Liquid argon TPC physics potential

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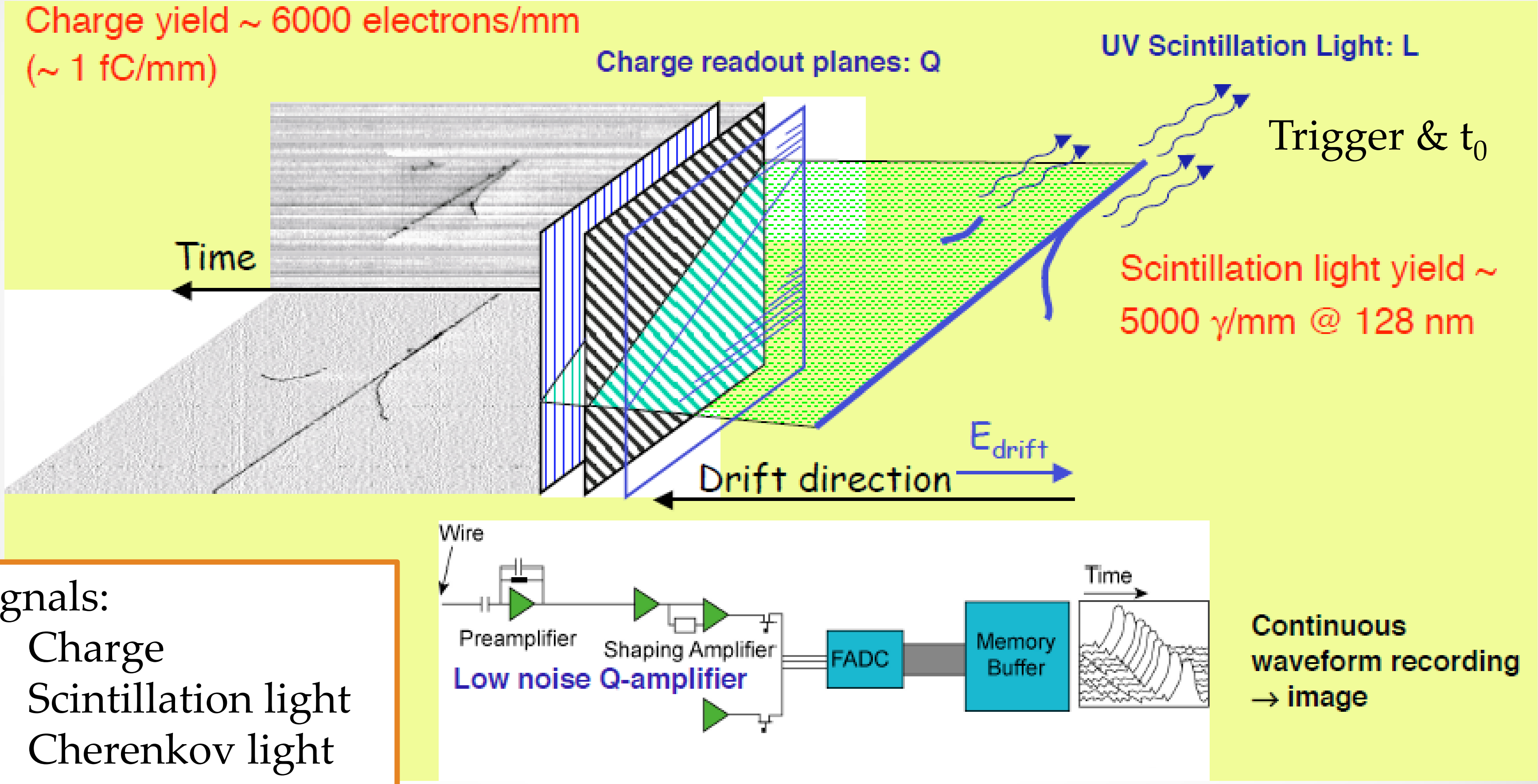
Outline

- Introducing liquid argon TPC
- Physics case
  - Accelerator neutrino physics
  - Study of atmospheric neutrinos
  - Nucleon decay search
  - Supernova neutrinos
  - Solar neutrinos
  - Indirect dark matter searches

LAr TPC concept

The Liquid Argon Time Projection Chamber: a new concept for Neutrino detectors, C. Rubbia CERN-EP/77-08 (1977)



Signals:

1. Charge
2. Scintillation light
3. Cherenkov light (if $\beta > 1/n$)

Some advantages of LAr TPC

- Fully active homogeneous detector
- Detailed 3D event topology reconstruction
- dE/dx with high density sampling (2% X_0) → PID
- Calorimetric energy measurement from contained showers
- Low detection threshold (<100 keV with charge amplification in a double phase LAr TPC)
- Scalable to large masses

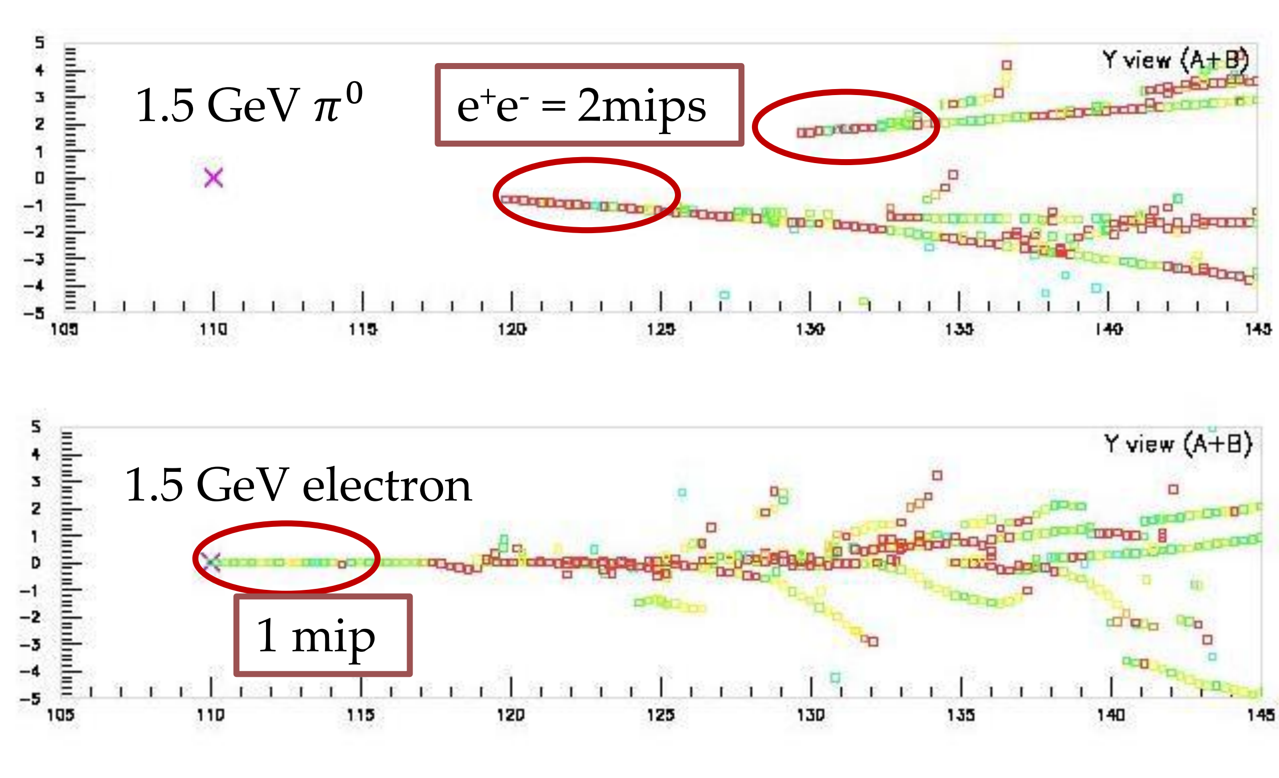
Excellent ν_e detector

Background from NCπ^0 is negligible

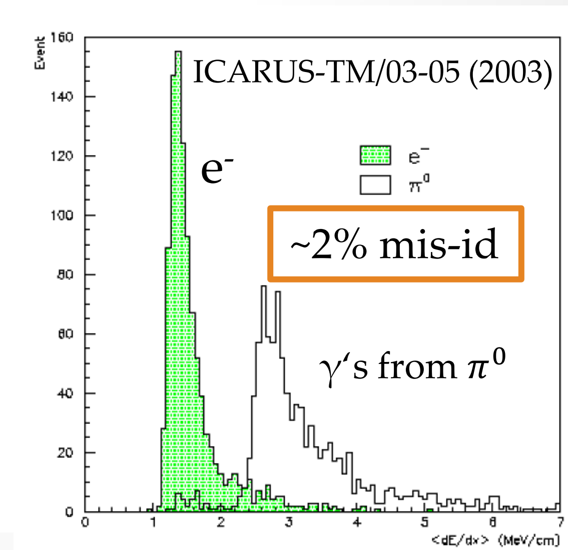
- Event topology
- Invariant mass
- e/γ separation

~100% π^0 rejection

Great for $\nu_\mu \rightarrow \nu_e$ measurements

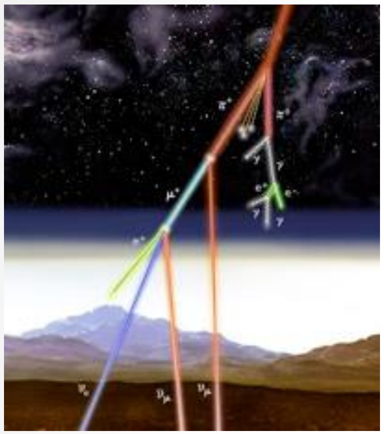


Separate electromagnetic tracks for electrons and photons based on <dE/dx> at the beginning of the track

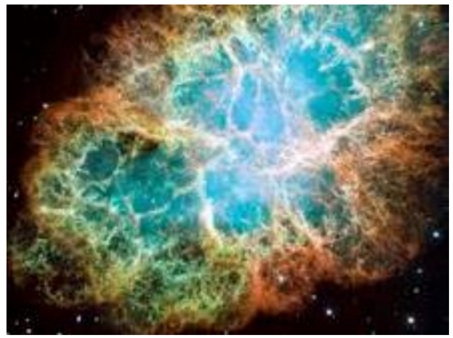


With large detectors …

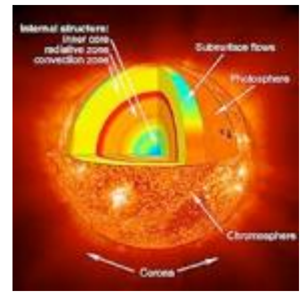
Atmosphere



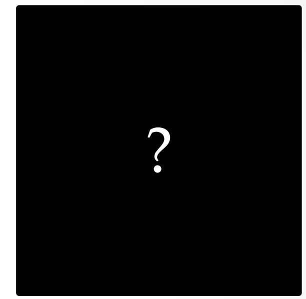
Supernova



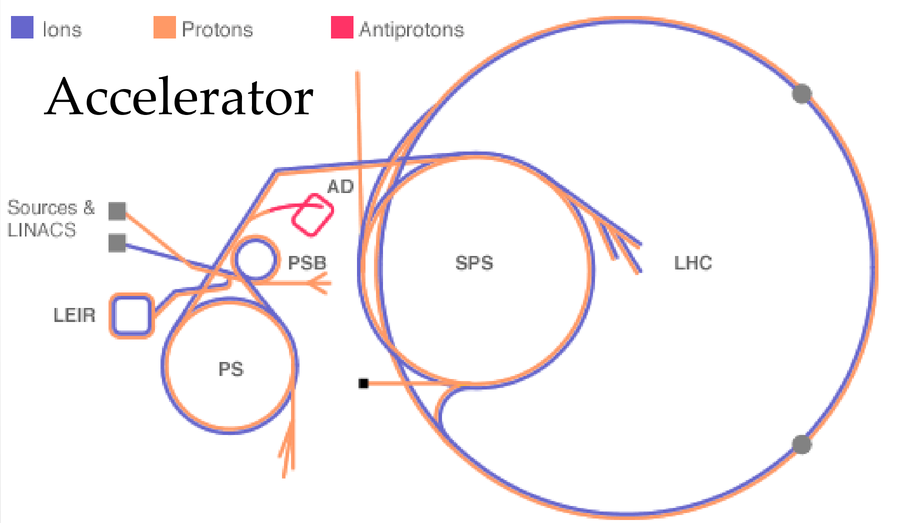
Sun



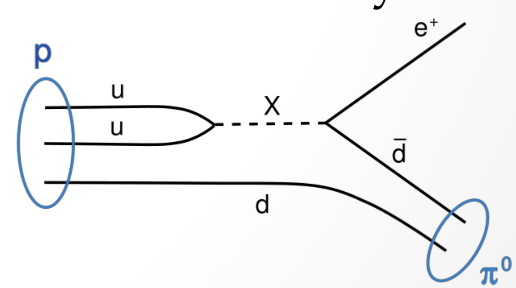
Dark matter



Accelerator

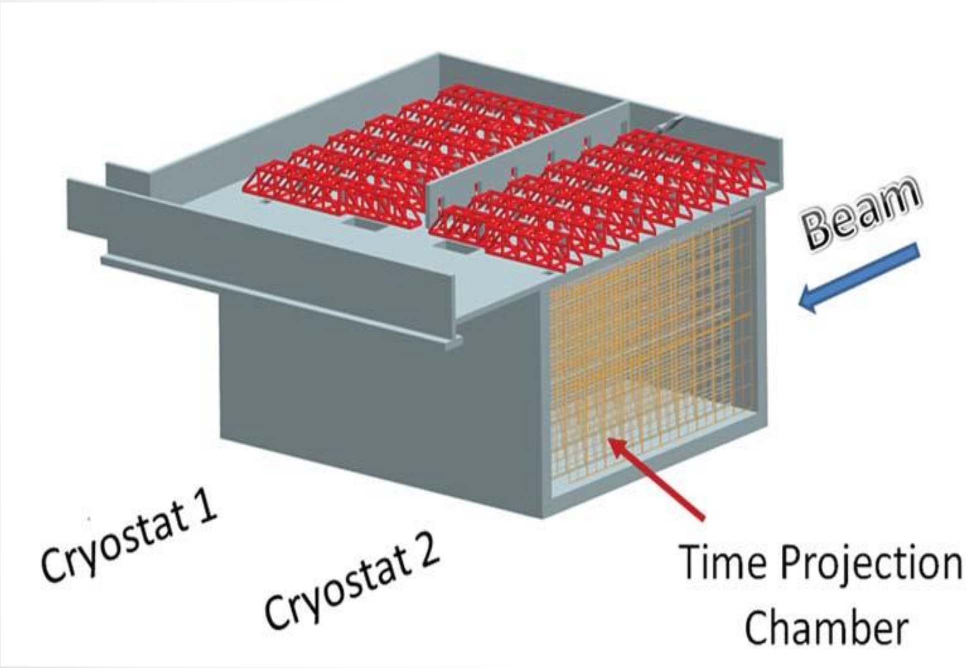


Nucleon decay



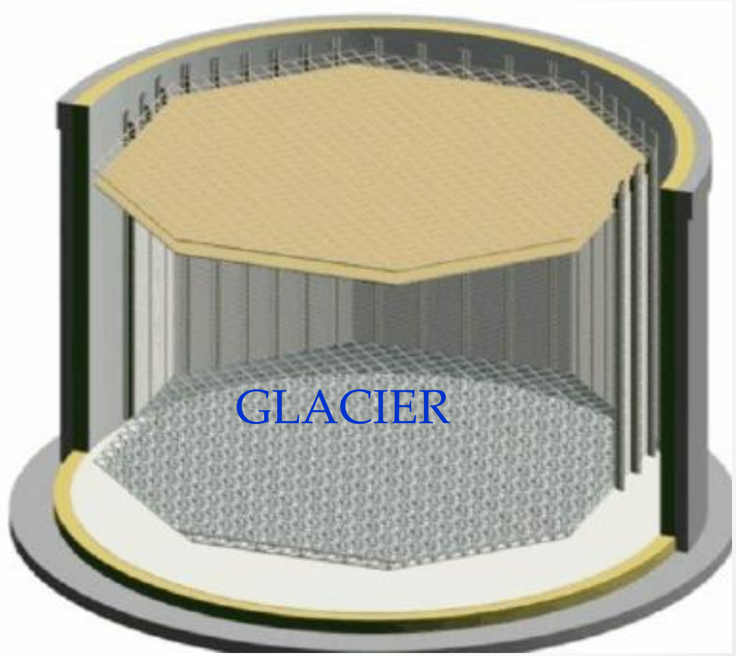
Proposals for very large LAr TPC detectors

LBNE



34 kton

LBNO



Double-phase LAr TPC
22.8 kton → ~70 kton

Physics case

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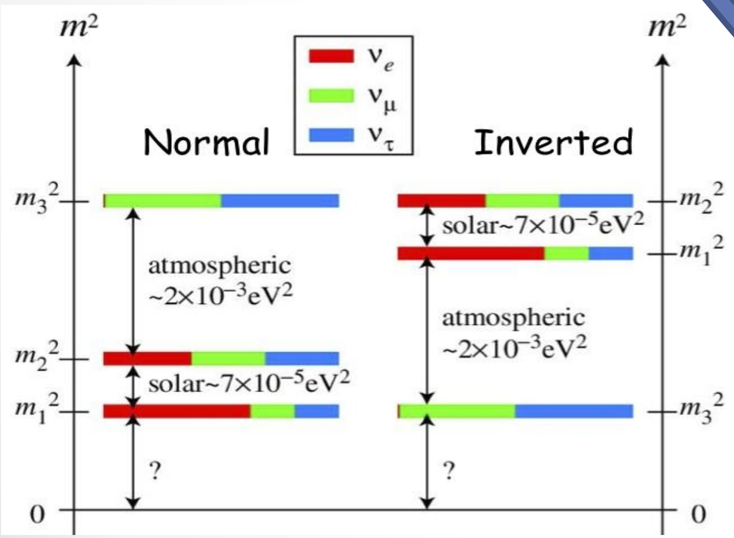
Physics with accelerator ν

Two big questions

1. Hierarchy of neutrino masses
   - Crucial to resolving leptonic CPV
   - Understanding origin of ν mass
   - Input to $0\nu\beta\beta$-decay experiments



2. Leptonic CP violation

$$U_{PMNS} = U_{\theta_{23}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} U_{\theta_{12}}$$

If $\delta \neq 0, \pi$ ➔ CP violation in lepton sector

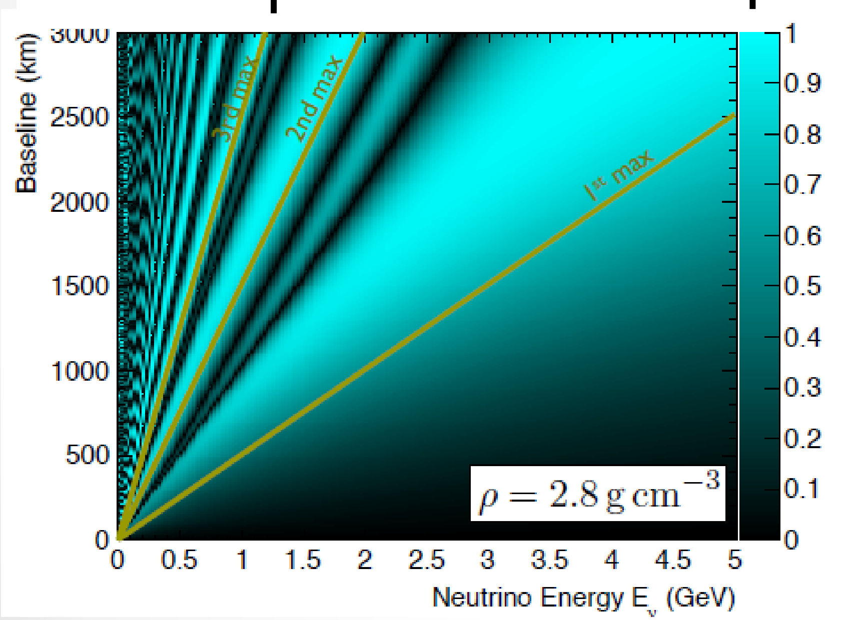
Connection with Leptogenesis?

Both questions can be addressed with conventional accelerator neutrino beams by studying $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

Resolving MH & CPV

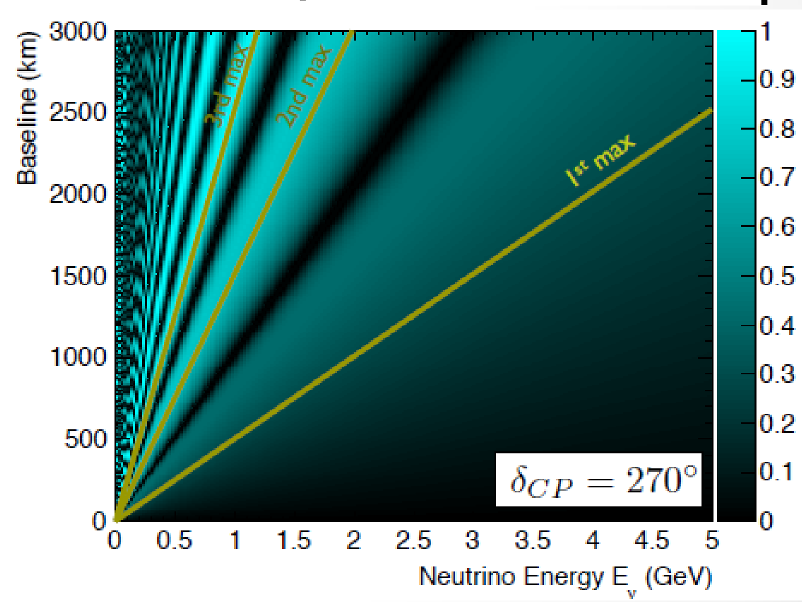
To determine MH & CPV disentangle matter-driven from CP-driven effects

$$\mathcal{A}_{CP}(\rho) \equiv \left| \left(\frac{P^{mat}(\nu) - P^{mat}(\bar{\nu})}{P^{mat}(\nu) + P^{mat}(\bar{\nu})} \right) \right|$$



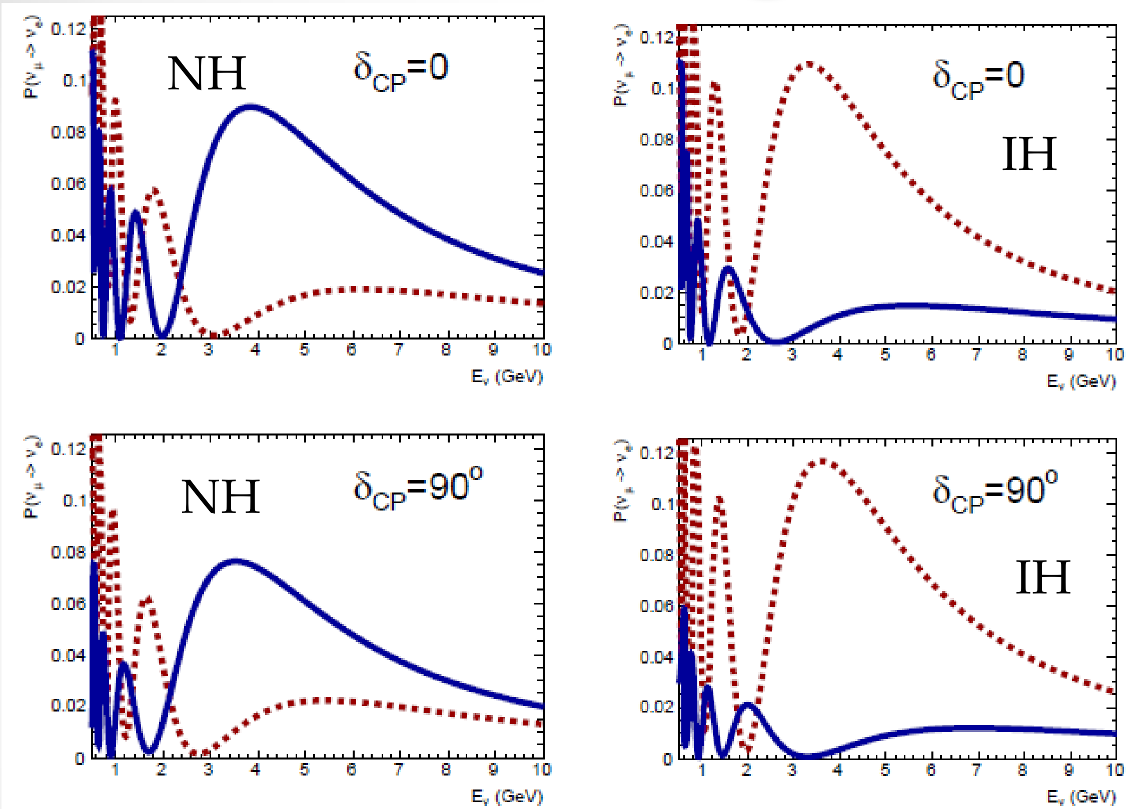
Matter asymmetry dominates around 1st maximum and becomes clear at large L

$$\mathcal{A}^{vac}_{CP}(\delta_{CP}) \equiv \left| \left(\frac{P^{vac}(\nu) - P^{vac}(\bar{\nu})}{P^{vac}(\nu) + P^{vac}(\bar{\nu})} \right) \right|$$



CP asymmetry increases towards higher order oscillation maxima

Resolving MH & CPV



$P_{\mu e}$ @ 2300 km

$\bar{P}_{\mu e}$ @ 2300 km

MH scenarios can be clearly distinguished due to suppression of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ($\nu_\mu \rightarrow \nu_e$) oscillations for NH (IH)

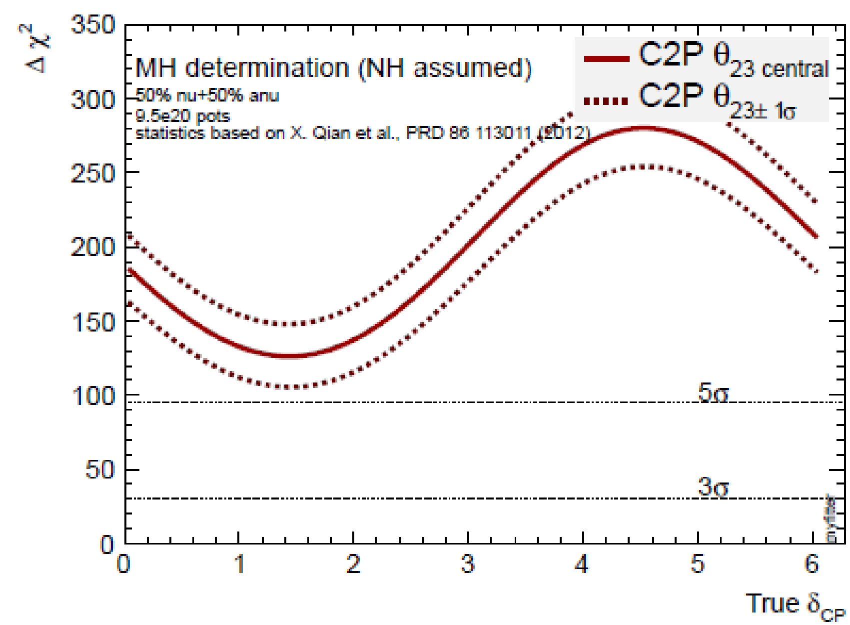
Wide band beam + LAr TPC → Measure L/E behaviour over 1st + 2nd oscillation maxima

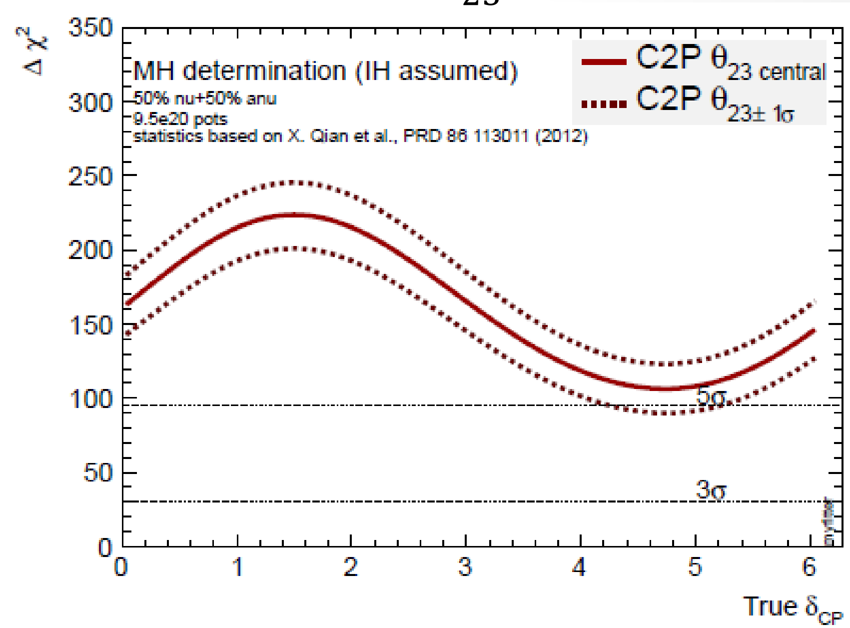
- Determine MH & CPV
- Verify 3-neutrino mixing paradigm

MH @ 2300 km

LBNO Phase I: active mass 22.8 kton LAr TPC
with ν beam from 700 kW CERN SPS

$\sin^2\theta_{23} = 0.440 \pm 0.044$





Conclusive MH determination after 6-7 years of running irrespective of true value of CPV phase δ

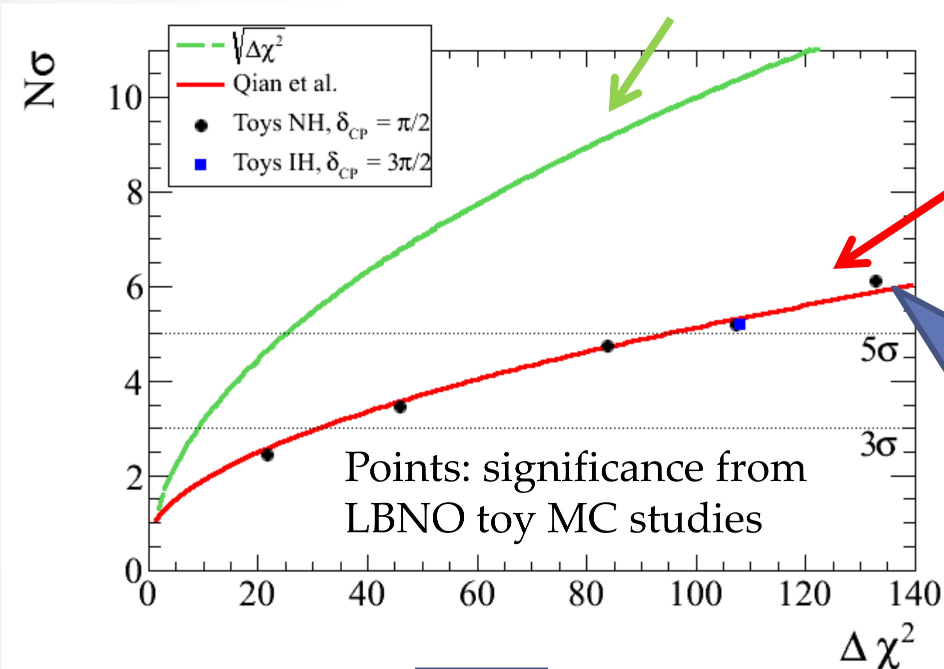
Statistical issue

Interpretation of significance in MH determination is tricky

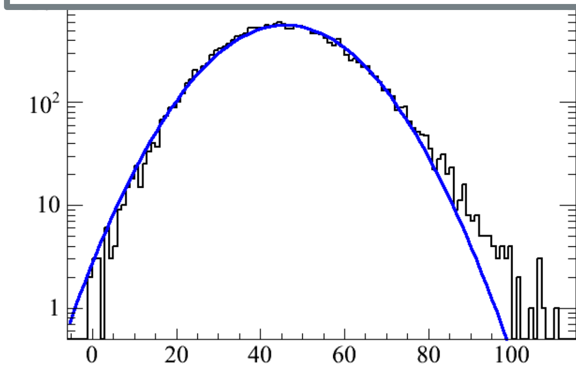
Overestimated if using naively $\sqrt{\Delta\chi^2}$

Qian et al., PRD 86, 113011 (2012)

$$\mathrm{PDF}(\Delta\chi^2) = \mathrm{Gaus}\left(\overline{\Delta\chi^2}, 2\sqrt{\overline{\Delta\chi^2}}\right)$$



Distribution of $\Delta\chi^2$ from toy MC



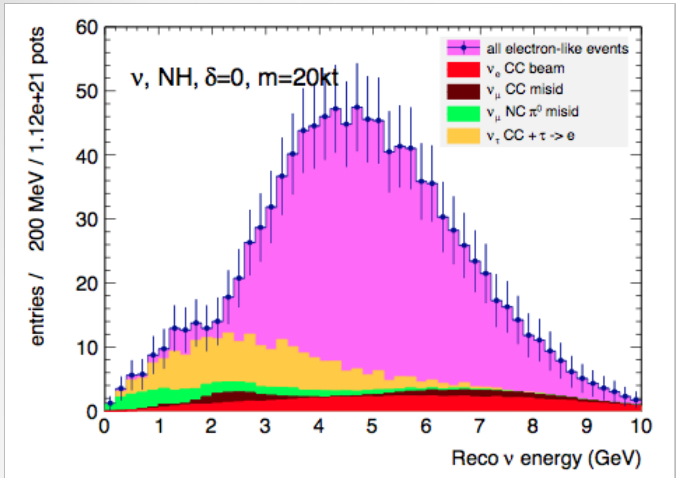
$\Delta\chi = \chi^2_{False} - \chi^2_{True}$

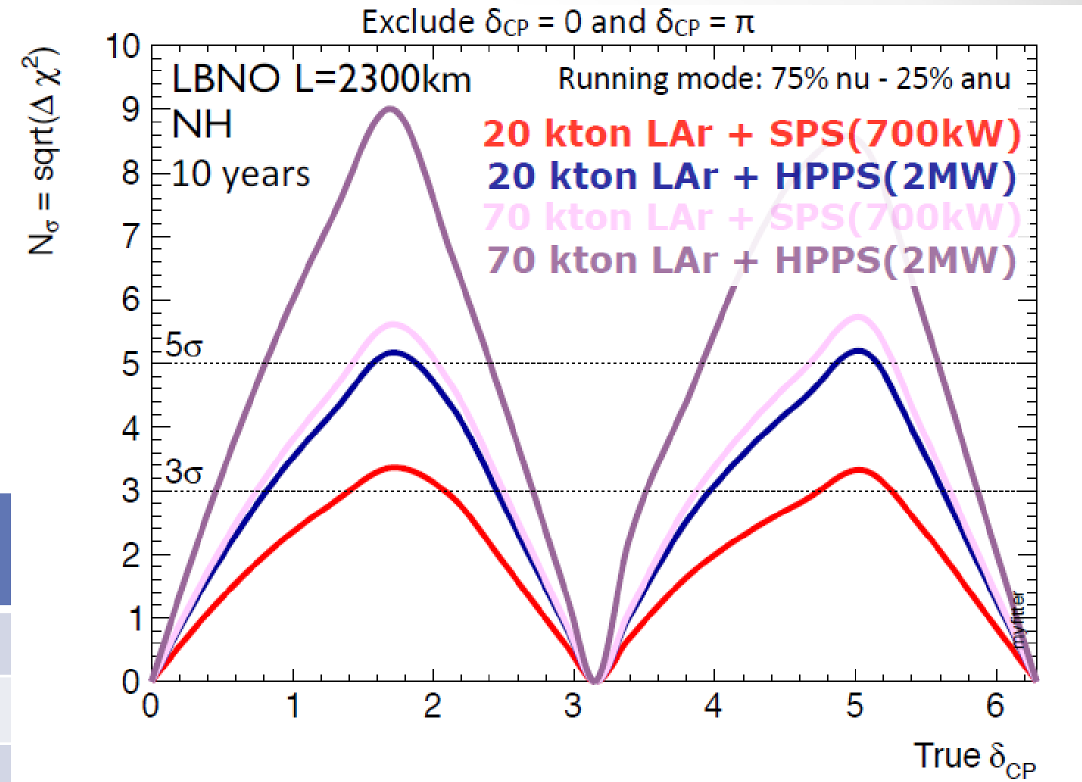
3σ: $\Delta\chi^2 = 30.96$

5σ: $\Delta\chi^2 = 94.66$

$$\Pr(\Delta\chi^2 \geq 0) = \int_0^\infty \mathrm{PDF}(\Delta\chi^2)\,d\Delta\chi^2$$

CPV @ 2300 km





	Central value	Uncertainty
L (km)	2300	Exact
$\Delta m^2_{21} (\times 10^{-5}\ \mathrm{eV}^2)$	7.6	Exact
$\|\Delta m^2_{31}\| (\times 10^{-3}\ \mathrm{eV}^2)$	2.4	± 3.75%
$\sin^2\theta_{12}$	0.31	Exact
$\sin^2 2\theta_{13}$	0.10	± 10%
$\sin^2\theta_{23}$	0.44	± 10%
Average density ρ (g/cm^3)	3.20	± 4%

	Uncertainty
Signal normalization (f_{sig})	± 5%
Beam electron contamination (f_{ν_e})	± 5%
Tau background normalization (f_{ν_τ})	± 20%
NC and mis-id ν_μ (f_{NC})	± 10%

Other oscillation channels

O(10^3) NC events / 50 kton x year:

$\nu_x \rightarrow \nu_x$ in NC channel (disappearance into sterile)

- Check for energy-dependent deficit in NC events in the far detector

O(10^2) CC ν_μ / 50 kton x years:

$\nu_\mu \rightarrow \nu_\tau$ oscillations @ oscillation maximum

Statistical determination of CC ν_τ events using several kinematic variables (e. g., E_{vis} & knowledge of beam direction to obtain p_T^{miss})

- Tau appearance measurement
- Constraint on CC ν_τ cross-section

Atmospheric ν

Expected rates

- CC $\nu_\mu + \bar{\nu}_\mu$: ~150 / kton / year
- CC $\nu_e + \bar{\nu}_e$: ~85 / kton / year
- CC $\nu_\tau + \bar{\nu}_\tau$: ~0.6 / kton / year

- Measurements of osc. parameters complimentary to acc-ν program
- ν_τ from oscillations of atmospheric ν_μ
  - ~12 events for 20 kton x years
  - Isolation of tau events with significance $> 4\sigma$ appears to be feasible (hep-ph/1008.2984)
- Make use of LAr TPC good energy and angular resolution to explore feature reach oscillation patterns of atm-ν

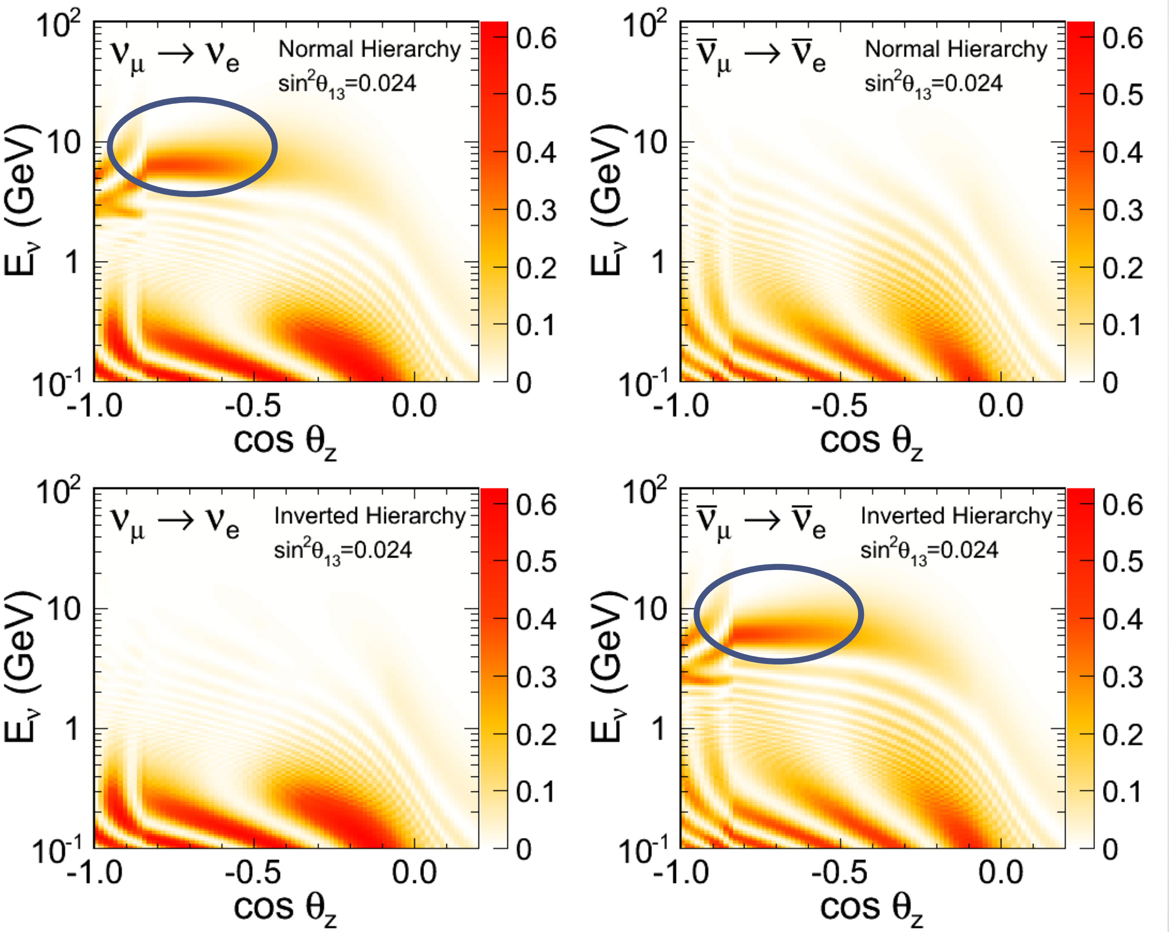
Probing Earth structure

hep-ex/1307.7335

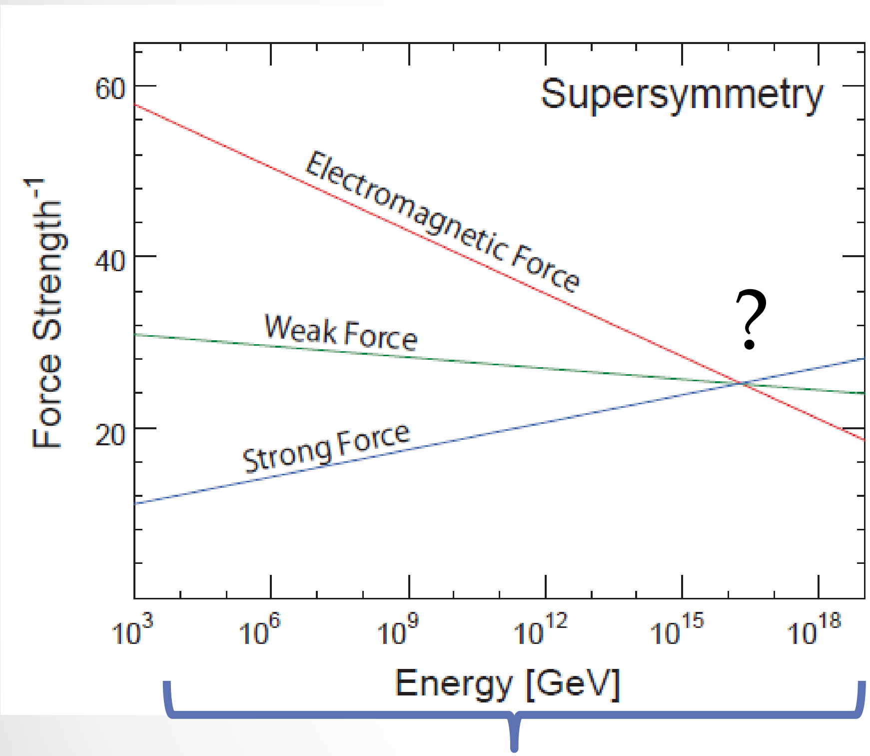
For large $\sin^2\theta_{13}$, MSW enhancement for 3-10 GeV up-going neutrinos (anti-neutrino) for NH (IH)

Abrupt shift for ν not crossing the core

A unique opportunity to obtain information on the Earth density profile ← "radiography" of the Earth's interior



Nucleon decay



Inaccessible with accelerators

- Running coupling constants → hint for grand unification (GU)
- Direct signature of GU is nucleon decay
- LAr offers good granularity and energy resolution
    - Access many decay channels

Lifetime predictions

From hep-ph/0701101

Model	Ref.	Modes	τ_N (years)
Minimal $SU(5)$	Georgi, Glashow [2]	$p \to e^+\pi^0$	$10^{30} - 10^{31}$
Minimal SUSY $SU(5)$	Dimopoulos, Georgi [11], Sakai [12] Lifetime Calculations: Hisano, Murayama, Yanagida [13]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	$10^{28} - 10^{32}$
SUGRA $SU(5)$	Nath, Arnowitt [14, 15]	$p \to \bar{\nu}K^+$	$10^{32} - 10^{34}$
SUSY $SO(10)$ with anomalous flavor $U(1)$	Shafi, Tavartkiladze [16]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$ $p \to \mu^+K^0$	$10^{32} - 10^{35}$
SUSY $SO(10)$ MSSM (std. $d=5$)	Lucas, Raby [17], Pati [18]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	$10^{33} - 10^{34}$ $10^{32} - 10^{33}$
SUSY $SO(10)$ ESSM (std. $d=5$)	Pati [18]	$p \to \bar{\nu}K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d=5$)	Babu, Pati, Wilczek [19, 20, 21], Pati [18]	$p \to \bar{\nu}K^+$ $p \to \mu^+K^0$ $B \sim (1-50)\%$	$\lesssim 2 \cdot 10^{34}$
SUSY $SU(5)$ or $SO(10)$ MSSM ($d=6$)	Pati [18]	$p \to e^+\pi^0$	$\sim 10^{34.9\pm1}$
Flipped $SU(5)$ in CMSSM	Ellis, Nanopoulos and Wlaker[22]	$p \to e/\mu^+\pi^0$	$10^{35} - 10^{36}$
Split $SU(5)$ SUSY	Arkani-Hamed, *et. al.* [23]	$p \to e^+\pi^0$	$10^{35} - 10^{37}$
$SU(5)$ in 5 dimensions	Hebecker, March-Russell[24]	$p \to \mu^+K^0$ $p \to e^+\pi^0$	$10^{34} - 10^{35}$
$SU(5)$ in 5 dimensions option II	Alciati *et.al.*[25]	$p \to \bar{\nu}K^+$	$10^{36} - 10^{39}$
GUT-like models from Type IIA string with D6-branes	Klebanov, Witten[26]	$p \to e^+\pi^0$	$\sim 10^{36}$

Somewhere >10^{34} years

Expected efficiencies & backgrounds

LBNO CERN-SPSC-EOI-007

Channel	Cut efficiency (%)	Total background in fiducial volume
(p1) $p \to e^+ \pi^0$	45.3	0.2
(p2) $p \to \pi^+ \bar{\nu}$	41.9	164
(p3) $p \to K^+ \bar{\nu}$	96.8	0.4
(p4) $p \to \mu^+ \pi^0$	44.8	1.6
(p5) $p \to \mu^+ K^0$	46.7	< 0.4
(p6) $p \to e^+ K^0$	47.0	< 0.4
(p7) $p \to e^+ \gamma$	98.0	< 0.4
(p8) $p \to \mu^+ \gamma$	98.0	< 0.4
(p9) $p \to \mu^- \pi^+ K^+$	97.6	0.2
(p10) $p \to e^+ \pi^+ \pi^-$	18.6	5
(n1) $n \to \pi^0 \bar{\nu}$	45.1	100
(n2) $n \to e^- K^+$	96.0	< 0.4
(n3) $n \to e^+ \pi^-$	44.4	1.6
(n4) $n \to \mu^- \pi^+$	44.8	5.2

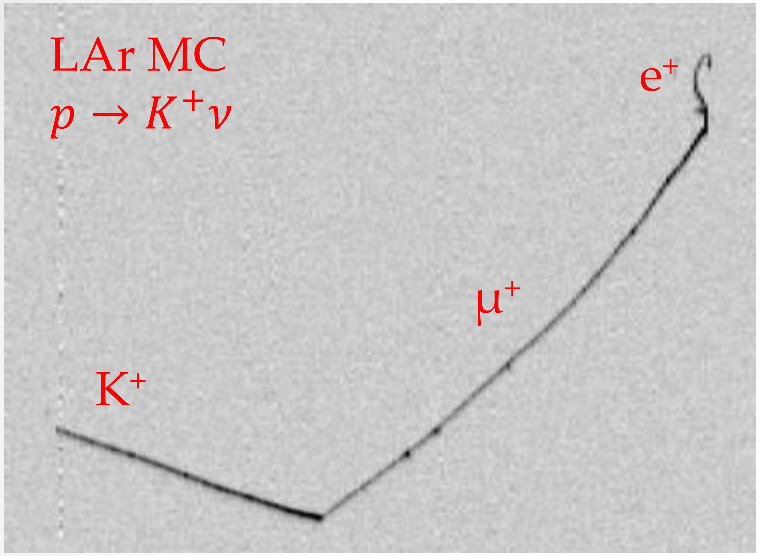
Background event numbers are normalized to 200 kton x years

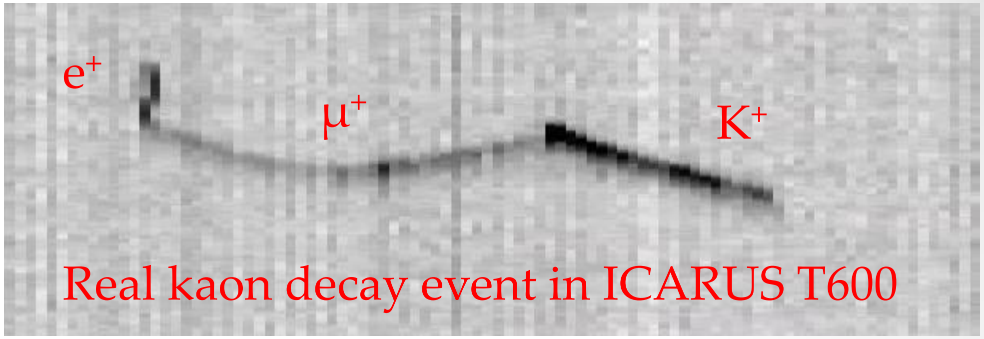
19 -- 98% efficiency

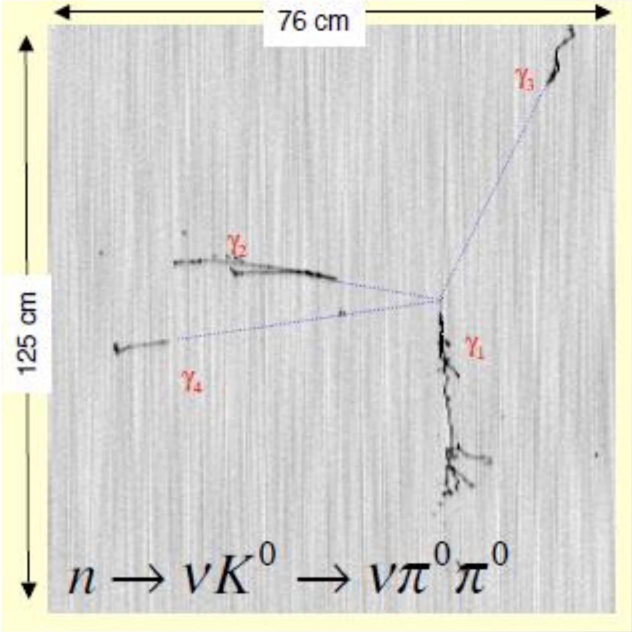
LAr detector can do well with many modes

- High efficiency 96-98% and low background for modes with a charged kaon (e.g., SUSY favoured $p \to K^+\bar{\nu}$)
- Clean measurement of modes with K_S^0
- Multi-prong decay modes
- High e/π^0 separation → high efficiency for decays to single γ modes
- Lepton + pion modes (e.g., $p \to e^+\pi^0$) efficiency comparable to WCh ← nuclear pion absorption

LAr TPC imaging power

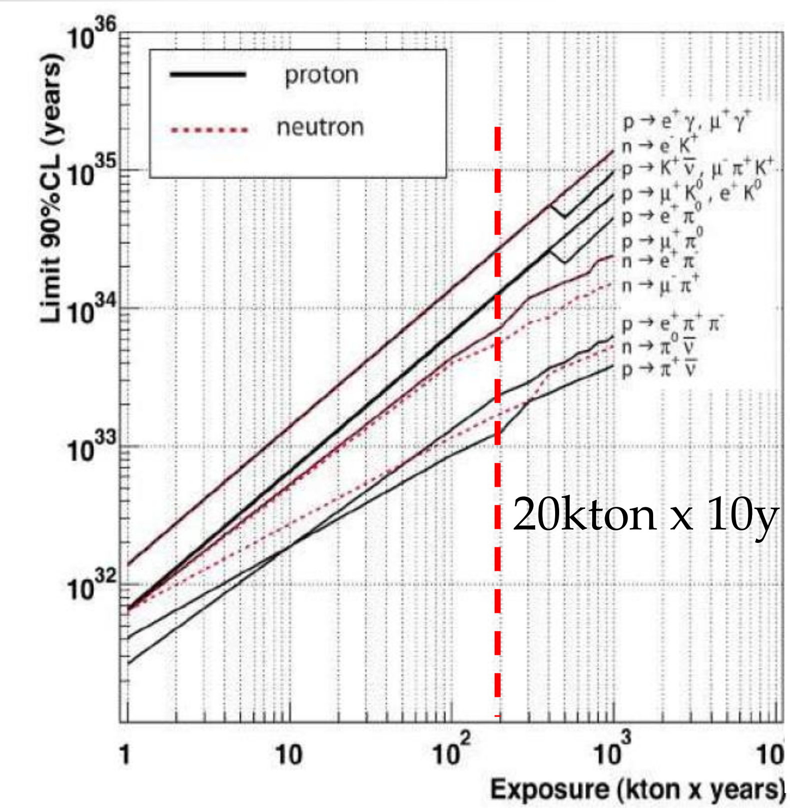


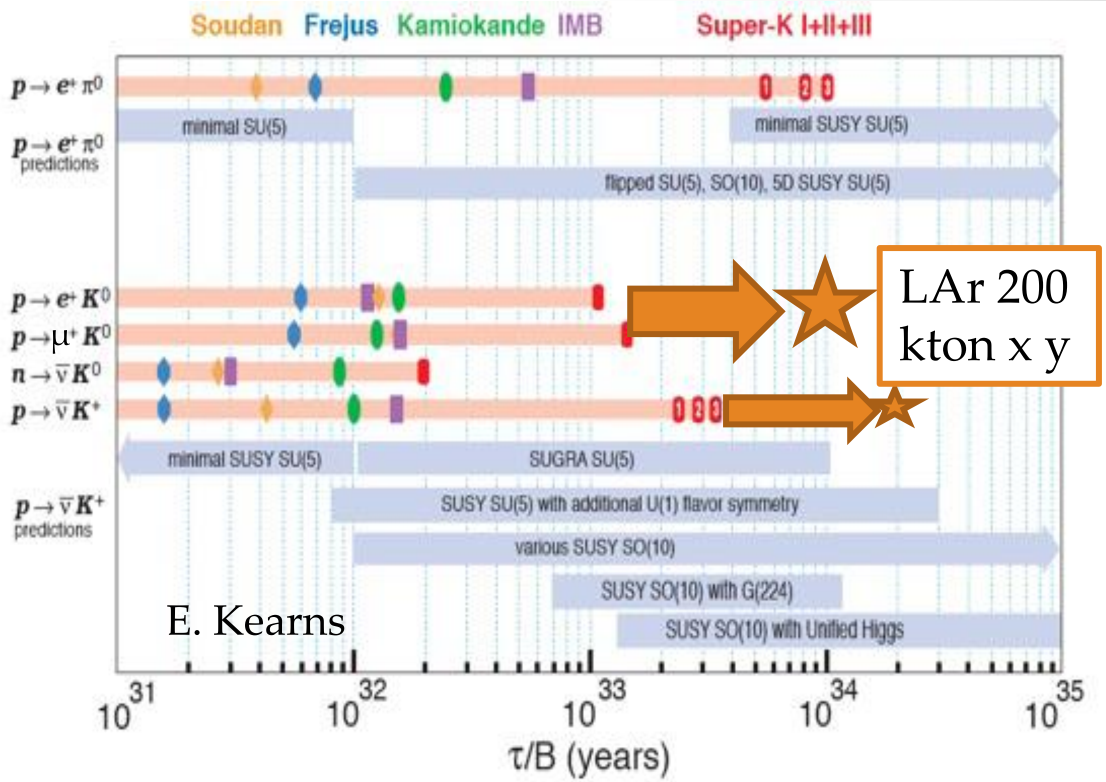




Expected sensitivity

hep-ph/0701101





LAr TPC with fiducial mass comparable to that of Super-K and running time of 10y can reach sensitivities $0.2 \times 10^{34} - 2.0 \times 10^{34}$ years depending on decay modes

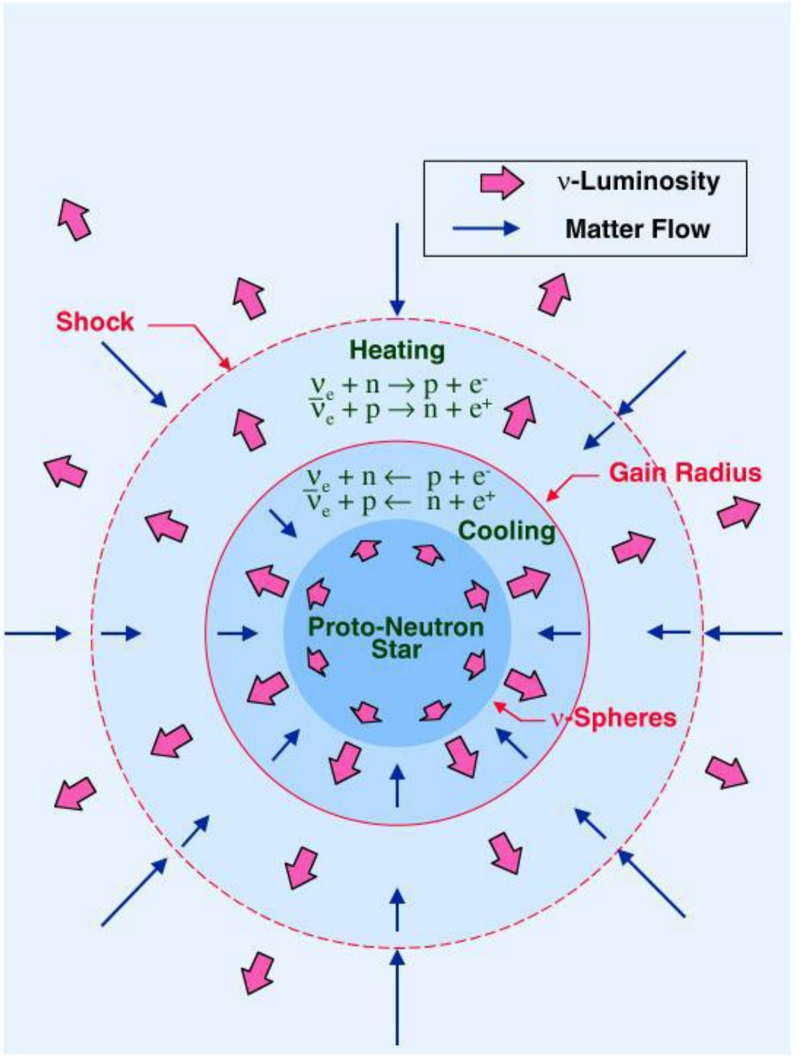
With O(100 kton) can reach ~10^{35} y limit for $p \to K^+\bar{\nu}$

Supernova neutrinos

~99% of the total energy carried by neutrinos

Only particles to provide the information about processes in the interior

- Explosion dynamics
- Proto-neutron star cooling
- Neutrino-neutrino interactions effects
- Flavour transformation in the core collapse supernova



Detecting SN ν's in LAr

- Elastic scattering (ES):

$$\nu(\bar{\nu}) + e^- \rightarrow \nu(\bar{\nu}) + e^-$$

- Charged current interactions (CC):

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*, Q_{th} = 1.5 \text{ MeV}$$

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*, Q_{th} = 7.48 \text{ MeV}$$

- Neutral current interactions (NC):

$$\nu(\bar{\nu}) + {}^{40}Ar \rightarrow \nu(\bar{\nu}) + {}^{40}Ar^*, Q_{th} = 1.46 \text{ MeV}$$

CC & NC channel separation via classification of photons from K, Cl, and Ar de-excitations / Absence of photons for ES

Supernova ν rates in LAr

hep-ph/0404151

Scenario I: expected events in 20 kton detector $\langle E_{\nu_e} \rangle = 11$ MeV, $\langle E_{\bar{\nu}_e} \rangle = 16$ MeV, $\langle E_{\nu_x} \rangle = \langle E_{\bar{\nu}_x} \rangle = 25$ MeV and luminosity equipartition			
Reaction	Without oscillation	Oscillations NH	Oscillations IH
ELAS	1330	1330	1330
ν_e**CC**	6240	31320	23820
$\bar{\nu}_e$**CC**	540	1110	2420
NC	30440	30440	30440
TOTAL	38550	64200	58010

Distance to SN 5 kpc is
Or
100 kton & SN @ 10 kpc

In principle, no threshold for electron detection ← burst occurs in narrow time window ~10sec

- 380 events from "neutronization burst"
- High statistics information on the total neutrino flux + $\nu_e/\bar{\nu}_e$ components → decoupling of osc. physics from SN physics

Supernova relic neutrinos

JCAP 0412:002,2004

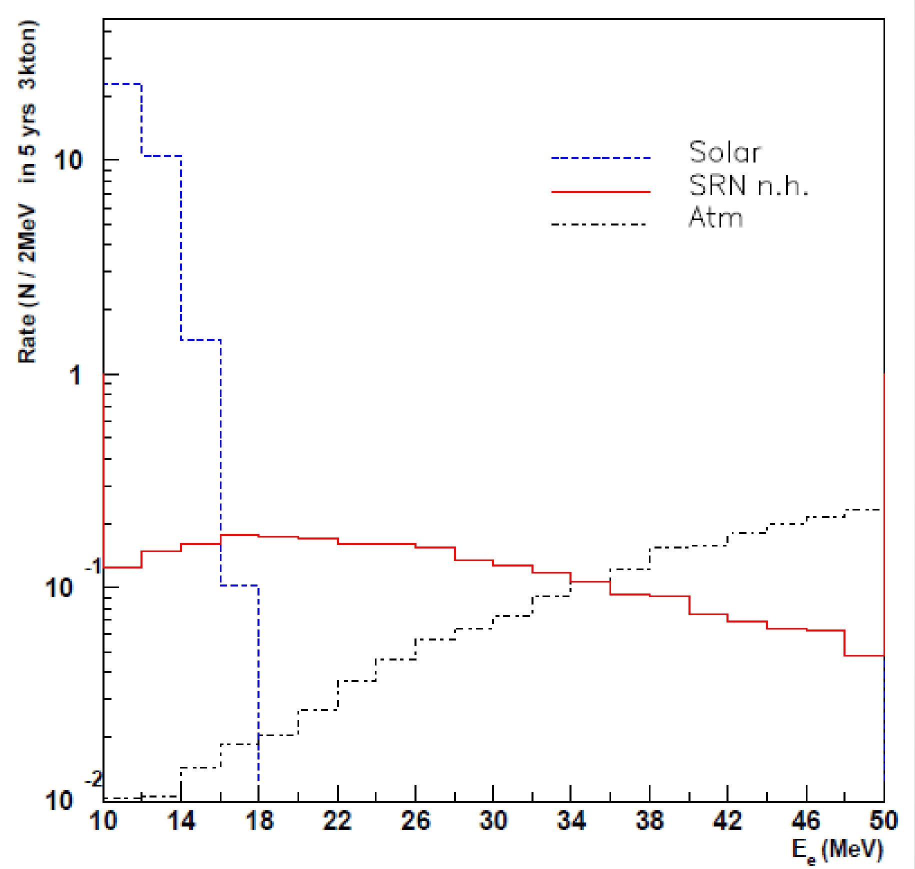
Detection of cumulative neutrino flux from all past SN:

- Cosmic SN rate
- Test average neutrino emission per SN

Principal mode:

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

@ 0.5 Mton x years
S/B = (40 – 60) / 30 in energy window $16 \leq E_e \leq 40$ MeV



The sensitivity will depend on achieved level of backgrounds in the window $16 \leq E \leq 40$ MeV

Solar neutrinos

- Solar neutrino detection:

$\nu_x + e^- \rightarrow \nu_x + e^-$, Elastic scattering

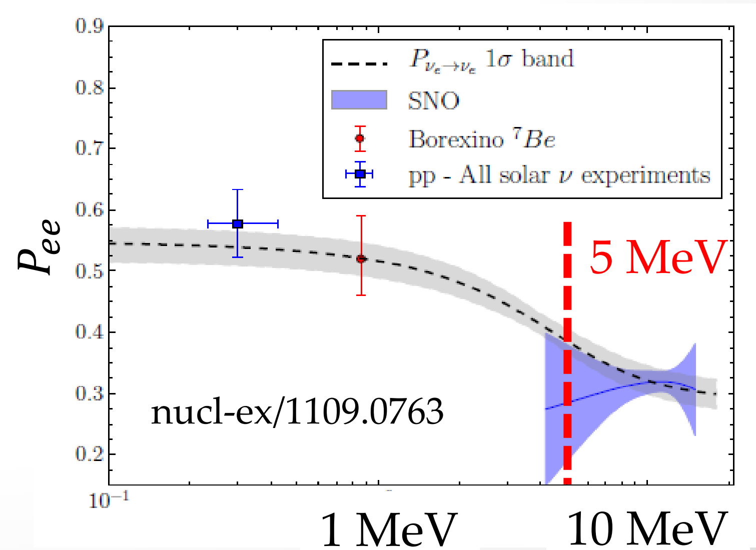
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$, $Q_{th} = 1.5$ MeV, CC reaction

Events (>5MeV) / kton /year

ES	CC
~450	~1600

- Threshold on primary electron energy at least 5 MeV ← reject background from natural rock radioactivity

Measure ES/CC ratio for B^8 neutrinos
→Accuracy will depend on achieved threshold, depth, and size of detector

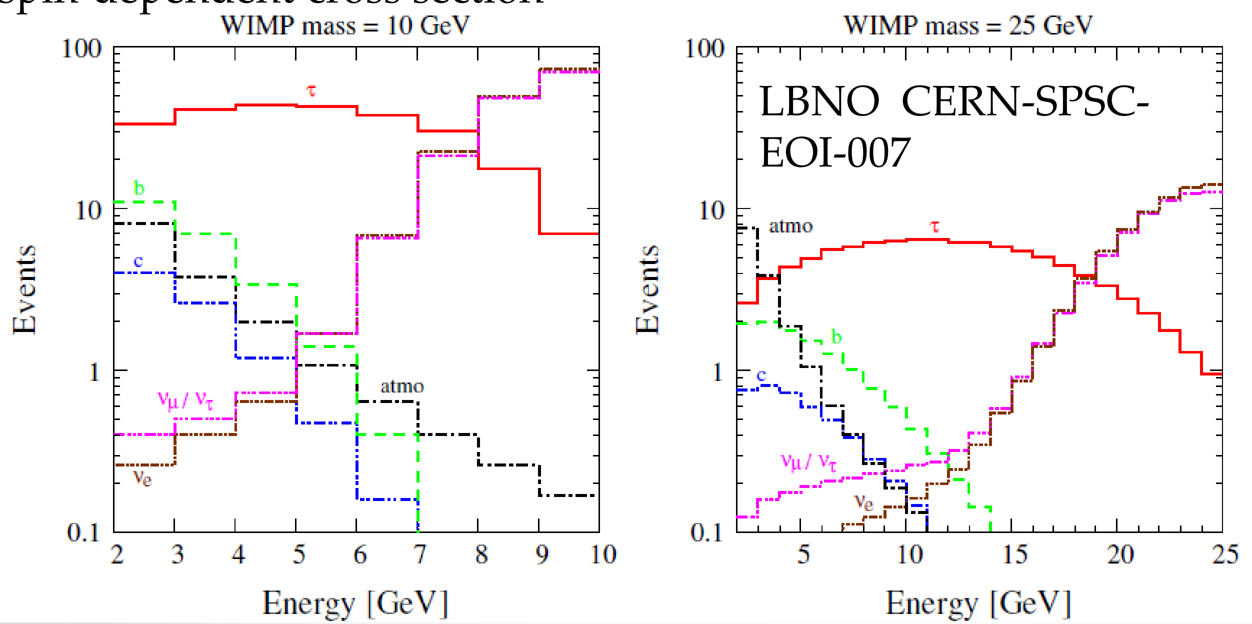


Indirect dark matter detection

- Gravitationally trapped WIMPs in the Sun → could annihilate to produce standard model particles → high energy neutrinos

- Look for energetic (anti)-ν pointing to the Sun

200 kton x years with 1fb DM-nucleon spin-dependent cross section



@ 200 kton x years: Sensitivity to WIMPS with 10 GeV mass: $(BR \times \sigma) \simeq 0.21$ fb at 90% C.L.

Conclusions

- LAr TPCs are excellent in providing bubble chamber-like event details
- A large scale LAr TPC will offer an access to a broad range of physics
- Extensive R&D efforts are on-going towards building tens of kton scale detector

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Extras

Event numbers: LBN(E/O)

Beam hep-ex/1307.7335	ν_μ unosc. CC	ν_μ osc. CC	ν_e beam CC	ν_μ NC	$\nu_\mu \to \nu_\tau$ CC	$\nu_\mu \to \nu_e$ CC $\delta_{CP} = -\pi/2,$	0,	$\pi/2$
LBNE low energy beam 80 GeV, 700 kW 9×10^{20} POT/year								
50 kt-years ν	7421	2531	63	1953	91	353	280	204
50 kt-years $\bar{\nu}$	2478	812	20	876	28	30	50	62

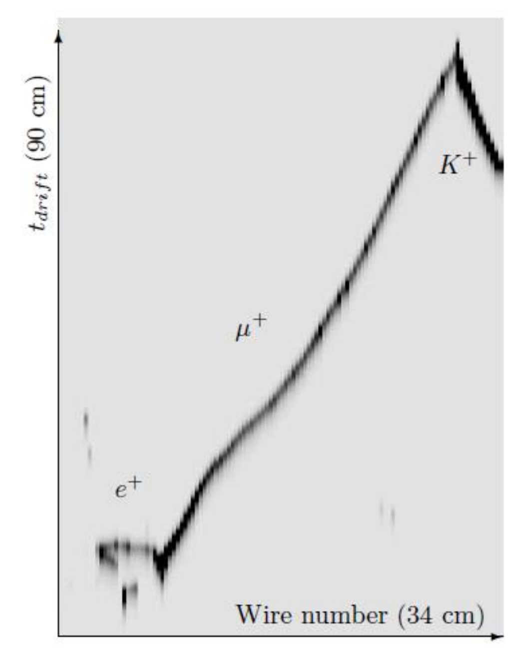
Beam	ν_μ unosc. CC	ν_μ osc. CC	ν_e beam CC	ν_μ NC	$\nu_\mu \to \nu_\tau$ CC	$\nu_\mu \to \nu_e$ CC $\delta_{CP} = -\pi/2,$	0,	$\pi/2$
LBNO: 2300 km NH 400 GeV, 750 kW 1.5×10^{20} POT/year								
50kt years ν	3447	907	22	1183	215	246	201	162
50kt years $\bar{\nu}$	1284	330	5	543	98	20	27	29

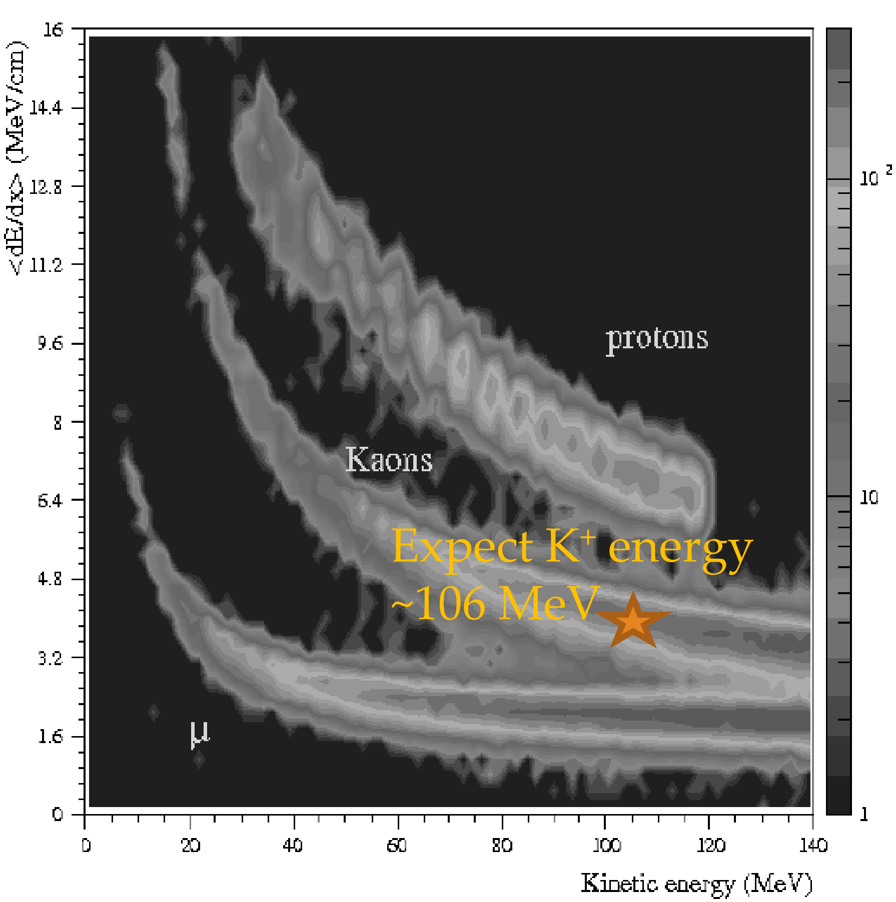
Kaon identification in LAr

hep-ph/0701101

Nucleon decay via

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





Cuts	(p3) $p \rightarrow K^{+}\bar{\nu}$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One kaon	96.8%	308	36	871	146	282	77
No other charged tracks, no π^0	96.8%	0	0	0	0	57	9
$E_{vis} < 0.8$ GeV	96.8%	0	0	0	0	1	0

Supernova ν detector comparison

hep-ph/0705.0116

Table 6. Summary of the expected neutrino interaction rates in the different detectors for a typical SN. The following notations have been used: CC, NC, IBD, *e*ES and pES stand for Charged Current, Neutral Current, Inverse Beta Decay, electron and proton Elastic Scattering, respectively. The final state nuclei are generally unstable and decay either radiatively (notation *), or by β^-/β^+ weak interaction (notation $^{-,+}$). The rates of the different reaction channels are listed, and for LENA they have been obtained by scaling the predicted rates from [65, 66].

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

Table 1. Basic parameters of the three detector (baseline) design.

	GLACIER	LENA	MEMPHYS
Detector dimensions			
type of cylinder	1 vert.	1 horiz.	$3 \div 5$ vert.
diam. (m)	70	30	65
length (m)	20	100	65
typical mass (kton)	100	50	$600 \div 800$

Relic supernova: detector comparison

Table 8. DSNB expected rates. The larger numbers of expected signal events are computed with the present limit on the flux by the Super-Kamiokande Collaboration. The smaller numbers are computed for typical models. The background from reactor plants has been computed for specific sites for LENA and MEMPHYS. For MEMPHYS, the Super-Kamiokande background has been scaled by the exposure.

Interaction	Exposure	Energy Window	Signal/Bkgd
GLACIER			
$\nu_e + {}^{40}Ar \to e^- + {}^{40}K^*$	0.5 Mton year 5 years	[16 – 40] MeV	(40-60)/30
LENA at Pyhäsalmi			
$\bar{\nu}_e + p \to n + e^+$ $n + p \to d + \gamma$ (2 MeV, 200 μs)	0.4 Mton year 10 years	[9.5 – 30] MeV	(20-230)/8
1 MEMPHYS module + 0.2% Gd (with bkgd at Kamioka)			
$\bar{\nu}_e + p \to n + e^+$ $n + Gd \to \gamma$ (8 MeV, 20 μs)	0.7 Mton year 5 years	[15 – 30] MeV	(43-109)/47

hep-ph/0705.0116