Neutrino Physics

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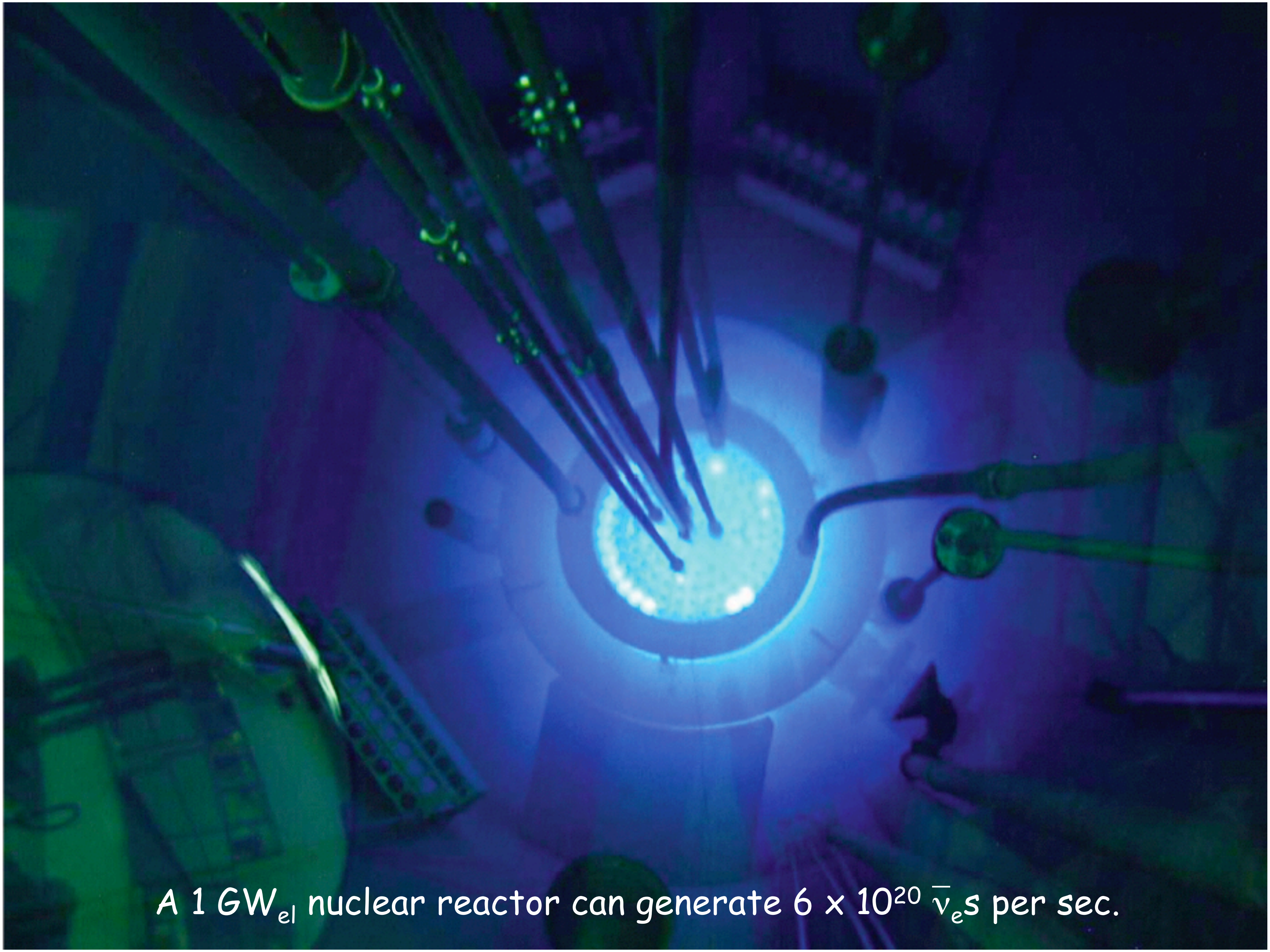
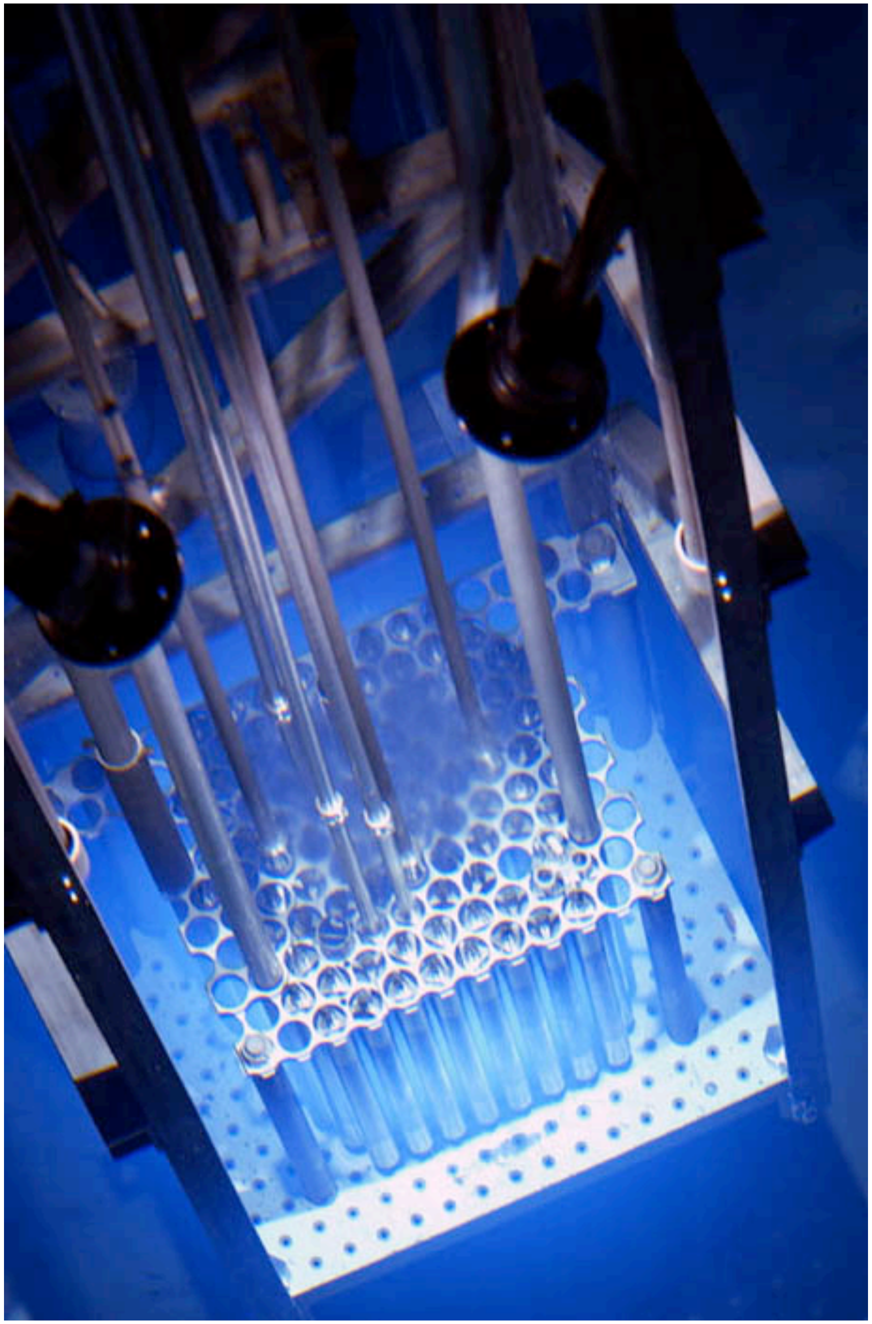
Outline

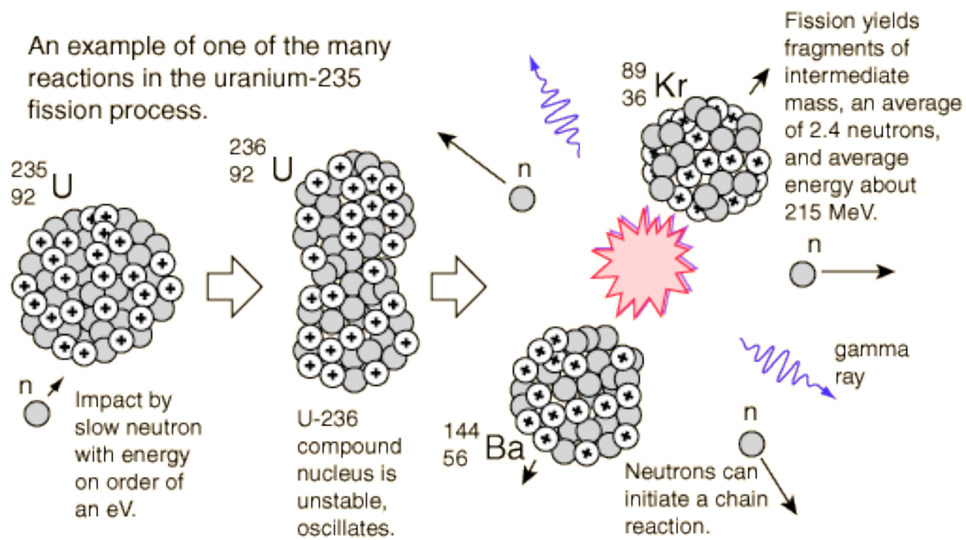
- Artificial sources
  - neutrino beams
  - nuclear reactor
- Natural sources
  - Active galactic nucleus
  - Supernova
  - Atmosphere
  - Sun
- Detecting particles
  - detecting charged particles
  - Cherenkov radiation
  - detecting photons
  - detecting low-energy neutrons
- Photomultiplier tubes

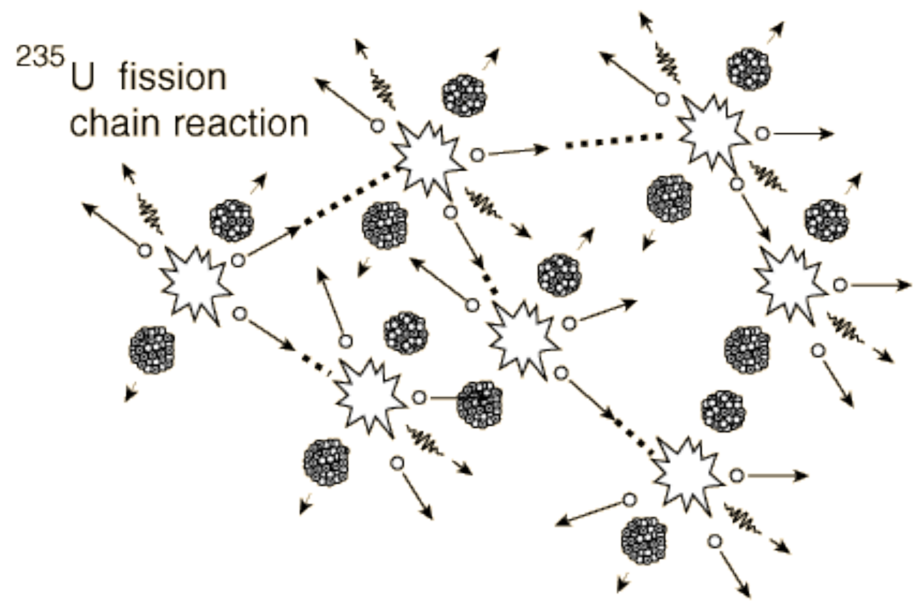


A 1 GW_{el} nuclear reactor can generate 6×10^{20} $\bar{\nu}_e$s per sec.

Chain Reaction







Producing Antineutrinos With Reactors

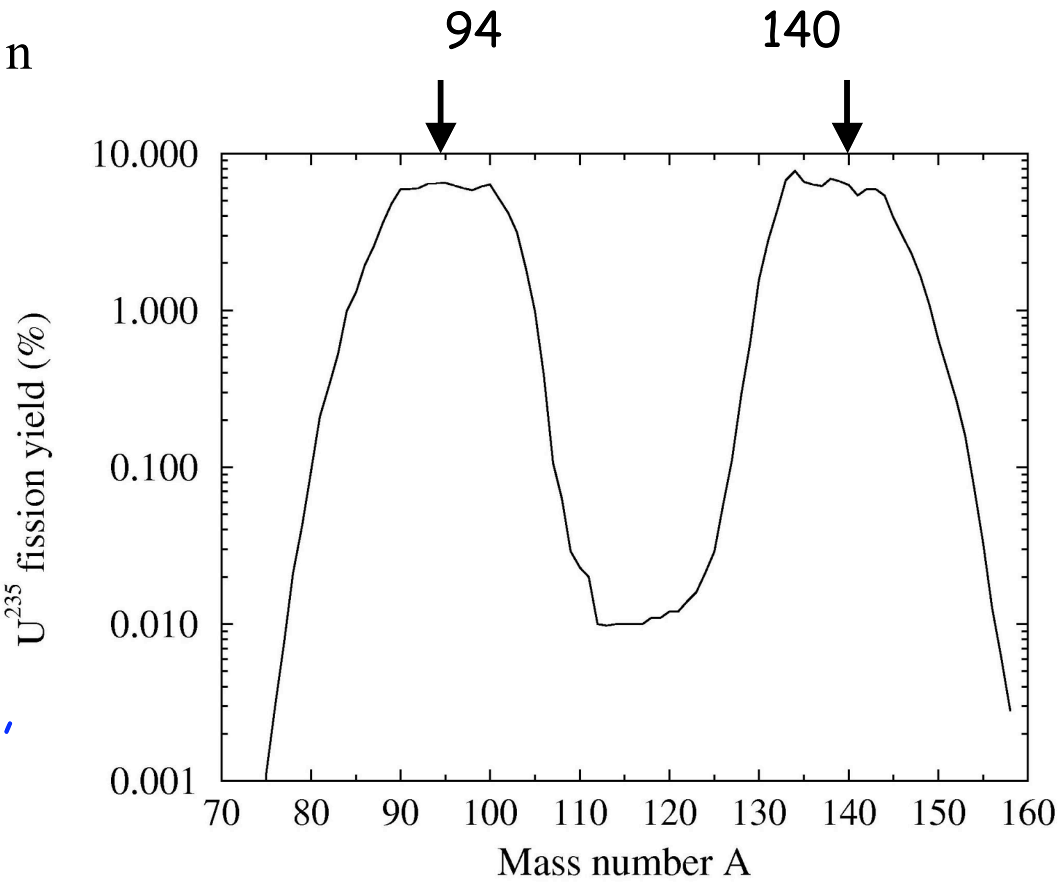
For ^{235}U fission, for instance,

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

where X_1 and X_2 are stable nuclei e.g.

$$^{94}_{40}Zr \qquad ^{140}_{58}Ce$$

which have a total of 98 protons and 136 neutrons, whereas ^{235}U has 143 neutrons. That is, on average, 6 neutrons must beta decay, giving 6 $\bar{\nu}_e$.



Energy Spectrum of Reactor Antineutrinos

- $\bar{\nu}_e$ associated with ^{235}U, ^{239}Pu and ^{241}Pu

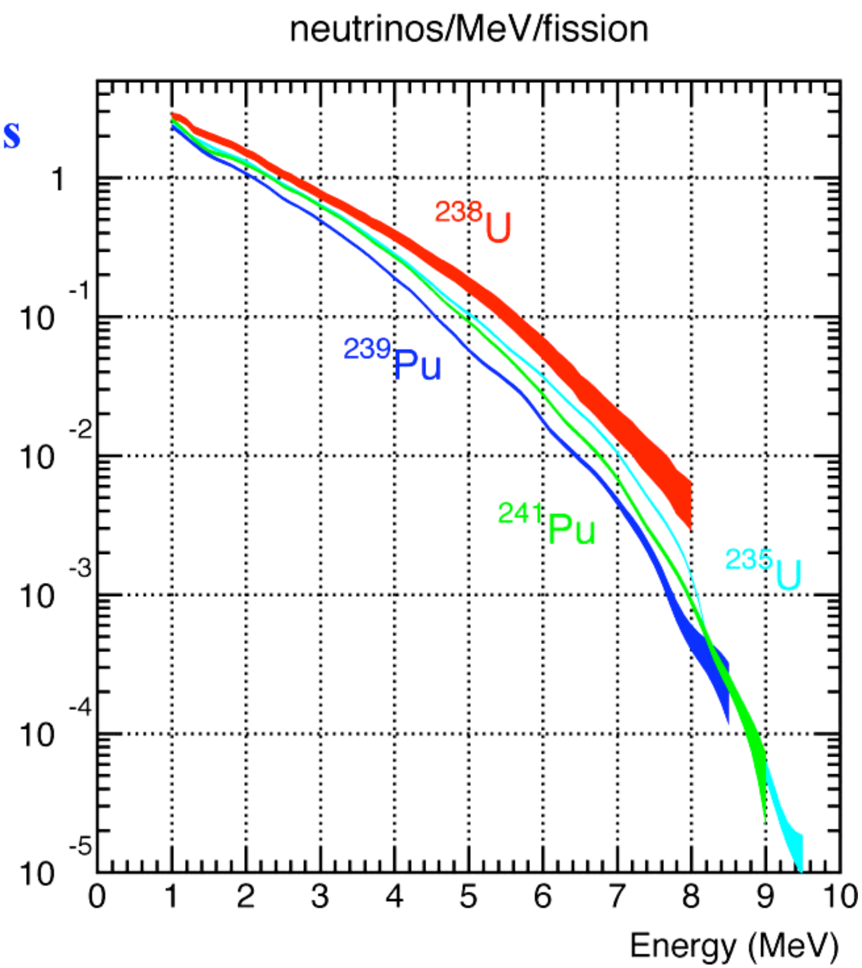
  measured β – spectra
  from thermal neutron fissions

  superposition of 30 hypothetical β-decay branches

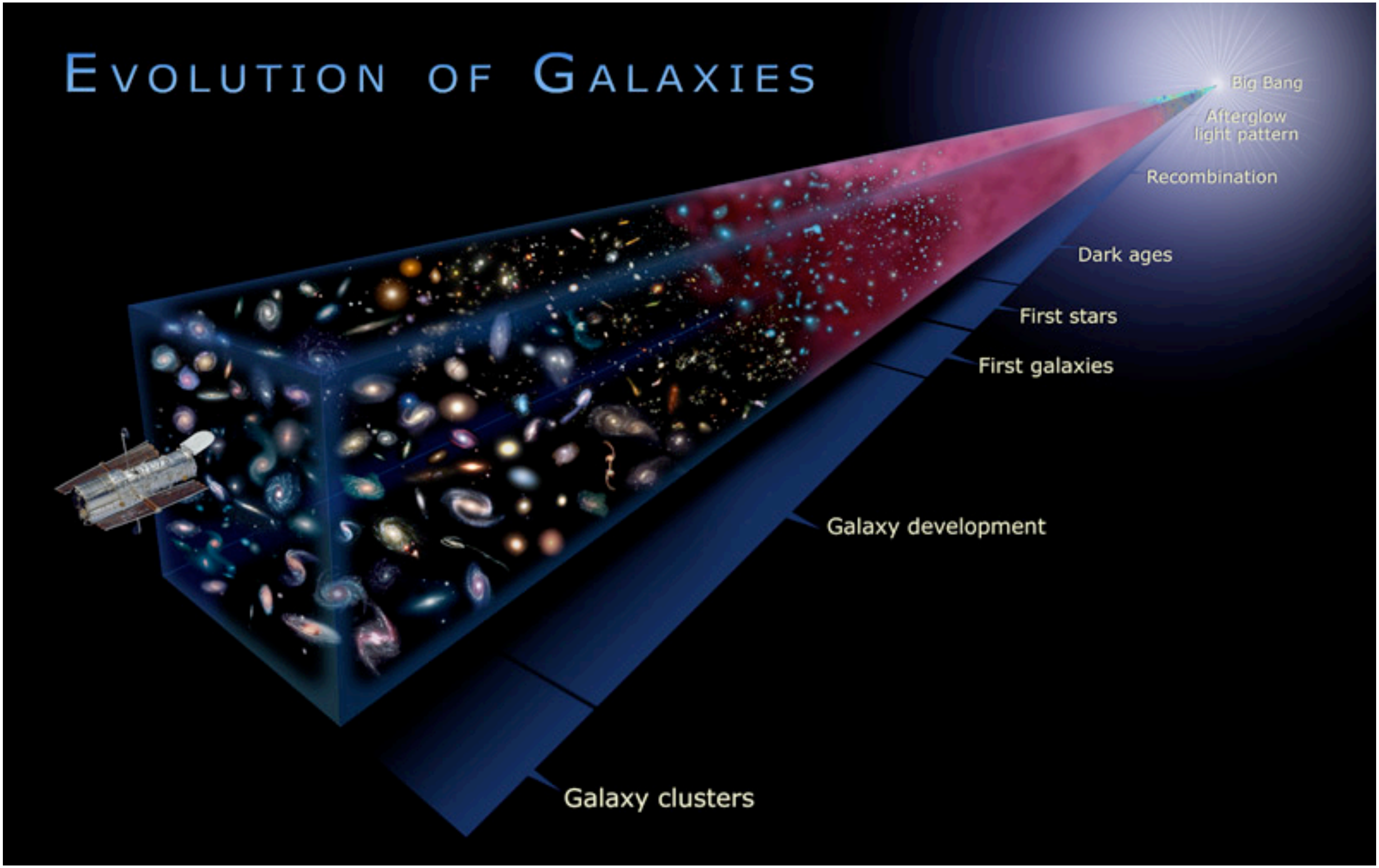
  conversion $E_e \longrightarrow E_\nu$

- $\bar{\nu}_e$ associated with ^{238}U

  calculation based on
  744 unstable fission products

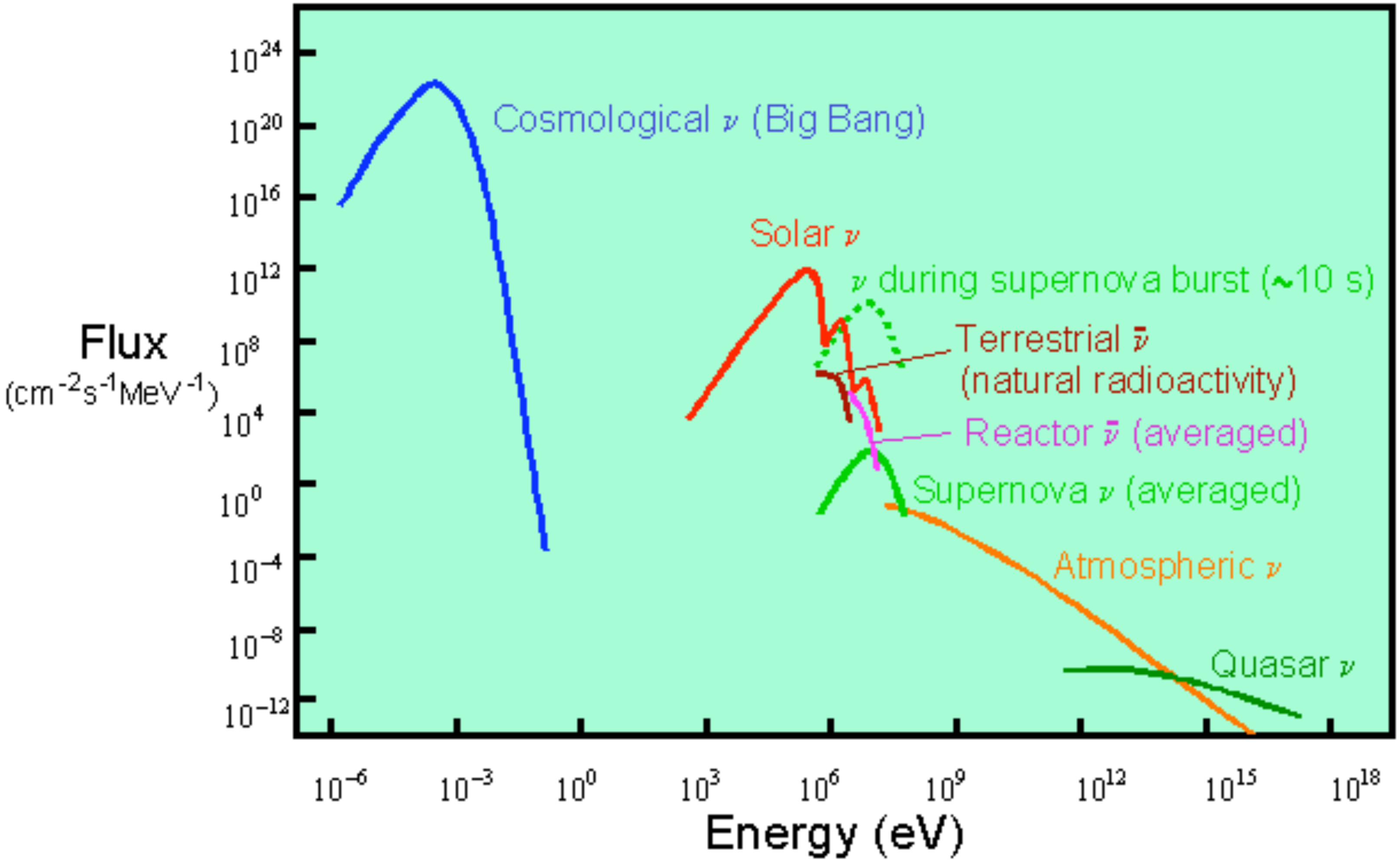


Evolution Of The Universe



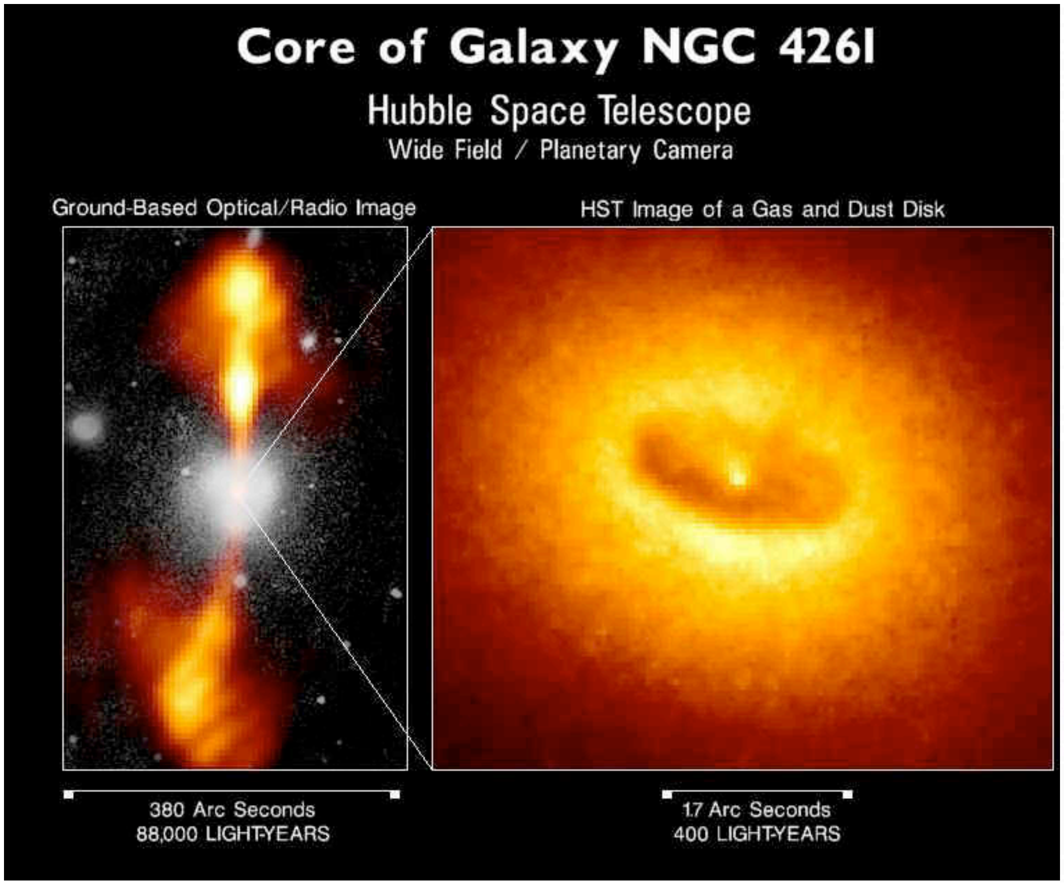
Neutrinos are created in the evolution of the Universe

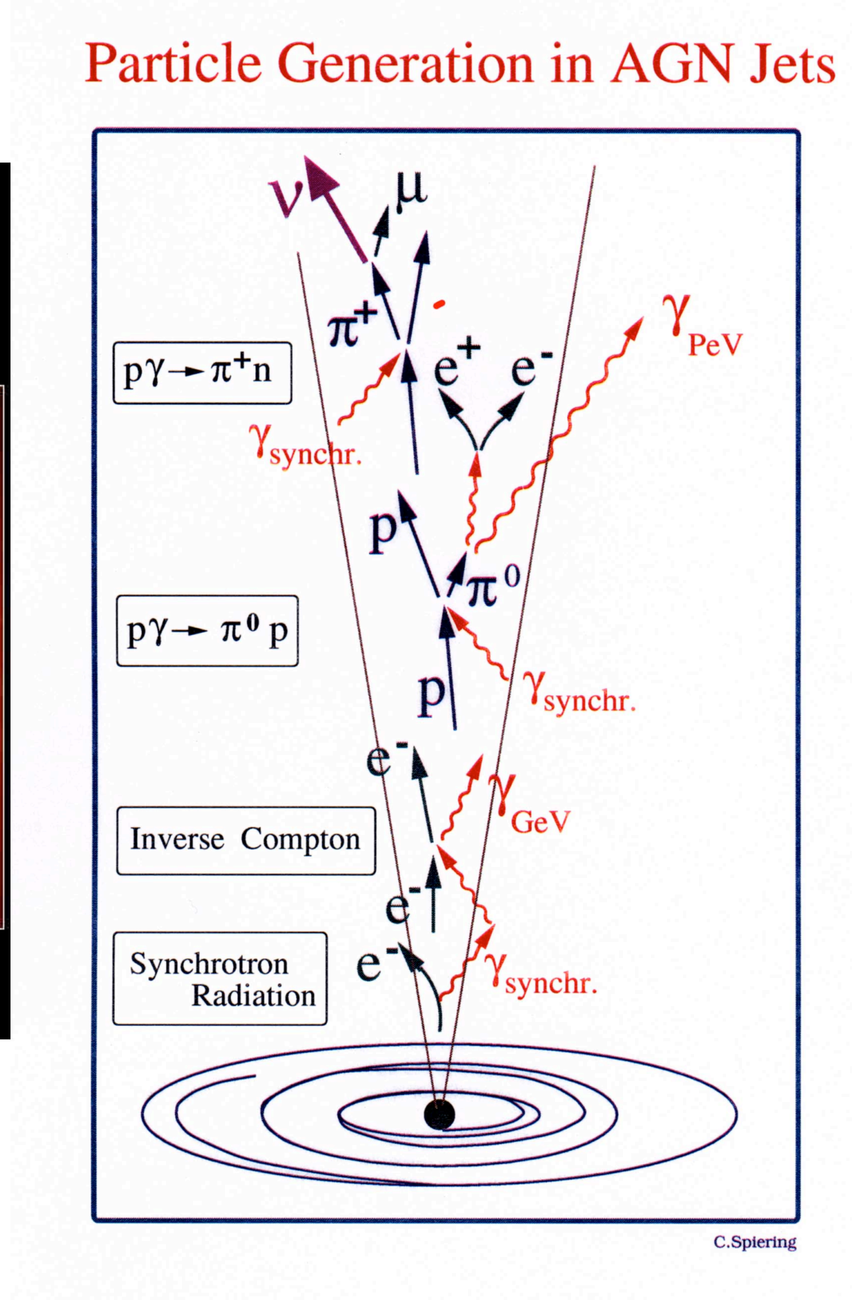
Sources of Neutrinos



Flux on earth of neutrinos from various sources, in function of energy

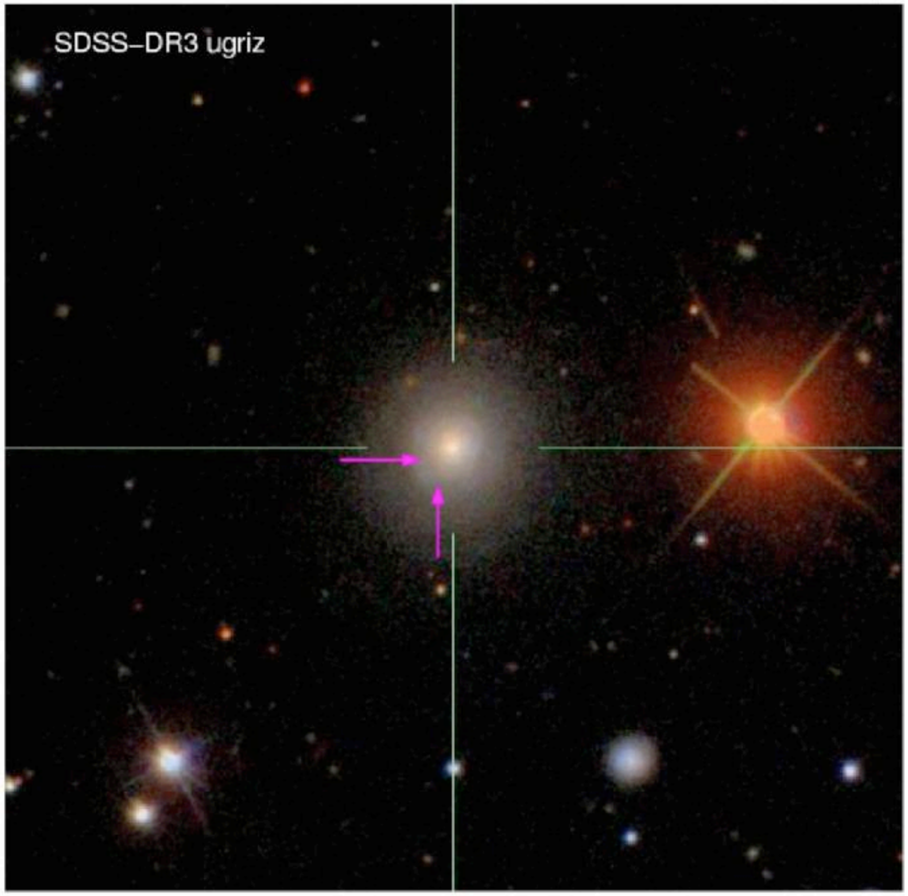
A Way To Generate High-energy Particles

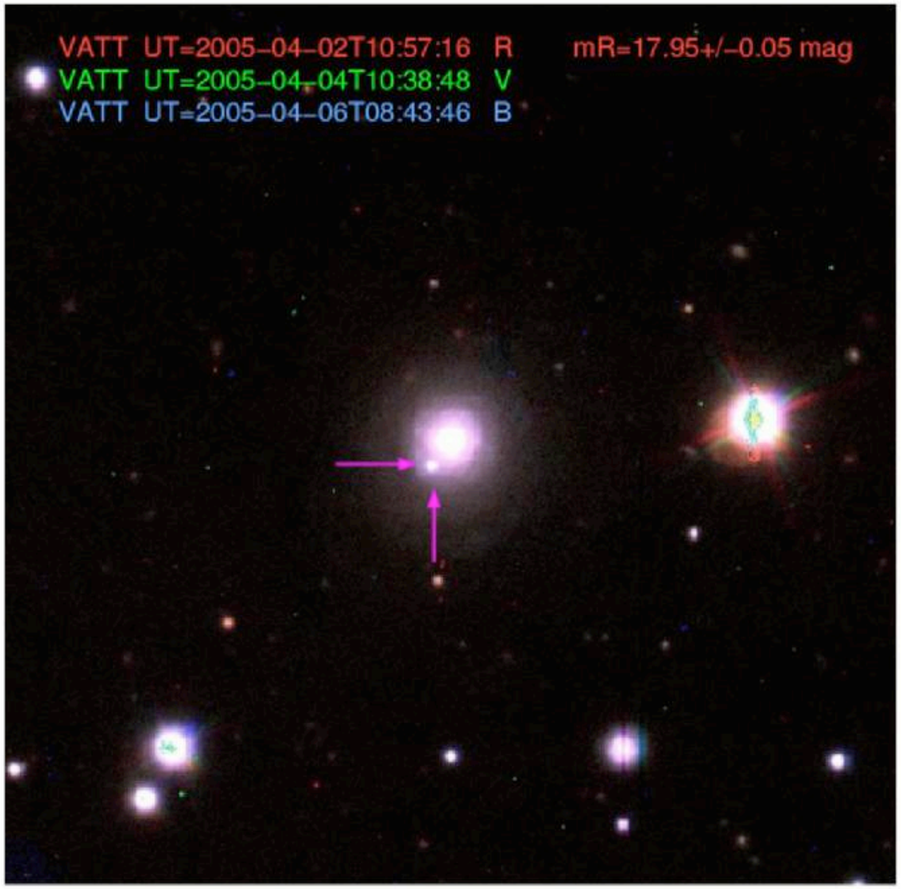




Supernova: Another Way To Produce Cosmic Ray And Neutrinos

SN in galaxy CGCG 223–029





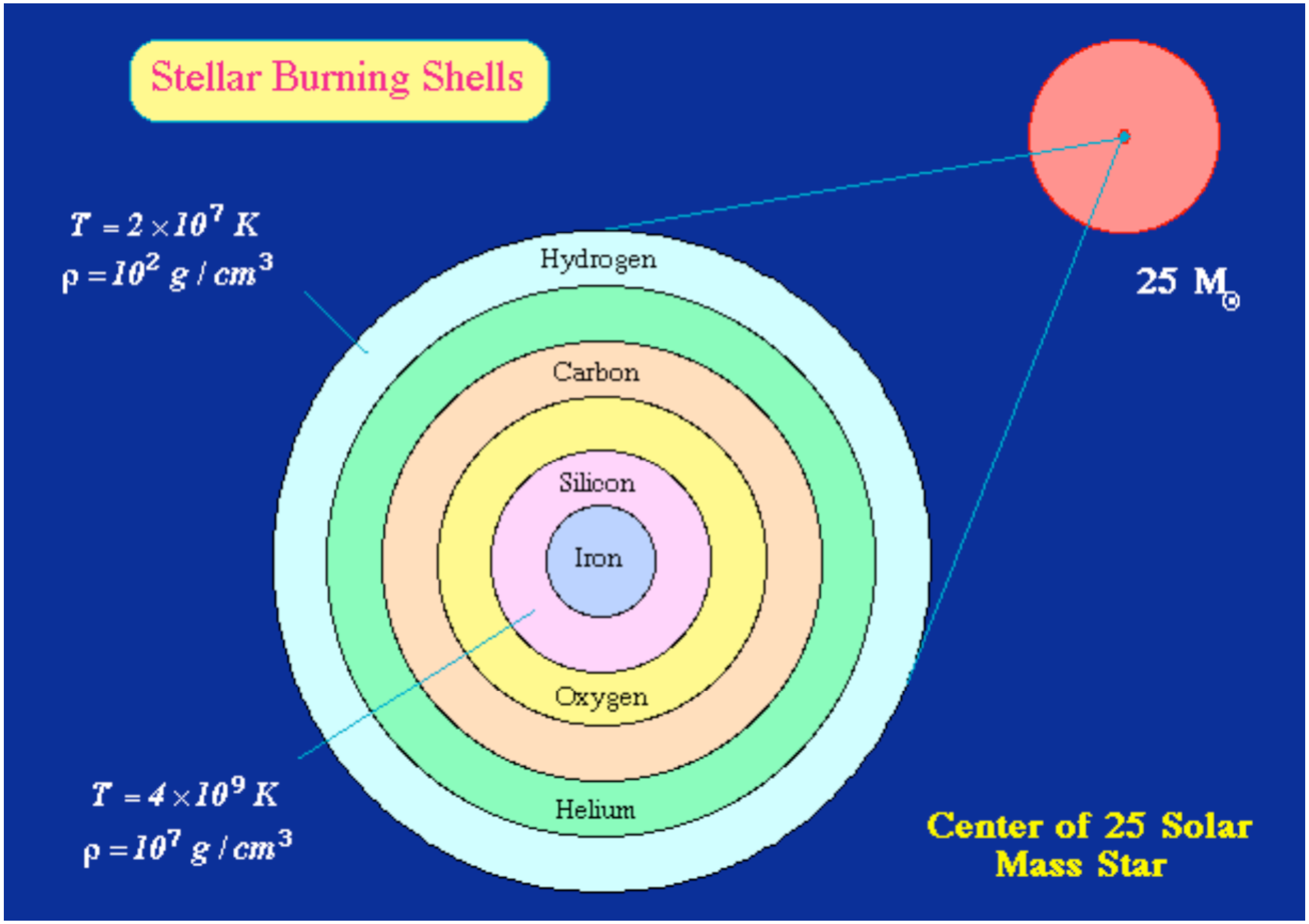
Host galaxy: 16:02:16.63 +42:55:00.9 J2000.0
Supernova: 16:02:17.04 +42:54:55.3 J2000.0 (4.5" E, 5.6" S of nucleus)

Dimensions of finding chart: ~3.5'x3.5'
Orientation: N up and E to the left

Discoverers: Rolf A. Jansen, Kazuyuki Tamura (ASU) & Norman A. Grogin (JHU)

VATT = Vatican Advanced Technology Telescope, Mt.Graham (AZ)
SDSS–DR3 = Sloan Digital Sky Survey – Data Release 3

Supernova Explosion: Production of Neutrinos

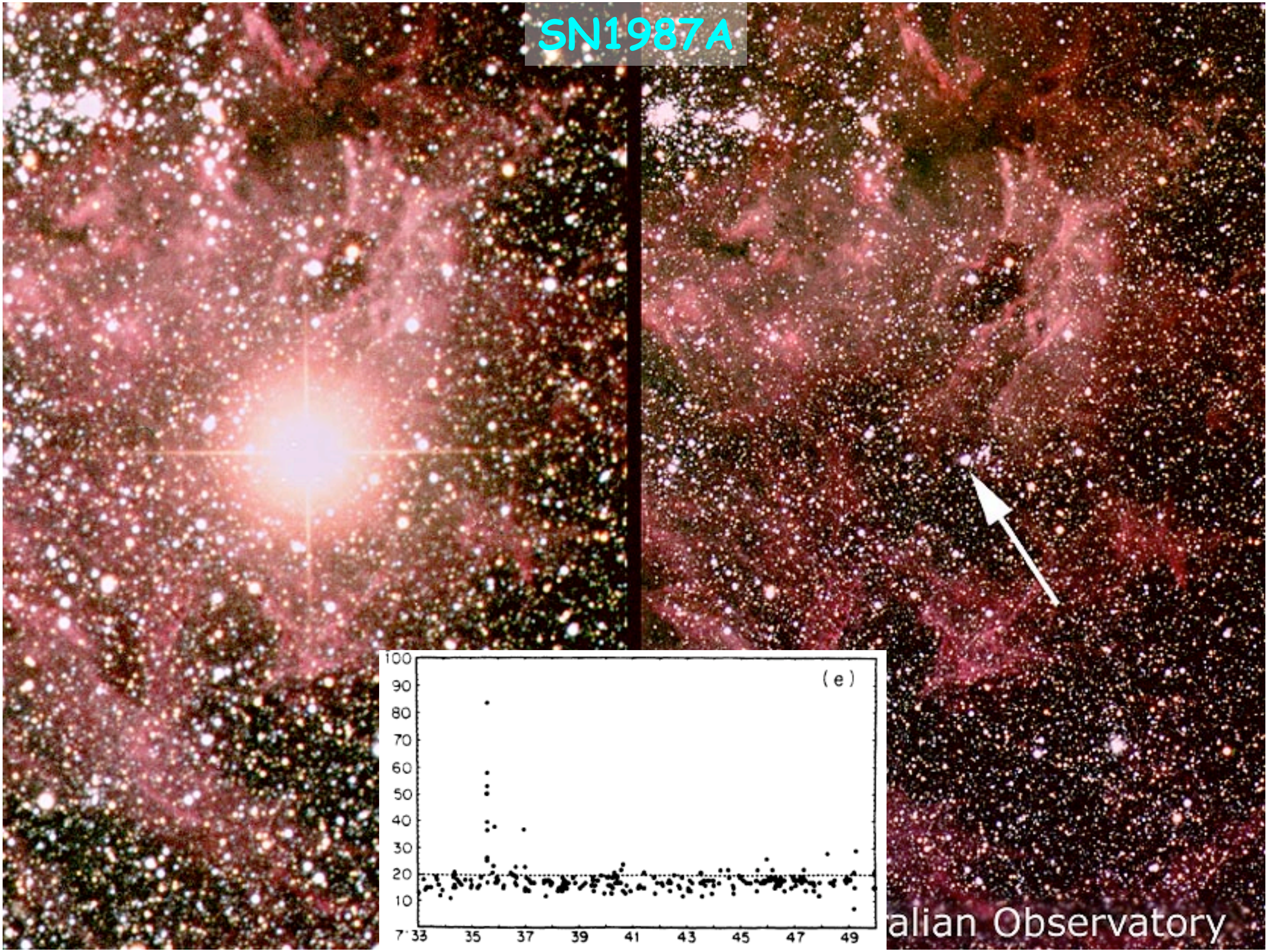


- When gravitational force is too strong, inside the iron core:

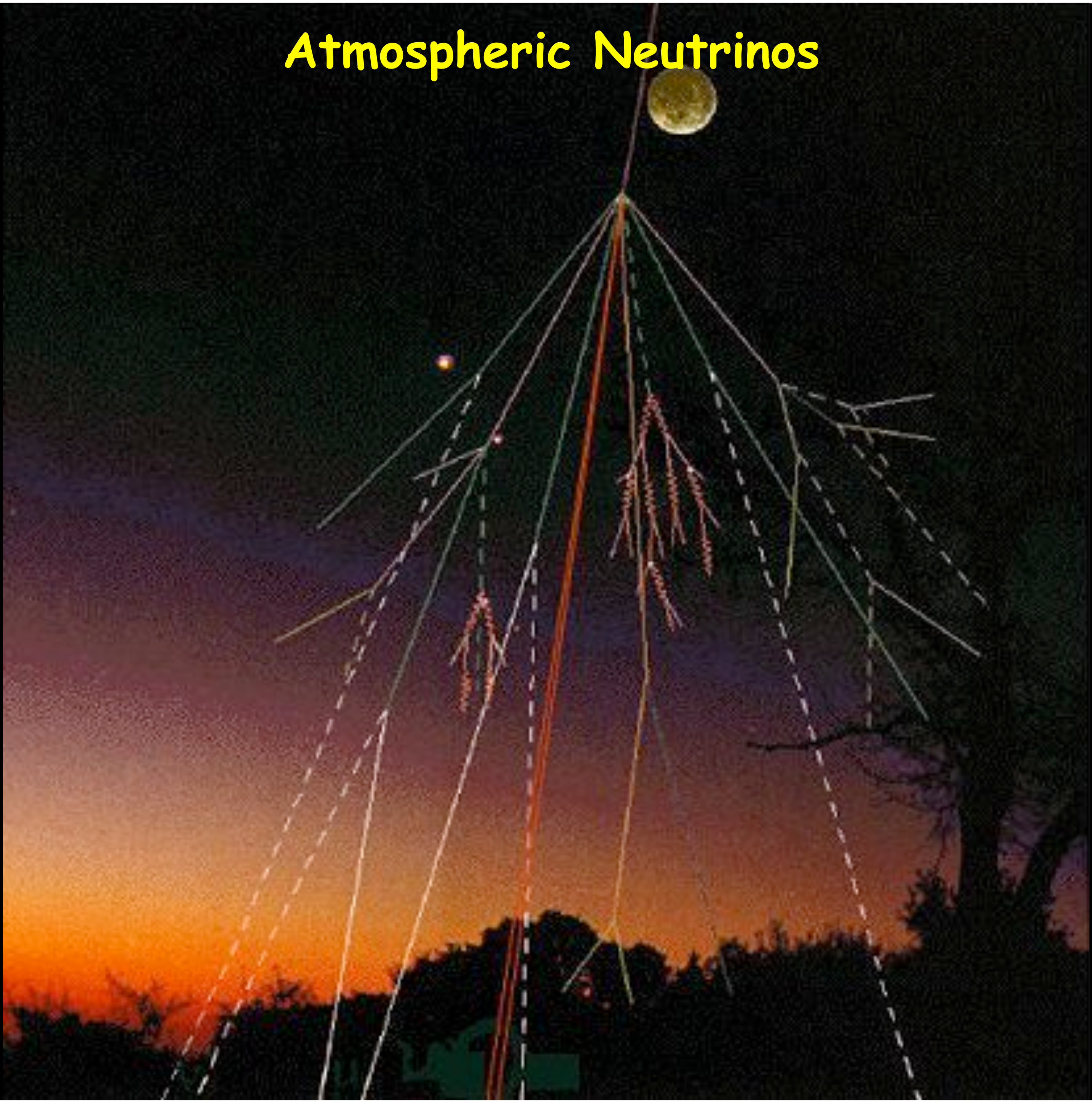
$$e^- + p \rightarrow n + \nu_e$$

- Neutrons can't be compressed anymore, the collapsing core rebounces and tears apart - supernova explosion and release ν_e

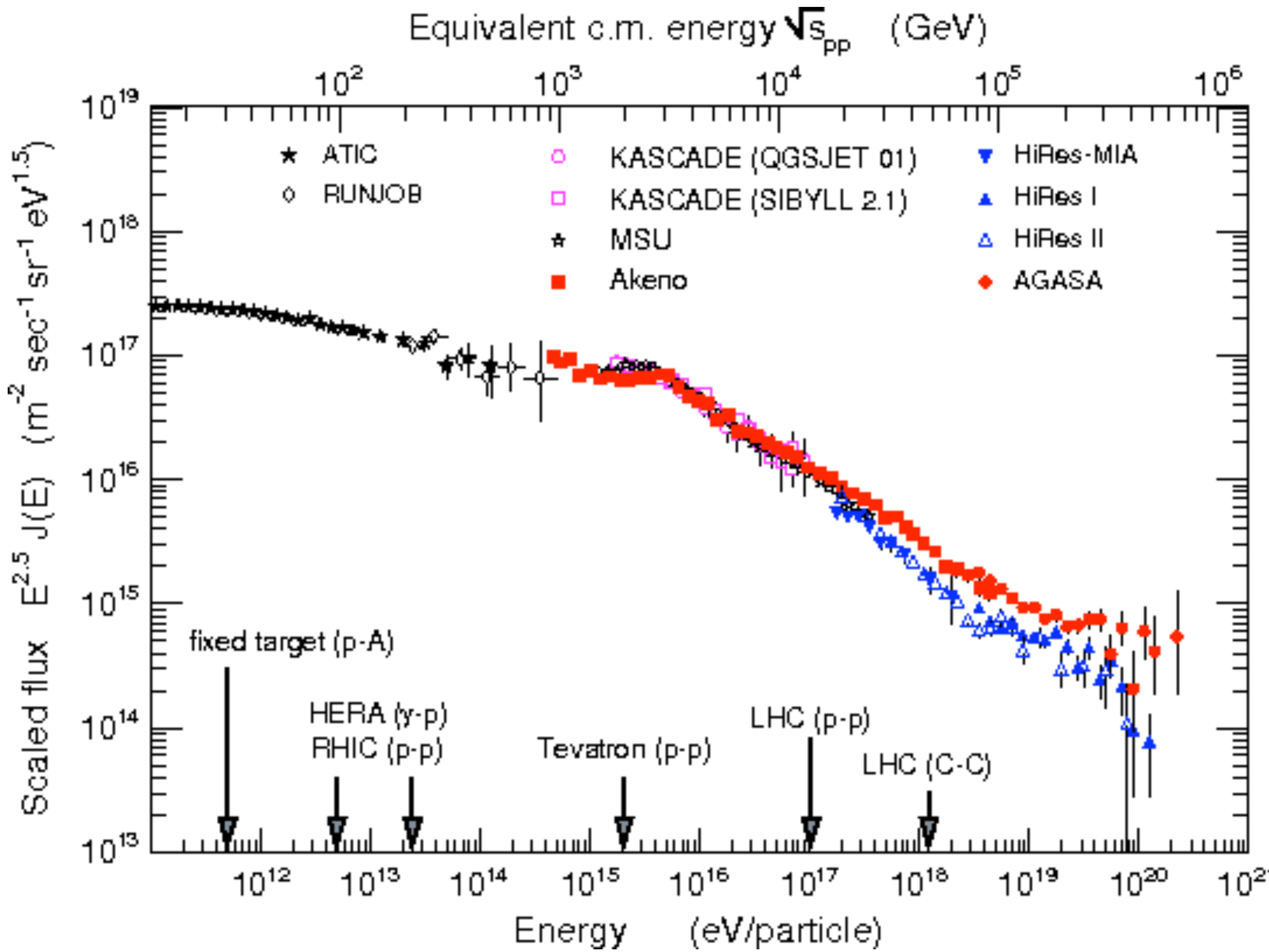
SN1987A


(e)
100
90
80
70
60
50
40
30
20
10
7:33
35
37
39
41
43
45
47
49
alian Observatory

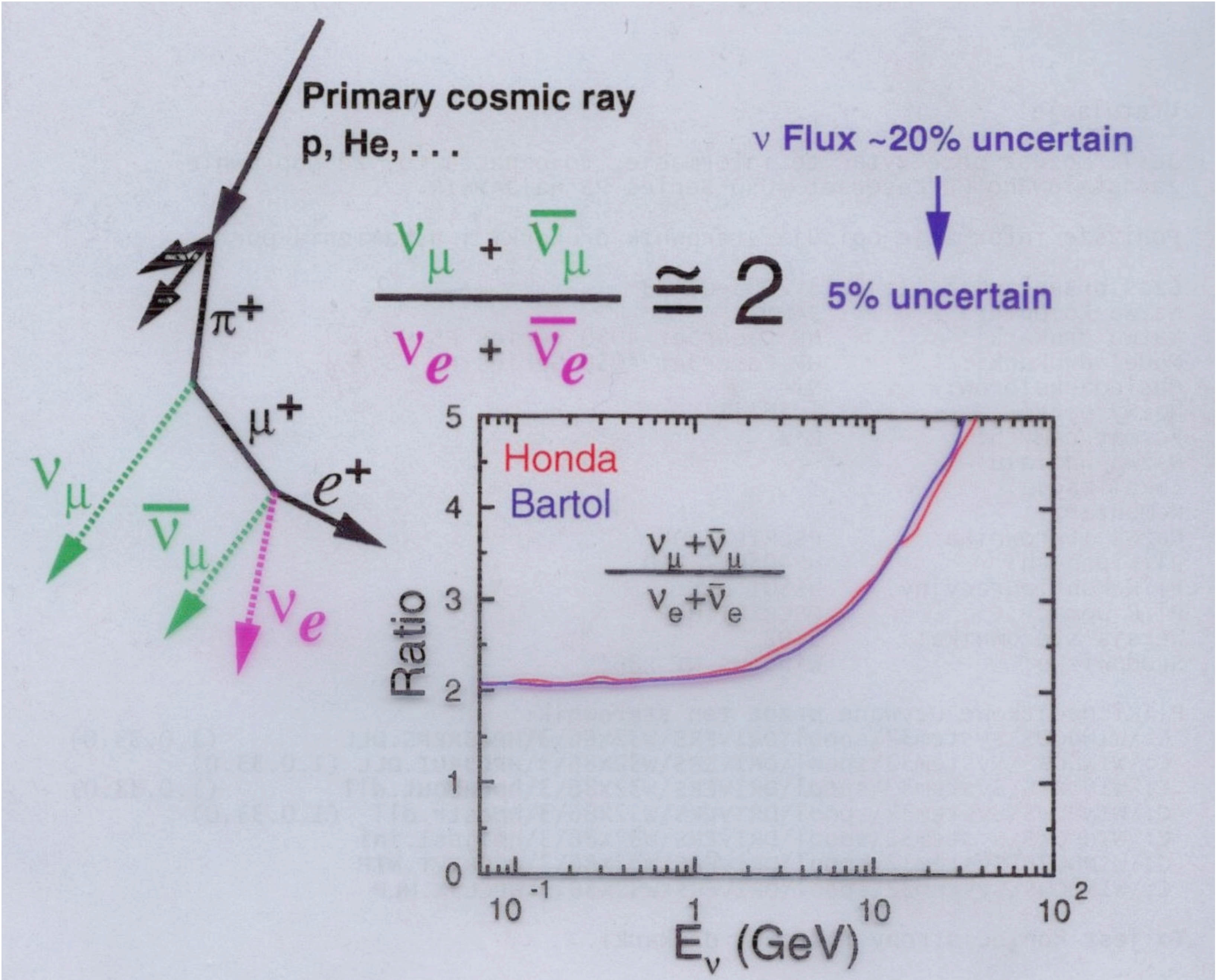
Atmospheric Neutrinos



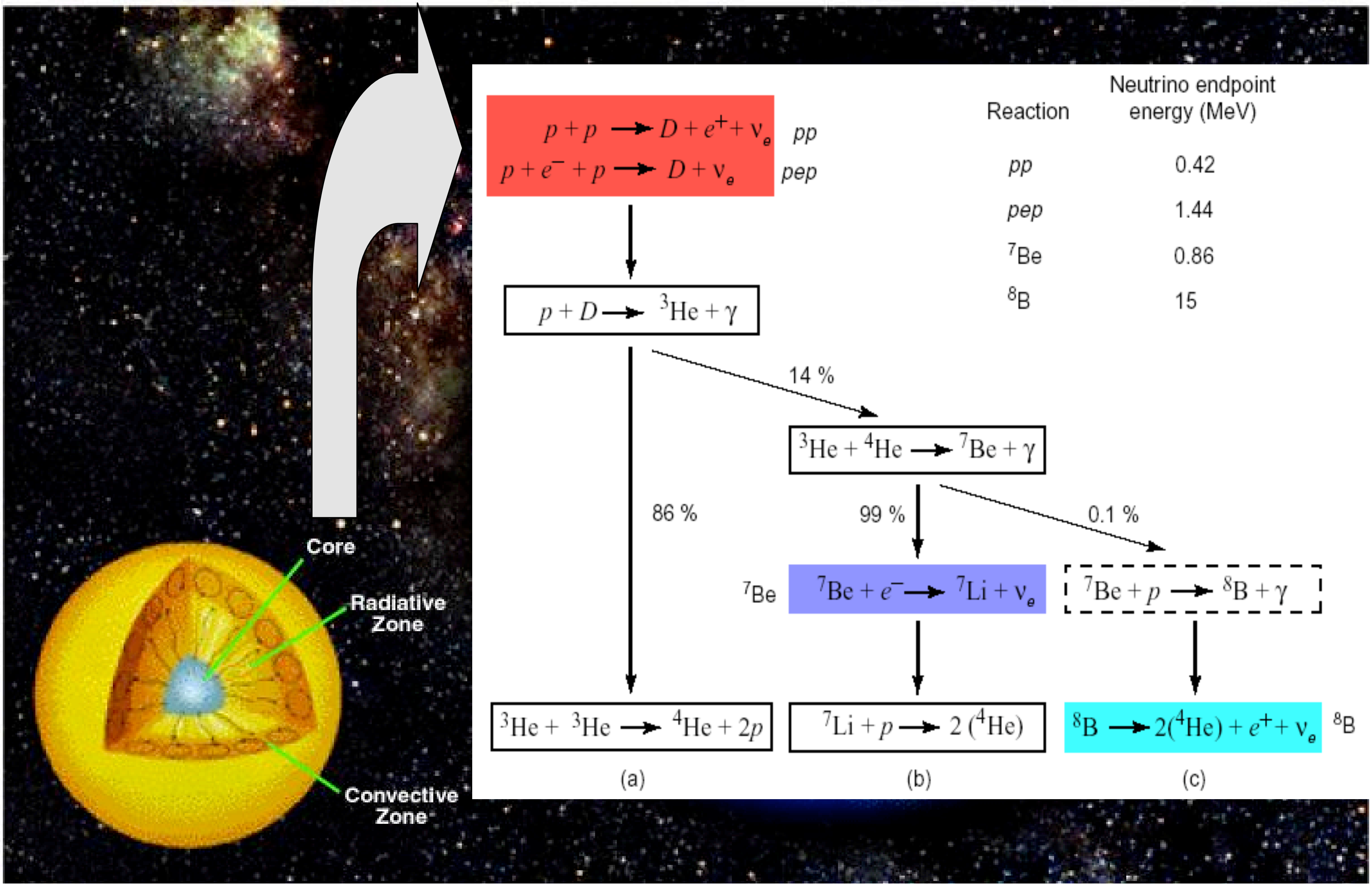
Cosmic Ray



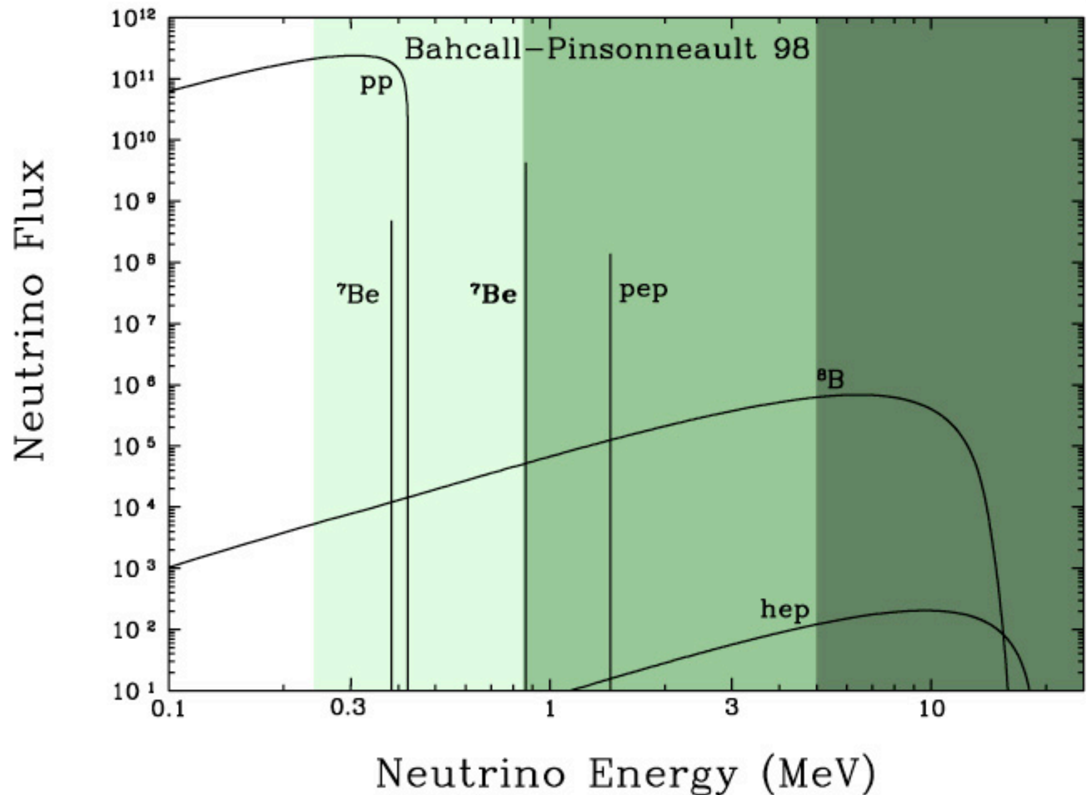
Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
ATIC
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
MSU
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
fixed target (p-A)
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
LHC (C-C)
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)



0.03 neutrinos/cm^2/s produced in the atmosphere by cosmic ray


Core
Radiative Zone
Convective Zone
$p + p \rightarrow D + e^{+} + \nu_e$ pp
$p + e^{-} + p \rightarrow D + \nu_e$ pep
$p + D \rightarrow {}^{3}He + \gamma$
14 %
86 %
${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
99 %
0.1 %
${}^{7}Be$
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$
${}^{7}Be + p \rightarrow {}^{8}B + \gamma$
${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$
${}^{7}Li + p \rightarrow 2\,({}^{4}He)$
${}^{8}B \rightarrow 2({}^{4}He) + e^{+} + \nu_e$ ${}^{8}B$
(a)
(b)
(c)
Reaction
Neutrino endpoint energy (MeV)
pp 0.42
pep 1.44
${}^{7}Be$ 0.86
${}^{8}B$ 15

Solar Neutrinos



The key overall reaction is:

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 25\ MeV$$

The flux of neutrino at Earth is:

$$\Phi_\nu = \frac{2L_{Sun}}{25\,MeV}\frac{1}{4\pi d^2} = 7\times10^{10}\,cm^{-2}s^{-1}$$

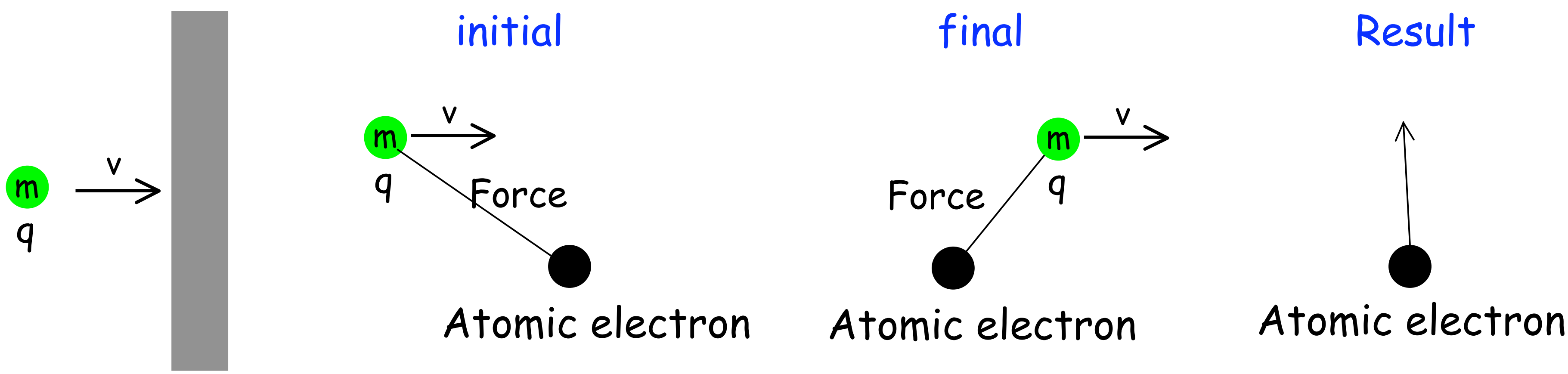
d = 1.5 × 10^8 km, distance of Earth from Sun

L_{sun} = 3.85 × 10^{26} W, solar luminosity

Detecting Particles

Detecting Charged Particles

For a charged particle going through matter:

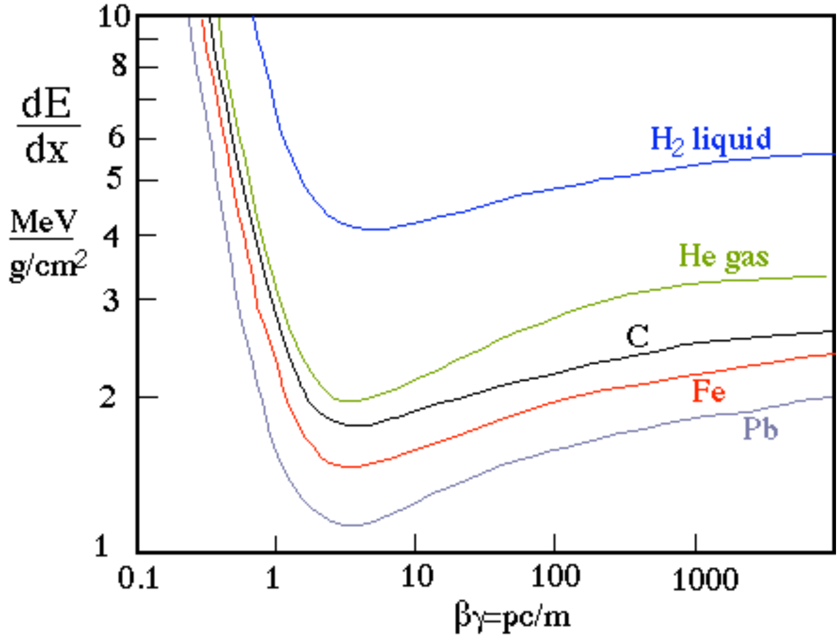


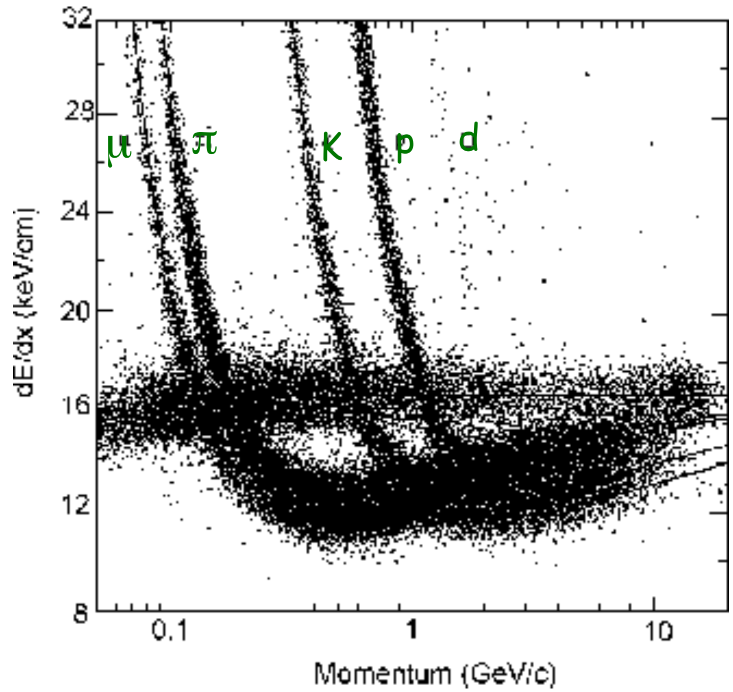
Some energy of the incident charged particle is used to release the atomic electron from its orbit, i.e. ionization. The amount of energy Loss is given by the Bethe-Bloch formula:

$$\frac{dE}{dx} = -\kappa z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e\gamma^2\beta^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

where z is the charge of the incident particle in units of the electron charge,
Z and A are the atomic and mass numbers of the medium respectively,
$\beta = v/c$
$\gamma\beta = p/m$, with p = momentum of the incident particle
δ is the density factor of the medium

Ionization Loss Of Charged Particles



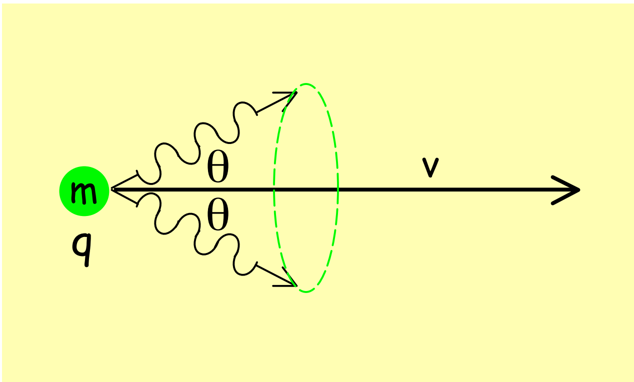


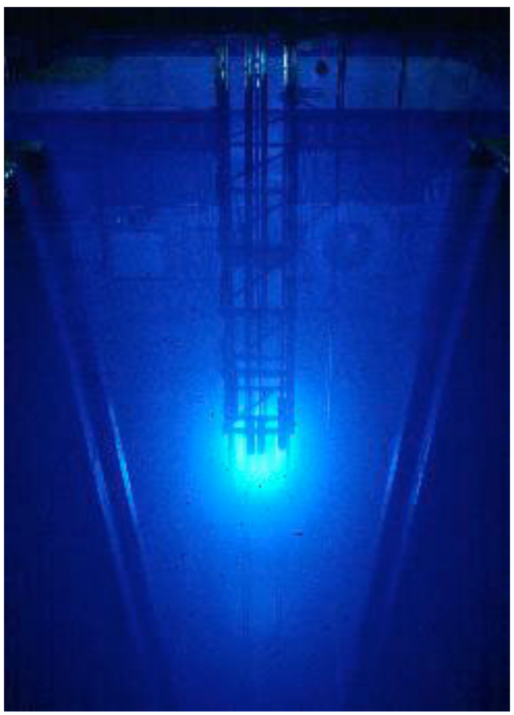
$$\frac{dE}{dx}\left[\frac{MeV}{cm}\right]=\frac{dE}{dx}\left[\frac{MeV}{\frac{g}{cm^2}}\right]\times\rho\left[\frac{g}{cm^3}\right]$$

where ρ is the density of the medium.

Cherenkov Radiation

- Photons are emitted when a charged particle moves faster than the speed of light in a medium:





The Cherenkov equation:

$$\cos\theta = \frac{1}{n\beta}$$

n is the index of refraction of the medium

For water n = 1.33, and $\beta = 1$, $\theta_{max} = 41°$

The number of photons emitted is:

$$\frac{dN}{dx} = 2\pi\alpha\left[1 - \frac{1}{n^2\beta^2}\right]\int\frac{d\lambda}{\lambda^2}$$

with α = 1/137, fine-structure constant.

More photons are emitted in short wavelength region

Detecting Photons

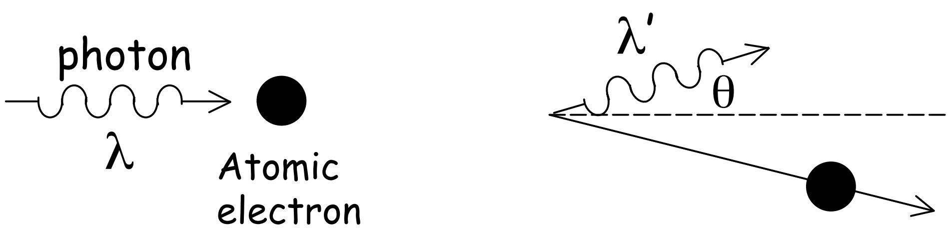
1. Photoelectric effect (for detecting a few eV photons):

$$T_{electron} = E_\gamma - \phi$$

Kinetic energy of electron

work function of material

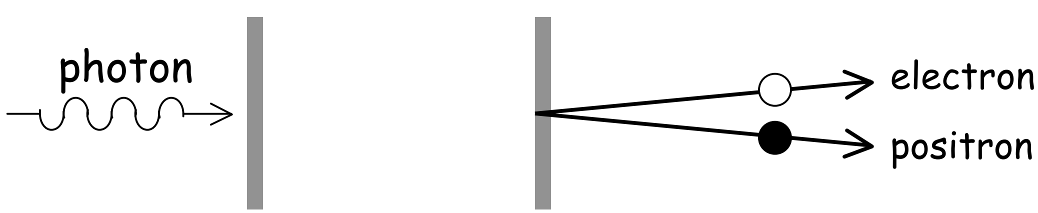
2. Compton scattering (for detecting x-ray photons):



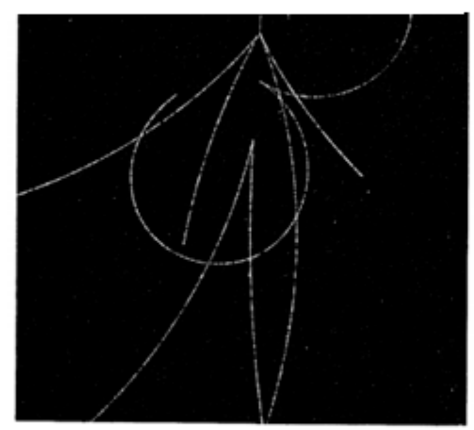
$$\lambda' - \lambda = \frac{h}{m_e}(1 - \cos\theta)$$

If $\lambda' > \lambda$, the photon loses energy to the electron

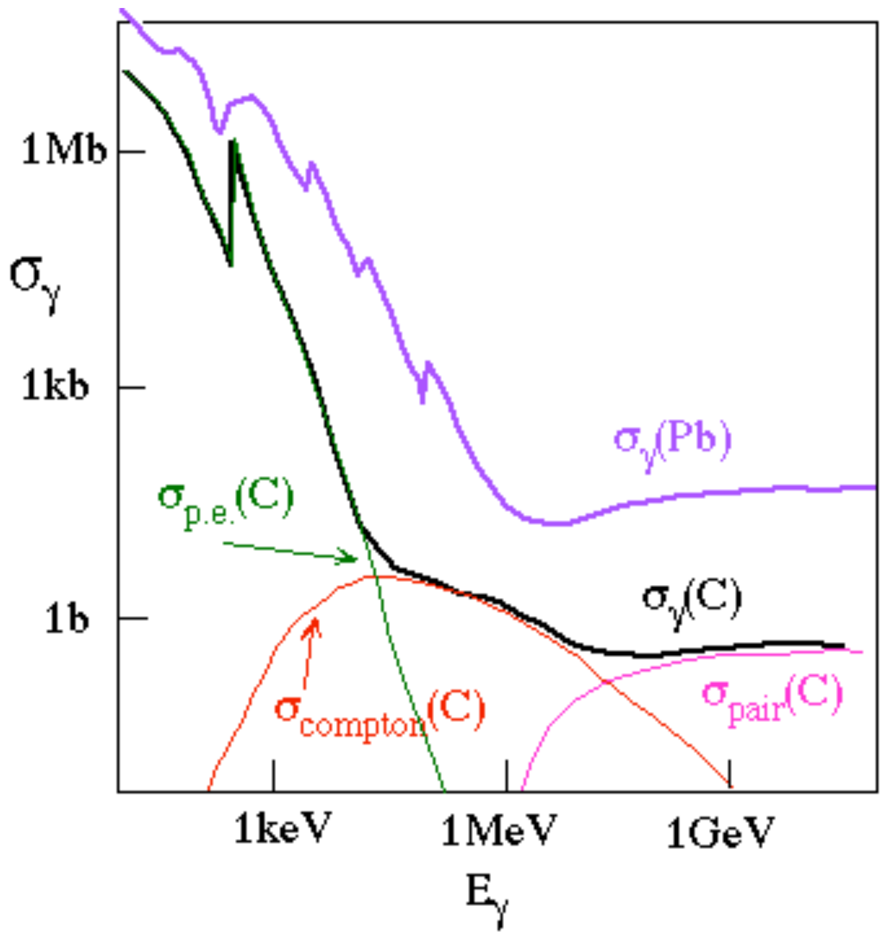
3. Pair production (for detecting MeV photons):



Material with high Z



Cross Section Of Photon Interactions



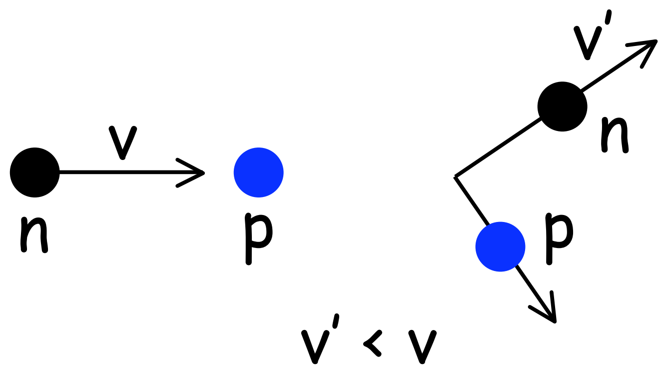
Detecting Thermal-energy Neutron

- Thermal-energy neutrons have kinetic energy:

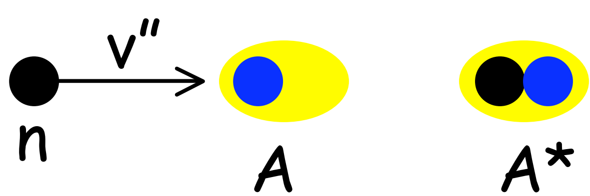
$$E_{kin} \sim kT \sim 1/40 \text{ eV (for room temperature)}$$

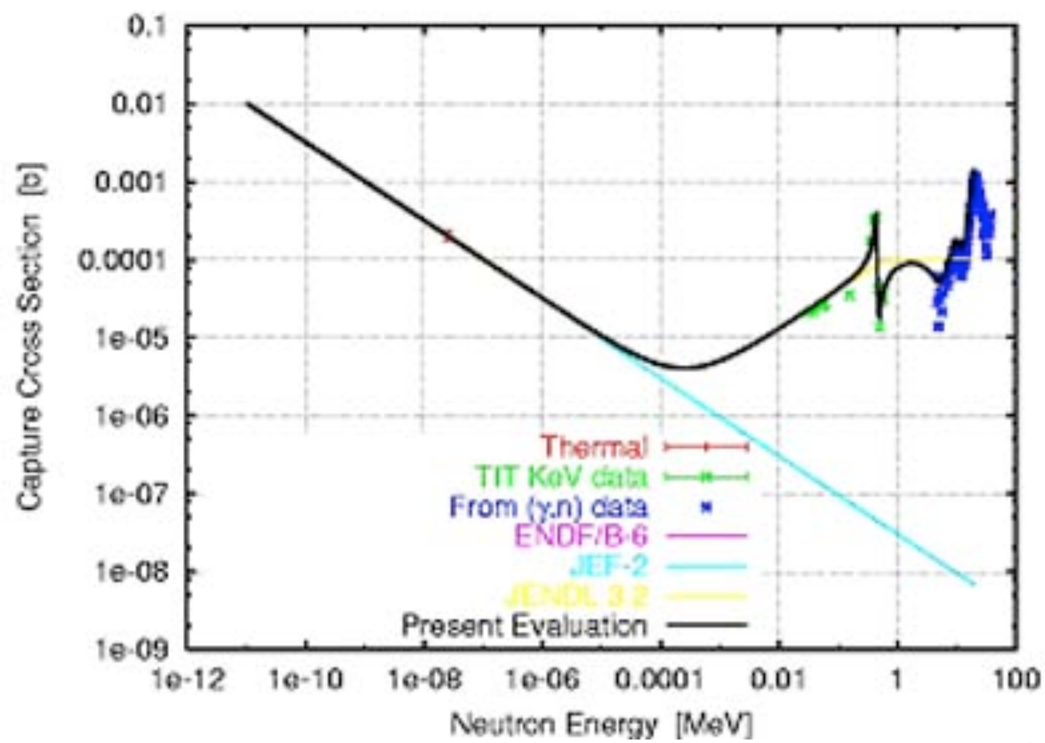
- A low-energy neutron loses its energy in the medium by colliding elastically with a proton

 - thermalization



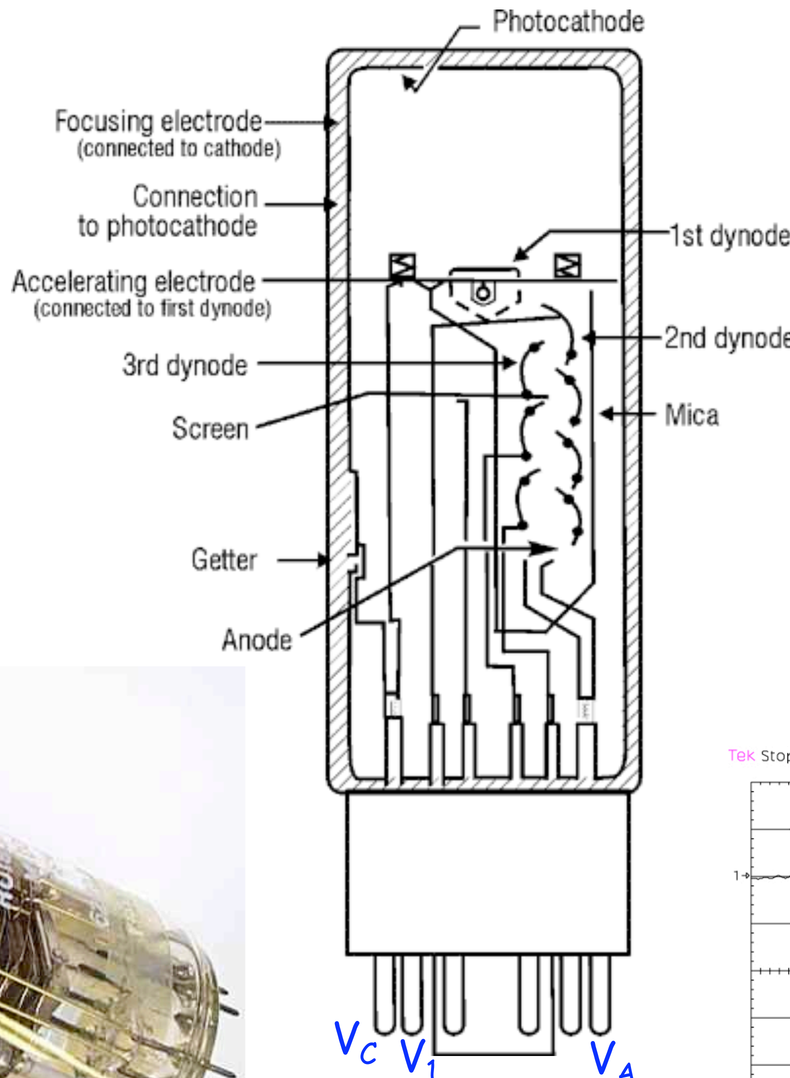
 - capture

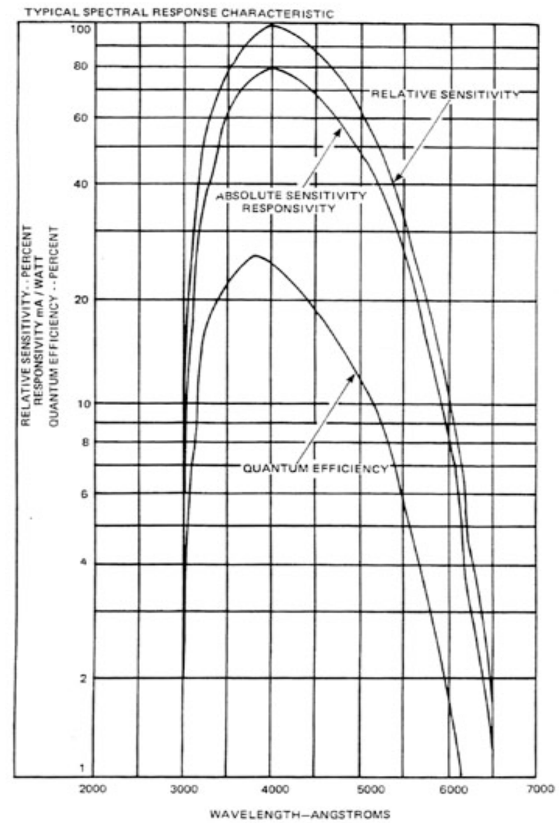


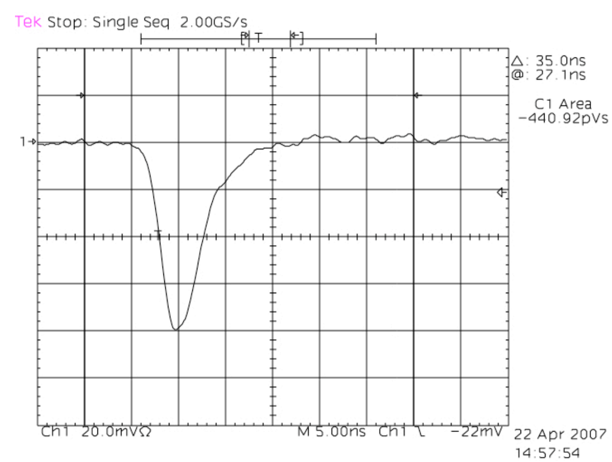


Detecting Optical Photons (Visible Light)

Photomultiplier tube







Summary

- Neutrinos are abundant
- Detect particles by letting them to interact in matter, converting their energy ultimately to something detectable, typically, via electromagnetic interactions
- Photomultiplier tube can detect even a single photon