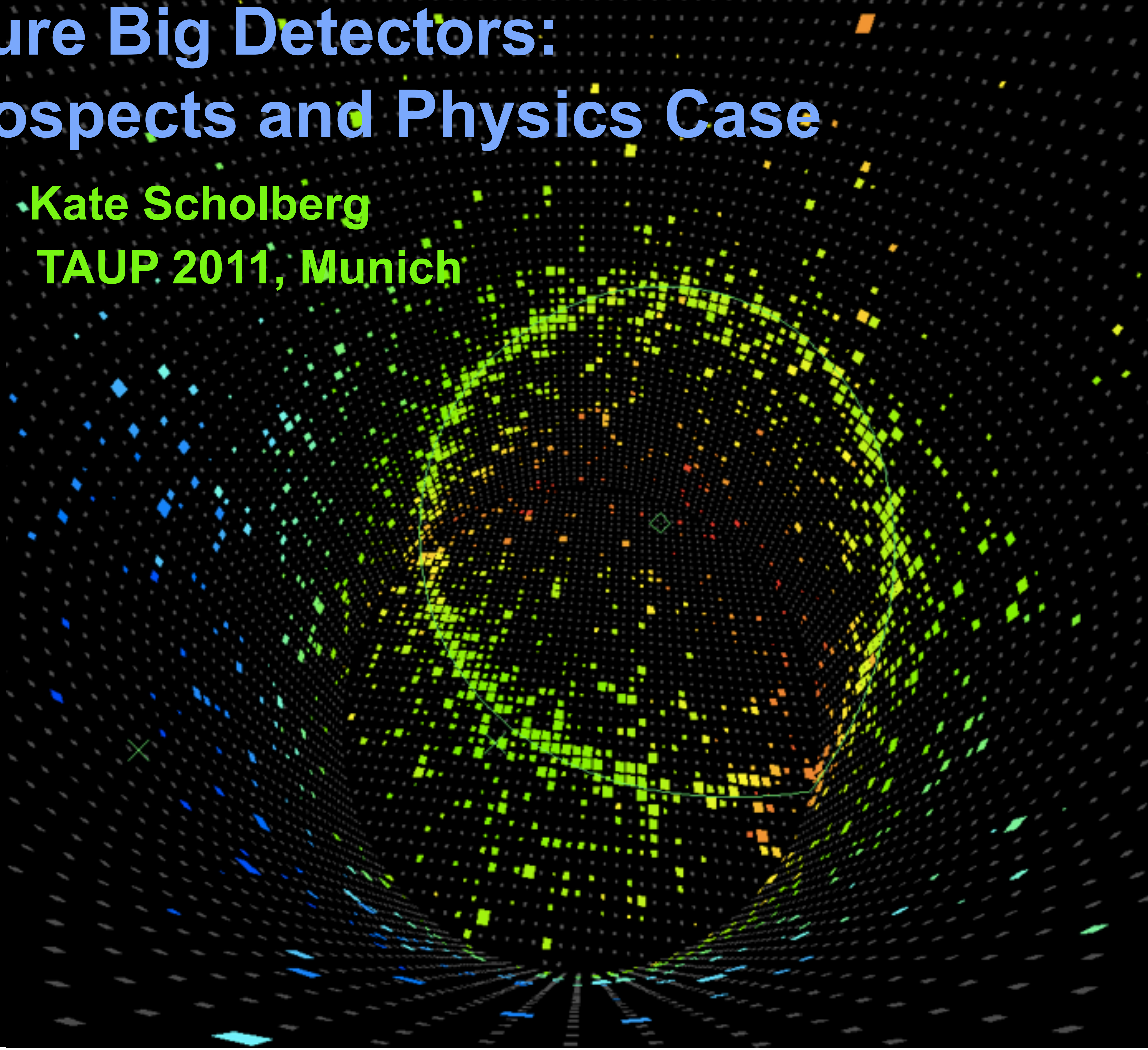
Future Big Detectors: Prospects and Physics Case

Kate Scholberg

TAUP 2011, Munich



OUTLINE

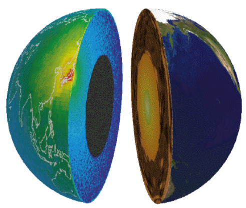
- Overview of large detector technologies
  - Water
  - Scintillator
  - Liquid Argon
- Future programs worldwide
- Physics reach: selected topics
- Summary

Underground Physics for the Next Decades

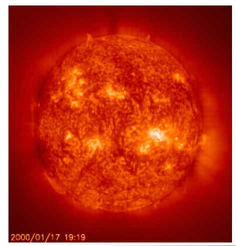
Wide range of energy scales & technical issues

“Wild”

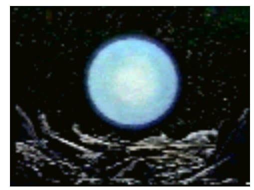
Geoneutrinos



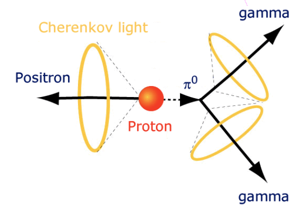
Solar neutrinos



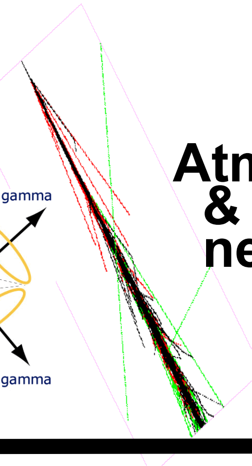
Supernova neutrinos



Proton decay

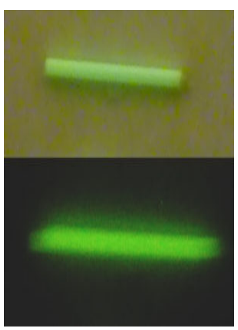


Atmospheric & cosmic neutrinos

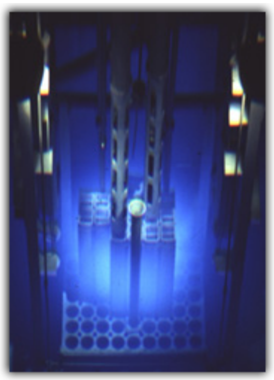


keV MeV GeV TeV

“Tame”

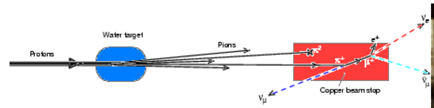


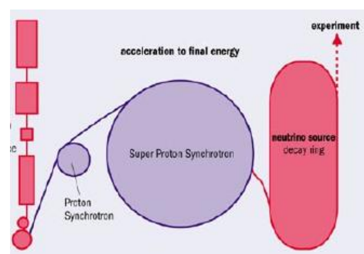
Artificial radioactive neutrino sources



Reactor neutrinos

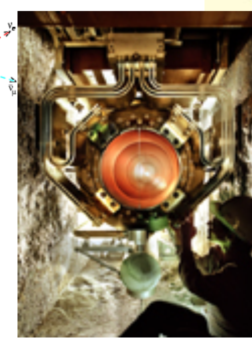
Stopped pion sources





Beta beams

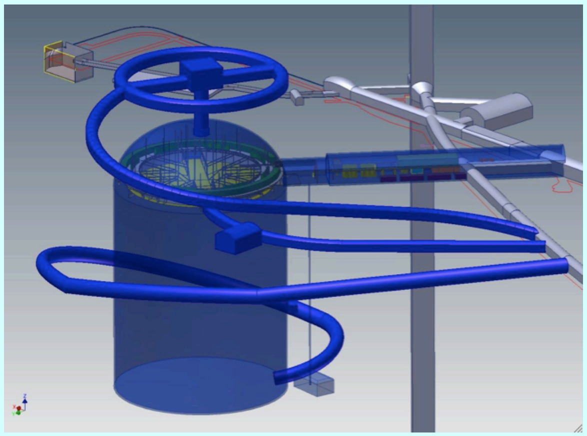
Super beams

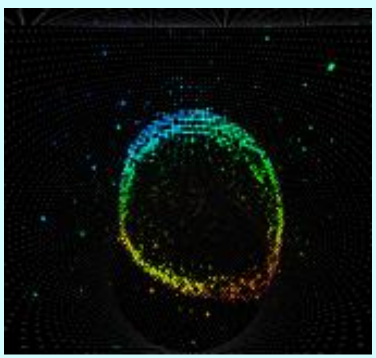


Neutrino factories

Possible large (multi-kton) detector technologies

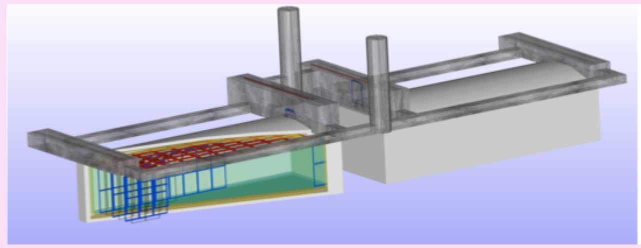
Water Cherenkov

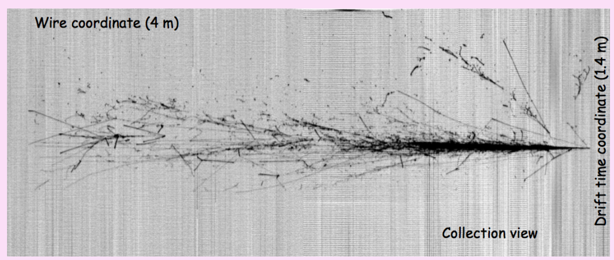




Cheap material, proven at very large scale

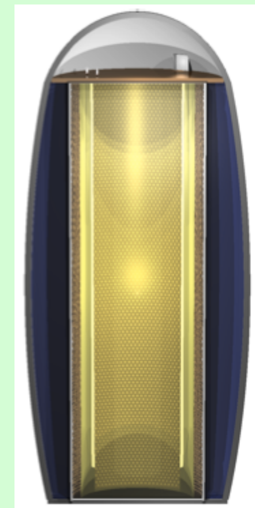
Liquid Argon

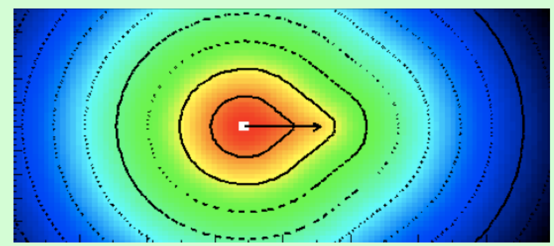




Excellent particle reconstruction

Liquid Scintillator

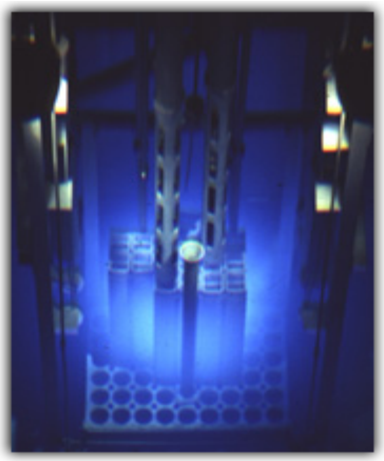




Low energy threshold

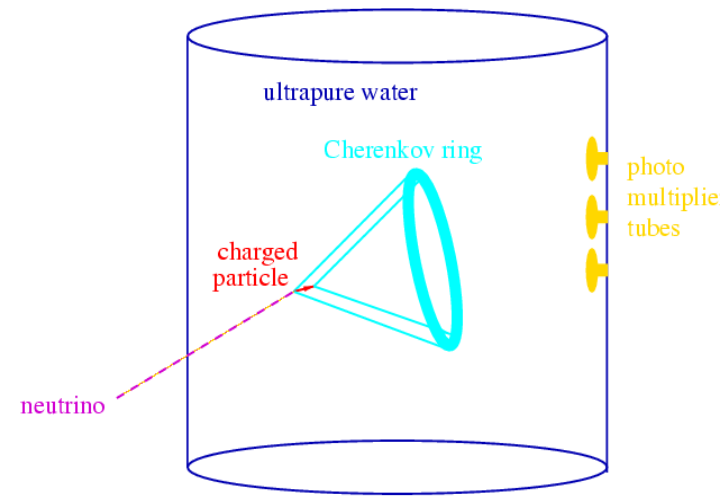
Water Cherenkov Detectors

Charged particles produced in neutrino interactions emit Cherenkov radiation if $\beta>1/n$



$$\cos\theta_C = \frac{1}{\beta n}$$

$\theta_C = 42^0$ for relativistic particle in water



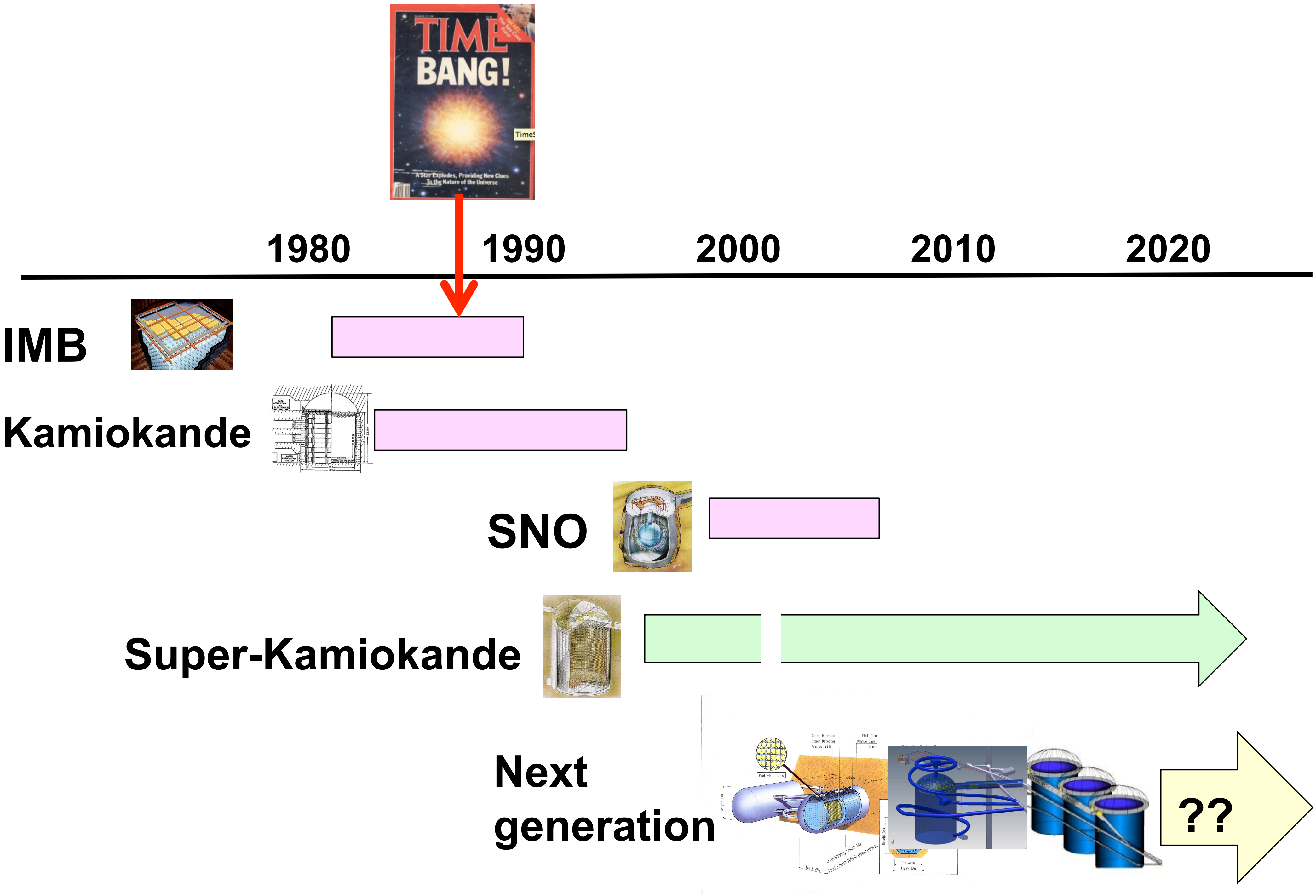
Thresholds (MeV)

$$E_{th} = \frac{m}{\sqrt{1-1/n^2}}$$

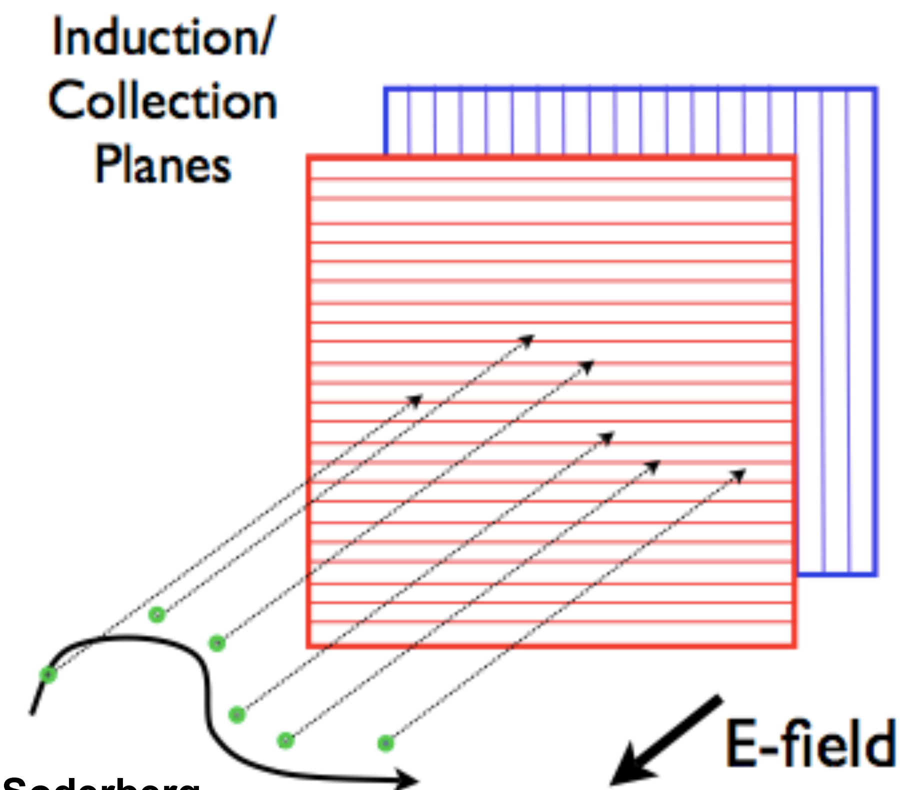
e	0.73 MeV
μ	150 MeV
π	200 MeV
p	1350 MeV

- Low light yield, but directional signal is helpful for reconstruction
- Loss of heavy/low energy particles due to Ch. threshold
- Possible enhancement with Gd for inverse beta decay tagging (John Beacom's talk)

Water Cherenkov detector instances



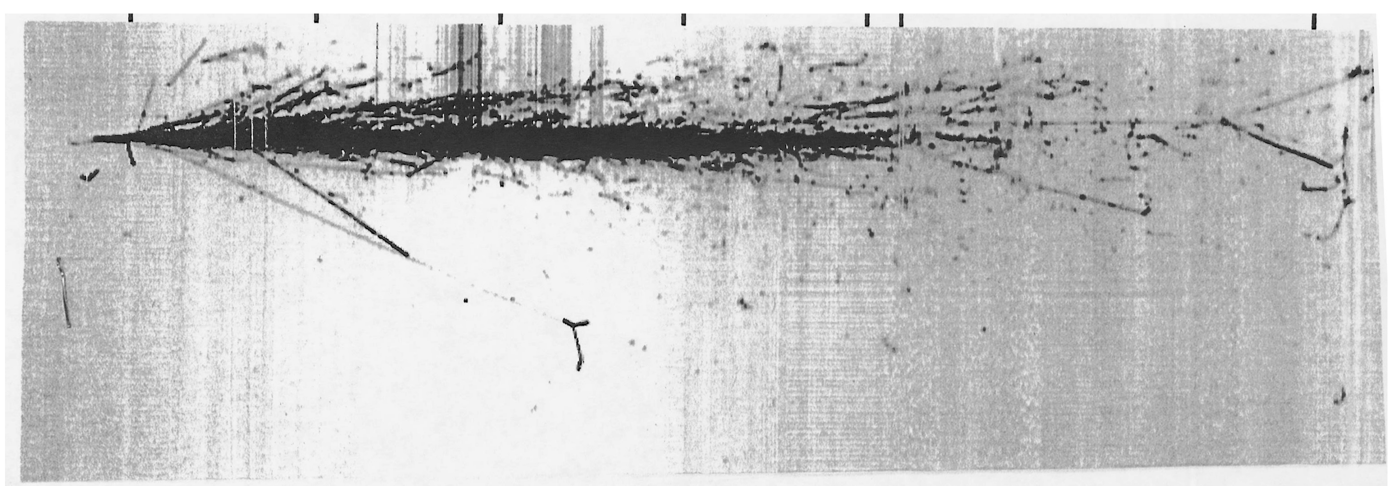
Liquid argon time projection chambers



M. Soderberg

Ionization charge drifted and collected; 3D track using time info

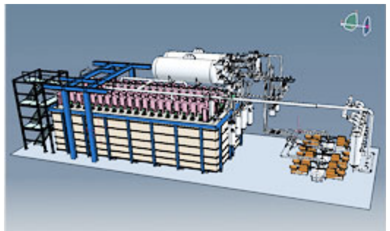
- very high quality particle reconstruction possible
- need scintillation light (photosensors) for absolute time
- require very high purity, cryogenic liquid



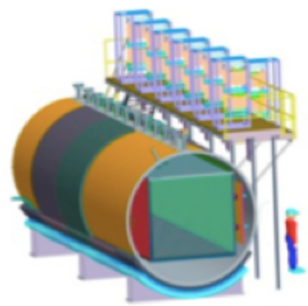
Large liquid argon detector instances

2000 2010 2020

Icarus

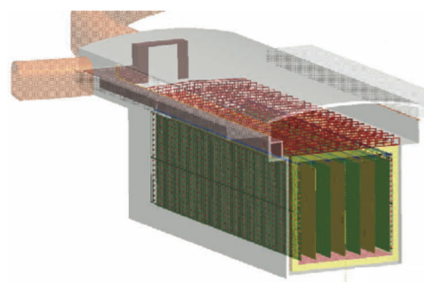


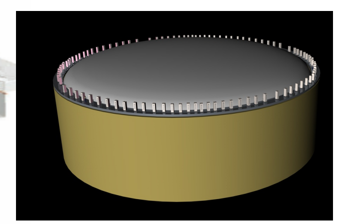
@CERN?

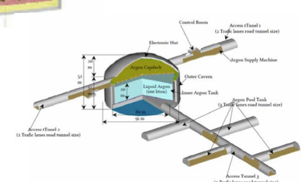


MicroBooNE

Next generation



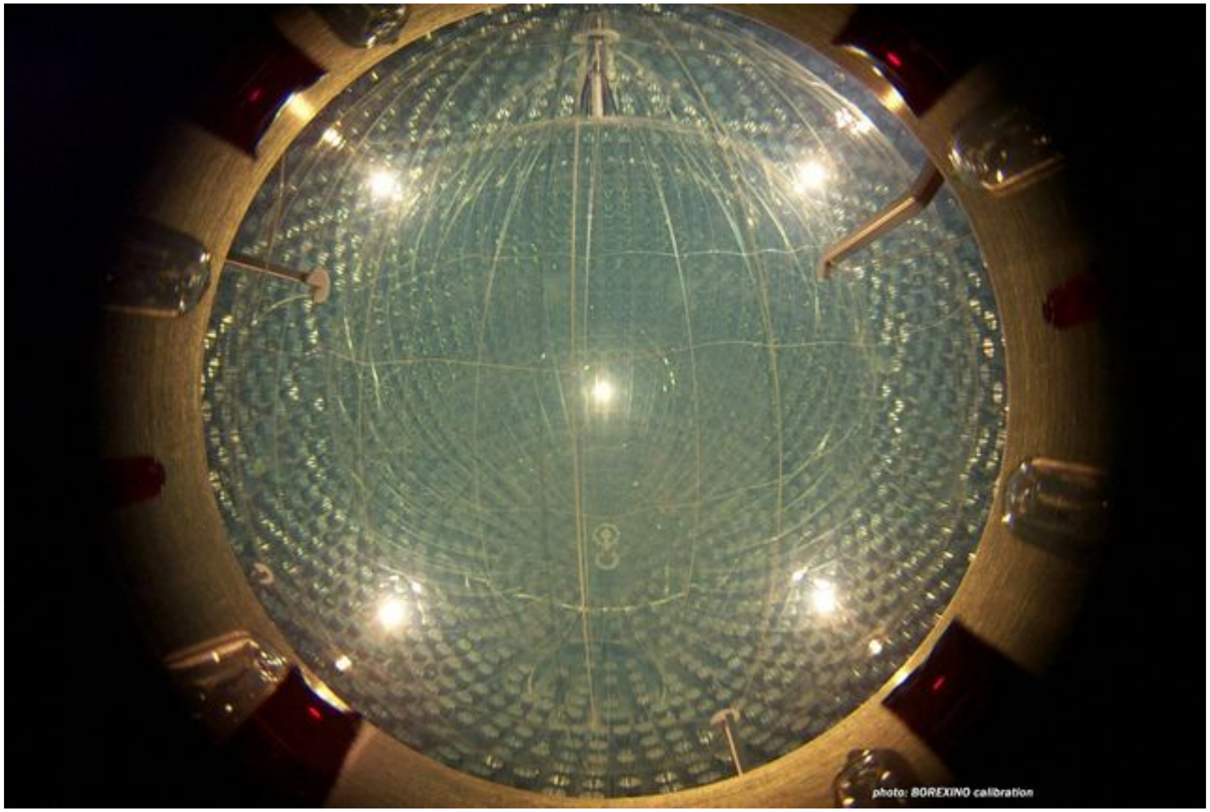




??

+ many `R&D' instances

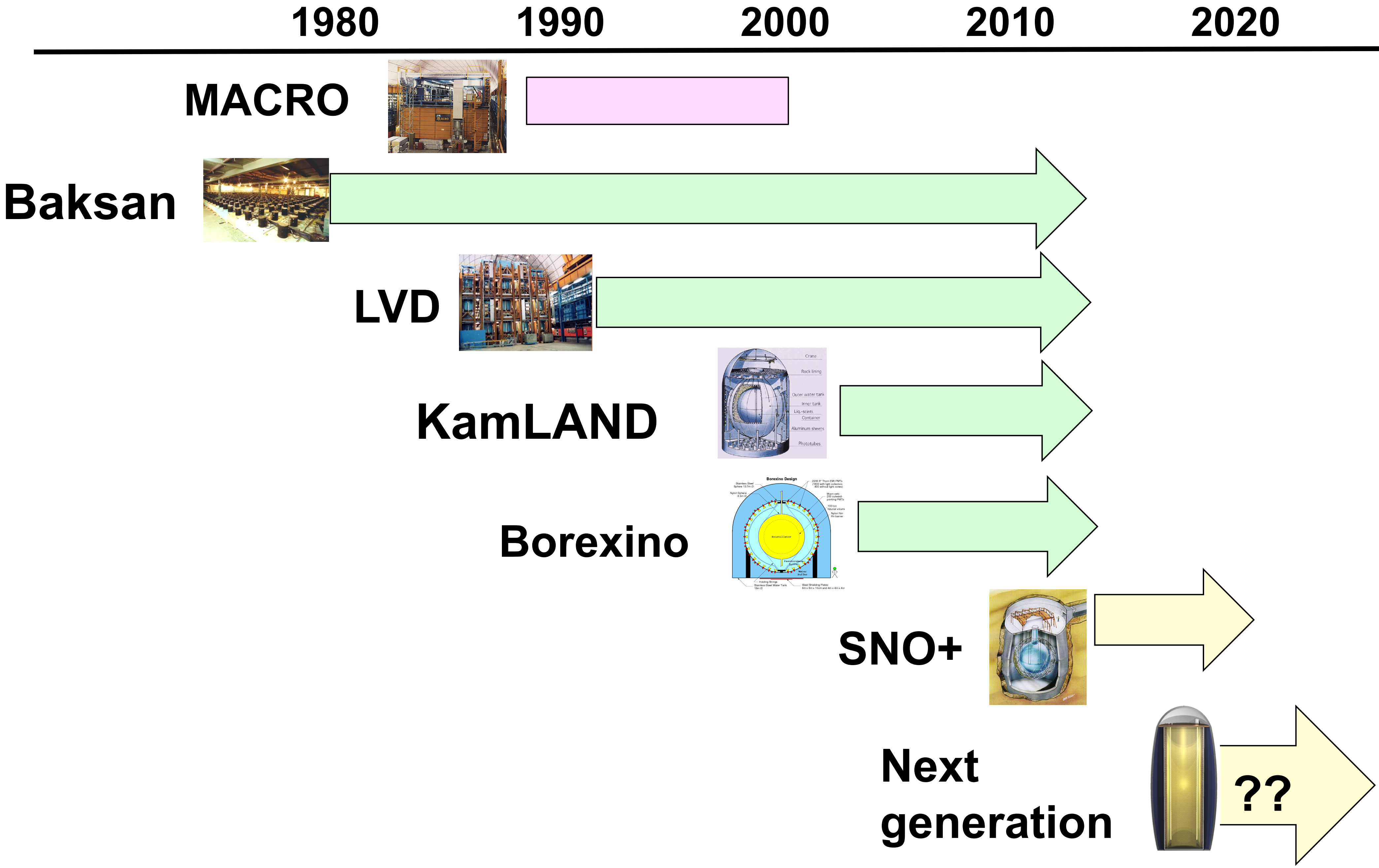
Liquid scintillator detectors



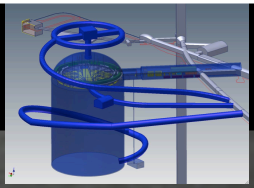
Liquid scintillator, $C_nH_{2n,}$ volume surrounded by photomultipliers

- ~50 times more light per MeV than Cherenkov
- low threshold, good energy resolution
- require extreme radioactive purity
- weak directionality (light is ~isotropic)
- particle reconstruction by photon timing

Liquid scintillator detector instances



Water Cherenkov



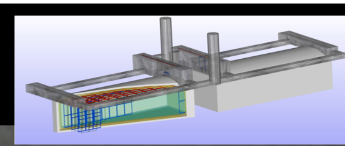
Pros

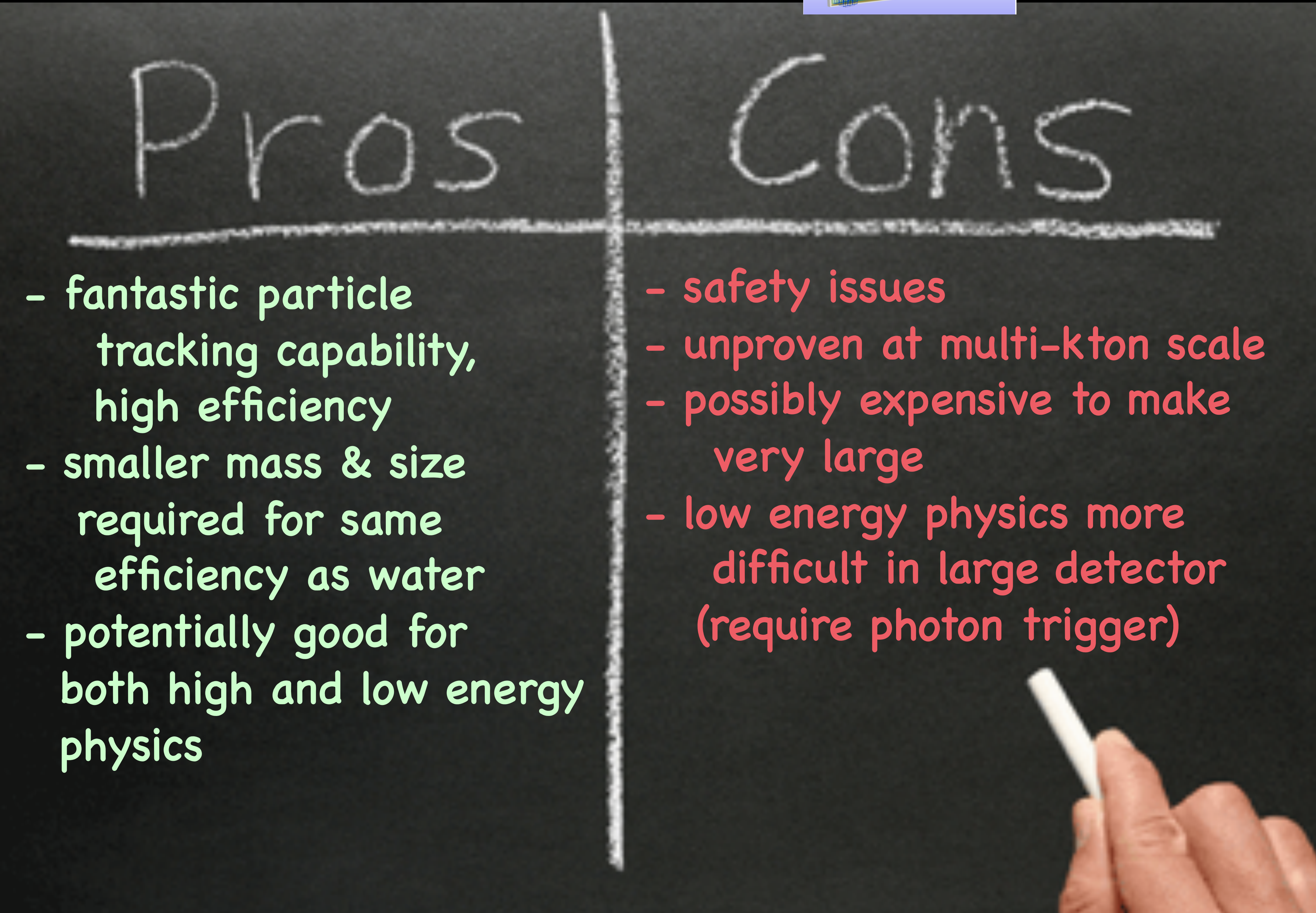
- cheap detector material!
  ➔can make big
- proven at multi-kton scale
- good reconstruction,
- angular information from
  Cherenkov ring
- some low energy
- physics reach,
  especially with Gd

Cons

- relatively few photons/MeV
- Cherenkov threshold means
  that heavy particles, and
  low energy γ's/e's
  may be invisible
- detector thresholds usually
  at least
  ~few MeV
- driving costs:
  PMTs, large
  cavity excavation

Liquid Argon





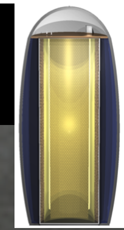
Pros

- fantastic particle tracking capability, high efficiency
- smaller mass & size required for same efficiency as water
- potentially good for both high and low energy physics

Cons

- safety issues
- unproven at multi-kton scale
- possibly expensive to make very large
- low energy physics more difficult in large detector (require photon trigger)

Liquid Scintillator



Pros

- very high light yield: low energy threshold, good energy resolution
- significant experience at kton scale
- some high energy reconstruction

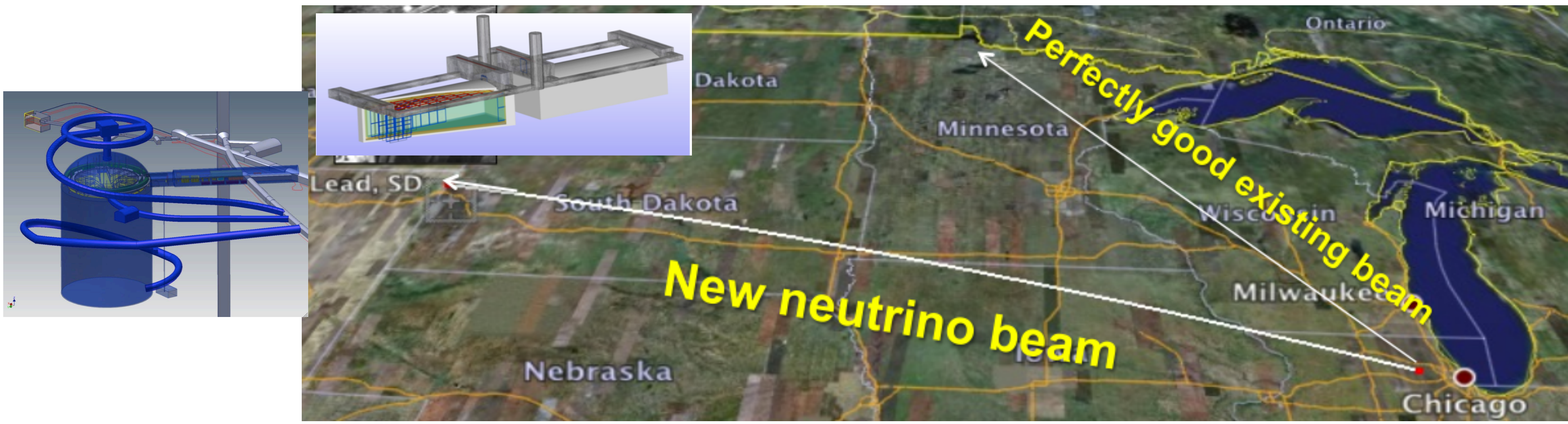
Cons

- more expensive material
- poor directionality, high energy event reconstruction hard
- stringent radioactive bg requirements
- PMTs, large cavity excavation also expensive

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)

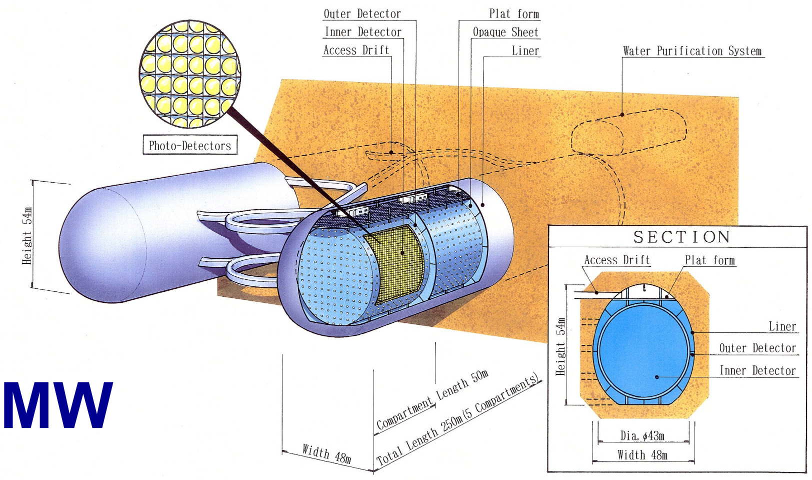
http://science.energy.gov/~/media/hep/hepap/pdf/june-2011/Review_of_Underground_Science_Report_Final.pdf

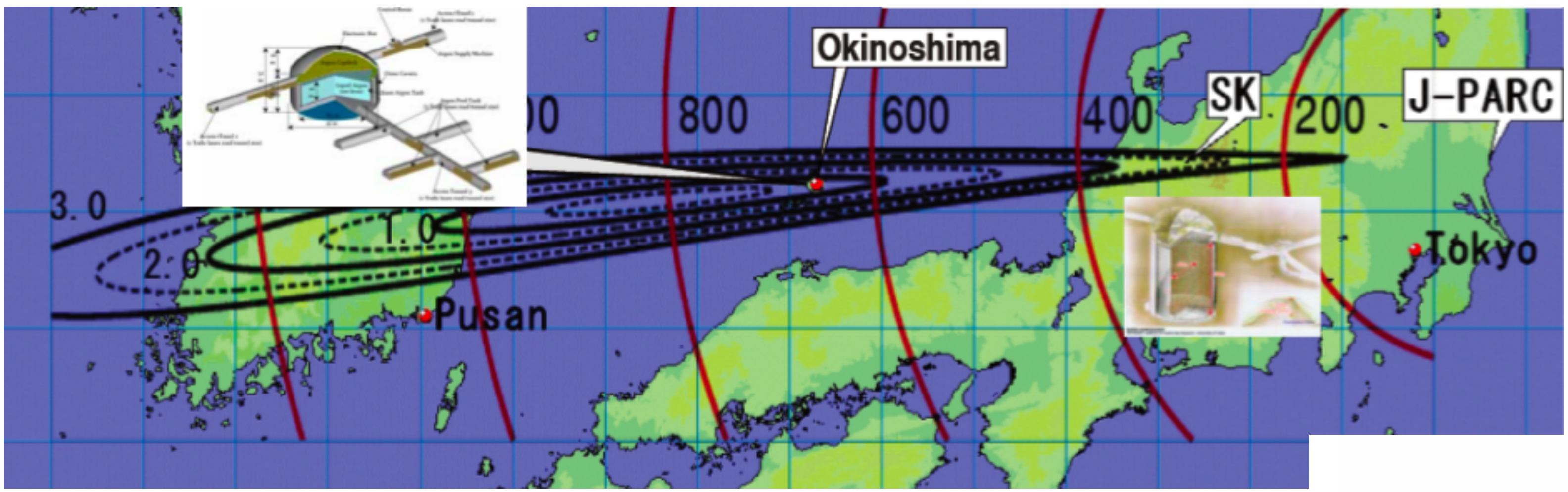
- collaboration planning technology decision ~ end of 2011

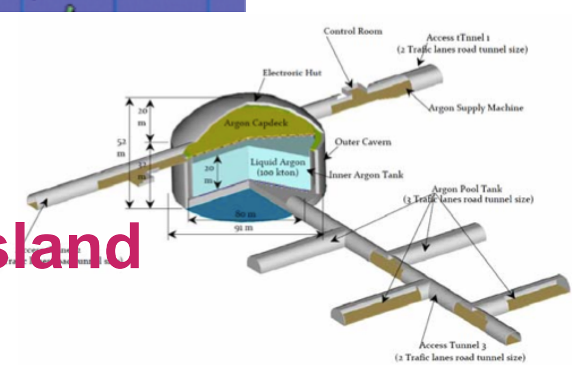
Future programs: Asia

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)







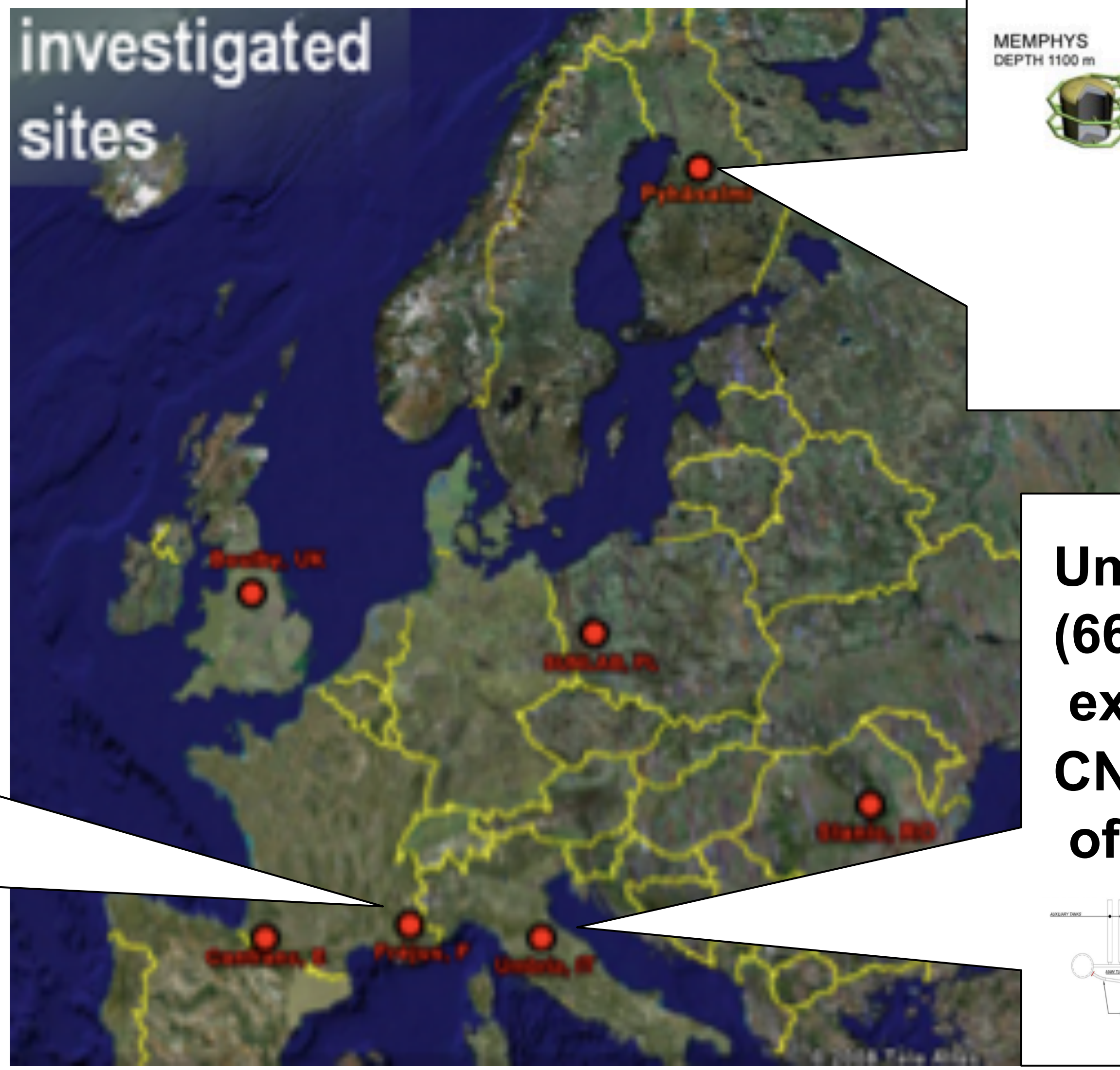
Also, ideas for 100 kton LAr at Okinoshima island
(R&D program started at KEK)

Future programs: Europe

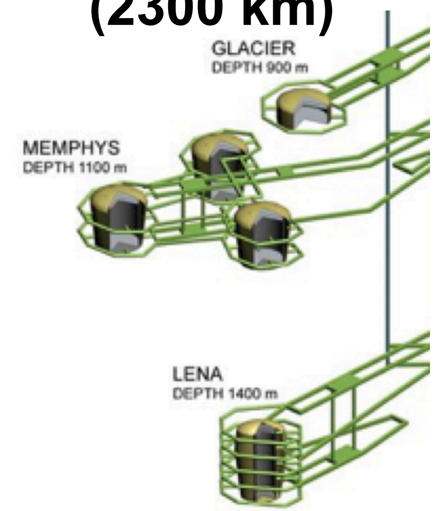
LAGUNA-LBNO

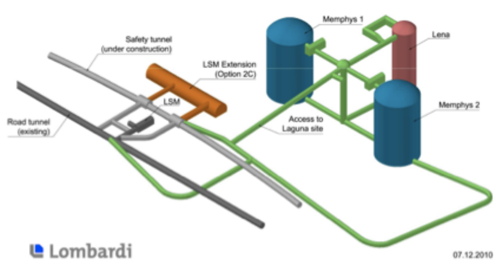
0.4-1.2 MW beam
from CERN,
130-2300 km
(Future:
β beam, ν factory)

MEMPHYS: 0.5 Mt water
GLACIER: 100 kt LAr
LENA: 50 kt scintillator



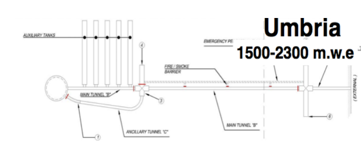
Pyhäsalmi
(2300 km)





Fréjus (130 km)

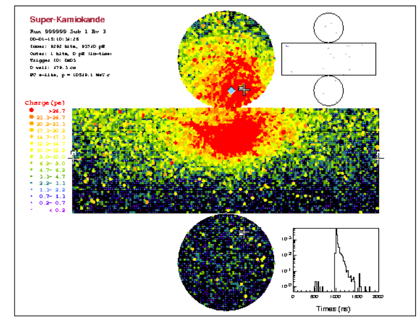
Umbria
(665 km,
existing
CNGS beam,
off-axis)



Selected physics topics

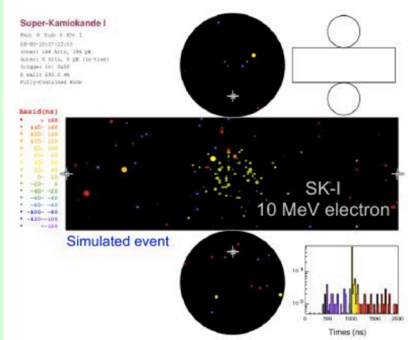
Long baseline neutrino oscillations
Atmospheric neutrinos
Proton decay

~GeV energies:
experimental issue is multi-particle reconstruction



Burst supernova neutrinos
Diffuse supernova neutrino background
Geoneutrinos

few to few tens of MeV energies:
experimental issues are light/charge collection, bg reduction



Neutrino oscillations

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

atmospheric ? solar

Remaining unknowns in the 3-flavor picture

Masses

$$m_1,\ m_2,\ m_3 \leftrightarrow \Delta m^2_{12},\ |\Delta m^2_{23}|,\ sign(\Delta m^2_{23}),\ m_i$$

✔ ✔ ? ?

Angles

(plus Majorana phases)

$$\theta_{12},\quad \theta_{23},\quad \theta_{13},\quad \delta$$

✔ ✔ ?

maximal?

close!

Going after CP violation & hierarchy with next, and next-next generation superbeams + large detectors at long baseline

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right)$$

Non-CP terms

Changes sign for antineutrinos

$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{13}}{\tilde{B}_\mp}\,\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

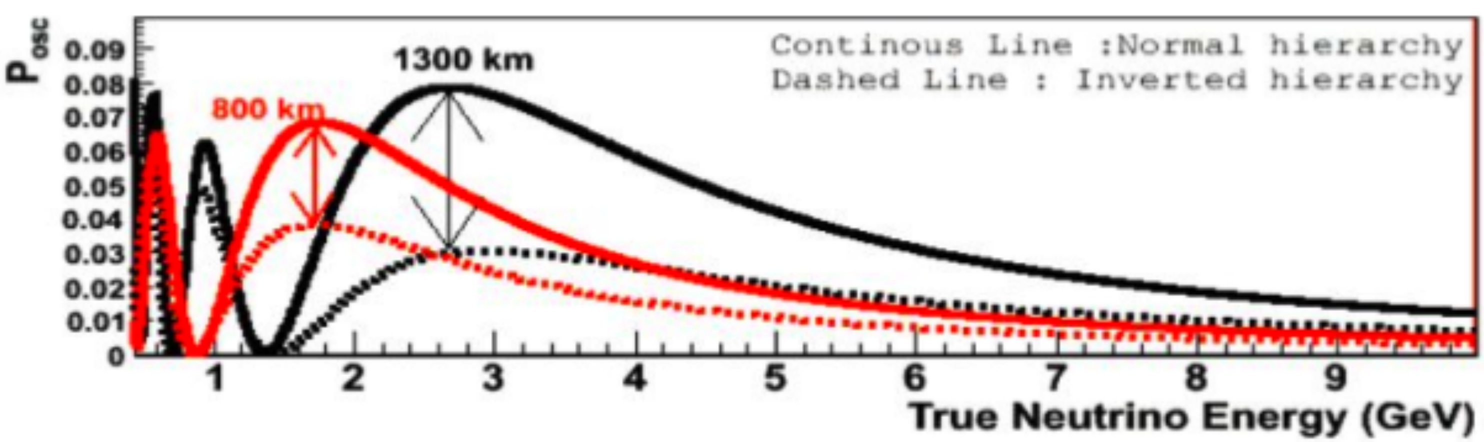
CP violating

$$\tilde{J} \equiv c_{13}\, \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu},\ \tilde{B}_\mp \equiv |A \mp \Delta_{13}|,\ A = \sqrt{2}G_F N_e$$

$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

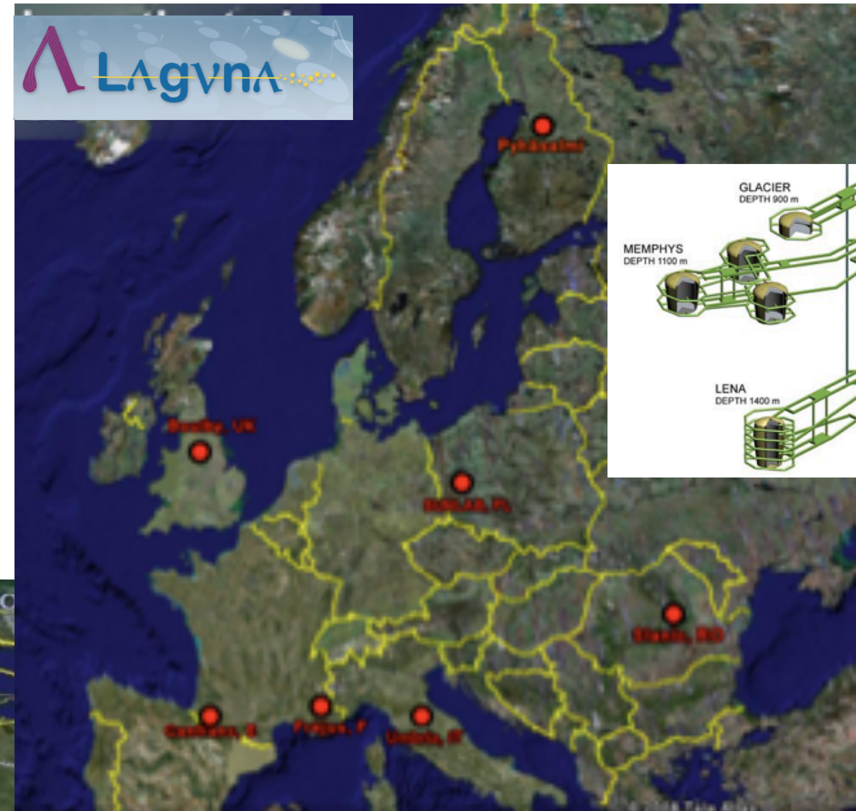
A. Cervera et al., Nuclear Physics B 579 (2000)

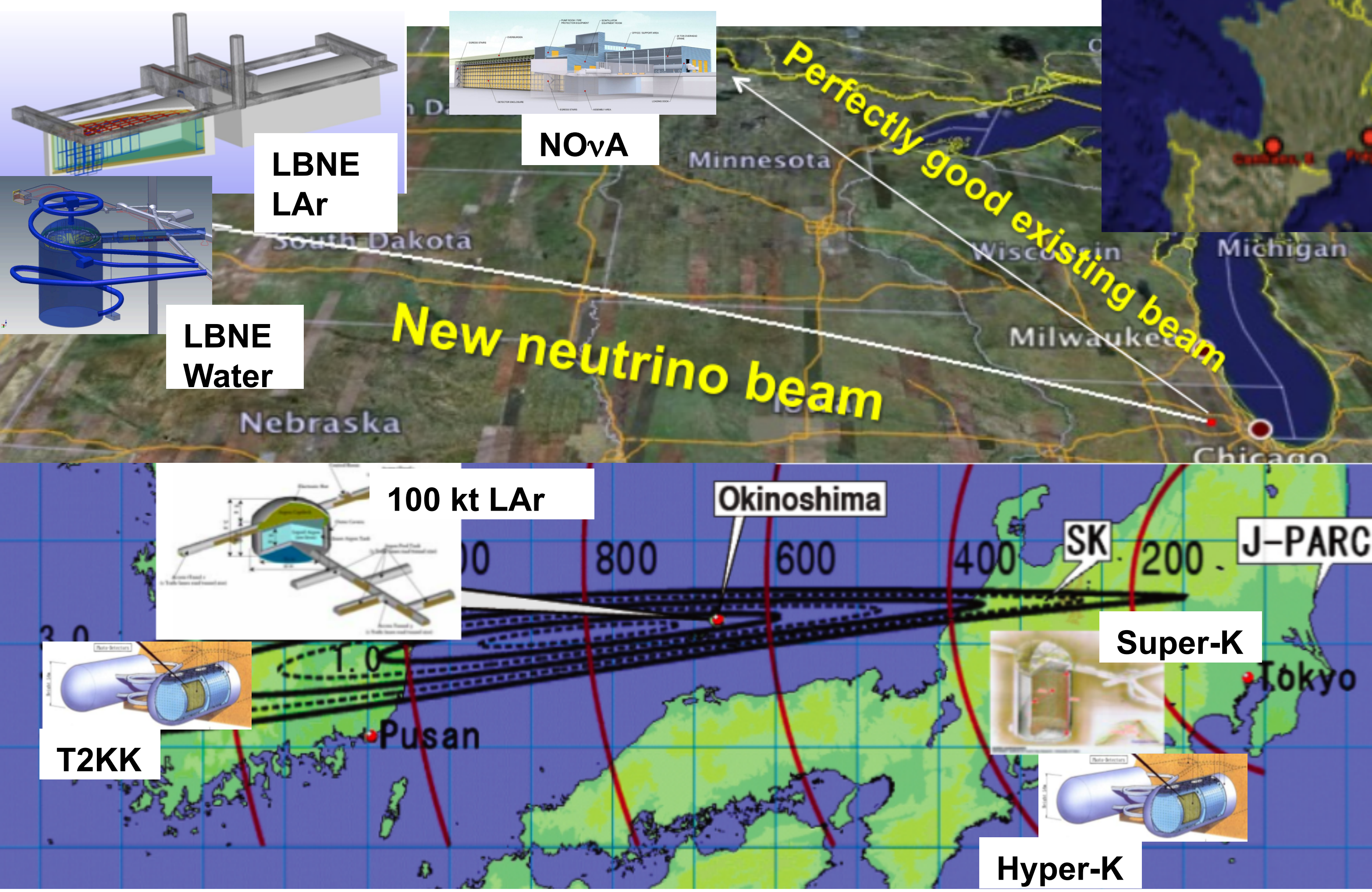


good sensitivity at ~1000-2500 km baseline, ~few GeV energy; need nus and antinus

Several programs working towards long baseline oscillation programs

US, Japan, Europe





And more future ideas:

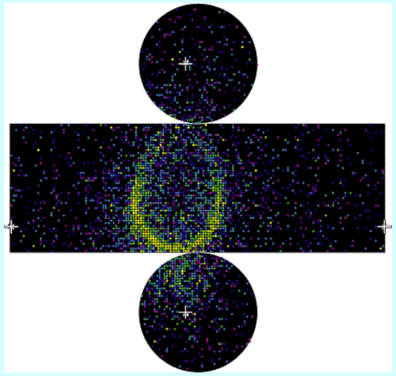
β beams,
ν factories,
cyclotrons,...

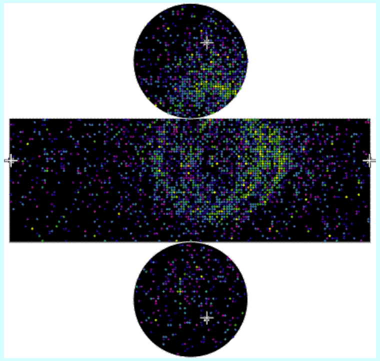
Detector choice issues for LBL physics

Need to reconstruct ~GeV neutrino interactions,
which often have multiple particles, complicated structure

Need to (for example) select ν_e from background

Water





e.g. NC single pions

$\pi^0 \rightarrow \gamma\gamma$

Good efficiency & bg rejection shown w/T2K; likely possible to do better

Good photon collection, and possibly better timing, may help: R&D for new photosensors underway

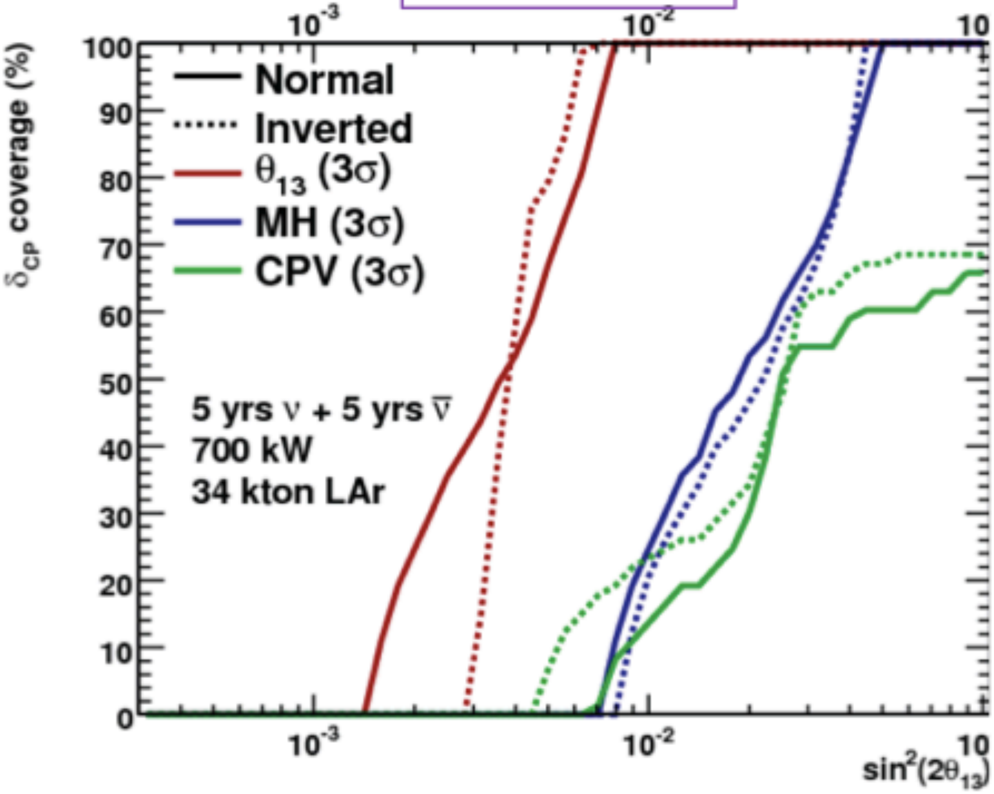
In principle, LAr can reconstruct entire interaction in detail

Efficiency higher, so required detector mass lower (factor ~6)

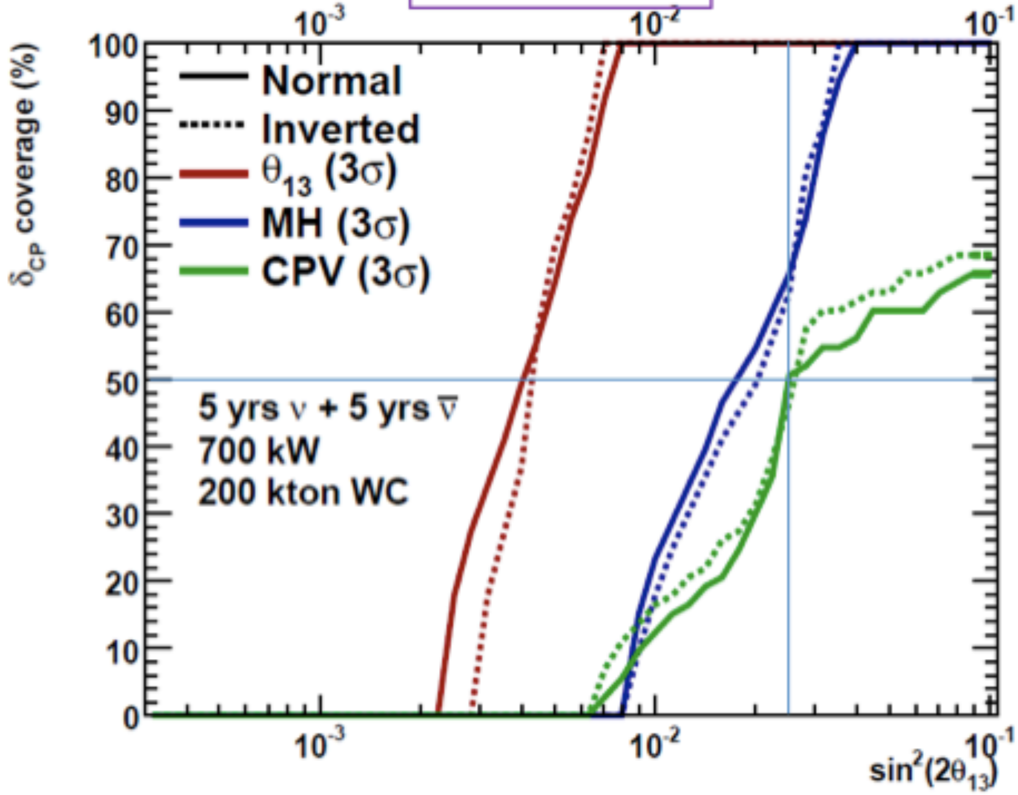
Example of sensitivity to oscillation parameters

LBNE sensitivity (1300 km baseline)

34 kt LAr TPC



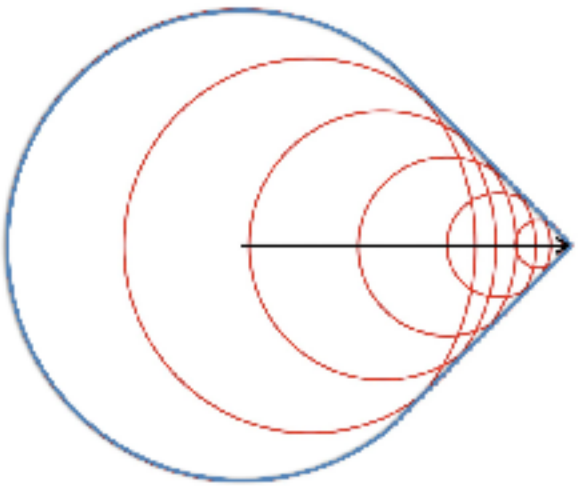
200 kt WCD

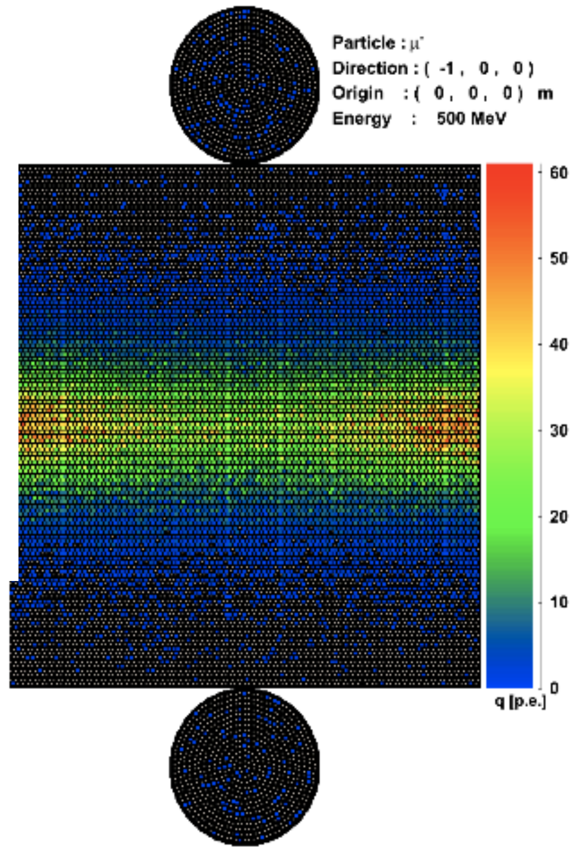


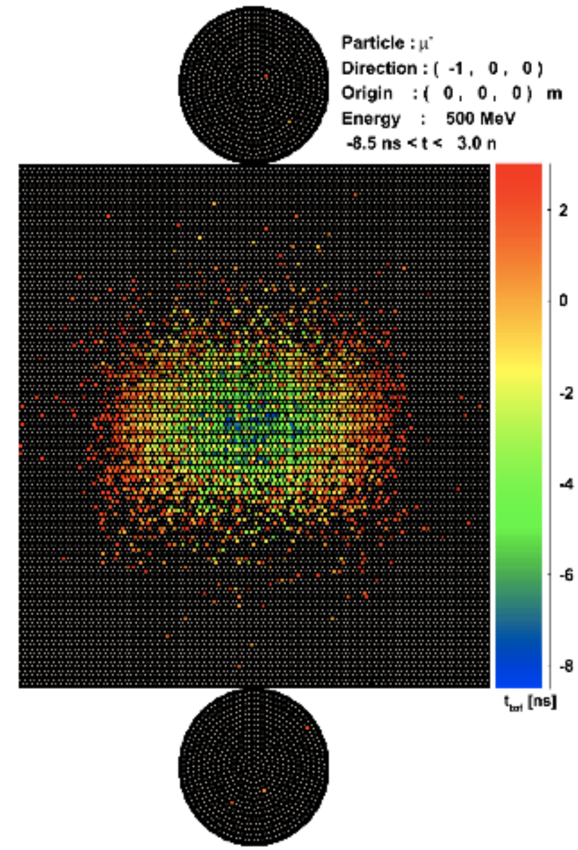
Note: 34 kton LAr ~ 200 kt WCD
because of better LAr efficiency

High energy event reconstruction may be possible in liquid scintillator

LENA arXiv.1104.5620 & refs







Use photon timing (first photon surface) to reconstruct track

- Good energy resolution (calorimetric)
- Particle ID possible
- Multiple tracks hard
- LBL oscillation BG rejection under study

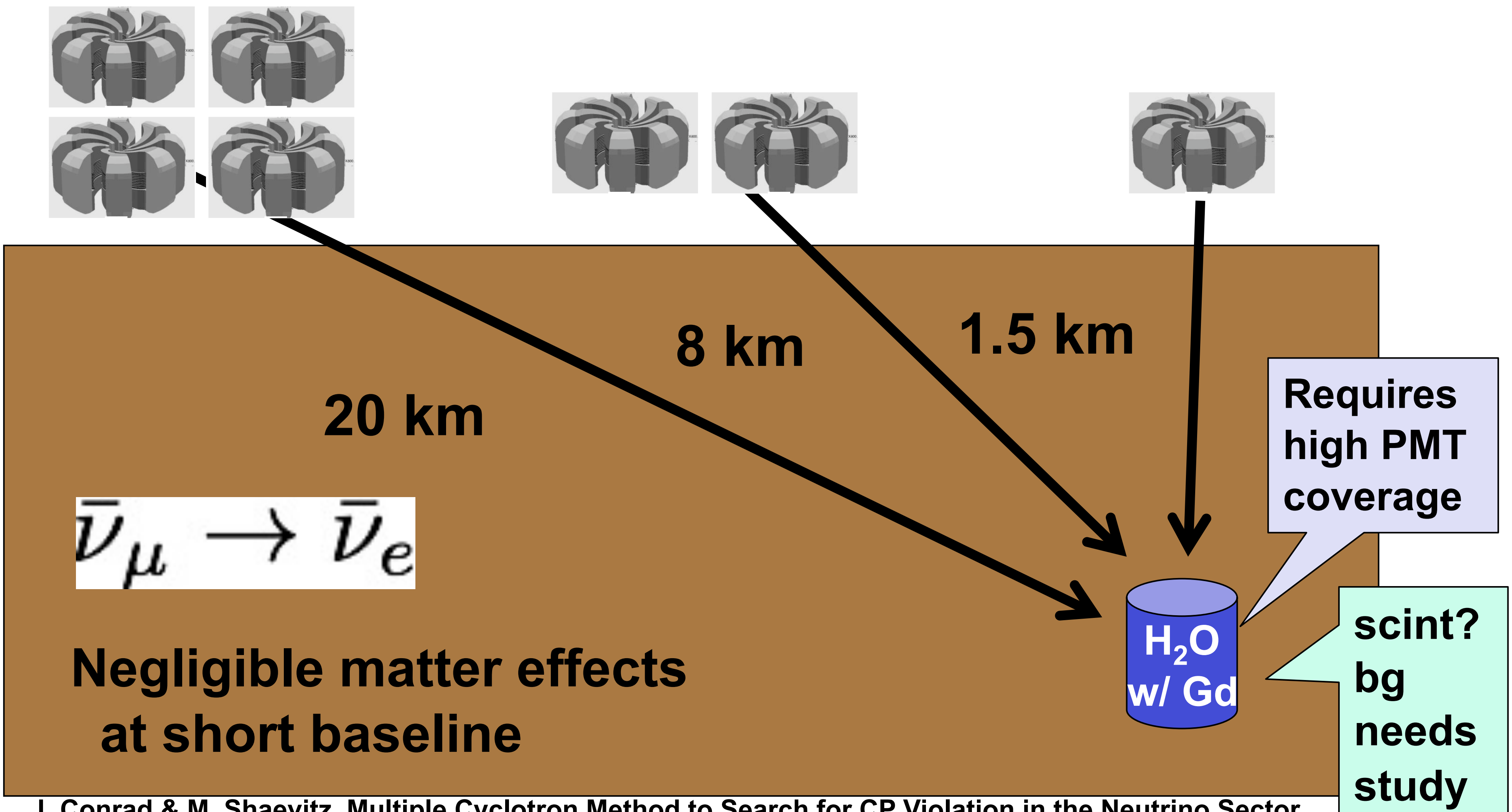
A different approach for ν CPV: DAEδALUS

Multiple stopped-pion neutrino sources:

L ~1.5-20 km

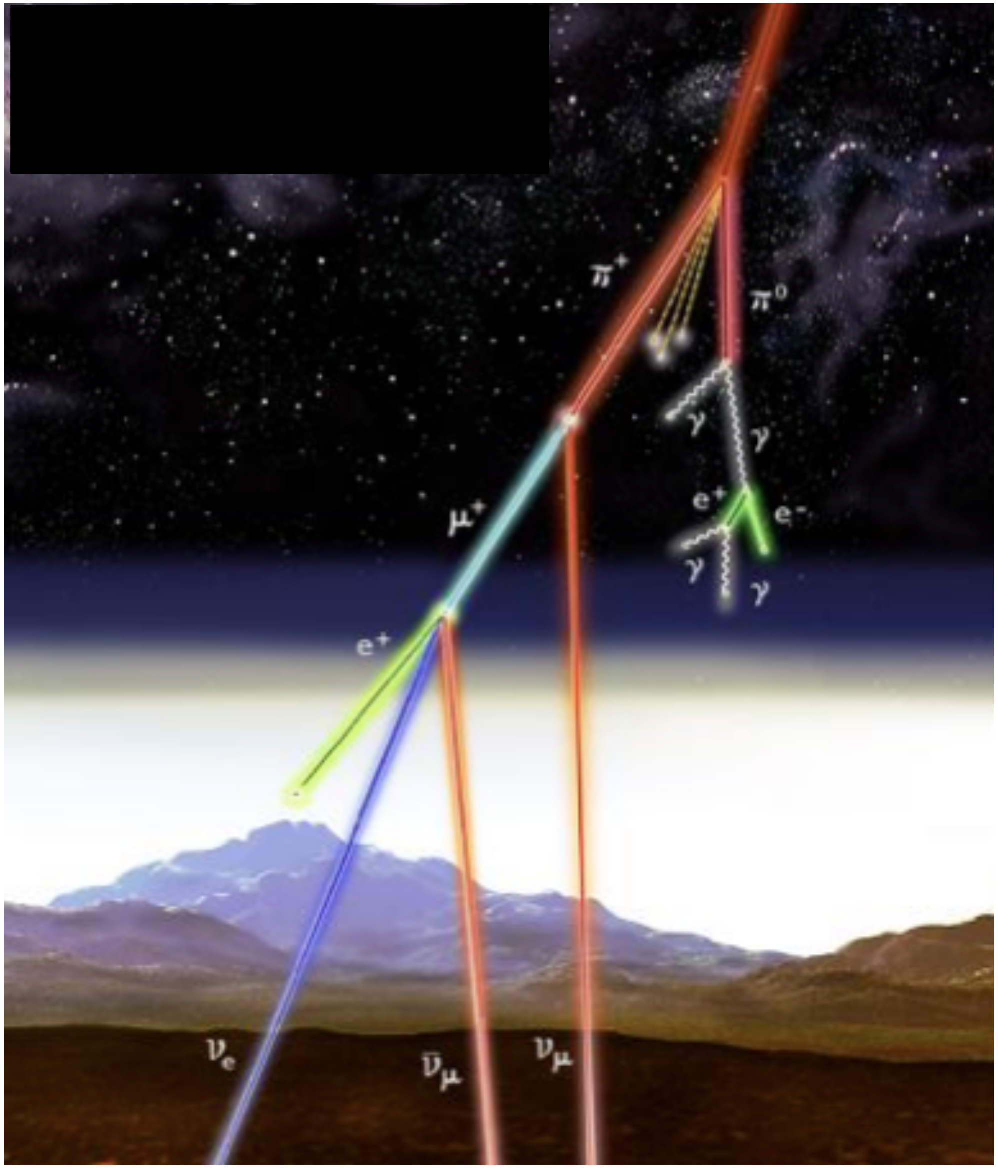
E ~10-50 MeV

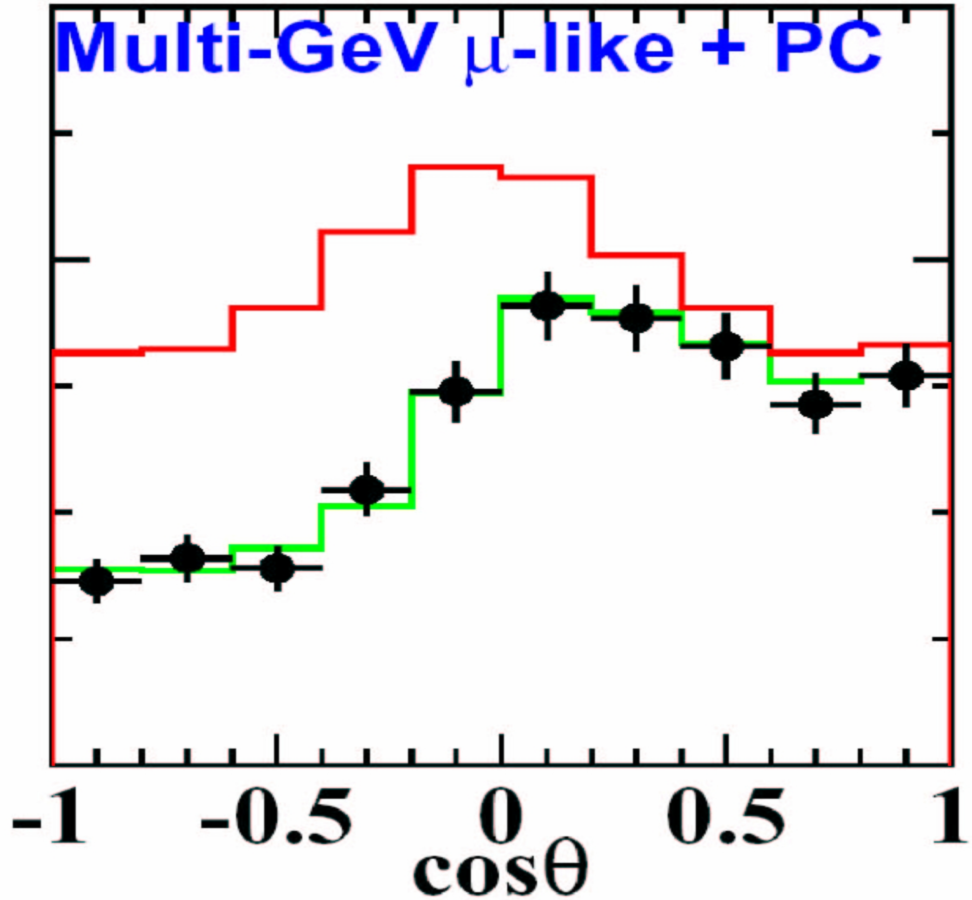
$$\frac{L}{E} \sim \frac{1000\ \mathrm{km}}{3000\ \mathrm{MeV}} \sim \frac{10\ \mathrm{km}}{30\ \mathrm{MeV}}$$



J. Conrad & M. Shaevitz, Multiple Cyclotron Method to Search for CP Violation in the Neutrino Sector, arXiv:0912.4079, Phys. Rev. Lett. 104, 141802 (2010)

Atmospheric neutrinos



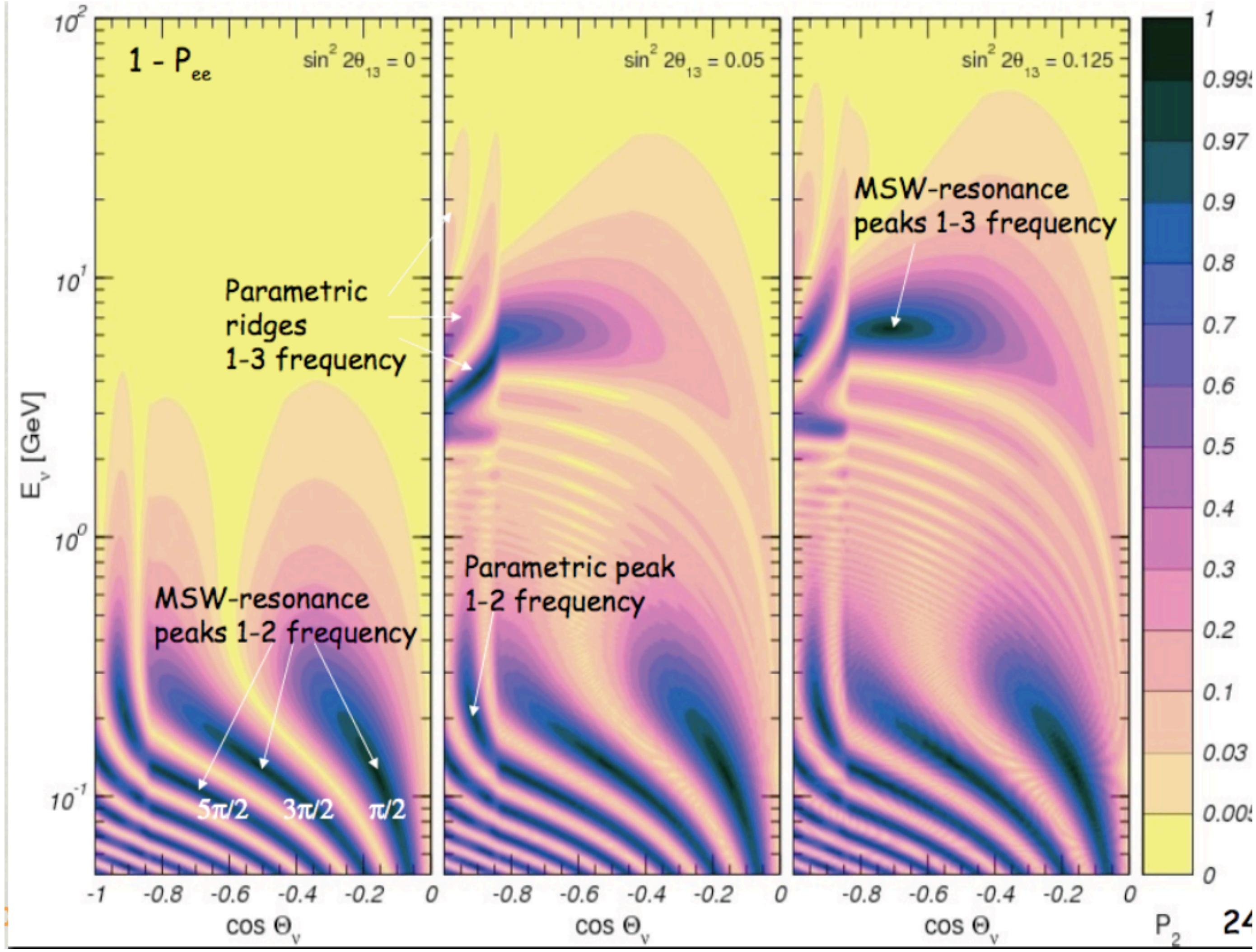


~0.1 GeV to ~TeV.
10-13,000 km pathlengths

First unambiguous evidence for neutrino mass and oscillations (1998) in Super-K

Precision atmospheric ν measurements

Angle-energy resonance depends on θ_{13} and mass hierarchy: oscillation (or geological?) info to be had



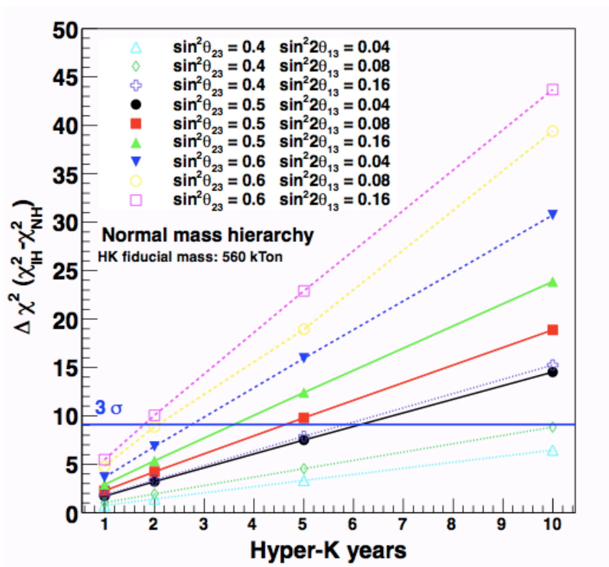
Requires high precision angular and energy resolution

Detector issues similar as for LBL: need good disentanglement of high energy particles in interaction, but also high statistics

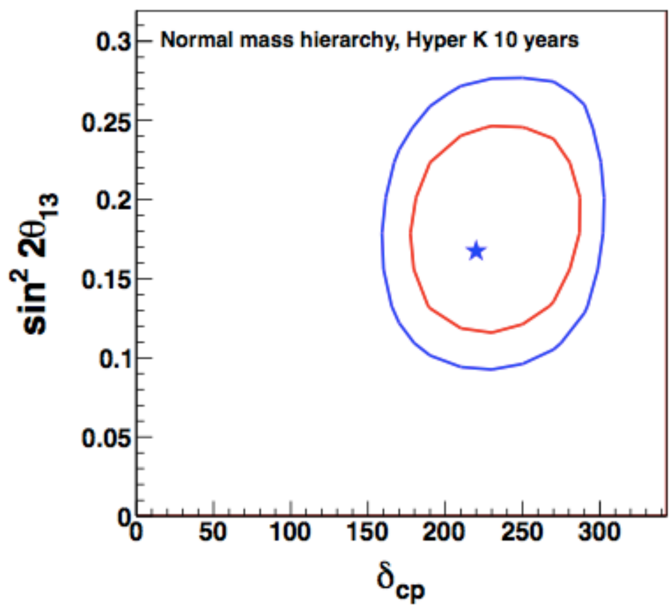
Example neutrino oscillation sensitivity plots for Hyper-K

NEW

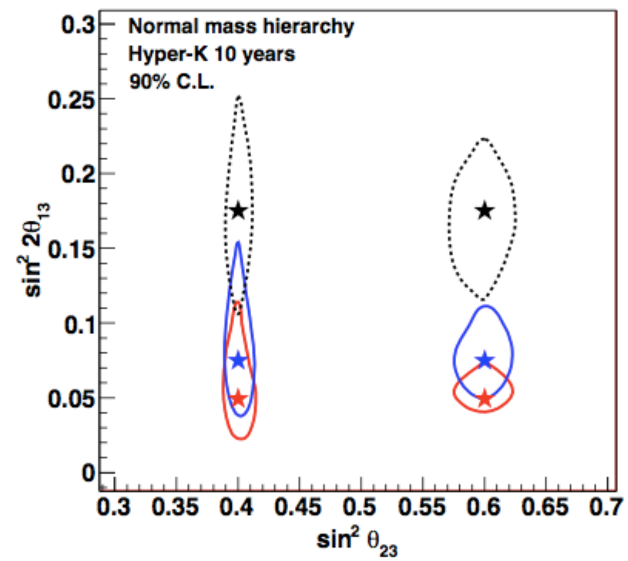
Hierarchy



CP δ



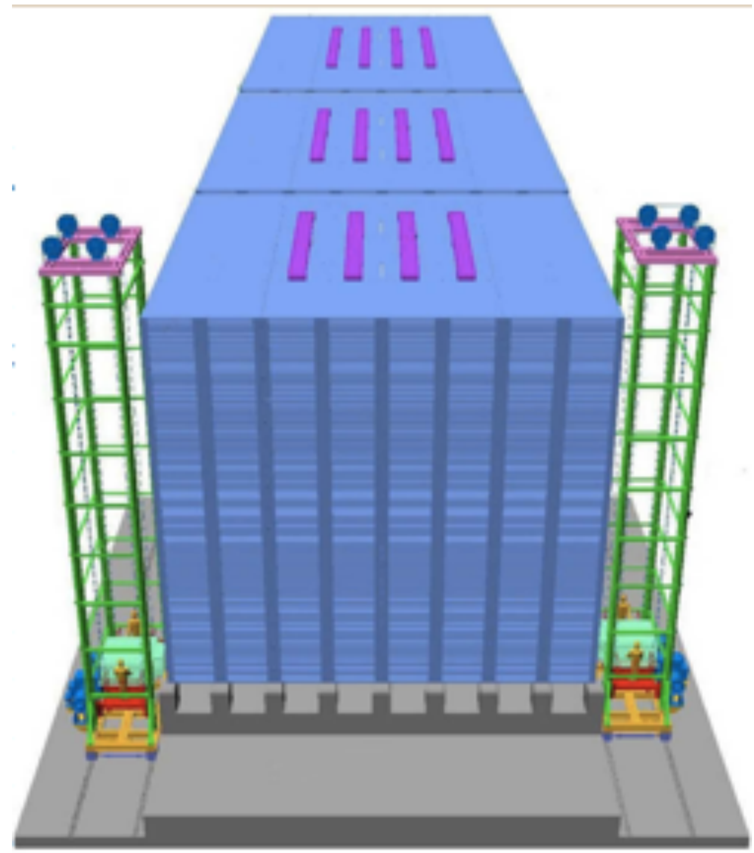
Octant of θ_{23}



$\sin^2 2\theta_{23} = 0.96 \ (\sin^2 \theta_{23} = 0.4 \text{ or } 0.6)$

Also: INO

India-based Neutrino Observatory



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

Baryon number violation

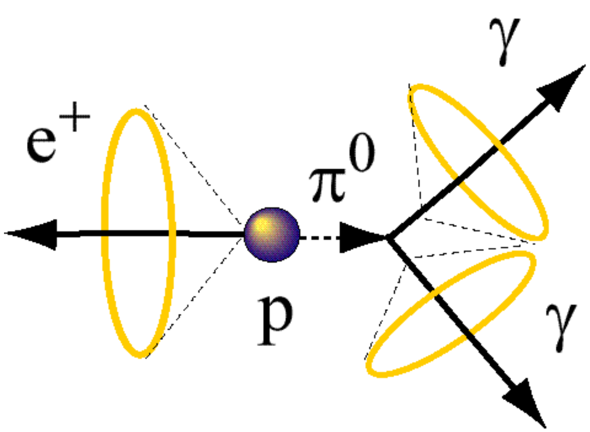
e.g. nucleon decay, $n\bar{n}$ oscillations

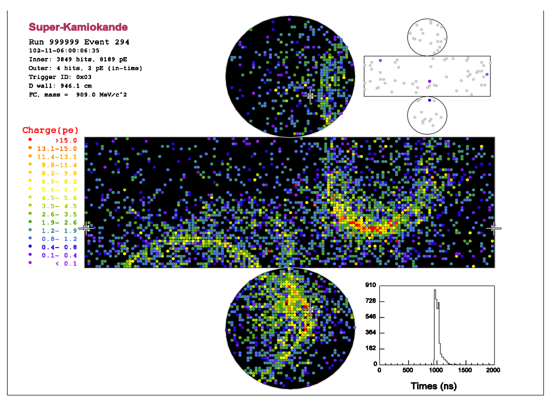
A 'smoking gun' for Grand Unified Theories

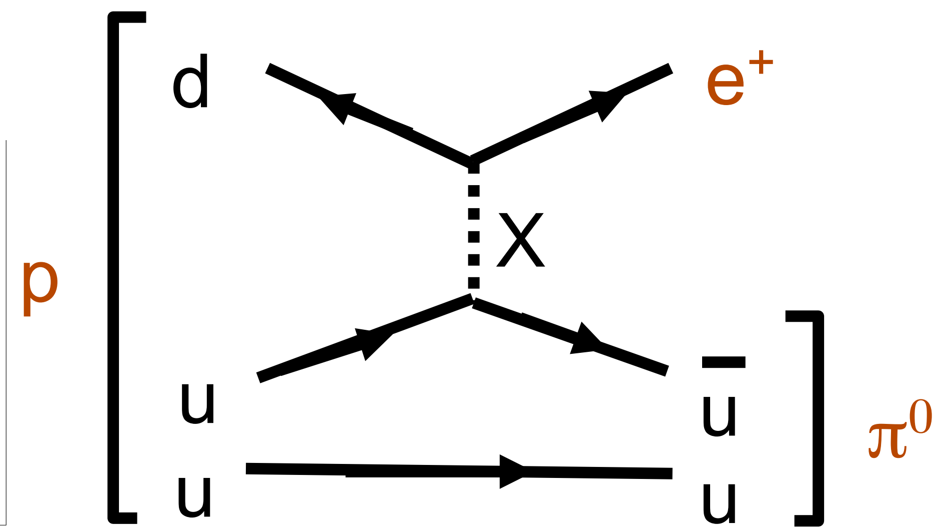
heavy X, Y bosons mediate transitions between
quarks and leptons (...many theoretical uncertainties in the rates)

Worst background is atmospheric ν's (can't shield from these!)

Golden Mode: $p \rightarrow e^+ \pi^0$

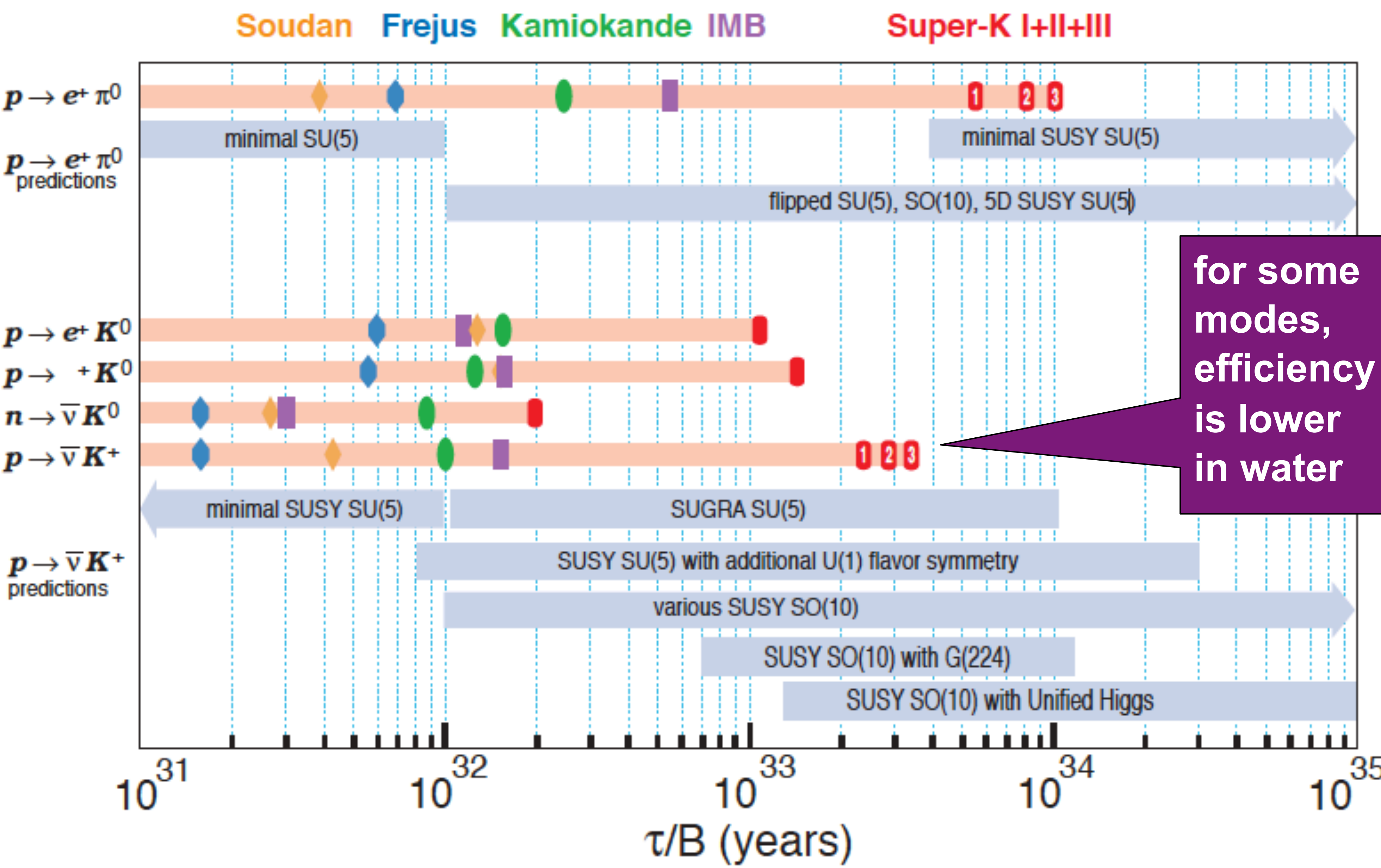






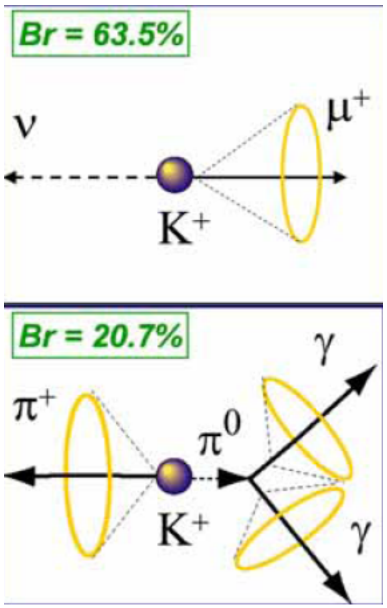
Lots of modes with varying theoretical motivations

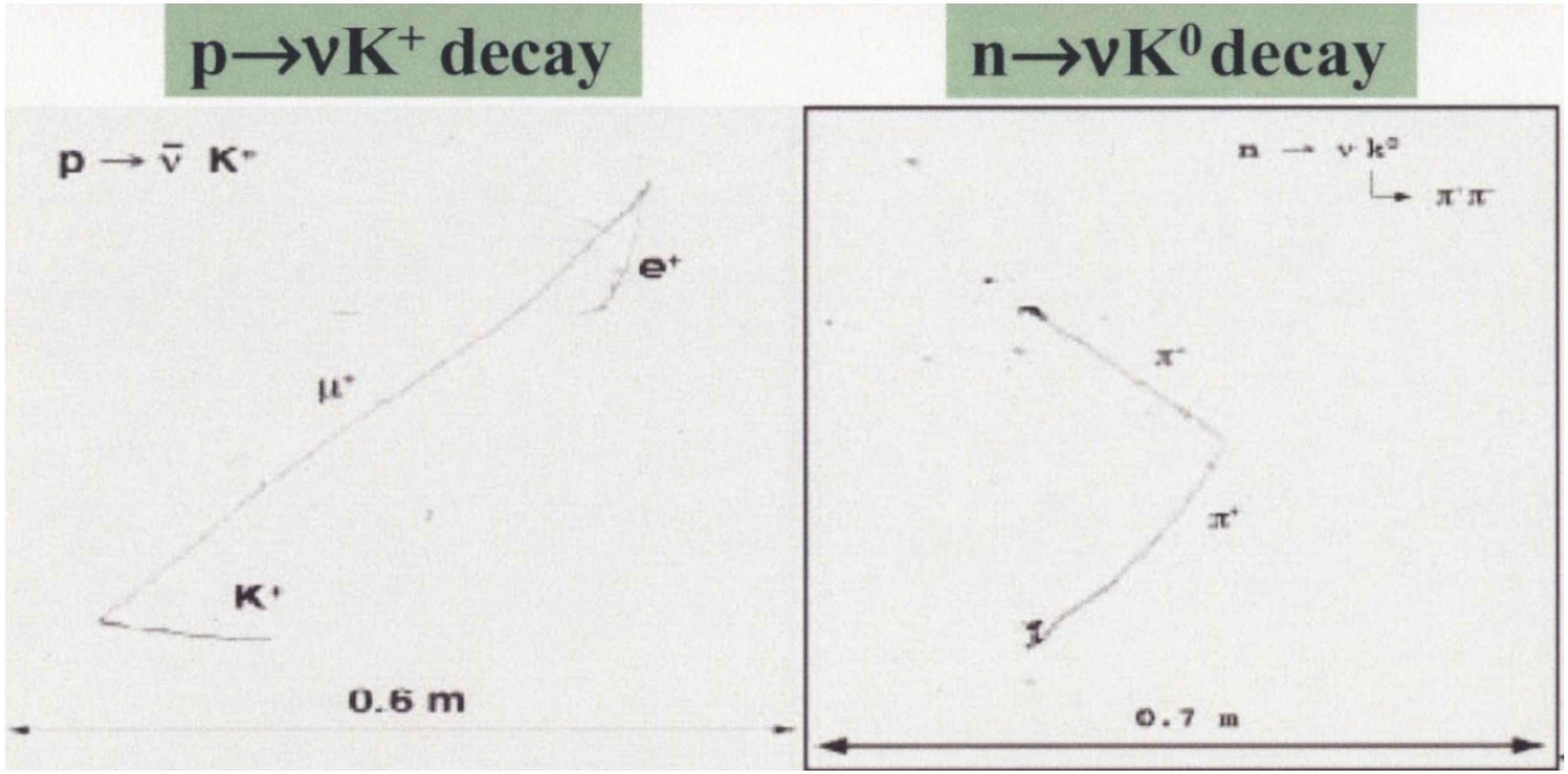
Super-K currently dominates the limits

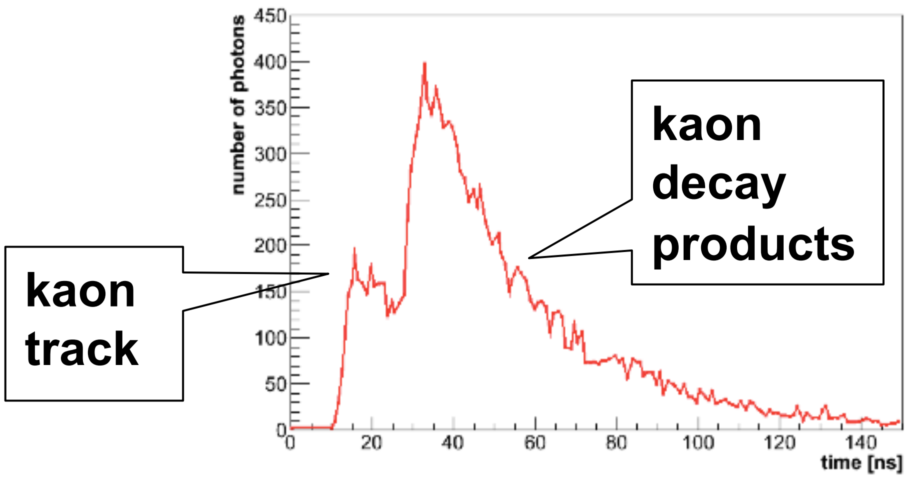


for some modes, efficiency is lower in water

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





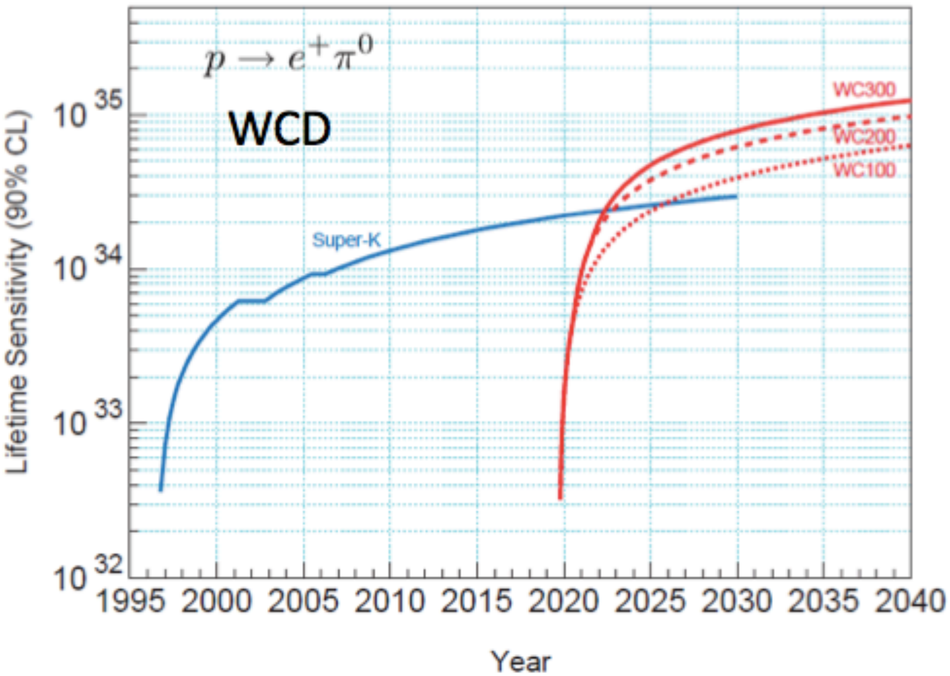


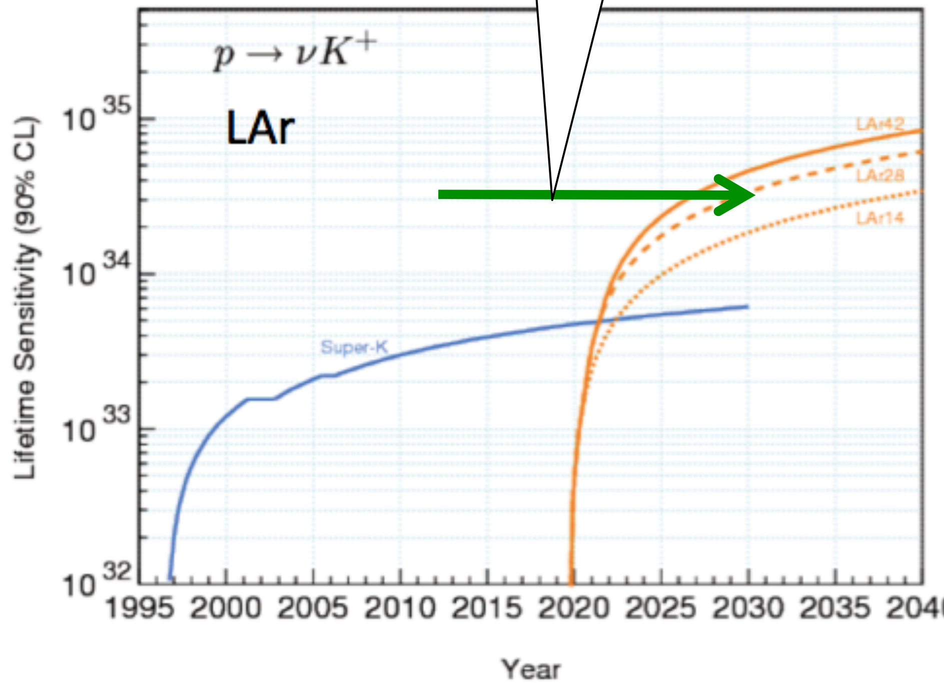
also a signature for this mode in scintillator (no Cherenkov threshold) using photon timing

(hep-ph/0511230)

Nucleon decay sensitivity vs time

LENA in 10 years





water best for this mode

argon best for this mode

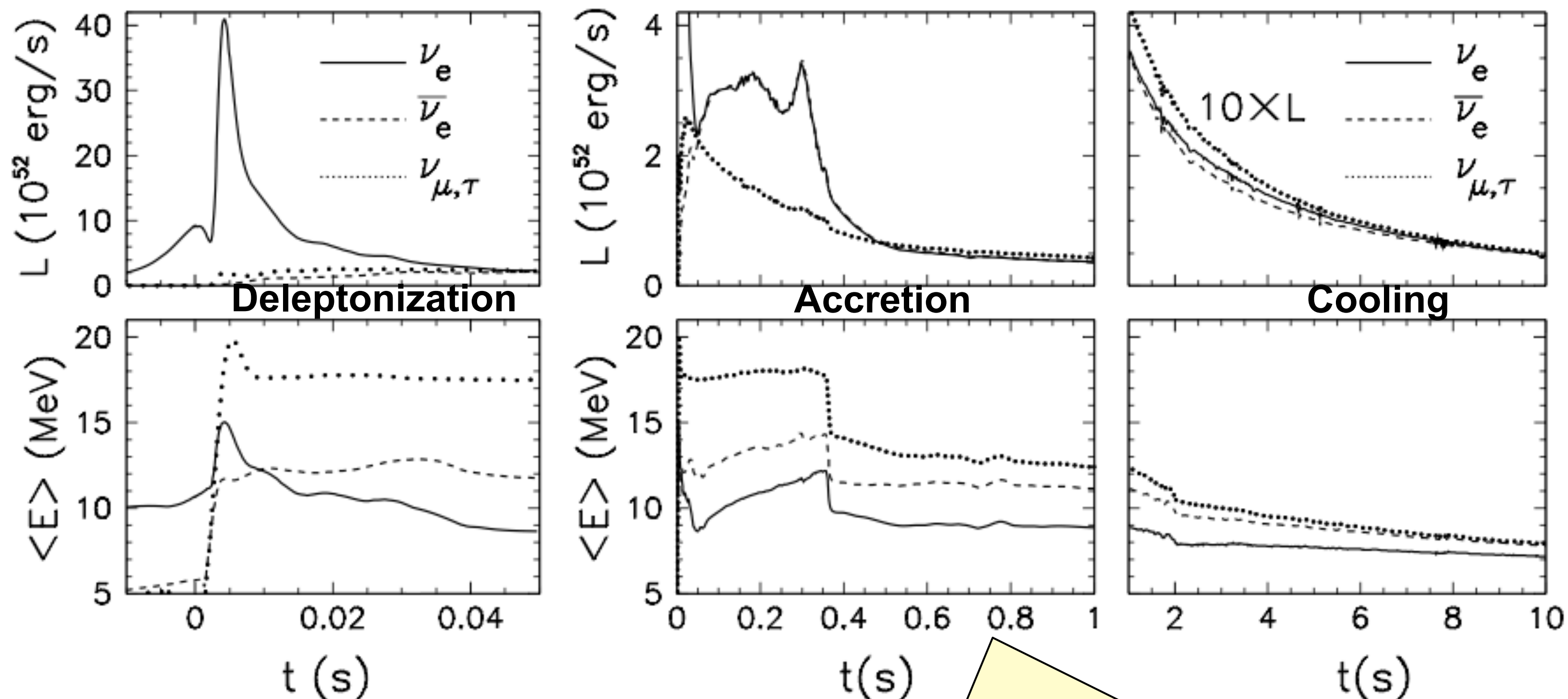
Core collapse supernova neutrinos

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

Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling



Detection would yield enormous particle physics & astro-physics info

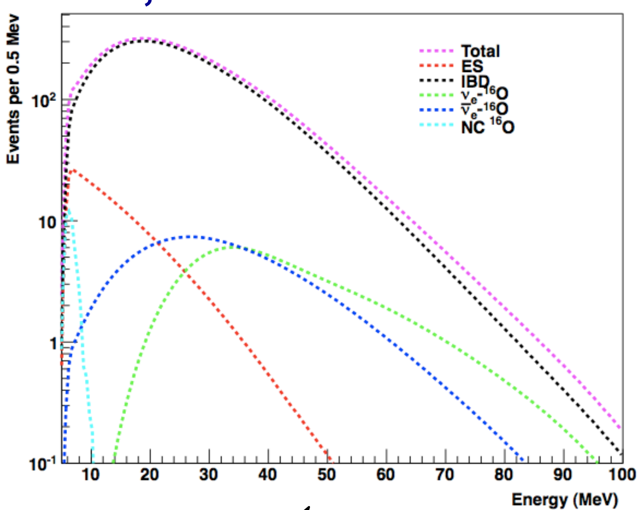
$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Fischer et al., arXiv:0908.1871
'Basel' model

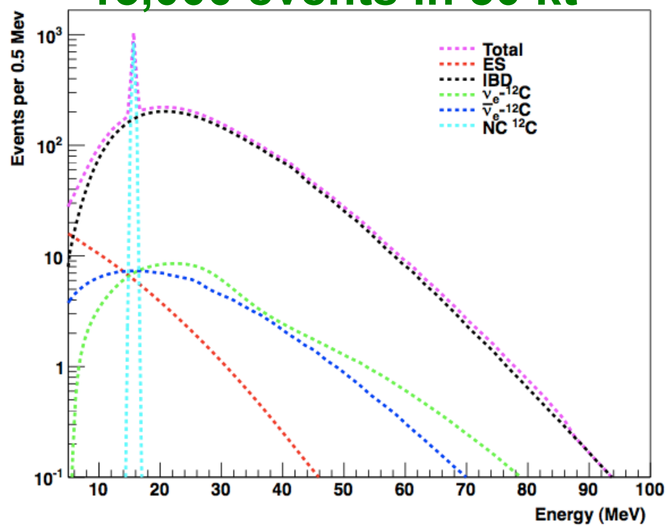
All detector types would observe copious neutrinos

Observed events at 10 kpc

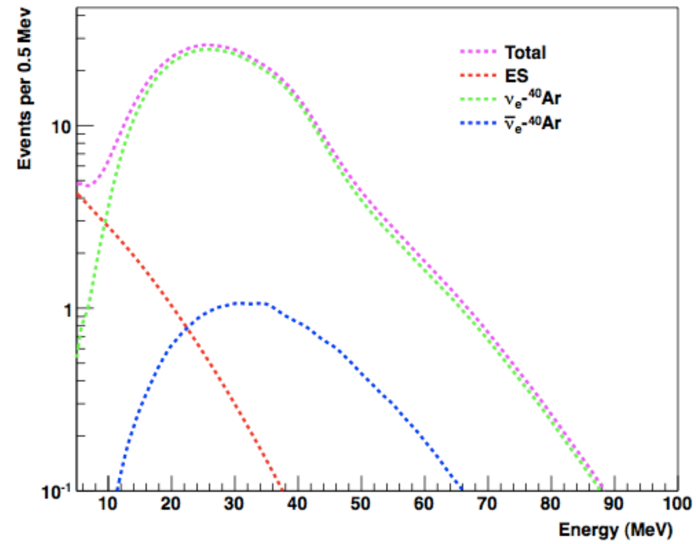
Water
25,000 events in 100 kt



Liquid scintillator
15,000 events in 50 kt



Liquid argon
1500 events in 17 kt



Nearly pure nuebar (inverse beta decay on free protons)

Also nearly pure nuebar, plus NC channels

Nearly pure nue!

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

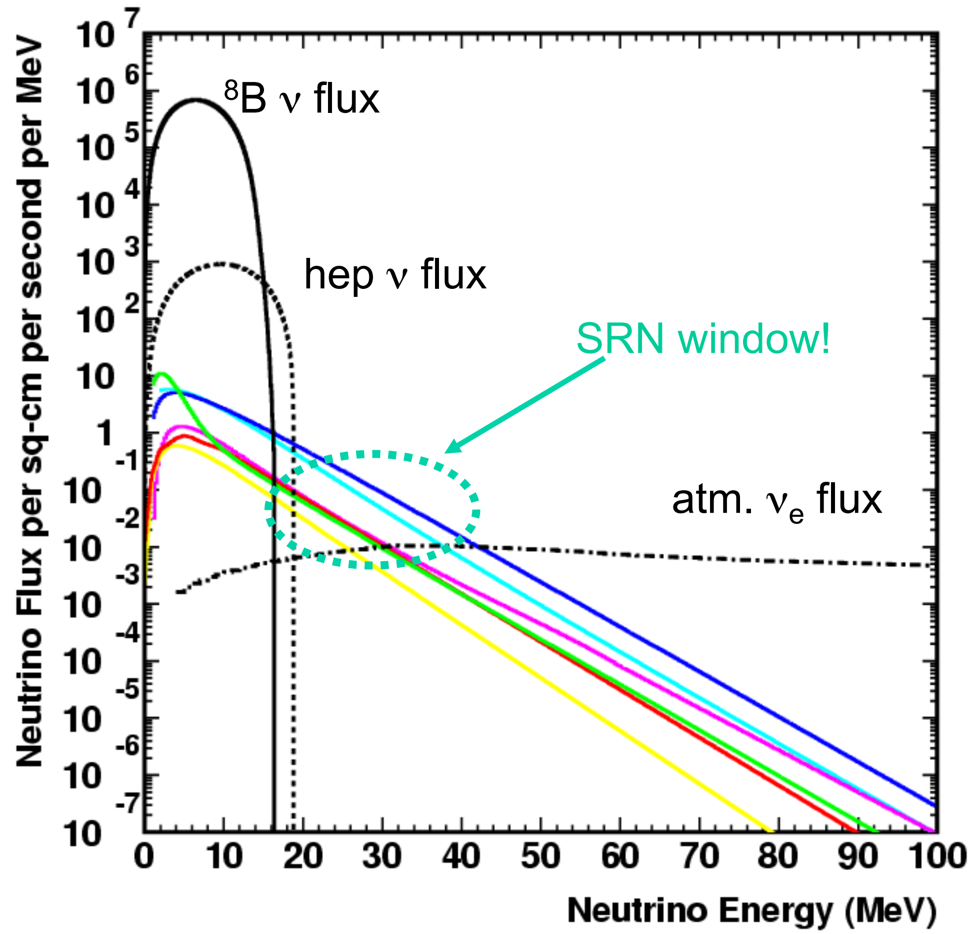
For the risk-averse: '*relic*' or diffuse SN ν's (DSNB)

(John Beacom's talk)

Learn about star formation rate, average SN ν emission

Difficulty is tagging ~10-50 MeV ν's (S/B poor if not in burst)

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



S/B w/ Gd in water for tagging IBD is promising

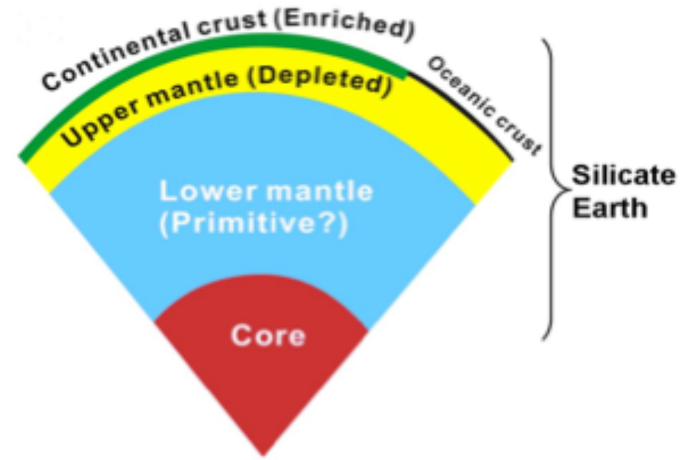
Scintillator also good (possible atmospheric ν NC bg)

Argon sees ν_e flux, unknown backgrounds

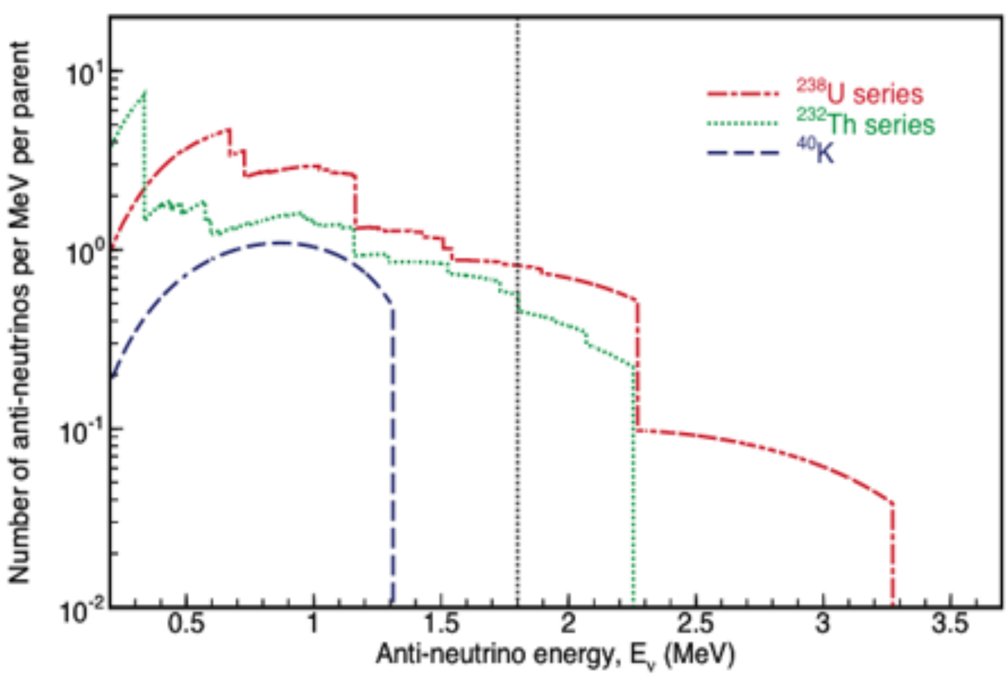
Geo-neutrinos

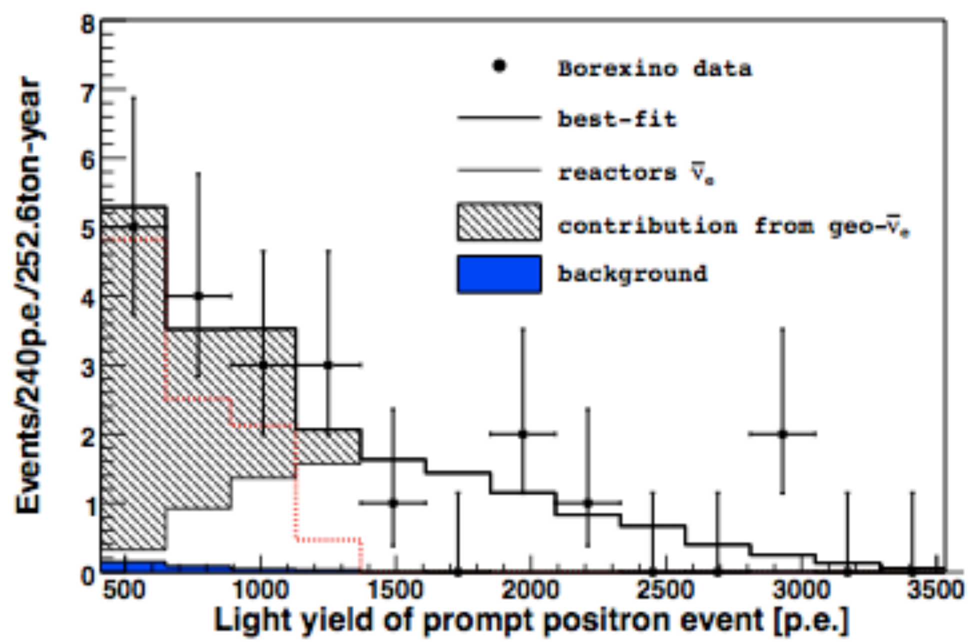
Fraction of Earth's heat from radioactivity is uncertain ... neutrinos can constrain geophysical models, measure U/Th

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



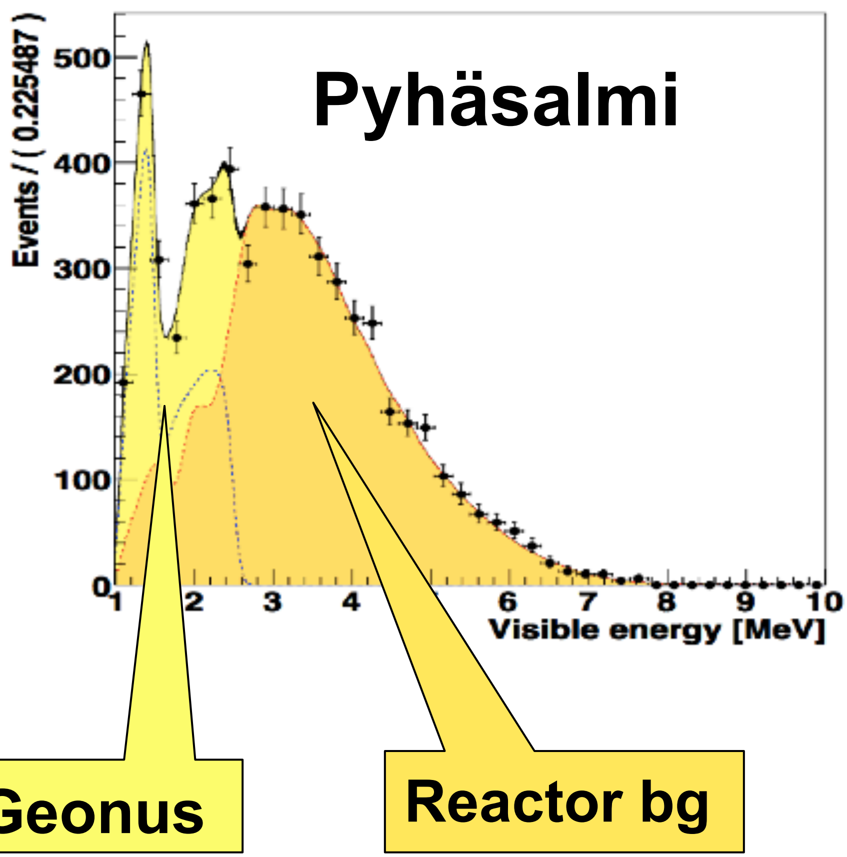
Bulk Silicate Earth model:
~1/2 of U, Th, K in crust
~1/2 of U, Th, K in mantle
~no U, Th, K in core

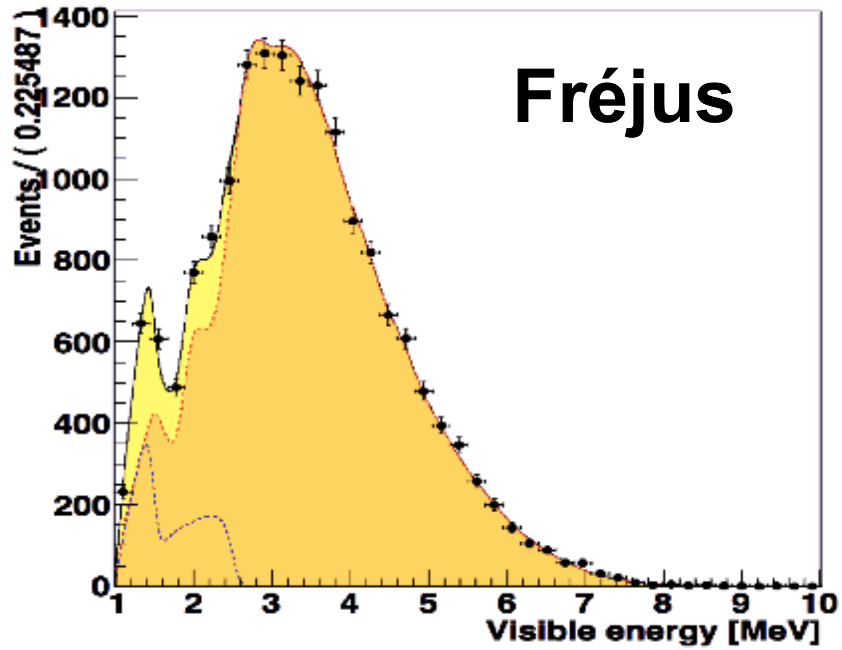




Best bet for geoneutrinos is scintillator, due to low energy threshold, good energy resolution & low radioactive bg

Reactor neutrino bg is the biggest issue

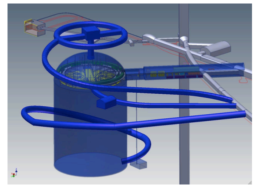
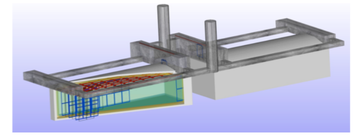




1 year statistics

LENA arXiv.1104.5620

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

More topics...

Solar neutrinos
Short baseline oscillations (‘oscillometry’)
  w/low energy radioactive sources
Reactor neutrinos
Cosmic neutrinos
Indirect WIMP DM searches
Neutrinoless double beta decay w/solute
Exotic particle searches
  (monopoles, fractionally charged particles,...)
The unexpected!

Excellent breadth for any technology...
even more with different
technologies worldwide

Summary

Very wide array of physics opportunities for large detectors underground...

Water, argon and scintillator have different strengths and weaknesses

A broad global program is highly desirable

*Note: detector technology R&D may be game-changing (e.g. cheap photosensors)

Backups

	Detector	Fid. mass, kton (modules)	PMTs (diameter, cm)	ξ	pe/MeV	Dates
scintillator	Baksan	0.33, scint (3150)	1/module (15)	segmented	40	1980–
	MACRO	0.6, scint (476)	2-4/module (20)	segmented	18	1989–2000
	LVD	1, scint. (840)	3/module (15)	segmented	15	1992–
	KamLAND	1, scint	1325 (43)+554 (51)*	34%	460	2002–
	Borexino	0.1, scint	2212 (20)	30%	500	2005–
	SNO+	0.78, scint	9438 (20)	54%	400–900	Future
water	IMB-1	3.3, H_2O	2048 (12.5)	1%	0.25	1982–1985
	IMB-2	3.3, H_2O	2048 (20)	4.5%	1.1	1987–1990
	Kam I	0.88/0.78, H_2O	1000/948 (50)	20%	3.4	1983–1985
	Kam II	1.04, H_2O	948 (50)	20%	3.4	1986–1990
	Kam III	1.04, H_2O	948 (50)	20%‡	4.3	1990–1995
	SK I	22.5, H_2O	11146 (50)	39%	6	1996–2001
	SK II	22.5, H_2O	5182 (50)	19%	3	2002–2005
	SK III+	22.5, H_2O	11129 (50)	39%	6	2006–
	SNO	1, D_2O/1.7 H_2O	9438 (20)	31% §	9	1999–2006

Possible enhancement:

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

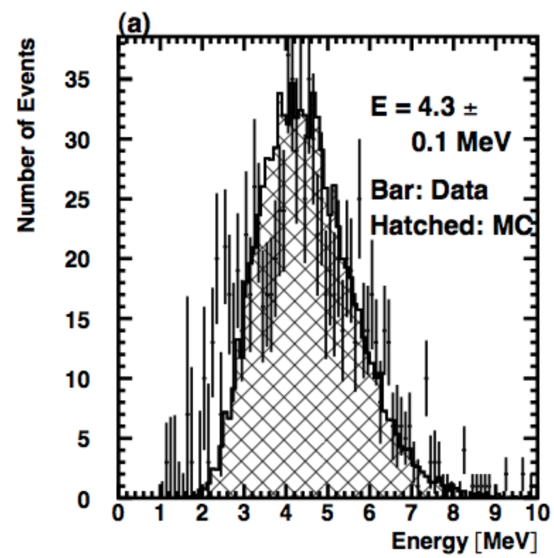
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

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*

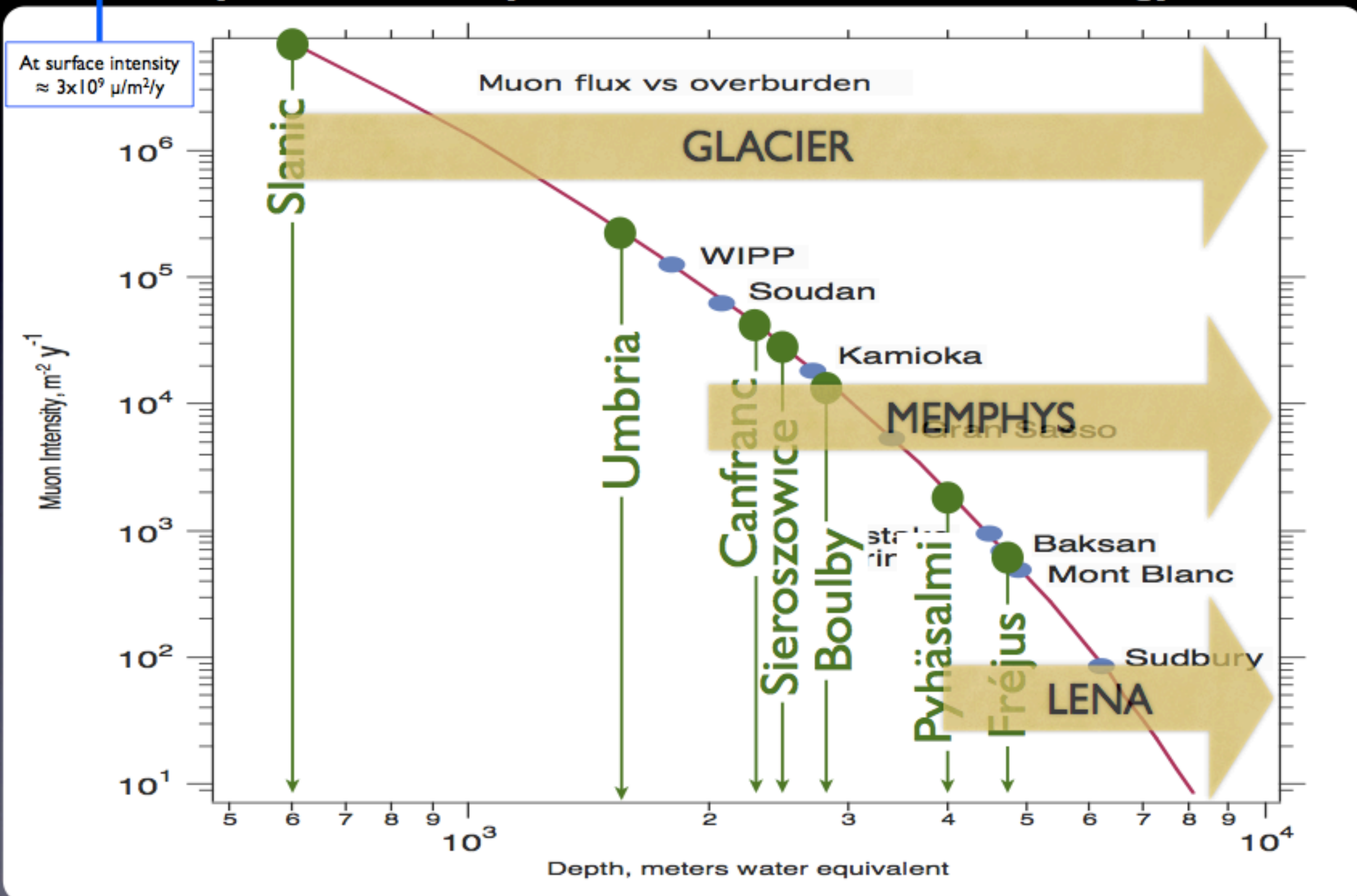
Table 1: Potential sites being studied with the LAGUNA design study.

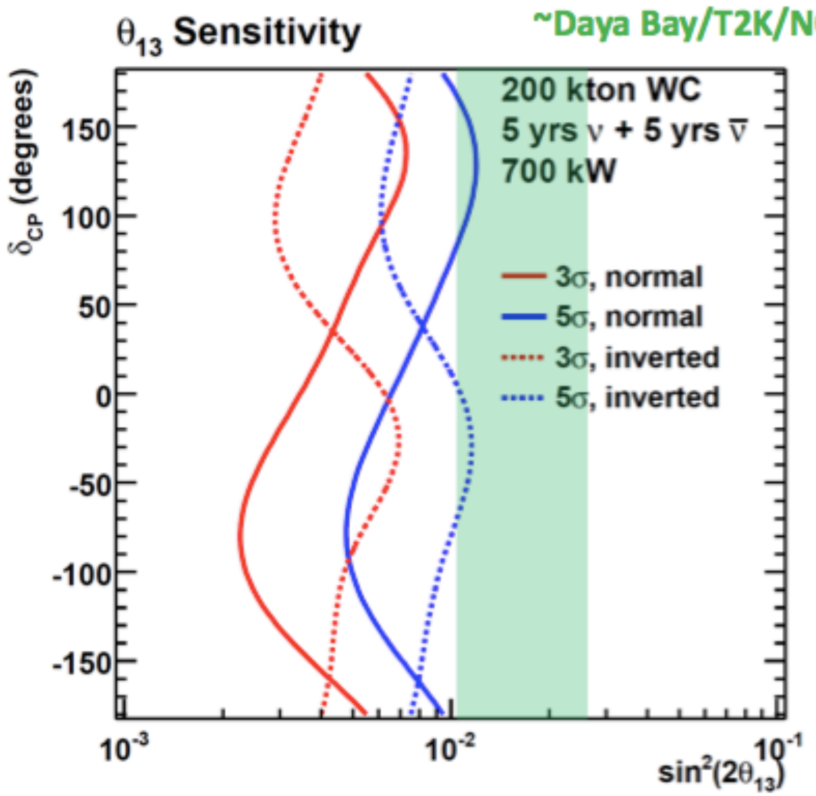
Location	Type	Envisaged depth m.w.e.	Distance from CERN [km]	Energy 1^{st} Osc. Max. [GeV]
Fréjus (F)	Road tunnel	$\simeq 4800$	130	0.26
Canfranc (ES)	Road tunnel	$\simeq 2100$	630	1.27
Umbria(IT) [a]	Green field	$\simeq 1500$	665	1.34
Sieroszowice(PL)	Mine	$\simeq 2400$	950	1.92
Boulby (UK)	Mine	$\simeq 2800$	1050	2.12
Slanic(RO)	Salt Mine	$\simeq 600$	1570	3.18
Pyhäsalmi (FI)	Mine	up to $\simeq 4000$	2300	4.65

[a] $\simeq 1.0\,^{\circ}$ off axis.

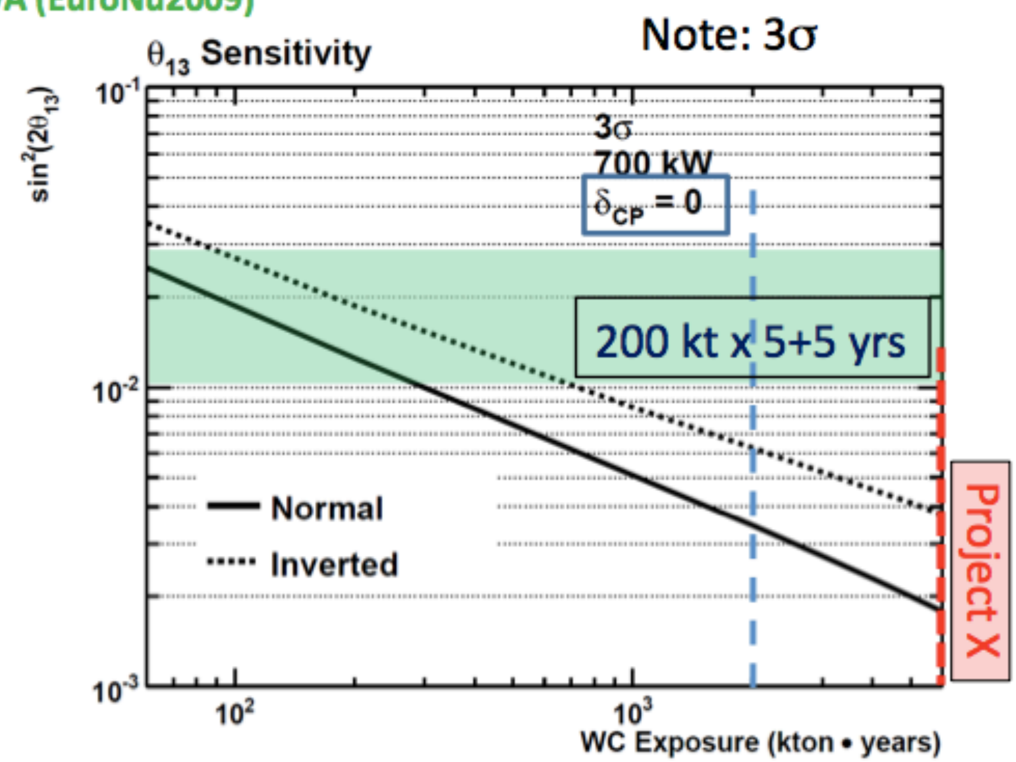
Various depths

Requirement depends on detector technology



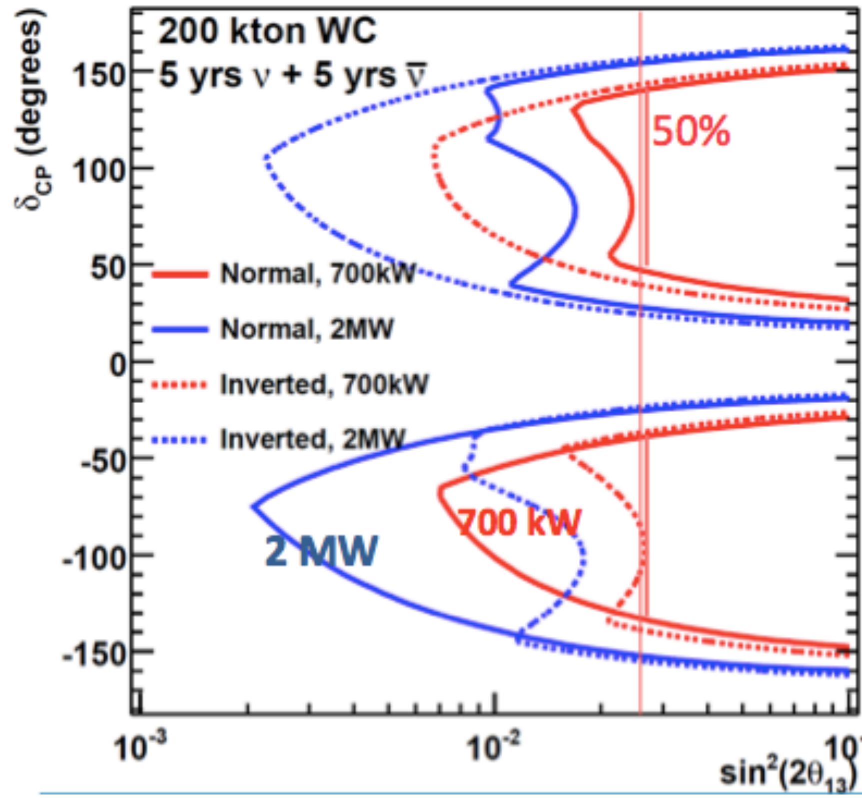


θ_{13} Sensitivity
~Daya Bay/T2K/NOvA (EuroNu2009)
200 kton WC
5 yrs ν + 5 yrs $\bar{\nu}$
700 kW
3σ, normal
5σ, normal
3σ, inverted
5σ, inverted
δ_{CP} (degrees)
$\sin^2(2\theta_{13})$

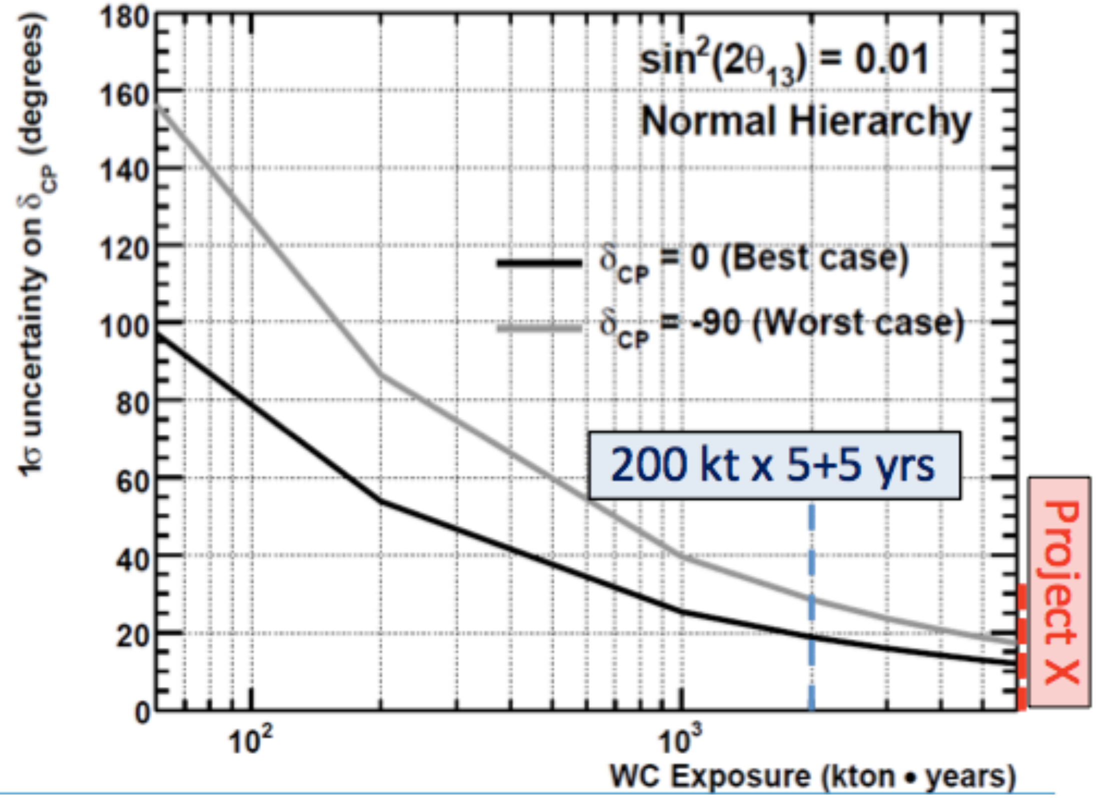


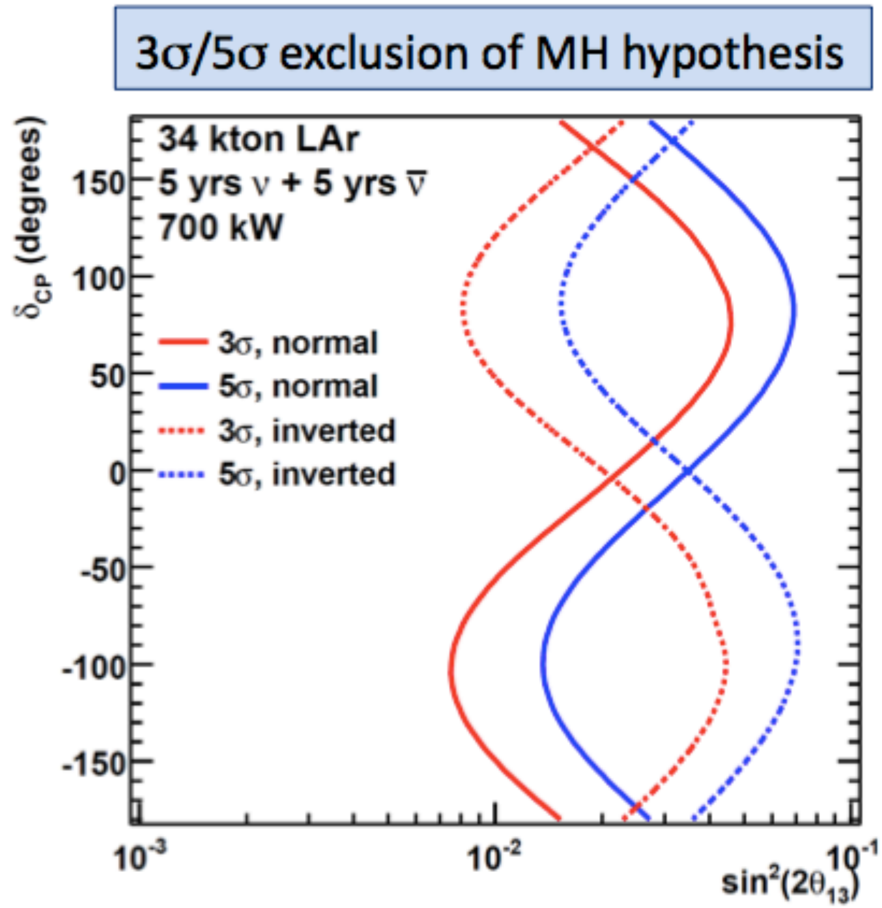
Note: 3σ
θ_{13} Sensitivity
3σ
700 kW
$\delta_{CP} = 0$
200 kt x 5+5 yrs
Normal
Inverted
Project X
$\sin^2(2\theta_{13})$
WC Exposure (kton • years)

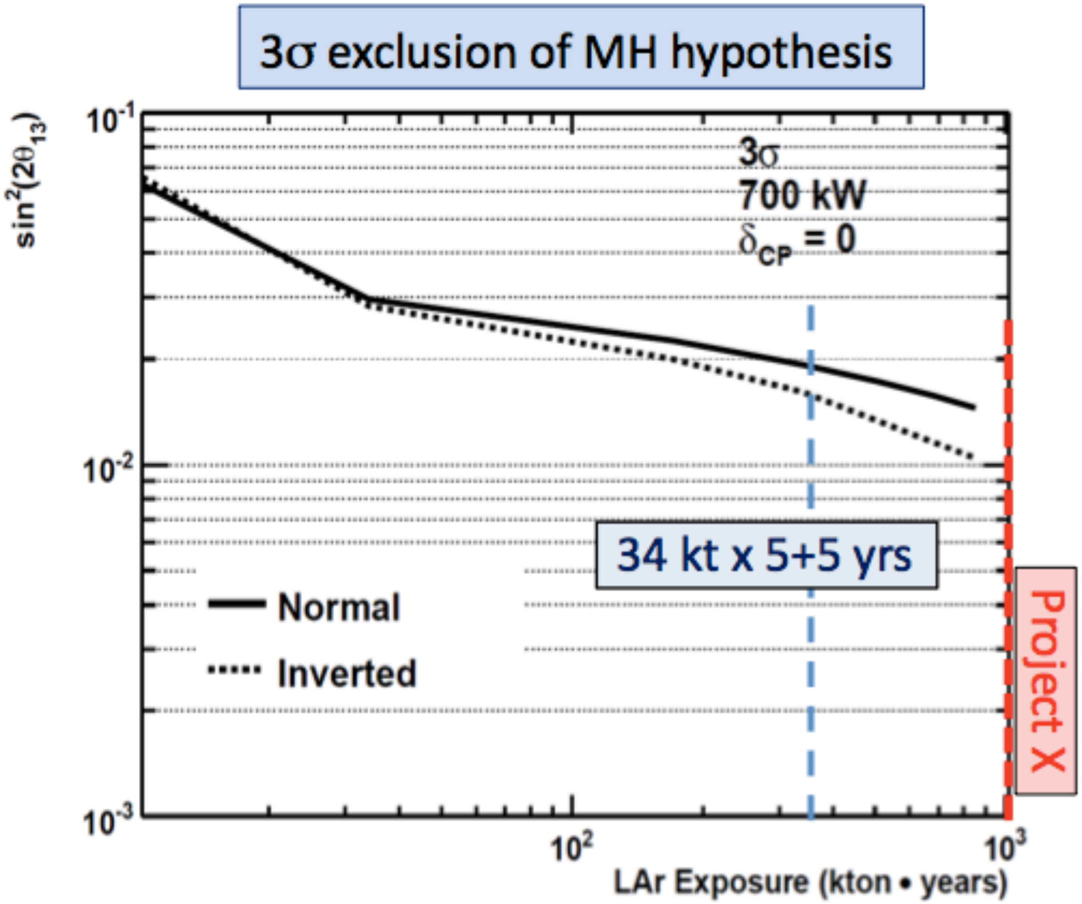
3σ exclusion of CP conserving δ_{CP}=0° or 180°



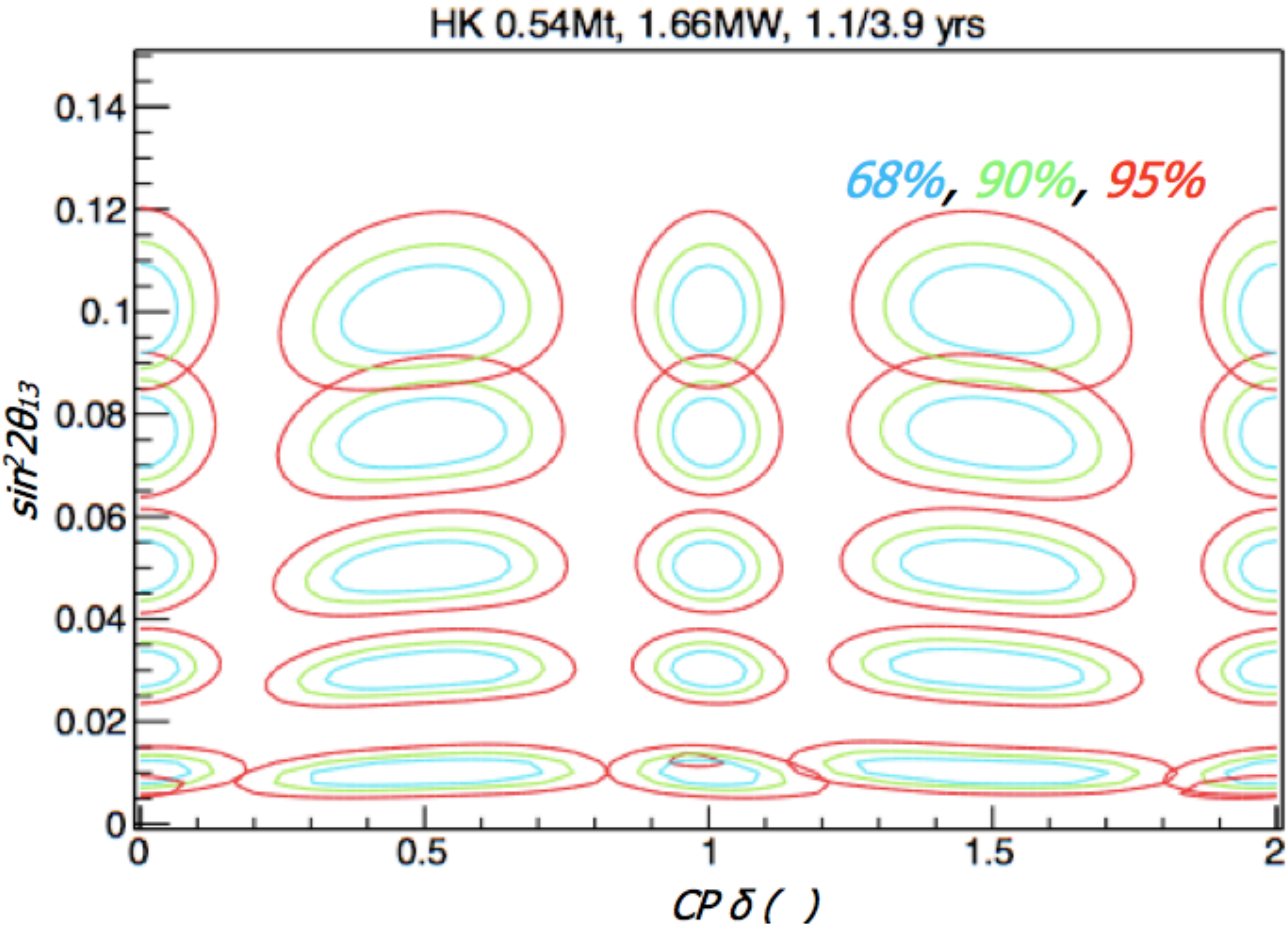
1σ resolution on δ_{CP} measurement




3σ/5σ exclusion of MH hypothesis
34 kton LAr
5 yrs ν + 5 yrs ν̄
700 kW
3σ, normal
5σ, normal
3σ, inverted
5σ, inverted
δCP (degrees)
sin²(2θ13)

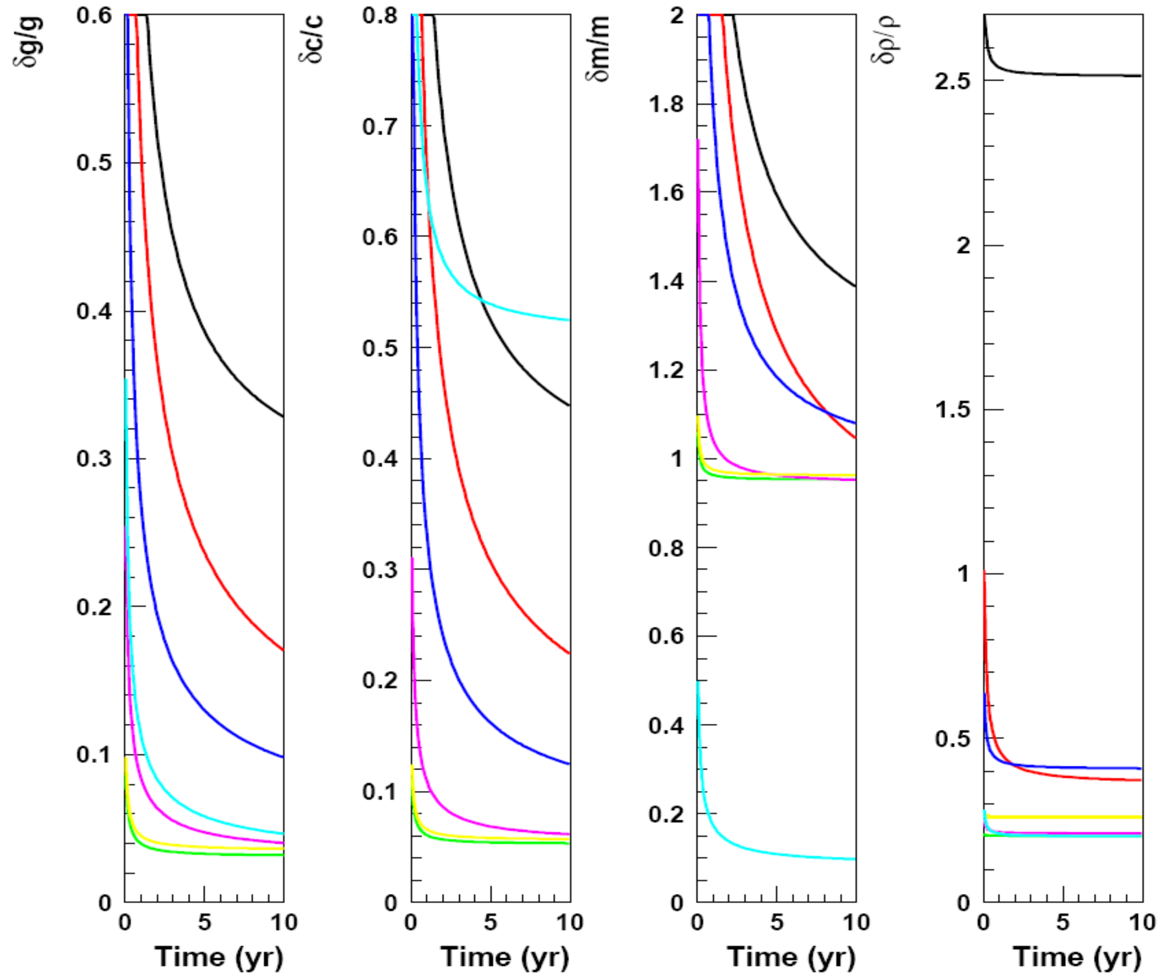

3σ exclusion of MH hypothesis
3σ
700 kW
δCP = 0
34 kt x 5+5 yrs
Normal
Inverted
Project X
sin²(2θ13)
LAr Exposure (kton • years)

Another example: CP δ measurement with Hyper-K + J-PARC upgrade



Geo-neutrino Sensitivity

Detector	$\times 10^{32}$ p^+
KamLAND	0.62
Borexino	0.18
SNO+	0.57
DUSEL	36.7
Baksan	4.0
LENA	36.7
Hanohano	7.34



Event rates

$$n = g + r$$

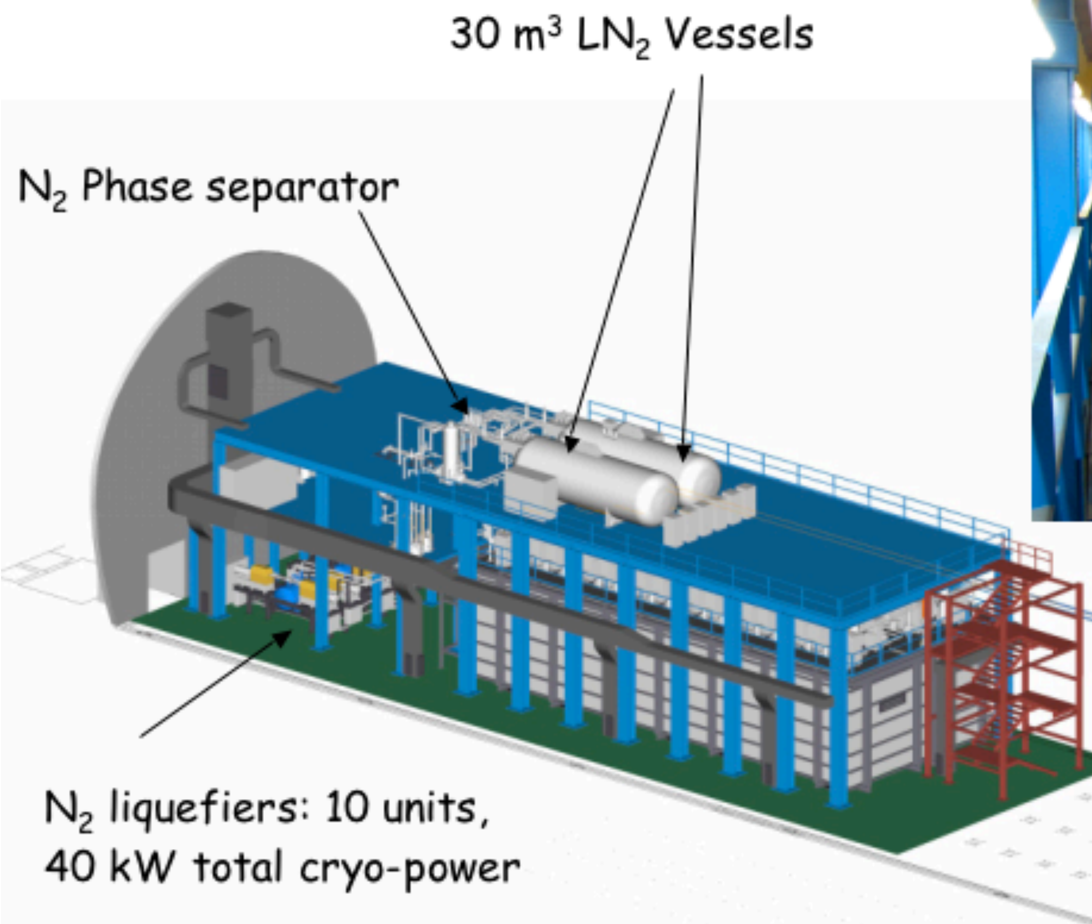
$$g = c + m$$

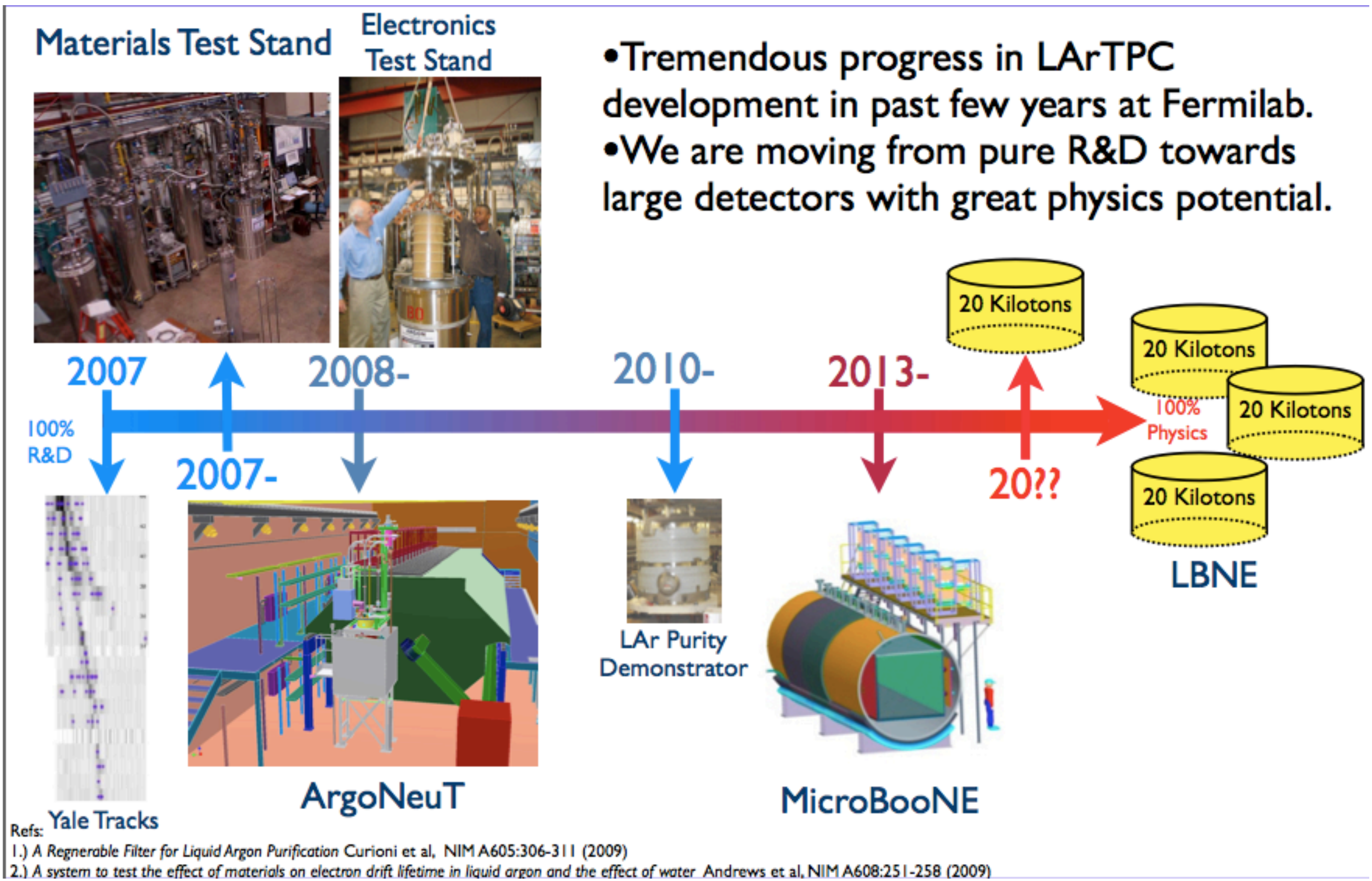
$$\rho = Th/U$$

Reference flux from Mantovani et al. 2004 hep-ph/0309013

w/ 50 kT-yr measure:
Geo-nus to ~5%
Crustal nus to ~6%
Th/U to ~20%

ICARUS T600 in LNGS Hall B





M. Soderberg, Neutrino 2010