LENA

Messengers of New Physics

11 Sep 12

NOW 2012, Otranto

Michael Wurm

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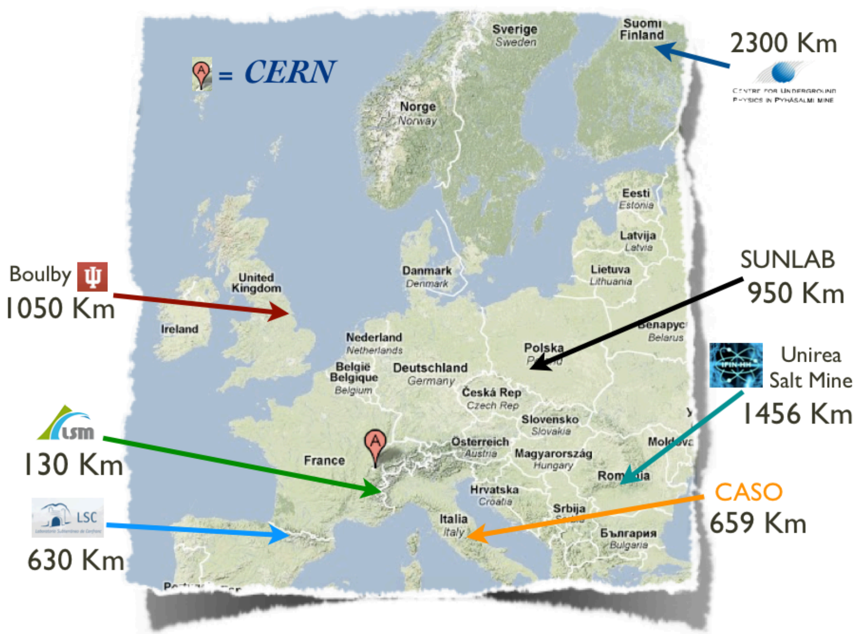
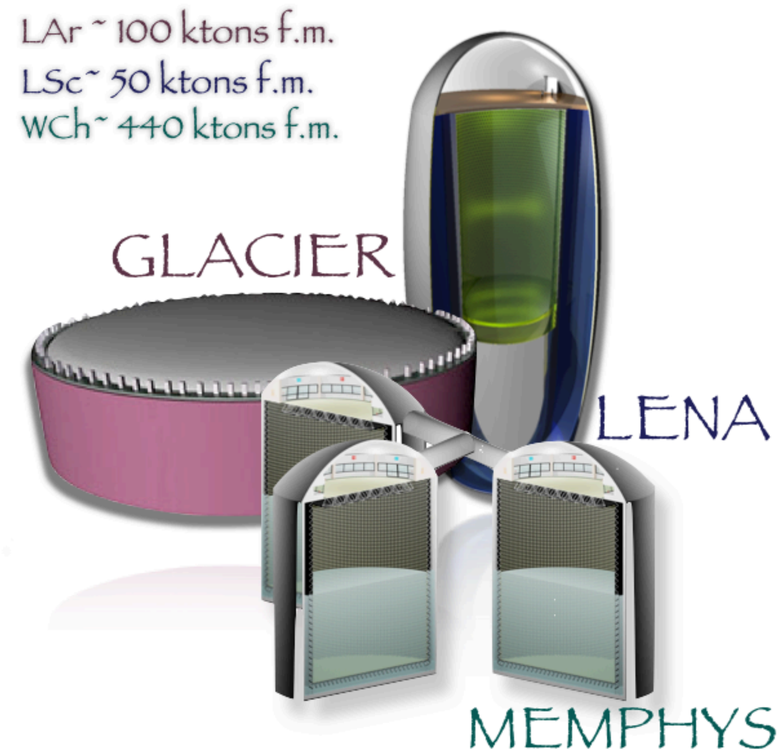
LAGUNA → LAGUNA-LBNO

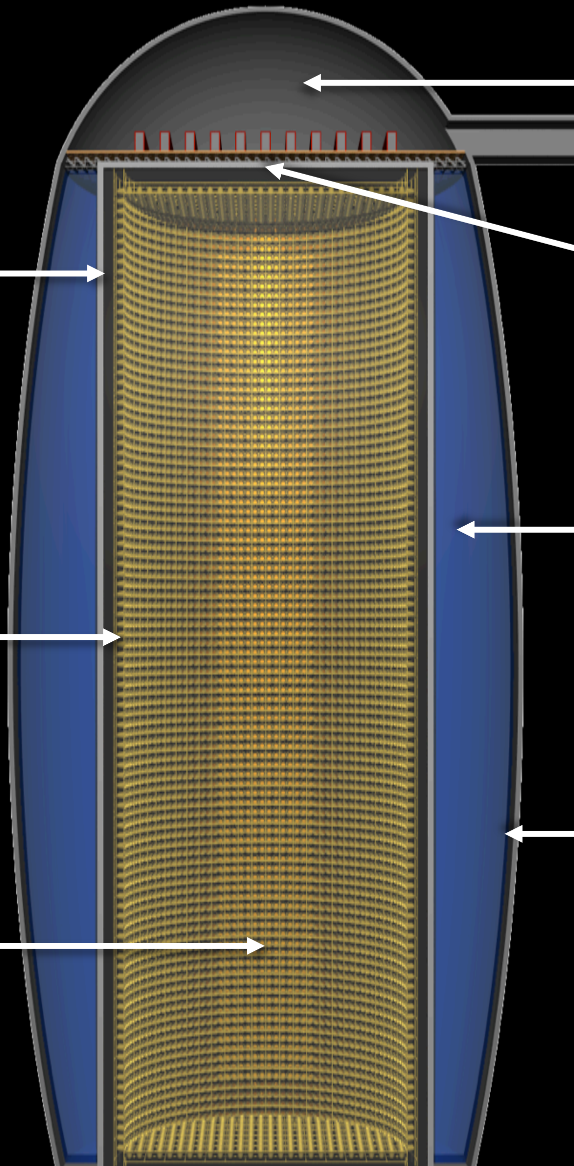
- Consortium of European science institutions and industry partners
- Design studies funded by the European Community (FP7)
- **LAGUNA:** detector site, cavern, and oscillation baselines (2008-11)
- **LAGUNA-LBNO:** detector tank, instrumentation, and beam source (2011-14)

Seven sites, three detector technologies





LENA detector layout



Liquid Scintillator
ca. 69kt LAB

Concrete Tank
r = 16m, h = 100m

PMT support structure
radius: 14m

32,000 12‘‘-PMTs
Winston cones
optical coverage: 30%

Optical shield

Active volume
ca. 50kt of LAB

Electronics Hall
dome of 15m height

Top Muon Veto
gas/solid scint. panels
vertical muon tracking

Water Cherenkov Veto
2000 PMTs, $\Delta r > 2m$
fast neutron shield
inclined muons

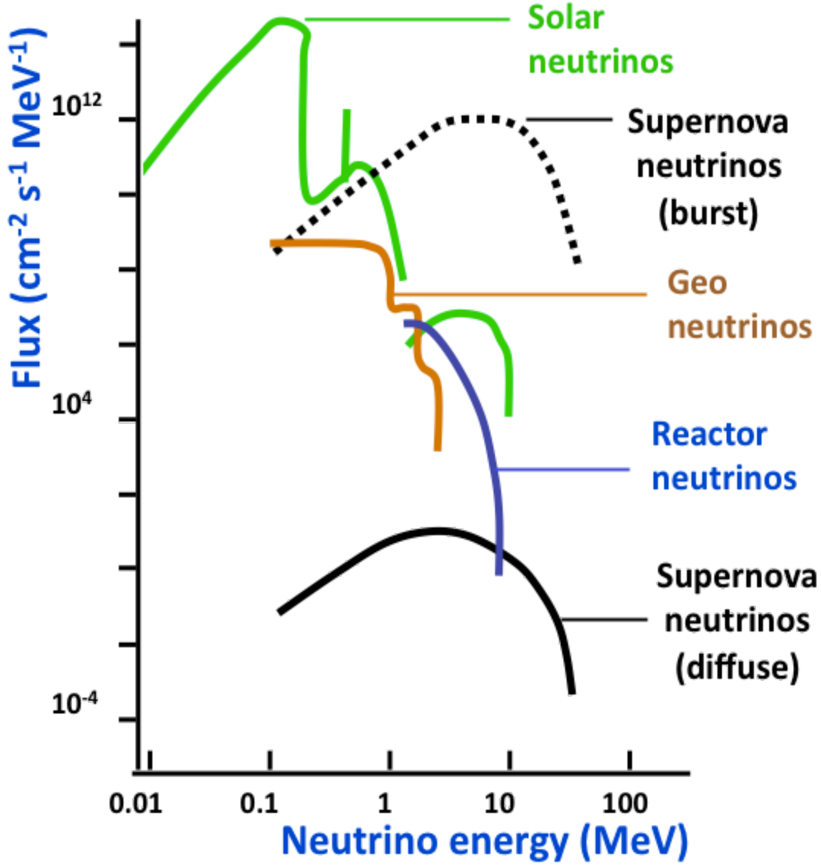
Egg-Shaped Cavern
about 10^5 m^3

Rock Overburden
at least 4000 mwe

LENA physics programme

Neutrinos at low energies

- Galactic Supernovae ν's — 10^4/SN
- DSNB — 10/yr
- Solar neutrinos — 10^4/d
- Dark matter annihilation
- Geoneutrinos — 10^3/yr
- Reactor neutrinos — $10^{3\text{-}4}$/yr
- Radioactive sources — 10^4/MCi
- Pion decay-at-rest beams



GeV energies

- Long-baseline neutrino beam
- Atmospheric neutrinos
- Proton decay

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GeV energies

- Long-baseline neutrino beam
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→ **Astrophysical neutrino sources**

- stellar core collapse/fusion processes
- Earth heat flow, elemental composition

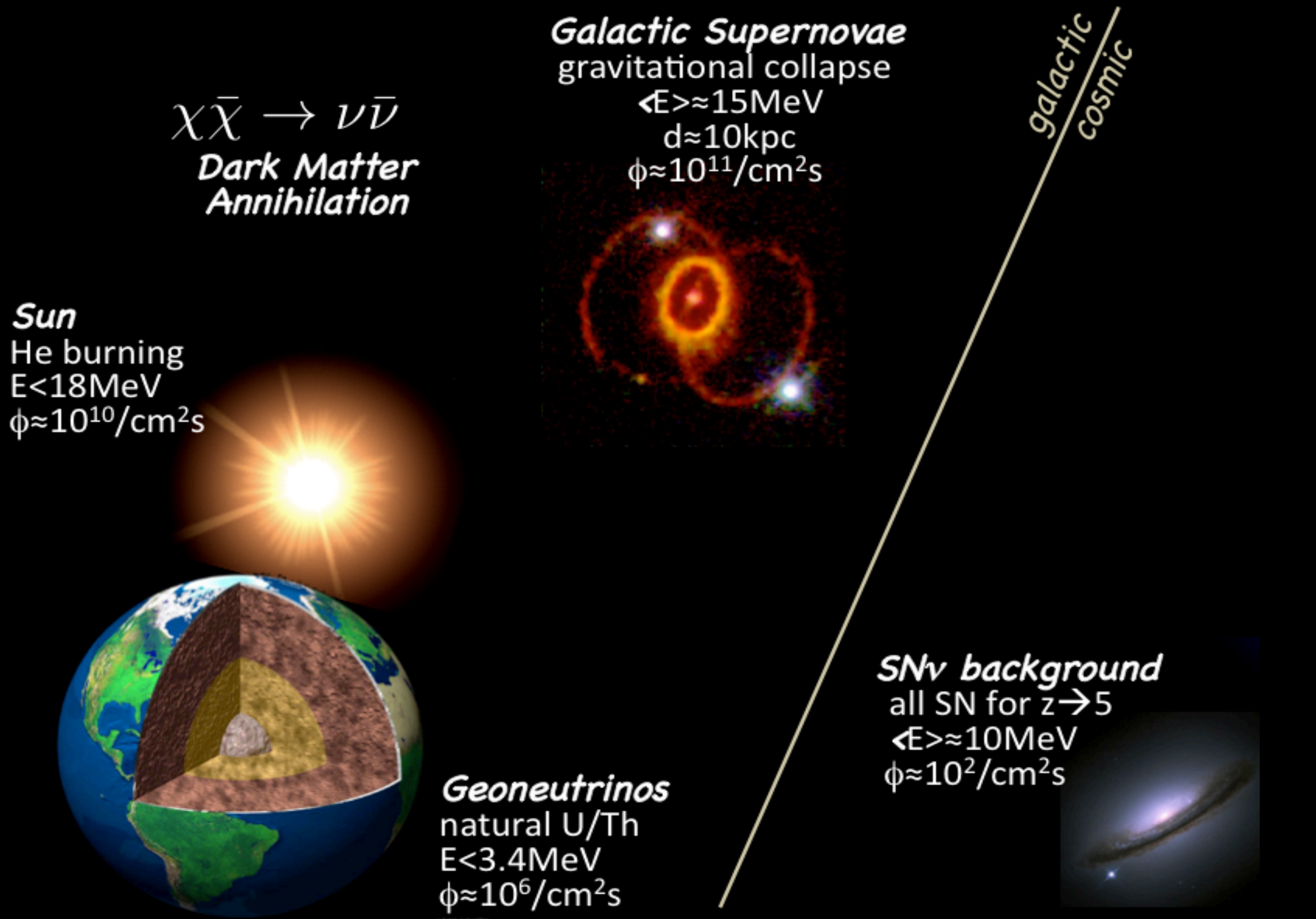
→ **Neutrino physics**

- mixing parameters
- neutrino mass hierarchy
- sterile flavors
- neutrino-antineutrino conversion
- non-standard interactions

→ **Particle physics**

- baryon number violation
- light dark matter

Astrophysical neutrino sources ...

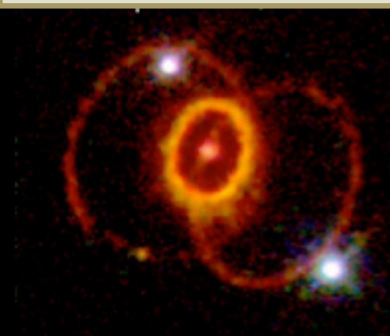


... and observations in LENA

$$\chi\bar{\chi} \rightarrow \nu\bar{\nu}$$

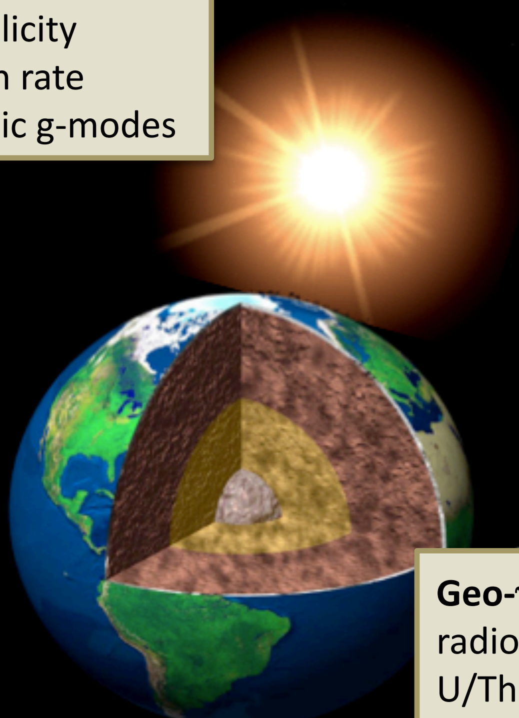
DM annihilation ν's
sensitive for $m_\chi \approx$ 10-100 MeV

Supernova ν's
observe core-collape phases
propagation of shock-wave
observe dim/failed SNe



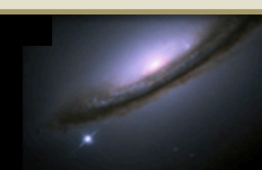
galactic
cosmic

Solar ν's
core metallicity
CNO fusion rate
helioseismic g-modes



Geo-ν's
radiogenic heat flow
U/Th ratio

DSNB
average spectral temperature
fraction of dim SNe



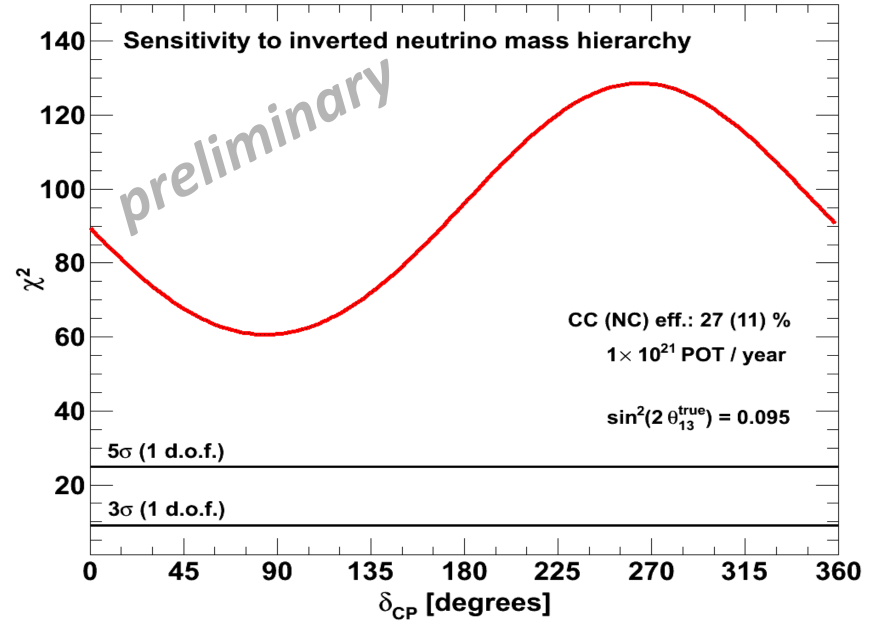
Neutrino mass hierarchy

Long-baseline neutrino beam

- 2288 km from CERN to Pyhäsalmi
  → large matter effectss
- LENA offers
  – calorimetric measurement ($\delta E \sim 8\%$)
  – pulse shape discrimination for NC

→ $>8\sigma$ effect for 10^{22} pot

→ further improved by particle tracking?



Neutrino mass hierarchy

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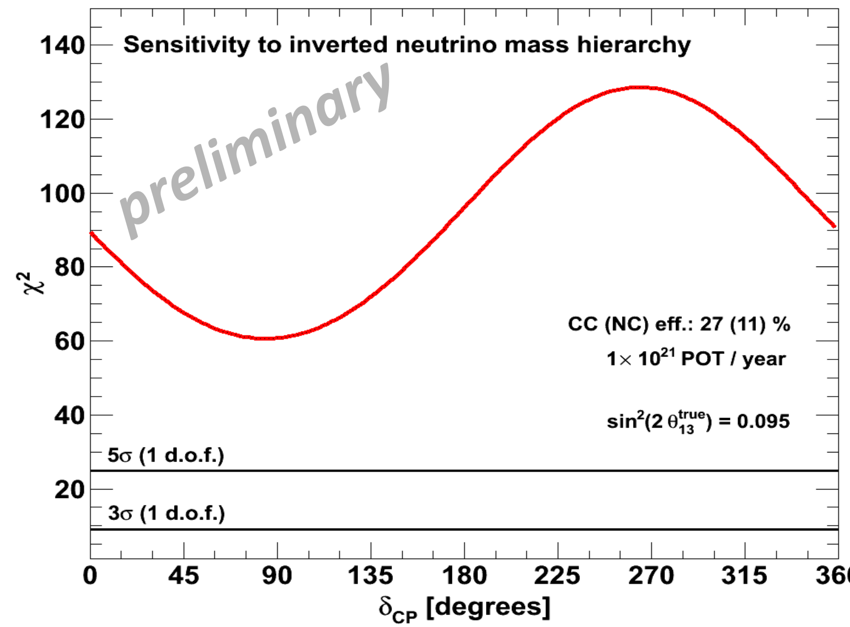
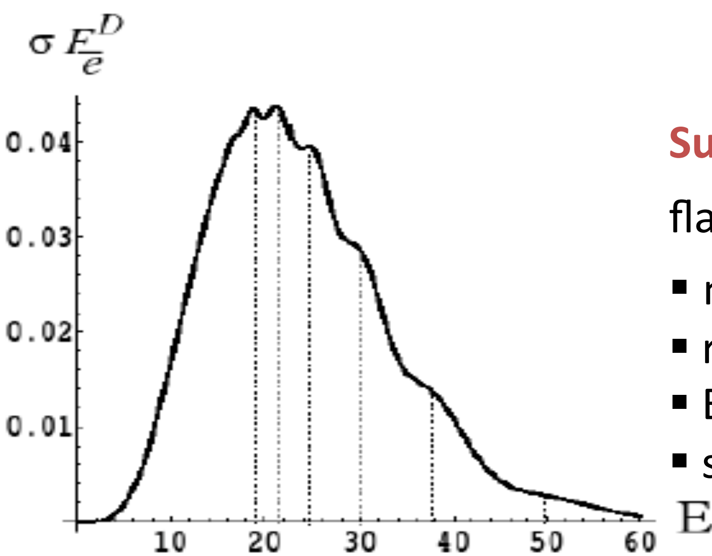




Supernova neutrinos

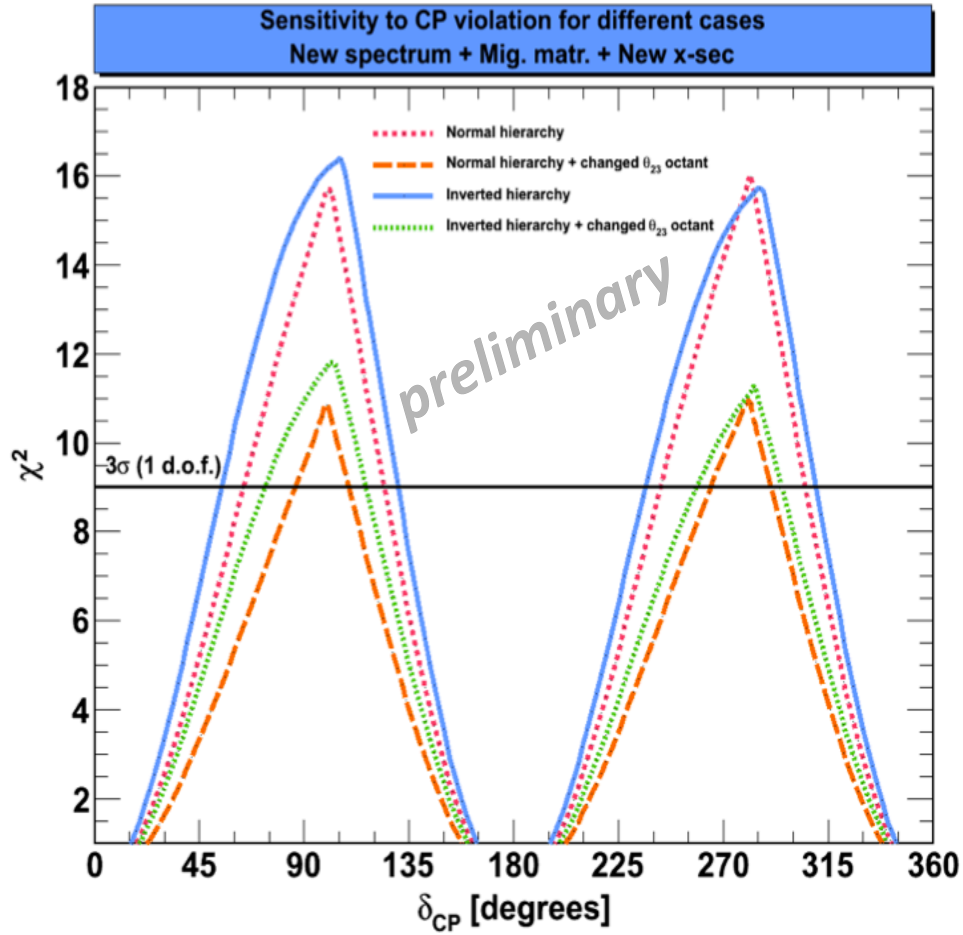
flavor- and energy-resolved detection in LENA

- neutronization burst
- resonant flavor conversion in SN envelope
- Earth matter effect → talk by Enrico Borriello
- signal rise time

CP-violating phase

Long-baseline neutrino beam

- more difficult than mass hierarchy
  → larger role of NC background
- for 10^{22} pot: 3σ coverage of up to 50% (depends on other parameters)
- further studies on-going



CP-violating phase

Long-baseline neutrino beam

- more difficult than mass hierarchy
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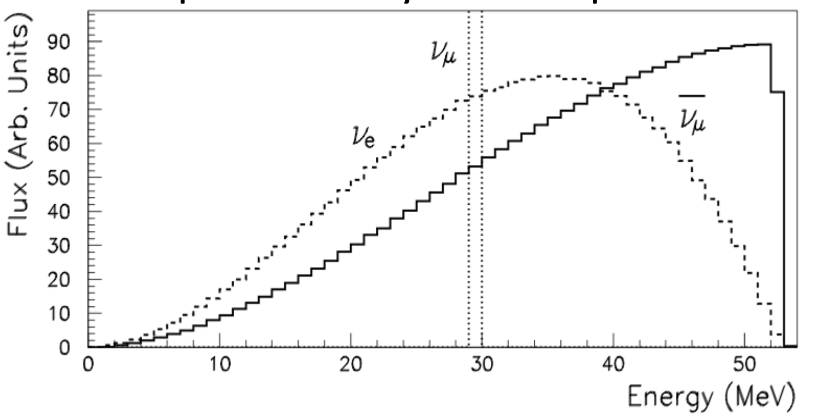
piDAR decay-at-rest spectra

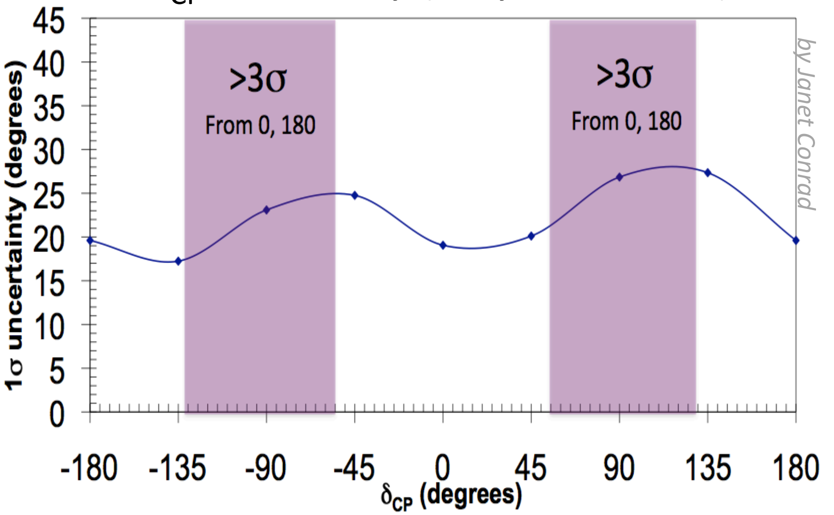


Pion decay-at-rest beam (DAEδALUS)

→ talk by Matt Toups on Friday

- $\pi^\pm$ from intense GeV proton source
- stopped π^+ decay → $\nu_\mu, \nu_e, \bar{\nu}_\mu$, but no $\bar{\nu}_e$!
- short baselines:
  – 1.5 km: beam normalization
  – 40 km: $\bar{\nu}_\mu$ → $\bar{\nu}_e$ appearance search
  – IBD signal has very low background
- result of a preliminary study:
  4.8MW & 10yrs → 42% coverage (3σ)

δ_{CP} sensitivity (10 yrs, 4.8MW)

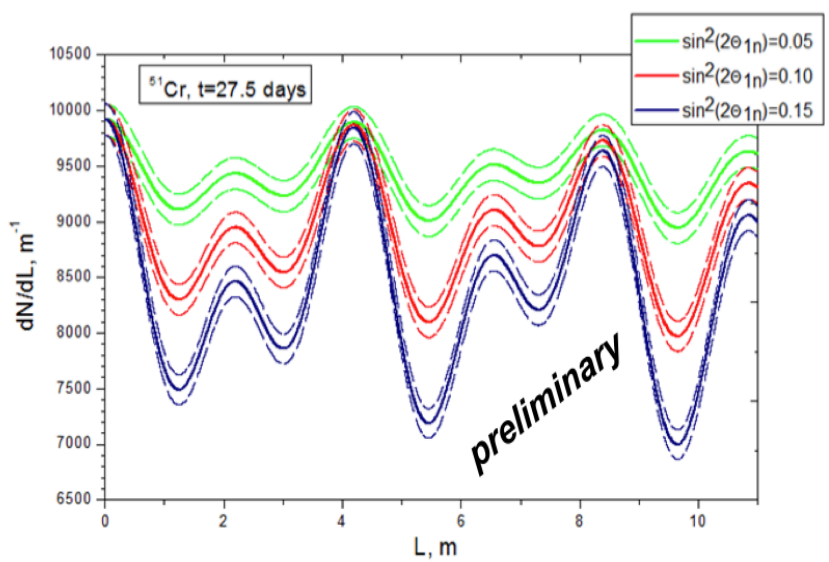


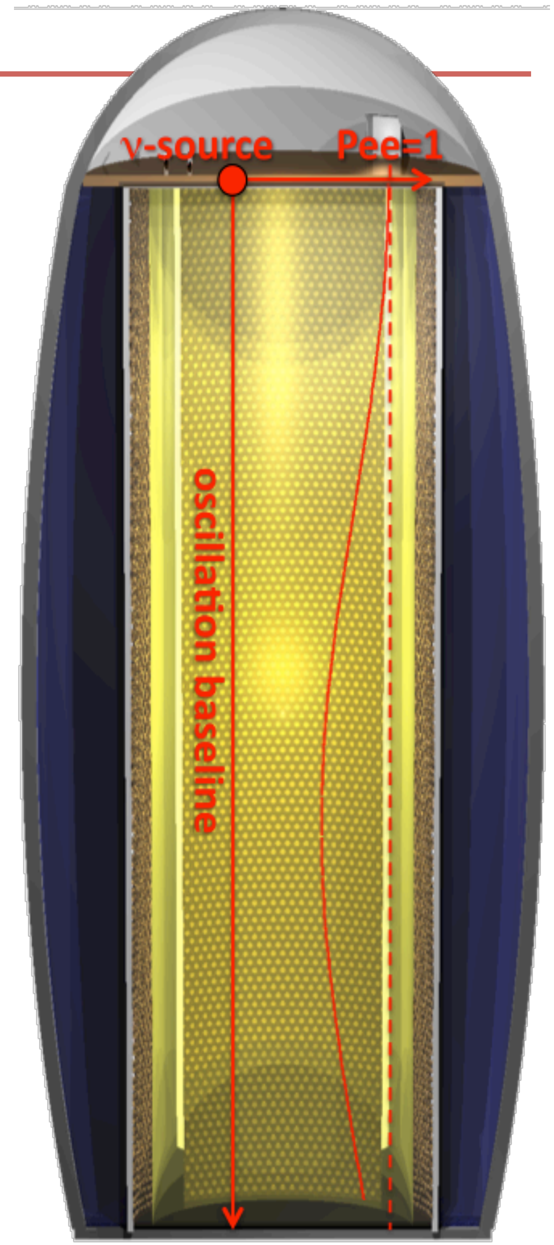
Sterile neutrinos

If evidence is found in 1st generation experiments, LENA offers the possibility to investigate scenarios (e.g. 3+1 vs. 3+2) in high-statistics measurements.

Radioactive sources → talk by Aldo Ianni

- monoenergetic ν_e (e.g. ^{51}Cr) or $\bar{\nu}_e$ (e.g. ^{90}Sr)
  → disappearance search: $\nu_e \rightarrow \nu_s$
- energy: ~1MeV → osc. length ~1m
  → observe oscillation pattern within detector





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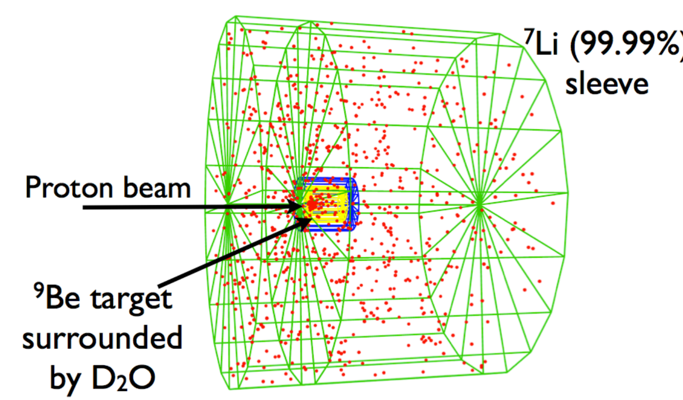

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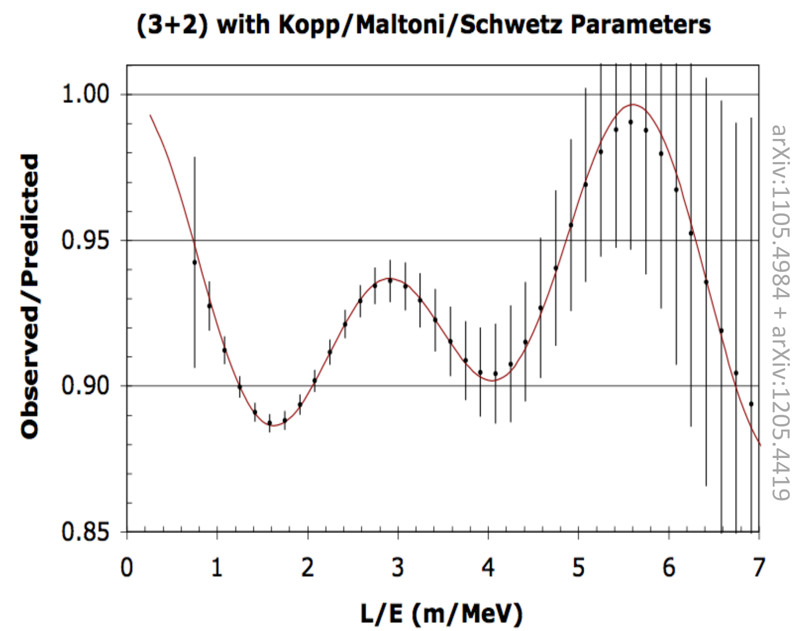
Decay-at-rest beams

- **IsoDAR:** beam-induced ^{8}Li decay
  → $\bar{\nu}_e$ beam of several MeV, disappearance
- **piDAR:** neutrinos at tens of MeV
  → L/E analysis of oscillation pattern

  two observation modes accessible:
  – $\nu_e \rightarrow \nu_s$ disappearance
  – $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance!



neutrino – antineutrino conversion

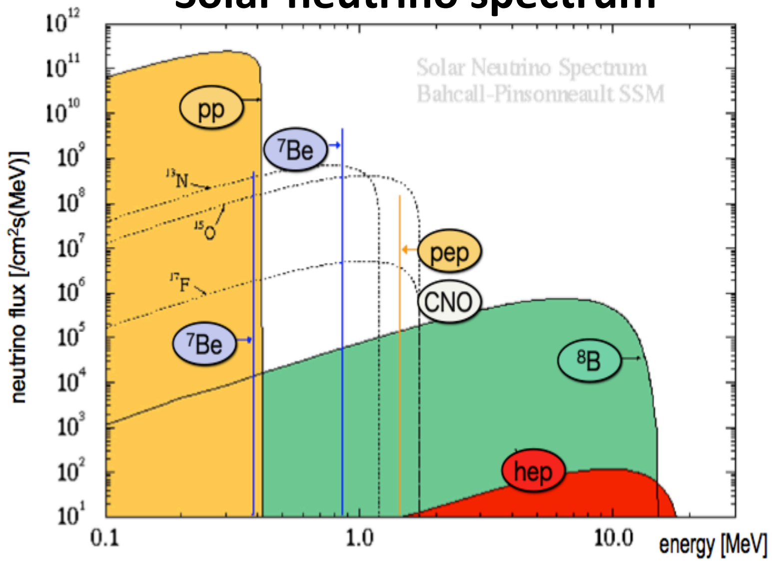
e.g. due to neutrino magnetic moment
and a strong magnetic field

Solar ^{8}B electron neutrinos

- no terrestrial $\bar{\nu}_e$ background above ~8 MeV
- best current limit by KamLAND (4.5kt·yr): conversion probability < 5.3x10^{-5} (90%CL)
- back-of-the-envelope calc. for LENA (0.5Mt·yr): conv. prob. < 3x10^{-7} to 5x10^{-6} (90%CL)

depends on pulse shape discrimination of atmospheric ν NC bg and DSNB flux

Solar neutrino spectrum



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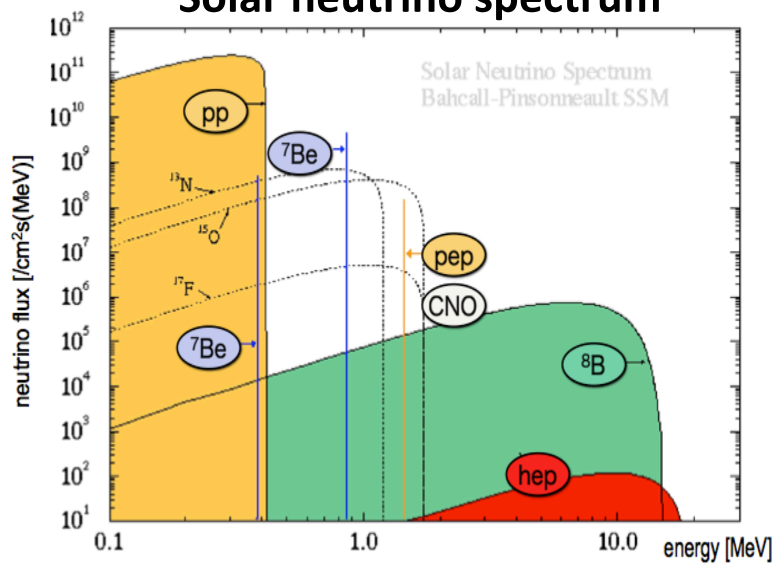
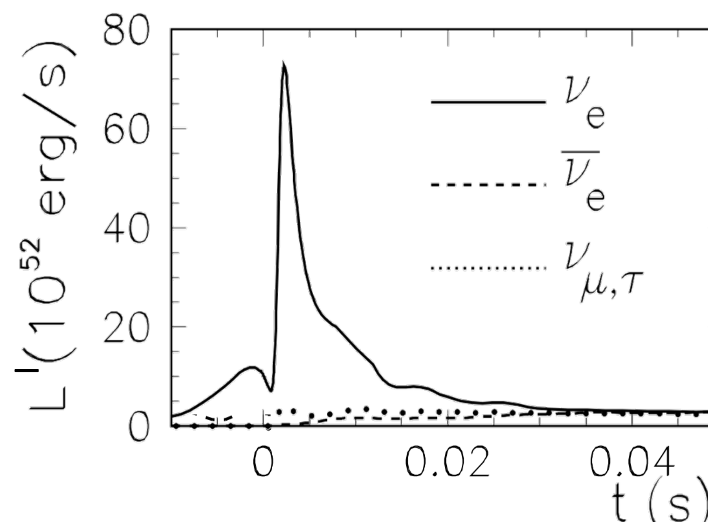


SN neutronization burst

ν_e flux around core collapse

→ ~2x10^2 ev. by νe/νp-scat.+^{12}C(CC)

→ additional $\bar{\nu}_e$ events?



Non-standard interactions

Solar matter effects

- transition from vacuum to matter-dominated oscillations from 1-5 MeV
- NSI change the expected survival probability in the transition region

Scanning transition region in LENA

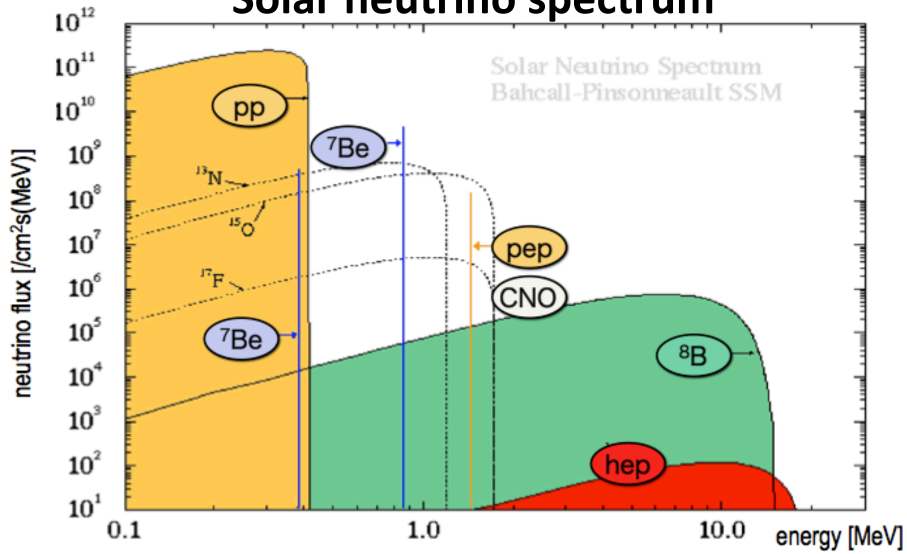
Elastic νe-scattering

- ^{7}Be line at 866 keV 10^4 /day
- pep line at 1.4 MeV   few 100 /day
- 8B down to 2-3 MeV   ~50 /day

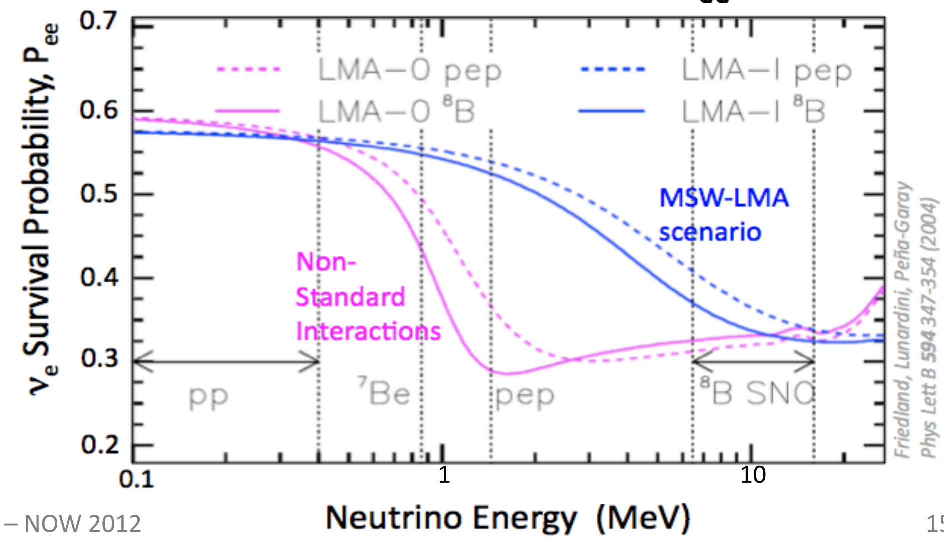
CC interaction on ^{13}C   ~10^3 /yr

- 2.2 MeV reaction threshold
- no de-convolution of recoil spectrum
- bg suppression by coincidence

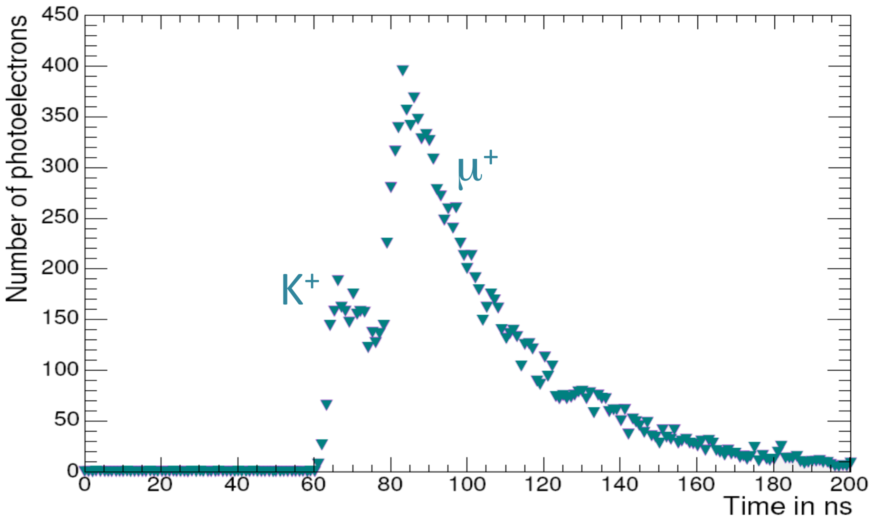
Solar neutrino spectrum



Survival probability P_{ee}



Proton decay into $K^+\bar{\nu}$



SUSY-favored decay mode

Signature $p \rightarrow K^+ \bar{\nu}$

$\hookrightarrow \mu^+\nu_\mu / \pi^0\pi^+$

→ kaon visible in liquid scintillator!

→ fast coincidence signature (τ_K = 13 ns)

→ signal efficiency: ~65% (atm. ν bg)

→ remaining background: <0.1 ev/yr

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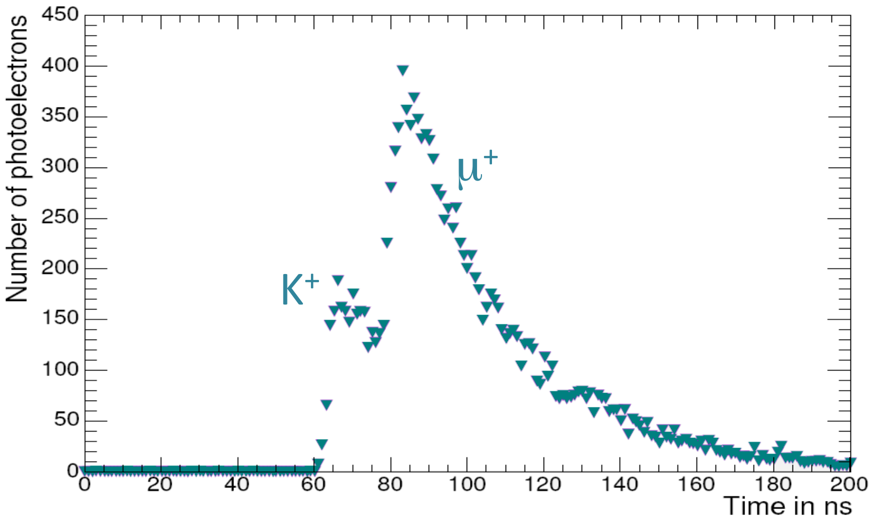

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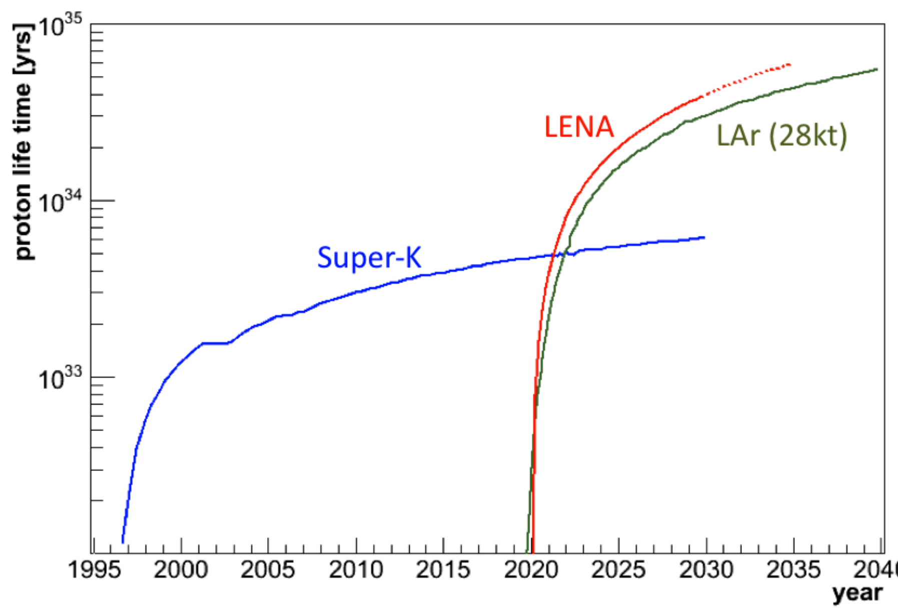
Limit for LENA if no event is observed in 10yrs (0.5 Mt·yrs):

τ_p **> 4x10^{34} yrs (90%C.L.)**



Conclusions

A liquid-scintillator detector on the scale of 50 kt will be a multipurpose ν observatory:

➔ **Astrophysical neutrino sources**

- stellar core collapse/fusion processes
- Earth heat flow, elemental composition

➔ **Neutrino physics**

- mixing parameters
- neutrino mass hierarchy
- sterile flavors
- neutrino-antineutrino oscillations
- non-standard interactions

➔ **Particle physics**

- baryon number violation
- light dark matter

Further reading

The next-generation liquid-scintillator neutrino observatory LENA

Michael Wurm,[1,2,*] John F. Beacom,[3] Leonid B. Bezrukov,[4] Daniel Bick,[2] Johannes Blümer,[5] Sandhya Choubey,[6] Christian Ciemniak,[1] Davide D'Angelo,[7] Basudeb Dasgupta,[3] Amol Dighe,[8] Grigorij Domogatsky,[4] Steve Dye,[9] Sergey Eliseev,[10] Timo Enqvist,[11] Alexey Erykalov,[10] Franz von Feilitzsch,[1] Gianni Fiorentini,[12] Tobias Fischer,[13] Marianne Göger-Neff,[1] Peter Grabmayr,[14] Caren Hagner,[2] Dominikus Hellgartner,[1] Johannes Hissa,[11] Shunsaku Horiuchi,[3] Hans-Thomas Janka,[15] Claude Jaupart,[16] Josef Jochum,[14] Tuomo Kalliokoski,[17] Pasi Kuusiniemi,[11] Tobias Lachenmaier,[14] Ionel Lazanu,[18] John G. Learned,[19] Timo Lewke,[1] Paolo Lombardi,[7] Sebastian Lorenz,[2] Bayarto Lubsandorzhiev,[4,14] Livia Ludhova,[7] Kai Loo,[17] Jukka Maalampi,[17] Fabio Mantovani,[12] Michela Marafini,[20] Jelena Maricic,[21] Teresa Marrodán Undagoitia,[22] William F. McDonough,[23] Lino Miramonti,[7] Alessandro Mirizzi,[24] Quirin Meindl,[1] Olga Mena,[25] Randolph Möllenberg,[1] Rolf Nahnhauer,[26] Dmitry Nesterenko,[10] Yuri N. Novikov,[10] Guido Nuijten,[27] Lothar Oberauer,[1] Sandip Pakvasa,[28] Sergio Palomares-Ruiz,[29] Marco Pallavicini,[30] Silvia Pascoli,[31] Thomas Patzak,[20] Juha Peltoniemi,[32] Walter Potzel,[1] Tomi Räihä,[11] Georg G. Raffelt,[33] Gioacchino Ranucci,[7] Soebur Razzaque,[34] Kari Rummukainen,[35] Juho Sarkamo,[11] Valerij Sinev,[4] Christian Spiering,[26] Achim Stahl,[36] Felicitas Thorne,[1] Marc Tippmann,[1] Alessandra Tonazzo,[20] Wladyslaw H. Trzaska,[17] John D. Vergados,[37] Christopher Wiebusch,[36] and Jürgen Winter[1]

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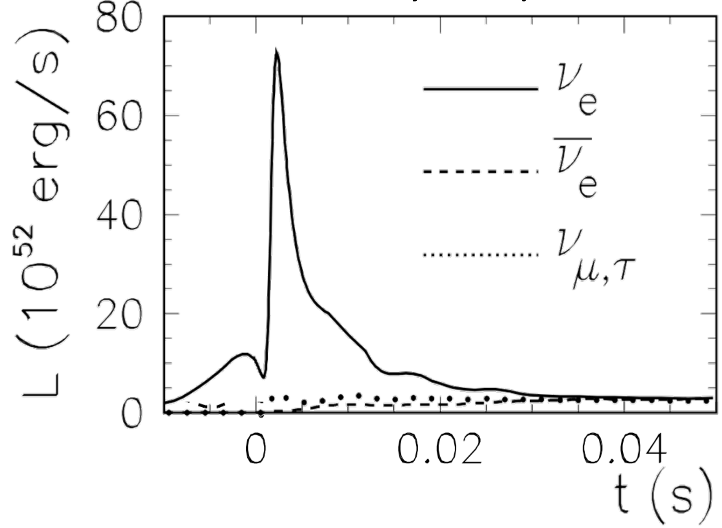
Backup Slides

SN neutrinos in LENA

ν flux around core collapse
→ ~10^2 ev. by $\nu e/\nu p$-scat.+^{12}C



ν_e from neutronisation burst

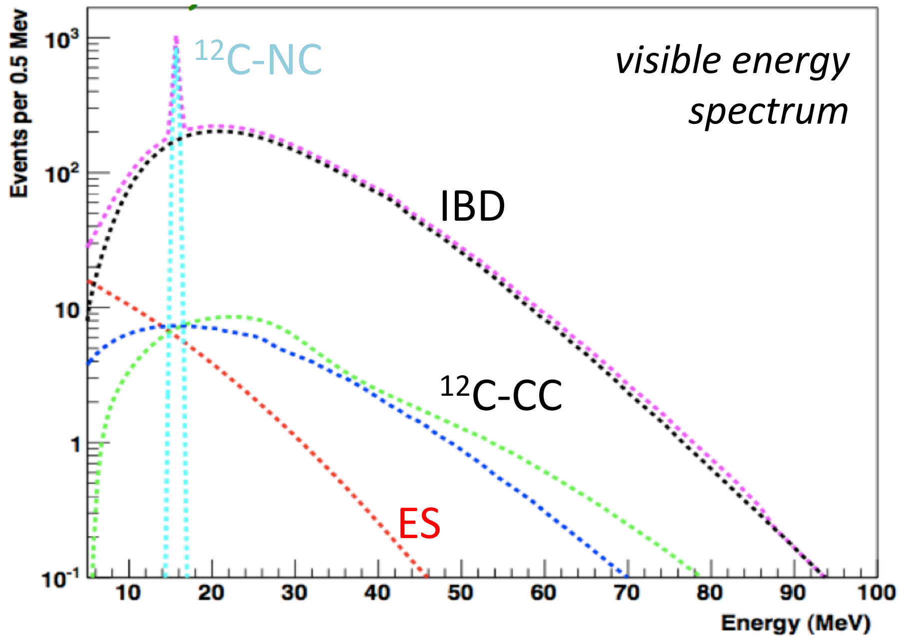
$\nu\bar{\nu}$ pairs of all flavors
from protoneutronstar cooling

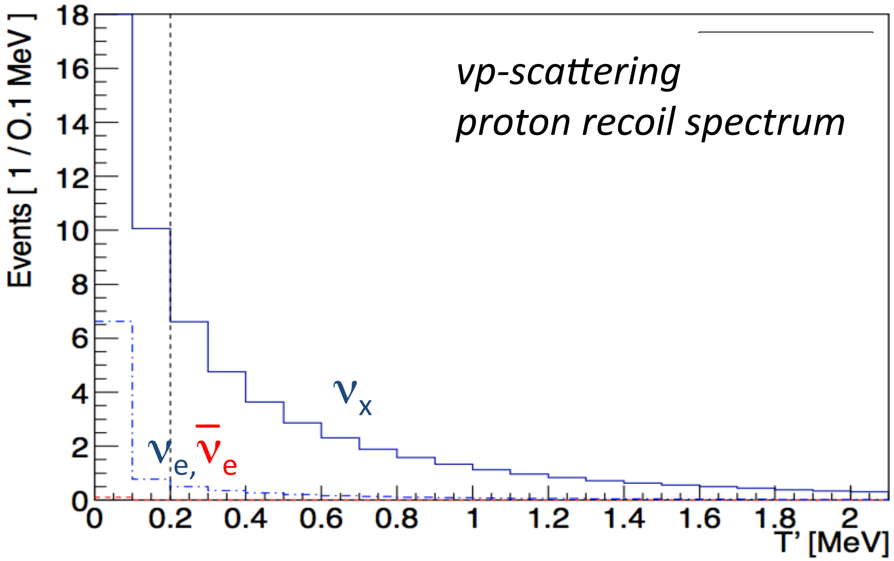
For galactic SN (10kpc, 8M$_\odot$, <E$_\nu$>=14MeV):
ca. $2\text{x}10^4$ events in 44kt target

Channel		Events	Threshold (MeV)	Spectrum
$\bar{\nu}_e\, p \rightarrow n\, e^+$	CC	$1.3\text{x}10^4$ *	1.8	✓
$\nu_e\, {}^{12}C \rightarrow {}^{12}N\, e^-$	CC	$3.4\text{x}10^2$	17.3	(✓)
$\bar{\nu}_e\, {}^{12}C \rightarrow {}^{12}B\, e^+$	CC	$1.8\text{x}10^2$	13.4	(✓)
$\nu\, {}^{12}C \rightarrow {}^{12}C^*\, \nu$	NC	$1.0\text{x}10^3$	15.1	✗
$\nu\, p \rightarrow p\, \nu$	NC	$2.6\text{x}10^3$	1.0	✓
$\nu\, e^- \rightarrow e^-\, \nu$	NC CC	$6.2\text{x}10^2$	0.2	✓

**roughly 2x the rate in Super-Kamiokande*

Expected signal from SN neutrinos





Signal above 10 MeV

- dominated by inverse beta decay
- coincidence signals allow to tag IBD and ^{12}C-CC reactions
- ^{12}C+ν_e/$\bar{\nu}_e$ separation by simultaneous fit to energy and decay spectra
- γ-peak from ^{12}C-NC reaction

→ **LENA can resolve the different interaction channels!**

Signal at 1 MeV

- dominated by ν-proton scattering
- sensitive on threshold by ^{14}C-decay
- extract νe-scattering by PSD?

→ **νp-scattering unique feature of liquid scintillator detectors**

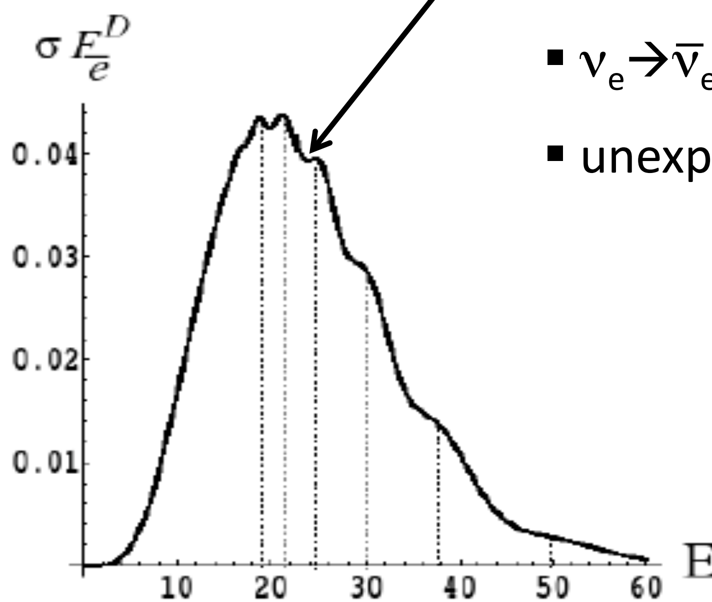
Expected physics output from SN neutrinos

Astrophysics

- detailed information on core-collapse (ν energy, flavor, time-profile)
  – initial neutronization burst
  – features of cooling phase
  – explosion shock-wave
- signals from dim SNe, black hole formation
- IBD: pointing to obscured SNe
- SNEWS, grav. wave exp.

Neutrino physics

- neutrino mass hierarchy by
  – neutronization burst
  – resonant flavor conversion in stellar envelope
  – Earth matter effect
  – signal rise time
- collective oscillations
- $\nu_e \rightarrow \bar{\nu}_e$ conversion
- unexpected effects ...



Backgrounds for DSN search in LENA

Detection via Inverse Beta Decay

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

neutron tagging allows discrimination of most single-event bg limiting the detection in SK

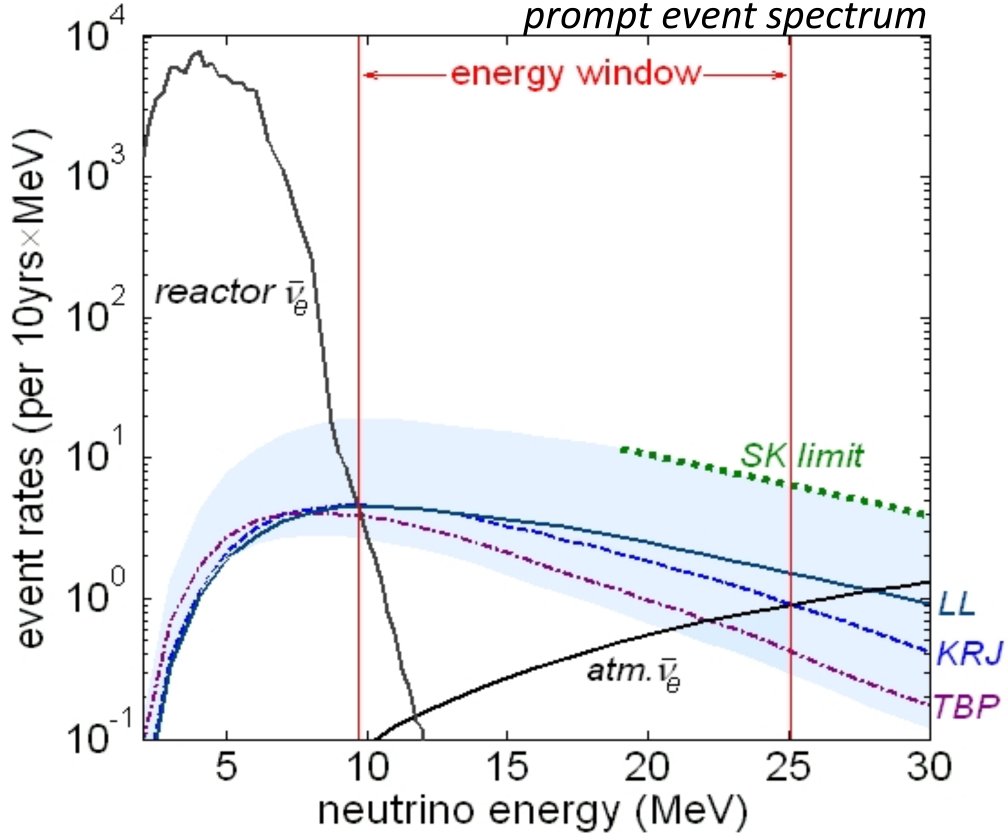
Remaining Background Sources

- reactor and atmospheric $\bar{\nu}_e$'s
- cosmogenic backgrounds:
  – fast neutrons and ^{9}Li: μ veto
  – atmospheric ν NC events: PSD

Scientific Gain

- first detection of DSN
- average SNν spectrum
- fraction of dim/failed SNe (?)

prompt event spectrum



Expected events: ~10^2 in 10 yrs
(in energy window from 10-25MeV

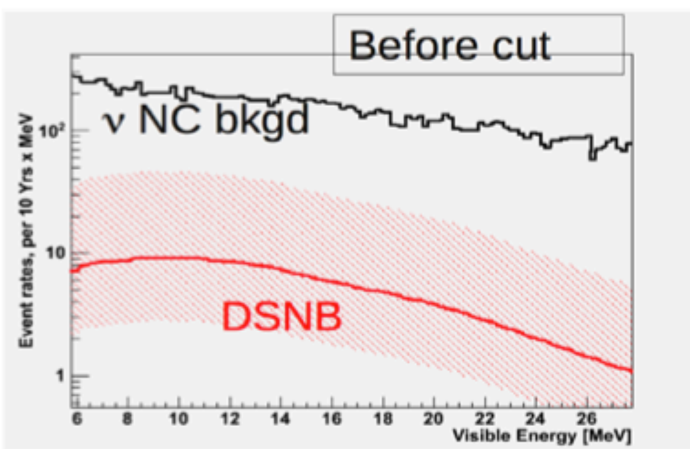
~2x of GADZOOKS! expectation

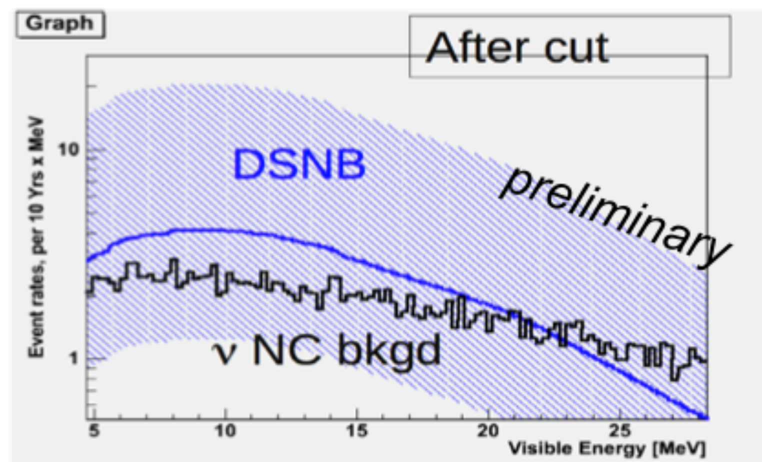
DSNB atmospheric ν NC background

- Cosmogenic produced neutrons
  - no problem if d > 4000 mwe
  - < 0.2 events / year
- Cosmogenic produced beta-neutron emitter (e.g. ^{9}Li)
  - no problem if d > 4000 mwe
  - < 0.1 events / year
- Atmospheric neutrino CC reaction
  - 10 < E / MeV < 30
- **Atmospheric neutrino NC reaction** – neutron production
  - data from KamLAND

n-scattering TOF exp. at MLL (Garching)

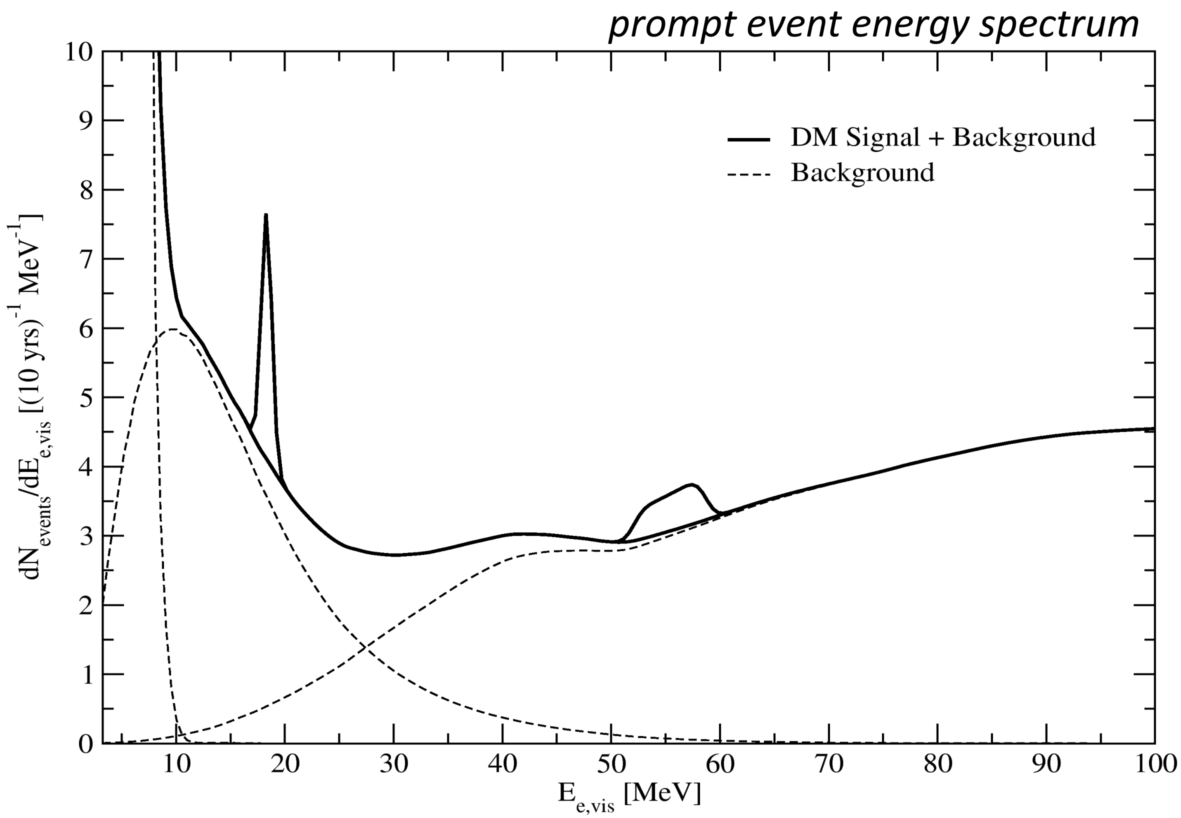
severe bg: reduction by pulse shape discrimination and/or statistical subtraction ?
Laboratory experiments indicate that a strong bg-reduction can be achieved !





***Preliminary** results: Monte-Carlo simulation based on recent results of PSD parameter on LAB scintillators*

Indirect light dark matter search

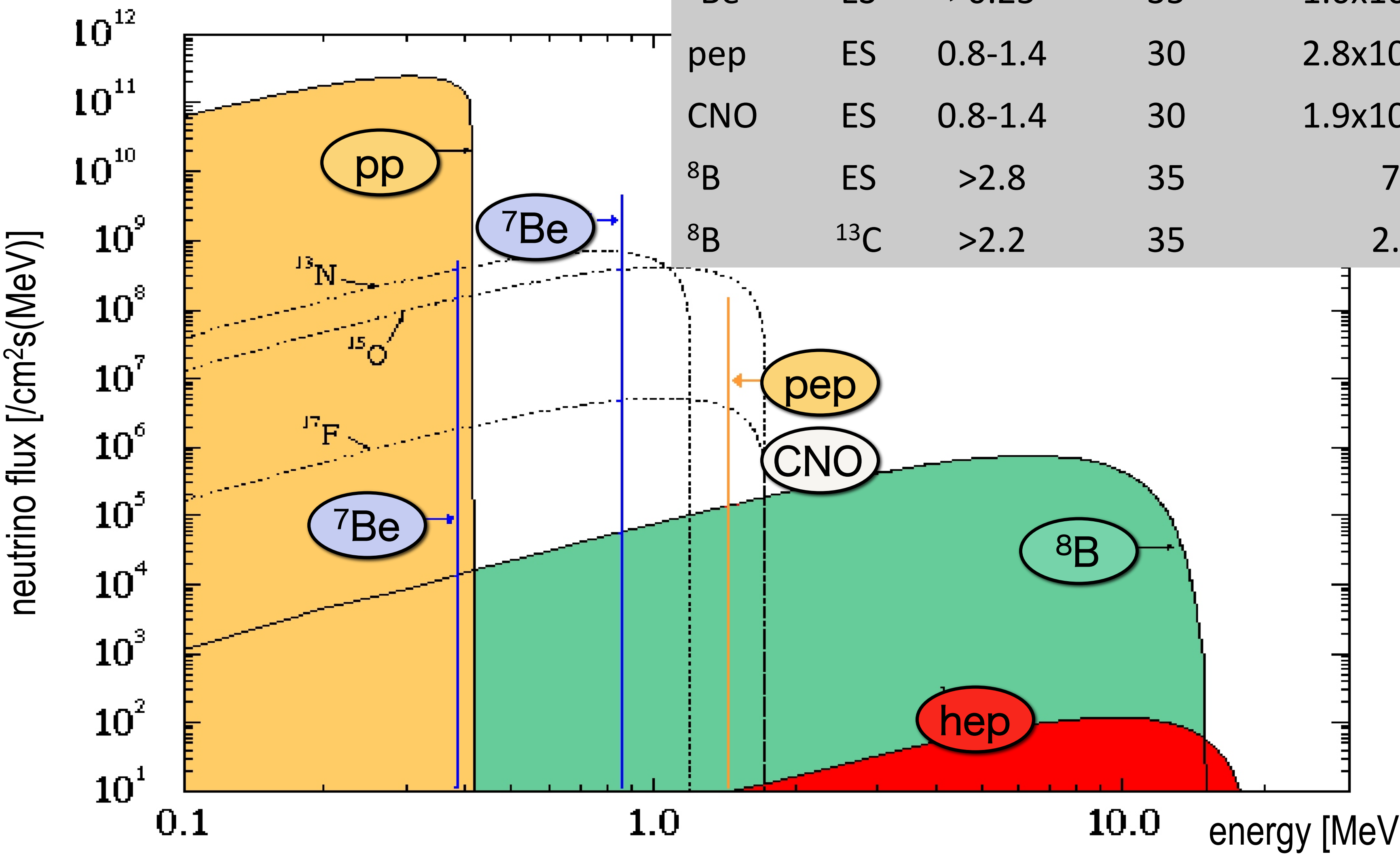


- low background level in IBD allows to search for $\bar{\nu}_e$ from $\chi\bar{\chi} \rightarrow \nu_e\bar{\nu}_e$
- signature for annihilation: peak at $E = m_\chi$, with m_χ = 10 ... 100 MeV.

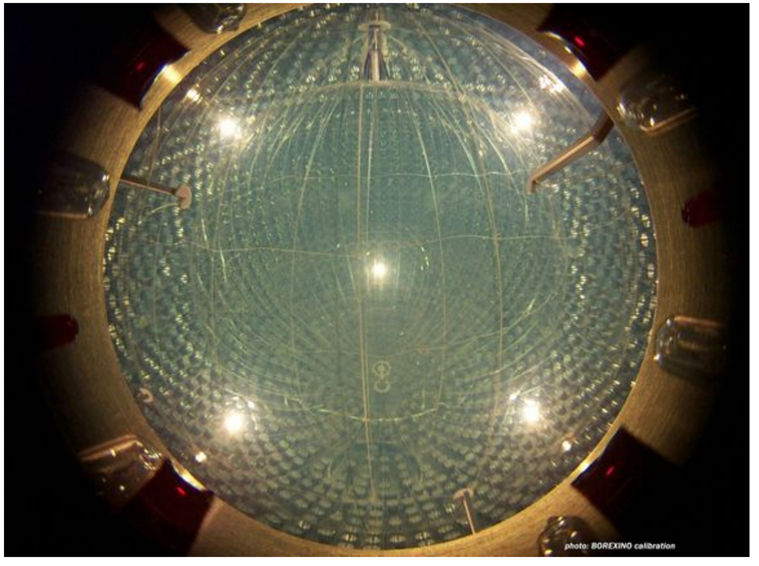
Solar neutrino signal in LENA

Liquid scintillator: – low energy thr
– required level (

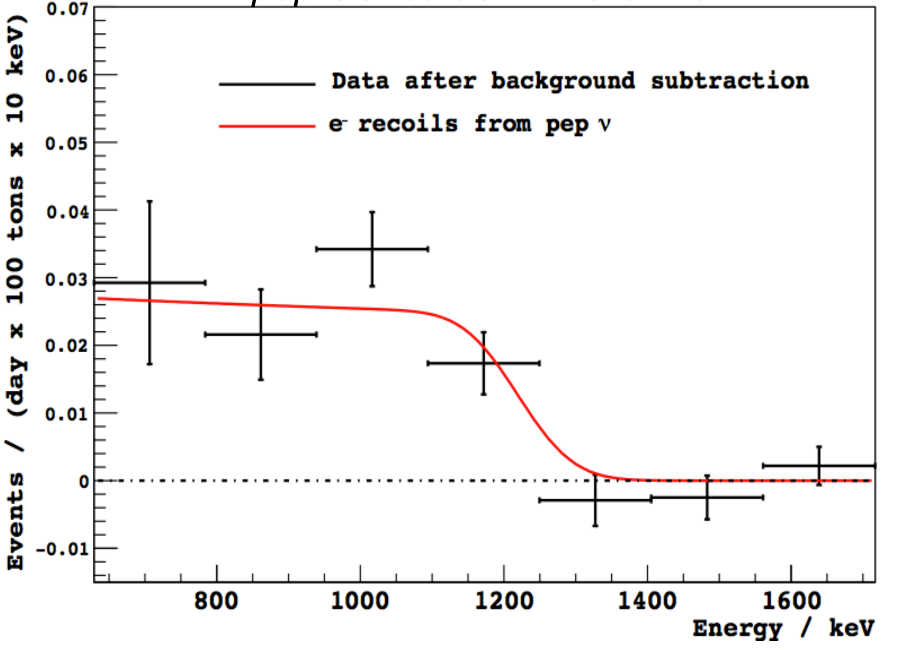
Source	Ch	E (MeV)	M_{fid} (kt)	Rate (d^{-1})
^{7}Be	ES	>0.25	35	$1.0x10^4$
pep	ES	0.8-1.4	30	$2.8x10^2$
CNO	ES	0.8-1.4	30	$1.9x10^2$
^{8}B	ES	>2.8	35	79
^{8}B	^{13}C	>2.2	35	2.4



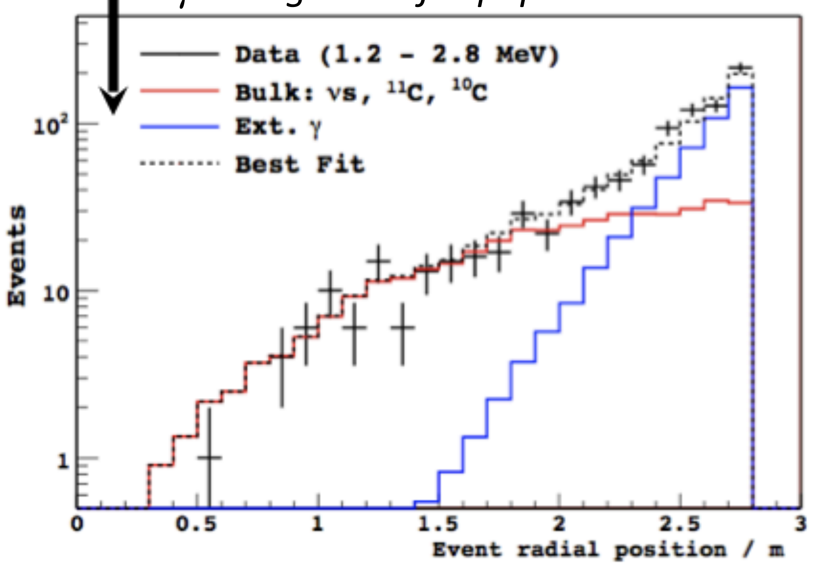
Gain compared to Borexino



pep-ν shoulder in Borexino



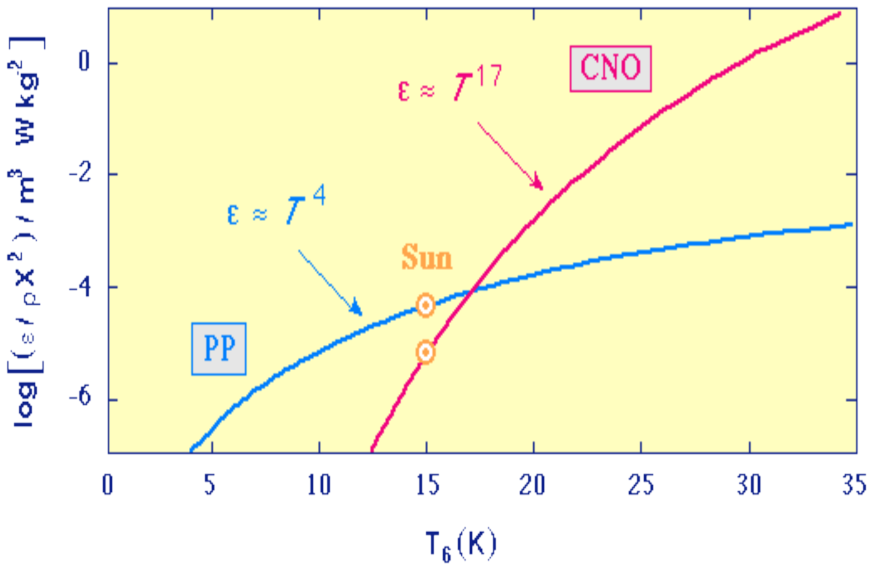
γ-background for pep-ν search



Borexino → LENA

- fiducial volume: >300 times larger
- 4000 mwe at Pyhäsalmi → cosmic backgrounds reduced by factor 3-5
- lower external γ background

Physics programme for solar neutrinoss

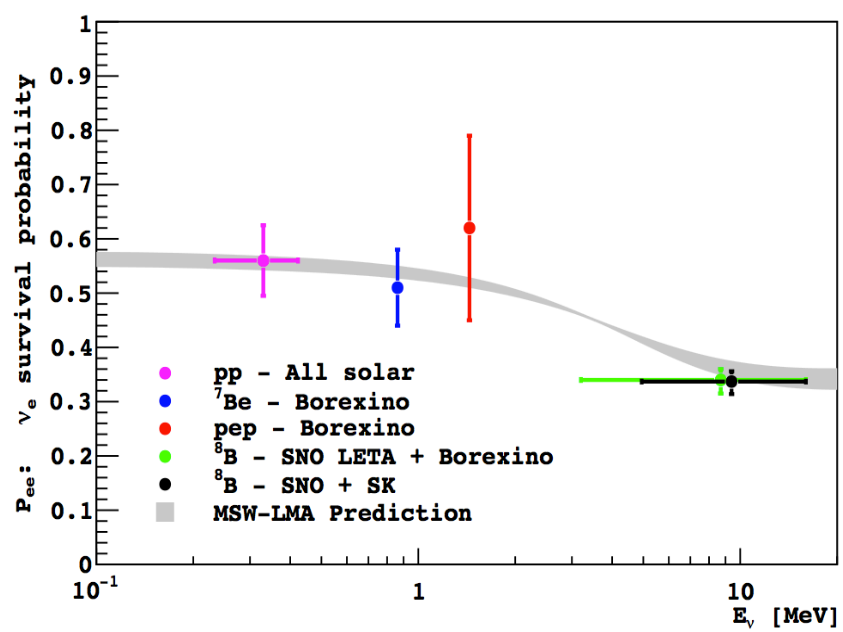


Astrophysics

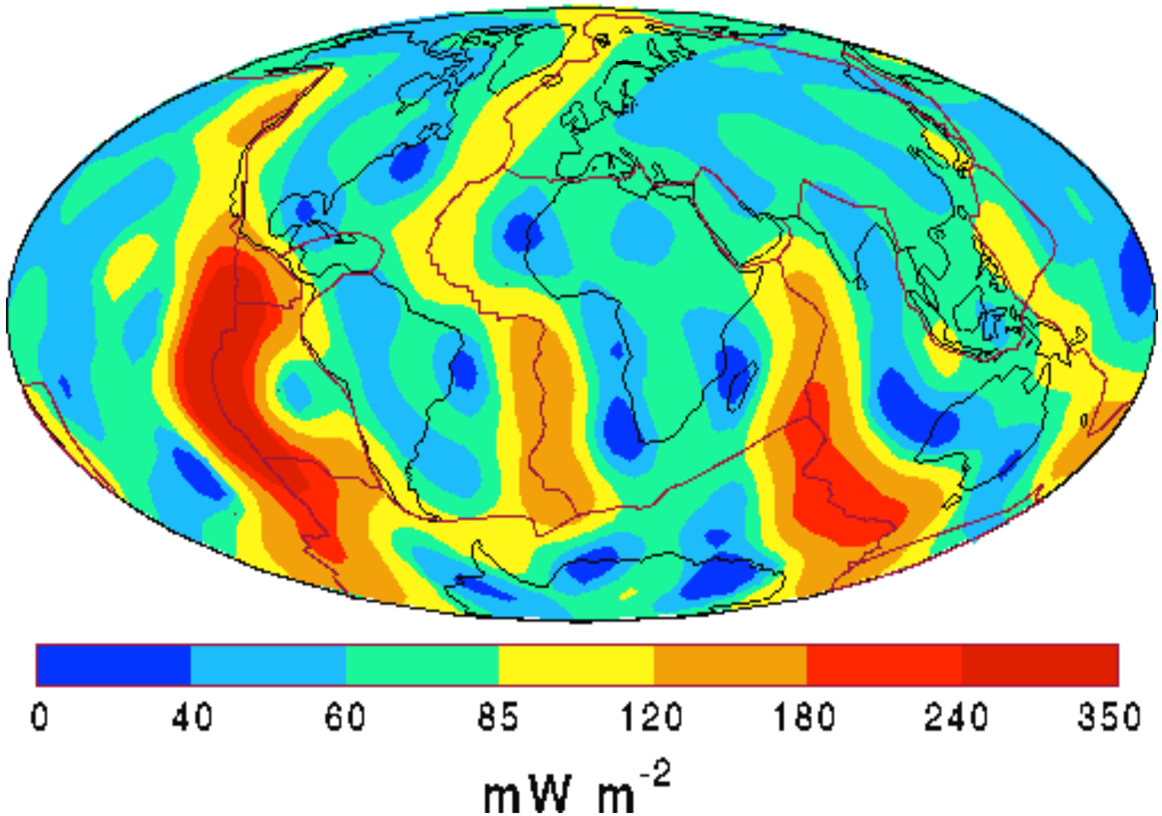
- contribution of CNO cycle to solar fusion rate
- metallicity of solar core
- presence of time variations in solar neutrino flux (10^{-3} level) → helioseismic g-modes ...

Neutrino physics

- precision measurement of P_{ee} in the matter-vacuum transition region (1-5 MeV) by pep and ^{8}B (CC) on ^{13}C → non-standard interactions etc.
- $\nu_e \rightarrow \bar{\nu}_e$ conversion



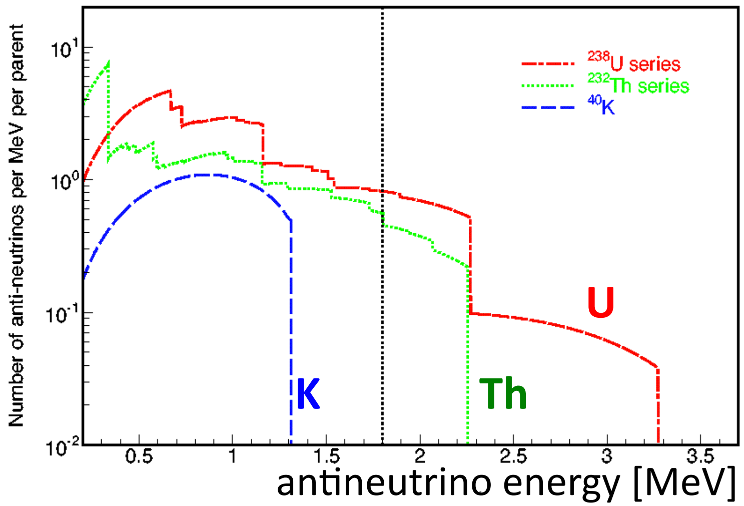
The Earth heat flow problem

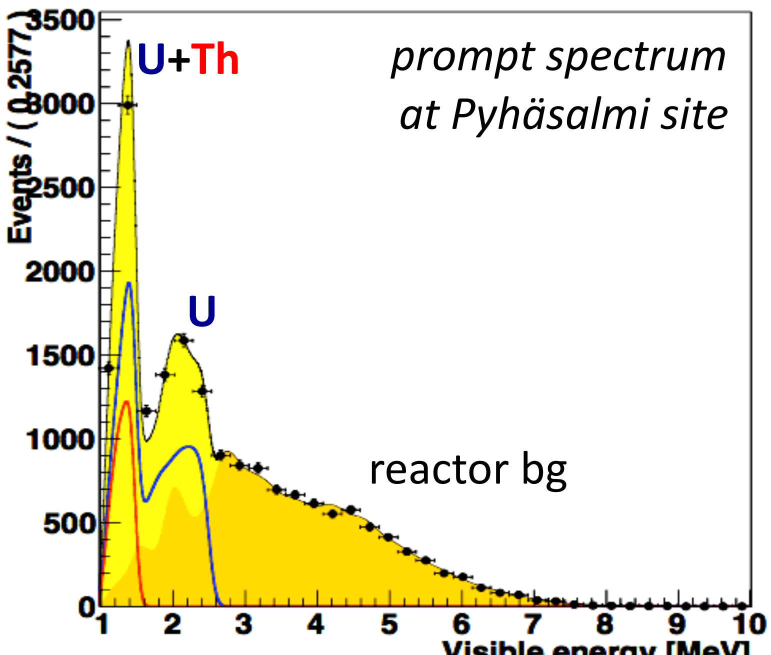


From surface measurement, the thermal power is determined to 47±2 TW.
Models determine the heat from radioactive decays of U, Th, K to 12-30 TW.

Is there a difference? And what accounts for the deficit?

Detection of geoneutrinos in LENA





IBD threshold of 1.8 MeV (only LS)

$\bar{\nu}_e$ by U/Th decay chains

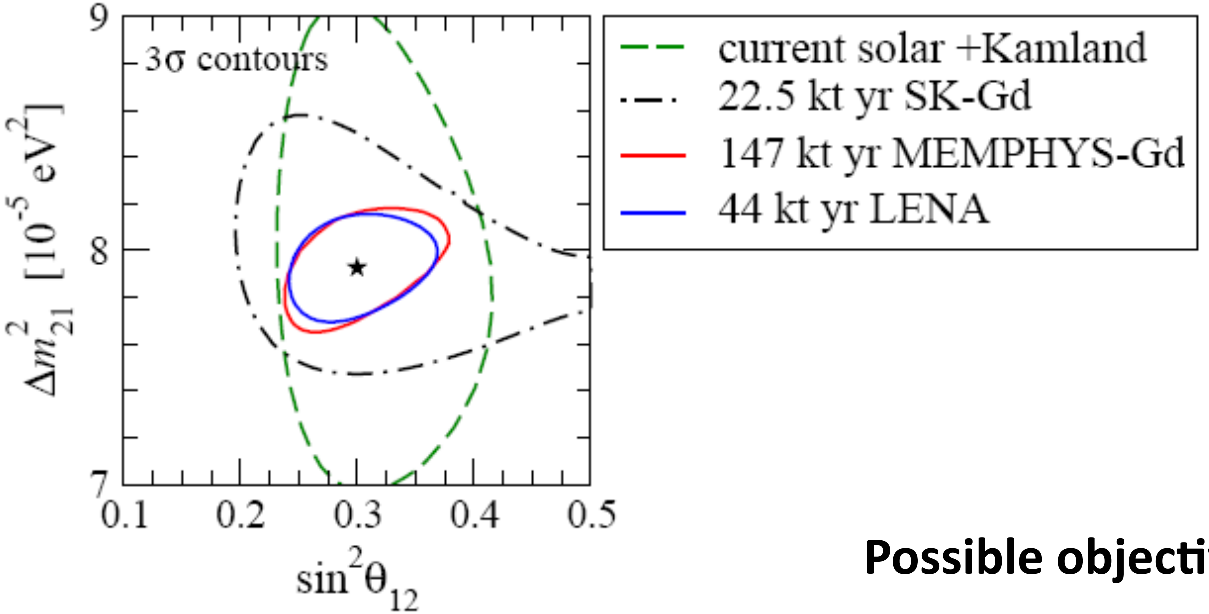
At Pyhäsalmi

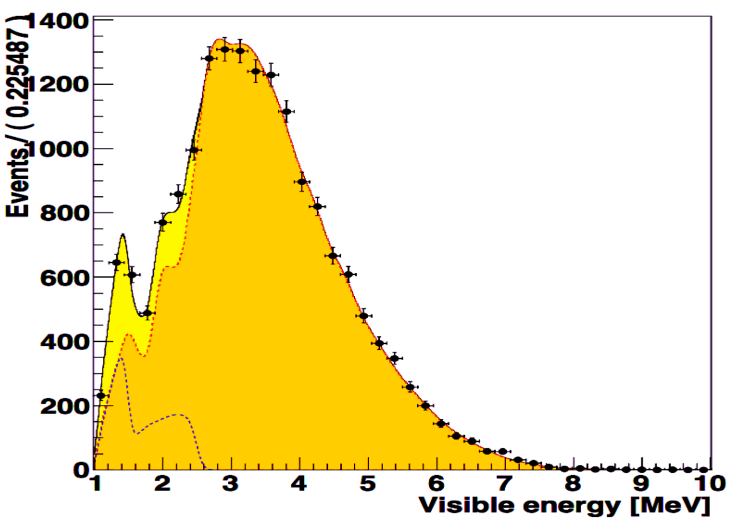
- expected geo-ν rate $2x10^3$ yr^{-1}
- reactor-ν background $7X10^2$

Scientific Gain

- contribution of U/Th decays to Earth's total heat flow → 1%
- relative ratio of U/Th → 5%
  → geochemistry: U/Th = 3.5 ... 4
- with several detectors at different sites: disentangle oceanic/continental crust
- test for hypothetical georeactor

Reactor neutrinos





Possible objectives

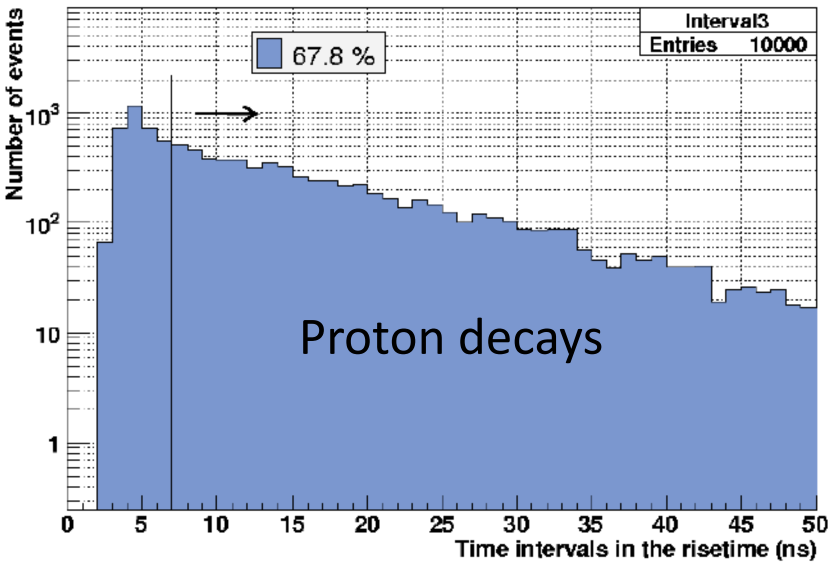
- Precision measurement of solar oscillation parameters, esp. Δm^2_{12}

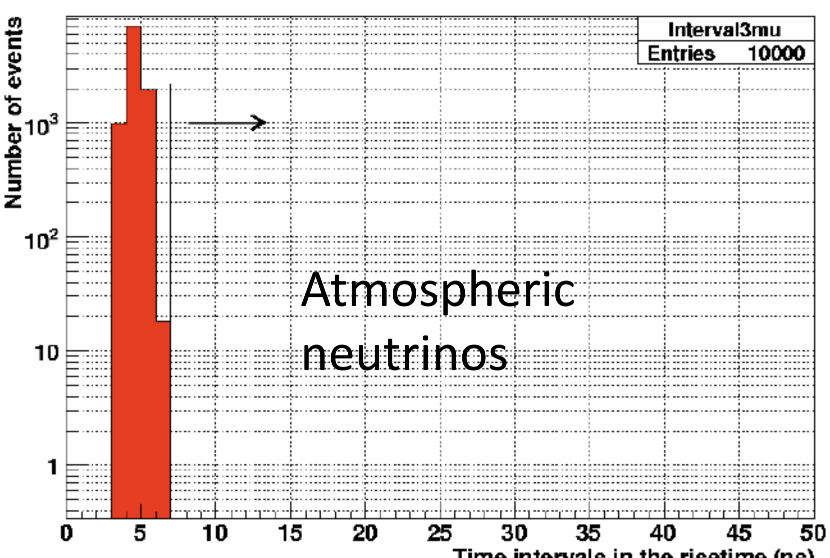
  @ Fréjus: $\sin^2 2\theta_{12}$ ~ 10% (3σ)

  Δm^2_{12} ~ 1% (3σ)

- Neutrino mass hierarchy by Δm^2_{13}-Δm^2_{23} interference in $P_{ee}(x)$ (but optimum distance is 60 km)

Proton decay into $K^+\bar{\nu}$





Signature $p \rightarrow K^+ \bar{\nu}$

$\hookrightarrow \mu^+\nu_\mu \,/\, \pi^0\pi^+$

coincidence: τ_K = 13 ns
energy: 250-450 MeV
modified by Fermi motion for ^{12}C

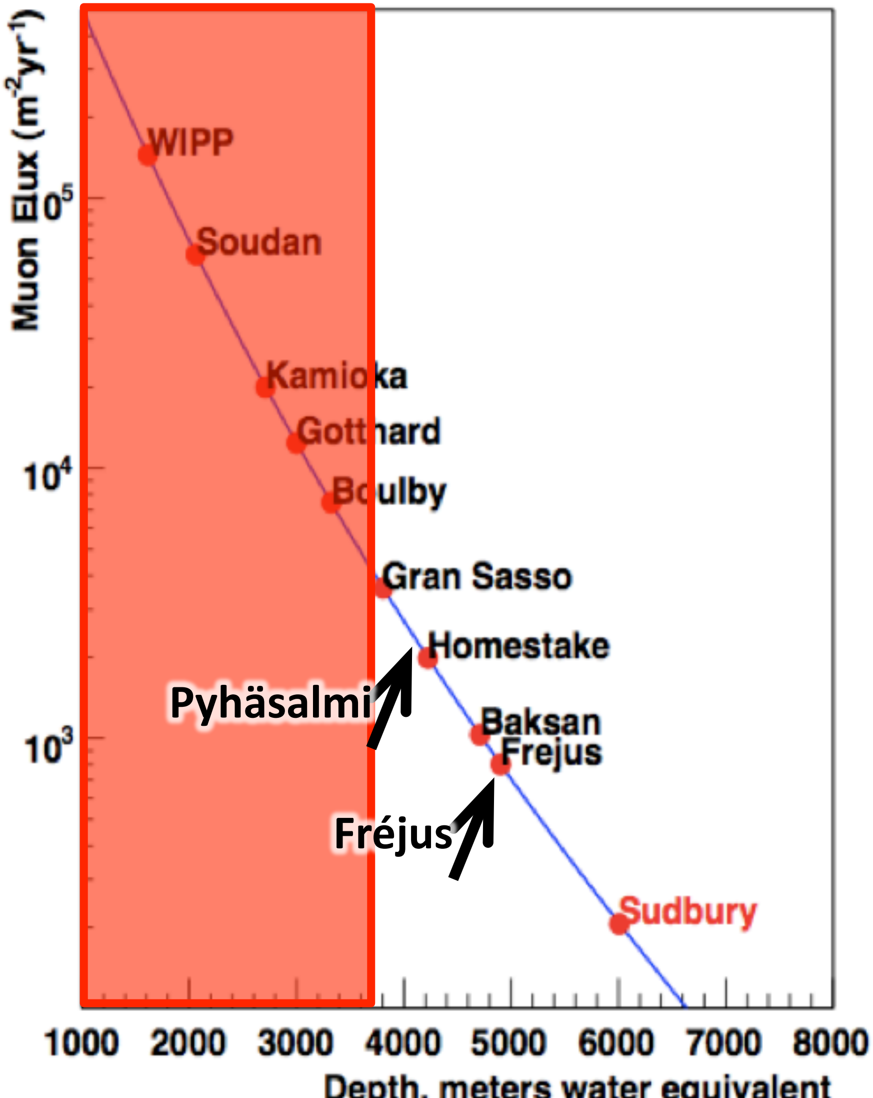
Background
atmospheric ν's rejected
by rise time cut: **efficiency 0.67**
hadronic channels: <1.2 per 1Mt·yr
(producing kaons) @ 4kmwe

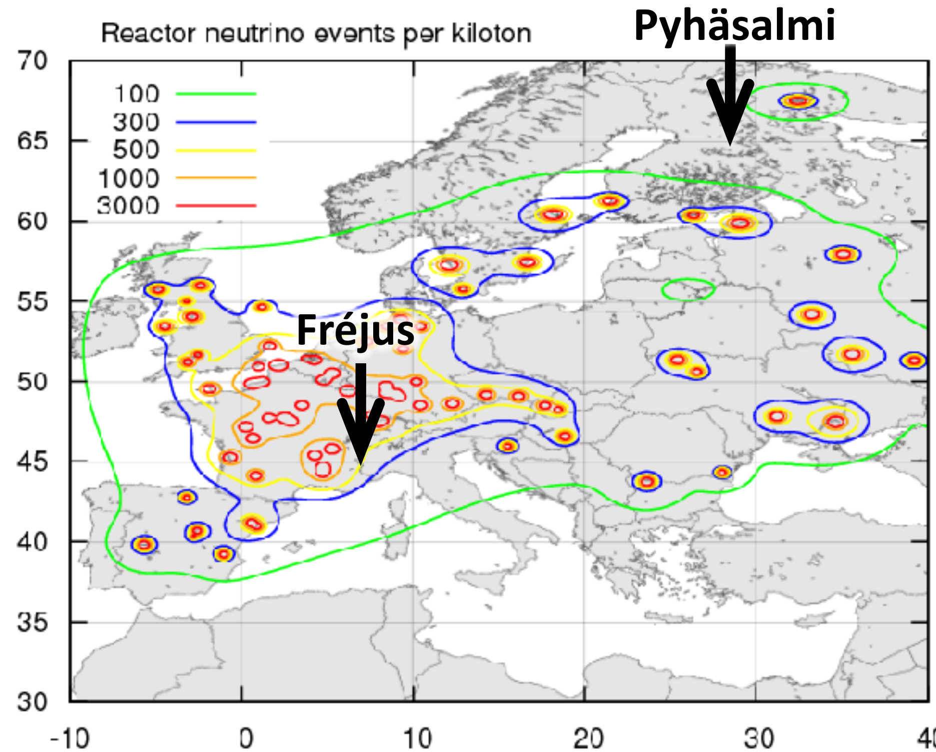
Current SK limit: 2.3×10^{33} yrs

Limit for LENA if no event is observed in 10yrs (0.5 Mt·yrs):

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

Cosmic vs. reactor background



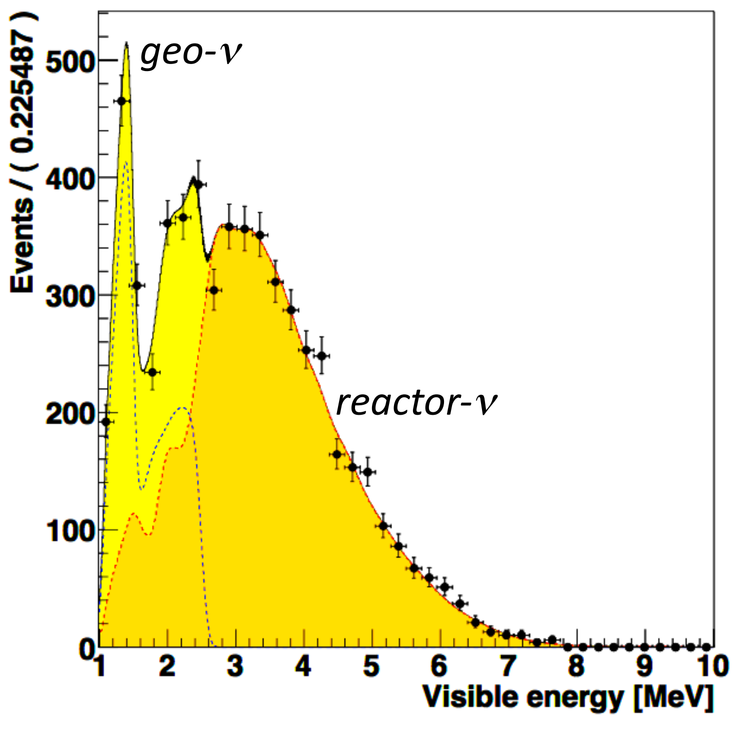


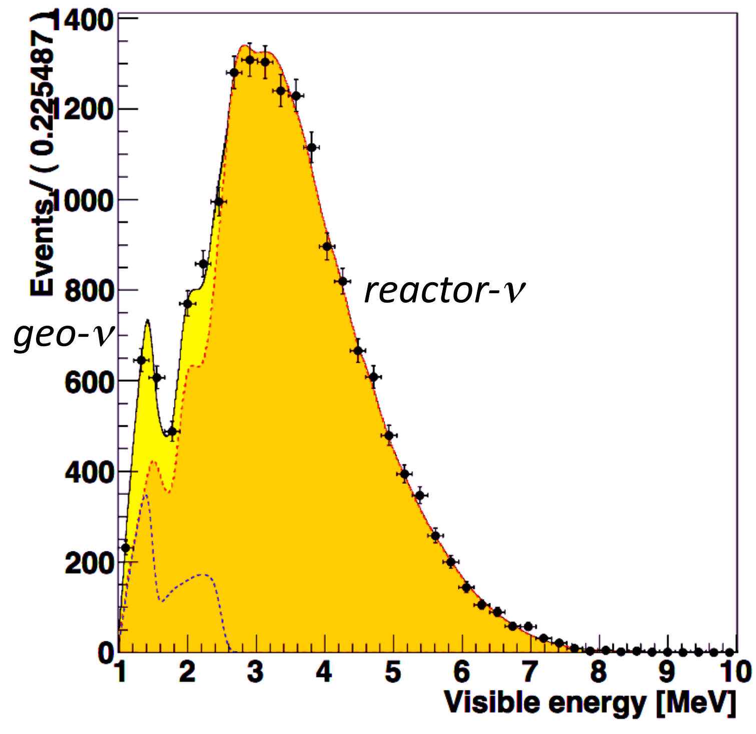
Possible LENA sites

- Pyhäsalmi:
  favorable for geo-νs and DNSB
- Fréjus:
  better shielding from cosmic rays

Geoneutrinos and reactor background

Event rates for 44 kt years of exposure.





Pyhäsalmi vs. Fréjus

Neutrino oscillometry

Concept: Short-baseline oscillation experiments using neutrinos from radioactive sources.

Radioactive neutrino sources

- ν_e (monoenergetic) from EC sources: ^{51}Cr, ^{37}Ar
- $\bar{\nu}_e$ (E=1.8-2.3MeV) from ^{90}Sr (^{90}Y), ^{144}Ce
- large activity necessary for ν_e: 1MCi or more

Oscillation baseline

- for Δm^2_{32} (θ_{13}): 750m for ^{51}Cr (747keV)
- for Δm^2_{41} (sterile): 1.3m

Scientific objectives

- check $P_{ee}(r)$ if θ_{13} is relatively large
- check CPT for ν and $\bar{\nu}$
- very sensitive in sterile ν searches ($\sin^2 2\theta \approx 10^{-3}$)