Astroparticle Physics in the Pyhäsalmi Mine

– high-energy cosmic rays (EMMA)
– $^{14}\text{C}/^{12}\text{C}$ experiment
– Laguna

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EMMA

Experiment with MultiMuon Array

Cosmic-ray composition between $10^{15}$ eV and $10^{16}$ eV (the knee region)
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EMMA – the knee

Equivalent c.m. energy $s_{pp}$ (GeV)

Scaled flux $E^{2.5} J(E)$ (m$^2$ sec$^{-1}$ sr$^{-1}$ eV$^{1.5}$)

Energy (eV/particle)

- ATIC
- PROTON
- RUNJOB
- KASCADE (QGSJET 01)
- KASCADE (SIBYLL 2.1)
- KASCADE-Grande (prel.)
- Akeno
- HiRes-MIA
- HiRes I
- HiRes II
- AGASA
- Auger 2007

NuPECC, JYFL, June 13, 2014 – 3/29 –
At high energies (at and above the knee) direct measurements not possible due to small flux

Indirect method: air shower

- large-area arrays at the ground measuring electrons and muons
- interactions at the atmosphere: fluorescence light, radio waves ($\sim$ankle)

Number of particles and their distribution at the ground depend on the primary cosmic-ray mass and energy

- the heavier and energetic particle, the more massive and wider spread air shower
- fluctuations quite large
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EMMA – The method (muon energy cut-off 50 GeV (or 75 m of rock))

![Graph showing muon density vs distance from core for different energies and particle types.](image-url)
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EMMA – 11 detector stations

Tracking station
Sampling station

10 m
75 m
45 m
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EMMA – DAQ running in 6 stations
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EMMA – Stations C, F ja G

**Cavern properties**
- pH ~ 3 (water)
- rel. hum. ~ 100%
- T ~ 10 °C

**Inside stations**
- rel. hum. ~ 40–60 %
- T ~ 20 °C

Good conditions
Cavern properties

pH $\sim$ 3 (water)
rel. hum. $\sim$ 100%
$T \sim$ 10 $^\circ$C
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EMMA – Tracks of muons, example 1

Number of tracks = 16
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EMMA – Tracks of muons, example 2

Station F

Station C
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EMMA – Tracks of muons, example 3

Station G

Station C

Station F

Station E
Simulations with CORSIKA+QGSJET01 for proton and iron, assuming spectral index as -2.7 for E<3 PeV and -3.1 for E>3 PeV.

The proton curve is normalised to the data at $N_{\text{tracks}}=5$, and the iron curve with the proton.
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EMMA – Collaboration

▶ University of Oulu
  ▶ Timo Enqvist,
    Jari Joutsenvaara,
    Pasi Kuusiniemi,
    Juho Sarkamo,
    Antto Virkajärvi

▶ University of Jyväskylä
  ▶ Kai Loo,
    Maciej Slupecki,
    Wladek Trzaska

▶ Russian Academy of Sciences
  ▶ Leonid Bezrukov, Bayarto Lubsandorzhiev, Valery Petkov

▶ Moscow Institute of Physics and Technology: Lev Inzhechik

▶ University of Aarhus: Hans Fynbo
Measurement of $^{14}\text{C}/^{12}\text{C}$ ratio in liquid scintillator
The aim is to find out such a liquid scintillator sample in which the content of $^{14}\text{C}$ is as small as possible.

$^{14}\text{C}/^{12}\text{C} < 10^{-18}$

Motivations

- detector development (JUNO, LENA)
  - Solar pp-$\nu$ observation in large detectors (>1 kton)
- the first experiment in the Pyhäsalmi mine that requires very low background

Starts in the end of 2014

- background (radon) measurements during summer
- delivery of copper shielding (bricks) during summer
- in the Laguna-cavern (depth of 1400 m, or 4000 mwe)
Radiation shielding

- ~3–4 tons of Cu
- ~2–3 tons of Pb
- nitrogen flux

In addition,

- parafin ~20 cm
- muon veto
- pulse digitalization
- ...
- ...

liquids, light guides and PMTs from Russia (RAS/INR in Moscow)
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$^{14}$C experiment – Solar neutrinos

**pp:**
\[ p^+ + p^+ \rightarrow 2\text{H} + e^+ + \nu_e \]

**pp:**
\[ p^+ + e^- + p^+ \rightarrow 2\text{H} + \nu_e \]

**pp:**
\[ 2\text{H} + p^+ \rightarrow 3\text{He} + \gamma \]

**pep:**
\[ p^+ + e^- + p^+ \rightarrow 2\text{H} + \nu_e \]

**hep:**
\[ 3\text{He} + p^+ \rightarrow 4\text{He} + e^+ + \nu_e \]

**pp:**
\[ 3\text{He} + 4\text{He} \rightarrow 7\text{Be} + \gamma \]

**pp:**
\[ 7\text{Be} + e^- \rightarrow 7\text{Li} + \nu_e \]

**ppI:**
\[ 3\text{He} + 3\text{He} \rightarrow 4\text{He} + 2p^+ \]

**pp:**
\[ 7\text{Be} + p^+ \rightarrow 8\text{B} + \gamma \]

**ppII:**
\[ 7\text{Li} + p^+ \rightarrow 4\text{He} + 4\text{He} \]

**ppII:**
\[ 7\text{Be} + p^+ \rightarrow 8\text{B} + \gamma \]

**ppIII:**
\[ 8\text{B} \rightarrow 8\text{Be}^* + e^+ + \nu_e \]

**ppII:**
\[ 8\text{Be}^* \rightarrow 4\text{He} + 4\text{He} \]
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$^{14}$C experiment – Solar neutrino spectrum
In Borexino $^{14}\text{C} / ^{12}\text{C} \approx 2 \times 10^{-18}$
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$^{14}$C experiment – Collaboration

- University of Oulu
  - Timo Enqvist,
  - Johannes Hissa,
  - Jari Joutsenvaara,
  - Pasi Kuusiniemi,
  - Juho Sarkamo,
  - Antto Virkajärvi

- University of Jyväskylä
  - Kai Loo,
  - Maciej Slupecki,
  - Wladek Trzaska

- Russian Academy of Sciences
  - Leonid Bezrukov, Bayarto Lubsandorzhiev

- Moscow Institute of Physics and Technology
  - Lev Inzhechik
LAGUNA
Large Apparatus for Grand Unification and Neutrino Astrophysics

and

LAGUNA–LBNO
– Long Baseline Neutrino Oscillations
Two EU-FP7 Design Studies

LAGUNA – Large Apparatus for Grand Unification and Neutrino Astrophysics

- seven possible sites in Europe
- three large detector options (WCH, LAR, LSC)
- 01.09.2008 – 31.08.2011, funding 1.7 M€ (FP7)
- technical questions and site selection

LAGUNA–LBNO – ... – Long Baseline Neutrino Oscillations

- two sites: Fréjus (France) and Pyhäsalmi (Finland)
- detectors: WCH in Fréjus, LAR and LSC in Pyhäsalmi
- 01.09.2011 – 31.08.2014, funding 4.9 M€ (FP7)
- detailed (infrastructure & physics) study

The last meeting in Hanasaari, Espoo, end of August

- release of all the results
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LAGUNA–LBNO – Consortium

13 countries, 45 institutions, ~300 members

France
CEA
CNRS-IN2P3
Sofregaz*

Germany
TU Munich
University Hamburg
Max-Planck-Gesellschaft
Aachen(**)
University Tübingen(**)

Spain
LSC
UA Madrid
CSIC/IFIC
ACCIONA*

Romania
IFIN-HH
Bucharest

Denmark
Aahurs(***)

Italy
AGT*

United Kingdom
Imperial College London
Durham
Oxford
QMUL
Liverpool
Sheffield
RAL
Warwick
Technodyne Ltd*
Alan Auld Ltd*
Ryhal Engineering*

Poland
IFJ PAN
IPJ
University Silesia
Wroclaw UT
KGHM CUPRUM*

CERN

Switzerland
University Bern
University Geneva
ETH Zürich
Lombardi Engineering*

Finland
University Jyväskylä
University Helsinki
University Oulu
Rockplan Oy Ltd*

Greece
Demokritos

(*)=industrial partners
(**)=associated
Astroparticle Physics in Pyhäskalmi

LAGUNA-LBNO – Three options – GLACIER, LENA and MEMPHYS

- **Cavern**
  - height: 115 m, diameter: 50 m
  - shielding from cosmic rays: ~4,000 m.w.

- **Muon Veto**
  - plastic scintillator panels (on top)
  - Water Cherenkov Detector
  - 1,500 phototubes
  - 100 kt of water
  - reduction of fast neutron background

- **Steel Cylinder**
  - height: 100 m, diameter: 30 m
  - 70 kt of organic liquid
  - 13,500 phototubes

- **Buffer**
  - thickness: 2 m
  - non-scintillating organic liquid
  - shielding external radioactivity

- **Nylon Vessel**
  - parting buffer liquid from liquid scintillator

- **Target Volume**
  - height: 100 m, diameter: 26 m
  - 50 kt of liquid scintillator
  - vertical design is favourable in terms of rock pressure and buoyancy forces

- **LENA** (50 kton)
- **MEMPHYS** (600–1000 kton)
- **GLACIER** (100 kton)
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LAGUNA-LBNO – Current status

- GLACIER (LAr) and/or LENA (LSC) in Pyhäsalmi, both at 1400 metres
  - LENA – one 50 kton tank
  - GLACIER – two 50 kton tanks

- To start with
  - LAr Demo of 1 kton in CERN (WA105)
  - LAr Pilot of 2.4 kton ($\times 2$) in Pyhäsalmi
Seven new drill holes, in total \(\sim 3.5\) km
- to ensure exact geotechnical properties
- to find possible weaker zones

Funding \(\sim 1.6M\) euros

In addition, 2 km of old drill holes currently analysed

All drillings done, analysis nearly done, report ready in fall 2014

A large weaker zone found, otherwise excellent rock
Astroparticle Physics in Pyhäsalmi
LAGUNA – physics topics

▶ LAGUNA (without an accelerator)
  ▶ Proton decay (GUTs, $\sim 10^{35}$ a), stability of matter
  ▶ Supernova neutrinos (3–6 SN/100 a), explosion mechanism
  ▶ Solar neutrinos, spectroscopy, metallicity
  ▶ Diffuse supernova neutrinos, stars birth rate
  ▶ Geo-neutrinos, the Earth interior

▶ LAGUNA–LBNO (with an accelerator)
  ▶ $\Theta_{13}$, $\nu$-mass hierarchy, neutrino properties
  ▶ CP-violation, asymmetry of matter and anti-matter

▶ Other topics (underground, non-LAGUNA)
  ▶ Search for dark matter (LAGUNA indirectly)
  ▶ Double-beta decay, neutrino mass
Astroparticle Physics in Pyhäsalmi
LAGUNA – Finnish participants

- University of Oulu
  - Timo Enqvist, Johannes Hissa
- University of Jyväskylä
  - Kai Loo, Jukka Maalampi, Wladek Trzaska
- University of Helsinki
  - Katri Huitu, Kari Rummukainen
- RockPlan Ltd, Helsinki
  - Guido Nuijten, Jarmo Roinisto and several others

- Site Investigations
  - Marko Aittola (University of Oulu)
EXTRAS
Former muon detectors from the DELPHI experiment at LEP (at CERN)

- a plank – 7 individual chambers
- mass 120 kg per plank
- chamber: 365 cm × 20 cm
- 3 signals per chamber

In total 84 planks (~250 m²)

- form the basis of the array

Position resolution is good: ~1 cm²

- needed by tracking

Ar (92%) : CO₂ (8%) at 1 bar

- min ~0.25 bar·ℓ/min /4 planks
SC16 detector
- $50 \times 50 \text{ cm}^2$, $H = 13 \text{ cm}$
- mass $\sim 20 \text{ kg per SC16}$
- 16 individual pixels of $12 \times 12 \text{ cm}^2 \times 3 \text{ cm}$ pixels
- APD light collection
- time resolution good: $\sim 1 \text{ ns}$

In total 96 SC16-detectors ($24 \text{ m}^2$), 1536 individual pixels

Designed especially for
- large muon multiplicities
- fast trigger
- initial guest for the arrival angle

Made by Russian Academy of Sciences
Astroparticle Physics in Pyhäsaalmi

EMMA – Limited Streamer Tube (LST) detectors

- Muon detectors of KASCADE–Grande experiment (Karlsruhe)
- To be used as the second detector layer at the edge of the array and at 45-level
- Arrived in Pyhäsaalmi at the end of May, 2012, to be done
  - read-out electronics and software
  - HV power supplied
- 60 LST modules
  - $\sim 180 \text{ m}^2$
- Properties
  - $2.9 \text{ m } \times 1.0 \text{ m}$
  - pixel size (PAD): $2 \text{ cm } \times 8 \text{ cm}$
  - gas: $\text{CO}_2$ at 1 bar
Total flux $\sim 7 \ell/\text{min} \ (\text{Ar:CO}_2, \ 92:8)$
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EMMA – gas handling
Ar (92%) from 600 ℓ dewar (LAr)
CO₂ (8%) from 30 kg bottle
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$^{14}\text{C} / ^{12}\text{C} \sim 10^{-18}$

$^{14}\text{C}$ experiment – Borexino, Gran Sasso

Scintillator
270 t PC+PPO (1.5 g/l)
contained in the
Inner Nylon Vessel
$R = 4.25 \text{ m}, 150 \text{ mm thick}$

Buffer Region
PC+DMP (5 g/l)
$4.25 \text{ m} < R < 6.75 \text{ m}$

Outer Nylon Vessel
$R = 5.50 \text{ m}$
($^{222}\text{Rn}$ barrier)

Steel Sphere
$R = 6.75 \text{ m}$
2212 PMTs
$1350 \text{ m}^3$

Water Tank
$\gamma$ and n shield
208 PMTs serve as Cherenkov
Muon Veto
$2100 \text{ m}^3$

Carbon Steel Plates

20 steel legs
Astroparticle Physics in Pyhäsalmi

LAr Demo at CERN – $6 \times 6 \times 6 \, m^3 \, (\sim 1 \, \text{kton})$, phase I

phase II: $12 \times 12 \times 12 \, m^3 \, [2.4 \, \text{kton}]$ in Pyhäsalmi
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LAr – 20 kton (phase III)
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LAr Demo

**LBNO-DEMO (CERN WA105)**

- TDR submitted to SPSC in April 2014
  - positive feedback → recommends to seek full funding
- SPC supportive, MTP (draft) now includes EHN1 extension.
  CERN Council to decide on budget at the June session.
  - Presently still considering 6x6x6m3 detector commissioning in March 2017.
  - Timescale will be hopefully better defined after the June Council meeting.
- Preparatory work ongoing with 3x1x1m3
  - Tank procurement: deadline for PE May 28th → adjudication in June!
  - *NA installation ?*
LAGUNA-Pilot?

- Technical and underground physics demonstrator
- Mass: 2.5-5 kton LAr
- Estimated event rates:
  - SN observatory (5’000 events for d=5 kpc)
  - Atmospheric neutrinos (∼1000 numu/nue/CC+NC events/year and ∼5 nutau CC/year) – “SubGeV” much better than in SK
  - Proton decay (20 kton x yr is competitive with SK in p→nu+K and many other multiple particle final states)
  - LBL beam? MH much better than NOvA!

- **Full cost** ≈ 50M€ (incl. excavation + civ. eng.)
- **Timescale** ≈ 4 years (incl. exc.+civ.eng.)
Elektroweak eigenstates ≠ mass eigenstates: \[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle
\end{pmatrix} = U \begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle
\end{pmatrix}
\]

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & e^{-i\delta} s_{13} \\
0 & 1 & 0 \\
-e^{i\delta} s_{13} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

atmospheric exp. \hspace{1cm} \text{solar exp.}

\[
\sin^2 \theta_{23} = 0.50^{+0.07}_{-0.06}
\]
\[
|\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3} \text{ eV}^2
\]

\[
\sin^2 \theta_{12} = 0.318^{+0.019}_{-0.016}
\]
\[
\Delta m^2_{21} = 7.59^{+0.23}_{-0.18} \times 10^{-5} \text{ eV}^2
\]

Hint for finite \( \theta_{13} \) from T2K, Minos!

T2K & Minos (June 2011) and Double-Chooz (November 2011): \( \theta_{13} \) non-zero with high probability