Physics with the large liquid-scintillator detector LENA

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Excellence Cluster for Fundamental Physics
'Structure and Origin of the Universe'

Neutrinos in Cosmology, Astro, Particle & Nuclear Physics
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LENA

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

Liquid Scintillator
ca. 50kt PXE/LAB

Inner Nylon Vessel
radius: 13m

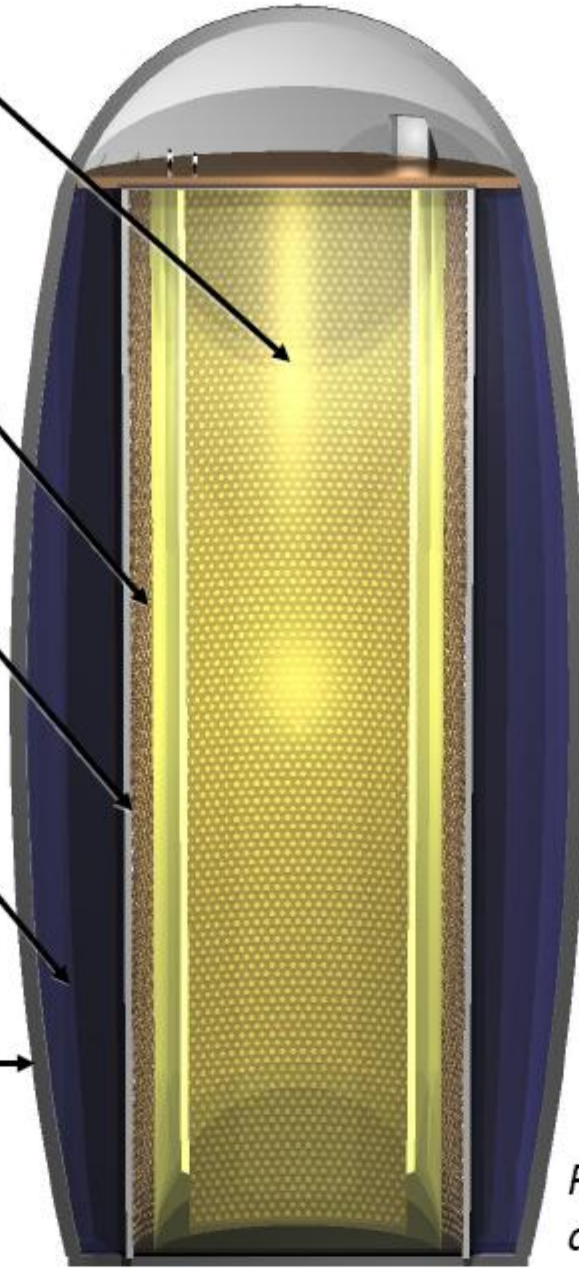
Buffer Region
inactive, Δr = 2m

Steel Tank, 13500 PMs
r = 15m, h = 100m,
optical coverage: .3

Water Cherenkov Veto
1500 PMTs, Δr > 2m
fast neutron shield

Egg-Shaped Cavern

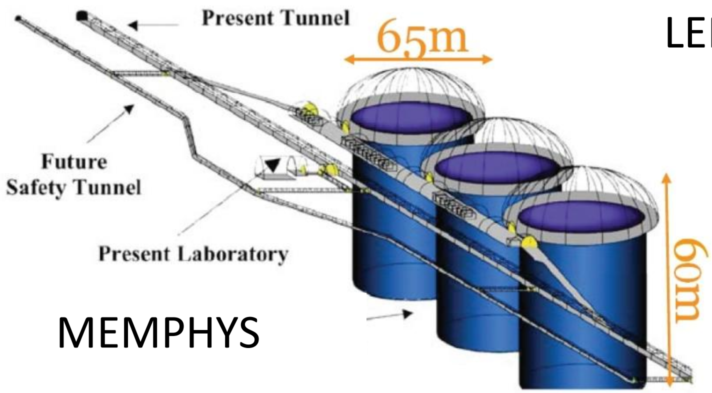
Overburden: 4000 mwe

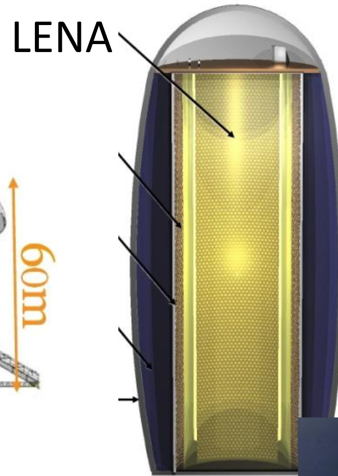


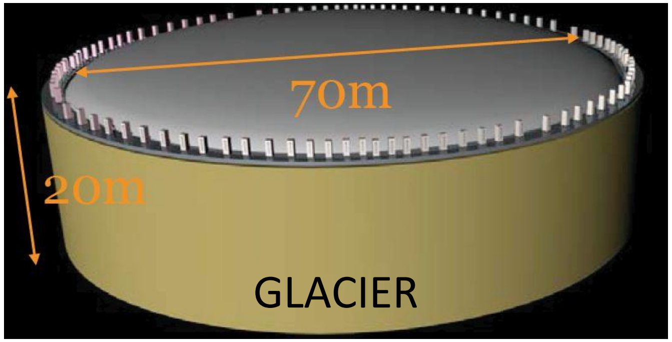
Pyhäsalmi design

Large Liquid Scintillator Detector

One of the 3 options studied in the LAGUNA design study:
FP7 funded feasibility study for European underground sites

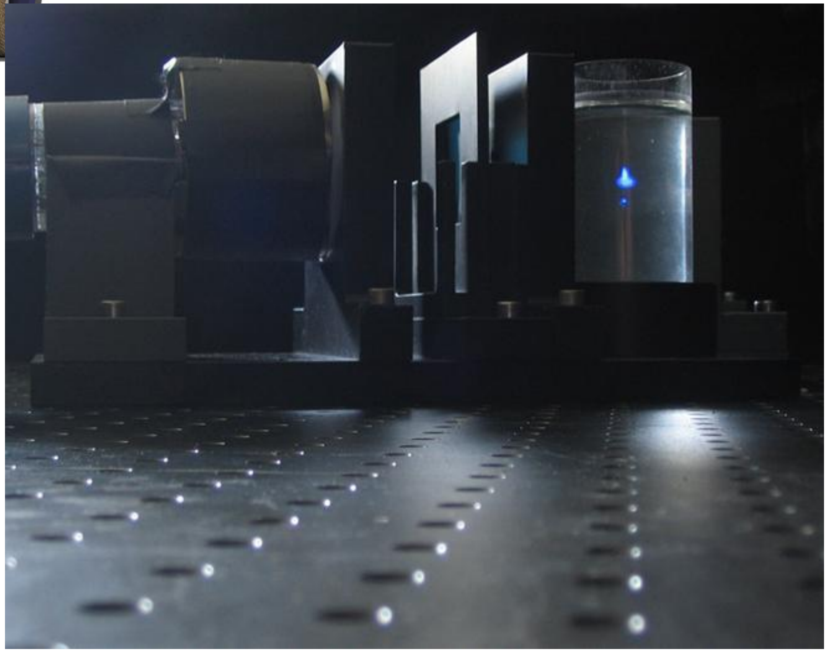






Optical properties demonstrated in laboratory measurements:

- absorption length > 20m
- scattering length ~ 20m
- fast time constant ~ 3ns (PXE)



⇒ suitable for LENA

LENA Physics goals

- Proton Decay
- Diffuse Supernova Neutrino Background
- Galactic Supernova Burst
- Solar Neutrinos
- Geo neutrinos
- Reactor neutrinos
- Beta-beam neutrinos
- Atmospheric neutrinos
- Dark Matter indirect search

Proton decay – Motivation

Non supersymmetric Grand Unified Theories

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

current best limit (Super-K): $\tau(p \rightarrow e^+\pi^0) \gtrsim 8.2 \cdot 10^{33}$ y (90% C.L.)

Phys.Rev.Lett. 102, 141801 (2009)

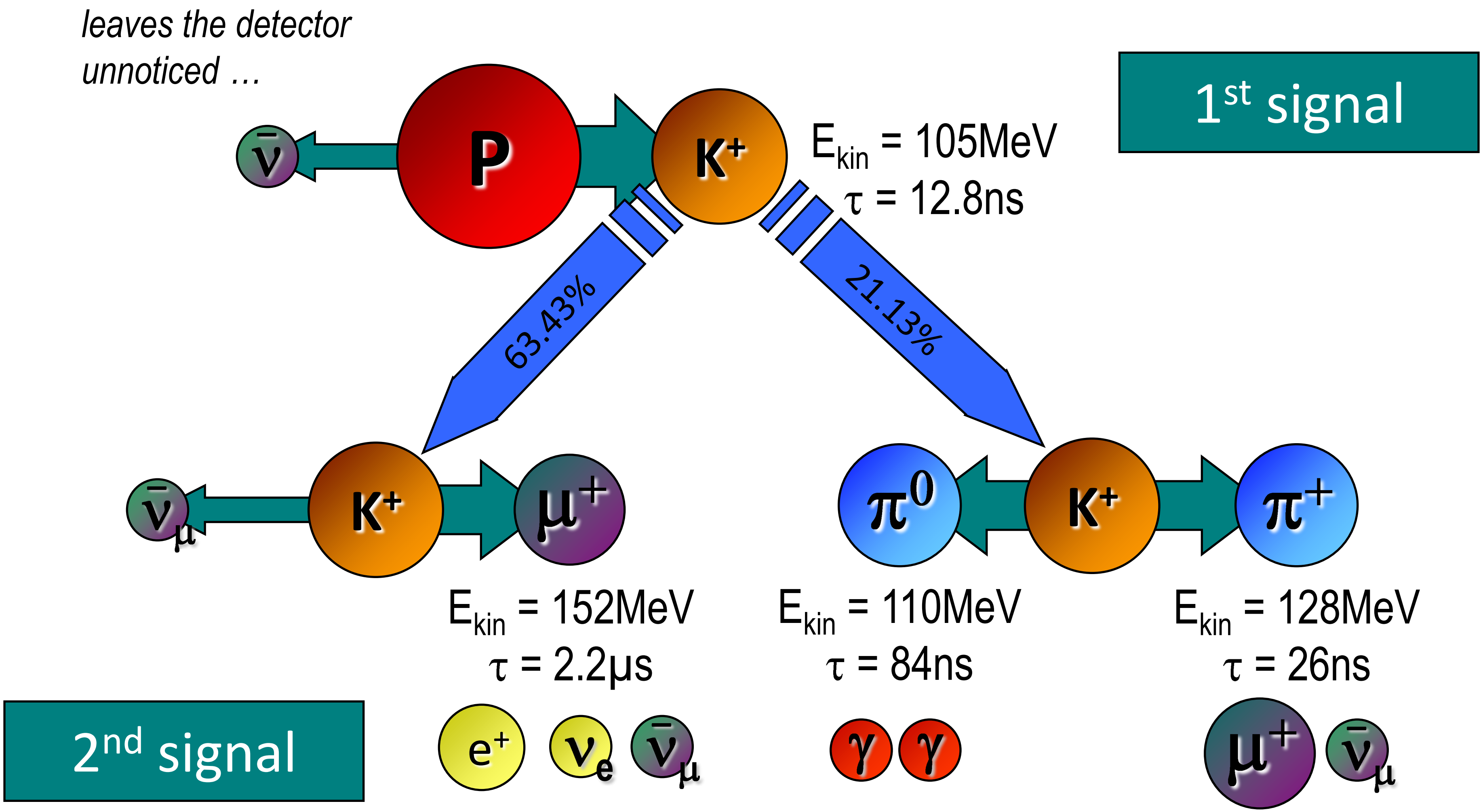
Supersymmetry (SUSY)

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

current best limit (Super-K): $\tau(p \rightarrow K^+\overline{\nu}) \gtrsim 2.3 \cdot 10^{33}$ y (90 % C.L.)

Proton decay channel $p \rightarrow K^+\bar{\nu}$

Event signature

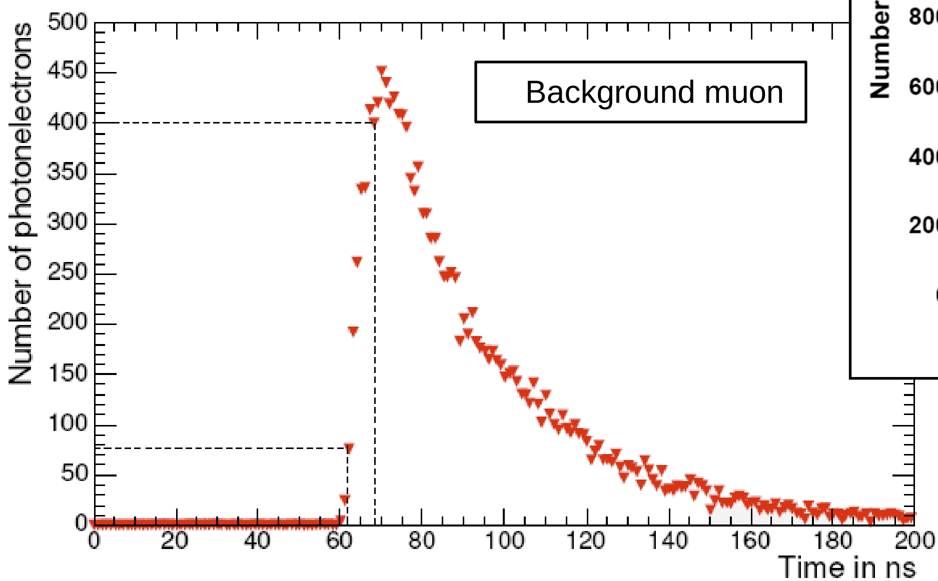


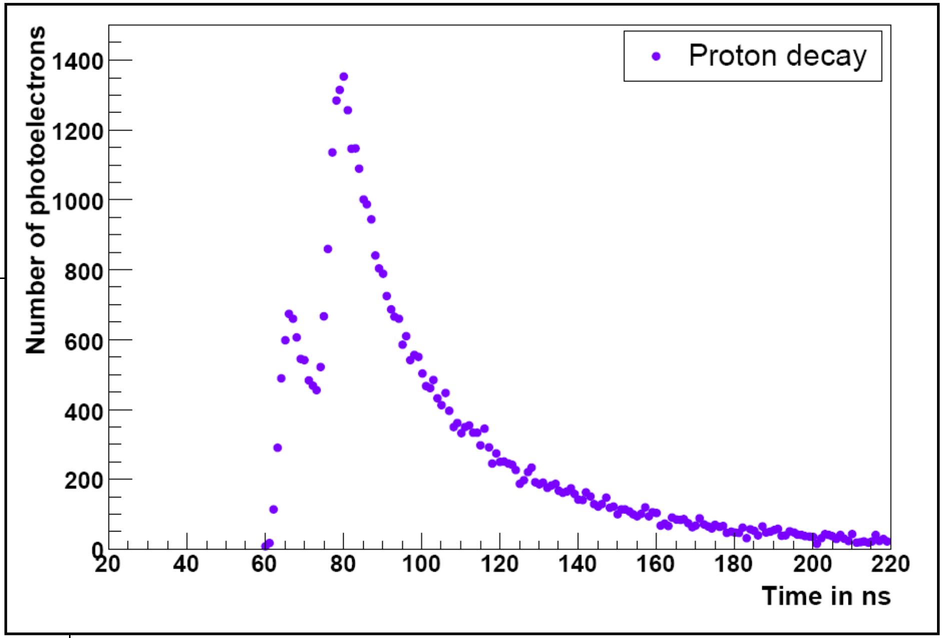
Proton decay channel $p \rightarrow K^+\bar{\nu}$

In a liquid scintillator detector: K^+ visible

$\Rightarrow$ 3-fold coincidence, the first 2 events are monoenergetic!
(plus position correlation)

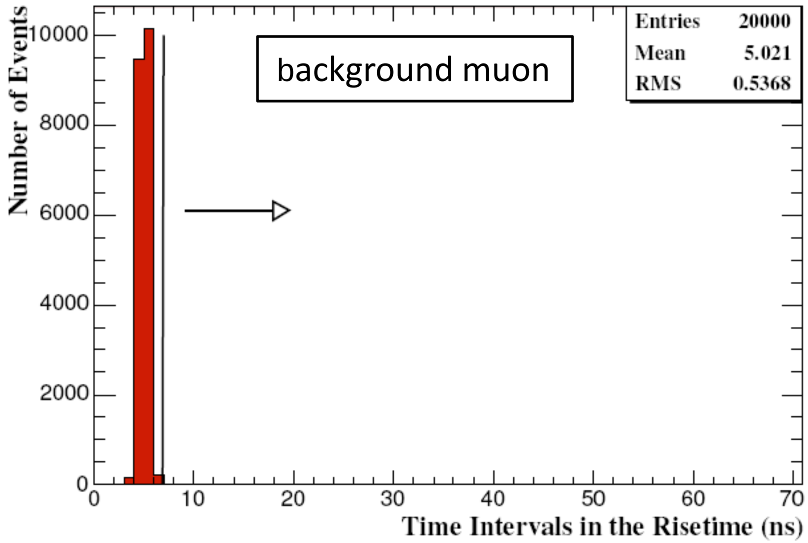
$\Rightarrow$ high efficiency and very good background rejection

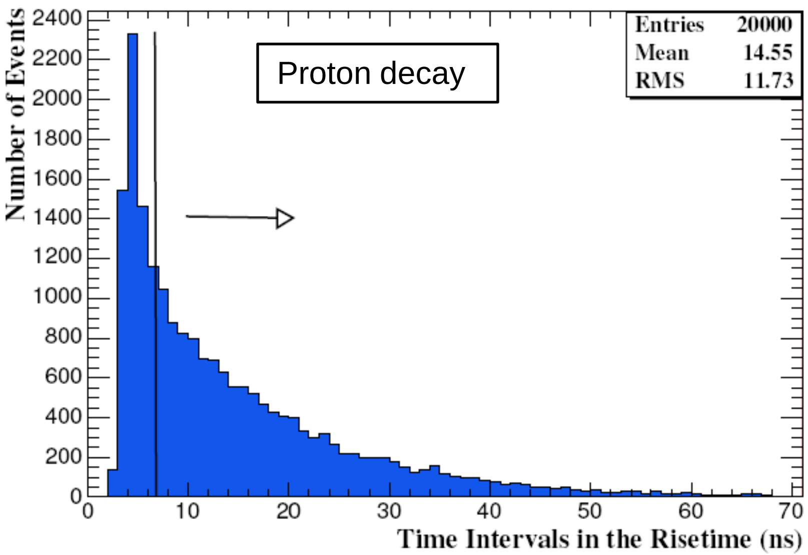




MC simulation with LY=180 p.e./MeV optical model of the detector using GEANT4

Background rejection





Efficiency of the rise-time cut for proton decay events: 65%

Background reduction factor
$B \approx 5 \times 10^{-5}$

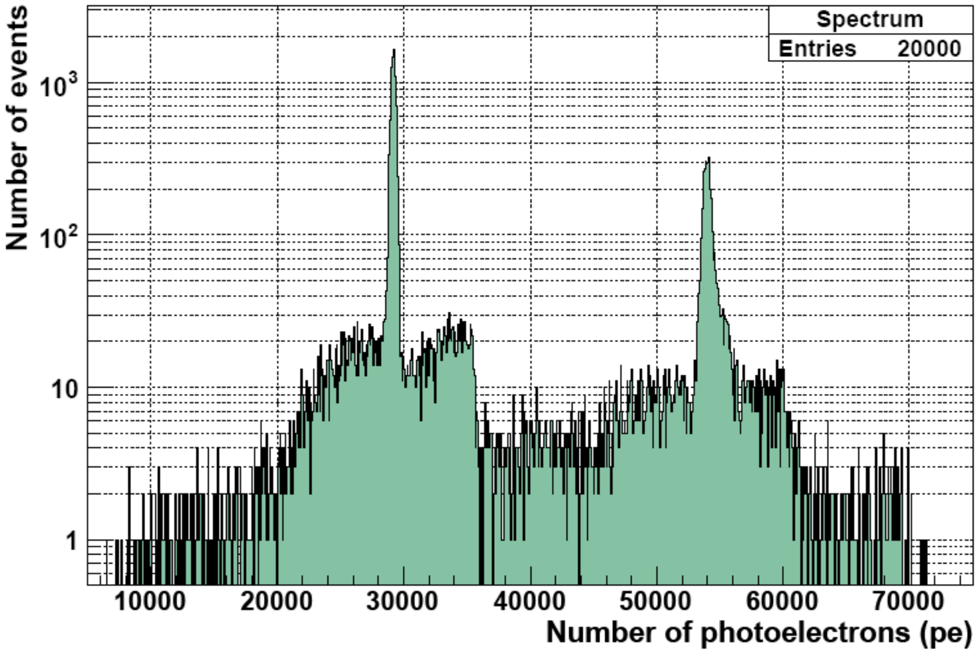
Remaining background sources (from atmospheric ν_μ)

$$\nu_\mu + p \rightarrow \mu^- + \pi^+ + p'$$

$$\nu_\mu + p \rightarrow \mu^- + K^+ + p$$

estimated rate: 0.064 yr^{-1}

Sensitivity to proton decay $p \rightarrow K^+\bar{\nu}$



Simulated energy spectrum of 20000 proton decay events into Kaon channel (light yield 180 p.e./MeV)

Two peaks:

- Kaon + Muon ~ 257 MeV
- Kaon + Pions ~ 459 MeV

Energy-cut efficiency ε_E=99.5%

Bound protons of ^{12}C included.

Potential of LENA (10 y measuring time)

- For Superkamiokande current limit: $\tau = 2.3 \cdot 10^{33}$ y
  - About 40 events in LENA and $\lesssim$ 1 background
- Limit at 90% (C.L) for no signal in LENA:
  - $\tau > 4.1 \cdot 10^{34}$ y with $\epsilon = 65\%$

Diffuse Supernova Neutrino Background

DSNB detection via inverse beta decay

- Free protons as target

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

Delayed signal (~200 μs)

Prompt signal

- **Threshold 1.8 MeV**

Spectroscopy of antineutrino flux: $E_e = E_\nu - 0.8$ MeV

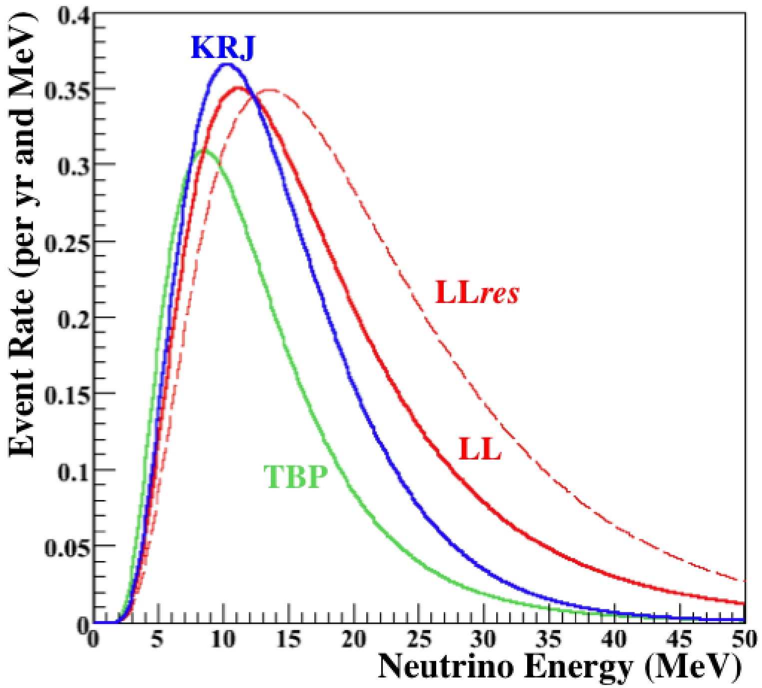
Suppress background via delayed coincidence method

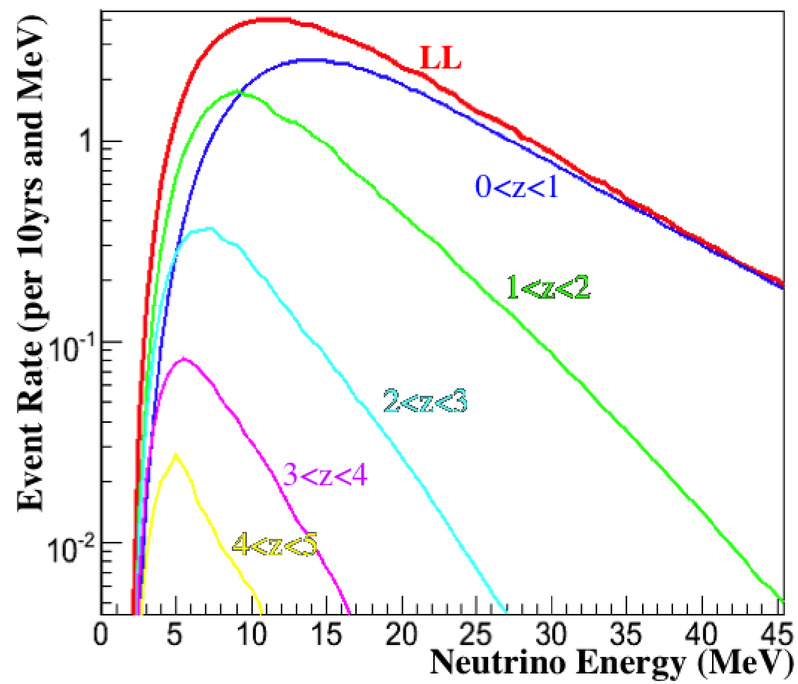
$$n + p \rightarrow D + \gamma \quad (2.2 \text{ MeV})$$

Position reconstruction allows to define a fiducial volume (suppress external background)

Diffuse Supernova Neutrino Background

Expected rates in LENA





... depend strongly on the used SN model.

Integral rate for 44 kt yrs and f_{SN}=1.0:

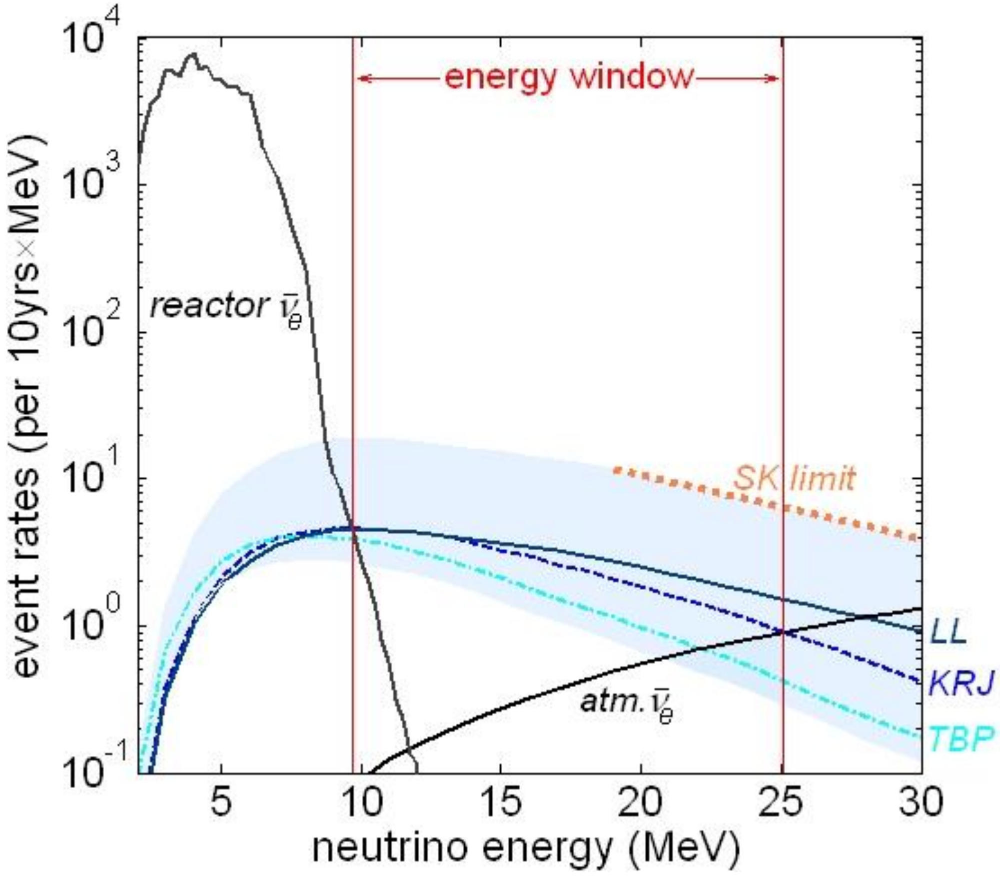
TBP	KRJ	LL	LL_{res}
4.7	6.1	6.8	7.7

Dominant flux contribution:

z<1 for E>10MeV
z>1 for E<10MeV

due to cosmic redshift.

Diffuse Supernova Neutrino Background



DSN event rate in 10yrs
inside the energy window from 9.7 to 25 MeV

dependent on SN model

LL:	110
KRJ:	100
TBP:	60

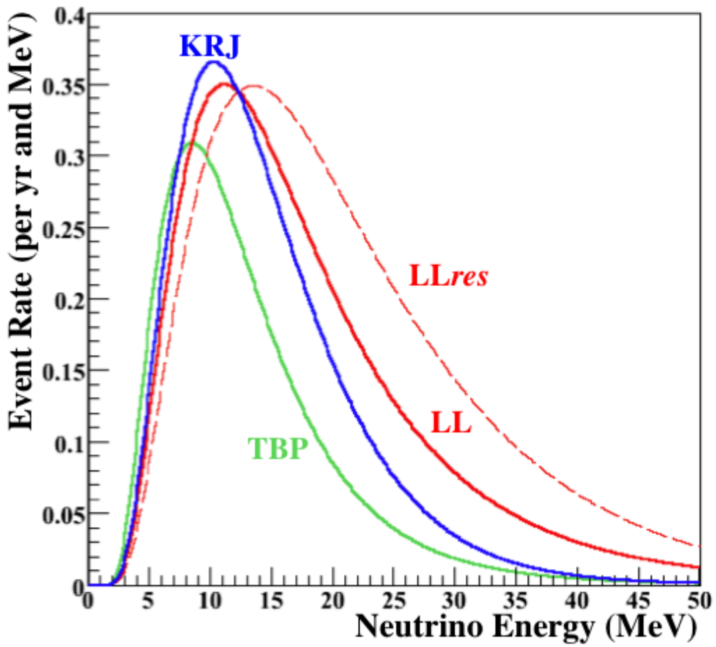
dependent on SNR

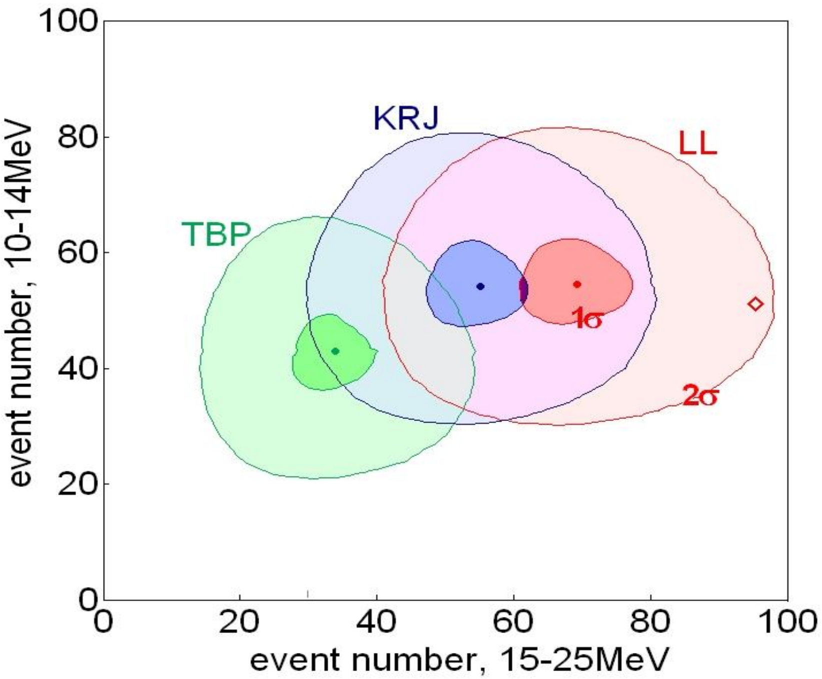
f_{SN}=0.7	17
f_{SN}=2.5	100
f_{SN}=4.2	220

background events < 1 y^{-1}

Diffuse Supernova Neutrino Background

- Excellent background rejection
- Energy window 10 to 30 MeV.
- High efficiency (100% with 50 kt target)
- High discovery potential in LENA
  ~2 to 20 events per year are expected
  (model dependent)





A galactic SN in LENA

$8\ M_{\odot}$ ($3 \cdot 10^{53}$ erg) at D = 10 kpc (galactic center)

In LENA detector: $\sim$15000 events

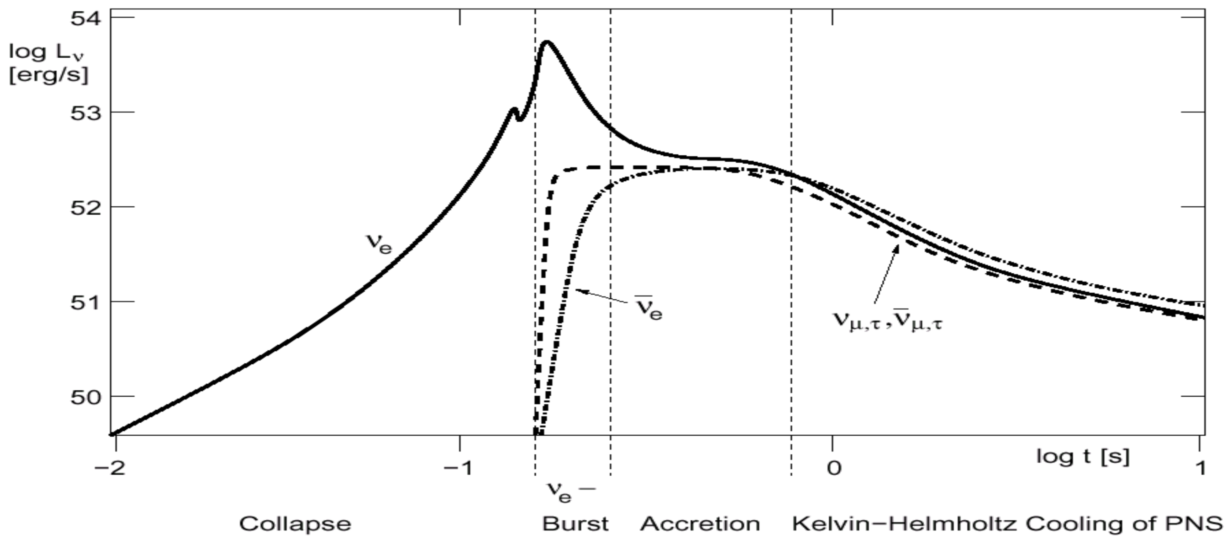
Possible reactions in liquid scintillator

- $\overline{\nu}_e + p \rightarrow n + e^+;\ n + p \rightarrow d + \gamma$ $\sim$ 7 500 - 13 800
- $\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B} + e^+;\ {}^{12}\mathrm{B} \rightarrow {}^{12}\mathrm{C} + e^- + \overline{\nu}_e$ $\sim$ 150 - 610
- $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N};\ {}^{12}\mathrm{N} \rightarrow {}^{12}\mathrm{C} + e^+ + \nu_e$ $\sim$ 200 - 690
- $\nu_x + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu_x;\ {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma$ $\sim$ 680 - 2 070
- $\nu_x + e^- \rightarrow \nu_x + e^-$ (elastic scattering) $\sim$ 680
- $\nu_x + p \rightarrow \nu_x + p$ (elastic scattering) $\sim$ 1 500 - 5 700

Diploma thesis by J.M.A. Winter (TU München)

A galactic SN in LENA

High statistics
energy dispersive
time dispersive
flavour resolving



Channel	Rate	Threshold (MeV)	Spectrum
$\bar{\nu}_e\, p \rightarrow n\, e^+$	8900	1.8	✓
$\nu_e\, {}^{12}C \rightarrow {}^{12}N\, e^-$	200	17.3	(✓)
$\bar{\nu}_e\, {}^{12}C \rightarrow {}^{12}B\, e^+$	130	13.4	(✓)
$\nu\, {}^{12}C \rightarrow {}^{12}C^*\, \nu$	860	15.1	✗
$\nu\, p \rightarrow p\, \nu$	2200	1.0	✓
$\nu\, e^- \rightarrow e^- \nu$	700	0.2	✓

A galactic SN in LENA

Discrimination of SN models

	TBP	KRJ	LL
$\nu_x + {}^{12}\mathrm{C}$	700	950	2100
$\nu_x + p$	1500	2150	5700

for a progenitor of $8M_{\odot}$ (10kpc distance)

Discrimination is possible independent from (collective) oscillations or resonant flavour transformation in the NC reactions

$$\nu_x + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu_x; \quad {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma$$

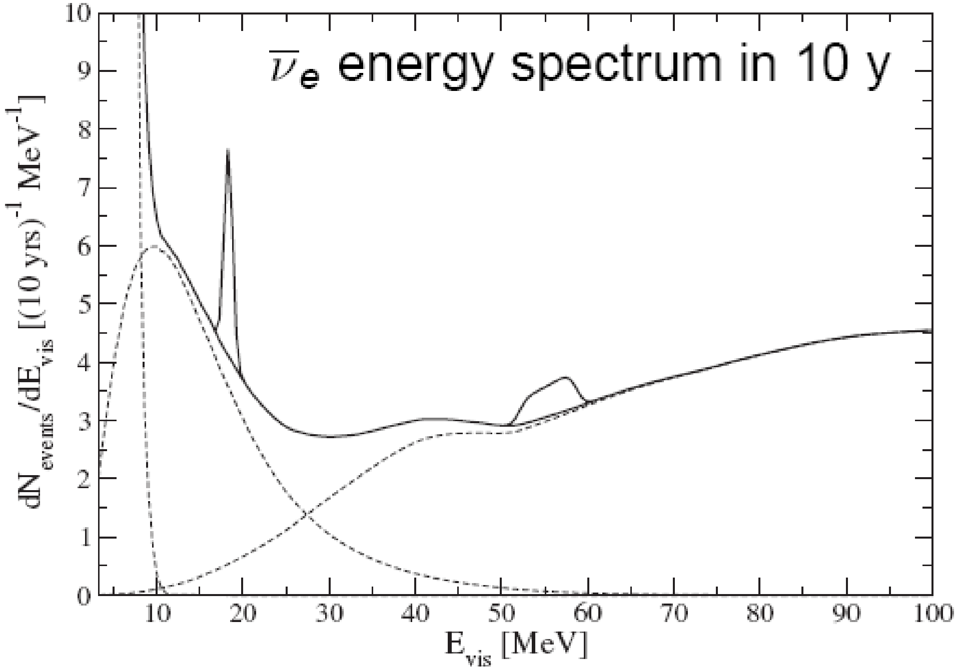
$$\nu_x + p \rightarrow \nu_x + p$$ (elastic scattering)

Observation of a galactic SN

What can we learn?

- Antielectron ν spectrum with high precision
- Electron ν flux with ~ 10 % precision
- Total flux via neutral current reactions
- Separation of SN models
- Spectroscopy of all ν flavors
- Time evolution of neutrino burst
- Details of SN gravitational collapse
- Chance to separate low/high Θ_{13} and mass hierarchy (normal/inverted)
- Coincidence with gravitational wave detectors

Indirect WIMP detection



S. Palomares-Ruiz and S. Pascoli, Phys. Rev. D 77, 025025 (2008)

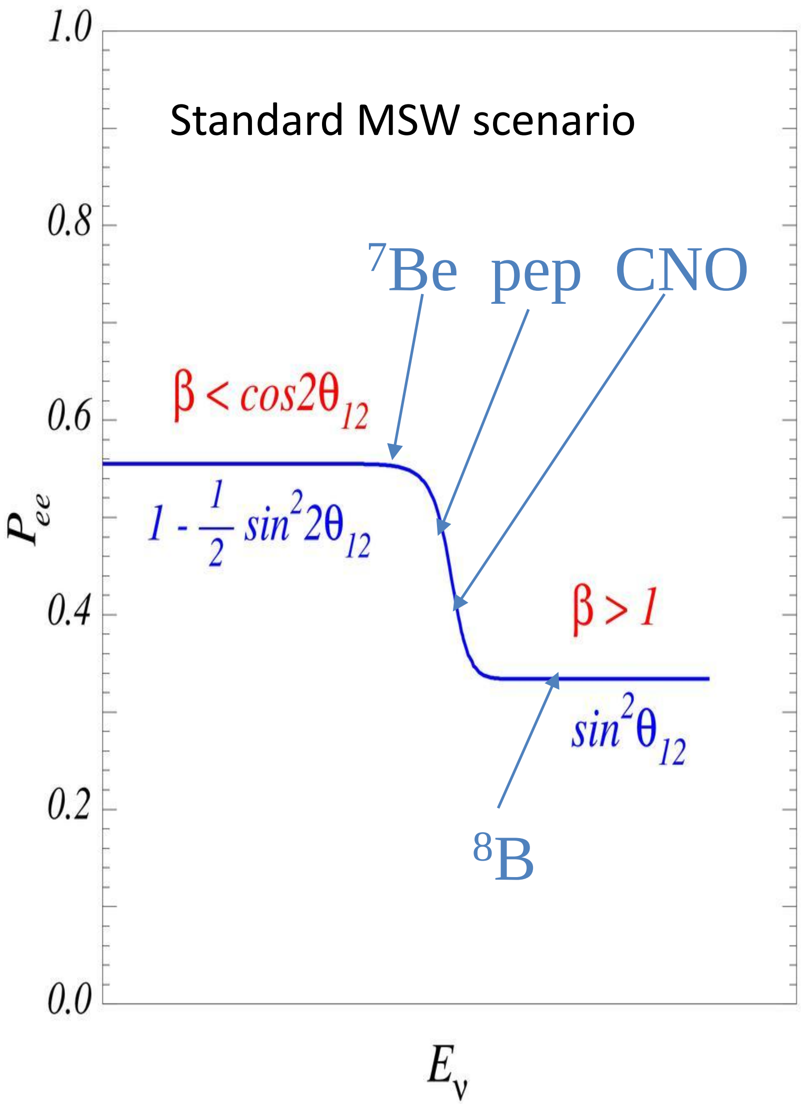
- Annihilation of light WIMPs

$$\chi\chi \rightarrow \nu\overline{\nu}$$

  - Clear signature of $\overline{\nu}_e$ in liquid scintillator
  - Background from reactor, atmospheric and diffuse supernove neutrinos

- Light WIMP mass between 10 and 100 MeV
- Annihilation under neutrino emission in the galactic halo
- Monoenergetic electron-antineutrino detection in LENA

Solar neutrinos in LENA



Rates of solar neutrino events

In the LENA fiducial volume:

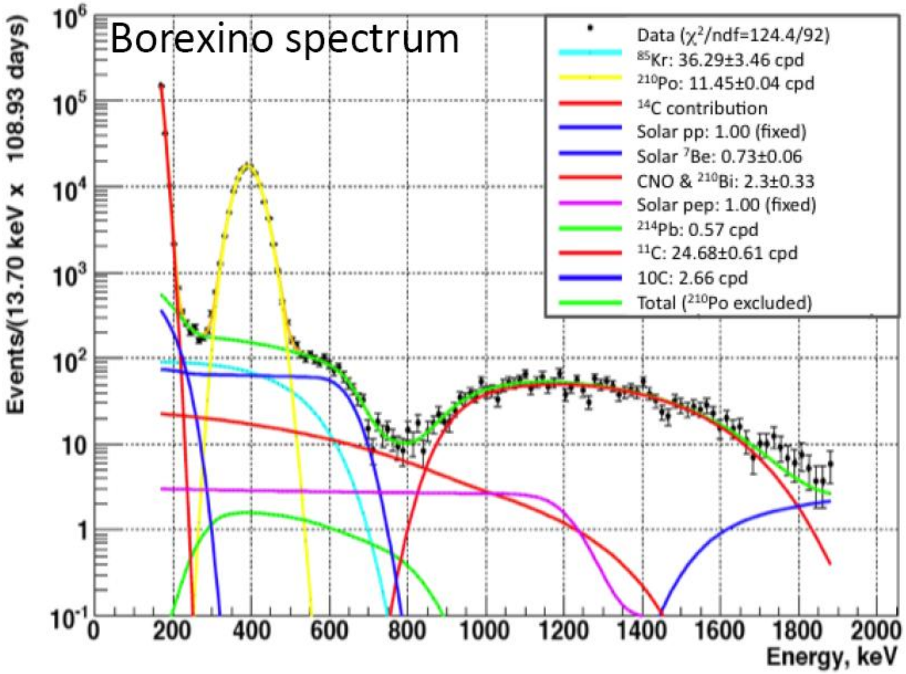
$$18 \cdot 10^3\ \mathrm{m}^3$$

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

Solar neutrinos in LENA

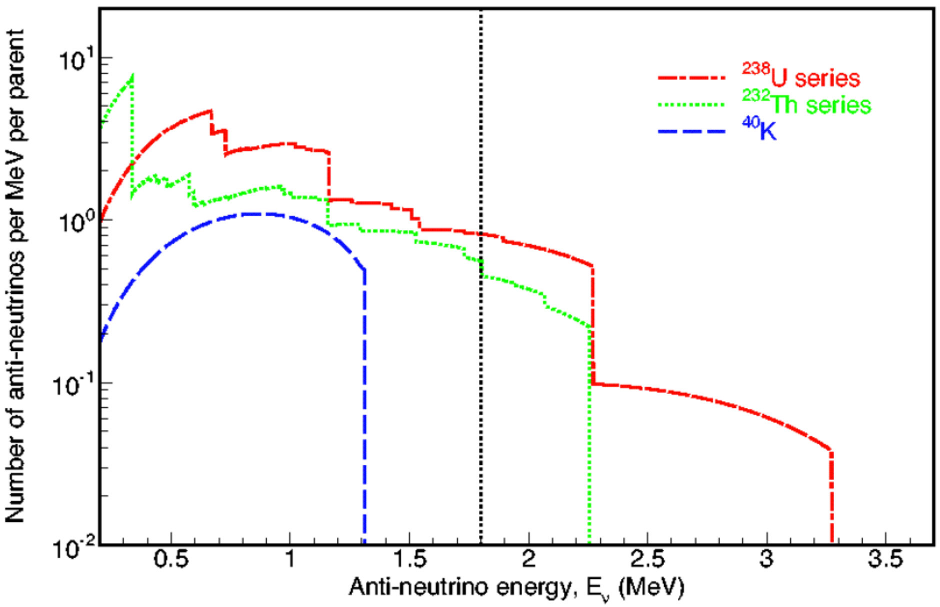
... assuming 18kt fiducial volume

Channel	Source	Neutrino Rate [d^{-1}]	
		BPS08(GS)	BPS08(AGS)
νe	pp	24.92±0.15	25.21±0.13
	pep	365±4	375±4
	hep	0.16±0.02	0.17±0.03
	^{7}Be	4984±297	4460±268
	^{8}B	82±9	65±7
	CNO	545±87	350±52
^{13}C	^{8}B	1.74±0.16	1.56±0.14



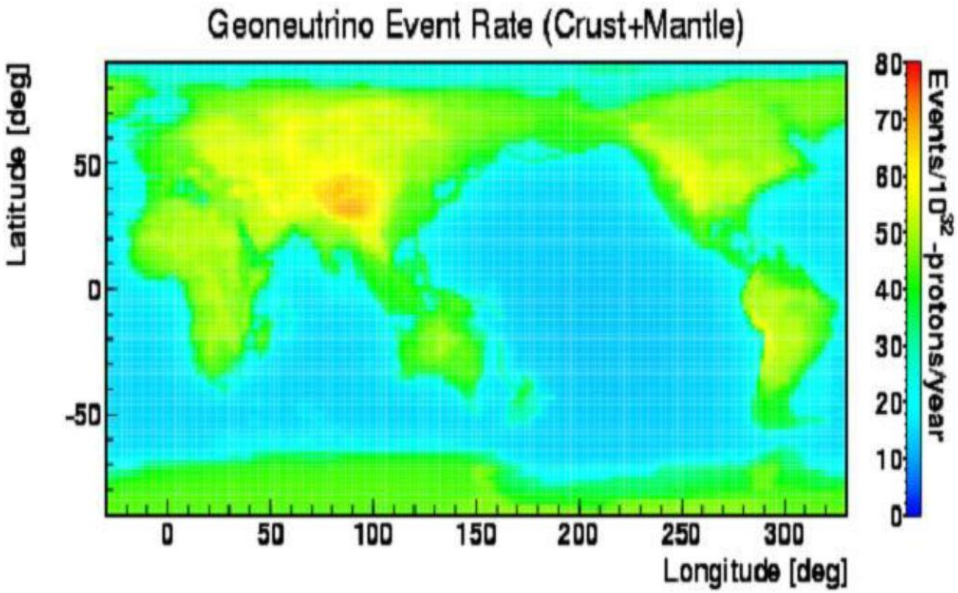
- **^{7}Be:** solar metallicity Z, search for rate modulations
  depends on radiopurity
- **pep:** Survival probability in the MSW-vacuum transition region
  depends on depth (^{11}C bg)
- **^{8}B:** Z, onset of MSW effect for energies between 2 and 5 MeV
  also cosmogenics
- **CNO:** solar Z, stellar evolution
  like pep

Geo-Neutrinos



Detect anti-neutrinos of the U, Th decay chains (inverse β-decay energy threshold is 1.8 MeV).

Expected event rate at Pyhäsalmi :
1.5x10^3 events/year in 50 kt
Background from reactors:
240 events/year in 50 kt
in the relevant energy window

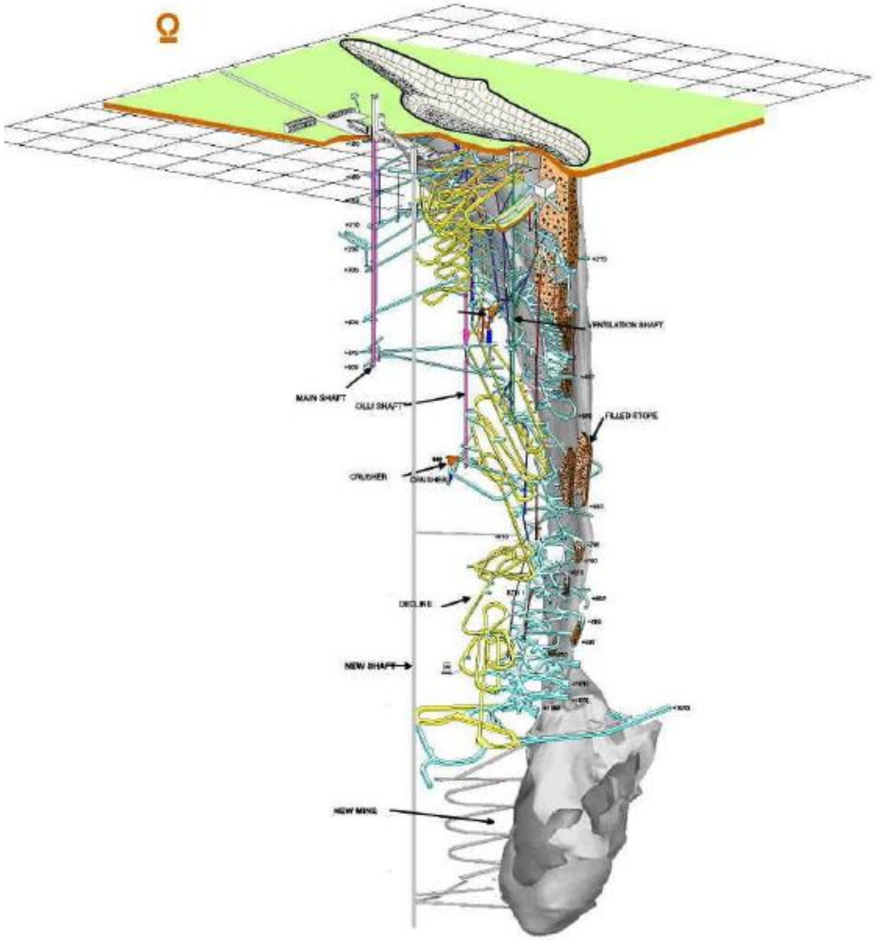


measure flux from crust and mantle

determine U/Th ratio

disentangle continental/oceanic crust with more than one detector location

Pre-feasibility study within LAGUNA



ROCKPLAN, Finland, together with TU München: pre-feasibility study for **a LENA detector at Pyhäsalmi**

- depth of 1400-1500 m possible
- geological study completed
- vertical detector position
- infrastructure (ventilation, electricity, etc.) considered
- construction time of cavern ~ 4 yrs
- first cost and time estimate for the whole project

Summary

LENA is a multi-purpose detector with high discovery potential.
Physics program covers particle physics, astrophysics and geo physics.
Very rare event searches as well as high-statistics measurements of astrophysical sources are possible.
Main advantages are good energy resolution, low energy threshold, and excellent background reduction capabilities.

Not covered in this talk:
LENA as a detector for long-baseline neutrino beam experiments (on-going work).