Future Neutrino detectors

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APC

Ecole Neutrino GiF-2011

Material from Nufact2011/EPS2011/LeptonPhoton2011/TAUP2011/…
Transparencies taken from Scholberg, Patzak, Raffelt, Schwetz, Luk, Lindner, Rebel,Rubbia, Efthimiopoulos, Kajita, Shahanan, Winter, Chakraborty, Beacom, Mondal, Bays, Svoboda,

Relevance of neutrinos for the 3 major questions of Astroparticle Physics (APIF/OECD definition)

1. What is the role of high energy phenomena in the formation of cosmic structures?

Multi-messenger studies (γ, CR, ν, GW)

Supernova neutrinos, High energy neutrinos for the origin of Cosmic Rays, limits of fundamental laws.

Neutrino Observatories (low and high energy)

2. What is the Universe made of?

Nature of dark matter and energy

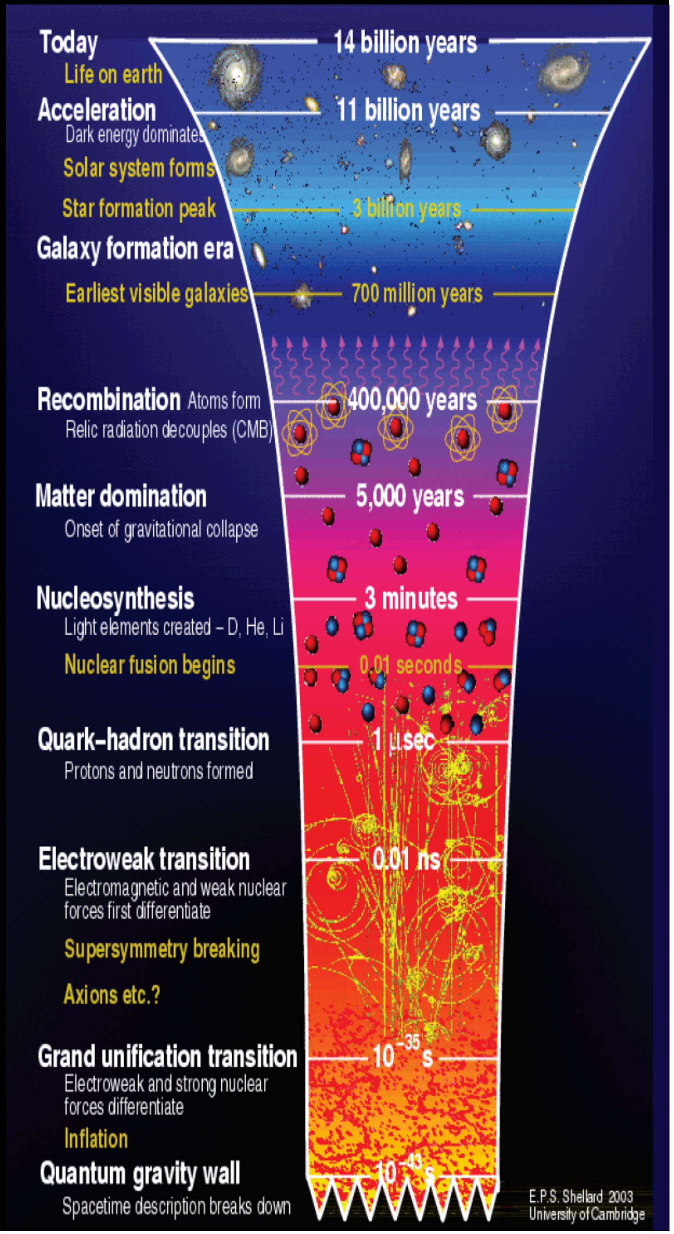
Sterile Neutrinos, Mass Varying Neutrinos, Indirect dark matter detection

Neutrino Oscillation Experiments and Observatories

3. Probe matter and interactions at the highest energies.

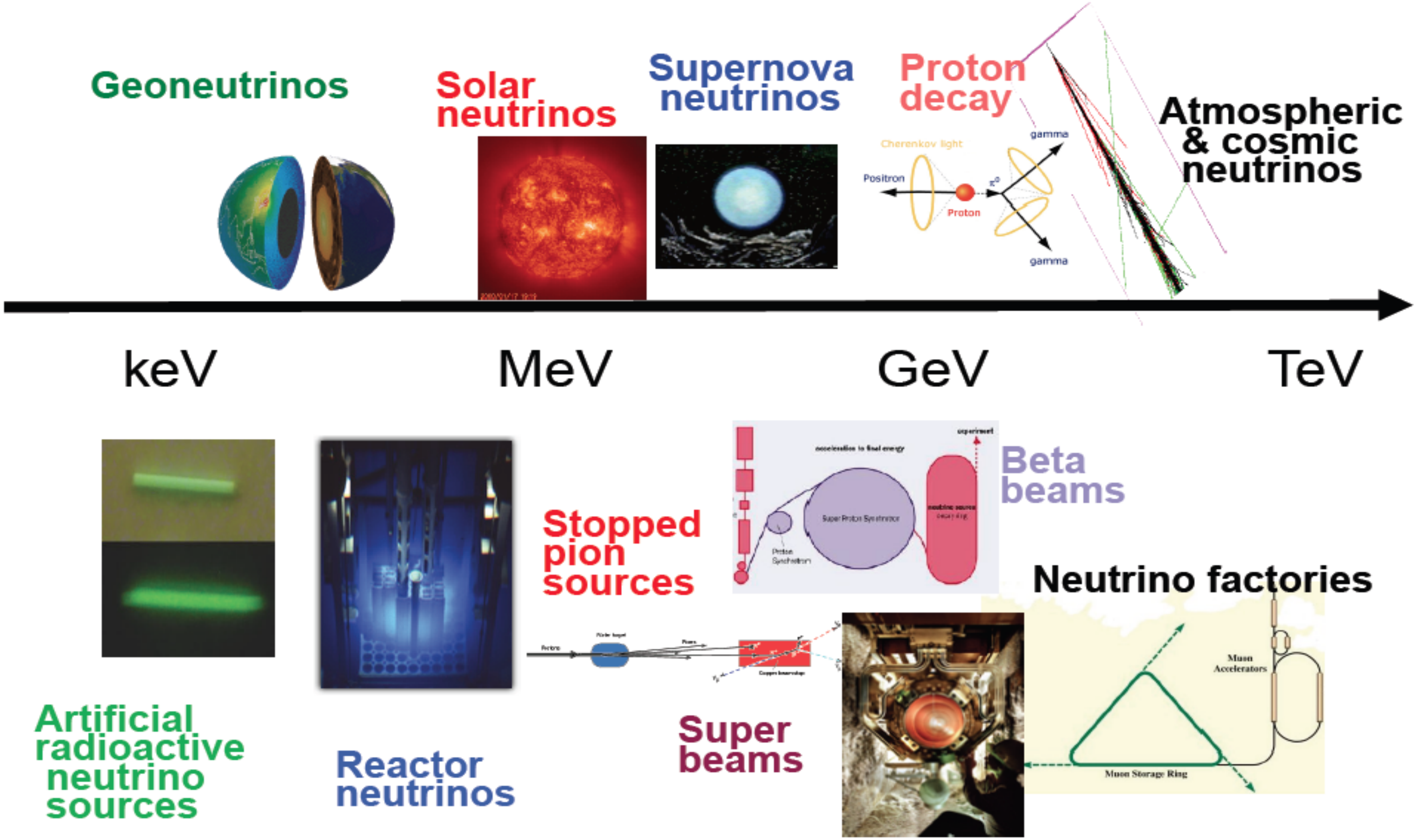
Rare decays: proton lifetime , neutrino properties

Neutrino Observatories, Neutrino Oscillation Experiments, Neutrino Mass experiments



Underground Physics for the Next Decades

Wide range of energy scales & technical issues



Outline*

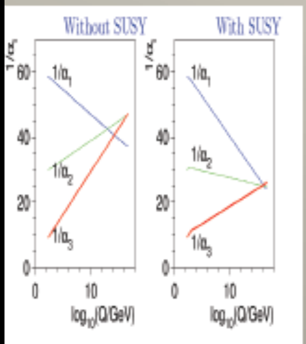
1) Person-made sources
   1. Present and short term results
   2. Long baseline oscillations
2) Cosmic sources and archaeology
   1. Solar system neutrinos
   2. Supernova neutrinos
   3. Proton decay,

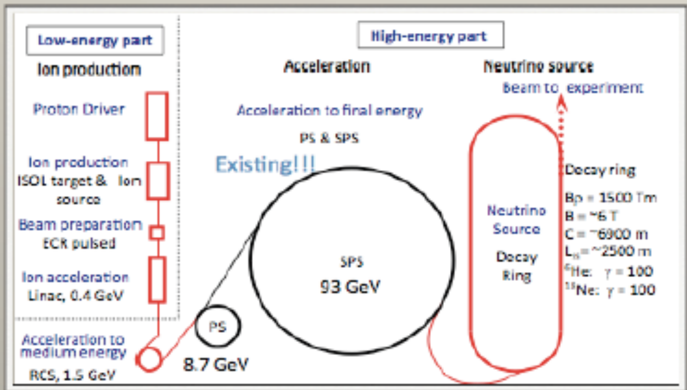
- Will not cover since covered , sterile neutrinos, exotic possibilities, neutrino mass detectors, or high energy neutrino observatories.
  - Some of the best physics may be with them.
- Assume technologies have been presented

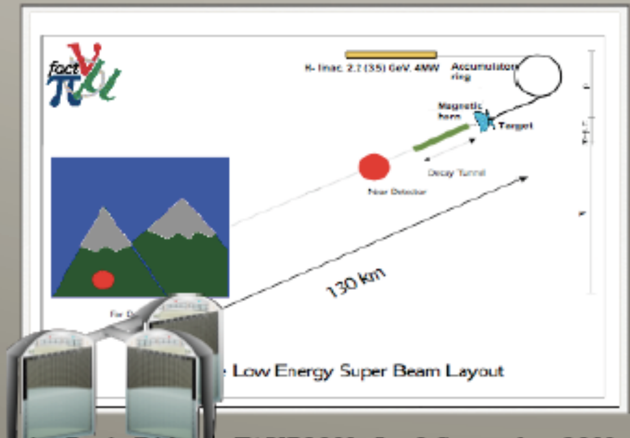
New megaton class, multipurpose detectors will allow to study these fundamental questions

Particle physics

Proton decay
θ13
CP-violation

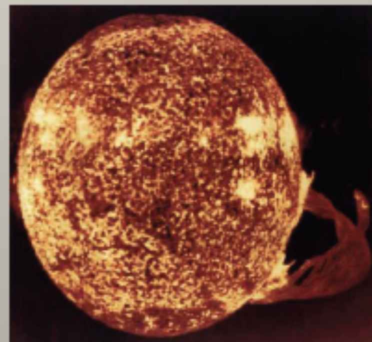


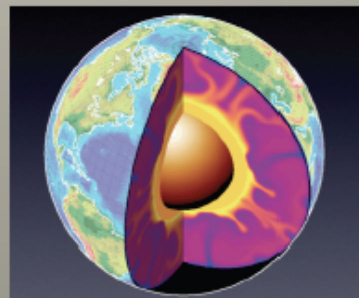




Neutrino astronomy

Supernova neutrinos
Diffuse SN neutrinos
Atmospheric Neutrinos
Solar neutrinos
Dark matter annihilation
Geo-neutrinos...





Person-made sources

Three-Flavor Neutrino Parameters

Atmospheric/K2K	CHOOZ	Solar/KamLAND	2σ ranges hep-ph/0405172
$37^\circ < \theta_{23} < 54^\circ$	$5^\circ < \theta_{13} < 11^\circ$	$30^\circ < \theta_{12} < 36^\circ$	

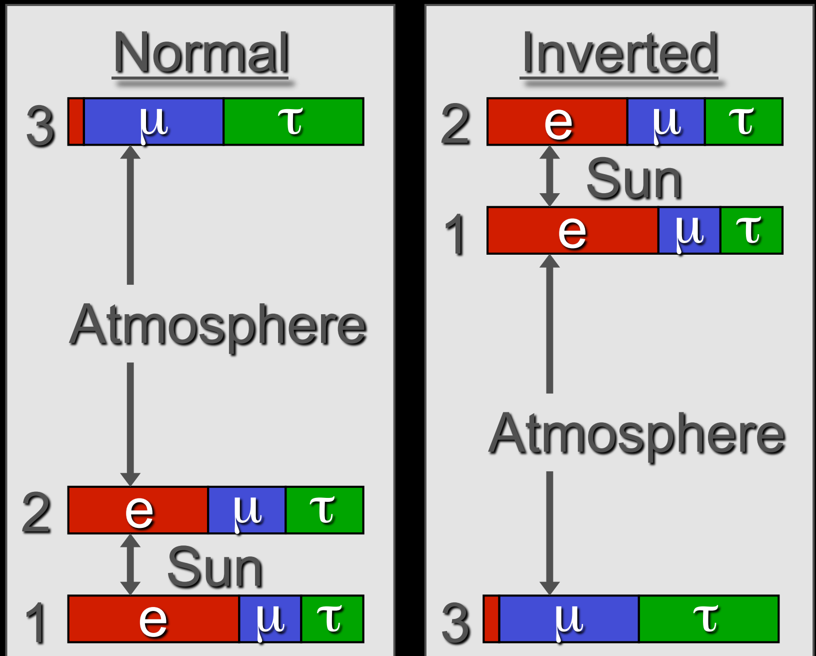
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & e^{-i\delta}s_{13}\\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\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

$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

Solar
75–92

Atmospheric
1400–3000

$\Delta m^2 / \mathrm{meV}^2$



Tasks and Open Questions

- Has θ_{13} been measured ?
- θ_{23} octant ?
- Mass ordering ?
- CP-violating phase δ ?
- Absolute masses ?
- Dirac or Majorana ?
- Sterile Neutrinos ?
- Lorentz violation, CPT ?
- Mass Varying Neutrinos ?

Effects of θ_{13}

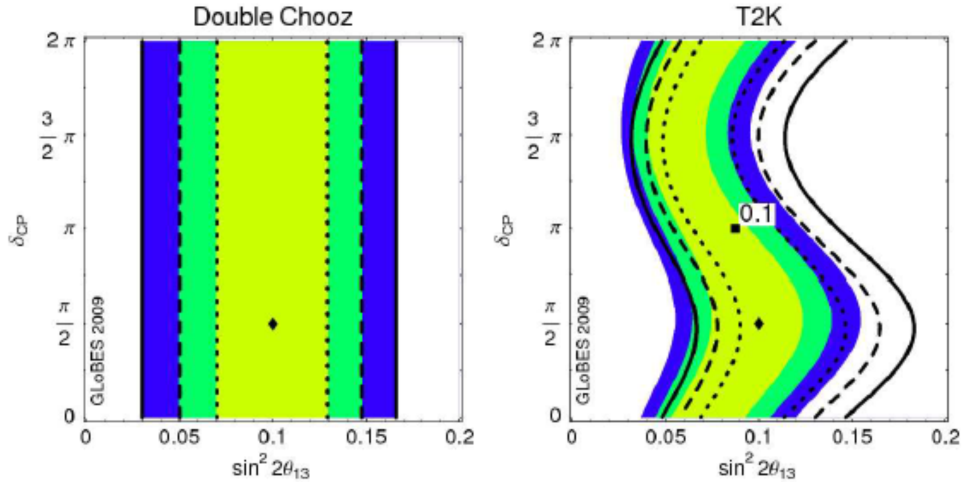
1. subleading effects in solar/KamLAND/atmospheric oscillations

2. transitions of ν_e involving Δm^2_{31}:

   2.1 $\bar{\nu}_e$ disappearance at reactors with $L \simeq 1$ km
   "clean" measurment of θ_{13}: $P \approx 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{31} L/4E)$

   2.2 $\nu_\mu \to \nu_e$ transitions at accelerator experiments
   complicated function of all osc parameters (CP phase δ)

simulation: assume $\sin^2 2\theta_{13} = 0.1$, $\delta = \pi/2$



Huber, Lindner, TS, Winter, 09

νe➔ νμ oscillation formula

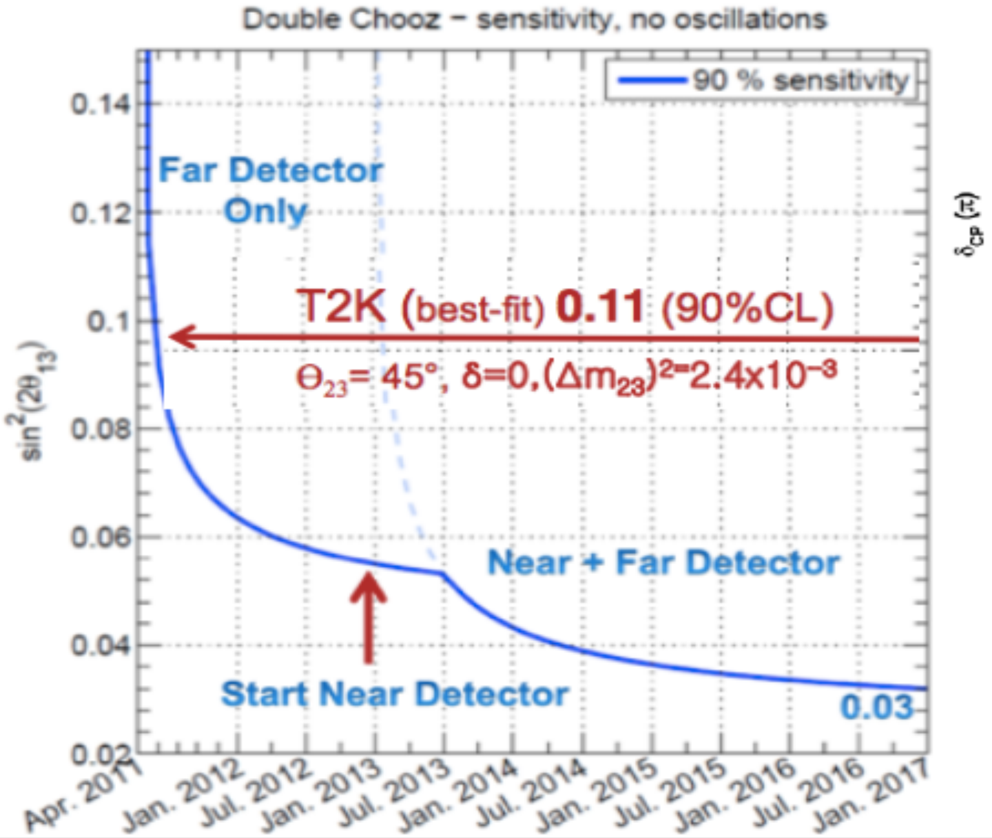
$$\begin{aligned} P_{e\mu} &\simeq \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2[(1\pm\hat{A})\Delta]}{(1\pm\hat{A})^2} \\ &\mp \alpha \sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta_{\mathrm{CP}}\sin(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1\pm\hat{A})\Delta]}{(1\pm\hat{A})} \\ &+ \alpha \sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\delta_{\mathrm{CP}}\cos(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1\pm\hat{A})\Delta]}{(1\pm\hat{A})} \\ &+ \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \end{aligned}$$

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}},\ \Delta \equiv \frac{\Delta m^2_{31}L}{4E},\ \hat{A} \equiv \frac{2\sqrt{2}G_F n_e E}{\Delta m^2_{31}}$$

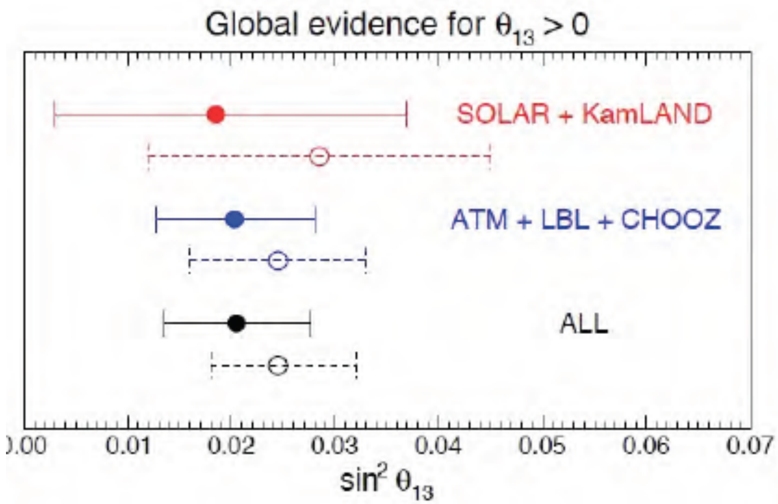
- Antineutrinos: $P_{\bar{e}\bar{\mu}} = P_{e\mu}(\delta_{\mathrm{CP}}, \rightarrow -\delta_{\mathrm{CP}}, \hat{A} \rightarrow -\hat{A})$

- **Cervera et al. 2000; Freund, Huber, Lindner, 2000; Huber, Winter, 2003; Akhmedov et al, 2004**
- **Corrections for large θ$_{13}$**
- Bimagic baseline at 2540 km ➔ high sensitivity to Mass hierarchy Raut et al.
-

Current Knowledge of θ_{13}



Fogli et al.,
arXiv: 1106.6028



solid line = old reactor $\bar{\nu}_e$ flux
dotted line = re-analyzed reactor $\bar{\nu}_e$ flux

$\sin^2 2\theta_{13} \sim 0.1$!?

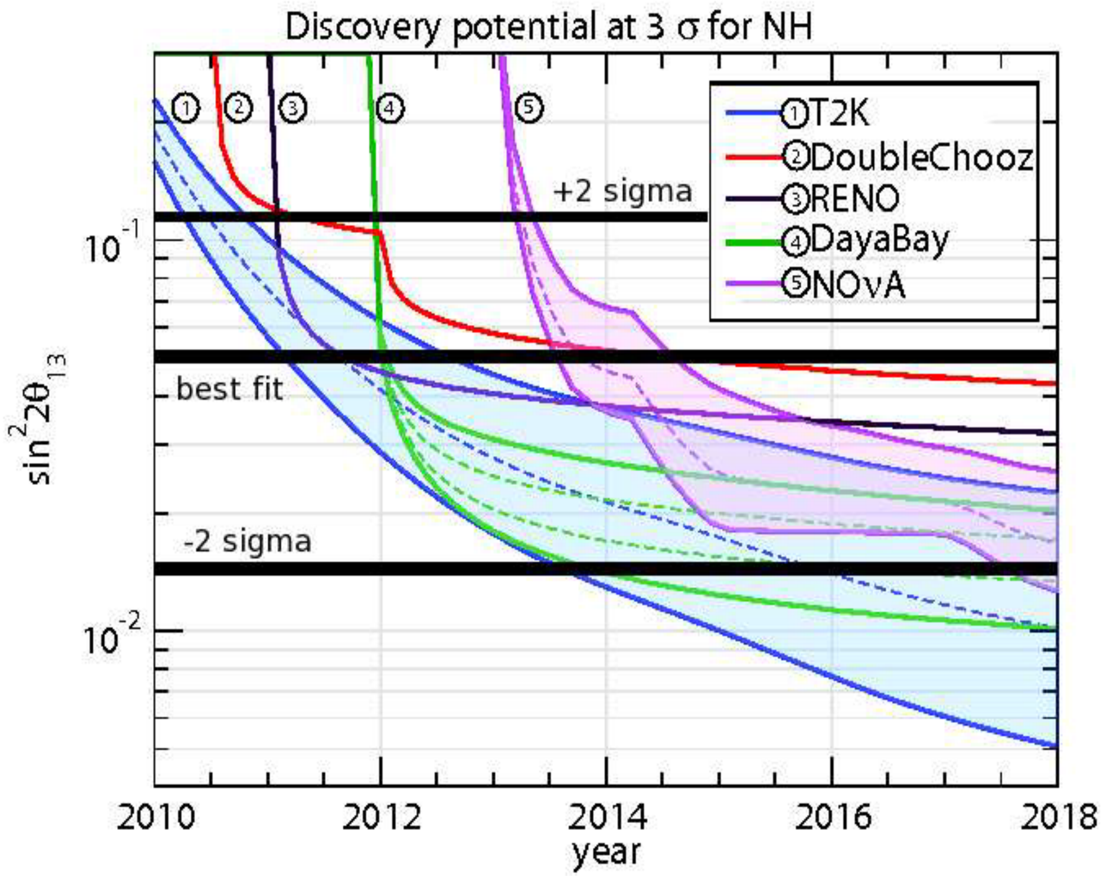
Despite the crisis jubilation in Greece for the « hint » of θ13*

Θ13 = Θυρα 13 = Gate 13

* « Borrowed » from Kam-Biu Luk, Lepton-Photon 2011,

Near term prospects for θ_{13}

upcoming reactor and accelerator experiments talk by K-B Luk

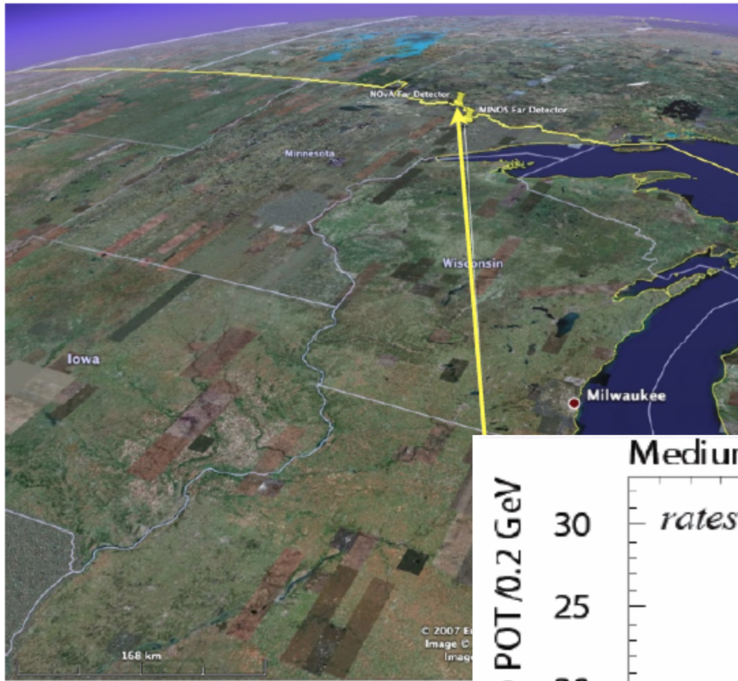


Mezzetto, TS, 10

NOvA

Relatively
Near term

- NOvA is a 810 km baseline neutrino oscillation experiment
- Searching for $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations
- Use near detector to understand beam at source, far to look for oscillations
- Primary physics goals include
  - Measurement of θ_{13}
  - Determining the ordering of mass hierarchy
  - Measure δ - CP violating phase
- Use equal exposures for ν and $\overline{\nu}$



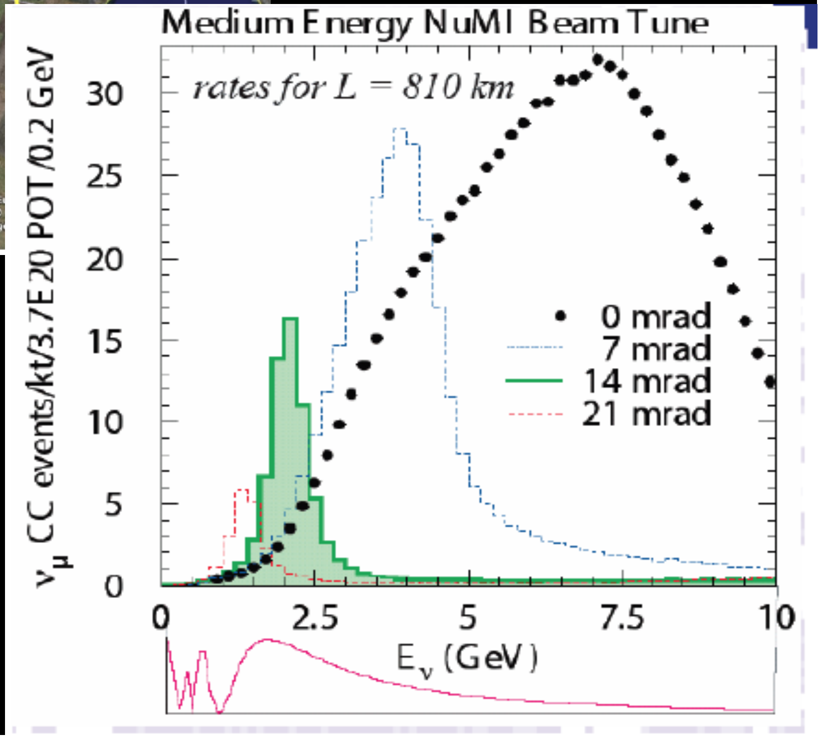
NUMI Beam (400 kW)➔ SNUMI-1 (700 kW)

Short tutorial:

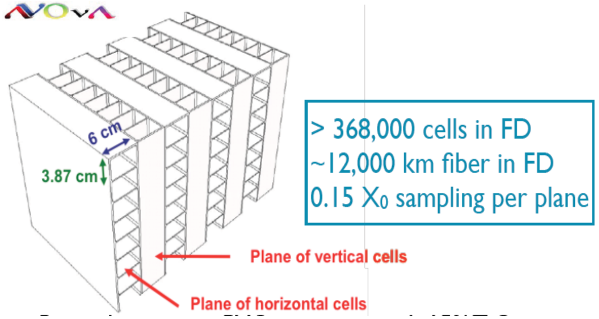
700 KW= 5,4 10^{13}pp at 120 GeV every 1,467 s

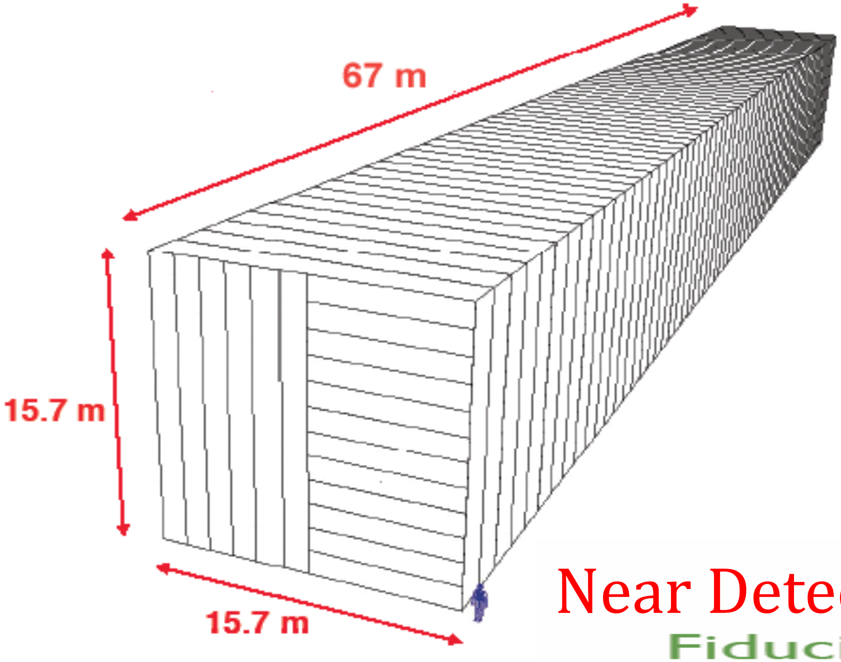
700 KW= 5,4 x 120 /1,467 *x 1,62*

For a 10^7s year ➔ 5,4/1,467 10^{20} pot= 3,7 10^{20} pot

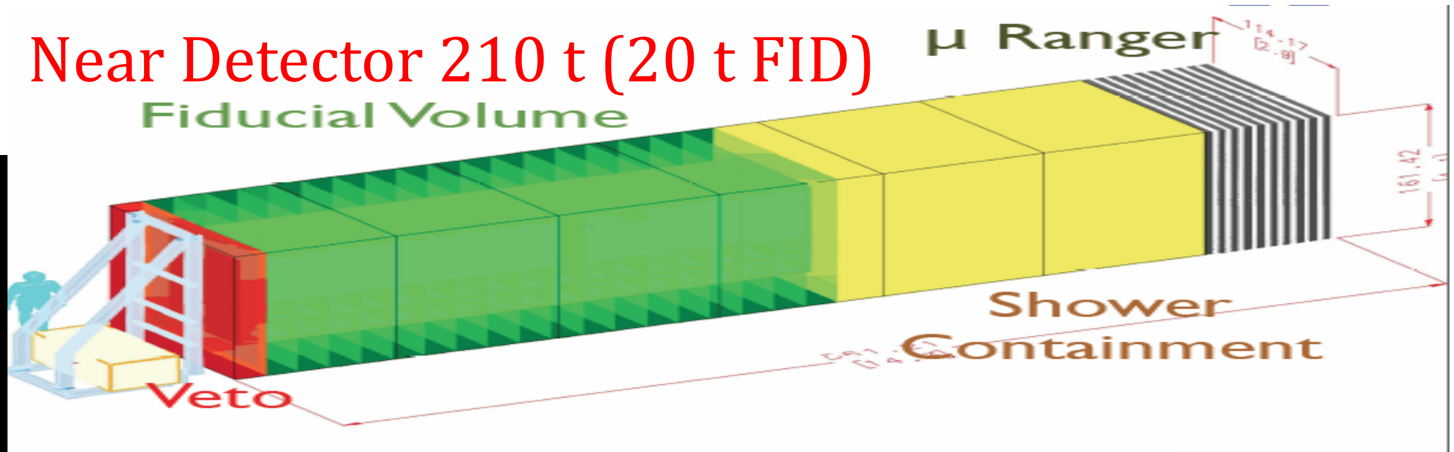


Far Detector





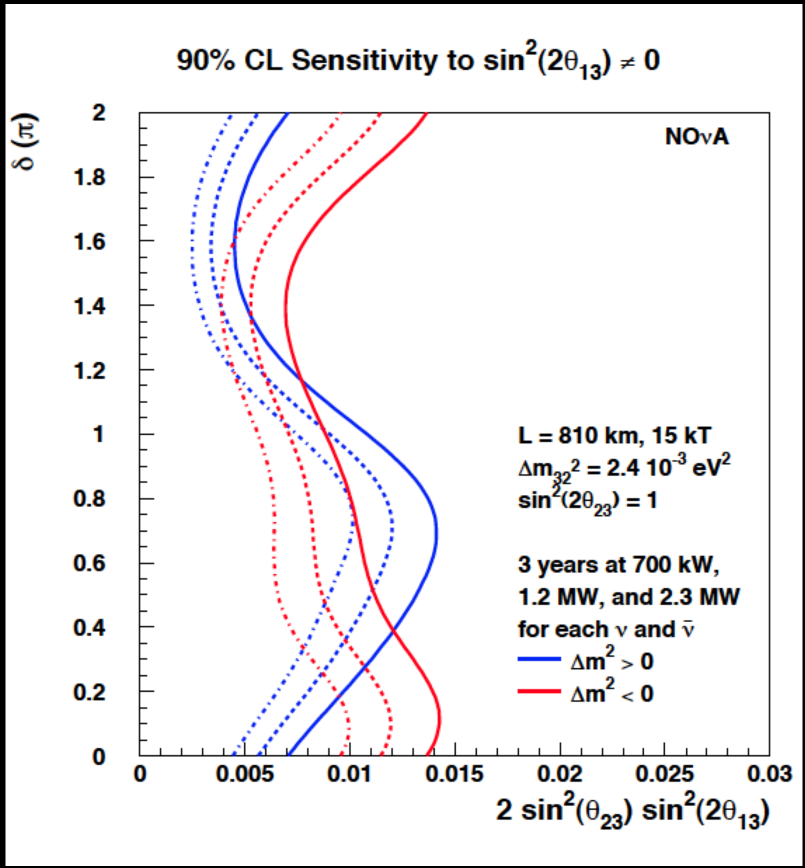
- 14 kt total mass, 70% scintillator
- 930 planes
- ~3 m water equivalent earth overburden of barite and concrete



SNUMI-1 beam turns on 2013, 2/3 of FD constructed, FD completion 2014

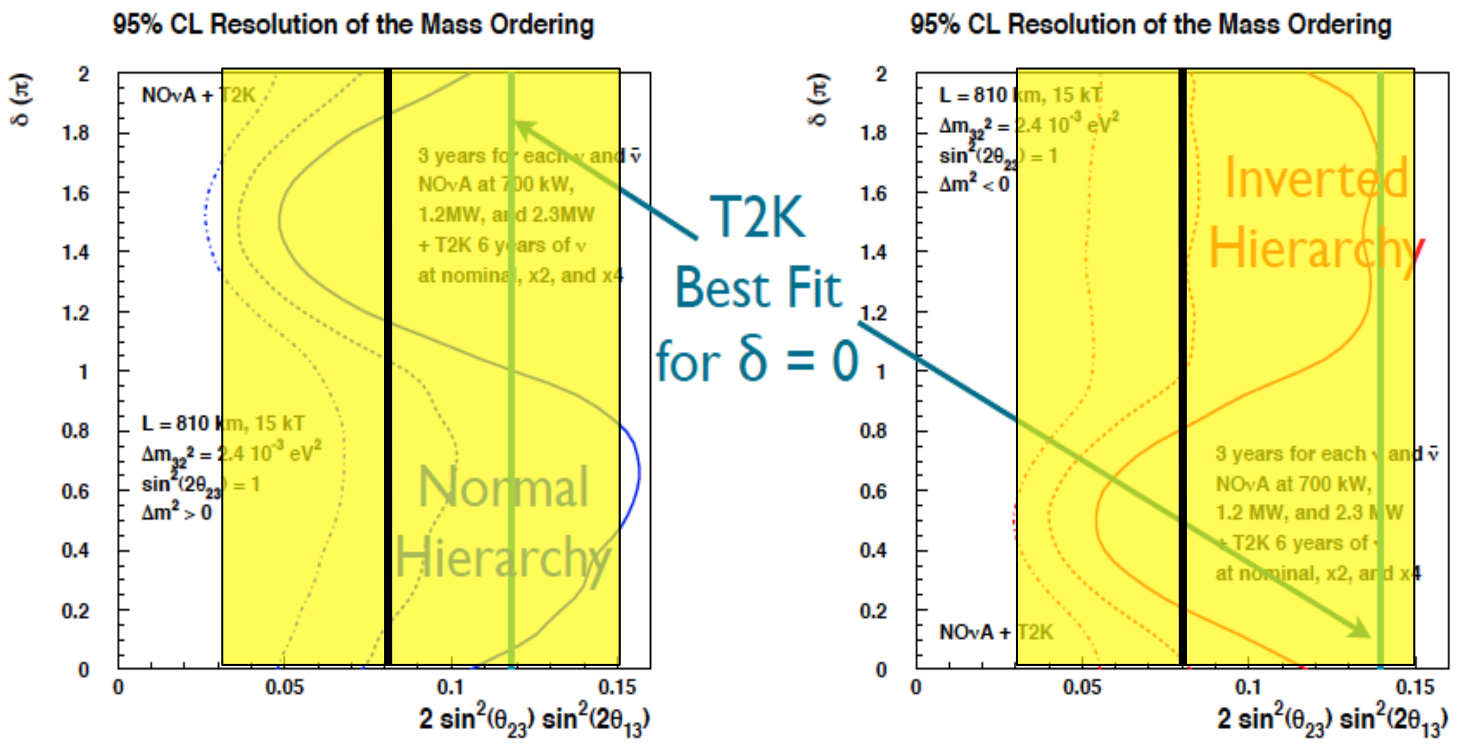
NOVA Physics reach (6 years after start → ca 2020)

Sensitivity to $\sin^2(2\theta 13) \approx 0.01$ as T2K, DayaBay etc

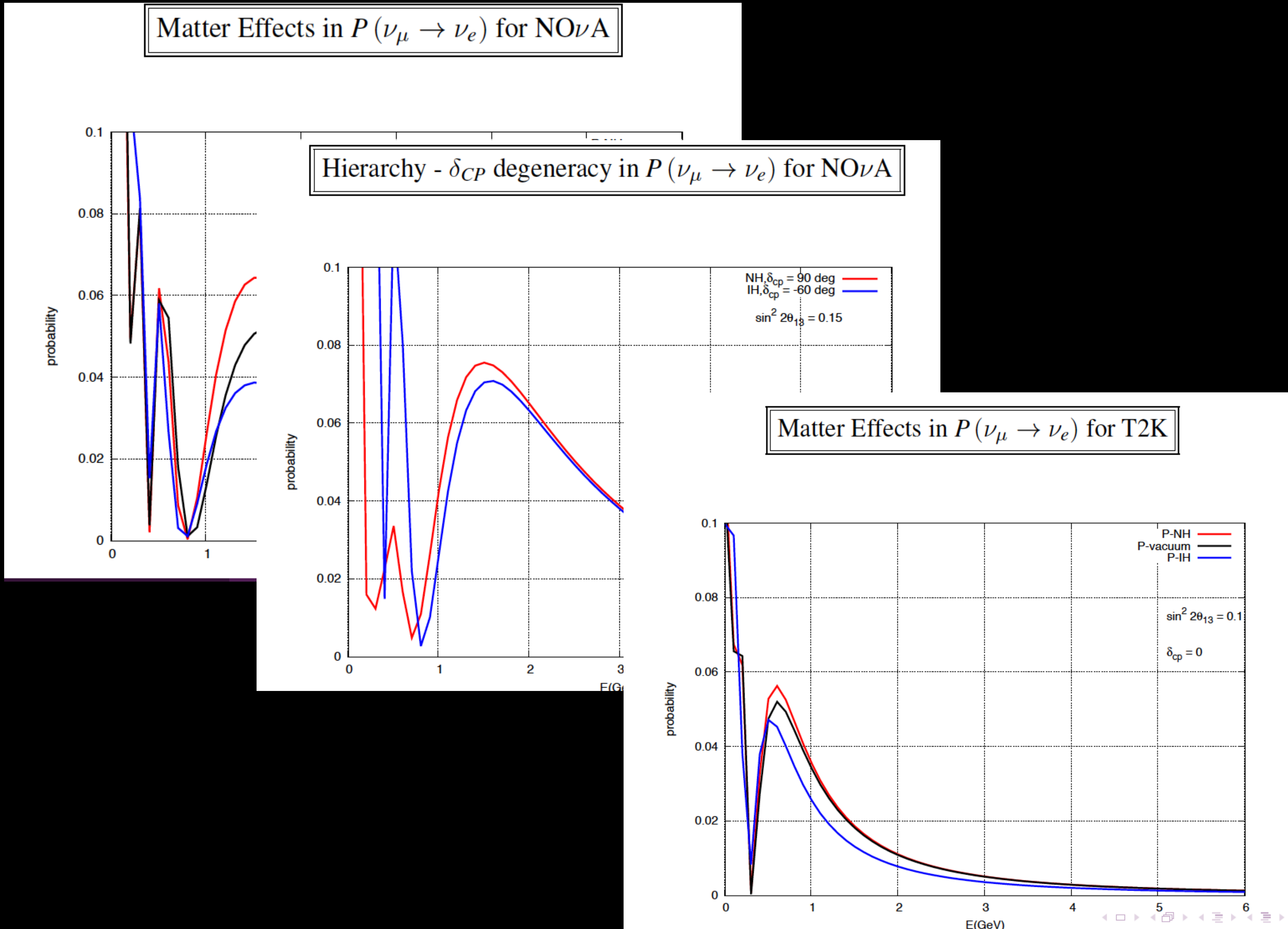


1. Resolution of Mass hierarchy ?
2. Resolution of θ23 ambiguity ?
3. Measure δ ?

Sensitivity to Mass Ordering



The mass hierarchy-CP violation degeneracy hurts NOVA
Adding T2K helps in the unfavourable CP violation region…
Sensitivities get better if CP sign known from elsewhere



Matter Effects in $P(\nu_\mu \to \nu_e)$ for NOνA
probability
Hierarchy - δ_{CP} degeneracy in $P(\nu_\mu \to \nu_e)$ for NOνA
NH,δ_{cp} = 90 deg
IH,δ_{cp} = -60 deg
$\sin^2 2\theta_{13} = 0.15$
probability
Matter Effects in $P(\nu_\mu \to \nu_e)$ for T2K
P-NH
P-vacuum
P-IH
$\sin^2 2\theta_{13} = 0.1$
$\delta_{cp} = 0$
probability
E(GeV)

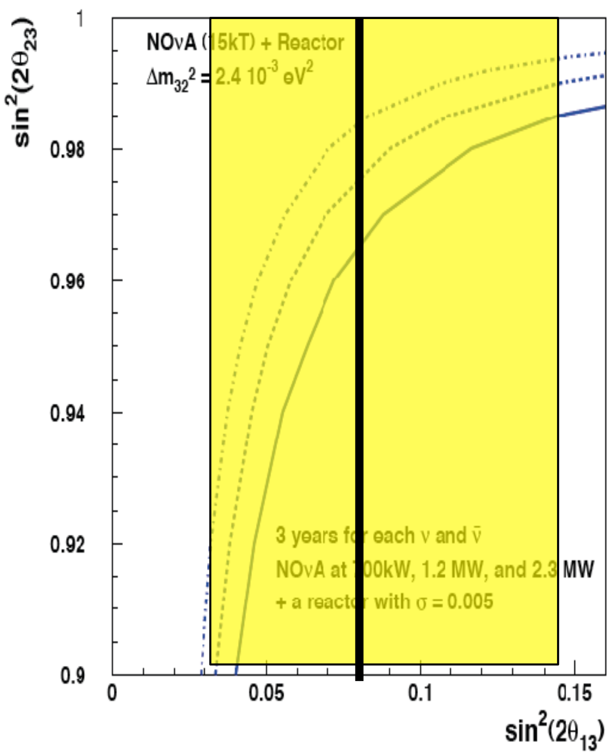
θ_{23} ambiguity

- Dominant term in $P(\nu_\mu \rightarrow \nu_e)$ for long-baseline accelerator is proportional to $\sin^2(\theta_{23})\sin^2(2\theta_{13})$
- But $\sin^2(2\theta_{23})$ is measured in long baseline ν_μ disappearance experiments

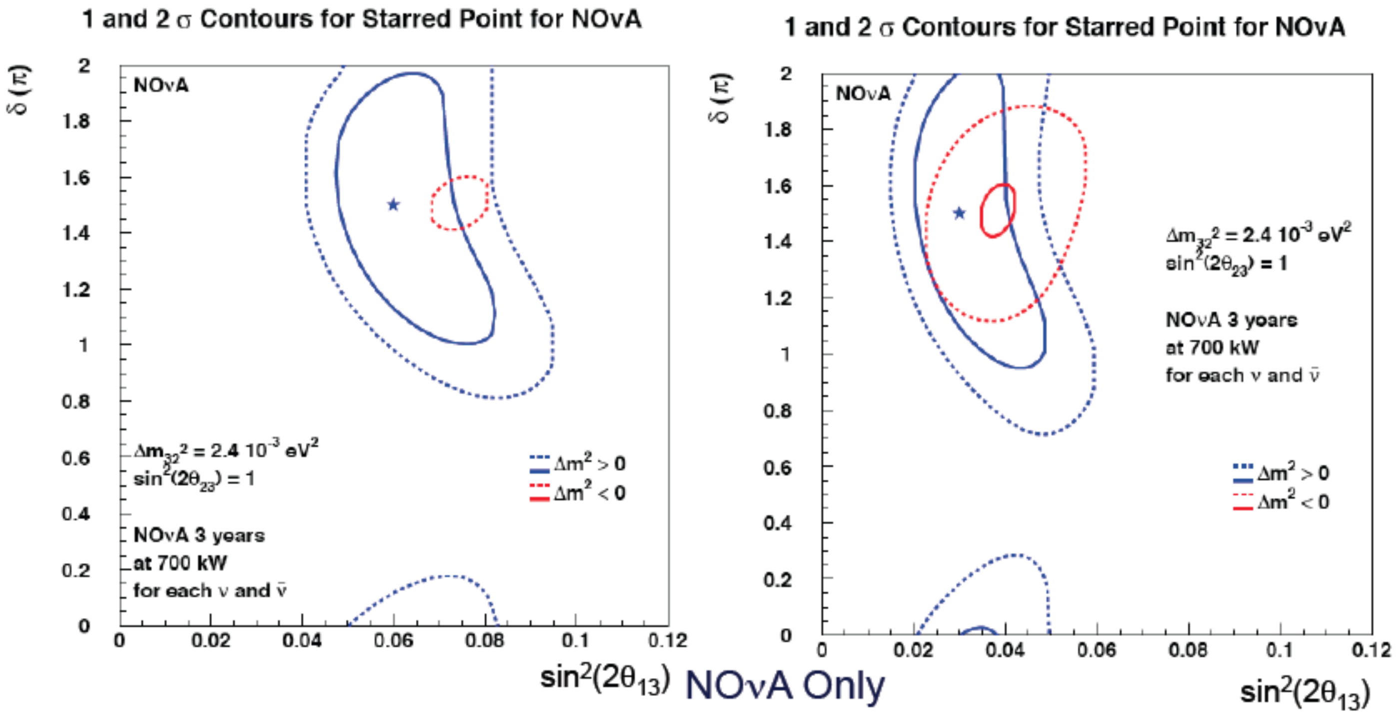
  Difference is significant for $\theta_{23} \neq \pi/4$

- Fortunately, reactor experiments are sensitive to $\sin^2(2\theta_{13})$ without θ_{23} factor
- Comparison of LB appearance and Reactor results can allow resolution ambiguity:

does ν_3 have more ν_μ ($\theta_{23}<\pi/4$) or ν_τ ($\theta_{23}>\pi/4$) ?



Best-case δ for normal MH



NOvA Only

Both scenarios: δ constrained to upper half of plane

Left: MH resolved at 95% CL

Right: MH not resolved

What will we know by 2018-2020 ? (M. Mezzetto-T.Schwetz hep-ph-1003.5800)

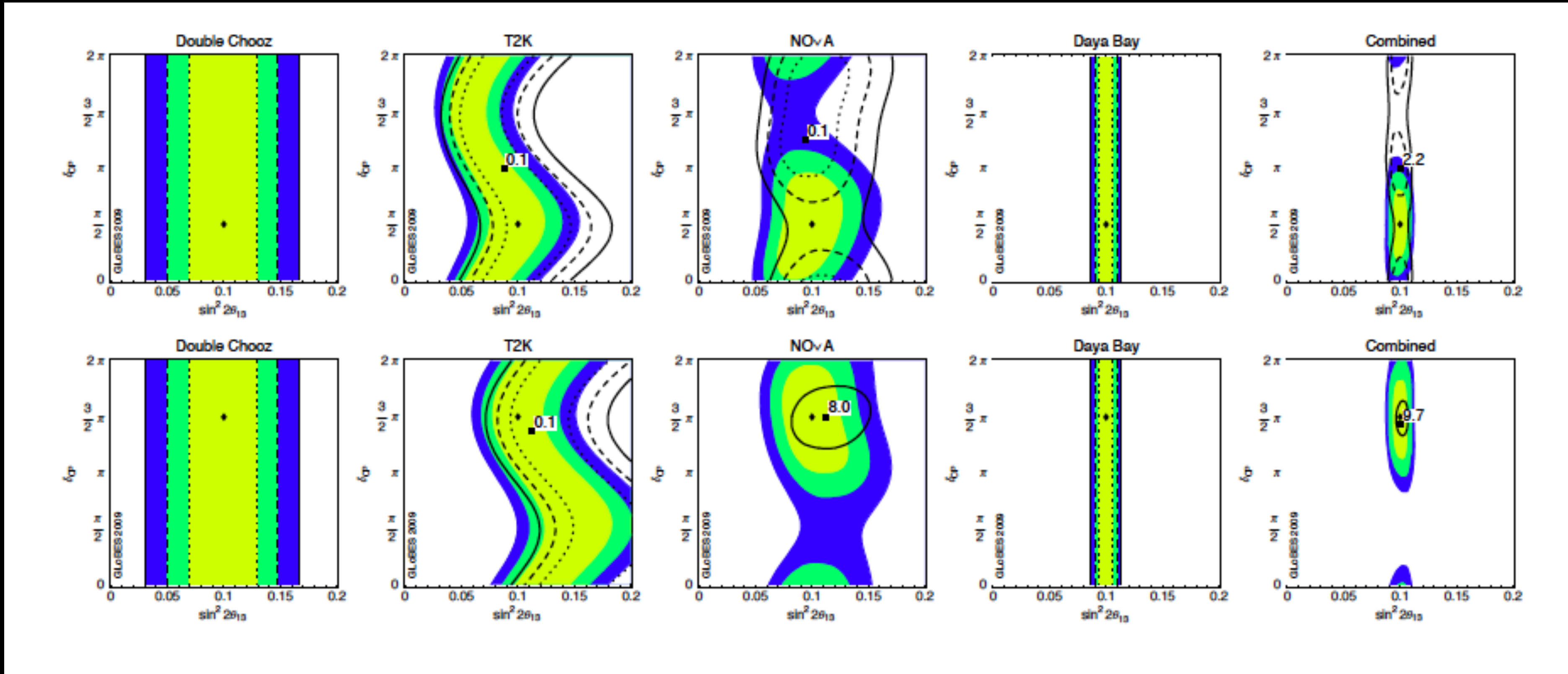


Figure 14. Exemplary fit results for Double Chooz, T2K, NOνA, Daya Bay, and the combination. Shown are fits in the θ_{13}-δ plane assuming $\sin^2 2\theta_{13} = 0.1$ and $\delta = \pi/2$ (upper row) and $\delta = 3\pi/2$ (lower row). A normal simulated hierarchy is assumed. The contours refer to 1σ, 2σ, and 3σ (2 dof). The fit contours for the right fit hierarchy are shaded (coloured), the ones for the wrong fit hierarchy are shown as curves. The best-fit values are marked by diamonds and boxes for the right and wrong hierarchy, respectively, where the minimum χ^2 for the wrong hierarchy is explicitly shown. Reprinted from Ref. [137], Copyright (2009), with permission from JHEP.

Future Large Detectors

EUROPE

... In a

LAGUNA

Large Apparatus for Grand Unification and Neutrino Astrophysics

2008 - 2011

1,7 M€ from EU

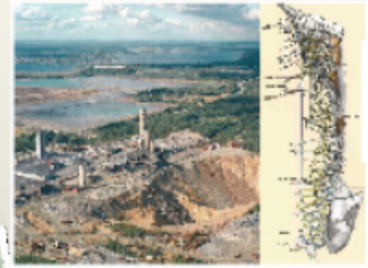
7 canditate sites:

- Boulby
- Fréjus
- Caso
- LSC
- Pyhäsalmi
- Sunlab
- IFIN-HH

Boulby mine
1050 Km

LSM
130 Km

LSC
630 Km



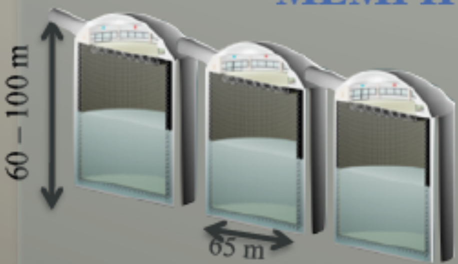
2300 Km, Pyhhäsalmi

SUNLAB
950 Km

Unirea Salt Mine

CASO, 659 Km

MEMPHYS



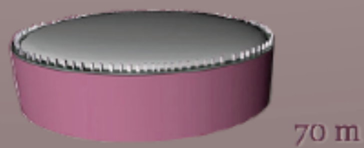
~ 440 ktons fiducial mass

Water Čerenkov

GLACIER

Liquid Argon

~ 100 ktons fiducial mass



LENA

Liquid Scintillator

~ 50 ktons fiducial mass

✓Laguna => very comprehensive evaluation of all sites, construction and costs

✓Laguna => baselines from 130 km to 2300 km available in Europe = advantage

✓Laguna => allowed to form a strong community in Europe (> 100 physicists and Ing.)

✓Laguna => showed the need to evaluate constraints and costs for the detector options

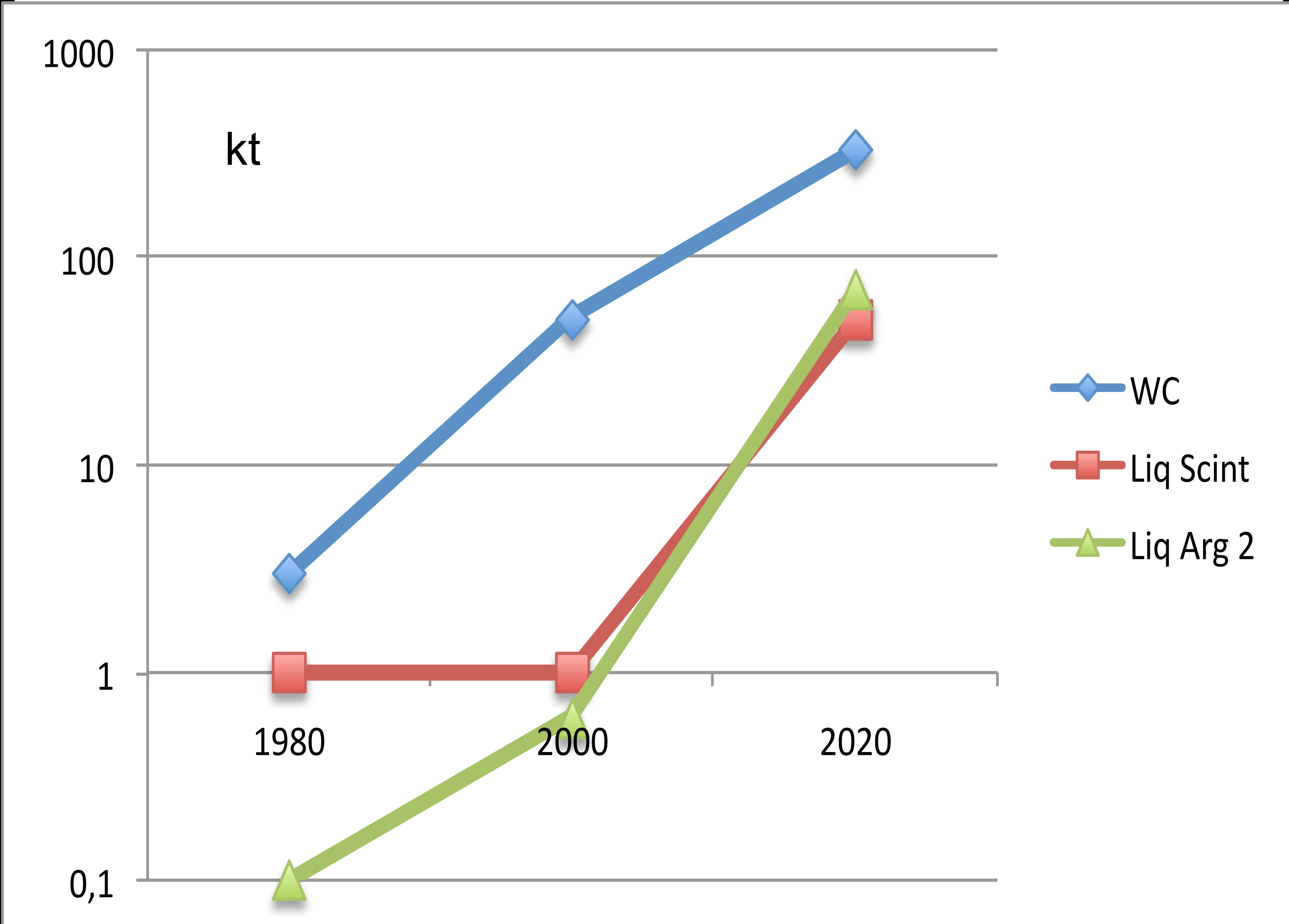
New program: Laguna-LBNO (one of the two fully financed by EC, 5M€)
Start September 2011 – End September 2014

- Laguna-LBNO: evaluate costs for detector construction and long term running (> 30y)
- Laguna-LBNO: investigates complementary beam options from CERN
- Laguna-LBNO: deep study of physics potential for the combination detector/site
- Laguna-LBNO: strengthens the community even more:

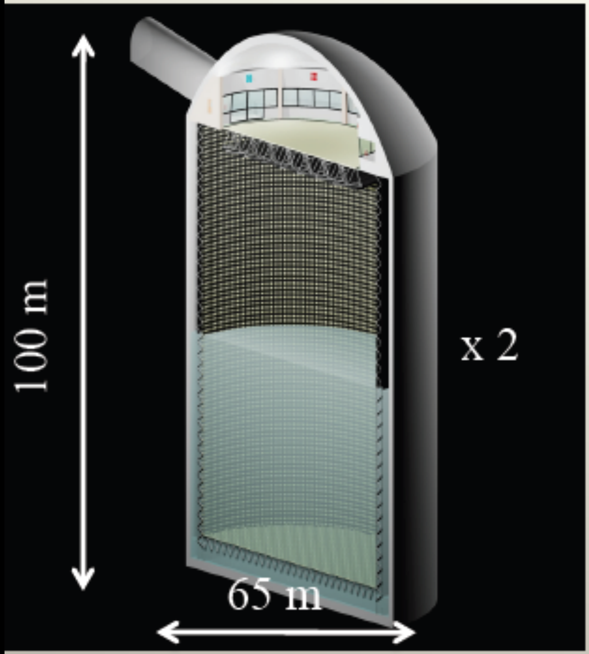
> 250 physicists, 13 countries, 39 beneficiaries

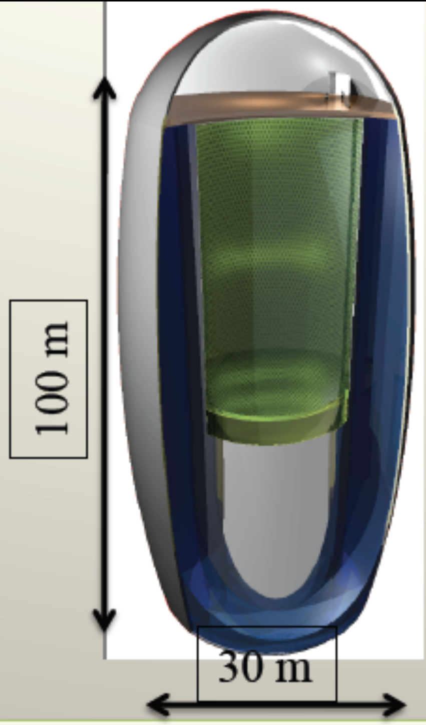
Focus on 3 options:

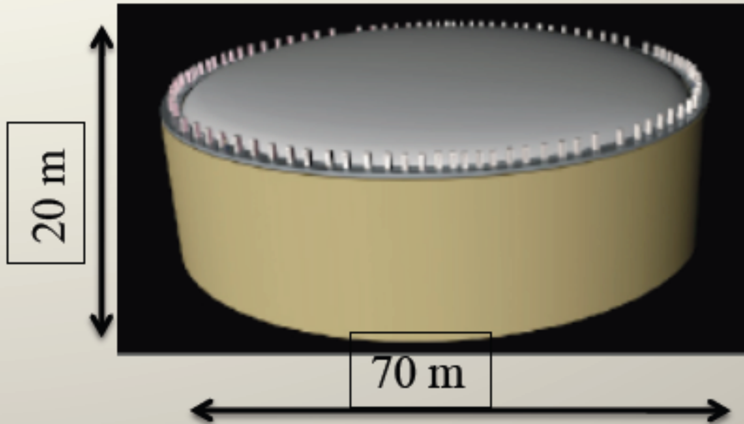
1. Shortest baseline (130 km), CERN -> Fréjus: no matter effects; clean measurement of LCPV
2. Longest baseline (2300 km), CERN -> Pyhhäsalmi: matter effect; mass hirarchy, LCPV
3. Upgrade existing CNGS (Umbria?)



1000
100
10
1
0,1
kt
1980
2000
2020
WC
Liq Scint
Liq Arg 2







Memphys
2 x 330 kt
220’000 8” or 10” PMT’s

QE > 25%
DR 1 to 300 p.e.
Time resolution 1 ns
Low after pulsing
Pressure 10 bars
Lifetime > 30 y

LENA
50 kt
55’000 8” PMT’s

QE > 25%
DR 0.2 MeV to 10 GeV
Time resolution < ns
Low after pulsing
Pressure 15 bars
Lifetime > 30 y

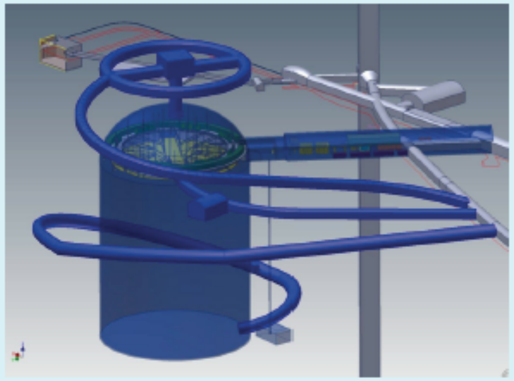
See talk by J. Winter

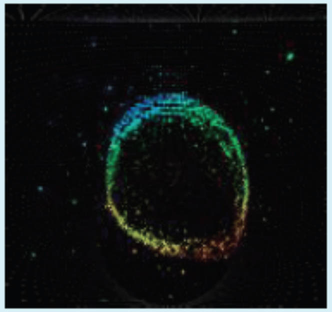
Glacier
100 kt
1’000 8” WLS-coated cryo PMT’s
27’000 cryogenic PMT’s

QE > 25%
Time resolution O ns
Lifetime > 30 y cryogenic!

See talk by A. Rubbia

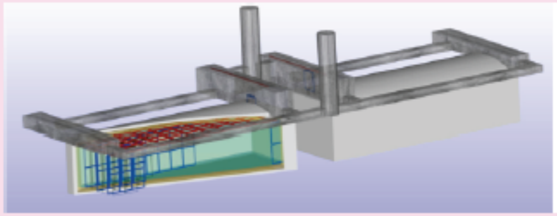
Water Cherenkov

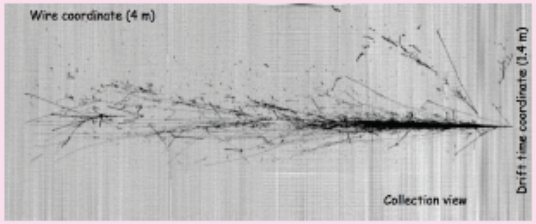




Cheap material, proven at very large scale

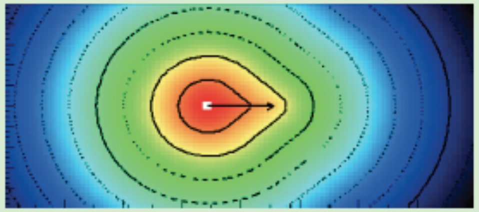
Liquid Argon



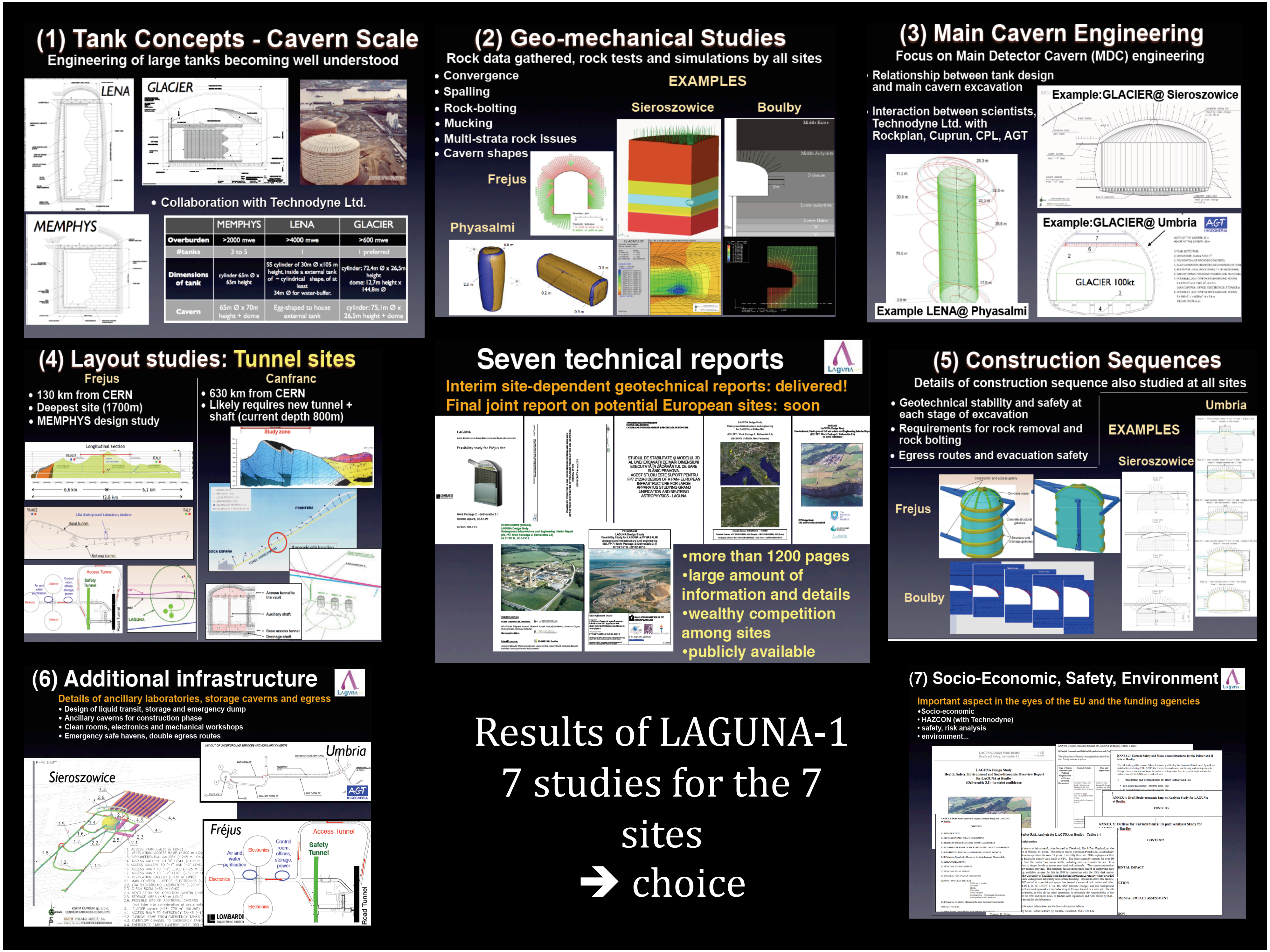


Excellent particle reconstruction

Liquid Scintillator



Low energy threshold



	MEMPHYS	LENA	GLACIER
Overburden	>2000 mwe	>4000 mwe	>600 mwe
#tanks	3 to 5	1	1 preferred
Dimensions of tank	cylinder 65m Ø x 65m height	SS cylinder of 30m Ø x105 m height, inside a external tank of ~ cylindrical shape, of at least 34m Ø for water-buffer.	cylinder: 72,4m Ø x 26,5m height dome: 12,7m height x 144,8m Ø
Cavern	65m Ø x 70m height + dome	Egg-shaped to house external tank	cylinder: 75,1m Ø x 26,5m height + dome

LAGUNA-LBNO sites

New conventional beams to be considered based on CNGS experience

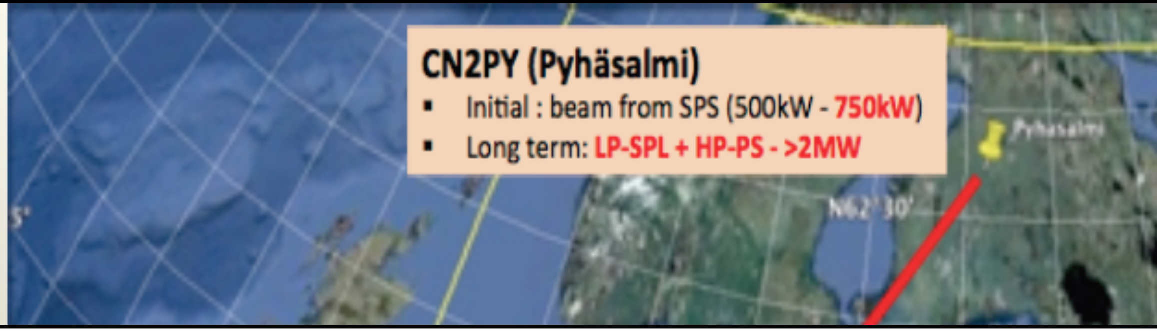


Table 1: Potential sites being studied with the LAGUNA design study.

Location	Type	Envisaged depth m.w.e.	Distance from CERN [km]	Energy 1st Osc. Max. [GeV]
Fréjus (F)	Road tunnel	4800	130	0.26
Canfranc (ES)	Road tunnel	1500-2700	630	1.27
Umbria(IT) [a]	Green field	1500-2300	665	1.34
Sierozsowice(PL)	Mine	1400	950	1.92
Boulby (UK)	Mine	3400-4000	1050	2.12
Slanic(RO)	Salt Mine	840	1570	3.18
Pyhäsalmi (FI)	Mine	2500-4000	2300	4.65

[a] $\simeq$1.0 ° CNGS off axis.

AR, arXiv:1003.1921

- [CERN-Umbria has an existing beam but is considered at lower priority (missing near detector, limited power upgrade scenarios)]

Courtesy: A. Rubbia

ν beams at CERN – future possibilities

Short timescale (~2015)

- Conventional LBL ν-beams from SPS (400 GeV)
  - Exploit the CNGS technology, sub-MW class facility, **CNGS+**
    - Intensity upgrade, new focusing scheme for low ν-beam energies
- Conventional SBL ν-beam from PS (20 GeV) – **PSNF**
  - Dedicated experiment on sterile neutrinos
  - Test bed for detector and targetry R&D, x-section measurements

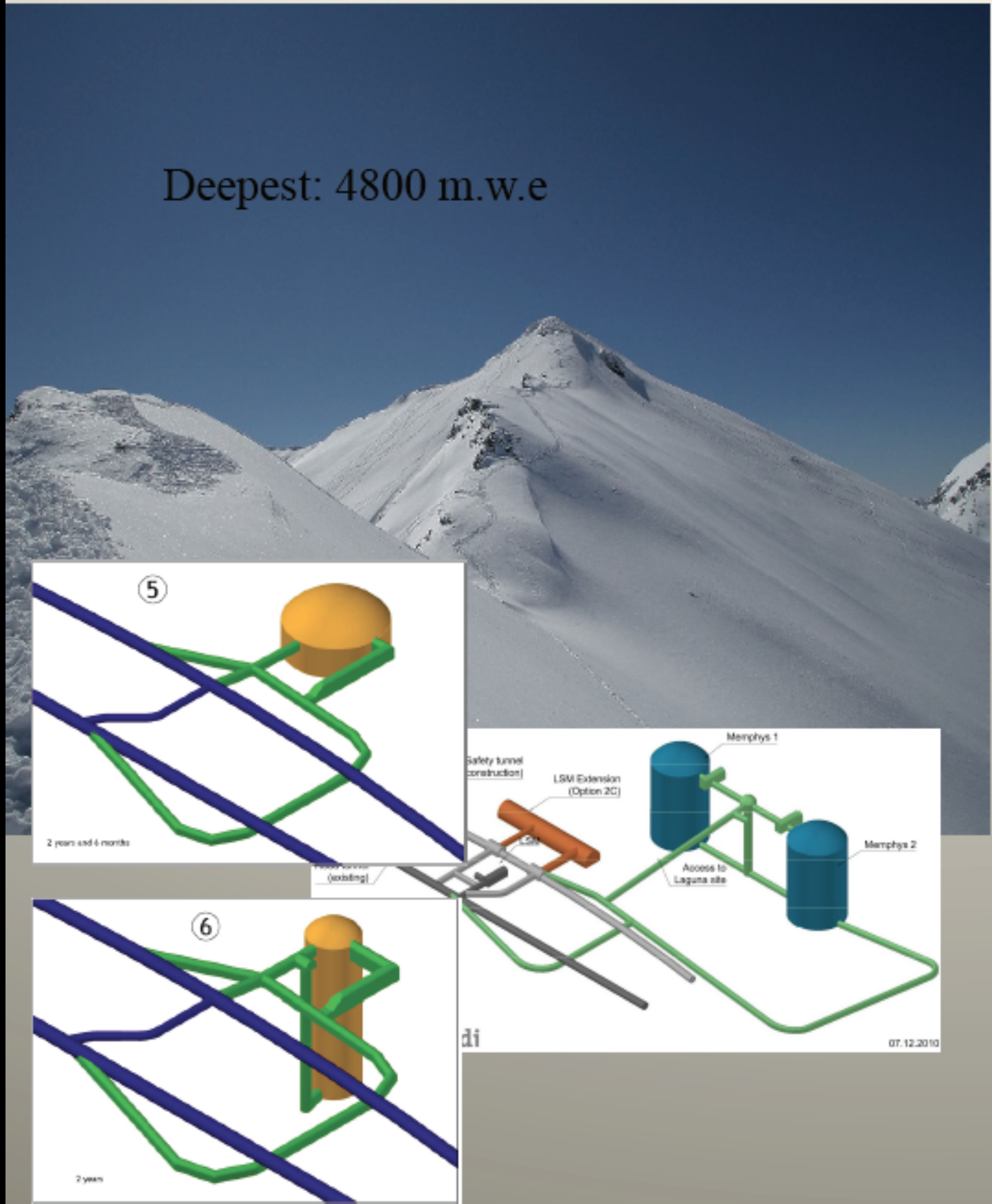
Medium timescale (~2020)

- Conventional LBL ν-beams from SPS (400 GeV)
  - CNGS++ beam to a new site (**CN2?**)
- Upgrade using LP-SPL as proton driver, new HPPS (30 GeV)
  - ~MW class facility (**CN2?-HP**)

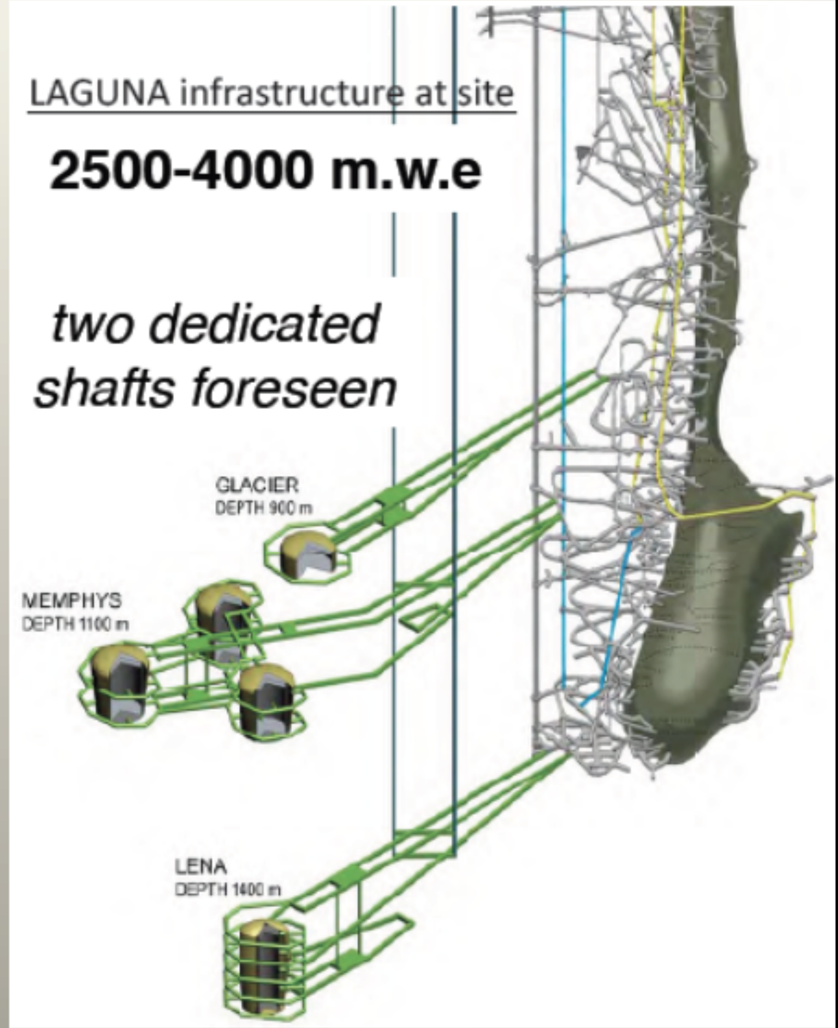
The BIG picture – ultimate facilities (~2030)

- Super beams, β-beams, Neutrino Factory
  - HP-SPL and new accelerators, MMW class facilities

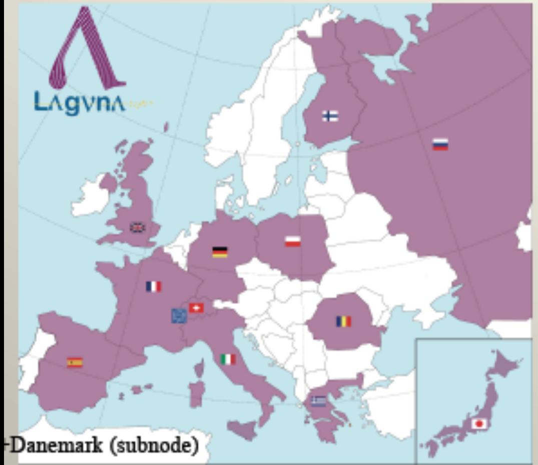
Fréjus Tunnel



Pyhäsalmi Mine



LAGUNA-LBNO consortium



13 countries, 45 institutions, ~300 members

France
CEA
CNRS-IN2P3
Sofregaz*

Germany
TU Munich
University Hamburg
Max-Planck-Gesellschaft
Aachen(**)
University Tübingen(**)

Poland
IFJ PAN
IPJ
University Silesia
Wroklaw UT
KGHM CUPRUM*

Greece
Demokritos

Switzerland
University Bern
University Geneva
ETH Zürich
Lombardi Engineering*

Finland
University Jyväskylä
University Helsinki
University Oulu
Rockplan Oy Ltd*

CERN

Spain
LSC
UA Madrid
CSIC/IFIC
ACCIONA*

United Kingdom
Imperial College London
Durham
Oxford
QMUL
Liverpool
Sheffield
RAL
Warwick
Technodyne Ltd*
Alan Auld Ltd*
Ryhal Engineering*

Romania
IFIN-HH
University Bucharest

Denmark
Aahrus(**)

Italy
AGT*

Russia
INR
PNPI

Japan
KEK

(=industrial partners
**=associated)*

Courtesy: A. Rubbia

The EU design study "menu"

2008

LAGUNA

-far detector "RI" for astroparticle and beam physics
-three detector options
-seven potential sites
-excavation costs
-industrial links

2011

LAGUNA-LBNO

-international consortium including EU, Japan and Russia
-two main far sites
-new conventional beam from SPS
-high energy MW-superbeam (HP-PS)
-near detector infrastructure
-detector magnetization
-detector construction and costs

2013

time

EuroNu

-international consortium
-low energy MW-superbeam (HP-SPL)
-beta beam
-neutrino factory
-costs
-comparison of facilities

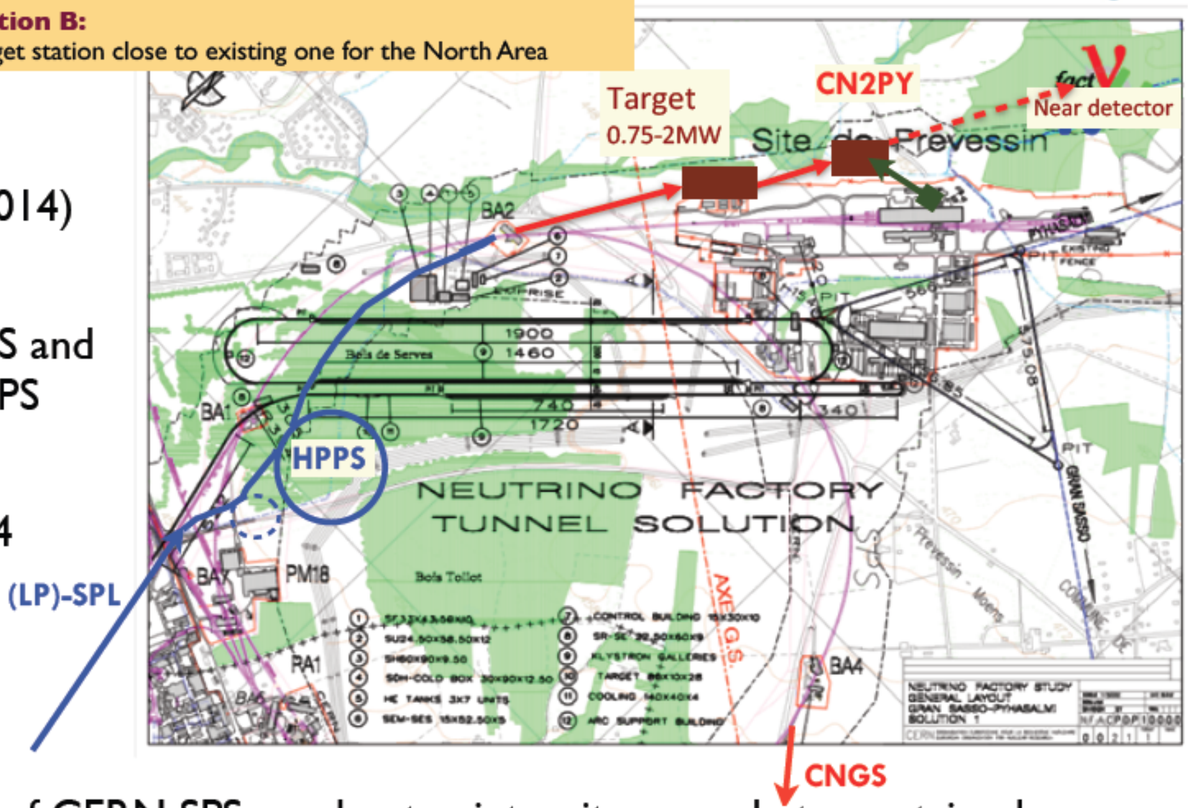
-Update European Strategy for Particle Physics

next step(s) ?

Courtesy: A. Rubbia

CERN CN2PY conventional beam option

- Feasibility of new beams approved by CERN study (LAGUNA-LBNO/2011-2014)
- New beam facility accepts protons from 400 GeV SPS and eventual new 50 GeV HP-PS
- Will produce conceptual design reports within 2014

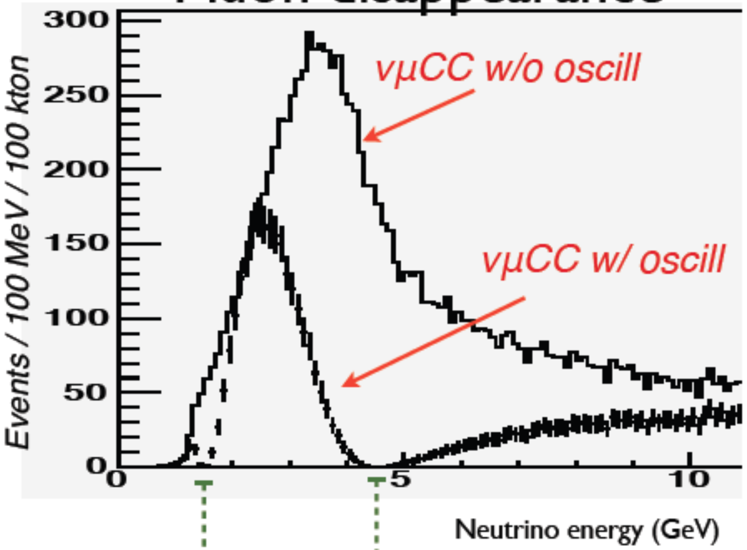


LAGUNA-LBNO:

- **Task 4.1** Study of impact of CERN SPS accelerator intensity upgrade to neutrino beams
- **Task 4.2** Feasibility of intensity upgrade of CNGS facility
- **Task 4.3** Conceptual design of the CN2PY neutrino beam
- **Task 4.4** Feasibility study of a 30-50 GeV high power PS
- **Task 4.5** Definition of the accelerators and beamlines layout at CERN
- **Task 4.6** Study of the Magnetic Configuration for the LAGUNA detector
- **Task 4.7** Definition of near detector requirements and development of conceptual design

CERN-Pyhäsalmi long baseline

Muon disappearance

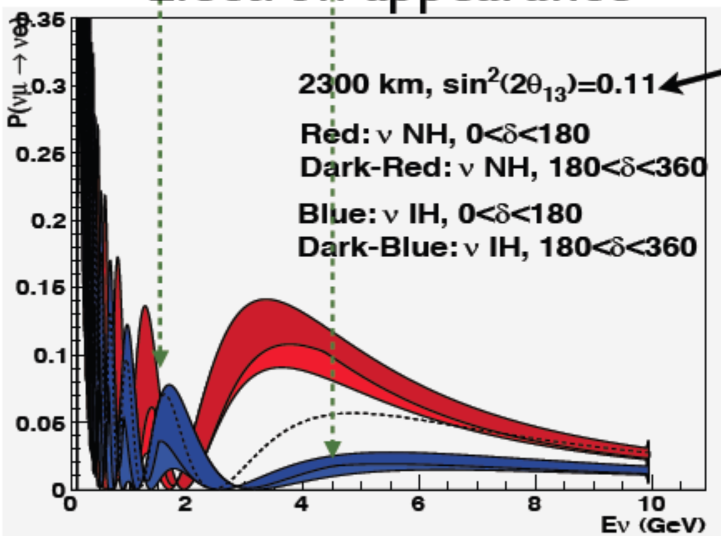


Goal ➠ θ_{23}, sgn(Δm^2_{23}), θ_{13}, δ independently with ν and $\bar{\nu}$

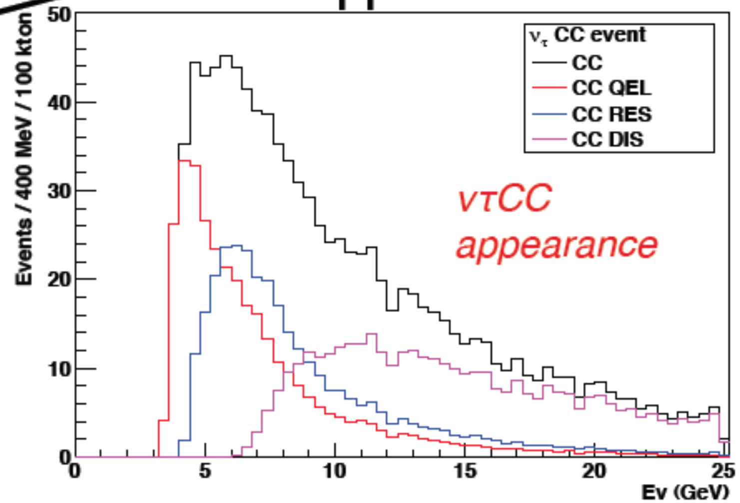
Event rates: CERN SPS 400 GeV
5 years @ 9.4×10^{19} pots/year

	Neutrino horn polarity $\sin^2 2\theta_{23}=1.0$, $\sin^2 2\theta_{13}=0.1$			
Distance/OA	ν_μCC	ν_eCC	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\tau$
Pyhäsalmi 2300 km 0.25 deg	17152	250	880	1018

Electron appearance



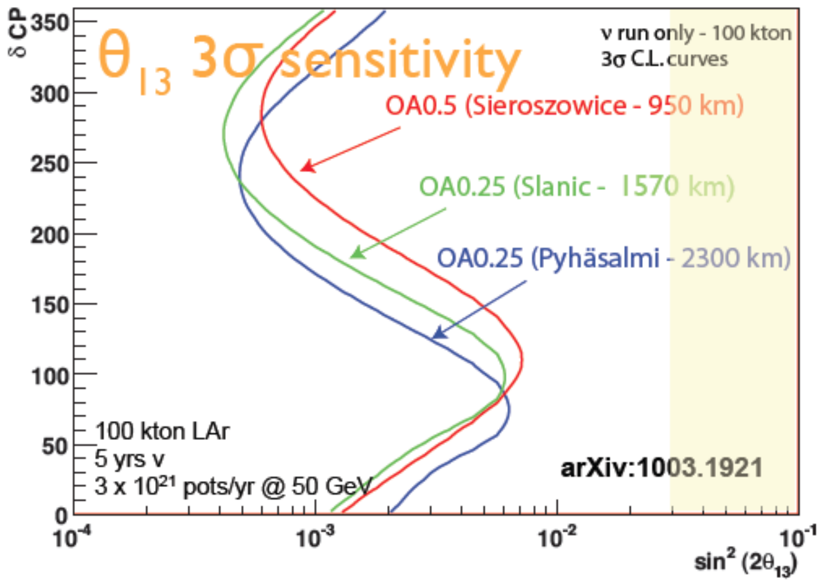
Tau appearance



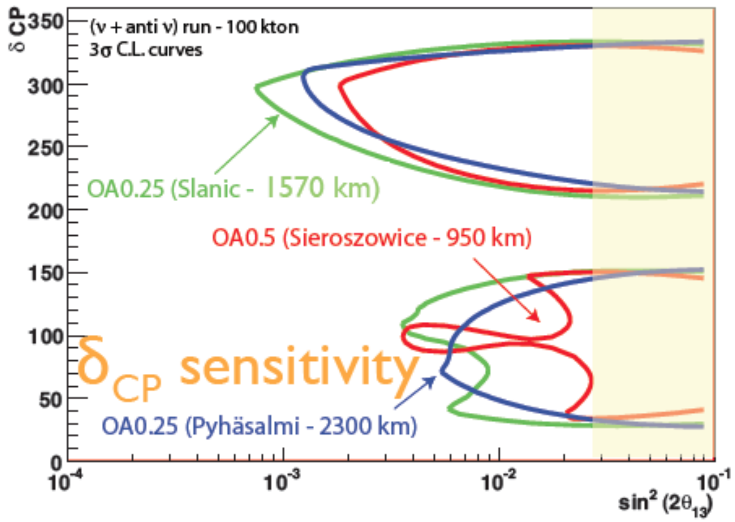
CERN-Pyhäsalmi long baseline

arXiv:1003.1921 [hep-ph]

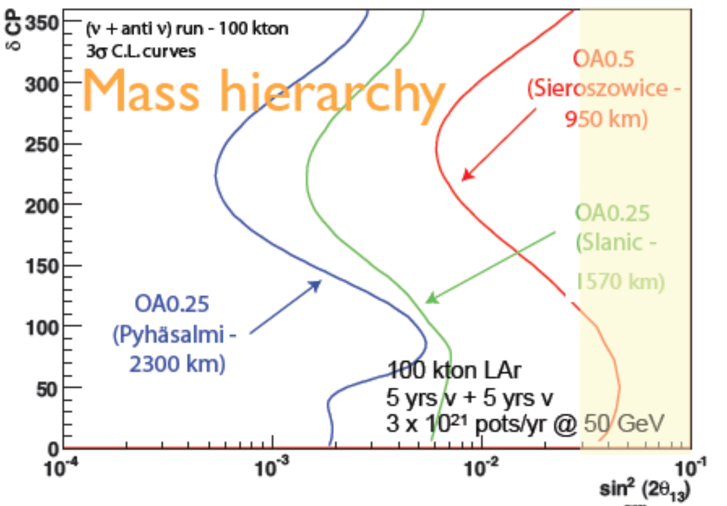
θ_{13} Sensitivity - CNXX NOvA Horns - 50 GeV protons



CP Discovery - CNXX NOvA Horns-50 GeV protons



Mass Hierarchy Exclusion - CNXX NOvA Horns-50 GeV protons



Event rate per year: 50 GeV HP-PS,
3 x 10^{21} pots/yr, 1.6 MW
100 kton liquid Argon (GLACIER option)

No Osc.	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC
positive horn 1 year	17257	110	203	7
negative horn 1 year	471	16	7577	32

CERN-Pyhäsalmi long baseline

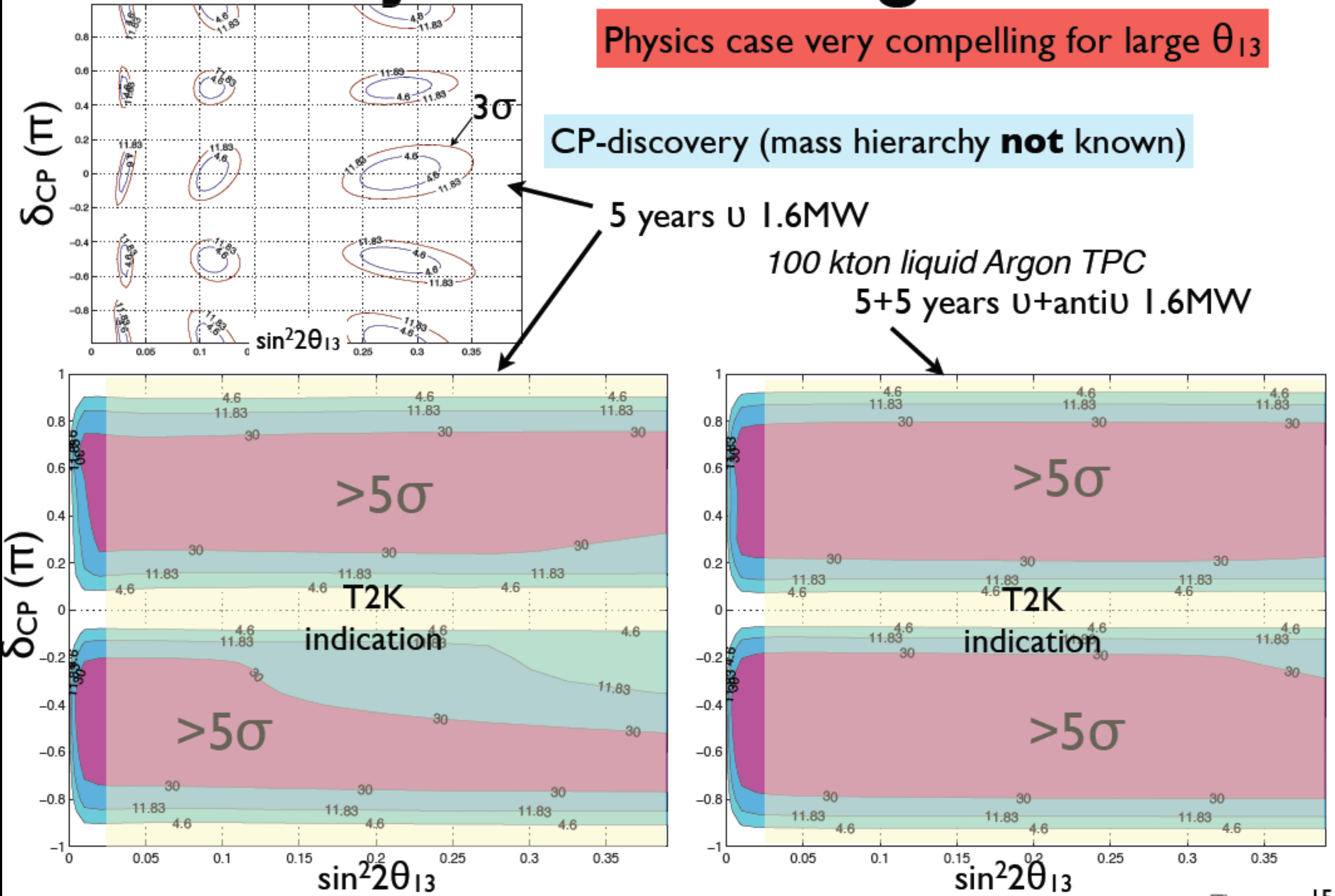
Physics case very compelling for large θ_{13}

CP-discovery (mass hierarchy **not** known)

5 years ν 1.6MW

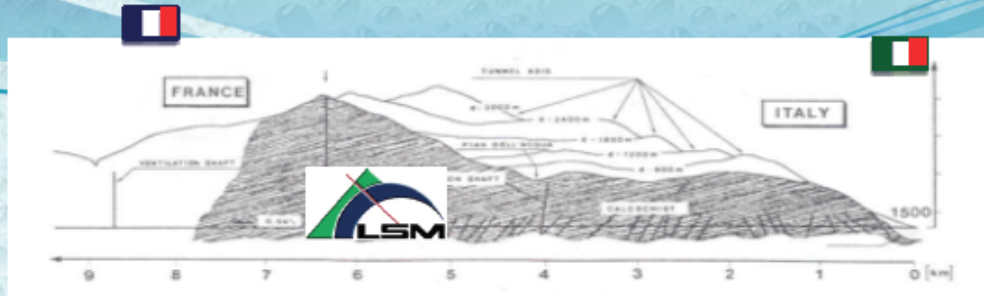
100 kton liquid Argon TPC

5+5 years ν+antiν 1.6MW

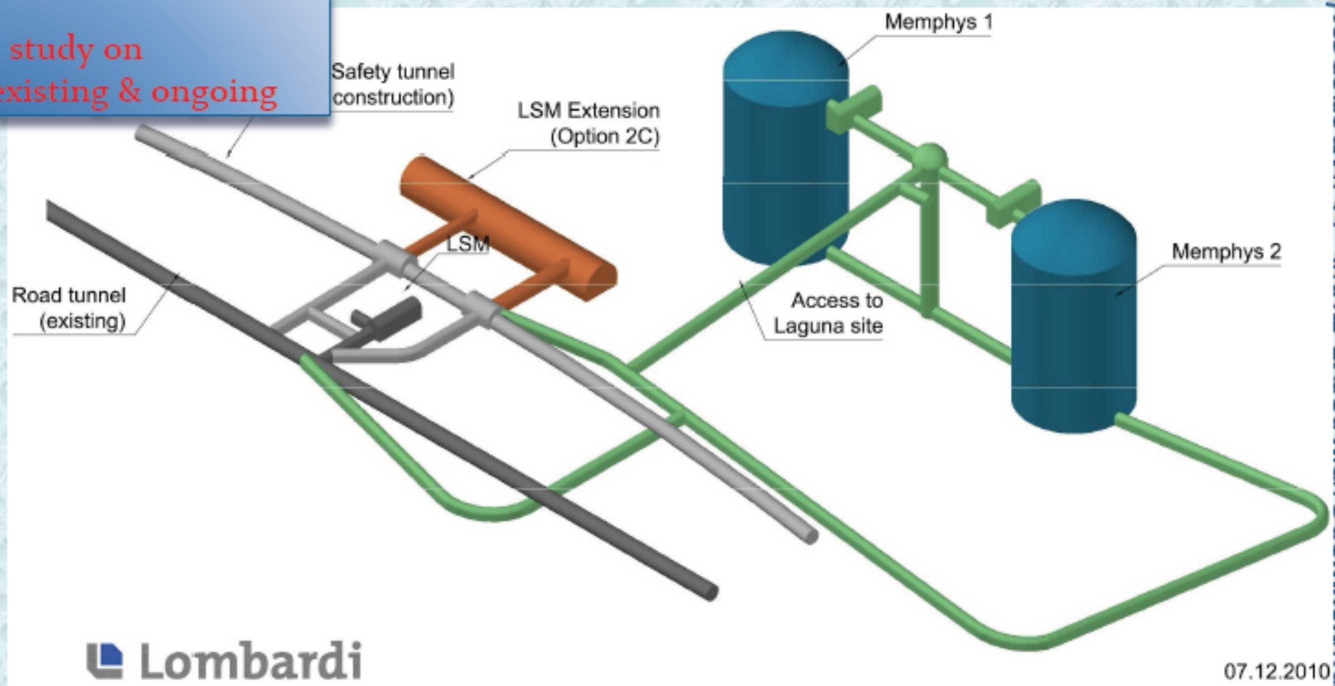


MEMPHYS

- Water Cherenkov ("cheap and stable")
- total fiducial mass: 500 kt
- 2 cylindrical modules 65 x 100 m
  - size limited by light attenuation length (λ~80m) and pressure on PMTs
  - readout : ~3 x 81k 12" PMTs, 30% geom. cover
  - PMT R&D + detailed study on excavation @Fréjus existing & ongoing

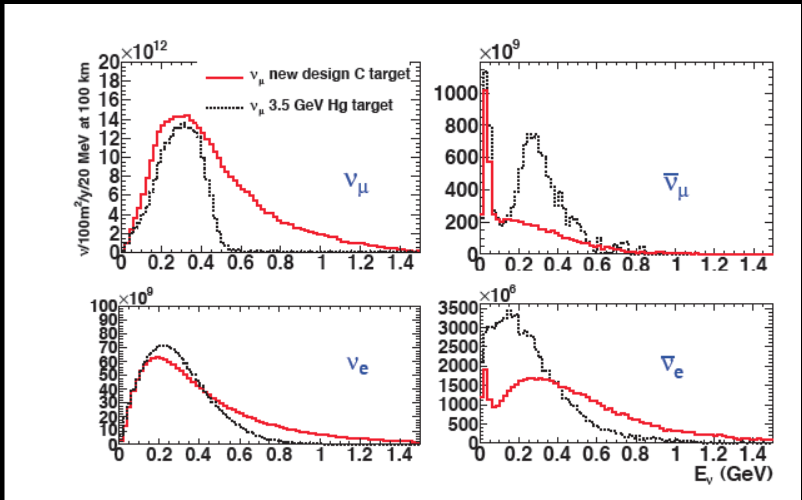


- 130 Km from CERN
- 4800 m.w.e.



http://www.apc.univ-paris7.fr/APC_CS/Experiences/MEMPHYS/

A new optimisation for the SPL beam
A. Longhin et al.



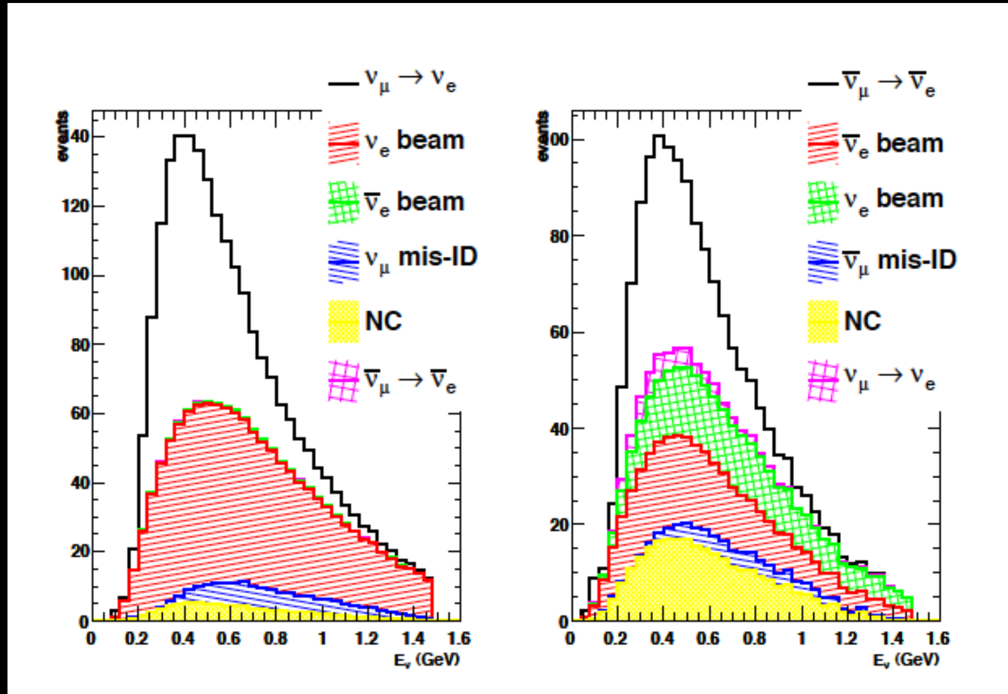
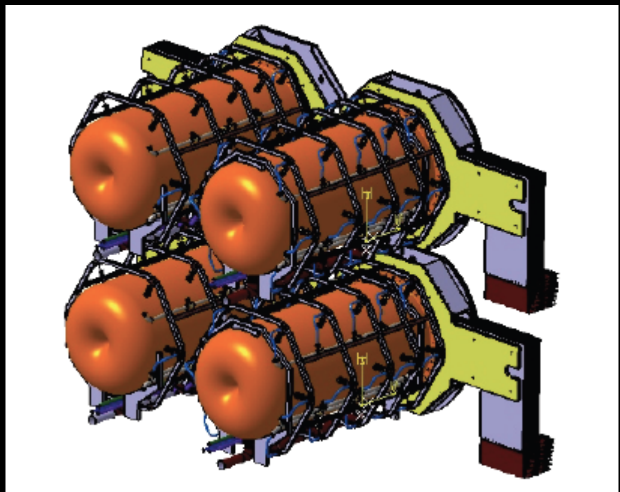


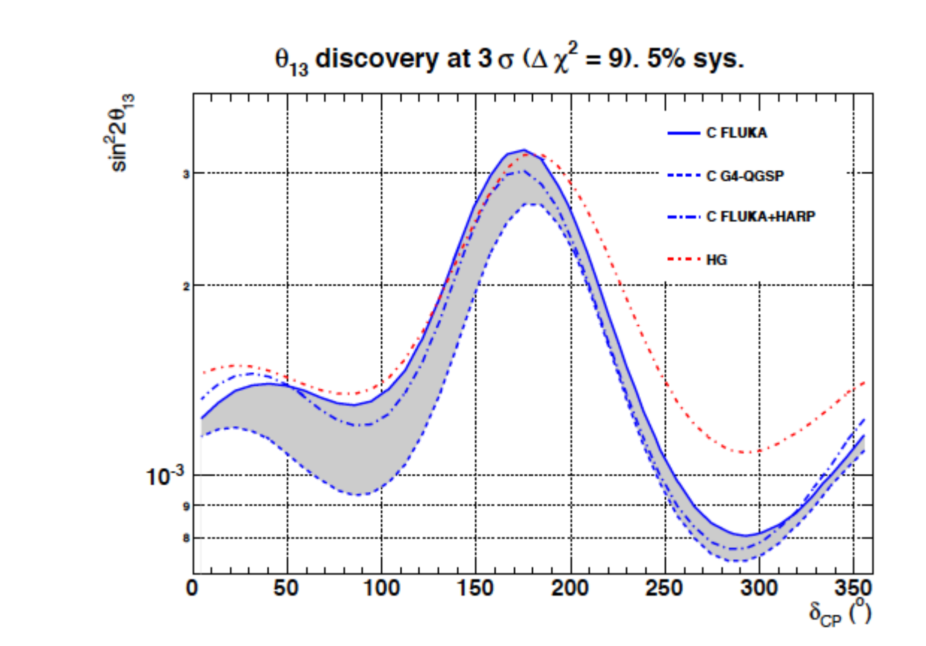
Fig. 14. Event rates in the MEMPHYS detector for $\sin^2 2\theta_{13} = 0.01$ and $\delta_{CP} = 0$ for 8+2 years of $\bar{\nu}+\nu$ running.

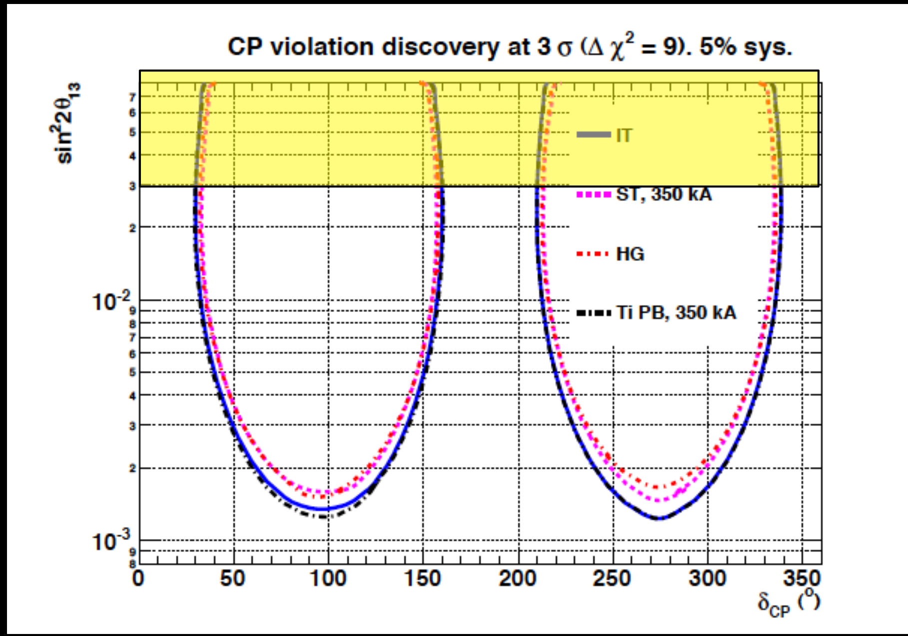


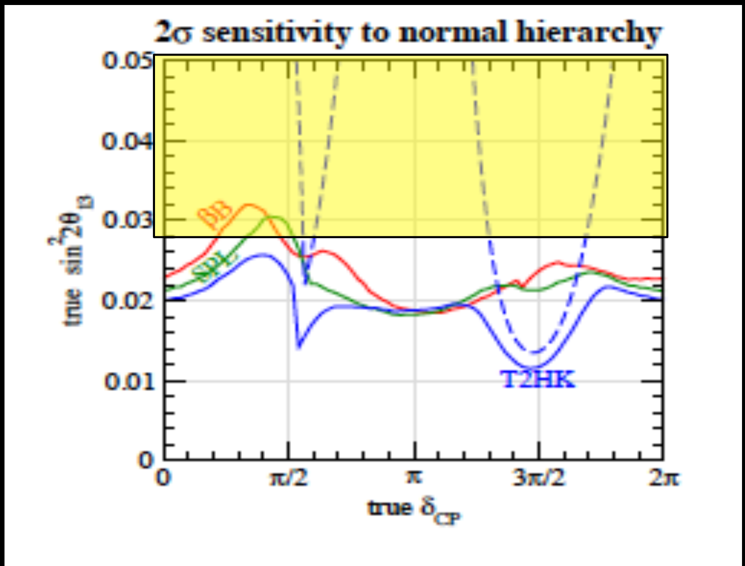
4 targets (M. Dracos et al)

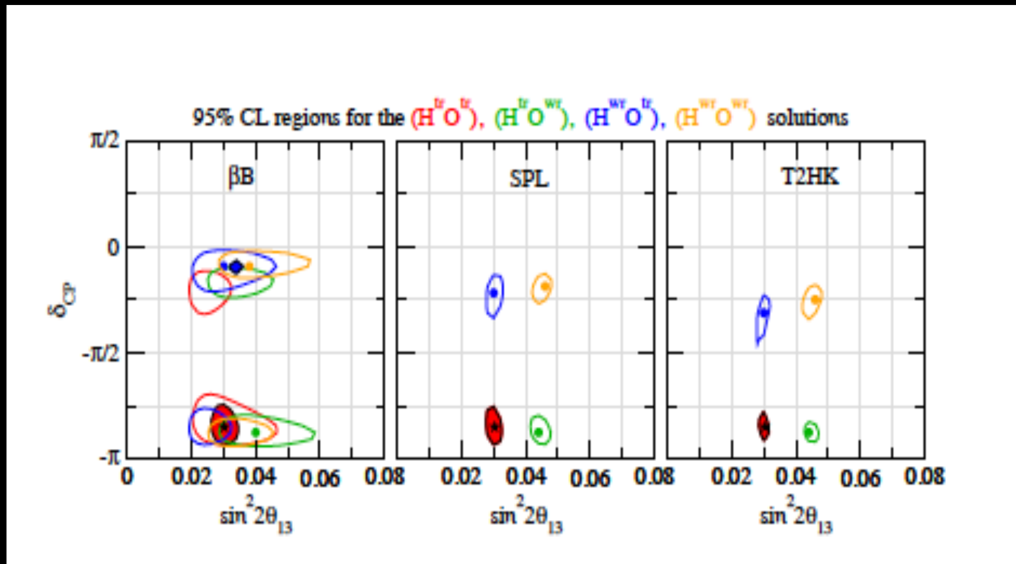
Physics reach of Memphys+SPL (New design)

LBL+ ATM (older studies, Campagne, Mezzetto, Maltoni, Schwetz)





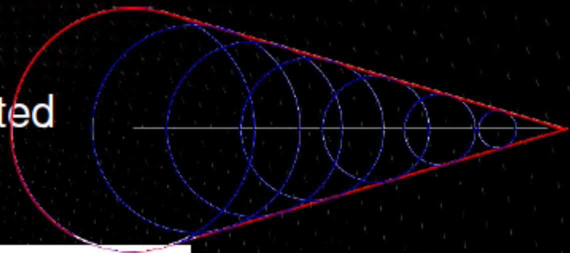


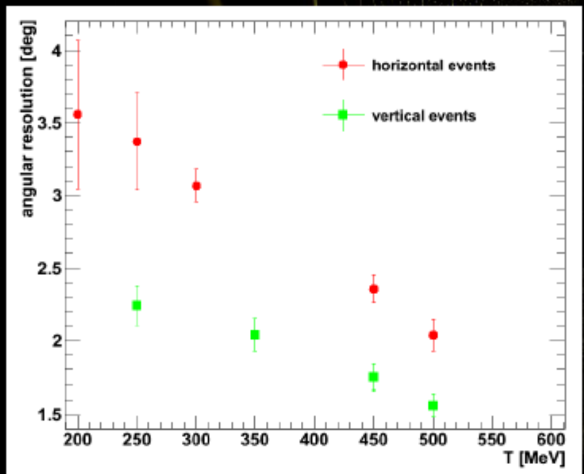


LENA

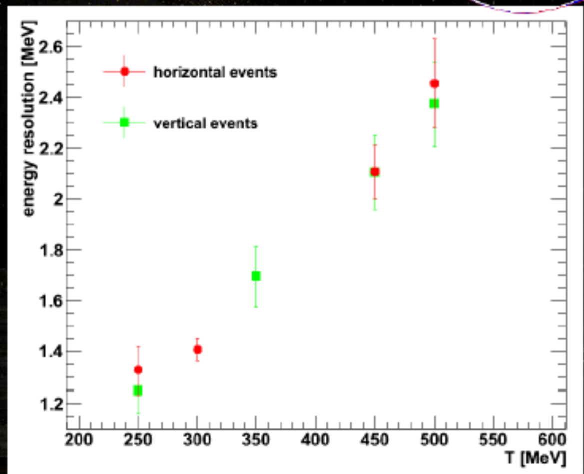
GeV Event Reconstruction

- Investigated in Monte Carlo simulations
- Identification of energy, momentum and flavour
- For tracks > O(10cm) distortion of the spherical light front emerging from track
- More precise method: LogLikeli Fit to the integrated charge and first hit times of each PMT (7 par fit)





Angular resolution



Energy resolution

Muons

LENA

Long-baseline Neutrinos

- Searching for θ_{13}, δ_{CP}, mass hierachy, and check for maximal θ_{23}
- Options currently investigated
  - Conventional ν beam CERN-Pyhäsalmi (2288 km)
    - Appearance experiment: $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$
    - Background due to NC π^0 production, further studies ongoing
  - Beta beam CERN-Fréjus (130 km)
    - discrimination of electron and muon by pulse-shape analysis:
      → efficieny for muons: ~90%
      → residual electrons: <1%
- LAGUNA-LBNO

What we urgently need
Sensitivity versus exposure ($)
Redo V. Barger et al. hep-ph0610301

Setup	POT ν/yr	t_ν [yr]	POT $\bar{\nu}$/yr	$t_{\bar{\nu}}$ [yr]	$P_{\rm Target}$ [MW]	L [km]	Detector technology	$m_{\rm Det}$ [kt]	$\mathcal{L}$ [Mt MW 10^7 s]
NOνA*	$10 \cdot 10^{20}$	3	$10 \cdot 10^{20}$	3	1.13	810	LArTPC	100	1.15
WBB+WC	$22.5 \cdot 10^{20}$	5	$45 \cdot 10^{20}$	5	1 (ν), 2 ($\bar{\nu}$)	1290	Water Cherenkov	300	7.65
WBB+LAr	$22.5 \cdot 10^{20}$	5	$45 \cdot 10^{20}$	5	1 (ν), 2 ($\bar{\nu}$)	1290	LArTPC	100	2.55
T2KK	$52 \cdot 10^{20}$	4	$52 \cdot 10^{20}$	4	4	295+1050	Water Cherenkov	270+270	17.28

TABLE I: Setups considered, numbers of protons on target per year (POT/yr) for the neutrino and antineutrino running modes, running times in which these be achieved, corresponding target power $P_{\rm Target}$, baselines L, detector technology, detector mass $m_{\rm Det}$, and exposure $\mathcal{L}$.

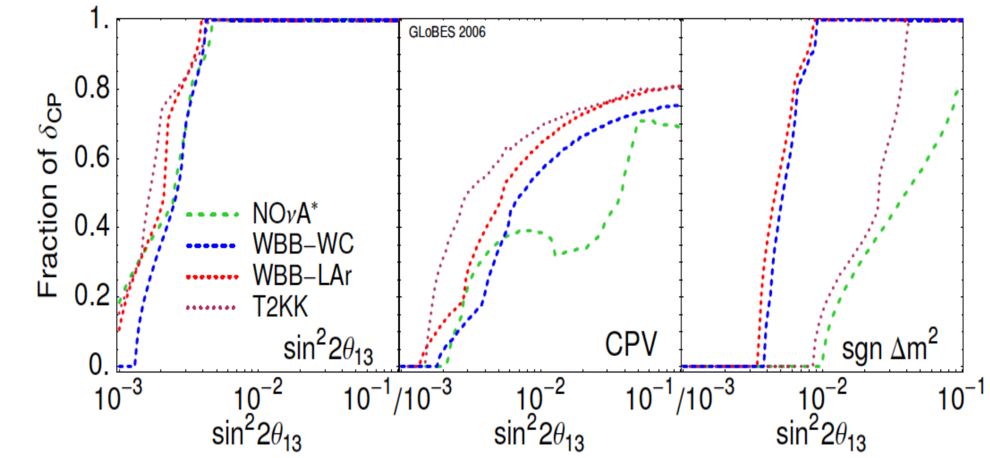


FIG. 1: Comparison of superbeam upgrades in the configurations of Table I at the 3σ C.L. The plots show the discovery reaches for a nonzero $\sin^2 2\theta_{13}$, CP violation, and the normal hierarchy. The "fraction of $\delta_{\rm CP}$", quantifies the fraction of all (true) values of $\delta_{\rm CP}$ for which the corresponding quantity can be measured.

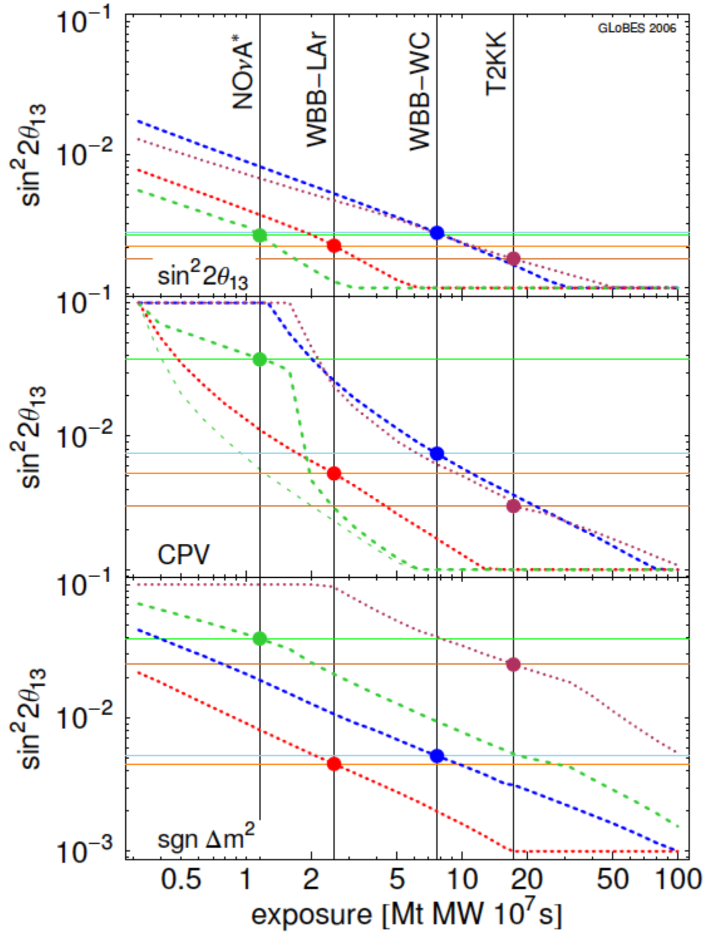
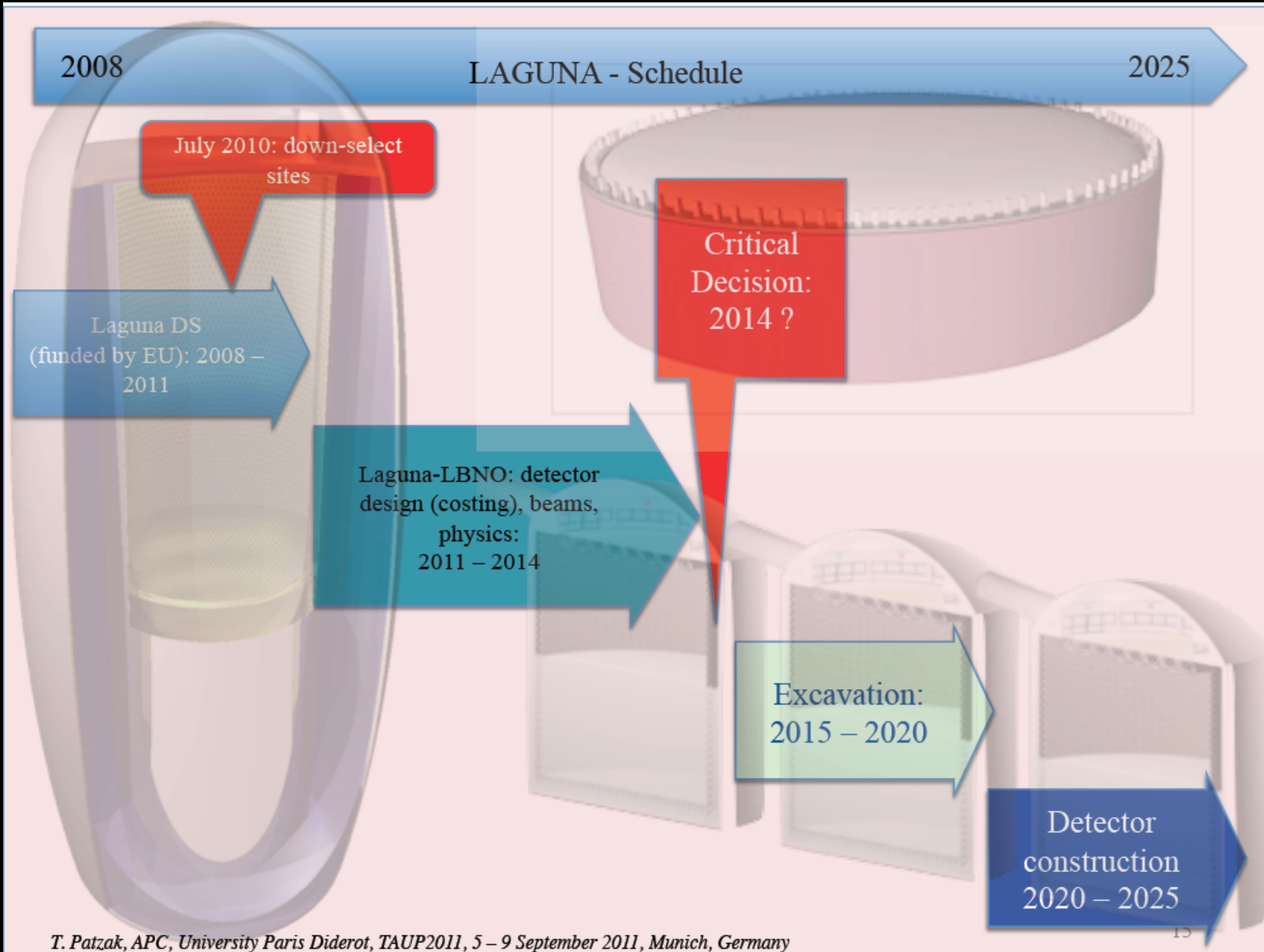
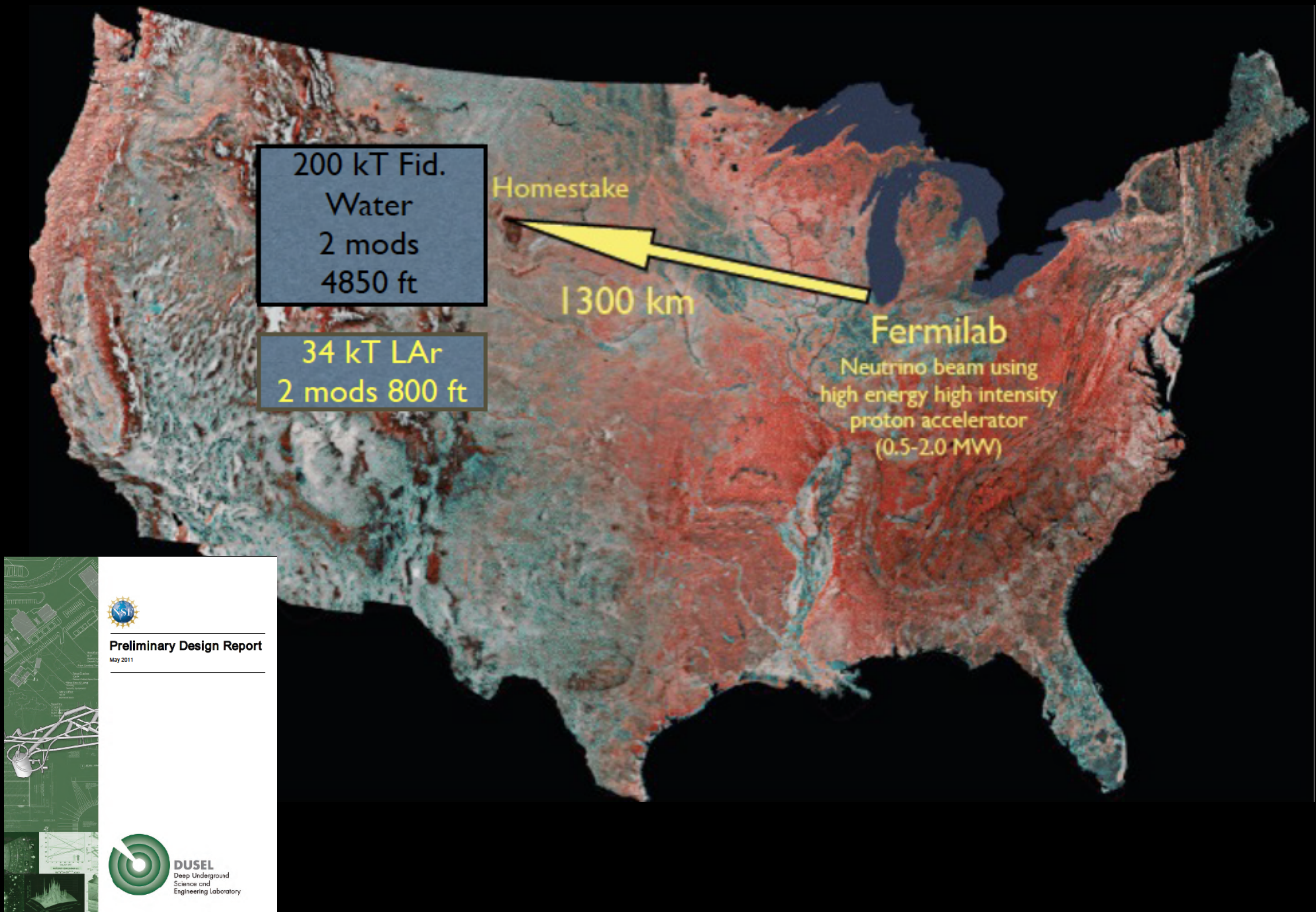


FIG. 2: The discovery reaches (at the 3σ C.L.) for nonzero $\sin^2 2\theta_{13}$, CP violation, and the normal hierarchy as functions of exposure. The line types are the same as in Fig. 1 except that the light curve in the CPV panel corresponds to the sensitivity of NOνA* under the assumption that the mass hierarchy is known to be normal. The vertical lines mark the proposed luminosities as listed in Table I. The curves correspond to a fraction of $\delta_{\rm CP}$ of 0.5, *i.e.*, the median of the distribution. This means that the performance will be better for 50% of all cases of $\delta_{\rm CP}$ and worse for 50% of all cases of $\delta_{\rm CP}$; it is sometimes referred to as the "typical value of $\delta_{\rm CP}$".


2008
LAGUNA - Schedule
2025
July 2010: down-select sites
Laguna DS (funded by EU): 2008 – 2011
Critical Decision: 2014 ?
Laguna-LBNO: detector design (costing), beams, physics: 2011 – 2014
Excavation: 2015 – 2020
Detector construction 2020 – 2025
T. Patzak, APC, University Paris Diderot, TAUP2011, 5 – 9 September 2011, Munich, Germany

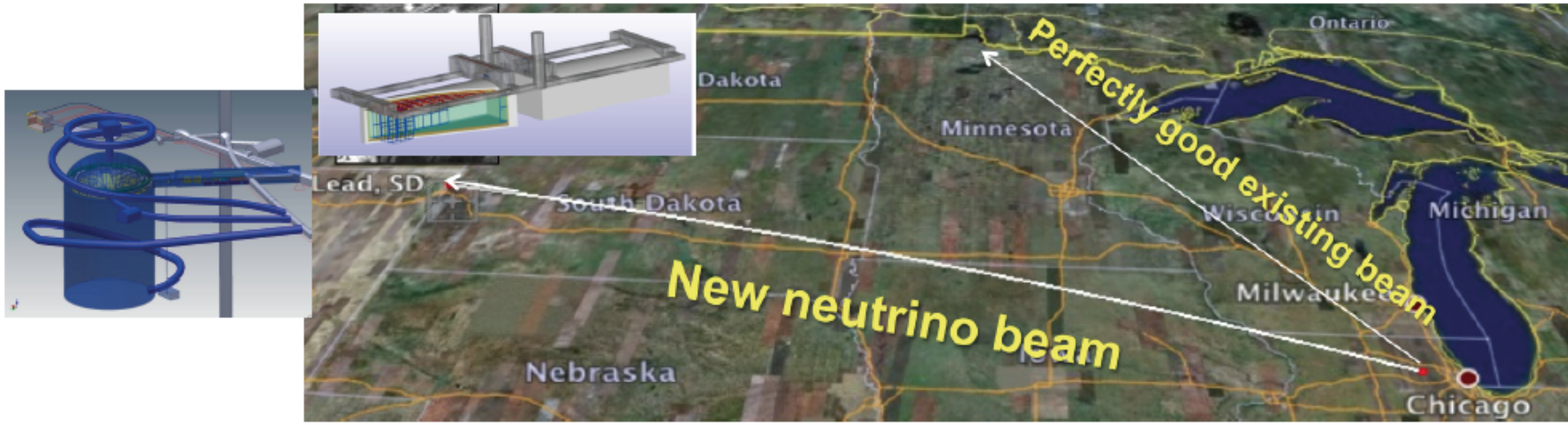
DUSEL


200 kT Fid.
Water
2 mods
4850 ft
34 kT LAr
2 mods 800 ft
Homestake
1300 km
Fermilab
Neutrino beam using
high energy high intensity
proton accelerator
(0.5-2.0 MW)
Preliminary Design Report
May 2011
DUSEL
Deep Underground
Science and
Engineering Laboratory

Future programs: United States

Long Baseline Neutrino Experiment (LBNE)

- Possible site: Homestake mine in South Dakota
- Under consideration:
  new 700 kW beam from FNAL with:
  200 kt fv water Ch. at 4850 ft w/ 12" HQE PMTs (~SK II)
  OR 34 kton LAr TPC at 800 ft (or deeper)
- Longer term: Project X (2 MW)



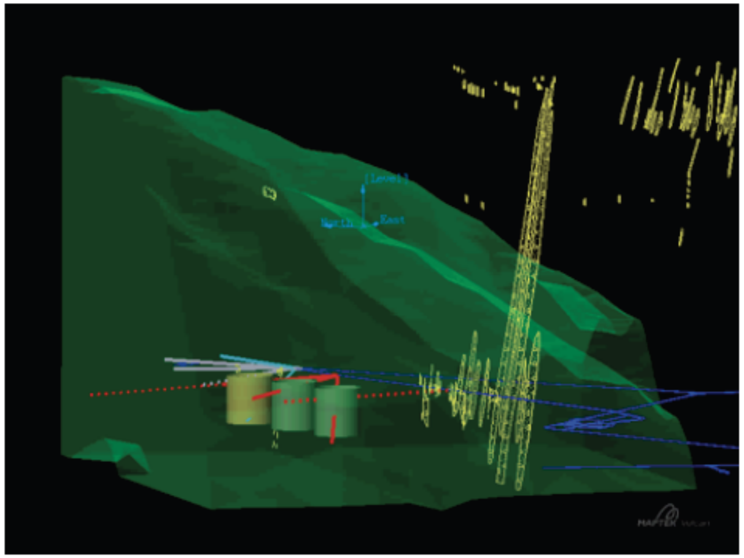
Status: - NSF will not build DUSEL
- DOE seriously considering taking on underground infrastructure @ Homestake (see `Marx committee' report)

http://science.energy.gov/~/media/hep/hepap/pdf/june-2011/Review_of_Underground_Science_Report_Final.pdf

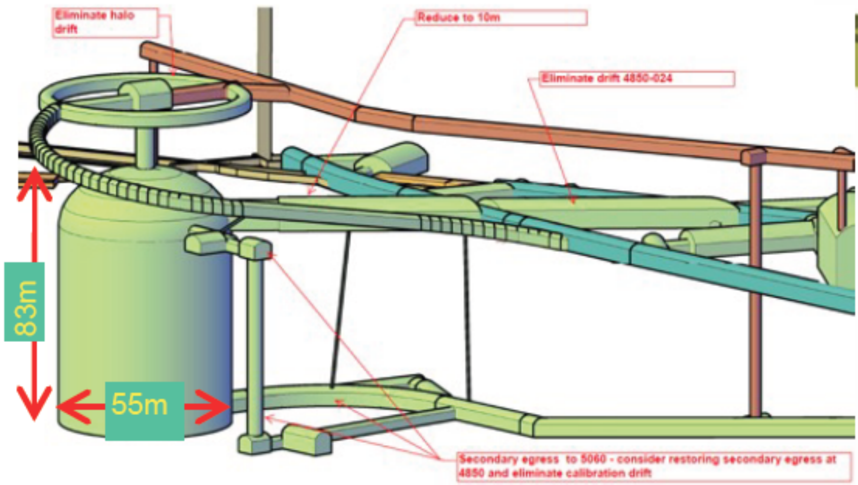
- collaboration planning technology decision ~ end of 2011

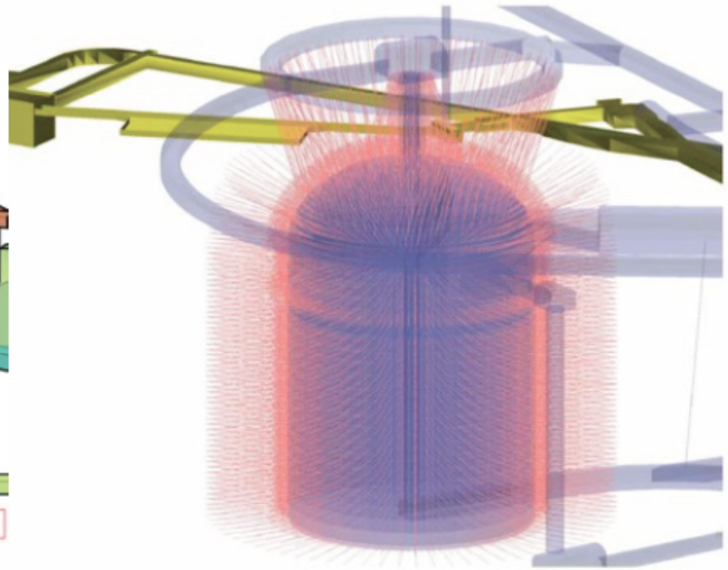
DUSEL

Site investigation and preliminary design



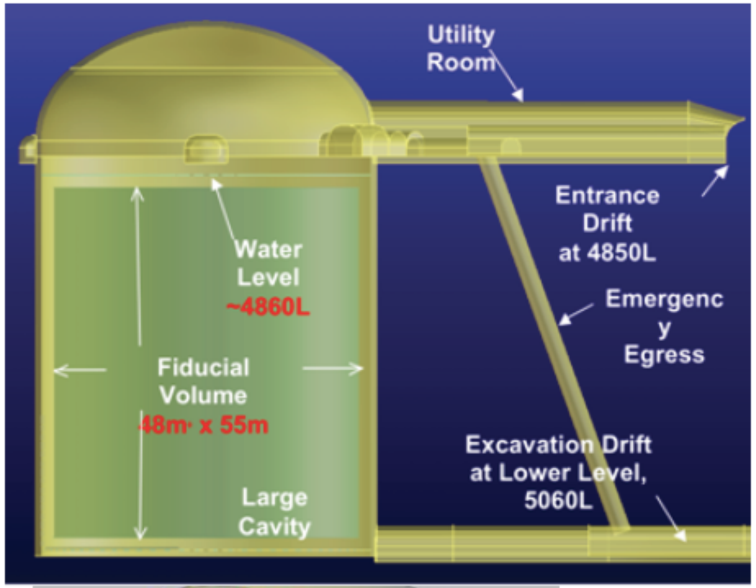
- Confidence in 55m span WCD cavity is high after much detailed design. (100kTon)
- Initial studies show that 200kTon could be possible

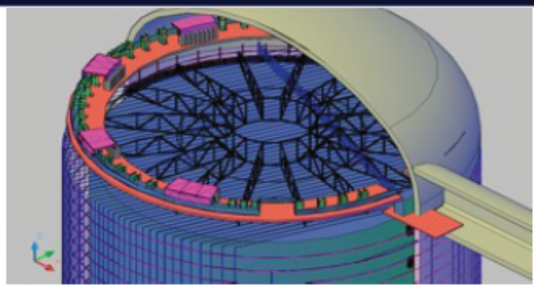




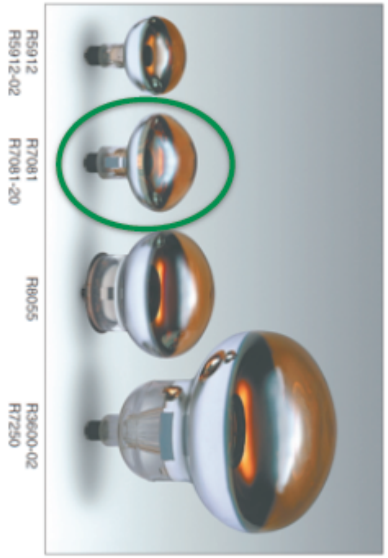
DUSEL

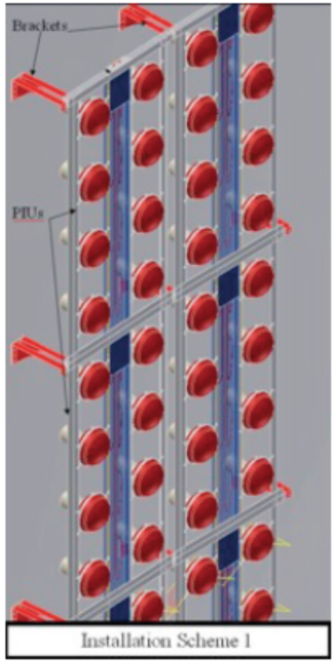
Water Cherenkov Detector





30k PMTs watching 100 ktons of ultra-pure water in each of two caverns



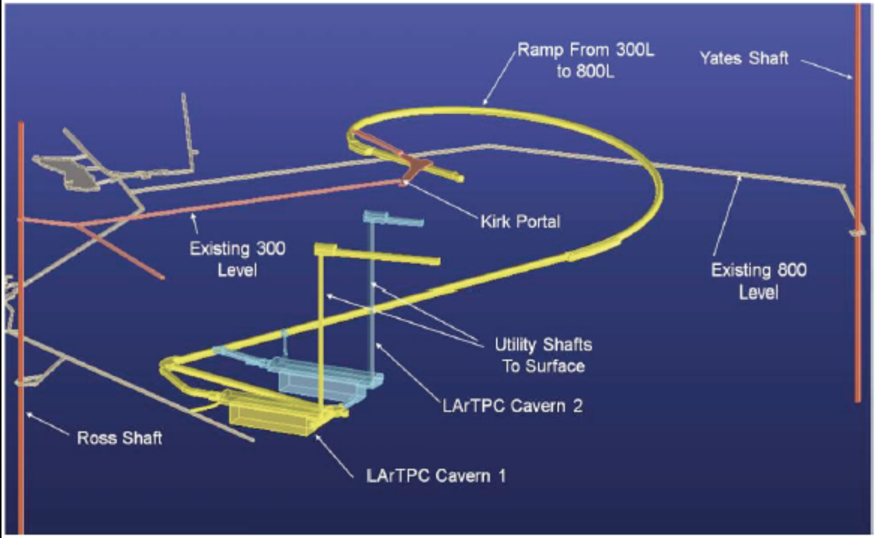


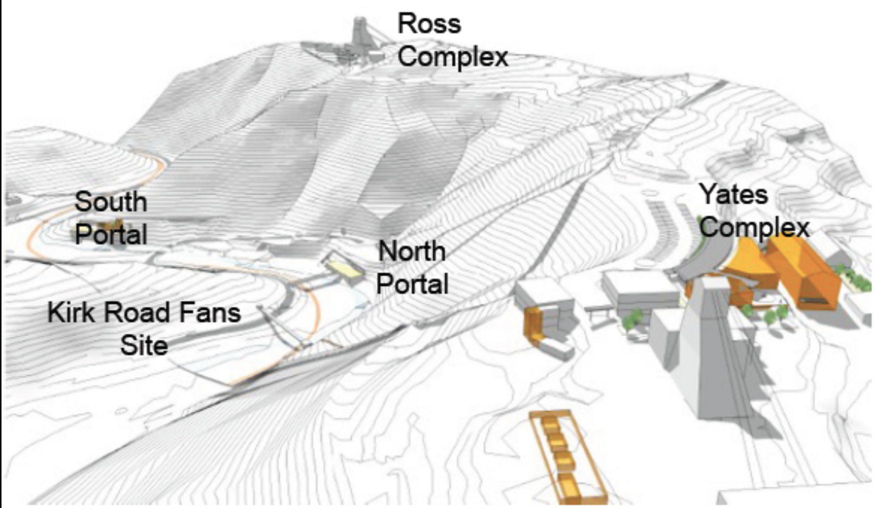
Also considering designs with a single detector of 150 ktons or 200 ktons fiducial mass (cavern up to 66 m diameter, 100 m high)

Liner and installation design are evolving.

DUSEL

Site proposal for 34 kTon liquid argon



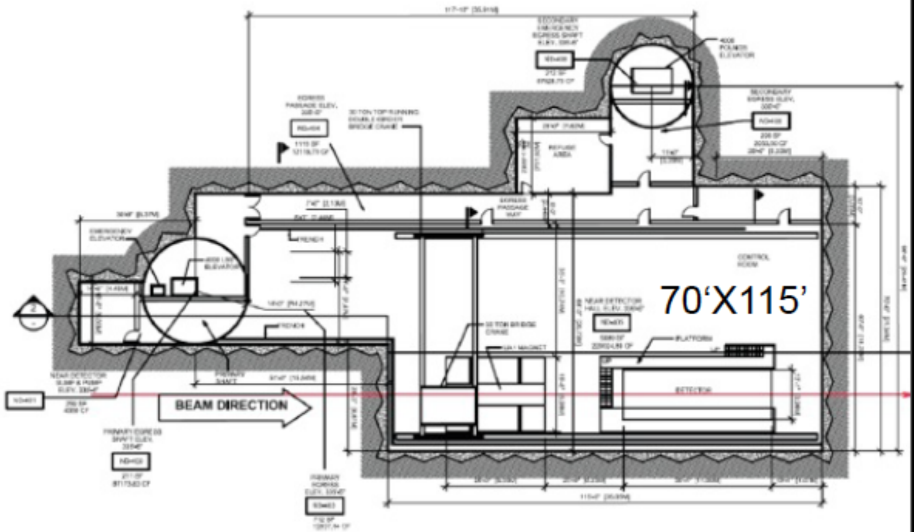


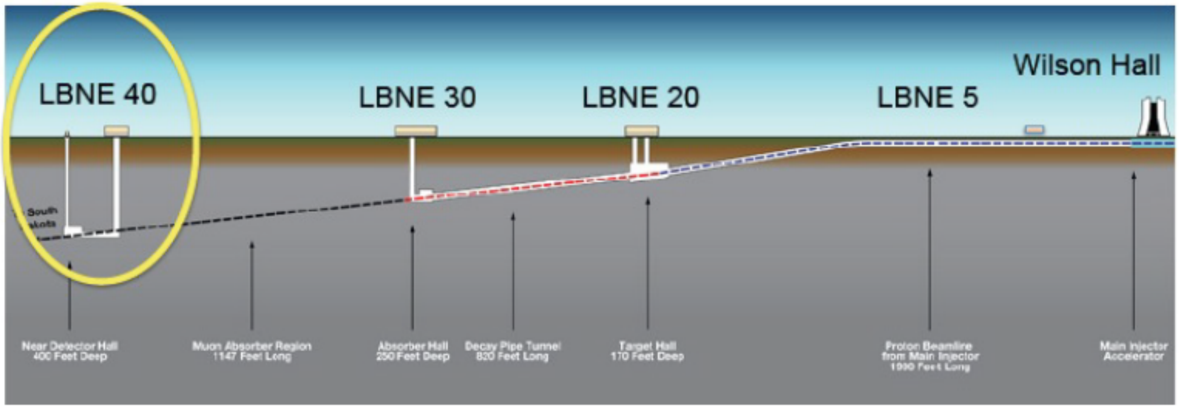
- Liquid Argon development is proposed to be at 800 ft level.
- Keep separated from rest of lab.
- Allow horizontal access through tunnel.
- Rock is not fully explored, but caverns are smaller.

DUSEL

Near Detector

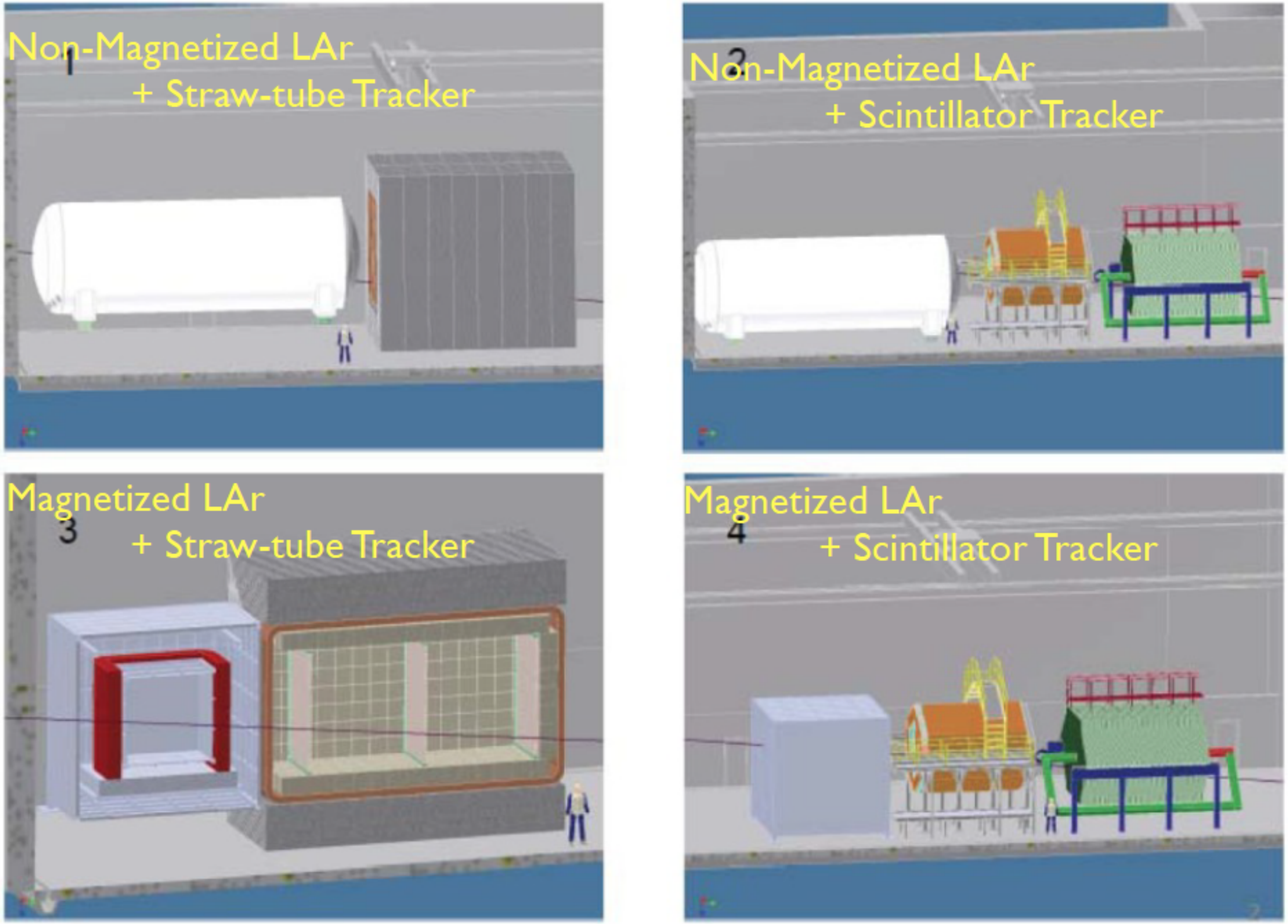
- Near detector essential for a CP experiment
- 4 options open
- Straw tube tracker
- LAR (with/without magnet)
- Scintillator



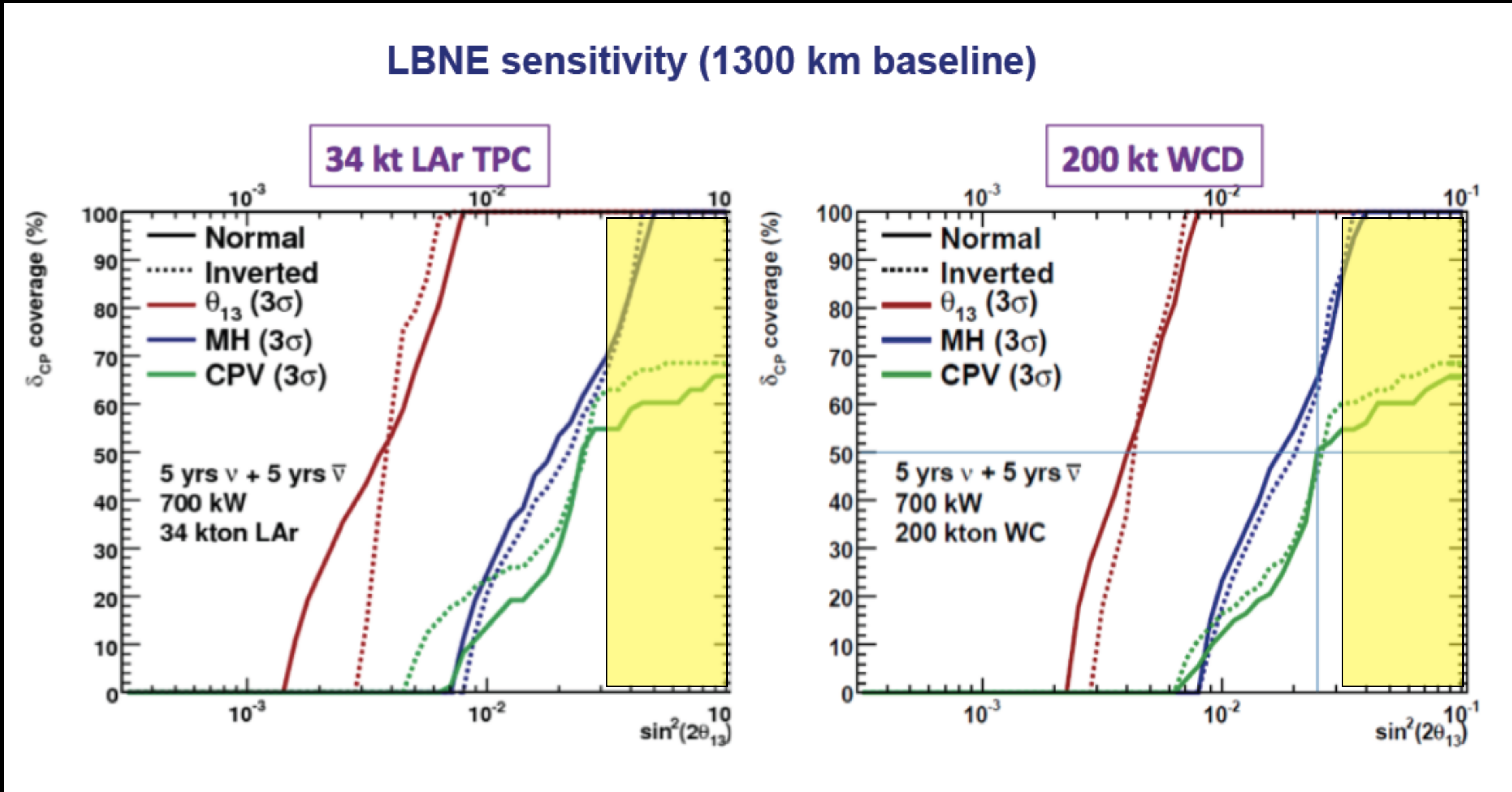


DUSEL

Near Detector Options



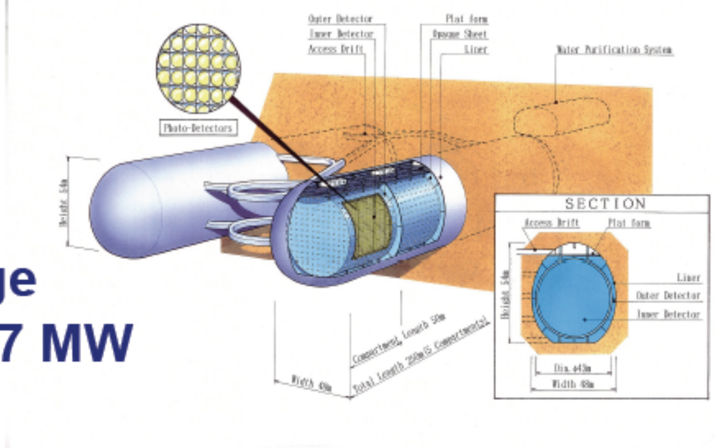
DUSEL

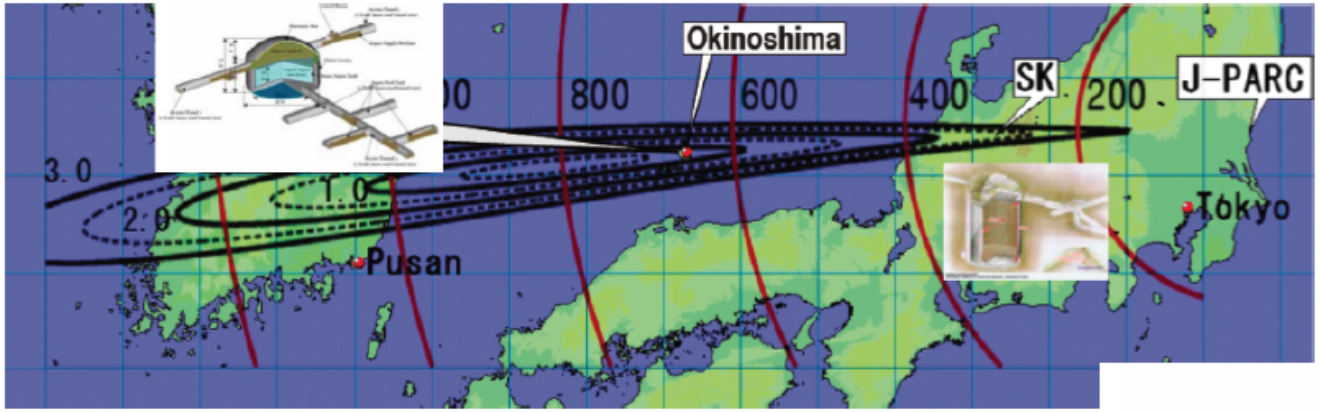

LBNE sensitivity (1300 km baseline)
34 kt LAr TPC
200 kt WCD
Normal
Inverted
θ13 (3σ)
MH (3σ)
CPV (3σ)
5 yrs ν + 5 yrs ν̄
700 kW
34 kton LAr
200 kton WC
δCP coverage (%)
sin²(2θ13)

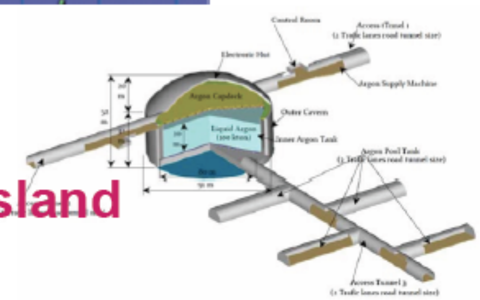
Future programs: Asia

Hyper-Kamiokande

- Tochibora mine, near Kamioka;
  sites under study (1500-1750 mwe)
- 540 kt fid; 10-20% SK-equiv coverage
- eventual upgrade to T2K beam to 1.7 MW
- LOI in progress (data start ~2018)







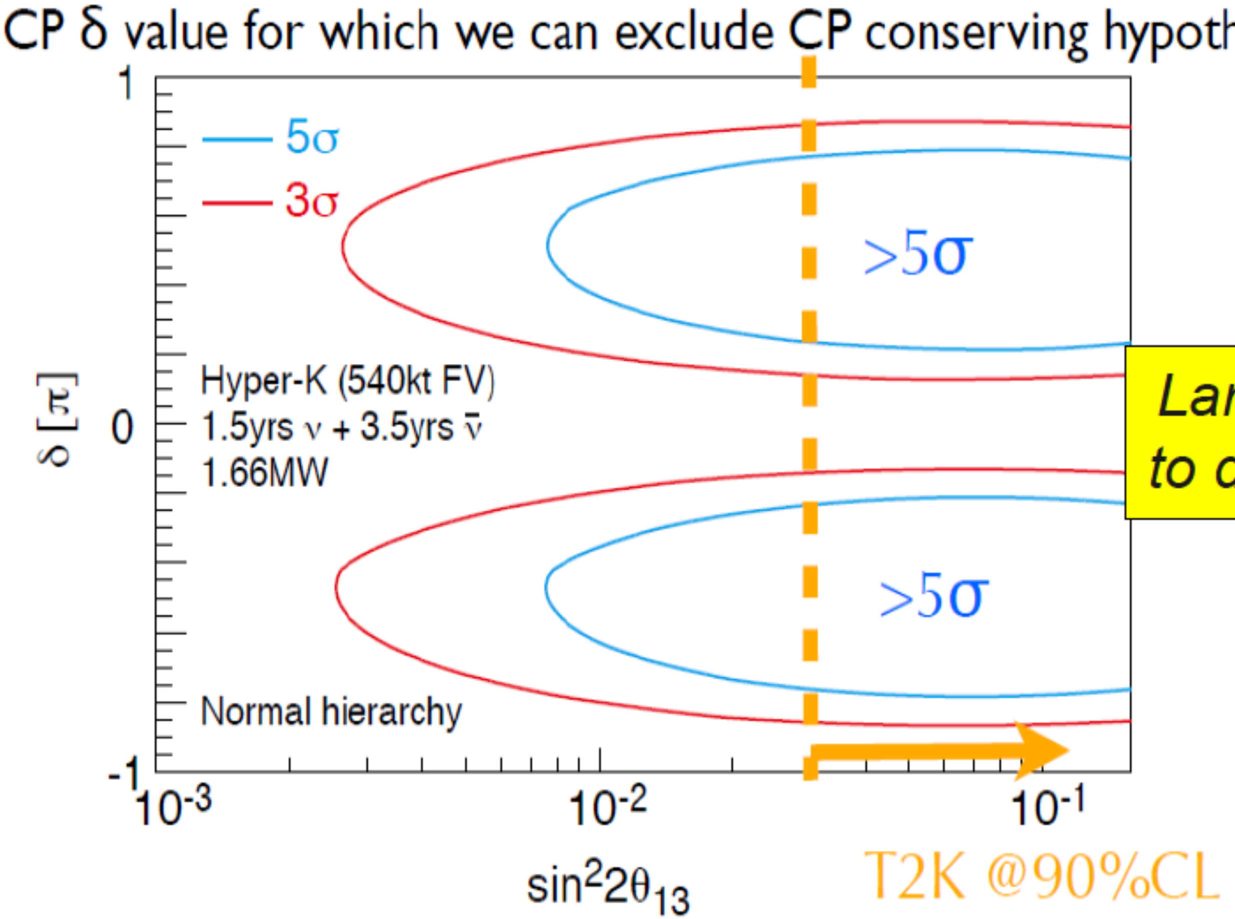
Also, ideas for 100 kton LAr at Okinoshima island
(R&D program started at KEK)

MR Power Improvement Scenario toward MW-class power frontier machine
— KEK Roadmap —

	Day1 Achieved ! (up to Jul.2010)	Next Step	KEK Roadmap
Power(MW)	0.1	0.45	>1.66
Energy(GeV)	30	30	30
Rep Cycle(sec)	3.2	2.2	**0.5**
No. of Bunch	6	8	8
Particle/Bunch	1.2×10^{13}	2.5×10^{13}	4×10^{13}
Particle/Ring	7.2×10^{13}	2.0×10^{14}	3×10^{14}
LINAC(MeV)	181	181	400
RCS	h=2	h=2	**h=1**

Combination of **High rep. cycle** and **High beam density** and **space charge handling**

J-PARC HK CPV sensitivity

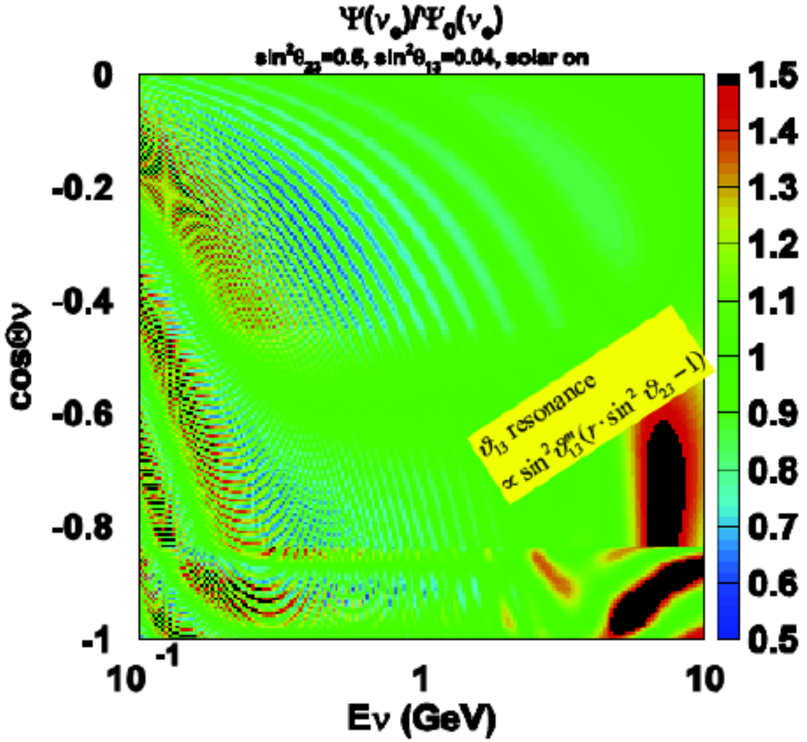


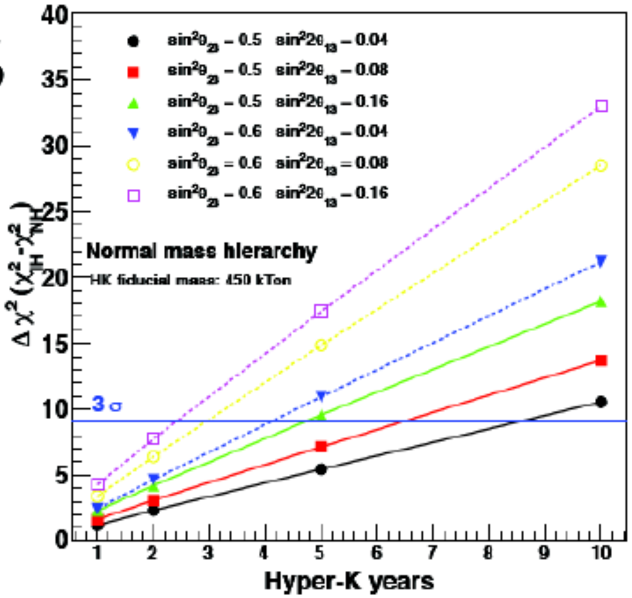
Large chance to determine δ

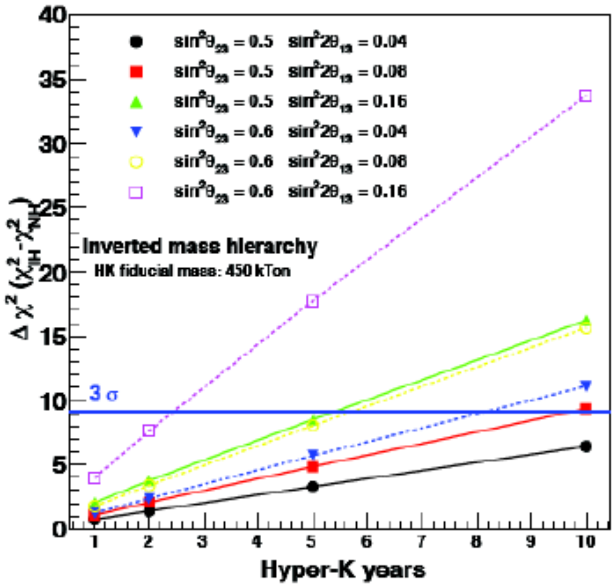
- 5% of systematic uncertainty is assumed
- mass hierarchy is assumed to be ***known***

determine together w/ atmospheric ν studies

Atmospheric ν studies (mass hierarchy)







- Normal mass hierarchy → resonance in ν_e appearance
- Inverted mass hierarchy → resonance in anti-ν_e

Good chance if θ_{23} and θ_{13} are large

2 and 3σ sensitivities for different OA angles with the Kamioka + Korea setup (1)

Conditions:

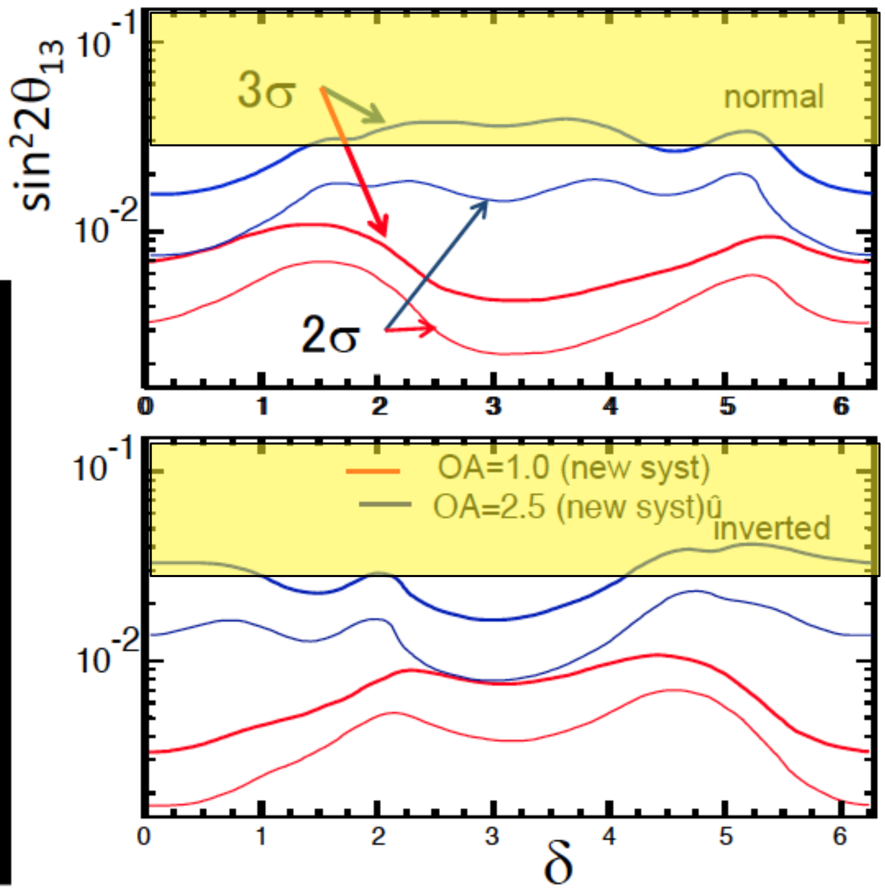
- 1.66 MW
- 5 years neutrino run + 5 years anti-neutrino run
- 0.27Mton water Ch. detectors in Kamioka and Korea

Systematic errors considered:

- BG normalization (for Kam.) 5%
- BG normalization (for Korea) 5%
- BG normalization between ν_e and anti-ν_e 5%
- BG spectrum shape 5%
- $\sigma(\nu_\mu)/\sigma(\nu_e)$ 5%
- $(\sigma(\nu_\mu)/\sigma(\nu_e))$ / $(\sigma(\text{anti-}\nu_\mu)/\sigma(\text{anti-}\nu_e)$ 5%
- Efficiency and energy scale diff. between Near, Kam and Korea detectors (3 error terms)

Mass hierarchy

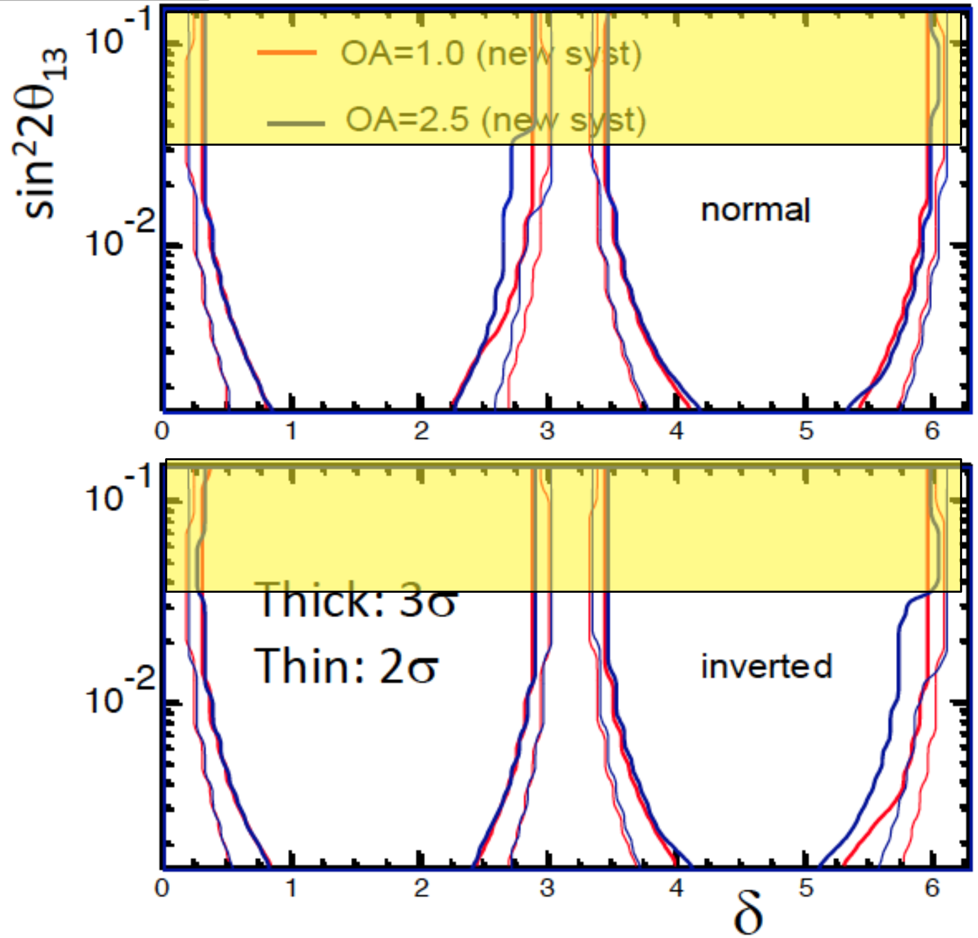
F.Dufour, NP08 (Updated)



2 and 3σ sensitivities for different OA angles with the Kamioka + Korea setup (2)

CP violation

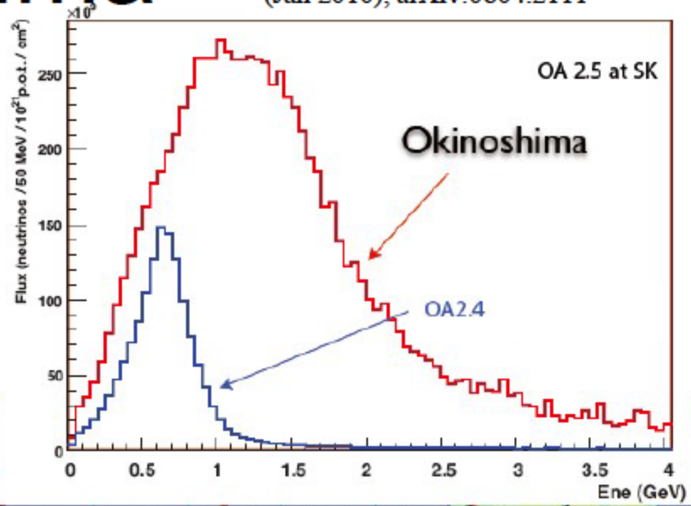
F.Dufour, NP08
(Updated)



- ◆Mass hierarchy: OA1.0 @Korea gives a very high sensitivity
- ◆CP violation: Sensitivity depends weekly on the beam option

J-PARC to Okinoshima

P32 proposal (Lar TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111



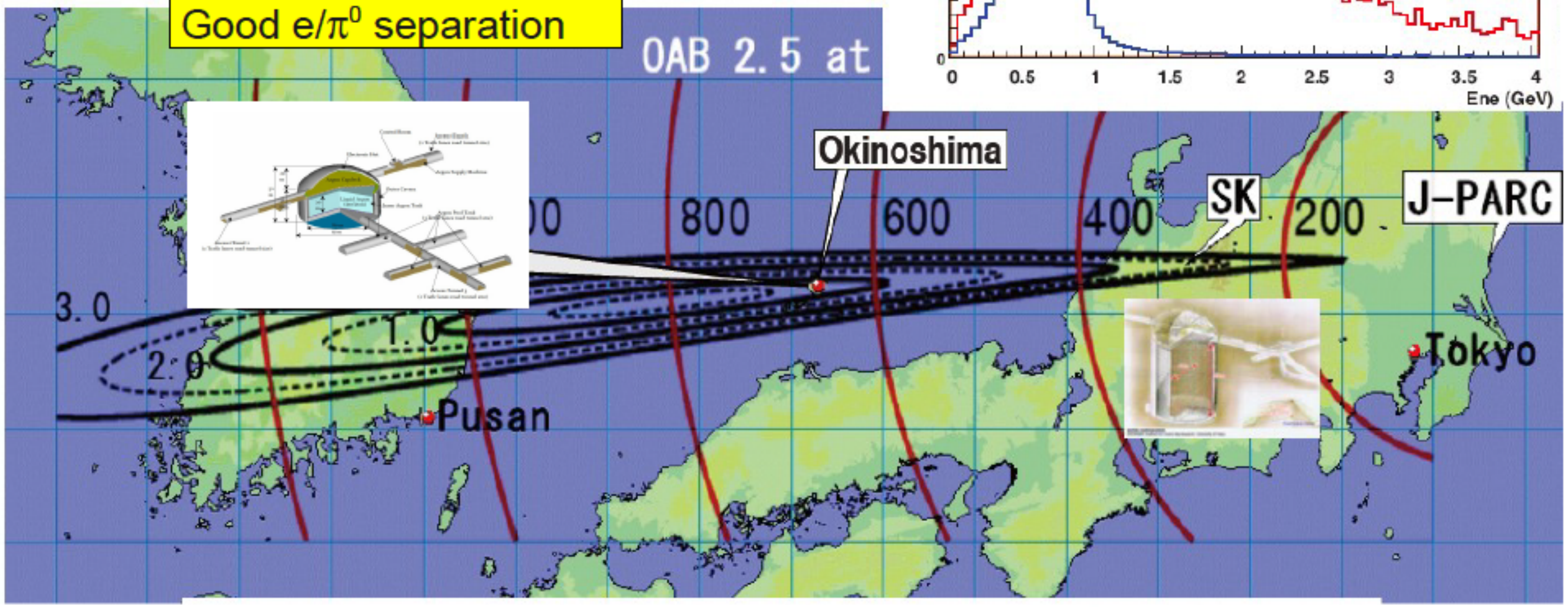
Distance = 658 km

Off-axis angle = 0.76°

(2.5° @ SK)

100 kton liquid Argon

Good Energy resolution
Good e/π^0 separation



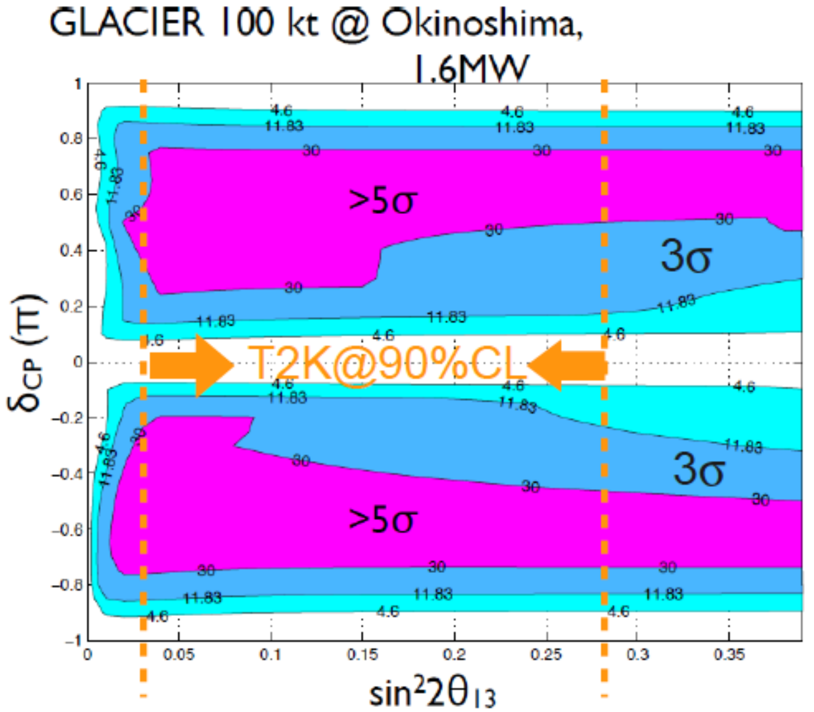
→ Extract δ_{CP} from fit of 1st & 2nd maximum

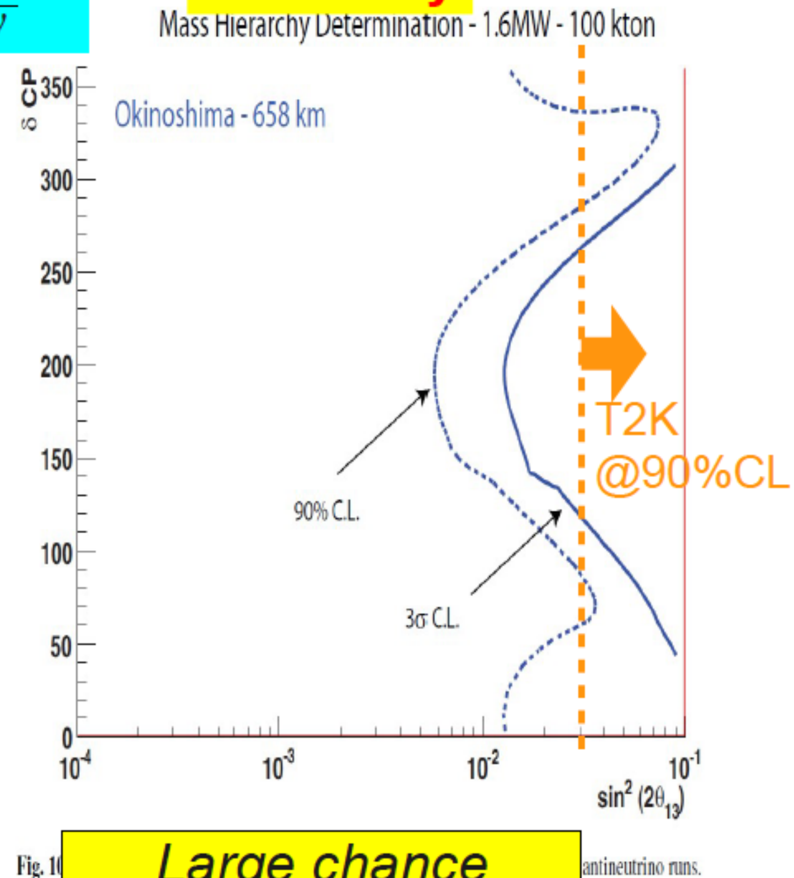
J-PARC to Okinoshima: Sensitivities

CP Violation

5 years ν +
5 years $\overline{\nu}$

Hierarchy





Mass hierarchy is assumed to be unknown
Perfect detector resolution is assumed

Large chance
to determine both δ
And mass hierarchy

INO site at Pottipuram

We have done a χ^2 analysis using the pull approach, as detailed in [1]. Fig. 2 shows the regions of $\sin^2\theta_{13}$ for which a maximal θ_{23} can be rejected at 3σ (yellow), 2σ (green) and 1σ (magenta) levels. The capability to resolve the octant ambiguity

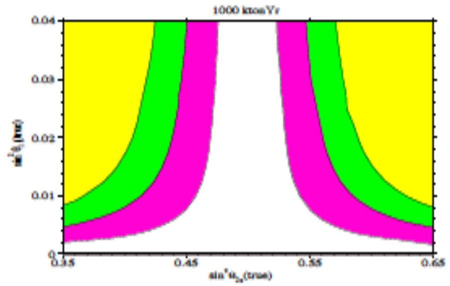
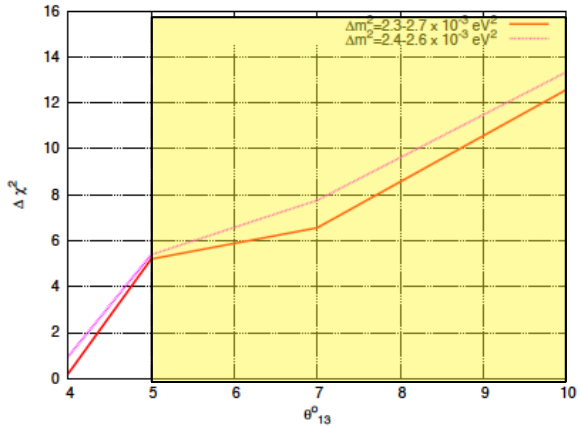
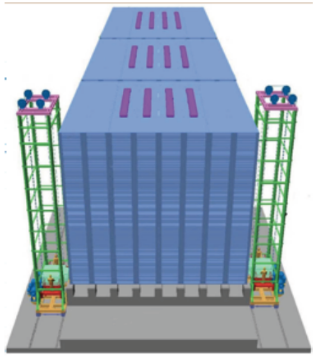


Fig. 2. Sensitivity to deviation from maximal θ_{23} in terms of θ_{13}



Also: INO India-based Neutrino Observatory



Focus on atmospheric neutrinos w/magnetized 50 kt iron calorimeter ICAL (get charge sign, nu vs nubar)

Projected to be completed within Six Years (2011-2017)

From conventional to super ν-beams

- A staged approach to intensity

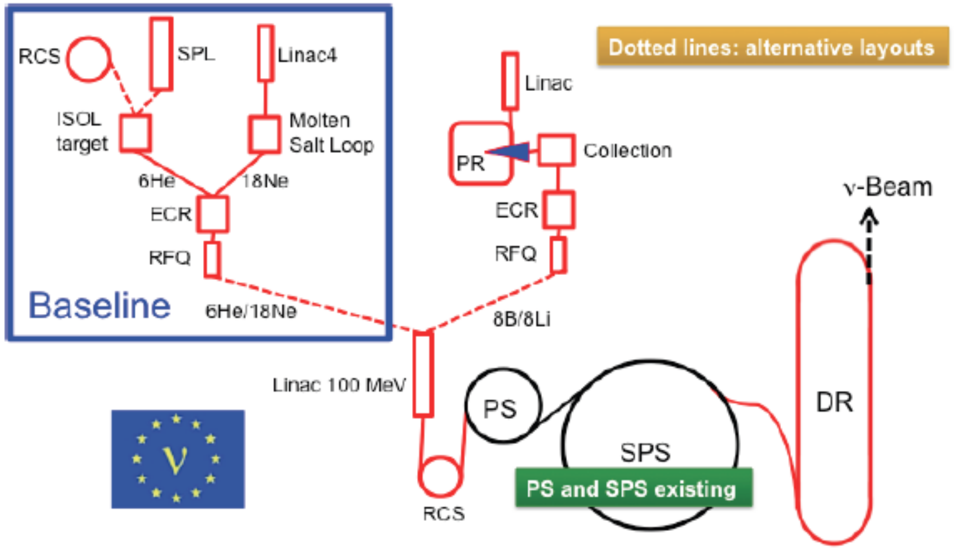
JPARC	T2K (300km) - 0.11MW operation in 2010	T2K (300km) – expected 0.75MW gradually ~2014	T2K (300km) T2O(658km) - expected 1.66MW operation, by >2014
FNAL	NUMI/MINOS (700km) – 0.3MW sustained operation	NUMI/NOVA (700km off-axis) – 0.75MW upgrade (~2013)	LBNE/DUSEL (1300 km) - 2MW operation requires Project-X
CERN	CNGS (732km) – 0.3MW sustained operation, 0.5MW if no beam sharing	CNGS+ (732km) or CN2PY (2300km) - 0.75MW "ultimate", requires SPS and injector upgrade	CN2PY(2300km) CN2FR(130km) - 2MW operation requires LP-SPL+HPPS, or HP-SPL+Accum

LAGUNA-LBNO, EUROν FP7 Design Studies

Prospects for long term upgrades with enhanced neutrino beams

Beta Beam :

Ion production ? Ion collection and bunching ? Ion acceleration ?

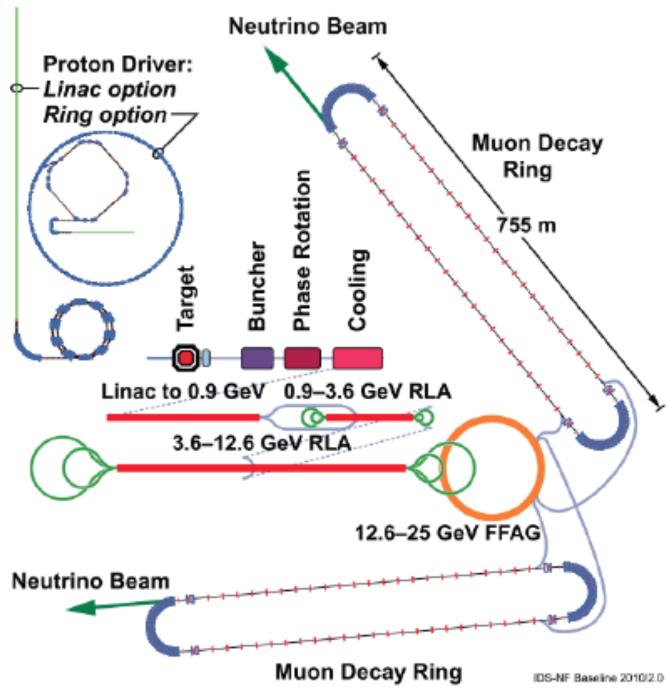


Bρ ~ 500 Tm, B = ~6 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

The considered LAGUNA-Fréjus with MEMPHYS is already an adequate far detector

Neutrino Factory:

High power target? Muon cooling ? Muon acceleration ?



The magnetization of the LAGUNA-Pyhäsalmi detector(s) will be considered. Alternatively, "hybrid" options are possible.

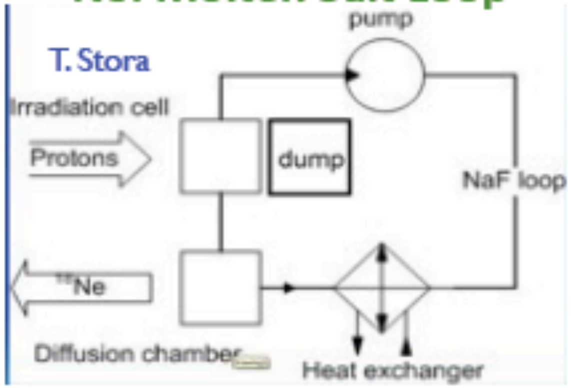
β–beam: isotope production

Type	Accelerator	Beam	I_{beam} mA	E_{beam} MeV	P_{beam} kW	Target	Isotope	Flux s^{-1}	Ok?
ISOL & n-converter	SPL	p	0.1	2 10^3	200	W/BeO	6He	5 10^{13}	(green)
ISOL & n-converter	Saraf/GANIL	d	15	40	600	C/BeO	6He	5 10^{13}	(green)
ISOL	Linac 4	p	6	160	700	19F Molten NaF loop	18Ne	1 10^{13}	(yellow)
ISOL	Cyclo/Linac	p	10	70	700	19F Molten NaF loop	18Ne	2 10^{13}	(yellow)
ISOL	LinacX1	3He	> 170	21	3600	MgO 80 cm disk	18Ne	2 10^{13}	(yellow)
P-Ring	LinacX2	7Li	0.160	25	4	d	8Li	?1 10^{14}	(red)
P-Ring	LinacX2	6Li	0.160	25	4	3He	8B	?1 10^{14}	(red)

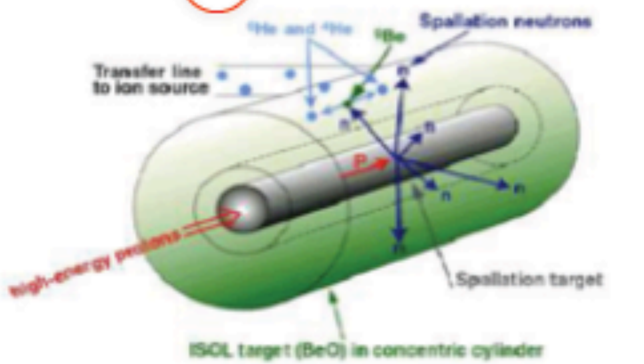
Green: Experimentally OK
Yellow: On paper may be OK
Red: Not OK yet

Baseline option (^{6}He and ^{18}Ne). ^{18}Ne production experiments in 2011.
^{8}Li can be produced in sufficient quantities with ISOL & n-converter

^{18}Ne: Molten Salt Loop

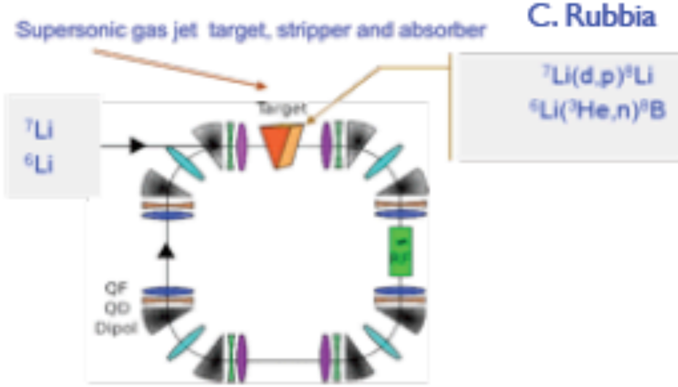


^{6}He & ^{8}Li : ISOL&n-converter



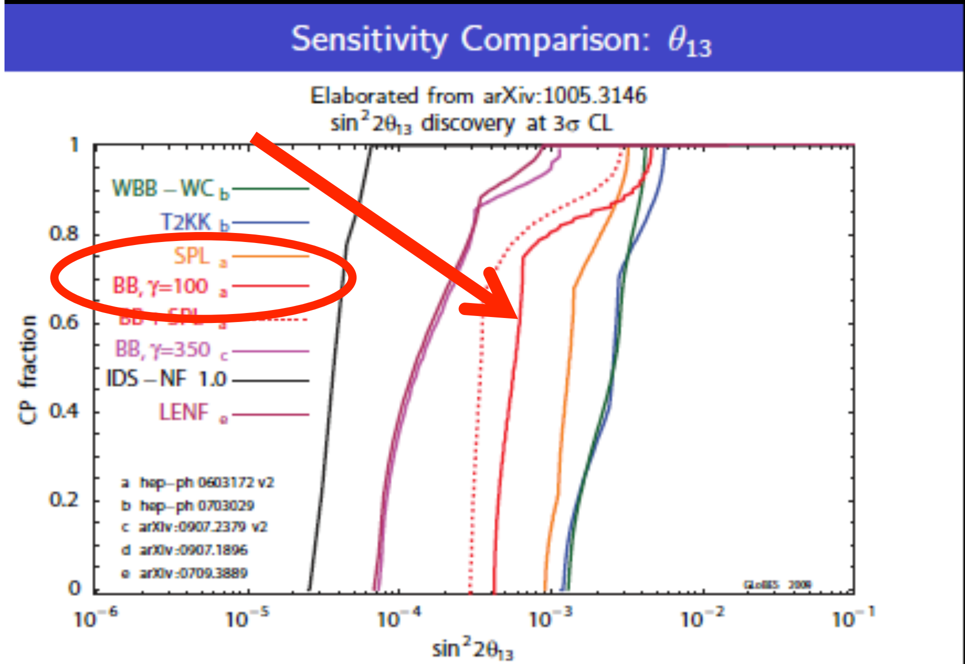
^{8}B & ^{8}Li : Production Ring

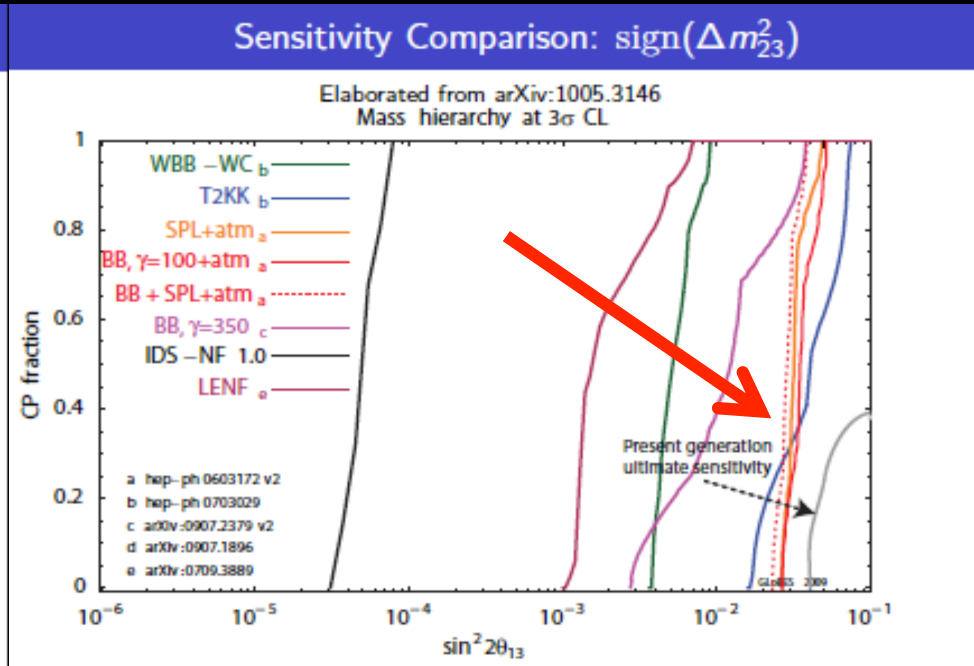
C. Rubbia

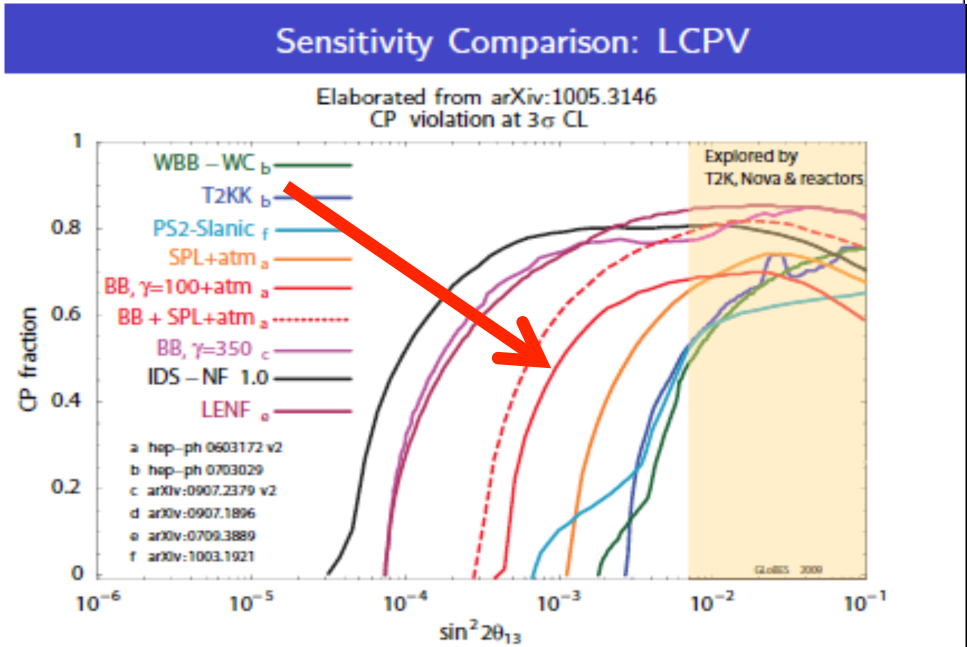


CERN-Frejus (low Q, γ= 100) betabeam starts appearing feasible (on paper)

Betabeam to Frejus





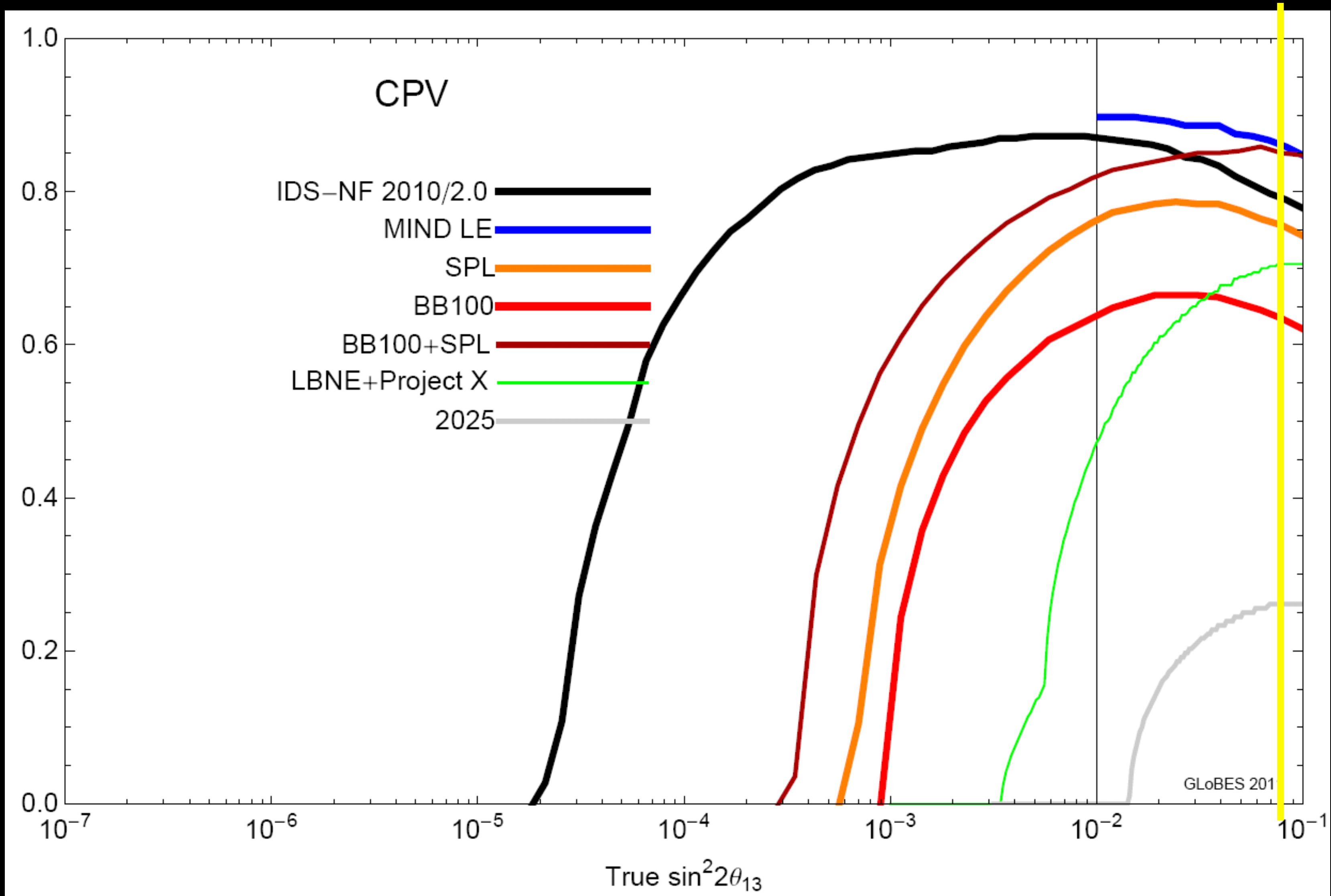


$\sin^2 2\theta_{13}$ ➔ 0.0004 (75% CP fraction)

For $\sin^2\theta_{13} \geq 0.03$ ➔ $\mathrm{Sign}(\Delta m_{23}{}^2)$ (75% CP fraction)

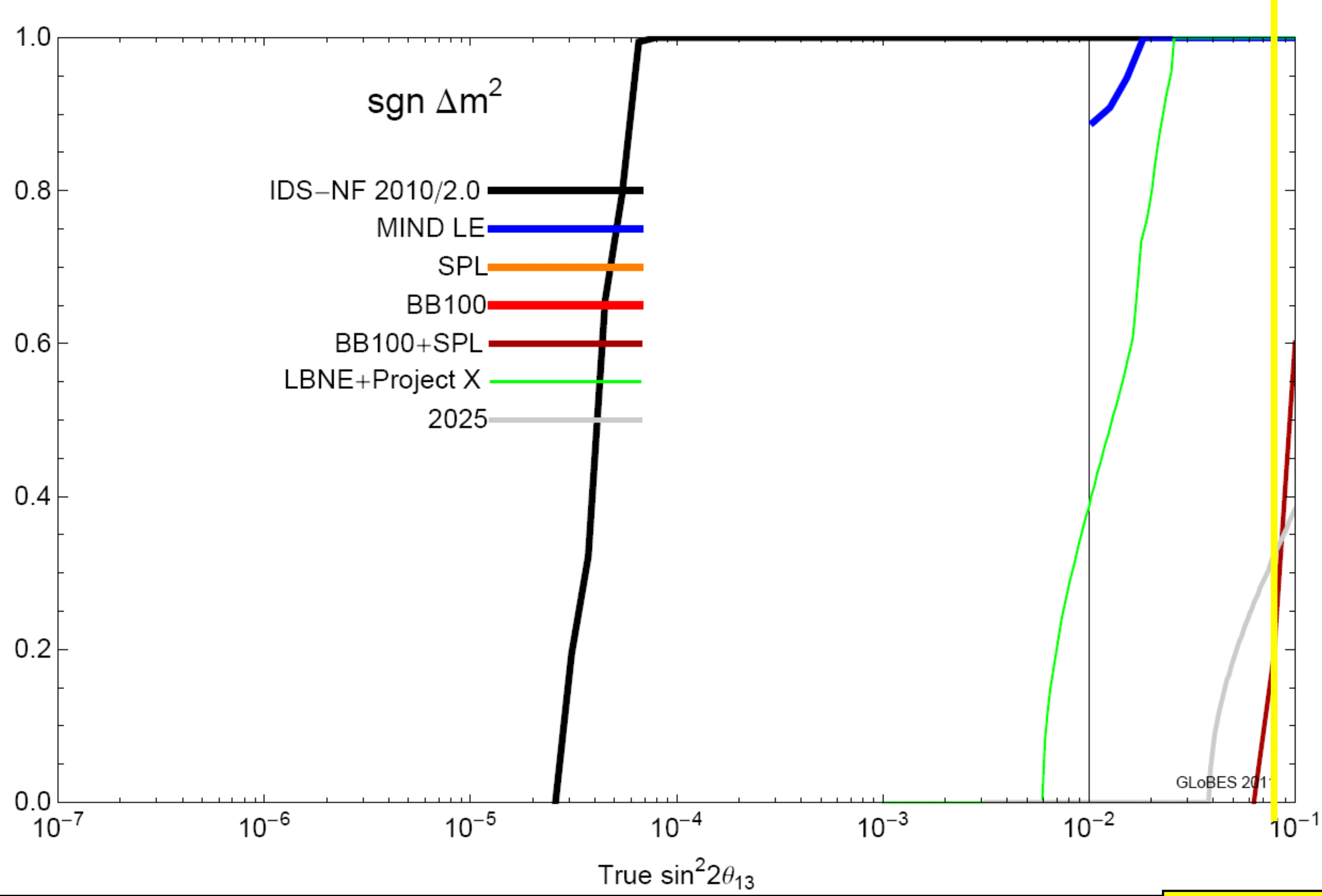
For $\sin^2\theta_{13} \geq 0.001$ ➔ δ_{CP} (60% CP fraction)

Betabeams, Neutrino factories etc. (New report)



Global fit
Fogli et al, 2011

Betabeams, Neutrino factories etc. (New report)



Global fit
Fogli et al, 2011

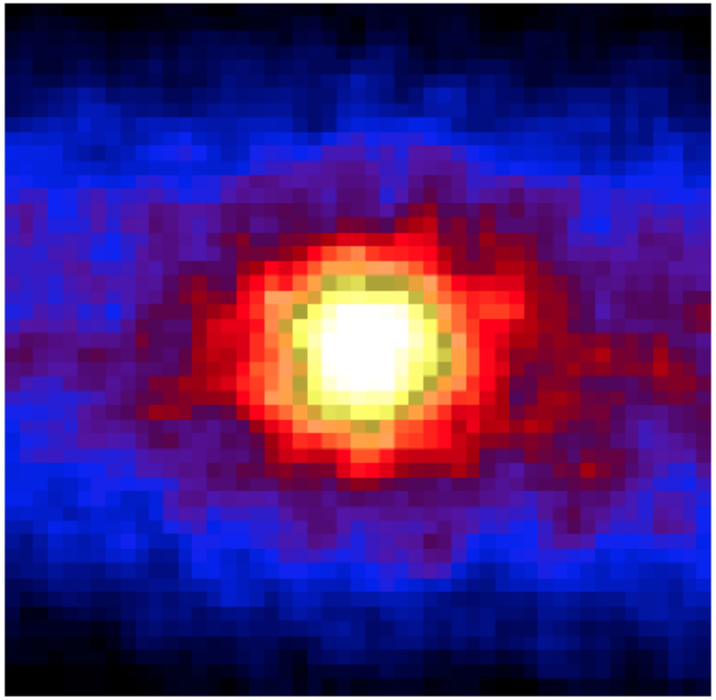
What strategy ?

- ✓ It seems as the value of θ_{13} with a few sigma will be known by end of 2012 (or new limits)
- ✓ If the value of θ_{13} remains in the present range a medium term superbeam program could be sufficient to probe the largest part of the parameter space
- ✓ Need to determine the mass hierarchy soon , either by a single experiment (bimagical distance Pyhaslmi ?) or 2 complementary detectors near/far
- ✓ We will probe the θ_{23} with atmospheric neutrinos
- ✓ We may know the preferred CPV quadrant by 2017-2018 but need dedicated experiments with large mass unless we are lucky (guerilla tactics ?)
- ✓ Exposure optimisation should be the name of the game
- ✓ Worldwide coordination should also be the name of the game

Cosmic sources

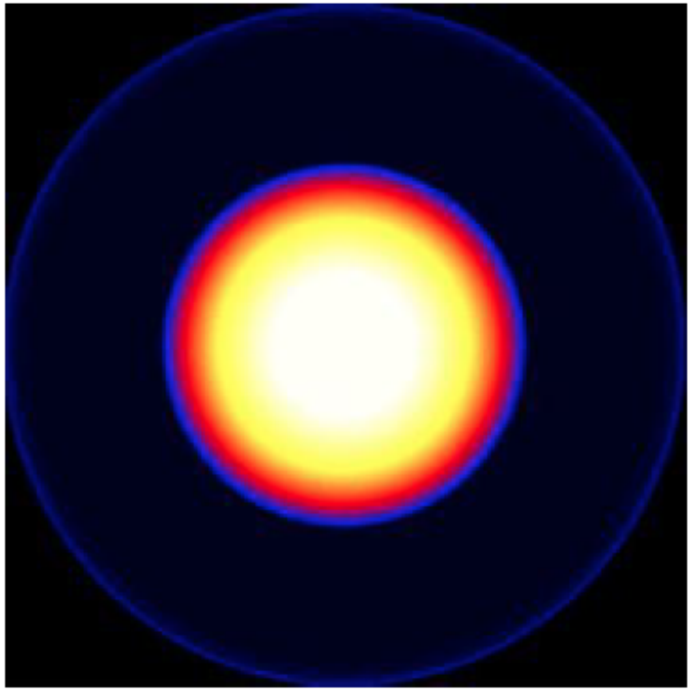
Solar System Neutrino Astronomy

Sun- SK



SK

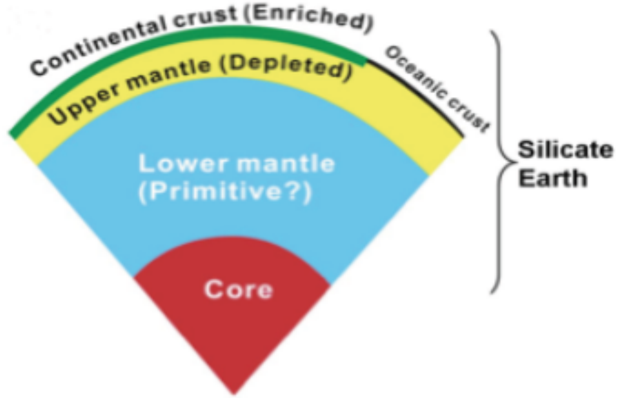
Earth--?



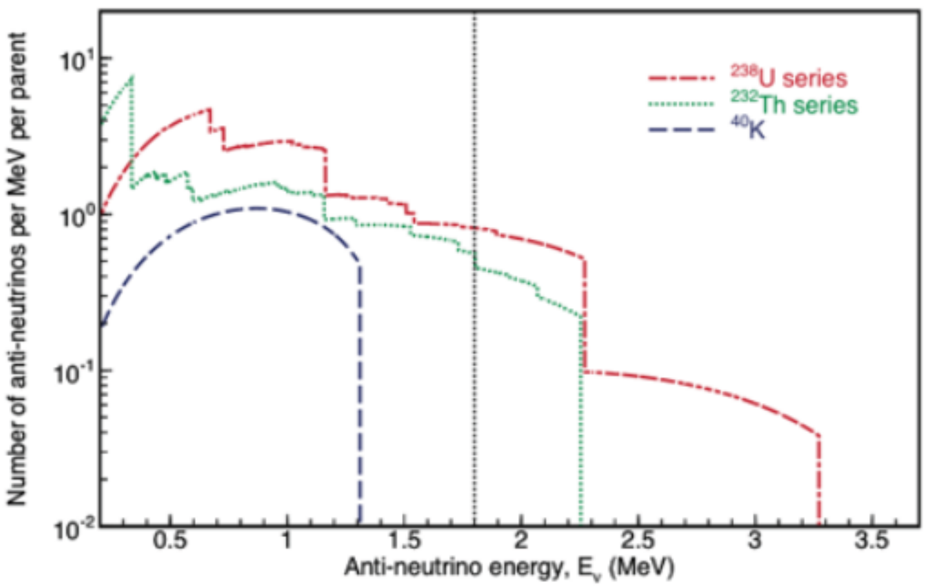
Geo-neutrinos

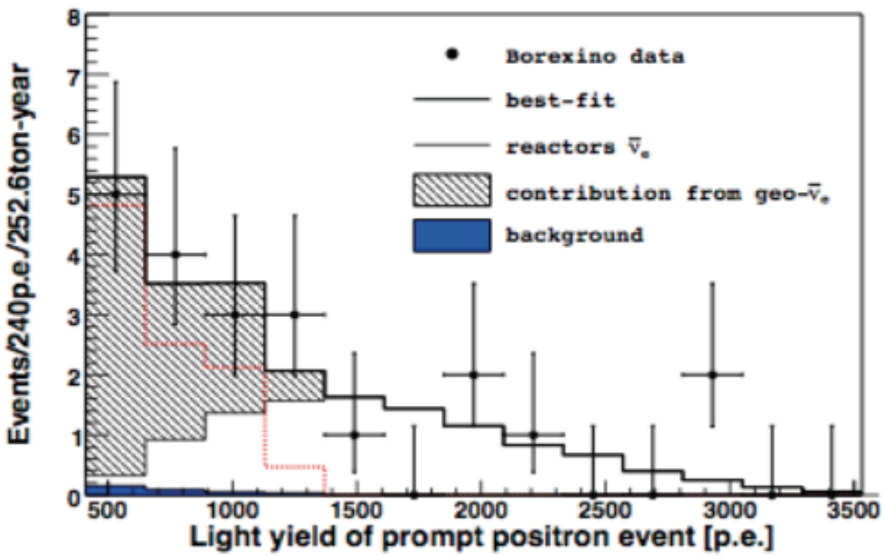
Fraction of Earth's heat from radioactivity is uncertain ... neutrinos can constrain geophysical models, measure U/Th

Recent (low significance) measurements from KamLAND and Borexino have proven feasibility



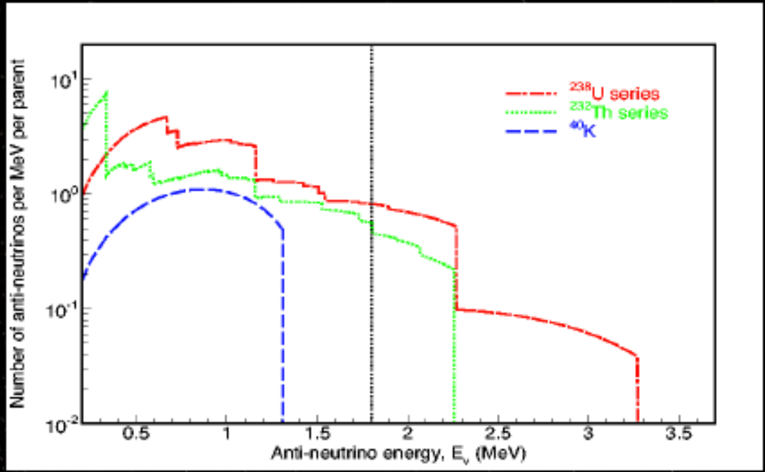
Bulk Silicate Earth model:
~1/2 of U, Th, K in crust
~1/2 of U, Th, K in mantle
~no U, Th, K in core





Geoneutrinos

- $\overline{\nu}_e$ produced by U/Th decay chains, Ka
- Detection reaction: inverse beta decay ~1000 events per year



Goals

- measure abundance of ^{238}U and ^{232}Th inside Earth crust and mantle
- quantify the radiogenic constribution to the total heat flux
- help to understand geophysical processes and origin and formation of Earth
- with a 2nd detector (like Hanohano): disentangle oceanic/continental crust

Within one year error on total ν flux in few % level

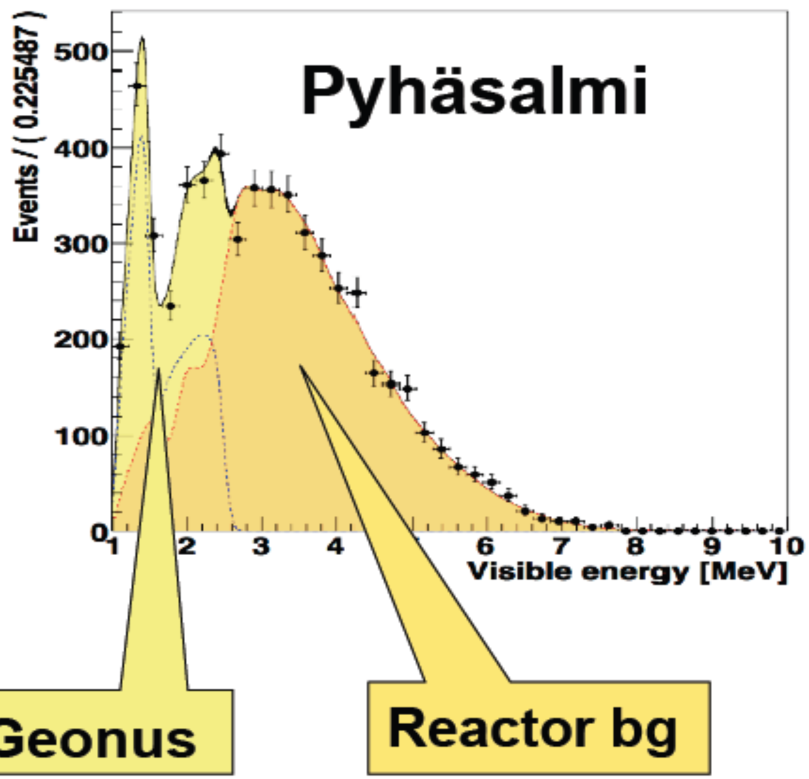
BSE model:
@Pyhäsalmi 50 TNU
@Fréjus 40 TNU

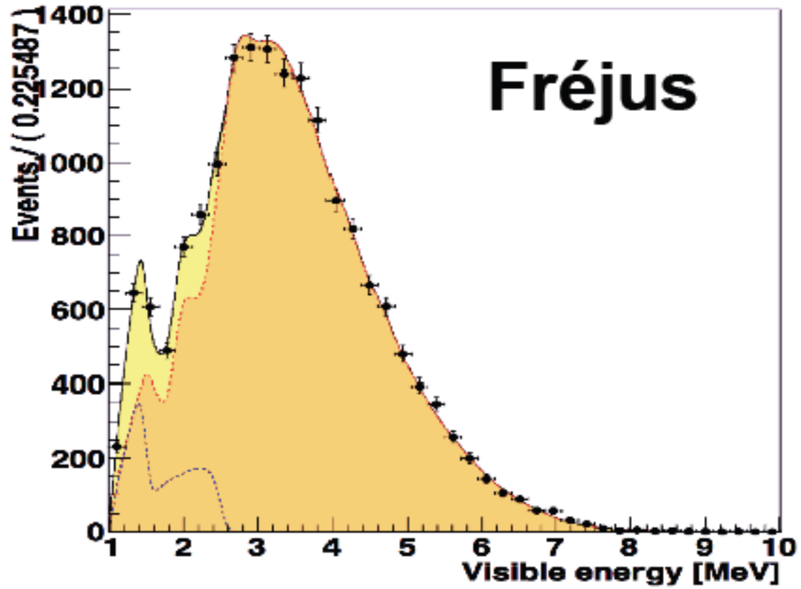
Background:

- Reactor Neutrinos
- ^{9}Li and ^{8}He: muon-induced ßn-emitter
- Fast neutrons and $^{12}C(\alpha,n)^{16}O$: each ~10 evts/year (MC)

Best bet for geoneutrinos is scintillator, due to low energy threshold, good energy resolution & low radioactive bg

Reactor neutrino bg is the biggest issue





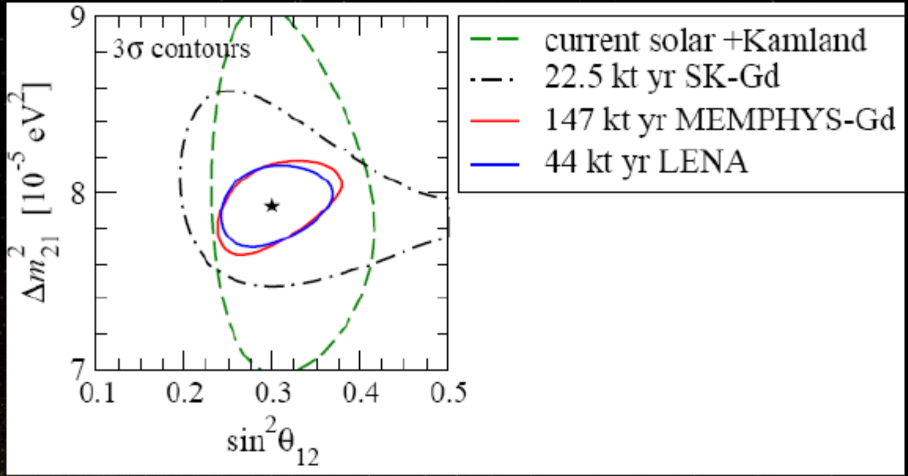
1 year statistics

LENA arXiv.1104.5620

LENA @ Fréjus

Short-Baseline Neutrino Oscillations

- Reactor Neutrinos $\bar{\nu}_e$
  - 50-25000 anti ν_e events per year, depending on detector site
  - anti-ν_e disappearance experiment
  - precision measurement of solar oscillation parameters θ_{12}, Δm^2_{12}
    - → after 1 y: 3 σ error Δm^2_{12} < 3%



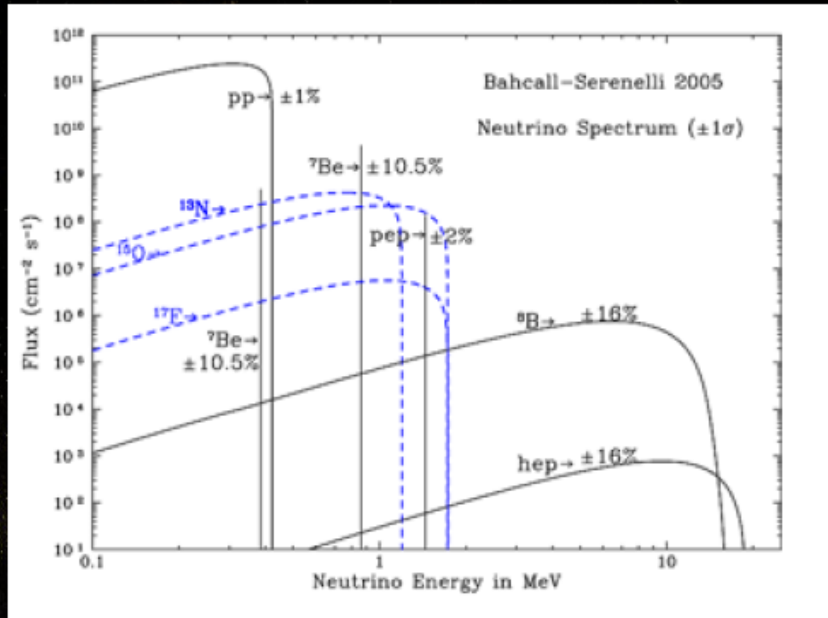
- Neutrino Oscillometry ν_e
  - strong EC-source (MCi) close to detector with E = O(100 keV) (^{51}Cr, ^{57}Se)
    - → sterile neutrinos
    - → θ_{13}, Δm^2_{13} (see poster from Kai Loo)

- Pion at rest decay
  - Search for sterile neutrinos
  - Search for θ_{13}, δ_{CP} (compare Daedalus)

Solar Neutrinos

Neutrino-electron scattering (low threshold)
→ Good shielding required (≥ 4 km.w.e.)

- High-statistic spectral observation and flux measurement
- Search for temporal modulations with ^{7}Be
  → 3σ dicovery potential for amplitudes as low as 0.5 % for frequencies O(10min)- O(100y)
- Precision test of the ν_e survival probability in the transition region
- Search for $\nu_e \rightarrow$ anti-ν_e conversion
- Test of SSM metallicity



Source	Channel	EW [MeV]	m_{fid} [kt]	Rate [cpd]
pp	$\nu e \rightarrow e \nu$	>0.25	30	40
pep		0.8−1.4	30	2.8×10^2
^{7}Be		>0.25	35	1.0×10^4
^{8}B		>2.8	35	79
CNO		0.8−1.4	30	1.9×10^2
^{8}B	^{13}C	>2.2	35	2.4

Core collapse supernova neutrinos

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of *all flavors* with ~MeV energies (energy *can* escape via ν's)

Timescale: *prompt* after core collapse, overall Δt~10's of seconds

~few SNae per century

Importance of Supernova Neutrino Detection

How do core-collapse supernovae explode?
How do they form neutron stars and black holes?
What are the nucleosynthesis products of supernovae?
What are the actions and properties of neutrinos?
What is the cosmic rate of black hole formation?
Which supernova-like events make neutrinos?
What else is out there that makes neutrinos?
....

We cannot solve key problems without detecting supernova neutrinos

Only neutrinos can reveal the interior conditions of collapsing stars

Detecting even a few neutrinos can often give decisive answers

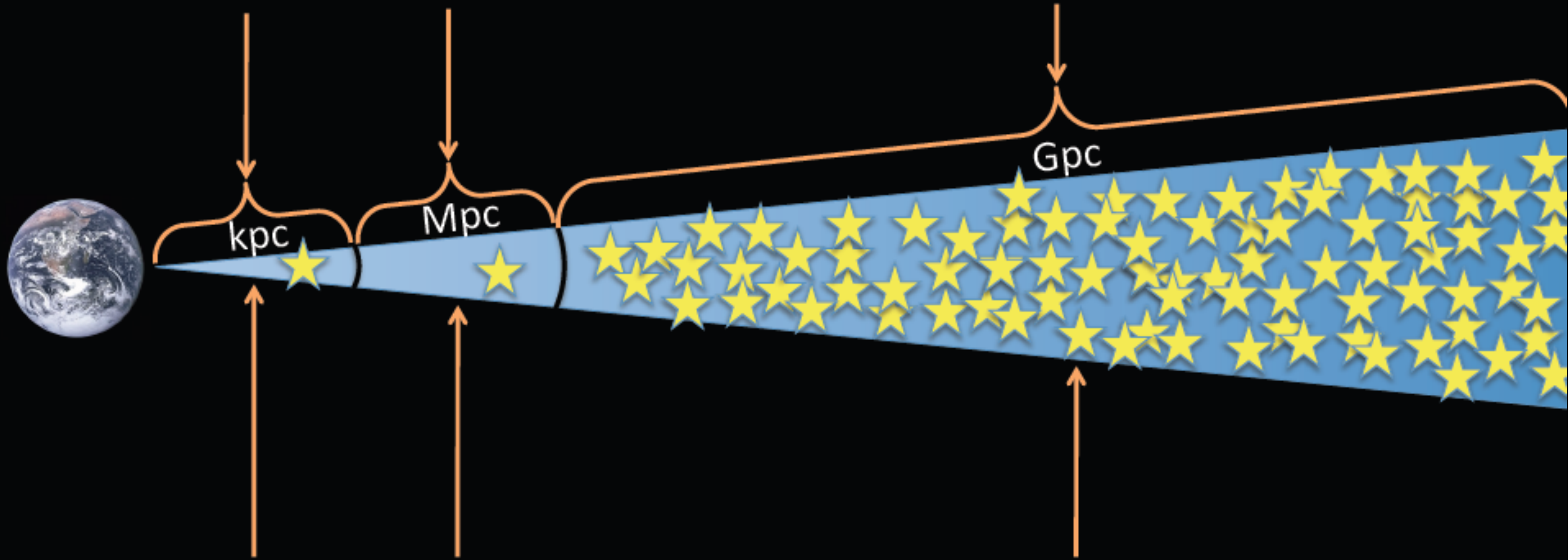
Will open new frontiers in observational neutrino astrophysics

Distance Scales and Detection Strategies

N >> 1 : Burst

N ~ 1 : Mini-Burst

N << 1 : DSNB



Rate ~ 0.01/yr

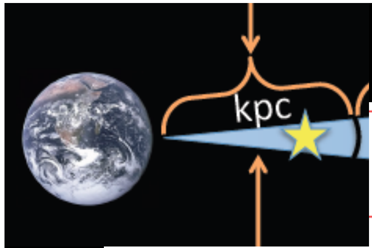
high statistics,
all flavors

Rate ~ 1/yr

object identity,
burst variety

Rate ~ 10^8/yr

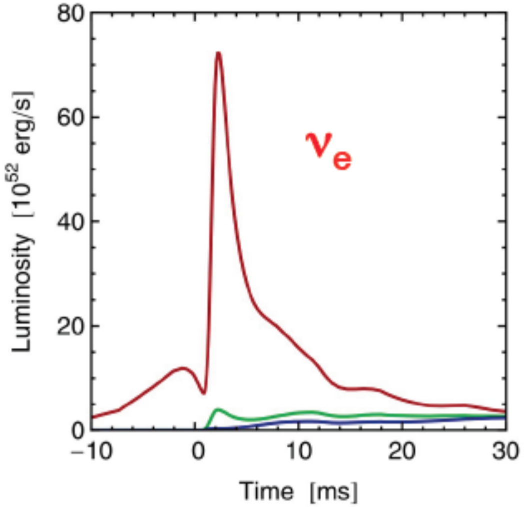
cosmic rate,
average emission



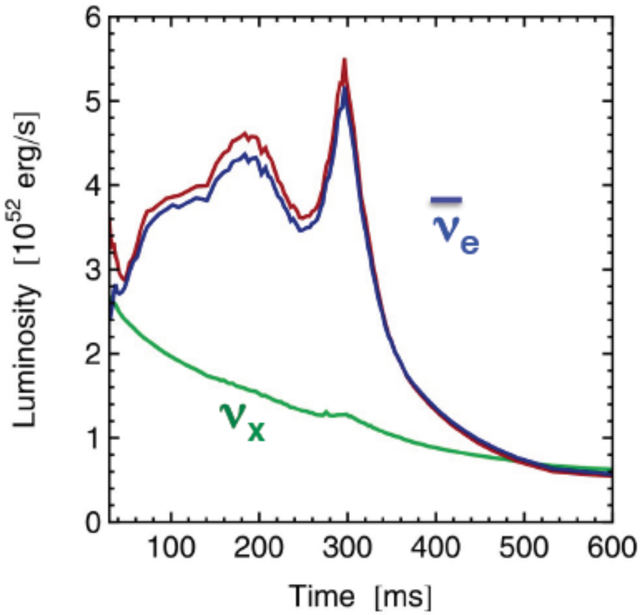
Neutrino Emission Phases

[Fischer et al. (Basel Simulations), A&A 517:A80,2010, 10. 8 M_{sun} progenitor mass]

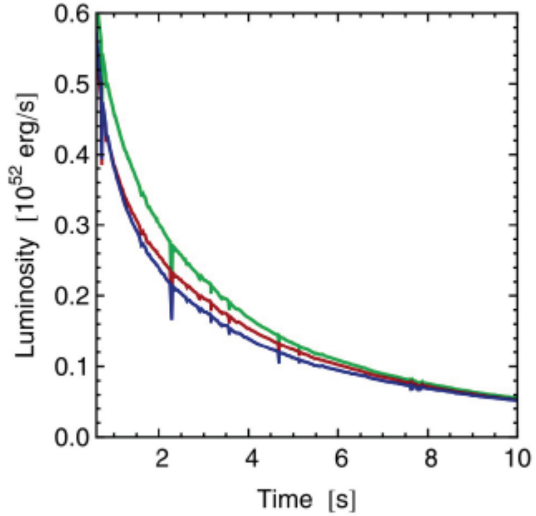
Neutronization burst



Accretion



Cooling



NEUTRONIZATION BURST (ν_e): E~10^{51} erg

Duration ~ 25 ms

THERMAL BURST (ν_e, $\bar{\nu}_e$, ν_x, $\bar{\nu}_x$) :~ E~ 10^{53} erg

Accretion: ~ 0.5 s ; Cooling: ~ 10 s

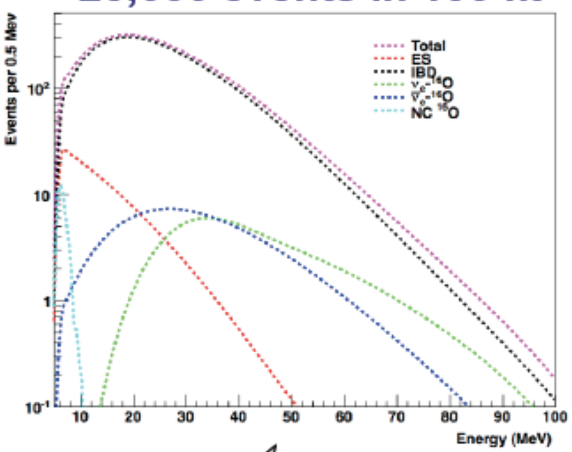
Large flux differences in Accretion Phase (best for oscillation effects!)

Cooling Phase : Equipartition of luminosity

All detector types would observe copious neutrinos

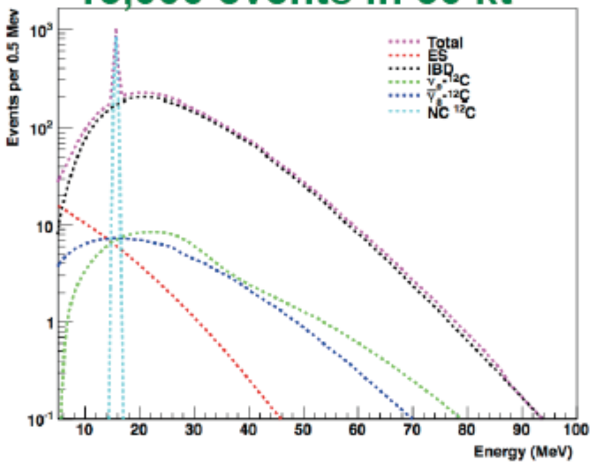
Observed events at 10 kpc

Water
25,000 events in 100 kt



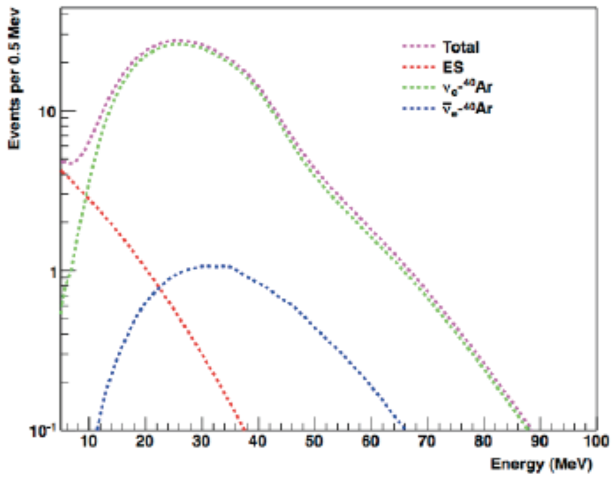
Nearly pure nuebar (inverse beta decay on free protons)

Liquid scintillator
15,000 events in 50 kt



Also nearly pure nuebar, plus NC channels

Liquid argon
1500 events in 17 kt



Nearly pure nue!

Signals are complementary... diversity in flavor sensitivity good for getting physics from the signal!

SN neutrino Flux at Earth

Earth Matter Effect:

$\cos^2\theta_{12} \longrightarrow P(\nu_1 \longrightarrow \nu_e)$

- Normal mass hierarchy

$$F^D_{\bar{\nu}_e} = \cos^2\theta_{12} F_{\bar{\nu}_e} + \sin^2\theta_{12} F_{\bar{\nu}_x} \Longrightarrow \text{Earth Matter}$$

- Inverted mass hierarchy
  - $\sin^2\theta_{13} \geq 10^{-3}$

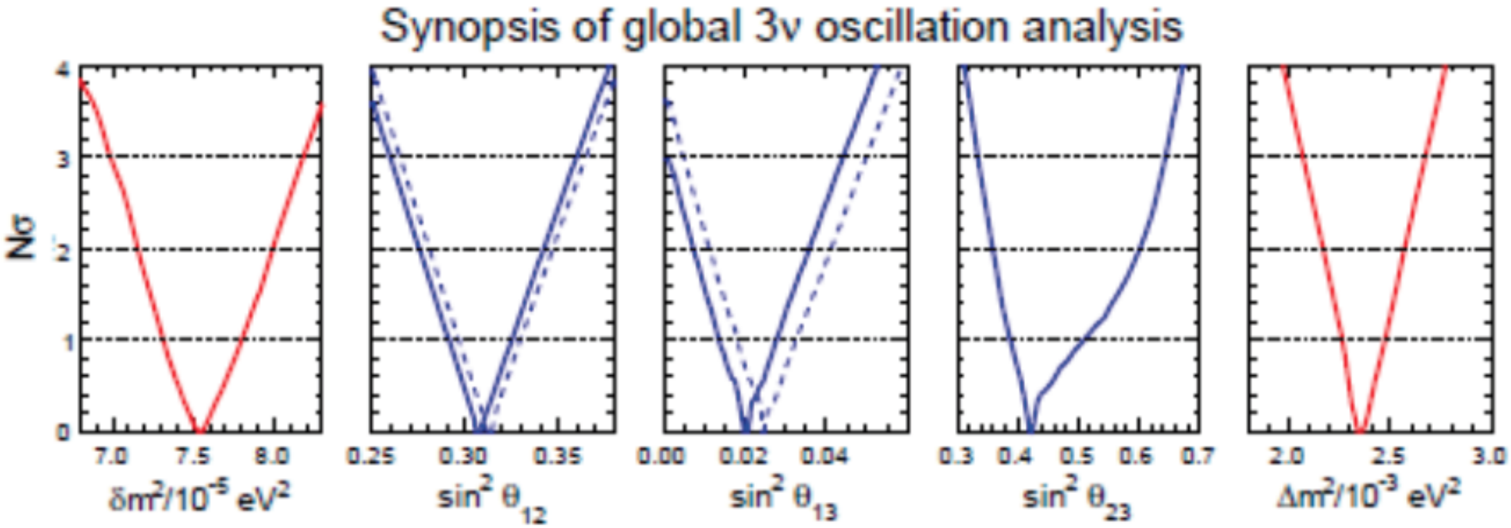
$$F^D_{\bar{\nu}_e} = F_{\bar{\nu}_x} \Longrightarrow \text{No Earth Matter}$$

  - $\sin^2\theta_{13} \leq 10^{-5}$

$$F^D_{\bar{\nu}_e} = \cos^2\theta_{12} F_{\bar{\nu}_e} + \sin^2\theta_{12} F_{\bar{\nu}_x} \Longrightarrow \text{Earth Matter}$$

Evidence of large θ_{13}

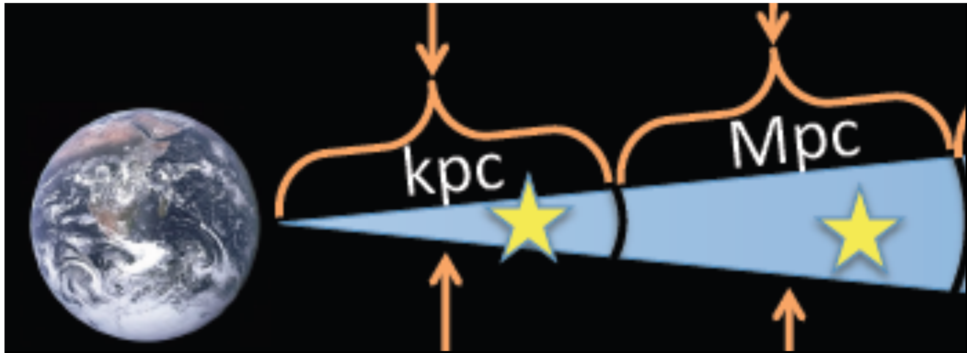
[Fogli, Lisi, Marrone, Palazzo, Rotunno, arxiv:1106.6028]
see talk by Lisi.



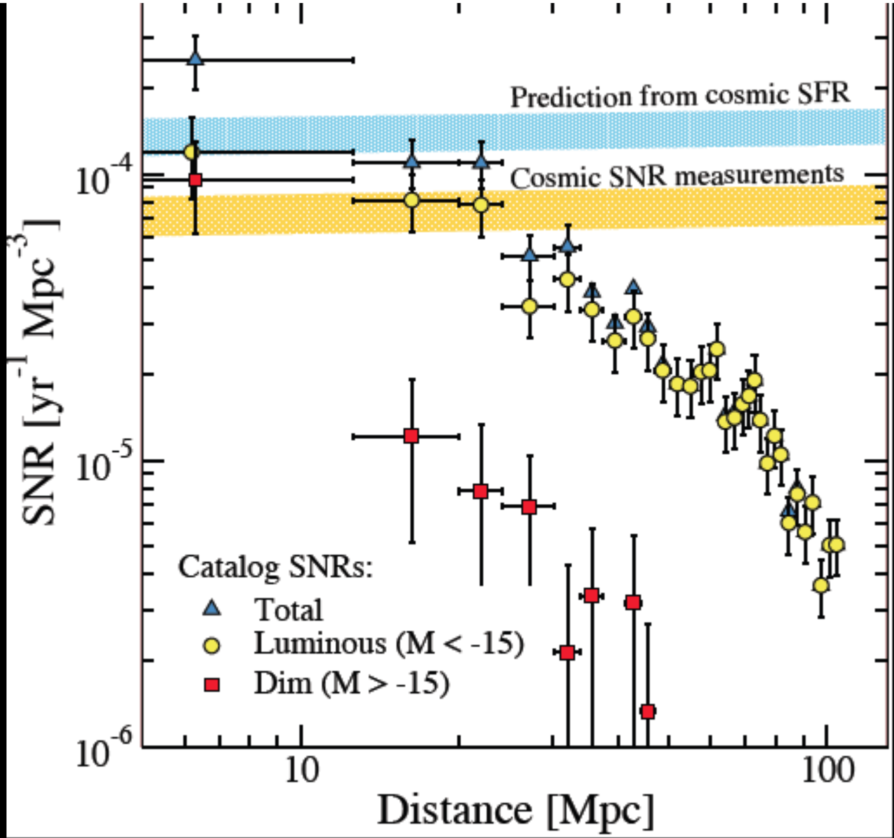
Matter suppression of collective oscillations during the accretion phase, the next galactic SN neutrino burst could become crucial to determine the neutrino mass hierarchy.

Study of observable signatures in progress.

Stay tuned !



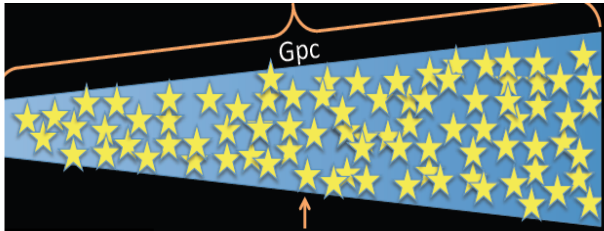
A supernova trigger



Horiuchi et al. (2011)

- Using star formation rates and recent catalogs one expects 1 SN /year <10 Mpc
- 9 have been observed <10 Mpc, in 3 last years = x3 the above estimate
- AT MEMPHYS(450kt) we expect
  - 20 ν events at 1 Mpc
  - 2 ν events at 3.3 Mpc
- Backgrounds 1/day
- For 1 Mton (or x2 present rates)
  - 50% Detection probability of equal or more than 1 event up to 5 Mpc
  - 50% detection probability of equal or more than 2 events up to 3 Mpc

- Two possible strategies:
  - See two events inside 10 seconds, Issue a SN alert
  - See an optical supernova, and examine a 10s time span around neutrinos seen and trigger:
    - Gravitational detectors, Neutrino telescopes



DSNB

Theoretical Framework

Signal rate spectrum in detector in terms of measured energy

$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu)\int_0^\infty \Big[(1+z)\,\varphi[E_\nu(1+z)]\Big]\Big[R_{SN}(z)\Big]\left[\left|\frac{c\,dt}{dz}\right|dz\right]$$

Third ingredient: Detector Capabilities (well understood)

Second ingredient: Supernova Rate (formerly very uncertain, but now known with high precision)

First ingredient: Neutrino spectrum (this is now the unknown)

Cosmology? Solved. Oscillations? Included. Backgrounds? See below.

First Ingredient: Supernova Neutrino Emission

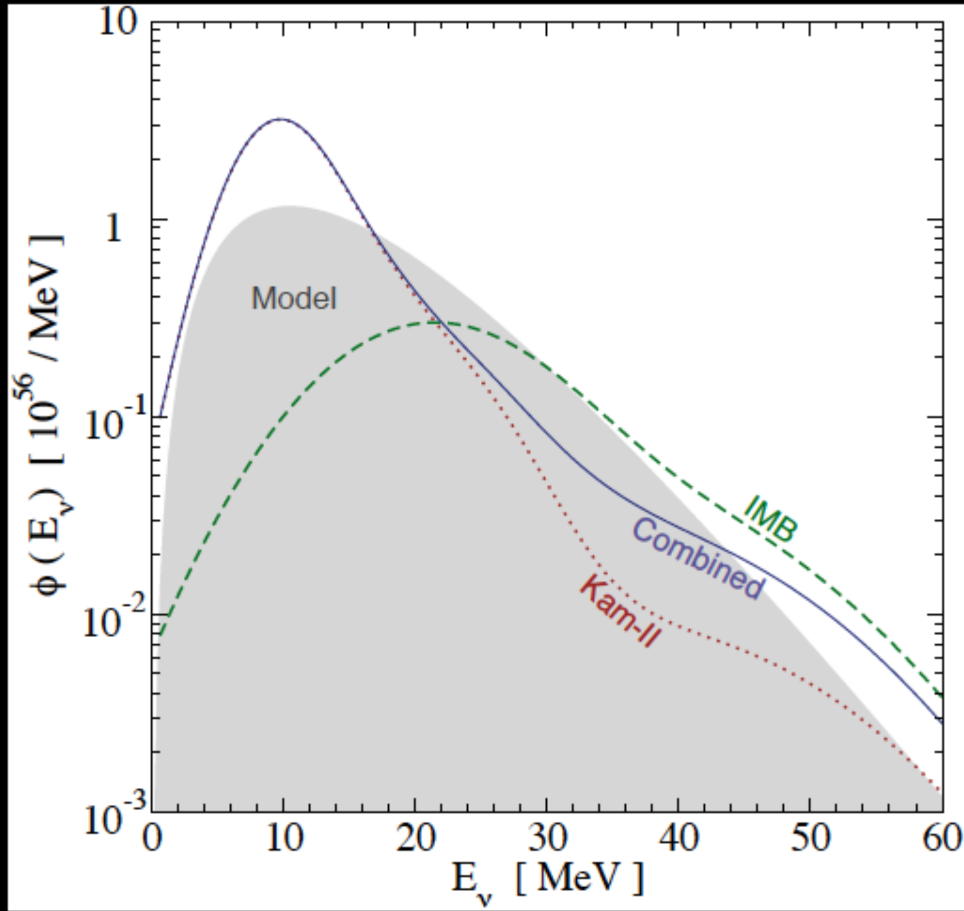
Core collapse releases ~ 3×10^{53} erg, shared by six flavors of neutrinos

Spectra quasi-thermal with average energies of ~ 15 MeV

Neutrino mixing surely important but actual effects unknown

Goal is to measure the received spectrum

Nonparametric reconstruction from SN 1987A data



Yuksel, Beacom (2007)

Second Ingredient: Cosmic Supernova Rate

Number of massive stars unchanging due to short lifetimes

$$\left(\frac{dN}{dt}\right) = 0 = +\left(\frac{dN}{dt}\right)_{\substack{\text{star}\\\text{birth}}} - \left(\frac{dN}{dt}\right)_{\substack{\text{bright}\\\text{collapse}}} - \left(\frac{dN}{dt}\right)_{\substack{\text{dark}\\\text{collapse}}}$$

Measured from N/τ using luminosity and spectrum of galaxies

(now high precision)

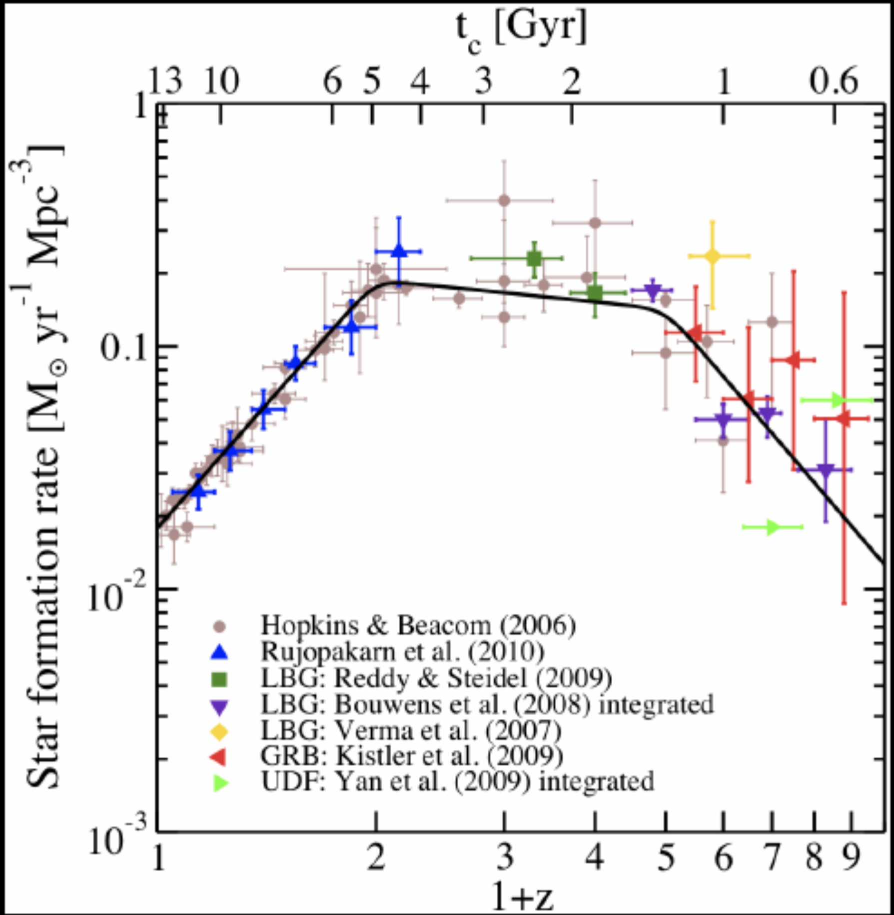
Measured from the core collapse supernova rate

(precision will improve rapidly)

Inferred from mismatch; can be measured by star disappearance; can be measured by DSNB

(frontier research area)

Predictions from Cosmic Star Formation Rate



Horiuchi, Beacom (2010)

Total star formation rate deduced from massive stars using initial mass function (IMF)

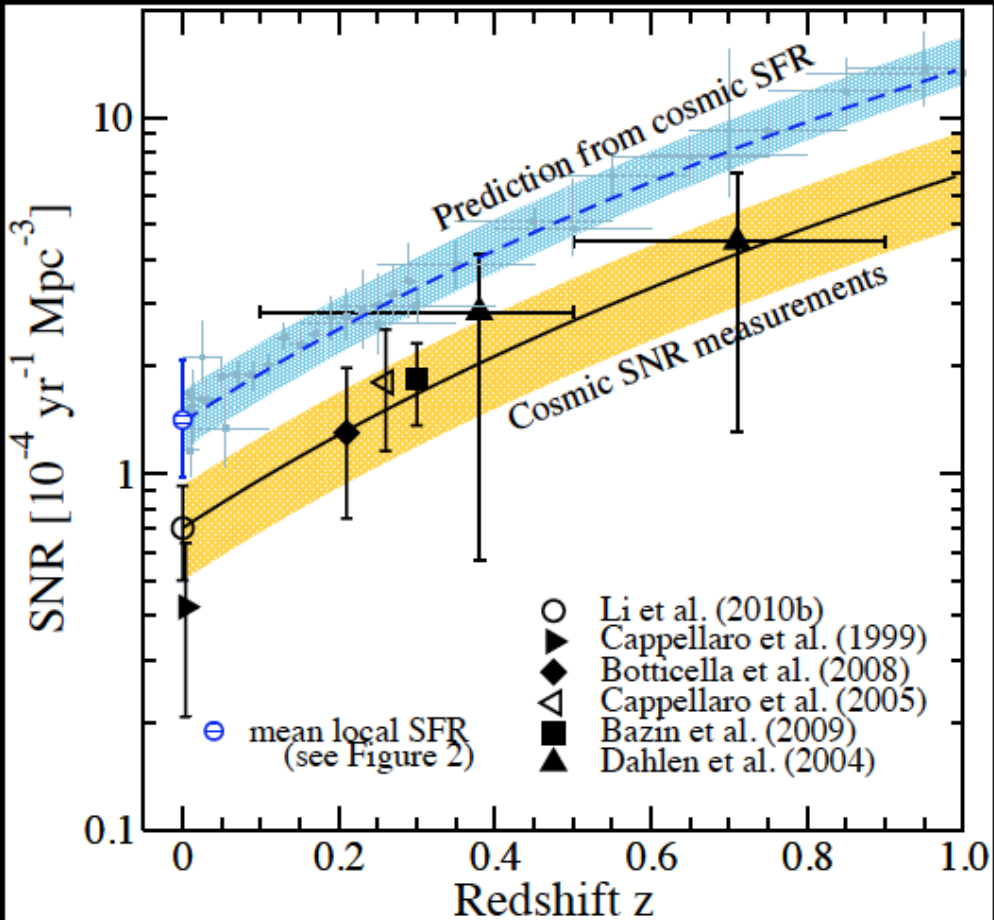
Impressive agreement among results from different groups, techniques, and wavelengths

Integral of R_{SF} agrees with data

$$R_{\rm SN}(z) \simeq \frac{R_{\rm SF}(z)}{143 M_\odot}$$

IMF uncertainty on R_{SN} small

Measured Cosmic Supernova Rate



Horiuchi et al. (2011);
see also Hopkins, Beacom (2006),
Botticella et al. (2008)

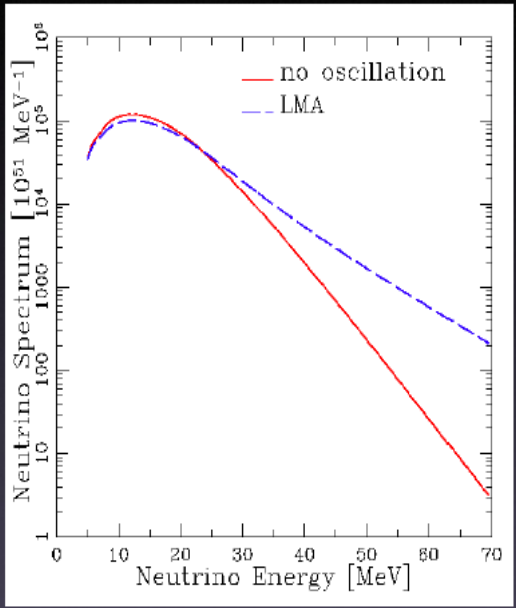
Measured cosmic supernova rate is half as big as expected, a greater deviation than allowed by uncertainties

Why?

There must be missing supernovae – are they faint, obscured, or truly dark?

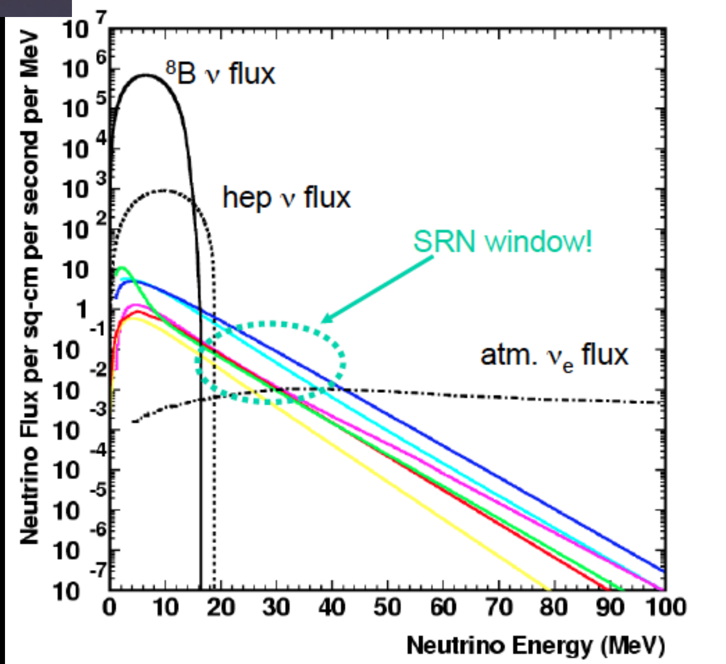
Preliminary Dahlen (2010) points near solid line, below preliminary Dahlen (2008)

Spectrum after Oscillation



- Here, we only consider the case of normal mass hierarchy.
- Oscillation enhances the high-energy tail.
  - But not dramatically at detectable energy range (<30 MeV).

diffuse SN ν's (DSNB)

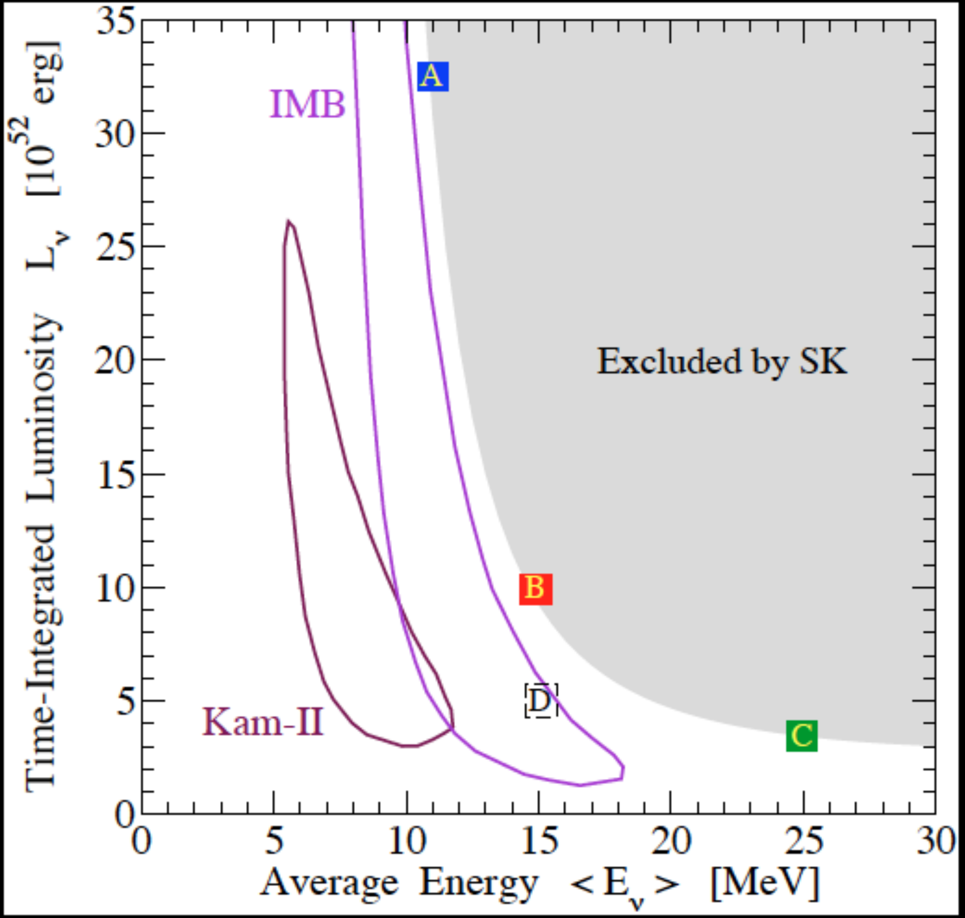


Limits on Supernova Neutrino Emission

2003 Super-Kamiokande limit:
$\Phi < 1.2\ cm^{-2}\ s^{-1}$ (90% CL)
for nuebar with $E_\nu > 19.3$ MeV

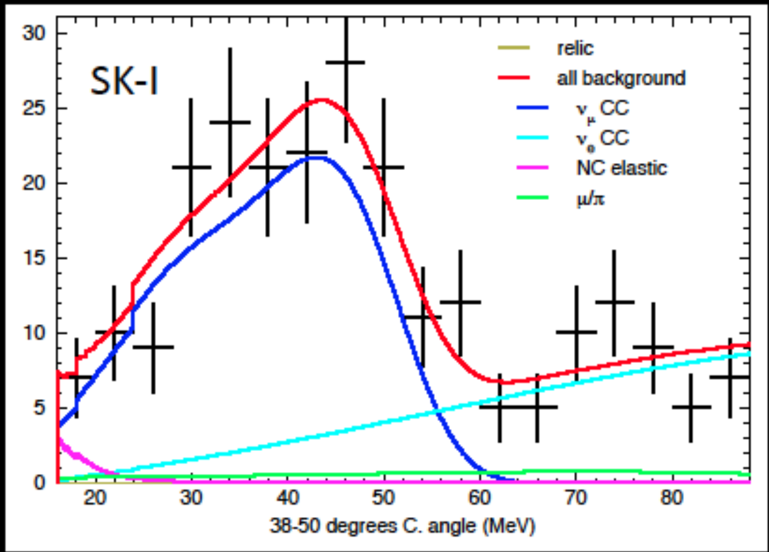
Supernova rate uncertainty is now subdominant; this limits the effective nuebar spectrum that includes mixing effects

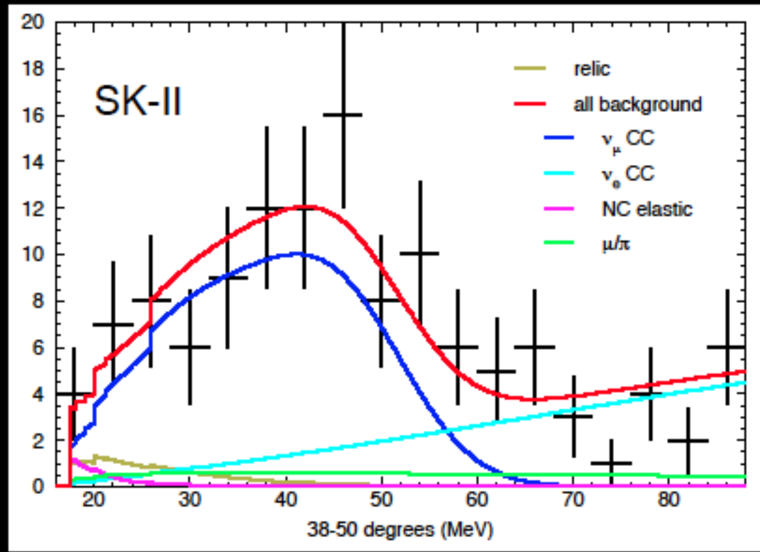
Within range of expectations from theory and SN 1987A!

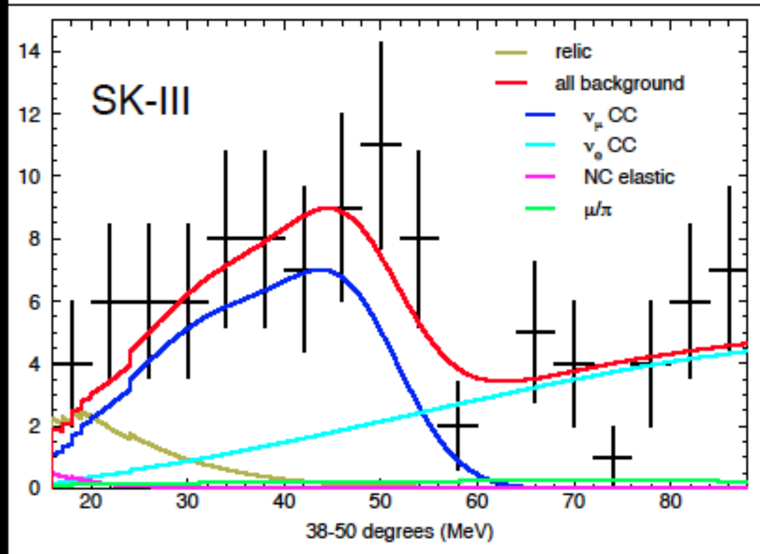


Yuksel, Ando, Beacom (2006);
SN 1987A fits from Jegerlehner, Neubig, Raffelt (1996)

Energy Spectrum Fits







SK-I:

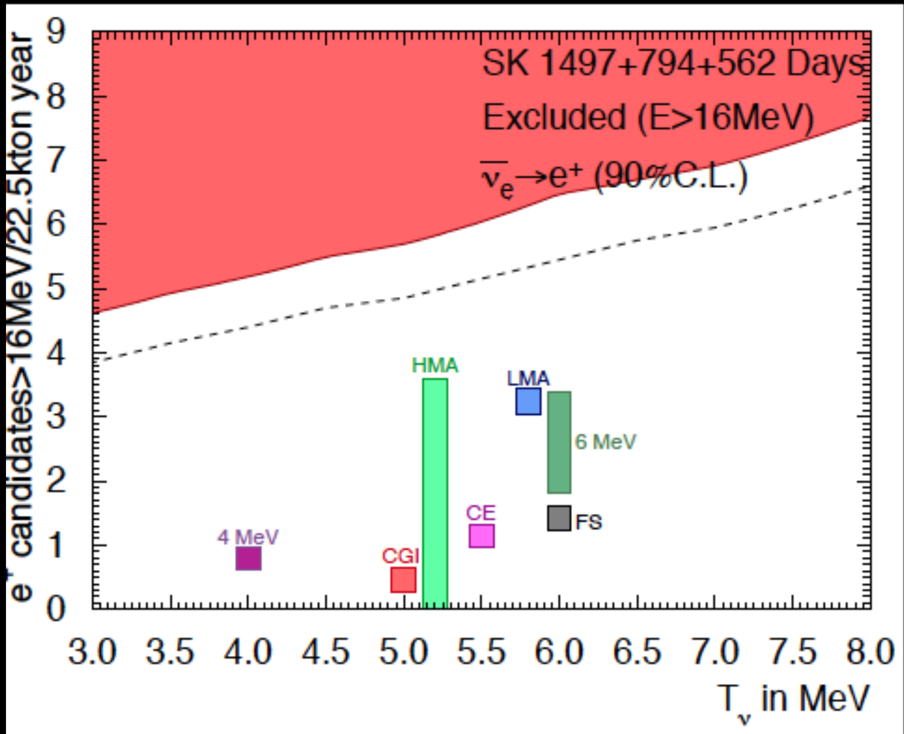
Best fit is slightly negative DSNB

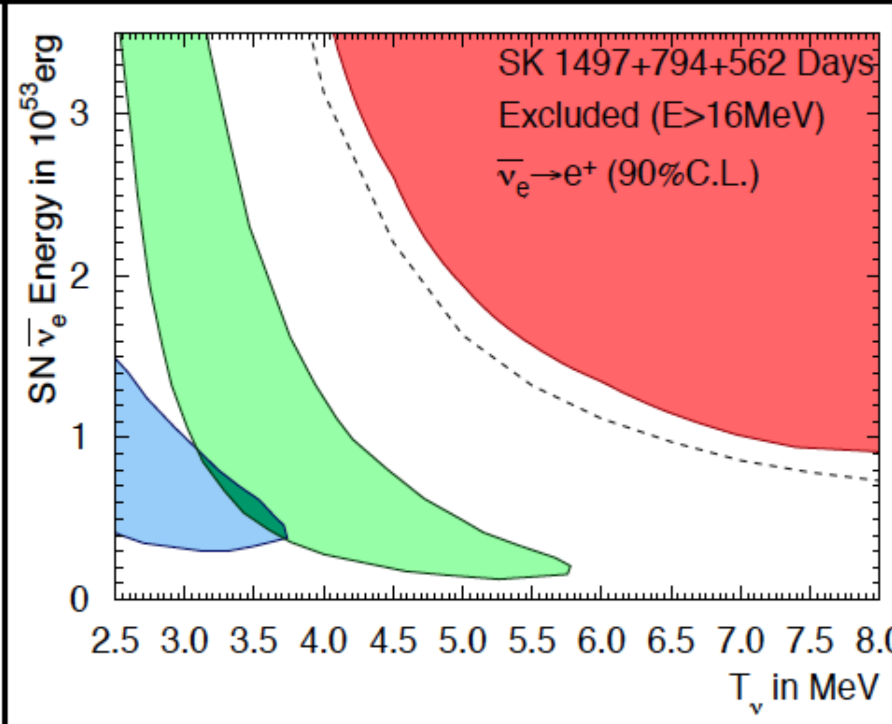
SK-II and SK-III:

Best fit is slightly positive DSNB

Forthcoming 2011 Super-Kamiokande Limits

To be *conservative*, new limits are a factor ~ 2 worse than before

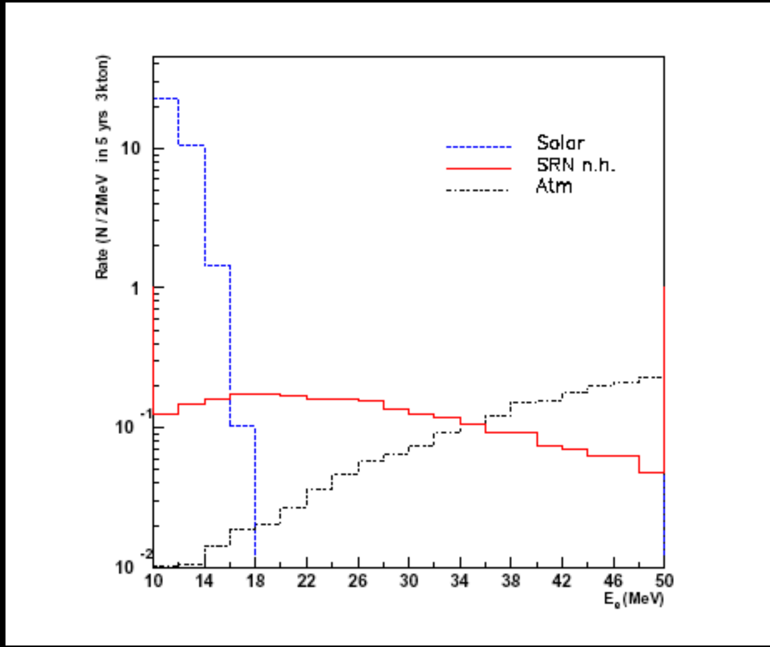




Must further decrease detector backgrounds and energy threshold

SRN at GLACIER (Cocco et al. hep-ph0408031)

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



- Good energy resolution

$$\frac{\sigma(E_e)}{E_e} = \frac{11\%}{\sqrt{E_e(\mathrm{MeV})}} + 2.5\%$$

- No sensitivity beyond z=1
- 2 irreducible backgrounds:
  - Solar and atmospheric ν_ε
  - 30% systematic on atm flux
- No background from
  - "invisible muon decays"
  - spallation from CR muons
  - NC recoils
- Dependence +-20% to beta slope
- Dependence on oscillation scenario

	mass hierarchy	θ_{13}	$P(\nu_e \rightarrow \nu_e)$	$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$
I	normal	large	$\sin^2\theta_{13}$	$\cos^2\theta_{12}$
II	inverted	large	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
III	normal/inverted	small	$\sin^2\theta_{12}$	$\cos^2\theta_{12}$

$$N_{SRN} = 57 \pm 12, \quad 16\,\mathrm{MeV} \leq E_e \leq 40\,\mathrm{MeV}$$

$$N_{SRN} = 43 \pm 12.$$

57 events for 500 kton-years and scenario I (4σ)

43 events for 500 kton-years and II

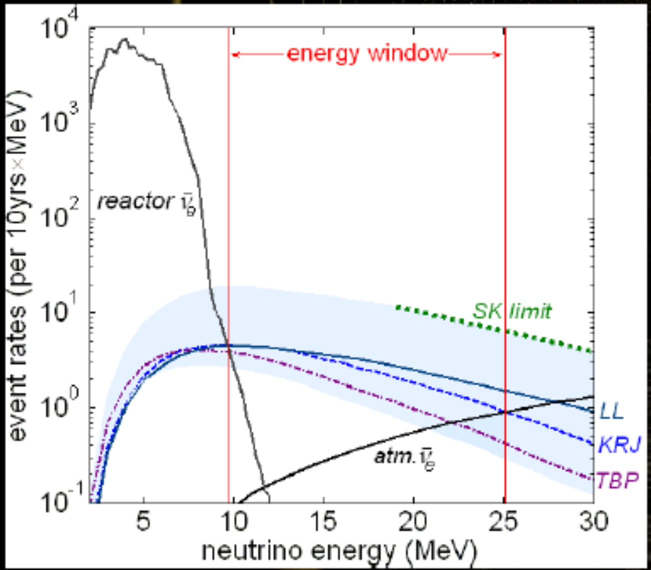
Diffuse SN Neutrinos

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

- Detection reaction: **inverse beta decay**
  - prompt signal from positron annihilation
  - delayed 2.2 MeV γ's from neutron capture (τ ~ 250 µs)

  → **good distinction from single events**
- Observation window: ~10-30 MeV
- Expected events: 35-70 in 10 years

  → spectroscopy possible if background under control



Background

- atm. and reactor $\bar{\nu}_e$ (both location dependant)
- ^{9}Li, ^{8}He: βn emitter
- spallation neutrons from the rocks
- fast neutrons
- NC atmospheric ν reactions

Supernova relic neutrino in MEMPHYS

5σ in a few years

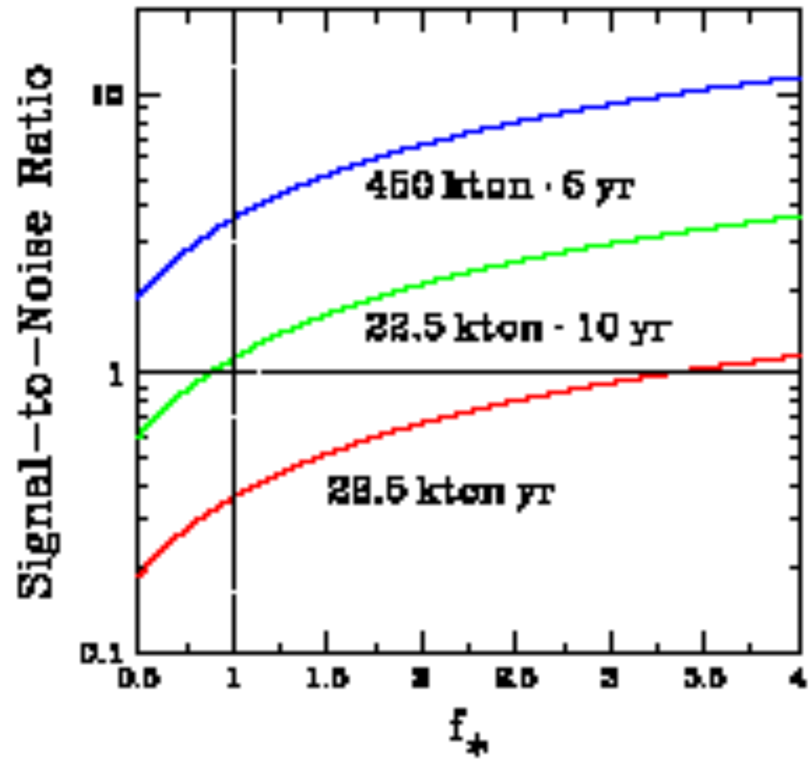


Figure 5. Signal-to-noise ratio S/N of SRNs at pure-water Čerenkov detectors (8), as a function of a correction factor f_* for the SFR model (4). LL is assumed for the original neutrino spectrum. Each line is labeled by the value of the effective volume $V_{\rm eff}$.

Possible enhancement:

use gadolinium to capture neutrons for tag of $\bar{\nu}_e$

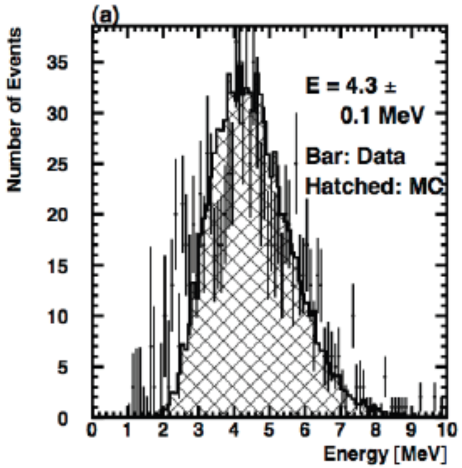
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

Gd has a huge n capture cross-section:
49,000 barns, vs 0.3 b for free protons;

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma \qquad \sum E_\gamma = 8\,MeV$$

Previously used in small scintillator detectors; may be possible for large water detectors with Gd compounds in solution

Beacom & Vagins, hep-ph/0309300
H. Watanabe et al., Astropart. Phys. 31, 320-328 (2009), arXiv:0811.0735



About 4 MeV visible energy per capture;
~67% efficiency in SK
➔ ***need good photocoverage***

Benefits of Neutron Tagging for DSNB

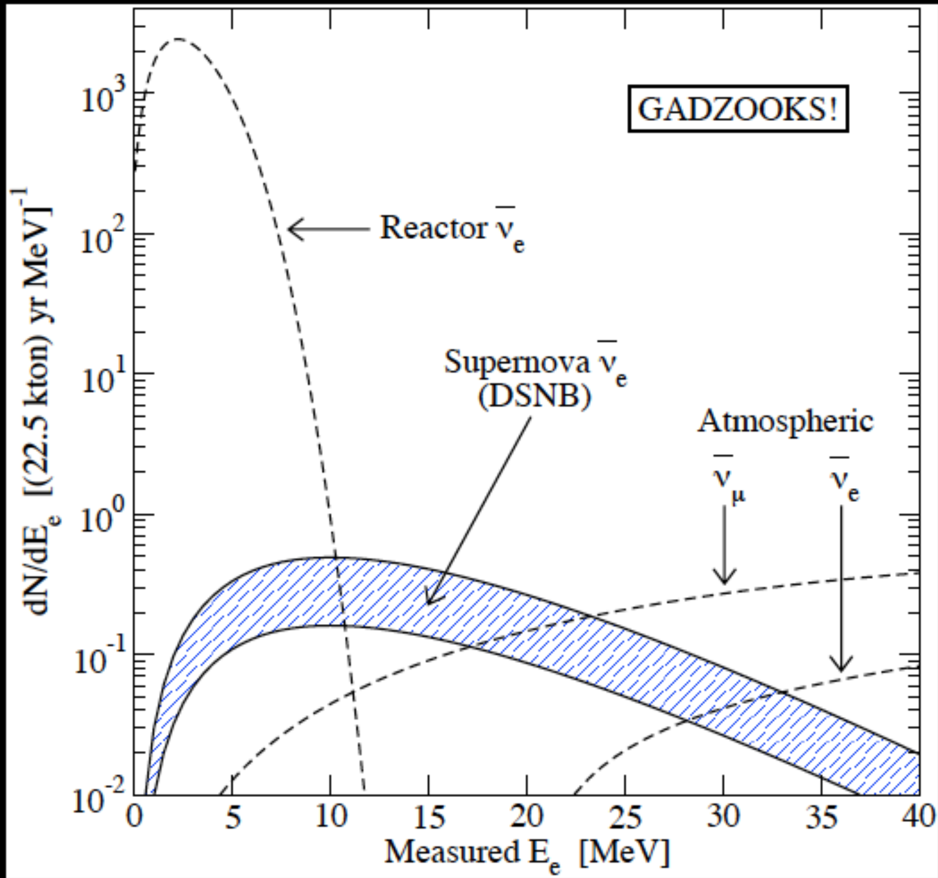
Solar neutrinos:
eliminated

Spallation daughter decays:
essentially eliminated

Reactor neutrinos:
now a visible signal

Atmospheric neutrinos:
significantly reduced

DSNB:
More signal, less background!

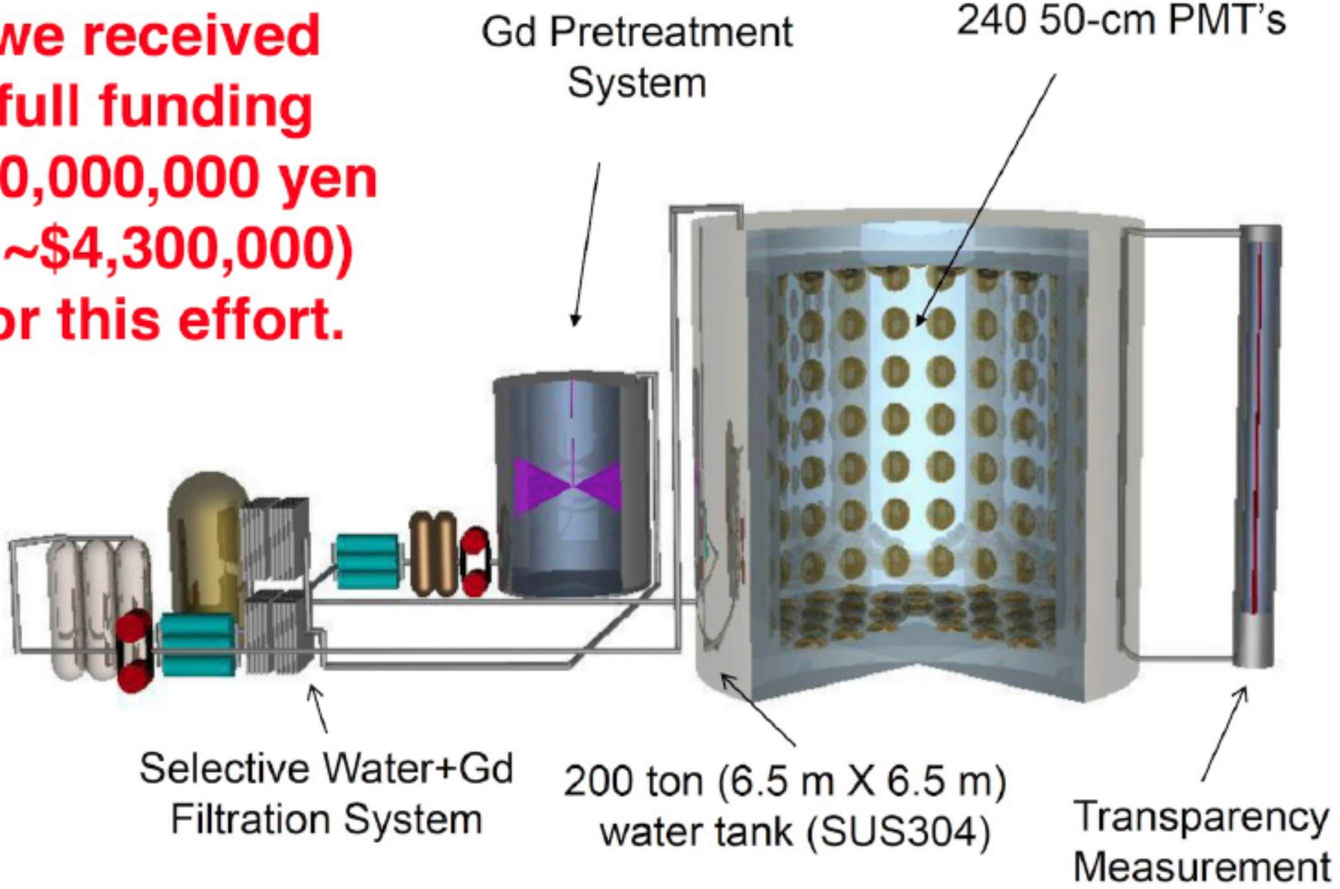


Beacom, Vagins (2004)

EGADS Proposal

EGADS Facility

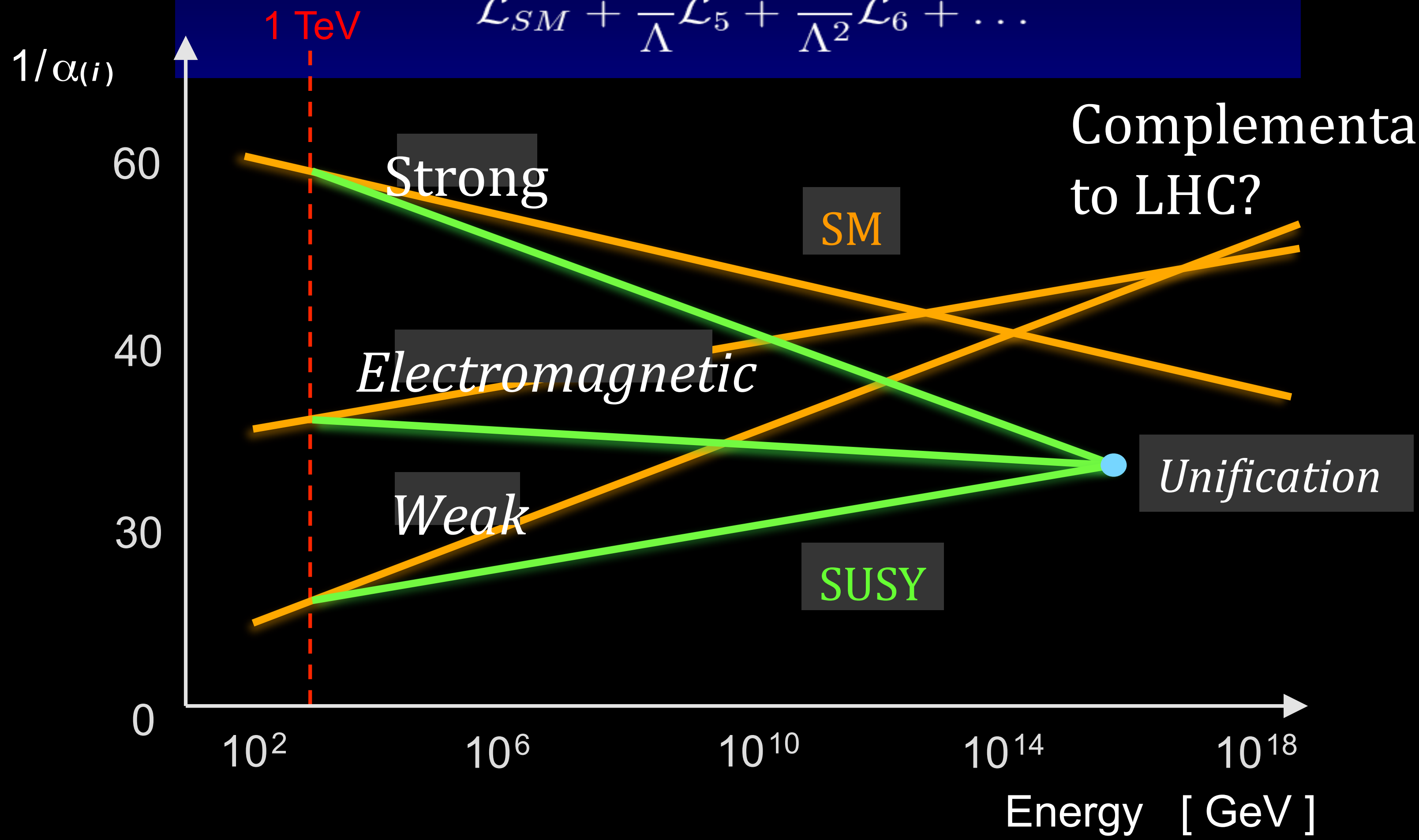
In June of 2009 we received full funding (390,000,000 yen = ~$4,300,000) for this effort.



Proton decay

The SM is an effective field theory, *ie*. at some high scale Λ new degrees of freedom will appear

$$\mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

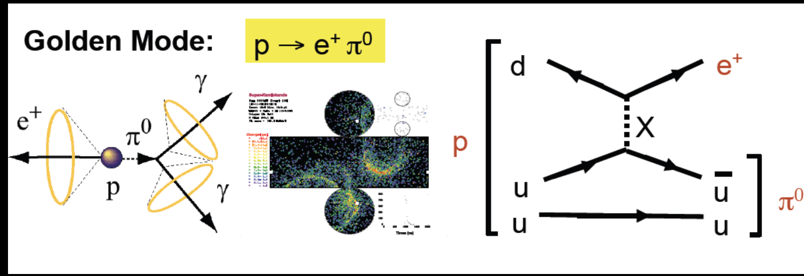


Complementarity to LHC?

Neutrino mass and proton decay are our best probes of these extensions

Proton decay

In 4D SUSY SU(5), SO(10) dimension 6 operators "M_{susy} independent" depend essentially on unification mass generically predict $\tau_p=10^{34}$-10^{36}y



$$\tau(p \to \pi^0 + e^+) \approx 5 \times 10^{36} \left(\frac{M_X}{3 \times 10^{16}\ \text{GeV}}\right)^4 \left(\frac{0.015\ \text{GeV}^3}{\beta_{lattice}}\right)^2 \text{ years.}$$

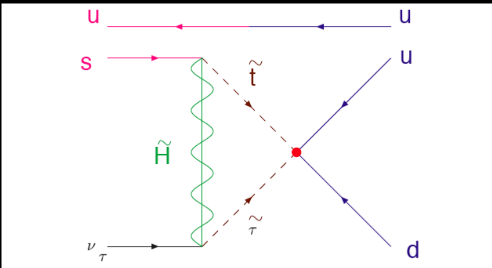
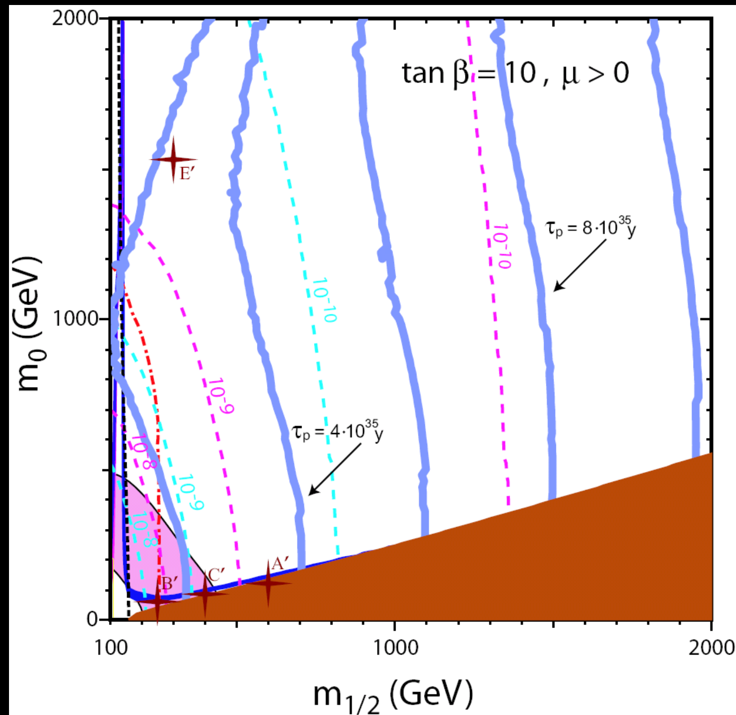


Figure 3. Higgsino and third generation stop - stau loop giving the dominant loop contribution to dimension 5 nucleon decay.

In 4D SUSY SU(5), SO(10) dimension 5 operators depend on sparticle spectrum (msusy), family structure, triplet higgs mass generically predict τ_p= 3 x10^{33}- 3x10^{34}y LHC interplay (Ellis et al.)

$$T(p \to K^+ + \bar{\nu}) \sim \frac{c^2}{M_T^{eff}} (\text{Loop Factor}) \frac{\beta_{lattice}}{f_\pi} m_p.$$

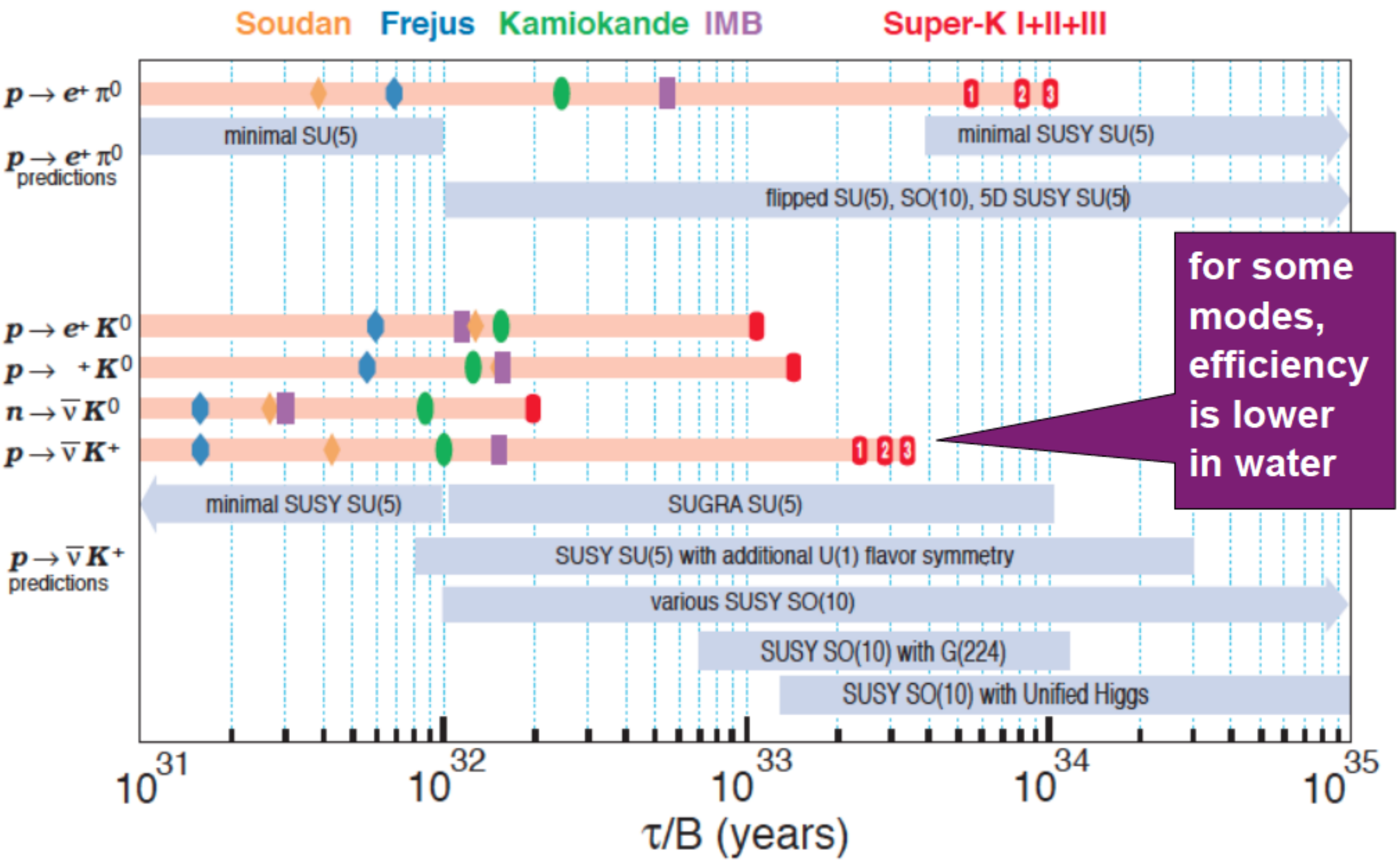
$$\tau(p \to K^+ + \bar{\nu}) < \left(\frac{1}{3} - 3\right) \times 10^{34} \left(\frac{0.015\ \text{GeV}^3}{\beta_{lattice}}\right)^2 \text{ years.}$$



- SUSY at 4D enhances dim 5 operators
- Unification in higher dimensions (5D,6D) suppresses dim 5 operators and enhances dim 6
- Complementarity of the two channels.

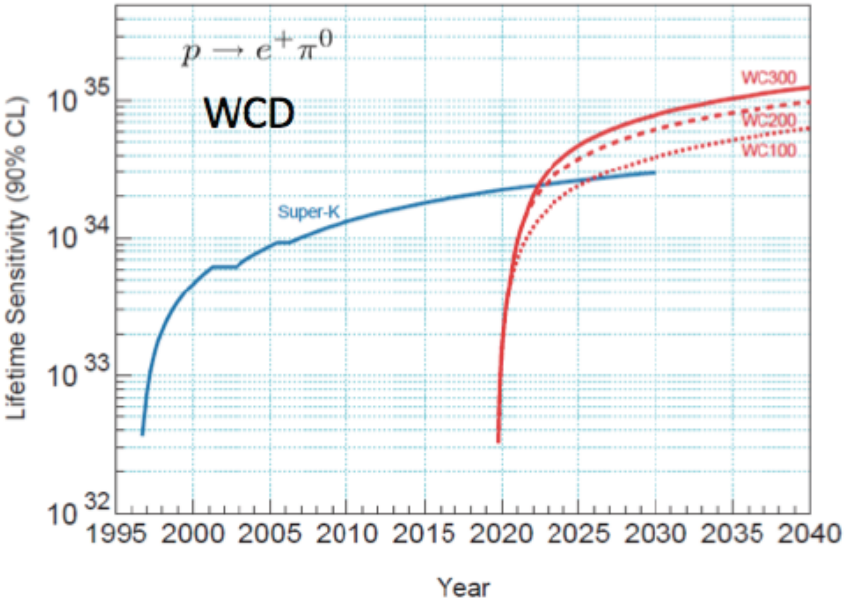
Lots of modes with varying theoretical motivations

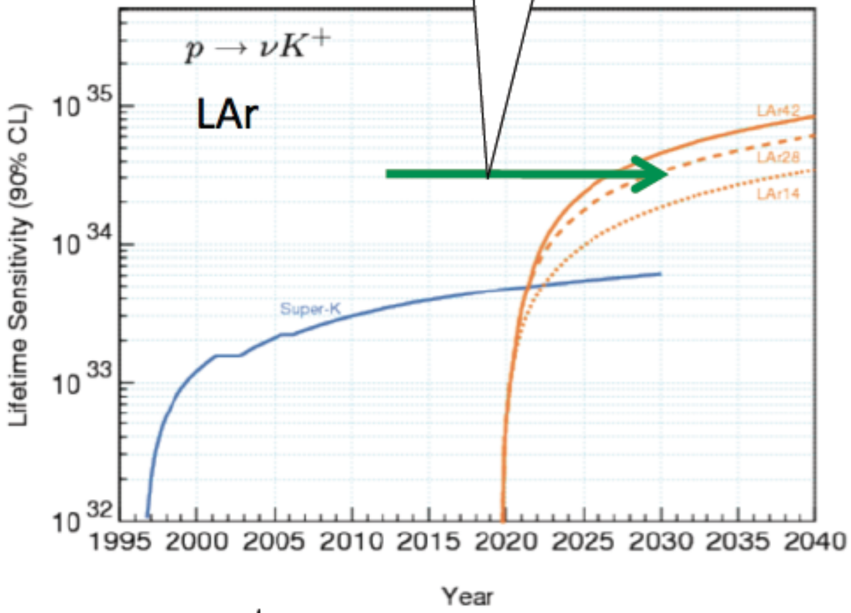
Super-K currently dominates the limits



Nucleon decay sensitivity vs time

LENA in 10 years

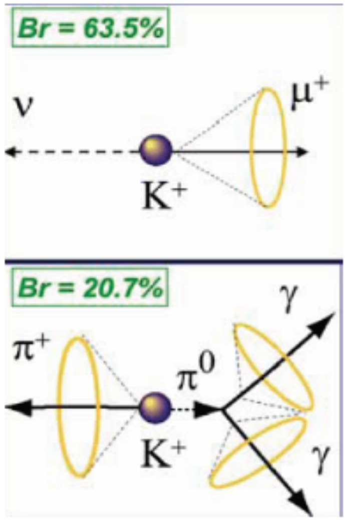


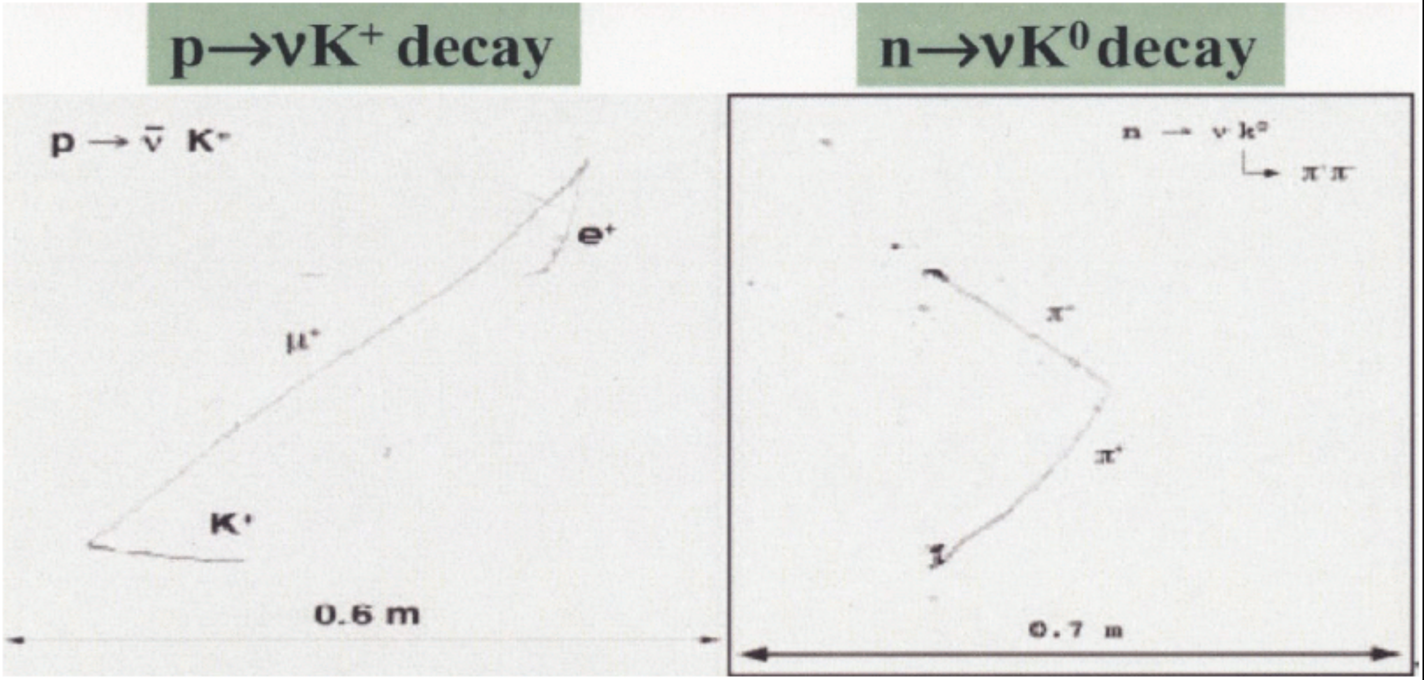


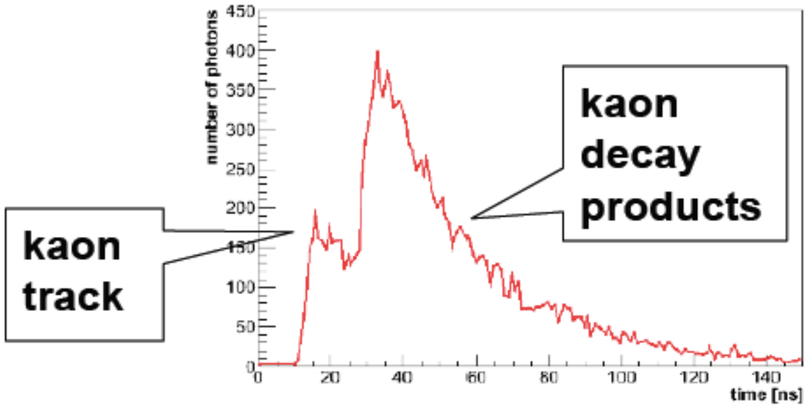
water best for this mode

argon best for this mode

For kaon modes, LAr does better due to excellent fine-grained tracking and lack of Cherenkov threshold

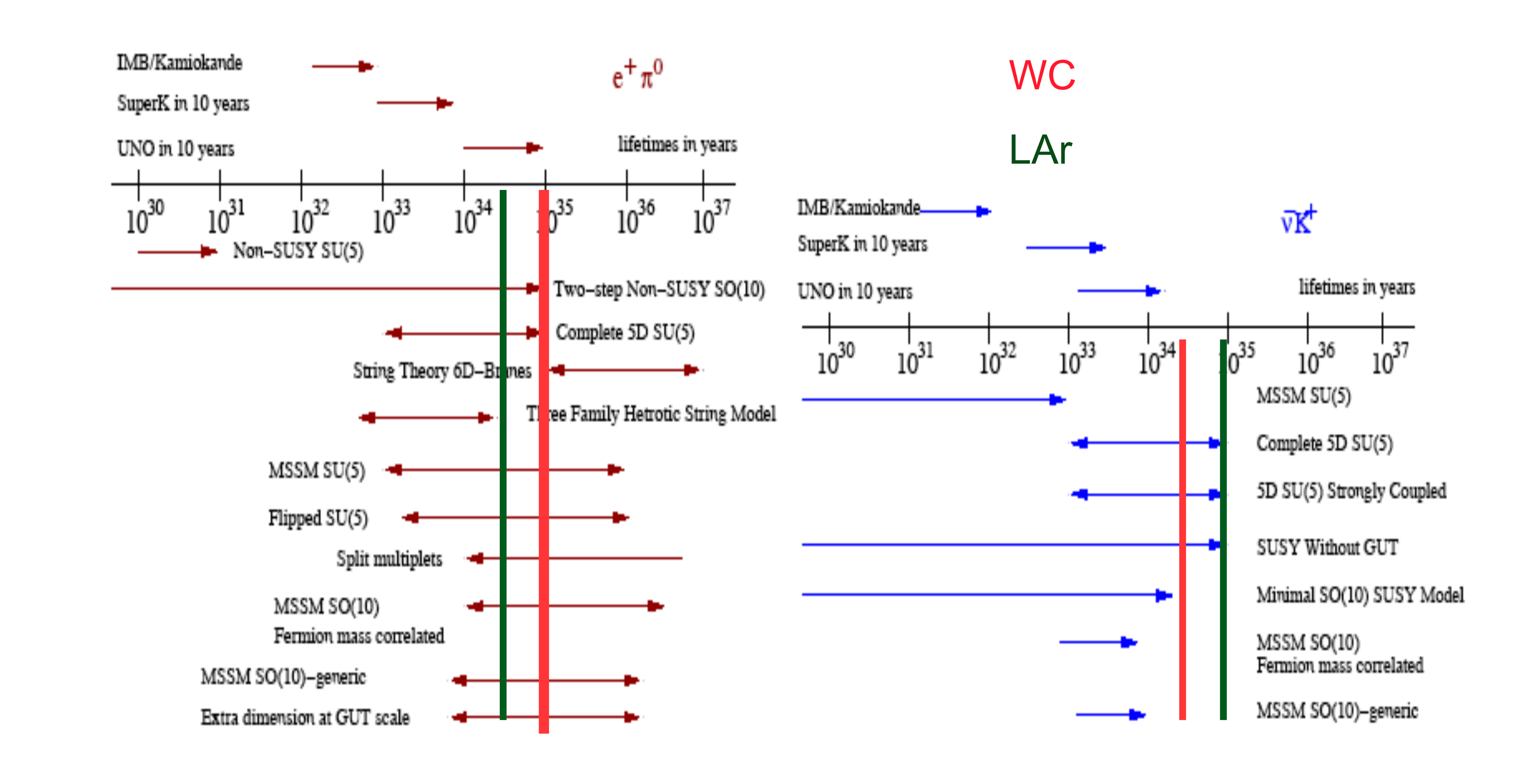




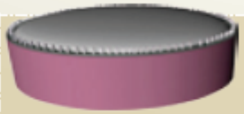


also a signature for this mode in scintillator (no Cherenkov threshold) using photon timing

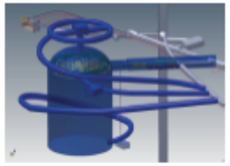
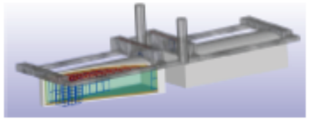
(hep-ph/0511230)


WC
LAr
IMB/Kamiokande
SuperK in 10 years
UNO in 10 years
$e^+\pi^0$
lifetimes in years
10^{30} 10^{31} 10^{32} 10^{33} 10^{34} 10^{35} 10^{36} 10^{37}
Non–SUSY SU(5)
Two–step Non–SUSY SO(10)
Complete 5D SU(5)
String Theory 6D–Branes
Three Family Hetrotic String Model
MSSM SU(5)
Flipped SU(5)
Split multiplets
MSSM SO(10)
Fermion mass correlated
MSSM SO(10)–generic
Extra dimension at GUT scale
IMB/Kamiokande
SuperK in 10 years
UNO in 10 years
$\bar{\nu}K^+$
lifetimes in years
10^{30} 10^{31} 10^{32} 10^{33} 10^{34} 10^{35} 10^{36} 10^{37}
MSSM SU(5)
Complete 5D SU(5)
5D SU(5) Strongly Coupled
SUSY Without GUT
Minimal SO(10) SUSY Model
MSSM SO(10)
Fermion mass correlated
MSSM SO(10)–generic

Outstanding physics goals

	 GLACIER	 LENA	 MEMPHYS
Total mass	100 Kton	50 kton	500 Kton
p -> $e\pi^{o}$ in 10 y	0.5 x 10^{35} y ε = 45%, ~1 BG event	?	1.2 x 10^{35} y ε = 17%, ~1 BG event
p -> ν K in 10 y	1.1 x 10^{35} y ε = 97%, ~1 BG event	0.4 x 10^{35} y ε = 65%, <1 BG event	0.15 x 10^{35} y ε = 8.6%, ~30 BG events
SN cool off at 10 Kpc	38·500 (all flavors) (64·000 if NH-L mixing)	20·000 (all flavors)	194·000 (mostly ν_ep->e $^+$n)
Sn in Andromeda	7 - (12 if NH-L mixing)	4 events	40 events
SN burst at 10 Kpc	380 ν_e CC (flavor sensitive)	~ 30 events	~ 250 ν-e elastic scattering
DSN	50	20-40	250 (2500 with Gd)
Atm. neutirnos	~1·100 events/y	5600/y	56·000 events/y
Solar neutrinos	324·000 events/y	?	91·250·000/y
Geo-neutirnos	0	~ 3·000 events/y	0

Summary of (some) large detector physics

			
	Water	**Liquid argon**	**Scintillator**
Long baseline oscillations	Yes, proven	Yes, good efficiency	Some reconstruction possible
Proton decay	Yes, $e^+\pi^0$	Yes, K ν	Yes, K ν
Atmospheric neutrinos	Yes, huge statistics	Yes, fine-grained reconstruction	Possibly
Supernova burst	Yes, anti-ν_e, huge statistics, pointing	Yes, ν_e	Yes, anti-ν_e + good NC, good statistics
DSNB	Yes, with Gd	ν_e, unknown bg	Possibly, bg under evaluation
Geoneutrinos	No	No	Yes

Need depth for all but LBO

NNN10

International policy context

- ✓ ASTROPARTICLE: The OECD GSF established in 2008 a WG to make a 2 year study of the options of world wide coordination
- ✓ On October 2010 the WG presented a report with 3 main items:
  1. A worldwide definition of the field, despite porous frontiers
  2. A roadmap of possible coordination issues
  3. The establishment of a more permanent forum for the discussion of coordination issues (first mandate 3 years). The forum *under the name APIF (Astroparticle Physics International Forum) will consist of officials of funding agencies that make significant investments in the field.* APIF *would be a subsidiary body of the OECD Global Science Forum.*
     - *First meeting April 5 2011 in Paris .*
- ✓ PARTICLE PHYSICS: *ICFA (24 July Paris, next meeting CERN October 2011)*
  - ✓ A steering committee was formed to provide guidance for a document describing opportunities for particle physics across the world. It will show the physics opportunities, and give a list of currently open questions and possible future ways to answer them

What is the *Astroparticle Physics International Forum* (APIF) supposed to do ?

1. Exchange information about relevant national and regional developments, plans and priorities. Regularly update the strategic vision of the OECD report.

2. Explore the prospects for joint actions (design studies for experiments, research and development)

3. Study options and solutions for governance structures and mechanisms for potential new international collaborative projects.

4. Consult on relevant generic science policy issues, such as access to research facilities and to data, or contributions to operating costs of facilities by users.

5. Analyse the needs and requirements for rare resources such as isotopes for detectors and, if appropriate, promote sharing or joint procurements.

6. Engage in a collective dialogue with governmental and non-governmental entities (space physics, high-energy physics, nuclear physics, astrophysics)

7. Develop strategies and procedures for promoting transfer of technology and other benefits to industry and to society in general.

APIF A roadmap of possible coordination issues

- The astroparticle physics community, despite its relatively short history, has achieved good levels of international coordination. Nevertheless, **the scale of the next generation of large infrastructures will require enhanced forms of international coordination.**
- In some areas **(e.g., dark matter, or neutrino mass searches)** a healthy diversity and competitiveness is desirable for the instruments under construction, even while procurement of rare materials needs to be coordinated, and convergence should be encouraged for future very large third-generation experiments.
- In other areas **(high energy gamma rays, charged cosmic rays, or high-energy neutrinos)** the small number of existing observatories worldwide already operate (or intend to operate) as single integrated worldwide networks. In these areas, the planning of future projects should include consideration of enabling policy issues such as governance, site selection, access to the experimental resources and to data, and operating costs.
- Lastly, there are very large-scale projects **(e.g., dark energy observatories, third-generation gravitational wave antennas and *"megaton"-scale proton decay and neutrino detectors*)** whose cost, complexity and multiple links to neighbouring scientific disciplines (astrophysics, cosmology, particle physics) ***present a strong case for worldwide convergence or, at a minimum, for avoidance of unnecessary duplication.***

What APIF is NOT supposed to do ?

- ✓It is not a new super-agency
  - ✓The activities of APIF would not pre-empt or interfere with national or regional mechanisms for planning, prioritising, authorising, funding or overseeing specific research projects.

- ✓It is not a scientific advisory body:
  - ✓As needed, APIF would seek information and advice from the international scientific community. It could invite individual experts, spokespersons of projects or members of scientific bodies to attend APIF meetings or to participate in subsidiary activities.
  - ✓The Working Group also recommends that the scientific community strengthen its activities aimed at ensuring vigorous, globally coherent progress in astroparticle physics. Specifically, the International Union of Pure and Applied Physics (IUPAP) could review and, if appropriate, adjust its mechanisms for promoting international scientific co-operation and discussions among scientists about the future of the field.

Conclusions

✓ It seems that we were lucky θ_{13}appeears to be large promising a rich harvest for "standard matrix determination". But, need to keep our eyes open to the unexpected (sterile neutrinos, Lorentz violation,…)

✓*The best strategy will be the right mixture of the two*

✓ Large detector technologies are complementary

✓*The best strategy would be at least a mixture of two technologies*

✓ Large detectors also are astroparticle physics observatories (supernova) and cosmological probes (proton decay)

✓*The best strategy would be a mixture of Astroparticle/Cosmology and particle physics goals*

✓This gives a multitude of possibilities across the world that need to be coordinated at least wrt to their goals

✓In Europe CERN, ASPERA strategies are in development, we need work to optimize along the above axes. The global NNN community should move to closer coordination forms. The OECD GSF Astroparticle Forum (APIF) could be a tool for promotion of a worldwide strategy

✓*The best strategy would be a mixture of a European strategy well embedded and coordinated in a global framework*