Cosmic Rays

IV Detection of neutral particles

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Neutral Cosmic Rays

- Neutral stable particles, gammas and neutrinos, constitute a small fraction of the high energy cosmic rays, but can reveal the CR sources, not being deflected by magnetic fields during the propagation
- **Gamma rays** bring informations on astrophysical sources, which can be acceleration sites of charged particle, being by-products of acceleration processes. However, they are attenuated during propagation (depending on their energy)
- **Neutrinos** are the ultimate messengers: they can travel cosmological distances without interacting. But for the same reason they are very challenging to detect on Earth

Gamma ray sources

- Gammas in the MeV-GeV range are expected to be mostly secondaries, produced from hadronic or leptonic processes:

Hadronic showers in the propagation of nuclei mostly produce gammas from π^0 decays

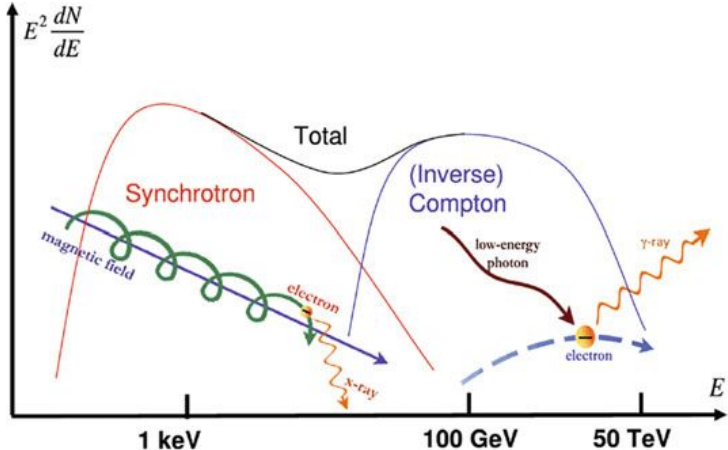
⇨ expect a wide "pion bump": a structure around $M(\pi^0)/2$=67.5 MeV, resulting from the convolution of the gamma energy in the pion frame and the pion boost distribution

Photoproduction can also be important in systems with high density of e.m. radiation

$$p\gamma \rightarrow \Delta^+ \rightarrow p\pi^0 \rightarrow p\gamma\gamma$$

Leptonic processes are

- Synchrotron radiation from electrons interacting with the B field (soft spectrum)
- "Inverse" Compton scattering with ambient, or even CMB photons
- The combination of the two ("Synchrotron Self Compton")



Gamma Spectral lines

- Emission at specific energy (~ MeV) from nuclear de-excitation or decays of unstable isotopes: signature for nucleosynthesis inside stars

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68; 1157
^{26}Al	1.04 10^6y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	2.0 10^6y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332
e^+	.... 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

- Search for line emission is also a powerful method to look for **annihilation signals** of still unknown particles (also of cosmological origin)

Propagation of Gamma rays

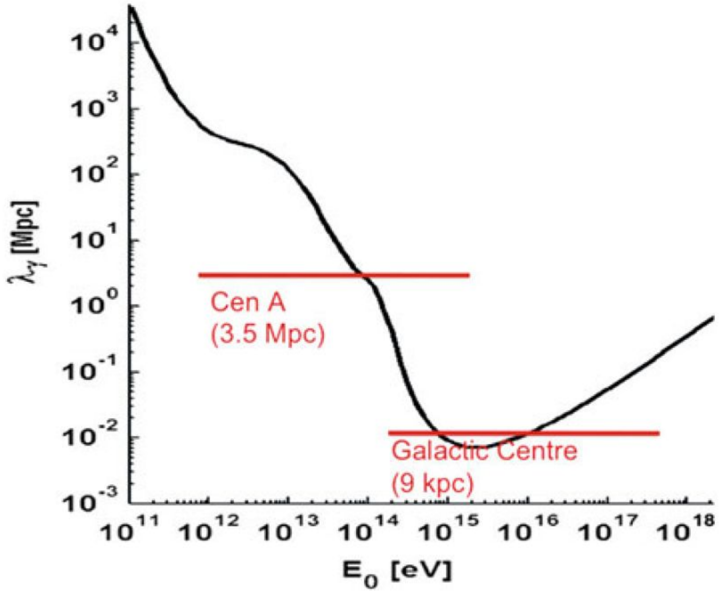
- Gamma rays are absorbed mainly through

$$\gamma + \gamma_{\text{background}} \rightarrow e^{+} + e^{-}$$

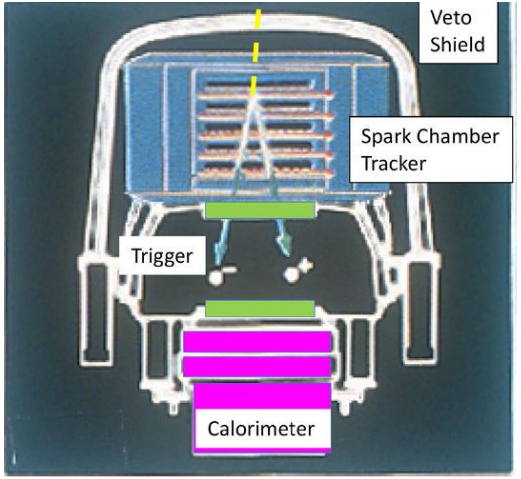
where the background photon can be

  - from the extragalactic background light (EBL), dominant below 10^5 GeV
  - from the cosmic background radiation (CMB), dominant in the range 10^5 GeV - 10^{10} GeV
  - from the radio background, import at ultra-high energy

- The mean free path indicates the transparency of the Universe to photon. Knowledge of the background photon spectra can put limits on new phenomena occurring on very large distances (like photon-axion couplings)



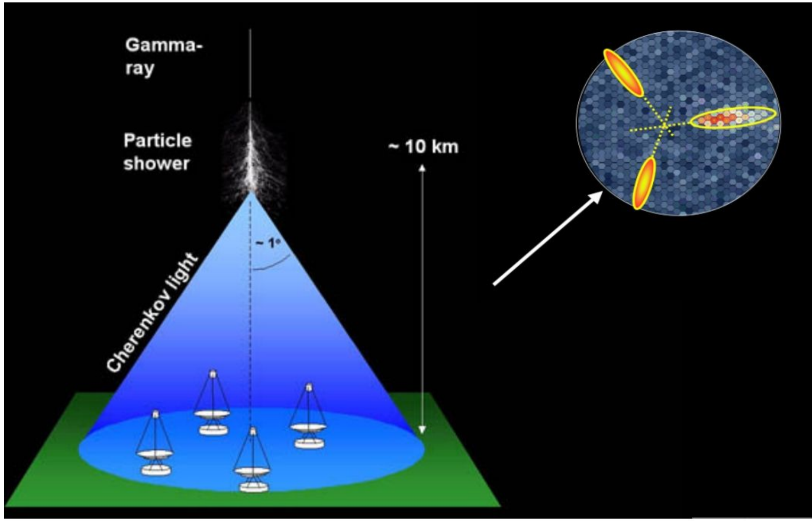
Gamma Detection



- As for the case of charged CR, experiments in **space** can cover the MeV-TeV range. For higher energies, larger sensitive volumes are needed (since the flux is too low and to contain the particle energy)
- Experiments use **calorimeters** to measure the energy, with high segmentation or additional tracking layers to measure the gamma arrival direction

- Gamma observatories above 1 TeV consist of large **ground-based arrays** detecting the **Cherenkov light** produced by atmospheric electromagnetic showers

⇨ best determination of the arrival direction



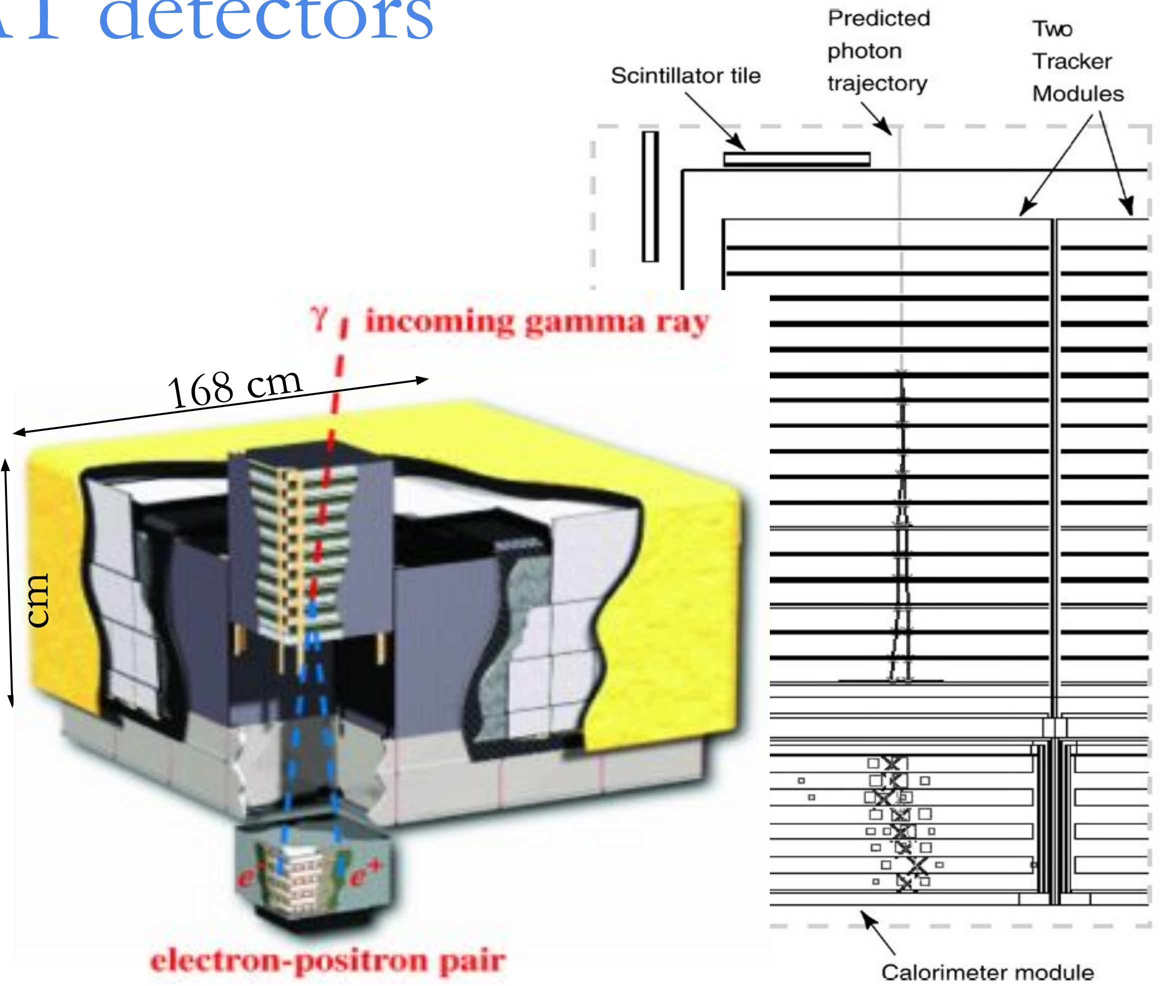
The Fermi-LAT Gamma Telescope

- Space telescope built to measure gamma rays in the 20 MeV-300 GeV range with best possible energy and angular resolution
- Dedicated satellite, launched in 2008
- Field of view: 70°
- Normally in “sky survey”: 4π coverage in 3 hours
- But can be pointed to any location in case of an interesting event

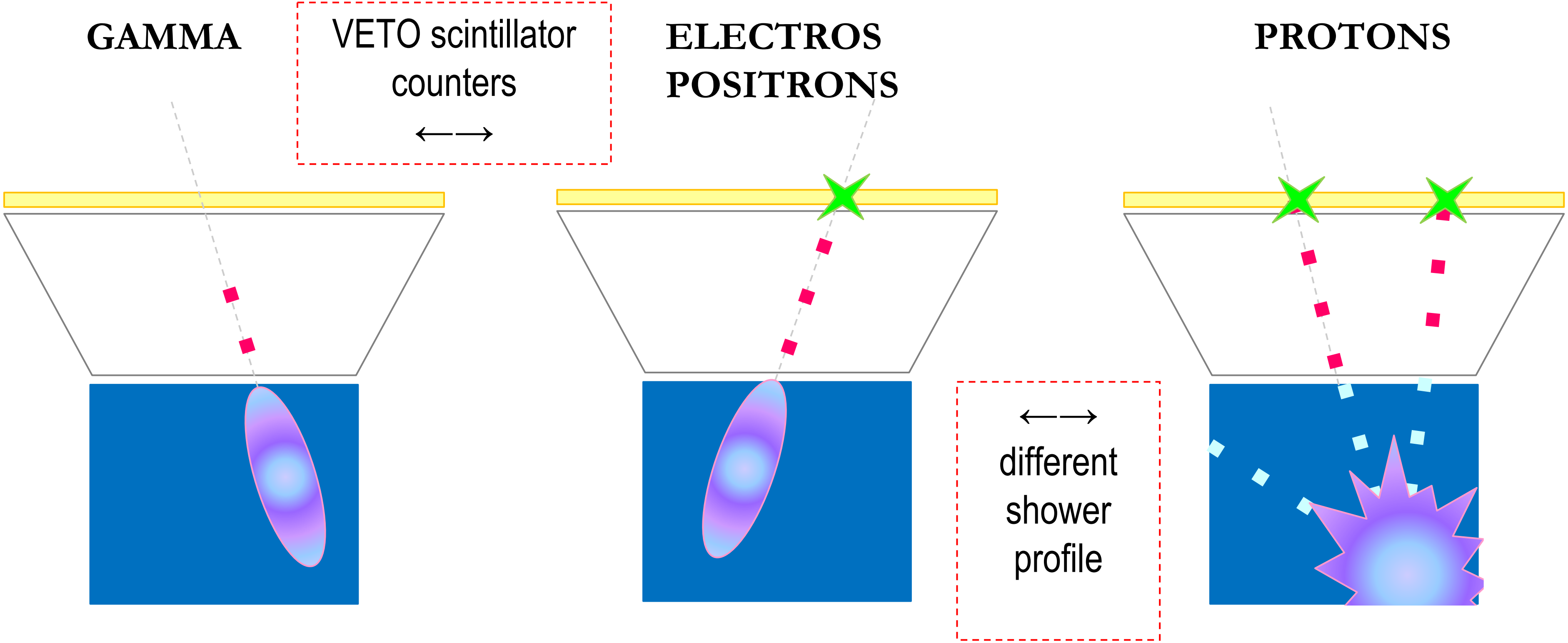
The Fermi-LAT detectors

Towers consisting of a

- converter/tracker (layers of W and Si detectors) to convert the gamma and measure its arrival angle from the first e+e- pair
- Electromagnetic calorimeter: CsI(TI) crystals for the energy measurement
- All enclosed in a scintillator tile veto
- Performance for E>10 GeV: σ(E)<6% σ(angle)=0.15°

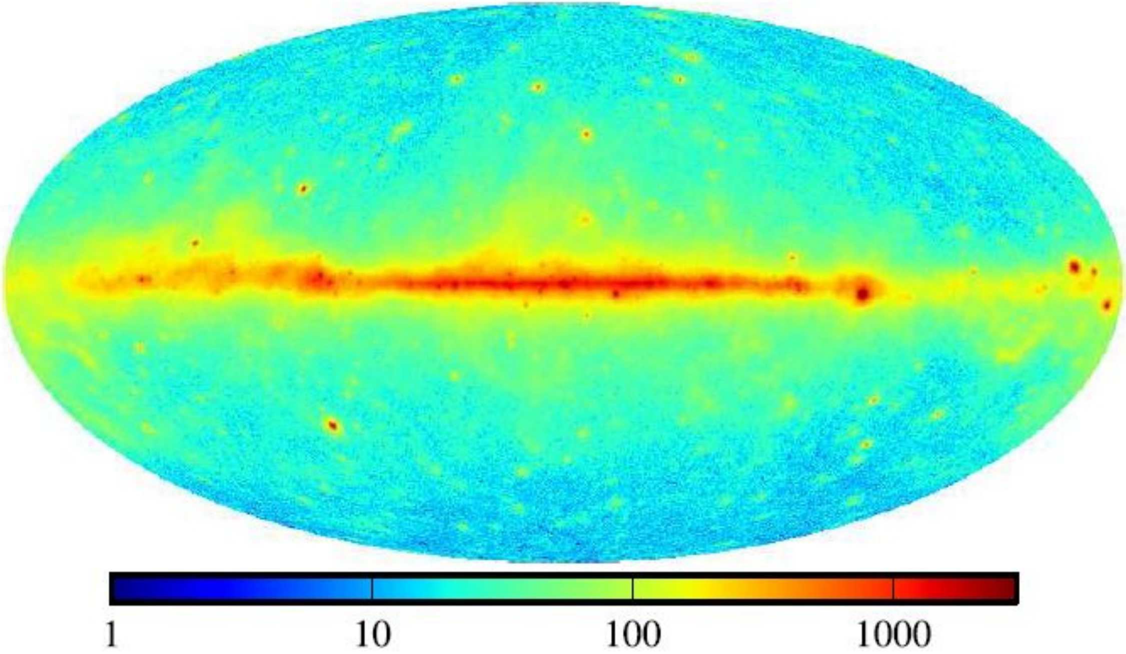


Gamma identification



Localization of Gamma sources

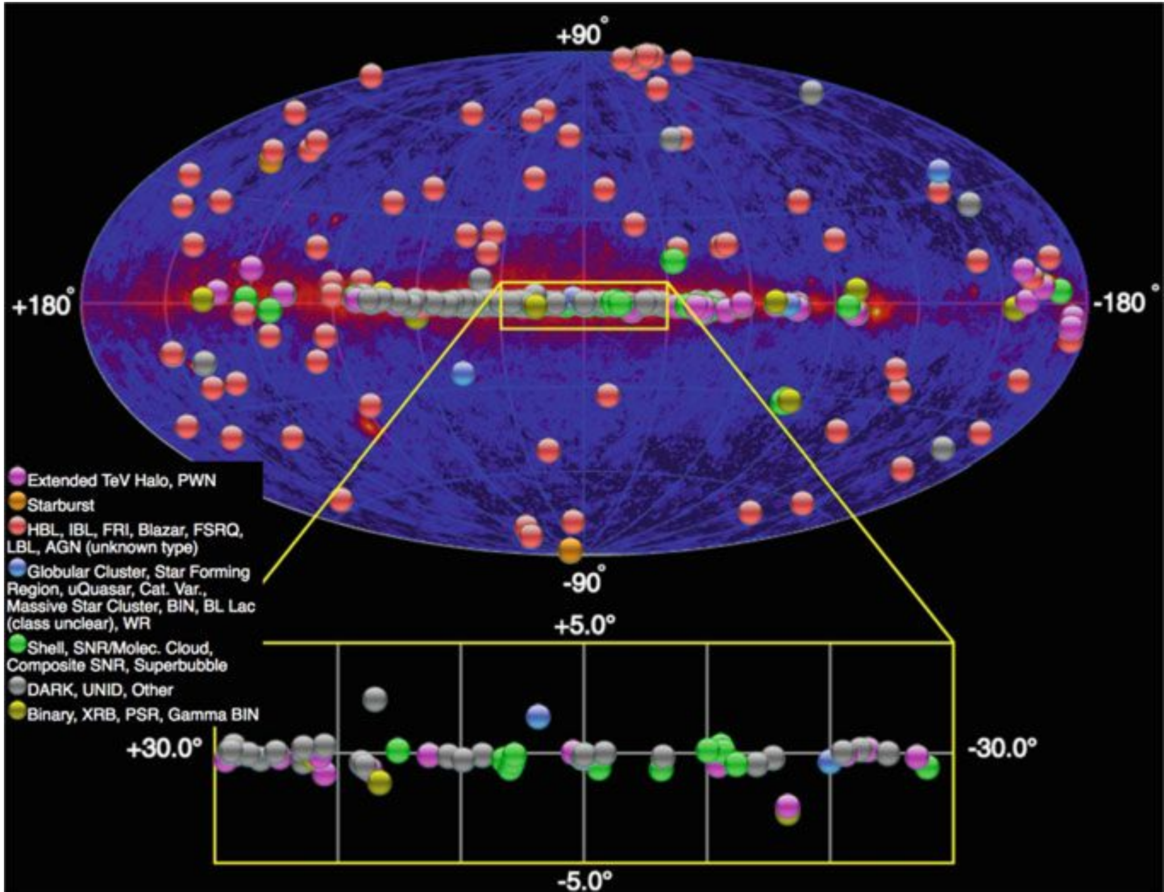
- The diffuse gamma spectrum is compatible with secondary production from charged CR
- The angular distribution clearly shows the galactic origin of most CR
- A halo is also present, compatible with CR halo interacting with the InterStellar Radiation Field
- **Point sources**, both galactic and extragalactic, are clearly visible



Counts between 200 MeV and 100 GeV

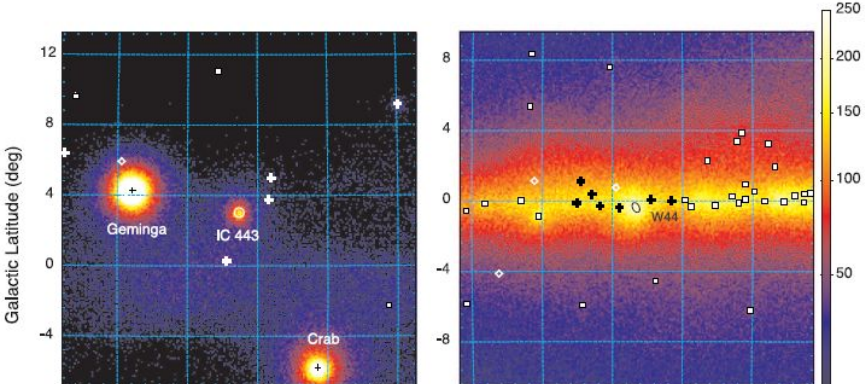
Point sources: the Fermi catalog

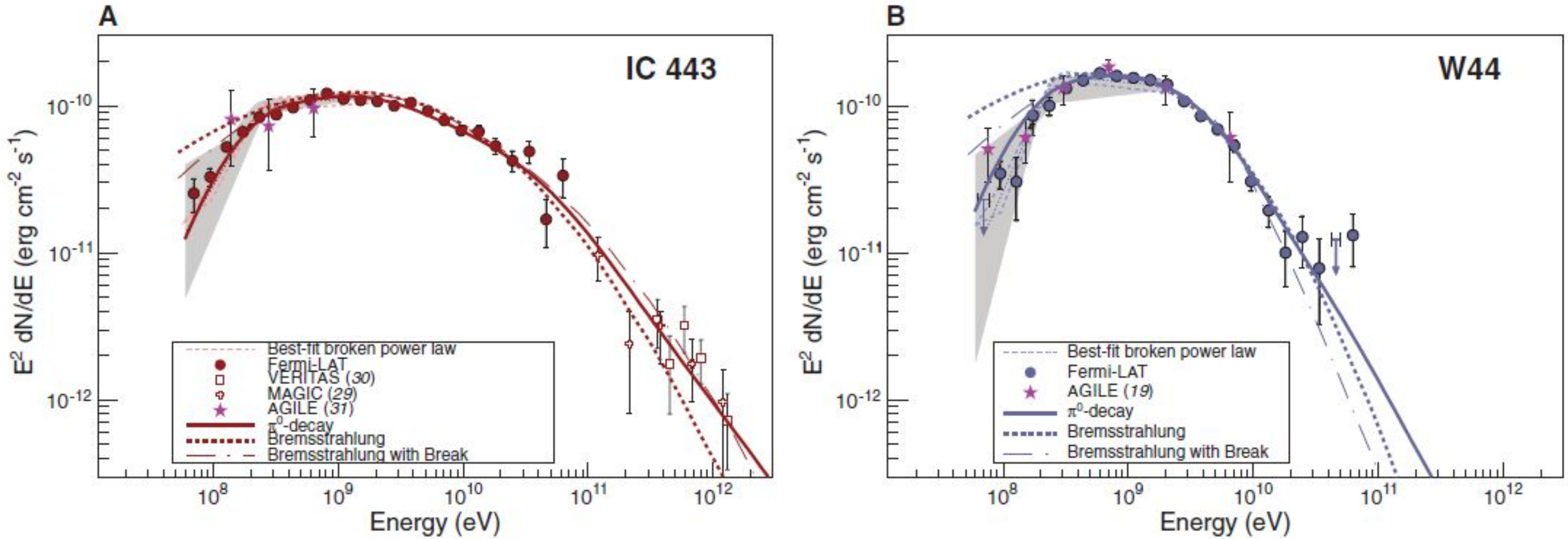
- 5065 sources above 4 sigma significance identified in 8 years
- 75 are spatially extended
- ⅓ are not associated to any known object (from other wavelenghts)
- More than 3130 of the identified or associated sources are active galaxies of the blazar class, 239 are pulsars



Hadronic showers in SNR!

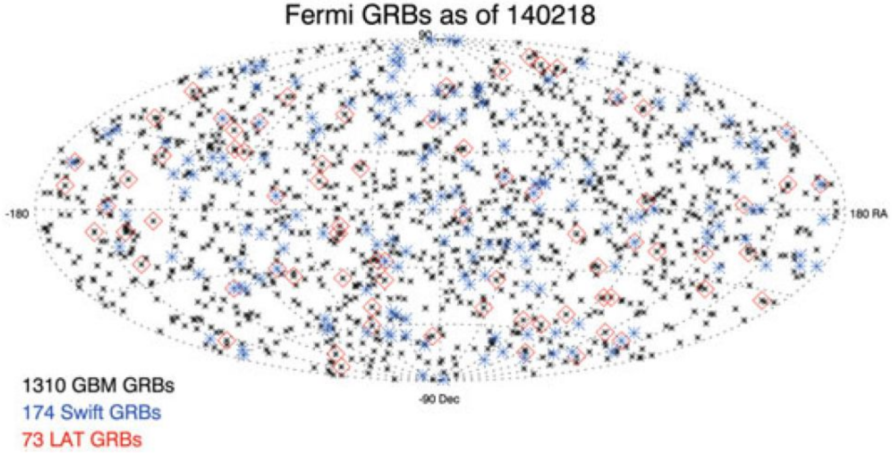
- SNR in molecular clouds: CR interacting with dense medium
- The characteristic “pion bumb” observed! Smoking gun for high-energy hadronic showers
- Considered as a proof for hadron acceleration in SNR (though it is not demonstrated that hadrons are accelerated within the SNR)



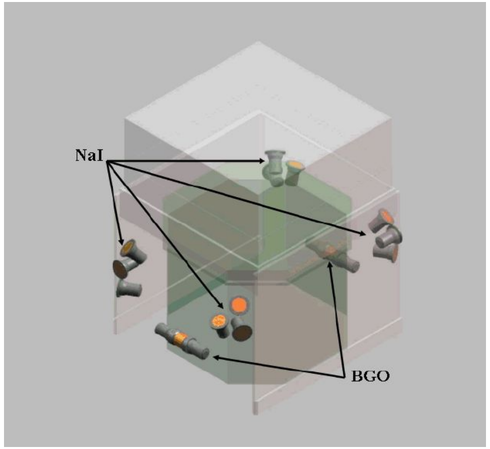


Gamma Ray Bursts

- Gamma detectors also observed transient phenomena that are very interesting to understand the dynamics of extreme phenomena
- **Gamma ray bursts** are very intense emissions in the MeV-GeV range in a short time: from few ms to few s, usually followed by afterglows of lower energy. Discovered (by chance) in the ‘70s, nowadays ~ 1 event/day is observed
- Typically very far, up to z=8 redshift
- Believed to be linked to very extreme events, like merging of two compact objects



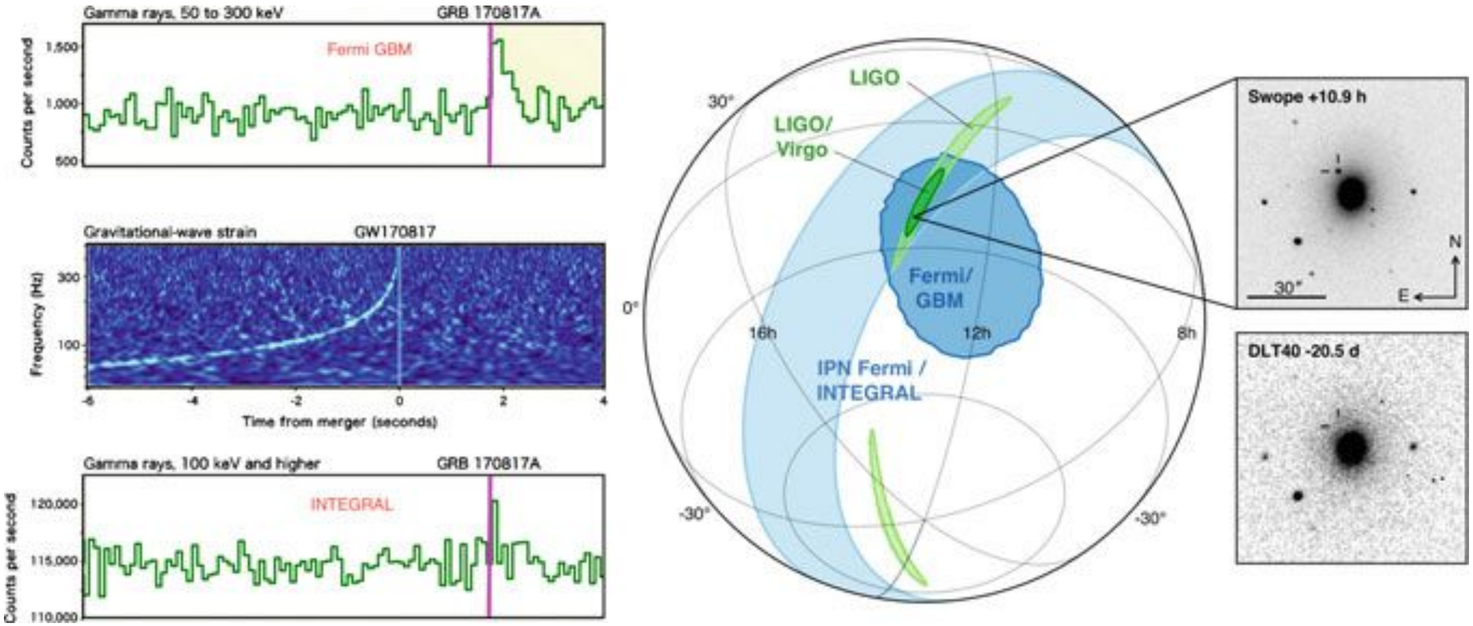
A dedicated instrument on the Fermi satellite extends the LAT capabilities toward lower energies: the **Gamma-ray Burst Monitor (GBM)**



It consists of twelve sodium iodide crystals for the 8 keV to 1 MeV range and two bismuth germanate crystals with sensitivity from 150 keV to 30 MeV, can detect gamma-ray bursts in that energy range across the whole of the sky not occluded by the Earth.

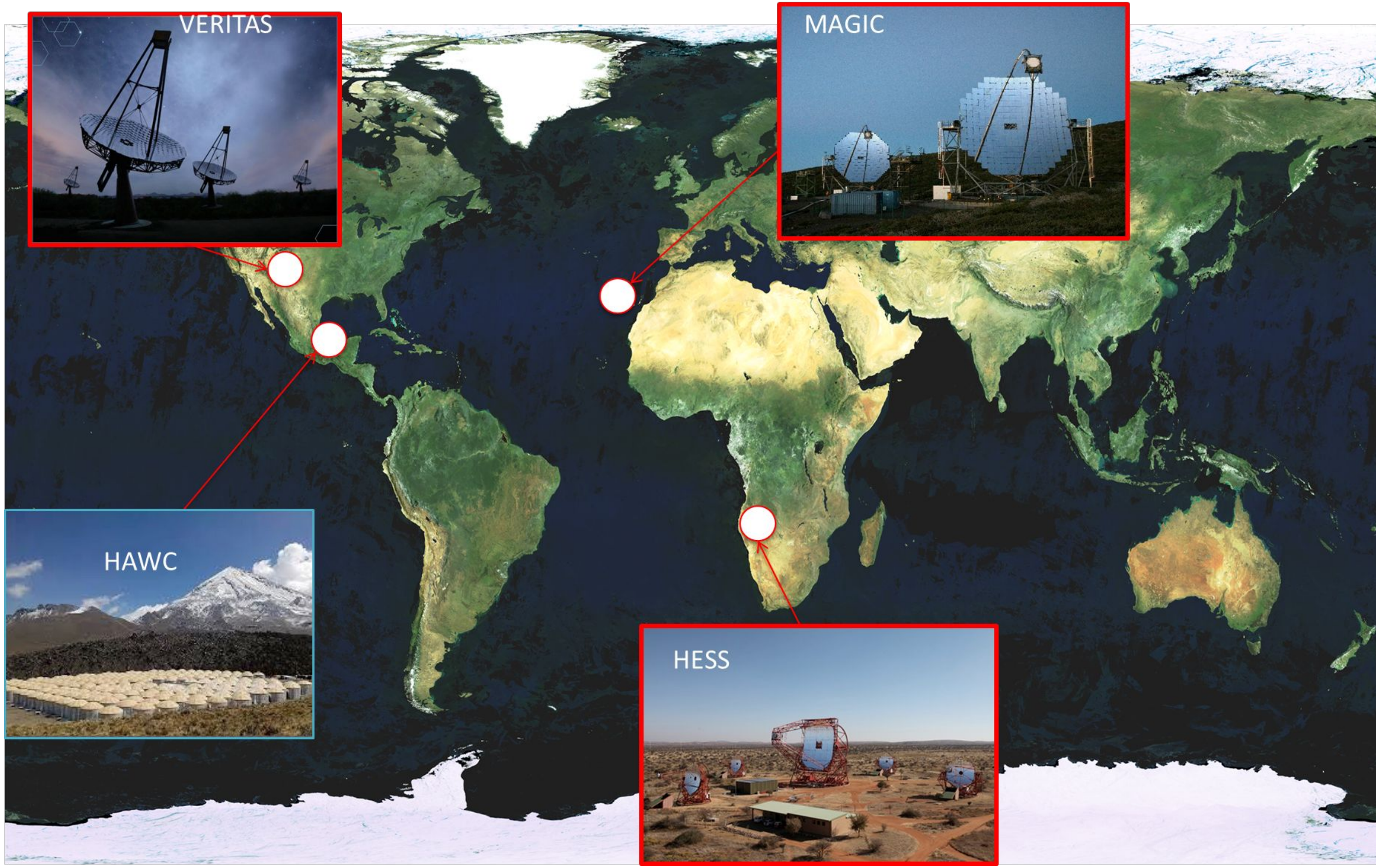
A merger event seen in GRB!

- Merger of two neutron star detected by gravitational waves on Aug 17th, 2017
- GRB observed after 1.7s, ~2s long
- Demonstration that GRB are produced in merger events
- Multimessenger astrophysics at work!



UHE Gamma rays: detection on the ground

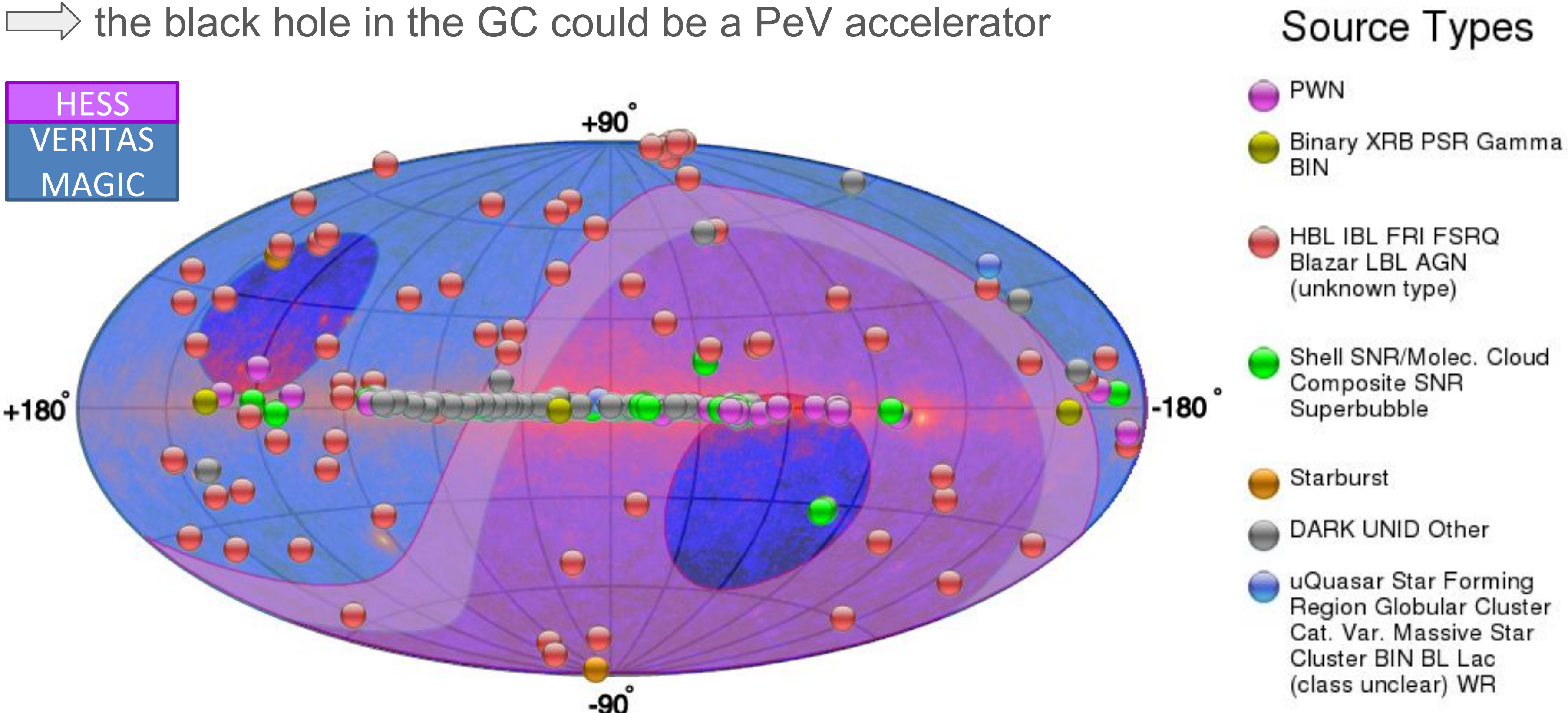
- Large telescope arrays covering a wide area to be sensitive to very low fluxes
- Telescope looking at Cerenkov light have the best sensitivity to the source position: about 0.1°
- The combination of current telescopes covers the entire sky



The TeV Sky

- ~160 sources > 1 TeV identified so far. Little evidence for signals above 10 TeV
- But hints from HESS of very high energy around the galactic center (GC)

⇨ the black hole in the GC could be a PeV accelerator

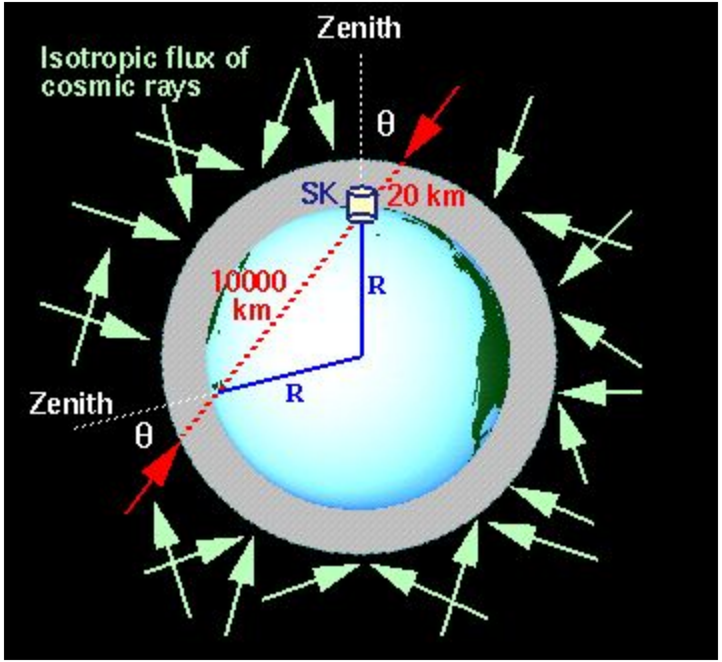


Neutrinos

- The most elusive particles, but also the most interesting cosmic messenger: propagate through the whole Universe, probe the nuclear reactions in stars
- Cosmic neutrinos have been detected
  - from the **Sun**
  - from **atmospheric showers**

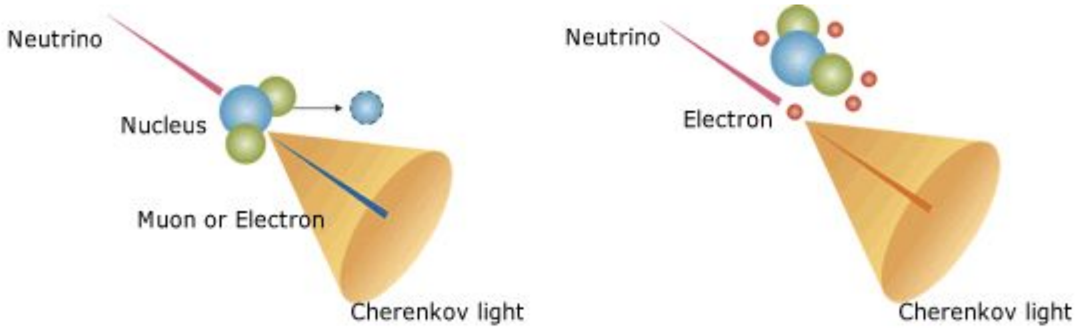
    in 1998, the SuperKamiokande detector (a massive underground water Cerenkov detector) finds evidence of a zenith-angle-dependent suppression of ν_μ (and not of ν_e). First evidence for **neutrino oscillations.** Oscillations in solar neutrinos was also eventually demonstrated in 2002

  - from a **Supernova** (1987)
  - from **astrophysical sources** (diffuse component), 2013

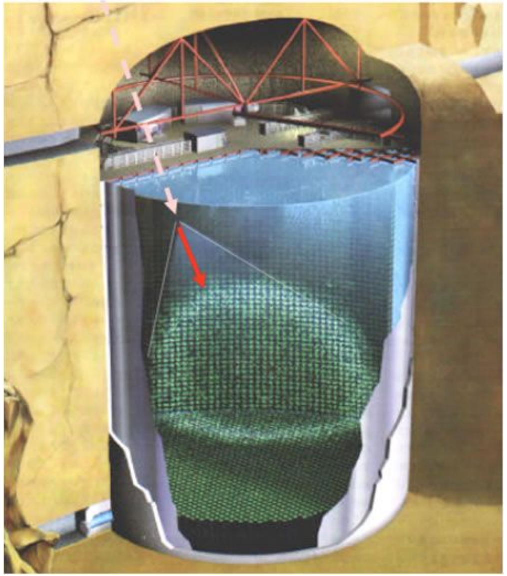


Neutrino detection

- The main technique is to observe the Cherenkov light emitted by the electron or muon produced by a charged-current interaction of ν_e or ν_μ
- The direction of the electron or muon is (almost) the same as the incoming neutrino



The generated charged particle emits the Cherenkov light.



SN1987a: the first "astrophysical" Neutrinos

- On February 23, 1987, SN explosion in the Large Magellanic Cloud (LMC), a galaxy satellite of the MilkyWay, ~50 kpc from the Earth
- The neutrino detectors available at the time detected a total of 25 events within 13 s, ~3 hours before the appearance of the visible light of the SN

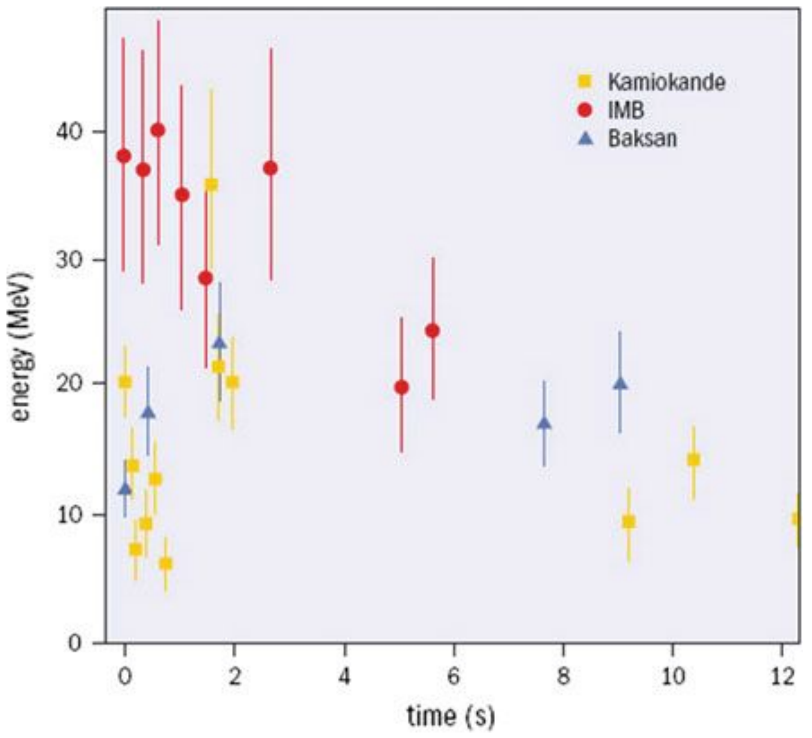
⇨ Very important confirmation of the models of SN explosion, predicting that ~99% of the energy is released as neutrinos

- Also used to better understand neutrinos:

mass: M< 10 eV

velocity: $|v-c|/c < 2\ 10^{-9}$

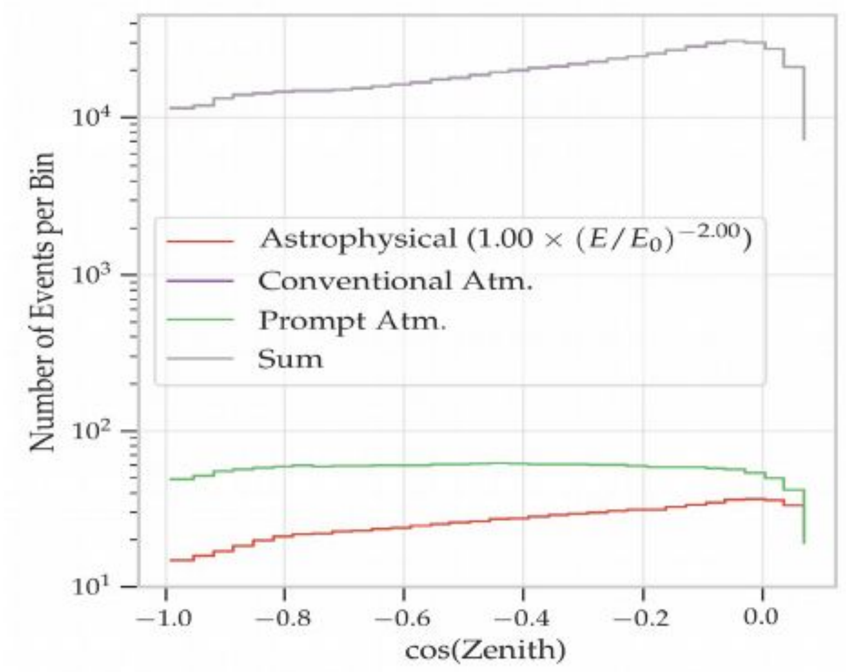
magnetic moment: $\mu<10^{-12}\ \mu_B$

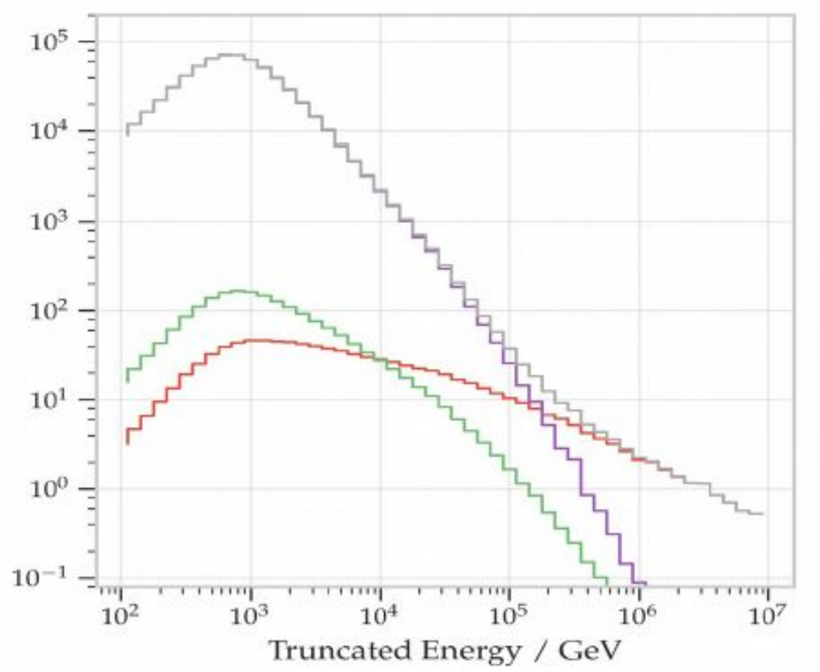


High-energy Astrophysical Neutrinos

Expected neutrino flux at high energy has three components:

- ❑ ‘Conventional’ atmospheric neutrinos from K/Pi decays in air-showers
- ❑ ‘Prompt’ atmospheric neutrinos from decays of charmed hadrons
- ❑ Isotropic flux of **astrophysical neutrinos** with power-law energy spectrum

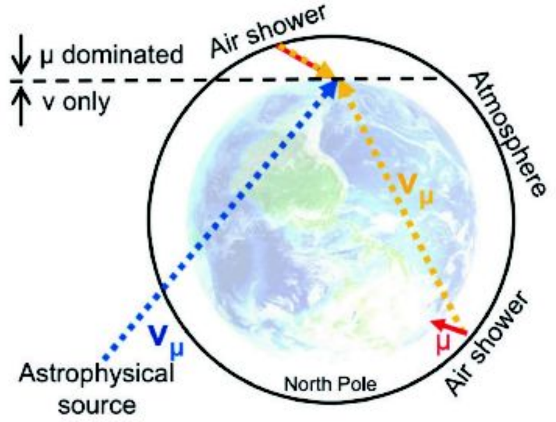


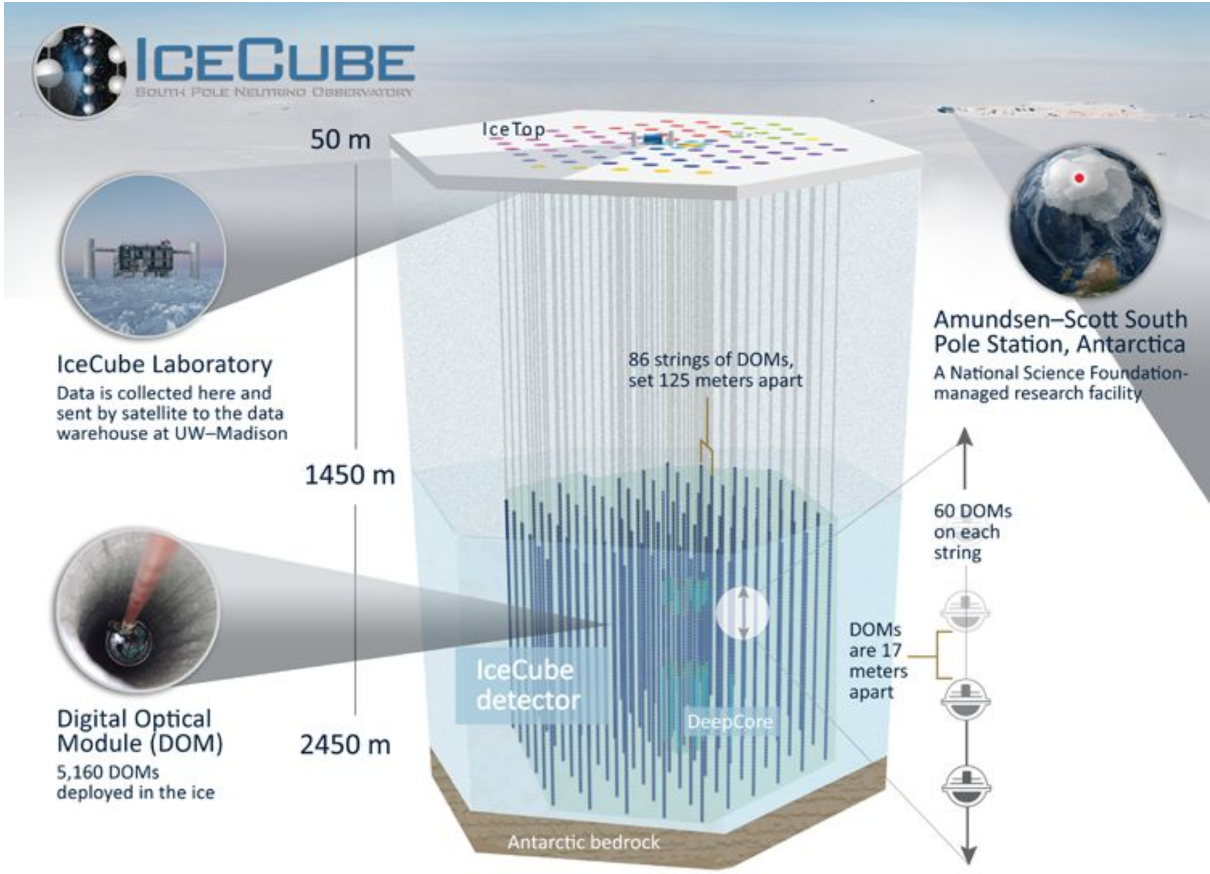


The IceCube experiment

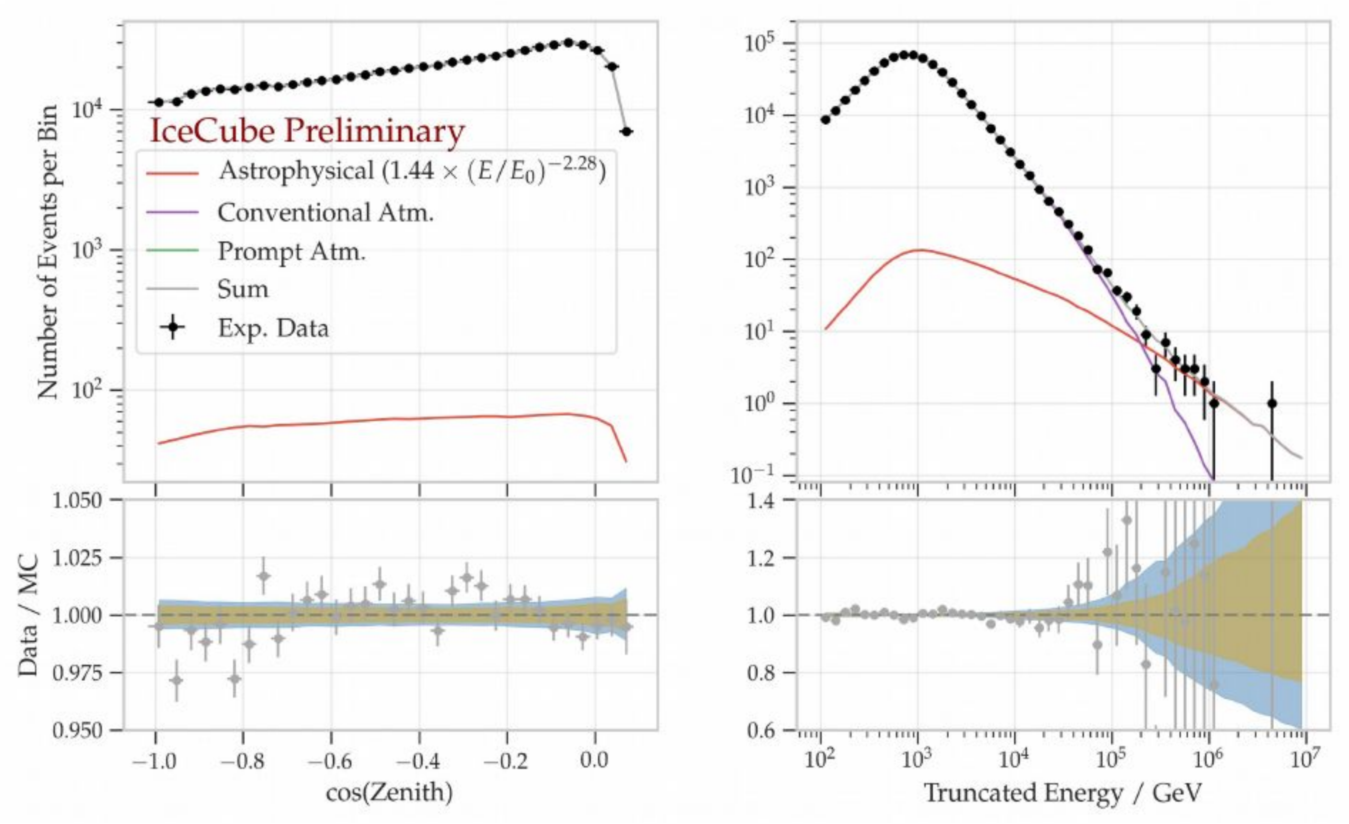
- 1 Km^3 of ice at the South Pole instrumented with photon detectors

⇨ huge Cherenkov detector sensitive to neutrinos from 100 GeV to the PeV scale and beyond

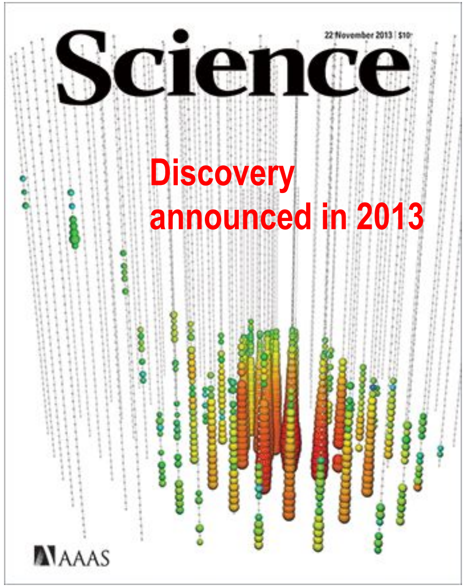




Astrophysical Neutrinos!



Best-fit distributions and experimental data (2010-2018)

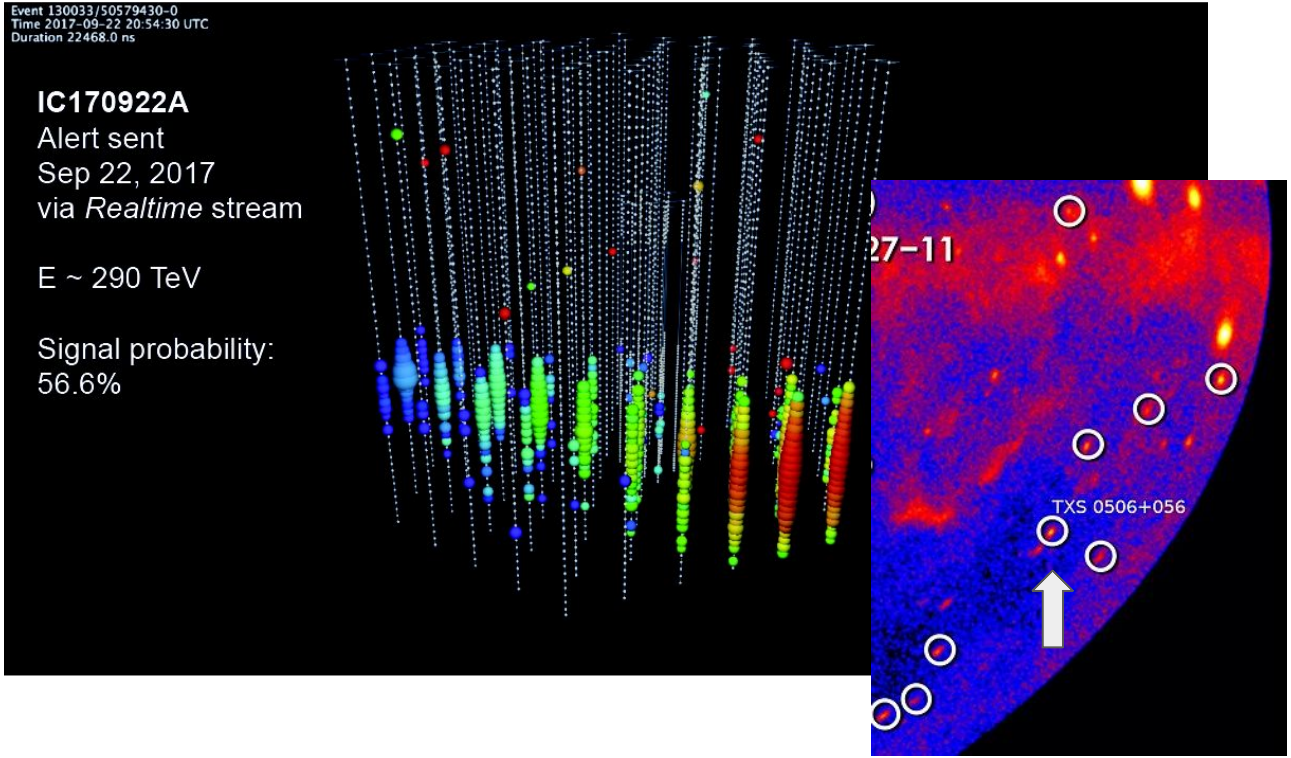


Detection rate of astrophysical neutrinos is ~ 1/month

The first UHE Neutrino in Multimessenger Astronomy

- On Sep 22, 2017 Icecube detects a **high energy neutrino** event with estimated energy ~ 300 TeV
- Fermi-LAT and the MAGIC array, see a **gamma flare** from a blazar in the sky region indicated by Icecube (about 1 degree accuracy) , up to 100 GeV

⇨ simultaneous gamma and neutrino emission indicate “hadronic” gamma emission from very energetic cosmic rays (~ 10 PeV)



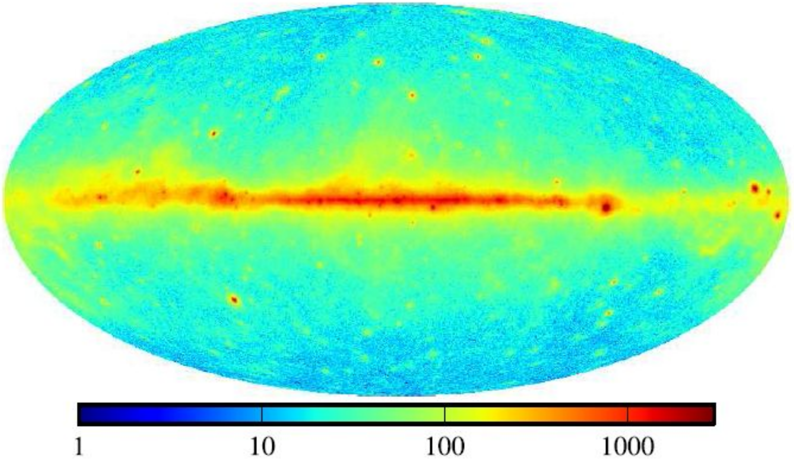
Third identified cosmic neutrino source, after the sun and SN1987a

The future

- Exciting first breakthrough from astronomy with high-energy gamma rays and neutrinos. Multimessenger astronomy became a reality with both probes
- Large experimental efforts ongoing to prepare the next generation of experiments, increasing the sensitivity by at least an order of magnitude
- Notable examples: the Cherenkov Telescope Array (CTA) gamma observatory (2 sites in the 2 hemispheres), and Icecube-Gen2 (~10 Km^3)

Backup Material

Results: Diffuse Gammas



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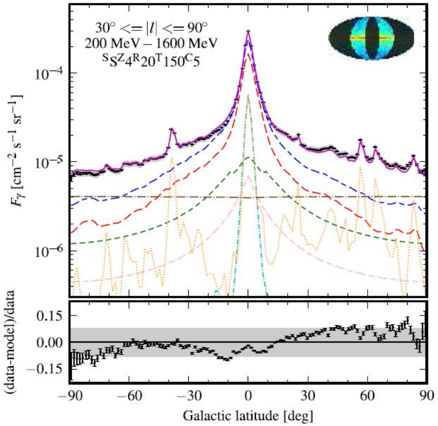
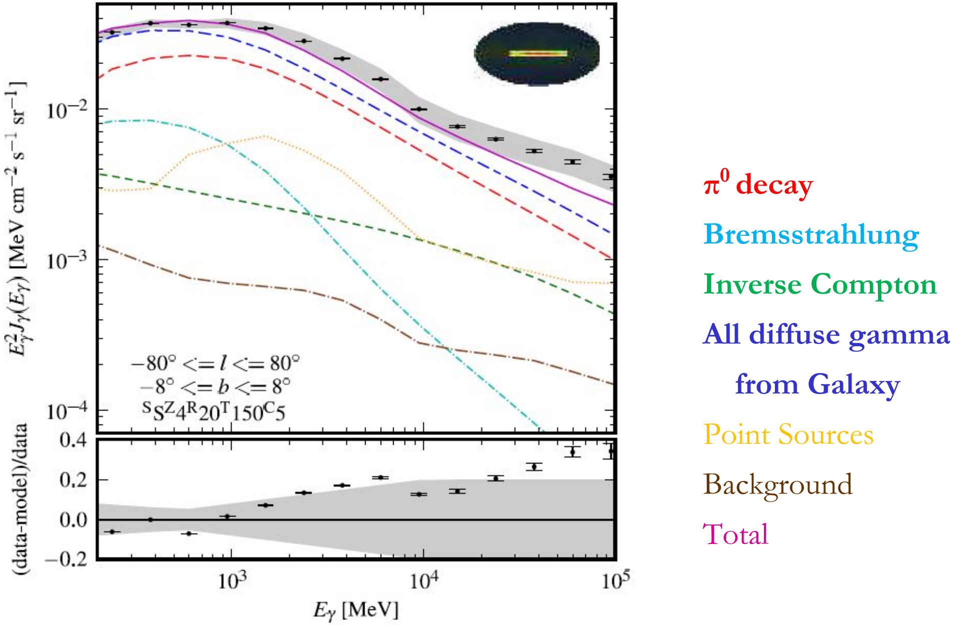
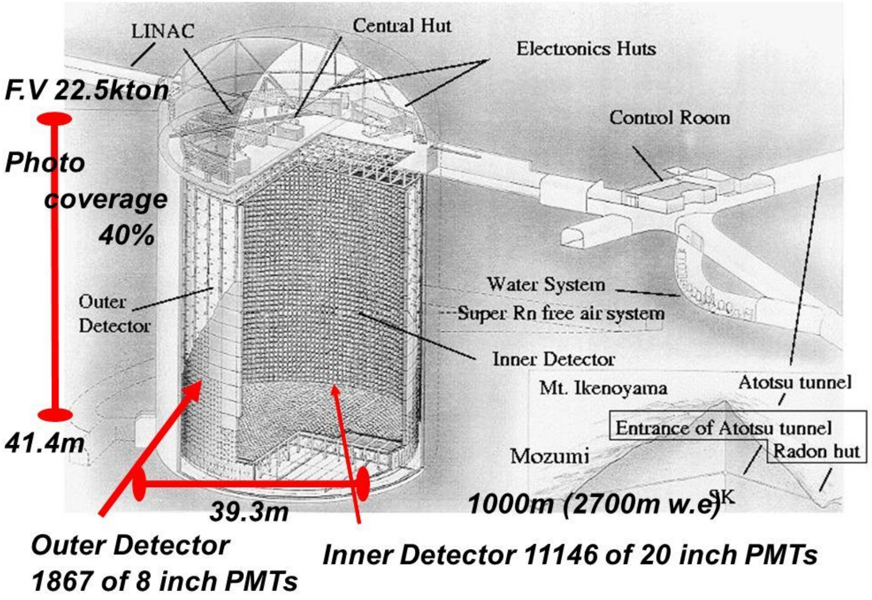
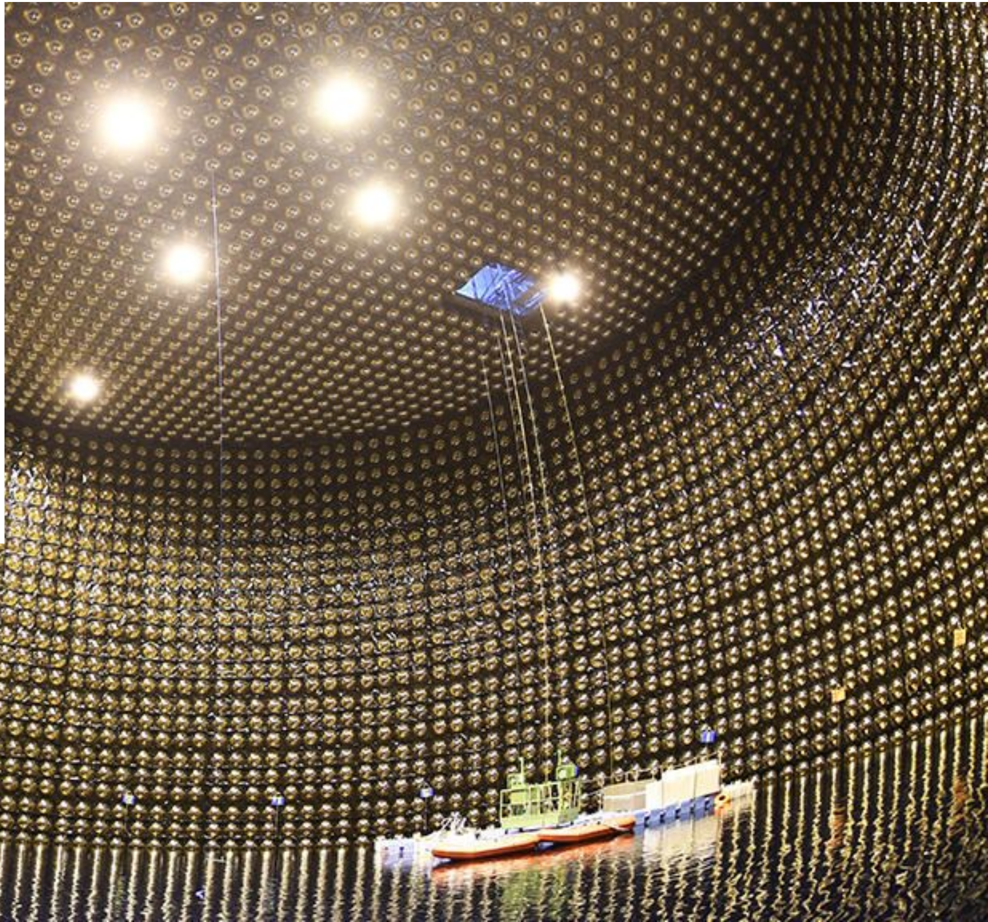


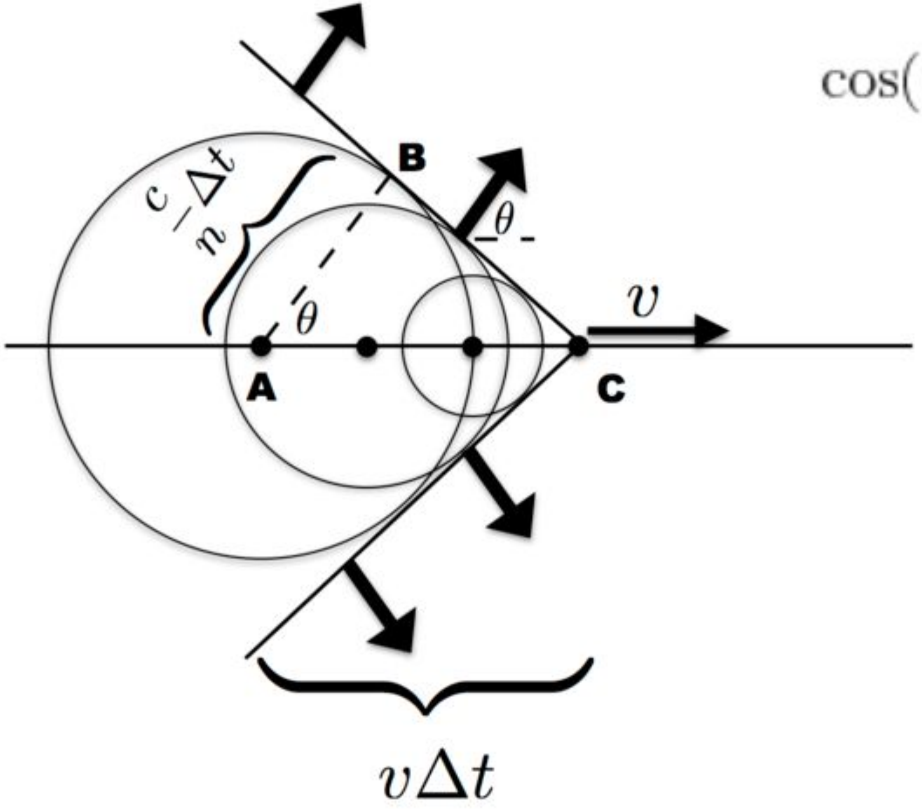


2,Super-Kamiokande detector





Cherenkov Radiation



$$\cos(\theta) = \frac{AB}{AC} = \frac{\frac{c}{n} \cdot \Delta t}{v \cdot \Delta t} = \frac{1}{\beta n}$$