united nations
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international atomic
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the
abdus salam
international centre for theoretical physics

ICTP 40th Anniversary

H4.SMR/1574-20

"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Neutrino Telescopes

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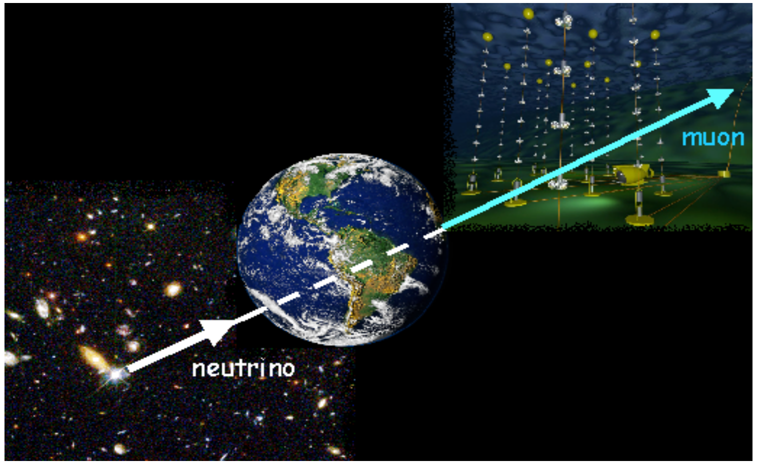
Neutrino Telescopes

John CARR
Centre de Physique des Particules de Marseille / IN2P3 / CNRS

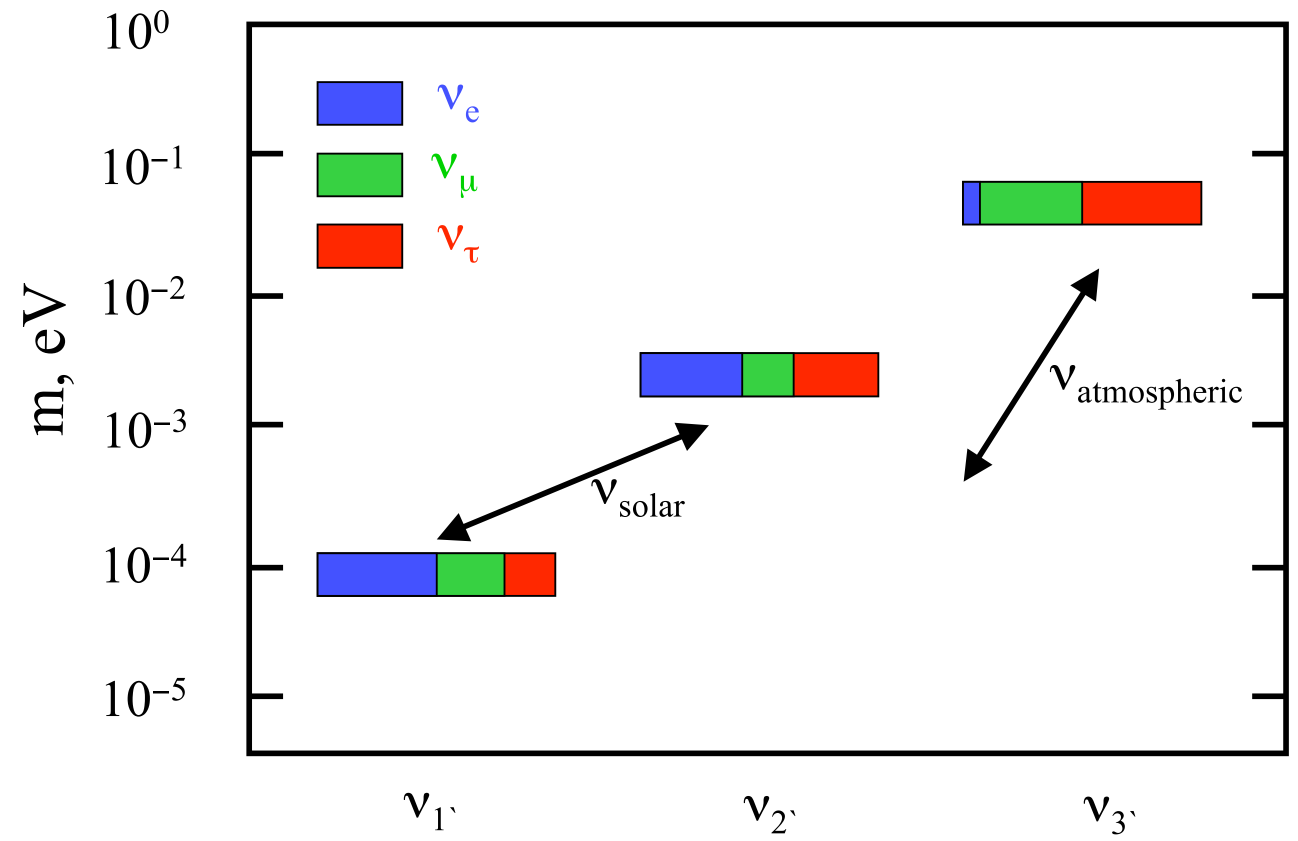


Lecture 1 Scientific motivation
Detection principals of neutrino telescopes

Lecture 2 Neutrino telescope projects
Existing results
Details of an example project

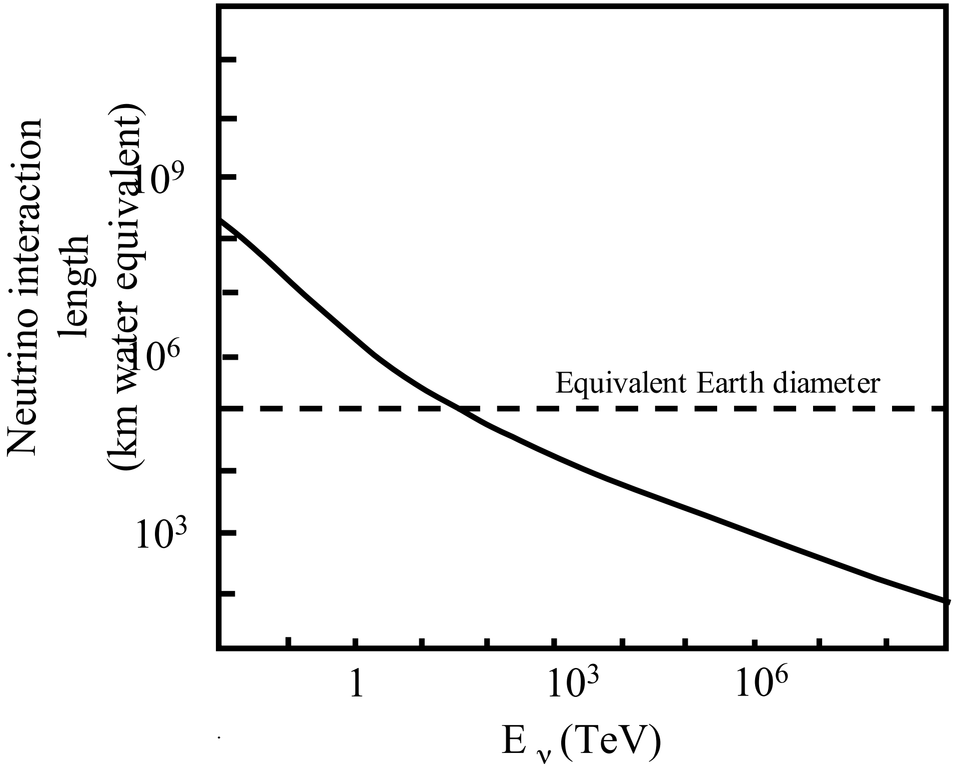
Neutrinos

Quarks		Leptons	
● u	● d	● e (electron)	• n_e (electron neutrino)
● c	● s	● m (muon)	• n_m (muon neutrino)
● t	● b	● t (tau)	• n_t (tau neutrino)



Neutrino Interactions in Matter

Interaction length of neutrinos vs energy



Astronomic sources and universe transparent to neutrinos

Earth transparent up to 100 TeV

Need massive detector

Probability of interaction ~ 10^{-5} / km water at 100 TeV

Astroparticle Physics
→ origin and structure of the universe

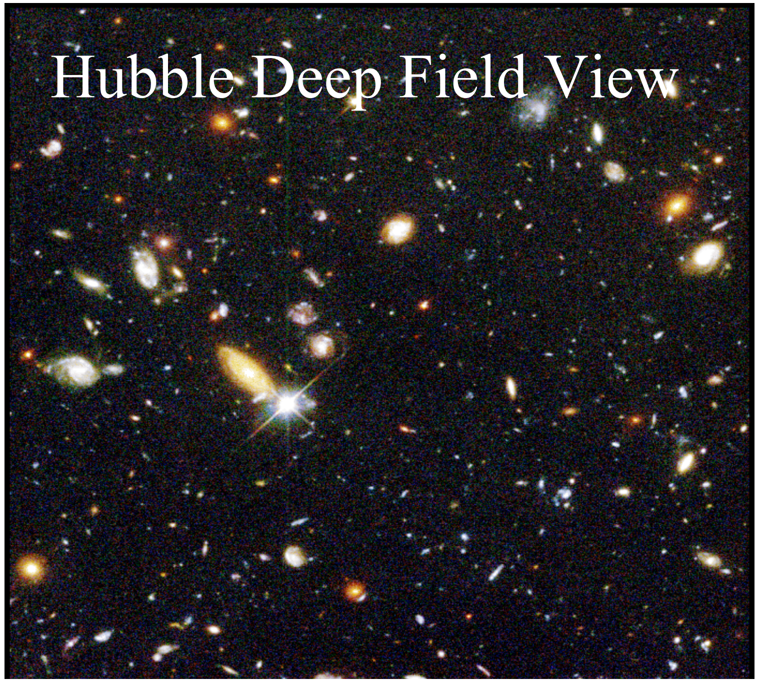
15 billion years ago

What happened in
first few minutes ?

evolution

How did
structure form ?

present time



What is
the present structure ?

Present Structure of Universe

Total average density in universe = 10^{-29} g/cm^{3}

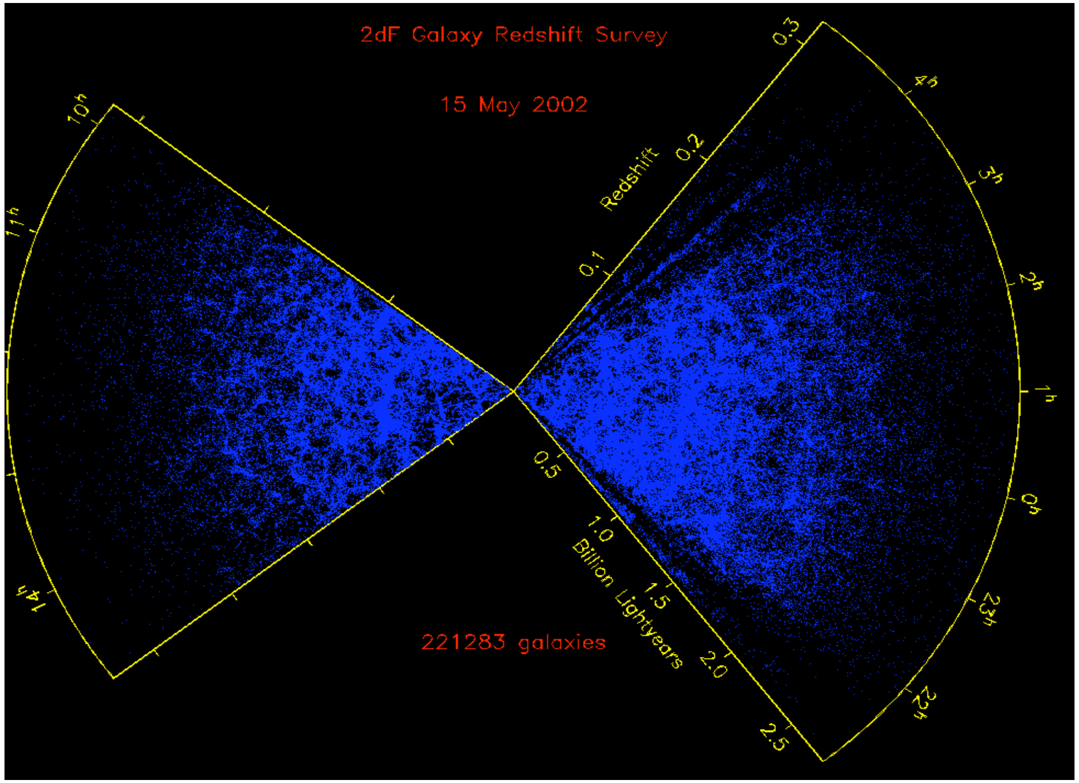
(= 5 10^{3} eV/cm^{3} = 5 H-atoms/m^{3})

Average fractions over whole universe

Radiation	0.02%
Luminous stars	0.4 %
Dark baryons	4 %
Cold Dark Matter	23 %
Dark Energy	73 %

Galaxies

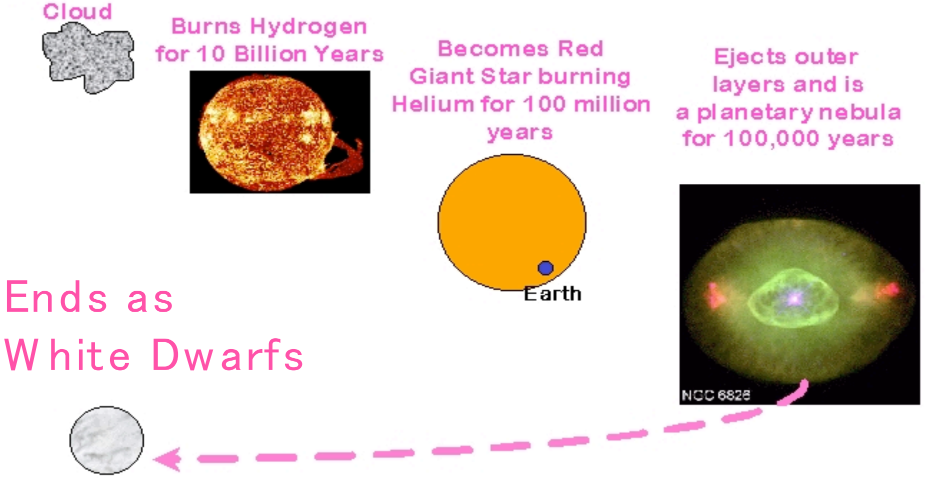
$> 10^6$ galaxies



Stars

~ 10^8 stars/galaxy

Evolution of small stars like sun



Forms in
Dust & Gas
Cloud

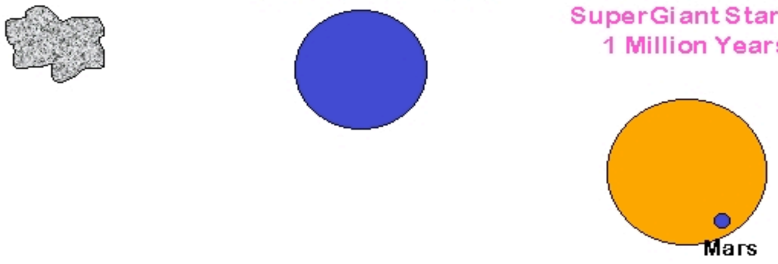
Burns Hydrogen
for 10 Billion Years

Becomes Red
Giant Star burning
Helium for 100 million
years

Ejects outer
layers and is
a planetary nebula
for 100,000 years

Ends as
White Dwarfs

Evolution of big stars

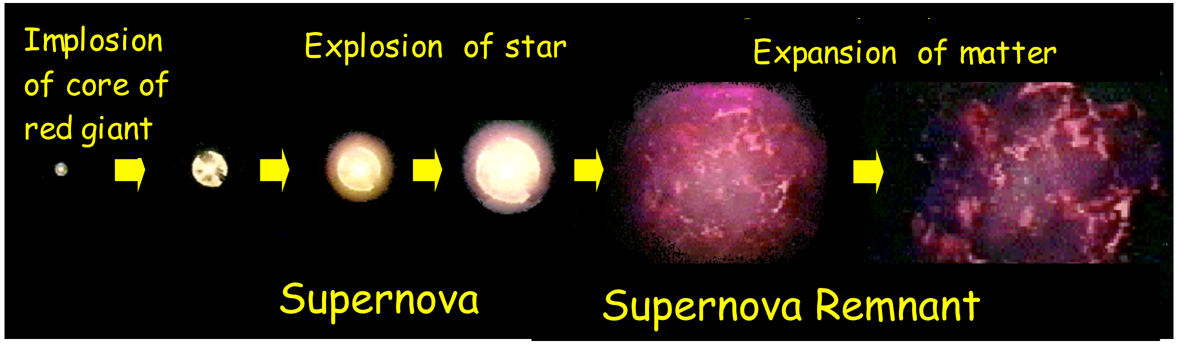


Form
Dust & Gas
Cloud

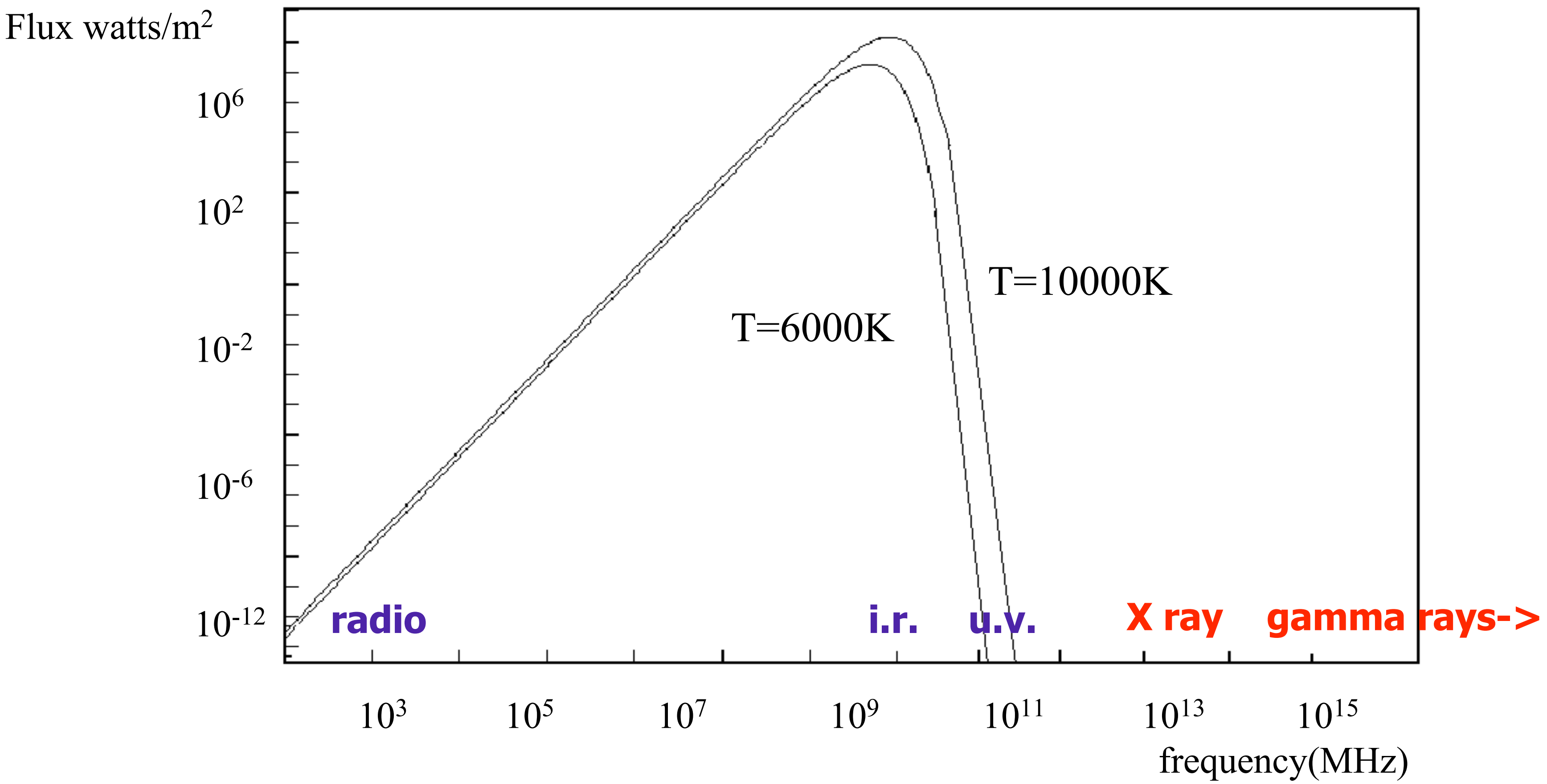
Burns Hydrogen
for 50 Million Years

Becomes Red
SuperGiant Star for
1 Million Years

Red giant explodes as Supernova



Thermal Radiation from Stars



Normal Stars surface temperature ~3000 to 30000K

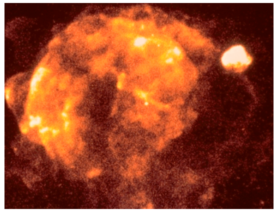
thermal radiation: radio → ultra -violet

non-thermal radiation: X-rays, gamma rays

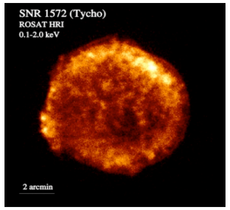
(higher in energy more extreme is the source)

SuperNovae Remnants

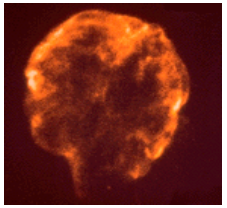
Vela

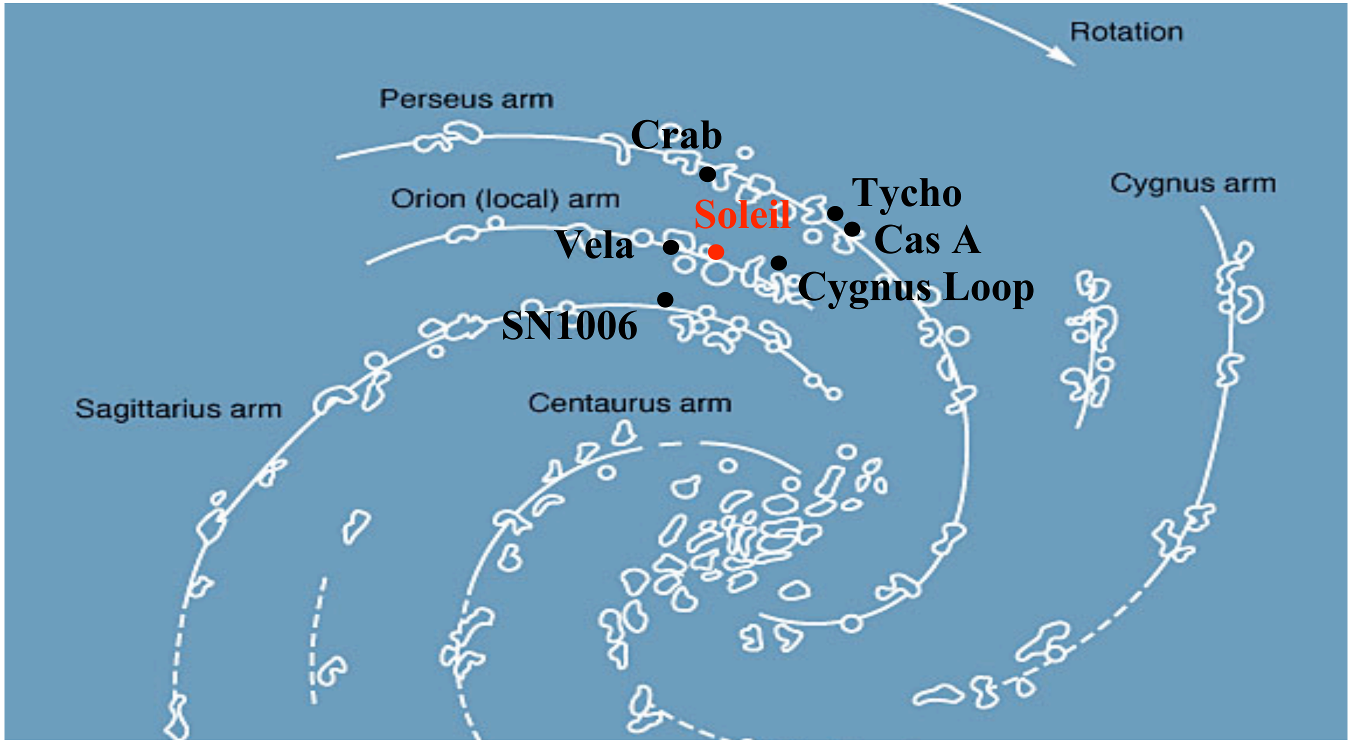


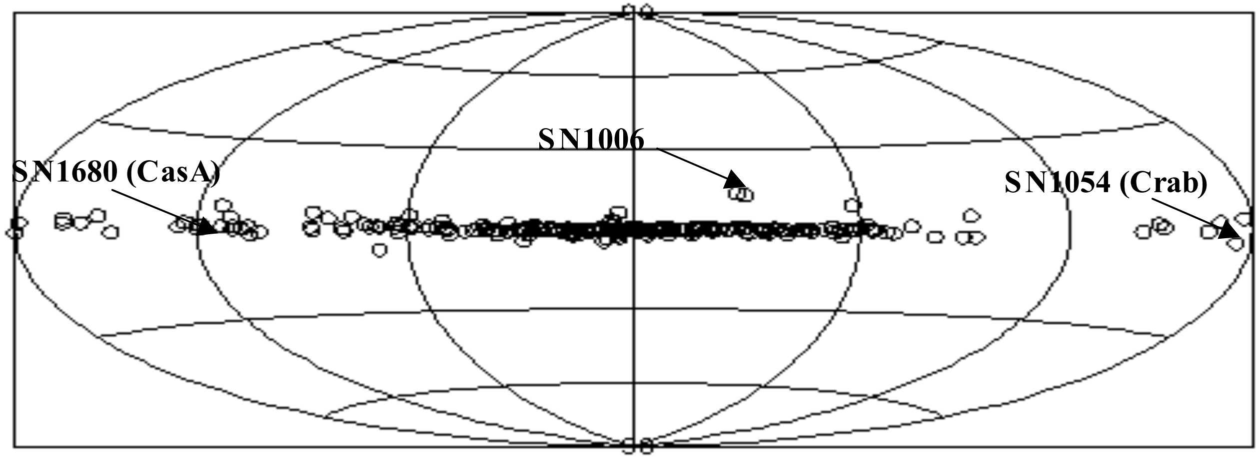
Tycho



Cygnus

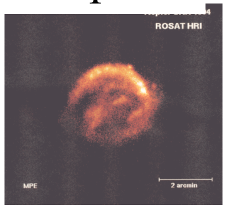




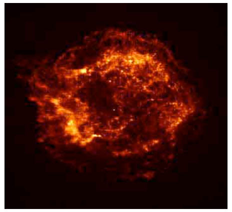


Crab

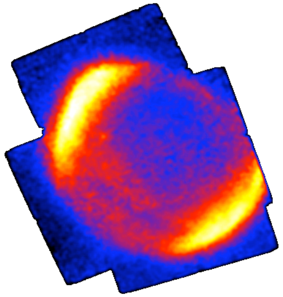
Kepler



Cas A

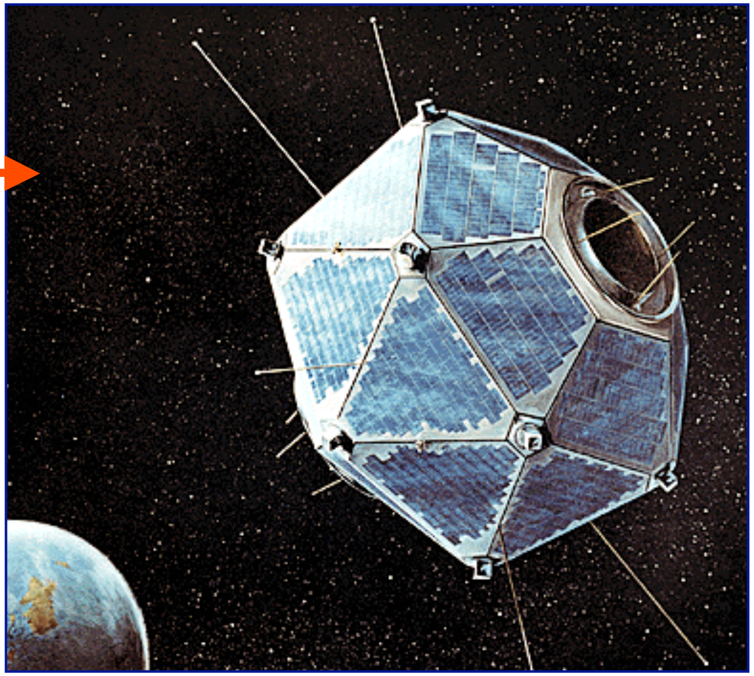


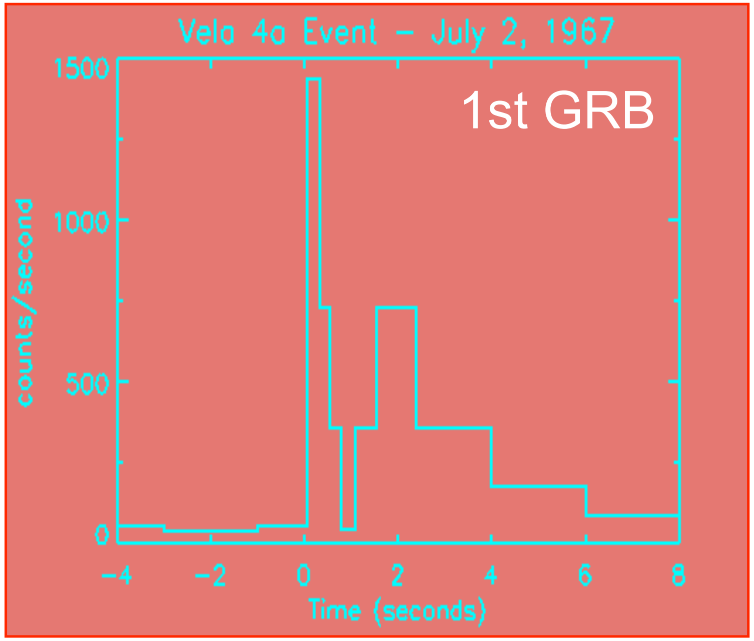
SN1006



Gamma-Ray Bursts

Gamma Ray Burst were first detected by the Vela satellites that were developed in the sixties to monitor nuclear test ban treaties.

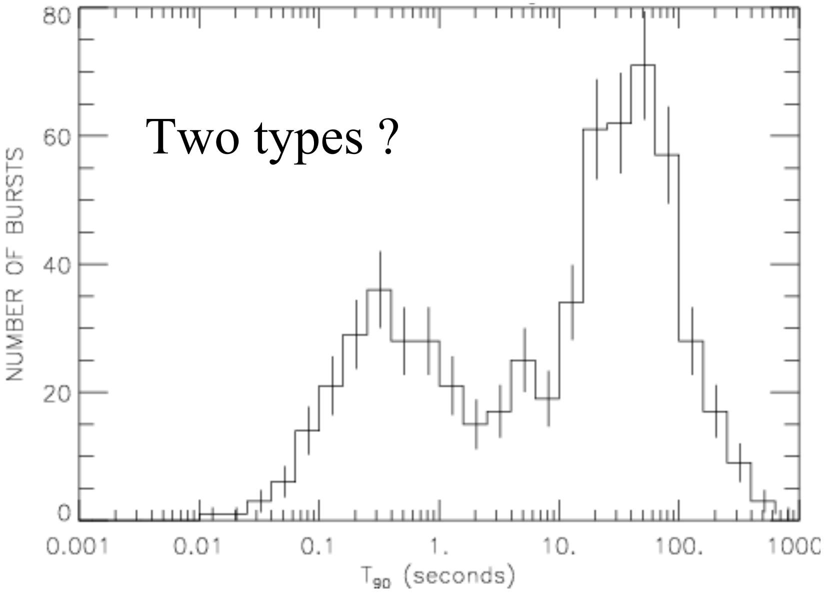




Gamma Ray Bursts

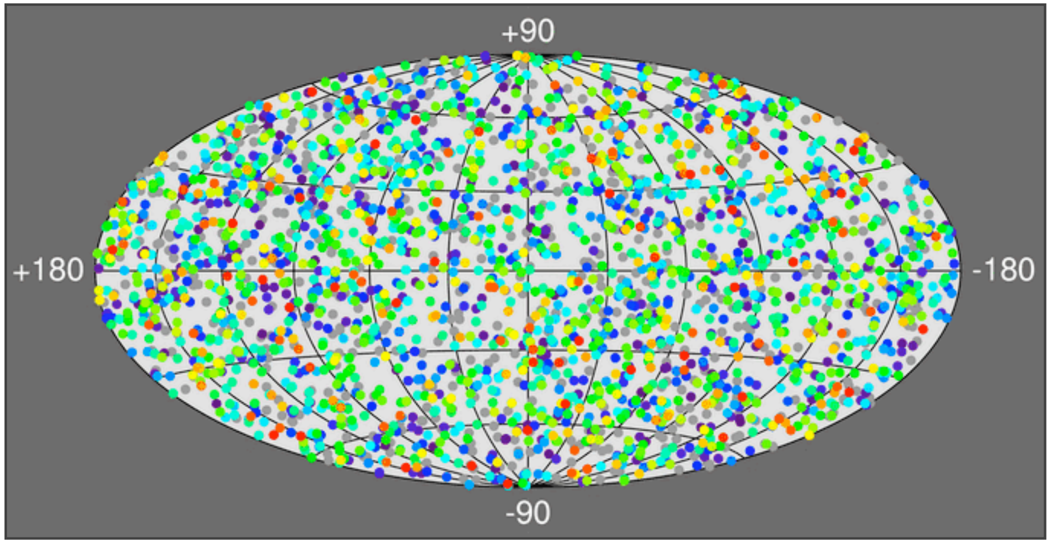
1-2 per day observed by BATSE

Burst duration



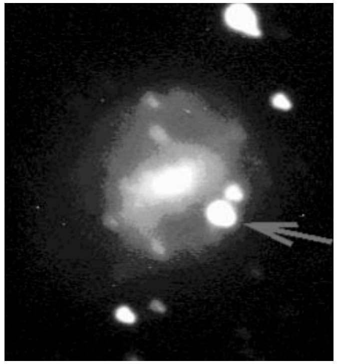
Two types ?

Isotropic sky distribution



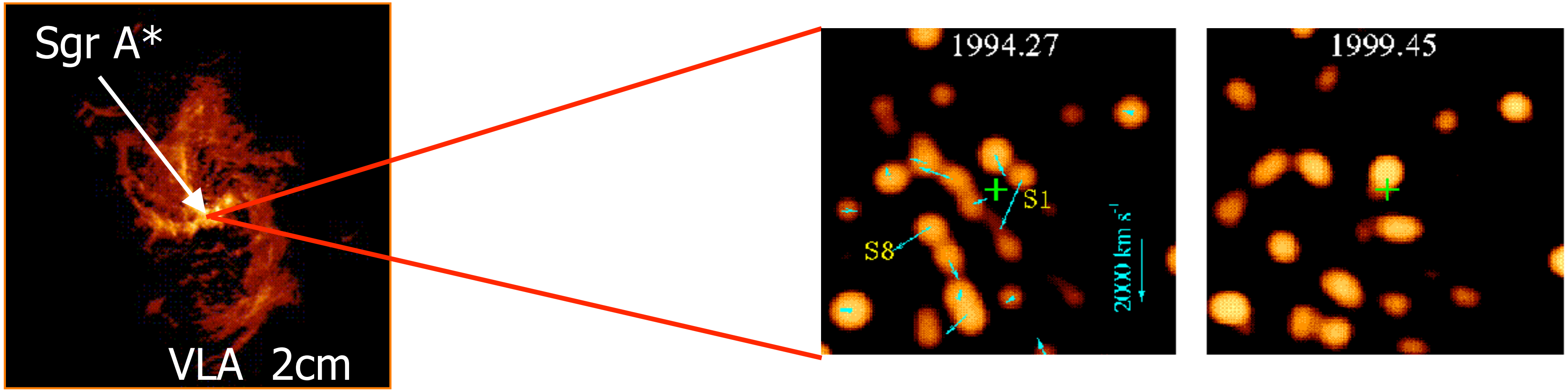
Redshifts measured for about 20
⇒ extragalactic distances

Some evidence for GRB on sites of previous supernova



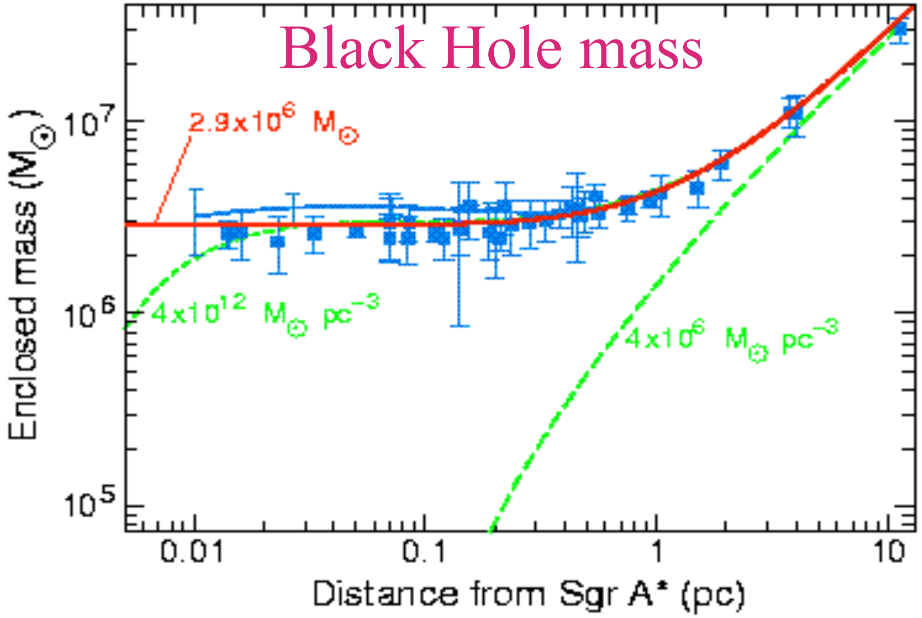
Black Holes

Black Hole at Centre of Milky Way Galaxy

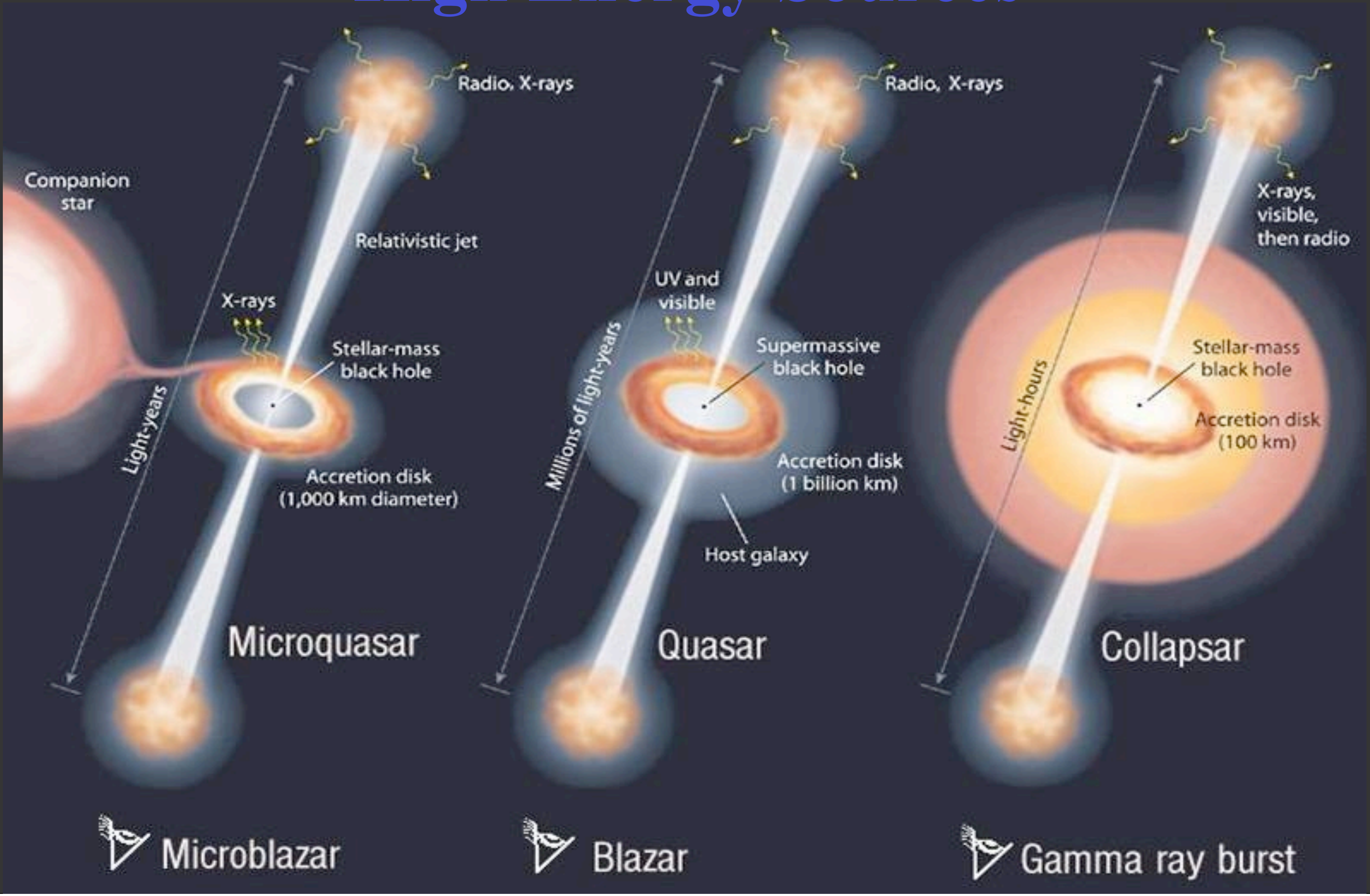


Radio

Infrared

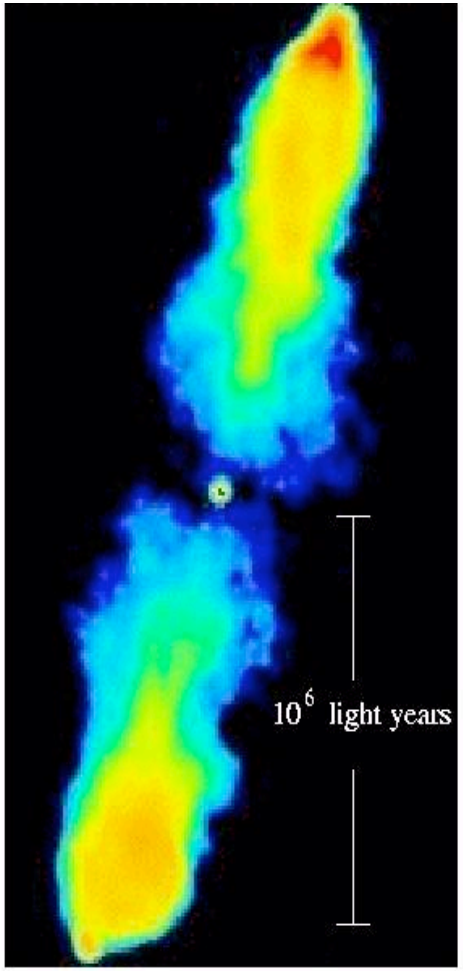


High Energy Sources

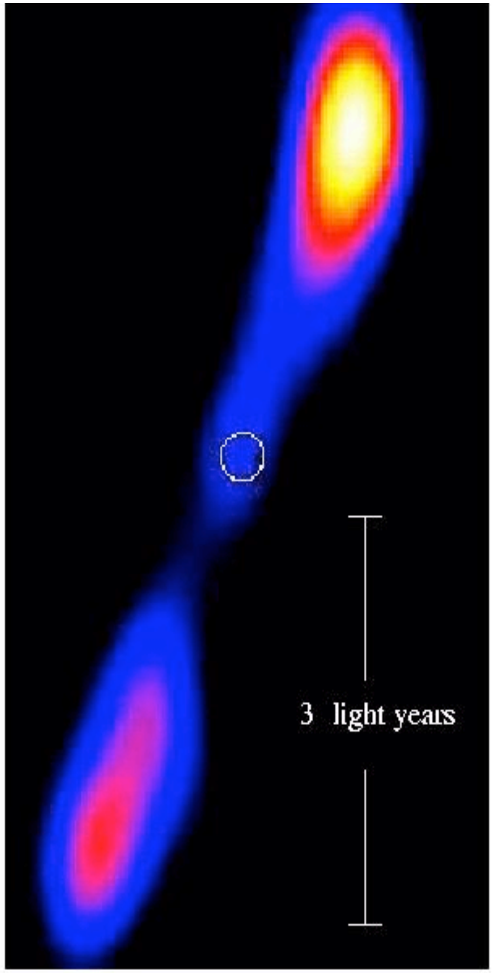


QUASARS & MICROQUASARS

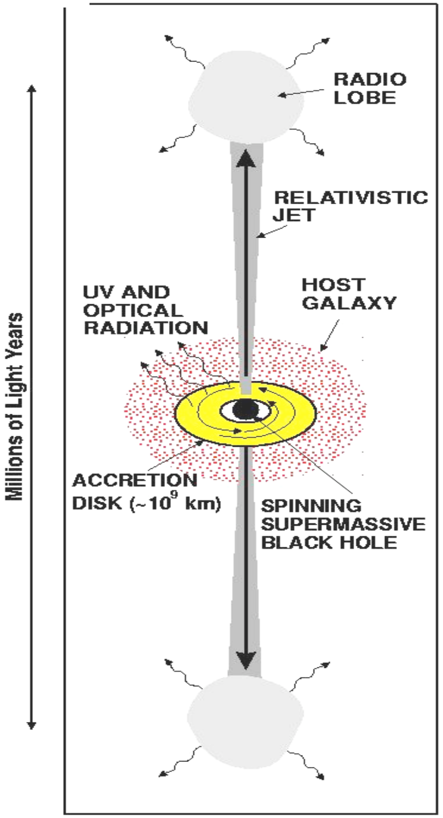
QUASAR



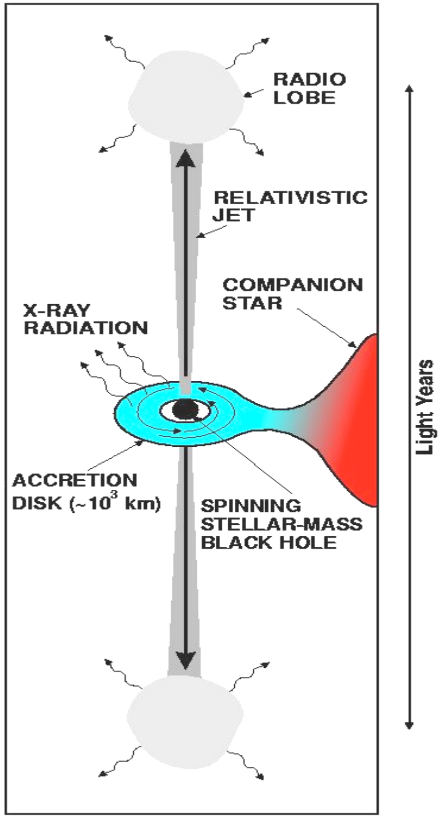
MICROQUASAR



QUASAR



MICROQUASAR

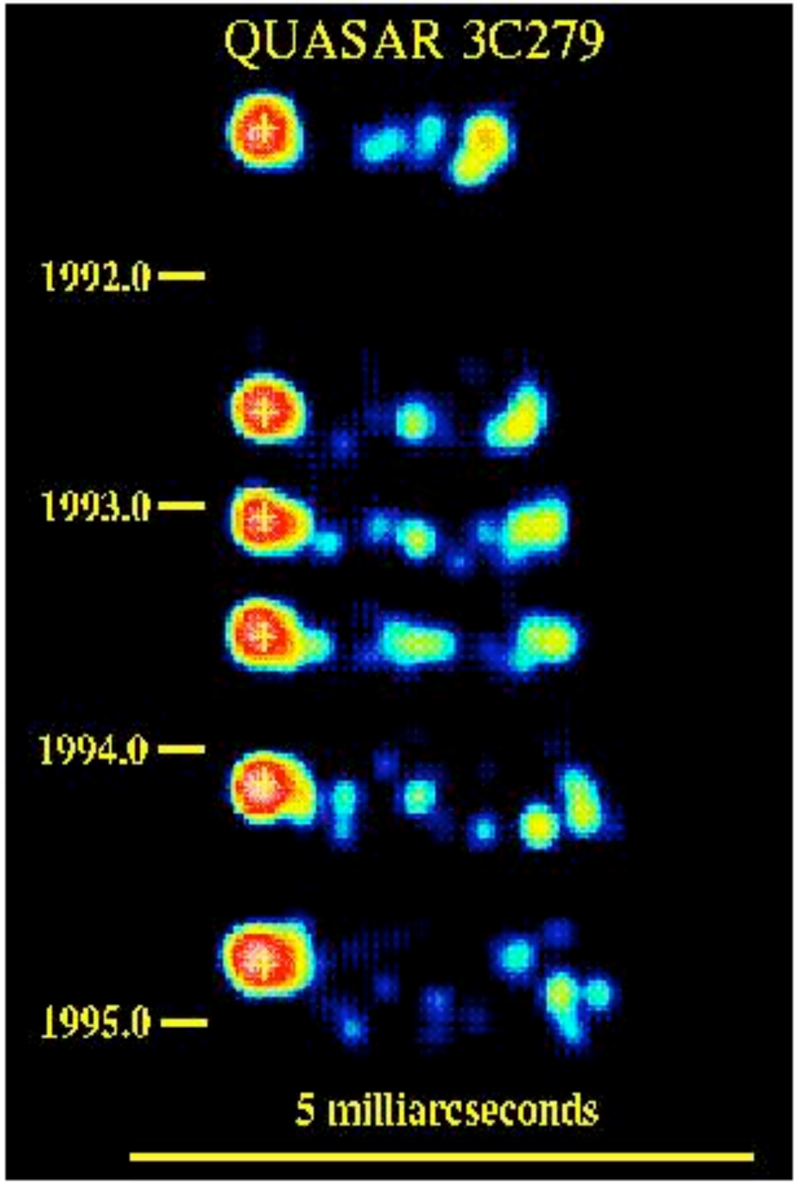


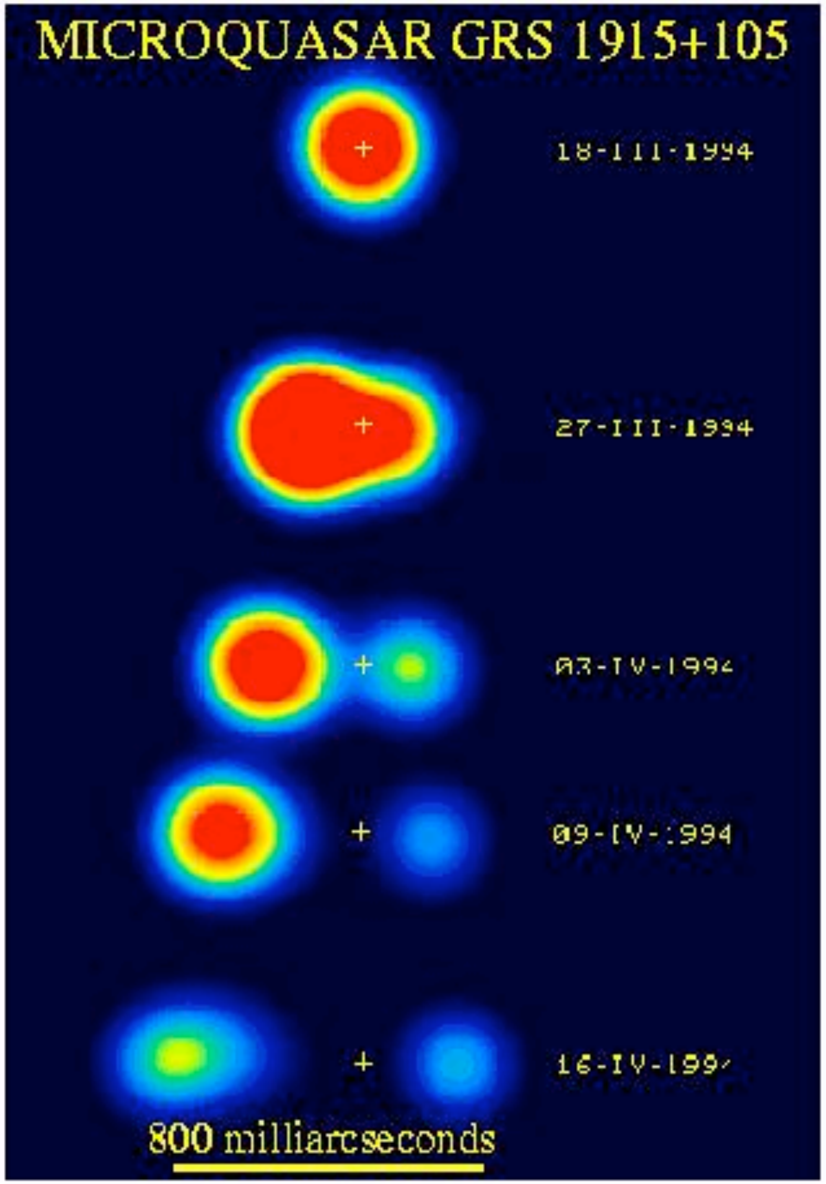
Central black hole

10^8- 10^9 $M_\odot$
10^2- 10^5 $M_\odot$

distant galaxies **local galaxy**

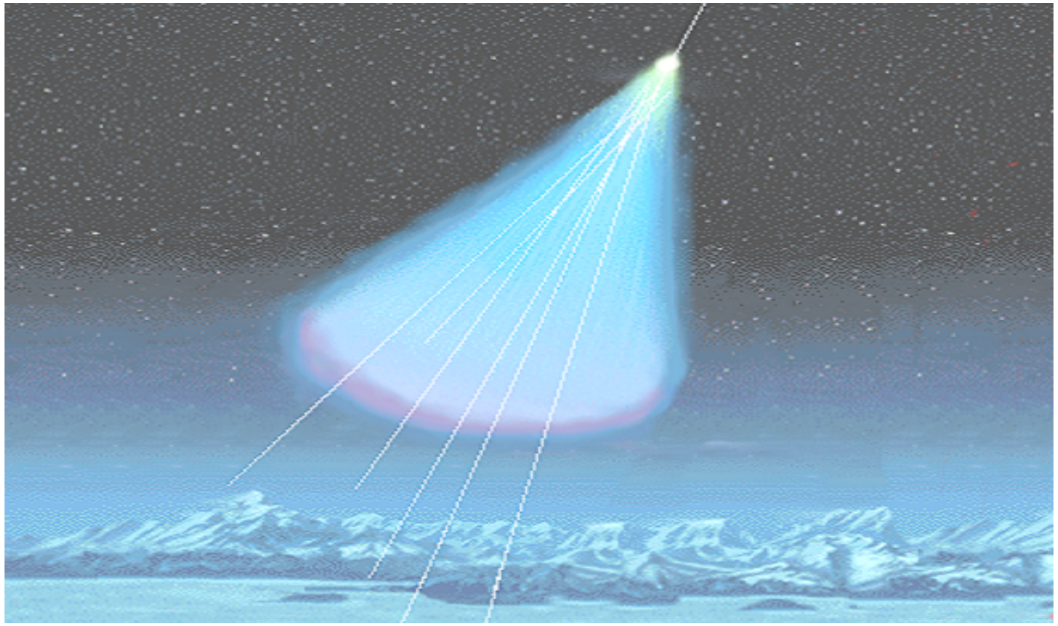
QUASARS & MICROQUASARS





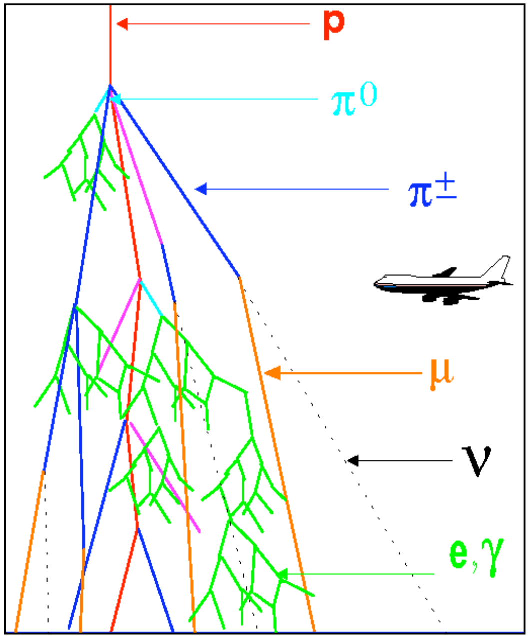
Cosmic Rays

Primary cosmic ray
produce showers in atmosphere



at ground level :~ 1 cm²/min (>1 GeV)

Primary:
p 80 %, α 9 %, n 8 %, …

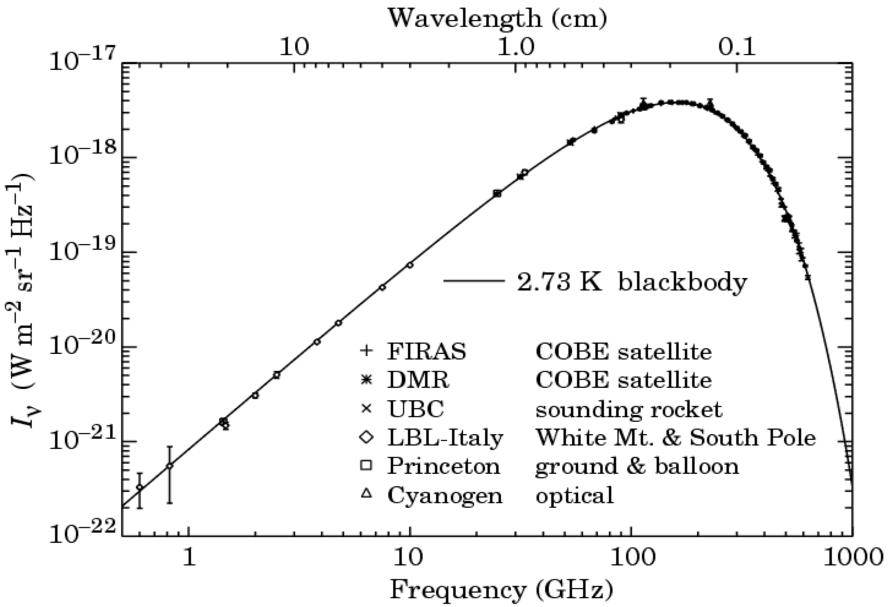


Secondary at ground level:
ν 68 %, μ 30 %, ...

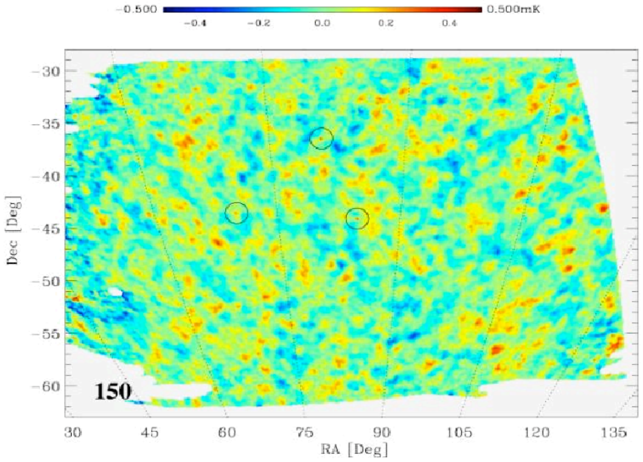
Energy density in galaxy = 0.5 eV / cm^3 ≈ energy in local starlight

Cosmic Microwave Background

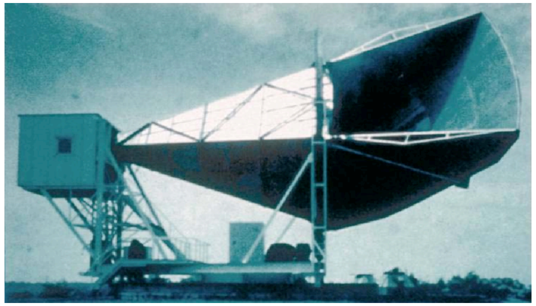
3K photon background
Relic of big bang



Boomerang data



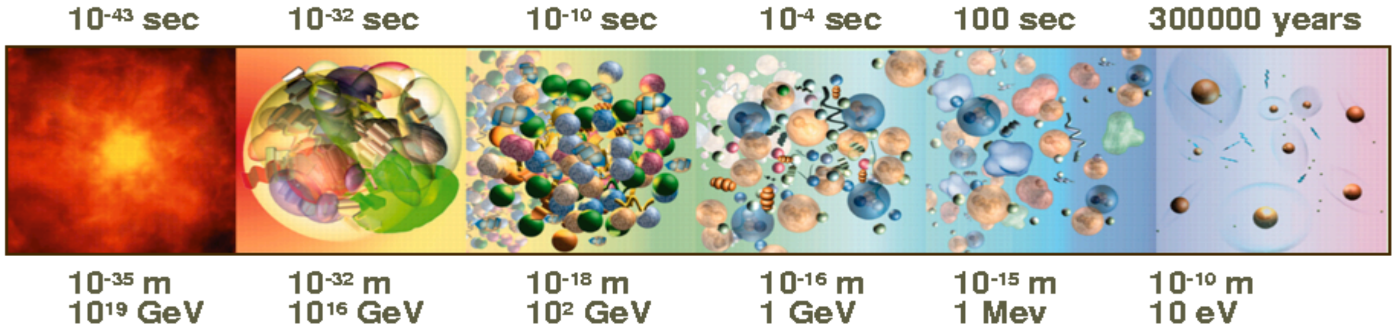
Discovery
Penzas and Wilson

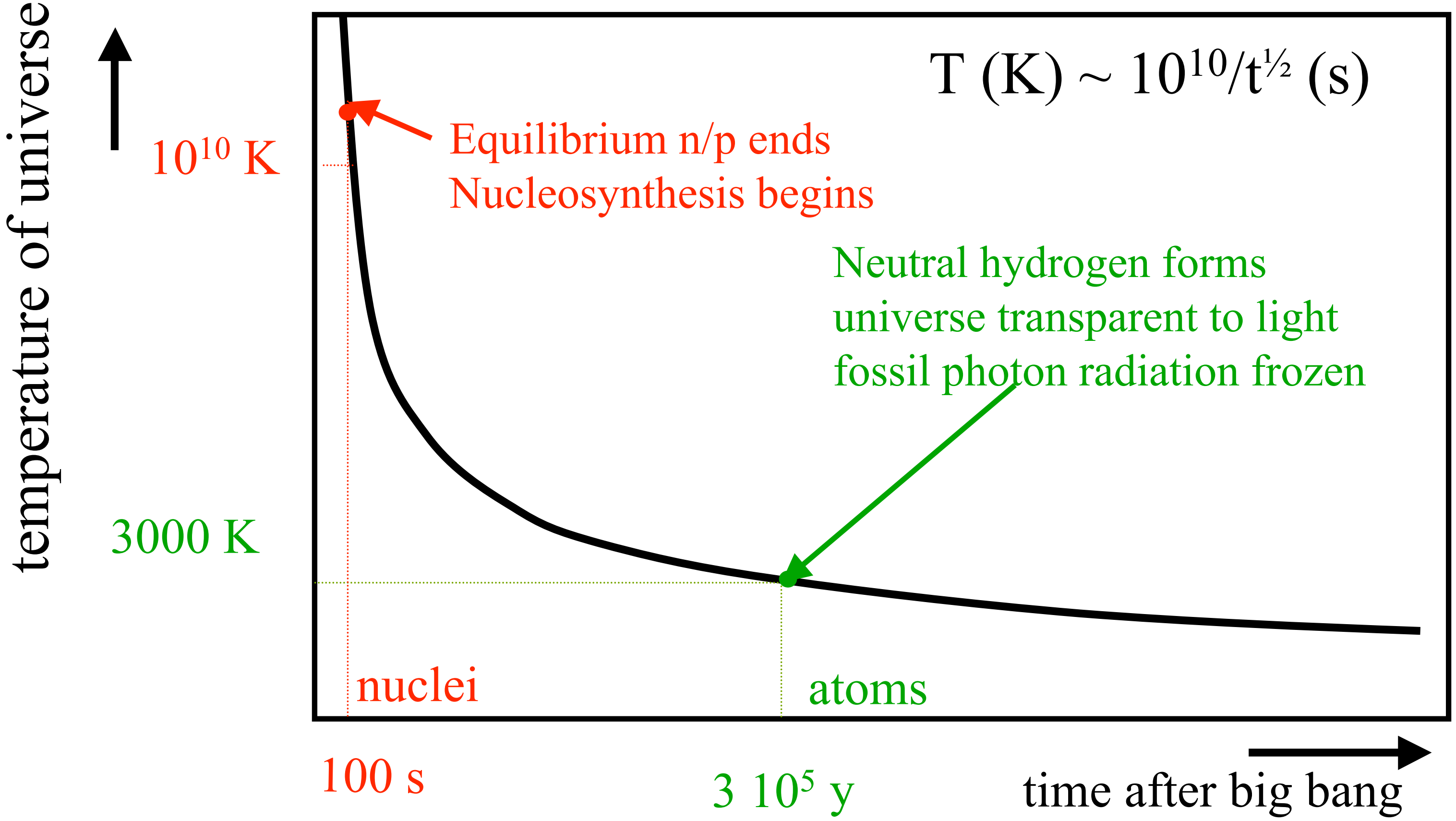


WMAP new data 2003 …

CMB = 0.005 % of total energy density
= 0.25 eV/ cm^3

Origin of the Universe : Big Bang





Multi-Messenger Astronomy

Radio

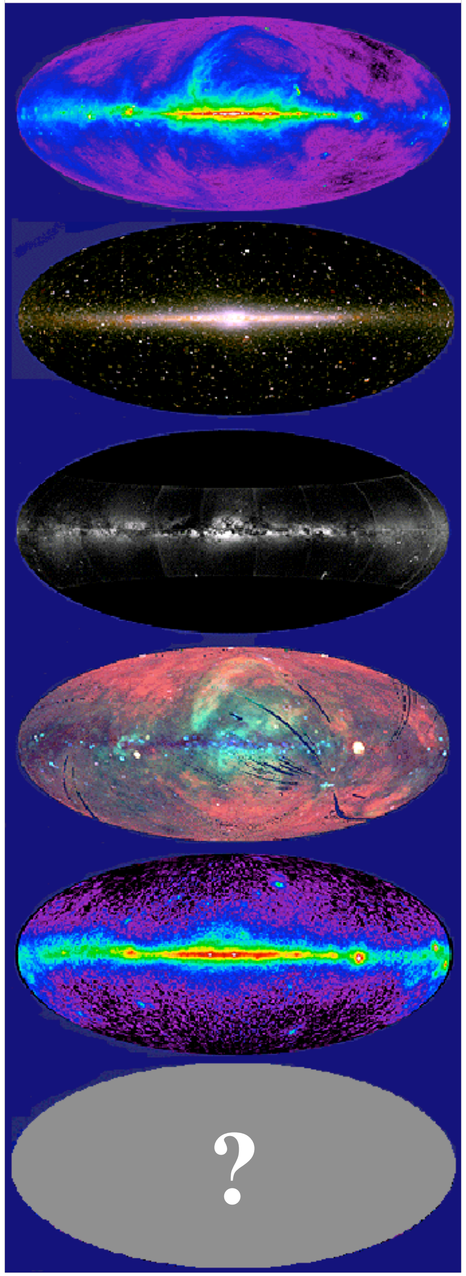
Infrared

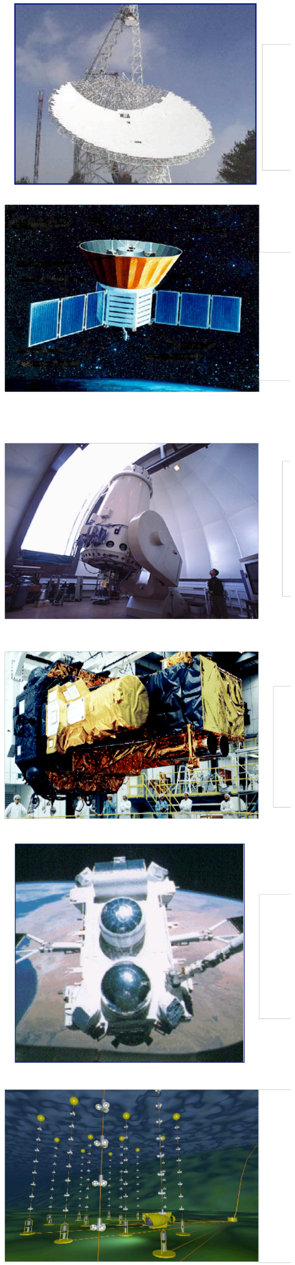
Visible light

X-ray

Gamma Ray

Neutrino





Production and transmission of neutrinos

Neutrinos produced in hadronic interactions of
high energy protons or nuclei

$p/A + p/g \to p^0 + p^\pm + \ldots$

$p^0 \downarrow g\,g$

$p^\pm \downarrow n_m\,m$

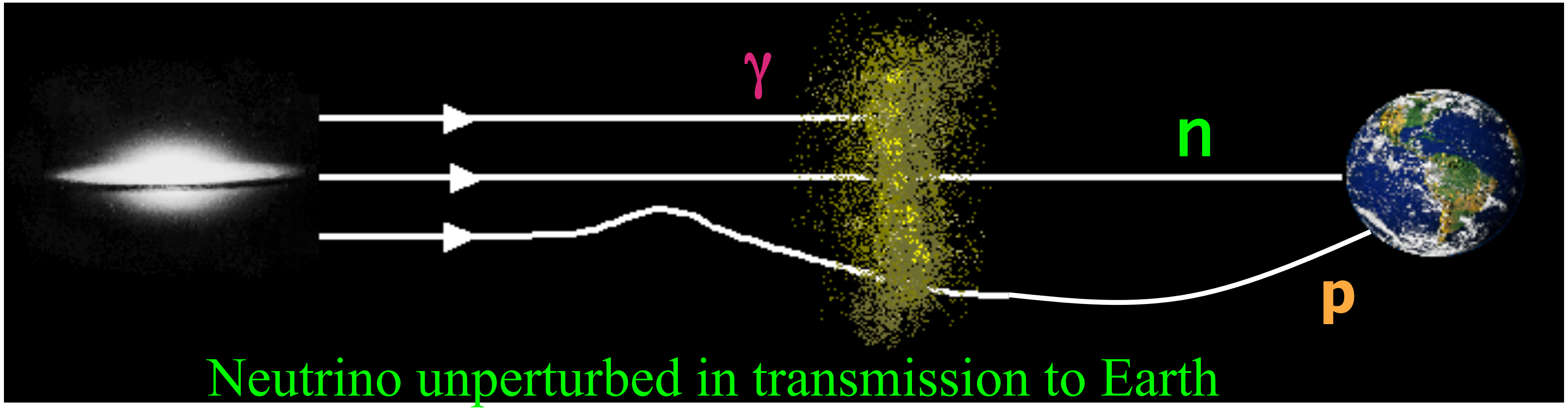
$m \downarrow n_m\,n_e\,e$

at source

$\nu_e : \nu_\mu : \nu_\tau$

$=$

$1 : 2 : 10^{-5}$



Neutrino unperturbed in transmission to Earth

at Earth

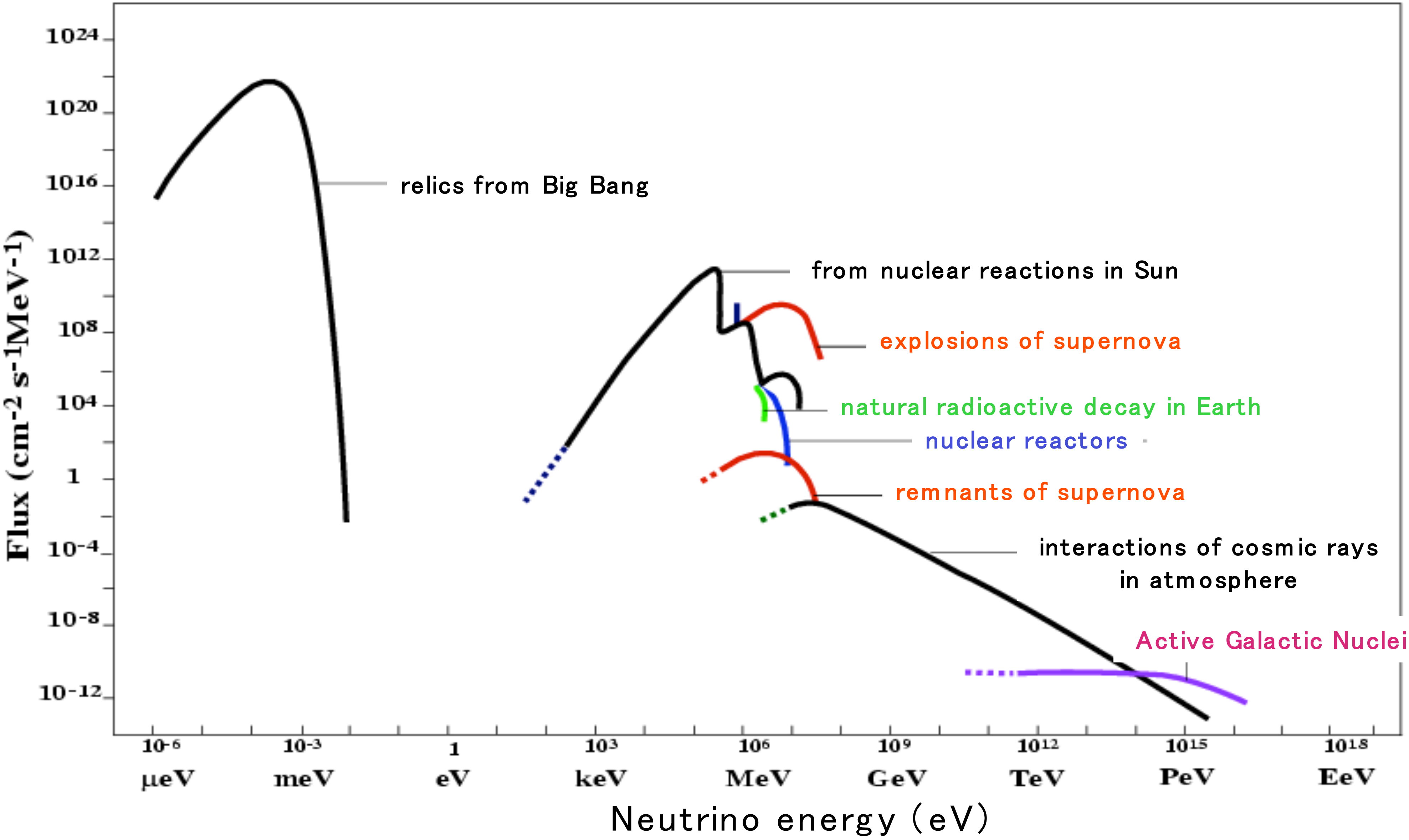
$\nu_e : \nu_\mu : \nu_\tau$

$=$

$1 : 1 : 1$

In transit : oscillations between flavours

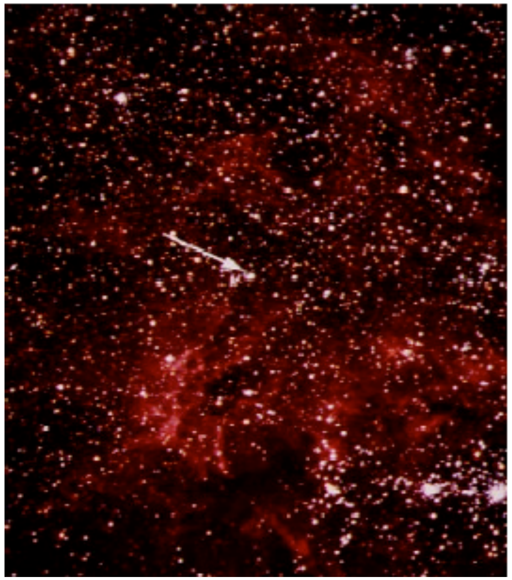
Neutrinos arriving at Earth



Supernova 1987a

Most distance source of neutrinos so far observed

L = 50 kpc (150 light years)



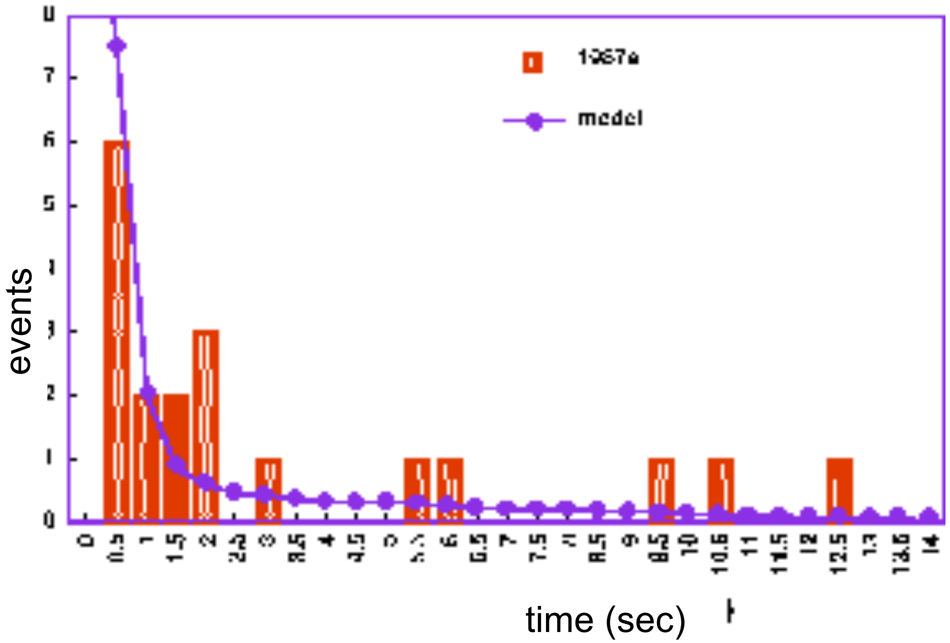
Night before, 23 feb

4 hours after explosion

neutrinos observed

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

$e^+ + e^- \rightarrow n_e + n_e, \; n_m + n_m$



Matter/Energy in the Universe

$$W_{\text{total}} = W_M + W_L \sim 1$$

matter dark energy

Matter:

$$W_M = W_b + W_\nu + W_{CDM} \sim 0.27$$

baryons neutrinos cold dark matter

Baryonic matter :

$W_b \sim 0.04$

stars, gas, brown dwarfs, white dwarfs

Neutrinos:

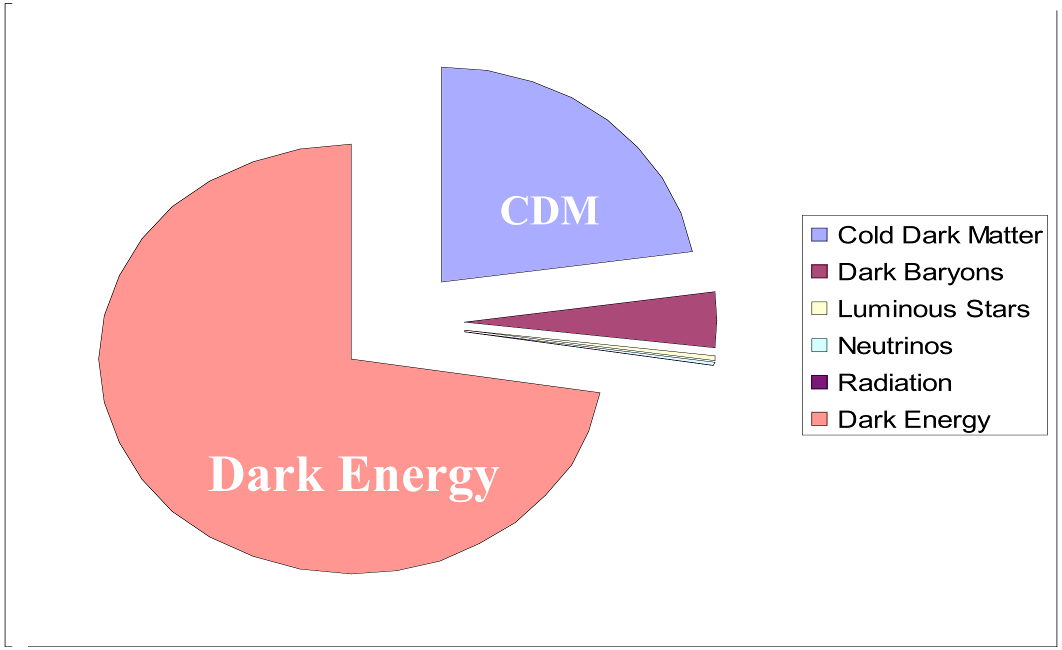
$W_\nu \sim 0.003$

if M(n) ~ 0.1 eV

Cold Dark Matter :

$W_{CDM} \sim 0.23$

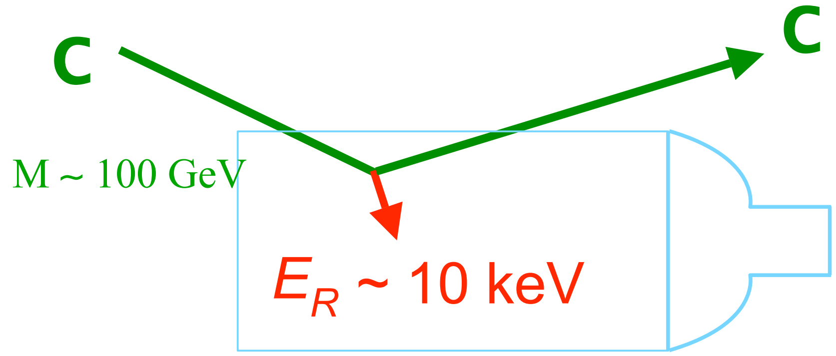
WIMPS/neutralinos, axions, …

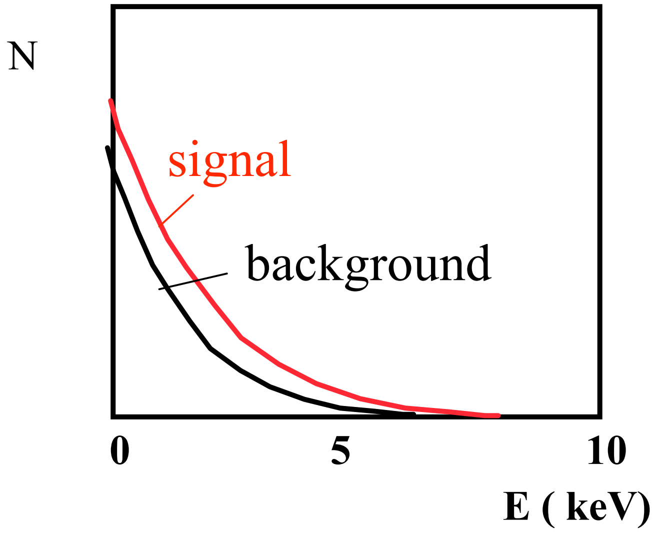


Detection of WIMPS

Direct

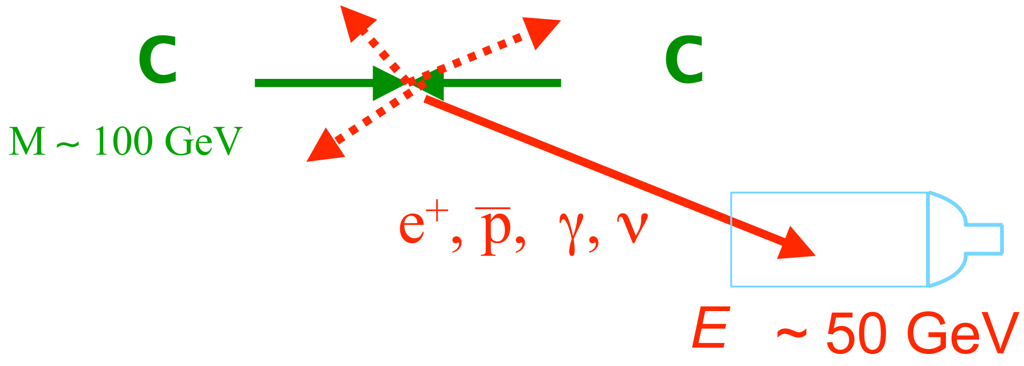
Halo: v ~ 300 km/sec

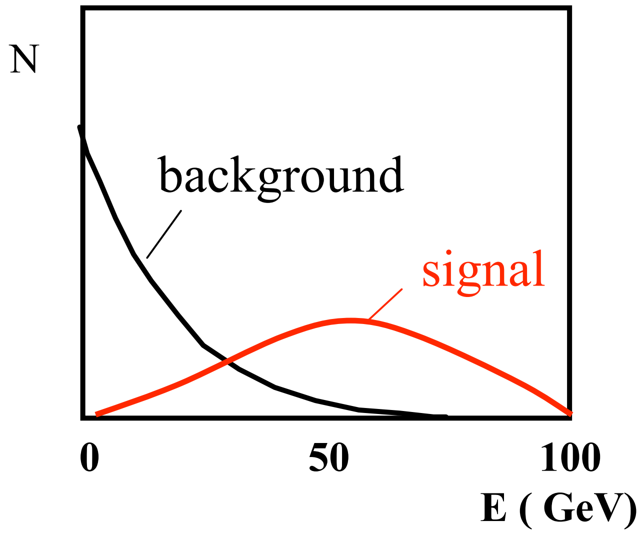




Indirect

Captured: v ~ at rest, or in Halo





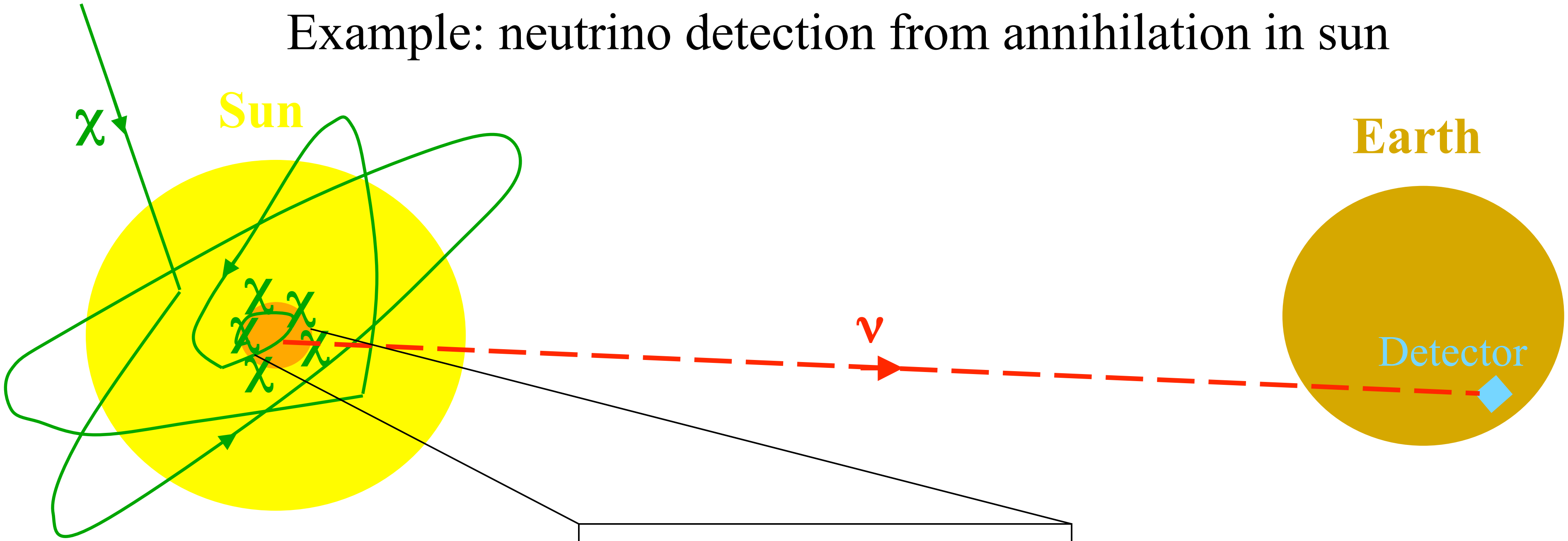
Indirect detection of WIMPS

Searches for annihilation in

Halo, Earth, Sun , Galactic Centre, other galaxies, …

various secondary particle signatures: e^+, p, D, ¯ γ, ν

Example: neutrino detection from annihilation in sun



WIMP looses energy
by elastic collisions
when $v < v_{escape}$ captured

c c ® ***WW, ff***
W, f ® **νX**

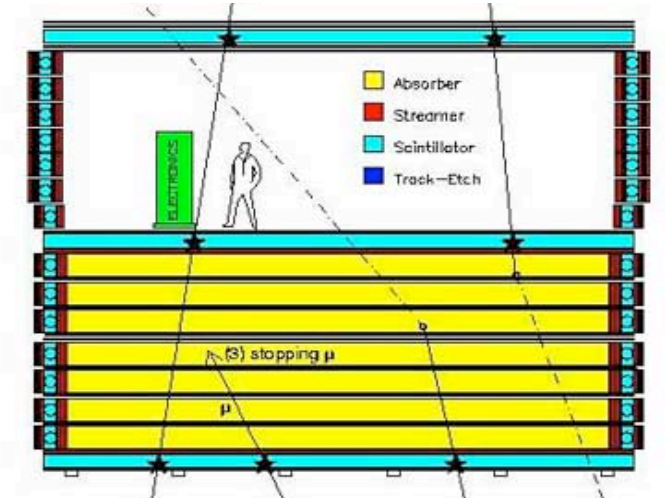
Detection principals

- Detection method(s)
    - Cherenkov light,
    - Acoustic/ radio

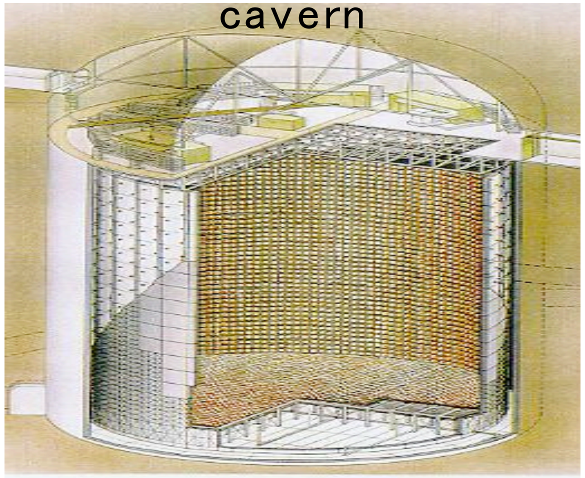
- Properties of the telescope
    - Effective area
    - Angular resolution
    - Energy resolution

Evolution of Neutrino Telescopes

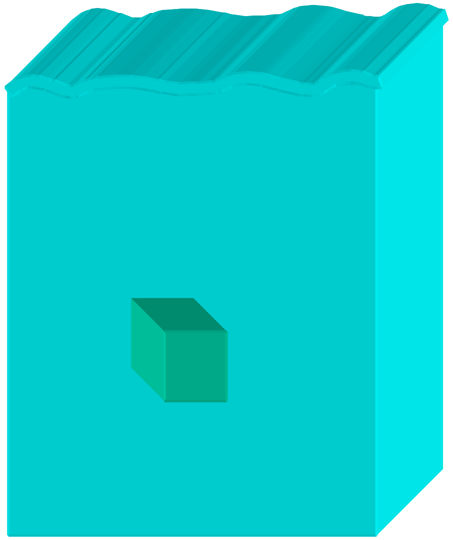
MACRO
4 K tonnes iron in cavern



SuperKamiokande
30 K tonnes water in cavern

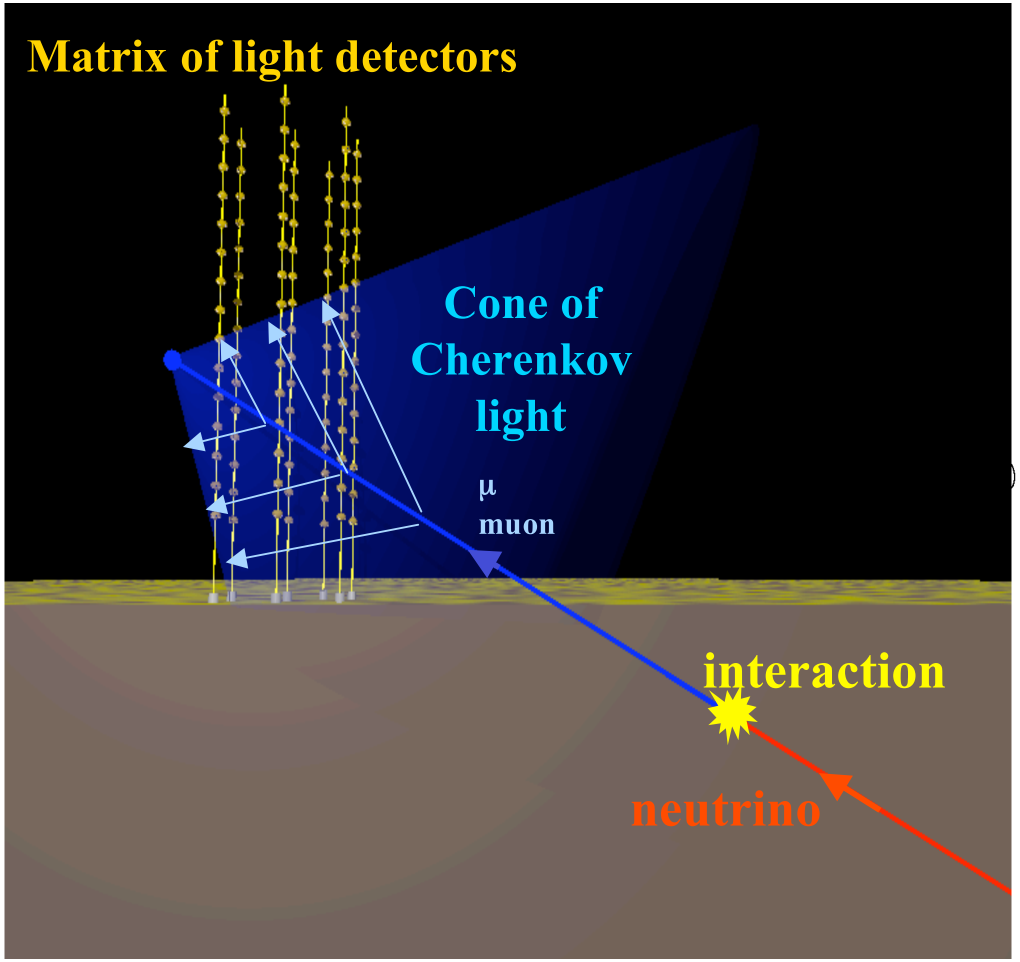


ANTARES
10 000 K tonnes water
In deep sea

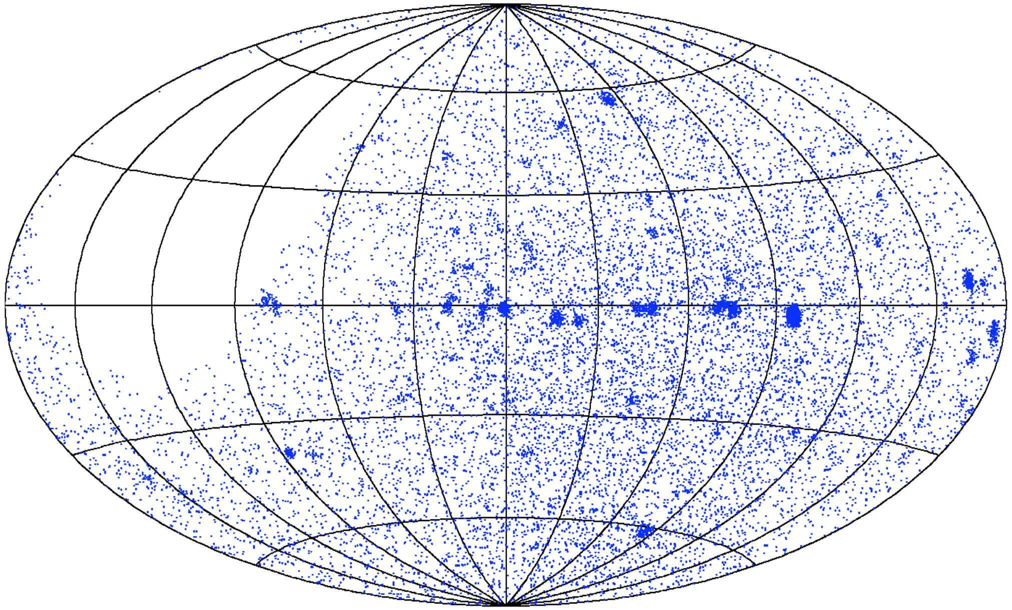


Need > 1000 m depth
to absorb light
and cosmics rays

Principle of Neutrino Astronomy

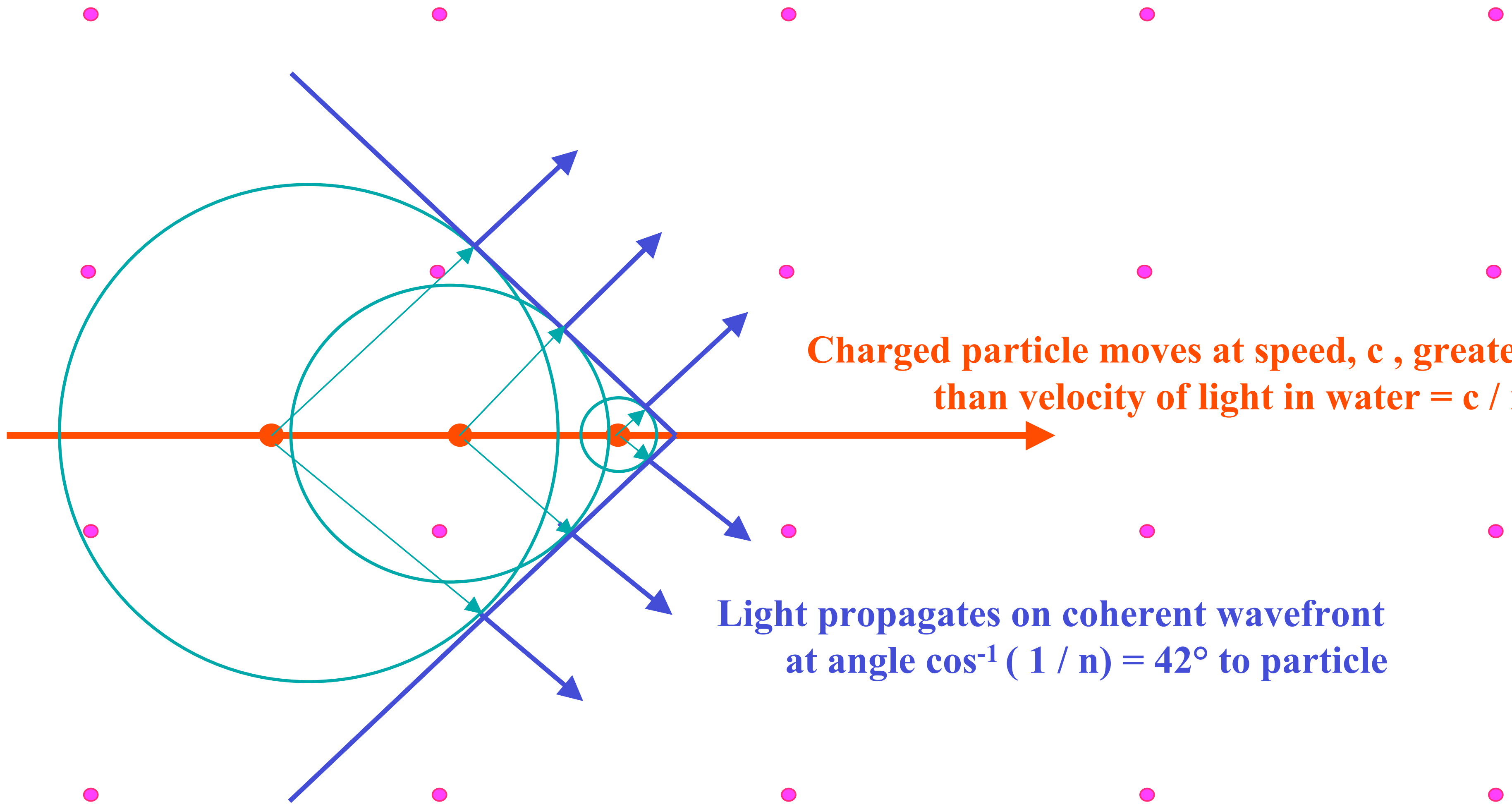


Sky Map
neutrino directions detected



(simulation)

Detect Cherenkov light from charged particles



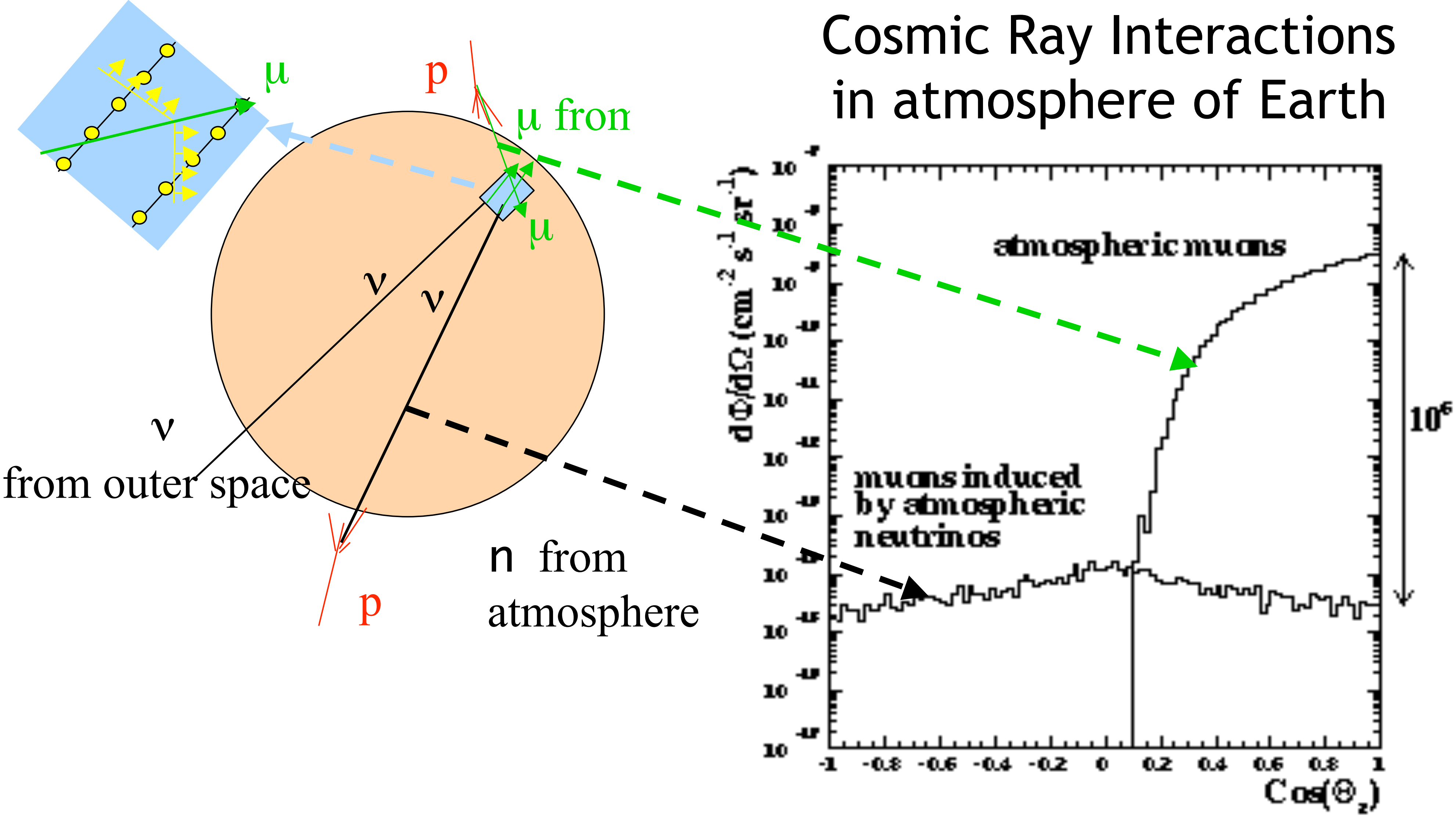
Charged particle moves at speed, c , greater than velocity of light in water = c / n

Light propagates on coherent wavefront at angle cos^{-1} (1 / n) = 42° to particle

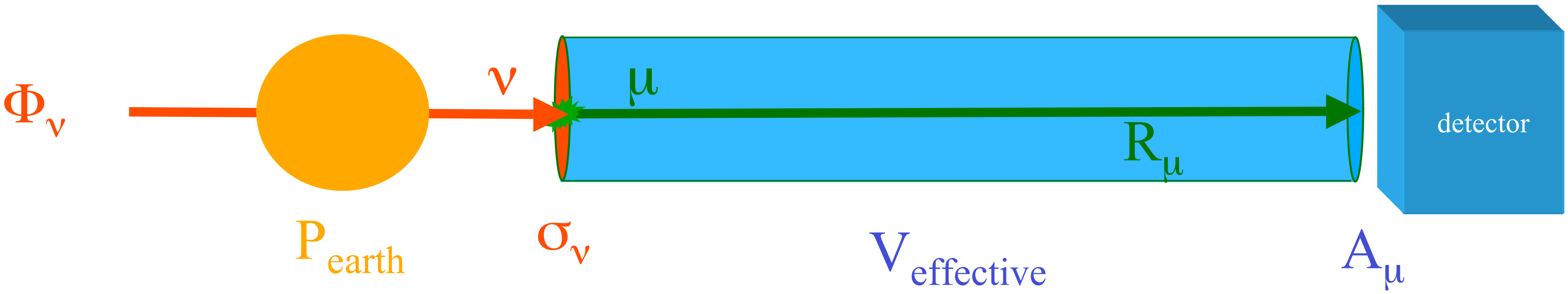
Detector consists of 3D matrix of photo-multipliers measuring arrival of light wavefront with precision ~ 1 nanosecond

Undersea Neutrino Telescope

Backgrounds from
Cosmic Ray Interactions
in atmosphere of Earth



Detected event rates



$$\text{Number events detected} = \Phi_\nu \times A_\nu$$

Φ_ν : Flux of neutrinos arriving at earth

A_ν : Effective area for neutrinos $= P_{earth} \times \sigma_\nu \times N_{target}$

P_{earth} : Transmission of neutrinos through earth

σ_ν : Neutrino cross-section / nucleon

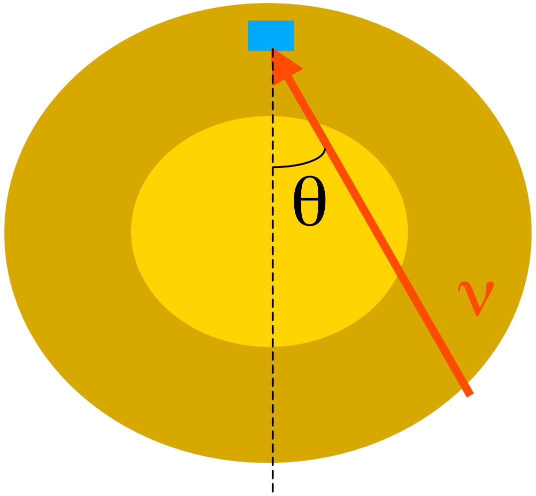
N_{target} : Number of target nucleons $= \rho \times N_{Avagadro} \times V_{effective}$

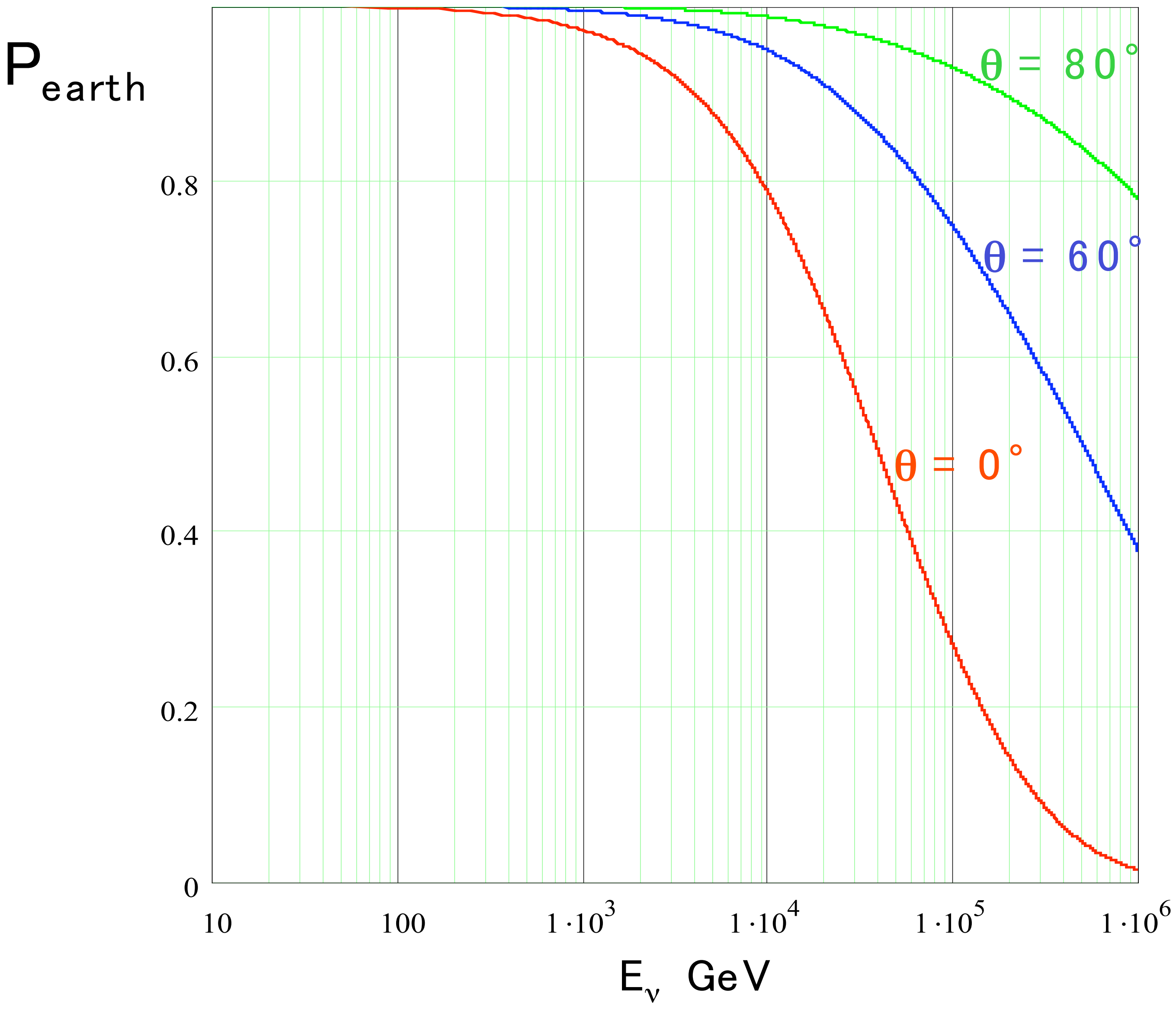
$V_{effective}$: Effective detection volume $= R_\mu \times A_\mu$

R_μ : Muon average range

A_μ : Effective detection area for muons

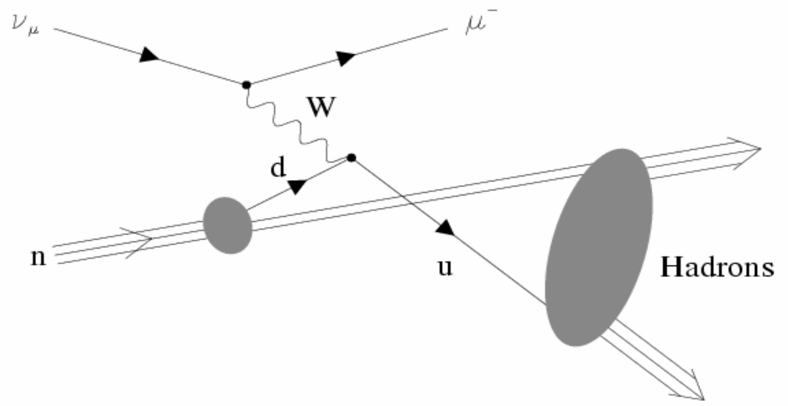
Absorption in Earth



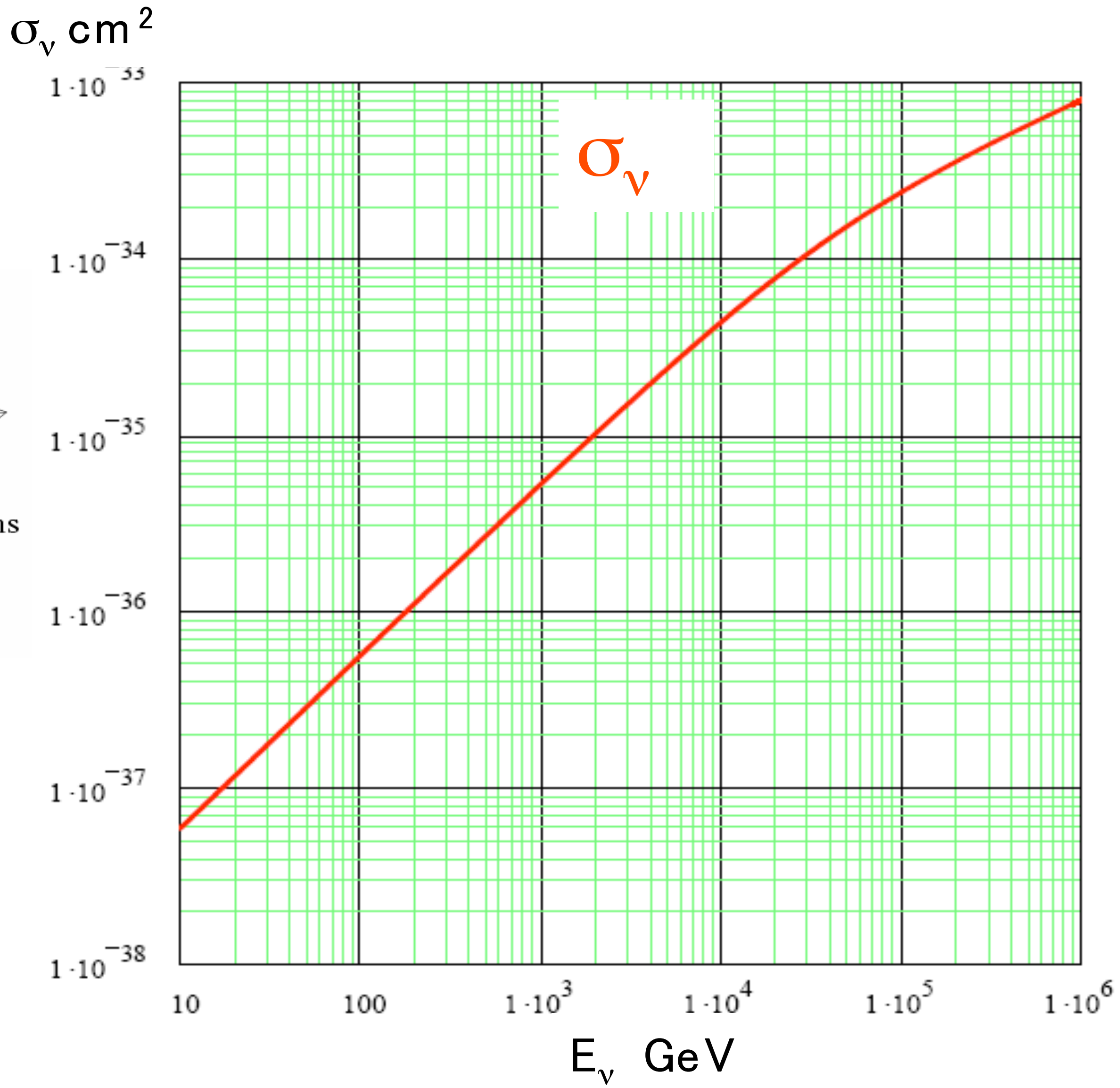


Neutrino cross-section

Deep inelastic scattering

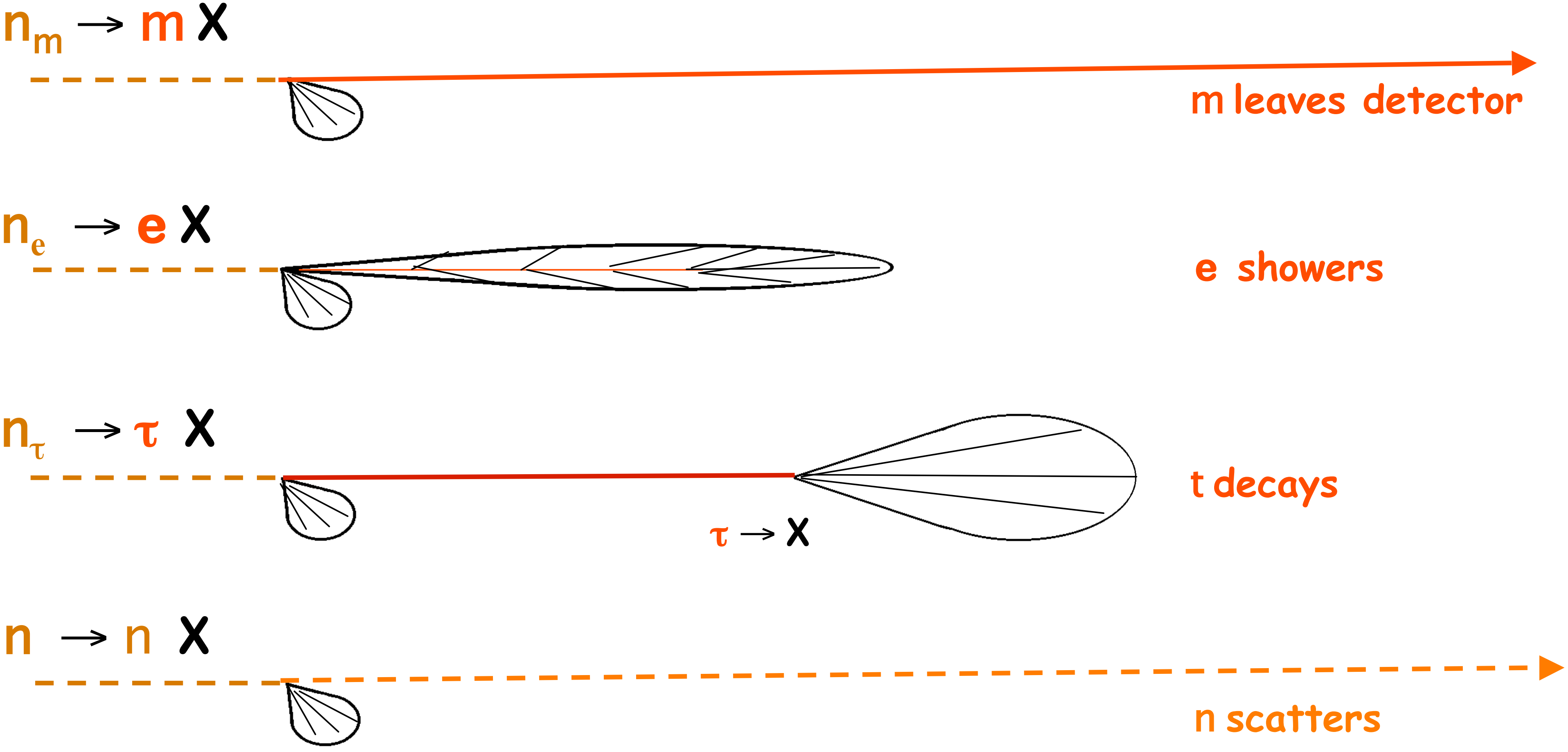


Detectors most sensitive to charged current interactions



Neutrino Interactions in water

3 flavours of neutrino, 2 types of interaction:
4 topologies of light production in water



$n_m \rightarrow m$ X

m leaves detector

$n_e \rightarrow e$ X

e showers

$n_\tau \rightarrow \tau$ X

t decays

$\tau \rightarrow$ X

$n \rightarrow n$ X

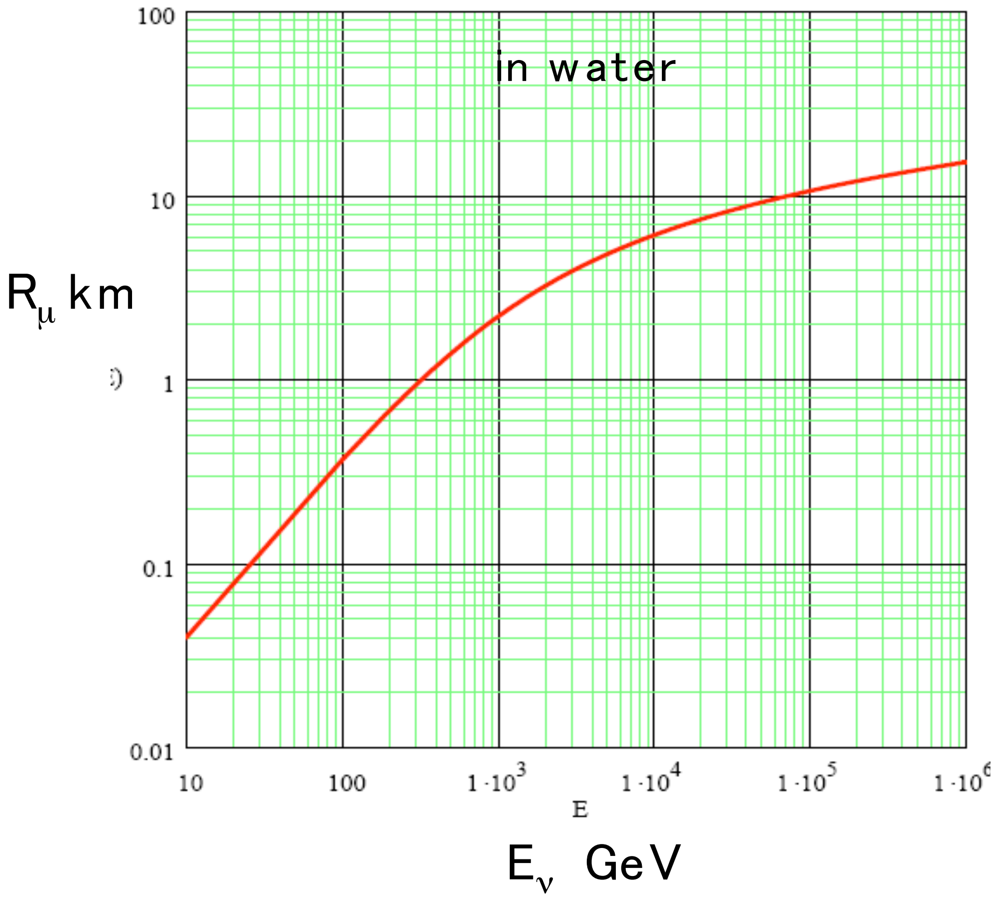
n scatters

Detector optimised for $n_m \rightarrow m$ X, other modes have lower detection efficiency

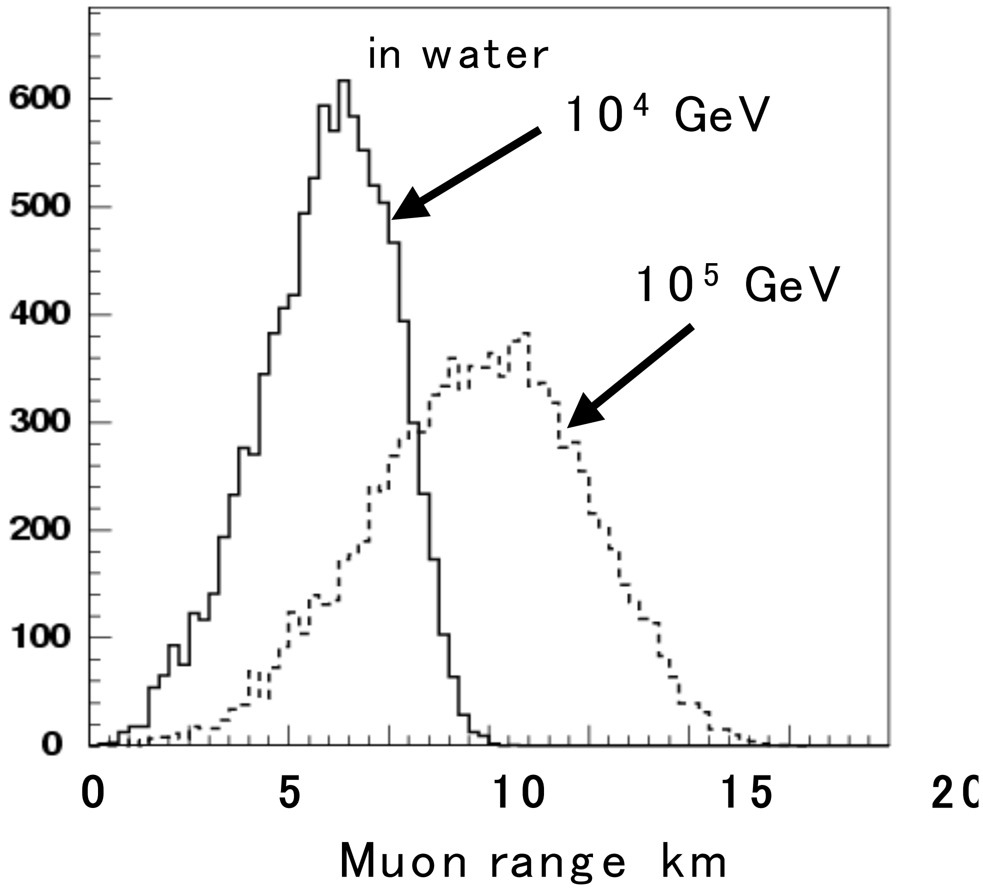
Muon Range

$V_{effective}$: Effective detection volume $= R_\mu \times A_\mu$

Average muon range :R_μ

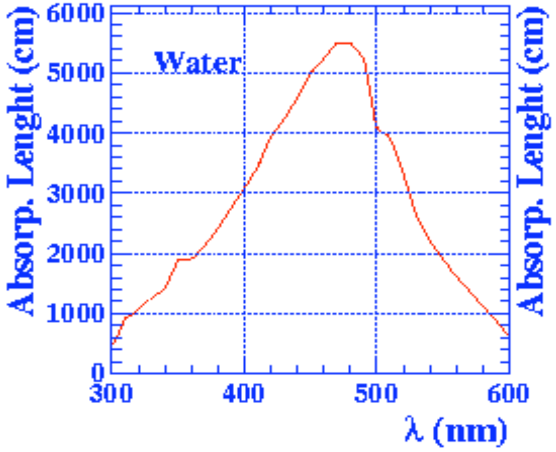


Distribution of muon ranges

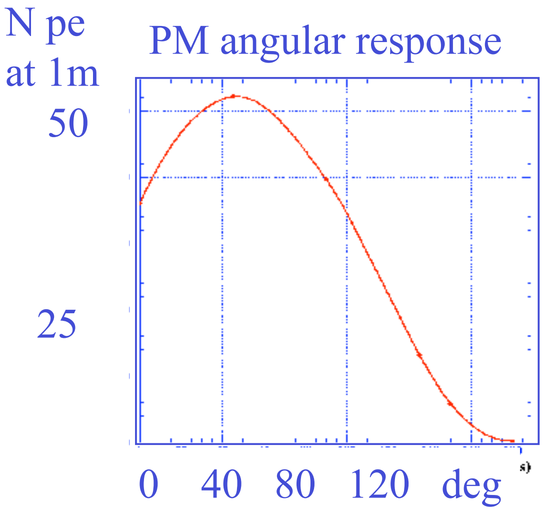


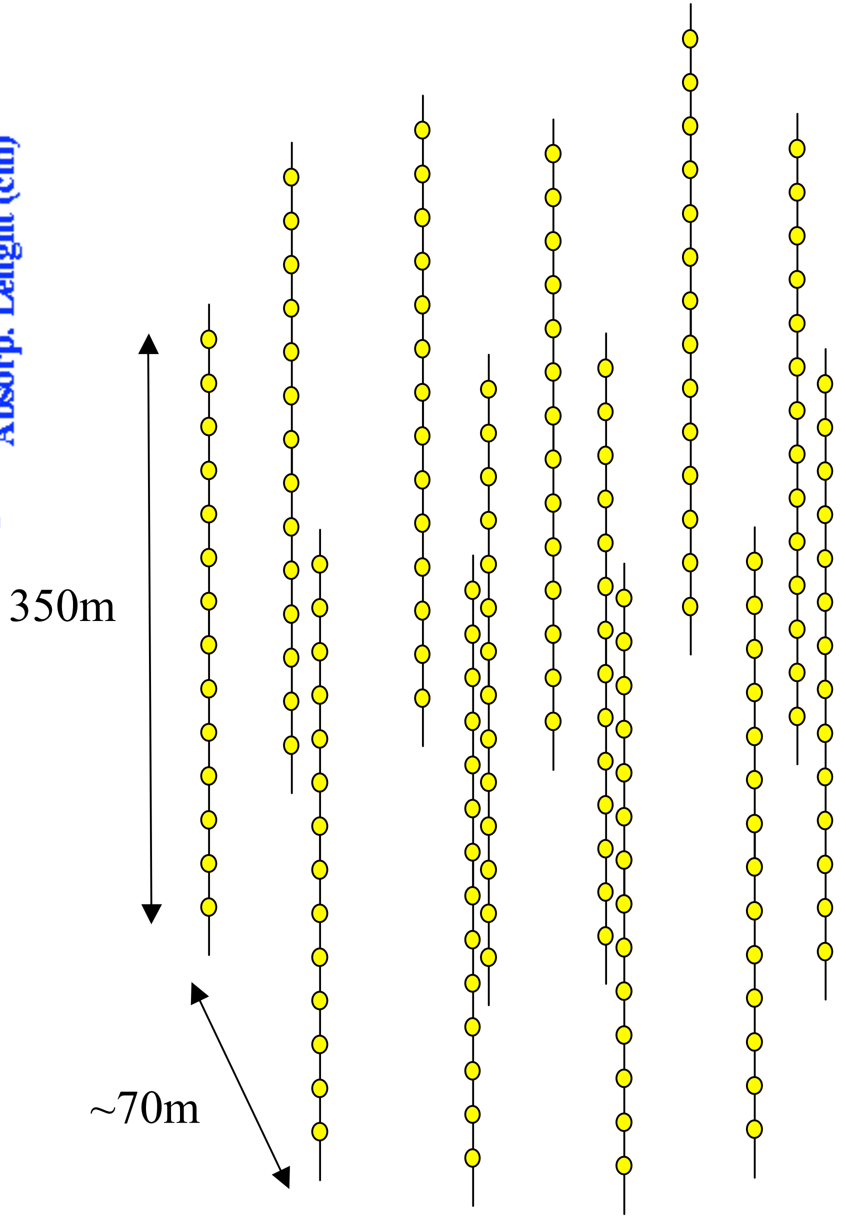
A_μ comes from simulations of detector

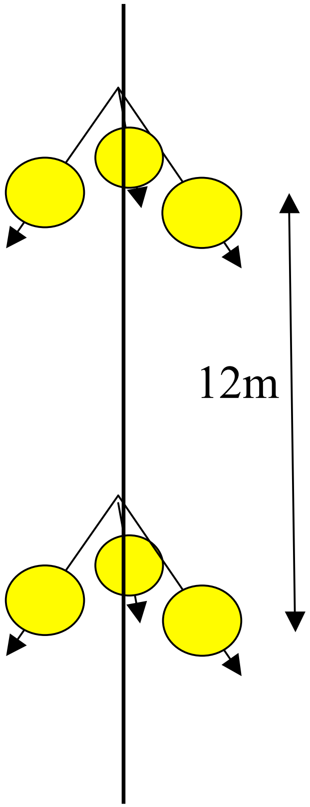
Water absorption



PM angular response

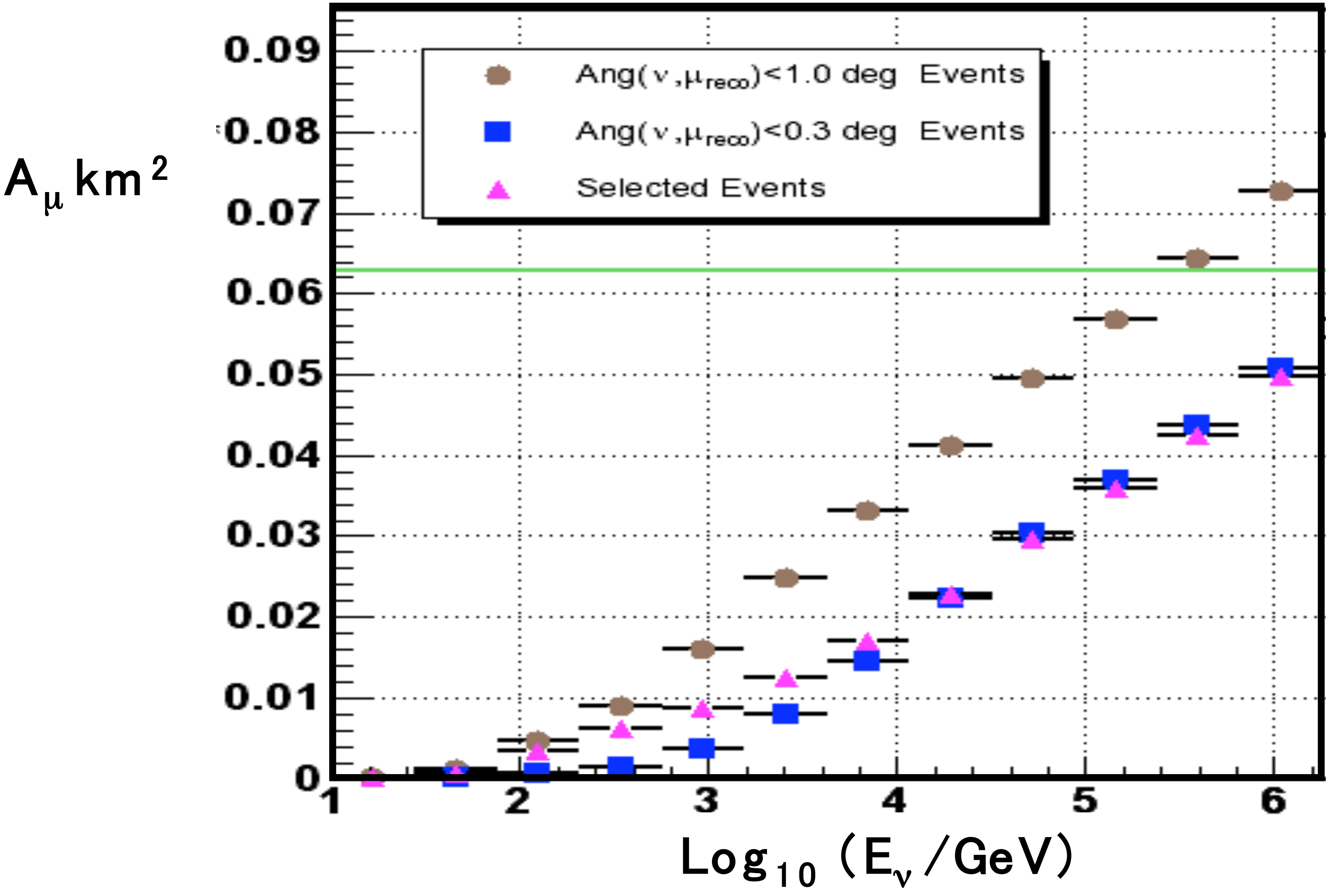




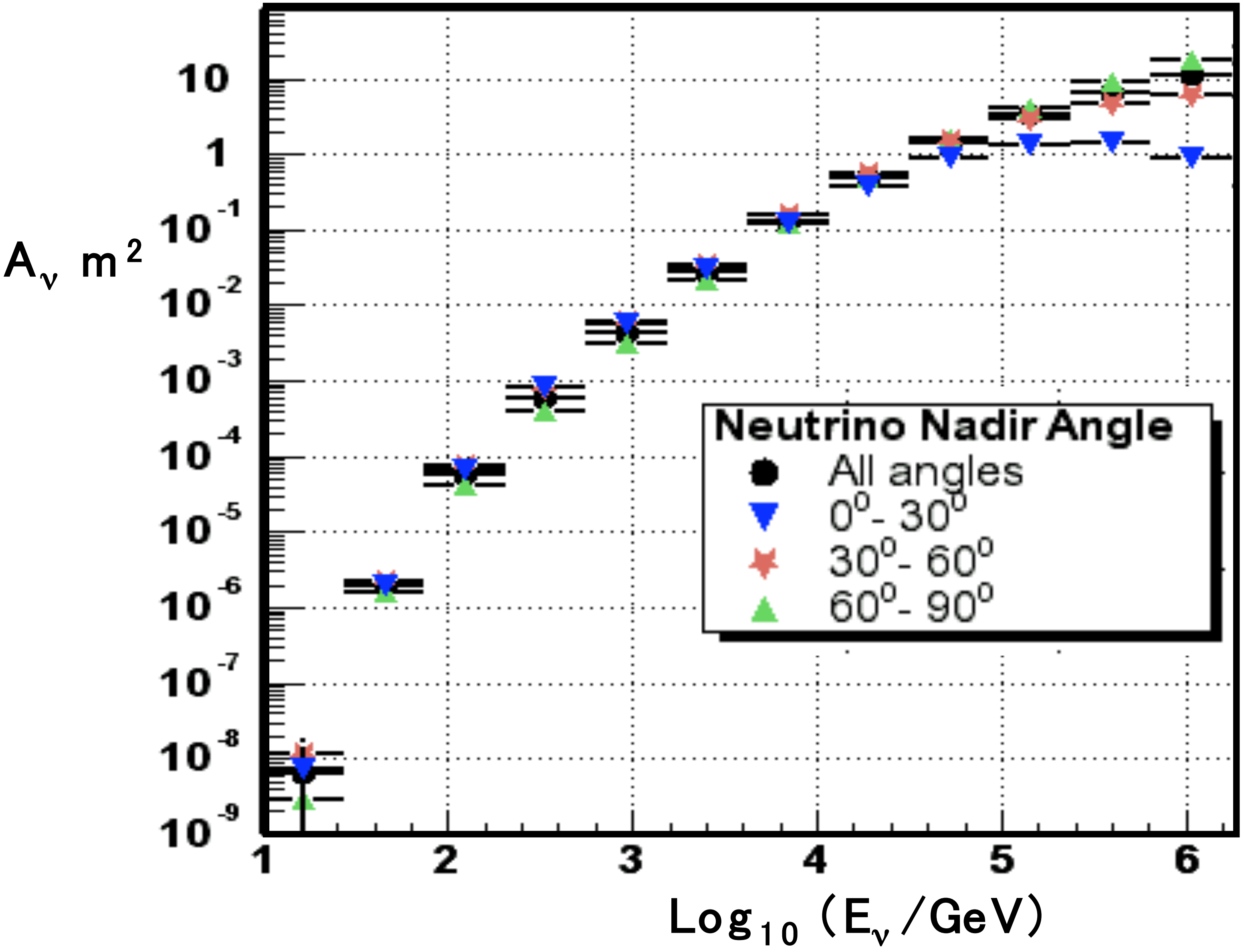


Muon Effective Detection Area

Effective area depends on data quality cuts



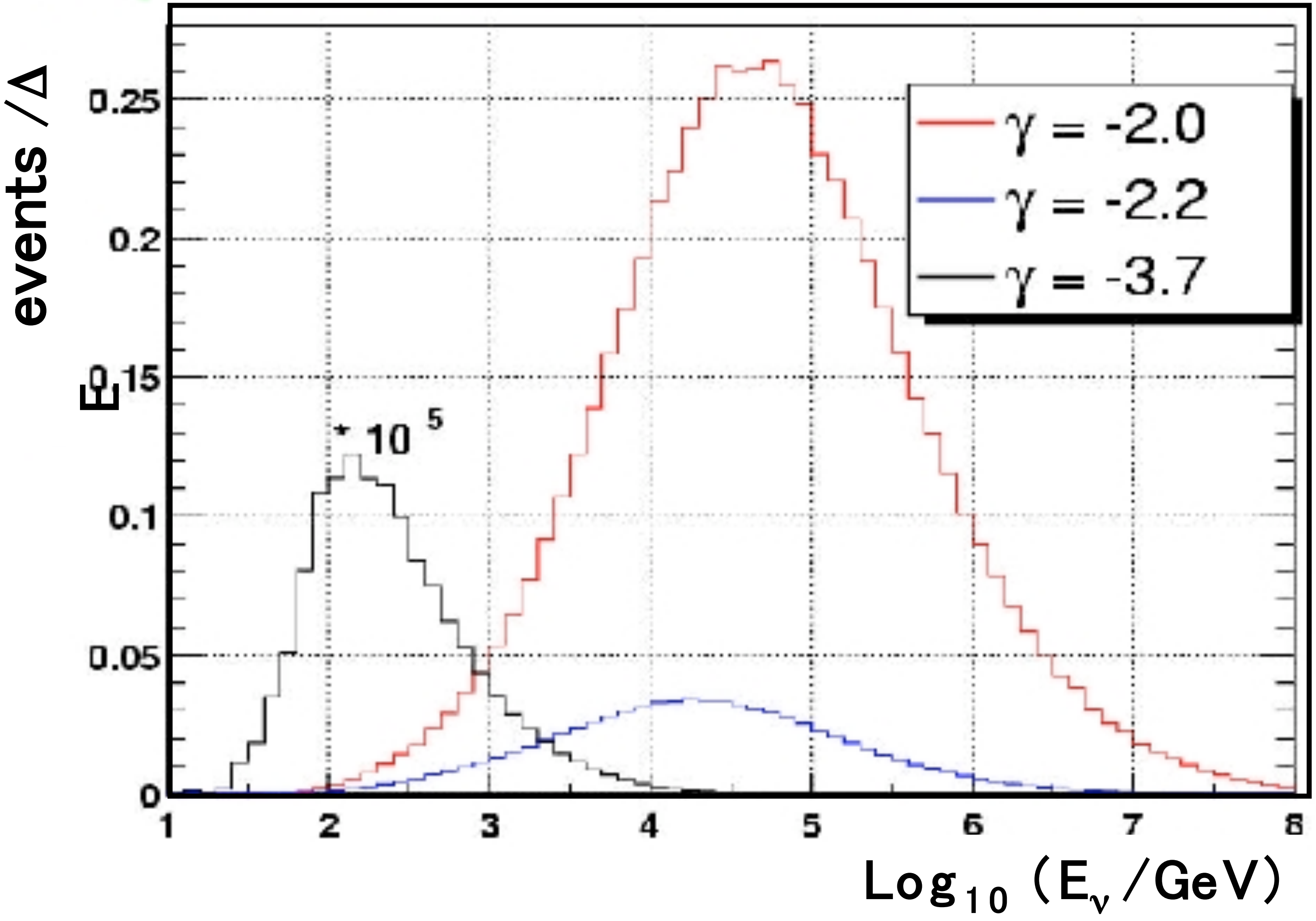
Neutrino Effective Area



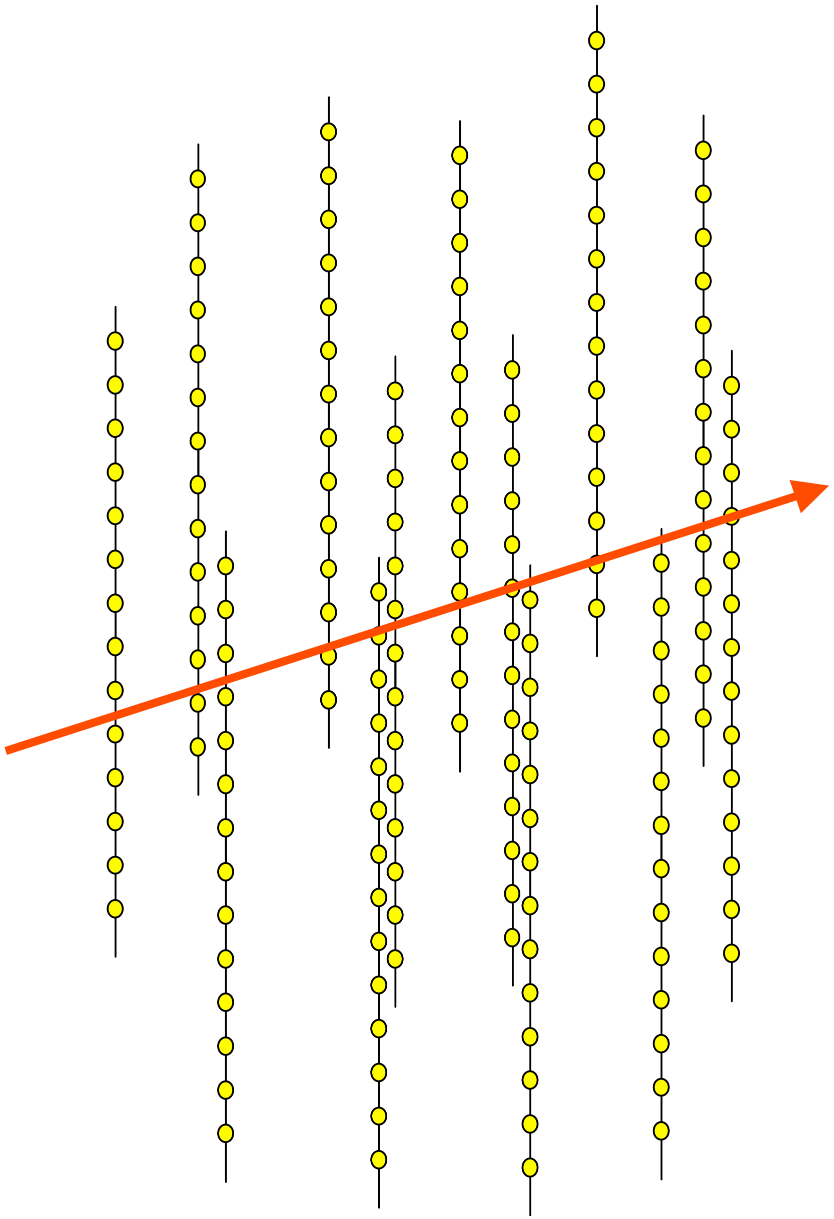
100 GeV	~1 cm^2
1 PeV	~10 m^2

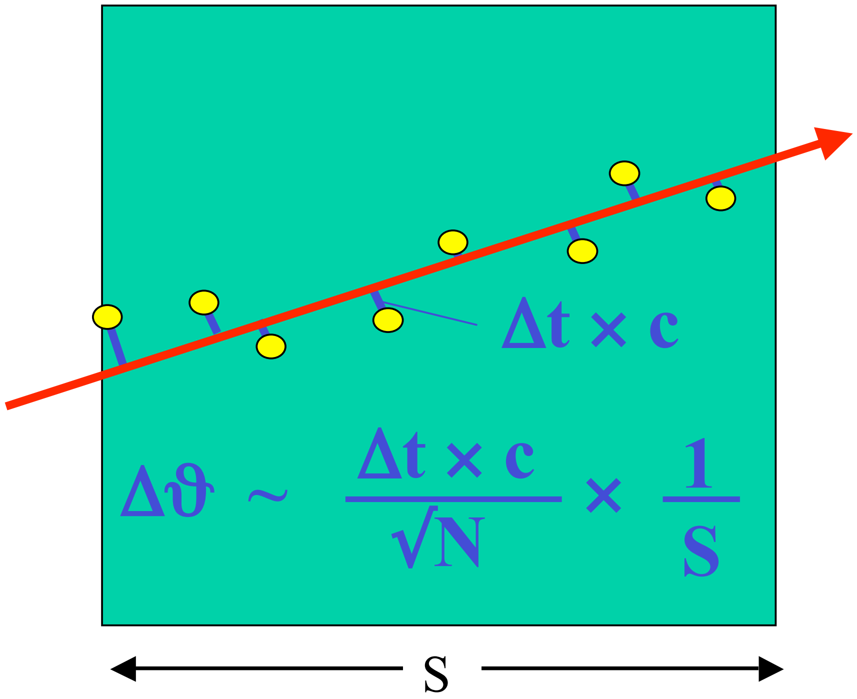
Detector Neutrino Effective Area

Detector response function for neutrino flux E^{γ}



Angular resolution of detector

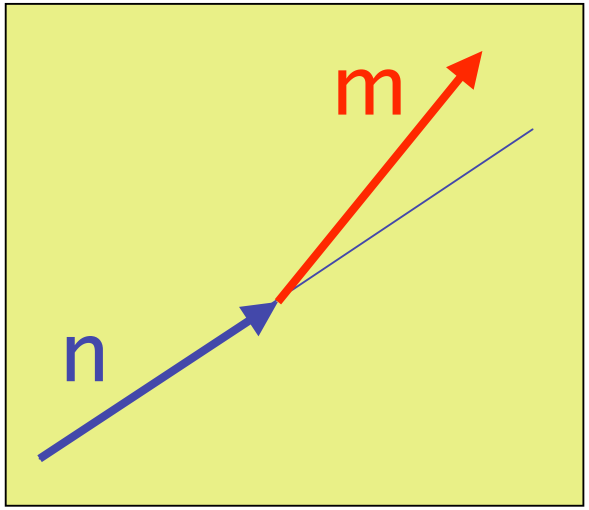




$$\Delta\vartheta \sim \frac{\Delta t \times c}{\sqrt{N}} \times \frac{1}{S}$$

Angular resolution depends on:
- timing resolution
- detector scale

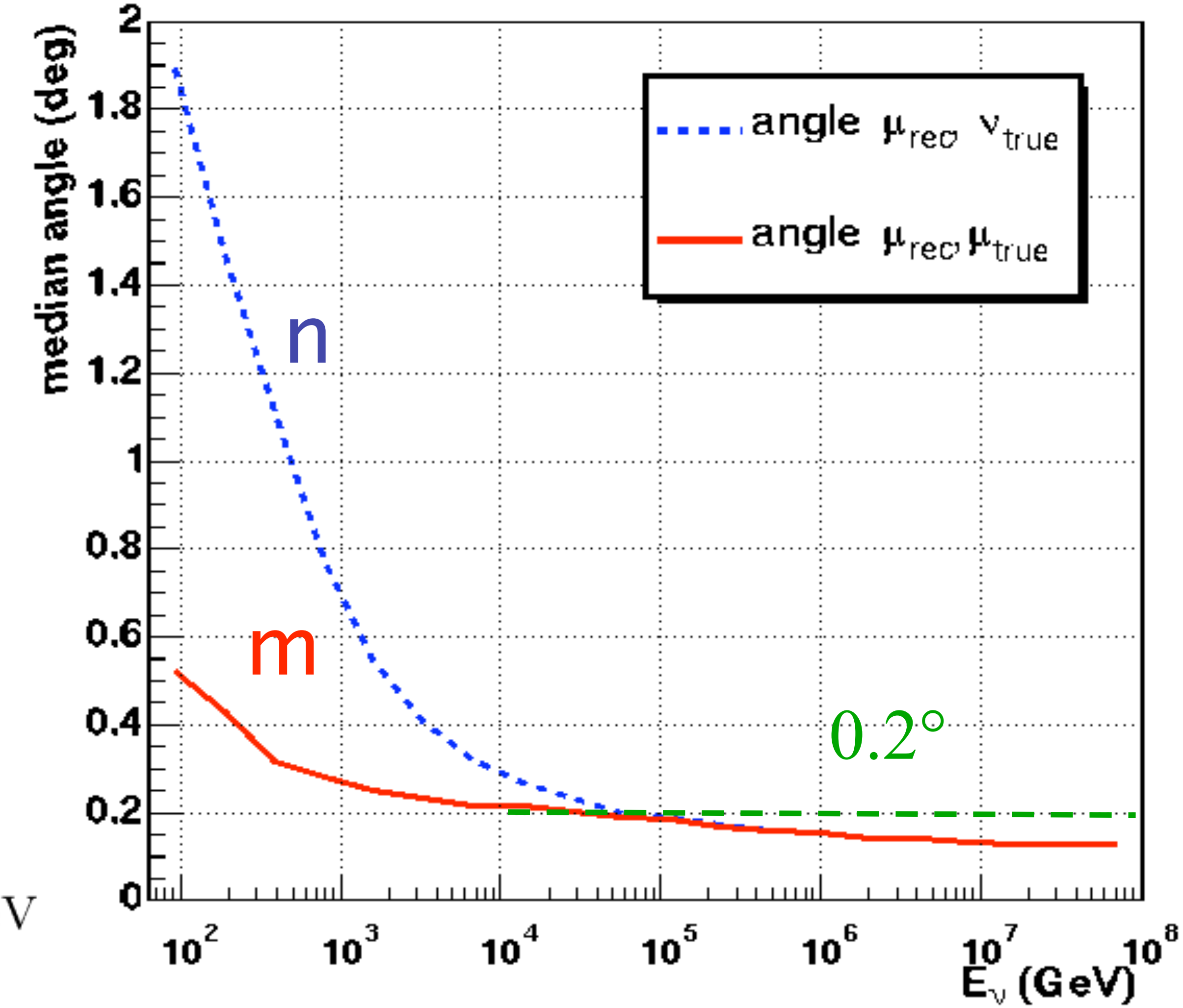
Angular Resolution



Deep inelastic scattering :

$$\sqrt{\langle\theta^2_{\mu\nu}\rangle} \approx \sqrt{\frac{m_N}{E_\nu}}$$

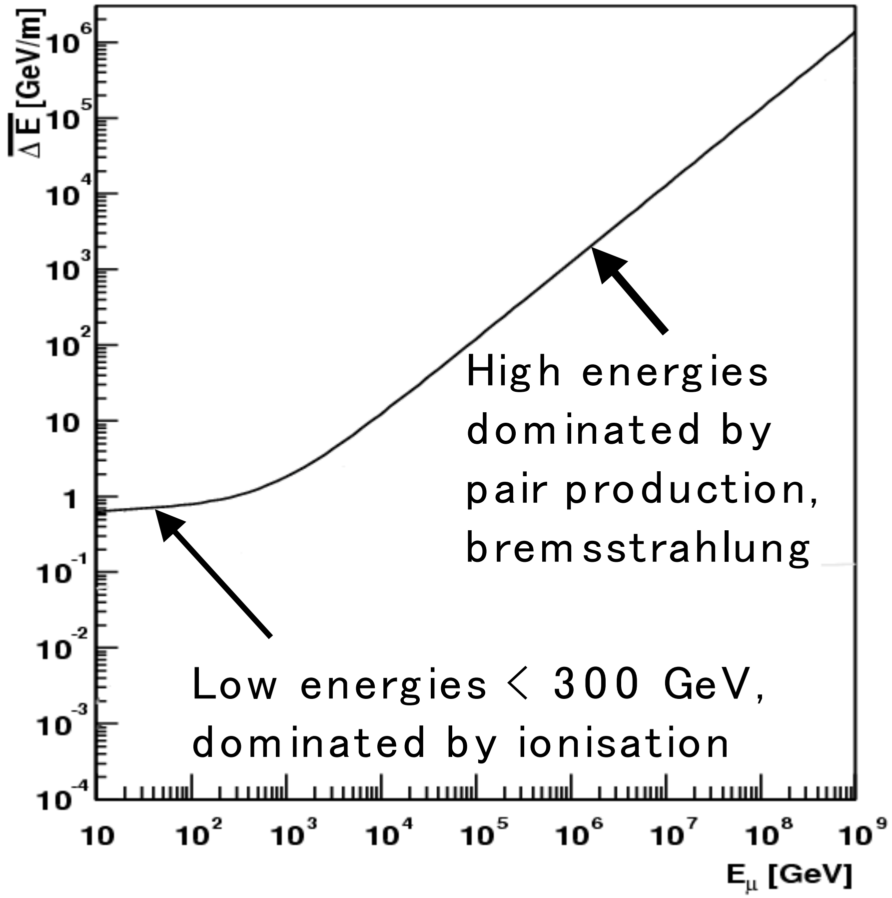
$$\langle\theta_{\mu\nu}\rangle = \frac{0,64^\circ}{(E_\nu/TeV)^{0,56}} \qquad E_\nu > 10\ \text{TeV}$$



~ 0.2° at 100 TeV :dominated by detector resolution

Energy measurement

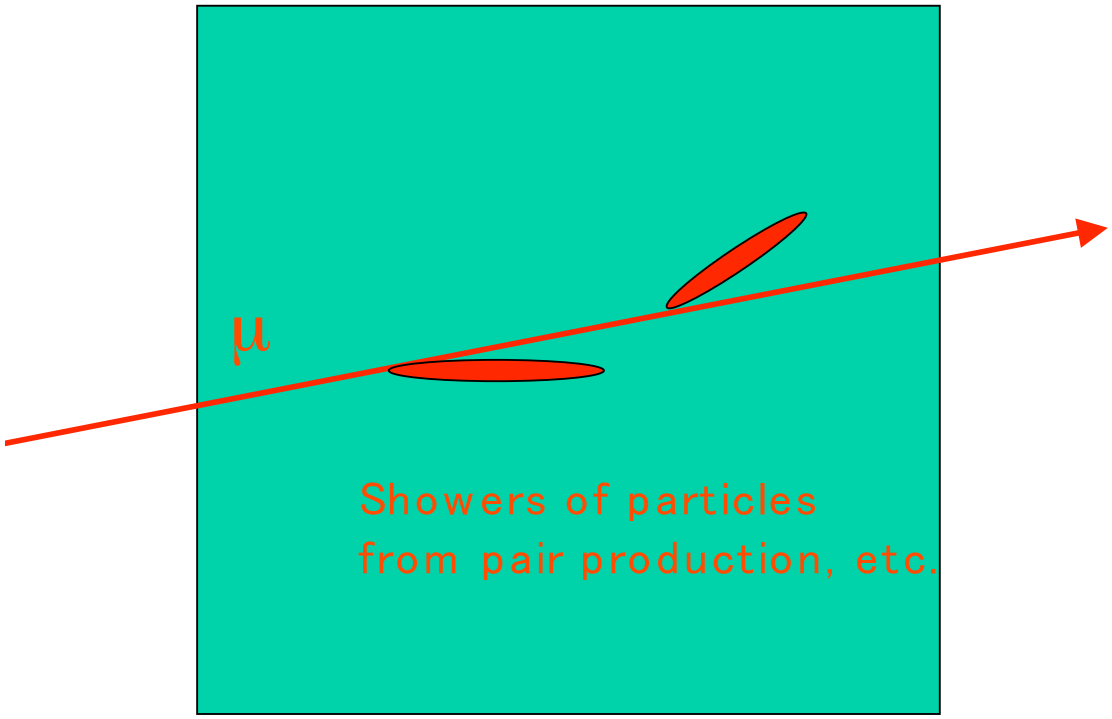
Average energy loss of muon in water



High energies dominated by pair production, bremsstrahlung

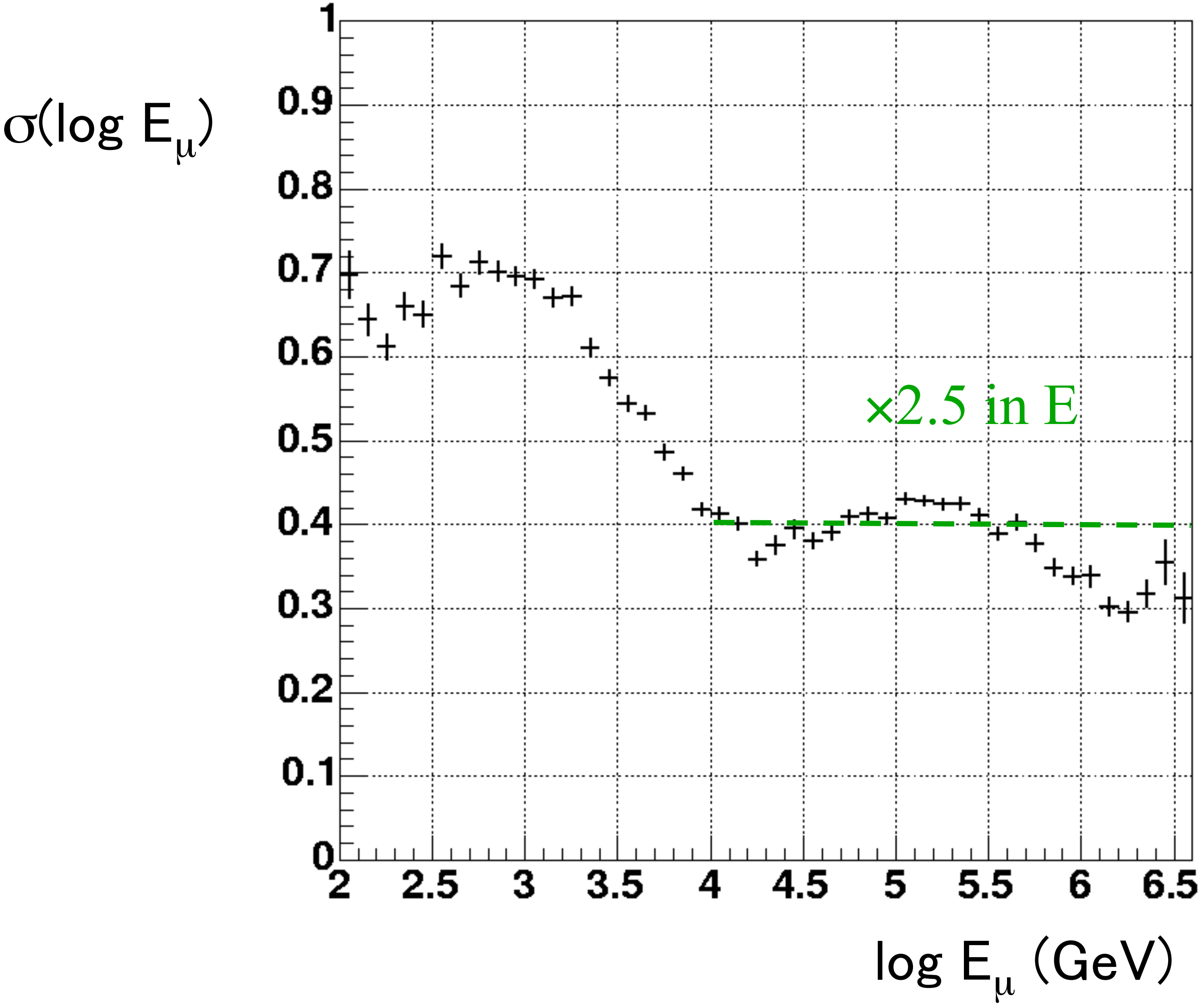
Low energies < 300 GeV, dominated by ionisation

At high energy dominated by stochastic processes



Showers of particles from pair production, etc.

Energy Resolution



Next lecture

Different Neutrino Telescope project
Technology of Neutrino Telescopes
Comparison of projects
Expectations for results
Existing results