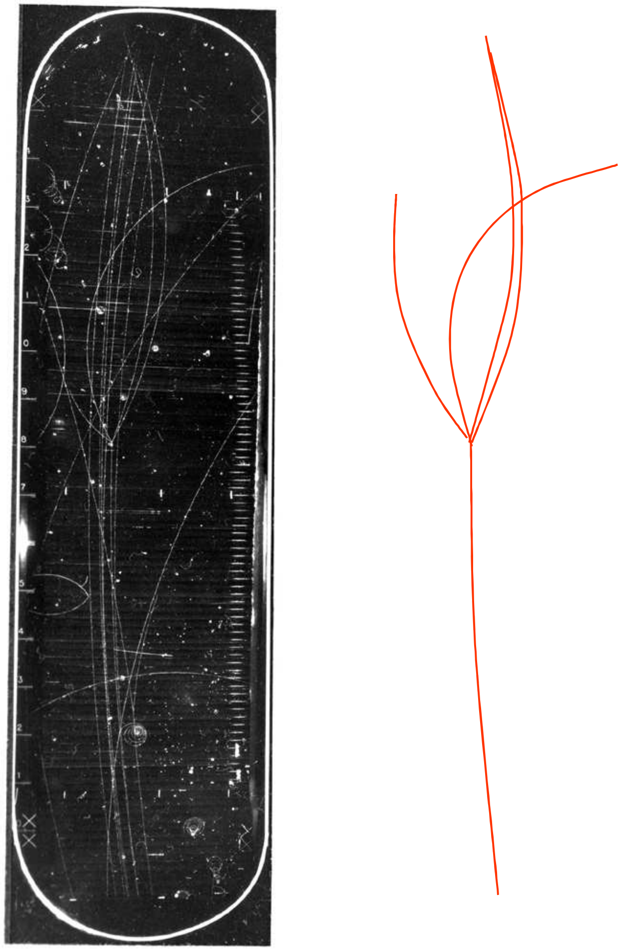
1952: Brookhaven 3 GeV “Cosmotron”

1954: Berkeley 6 GeV “Bevatron”

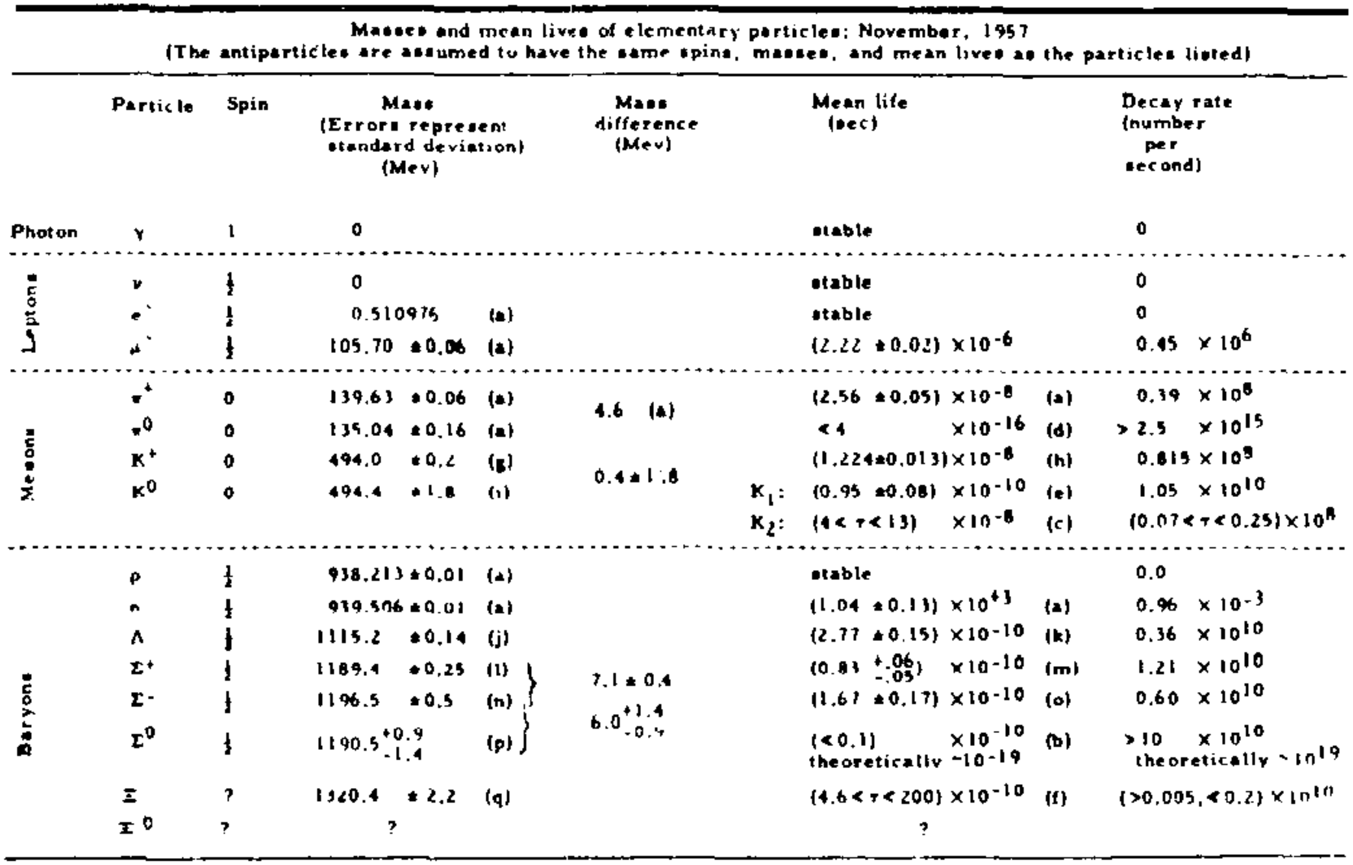
1 eV is the energy of an electron accelerated from rest through a potential difference of 1 volt. 1 e = $6.02\text{x}10^{-19}$ Coulombs. Normally used to describe energies of fundamental particles: A tennis ball might have a kinetic energy of 10^{19} eV... but so do some cosmic rays.

New Detectors: Bubble Chambers

The Berkeley 72 inch liquid hydrogen bubble chamber



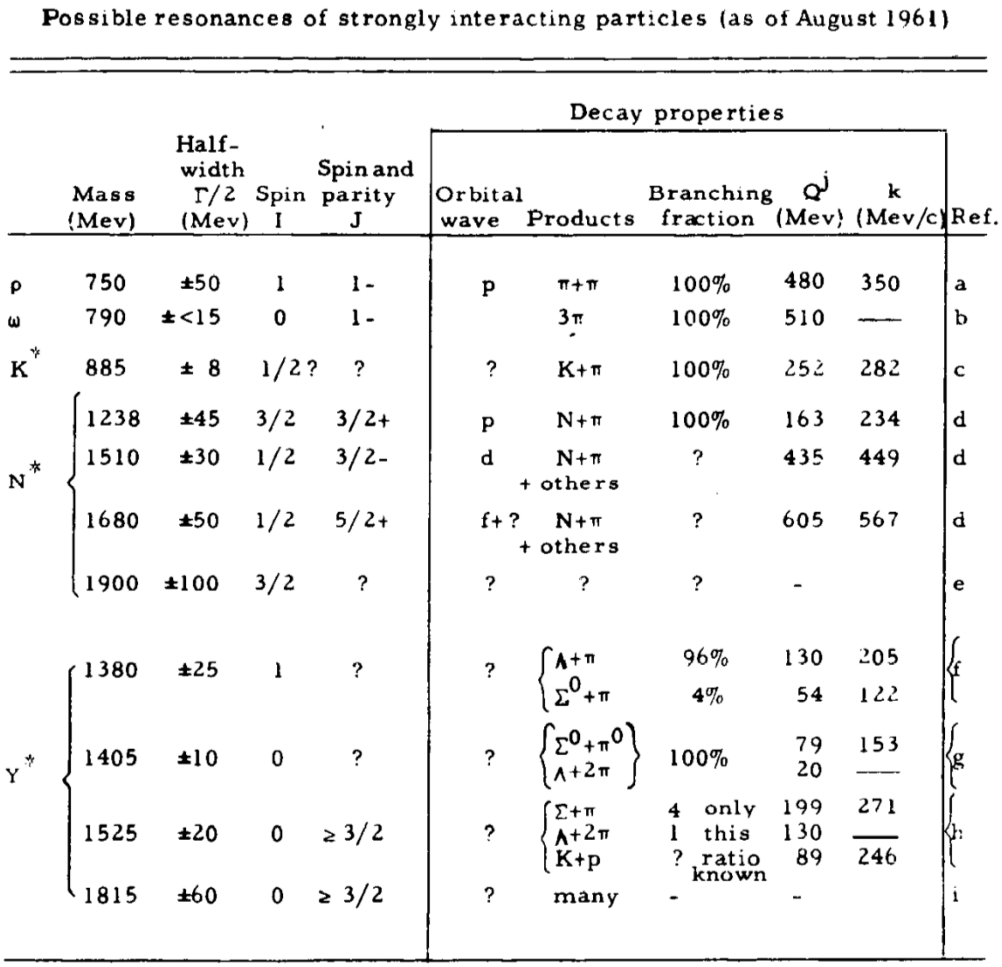
Known Particles in 1957



Masses and mean lives of elementary particles: November, 1957
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particles listed)

	Particle	Spin	Mass (Errors represent standard deviation) (Mev)	Mass difference (Mev)	Mean life (sec)	Decay rate (number per second)
Photon	γ	1	0		stable	0
Leptons	ν	$\frac{1}{2}$	0		stable	0
	e^-	$\frac{1}{2}$	0.510976 (a)		stable	0
	μ^-	$\frac{1}{2}$	105.70 ± 0.06 (a)		$(2.22 \pm 0.02) \times 10^{-6}$	0.45×10^{6}
Mesons	π^+	0	139.63 ± 0.06 (a)	4.6 (a)	$(2.56 \pm 0.05) \times 10^{-8}$ (a)	0.39×10^{8}
	π^0	0	135.04 ± 0.16 (a)		$< 4 \times 10^{-16}$ (d)	$> 2.5 \times 10^{15}$
	K^+	0	494.0 ± 0.2 (g)	0.4 ± 1.8	$(1.224 \pm 0.013) \times 10^{-8}$ (h)	0.815×10^{8}
	K^0	0	494.4 ± 1.8 (i)		K_1: $(0.95 \pm 0.08) \times 10^{-10}$ (e)	1.05×10^{10}
					K_2: $(4 < \tau < 13) \times 10^{-8}$ (c)	$(0.07 < \tau < 0.25) \times 10^{8}$
Baryons	p	$\frac{1}{2}$	938.213 ± 0.01 (a)		stable	0.0
	n	$\frac{1}{2}$	939.506 ± 0.01 (a)		$(1.04 \pm 0.13) \times 10^{+3}$ (a)	0.96×10^{-3}
	Λ	$\frac{1}{2}$	1115.2 ± 0.14 (j)		$(2.77 \pm 0.15) \times 10^{-10}$ (k)	0.36×10^{10}
	Σ^+	$\frac{1}{2}$	1189.4 ± 0.25 (l)	7.1 ± 0.4	$(0.83\, ^{+.06}_{-.05}) \times 10^{-10}$ (m)	1.21×10^{10}
	Σ^-	$\frac{1}{2}$	1196.5 ± 0.5 (n)	$6.0^{+1.4}_{-0.9}$	$(1.67 \pm 0.17) \times 10^{-10}$ (o)	0.60×10^{10}
	Σ^0	$\frac{1}{2}$	$1190.5^{+0.9}_{-1.4}$ (p)		$(< 0.1) \times 10^{-10}$ (b) theoretically $\sim 10^{-19}$	$> 10 \times 10^{10}$ theoretically $\sim 10^{19}$
	Ξ	?	1320.4 ± 2.2 (q)		$(4.6 < \tau < 200) \times 10^{-10}$ (f)	$(> 0.005, < 0.2) \times 10^{10}$
	Ξ^0	?	?		?	

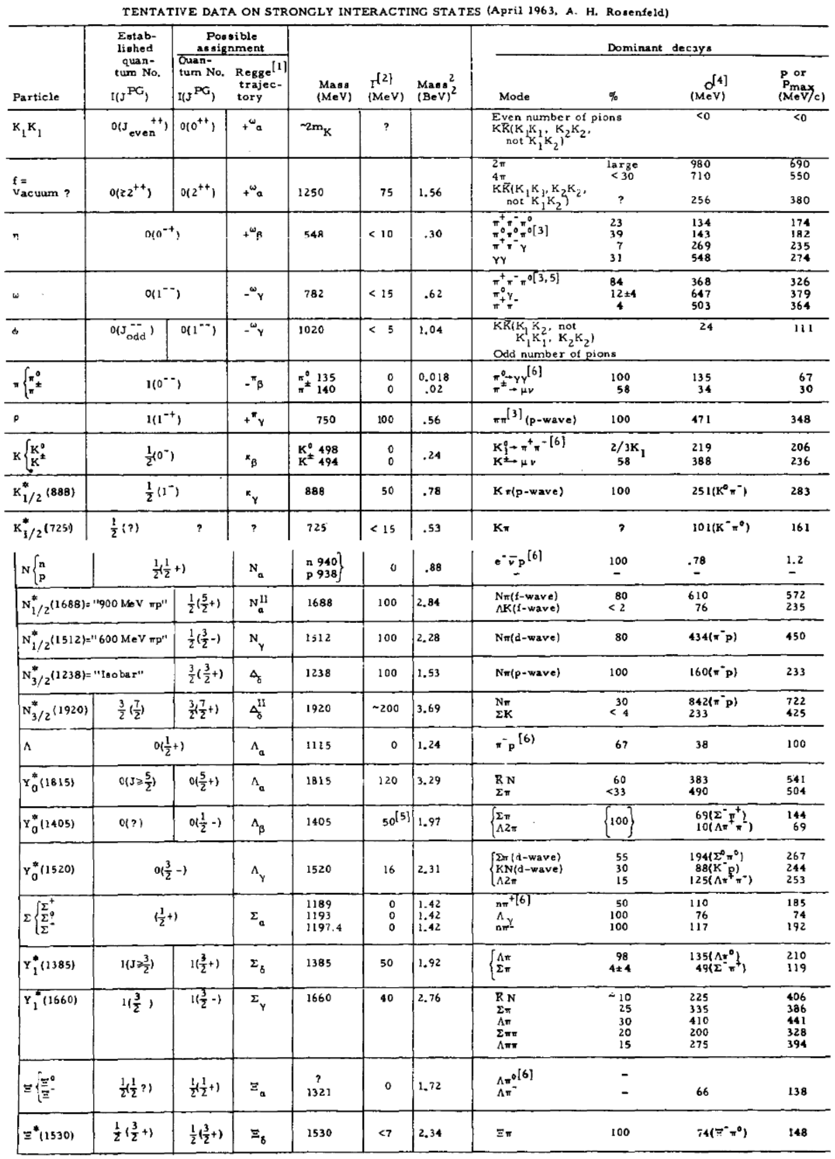
Strongly Interacting Particles: 1961



Possible resonances of strongly interacting particles (as of August 1961)

	Mass (Mev)	Half-width $\Gamma/2$ (Mev)	Spin I	Spin and parity J	Decay properties					Ref.
					Orbital wave	Products	Branching fraction	Q^j (Mev)	k (Mev/c)	
ρ	750	±50	1	1-	p	$\pi+\pi$	100%	480	350	a
ω	790	±<15	0	1-		3π	100%	510	——	b
K^*	885	± 8	1/2?	?	?	$K+\pi$	100%	252	282	c
N^*	1238	±45	3/2	3/2+	p	$N+\pi$	100%	163	234	d
	1510	±30	1/2	3/2-	d	$N+\pi$ + others	?	435	449	d
	1680	±50	1/2	5/2+	f+?	$N+\pi$ + others	?	605	567	d
	1900	±100	3/2	?	?	?	?	-		e
Y^*	1380	±25	1	?	?	$\Lambda+\pi$ $\Sigma^0+\pi$	96% 4%	130 54	205 122	f
	1405	±10	0	?	?	$\Sigma^0+\pi^0$ $\Lambda+2\pi$	100%	79 20	153 ——	g
	1525	±20	0	≥ 3/2	?	$\Sigma+\pi$ $\Lambda+2\pi$ $K+p$	4 only 1 this ? ratio known	199 130 89	271 —— 246	h
	1815	±60	0	≥ 3/2	?	many	-	-		i

Strongly Interacting Particles: 1963



TENTATIVE DATA ON STRONGLY INTERACTING STATES (April 1963, A. H. Rosenfeld)

Particle	Established quantum No. $I(J^{PG})$	Possible assignment: Quantum No. $I(J^{PG})$	Possible assignment: Regge trajectory[1]	Mass (MeV)	Γ[2] (MeV)	Mass^2 (BeV)^2	Dominant decays: Mode	%	Q[4] (MeV)	p or p_{max} (MeV/c)
K_1K_1	$0(J_{even}^{++})$	$0(0^{++})$	$+^{\omega}\alpha$	$\sim 2m_K$	?		Even number of pions $K\bar{K}(K_1K_1, K_2K_2,$ not $K_1K_2)$		<0	<0
f = Vacuum ?	$0(\geq 2^{++})$	$0(2^{++})$	$+^{\omega}\alpha$	1250	75	1.56	2π 4π $K\bar{K}(K_1K_1, K_2K_2,$ not $K_1K_2)$	large < 30 ?	980 710 256	690 550 380
η	$0(0^{-+})$		$+^{\omega}\beta$	548	< 10	.30	$\pi^+\pi^-\pi^0$ $\pi^0\pi^0\pi^0$[3] $\pi^+\pi^-\gamma$ $\gamma\gamma$	23 39 7 31	134 143 269 548	174 182 235 274
ω	$0(1^{--})$		$-^{\omega}\gamma$	782	< 15	.62	$\pi^+\pi^-\pi^0$[3,5] $\pi^0\gamma$ $\pi^+\pi^-$	84 12±4 4	368 647 503	326 379 364
ϕ	$0(J_{odd}^{--})$	$0(1^{--})$	$-^{\omega}\gamma$	1020	< 5	1.04	$K\bar{K}(K_1K_2,$ not $K_1K_1, K_2K_2)$ Odd number of pions		24	111
$\pi\begin{cases}\pi^0\\ \pi^\pm\end{cases}$	$1(0^{--})$		$-^{\pi}\beta$	π^0 135 $\pi^\pm$ 140	0 0	0.018 .02	$\pi^0\to\gamma\gamma$[6] $\pi^\pm\to\mu\nu$	100 58	135 34	67 30
ρ	$1(1^{-+})$		$+^{\pi}\gamma$	750	100	.56	$\pi\pi$[3] (p-wave)	100	471	348
$K\begin{cases}K^0\\ K^\pm\end{cases}$	$\frac{1}{2}(0^-)$		κ_β	K^0 498 $K^\pm$ 494	0 0	.24	$K_1^0\to\pi^+\pi^-$[6] $K^\pm\to\mu\nu$	2/3K_1 58	219 388	206 236
$K^*_{1/2}$ (888)	$\frac{1}{2}(1^-)$		κ_γ	888	50	.78	$K\pi$(p-wave)	100	251($K^0\pi^-$)	283
$K^*_{1/2}$(725)	$\frac{1}{2}(?)$	?	?	725	< 15	.53	$K\pi$	?	101($K^-\pi^0$)	161
$N\begin{cases}n\\ p\end{cases}$	$\frac{1}{2}(\frac{1}{2}+)$		N_α	n 940 p 938	0	.88	$e^-\bar{\nu}p$[6] –	100 –	.78 –	1.2 –
$N^*_{1/2}$(1688)="900 MeV πp"		$\frac{1}{2}(\frac{5}{2}+)$	N_α^{II}	1688	100	2.84	$N\pi$(f-wave) ΛK(f-wave)	80 < 2	610 76	572 235
$N^*_{1/2}$(1512)="600 MeV πp"		$\frac{1}{2}(\frac{3}{2}-)$	N_γ	1512	100	2.28	$N\pi$(d-wave)	80	434(π^-p)	450
$N^*_{3/2}$(1238)="Isobar"		$\frac{3}{2}(\frac{3}{2}+)$	Δ_δ	1238	100	1.53	$N\pi$(p-wave)	100	160(π^-p)	233
$N^*_{3/2}$(1920)	$\frac{3}{2}(\frac{7}{2})$	$\frac{3}{2}(\frac{7}{2}+)$	Δ_δ^{II}	1920	~200	3.69	$N\pi$ ΣK	30 < 4	842(π^-p) 233	722 425
Λ	$0(\frac{1}{2}+)$		Λ_α	1115	0	1.24	π^-p[6]	67	38	100
Y_0^*(1815)	$0(J\geq\frac{5}{2})$	$0(\frac{5}{2}+)$	Λ_α	1815	120	3.29	$\bar{K}N$ $\Sigma\pi$	60 <33	383 490	541 504
Y_0^*(1405)	0(?)	$0(\frac{1}{2}-)$	Λ_β	1405	50[5]	1.97	$\Sigma\pi$ $\Lambda 2\pi$	100	69($\Sigma^-\pi^+$) 10($\Lambda\pi^+\pi^-$)	144 69
Y_0^*(1520)	$0(\frac{3}{2}-)$		Λ_γ	1520	16	2.31	$\Sigma\pi$(d-wave) KN(d-wave) $\Lambda 2\pi$	55 30 15	194($\Sigma^0\pi^0$) 88(K^-p) 125($\Lambda\pi^+\pi^-$)	267 244 253
$\Sigma\begin{cases}\Sigma^+\\ \Sigma^0\\ \Sigma^-\end{cases}$	$(\frac{1}{2}+)$		Σ_α	1189 1193 1197.4	0 0 0	1.42 1.42 1.42	$n\pi^+$[6] $\Lambda\gamma$ $n\pi^-$	50 100 100	110 76 117	185 74 192
Y_1^*(1385)	$1(J\geq\frac{3}{2})$	$1(\frac{3}{2}+)$	Σ_δ	1385	50	1.92	$\Lambda\pi$ $\Sigma\pi$	98 4±4	135($\Lambda\pi^0$) 49($\Sigma^-\pi^+$)	210 119
Y_1^*(1660)	$1(\frac{3}{2})$	$1(\frac{3}{2}-)$	Σ_γ	1660	40	2.76	$\bar{K}N$ $\Sigma\pi$ $\Lambda\pi$ $\Sigma\pi\pi$ $\Lambda\pi\pi$	~10 25 30 20 15	225 335 410 200 275	406 386 441 328 394
$\Xi\begin{cases}\Xi^0\\ \Xi^-\end{cases}$	$\frac{1}{2}(\frac{1}{2}?)$	$\frac{1}{2}(\frac{1}{2}+)$	Ξ_α	? 1321	0	1.72	$\Lambda\pi^0$[6] $\Lambda\pi^-$	– –	 66	 138
Ξ^*(1530)	$\frac{1}{2}(\frac{3}{2}+)$	$\frac{1}{2}(\frac{3}{2}+)$	Ξ_δ	1530	<7	2.34	$\Xi\pi$	100	74($\Xi^-\pi^0$)	148

Fundamental Particles of Matter

$$\begin{array}{c} Q=+2/3 \\ Q=-1/3 \end{array} \qquad \left.\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}\right\} \text{Quarks}$$

$$\begin{array}{c} Q=0 \\ Q=-1 \end{array} \qquad \left.\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}\right\} \text{Leptons}$$

- Hadrons are made of quarks:
  - Baryons are (qqq): $p=(uud)$, $n=(udd)$, $\Lambda^0=(uds)$
  - Mesons are $(q\overline{q})$: $\pi^+=(u\overline{d})$, $\pi^-=(d\overline{u})$, $K^+=(u\overline{s})$
- Grouped into three families with increasing mass... Why? We still have no idea!

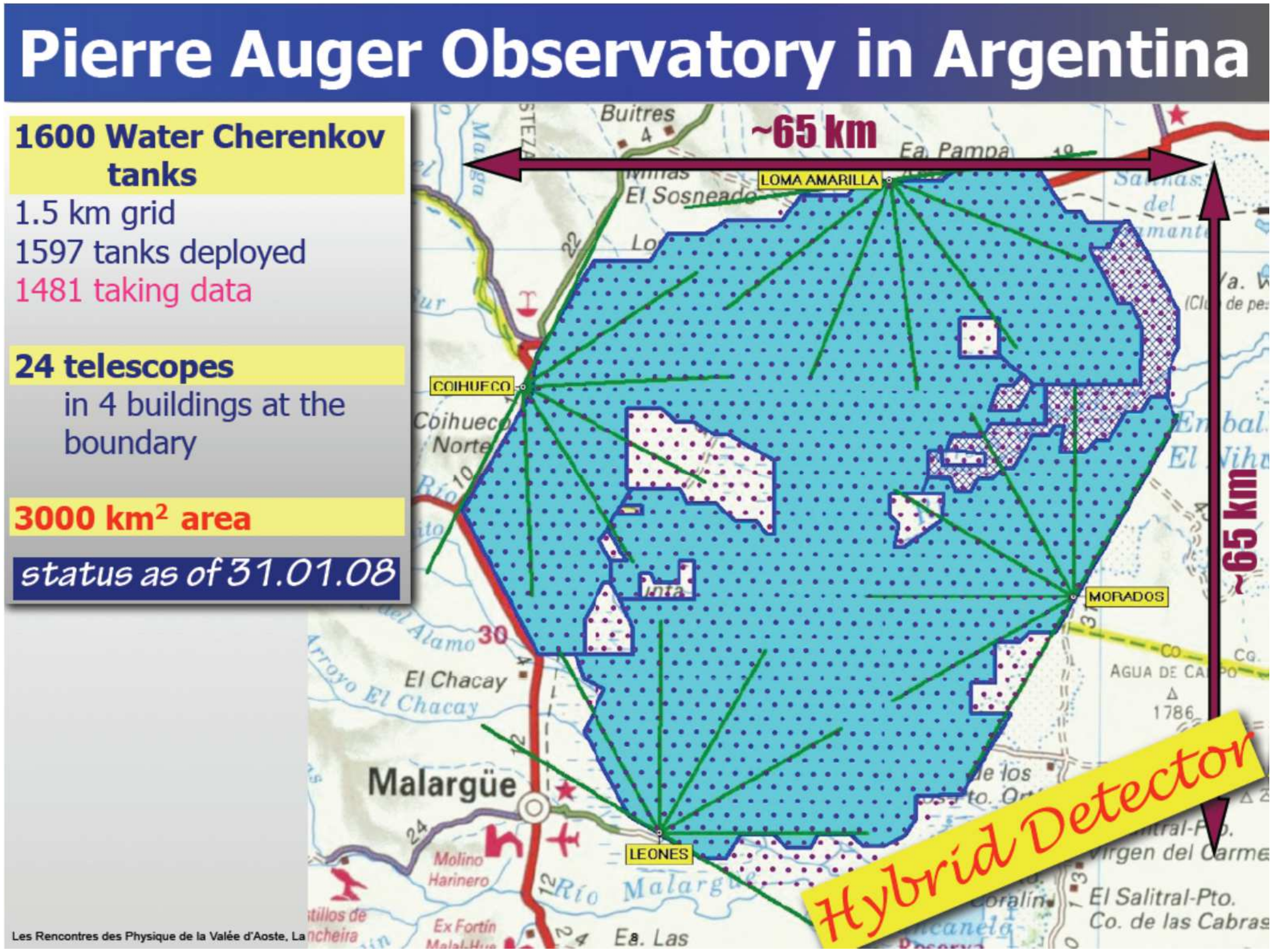
Back to Cosmic Rays

- In 1938, Pierre Auger was studying cosmic rays in the Alps.
- He observed that two detectors located many meters apart detected particles at exactly the same time.
- Discovery of Extensive Air Showers:
  - secondary particles produced in the collision of a high energy primary particle with air
  - he estimated the energies of some of the primary particles to be 10^{15} eV
- Rossi (USA) and Zatsepin (Russia) constructed arrays of detectors to study air showers.

The State of the Art

Detect Cherenkov light when a muon passes through a tank of water

The State of the Art



Pierre Auger Observatory in Argentina

1600 Water Cherenkov tanks

1.5 km grid

1597 tanks deployed

1481 taking data

24 telescopes

in 4 buildings at the boundary

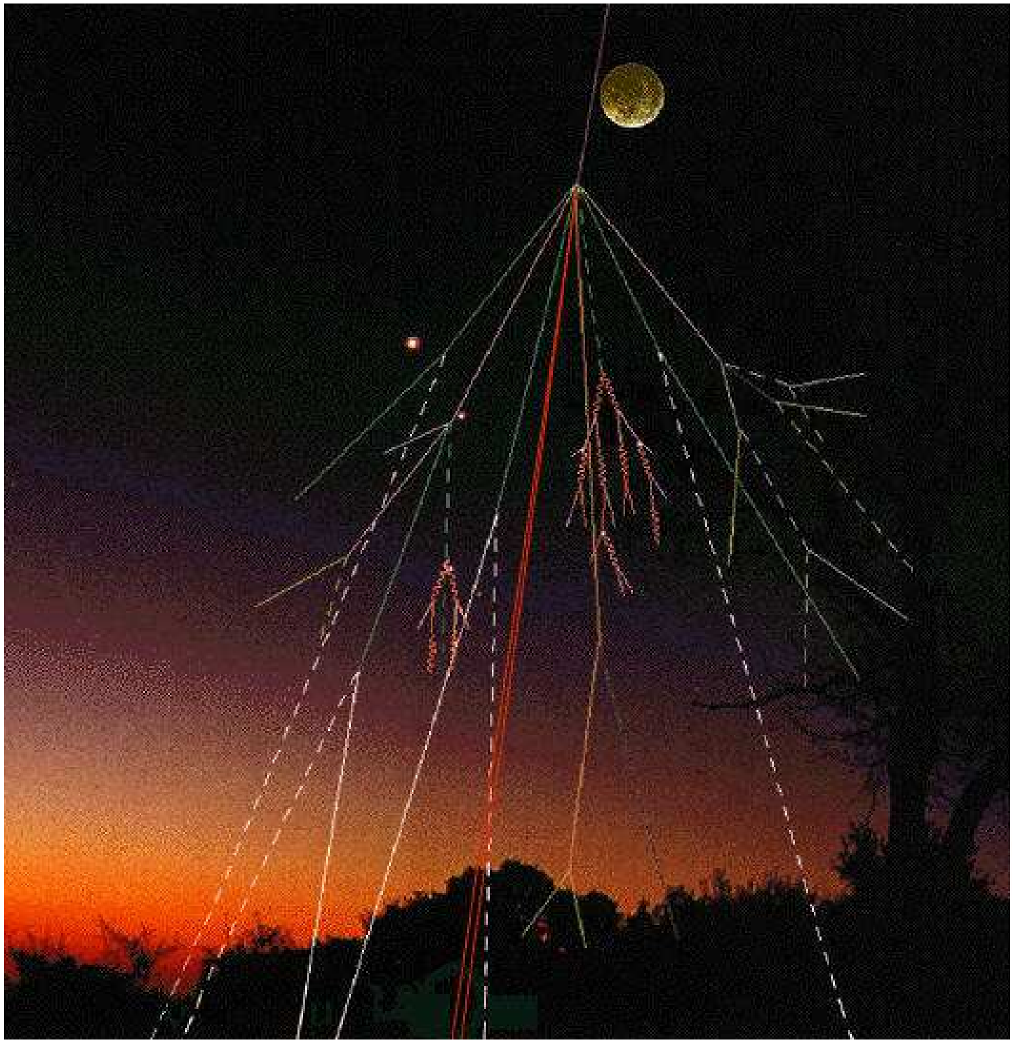
3000 km^2 area

status as of 31.01.08

Les Rencontres des Physique de la Valée d'Aoste, La

Air Showers

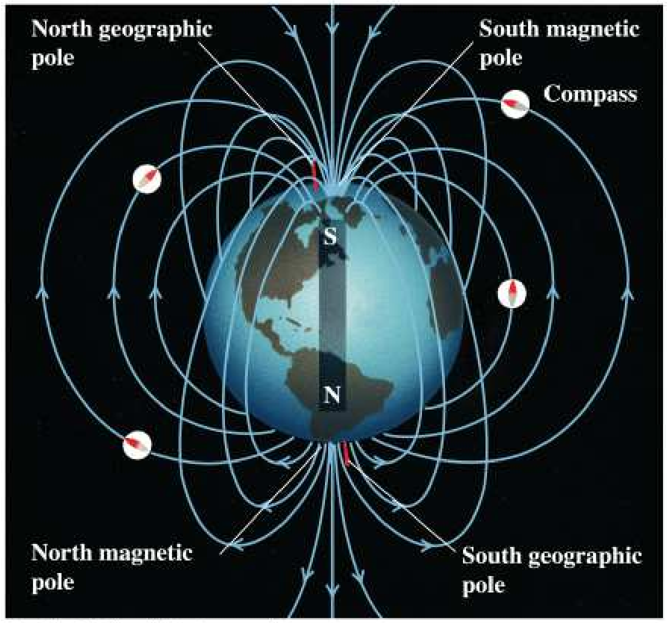
- Primary particles are mostly protons
- They interact with nuclei of atoms in the upper atmosphere producing showers of pions
- Neutral pions decay immediately to photons, photons produce e^+e^- pairs
- Pions also interact with nuclei, but also decay to muons
- Muons do not interact with nuclei:
  - They lose energy as the ionize air
  - but many reach sea level

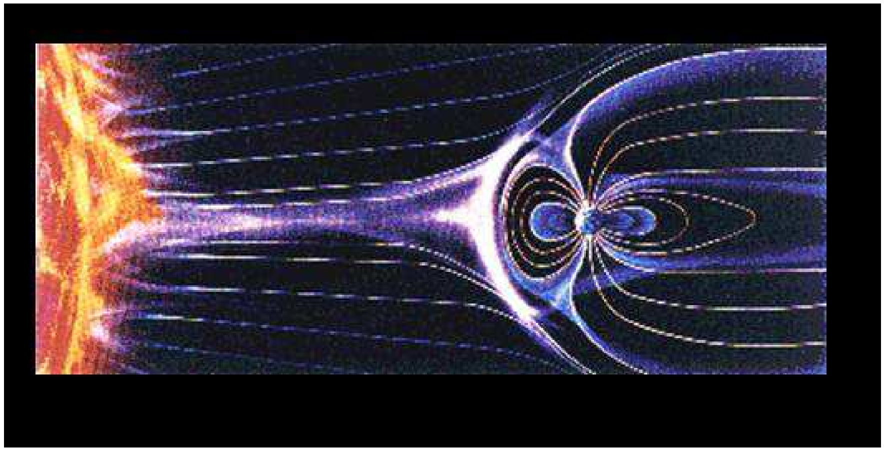


Properties of Primary Particles

- Primary composition:
  - 90% protons
  - 9% helium nuclei
  - 1% electrons

  (depends on energy)
- Charged particles deflected by magnetic fields
  - Near the earth's magnetic field
  - In the galaxy's magnetic field
  - In the magnetic fields between galaxies
- Local magnetic field caused by earth's dipole (latitude effect) and by the solar wind (day/night effect)
- When cosmic rays arrive, they generally don't point back to their source.

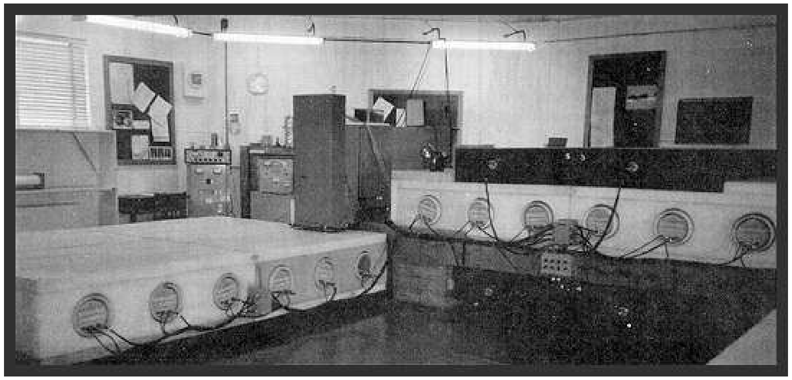




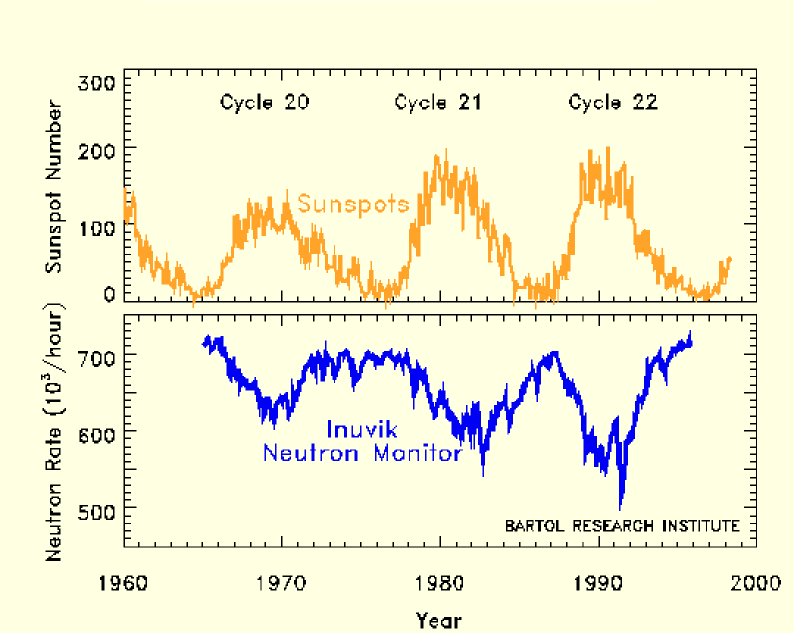
Do they come from the sun?

- The "solar wind" consists of hot particles with enough kinetic energy to escape the sun's gravity: $$v = \sqrt{\frac{2GM}{r}}$$ (618 km/s)

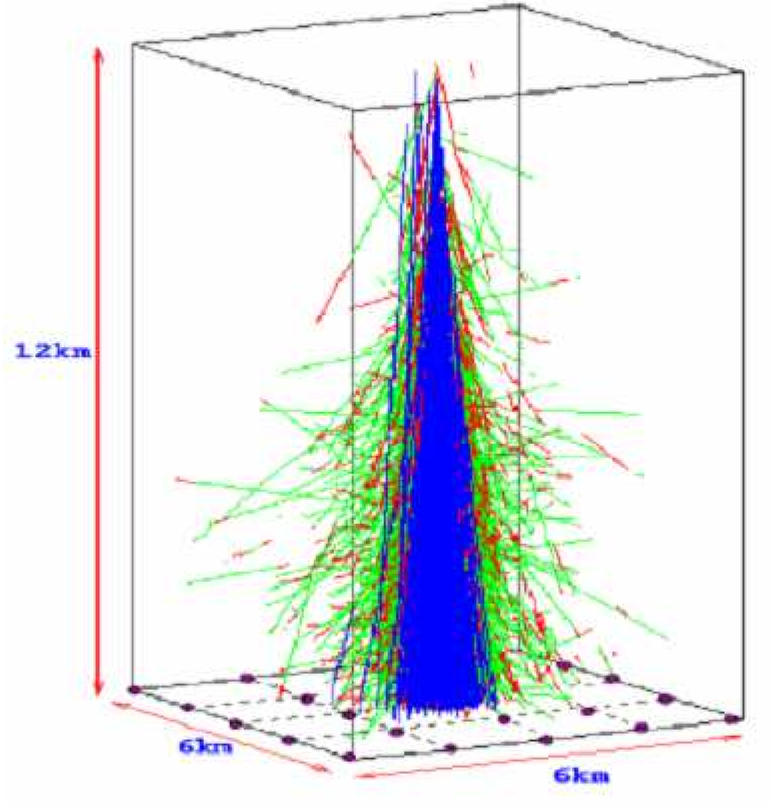
- Most have energies less than a few GeV
- *These don't produce extensive air showers!*
- Do produce neutrons...



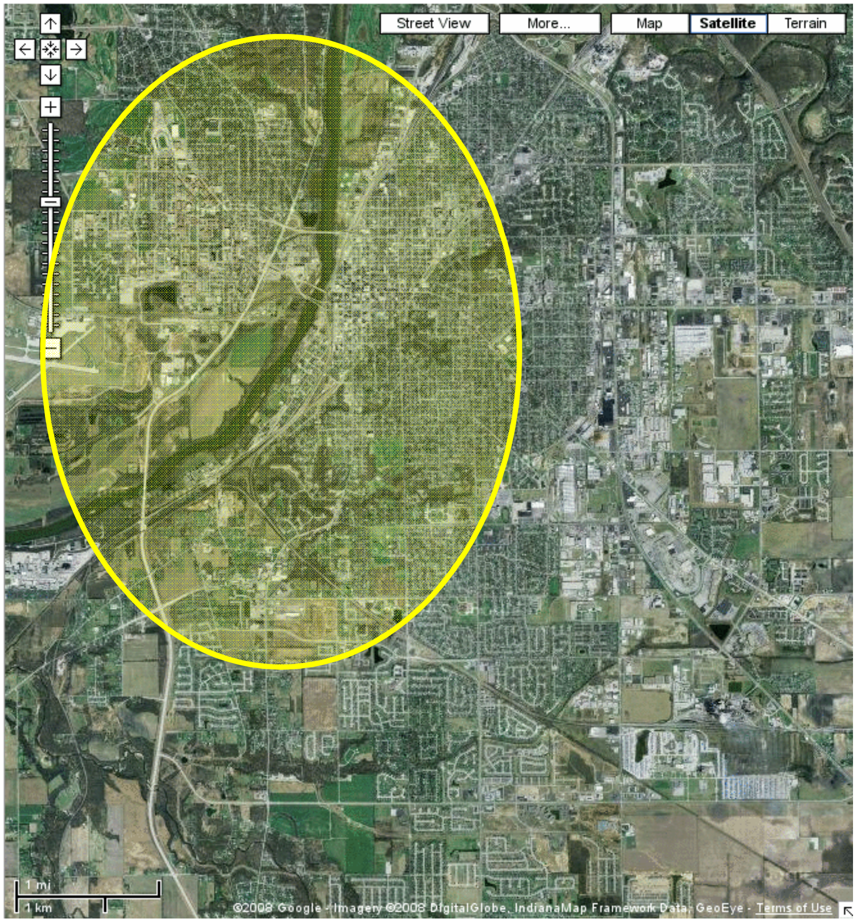
$$n + B \rightarrow Li + He$$



How big is the “footprint”?



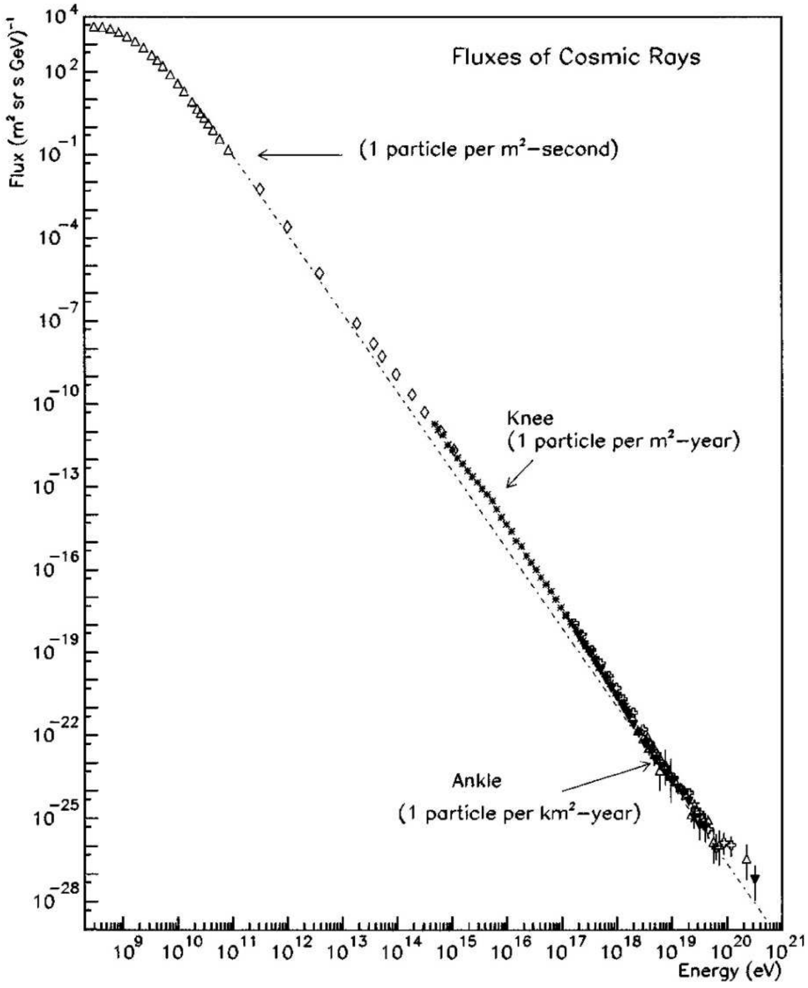
Typically a few km across, but not 10’s of km.



This is about the size of Lafayette...

Energy Spectrum

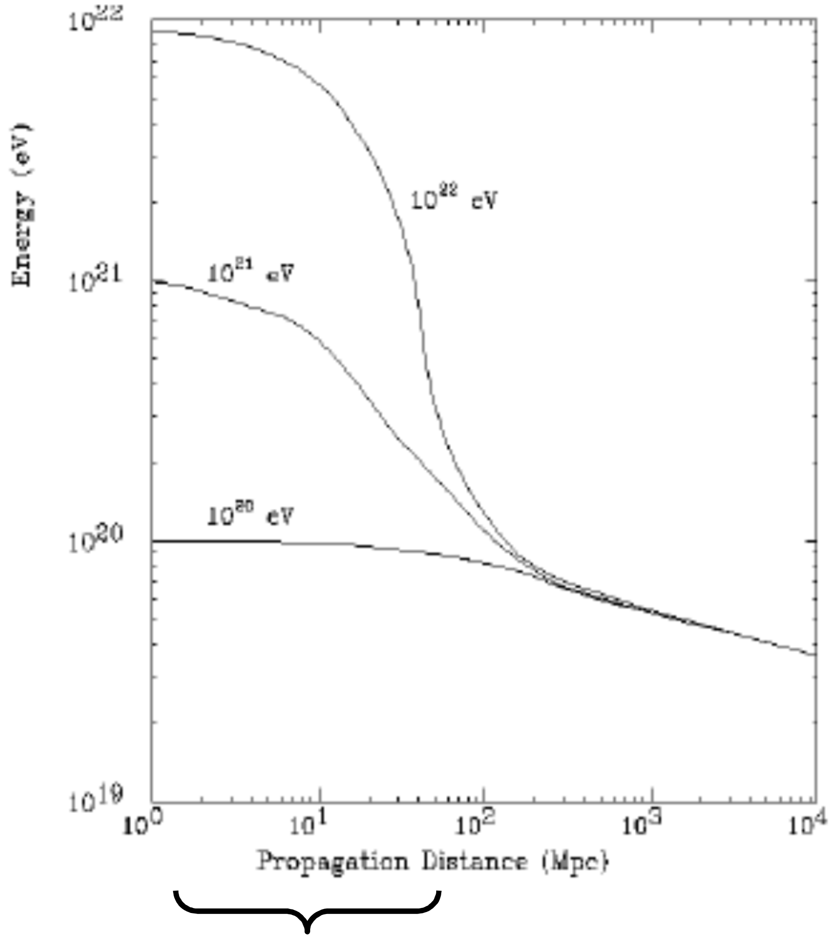
- Lots are low energy
- Some are high energy
  - Possibly accelerated in magnetic fields around stars
- Very few are ultra high energy
  - about 1 per square km per century with energy > 10^{20} eV
  - Probably come from within our own galaxy...



Greisen-Zatsepin-Kuzmin cutoff

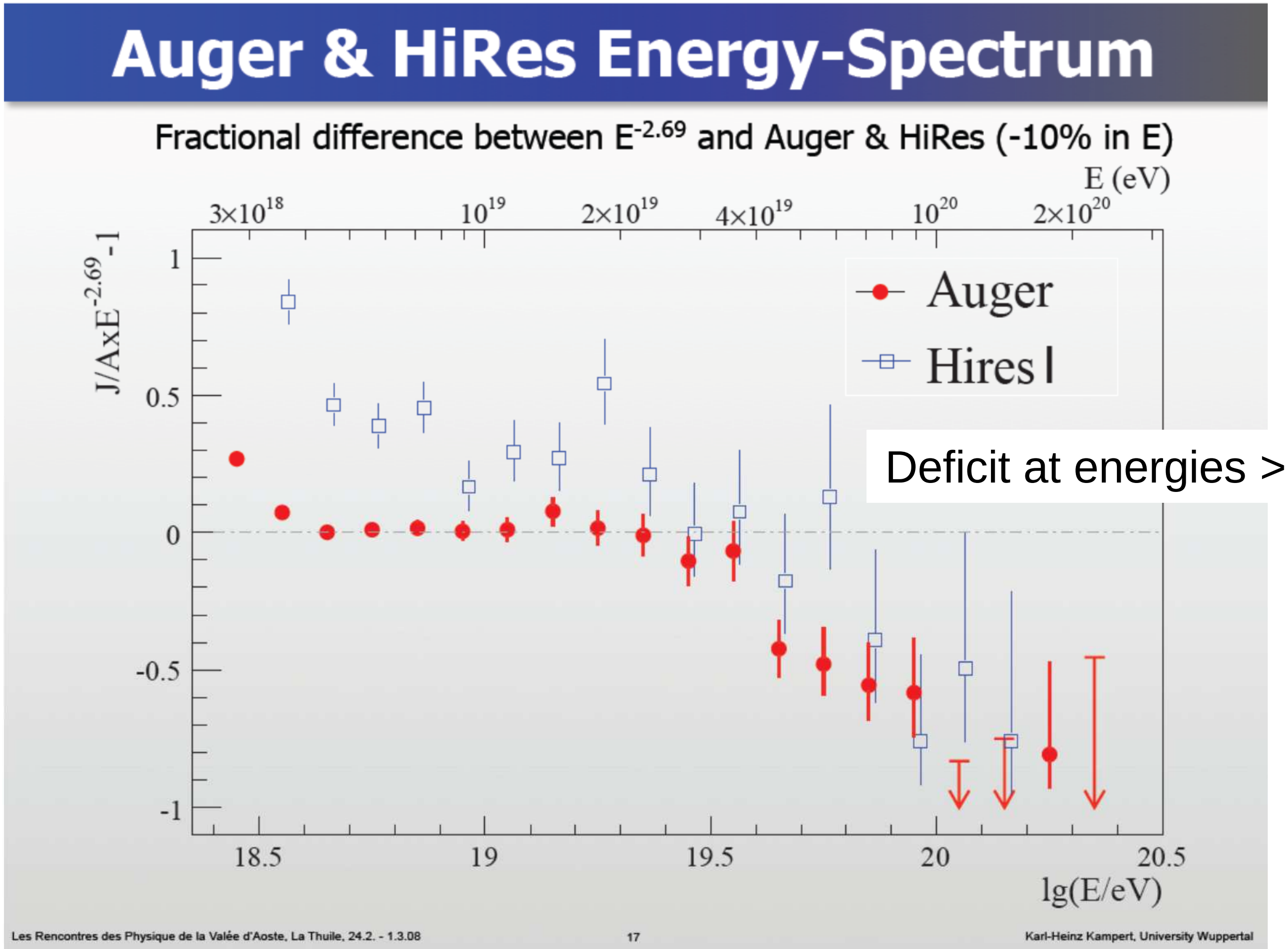
- High energy photons can break apart protons:

  $\gamma + p \rightarrow N + \text{pions}$
- Equivalently, at very high energies, a proton can “collide” with a low energy photon
- The universe is full of low energy photons
  - the cosmic microwave background radiation
- Very high energy protons can’t travel too far without interacting with the CMB photons



Typical sizes of galactic clusters

Recent Experiments think they see this...



Auger & HiRes Energy-Spectrum

Fractional difference between $E^{-2.69}$ and Auger & HiRes (-10% in E)

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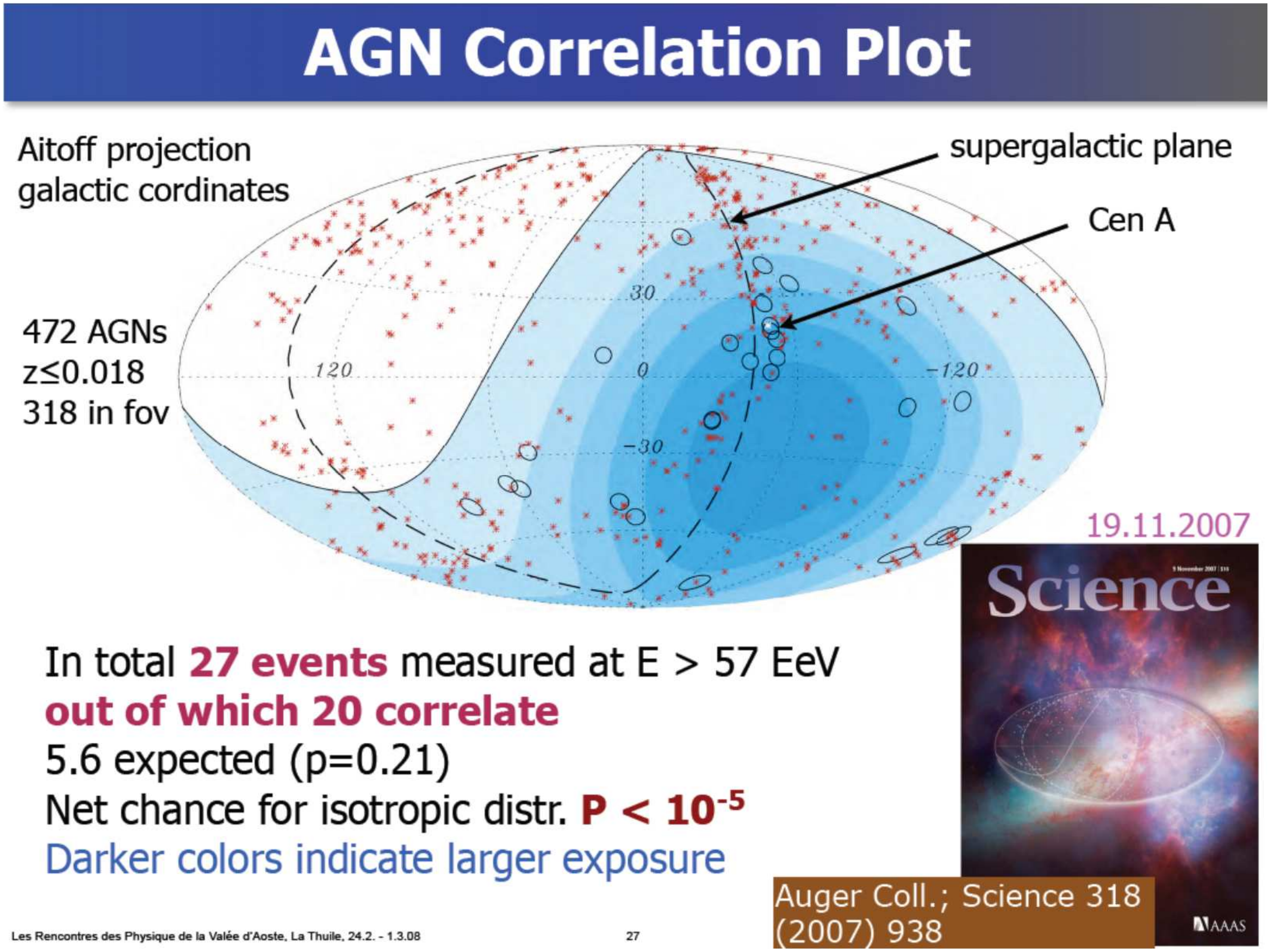
Karl-Heinz Kampert, University Wuppertal

Deficit at energies > 10^{19} eV



AGN Correlation Plot

Aitoff projection
galactic cordinates

472 AGNs
z≤0.018
318 in fov

supergalactic plane

Cen A

19.11.2007

In total **27 events** measured at E > 57 EeV
out of which 20 correlate
5.6 expected (p=0.21)
Net chance for isotropic distr. **$P < 10^{-5}$**
Darker colors indicate larger exposure

Auger Coll.; Science 318 (2007) 938

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Point Sources?

Connection with Lightning?

- The electric fields in clouds is not strong enough to ionize the air
- Something else must trigger lightning
- An extensive air shower *could* produce enough ionization to start the runaway breakdown resulting in lightning
- But this hasn't been conclusively demonstrated...

➔ See Scientific American article, Januray 2008.

Summary

- Who would have thought that leaky electrometers would lead here?
- Led to the birth of accelerator based particle physics
- Still a very active topic of research today
- The Fermilab cosmic ray detector can emulate many of these studies.