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Neutrino Telescopes I

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Outline

LECTURE 1

- Introduction to neutrinos
- Scientific motivation
- Signal and background
- Detector design
- Pioneers

LECTURE 2

- Scientific results
  - IceCube
  - ANTARES
- Next future
  - KM3NeT

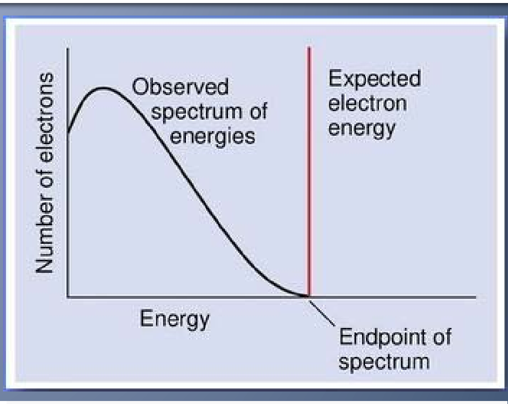
Standard Model

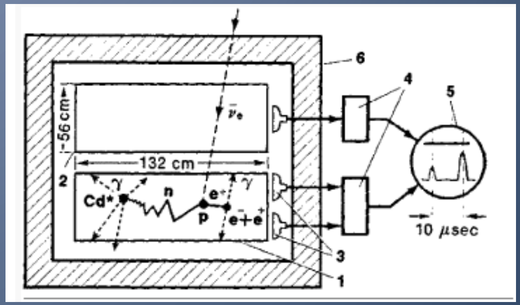
quarks	u up	c charm	t top	γ photon	force carriers
	d down	s strange	b bottom	g gluon	
leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson	
	e electron	μ muon	τ tau	W W boson	

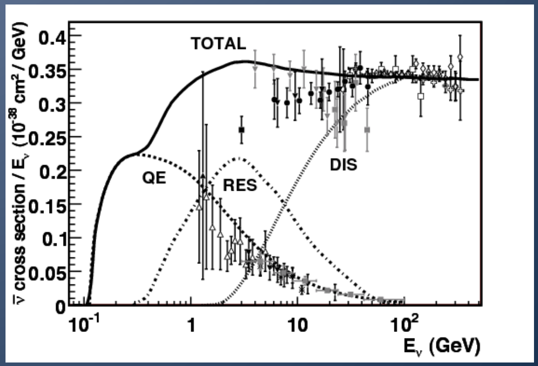
H
Higgs

Neutrinos

- Neutrinos were proposed by W. Pauli in 1930 as a "desperate solution" to the problem of non conservation of energy and angular momentum in beta decays
- They were discovered in 1956 by Reines and Cowan using a detector close to a nuclear reactor
- Very low cross section: a typical solar neutrino (E~0.3 MeV) would have a 50% probability of crossing a lead wall of a width of 5 light-years (but it grows with energy)







Neutrino sources

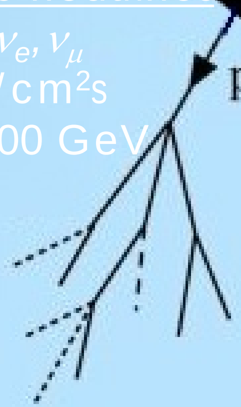
Big Bang
$\rho\nu = 330\ /\ \mathrm{cm}^3$
$E_\nu = 0.0004\ \mathrm{eV}$
($1\ \mathrm{MeV} = 1.6 \times 10^{-13}\mathrm{J}$)

AGNs/GRBs/others?
$E^{-2}\Phi_\nu^{\,Earth} \sim 10^{-8}\ \ \nu\ \mathrm{GeV/\ cm^2 s\ sr}$
$E_\nu \sim 100\ \mathrm{TeV} - \mathrm{PeV}$

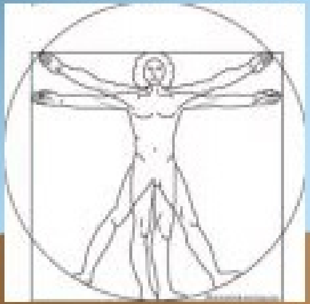
SN1987
$E_\nu \sim \mathrm{MeV}$

Sun
ν_e
$\Phi_\nu^{\,Earth} = 6 \times 10^{10}\ \nu\ /\ \mathrm{cm}^2\mathrm{s}$
$E_\nu \sim 0.1 - 20\ \mathrm{MeV}$

Atmospheric neutrinos
$\bar\nu_e, \bar\nu_\mu, \nu_e, \nu_\mu$
$\Phi_\nu \sim 1\ \nu\ /\mathrm{cm}^2\mathrm{s}$
$E_\nu \sim 0.1 - 100\ \mathrm{GeV}$



Human body
$\Phi_\nu = 340 \times 10^6\ \nu/\mathrm{day}$

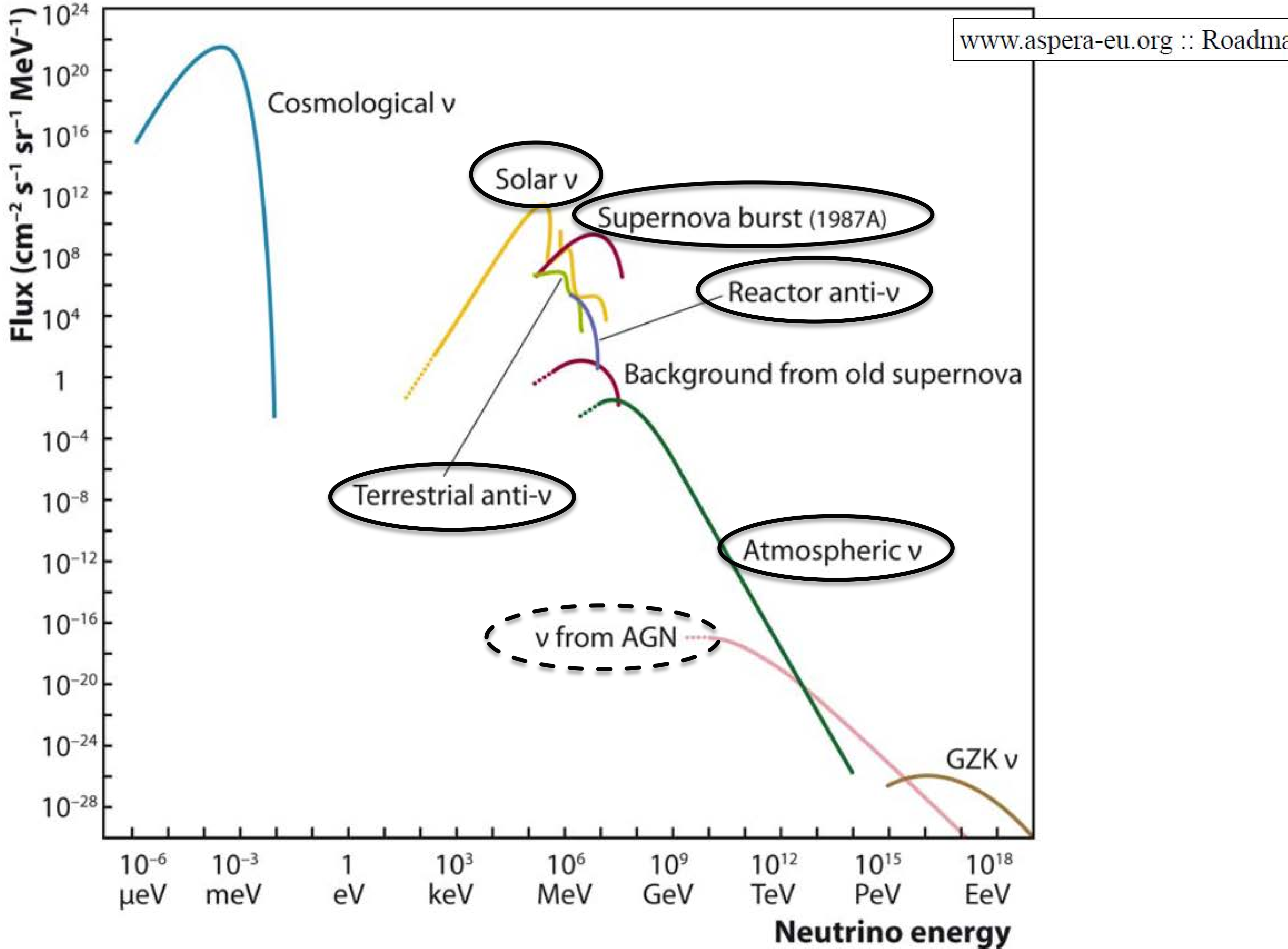


Nuclear reactors
$E_\nu \sim$ few MeV

Terrestrial radioactivity
$\Phi_\nu \sim 6 \times 10^6\ \nu/\mathrm{cm}^2\mathrm{s}$

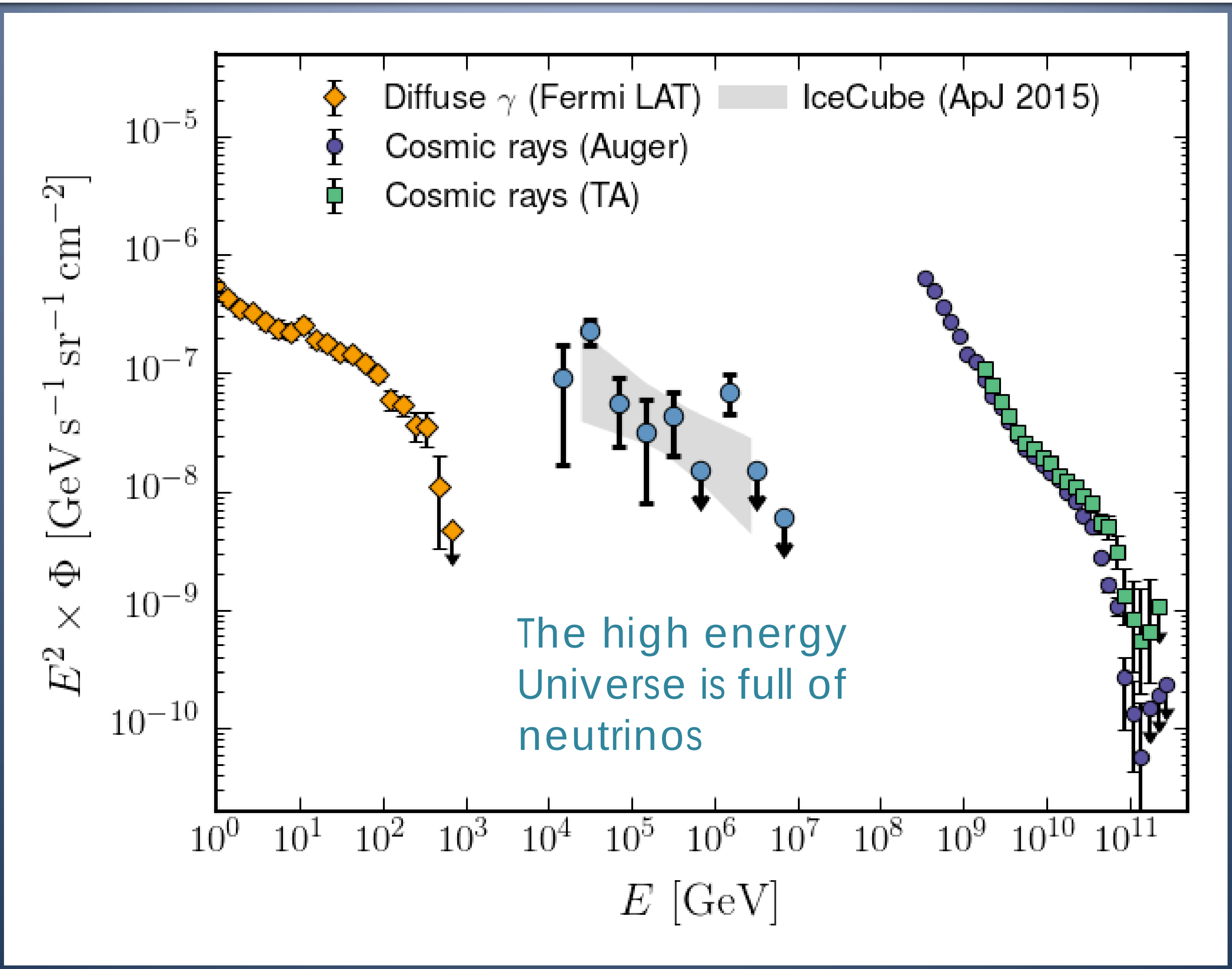
Accelerators
$E_\nu \simeq 0.3 - 30\ \mathrm{GeV}$

F. Halzen



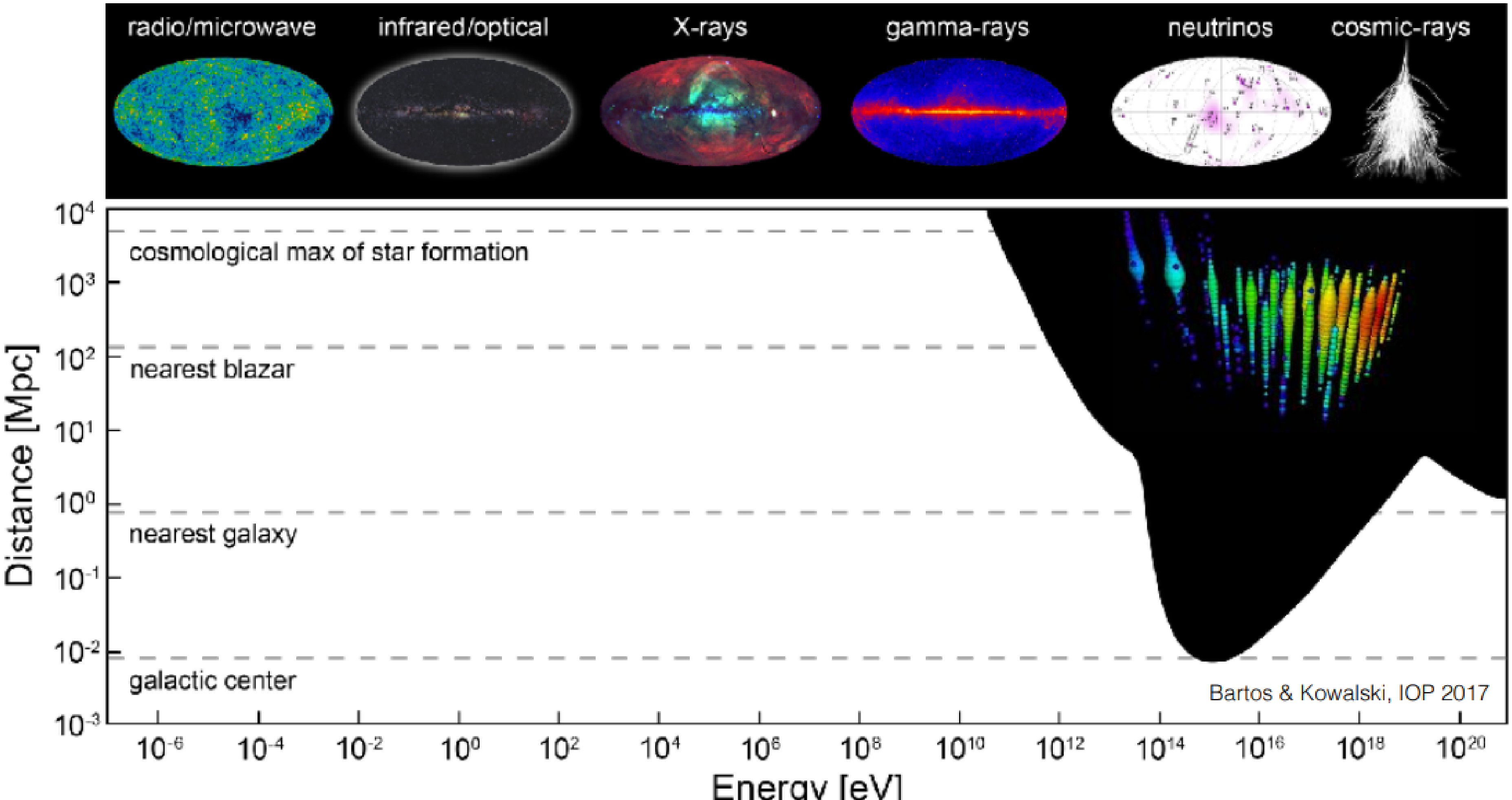
www.aspera-eu.org :: Roadma
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

Cosmic fluxes



Kowalksi, Neutrino 2016, adapted from L. Mohrmann

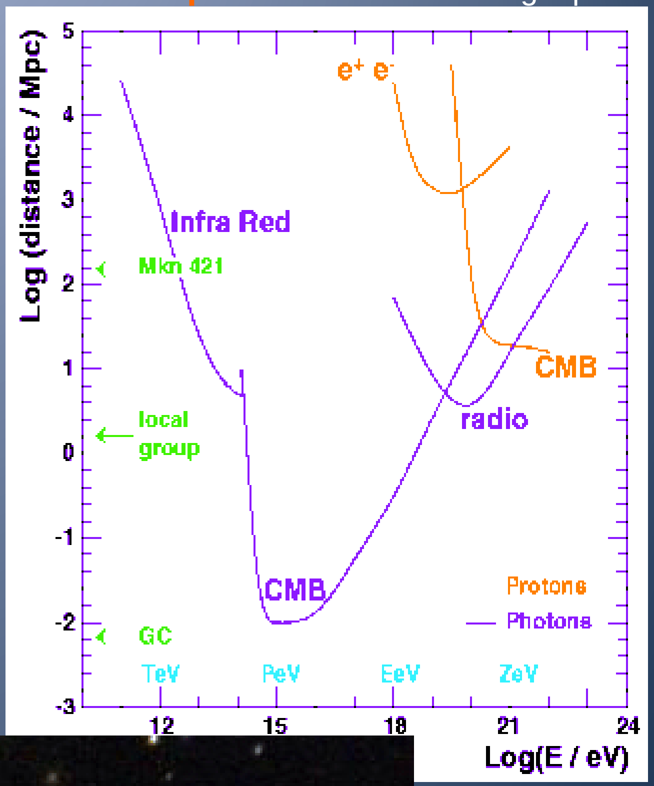
The Universe: how to look at it?

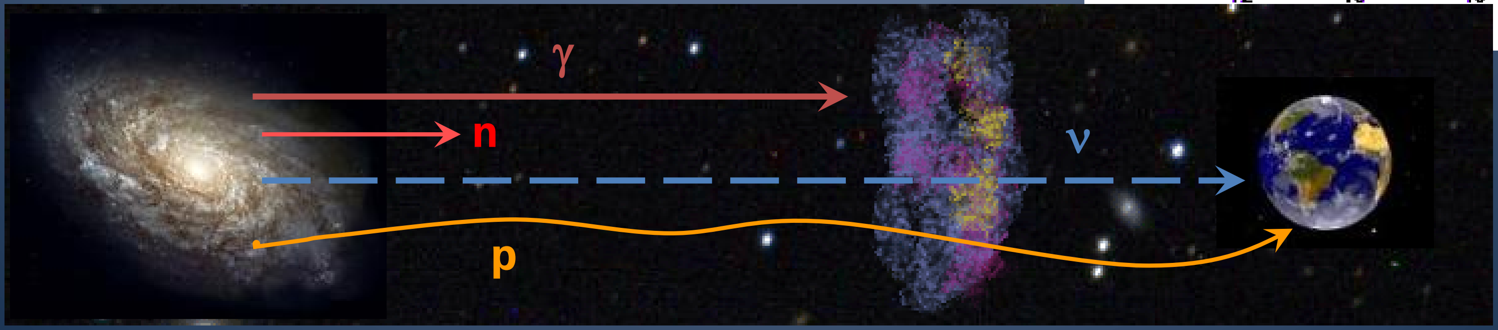


Neutrino Astronomy

- Advantages:
  - Photons: interact with CMB and matter
  - Protons: interact with CMB and are deflected by magnetic fields
- Drawback: large detectors (~GTon) are neded

Photon and proton mean free range path





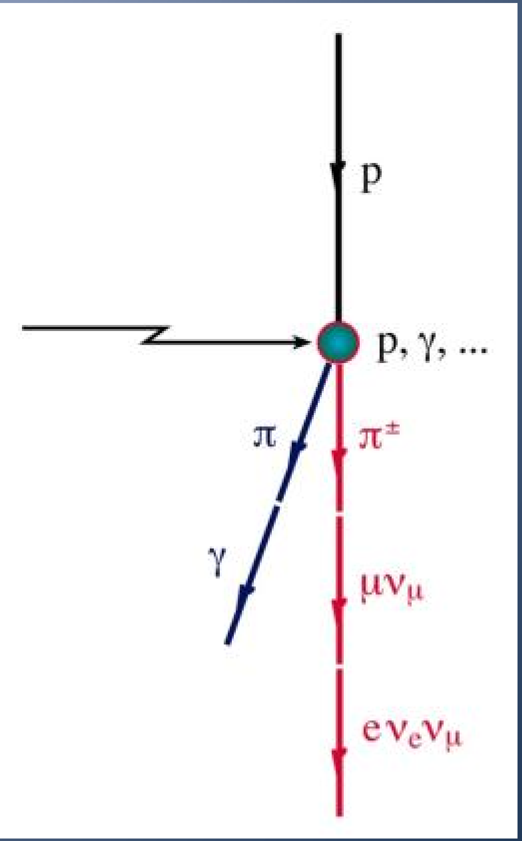
Production Mechanism

- Neutrinos are expected to be produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \rightarrow \pi^{\pm}(K^{\pm}\ldots) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

$$\mu^{\pm} \downarrow e^{\pm} + \bar{\nu}_{e}(\nu_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

Cosmic rays



- Gamma rays are also produced in these processes, after the decay of the neutral pion

$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\,\gamma + Y$$

Gamma ray astronomy

Multimessenger Era

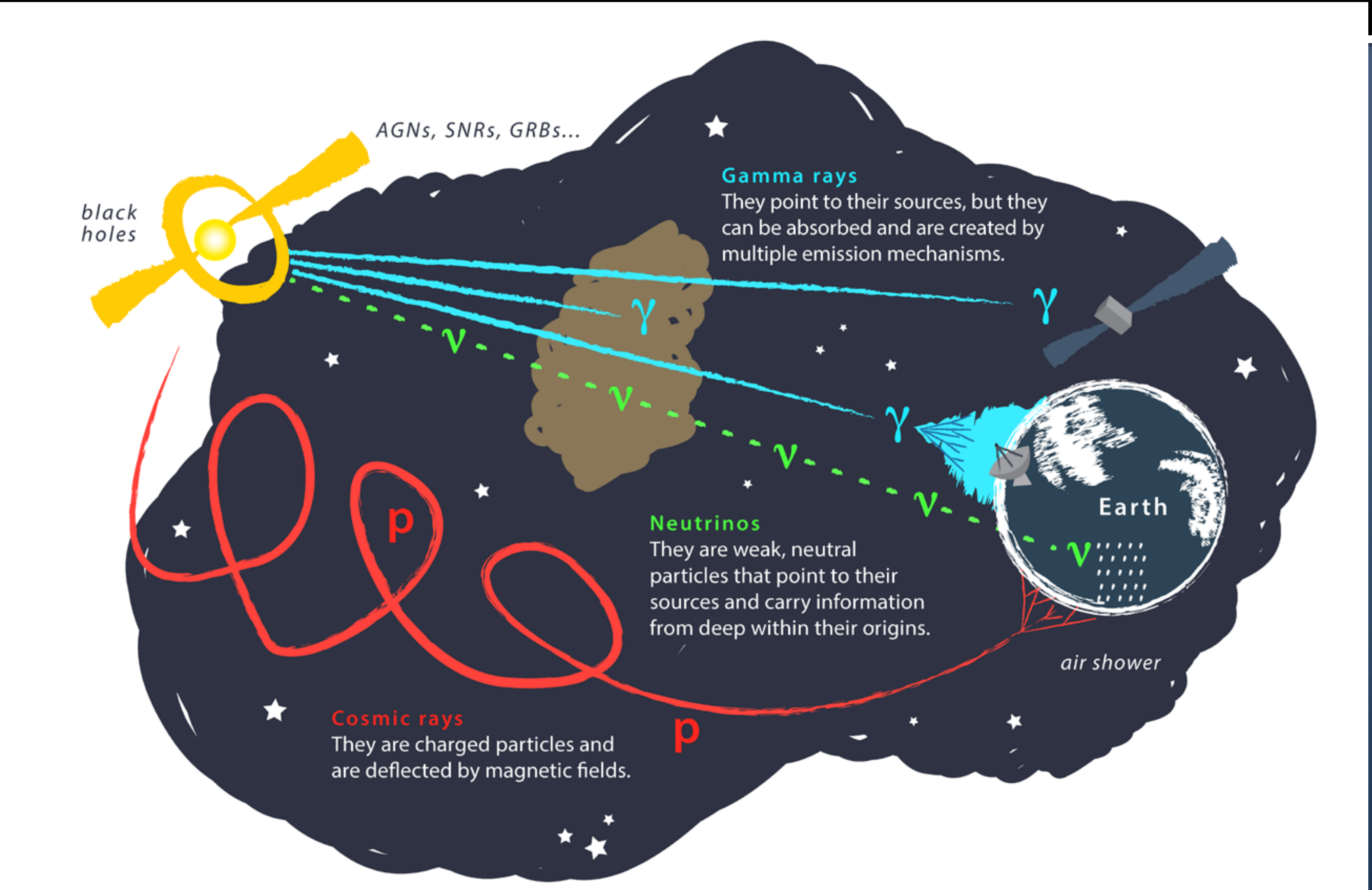
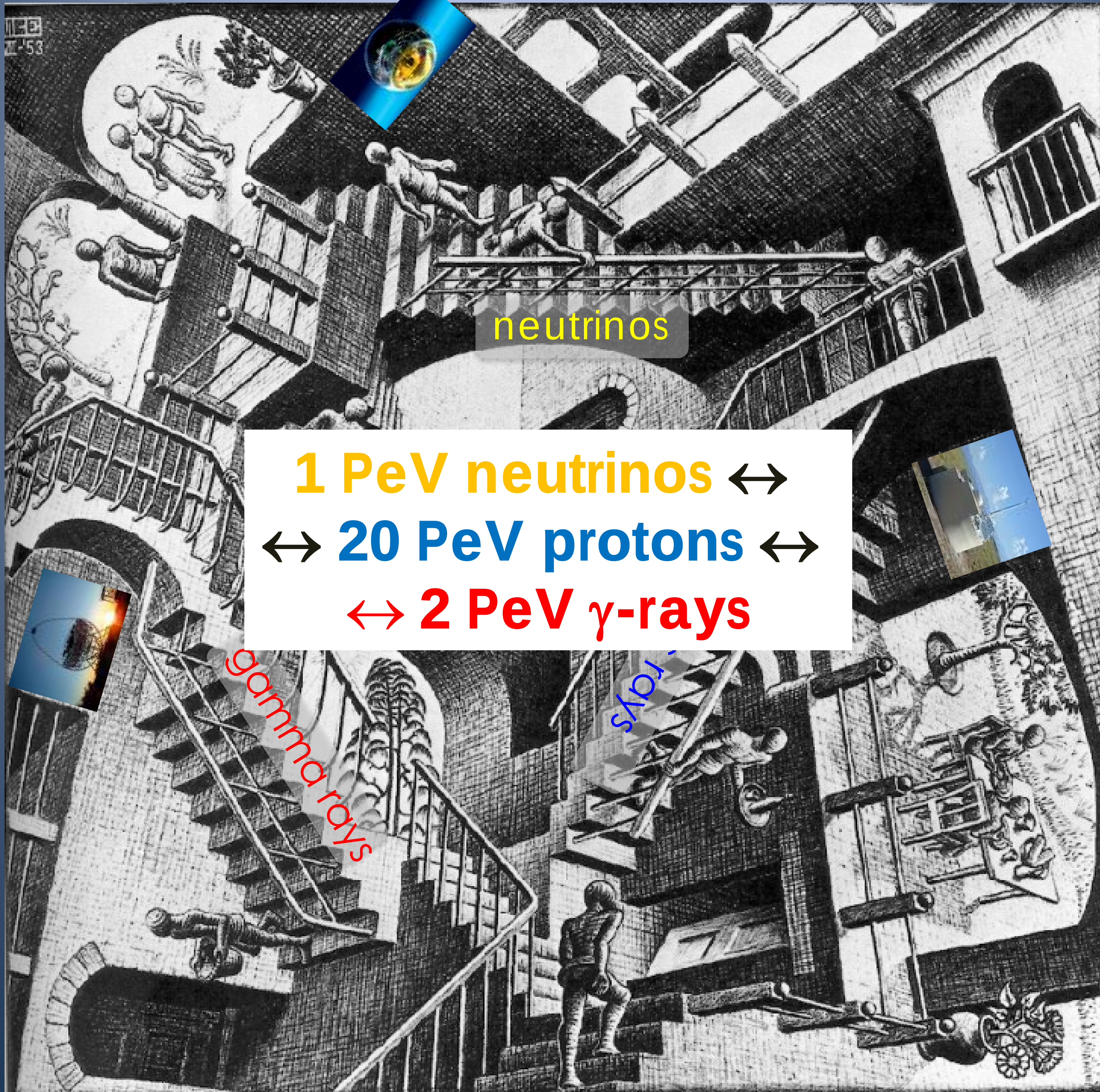


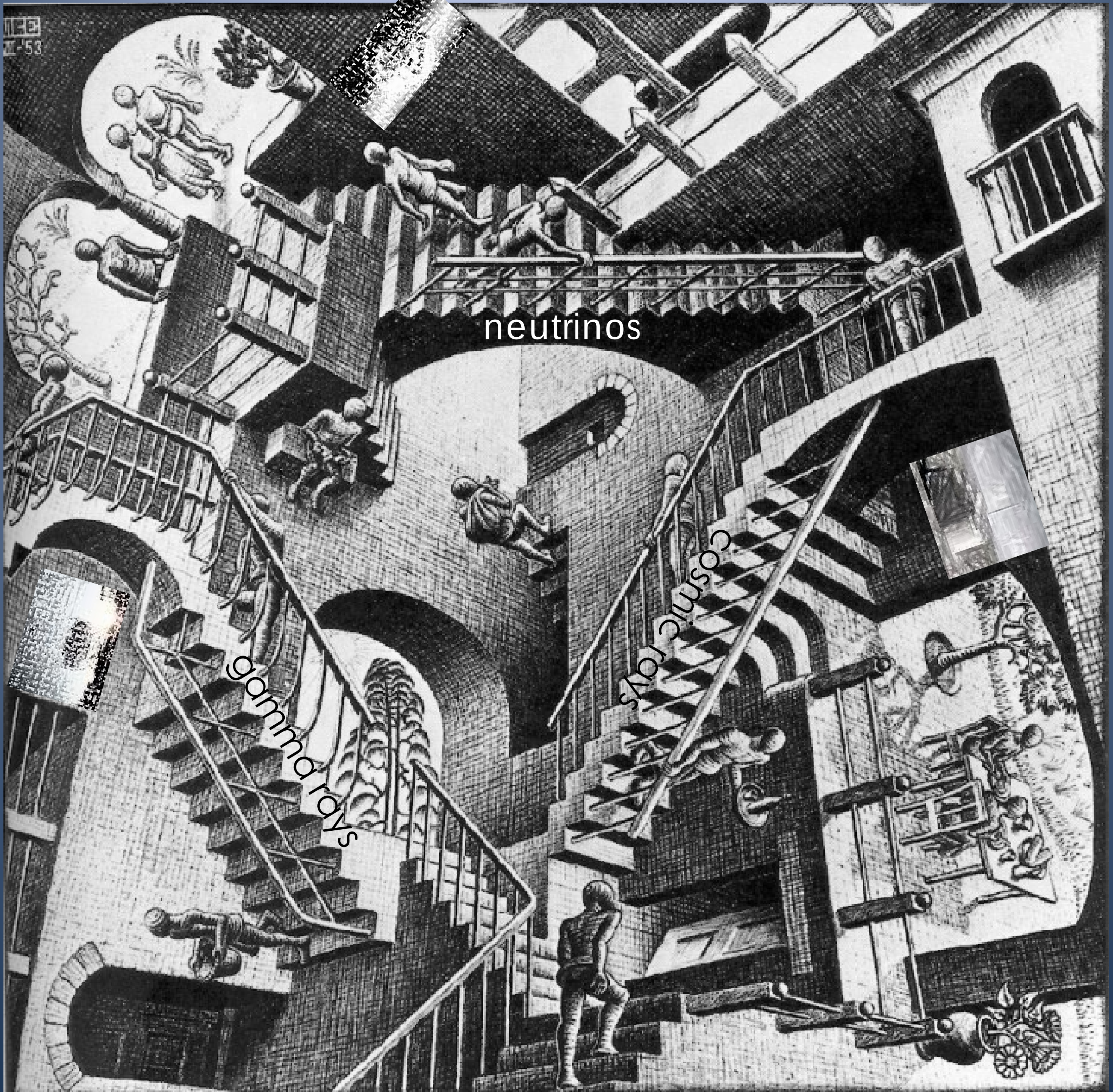
Image: J.A. Aguilar, J. Yang



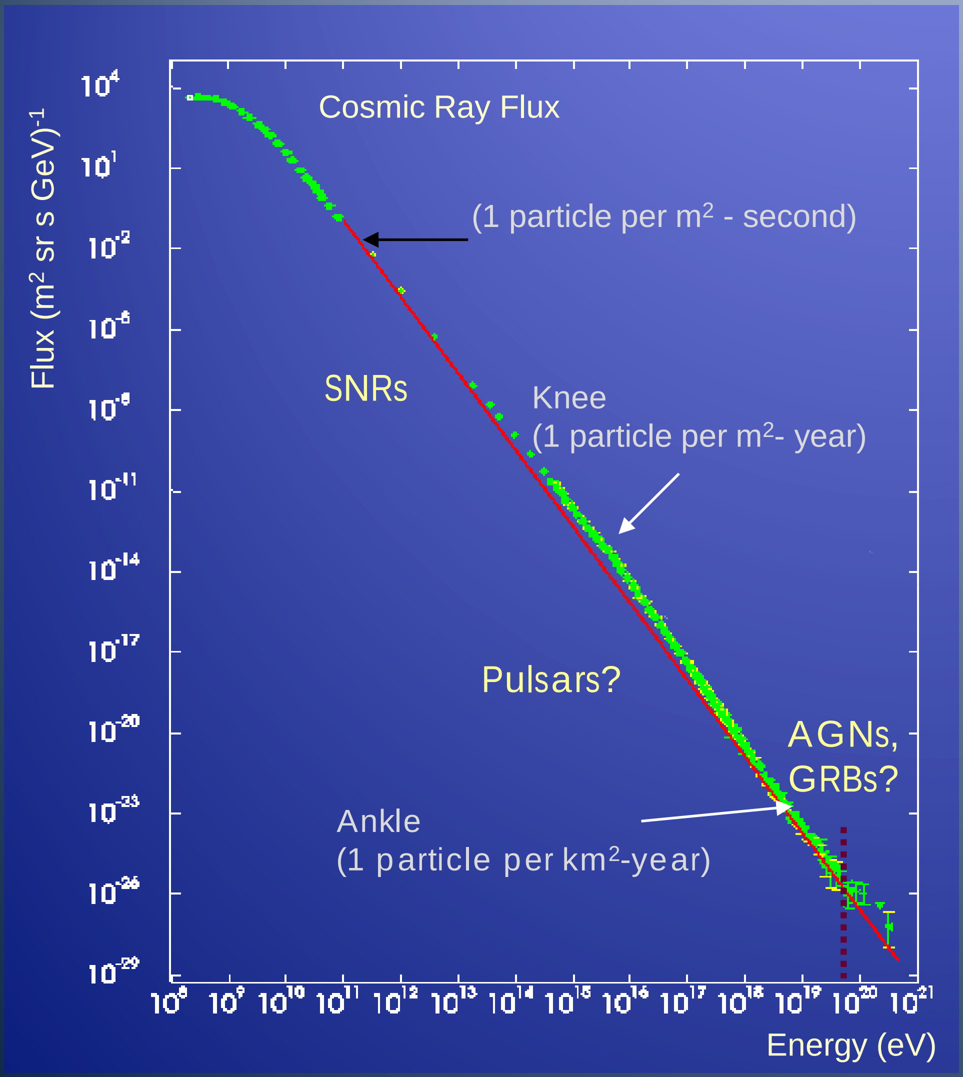
1 PeV neutrinos ↔

↔ 20 PeV protons ↔

↔ 2 PeV γ-rays


neutrinos
cosmic rays
gamma rays

Cosmic Rays



- Cosmic rays follow a power law:

$$\frac{dN}{dE} \propto E^{-\gamma} \begin{cases} \gamma = 2.7 \\ \gamma = 3.0 \\ \gamma = 2.7 \end{cases}$$

the knee

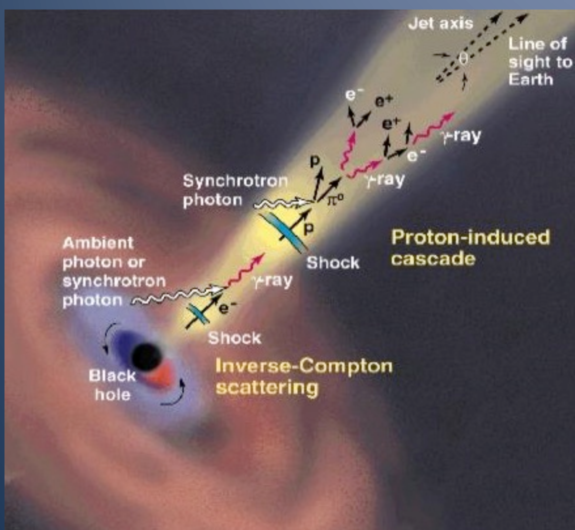
the ankle

- Beyond ~5×10^{19} eV, the flux should vanish due to the interaction of protons with the CMB (GZK limit). But a cut-off could also be due to limit in the accelerator energy.

- High energy neutrinos could give information about the origin of cosmic rays.

High energy photons

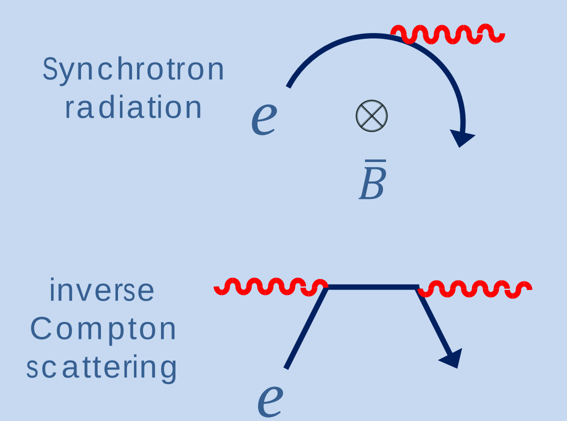
- The observation of TeV photons can be explained by
  - leptonic processes (inverse Compton, synchrotron) or
  - the decay of neutral pions produced in hadronic interactions ($\rightarrow$neutrino production).



acceleration in AGNs

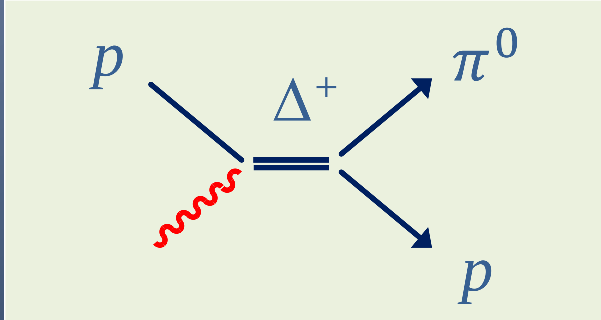
vs

leptonic

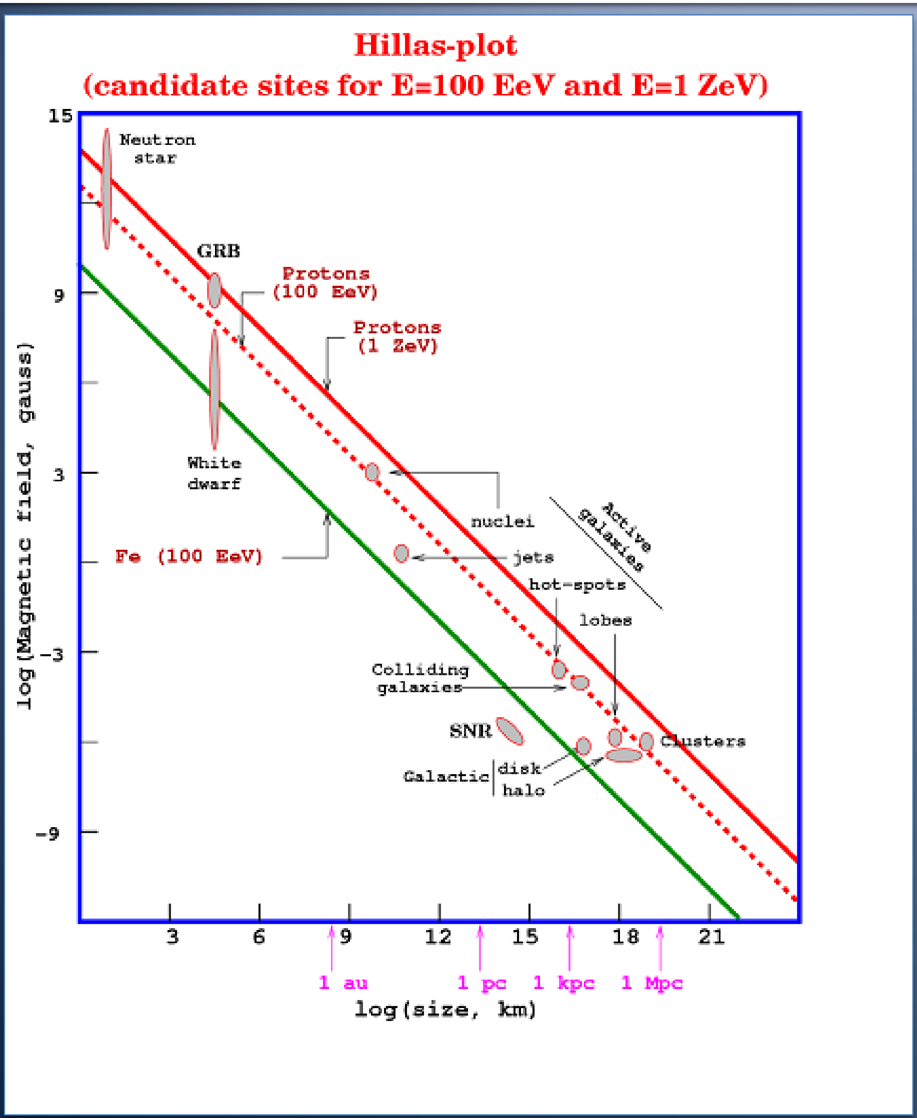


hadronic

$$\pi^0 \longrightarrow \gamma\gamma$$



Hillas plot



- Containment condition: Larmor radius has to be larger than accelerator size

$$E_{max} \approx 10^{18}\,\mathrm{eV} \cdot Z \cdot \left(\frac{R}{\mathrm{kpc}}\right) \cdot \left(\frac{B}{\mu G}\right)$$

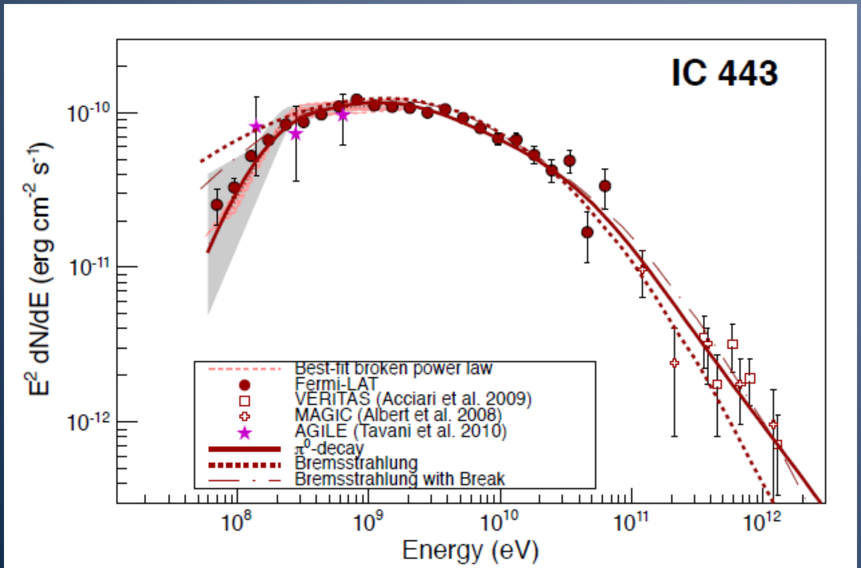
- Not many astrophysical objects fulfill the conditions needed to accelerate cosmic rays to the highest energies

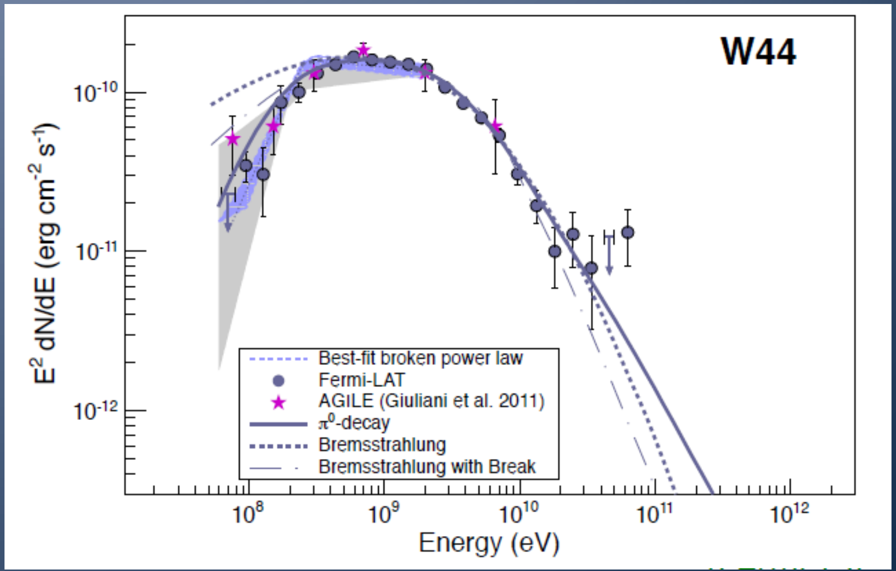
Supernova Remnants

- Formed after the explosion of a supernova by the expelled material colliding with the interstellar medium
- Two main categories:
  - Pulsar Wind Nebulae (or plerions), which have a pulsar in its center
  - Shell-type SNRs

Galactic Cosmic Rays

- Fermi (γ-rays) results on IC 443 W44 supernova remnants seem to indicate a better agreement of hadronic models for low energy → origin of low energy CRs?

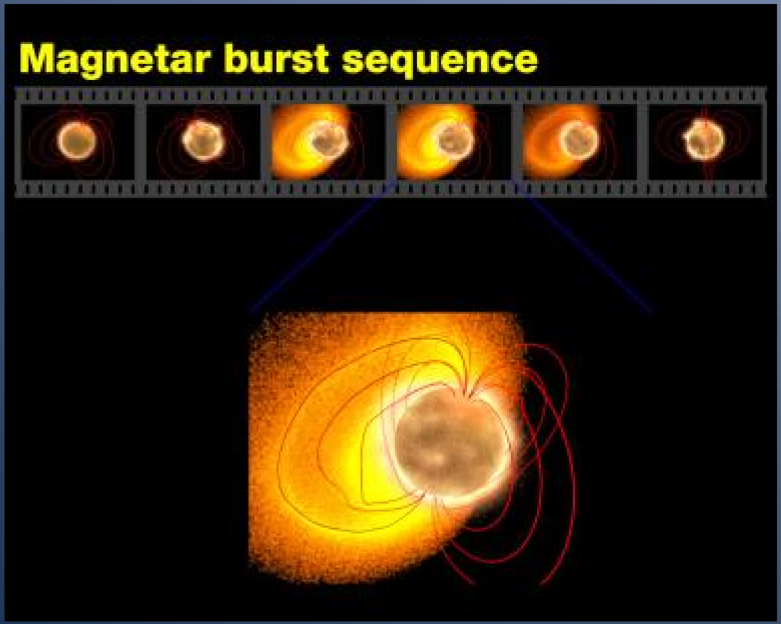




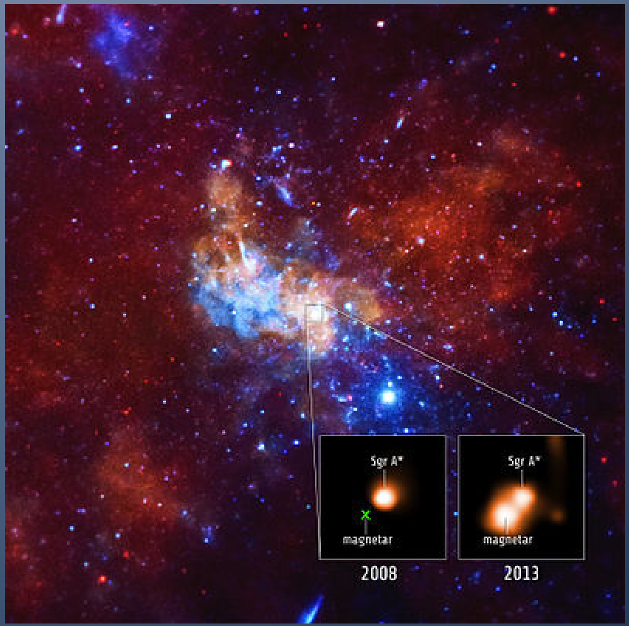
Magnetars

- Isolated neutron stars with surface dipole magnetic fields ~10^{15} G, much larger than ordinary pulsars.

- Seismic activity in the surface could induce particle acceleration in the magnetosphere



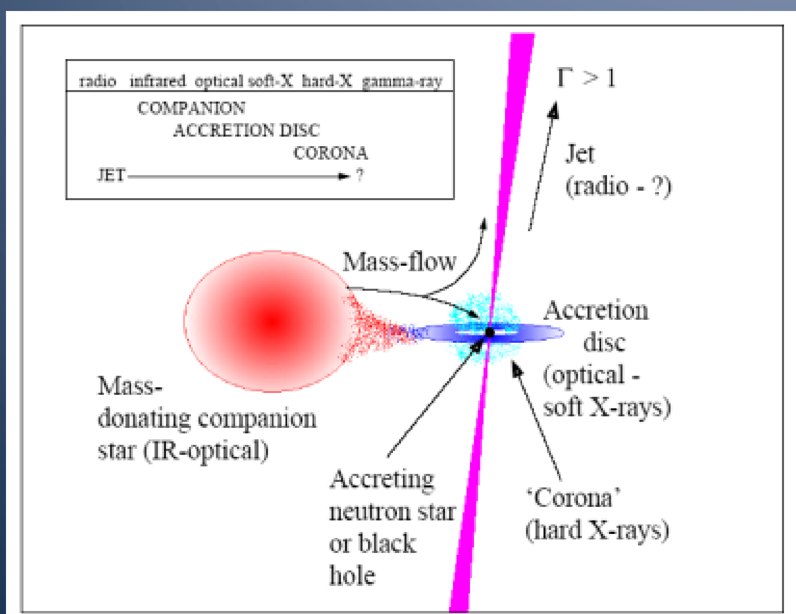
SGR 1745-2900

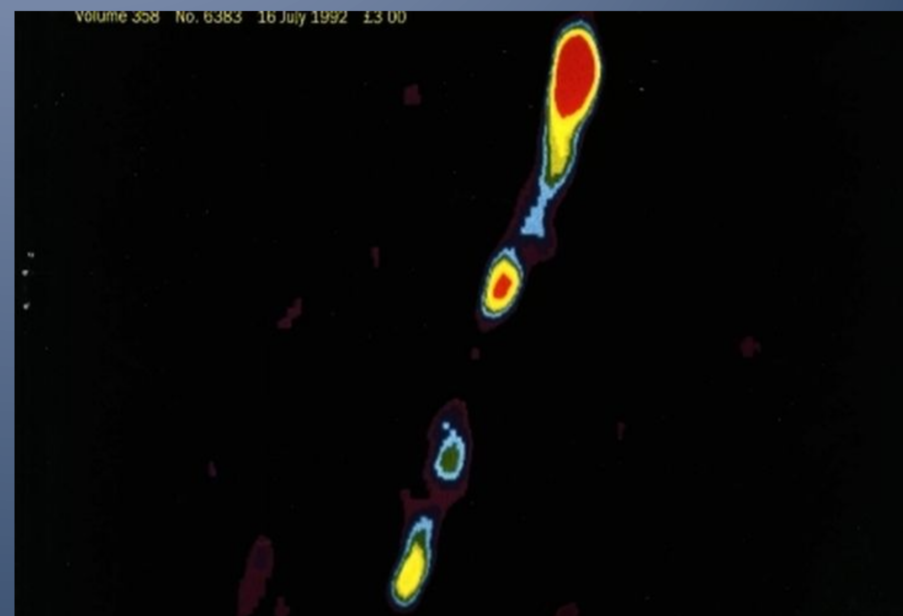


Microquasars

- Micro-quasars: a compact object (BH or NS) towards which a companion star is accreting matter
- Particle acceleration up to high energies in the jets

Cygnus X-1



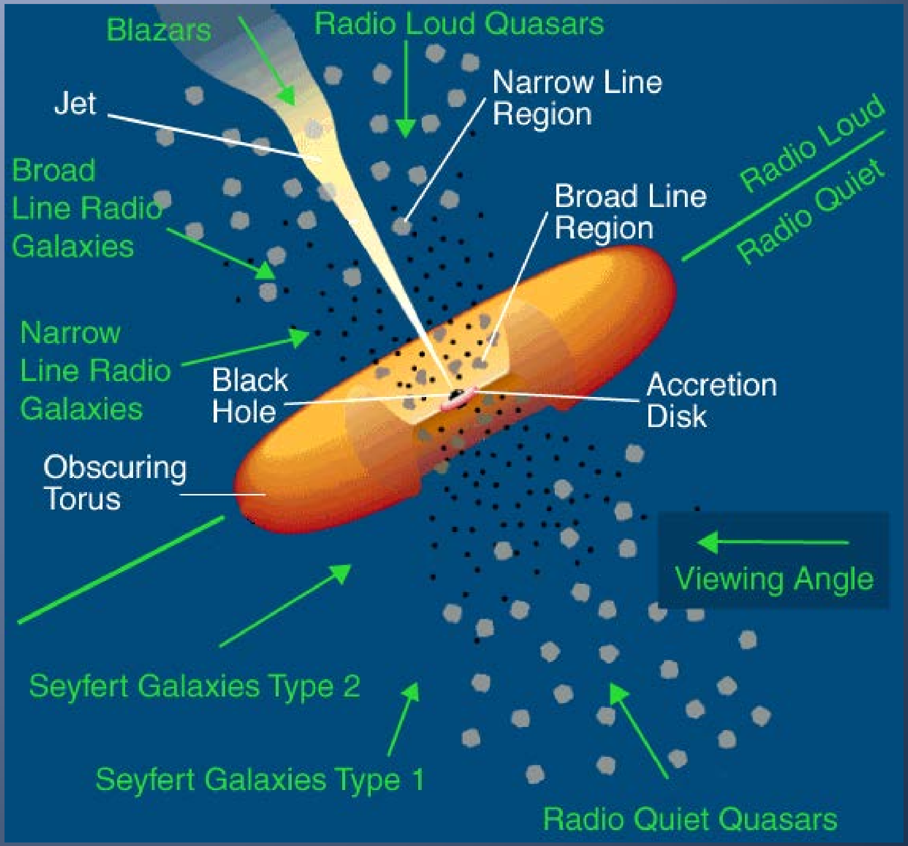


Fender 2002

Active Galactic Nuclei

- Active Galactic Nuclei includes Seyferts, quasars, radio galaxies and blazars.
- Standard model: a super-massive (10^6-10^8 M_o) black hole towards which large amounts of matter are accreted.

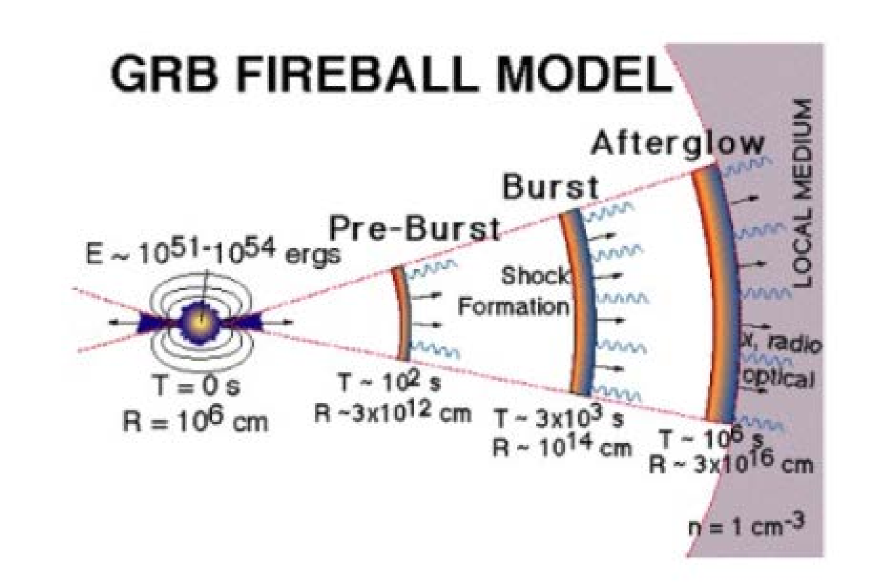
Centaurus A

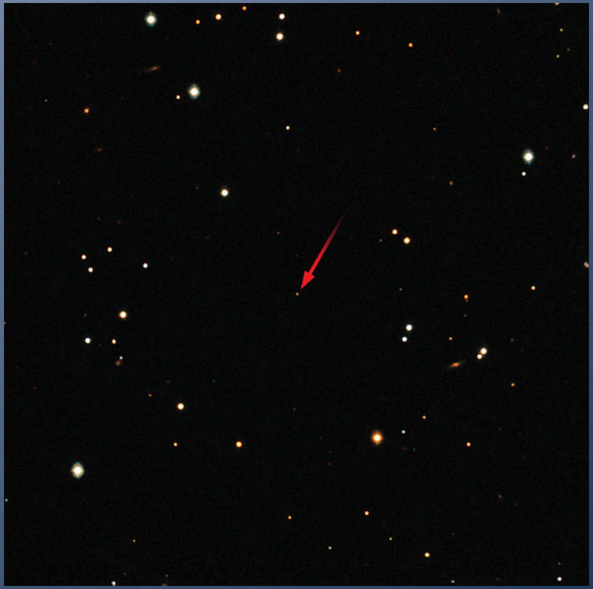


Schematic view of AGN and classification according to viewing angle

Gamma Ray Bursts

- GRBs are brief explosions of γ rays (often + X-ray, optical and radio).
- In the fireball model, matter moving at relativistic velocities collides with the surrounding material. The progenitor could be a collapsing super-massive star (short GRBs, 0.5 s) or the merging of two compact objects (long GRBs, 30 s)





GRB 151027B

Starbust Galaxies

- Starburst galaxies are characterized by the existence of regions with a very high star formation rate
- A galactic scale wind blows out large amounts of mass into the intergalactic medium driven by the collective effect of supernova explosions and massive star winds

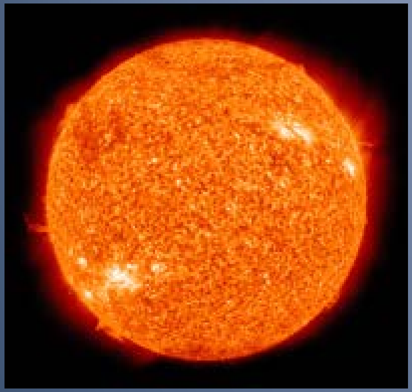
Composite image (HST/WIYN) of M82 and its optical bright superwind

Dark matter

- WIMPs (neutralinos, KK particles) are among the most popular explanations for dark matter
- They would accumulate in massive objects like the Sun, the Earth or the Galactic Center
- The products of such annhiliations would yield “high energy” neutrinos, which can be detected by neutrino telescopes

Sources for DM searches

Sun



Galactic Centre

Dwarf galaxies

Earth

Galactic Halo

Galaxy clusters

Ultra-high energy neutrinos

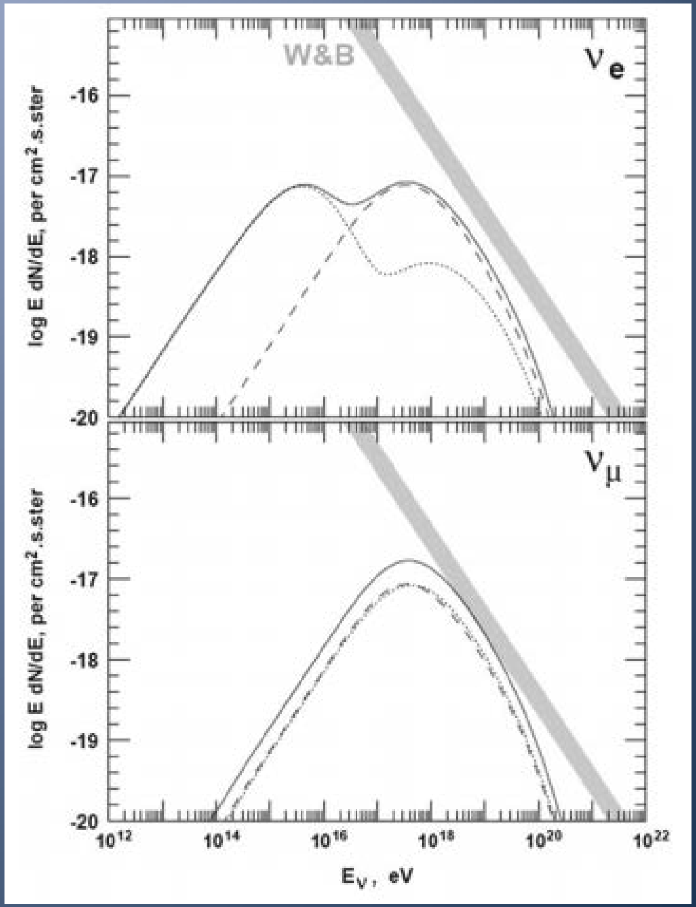
- GZK cutoff: Protons interact with cosmic microwave background, which limits its range at high energies:

  $p\ \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n\ \pi^+$ (or $p\ \pi^0$)

- CRs above the GZK cut-off (~5×10^{19} eV) have an absorption length of 200 Mpc (local Universe)
- The GZK cut-off also leads to a measurable to neutrinos

$$\pi \rightarrow \mu + \nu_\mu \rightarrow e + \nu_\mu + \nu_e + \nu_\mu$$

guaranteed source of neutrinos!
(peaking about <u>10^{18} eV</u>)



(but it <u>depends</u> on composition, spectrum, distribution and cosmological evolution of sources): v.g.: more neutrinos in proton dominated models

Scientific Scope

- Origin of cosmic rays
- Hadronic vs. leptonic signatures
- Neutrino mass ordering
- Dark matter

Detector size

Limitation at high energies:
Fast decreasing fluxes E^{-2}, E^{-3}

Limitation at low energies:
-Short muon range
-Low light yield
-^{40}K (in water)

Detector density

Supernovae

Oscillations-Mass ordering

Dark matter

Astrophysical neutrinos

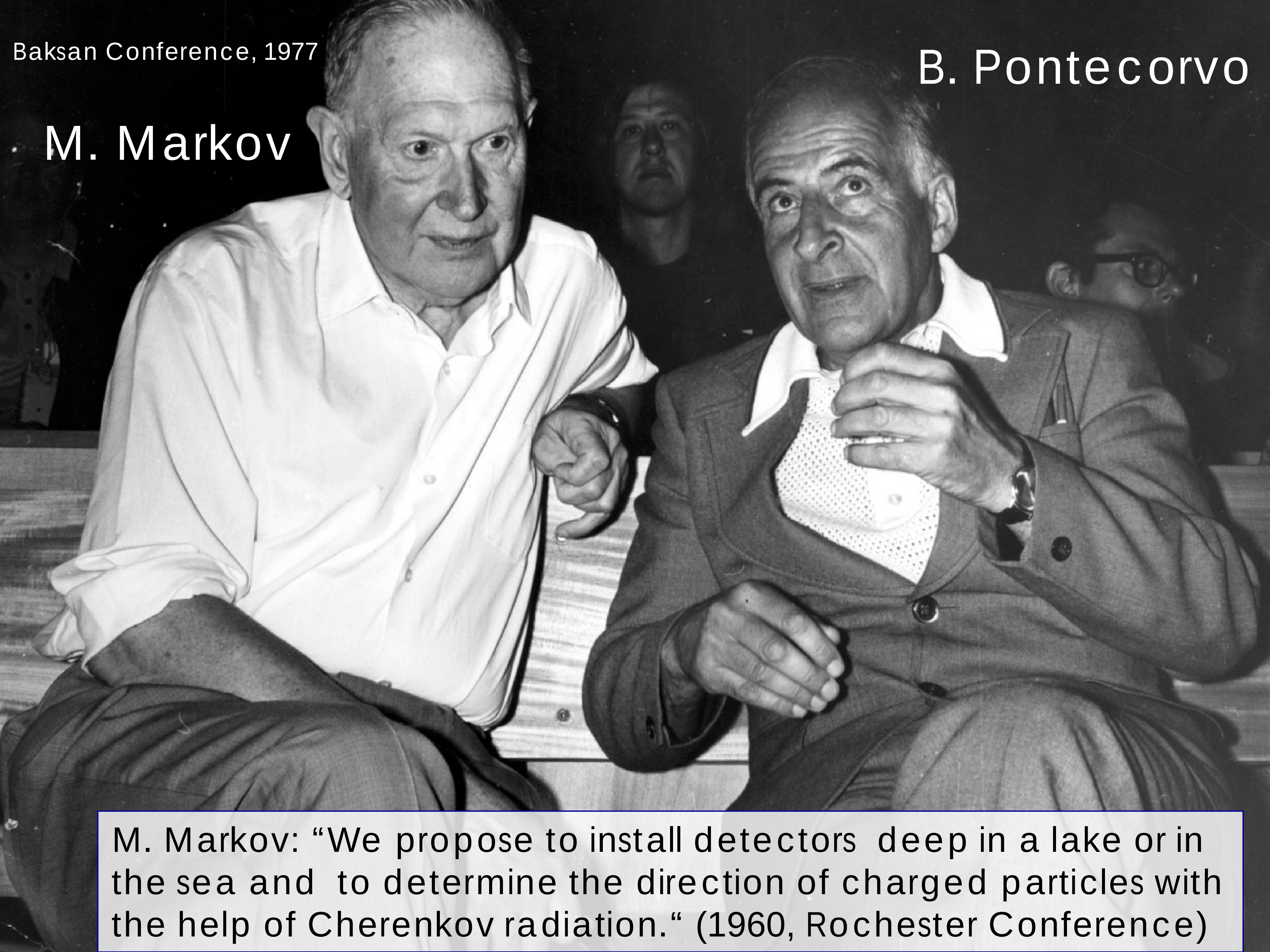
GZK

MeV GeV TeV PeV EeV

Other physics: monopoles, nuclearites, Lorentz invariance, etc…

Neutrino detection techniques

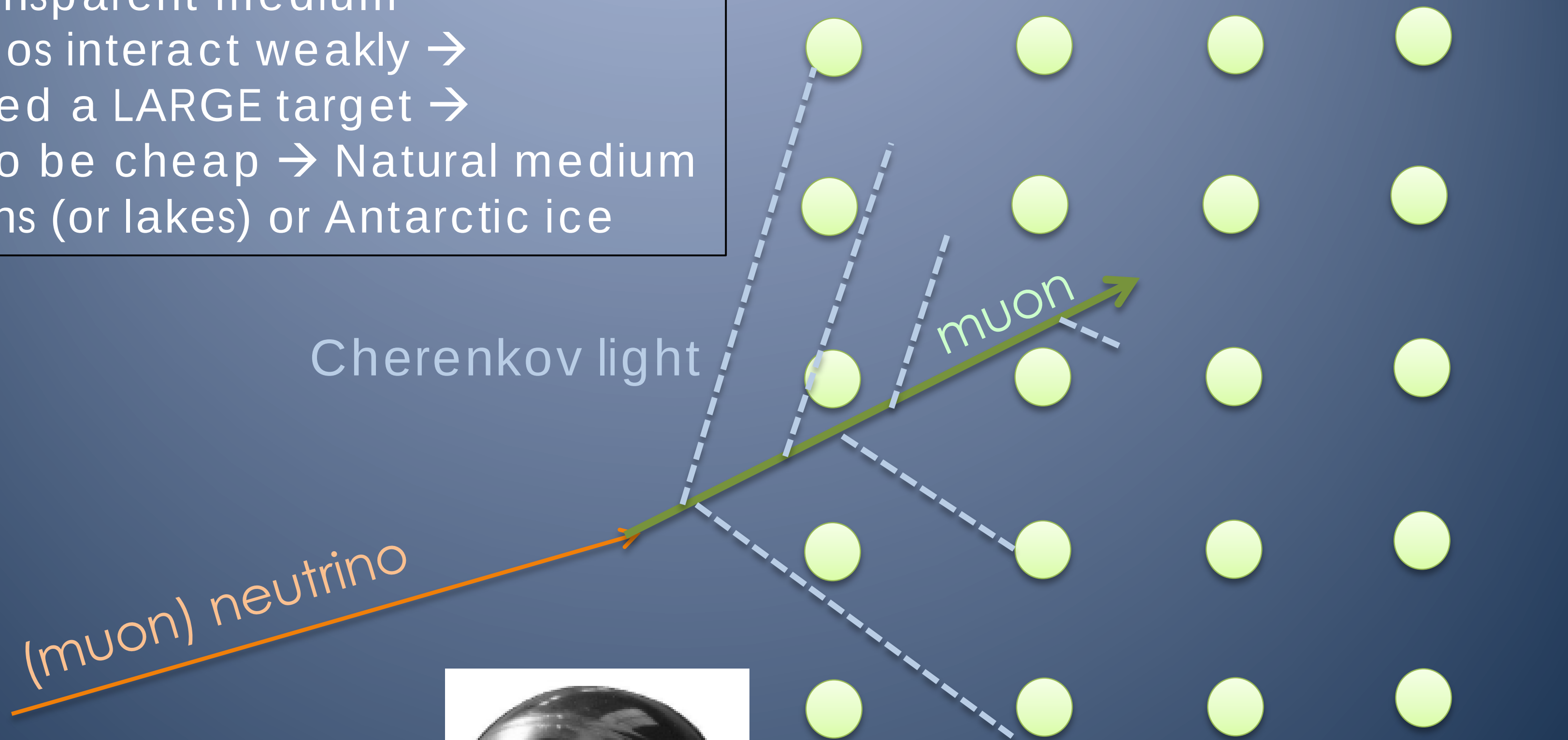
- Optical Cherenkov:
  - In Ice: AMANDA, IceCube
  - In water: Baikal, ANTARES, KM3NeT
- Atmospheric showers:
  - On earth: Auger
  - In space: JEM-EUSO
- Radio:
  - On earth: RICE, ARIANNA, LOFAR
  - Balloon: ANITA
- Acoustic:
  - AMADEUS, SPATS

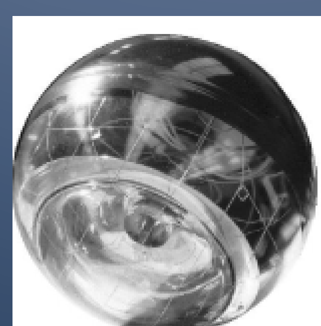


M. Markov: “We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.“ (1960, Rochester Conference)

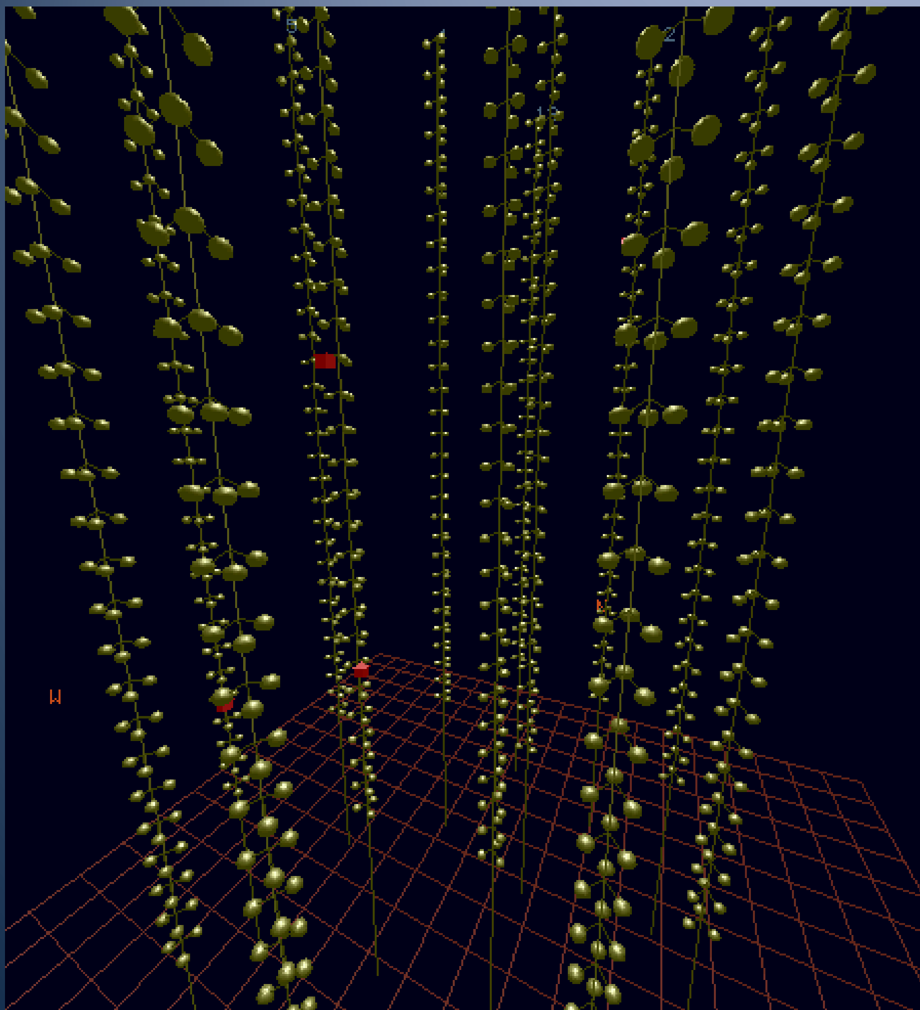
Detection Principle

Where to put the detector?
1) In a transparent medium
2) Neutrinos interact weakly →
→ We need a LARGE target →
→ It has to be cheap → Natural medium
→ Oceans (or lakes) or Antarctic ice



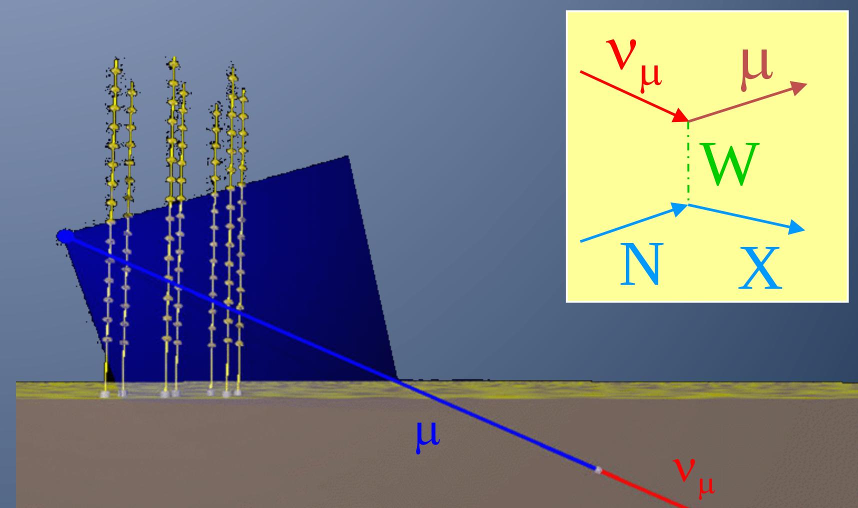


Detection Principle



1.2 TeV muon traversing ANTARES

- The neutrino is detected by the Cherenkov light emitted by the muon produced in the CC interaction.



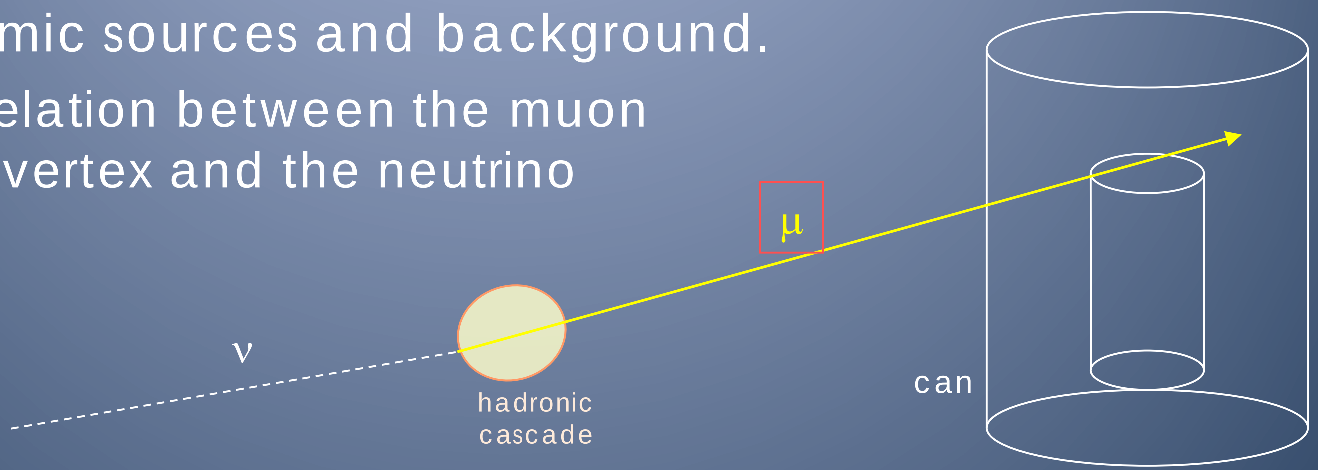
- Position and time information of hits in the PMTs allows us to reconstruct the original direction

Muon Energy Reconstruction

Some remarks

- Energy reconstruction is important to discriminate between cosmic sources and background.

  There is a correlation between the muon energy at the vertex and the neutrino energy.



can=volumen within which light can reach the detector

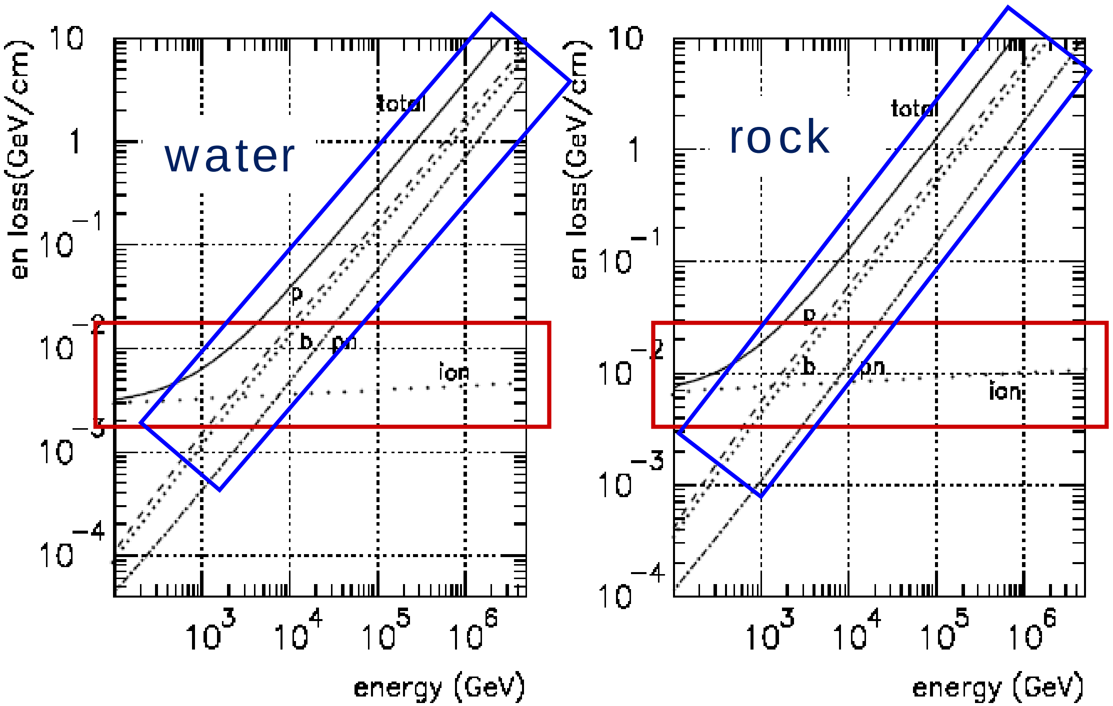
- The muon energy is not a well defined quantity (if the vertex is outside the can) due to muon energy losses.
- If the interaction vertex is inside the can, we will consider the muon energy as the energy of the muon at the interaction vertex.

Muon Energy Loss

- The muon energy reconstruction is based on the fact that the higher its energy, the higher the energy loss along its track.

$$\frac{dE}{dx} = \left.\frac{dE}{dx}\right|_I + \left.\frac{dE}{dx}\right|_p + \left.\frac{dE}{dx}\right|_b + \left.\frac{dE}{dx}\right|_{pn} \Rightarrow -\left\langle \frac{dE}{dx} \right\rangle = \alpha + \beta E$$

$\alpha \approx 2.67$ GeV g^{-1}cm^{-2}
$\beta \approx 3.40 \cdot 10^{-6}$ g^{-1} g cm^{-2}
(in water)

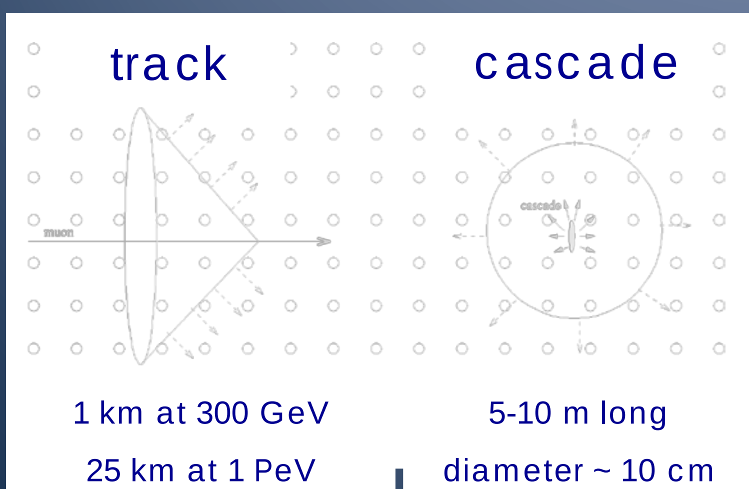


Two different regions:

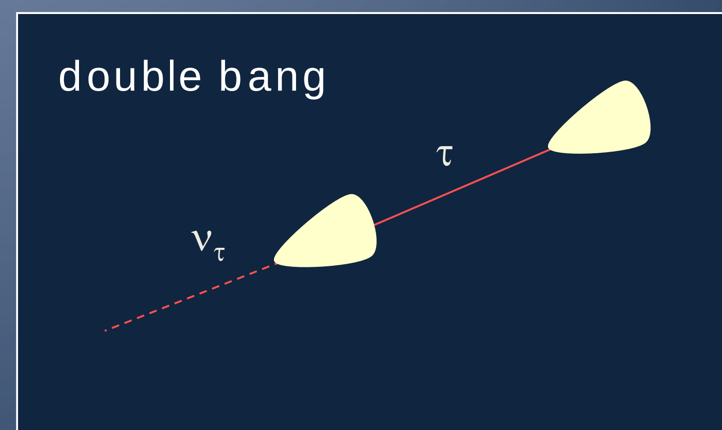
- $E\mu < \varepsilon_c$: Losses dominated by ionization (smooth but almost energy independent).
- $E\mu > \varepsilon_c$: Losses dominated by radiative processes (pair production, bremsstrahlung and photonuclear interaction). **Very stochastic**.

Other signatures

- Cascades are an important alternative signature: detection of electron and tau neutrinos.
- Also neutral interaction contribute (only hadronic cascade)

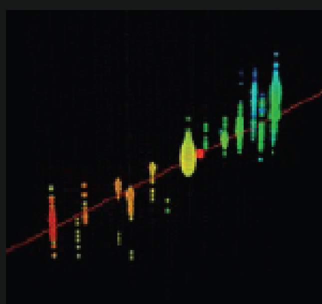


- Clear signature of oscillations.
- ANTARES is too small to detect double bang signature (they are too rare)
- However, cubic-kilometer telescopes could detect them
- Maximum sensitivity at 1-10 PeV



Channels

CC Muon Neutrino



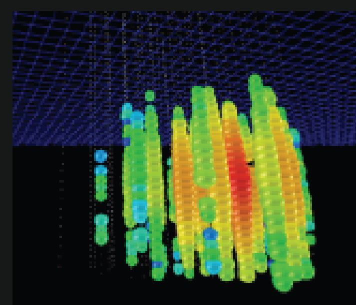
$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
$< 1°$ angular resolution

in water: 0.1-0.3 degrees

Neutral Current / Electron Neutrino



$$\nu_e + N \rightarrow e + X$$

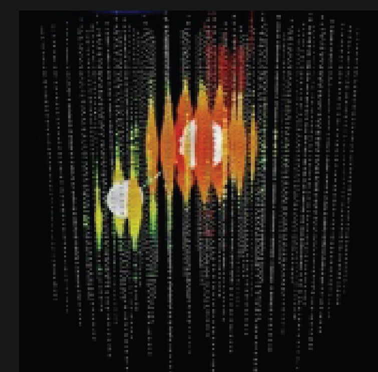
$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

$\approx \pm 15\%$ deposited energy resolution
$\approx 10°$ angular resolution

in water: 2-4 degrees!

CC Tau Neutrino

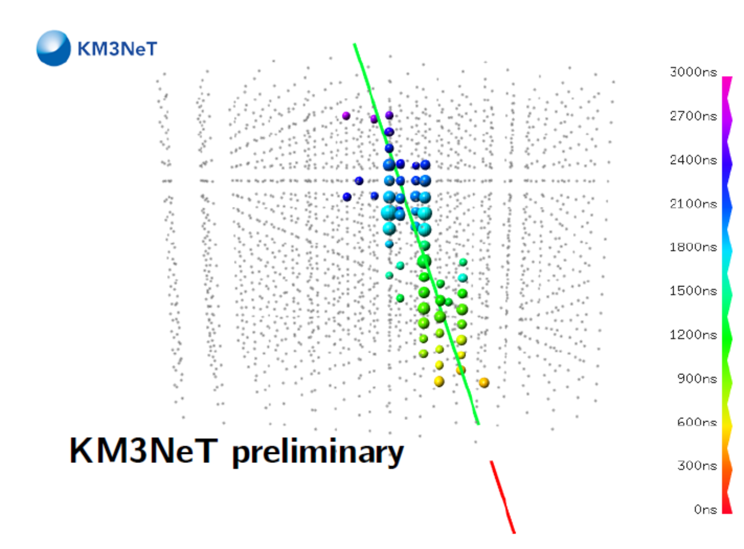


$$\nu_\tau + N \rightarrow \tau + X$$

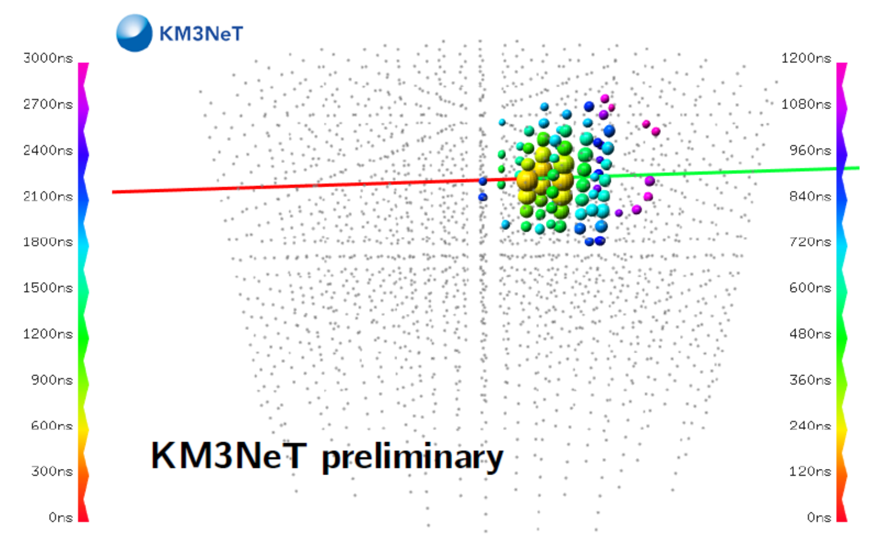
"double-bang" and other signatures (simulation)

(not observed yet)

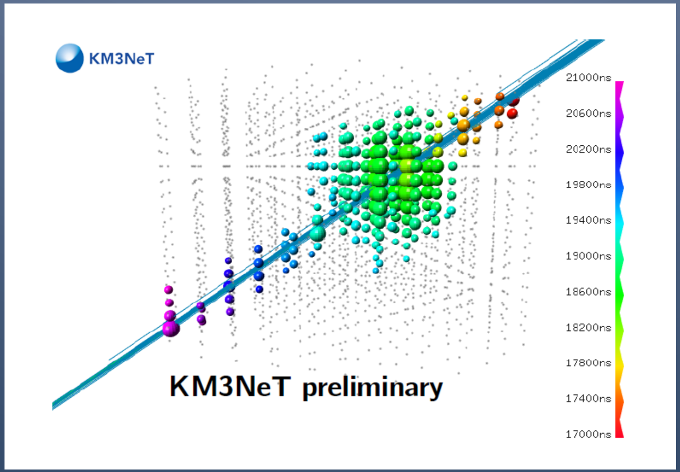
Channels



track



cascade

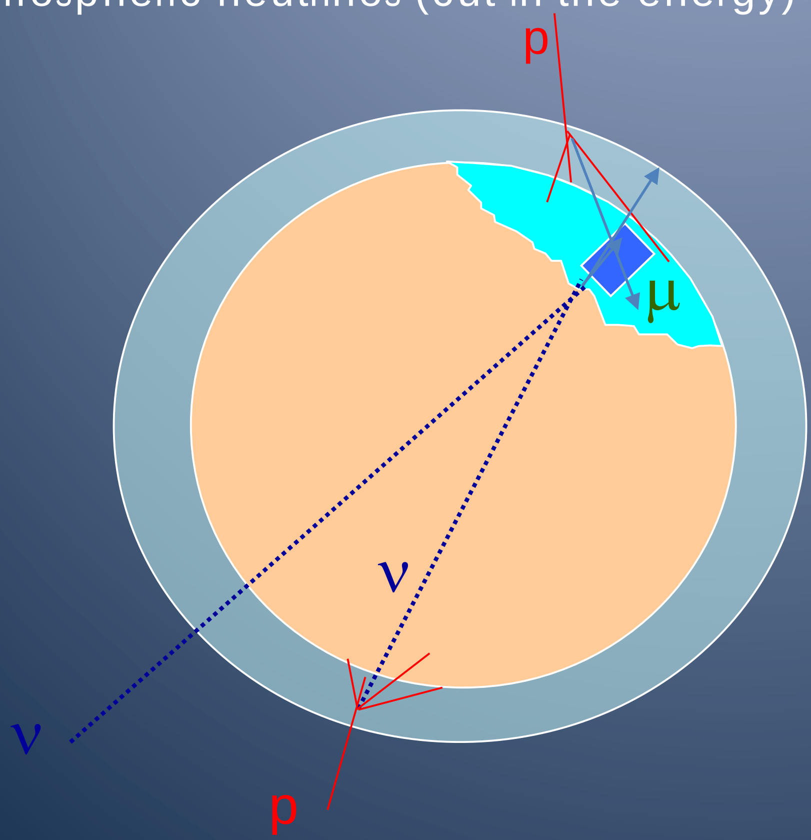


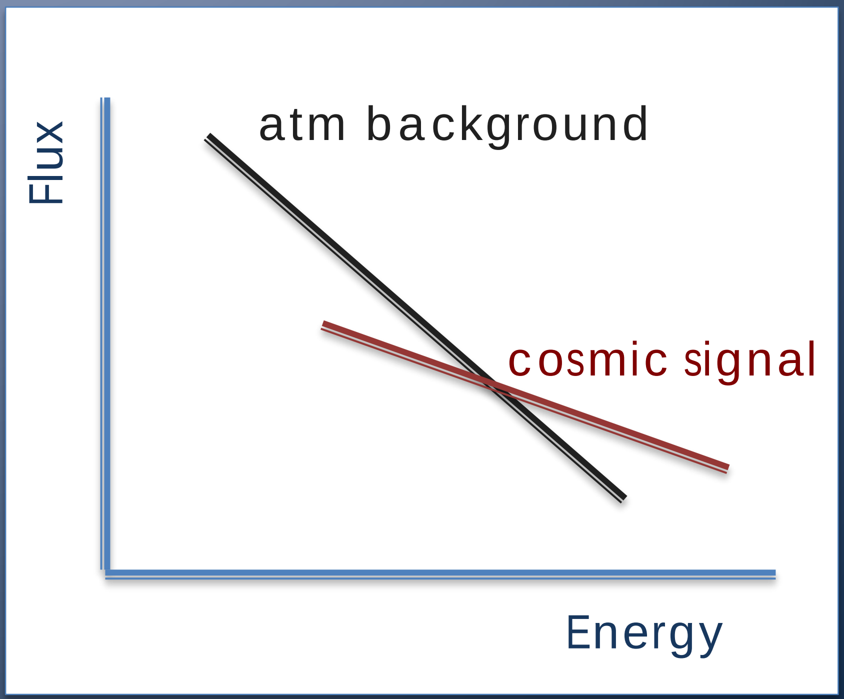
1 PeV atm. nu
+ muon bundle

Physical Background

- There are two kinds of background:
  - Muons produced by cosmic rays in the atmosphere (→ detector deep in the sea and selection of up-going events)
  - Atmospheric neutrinos (cut in the energy)

$$p \to \pi^+(+K^+ ...) \to \mu^+ + \nu_\mu$$
$$\mapsto e^+ + \overline{\nu}_\mu + \nu_e$$



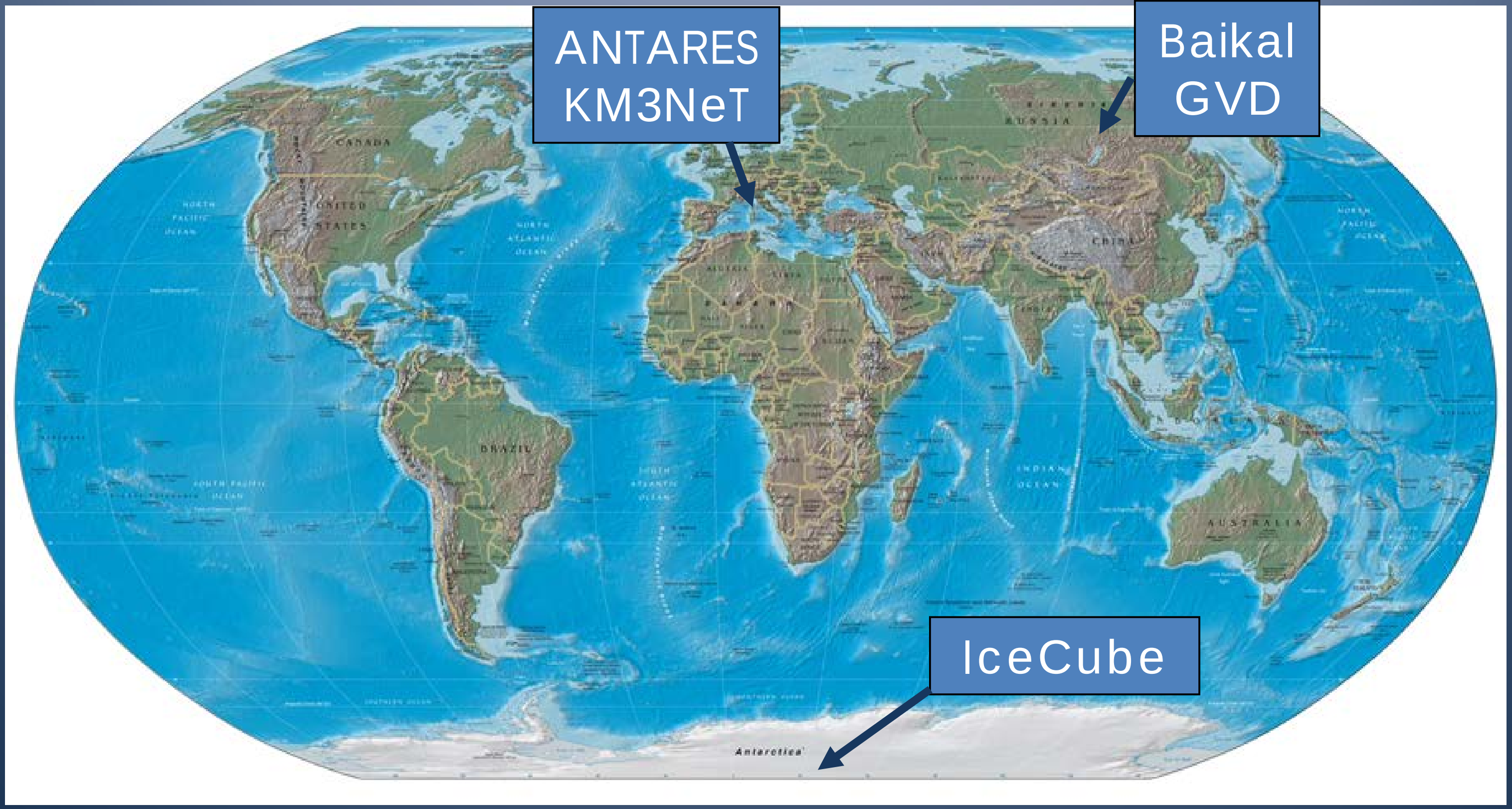


Let's design a neutrino telescope! (I): Location

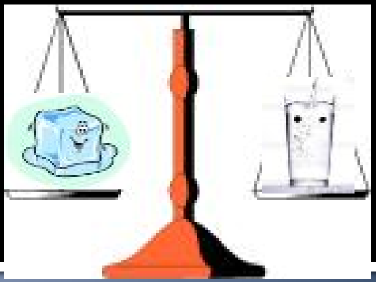
- Given the detection principle, we need large (see later) quantities of a transparent medium: water/ice
  - Ocean: Mediterranean has large depths (2500-3500 m) close to the coast
  - Lake: Baikal lake has the advantage of a surface freezing in winter (easier deployment) but not very deep
  - Antarctic: close to South Pole, where Amundsen-Scott infrastructures are

NTs in the world

- Several projects are working/planned, both in ice and ocean and lakes.



Water vs Ice

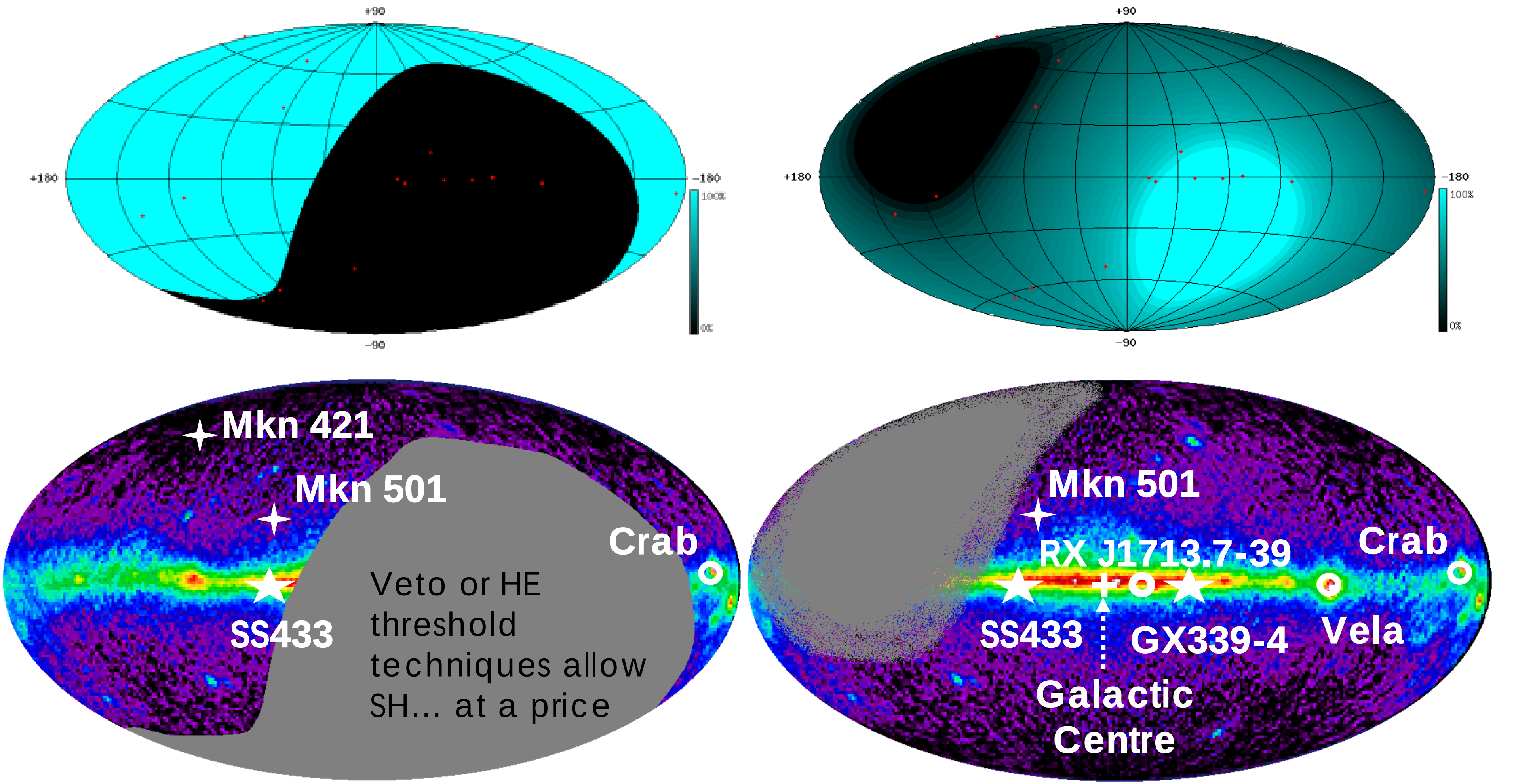


- Advantages of <u>oceans</u>:
  - Larger scattering length $\rightarrow$ better angular resolution
  - Weaker depth-dependence of optical parameters
  - Possibility of recovery
  - Changeable detector geometry
- Advantages of <u>ice</u>:
  - Larger absorption length
  - No bioluminescence, no ^{40}K background, no biofouling
  - Easier deployment
  - Lower risk of point-failure
- Anyway, a detector in the Northern Hemisphere in necessary for complete sky coverage (Galactic Center!), and it is only feasible in the ocean.

Regions observed by NTs

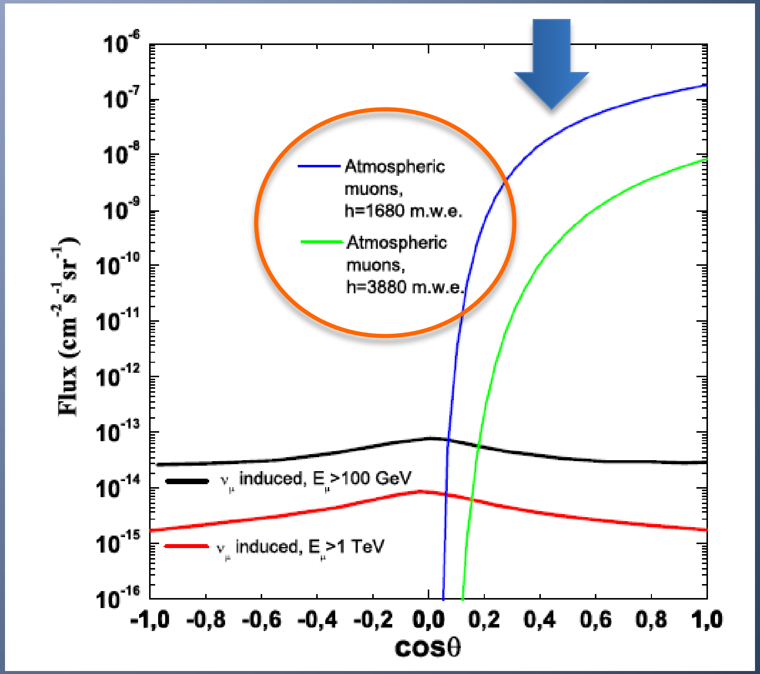
IceCube (South Pole)
(ang. res.: 0.5°)

ANTARES/KM3NeT (43° North)
(ang. res.: ~0.3°/0.1°)



Let’s design a neutrino telescope! (II): Depth

- The main “physical” background comes from atmospheric muons
- At first order, the deeper the better but:
  - Antarctic/Lake: bedrock puts a limit in depth (but depth enough at South Pole)
  - Sea: at some point, too much depth increases too much the difficulties (water pressure), increasing the cost and the failure risk



Let's design a neutrino telescope! (III): Size

Detection rate

$$\frac{N_\nu}{T} = \int \mathrm{d}E_\nu \cdot \frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu}(E_\nu) \cdot A_\nu^{\mathrm{eff}}(E_\nu)$$

A_{eff} is the effective area:

$$A_\nu^{\mathrm{eff}}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E_{\mathrm{thr}}^{\mu}) \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$$

(next slides)

Reference neutrino flux for galactic sources:
(similar reasoning using extragalactic)

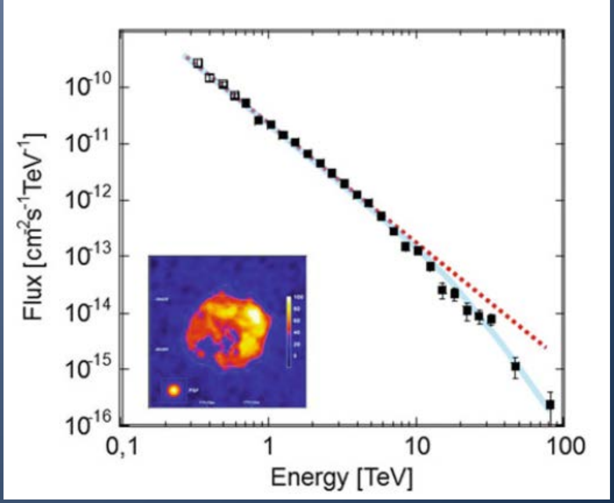
$$\Phi_{\nu_\mu}(E) \simeq \frac{1}{2}\Phi_\gamma(E)$$

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \Phi_\nu^0 E_\nu^{-2} = 10^{-11} E_\nu^{-2}\ \mathrm{TeV\ s^{-1} cm^{-2}}$$

Some assumptions:

- mostly hadronic origin in gamma rays
- no gamma ray absorption
- $\pi^\pm$ decay before interacting and $\mu^\pm$ decay without energy losses
- size of source large so oscillations produce flavour ratios 1:1:1 at Earth

gamma-ray flux of RXJ1713.7-3946 as measured by HESS



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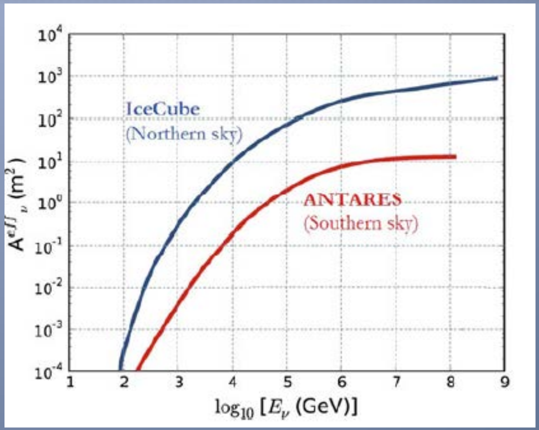
Let's design a neutrino telescope! (III): Size

A_{eff} is the effective area:

$$A_\nu^{\mathrm{eff}}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E^\mu_{\mathrm{thr}}) \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$$

A is geometrical projected area



Effective area for IceCube and ANTARES in standard point source searches (At ~PeV the Earth starts to be opaque to neutrinos)

$P_{\nu\mu}$ (E_ν, E^μ_{thres}) is the probability to produce a muon above detection threshold

$$P_{\nu\mu} = N_A \int_0^{E_\nu} \frac{d\sigma_\nu}{dE_\mu}(E_\mu, E_\nu) \cdot R_{\mathrm{eff}}(E_\mu, E^\mu_{\mathrm{thr}}) dE_\mu$$

Good approximation (Gaisser, 1996):

$$\begin{aligned} P_{\nu\mu} &\simeq 1.3\ 10^{-6} E_\nu^{2.2}, \quad \text{for } E_\nu = 10^{-3} - 1\ \mathrm{TeV} \\ &\simeq 1.3\ 10^{-6} E_\nu^{0.8}, \quad \text{for } E_\nu = 1 - 10^3\ \mathrm{TeV} \end{aligned}$$

ε is the fraction of the muons above threshold which are detected (trigger-reconstruction-quality cuts)

$e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$ takes into account neutrino absorption

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Let's design a neutrino telescope! (III): Size

- We'll assume that muons above 1 TeV have a constant probability of being detected

$$\frac{N_\nu}{T} = \int_{1\ \mathrm{TeV}}^{10^3\ \mathrm{TeV}} \mathrm{d}E_\nu \cdot (\Phi_\nu^0 E_\nu^{-2}) \cdot A \cdot (P_\circ E_\nu^{0.8}) \cdot \epsilon = 0.5\ 10^{-16} \cdot A \cdot \epsilon\ \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

- If the geometrical transverse area is about **1 km^3** and ε=0.1, we find an event rate above 1 TeV about 10^3 cm^2 of **1.5 ev/year**

- Notes:
  - Do not forget backgrounds! (atmospheric muons and atmospheric neutrinos)
  - No cut-off has been included in the flux, which could decrease rates by a factor 5-10

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Let's design a neutrino telescope! (IV): Geometry

- How many light sensors?
  - Typically, 10 photoelectrons (p.e.) are detected per PMT
  - Let's assume that a signal in at least 10 PMTs are needed to reconstruct a muon track, so we need about 100 p.e.
  - For 10'' PMTs, A_{PMT}=0 .05 m^2
  - ε_{PMT}=0.25 → ε_{OM}=0.20, when OM glass absorption, etc. are included
  - Effective volume of each PMT would be $V_{\text{pmt}} = A_{\text{pmt}} \times \lambda_{\text{abs}} \simeq 2.5\ m^3$
  - The ratio R between effective PMT volume and the instrumented volume (1 km^3) is

$$R = \frac{V_{\text{pmt}} \times N_{\text{pmt}}}{10^9\ \text{m}^3} = 2.5 \times 10^{-9} N_{\text{pmt}}$$

  - The total number of Cherenkov photons emitted is N_C ~ 3.5 x 10^7, therefore:

$$N_{p.e.} = N_C \times R \times \epsilon_{\text{om}} \simeq (3.5 \times 10^7) \cdot (2.5 \times 10^{-9} N_{\text{pmt}}) \cdot \epsilon_{\text{om}} \\ = 1.8 \times 10^{-2} N_{\text{pmt}}$$

  - If we require N_{pe}~100, then:

$$N_{\text{pmt}} \simeq 100/1.8 \times 10^{-2} \simeq 5000$$

→ About 5000 Optical Modules in a cubic kilometre are needed

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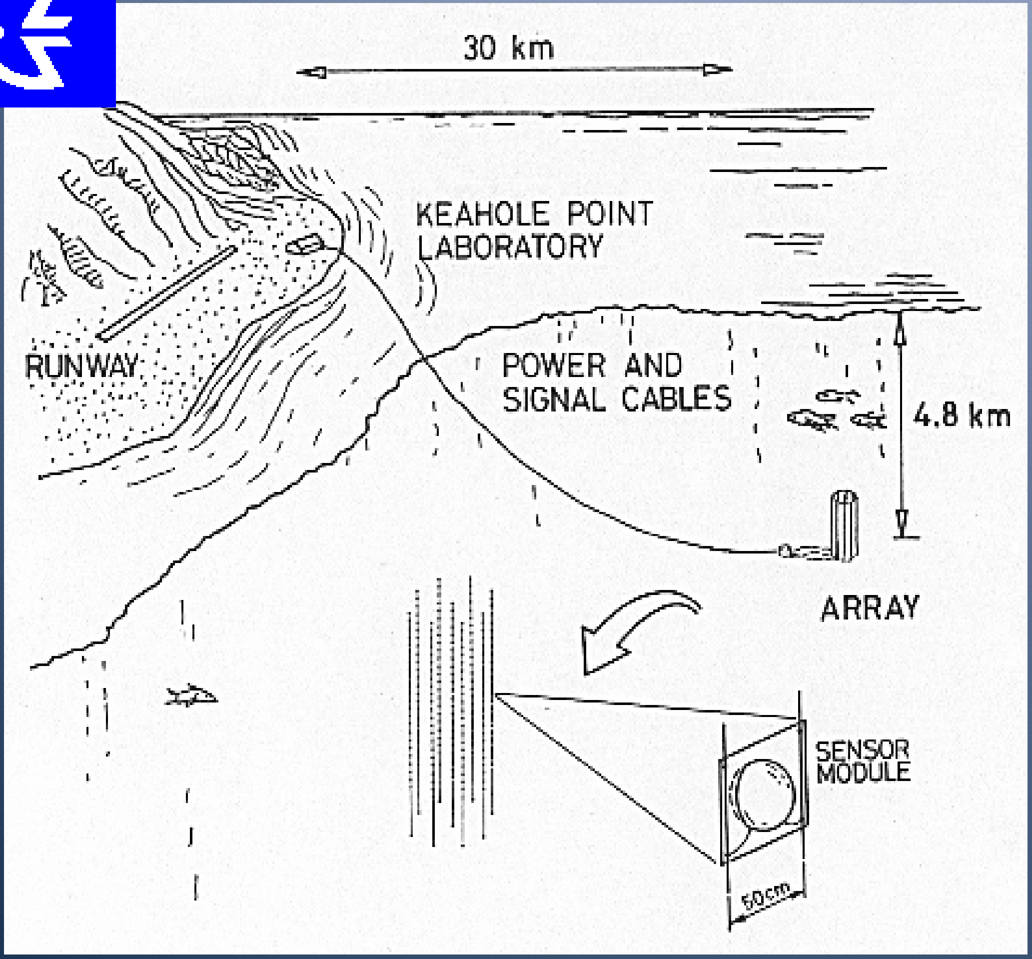
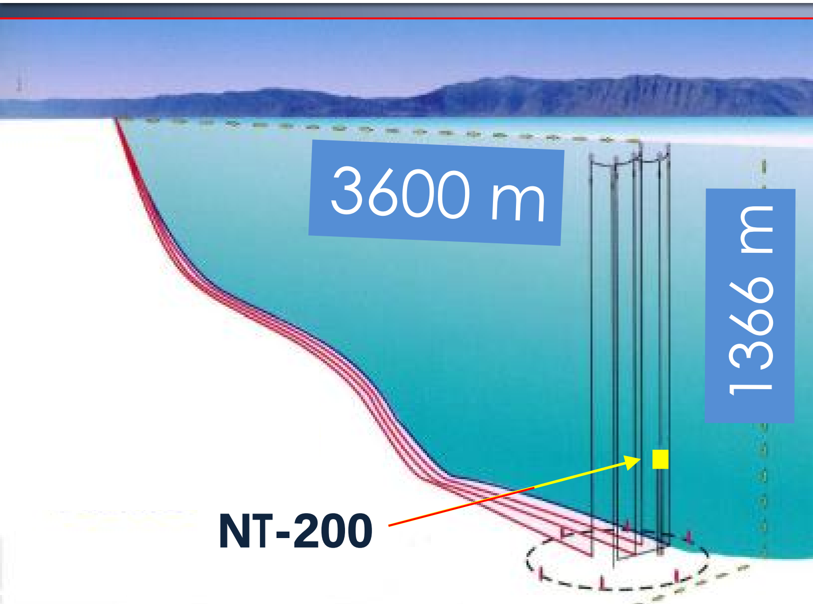
Pioneers

DUMAND



- History of the project:
- 1975: first meetings for underwater detector in Hawaii
- 1987: Test string
- 1988: Proposal: “The Octagon” (1/3 AMANDA)
- 1996: Project cancelled

Baikal

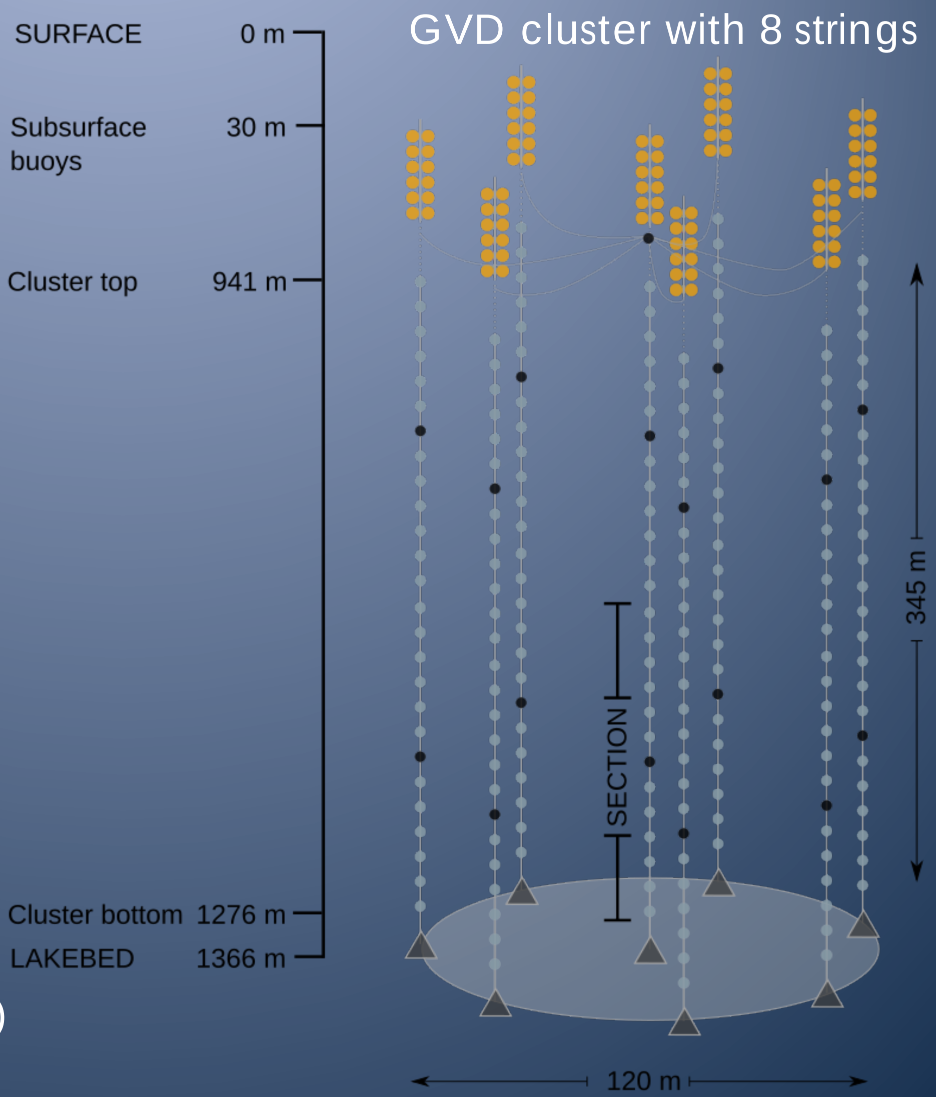


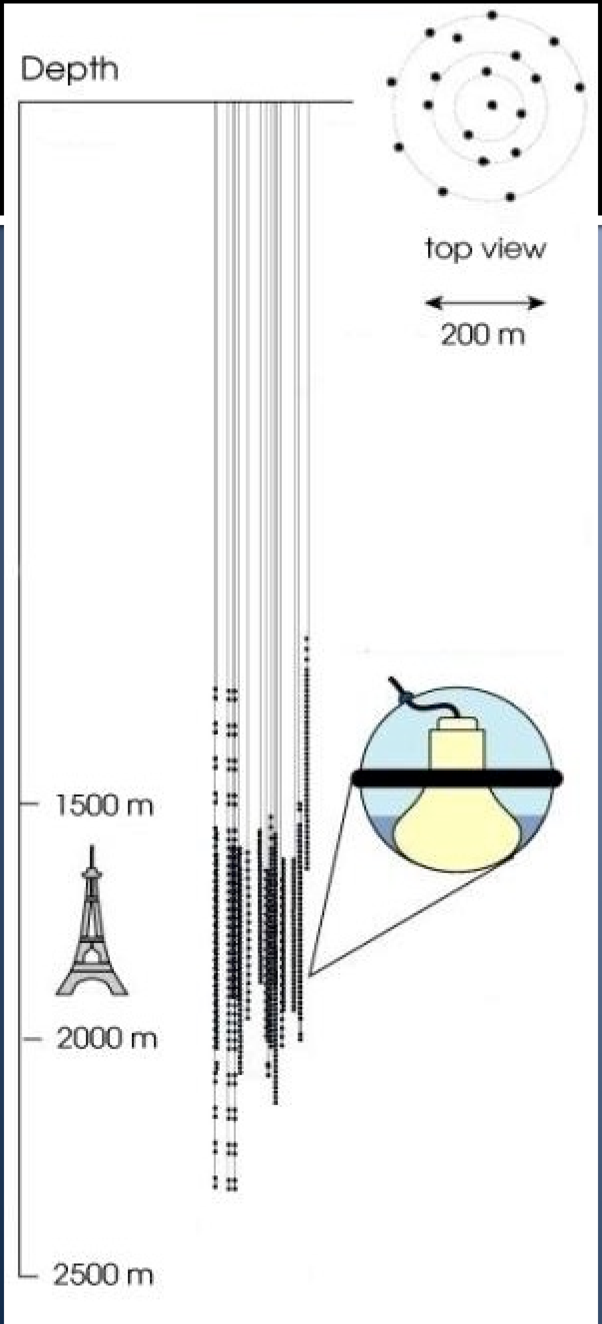
- History of the project
- since 1980: site studies
- 1984 first stationary string
- 1993 NT-36 started
- 1994 first atmospheric neutrino identified
- 1998 NT-200 commissioned
- 2005: NT200+ commissioned

GVD (beyond Baikal)

Status and plans

- First GVD cluster operated within 2016
- Second cluster deployed in 2017 (failure after two months of operation
- Two new clusters planned for 2018
- Phase 1 will have 8 clusters (0.4 km^3)
- Phase 2 will be 1.5 km^3

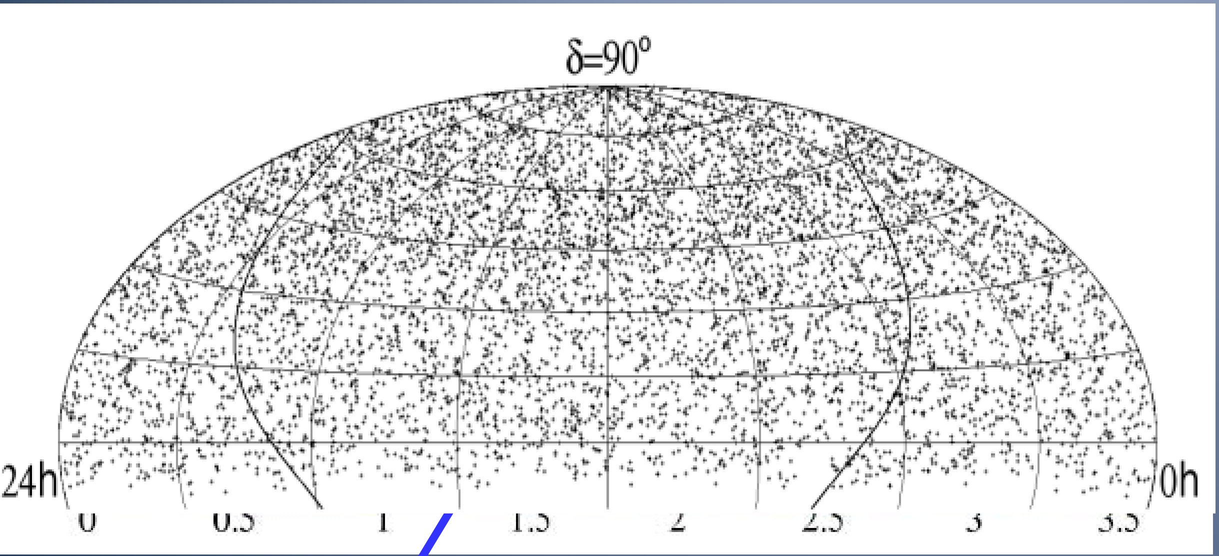




AMANDA

- 1997-99: AMANDA-B10
- (inner lines of AMANDA-II)
  - 10 strings
  - 302 PMTs
- Since 2000: AMANDA-II
  - 19 strings
  - 677 OMs
  - 20-40 PMTs / string
- Latter merged into IceCube
- May 2009: switched off

AMANDA



Equatorial sky map of 6595 events recorded by AMANDA II in 2000-2006

The most significant point has 3.4σ but this should happen 95% of the time with the present statistics.

26 sources selected for search

Source	Φ_{90}	p-value
Crab Nebula	9.27	0.10
MGRO J2019+37	9.67	0.077
Mrk 421	2.54	0.82
Mrk 501	7.28	0.22
LS I +61 303	14.74	0.034
Geminga	12.77	0.0086
1ES 1959+650	6.76	0.44
M87	4.49	0.43
Cygnus X-1	4.00	0.57

For 26 sources, $p \leq 0.0086$ occurs 20% of the time for at least one source.