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lecture cource on

Astroparticle physics

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1.5 Cosmic-ray sources

Sources, acceleration mechanisms, propagation, ...

- The origin of cosmic rays is one of the major unsolved astrophysical problem
- Candidate (or possible) sites for cosmic-ray production and/or acceleration
  - supernova explosions (shock front)
  - neutron stars (pulsars)
  - accreting black holes (or other binary systems)
  - centres of active galactic nuclei (AGN)
  - "external acceleration" in the interstellar or intergalactic medium (extensive magnetic gas clouds)
  - decay of relics of Big Bang (topological defects, domain walls or cosmic strings) [top-down models]
- Large number of models for cosmic-ray acceleration have been developed
  - actual acceleration mechanisms are not completely understood and identified
  - it is also possible that various mechanisms together produce cosmic rays of different energies

1.5 Cosmic-ray sources – shock acceleration

Supernova explosion

- Supernova explosion produces elements up to iron (Z=26)
  - can also include $_{27}$Co and $_{28}$Ni
- Estimation for the maximum energy of cosmic rays by supernova explosion (Greisen, chapter 11)

$$\mathrm{E}_{\mathrm{max}} \leq \frac{3}{20} \cdot \frac{u}{c} \cdot Ze \cdot B \cdot (uT_A)$$

For 10 $\mathrm{M}_{\mathrm{SUN}}$ ejected at $5{\times}10^8$ cm/s into the nominal ISM with 1 proton per cm^3, and assuming $T_A \sim 1000$ years and $B_{\mathrm{ISM}} \sim 3\ \mu\mathrm{G}$

$$\mathrm{E}_{\mathrm{max}} \leq Z \cdot 3 \times 10^4 \quad \mathrm{GeV} \qquad (*)$$

$Z = 1$ (p) : $\mathrm{E}_{\mathrm{max}} \approx 30$ TeV
$Z = 26$ (Fe) : $\mathrm{E}_{\mathrm{max}} \approx 1000$ TeV $= 1$ PeV

1.5 Cosmic-ray sources – shock acceleration

Supernova explosion

- The equation (*) "holds" for an average SN explosion, but includes large uncertainties and oversimplifications
- Some other models or estimations suggest slightly higher maximum energies
  - A good round number to be used as the maximum energy for cosmic-ray acceleration by supernova explosions (shock waves) is

$$E_{max} \sim 100 \text{ TeV}$$

- Conclusion: The equation (*), particle acceleration at supernova shock waves, would account for the origin of the bulk of cosmic rays
- Then, how to accelerate energies greater than $\sim$100 TeV (i.e. above the knee region)?

1.5 Cosmic-ray sources

Acceleration to 100 TeV and higher

- The equation

$$E_{\mathrm{max}} \leq \frac{3}{20} \cdot \frac{u}{c} \cdot Ze \cdot B \cdot (uT_A)$$

  does not explain origin of cosmic rays with energies greater than $\sim$100 TeV
- Higher energies can be obtained (still in SN explosions) by the same equation
  - by increasing the magnetic field (strength and/or orientation)
  - by increasing the time-scale of the acceleration
- Some other acceletarion mechanisms may also be active in the galaxy
  - below 10^{18}–10^{19} eV : galactic origin
  - above 10^{18}–10^{19} eV : extragalactic origin

1.5 Cosmic-ray sources – diffuse sources

Supernova shock waves

- Supernova explosion shock wave mechanism may itself accelerate particles at higher energies
  ☞ Not always average explosion or interstellar medium
  - magnetic field strength and orientation
  - environment
- Magnetic field orientation
  By having B perpendicular instead of parallel (to the direction of propagation of the shock front)
  ☞ increase the B (and E_{max}) by a factor of 10 or more
- Environment
  SN1987A: exploded into an "enriched" environment (riched by its progenitor)
  ☞ E_{max} could be higher by 1–2 order of magnitudes
- In total: $E_{max} \sim 10$ PeV

1.5 Cosmic-ray sources – new supernova remnants

Neutron stars (pulsars)

- Pulsars and X-ray binaries in young supernovae have one advantage over the supernova shock waves
  - magnetic field much higher around the collapsed object than in the interstellar medium
- Accelation powered by the rotational energy

$$E_{max} \approx \frac{e \cdot B \cdot R^3 \cdot \Omega^2}{\sqrt{3} \cdot c^2}$$

  where B is the magnetic field strength, R the radius and Ω the angular frequency of the neutron star
- Typical 10-ms pulsar with a 10^{12} G surface magnetic field

$$E_{max} \sim 10^5 \text{ TeV} = 100 \text{ PeV} \quad (10^{17} \text{ eV})$$

2 Astroparticle physics experiments

Past, currend and future experiments

2.0 Why deep underground ?

Study of rare phenomenom

A signal in large detector once per week ... once a month ... once per year ...

- neutrinos (several sources)
- dark matter, matter unstability

The μ-flux from cosmic rays at the surface is: $\Phi \sim 150\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$

☞ **background and noise**

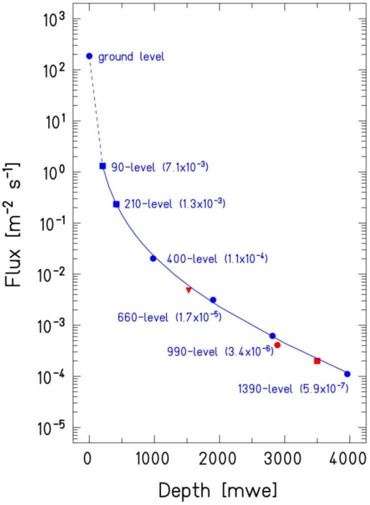
Muons can penetrate deep underground

- 660-level: $\sim 10\ \mu\ \mathrm{m}^{-2}\ \mathrm{h}^{-1}$
- 1390-level: $\sim 0.5\ \mu\ \mathrm{m}^{-2}\ \mathrm{h}^{-1}$

The depth is often expressed as water-metre-equivalent (mwe):

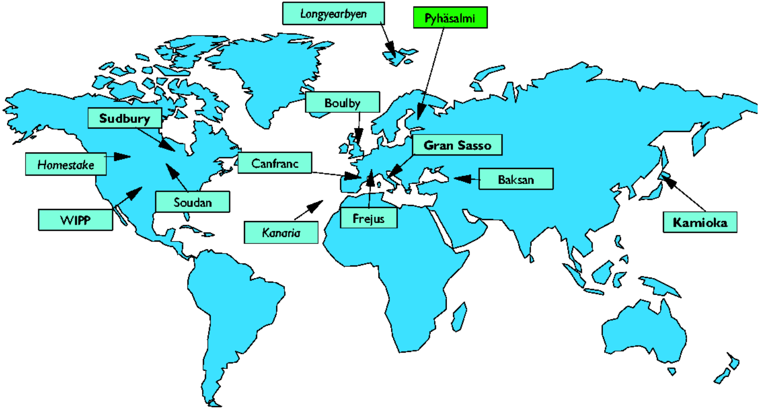
mwe = verical depth [m] $\times$ rock density [g/cm^3]

(Pyhäsalmi: $1400 \times 2.85 \Longleftrightarrow 4000$ mwe)



2.0 World's Underground Laboratories

mines and tunnels



The three largest underground laboratories at the moment are **Sudbury** (Canada), **Kamioka** (Japan) and **Gran Sasso** (Italy)

2.1 The chlorine experiment

(Homestake experiment) by Raymond Davis, Jr.

- The start of a new field in which neutrinos were used to study the inner part of the sun
- Purpose
  - to confirm the fusion theory of solar power generation (Standard Solar Model – SSM – by John N. Bahcall) by measuring solar neutrinos (ν_e)
- Constructed at the late 1960's (lead by Raymond Davis, Jr.)
  - Homestake gold mine, South Dakota, US
  - depth 4850 feet (4100 mwe)
  - tank 48 feet long $\times$ 20 feet diameter, 3.8×10^5 ℓ
- 615 tons of perchloroethylene (C_2Cl_4)
  - cleaning liquid (easy to obtain, not expensive, good chemical properties)
  - number of ^{37}Cl atoms: 2.16×10^{30}
- Detected ν_e by a radiochemical method
  - $\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$, $\qquad E_{thr} = 0.8$ MeV, $t_{1/2} = 35$ days

2.1 The chlorine experiment

And the solar neutrino problem

- Neutrino sensitivity: ^{7}Be, ^{8}B
- Operated continuously 1970–1994

- Expectations
  - prediction (by SSM): one ^{37}Ar atom observed per day
  - observation: one atom per 2.5 days
- **Solar neutrino problem**

- Several experiments (with various techniques) could not solve the problem for $\sim$30 years
- In 2002, SNO in Sudbury, Canada $\Longrightarrow$ neutrino oscillation

- In 2002, the Nobel price for Raymond Davis, Jr. (and Masatoshi Koshiba)

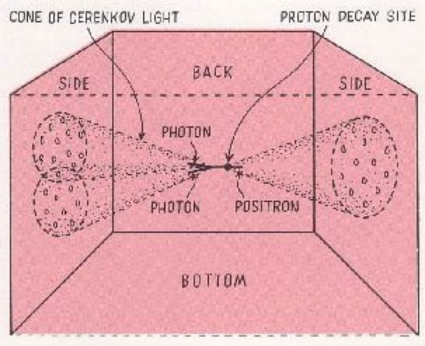
2.2 The IMB detector

Irvine–Michigan–Brookhaven

- Operated from early 1980's to early 1990's
- University of California (Irvine), University of Michigan, Brookhaven National Laboratory
- Morton salt mine, Mentor, Ohio, on the shore of Lake Erie
  - depth 1900 feet (∼550 m)
- Aim to observe the proton decay
  "Are diamonds really forever?
  An experiment to determine the ultimate stability of matter"
  - the first experiment dedicated to the proton decay
- Tank dimensions: 17 m × 17.5 m × 23 m (∼cubic)
  - muon rate: $R_\mu \approx 3$ Hz
- Filled with ultrapure H_2O of 2.5×10^6 gallons (≈10 milj. litres)
  - $\sim10^{31}$ protons

2.2 The IMB detector

Irvine–Michigan–Brookhaven



- Water Cherenkov detector
  - filled with 2048 PMTs
- Decay channel:
  - $p \longrightarrow \pi^0 + e^+$
    $\longrightarrow \gamma + \gamma + e^+$

- Did not observed any proton decays, but
  Observed signal of 8 neutrinos from the supernova SN1987A
  (more details next week)

2.3 Japanese experiments

Kamioka mine

- Kamioka mine at Japanese Alps
- Depth 1 km (2700 mwe)
- Horizontal

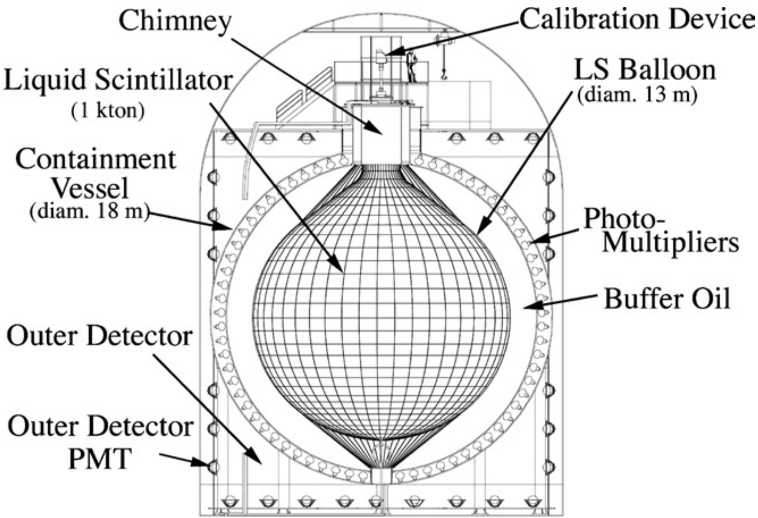
- KamLAND – Kamioka Liquid Scintillator Antineutrino Detector
  - 1000 tons
  - Measures antineutrinos from 53 surrounded nuclear power plants
  - The first detector (and only so far) that have been observed geologically produced antineutrinos, geoneutrinos

- KamiokaNDE $\longrightarrow$ KamiokaNDE II $\longrightarrow$ Super–K
  Kamioka Nucleon Decay Experiment
  - Designed for proton decay, solar and atmospheric neutrinos
  - 50 kton of ultra-pure water
  - $\sim$12000 20-inch PMTs

  $\longrightarrow$ Hyper-K

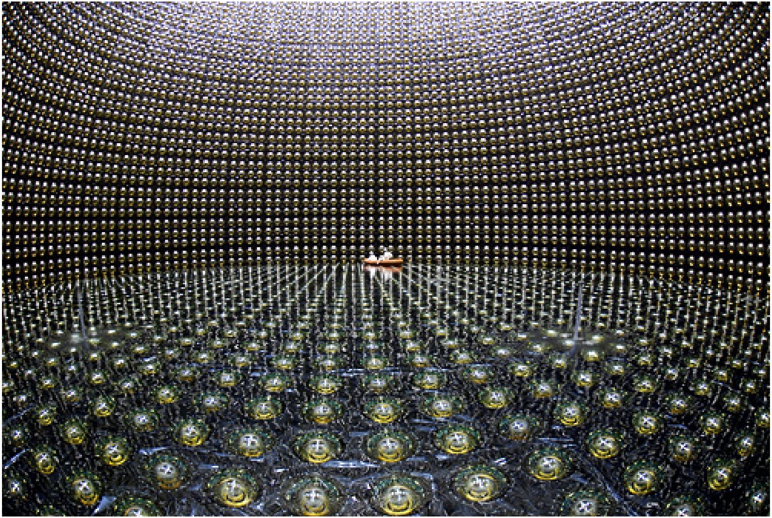
2.3 Japanese experiments

KamLAND



2.3 Japanese experiments

Super-K



2.4 SNO and Borexino

Solar neutrino experiments

- SNO – Sudbury Neutrino Observatory (Depth 2 km)
- First years filled with H_2O, then D_2O (solved the solar neutrino problem) and now being filled with liquid scintillation material

- Borexino is liquid scintillation detector is Gran Sasso, Italy
- Mass 300 tons
- Solar neutrino spectroscopy

- More details about the both detectors and their results next week

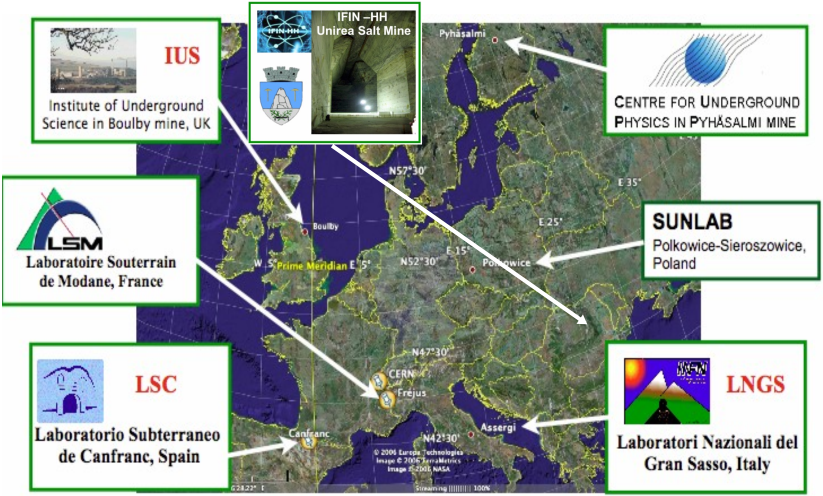
2.5 LAGUNA – future experiments

Large Apparatus for Grand Unification and Neutrino astrophysics – 1

- Project for a Design Study at EU 7th Framework Programme
  - infrastructure study, 2 years (01.07.2008 – 30.06.2010)
  - funding of 1.7 million euros
  - coordinated by André Rubbia, ETH Zürich
- $\sim$20 institutes and industrial partners from $\sim$10 countries
  - almost 100 physicists (new persons can still join in)
  - university of Oulu and Jyväskylä, and Kalliosuunnittelu Oy Rockplan Ltd (Helsinki) from Finland
- Includes three large-scale detectors
  - MEMPHYS – MEgaton Mass PHYSics
  - GLACIER – Giant Liquid Argon Charge Imaging ExpeRiment
  - LENA – Low Energy Neutrino Astrophysics
- Seven possible sites in Europe ☞
  - Boulby, Canfranc, Fréjus, Pyhäsalmi, Slanic, SUNlab, Umbria

2.5 LAGUNA – future experiments

Seven possible sites: Boulby (UK), Canfranc (Spain), Fréjus (France), Regione Umbria (Italy), Pyhäsalmi (Finland), Slanic (Romania), SUNlab (Poland)



2.5 LAGUNA – future experiments

Large Apparatus for Grand Unification and Neutrino Astrophysics – 2

- Physics goals
  - neutrino physics
    supernova neutrinos (diffuse and galactic), solar neutrinos, atmospheric neutrinos, reactor neutrinos, geoneutrinos
  - proton decay
  - dark matter
- JCAP 11 (2007) 011 : Large underground, liquid-based detectors for astro-particle physics in Europe: scientific case and prospects (arXiv:0705.0116v2 [hep-ph])
- Expected detector life-time 30–50 years
- Output of the DS
  - a common proposal at 2010 for the realisation of one or more of the detectors

2.5 LAGUNA – future experiments

Detector options

MEMPHYS – MEgaton Mass PHYSics

- water Cherenkov detector
- requires depth of 1200 m of rock (or more)
- preferred site Fréjus, France

GLACIER – Giant Liquid Argon Charge Imaging ExpeRiment

- liquid argon detector
- depth of $\sim$300 m of rock (or more)
- all sites possible

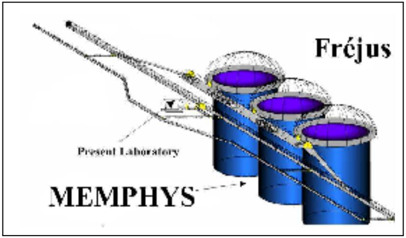
LENA – Low Energy Neutrino Astrophysics

- liquid scintillation detector
- requires depth of 1400 m of rock (or more)
- preferred site Pyhäsalmi, Finland

2.5 LAGUNA – MEMPHYS

MEgaton Mass PHYSics

- French initiative



- water cherenkov of 400–1000 kton
- Extrapolation of Super-Kamiokande (50 kton)

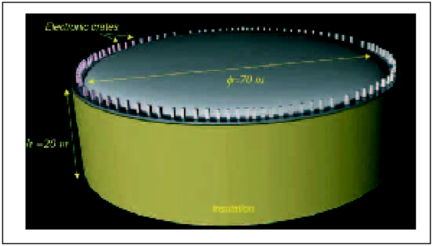
- Requires depth of 1200 m of rock (or more)
- A pre-feasibility study for the Fréjus site
  - several 200 kton tanks
  - up to 5 shafts possible
- Similar ideas elsewhere
  - UNO at USA
  - Hyper-Kamiokande at Japan

2.5 LAGUNA – GLACIER

Giant Liquid Argon Charge Imaging ExpeRiment

▶ Proposed by ETH Zürich (André Rubbia *et al.*)

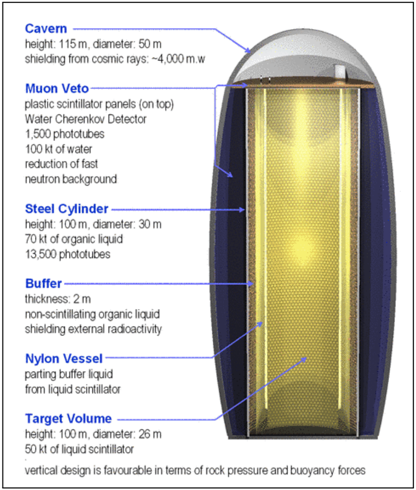
- Optimal size 100 kton
- Technology previously applied in ICARUS (at Gran Sasso)
- Tracking detector, good energy resolution
  - Depth ∼300 m of rock or more
- Versatile for a large energy range above 5 MeV



2.5 LAGUNA – LENA

Low Energy Neutrino Astrophysics

- Proposed by TU Munich (Franz von Feilitzsch *et al.*)



- Liquid scintillator of 50 kton
- Experience from Borexino (∼300 ton, at Gran Sasso)
- Requires
  - depth of 1400 m of rock
  - low reactor-neutrino flux
- A pre-feasibility study completed by Rockplan Ltd for Pyhäsalmi
  - funded by TU Munich
- Price tag 300–400 million euros (infra 10–15 %)
- Able to detect antineutrinos from the Earth (geoneutrinos)

2.5 LAGUNA – Physics

Proton decay in the LENA detector

- Proton decay predicted by Grand Unified Theories (GUT)
- The current limit for τ_p from SuperK: $\tau_\mathrm{p} = 2.3\times10^{33}$ y
  - to observe 1 proton decay with $\tau_\mathrm{p} = 2.3\times10^{33}$ y per year, number of atoms in a detector should be 2.3×10^{33} ($\longrightarrow \sim$5 kton)
- In LENA, the proton decay would be observed via $\mathrm{p} \longrightarrow \mathrm{K}^+ + \bar{\nu}$
  - $\mathrm{K}^+ \longrightarrow \mu^+ + \bar{\nu}_\mu$ (63 %), $\quad \tau_\mathrm{K} = 12.8$ ns
    $\longrightarrow \pi^0 + \pi^+$ (21 %)

    ☞ clear double-peak structure from kaon and its decay $\sim$257 MeV (K+μ) and $\sim$459 MeV (K+π)
  - decay channel favoured in many Supersymmetric theories
  - LENA would see 40 proton-decay events in 10 years with 1 background event†

    † [see: T. Marrodán Undagoitia *et al.*, Phys. Rev. D 72 (2005) 075014]
- If no event is seen in 10 years ☞ $\tau_\mathrm{p} > 4\times10^{34}$ y

2.5 LAGUNA – Physics

Supernova neutrinos

Explosion of a heavy star (over 8 M_{SUN})

- ☞ no more nuclear fuel to burn
- ☞ rate: 1 – 3 per century in our galaxy

The brightest object at the sky, even the largest mount (99%) of the energy is released by neutrinos

SN produces heavy elements

- ☞ nuclear reactions $\longrightarrow$ iron
- ☞ supernova $\longrightarrow$ uranium

Neutrino pulse can be observed with sensitive detectors

- ☞ it takes approximately 20 seconds
- ☞ arrives before light
- ☞ information on both SN and SN-ν

One SN-ν pulse is observed:
SN1987A – 19 observed neurinos

- ☞ the birth of neutriino astronomy

LENA at Pyhäsalmi would observe several thousends SN-ν events

2.5 LAGUNA – Physics

Supernova neutrino detection in LENA

Assuming a star of $8\times M_{sun}$ (3×10^{53} erg) at D = 10 kpc

☞ In LENA detector ∼15000 events†

- $\bar{\nu}_e + p \rightarrow n + e^+$; $n + p \rightarrow d + \gamma$ ∼7500 – 13800
- $\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$; ${}^{12}B \rightarrow {}^{12}C + e^- + \bar{\nu}_e$ ∼150 – 610
- $\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$; ${}^{12}N \rightarrow {}^{12}C + e^+ + \nu_e$ ∼200 – 690
- $\nu_x + {}^{12}C \rightarrow {}^{12}C^* + \nu_x$; ${}^{12}C^* \rightarrow {}^{12}C + \gamma$ ∼680 – 2070
- $\nu_x + e^- \rightarrow \nu_x + e^-$ (elastic scattering) ∼680
- $\nu_x + p \rightarrow \nu_x + p$ (elastic scattering) ∼1500 – 5700

† [Teresa Marrodán at NNN08, Paris]

2.5 LAGUNA – Physics

Geoneutrino detection with the LENA detector

- Neutrinos from radioactive decay from the Earth
- Detection via inverse β-decay ($\bar{\nu}_e + \mathrm{p} \longrightarrow \mathrm{n} + \mathrm{e}^+$)
  - ☞ LENA at Pyhäsalmi: ~1000 events/year†
  - ☞ main background from nuclear-reactor neutrinos
  - ☞ Pyhäsalmi favourable site due to low background
- Purposes
  - ☞ Measurement of radiogenic contribution to terrestial heat (~40 TW)
  - ☞ Test of assumptions (models) for the composition of crust, mantle and core
- The interior of the Sun is known much better than the interior of the Earth!

† [see: Kathrin A. Hochmuth *et al.*, Astropart. Phys. 27 (2007) 21–29]

2.5 LAGUNA – future experiments

Conclusions

- LAGUNA Design Study ends at autumn 2010
  ☞ proposal for the site(s) and detector type(s)
  ☞ it is very probable that one detector will be built after the DS finished
- New large-volume detectors would provide a versatile physics programme
- No infrastructure exists for future large-scale detectors
- Finland has excellent possibilities to host a new large-scale underground facility
  - Pyhäsalmi mine in Pyhäjärvi
  - Pre-feasibility study done by Rockplan Ltd
- US and Japan: UNO and Hyper-K