Large Liquid Scintillator Detectors for Neutrinos and Nucleon Decays

L. Oberauer, TU München
Physik-Department
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Content

- Detector scheme
- Solar neutrinos
- Supernova neutrino burst
- Diffuse Supernova Neutrino Background
- Geo-neutrinos
- Proton decay

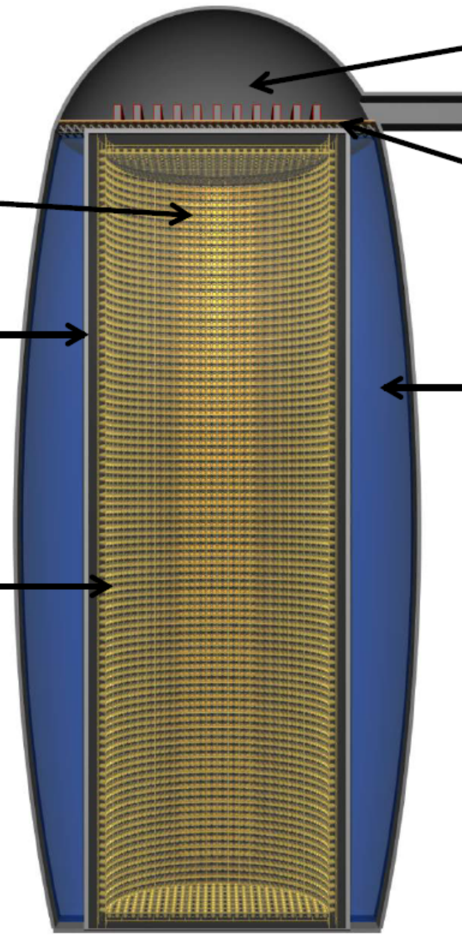
LENA

Liquid Scintillator
Active Mass = 50.8kt of LAB

Concrete Tank (+Steel Sheets)
r = 16m, h = 100m
Wall Thickness = 60cm
Total Mass = 69.1kt of LAB

PMT Support Structure
Inner face at r = 14m, h = 96m

about 30,000 12''-PMTs
with Winston cones
optical coverage: 30%



Electronics Hall
dome of 15m height

Top Muon Veto
vertical muon tracking

Water Cherenkov Veto
4000 8` PMTs, D_{min} > 2m
fast neutron shield
inclined muons

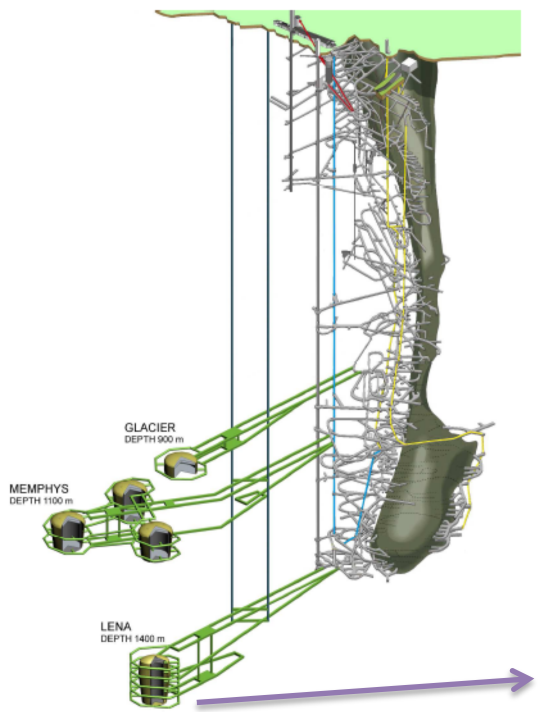
Egg-Shaped Cavern
about 200000 m^3

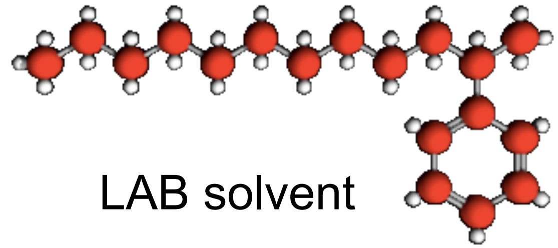
Rock Overburden
4000 mwe

LENA design study (LAGUNA consortium) for Pyhäsalmi (Finland)

arxive:1104.5620

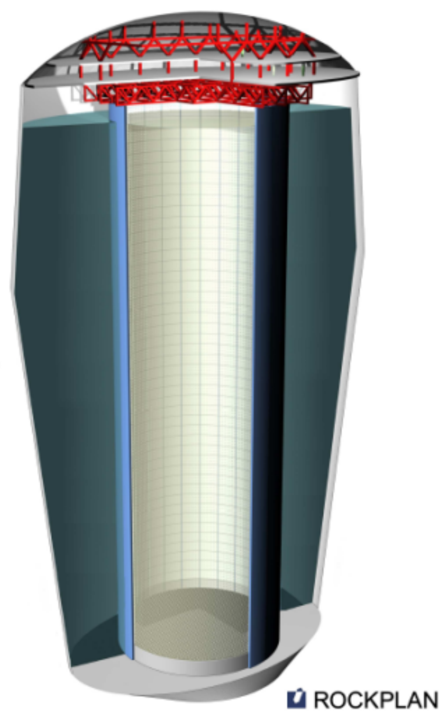
LENATechnology: Status & Development





LAB solvent

3 g/l PPO



Properties of LAB	
Chemical data	
Chemical formula	$C_{18}H_{30}$
Molecular weight	241
Density	0.863 kg/l
Viscosity	4.2 cps
Flash Point	140 °C
HMIS ratings	
Health	1
Flammability	1
Reactivity	0
Optical parameters	
Index of refraction	1.49
Attenuation length	~15 m
Absorption length	40 m
Abs.-reemission length	60 m
Rayleigh scattering length	40 m

Solar Neutrinos in LENA

Solar Neutrino Physics

- Big success in the past
- Neutrinos are massive
- Neutrinos mix: $\sin^2 2\Theta_{12} = 0.314$
- Mass hierarchy: $m^2_2 - m^2_1 = + 7.9 \times 10^{-5}\ eV^2$
- Solar Neutrino problem solved

...but two questions are open

❖ *Solar metallicity ?*

❖ *MSW effect in ^8B – spectrum ?*

What can LENA do, to answer this questions ?

Solar neutrino detection in LENA

Scenario: LENA in Pyhäsalmi (Finland) at 4060 mwe

- Elastic neutrino electron scattering

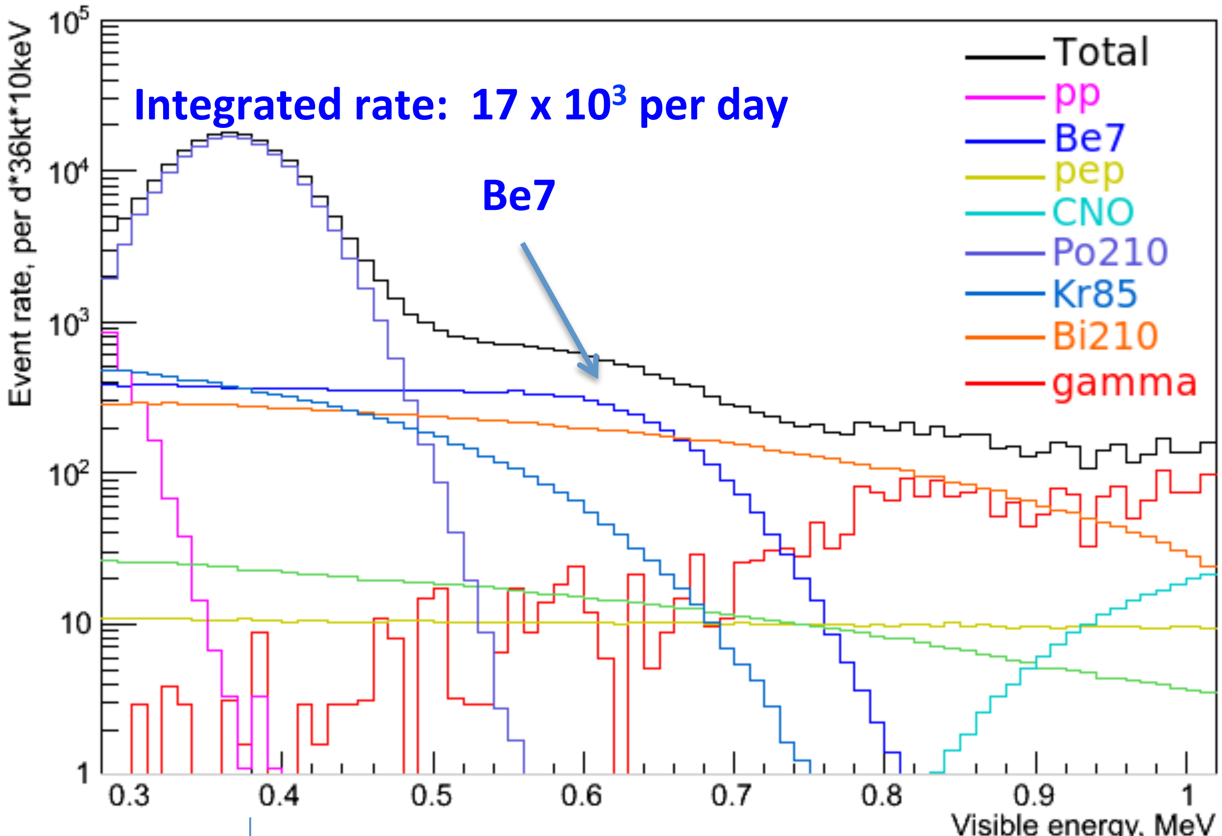
  as in Borexino, SNO+

  in principle all solar neutrino branches

- CC – reaction $\nu_e(^{13}C,^{13}N)e^-$

  for solar ^8B - neutrinos

Low E spectrum with backgrounds



Background rates:

Po210: 488.8 c/(d*100t)
Bi210: 41.6 c/(d*100t)
Kr85: 34.8 c/(d*100t)

...all from Borexino 2011 paper

C11: 5.6 c/(d*100t)
C10: 0.11 c/(d*100t)
Be11: 0.007 c/(d*100t)

Cosmogenic bg = 1/5 Borexino

^{210}Po position with k_b = 0.107 mm/MeV (alpha)

Search on small periodic variations

The high statistics in the **^{7}Be – rate** allows to search on small periodic flux variations

Search for modulations of the solar ^{7}Be flux in the next-generation neutrino observatory LENA

M. Wurm,[1,*] F. von Feilitzsch,[1] M. Göger-Neff,[1] T. Lewke,[1] Q. Meindl,[1]
R. Möllenberg,[1] L. Oberauer,[1] W. Potzel,[1] M. Tippmann,[1] and J. Winter[1]

[1] *Physik-Department E15, Technische Universität München, James-Franck-Str., D-85748 Garching, Germany*

(Dated: November 12, 2010)

Motivation: *Day/Night Matter effect, Correlations to the solar cycle, Helioseismic waves in the neutrino-sphere...*

Search on small periodic variations

$$N(t) = N_0 \cdot (1 + A \cdot \sin(t/T + \varphi))$$

„Lomb-Scargle“ power P to find modulations:

$$P = \frac{1}{\sqrt{2\sigma^2}} \left(\frac{\left[\sum_{i=1}^{n} w_i (N(t_i) - N_0) \cos\left(2\pi \frac{t_i - \phi}{T}\right)\right]^2}{\sum_{i=1}^{n} w_i \cos^2\left(2\pi \frac{t_i - \phi}{T}\right)} + \frac{\left[\sum_{i=1}^{n} w_i (N(t_i) - N_0) \sin\left(2\pi \frac{t_i - \phi}{T}\right)\right]^2}{\sum_{i=1}^{n} w_i \sin^2\left(2\pi \frac{t_i - \phi}{T}\right)} \right)$$

here we use $w = w_i$ (they all cancel)

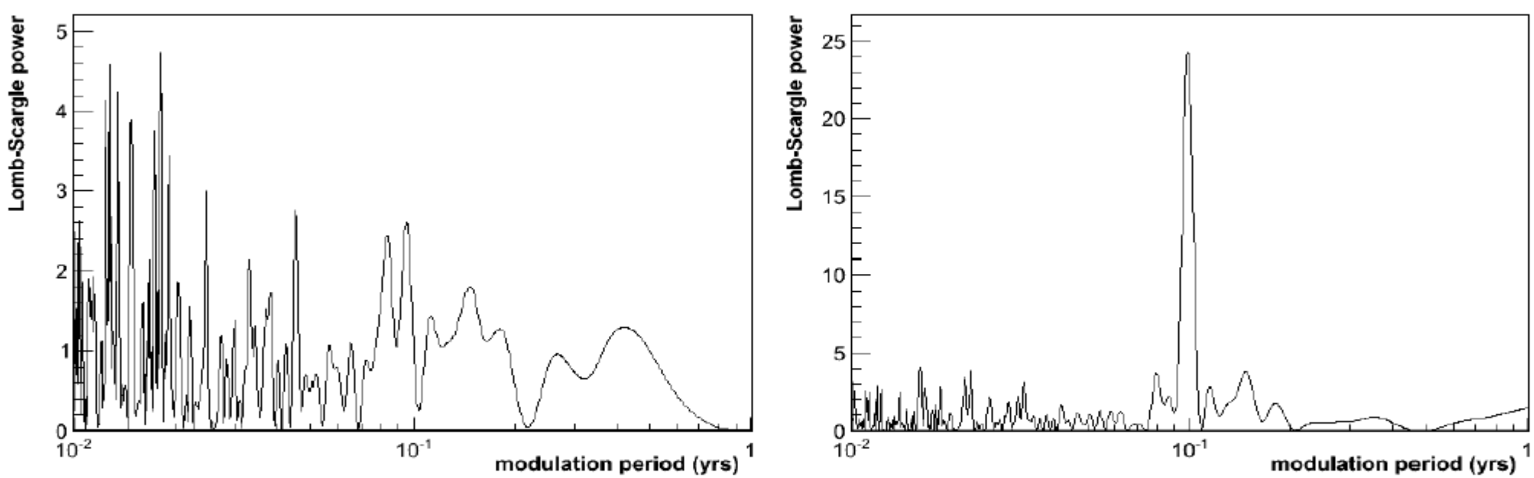


FIG. 2: Lomb-Scargle periodigrams for a MC data set of 2 years measurement time. *Left:* White noise spectrum. *Right:* A modulation of 2 % relative amplitude and a period of 0.1 years was included. A corresponding peak is visible at the indicated period, that is also clearly exceeding the regular white noise level.

Sensitivities

Day / Night effect $A = 10^{-3}$ sensitivity could be reached

Gravity driven helioseismic waves are confined to the inner regions of the Sun

Do they exist? SOHO hints to a $f = 220{,}7\ \mu$Hz signal

A. Jimenez and R. A. Garcia, Astrophys. J. Suppl. **184**, 288 (2009), astro-ph/0908.0562.

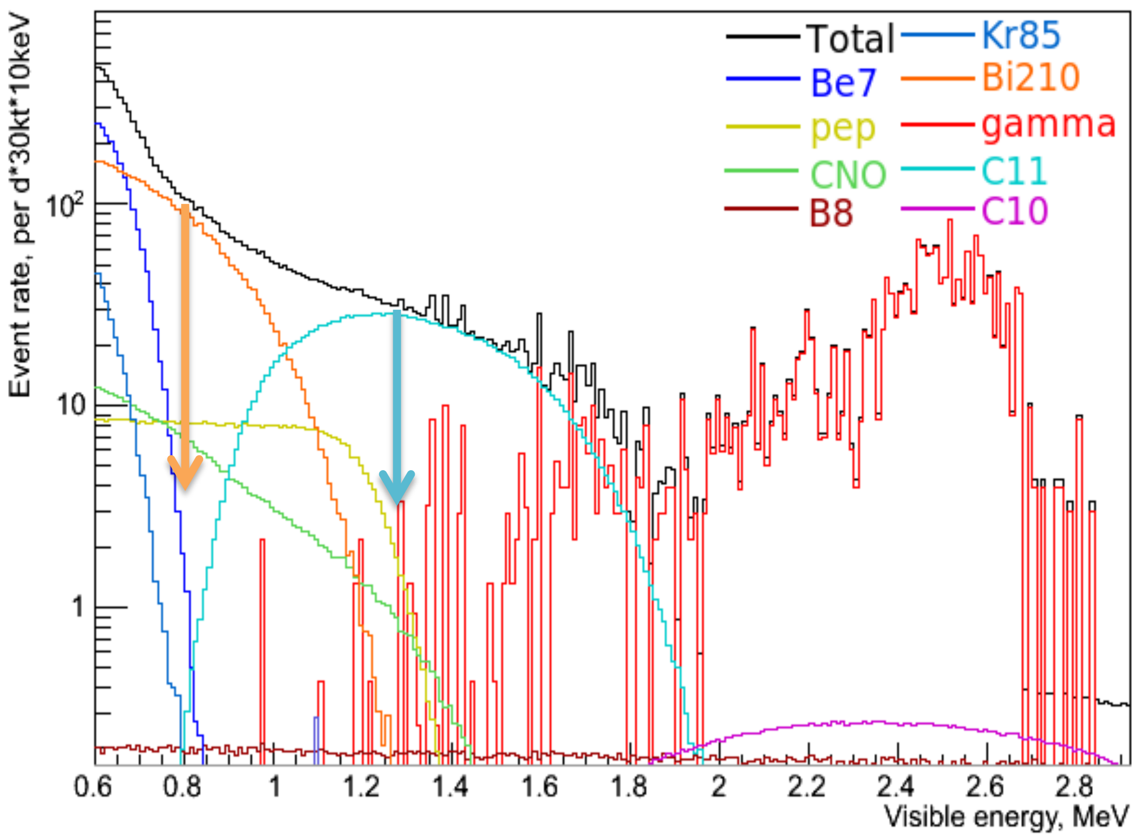
Current best limit on a corresponding solar neutrino modulation comes from SNO $A < 0.1$

SNO Collaboration, B. Aharmim *et al.*, Astrophys. J. **710**, 540 (2010), astro-ph/0910.2433.

With LENA sensitivites of $A \sim 0.005$ could be reached

(i.e. 90% discovery chance for > 3 sigma)

pep- and CNO neutrinos

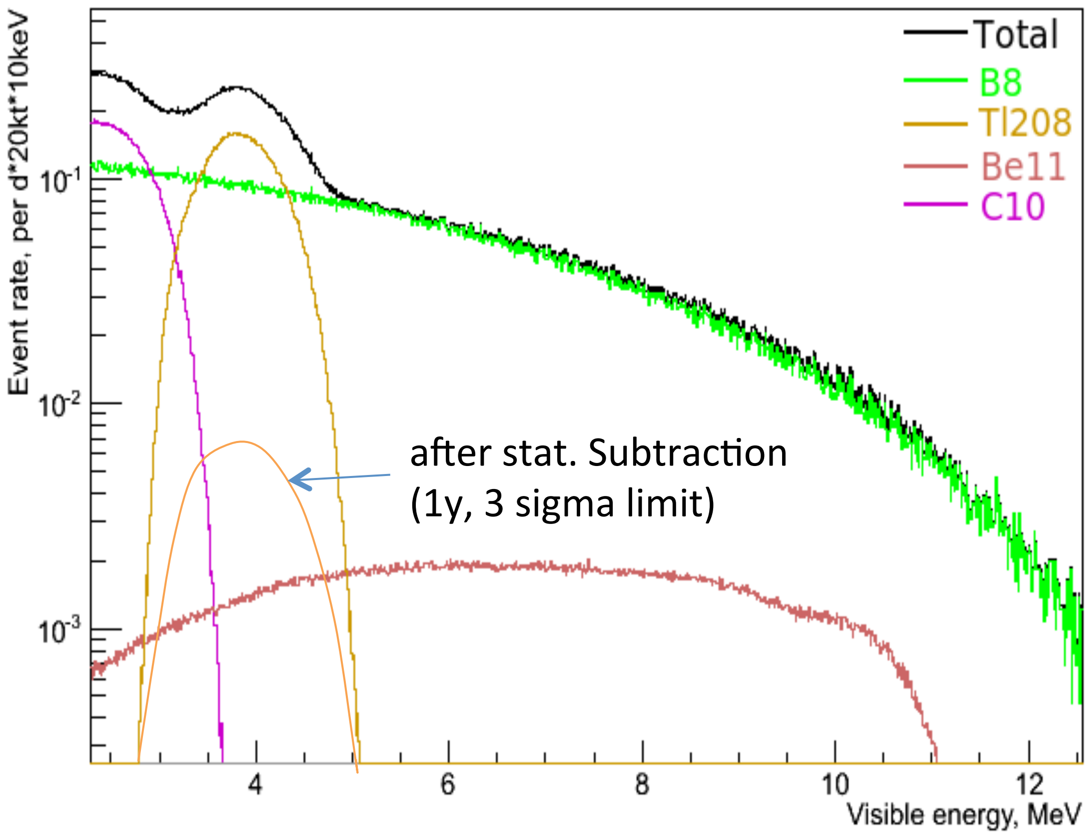


Rate pep: 342 (per day in 30 kton)
Rate CNO: 156 (per day in 30 kton)

Roadmap for successful pep and CNO measurement:

- Fid. Mass 30 kton (kill ext. gammas)
- Reduce cosmogenic ^{11}C via 3-fold coinc. by factor 10
- Tag ^{210}Bi (the „big enemy") via ^{210}Po alpha counting (saecular equilibrium necessary)
- Subtract ^{210}Bi statistically
- Win pep and CNO if LENA ^{210}Bi bg < **$10 - 10^2$** Borexino bg
- Separate pep and CNO via spectral analysis (pep – „shoulder")

^{8}B-neutrino detection



Roadmap for a low E measurement:

- Fid. Mass 20 kton (kill ext. Gammas)
- ^{10}C cosmogenic background direct rejection via muon veto
- ^{208}Tl intrinsic background statistical substraction via Bi-Po counting

(here Borexino value from 2007 is assumed)

After 1 y: remaining bg rate (3σ limit) < 10^{-2}

If ^{208}Tl bg in LENA = 100 x Borexino

-> signal / bg ~ 1

(after 1 year, 3 sigma limit)

Neutrino rate: 38 / (per day in 20 kton)

energy threshold 2 MeV reachable

The ^{13}C - reaction

cc – reaction: $\nu_e + {}^{13}\mathrm{C} \rightarrow {}^{13}\mathrm{N(gnd)} + e^-$

$Q = 2.22$ MeV ⟹ only ^{8}B solar neutrinos are detectable

$E_e = E_\nu - Q + m_e$ ⟹ Neutrino spectroscopy by an event to event basis

$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + \nu_e + e^+$ $\tau = 862.6$ s. $\log(ft/\mathrm{s})^{\mathrm{exp}} = 3.667 \pm 0.001$

This offers *delayed coincidence* technique for LENA (prompt + delayed signal)
$E_{\mathrm{vis,\ delayed}} = [1.02\ \mathrm{MeV},\ 2.22\ \mathrm{MeV}]$
efficient for *background rejection*

A. Ianni et al. (2005), J. Arafune et al. (1989), M. Fukugita et al., (1990)

^{13}C – event rate in LENA

Natural abundance of ^{13}C:	$y = 1.07\ \%$
Number of ^{13}C nuclei (50 kton LAB scint.):	$n_{13} = 2.4 \times 10^{31}$
Solar ^{8}B neutrino flux:	$\Phi = 5.8 \times 10^{6}\ cm^{-2}s^{-1}$
Survival probability (MSW effect):	$p_{ee} = 0.3$
Average cross section for solar ^{8}B neutrinos:	$\langle\sigma\rangle = 8.57 \times 10^{-43}\ cm^{2}$

Event rate (without cuts): $R = n_{13}\ \Phi\ p_{ee} \langle\sigma\rangle \sim 3$ / day

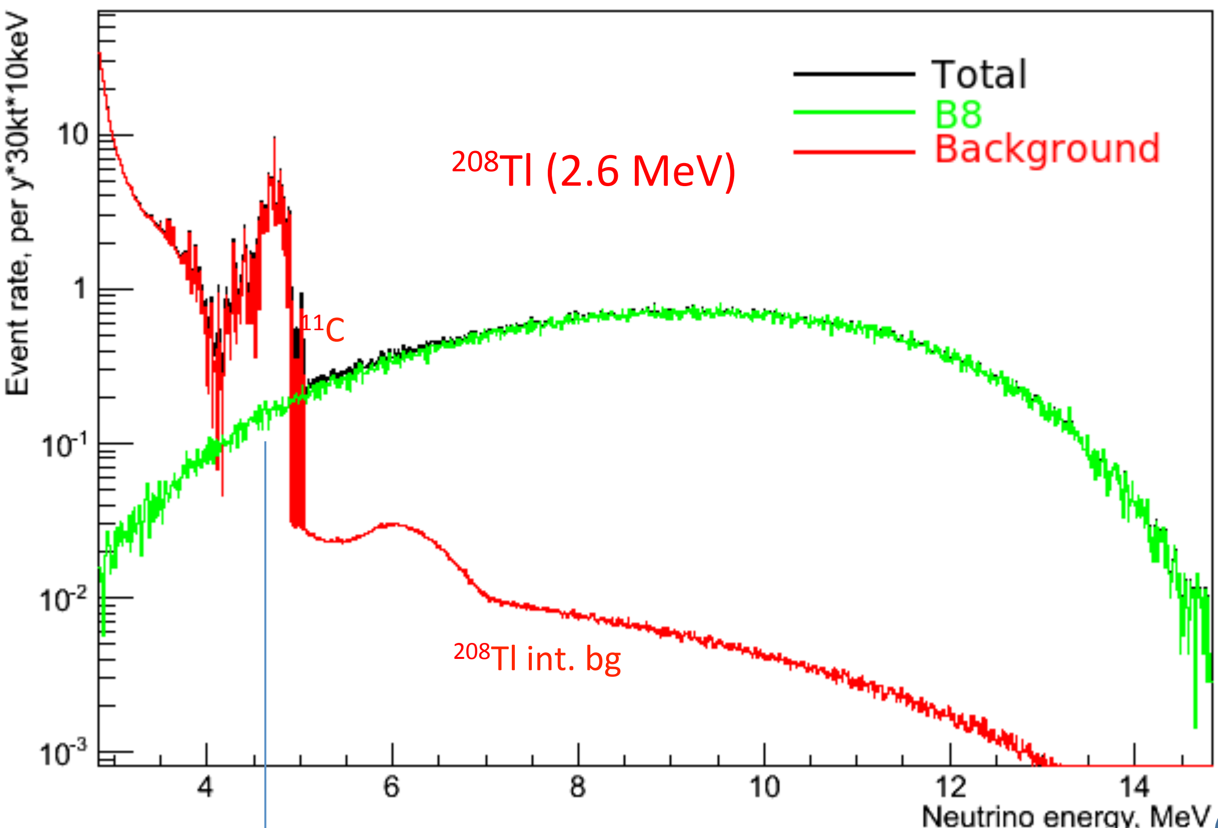
Preliminary Monte-Carlo studies suggest:

$M_{fiducial} \sim 30$ kton

Detection efficiency ~ 0.75 — $R_{Lena}(2.2\ \text{MeV}) \sim 1.2$ / day

What can we do with this signal ?

Background considerations



Accidental coincidences

Cuts:
Fiducial 30 kton
Time 3 x τ
Position 30 cm

Efficiency 75 %

No statistical subtraction

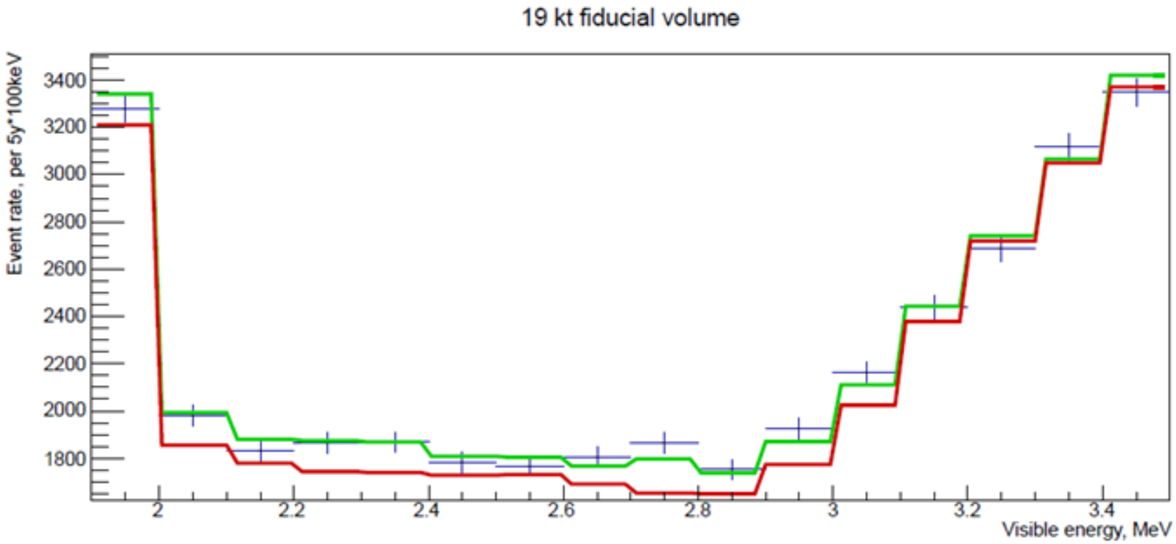
Neutrino rate

R ~ 425 / y (after cuts)

Statistical subtraction (after 1y) yields
Signal / Background ~ 1 (4 to 5 MeV)

Neutrino energy threshold 4 MeV reachable

Is the up-turn observable ?



LENA
4000 m.w.e.
19 kton fid. Vol.

5 years measuring time
Simulated data
MSW-LMA solution
P_ee=const

measuring time	prob. for a $3\,\sigma$ excl.	prob. for a $5\,\sigma$ excl.
1 years	40.5 %	2.5 %
2 years	94.9 %	43.4 %
3 years	99.9 %	92.5 %
4 years	100 %	99.8 %
5 years	100 %	100 %

Yes, **LENA** can probe the MSW up-turn at >5 sigma in less than 5 years

Solar Neutrinos in LENA Conclusions

- Very high statistics in ^{7}Be allows to search for small flux fluctuations
- CNO- and pep-neutrino measurement possible, if ^{210}Bi bg < 10 to 100 (Borexino)
- Solar ^{8}B-spectrum from 3 MeV via elastic scattering off electrons, if ^{208}Tl bg < 100 (Borexino)
- Solar ^{8}B-spectrum via ^{13}C charged current reaction from 4 MeV (~ 425 counts / year)
- Test of the MSW-effect via a combined analysis of ν-e scattering and ^{13}C cc reaction

Background calculations and spectral analysis by PhD thesis from Randolph Möllenberg (TUM)

Supernova Neutrino Burst

LENA and a galactic supernova

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

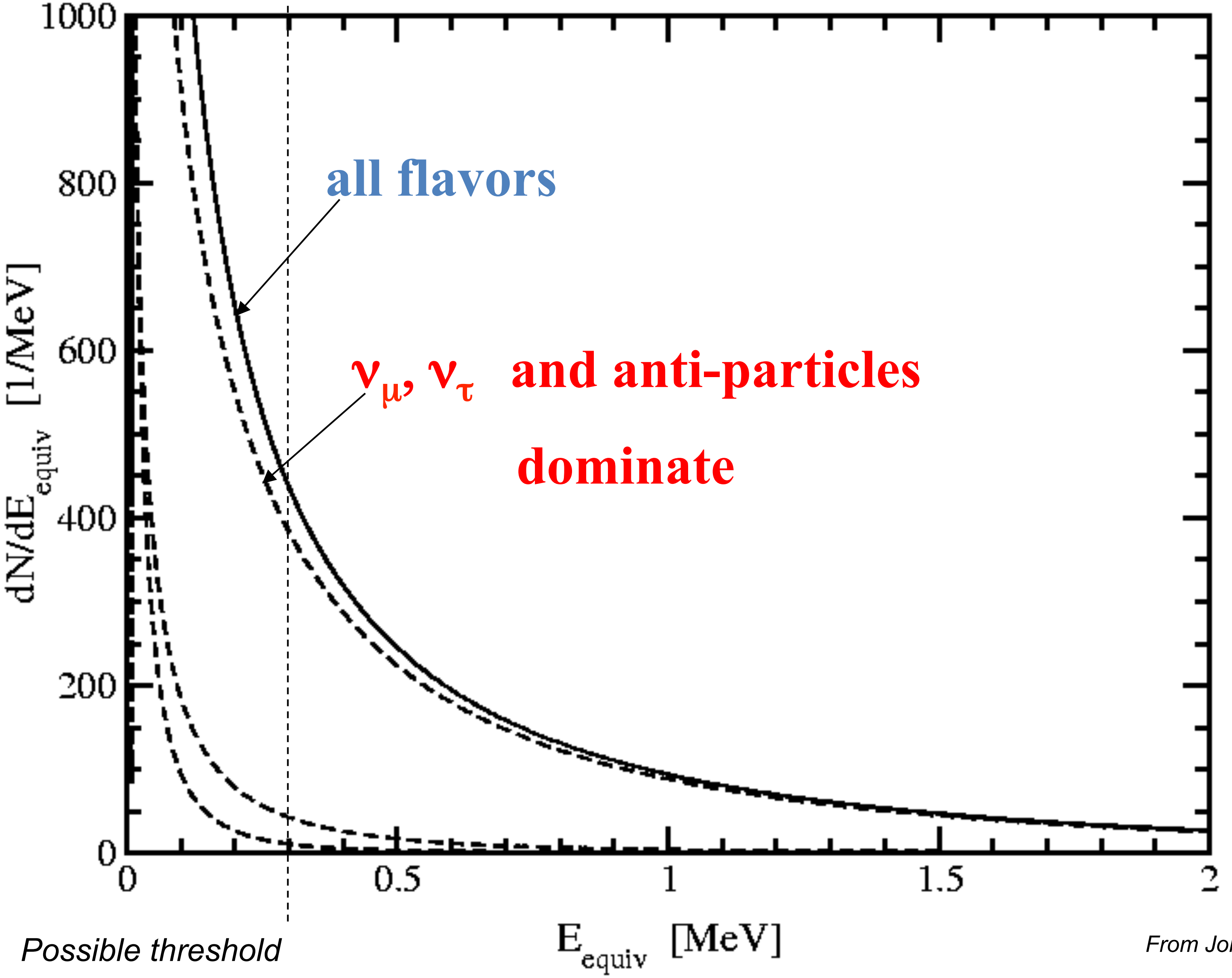
In LENA detector: $\sim$15000 events

Possible reactions in liquid scintillator

1. $\overline{\nu}_e + p \rightarrow n + e^+$; $n + p \rightarrow d + \gamma$ $\sim$7 000 - 13 800
2. $\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B} + e^+$; ${}^{12}\mathrm{B} \rightarrow {}^{12}\mathrm{C} + e^- + \overline{\nu}_e$ $\sim$150 - 610
3. $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$; ${}^{12}\mathrm{N} \rightarrow {}^{12}\mathrm{C} + e^+ + \nu_e$ $\sim$200 - 690
4. $\nu_x + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu_x$; ${}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma$ $\sim$680 - 2 070
5. $\nu_x + e^- \rightarrow \nu_x + e^-$ (elastic scattering) $\sim$700
6. $\nu_x + p \rightarrow \nu_x + p$ (elastic scattering) $\sim$1 500 - 5 700

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

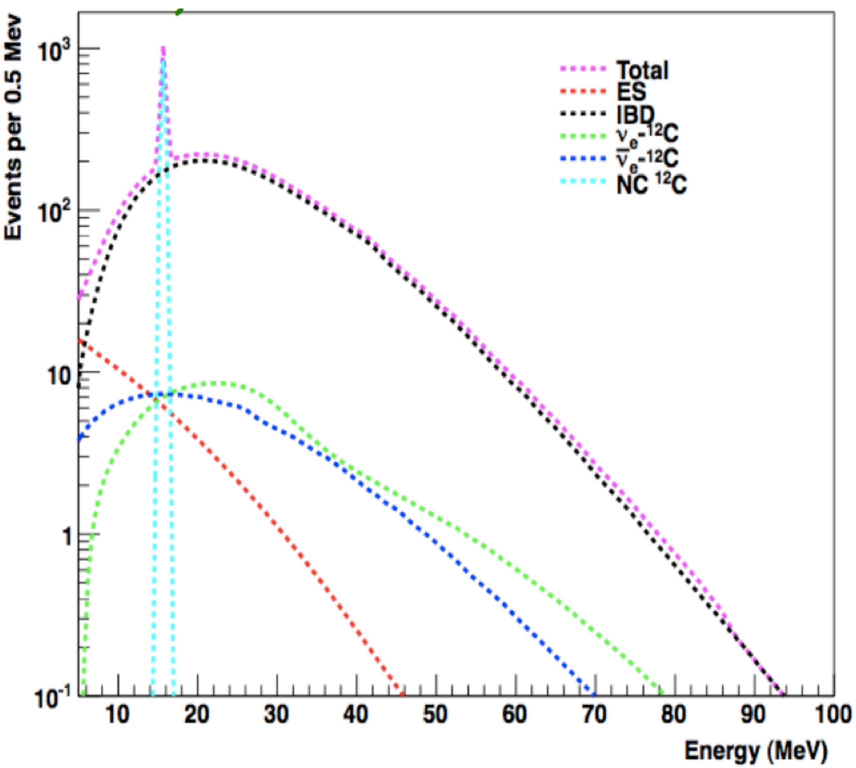
Neutrino elastic scattering off protons



From John Beacom

Analysis and Physics goals

LENA spectrum *K. Scholberg, Taup 2011*



Observables

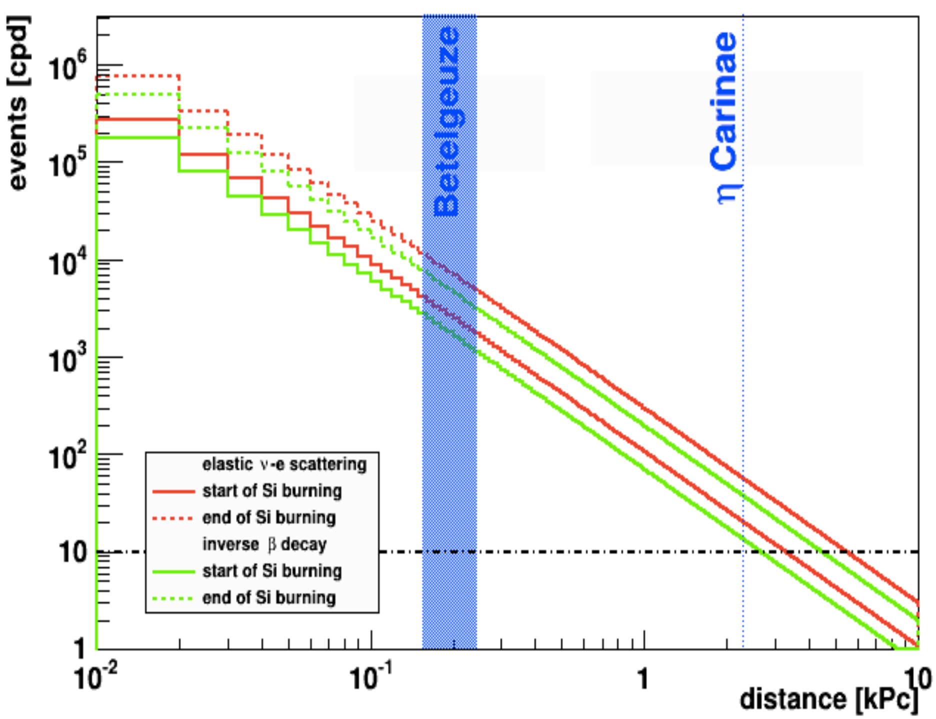
- **$\bar{\nu}_e$ spectrum**
  - *very high statistics*
  - *free of background*
- **ν_e spectrum**
  - *~ (5-10) % accuracy*
- **Total flux** of all active neutrinos
  - *via ^{12}C-nc reaction*
- ν_μ ν_τ sum spectrum
  - *via scattering on p*

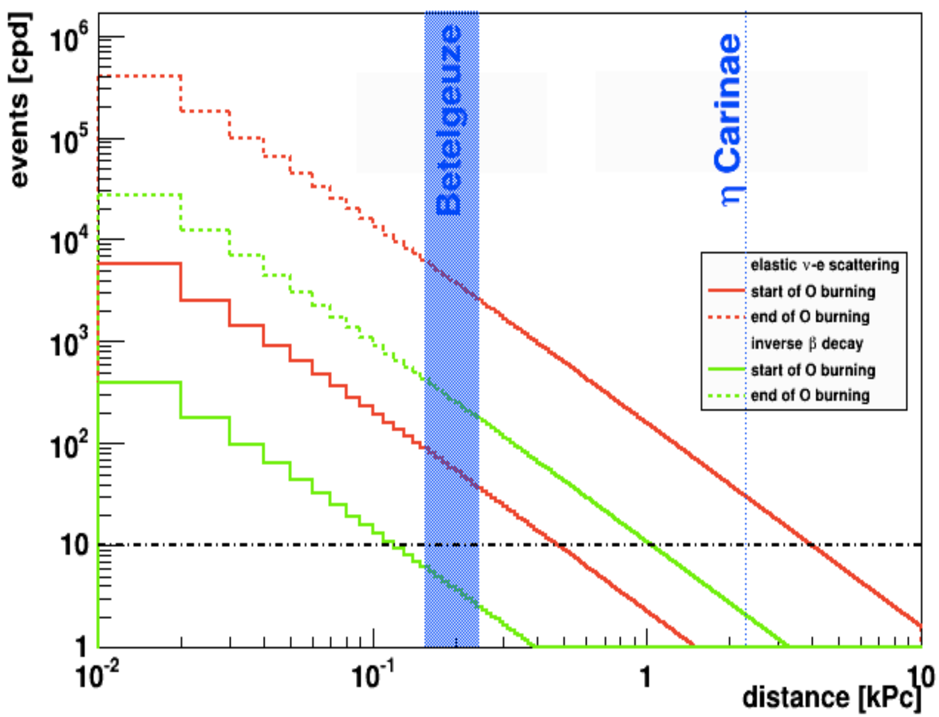
Astro- and Neutrino physics

- Observation of Initial **neutronisation burst**
- Time resolved **cooling phase**
- **Separation of SN models**
  - *due to large NC statistics – independent from oscillation physics*
- Information on **Mass hierarchy, Theta_13**
  - *matter effects in the SN and Earth*
  - *collective oscillations*
- Trigger for **Gravitational wave antenna**

Pre-SN neutrino detection

fusion stage	t	$\langle E \rangle$ [MeV]	L [erg/s]
C	0.03-2.82 ky	0.71	$7.4 \cdot 10^{39}$
Ne	0.03-0.73 y	0.99	$1.2 \cdot 10^{43}$
O	0.01-4.77 y	1.13	$7.4 \cdot 10^{43}$
Si	0.2-18.3 d	1.85	$3.1 \cdot 10^{45}$





Diffuse Supernova Neutrinos

Detection of DSNB flux

Isotropic flux of all SNν's emitted in the history of the Universe.

Faint signal: $\Phi_\nu \approx 10^2$ /cm²s

Detection of $\bar{\nu}_e$ by inverse β decay:

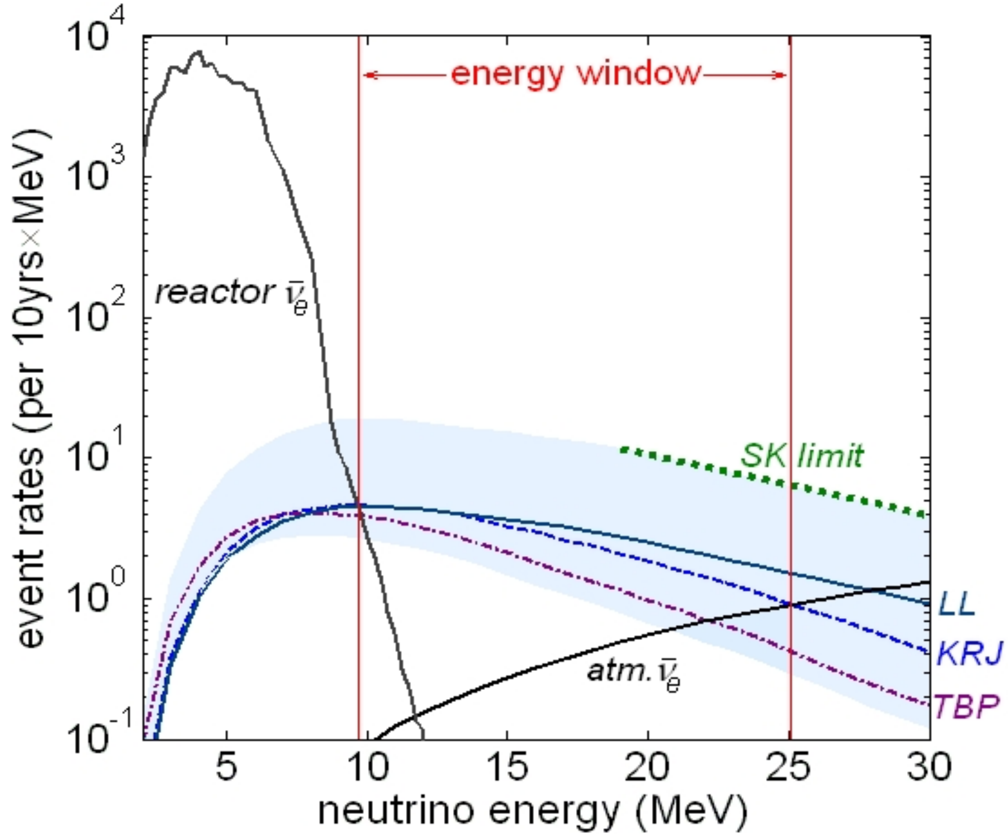
$\bar{\nu}_e + p \rightarrow e^+ + n$

Remaining background sources

- reactor and atmospheric ν_e's
- cosmogenic backgrounds

Scientific gain

- first detection of DSNB
- information on average SNν spectrum

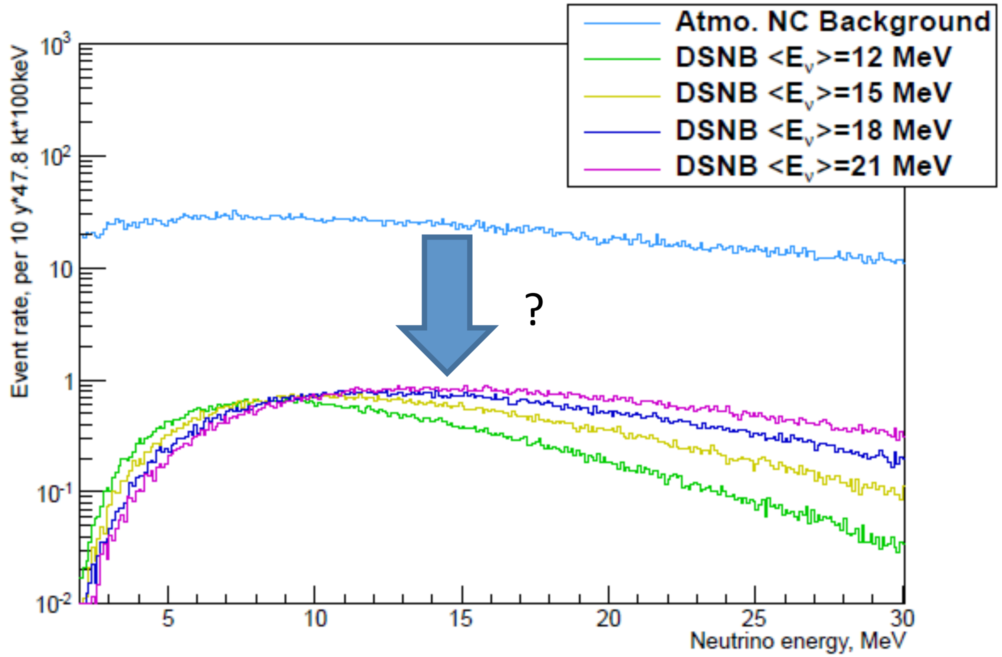


Expected rate: 2-20 $\bar{\nu}_e$ /(50 kt y)
(in energy window from 10-25MeV)

Most dangereous bg:
Atmospheric ν nc events on ^{12}C

Factor ~ 20 above signal
Only ~ 40% can be tagged (via ^{11}C)

PSD techniques applicable ?
Labor measurements at TUM
LENA MC simulations



Reaction channel	Branching ratio
(1) $\nu_x + {}^{12}C \rightarrow \nu_x + n + {}^{11}C$	40.6 %
(2) $\nu_x + {}^{12}C \rightarrow \nu_x + p + n + {}^{10}B$	20.1 %
(3) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + n + {}^{9}Be$	16.0 %
(4) $\nu_x + {}^{12}C \rightarrow \nu_x + p + d + n + {}^{8}Be$	7.0 %
(5) $\nu_x + {}^{12}C \rightarrow \nu_x + \alpha + p + n + {}^{6}Li$	6.6 %
other reaction channels	9.7 %

Atmospheric neutrino events as bg for DSNB neutrino search via IBD in LENA

Results on PSD in LENA

Background source	Rate [10 y]
Reactor neutrinos	2.1
Atmospheric $\bar{\nu}_e$	2.4
^{9}Li $\beta^- - n$	< 0.01
Fast neutrons	0.6
Atmospheric NC	25.1
Sum	30.2
DSNB ($\langle E_\nu \rangle = 12\,\text{MeV}$)	19.3

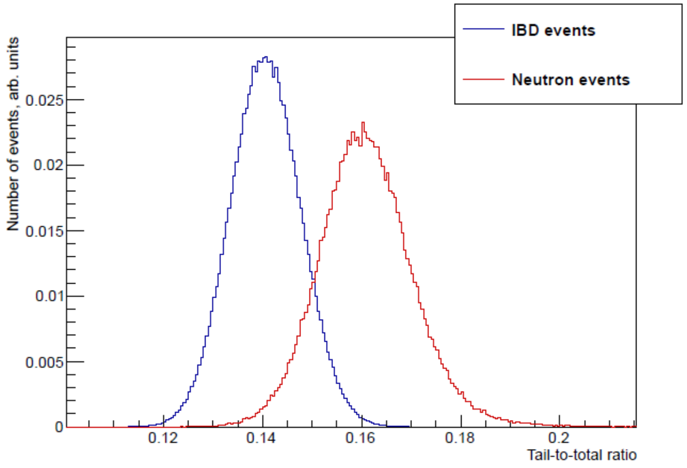


Figure 6.12: The tail-to-total ratio for IBD (denoted in blue) and neutron events (denoted in red) in the center of LENA with $E_{vis} = 9.2\,\text{MeV}$.

$\langle E_\nu \rangle$	Expected DSNB events [10 y]	5 % background uncertainty	25 % background uncertainty
12 MeV	19.3	$3.0\,\sigma$	$1.5\,\sigma$
15 MeV	27.7	$4.1\,\sigma$	$2.1\,\sigma$
18 MeV	34.0	$5.0\,\sigma$	$2.6\,\sigma$
21 MeV	38.0	$5.6\,\sigma$	$2.9\,\sigma$

- Detection with $3\,\sigma$ sign. possible if the background expectation is known with 5 % uncertainty
- For $\langle E_\nu \rangle > 18\,\text{MeV}$, a $5\,\sigma$ detection of the DSNB is possible

DSNB exclusion power after 10y measurement

Assumption: no DSNB signal, only background

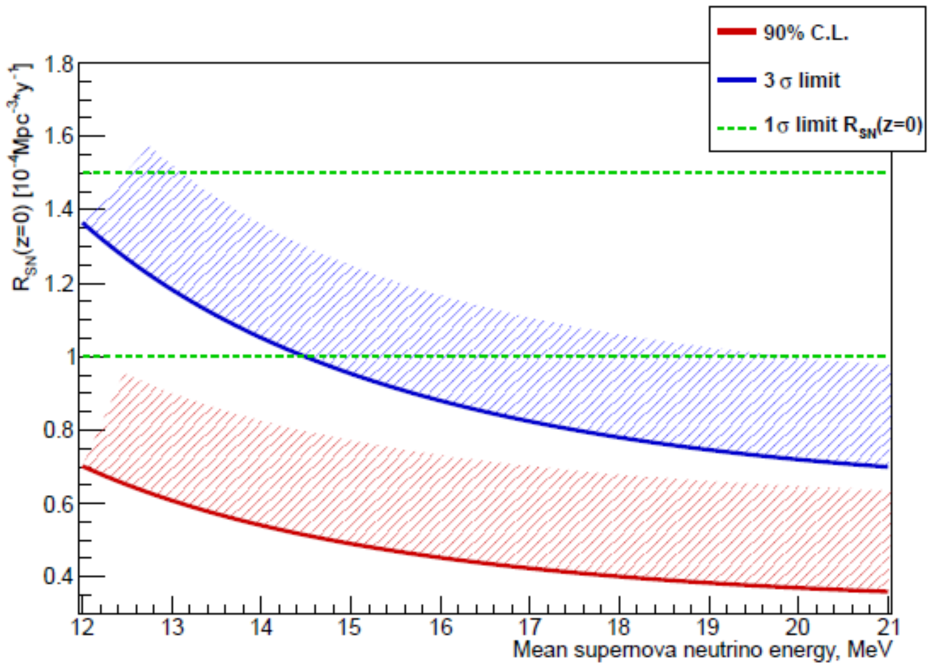
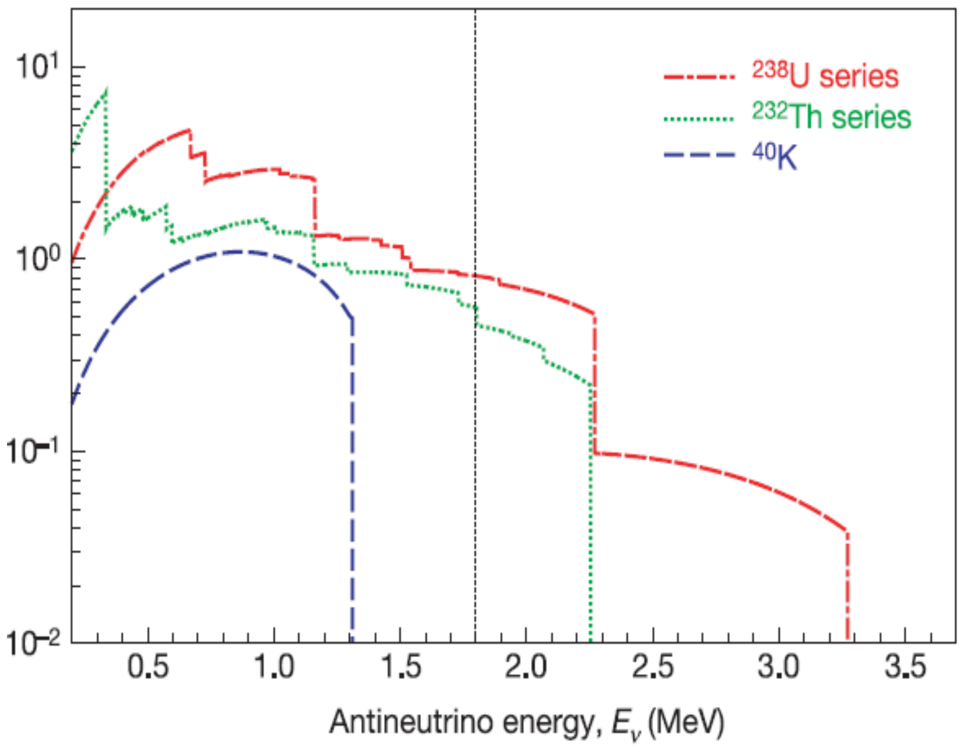


Figure 6.17: The $3\,\sigma$ (depicted in blue) and 90 % C.L. (depicted in red) exclusion contours for the supernova rate $R_{SN}(z=0)$ and the mean supernova neutrino energy, assuming 5 % background uncertainty and that no DSNB signal was detected ($N_{det} = \langle N_{bg} \rangle$). For comparison, the current $1\,\sigma$ confidence interval for $R_{SN}(z=0)$ is also depicted (green dashed line).

Geo Neutrinos

Geo Neutrino Detection in LENA

Geo-Neutrino spectrum



Uranium- and Thorium– radioactive decay chains (beta decays)

Detection via inverse beta decay ($E_{threshold}$ = 1.8 MeV)

Event rate corresponds to the radioactive contribution to the Earths heat production

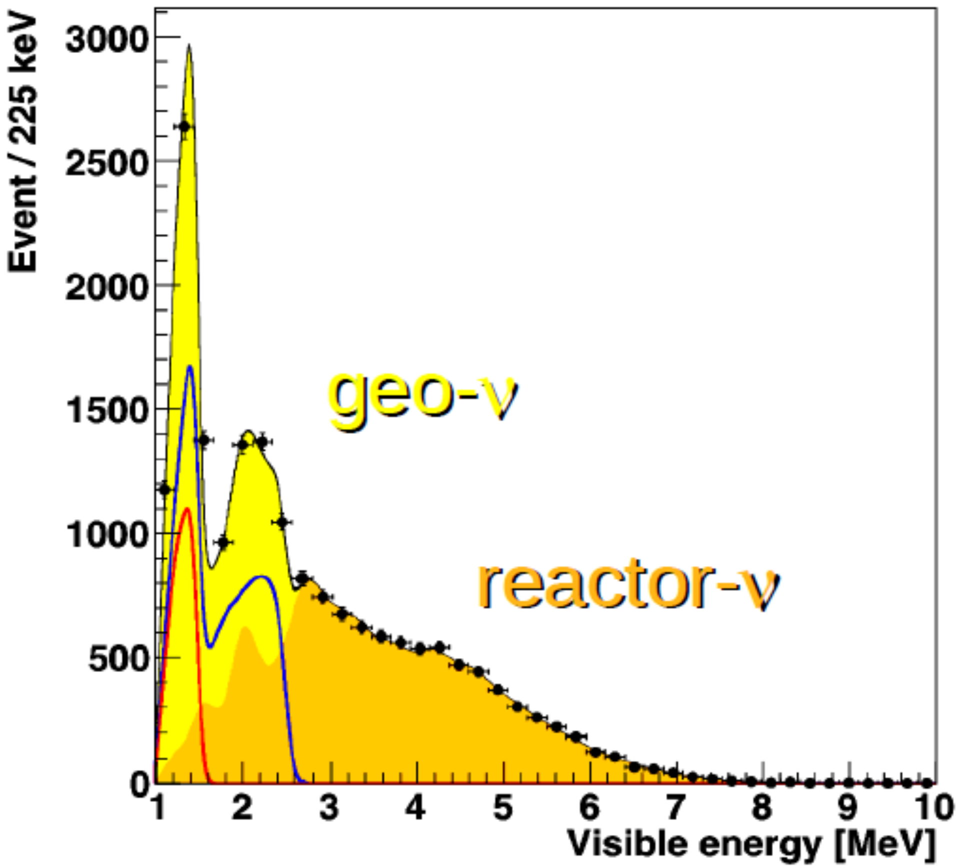
Intrinsic background basically negligible

Irreducible background from nuclear power reactors (E_{max} ~ 8 MeV)

Statistic subtraction possible

Geo-Neutrinos

Separation U / Th contribution
> 5 sigma after 5 years at Pyhäsalmi



At Pyhäsalmi

- expected geo-ν rate: 2×10^3
- reactor-ν background: 7×10^2

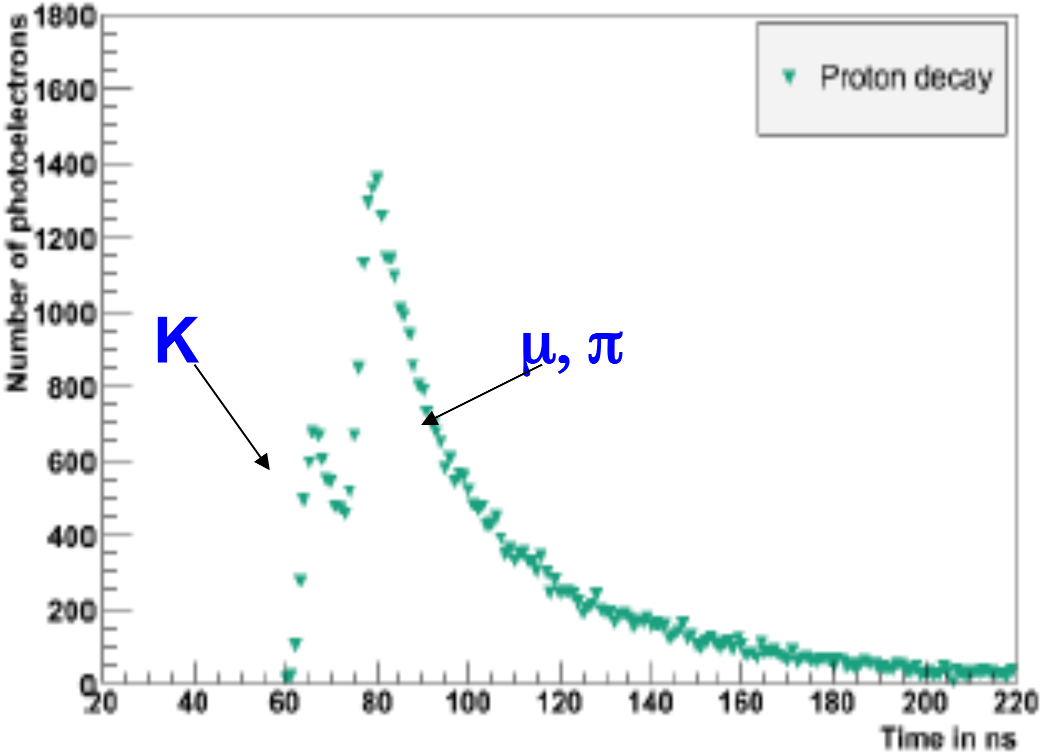
What can we learn?

- contribution of U/Th decays to Earth's total heat flow → 1%
- relative ratio of U/Th → 5%
- with several detectors at different sites: disentangle oceanic/continental crust
- test for hypothetical georeactor

Proton Decay

LENA and proton decay

- High efficiency and very good background rejection for $p \rightarrow K^+ \nu$



K and μ, π from successive K decay

K -> $\mu\ \nu$ (68 %)

K -> 2 and 3 π (31 %)

(12 nsec)

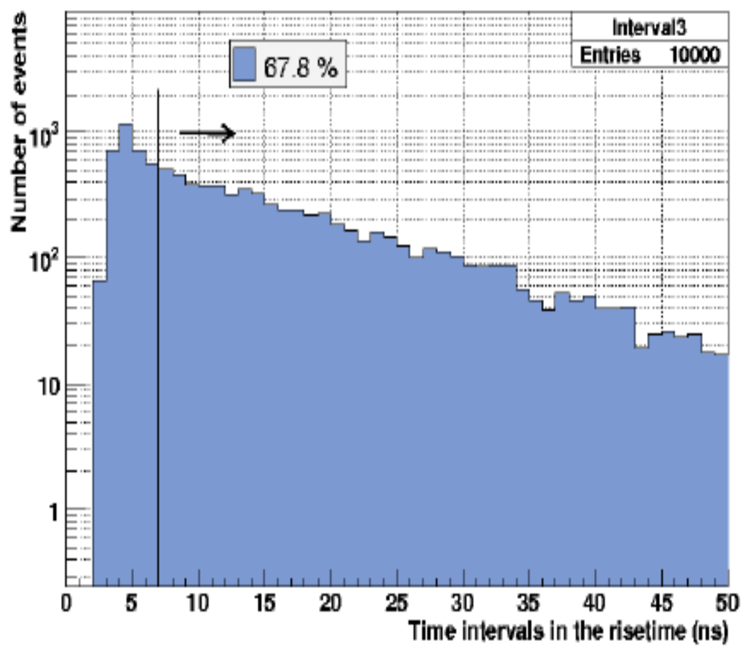
Background rejection

Main background: atmospheric neutrino interactions in the target

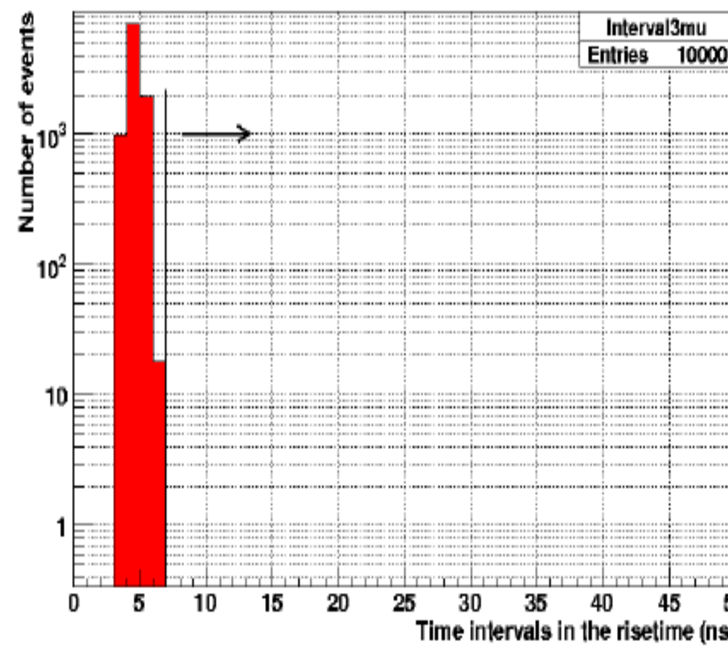
Background rejection: pulse shape discrimination

- Proton decay efficiency: 68%
- Background rejection 10^{-4}

Rise time distribution proton decays (MC)



Rise time distribution atmospheric neutrinos (MC)



LENA and proton decay

- High sensitivity to p -> K ν
  (eff. ~ 68% roughly 10 x SK

  Limit (90% cl) after 10 years: **$\tau \sim 5 \times 10^{34}$ y**

- Sensitive to a variety of decay channels
  "invisible" modes, e.g. n -> $\nu\ \nu\ \nu$

- For e.g. p -> $e^+ \pi^0$ we expect ~ 10^{33} y
  (work in progress)

T. Marrodan et al., Phys. Rev. D72, 075014 (2005)

Conclusions

- Solar Neutrinos: probing MSW up-turn, CNO, high statistical ^{7}Be-neutrinos
- SN: separation between ν_e and $\bar{\nu}_e$, and between ν_e, $\bar{\nu}_e$ versus $\nu_\mu + \nu_\tau$
- DSNB: > 3 sigma discovery potential and test of SN predictions
- GEO: separation between U- and Th-contribution and test of geophysical models
- Nucleon Decay: 5×10^{34} y limit after 10y for $p \rightarrow K^+ \nu$

Spare slights

Input parameter of calculations

The solar neutrino fluxes according to astro-ph/0412440v3 (BS05(AGS,OP) were used [cm^-2 s^-1]:
pp: 6.06e10
pep: 1.45e8
hep: 8.25e3
7Be: 4.34e9
8B: 4.51e6
13N: 2.01e8
15O: 1.45e8
17F: 3.25e6

The MSW effect was included according to hep-ph/0404083, distribution of the neutrino sources according to astro-ph/0412440v3 (values of the mixing matrix were choosen according to pdg 2012).

Background rates:

Po210: 488.8 counts/(day*100t)
Bi210: 41.6 counts/(day*100t)
Kr85: 34.8 counts/(day*100t)
C11: 28.0 counts/(day*100t)
according to the Borexino Be7 paper from 15.07.2011 (the used data was recorded between 16.05.2007 and 02.05.2010).

C10: 0.54 counts/(day*100t)
Be11: 0.035 counts/(day*100t)
Tl208: 0.084 counts/(day*100t)
according to the Borexino B8 paper (29.4.2010)

The background rates for the cosgenically produced isotopes C10,C11 and Be11 we reduced by a factor of 5, due to the reduced muon flux at phyhäsalmi

C14: 3e6 counts/(day*100t) according to Alimonti, G.; et al. (1998). "Measurement of the 14C abundance in a low-background liquid scintillator". Physics Letters B 422 (1–4): 349–358

Event rates:

elastic neutrino scattering:

Be7: 8.6e3 counts/(day*36kt) (above 300 keV)
pep: 342 counts/(day*30kt) (above 700 keV)
CNO: 156 counts/(day*30kt) (above 700 keV)
B8: 38 counts/(day*20kt) (above 3 MeV)

C13 channel:

above 4 MeV (75% detection efficiency)
B8: 283 counts/(y*20kt)

Alpha beta discrimination was applied (95% beta acceptance, 99.7% alpha discrimination)

kb values:
e-: 0.15 mm/MeV
alpha: 0.107 mm/MeV

according to measurements of the DC veto scintillator (Thesis "Ionization quenching by Low Energy Electrons in the Double Chooz Scintillators by Stefan Wagner, and measurements by Christian Abele)