Design Considerations for a θ_{13} Reactor Neutrino Experiment with Multiple Detectors

Karsten M. Heeger

Lawrence Berkeley National Laboratory

Issues of Interest

Baseline

Detector Locations

Detector Size and Volume

Detector Shape

Detector Target and Detection Method

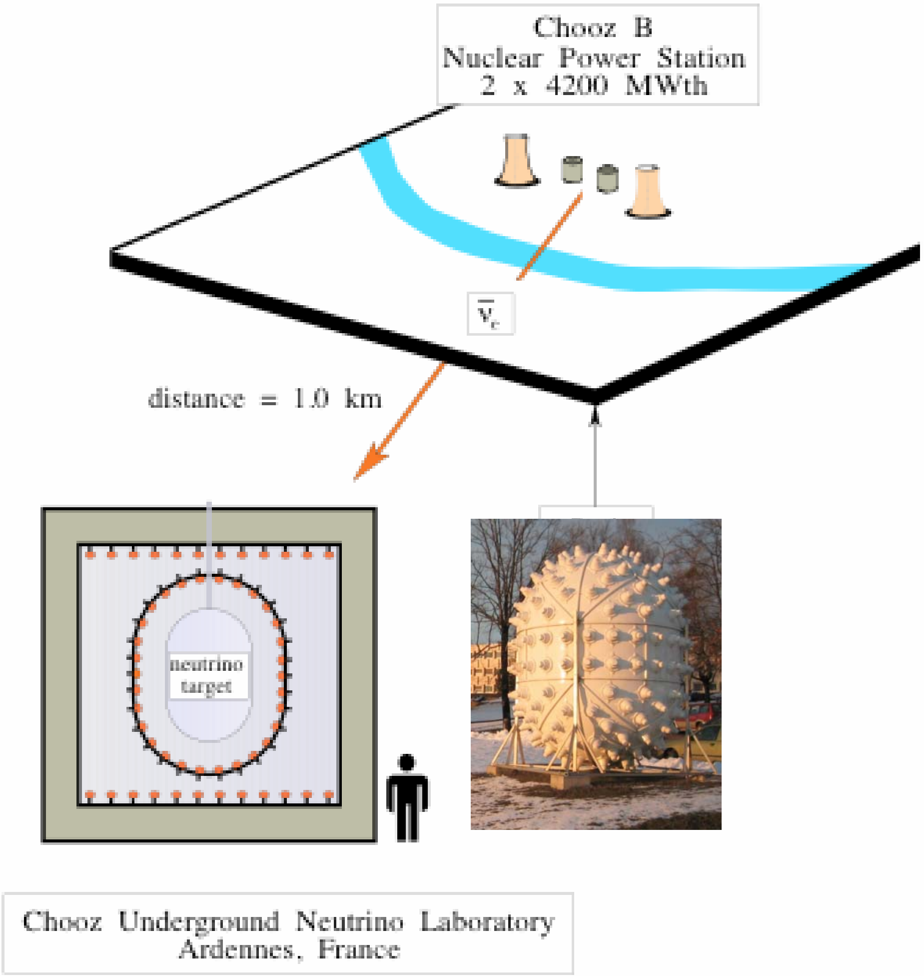
Depth and Overburden

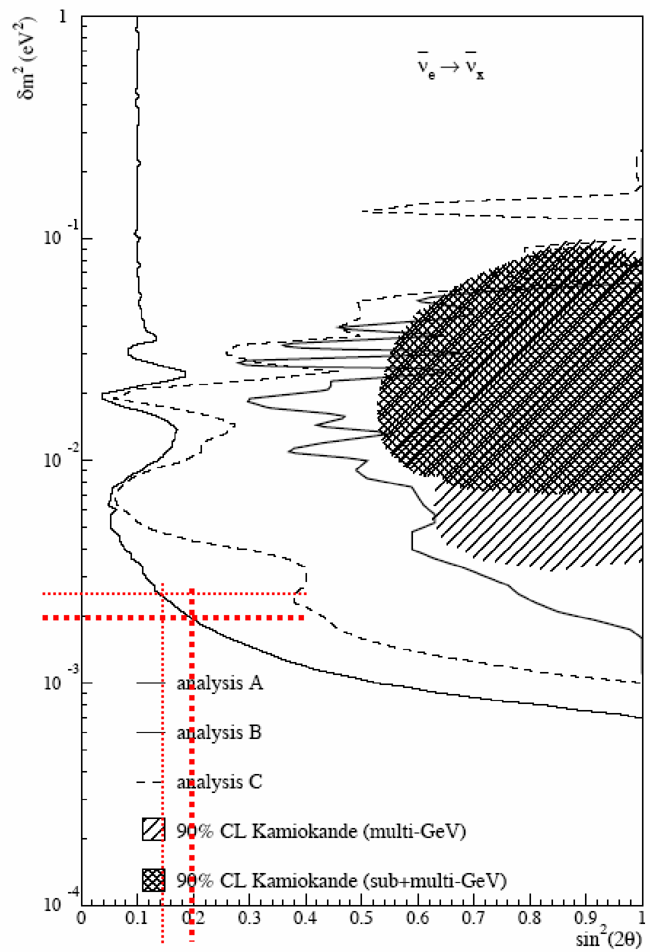
Muon Veto and Effficiency

Calibrations

Current Knowledge of θ_{13} from Reactors

Reactor anti-neutrino measurement at 1 km at Chooz + Palo Verde: $\overline{\nu}_e \rightarrow \overline{\nu}_x$





M. Appollonio, hep-ex/0301017

Chooz

Systematics

Table 10. Contributions to the overall systematic uncertainty on the absolute normalization factor.

parameter	relative error (%)
reaction cross section	1.9% *theor.*
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%

kinetic energy spectrum	2.1%
detector response	1.7%
total	2.7%

Ref: Apollonio et al., hep-ex/0301017

neutron capture:

lowest efficiency, largest relative error

Table 6. Summary of the neutrino detection efficiencies.

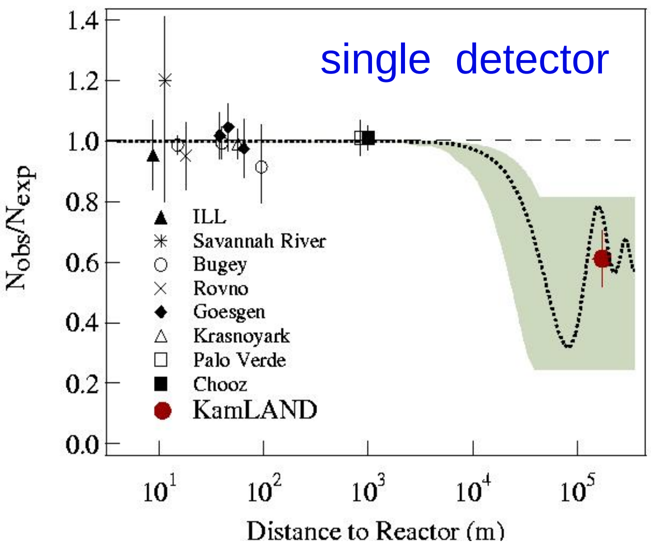
selection	$\epsilon(\%)$	rel. error (%)
positron energy*	97.8	0.8
positron-geode distance	99.9	0.1
neutron capture	84.6	1.0
capture energy containment	94.6	0.4
neutron-geode distance	99.5	0.1
neutron delay	93.7	0.4
positron-neutron distance	98.4	0.3
neutron multiplicity*	97.4	0.5
combined*	69.8	1.5

*average values

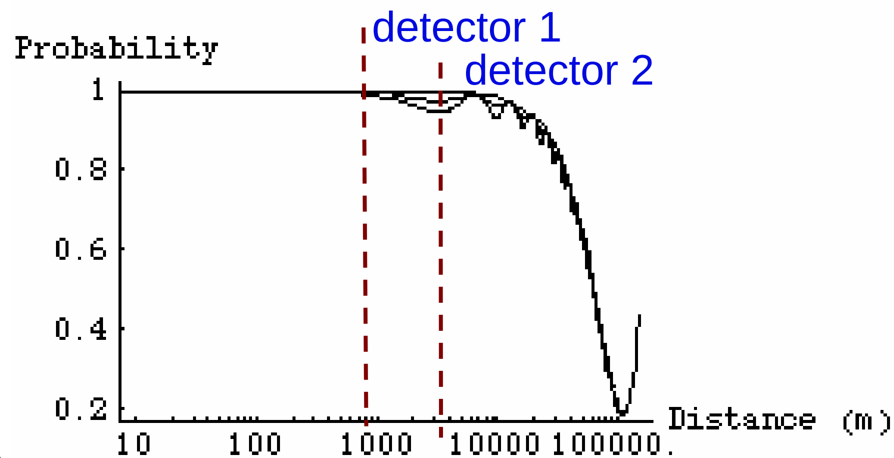
Absolute measurements are difficult!

Reactor Neutrino Measurement of θ_{13}

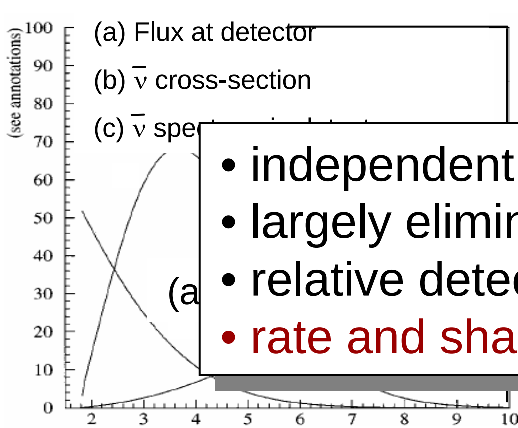
Present Reactor Experiments



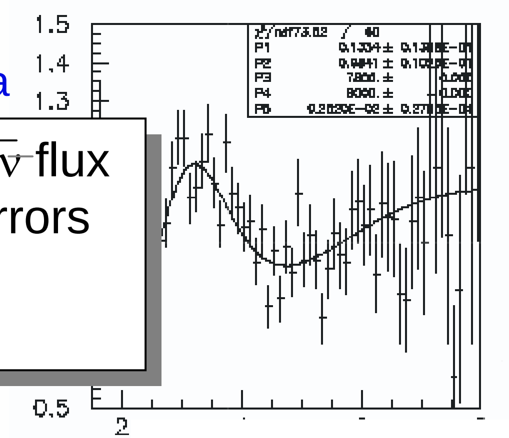
Future θ_{13} Reactor Experiment



Absolute Flux and Spectrum



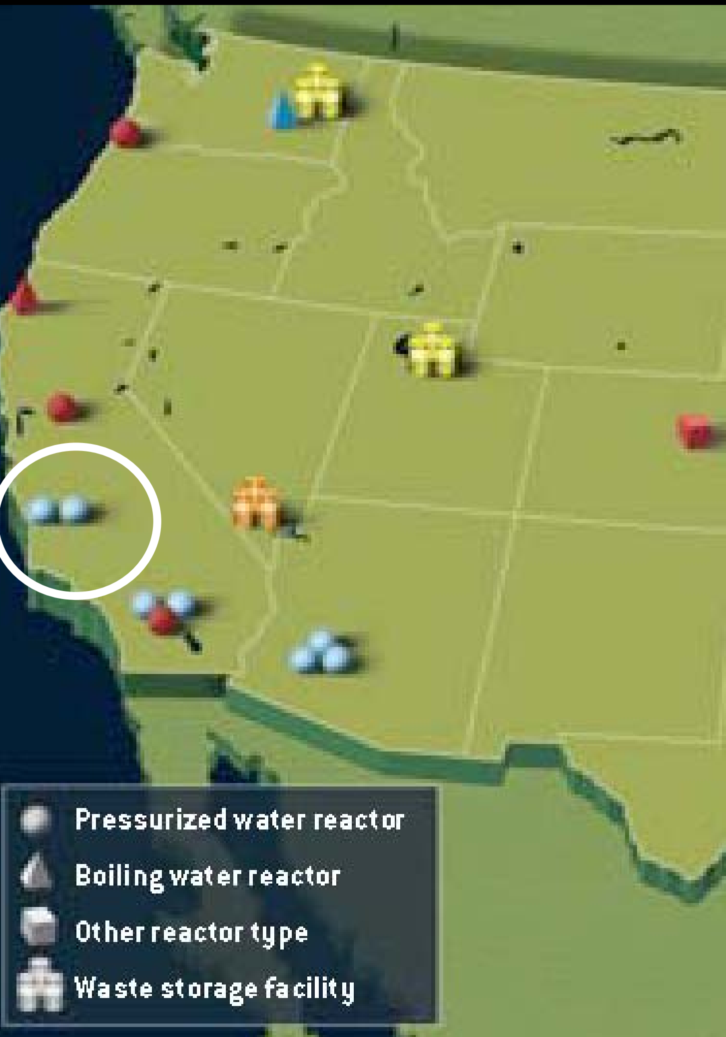
Ratio of Spectra

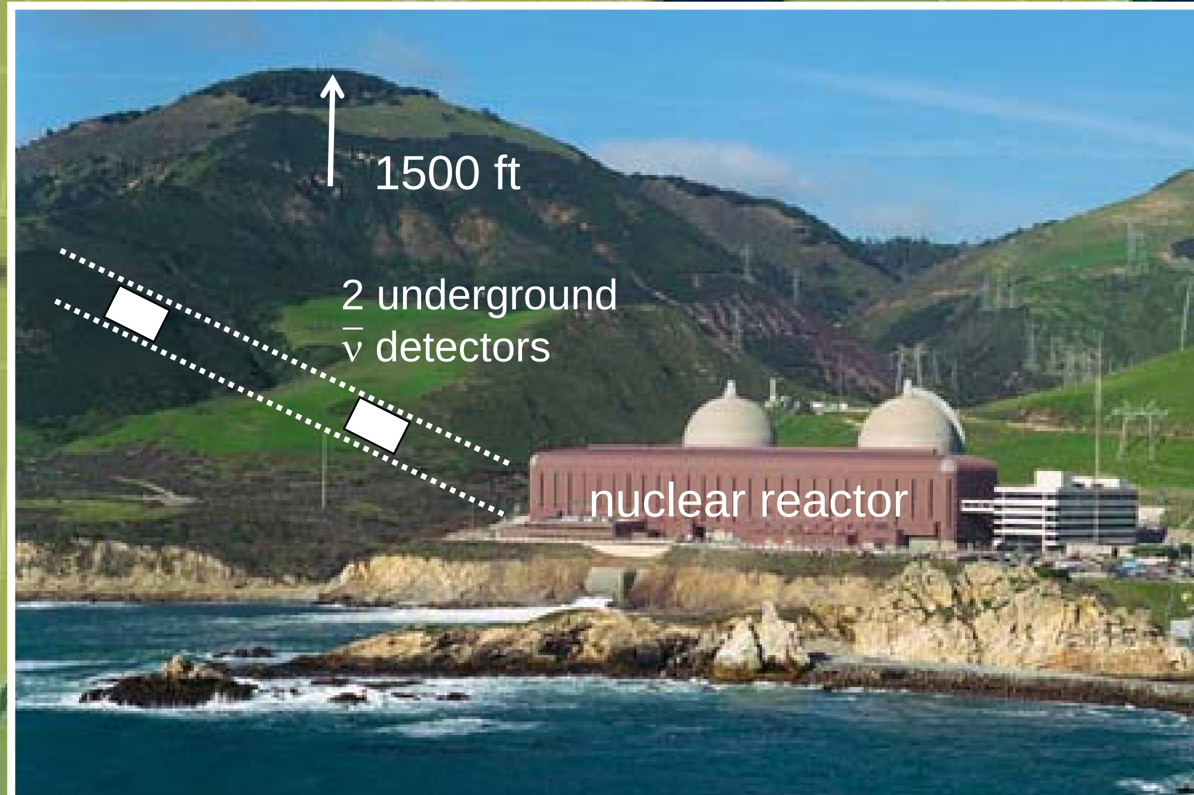


- independent of absolute reactor $\bar{\nu}$ flux
- largely eliminate cross-section errors
- relative detector calibration
- rate and shape information

Baseline

Diablo Canyon - An Example





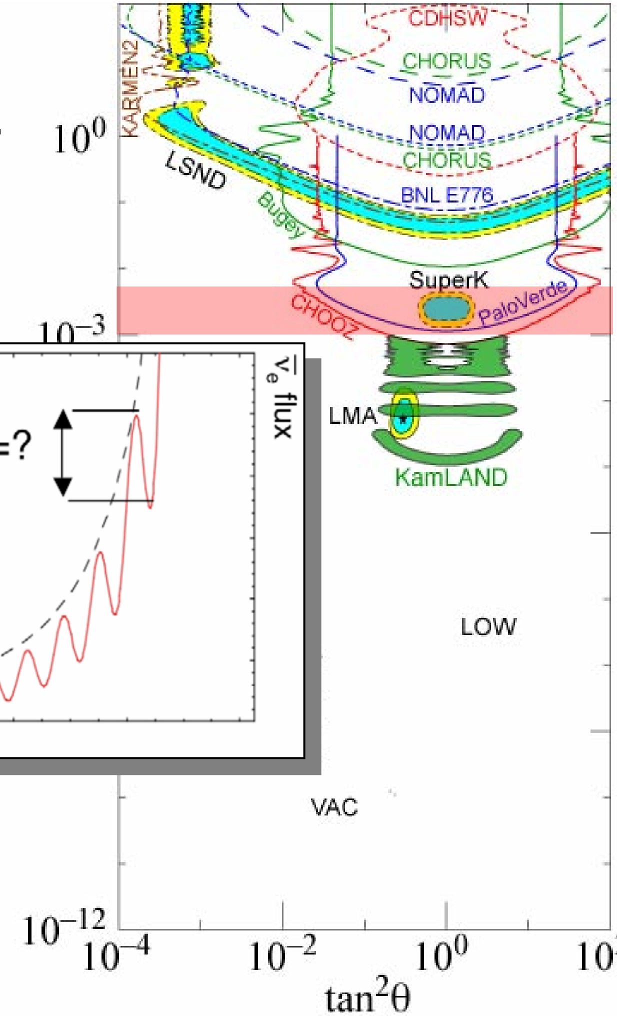
- ***Powerful*** (two reactors 3.1+ 3.1 GW E_{th})
- ***Overburden*** (up to 700 mwe)
- ***Infrastructure*** (roads, controlled access)

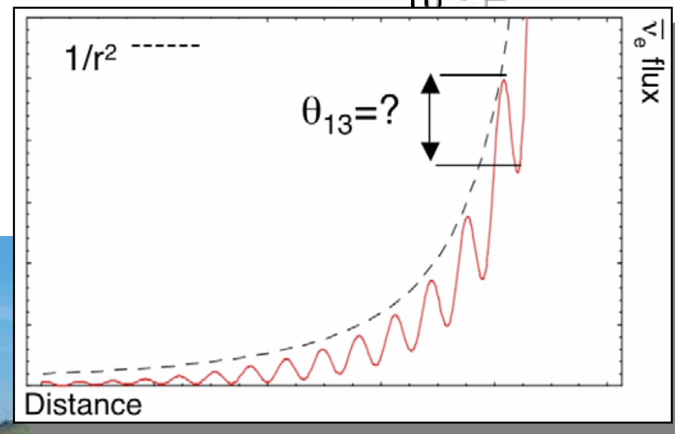
Measuring θ_{13} with Reactor Neutrinos

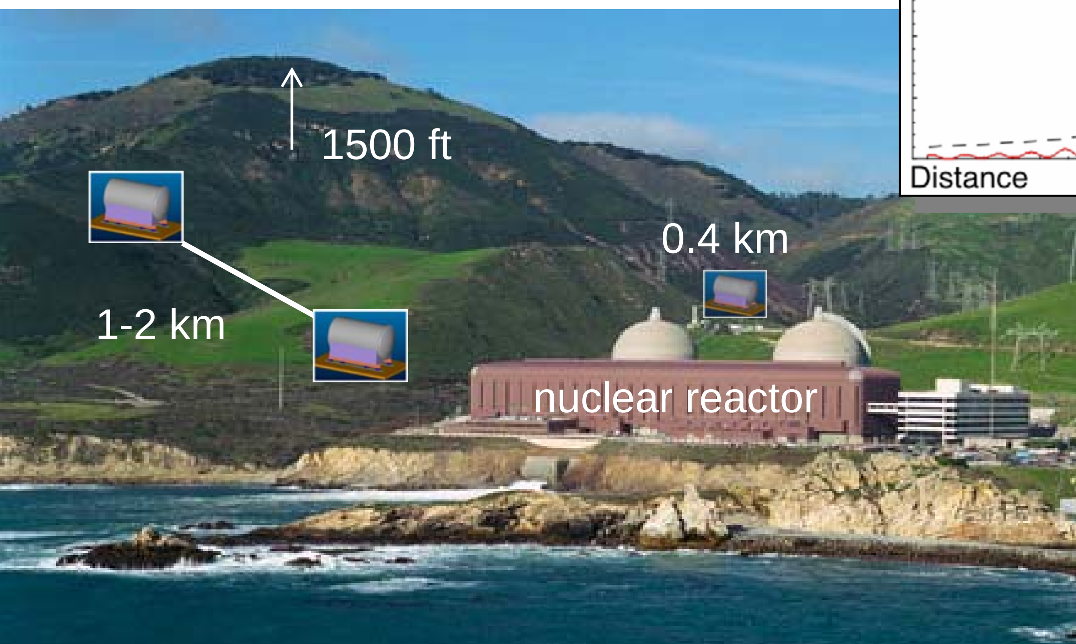
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}{}^2 L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

$$- \sin^2 2\theta_{sterile} \sin^2 \frac{\Delta m_{sterile}{}^2 L}{4E_\nu}$$

atmospheric frequency dominant,
sterile contribution possible





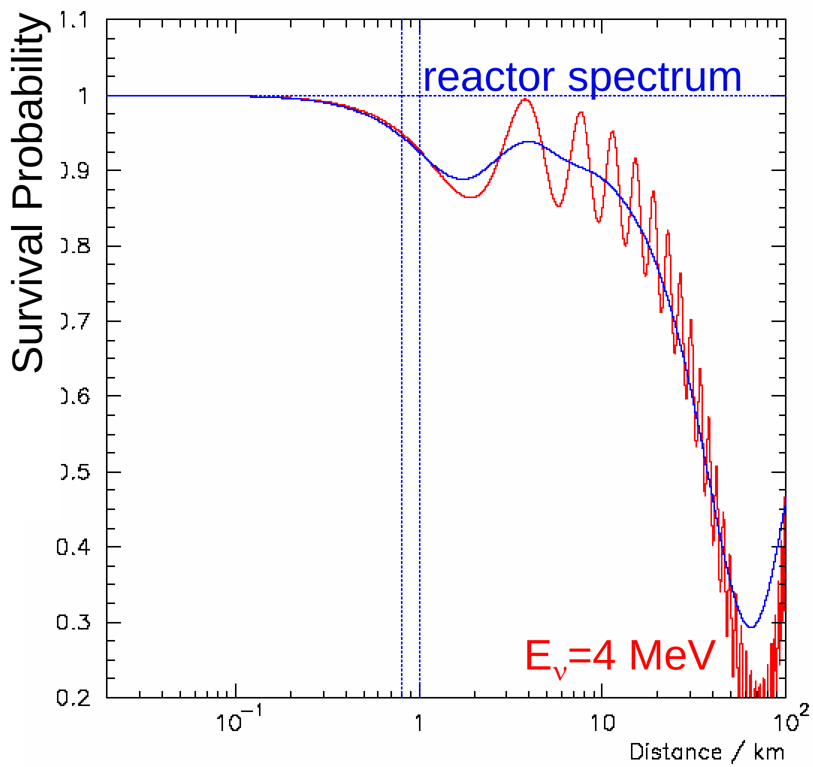


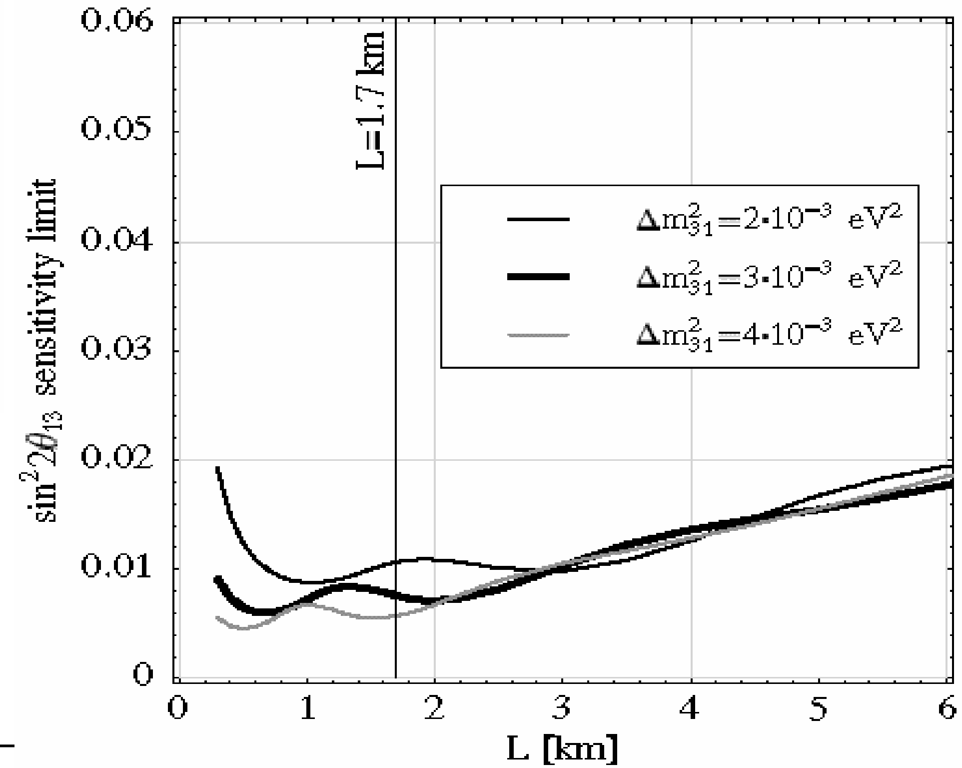
$\bar{\nu}_e + p \rightarrow e^+ + n$

- 2-3 underground scintillator $\bar{\nu}$ detectors, 50-100 t
- study relative rate difference and spectral distortions
- projected sensitivity: $\sin^2 2\theta_{13} \approx 0.01$-$0.02$

coincidence signal
prompt e^+ annihilation
delayed n capture (in μs)

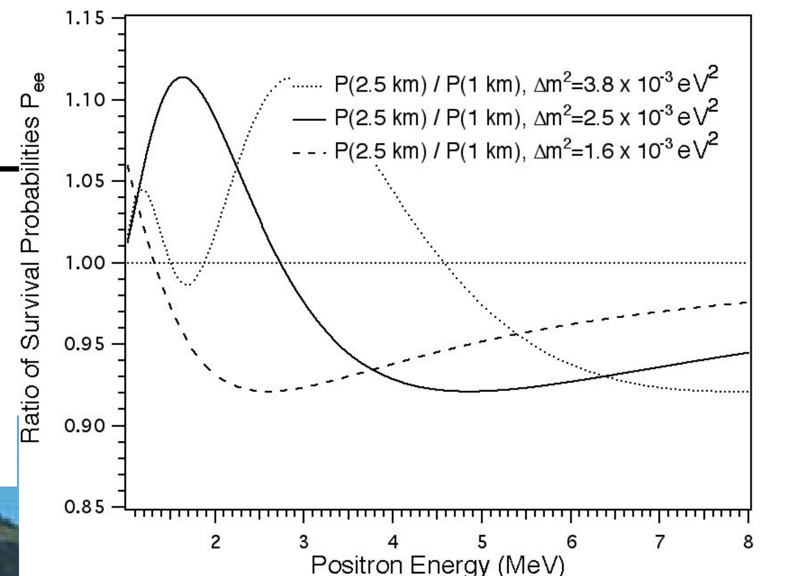
Optimum Baseline for a Rate Experiment





Ref: Huber et al. hep-ph/0303232

Detector Baseline



- Detector baselines sensitive to Δm_{atm}^2.
- Tunnel (1-2 km) + fixed detector (0.4 km)

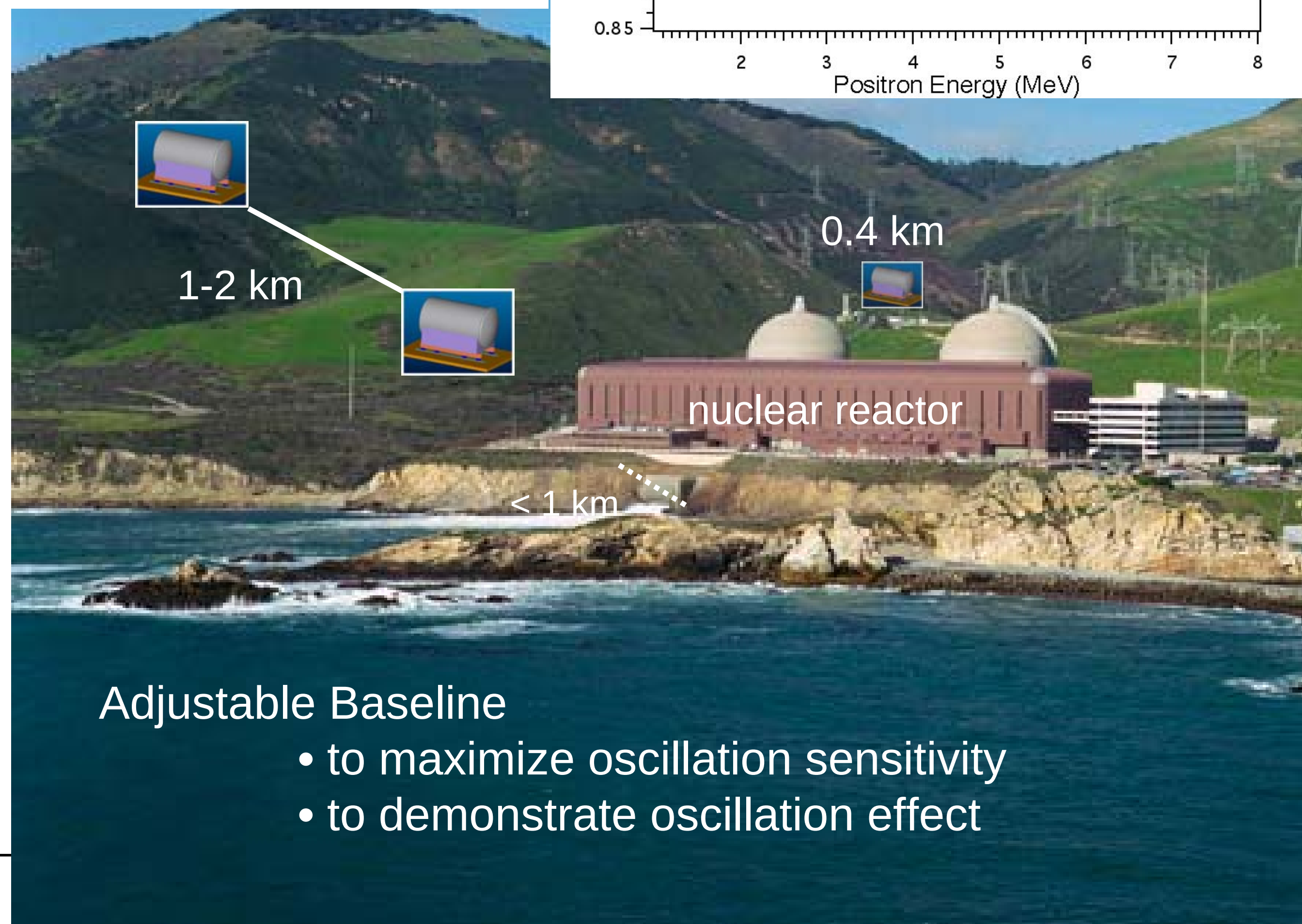
preserves option to adjust/optimize baseline

Near detector

Normalizes flux for rate analysis.

Far detectors

Range of distance useful for shape analysis, more robust to Δm_{atm}^2.



Adjustable Baseline

- to maximize oscillation sensitivity
- to demonstrate oscillation effect

Detector Locations

Flux Systematics with Multiple Reactor Cores

QuickTime?and a TIFF (Uncompressed) decompressor are needed to see this picture.

$$\Phi_i = \phi_A^0 \frac{1}{R_A^2} P_A + \phi_B^0 \frac{1}{R_B^2} P_B$$

Indivual reactor flux contributions and systematics cancel *exactly* if

Condition I: $\frac{R_A{}^2}{R_B{}^2} = const.$ *$1/r^2$ fall-off of reactor flux the same for all detectors.*

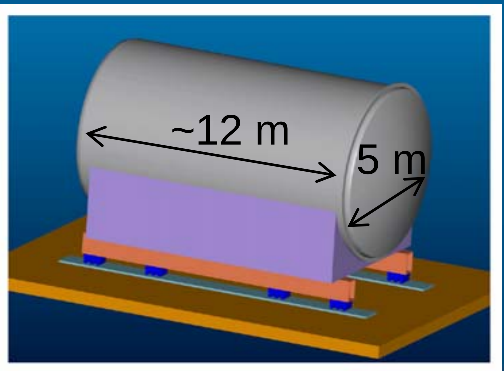
Condition 2: $P_A \cong P_B \cong P$ *Survival probabilities are approximately the same*

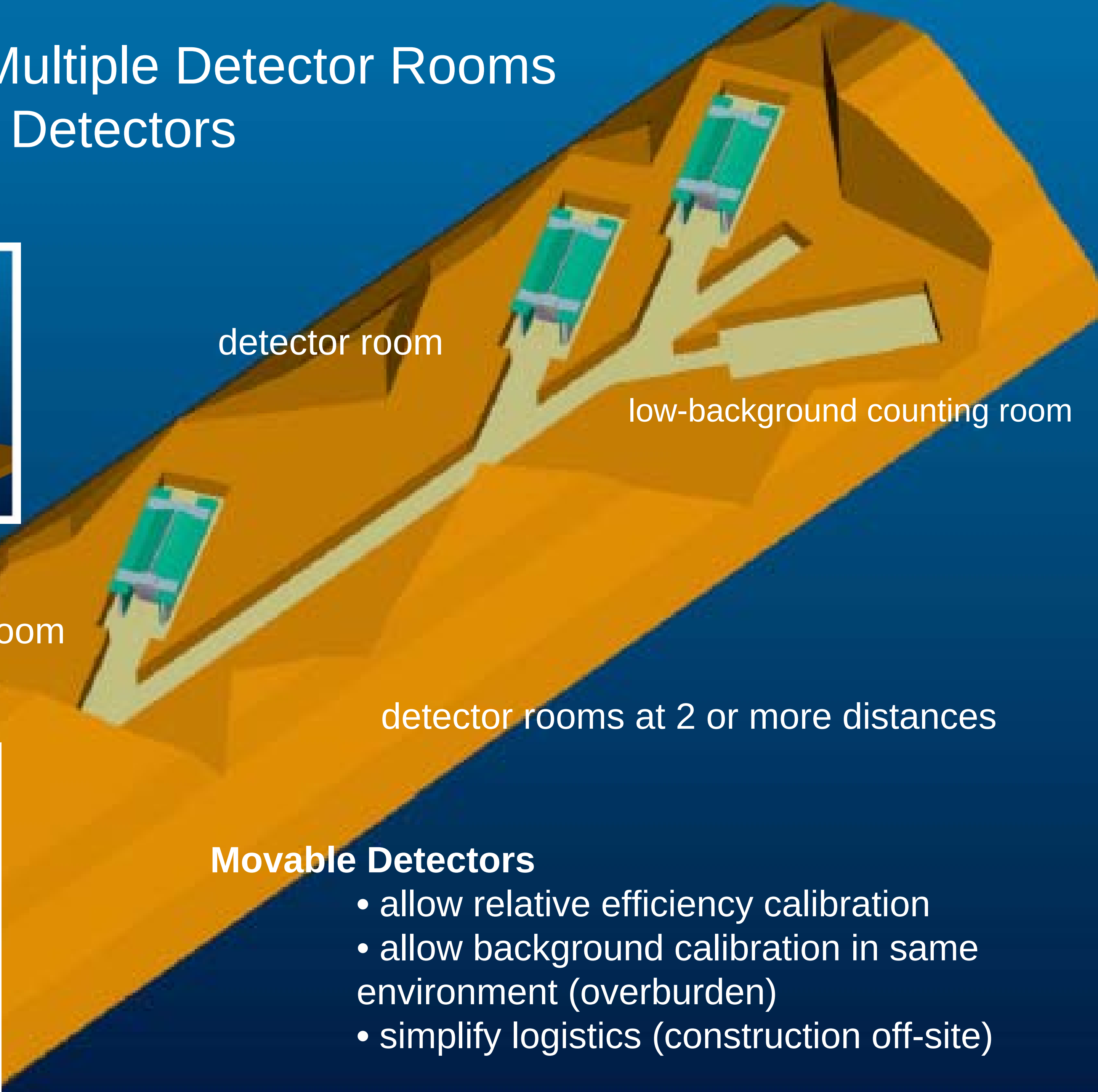
→ Approximate flux cancellation possible at other locations

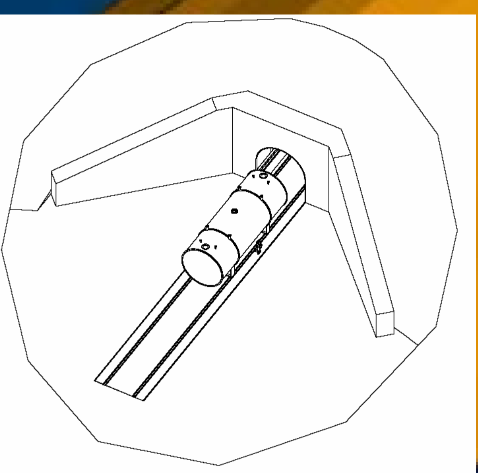
	Relative Error Between Detector 1 and 2	
	rate	**shape**
Relative flux error (1%)	< 0.3%	< 0.01%
Reactor core separation (100 m)	< 0.14%	< 0.1%
Finite detector length (10 m)	< 0.2%	< 0.1%

→ Shape analysis largely insensitive to flux systematics.
→ Distortions are robust signature of oscillations.

Tunnel with Multiple Detector Rooms and Movable Detectors







Movable Detectors

- allow relative efficiency calibration
- allow background calibration in same environment (overburden)
- simplify logistics (construction off-site)

Detector Size and Volume

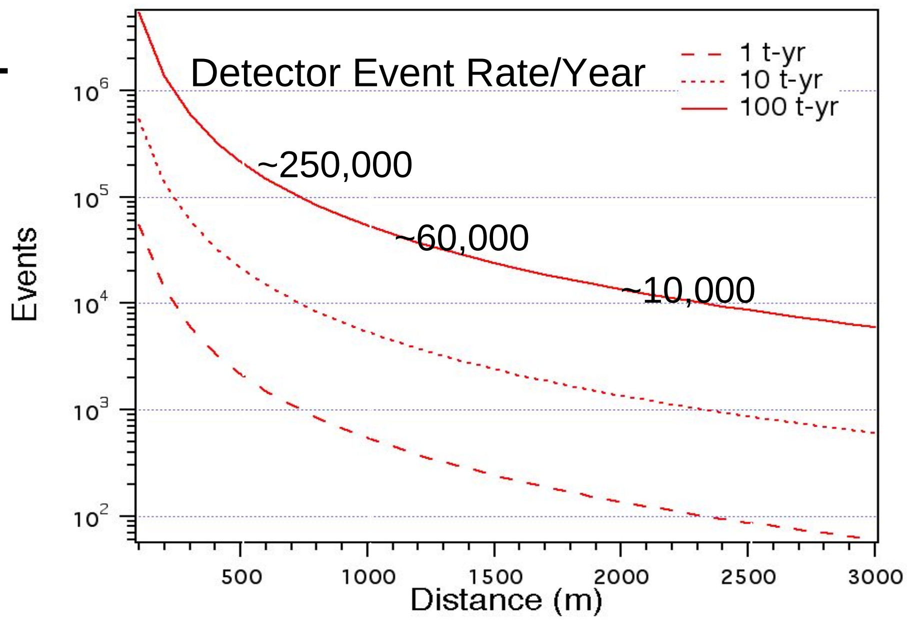
Detector Size

Statistical Error

σ_{stat} ~ 0.5% for **L** = 300t-yr

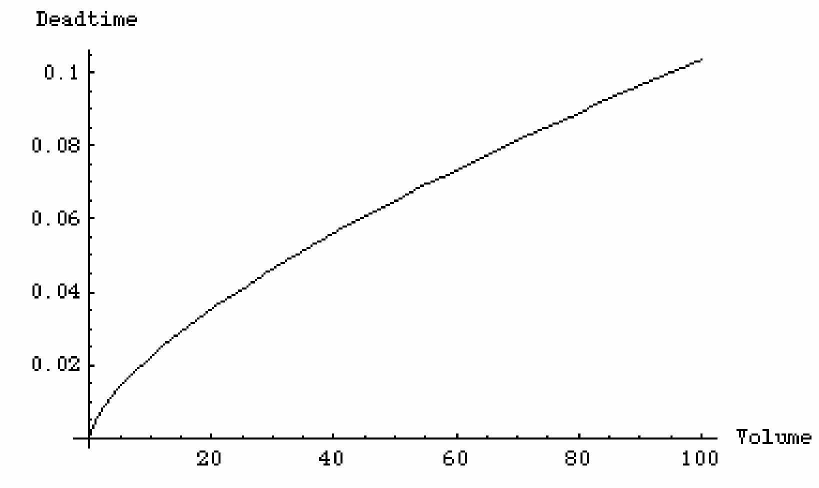
Nominal data taking: 3 years (?)

Interaction rate: 300 /yr/ton at 1.8 km



Fiducial volume > 30 ton at 1.8 km

Muon Flux and Deadtime



Muon veto requirements increase with volume.

Perhaps we want 2 x 25 t detectors?

Detector Shape and Experimental Layout

Cylindrical vs Spherical? Modular?

Access, Infrastructure, and Logistics

movable detector in tunnel, or built in place

Muon veto efficiency

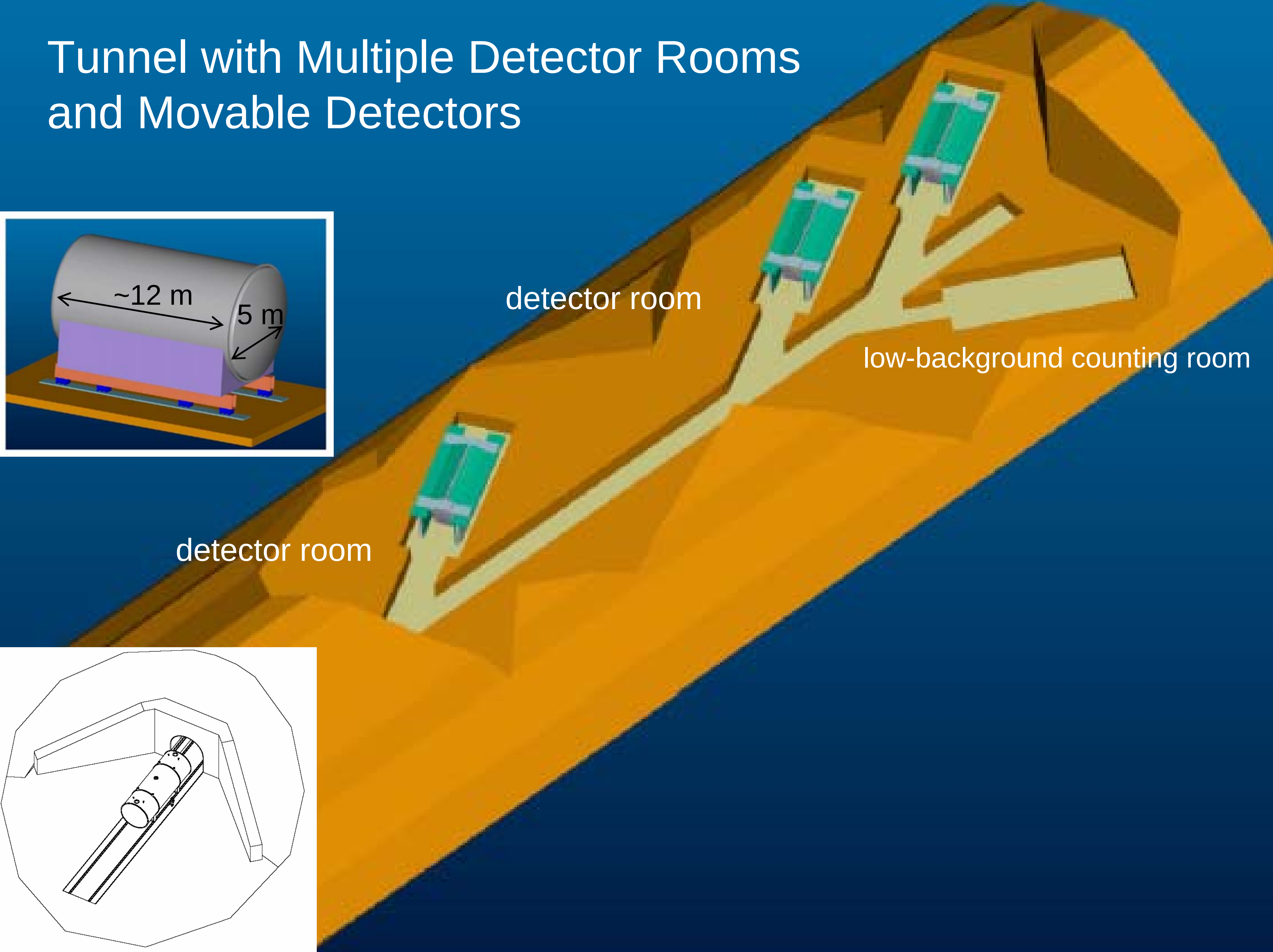
what is most cost effective?

Backgrounds

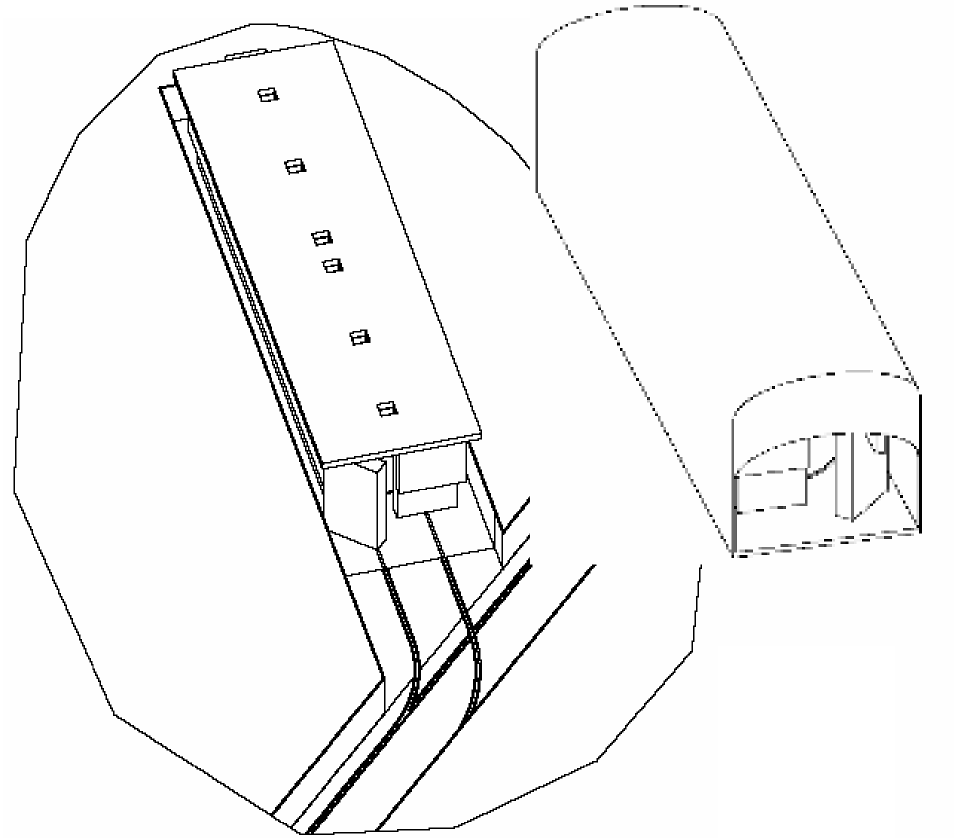
spherical symmetry easier to understand

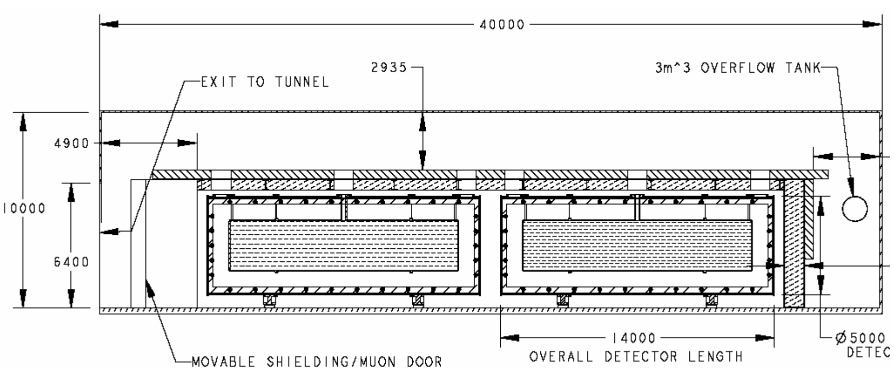
Fiducial volume and total volume

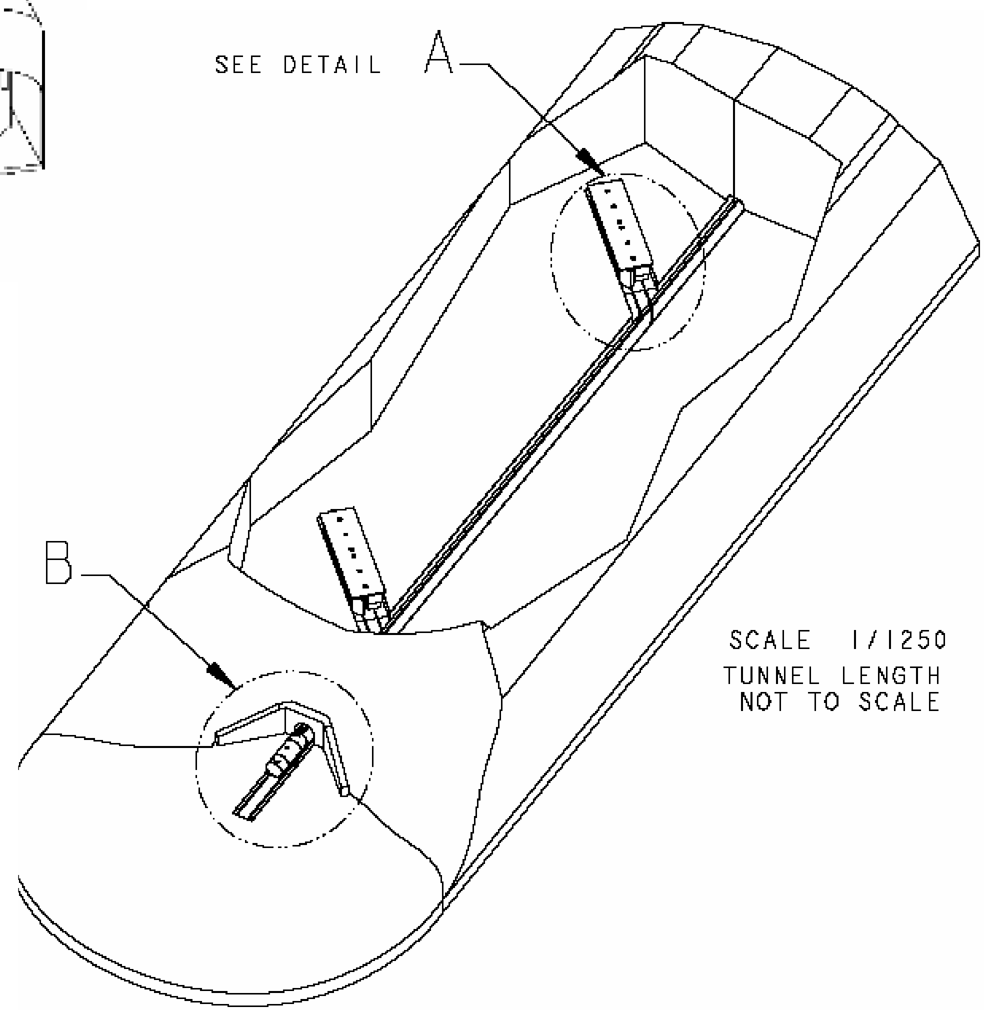
Tunnel with Multiple Detector Rooms and Movable Detectors



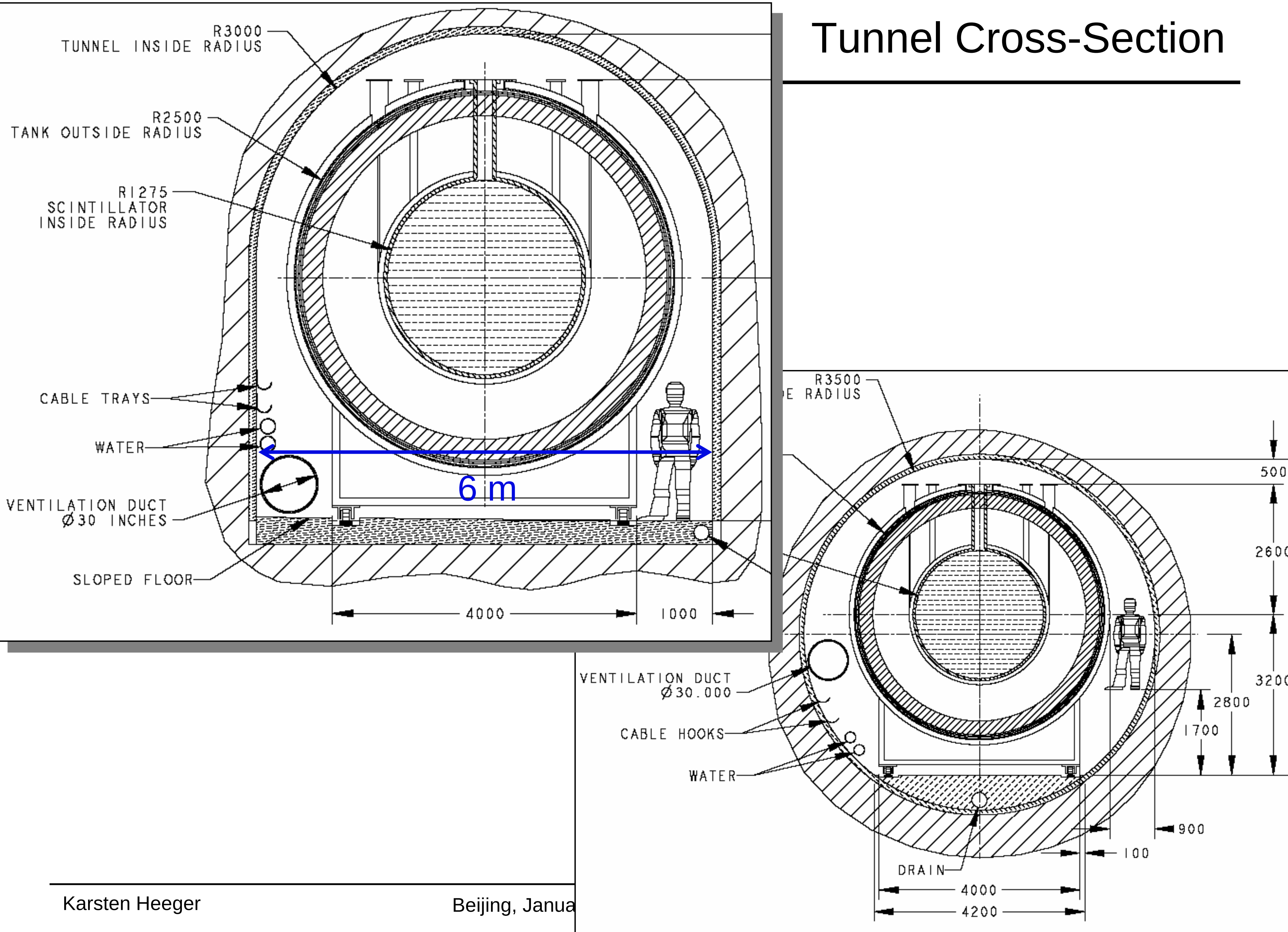
Tunnel and Detector Halls



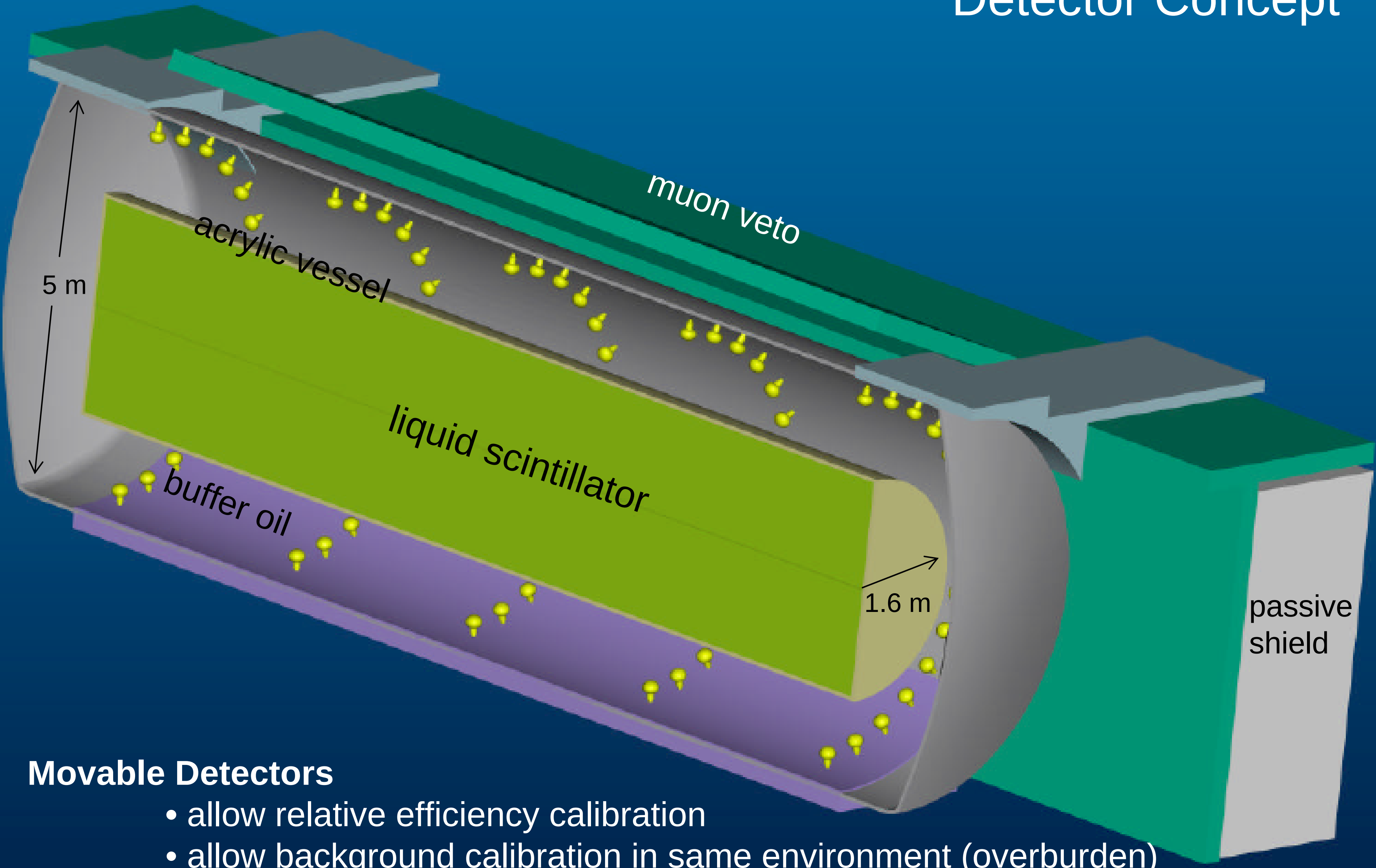




Tunnel Cross-Section



Detector Concept

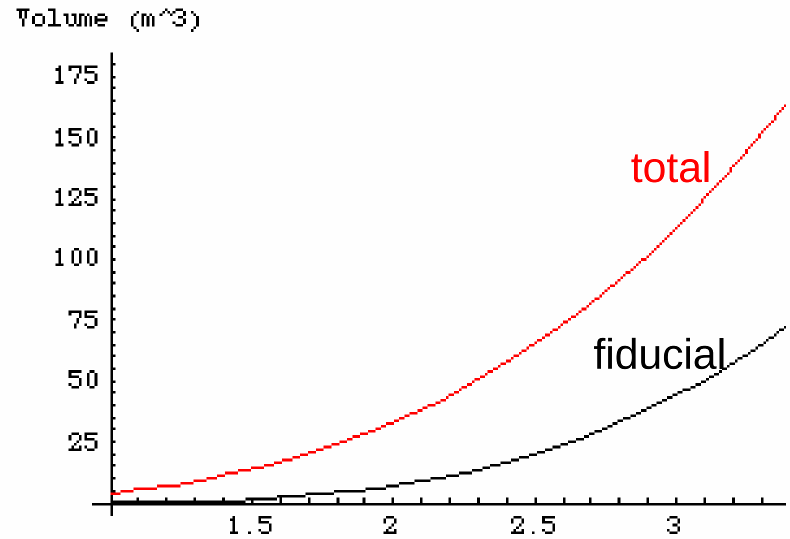


Movable Detectors

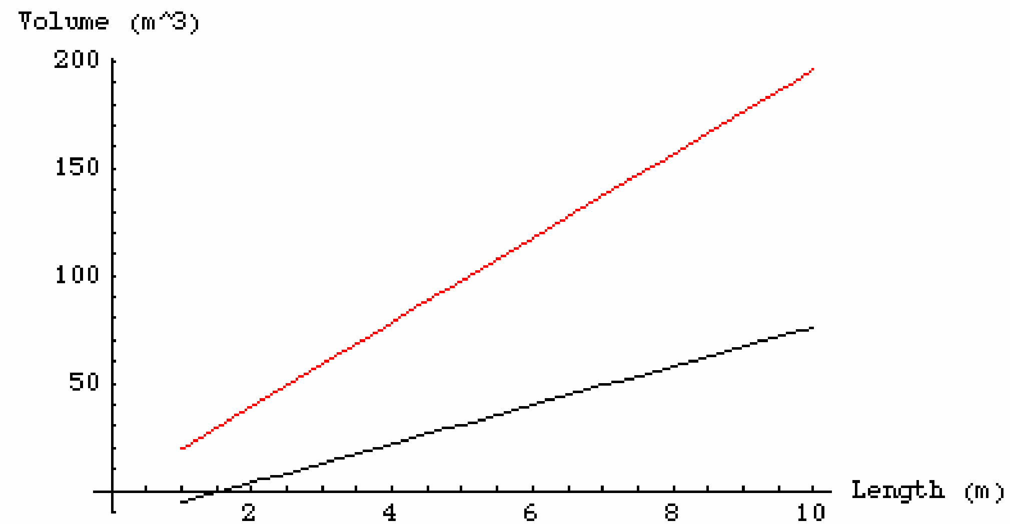
- allow relative efficiency calibration
- allow background calibration in same environment (overburden)
- simplify logistics (construction off-site)

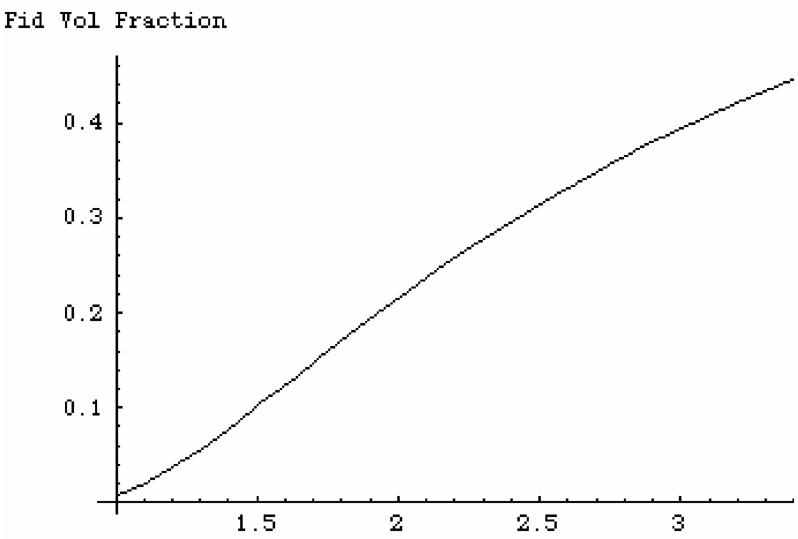
Cylindrical vs Spherical - What is more economical?

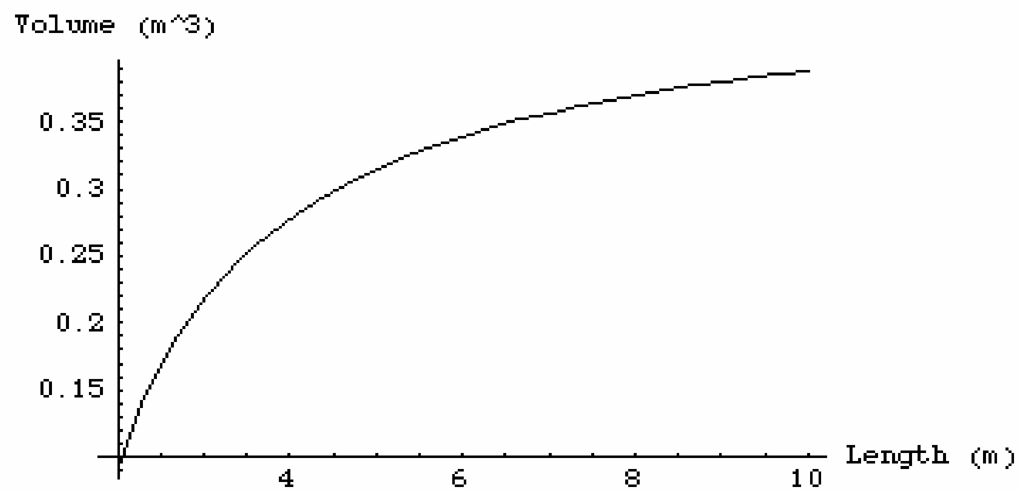
sphere



cylinder



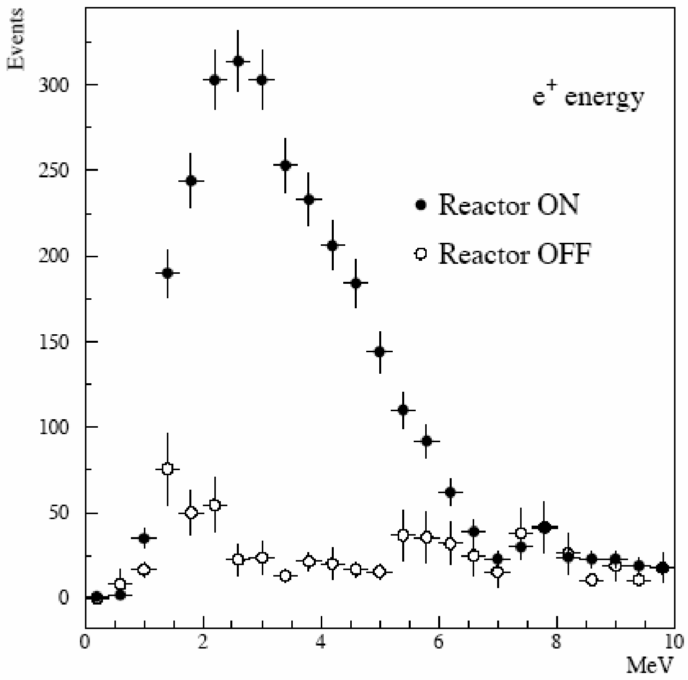




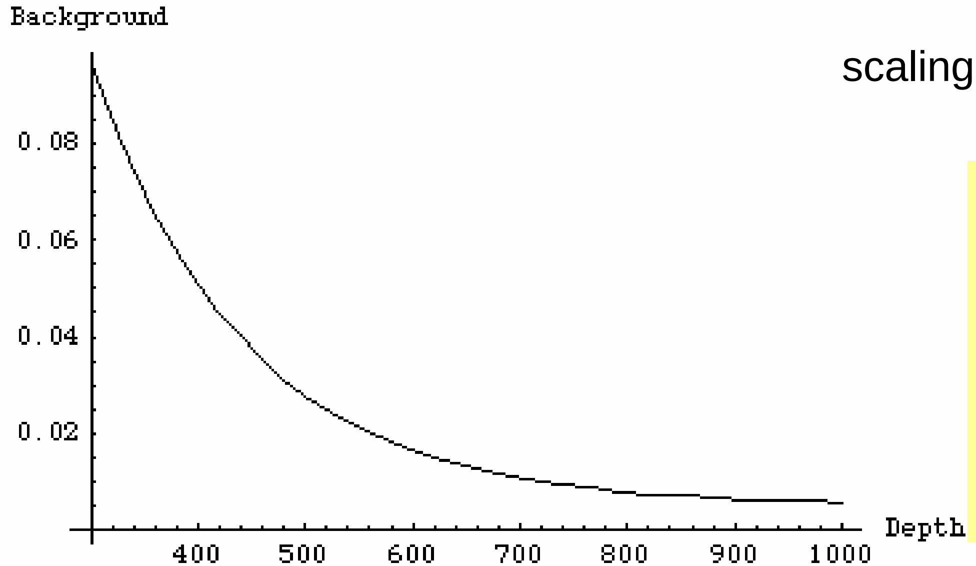
Depth and Overburden

Overburden

Goal	Background/Signal < 1%
	background = accidental + correlated
Chooz	candidate events
	reactor on 2991
	reactor off 287 (bkgd)



Minimum overburden



scaling Chooz background with muon spectrum that generates spallation backgrounds

bkgd	depth (mwe)
10%	300
< 5%	> 400
< 2%	> 560
< 1%	> 730

Muon-Induced Production of Radioactive Isotopes in LS

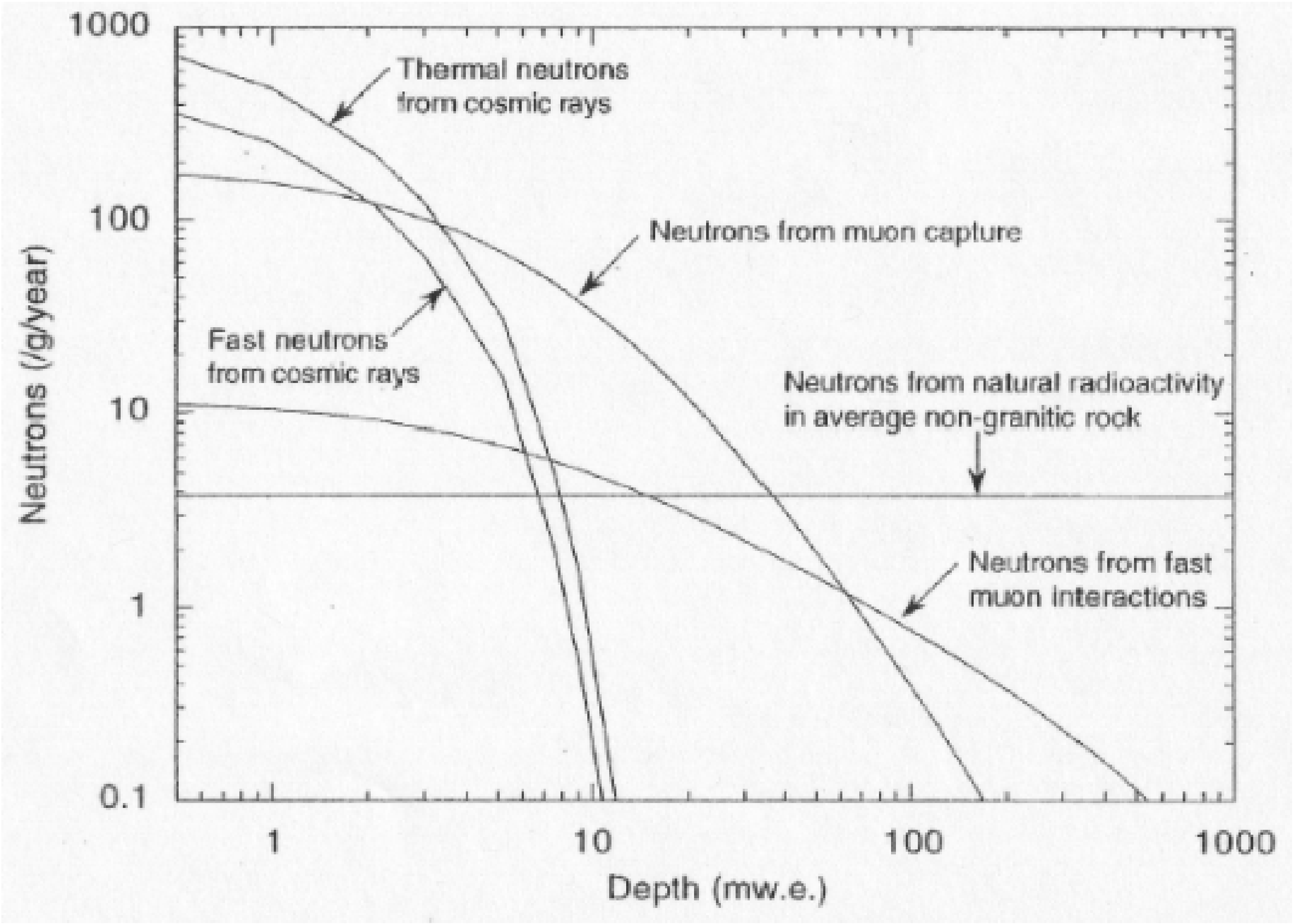
	Isotope	$T_{1/2}$	E_{max} (MeV)	Type
β^-	^{12}B	0.02 s	13.4	Uncorrelated
	^{11}Be	13.80 s	11.5	Uncorrelated
	^{11}Li	0.09 s	20.8	Correlated
	^{9}Li	0.18 s	13.6	
	^{8}Li	0.84 s	16.0	
	^{8}He	0.12 s	10.6	
	^{6}He	0.81 s	3.5	Uncorrelated
β^+, EC	^{11}C	20.38 m	0.96	
	^{10}C	19.30 s	1.9	
	^{9}C	0.13 s	16.0	Uncorrelated
	^{8}B	0.77 s	13.7	Uncorrelated
	^{7}Be	53.3 d	0.48	Uncorrelated

correlated:
β-n cascade, τ~few 100ms.
Only ^{8}He, ^{9}Li, ^{11}Li (instable isotopes).

uncorrelated:
single rate dominated by ^{11}C

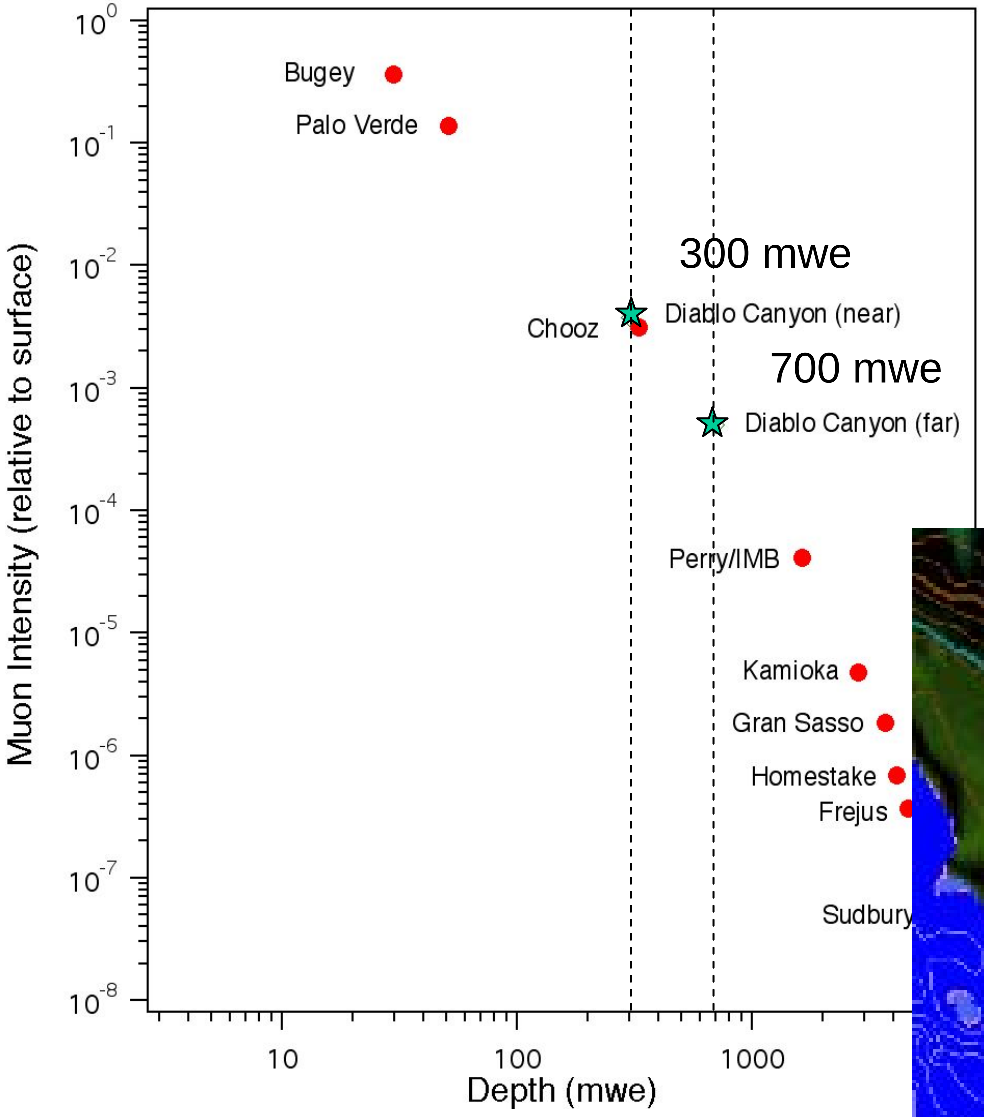
rejection through muon tracking and depth

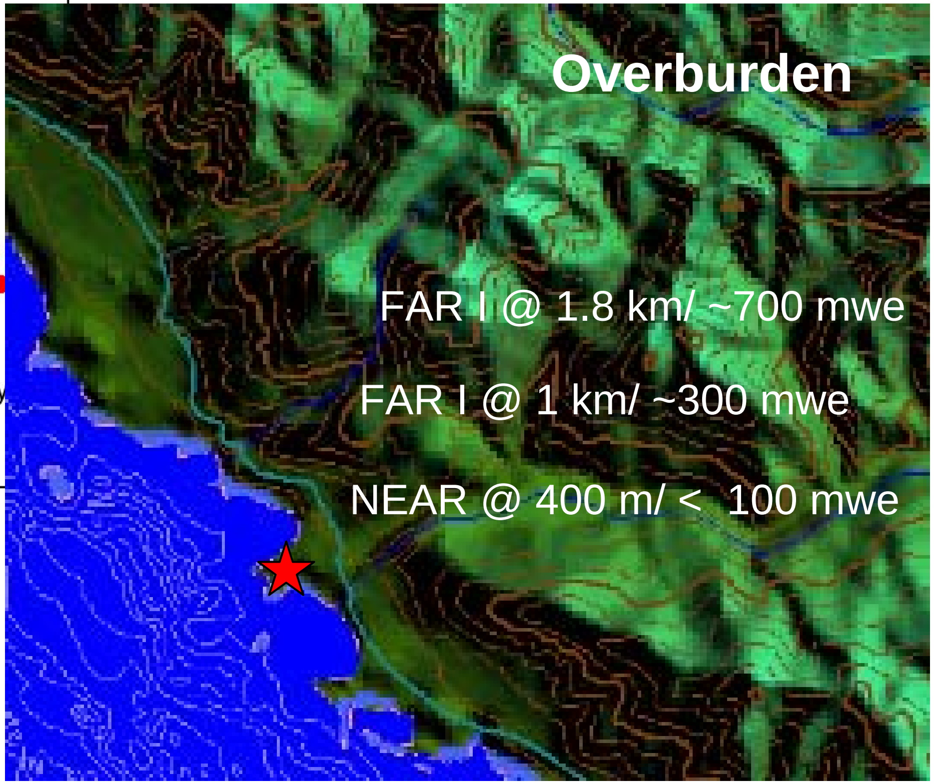
Neutron Production in Rock



A. da Silva
PhD thesis, UCB 1996

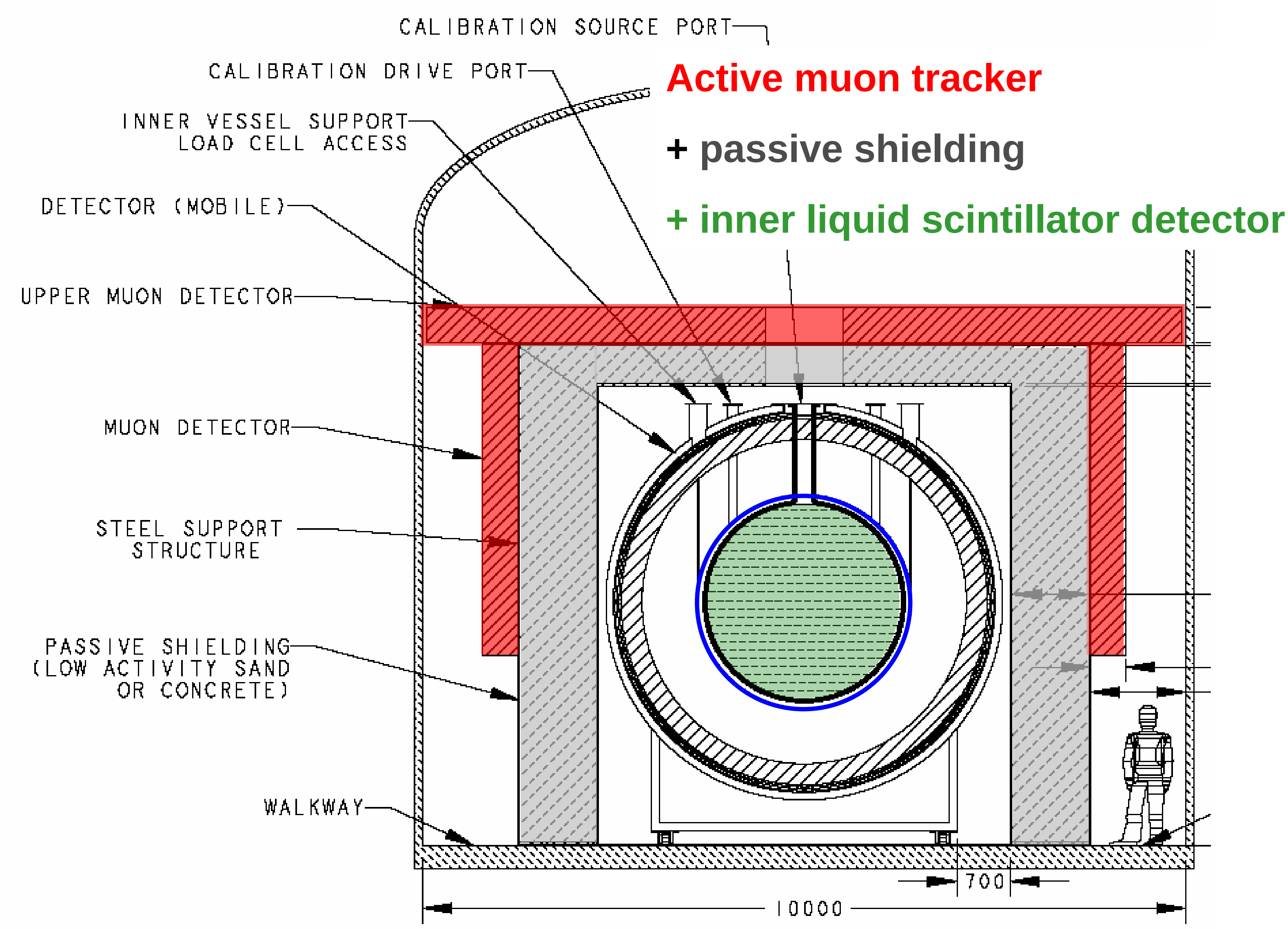
Overburden and Muon Flux





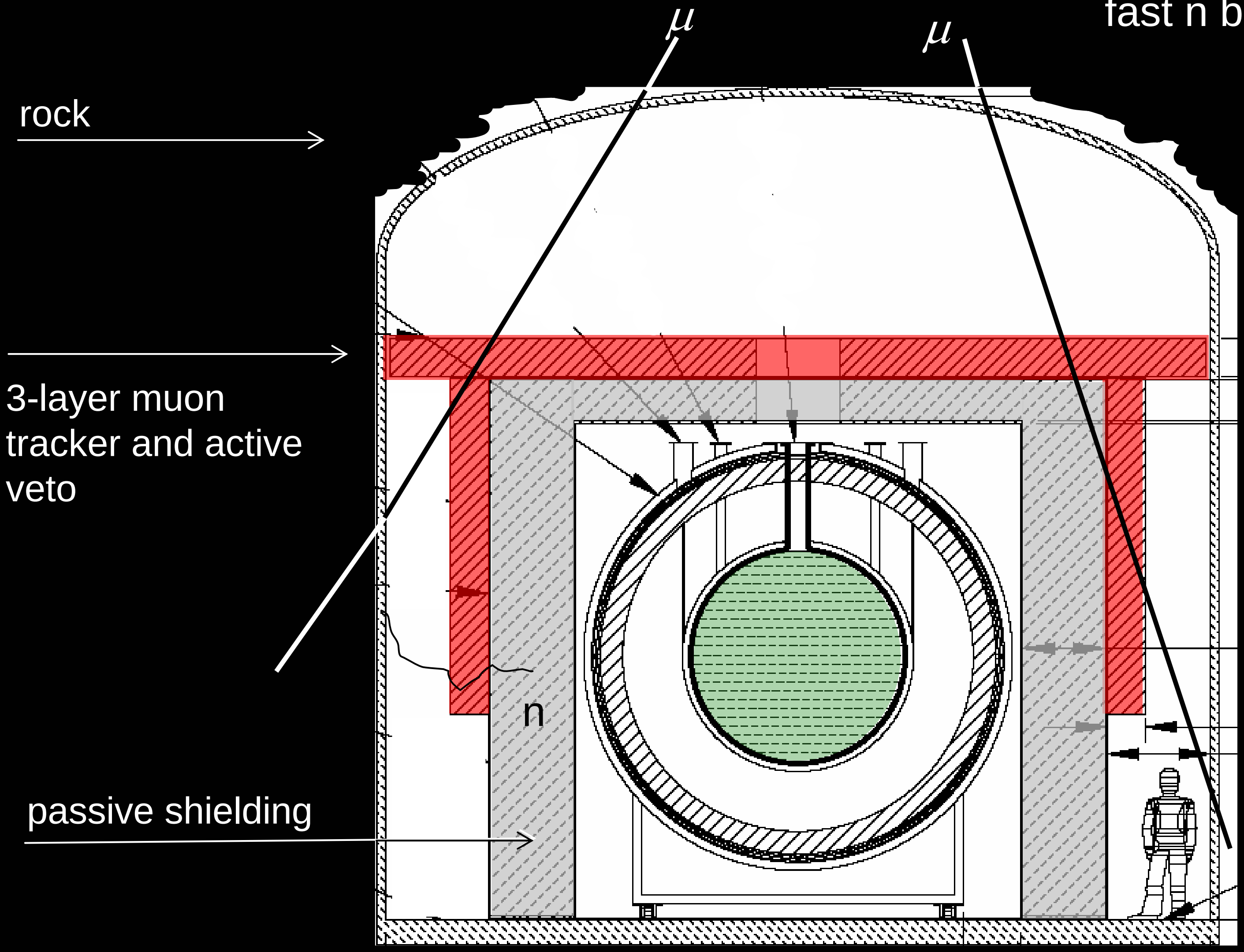
Muon Veto and Efficiency

Detector and Shielding Concept



Detector and Shielding Concept

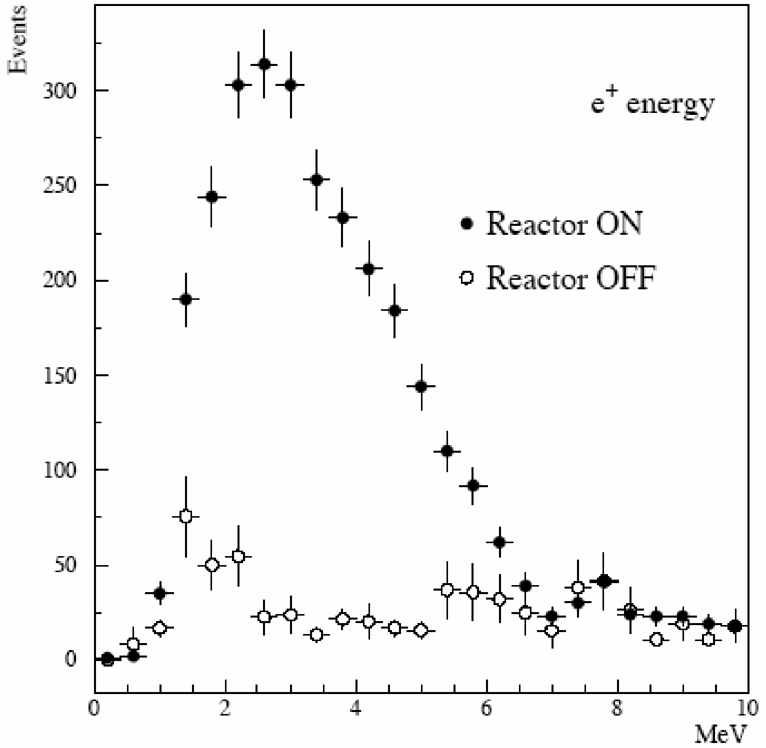
→ allows you to measure fast n backgrounds



Muon Veto and Efficiency

Chooz have 98% (?)

> 99.5% possible (?)



event candidates

reactor on	2991
reactor off	287

Chooz has 9.5% irreducible background, presumably due to spallation backgrounds. Improvement in muon veto can reduce backgrounds.

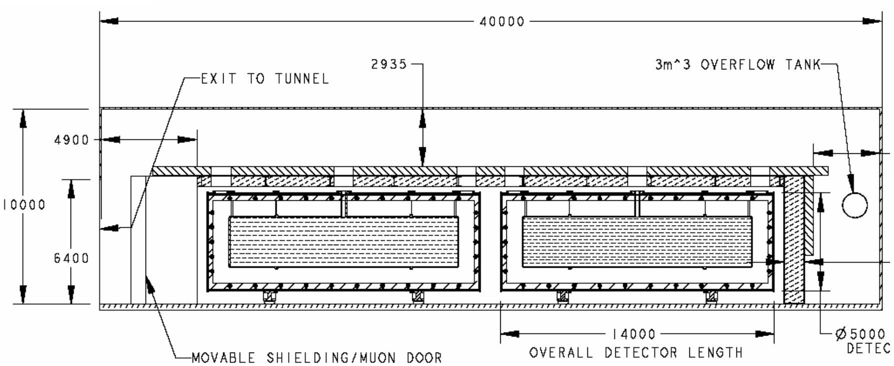
bkgd	muon veto efficiency
10%	98%
2%	99.5%
< 0.5%	99.9%

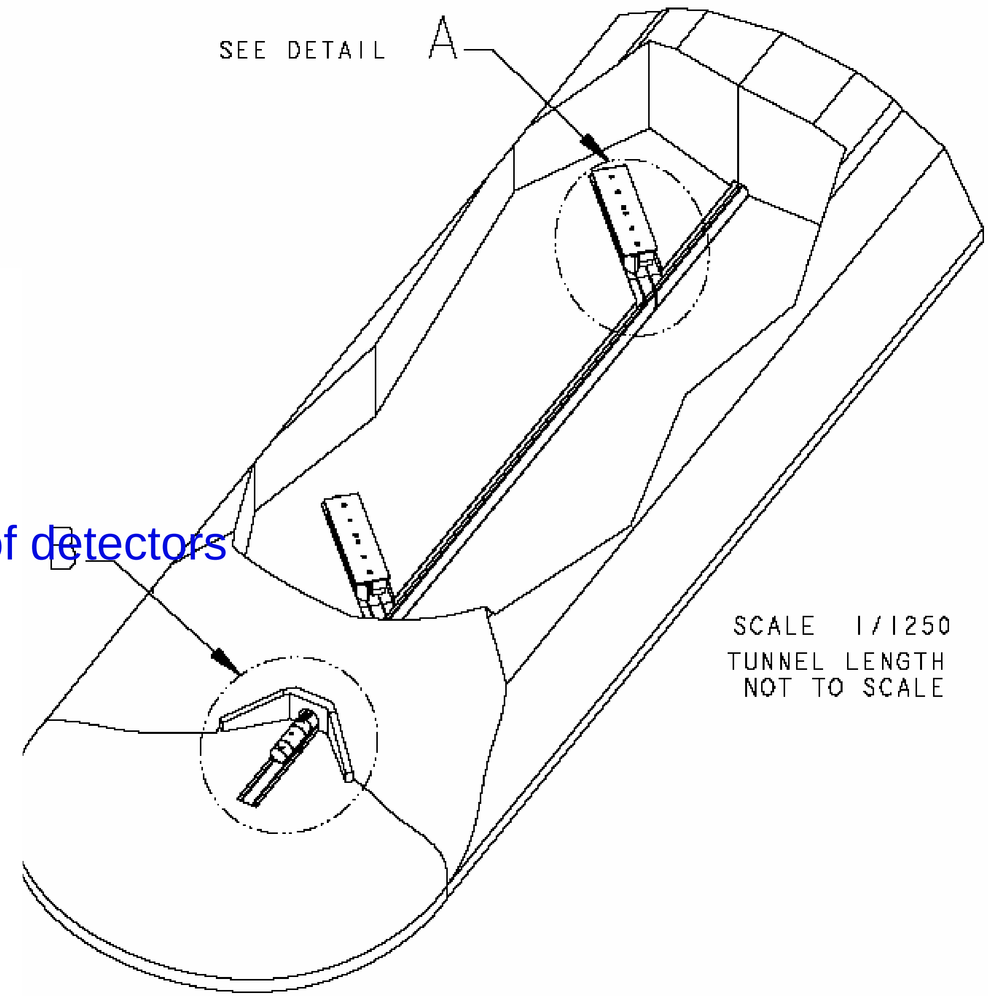
Calibrations

Relative Detector Calibration

Neutrino detection efficiency

in same location (under same overburden) to have same backgrounds





Energy response and reconstruction of detectors

can be done with movable calibration system

Calibration Systems (I): Inner Liquid Scintillator

Inner Deployment System

• Modeled after SNO:

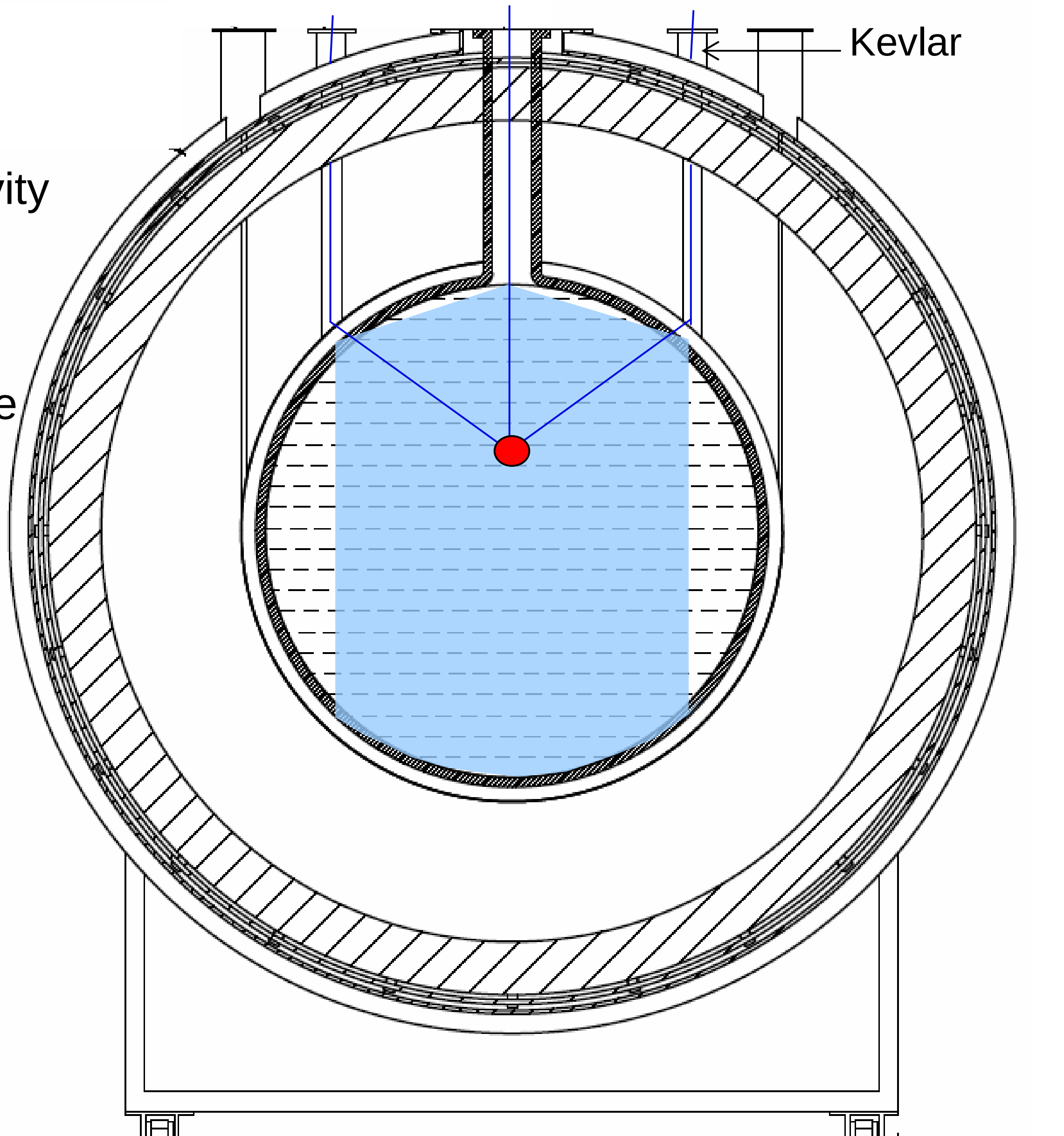
- Kevlar ropes and gravity used to position source

• Calibrates most of inner volume

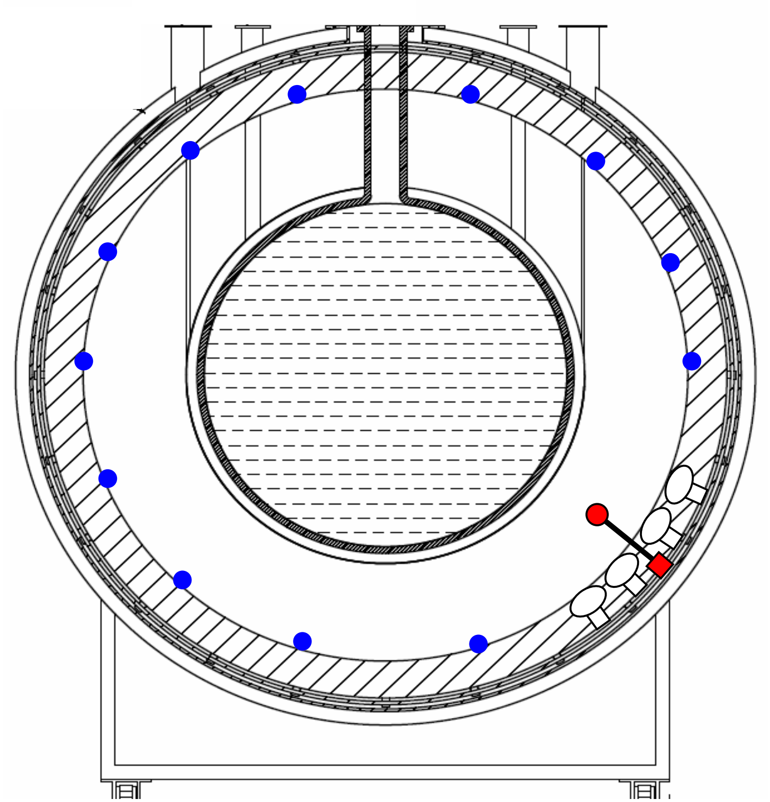
• Can deploy passive and active calibration sources:

γ
neutron
laser
e^{-} (e^{+} ?)

• Minimum amount of material introduced into the detector



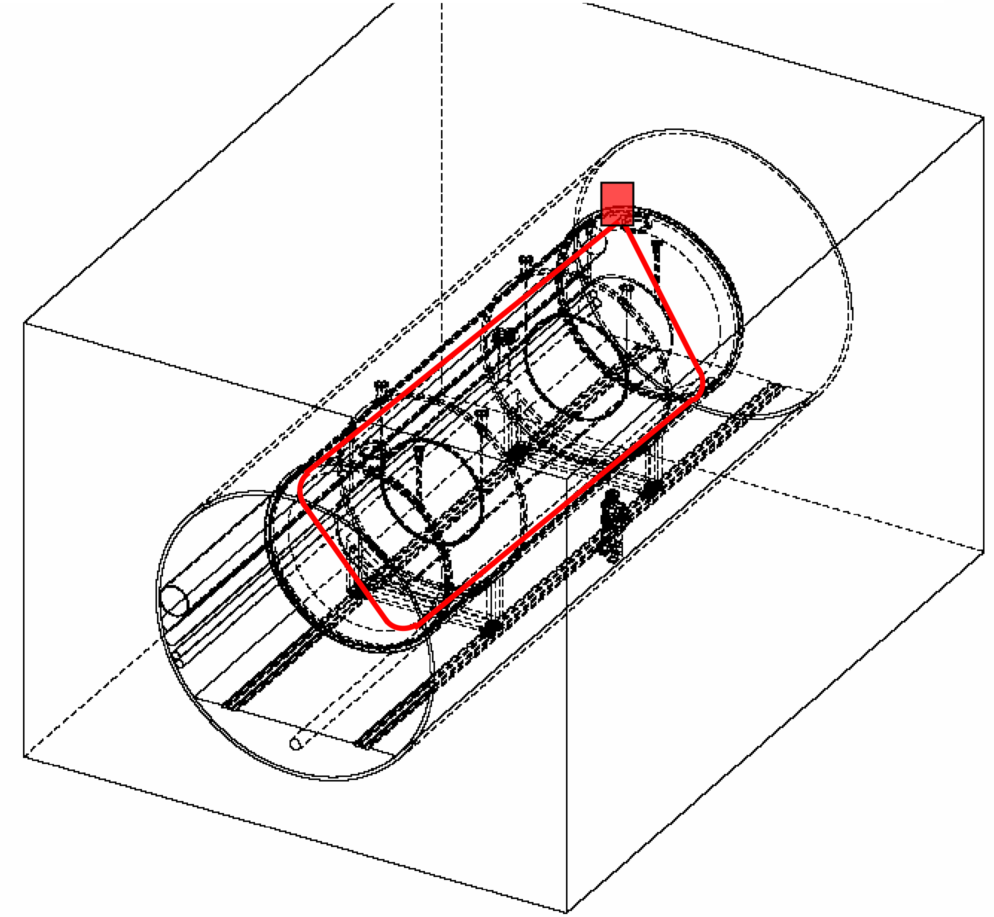
Calibration Systems (II): Buffer Oil Region



Fixed LED's

Calibration Track

Passive calibration source mounted on track.
Allows calibration at fixed distance from PMT.
Automatic calibration, 'parked' outside tank.



Fiducial Volume

Inner Detector

• Precise determination of mass of inner liquid scintillator;

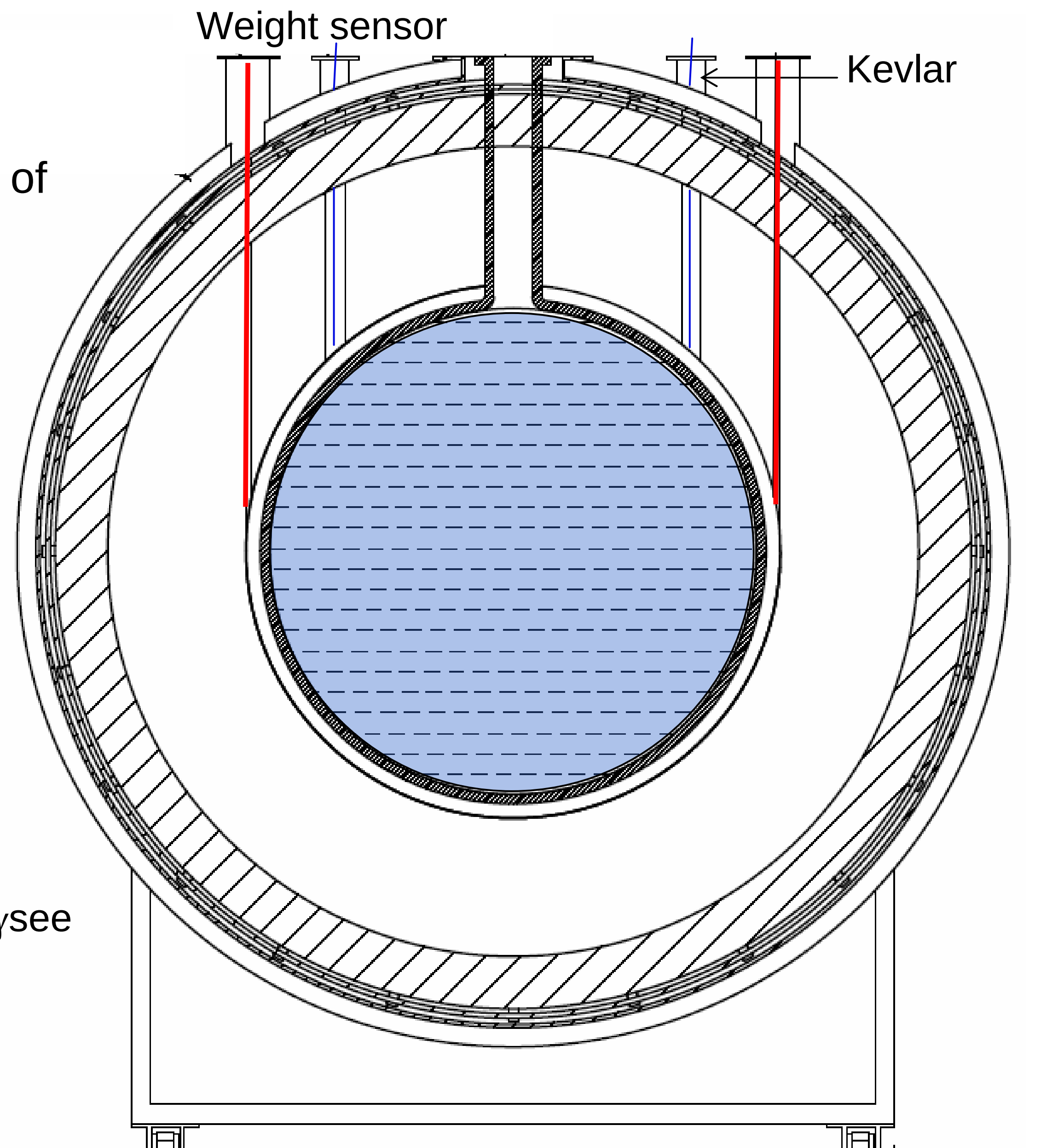
- fill volume (< 0.5%)
- weight

• Outstanding R&D Issues

1. Gd-doping?

2. Position reconstruction?

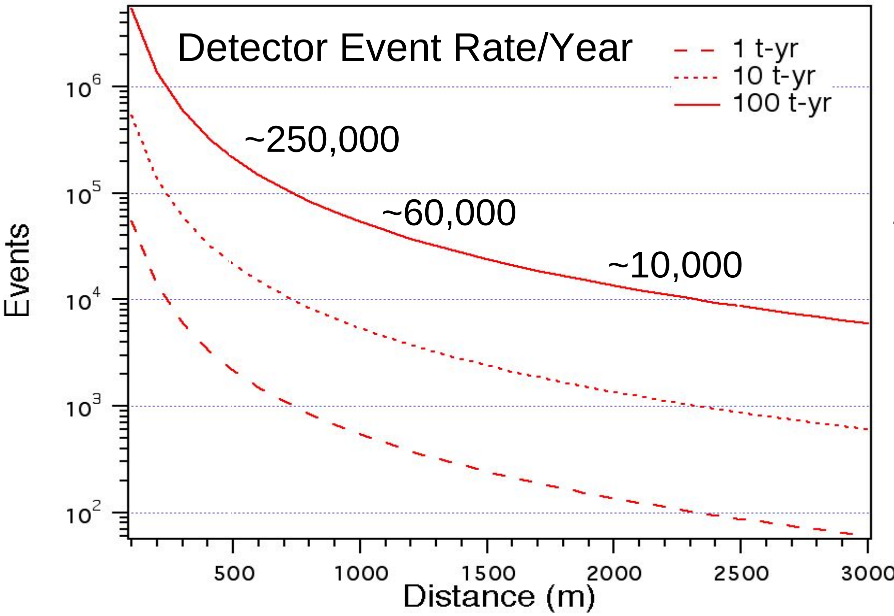
3. Scintillating buffer volume?
(scintillating buffer around target to γsee from e^+ capture and Gd decays)

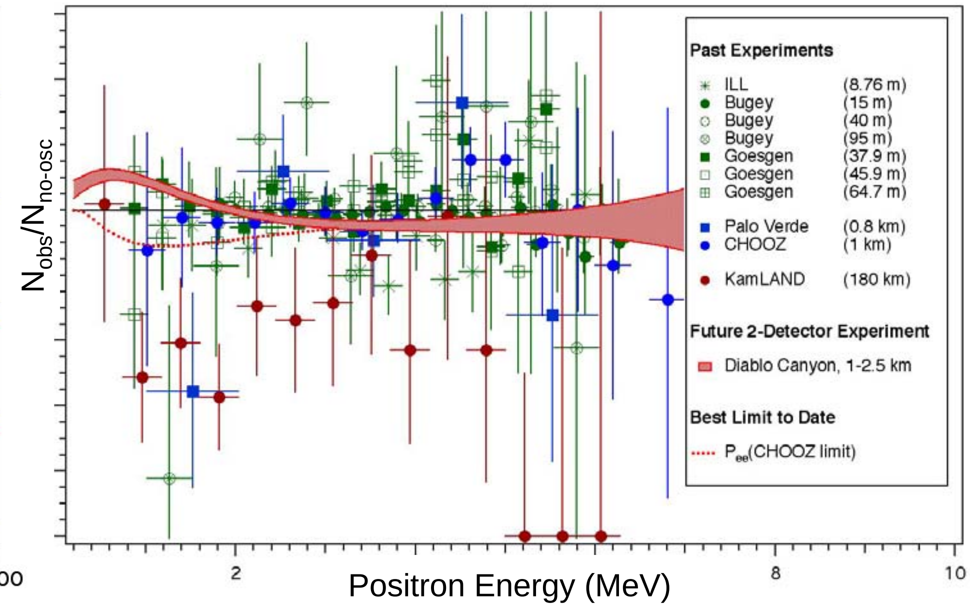


Need to overconstrain experiment

Nothing can replace good data …. overburden critical

Statistics and Systematics





Statistical error: σ_{stat} ~ 0.5% for **L** = 300t-yr

Reactor Flux	• near/far ratio, choice of detector location	$\sigma_{flux} < 0.2\%$
Detector Efficiency	• near and far detector of same design • calibrate *relative* detector efficiency	$\sigma_{rel\ eff} \leqslant 1\%$
Target Volume &	• no fiducial volume cut	$\sigma_{target} \sim 0.3\%$
Backgrounds	• external active and passive shielding	$\sigma_{acc} < 0.5\%$ $\sigma_{n\ bkgd} < 1\%$

Total Systematics σ_{syst} ~ 1-1.5%