# Potential of the large liquid scintillator detector LENA in particle and astrophysics

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# Outline

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   - Physics goals
   - Proposed LENA Detector
   - Possible Locations
2. Physics
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   - Supernovae Relic Neutrinos
   - Geoneutrinos
   - Proton Decay
3. Summary and Outlook

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# Physics Goals

**L**ow **E**nergy **N**eutrino **A**stronomy

Supernovae Neutrinos

Geoneutrinos

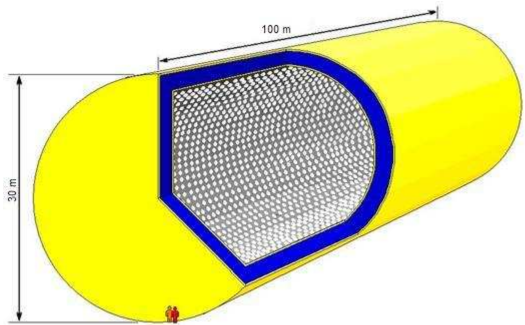
Relic Supernovae Neutrinos

Neutrino Properties

Solar Neutrinos

Proton Decay

# Proposed LENA Detector




**Volume**

$\sim$ 100 m length $\times$ 30 m $\varnothing$

**Liquid Scintillator**

45.000 ton PXE

**Photomultipliers**

12.000 units 30% surface

**Photoelectron yield**

110 pe/MeV

'Centre for Underground Physics' in Pyhäsalmi

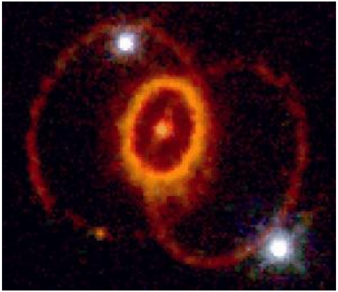

'Nestor Base'
close to the coast at Pylos

# Supernovae Neutrinos

First SN measurement:

SN1987A

- Kamiokande: 11 events
- IMB: 8 events



- D = 10 kpc (center of our galaxy)
- 8 $M_\odot$ ($\Delta E = 2.65.10^{53}$ erg)

In LENA detector:
$\sim$20000 events

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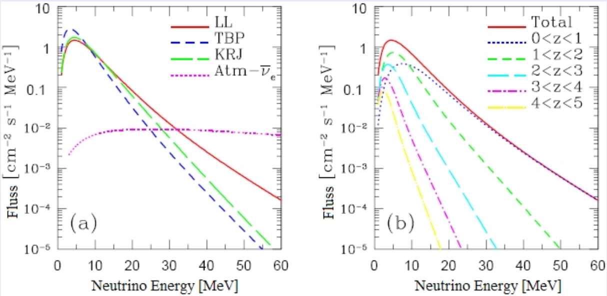
# Detection of Supernovae Neutrinos

- $\overline{\nu}_e + p \rightarrow n + e^+$ (Q=1.8 MeV)
  $n + p \rightarrow d + \gamma$;  $E_\gamma = 2.2$ MeV  ~8700 events
- $\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B} + e^- +$ (Q=17.3 MeV)
  ${}^{12}\mathrm{B} \rightarrow {}^{12}\mathrm{C} + e^+ + \overline{\nu}_e$; $\tau_{1/2} = 20.20$ ms  ~494 events
- $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$ (Q=13.4 MeV)
  ${}^{12}\mathrm{N} \rightarrow {}^{12}\mathrm{C} + e^+ + \nu_e$; $\tau_{1/2} = 11.00$ ms  ~85 events
- $\nu_x + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu_x$
  with ${}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma$;  $E_\gamma = 15.11$ MeV  ~2925 events
- $\nu_x + e^- \rightarrow \nu_x + e^-$ (elastic scattering)  ~610 events
- $\nu_x + p \rightarrow \nu_x + p$ (elastic scattering)
  Detector energy threshold: $E_{th} = 0.2$ MeV  ~7370 events

# Supernovae Relic Neutrinos

## Theoretical Models for the Spectrum




- Current limit: Super-Kamiokande experiment
  - Energy threshold of 19.3 MeV
  - Limit for the Flux: 1.2 cm$^{-2}$ s$^{-1}$

SRN Background:

- Reactor $\overline{\nu}_e$'s up to 13.3 MeV
- Unseen $\mu$'s from atmospheric neutrinos $\nu_\mu$ above 18 MeV
- Spallation products from cosmic $\mu$'s up to 19 MeV
- Atmospheric $\overline{\nu}_e$'s above 30 MeV

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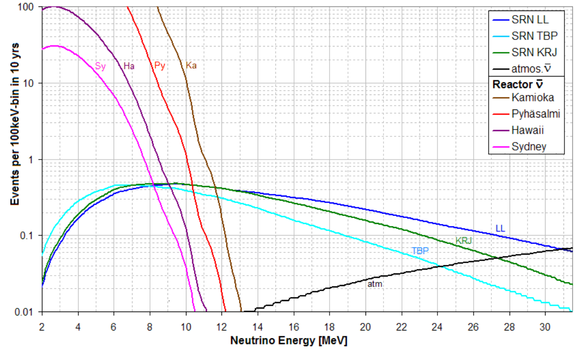
# Detection of Supernovae Relic Neutrinos

## Sensitivity for different locations (by Michael Wurm)




In LENA detector:
(44 kt fiducial volume)

- $\overline{\nu}_e + p \rightarrow n + e^+$
- $n + p \rightarrow d + \gamma$
  - $E_\gamma = 2.2$ MeV

Event rate in 10 y:

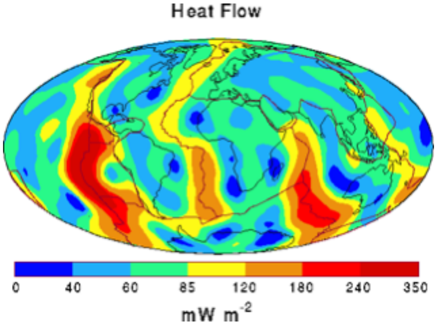
- LL: $\sim$ 42 events
- TBP: $\sim$ 20 events

(discrimination power at 90% C.L.)

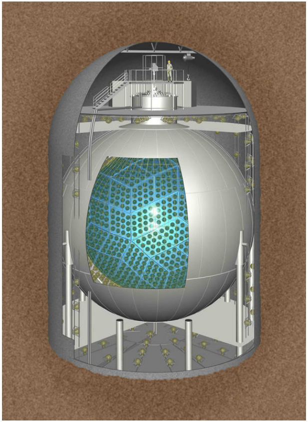
- Valuable information about Star Formation Rate for close Universe (0 < z < 1)

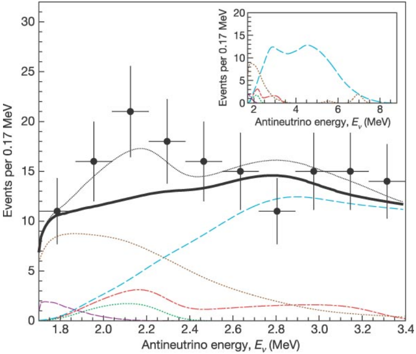
# Geoneutrino Problem

- Unexplained source of heat flow on Earth
- Unknown contribution of natural radioactivity
- How are $^{238}U$, $^{232}Th$ distributed on core, mantle and crust?
- Is it possible to have a nuclear reactor in the center of the Earth?



# Geoneutrino First Detection: KamLAND Experiment






- $\overline{\nu}_e + p \rightarrow n + e^+$
- 4.5 - 54.2 events at 90% C.L.
- Detector lifetime: 749.1±0.5 d

- In LENA detector:

  ∼ 3000 events/y

  (Kathrin Hochmuth)

# Proton Decay: Theoretical Predictions

## GUT SU(5)

Dominant decay mode: $p \rightarrow e^+\pi^0$ $\tau \sim 10^{31}$ y

- Superkamiokande: $\tau \gtrsim 5.4 \cdot 10^{33}$ y (90% C.L.)

## Supersymmetry (SUSY)

Dominant decay mode: $p \rightarrow K^+\overline{\nu}$ $\tau \lesssim 10^{35}$ y

- Superkamiokande: $\tau \gtrsim 2.3 \cdot 10^{33}$ y (90 % C.L.)

## Supergravity

Dominant mode: $p \rightarrow \pi^+\overline{\nu}$ BR: 65.7 %
Second mode: $p \rightarrow K^+\overline{\nu}$ BR: 33.5 %

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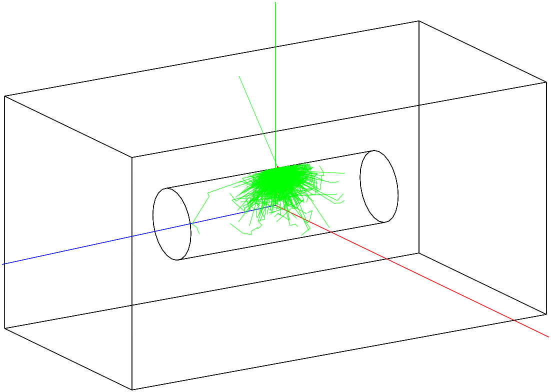
# Simulation with Geant4



- Monte Carlo calculations
- Scintillation
- Light propagation
  - Absorption length
  - Scattering length
- Quenching factors
  - Birk's formula
- Photomultipliers:
  - Time jitter $\sigma = 1$ 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
- $\pi^+ \to \mu^+\nu_\mu$  $\pi^0 \to \gamma\gamma$

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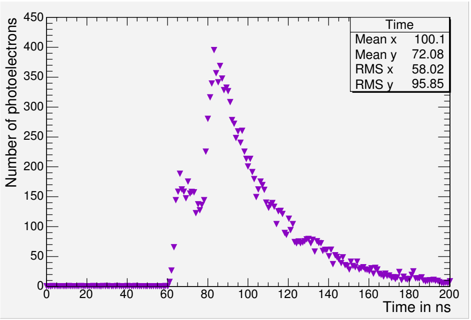
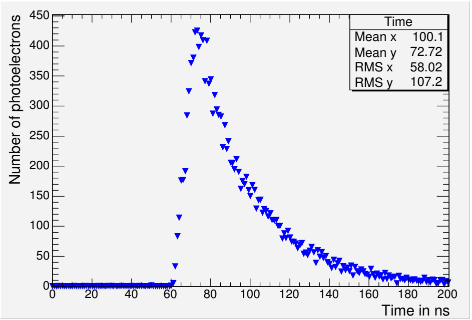
# Signals of Proton Decay in LENA

- Kaon decay after 18 ns




- Kaon decay after 5 ns

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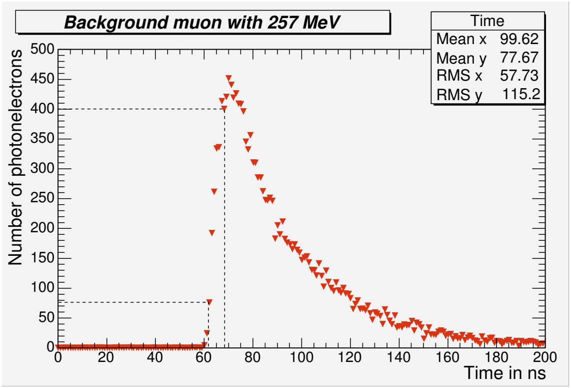
# Background: Muon Production by Atmospheric $\nu_\mu$




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

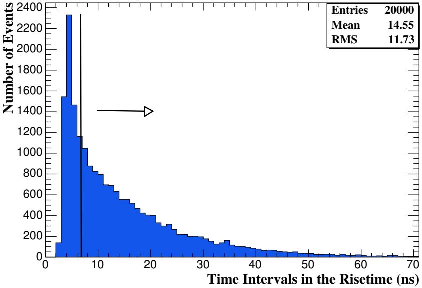
**Background rate from Superkamiokande**

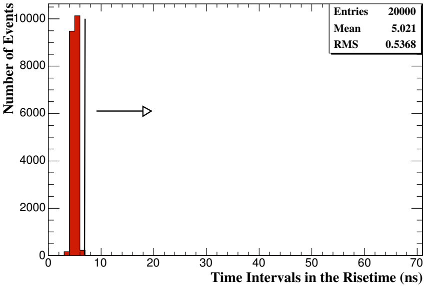
$\Gamma = 4.8 \cdot 10^{-2}$ $(MeV^{-1}kt^{-1}y^{-1})$

- Pulse shape analysis
  - Risetime

# Background Rejection: Time Cut

- Efficiency: $\varepsilon_T = 0.65$




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

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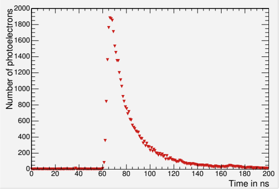
# Background: Hadron Production by Atmospheric $\nu_\mu$

## Pion Production

- $\nu_\mu + p \rightarrow \mu^- + \pi^+ + p'$
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \tau_{\pi^+} = 26$ ns
  - $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$

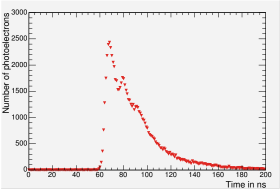



## Kaon Production

- $\Delta S = 1$ 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
  - $\Lambda^0 \rightarrow n + \pi^0$

  $\nu_\mu + n \rightarrow \mu^- + K^+ + \Lambda^0 + \pi^0$

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

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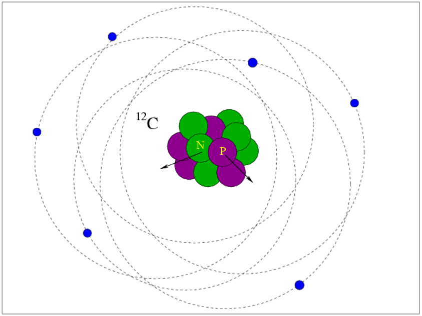
# Protons from $^{12}C$: Nuclear Effects



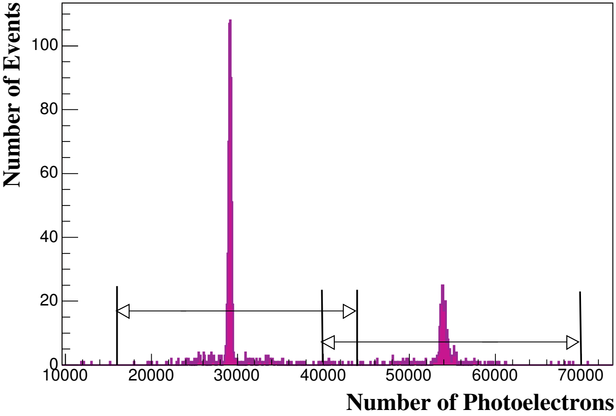

## Binding energy

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

## Fermi Motion

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

# Background Rejection: Energy cut




- Two peaks:
  - Kaon + Muon $\sim 257$ MeV
  - Kaon + Pions $\sim 459$ 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)

# Summary and Outlook

- Summary
  - Technical feasibility studies very promising
  - Flavour sensitivity in Supenovae Neutrino measurements
  - Possibility to measure Supernova Relic Neutrinos for the first time
  - High statistics on geoneutrino flux ( $\sim$ 3000 events/y)
  - A proton lifetime of $\tau \sim 4 \cdot 10^{34}$ y reachable in LENA
    *(T. Marrodán et al., Phys. Rev. D 72 (2005) 075014)*

- Outlook
  - Detector design studies
  - LENA project proposal
  - Technical feasibility studies

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