Archimedes & Honey Bees

Design Considerations for Large Monolithic Detectors

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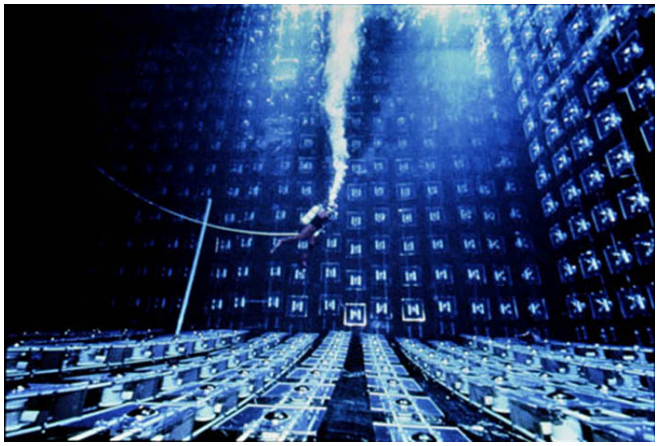
4/12/2018

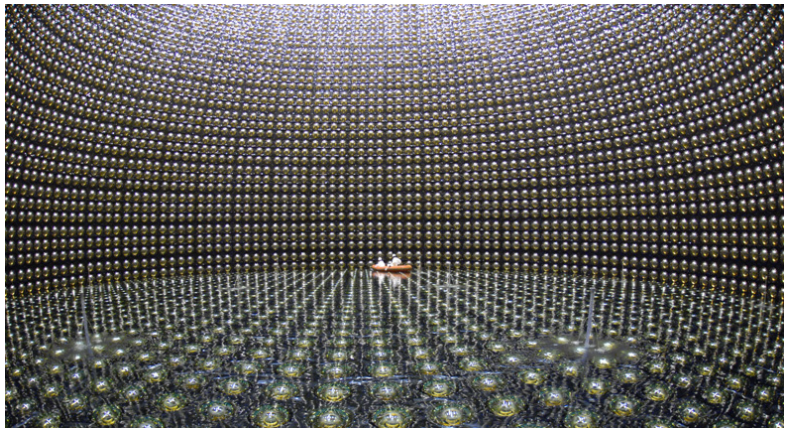
Outline

- **Shape- Target volume : Effective photocathode area**
  - **Interaction rate : Cost of PMTs + electronics**
- **Light concentrators (LCs) recover solid angle lost to buffer**
  - **SNO+, Borexino use inexpensive, low radioactivity LCs**
- **Elevated tanks reduce concrete footprint and radioactivity**
- **Light collection potential determined by tessellation**
  - **Hexagonal (91%) beats square (78%) beats triangle (61%)**

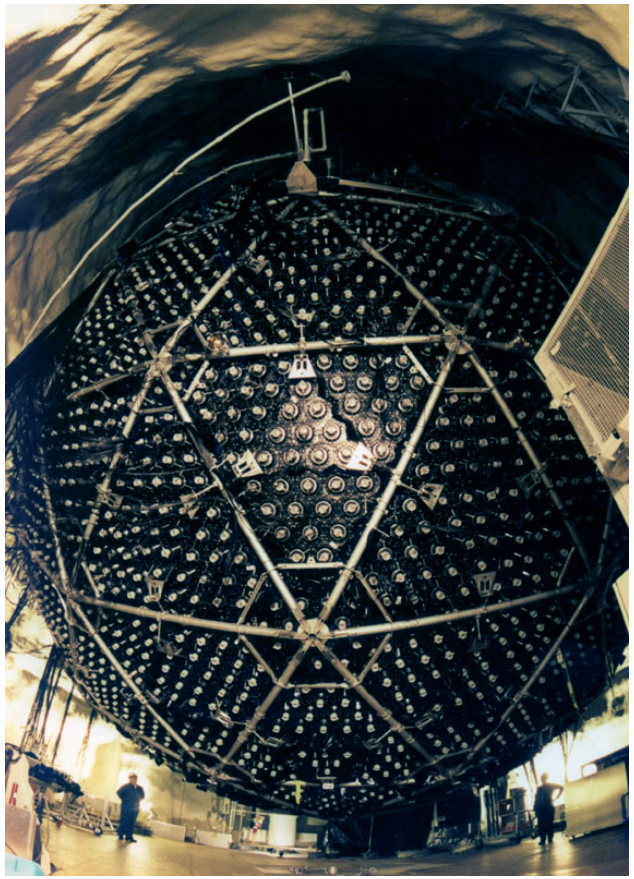
Detector Shapes



IMB- ~cube



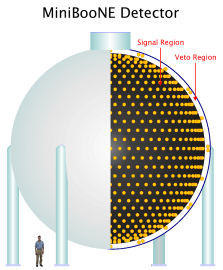
SK- cylinder



SNO- sphere

TABLE I. Comparison of the geometric factors relating volumes, surface areas, and characteristic lengths of the cube, cylinder, and sphere for the cases of fixed area and fixed volume.

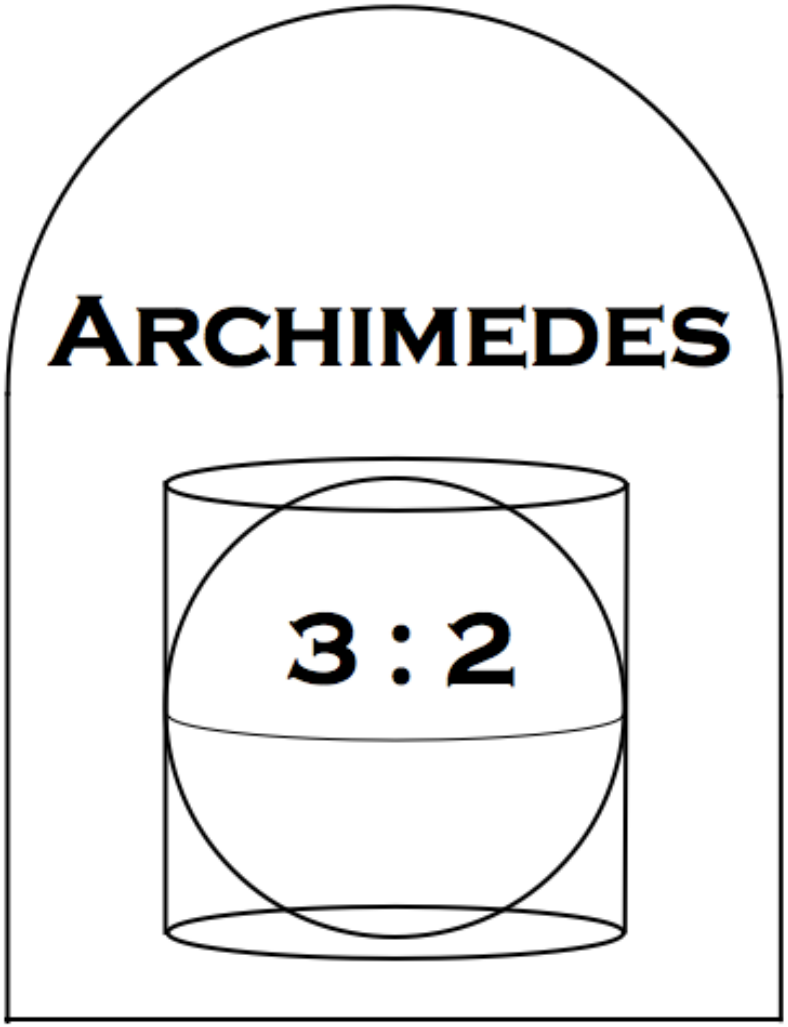
	Cube	Cylinder	Sphere
Volume (fixed area)	$\sqrt{\pi}/2$	1	$\sqrt{3/2}$
Area (fixed volume)	$\sqrt[3]{4/\pi}$	1	$\sqrt[3]{2/3}$
Radius (fixed volume)	$\sqrt[3]{\pi/4}$	1	$\sqrt[3]{3/2}$
Radius (fixed area)	$\sqrt{\pi}/2$	1	$\sqrt{3/2}$



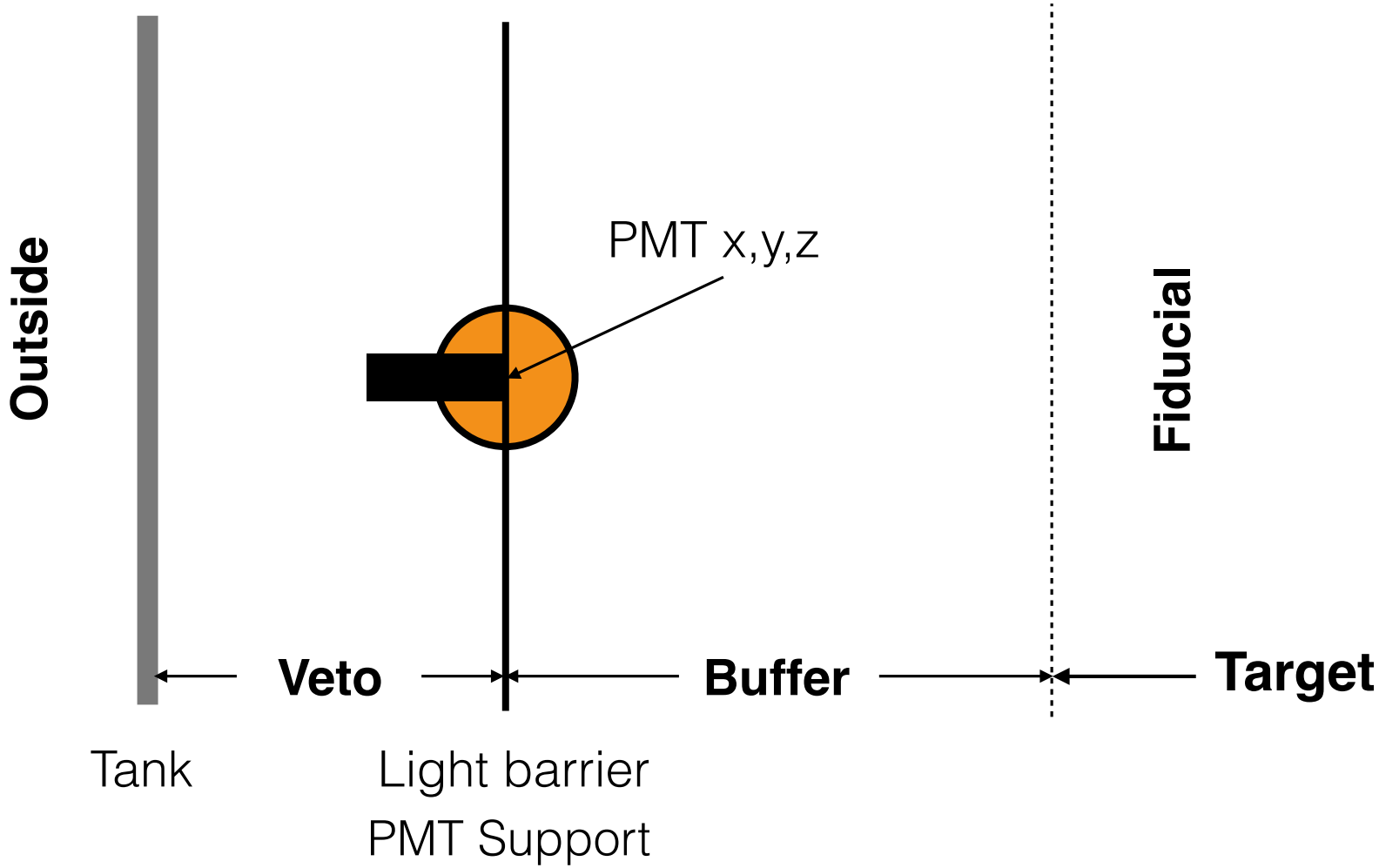
MiniBooNE - sphere

Archimedes

- **Cylinder ($h = 2r$) : Sphere (r)**
  - **Volume- V_c:V_s is 3:2**
  - **Area- A_c:A_s is 3:2**
- $r_s / r_c = (V_s / V_c) * (A_c / A_s)$
- $V_s / V_c = (3/2)^{+1/2}$ **(fixed area)**
- $A_s / A_c = (3/2)^{-1/3}$ **(fixed volume)**
- **Sphere is most effective shape for collecting light from enclosed volume**



Definitions



Target Volume Uncertainty

- **Important for absolute signal rate measurement**
- **d*V* = *A* d*r***
- **Sphere : Cylinder : Cube 1.000 : 1.145 : 1.241**
- **Sphere capable of most precise rate measurement**

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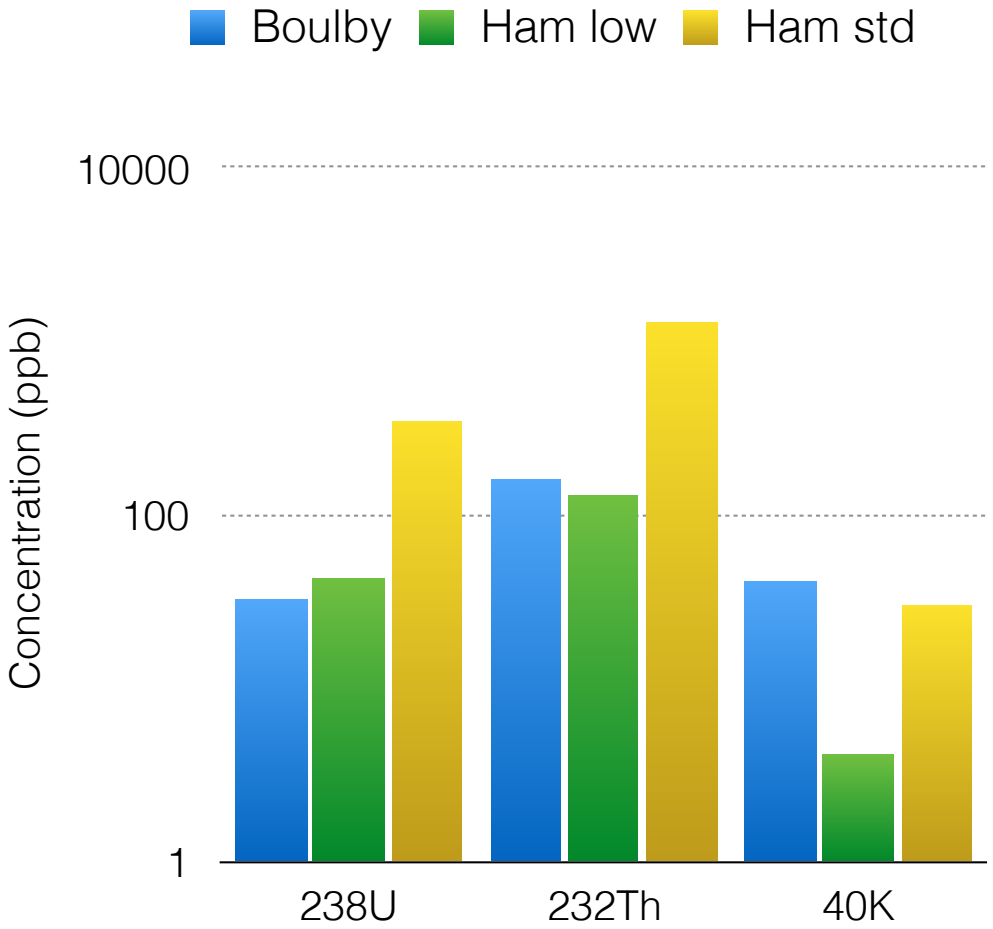
Radius (fixed area)	$\sqrt{\pi}/2$	1	$\sqrt{3/2}$

Radioactivity in PMT glass

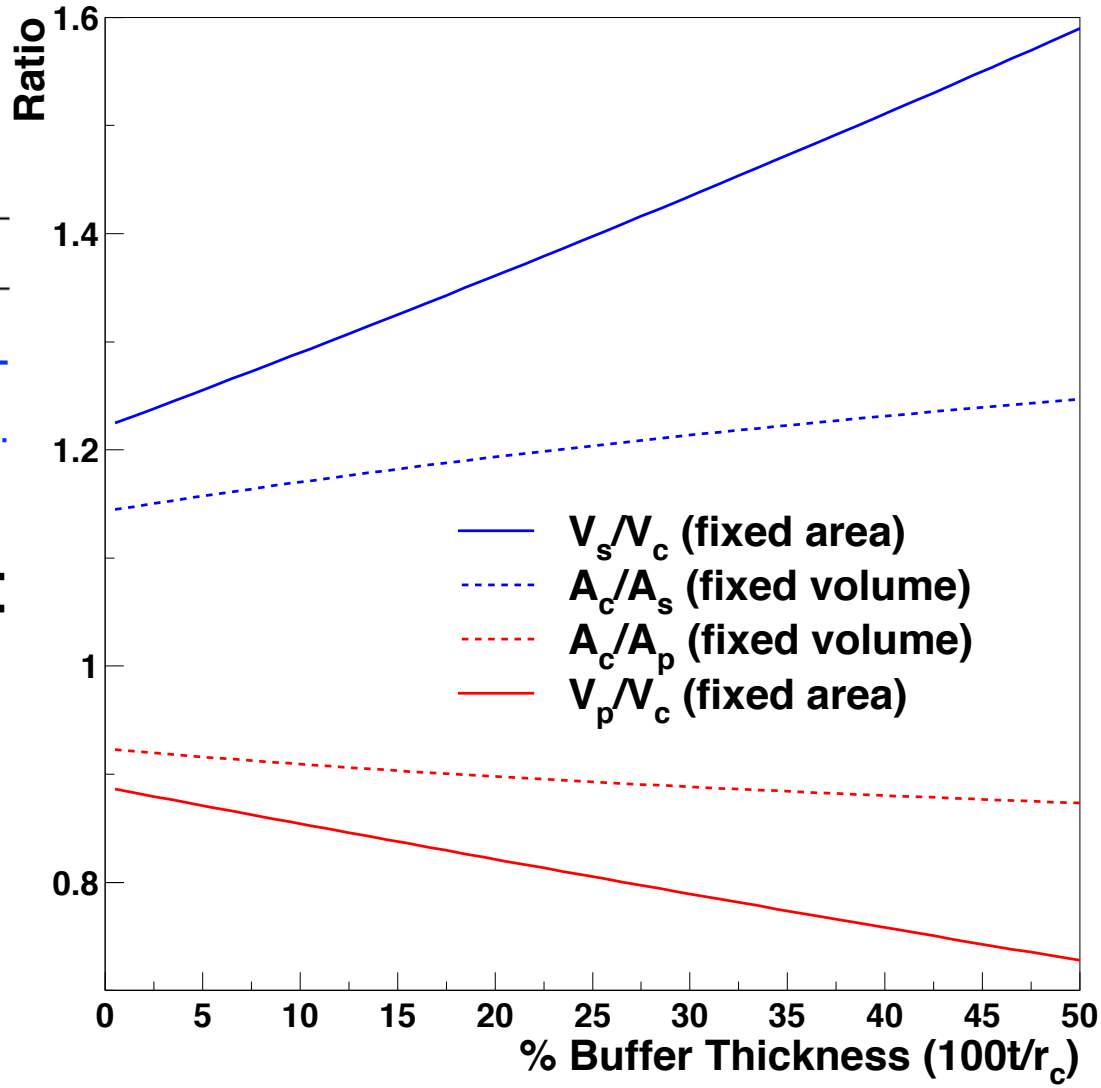


- **Radioactivity of PMT glass comparable to Boulby rock (halite)**
- **1.4 kg / 10-in PMT**
- **~1 tonne glass / 1000 PMTs**
- **PMT radioactivity demands buffer**

Shape Factors w/ Buffer

	Cube	Cylinder	Sphere
Volume (fixed area)	$\sqrt{\pi}/2$	1	$\sqrt{3/2}$
Area (fixed volume)	$\sqrt[3]{4/\pi}$	1	$\sqrt[3]{2/3}$

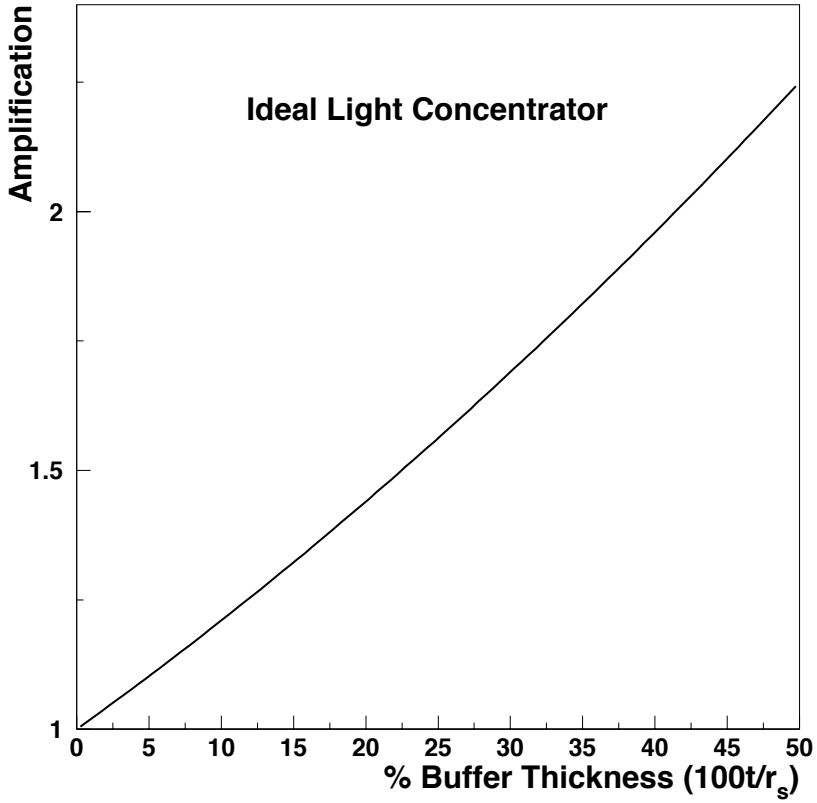
- **Table values at intercept**
- **Buffer thickness further differentiates shapes**
- **Sphere gets better**



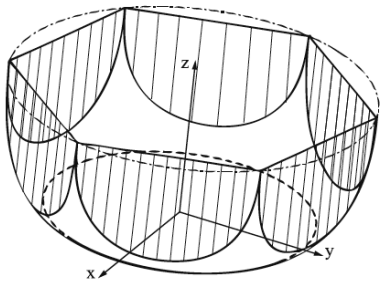
Buffer thickness as percentage of radius of cylinder

Light Concentrators- LCs

- **Buffer reduces solid angle of PMT, diminishes % PC coverage**
- **LCs effectively recover lost solid angle**
- **LCs can block light from radioactivity in its PMT from reaching neighboring PMTs**
- **Proven on spherical SNO and Borexino (maybe Jinping next)**
- **Significant amplification of light collection (SNO ~1.7, Borexino ~2.5)**
- **Cost few % of PMTs; negligible radioactivity**
- **Jinping hexagonal design**

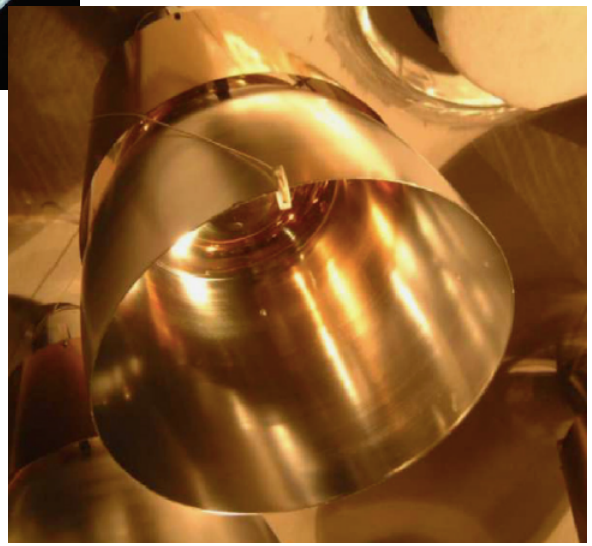


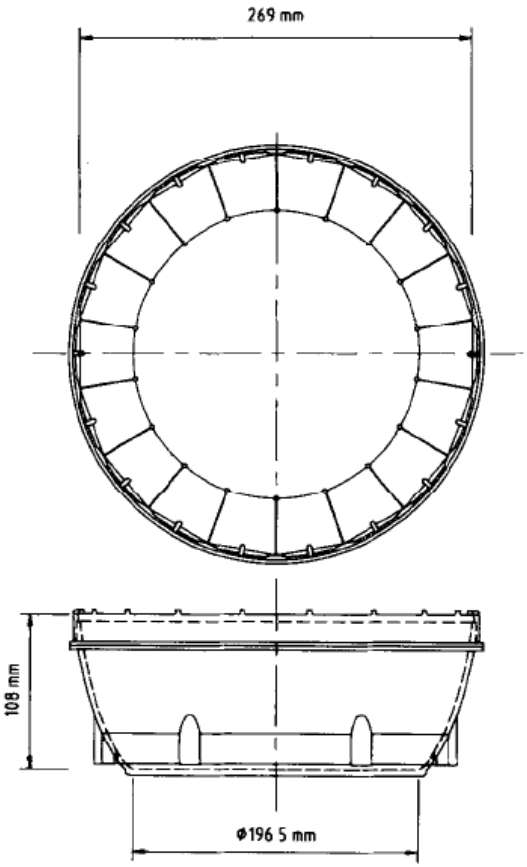
Buffer thickness as percentage of radius of sphere



Amp ~ A_{PMT} / A_{Target}

LCs in Practice



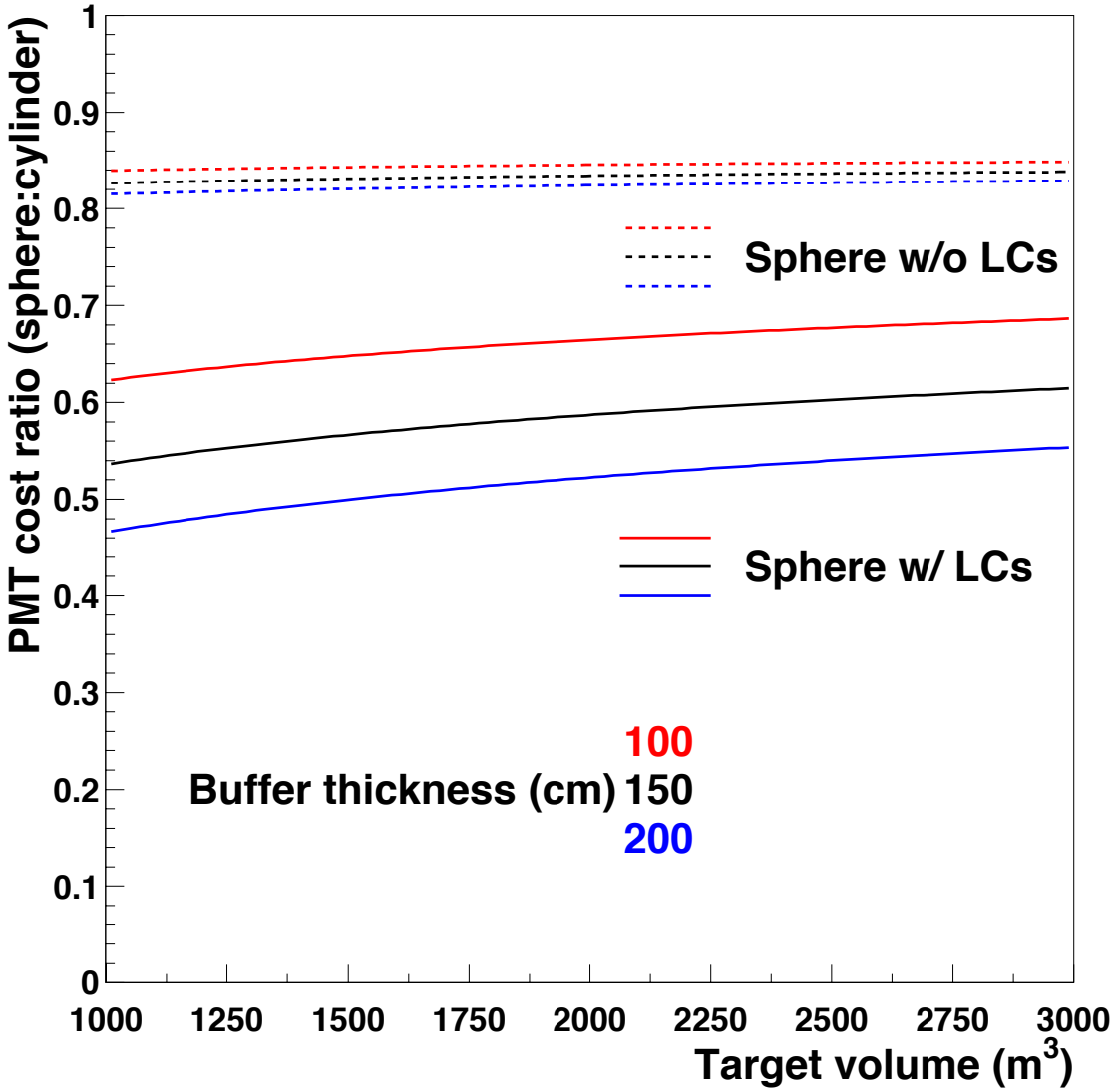


Borexino- anodized spun aluminum (Amp ~ 2.5; Cost ~ 100€ ea.)

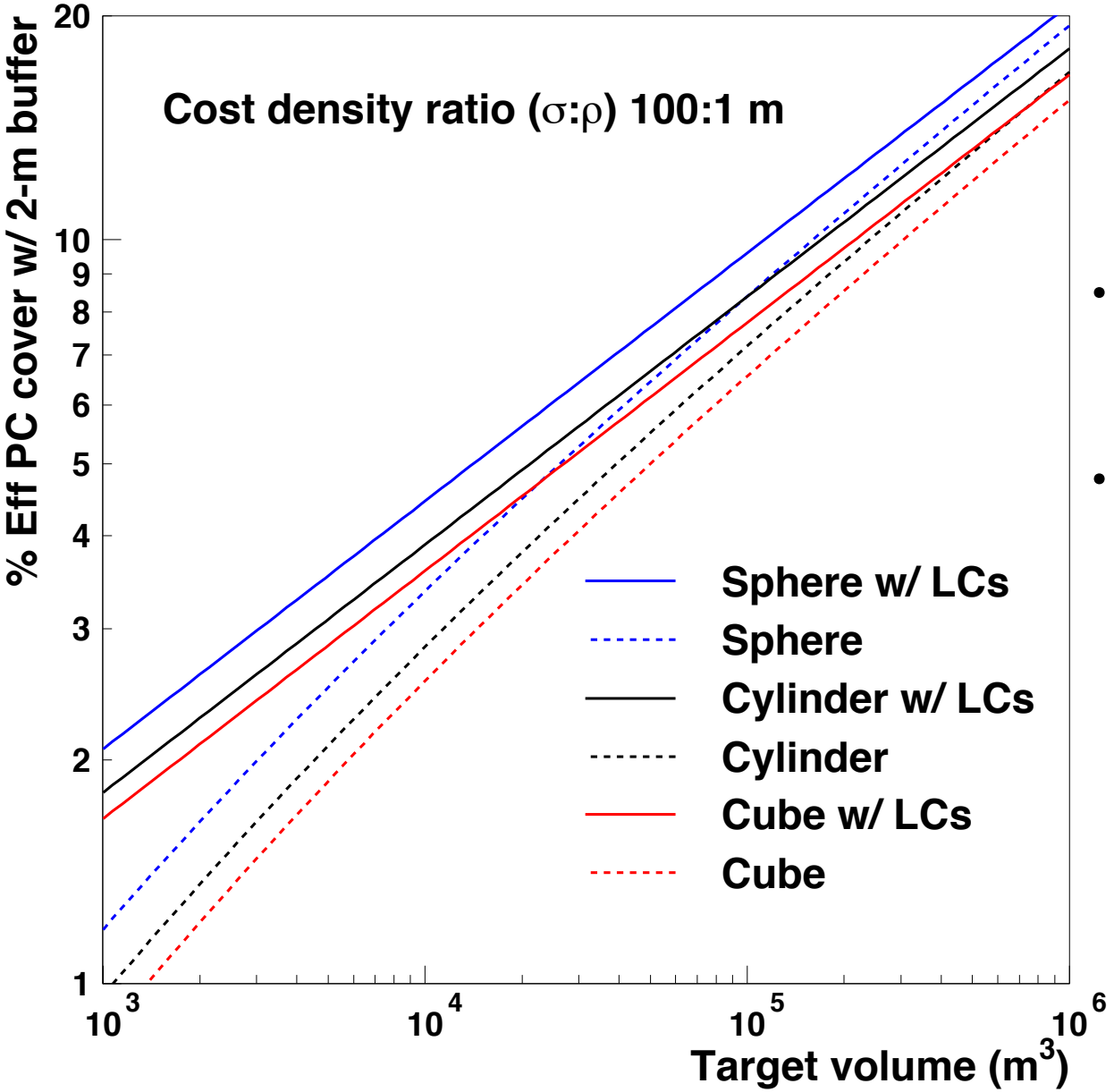
SNO- dielectric-coated aluminum plates (Amp ~ 1.7; Cost ~ $35 ea.)

Relative Cost of PMTs

- **Cost ($, radioactivity, implosion risk, readout electronics, power) for same *effective* PC coverage**
- **Spherical detector uses PMTs efficiently, <85% of cylinder**
- **Spherical detector facilitates use of light concentrators**
- **Spherical detector w/ LCs could use up to factor of 2 fewer PMTs than cylindrical detector w/o LCs**

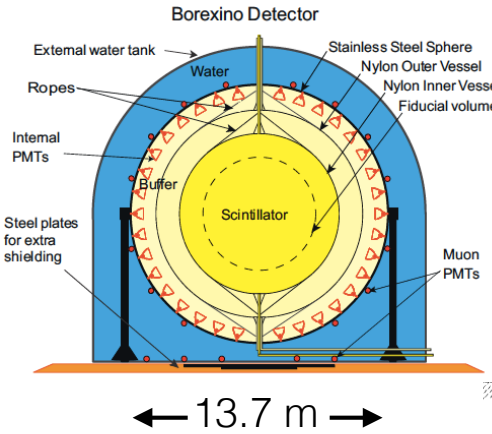


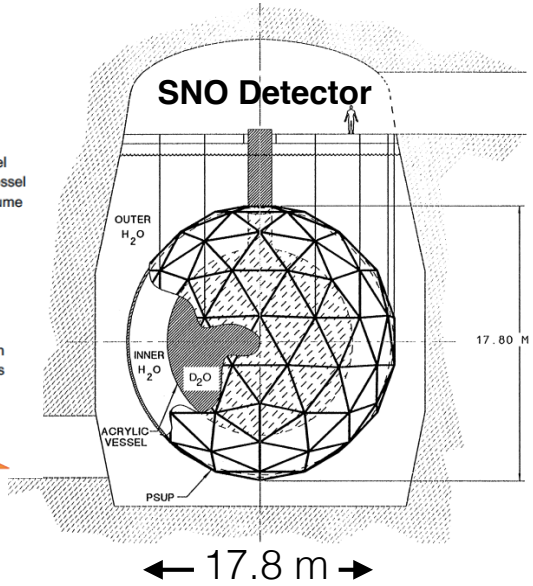
Sphere is Superior

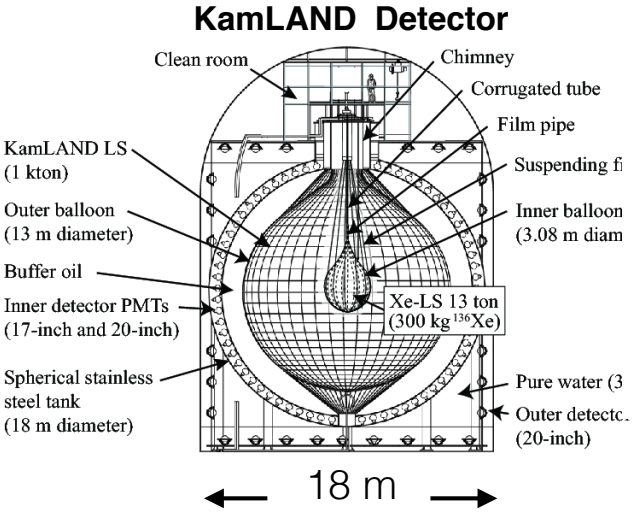


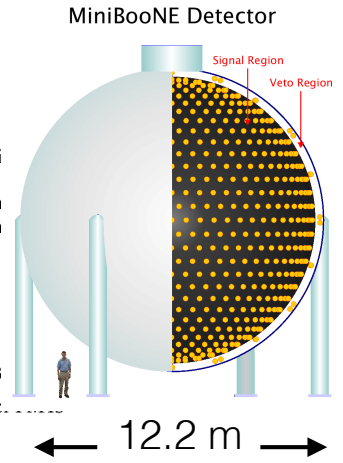
- **Ex. Equal cost- PMT and target volume**
- **Sphere is most effective detector shape for light collection**

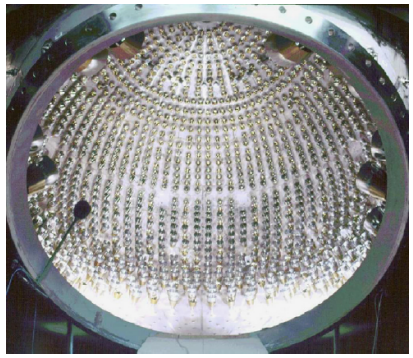
Spherical Detectors

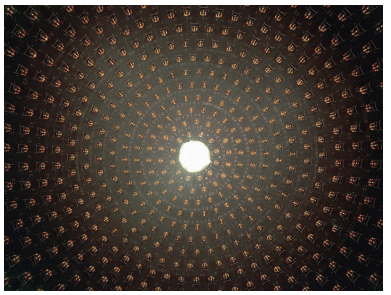










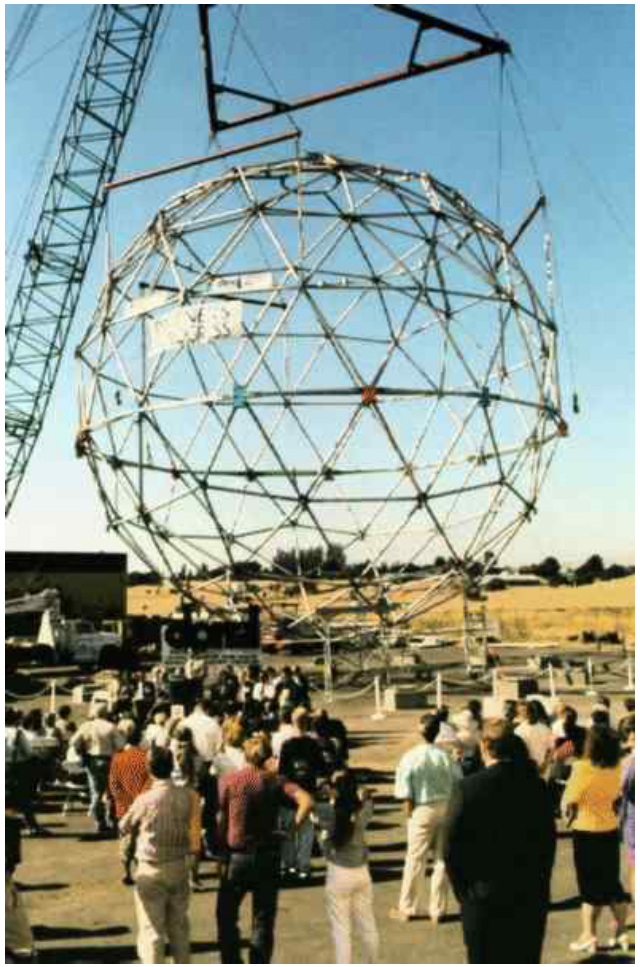


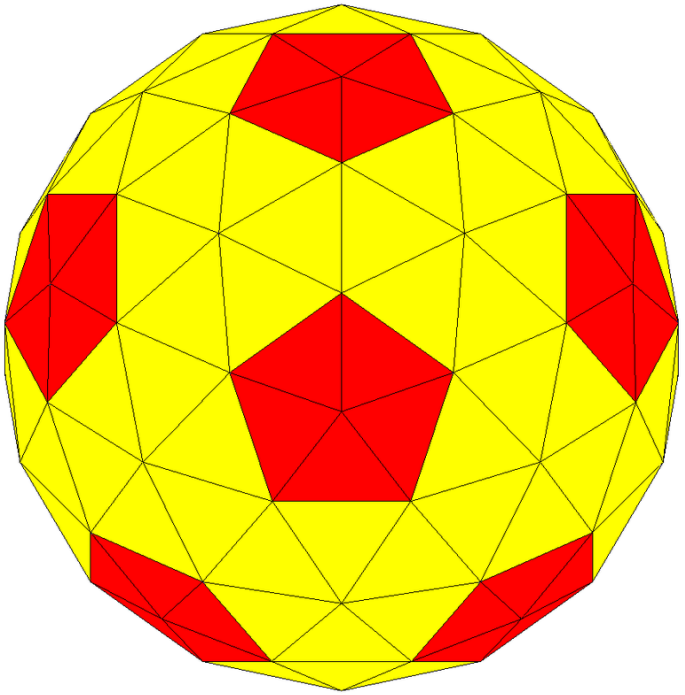
3 / 4 steel tanks

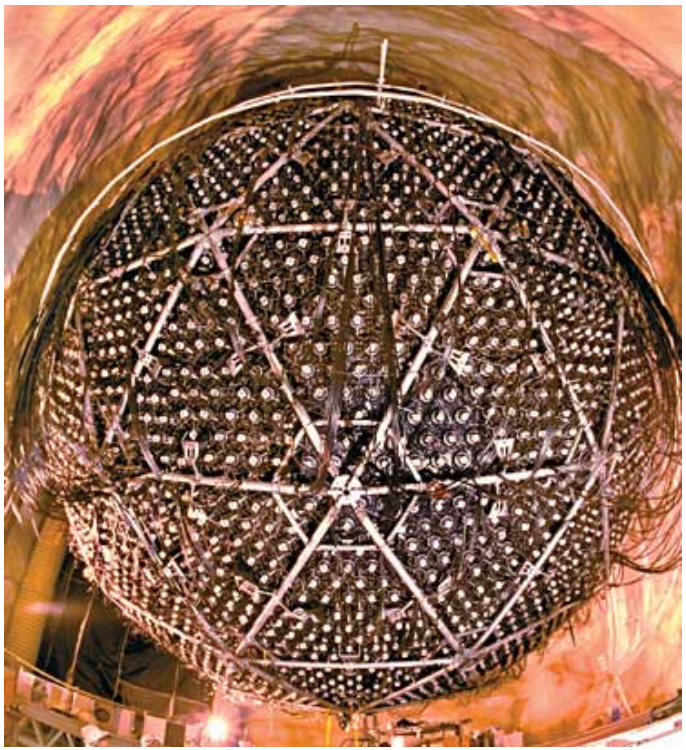
3 / 4 transparent inner vessel w/ liquid different than in buffer

Any examples of cylindrical detector with inner vessel?

SNO PMT Support







3v geodesic w/ 92 vertices
270 struts

Hexagonal lattice

Gaps along struts

Borexino PMT Support

- **PMTs supported by stainless steel sphere**

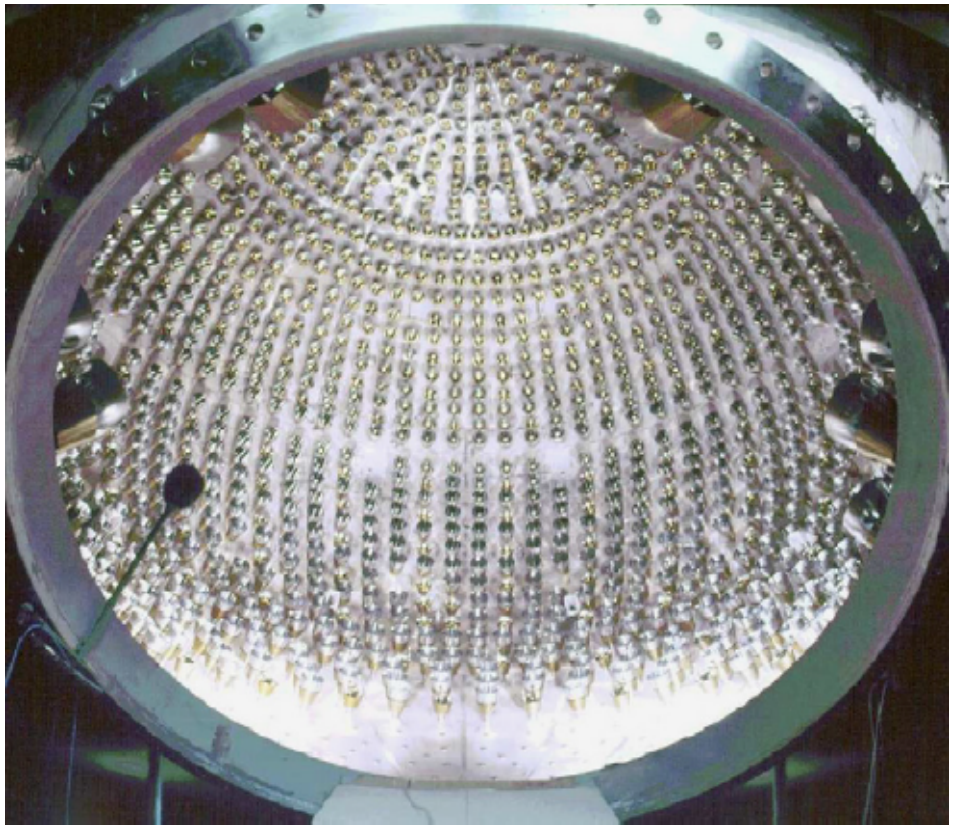
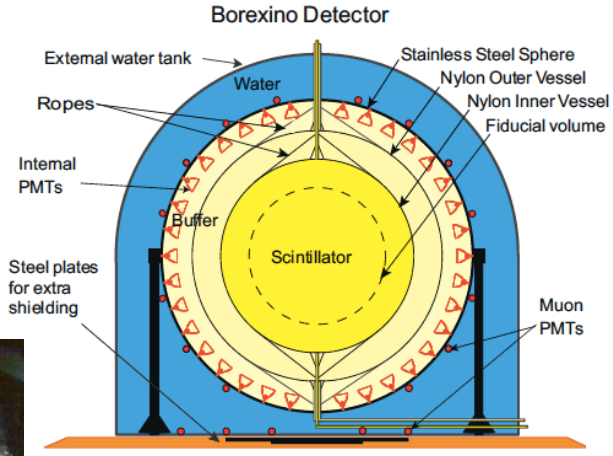
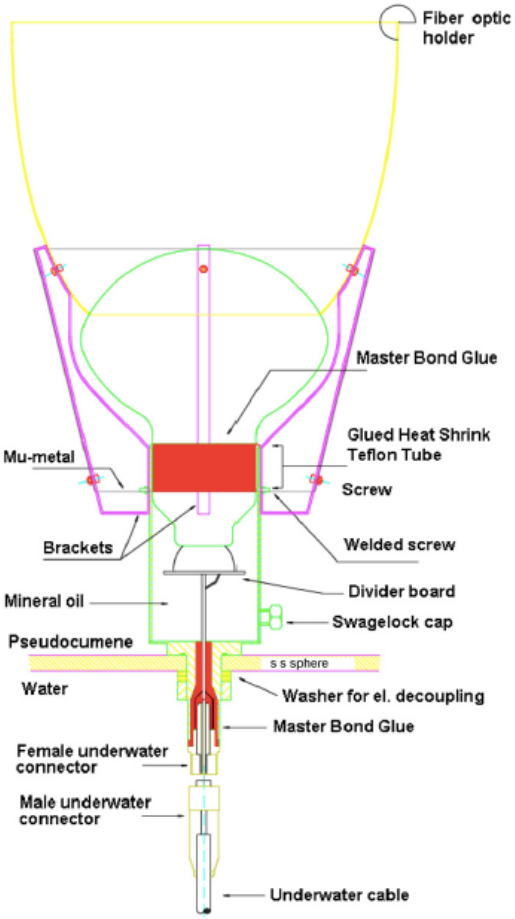


Fig. 3. Inner surface of the Stainless Steel Sphere. The picture is taken from the main SSS door, and shows the internal surface of the sphere with PMTs evenly mounted inside. The total number of PMTs is 2212.



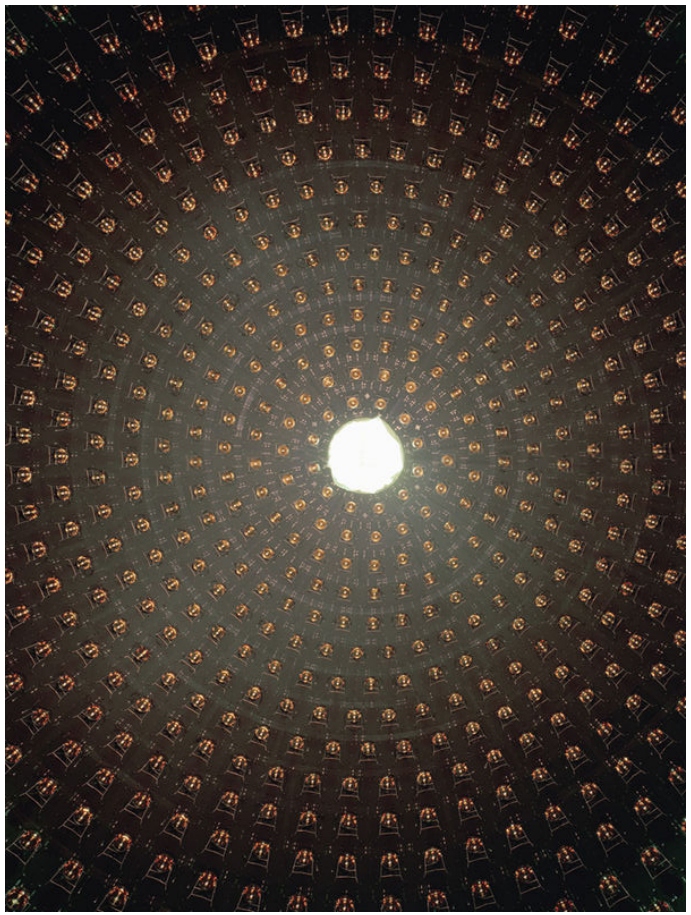
←13.7 m→

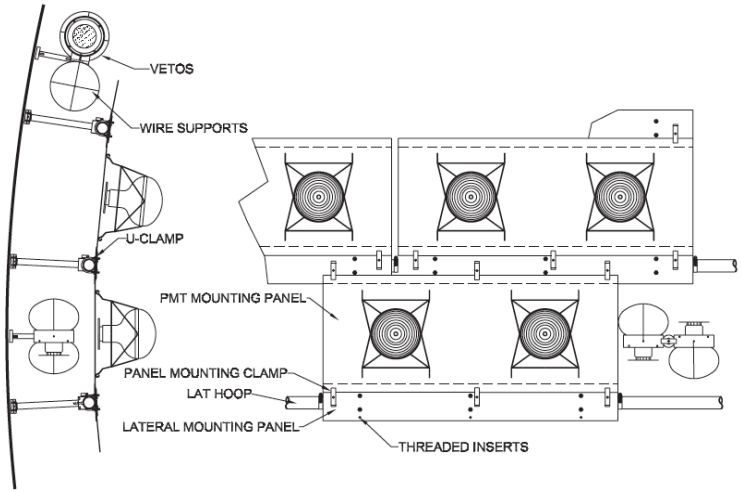
Veto

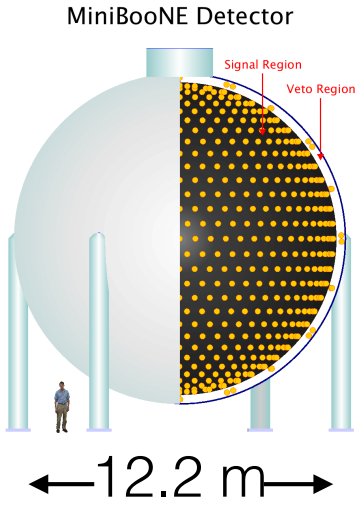


MiniBoone PMT Support

- **Veto and inner detector PMTs mounted inside steel sphere**







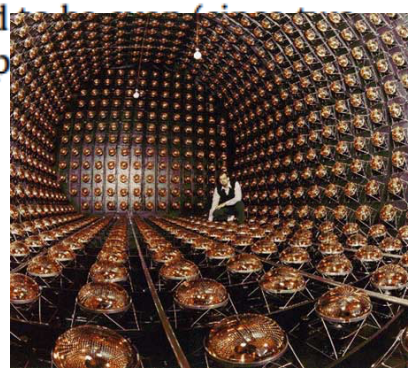
34 *A.A. Aguilar-Arevalo et al. / Nuclear Instruments and*

to uniformly distribute the main PMTs over the inner surface of the optical barrier and the veto PMTs over the tank wall.

It is not possible to distribute the phototubes over a sphere with exact uniformity. For reasons of structure and ease of installation, the PMTs were deployed in evenly spaced horizontal rows. The number of tubes in each row had

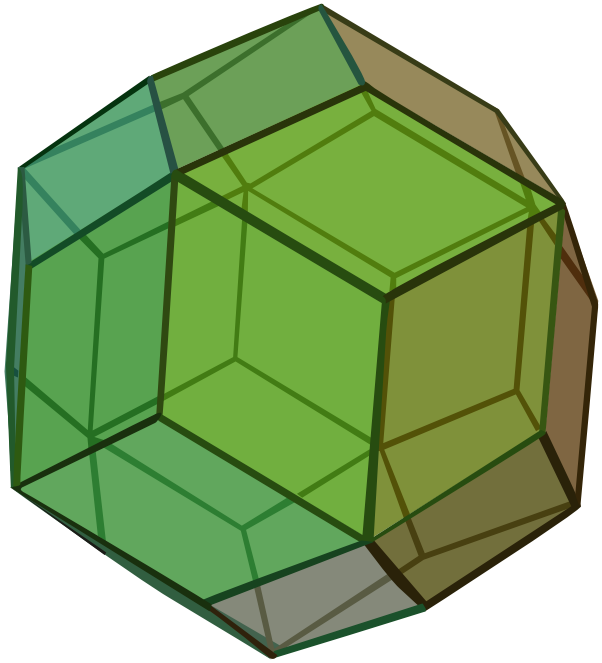
tubes were placed on each panel of the op

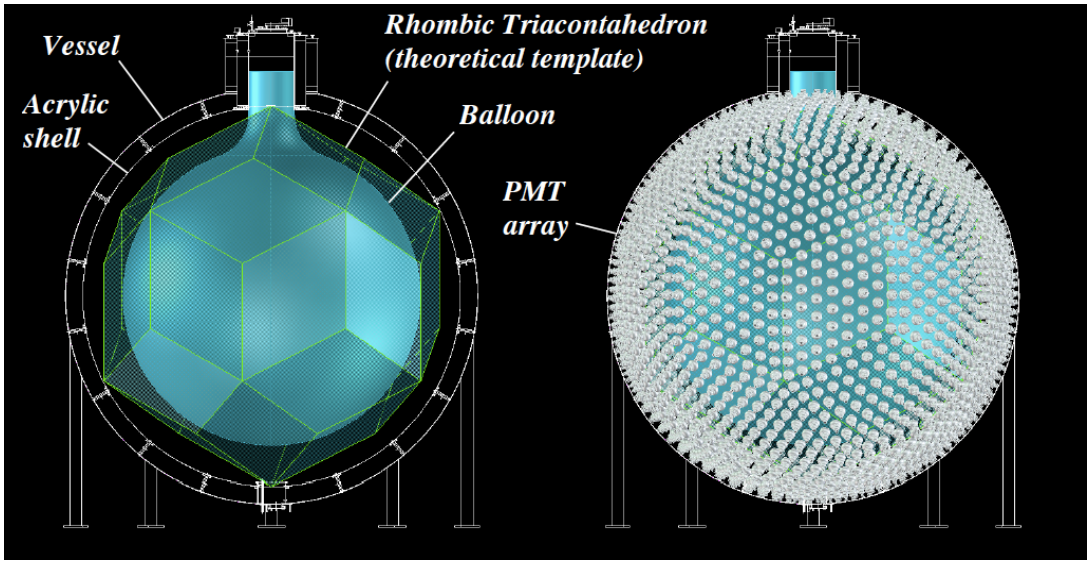
PMTs + supports recycled from LSND

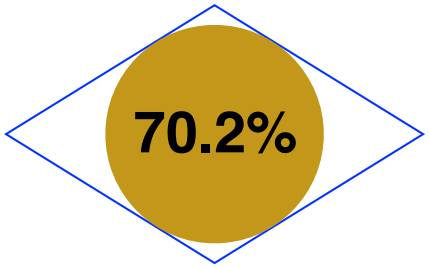


KamLAND PMT Support

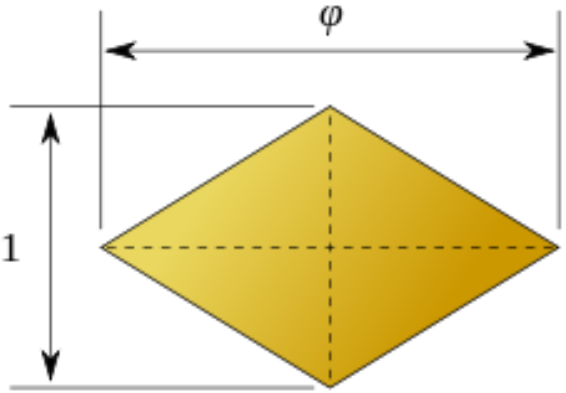
Rhombic triacontahedron (30 rhombic faces)

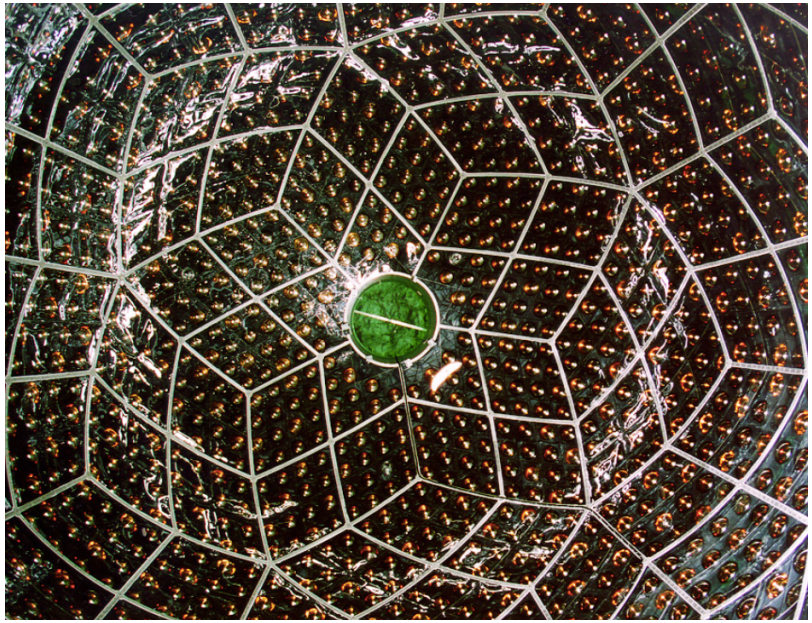






Golden Rhombus

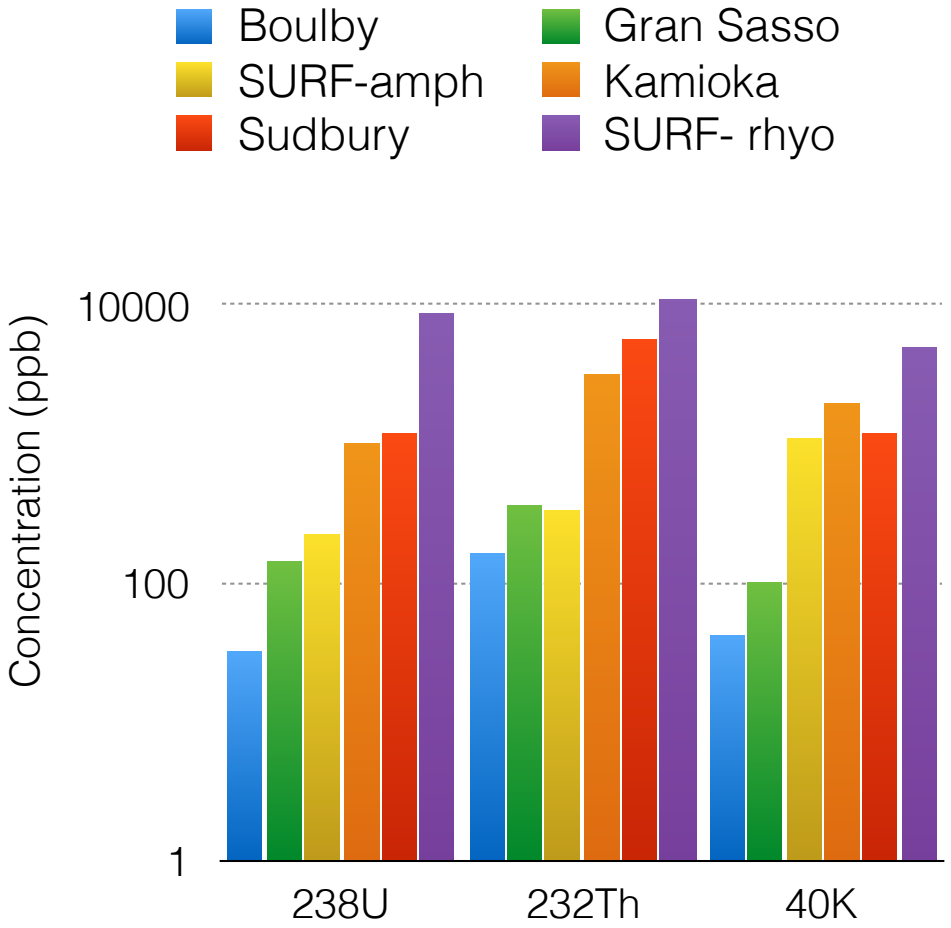


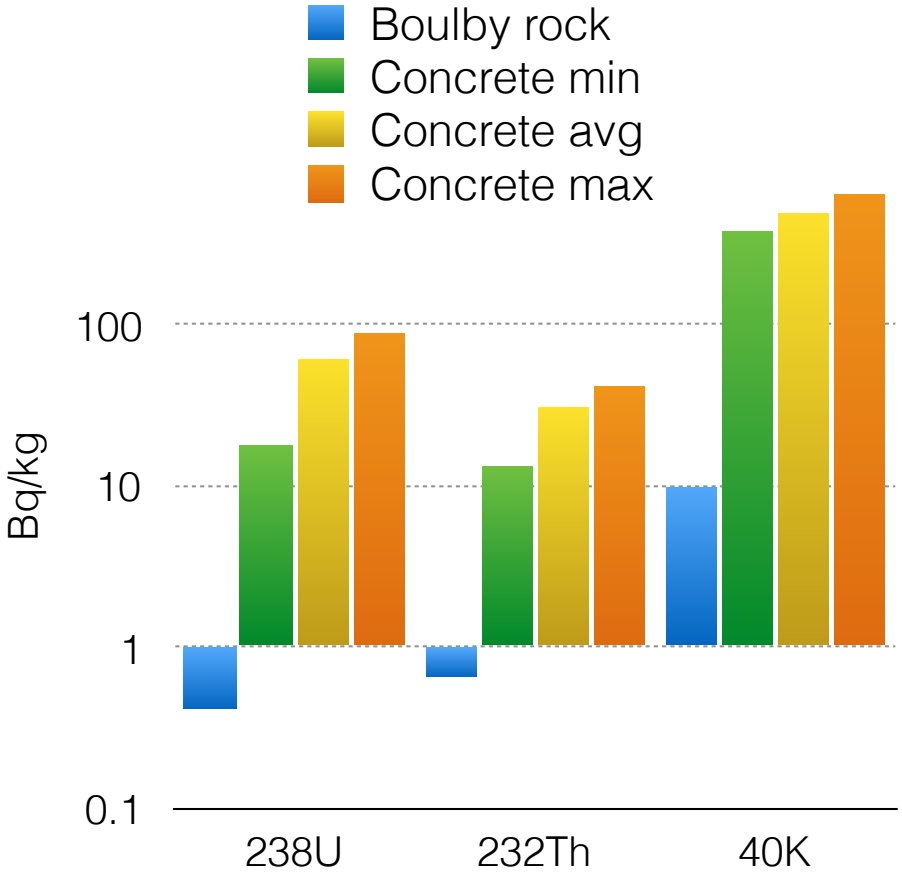


Radioactivity in Cavern Rock

Concrete radioactivity precludes some experiments?

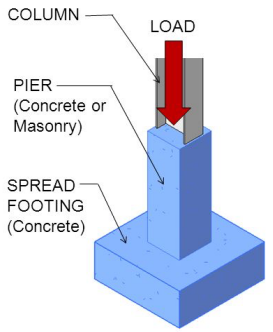
Might need to minimize use of concrete





Ground-level vs Elevated Tank

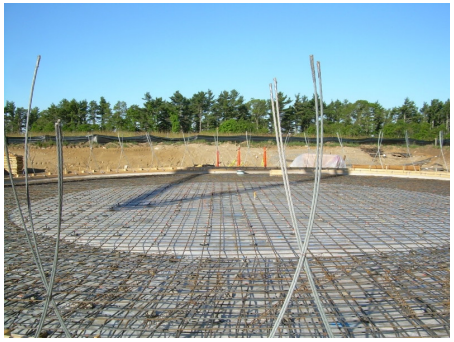
- **Tank bottom covered, inhibiting**
  - **access, inspection, maintenance, plumbing, etc.**
- **Foundation requirements**
  - **large full area concrete pad plus gravel sub-base for drainage**



- **Tank bottom exposed, facilitating**
  - **access, inspection, maintenance, plumbing, etc.**
- **Foundation requirements**
  - **shielded, sub-surface footings support tank columns**

Ground-Level Tank Foundation

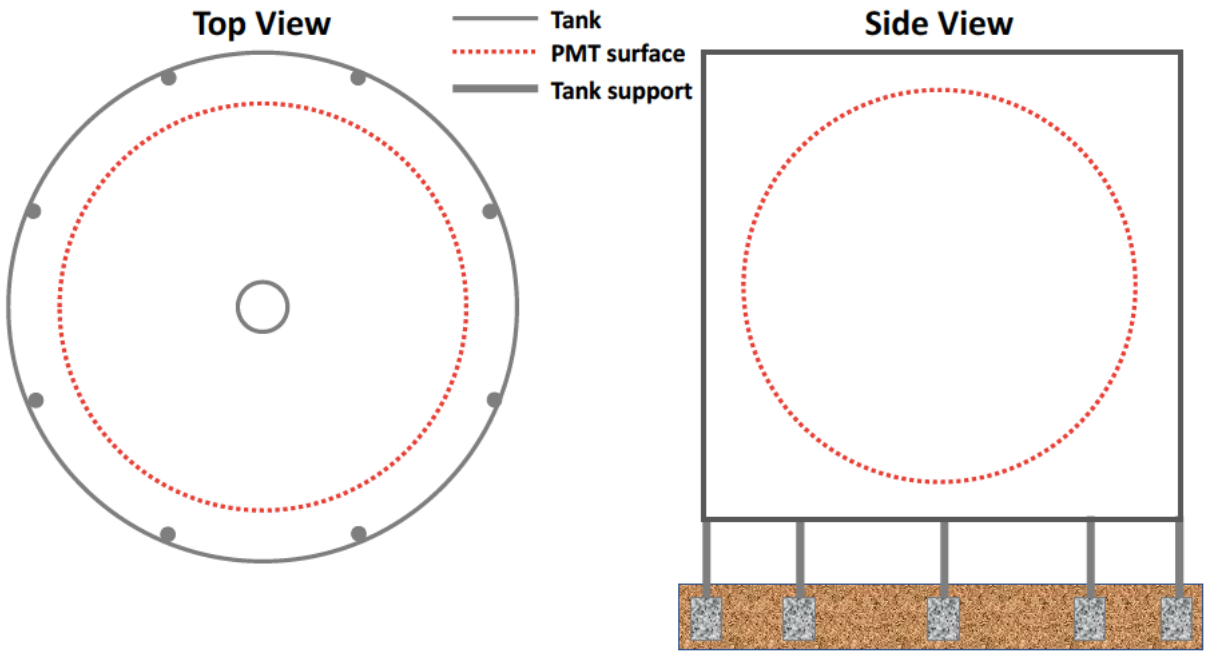


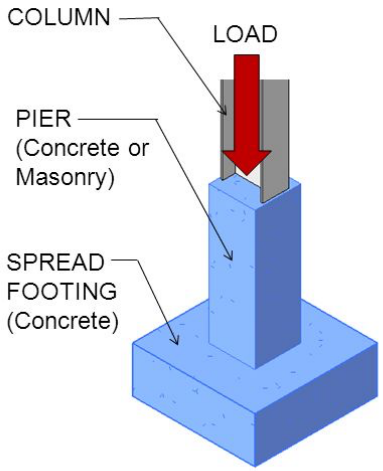



- **Big operation above ground. What is cost underground?**
- **Many 100 tonnes of concrete plus ~2x for gravel sub-base**
- **~ GBq of radioactivity**

Elevated Tank Foundation

- **Tank base supported on columns on top of footings**
- **Small foundation footprint with subsurface concrete footings to shield radioactivity**

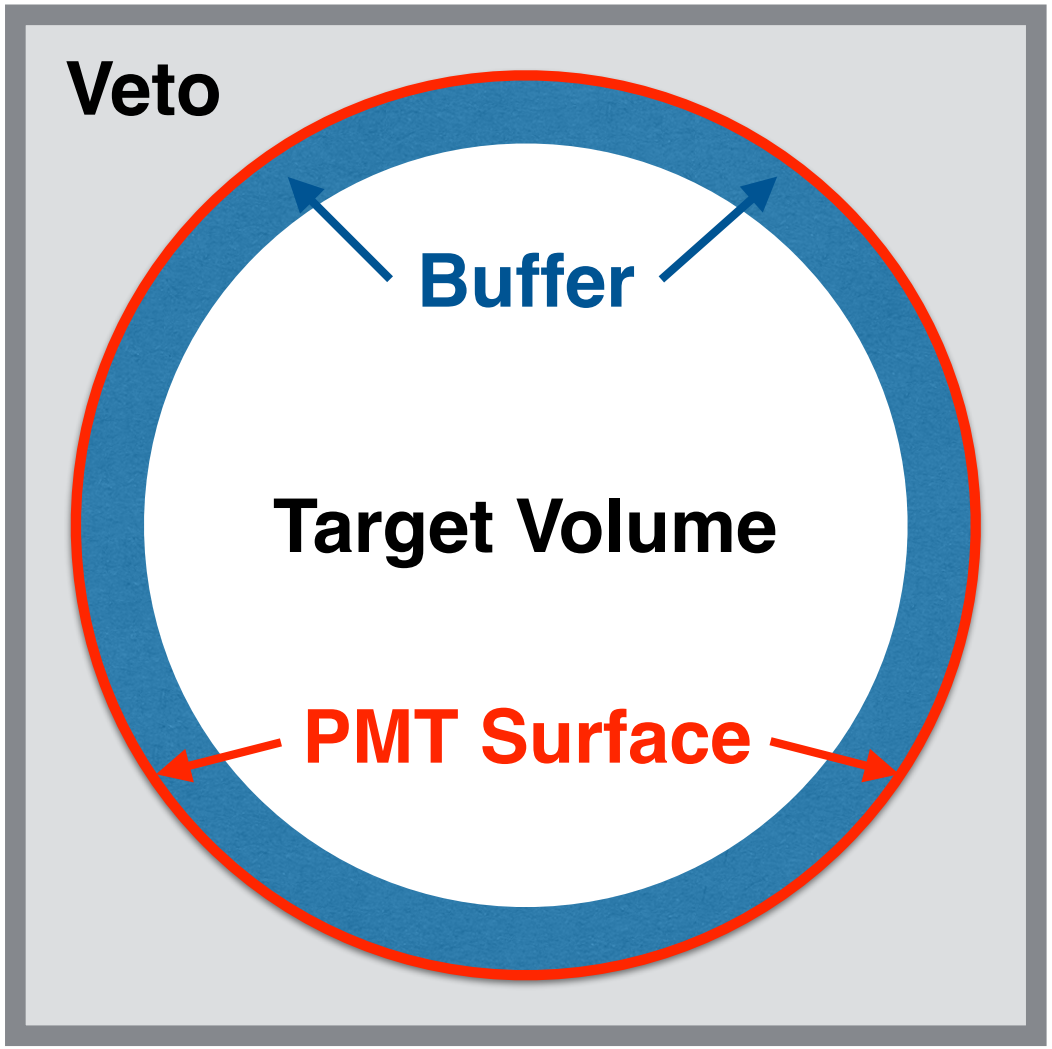




Space under detector free for water system, sump, etc.

Spherical Detector in Cylindrical Tank

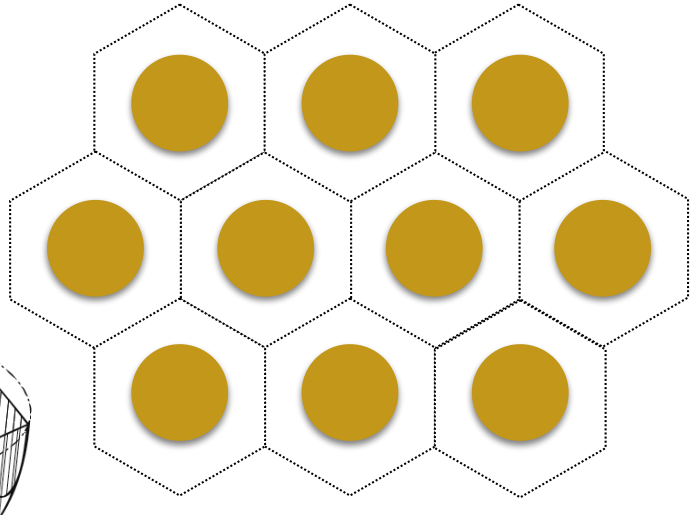
- **Extra veto thickness volume at corners**
- **PMT support and installation procedure under development**
- **Lose some target volume compared with cylindrical detector**

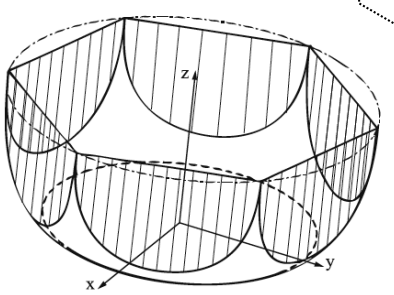


Honey Bees

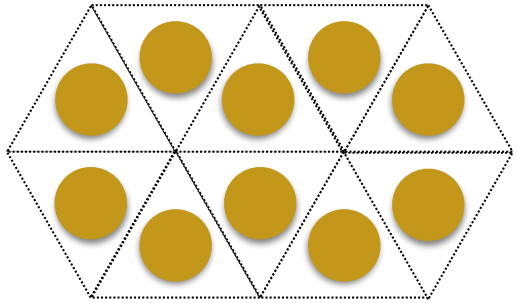
- **Hexagonal tiling *minimizes* amount of wax needed for walls of cells in beehive**

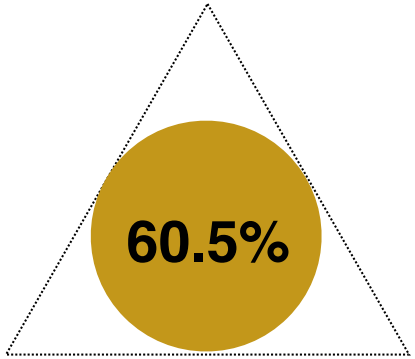
- **Hexagonal tiling *maximizes* light collection potential of photosensor in detector**

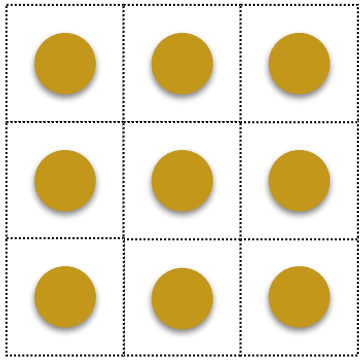


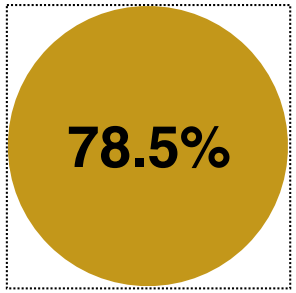


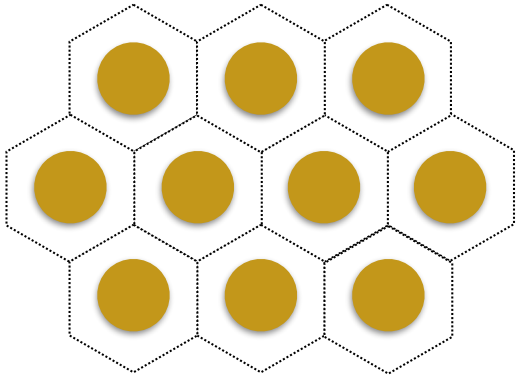
Light Collection Potential

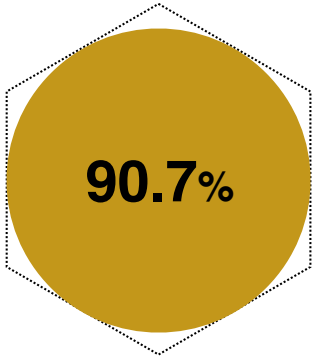








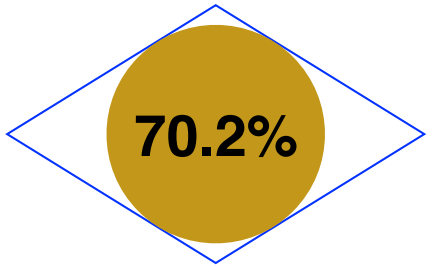




Three regular tessellations: N_sides = 3, 4, 6

Of the regular polygons with equal area, the hexagon circumscribes the biggest circle

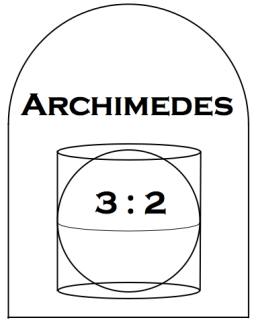
Hexagonal tiling provides the greatest light collection potential, adapts to light concentrator



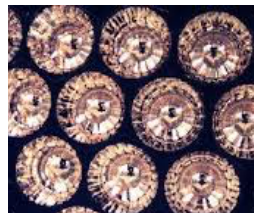
Rhombic tri-acontahedron

Summary

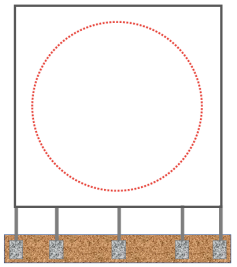
Archimedes: Spherical detector minimizes PMT cost, radioactivity, risk of schedule slip, target volume uncertainty, implosion risk, electronics channels, power, etc.



Spherical detector naturally accommodates light concentrators (upgrade for 1.5x more light or fewer PMTs and radioactivity)



Elevated tank reduces concrete footprint, allows access to bottom, frees some space underneath detector



Honey Bees: Hexagonal tiling maximizes light collection potential. Cannot strictly implement on spherical or cylindrical surface

Simulations of spherical detector using RAT-PAC/ WATCHMAKERS in progress