Astroparticle Physics in the Pyhäsalmi Mine

– high-energy cosmic rays (EMMA)

– $^{14}C/^{12}C$ experiment

– Laguna

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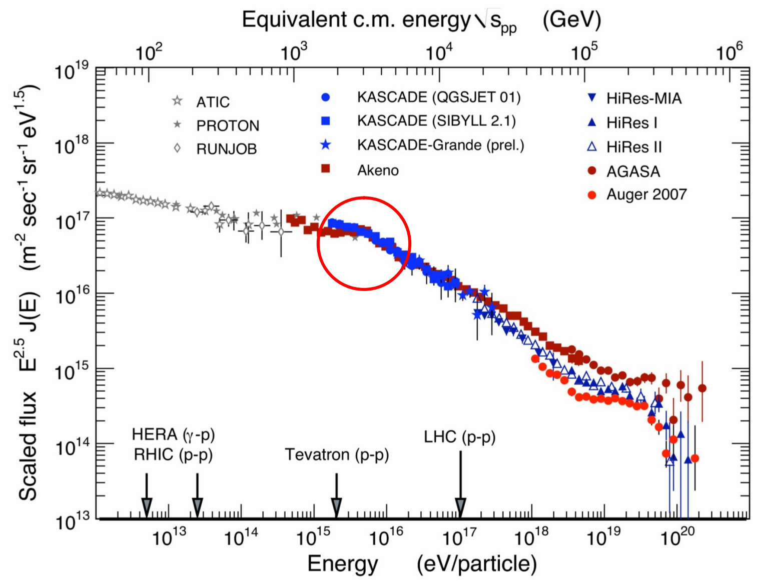
EMMA

Experiment with MultiMuon Array

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

Astroparticle Physics in Pyhäsalmi

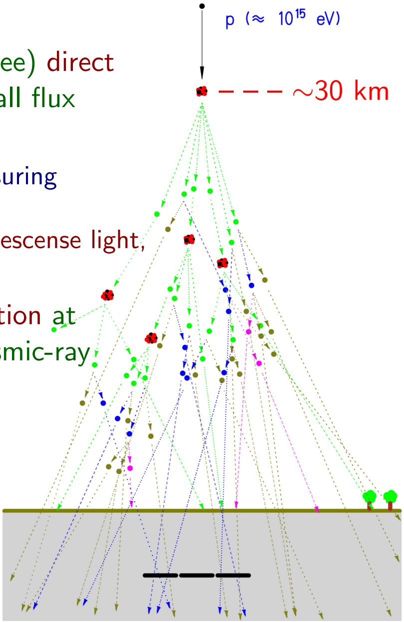
EMMA – the knee



Astroparticle Physics in Pyhäsalmi

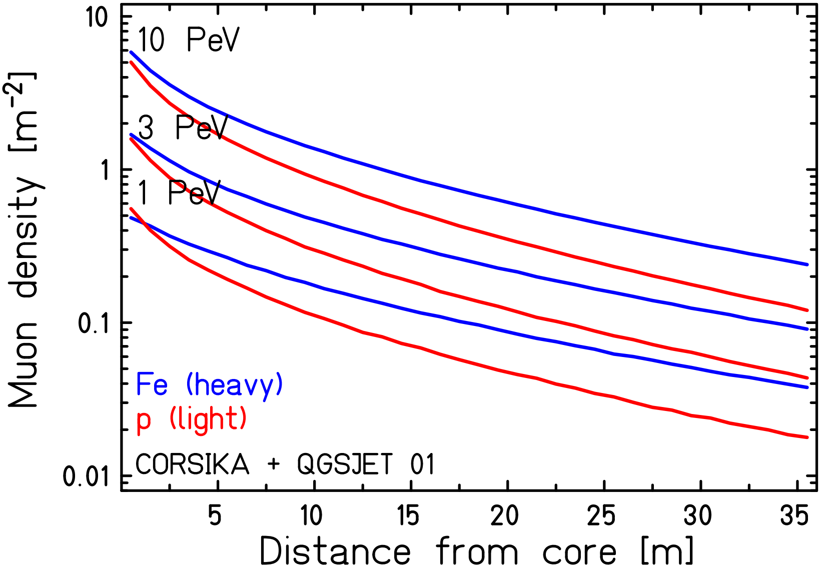
EMMA – Air shower

- 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: fluorescense 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



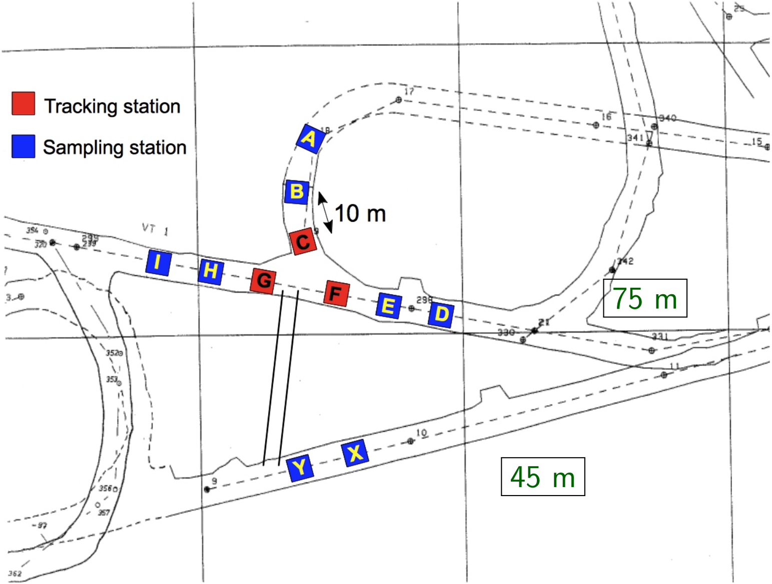
Astroparticle Physics in Pyhäsalmi

EMMA – The method (muon energy cut-off 50 GeV (or 75 m of rock))



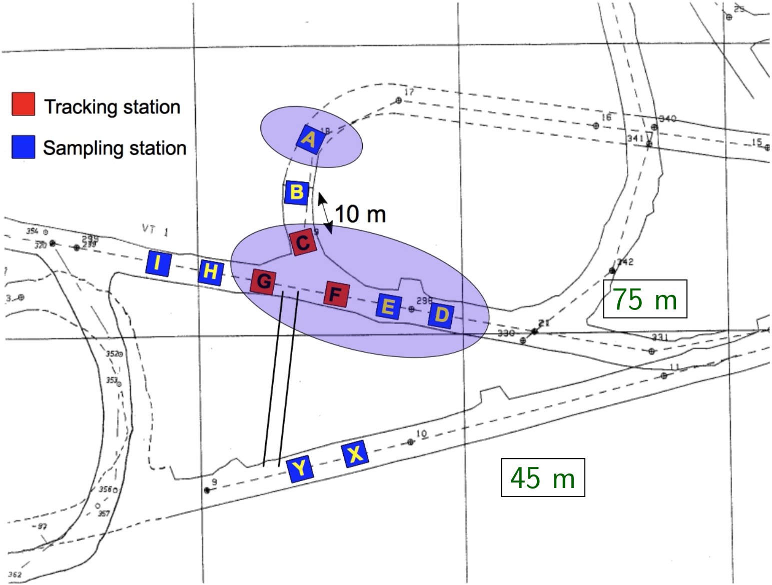
Astroparticle Physics in Pyhäsalmi

EMMA – 11 detector stations



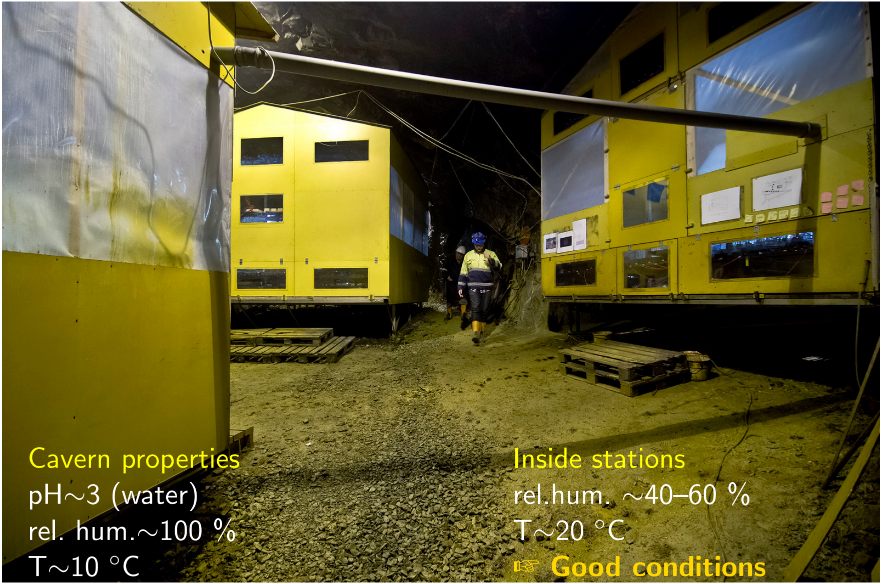
Astroparticle Physics in Pyhäsalmi

EMMA – DAQ running in 6 stations



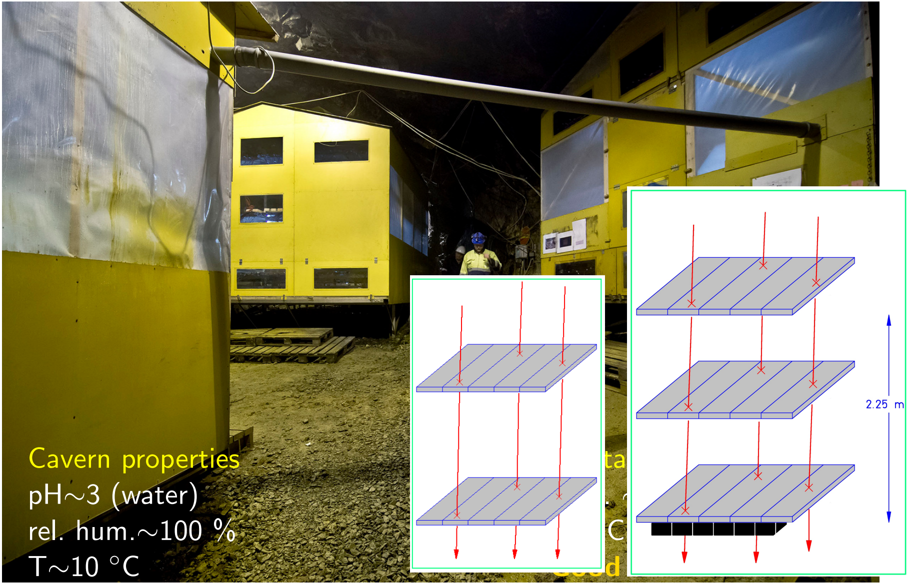
Astroparticle Physics in Pyhäsalmi

EMMA – Stations C, F ja G



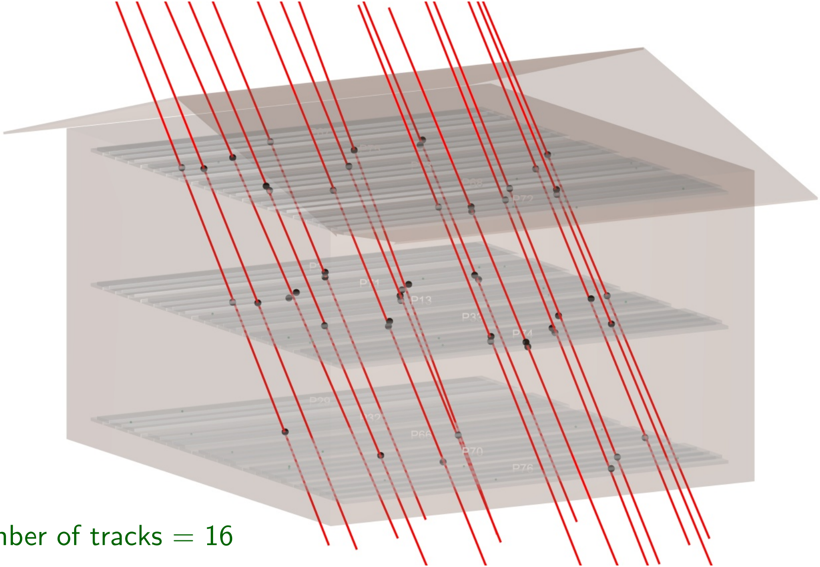
Astroparticle Physics in Pyhäsalmi

EMMA-koe – Stations C, F ja G



Astroparticle Physics in Pyhäsalmi

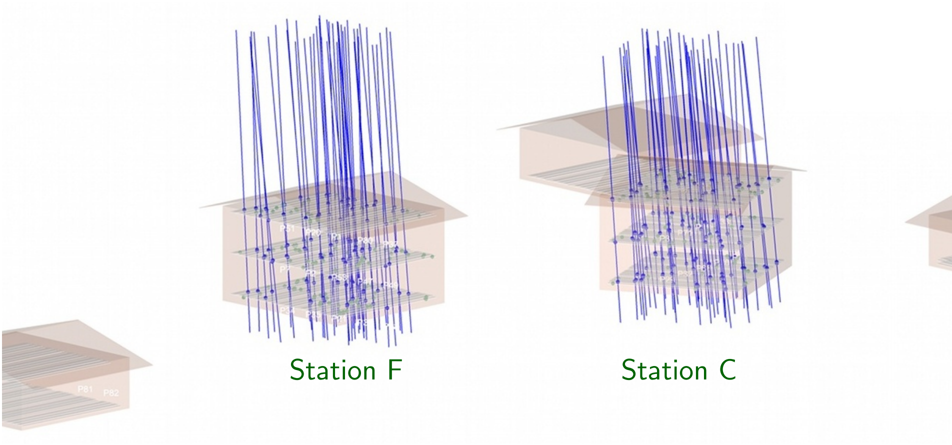
EMMA – Tracks of muons, example 1



Number of tracks = 16

Astroparticle Physics in Pyhäsalmi

EMMA – Tracks of muons, example 2

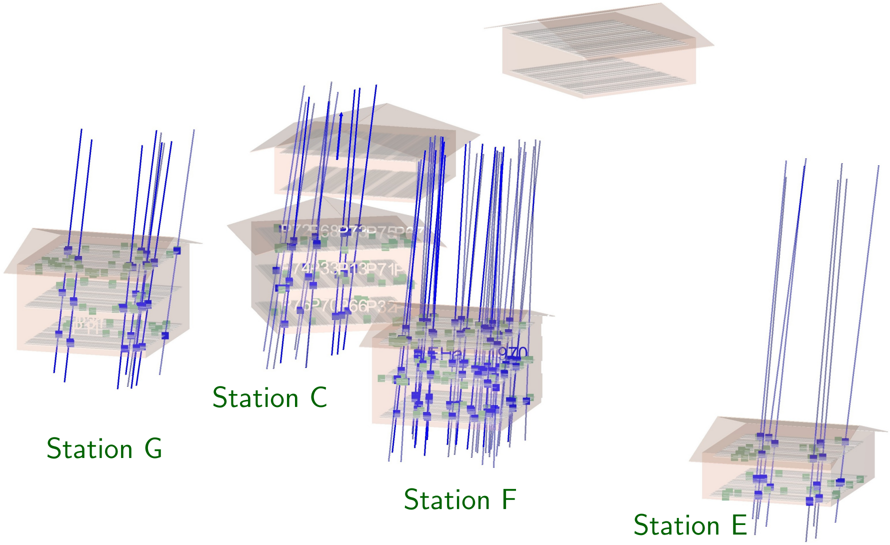


Station F

Station C

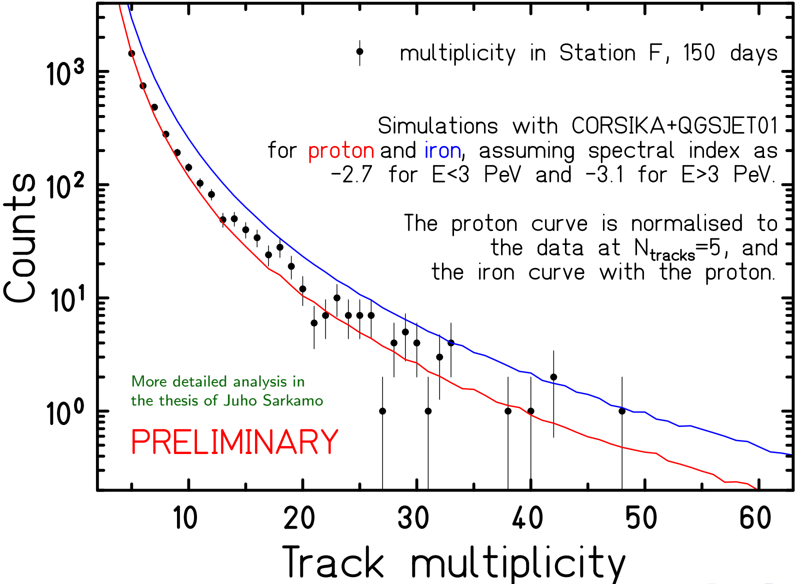
Astroparticle Physics in Pyhäsalmi

EMMA – Tracks of muons, example 3



Astroparticle Physics in Pyhäsalmi

EMMA – Muon multiplicities (150 days, 12/2012 – 04/2013)



Astroparticle Physics in Pyhäsalmi

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 $^{14}C/^{12}C$ ratio in liquid scintillator

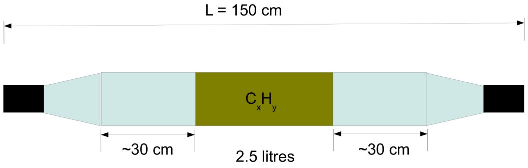
Astroparticle Physics in Pyhäsalmi

^{14}C experiment

- The aim is to find out such a liquid scintillator sample in which the content of ^{14}C is as small as possible
  - $^{14}\mathrm{C}/^{12}\mathrm{C} < 10^{-18}$
- Motivations
  - detector development (JUNO, LENA)
    - Solar pp-ν 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)

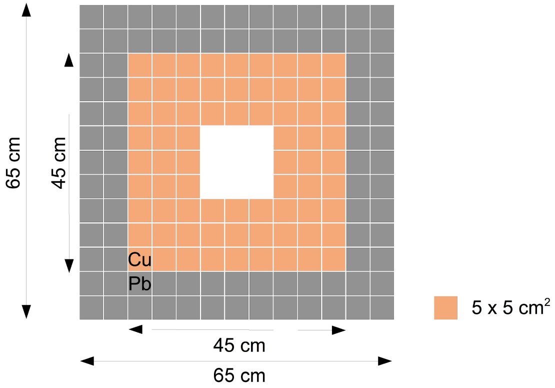
Astroparticle Physics in Pyhäsalmi

^{14}C experiment – the detector



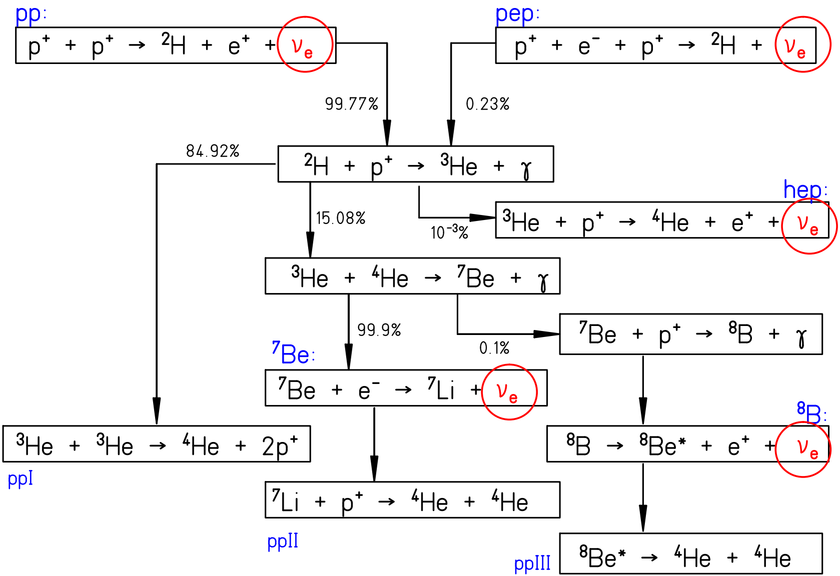
- liquids, light guides and PMTs from Russia (RAS/INR in Moscow)

- Radiation shielding
  - ∼3–4 tons of Cu
  - ∼2–3 tons of Pb
  - nitrogen flux
- In addition,
  - parafin ∼20 cm
  - muon veto
  - pulse digitalization
  - ...
  - ...



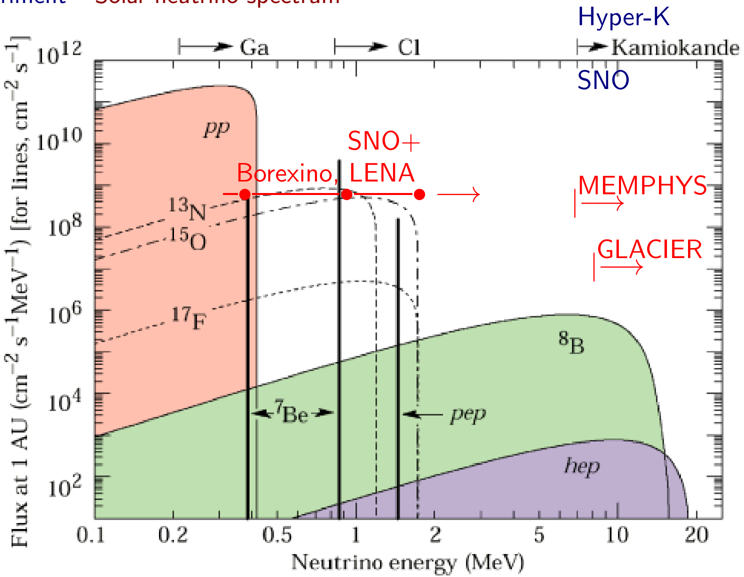
Astroparticle Physics in Pyhäsalmi

^{14}C experiment – Solar neutrinos



Astroparticle Physics in Pyhäsalmi

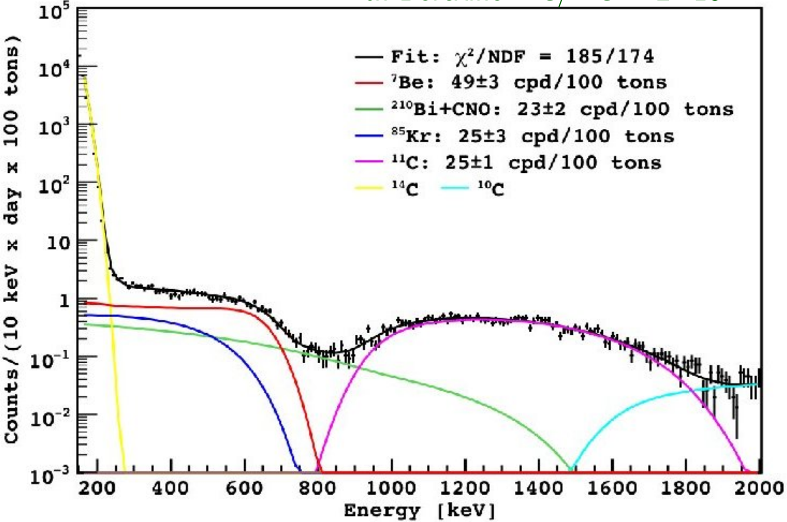
^{14}C experiment – Solar neutrino spectrum



Astroparticle Physics in Pyhäsalmi

^{14}C experiment – Borexino, ^{7}Be neutrino spectrum

In Borexino $^{14}C/^{12}C \approx 2\times10^{-18}$



Astroparticle Physics in Pyhäsalmi

^{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

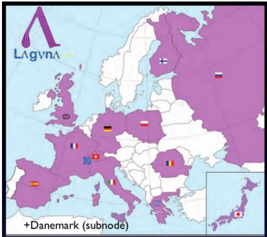
Astroparticle Physics in Pyhäsalmi

LAGUNA–LBNO – General

- 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
  - open meeting (https://www.jyu.fi/fysiikka/en/laguna2014)

Astroparticle Physics in Pyhäsalmi

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(**)

Switzerland
University Bern
University Geneva
ETH Zürich
Lombardi Engineering*

Finland
University Jyväskylä
University Helsinki
University Oulu
Rockplan Oy Ltd*

CERN

Poland
IFJ PAN
IPJ
University Silesia
Wroklaw UT
KGHM CUPRUM*

Greece
Demokritos

Spain
LSC
UA Madrid
CSIC/IFIC
ACCIONA*

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

Romania
IFIN-HH
Bucharest

Denmark
Aahrus(**)

Italy
AGT*

Russia
INR
PNPI

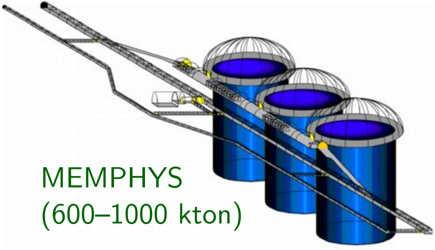
Japan
KEK

(*=industrial partners
**=associated)

Astroparticle Physics in Pyhäsalmi

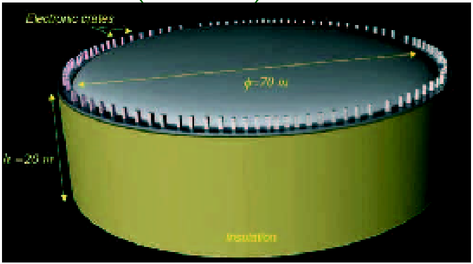
LAGUNA-LBNO – Three options – GLACIER, LENA and MEMPHYS

LENA (50 kton)



MEMPHYS
(600–1000 kton)

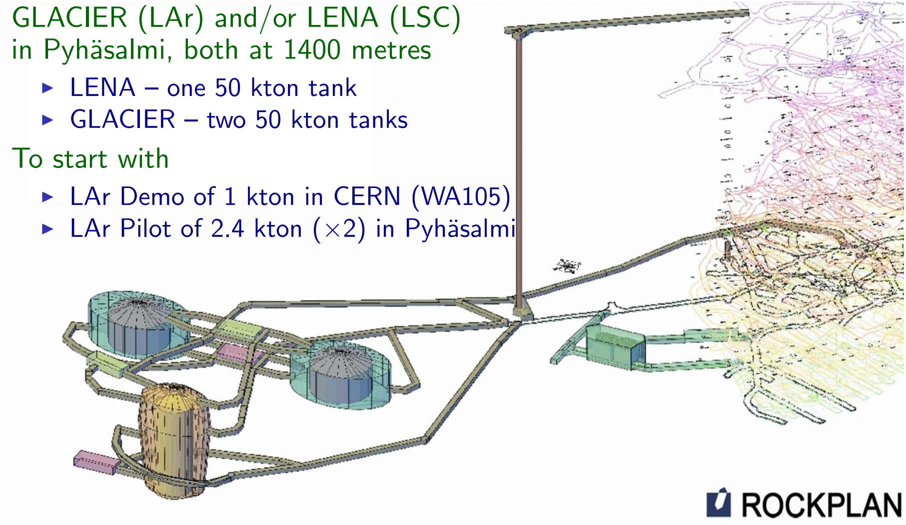
GLACIER (100 kton)



Astroparticle Physics in Pyhäsalmi

LAGUNA-LBNO – Current status

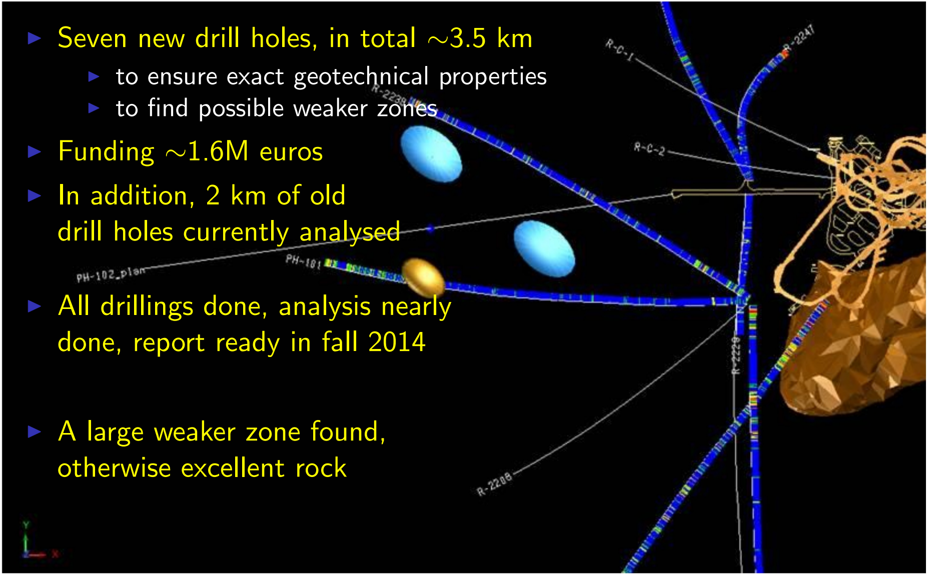
- GLACIER (LAr) and/or LENA (LSC) in Pyhäsalmi, both at 1400 metres
  - LENA – one 50 kton tank
  - GLACIER – two 50 kton tanks
- To start with
  - LAr Demo of 1 kton in CERN (WA105)
  - LAr Pilot of 2.4 kton ($\times 2$) in Pyhäsalmi



Astroparticle Physics in Pyhäsalmi

LAGUNA – Site investigations

- Seven new drill holes, in total ~3.5 km
  - to ensure exact geotechnical properties
  - to find possible weaker zones
- Funding ~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)
  - Θ_{13}, ν-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

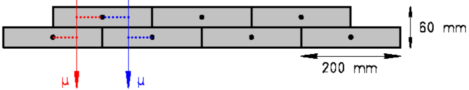
- Site Investigations
  - Marko Aittola (University of Oulu)

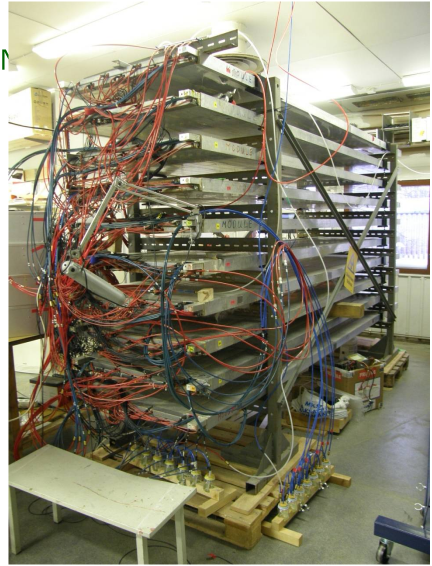
EXTRAS

Astroparticle Physics in Pyhäsalmi

EMMA – drift chambers

- 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 ($\sim$250 m^2)
  - form the basis of the array
- Position resolution is good: $\sim$1 cm^2
  - needed by tracking
- Ar (92%) : CO_2 (8%) at 1 bar
  - min $\sim$0.25 bar$\cdot\ell$/min /4 planks

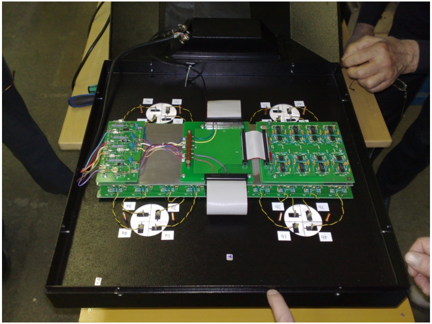




Astroparticle Physics in Pyhäsalmi

EMMA – scintillation detectors

- SC16 detector
  - 50×50 cm^2, H = 13 cm
  - mass $\sim$ 20 kg per SC16
  - 16 individual pixels of 12×12 cm^2 $\times$ 3 cm pixels
  - APD light collection
  - time resolution good: $\sim$1 ns
- In total 96 SC16-detectors (24 m^2), 1536 individual pixels
- Designed especially for
  - large muon multiplisities
  - fast trigger
  - initial guest for the arrival angle
- Made by Russian Academy of Sciences



Astroparticle Physics in Pyhäsalmi

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 Pyhäsalmi at the end of May, 2012, to be done
  - read-out electronics and software
  - HV power supplied
- 60 LST modules
  - $\sim 180\ \mathrm{m}^2$
- Properties
  - $2.9\ \mathrm{m} \times 1.0\ \mathrm{m}$
  - pixel size (PAD): $2\ \mathrm{cm} \times 8\ \mathrm{cm}$
  - gas: CO_2 at 1 bar

Astroparticle Physics in Pyhäsalmi

EMMA – gas handling

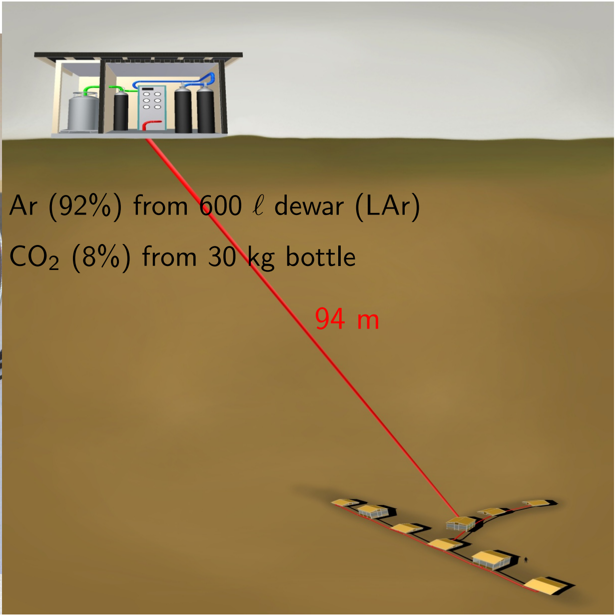
Total flux $\sim 7\ \ell/\mathrm{min}$ ($Ar:CO_2$, 92:8)

Astroparticle Physics in Pyhäsalmi

EMMA – gas handling

Astroparticle Physics in Pyhäsalmi

EMMA – gas handling

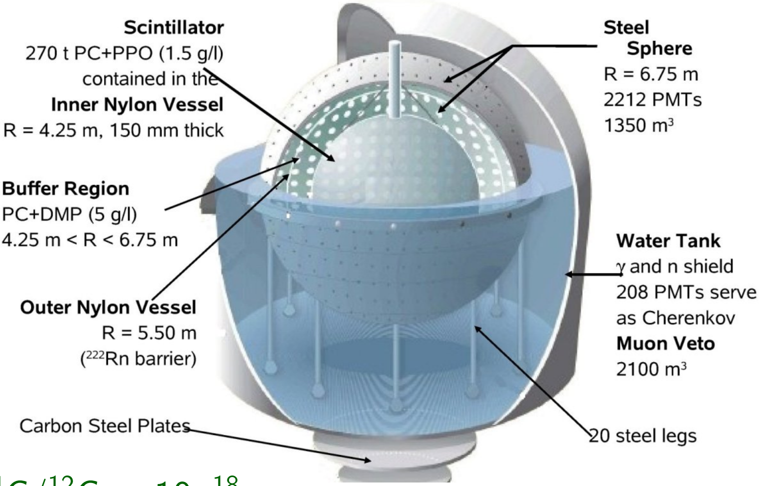


Ar (92%) from 600 ℓ dewar (LAr)

CO_2 (8%) from 30 kg bottle

Astroparticle Physics in Pyhäsalmi

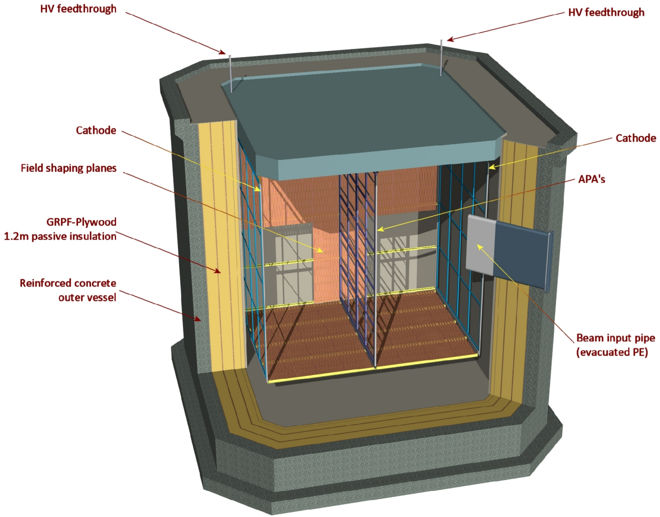
^{14}C experiment – Borexino, Gran Sasso



$$^{14}\mathrm{C}/^{12}\mathrm{C} \sim 10^{-18}$$

Astroparticle Physics in Pyhäsalmi

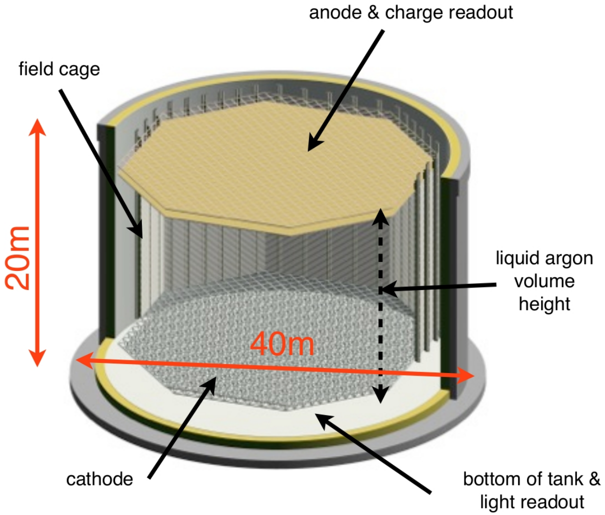
LAr Demo at CERN – $6\times6\times6$ m^3 ($\sim$1 kton), phase I



- phase II: $12\times12\times12$ m^3 [2.4 kton] in Pyhäsalmi

Astroparticle Physics in Pyhäsalmi

LAr – 20 kton (phase III)



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 — Murphy
  - Tank procurement: deadline for PE May 28th → adjudication in June !
  - Aggressive timescale (2014-2015)
  - *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.)

Astroparticle Physics in Pyhäsalmi

LAGUNA – Neutrino properties

Elektroweak eigenstates $\neq$ mass eigenstates: $\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric exp.}} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar exp.}}$$

$$\boxed{\begin{aligned} \sin^2\theta_{23} &= 0.50^{+0.07}_{-0.06} \\ |\Delta m^2_{31}| &= 2.40^{+0.12}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2 \end{aligned}}$$

$$\boxed{\begin{aligned} \sin^2\theta_{12} &= 0.318^{+0.019}_{-0.016} \\ \Delta m^2_{21} &= 7.59^{+0.23}_{-0.18} \times 10^{-5}\,\mathrm{eV}^2 \end{aligned}}$$

Hint for finite θ_{13} from T2K, Minos!

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