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Astroparticle Physics

CUPP, Cosmic Rays, and Supernova Neutrinos

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Content of the Lecture

- Underground Laboratories &Underground Physics
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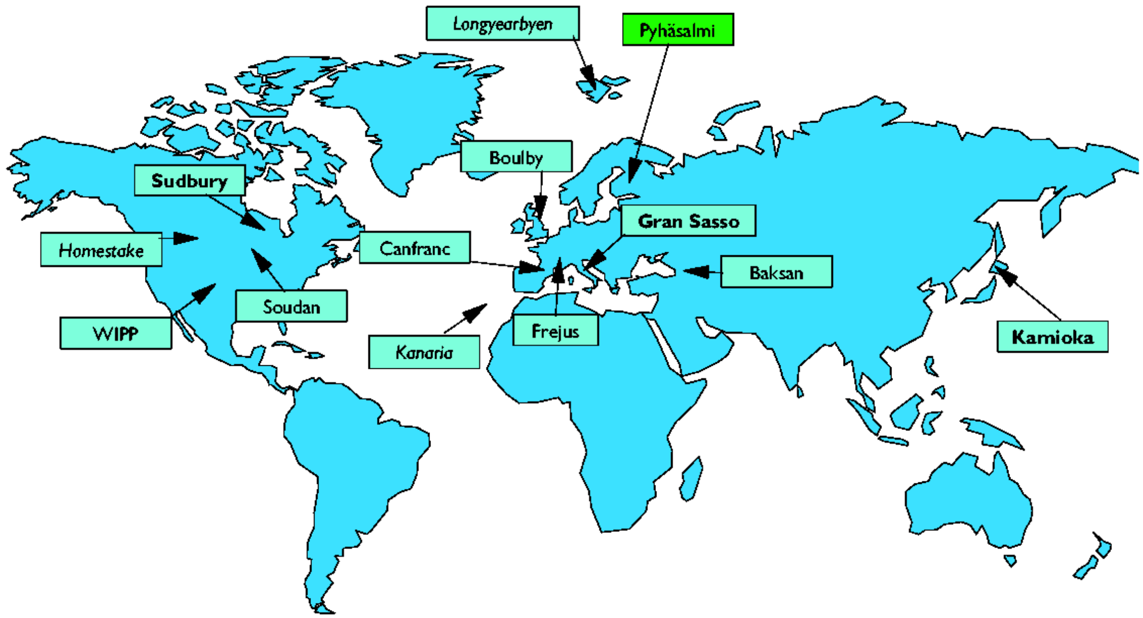
  - Neutrino & Supernova properties
  - Supernova SN1987A
  - A new TPC for SN detection

Underground Laboratories and Underground Physics

World's Underground Laboratories

mines and tunnels



The three largest underground laboratories at the moment are

- SNO, Sudbury, Canada ☞ Measurement of solar neutrinos
- Kamioka, Japan ☞ Measurement of atmospheric neutrinos
- Gran Sasso, Italy

Underground Laboratories

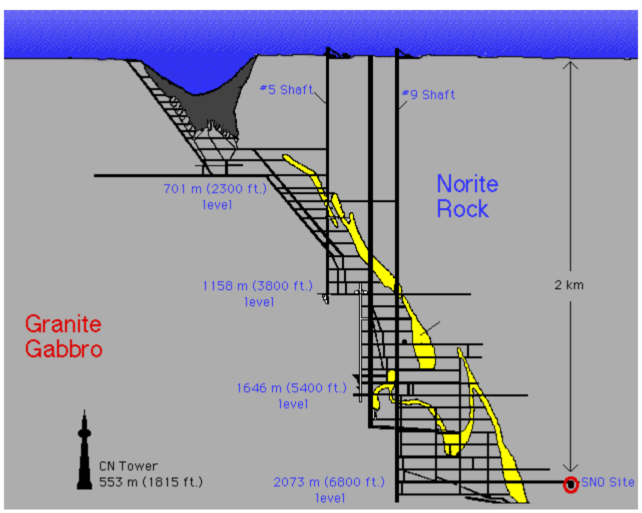
- There exists ∼dozen underground laboratories in the World
- Both tunnels and mines
  - mines have slant surface (better shielding)
  - tunnels have easier access (by cars)
- New caverns recently built for SNO and Canfranc,
  Extensions planned for Frejus and Boulby,
  New underground laboratory also expected in the US
- The depth usually given in metre-water-equivalent units (mwe):
  mwe $=$ vertical distance [m] $\times$ rock density [g/cm^3]
  (in Pyhäsalmi: 1400 m $\Longleftrightarrow$ 1400 $\times$ 2.85 $=$ 4000 mwe)
- The future experiment require megaton-scale detectors
  - depth $\leq$ 4000 mwe
  - such caverns still doesn't exist

The Sudbury Neutrino Observatory (SNO)

an example

The laboratory

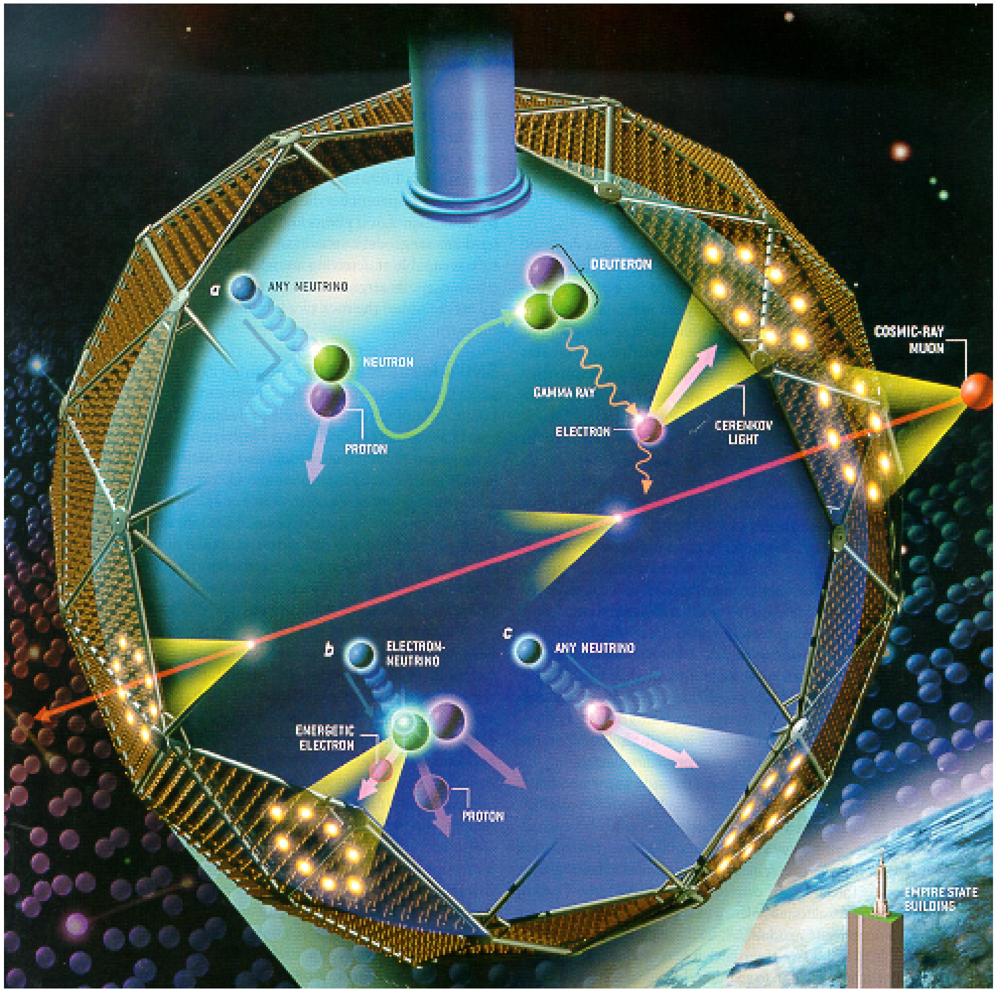
- large centre of mining operation
- the Depth : 2073 m (6010 mwe)
- access by elevator and narrow tunnel



The detector

- water Čerenkov detector
- spherical, diameter 12 m
- 1000 tons of ultrapure H_2O or D_2O
- ultrapure H_20 shield
- 9450 20-cm PMTs
- $\sim$55% of the light produced 7 m of the centre of the detector will strike a PMT

Heavy Water Čerenkov Detector at SNO



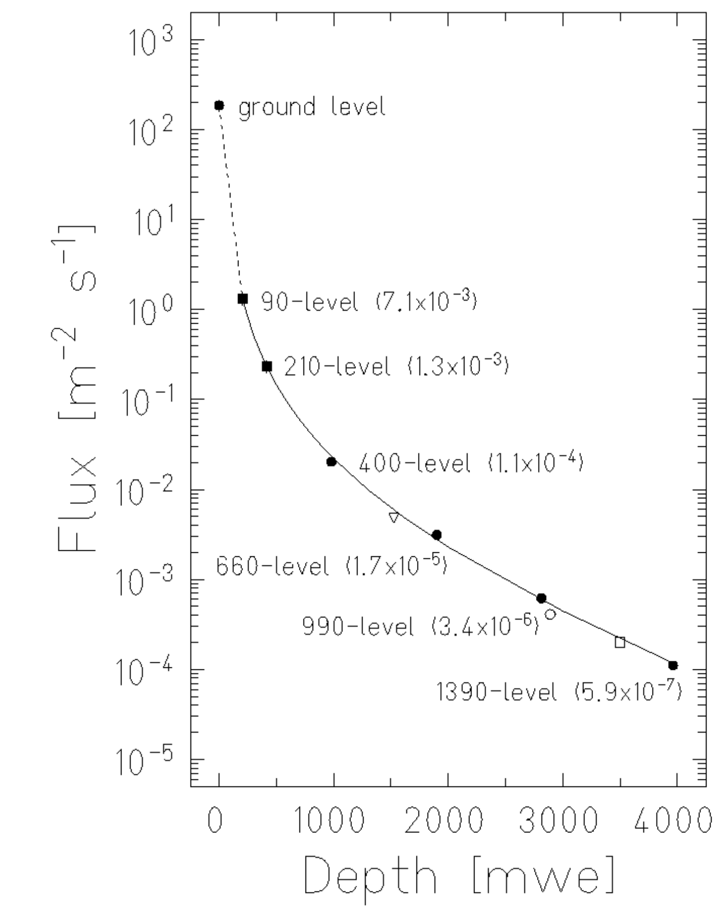
Underground Physics

Generally all experiments related to weak interaction processes should be performed underground (or underwater)

- neutrino studies (of astroparticle sources)
  - sun, supernova, air shower (atmosphere)
  - large-scale detectors
- (neutrinoless) double-beta decay
  - small- to medium-scale detectors & ultra-clean materials
- dark matter experiments
  - small- to medium-scale detectors & ultra-clean materials
- geoneutrinos (neutrinos from the Earth's core and crust)
  - large-scale detectors
  - distant from nuclear reactors (Hawaii)
- cosmic-ray experiments
  - usually at the surface, but some experiments have been done
- neutrino factory (future)
  - accelerator-produced neutrinos

What Drives Physics Underground ?

- Goal: **protection from cosmic rays**
- cosmic-ray (secondary) flux at the surface ∼150 $m^{-2} \cdot s^{-1}$
- Electrons, positrons, fotons and hadrons stop into the surface
- **Muons may penetrate extremely deep underground**
  - direct background from primary muons
  - secondary background from spallation reaction products (neutrons)
- Needs hundreds of metres of rock for shielding



In the Figure, the reduction of the muon flux in the Pyhäsalmi mine is shown as a function of the depth

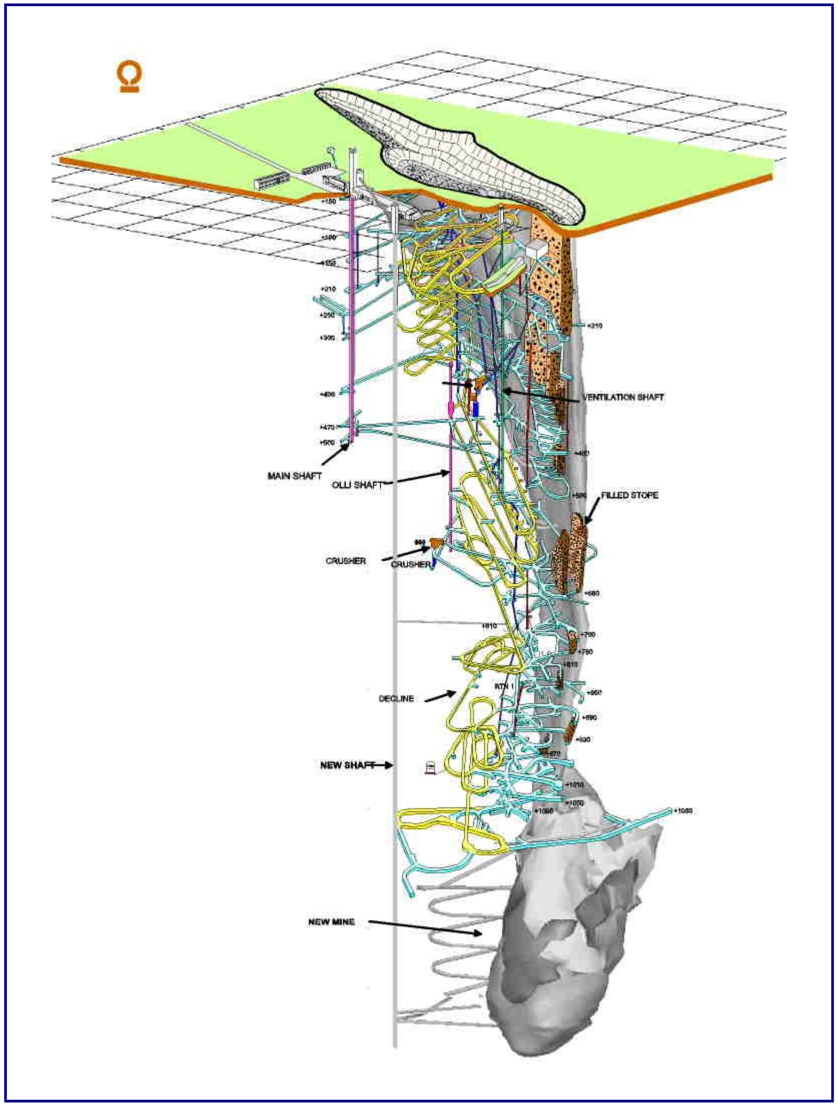
muon_flux.tex

Underground Laboratories

Pyhäsalmi Mine

Pyhäsalmi mine

The Pyhäsalmi Mine



- The deepest operational base-metal mine in Europe, run by Pyhäsalmi Mine Ltd (owned by Inmet Mining Corporation, Canada)
- Produces zinc, copper and pyrites
- The mining operation in the new mine started in 2001
- The new mine extends down to 1440 metres underground. The old mine, where mining operation is not active, extends to 1050 metres, and can be used for scientific experiments
- Access via the decline by trucks or four-wheel vechicles
- Low background radiation

Advantages of the Pyhäsalmi Mine

- DEEP
  The deepest operational base-metal mine in Europe (1410 m, 4000 mwe)
- DISTANCE
  A long way to CERN (2288 km) and far away from nuclear reactors
- VOLUME
  New large-volume spaces and cavern can be excavated
- INFRASTRUCTURE
  Good traffic conditions around a year, modern infrastructure
- Very stable bedrock
- Public local support

CUPP

Centre for Underground Physics in Pyhäsalmi mine

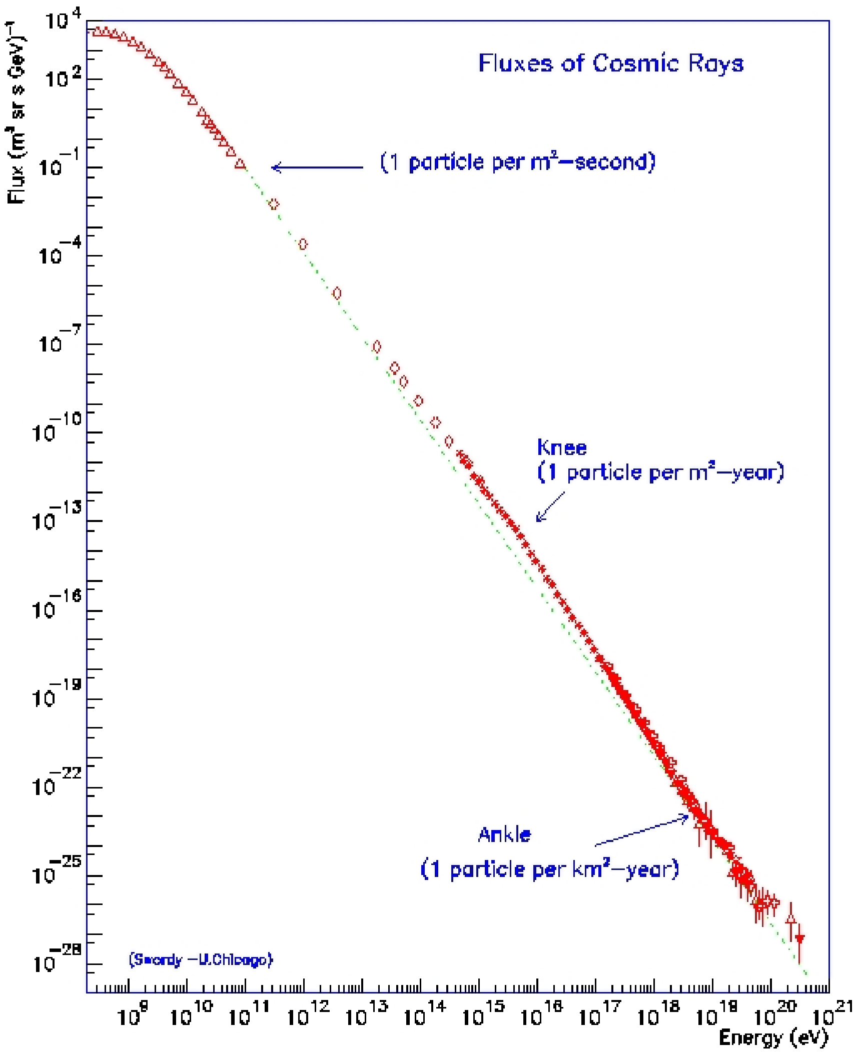
The aim is to establish an international laboratory of underground physics (particle and nuclear physics)

- first ideas about the laboratory around 1993 when the mining operation seemed to stop
- EU project fundings for 1997 – 1999, 1999 – 2001, 2001 – 2003, and 2004 – 2006
- in the beginning background properties were studies, and the suitability for scientific work
- first larger-scale experiment now under construction: cosmic-ray experiment EMMA
- second experiment under consideration: TPC supernova detector
- work still in the old part of the mine
- Future (large-scale) possibilities: LENA, neutrino factory

Cosmic Rays

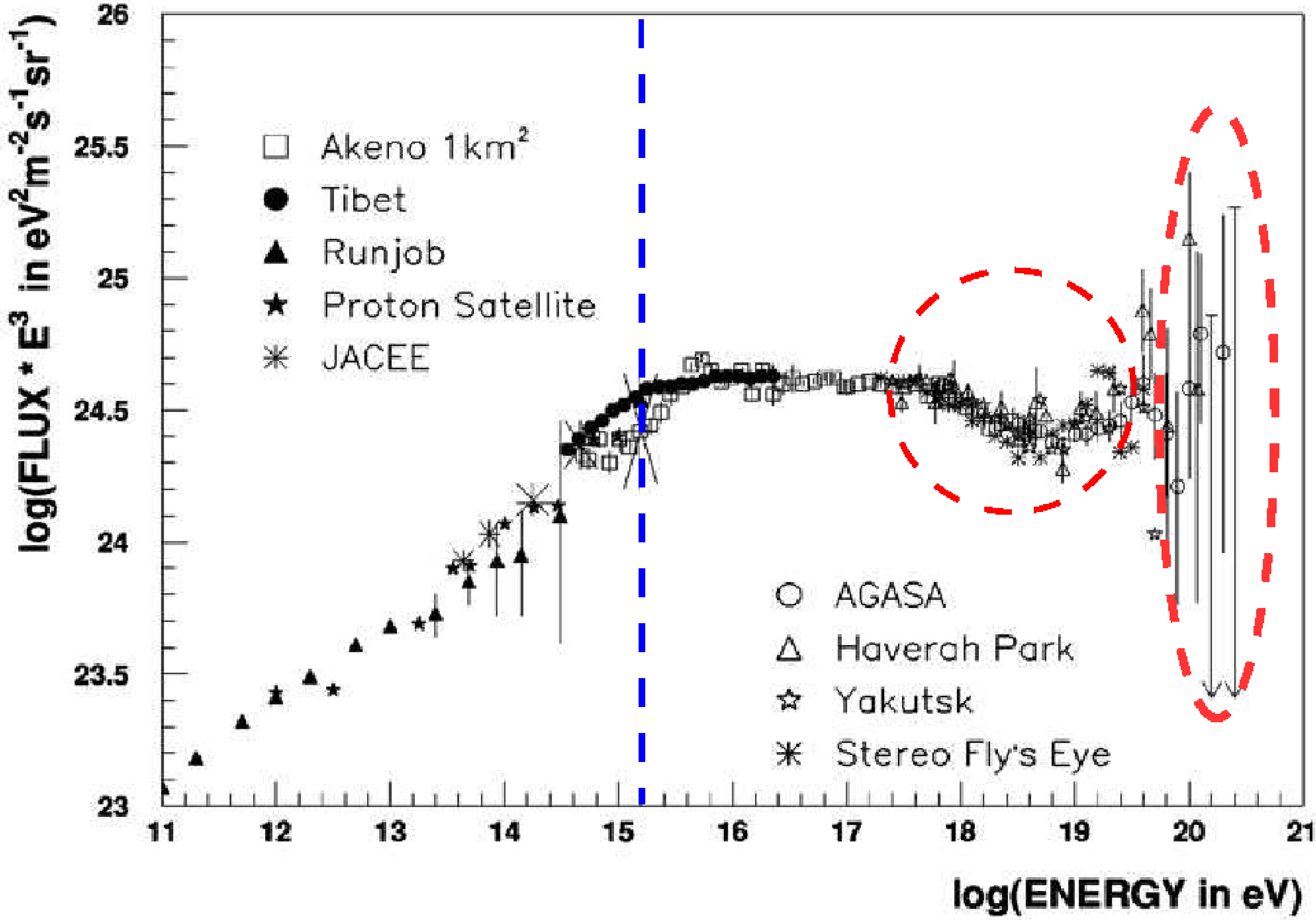
General

Introduction on Cosmic Rays (1)



- Studied several decades (since 1912) by balloons, arrays, satellites, ...
- Historical reasons: cosmic rays $\Longleftrightarrow$ γ, e^-, p, heavy nuclei, ...
- Two or three changes in the slope of the spectrum
  - knee at E $\sim 10^{15} - 10^{16}$ eV
  - ankle at E $\sim 10^{18} - 10^{19}$ eV
  - ☞ different production or acceleration mechanism
- GZK-cutoff at E $\sim 10^{19} - 10^{20}$ eV
  - collision with CMB
- In energy, the spectrum is reliably known up to GZK-cutoff

All-Particle Spectrum of Cosmic Rays



Introduction on Cosmic Rays (2)

- The composition is poorly known
  - mostly protons, also alphas, ..., iron
- Aim of the research:
  Find out cosmic ray sources and origins
- Difficult of observe and locate directly
  - γ's points to the source
  - charged particles bend in the magnetic fields
- Method: measure the cosmic ray composition
  - mass and/or elemental
  - can be measured directly up to $\sim 10^{14}$ eV (100 TeV)
  - at higher energies indirect measurement:
    Extensive Air Showers (EAS)

  ☞ developing theoretical models that can produce measured composition

Introduction on Cosmic Rays (3)

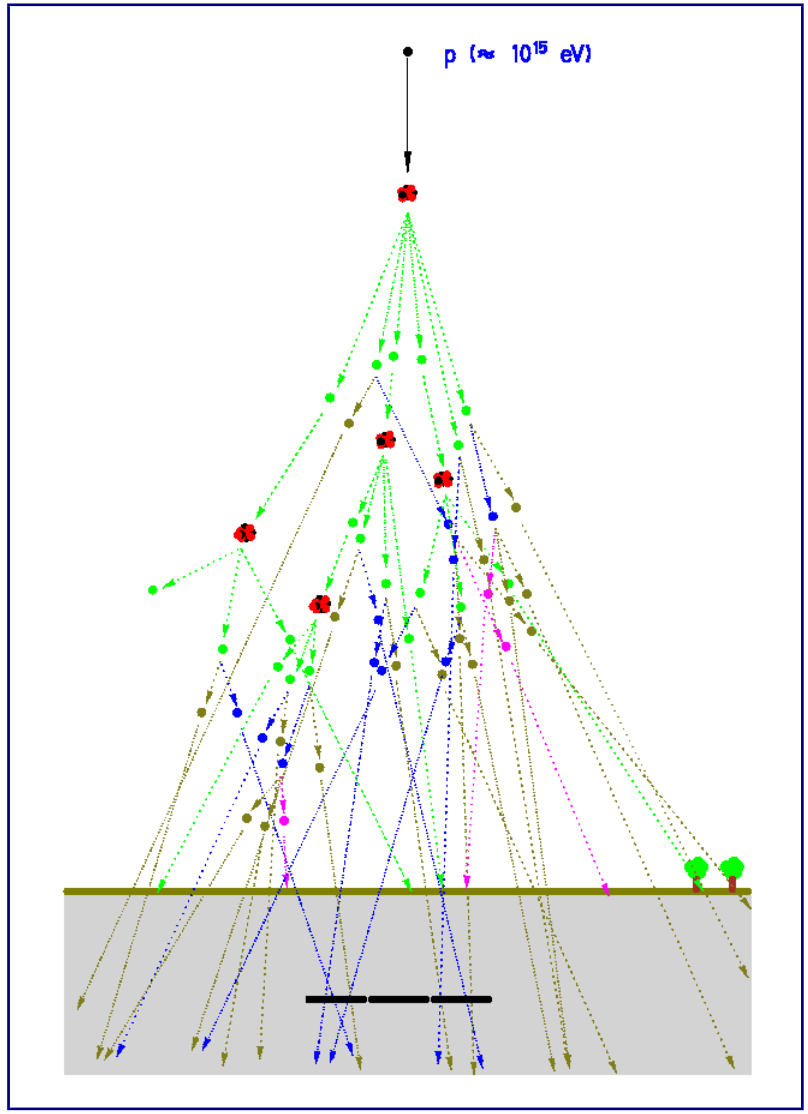
- Source candidates (no experimental evidence yet):
  - supernova remnants (shock waves)
  - pulsars (neutron stars), AGN's (quasars), GRB's, decay of massive particles, ...
  - $< \sim 10^{18}$ eV: galactic origin
  - $> \sim 10^{18}$ eV: extra-galactic origin

  ☞ ankle could represent transition from galactic sources to extra-galactic sources (?)

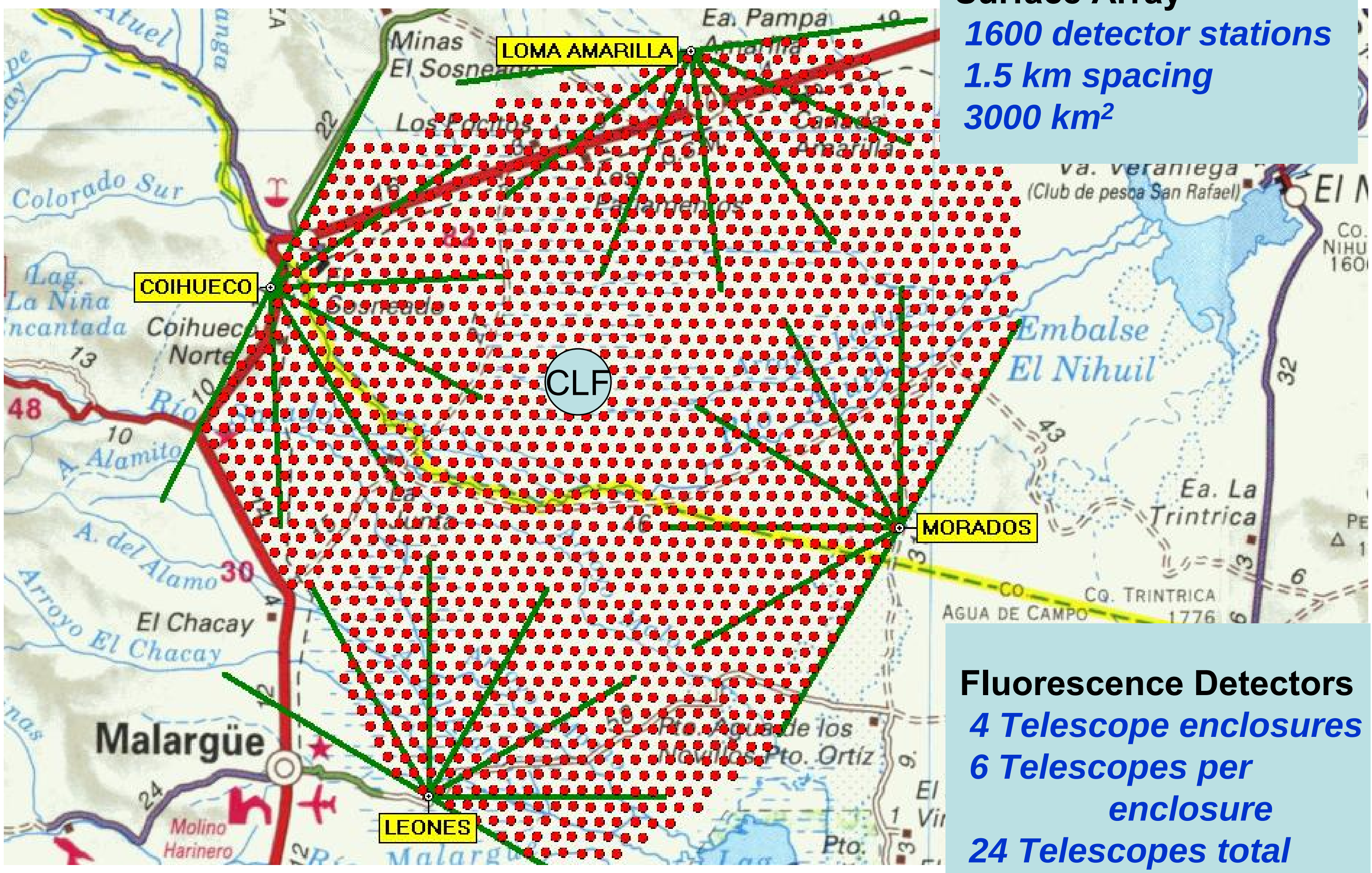
- Cosmic Ray research at high energies (knee and above) is very active (tens of different experiment)
  - at highest energies: Pierre Auger
  - at the knee region: KASKADE-Grande
- Results VERY model dependent
  - interactions at these high energies not known accurately enough (LHC may help)

Introduction on Extensive Air Shower

- High-energy cosmic particle hits into atmosphere atom
- (Extensive) Air Shower is created
  - contains $\sim 10^6$ particles: p, n, π, κ, e^-, e^+, γ's
- Most of particles stop on the Earth surface
  - muons may penetrate several hundreds of metres underground
  - neutrinos penetrate Earth
- Consequence
  - muons cause background for sensitive neutrino experiments
  - can also be studied underground ☞ EMMA



Pierre Auger Array



Surface Array

1600 detector stations

1.5 km spacing

3000 km²

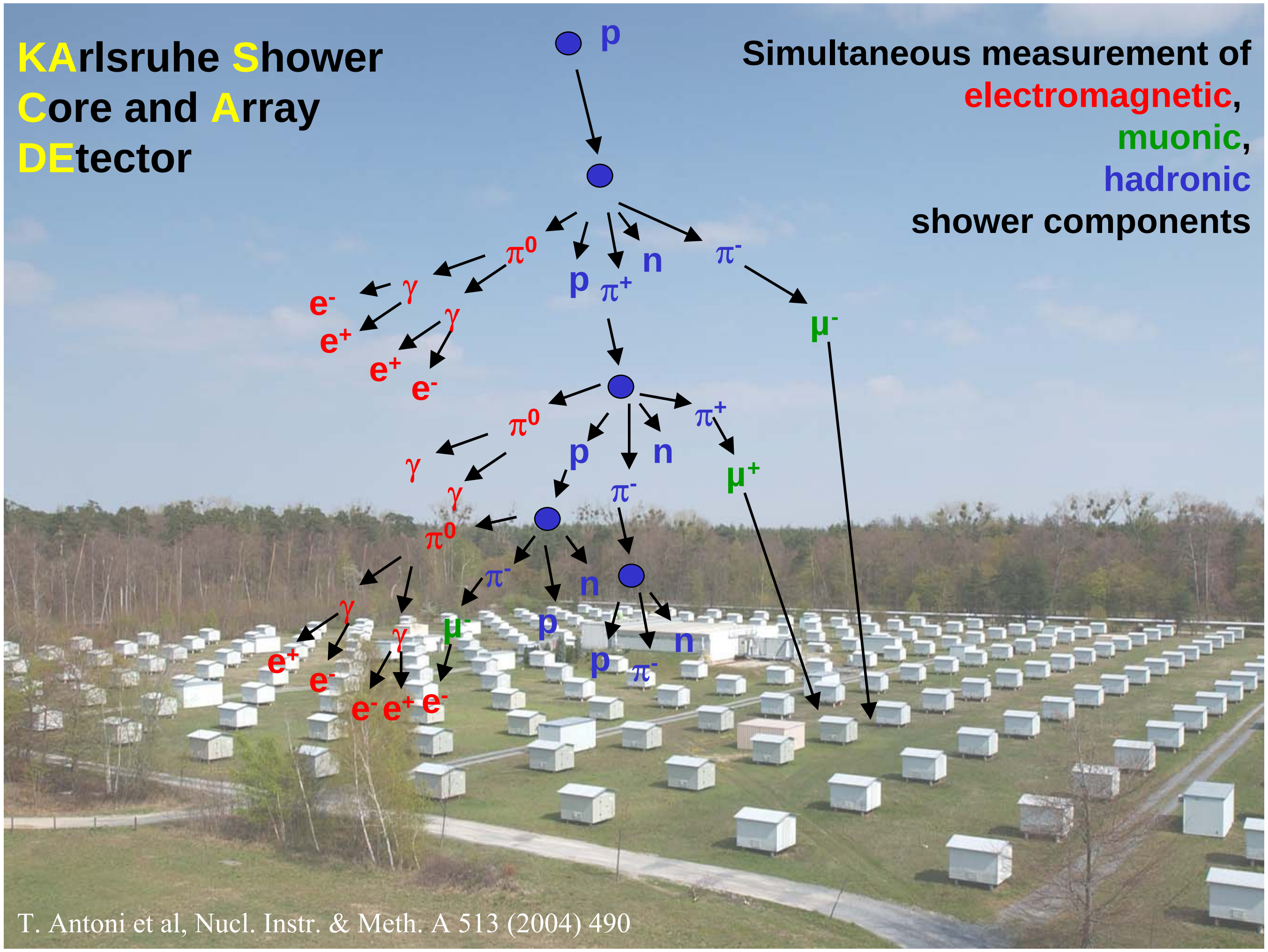
Fluorescence Detectors

4 Telescope enclosures

6 Telescopes per enclosure

24 Telescopes total

KASCADE



kaskade.tex

Cosmic Rays

EMMA – Experiment with MultiMuon Array

Introduction of the Experiment

The aim of the EMMA is to detect high-energy muons formed in the upper part of an air shower, by filtering out low-energy muons with the rock overburden

- To be carried out in the depth of 85 metres in the Pyhäsalmi mine, Pyhäjärvi, Finland.
  ☞ the cut-off is about 45 GeV

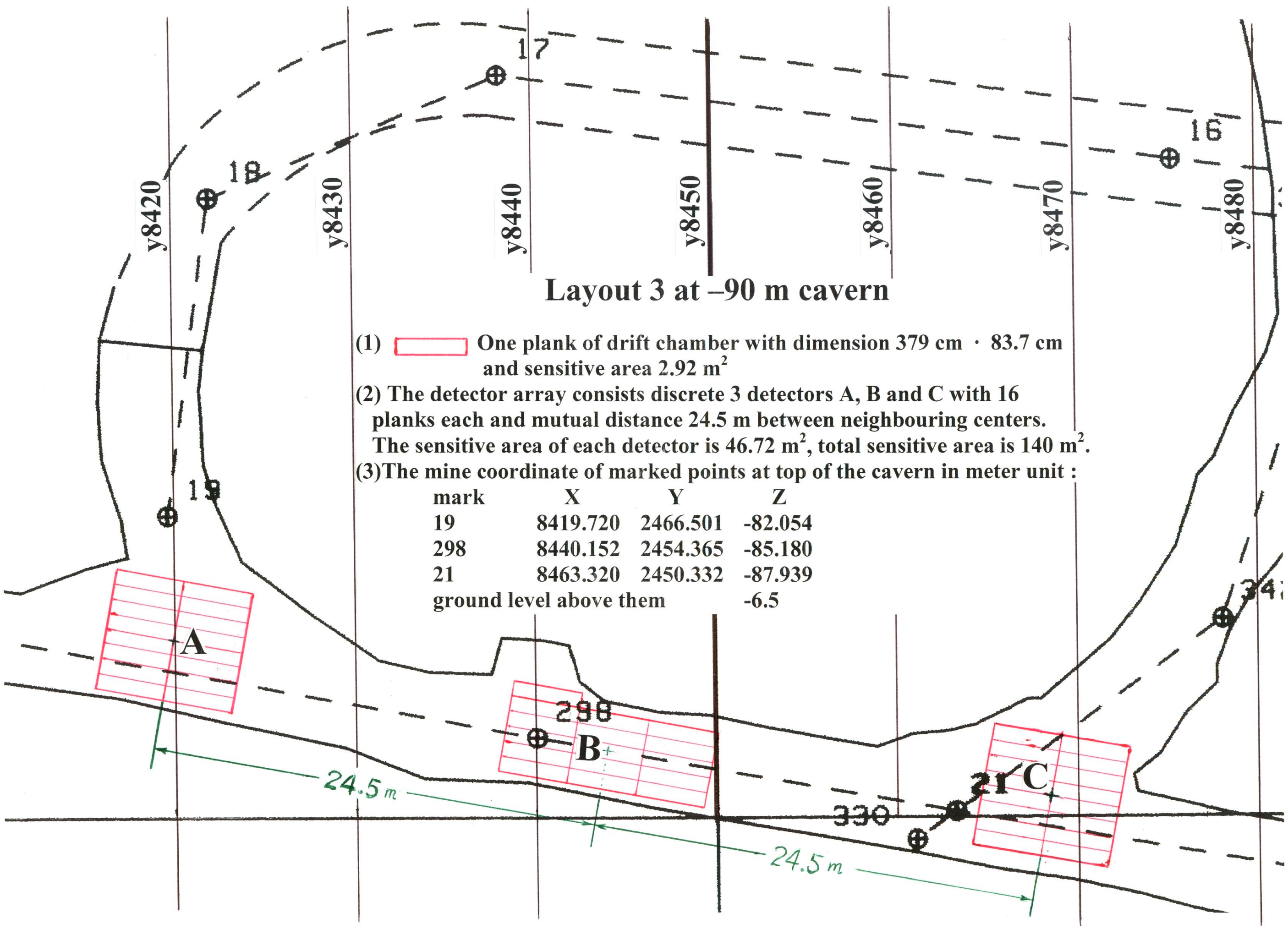
The purpose is

① to study the composition of cosmic rays at the knee region (10^{15} – 10^{16} eV), and

② to learn something from the physics of the upper part of the air shower

- Existing caverns and existing detectors are used
  ☞ low-cost experiment
- Not the first underground cosmic-ray experiment, but EMMA is enable to measure the Lateral Distribution Function of muons

Detector Layout
at the depth of 85 metres



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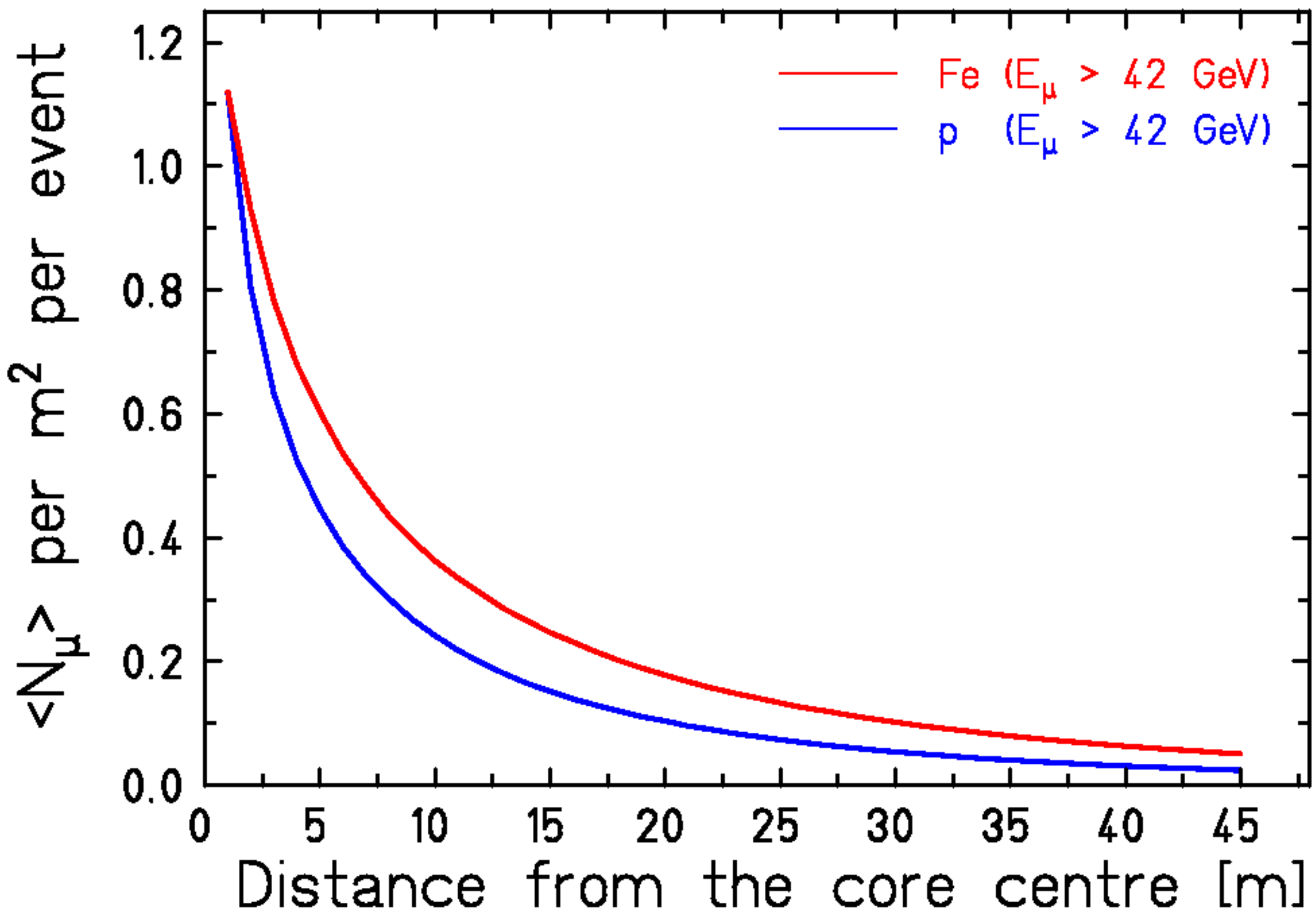
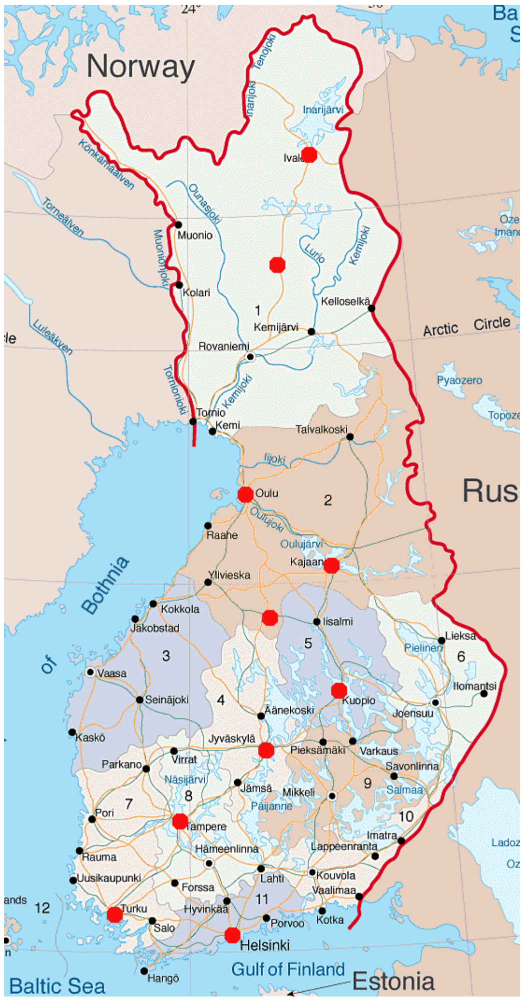
Muon LDF



Fe (E_μ > 42 GeV)
p (E_μ > 42 GeV)
<N_μ> per m² per event
Distance from the core centre [m]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45

Kouluprojekti



- Laaja verkosto kosmisen säteilyn ilmaisimia
  - ☞ koulujen yhteyteen läpi koko Suomen
  - ☞ Pyhäsalmen laboratorioon pintailmaisimet
- Koulut osallistuvat rakentamiseen ja ylläpitoon
  - ☞ tiede- ja teknologiaoppimishanke
  - ☞ innostaa lapsia tieteeseen, opettajat apuna
- Suunnitteluvaiheessa, rahoitusta jonkin verran
- Euroopassa ja Amerikassa vastaavia projekteja
  - ☞ Yhteistyö Euroopassa käynnistymässä
- Koordinointi
  - ☞ Koordinointiryhmä perustettu (pj. Prof. Jukka Maalampi, JYFL)
  - ☞ monet yliopistot ja AMK:t mukana
  - ☞ herättänyt jo kiinnostusta monessa koulussa
- Keskuspaikka CUPPin yhteyteen Pyhäjärvelle

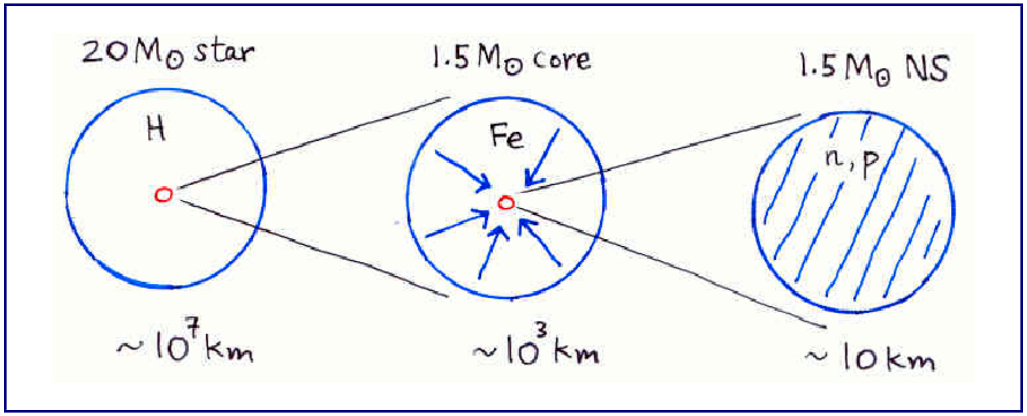
Supernova Neutrinos

General

(Short) Introduction on Neutrino Properties

- Three flavors (types): **electron**, **muon** and **tau** neutrinos, and their anti-neutrinos
- Recent data from SNO and from SK demonstrated that **neutrinos oscillate**
  ☞ **neutrinos have mass**
  - SK : atmospheric $\nu_\mu \longrightarrow \nu_\mathrm{x}$ (not ν_e)
    SNO : solar $\nu_\mathrm{e} \longrightarrow \nu_{\mu\tau}$
- Interact extremely weakly with matter
  - Observation of neutrinos gives information on the source
    ☞ investigation of the supernova core collapse or the interior of the Sun ($\sim$2 sec for ν to get from centre to surface, gammas are captured)
  - **very** difficult to observe experimentally (needs huge-size detectors)
- Neutrino sources
  - Sun (ν_e), Supernova (all)
  - Atmosphere ($\nu_{\mu\tau}$)
  - Nuclear reactors, Earth's crust (β-decay of fission fragments, $\bar{\nu}_\mathrm{e}$)
  - Accelerator (super- and β-beams, ν_e, $\bar{\nu}_\mathrm{e}$; muon factory, $\nu_{\mu\tau}$)

Supernova Properties
(1) Energy release

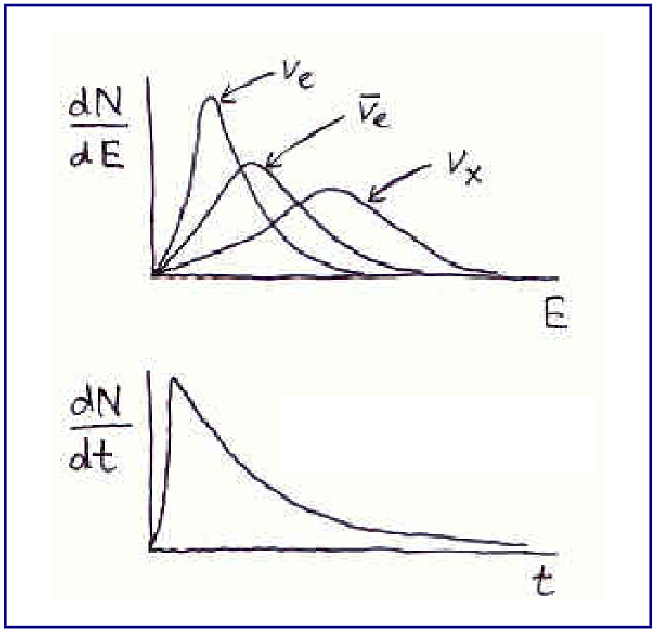


$$\Delta E_B \approx \frac{3}{5}\frac{GM_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{GM_{core}^2}{R_{core}} \approx 3 \times 10^{59}\ \text{MeV} \approx 3 \times 10^{46}\ \text{J}$$

- Kinetic energy of explosion $\approx 10^{-2} \cdot \Delta E_B$
- EM radiation (incl. optically visible part) $\approx 10^{-4} \cdot \Delta E_B$
- Rest, ~99%, of the energy is taken away by neutrinos
  - ☞ ~1% of ν_e from an initial breakout burst
  - ☞ ~99% are $\nu\bar{\nu}$ **pairs of all flavors** from the cooling phase

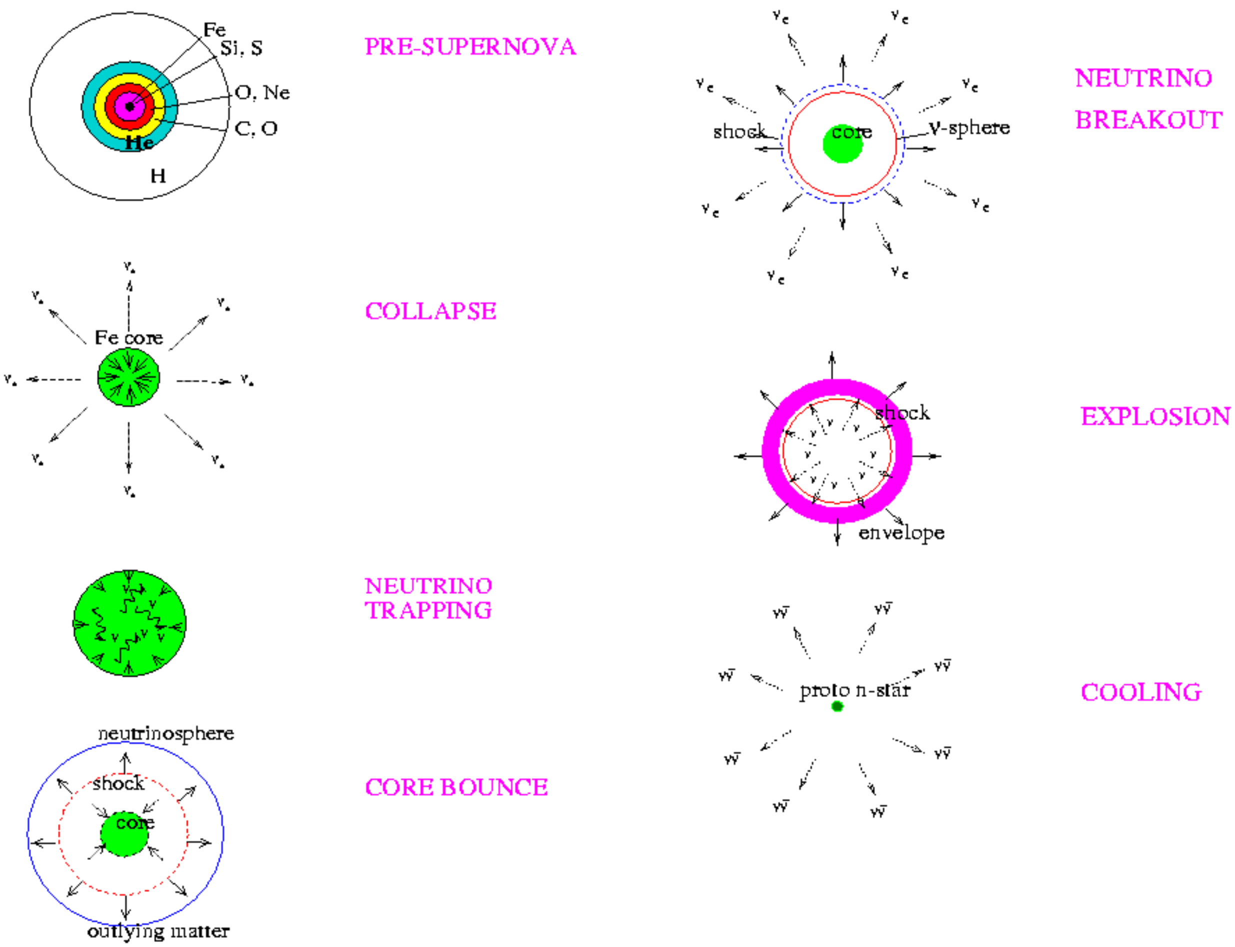
Supernova Properties
(2) Neutrino emission

- The Energy of emitted neutrinos can be described by Boltzmann distribution
  $\langle E_{\nu_e} \rangle \approx 11$ MeV
  $\langle E_{\bar{\nu}_e} \rangle \approx 16$ MeV
  $\langle E_{\nu_{\mu\tau}} \rangle \approx 25$ MeV
- Neutrinopulse is quite short:
  ☞ duration $\sim 10 - 20$ s
- Luminosities ∼equal:
  ☞ $L_{\nu_e}(t) \approx L_{\bar{\nu}_e}(t) \approx L_{\nu_{\mu\tau}}(t)$
- Number of emitted neutrinos:
  $\sim \mathbf{10^{58}}$ of all types



- Number of expected supernova explosions in our Galaxy: $\sim$ **3 ± 1 per century**
- The latest (observed) SN in our Galaxy: **October 9, 1604**

Supernova Properties
(3) Core collapse



SNiii.tex

Supernova Neutrinos
what they can tell ?

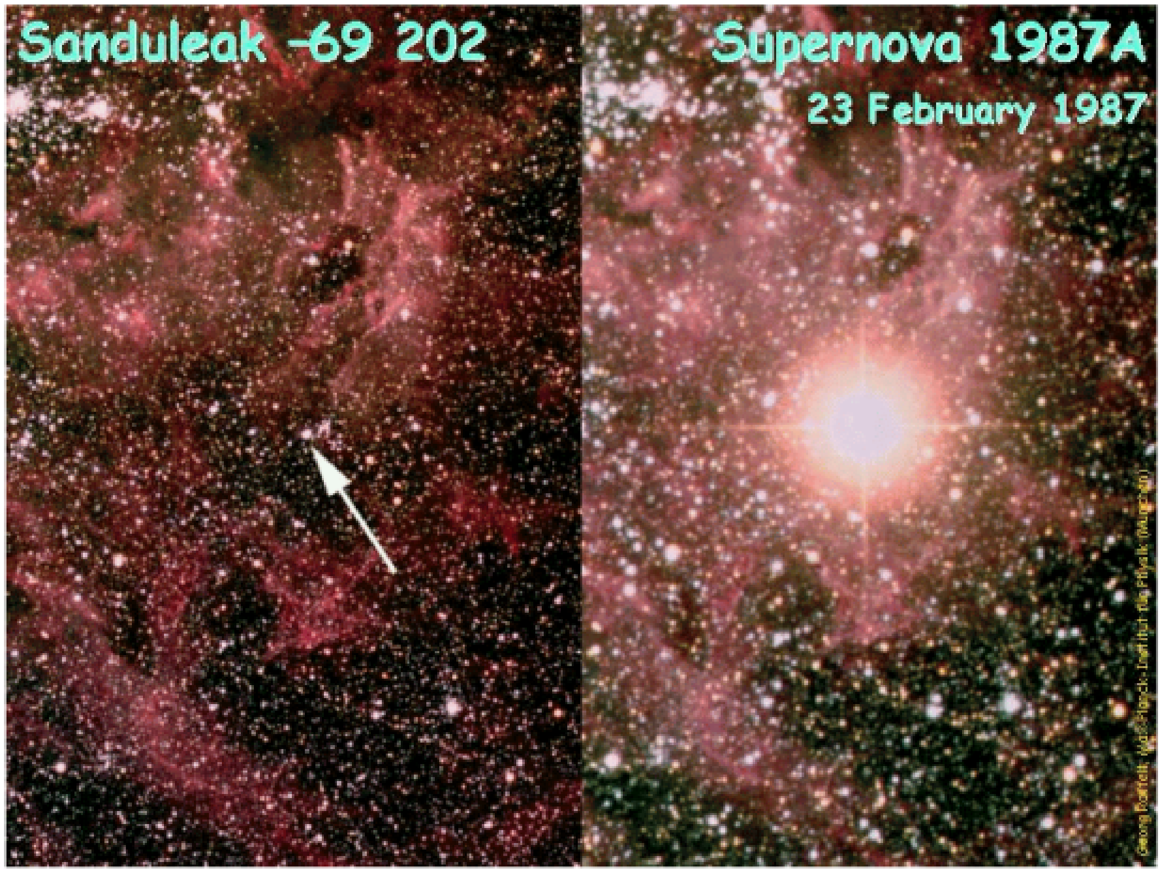
Neutrino Physics

- neutrino absolute mass (with some accuracy)
- neutrino oscillations

Supernova Core Collapse Physics

- Information about
  - explosion mechanism, supernova evolution in time
  - convection, hydrodynamics instabilities
  - proto neutron-star EoS
  - black hole formation mechanism
  - neutrino roles in r-process (in production of heavy elements)
- Signatures (by measuring flavour, energy and time structure of the neutrino burst)
  - pulse risetime and shape
  - breakout, luminosity cutoff (+ black hole formation)
  - pulsation
  - cooling

Supernova 1987A



Supernova 1987A
(1) General Properties

- Astronomical Event of the Decade
- 167000 light years away, in the Large Magellanic Cloud (5 times further than the average distance expected for a Galactic supernova)
- Only stellar collapse, so far, from which neutrinos have been detected
- 20 neutrinos were detected by Kamiokande and IMB (Irvine Michigan Brookhaven experiment) detectors (water Čerenkov)
- In addition, some events were also registered at Baksan and Mont Blanc detectors (liquid scintillator)

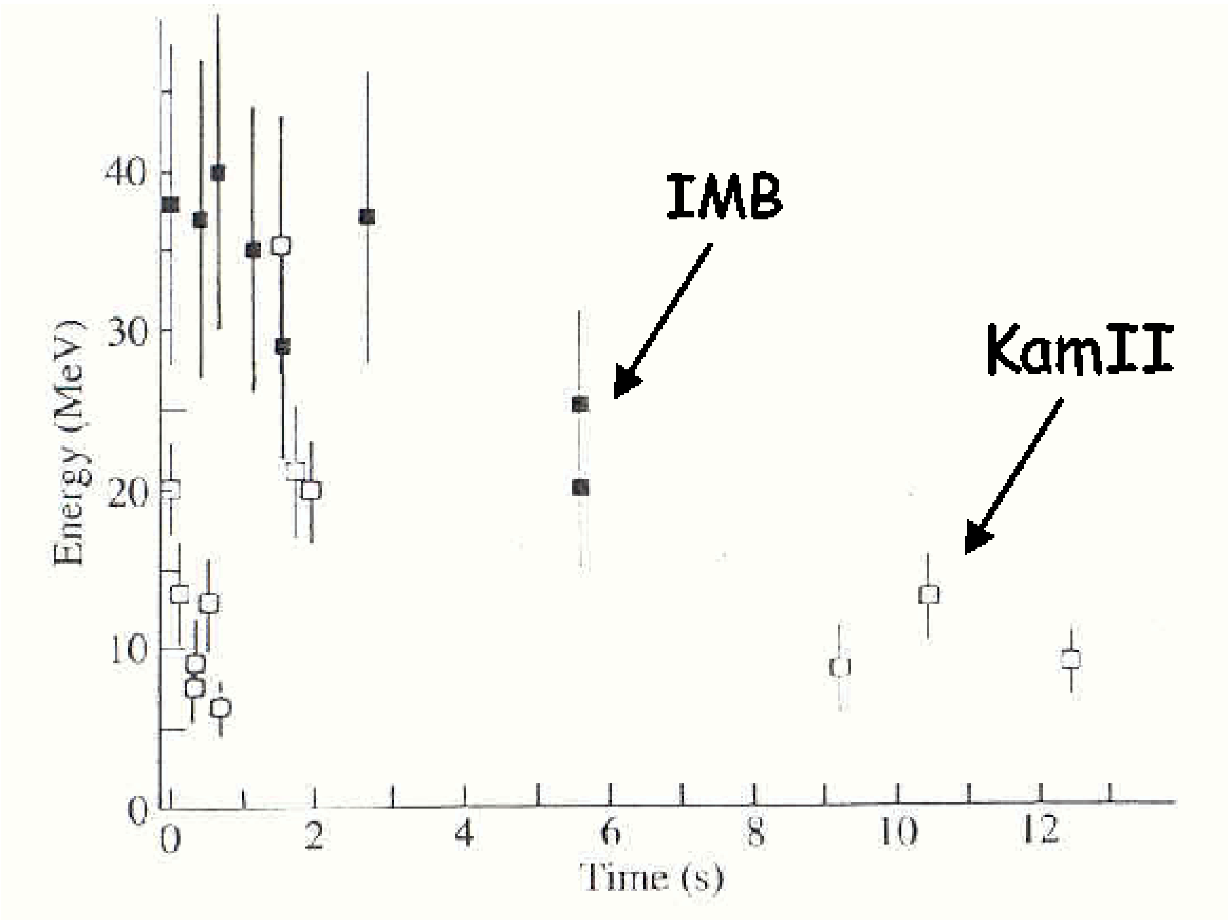
Supernova 1987A
(2) Kamiokande II and IMB Detectors

- Both detectors were designed to search for proton decay
- Water Čerenkov detectors, surrounded by PMTs
- Kamiokande II at 2700 mwe, IMB at 1570 mwe
- IMB had about 10 times larger mass
  - ☞ it was less sensitivity to low-energy events because of higher background rates
  - ☞ it also had lower efficiency in the collection of Čerenkov light
- Energy threshold in the IMB was about 20 MeV, and in Kamiokande II about 6 MeV

Supernova 1987A
(3) Measured Neutrino Signal

Event no.	Time(UT) on Feb. 23	Energy [MeV]	Angle [deg.]	Event no.	Time(UT) on Feb. 23	Energy [MeV]	Angle [deg.]
K-1	7:35:35.00	20.0±2.9	18±18	IMB-1	7:35:41.37	38±7	80±10
K-2	35.11	13.5±3.2	40±27	IMB-2	41.79	37±7	44±15
K-3	35.20	7.5±2.0	108±32	IMB-3	42.02	28±6	56±20
K-4	35.32	9.2±2.7	70±30	IMB-4	42.52	39±7	65±20
K-5	35.51	12.8±2.9	135±23	IMB-5	42.92	36±9	33±15
K-6	35.69	6.3±1.7	68±77	IMB-6	44.06	36±6	51±10
K-7	36.54	35.4±8.0	32±16	IMB-7	46.38	19±5	42±20
K-8	36.73	21.0±4.2	30±18	IMB-8	46.96	22±5	104±20
K-9	36.92	19.8±3.2	38±22				
K-10	44.22	8.6±2.7	122±30				
K-11	45.43	13.0±2.6	49±26				
K-12	47.44	8.9±1.9	91±39				

Supernova 1987A
(4) Measured Energy Spectrum



Supernova 1987A
(5) What were learned ?

- about 600 scientific articles published (of all topics)

- Pre-existing calculations were in quite good agreement with the observed neutrino burst

- Quite low statistics, and only $\bar{\nu}_{\mathrm{e}}$ were detected
  ☞ important aspects of the theory could not be tested, for example, most of the energy is believed to be emitted in higher-temperature muon and tau neutrinos (and anti-neutrinos)

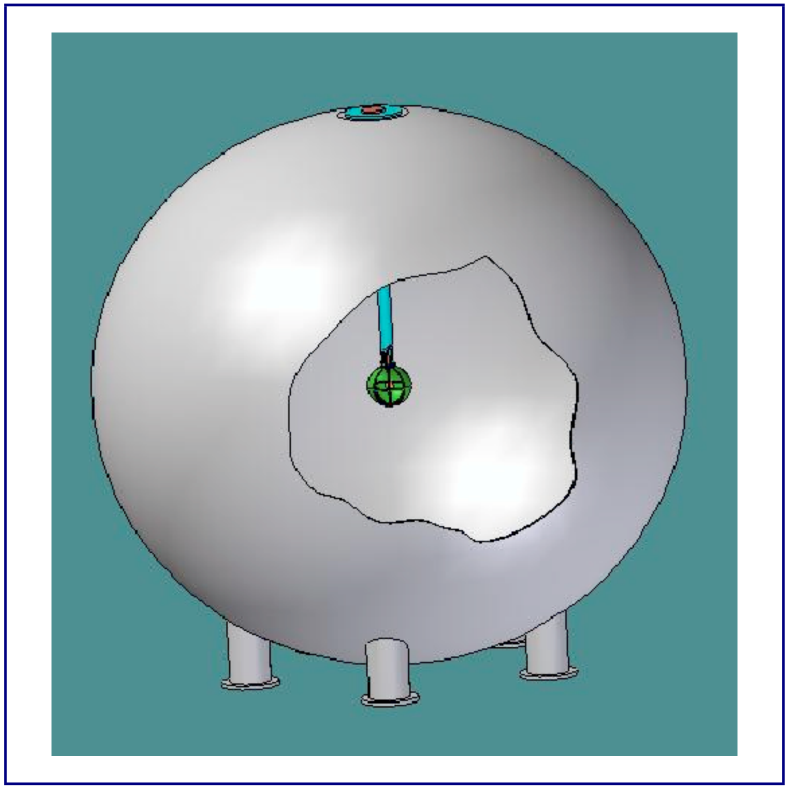
- New limits were obtained, for example, on the mass, charge, magnetic moment, decay rate, limiting velocity

  ☞ $\mathrm{m}(\bar{\nu}_{\mathrm{e}}) \leq 15 \sim 30$ eV

Supernova Neutrinos

A Spherical TPC Detector for Supernova Neutrino Observation

Experimental Setup



Idea of Yannis Giomataris (Saclay) et al.

- arXiv:hep-ex/0503029: A network of neutral current spherical TPC's for dedicated supernova detector
- developed from the NOSTOS proposal: NIMA 530 (2004) 330

High-pressure (10 bar Xe, 30–60 bar Ar) diameter 4–6 metres, Micromegas for readout

One possible site of the network: Pyhäsalmi Mine (660-level)

Neutrino coherent scattering ☞

+ large cross section: $\sigma(E_\nu) \approx 10^{-38}$ cm^2 MeV^{-2} at $E_\nu = 20$ MeV, xenon
– challence to measure low-energy recoil (for Xe $\sim$7 keV in average)

Supernova Neutrino Events
a simple estimation (1)

- Supernova neutrino spectrum:

$$f_\nu(E_\nu) = \frac{1}{T_\nu^3 F_2(\eta)} \frac{E_\nu^2}{\exp\{E_\nu/T_\nu - \eta\} + 1}$$

$(T_\nu, \eta) = (4,0), (5,0), (8,0)$ for ν_e, $\bar{\nu}_e$, ν_x.

- Luminosity at the Earth:

$$L_\nu = \frac{1}{4\pi D^2} \frac{W_\nu}{< E_\nu >}$$

$W_\nu = 2 \times 10^{59}$ MeV (total), $<E_\nu> = T_\nu \ F_3(\eta) \ / \ F_2(\eta)$, $D = 10$ kpc.

- Cross section:

$$\sigma(E_\nu) = C \times N_n^2 \times E_\nu^2, \quad C \approx 4.242 \times 10^{-45} \ \mathrm{cm}^2 \ \mathrm{MeV}^{-2}$$

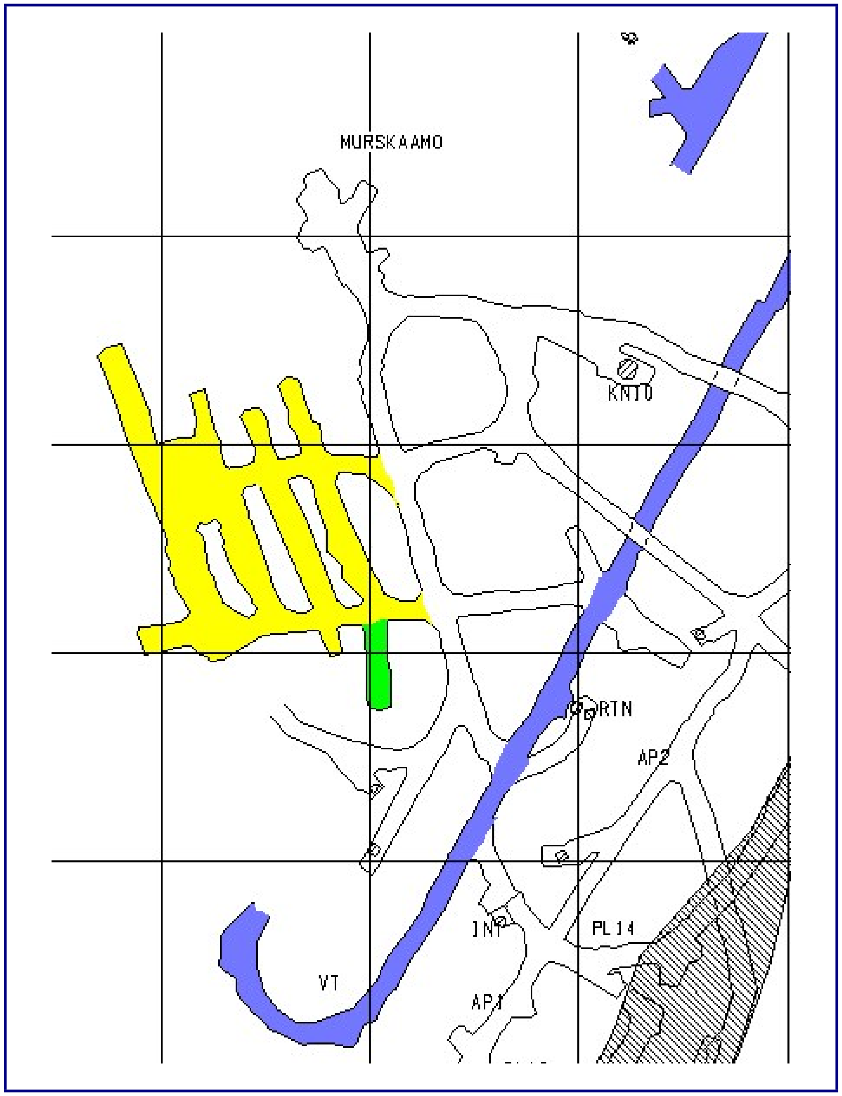
Supernova Neutrino Events
a simple estimation (2)

- Number of events:

$$N_\nu = N_{at} \int L_\nu \times f_\nu(E_\nu) \times \sigma(E_\nu)\, dE_\nu$$

- Integration (for xenon): $N_{\nu_e} = 10$, $N_{\bar{\nu}_e} = 15$, $N_{\nu_x} = 70$ (total = 95).
  For argon, factor 12 smaller (total = 8).
- No oscillations assumed.
- Ideal detector (no energy threshold, no quenching, ...).
- Detector: $\Phi = 4$ m, p = 10 atm.
- N_{at} is number of atoms.

Layout of 660-level



- The Depth of 660 metres corresponds to 1900 m.w.e
- Available space for experiments (yellow)
  ☞ largest area $\sim$ 30 m $\times$ 10 m $\times$ 8 m
- Old lunch room (green area)
- Muon flux measured close to lunch room:
  ☞ $\Phi_\mu = (3.2 \pm 0.3) \times 10^{-3}$ m^{-2}s^{-1}

Number of muons crossing an area of 12 m^2 in 20 sec: $\mathbf{N_\mu = 0.8}$