Search for proton decay and dark matter with liquid scintillators

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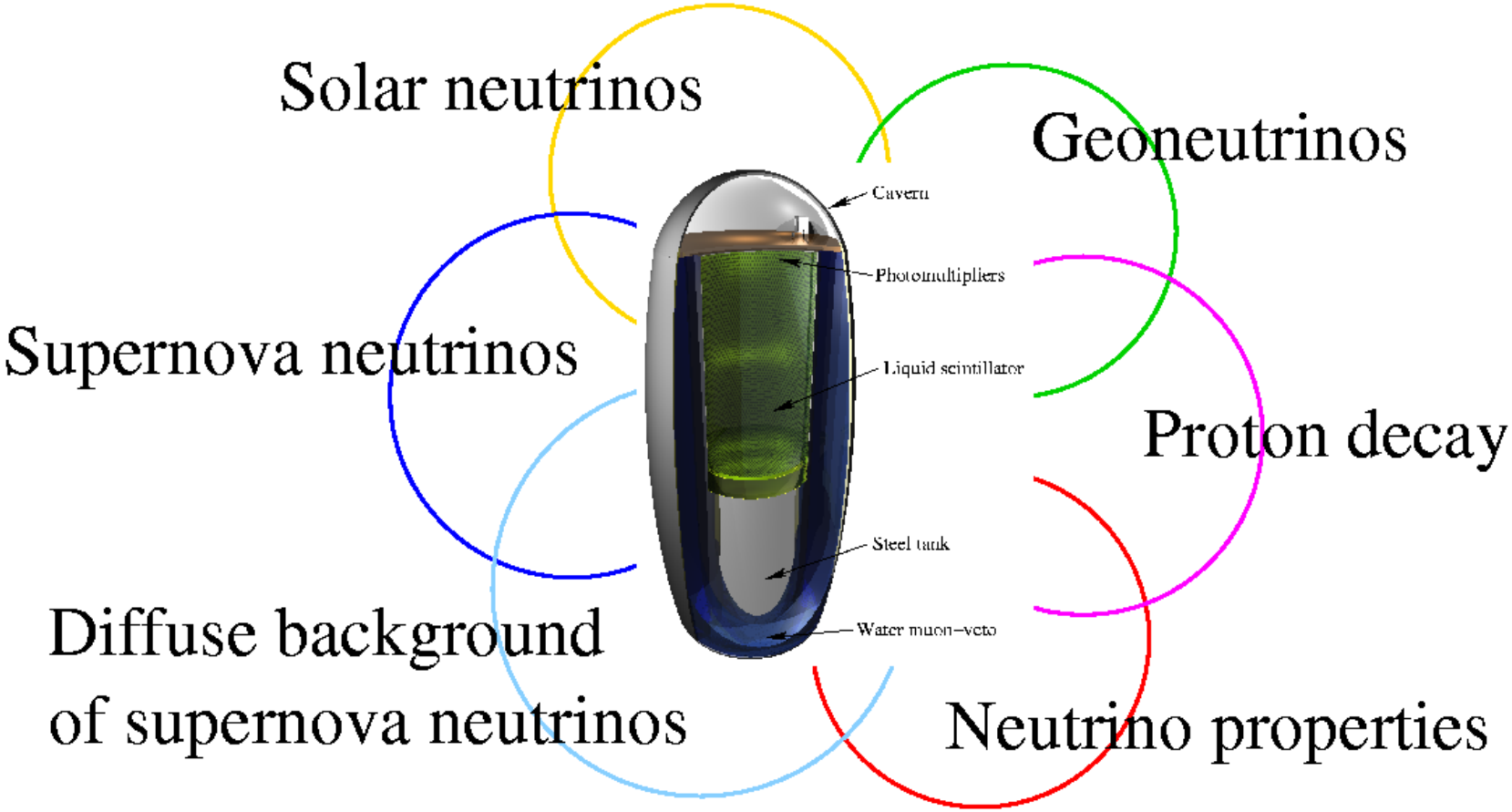
Outline

Outline

Low Energy Neutrino Astronomy



DETECTOR LAYOUT

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

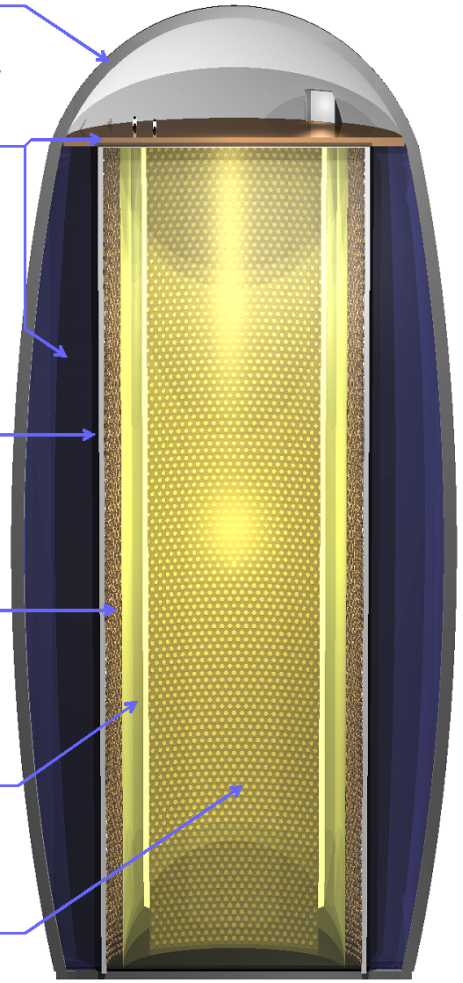
Muon Veto
plastic scintillator panels (on top)
Water Cherenkov Detector
1,500 phototubes
100 kt of water
reduction of fast
neutron background

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

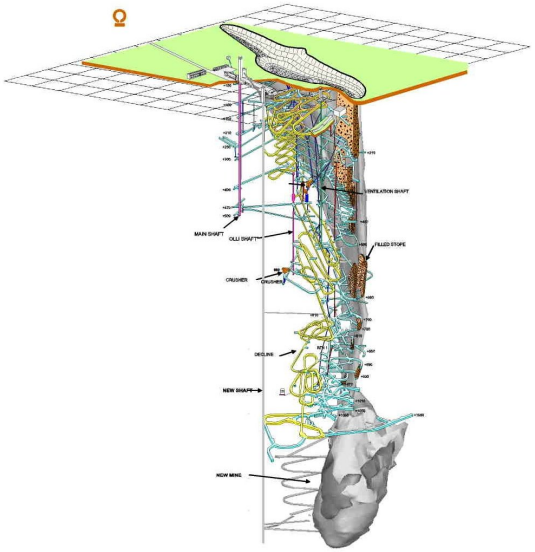
Nylon Vessel
parting buffer liquid
from liquid scintillator

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

- 50 kt of scintillator with 180 pe/MeV
- Underground location
- Pre-feasibility study: Pyhäsalmi site



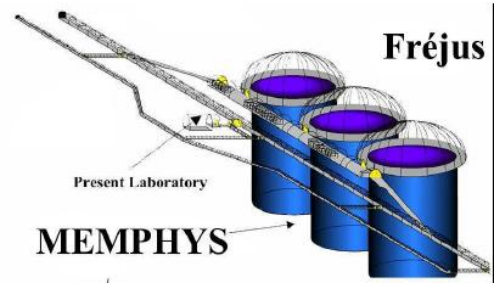
LENA status

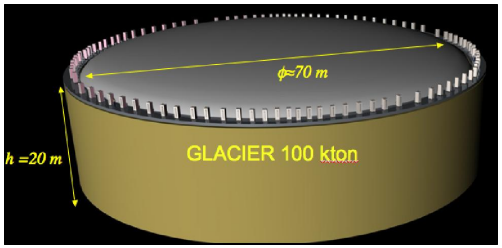
- 2003: LENA detector-concept was proposed
- 2003 - 2007: Study of physics potential and technical feasibility studies
- End of 2007: First study of an underground location
- 2008 - 2010: LAGUNA European design-study

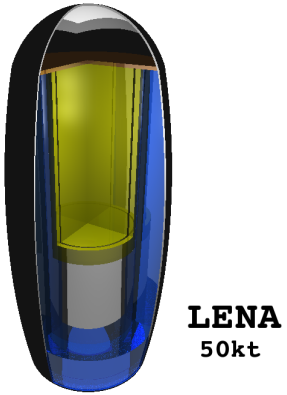
LAGUNA: **L**arge **A**pparatus for **G**rand **U**nification and **N**eutrino **A**strophysics

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

LAGUNA detector concepts







- MEMPHYS - MEgaton Mass PHYSics
  - 80 m heigth $\times$65 m $\varnothing$
  - $\sim$500 kt water Cherenkov detector
  - 81 000 PMTs per shaft (30% coverage)
- GLACIER - Giant Liquid Argon Charge Imaging ExpeRiment
  - 20 m heigth $\times$70 m $\varnothing$
  - $\sim$ 100 kt liquid Ar TPC
  - Light (28 000 PMTs) + charge readout
- LENA - Low Energy Neutrino Astronomy
  - 100 m long $\times$ 30 m $\varnothing$
  - $\sim$ 50 kt liquid scintillator
  - 13 500 PMTs for 30% coverage

Outline

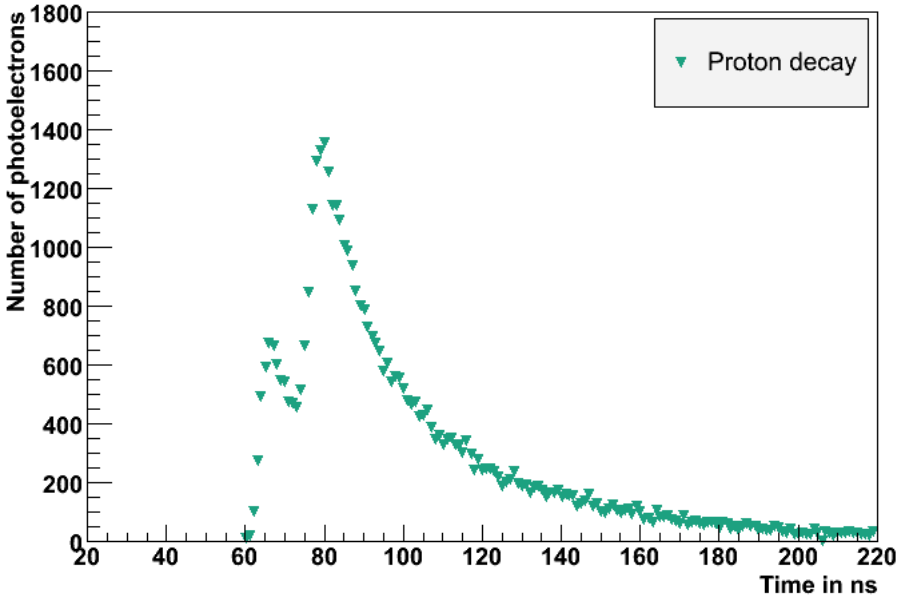
Proton decay

- Theoretically favored modes
  - $p \rightarrow e^+\pi^0$
  - $p \rightarrow K^+\overline{\nu}$ -> clear signature in liquid scintillators
- Predicted lifetimes: $\tau \sim 10^{34}$ y
- Super-Kamiokande best limits:
  $\tau(p \rightarrow e^+\pi^0) \gtrsim 5.4 \cdot 10^{33}$ y (90% C.L.)
  $\tau(p \rightarrow K^+\overline{\nu}) \gtrsim 2.3 \cdot 10^{33}$ y (90 % C.L.)

Free proton decay $p \rightarrow K^+\overline{\nu}$

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

- $K^+ \rightarrow \mu^+\nu_\mu$ 63.43%
  - $T(\mu^+) = 152$ MeV
- $K^+ \rightarrow \pi^+\pi^0$ 21.13%
  - $T(\pi^+) = 108$ MeV
  - $T(\pi^0) = 110$ MeV



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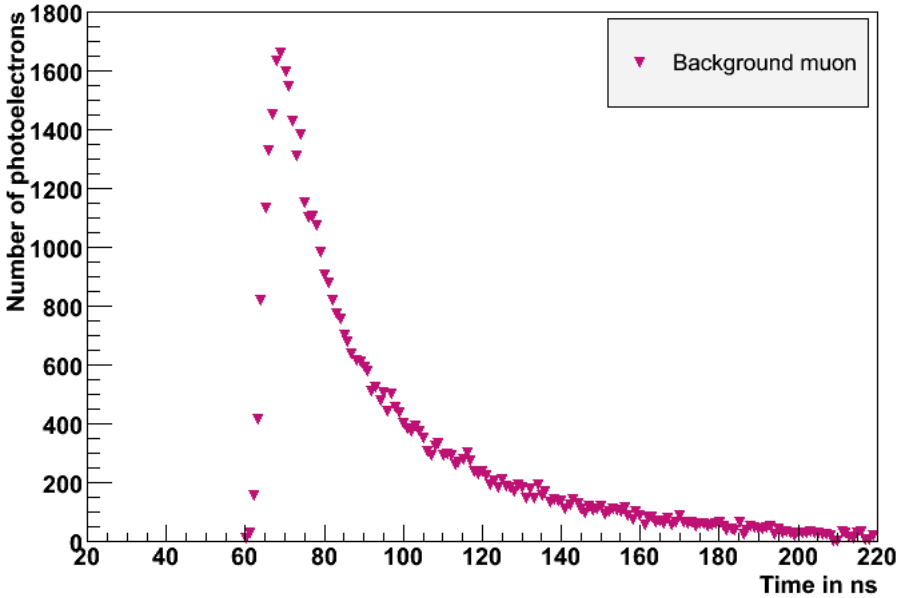
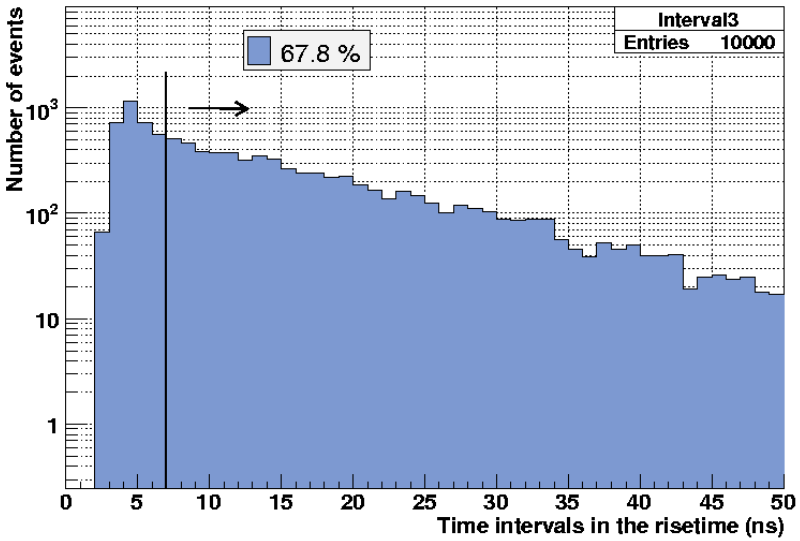
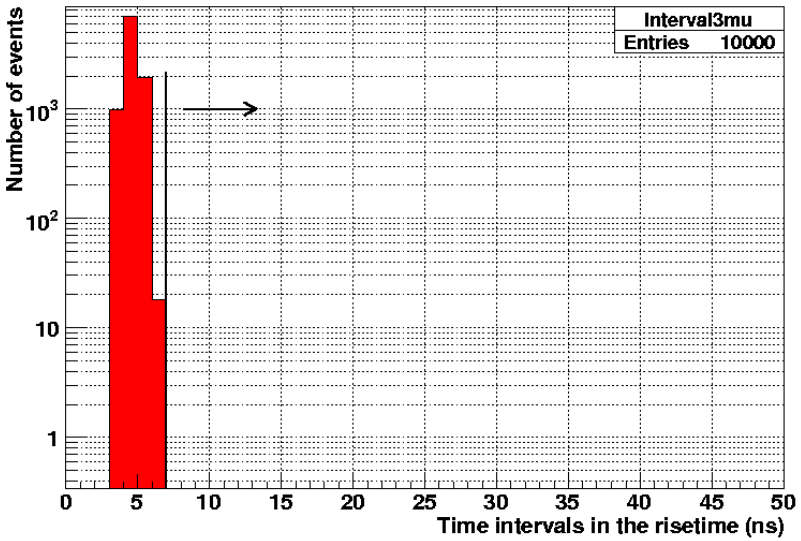
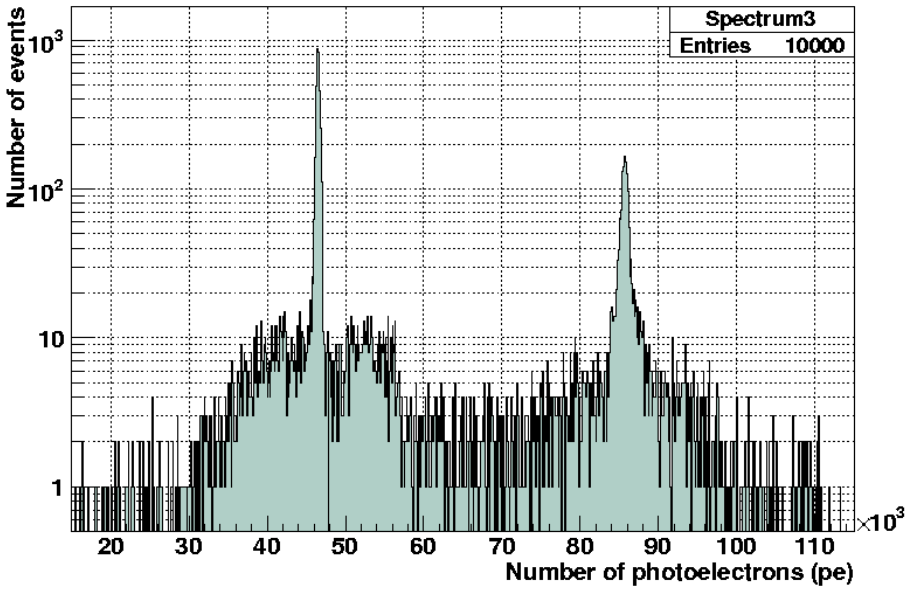


Background rejection





- Pulse-shape analysis on the risetime
- proton decay efficiency of $\sim 65\%$



- Energy spectrum (180 pe/MeV)
- Two peaks:
  - Kaon + Muon: ~ 257 MeV
  - Kaon + Pions: ~ 459 MeV
- Efficiency: $\varepsilon_E = 0.995$
- Included: protons from ^{12}C

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 $\epsilon = 65\%$

Phys. Rev. D 72, 075014 (2005)

Supernova detection

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

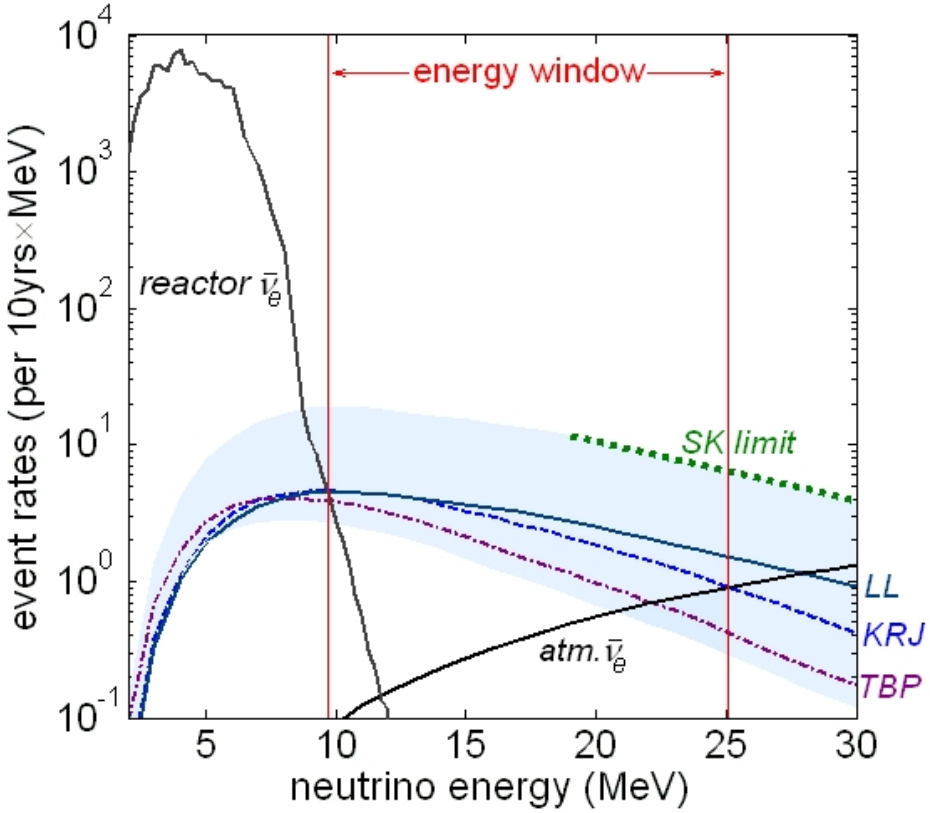
In LENA detector: ~15000 events

Possible reactions in liquid scintillator

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

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:

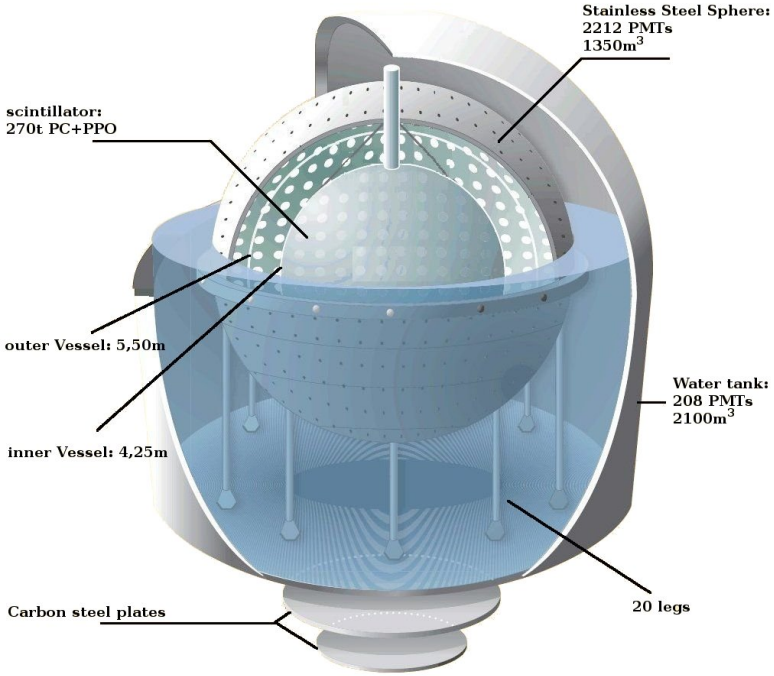
- LL: $\sim$ 110 events
- TBP: $\sim$ 60 events

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

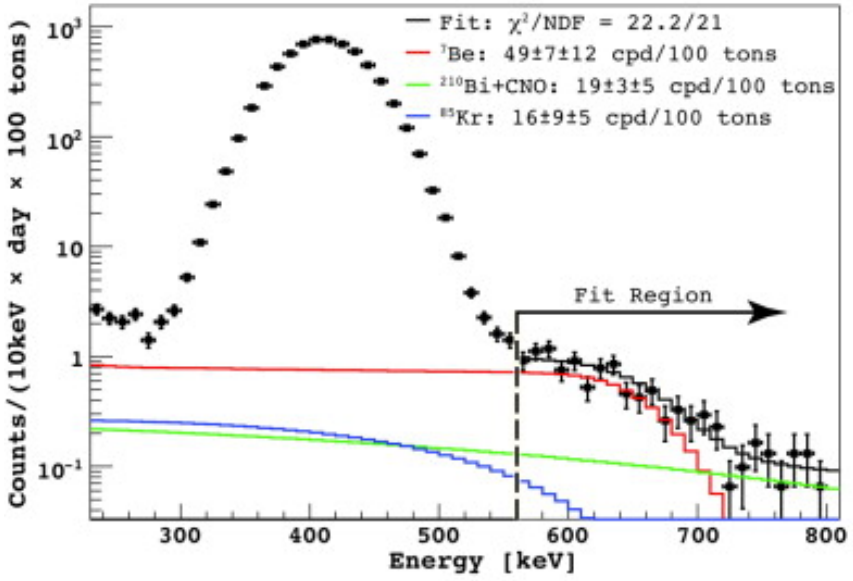
M. Wurm *et al.*, Phys. Rev. D75 023007 (2007)

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

Solar neutrinos



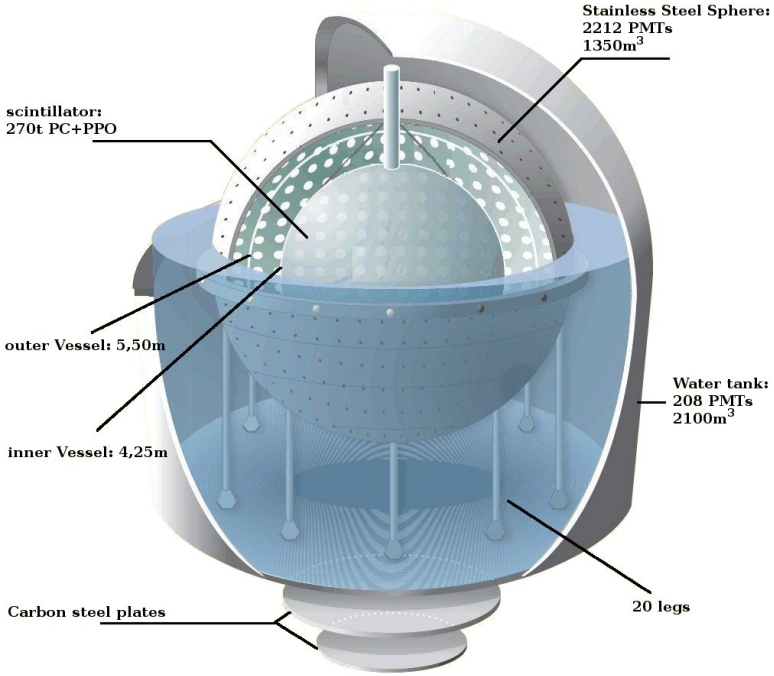
- Detection reaction: $\nu_e e^- \rightarrow \nu_e e^-$
- Sphere of 14 m ∅
- 300 tons of liquid scintillator



- Borexino experiment

-> First ^{7}Be neutrino measurement (2007)

Solar neutrinos



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Rates of solar neutrino events

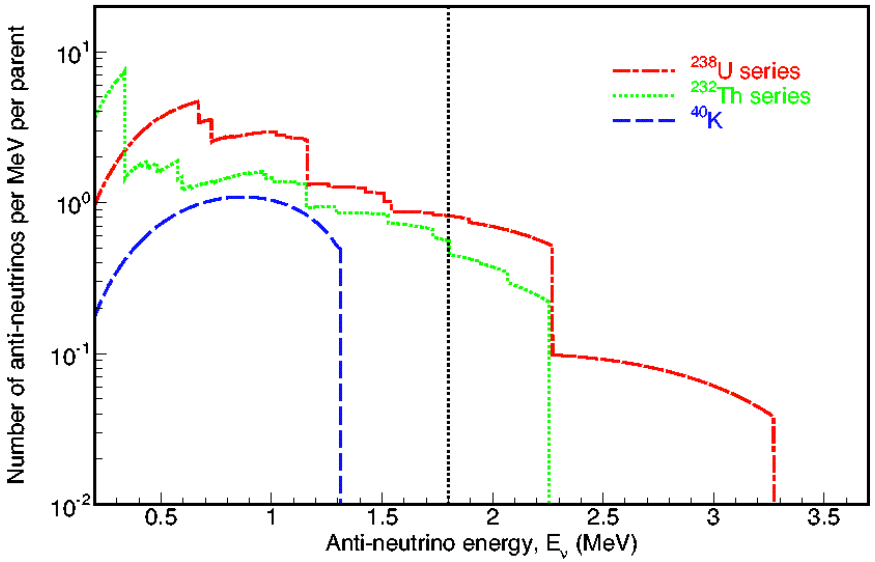
In the LENA fiducial volume:

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

- ^{7}Be ν's: $\sim$ 5400 d^{-1}
  - Small time fluctuations
- pep ν's: $\sim$ 150 d^{-1}
  - Information about the pp-flux $\rightarrow$ Solar luminosity in ν's
- 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:

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

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

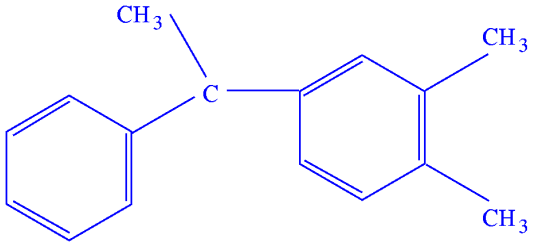
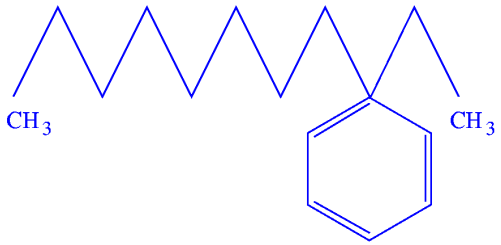
- In LENA detector: $\sim$ (400-4000) events/y (Scaling KamLAND results)
- ^{238}U/^{232}Th separation due to spectral form

Outline

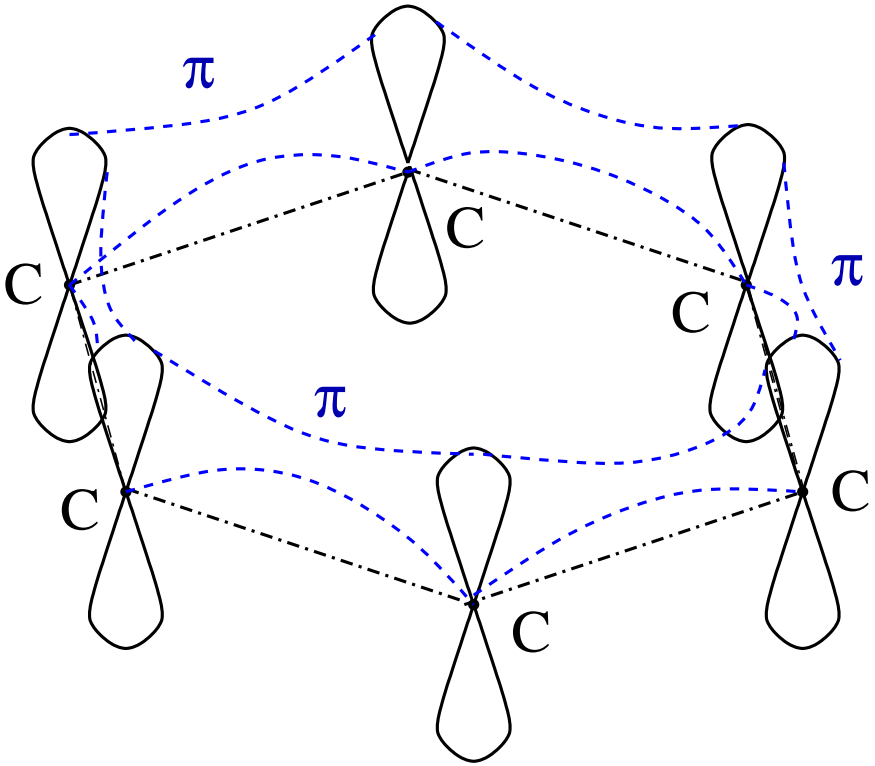
Why liquid scintillators for neutrino experiments?

- Enable large detector volumes ($\sim$ ton)
- Low energy threshold ($\sim$ hundreds of keV)
- Good energy resolution (10% at 10 MeV)
- Fast detector: position reconstruction ($\sim$ cm)
- Particle discrimination (α/β)
- High cross section for $\overline{\nu}_e$

Organic liquid scintillators

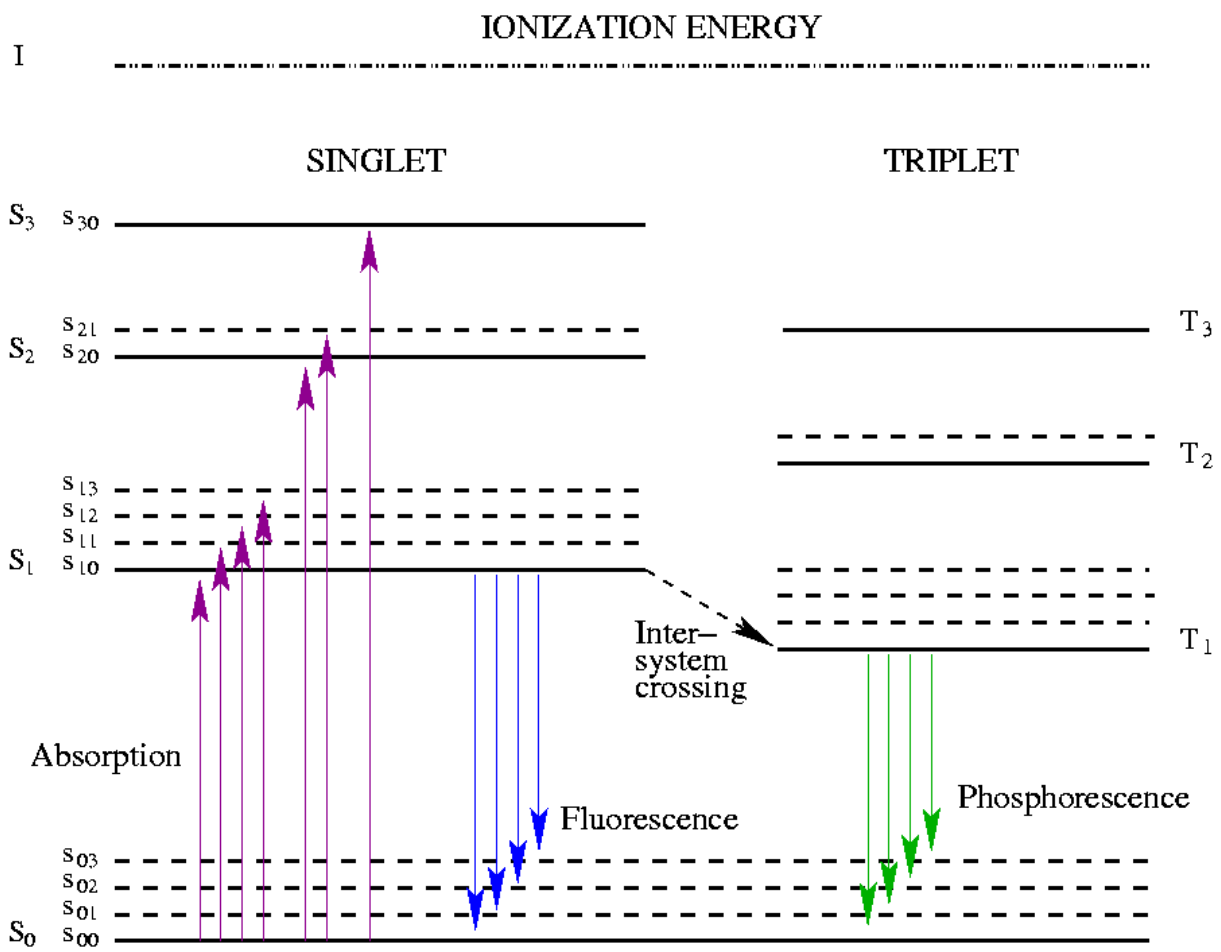
Solvent	phenyl-o-xylylethan	linear-alkyl-benzene
Short name	PXE	LAB
		
Formula	$C_{16}H_{18}$	$C_9H_{12}+(CH_2)_m$ m=7-10
Density	0.986 kg/ℓ	0.863 kg/ℓ
Absorption	270 nm	260 nm
Emission	290 nm	283 nm

Benzene structure



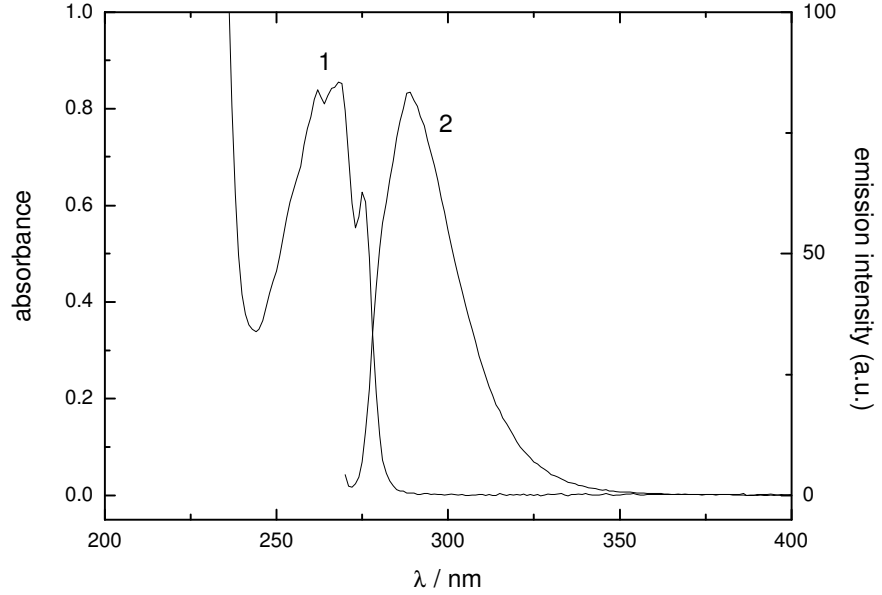
- Aromatic compounds
- Hybridization of carbon atoms
  - $1s^2\ 2s^1\ 2p^3$
- Double bound produce delocalized orbital
- π-orbitals in benzene produce luminiscence

π-orbital energy levels

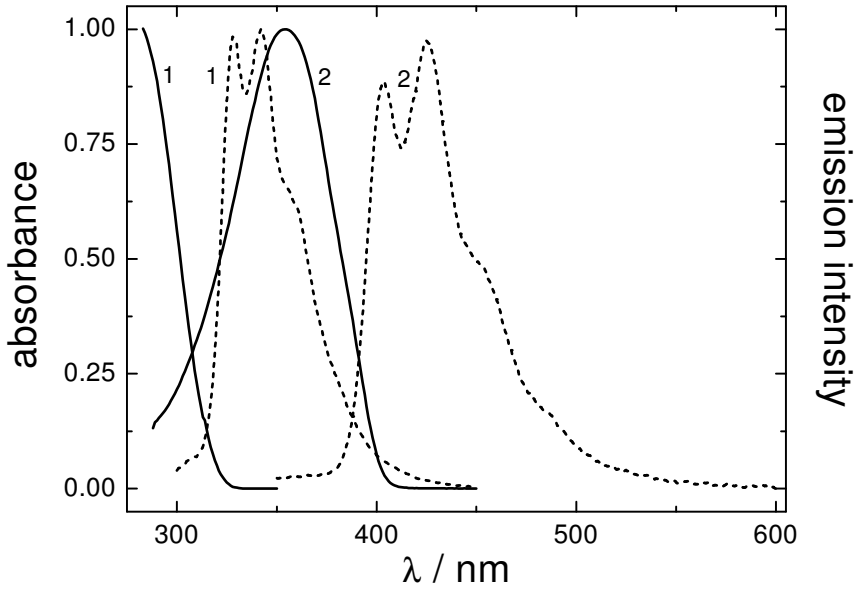


- Singlet spin-states
  - $S_{10} \rightarrow S_{0i}$
  - Fast decay $\sim$ several ns
- Triplet spin-states
  - $T_1 + T_1 \rightarrow S_{10} + S_{0i}$
  - Slow rate $\sim$ hundreds of ns
  - Dependence on the ionization density

Multi-component scintillators



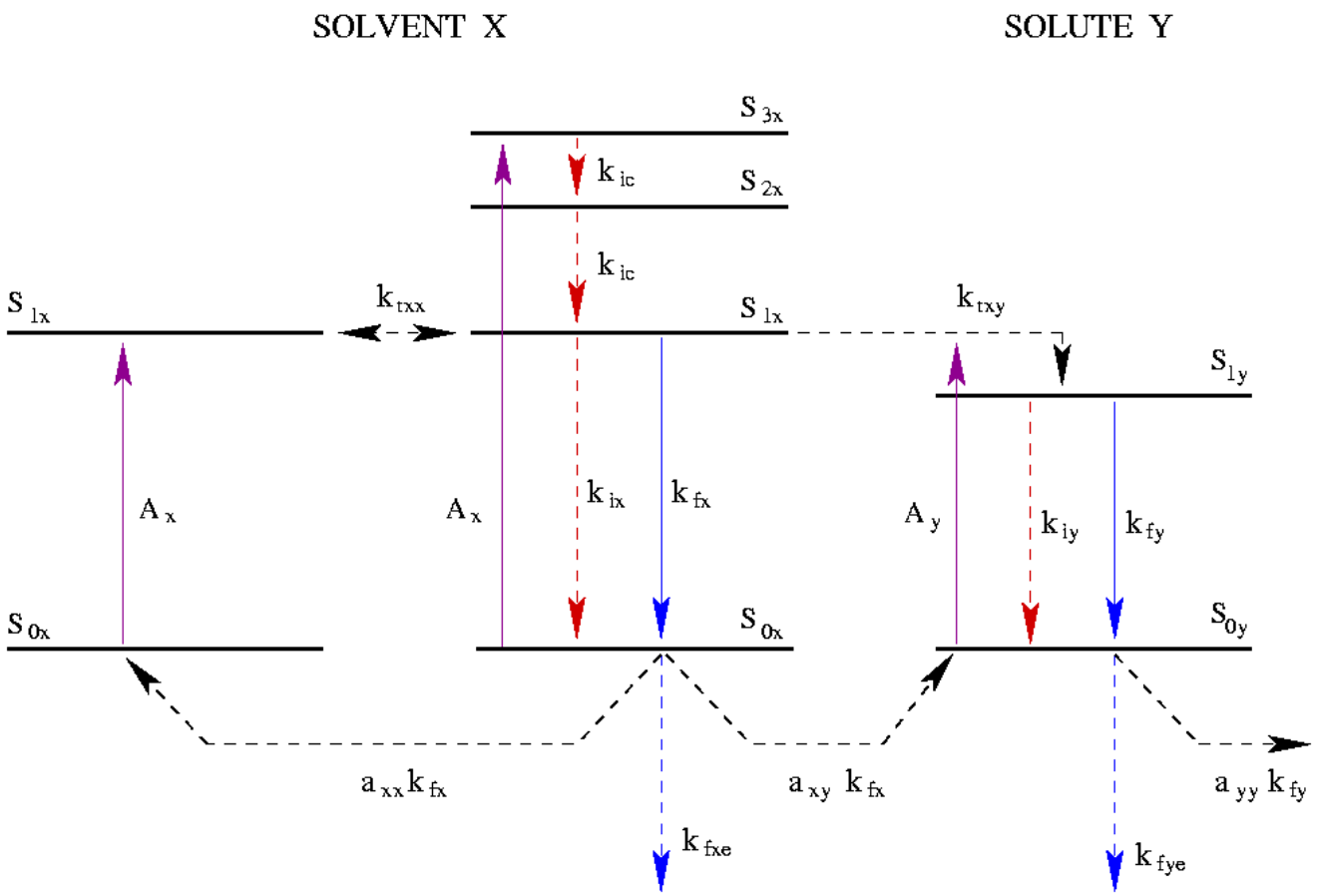
Absorption (1) and emission (2) spectrum of PXE disolved in cyclohexane



Absorption (full lines) and emission (dashed lines) spectra of the fluors: p-Tp (1) and bisMSB (2)

- Problem: Solvent emission spectrum overlaps with its absorption
- Solution: Further organic additives (wavelength-shifters)
- Large overlap between solvent emission and solute absorption minimizes light losses

Two component scintillator



- Liquid solvent
  - 20-30 ns lifetime
  - Energy transfer to solute
- few g/ℓ solute powder
  - 2-6 ns lifetime

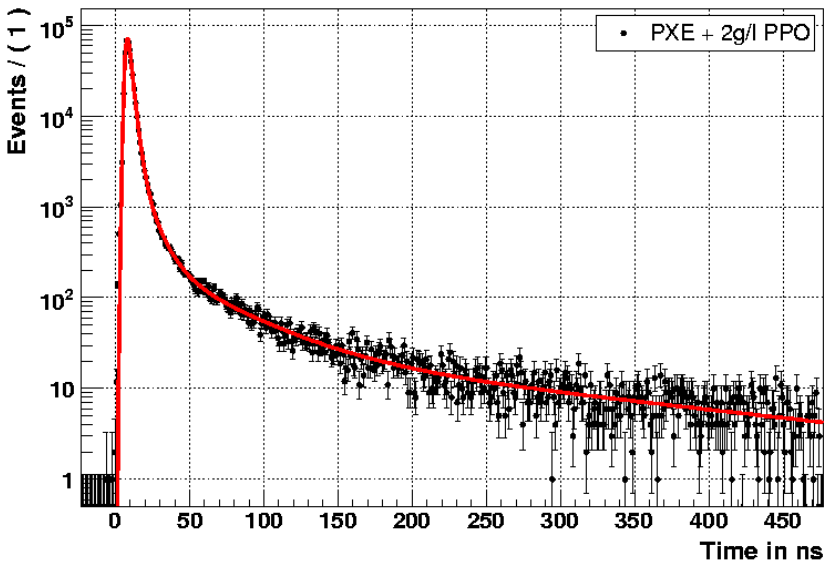
The light output

- High light yield
  $\rightarrow$ good energy resolution + low energy threshold
  - Efficient transformation of deposited energy into photons
  - Efficient energy transfer from the solvent to the solute

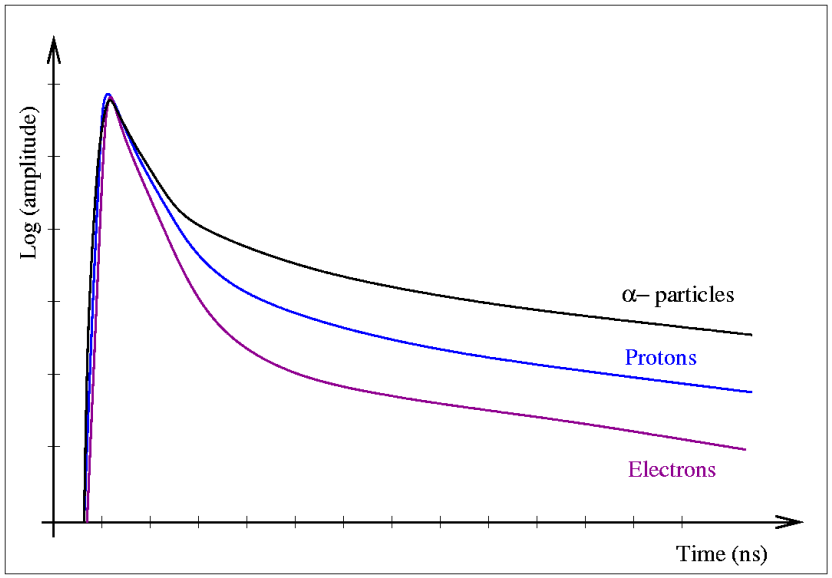
- Understanding of quenching effects
  - For particles heavier than electrons: high ionization density
    $\rightarrow$ light losses: slow recombination time
    $\rightarrow \quad S^* + S^* \rightarrow S^+ + S_0 + e^-$
  - Empirical Birk's parametrization:

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{A\frac{\mathrm{d}E}{\mathrm{d}x}}{1+kB\frac{\mathrm{d}E}{\mathrm{d}x}}$$

Fluorescence decay time



Measurement of a signal from energy deposition by an electron



Scheme of the pulse shape for different particles types

- Main component: lifetime of the S_1 state
- For high $\frac{dE}{dx}$: $T_1 + T_1 \rightarrow S_1 + S_0$ rate increases

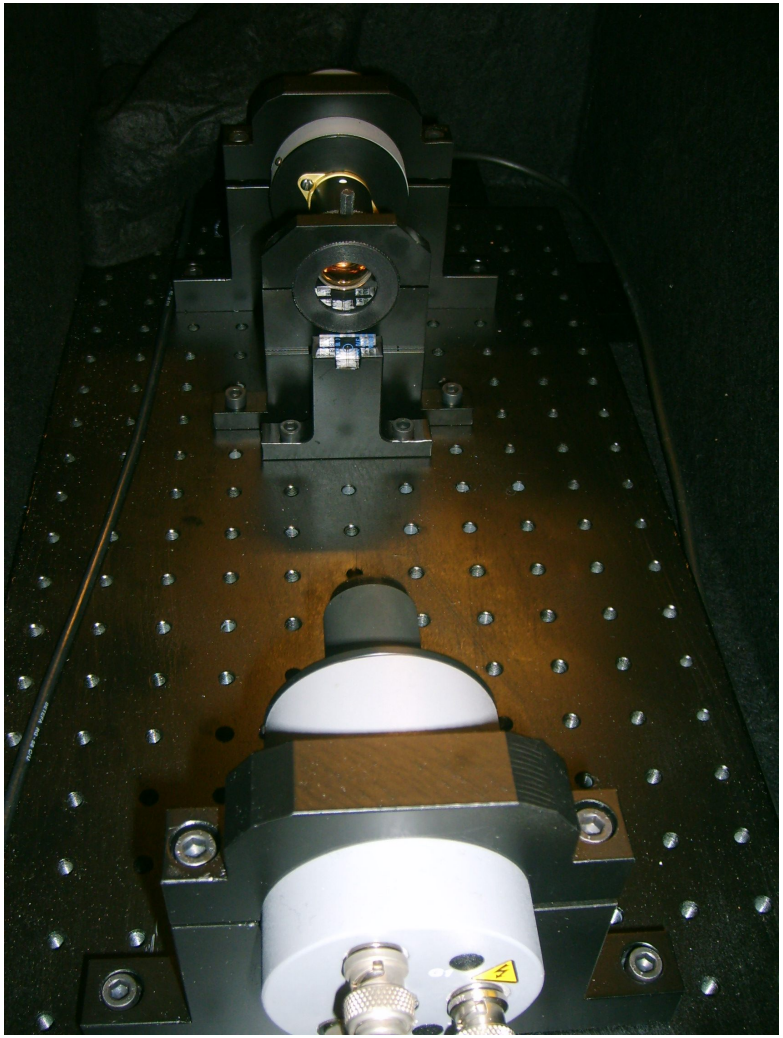
Light propagation

- Absorption by organic impurities in the solvent
  $\longrightarrow$ chemical purity of the solvent
- Scattering: Rayleigh and Mie processes
  $\longrightarrow$ Scintillator purification:
  water extraction and column purification
- Absorption and reemission by the solute

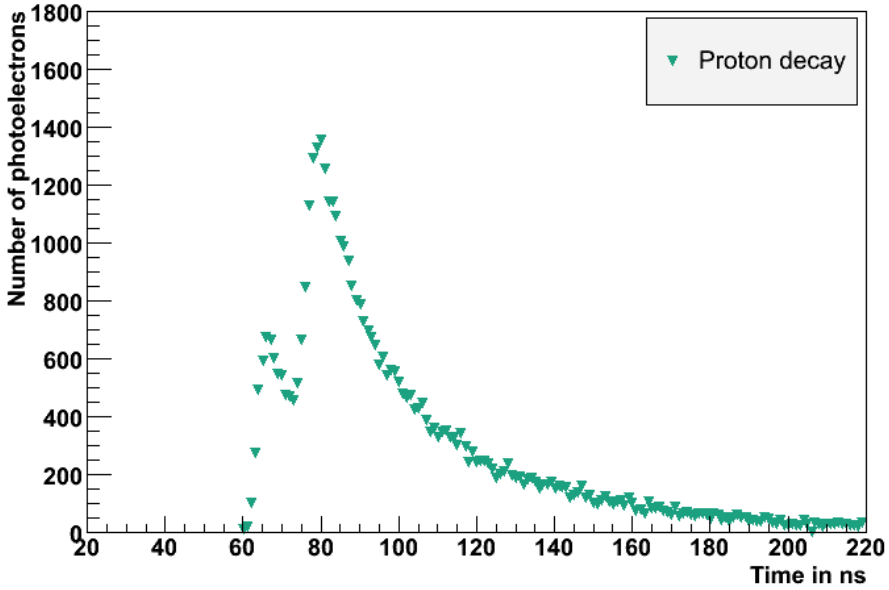
$$I = I_0 \cdot e^{-\frac{x}{\lambda_a}} \cdot e^{-\frac{x}{\lambda_s}}, \qquad \frac{1}{\lambda} = \frac{1}{\lambda_a} + \frac{1}{\lambda_s}$$

Outline

Fluorescence decay-time measurements

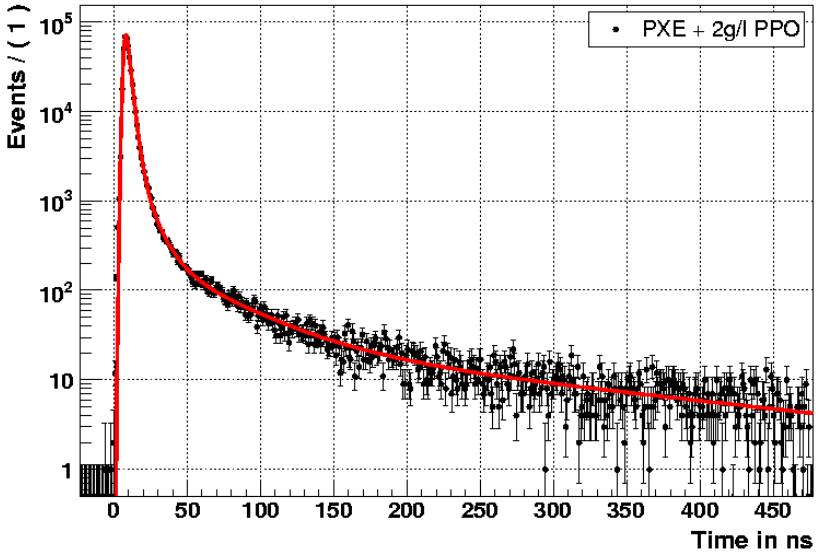


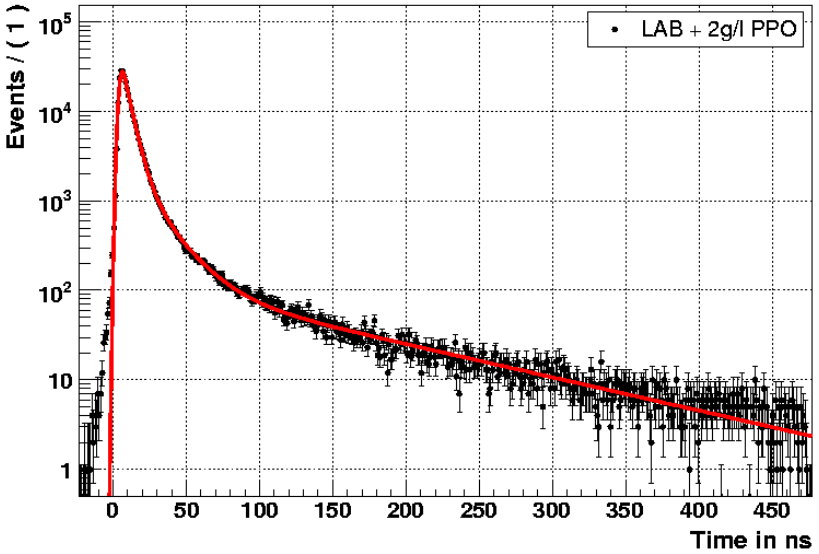
- Motivation: PD identification



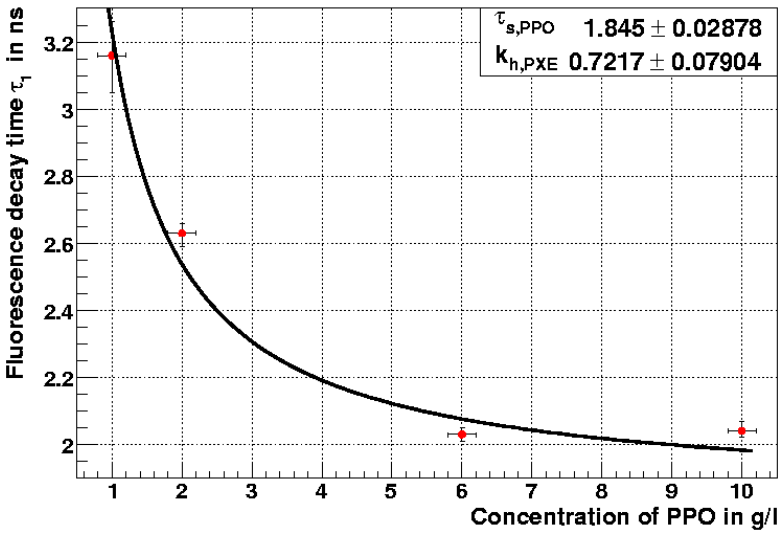
- Photon counting method
- ^{54}Mn source: 834 keV γ's
- PMT's time jitter: $\sigma = 0.9$ ns

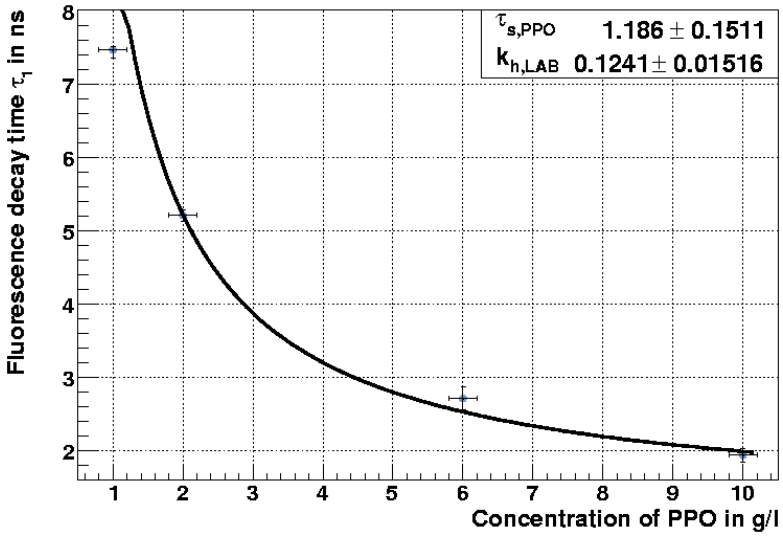
Photon emission distribution

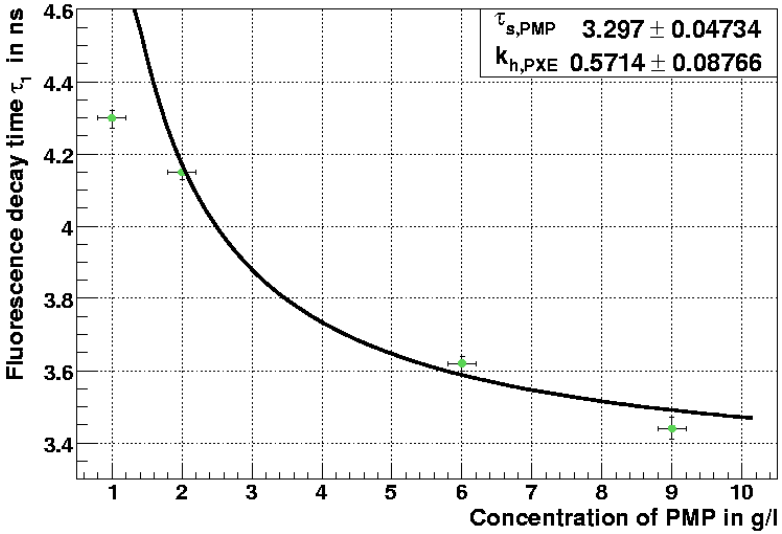




- A short constant τ_1, 2-8 ns -> 60 to 95% of the light
  Related to $S_1 \rightarrow S_0$ transition
- Mixtures based on LAB are slower than those with PXE
- Influence of the τ_1 on the proton decay sensitivity
  - $\tau > 4.2 \cdot 10^{34}$ y for $\tau_1 = 3$ ns
  - $\tau > 3.5 \cdot 10^{34}$ y for $\tau_1 = 6$ ns







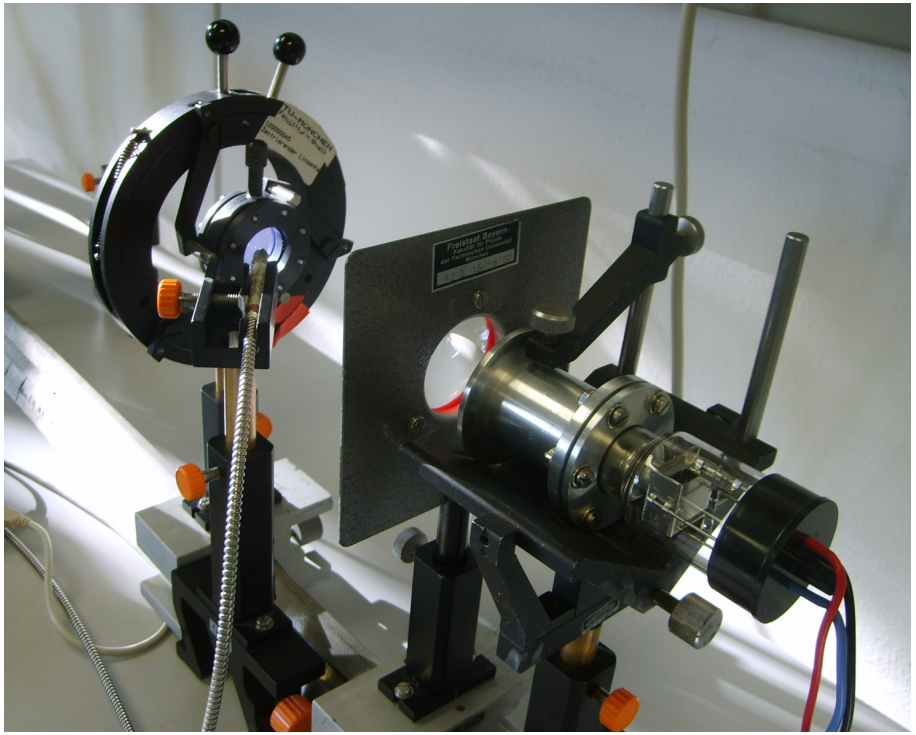
- Evolution of the shortest decay time with solute concentration

  PXE - PPO, LAB - PPO, PXE - PMP

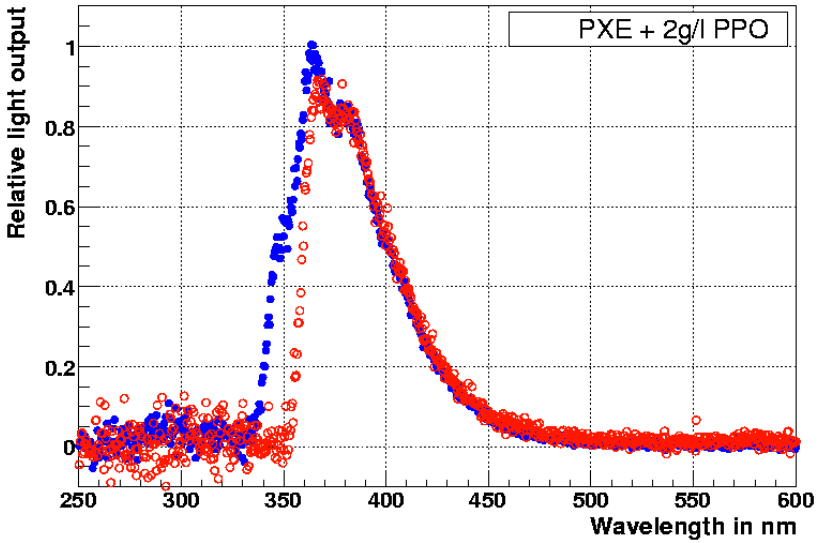
$$t(c) = t_0 + \frac{1}{k_{xy} \cdot c}$$

Rev. Sci. Instrum. 80, 043301 (2009)

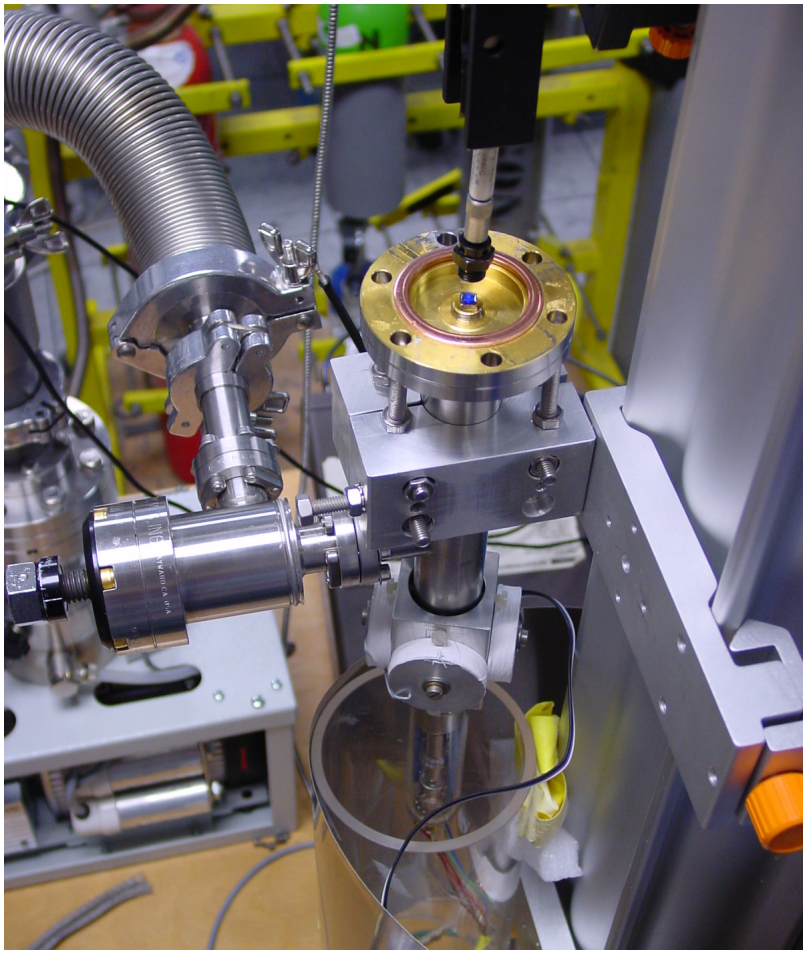
Scintillator spectra: UV-Lamp



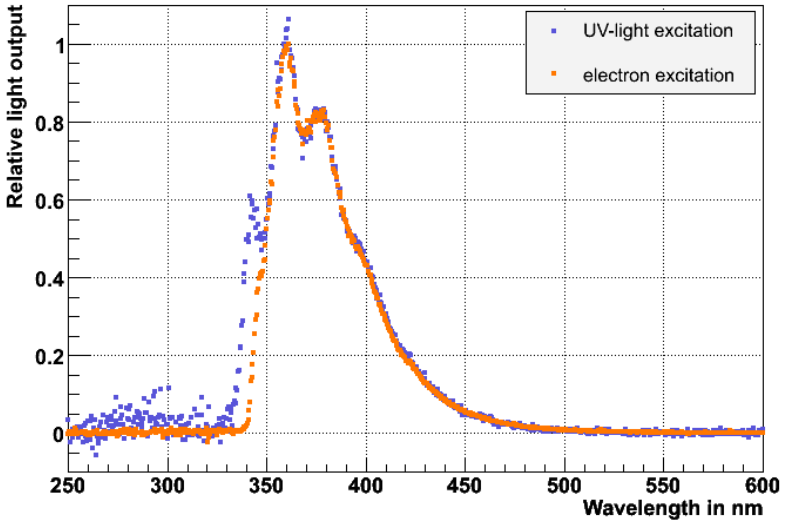
- UV-radiation: Deuterium lamp
- Spectroscopy of the emitted light



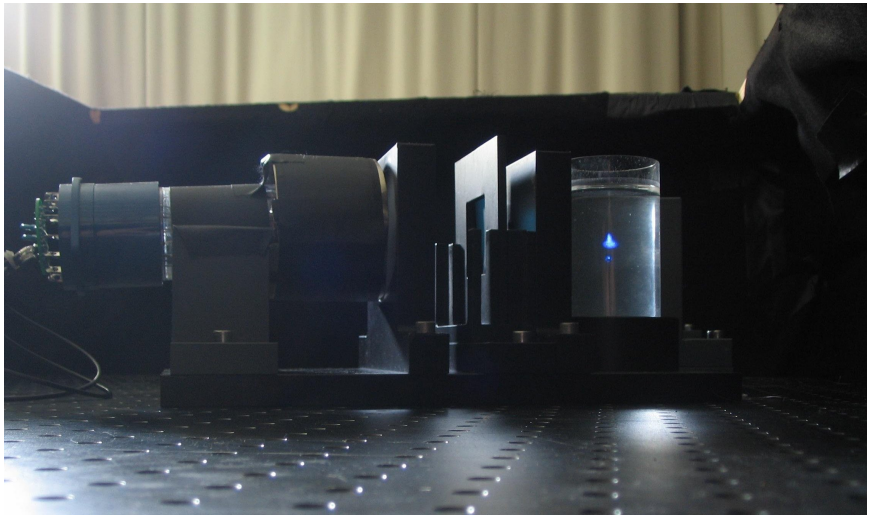
Scintillator spectra: electron beam



- ∼10 keV electron beam
- Evacuated small accelerator (10-15 kV)
- Window for the electrons: thin (300 nm) silicon nitrate membrane



Scattering length measurements



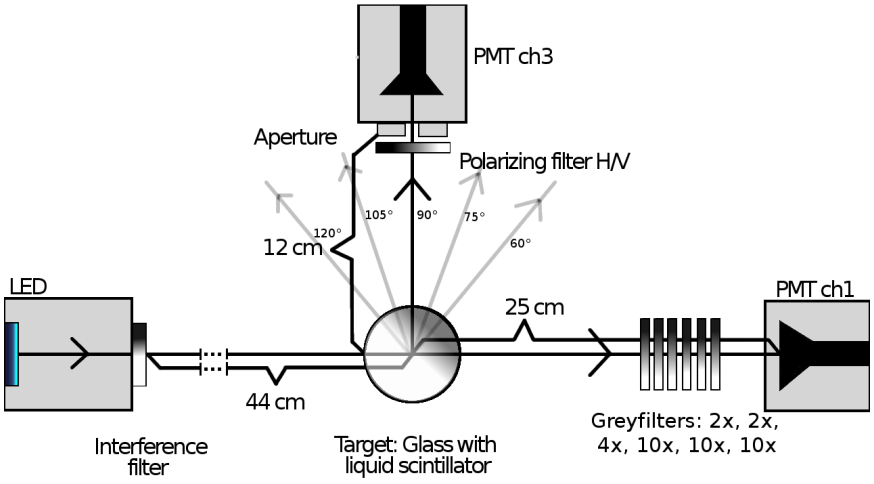
- LED light source
- Detection with PMTs
- Selection of the wavelength with color filters

- Results @ 430 nm

Scintillator	λ_s in m
PXE	13.6 ± 1.7
LAB	25 ± 3
Dodecan	44 ± 7

- Systematic errors from filter efficiencies, PMT efficiencies and solid angle determination
- Study of polarized and unpolarized light

Scattering length measurements



- LED light source
- Detection with PMTs
- Selection of the wavelength with color filters

- Results @ 430 nm

Scintillator	λ_s in m
PXE	13.6 ± 1.7
LAB	25 ± 3
Dodecan	44 ± 7

- Systematic errors from filter efficiencies, PMT efficiencies and solid angle determination
- Study of polarized and unpolarized light

Outline

Summary

- Lena physics
  - Good sensitivity for proton decay via $p \rightarrow K^{+}\overline{\nu}$
  - Supernova and solar neutrinos
  - Geoneutrino measurements
- Organic liquid scintillator
  - Microscopic model presented
  - Experiments to light production: fluorescence and spectroscopy
  - Dependence of the proton decay sensitivity on the scintillator choice
  - Study of light propagation: scattering lengths

Outline

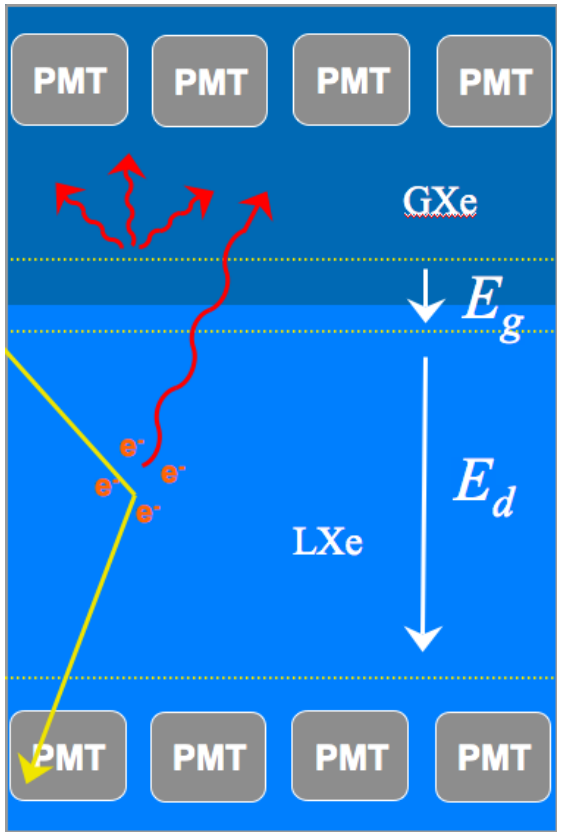
Liquid xenon investigation

Two-phase xenon detector at UZH

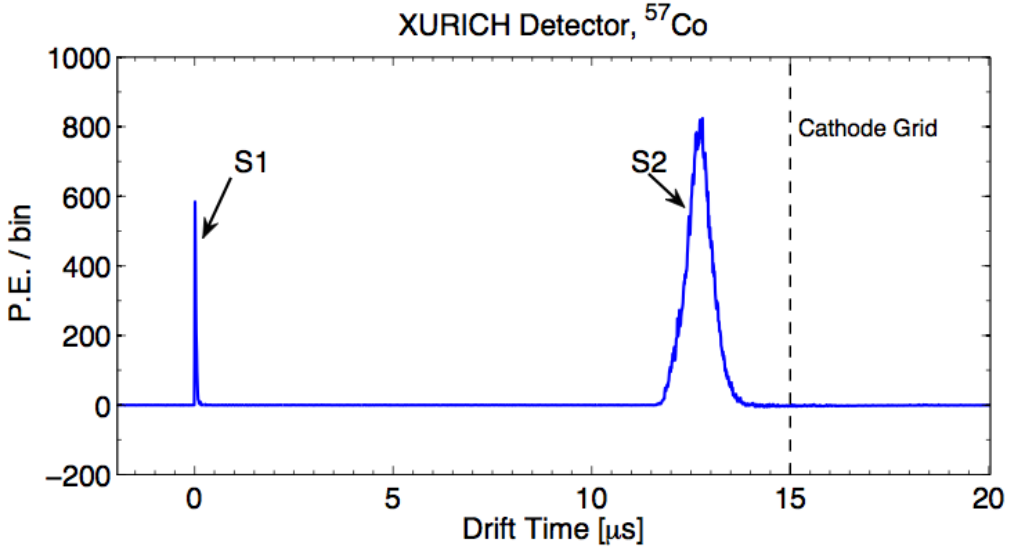
Target mass: $\sim$ 0.1 kg

- Study of xenon scintillation mechanism
- Investigate light and charge production by different types of particles (electron/neutron)
- Test of calibration sources for Xenon detectors

Two phase noble gas detector

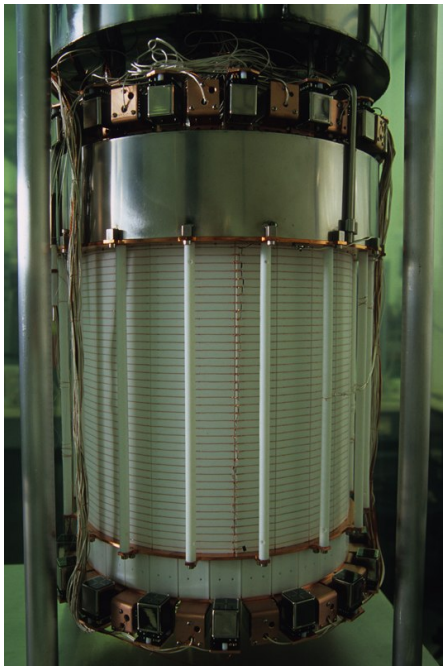


- Scintillation signal (S1)
- Charge drift to the liquid-gas surface
- Proportional signal (S2)

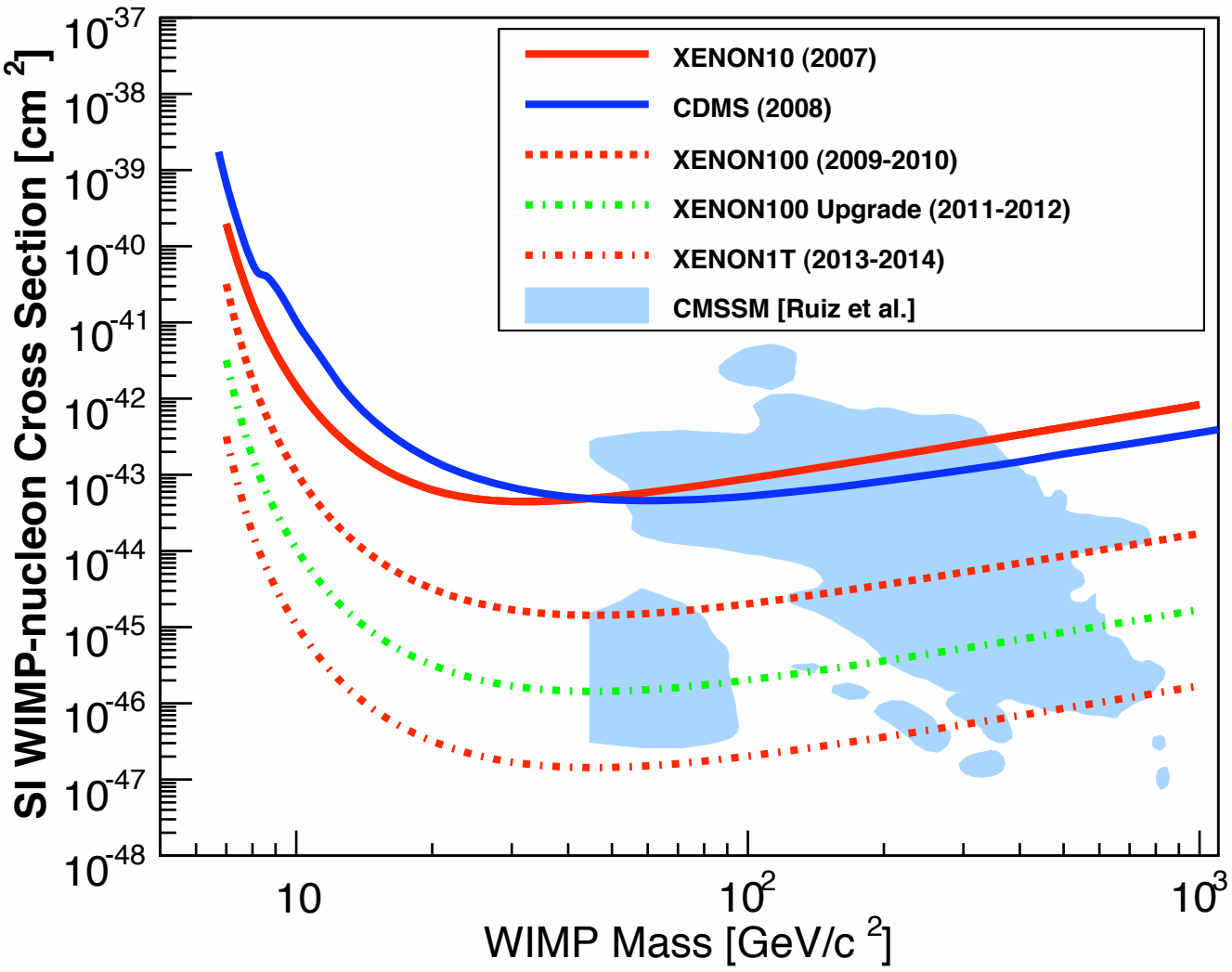


XENON100 experiment

- 65 kg fiducial volume
- Located at the Gran Sasso Laboratory in Italy



- Indirect dark matter evidence
- WIMP detection through their interaction with Xe nuclei
- Potential to study theoretically favored mass and cross section regions


XENON10 (2007)
CDMS (2008)
XENON100 (2009-2010)
XENON100 Upgrade (2011-2012)
XENON1T (2013-2014)
CMSSM [Ruiz et al.]
SI WIMP-nucleon Cross Section [cm 2]
WIMP Mass [GeV/c 2]
10
10^2
10^3
10^-37
10^-38
10^-39
10^-40
10^-41
10^-42
10^-43
10^-44
10^-45
10^-46
10^-47
10^-48