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Workshop on Grand Unification and Proton Decay

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Low energy neutrino astronomy and proton decay with LENA

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Low energy neutrino astronomy and proton decay with LENA

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Outline

Outline

Physics Goals

Low **E**nergy **N**eutrino **A**stronomy

Supernovae Neutrinos

Diffuse Background of Supernovae Neutrinos

Solar Neutrinos

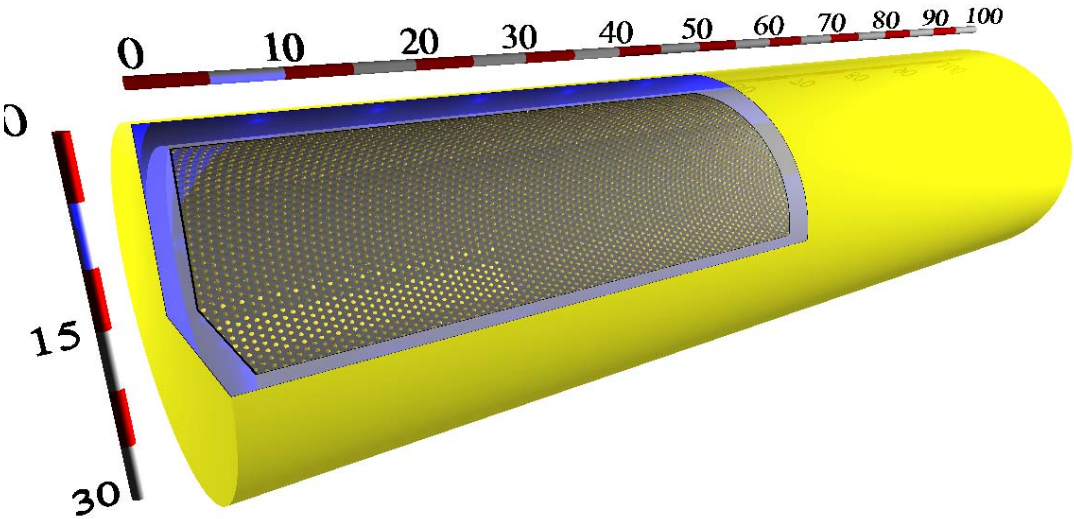
Geoneutrinos

Neutrino Properties

Proton Decay

LENA - Low Energy Neutrino Astronomy

Detector scheme



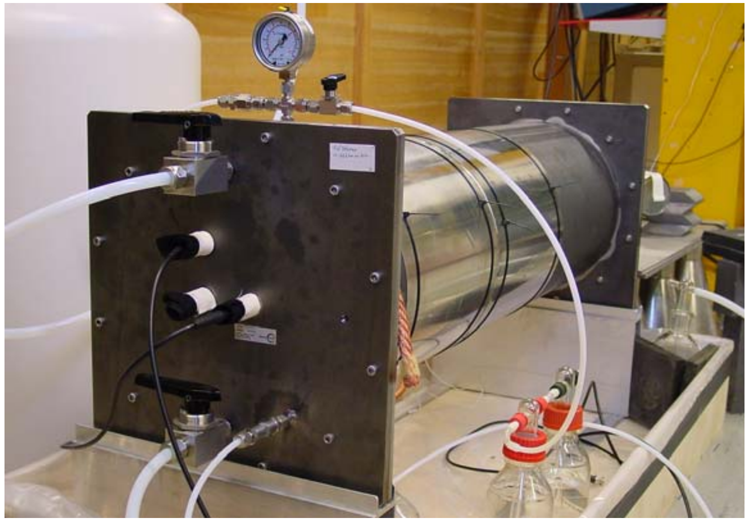
- Size
  - 100 m length
  - 30 m ∅
- Liquid Scintillator
  - ∼ 50 kton PXE
- Photomultipliers
  - 13 500 units
  - 30% coverage
- Photoelectron yield
  - 110 pe/MeV
- Underground location

Liquid scintillator measurements at TUM

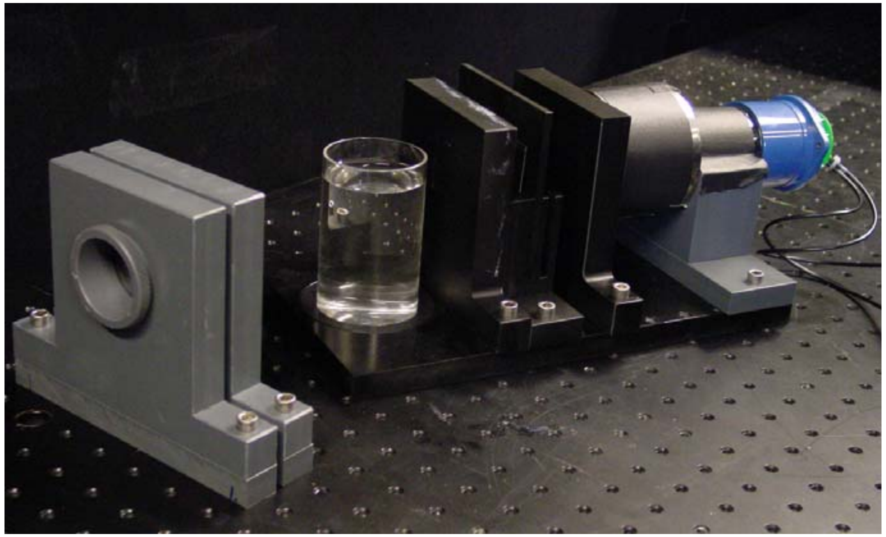
Why liquid scintillators?

- Good energy resolution
- Low energy threshold

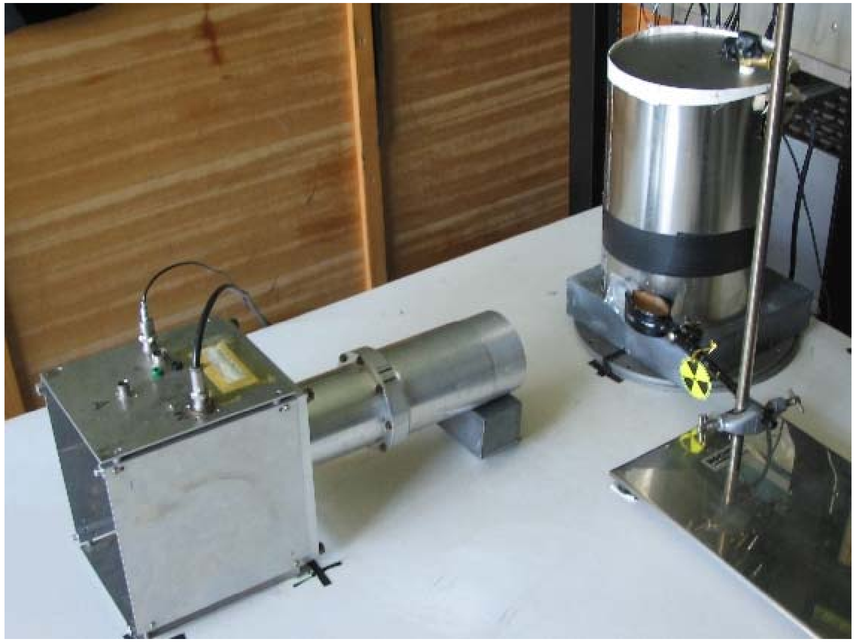
Attenuation length $\lambda \sim 10$ m



Scattering length $\lambda_s \sim 30$ m

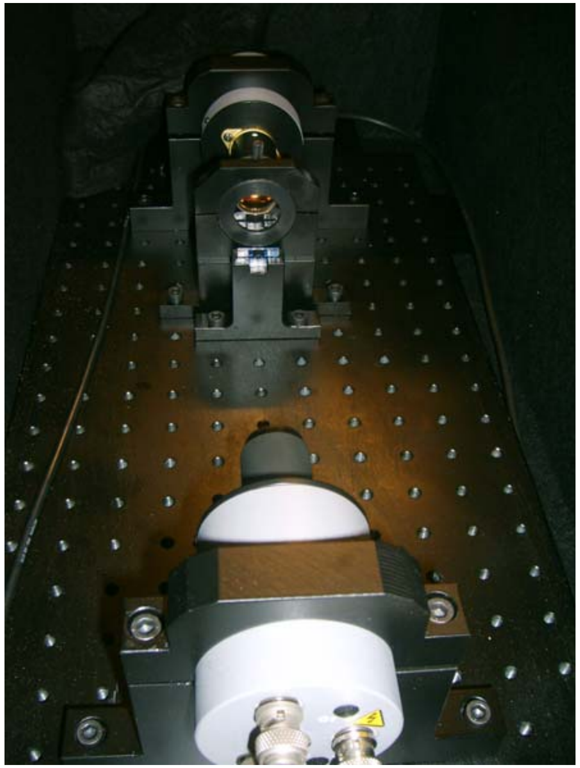


Light yield



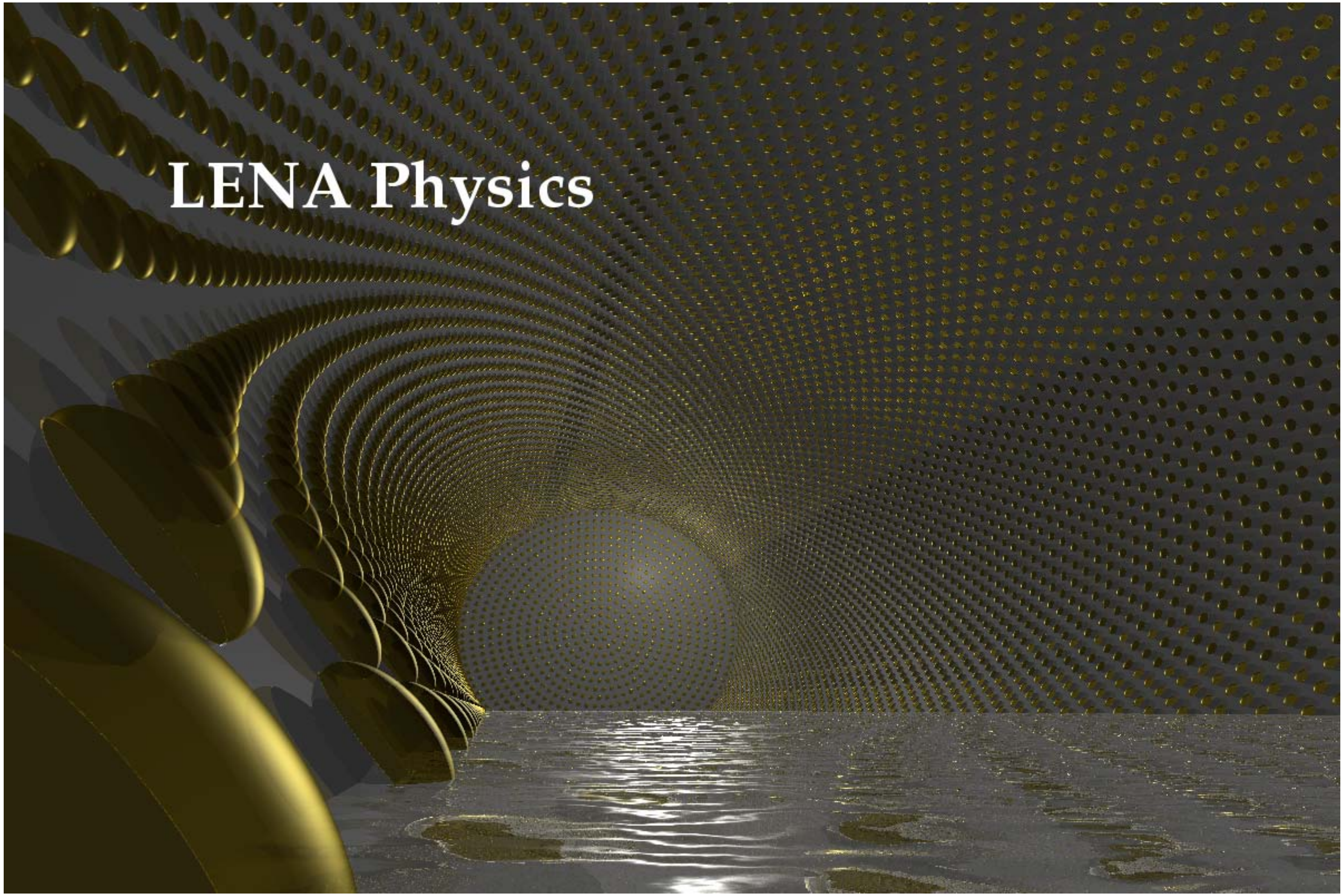
- Number of pe/MeV
- Dependence on wavelength shifter concentration

Fluorescence time



- Exponential time constants for different scintillators

Outline


LENA Physics

Proton Decay

Non supersymmetric Grand Unified Theories

Dominant decay mode: $p \rightarrow e^+\pi^0$ $\tau \sim 10^{36}$ y

Supersymmetry (SUSY)

Dominant decay mode: $p \rightarrow K^+\overline{\nu}$ $\tau \sim 10^{34}$ y

- Superkamiokande: $\tau(p \rightarrow e^+\pi^0) \gtrsim 5.4 \cdot 10^{33}$ y (90% C.L.)
  $\tau(p \rightarrow K^+\overline{\nu}) \gtrsim 2.3 \cdot 10^{33}$ y (90 % C.L.)

Detection of Supernovae Neutrinos

- D = 10 kpc (center of our galaxy)
- 8 $M_\odot$ ($\Delta E = 2.65 \cdot 10^{53}$ erg)

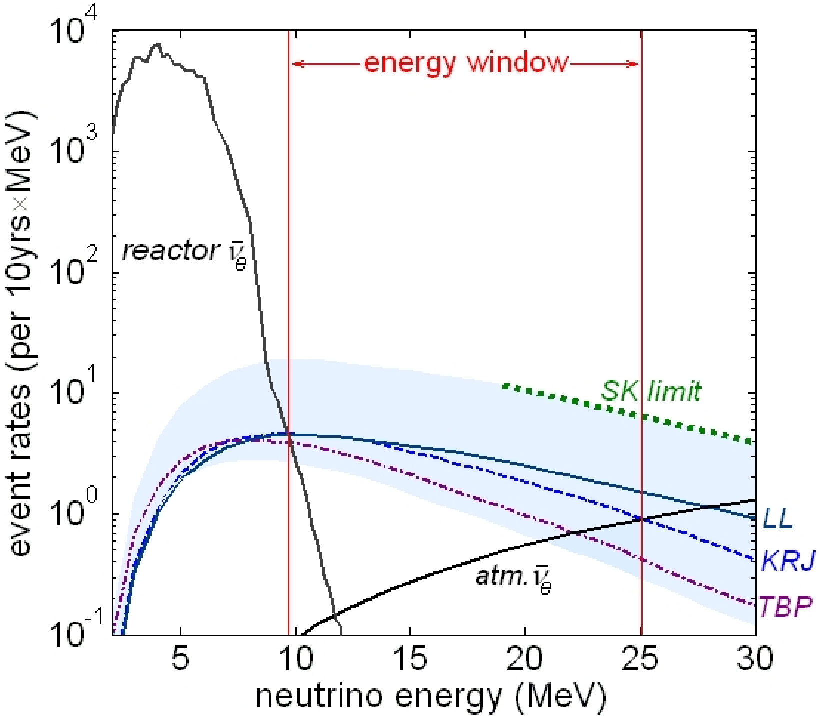
In LENA detector: $\sim$20000 events

Possible reactions in liquid scintillator

- $\overline{\nu}_e + p \rightarrow n + e^+;\ n + p \rightarrow d + \gamma$ $\sim$9000 events
- $\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B} + e^+;\ {}^{12}\mathrm{B} \rightarrow {}^{12}\mathrm{C} + e^- + \overline{\nu}_e$ $\sim$500 events
- $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N};\ {}^{12}\mathrm{N} \rightarrow {}^{12}\mathrm{C} + e^+ + \nu_e$ $\sim$90 events
- $\nu_x + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu_x;\ {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma$ $\sim$3000 events
- $\nu_x + e^- \rightarrow \nu_x + e^-$ (elastic scattering) $\sim$600 events
- $\nu_x + p \rightarrow \nu_x + p$ (elastic scattering) $\sim$7000 events

Diffuse Background of Supernovae Neutrinos

$\overline{\nu}_e$-neutrino spectrum



In LENA detector: (44 kt f.v.)

- $\overline{\nu}_e + p \rightarrow n + e^+$

Event rate in 10 y:

- LL: $\sim$ 110 events
- TBP: $\sim$ 60 events

(discrimination power at $> 2\,\sigma$)

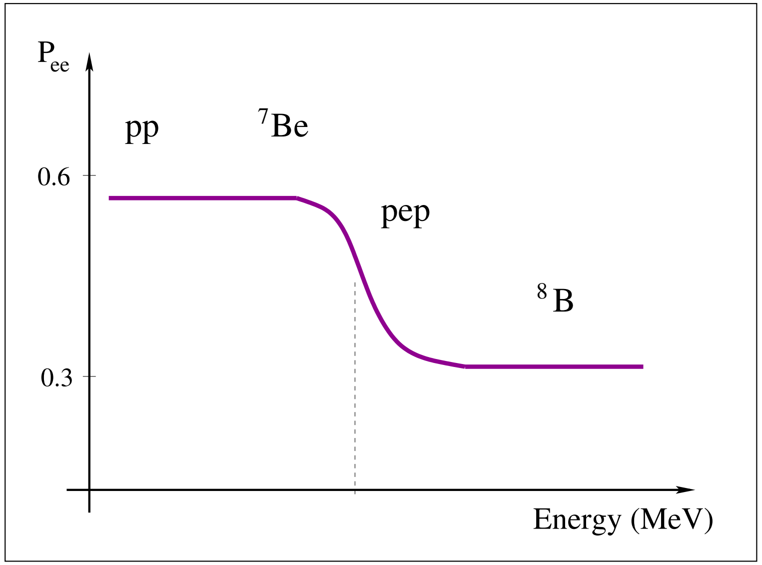
Phys. Rev. D75 023007 (2007) and astro-ph/0701305

Current limit: Super-Kamiokande

- Energy threshold of 19.3 MeV
- Limit for the Flux: $1.2\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Information about Star Formation Rate for (0 < z < 1)

Solar Neutrinos



Spectrum deformation due to the MSW effect

Rates of solar neutrino events

In the LENA fiducial volume:

$$18 \cdot 10^3 \text{ m}^3$$

- ^{7}Be ν's: $\sim$ 5400 d^{-1}
  - Small time fluctuations
- pep ν's: $\sim$ 150 d^{-1}
  - Solar luminosity in ν's: information about the pp-flux
- CNO ν's: $\sim$ 210 d^{-1}
  - Important for heavy stars
- ^{8}B ν's: CC on ^{13}C: $\sim$ 360 y^{-1}

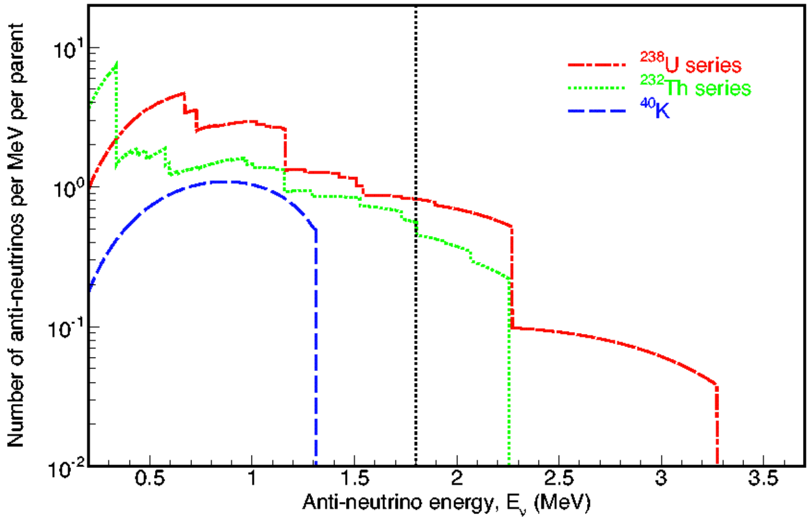
Geoneutrinos

- Unexplained source of heat flow on Earth
- Unknown contribution of natural radioactivity
- How are ^{238}U, ^{232}Th distributed in core, mantle and crust?

In liquid scintillator:

- $\overline{\nu}_e + p \rightarrow n + e^+$

Astropart. Phys. 27 (2007) 21 and hep-ph/0509136

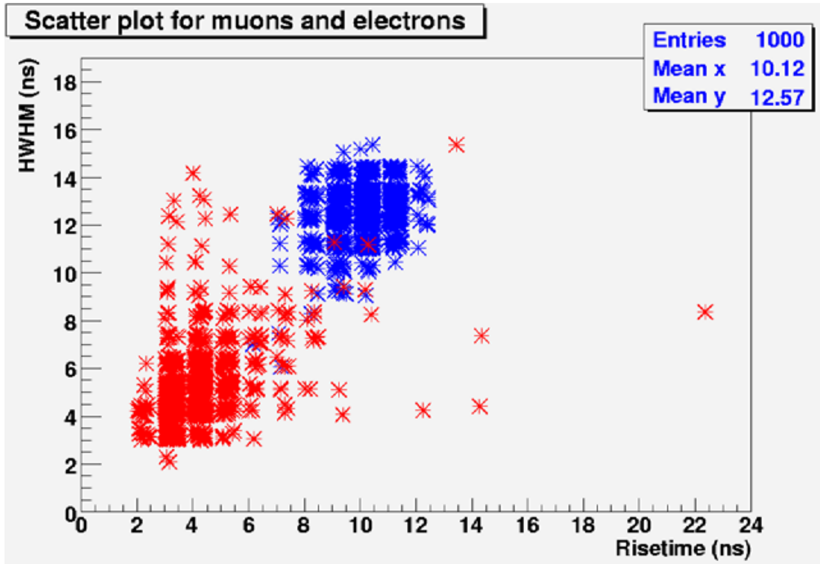


- In LENA detector: $\sim$ (400-4000) events/y

(Scaling KamLAND results)

On-going work: LENA for Betabeams

HWHM (ns) vs. risetime (ns)



Scatter plot for muons and electrons of 1.2 GeV

- Electron/muon separation:
  - Pulse shape discrimination
  - Electron detection from the decay of the muon
- For energies between 0.2 and 1.2 GeV
  - Muon appearance: $\sim$ 90 %
  - Electron background: $\sim$ 0.5 %
- Good energy resolution
- Background due to π or kaon production

Outline

Some of the possible decay channels

- $p \rightarrow e^+\pi^0$
- $p \rightarrow e^+K^0$
- $p \rightarrow e^+\eta$
- $p \rightarrow e^+\rho$
- $p \rightarrow e^+\omega$

- $p \rightarrow \mu^+\pi^0$
- $p \rightarrow \mu^+K^0$
- $p \rightarrow \mu^+\eta$
- $p \rightarrow \mu^+\rho$
- $p \rightarrow \mu^+\omega$

- $p \rightarrow K^+\overline{\nu}_i$
- $p \rightarrow \pi^+\overline{\nu}_i$
- $p \rightarrow \rho^+\overline{\nu}_i$
- $p \rightarrow \omega^+\overline{\nu}_i$
- ... and others

Why $p \rightarrow K^+\overline{\nu}_i$?

- $p \rightarrow e^+\pi^0$
- $p \rightarrow e^+K^0$
- $p \rightarrow e^+\eta$
- $p \rightarrow e^+\rho$
- $p \rightarrow e^+\omega$

- $p \rightarrow \mu^+\pi^0$
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- $p \rightarrow K^+\overline{\nu}_i$
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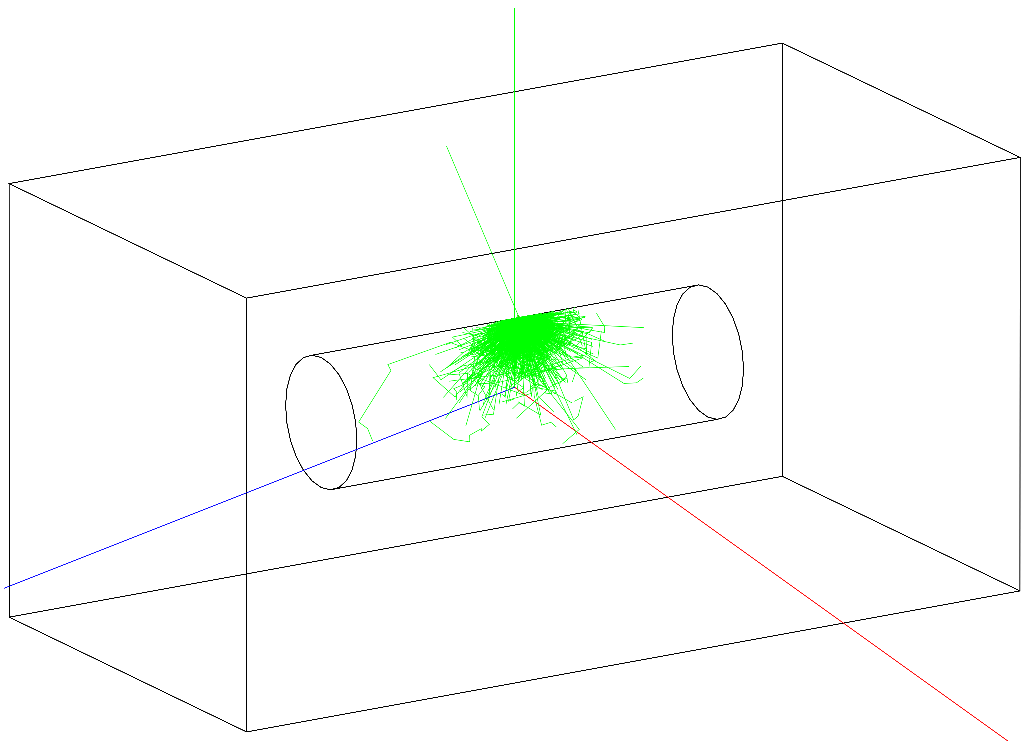
- $p \rightarrow \rho^+\overline{\nu}_i$
- $p \rightarrow \omega^+\overline{\nu}_i$
- ... and others

- Clear signature in liquid scintillator
- Favoured by Supersymmetry

Simulation with Geant4



- Monte Carlo calculations
- Scintillation
- Light propagation
  - Absorption length
  - Scattering length
- Quenching factors
  - Birk's formula
- Photomultipliers:
  - Time jitter: $\sigma = 1\ \mathrm{ns}$
  - Efficiency: $\varepsilon = 0.17$

Free Proton Decay

Event Structure: $p \to K^+ \overline{\nu}$

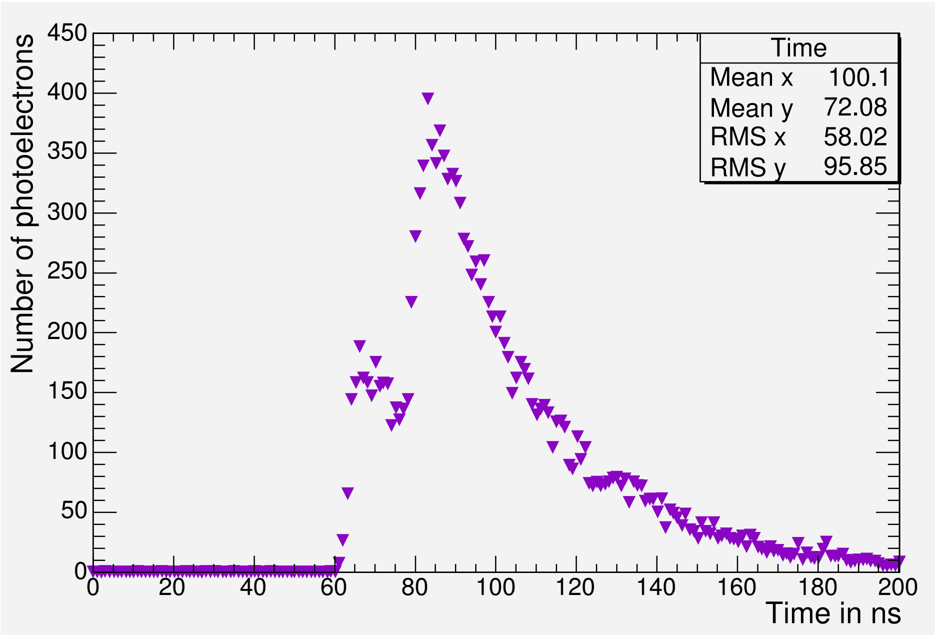
$$T(K^+) = 105 \text{ MeV}$$
$$\tau(K^+) = 12.8 \text{ ns}$$

- $K^+ \to \mu^+ \nu_\mu$ 63.43%
  - $T(\mu^+) = 152$ MeV
  - $\tau(\mu^+) = 2.2\ \mu$s
- $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$

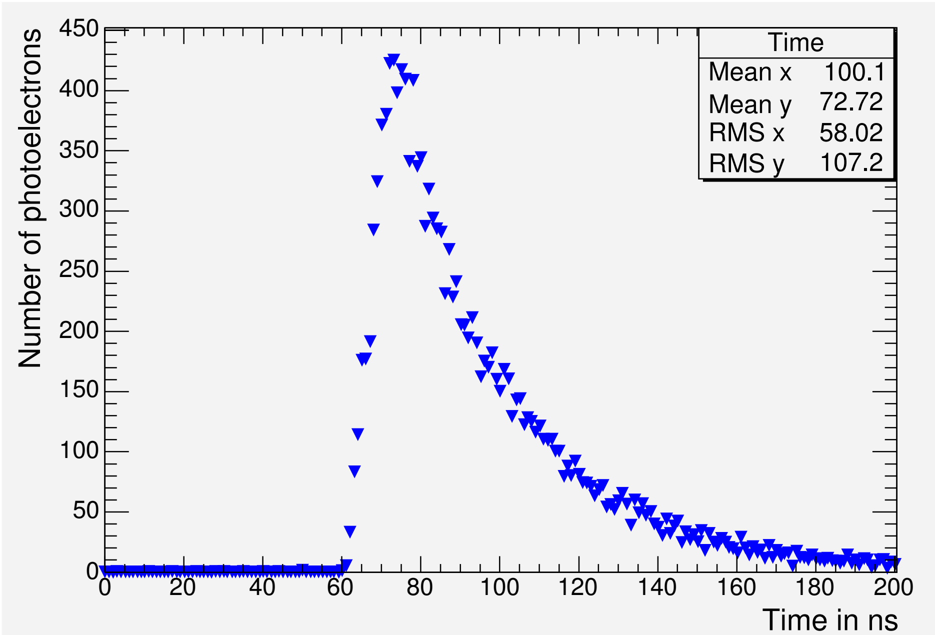
- $K^+ \to \pi^+ \pi^0$ 21.13%
  - $T(\pi^+) = 108$ MeV
  - $\tau(\pi^+) = 26$ ns
  - $T(\pi^0) = 110$ MeV
  - $\tau(\pi^0) = 8.4 \cdot 10^{-8}$ ns
- $\pi^+ \to \mu^+ \nu_\mu$ $\pi^0 \to \gamma\gamma$

Signals of Proton Decay in LENA

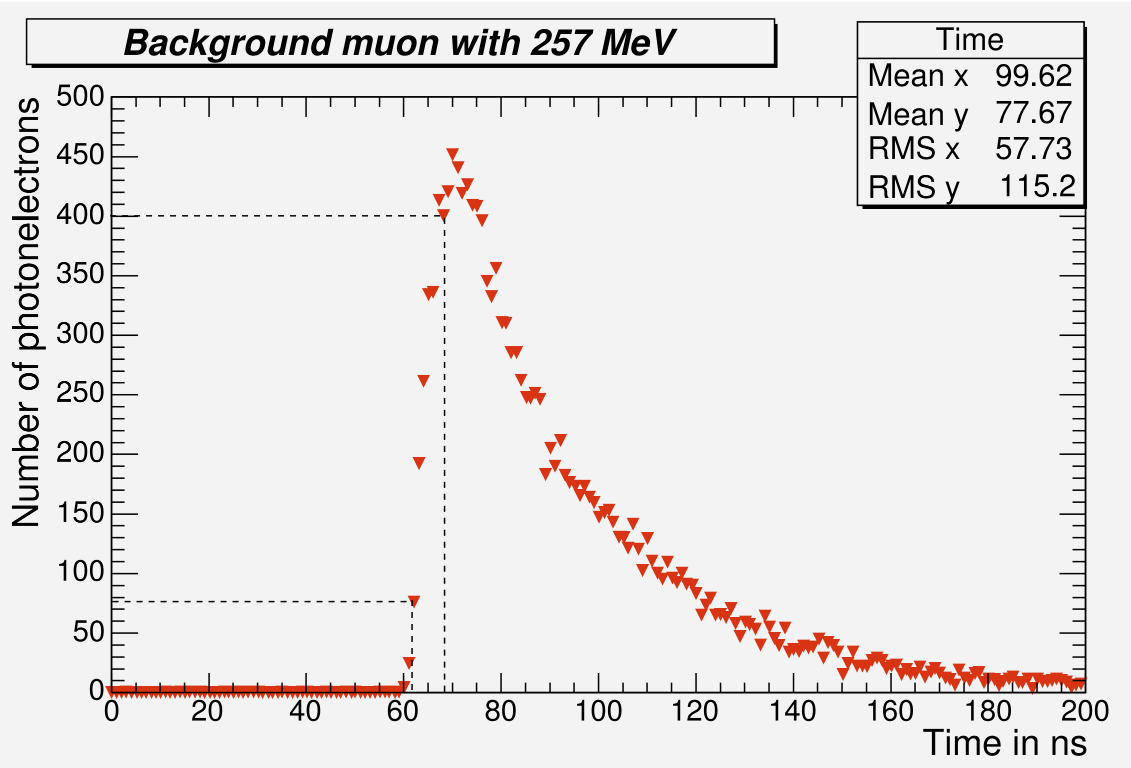
- Kaon decay after 18 ns



- Kaon decay after 5 ns



Background: Muon Production by Atmospheric ν_μ



- $\nu_\mu + N \rightarrow \mu^- + N'$

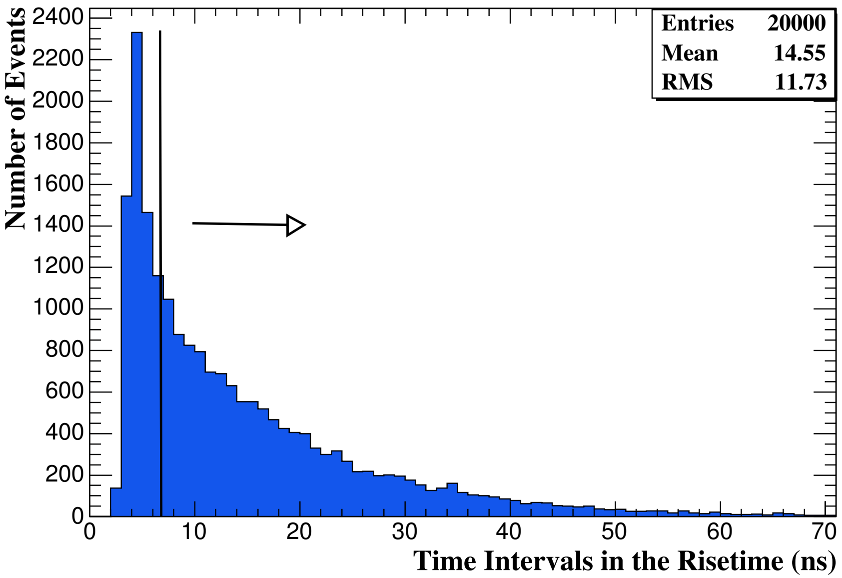
Background rate from Superkamiokande

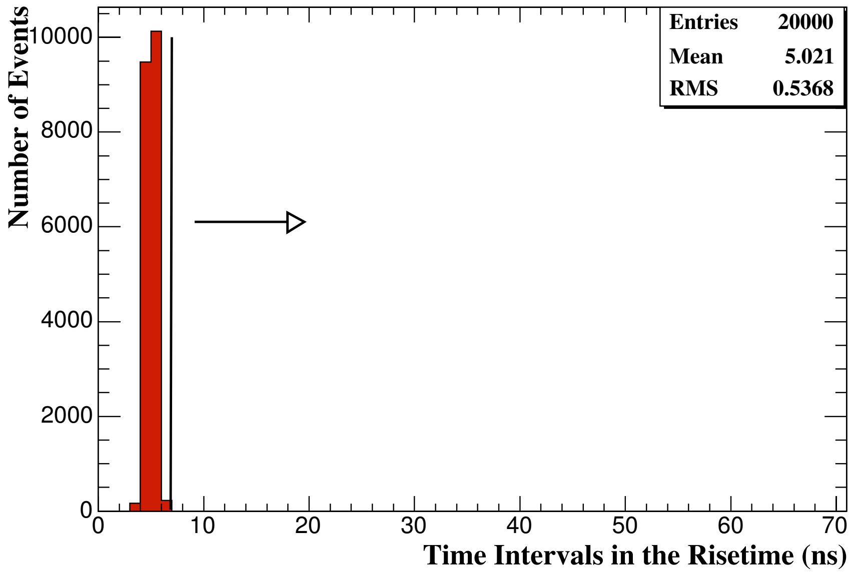
$\Gamma = 4.8 \cdot 10^{-2}$ $(MeV^{-1} kt^{-1} y^{-1})$

- Pulse shape analysis
  - Risetime

Background Rejection: Time Cut

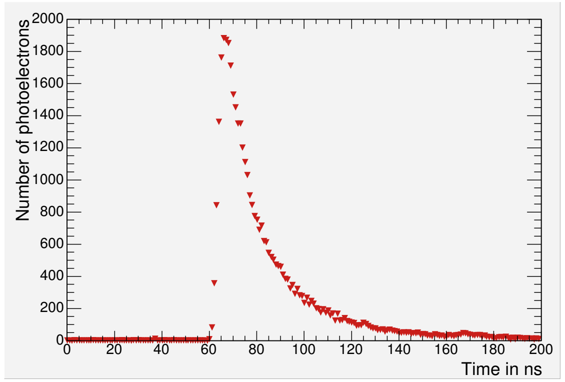
- Efficiency: $\varepsilon_T = 0.65$





- Background suppression: $B \sim 5 \cdot 10^{-5}$

Background: Hadron Production by Atmospheric ν_μ



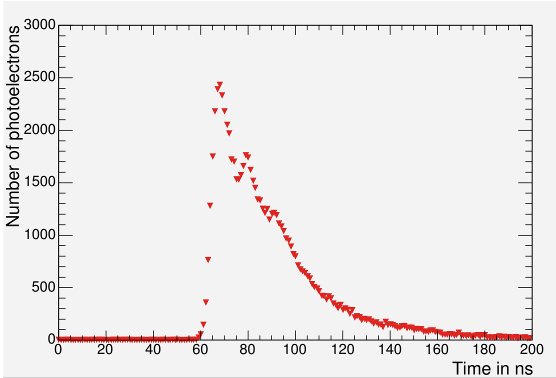
Pion Production

- $\nu_\mu + p \rightarrow \mu^- + \pi^+ + p'$
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \tau_{\pi^+} = 26$ ns

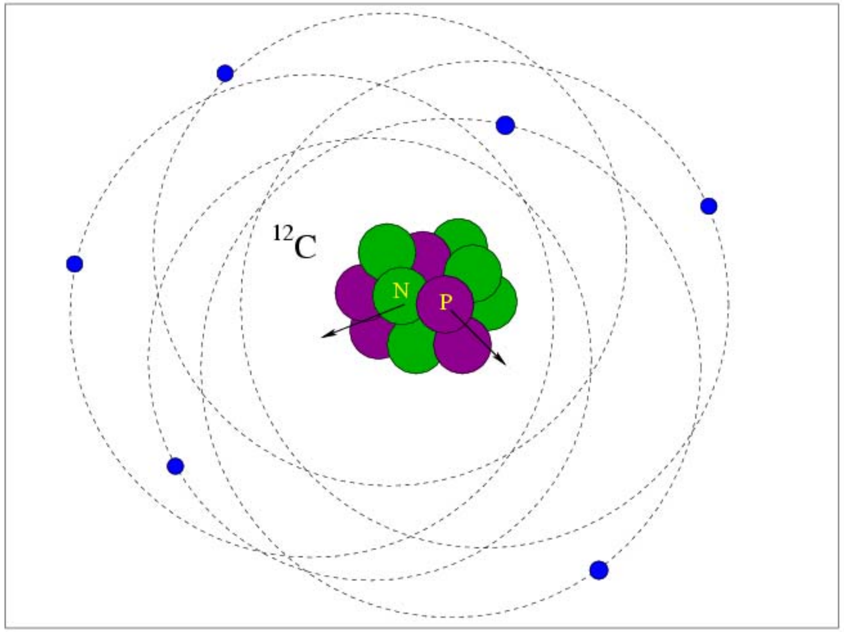
Kaon Production

- $\Delta S = 1$ CC:
  $\nu_\mu + p \rightarrow \mu^- + K^+ + p$
- $\Delta S = 0$ CC:
  $\nu_\mu + n \rightarrow \mu^- + K^+ + \Lambda^0$
  - $\Lambda^0 \rightarrow p + \pi^- \quad \tau_{\Lambda^0} = 0.26$ ns
  - $\Lambda^0 \rightarrow n + \pi^0$

Calculated background rate: $0.064\ \mathrm{y}^{-1}$



Protons from ^{12}C: Nuclear Effects



Binding energy

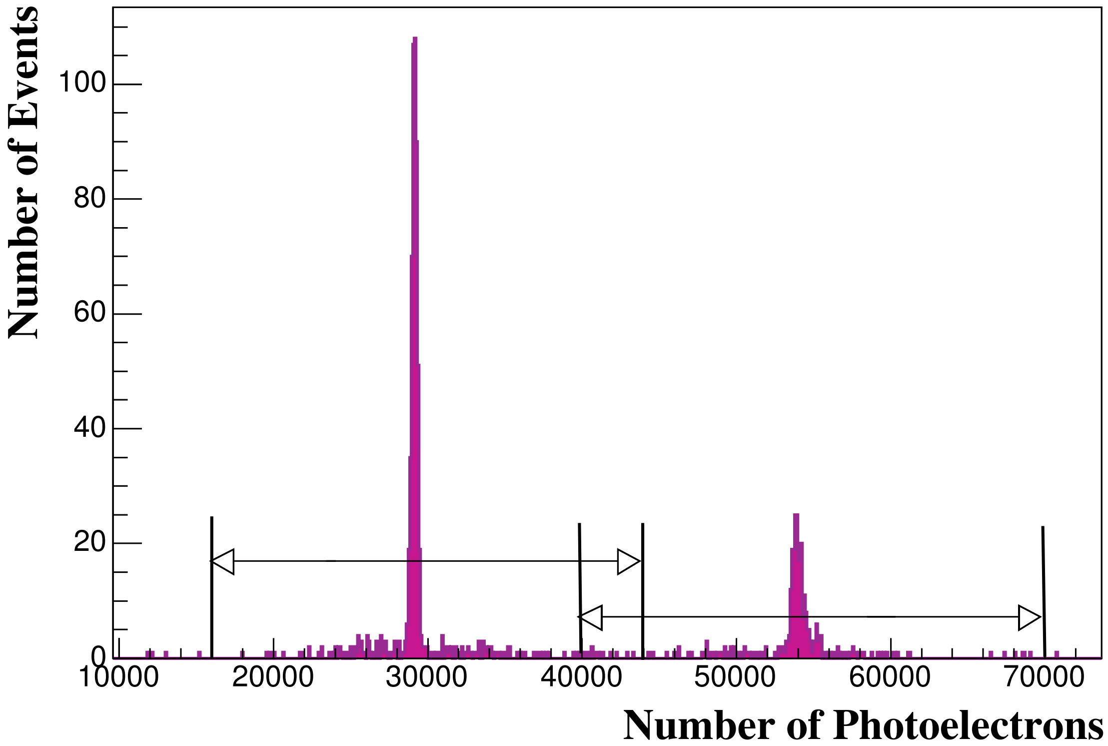
- S-state: $\sim$ 37 MeV
- P-state: $\sim$ 16 MeV

Fermi Motion

- Momenta up to $\sim$ 250 MeV/c

Background Rejection: Energy cut

Energy spectrum
(1000 free proton decay events)



- Two peaks:
  - Kaon + Muon $\sim 257\ \mathrm{MeV}$
  - Kaon + Pions $\sim 459\ \mathrm{MeV}$
- Efficiency: $\varepsilon_E = 0.995$

Proton Decay Sensitivity

- Activity of proton decay: $A = \varepsilon N_p t_m / \tau$
- Total efficiency: $\varepsilon = \varepsilon_E \cdot \varepsilon_T = 0.65$
- Protons in the detector: $N_p = 1.4 \cdot 10^{34}$
- Measuring time: t_m = 10 y

Potential of LENA

- For Superkamiokande current limit: $\tau = 2.3 \cdot 10^{33}$ y
  - 40 events in LENA
  - $\lesssim$ 1 background
- No signal in LENA:
  - $\tau > 4 \cdot 10^{34}$ y 90% (C.L.)

Phys. Rev. D72 075014 (2005) and hep-ph/0511230

Proton decay

- $p \longrightarrow e^+\pi^0$
- $p \longrightarrow e^+K^0$
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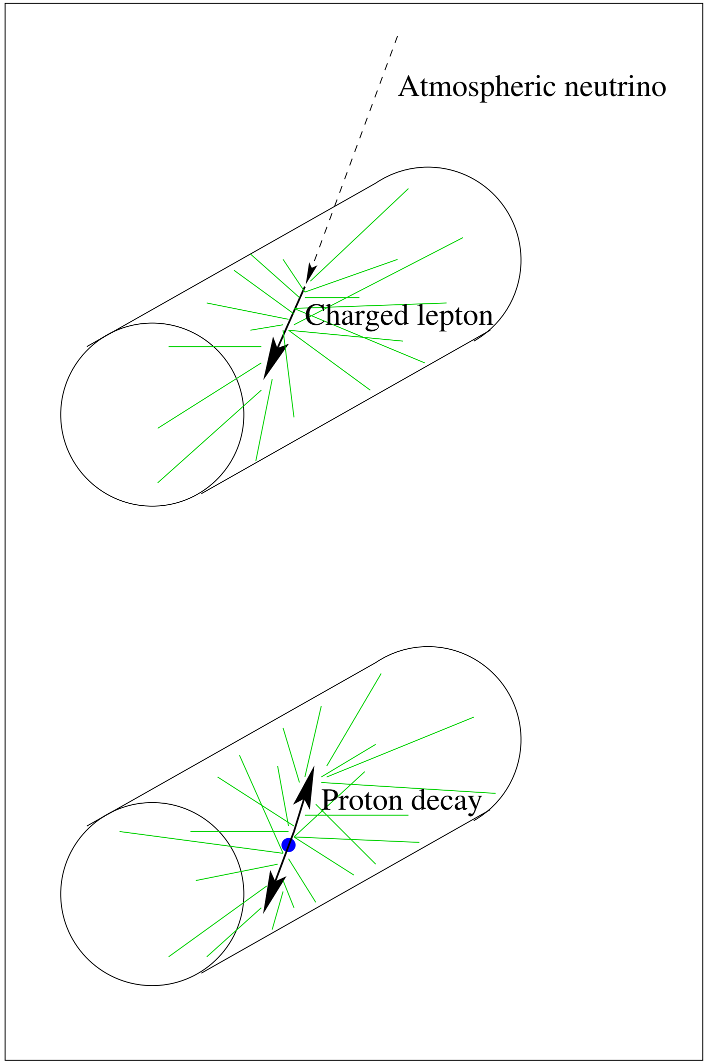
- $p \longrightarrow \omega^+\overline{\nu}_i$
- ... and others

Event Structure: $p \rightarrow e^{+}\pi^{0}$

$$T(e^{+}) = 459 \text{ MeV}$$
$$T(\pi^{0}) = 344 \text{ MeV}$$

- Background rejection:
  - Narrow energy cut (938 MeV) $\rightarrow$ Efficiency: $\varepsilon_E = 0.33$
  - Atmospheric neutrinos $\rightarrow$ Background rate: $B \lesssim 1 \text{ y}^{-1}$
- Protons from Carbon
  - Energy cut can be performed as total energy is ~938 MeV
  - 60 % of the π^{0} interact with the nucleus

- Further background rejection:
  - Background event: through-going charge lepton
  - Proton decay: Two particles in opposite directions
- Direction reconstruction:
  - Photon distribution
  - Arrival time of the photons



Proton decay

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- $p \rightarrow K^+\overline{\nu}_i$
- $p \rightarrow \pi^+\overline{\nu}_i$
- $p \rightarrow \rho^+\overline{\nu}_i$
- $p \rightarrow \omega^+\overline{\nu}_i$
- ... and others

- LENA would be sensitive to all these channels
- Sensitivities have to be calculated

Outline

LAGUNA

Large Apparatus for Grand Unification and Neutrino Astrophysics

- APC, Paris, France
- CEA, Saclay, France
- CPPM, IN2P3-CBRS, Marseille, France
- CUPP, Pyhäsalmi, Finland
- ETHZ, Zürich, Switzerland
- Institute for Nuclear Research, Moscow, Russia
- IPNO, Orsay, France
- LAL, IN2P3-CNRS, Orsay, France
- LPNHE, IN2P3-CNRS, Paris, France
- Max Planck für Kernphysik, Heidelberg, Germany

LAGUNA scientific paper, arXiv: 0705.0116 [hep-ph]

- Max Planck für Physik, München, Germany
- Technische Universität München, Germany
- Universidad de Granada, Spain
- Universität Hamburg, Germany
- University of Bern, Switzerland
- University of Helsinki, Finland
- University of Jyväskylä, Finland
- University of Oulu, Finland
- University of Padova, Italy
- University of Silesia, Katowice, Poland
- University of Sheffield, UK

Physics of LAGUNA: Particle Physics

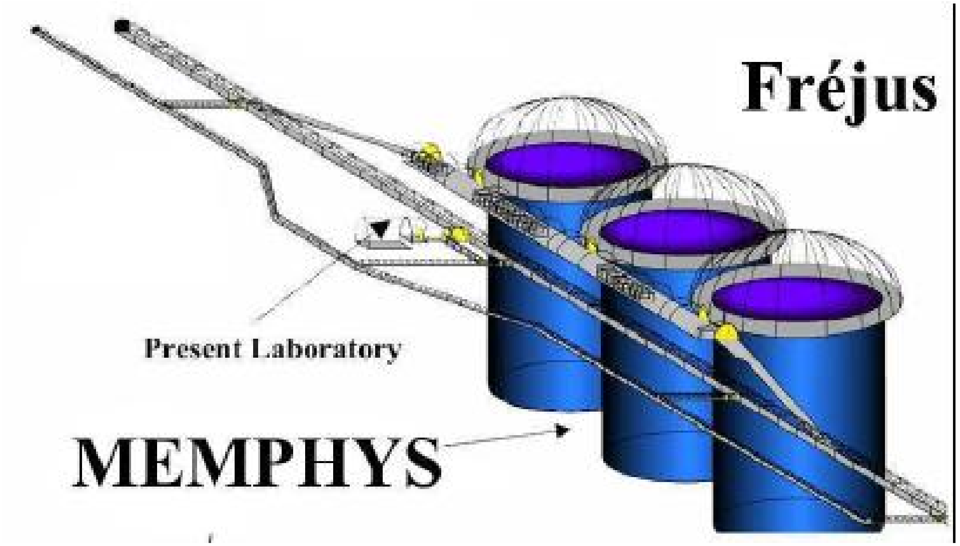
- Proton decay
- Neutrino Properties
  - Atmospheric neutrinos:
    - Improve the measurement of $D_{23} \equiv \sin^2\theta_{23} - 1/2$
  - Reactor:
    - Precise measurement on $\Delta^2 m_{12}$ and $\sin^2\theta_{12}$
  - Detectors for accelerator experiments: θ_{13} and δ_{CP}
    - Beta beams
    - Super beams
    - Neutrino factories

Physics of LAGUNA: Low Energy Neutrino Astrophysics

- Supernovae explosion
  - High statistics in the energy spectrum of different ν-flavours
  - Time evolution of the neutrino emission
  - Neutrino properties: oscillation parameters
- Diffuse background of supernova neutrinos
  - Understanding of the explosion mechanism of a SN
- Solar neutrinos
  - High statistics measurements
- and Geophysics
  - Measuring radioactivity of the Earth with geoneutrinos

MEMPHYS - MEgaton Mass PHYSics

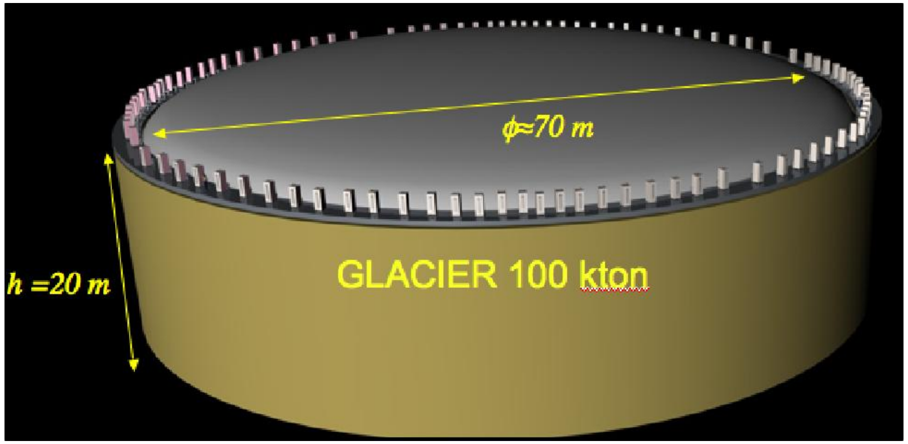
Detector scheme



- Size of each shaft
  - 80 m heigth
  - 65 m ∅
- Water Cherenkov Effect
  - $\sim$ 500 kton pure water
- Photomultipliers
  - 81 000 units per shaft
  - 30% coverage

GLACIER - Giant Liquid Argon Charge Imaging ExpeRiment

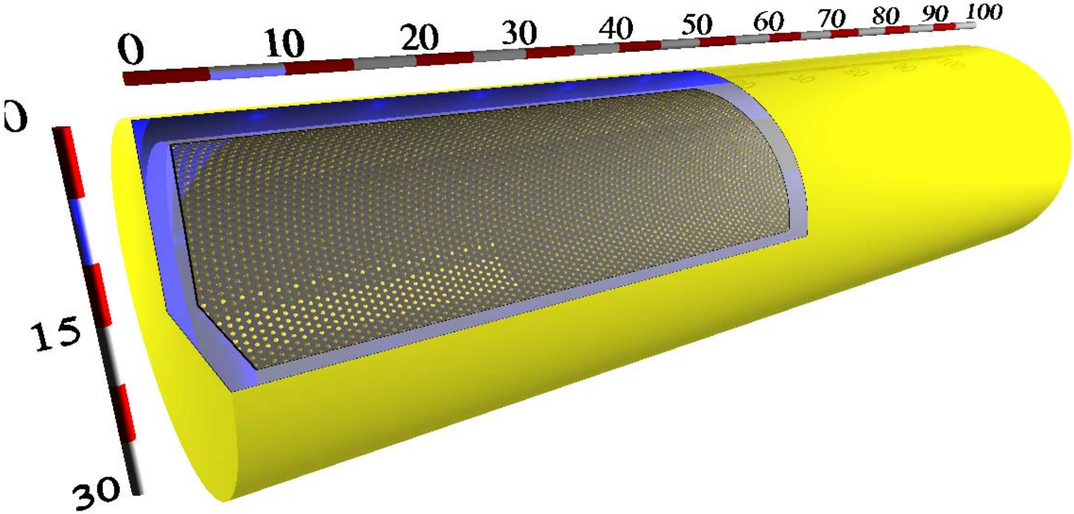
Detector scheme



- Size
  - 20 m heigth
  - 70 m ∅
- Liquid Argon TPC
  - $\sim$ 100 kton liquid argon
- Readout system
  - e^- drift: amplification with LEMs in the gas phase
  - Cherenkov Light: 27 000 PMTs 20% coverage
  - Scintillation Light: 1 000 PMTs

LENA - Low Energy Neutrino Astronomy

Detector scheme



- Size
  - 100 m length
  - 30 m ∅
- Liquid Scintillator
  - $\sim$ 50 kton PXE
- Photomultipliers
  - 13 500 units
  - 30% coverage
- Photoelectron yield
  - 110 pe/MeV

Possible locations

- New facilities or extensions are required!
- Criteria:
  - Depth, distance to reactors, distance to accelerators ...

Candidate laboratories:

- Underground Science in Boulby mine (UK)
- Underground Science in Pyhäsalmi mine (Finland)
- Polkowice-Sieroszowice mine (Poland)
- Laboratoire Souterrain de Modane (France)
- Laboratorio Subterráneo de Canfranc (Spain)

LAGUNA working activities: ∼60 scientists

- A scientific case document written (arXiv:0705.0116)
- An European proposal for a Design Study is submitted
- Since April 2006 regularly meetings coordinate LAGUNA
- Working groups:
  - WP1: Underground infrastructure
  - WP2: Underground tanks
  - WP3: Tank instrumentation
  - WP4: Pure liquid procurement
  - WP5: Safety and environment
  - WP6: Underground science optimization and outreach
  - WP7: Management and coordination

Outline

Summary

- LENA
  - Good sensitivitvy for proton decay via $p \to K^+ + \overline{\nu}$
  - On-going activities in further proton decay channels
  - Detection of solar and supernova neutrinos
  - High statistics on geoneutrinos
  - Feasibility studies for LENA as beta beam detector
  - Technical feasibility studies
- LAGUNA
  - The physics motivation of this comunity has been presented
  - Three detector approaches are proposed