Perspectives for the next generation of liquid-scintillator neutrino experiments

Gentner-Colloquium
for Astroparticle Physics
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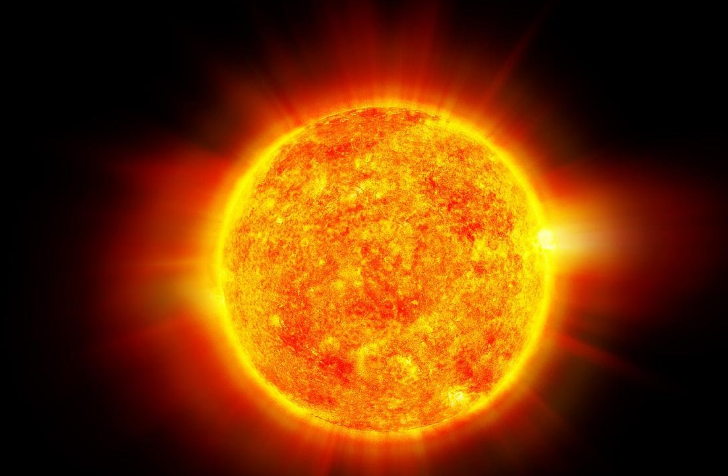
Outline

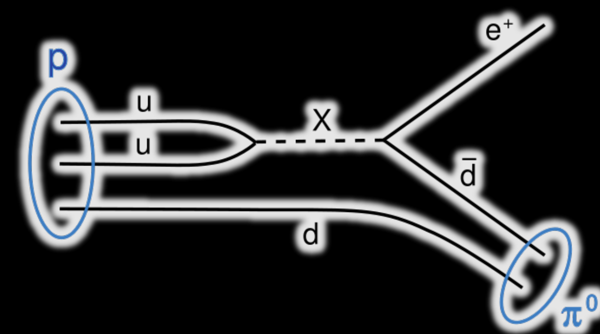
Next-generation neutrino detectors

- Physics program
- Detector technologies



Future liquid-scintillator detectors

- **JUNO** – neutrino mass hierarchy and precise mixing parameters
- **LENA** – neutrino astrophysics, long-baseline oscillations, nuleon decay ...



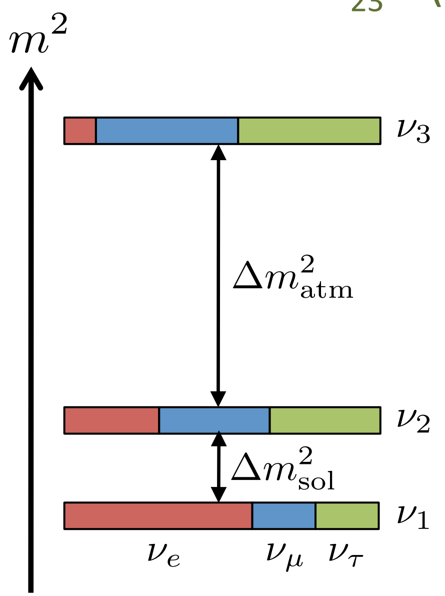
Neutrino oscillations: Current status

$$\mathbf{U}_{\mathbf{3}\times\mathbf{3}} = \mathbf{U}_{\mathrm{PMNS}}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates — *atmospheric mixing* — *reactor mixing & CP violation* — *solar mixing* — *mass eigenstates*

$\theta_{23} \approx (45\pm9)°$ — $\theta_{13} \approx (8.9\pm1.4)°$, δ_{CP}=? — $\theta_{12} \approx (34\pm3)°$



mixing angles : $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

CP violating phase : δ

mass squared differences :

- $\Delta m^2_{\mathrm{sol}} = \Delta m^2_{21} \approx (7.5 \pm 0.6) \cdot 10^{-5}\,\mathrm{eV}^2$
- $\Delta m^2_{\mathrm{atm}} = \Delta m^2_{32} \approx \Delta m^2_{31} \approx (2.4 \pm 0.2) \cdot 10^{-3}\,\mathrm{eV}^2$

Neutrino oscillations: Unresolved issues

Are there more than 3 light neutrino flavors?

Do sterile neutrinos exist?

Is there CP violation in the leptonic sector?

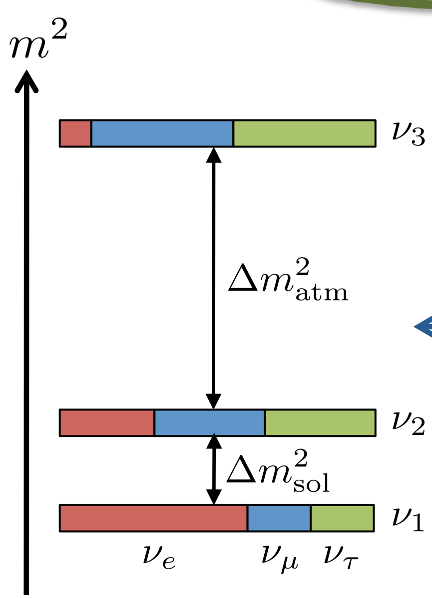
Is it large enough to motivate the matter-antimatter asymmetry?

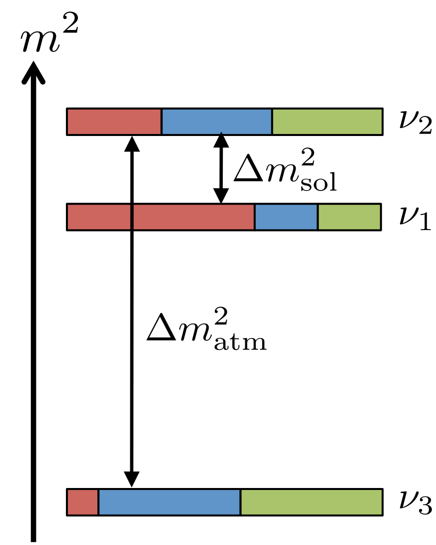
Is θ_{23} maximal?

$\theta_{23} \approx (45 \pm 9)°$ → δ_{CP}=?

What is the sign of Δm^2_{32}?

Is the neutrino mass hierarchy inverted?





- $\Delta m^2_{\mathrm{atm}} = \Delta m^2_{32} \approx \Delta m^2_{31} \approx \pm(2.4 \pm 0.2)\,\mathrm{eV}^2$

Observation of astrophysical sources

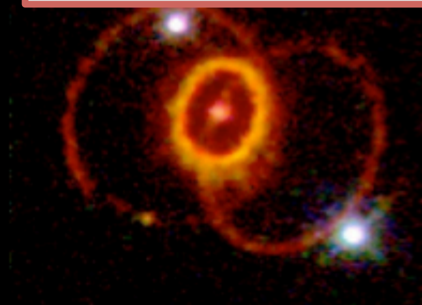
Indirect DM search

→ discover DM or extend excluded parameter space

Supernova neutrinos

ν burst established

→ extract information on core-collapse and neutron star formation



galactic

cosmic

Solar neutrinos

pp-chain measured

→ CNO neutrino flux

→ study solar interior

Observation Range
<1 to 50 MeV

Geoneutrinos

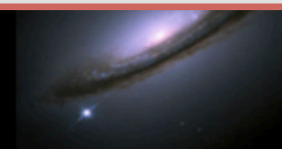
now: 4σ observation

→ geology: radiogenic heat, U/Th conc.

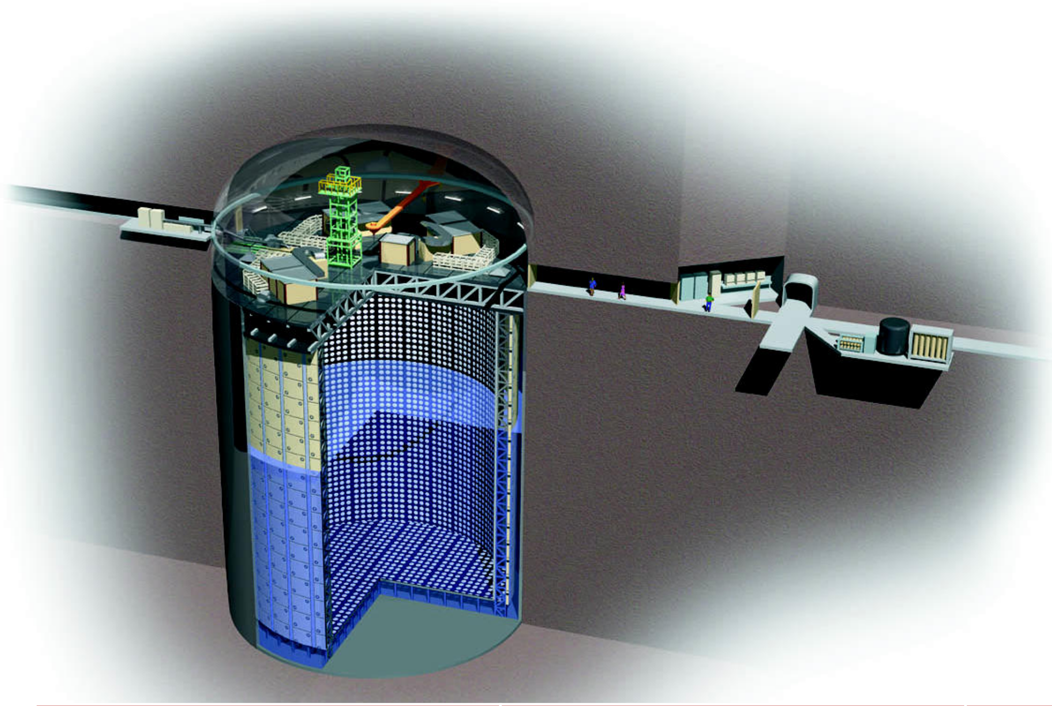
Diffuse SN neutrinos

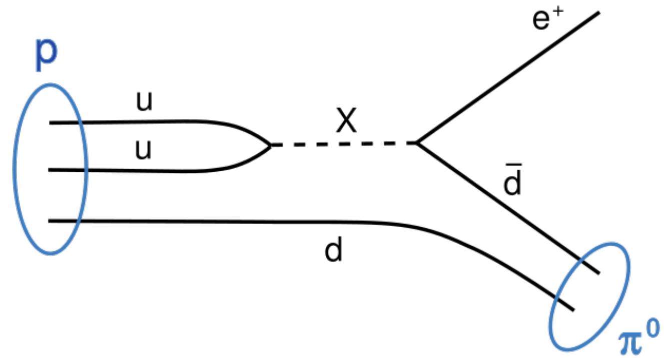
still unobserved

→ discovery, z-dep. SN rate and average spectrum



Search for nucleon decay

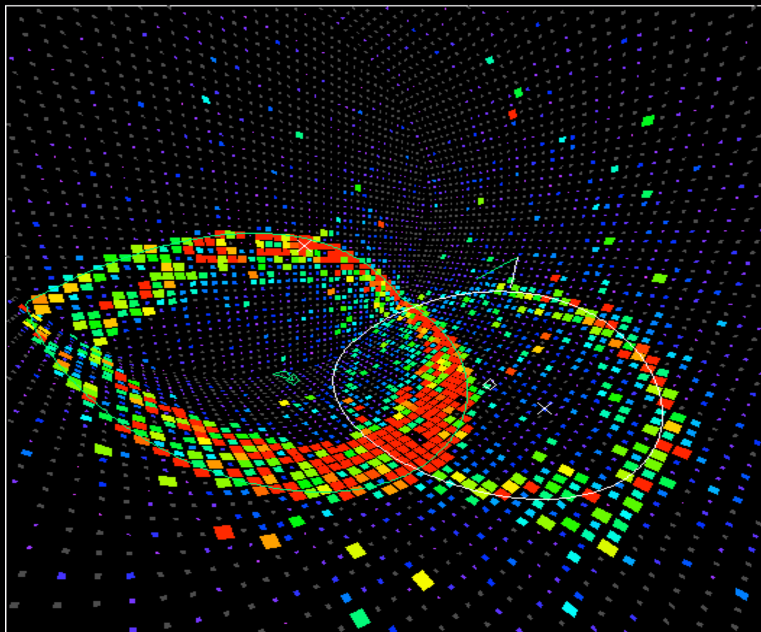


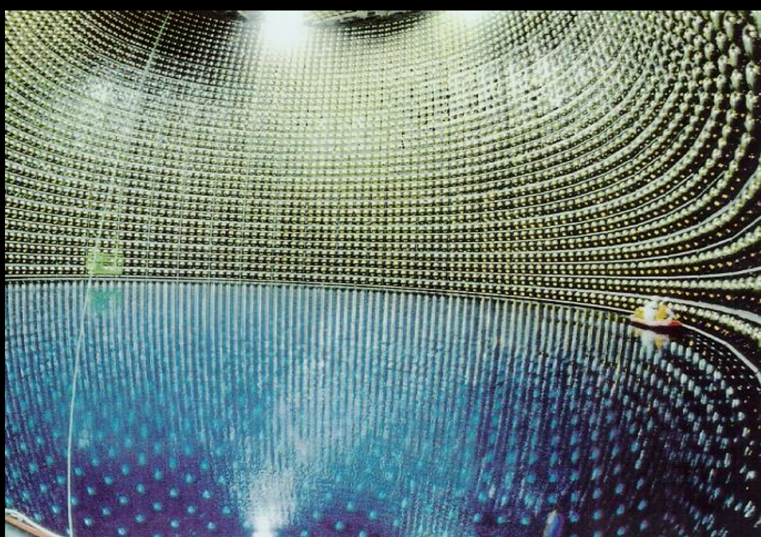


Decay channel	Preferred by	Life time limit (from Super-K)	Best technology
$p \rightarrow \pi^0 e^+$	Standard GUTs	8×10^{33} yrs	Water Cherenkov
$p \rightarrow K^+ \bar{\nu}$	SUSY/SUGRA	2×10^{33} yrs	Scintillator/LAr
others (many)		10^{33} yrs	LAr (?)

→ ***main requirement: event discrimination at ~1 GeV energy***

Detector technologies: Water-Cherenkov





Characteristics at MeV energies

- Photoelectron yield: <10 pe/MeV
  → threshold: ~5 MeV
  $\Delta E/E \approx 30\%/\sqrt{E}$
- Directionality from Cherenkov cone
- Moderate background discrimination
- Easy realization of great target masses
  → large count rates

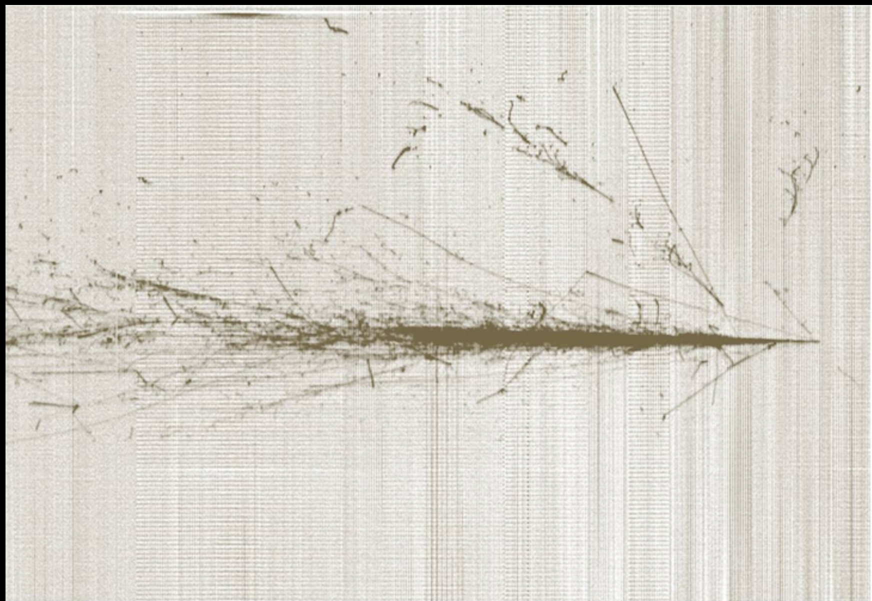
Performance at GeV energies

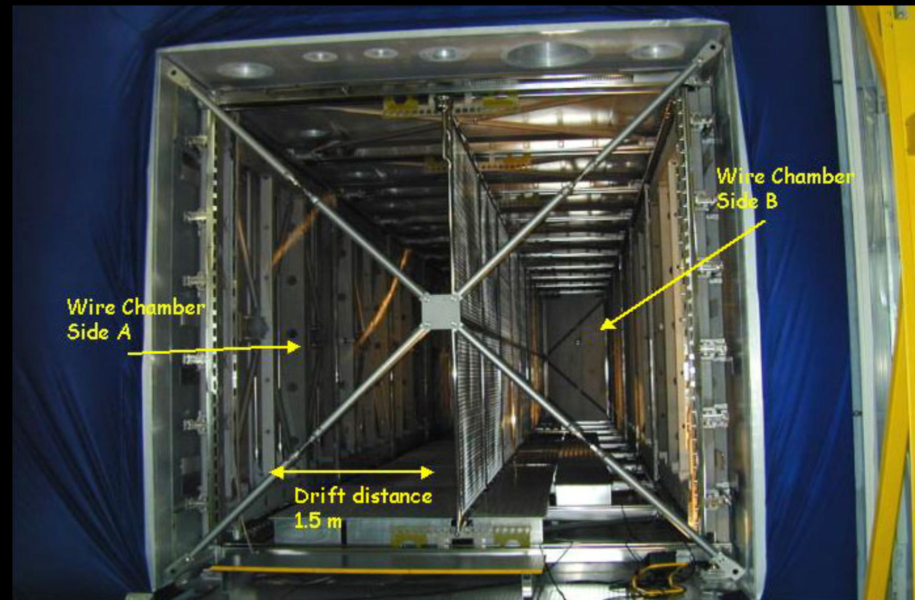
- Good vertex reconstruction for small number of particles (E_ν<1 GeV)
- Good flavor and CC/NC event separation
- Relatively coarse energy resolution: >20%

Running detectors

- Super-Kamiokande: 22.5 kt fiducial mass

Detector technologies: Liquid-Argon





Performance at GeV energies

- Superior spatial resolution
  → allows reconstruction of multi-GeV neutrino vertices
- Calorimetric measurement
  → precise energy resolution
- Very potent event ID predicted

Characteristics at MeV energies

- Potentially very interesting channels complementary to WCh and LSc
- Depends on radiopurity levels, realized energy threshold, trigger

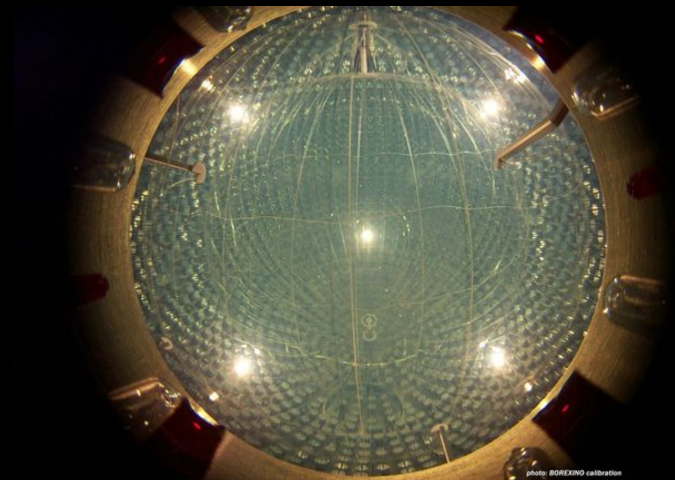
Running detectors

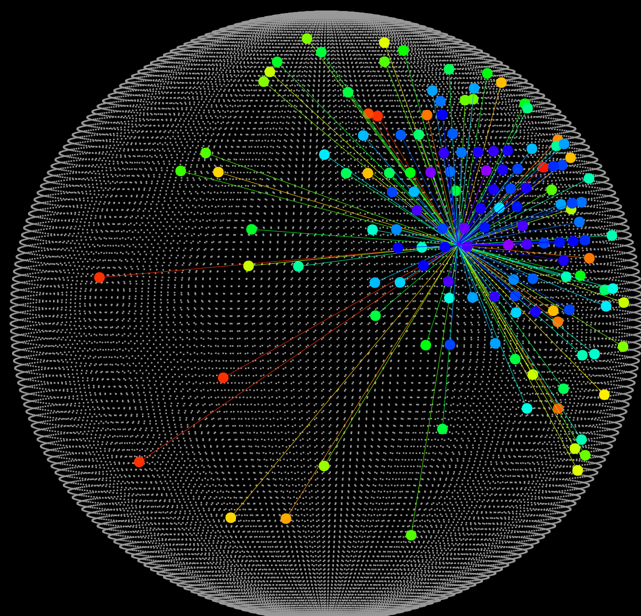
- ICARUS (600t)

Detector technologies: Liquid-Scintillator

Characteristics at MeV energies

- High photoelectron yield: 500pe/MeV
  →0.2 MeV threshold, $\Delta E/E \approx 5\%/\sqrt{E}$
- Potent background discrimination: coincidence signals, pulse shaping
- Effective techniques for radiopurification
- No directionality





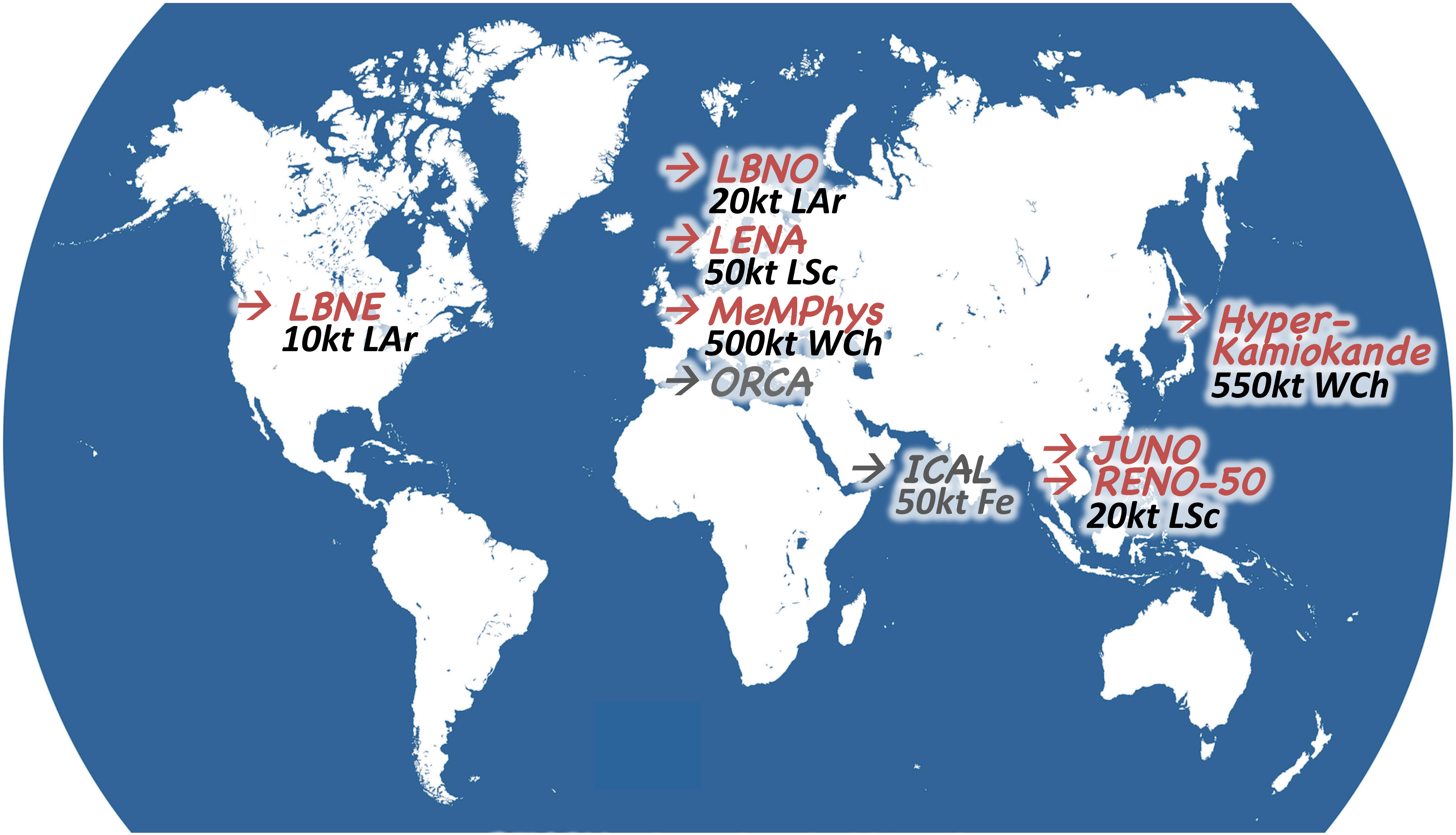
Performance at GeV energies

- Basic tracking capabilities
- Calorimetric energy measurement
  → energy resolution <10%
- Particle ID and complex event topologies: under development

Running detectors

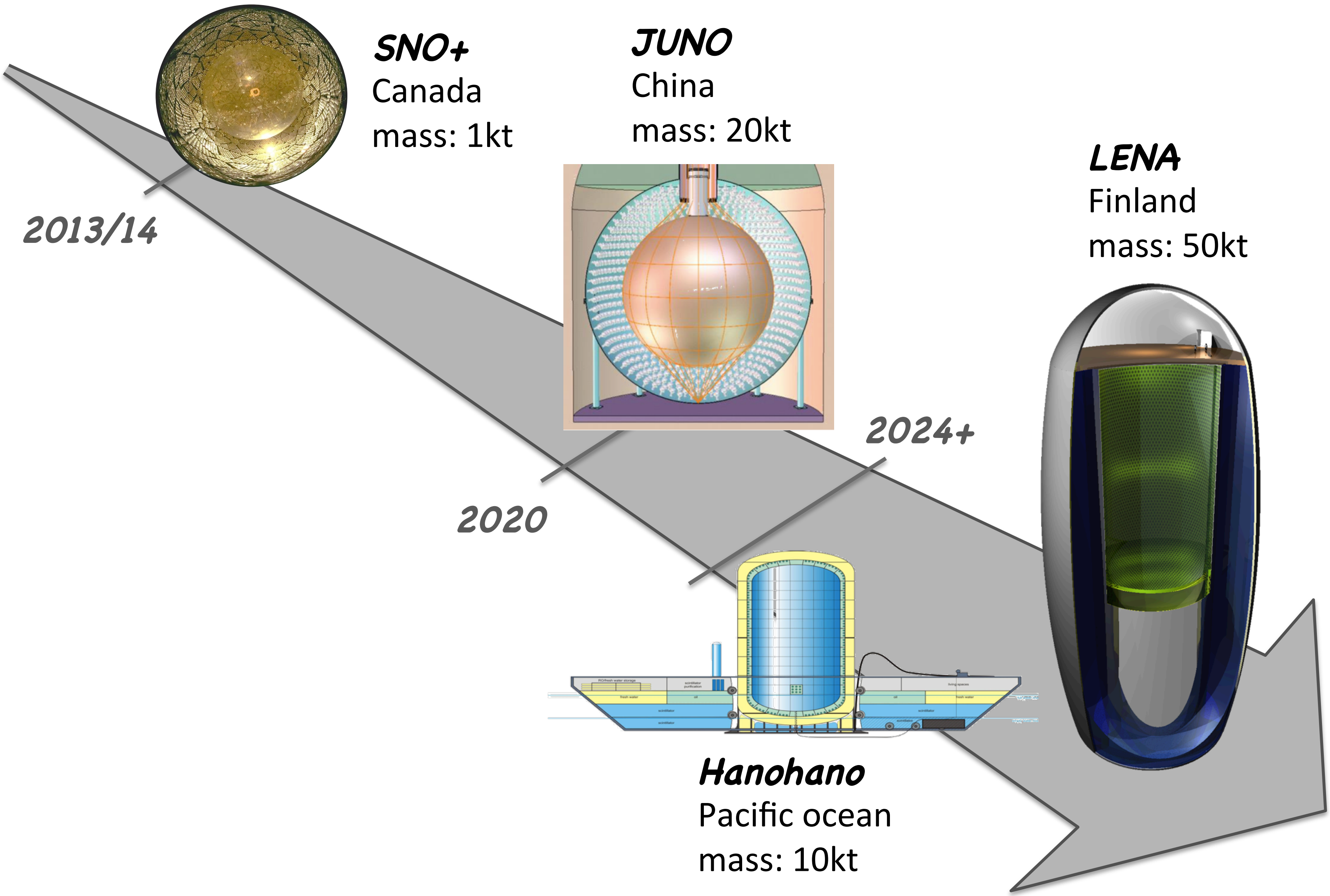
- KamLAND (1kt), Borexino (300t), SNO+

Proposed next-generation projects

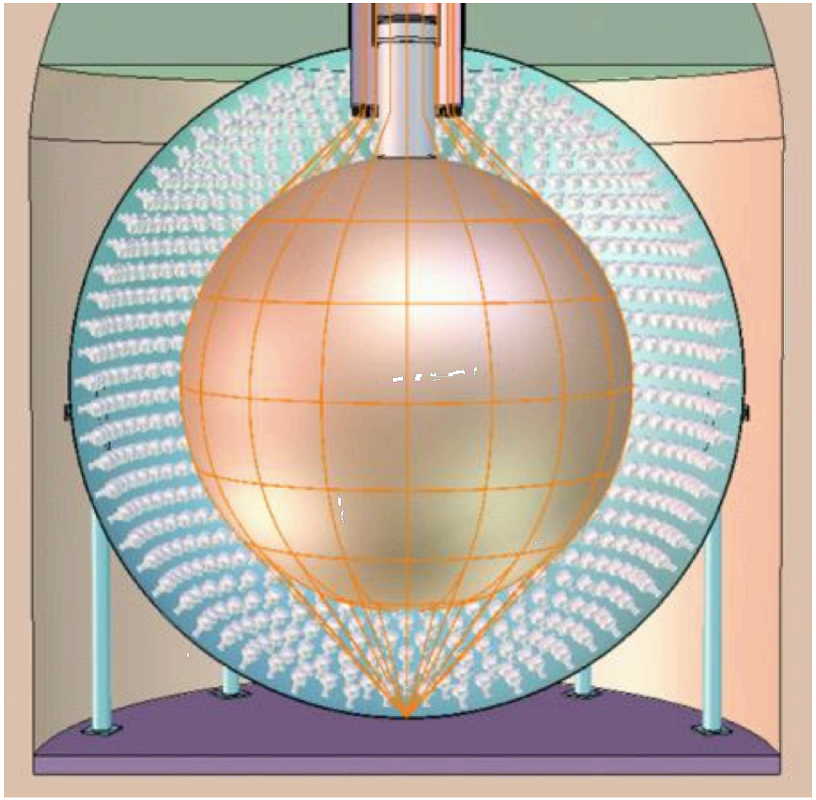


PINGU – low-threshold IceCh

Future liquid-scintillator detectors



JUNO Experiment



- Reactor antineutrino experiment
- Target mass: 20 kt (LAB)
- Energy resolution: 2-3 % @ 1MeV

Physics Program

→ **Neutrino Mass Hierarchy**

→ **Precision measurement of mixing parameters**

→ **Supernova neutrinos, DSNB**

→ Solar neutrinos

→ Geoneutrinos

→ Sterile neutrinos

→ Atmospheric neutrinos

→ Exotic searches

JUNO – Mass Hierarchy Determination

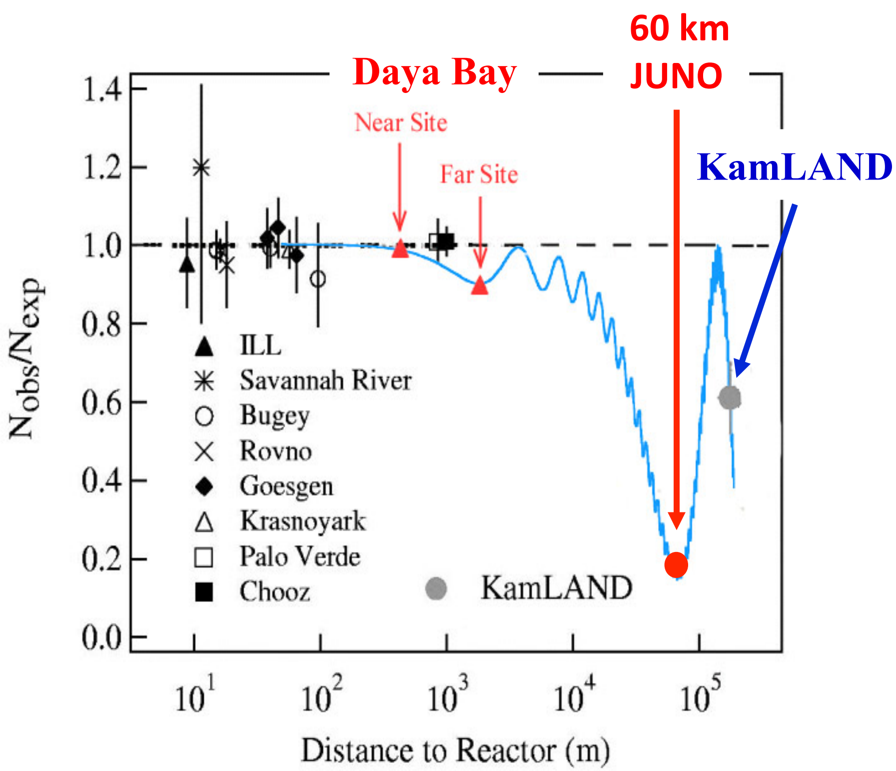
- detector at 1st solar osc. maximum
- interference of sub-dominant oscillations via Δm^2_{32} and Δm^2_{31}

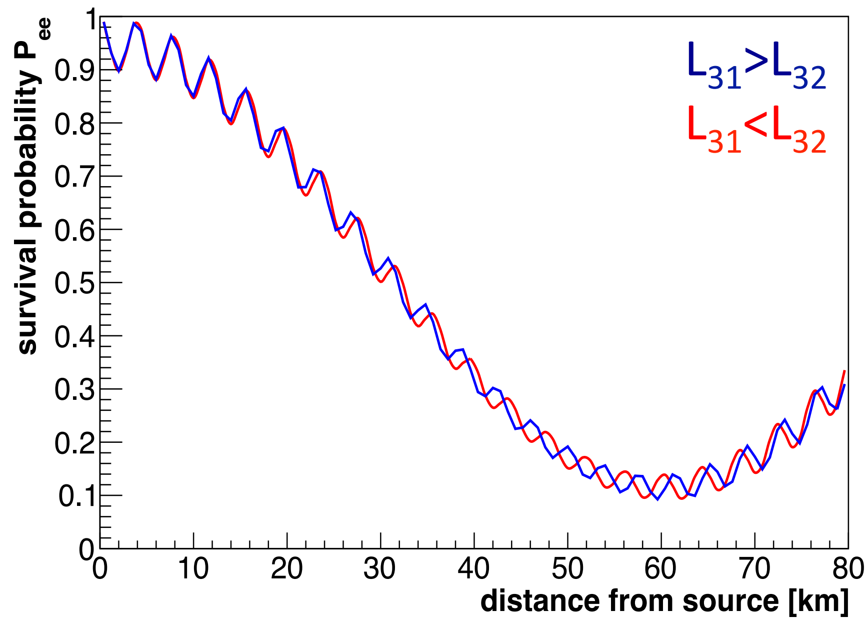
→ phase depends on MH

[S.T. Petcov et al., PLB533 (2002) 94

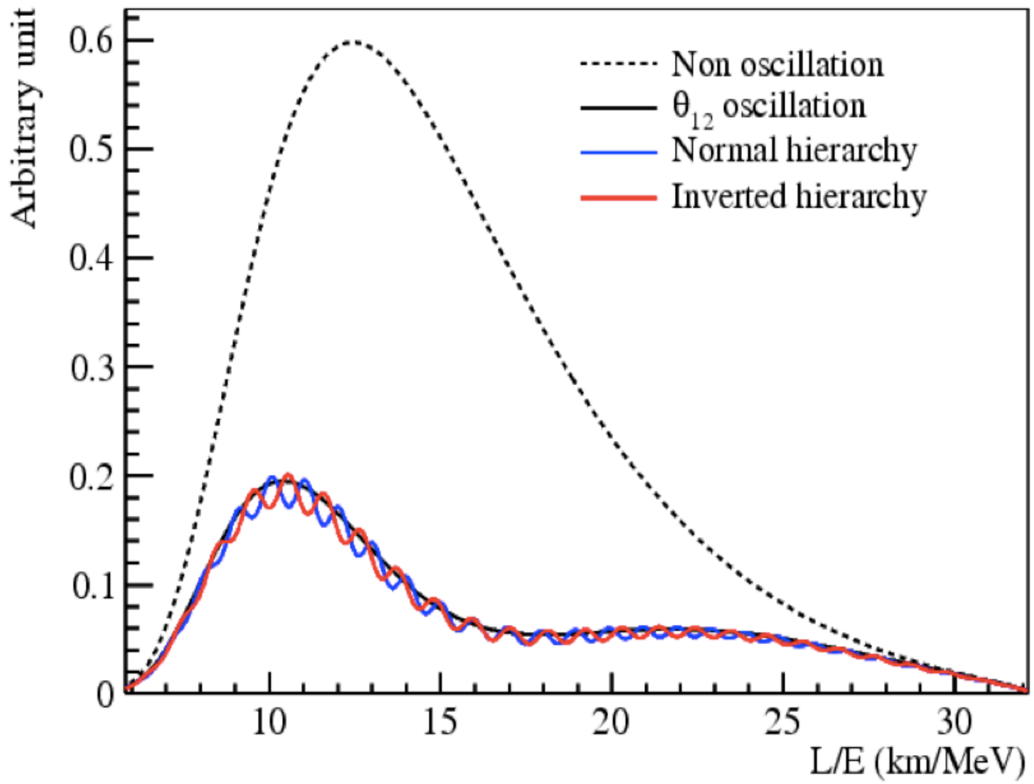
Survival probability

$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$
$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$





JUNO – Signature of Mass Hierarchy



- subdominant effect → large statistics
- separation of wiggles → excellent energy resolution
- reactor neutrino energies (<8MeV) → low threshold

} liquid scintillator detector (20kt)

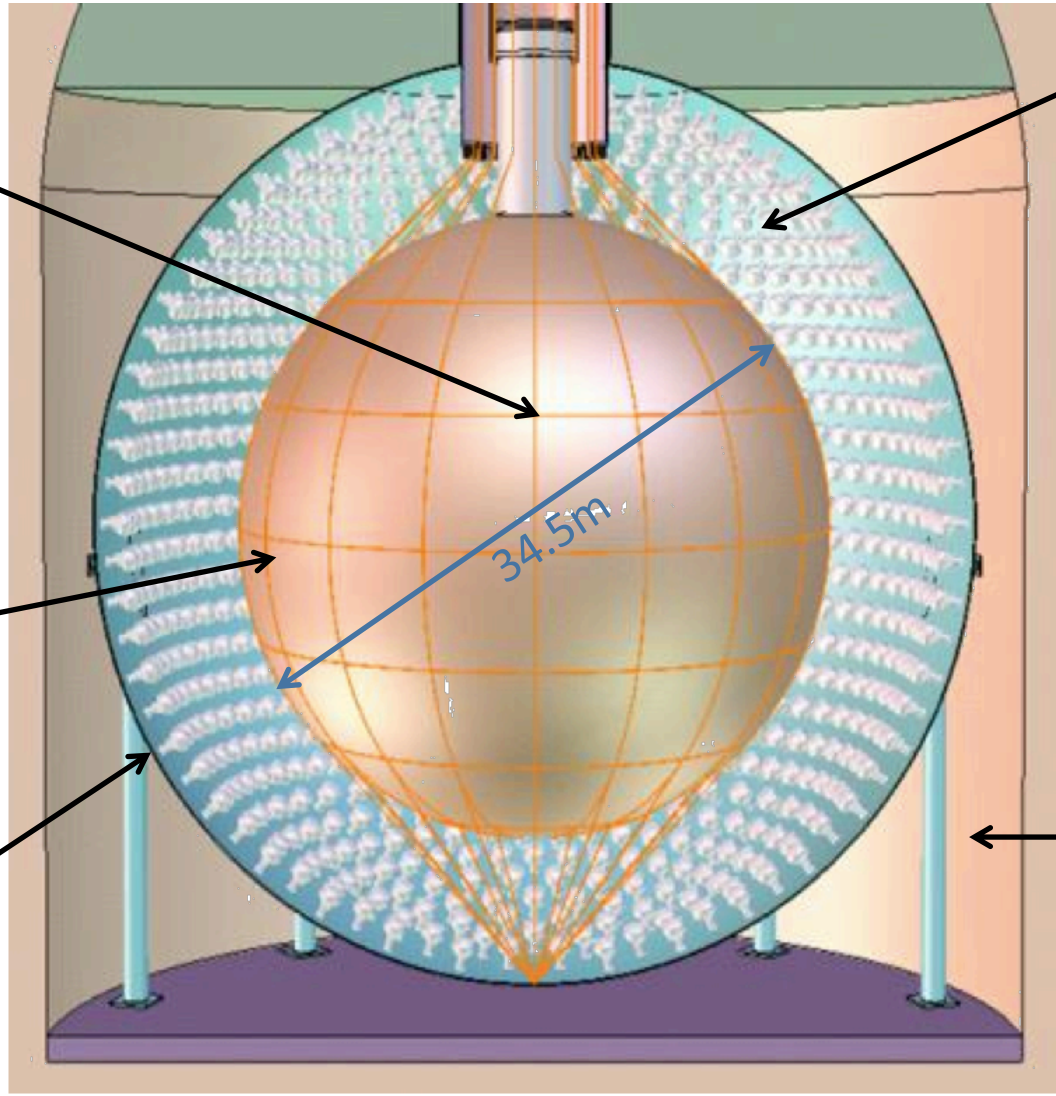
JUNO – Detector Layout

Scintillator target:
20kt LAB
λ≈30m

→excellent light yield & transparency

Vessel:
acrylic
or nylon

Steel tank
+ inactive
buffer

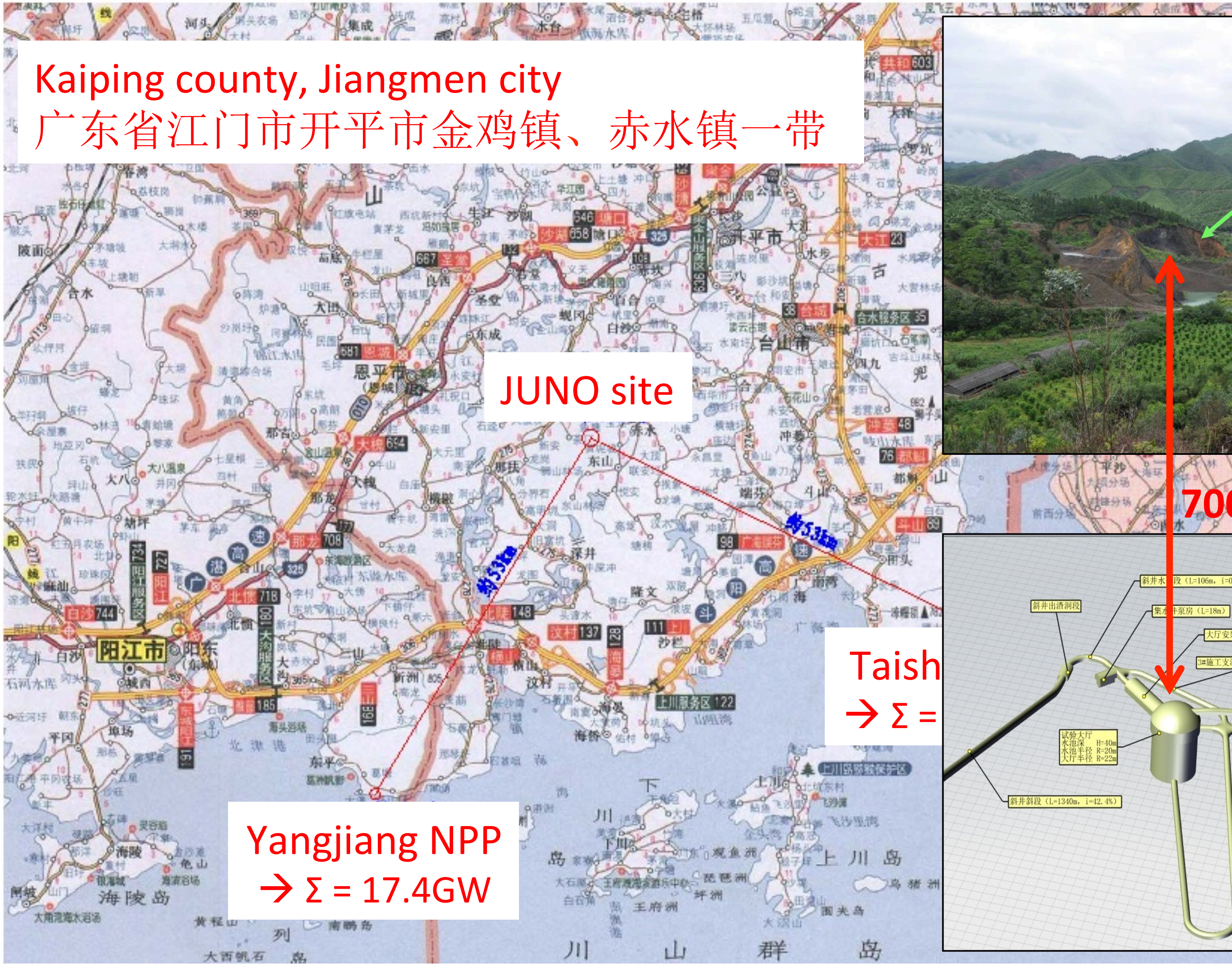


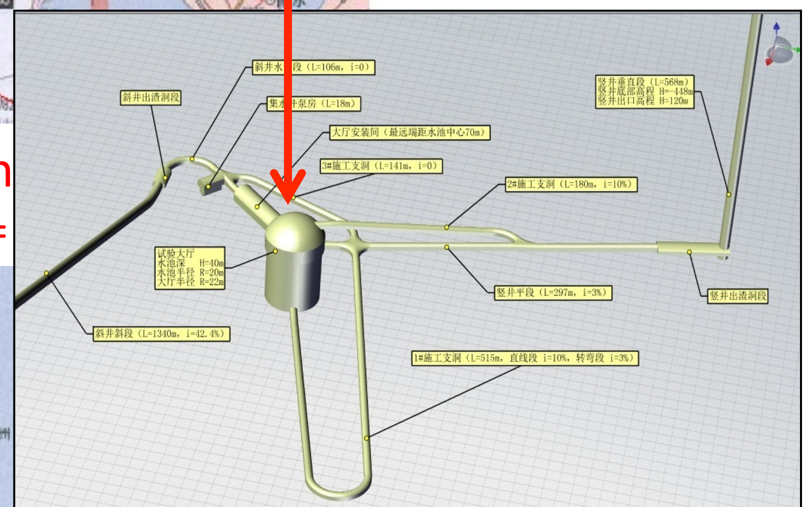
Photosensors:
~15k 20'' PMTs
80% coverage

→ high light collection efficiency

20kt water
Cherenkov
muon veto

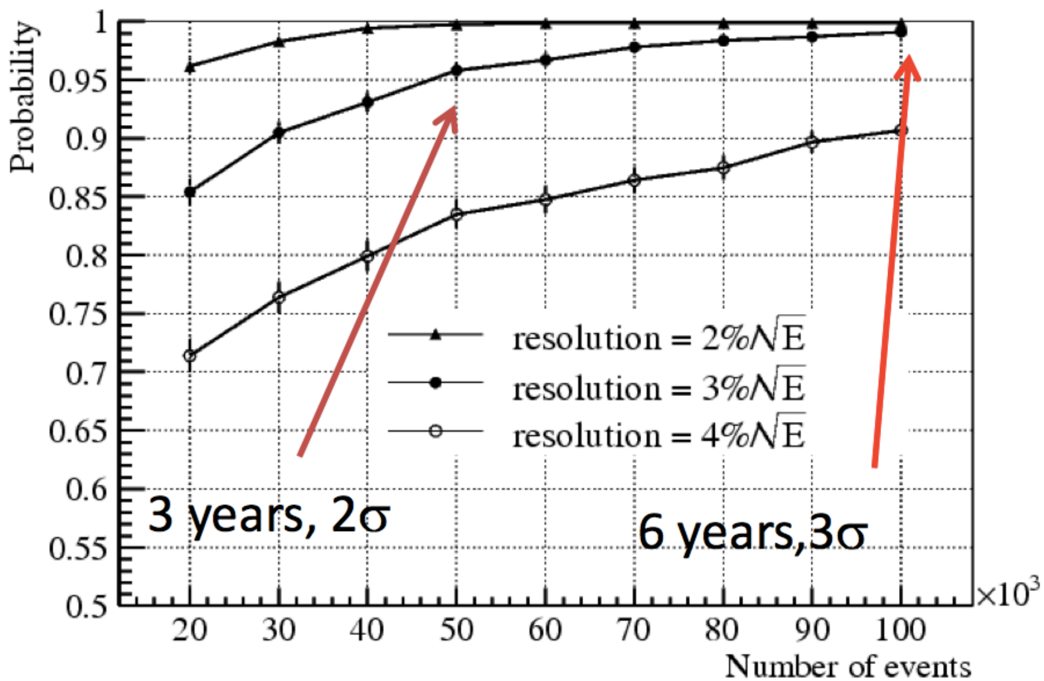
JUNO – Site and baselines





JUNO – Sensitivity for mass hierarchy

- In this analysis: Fourier transform of the spectrum
- Most important parameters:
  Energy resolution and energy-scale **linearity**



in default setup:

- Reactor power: 34 GW
- Baseline: 58 km
- ΔE/E = 3% @ 1MeV

→ **MH at 3σ after 6 yrs**

Alternative: Long-Baseline Oscillations

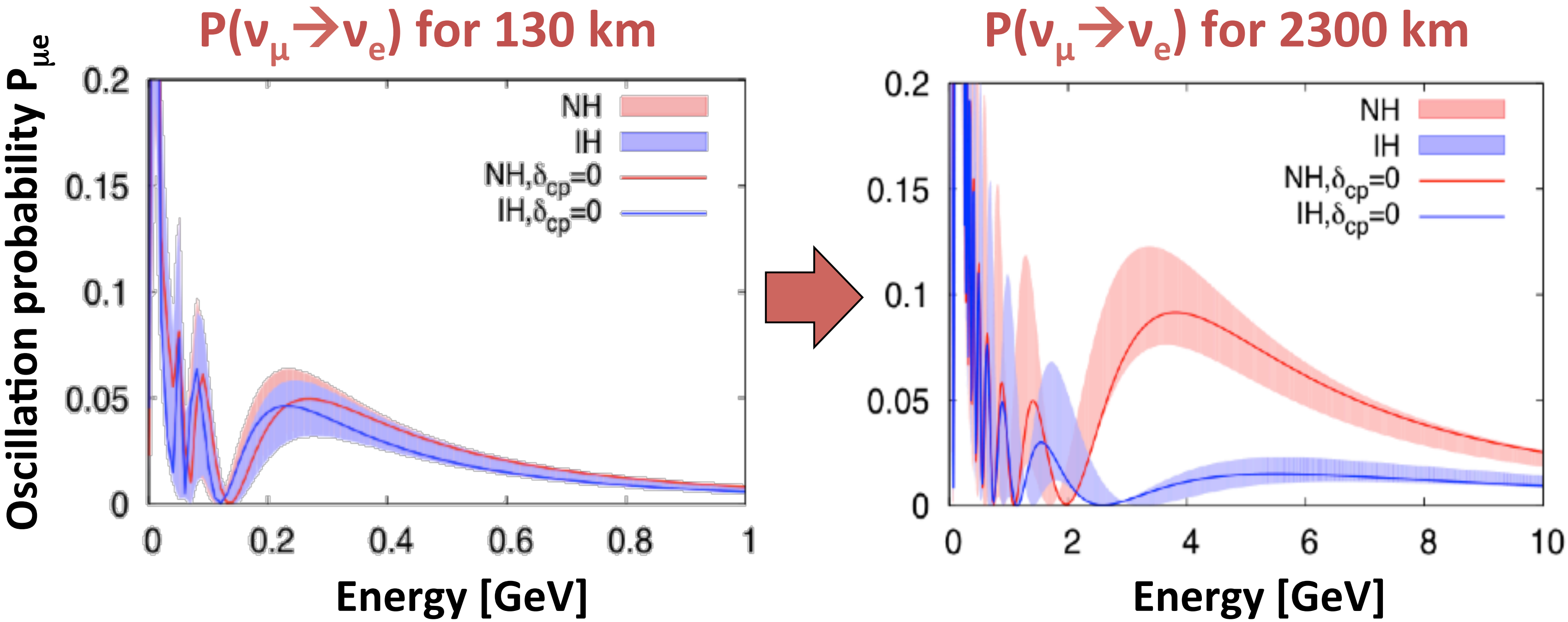
- Sensitivity based on matter effects changing oscillation probabilities at first oscillation maximum (atmospheric Δm^2)

  Normal hierarchy → Amplitude increases for neutrinos

  Inverted hierarchy → Amplitude increases for antineutrinos

Alternative: Long-Baseline Oscillations

- Sensitivity based on matter effects changing oscillation probabilities at first oscillation maximum (atmospheric Δm^2)
- Size of effect increases with neutrino energy/baseline length



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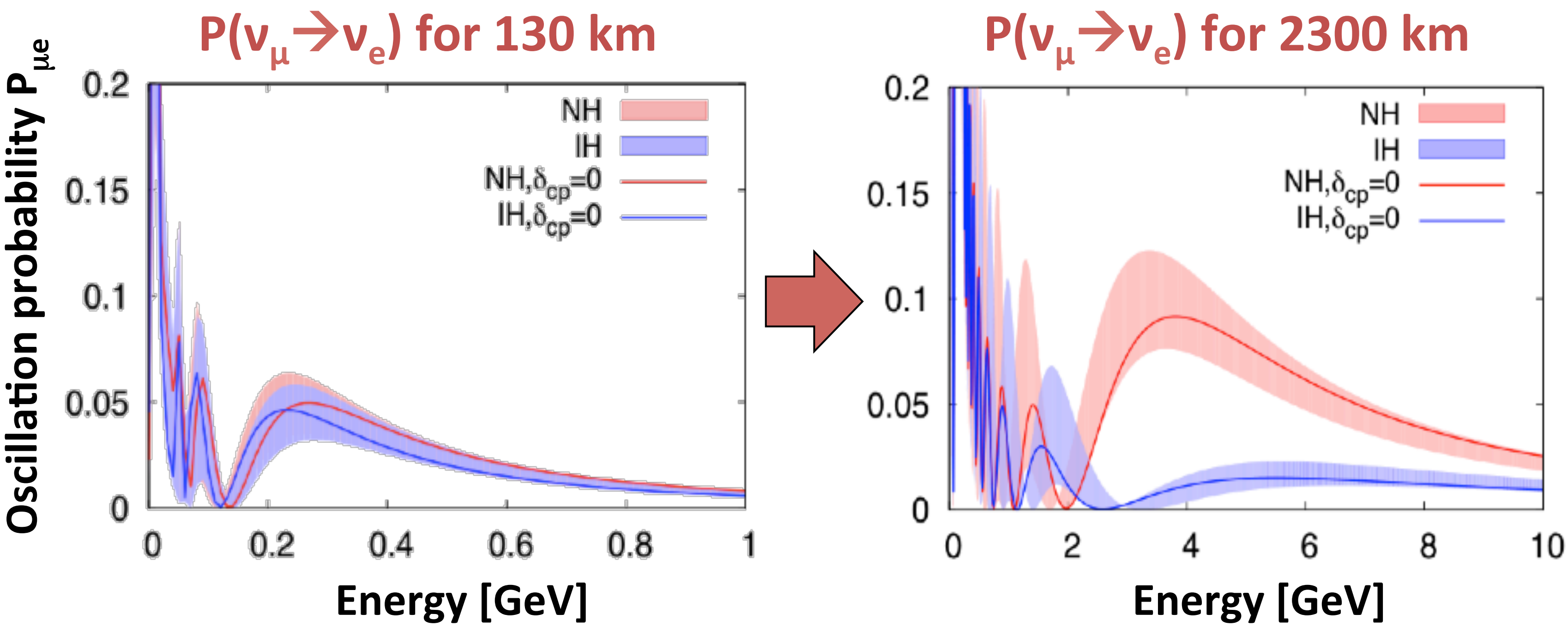
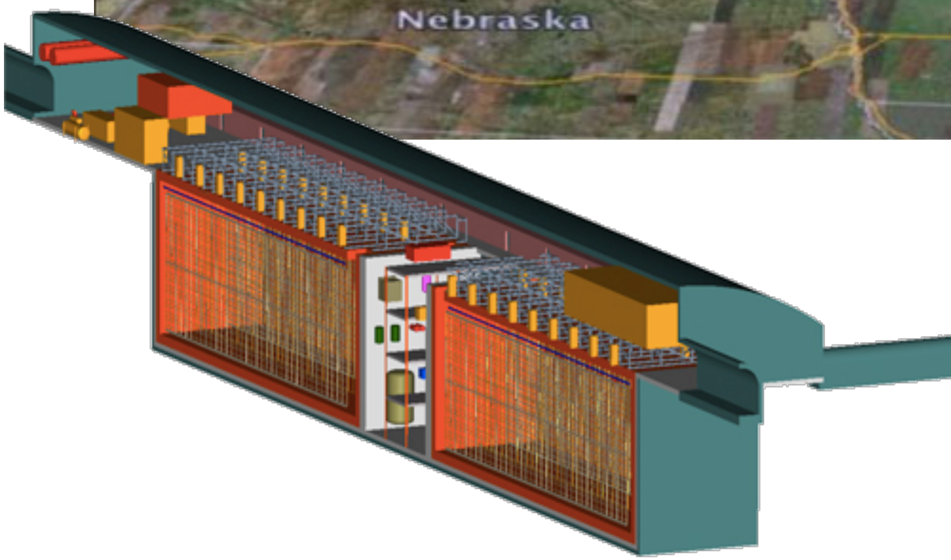


→ multi-GeV neutrino beams with baseline of $>10^3$ km
→ atmospheric neutrinos (baselines from 20 – 10^4 km)

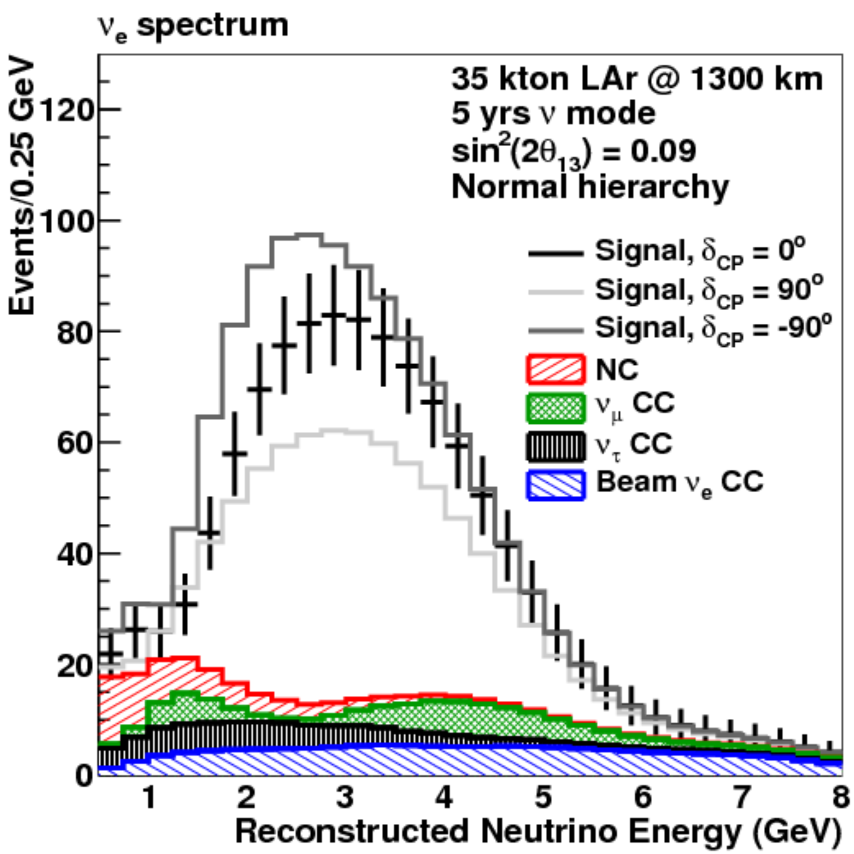
Long Baseline Neutrino Experiment LBNE (US)



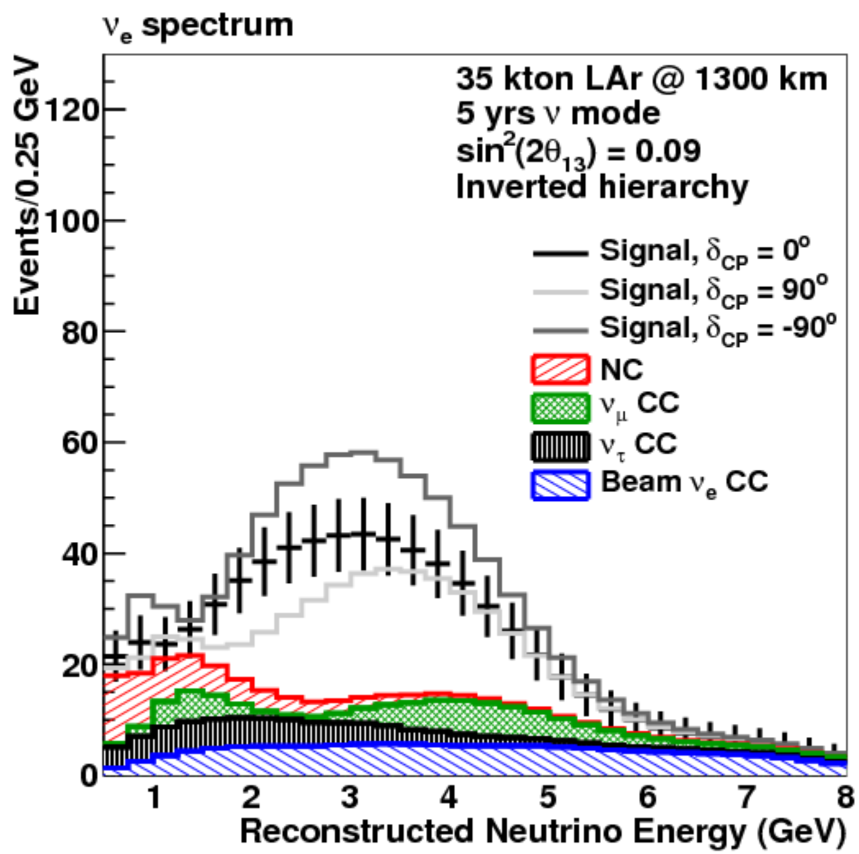
- Oscillation baseline: 1300 km Fermilab → Homestake mine
- Far Detector: Liquid Argon TPC target mass of 10kt→35kt

LBNE: $\nu_\mu \rightarrow \nu_e$ Appearance Signal

normal hierarchy



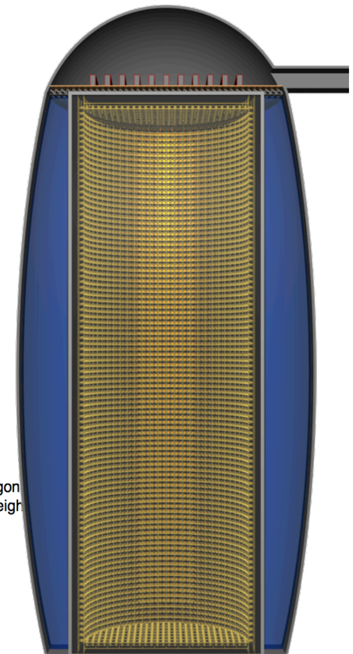
inverted hierarchy



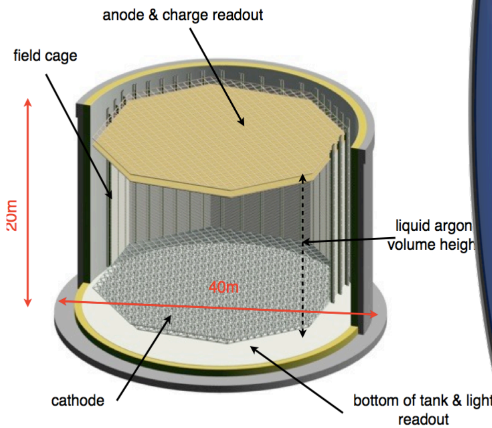
→ **MH discrimination at ~4σ significance (configuration/δ_{CP})**

European LAGUNA-LBNO Design Study

LENA →

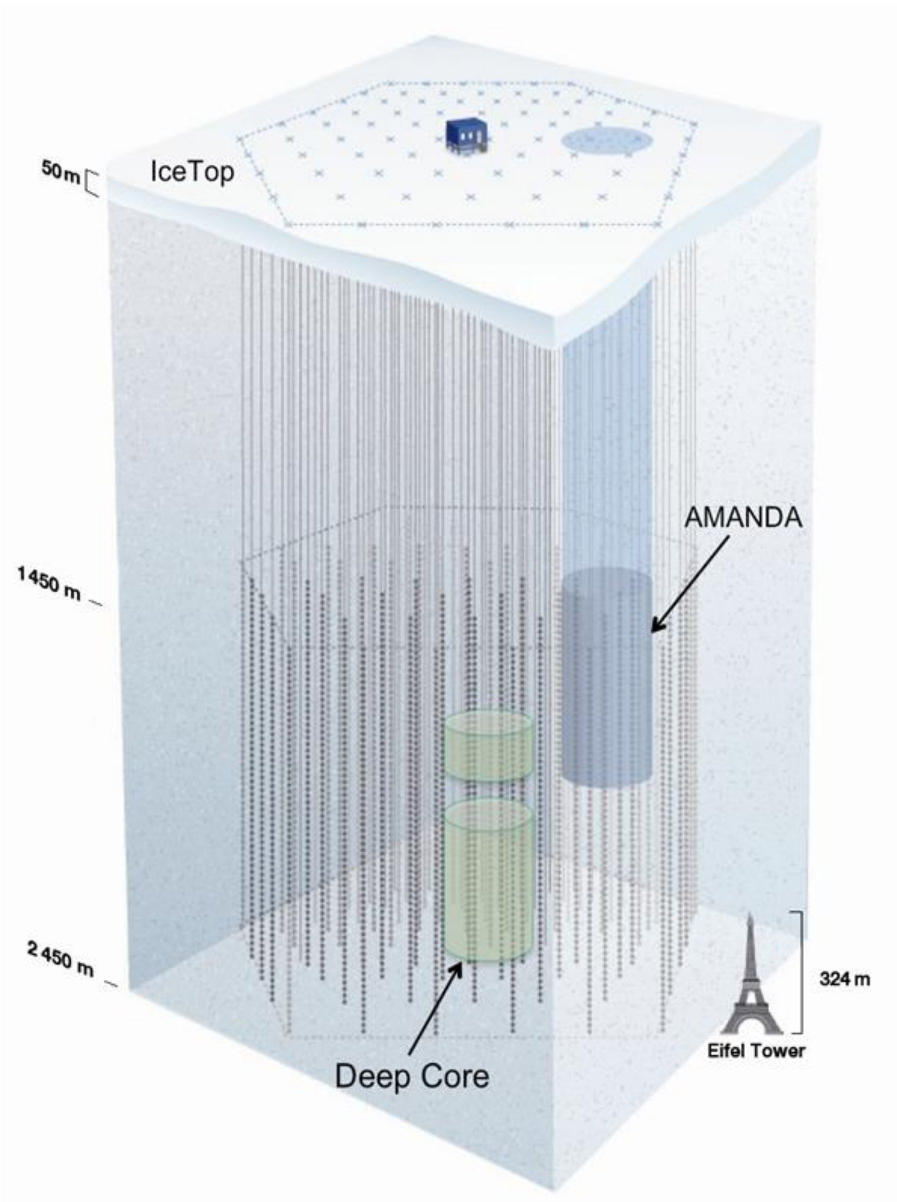


↓ LBNO



- Oscillation baseline: 2300 km
  CERN → Pyhäsalmi mine
- **Expected sensitivity:**
  Liquid Argon TPC (20kt): >5σ
  Liquid Scintillator (50kt): (3-5)σ

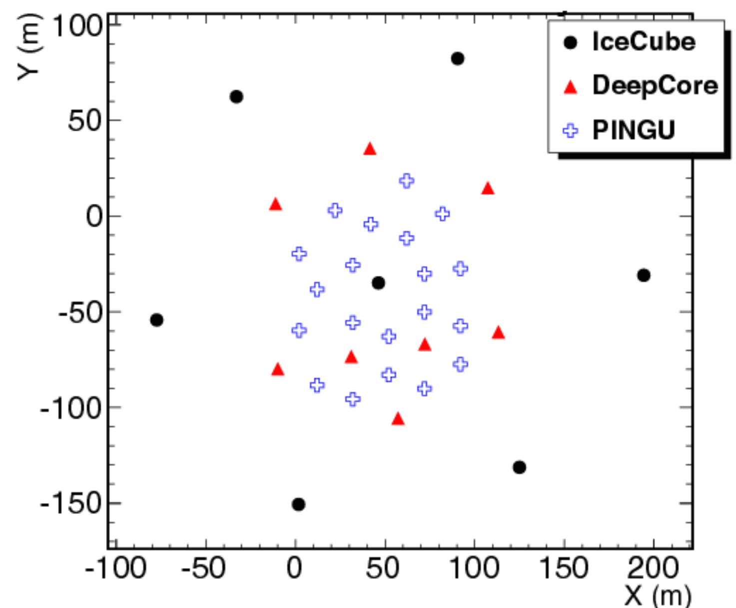
PINGU – Atmospheric Neutrinos



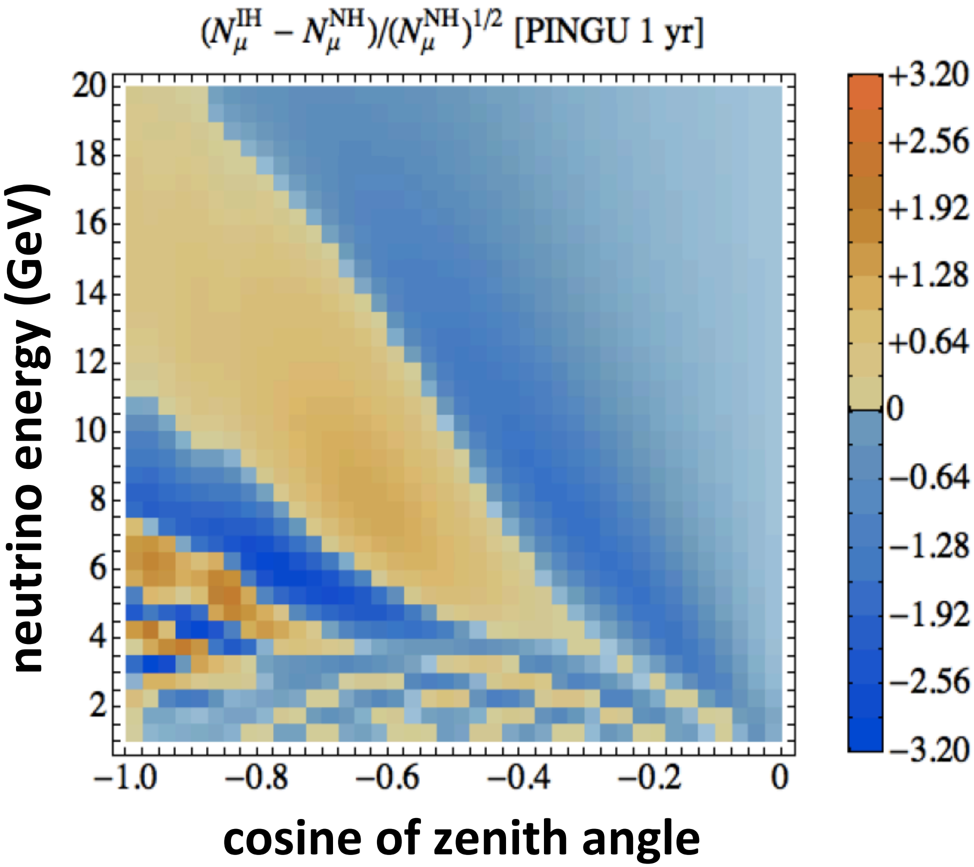
low statistics
→ *large detector (✓)*

oscillation at low energy
→ *low threshold (1GeV)*

Low-Energy Extension
20 extra strings inserted into DeepCore array



MH Imprint on Atmospheric ν Oscillations



significance of deviation = *(expected event number IH – NH)* / *(expected event number NH)½*

Oscillation mode

→ $\nu_\mu/\bar{\nu}_\mu$ disappearance

Influence of Hierarchy

→ matter effect affects either ν or $\bar{\nu}$ sector

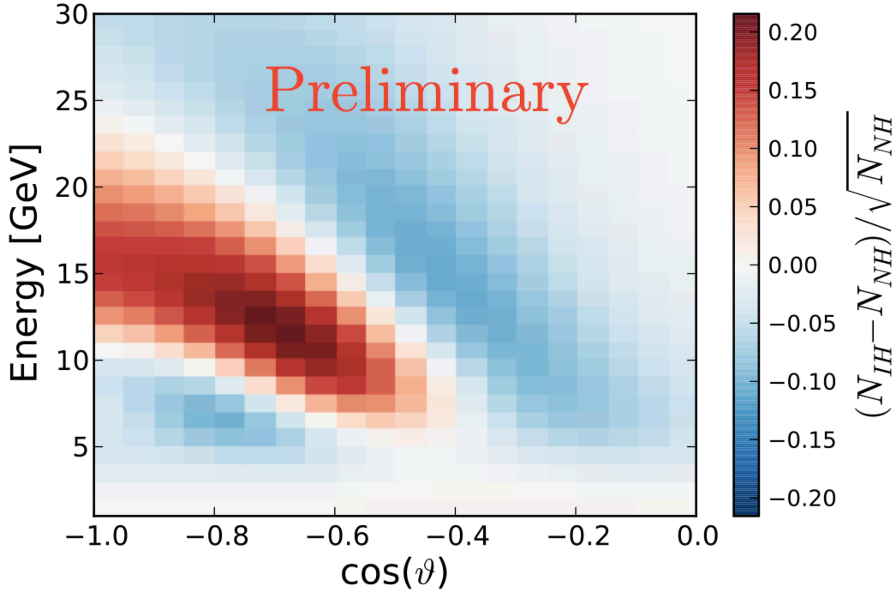
Detectors

→ only detect sum of $\nu_\mu+\bar{\nu}_\mu$

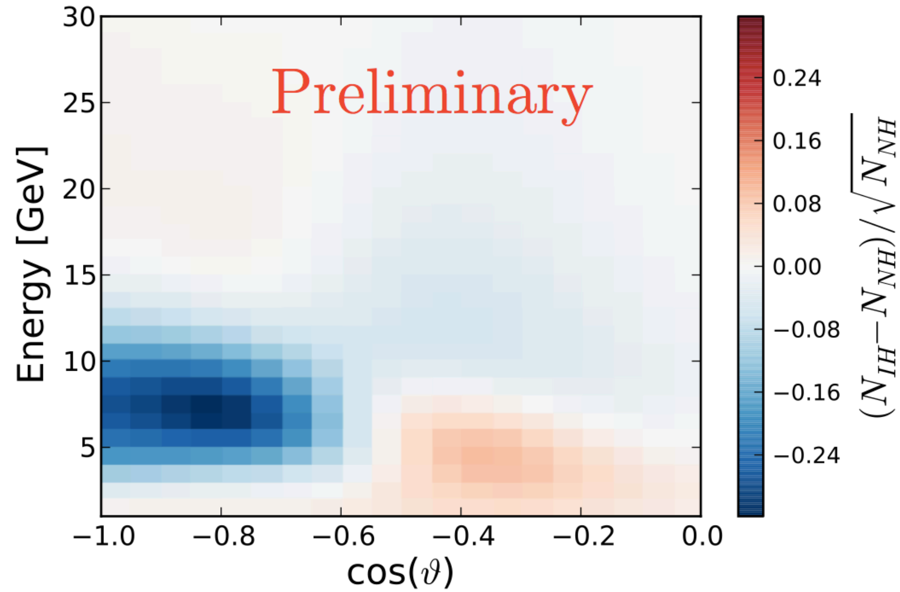
→ but difference in cross-sections $\frac{\sigma(\nu_\mu)}{\sigma(\bar{\nu}_\mu)} \approx 2$

PINGU – Signal and Sensitivity

track-like events (ν_μ)



shower-like events ($\nu_{e,\tau}$)

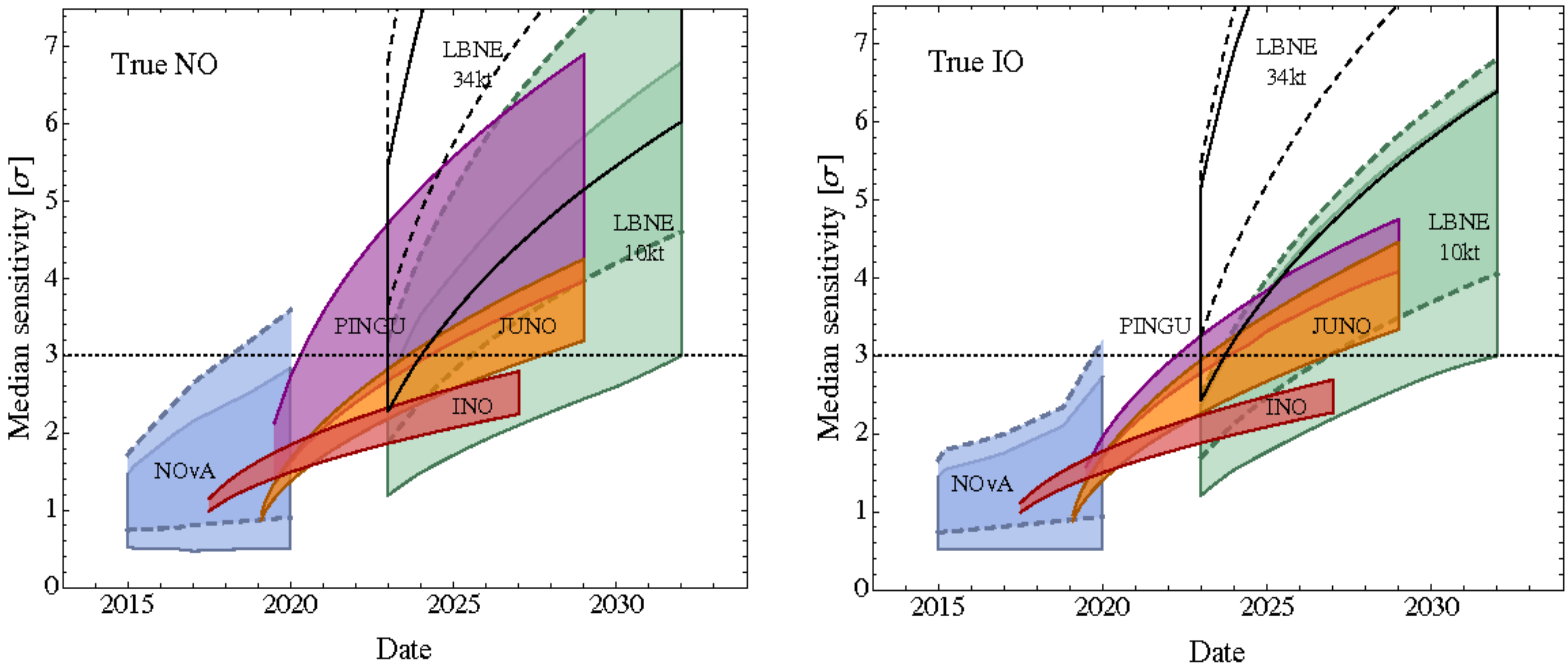


Mass hierarchy sensitivity

- original paper by Akhmedov et al. (3-10)σ
- PINGU letter of intent 3.5σ after 3yrs

Projected Sensitivity for Mass Hierarchy

[M. Blennow et al., 1311.1822]



Sensitivity depends mainly on:

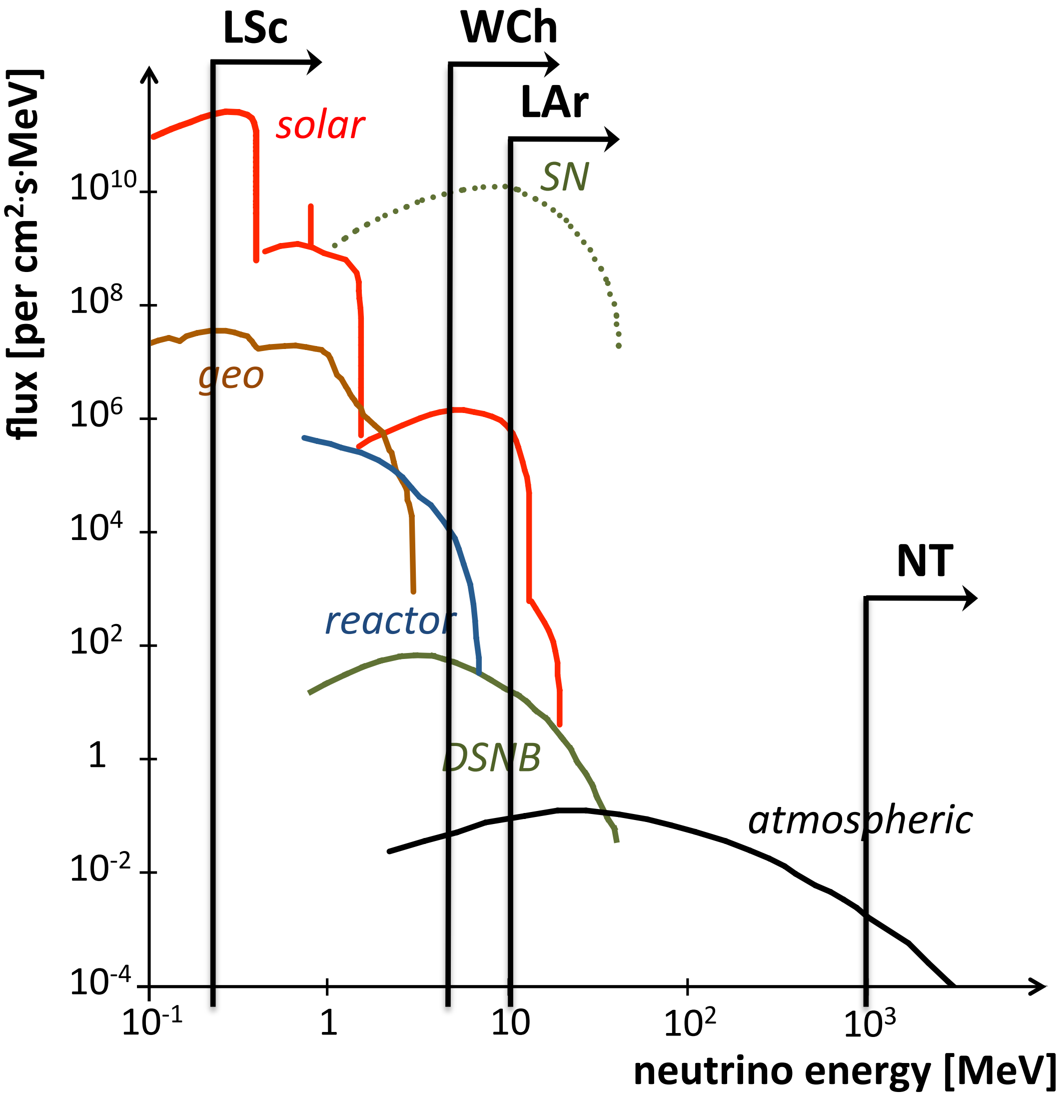
- **JUNO:** Energy resolution (3.5 – 3 %)
- **PINGU, INO:** True value of θ_{32}
- **NOvA, LBNE:** True value of δ_{CP}

Precision Measurement of Mixing Parameters

- Fundamental to the standard model and beyond
- Probing the **unitarity of U_{PMNS}** to ~1% level!

Parameter	Current	Projected	Experiment
Δm^2_{21}	**3%**	**0.6%**	**JUNO**
Δm^2_{31}	**5%**	**0.6%**	**JUNO**
$\sin^2\theta_{12}$	**6%**	**0.7%**	**JUNO**
$\sin^2\theta_{23}$	20%	2.5-10%	PINGU
$\sin^2\theta_{13}$	14%	5%	Daya Bay
δ_{CP}	–	≠0 (3σ?)	LBL

Large Detectors as Neutrino Observatories



- **Neutrino telescopes**
  access to integral signal of a galactic Supernova
- **Liquid Argon**
  sensitive to SN/DSNB (?)
  threshold/target mass
- **Water Cherenkov**
  DSNB – Gd-doping?
  threshold depends on mass, optical coverage
- **Liquid Scintillator**
  solar & geoneutrinos
  threshold depends on radiopurity & cosmics

LENA Experiment

- Observatory for “natural“ neutrinos
- Target: 50 kt of liquid-scintillator
- Optimized for low-background levels: radiopurity + rock shielding

Focus on neutrino observation

→ **Supernova neutrinos**

→ **Diffuse SN neutrino background**

→ **Solar neutrinos**

→ **Geoneutrinos**

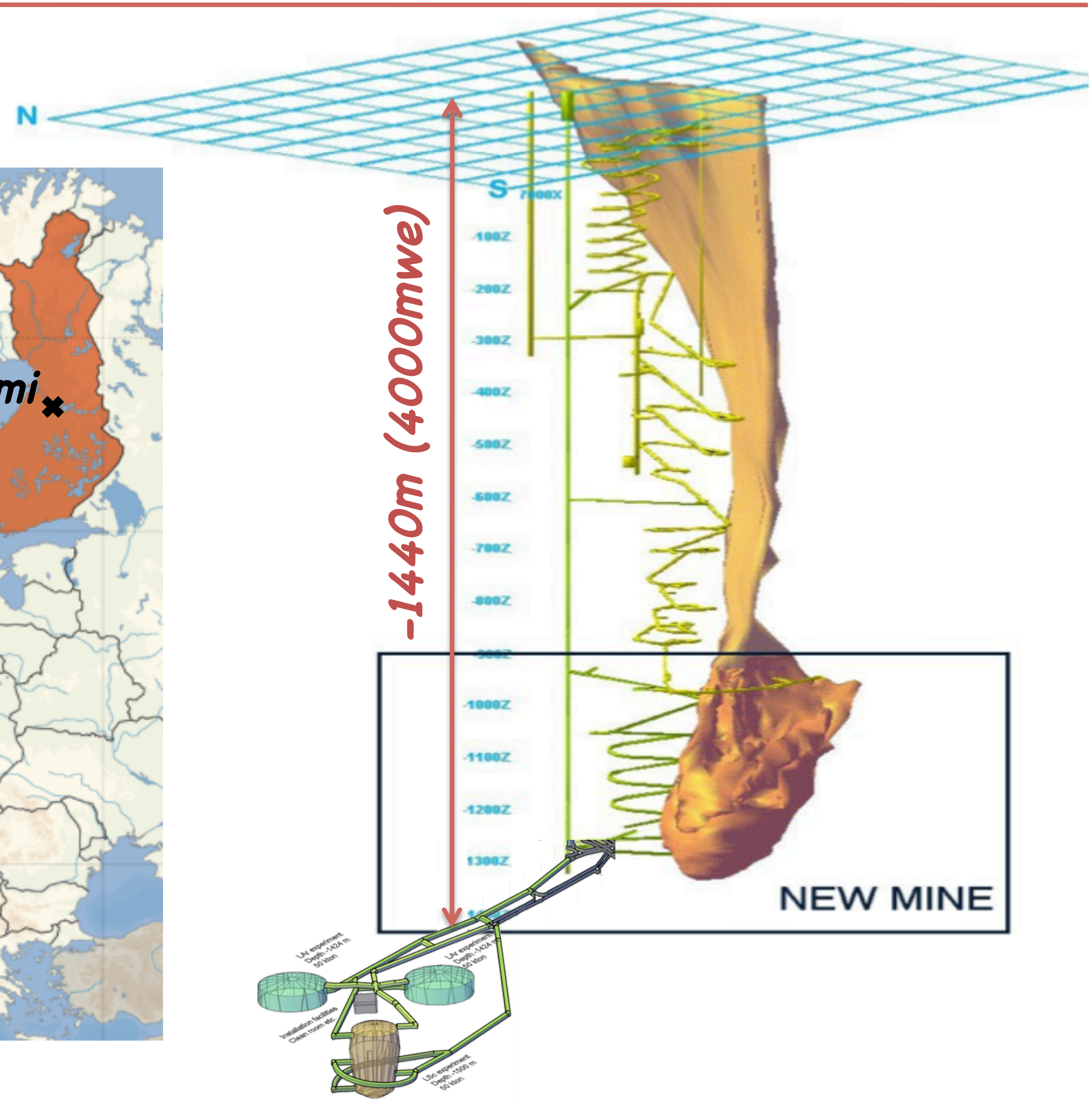
But also particle physics

→ Neutrino oscillations (MH, δ_{CP})

→ Non-standard searches (NSI, ν_s)

→ **Proton decay**

LENA at the Pyhäsalmi mine (Finland)



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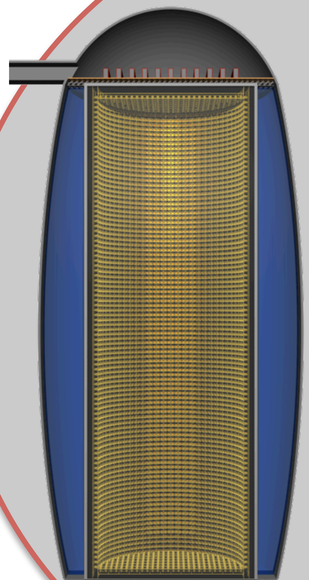
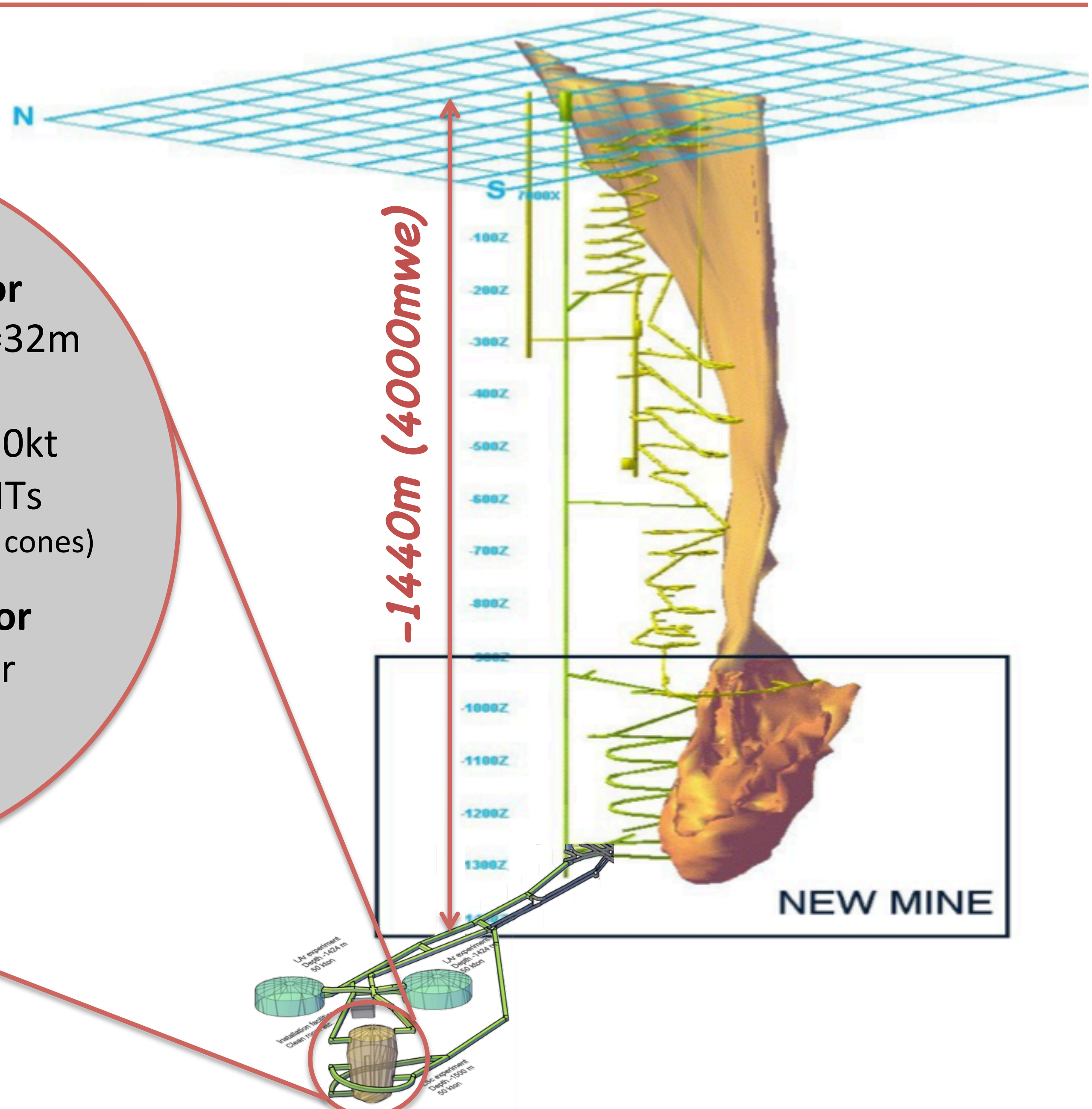


Inner Detector

- h=100m, d=32m
- 70kt of LS
- active vol. 50kt
- 32k 12''-PMTs
  (encapsulated, cones)

Outer Detector

- 100 kt water
- 2k PMTs



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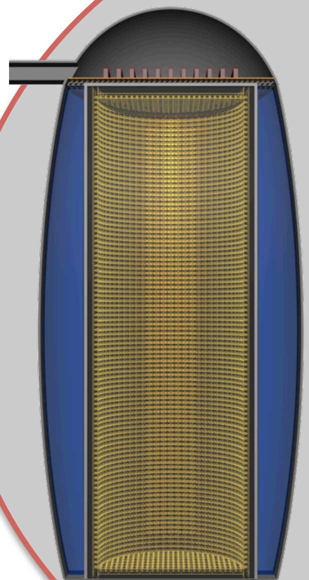

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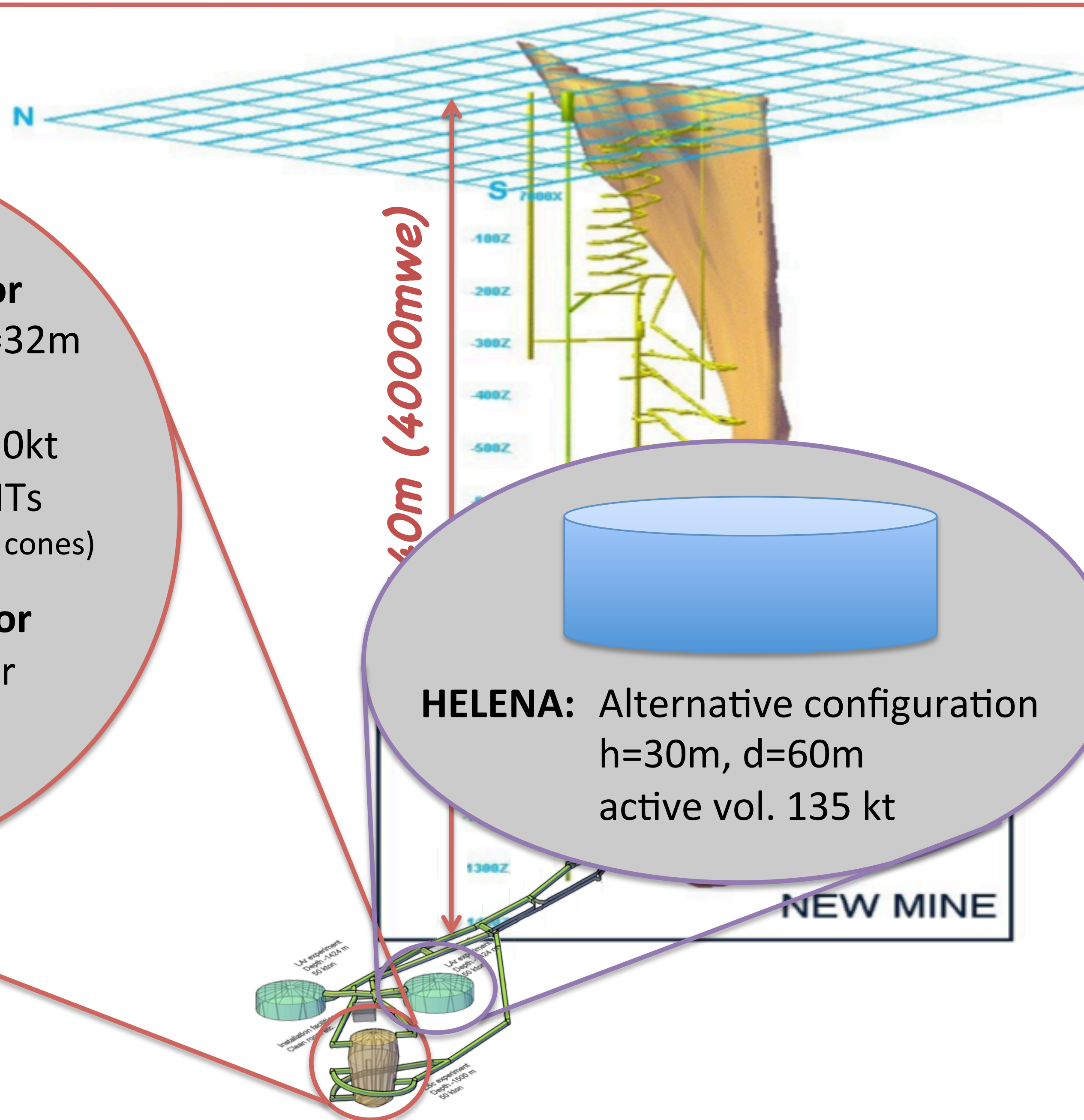
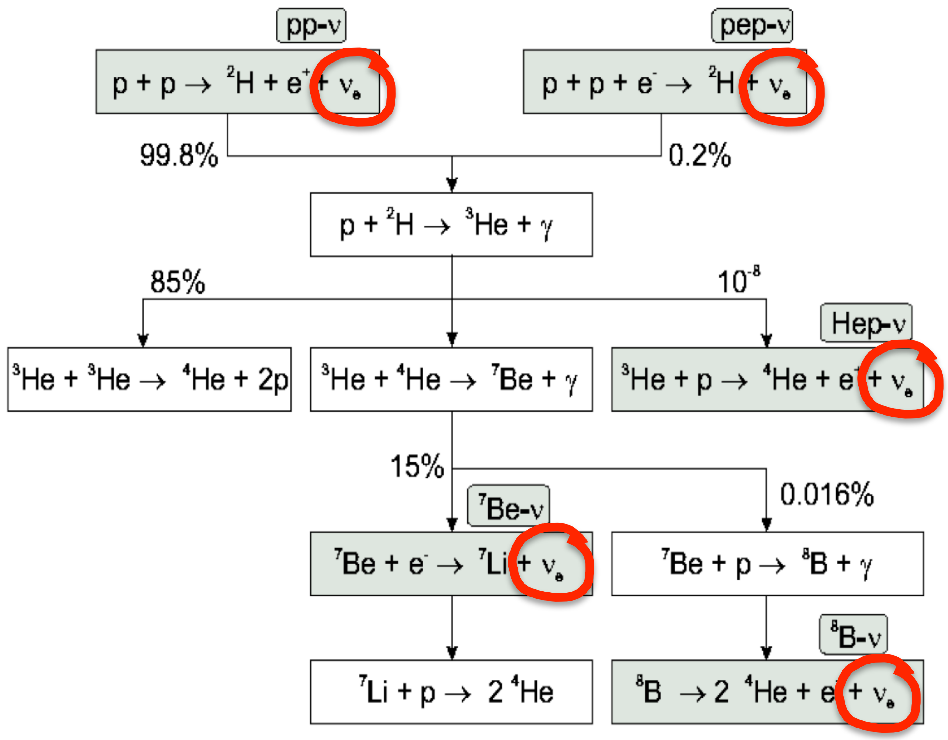


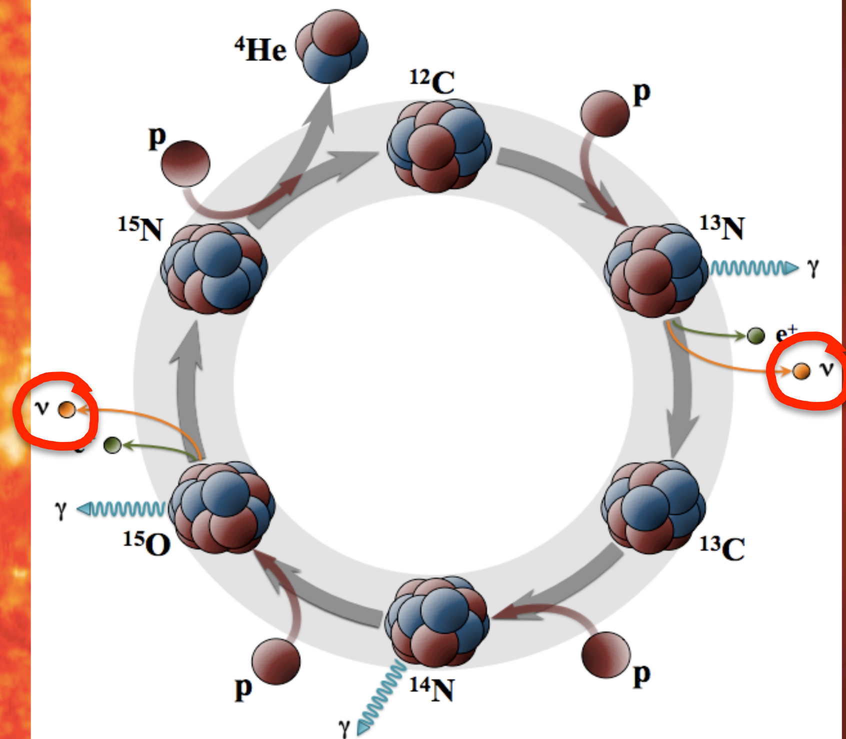
HELENA: Alternative configuration
h=30m, d=60m
active vol. 135 kt

Thermonuclear fusion in the sun

pp chain *→ ~99% of released energy*



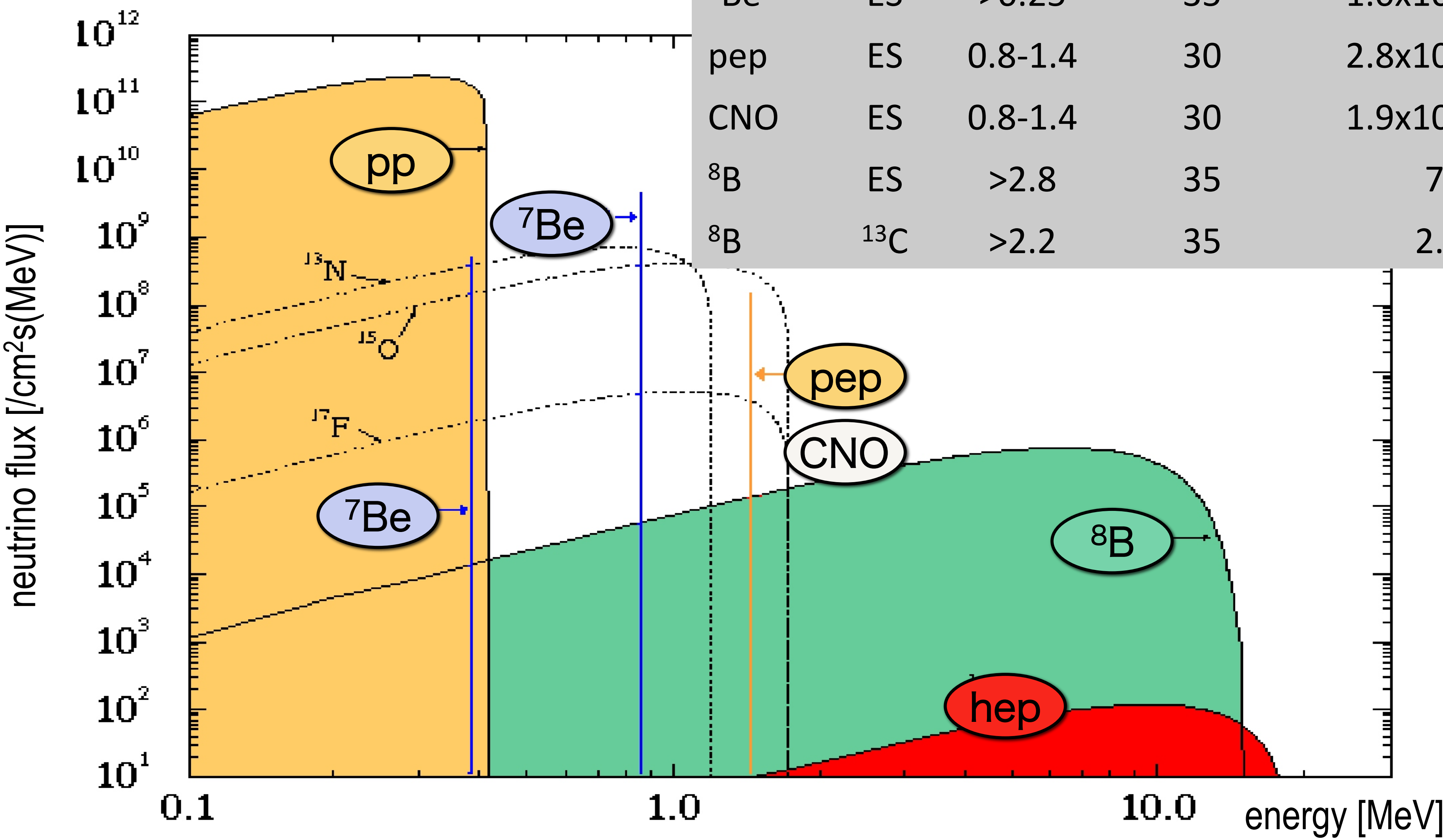
~1% (?) ← ***CNO cycle***



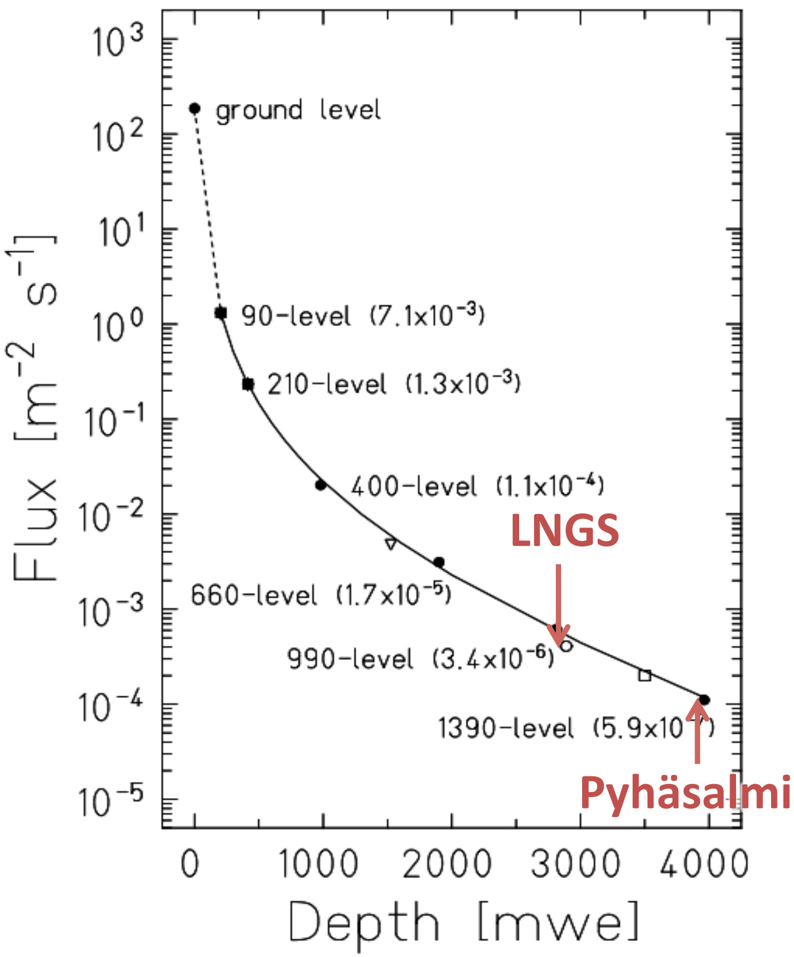
Solar neutrino signal in LENA

Expected rates for LENA:

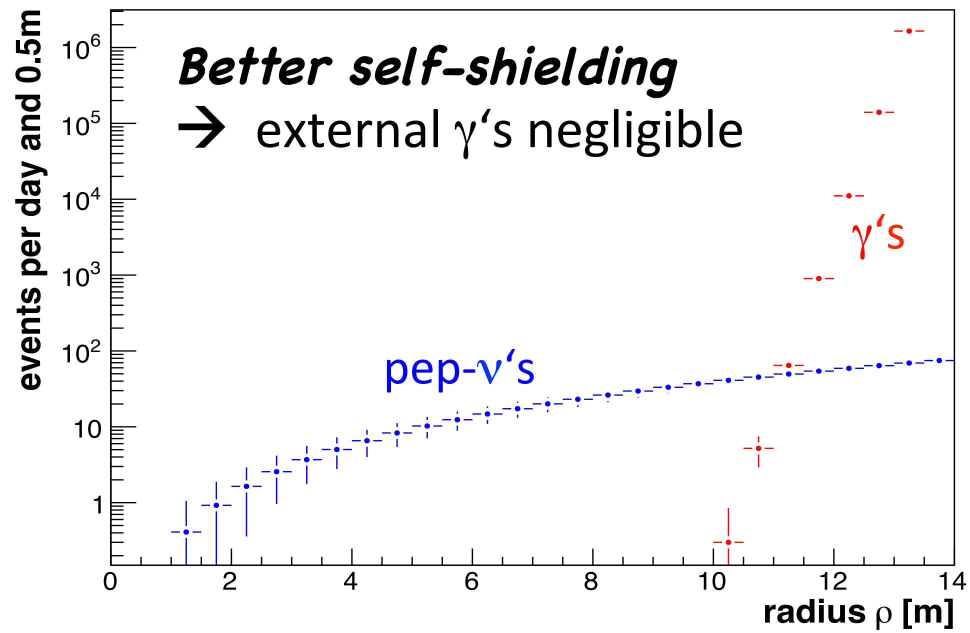
Source	Ch	E (MeV)	M_{fid} (kt)	Rate (d^{-1})
^{7}Be	ES	>0.25	35	$1.0x10^{4}$
pep	ES	0.8-1.4	30	$2.8x10^{2}$
CNO	ES	0.8-1.4	30	$1.9x10^{2}$
^{8}B	ES	>2.8	35	79
^{8}B	^{13}C	>2.2	35	2.4



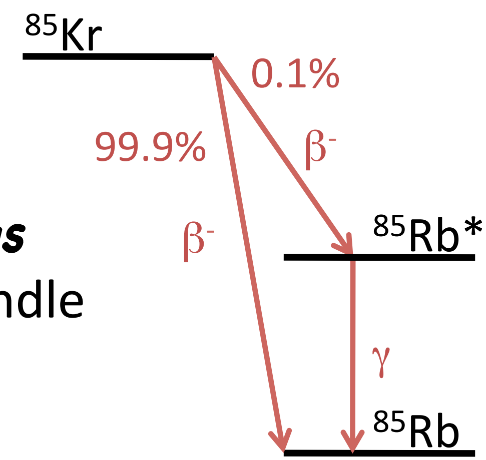
Can LENA do better than Borexino?



Increase in overburden
→ cosmic background reduced by factor 3-5

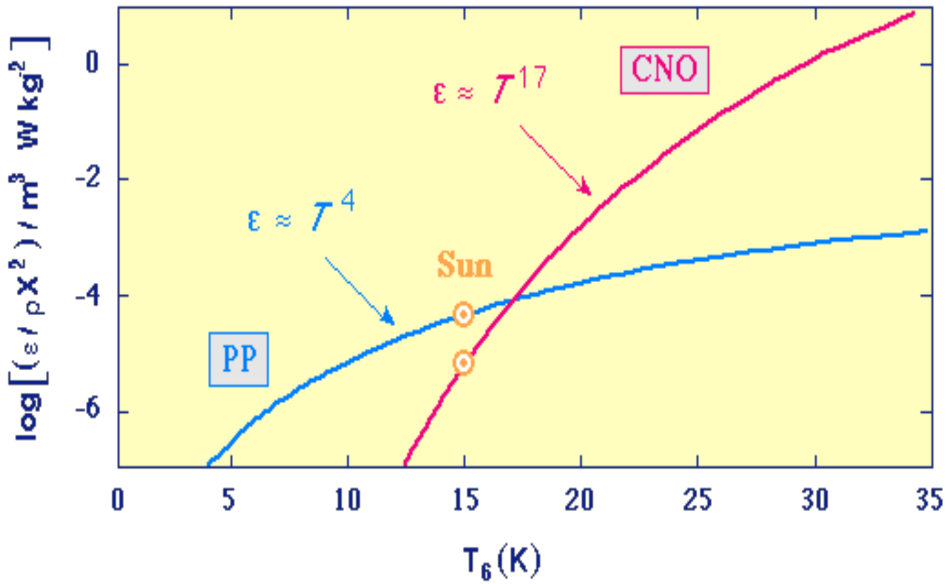


Better self-shielding
→ external γ's negligible



High-statistics tagging of rare decay branchings
→ additional handle on internal backgrounds

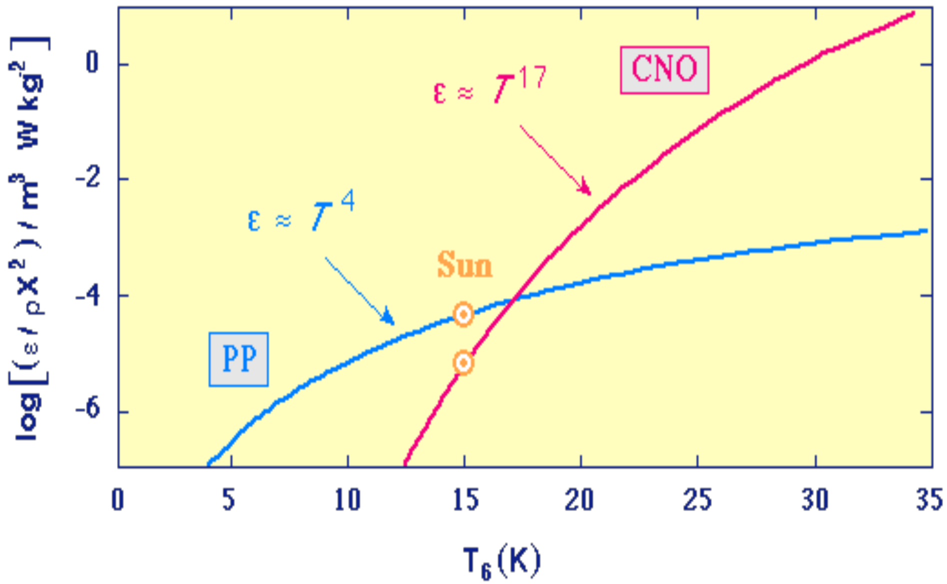
Physics programme for solar neutrinos



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 ...

Physics programme for solar neutrinos



Neutrino physics, e.g.

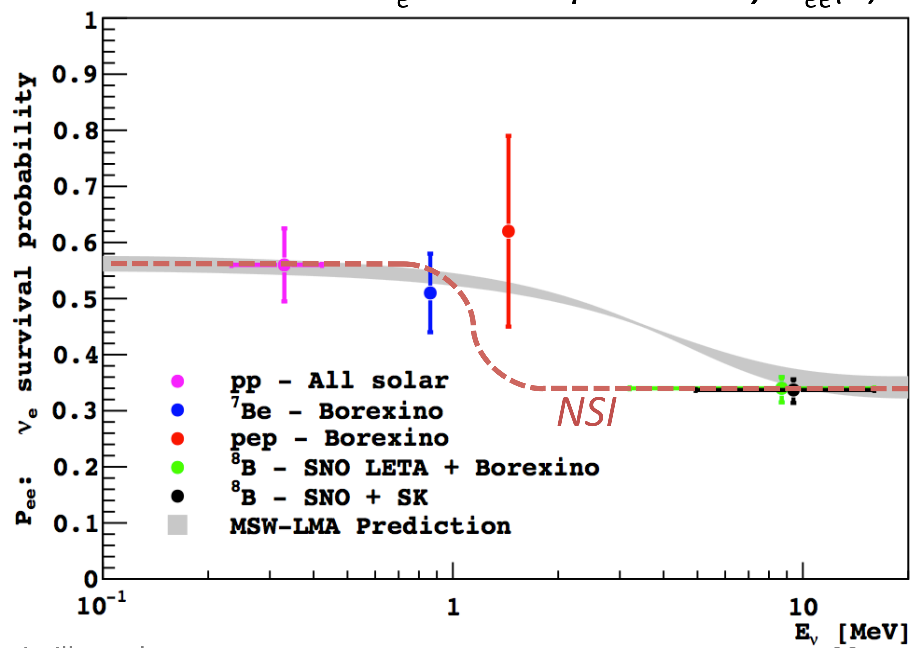
precision measurement (~5σ) of

P_{ee}(E) in MSW transition region

→ non-standard interactions

→ light sterile neutrinos ($\Delta m^2 \approx 0.1$ eV^2)

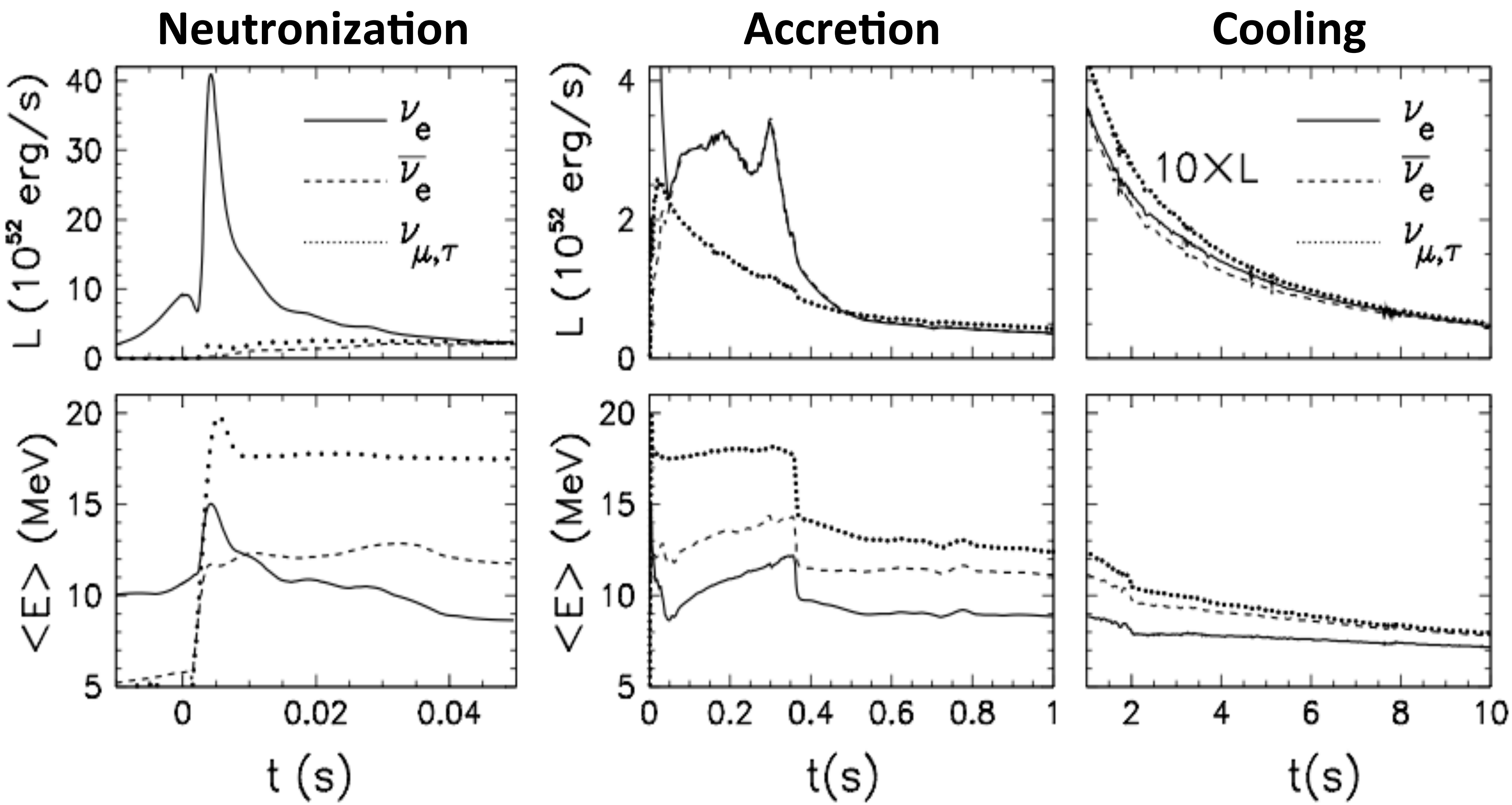
ν_e survival probability $P_{ee}(E)$



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 ...

Supernova neutrino signal



→ requires high-statistics and flavor-resolved measurement

SN signal in LENA

Event rates expected for a galactic core-collapse SN:

10kpc – $8M_{\odot}$ – $\langle E_{\nu} \rangle$=14MeV

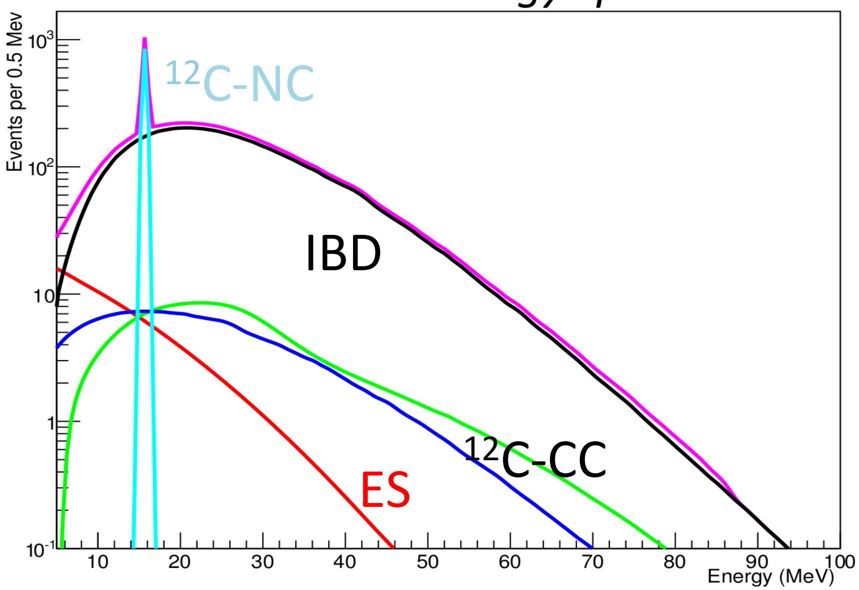
	Channel		Events	Threshold (MeV)	Spectrum
(1)	$\bar{\nu}_e\, p \rightarrow n\, e^+$	CC	1.3×10^4	1.8	✓
(2)	$\nu_e\, {}^{12}C \rightarrow {}^{12}N\, e^-$	CC	3.4×10^2	17.3	(✓)
(3)	$\bar{\nu}_e\, {}^{12}C \rightarrow {}^{12}B\, e^+$	CC	1.8×10^2	13.4	(✓)
(4)	$\nu\, {}^{12}C \rightarrow {}^{12}C^*\, \nu$	NC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

→ $\Sigma \approx 1.7 \times 10^4$

- primary detection channel is **inverse beta decay** (1) → $\bar{\nu}_e$
- CC/NC on **carbon** (2-4) and **ν-proton** scattering (5) channels in LSc provide important **information on other flavors**
- **flavor discrimination** by event signatures (e.g. fast coincidences)

Supernova neutrino physics in LENA

Neutrino event energy spectrum



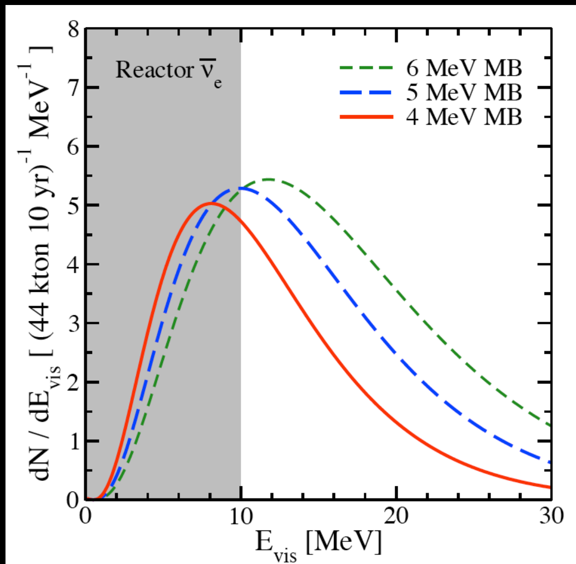
Observables

- high-statistics $\bar{\nu}_e$ spectrum
- ν_e spectrum (few 100 ev)
- $\nu_{\mu,\tau}$ sum spectrum (few 10^3)
- total flux

Astro- and neutrino physics

- Initial neutronization burst
- Time-resolved cooling phase
- Neutrino temperature w/ and w/o oscillations (CC/NC)
- Neutrino mass hierarchy from SN/Earth matter effects
- $\nu \rightarrow \bar{\nu}$ conversion from neutronization burst
- Trigger for gravitational wave antennae

Diffuse Supernova Neutrino Background (DSNB)

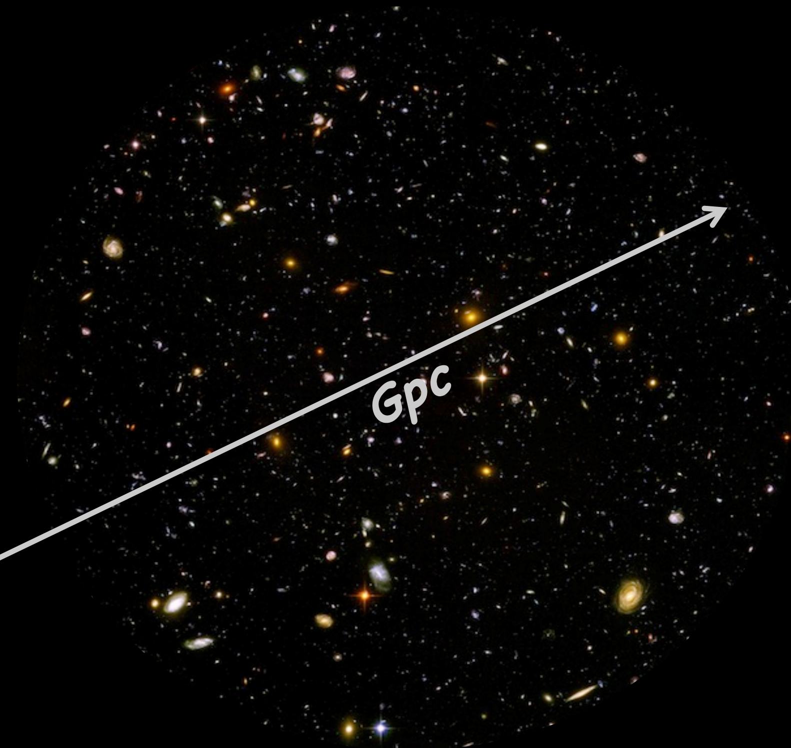


DSNB spectrum

average SN spectrum

redshifted by cosmic expansion

flux: ~10^2 /cm^{2}s



milky way

3 SN per 100yr

present ν detectors

neighbouring galaxy clusters

~1SN per year

single bursts need Mton++ detectors

DSNB

10^8SN per year

average flux

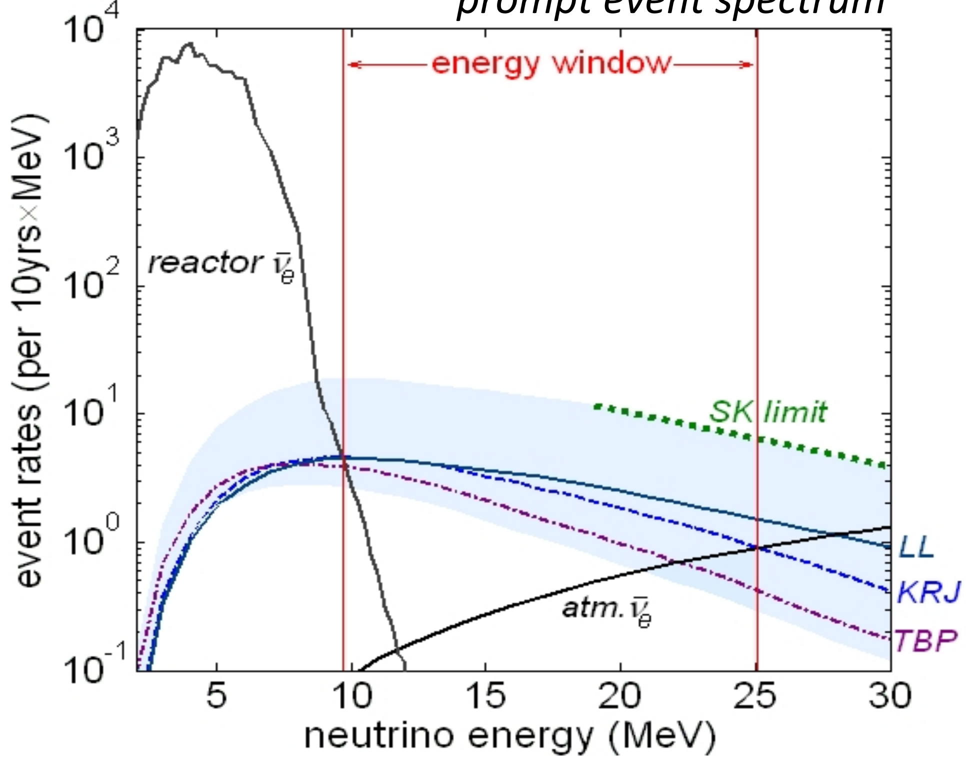
DSNB signal in LENA

- Detection by inverse β-decay:

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

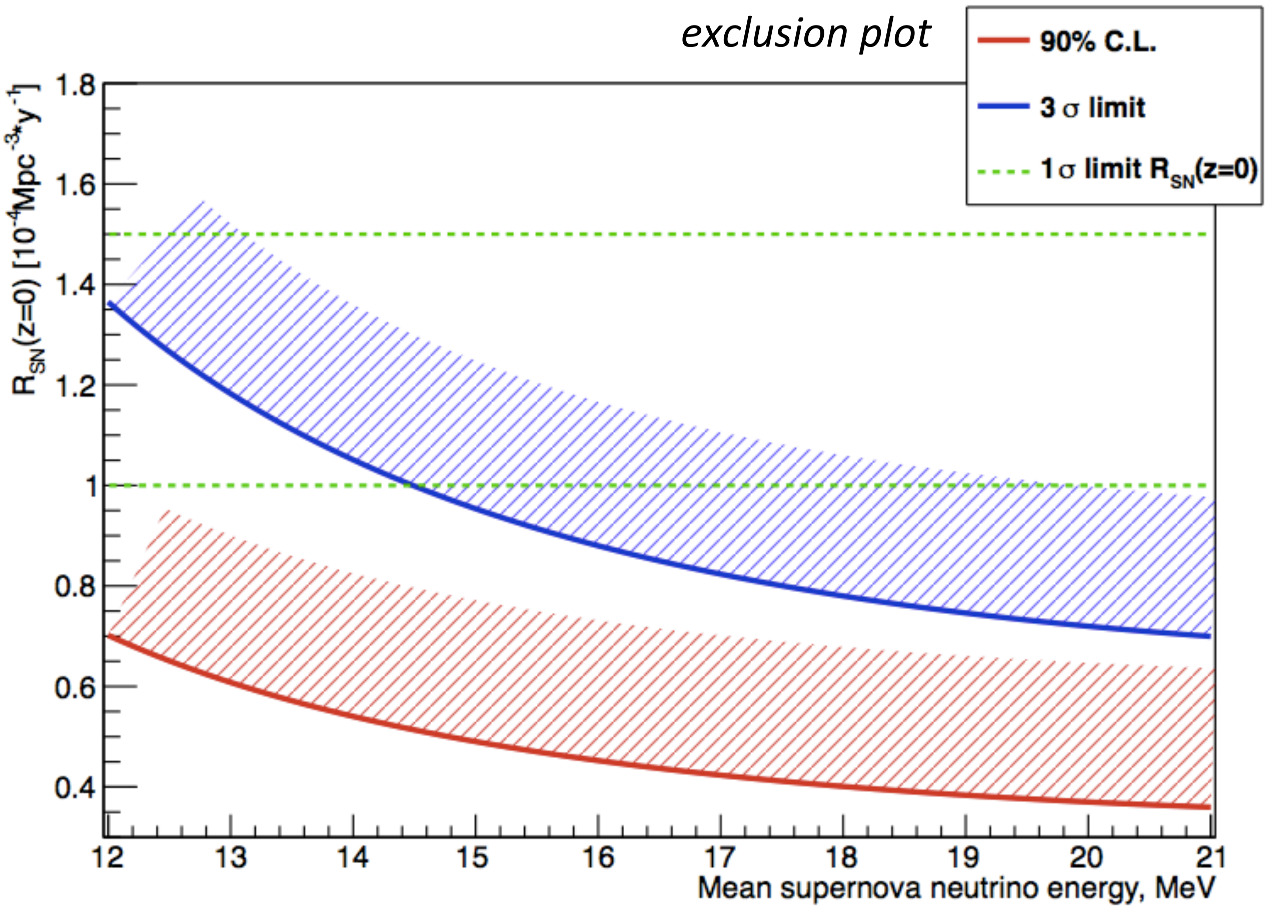
- coincidence signature
  → background suppression
- Energy window: 10-25 MeV
- Most important background:
  atmospheric ν NC events
  → S:B-ratio ≥1 by pulse shape
- **Expected event rate after pulse-shape cuts: ~5 /yr**

prompt event spectrum



LENA's sensitivity for the DSNB

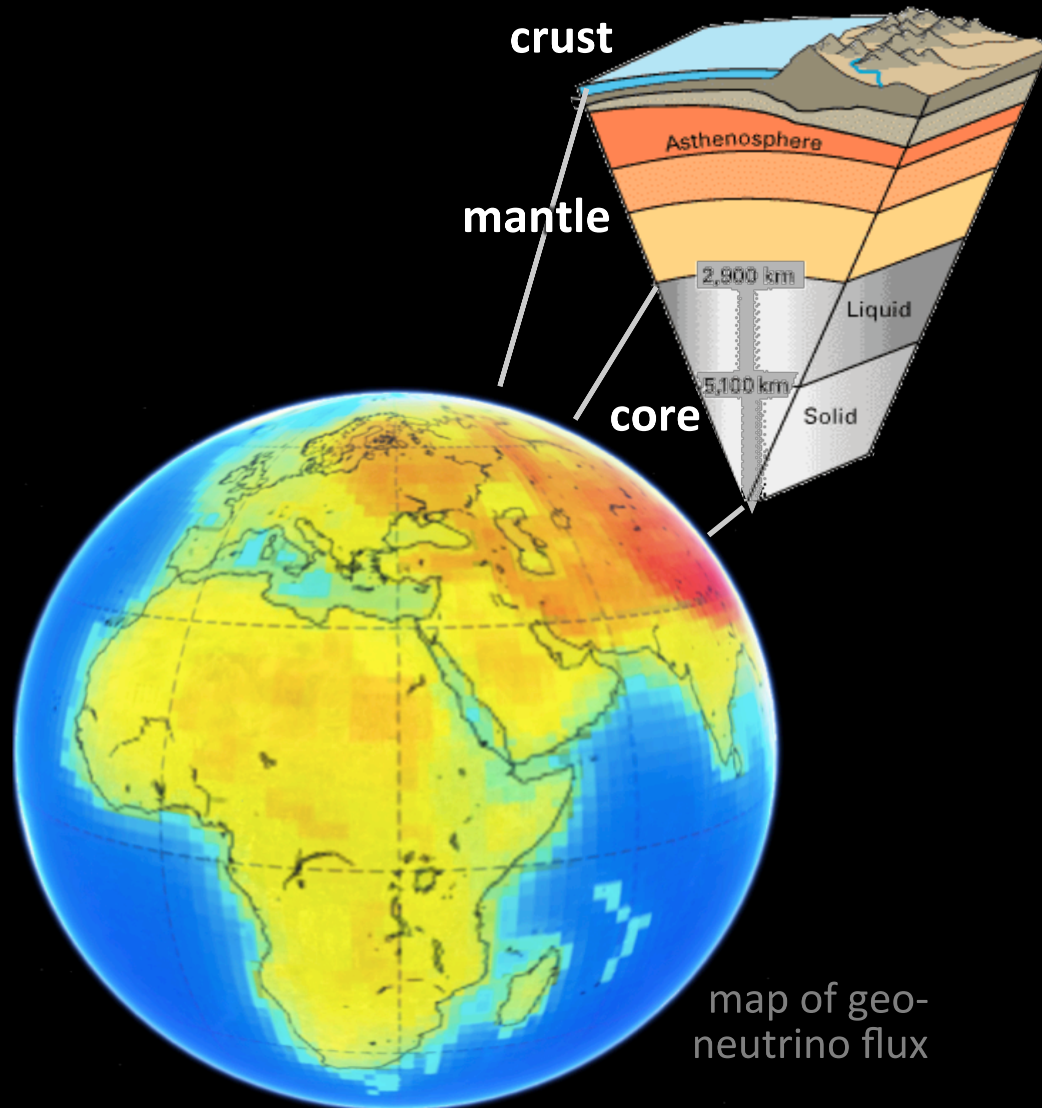
- based on current models: evidence at 3-5 σ after 10 yrs
- if no signal is seen: SK flux limit improved by factor 8:



Geoneutrinos

Geoneutrinos produced by natural ^{40}K, ^{238}U and ^{232}Th

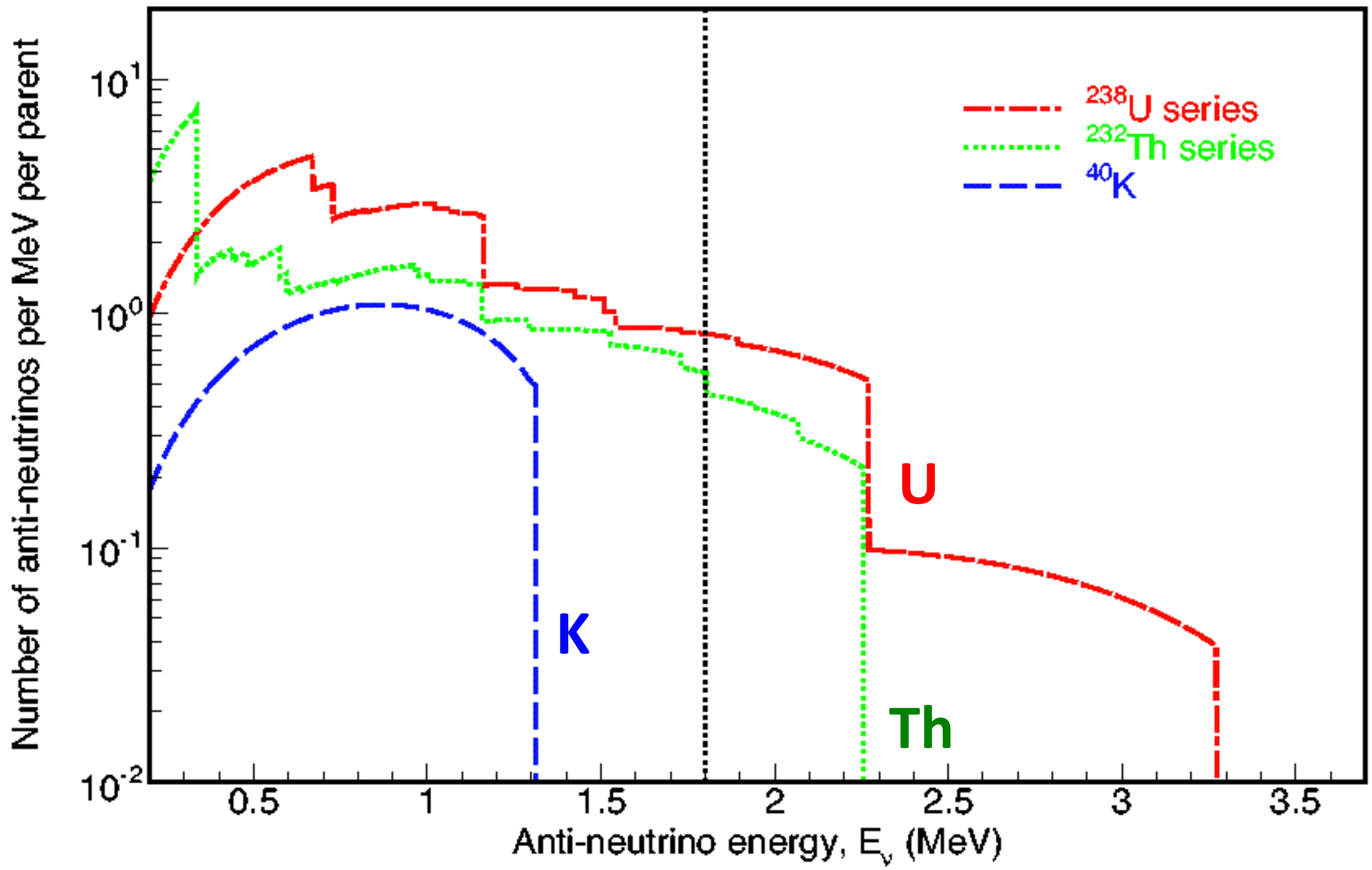
- Flux dominated by the Earth's crust
- scales with crust thickness
  – most from continents
  – less from oceanic crust
- Some contribution from the mantle
- Earth's core is supposed to be depleted in radioisotopes



map of geo-neutrino flux

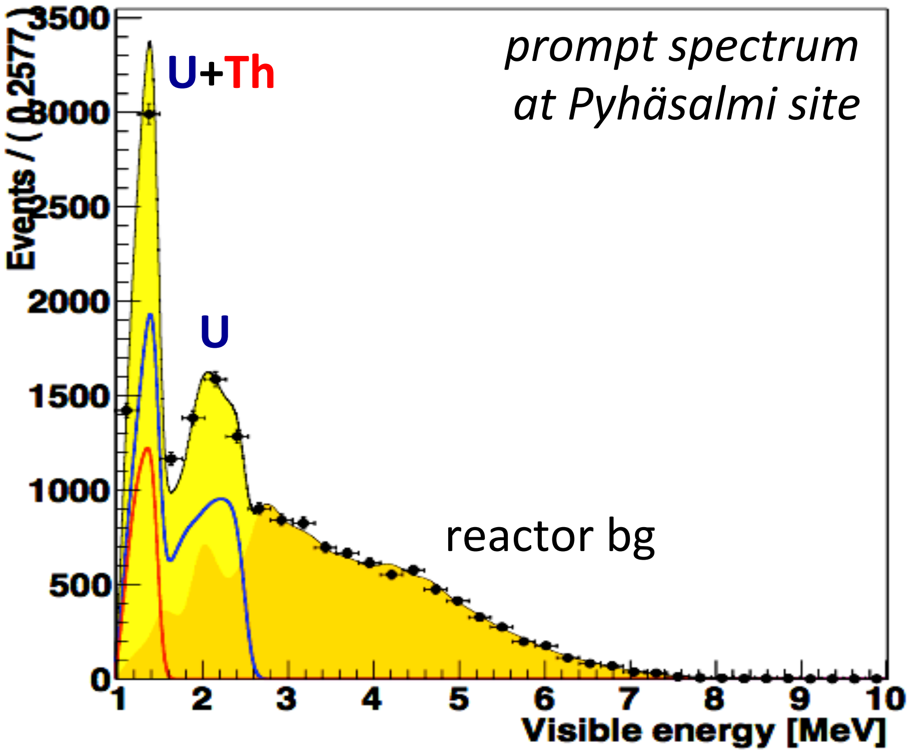
Composition of geoneutrino spectrum

intrinsic threshold of IBD



- Low endpoint energy (3.3 MeV) → only detectable by LSc detectors
- Different end-points of U/Th spectra → can be separated by spectral shape

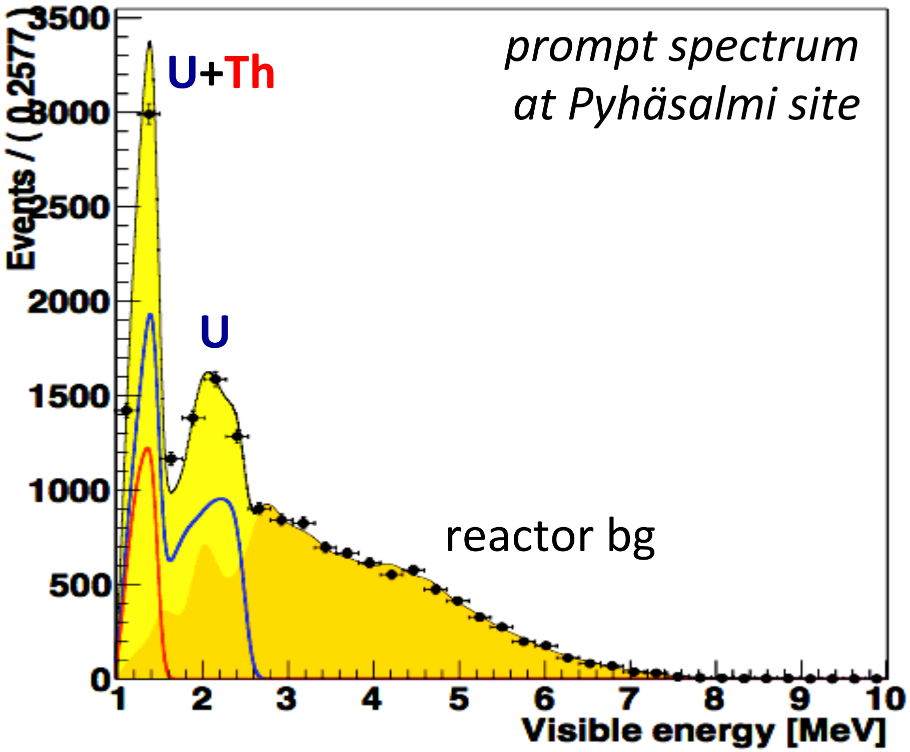
Detection of geoneutrinos in LENA



Expected signal at Pyhäsalmi

- geoneutrino rate $2\text{x}10^3\ \text{yr}^{-1}$
- reactor-ν background $7\text{X}10^2$

Detection of geoneutrinos in LENA



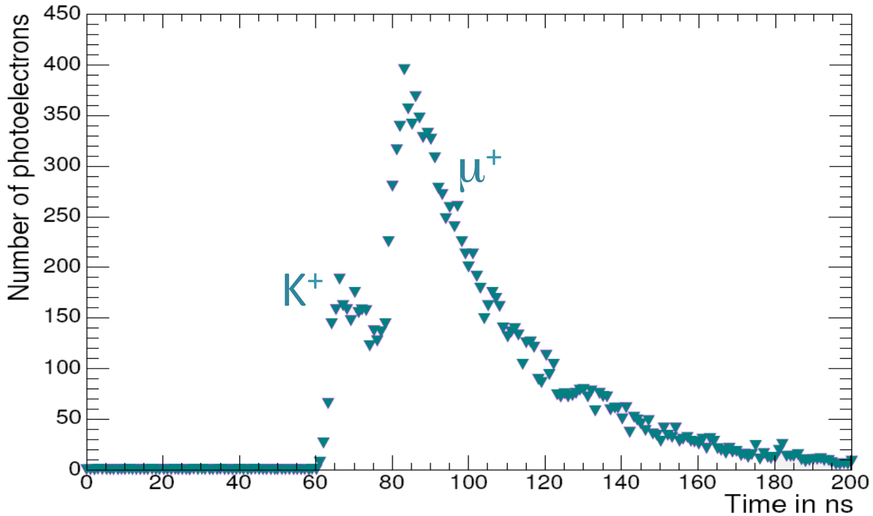
Expected signal at Pyhäsalmi

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

Output for geophysics/chemistry

- Urey ratio: fraction of radiogenic heat production to total heat flow
  → geochemistry: 0.3 ... 1
  → **in LENA: U/Th fraction to 1%**
- ratio of U/Th abundances
  → geochemistry: U/Th = 3.5 ... 4
  → **in LENA: 5% rel. unc.**
- Oceanic vs. continental crust contributions to geoneutrino flux
  → needs detectors at different sites

Proton decay into kaon and antineutrino



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)

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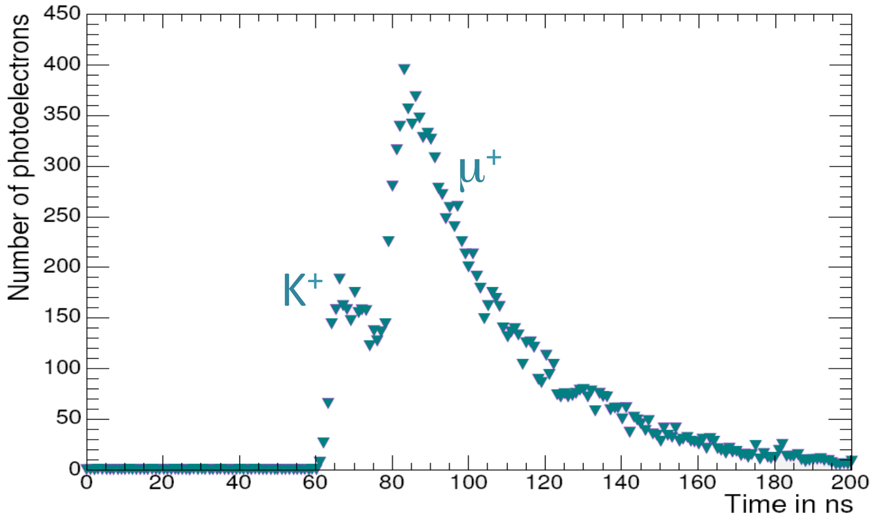

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→ kaon visible in liquid scintillator!

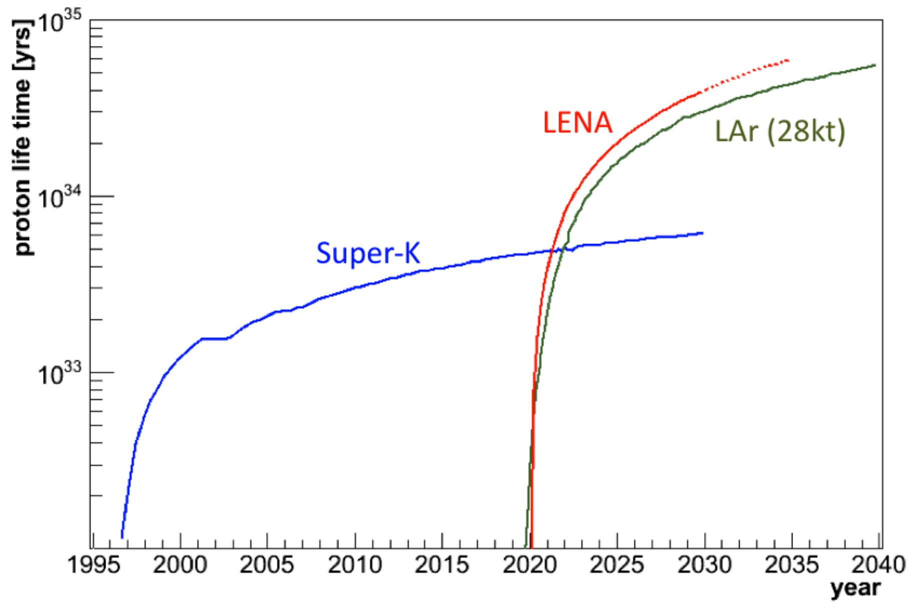
→ fast coincidence signature (τ_K = 13 ns)

→ signal efficiency: ~65% (atm. ν bg)

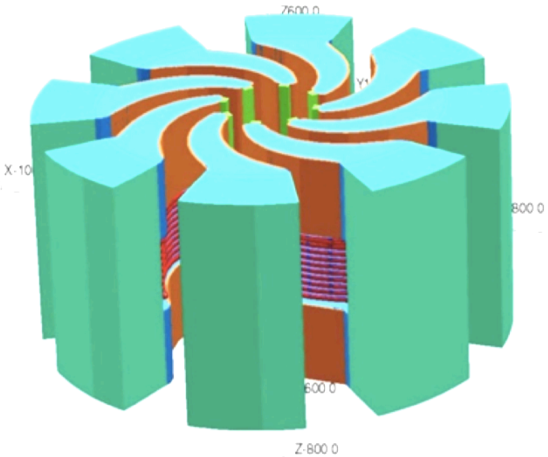
Expected background: <0.1 /yr

→ no event observed in 10yrs:

τ_p > 4x10^{34} yrs (90%C.L.)

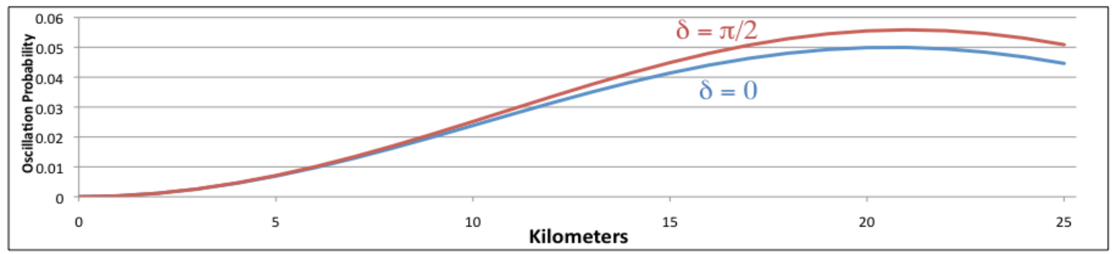


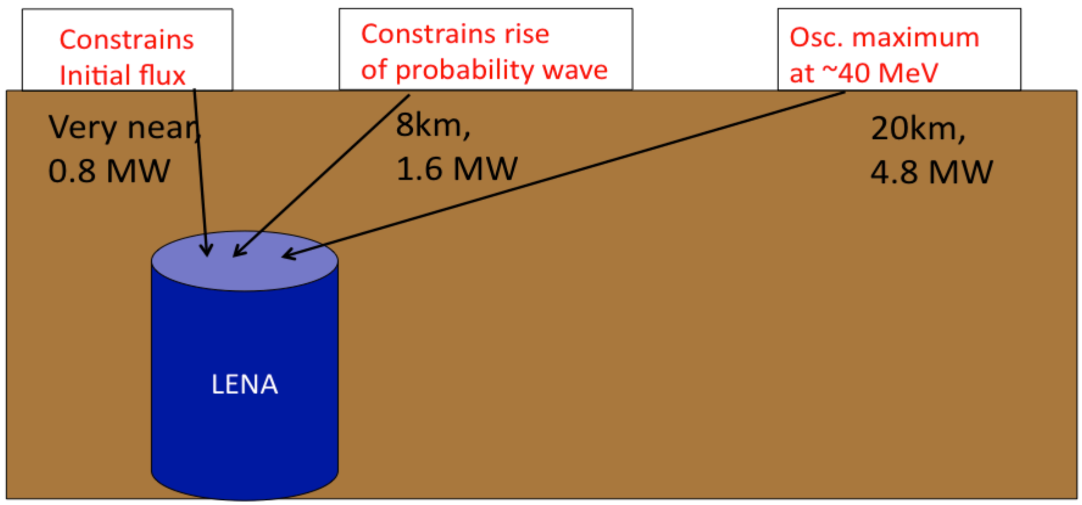
LENA: Neutrino physics with artificial sources



π^+ decay-at-rest beam (DAEδALUS)

- ν_e, ν_μ, $\bar{\nu}_\mu$ with E<50MeV, but no $\bar{\nu}_e$
- high-power cyclotrons at 3 different baselines
  → from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations: **CP phase** at ~3σ





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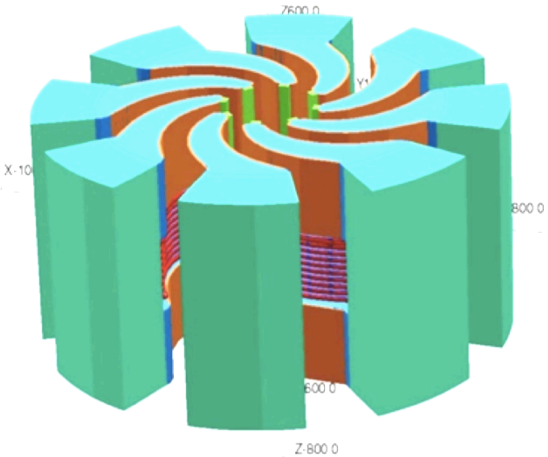

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- close-by cyclotron:
  → **sterile neutrinos** in $\nu_e \rightarrow \nu_s$ disappearance
  and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance modes
  → allows test of all anomalies

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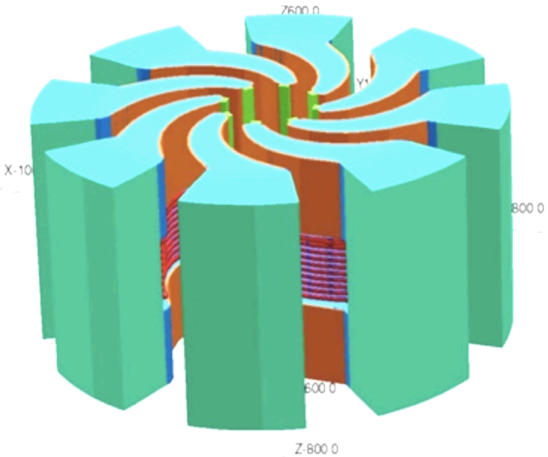

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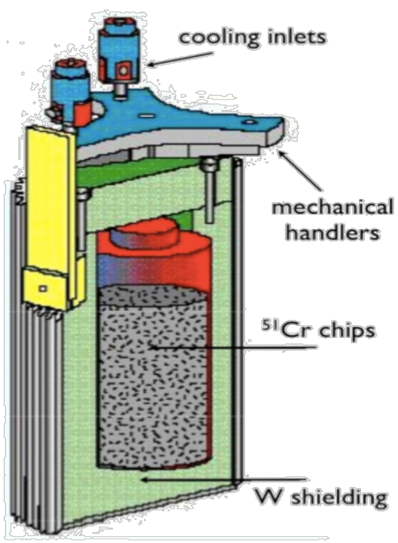

Radioactive sources

- ν_e, $\bar{\nu}_e$ at <3 MeV

→ 2nd generation **sterile neutrino** experiment based on $\nu_e \rightarrow \nu_s$ disappearance

→ discern (3+N) scenarios etc.

Conclusions

- Liquid-scintillator detectors have proven as versatile tools for the detection of low-energy neutrinos and their oscillations.
- For the next generation of large-volume neutrino detectors, liquid-scintillator experiments are still an interesting choice:

  → **JUNO** will determine the MH with good sensitivity, on a short time scale and with independent systematics (+precision measurement of oscillation parameters)

  → **LENA** will be unique in its sensitivity for astrophysical neutrinos and has the potential to give important contributions to oscillation and particle physics.

Backup Slides

Detector technologies

Detector technology	**Water Cherenkov**	**Liquid Scintillator**	**Liquid Argon**
Target mass	500 kt	50 kt	20 kt
Energy threshold	5-10 MeV	0.2 MeV	10-20 MeV (?)
Maximum energy	few GeV	few GeV	few GeV
Best performance	10 MeV – 1 GeV	0.5 – 50 MeV	1 – 10 GeV
Remarks	LE program depends on Gd-doping	HE program depends on reco development	LE program depends on overburden, detector cleanliness

Competing experiments

Project	Technology	Target mass (kilo-ton)	Overburden (mwe)	Site
Hyper-Kamiokande	WCh	560	1750	Kamioka
MeMPhys	WCh	500	4800 ?	Fréjus Garpenberg
JUNO	LSc	20	2000	Kaiping
LENA	LSc	50	4000	Pyhäsalmi
GLACIER/ LBNO	LAr	20	4000	Pyhäsalmi
LBNE	LAr	10	0? 4400?	Homestake

Proposed Super-Beams

Acronym	from	to	Baseline (km)	Beam power (MW)
LBNE	Fermilab	Homestake	1300	0.7 – 2.3
LBNO/C2PY	CERN	Pyhäsalmi	2300	0.7 – 2.0
C2FR	CERN	Fréjus	130	0.7 – 2.0
P2PY	Protvino	Pyhäsalmi	1100	0.5
ESSvSB	Lund	Garpenberg	540	5.0
T2HK	Tokai J-PARC	Kamioka	300	1.66

Neutrino physics

Item	500 kt – Water Cherenkov	50 kt – Liquid Scintillator	20 kt Liquid Argon	Others
Mass hierarchy	atmospheric ν's → 3σ (?)	LENA+C2PY >5σ JUNO >3.5σ	LBNO > 5σ LBNE > 3σ (?)	PINGU > 6σ
CP phase	T2HK, ESSνSB, C2FR → 5σ	LENA+beam →? +DAEδALUS→3σ	LBNO → 3σ upgrade → 5σ LBNE → 3σ	
2^{nd} gen. sterile ν's	no	source exp., iso/piDAR >5σ	?	
NSI etc., e.g. solar ν's	^{8}B-ν's: day-night +Gd: $\nu_e \rightarrow \bar{\nu}_e$ conv.	^{7}Be day-night $\nu_e \rightarrow \bar{\nu}_e$ conv. P_{ee}(MSW) >5σ	no	
0νββ-decay	no	^{136}Xe-doping (200 tons+)	no	many ideas, but hardly as large in mass

Neutrino observation

Item	500 kt – Water Cherenkov	Gd-doped Water	50 kt – Liquid Scintillator	20 kt – Liquid Argon
Solar neutrinos	^{8}B-ν only	^{8}B-ν only	CNO ν flux, metallicity, ^{7}Be modulation	^{8}B-ν (?)
Supernova neutrinos	10^5 events ($\bar{\nu}_e$) no flavor separation (?)	+ separation ν_e vs. $\bar{\nu}_e$	2×10^4 events separation of ν_e, $\bar{\nu}_e$ and $\nu_{\mu,\tau}$	10^4 events (?) mostly ν_e/NC
Diffuse SN ν background	~30 /yr S/B 1:7	~80 /yr S/B 2:1 (?)	~5 /yr S/B 1:1	no?
Geoneutrinos	no	no	ν flux → 1% U/Th ratio 5%	no
Indirect dark matter search	no	annihilation $\bar{\nu}_e$ 10-100 MeV	annihilation $\bar{\nu}_e$ 10-100 MeV	no?

Proton decay searches

Channel (after 10 yrs)	25 kt water – Super-K	500 kt – Water Cherenkov	50 kt – Liquid Scintillator	20 kt – Liquid Argon
$p \rightarrow \pi^0 e^+$	8×10^{33} yrs (SK-I-II)	$>1 \times 10^{35}$ yrs	yes?	1×10^{34} yrs
$p \rightarrow K^+ \nu$	2×10^{33} yrs (SK-I)	4×10^{34} yrs	4×10^{34} yrs	2×10^{34} yrs
$p \rightarrow$ others	$\sim 10^{33}$ yrs (SK-I-II-III)	$\sim 10^{34}$ yrs	?	$\sim 10^{34}$ yrs
$n \rightarrow \bar{n}$	2×10^{32} yrs (SK-I)	$>2 \times 10^{33}$ yrs (?)	?	yes?

proton life time limits at 90% C.L.

Mass hierarchy

Experimental approaches

- Large matter effects at high neutrino energies/long baselines
  → very long baseline beams (>1000 km), atmospheric neutrinos
- Interference terms of Δ_{13} and Δ_{23}-driven oscillations
  → medium-distance reactor experiments (60 km)

Sensitivities

▪ GLACIER, LENA and C2PY	>5σ	long time scale, beam (?)
▪ GLACIER, LENA and P2PY	3-5σ	
▪ LBNE	→3σ (?)	
▪ T2HK, C2FR, ESS		no sensitivity
▪ PINGU, ORCA (?)	>5σ	5 yrs, atmospheric ν's
▪ Hyper-Kamiokande, INO	→3σ (?)	10 yrs
▪ JUNO	>3.5σ	fast, reactor ν's

CP violation

Experimental approaches

- Difference in $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ probabilities
  → long-baseline superbeam (at short baselines @ 2^{nd} maximum)
- Dependence of $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ probability on baseline
  → π^+ decay-at-rest neutrino sources at two (3) different baselines
  → allows superbeams to run only in ν-mode to increase sensitivity

Sensitivities

GLACIER & P/C2PY:	20kt, 0.7MW, 10yrs	3σ	40% coverage
	70kt, 2MW, 10yrs	5σ	54% coverage
LBNE (full)		3σ	40% coverage
MeMPhys & ESS			5σ 45% coverage
T2HK or MeMPhys & C2FR		5σ	15% coverage
LENA & DAEδALUS		3σ	45% coverage

- LENA & P/C2PY: now ~2σ, might increase with reco capabilities