Low Background, Gravitational Waves, and N-Nbar Detector at DUSEL

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DURA Meeting, FNAL

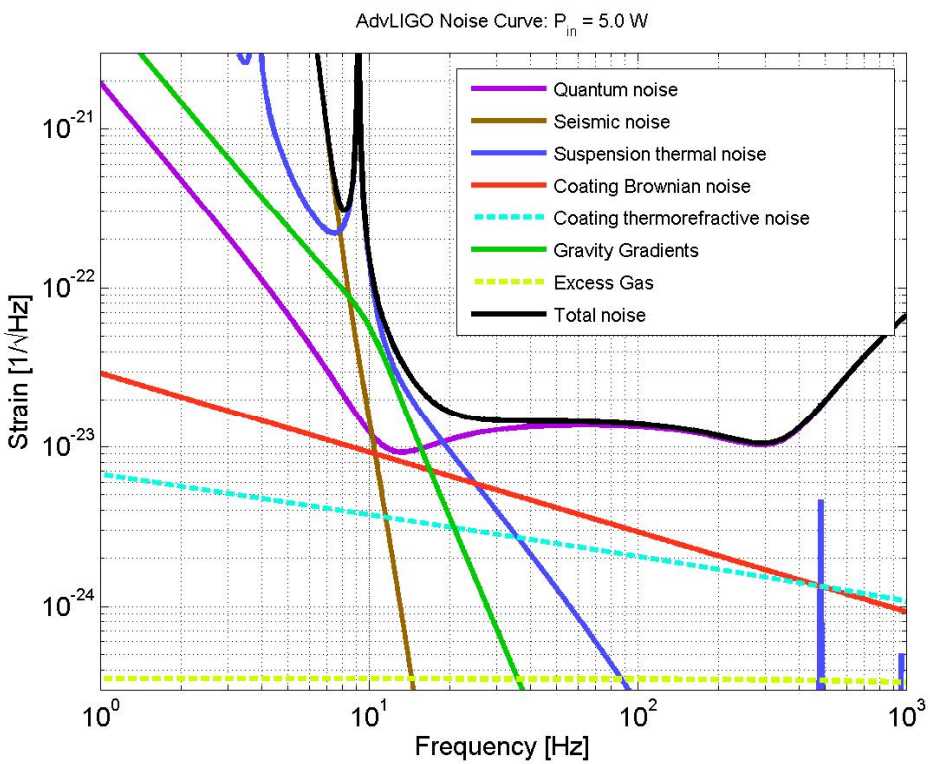
Sep. 3, 2010

Overview

- Laser-interferometric gravitational-wave detectors
- Atom-interferometric gravitational-wave detectors (for Mark Kasevich)
- N-Nbar detector (for Yuri Kamyshkov)
- Low Backgrounds (Prisca Cushman)

Laser-Interferometric Gravitational Wave Detectors

- Second generation gravitational-wave detectors (Advanced LIGO, Advanced Virgo) will be limited >10 Hz.
- Strong scientific motivation for 0.1-10 Hz band:
  - » Stochastic background from the early Universe.
  - » Intermediate mass black holes.
  - » Pulsars, neutron stars.
  - » Dark energy probes.
- Several limiting noise sources below 10 Hz, each being addressed.
- Seismic and newtonian noise:
  - » Third generation detectors will likely be built underground.
  - » LCGT (Japan), ET (Europe).

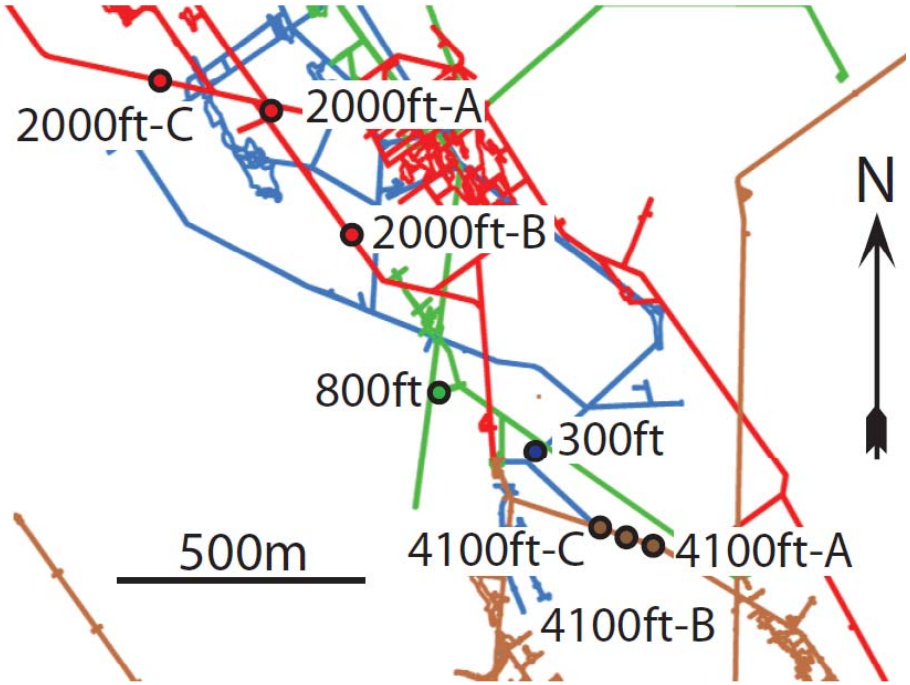


Newtonian Noise

- Or gravity gradient noise: fluctuations in the local gravitational field.
- On surface, estimate equivalent strain of ~10^{-20} $Hz^{-1/2}$, at 1 Hz.
  - Need ~10^3x suppression at 1 Hz.
- Three dominant contributions:
  - Atmospheric fluctuations: negligible underground due to controlled environment.
  - Human factor (traffic etc): strongly suppressed underground due to limited access, controlled use of machinery etc.
  - Seismic noise: significantly reduced underground (10x at 1 Hz).
- Need another 100x suppression of seismic Newtonian noise:
  - Measure the seismic motion “everywhere”, subtract its gravitational effects.
- In a stationary, infinite, uniform medium, one measurement is enough.
  - In reality, surface effects, fault lines, density fluctuations may matter.
  - May need an array of seismometers.
- Need to quantify these effects.
  - Measurements and finite-element modeling!

DUGL at DUSEL

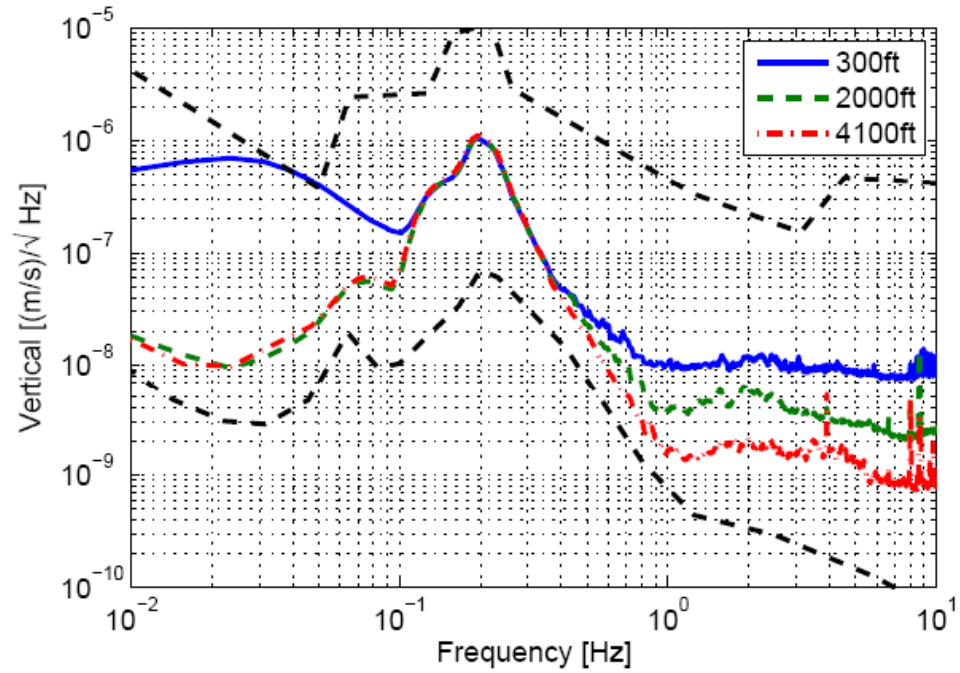
- Deep Underground Gravity Lab at DUSEL:
  - » Minnesota, Caltech, NIKHEF, Columbia, Florida, Carleton.
  - » Characterize the low gravitational and vibrational background at Homestake.
  - » Inform the design of a Third Generation gravitational-wave detector.
  - » Geophysics: seismic wave propagation, local seismic activity (Homestake mine and Black Hills area).
  - » Torsion balance experiments for equivalence principle tests, rotational modes of the Earth.
- Array of synchronized seismic stations:
  - » 8 stations, probing the available volume.

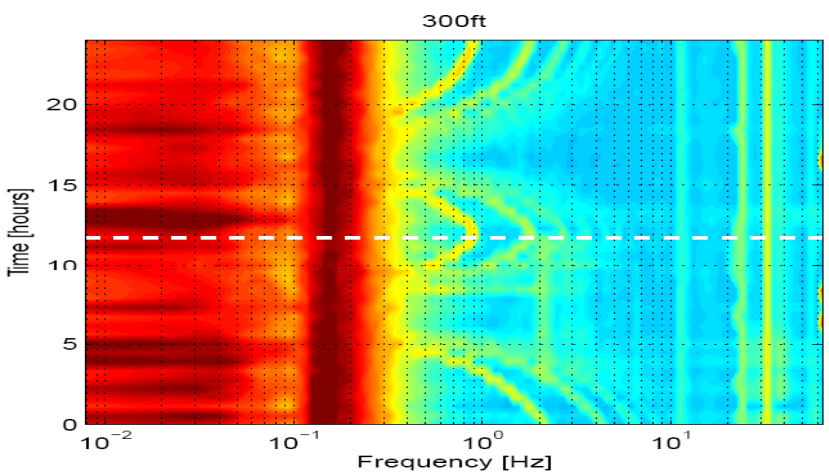


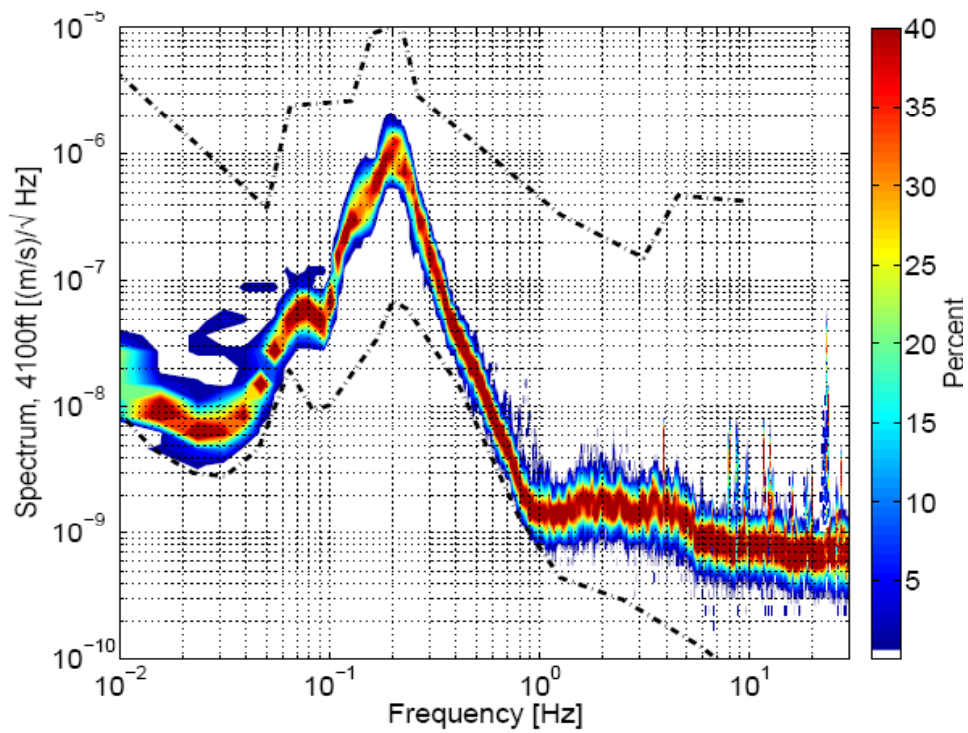
Each station:
- High sensitivity broadband seismometer
- Environment monitors (T,p,B…)
- Timing: sub-1 us, aLIGO prototype

First Results

- Seismic noise level at several depths.
  - ~10x quieter than LIGO sites at 1 Hz.
- Matches (or even surpasses) the Peterson 1993 low-noise model.
  - Very quiet seismic environment.
  - Of interest in geophysics.
- Observe various local effects:
  - Ventilation maintenance at 300 ft.
  - Blasting, at Homestake and elsewhere.
- Accepted for publication in CQG.



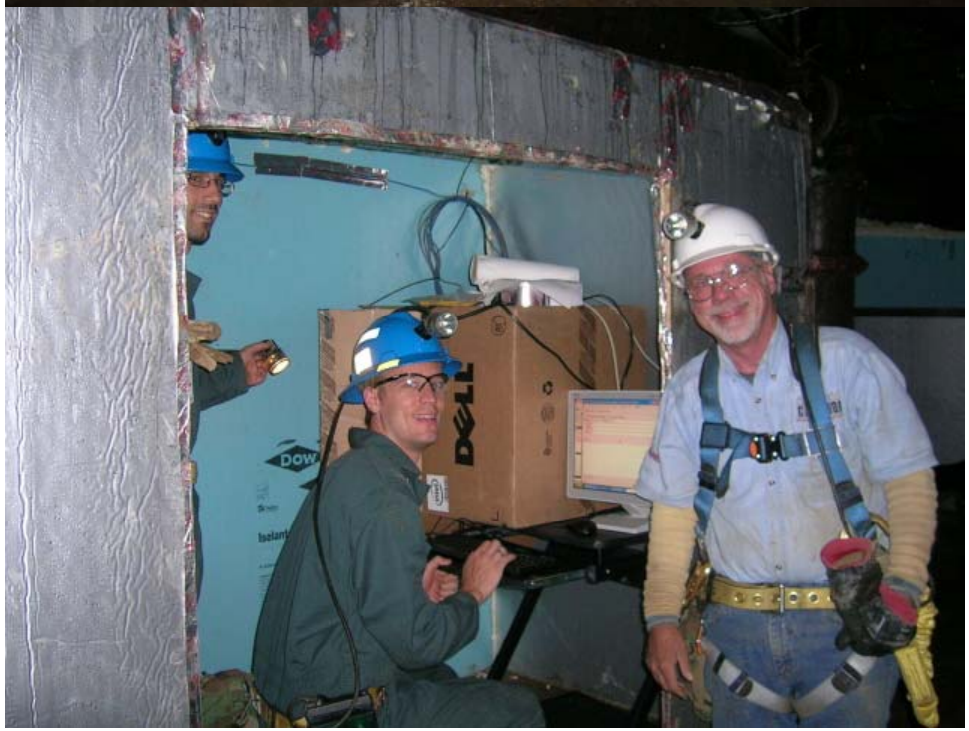




Requirements

- Remote locations, blind alleys.
- Concrete pad on bedrock.
- Nested polyurethane huts.
  - » Including huts for DAQ.
- 110V power (with UPS).
- Optical fibers (network and timing).
- Surface computing: merge/package data from all stations, send it out.

- Long term: build ~50 stations, spanning the available depth and horizontal extent of the mine.
  - » 3D tomography.
  - » Study effects of of fault lines, density non-uniformity etc.



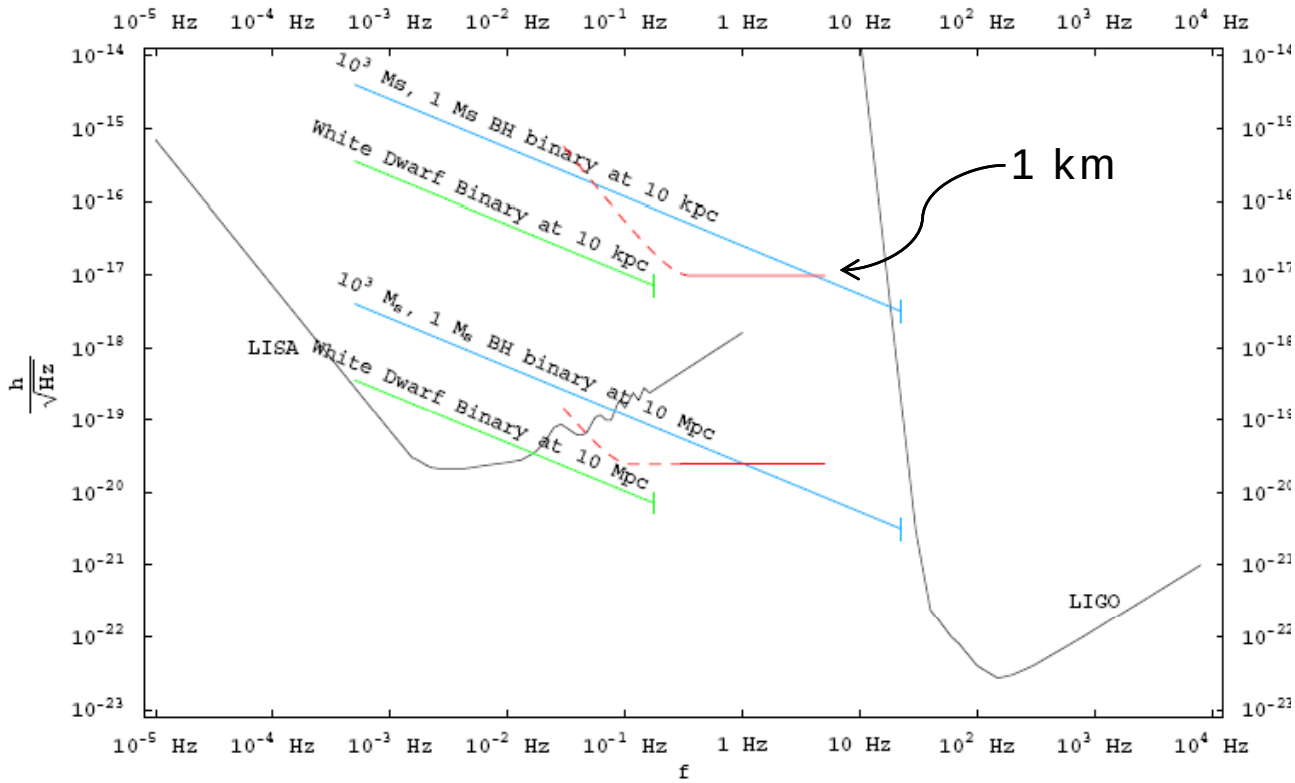
Atom-Interferometric Gravitational-Wave Detector

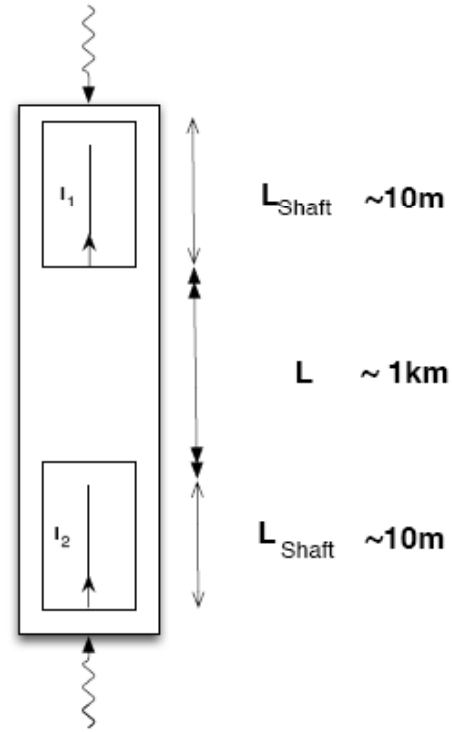
(for Mark Kasevich)

- Atom interferometry technology already applied in various fields.
  - Gradiometers, gravimeters, atomic clocks, gyroscopes…

- Two atom-interferometer configuration can be used to search for gravitational waves.
  - Focus on low frequencies, ~0.1-10 Hz.
  - Same scientific motivation as in the case of laser-interferometer detectors.

DUSEL/Terrestrial Atom Interferometer





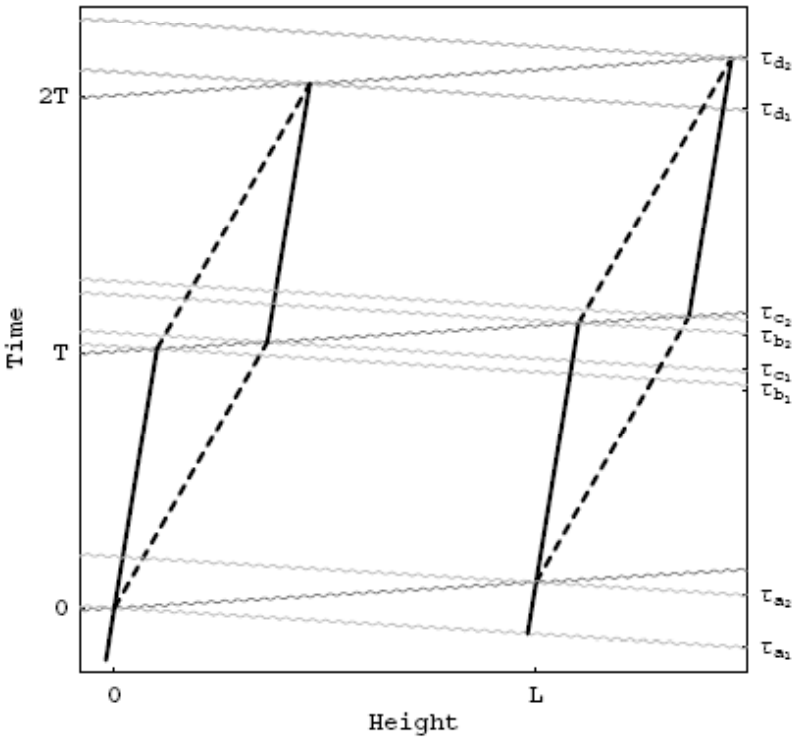
Setup	L	k_{eff}	T	I_L	Phase Sensitivity	f_d
Terrestrial 1	1 km	1.6×10^9 m^{-1}	1.4 s	10 m	10^{-4} rad	10 Hz
Terrestrial 2	4 km	1.6×10^{10} m^{-1}	4.5 s	100 m	10^{-5} rad	10 Hz

S. Dimopoulos, P. W. Graham, J. M. Hogan, M. A. Kasevich, and S. Rajendran, Phys. Rev. D **78**, 122002 (2008).

Gravity wave detection

Metric:

$$ds^2 = dt^2 - (1 + h\sin(\omega(t-z)+\phi_0))\,dx^2 - (1 - h\sin(\omega(t-z)+\phi_0))\,dy^2 - dz^2$$



Differential accelerometer configuration for gravity wave detection.

Atoms provide inertially decoupled references (analogous to mirrors in LIGO)

Gravity wave phase shift through propagation of optical fields.

Gravity wave induced phase shift:

$$\Delta\phi \sim h\,L\,\sin^2(\omega T/2)$$

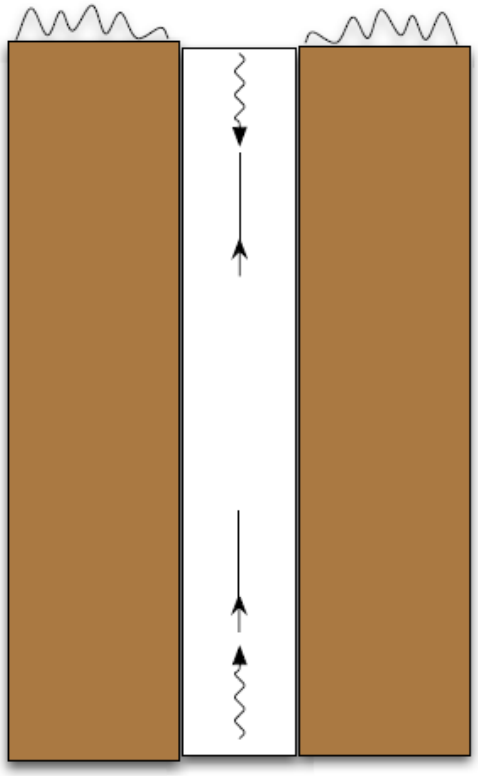
h is strain, L is separation, T is pulse separation time, ω is frequency of wave

Previous work: B. Lamine, et al., Eur. Phys. J. D **20**, (2002); R. Chiao, et al., J. Mod. Opt. **51**, (2004); S. Foffa, et al., Phys. Rev. D **73**, (2006); A. Roura, et al., Phys. Rev. D **73**, (2006); P. Delva, Phys. Lett. A **357** (2006); G. Tino, et al., Class. Quant. Grav. **24** (2007).

Stanford laboratory proof-of-concept

Long free-fall enables ground-based assessment of possible space-based sensor implementations.

Technical challenges



Seismic fluctuations give rise to Newtonian gravity gradients which can not be shielded.

Benefit from DUSEL seismic environment.

- Seismic and Newtonian gravity noise.
  - Similar to laser-interferometers.
- Advanced, high flux atom source development:
  - High rep rate, high flux source of cold atoms
  - 10 Hz, 10^8 atoms/shot
  - Requires incremental advances in current technology
- Large momentum transfer atom optics
  - Enhances sensitivity
  - Demonstrated N ~ 10
  - Desired N ~ 100
  - Work in progress

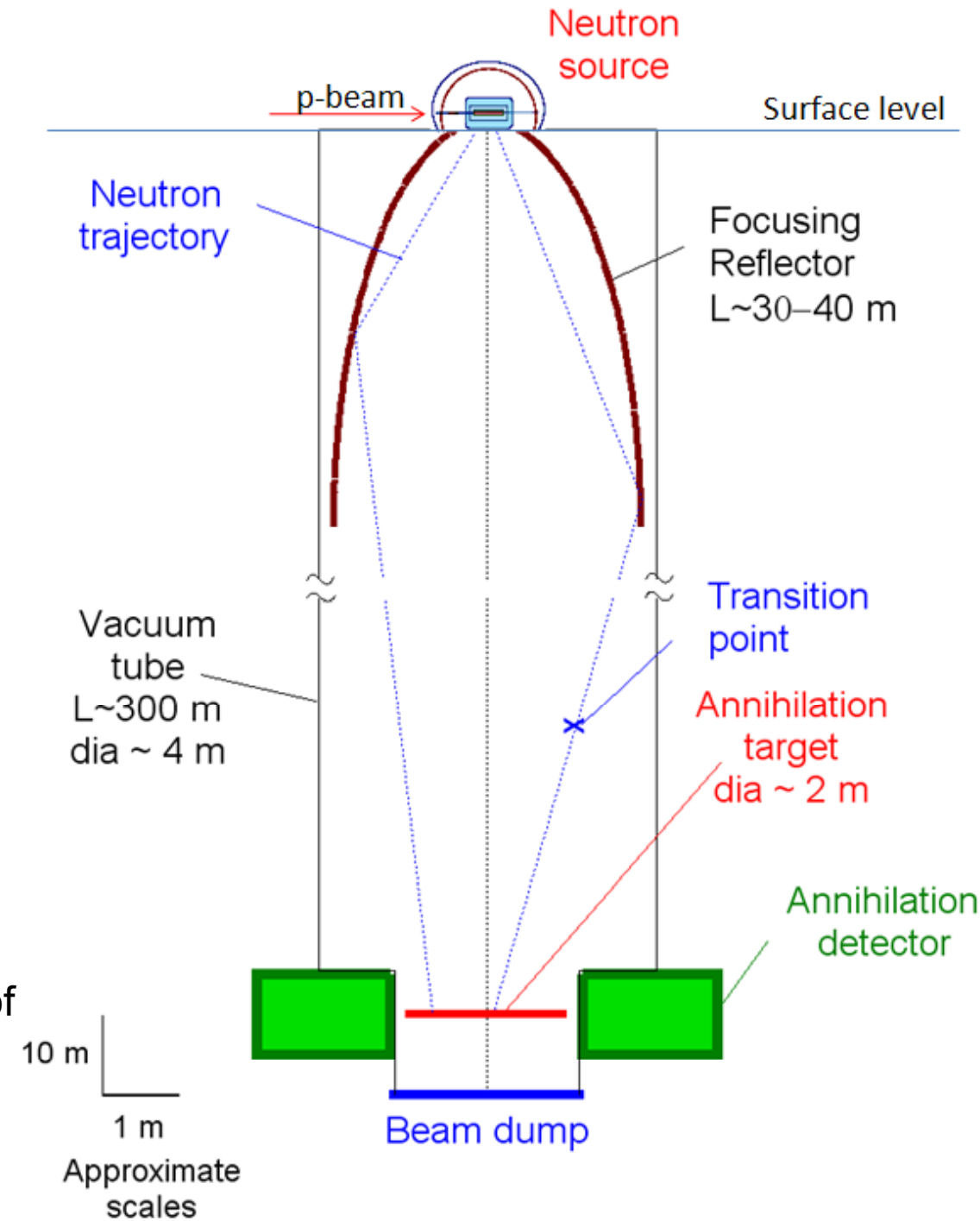
N-Nbar Collaboration

(for Yuri Kamyshkov)

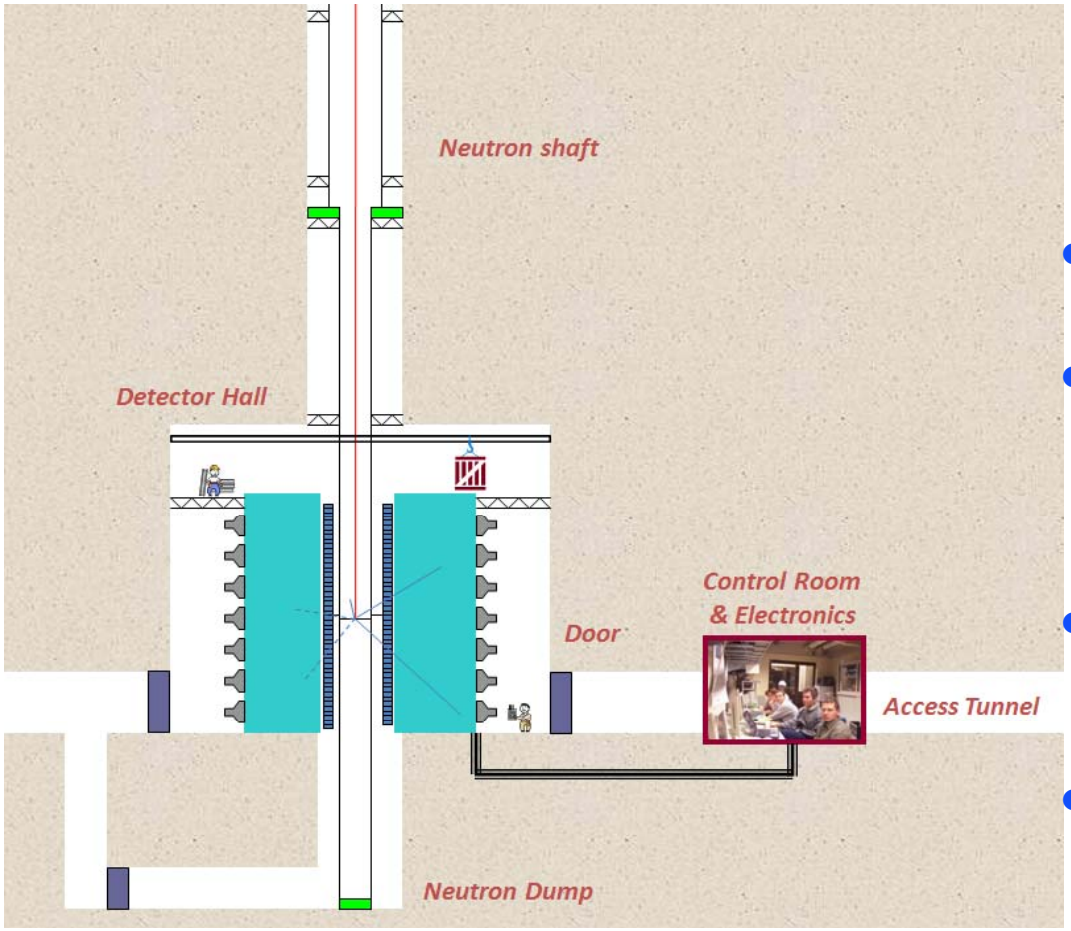
- Neutron-antineutron oscillation would reveal physics beyond the Standard Model.
  - » Baryon instability (decay, oscillations)
  - » New force of nature
  - » B-L violation scale
  - » Quark-lepton unification
- N-Nbar experiment at DUSEL has the potential to improve sensitivity ~1000 times.
- With small changes, can measure reduction in neutron flux – search for mirror matter (alternative to SUSY dark matter).
- Proposed for beyond the Initial Suite of Experiments.

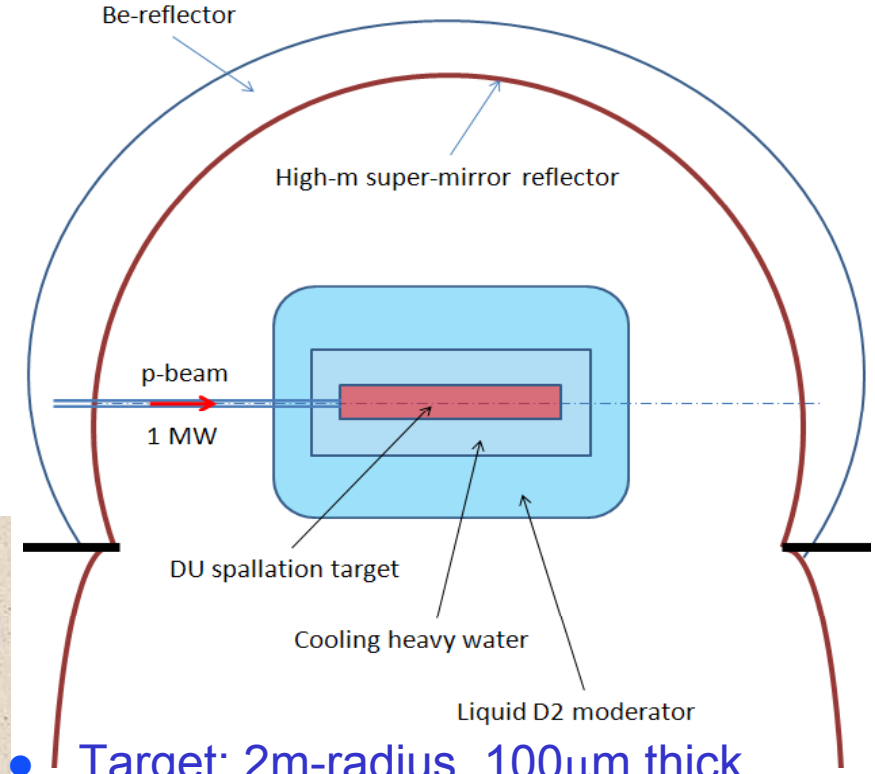
Experiment Design

- Create slow neutrons on surface: compact accelerator with spallation target.
- Inject them into a vertical vacuum tube, >300m long.
- Focus the beam with super-mirror reflector.
- Some neutrons oscillate into antineutrons.
- Antineutrons interact with the carbon annihilation target, producing several pions.
- Zero-background: observation of a single event is a detection.
- Beam dump at the bottom.



- Source: cyclotron producing a proton beam onto a depleted uranium spallation target.
- Cooling: heavy water and liquid deuterium, producing slow neutrons.
- Beryllium or graphite dome as neutron reflector.





- Target: 2m-radius, 100μm thick carbon film.
- Detector hall: 16m high, 12m diameter.
  - Tracker, calorimeter, cosmic veto.
- Vacuum tube continues down another 20m where the beam dump is installed.
- Need access to both detector and beam dump, as well as a control room near detector.

Requirements and Hazards

- Vertical vacuum tube, at least 200m long, 4-5m diameter.
  - » As long as possible (sensitivity ~ length^2).
  - » Existing or new shaft or winze.
  - » Vacuum <10^{-4} Pa (10^{-6} mbar).
  - » Active magnetic compensation to suppress Earth's magnetic field to ~1nT
- Source could be on surface or at a deeper level.
  - » But there are important cooling power requirements.
- Require access to source, detector, beam dump, and multiple mid-levels (pumps, magnets etc).
- Hazards:
  - » Large vacuum volume.
  - » Radiation hazards (source, beam dump).

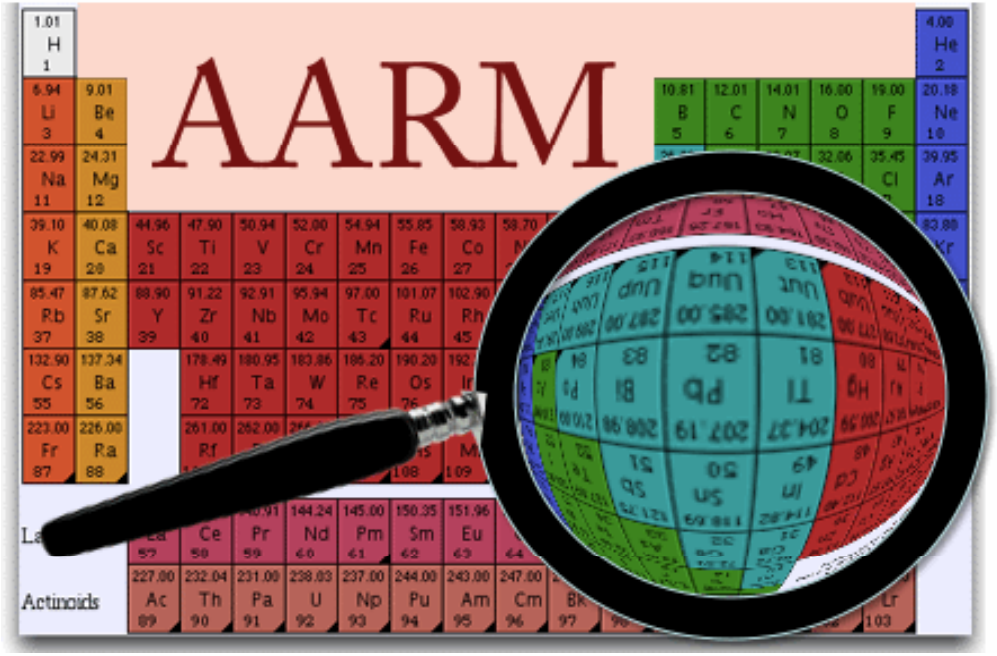
Assay and Acquisition of Radiopure Materials

Principle Investigators

Priscilla Cushman (University of Minnesota)
Dongming Mei (University of South Dakota)
Kara Keeter (Black Hills State University)
Richard Schnee (Syracuse University)

Engineering Consortium

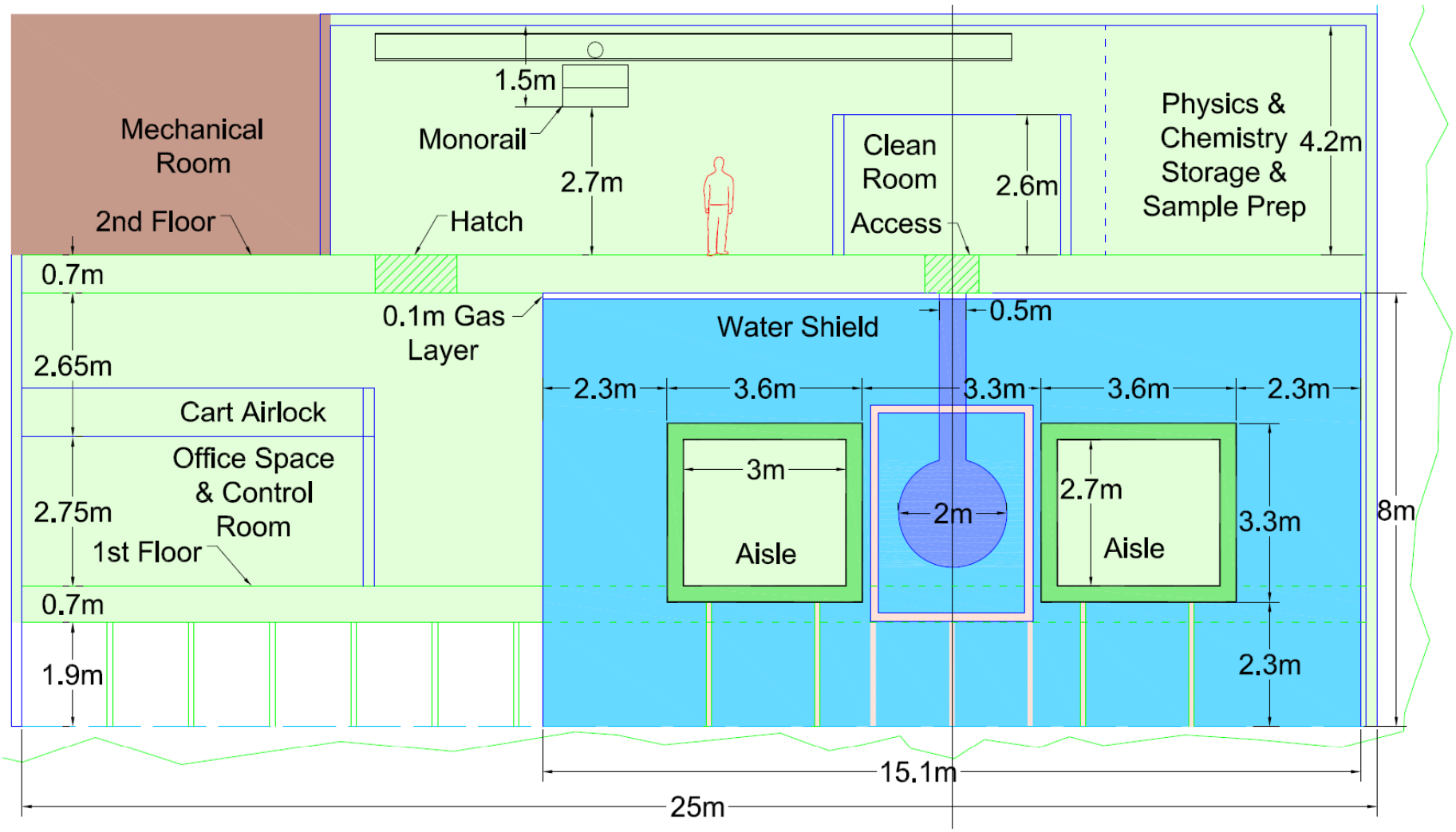
CNA Consulting Engineers (Lee Petersen)
Dunham Associates
Miller Dunwiddie Architecture, Inc



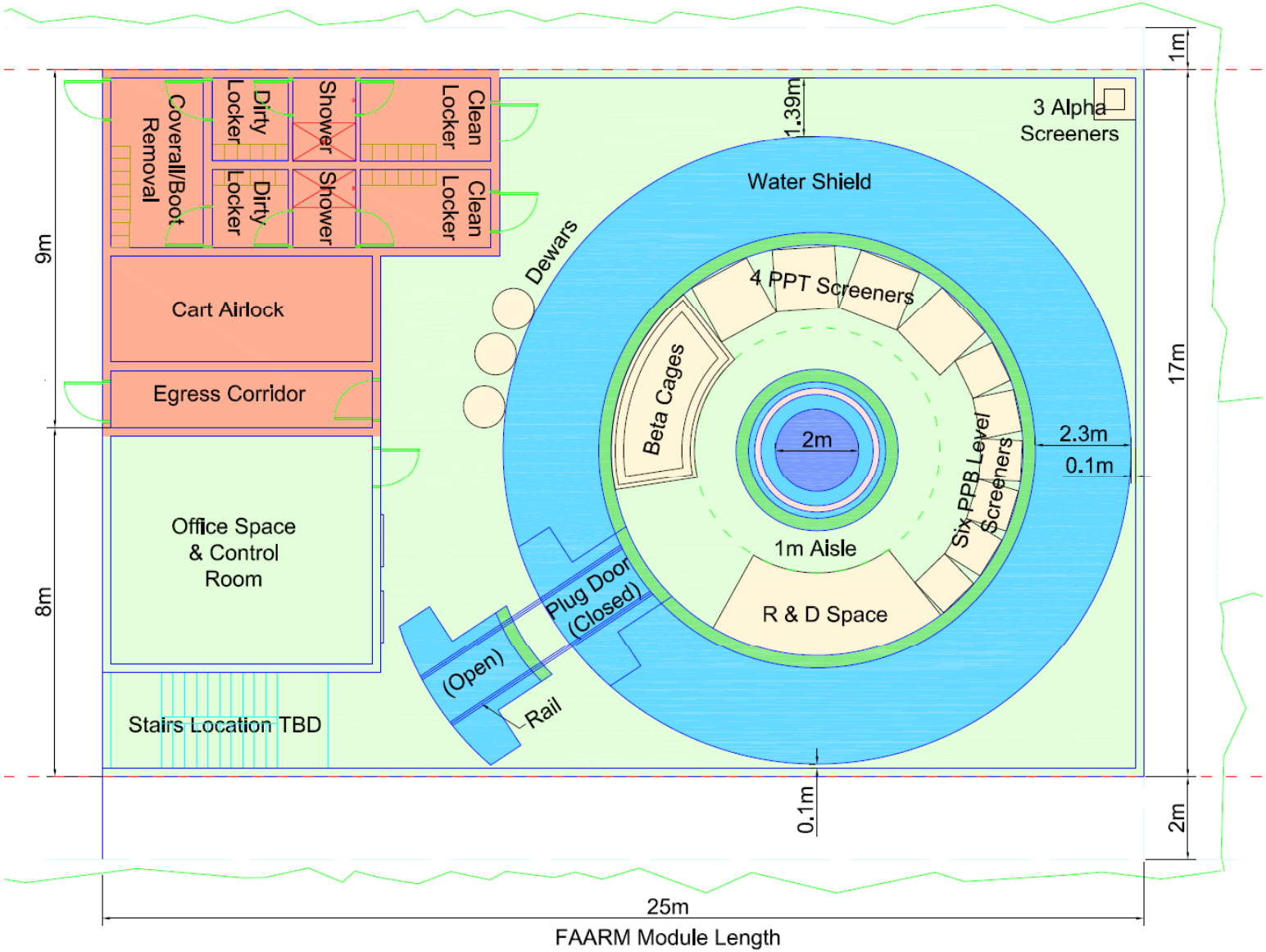
An NSF S4 (~ $1M) was awarded for these specific tasks

- Characterize radon, neutron, gamma, and alpha/beta backgrounds at Homestake
- Develop a conceptual design for a common, dedicated facility (**FAARM**) for low background counting and other assay techniques
- Assist where appropriate in the creation of common infrastructure required to perform low background experiments.
- Perform targeted R&D for ultra-sensitive screening and water shielding

FAARM is the
FACILITY for Assay and Acquisition of Radiopure Materials



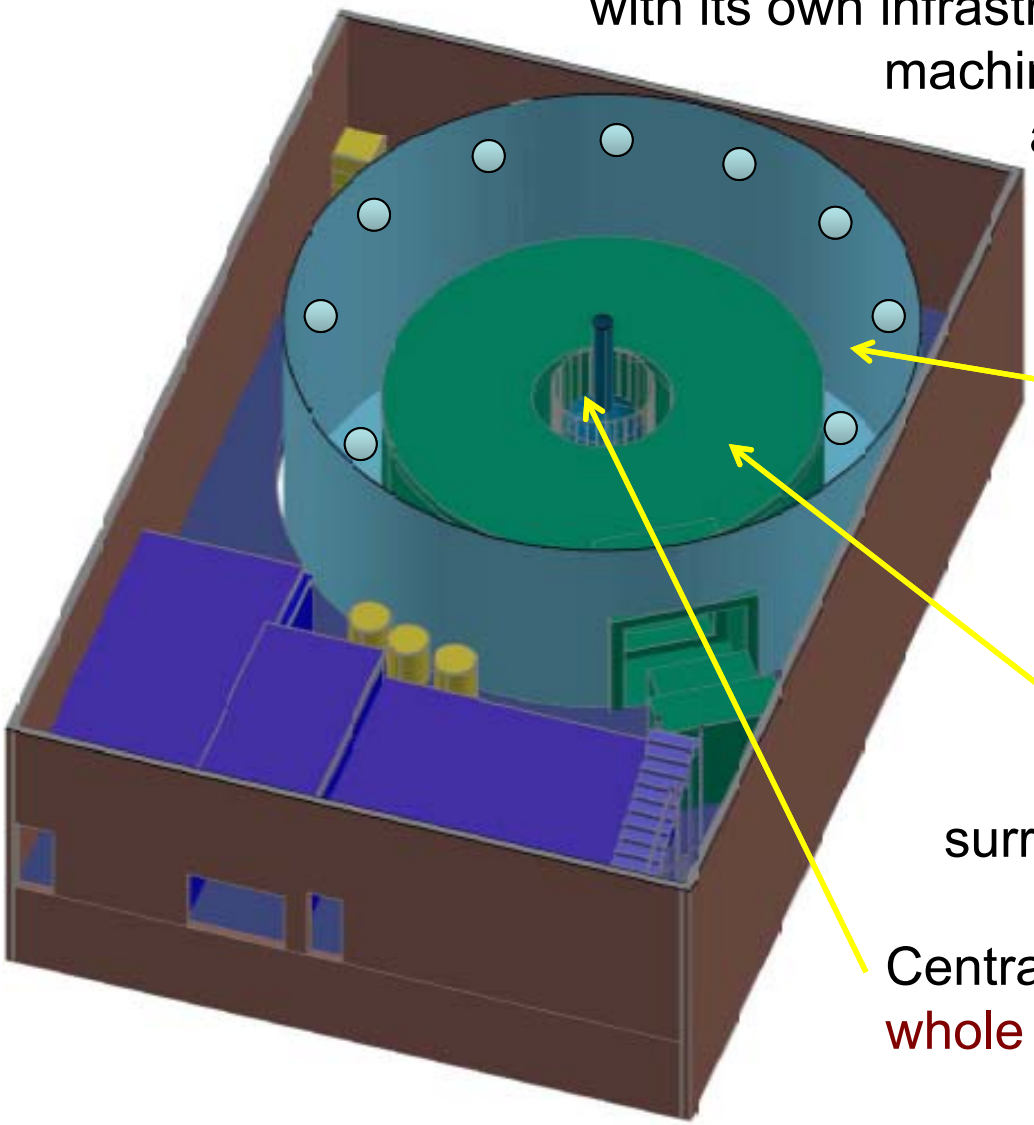
FAARM First Floor



FAARM is located on the 4850 level

Entire facility is a self-contained class 10,000 clean room with its own infrastructure, incl. safety, showers, offices, machine shop, plus clean rooms for assembly, sample storage, etc…

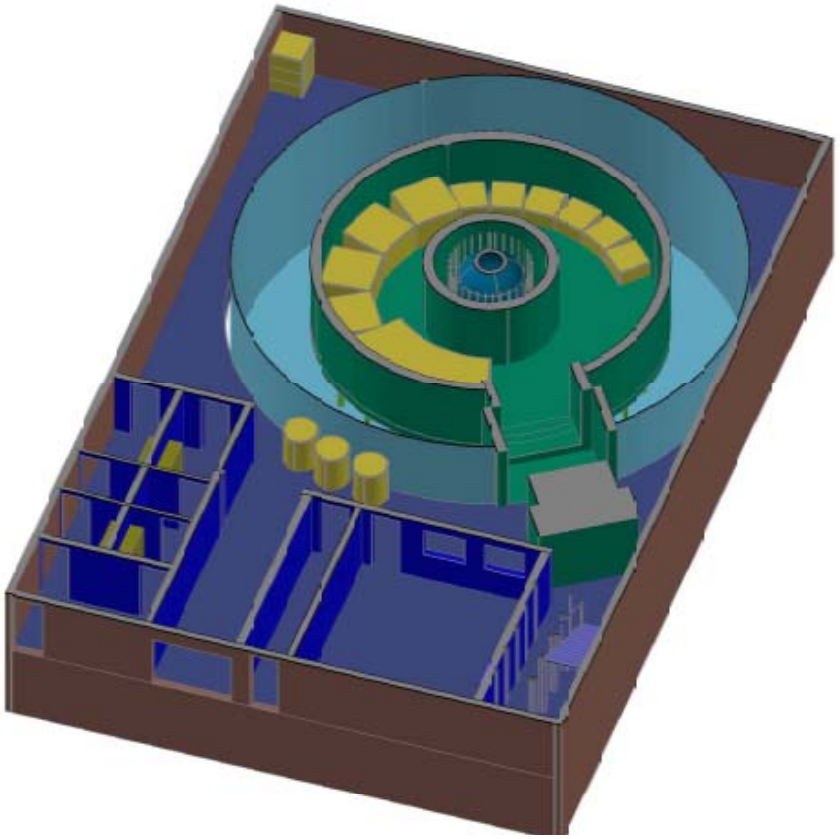
Designed to accommodate all users: physics/bio/geo



15m diam x 8m high stainless tank
(standard tank construction)
pure water with PMT muon veto
(upgrades: LS or B-loading)

Acrylic Tunnel Lab with screeners
(standard aquarium construction)
surrounded by a 2.3 m thick water shield

Central slot reserved for ultra-sensitive whole body counter or germanium array

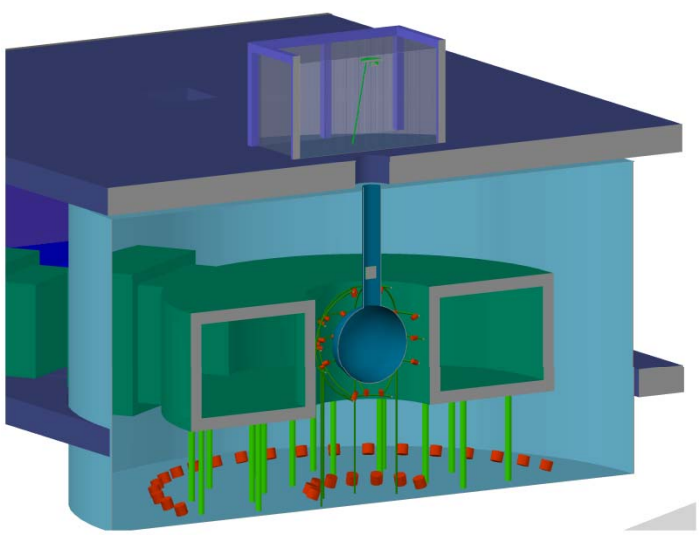


Inner Tunnel Lab

γ-flux 7.974×10^{-5} $cm^{-2}\ s^{-1}$
n-flux 4.817×10^{-10} $cm^{-2}\ s^{-1}$

4 < ppt (GeMPI, arrays)
6 < ppb (well, clover, coax)
2 Beta Cages
Prototyping Space
(DM or $0\nu\beta\beta$ or novel assay)

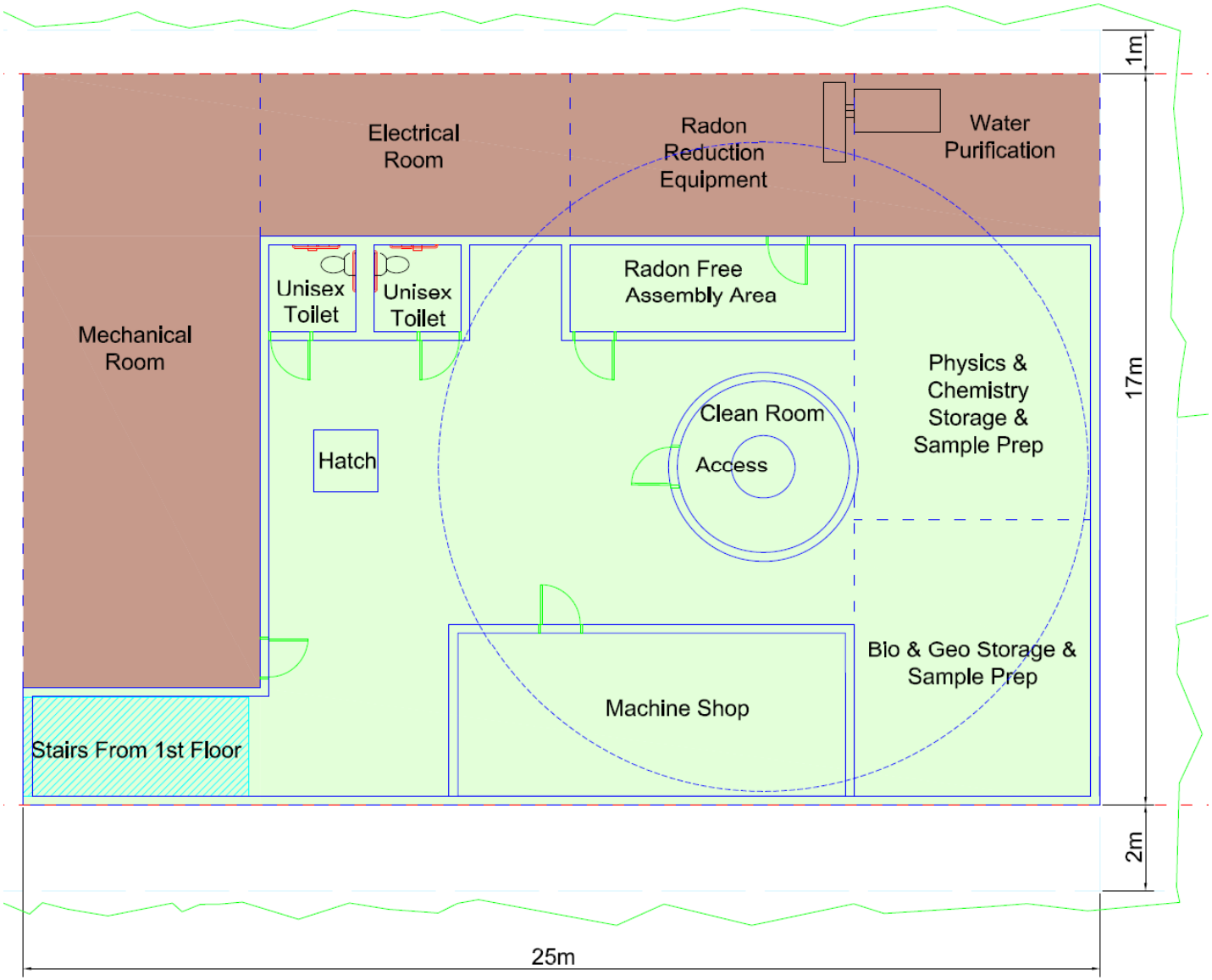
Radon Mitigation
Common cryogen plumbing and
LN boil-off for screeners



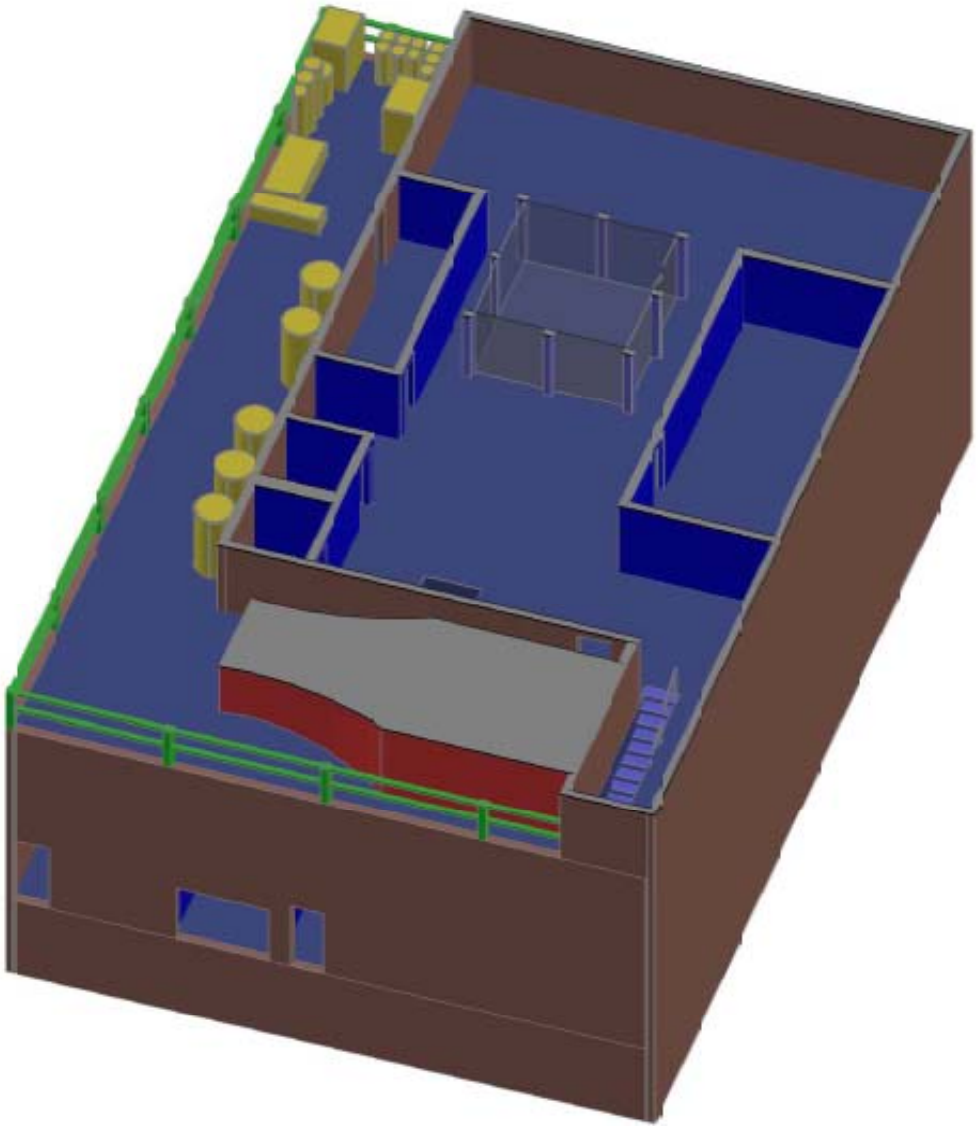
Central Pool

0.1 counts/day, E > 250 keV
sensitivity of 10^{-14} g/g U/Th 10^{-12} g/g K
modeled on Borexino CTF
2m diam nylon vessel filled with LS
Observed by low rad QUPIDs
Top-loading from dedicated Clean Room

FAARM Second Floor



FAARM utilities accessed from outside building



Complete Resource-loaded Schedule
S4 ➔ FAARM

Schedule

2009-14: Complete design, R&D, simulation, Homestake characterization
2014-17: photodetectors, nylon vessel, LS and water purification systems, Rn reduction, detailed engineering
2017-18: Civil construction (building & infrastructure, tank, tunnel)
2018-19: Installation and commissioning

Cost

7.2 M in equipment, M&S, contracted structures
1.6 M in labor: *0.7M scientific staff (mostly base funding)*
0.9M engineering

Minimal Functionality could be achieved with
$ 3 M instrumented pure water shield with inner lab
(includes Rn mitigation, clean room protocols for inner lab, water purification)

Can then add **$ 2.5 M** for the LS whole body screener
Later you might add infrastructure: **$ 3 M** for a building.

Model for Deployment

We have 8 years to move from a model of

dedicated screeners ➔ centrally managed system

This will require the entire community to

Determine needs for next decade

Form a coherent community with official reps to each experiment

through AARM S4 (Nov 12-13 collab meeting)

through Low Radioactivity Techniques (Aug 28-29, and new wiki)

Build up capacity (in multiple sites)

Seek out new funding sources and proposals for shared equipment

Tie this to DUSEL via

lease arrangements, matching funds, MOUs (?)

Fund a dedicated effort to design the ultra-sensitive central pool assay

2018: Move the most sensitive screeners into FAARM shield

Collect less sensitive screeners as needed under one roof.

Install the central pool assay

Extra Slides

Elements of FAARM

Entire facility is class 10,000 clean room, < 20 Bq/m^3

Several class 1000 clean rooms
Ateko (NEMO facility provided 0.01 Bq/m^3 breathable air at 150 m^3/h)
Radon-mitigated zones (<1 Bq/m^3) and assembly areas (<0.1 Bq/m^3)
Radon-free storage and unified LN system
Wet benches, clean machining, hoods, etc

Instrumented Water Shield with toroidal interior acrylic room

Houses ultra-sensitive screeners (GeMPI style, BetaCages)
Reduce cost of individual lead shielding ($2M savings)
Active Muon veto, Neutron & Gamma shielding
Outer shield of Immersion Tank, Space for Experiments & R&D Prototypes

Top-loading Immersion Tank

Modeled on the Borexino CTF
Whole body counting with 0.1 counts/day, E > 250 keV
U/Th at .01/.04 ppt, surface α,β at < 1 count/m^2/day (unsealed)
6 x 10^{-6} cts/kg/keV/day from Compton continuum
OPTION: *Could be replaced by highly segmented germanium*

Elements of FAARM

Served by a trained technical staff

Develop staff in the Early Screening Program (DULBCF)
Scheduling tools to optimize efficient use of screeners
Integrate with worldwide screening
In-house analysis tools and database
Transition the screening in a phased manner

Less sensitive screeners benefit from common facility

outside shield but inside clean area

Radon emanation, XIA alpha screeners, conventional HPGe

Areas for bio/geo/physics assembly

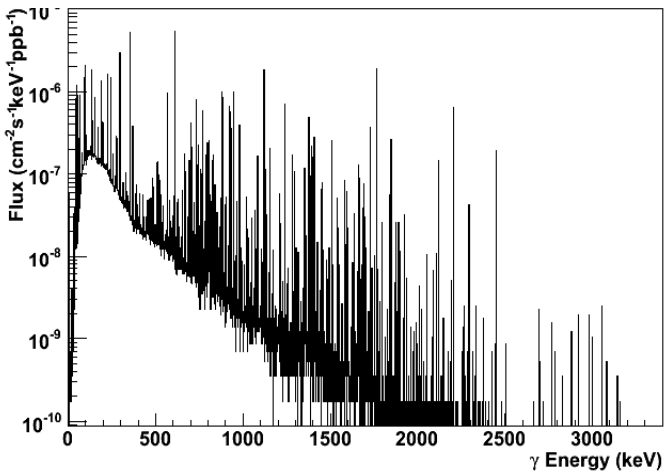
Intellectual center for a new field of low background studies

Water Shield Simulations

Optimize shield thickness

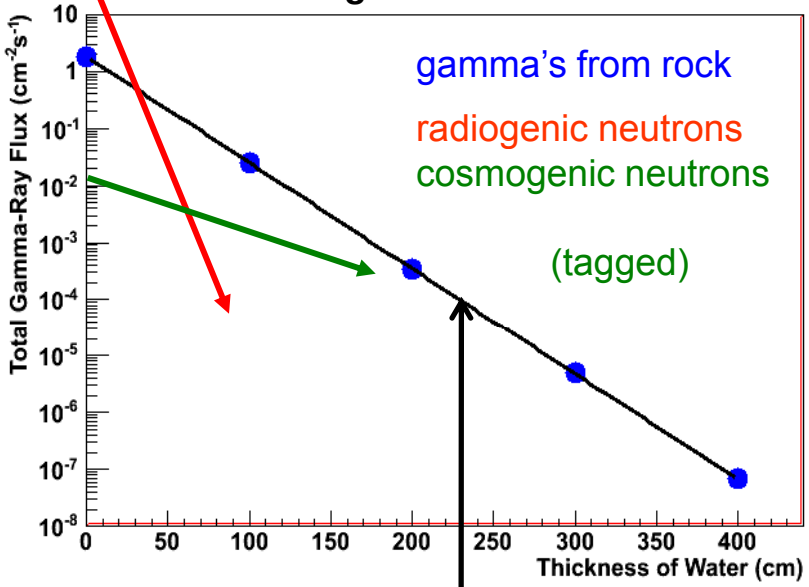
Rock (Homestake 4850')

^{238}U 0.55 ppm ^{232}Th 0.3 ppm ^{40}K 2.21%



X

Attenuation through Water + Stainless Steel



Contam	Stainless Steel		Acrylic
^{238}U	0.1 ppb	9.5×10^{-6}	24 ppt
^{232}Th	0.1 ppb	2.3×10^{-6}	14 ppt
^{40}K	0.028 ppb	1.2×10^{-6}	2.4×10^{-4} ppb
^{60}Co	4.6×10^{-10} ppb	6.4×10^{-5}	
	Total:	7.7×10^{-5}	Total: ~10^{-5}

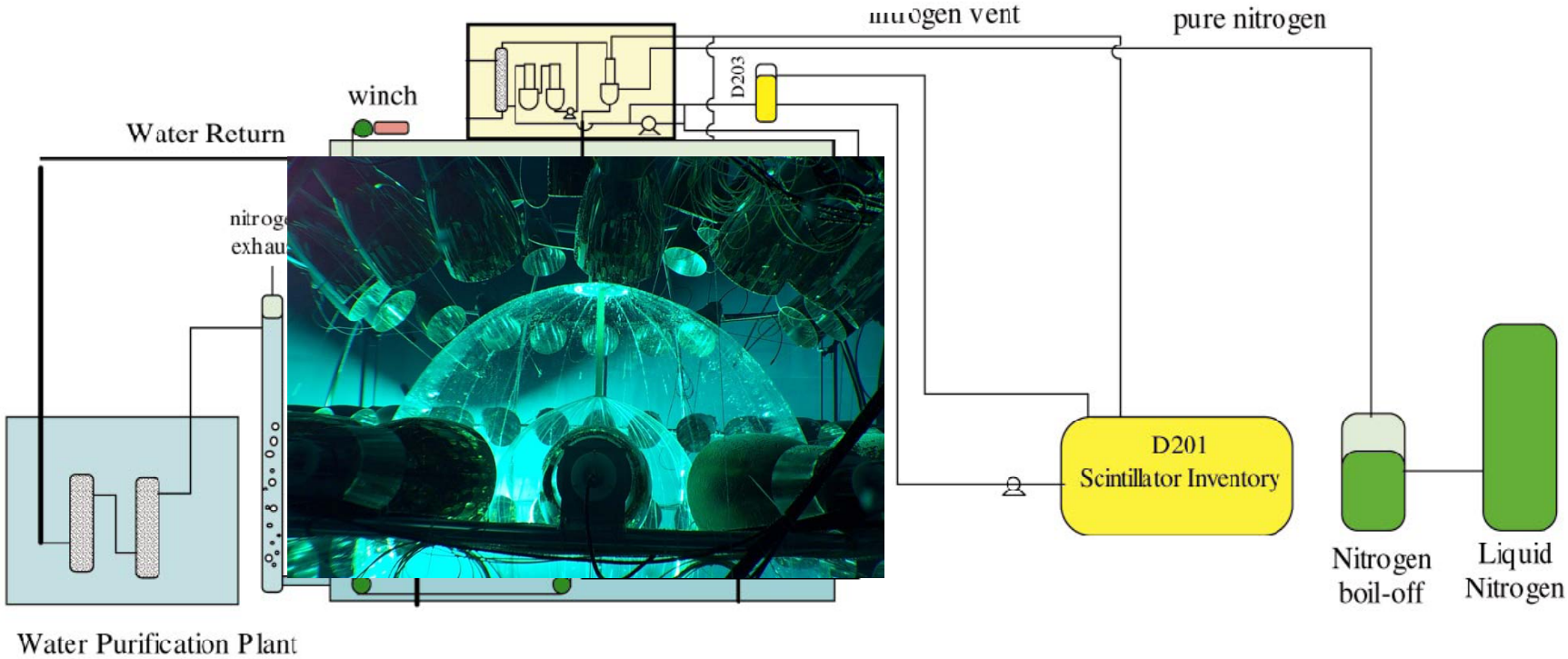
vs

Cavern radioactivity
after 2.3 m thick wall

γ 7.974×10^{-5} /cm^2/s
n 4.817×10^{-10} /cm^2/s

Borexino Counting Test Facility

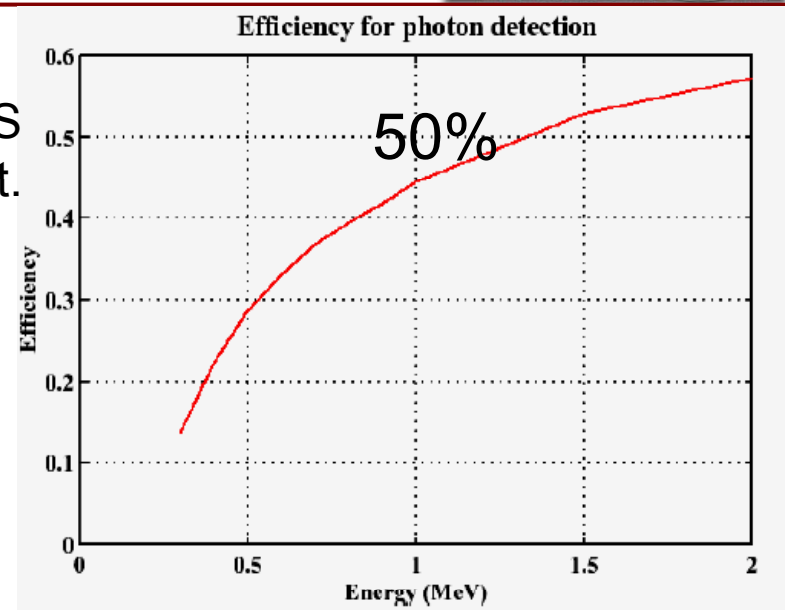
- 4 tonnes of scintillator (PC + 1.5 g/L PPO)
- 1m radius 500μm Nylon vessel for scintillator
- 2 m radius “shroud” vessel to shield Rn
- 3.6 p.e./PMT for 1 MeV electron
- Muon veto PMTs on floor
- 100 PMTs (Optical coverage: 21%)
- Buffer of water – 2.3m vessel to PMT
- Energy saturation: 6 MeV



CTF-like Immersion Tank for Screening

Water shield becomes outer shroud and veto
Low radioactivity QUPIDs can be placed closer to LS
Bigger 2 m diam. nylon bag filled with LAB Liq. Scint.
Established purification methods
(10^{-16} g/g U/Th andd 10^{-14} g/g K)

- *Distillation (also removes Rn)*
- *Water extraction*
- *N_2 stripping*
- *Solid-column adsorption*



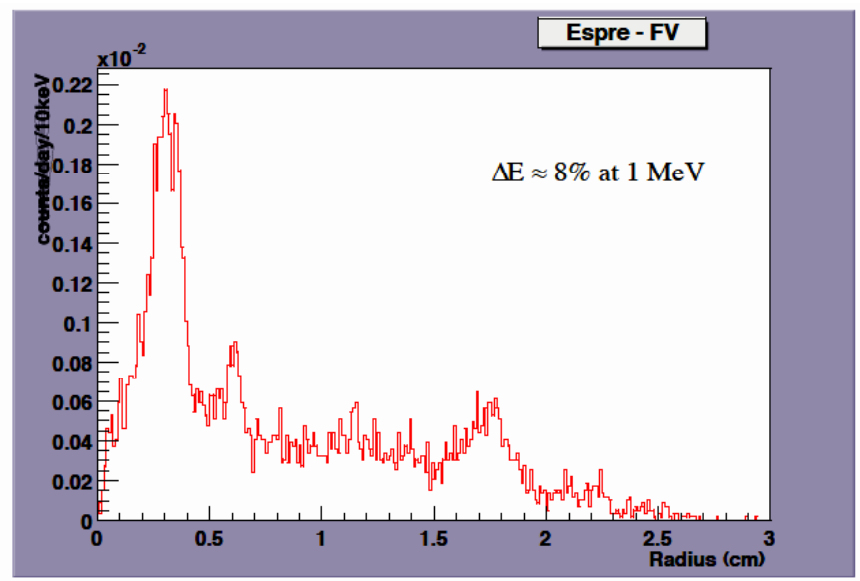
Sensitive to

- *bulk gammas*
- *betas and alphas from surface*
- *betas inside 50 μm nylon sample bag*

Moderate energy resolution & Efficiency

Distinguish

- β:γ via event reconstruction
- α via pulse shape



Need a Rational Plan until 2018 and how to transition to FAARM

Sanford Lab does NOT have enough room in Davis, nor funds to purchase screeners

Utilize existing underground sites and screeners until FAARM is ready
Then - move the most sensitive screeners into FAARM shield
collect less sensitive screeners as needed under one roof.

Most important aspect of FAARM is the active SHIELD
- Shield transforms sensitive screeners into ultra-sensitive
- Central pool can house a 3rd generation screener
- Shield has been optimized for COST:
  - ~ $200k per Screener + Shield for prototype experiments

Move from model of dedicated screeners to a centrally managed system
- Determine needs for next decade
- Begin to build a coherent team and staff
- More efficient scheduling and new shared purchase schemes
- Find new sources of funding: EPSCOR, Sanford, University infrastructure …