Hunt for Red October 2: Electric Boogaloo

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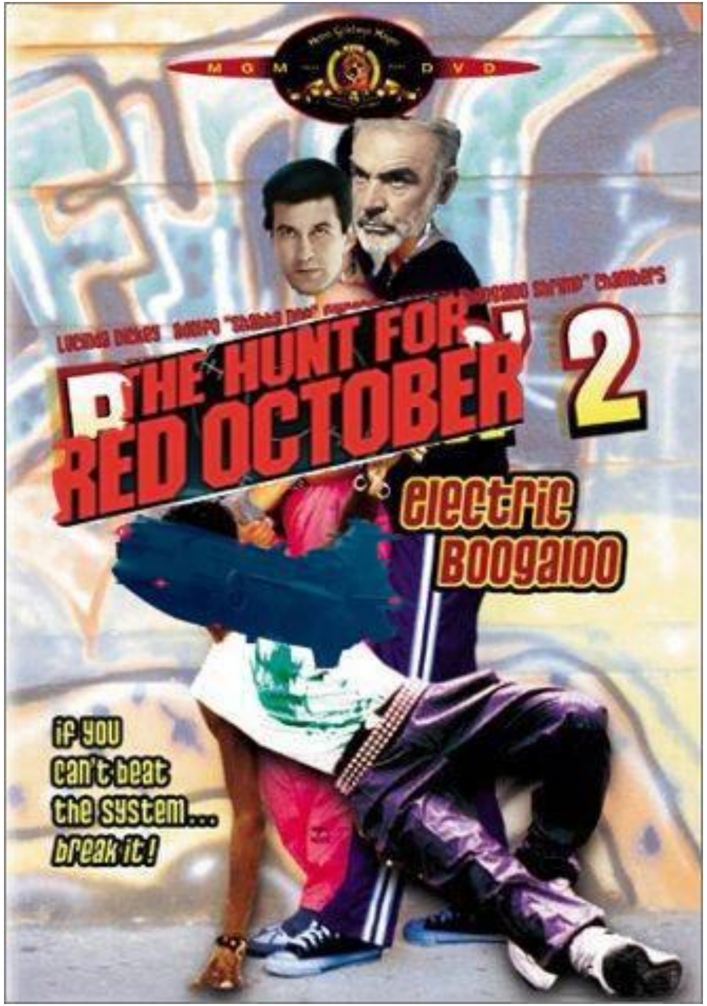
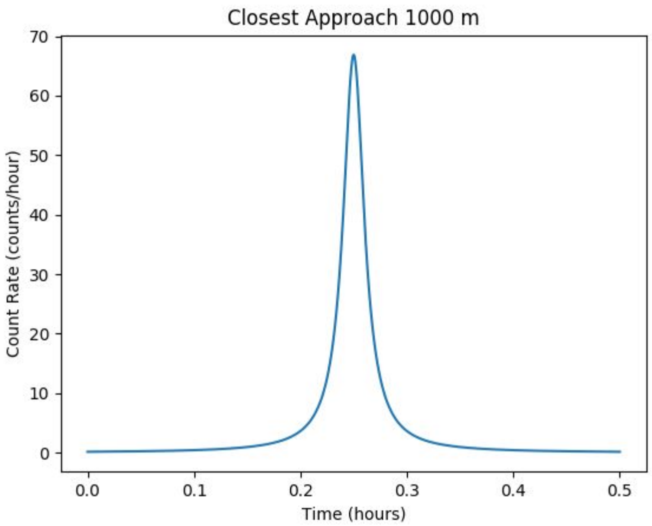


Signal Rate

- Use Double Chooz far detector to estimate signal rate:
  - 0.35 tons Gd-LS, 1050 m, 6.8 GW average power
  - 66.0 (+-1.3) expected events per day
  - Reactor flux goes like power/distance^2
  - A nuclear sub has a max power of 150 MW:

$$R(t) = \frac{(1050\,\mathrm{m})^2}{r(t)^2} \times \frac{150}{6800} \times 66\,\frac{\text{counts}}{\text{day*detector}}$$

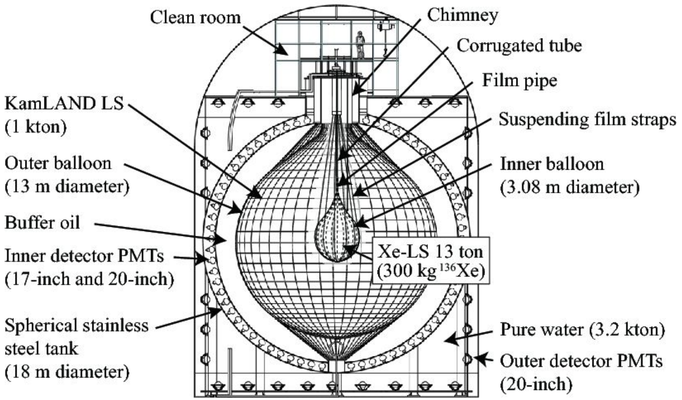
- Nuclear Sub Max Speed = 45 knots = 83.34 km/h
  - The total number of expected signal counts is shown to the right for 1000 copies of the Double Chooz detector
  - (Note that total counts goes like 1/d0)



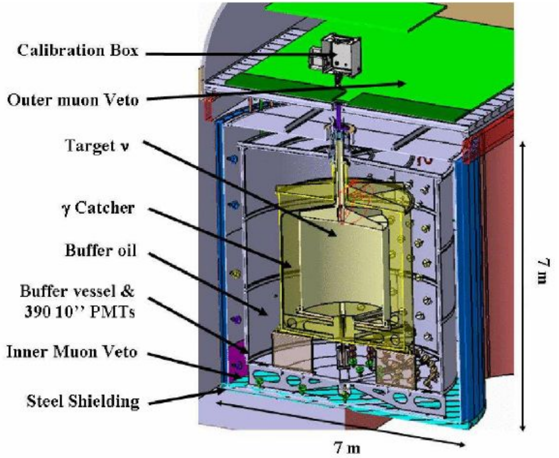
Dist d0 (m)	Counts
500	5.0
1000	2.5
2000	1.3

Background Rate

- We consider three background rates:
  - 0: Gives an idea of the best limits we could place
  - 0.07 counts/day/detector
    - Kamland reported 75.2 background events in 1154 days
    - Kamland had 2700 mwe overburden, better veto capabilities, and cleaner LS than Double Chooz
  - 7 counts/day/detector
    - Expected Double Chooz Background Rate
    - Double Chooz only had 300 mwe overburden



Search for double-beta decay of 136136Xe to excited states of 136136Ba with the KamLAND-Zen experiment - KamLAND-Zen Collaboration (Asakura, K. et al.) Nucl.Phys. A946 (2016) 171-181 arXiv:1509.03724 [hep-ex]



Mezzetto, Mauro & Schwetz-Mangold, Thomas. (2010). TOPICAL REVIEW: theta13: phenomenology, present status and prospect. Journal of Physics G-nuclear and Particle Physics - J PHYS G-NUCL PARTICLE PHYS. 37. 10.1088/0954-3899/37/10/103001.

The Strait of Gibraltar

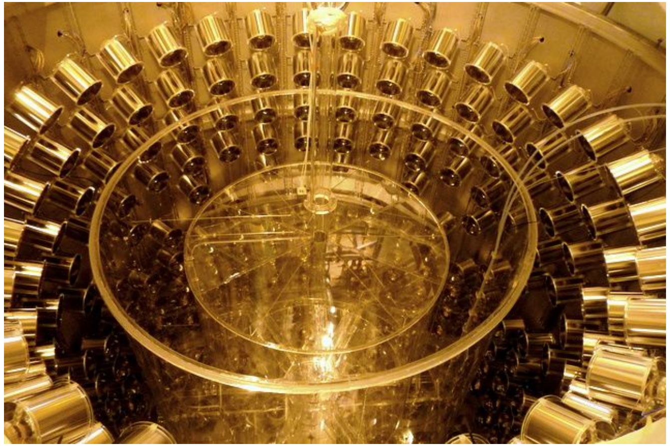
- Depth 300 to 900 m
- 14.3 km wide at narrowest point
- Place a string of detectors 300 m deep, across the narrowest part of the Strait
  - Nuclear subs have a max diving depth of 300 m -> Vertical separation ~ 150 m
  - At the point of closest approach, if the sub is on the edge of the straight, then the average value of 1/r^2 is:

$$\frac{1}{r_{0,avg}^2} = \frac{1}{14km} * \int_0^{14km} \frac{1}{x^2+(150m)^2} dx \rightarrow r_{0,avg} = 1160m$$

We can model our system as a single (very) large detector, where we need to be able to detect ships that are within 1160 m of the detector

Costs

- The Double Chooz budget was O(10^7)
- A nuclear sub costs O(10^10)
- -> We can make 1000 Double Chooz detectors for the cost of a nuclear sub



X 1000 =

Can we set up an alarm that would sound if a sub passes by?

We'll do a few tests, with different copies of a Double Chooz-like detector, with different background rates.

We assume the sub passes by at 1000 m.

Dist d0 (m)	Counts
500	5.0
1000	2.5
2000	1.3

Single Detector

Let’s first consider the case where we only have one detector.

In one case, we’ll have Double Chooz’s background rate of 7.1 counts/day

In the other, more optimistic, case, we’ll have KamLAND’s background rate of 0.065 counts/day.

Is it at all feasible to detect a nuclear sub passing by?

Single Detector

It’s pretty easy to see that the answer is a very loud

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NO!

Single Detector

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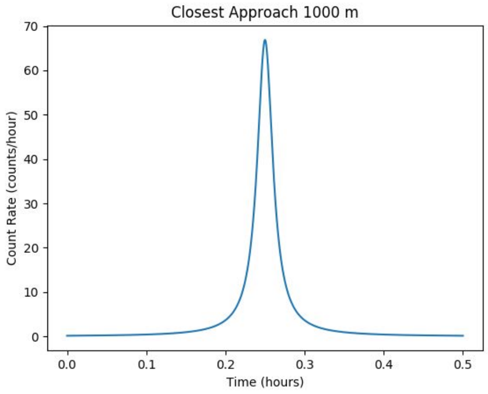
NO! >:(

Single Detector

Take the expected number of events in *1000* detectors from a passing submarine at a distance of 1000 meters. The number of counts seen would be poisson distributed with mean ν = 2.5/1000.

This mean that the detector has a $e^{2.5/1000}$ = 99.75% chance of seeing *no* neutrinos from a passing sub. Even if we had 0 background, this would be an awful detector.



Dist d0 (m)	Counts
500	5.0
1000	2.5
2000	1.3

Single Detector

So a single detector definitely wouldn’t work. How about, 10, 100?

One Thousand Detectors

Let’s skip to 1000 detectors. Let’s consider two cases again

In one case, we’ll have Double Chooz’s background rate of 7.1 counts/day

In the other, more optimistic, case, we’ll have KamLAND’s background rate of 0.065 counts/day.

In this case our expected mean signal is 2.5 counts

Dist d0 (m)	Counts
500	5.0
1000	2.5
2000	1.3

Double Chooz Background 7.1 counts/day/detector

Suppose our 1000 detector have the same rate of backgrounds as Double Chooz. A sum of n = 1000 poisson distributions with mean ν = 7.1 is equivalent to a single poisson distribution with mean nν.

So we expect a mean of 7100 background events per day.

Again, for a sub passing by, we would expect 2.5 events.

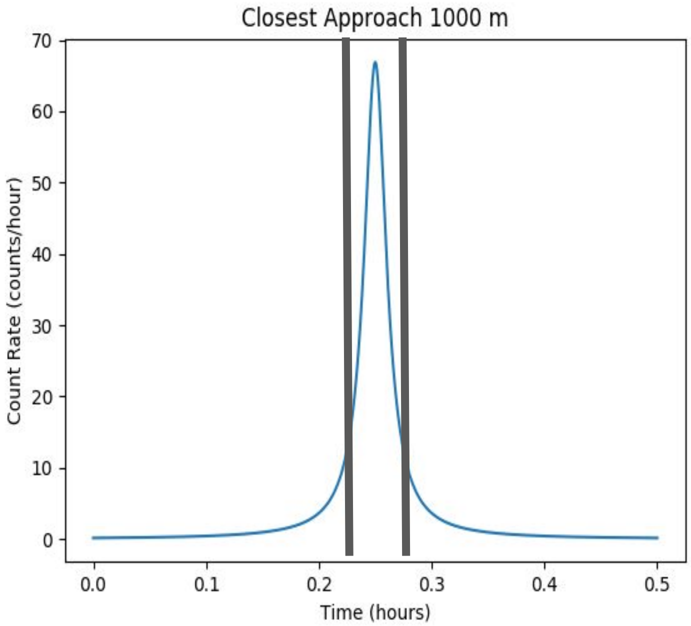
Dist d0 (m)	Counts
500	5.0
1000	2.5
2000	1.3

Double Chooz Background 7.1 counts/day/detector

Let’s cheat:

We’ll assume that all events are deposited in a 3 minute window

Suppose that a sub passing by emits 14 neutrinos that are detected in the 1000 detectors. This has a 5σ probability, so very unlikely to happen.



Double Chooz Background 7.1 counts/day/detector

If we have an average of 7100 background events per day, then we will expect 14.8 background events per 3 minutes. Finding 14+14.8 ≈ 29 events with a background of 14 has a 3σ probability.

So unlikely to happen accidentally….right?

Double Chooz Background 7.1 counts/day/detector

If we have an average of 7100 background events per day, then we will expect 14.8 background events per 3 minutes. Finding 14+14.8 ≈ 29 events with a background of 14 has a 3σ probability.

So unlikely to happen accidentally….right?

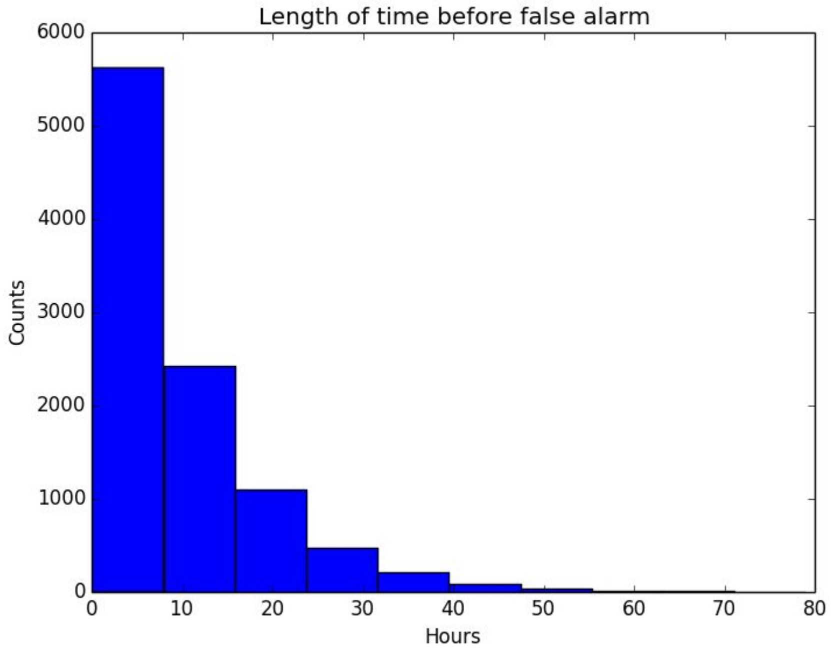
NO! >:O

Double Chooz Background 7.1 counts/day/detector

I simulated 10000 experiments where I plot how quickly it takes to raise a false alarm.

On average, more than once a day.

This assumed a very optimistic scenario of neutrino detection, so the reality is much worse.



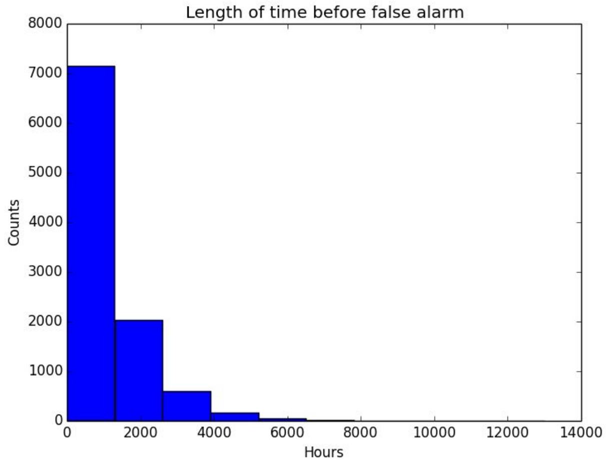
Double Chooz Background 7.1 counts/day/detector

I’d rather not accidently start a nuclear war, so we conclude that 1000 Double Chooz-like detectors does not work.

KamLAND Background 0.065 counts/day/detector

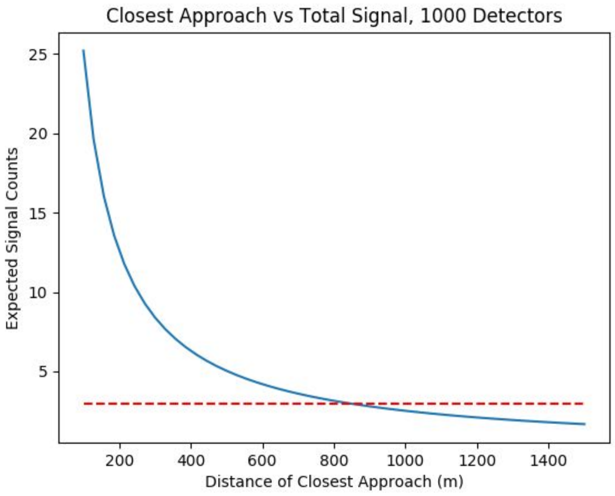
Let’s again assume 1000 detectors, but this time with KamLAND backgrounds of 0.065/counts/day/detector = 65 counts/day = 0.135 counts/3minutes.

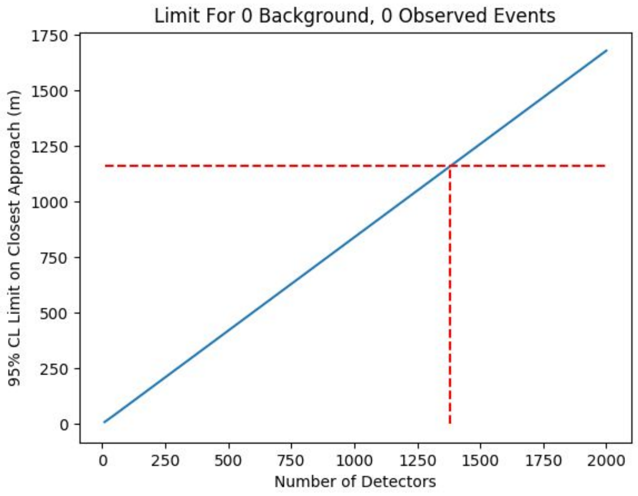
We assume that the sub emits 3 neutrinos that are detected. We follow the same procedure as before, and we find that the we would get false alarms every ~0.5 years



0 Background Limit

- If 0 counts are observed, the 95% CL limit on the signal is 3 counts

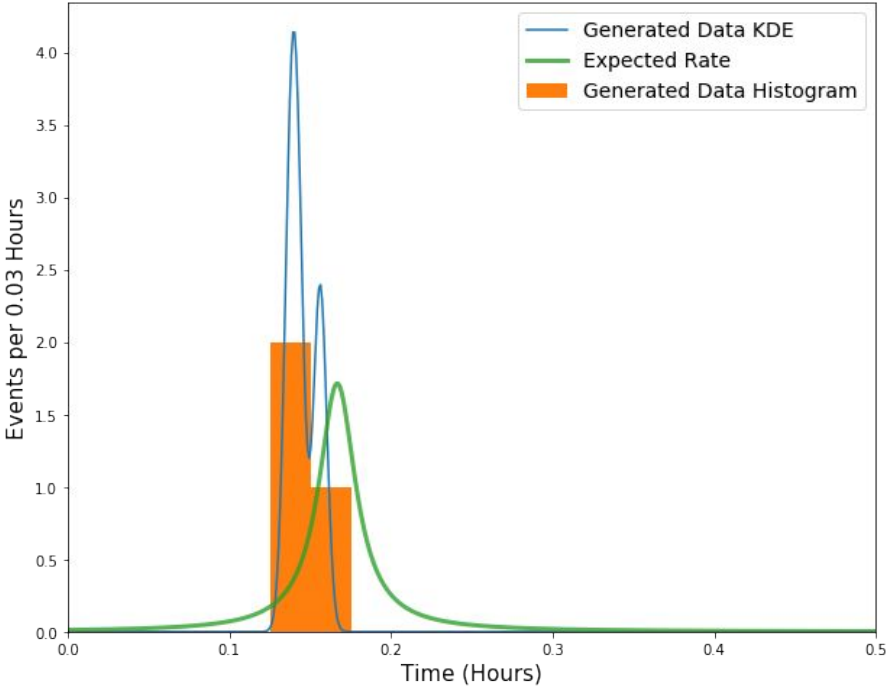




- Counts goes like N/d0 -> the d0 limit we can place increases linearly with N
- 1380 detectors are required for a 1160 m limit

Simulate the Passage of a Submarine

- Given a constant background rate and time-varying signal rate, randomly generate events within a given window of time (30 minutes)
- Example of simulation output with zero background, t0=10 min, d0=1160 m



Parameter Estimation

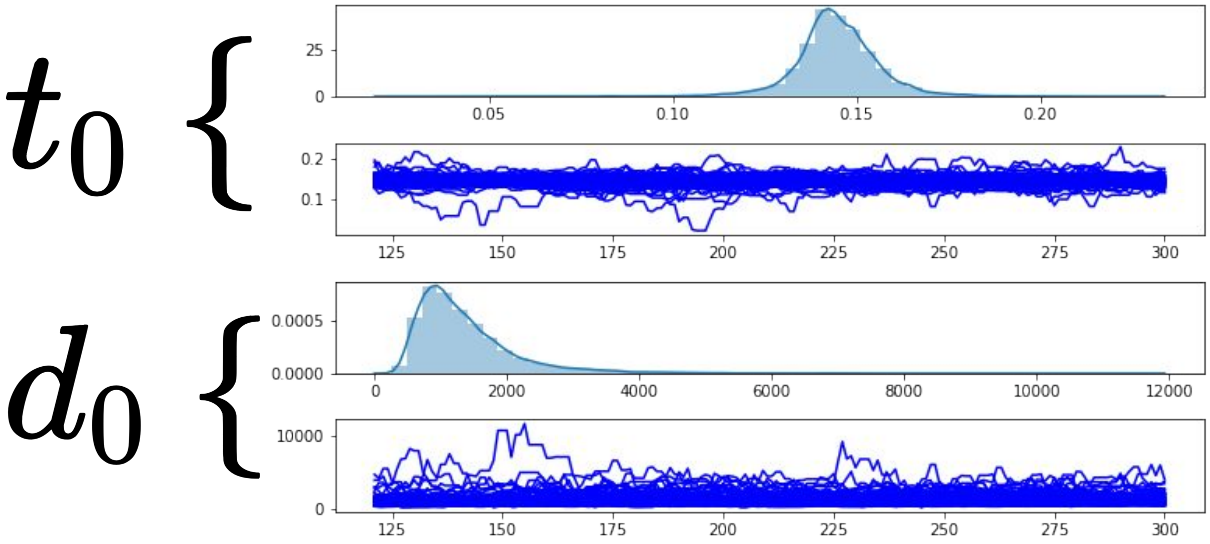
- Use Bayesian inference to do parameter estimation for t0 and d0
- Use 2-parameter likelihood function defined by

$$\mathcal{L}(t_0, d_0) = \text{Poiss}\left(N_{\text{Obs}} \mid N_{\text{Exp}}\right) \times \prod_{i=1}^{N_{\text{Obs}}} \left[\frac{R(t_i \mid t_0, d_0)}{N_{\text{Obs}}}\right]$$

- Use flat priors in t0 (defined by the time window you’re looking at/simulated) and d0 (defined by the geography of the river)
- Use MCMC to compute marginal posterior distributions for both model parameters
- Report point estimates for marginal posteriors using 16-50-84th percentile

Example Result of MCMC

Marginal posteriors and walker traces for zero background, 1380 detectors, t0=10 min, d0=1160 m:



$$t_0 : 8.6^{+0.6}_{-0.5} \text{ min}$$

$$d_0 : 1173.2^{+763.1}_{-428.9} \text{ m}$$

t0 is underestimated because we saw an upward fluctuation in the number of events before 10 min

Results of MCMC for multiple background levels

Keep t0=10 min, d0= 1000 m, vary number of detectors

	0 cts/day	0.065 cts/day	7.1 cts/day
1,000 detectors	$t_0 : 10.3^{+0.9}_{-0.9}$ min $d_0 : 1517.6^{+1894.2}_{-712.8}$ m	$t_0 : 17.5^{+8.7}_{-11.9}$ min $d_0 : 7898.7^{+4481.9}_{-4409.4}$ m	$t_0 : 9.7^{+13.2}_{-0.2}$ min $d_0 : 497.8^{+7241.8}_{-301.3}$ m
10,000 detectors	$t_0 : 9.8^{+0.2}_{-0.2}$ min $d_0 : 1051.7^{+212.6}_{-190.3}$ m	$t_0 : 9.9^{+0.5}_{-0.5}$ min $d_0 : 1246.6^{+327.8}_{-431.8}$ m	$t_0 : 10.4^{+10.5}_{-4.1}$ min $d_0 : 3330.4^{+6917.9}_{-2675.4}$ m
100,000 detectors	$t_0 : 10.1^{+0.1}_{-0.1}$ min $d_0 : 1095.6^{+61.9}_{-60.8}$ m	$t_0 : 10.1^{+0.1}_{-0.1}$ min $d_0 : 1047.0^{+61.7}_{-52.8}$ m	$t_0 : 10.6^{+11.1}_{-2.4}$ min $d_0 : 5325.1^{+6169.1}_{-3981.0}$ m

Very good at estimating t0 when backgrounds are low. Uneven errors in high background column due to prior in t0 from 0 to 30 min.

d0 estimation improves with added detectors, except for with high background rates

Caution! These parameter estimations are derived from single simulations, each of which is a random variable. To account for statistical uncertainties, many simulations would need to be done. Large detector volumes -> better statistics -> single simulation is more reliable estimate for parameter estimation performance

Thanks for listening :D

Backup Slides

TABLE I: Estimated backgrounds for $\overline{\nu}_e$ in the energy range between $0.9\ \mathrm{MeV}$ and $8.5\ \mathrm{MeV}$ after event selection cuts.

Background		Period 1 (1486 days)	Period 2 (1154 days)	Period 3 (351 days)	All Periods (2991 days)
1	Accidental	76.1 ± 0.1	44.7 ± 0.1	4.7 ± 0.1	125.5 ± 0.1
2	^{9}Li/^{8}He	17.9 ± 1.4	11.2 ± 1.1	2.5 ± 0.5	31.6 ± 1.9
3	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}_{\mathrm{g.s.}}$, elastic scattering	160.4 ± 16.4	16.5 ± 3.8	2.3 ± 1.0	179.0 ± 21.1
3	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}_{\mathrm{g.s.}}$, $^{12}\mathrm{C}(n, n')^{12}\mathrm{C}^{*}$ (4.4 MeV γ)	6.9 ± 0.7	0.7 ± 0.2	0.10 ± 0.04	7.7 ± 0.9
4	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}^{*}$, 1st e.s. (6.05 MeV $e^{+}e^{-}$)	14.6 ± 2.9	1.7 ± 0.5	0.21 ± 0.09	16.5 ± 3.5
4	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}^{*}$, 2nd e.s. (6.13 MeV γ)	3.4 ± 0.7	0.4 ± 0.1	0.05 ± 0.02	3.9 ± 0.8
5	Fast neutron and atmospheric neutrino	< 7.7	< 5.9	< 1.7	< 15.3
Total		279.2 ± 22.1	75.2 ± 7.6	9.9 ± 2.1	364.1 ± 30.5

Total Signal Counts as a Function of Time

$$R(t) = \frac{(1050\,\mathrm{m})^2}{r(t)^2} \times \frac{150}{6800} \times 66\,\frac{\text{counts}}{\text{day*detector}} \qquad r(t) = \sqrt{d_0^2 + (v(t-t_0))^2}$$

$$\text{Counts} = \int_{-\infty}^{\infty} R(t)dt = \int_{-\infty}^{\infty} \frac{1.6\times10^6\,\text{m\^{}2 counts per day per detector}}{\sqrt{d_0^2+(v(t-t_0)^2}}$$

$$= \frac{1.6\times10^6\ \text{m\^{}2 counts per day per detector}}{vd_0}\tan^{-1}\ \frac{v(t-t_0)}{d_0}\Big|_{-\infty}^{\infty}$$

$$= \pi \times 1.6 \times 10^6\ \text{m\^{}2 counts per day per detector}\ \frac{1}{vd_0}$$

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v=83.5 km/hr, d0=1000 m, 10,000 Detectors -> 25 Counts

Example of Simulation Results for higher counts

Background: 7.1 events/day
d0 = 500 m, t0 = 10 min, 10,000 detectors

$$N_{\text{Exp}} = 1530$$

$$N_{\text{Obs}} = 1527$$