Neutrino astrophysics and particle physics in LAGUNA

Teresa Marrodán Undagoitia
marrodan@physik.uzh.ch

Universität Zürich

Seminars on Astroparticle Physics,
DESY, Hamburg, 03.05.2010

Outline

Outline

LAGUNA

Large Apparatus for Grand Unification and Neutrino Astrophysics

- European underground laboratory design study (2008 – 2010) funded with 1.7 ME by the EU
- Study of seven possible locations:
  - Canfránc (Spain)
  - Fréjus (France)
  - Boulby (England)
  - Pyhäsalmi (Finland)
  - Sieroszewice (Poland)
  - Slanic (Romania)
  - Umbria (Italy)

Scientific paper: D. Autiero *et al.*, JCAP 0711, 011 (2007)

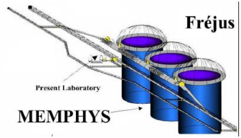
Physics of LAGUNA: Low Energy Neutrino Astrophysics

- Supernova explosion
  - Measurement of 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 $\rightarrow$ solar modulation
- and Geophysics
  - Measuring radioactivity of the Earth with geoneutrinos

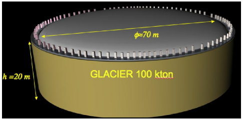
Physics of LAGUNA: Particle physics

- Proton decay
  - Mainly $p \to K^+ \overline{\nu}$ and $p \to e^+ \pi^0$
- Atmospheric neutrinos:
  - Improve the measurement of $\sin^2\theta_{23}$
- Reactor neutrinos:
  - Precise measurement on Δm^2_{12} and $\sin^2\theta_{12}$
- Detectors for accelerator experiments:
  θ_{13}, δ_{CP} and mass hierarchy
  - Beta beams
  - Super beams
  - Neutrino factories

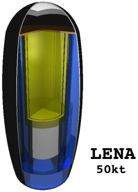
LAGUNA detector concepts



- MEMPHYS - MEgaton Mass PHYSics
  - tanks of 60 m heigth $\times$65 m $\varnothing$
  - $\sim$ 440 kt water Cherenkov detector



- GLACIER - Giant Liquid Argon Charge Imaging ExpeRiment
  - 20 m heigth $\times$70 m $\varnothing$
  - $\sim$ 100 kt liquid Ar TPC

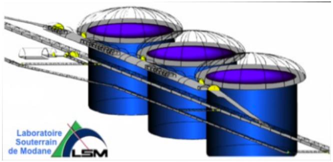


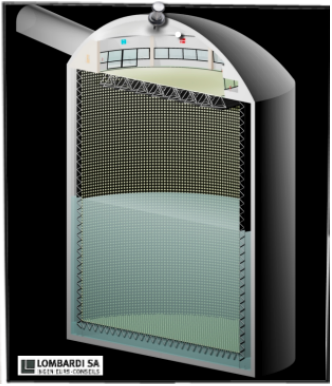
- LENA - Low Energy Neutrino Astronomy
  - 100 m long $\times$ 30 m $\varnothing$
  - $\sim$ 50 kt liquid scintillator

LAGUNA Design Study

- Design Study (EU funded): 2008 - 2010
- Prioritize the sites and down-select: July 2010
- Prioritize detector options: 2011 - 2012
- Phase 1 construction: 2012 - 2016

Outline

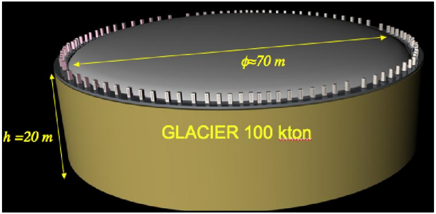


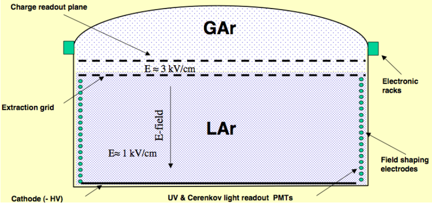


MEMPHYS

MEgaton **M**ass **PHYS**ics

- 3 (or 5) cylindric modules
  60 x 65 m each
- Fiducial mass 440 kt water
- Readout: $\sim$ 70 000 PMTs of 10-12 inch per shaft
  $\rightarrow$ 30% coverage
- Size limited by the attenuation length ($\lambda \sim 80$ m) and the pressure on the PMTs
- Option of adding gadolinium





GLACIER

Giant **L**iquid **A**rgon **C**harge **I**maging **E**xpe**R**iment

- 20 m heigth $\times$ 70 m $\varnothing$
- 100 kt liquid Ar TPC
- Scintillation light detected by $\sim$28 000 PMTs
- e^- drift in 1 kV/cm field
- LEMs for charge amplification
- Charge readout on top

DETECTOR LAYOUT

Cavern
height: 115 m, diameter: 50 m
shielding from cosmic rays: ~4,000 m.w

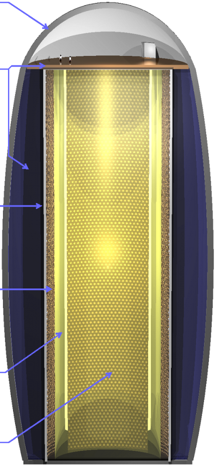
Muon Veto
plastic scintillator panels (on top)
Water Cherenkov Detector
1,500 phototubes
100 kt of water
reduction of fast
neutron background

Steel Cylinder
height: 100 m, diameter: 30 m
70 kt of organic liquid
13,500 phototubes

Buffer
thickness: 2 m
non-scintillating organic liquid
shielding external radioactivity

Nylon Vessel
parting buffer liquid
from liquid scintillator

Target Volume
height: 100 m, diameter: 26 m
50 kt of liquid scintillator



vertical design is favourable in terms of rock pressure and buoyancy forces

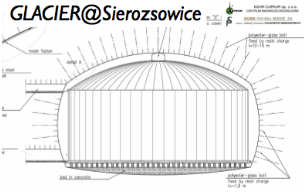
LENA

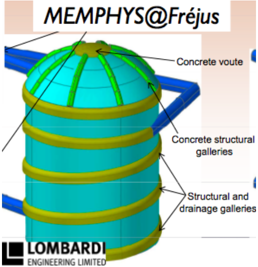
Low **E**nergy **N**eutrino **A**stronomy

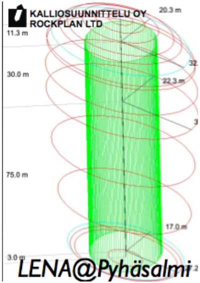
- Size: 100 m length $\times$ 30 m $\varnothing$
- 50 kt of organic scintillator
- $\sim$15 000 photosensors (including water veto)
- About 180 pe/MeV light yield
- Current design:
  vertical cylinder

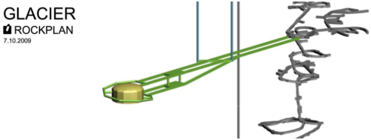
Typical questions addressed in LAGUNA:

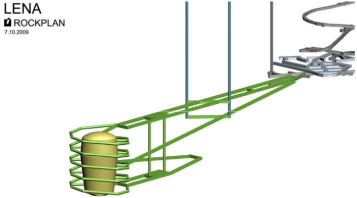
- rock mechanics of caverns
- design of tanks in relation to sites
- overburden vs. detector options
- logistic: transport, access, delivery of liquids
- safety (tunnel vs. mine) and environment (rock removal)
- relative costs

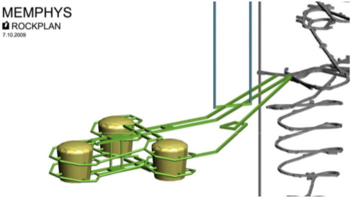












Underground construction

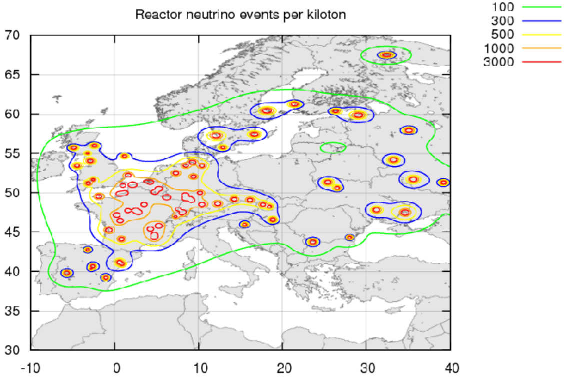
- Stability of the cavity
- Tunnels, access ...

- GLACIER
  - Depth: 2 500 m.w.e.
- LENA
  - at 4 000 m.w.e.
- MEMPHYS
  - at 3 000 m.w.e.

$\longrightarrow$ artistic impressions by Rockplan

Detector location: Reactor neutrinos

- Depth
  - Fast neutron background
  - Trigger rate
- Reactor neutrinos
  - Background for DSNB
  - Signal for an oscillation experiment



from J. Peltoniemi and K. Loo

Outline

Proton Decay

Non supersymmetric Grand Unified Theories

Dominant decay mode: $p \to e^+\pi^0$ $\tau \leq 1.4 \cdot 10^{36}$ y

Supersymmetry (SUSY)

Dominant decay mode: $p \to K^+\overline{\nu}$ $\tau \sim (0.3 - 3) \cdot 10^{34}$ y

Extra dimensions (6D)

Dominant decay mode: $p \to e^+\pi^0$ $\tau \sim 10^{35}$ y

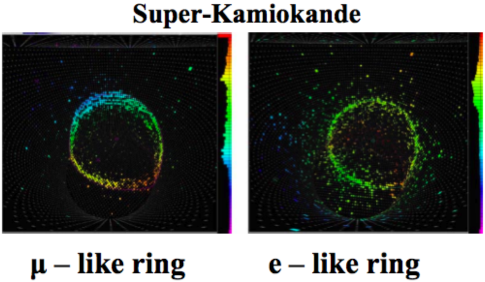
(Limits from P. Nath 2006 and S. Raby 2002)

- Superkamiokande: $\tau(p \to e^+\pi^0) \gtrsim 8.2 \cdot 10^{33}$ y (90% C.L.)
  $\tau(p \to K^+\overline{\nu}) \gtrsim 2.3 \cdot 10^{33}$ y (90 % C.L.)

Proton decay in MEMPHYS

- High efficiency in the identification of $p \rightarrow e^+\pi^0$
  - Two electron-like Cherenkov rings in opposite directions

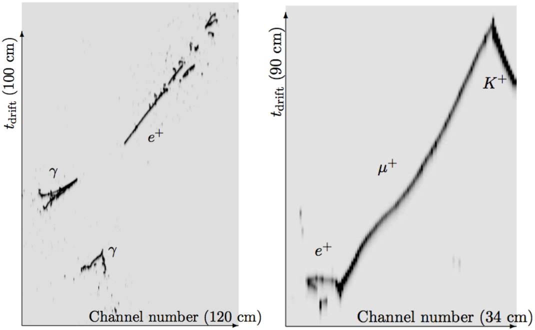
  $\rightarrow$ Sensitivity: $\tau > 1.0 \cdot 10^{35}$ y in 10 years



- Detection of $p \rightarrow K^+\overline{\nu}$ using the decay particles

  $\rightarrow$ Sensitivity: $\tau > 2 \cdot 10^{34}$ y in 10 years

Proton decay in GLACIER



$p \to e^+\pi^0$ $p \to K^+\overline{\nu}$

Simulation of proton decay events

- High sensitivity due to excellent tracking capabilities
- 3D position reconstruction

$\to$ Sensitivity for $p \to e^+\pi^0$
$\tau > 4 \cdot 10^{34}$ y in 10 y

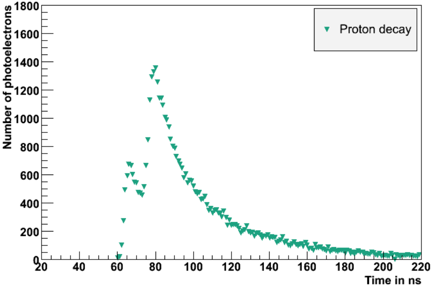
$\to$ Sensitivity for $p \to K^+\overline{\nu}$
$\tau > 6 \cdot 10^{34}$ y in 10 y

A. Bueno *et al.*, JHEP04 (2007) 041

Proton decay in LENA

$$p \rightarrow K^+\overline{\nu}$$

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



Potential of LENA in 10 y:

- For Superkamiokande current limit: $\tau = 2.3 \cdot 10^{33}$ y
  - About 40 events and $\lesssim$ 1 bg
- Limit at 90% (C.L) for no detected signal:
  - $\tau > 4 \cdot 10^{34}$ y

Phys. Rev. D, 72, 075014 (2005) and hep-ph/0511230

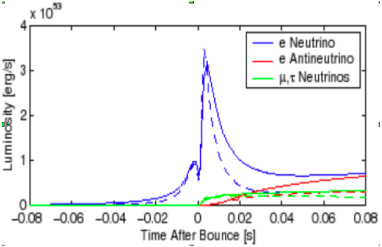
$\longrightarrow$ Efficiency for other decay channels depend on tracking capabilities

SUPERNOVA DETECTION

8 $M_\odot$ ($3 \cdot 10^{53}$ erg)

at D = 10 kpc (galactic center)

- Total rates:
  - GLACIER: ∼ 55 000 events
  - LENA: ∼ 15000 events
  - MEMPHYS: ∼ 200 000 events



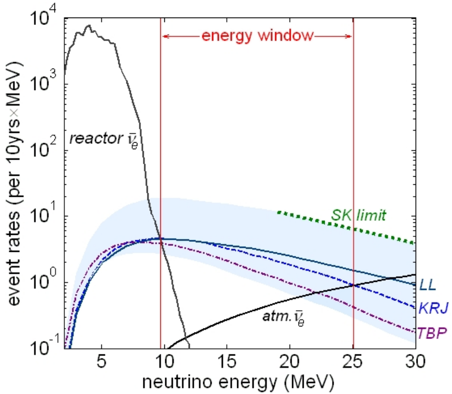
- Time evolution of the neutrino flux
- Detection of different flavours
- Neutrino mean energies

Supernova neutrino rates

MEMPHYS		LENA		GLACIER	
Interaction	Rates	Interaction	Rates	Interaction	Rates
$\bar{\nu}_e$ IBD	2×10^5	$\bar{\nu}_e$ IBD	9.0×10^3	$\nu_e^{CC}(^{40}Ar, ^{40}K^*)$	2.5×10^4
$\overset{(-)}{\nu}{}_e^{CC}(^{16}O, X)$	1×10^4	ν_x pES	7.0×10^3	$\nu_x^{NC}(^{40}Ar^*)$	3.0×10^4
ν_x eES	1×10^3	$\nu_x^{NC}(^{12}C^*)$	3.0×10^3	ν_x eES	1.0×10^3
		ν_x eES	6.0×10^2	$\bar{\nu}_e^{CC}(^{40}Ar, ^{40}Cl^*)$	5.4×10^2
		$\bar{\nu}_e^{CC}(^{12}C, ^{12}B^+)$	5.0×10^2		
		$\nu_e^{CC}(^{12}C, ^{12}N^-)$	8.5×10^1		
Neutronization burst rates					
MEMPHYS	60	ν_e eES			
LENA	70	ν_e eES/pES			
GLACIER	380	$\nu_x^{NC}(^{40}Ar^*)$			

Diffuse Background of Supernova Neutrinos (DSNB)

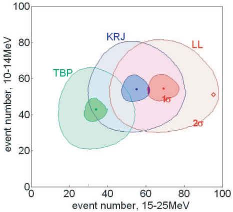
$\overline{\nu}_e$-neutrino spectrum



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

Event rate in 10 y:

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



M. Wurm *et al.*, Phys. Rev. D75 023007 (2007)

Information about Star Formation Rate for 0 < z < 1

DSNB in MEMPHYS and GLACIER

MEMPHYS

- Adding 0.2% gadolinium
- $\overline{\nu}_e + p \rightarrow n + e^+$
- $n + Gd \rightarrow \gamma$ (8 MeV)

$\rightarrow$ rejection of *invisible muons*

- (43 - 109) signal and 47 bg events in 5 years

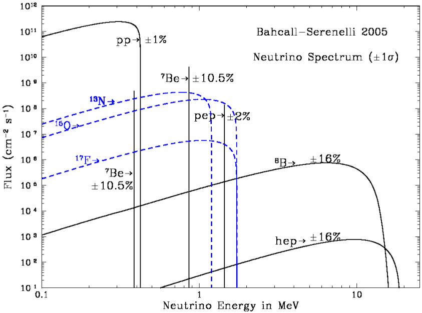
GLACIER

- $\nu_e +^{40} \mathrm{Ar} \rightarrow e^- +^{40} \mathrm{Ar}^*$
- + associated gamma cascade
- Background from solar and low energy atmospheric ν's
- (40 - 60) signal and 30 bg events in 5 years

LAGUNA scientific paper, D. Autiero *et al.*, JCAP 0711, 011 (2007)

Solar neutrinos

Predicted solar ν-spectrum



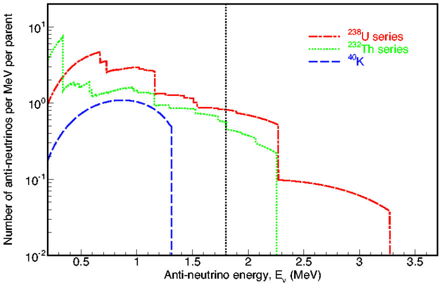
- MEMPHYS
  - Direction to separate from background events
  - ^{8}B ES: 1.1×10^{5} events in 1 y

- GLACIER
  - $\nu_x e^- \rightarrow \nu_x e^-$
  - $\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{Ar}^*$
  - However, threshold of 5 MeV on the e^- energy
  - ^{8}B ES: 4.5×10^{4} events in 1 y

- LENA
  - ^{7}Be ν's: $\sim 5400\ \mathrm{d}^{-1}$
  - $\rightarrow$ search for time modulations
  - pep ν's: $\sim 150\ \mathrm{d}^{-1}$
  - CNO ν's: $\sim 210\ \mathrm{d}^{-1}$
  - ^{8}B ν's: CC on ^{13}C: $\sim 360\ \mathrm{y}^{-1}$

Geoneutrinos

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



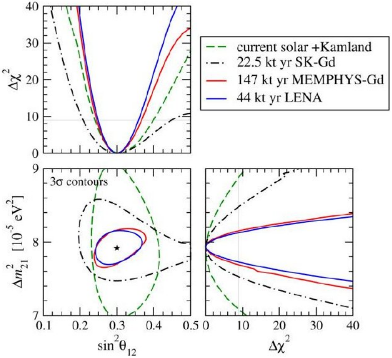
In water or liquid scintillator:

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

- In LENA: $\sim$ (400-4000) events/y (scaling KamLAND results)

K. Hochmuth *et al.*, Astropart. Phys. 27 (2007) 21

Reactor neutrinos



S. T. Petcov and T. Schwetz, Phys. Lett. B642, 487 (2006)

- Determination of θ_{12} and Δm^2_{12}
  - For the Fréjus location
  - After one year measuring time, 3σ precision on oscillation parameters:
    $\rightarrow$ 20% on θ_{12} and 3% on Δm^2_{12}
  - for 147 kt Cherenkov detector with 0.1% Gd and 44 kt liquid scintillator

J. Kopp *et al.*, JHEP 01, 053 (2007)

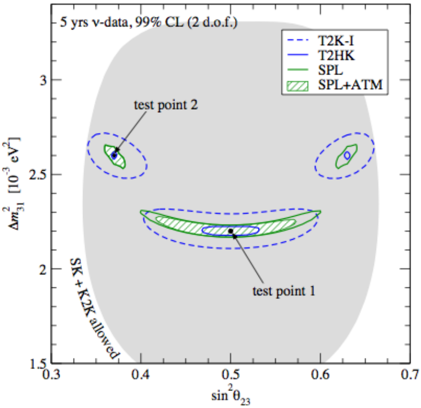
- Using a mobile $\overline{\nu}_e$ source (e.g. a nuclear powered ship)
  - For an underwater detector location
    $\rightarrow$ $\sin^2 2\theta_{13} < 0.004$ after about 3 years in LENA

Neutrino beams

- Baselines from CERN to the LAGUNA possible labs:
  - Canfránc $L = 630\,\text{km}$
  - Fréjus $L = 130\,\text{km}$
  - Boulby $L = 1\,050\,\text{km}$
  - Pyhäsalmi $L = 2\,300\,\text{km}$
  - Sieroszewice $L = 950\,\text{km}$
  - Slanic $L = 1\,570\,\text{km}$
  - Umbria $L = 700\,\text{km}$

Neutrino beams in MEMPHYS

- CERN to Frejus
  $\rightarrow$ 130 km distance
- The main goals for super-beam and beta-beam:
  - search for θ_{13}
  - searching for possible leptonic CP violation;
  - determining the mass hierarchy and the θ_{23} value.



J.E. Campagne, M. Maltoni, M. Mezzetto and T. Schwetz, JHEP 0704, 003 (2007), arXiv:hep-ph/0603172

Neutrino beams in GLACIER

- Updated **CNGS** beam
  - GLACIER at 0.75° off-axis $\sin^2 2\theta_{13} > 0.004$ at 3σ

    A. Meregaglia and A. Rubbia, JHEP11 (2006) 032, hep-ph/0609106

- **CERN - SPL**: Super beam project
  - ν_μ disappearance
  - $\nu_\mu \to \nu_e$ appearance

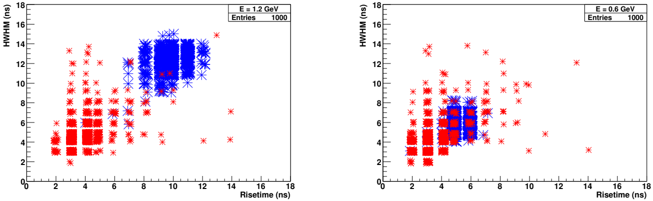
- **Beta beams (βB)**:
  - Pure ν_e or $\overline{\nu}_e$ beam from ^{18}Ne and ^{6}He

$\longrightarrow$ possibility to have a magnetized detector

A. Badertscher *et al.*, NIM A 555 (2005) 294, physics/0505151

Neutrino beams with LENA

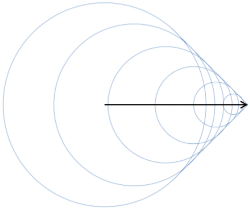
- Evaluation of muon/electron separation



- Evaluation of track reconstruction:

→ High energy particles create along their track a light front very similar to a Cherenkov cone

J. Learned (arXiv:0902.4009) and J. Peltoniemi (arXiv:0909.4974)



Outline

Summary

- LAGUNA design study
  - Investigation of possible sites ongoing
  - Final report July 2010
- Three detector concepts under discussion:

  GLACIER (LAr), MEMPHYS (water) and LENA (scintillator)
- Physics objectives:
  - Neutrino astrophysics

  $\longrightarrow$ first detection of DSNB
  - Proton decay

  $\longrightarrow$ one order of magnitude improvement in sensitivity, important input for theories beyond the standard model
  - Neutrino oscillations