# Water Cherenkov ν-Detectors & GEANT4

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# Cherenkov photon emission

If the velocity of a particle is such that

$$v_p > c/n(\lambda)$$

where $n(\lambda)$ → the index of refraction of the material,

a pulse of light is emitted around the particle direction with an opening angle ($\theta_c$ )

## Cherenkov photon emission

- A charged particle moves faster than the phase velocity of light in a medium →

  electrons interacting with the particle can emit coherent photons while conserving energy and momentum

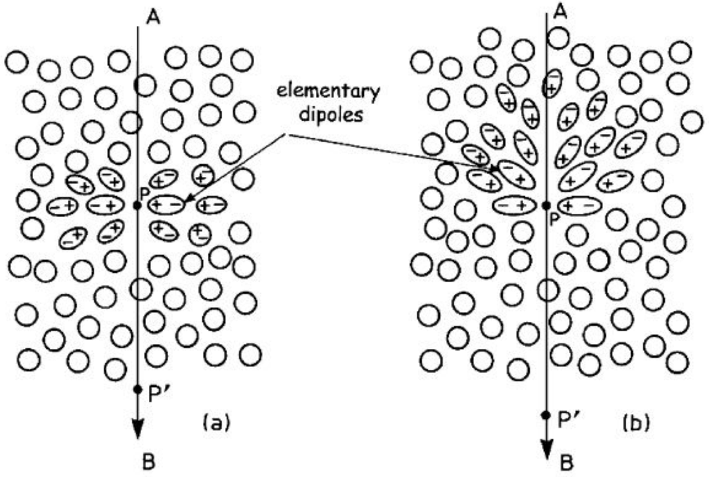
- It is actually not the particle that emits light, but the bounded (dielectric) electrons of the immediately surrounding medium
- Emission is coherent →

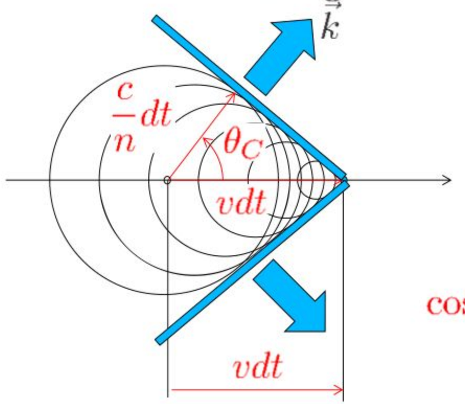
  in phase with the particle velocity

- Discovery: Cerenkov and Vavilov in 1934
- Explanation: Tamm and Frank in 1937

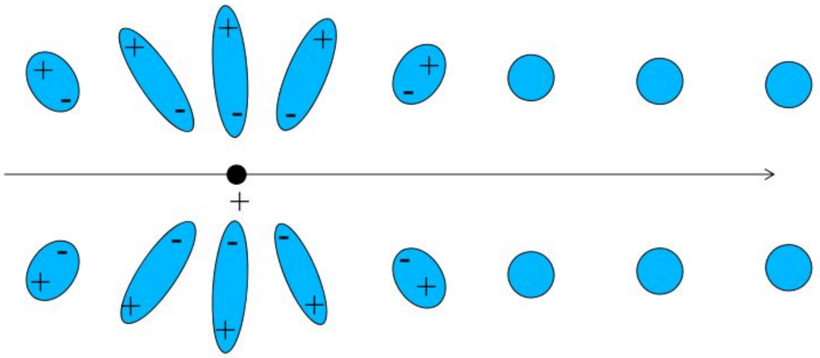
# Cherenkov photon emission

- Dielectric medium electrons polarized by a moving charged particle
- De-excitation gives rise to a coherent radiation
- Same basic process as energy loss (Bethe, Fermi)




$$\cos\theta_C = \frac{c}{nv} = \frac{1}{n\beta}$$



# Cherenkov photon emission

The energy emitted per unit length $dx$ travelled by the particle per unit of angular frequency $d\omega$ is:

$$dE = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right)dx d\omega$$

provided that $\beta = \frac{v}{c} > \frac{1}{n(\omega)}$ . Here $\mu(\omega)$ and $n(\omega)$ are the frequency-dependent permeability and index of refraction of the medium, $q$ is the electric charge of the particle, $v$ is the speed of the particle, and $c$ is the speed of light in vacuum.

Consequences:

- the **yield** of photons is **flat** versus these photons energy $(h\nu)$.
- the **yield** of photons is $\propto \lambda^{-2} \Rightarrow$ prominent at small wavelengths (UV)
- the spectrum is continuous $\neq$ fluorescence

# Cherenkov photon emission

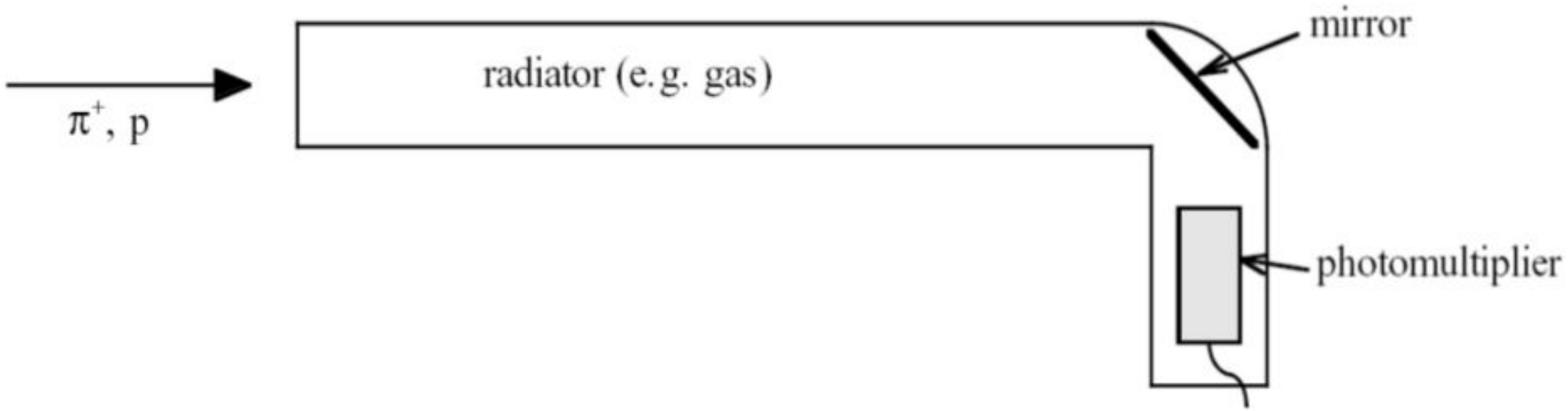
The total amount of energy radiated per unit length is:

$$\frac{dE}{dx} = \frac{q^2}{4\pi} \int_{v > \frac{c}{n(\omega)}} \mu(\omega)\omega \left(1 - \frac{c^2}{v^2 n^2(\omega)}\right) d\omega$$

This integral is done over the frequencies $\omega$ for which the particle's speed $v$ is greater than speed of light of the media $\frac{c}{n(\omega)}$. The integral is non-divergent because at high frequencies the refractive index becomes less than unity.

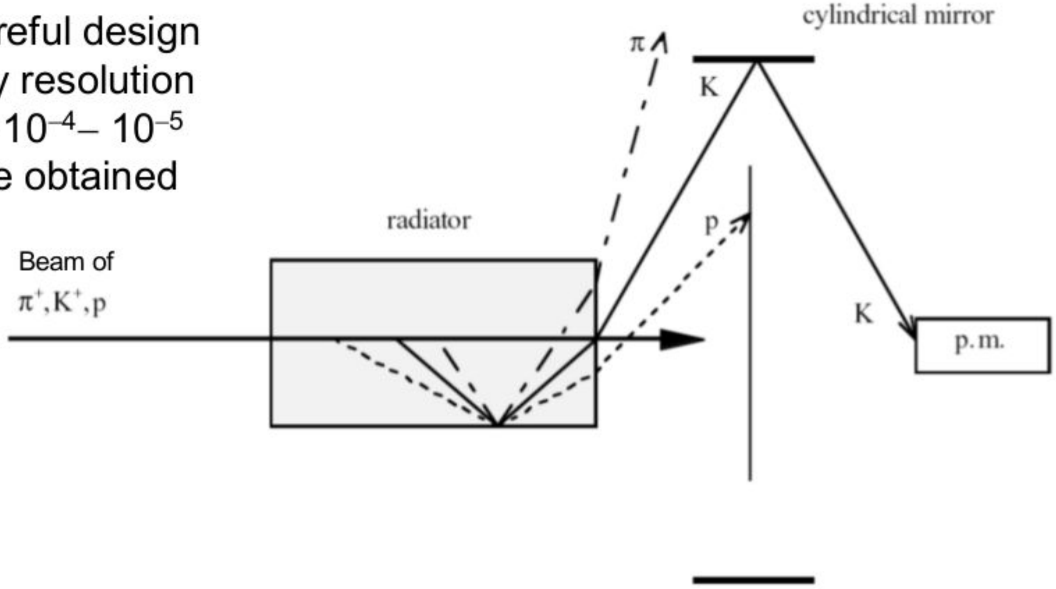
$$\frac{dE}{dx} = \frac{q^2}{4\pi} \int_{v > \frac{c}{n(\omega)}} \mu(\omega)\omega \left(1 - \frac{1}{\beta^2 n^2(\omega)}\right) d\omega$$

# A basic Cherenkov detector

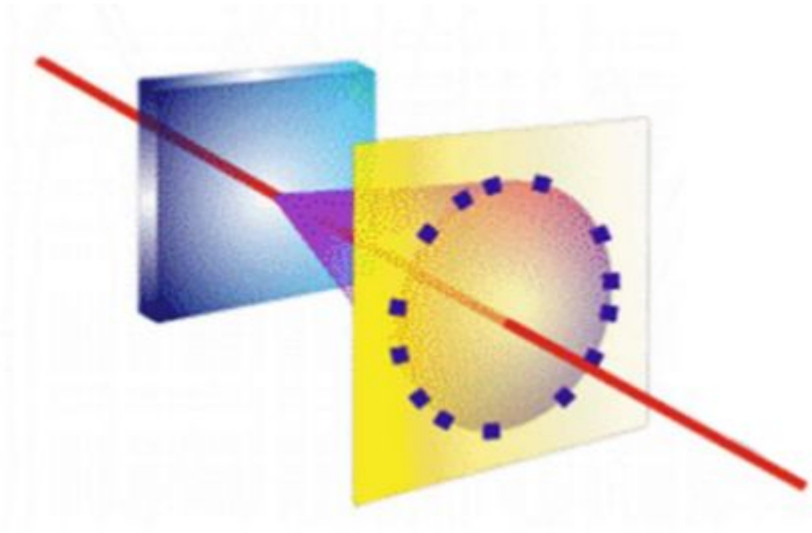


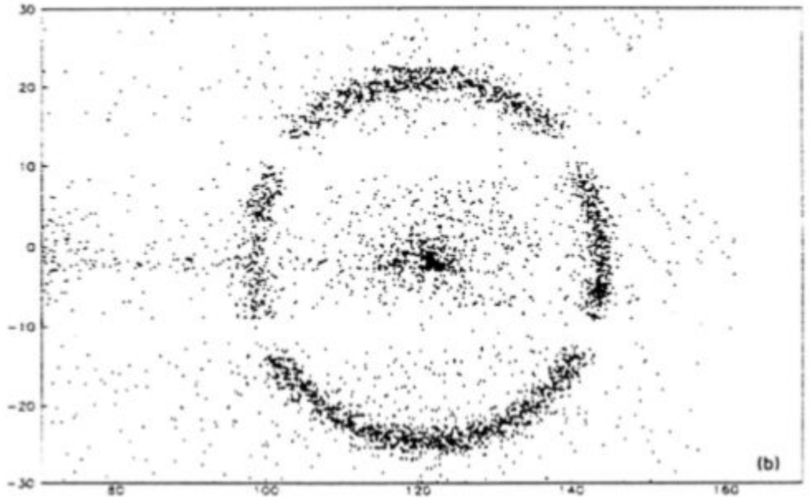
# Distinguishing Particles using a Cherenkov detectors

With careful design
velocity resolution
$\sigma_\beta/\beta \approx 10^{-4} - 10^{-5}$
can be obtained



# Detection Basics

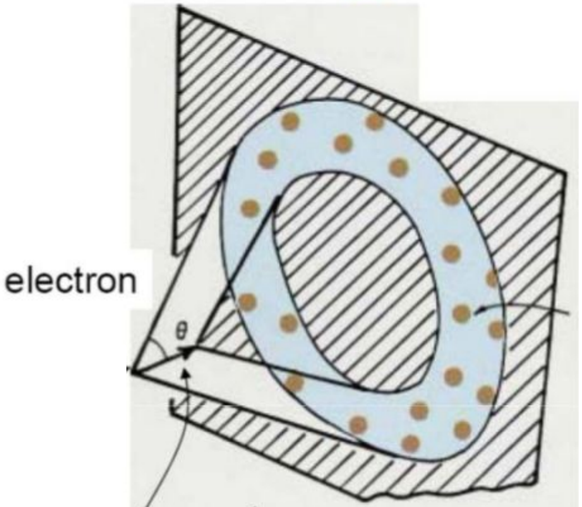




# Cherenkov radiator options

| Material | n-1 | $\beta_c$ | $\theta_c$ | photons/cm |
|---|---|---|---|---|
| solid natrium | 3.22 | 0.24 | 76.3 | 462 |
| Lead sulfite | 2.91 | 0.26 | 75.2 | 457 |
| Diamond | 1.42 | 0.41 | 65.6 | 406 |
| Zinc sulfite | 1.37 | 0.42 | 65 | 402 |
| silver chloride | 1.07 | 0.48 | 61.1 | 376 |
| Flint glass | 0.92 | 0.52 | 58.6 | 357 |
| Lead crystal | 0.67 | 0.6 | 53.2 | 314 |
| Plexiglass | 0.48 | 0.66 | 47.5 | 261 |
| Water | 0.33 | 0.75 | 41.2 | 213 |
| Aerogel | 0.075 | 0.93 | 21.5 | 66 |
| Pentan | 1.70E-03 | 0.9983 | 6.7 | 7 |
| Air | 2.90E-03 | 0.9997 | 1.38 | 0.3 |
| He | 3.30E-05 | 0.999971 | 0.46 | 0.03 |

# Cherenkov in water




$$\cos\theta = \frac{1}{n\beta}$$

n=1.34 in water

⇨ $\theta$ =42deg. for $\beta$ =1

- No. of Cherenkov photons with wavelength 300-600 nm, emitted by a relativistic particle per cm is about 340

We require,

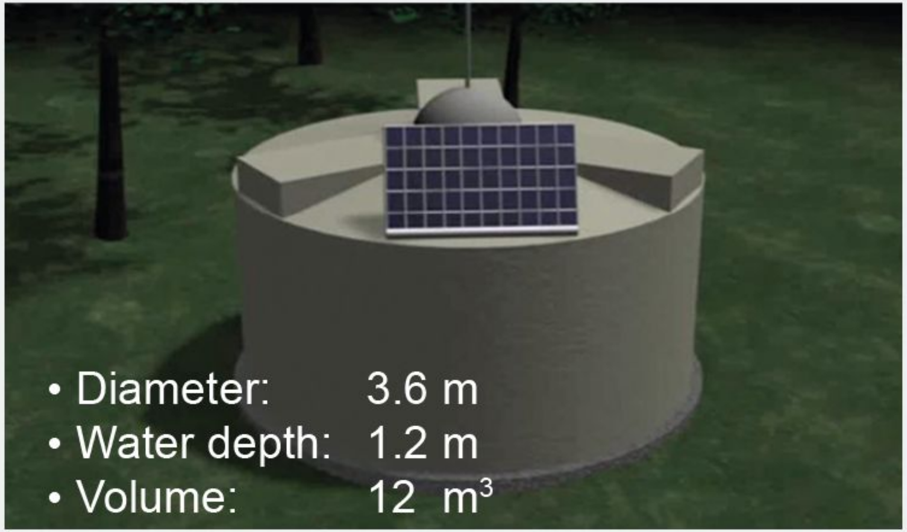
- Efficient detection of the photons
- Large Photodetectors

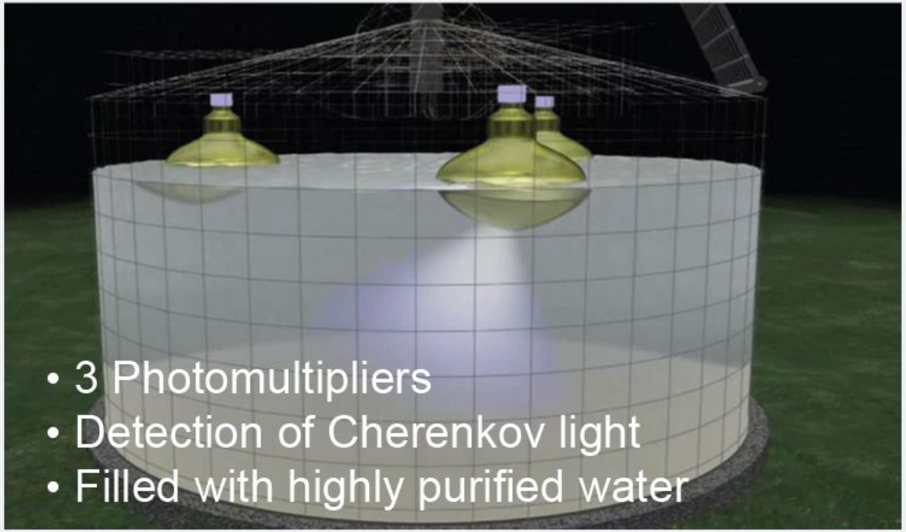
# Water Cherenkov Detector in Auger Experiment

**Surface Detector**

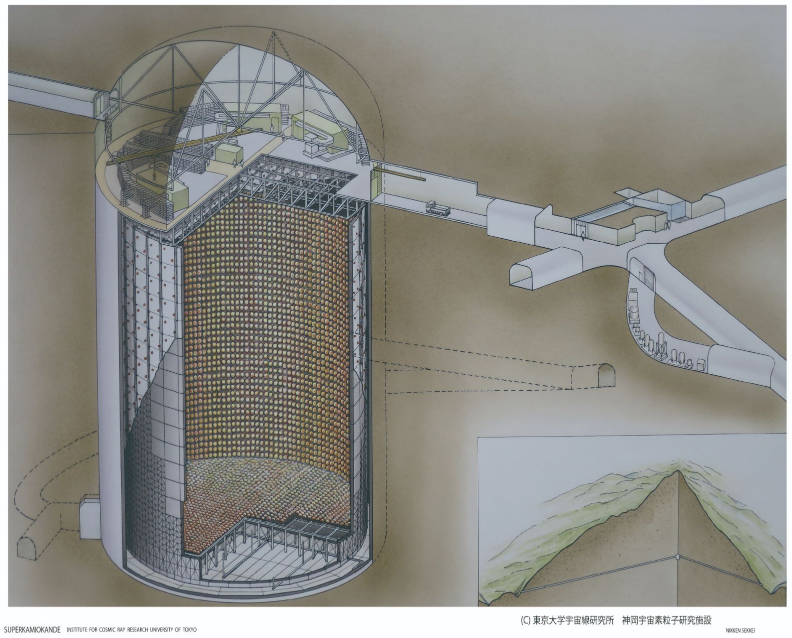
1,660 surface detector stations

(1,500 m apart from each other)



# Super-Kamiokande Neutrino Experiment



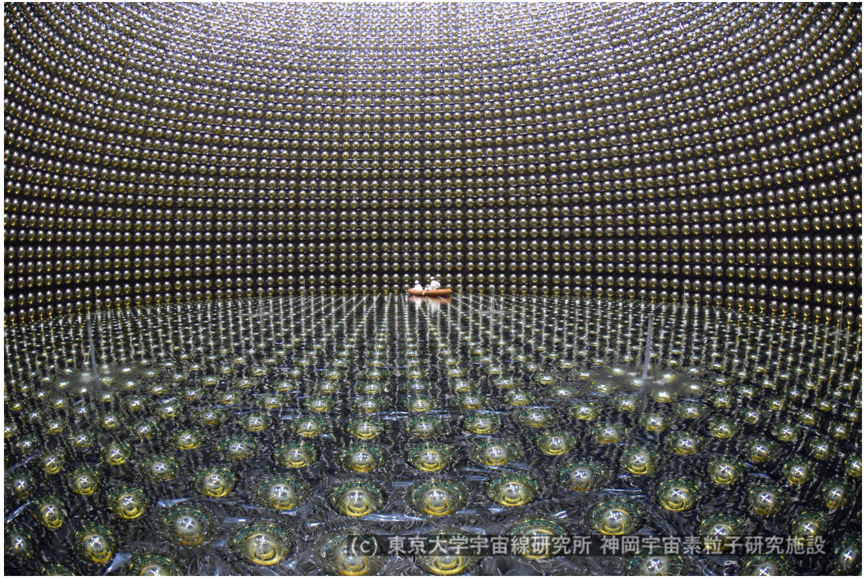

- A cylindrical (39.3 m dia & 41.4 m) high stainless steel tank, PMTs installed to the detector wall.
- 50 kt water.
- The PMT support structure divides the tank into two distinct, optically isolated volumes:

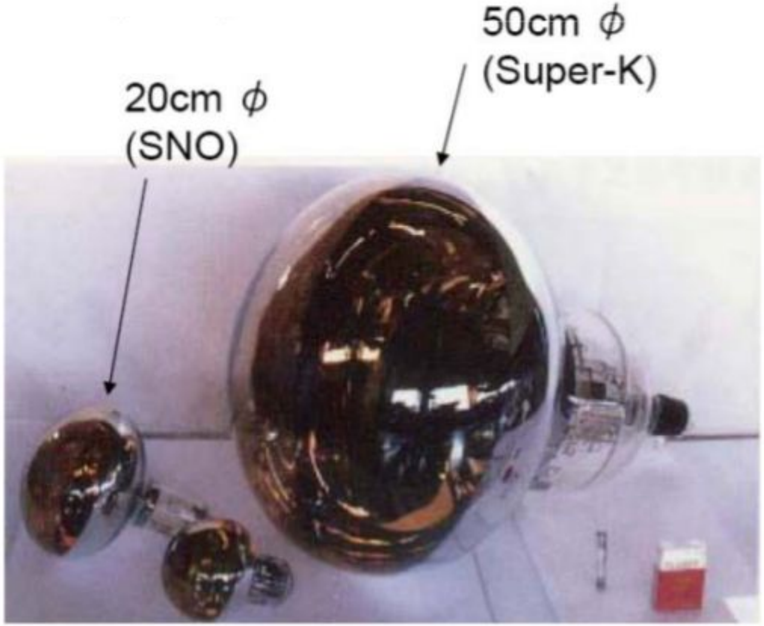
  inner detector (ID)

  outer detector (OD)

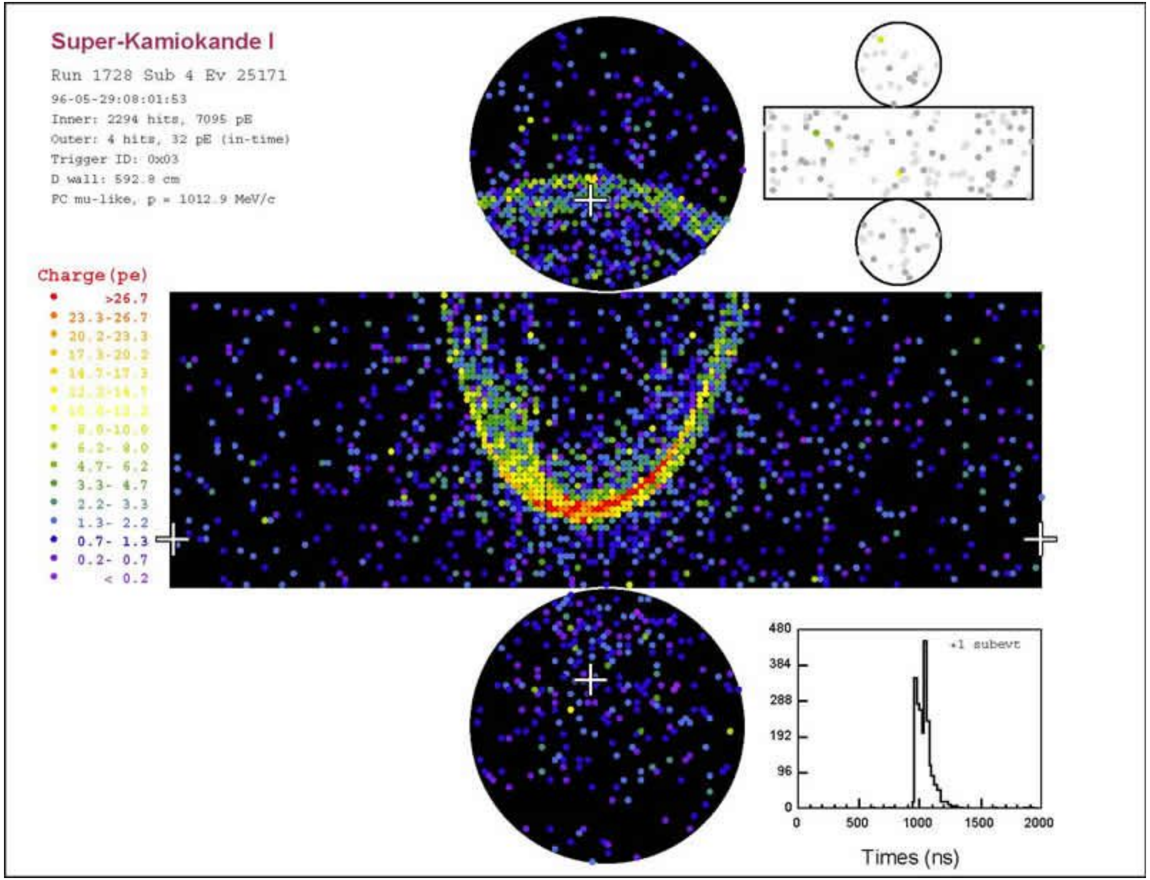
- The inwarded PMTs are installed to the ID wall and the outwarded PMTs to the OD wall.

# Super-Kamiokande Neutrino Experiment: Detectors



# Cherenkov at SK

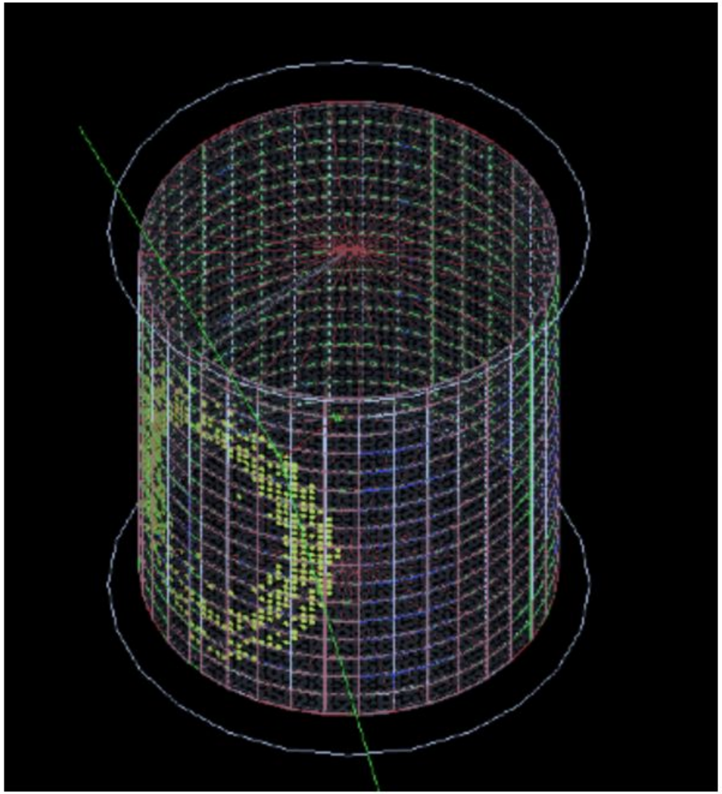


# A Water Cherenkov Simulator Framework

WCSim

- Open-source
- GEANT4-based code for water cherenkov detectors.

https://github.com/Wcsim/WCSim



# What can we do?

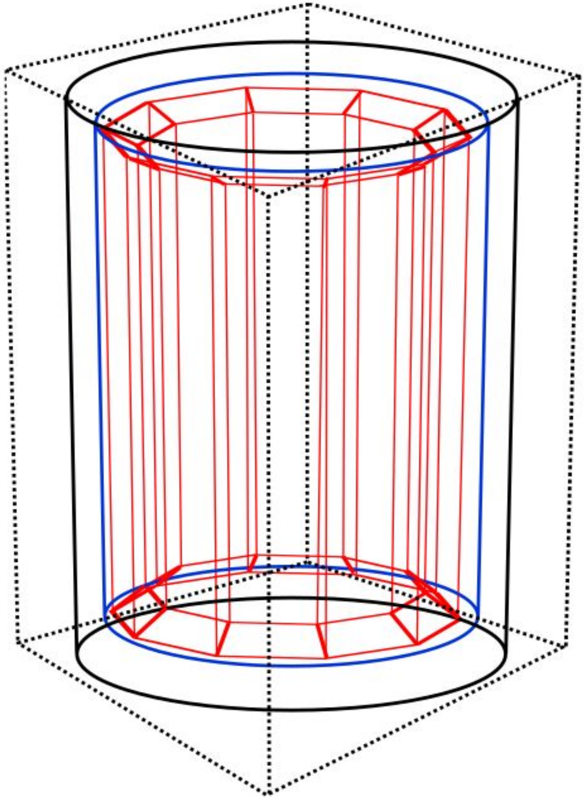
- Construct the Detector
- Particle Interactions
- Detector Outputs
- Trigger
- Digitization of the Output
- Output Storage & Further Analysis

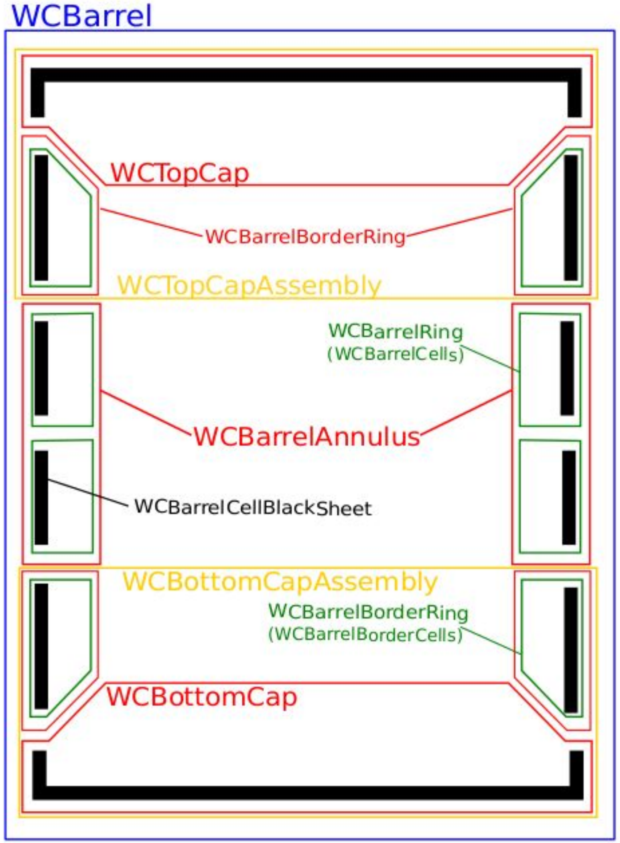
```
WCSimConstructCylinder.cc                 WCSimRootEvent.cc
WCSimConstructEggShapedHyperK.cc          WCSimRootGeom.cc
WCSimConstructGeometryTables.cc           WCSimRootOptions.cc
WCSimConstructMaterials.cc                WCSimRootTools.cc
WCSimConstructPMT.cc                      WCSimRunAction.cc
WCSimDarkRateMessenger.cc                 WCSimRunActionMessenger.cc
WCSimDetectorConfigs.cc                   WCSimStackingAction.cc
WCSimDetectorConstruction.cc              WCSimSteppingAction.cc
WCSimDetectorMessenger.cc                 WCSimTrackInformation.cc
WCSimEnumerations.cc                      WCSimTrackingAction.cc
WCSimEventAction.cc                       WCSimTrajectory.cc
WCSimLC.cc                                WCSimTuningMessenger.cc
WCSimPhysicsListFactory.cc                WCSimTuningParameters.cc
WCSimPhysicsListFactoryMessenger.cc       WCSimVisManager.cc
WCSimPmtInfo.cc                           WCSimWCAddDarkNoise.cc
WCSimPMTObject.cc                         WCSimWCDAQMessenger.cc
WCSimPMTQE.cc                             WCSimWCDigi.cc
WCSimPrimaryGeneratorAction.cc            WCSimWCDigitizer.cc
WCSimPrimaryGeneratorMessenger.cc         WCSimWCHit.cc
WCSimRandomMessenger.cc                   WCSimWCPMT.cc
WCSimRootDict.cc                          WCSimWCSD.cc
WCSimRootDict.h                           WCSimWCTrigger.cc
WCSimRootDict_rdict.pcm
```

# WCSim Geometry

- Consists of a cylindrical detector
- src/WCSimConstructCylinder.cc
- WCSimDetectorConstruction::ConstructCylinder()
- The inner detector : blacksheet and PMTs
- Active element: PMTs
- Blacksheet: goes around the back of the PMTs, reduces reflections and optically separates the inner and outer detector

# Detector construction



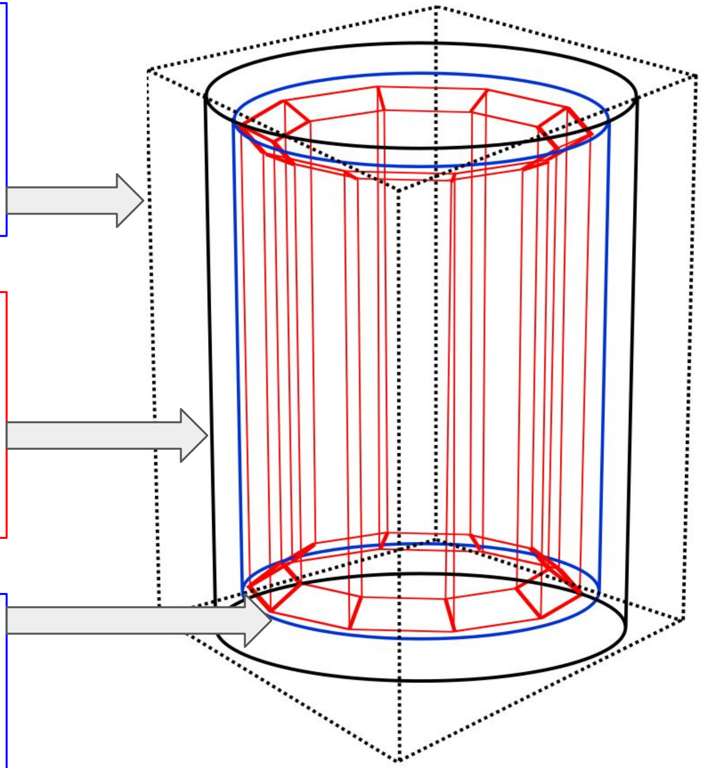


# Hierarchy of Volumes

World Volume = ExpHall
File = src/WCSimDetectorConstruction.cc
Shape = Rectangular Box
Material = Air

Daughter Volume = WC
File = src/WCSimConstructCylinder.cc
Shape = Tubs
Material = Air

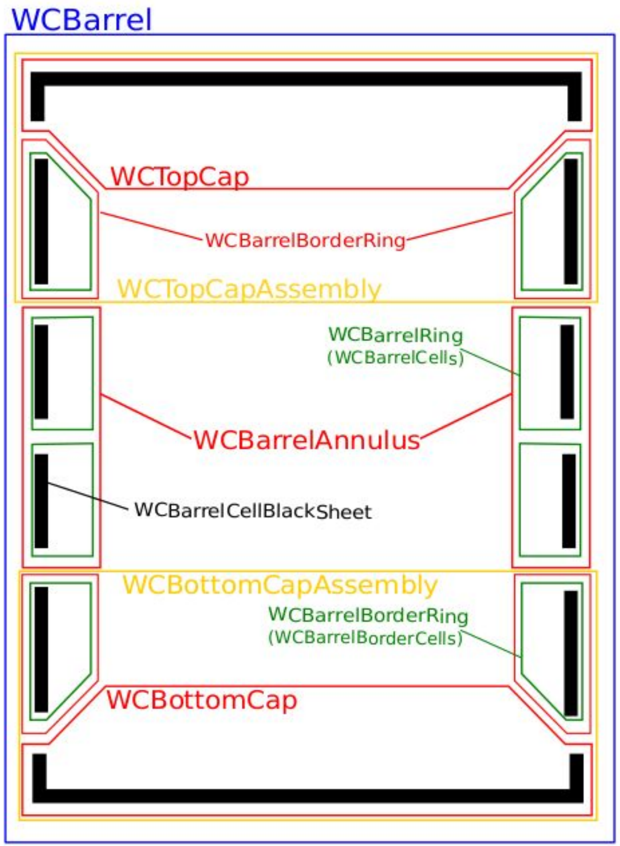
Daughter Volume = WCBarrel
File = src/WCSimConstructCylinder.cc
Shape = Tubs
Material = Water



# Hierarchy of Volumes

- WCBarrel consists of: PMTs and blacksheets

- It is divided into two parts :
  the annulus (WCBarrelAnnulus) &
  the caps (WCTopCapAssembly
  and WCBottomCapAssembly)



# Hierarchy of Volumes

WCBarrelAnnulus

⇩

WCBarrelRing

⇩

WCBarrelCell

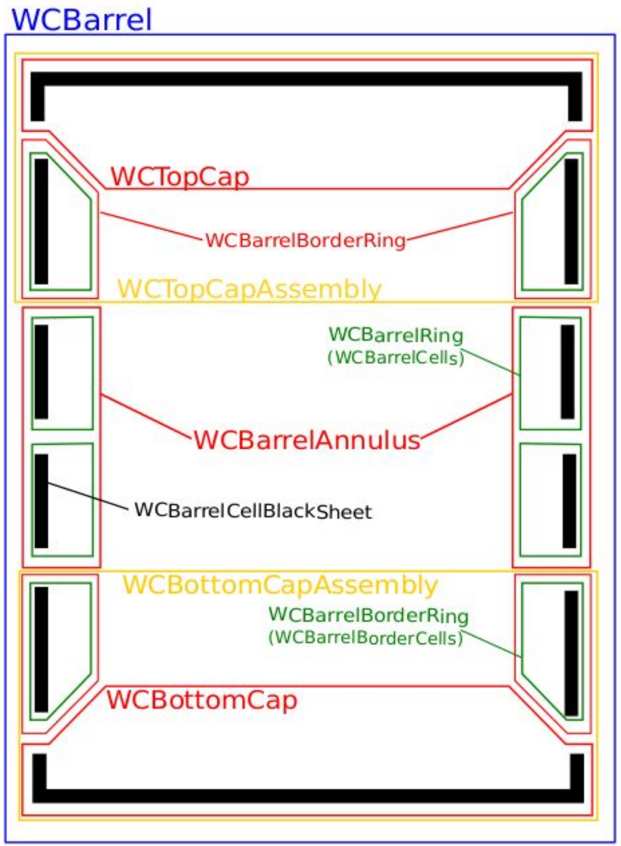
[Contains one or more PMTs  WCPMT) and the blacksheet ( WCBarrelCellBlackSheet ).
Each cell is flat, represents one modular detector section.]

WCTopCapAssembly/
WCBottomCapAssembly
(Two mirrored volumes that close the ends of the barrel)

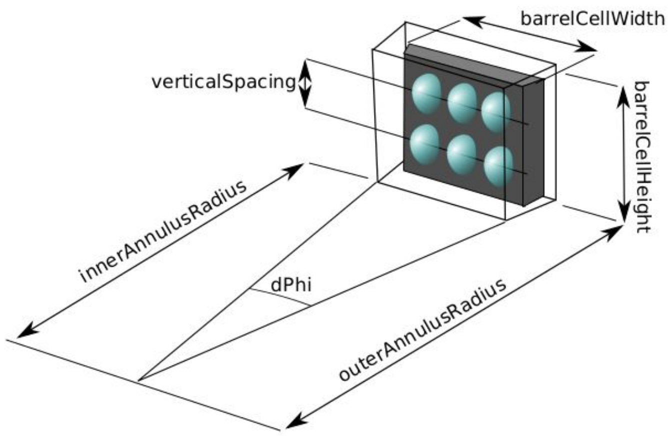
⇩

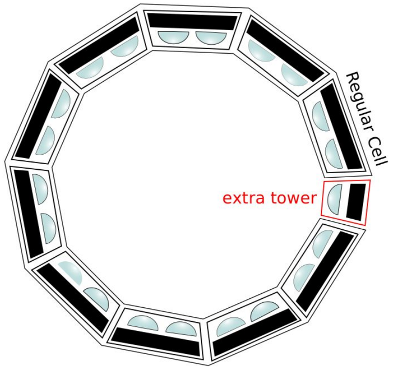
WCBarrelBorderRing

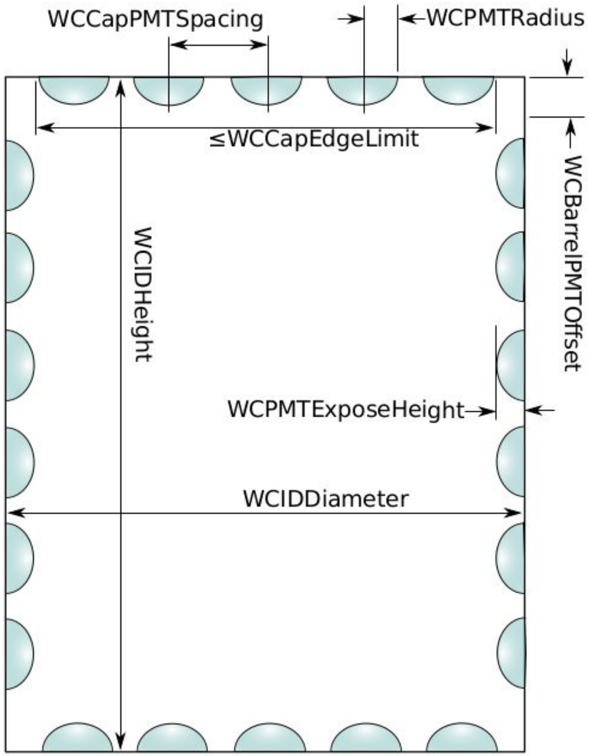
[This volume connects the annulus to the cap.
It is essentially the uppermost (or lowermost) ring of PMTs]

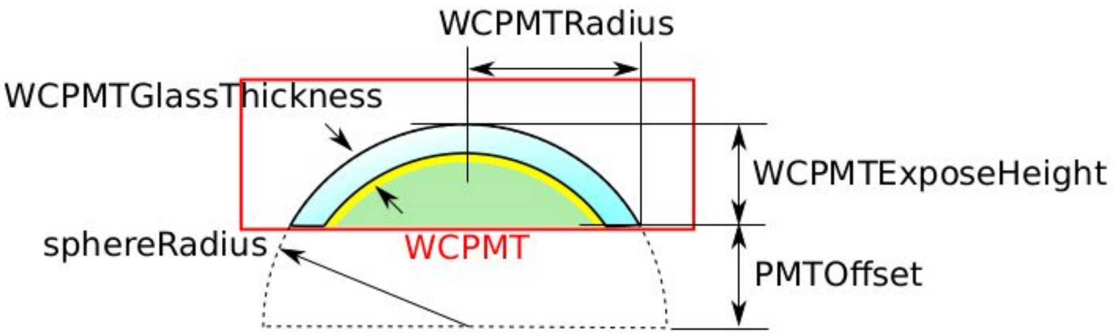


# Detector construction



# Super-K geometry

```
void WCSimDetectorConstruction :: SetSuperKGeometry ()
{
WCSimPMTObject * PMT = CreatePMTObject ( " PMT20inch " );
WCPMTName = PMT - > GetPMTName ();
WCPMTExposeHeight = PMT - > GetExposeHeight ();
WCPMTRadius = PMT - > GetRadius ();
WCPMTGlassThickness = PMT - > GetPMTGlassThickness ();
WCIDDiameter = 33.6815* m ;
WCIDHeight= 36.200* m ;
WCBarrelPMTOffset = 0.0715* m ; // offset from vertical
WCBarrelNumPMTHorizontal = 150;
WCBarrelNRings = 17.;
WCPMTperCellHorizontal = 4;
WCPMTperCellVertical = 3;
WCCapPMTSpacing = 0.707* m ;
WCCapEdgeLimit = 16.9* m ;
WCBlackSheetThickness = 2.0* cm ;
WCAddGd = false ;
}
```

***Thank you for the kind attention!***