Neutrino Oscillations and Astroparticle Physics (1)

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① Introduction to Astroparticle Physics
Neutrinos
- Number
- Dirac and Majorana Neutrinos
- Mass Measurements
- Double Beta Decay
- Mixing

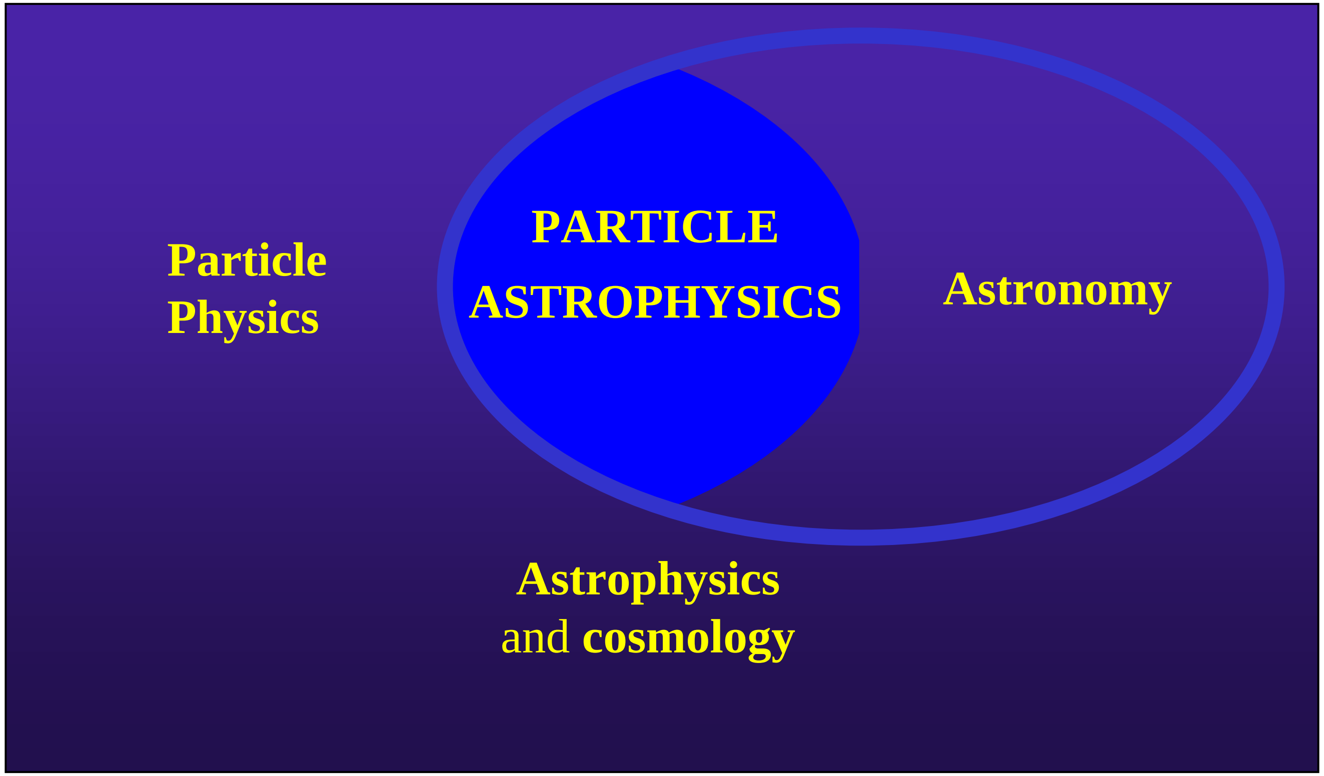
k Neutrino Oscillations

l Cosmology

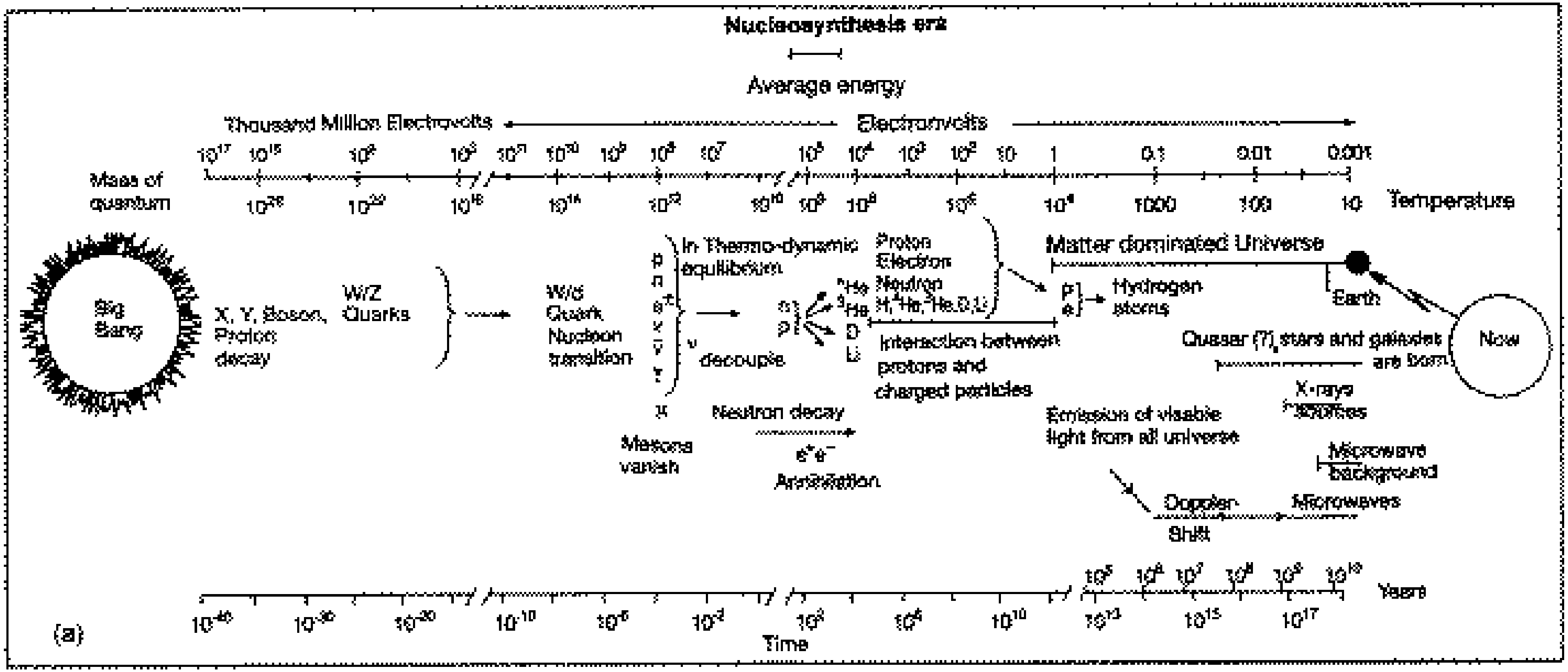
m Dark Matter

n High Energy Astronomy

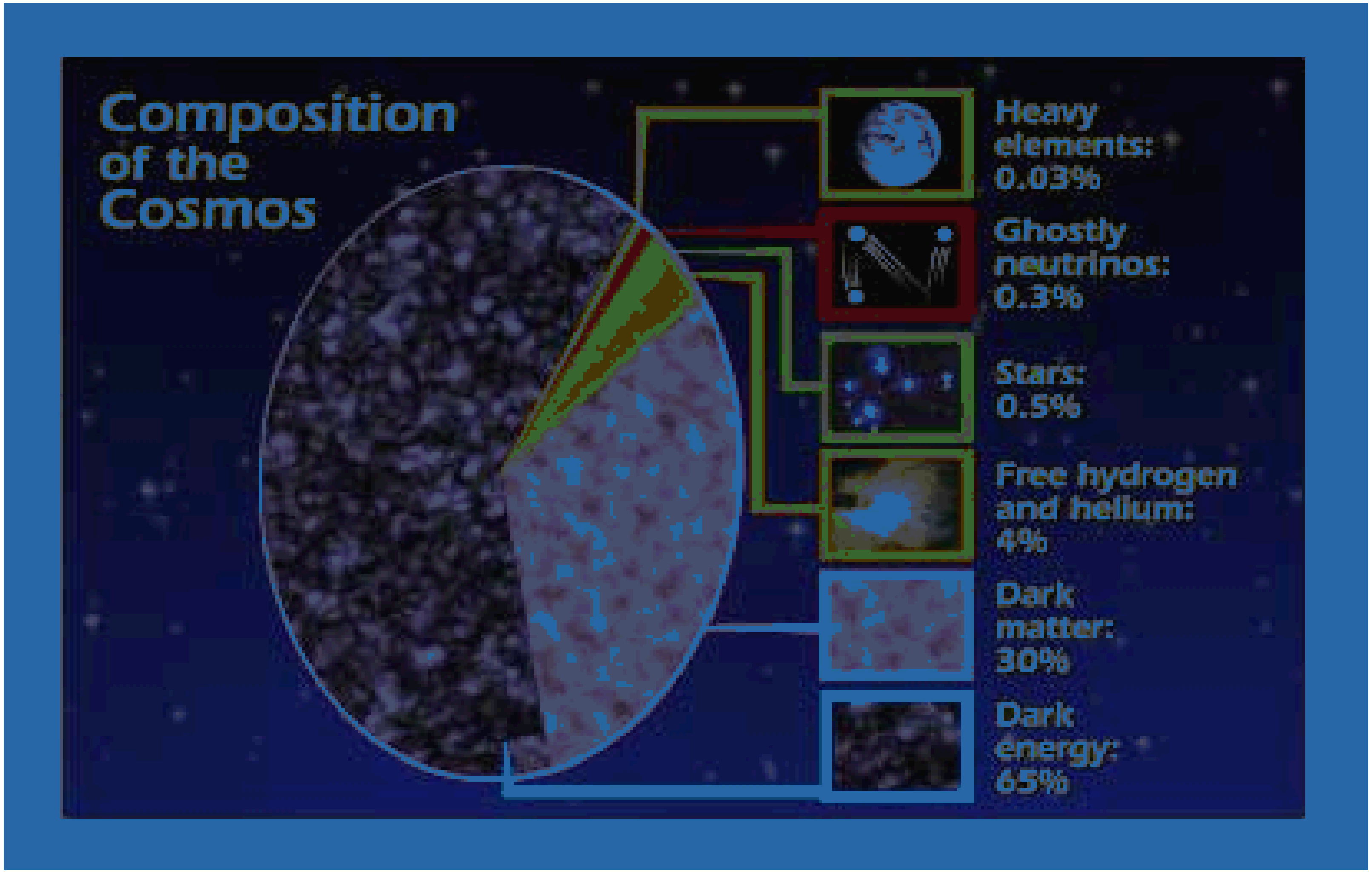
What is Astroparticle physics ?

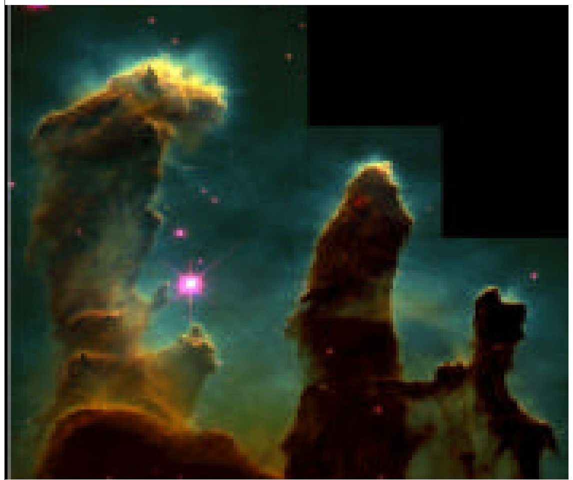


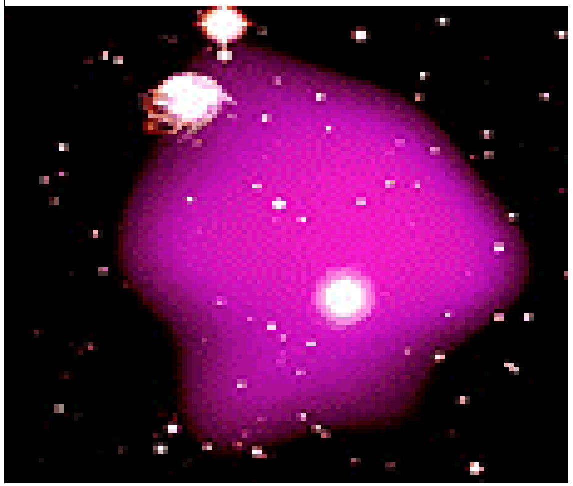
Story of the Universe



Make-up of Universe







Dark Matter

Evidence :

Need to hold together Galaxy Clusters

Explain Galaxy Rotation velocities

Astronomy object candidates :

Brown Dwarfs (stars mass <0.1 M_{sun} no fusion)

- some but not enough

White Dwarfs (final states of small stars)

- some but not enough

Neutron Stars/Black Holes (final states of big stars.)

- expected to be rarer than white dwarfs

Gas clouds

- 75% visible matter in the universe, but observable

Particle Physics candidates:

Neutrinos

- Evidence for mass from oscillation, not enough for all

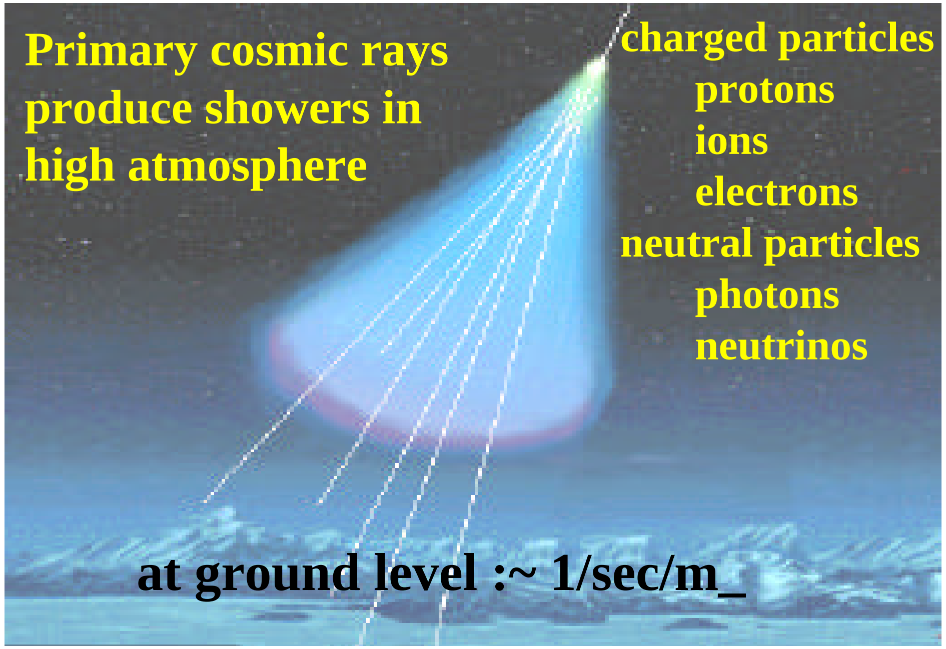
Axions

- Difficult to detect ….

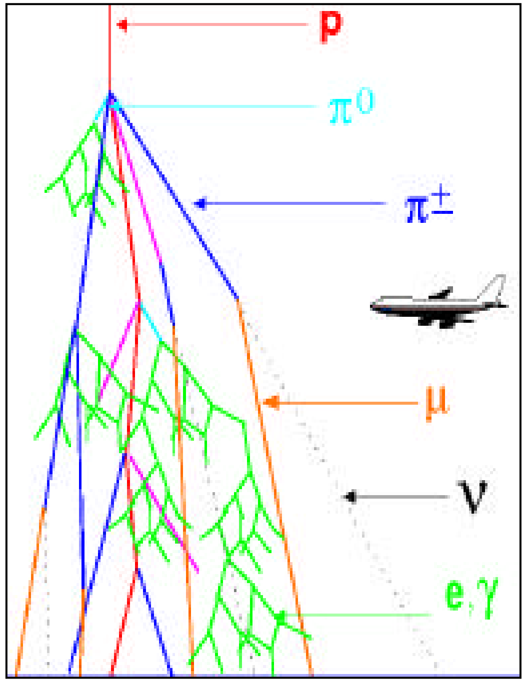
Neutralinos

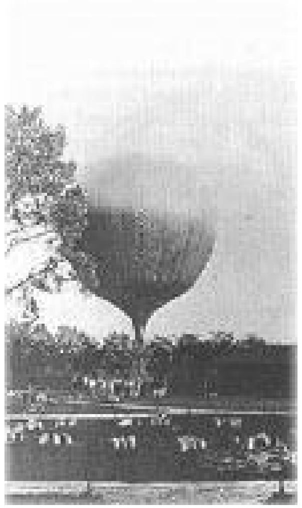
- Particle Physicist Favourite !

Cosmic Rays



Primary:
p 80 %, α 9 %, n 8 %
e 2 %, heavy nuclei 1 %
γ 0.1 %, ν 0.1 % ?





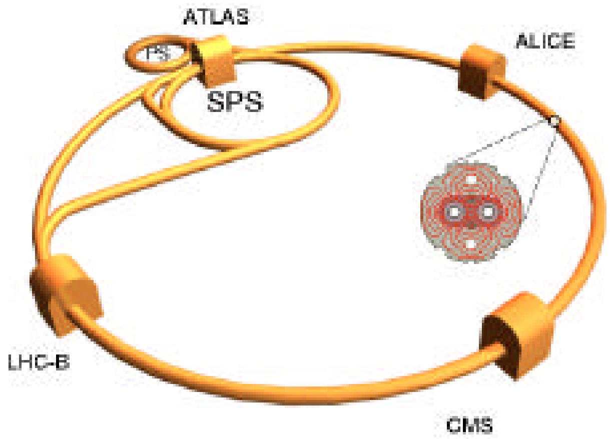
100 years after discovery by Hess origin still uncertain

Secondary at ground level:
ν 68 %
μ 30 %
p, n, ... 2 %

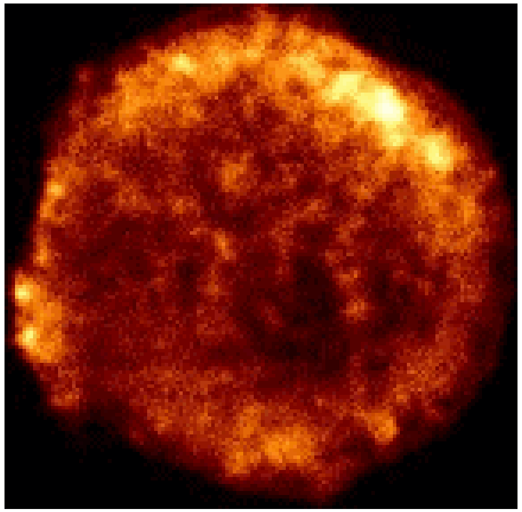
Particle Acceleration

E ∝ BR

Large Hadron Collider



Tycho SuperNova Remnant

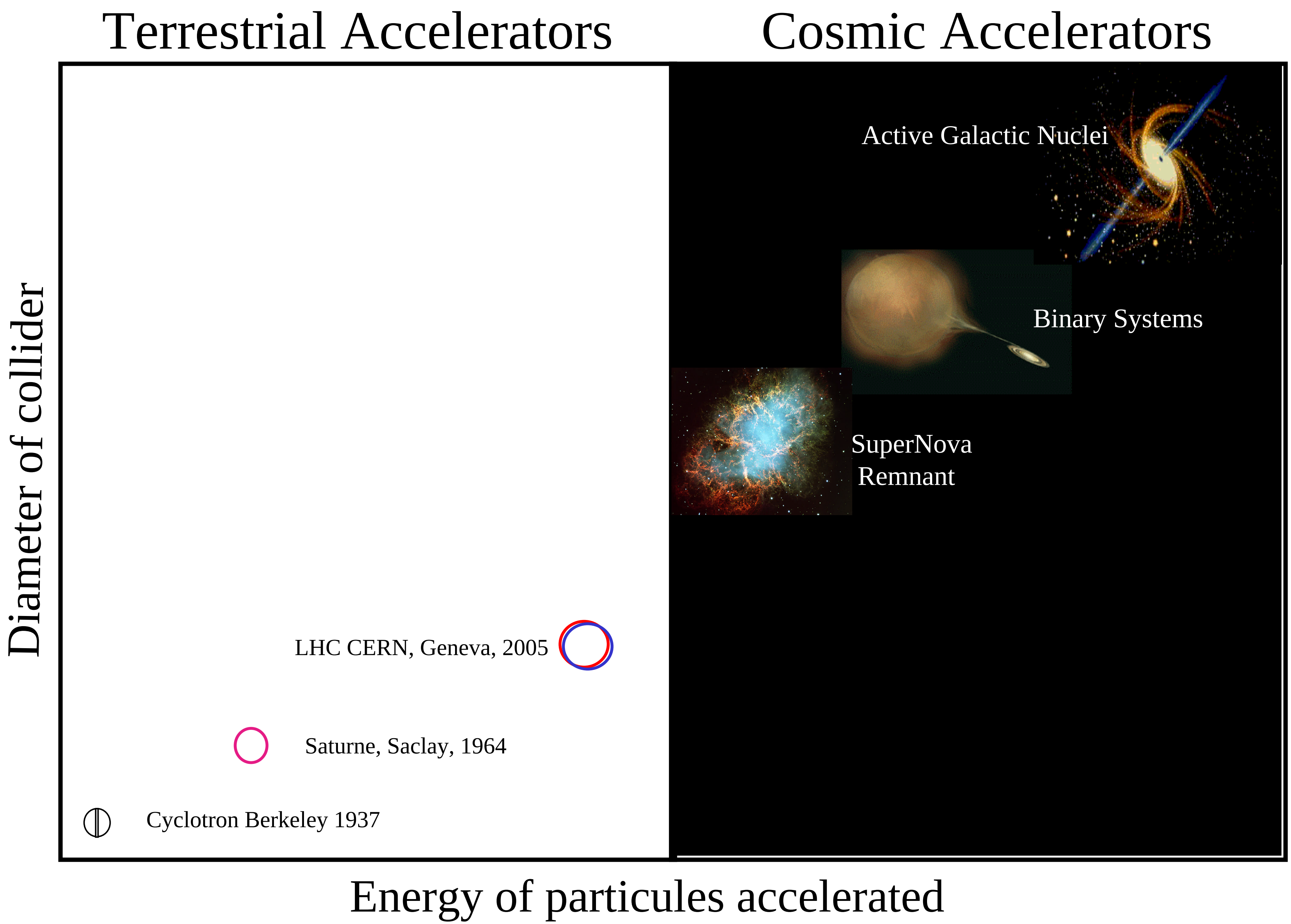


R 10 km, B 10 T E 10 TeV

R 10^{15}km, B 10^{-10}T E 1000 TeV

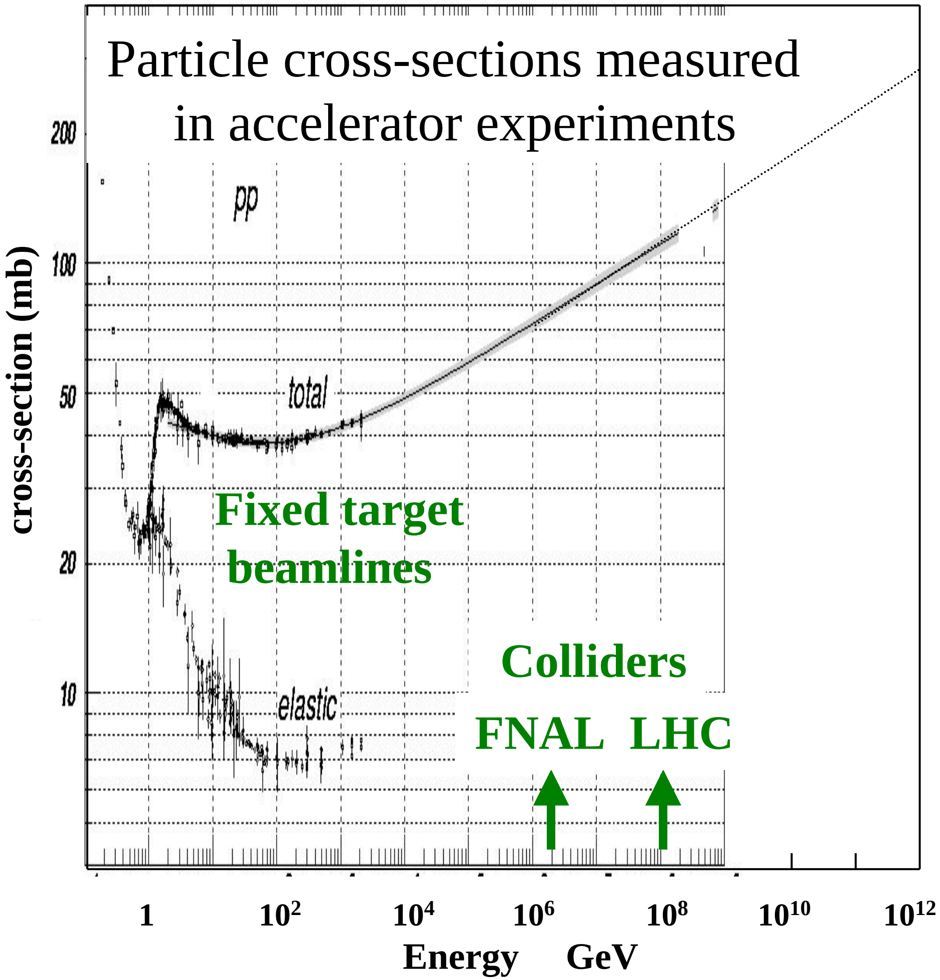
(NB. E Z → Pb/Fe higher energy)

Particle Physics ⇒ Particle Astrophysics

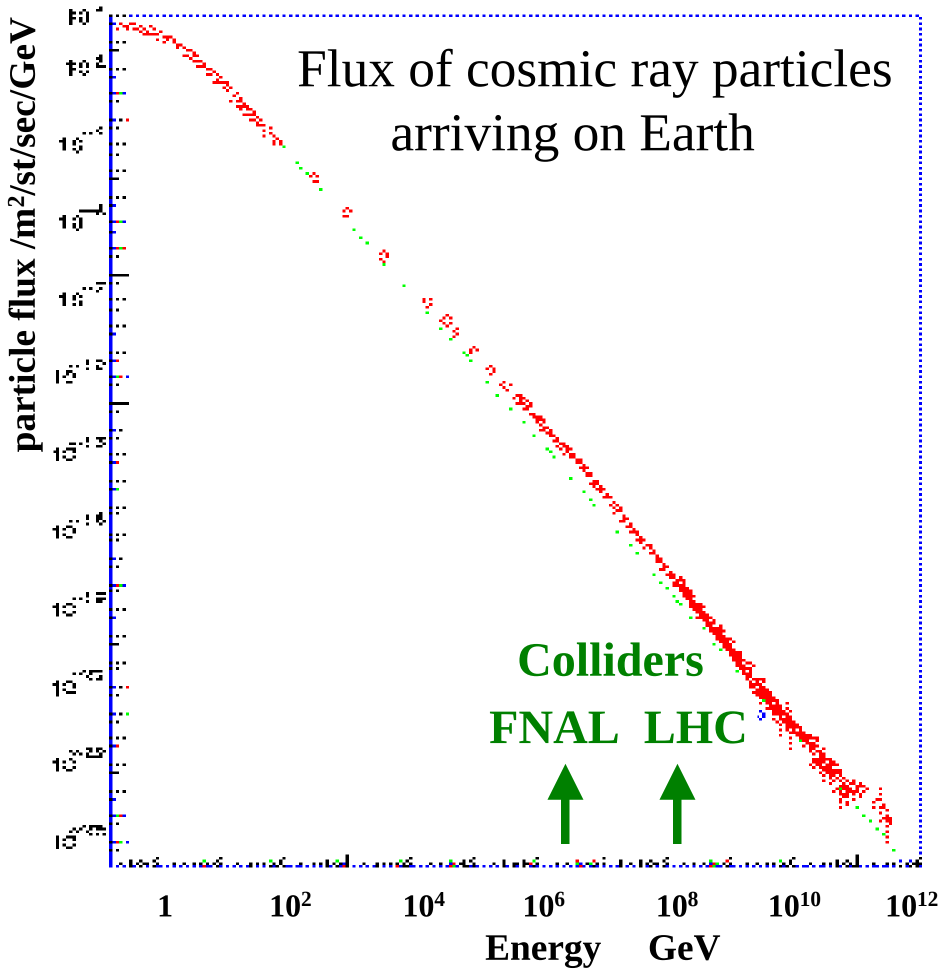


Ultra High Energy from Cosmic Rays

From laboratory accelerators

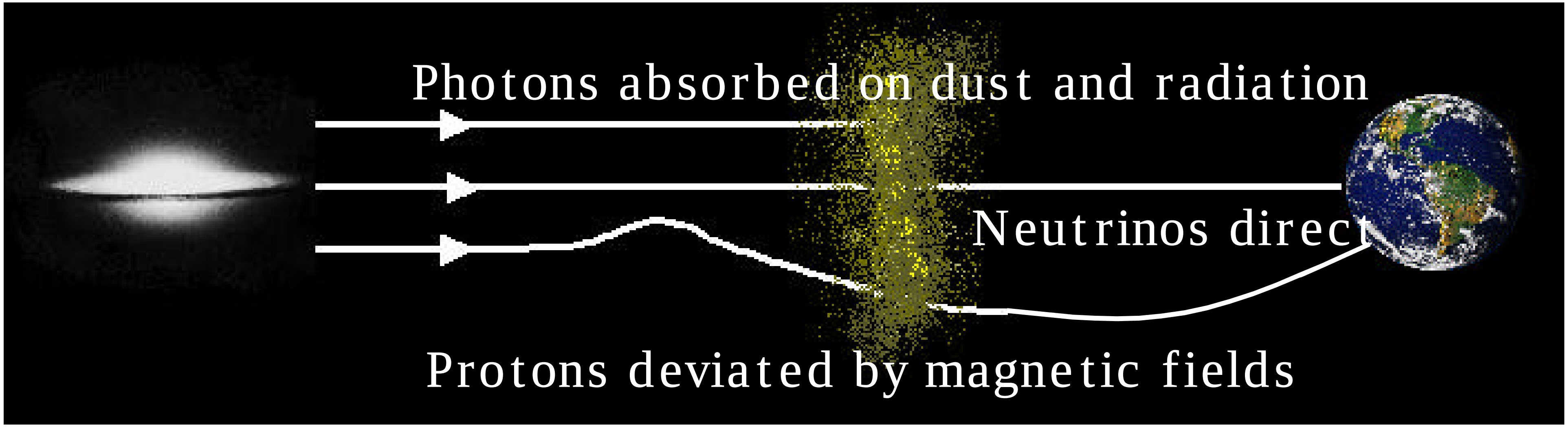


From cosmic accelerators



Ultra High Energy Particles arrive from space for free: make use of them

Multi-Messanger Astronomy



		cut–off	mean free path
γ–rays:	$\gamma + \gamma_{2.7k}$	$>10^{14}$eV	10 Mpc
proton:	$p + \gamma_{2.7k} \rightarrow \pi^0 + X$	$>5.10^{19}$eV	50 Mpc
nuclei:	photo–disintegration	$>5.10^{19}$eV	50 Mpc
neutrinos:	$\nu + \nu_{1.95K} \rightarrow Z+X$	$>4.10^{22}$eV	(40 Gpc)

$\Delta\theta$(rad)= L(kpc) Z B(μG)/E(EeV)

Galaxy B=2μG, Z=1, L=1kpc –> $\Delta\theta$ =12deg at 10^{19}eV

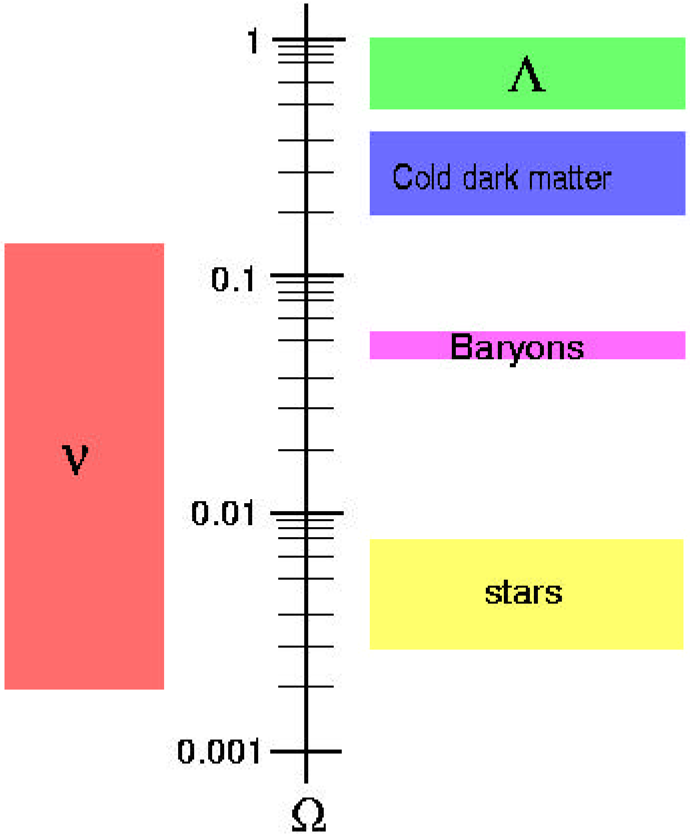
Neutrino Mass in the Universe

Current knowledge of energy and mass distribution in the universe ($\Omega = 1$, flat) $\rightarrow$

Big Bang theory: relic neutrinos: $N_\nu \approx 10^9 N_B$

Structure formation: $\rho_\nu < 0.15 \rho_c$

- $\Rightarrow 1/3 \sum_i m(\nu_i) < 2\,\mathrm{eV}/c^2$ (for stable ν)



Neutrino mass (and mixing) concern:

- relic neutrinos, dark matter and evolution of the universe
- anisotropies of cosmic microwave background
- structure formation
- supernovae & r-process, . . .

$\Rightarrow$ eV neutrino masses are very important

Neutrino History

1931 - Predicted by Pauli

1934 - Fermi develops a theory of radioactive decays and invents name neutrino

1959 - Discovery of neutrino (ν_e) is announced by Cowan and Reines

1962 - Experiments at Brookhaven and CERN discover the second neutrino: ν_μ

1968 - First evidence that solar neutrino rate half expectation: "solar neutrino problem”

1978 - Tau particle is discovered at SLAC by Perl et al.: infer third neutrino

1985 - First reports of a non-zero neutrino mass (still not confirmed)

1987 - Kamiokande and IMB detect bursts of neutrinos from Supernova 1987A

1988 - Kamiokande reports only 60% of the expected number of atmospheric ν_μ

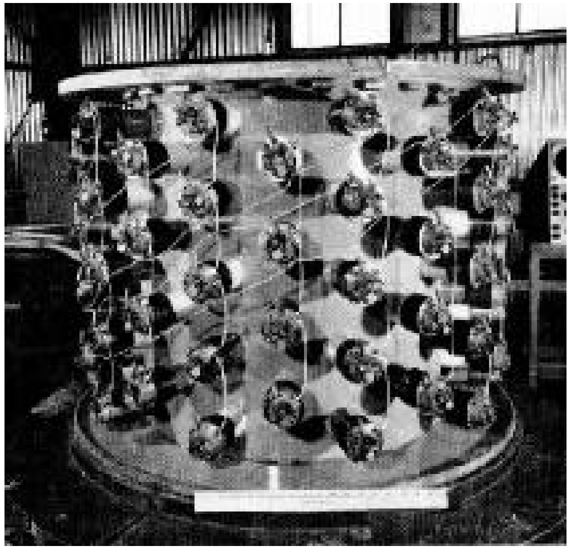
1989 - Experiments at LEP determine three neutrinos from Z line width

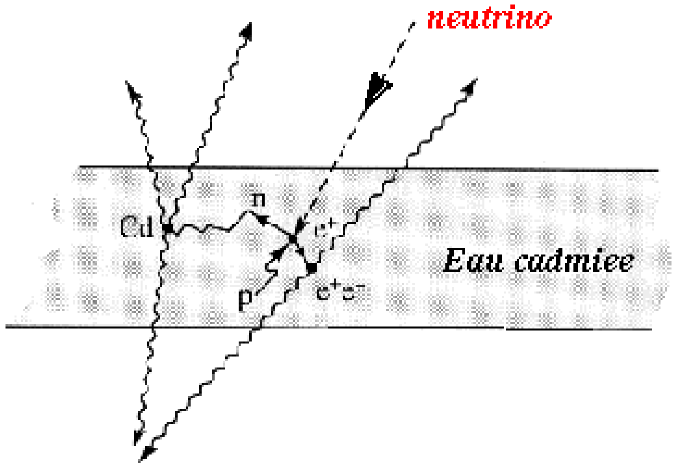
1997 - Super-Kamiokande see clear deficits of atmospheric ν_μ and solar ν_e

1998 - The Super-Kamiokande announces evidence of non-zero neutrino mass

2000 - DONUT experiment claims first observation of tau neutrinos

First observation of Neutrino



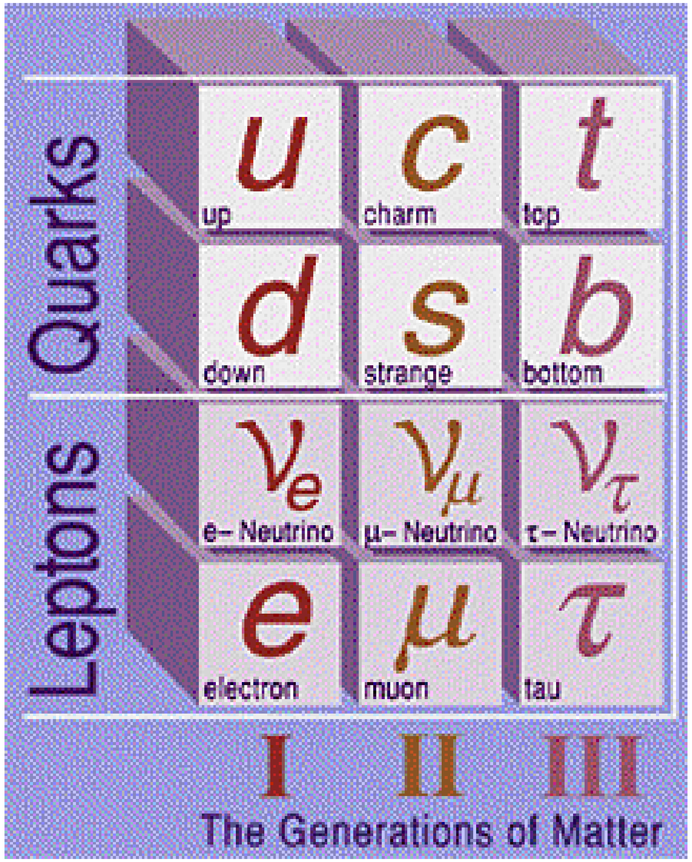


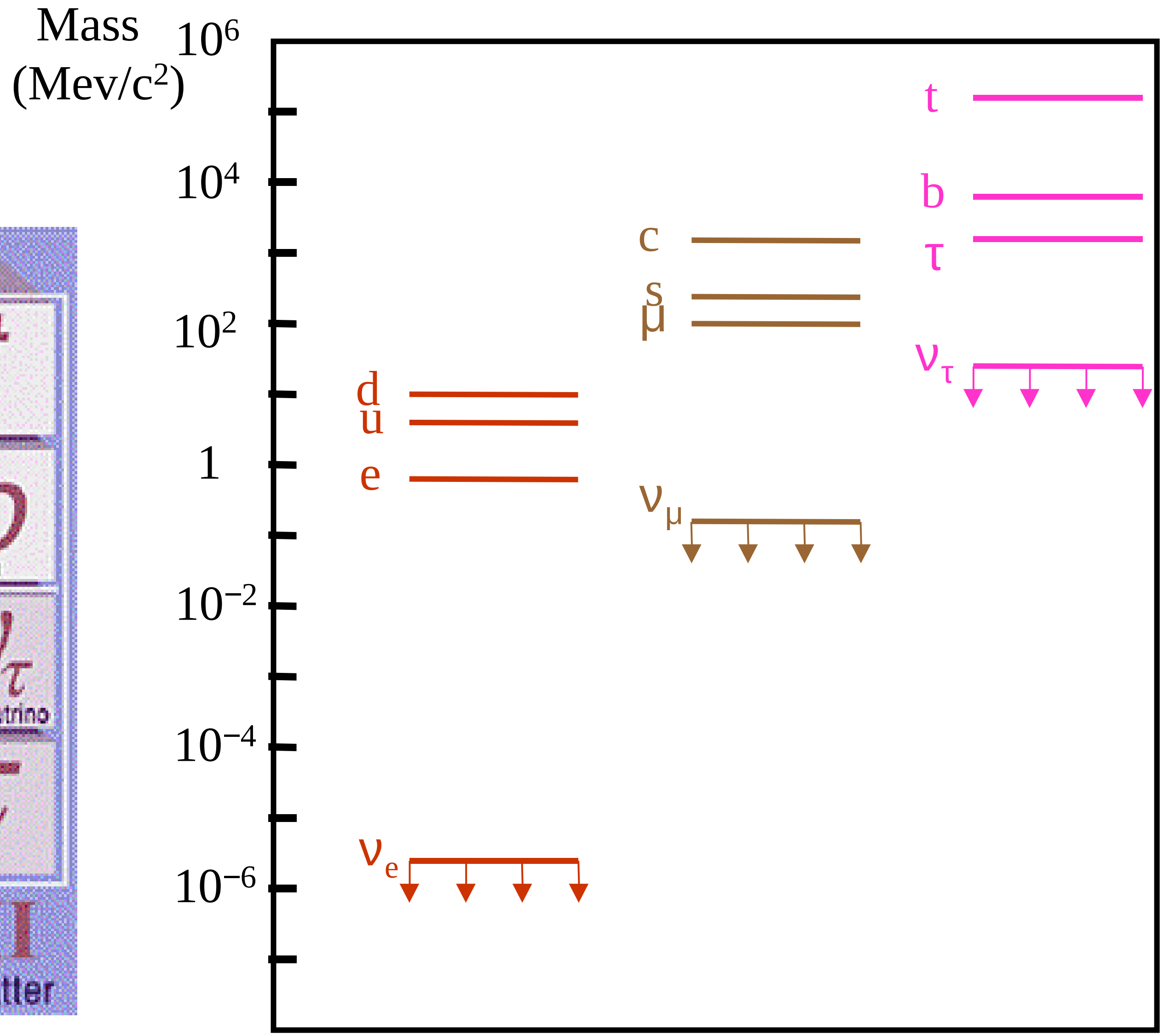
Reines and Cowan 1959:

Target made of 400 l water and cadmium chloride near reactor.

The anti-neutrino coming from the nuclear reactor interacts with a proton of the target matter, giving a positron and a neutron. The positron annihilates with an electron of the surrounding material, giving two simultaneous photons and the neutron slows down until it is eventually captured by a cadmium nucleus, implying the emission of photons some 15 microseconds after those of the positron annihilation. All those photons are detected and the 15 microseconds identify the neutrino interaction.

Three Generations of Particles

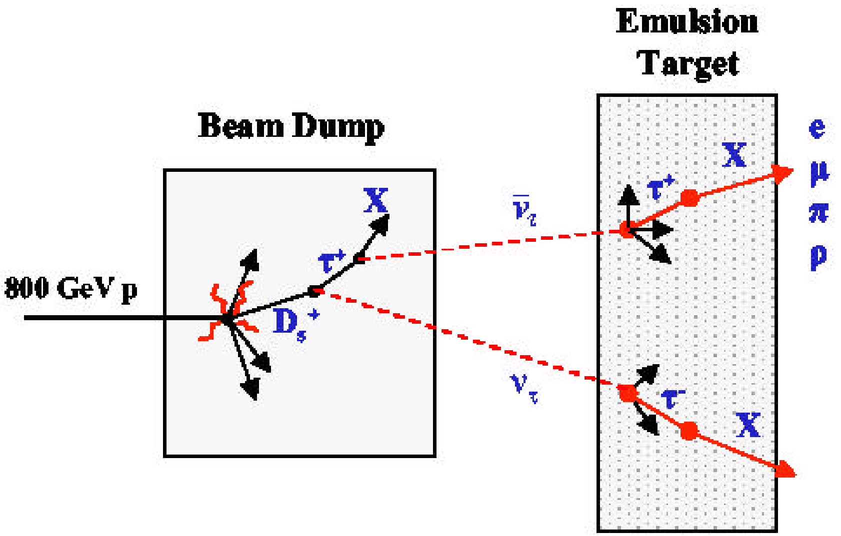




At present only limits of absolute masses of neutrinos
Oscillations give neutrino mass differences

Discovery of ν_τ (?)

DONUT experiment, FNAL



- **Direct observation of the ν_τ :**

$$\nu_\tau + N \rightarrow \tau^- + X$$

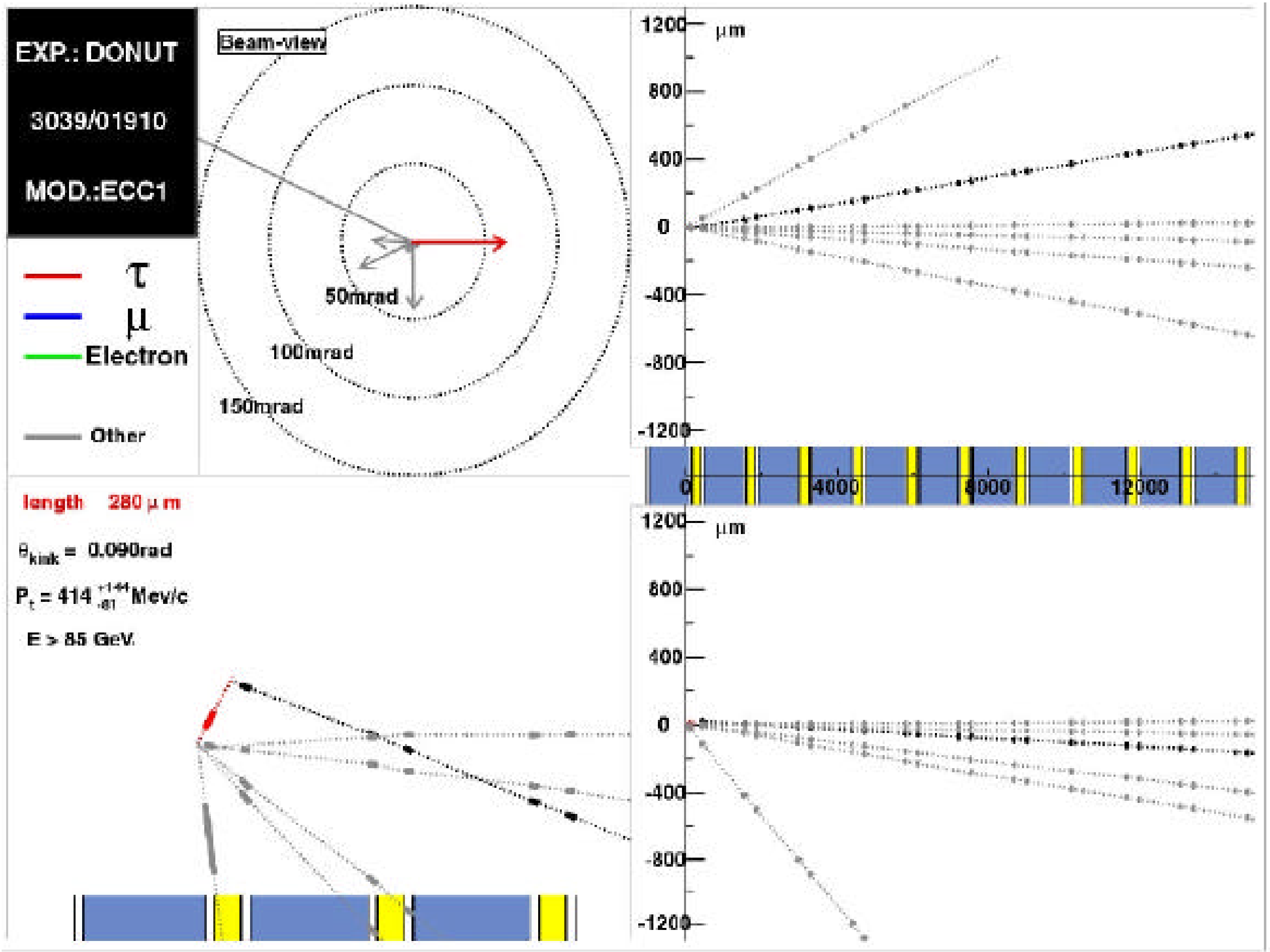
- **Detection of the ν_τ- Tau decay topology :**
  - $\gamma c \tau \approx 2mm$ decay angle ≈ 50mrad
  - 86 % of its decays produce only one charged particle.

- **Production of the neutrino beam :**

$$p + N \rightarrow D^+s + X$$
$$\hookrightarrow \tau^+ + \nu_\tau$$
$$\hookrightarrow \bar{\nu}_\tau + \ldots$$

neutrino beam : 5 % ν_τ - 95 % ν_μ, ν_e

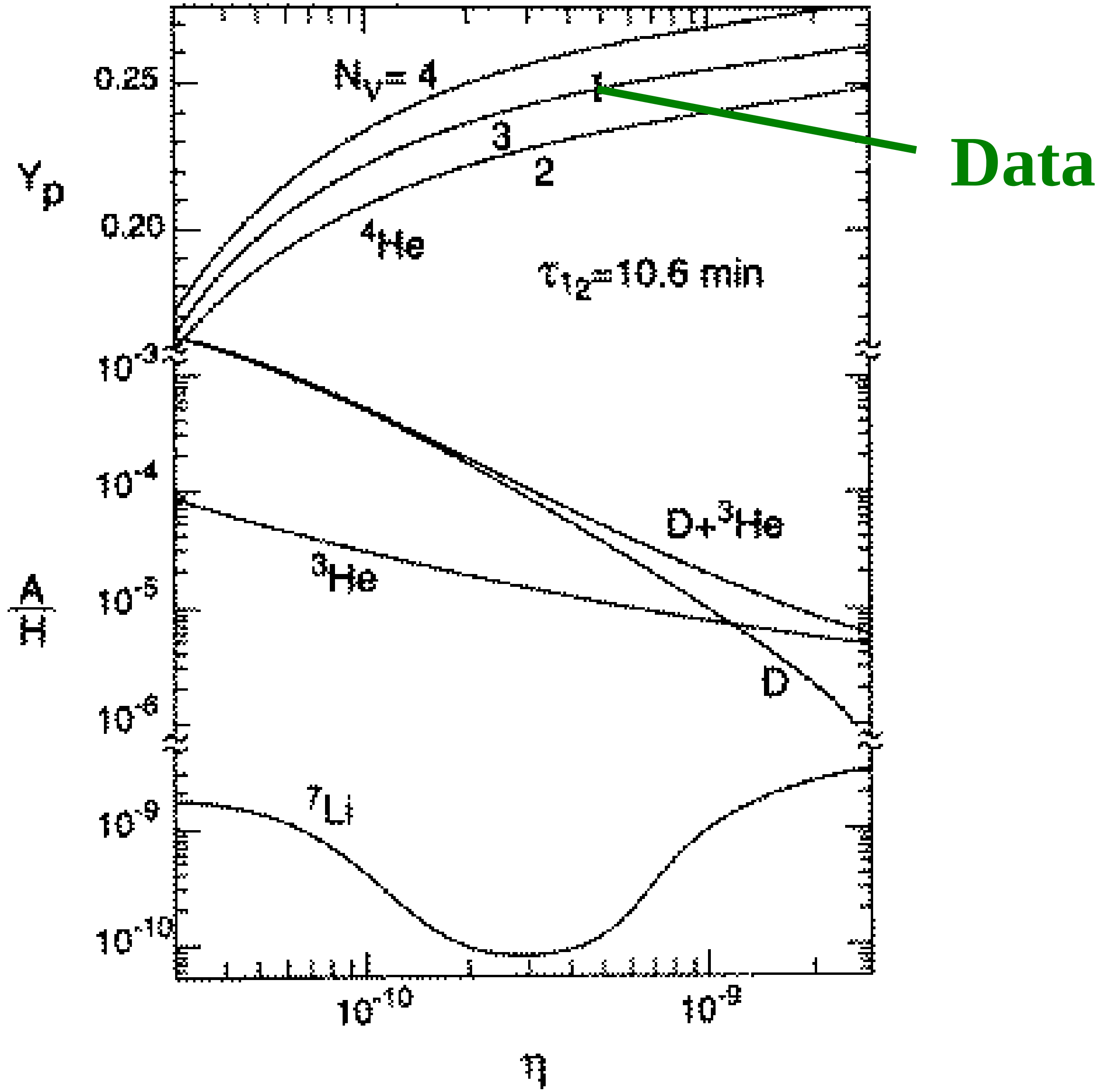
Discovery of ν_τ(?)



4 ν_τ events identified

Number of Neutrino Families

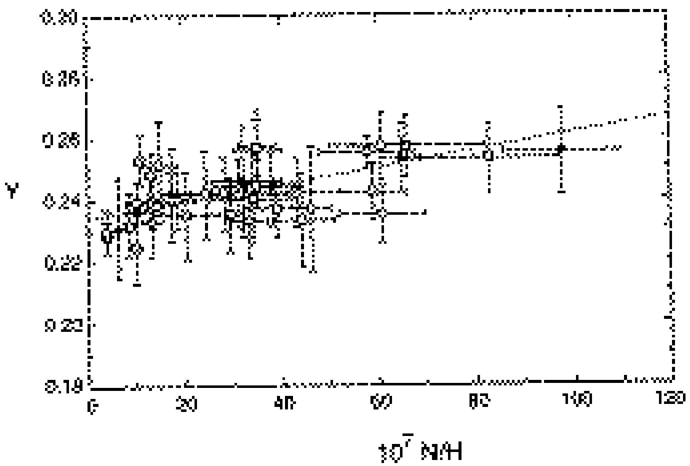
From Big Bang Nucleosynthesis



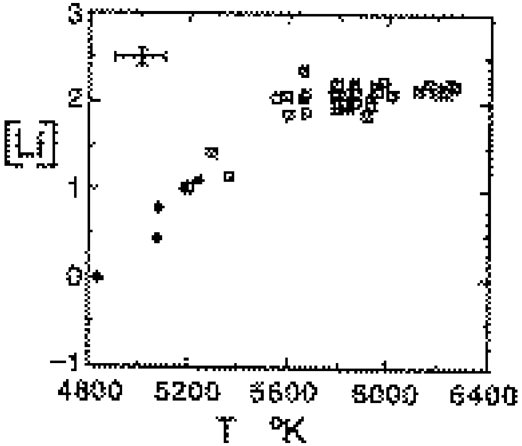
Number of Neutrino Families

From Big Bang Nucleosynthesis

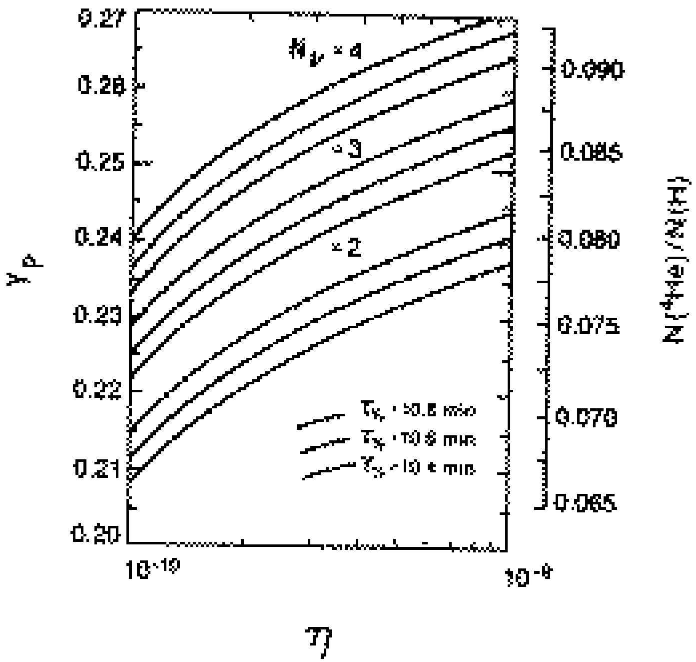
Fraction ^{4}He



Fraction Li



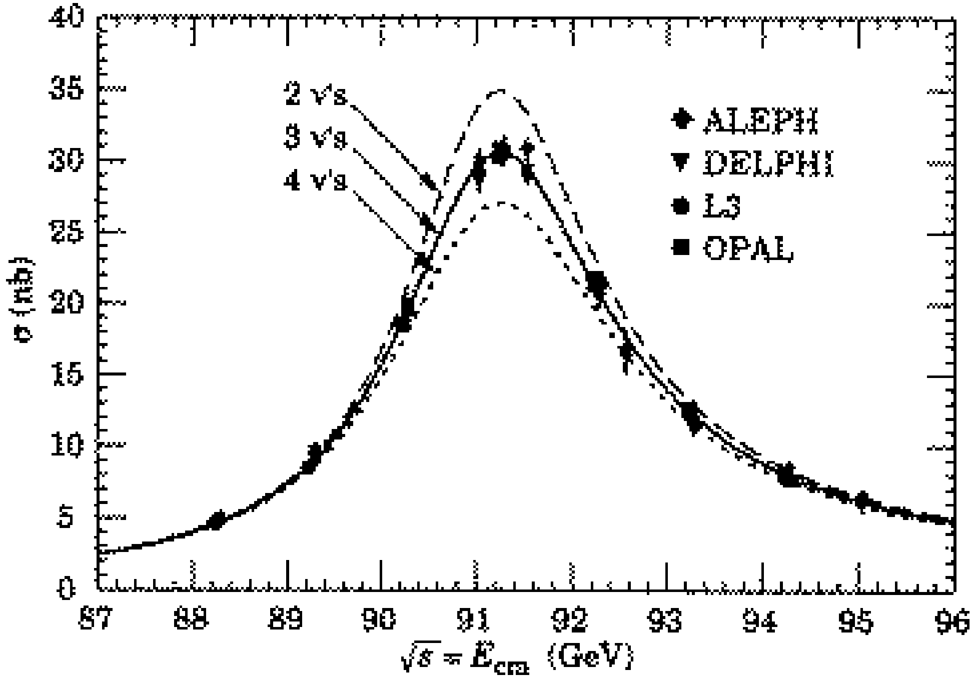
Dependence on Neutron lifetime



Lifetime (s)	Reference
918 ± 14	[Chr72]
903 ± 13	[Kos86]
891 ± 9	[Spi88]
876 ± 21	[Las88]
877 ± 10	[Pau89]
888 ± 3	[Mam93]
878 ± 30	[Kos89]
894 ± 5	[Byr90]
888.4 ± 4.2	[Nes92]
882.6 ± 2.7	[Mam89]
887.0 ± 2.0	[PDG94]

Number of Neutrino Families

Measurements from LEP of width of Z resonance



	ALEPH	DELPHI	L3	OPAL	Average
M_Z	91.187	91.187	91.195	91.182	91.187
	±0.013	±0.013	±0.013	±0.013	±0.007 (LEP)
Γ	2501	2483	2494	2483	2490
	±56	±56	±56	±54	±52
Γ_e	84.61	83.31	83.43	83.63	83.83
	±0.49	±0.54	±0.52	±0.53	±0.3
Γ_μ	83.62	84.15	83.72	83.83	83.84
	±0.75	±0.77	±0.79	±0.65	±0.39
Γ_τ	84.18	83.55	84.04	82.90	83.68
	±0.79	±0.91	±0.94	±0.77	±0.44
Γ_{lepton}	84.40	83.56	83.49	83.55	83.84
	±0.43	±0.45	±0.46	±0.44	±0.27
Γ_{hadron}	1746	1723	1746	1743	1740.7
	±10	±10	±10	±10	±5.9
Γ_{inv}	450	509.4	540	539	517
	±88	±7	±120	±43	±22
N_ν	2.983	3.057	2.981	2.946	2.991
	±0.034	±0.040	±0.050	±0.045	±0.016

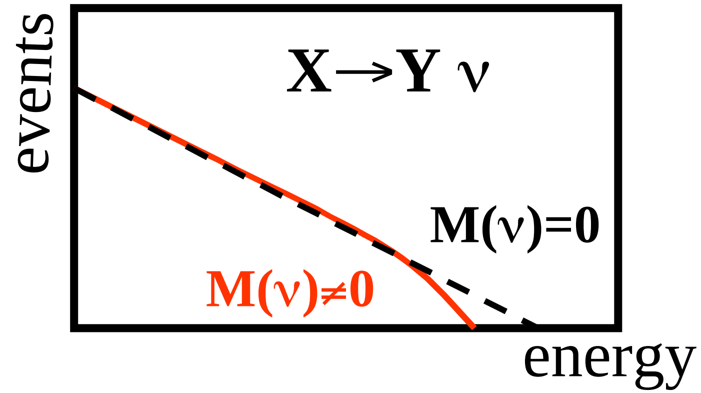
$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\nu\bar{\nu}}} = \frac{\Gamma_{e^+e^-}}{\Gamma_{\nu\bar{\nu}}}\left[\sqrt{\frac{12\pi\,\Gamma_{had}}{m_Z^2\,\sigma_{had}\,\Gamma_{e^+e^-}}} - \frac{\Gamma_{had}}{\Gamma_{e^+e^-}} - 3\right]$$

N_ν = 2.994±0.012

Neutrino Mass Measurements

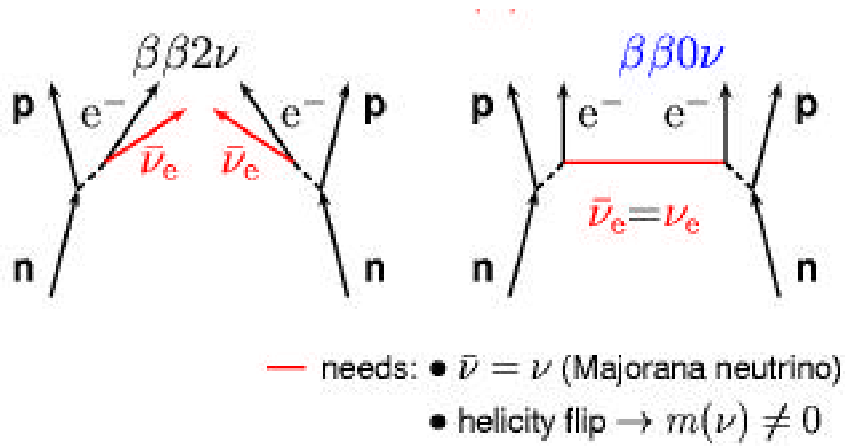
Direct mass measurements

- Time-of-flight measurements from distant objects
- Kinematics of Weak Decays



Indirect searches (effects which only exist if M(ν) ≠ 0)

- Neutrino Oscillations
- Neutrinoless Double Beta Decay



Dirac and Majorana Neutrinos

(See Akhmedov ‘ Neutrino physics ’ : hep-ph/0001264)

For massive fermion, mass term in Lagrangian:

$$-\mathcal{L}_m = m\bar{\psi}\psi = \overline{(\psi_L + \psi_R)}(\psi_L + \psi_R) = \overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L$$

Mass term couples left and right-handed components: $\psi = \psi_L + \psi_R$

Dirac Neutrino: left and right-handed fields completely independent
Majorana Neutrino : left and right-handed fields charge conjugates

$\psi_R = (\psi_L)^c = (\psi^c)_R$ then: $\psi = \psi_L + \eta(\psi^c)_R = \psi_L + \eta(\psi_L)^c$

so: $\psi^c = \eta^* \psi$: Majorana field is self charge-conjugate

Majorana neutrino is its own anti-particle

Dirac and Majorana masses

Mass matrices : Dirac m_D, Majorana $m_{L,}$ m_R

n species of neutrino: n × n complex matrices

General neutrino mass term in Lagrangian:

$$-\mathcal{L}_m = \frac{1}{2}\nu_L^T C\, m_L\, \nu_L + \overline{\nu}_L\, m_D^*\, \nu_R + \frac{1}{2}\nu_R^T C\, m_R^*\, \nu_R + h.c.$$

$$= \frac{1}{2}\, n_L^T C \mathcal{M}\, n_L + h.c.$$

where:

$$\mathcal{M} = \begin{pmatrix} m_L & m_D \\ m_D^T & m_R \end{pmatrix}$$