Neutrino Telescope Simulation (NTSim)

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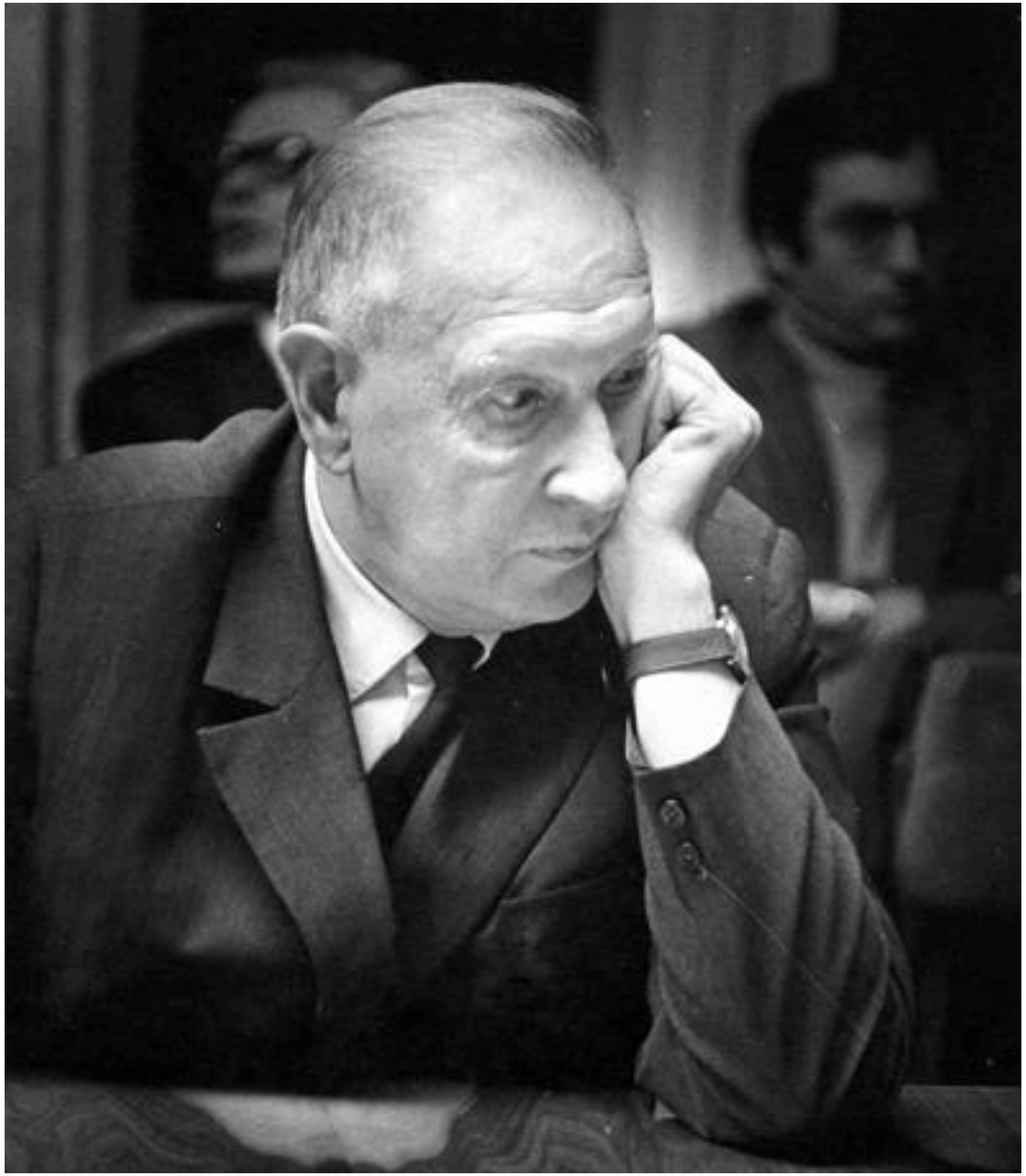
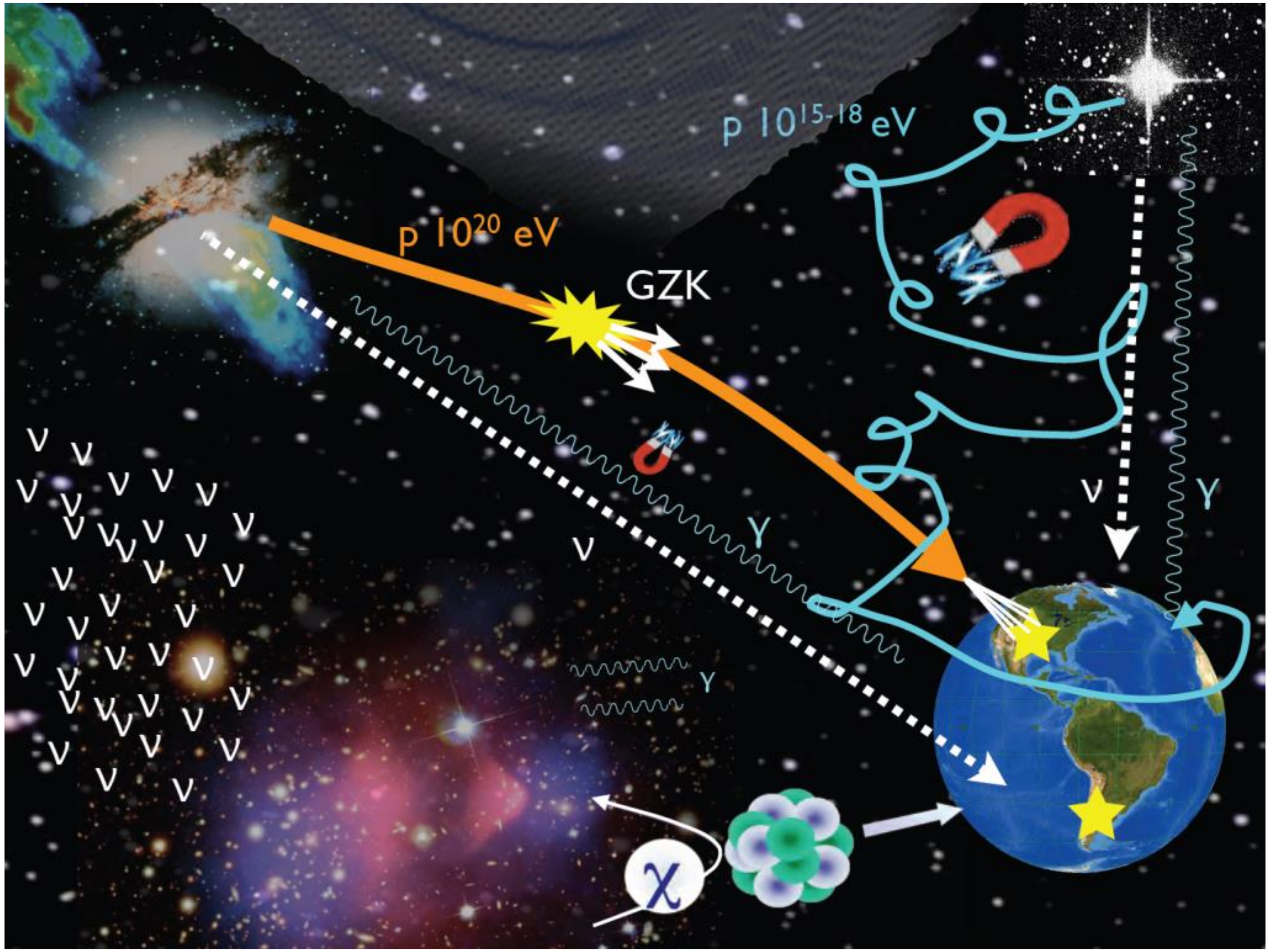
Astrophysical neutrinos detection

- Moses Markov (1960) proposed creating a network of optical detectors in a transparent natural environment (water/ice) to register optical flashes (Cherenkov radiation) from neutrino interactions.



Astrophysical neutrinos detection

- **Principle 1:** Neutrinos interact very weakly with matter (via weak and gravitational forces) - they can propagate enormous large distances without changing their trajectory.
- **Sources:** AGNs, GRBs, SMBHs, etc. (arXiv:2311.00281)

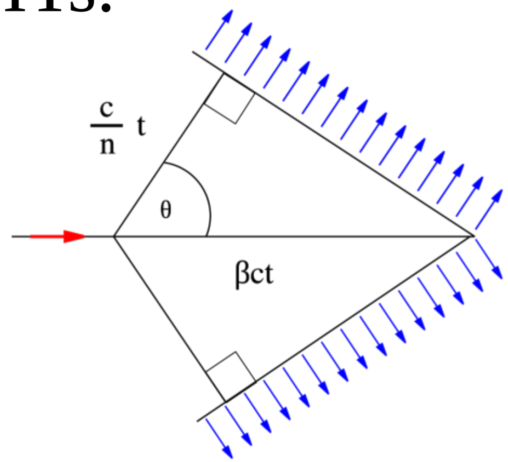


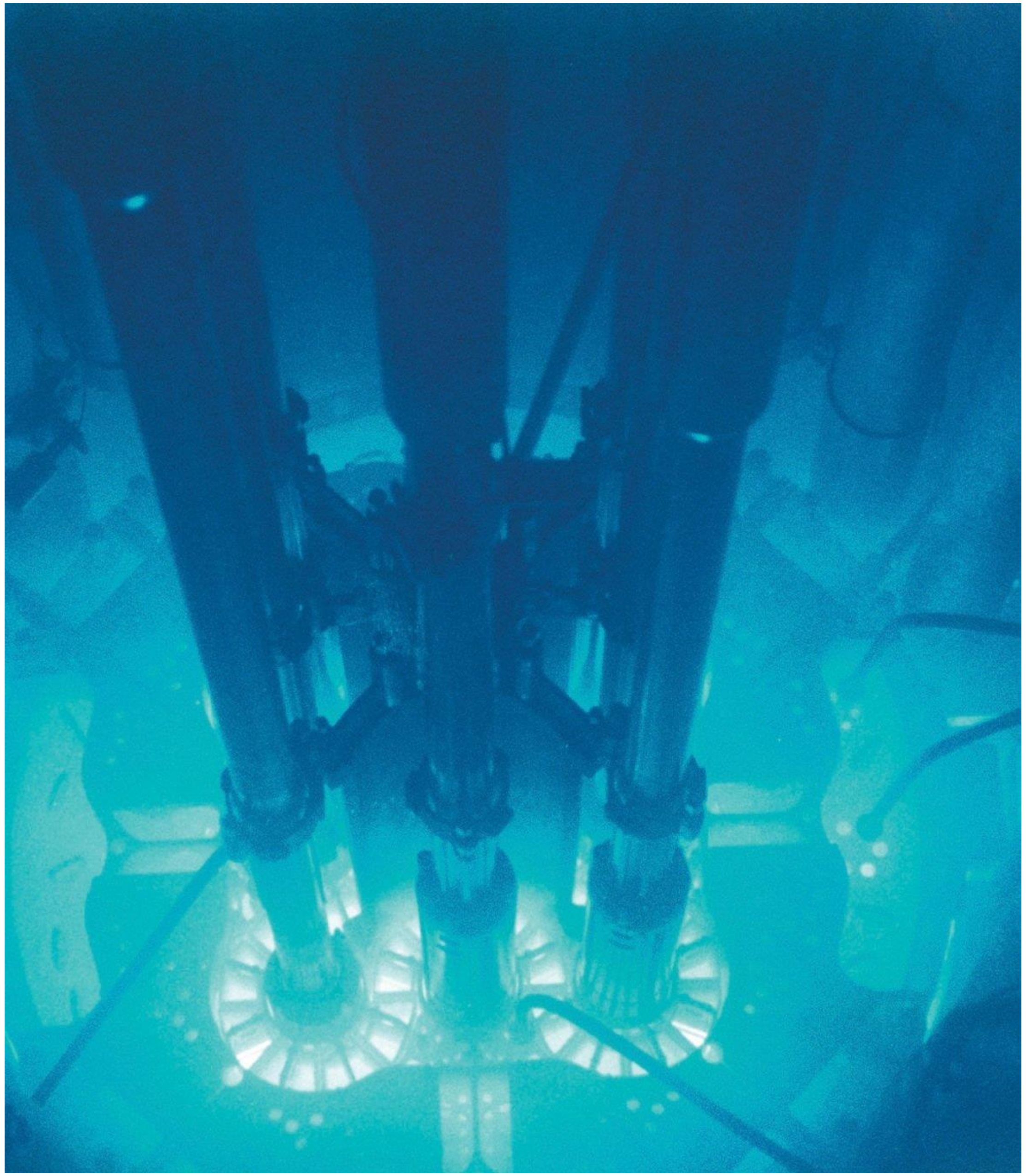
Astrophysical neutrinos detection

- **Principle 2:** Neutrinos can interact with nucleons in water or ice, generating high-energy charged particles that generate Cherenkov radiation detected in the PMTs.

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2} sin^2\theta -$$

Frank-Tamm formula

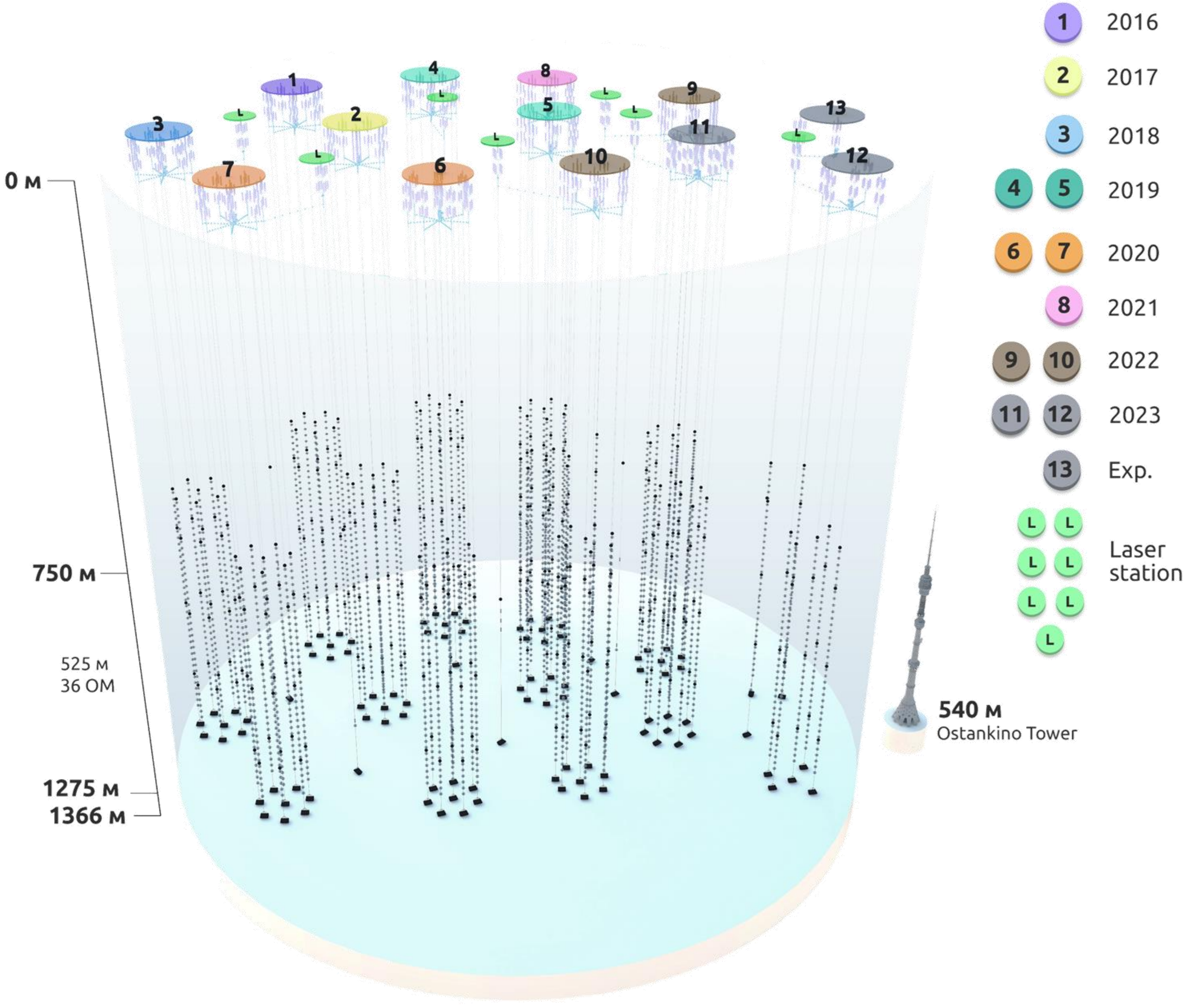




Baikal-GVD

- GVD – Gigaton Volume Detector
- Current geometrical volume ≈ 0.5 km^3
- Effective volume for E ≈ 100 TeV ~ 0.1 km^3 for tracks per cluster
- 36 Optical Modules (OMs) per 1 string
- 8 strings in 1 cluster
- Total 12 clusters
- 3456 ($+exp. \& \, lasers$) OMs

(Proc. Sci. ICRC2021, 395, 002)



Baikal GVD 2024

Дневник Баира Шайбонова

Joint Institute
for Nuclear Research

3 марта. День семнадцатый

Underlying principles

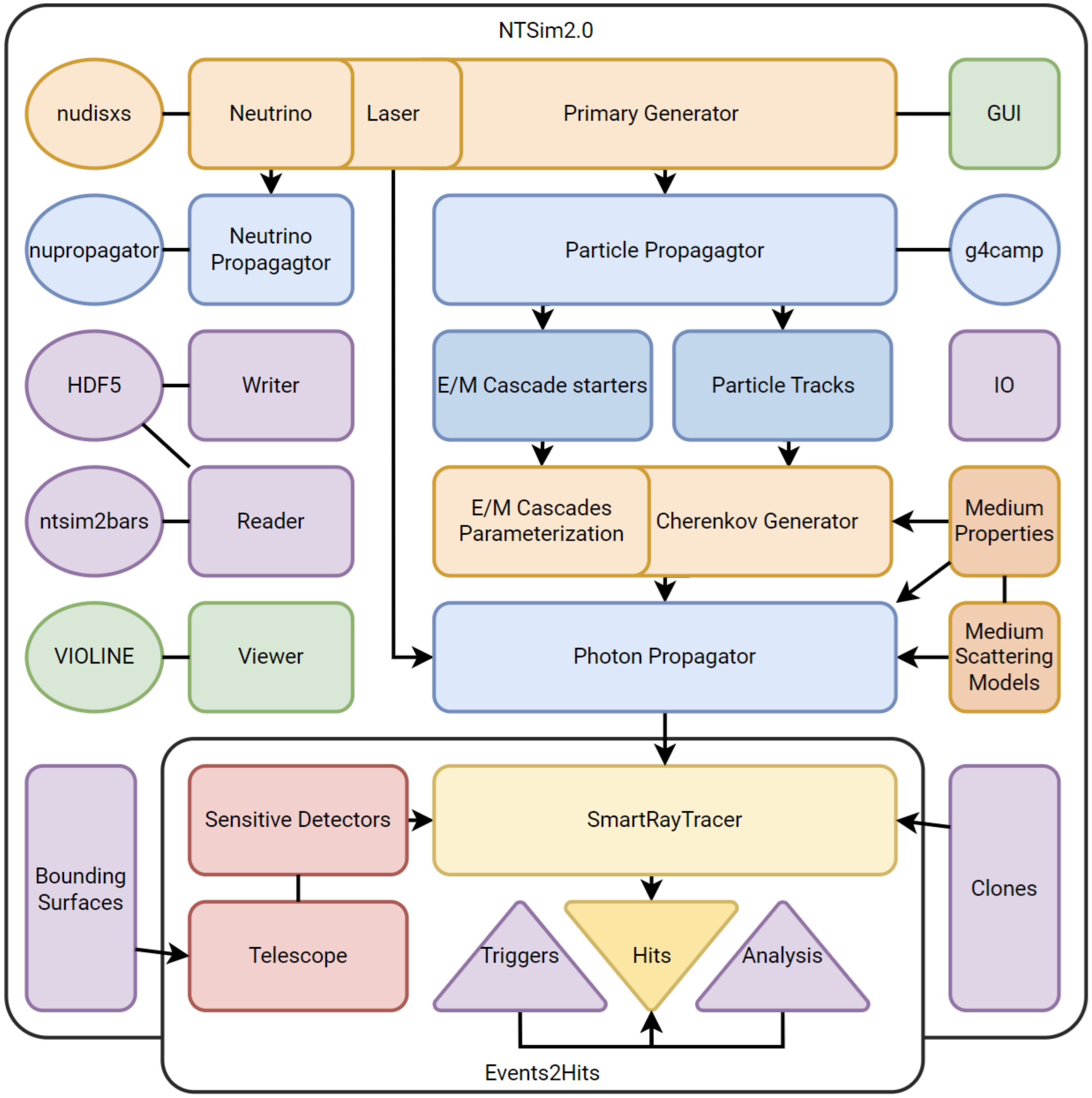
Simulation quality/rapidity

- Parameterization of e/m cascades
- Simulation of Cherenkov photons
- Intersection of Cherenkov photons with a Cluster/String/OM to calculate the response

Modularity

- NTSim – basic engine
- g4camp – based on [Geant4](#) with [geant4_pybind](#)
- Telescope – the response calculation for broad range of neutrino telescopes

User friendly →Python, GUI

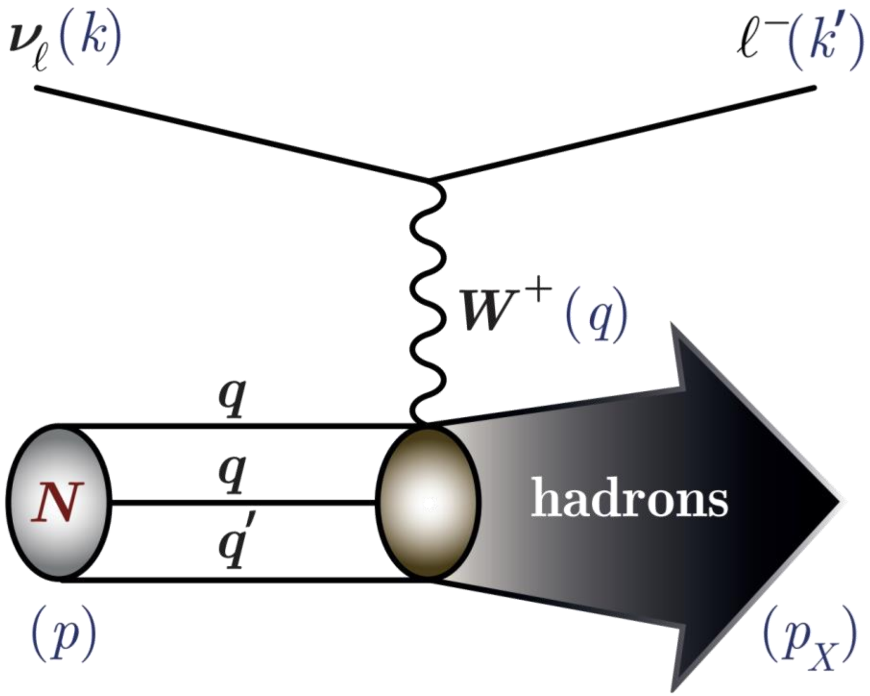


NTSim Structure: Primary Generators

- Particle generators are needed to initialize an event that will be simulated in NTSim.
- NuGen
  - based on nupropagator and nudisxs
  - initializes the event of neutrino-nucleon interaction via CC or NC with the generation of lepton, pion and recoil nucleon
- ToyGen
  - based on g4camp (documentation)
  - initializes the primary particle from Geant4
- Laser + Diffuser
- SolarPhotons

NTSim Generators: NuGen

- Target: proton/neutron
- Energy range: Deep Inelastic Scattering (DIS) - $[10^1, 10^8]$ GeV



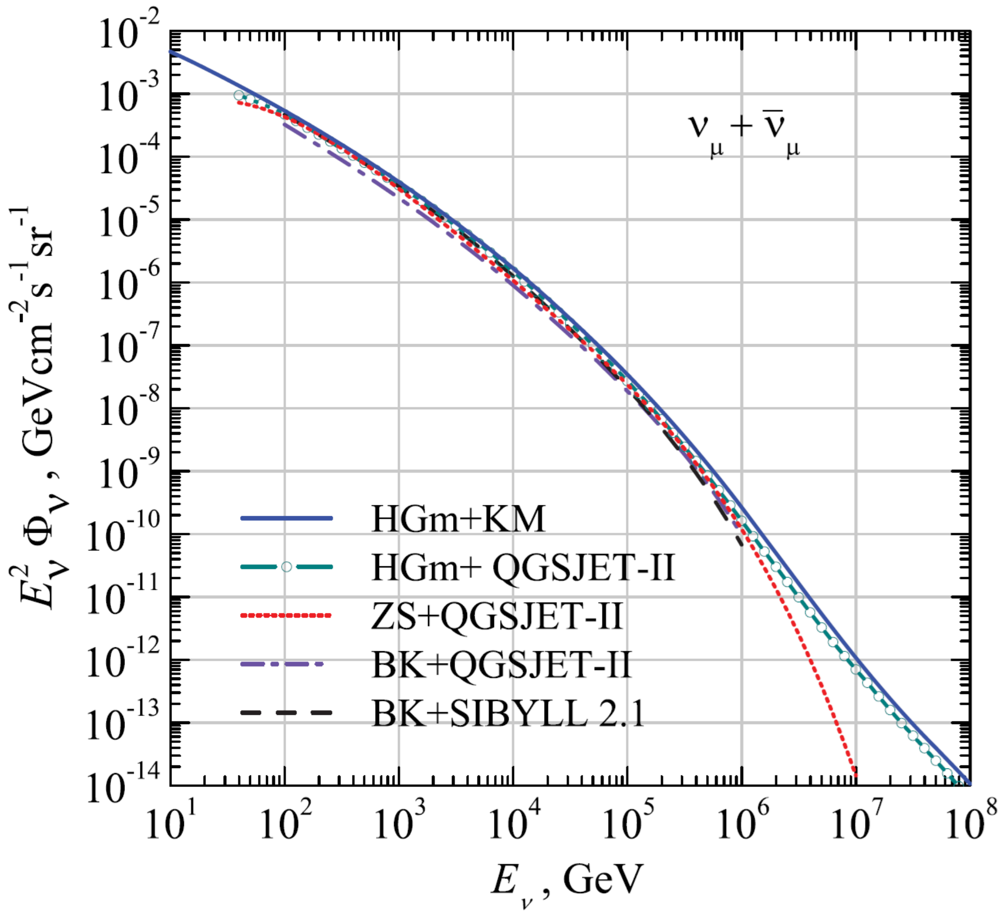
- $\frac{d^2\sigma}{dxdy} = \frac{G_F^2}{2\pi} \frac{s}{\left(1+Q^2/M_W^2\right)^2} \mathcal{R},$
- $\mathcal{R} = \sum_{i=1}^{5} A_i(x, y, E_l) F_i(x, Q^2)$
- $F_i(x, Q^2)$ – structural functions

Structural functions are expressed in terms of experimentally measured Parton Distribution Functions (PDF) → LHAPDF library

NTSim Generators: NuGen

- Neutrino flux: atmospheric $\nu_\mu + \bar{\nu}_\mu$ (conventional & prompt)

(arXiv:1407.3591)



NTSim Generators: NuGen

- Neutrino flux: atmospheric $\nu_\mu + \bar{\nu}_\mu$ (conventional & prompt)

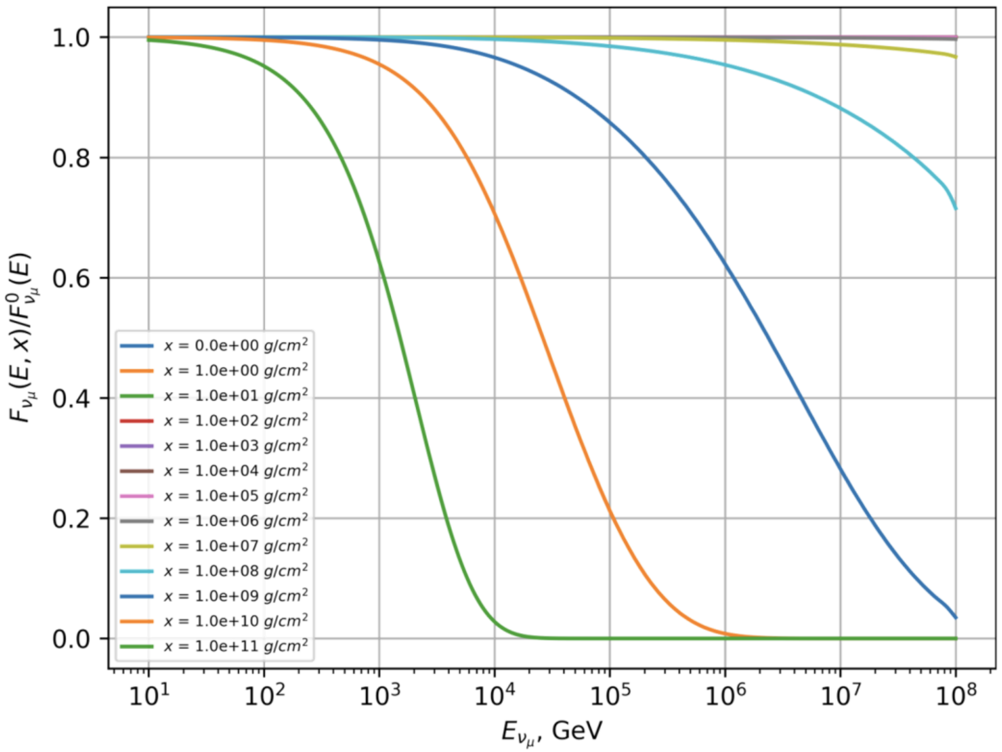
(arXiv:1407.3591)

- Propagate through the Earth: Z-factor

(arXiv:hep-ph/9804301)

$$\frac{\partial F_\nu(E,x)}{\partial x} = \frac{1}{\lambda_\nu(E)}\left[\int_0^1 \frac{dy}{1-y}\Phi_\nu(y,E)F_\nu(E_y,x) - F_\nu(E,x)\right]$$

- $x = \int_0^L dL'\rho(L')$
- $\Phi_\nu(y,E) = \lambda_\nu(E)\sum_T N_T \frac{d\sigma_{\nu T\to\nu X}(y,E_y)}{dy}$
- $\frac{1}{\lambda_\nu(E)} = \sum_T N_T \sigma_{\nu T}^{tot}(E)$



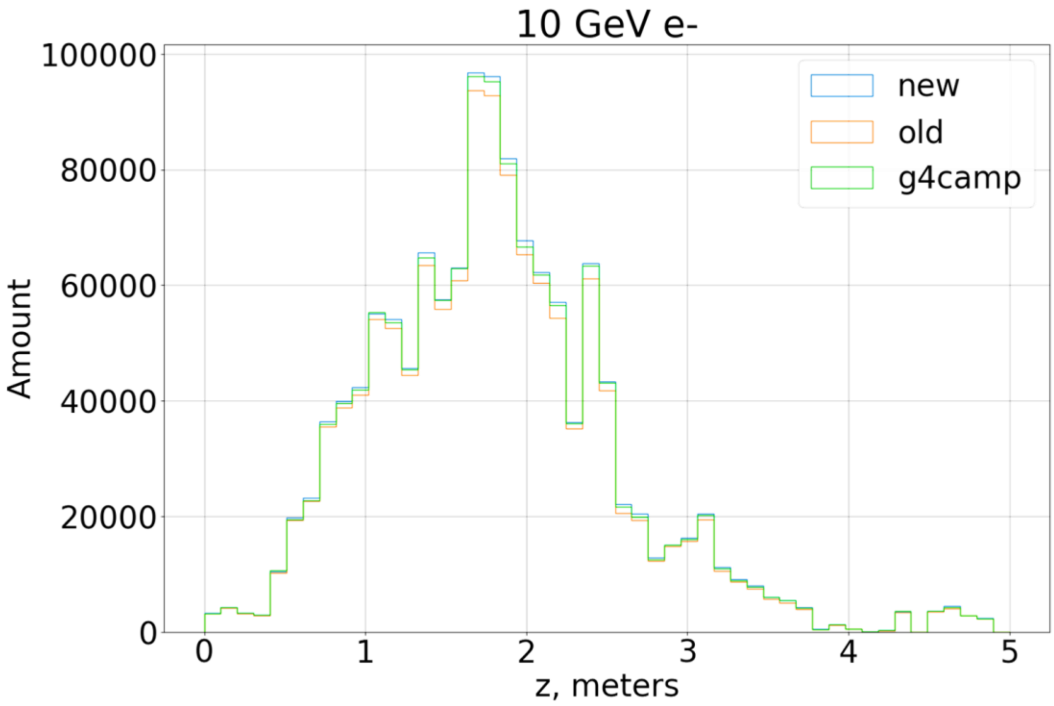
The ratio of the atmospheric $(\nu_\mu + \bar{\nu}_\mu)$ flux at depth x to the initial neutrino spectrum.

NTSim Structure: Propagators

- Propagators are responsible for the propagation of particles in the medium.
- ParticlePropagator
  - based on g4camp (documentation)
  - simulates the passage of particles above the Cherenkov threshold through matter via the Geant4 toolkit
- NuPropagagtor
  - based on nupropagator
  - reconstructs the track of the primary neutrino that flew through the Earth
- MCPhotonTransporter
  - Monte-Carlo simulation of photon scattering using a medium scattering model (Henyey-Greenstein)
- Radio Transport Equation (RTE) – (arXiv:2401.15698)

NTSim Structure:
Cherenkov Generator

- Cherenkov generators produce Cherenkov photons either from segments of charged particle tracks or from parameterization of electromagnetic cascades.
- CherenkovGenerator
  - Tracks
    - The improvement in the simulation speed of Cherenkov photons was achieved due to their joint generation and rotation



NTSim Structure:
Cherenkov Generator

- Cherenkov generators produce Cherenkov photons either from segments of charged particle tracks or from parameterization of electromagnetic cascades.
- CherenkovGenerator
  - Tracks
  - Cascades (under validation)
    - amount of e^-/e^+ are parametrized
    - gamma distribution, Greisen approximation
    - longitudinal and zenith parameterization
    - variation of MC parameters for individual e/m cascades
    - energy range is $[10^1, 10^4]$ GeV

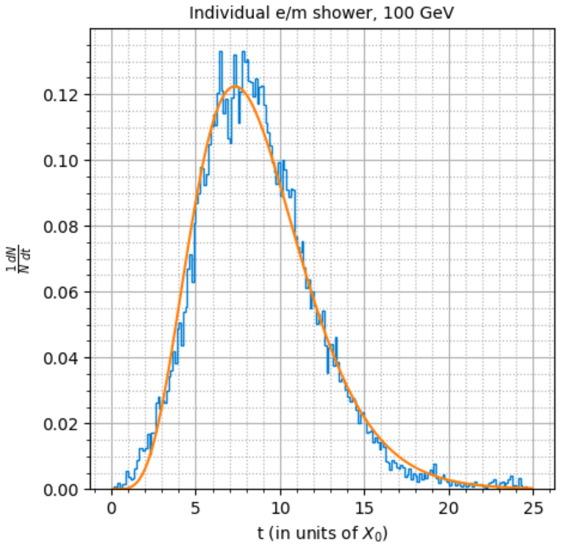
Cherenkov Generator: E/m cascades

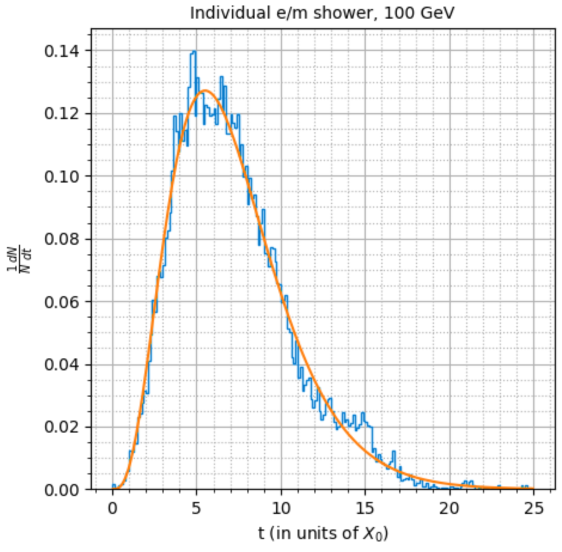
Gamma distribution

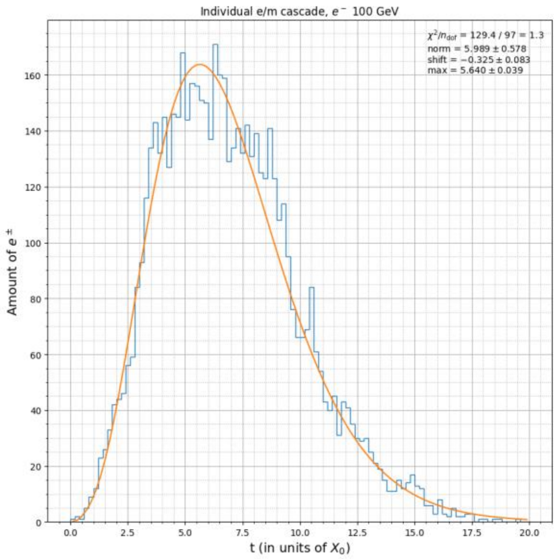
- $f(t|\alpha,\beta) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} t^{\alpha-1} e^{-\beta t}$,
  - $\alpha > 0, \beta > 0$

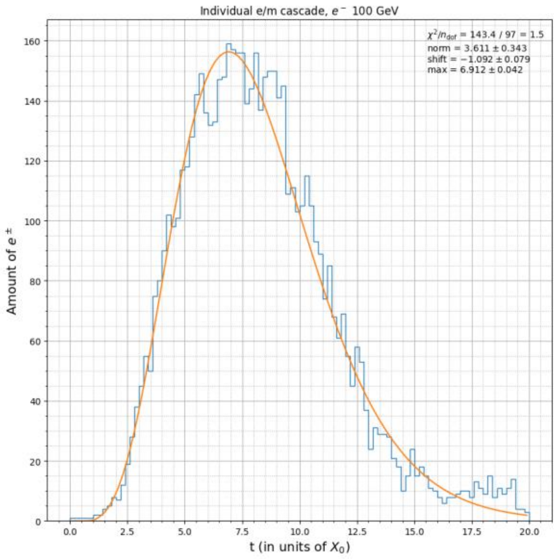
Modified Greisen approximation (arXiv:0809.0190)

- $N_{e^{\pm}}(t|a,b,t_{max}) = \frac{0.31 \cdot a(E_{th})}{\sqrt{y(E_0,E_c)}} s(t_1,y)^{-1.5 \cdot t_1} e^{t_1}$
  - $s(t_1,y) = \frac{3 \cdot t_1}{t_1 + 2 \cdot y(E_0,E_c)} \Theta(t_1)$
  - $t_1 = t + b(E_{th}), \quad y(E_0,E_c) = t_{max}(E_0,E_c) + b(E_{th})$



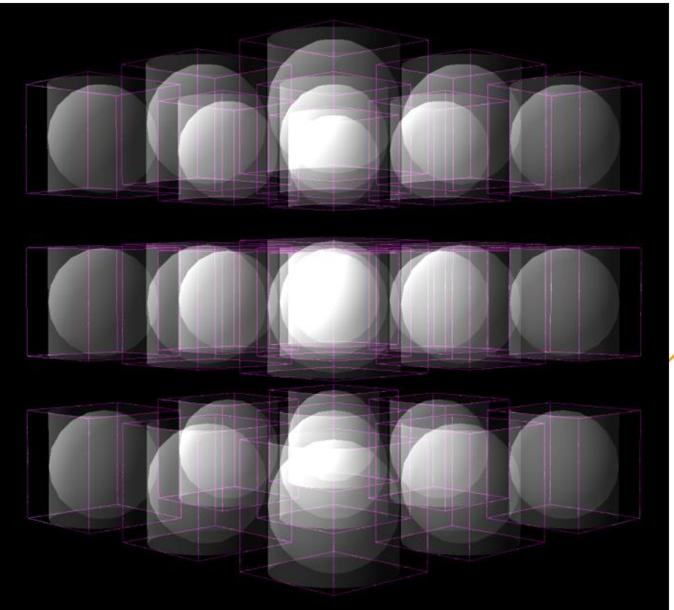


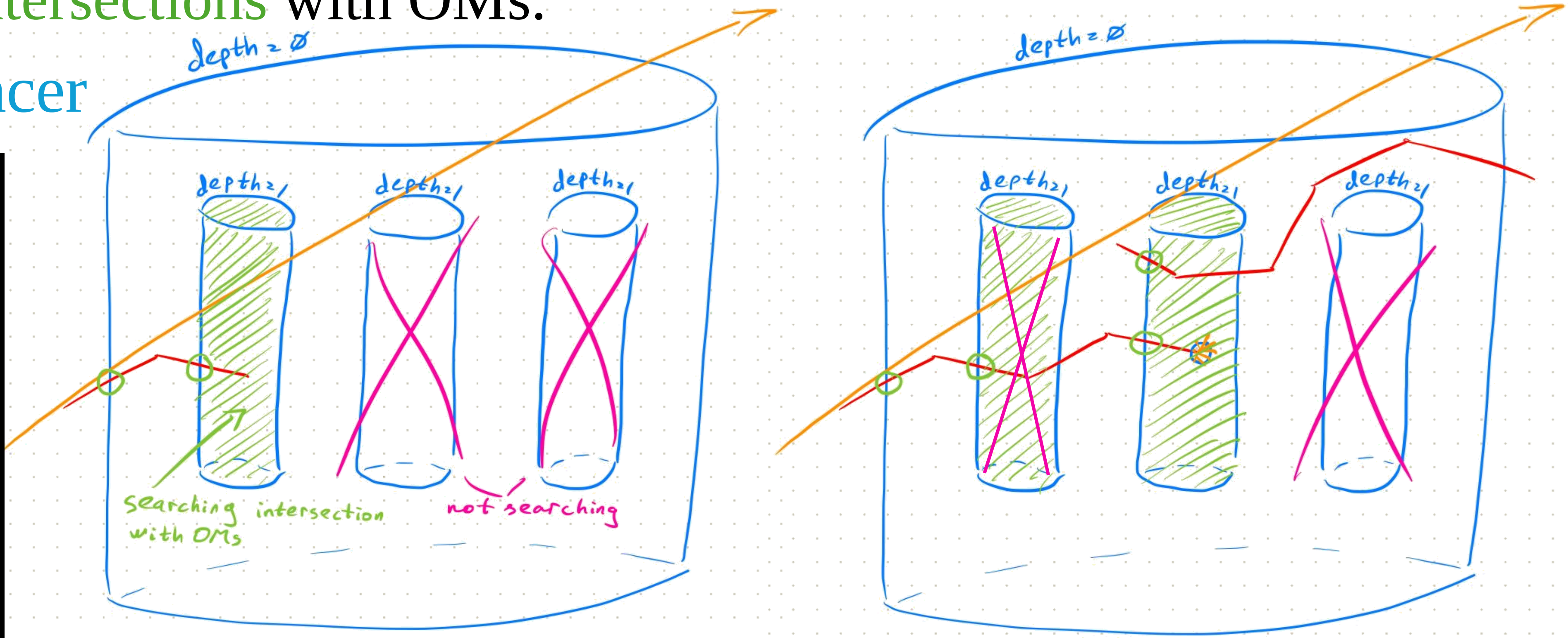




NTSim Structure: Ray Tracer

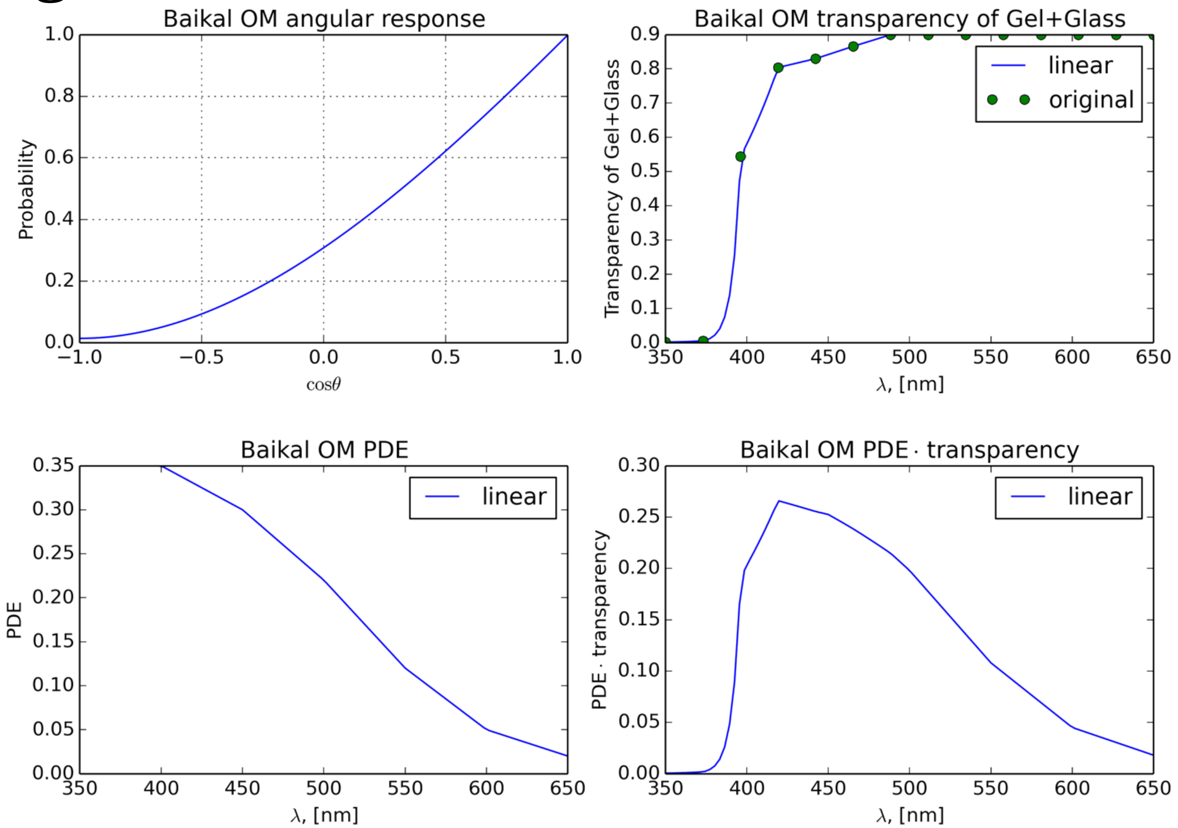
- The Ray Tracer algorithm is used to find where Cherenkov photon tracks intersect with bounding surfaces, followed by a search for intersections with OMs.
- SmartRayTracer





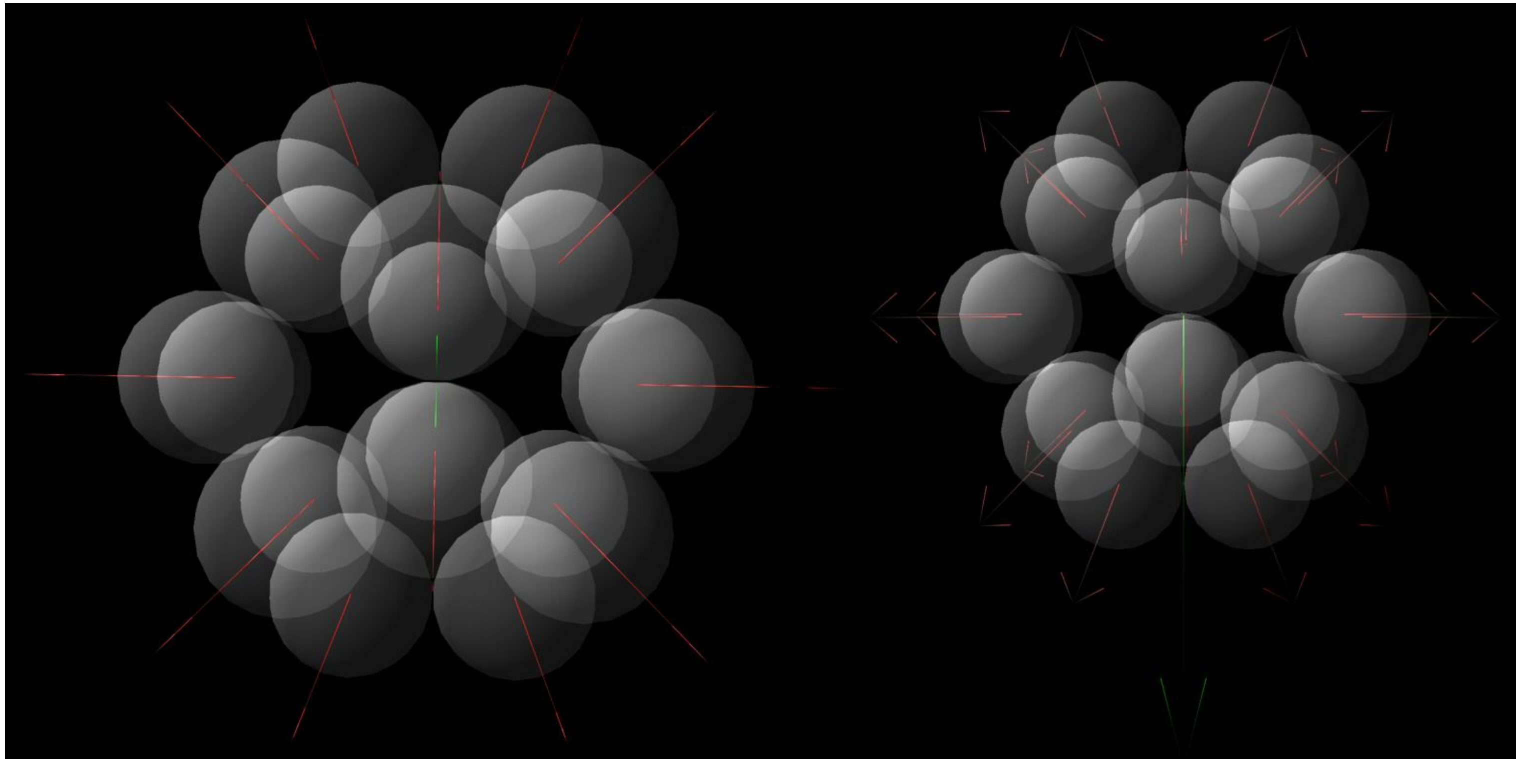
NTSim Structure:
Sensitive Detectors

- It has become possible to create an arbitrary optical detector with the possibility of adding detector effects.
- BGVDSensitiveDetector

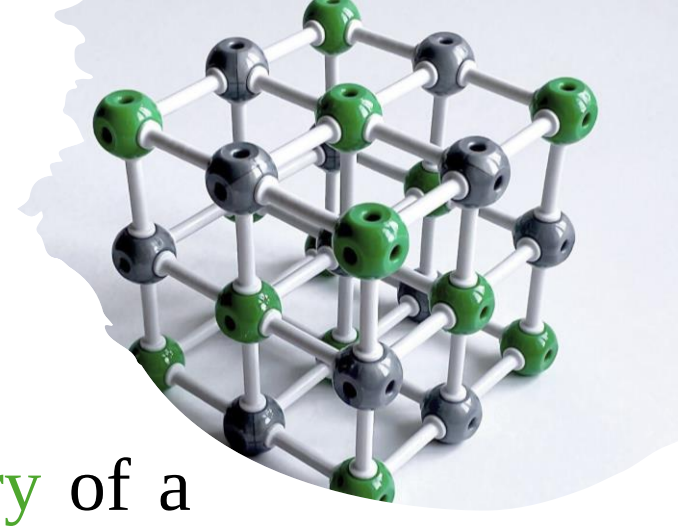


NTSim Structure:
Sensitive Detectors

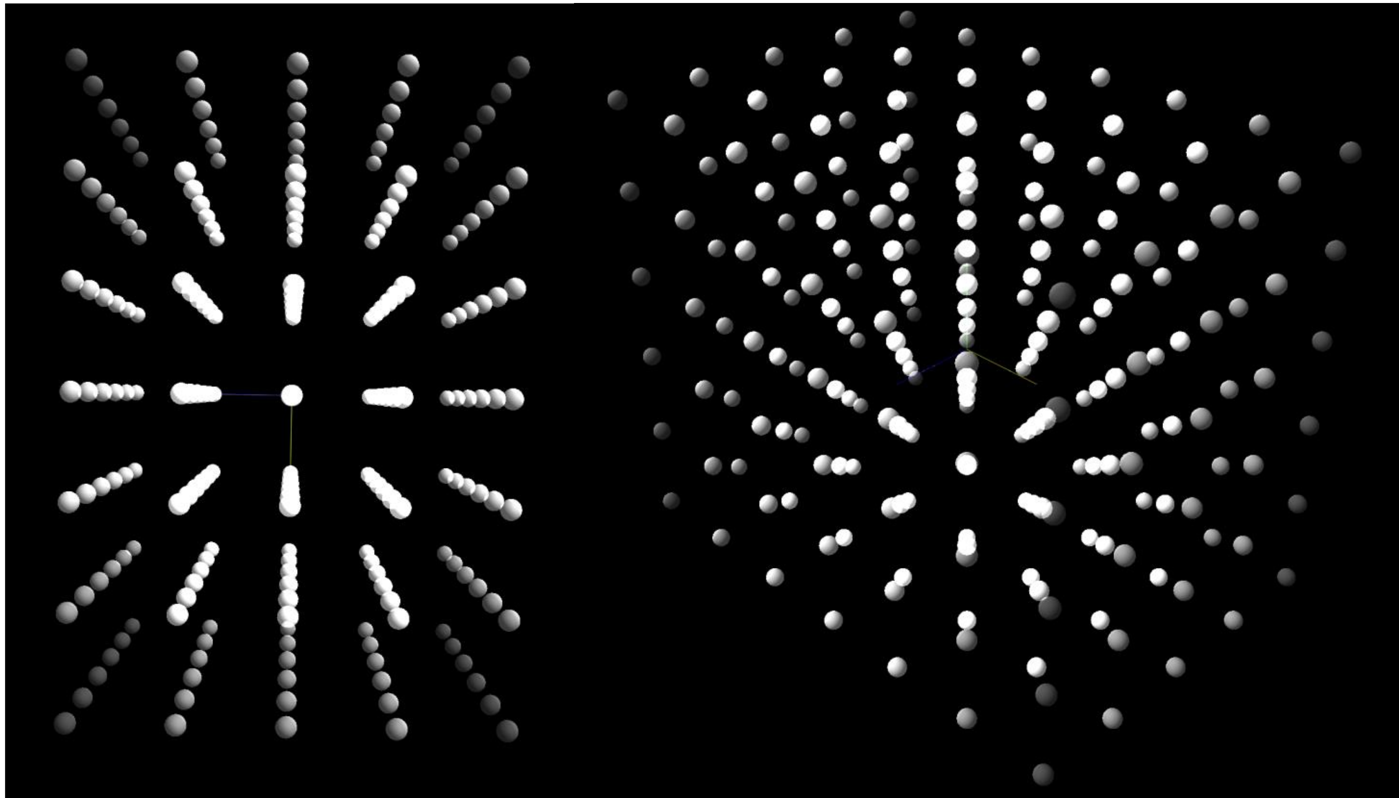
- It has become possible to create an arbitrary optical detector with the possibility of adding detector effects.
- BGVDSensitiveDetector
- FlyEyeSensitiveDetector
- …



NTSim Structure: Telescopes

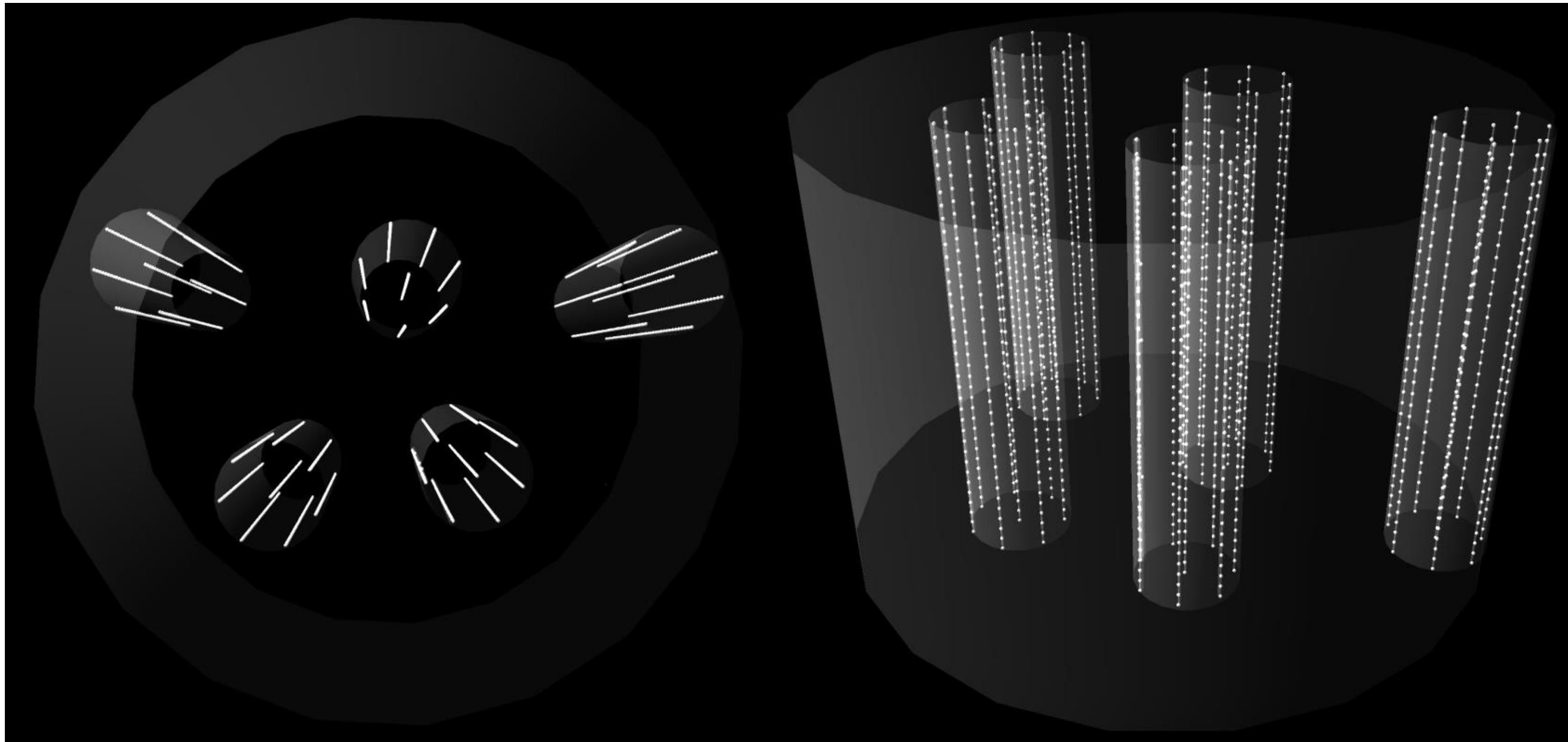


- It has become possible to create an arbitrary geometry of a neutrino telescope in NTSim.
- SimpleTelescope

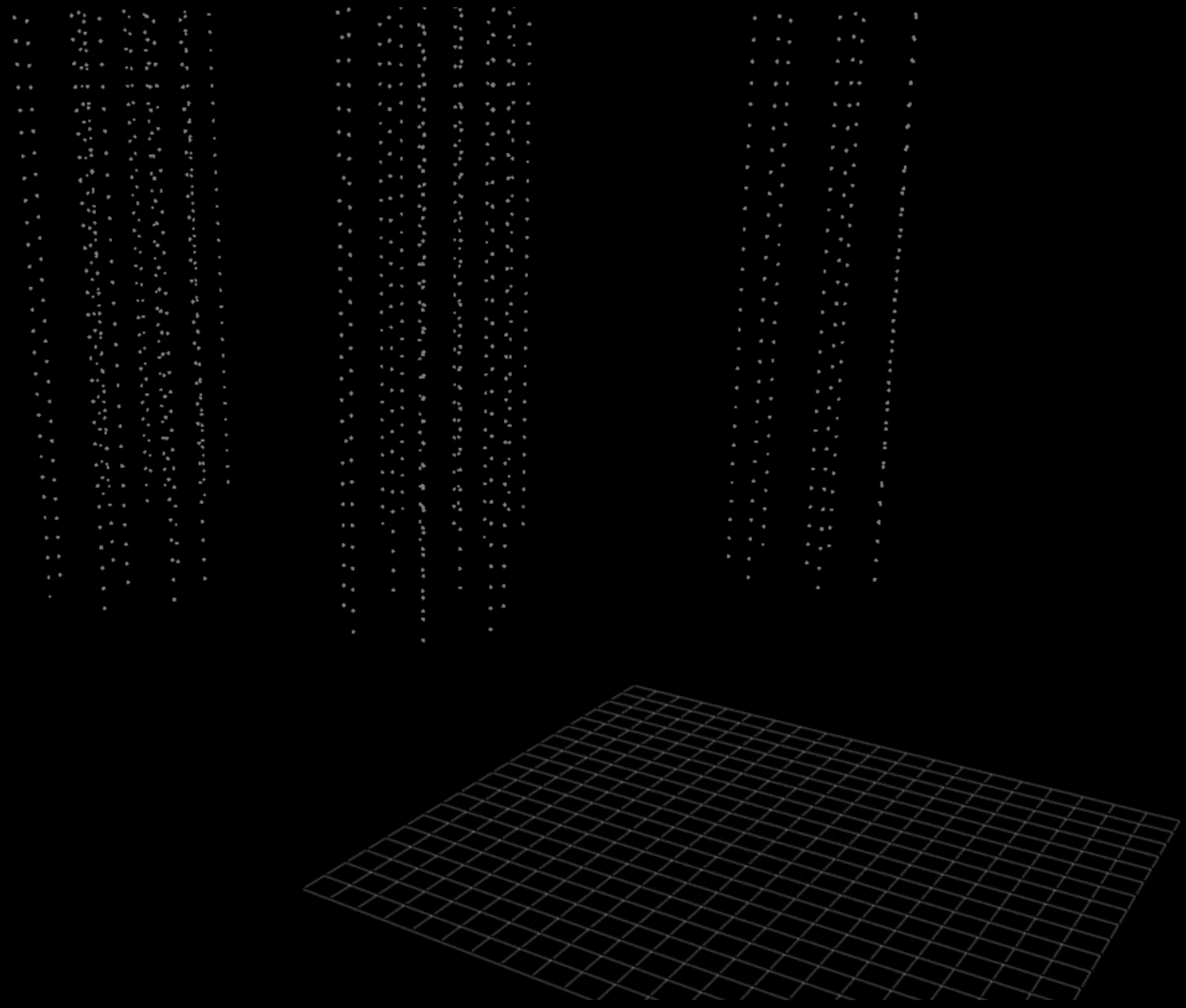


NTSim Structure: Telescopes

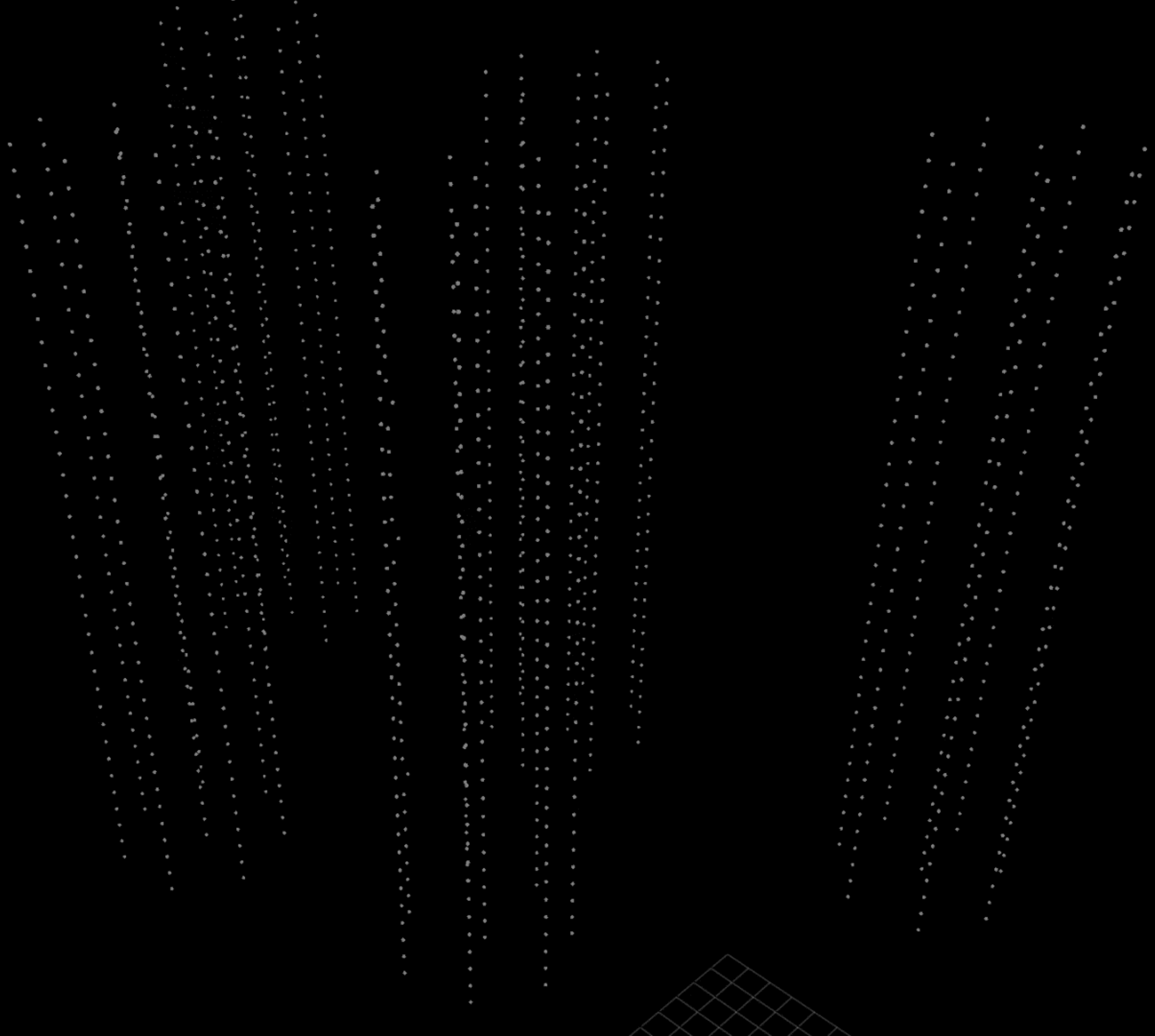
- It has become possible to create an arbitrary geometry of a neutrino telescope in NTSim.
- SimpleTelescope
- BGVDTelescope



$\nu_\mu n \to \mu^- \pi^+ n$

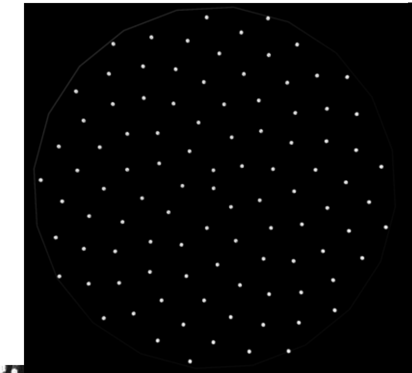


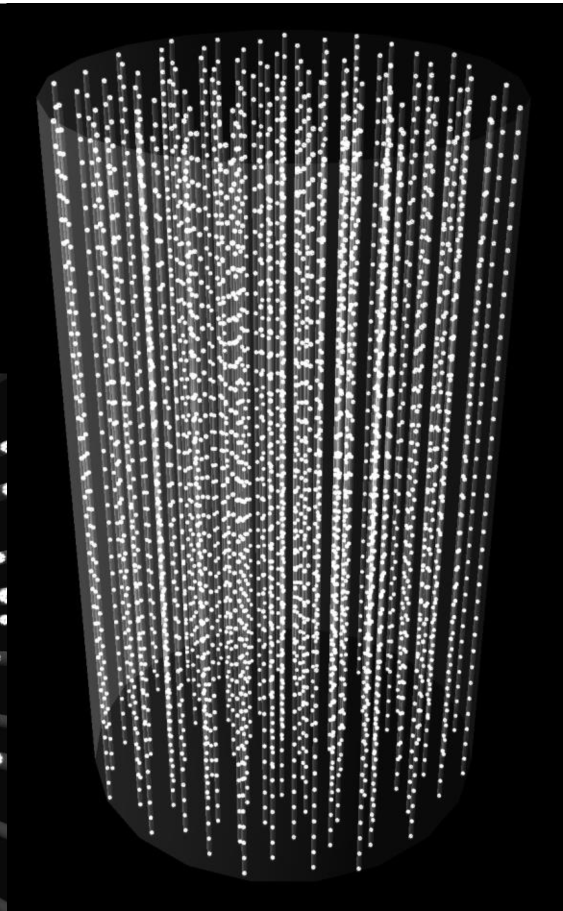
$\mu^-, 4\ TeV$

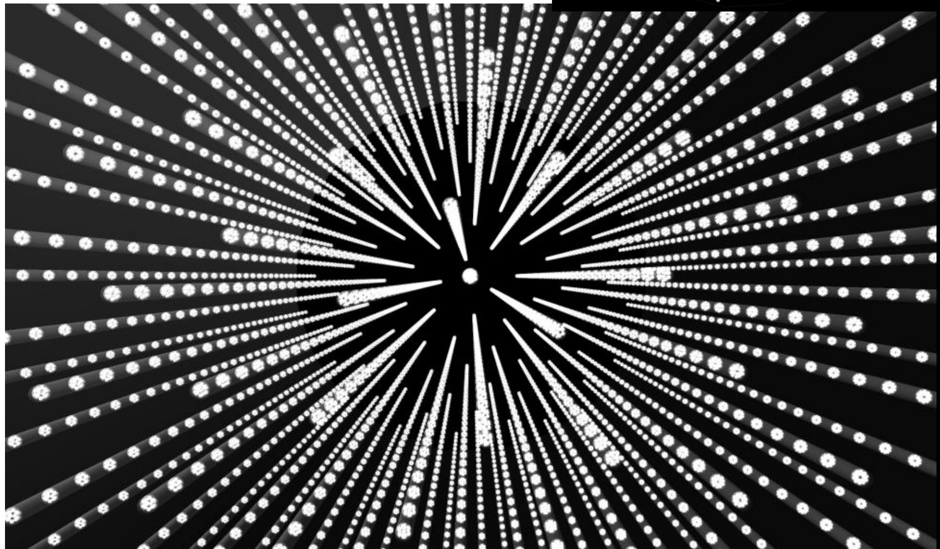


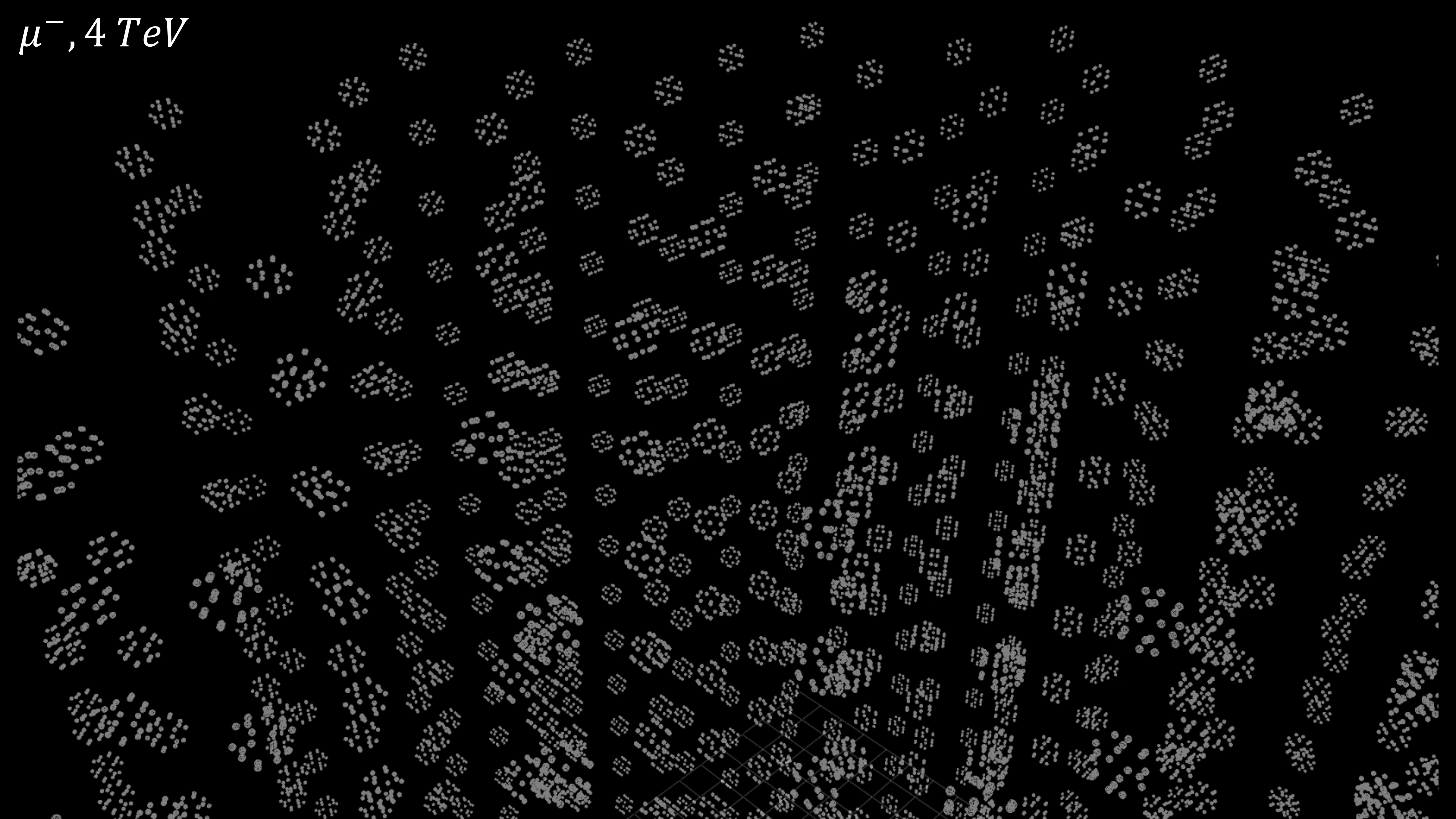
NTSim Structure: Telescopes

- It has become possible to create an arbitrary geometry of a neutrino telescope in NTSim.
- SimpleTelescope
- BGVDTelescope
- SunflowerTelescope



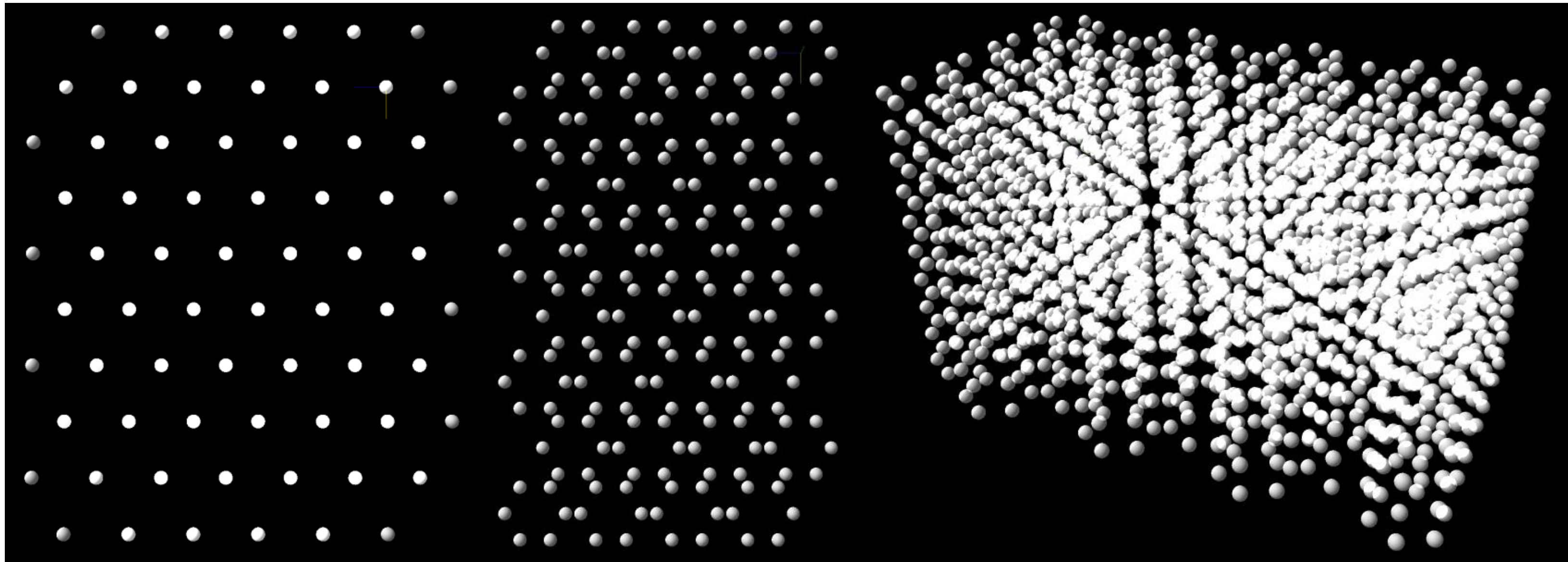


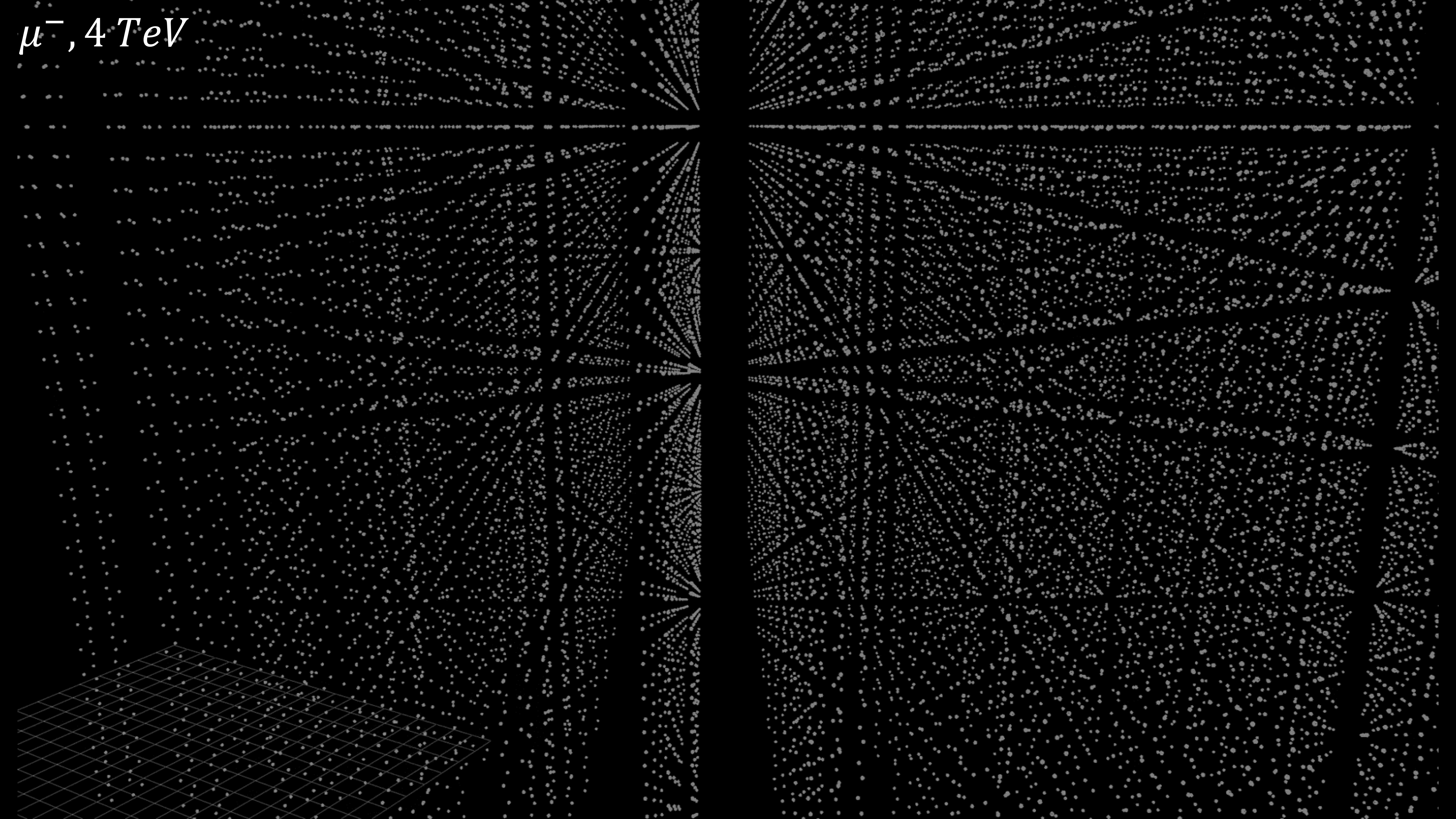



μ^-, 4 TeV

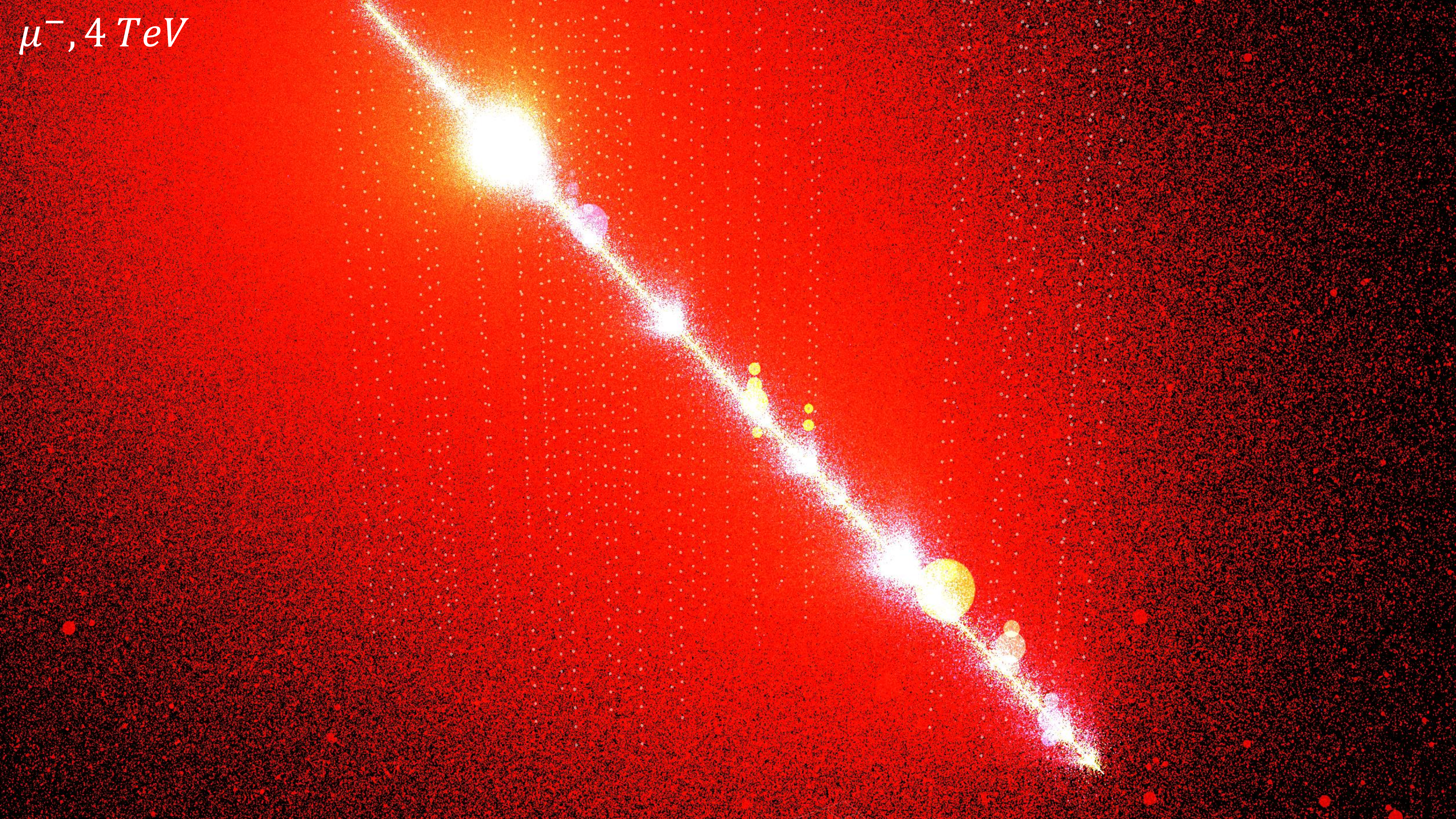
NTSim Structure: Telescopes

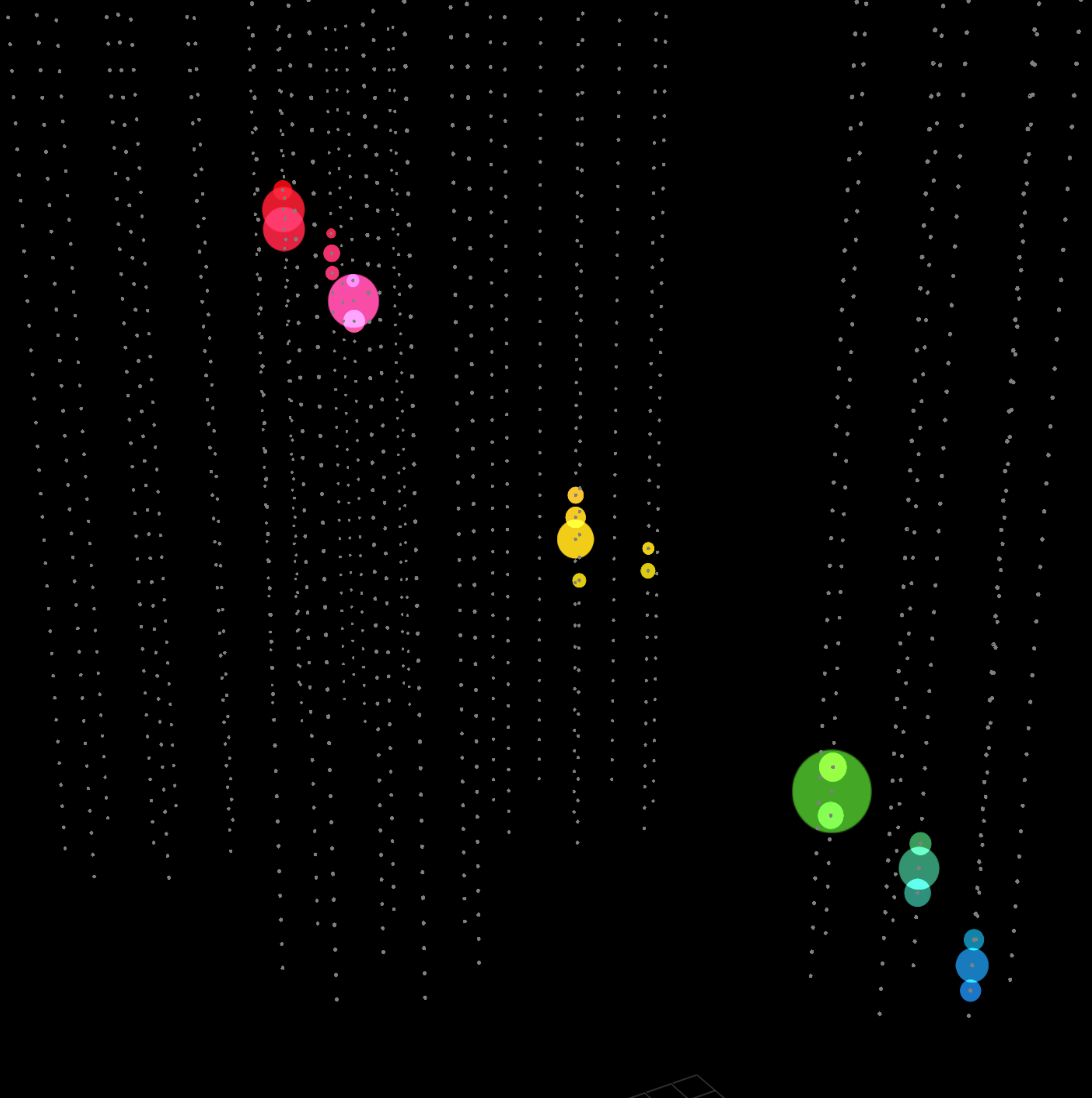
- It has become possible to create an arbitrary geometry of a neutrino telescope in NTSim.
- SimpleTelescope
- BGVDTelescope
- SunflowerTelescope
- HoneycombTelescope
- …

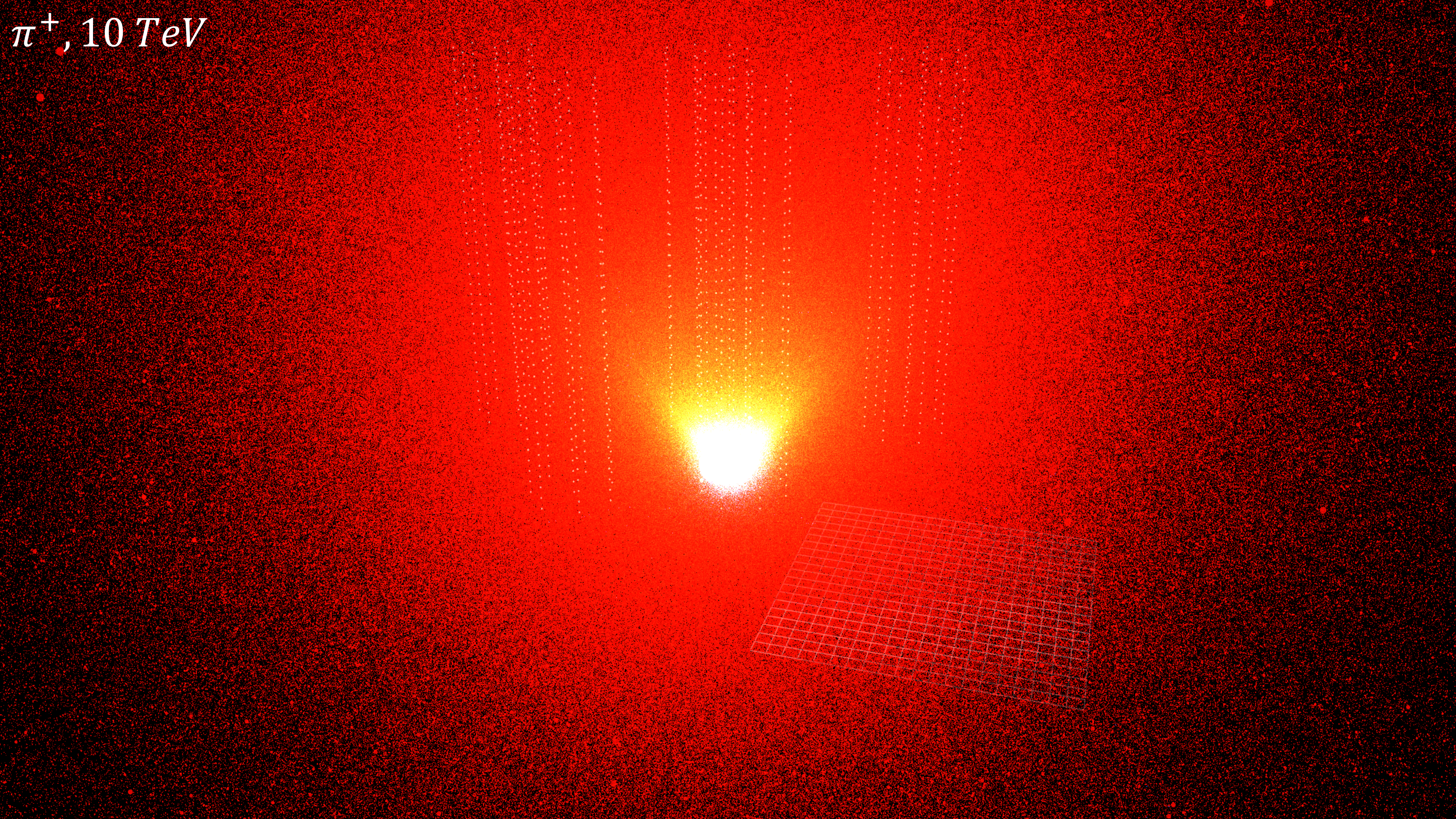


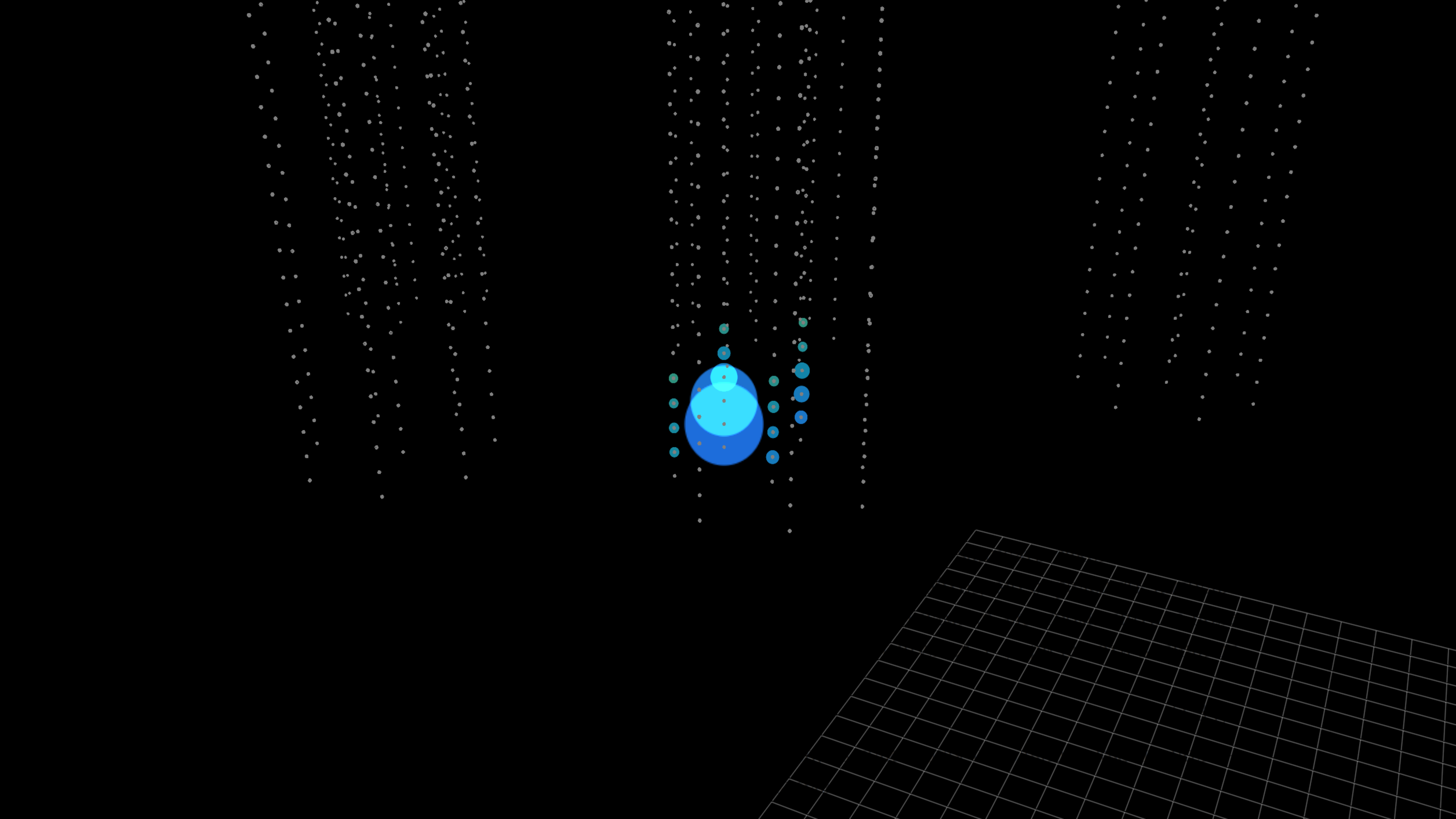


$\mu^-, 4\ TeV$


$\mu^-, 4\ TeV$




$\pi^+, 10\ TeV$



Summary

Key points:

- The NTSim provides a complete chain of neutrino event simulation and detector response.
- The package is easy to install via PyPI.
- To enhance efficiency, we utilize intelligent methods such as parameterizing e/m cascades, generating Cherenkov photons within the package, and rapid searching for hits.
- Top priority for the construction of next-generation neutrino telescopes such as TRIDENT or HUNT and reconstruction events in the Baikal-GVD.

Main NTSim modules:

- PrimaryGenerator: Generates primary interaction vertex using NuGen/ToyGen.
- Propagator: Propagates particles through the medium using Particulerator and MCPhotonTransporter.
- CherenkovGenerator: Generates Cherenkov photons from charged particle tracks and e/m cascades.
- RayTracer: Searches for segments of Cherenkov photon tracks intercepted by optical modules.
- Telescope: enables users to create their own neutrino telescope topologies.

Our team

- Dmitry Naumov (JINR)
- Dmitry Zaborov (INR RAS)
- Vladimir Allakhverdyan (JINR)
- Sergey Zavyalov* (JINR/MSU)
- Daniil Zubchenko (MSU)
- Irina Perevalova (ISU)
- Anna Belyakova (ISU)
- Ilya Chernousov (ISU)
- Yan Dubovik (Dubna)

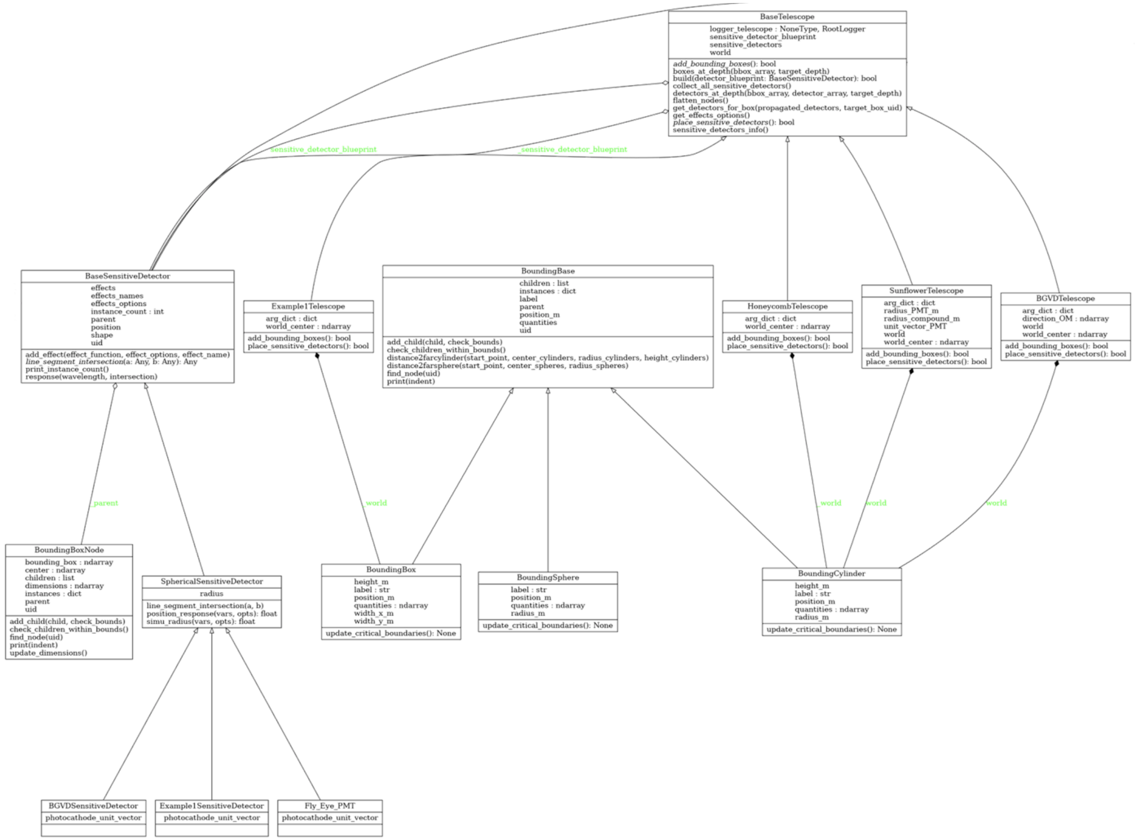
Thank you for your attention

Back-Up

Why is simulation needed?

Objectives of simulation

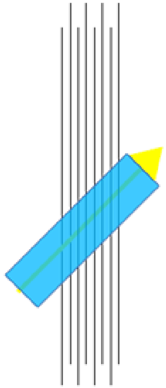
- Before the experiment
  - Optimization of the neutrino telescope design
  - Determination of the effective volume/area of the telescope
  - Calculation of expected signal values and background processes.
- Data analysis
  - Reconstruction of neutrino events
  - Comparison of analysis results with theoretical predictions



Baikal-GVD

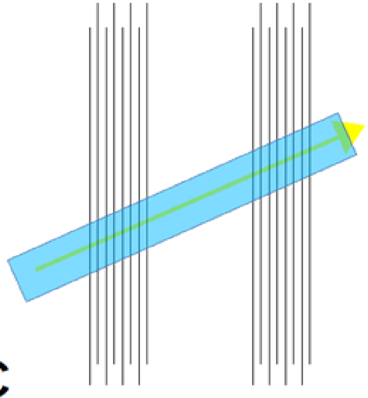
Event types

Single-cluster tracks



- Low energy threshold
- Optimal sensitivity to nearly vertical tracks
- 90% of recorded track events

Multi-cluster tracks

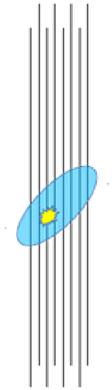


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- Best angular resolution

ν_μ CC

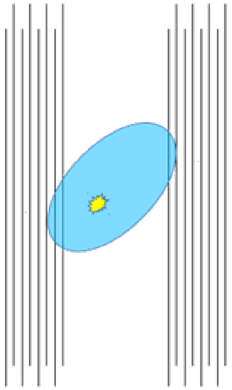
NC, ν_e ν_τ CC

Single-cluster cascades



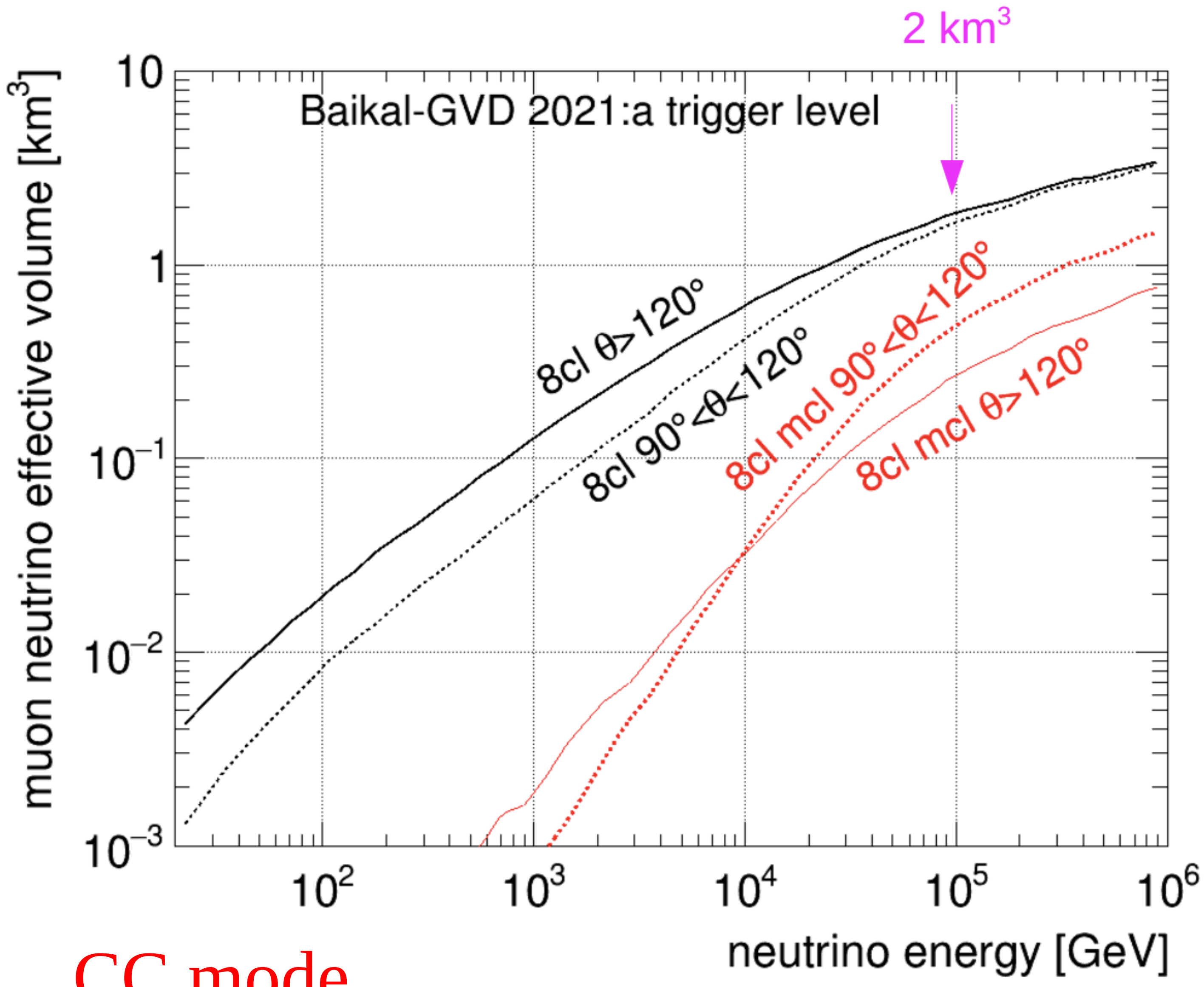
- High energy threshold
- Good energy resolution
- Relatively rare events

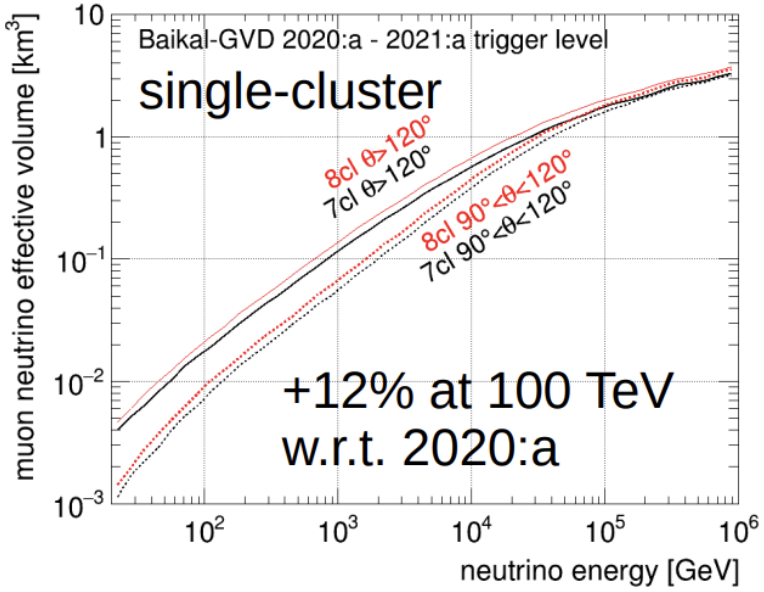
Multi-cluster cascades

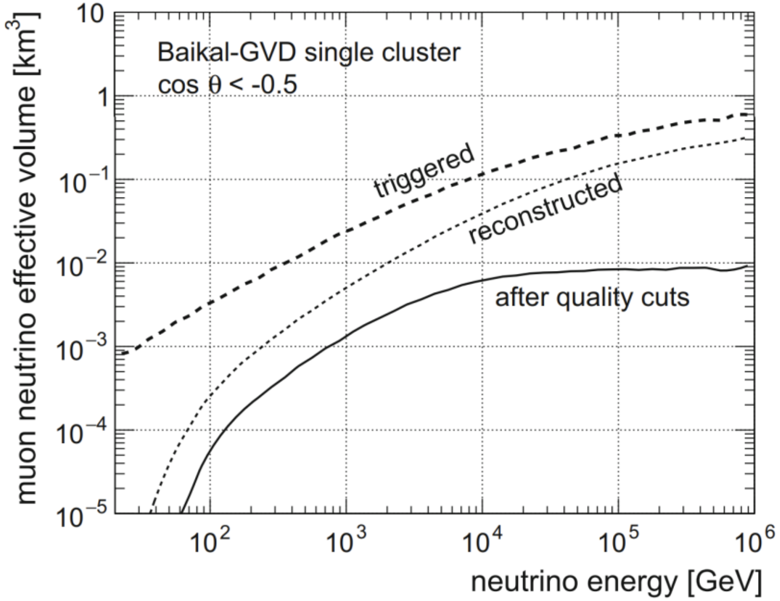


- Very high energy threshold
- Excellent energy resolution
- Very rare events

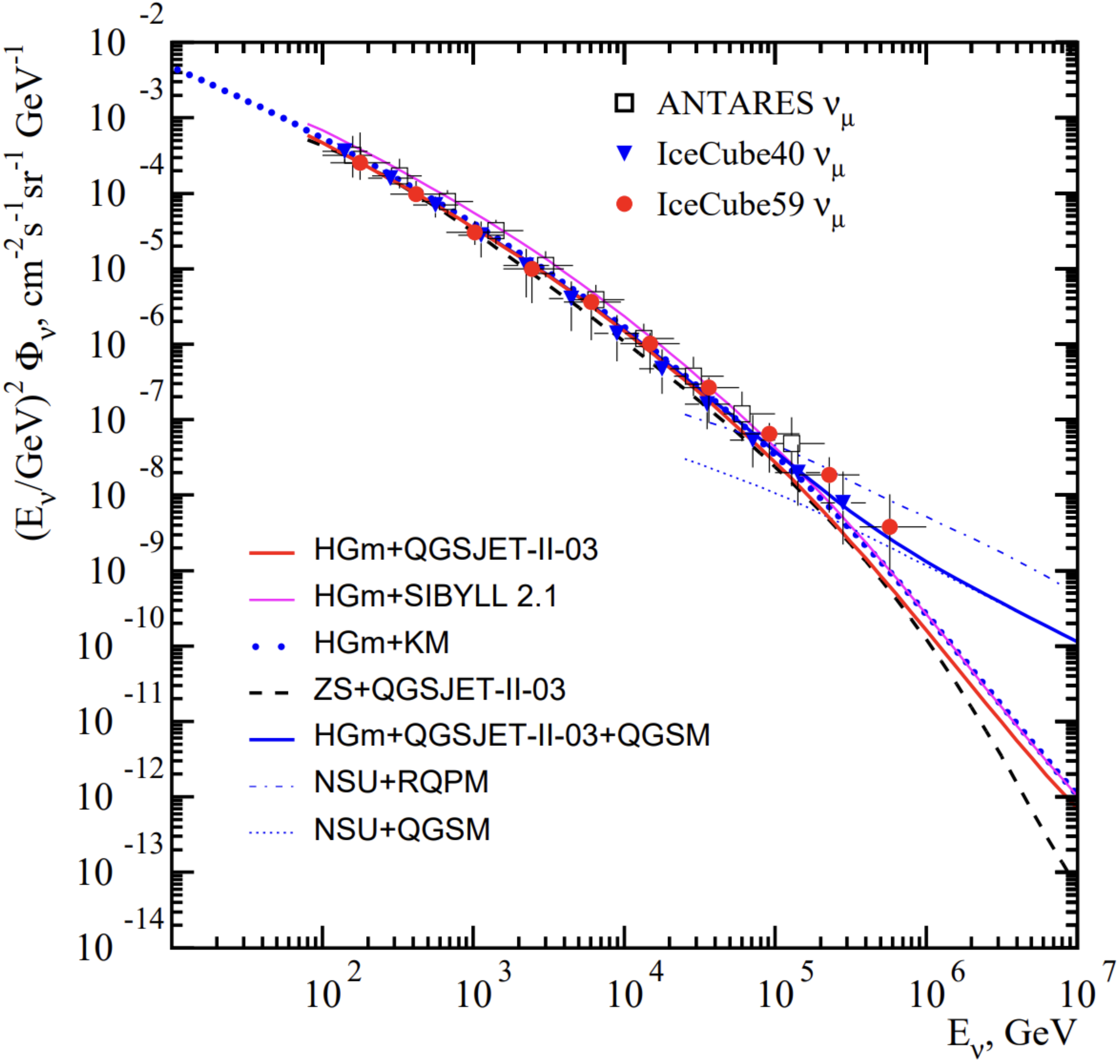
Effective volume at trigger level







CC mode



ANTARES ν_μ
IceCube40 ν_μ
IceCube59 ν_μ
HGm+QGSJET-II-03
HGm+SIBYLL 2.1
HGm+KM
ZS+QGSJET-II-03
HGm+QGSJET-II-03+QGSM
NSU+RQPM
NSU+QGSM
$(E_\nu/GeV)^2\,\Phi_\nu$, cm^{-2}s^{-1}sr^{-1} GeV^{-1}
E_ν, GeV

Structure functions

Реакция	$F_2^{\rm PM}/(2x)$
νp	$d_N \cos^2\theta_C + s_N \sin^2\theta_C + \overline{u}_N + \overline{c}_N +$ $\theta(x_{cs}-x)\,\theta(E_\nu - E_{cs})\left[d_c\sin^2\theta_C + s_c\cos^2\theta_C\right] +$ $\theta(x_{cd}-x)\,\theta(E_\nu-E_{cd})\left[d_c\sin^2\theta_C\right]$
νn	$u_N\cos^2\theta_C + s_N\sin^2\theta_C + \overline{d}_N + \overline{c}_N +$ $\theta(x_{cs}-x)\,\theta(E_\nu-E_{cs})\left[u_N\sin^2\theta_C + s_c\cos^2\theta_C\right]$
$\overline{\nu} p$	$u_N\cos^2\theta_C + c_N\sin^2\theta_C + \overline{d}_N + \overline{s}_N +$ $\theta(x_{c\overline{s}}-x)\,\theta(E_\nu-E_{c\overline{s}})\left[\left(u_N+\overline{d}_c-\overline{d}_N\right)\sin^2\theta_C + \left(c_N+\overline{s}_c-\overline{s}_N\right)\cos^2\theta_C\right] +$ $\theta(x_{c\overline{d}}-x)\,\theta(E_\nu-E_{c\overline{d}})\left[\left(u_N+\overline{d}_c-\overline{d}_N\right)\sin^2\theta_C + c_N\cos^2\theta_C\right]$
$\overline{\nu} n$	$d_N\cos^2\theta_C + c_N\sin^2\theta_C + \overline{u}_N + \overline{s}_N +$ $\theta(x_{c\overline{s}}-x)\,\theta(E_\nu-E_{c\overline{s}})\left[d_N\sin^2\theta_C + \left(c_N+\overline{s}_c-\overline{s}_N\right)\cos^2\theta_C\right]$

Реакция	$F_3^{\rm PM}/2$
νp	$d_N \cos^2\theta_C + s_N \sin^2\theta_C - \overline{u}_N - \overline{c}_N +$ $\theta(x_{cs}-x)\,\theta(E_\nu - E_{cs})\left[d_c\sin^2\theta_C + s_c\cos^2\theta_C\right] +$ $\theta(x_{cd}-x)\,\theta(E_\nu-E_{cd})\left[d_c\sin^2\theta_C\right]$
νn	$u_N\cos^2\theta_C + s_N\sin^2\theta_C - \overline{d}_N - \overline{c}_N +$ $\theta(x_{cs}-x)\,\theta(E_\nu-E_{cs})\left[u_N\sin^2\theta_C + s_c\cos^2\theta_C\right]$
$\overline{\nu} p$	$u_N\cos^2\theta_C + c_N\sin^2\theta_C - \overline{d}_N - \overline{s}_N +$ $\theta(x_{c\overline{s}}-x)\,\theta(E_\nu-E_{c\overline{s}})\left[\left(u_N-\overline{d}_c+\overline{d}_N\right)\sin^2\theta_C + \left(c_N-\overline{s}_c+\overline{s}_N\right)\cos^2\theta_C\right] +$ $\theta(x_{c\overline{d}}-x)\,\theta(E_\nu-E_{c\overline{d}})\left[\left(u_N-\overline{d}_c+\overline{d}_N\right)\sin^2\theta_C + c_N\cos^2\theta_C\right]$
$\overline{\nu} n$	$d_N\cos^2\theta_C + c_N\sin^2\theta_C - \overline{u}_N - \overline{s}_N +$ $\theta(x_{c\overline{s}}-x)\,\theta(E_\nu-E_{c\overline{s}})\left[d_N\sin^2\theta_C + \left(c_N-\overline{s}_c+\overline{s}_N\right)\cos^2\theta_C\right]$

$$F_4(x,Q^2) \approx \frac{1}{2}\left(\frac{F_2(x,Q^2)}{2x} - F_1(x,Q^2)\right) = \frac{1}{2}\left(\frac{1}{\mathfrak{D}(x,Q^2)} - 1\right)F_1,$$

$$F_5(x,Q^2) \approx \frac{F_2(x,Q^2)}{2x} = \frac{F_1(x,Q^2)}{\mathfrak{D}}.$$

$$F_1(x,Q^2) = \left(1 - a + a\mathfrak{D}(x,Q^2)\right)F_1^{\rm PM}(x,Q^2),$$

$$F_2(x,Q^2) = \left[a + (1-a)/\mathfrak{D}(x,Q^2)\right]F_2^{\rm PM}(x,Q^2),$$

$$\mathfrak{D}(x,Q^2)F_2(x,Q^2) = 2xF_1(x,Q^2)$$

$$\mathfrak{D}(x,Q^2) = \frac{1}{1+R(x,Q^2)}\left(1+\frac{Q^2}{\nu^2}\right)$$

$$F_L(x,Q^2) = \left(1+Q^2/\nu^2\right)F_2(x,Q^2) - 2xF_1(x,Q^2)$$

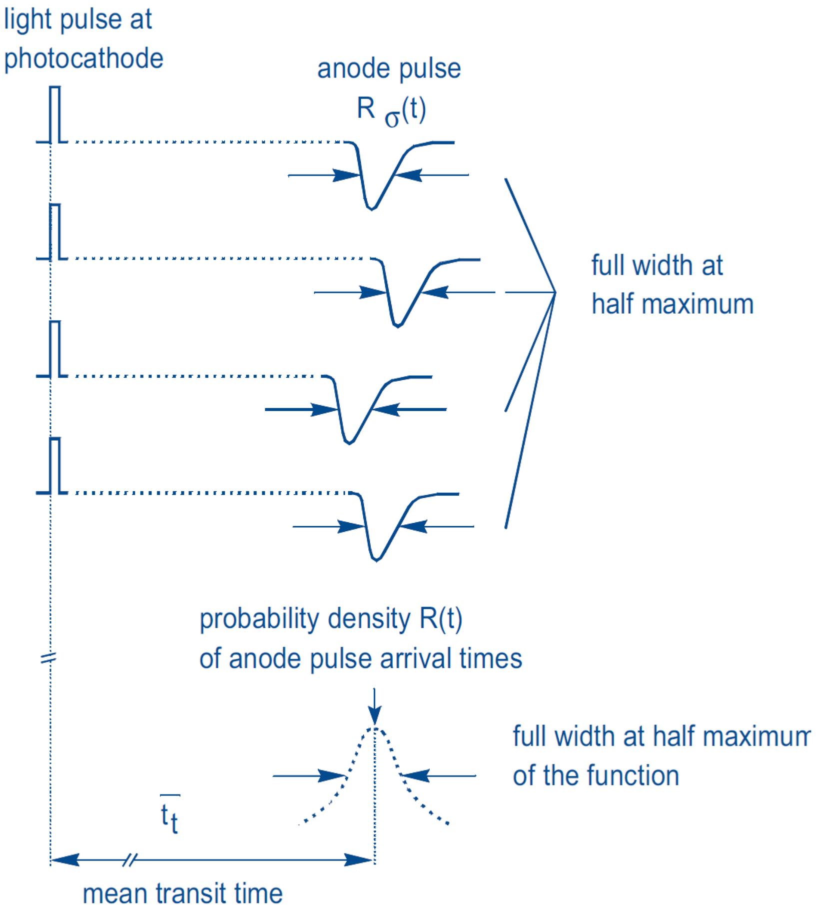
$$W_{\alpha\beta}(p,q) = -g_{\alpha\beta}W_1 + \frac{p_\alpha p_\beta}{M^2}W_2 - i\frac{\epsilon_{\alpha\beta\gamma\delta}p^\gamma q^\delta}{2M^2}W_3 + \frac{q_\alpha q_\beta}{M^2}W_4 + \frac{p_\alpha q_\beta + q_\alpha p_\beta}{2M^2}W_5 + i\frac{p_\alpha q_\beta - q_\alpha p_\beta}{2M^2}W_6.$$

$$W_1^{\rm DIS}(x,Q^2) = F_1(x,Q^2), \quad W_n^{\rm DIS}(x,Q^2) = w^{-1}F_n(x,Q^2)$$

$n = 2,\ldots,6,\ Q^2 = -q^2,\ x = Q^2/2(pq),\ w = (pq)/M^2.$

NTSim Structure: Triggers

- Triggers allow to perform an initial analysis of MC data before converting to BARS
- BGVDTrigger
  - Transit time spread*
  - Single-cluster trigger (arXiv:2106.06288)
    - two neighboring OMs within the same section
    - 100 ns time window
    - hits magnitude: $A_1 = 3.5$, $A_2 = 1.7$ p.e.
    - 5 μs event time frame



*without any diffuseness of the signal