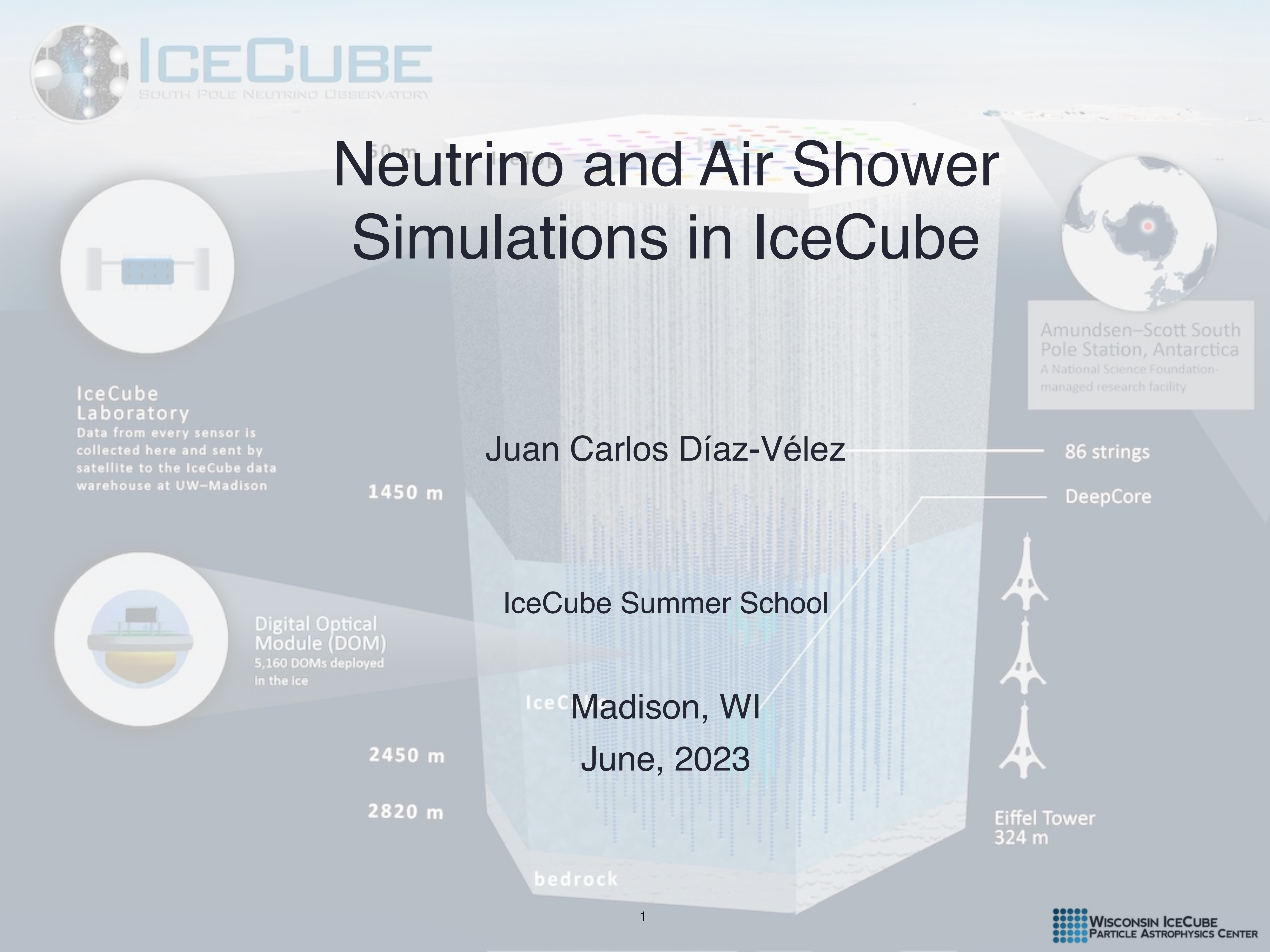
Neutrino and Air Shower Simulations in IceCube

Juan Carlos Díaz-Vélez

IceCube Summer School

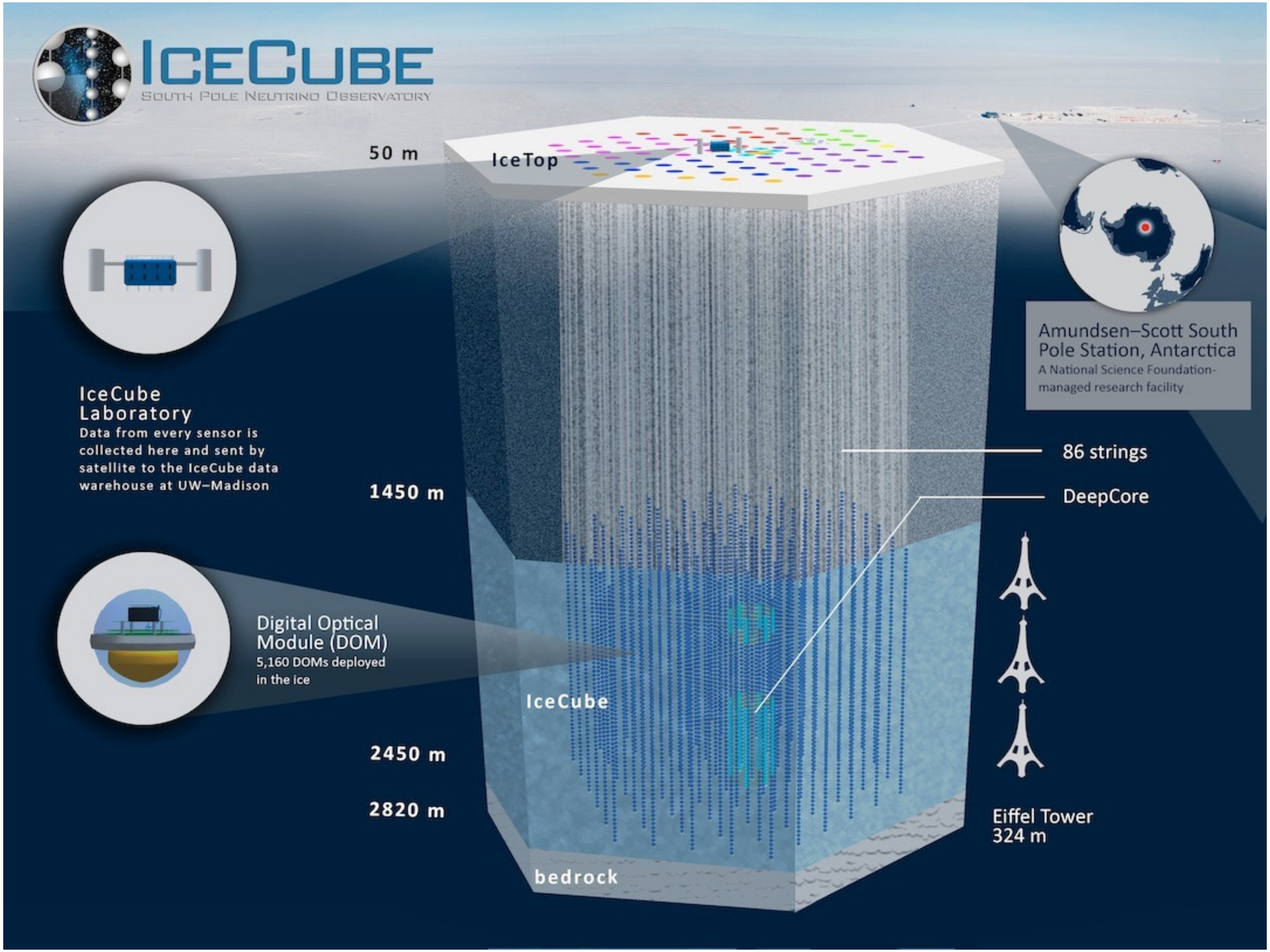
Madison, WI

June, 2023


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceCube Laboratory
Data from every sensor is collected here and sent by satellite to the IceCube data warehouse at UW–Madison
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
86 strings
DeepCore
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceC
2450 m
2820 m
Eiffel Tower
324 m
bedrock

Wisconsin IceCube Particle Astrophysics Center

The IceCube Observatory


ICECUBE
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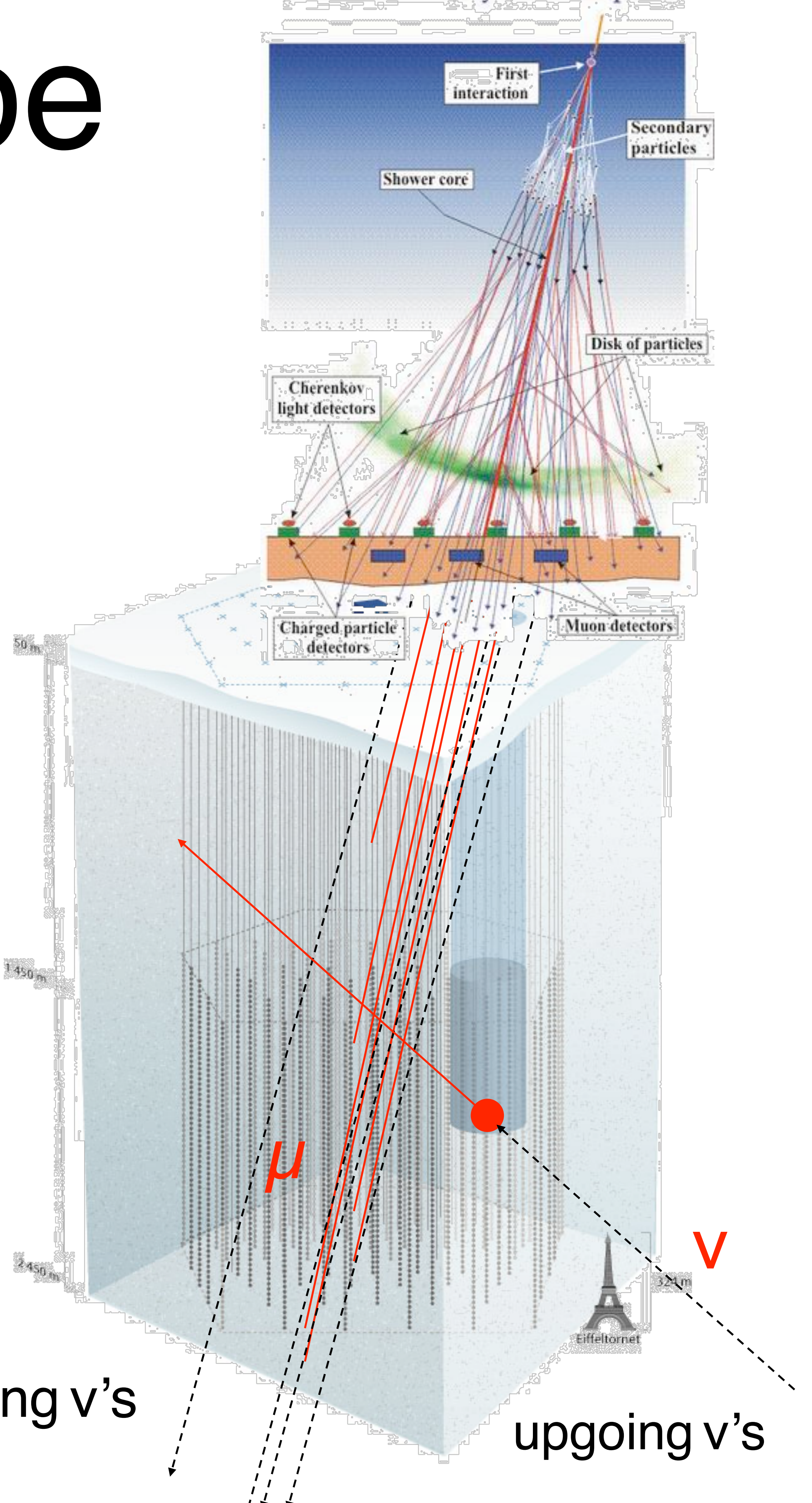
A National Science Foundation-managed research facility
86 strings
DeepCore
Eiffel Tower
324 m

Events in icecube

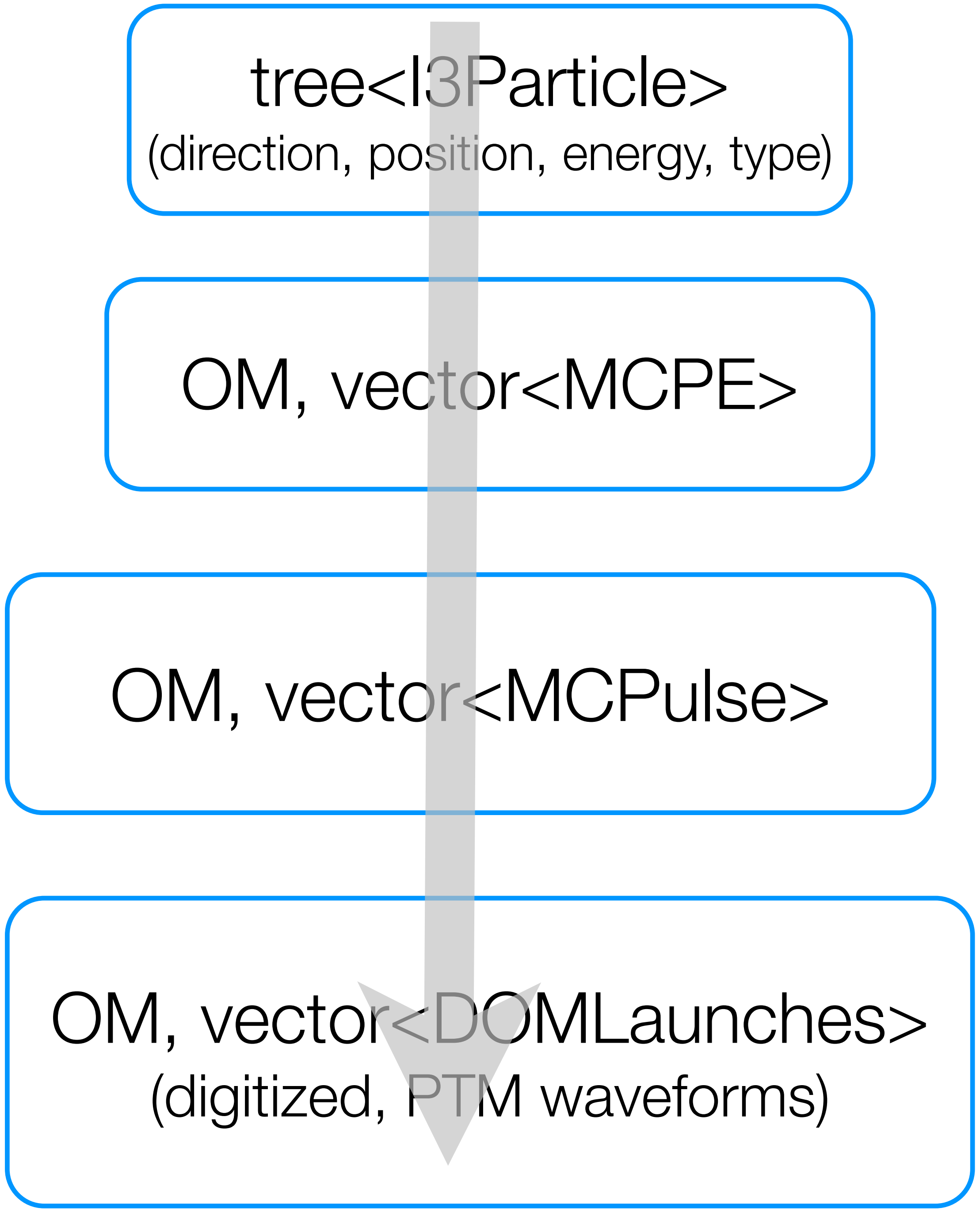
- Air shower detection @ surface
- Penetrating muon detection in deep ice
- Events dominated by cosmic ray muons : 10^6 μ for every ν that interacts in IceCube
- Atmospheric ν’s



downgoing ν’s

upgoing ν’s

Simulation



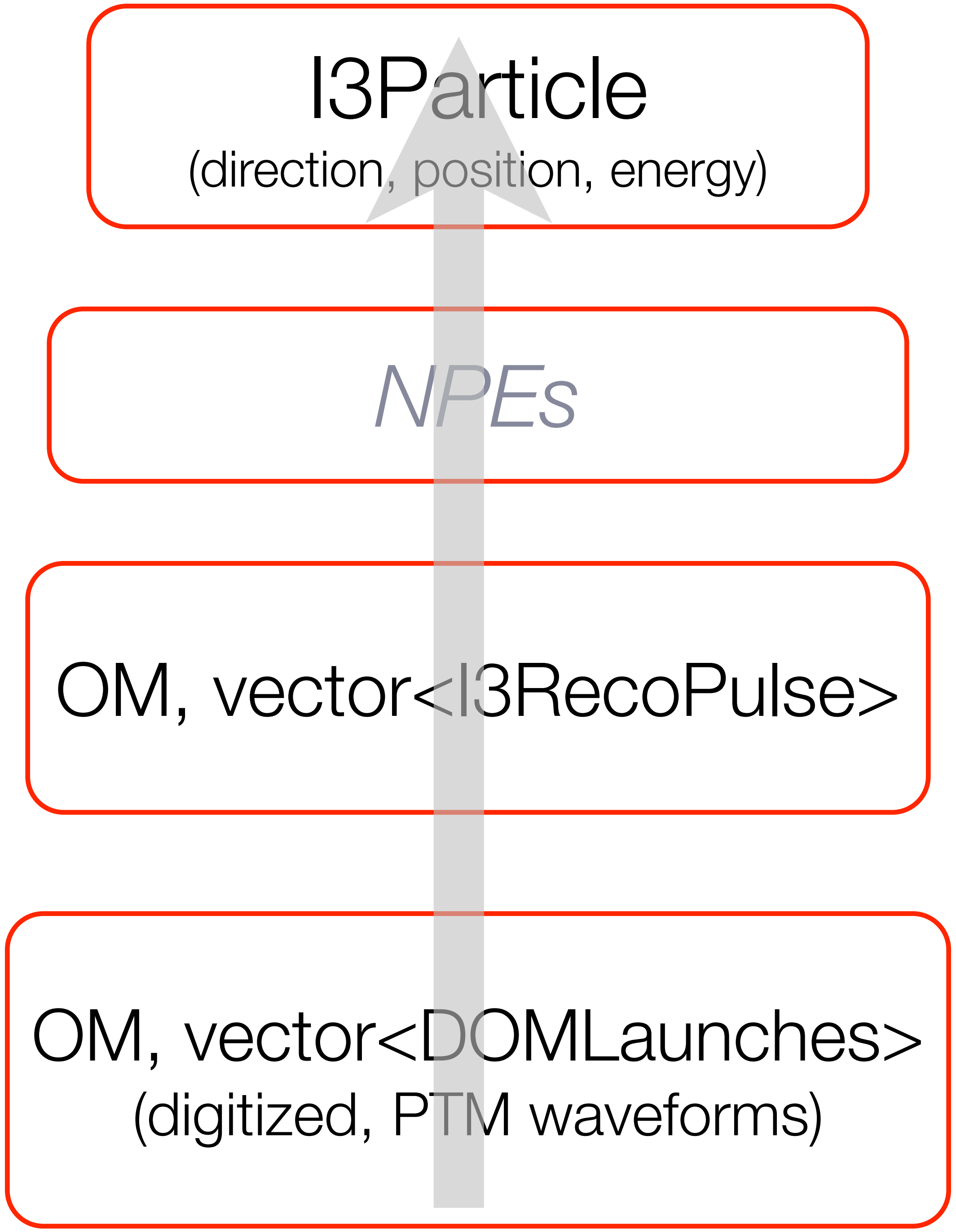
tree<I3Particle>
(direction, position, energy, type)

OM, vector<MCPE>

OM, vector<MCPulse>

OM, vector<DOMLaunches>
(digitized, PTM waveforms)

Reconstruction

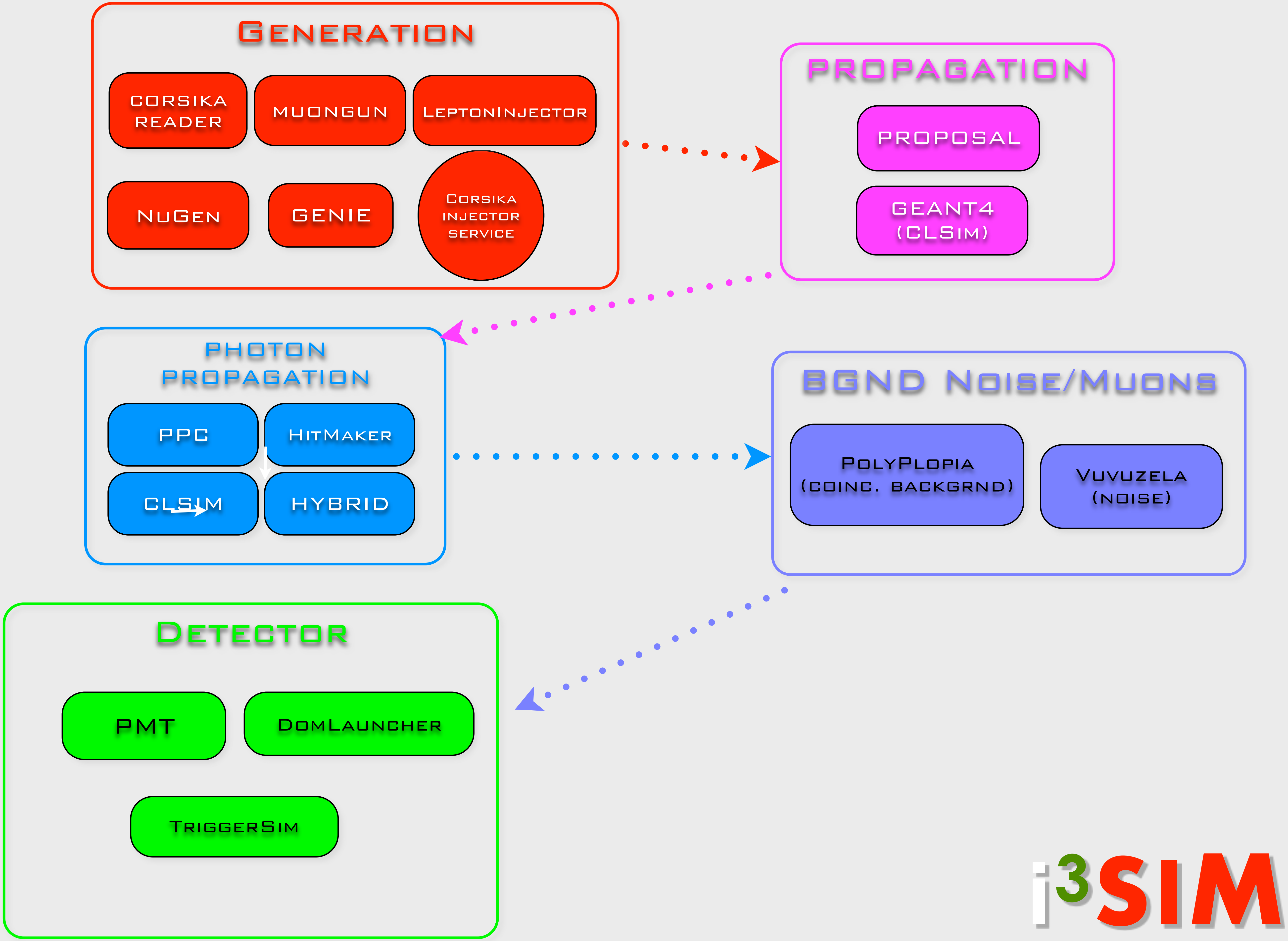


I3Particle
(direction, position, energy)

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

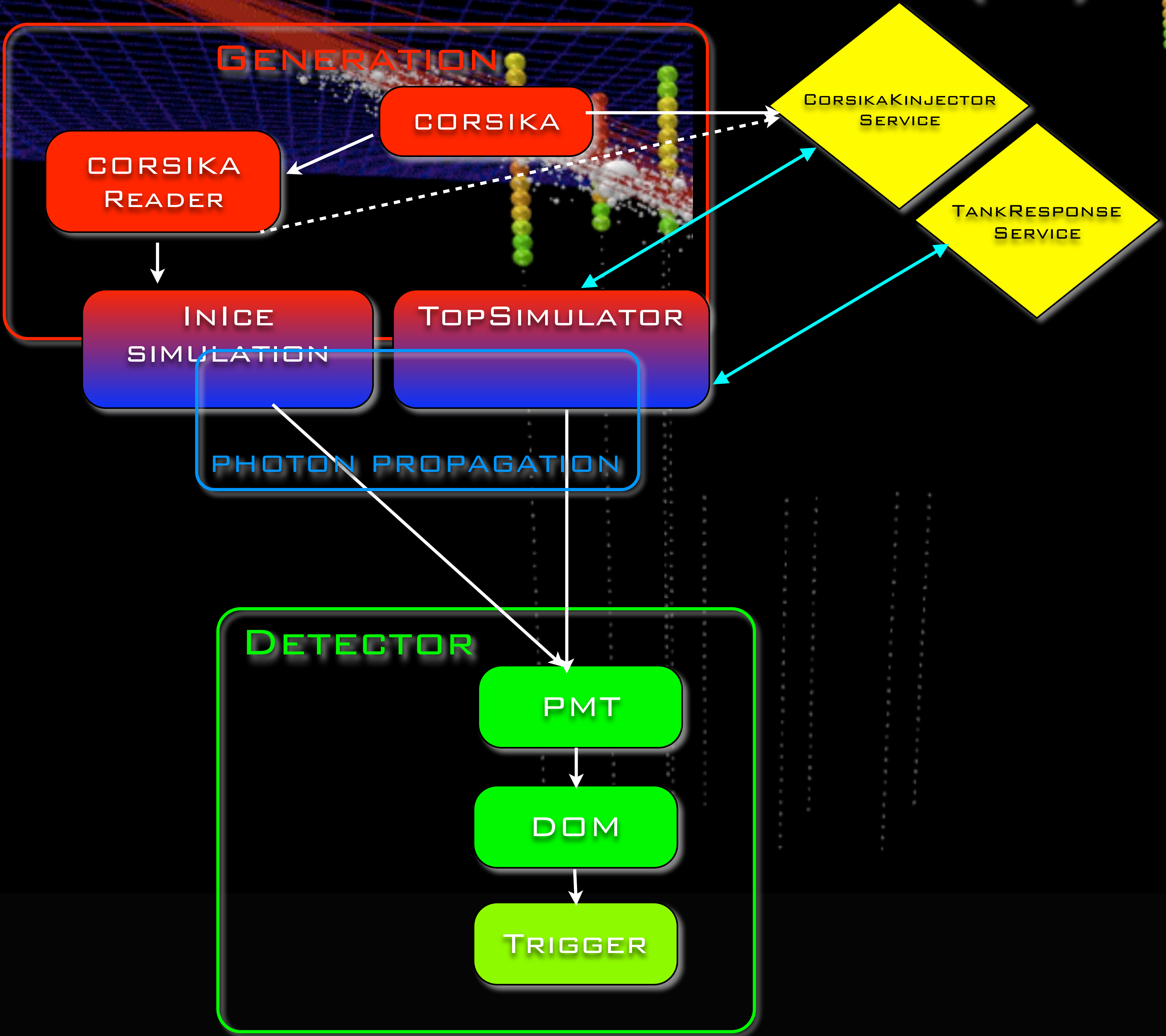
PMT

DomLauncher

TriggerSim

i^{3}SIM

simulaton chain (IT)

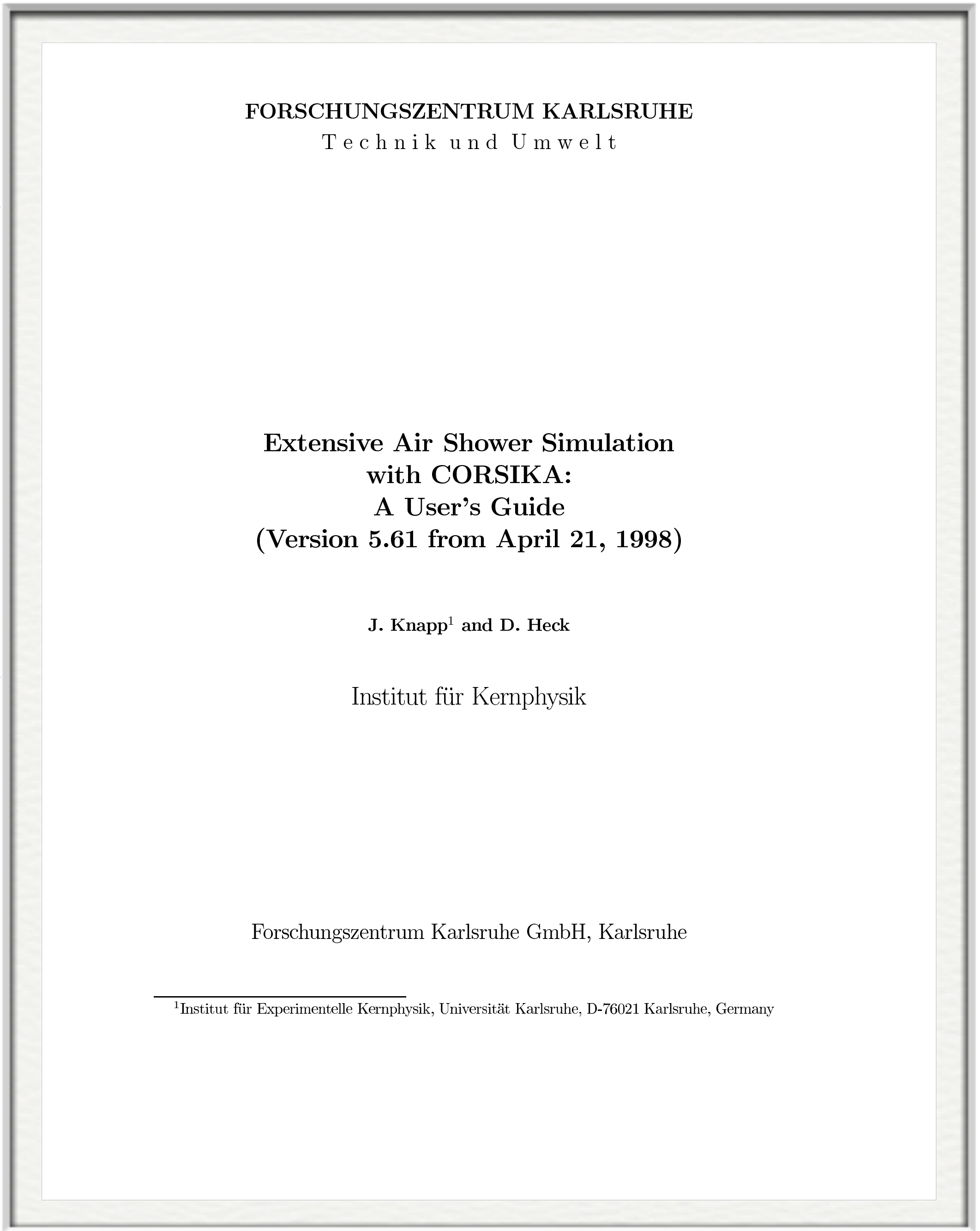


Generators : CORSIKA

(**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

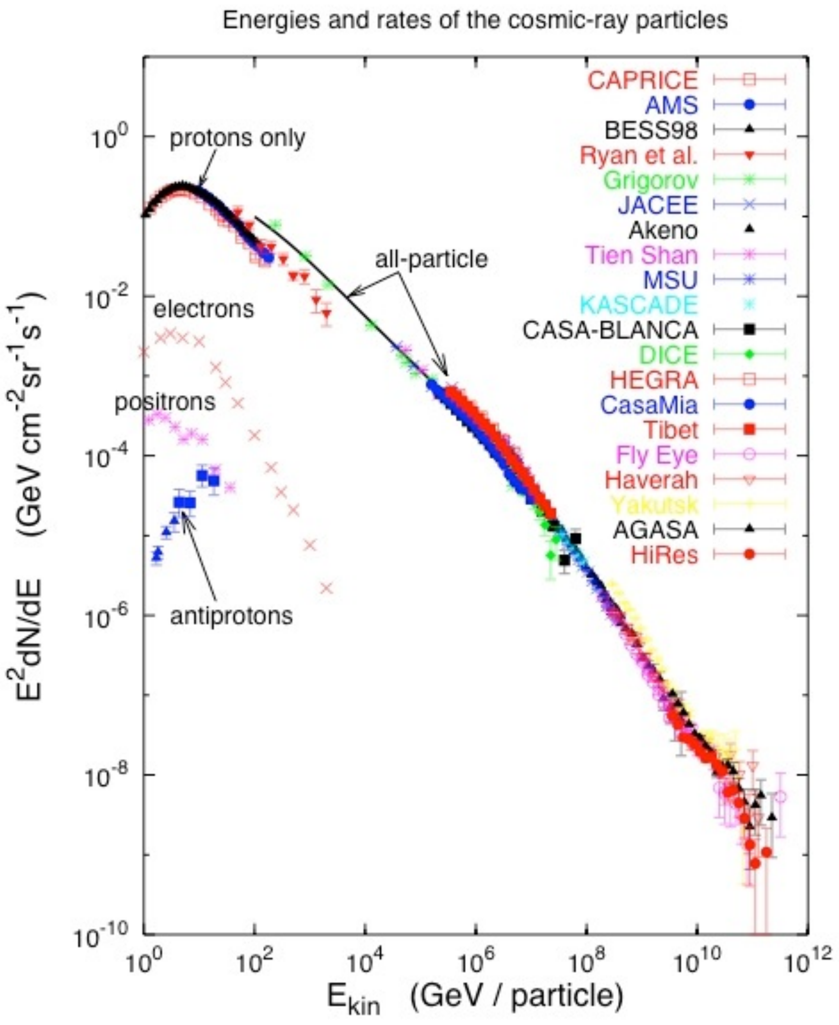
Forschungszentrum Karlsruhe GmbH, Karlsruhe

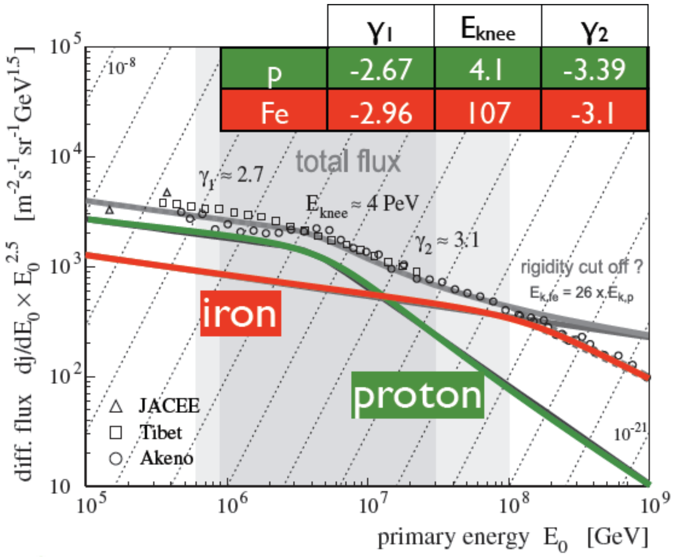
[1] Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany

Generators : CORSIKA

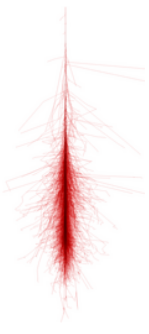
(**CO**smic **R**ay **SI**mulations for **KA**scade)

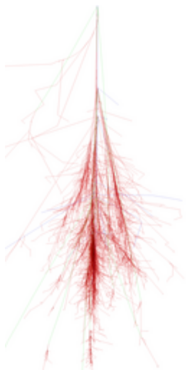
- weighted events : artificially flat spectrum
  - better livetime efficiency @ 10 TeV but poor efficiency @ TeV
  - energy-targeted generation of (H,He,CNO,Mg,Fe) with $E^{-1(2)}$

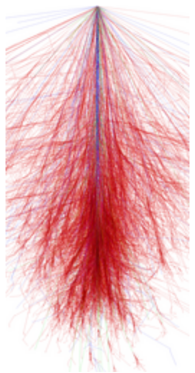


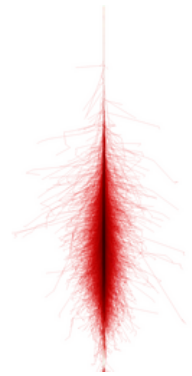


	γ_1	E_{knee}	γ_2
p	-2.67	4.1	-3.39
Fe	-2.96	107	-3.1


gamma shower


Proton shower


Iron shower


Muon shower

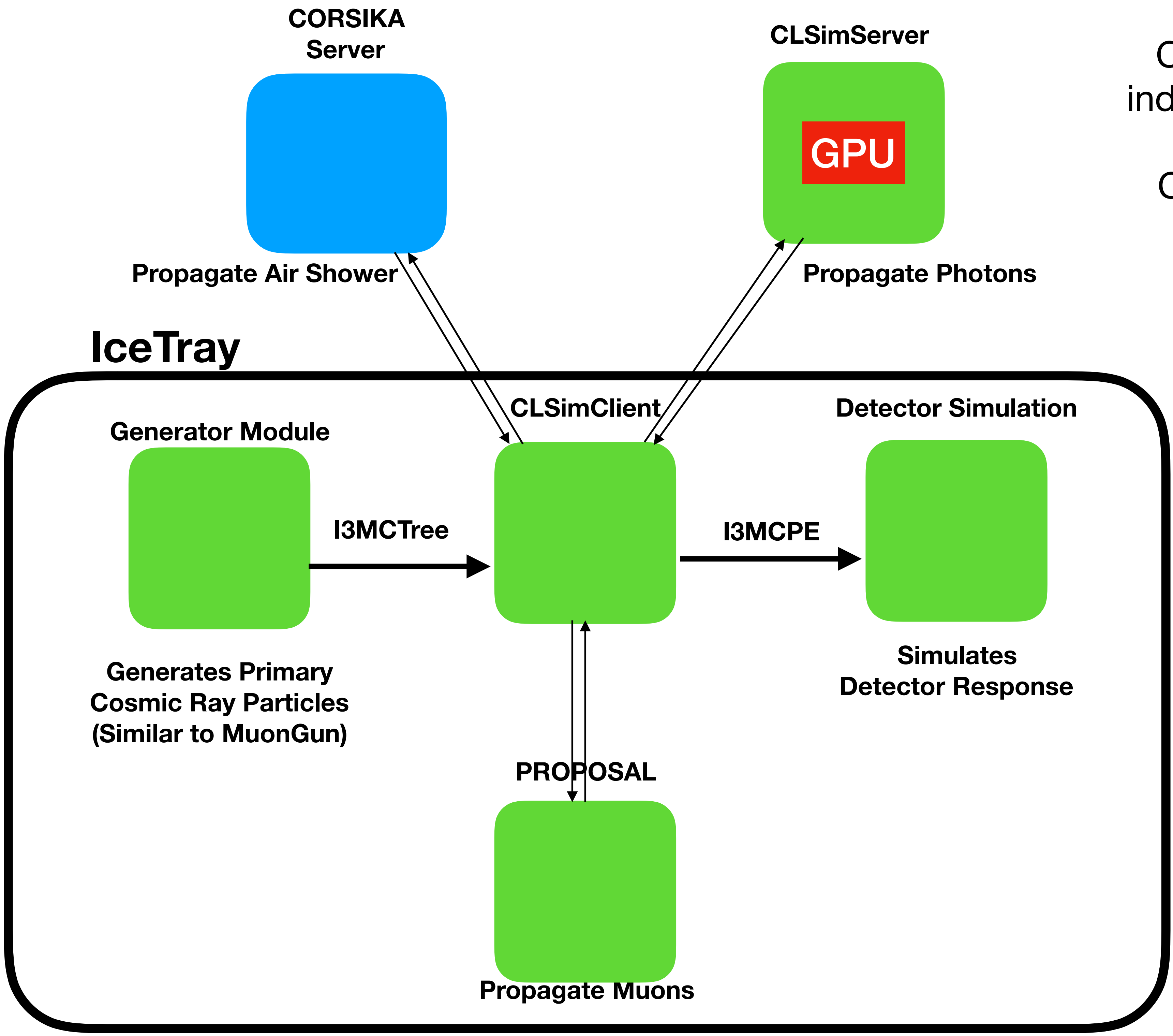
DYNSTACK in CORSIKA

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

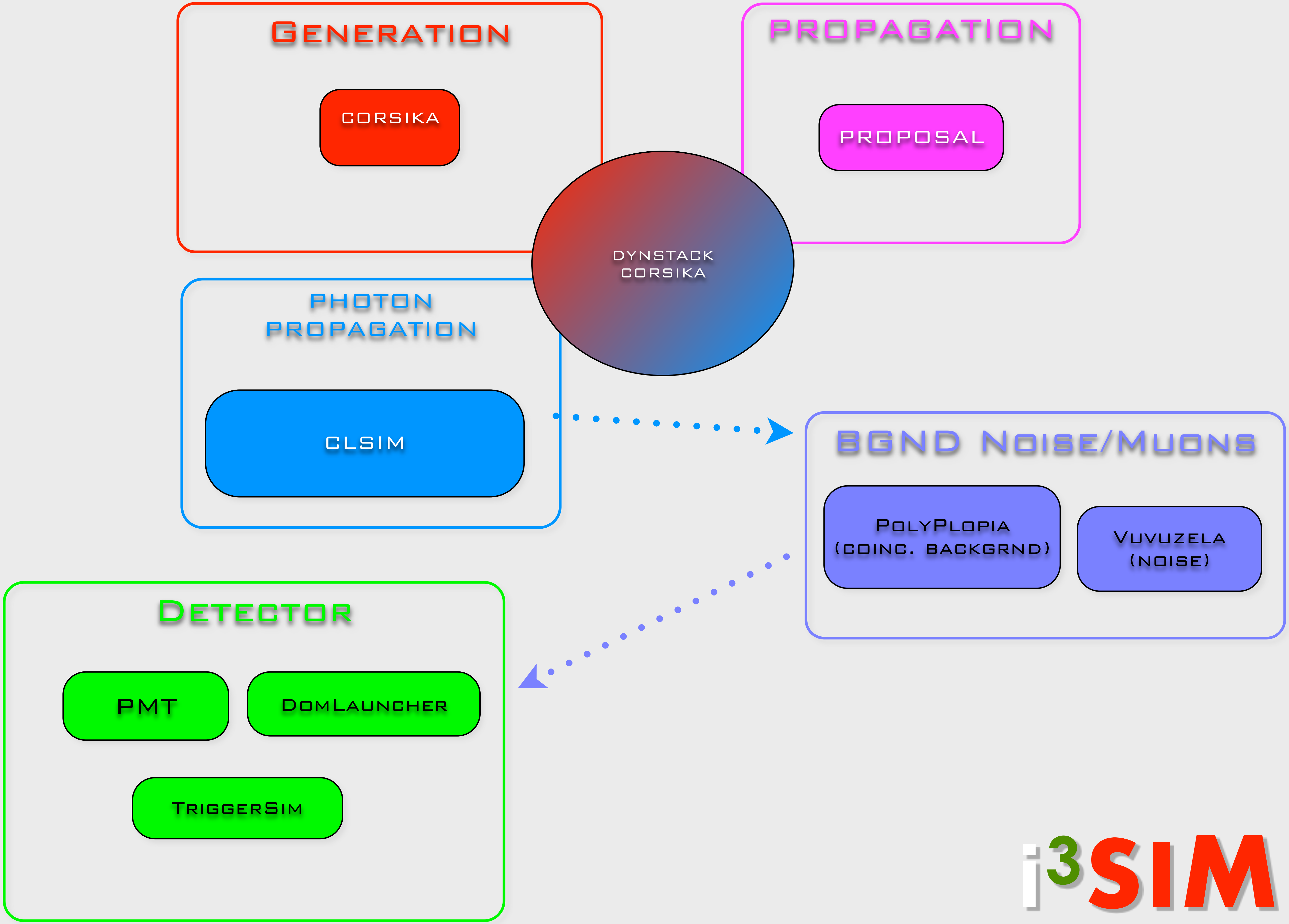
DYNSTACK in CORSIKA



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



Generation

CORSIKA

PROPAGATION

PROPOSAL

DYNSTACK CORSIKA

PHOTON PROPAGATION

CLSIM

BGND Noise/Muons

PolyPlopia (coinc. backgrnd)

Vuvuzela (noise)

Detector

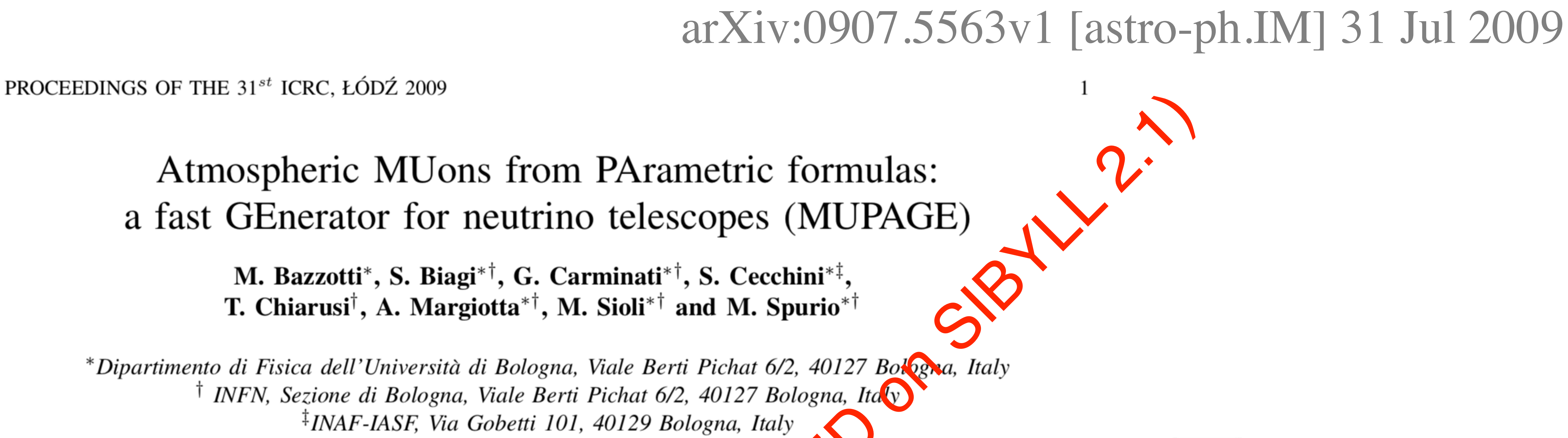
PMT

DomLauncher

TriggerSim

i^{3}SIM

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
‡INAF-IASF, Via Gobetti 101, 40129 Bologna, Italy

OUTDATED! (BASED on SIBYLL 2.1)

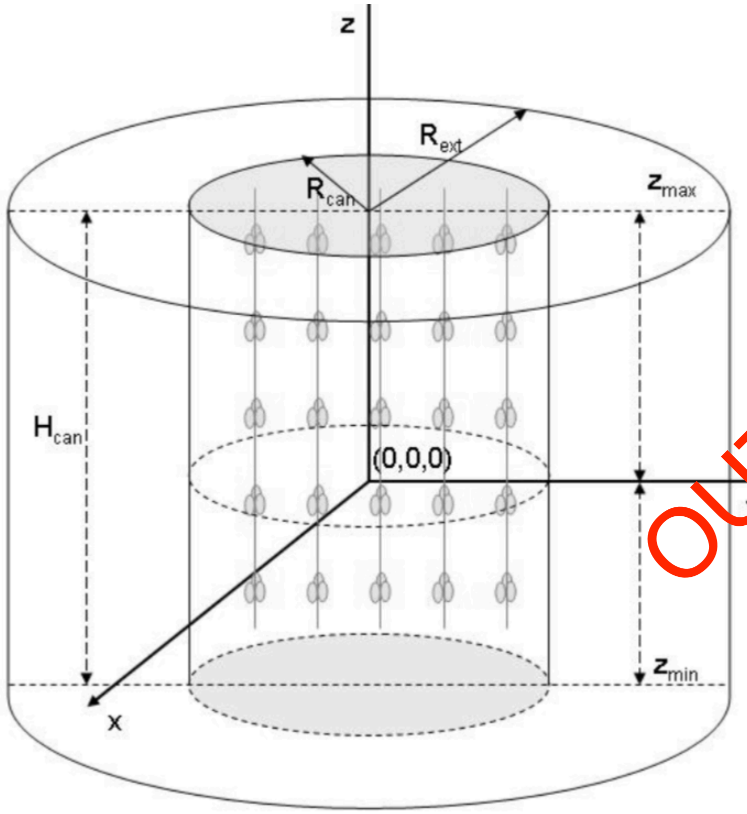
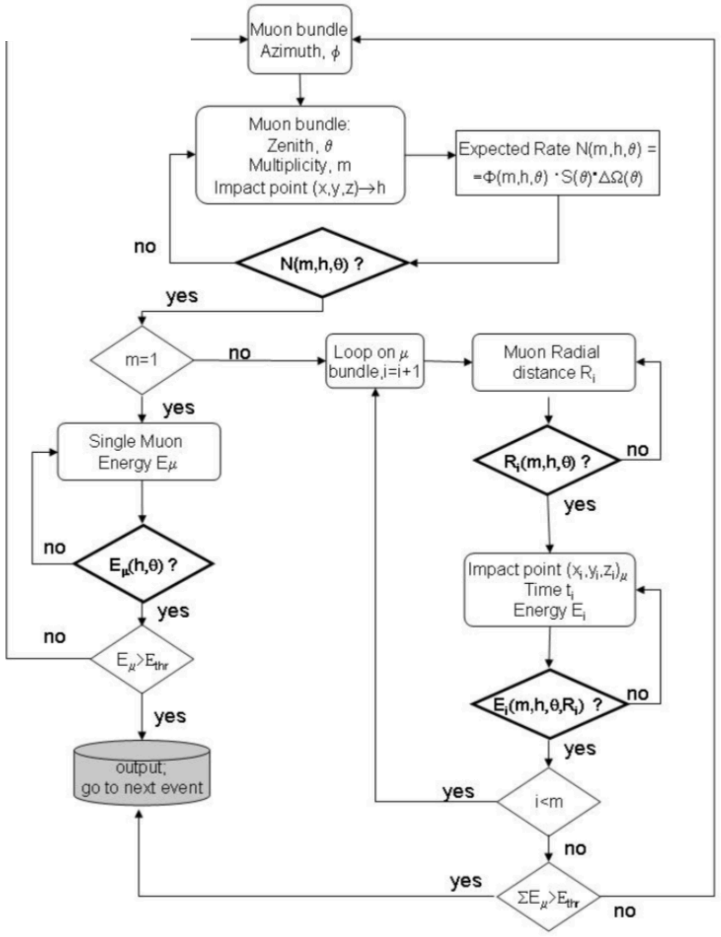
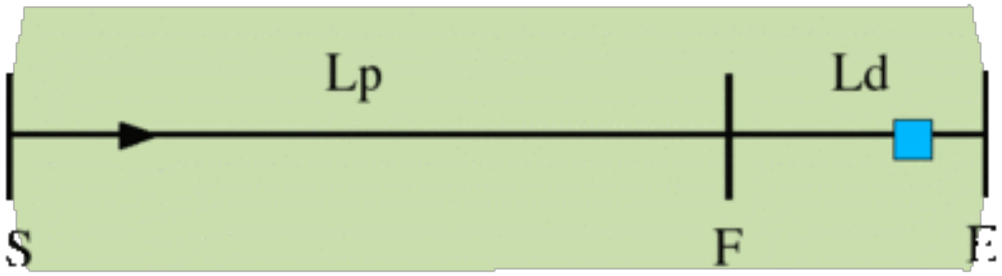


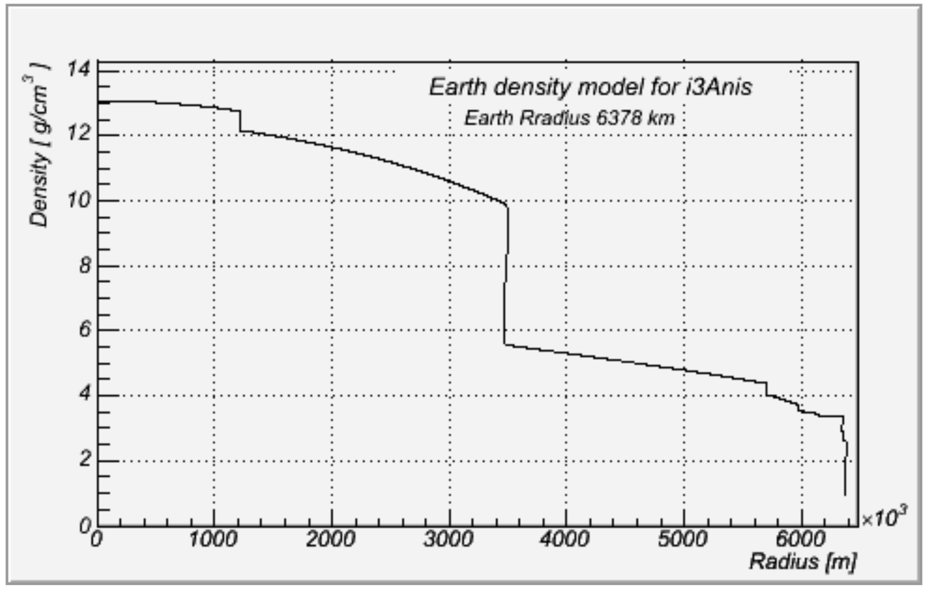
Fig. 1: Sketch of some input parameters. The cylinder surrounding the instrumental volume is the *can*, with radius R_{can} and height H_{can}. The events are generated on an extended can with R_{ext}. The origin of the coordinate system does not have to be located at the center of the detector. The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



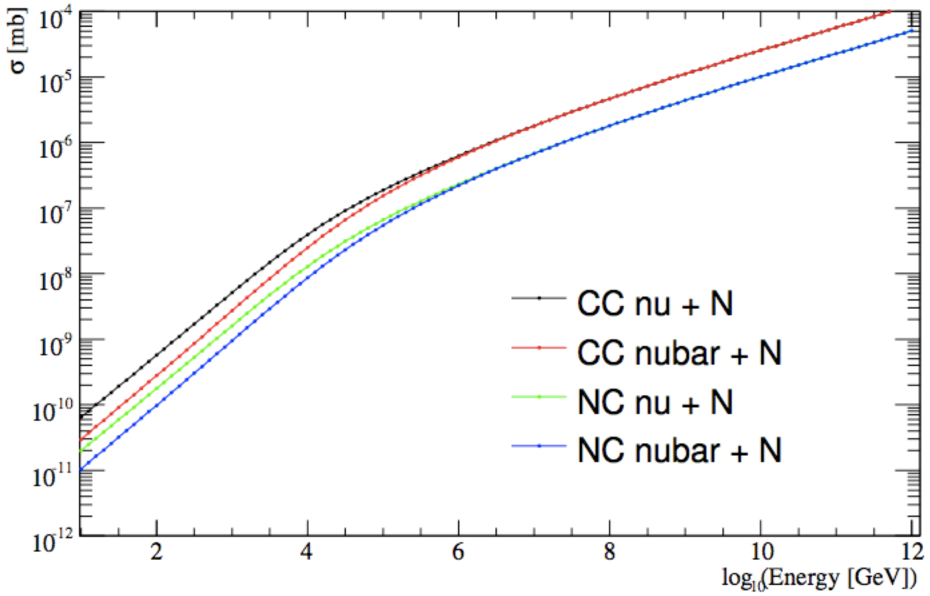
neutrino-generator



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

LeptonInjector/LeptonWeighter

- LeptonInjector and LeptonWeighter are designed for large-volume Cherenkov neutrino telescopes such as IceCube.
- The neutrino event generator allows for quick and flexible simulation of neutrino events within and around the detector volume
- Implements the leading Standard Model neutrino interaction processes relevant for neutrino observatories:
  - neutrino-nucleon deep-inelastic scattering
  - neutrino-electron annihilation.

This is publicly available code.

https://arxiv.org/abs/2012.10449

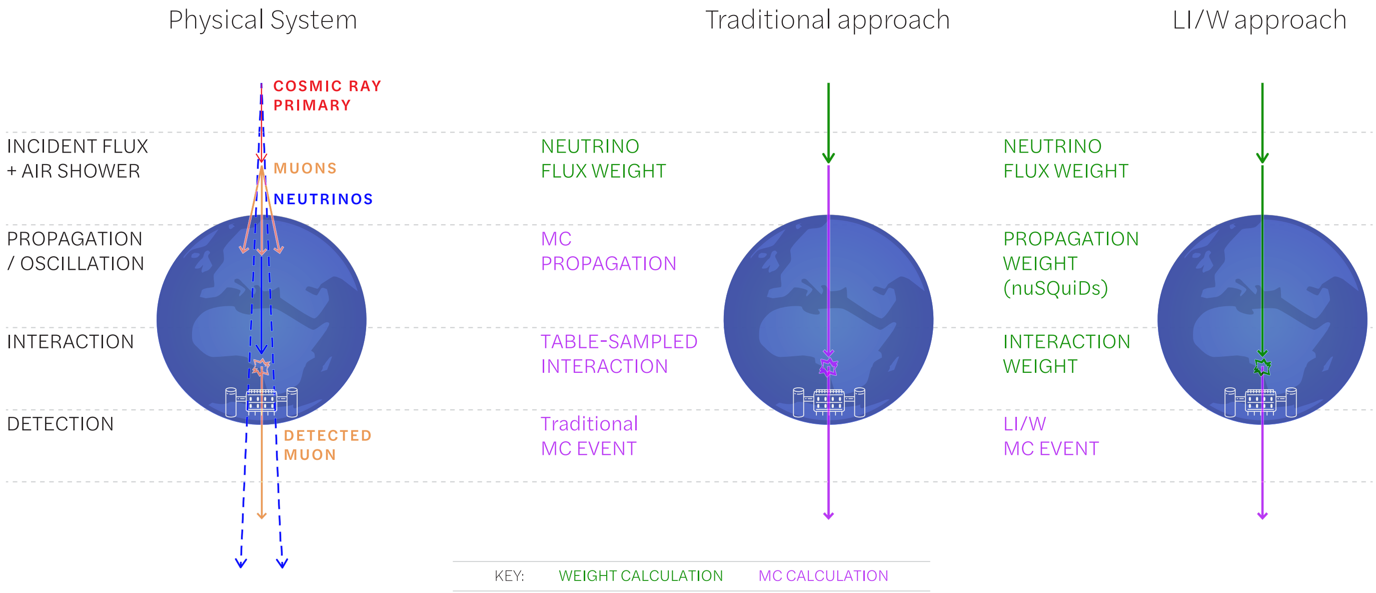


Figure 1.1: A diagram illustrating the different event generation and weighting steps for traditional methods compared with the `LeptonInjector` and `LeptonWeighter` philosophy.

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.

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).

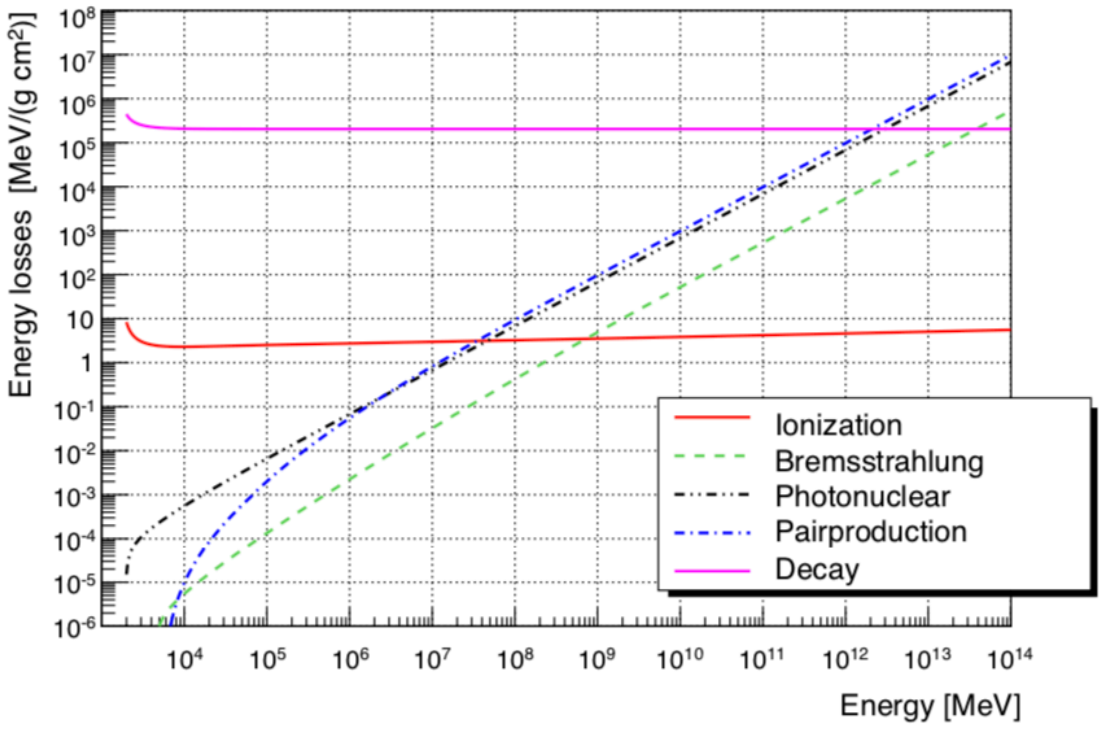


Fig. 31. Continuous energy loss of taus in ice in the energy range from 10^3 MeV to 10^{14} MeV. The graph shows the energy losses of the four interactions and the probability of decay multiplied by the primary particle energy.

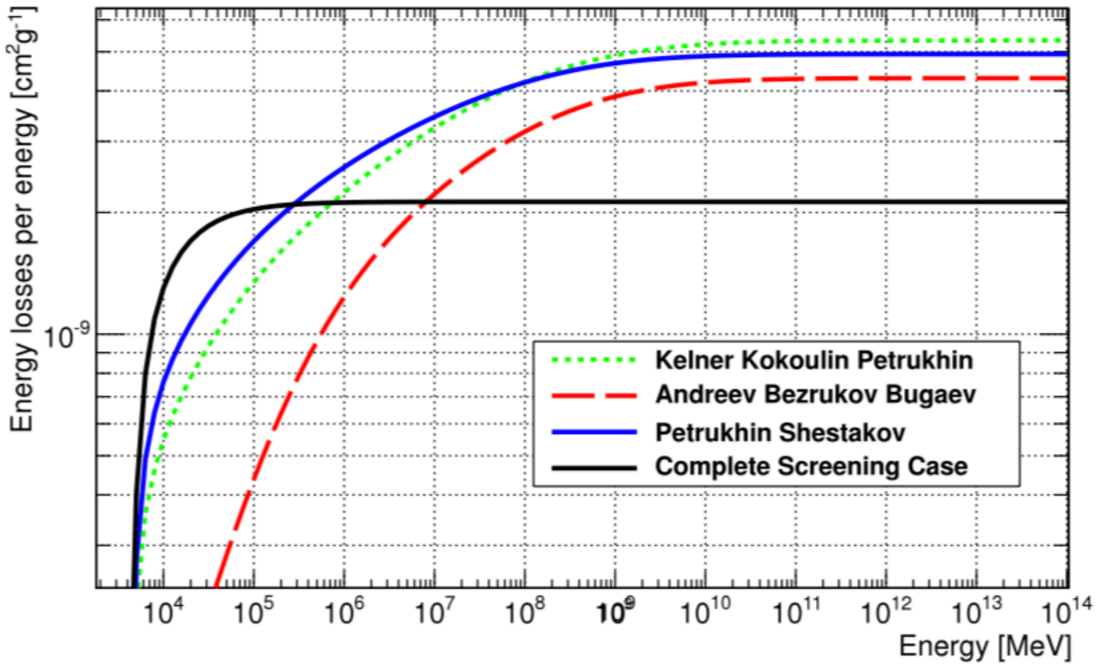
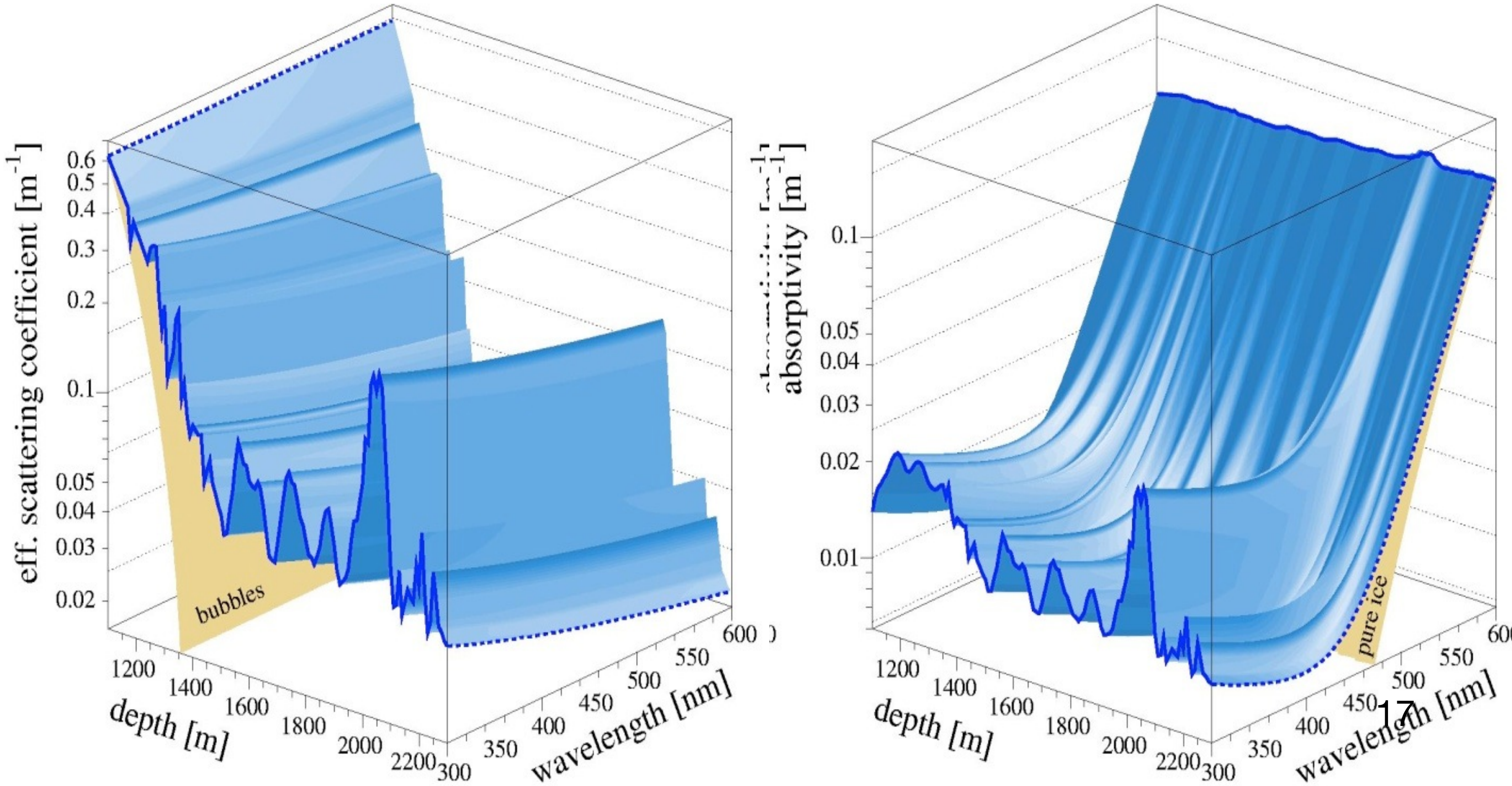


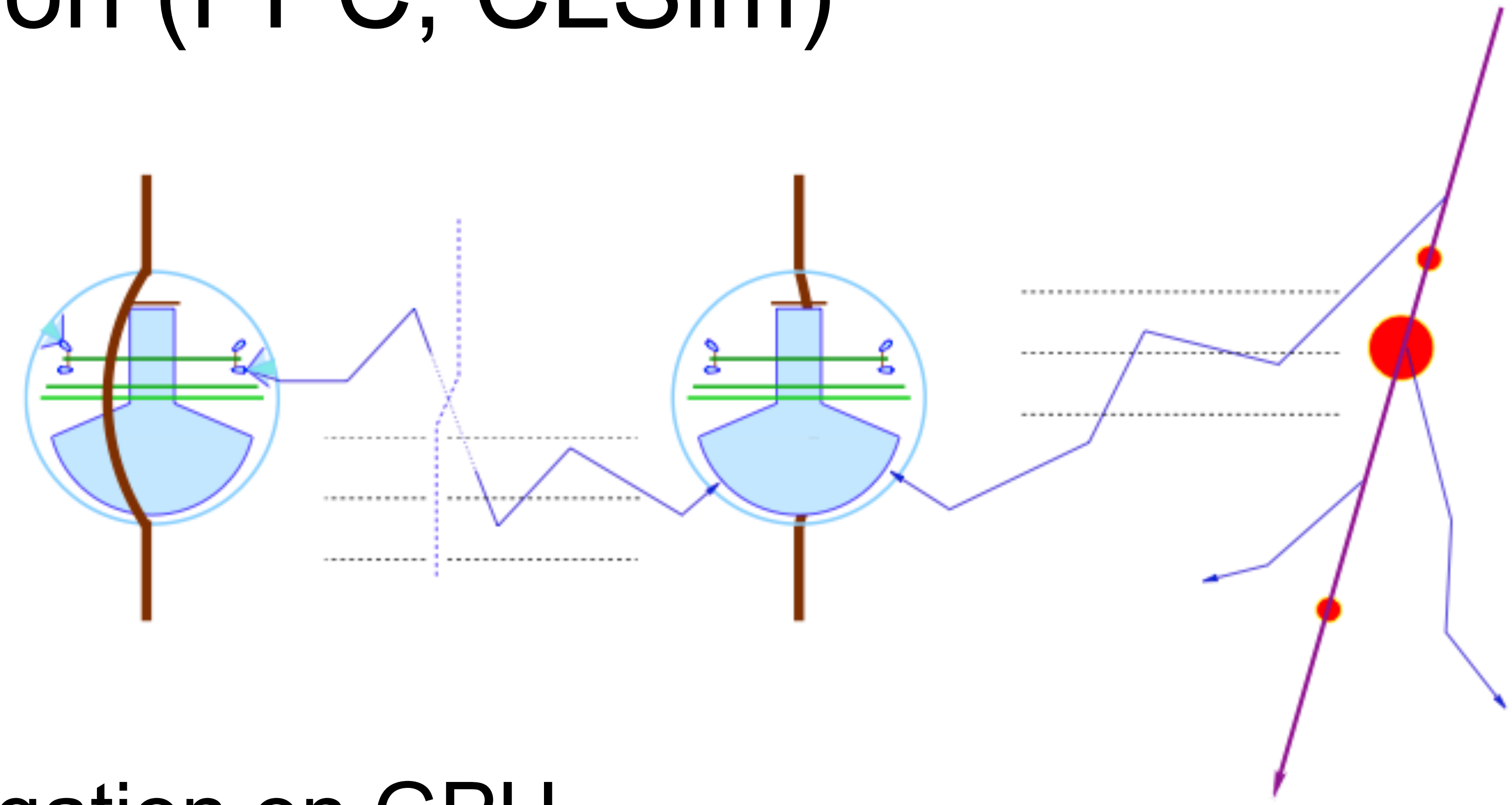
Fig. 4. Continuous energy loss of taus caused by Bremsstrahlung in the energy range from $2 \cdot 10^3$ MeV to 10^{14} MeV. The figure shows the same four possible parametrizations as Fig. 2.

Photon Propagation

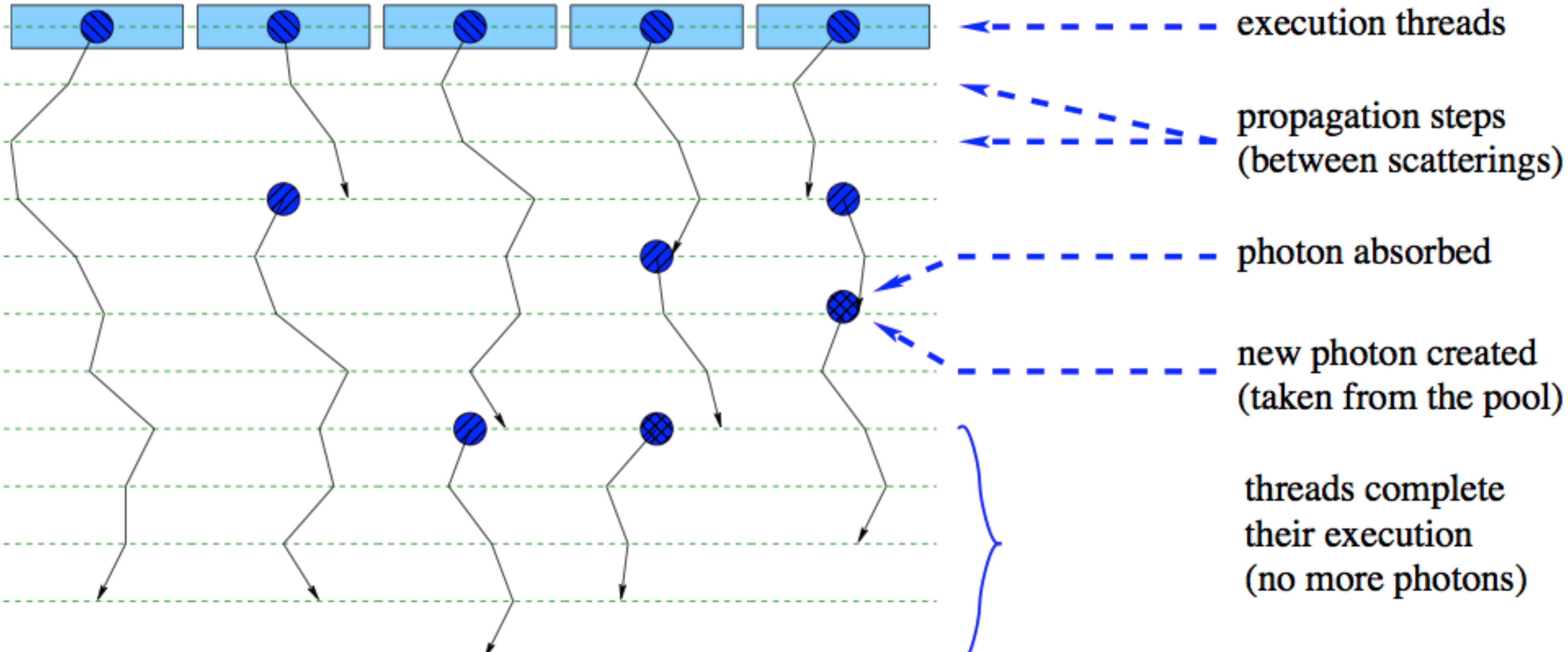
- μ energy lost + cascades ➙ photons ➙ p.e.
  - Photon propagation : ice properties + PMT response + DOM glass/gel
    - Pre-generated lookup splined table :
      - I3PhotonicsHitMaker
      - Amplitude and time distribution
    - Direct photon tracking
      - CLSim
      - PPC
    - Hybrid photon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



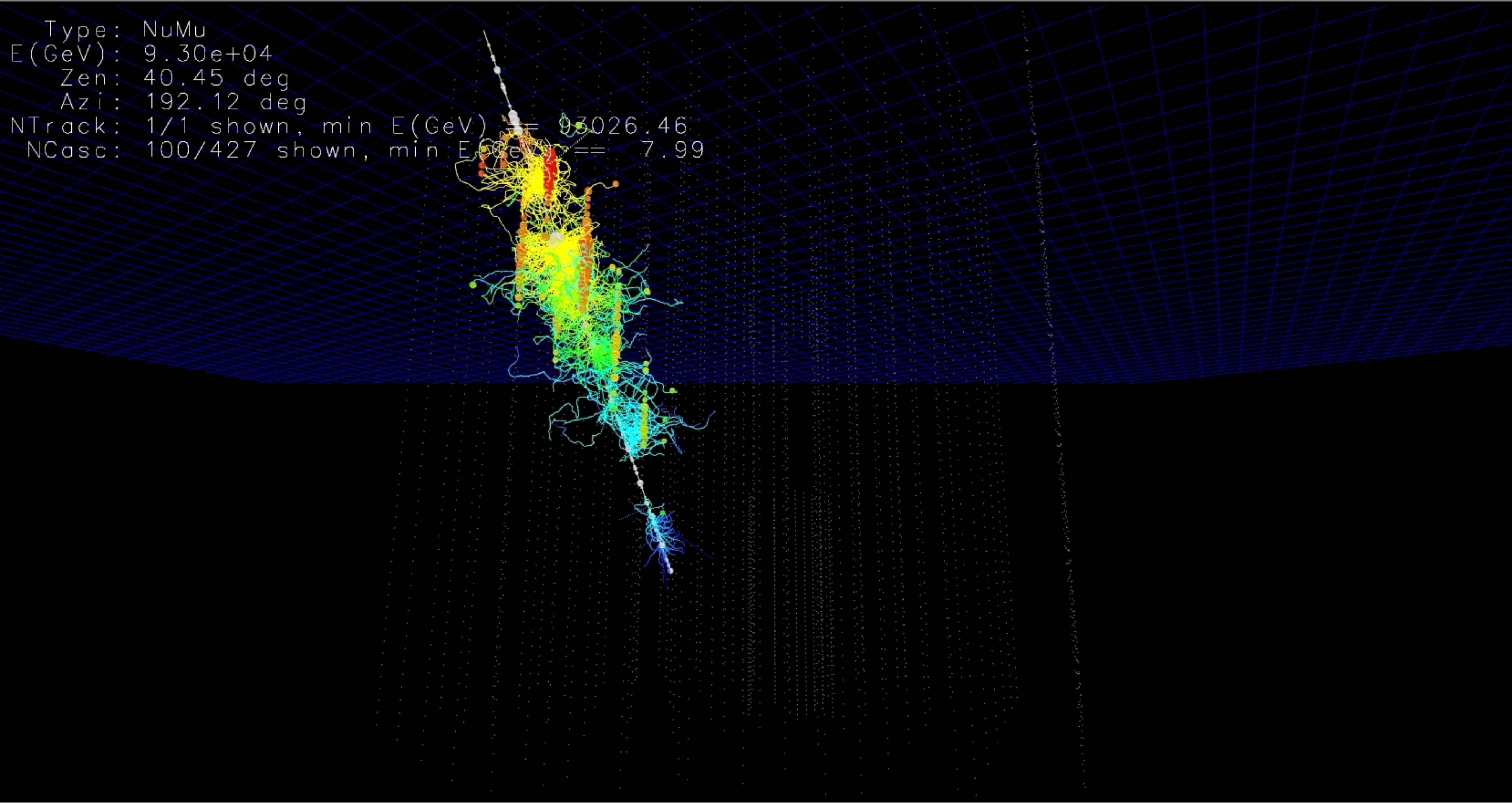
Photon Propagation (PPC, CLSim)



Direct photon propagation on GPU



Photon Propagation (PPC, CLSim)



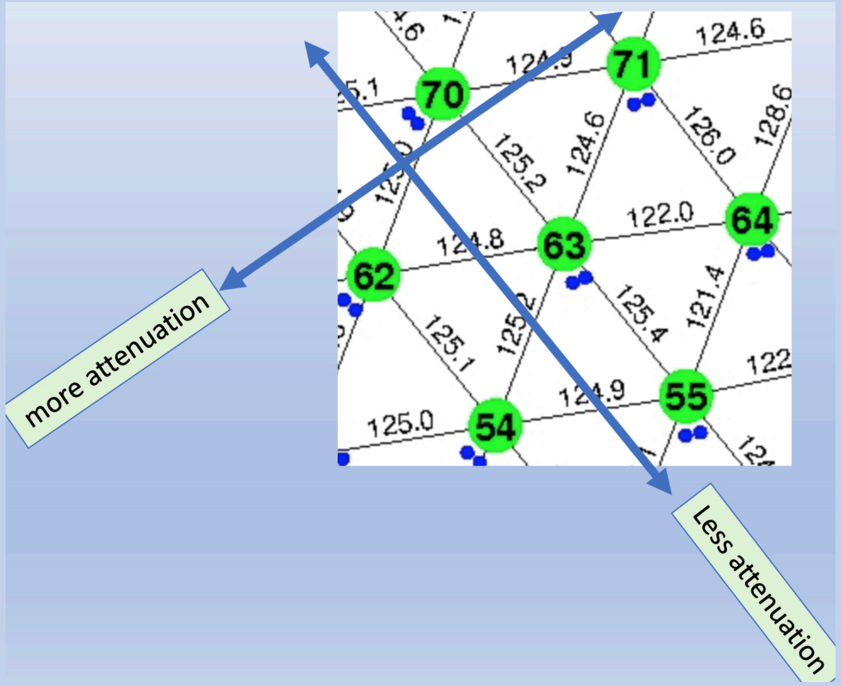
```
   Type: NuMu
E(GeV): 9.30e+04
    Zen: 40.45 deg
    Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
 NCasc: 100/427 shown, min E(GeV) ==   7.99
```

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

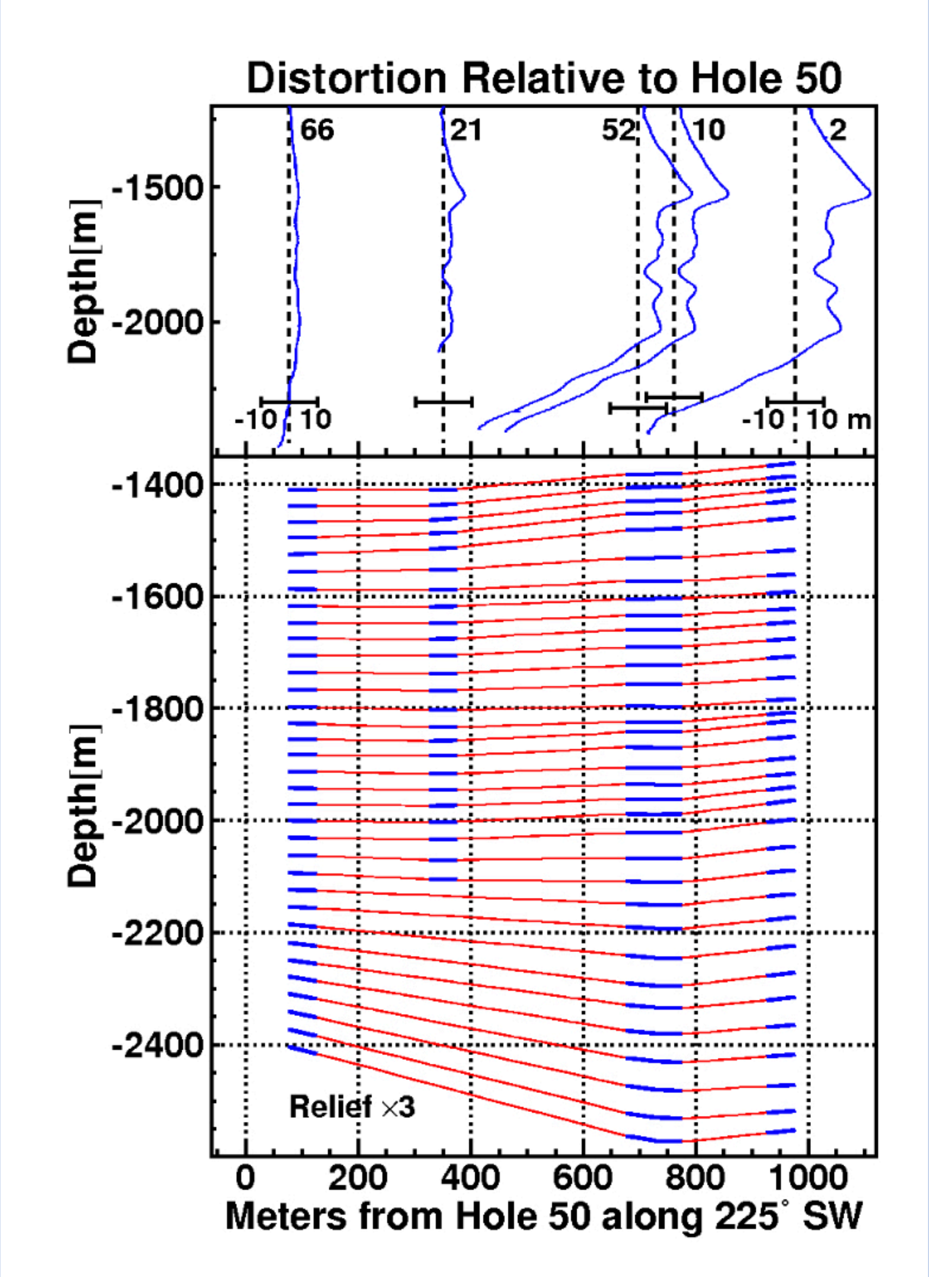
Photon Propagation: Ice Models

AMANDA ice models:			model error
bulk, f125, mam, mamint, stdkurt, sudkurt, kgm, …			
millennium (published 2006) → AHA (2007)			55%
IceCube ice models:			
WHAM	(2011)		42%
SPICE 1	(2009)		29%
SPICE 2, 2+, 2x, 2y	(2010)	added ice layer tilt	
SPICE Mie	(2011)	fit to scattering function	29%
SPICE Lea	(2012)	fit to scattering anisotropy	20%
SPICE (Munich)	(2013)	7-string, LED unfolding	17%
SPICE^3 (CUBE)	(2014)	llh fixes, DOM sensitivity fits	11%
SPICE 3.0	(2015)	improved RDE, ang. sens. fits	10%
SPICE 3.1, 3.2	(2016)	85-string, correlated model fit	<10%
SPICE HD, 3.2.2	(2017)	direct HI and DOM sens., cable, DOM tilt	
SPICE EMRM	(2018)	absorption-based anisotropy	*single*
SPICE BFR	(2020)	birefringence-based anisotropy	*LEDs*

Dmitry Chirkin, Martin Rongen



Dmitry Chirkin, Martin Rongen



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.

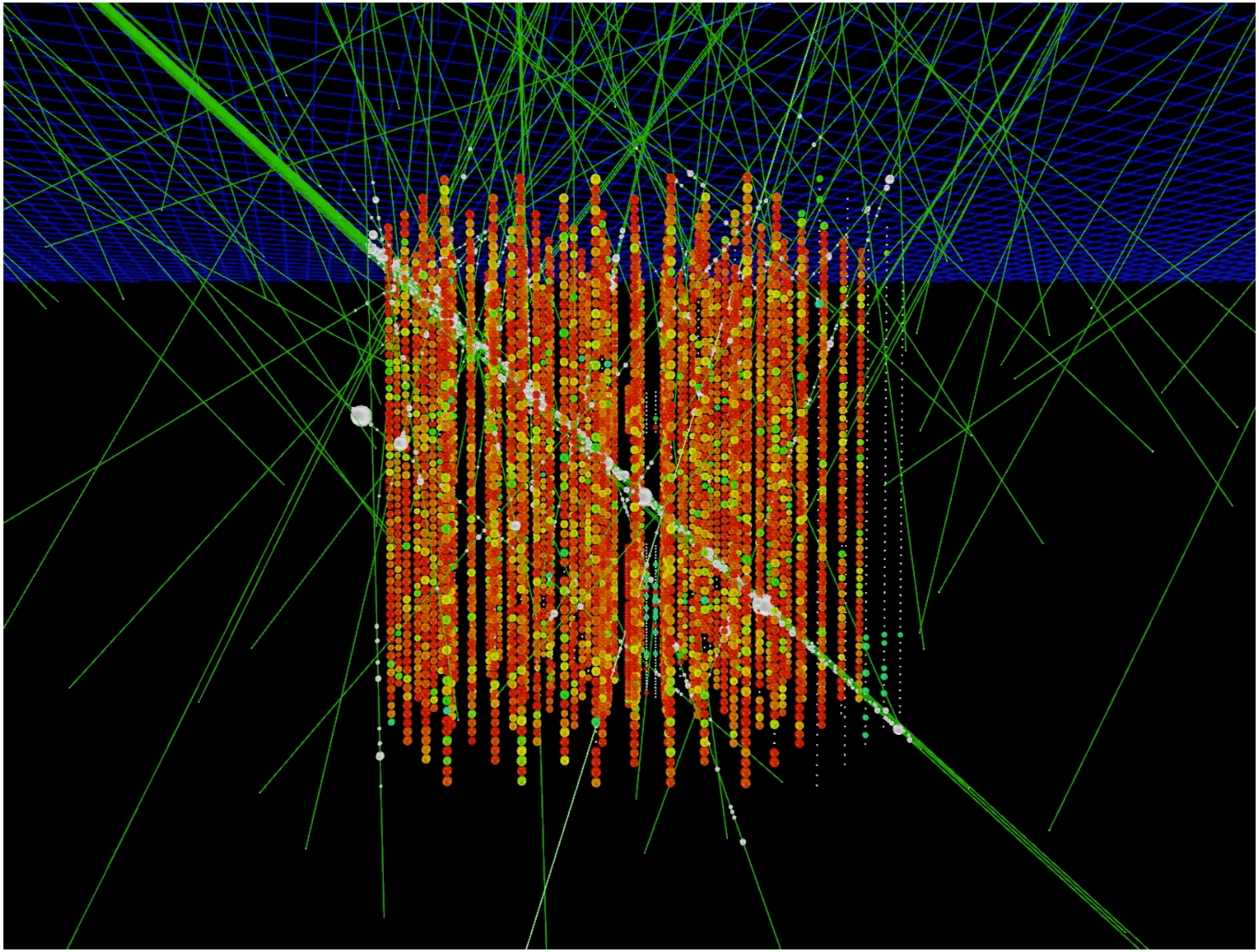
- poly**plopia::MPHitFilter**
  - Removes events that don’t produce light in the detector and removes branches of I3MCTrees whose particles don’t produce enough PEs in the detector,
  - Reduces the storage requirements.

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

Polyplopia

(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

+

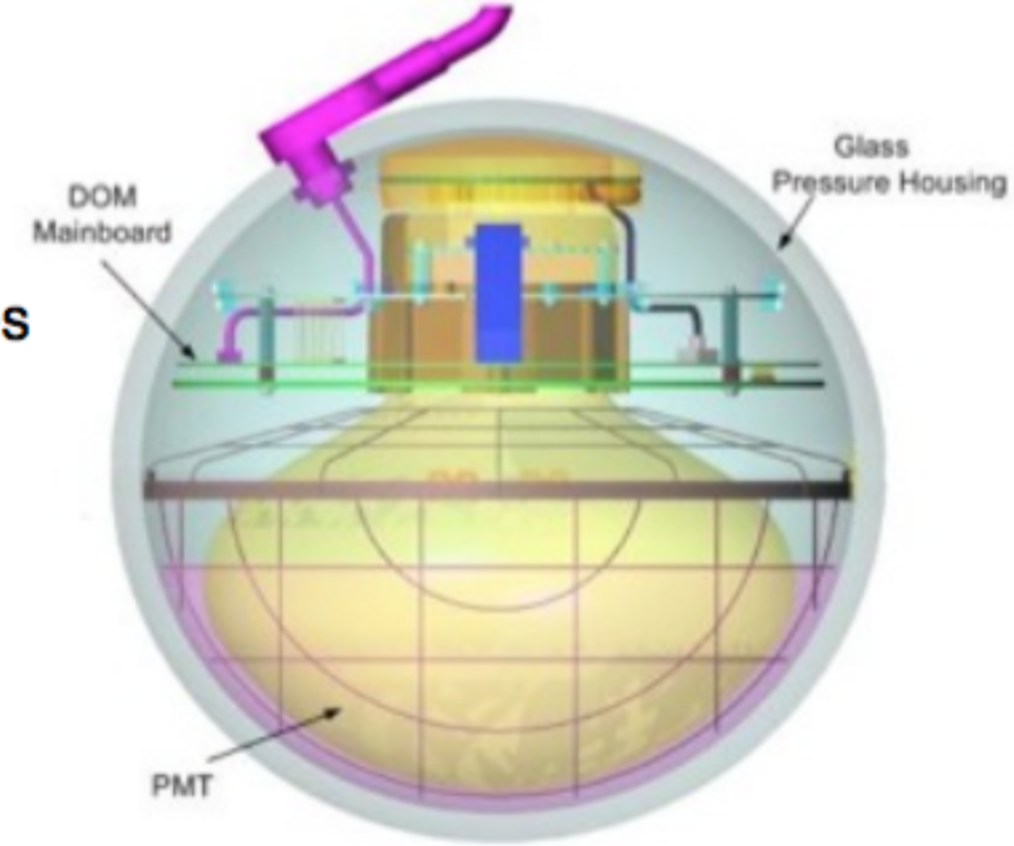
Radioactive Decay in Glass
[Poisson process]

~ ms Timescales

Energy deposited in glass

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

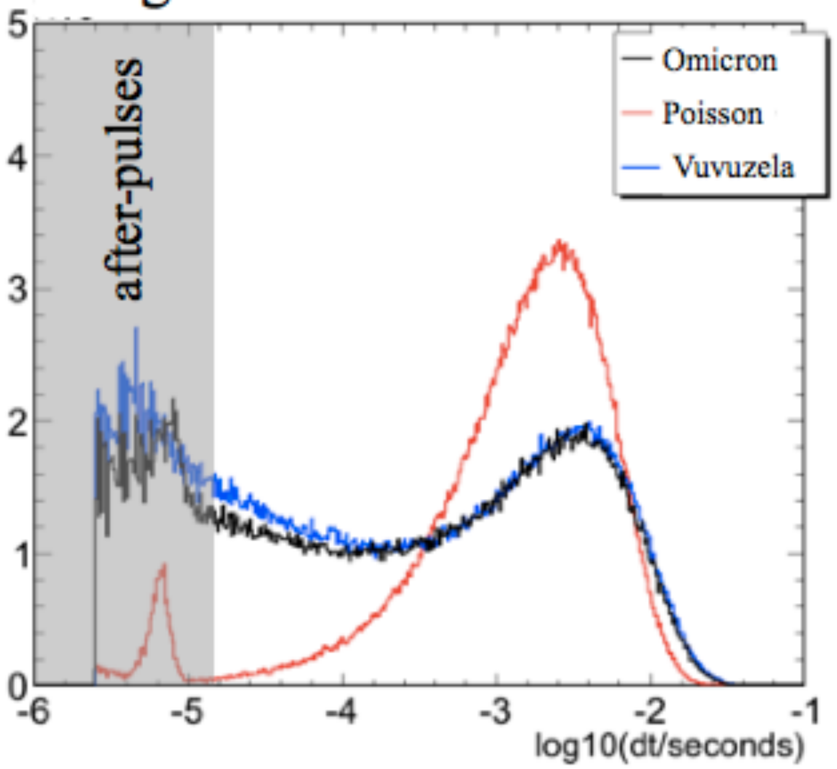
$\lesssim$ 500 μs Timescales



Noise Generation

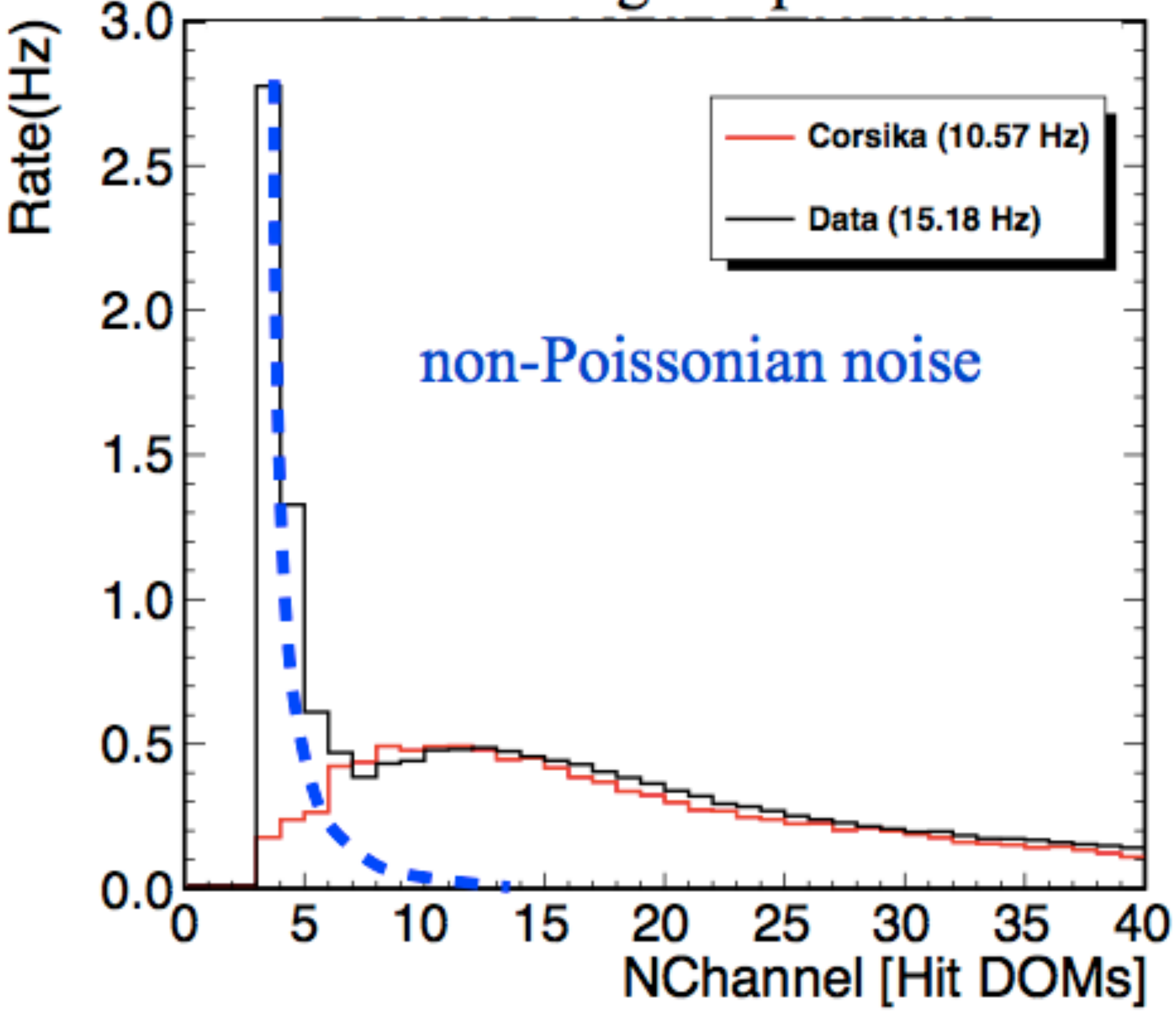
Previous simulation used simplified Poissonian model. Vuvuzela uses exponential for **thermal** and **radioactive decays** and log-normal for **scintillation**.

Long Time-Scale Noise Profile



*Courtesy of M.Larson (U.Alabama)

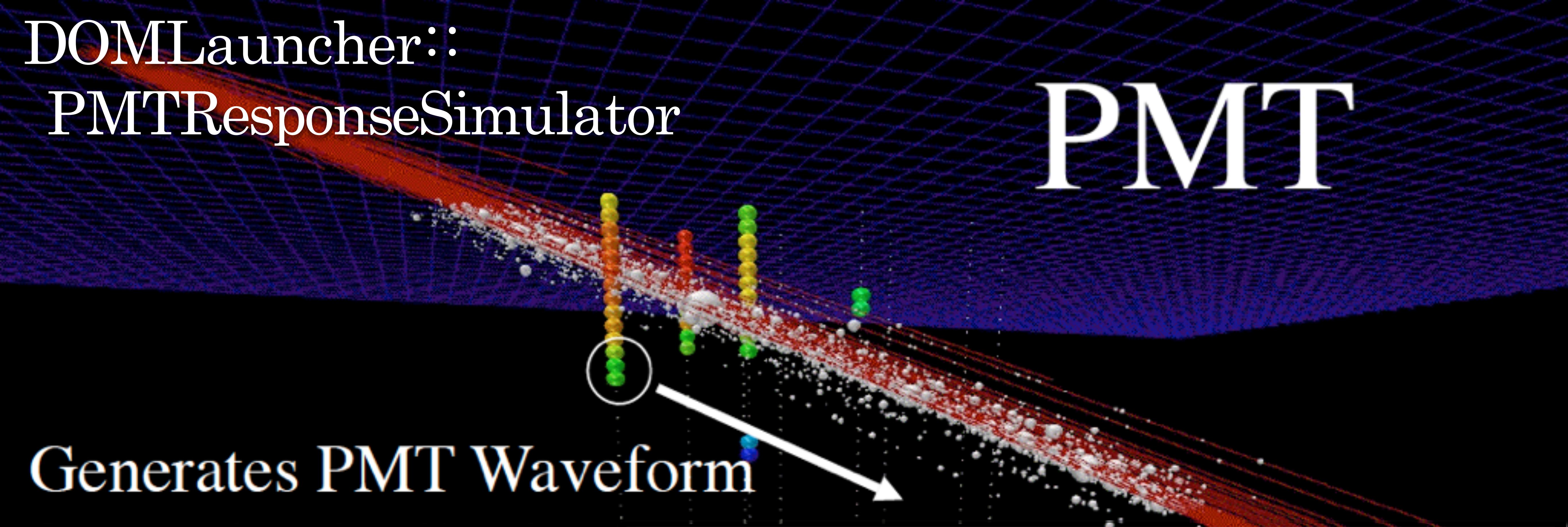
Events Passing DeepCore Filter



*Courtesy of J.Koskinen (PSU)

DOMLauncher:: PMTResponseSimulator

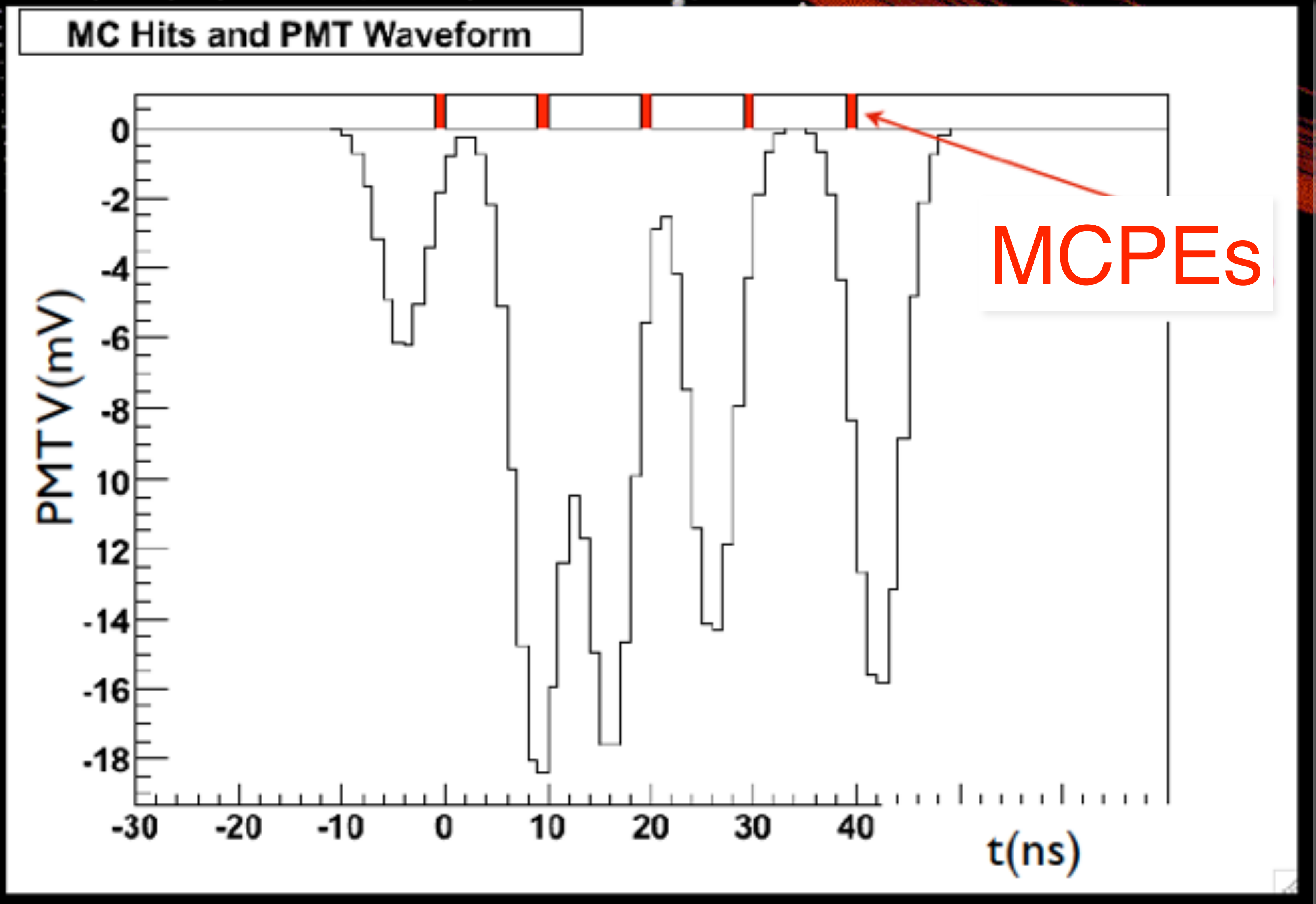
PMT



Generates PMT Waveform

From distribution of (combined) MCPEs.

Outputs I3MCPulseSeries for each DOM.

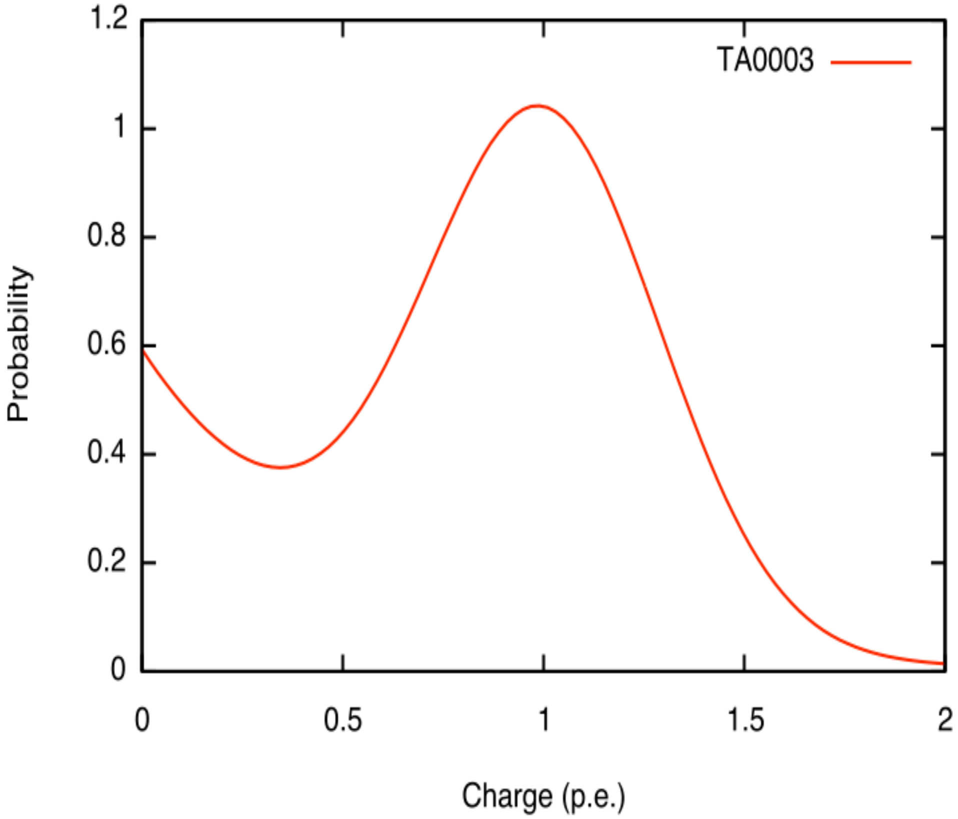

MC Hits and PMT Waveform

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

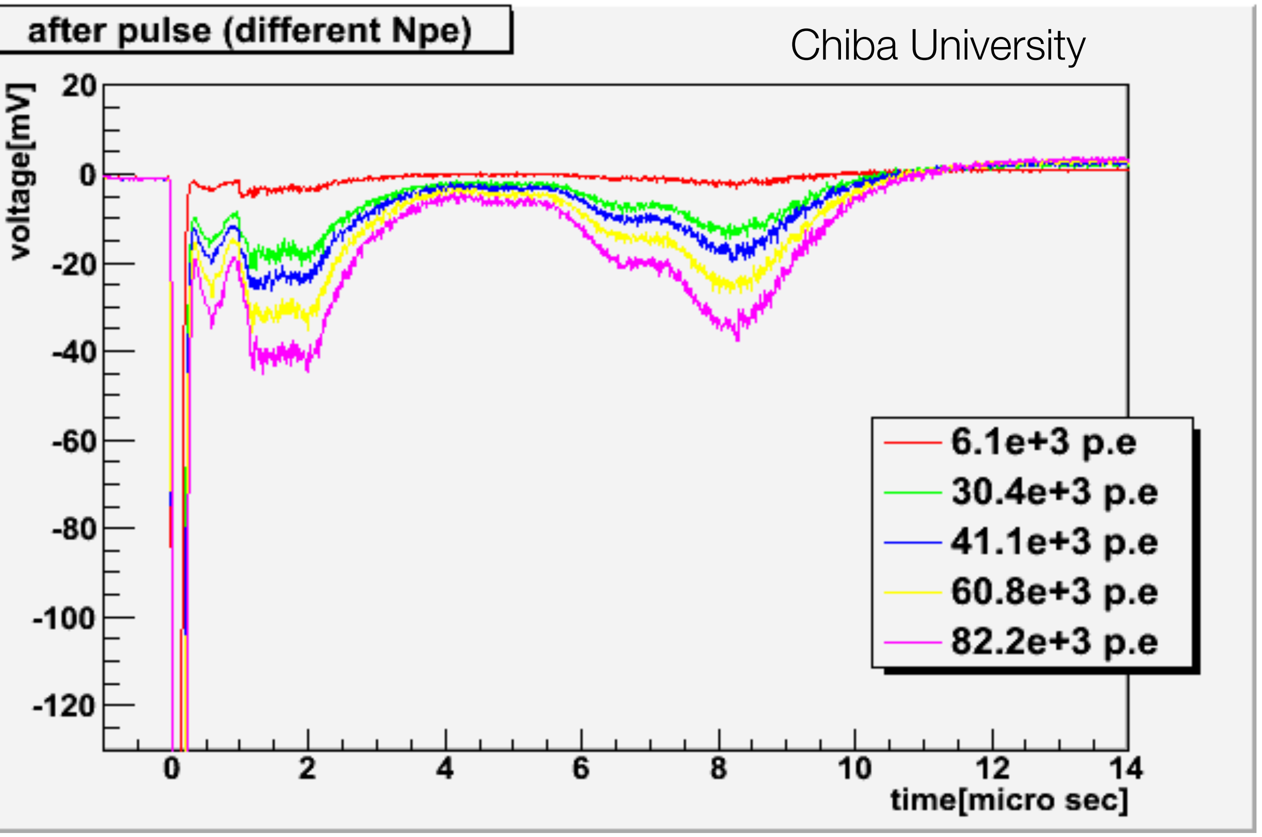
http://software.icecube.wisc.edu/documentation/projects/DOMLauncher/index.html

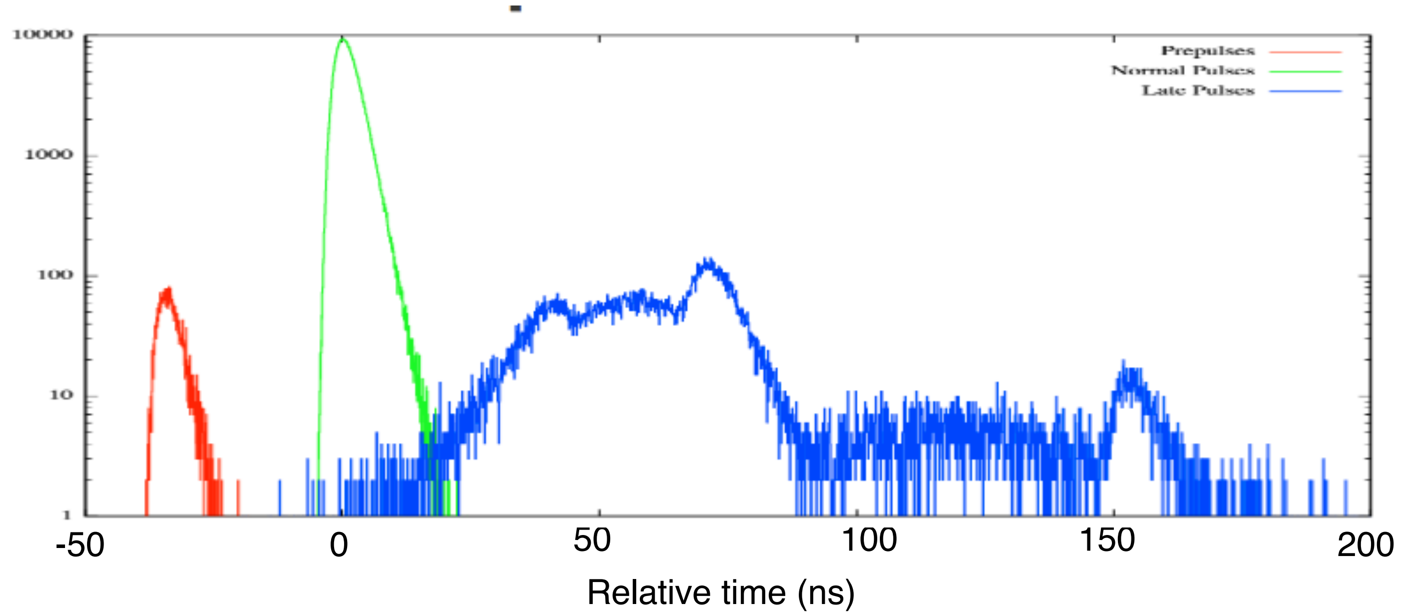
PAL pulses

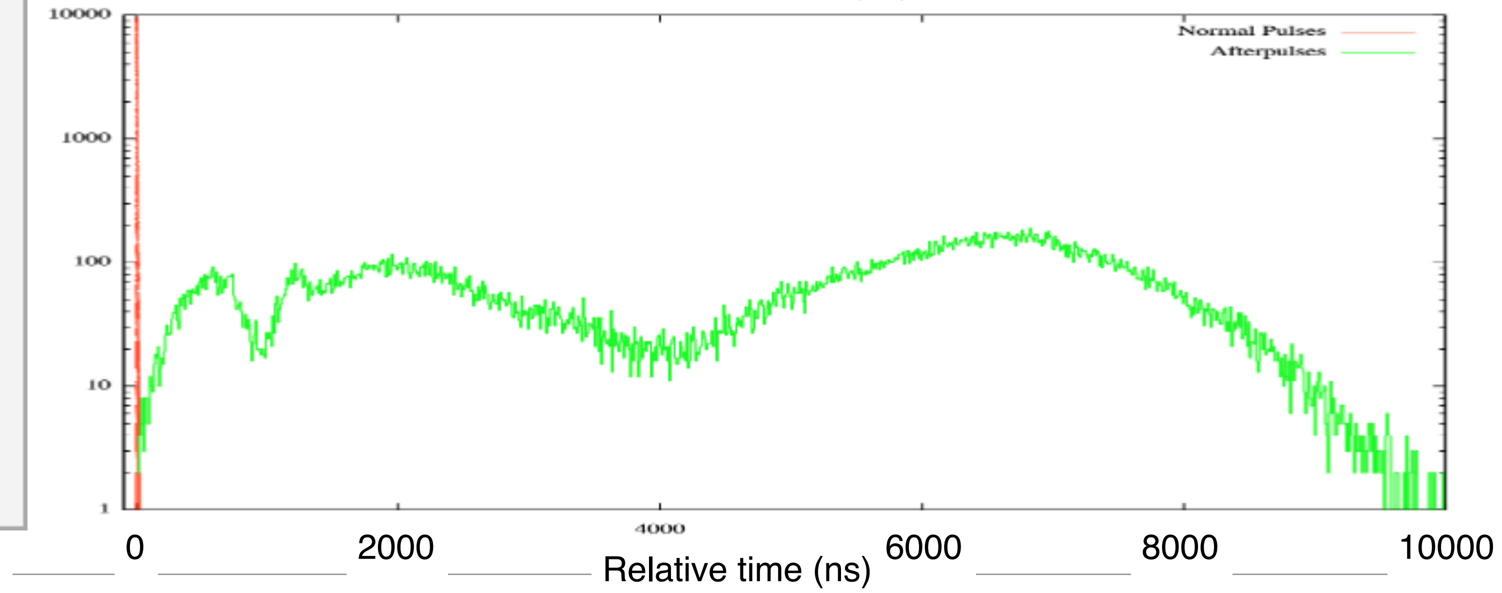
Pre-pulses: photoelectrons ejected from the first dynode,

Late pulses: electrons backscatter from dynode to cathode.

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

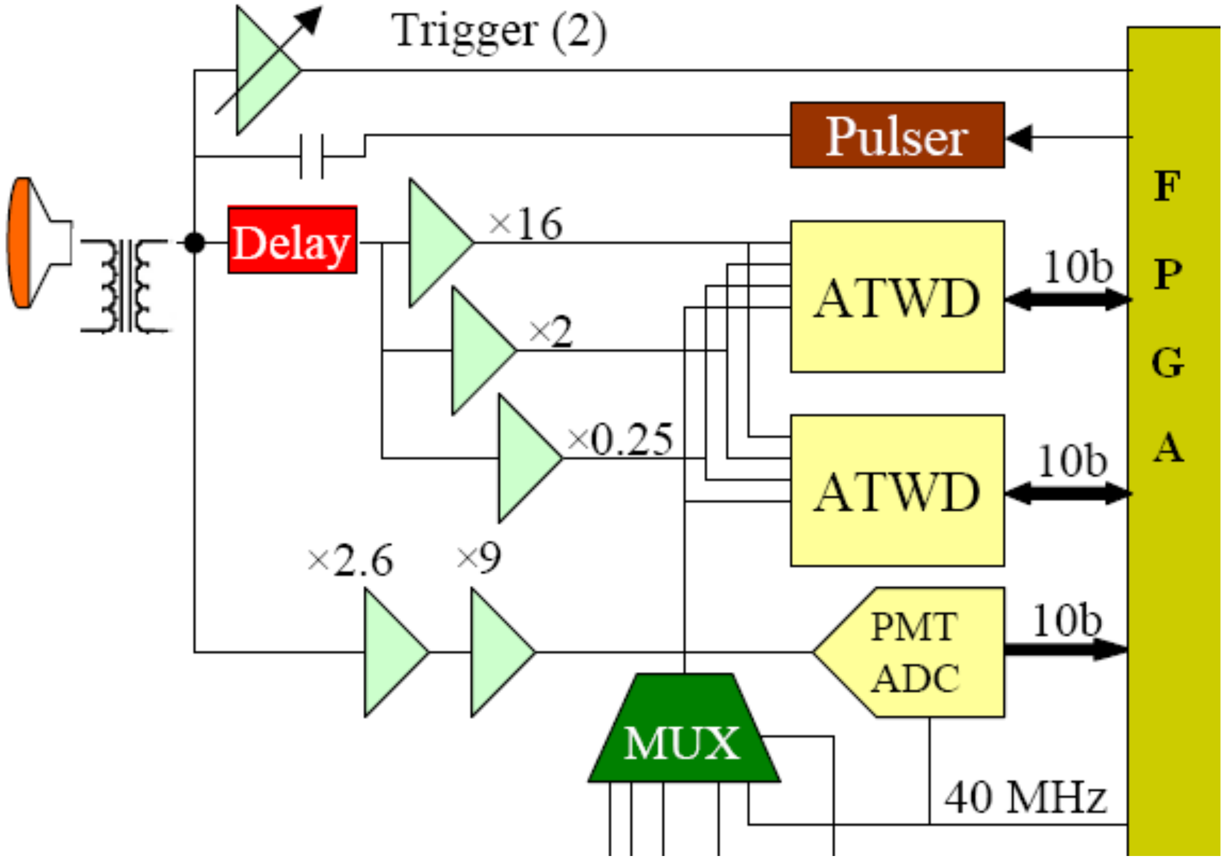


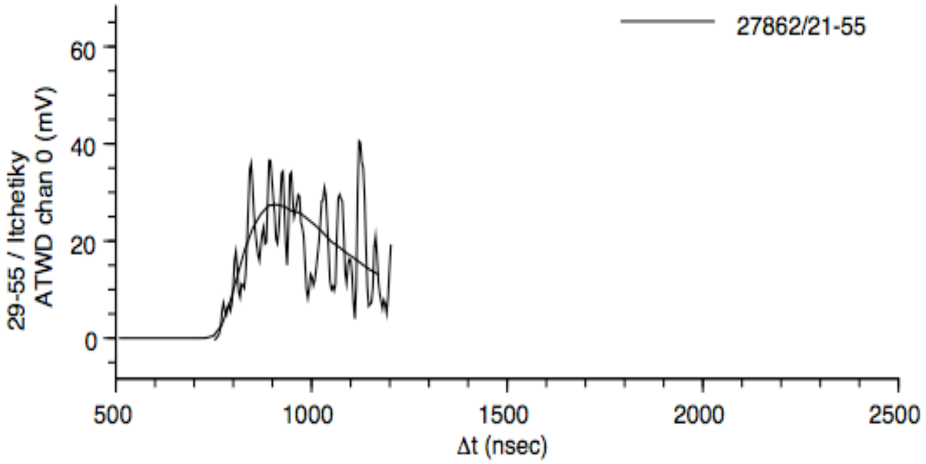


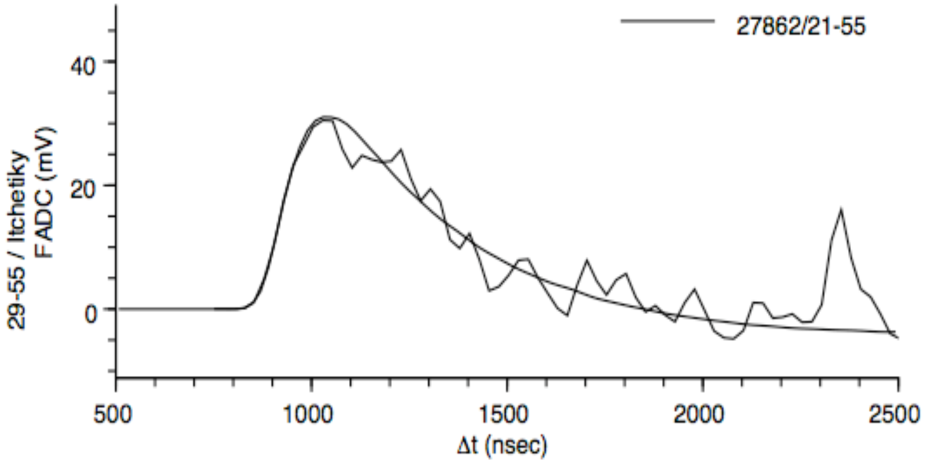


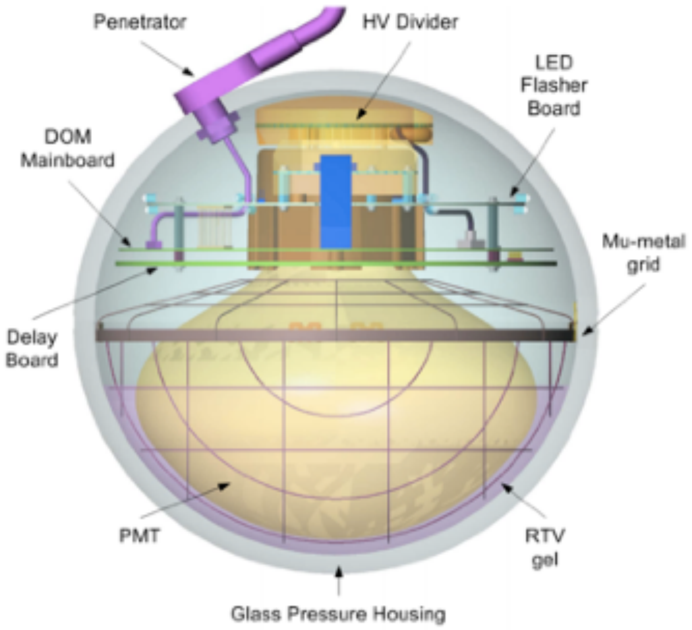
DOMLauncher: DOM electronics simulation

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

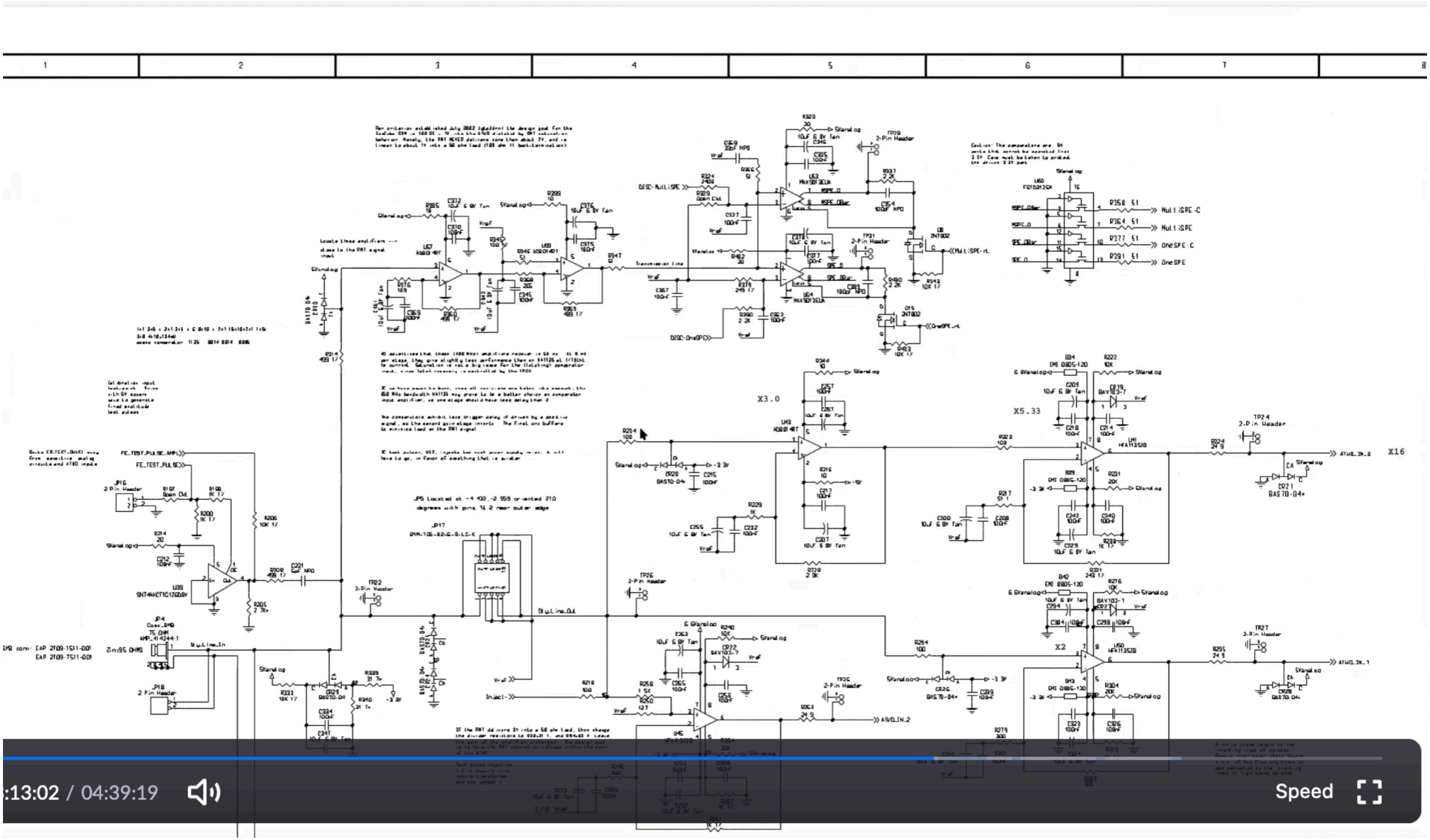








DOMLauncher: DOM electronics simulation



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)

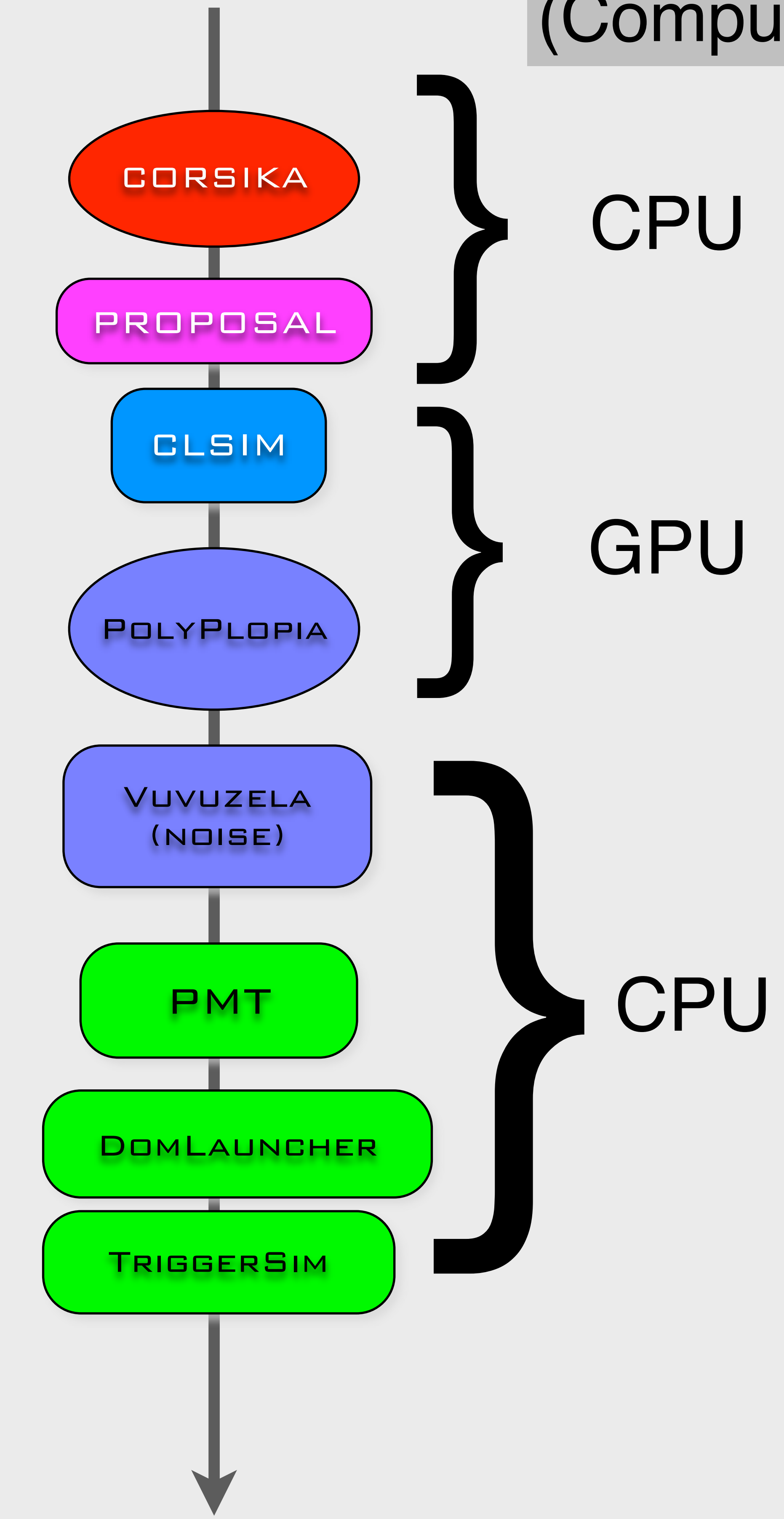
- **String** trigger (a.k.a. Cluster trigger in DAQ-land)
  - *N* HLC hits out of *M* DOMs on a string in a time window
  - Example: 5 hits from a run of 7 adjacent DOMs in a time window of 1500 ns

- **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

- ~~**Fixed Rate** trigger~~, **Min**imum **Bias** trigger, ~~**Calibration** trigger~~

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.
- **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)

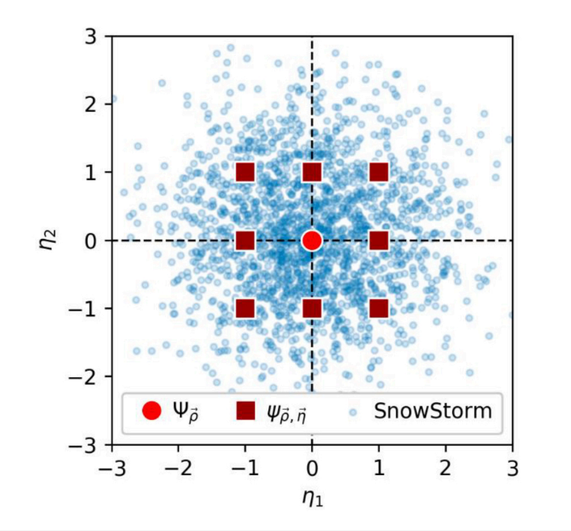
```
$  python nugen.py -h

                    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
                    …
```

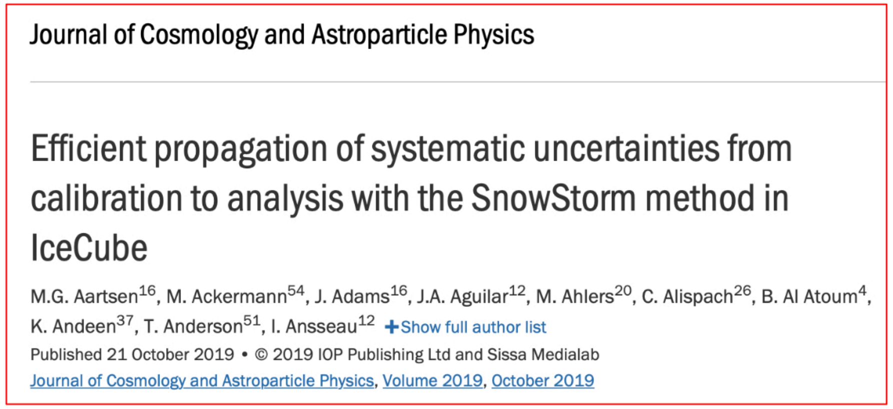
simprod-scripts (SnowSuite)

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

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

```
simprod-scripts/resources/scripts/SnowSuite/

├──── 1-process-Gen.py
├──── 2-Polyplopia.py
├──── 2-Propagate.py
├──── 3-Snowstorm.py
├──── 4-process-Weight.py
├──── demo
|     └──── SimpleInjector.py
├──── iceprod2
|     ├──── iceprod_config_example.json
|     ├──── load_env
|     └──── source_env
├──── jobs
|     └──── condor_manager.py
├──── Snowstorm_Cfg.yml
├──── Snowstorm_FullSystematics.yml
├──── Snowstorm_NominalIce_Cfg.yml
└──── utils.py
```




Journal of Cosmology and Astroparticle Physics

Efficient propagation of systematic uncertainties from calibration to analysis with the SnowStorm method in IceCube

M.G. Aartsen[16], M. Ackermann[54], J. Adams[16], J.A. Aguilar[12], M. Ahlers[20], C. Alispach[26], B. Al Atoum[4], K. Andeen[37], T. Anderson[51], I. Ansseau[12] +Show full author list

Published 21 October 2019 • © 2019 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2019, October 2019

simprod-scripts

Exercise: Running scripts**:**

You can run on **cobalt**

```
$ ssh cobalt
```

or, preferably, 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

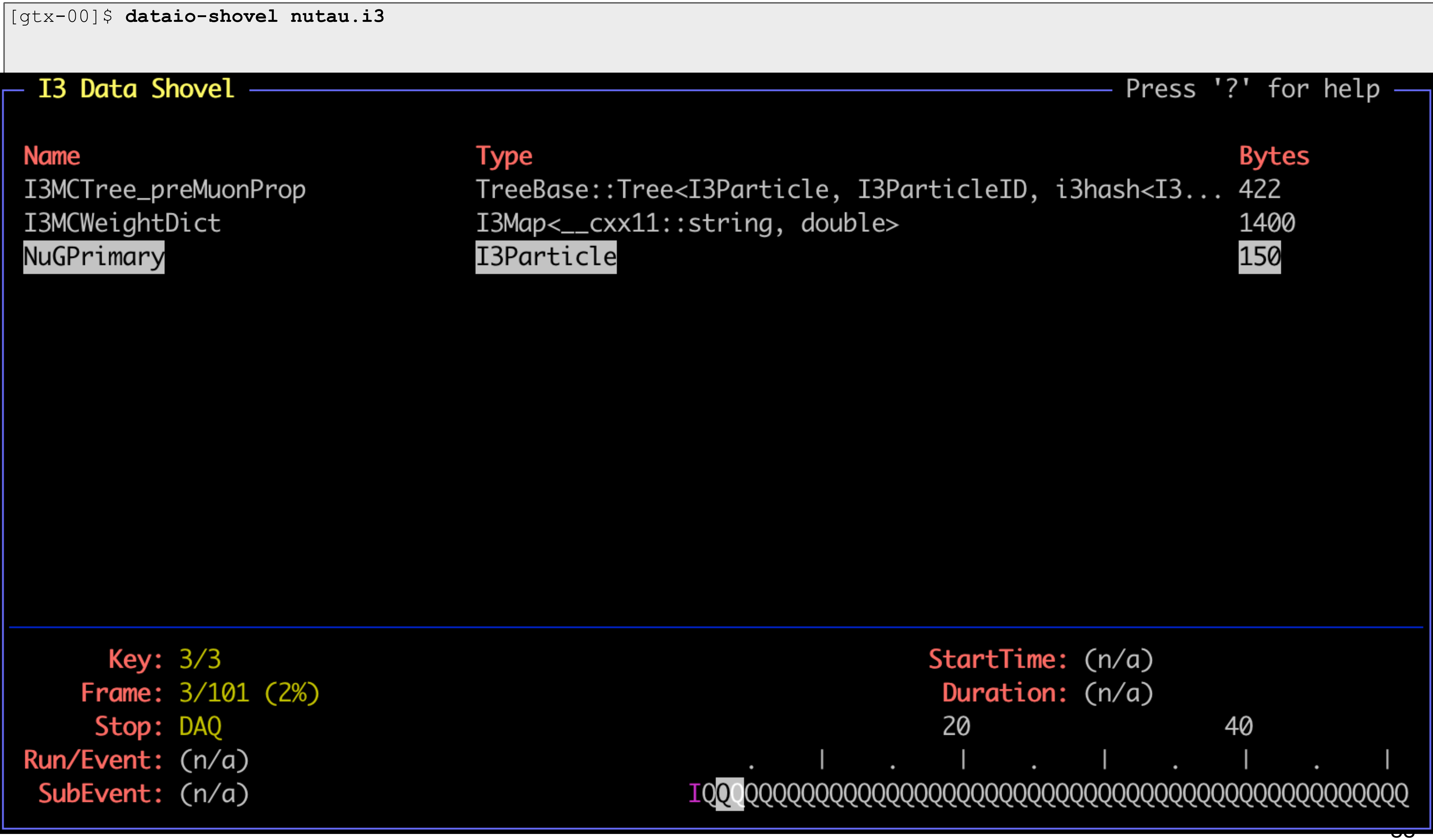
simprod-scripts

Exercise: Running scripts:

```
icecube@M16:~$ ssh submitter
[submitter]$
[submitter]$ condor_submit -interactive 'request_gpus=1'
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-v4.2.0/icetray-env icetray/v1.3.3
************************************************************************
*                                                                      *
*                   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-shovel nutau.i3
```

simprod-scripts

Exercise: Running scripts:



```
[gtx-00]$ dataio-shovel 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)                               IQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQ
```

simprod-scripts

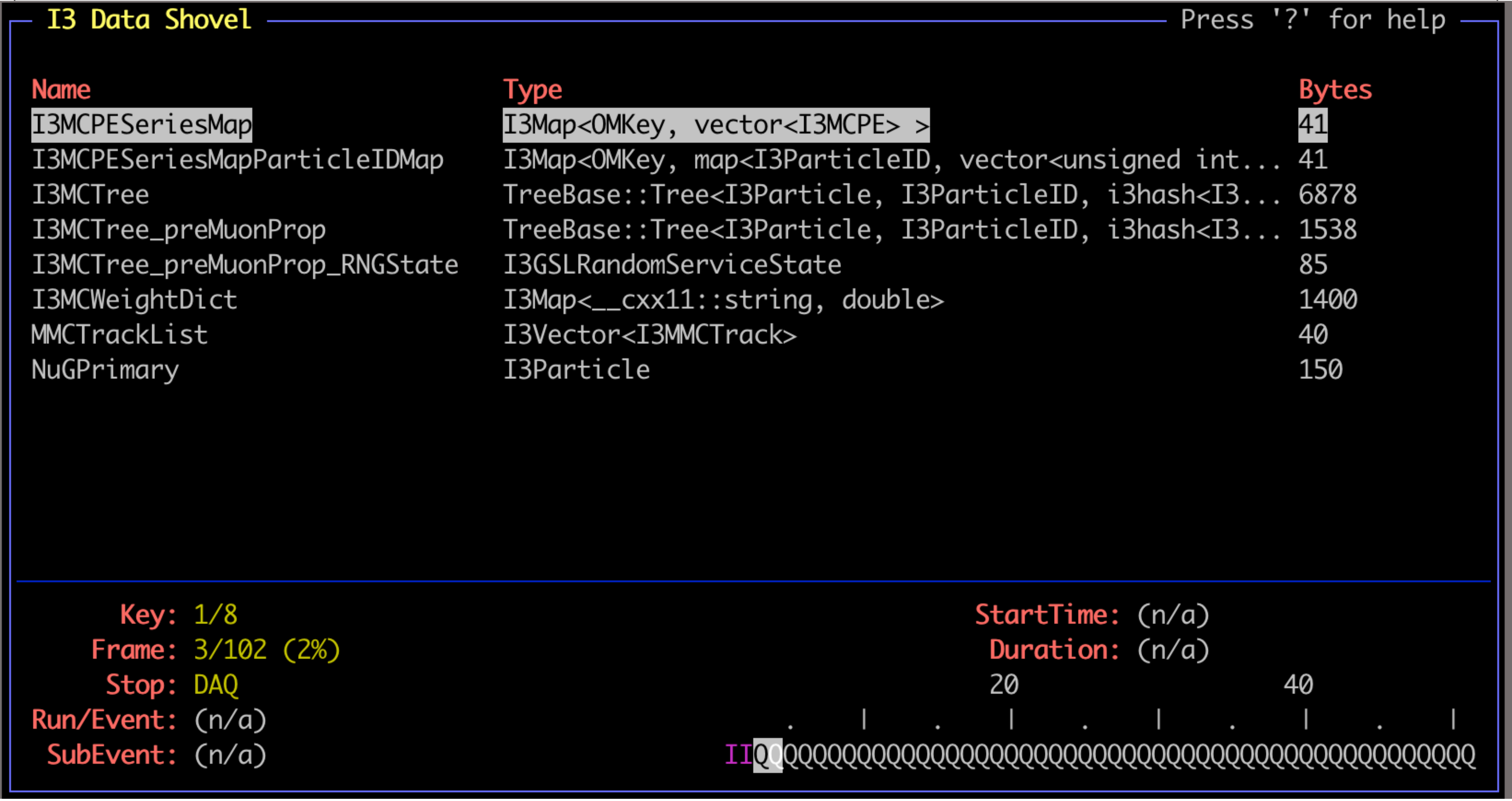
Exercise: Running scripts:

```
[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-shovel 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-shovel det.i3
```

simprod-scripts

Exercise: Running scripts:

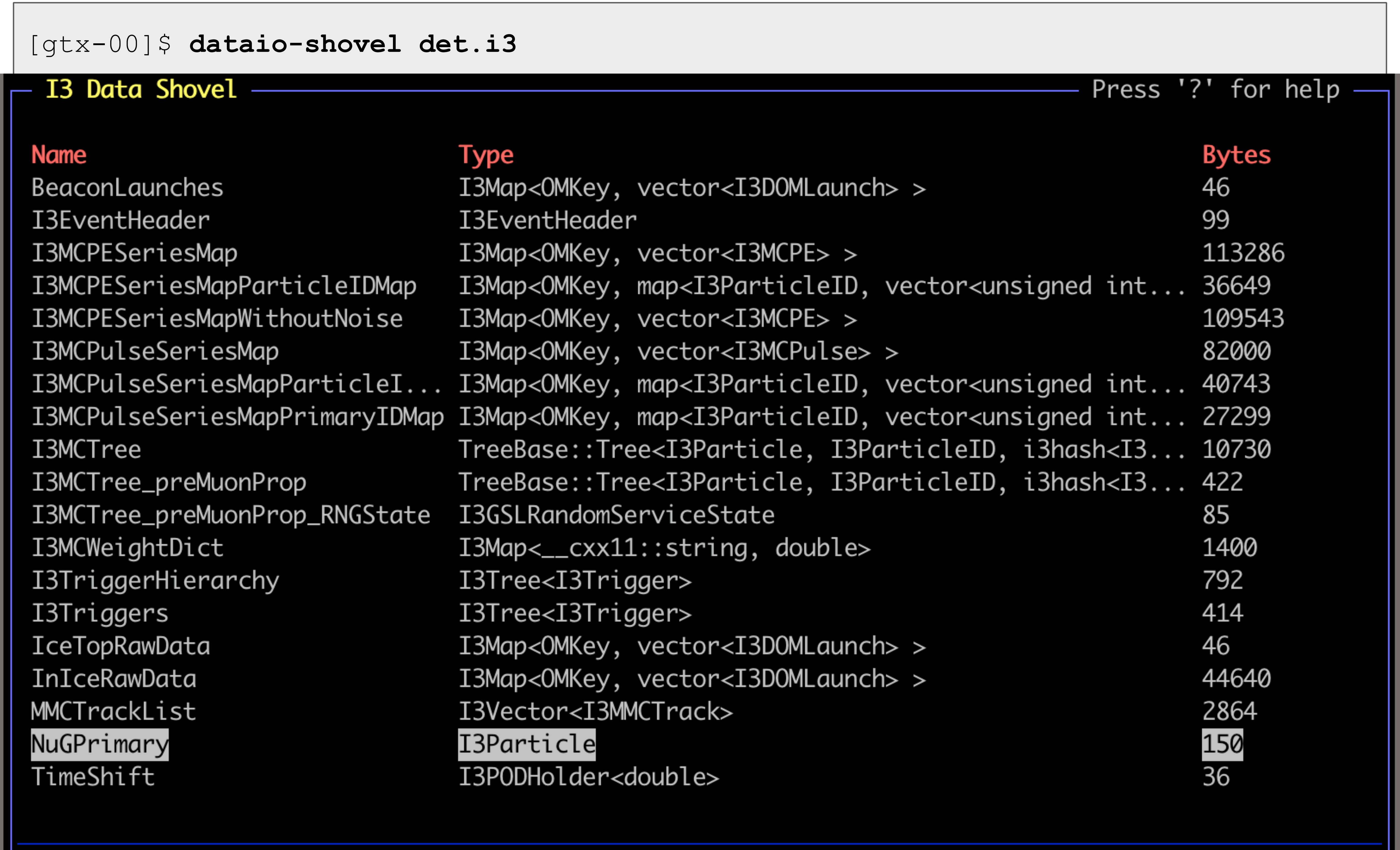
```
[gtx-00]$ dataio-shovel mcpes.i3
```



```
 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-shovel 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

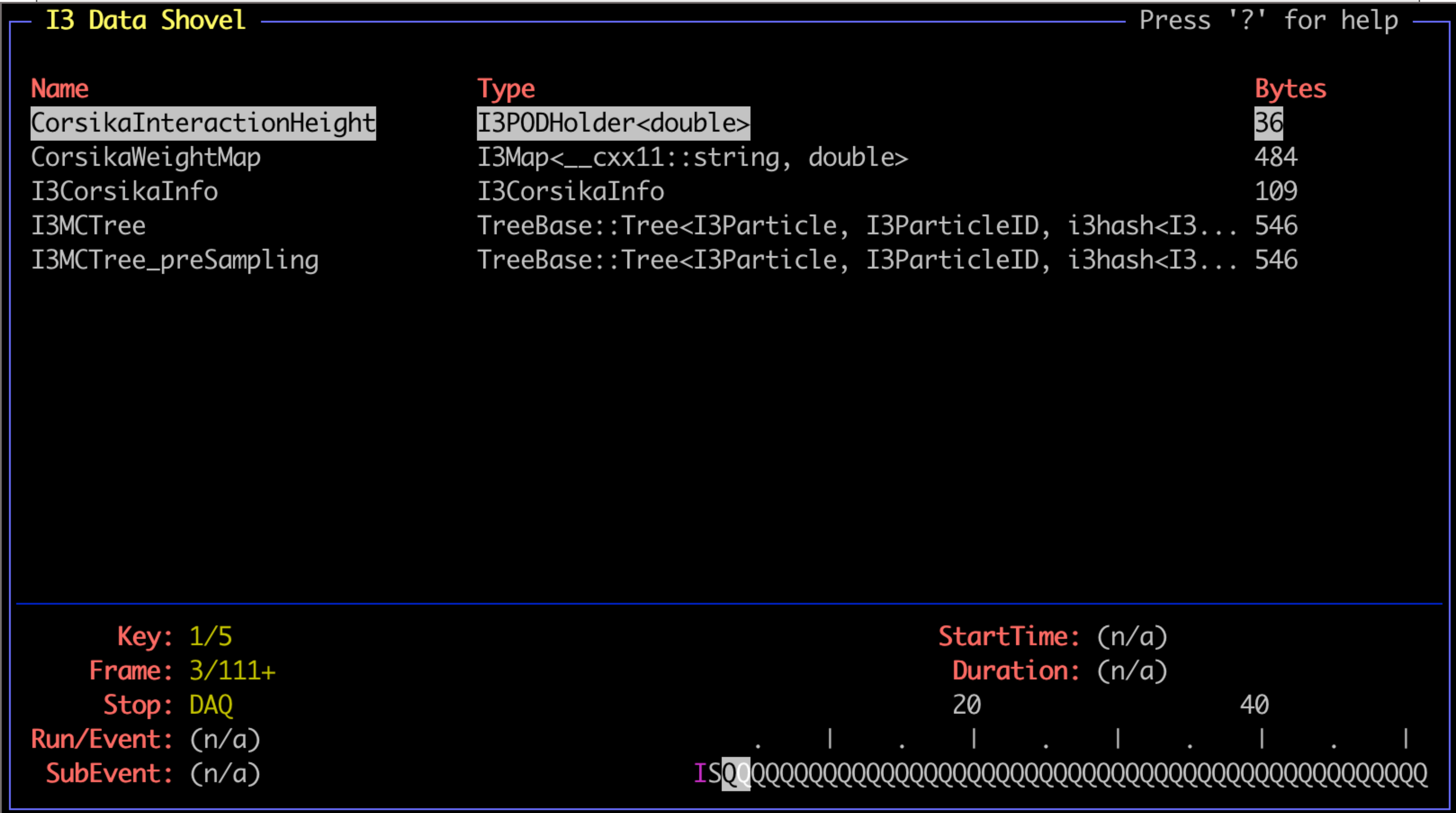
Exercise: Running scripts**:**

```
[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-shovel 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-shovel det_wcoinc.i3
```

simprod-scripts

Exercise: Running scripts:

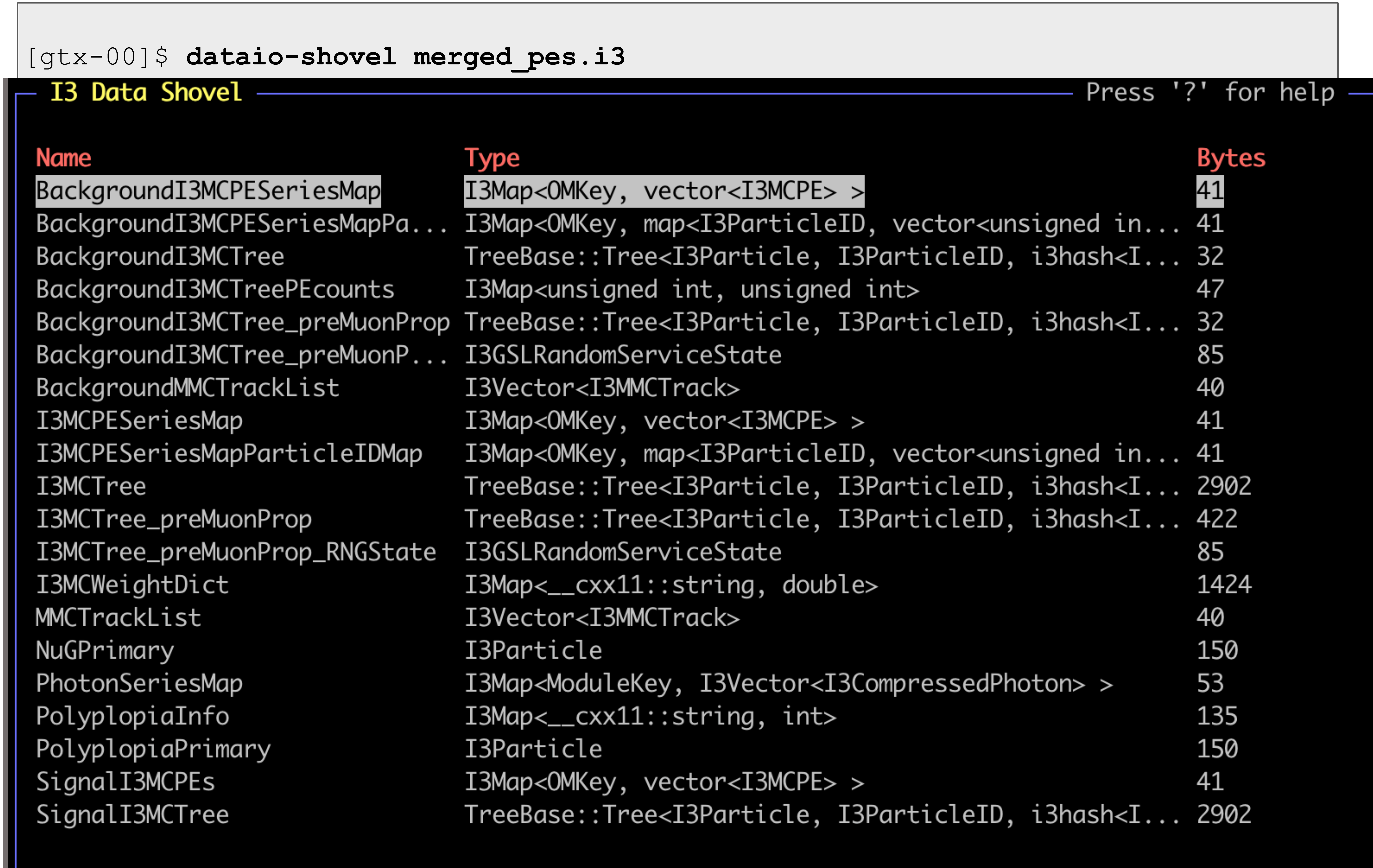
```
[gtx-00]$ dataio-shovel corsika_bg.i3
```



```
 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)                              ISQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQQ
```

simprod-scripts

Exercise: Running scripts:

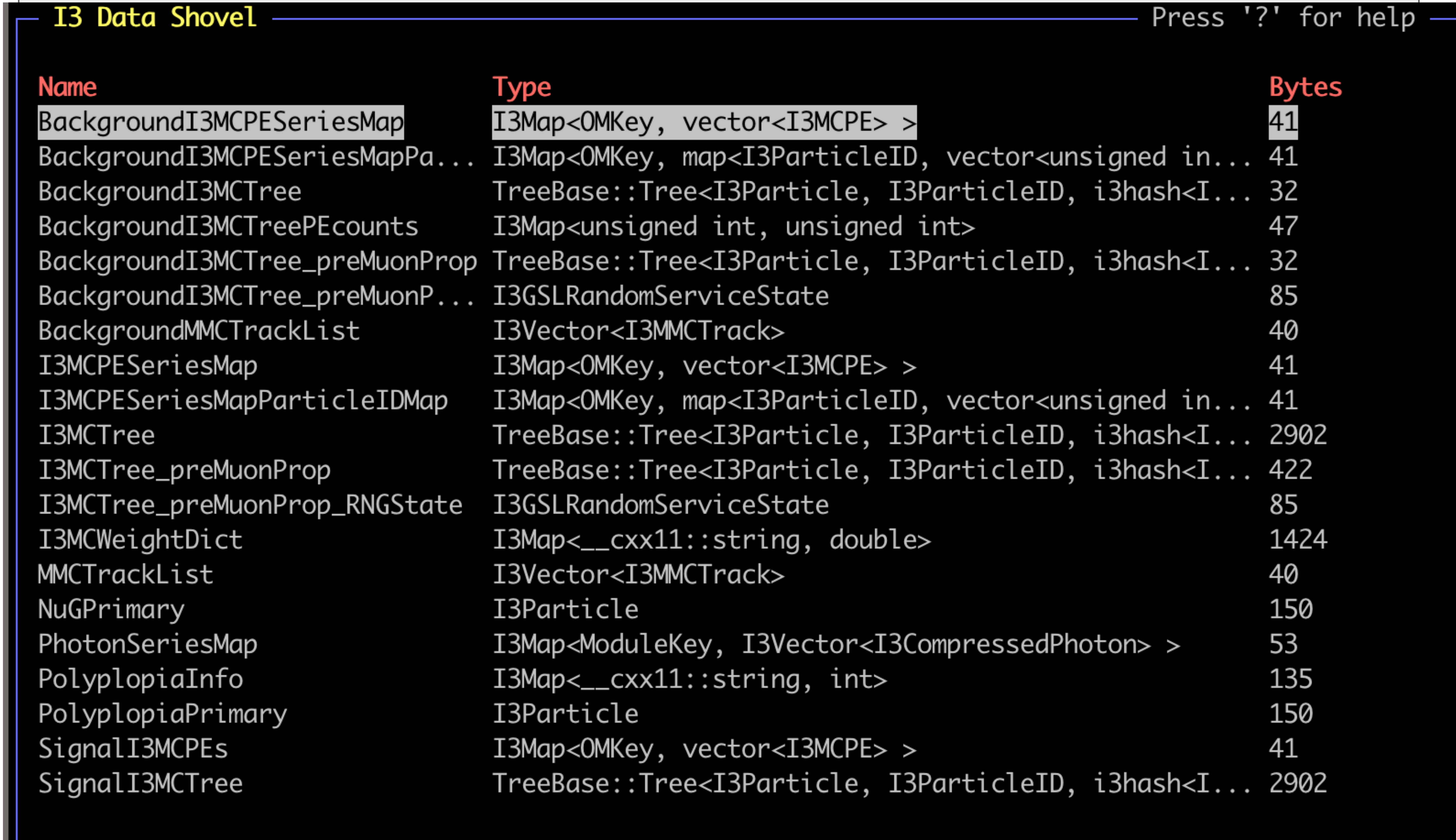


```
[gtx-00]$ dataio-shovel merged_pes.i3
 I3 Data Shovel                                                   Press '?' for help

 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

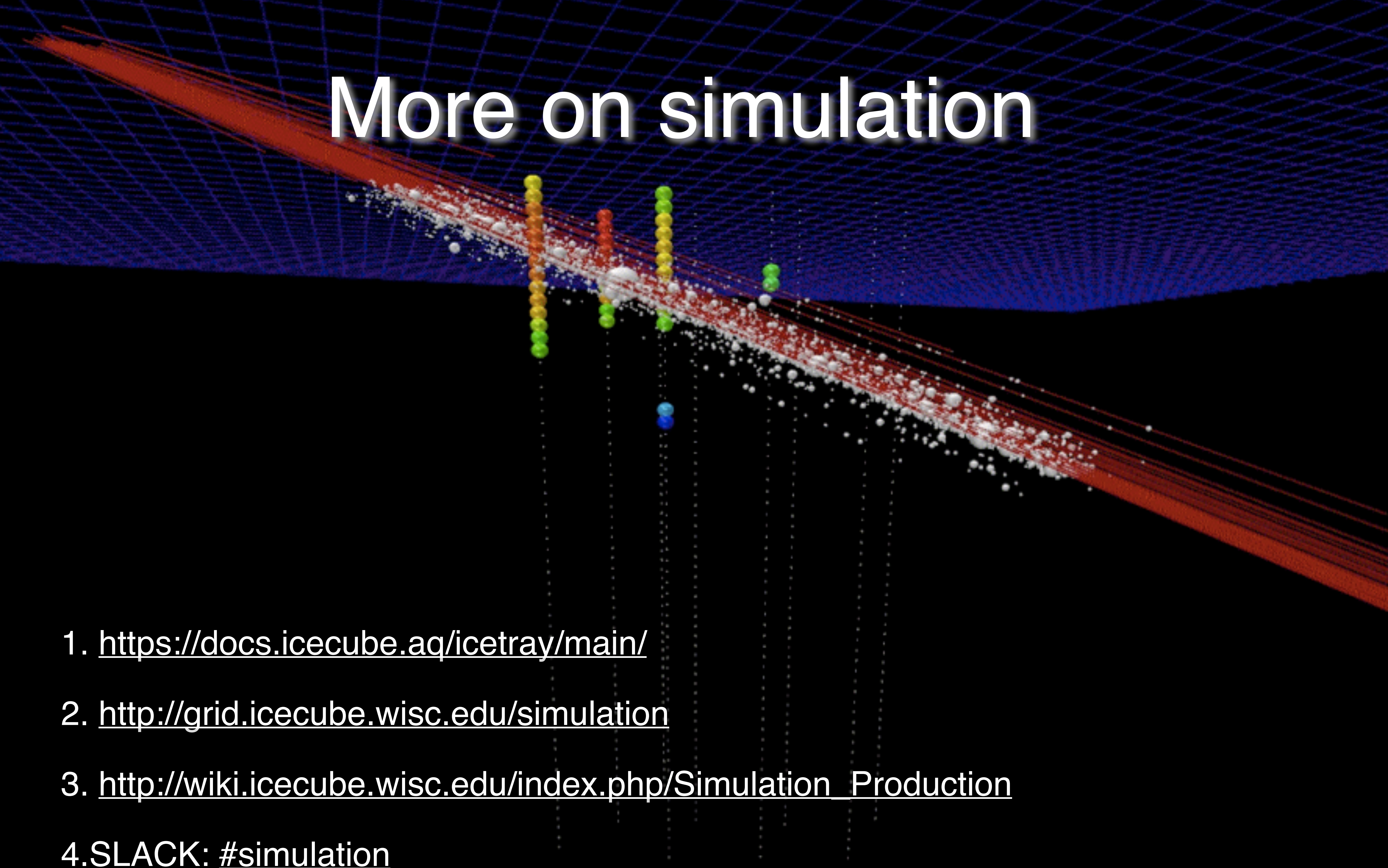
Exercise: Running scripts:

```
[gtx-00]$ dataio-shovel 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
```

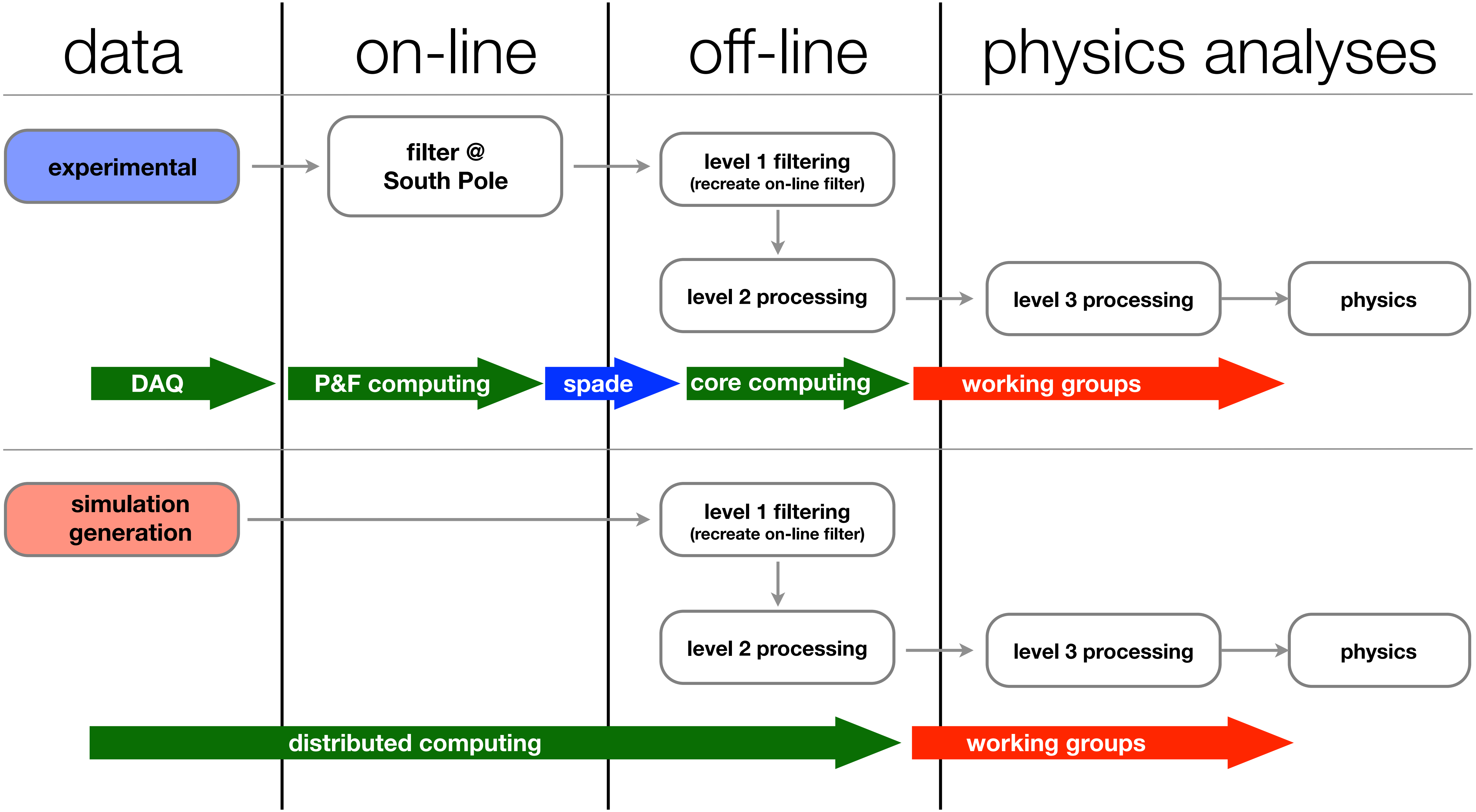
More on simulation



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

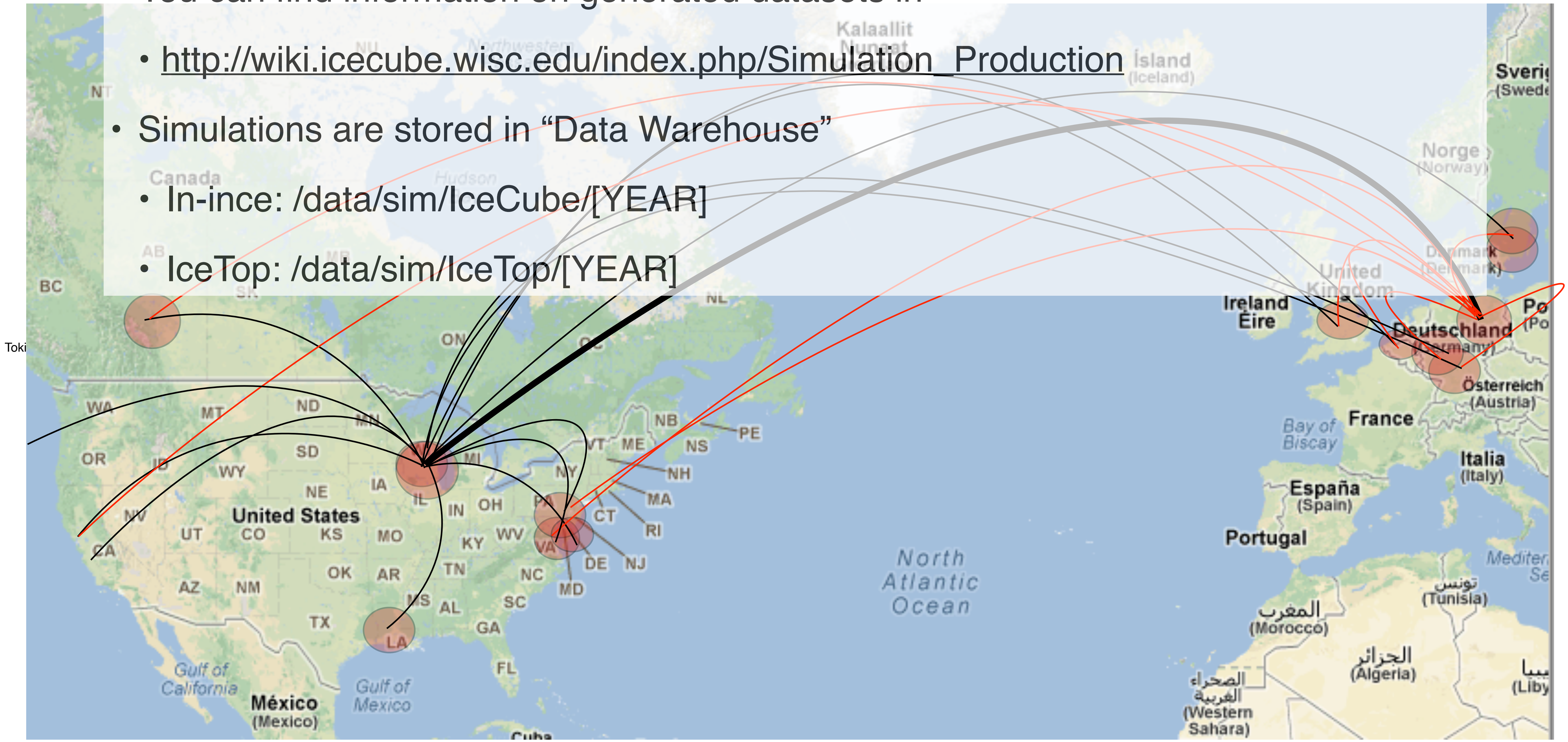
```
[gtx-00]$  python filterscripts/resources/scripts/SimulationFiltering.py -h

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]

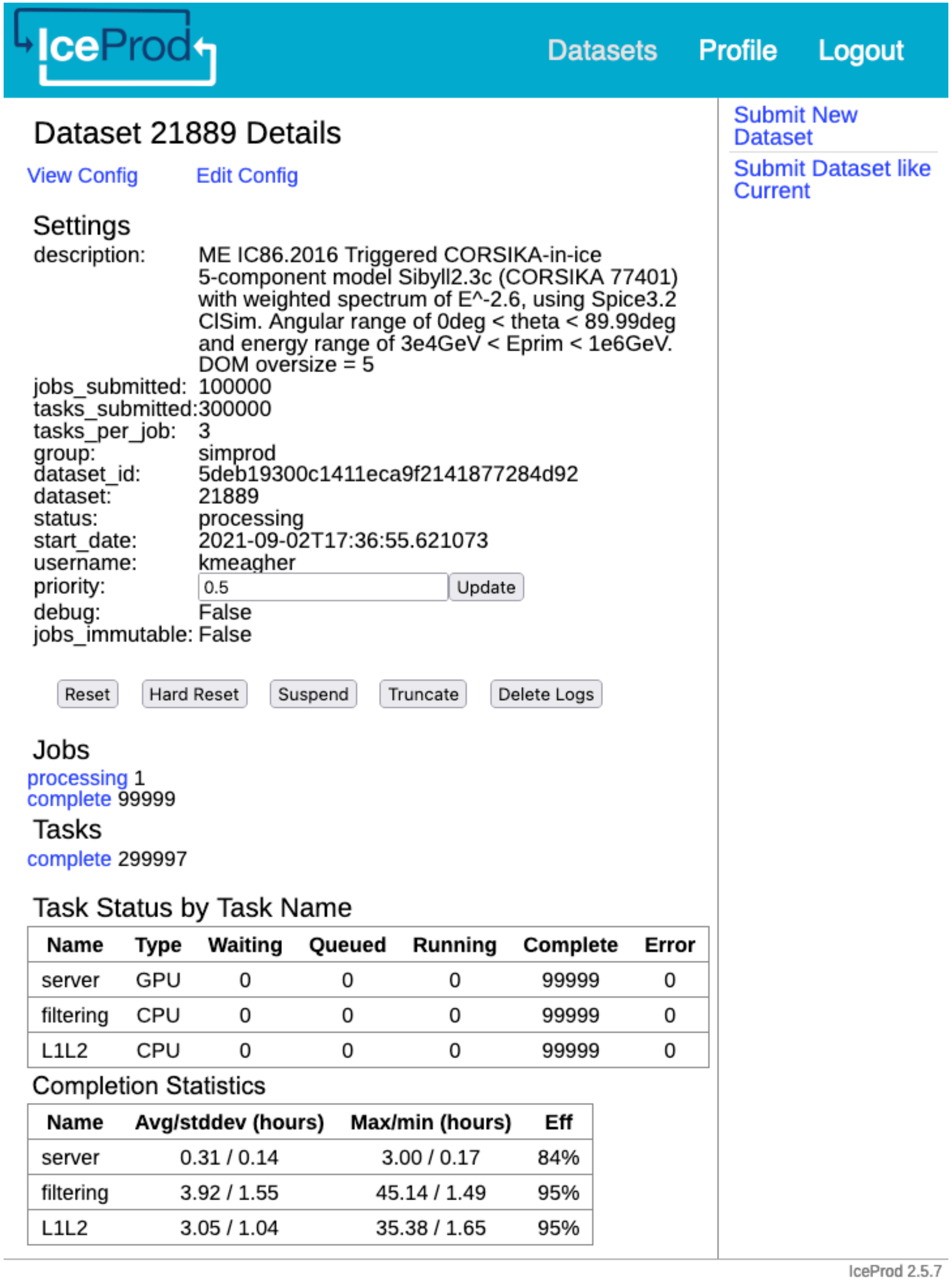


IceProd2

Distributed Computing

- IceCube Specific scheduler for the grid
- Used by simulation production to create official datasets
- Describe jobs to run using json
- Handles File transfers to data warehouse
- Uses web interface

- Data provenance
  - Configuration
    - which software, what versions,
  - when/where it ran, ...
- Dataset submission
  - Monitor job status, resource usage
  - Retry failed jobs - resubmit with different requirements



Dataset 21889 Details

Settings

description:	ME IC86.2016 Triggered CORSIKA-in-ice 5-component model Sibyll2.3c (CORSIKA 77401) with weighted spectrum of E^-2.6, using Spice3.2 ClSim. Angular range of 0deg < theta < 89.99deg and energy range of 3e4GeV < Eprim < 1e6GeV. DOM oversize = 5
jobs_submitted:	100000
tasks_submitted:	300000
tasks_per_job:	3
group:	simprod
dataset_id:	5deb19300c1411eca9f2141877284d92
dataset:	21889
status:	processing
start_date:	2021-09-02T17:36:55.621073
username:	kmeagher
priority:	0.5
debug:	False
jobs_immutable:	False

Jobs

processing 1
complete 99999

Tasks

complete 299997

Task Status by Task Name

Name	Type	Waiting	Queued	Running	Complete	Error
server	GPU	0	0	0	99999	0
filtering	CPU	0	0	0	99999	0
L1L2	CPU	0	0	0	99999	0

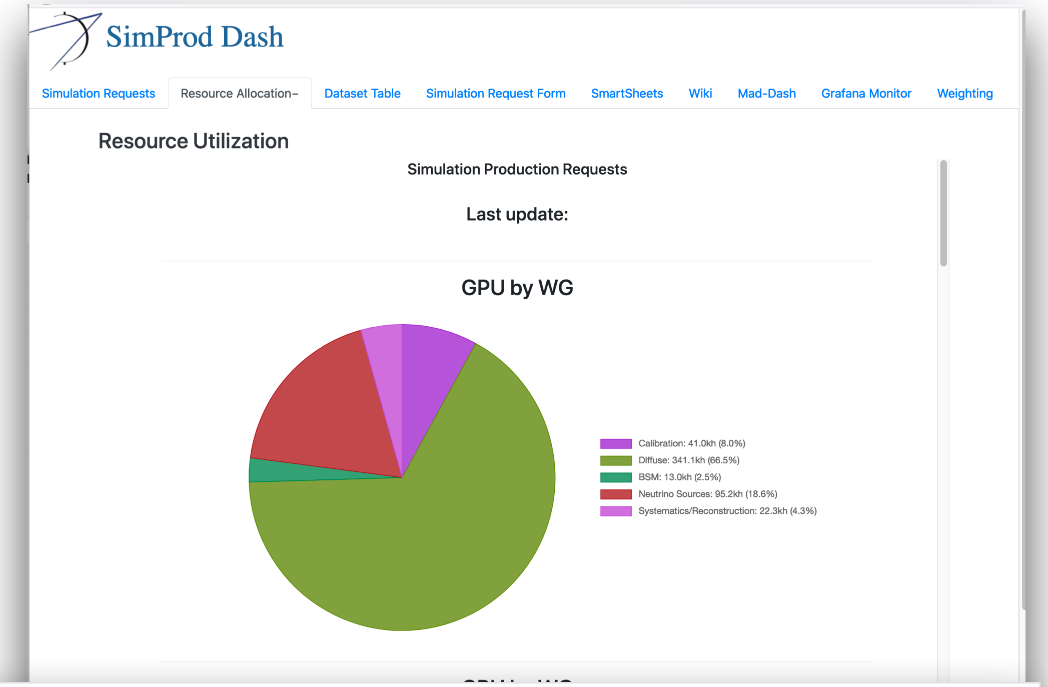
Completion Statistics

Name	Avg/stddev (hours)	Max/min (hours)	Eff
server	0.31 / 0.14	3.00 / 0.17	84%
filtering	3.92 / 1.55	45.14 / 1.49	95%
L1L2	3.05 / 1.04	35.38 / 1.65	95%

Simprod DashBoard

https://grid.icecube.wisc.edu/simulation/DashBoard

- Catalog of official MC datasets
- Simulation Requests
- Dataset and resource Monitoring



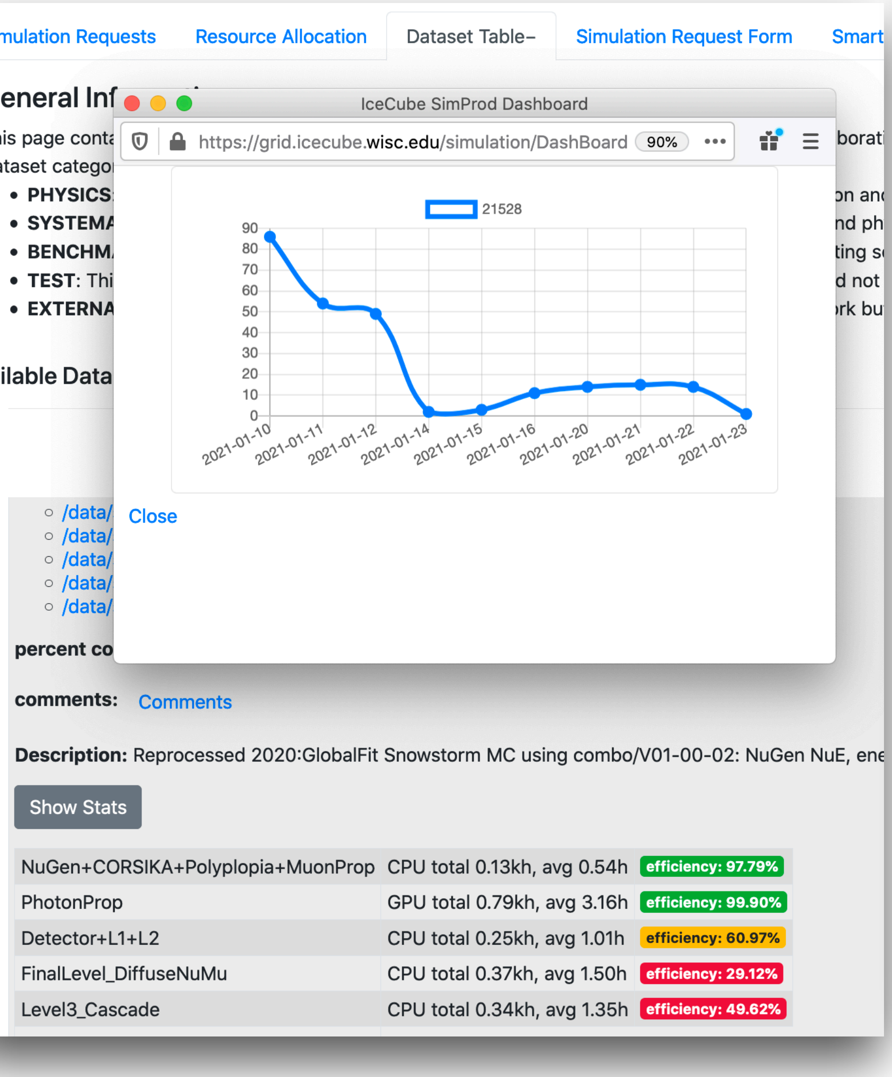
Resource Utilization

Simulation Production Requests

Last update:

GPU by WG

Calibration: 41.0kh (8.0%)
Diffuse: 341.1kh (66.5%)
BSM: 13.0kh (2.5%)
Neutrino Sources: 95.2kh (18.6%)
Systematics/Reconstruction: 22.3kh (4.3%)



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- PHYSICS ... on and
- SYSTEMA ... nd ph
- BENCHMA ... ting s
- TEST: Thi ... d not
- EXTERNA ... rk bu

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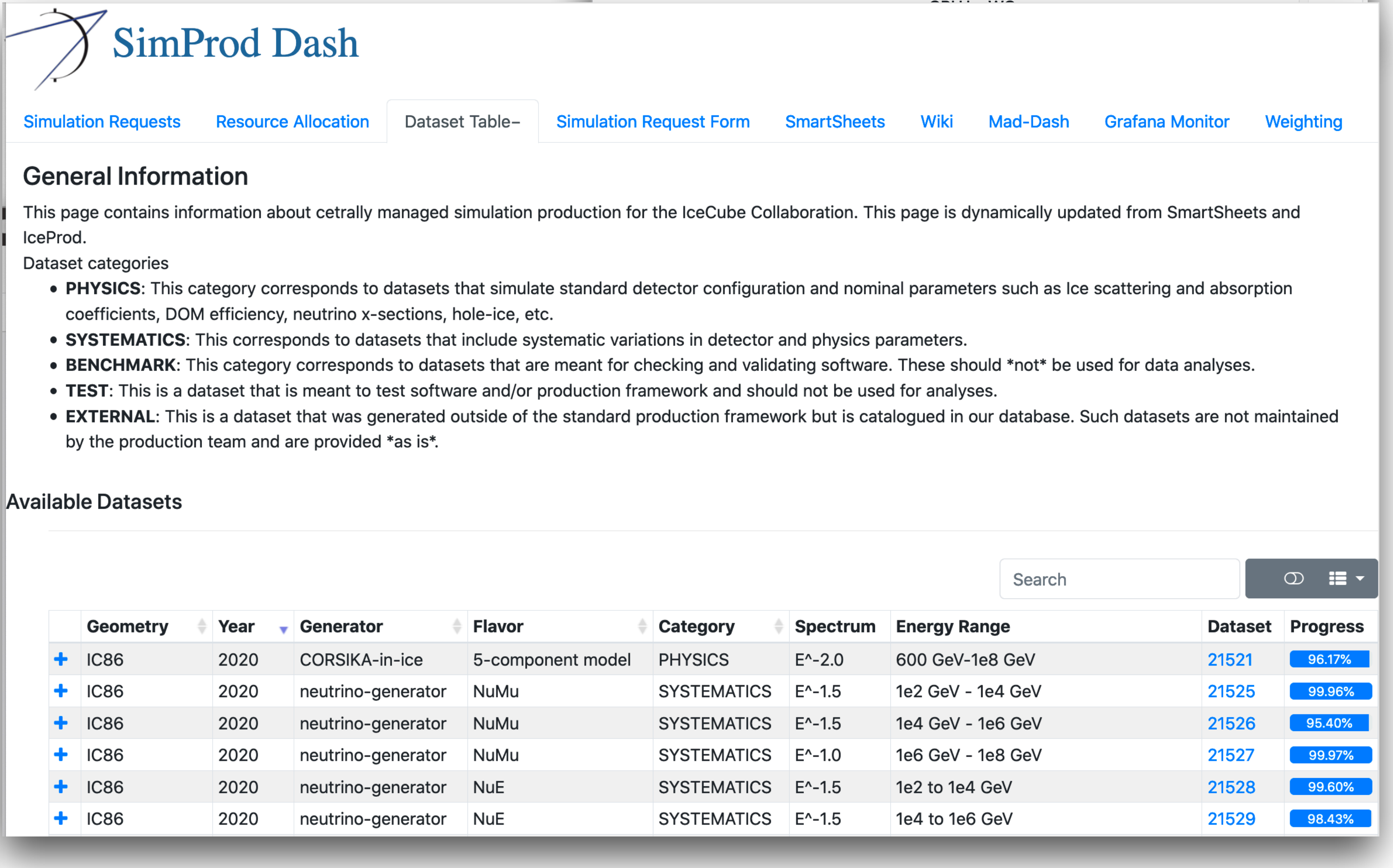
comments: Comments

Description: Reprocessed 2020:GlobalFit Snowstorm MC using combo/V01-00-02: NuGen NuE, ene

Show Stats

NuGen+CORSIKA+Polyplopia+MuonProp	CPU total 0.13kh, avg 0.54h	efficiency: 97.79%
PhotonProp	GPU total 0.79kh, avg 3.16h	efficiency: 99.90%
Detector+L1+L2	CPU total 0.25kh, avg 1.01h	efficiency: 60.97%
FinalLevel_DiffuseNuMu	CPU total 0.37kh, avg 1.50h	efficiency: 29.12%
Level3_Cascade	CPU total 0.34kh, avg 1.35h	efficiency: 49.62%



General Information

This page contains information about cetrally managed simulation production for the IceCube Collaboration. This page is dynamically updated from SmartSheets and IceProd.

Dataset categories

- **PHYSICS**: This category corresponds to datasets that simulate standard detector configuration and nominal parameters such as Ice scattering and absorption coefficients, DOM efficiency, neutrino x-sections, hole-ice, etc.
- **SYSTEMATICS**: This corresponds to datasets that include systematic variations in detector and physics parameters.
- **BENCHMARK**: This category corresponds to datasets that are meant for checking and validating software. These should *not* be used for data analyses.
- **TEST**: This is a dataset that is meant to test software and/or production framework and should not be used for analyses.
- **EXTERNAL**: This is a dataset that was generated outside of the standard production framework but is catalogued in our database. Such datasets are not maintained by the production team and are provided *as is*.

Available Datasets

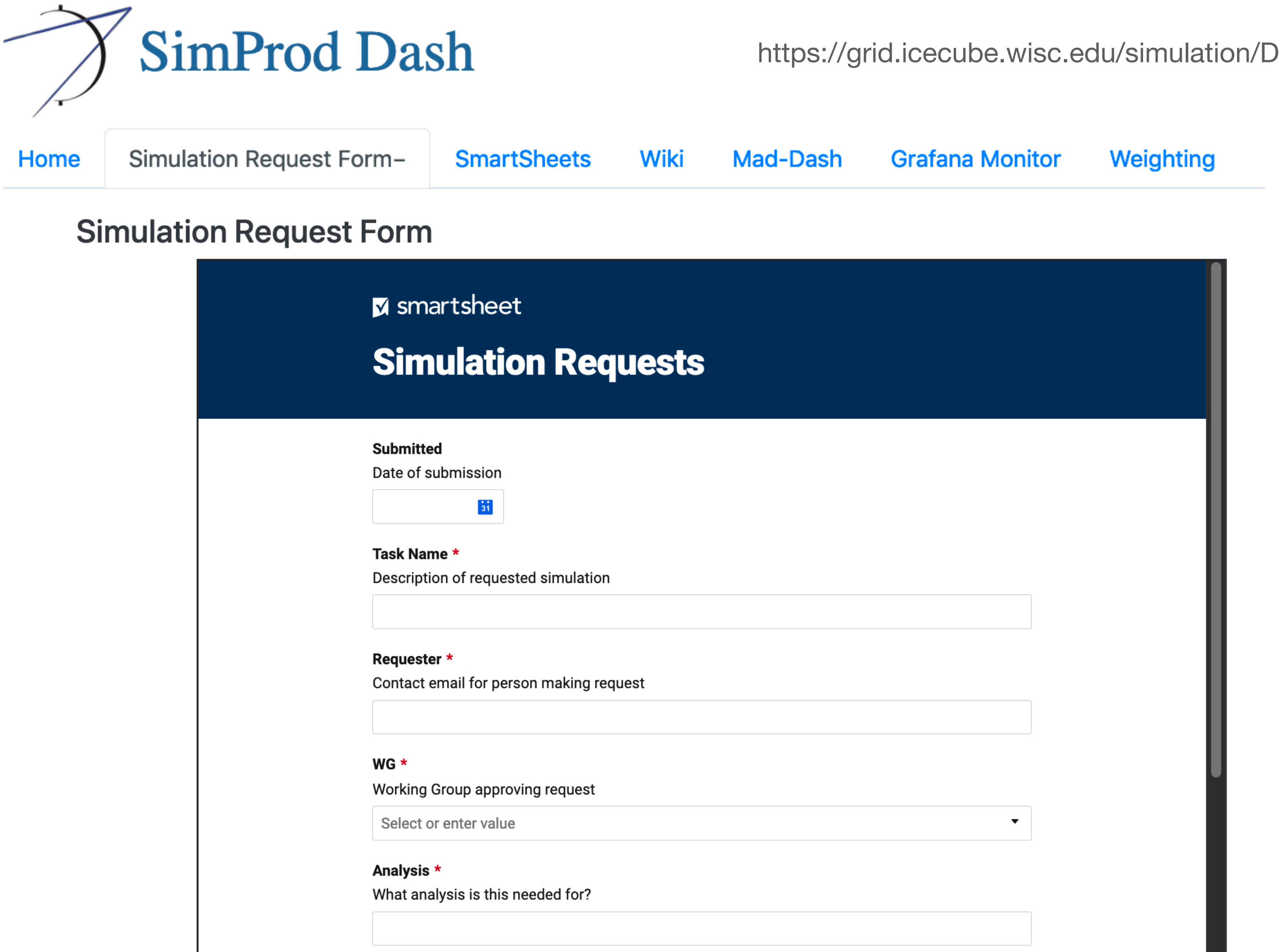
	Geometry	Year	Generator	Flavor	Category	Spectrum	Energy Range	Dataset	Progress
+	IC86	2020	CORSIKA-in-ice	5-component model	PHYSICS	E^-2.0	600 GeV-1e8 GeV	21521	96.17%
+	IC86	2020	neutrino-generator	NuMu	SYSTEMATICS	E^-1.5	1e2 GeV - 1e4 GeV	21525	99.96%
+	IC86	2020	neutrino-generator	NuMu	SYSTEMATICS	E^-1.5	1e4 GeV - 1e6 GeV	21526	95.40%
+	IC86	2020	neutrino-generator	NuMu	SYSTEMATICS	E^-1.0	1e6 GeV - 1e8 GeV	21527	99.97%
+	IC86	2020	neutrino-generator	NuE	SYSTEMATICS	E^-1.5	1e2 to 1e4 GeV	21528	99.60%
+	IC86	2020	neutrino-generator	NuE	SYSTEMATICS	E^-1.5	1e4 to 1e6 GeV	21529	98.43%

Sim-Prod Requests

Need high statistics simulations?

1. Discuss with your WG
2. Submit a request
3. Priority will be evaluated by tech leads

https://grid.icecube.wisc.edu/simulation/DashBoard/#simreqform



SimProd Dash

Simulation Request Form

Simulation Requests

Submitted
Date of submission

Task Name *
Description of requested simulation

Requester *
Contact email for person making request

WG *
Working Group approving request
Select or enter value

Analysis *
What analysis is this needed for?

Weighting

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

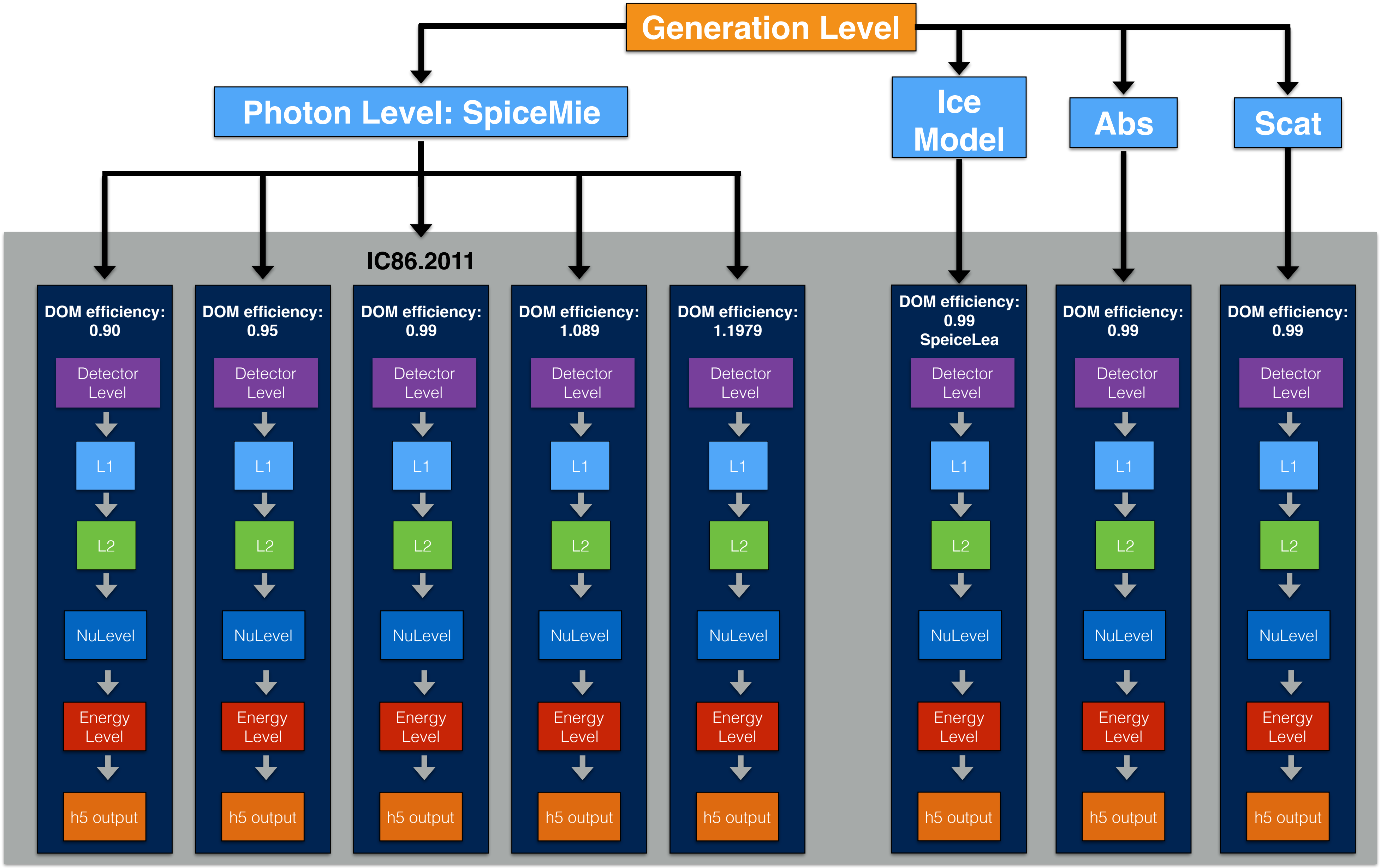
Old IceTray weighting project:
https://icecube.wisc.edu/~juancarlos/simulation/Bootcamp_2020_Simulation_Weighting.html

Backup

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

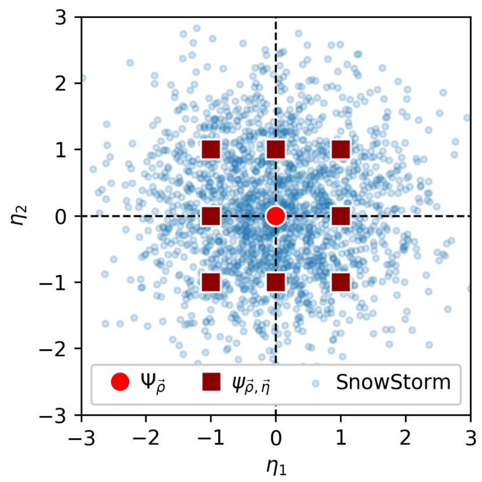
SnowStorm Simulation Chain – SnowStorm

- Based on “standard” simulation chain

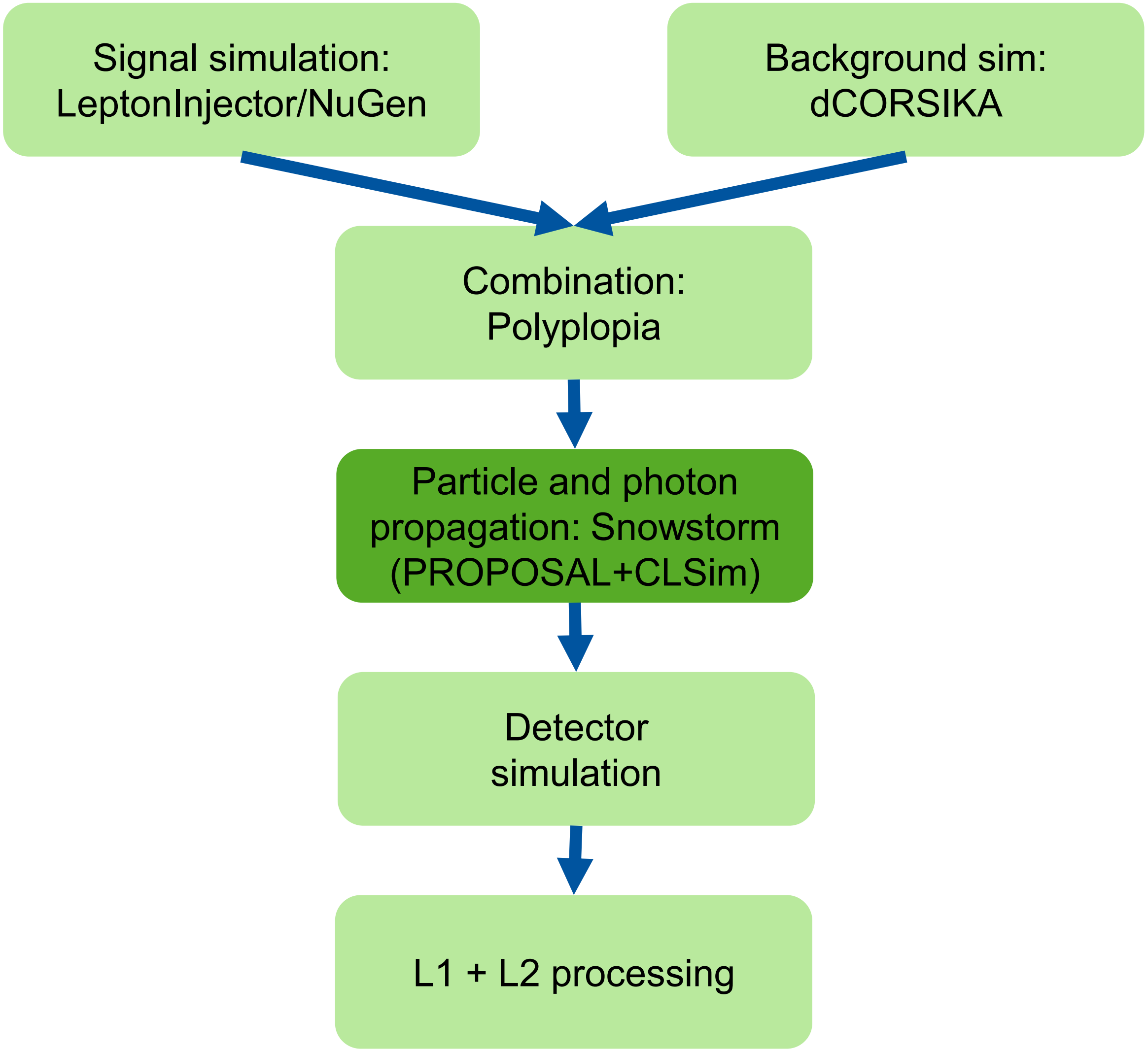
- Merge of signal+background I3MCTrees before any particle or photon propagation
→ Ensures that all particles get treated/propagated with the exact same parameters/settings further on

➢ 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)



Signal simulation: LeptonInjector/NuGen

Background sim: dCORSIKA

Combination: Polyplopia

Particle and photon propagation: Snowstorm (PROPOSAL+CLSim)

Detector simulation

L1 + L2 processing

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

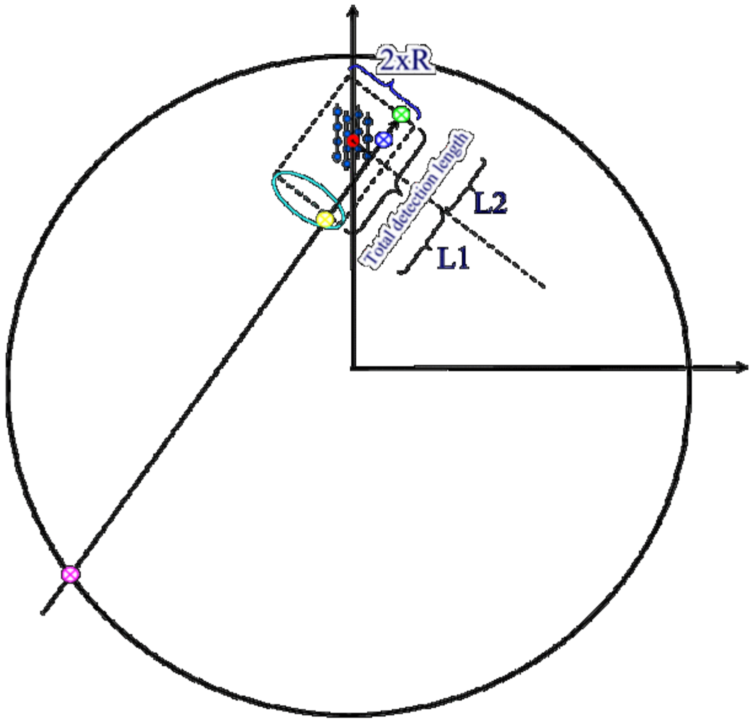
$$\Phi_0 \propto \Phi E^\delta$$

- 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)



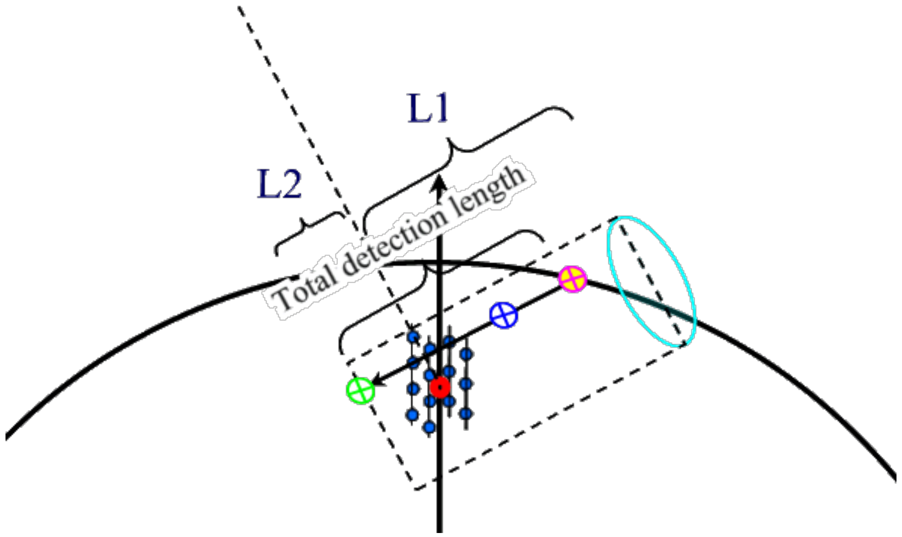
- It forces an interaction within a volume around the dector and computes the probability of this interaction

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

where $Pint = TotalInteractionProbabilityWeight$, $E^{-\gamma}$ 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