Neutrino and Air Shower Simulations in IceCube

Juan Carlos Díaz-Vélez

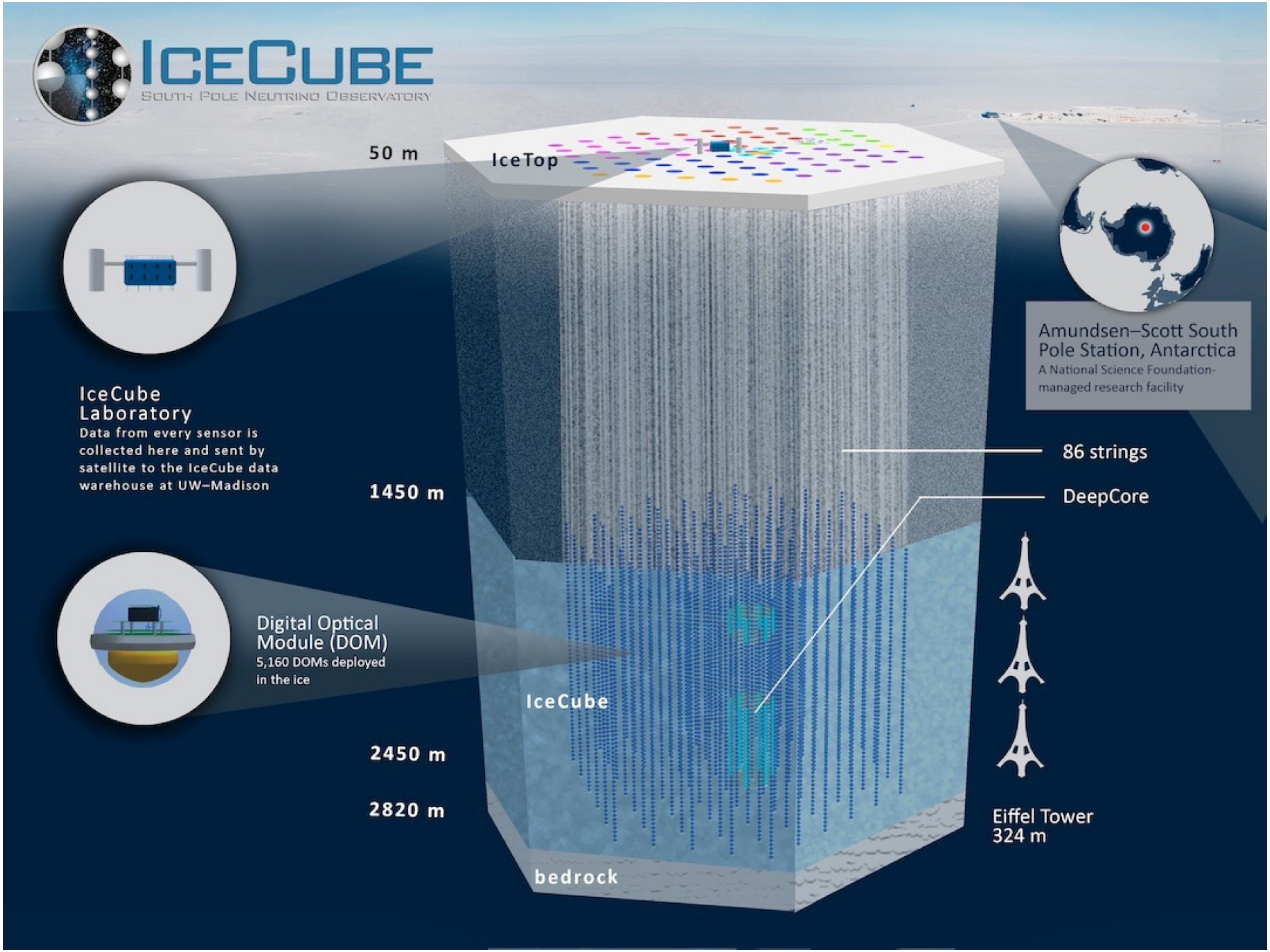
IceCube Bootcamp

Madison, WI

June, 2021

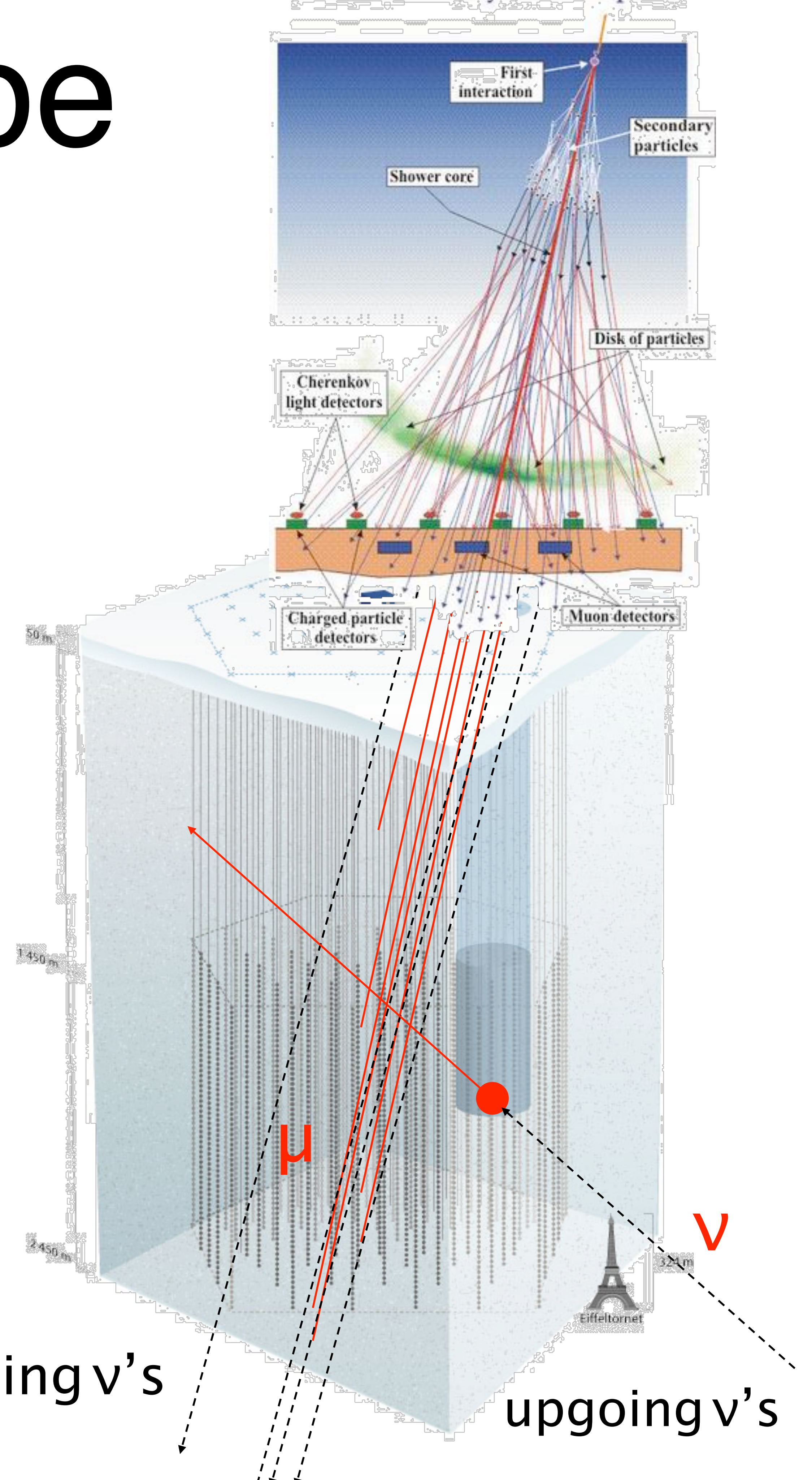
Wisconsin IceCube Particle Astrophysics Center

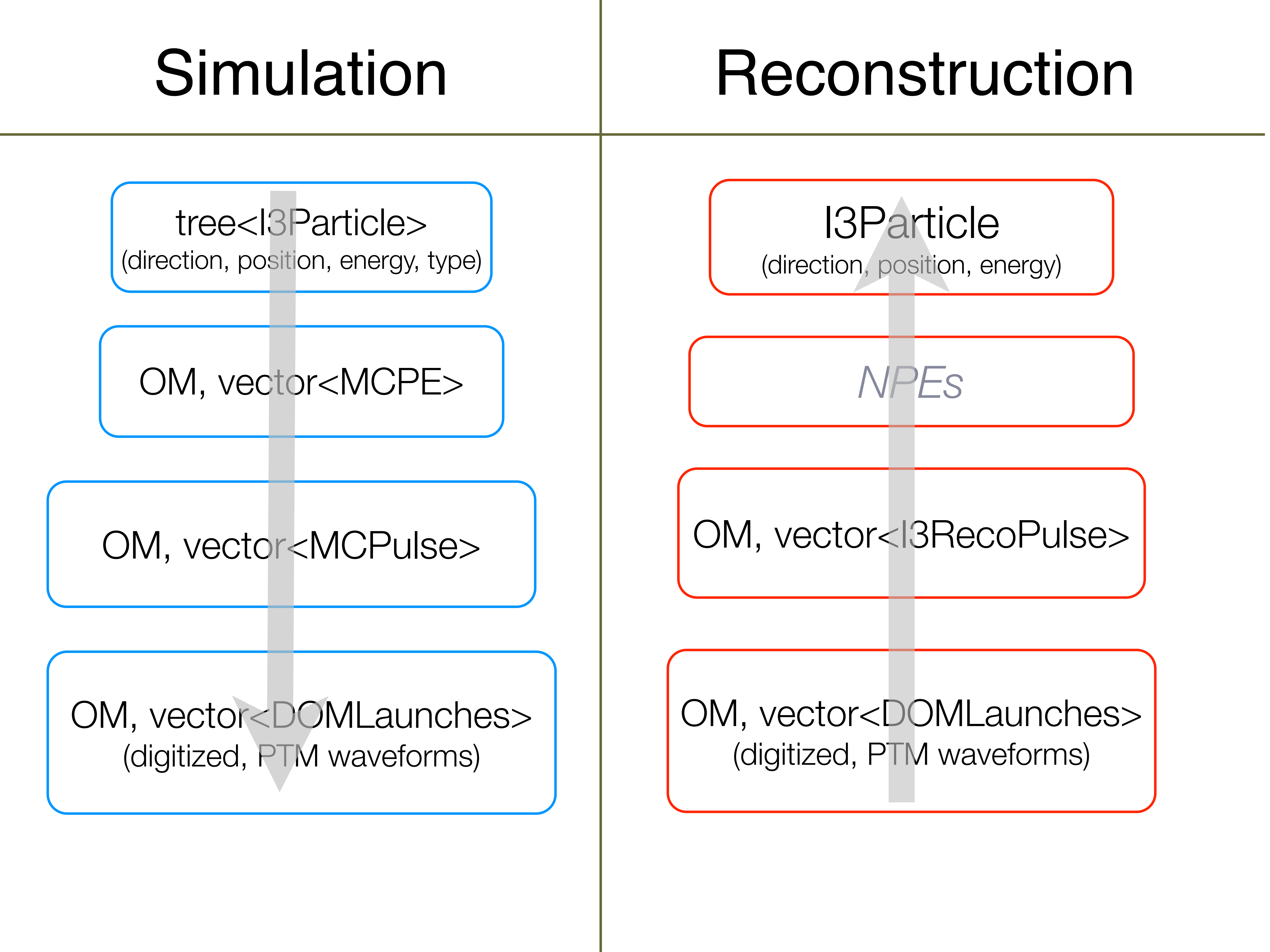
The IceCube Observatory

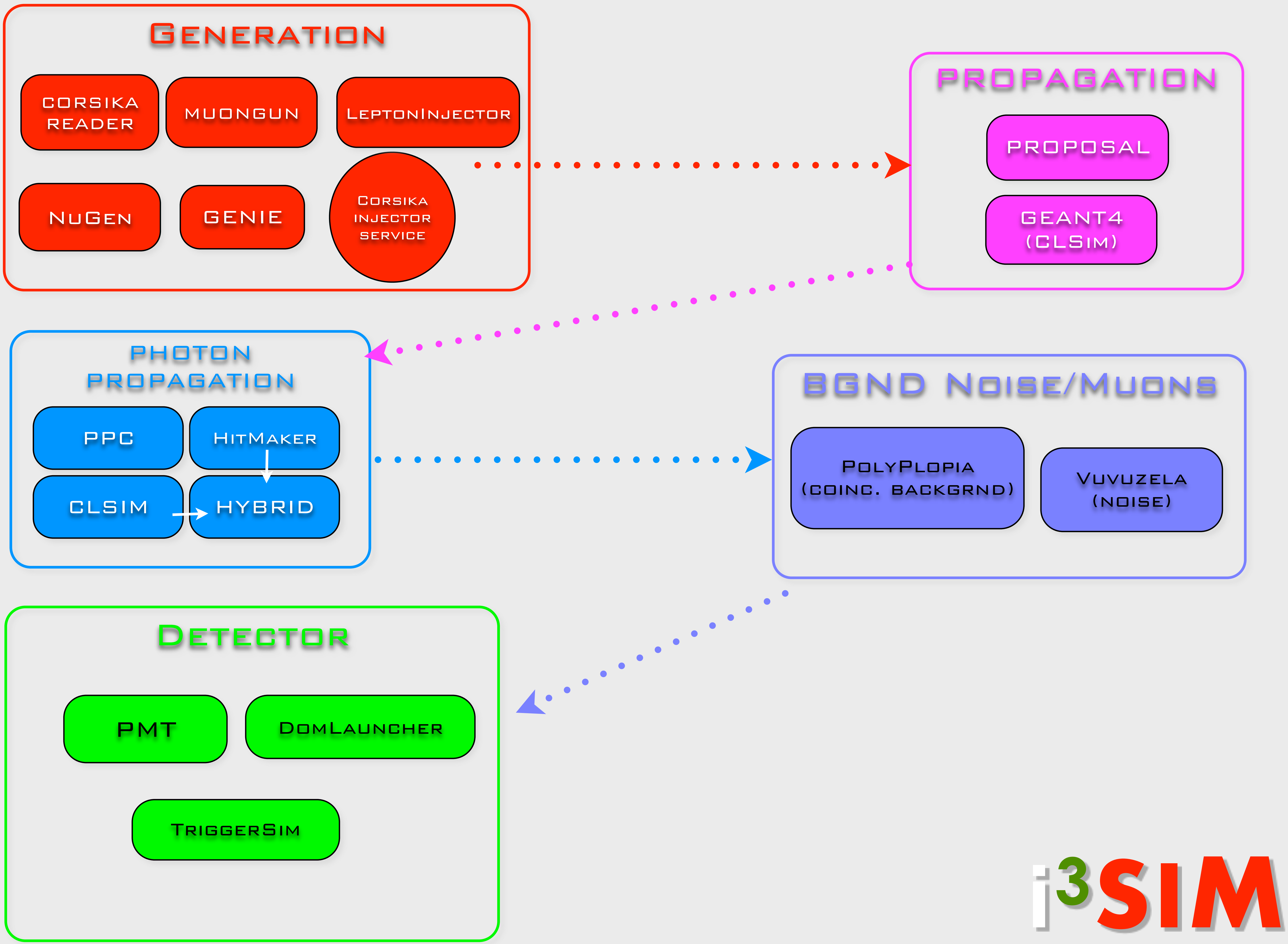


Events in icecube

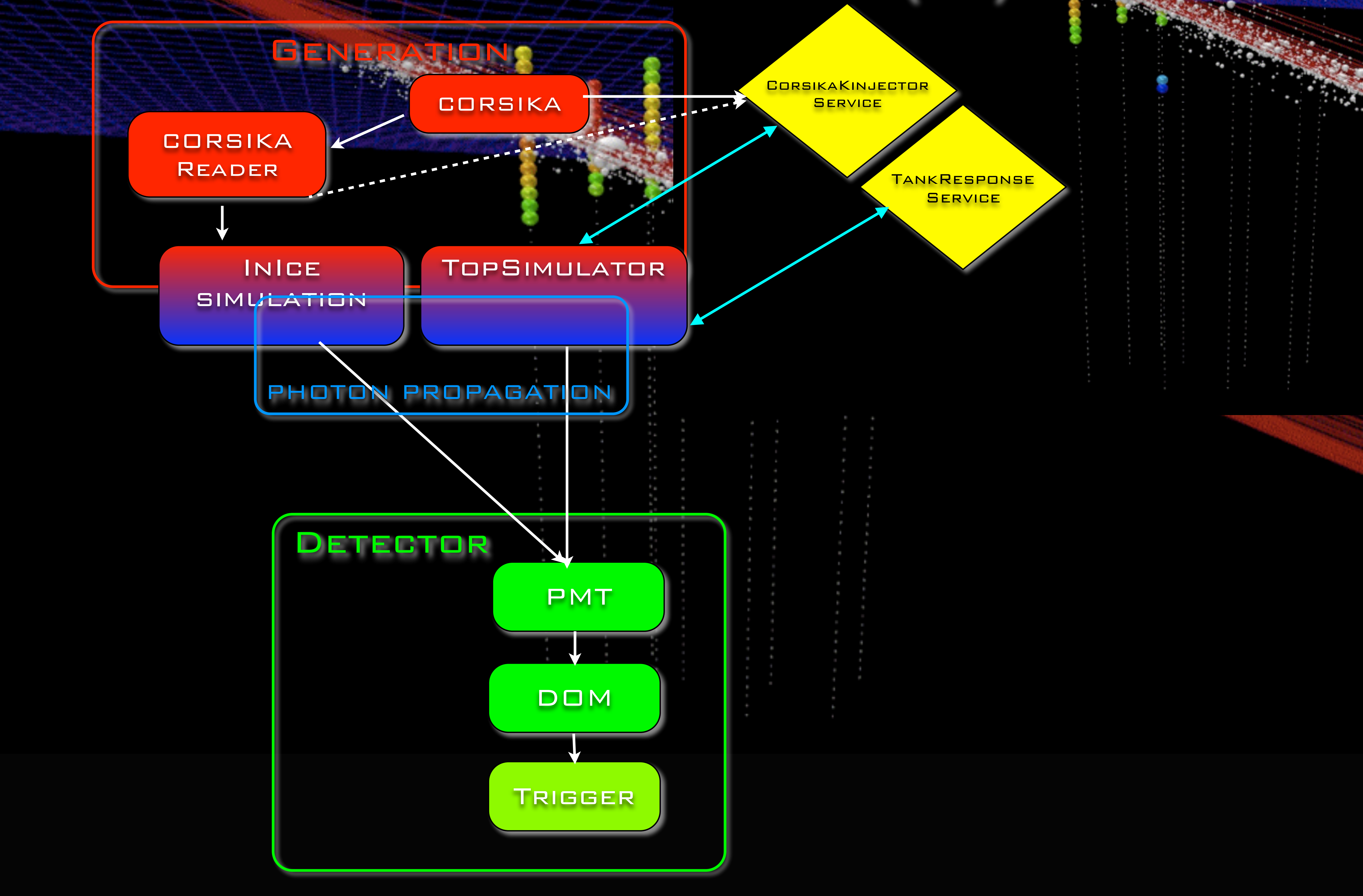
- Air shower detection @ surface
- Penetrating muon detection in deep ice
- Events dominated by cosmic ray muons : 10^6 μ for every ν that interacts in IceCube
- Atmospheric ν's




Simulation
Reconstruction
tree<I3Particle>
(direction, position, energy, type)
OM, vector<MCPE>
OM, vector<MCPulse>
OM, vector<DOMLaunches>
(digitized, PTM waveforms)
I3Particle
(direction, position, energy)
NPEs
OM, vector<I3RecoPulse>
OM, vector<DOMLaunches>
(digitized, PTM waveforms)


Generation
CORSIKA READER
MUONGUN
LeptonInjector
NuGen
GENIE
Corsika injector service
PROPAGATION
PROPOSAL
GEANT4 (CLSim)
PHOTON PROPAGATION
PPC
HitMaker
CLSIM
HYBRID
BGND Noise/Muons
PolyPlopia (coinc. backgrnd)
Vuvuzela (noise)
Detector
PMT
DomLauncher
TriggerSim
i3SIM

simulaton chain (IT)



Generators

- Cosmic-ray Air Showers:
  - **CORSIKA** (FORTRAN stand-alone)
  - **dynstack-corsika** (parallel corsika client/server w clsim)
  - **corsika-reader**: IceTray reader for standard format (deprecated)
  - **CorsikaInjectorService** (IceTop)
- Muons:
  - **MuonGun**: parametrization of flux of atm. muons under the ice.
- Neutrinos:
  - **neutrino-generator**: injects neutrinos, propagates them through Earth, forces interaction in detector volume.
  - **genie-icetray**: detailed simulation of neutrino interactions with GENIE. (Used for low-energy simulations)
  - **LeptonInjector / NuFSGen** (not yet available): weighted leptons+weights to account for flux models, interaction models, in-earth propagation, etc.

Generators (cont.)

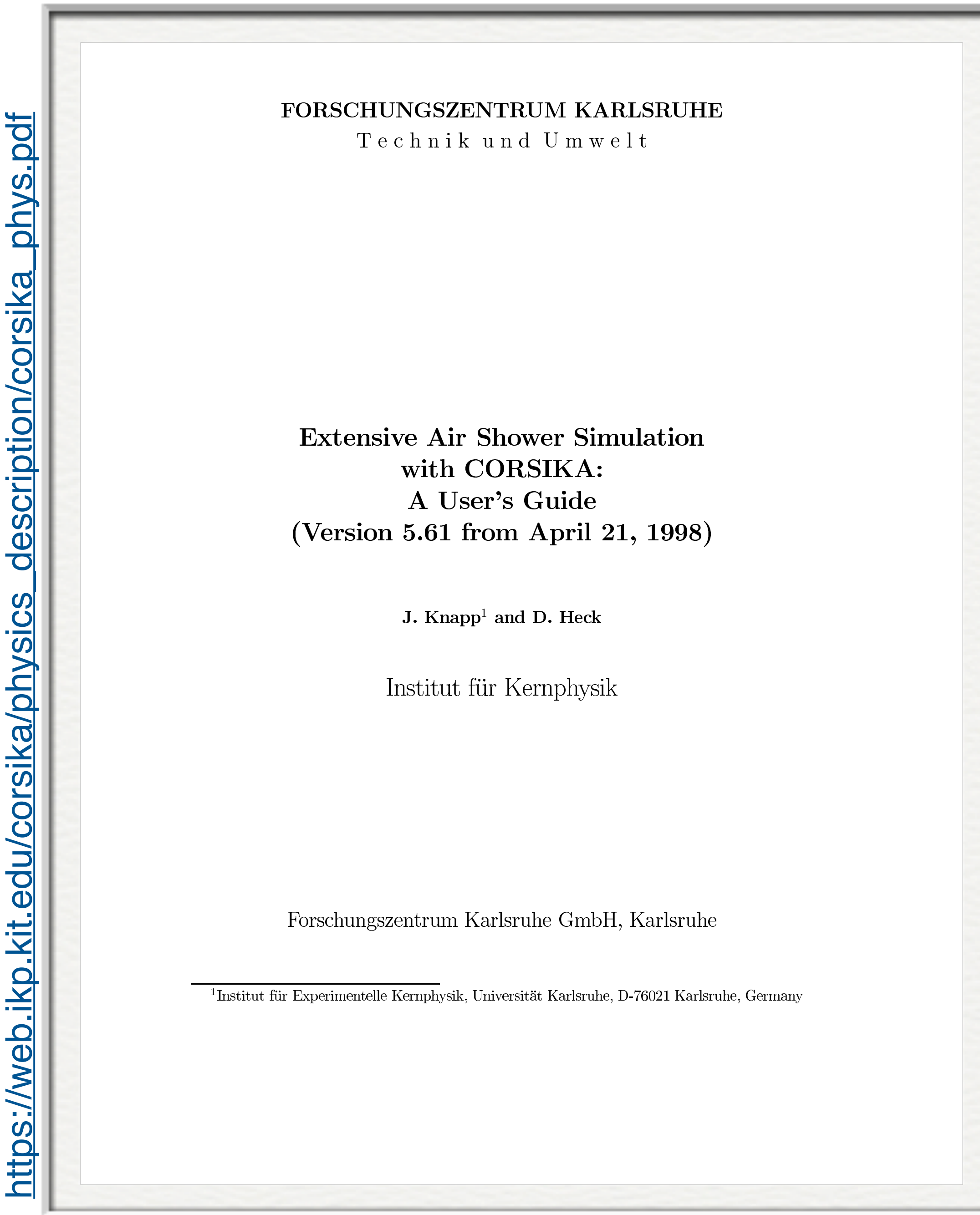
- Other:
  - **wimpsim-reader**: IceTray interface for WimpSim (FORTRAN stand-alone)

Generators : CORSIKA

(**CO**smic **R**ay **SI**mulations for **KA**scade)

- Particles are tracked through the atmosphere until they undergo reactions with the air nuclei or - in the case of instable secondaries - decay.
- The hadronic interactions at high energies may be described by several reaction models alternatively:
  - *VENUS*, *QGSJET*, and *DPMJET* (Gribov-Regge theory),
  - SIBYLL (minijet model).
  - *neXus*, *EPOS* (combination of *QGSJET* and *VENUS*).
  - *HDPM* (Dual Parton Model).
- Hadronic interactions at lower energies:
  - *GHEISHA*, *FLUKA* , or *UrQMD* models.
- For electromagnetic interactions
  - Tailored version of *EGS4*.
  - Analytical *NKG* formulas.

https://web.ikp.kit.edu/corsika/physics_description/corsika_phys.pdf



FORSCHUNGSZENTRUM KARLSRUHE
Technik und Umwelt

Extensive Air Shower Simulation
with CORSIKA:
A User's Guide
(Version 5.61 from April 21, 1998)

J. Knapp[1] and D. Heck

Institut für Kernphysik

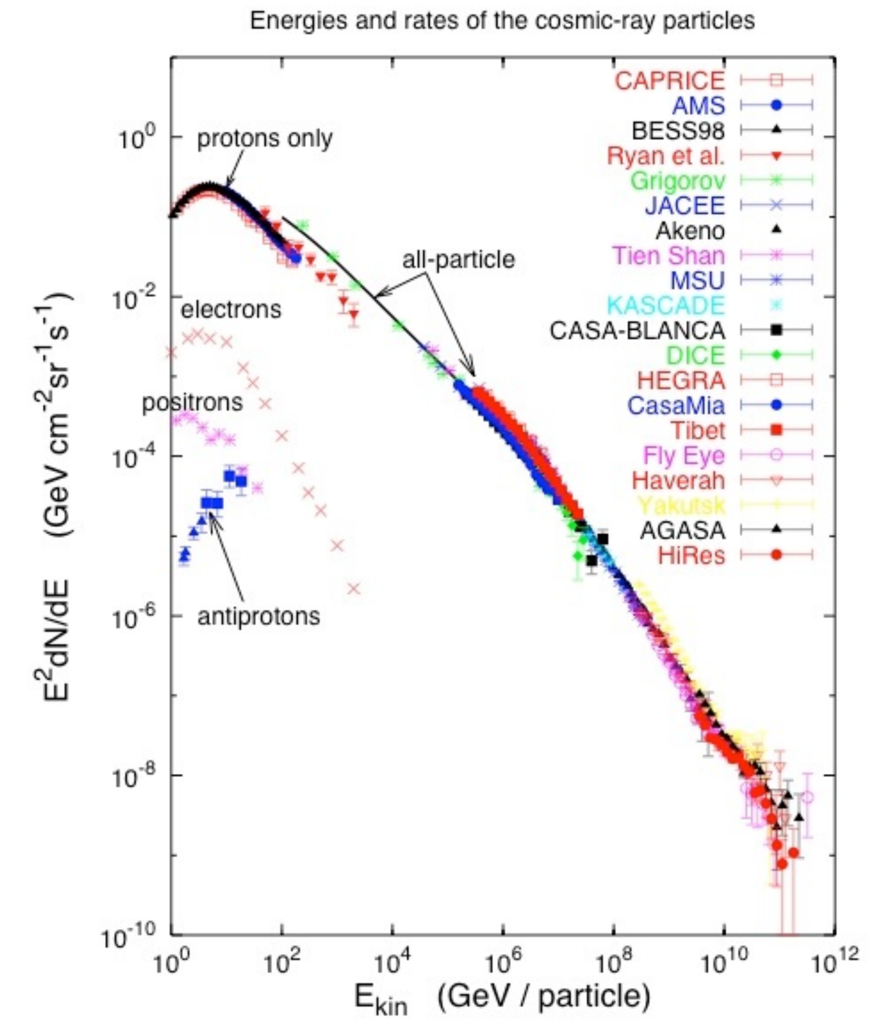
Forschungszentrum Karlsruhe GmbH, Karlsruhe

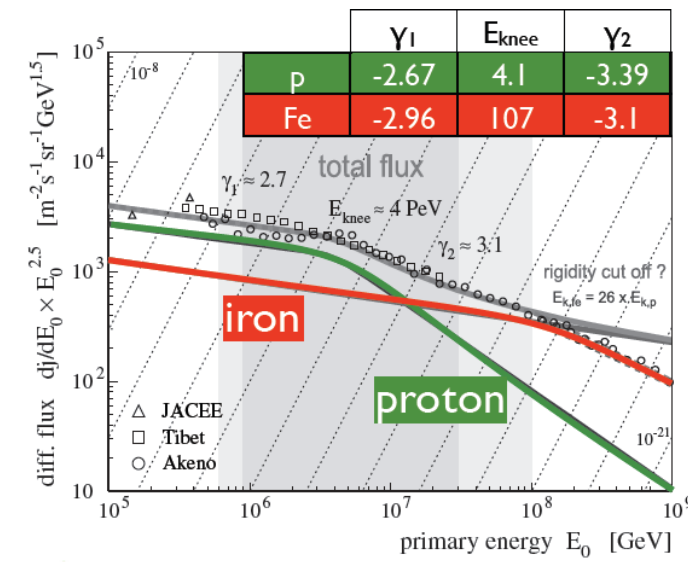
[1] Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany

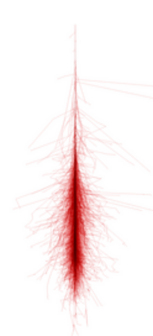
Generators : CORSIKA

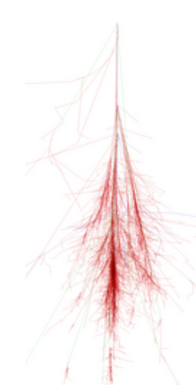
(**CO**smic **R**ay **SI**mulations for **KA**scade)

- weighted events : artificially flat spectrum
  - better livetime efficiency @ 10 TeV but poor efficiency @ TeV
  - energy-targeted generation of (H,He,CNO,Mg,Fe) with $E^{-1(2)}$

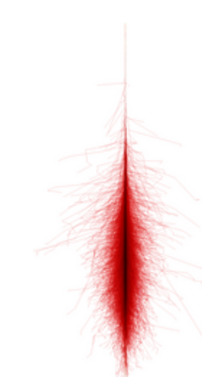





gamma shower


Proton shower


Iron shower


Muon shower

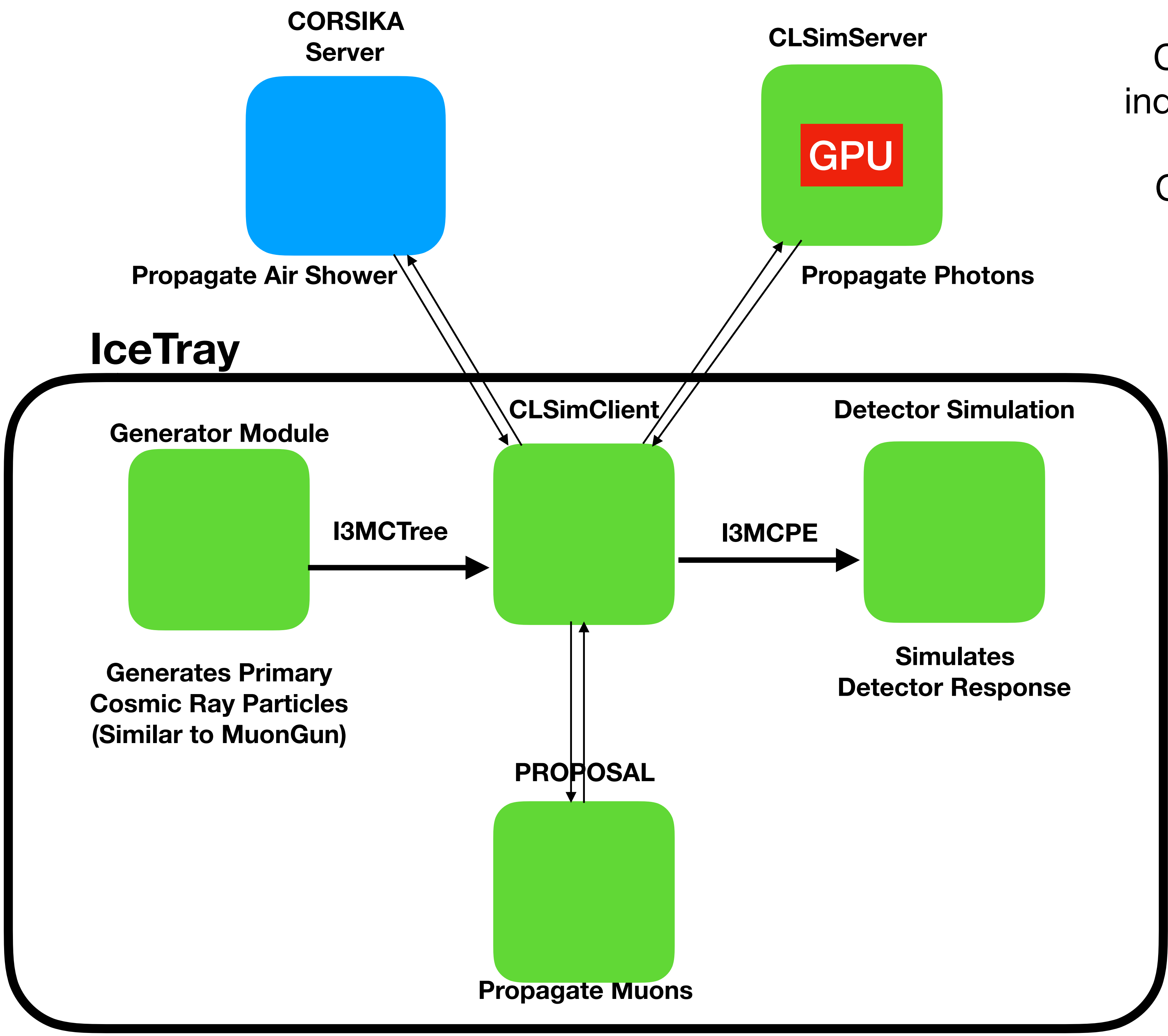
DYNSTACK in CORSIKA

Kevin Meagher & Jakob van Santen

- Replaces CORSIKA's post-reaction particle stack with a C++11 plugin
- General API for doing things like the neutrino kill threshold, plus helpful extras (take configuration from the steering card, manipulate event headers/trailers, etc)
- In mainline CORSIKA since 7.56 (modulo typos)
- Write plugins in C++11 without touching corsika.F, depend only on the standard library
- Build a better CORSIKA for in-ice background simulation.
- Reduce memory and disk requirements for high energy simulations.

Analysis-specific, targeted background simulation

DYNSTACK in CORSIKA



CLSimClient passes individual particles from the MCTree to the CORSIKA Server, to PROPOSAL to the CLSimServer

I3MCPE are created directly from the output of each individual CLSim propagation

K. Meagher

MuonGun (IceCube implementation of MUPAGE)

arXiv:0907.5563v1 [astro-ph.IM] 31 Jul 2009

Atmospheric MUons from PArametric formulas: a fast GEnerator for neutrino telescopes (MUPAGE)

M. Bazzotti*, S. Biagi*†, G. Carminati*†, S. Cecchini*‡,
T. Chiarusi†, A. Margiotta*†, M. Sioli*† and M. Spurio*†

*Dipartimento di Fisica dell'Università di Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy
† INFN, Sezione di Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy
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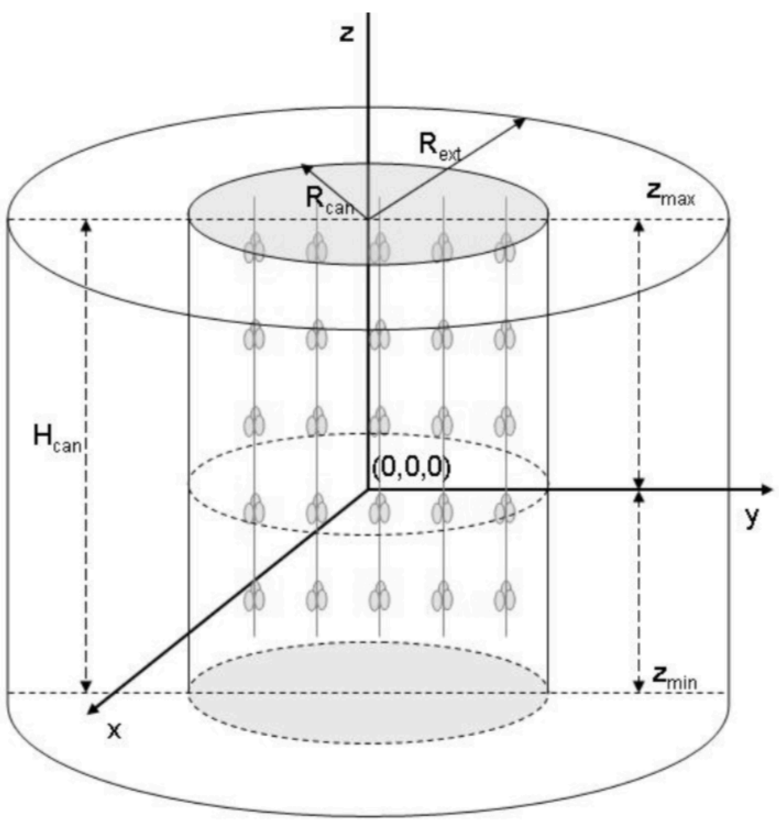
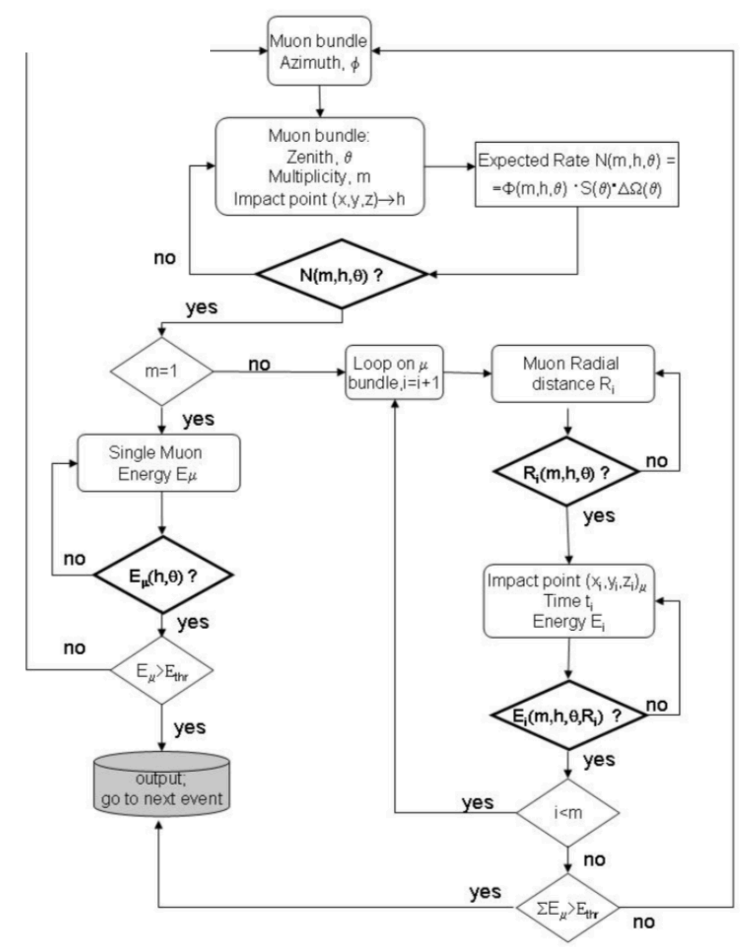


Fig. 1: Sketch of some input parameters. The cylinder surrounding the instrumental volume is the *can*, with radius $R_{\rm can}$ and height $H_{\rm can}$. The events are generated on an extended can with $R_{\rm ext}$. The origin of the coordinate system does not have to be located at the center of the detector. The lower disk is at a depth $H_{\rm max}$ with respect to the sea/ice surface.



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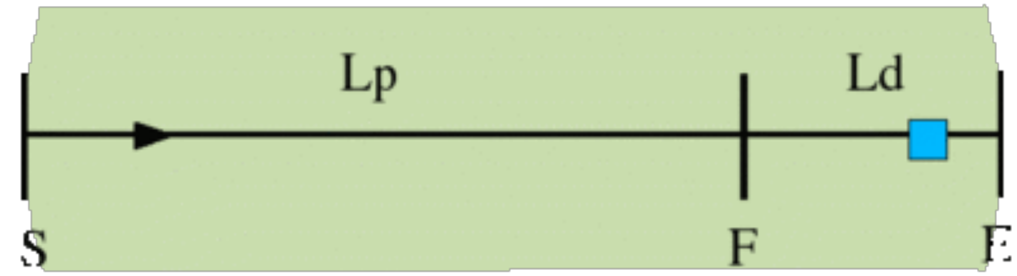
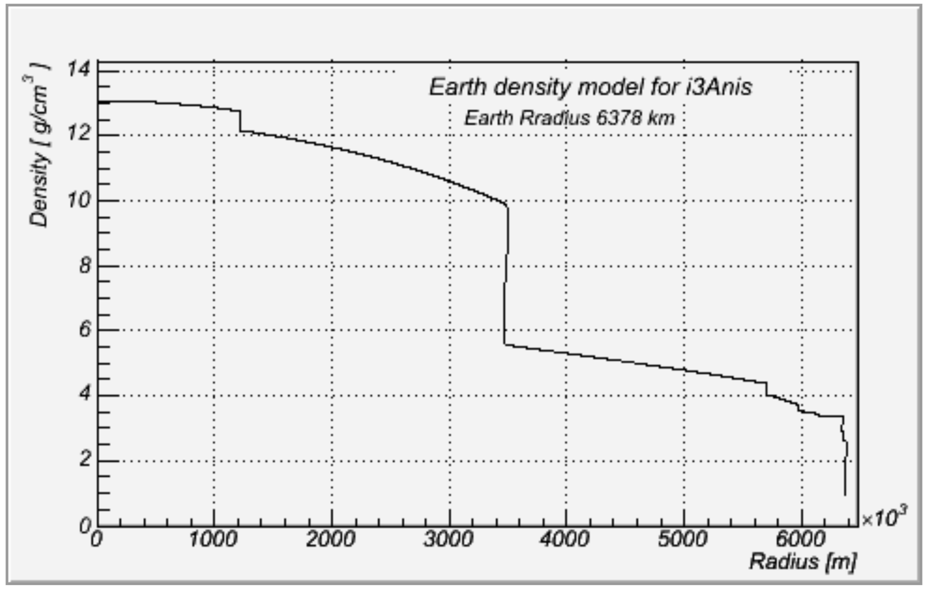
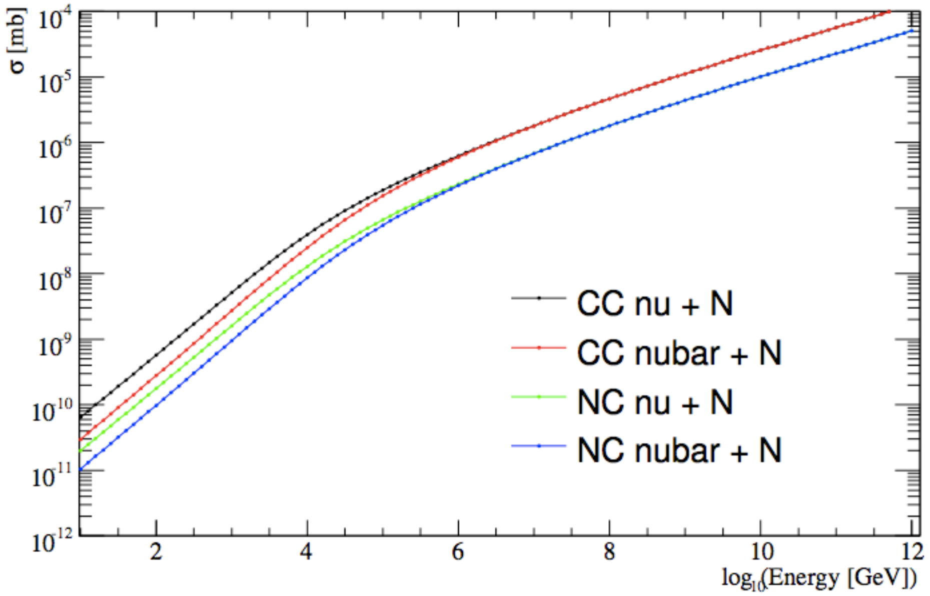
neutrino-generator



1. Calculate total path length inside the Earth using injected neutrino geometry.
    a. Separate the total path length into propagation area (SF) and
    b. detection volume (FE).
2. Define a step length dx[m] using propagation area and step number.
3. For each step:
    a. Calculate a column depth and Earth's density at the step point.
    b. Calculate a total cross section at the step point.
    c. Calculate a probability that the injected neutrino interacts within the step. Try Monte-Carlo, and decide whether an interaction happened within the step.
    d. If interaction occurred: choose interaction randomly.
        i. If CC-interaction is selected with injection particle NuMu or NuE, break (event is killed).
        ii. else, generate secondaries and continue to next step.
    e. If nothing happens, continue next step.
4. Finish propagation when injected neutrino + secondaries reach surface of detection volume (point F), then process a weighted interaction.



- produce a $E^{-\gamma}$ ν_μ, ν_e, ν_τ with
    - PRELIM Earth's density model



    - parton distribution functions
    - prop & interaction of neutrinos into a weight

Lepton propagation

https://doi.org/10.1016/j.cpc.2013.04.001

- **PROPOSAL:** parametrized interactions with the medium. Comp. Phys. Com. 184, 9 (2013), p2070-2090
  - Stochastic energy losses include:
    - ionization
    - electron-pair production
    - bremsstrahlung
    - photo-nuclear interaction
    - decay
- **GEANT4:** Detailed particle propagation in media. https://geant4.web.cern.ch/
  - 3rd-party G4 library used by CLSim to propagate leptons for low-energy simulations (CPU-intensive).

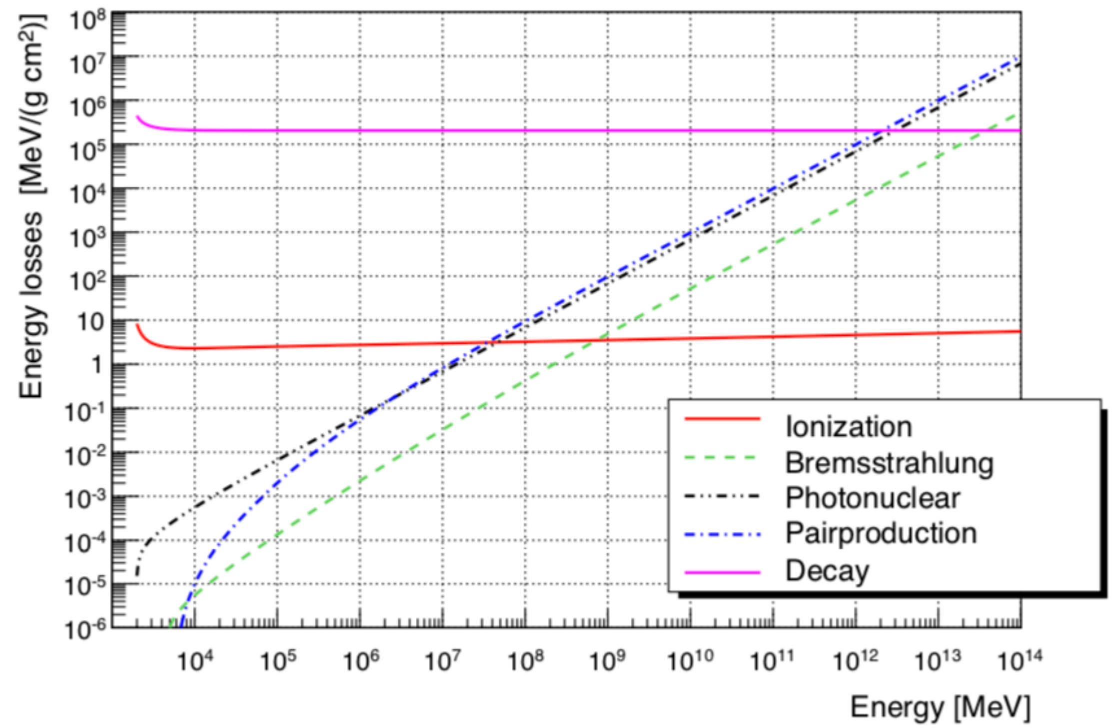


Fig. 31. Continuous energy loss of taus in ice in the energy range from 10^3 MeV to 10^{14} MeV. The graph shows the energy losses of the four interactions and the probability of decay multiplied by the primary particle energy.

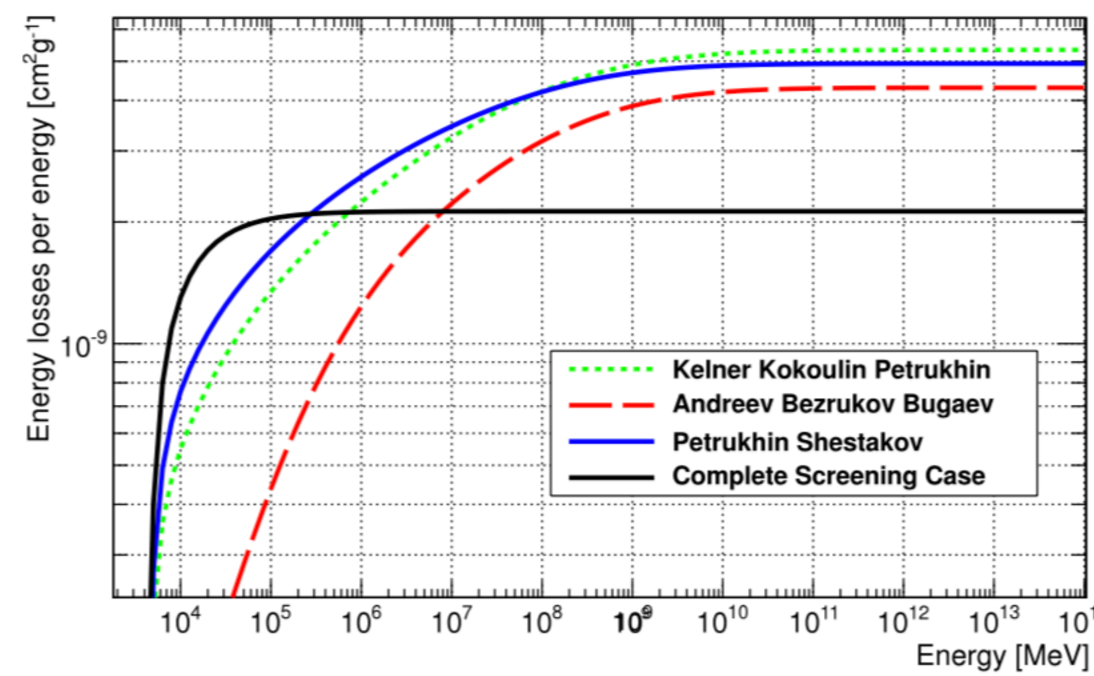
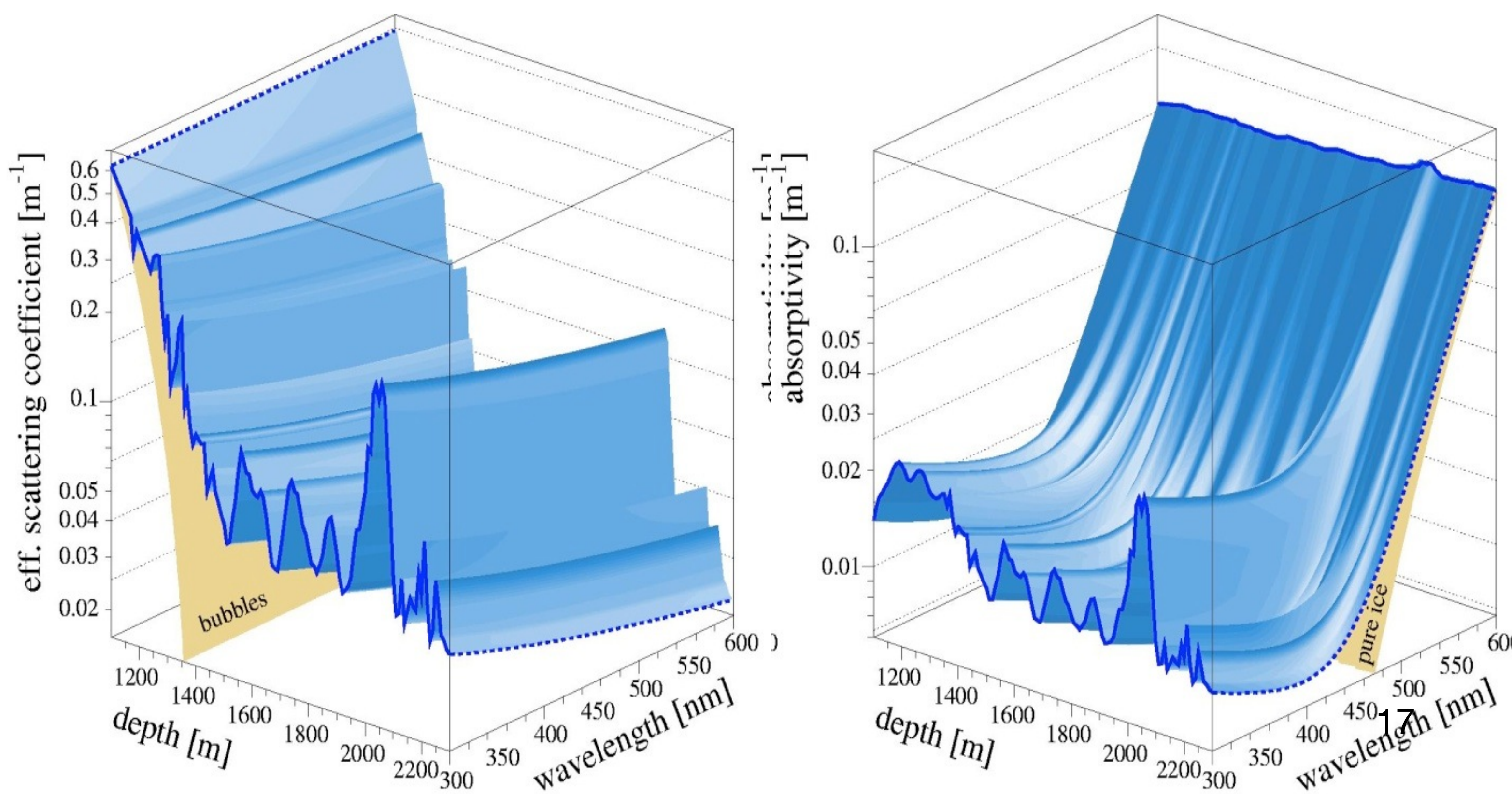


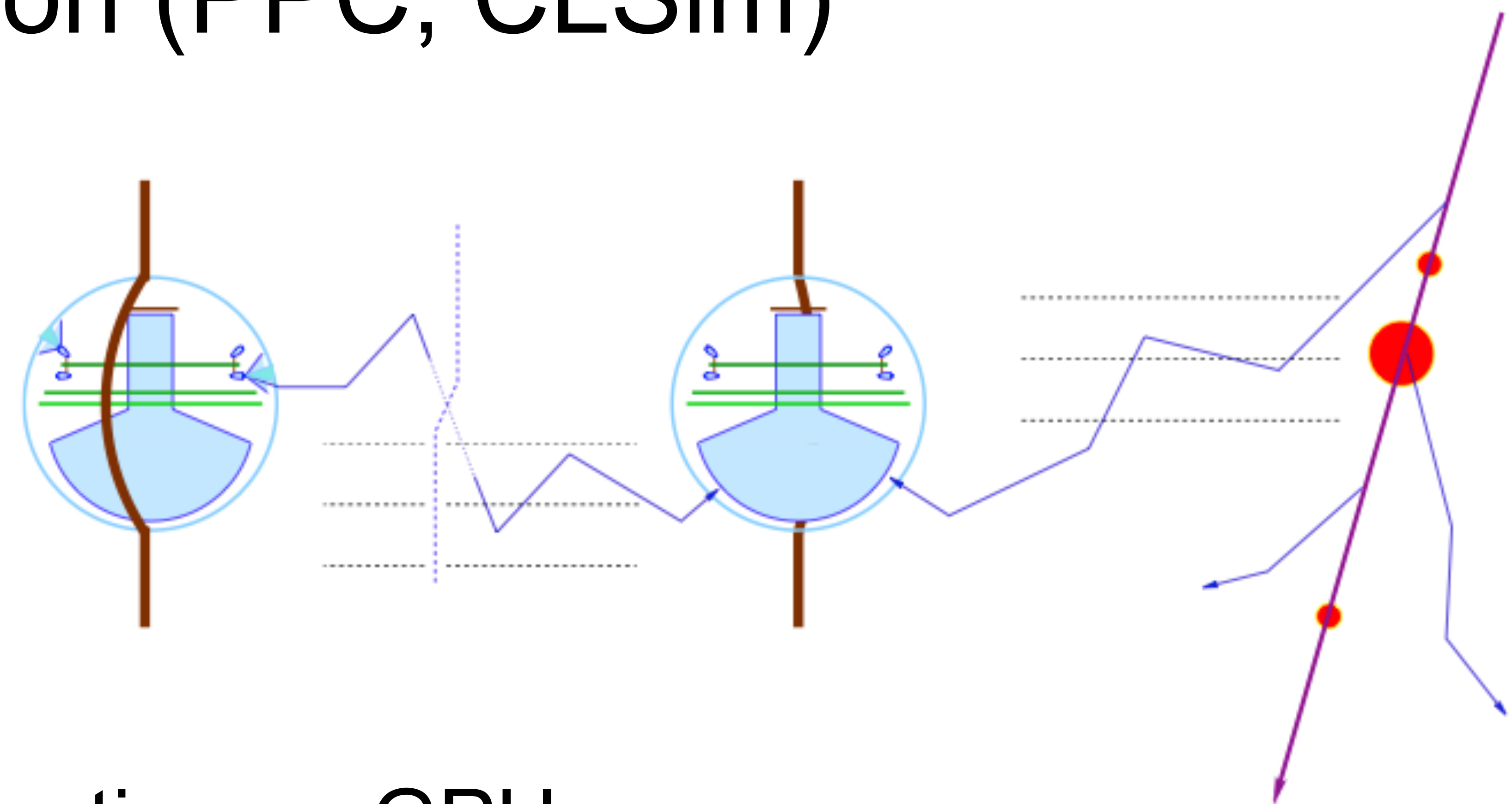
Fig. 4. Continuous energy loss of taus caused by Bremsstrahlung in the energy range from $2 \cdot 10^3$ MeV to 10^{14} MeV. The figure shows the same four possible parametrizations as Fig. 2.

Photon Propagation

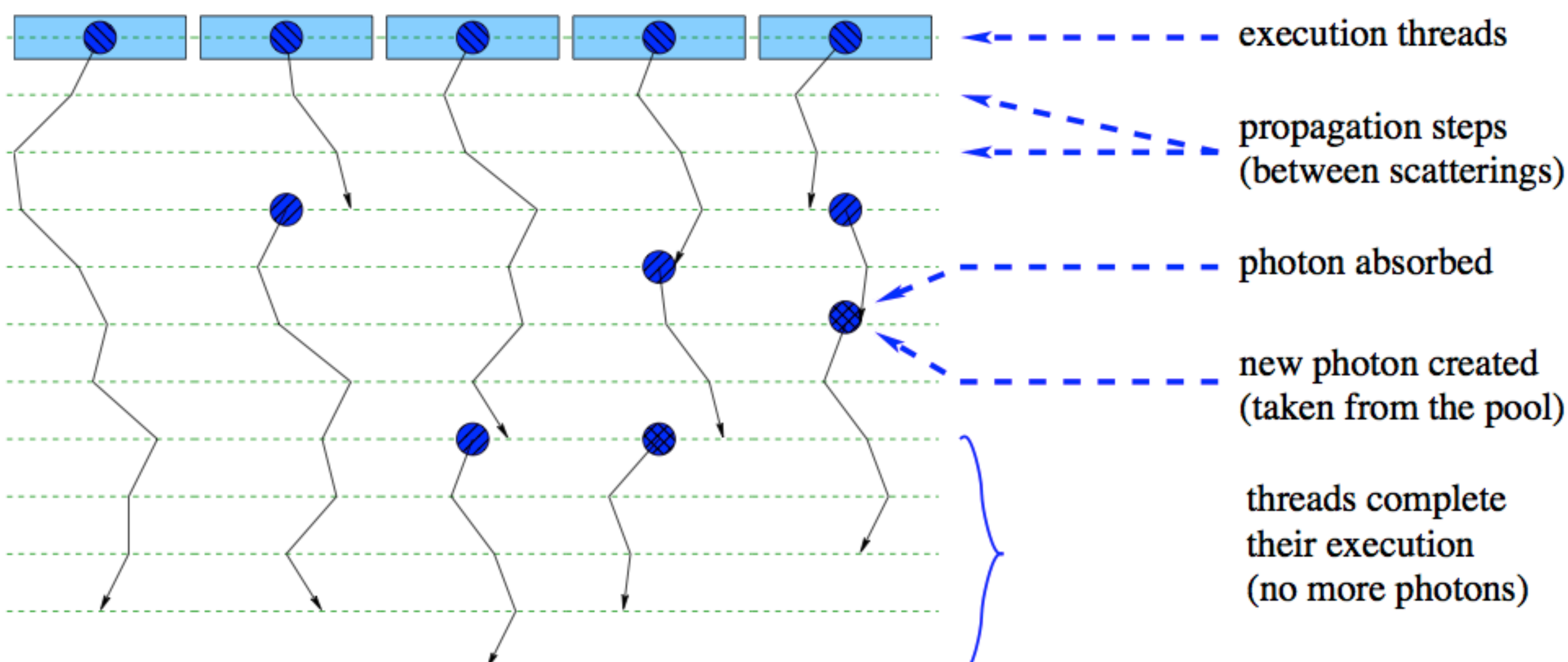
- μ energy lost + cascades ➙ photons ➙ p.e.
  - Photon propagation : ice properties + PMT response + DOM glass/gel
    - Pre-generated lookup splined table :
      - I3PhotonicsHitMaker
      - Amplitude and time distribution
    - Direct photon tracking
      - CLSim
      - PPC
    - Hybrid photon tracking
      - HitMaker + CLSim



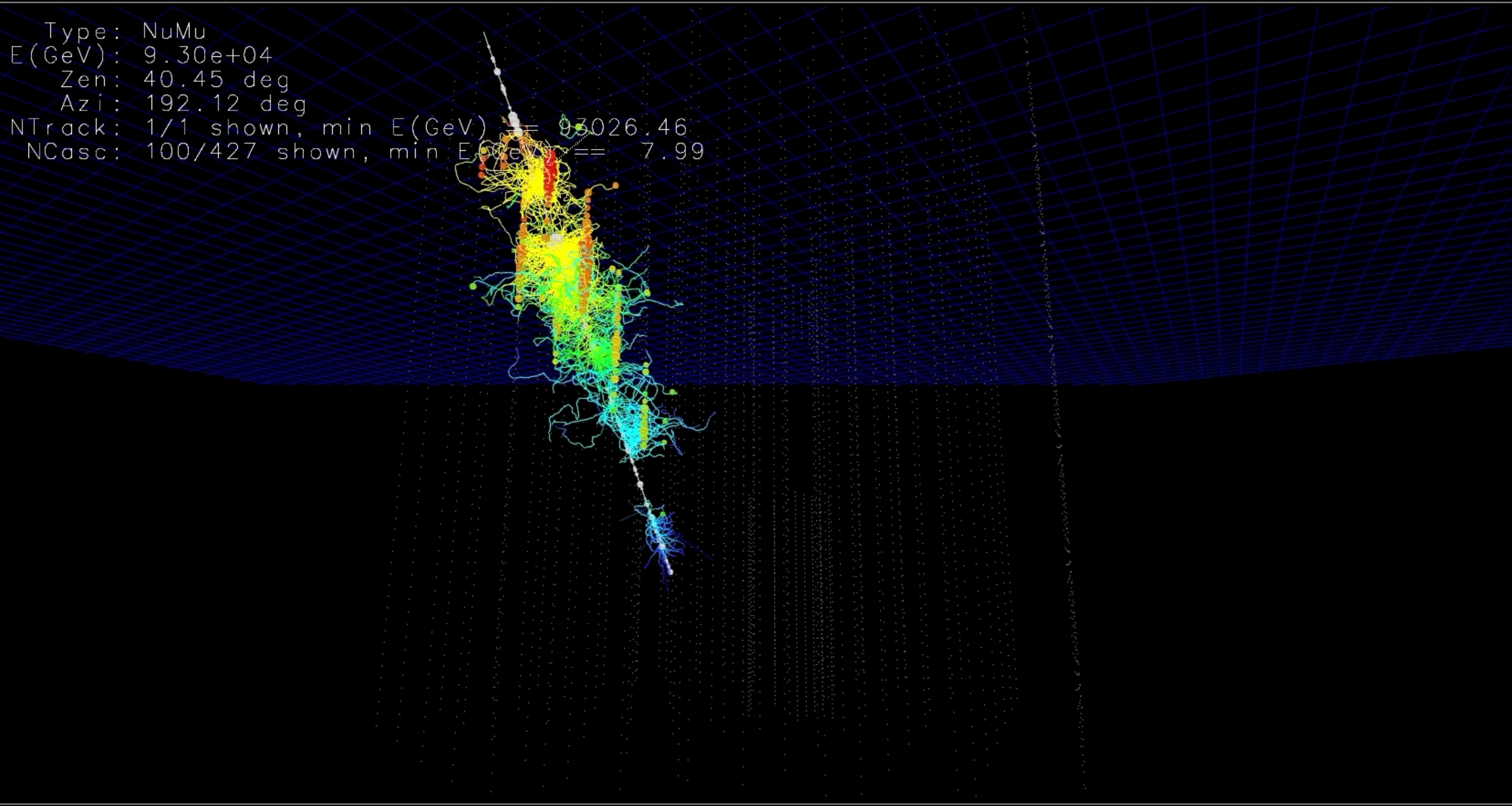
Photon Propagation (PPC, CLSim)



Direct photon propagation on GPU



Photon Propagation (PPC, CLSim)



http://icecube.wisc.edu/~ckopper/muon_with_photons.mov

Polyplopia

(from gr., πολύς - polús, “many,”, and ὄψ-ops , "vision")

Coincident atmospheric shower events in IceCube

- poly**plopia::PoissonMerger**
  - Injects background event read from a separate file on top of primary events in the chain by sampling from a Poisson distribution over a time window Δt.
  - Also makes use of a *CoincidentEventService* that could be drop-in replaced with other event services such as a MuonGun-based service.
  - Writes a separate I3MCTree with background particles.
  - Writes a combined I3MCPE map for signal and background.

- poly**plopia::MPHitFilter**
  - Removes events that don’t produce light in the detector and removes branches of I3MCTrees whose particles don’t produce enough PEs in the detector,
  - Reduces the storage requirements.

- It is then up to the trigger-sim to split up Q-frames into P-frames events based on triggers.

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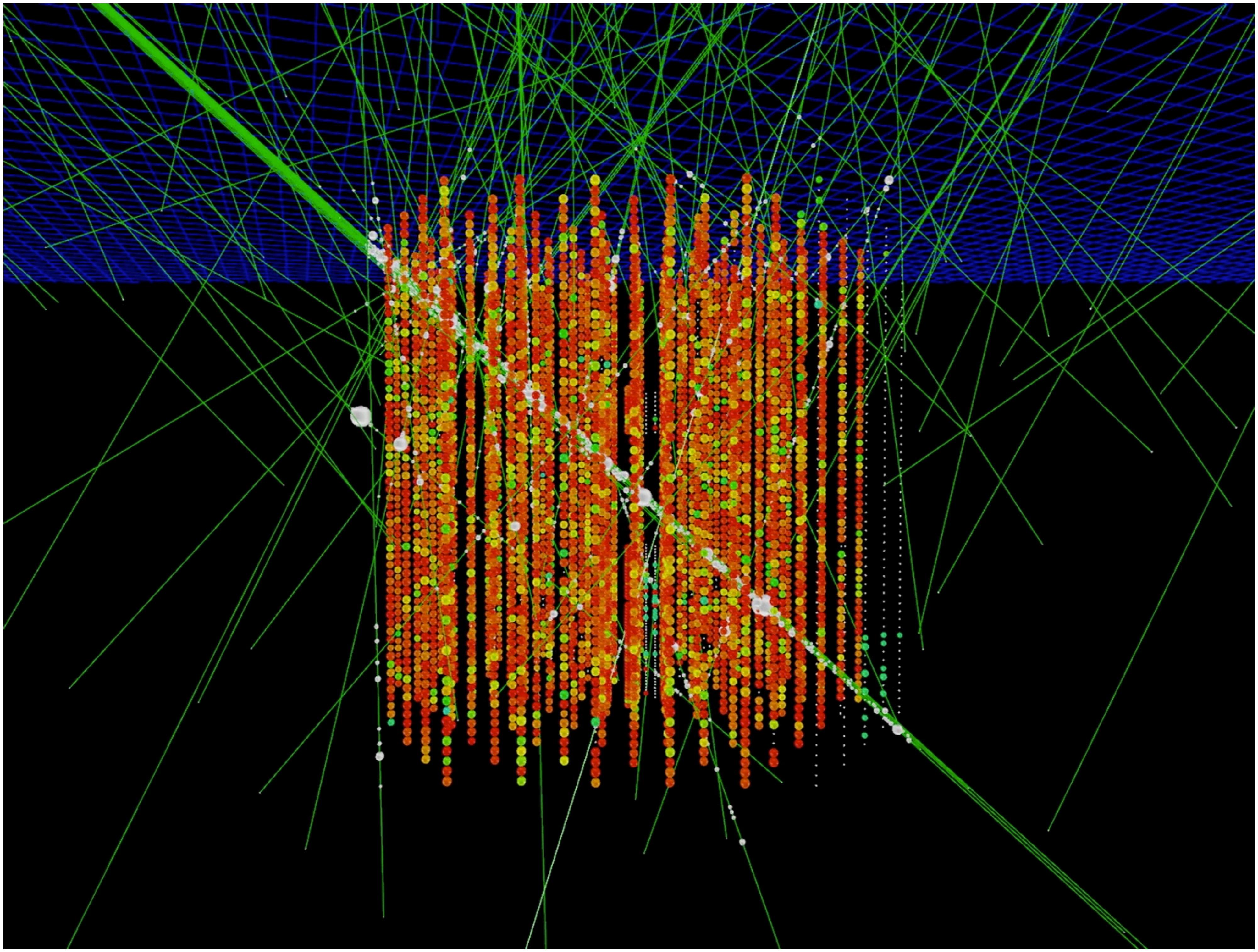
(from gr., πολύς - polús, "many,", and ὄψ-ops , "vision")

Coincident atmospheric shower events in IceCube



http://icecube.wisc.edu/~juancarlos/video/10msec_w_noise.mp4

Noise Generation

—> (MCPEs)

Noise Model

Thermal Noise (~few Hz)
[Poisson process]

~ ms Timescales

+

Radioactive Decay in Glass
[Poisson process]

~ ms Timescales

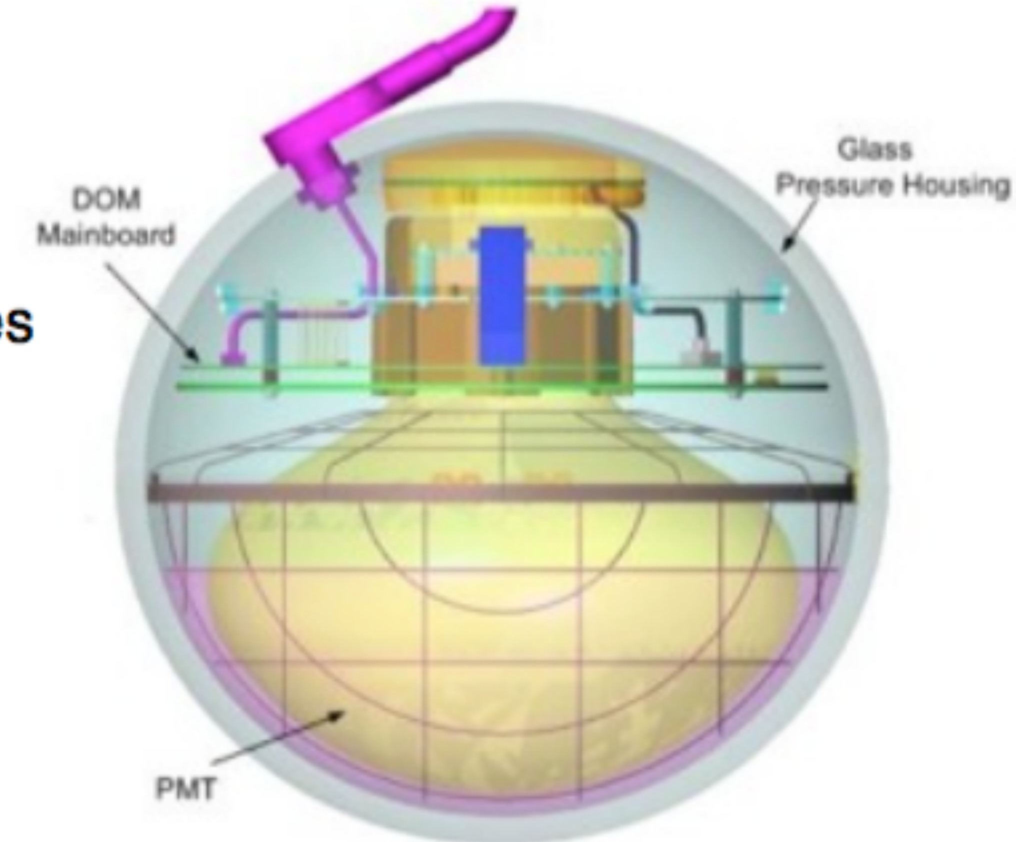
↓

Energy deposited in glass

↓

Glass scintillates/fluoresces
over long timescale
[Log-normal]

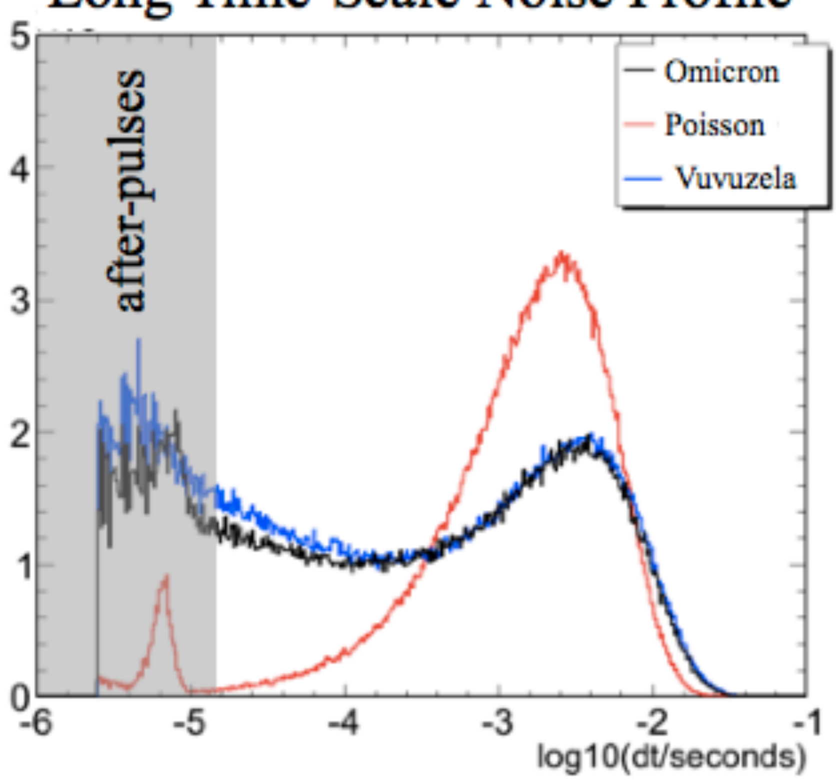
≲ 500 µs Timescales



Noise Generation

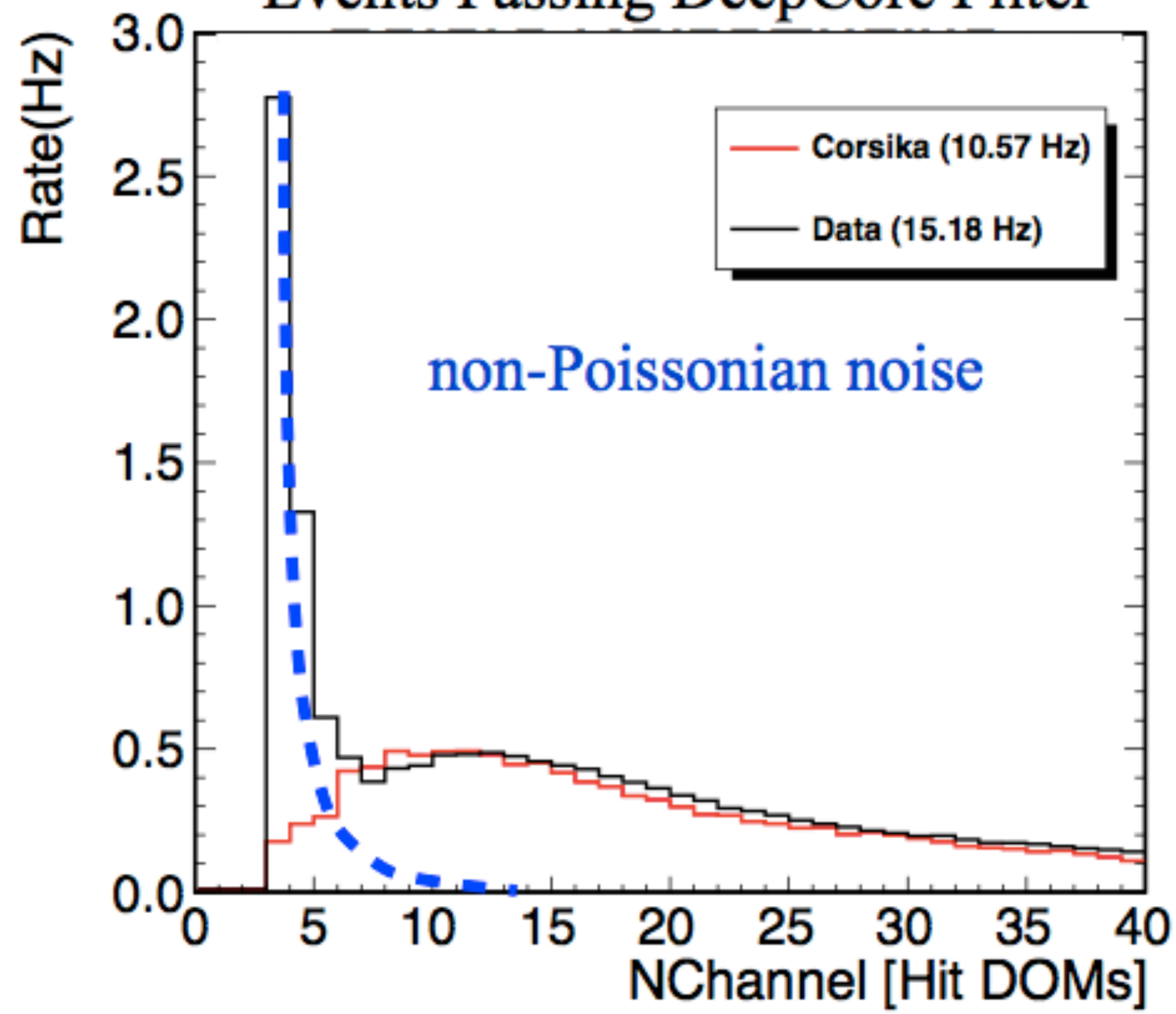
Previous simulation used simplified Poissonian model. Vuvuzela uses exponential for **thermal** and **radioactive decays** and log-normal for **scintillation**.

Long Time-Scale Noise Profile



*Courtesy of M.Larson (U.Alabama)

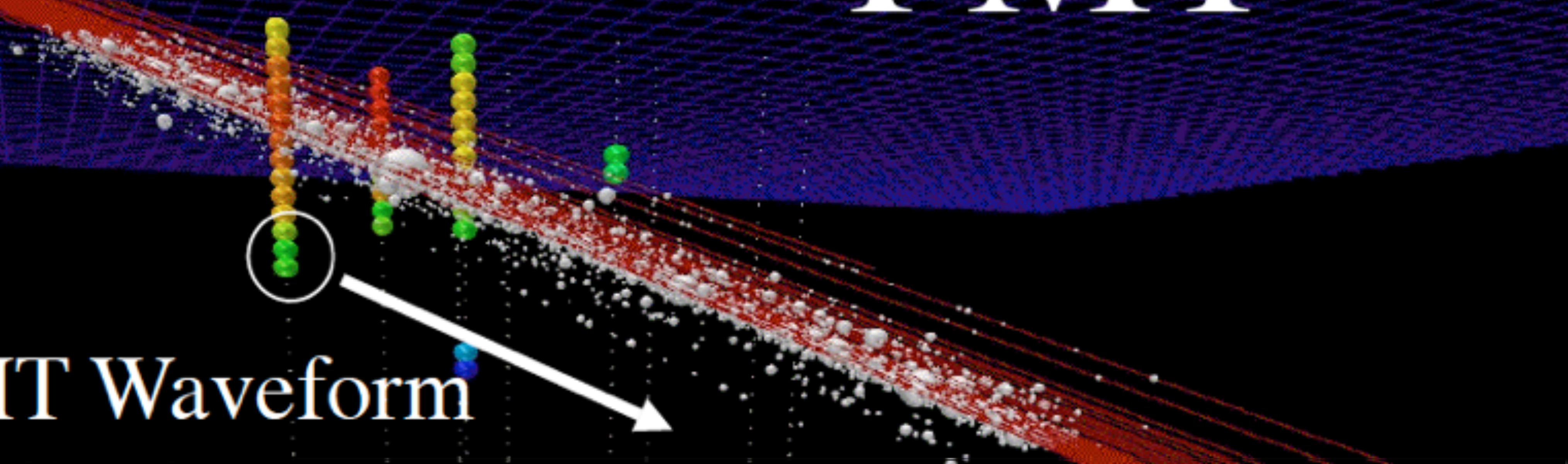
Events Passing DeepCore Filter



*Courtesy of J.Koskinen (PSU)

DOMLauncher::
PMTResponseSimulator

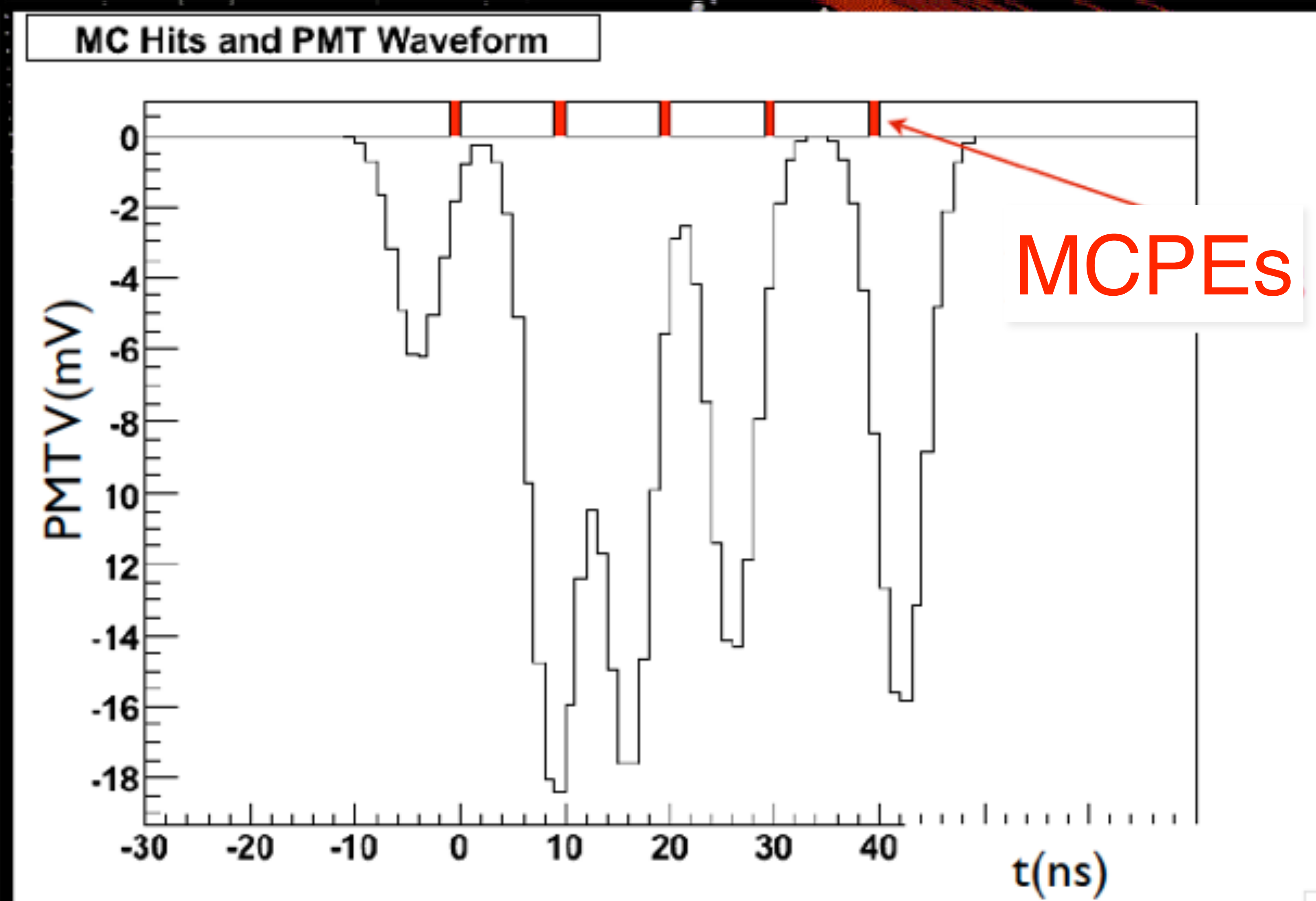
PMT



Generates PMT Waveform

From distribution of (combined) MCPEs.

Outputs I3MCPulseSeries for each DOM.

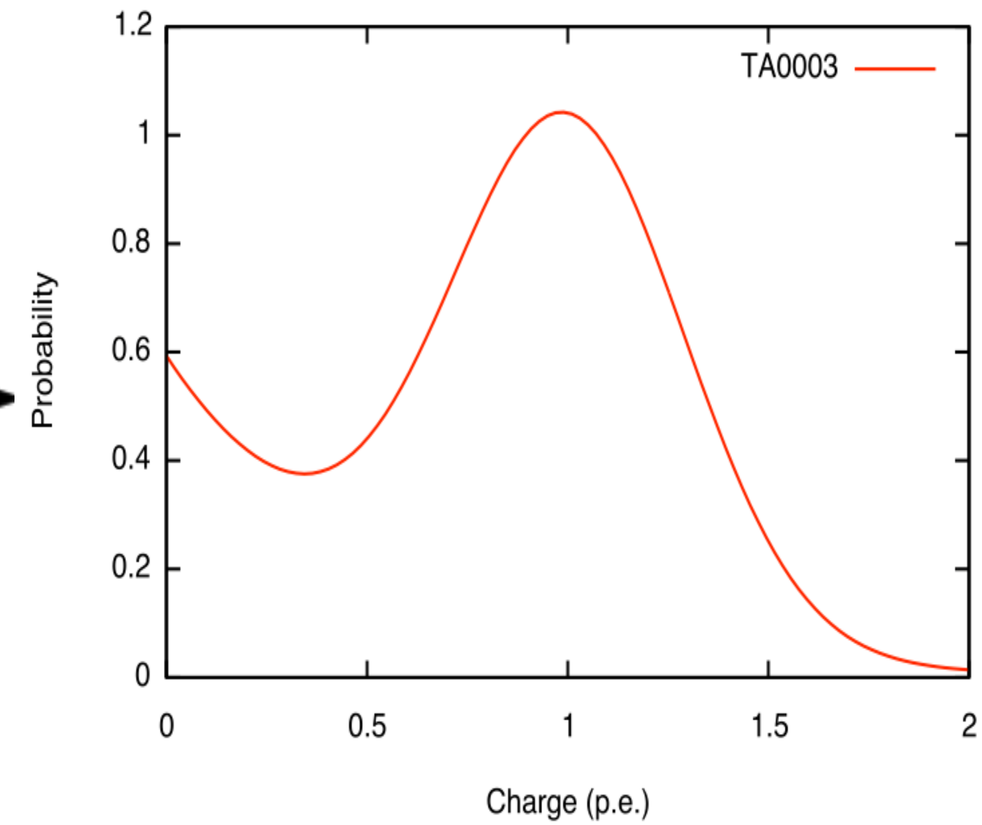


PMTResponseSimulator

Input: I3MCPEs
Output: I3MCPulses

Processing MCPEs :

- Give each MCPE a weight corresponding to the pulse charge that photon would yield.
- Generate prepulses, late pulses and after pulses.
- Apply time jitter.
- Simulate the effect of saturation.



Weights fromSPE Charge Distribution

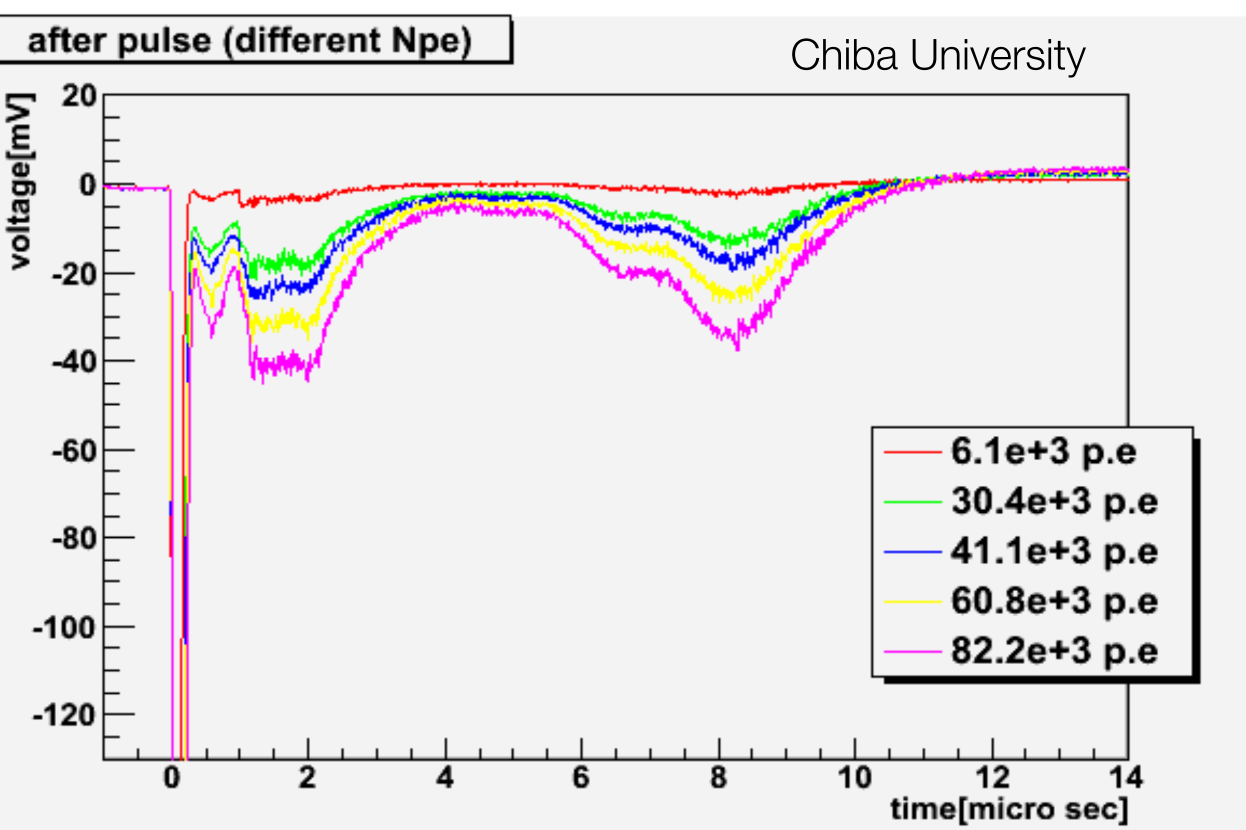
http://software.icecube.wisc.edu/documentation/projects/DOMLauncher/index.html

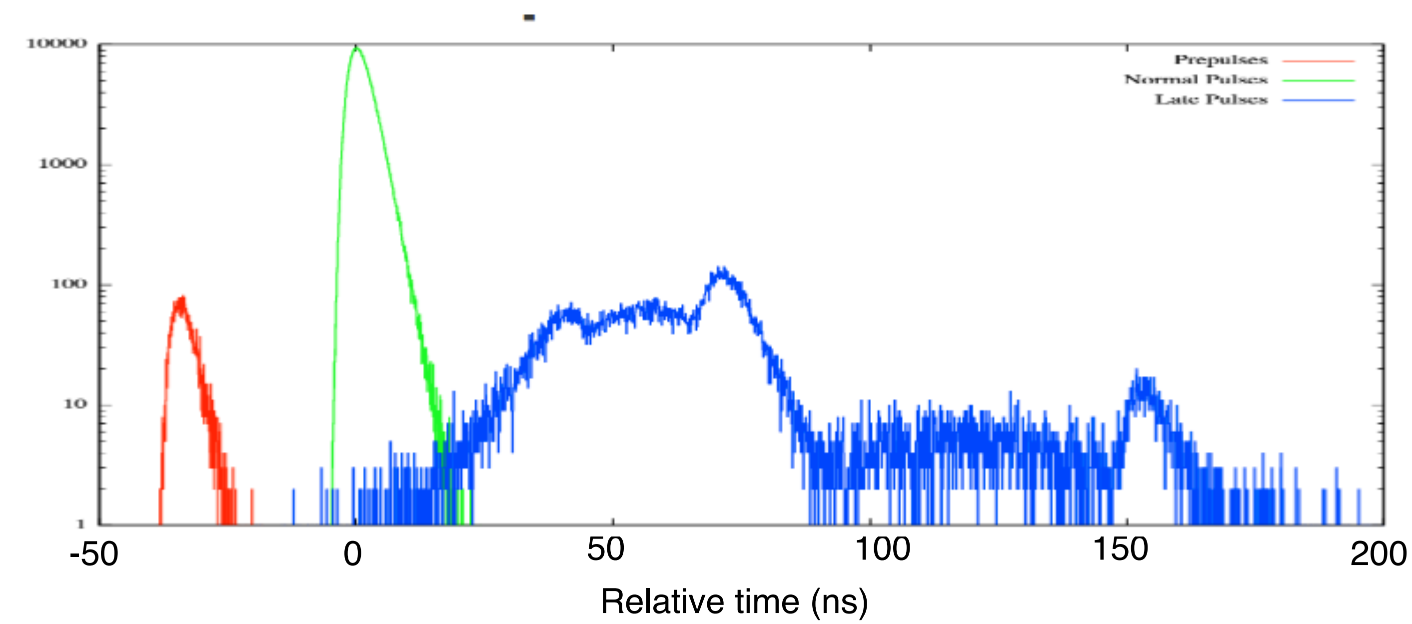
PAL pulses

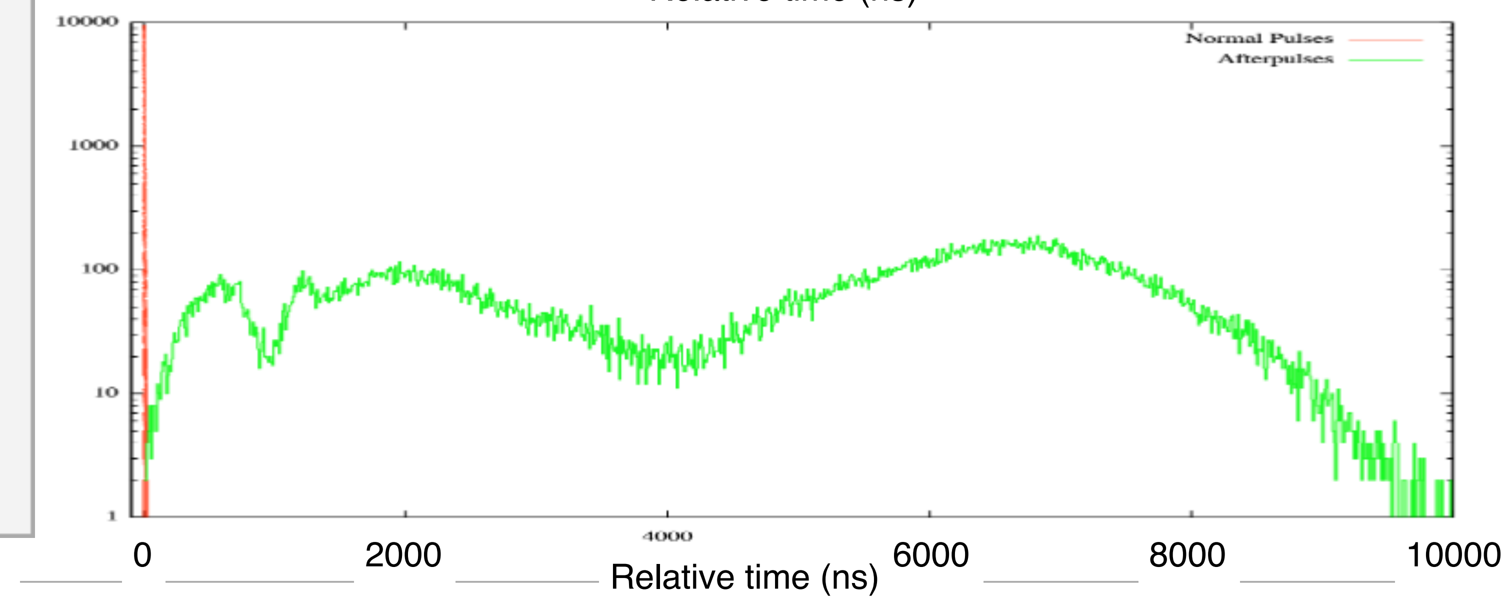
Pre-pulses: photoelectrons ejected from the first dynode,

Late pulses: electrons backscatter from dynode to cathode.

After-pulses: ionization of residual gases by electrons accelerated in the space between dynode.

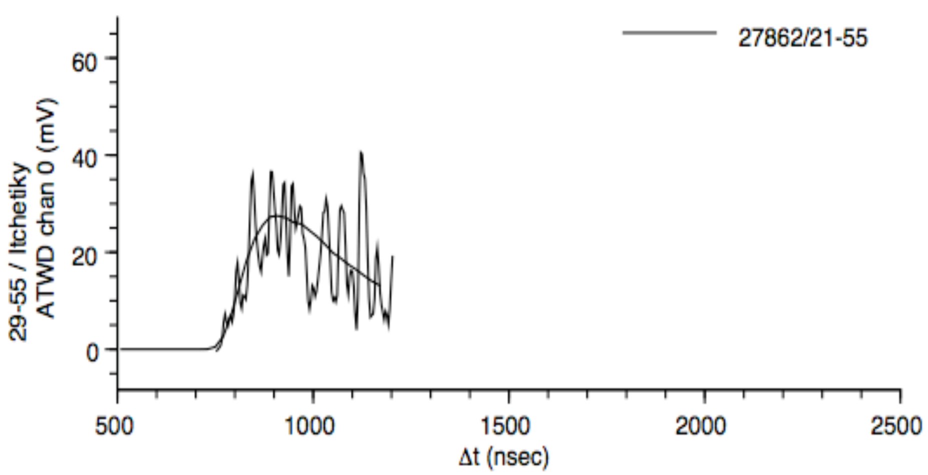


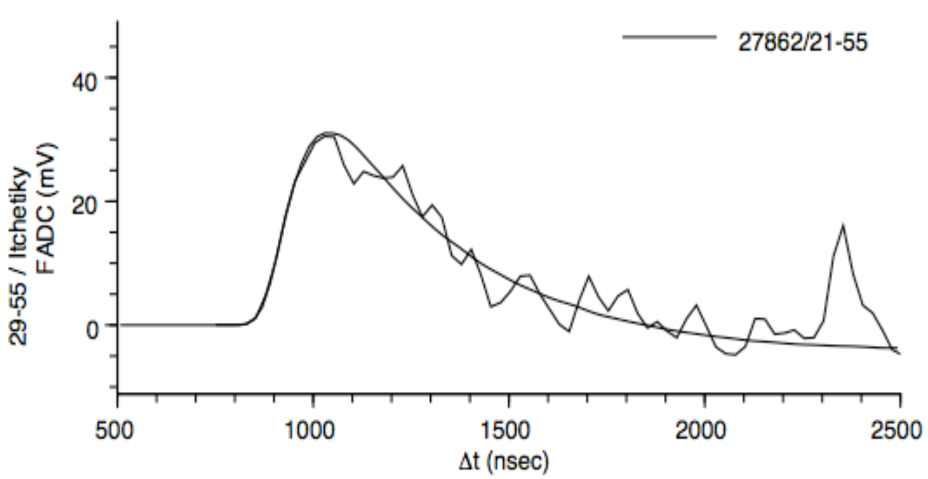


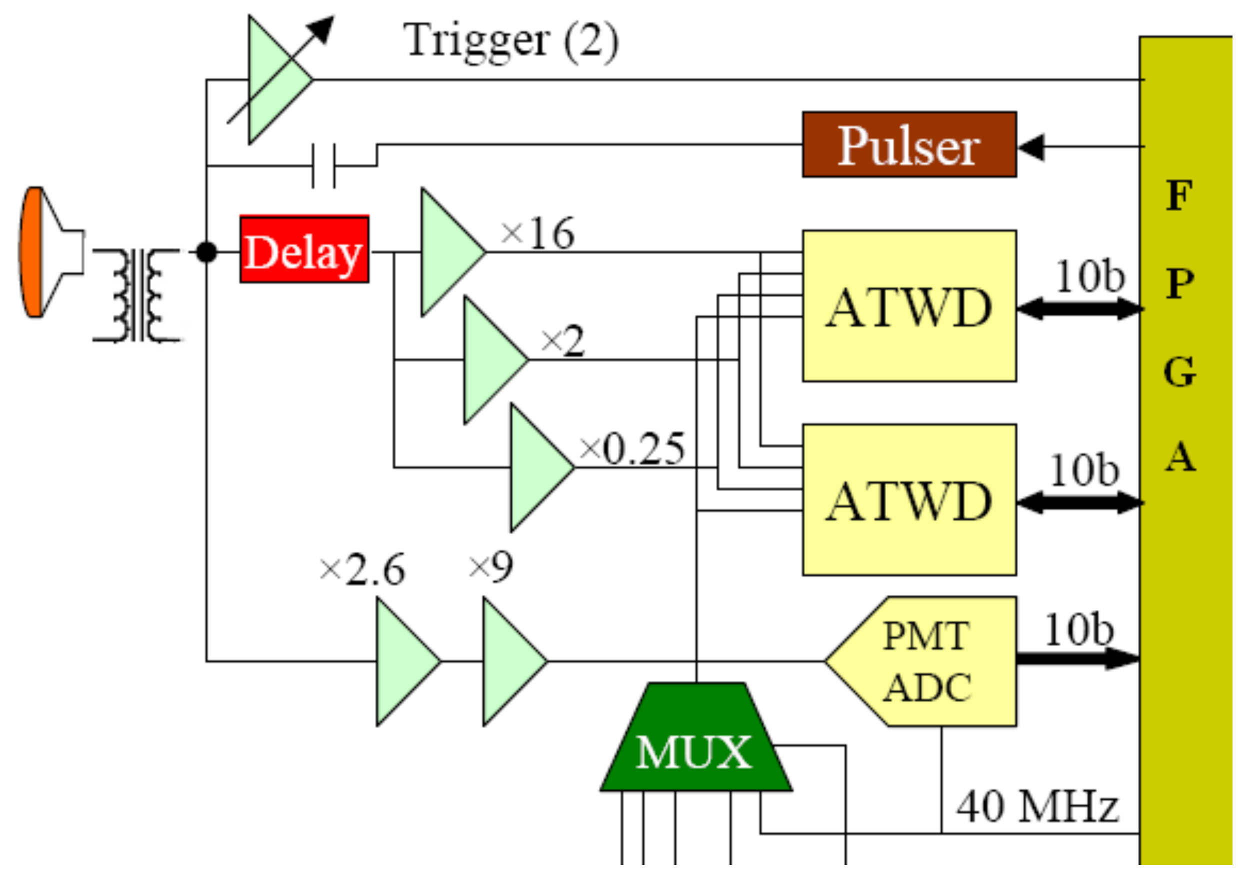


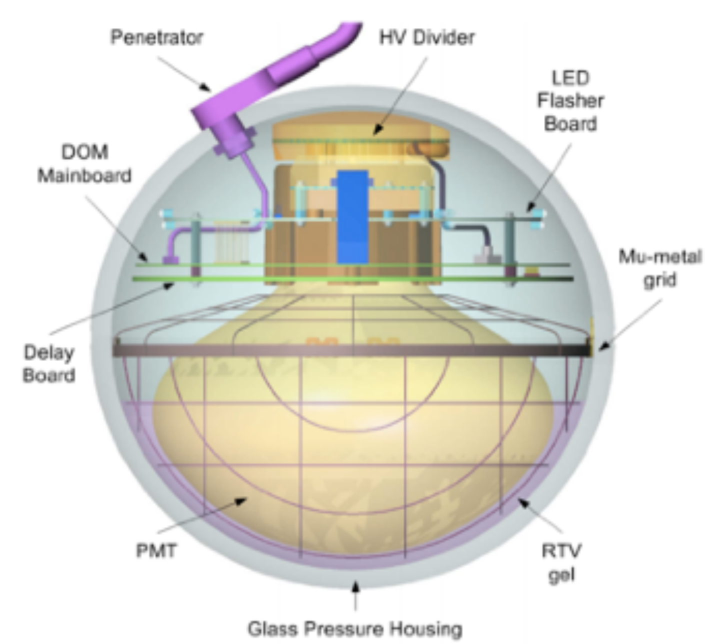
DOMLauncher: DOM electronics simulation

- Discriminator
- LC-logic
- Digitization
- Simulated effects
  - Electronic noise in the digitizers
  - Beacon launches (CPU triggered launches)
  - The FPGA Clock phase
  - RAPcal time uncertainty









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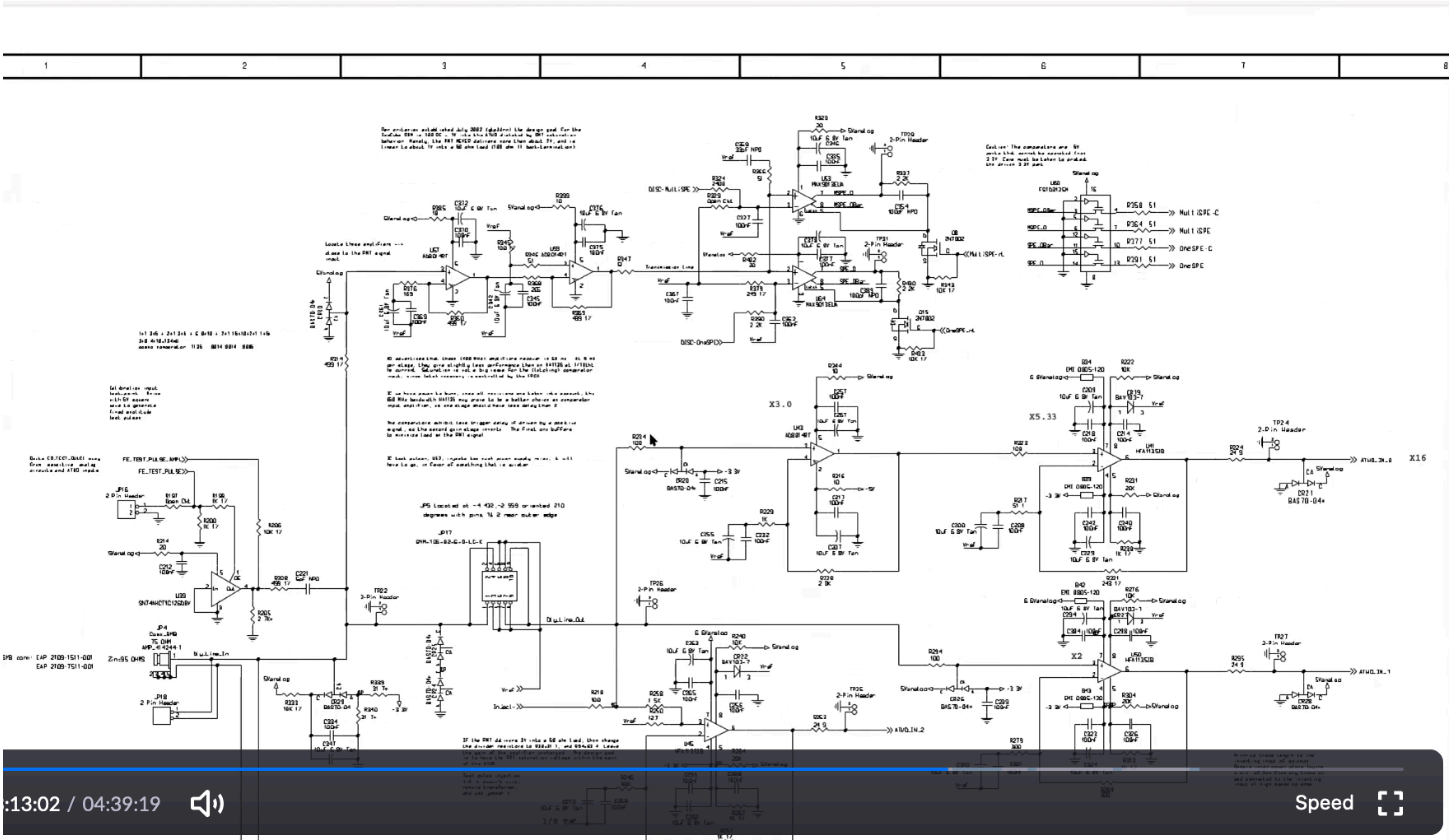


Trigger Simulation

- **S**imple **M**ultiplicity **T**rigger (SMT)
  - *N* HLC hits or more in a time window
  - Example: InIce SMT8 with N_hits ≥ 8 in 5 μs
  - readout window around this captures early and late hits (-4 μs, +6 μs)

- **String** trigger (a.k.a. Cluster trigger in DAQ-land)
  - *N* HLC hits out of *M* DOMs on a string in a time window
  - Example: 5 hits from a run of 7 adjacent DOMs in a time window of 1500 ns

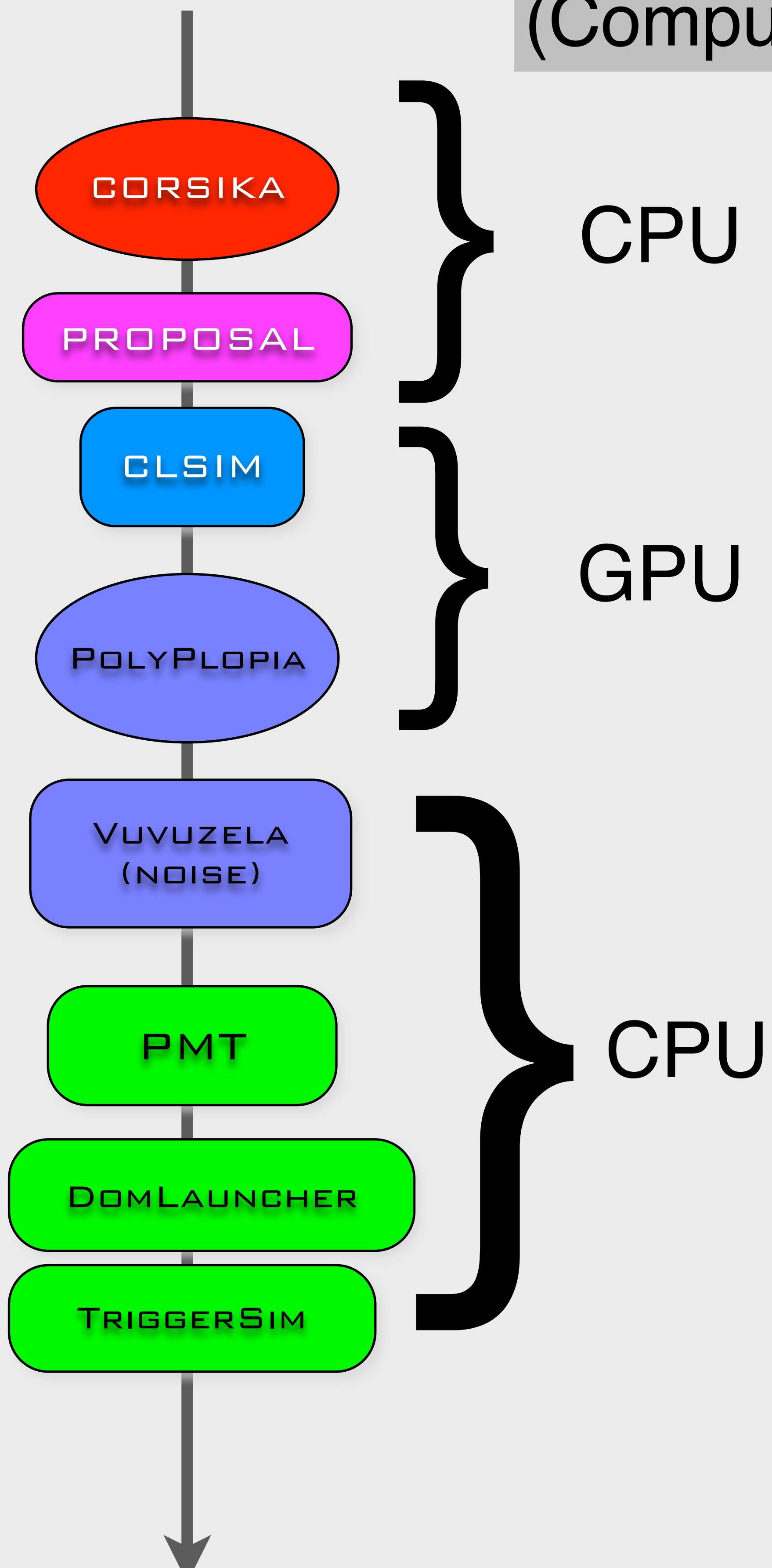
- **Volume** trigger (a.k.a Cylinder trigger in DAQ-land)
  - simple majority of HLC hits (SMT4) with volume element including one layer of strings around a center string
  - cylinder height is 5 DOM-layers (2 up and down from the selected DOM).

- **Slo**w **P**article trigger (SLOP)
  - slow-moving hits along a track
  - lengths of the order of 500μs and extending up to milliseconds

- ~~**F**ixed **R**ate **t**rigger~~, **Min**imum **Bias** trigger, ~~**Calibration** trigger~~

i3SIM

The Shish Kabob
(Computing Resource Optimization)



- Optimizing the shish kabob:
  - Different parts of the simulation chain have different resource requirements.
    - CORSIKA is CPU-intensive and requires little RAM
    - Photon propagation run almost exclusively on GPUs
    - Detector simulation is CPU bound and requires more memory.
- Things to keep in mind:
  - Running the whole chain on a GPU node will waste GPU resources and limit your throughput.
  - Intermediate storage:
    - breaking up chain requires transfering/storing intermediate files.
  - Reduce complexity in workflow

Simprod-Scripts

http://software.icecube.wisc.edu/documentation/projects/simprod_scripts/index.html

This project is a collection of scripts, tray segments and IceProd modules used in simulation production. The aim is to provide a central place with standard segments for running simulation in both production and privately.

- **Tray Segments**: IceTray meta-modules that contain several I3Modules with default parameters.
- ~~**IceProd modules**: basic wrappers around tray segments that provide an interface for IceProd.~~
- **Scripts**: collection of python scripts used in simulation production
- **Examples**: The directory simprod-scripts/resources/examples contains a collection of example scripts for running IPModules
- **Tests:** are run on the build-bots to check that the different parts of the simulation are not broken with each commit to the software repository.

Simprod-Scripts

http://software.icecube.wisc.edu/documentation/projects/simprod_scripts/index.html

Tray Segments $I3_SRC/simprod-scripts/python/segments

Calibration

DetectorSim

GenerateAirShowers

GenerateCosmicRayMuons

GenerateFlashers

GenerateIceTopShowers

GenerateIceTopShowers

GenerateNeutrinos

GenerateNoiseTriggers

HybridPhotonicsCLSim

Polyplopia

PropagateMuons

simprod-scripts

Scripts: $I3_SRC/simprod-scripts/resources/scripts

(run the individual pieces as broken down by production tasks)

```
$  python nugen.py -h

                    Usage: nugen.py [options]

                    Options:
                      -h, --help            show this help message and exit
                      --no-execute          boolean condition to execute
                     --outputfile=OUTPUTFILE
                                            Output filename
                      --summaryfile=SUMMARYFILE
                                            XMLSummary filename
                      --mjd=MJD             MJD for the GCD file
                      --seed=RNGSEED        RNG seed
                      —UseGSLRNG
                    …
```

simprod-scripts

Exercise: Running scripts**:**

For this exercise, you won't be able to use the VM.

You can run on **cobalt**

ssh cobalt

or you can run an interactive job on **NPX** with **GPU**

ssh submit

The following slides will assume you are on **submit** (AKA NPX)

commands ending with '\' indicate that the next line is a continuation of the current line

simprod-scripts

Exercise: Running scripts:

```
icecube@M16:~$ ssh submitter
[submitter]$
[submitter]$ condor_submit /data/sim/sim-new/bootcamp16/interactive_gpu.condor -interactive
Submitting job(s).
1 job(s) submitted to cluster 120263704.
Waiting for job to start…
Welcome to slot1@gtx-00.icecube.wisc.edu!

[gtx-00]$ cd $_CONDOR_SCRATCH_DIR
[gtx-00]$ cp /cvmfs/icecube.opensciencegrid.org/data/GCD/ \
  GeoCalibDetectorStatus_2020.Run134142.Pass2_V0.i3.gz gcdfile.i3.gz

[gtx-00]$ /cvmfs/icecube.opensciencegrid.org/py3-v4.1.1/icetray-env icetray/stable
************************************************************************
*                                                                      *
*                   W E L C O M E  to  I C E T R A Y                   *
*                                                                      *
*               Version icetray.stable     git:f5d21802                *
*                                                                      *
*                You are welcome to visit our Web site                 *
*                        http://icecube.umd.edu                        *
*                                                                      *
************************************************************************
[gtx-00]$ python $I3_BUILD/simprod-scripts/resources/scripts/nugen.py \
                 --outputfile nutau.i3 --nevents 100 \
                  --seed=123 --procnum 0  --nproc=1 \
                  --FromEnergy 1e5 --ToEnergy 1e6 --NuFlavor NuTau --UseGSLRNG

[gtx-00]$ dataio-pyshovel nutau.i3
```

simprod-scripts

Exercise: Running scripts:

```
[gtx-00]$ dataio-pyshovel nutau.i3
```

```
I3 Data Shovel                                                    Press '?' for help

Name                              Type                                                   Bytes
I3MCTree_preMuonProp              TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I3...  422
I3MCWeightDict                    I3Map<__cxx11::string, double>                         1400
NuGPrimary                        I3Particle                                             150

      Key: 3/3                                                  StartTime: (n/a)
    Frame: 3/101 (2%)                                            Duration: (n/a)
     Stop: DAQ                                                   20                    40
Run/Event: (n/a)                                      .    |    .    |    .    |    .    |    .    |
 SubEvent: (n/a)                                     IQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQ
```

simprod-scripts

Exercise: Running scripts**:**

```
[gtx-00]$ python $I3_BUILD/simprod-scripts/resources/scripts/clsim.py \
            --gcdfile gcdfile.i3.gz \
            --inputfilelist nutau.i3 --outputfile mcpes.i3   \
            --seed 123 --procnum 0 --nproc 1 --no-RunMPHitFilter \
            --UseGPUs --UseGSLRNG

[gtx-00]$ dataio-pyshovel mcpes.i3

[gtx-00]$ python $I3_BUILD/simprod-scripts/resources/scripts/detector.py \
            --gcdfile gcdfile.i3.gz \
            --inputfile mcpes.i3 --outputfile det.i3 \
            --seed 123 --procnum 0 --nproc 1 --RunID 123 —UseGSLRNG

[gtx-00]$ dataio-pyshovel det.i3
```

simprod-scripts

Exercise: Running scripts:

```
[gtx-00]$ dataio-pyshovel mcpes.i3
```

```
 I3 Data Shovel                                                    Press '?' for help

 Name                            Type                                                  Bytes
 I3MCPESeriesMap                 I3Map<OMKey, vector<I3MCPE> >                         41
 I3MCPESeriesMapParticleIDMap    I3Map<OMKey, map<I3ParticleID, vector<unsigned int... 41
 I3MCTree                        TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I3... 6878
 I3MCTree_preMuonProp            TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I3... 1538
 I3MCTree_preMuonProp_RNGState   I3GSLRandomServiceState                               85
 I3MCWeightDict                  I3Map<__cxx11::string, double>                        1400
 MMCTrackList                    I3Vector<I3MMCTrack>                                  40
 NuGPrimary                      I3Particle                                            150

       Key: 1/8                                          StartTime: (n/a)
     Frame: 3/102 (2%)                                    Duration: (n/a)
      Stop: DAQ                                                   20                  40
 Run/Event: (n/a)                                    .    |    .    |    .    |    .    |    .    |
  SubEvent: (n/a)                                  IIQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQ
```

simprod-scripts

Exercise: Running scripts:

```
[gtx-00]$ dataio-pyshovel det.i3
```

```
I3 Data Shovel                                                              Press '?' for help

Name                              Type                                                    Bytes
BeaconLaunches                    I3Map<OMKey, vector<I3DOMLaunch> >                      46
I3EventHeader                     I3EventHeader                                           99
I3MCPESeriesMap                   I3Map<OMKey, vector<I3MCPE> >                           113286
I3MCPESeriesMapParticleIDMap      I3Map<OMKey, map<I3ParticleID, vector<unsigned int...   36649
I3MCPESeriesMapWithoutNoise       I3Map<OMKey, vector<I3MCPE> >                           109543
I3MCPulseSeriesMap                I3Map<OMKey, vector<I3MCPulse> >                        82000
I3MCPulseSeriesMapParticleI...    I3Map<OMKey, map<I3ParticleID, vector<unsigned int...   40743
I3MCPulseSeriesMapPrimaryIDMap    I3Map<OMKey, map<I3ParticleID, vector<unsigned int...   27299
I3MCTree                          TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I3...   10730
I3MCTree_preMuonProp              TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I3...   422
I3MCTree_preMuonProp_RNGState     I3GSLRandomServiceState                                 85
I3MCWeightDict                    I3Map<__cxx11::string, double>                          1400
I3TriggerHierarchy                I3Tree<I3Trigger>                                       792
I3Triggers                        I3Tree<I3Trigger>                                       414
IceTopRawData                     I3Map<OMKey, vector<I3DOMLaunch> >                      46
InIceRawData                      I3Map<OMKey, vector<I3DOMLaunch> >                      44640
MMCTrackList                      I3Vector<I3MMCTrack>                                    2864
NuGPrimary                        I3Particle                                              150
TimeShift                         I3PODHolder<double>                                     36
```

simprod-scripts

Exercise: Running scripts**:**

```
[gtx-00]$ python $I3_BUILD/simprod-scripts/resources/scripts/corsika.py \
            --nshowers 10000 --outputfile corsika_bg.i3 --seed 1234 \
            --CORSIKAseed=123 --ranpri 2  \
            --corsikaVersion v6960-5comp \
            --corsikaName dcorsika --UseGSLRNG  \
            --skipoptions compress

[gtx-00]$ dataio-pyshovel corsika_bg.i3

[gtx-00]$ python $I3_BUILD/simprod-scripts/resources/scripts/polyplopia.py  \
          --gcdfile gcdfile.i3.gz \
          --inputfile mcpes.i3 --outputfile merged_pes.i3 \
          --seed 1234 \
          --backgroundfile corsika_bg.i3 --mctype NuTau \
          --UseGSLRNG

[gtx-00]$ python $I3_BUILD/simprod-scripts/resources/scripts/detector.py \
            --gcdfile  gcdfile.i3.gz \
            --inputfile merged_pes.i3 --outputfile det_wcoinc.i3 \
            --seed 123 --RunID 123 --UseGSLRNG

[gtx-00]$ dataio-pyshovel det_wcoinc.i3
```

simprod-scripts

Exercise: Running scripts:

```
[gtx-00]$ dataio-pyshovel corsika_bg.i3
```

```
I3 Data Shovel                                                         Press '?' for help

Name                         Type                                                 Bytes
CorsikaInteractionHeight     I3PODHolder<double>                                  36
CorsikaWeightMap             I3Map<__cxx11::string, double>                       484
I3CorsikaInfo                I3CorsikaInfo                                        109
I3MCTree                     TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I3... 546
I3MCTree_preSampling         TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I3... 546

       Key: 1/5                                      StartTime: (n/a)
     Frame: 3/111+                                    Duration: (n/a)
      Stop: DAQ                                          20                  40
 Run/Event: (n/a)                              .    |    .    |    .    |    .    |    .    |
  SubEvent: (n/a)                            ISQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQ
```

simprod-scripts

Exercise: Running scripts:

```
[gtx-00]$ dataio-pyshovel merged_pes.i3
```

```
I3 Data Shovel                                                                              Press '?' for help

Name                              Type                                                     Bytes
BackgroundI3MCPESeriesMap         I3Map<OMKey, vector<I3MCPE> >                            41
BackgroundI3MCPESeriesMapPa...    I3Map<OMKey, map<I3ParticleID, vector<unsigned in...     41
BackgroundI3MCTree                TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I...     32
BackgroundI3MCTreePEcounts        I3Map<unsigned int, unsigned int>                        47
BackgroundI3MCTree_preMuonProp    TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I...     32
BackgroundI3MCTree_preMuonP...    I3GSLRandomServiceState                                  85
BackgroundMMCTrackList            I3Vector<I3MMCTrack>                                     40
I3MCPESeriesMap                   I3Map<OMKey, vector<I3MCPE> >                            41
I3MCPESeriesMapParticleIDMap      I3Map<OMKey, map<I3ParticleID, vector<unsigned in...     41
I3MCTree                          TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I...     2902
I3MCTree_preMuonProp              TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I...     422
I3MCTree_preMuonProp_RNGState     I3GSLRandomServiceState                                  85
I3MCWeightDict                    I3Map<__cxx11::string, double>                           1424
MMCTrackList                      I3Vector<I3MMCTrack>                                     40
NuGPrimary                        I3Particle                                               150
PhotonSeriesMap                   I3Map<ModuleKey, I3Vector<I3CompressedPhoton> >          53
PolyplopiaInfo                    I3Map<__cxx11::string, int>                              135
PolyplopiaPrimary                 I3Particle                                               150
SignalI3MCPEs                     I3Map<OMKey, vector<I3MCPE> >                            41
SignalI3MCTree                    TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I...     2902
```

simprod-scripts

Exercise: Running scripts:

```
[gtx-00]$ dataio-pyshovel merged_pes.i3
```

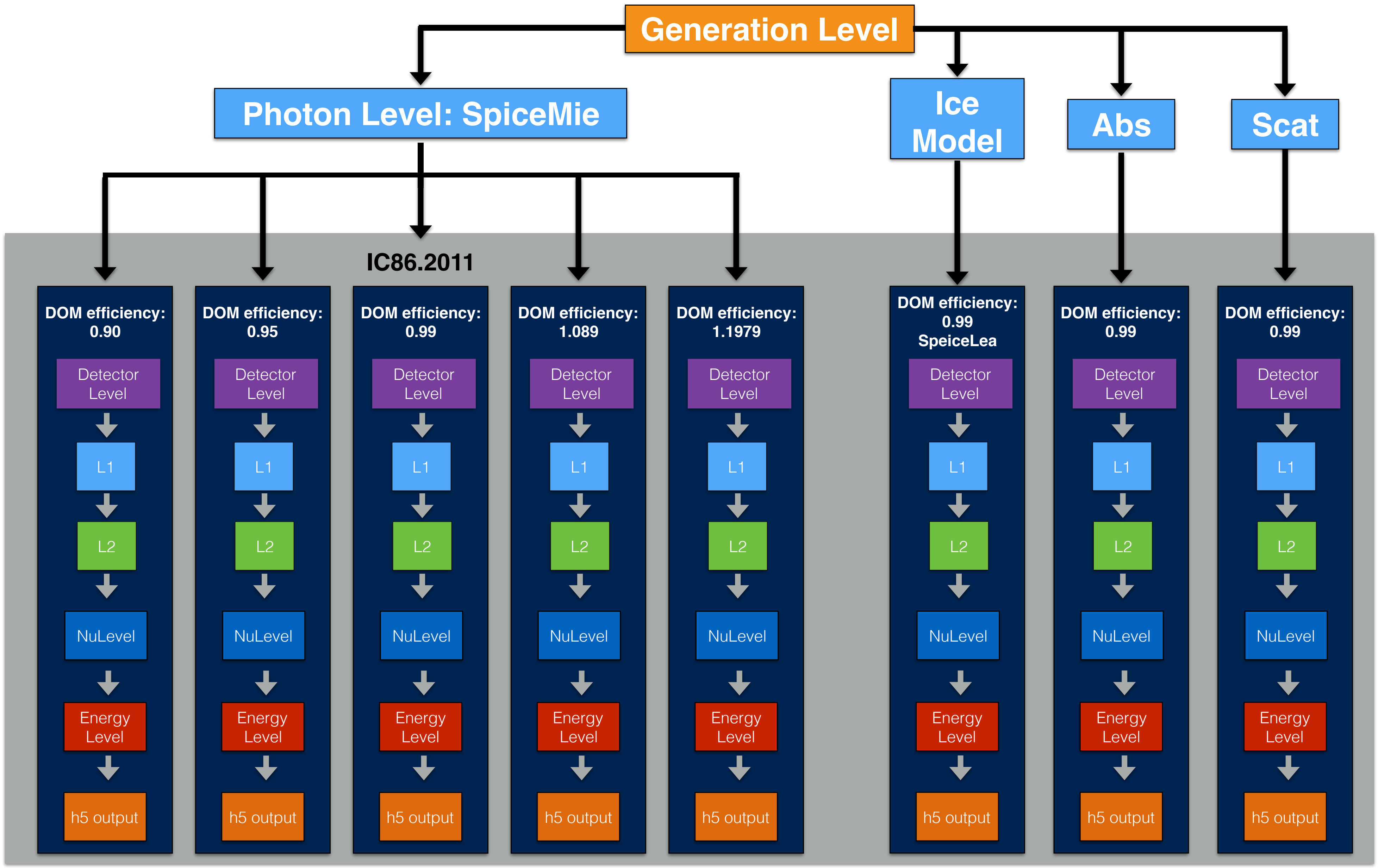
```
 I3 Data Shovel                                                        Press '?' for help

Name                              Type                                                Bytes
BackgroundI3MCPESeriesMap         I3Map<OMKey, vector<I3MCPE> >                       41
BackgroundI3MCPESeriesMapPa...    I3Map<OMKey, map<I3ParticleID, vector<unsigned in... 41
BackgroundI3MCTree                TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I... 32
BackgroundI3MCTreePEcounts        I3Map<unsigned int, unsigned int>                   47
BackgroundI3MCTree_preMuonProp    TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I... 32
BackgroundI3MCTree_preMuonP...    I3GSLRandomServiceState                             85
BackgroundMMCTrackList            I3Vector<I3MMCTrack>                                40
I3MCPESeriesMap                   I3Map<OMKey, vector<I3MCPE> >                       41
I3MCPESeriesMapParticleIDMap      I3Map<OMKey, map<I3ParticleID, vector<unsigned in... 41
I3MCTree                          TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I... 2902
I3MCTree_preMuonProp              TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I... 422
I3MCTree_preMuonProp_RNGState     I3GSLRandomServiceState                             85
I3MCWeightDict                    I3Map<__cxx11::string, double>                      1424
MMCTrackList                      I3Vector<I3MMCTrack>                                40
NuGPrimary                        I3Particle                                          150
PhotonSeriesMap                   I3Map<ModuleKey, I3Vector<I3CompressedPhoton> >     53
PolyplopiaInfo                    I3Map<__cxx11::string, int>                         135
PolyplopiaPrimary                 I3Particle                                          150
SignalI3MCPEs                     I3Map<OMKey, vector<I3MCPE> >                       41
SignalI3MCTree                    TreeBase::Tree<I3Particle, I3ParticleID, i3hash<I... 2902
```

Simulating Systematic Uncertainties

Example: High-Energy Sterile Neutrino MC Generation

Spencer N. Axani



Generation level:

- MuonInjector
- Spectrum = E^{-2}
- Energy = 2E2 to 1E6 GeV
- NEvents = 1.2e9 events

Photon Level:

- DOM efficiency: 1.1979
- SpiceMie

It took almost a year to produce this MC for the IC86.2011 analysis.

We do not have the resources to do this for a 6 year analysis.

We need to find ways to optimize and cut back!

SnowStorm

https://events.icecube.wisc.edu/event/118/contributions/6499/attachments/5362/6082/DiffuseParallel_Brussels_SnowStormMCGlobalfit.pdf

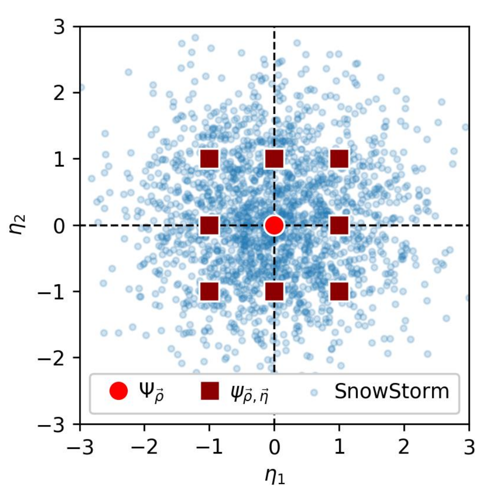
Erik Ganster

SnowStorm Simulation Chain – SnowStorm

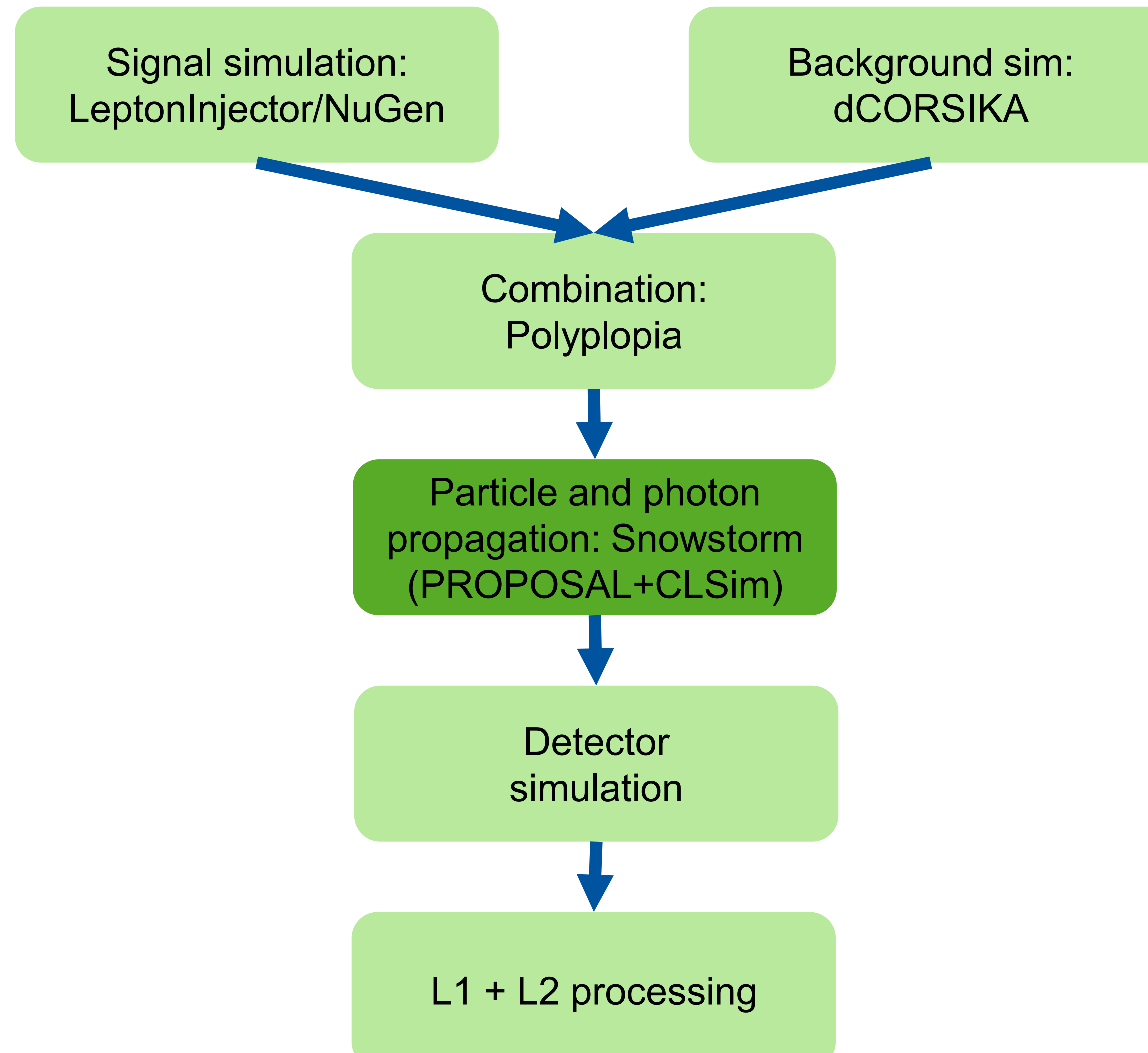
- Based on “standard” simulation chain
- Merge of signal+background I3MCTrees before any particle or photon propagation
  → Ensures that all particles get treated/propagated with the exact same parameters/settings further on

➢ Main SnowStorm simulation step:
  ➢ Particle (muon) propagation with PROPOSAL
  ➢ Photon propagation using CLSim

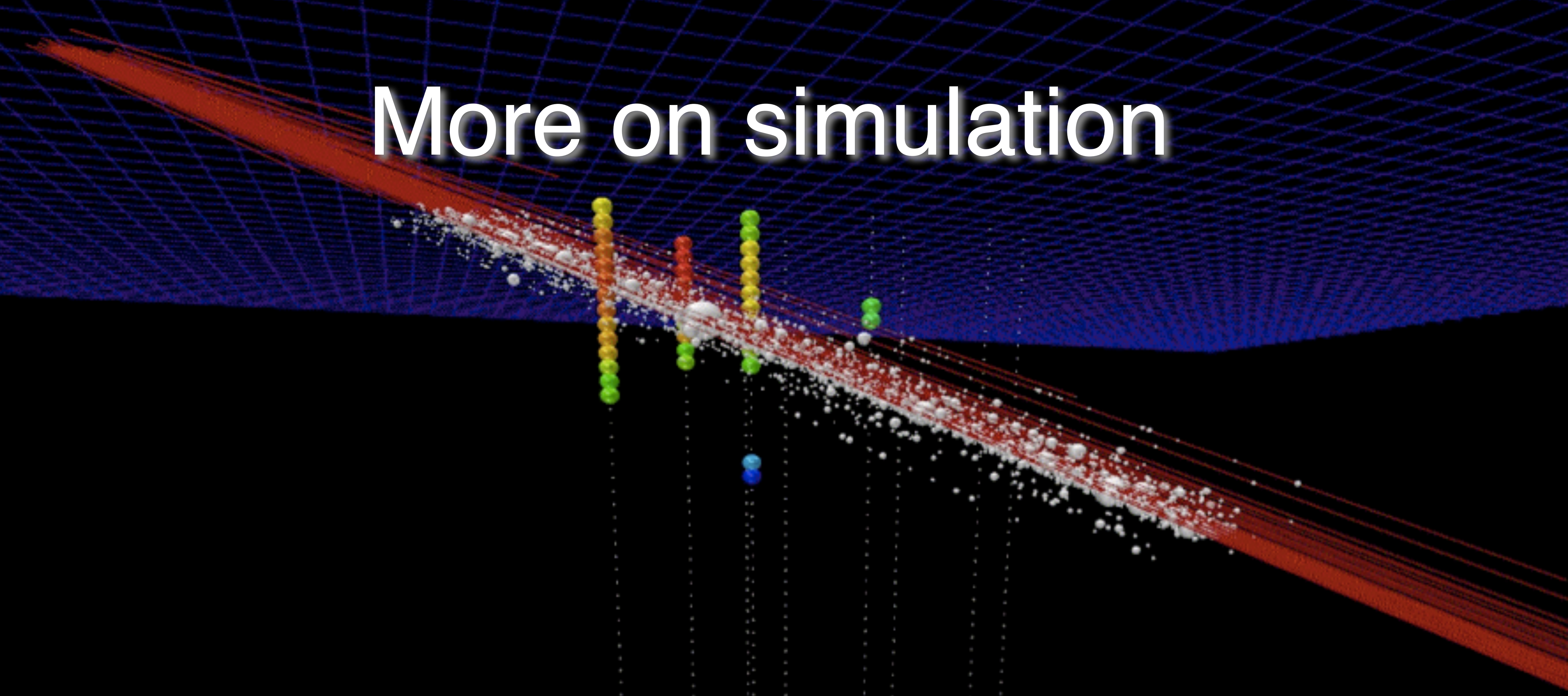
➢ Perturbing the ice model properties for chunks of frames using the *SnowStorm perturber*



SnowStorm short: Continuos variation of nuisance parameters (detector systematics) (blue) instead of discrete sets for specific values (red)

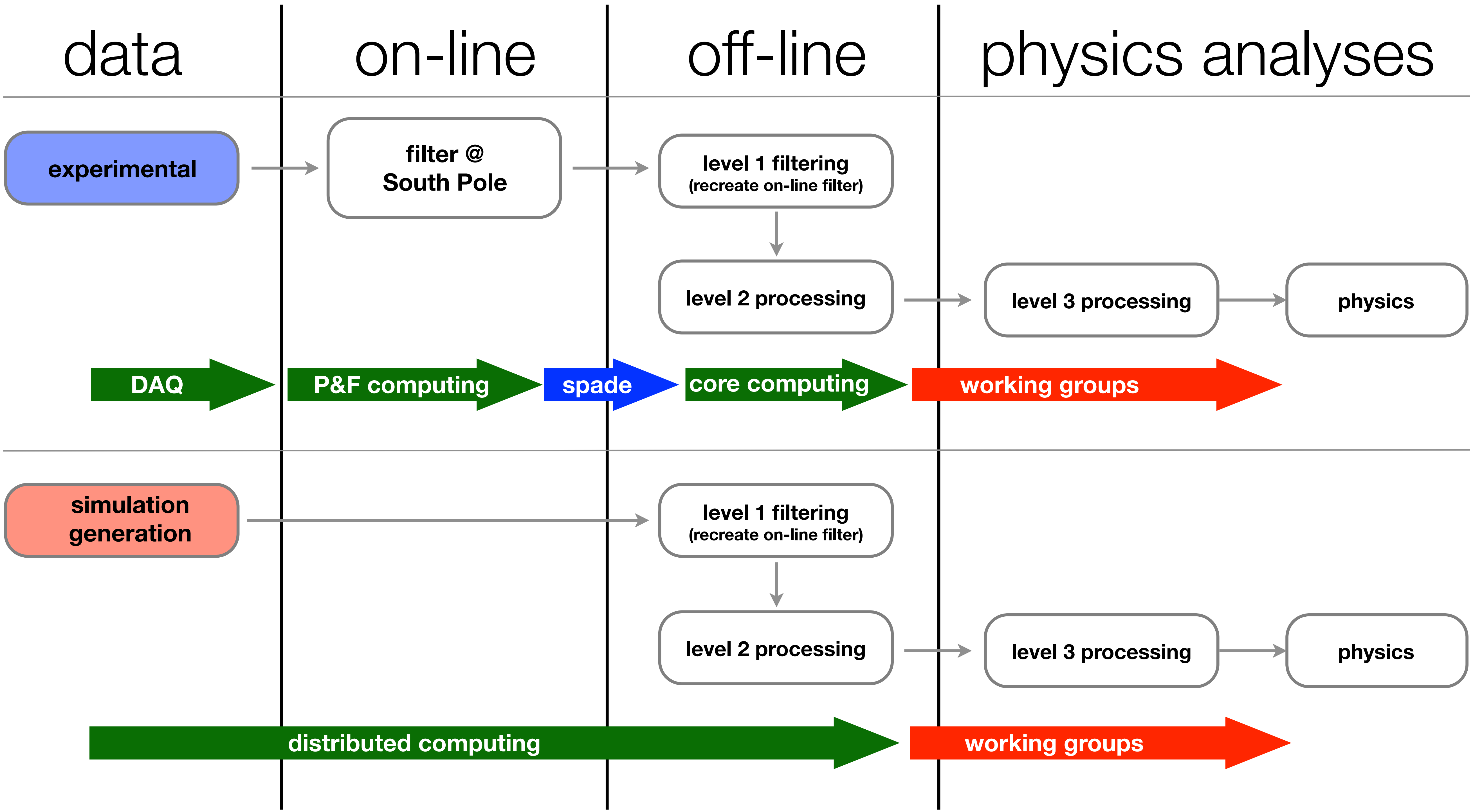


More on simulation



1. https://docs.icecube.aq/icetray/main/
2. http://grid.icecube.wisc.edu/simulation
3. http://wiki.icecube.wisc.edu/index.php/Simulation_Production
4. SLACK: #simulation

flow of experimental and simulation data



Simulating the online filter and L2 processing

```
[gtx-00]$  python filterscripts/resources/scripts/SimulationFiltering.py -h

usage: SimulationFiltering.py [-h] [-i INFILE] [-g GCDFILE] [-o OUTFILE]
                              [-n NUM] [--qify]
                              [--MinBiasPrescale MINBIASPRESCALE]
                              [--photonicsdir PHOTONICSDIR] [--enable-gfu]
                              [--log-level LOG_LEVEL] [--log-filename LOGFN]
                              [--needs_wavedeform_spe_corr]

optional arguments:
  -h, --help            show this help message and exit
  -i INFILE, --input INFILE
                        Input i3 file(s) (use comma separated list for
                        multiple files)
  -g GCDFILE, --gcd GCDFILE
                        GCD file for input i3 file
  -o OUTFILE, --output OUTFILE
                        Output i3 file
  -n NUM, --num NUM     Number of frames to process
  --qify                Apply QConverter, use if file is P frame only
  --MinBiasPrescale MINBIASPRESCALE
                        Set the Min Bias prescale to something other than
                        default
  --photonicsdir PHOTONICSDIR
                        Directory with photonics tables
  --enable-gfu          Do not run GFU filter
  --log-level LOG_LEVEL
                        Sets the logging level (ERROR, WARN, INFO, DEBUG,
                        TRACE)
  --log-filename LOGFN  If set logging is redirected to the specified file.
  --needs_wavedeform_spe_corr
                        apply_spe_corection in wavedeform.
```

Simulating the online filter and L2 processing

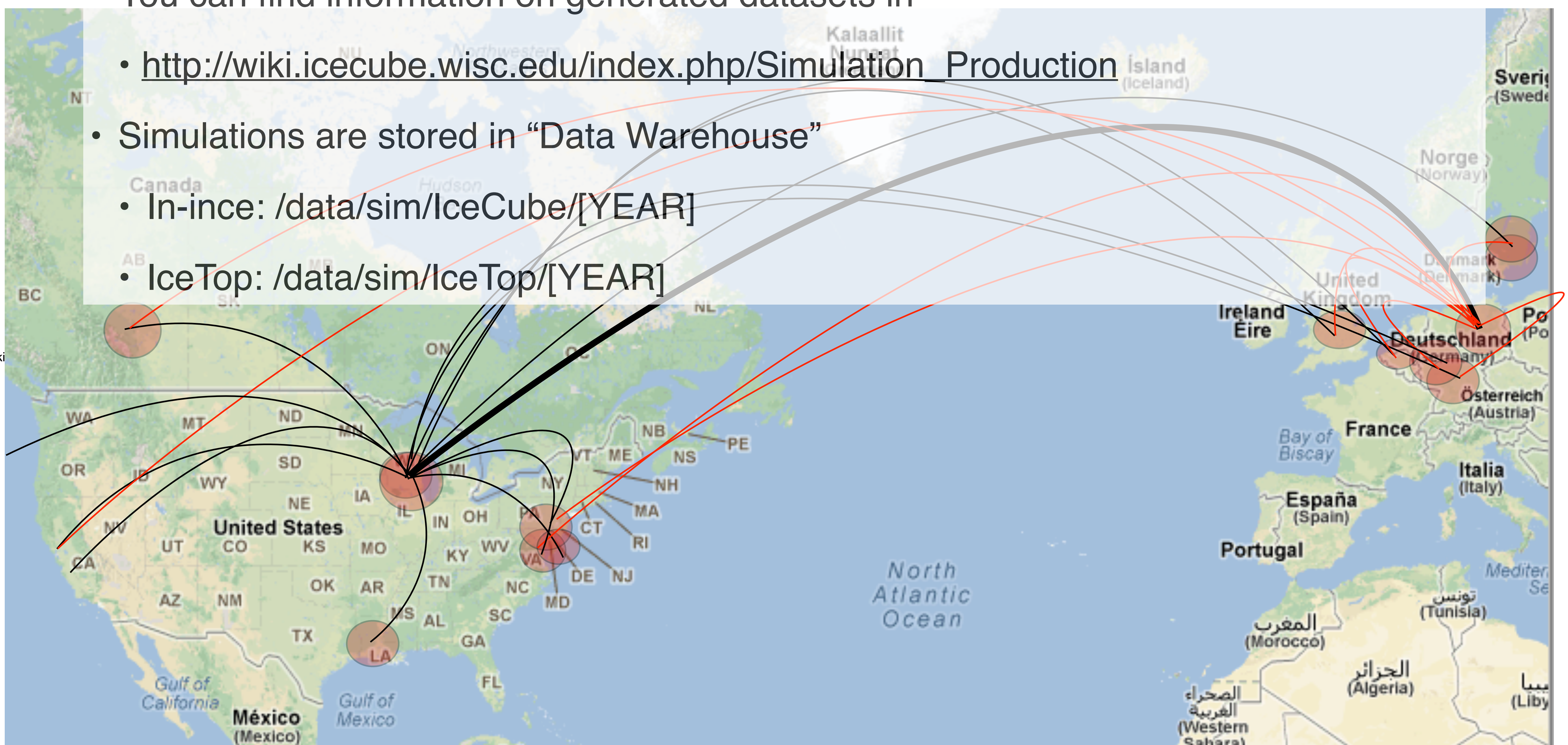
```
[gtx-00]$  python filterscripts/resources/scripts/offlineL2/process.py -h

usage: process.py [-h] [-s] [-i INFILE] [-g GCDFILE] [-o OUTFILE] [-n NUM]
                  [--dstfile DSTFILE] [--gapsfile GAPSFILE]
                  [--icetopoutput ICETOPOUTPUT] [--eheoutput EHEOUTPUT]
                  [--slopoutput SLOPOUTPUT] [--rootoutput ROOTOUTPUT]
                  [--photonicsdir PHOTONICSDIR] [--log-level LOG_LEVEL]
                  [--log-filename LOGFN]

optional arguments:
  -h, --help            show this help message and exit
  -s, --simulation      Mark as simulation (MC)
  -i INFILE, --input INFILE
                        Input i3 file(s) (use comma separated list for
                        multiple files)
  -g GCDFILE, --gcd GCDFILE
                        GCD file for input i3 file
  -o OUTFILE, --output OUTFILE
                        Output i3 file
  -n NUM, --num NUM     Number of frames to process
  --dstfile DSTFILE     DST root file (should be .root)
  --gapsfile GAPSFILE   gaps text file (should be .txt)
  --icetopoutput ICETOPOUTPUT
                        Output IceTop file
  --eheoutput EHEOUTPUT
                        Output EHE i3 file
  --slopoutput SLOPOUTPUT
                        Output SLOP file
  --rootoutput ROOTOUTPUT
                        Output root file
  --photonicsdir PHOTONICSDIR
                        Directory with photonics tables
  --log-level LOG_LEVEL
                        Sets the logging level (ERROR, WARN, INFO, DEBUG,
                        TRACE)
  --log-filename LOGFN  If set logging is redirected to the specified file.
```

Simulation Production

- You will typically not be generating you own simulation.
- Simulating IceCube takes many computing cycles
- The collaboration utilizes distributed computing resources from around the world
- You can find information on generated datasets in
  - http://wiki.icecube.wisc.edu/index.php/Simulation_Production
- Simulations are stored in “Data Warehouse”
  - In-ince: /data/sim/IceCube/[YEAR]
  - IceTop: /data/sim/IceTop/[YEAR]



CORSIKA weights

- CORSIKA produces events according to the flux given by $$\frac{\mathrm{d}N}{\mathrm{d}E\,\mathrm{d}t\,\mathrm{d}\Omega\,\mathrm{d}A} = \Phi(E)$$
- The number of events generated is $$N = \int_T \mathrm{d}t \int_\Omega \mathrm{d}\Omega \int a\,\Phi\,\mathrm{d}E \quad = T\Omega A_{sum} \int \Phi\,\mathrm{d}E$$
- And the effective livetime of the simulation is given by $$T = \frac{N}{\Omega A_{sum} \Phi^{sum}}$$
- where

$$\Phi^{sum} \equiv \int_{E_{min}}^{E_{max}} \Phi\,\mathrm{d}E$$

- The rate of events is R = n/T
- The CORSIKA spectrum is biased with a factor E^{δ} resulting in a flux

$$\Phi_0 \propto \Phi E^{\delta}$$

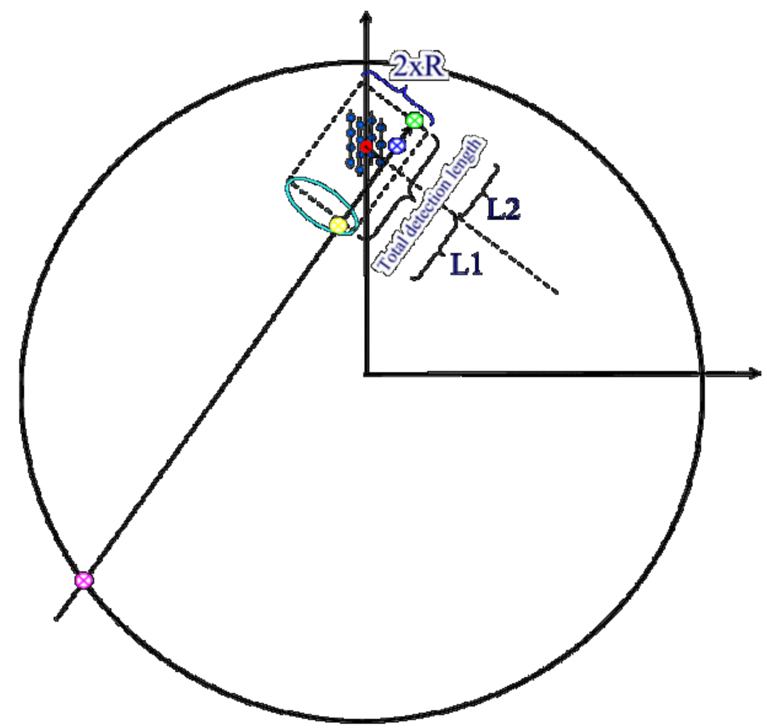
- And each event is assigned a weight

$$w(E) = \left(\frac{E_0}{E}\right)^{\delta}$$

neutrino-generator

- Calculates the propagation probability (i.e. that the neutrino will reach the detector)

- It forces an interaction within a volume around the dector and computes the probability of this interaction

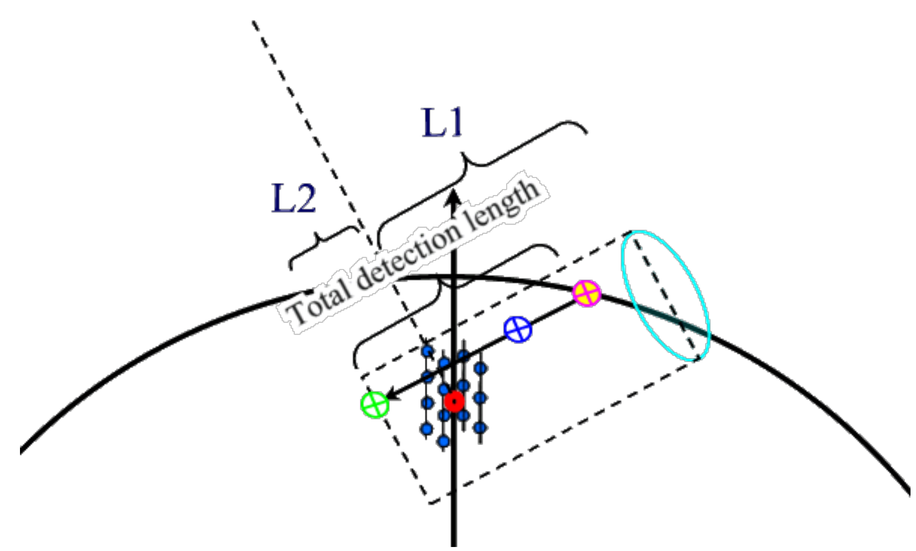


$$OneWeight = \left(\frac{P_{int}}{E^{-\gamma}}\right) \cdot \int_{E_{min}}^{E_{max}} E^{-\gamma} dE \cdot Area \cdot \Omega \cdot T[GeV \cdot cm^2 \cdot sec \cdot sr]$$

where $P_{int} = TotalInteractionProbabilityWeight$, $E^{-\gamma}$ is the neutrino generation energy spectrum shape, $Emin$ and $Emax$ is the minimum and maximum generation energy of neutrinos, $Area$ is the generation surface, Ω the generation solid angle and $T = 1sec$ is the timescale.

- The weight corresponding to a given theoretically motivated neutrino flux is

$$w_i = \frac{OneWeight_i}{NEvents} \times \frac{d\Phi_\nu(E_\nu)}{dE_\nu}$$



- For more details on how to use OneWeight see:

https://docushare.icecube.wisc.edu/dsweb/Get/Document-44937/OneWeight.pdf

Weighting

SimWeights:
https://icecube.wisc.edu/~juancarlos/simulation/Bootcamp_2021_Simulation_Weighting.html

Old IceTray weighting project:
https://icecube.wisc.edu/~juancarlos/simulation/Bootcamp_2020_Simulation_Weighting.html