Search for Baryon and Lepton Number Violations

International Workshop

LBNL, September 20-22, 2007

Experimental Summary

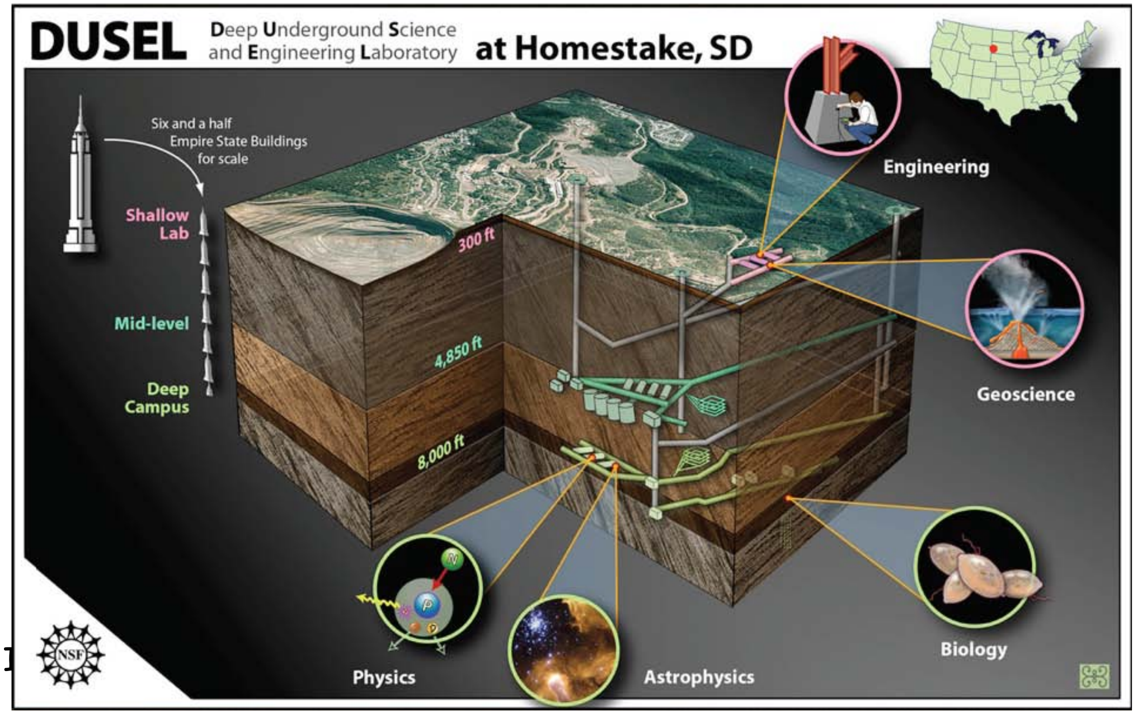
3 days of very interesting talks: I cannot possibly cover everything!

I will try to give you the flavor for a field that uses many different techniques in the quest to explore the (non)conservation of B and L:

- Huge Cherenkov detectors
- Underwater detectors
- Small(er) very low background ββ-decay detectors
- Large liquid scintillator detectors
- Nuclear reactors on top of mine shafts
- Particle accelerators experiments

…and symbiotic relationship with more: long baseline experiments, gravity studies with atomic physics techniques…

Most experiments are very good matches with DUSEL



Unlike other conservation laws that are deeply connected with symmetries of Nature

There are no fundamental reasons to require that
- **baryon number (B)**
- **lepton number (L) and**
- **lepton flavor number (LF)**

are conserved.

Hitoshi Murayama will summarize the theoretical prejudice about whether such quantum numbers "should" be conserved or not, and how their possible violation is connected with physics beyond the SM.

I will simply take the point of view that the conservations of B, L and LF are empirical facts and review the experimental data and plans for the future.

LF

We do know that LF number is not conserved in Nature

This occurs in the neutrino sector and manifests itself with Neutrino Oscillations

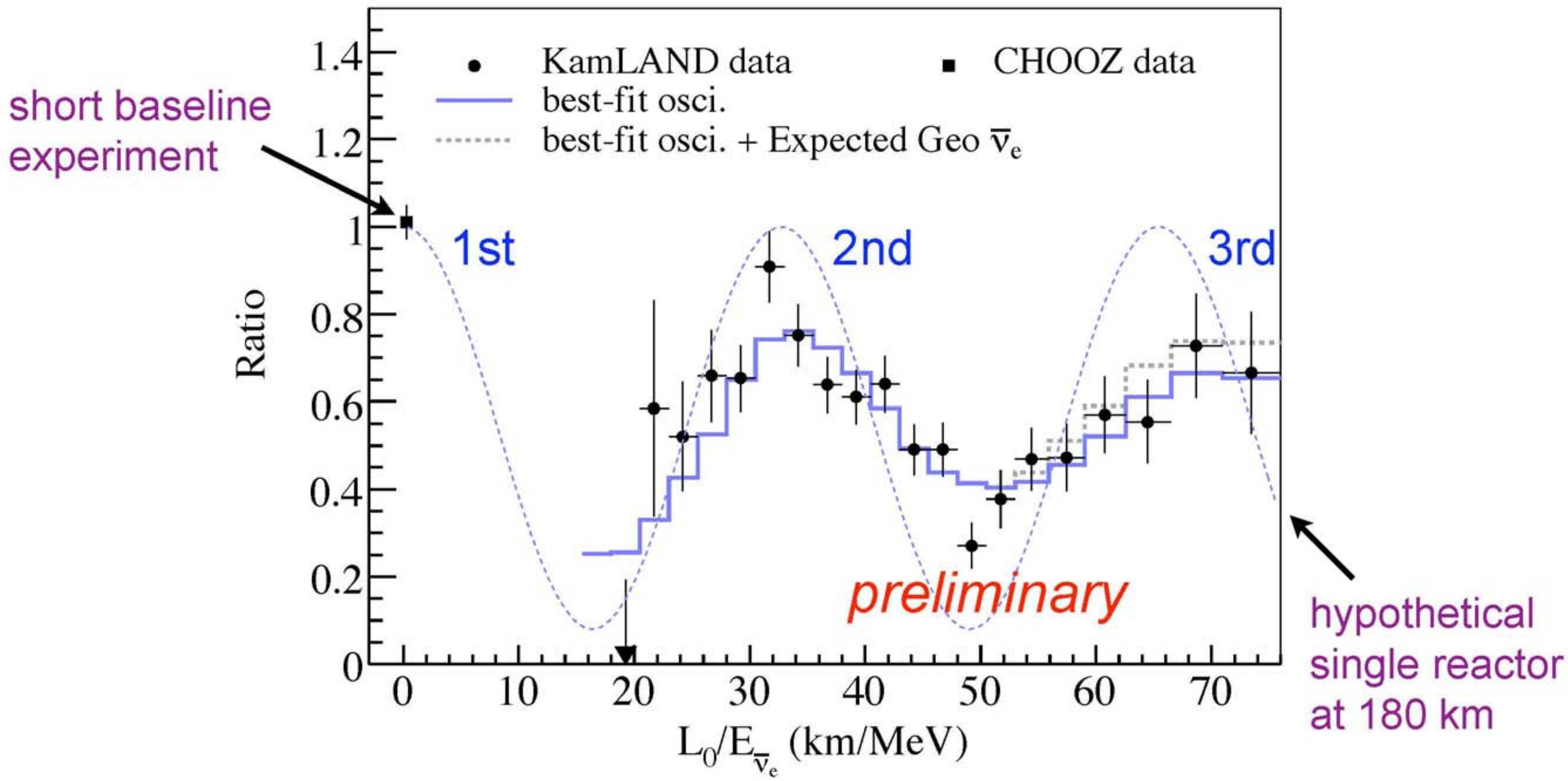
The weak interaction eigenstate $|\nu_j\rangle$ is a superposition of mass eigenstates $|\nu_j\rangle = \sum_j U_{jl} |\nu_l\rangle$

Propagation is described in terms of mass eigenstates and production/detection in terms of flavor eigenstates,

so that a LF violating "probability of transition" can be defined as

$$P(\nu_{j'} \to \nu_j, L) = \left| \sum_l U_{lj} U^*_{j'l} e^{-i(m_l^2/2E)L} \right|^2$$

The oscillatory nature of P and, hence, the fact that different flavors really turn into each other is directly shown by some of the experiments



KamLAND talk, TAUP 2007, Sendai, Japan

The knowledge of LF violation is summarized by U that was measured by a multitude of experiments

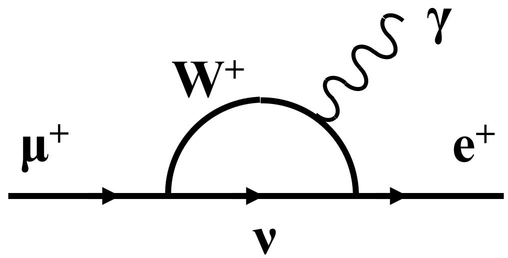
$$\mathbf{U} = \begin{pmatrix} \mathbf{U}_{e1} & \mathbf{U}_{e2} & \mathbf{U}_{e3} \\ \mathbf{U}_{\mu 1} & \mathbf{U}_{\mu 2} & \mathbf{U}_{\mu 3} \\ \mathbf{U}_{\tau 1} & \mathbf{U}_{\tau 2} & \mathbf{U}_{\tau 3} \end{pmatrix} =$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\alpha/2+i\beta} \end{pmatrix}$$

Atmospheric ν K2K Minos	Chooz/Palo Verde Off axis beam exp Future reactors	Solar ν KamLAND Future solar ν exp.
θ_{23}~45°	θ_{13}<7° @ 90%CL	θ_{12}~32°

Mixing angles are generally very large

Note that LF violation in ν oscillations implies that LF is also violated with charged lepton processes:



The branching ratio with respect to the standard LF-conserving decay scales with

$$(\Delta m_\nu^2/M_W^2)^2$$

and is hence really tiny [$\sim 10^{-48} \times (\Delta m_\nu^2(eV^2))^2$]

So searches for

-μN→eN' conversion BR<1.2×10^{11} *(PRL 83 (1999) 1521)*

goal BR<2×10^{17} ***Molzon this workshop***

or LFV in Υ-decays and τ-decays ***Iijima, Tobe, Savinov, Swain this workshop***

rely on some other LF violating new physics

Why was flavor violation in the quark sector obvious from the beginning while it took decades to achieve the same result for leptons (where the mixing is larger)?

This is basically an experimental question:

1) Neutrino masses are too small to support decays, the smoking gun for mixing in the quark sector

2) The small neutrino cross sections make it very hard to study them

For these reasons, basically unrelated to the physics of LF violation, the phenomenology of mixing is very different in the quark and lepton sector

Keep this in mind when searching for B and L violations!

B and L non-conservation classification

It is sometimes useful to classify B and L violation modes according to selection rules on B-L

Because of angular momentum conservation a baryon or lepton cannot decay into a boson

For fermion → fermion transitions, angular momentum conservation requires that

$$|\Delta(B-L)|=0,\ 2,\ \ldots$$

(spin ½ nucleon goes into 1 or 3 or … leptons)

$|\Delta(B-L)|=0$ modes may seem more "natural" (simpler), but there is no reason for this statement (ie also B-L is nothing else but an empirical conservation)

Some general statements on B-L non-conservation

In some very general sense, one can say that in stable matter
B-L = # protons + # neutrons + # electrons ≠ 0 !

On a cosmological scale it is not clear
whether B-L of the universe is 0:

- *neutral matter*
- *plasmas*
- *free electrons*
- *relic neutrinos*

the total accounting is unclear

So, while we may classify B and L violation respect to what B-L does,

we should practice equal opportunity and search for both $\Delta|B-L| = 0$ and 2

Many B-L conserving nucleon decay modes have limits from

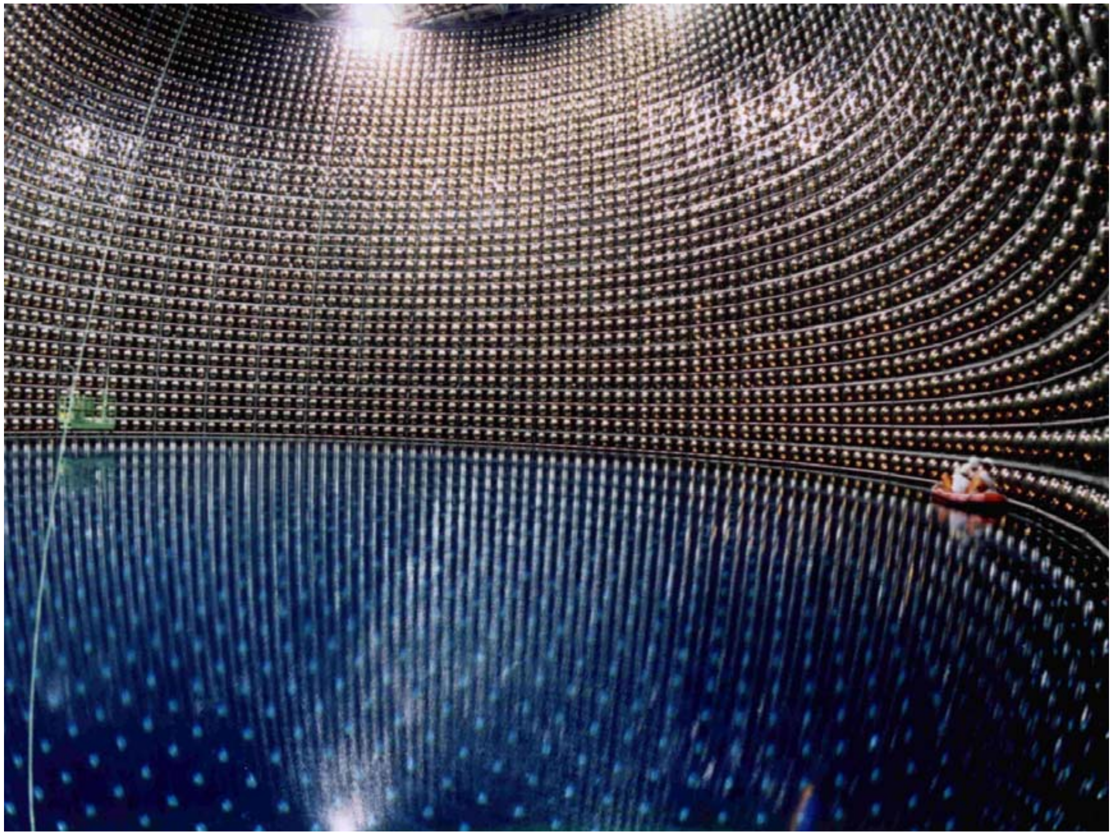
Super-K, Soudan-2, IMB3, Kamiokande, Fréjus

M. Shiozawa, SK

(p decay motivated early water Cherenkov detectors!)

Summary of Nucleon Decay Searches

mode	exposure (kt· yr)	εB_m (%)	observed event	B.G.	τ/B limit (10^{32} yrs)
$p \to e^+ + \pi^0$	141	[illegible]	[illegible]	[illegible]	84
$p \to \mu^+ + \pi^0$	141	[illegible]	[illegible]	[illegible]	67
$p \to e^+ + \eta$	92	[illegible]	[illegible]	[illegible]	23
$p \to \mu^+ + \eta$	92	[illegible]	[illegible]	[illegible]	13
$n \to \bar{\nu} + \eta$	45	[illegible]	[illegible]	[illegible]	5.6
$p \to e^+ + \rho$	92	[illegible]	[illegible]	[illegible]	5.6
$p \to e^+ + \omega$	92	[illegible]	[illegible]	[illegible]	3.8
$p \to e^+ + \gamma$	92	[illegible]	[illegible]	[illegible]	98
$p \to \mu^+ + \gamma$	92	[illegible]	[illegible]	[illegible]	82
$p \to \bar{\nu} + K^+$	92				23
$K^+ \to \nu\mu^+$ (spectrum)		[illegible]	--	--	6.4
prompt $\gamma + \mu^+$		[illegible]	[illegible]	[illegible]	10
$K^+ \to \pi^+\pi^0$		[illegible]	[illegible]	[illegible]	7.8
$n \to \bar{\nu} + K^0$	92				1.3
$K^0 \to \pi^0\pi^0$		[illegible]	[illegible]	[illegible]	1.3
$K^0 \to \pi^+\pi^-$		[illegible]	[illegible]	[illegible]	0.69
$p \to e^+ + K^0$	92				10
$K^0 \to \pi^0\pi^0$		[illegible]	[illegible]	[illegible]	8.4
$K^0 \to \pi^+\pi^-$					
2-ring		[illegible]	[illegible]	[illegible]	3.5
3-ring		[illegible]	[illegible]	[illegible]	1.6
$p \to \mu^+ + K^0$	92				13
$K^0 \to \pi^0\pi^0$		[illegible]	[illegible]	[illegible]	7.0
$K^0 \to \pi^+\pi^-$					
2-ring		[illegible]	[illegible]	[illegible]	4.4
3-ring		[illegible]	[illegible]	[illegible]	3.6



Moderate backgrounds are required

However the decay energies are large (M_p ~ 1 GeV) so that natural radioactivity is generally not a problem

An important irreducible background: atmospheric neutrino interactions (…ν oscillation via atm ν was a "by product" of p-decay detectors…)

Example: $p \rightarrow e^+\pi^0$, $\pi^0 \rightarrow \gamma\gamma$

3 low energy showers (fuzzy rings)

Efficiency ~45%
Background 0.4 events in 141 kton yr
$\tau > 8.4\times10^{33}$ yr at 90% CL

Example: $p \rightarrow \bar{\nu} K^+$
$\quad \hookrightarrow \mu^+ \nu$

1) look for fixed P=236 MeV/c μ:

background non-zero
efficiency·BR = 36%
τ > 4.2×10^{32} yr at 90% CL

2) μ + ^{15}N de-excitation γ (6.3MeV) after appropriate delay:

background 0.7 ev in 92 kton yr
efficiency·BR = 8.6%
τ > 1×10^{33} yr at 90% CL

Example: $p \rightarrow \bar{\nu} K^+$
$\quad \hookrightarrow \pi^+ \pi^0$

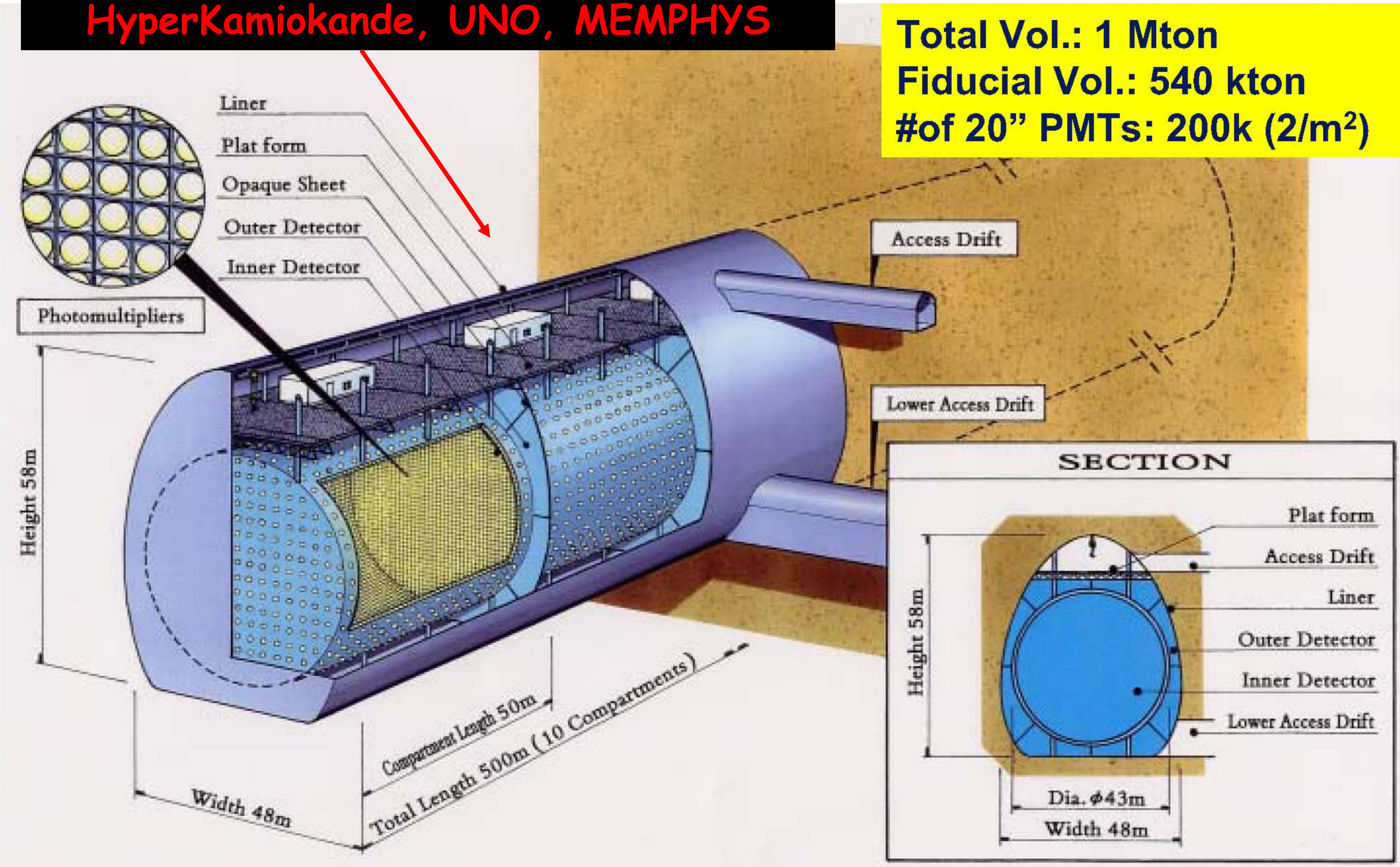
3) 3 rings (2 from γ showers, 1 from π^+):

background 0.6 ev in 92 kton yr
efficiency 6%
τ > 7.8×10^{32} yr at 90% CL

2) and 3) together give τ > 2.3×10^{33} yr at 90% CL

The next p-decay experiments proposed: HyperKamiokande, UNO, MEMPHYS

Total Vol.: 1 Mton
Fiducial Vol.: 540 kton
#of 20” PMTs: 200k (2/m^2)



Main technical challenges of a Mton scale water cherenkov detector:

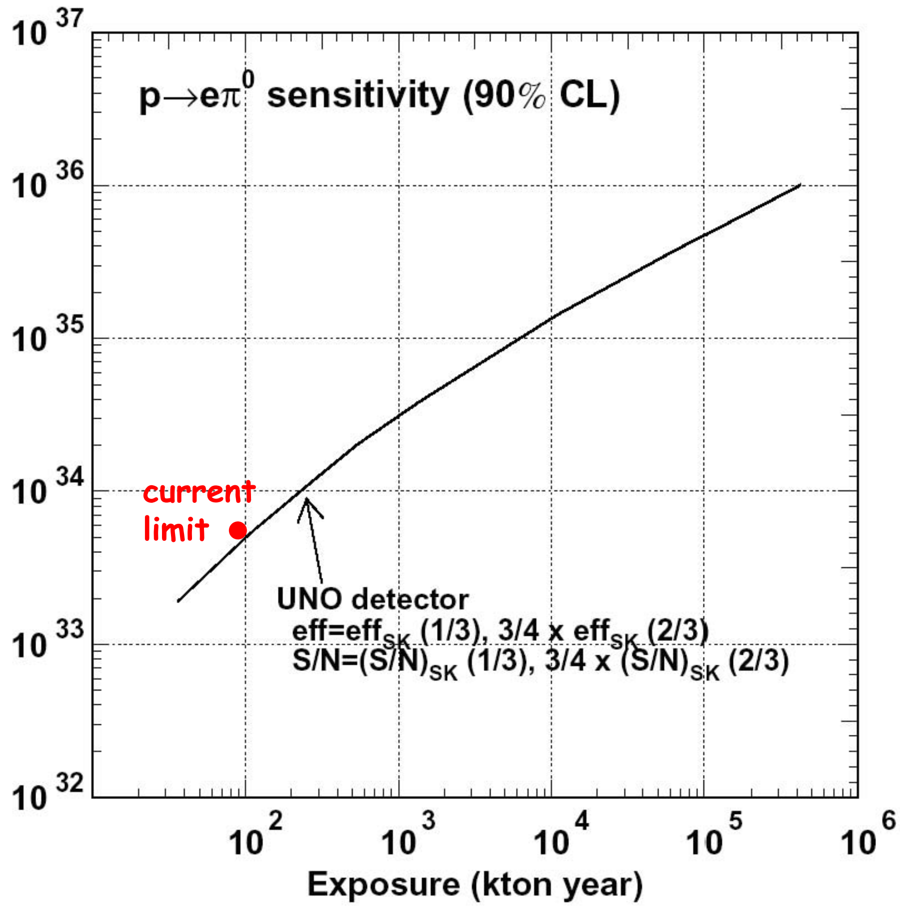
- Light attenuation length
- PMT pressure resistance
- Excavation/rock mechanics
- Cost

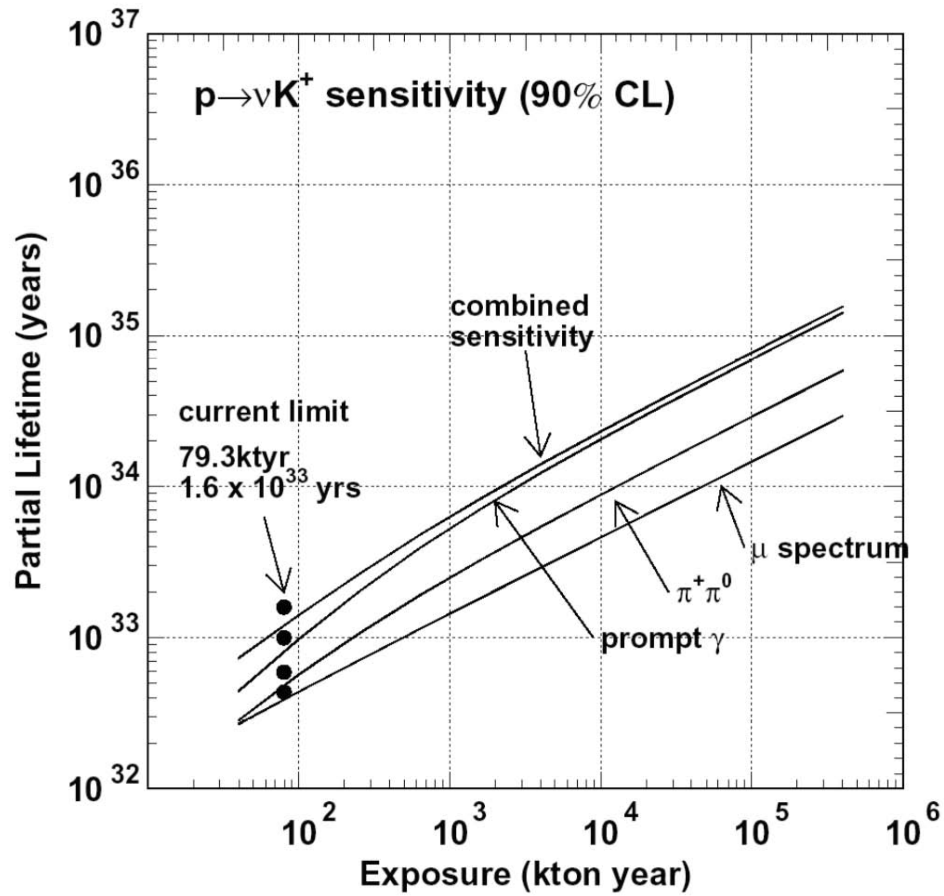
Because of limitations in rock mechanics make it like a long tunnel
Because of limited light attenuation length need internal PMT walls
If it has to be optically segmented why not make mechanically independent cavities → - Staged construction
- Versatility (some cavities could later be filled with Gd loaded H_2O some with scintillator…)

Different approach: *Sink a sphere (or set of spheres) in the ocean:*

- PMTs in pressure hulls
- Detector container only a light, water, fish barrier
- No excavation cost
- Basically trade mine engineering with ocean engineering
  → *TITAND 5Mton*

Sensitivity (UNO detector)





$\Delta(B-L)=2$ processes

- **n → $\nu\bar{\nu}\nu$**

  this actually represents Nucleon → "invisible stuff",
  so it includes Δ(B-L) = 0, 2, …
  (depending on the combination of $\bar{\nu}$ and ν)

- **n ←→ $\bar{\text{n}}$ oscillations**

  here ΔL = 0 and ΔB = 2

- ***0νββ decay***

  requires neutrinos to be 2-component Majorana particles,
  so ν ←→ $\bar{\nu}$
  ΔL = 2 and ΔB = 0

- $\tau^- \rightarrow n + \pi^-$ **and** $\Lambda^0 \rightarrow \mu^- + \pi^+$

ΔL = -1	***ΔL = 1***
ΔB = 1	***ΔB = -1***
Δ(B-L)=+2	***Δ(B-L)=-2***

$n \rightarrow \nu\nu\bar{\nu}$

E. Kolbe and Y. Kamyshkov
Phys.Rev.D67:076007, 2003

Invisible mode: signature is the de-excitation of the nucleus from where the n disappears

Example: n is in a ^{12}C nucleus

Interesting signatures have a complex sequence of particles in the final state

Mode	Br %	Hits	3-rd hit $T_{\frac{1}{2}}$, Q_{EC}
n disappearance			
$^{11}C^* \rightarrow n + {}^{10}C$ ↳ β^+	3.0	3	19.3 s, 3.65 MeV
$^{11}C^* \rightarrow n + \gamma + {}^{10}C$ ↳ β^+	2.8	3	19.3 s, 3.65 MeV
nn disappearance			
$^{10}C^* \rightarrow n + {}^{9}C$ ↳ β^+	6.2	3	0.127 s, 16.5 MeV
$^{10}C^* \rightarrow n + p + {}^{8}B$ ↳ β^+, α	6.0	3	0.77 s , 18 MeV

Double coincidence from the neutron with capture
Followed by the decay of the daughter nucleus ground state

→low background

→Large (~30%) uncertainty on Br calculation

KamLAND results for ^{12}C

mode	data sample	evts obs	meas. accidental bckgnd	τ (yr) @90% CL	Present Sensitivity (yr)
n dis	838 ton·yr	1	0.82±0.26	$>5.8\times10^{29}$	$\sim9\times10^{29}$
nn dis	1119 ton·yr	0	0.018±0.010	$>1.4\times10^{30}$	$\sim2.8\times10^{30}$

Kozlov, this workshop
PRL 96 (2006) 101802

SNO results for ^{16}O

mode	τ (yr) @90% CL
n dis	$>1.9\times10^{29}$
nn dis	$>4.9\times10^{25}$

Bergevin, this workshop
Ahmed, PRL 92 (2004) 102004

Some $|\Delta(B-L)|=2$ nucleon decay modes from PDG'06+

(B–L)≠0 modes	Limit at 90% CL	S/B	Exp. & year
$n \to e^-\pi$	>6.5×10^{31} yr	0/1.6	IMB'88
$n \to \mu^- K^+$	>5.7×10^{31} yr	0/2.8	Fréjus'91
$p \to e^-\pi^+\pi^+$	>3.0×10^{31} yr	1/2.5	Fréjus'91
$n \to \mu^-\pi^+\pi^0$	>3.4×10^{31} yr	0/0.78	Fréjus'91
$p \to e^-\pi^+K^+$	>7.5×10^{31} yr	81/127	IMB3'99
$p \to \mu^-\pi^+K^+$	>2.45×10^{32} yr	3/4	IMB3'99
$n \to \nu\gamma$	>2.8×10^{31} yr	163/145	IMB3'99
$n \to \nu\gamma\gamma$	>2.19×10^{32} yr	5/7.5	IMB3'99
$p \to \nu\nu e^+$	>1.7×10^{31} yr	152/153.7	IMB3'99
$p \to \nu\nu\mu^+$	>2.1×10^{31} yr	7/11.23	Fréjus'91
$n \to e^+e^-\nu$	>2.57×10^{32} yr	5/7.5	IMB3'99
$n \to \mu^+\mu^-\nu$	>7.9×10^{31} yr	100/145	IMB3'99
$n \to \nu\nu\bar{\nu}$	>1.9×10^{29} yr	686.8/656	SNO'04
$n \to \nu\nu\bar{\nu}$	>5.8×10^{29} yr	0/0.82	KamLAND'06

- These limits are lower than for $\Delta(B-L)=0$ modes because of sizeable backgrounds
- In the presence of background, sensitivity scales as $\sim\sqrt{kt \times yr}$
- Hard to claim a discovery in a background-dominated measurement

Table by Yu.A.Kamyshkov

$n - \bar{n}$ oscillations: bound neutrons

Example: in light water…

→ n in ^{16}O becomes $\bar{n}$, annihilates into πs

→ some πs are absorbed in the nucleus,

others emerge and provide the signature

Need to understand nuclear suppression factor R (filtering the pions before they come out) to get to the interesting physics $\tau_{free} = (\tau_{bound} / R)^{1/2}$

The largest detector, SuperK, observes 20 evts,
expect bkgd 21.3 (from atmospheric neutrinos)

$\tau_{bound}=1.77\times10^{32}$ yr at 90% CL

$R_{O16}=1\cdot10^{23}\ s^{-1}$

$\tau_{free}=2.36\times10^{8}\ s^{-1}$

Ganezer, this workshop

SNO is smaller, so the sensitivity on τ_{bound} is not as good as SK's

But

R_{D2} = 0.25 x 10^{23} s^{-1}

R_{O16} = 1×10^{23} s^{-1}

→ expect a free-n sensitivity of

τ_{free}~ 3.5 x 10^8 s

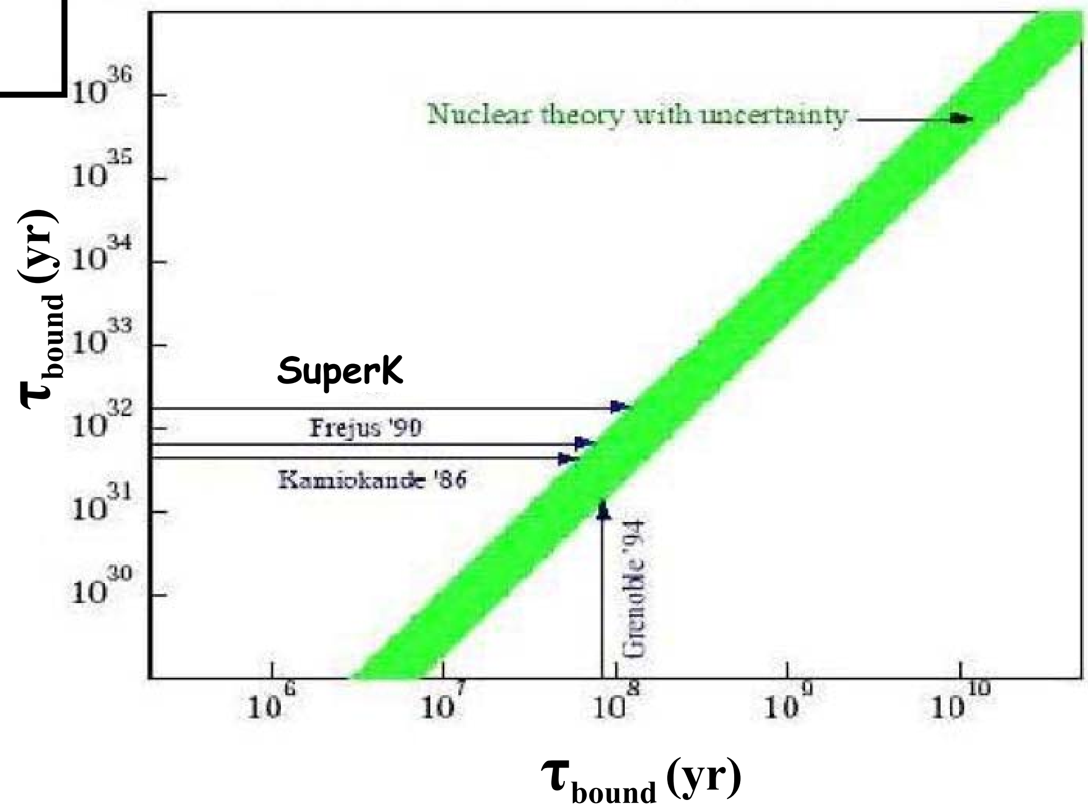
dominated by the D2 channel

Bergevin, this workshop

Also, from Soudan-II

$\tau_{bound(iron)}$= 7.2×10^{31} yr

Ultimately background limited



$n - \bar{n}$ oscillations: free neutrons

$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$ mixed $n - \bar{n}$ QM state

α is the mixing angle and contains all the new physics

The Hamiltonian of the system is

n lifetime

$$H = \begin{pmatrix} \frac{p^2}{2m} + m - \frac{i}{2\tau_n} + V_n & \alpha \\ \alpha & \frac{p^2}{2m} + m - \frac{i}{2\tau_n} + V_{\bar{n}} \end{pmatrix}$$

Same for n and $\bar{n}$

Interactions that are different for n and $\bar{n}$:
example $\Delta V_{mag} = \mu_n H$ where the neutron magnetic moment $\mu_n \sim 6\times10^{-8}$ eV/T

The probability of n – n̄ transition at time t_{osc} is

$$P_{n\bar{n}}(t_{osc}) = \frac{\alpha^2}{\alpha^2 + \left(\frac{\mu_n H}{2}\right)^2} \sin^2\left(t_{osc}\sqrt{\alpha^2 + \left(\frac{\mu_n H}{2}\right)^2} \right)$$

Having neglected the decay term $e^{-\frac{t_{osc}}{\tau_n}}$

which is reasonable if $t_{osc} << \tau_n \sim 15$ min

If magnetic fields are well shielded [H < 1nT] → $\frac{\mu_n H}{2} << \alpha$

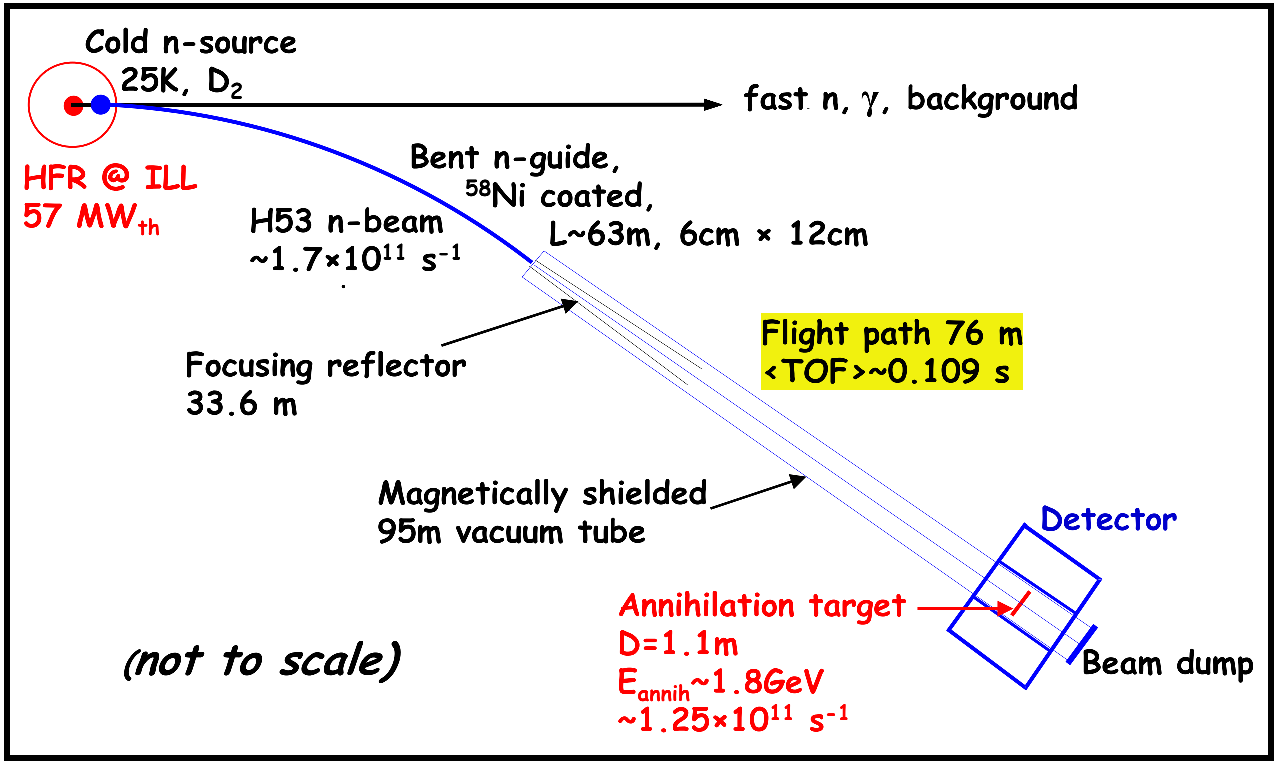
$$P_{n\bar{n}}(t_{osc}) = \sin^2(\alpha \cdot t_{osc}) \sim \alpha^2 \cdot t_{osc}^2$$

So the sensitivity of a measurement of P is proportional to $N_n \times t_{osc}^{\,2}$

N_n: number of neutrons/s

t_{osc}: n flight/storage time

Heidelberg-ILL-Padova-Pavia @ ILL 1991



No background:

1 event is a discovery !

$L \sim 90\text{m} \rightarrow t_{osc} \sim 0.109\ \text{s}$

Measure $P_{nn} < 1.606 \times 10^{-18}$

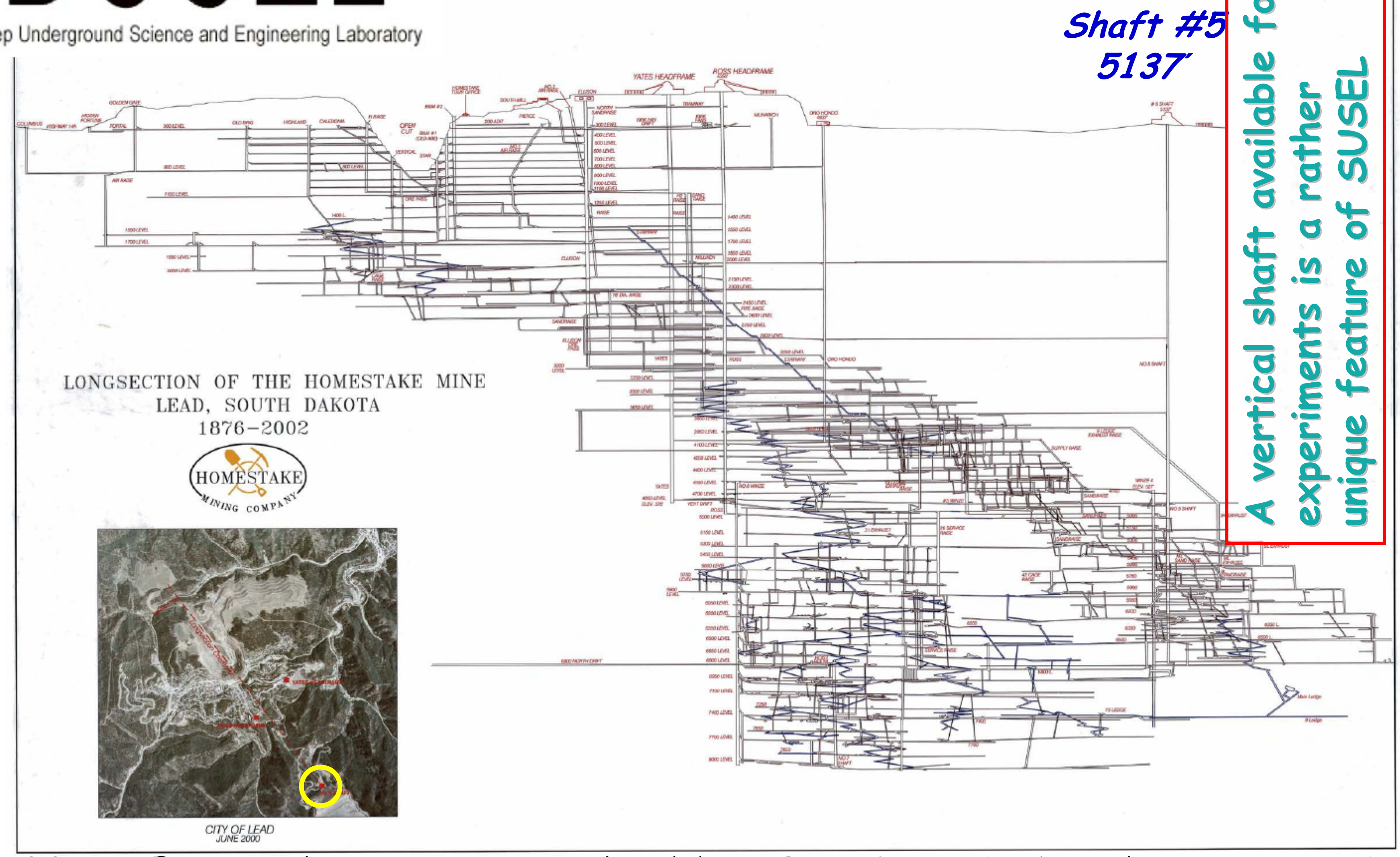
$$\tau_{n\bar{n}} \geq 8.6 \times 10^{7}\ sec$$

M.Baldo-Ceolin M. et al.,
Z. Phys., C63 (1994) 409

HOMESTAKE DUSEL

Deep Underground Science and Engineering Laboratory

Homestake can provide not only deep horizontal levels but <u>also vertical shafts for physics experiments</u>

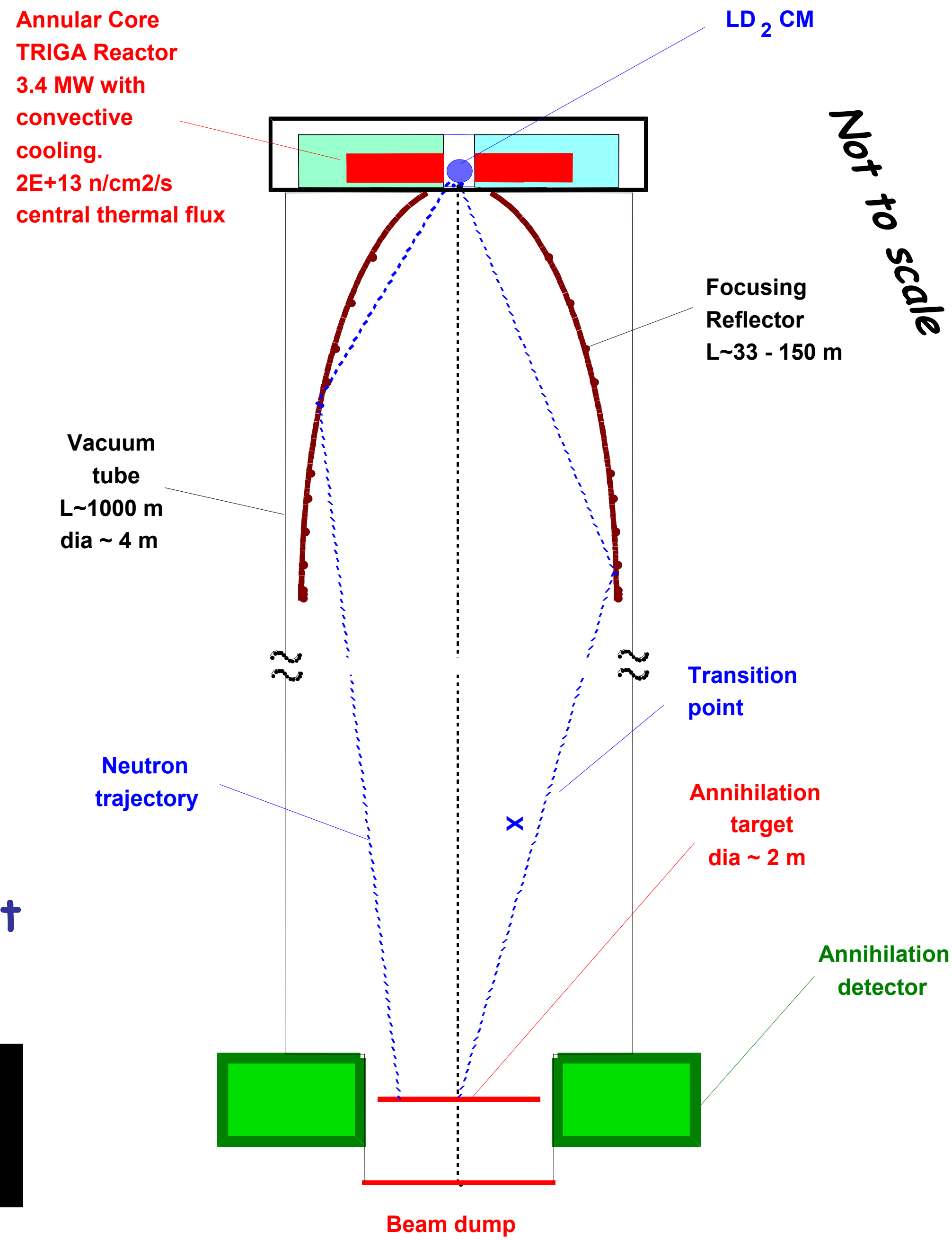


A vertical shaft available for experiments is a rather unique feature of SUSEL

n - $\bar{n}$ search experiment with vertical layout at Homestake

- Dedicated small-power reactor with cold neutron moderator
  → V_n ~ 1000 m/s
- Vertical shaft ~1000 m deep
  → No gravity-induced beam defocusing, use all ns
- Large (5m diam) vacuum tube, focusing reflector; Earth mag field compensation to ~ nT
- Detector (similar to ILL n - $\bar{n}$ detector, turned 90°) at the bottom of the shaft

Should have a sensitivity >3×10^9



The future of n-$\bar{n}$ oscillations

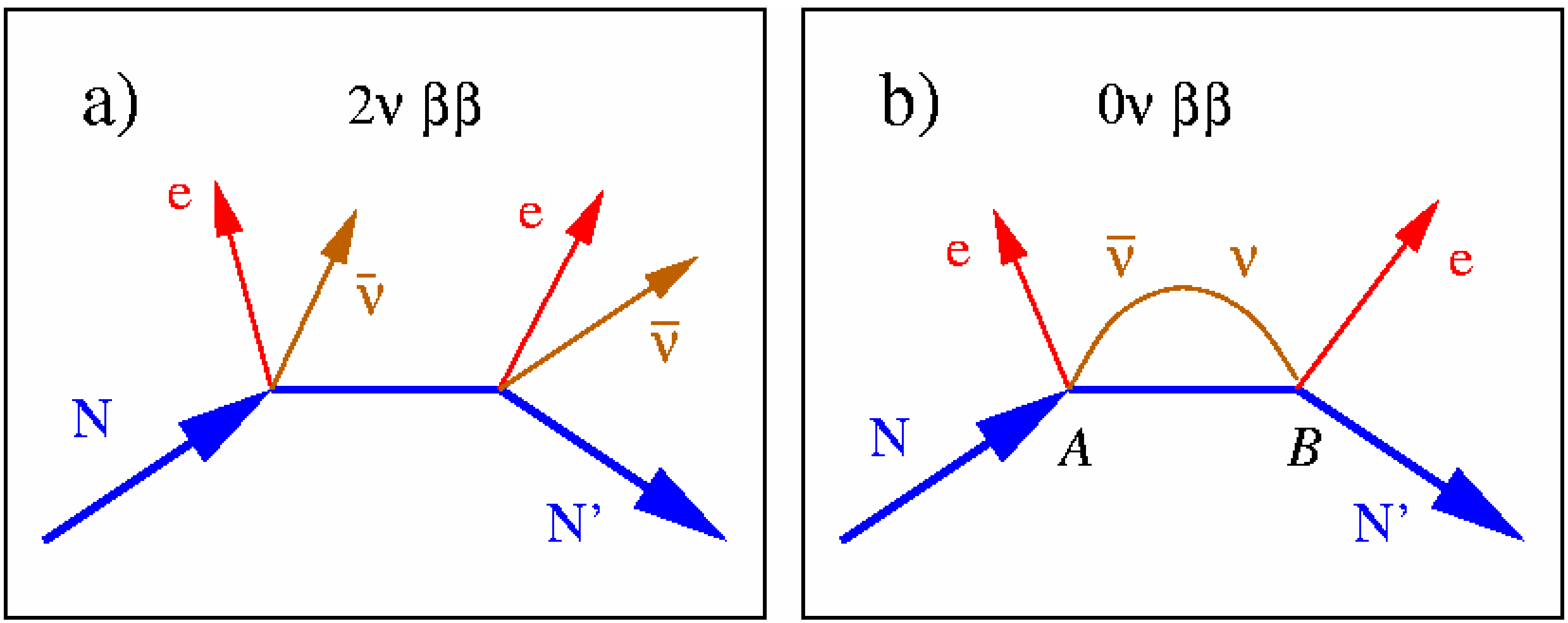
Exp.	technique	Present τ_{free} (s) 90% CL	Future Parameters	τ_{free} (s) 90% CL	Issues
ILL	Cold n horiz. beam	0.86×10^8	-	-	Finished
SK	Intranuclear ^{16}O	2.36×10^8	-	$\sqrt{(N\times t)}$	Background 0.5Mton ultimate ?
SNO	Intranuclear ^{2}D	-	-	3.5×10^8	Background No upgrade
DUSEL	Cold n vert. beam	-	3yr, Cold 3yr, VeryC	3×10^9 ?	
Bottle	UCN in a bottle	-	4yr, 3.5MW Young 200kW beam Masuda	2.7×10^8 3×10^9 ?	
Mirror n	n EDM trap	103(95%CL) 414	Knecht Serebrov	10^3 - 10^4 10^5	DUSEL?

There are two varieties of ββ decay

2ν mode:
a conventional
2nd order process
in nuclear physics

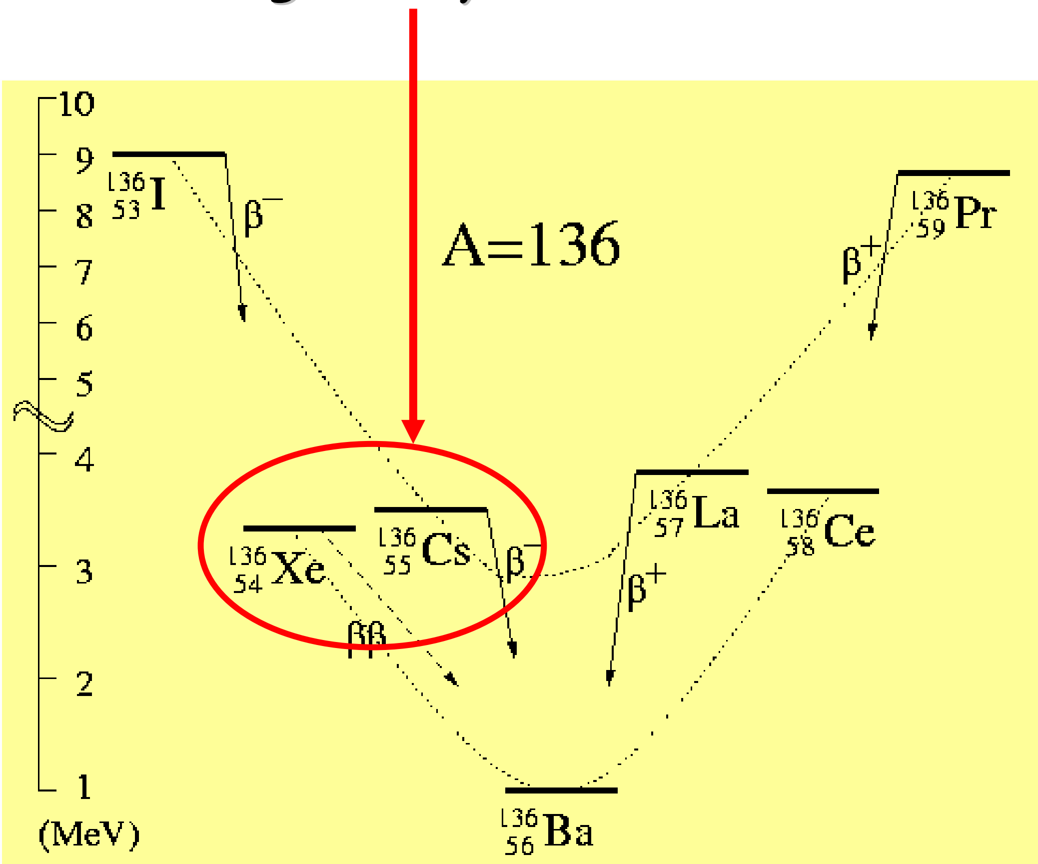
0ν mode: a hypothetical process can happen only if:
- $M_\nu \neq 0$
- $\nu = \bar{\nu}$
- $|\Delta L|=2$
- $|\Delta(B-L)|=2$

See Boris Kayser, this workshop



Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

If $0\nu\beta\beta$ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \; G^{0\nu\beta\beta}(E_0, Z) \; \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models with ~30% accuracy

$G^{0\nu\beta\beta}$ a known phasespace factor

$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \left| \sum_{i=1}^{3} U_{e,i}^2 m_i \; \varepsilon_i \right|$$

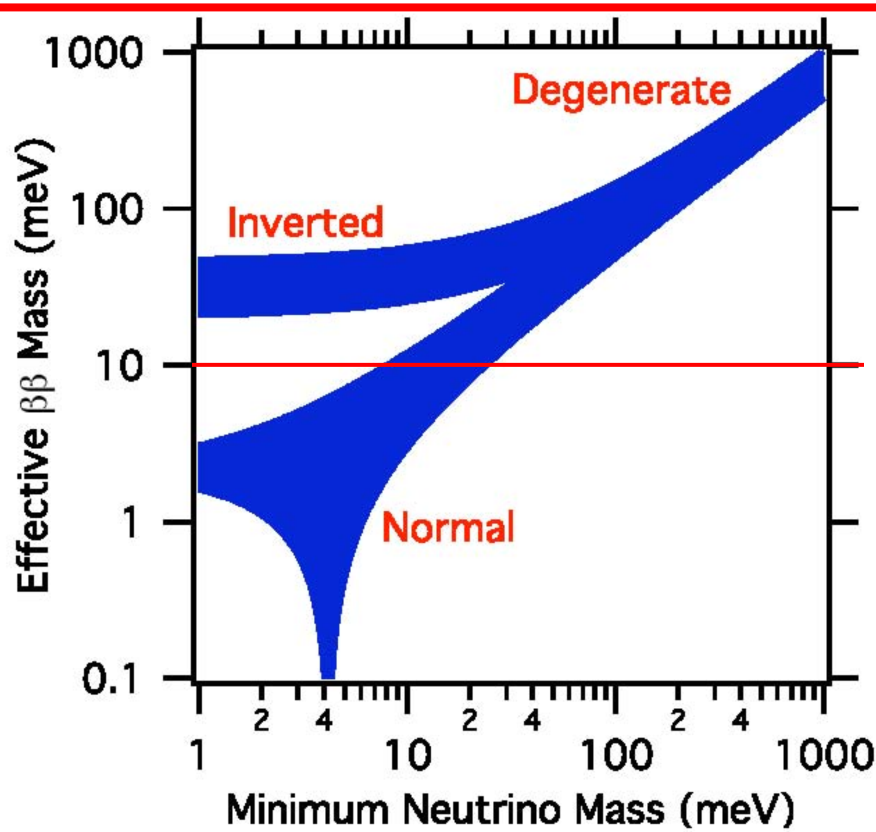
effective Majorana ν mass
($\varepsilon_i = \pm 1$ if CP is conserved)

Cancellations are possible…

In the last 10 years there has been a transition

1) From a few kg detectors to 100s or 1000s kg detectors
→ Think big: qualitative transition from cottage industry to large experiments

2) From "random shooting" to the knowledge that at least the inverted hierarchy will be tested



Approx sensitivity limit of the projects considered

From F.Avignone, S.Elliott, J.Engel arXiv:0708.1033 (2007)

ββ decay experiments are at the leading edge of "low background" techniques

- Final state ID: 1) "Geochemical": search for an abnormal abundance of (A,Z+2) in a material containing (A,Z)
  2) "Radiochemical": store in a mine some material (A,Z) and after some time try to find (A,Z+2) in it
  - \+ Very specific signature
  - \+ Large live times (particularly for 1)
  - \+ Large masses
  - \- Possible only for a few isotopes (in the case of 1)
  - \- No distinction between 0ν, 2ν or other modes
- "Real time": ionization or scintillation is detected in the decay
  a) "Homogeneous": source=detector
  b) "Heterogeneous": source≠detector
  - \+ Energy/some tracking available (can distinguish modes)
  - \+ In principle universal (b)
  - \- Many γ backgrounds can fake signature
  - \- Exposure is limited by human patience

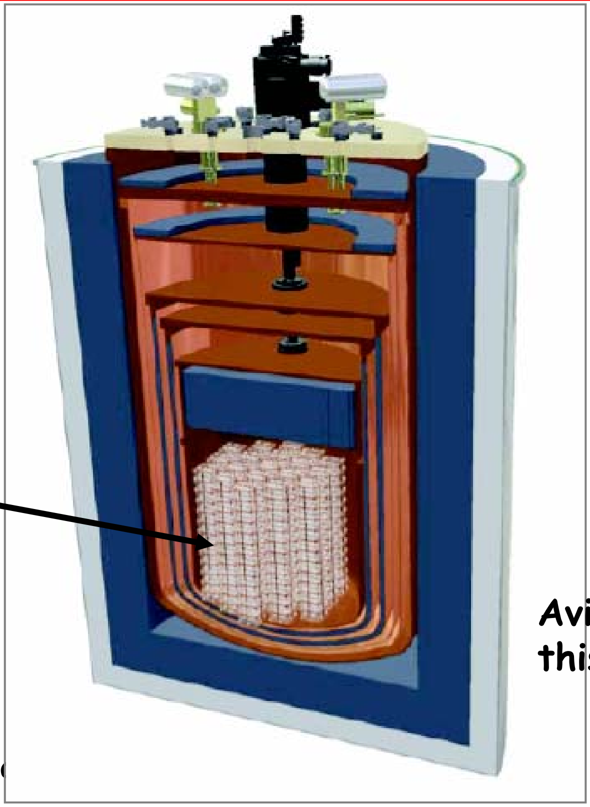
Real time is needed to discover ν masses
→ *technique of choice of modern experiment*

In all cases (but ^{130}Te) isotopic enrichment needed (on a grand scale!)
→ *one more reason to have background-free experiments!*

Mostly use homogeneous detectors

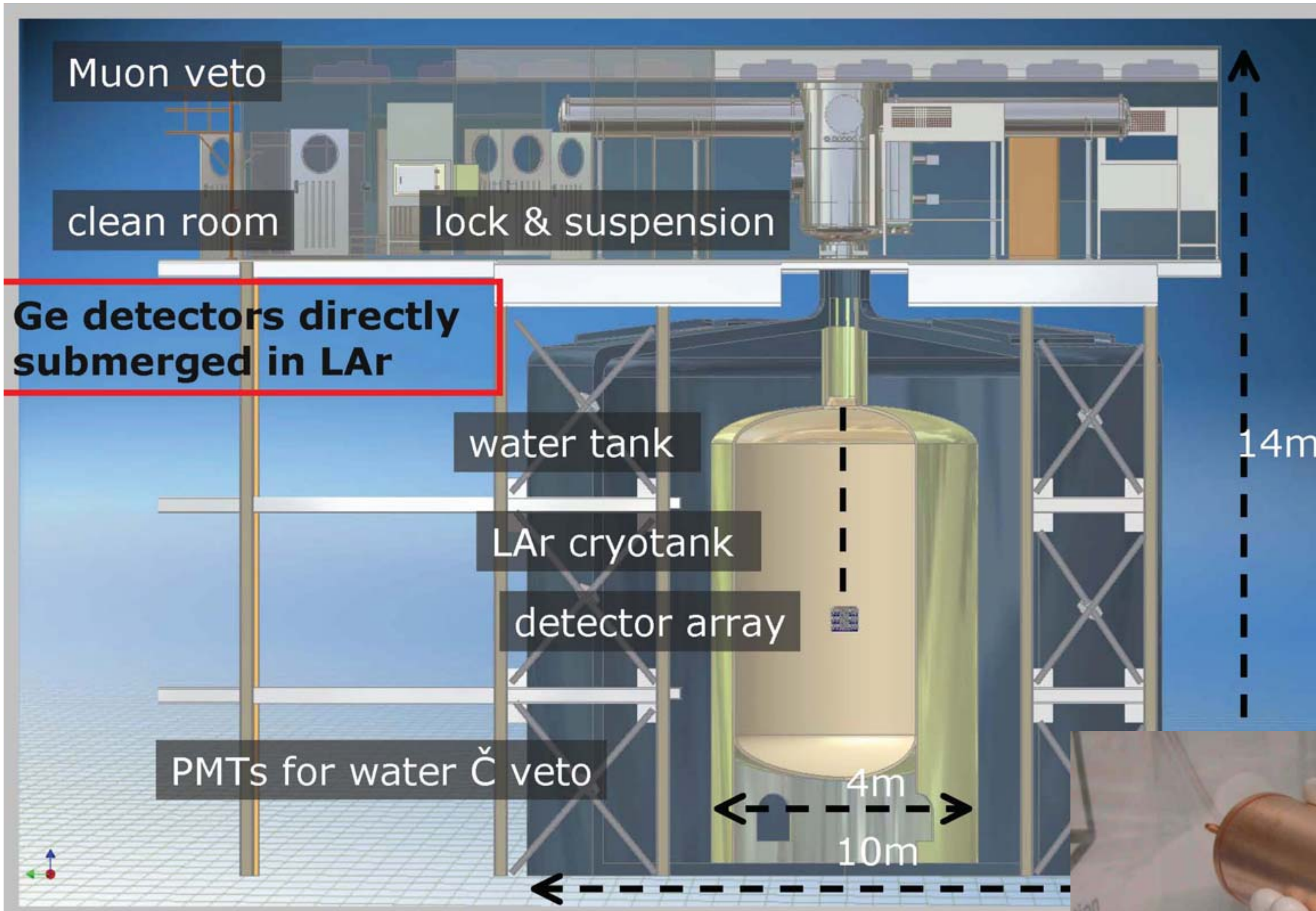
Final state ID may be also needed to reach the ultimate sensitivity

No enrichment needed:
Cuore: 741kg of ^{130}Te
in ^{nat}TeO crystals
at mK temperatures



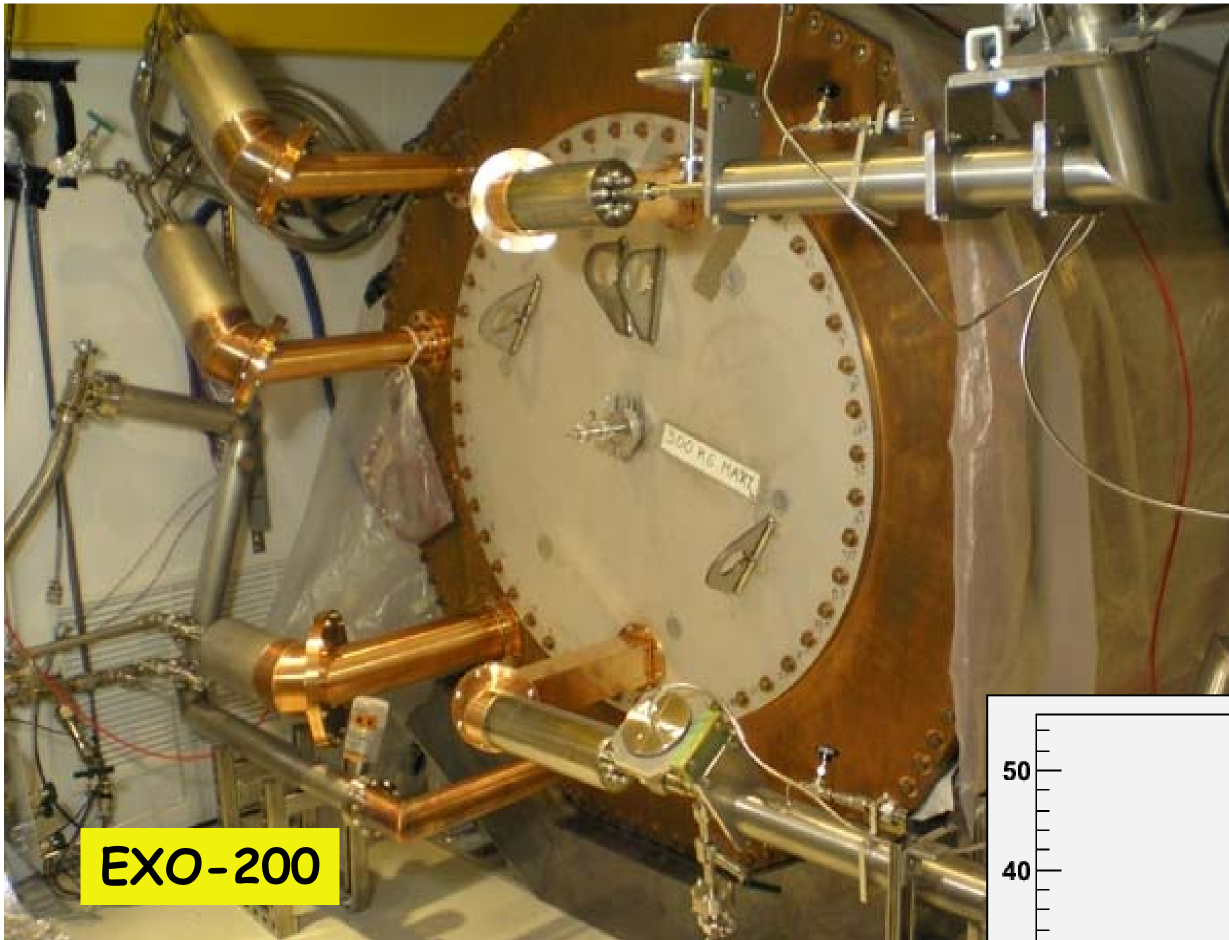
Avignone,
this workshop

The ^{76}Ge experiments



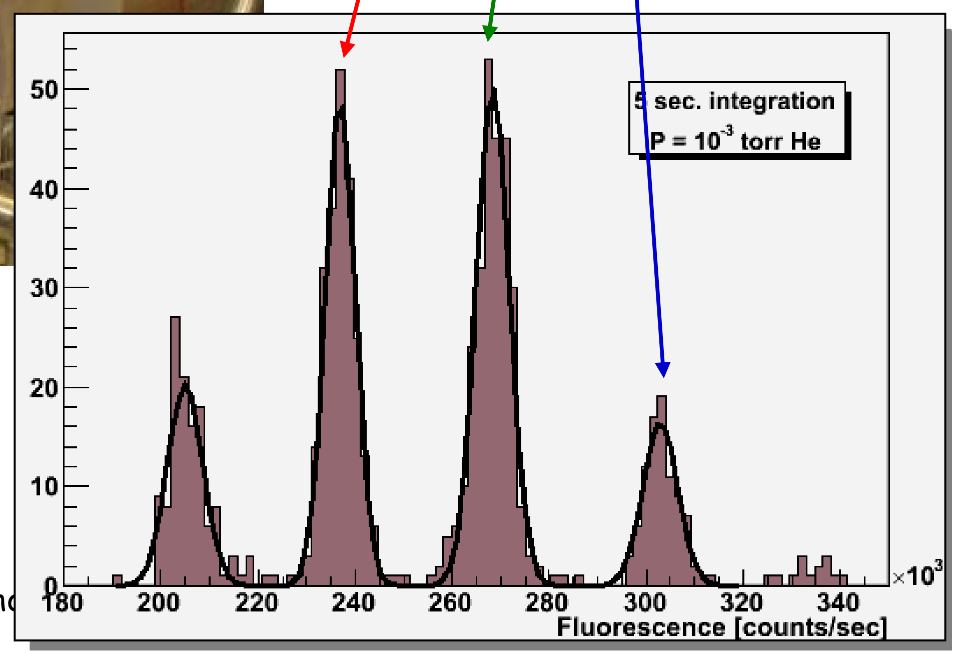
Gerda at Gran Sasso
Liu, this workshop

EXO: matching real time detection with final state tagging

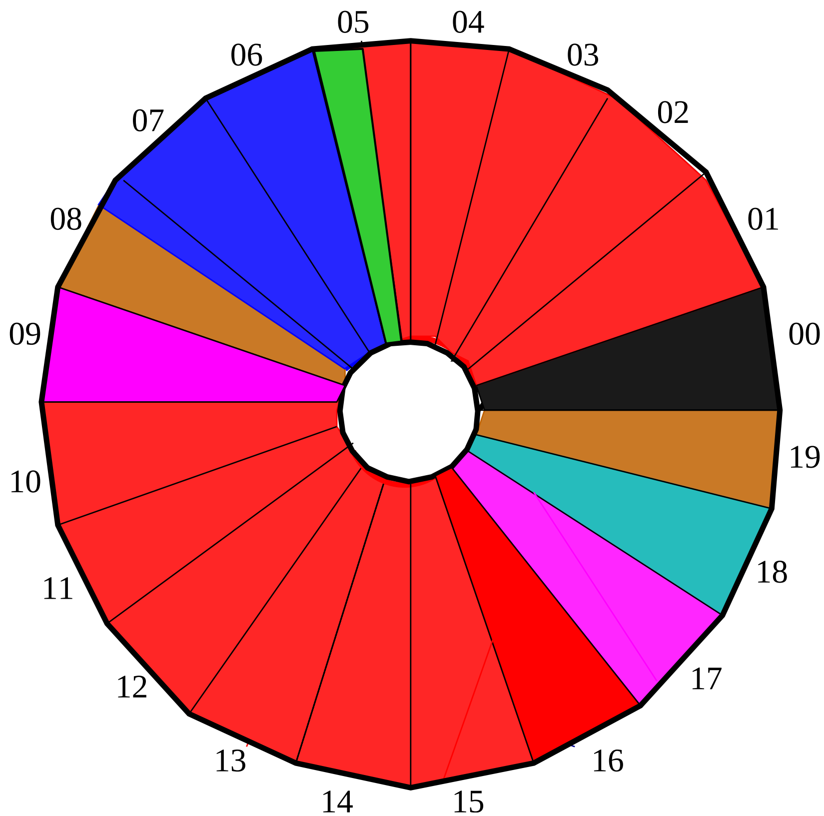


Green, this workshop

Fluorescence from
1, 2, 3 Ba-ions



NEMO, the heterogeneous detector, "a 2νββ-factory"



^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

ββ2ν measurement

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

^{nat}Te 491 g

Cu 621 g

External bkg measurement

Barabash, this workshop

Conclusion