Simulation of Noble Liquid Detectors Using RAT

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AARM—March, 21, 2014

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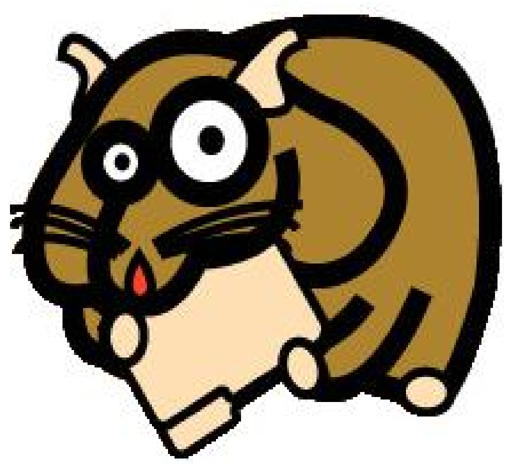
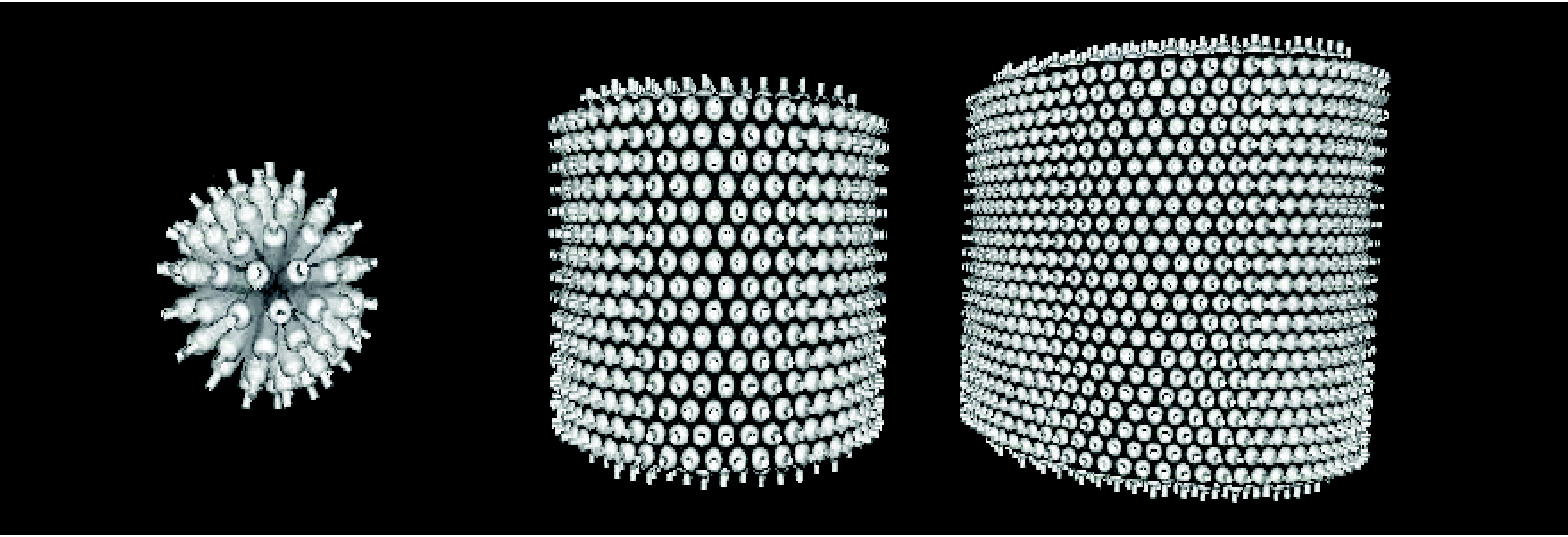


Motivation

- Build a fundamental physical model that incorporates all details from fundamental physics to data on disk
- Calibrate/constrain the model with data from experiments and test benches
- Make predictions about backgrounds and signals in existing and future detectors
- Provide a framework that allows physics and geometry to be shared across a range of experiments



What is RAT?

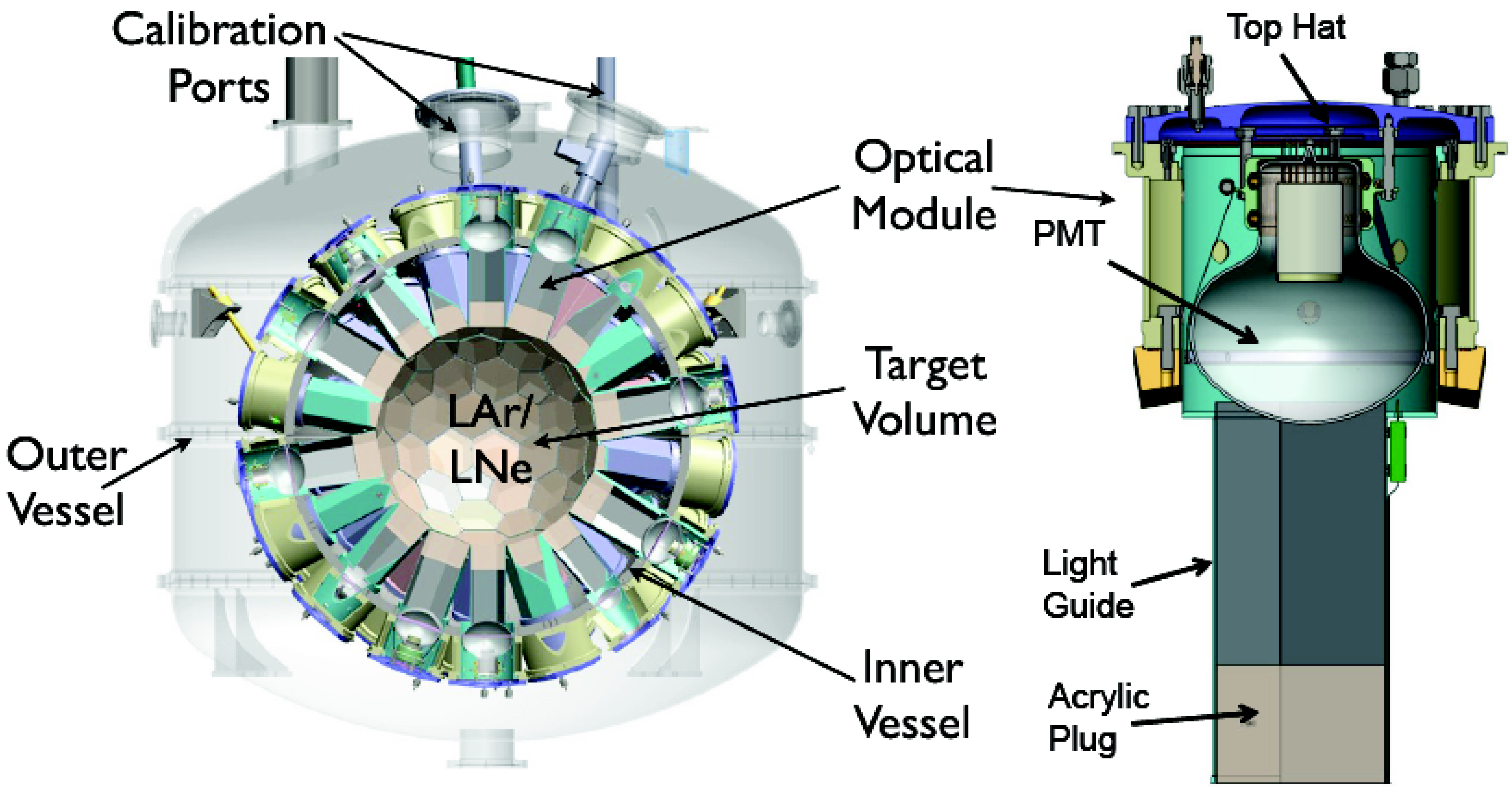
- Reactor Analysis Tool: start of a program created by the Braidwood collaboration to simulate and analyze data from a liquid scintillator experiment
- RAT (is an) Analysis Tool: evolution of RAT into a more generic package (S. Seibert) used by MiniCLEAN, DEAP-3600, SNO+

- Builds on several existing packages:
  - GEANT4.9.5: basic physics and Monte Carlo
  - ROOT: Event I/O, RooFit, data structure, etc
  - GLG4sim: physics and geometry specific to scintillator/PMT experiment (G. Horton-Smith, KamLAND)
  - SNOMAN: no code, but 10 years of software design ideas

- Framework for simulation and analysis of scintillator/PMT detectors:
  - GEANT physics with custom additions
  - Convenient interface to arbitrary GEANT geometries
  - Collection of event generators
  - Database for managing optics, material properties, run configurations, etc
  - Data structure for storing both MC and data
  - Event level analysis

MiniCLEAN

- Much of the RAT development has been in the context of MiniCLEAN and similar single phase noble liquid dark matter detectors
- 92 optical modules: wavelength shifting film, acrylic plug, light guide, PMT
- Inner detector complete at SNOLAB (6000 mwe) in radon reduced clean room



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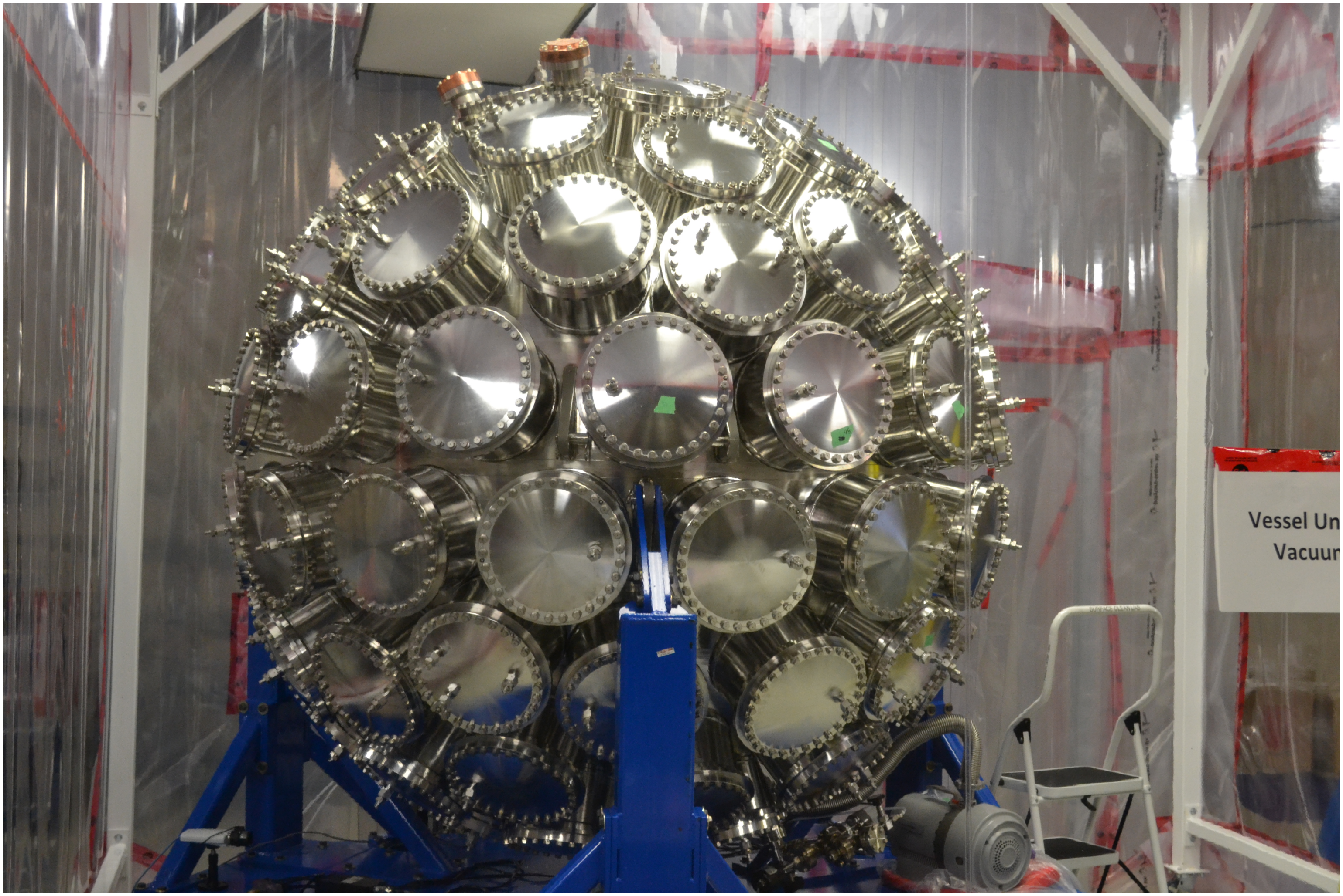
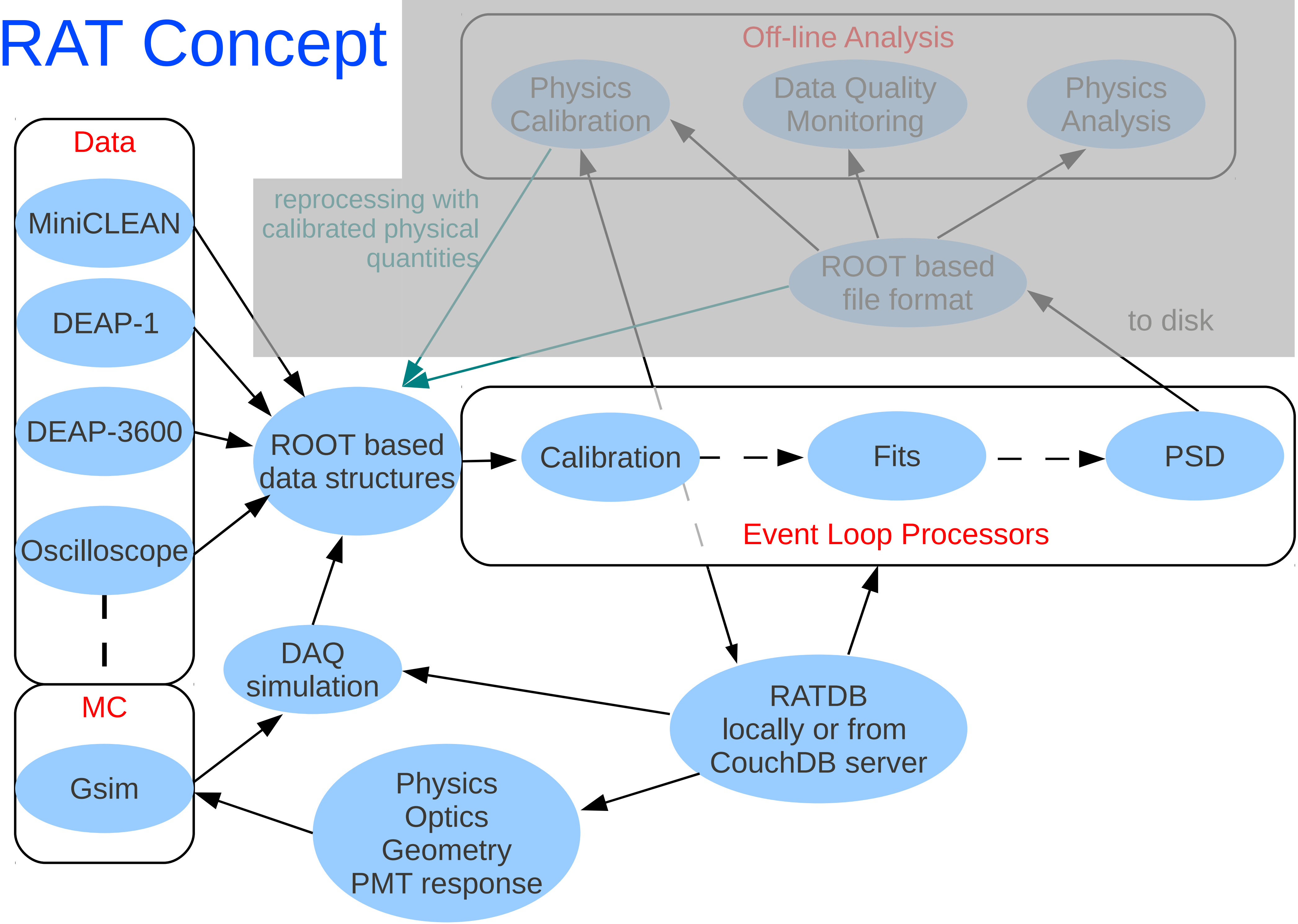


RAT Concept



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RATDB locally or from CouchDB server
Physics Optics Geometry PMT response

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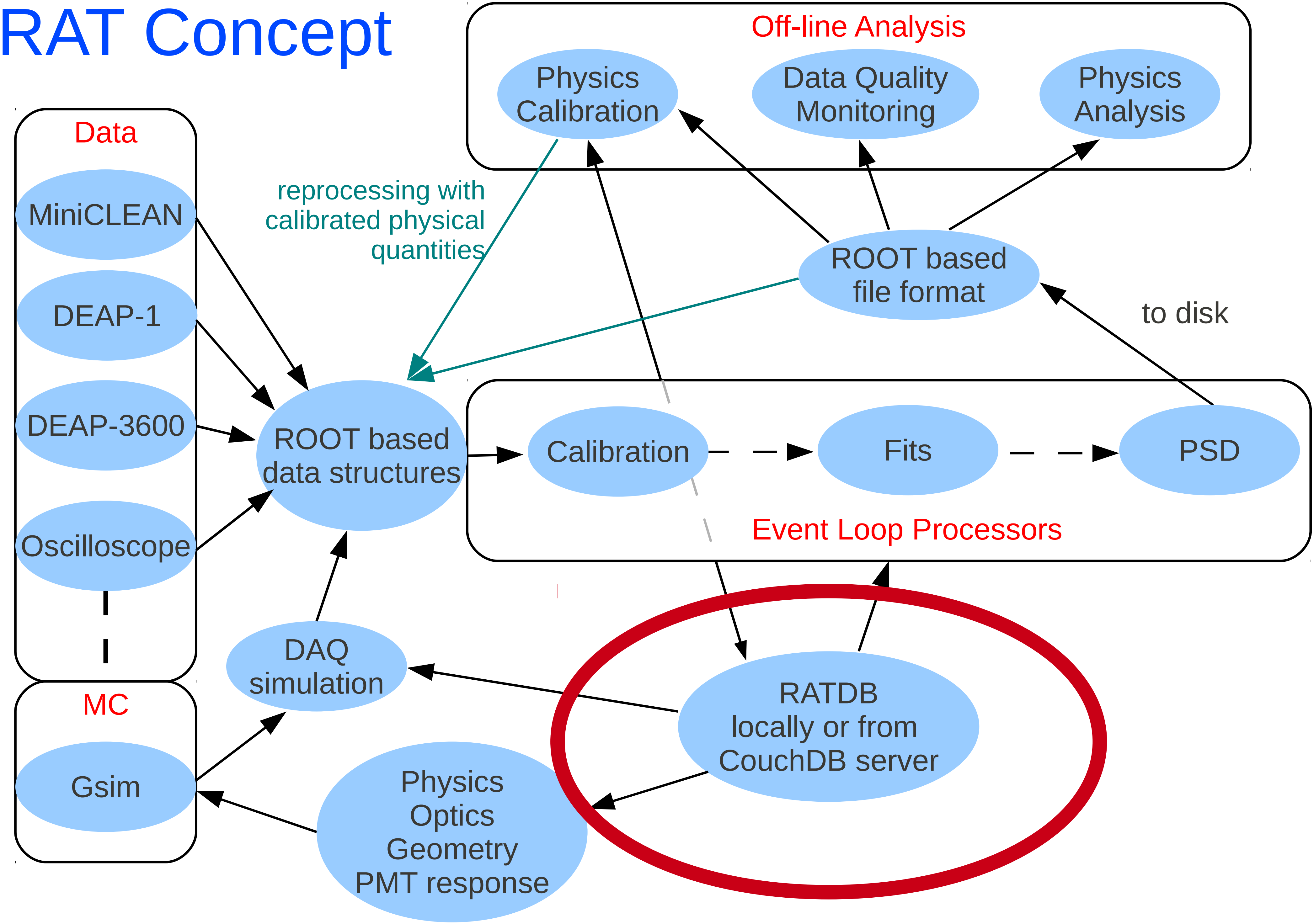

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RATDB

- Lightweight in-memory database for storing all geometry, optics, DAQ, processor control, etc. constants with optional time dependence
- Key-value storage for int, double, string, arrays of each, or JSON objects
- Name and optional index define tables, run_range gives time dependence
- User can override database settings globally from macro:

```
/rat/db/set MATERIAL[cryostat_vacuum] pressure 6.4e-6
```

- C++ and python APIs to access database externally:

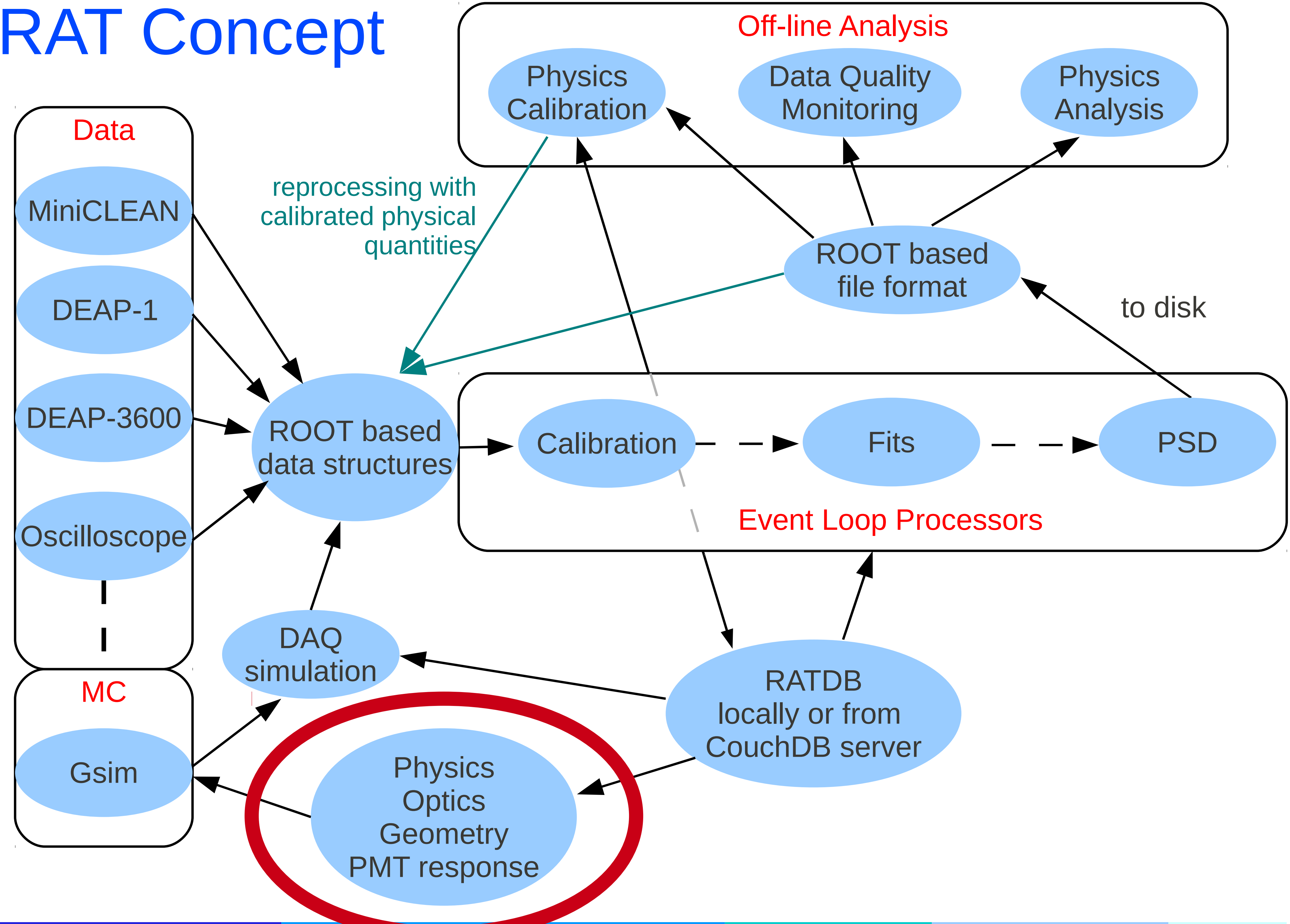
```
from rat import *
db = RAT.DB.Get()
db.LoadDefaults()
loptics = db.GetLink("OPTICS")
db.Load("MiniCLEAN")
```

```
#include <RAT/DB.hh>
RAT::DB* db = RAT::DB::Get();
db->LoadDefaults();
RAT::DBLinkPtr loptics = db->GetLink(“OPTICS”);
db->Load(“MiniCLEAN”);
```

- CouchDB server mode manages time dependent quantities and maintains configurations used in production analysis

```
db->SetServer(“http://localhost:5984/ratdb/”);
db->SetDefaultRun(10000);
```

RAT Concept



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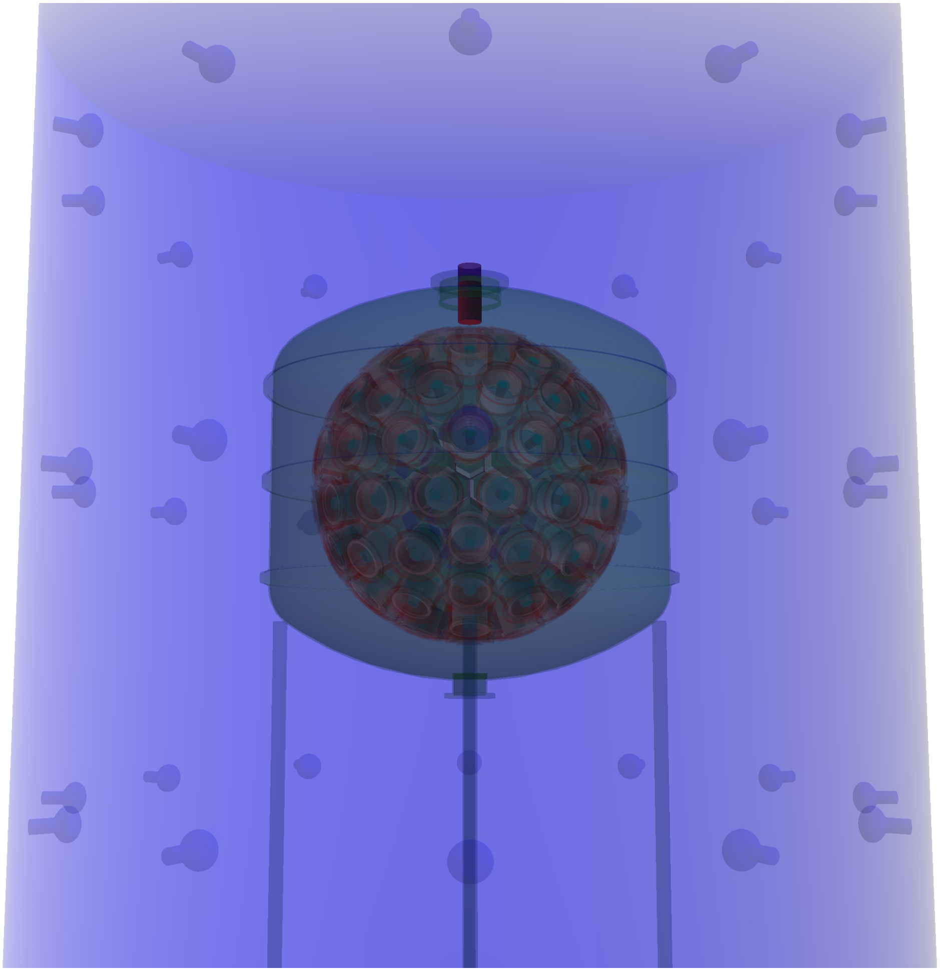
RAT Geometries

- RAT geometries are configured by RATDB tables:
  - Wrappers for standard GEANT geometry classes
  - Assortment of flexible custom geometries for more specific uses
  - GLG4 PMT physical model for elliptical photocathode PMTs



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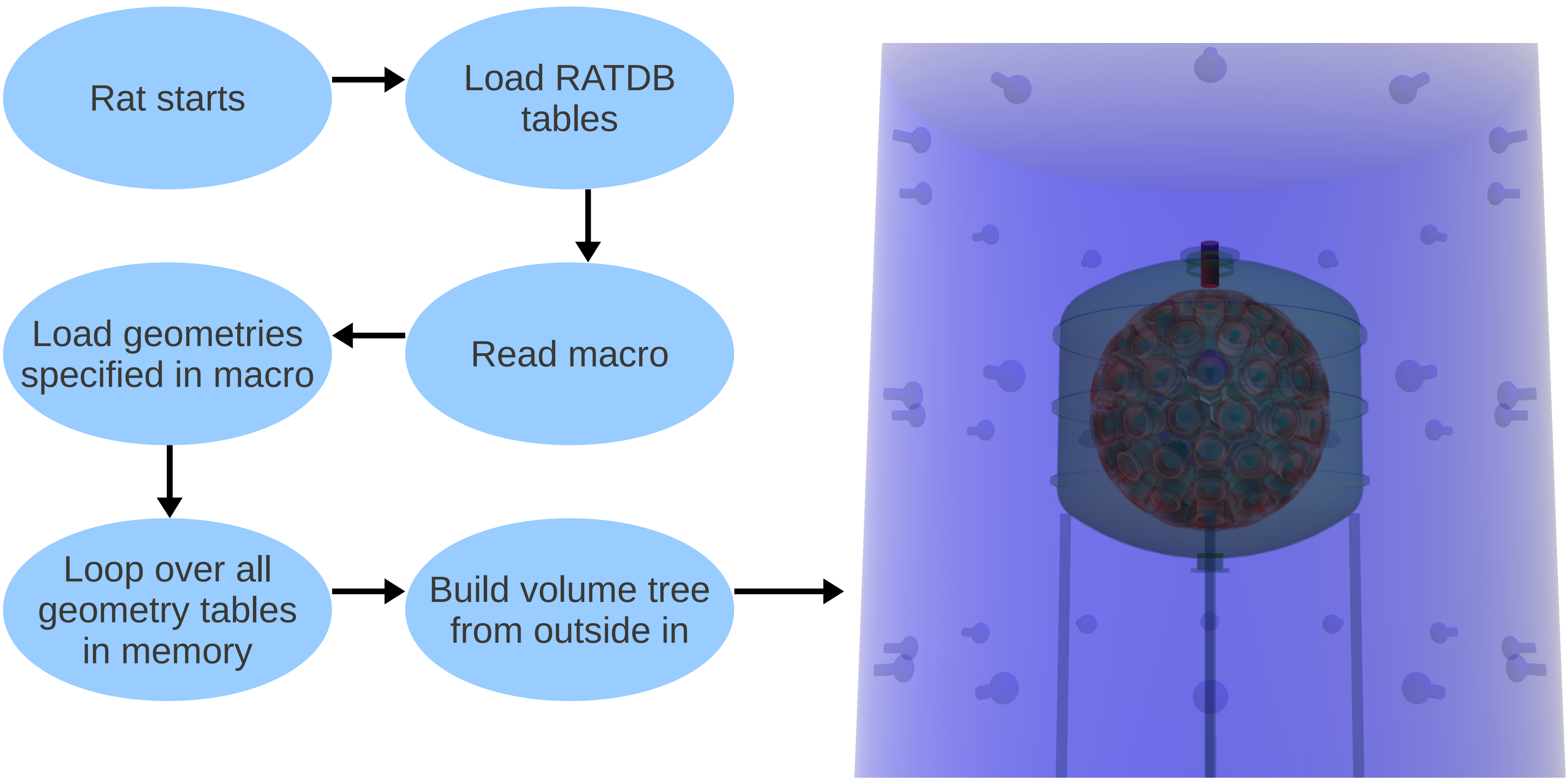
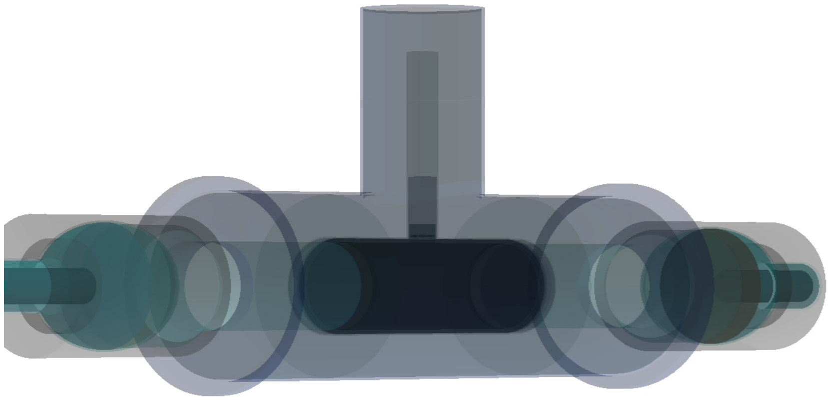


RAT Geometries

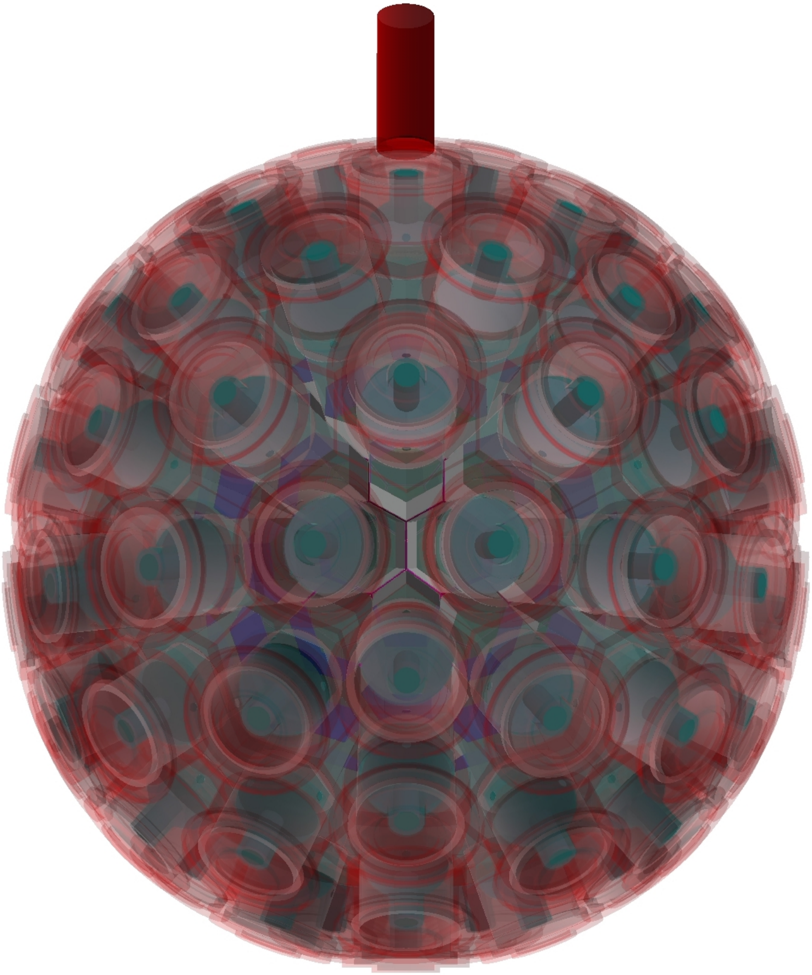
- Database controlled geometry has several advantages:
  - Addition of arbitrary new volumes of predefined shapes
  - Exclusion of volumes to disentangle physics or for geometry testing
  - Modification of materials, shapes, dimensions, optics
  - Creation of arrays of volumes with arbitrary rotations and offsets

- For complex geometries, geometry tables can be constructed in python which has several advantages to text based format (still no compilation or C++ required, DEAP-1 geometry below):
  - Variables and math operations for getting volumes sized and placed
  - Iteration over geometry tables
  - Logical operations for manipulating dependent volumes through user macros



RAT Geometries

- User specifies geometry in macro, detailed geometries exist for:
  - MiniCLEAN (below)
  - MicroCLEAN
  - DEAP-3600
  - DEAP-1
  - SNO+
  - Various test benches



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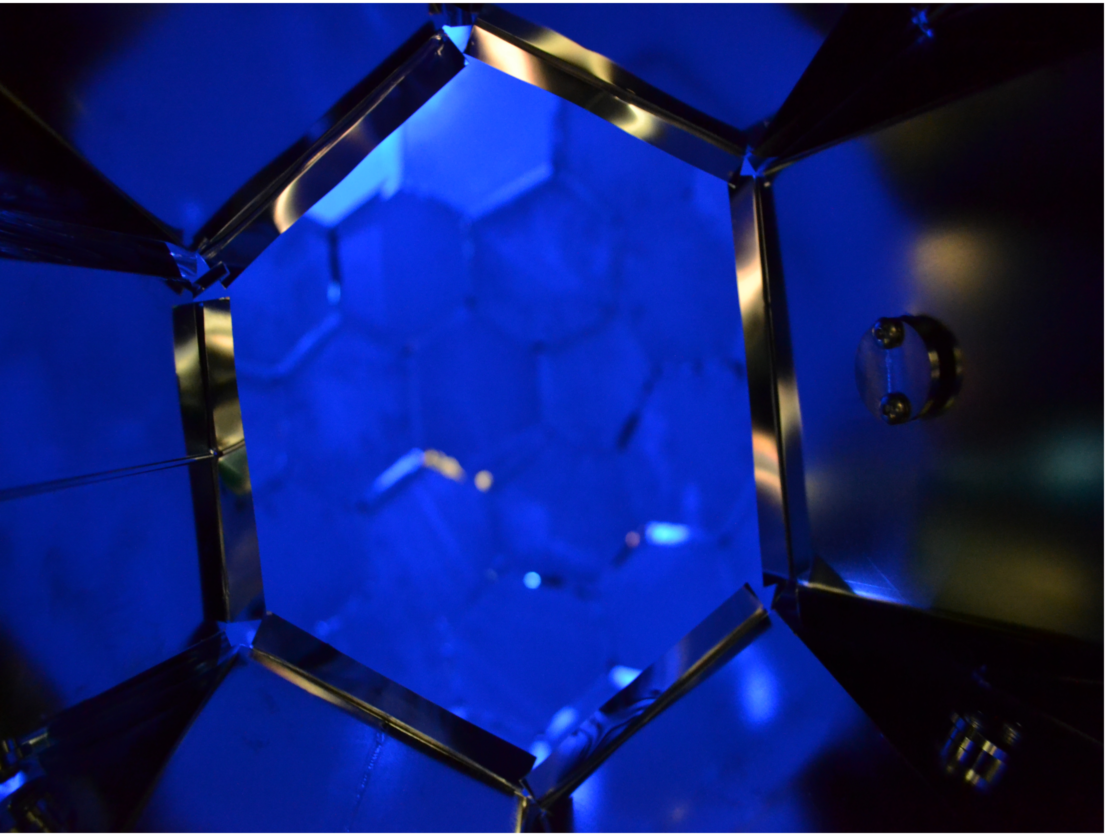
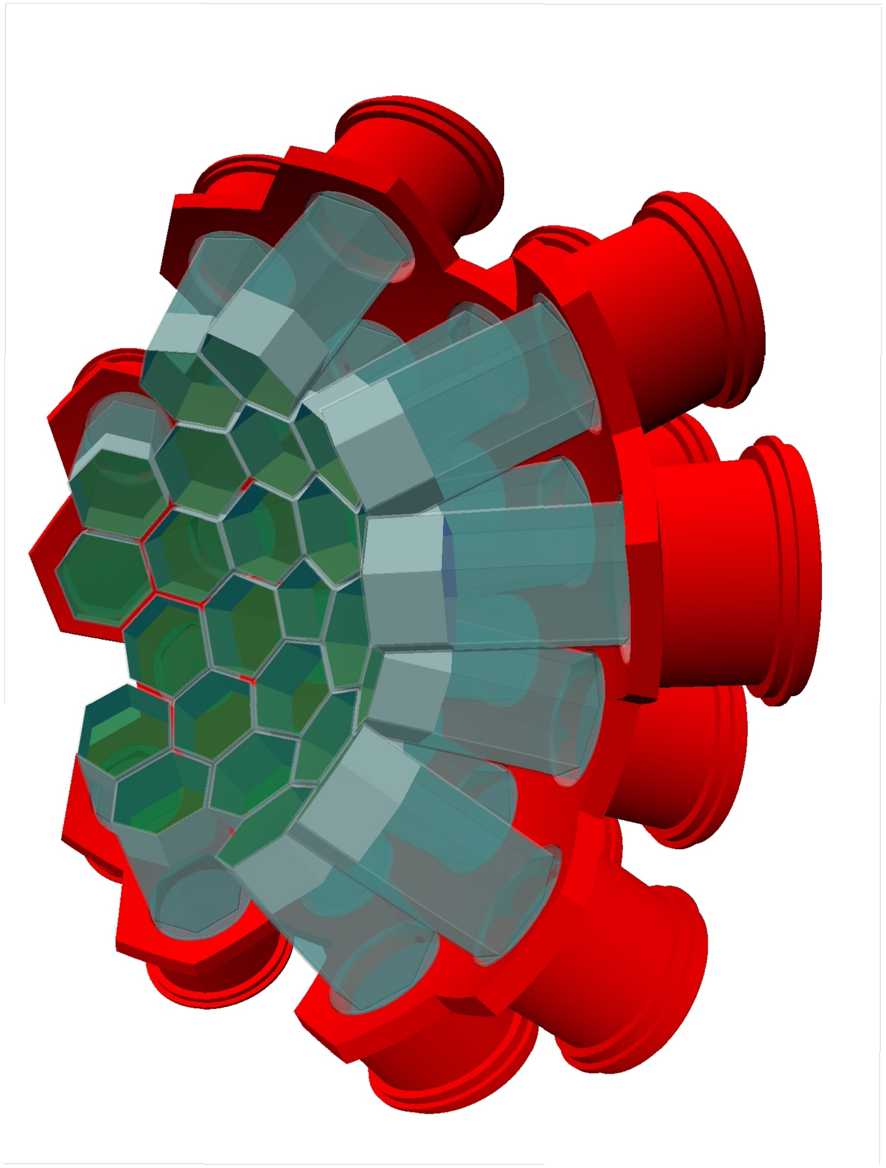
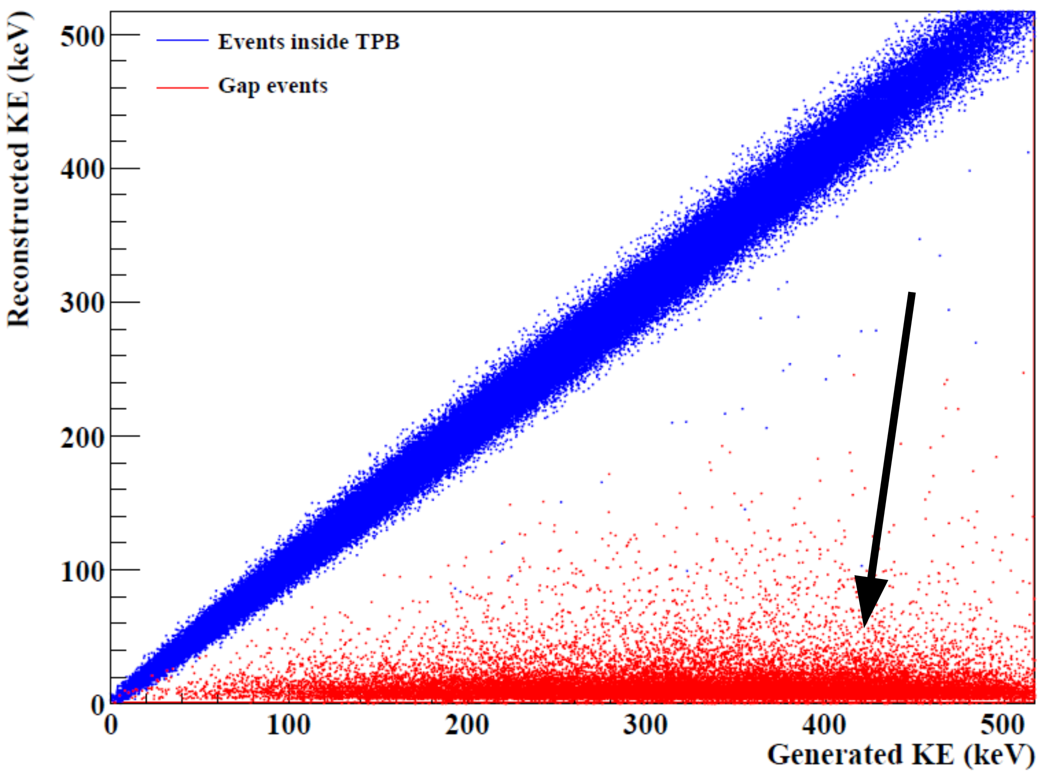
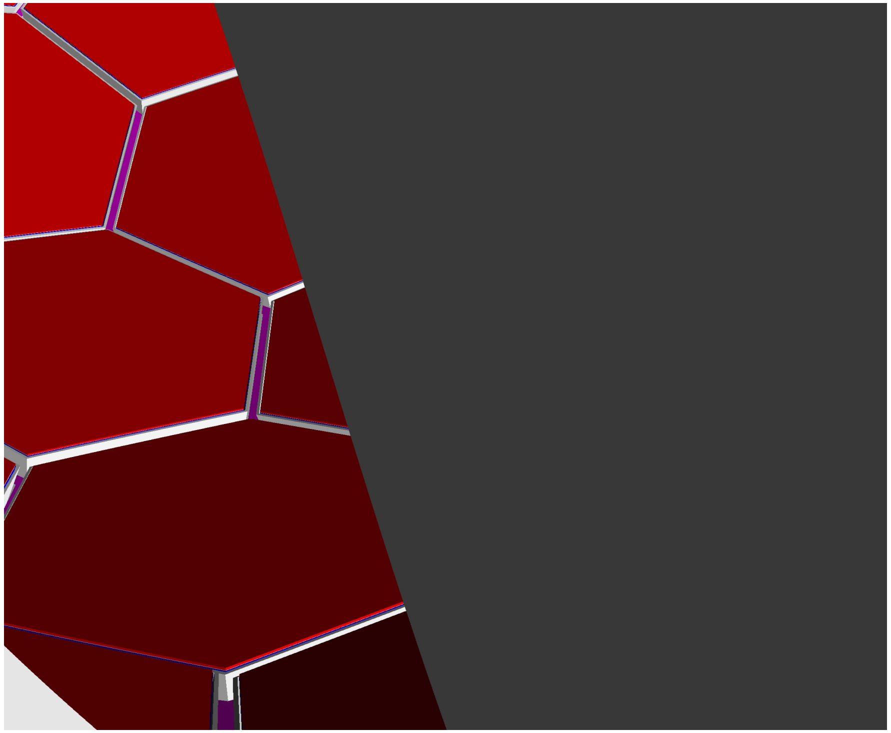




Simulation Assisted Design

- Detailed simulation of the MiniCLEAN geometry revealed a potentially large background at low energies
- ^{39}Ar with poor coverage between cassettes increased low visible energy event rate by a factor of ~100
- Added baffles to block light from these events in final design





Physics Simulation

- Tarball for installation of GEANT4.9.5, ROOT, and RAT across various platforms maintained with easy installation:

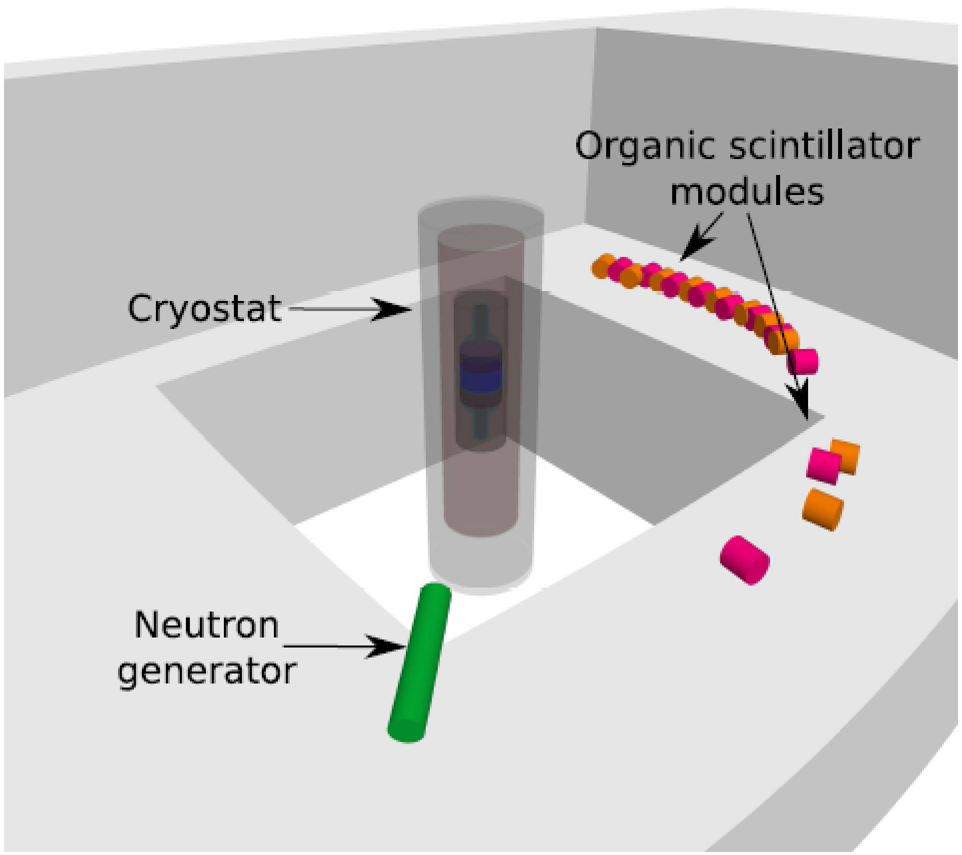
```
tar -xvjf ratcage.tar.bz2
cd ratcage
make
[wait an hour]
source env.sh
```

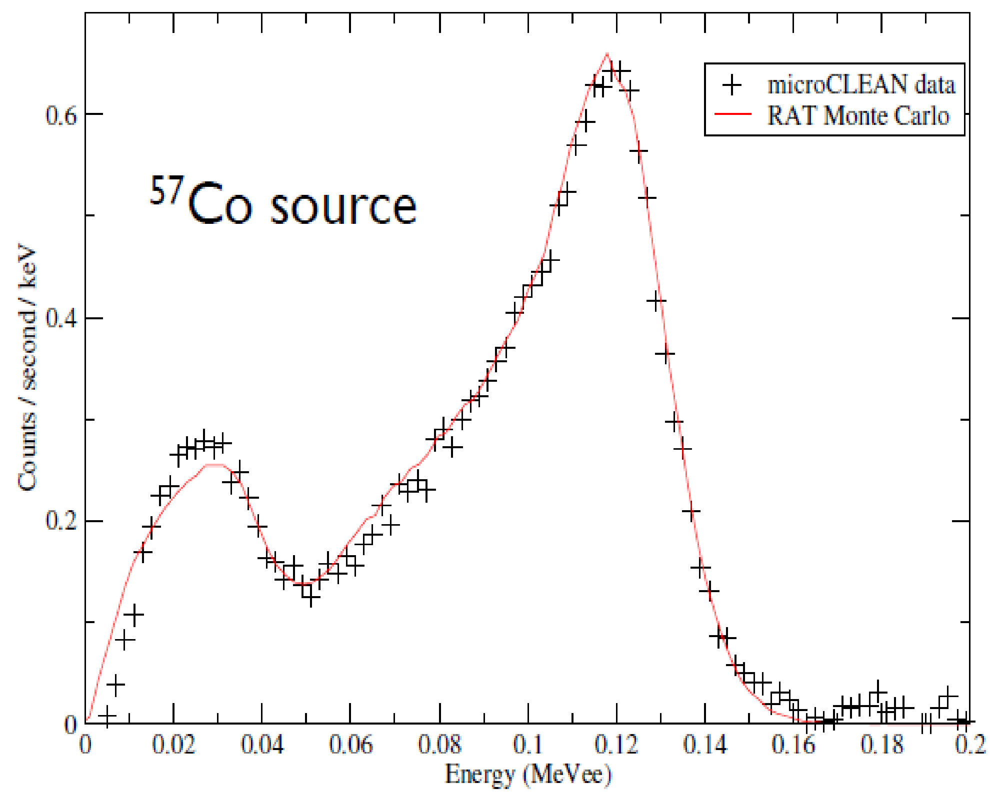
- Relevant GEANT4 processes are instantiated and can be selectively disabled for verification and testing
- Extension on GLG4Scint for detailed particle dependent scintillation physics in noble liquids, plastic scintillators, TPB, reflector materials, etc
- Noble liquid scintillation can be optionally handled by NEST
- Extended optical boundary physics class for wavelength shifters
- Extension on the GLG4 PMT optical model for detailed PMT optics
- Data structure optionally stores all particle tracking information for debugging and verification

Physics Simulation

- Physics used in MiniCLEAN/DEAP simulation constrained by results from existing data
- MicroCLEAN neutron calibration geometry below

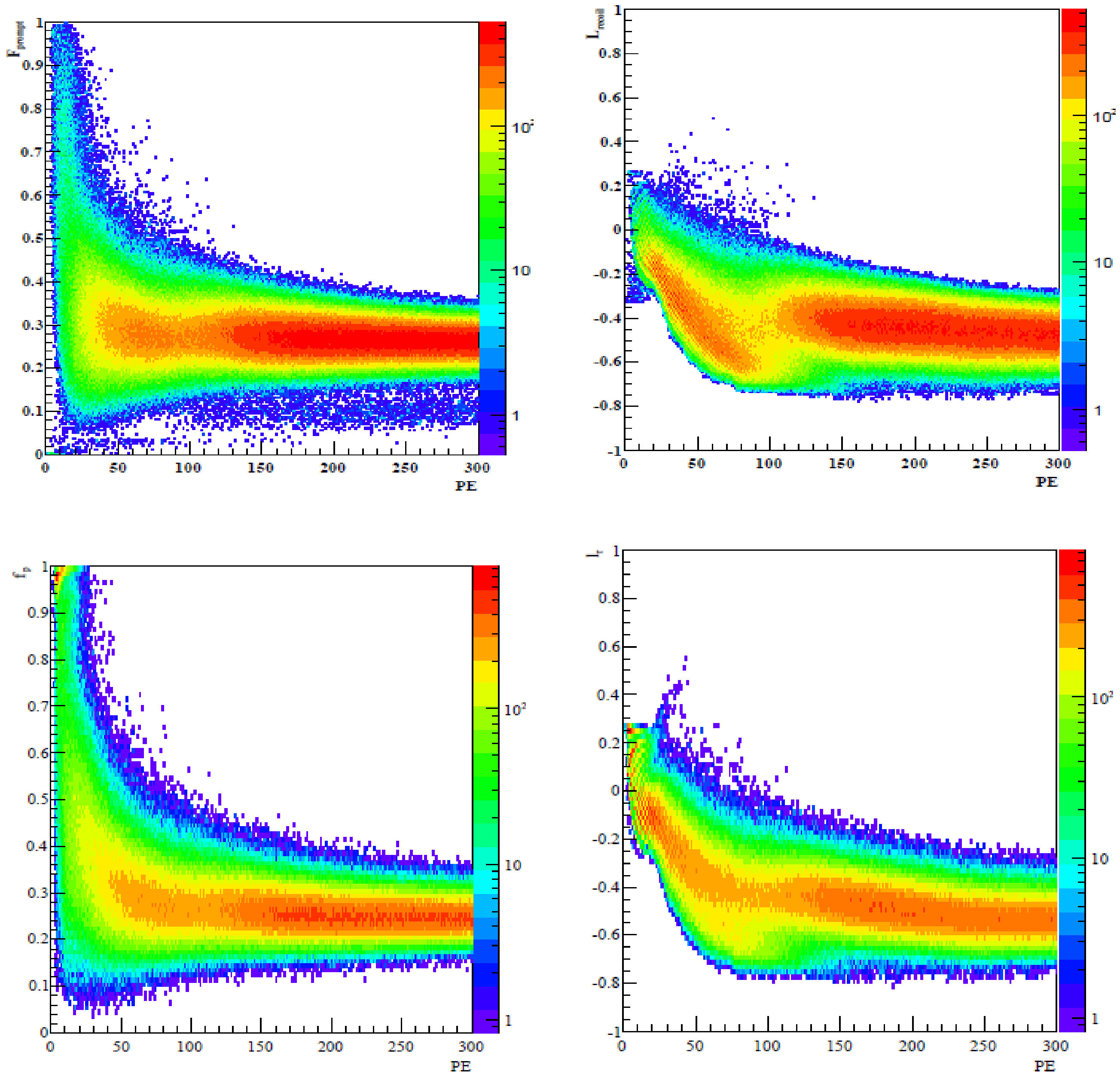
Global light collection efficiency for MiniCLEAN constrained by MicroCLEAN measurements—single parameter with 3% correction





DEAP-1 PSD Simulation

- DEAP-1 tagged ^{22}Na MC (top), data (bottom)
- Prompt fraction (left), likelihood based PSD (right)
- PSD measurement was limited to > 120 PE, thought to be due to statistical limitations
- Simulation of the detailed geometry and trigger along with likelihood based PSD developed in MiniCLEAN MC revealed a PSD background due to pileup of Cerenkov events from 1.3 MeV gamma



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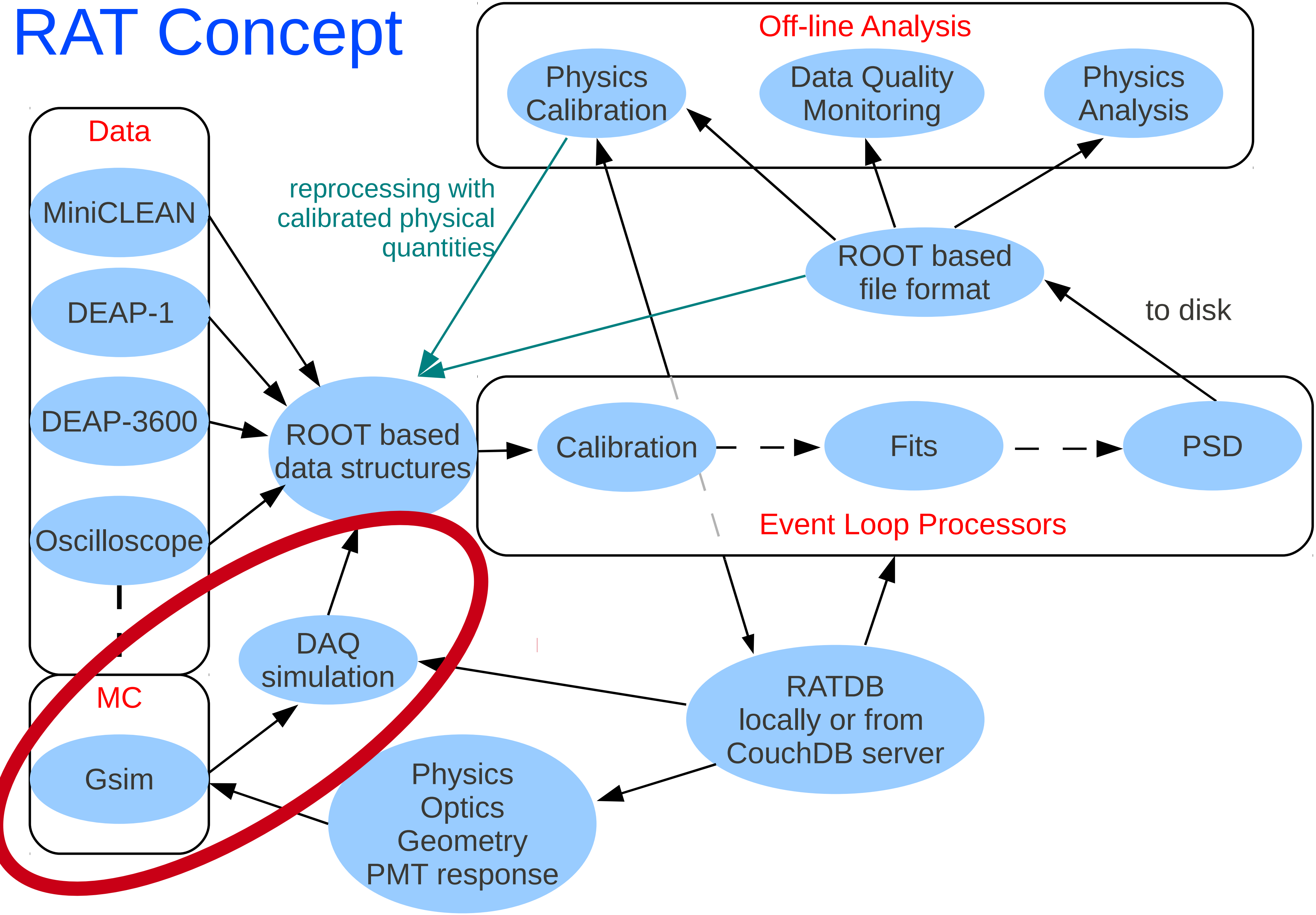

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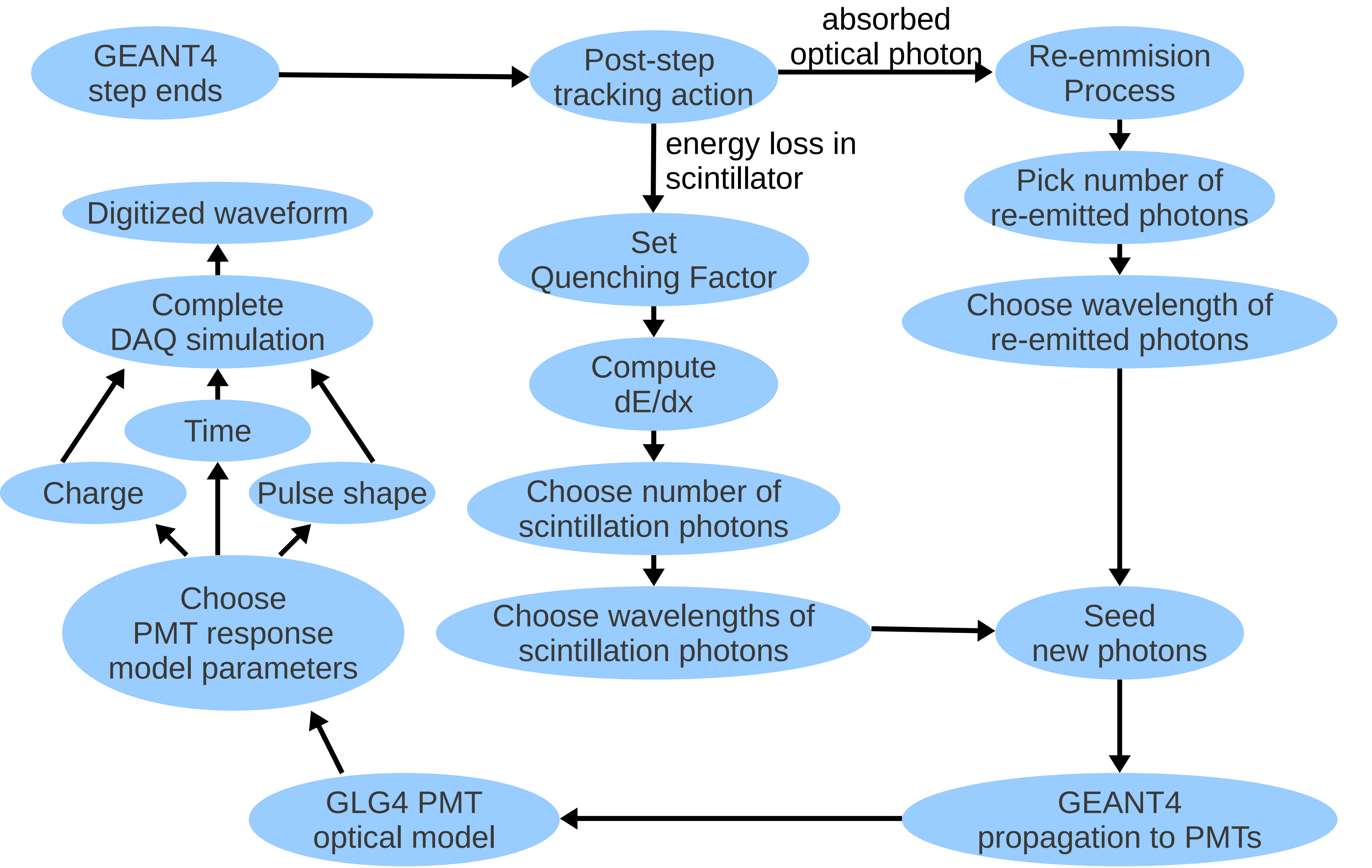
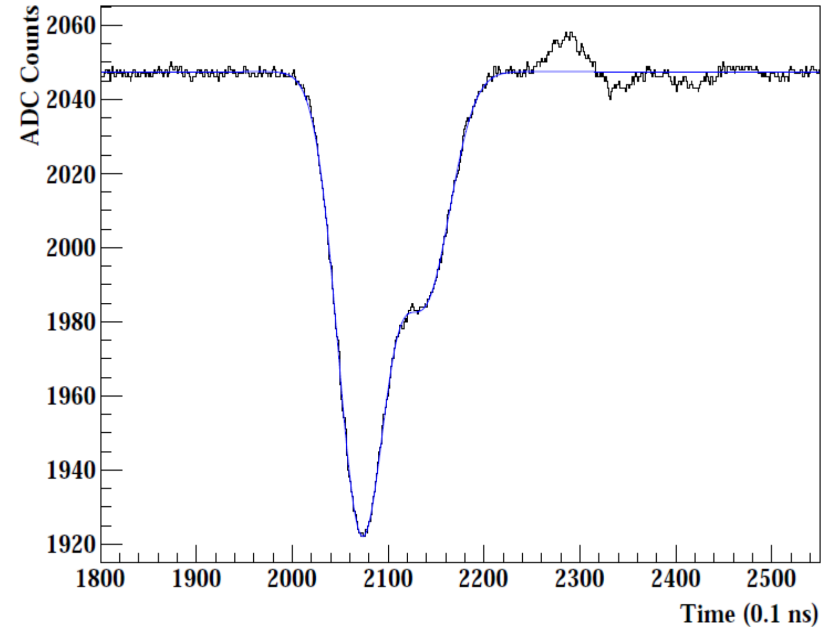
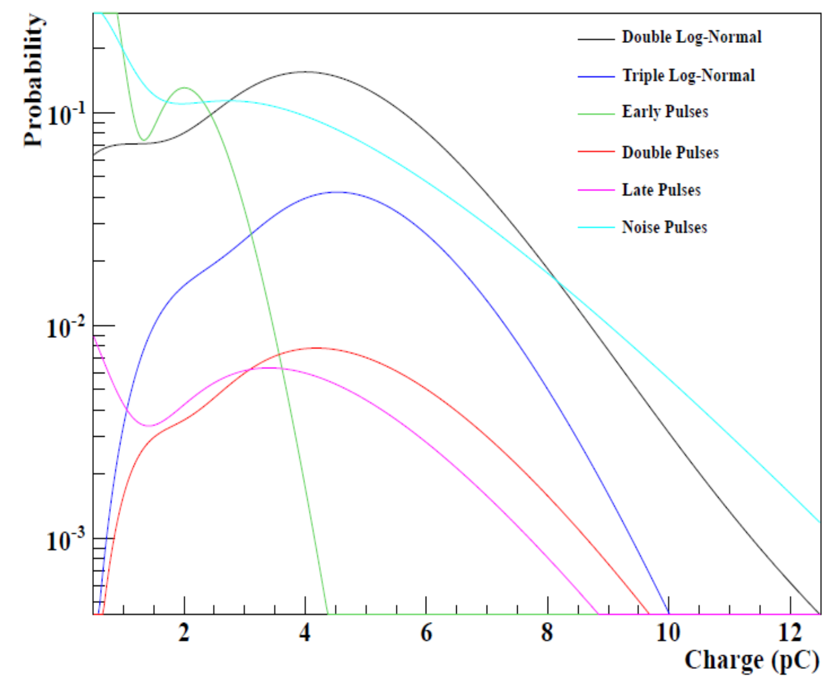
GEANT4 Track Step to Digitized Waveform



PMT Response and DAQ Simulation

- PMT response:
  - Based on measurements in cryogenic setup at LANL
  - Log-normal modeling of pulse shape (top)
  - Timing for double/late/after/pre-pulsing
  - Measured charge distributions for various pulse types (bottom)
  - Details: http://iopscience.iop.org/1748-0221/8/09/C09004/
- DAQ simulation:
  - Produces time dependent waveform based on simulated PMT pulses on a channel
  - Supports CAEN V1720 and V1740, generic high frequency oscilloscope
  - Includes zero-length encoding features
  - Electronics noise from calibration runs
  - Includes Nhit trigger simulation
  - Software trigger reduction as used in DAQ
  - < 1 ms / event processing time





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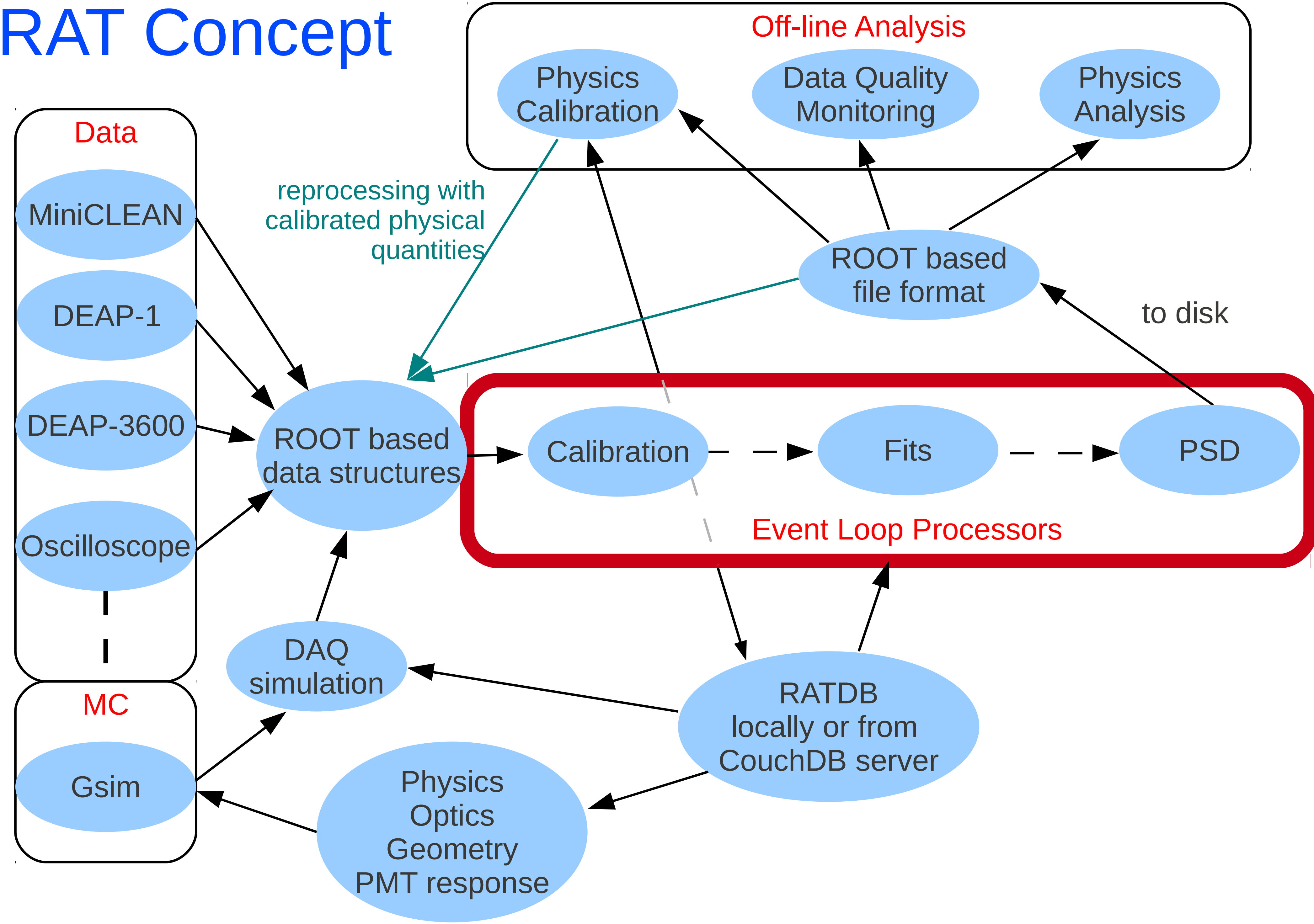

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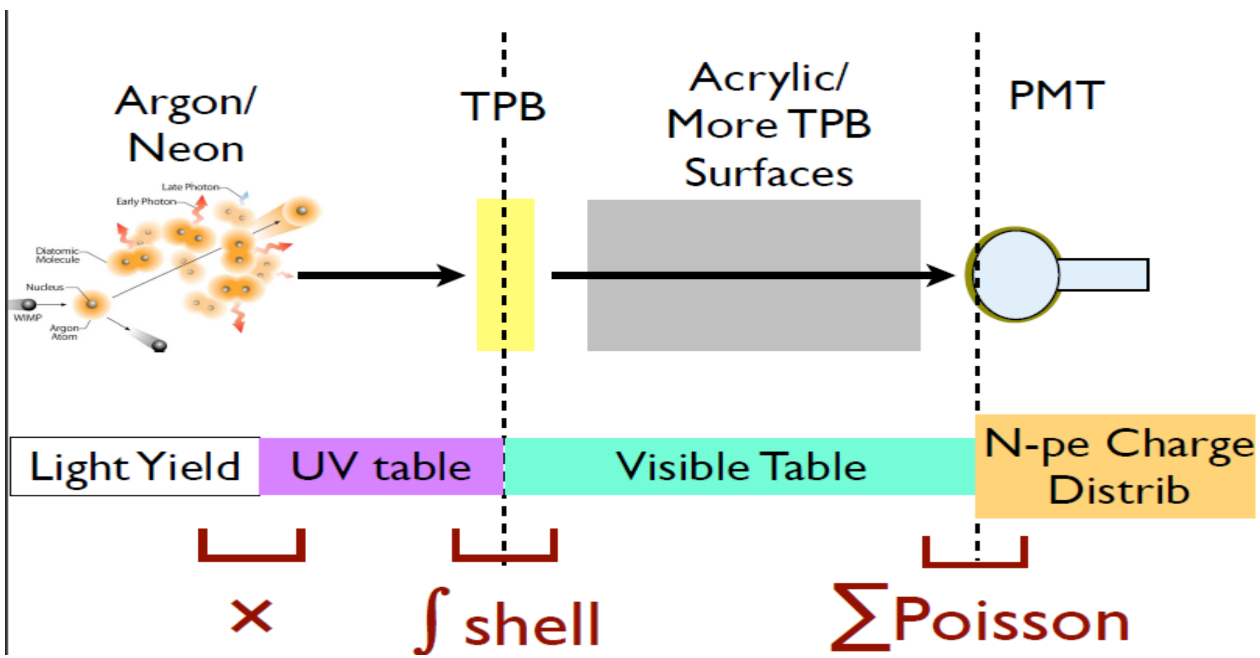
Event Processors

- RAT::Processor is a generic base class for operations on single events (calibration, reconstruction, PSD, filling histograms, applying cuts, etc)
- Processors can be written in either C++ or python
- User can include external python processors from macro
- Can override default processor configurations with inherited set functions
- Support for processors to run GEANT4 mini-simulations at the start of a run to determine physical properties of the detector
- Processors can write arbitrary TObjects to a directory in the output file
- Processors can be run multiple times in a single job

```
class Processor {
public:
  Processor(string _name);
    virtual void SetI(string param, int value);
    virtual void SetD(string param, double value);
    virtual void SetS(string param, string value);
    virtual Processor::Result Event(DS::Root *ds);
};
```

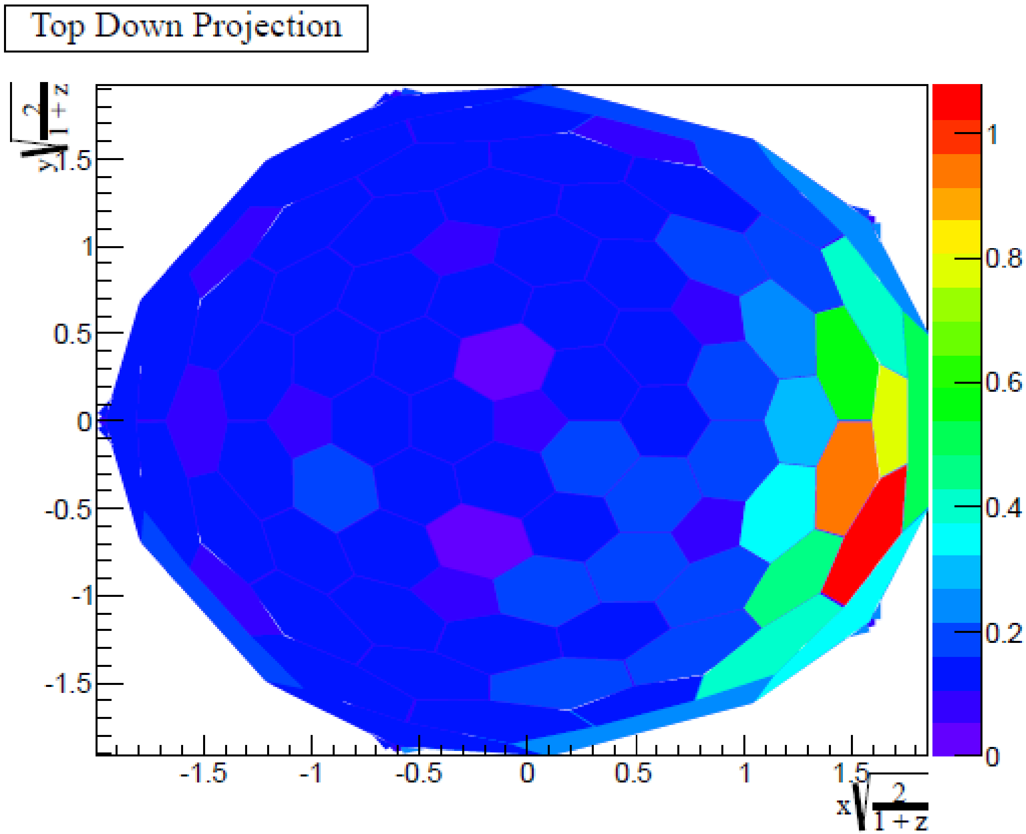
Processor Examples

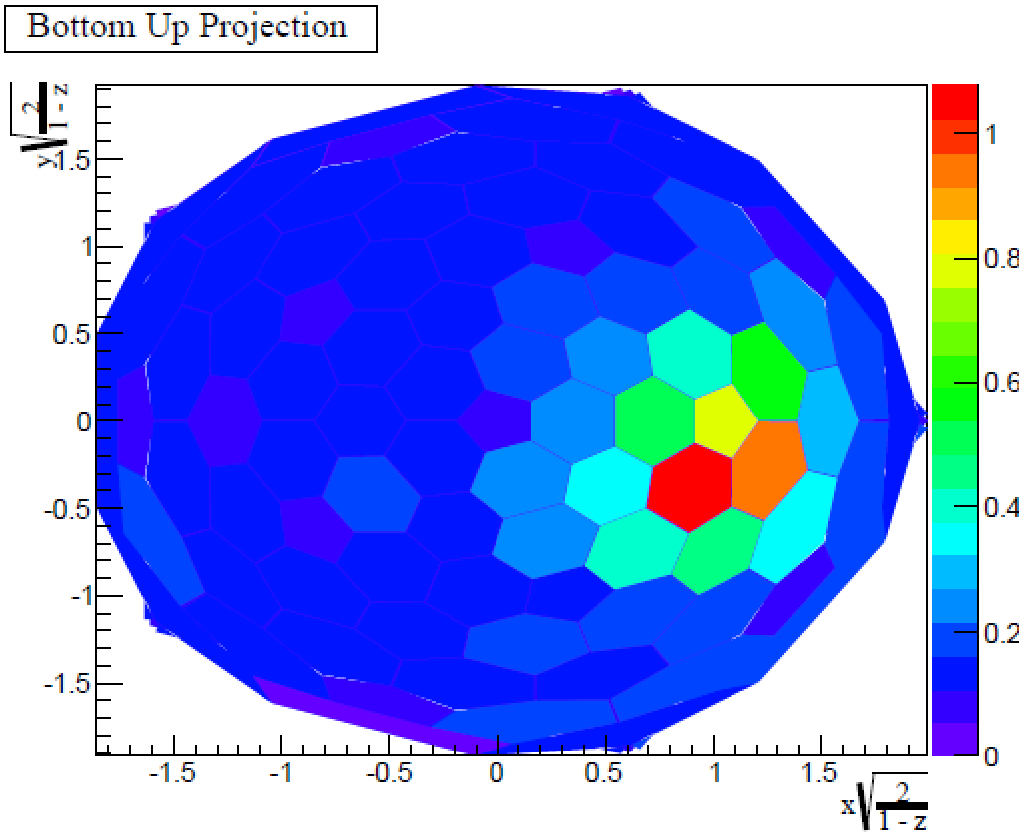
- Position reconstruction:
  - Run mini-simulations at startup to determine mean TPB radius and light yield (or load table from previous job)
  - Build PDFs using min-simulation and PMT detection probabilities
  - Maximum likelihood fit for position (and simultaneously energy optionally) using previous pass of Bayesian single PE counting
  - Store position and likelihood fit information in data structure
  - Update priors for Bayesian single PE counting, run iteratively



Processor Examples

- Monitor illumination of the detector
  - Integrates PE times over the course of a run
  - Does not populate data structure
  - Stores histograms for the run in the output file
  - Projections of illumination of MiniCLEAN by a UV LED in vacuum below (data not MC!)





Sample Macros

- Simulating and analyzing 39Ar in MiniCLEAN
- Would run with:
  - rat -o ouput.root macro.mac

```
/glg4debug/glg4param omit_muon_processes 1.0
/glg4debug/glg4param omit_hadronic_processes 1.0

/rat/db/set DETECTOR experiment "MiniCLEAN"
/rat/db/set DETECTOR geo_file "MiniCLEAN/MiniCLEAN.geo"

/run/initialize

/rat/proc daq
/rat/proc calibrate
/rat/proc pulseIntWindow
/rat/proc fprompt
/rat/proc singlepe
/rat/proc shellfit
/rat/proc singlepe
/rat/procset mode 3
/rat/proc lrecoil

/rat/proc count
/rat/procset update 10

# output filename specified at command line
/rat/proclast outroot

# combination energy/position generator
/generator/add combo spectrum:fill
/generator/vtx/set e- Ar39_beta
/generator/pos/set 0.0 0.0 0.0

/generator/rate/set 500.0
/run/beamOn 10000
```

Disable some physics not relevant to this run

Load MiniCLEAN ratdb tables and specify geometry

Build geometry, initialize physics, setup run

Processor list: calibrate, find pulses, pulse-shape discrimination

Generate 39Ar events with spectrum in database filling the volume at the origin of the global coordinate system

Generate 10,000 events Poisson distributed in time at 500 Hz

Sample Macros

- Analyzing LED data from MiniCLEAN

```
/glg4debug/glg4param omit_muon_processes  1.0
/glg4debug/glg4param omit_hadronic_processes  1.0

/rat/db/set DETECTOR experiment "MiniCLEAN"
/rat/db/set DETECTOR geo_file "MiniCLEAN/MiniCLEAN.geo"

/rat/db/set GEO[cryoliquid] mother "cryopit"
/rat/db/set MATERIAL[cryostat_vacuum] density 8.3e-9
/rat/db/set MATERIAL[cryostat_vacuum] pressure 6.4e-6
/rat/db/set GEO[cryoliquid] material "cryostat_vacuum"
/rat/db/set GEO[inner_cryoliquid] material "cryostat_vacuum"

# build geometry setup run
/run/initialize

/rat/proc python
/rat/procset class "ratproc.DeltaT()"

/rat/proc calibrate
/rat/proc pulseIntWindow
/rat/proc fprompt
/rat/proc fitcentroid
/rat/procset rescale 0.533

/rat/proc hwtriggerselector
/rat/procset add_trigger "CAL1"
/rat/proc illuminationhist
/rat/proc count
/rat/procset update 1000

# input and output filenames specified at command line
/rat/proclast outroot
/rat/indcdaq/read_default
```

Disable some physics not relevant to this run

Load MiniCLEAN ratdb tables and specify geometry

Modify the geometry for putting the detector in its current state

Python processor

Some C++ analysis processors: calibration, pulse finding, etc

Override default charge centroid scale factor

Select only LED triggers for the following processors for the illumination plot

Read in raw data in the compressed DCDAQ format

Summary

- RAT provides a framework for:
  - Standard GEANT4 physics
  - Custom physics additions
  - Simple interface for building detailed GEANT4 geometries
  - Collection of physics event generators
  - Event level analysis
- This is used to build a fundamental model of various detectors
- Data from existing simulated detectors feeds back into the model to constrain the physics
- This predictive power of this approach is used in modeling current detectors and for future design