Advances in Neutrino Technology
Philadelphia - October 10-12, 2011

The neutrino observatory LENA

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Outline

- LENA design
- PMTs and Readout Electronics
- Liquid Scintillator
- Physics goals: from low to high-E physics
- Summary

Philadelphia perspective...

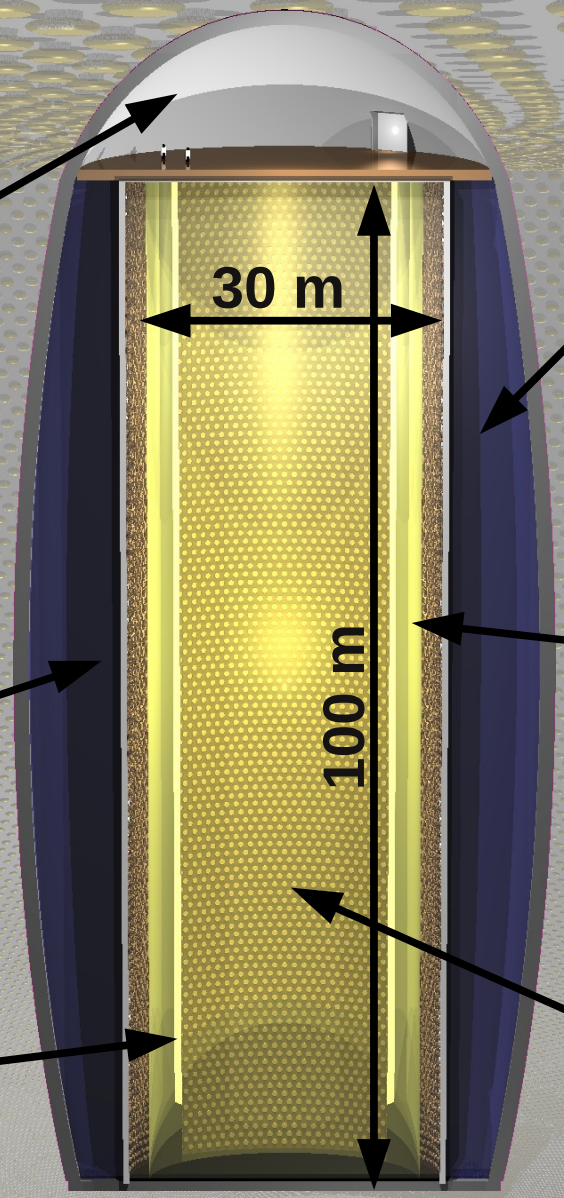
LENA Design

Cavern
Height 115 m
Diameter 50 m
- Shielding of cosmic rays with 4000 m.w.e.
- Egg-shaped for increased stability

Steel Tank
Height 100 m
Diameter 30 m

~65,000 PMTs (8“) with Winston Cones (1.75 x)

Nylon Vessel
between buffer and target volume



Muon Veto
- plastic scintillator panels on top
- 100 kt Water Cerenkov Detector with 5,000 8" PMTs

→ fast neutron background reduction

Buffer Volume
Thickness 2m
Non-scint. organic liquid shielding external radioactivity

Target Volume
Height 100 m
Diameter 26 m

50 kt of organic liquid scintillator

LENA Design

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Height 115 m
Diameter 58 m
• Shielding of cosmic rays with 4000 m.w.e.
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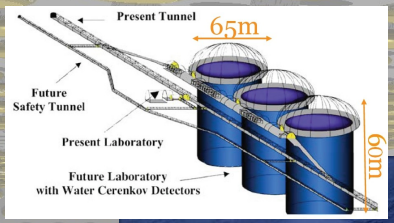
between buffer and target volume

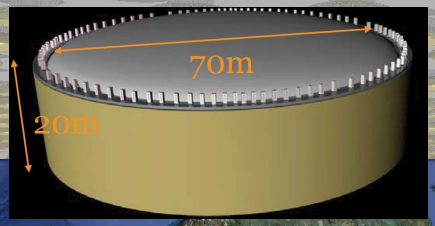
Target Volume
Height 100 m
Diameter 26 m
50 kt of organic liquid scintillator

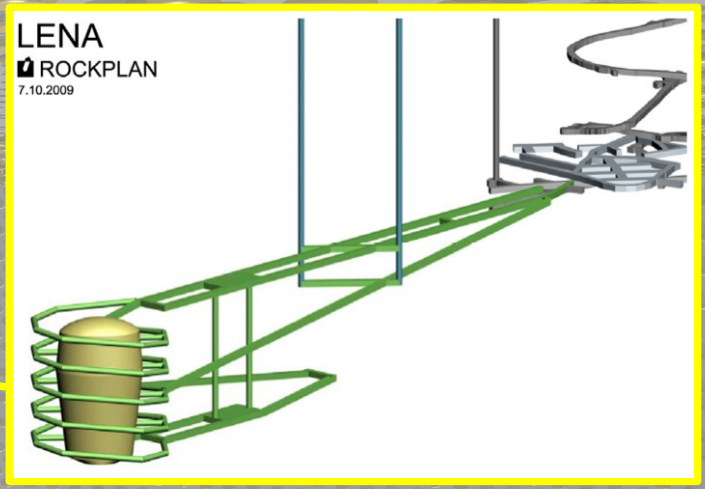
Detector properties

- **Good Energy Resolution**
  ~ 200 photoelectrons per MeV
- **Low Detection Threshold**
  ~200 keV (due to intrinsic ^{14}C background)
- **Excellent Background Reduction**
  - coincidence signals (inverse beta decay)
  - pulse shape discrimination
- **Radiopurity**
  → experience from Borexino
- **Self-shielding** monolithic detector shield its central volume against external backgrounds

LAGUNA site study





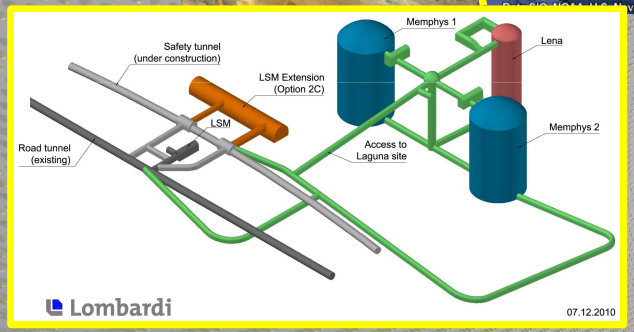


LAGUNA site study
(Large Apparatus for Grand Unification and Neutrino Astronomy)

- EU funded FP7 study
- 3 detectors, 7 locations

Possible LENA locations (>4 km.w.e)

→ Pyhäsalmi (FIN)
→ Fréjus (F)



Dedicated talks:

→ Site comparison: W. Trzaska
→ Geotechn. studies @ Pyhäsalmi: G. Nuijten

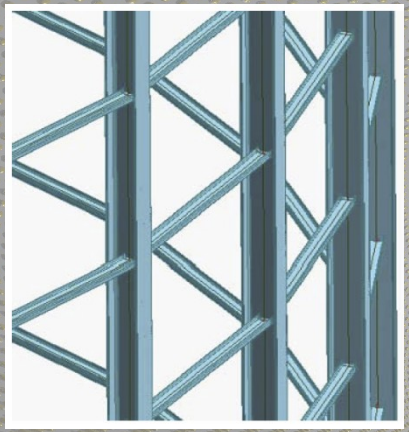
LENA tank design

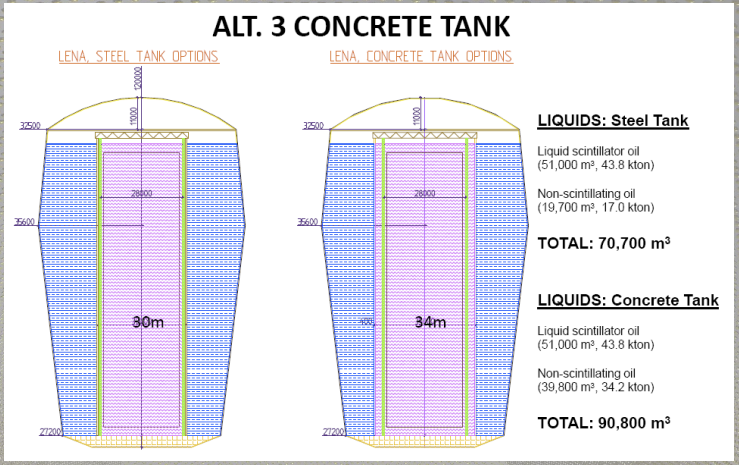
- **Steel**

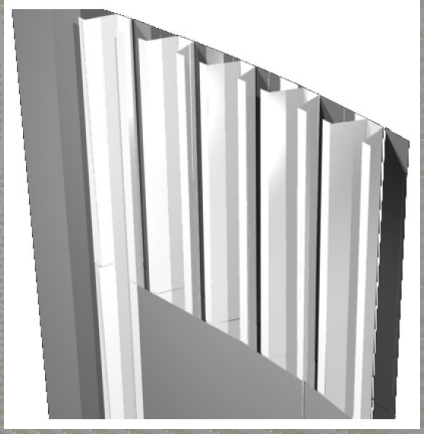
  i. Conventional Steel Tank: well known technology, but expensive
  ii.Sandwich Steel Tank: cost effective, yet mechanically challenging

- **Concrete**
  - bigger tank due to internal radioactivity → more LS, bigger excavation
  - Cheaper than steel and more stable
    → in total not more expensive

  i. Sandwich Concrete Tank: well known technology, yet slow to build
  ii.Hollow Core Concrete Tank: mechanically strong, little known technology







Detector performance

Scintillator
- Decay Times
- Light Yield
- Attenuation length
- Scattering lenght
- Radiopurity
- ...

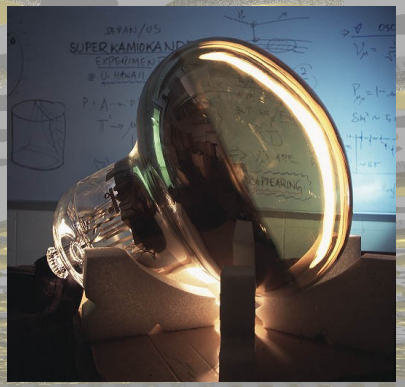
Photosensors
- Photo detection efficiency
- Spectral response
- Optical coverage
- Granularity
- ...

Electronics
- Dynamic Range
- Trigger
- Sampling
- ...

Monte Carlo simulations

Physics program and potential

Photosensors



→ See talk this afternoon

- Good energy resolution
  - ~30% optical coverage
  - 3000m² effective photosensitive area
  - Light yield ≥ 200 pe/MeV
- Good timing resolution

PMT Ø	# PMTs in ID	
	No light concentrators	Light concen-trators (1.75)
5''	329,300	188,200
8''	110400	63,000
10''	82,300	47,000
20''	21,600	12,300

PMT testing in Garching and Borexino test stand @LNGS

→ characteristics of possible PMTs
- afterpulses
- time jitter...

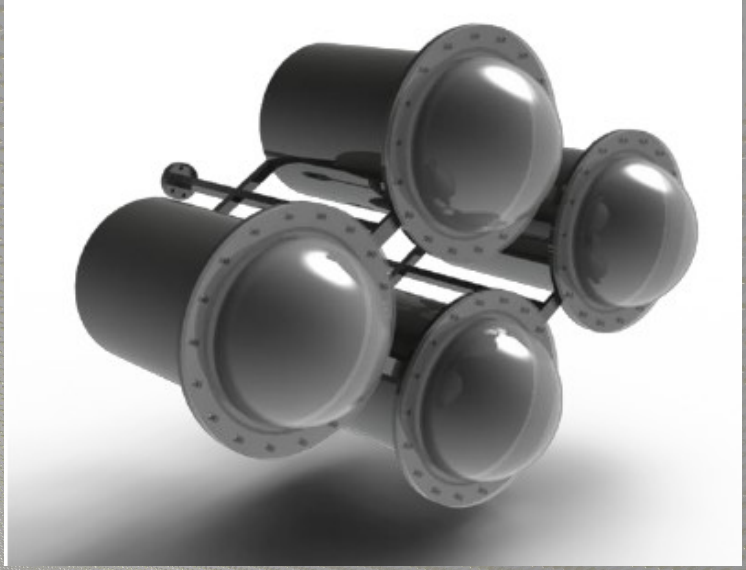
- collaborations with
  - MEMPHYS (PICS, PMm2), KM3Net
  - INFN Milano, LNGS, Tübingen
  - ETEL, Hamamatsu

PMTs are probably the only photo sensor type which can fulfill all requirement classes

Electronics

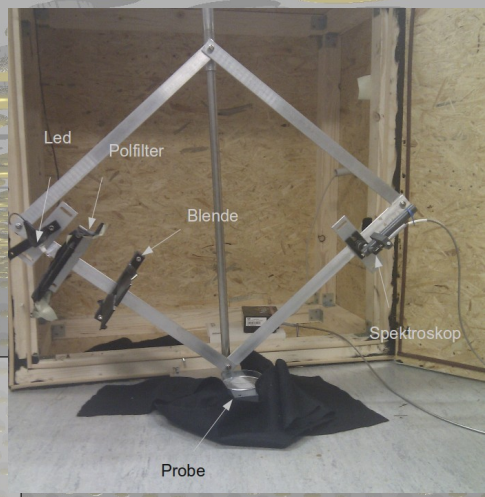
- PMTs as sensors
- Requirements
  - Large dynamic range: single p.e. - few 100 p.e. per channel
  - ns timing (1-2 GS/s)
  - Zero dead time → sufficient onboard memory

- 2 solutions investigated
  1. FADC for all PMTs: expensive
  2. Customised ASIC boards for small PMT arrays:
     investigated by Pmm2 group for MEMPHYS detector



Liquid Scintillator

→ Mixture of organic solvent + fluor (wavelength shifter)



Properties investigated

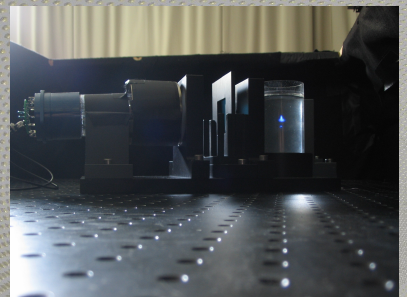
in small scale experiments

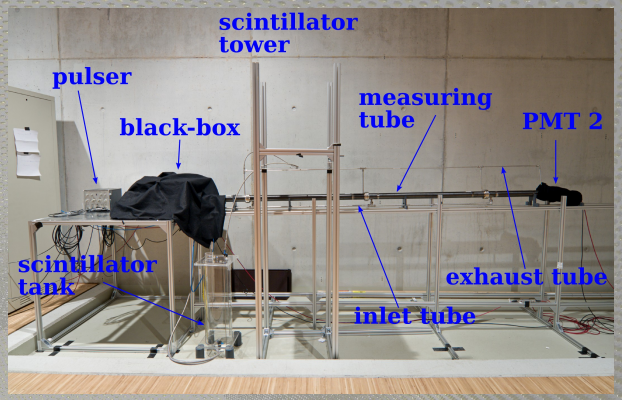
- Light yield
- Attenuation length
- Scattering length
- Refraction index
- Gamma Quenching
- Proton Quenching
- Fluorescence Decay Constants
- Scintillation Spectra

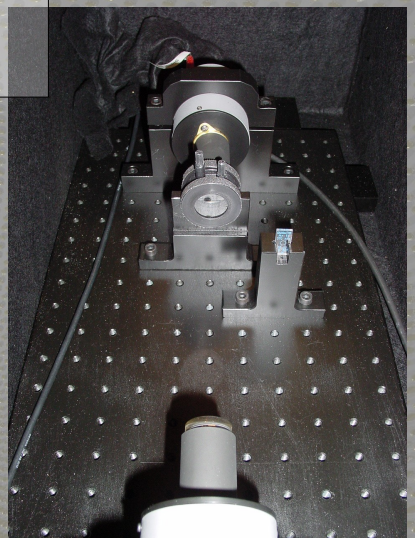
Solvents:
- LAB
- PXE
- DIN, Tetradecane (non-scint.)

Fluor:
- PPO
- PMP
- pTP
- bisMSB

→ input for LENA MC to investigate physics potential

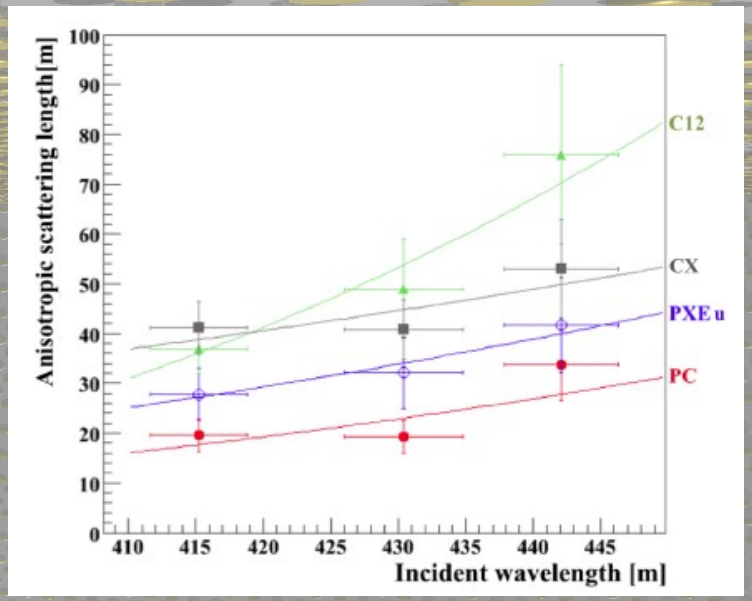




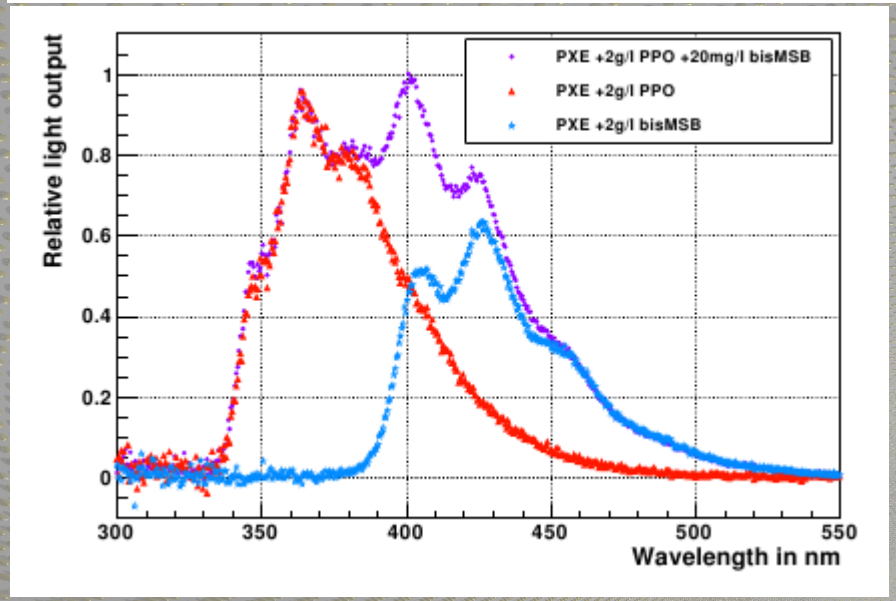


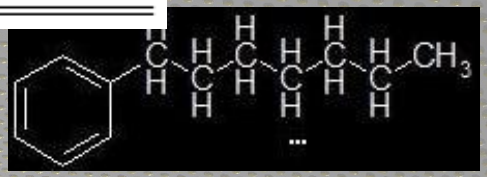
Scintillator properties

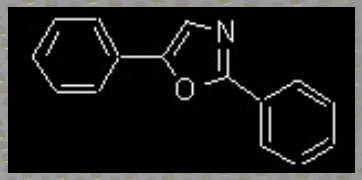
Environmental issues
- radiopurity
- flammability
- toxity



Solvents	Wavelength shifters 1st	2nd	Y [%] [258]	n_1 [%] [268, 269]	τ_1 [ns] [268, 269]
PXE +	2 g/ℓ PMP	-	79.1 ± 3.1	95.9 ± 0.02	4.15 ± 0.02
+	2 g/ℓ PPO	+ 20 mg/ℓ Bis-MSB	102.0 ± 3.3	85.3 ± 1.4	2.61 ± 0.05
LAB +	2 g/ℓ PMP	-	83.9 ± 3.0	85.1 ± 0.9	8.53 ± 0.15
+	2 g/ℓ PPO	+ 20 mg/ℓ Bis-MSB	99.7 ± 3.2	77.7 ± 0.8	5.21 ± 0.005
DIN +	1.5 g/ℓ PPO	-	-	86.2 ± 0.2	6.95 ± 0.02







Preferred scintillator mixture:
LAB + PPO (2 g/l)+ bisMSB (20 mg/l):
- **largest absorption length**
- **good light yield, timing**
- **good availability**

LENA Physics goals overview

Low-Energy Neutrino Physics

- Galactic Supernova Neutrinos
- Diffuse SN Background Neutrinos
- Solar Neutrinos
- Geoneutrinos
- Short-baseline Neutrino Oscillations
- Neutrinos from DM annihilation

GeV Physics

- Nucleon Decay Search
- Long Baseline Neutrino Beams
- Atmospheric Neutrinos

Supernova Neutrinos

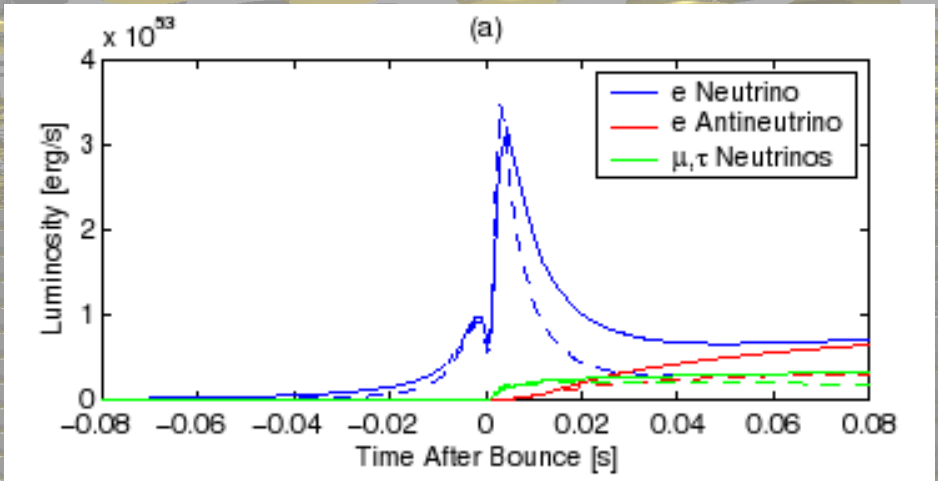
→ Neutrinos from a Galactic Core-Collapse SN
→ Neutrinos from Diffuse SN Background

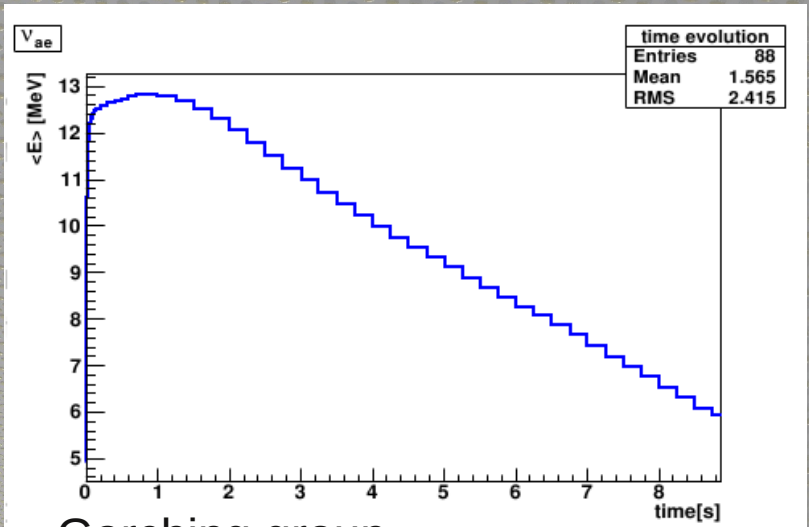
- **SN physics**
  - Galactic SN ν
    - high-statistic measurement
    - determine detailed 'light curves' and spectra for each flavour
    - Neutronization burst observation
  - DSNB
    - average $\bar{\nu}_e$ spectrum, exclusion of extreme SN scenarios
    - first observation

- **Neutrino properties**
  - Matter effects on neutrino oscillations in SN envelope (MSW, collective osc.) and Earth → θ_{13}, neutrino mass hierachy

Galactic SN Neutrinos

- **Core collapse SN**
  → **neutronization** (10ms)
  - ν_e: ~40 from νe, ~90 from νp scattering
  → **accretion** (100ms)
  - Largest spectral differences between flavours
  → **cooling phase** (10 s)
  - **all flavours**, thermal spectra
- Rate calculations assuming
  - M ~ 8 M_{solar} progenitor
  - 10 kpc distance
  - Luminsosity equipartition

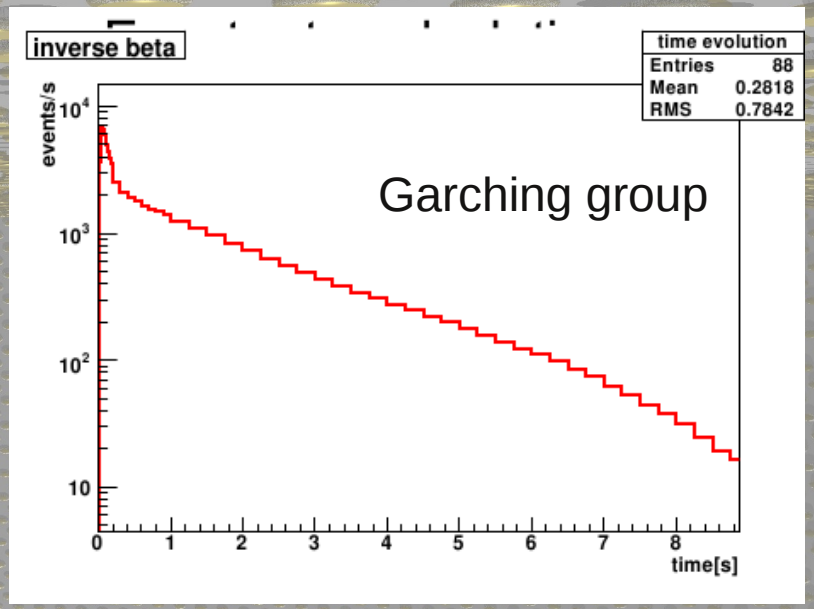




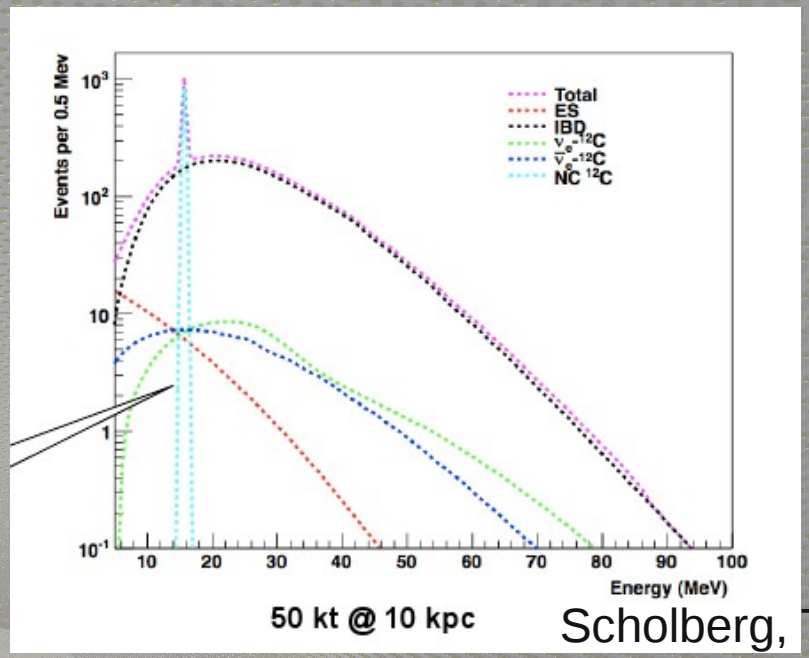
Garching group

Galactic SN Neutrinos

- Golden Channel: inverse beta decay
  ≥ 10,000 events $\bar{\nu}_e + p \rightarrow n + e^+$
- Additional: elastic scattering off protons, electrons, and ^{12}C (NC and CC)
  → all flavours accessible!
  6 different reaction channels allowing for time-resolved flux measurement and spectroscopy



			Events for <E> values		
Reaction	**Type**	**E_{thr}**	**12 MeV**	**14 MeV**	**16MeV**
$\bar{\nu}_e + p \rightarrow n + e^+$	CC	1.8 MeV	**$1.4\ 10^4$**	**$1.6\ 10^4$**	**$1.9\ 10^4$**
$\nu + p \rightarrow \nu + p$	NC	2 MeV	**$4.1\ 10^3$**	**$6.9\ 10^3$**	**$1.0\ 10^4$**
$\nu + e \rightarrow \nu + e$	NC	0.4 MeV	**840**	**840**	**840**
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$ ${}^{12}C^* \rightarrow {}^{12}C + \gamma$	NC	15.11MeV	**110**	**220**	**380**
$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$ ${}^{12}B \rightarrow {}^{12}C + e + \nu_e$	CC	14,39 MeV	**20**	**30**	**45**
$\nu_e + {}^{12}C \rightarrow {}^{12}N + e$ ${}^{12}N \rightarrow {}^{12}C + e^+ + \bar{\nu}_e$	CC	17,34 MeV	**50**	**75**	**100**



Scholberg, TAUP

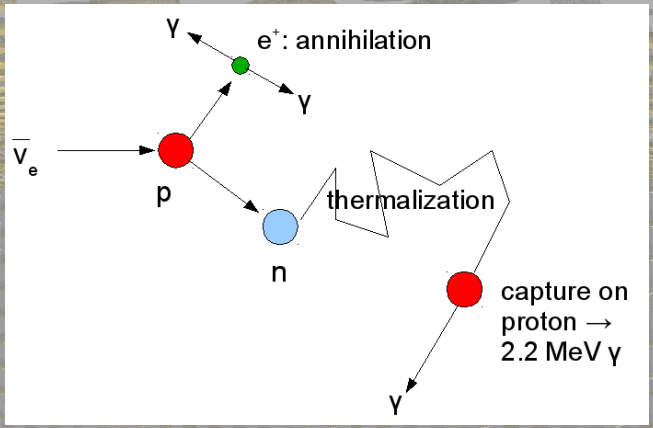
Diffuse SN Neutrinos

- Detection reaction: **inverse beta decay**

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

  - prompt signal from positron annihilation
  - delayed 2.2 MeV γ 's from neutron capture ($\tau \sim 250\ \mu s$)

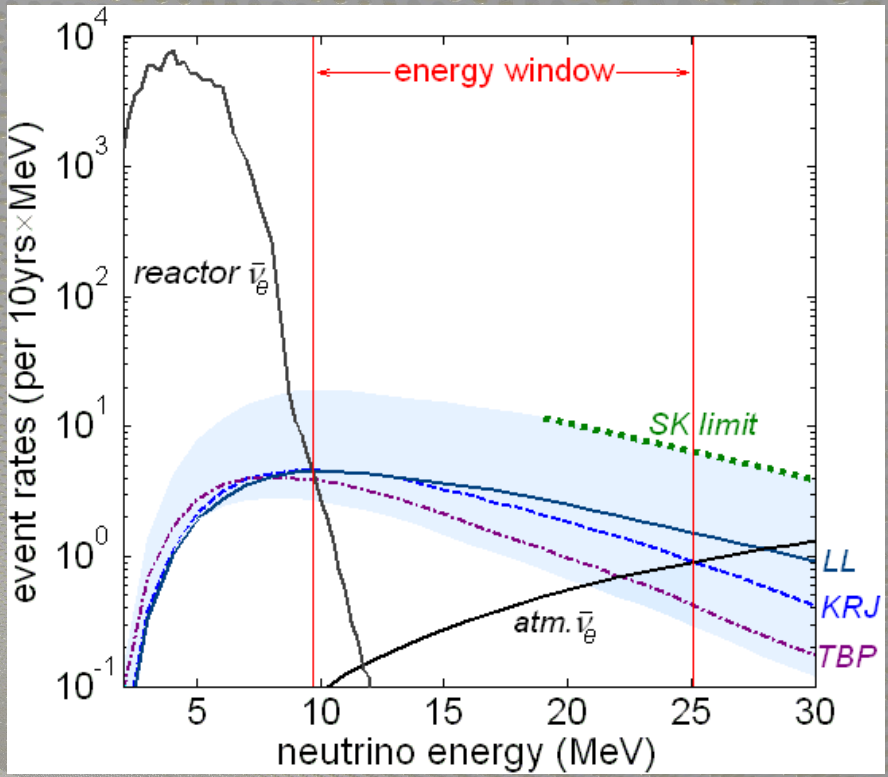
  → **good distinction from single events**



- Observation window: ~10-30 MeV limeted by atm. and reactor neutrinos

- Expected events: 35-70 in 10 years

  → spectroscopy possible if background under control



DSNB background

- **Atmospheric and reactor electron anti-neutrinos** (both location dependant):
  irreducible → define observation window

- **Cosmogenic ^{9}Li, ^{8}He**
  - produced by cosmic muons
  - β-n emitter
  - mimick delayed coincidence signal

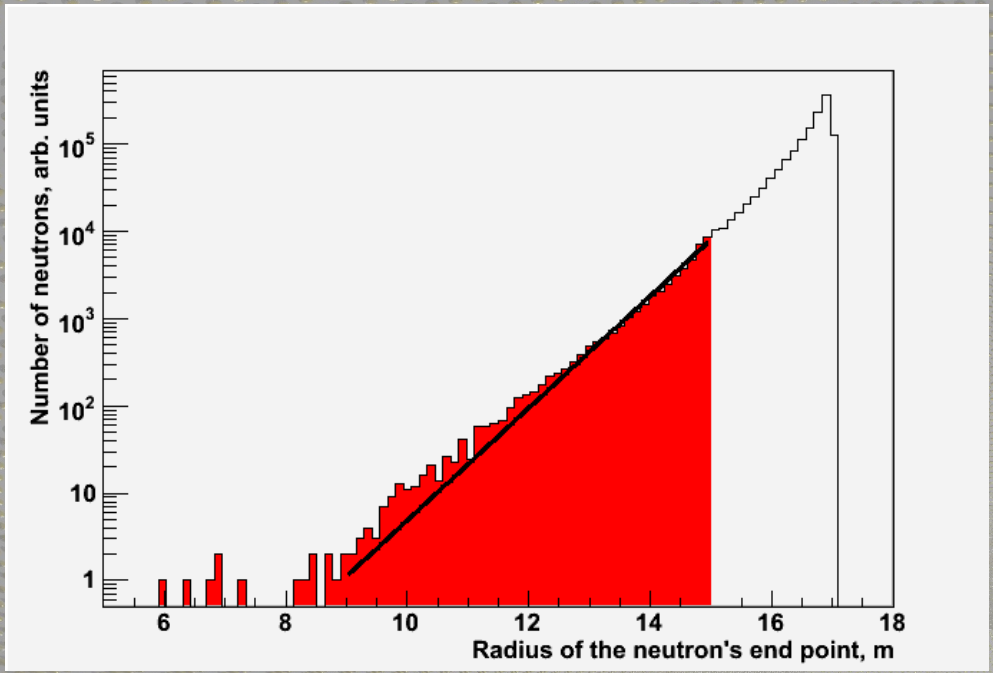
Reduction technique:

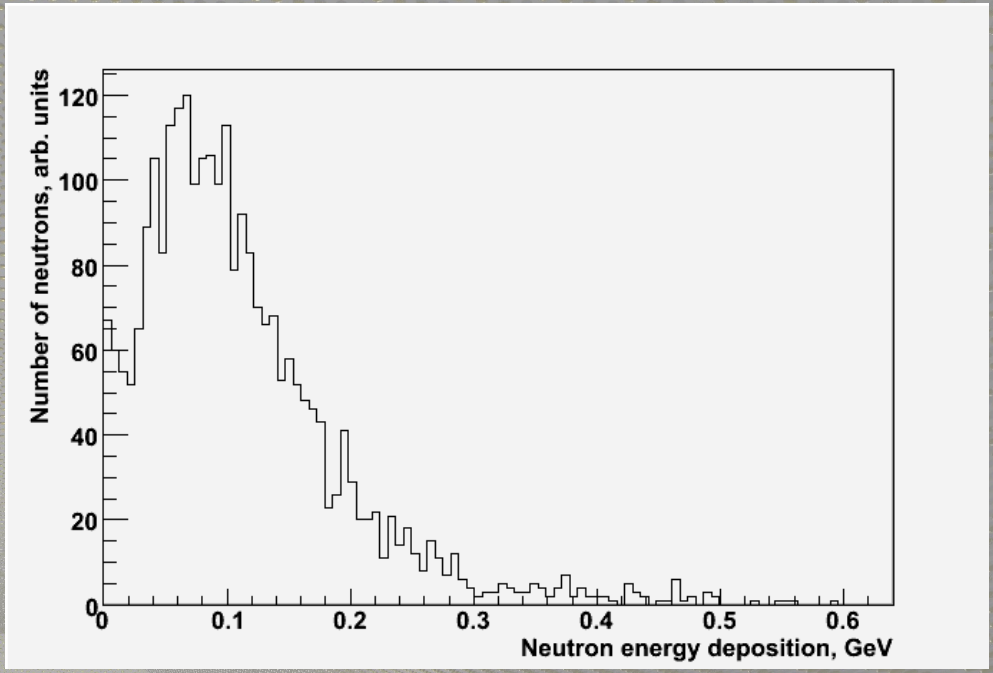
- **energy cut**, discarding ^{8}He
- **combined spatial and time cut** suppressing ^{9}Li:
  veto a cylinder of 2 m around muon track for 1 s ($>5T_{1/2}$)

  → residual ^{9}Li rate of ~2% with a negligible dead time of ~ 0.1%

DSNB background

- **Fast neutrons**
  - produced in the surrounding rock by undetected cosmic muons
  - thermalization + n capture mimick IBD
  - Monte Carlo study performed in 2 steps
    i) simulation of neutron energy and angle in spallation process (muon propagaion in limestone, <E> = 300 GeV @4 km.w.e.)
    ii) simulation of neutron propagation in the scintillator

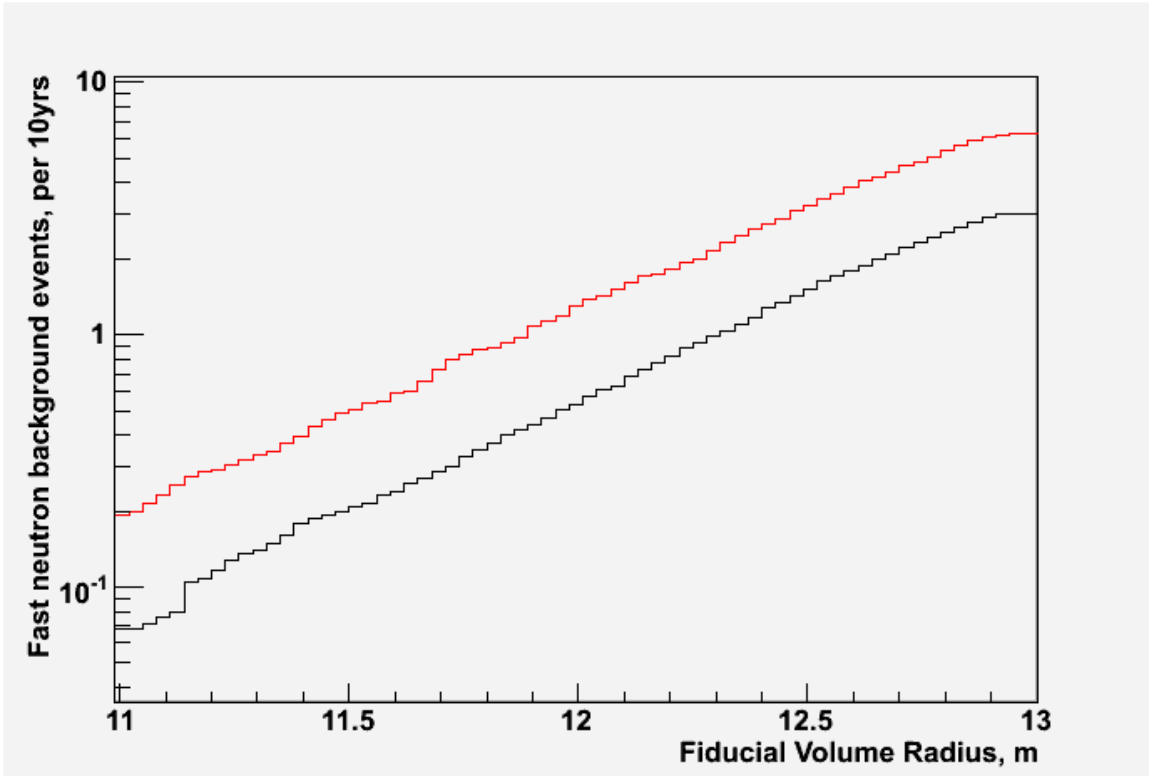




DSNB background

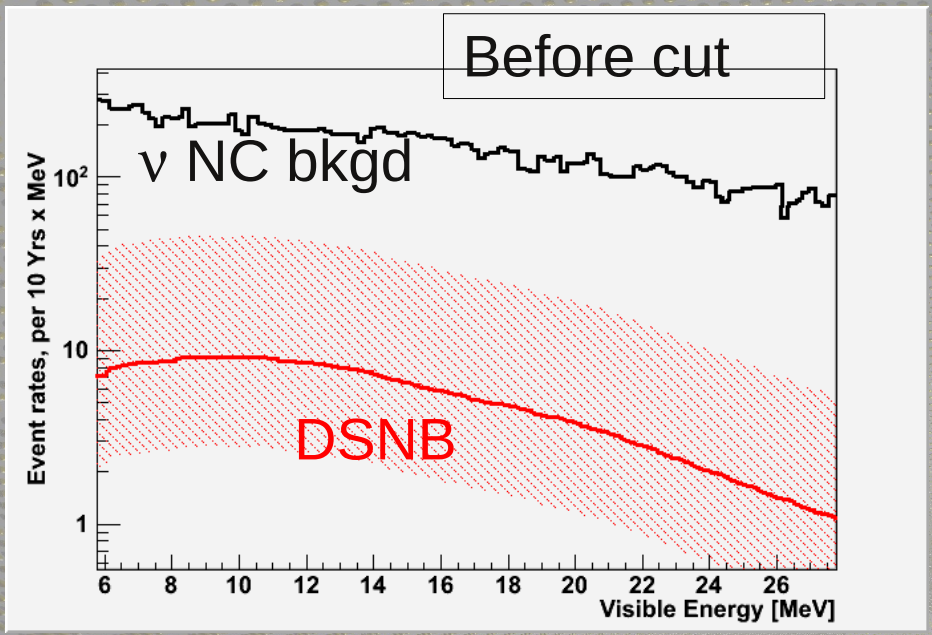
Reduction of fast neutrons

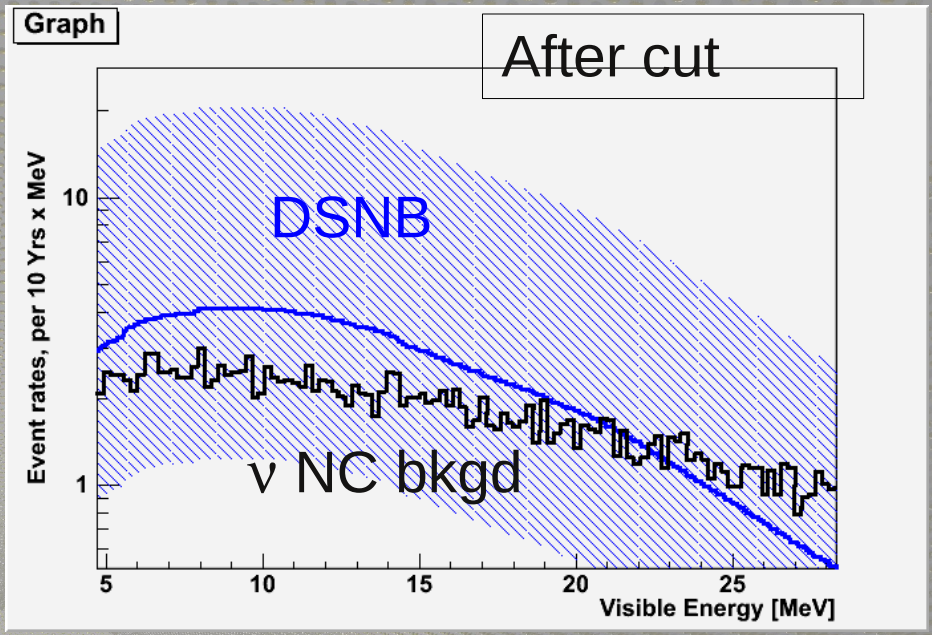
- rejection of multiple neutron events (30-40%)
- fiducial volume cut: 0.2 events/yr for 10m
- pulse shape analysis (p recoil vs e-like)
  reduces background to 0.12 evts/yr (with 12m fiducial volume)



DSNB background

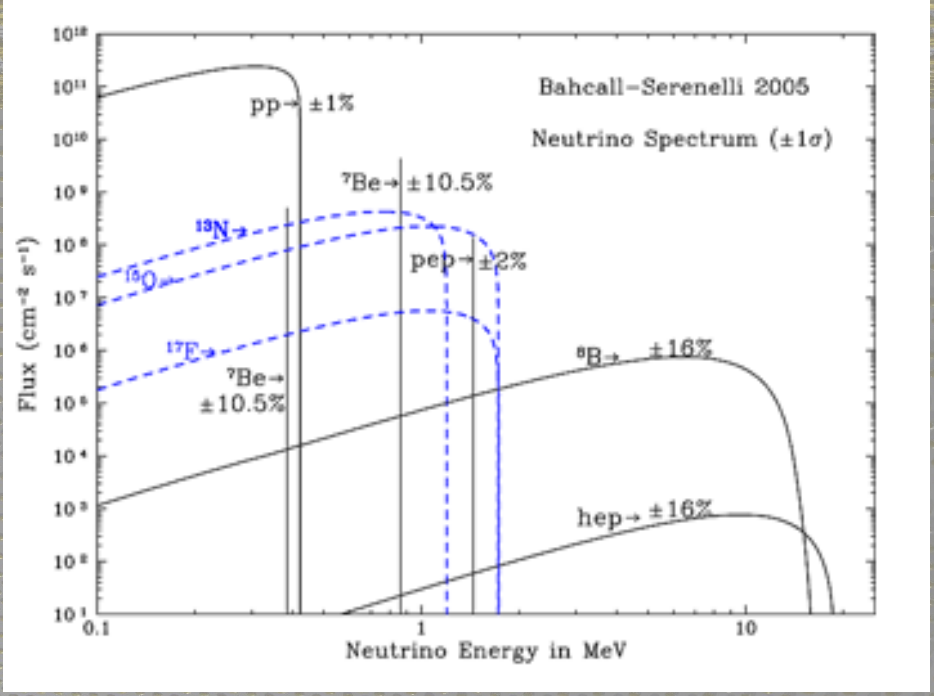
- severe background: **NC interactions of atmospheric neutrinos**
  - knocking out neutron of ^{12}C: $\nu + {}^{12}C \rightarrow {}^{11}C^* + n$
  - n thermalization + n capture mimick IBD
- background reduction
  - tagging β+ decay of ^{11}C
  - $^{11}C^*$: deexcitation via emission of p,n, or α → pulse shape analysis
  - Monte Carlo study performed (Genie and G4)
- Small-scale experiments and MC studies indicate that effective reduction can be achieved





Solar Neutrinos

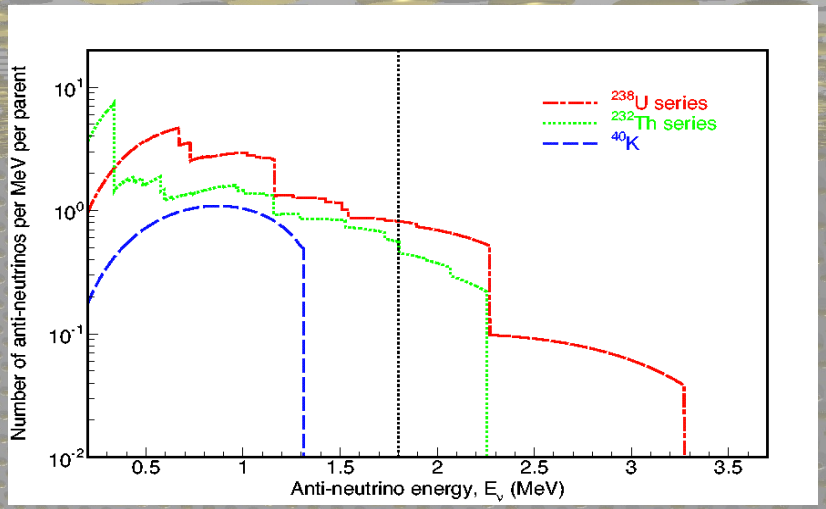
- Neutrino-electron scattering (low threshold)
  → Good shielding required (≥ 4 km.w.e.)
  - **High-statistic** spectral observation and flux measurement
  - Search for **temporal modulations** with ^{7}Be
    → 3σ dicovery potential for amplitudes as low as 0.5 % for frequencies O(10min)- O(100y)
  - Precision test of the ν_e survival probability in the transition region
  - Search for $\nu_e \rightarrow$ anti-ν_e conversion
  - Test of SSM metallicity



Source	Channel	EW [MeV]	m_{fid} [kt]	Rate [cpd]
pp	$\nu e \rightarrow e\nu$	>0.25	30	40
pep		0.8−1.4	30	2.8×10^{2}
^{7}Be		>0.25	35	1.0×10^{4}
^{8}B		>2.8	35	79
CNO		0.8−1.4	30	1.9×10^{2}
^{8}B	^{13}C	>2.2	35	2.4

Geoneutrinos

- $\bar{\nu}_e$ produced by U/Th decay chains, Ka
- Detection reaction: inverse beta decay ~1000 events per year, location dependant



Goals

- measure abundance of ^{238}U and ^{232}Th inside Earth crust and mantle
- quantify the radiogenic constribution to the total heat flux
- help to understand geophysical processes and origin and formation of Earth
- with a 2nd detector (like Hanohano): disentangle oceanic/continental crust

Within one year error on total ν flux in few % level

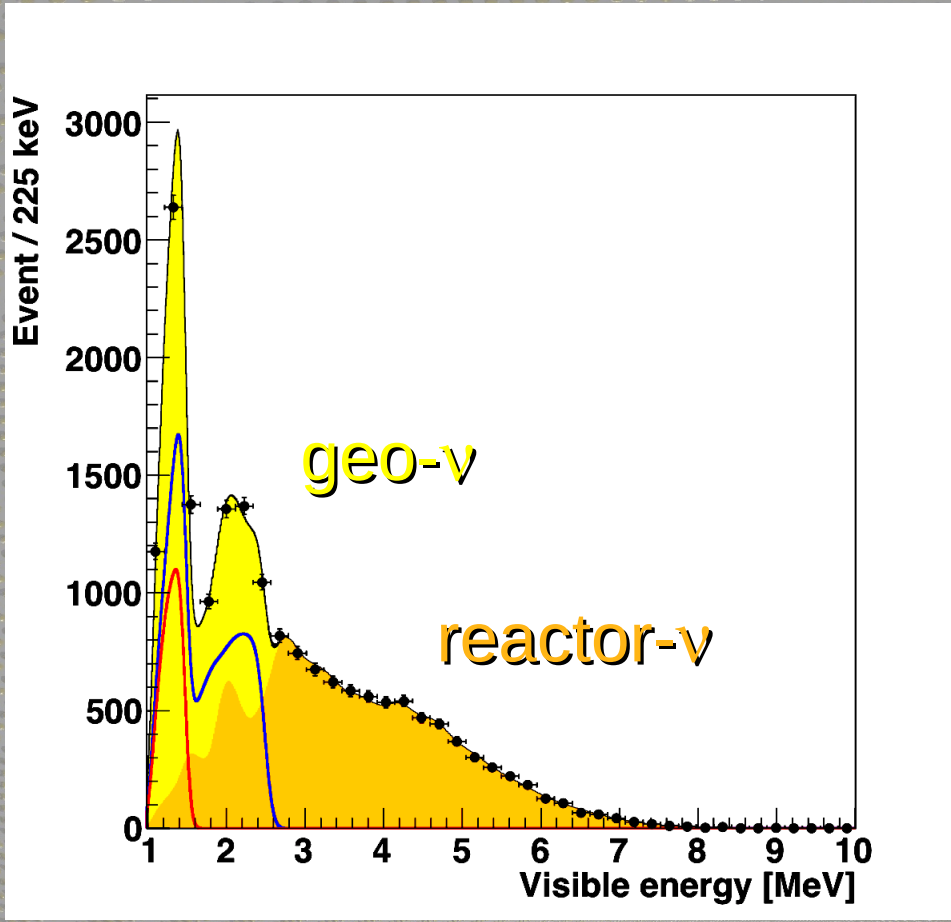
BSE model:
@Pyhäsalmi 50 TNU
@Fréjus 40 TNU

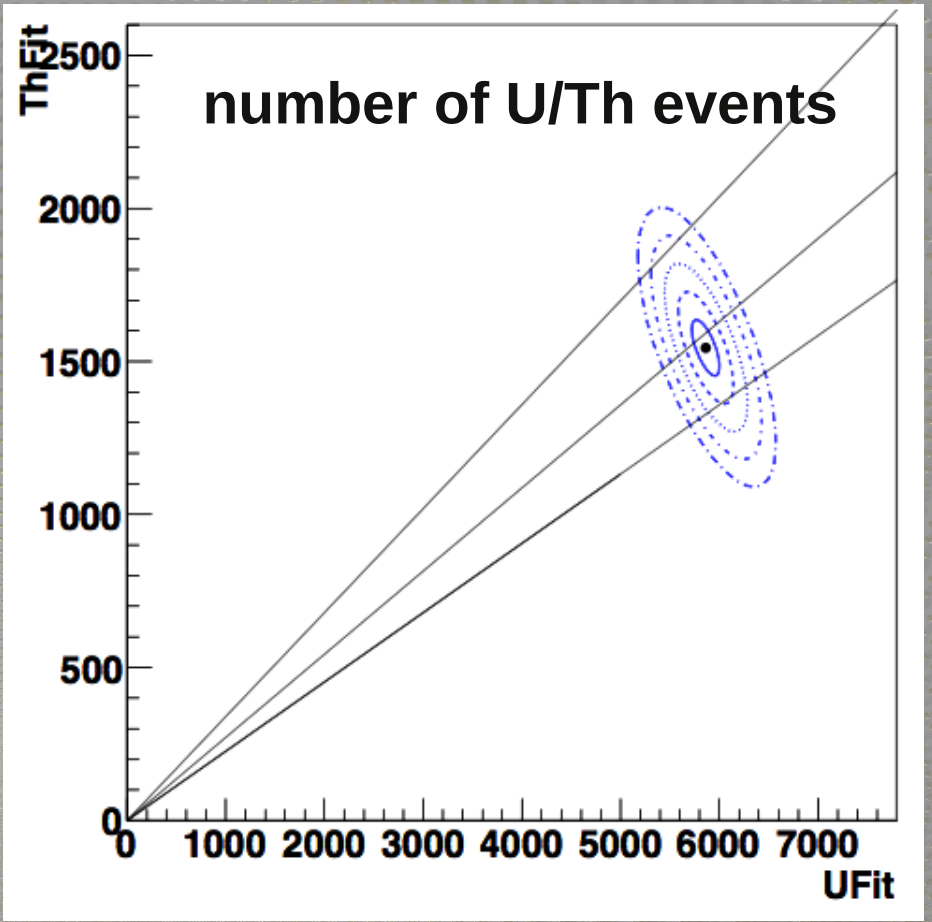
Background:

- Reactor Neutrinos
- ^{9}Li and ^{8}He: muon-induced ßn-emitter
- Fast neutrons and $^{12}C(\alpha,n)^{16}O$:
each ~10 evts/year (MC)

Geoneutrinos

- After 5 years of measurement: Disentagnlement of contributions from **U** and **Th** in Pyhäsalmi
- fixed chondritic U/Th ratio: ±20% with 5 σ

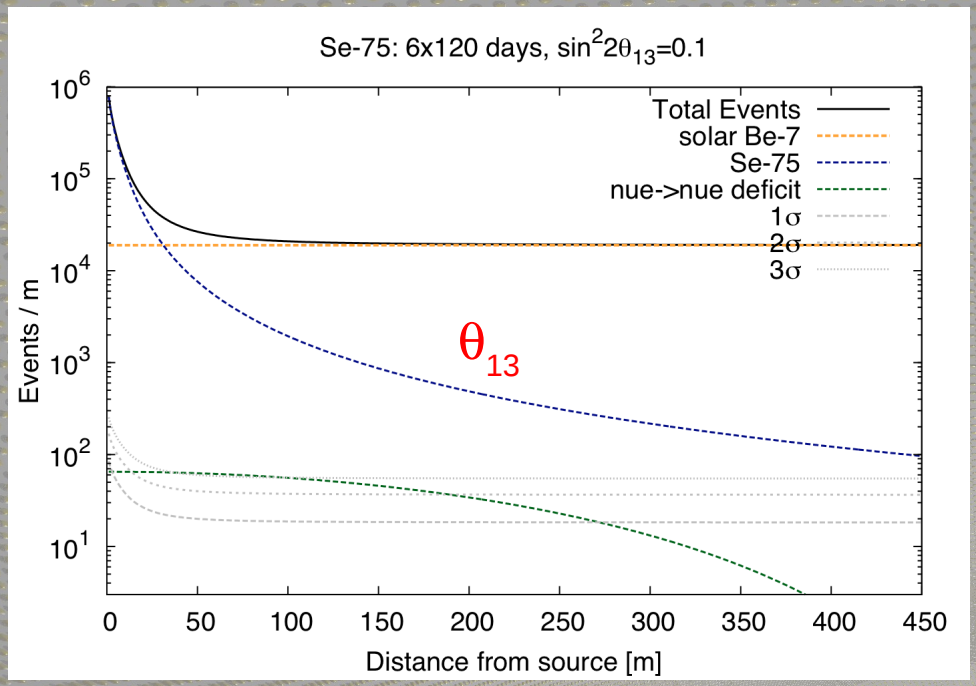


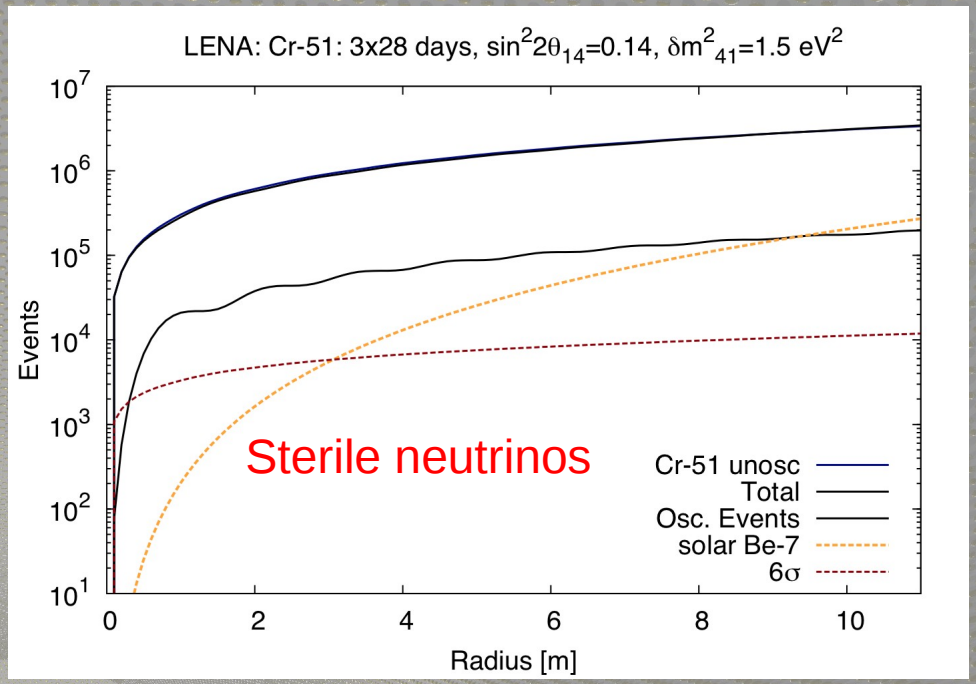


Short-Baseline Neutrino Oscillations

- **Neutrino Oscillometry ν_e**
  - strong EC-source (MCi) close to detector with E = O(100 keV) (^{51}Cr, ^{57}Se)
    → sterile neutrinos
    → θ_{13}, Δm^2_{13}
- Background: solar ^{7}Be neutrinos

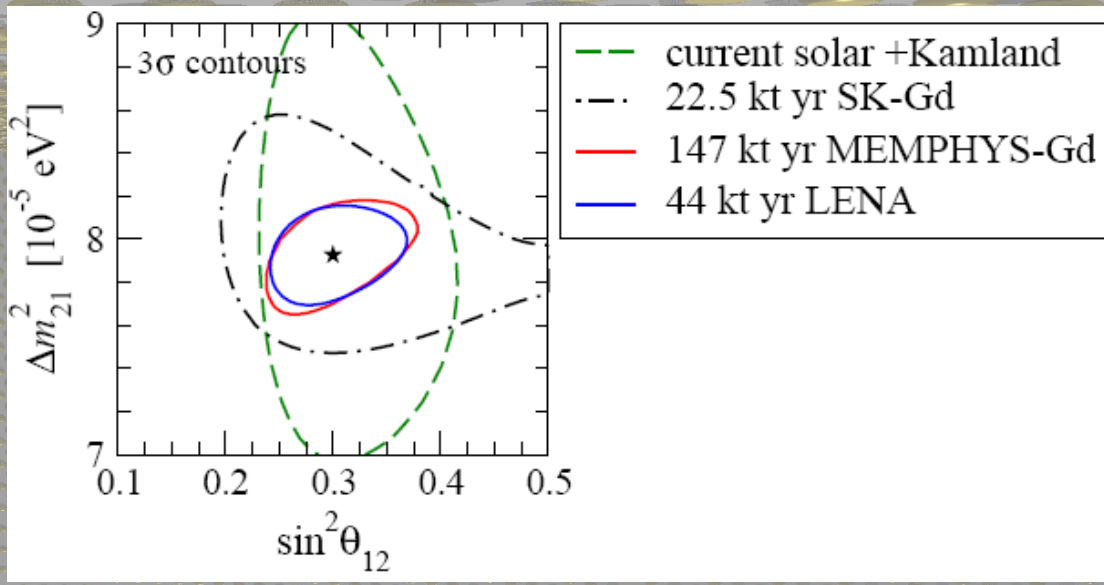
Nuclide	$T_{1/2}$ (d)	E_ν (keV)
^{51}Cr	28	747
^{75}Se	120	450

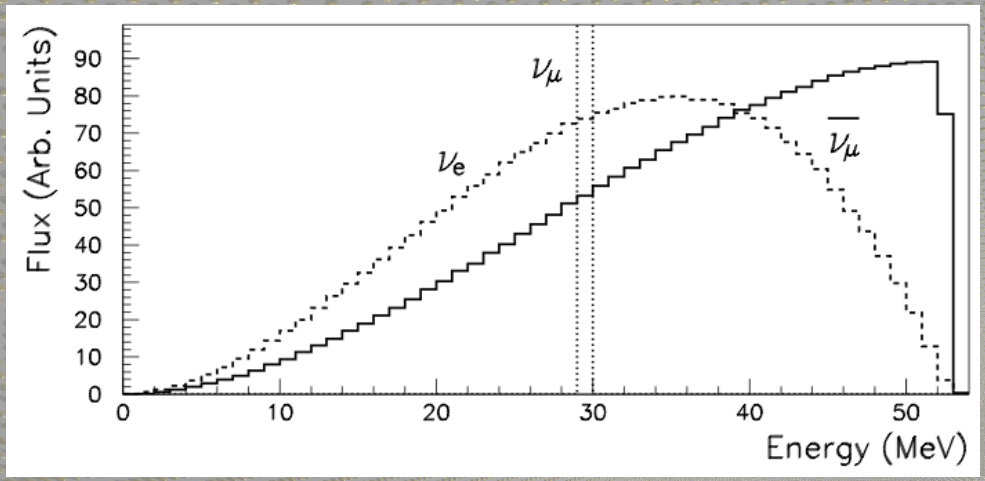




Short-Baseline Neutrino Oscillations

- Reactor Neutrinos $\bar{\nu}_e$
  - 50-25000 anti ν_e events per year, depending on detector site
  - anti-ν_e disappearance experiment
  - precision measurement of solar oscillation parameters θ_{12}, Δm^2_{12}
  - → after 1 y: 3 σ error Δm^2_{12} < 3%





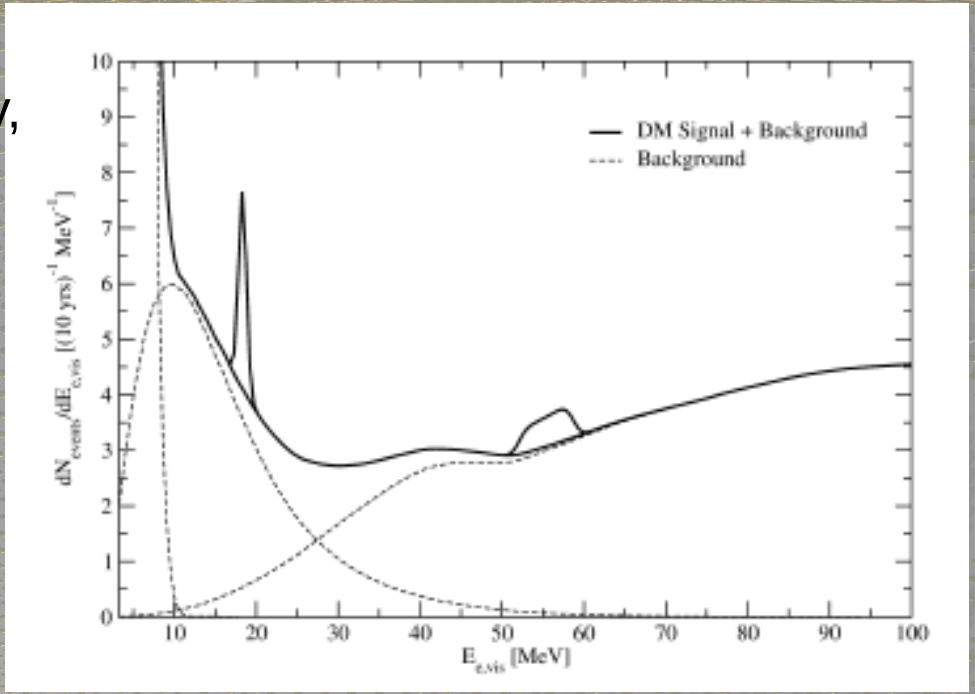
- Pion at rest decay
  - Search for sterile neutrinos
  - Search for θ_{13} , δ_{CP} (compare Daedalus)

DM and 0νββ

- **Indirect Dark Matter Search:**

  Neutrinos from DM annihilation/decay $\bar{\nu}_e$
  - Detection via inverse beta decay
  - Regions with high Dark Matter density, e.g. in the galactic center
  - Assuming MeV DM,

    $\langle sv \rangle = 3 \cdot 10^{-26}\ cm^3 s^{-1} / \quad t_c \sim 10^{24}\ s$
  - Monoenergetic peaks



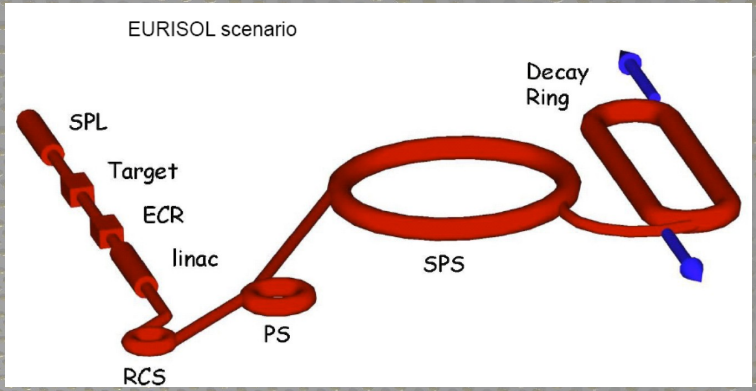
Palomares-Ruiz, Pascoli, Phys, Rev. D77, 025025 (2008)

- **0ν2β with ^{136}Xe**
  - ^{136}Xe dissolved in the liquid scintillator
  - Solubility in liquid scintillator: ~ 2% in weight

    → potentially 200 tons of active mass or more
  - High PMT coverage might be required

High-Energy Physics

- Proton Decay
- Neutrino beam
- Tracking



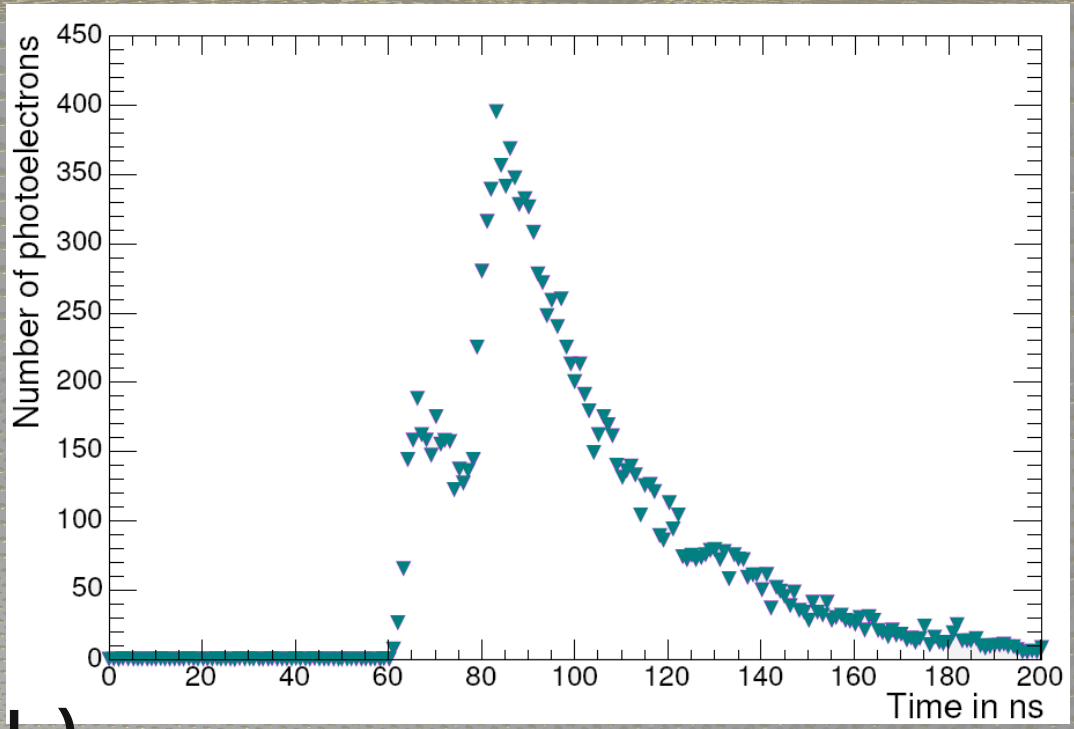
Proton Decay

- **$p \rightarrow K^+\nu$** (minimal SUSY SU(5))

  $K^+ \rightarrow \mu^+\nu_\mu \,/\, \pi^0\pi^+$

  - coincidence of K/μ provides clear signature
  - efficiency: 65%
  - background: atmospheric ν's (creating hadrons)
  - Expected Rates in 10 years
    - current SK limit: 40 events
    - background: 1 event
    - no observation:

      $\tau_p > 4\times10^{34}$ yrs (90% C.L.)

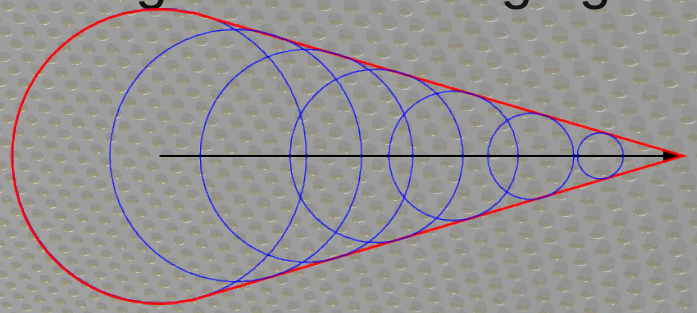


- **$p \rightarrow \pi^0 e^+$** (GUT SU(5))

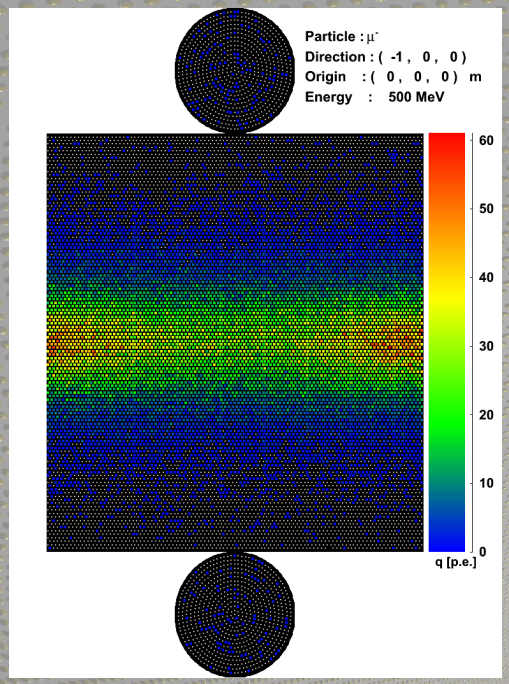
  - Y-shaped shower signature, tracking needed

GeV Event Reconstruction

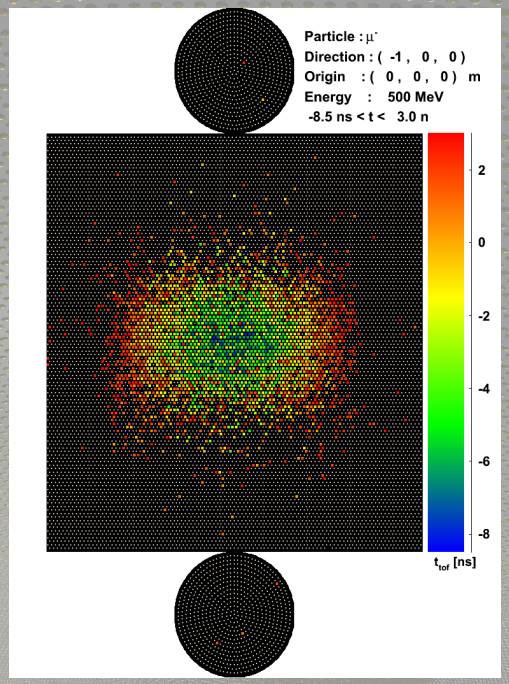
- Investigated in Monte Carlo simulations
- Identification of energy, momentum and flavour
- For tracks > O(10cm) distortion of the spherical light front emerging from track



Muons



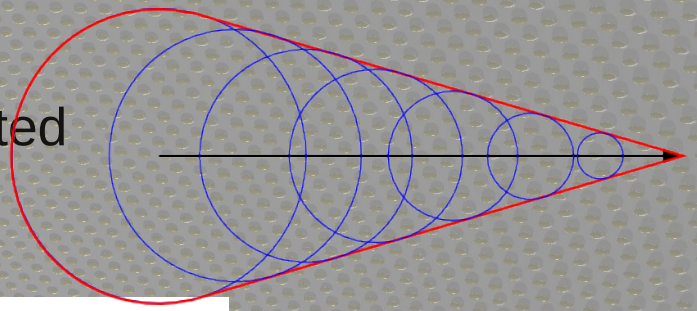
Integrated charge distribution

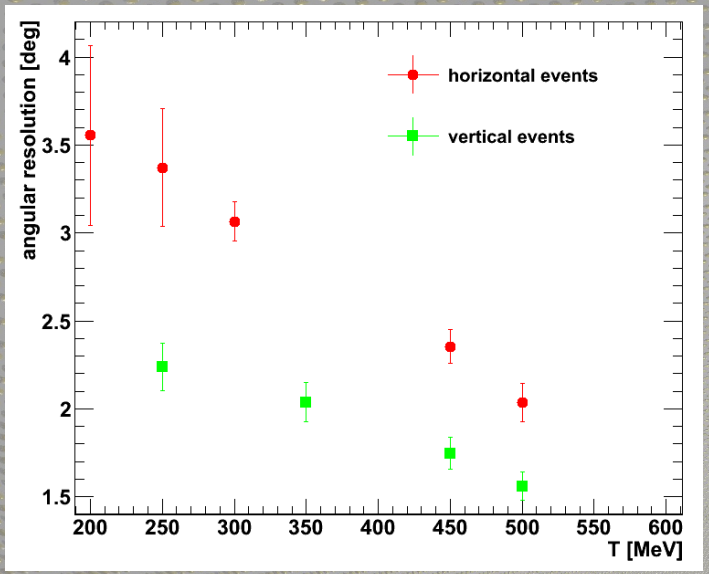


First hit distribution (TOF corrected)

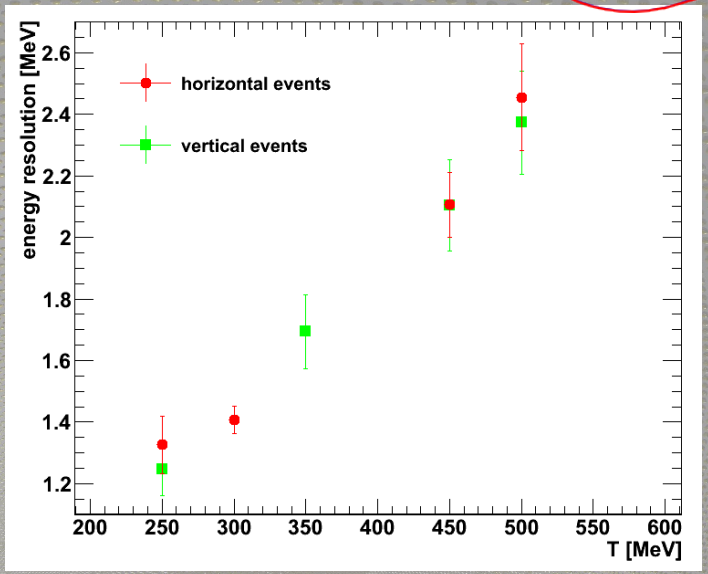
GeV Event Reconstruction

- Investigated in Monte Carlo simulations
- Identification of energy, momentum and flavour
- For tracks > O(10cm) distortion of the spherical light front emerging from track
- More precise method: LogLikeli Fit to the integrated charge and first hit times of each PMT (7 par fit)





Angular resolution



Energy resolution

Muons

Long-baseline Neutrinos

- Searching for θ_{13}, δ_{CP}, mass hierachy, and check for maximal θ_{23}
- Options currently investigated
  - Conventional ν beam CERN-Pyhäsalmi (2288 km)
    - Appearance experiment: $\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{e}$
    - Background due to NC π^0 production, further studies ongoing
  - Beta beam CERN-Fréjus (130 km)
    - discrimination of electron and muon by pulse-shape analysis:
      → efficieny for muons: ~90%
      → residual electrons: <1%
- Will be investigated in LAGUNA-LBNO FP7 study

LENA Whitepaper

The next-generation liquid-scintillator neutrino observatory LENA

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arXiv:1104.5620

97 people from 37 universities and institutes in different 13 countries!

Summary

- Liquid scintillator is a very attractive detection target for a next-generation large-volume neutrino observatory
  - Proven technology: wealth of results from KamLAND and Borexino
  - Broad physics programme: Particle Physics, Astrophysics, Geophysics...
  - Wide energy range: sub-MeV to GeV
- Growing community in the field: LAGUNA, LAGUNA-LBNO, LENA Whitepaper

Thank you for your attention!