Future Perspective

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The neutrino flux at Earth

Neutrino is one of the most elusive particles but also very abundant in the universe

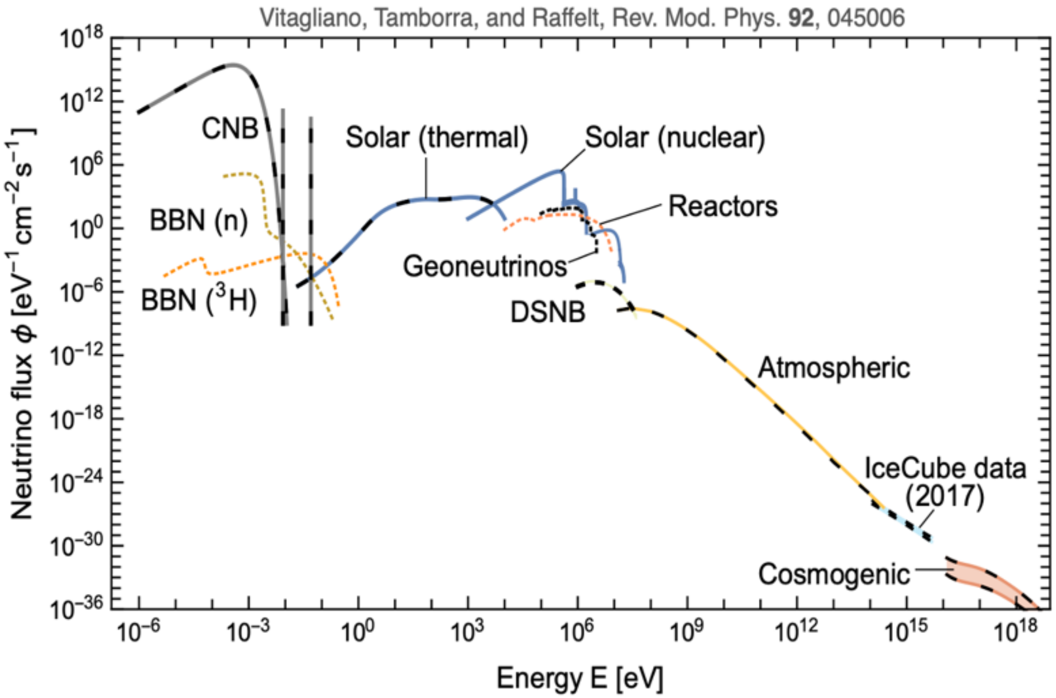
Neutrino flux at Earth covers over 24 orders of magnitude for energy and 50 orders for the flux

Special neutrino features:
- no deflected and absorbed
- brings memory of energy and direction of source
- able to escape from dense environment

Neutrino probes many different fields of Physics
- fundamental particle physics
- dark-matter detection
- Solar physics
- neutrino astronomy
- geophysics
- …other related topics.

→ **Require many different experimental approaches**

Flux of neutrino and antineutrino at Earth of different sources vs. energy integrated over directions and summed over flavors



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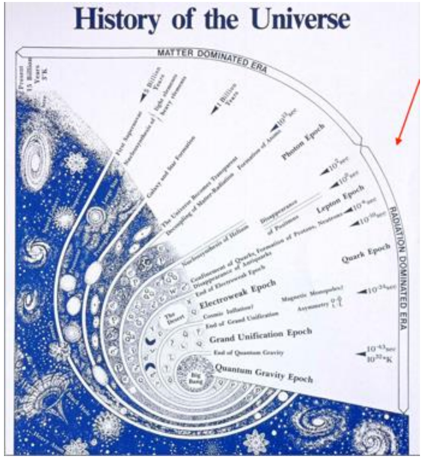
COSMIC NEUTRINO BACKGROUND (CNB)

Cosmic Neutrinos Background are a thermal relic from the hot early Universe when in was about 1s old.

Temperature: T_ν=1.95 K = 0.168 meV; Number density: n_ν=112/cm3

The CNB consists essentially of an equal mixture of all flavors.

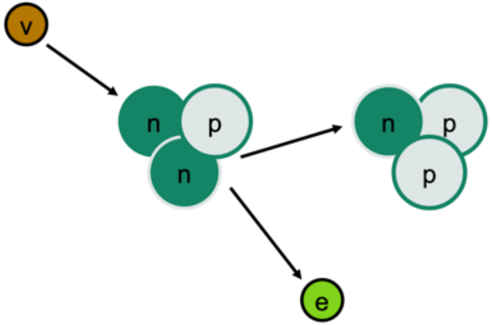


<u>It is the largest neutrino density at Earth, but yet it has never been measured.</u>

The CNB detection issues are :
- Baryon asymmetry
- Dark energy and dark matter
- Cosmological constant and inflation

Experimental realization for directly measuring the CNB remains currently extremely challenging

One of the most realistic approach uses inverse β decay notably on tritium pursued by the PTOLEMY project at LNGS



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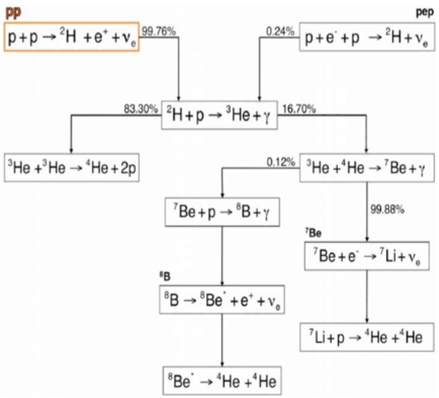
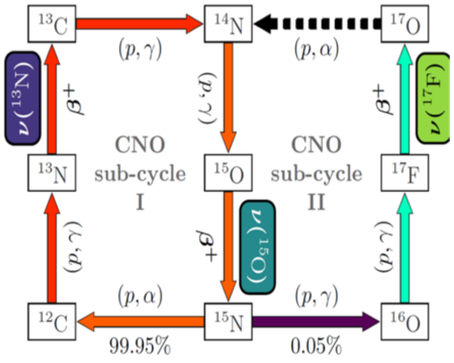
In the keV range, the Sun produces neutrino pairs of all flavors by thermal processes:
plasmon decay, Compton process, electron bremsstrahlung
Thermal solar neutrinos has never been shown even if is the dominant ν ν̄ flux at Earth at Eν ≲ 4 keV

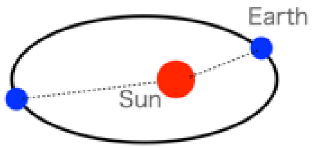
The Sun emits 2.3% of its nuclear energy production in the form of MeV-range electron neutrinos

The Sun produces nuclear energy by hydrogen fusion to helium that proceeds through pp chains (exceeding 99%) and the rest through the CNO cycle.

Flux change by 3.4% in the course of the year due to the ellipticity of Earth's orbit.







At the Neutrino 2020 conference Borexino announced the first measurement of solar CNO neutrinos (significance of ~7σ)

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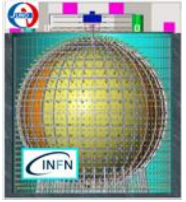
Future solar neutrinos detectors

Solar neutrino measurements historically was connected with the discovery of flavor conversion and matter effect

Prime targets of future solar neutrino precision experiments:
- Neutrino is a powerful tool to directly revealing solar physical processes
- detailed chemical abundances in the solar core
- precision study for Solar Standard Model (SSM) and Stellar models

The largest neutrino observatory will be Hyper-Kamiokande

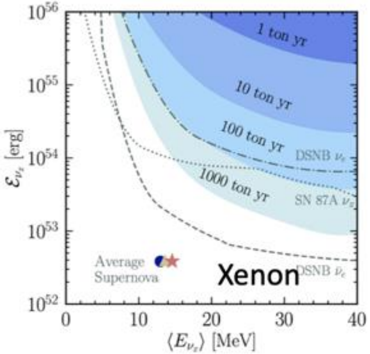


SNO+, 1kton of WC and 0.8 kton of LS (decommissioned SNO detector)

JUNO, in China a 20 kton reactor LS neutrino experiment

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE: LAr scintillator, built for long-baseline neutrino oscillations, have also solar neutrino detection capabilities



WIMP direct detection experiments will be competitive in the detection of solar neutrinos

XENON NT at LNGS already measured solar neutrino !!!

the XENONnT collaboration announced the first measurement of low-energy nuclear recoils from neutrinos produced in nuclear reactions inside the sun, particularly those involving the element boron

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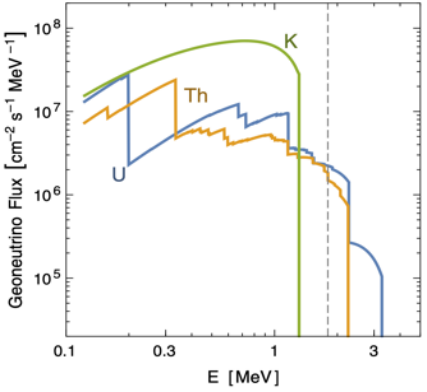
Geoneutrinos: detection and perspective

Geoneutrinos are primarily $\bar{\nu}_e$ produced in decays of radio-active elements with lifetime comparable to the age of Earth (so-called heat-producing elements HPEs)

Around 99% of geoneutrinos comes from the decay chains of $_{232}$Th, $_{238}$U, and $_{40}$K.



The main detection channel is the inverse beta decay, with a kinematical Thr= 1.806 MeV

The large flux from 40K is not detectable → The large fraction arises from $_{232}$Th, $_{238}$U

The first reported geoneutrino detection was by KamLAND in 2005 1000t LS detector

A second experiment that detected geoneutrinos was Borexino 300t LS.

Geoneutrinos observation in KamLAND and Borexino was highly significant, but better statistics is needed

→ Several experiments, in different stages of development, will improve our knowledge.

SNO+ in Canada expects a geoneutrino rate of 20/yr

JUNO in China also plans to measure geoneutrinos

Proposed: Hanohano (Hawaii Anti-Neutrino Observatory)
5 kton detector on the oceanic crust *(arXiv:0810.4975)*

Geoneutrinos detection carry information on:
- plate tectonics Earth model
- mantle convection
- planetary heat budget and composition
- magnetic-field generation

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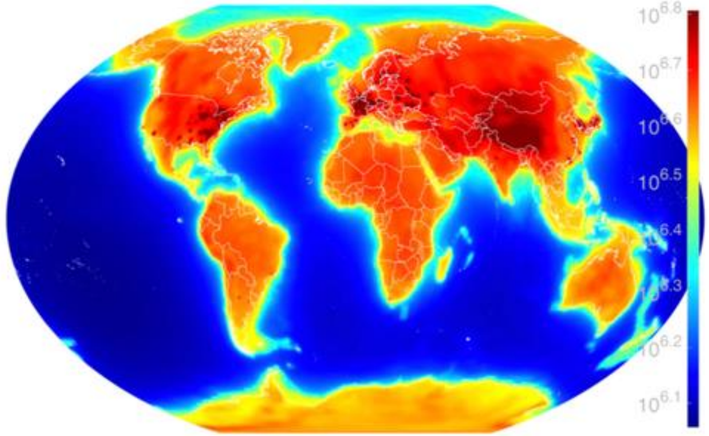
In nuclear power reactors a few percent of their energy production is released in the form of MeV-range ν^-_e from the β decay of neutron-rich nuclei ($_{235}$U, $_{239}$Pu, $_{238}$U, $_{241}$Pu)

In contrast to accelerators, reactors produce a diffuse flux.
Reactor neutrino flux is a few percent of the geoneutrino flux, but can dominate in some geographic regions.

Reactor neutrinos have been always fundamental to the study of neutrino properties: such as mixing angles and mass differences

Several reactor neutrino experiments (KamLAND, Daya Bay, RENO, and Double-Chooz) have been designed.

The frontier of reactor neutrino measurements will be the JUNO detector

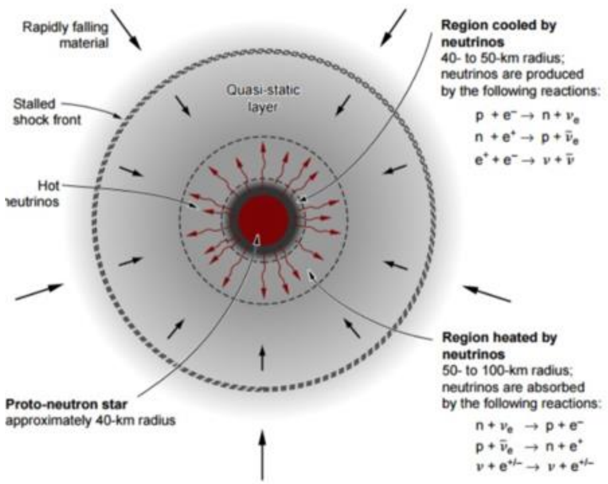


Global map of ν^-_e from U and Th in Earth and from reactors
Spots are due to Power Reactors

Supernova neutrinos

Supernova (SN) explosion:
the gravitational core collapse of a massive star within a few seconds releases the binding energy in form of neutrinos burst

$$E_b \simeq \frac{3}{5}\frac{G_N M_{NS}^2}{R_{NS}} \simeq 3 \times 10^{53}\ \text{erg} \simeq 2 \times 10^{59}\ \text{MeV}$$



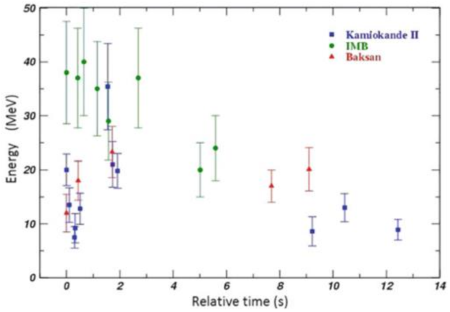
This large amount of energy appears in the form of neutrinos:

$E_\nu \simeq 10 - 15$ MeV

$E_b/E_\nu \rightarrow \simeq 3 \times 10^{57}$ particles for each of the six ν and $\bar{\nu}$ species.

Feb 23 1987. Type II SN1987A was the first supernova from which neutrinos were observed.
In the **Large Magellanic Cloud**, a small galaxy satellite of our Milky Way **(≃ 50 ± 5 kpc from Earth)**

Two Water Cherenkov Detectors observed neutrino events, in a 13 s interval :
Kamiokande-II (12 events) and
the Irvine Michigan Brookhaven experiment (IMB) (8 events)



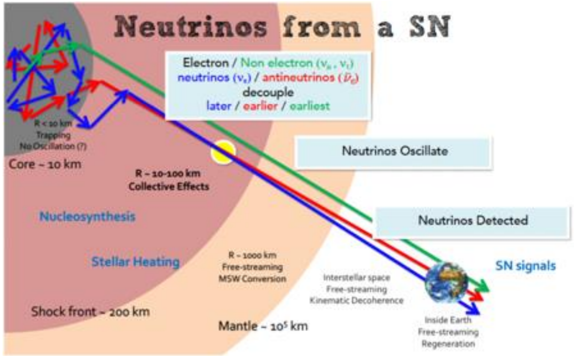
Supernova neutrinos detection perspective

Neutrino burst from the next SN explosion is one of the most targets of next neutrino astronomy

Neutrinos provide very early a direct view into the core collapse process without being altered

Next SN detector properties:

- rare rate: ~1-3 SN expected explosion per century
- long term observation
- neutrino flavor, energy, time and direction, event-by-event
- large mass: event rates scale ~ linearly with detector mass



The next nearest SN would provide high statistics in Super-Kamiokande, IceCube, or upcoming large detectors such as Hyper-Kamiokande or DUNE.

The SuperNova Early Warning System (SNEWS): an international network of detectors.

At LNGS LVD has been stopped (however it is still on-going)
and also XENON NT and Darkside at LNGS could detect SN neutrinos

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Diffuse Supernovas Neutrinos Background (DSNB)

All collapsing stars (few per seconds) in the Universe provide a neutrino cosmic background (DSNB)
It dominates neutrino flux at Earth for energy range 10 – 25 MeV

The DSNB has not yet been detected.

Restrictive upper limits exist, based on inverse beta-decay experiments
Super-Kamiokande I, II, and III water Cherenkov detector
Super-Kamiokande phase IV with neutron tagging
KamLAND liquid-scintillator detector

Next DSNB detectors: identification and rejection of several backgrounds that can mimic DSNB events.

Enhanced n tagging capabilities in SK

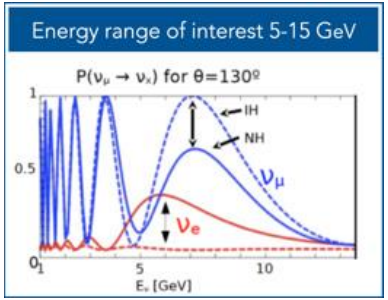
Large-mass liquid scintillator

Massive scale Water Cherenkov detector
arxiv:1805.04163

Unique opportunity for ν_e sensitivity with ^{40}Ar target
arxiv:2002.03005
JCAP12(2004)002

Cosmic rays entering the atmosphere scatter and produce secondary particles.
Decay of charged mesons (mainly pions and kaons) produce neutrinos in range 0.1 GeV and 10 TeV

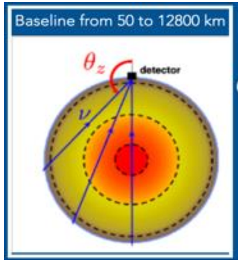
Atmospheric neutrinos are used to measure neutrino mass and mixing parameters with high precision



The main experimental facilities sensitive to atmospheric neutrinos are so far IceCube, Super-Kamiokande, SNO and MINOS.

Next atmospheric neutrino detectors:

IceCube DeepCore : a denser detector added to the IceCube array and dedicated to the detection of neutrinos with energy below 100 GeV



Neutrino Mass Ordering measuring atmospheric neutrinos crossing the Earth

The deep-sea Cherenkov detectors Km3NeT ORCA is dedicated to measure atmospheric neutrinos in order to study flavor-oscillation physics**.**

High Energy neutrino (Tev - PeV energy range)

Neutrinos is a perfect astrophysical messengers:

- unabsorbed by matter

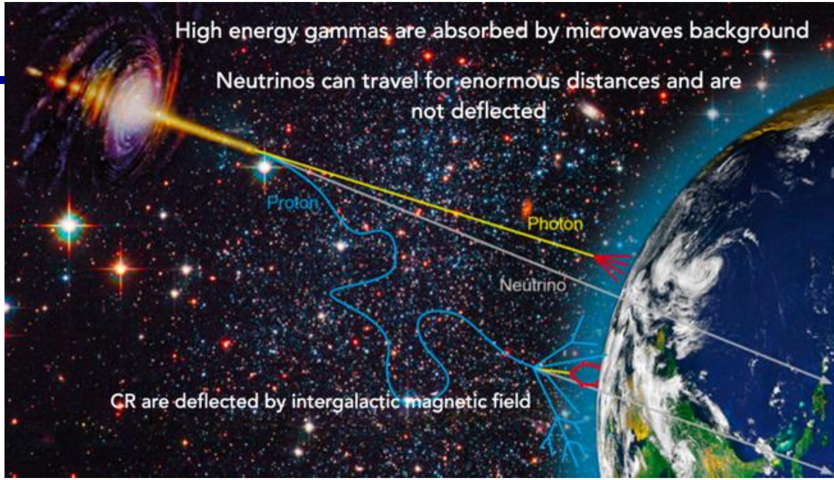
- not deviated by magnetic fields

- adronic signature: unlike gamma-rays (also produced in leptonic processes)

neutrinos are created only in hadronic processes

- multi Messenger Astronomy: correlated in time/direction with electromagnetic and gravitational waves

Neutrino probe for astrophysical sources and processes



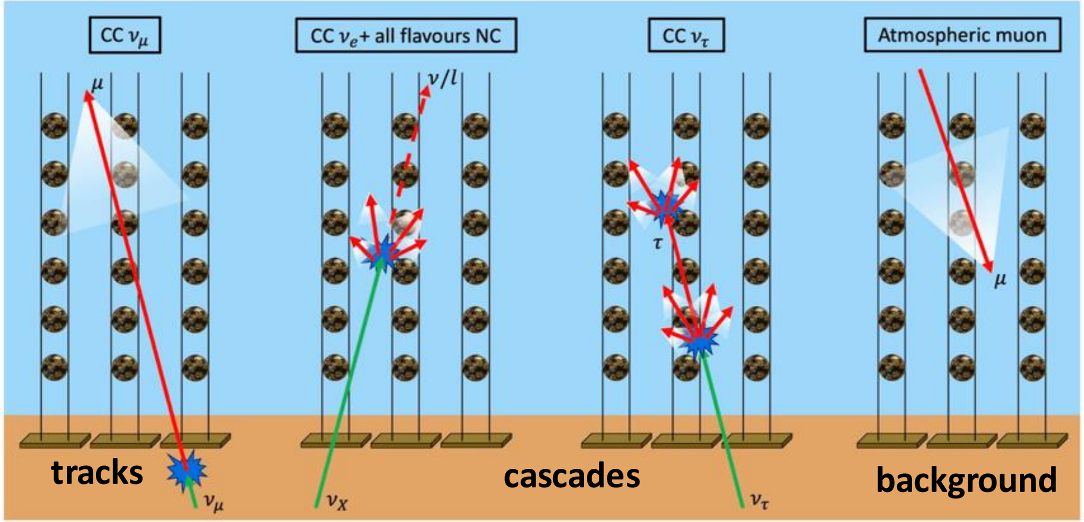
Detector layout **(M. Markov , 1960)**

Large volumes of water/ice instrumented with 3D-arrays of photodetectors into optical modules

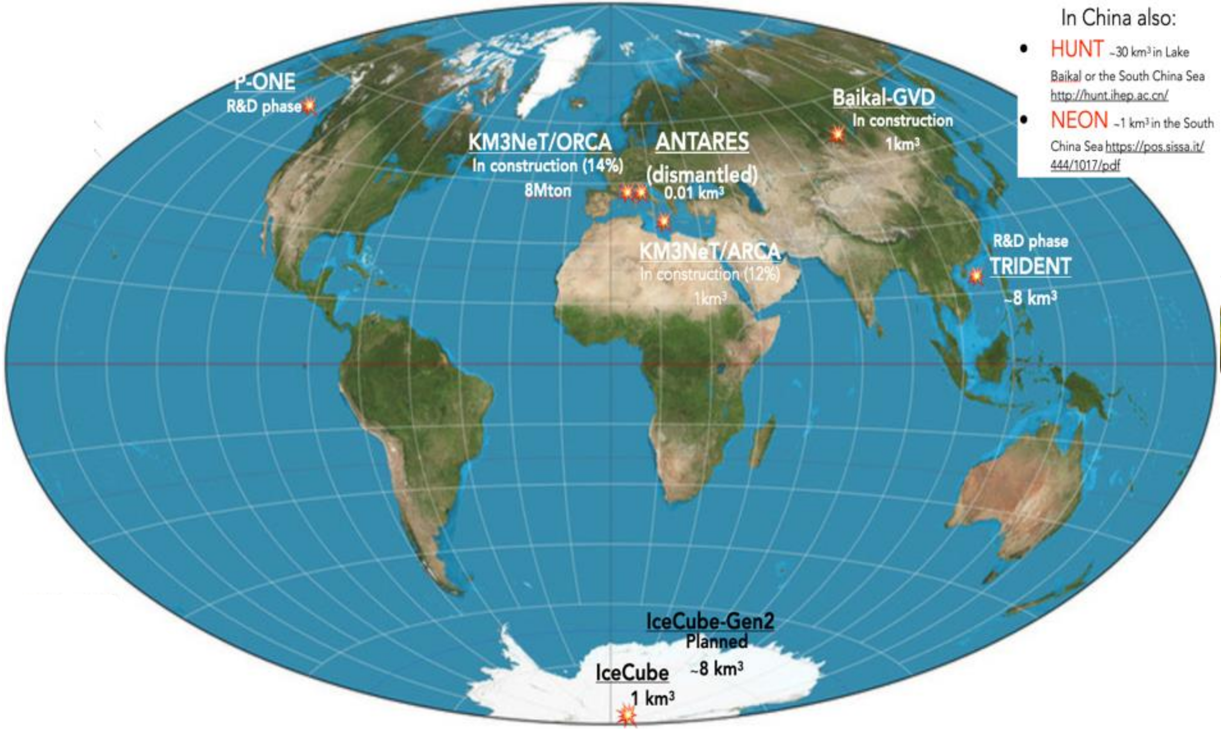
Detection of Cherenkov photons emitted by relativistic charged secondary leptons from ν

Tracks: very long path (~ km)
High angular resolution

Cascades: small path (some tens of meters)
Good Energy resolution

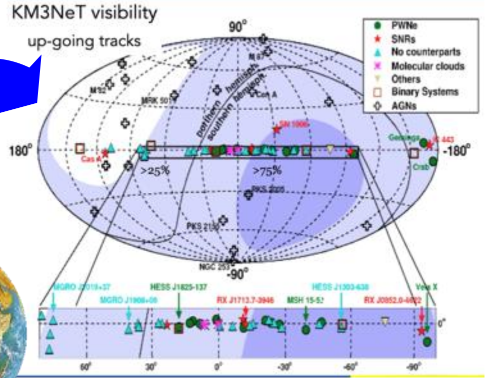


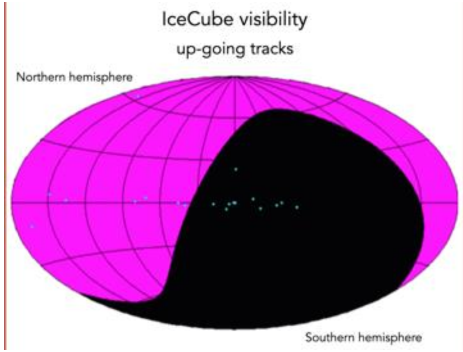
The High Energy neutrino detectors around the world



In China also:

- HUNT ~30 km³ in Lake Baikal or the South China Sea http://hunt.ihep.ac.cn/
- NEON ~1 km³ in the South China Sea https://pos.sissa.it/444/1017/pdf





Operating: ICECUBE since 2011 (1 km³), **ANTARES** since 2008 (0.01 km³) (dismantled)
In construction: **KM3NeT ORCA/ARCA** (1 km³), **GVD-Baikal** (1 km³),
Next designed : ICECUBE-Gen2 (8 km³), **P-One** (R&D Canada), **Trident** (R&D China, 8 km³)

Data from Northern Hemisphere needed for full sky coverage

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Cosmogenic neutrinos

HE cosmogenic neutrinos is expected produced by GZK effect of the UHECRs (up to 10^{20} eV) through CMB and EBL according two models (Berezinsky, Zatsepin*)*

Never been detected. Cosmogenic neutrinos are an important complementary measurement to charged UHECR Strongly depends on the cosmic-ray composition and the cosmological evolution of the sources

Neutrino E < 10 PeV range

IceCube and **IceCube-Gen2** is currently under planning
KM3NeT (better sensitivity to Galactic sources).

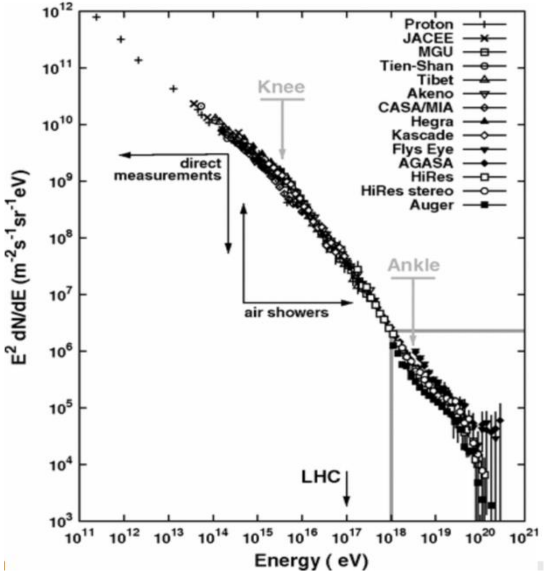
Neutrino E > 10 PeV range

expected fluxes are too low for km3-scale detectors→ different techniques than Cherenkov are needed
Identification of radio ($E_\nu > 10^{17}$eV) or acoustic ($E_\nu > 10^{19}$eV) emissions from neutrino interactions

GRAND. 200 000-antenna array is currently being developed, Mongolia, China. *[arXiv:1708.05128].)*
ARIANNA a hexagonal radio array, in Antarctica. *(Astropart. Phys. 70, 12.),*
The Askaryan Radio Array is currently being developed at the SouthPole *(Astropart.Phys.35,457.)*

Using existing arrays of acoustic receivers in water or ice in Cherenkov neutrino telescopes
ICECUBE, **BAIKAL-GVD** and **KM3NeT** *(Nucl. Part. Phys. Proc. 273–275, 406–413 (2016))*

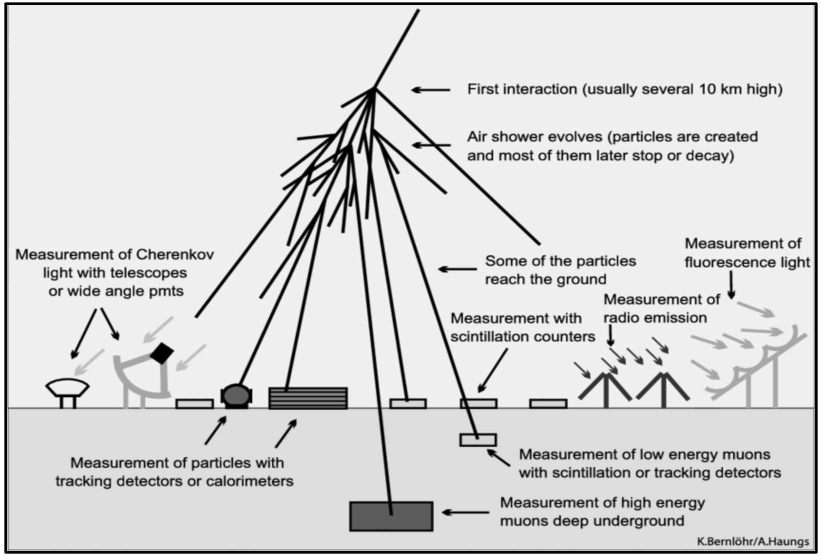
Ground based cosmic particle detectors



Cosmic reaching the Earth's atmosphere with an approximatively isotropic flux with energy that varies from 10^9 eV up to 10^{20} eV,

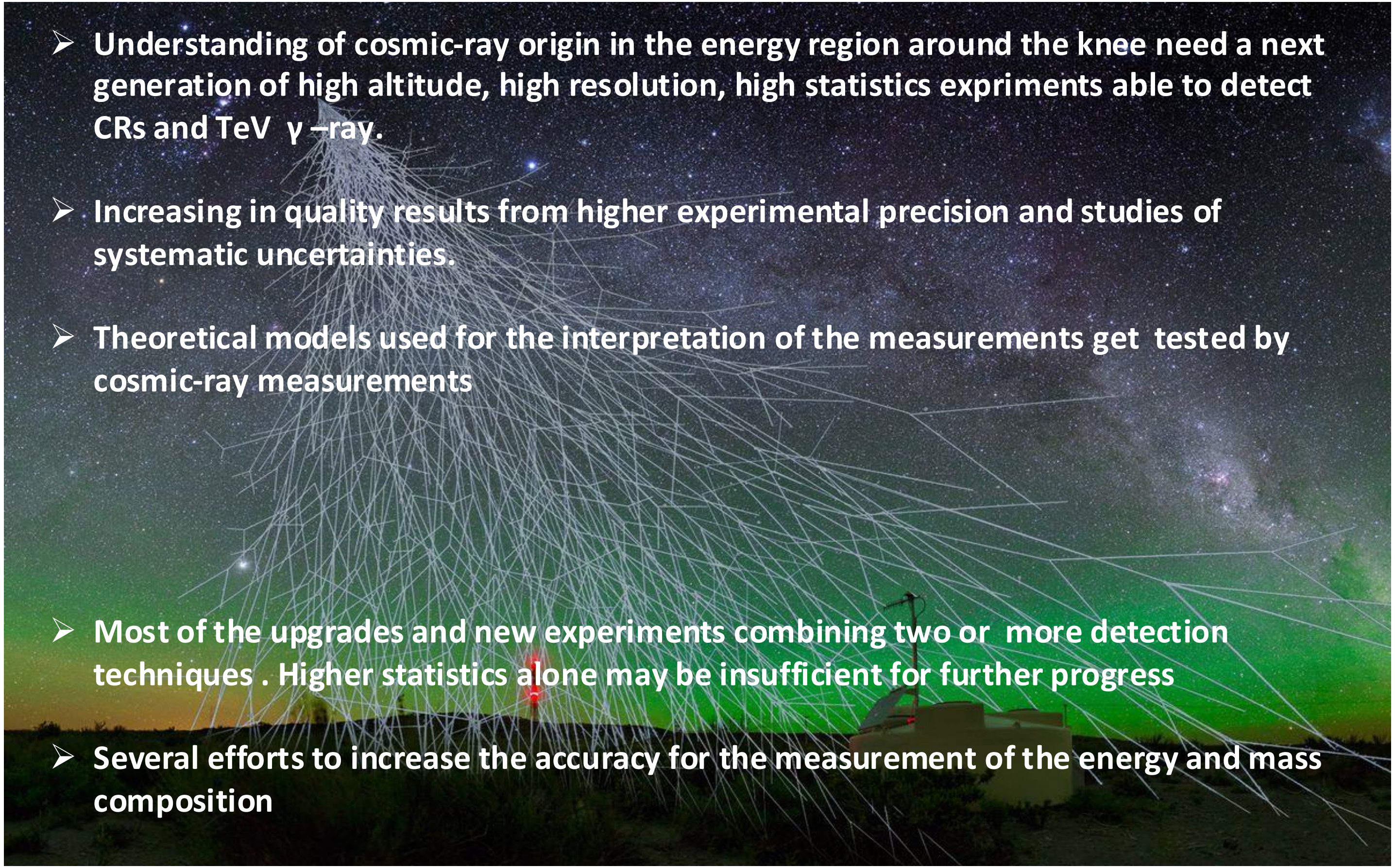
The flux of CR entering the Earth's atmosphere above 10^{15} eV drops below a few tens of particle per square meters per year → It is no possible to detect directly the incident particles above the atmosphere before they interact.

Above 10^{15} eV direct experiments are thus replaced with ground-based instruments that cover up to thousands of km^2: the extensive air shower (EAS) arrays



The main techniques used to measure EAS can be classified as follows:
- detectors that measure the particle componet of the shower at the ground
- detectors that measure the radiation produced by the propagation of the EAS in the atmosphere (Cherenkov light, Fluorescence light, radio signals)
- detectors underground that measures muons component

World status and next strategy for Cosmic ray study



- Understanding of cosmic-ray origin in the energy region around the knee need a next generation of high altitude, high resolution, high statistics expriments able to detect CRs and TeV γ –ray.
- Increasing in quality results from higher experimental precision and studies of systematic uncertainties.
- Theoretical models used for the interpretation of the measurements get tested by cosmic-ray measurements
- Most of the upgrades and new experiments combining two or more detection techniques . Higher statistics alone may be insufficient for further progress
- Several efforts to increase the accuracy for the measurement of the energy and mass composition

Ground based detectors for VHE gamma ray

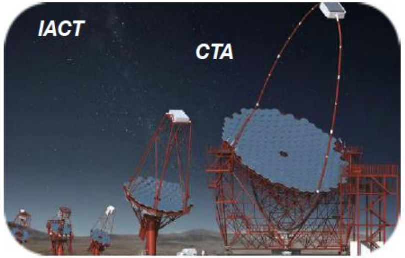
Gamma rays astronomy at energies of TeV is outside the possibility of space-based experiment

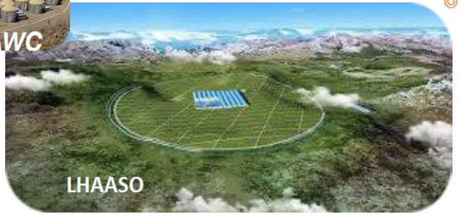
VHE (100 GeV-100TeV) gamma rays can only be studied by means of ground based detector

Two separate methods measure indirectly VHE gamma rays.

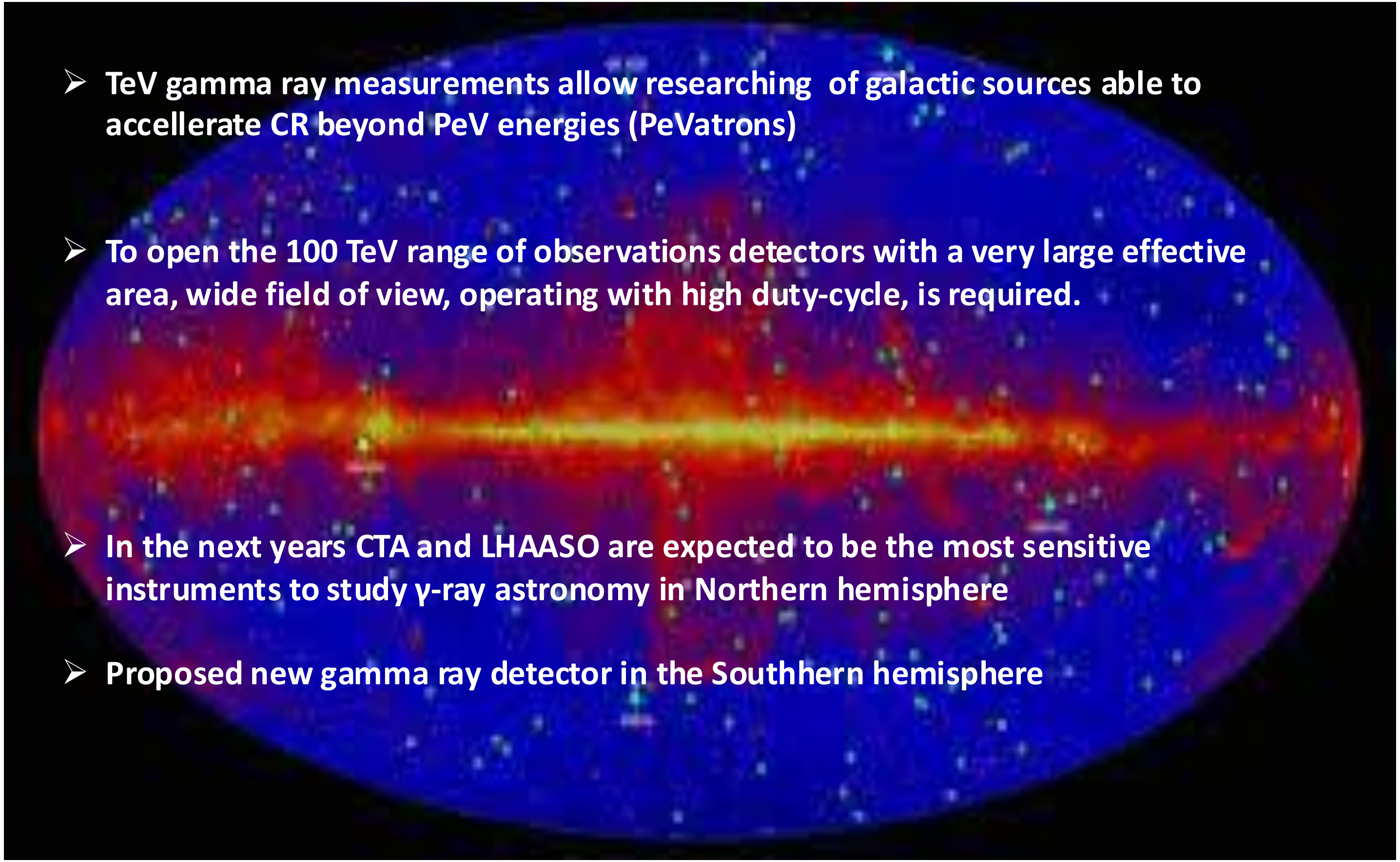
- **Surface arrays of particle detectors**
- **Imaging Atmospheric Cherenkov Telescopes (IACTs)**

Cherenkov Atmospheric Telescopes
- 20% duty-cycle
- Pointing (few degrees FoV)
- Energy threshold down to 10s GeV
- Good energy and angular resolution





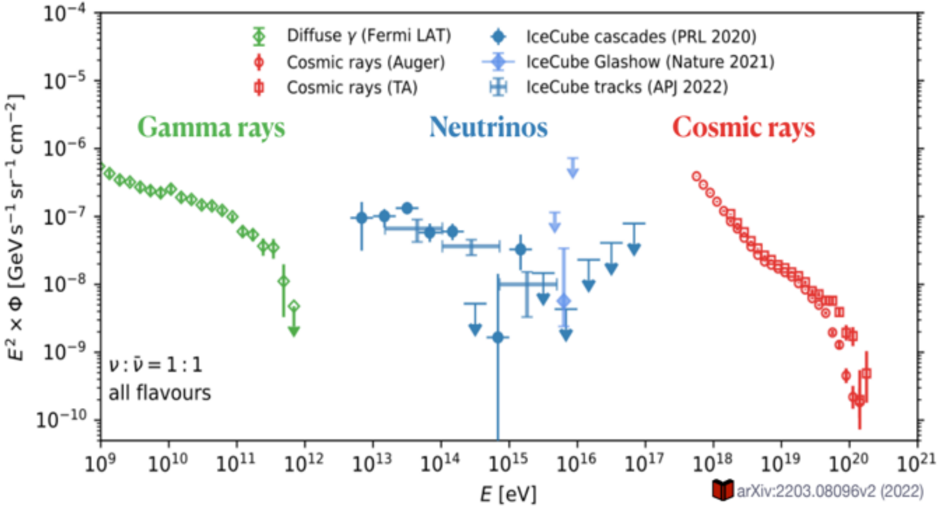
Particle Detector Arrays
- 100% duty-cycle
- Wide-field of View (~ steradian)
- Energy range 100s GeV up to 100s TeV
- Long exposure and accurate background determination



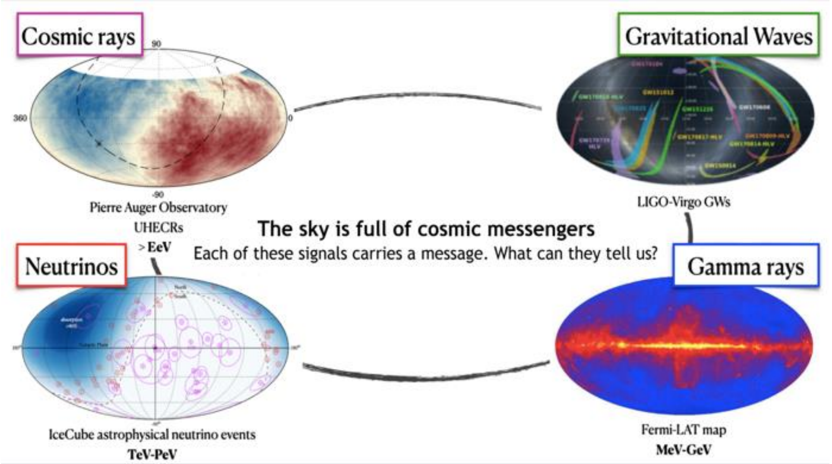
- TeV gamma ray measurements allow researching of galactic sources able to accellerate CR beyond PeV energies (PeVatrons)
- To open the 100 TeV range of observations detectors with a very large effective area, wide field of view, operating with high duty-cycle, is required.
- In the next years CTA and LHAASO are expected to be the most sensitive instruments to study γ-ray astronomy in Northern hemisphere
- Proposed new gamma ray detector in the Southhern hemisphere

Multi-messenger astronomy

A complete picture of the high-energy Universe is necessarily multi-messenger in nature

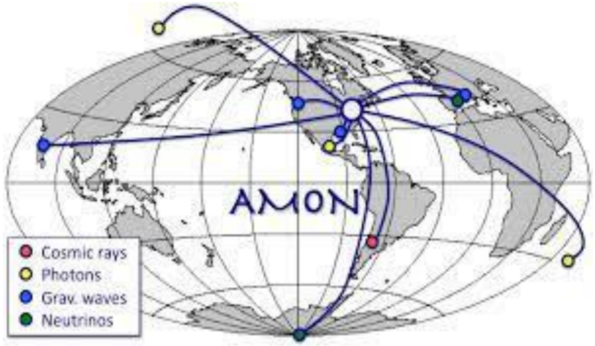


Coincident detections of different messengers



General Cordinates Network (GCN)
Astrophysical Multimessenger Observatory Network (AMON)

- collaborating observatories to astrophysical transients
- enabling rapid follow-up of astrophysical sources
- alert from neutrinos detectors
- searching for coincidences in sub-threshold data



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