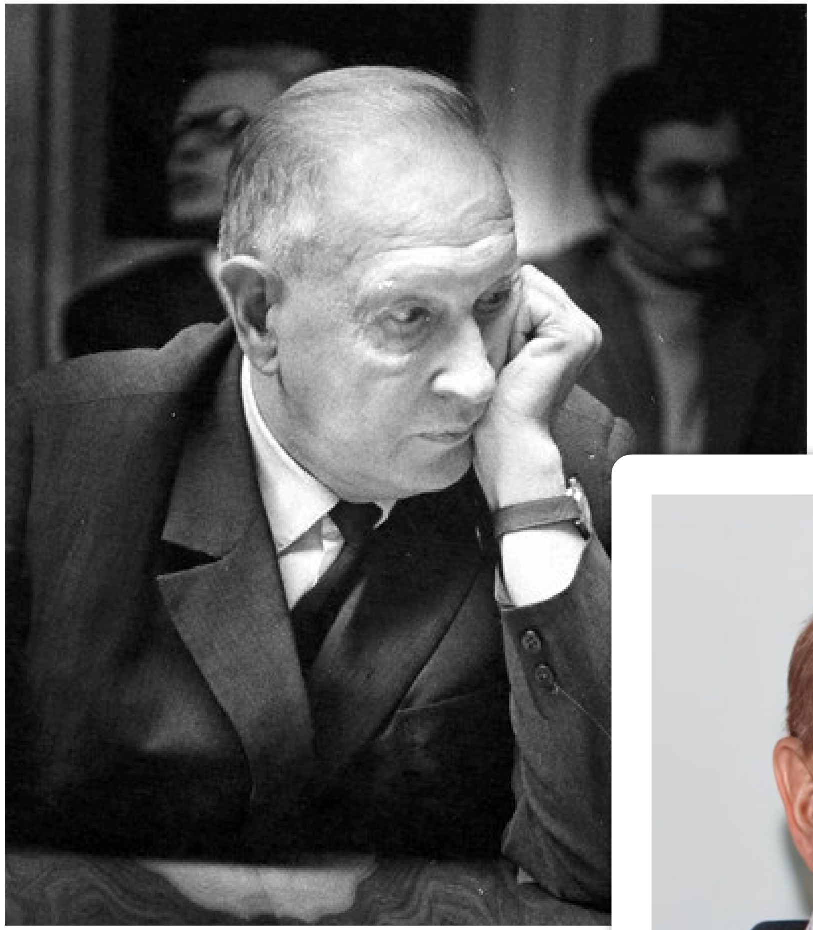
Astrophysical neutrino detection

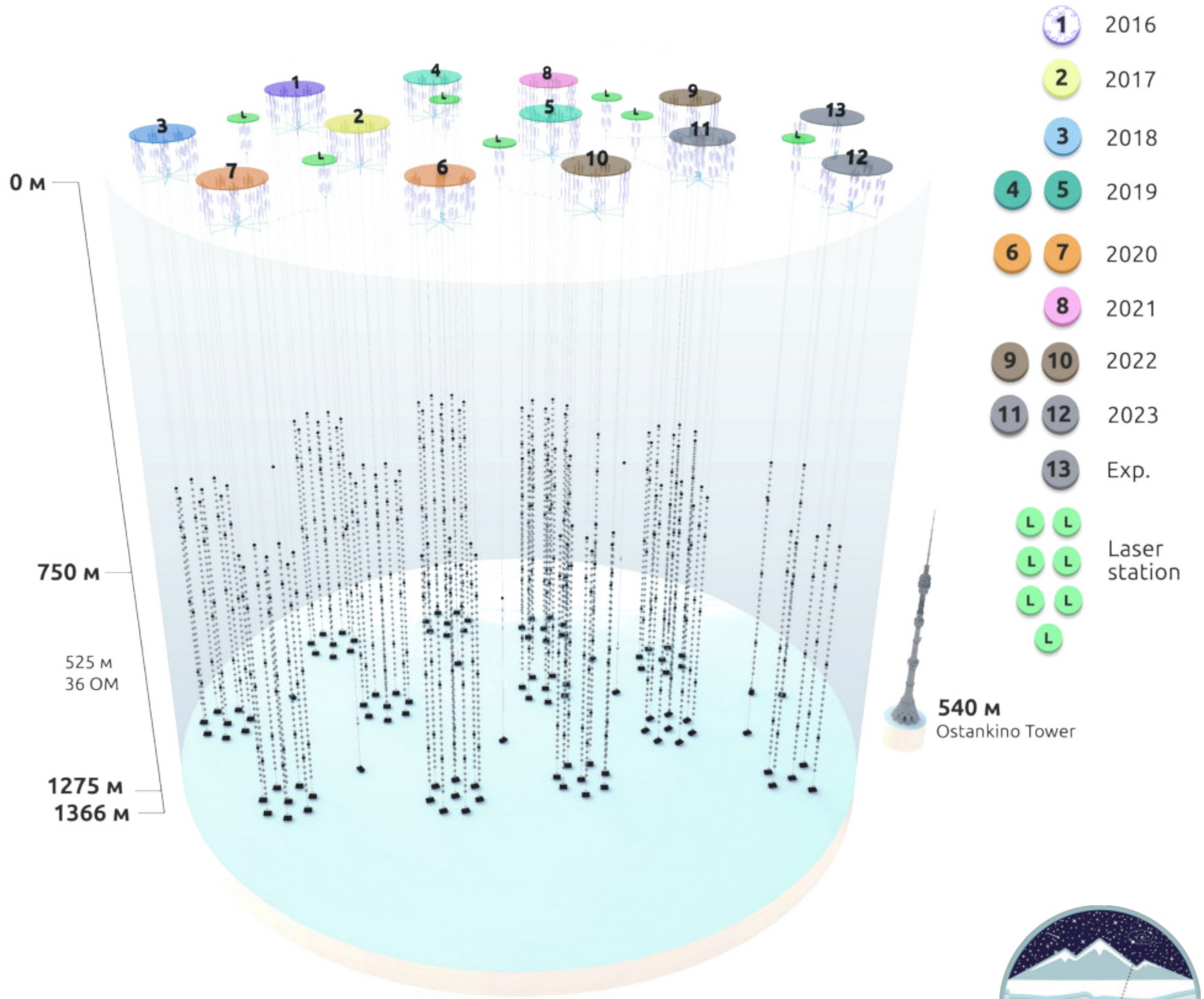
- Moses Markov & Igor Zhelezny proposed (1960) creating a network of optical detectors in a transparent natural environment (water/ice) to register optical flashes (Cherenkov radiation) from neutrino interactions.

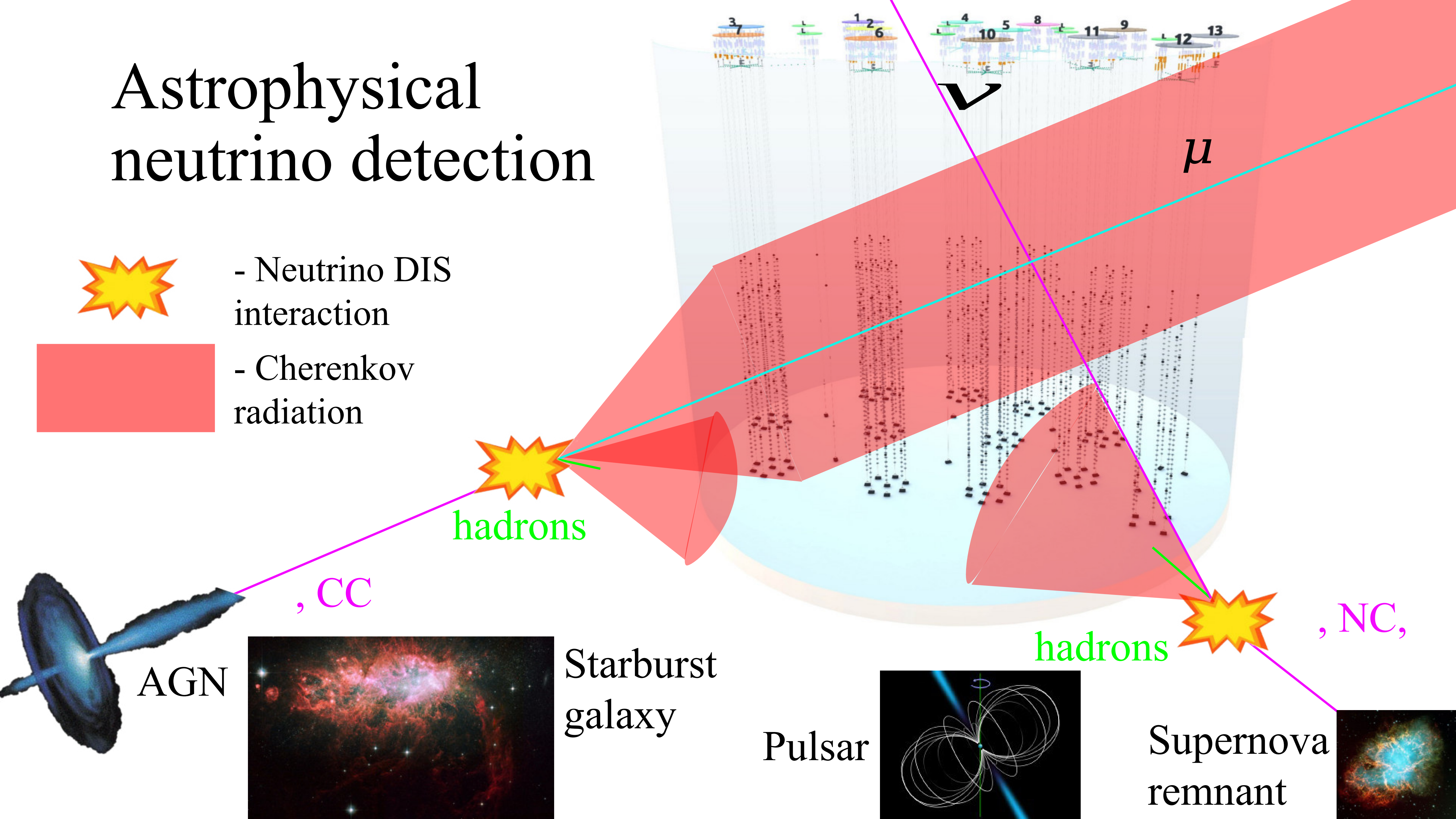


Baikal-GVD

- GVD – Gigaton Volume Detector
- Current instrumental volume
- 36 Optical Modules (OMs) per 1 string
- 8 strings in 1 cluster
- Total 13 clusters
- 4032 OMs

([Proc. Sci. ICRC2021, 395, 002](#))




Astrophysical
neutrino detection
- Neutrino DIS
interaction
- Cherenkov
radiation
ν
μ
hadrons
, CC
hadrons
, NC,
AGN
Starburst
galaxy
Pulsar
Supernova
remnant

Goals and purposes of the work

- Designing the NTSim software package for modelling neutrino telescope.
- Developing a neutrino generator for simulating the passage of neutrinos through the Earth.
- Creating a Cherenkov generator to simulate the production of Cherenkov photons.
- Developing parameterization methods for the longitudinal and angular distribution of Cherenkov photons from high-energy electromagnetic cascades.
- Evaluating the efficiency of neutrino-induced event detection in the Baikal-GVD experiment.

Underlying principles

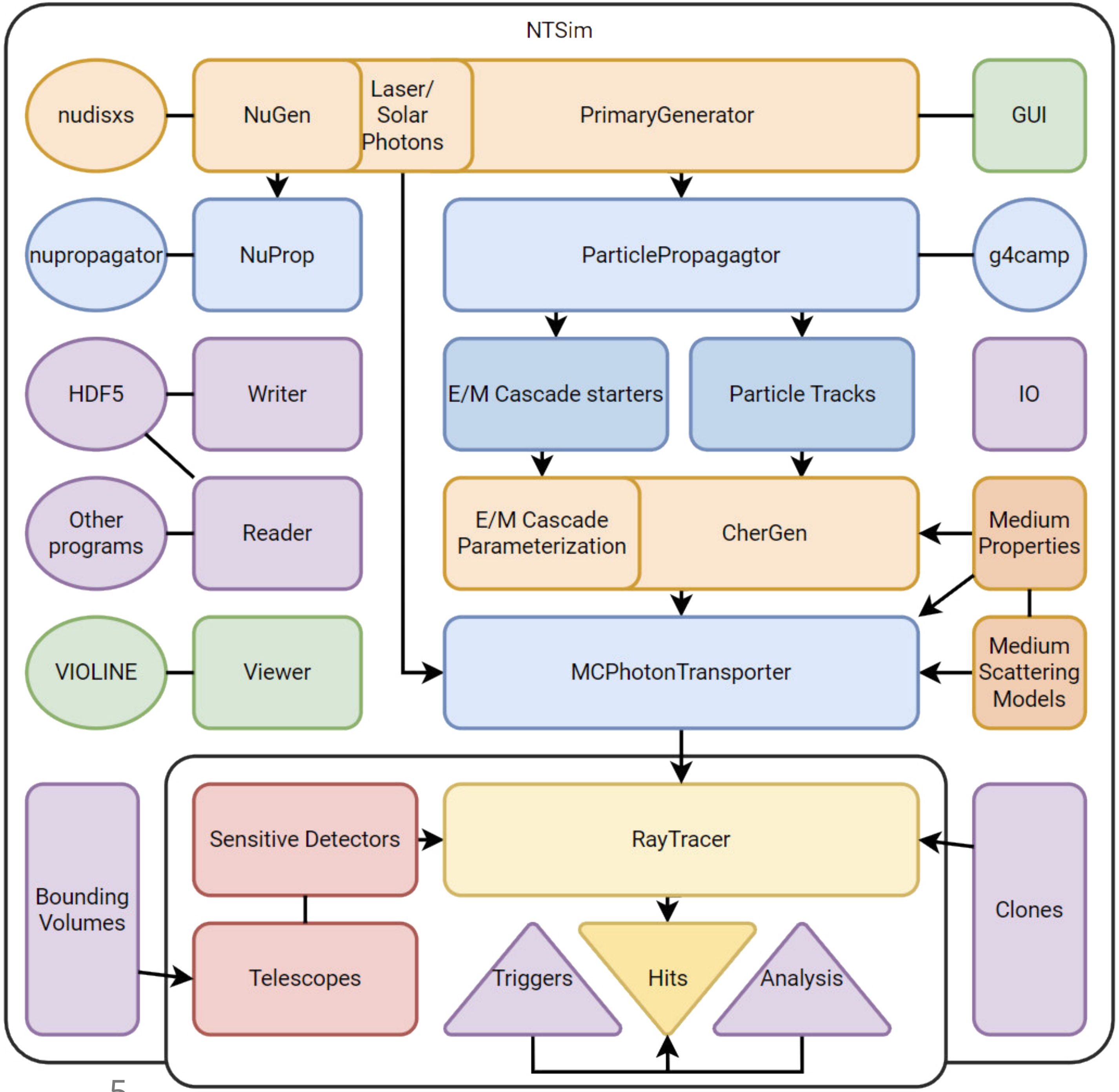
Simulation quality/efficiency

- Parametrization 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 vast range of neutrino telescopes

User friendly →Python, GUI



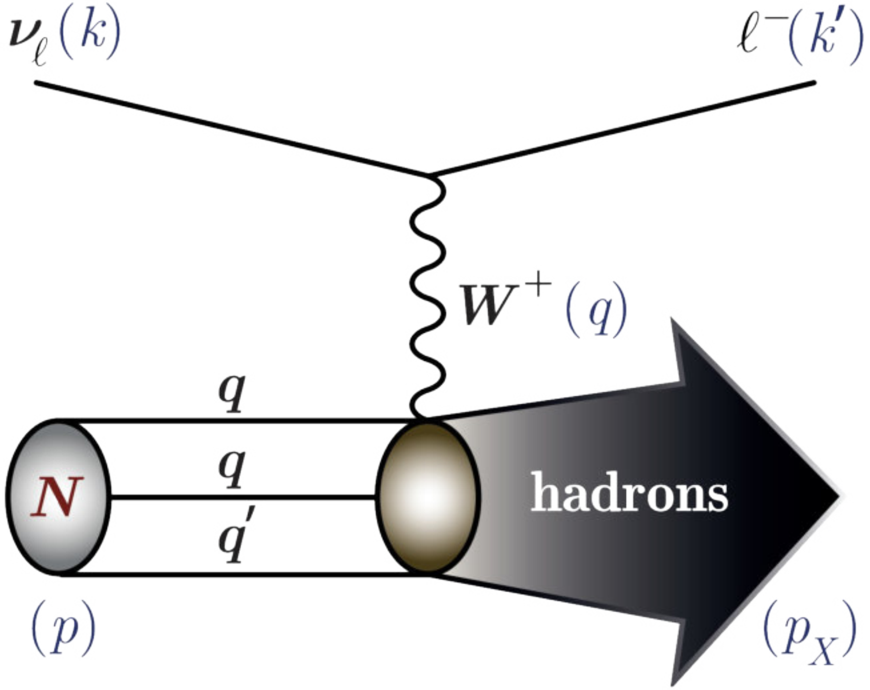
NTSim Structure: Primary Generators

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) - GeV



Experimentally measured Structure functions are expressed in terms of Parton Distribution Functions (PDFs) → LHAPDF library

NTSim Generators: NuGen

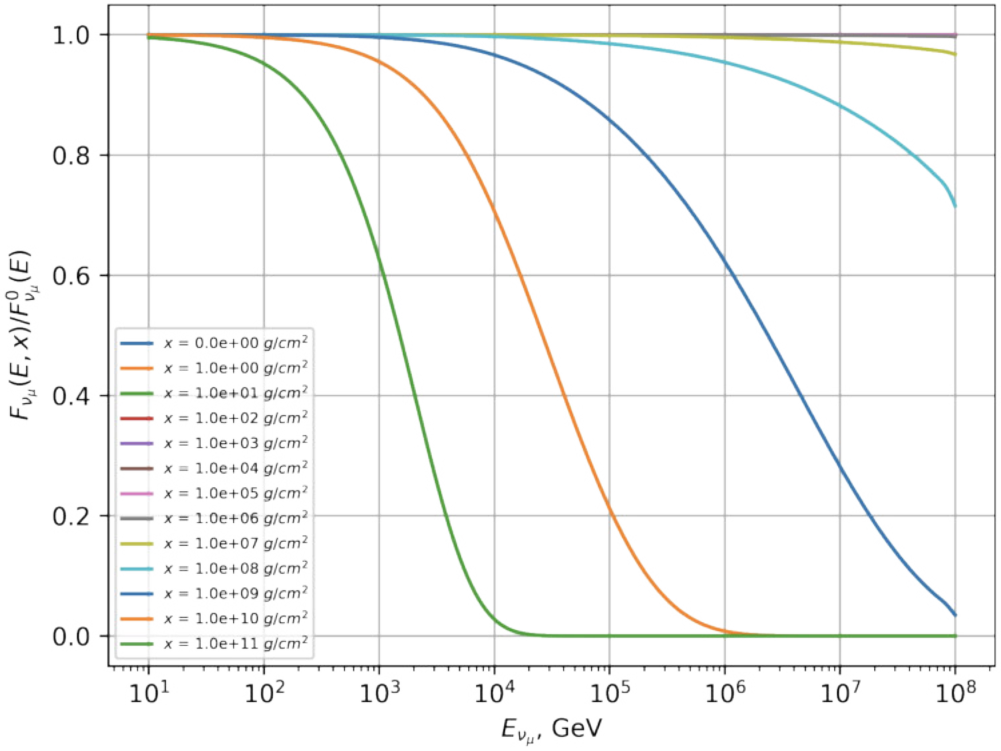
- Propagate through Earth: Z-factor method

(arXiv:hep-ph/9804301)

  - \- column depth
  - \- neutrino interaction length

,

,

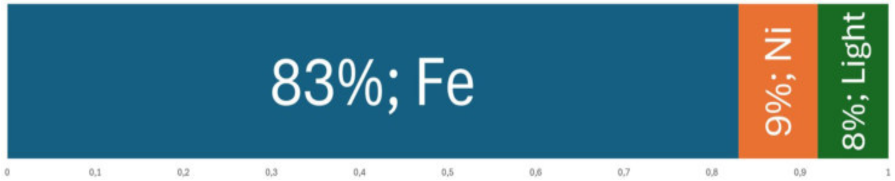


The ratio of the atmospheric flux at depth to the initial neutrino flux.

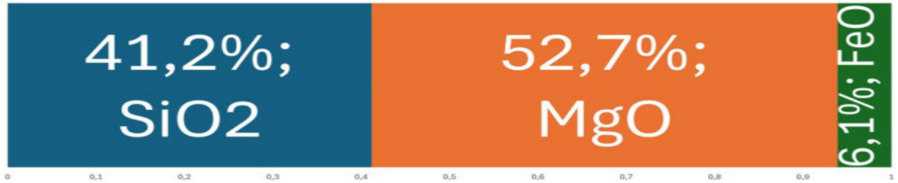
NTSim Generators: NuGen

Preliminary reference Earth model (PREM):

- Core:

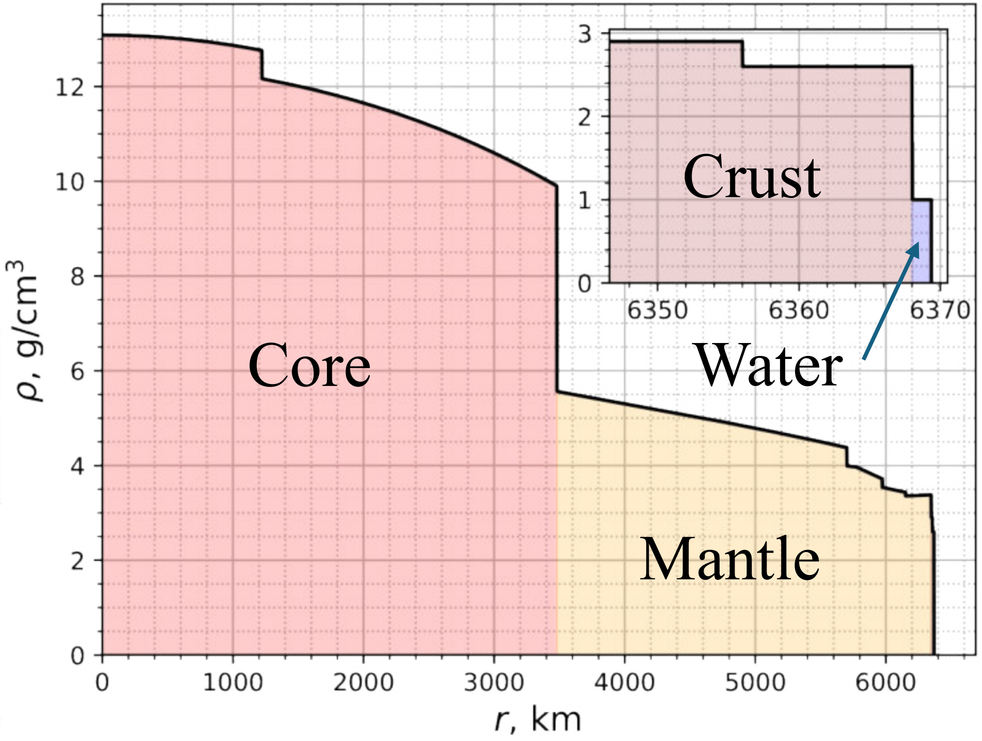


- Mantle:

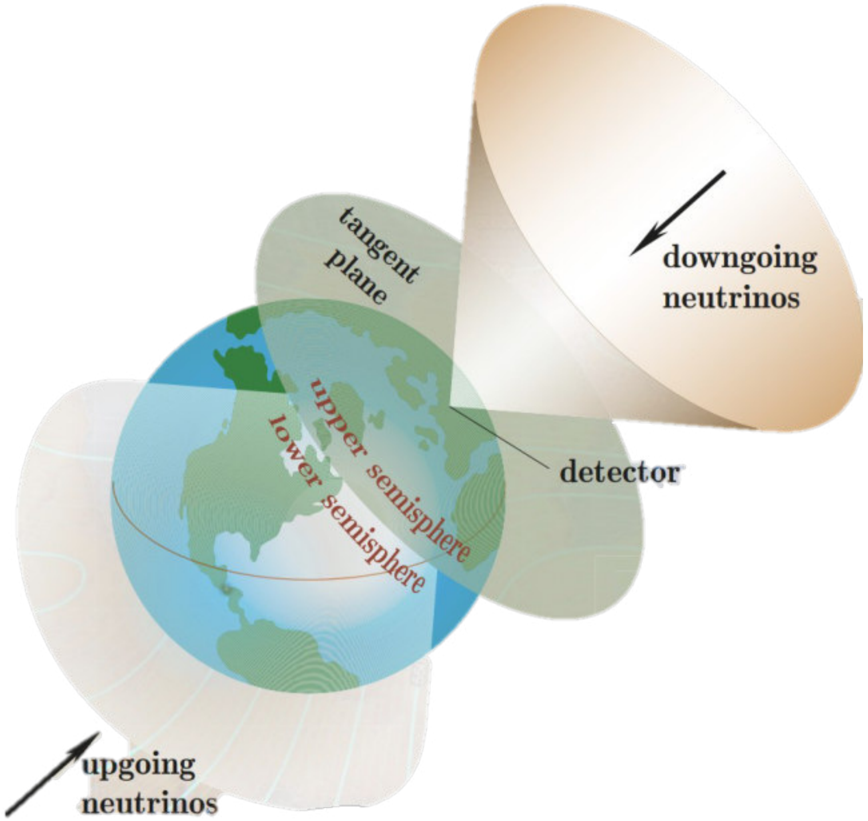


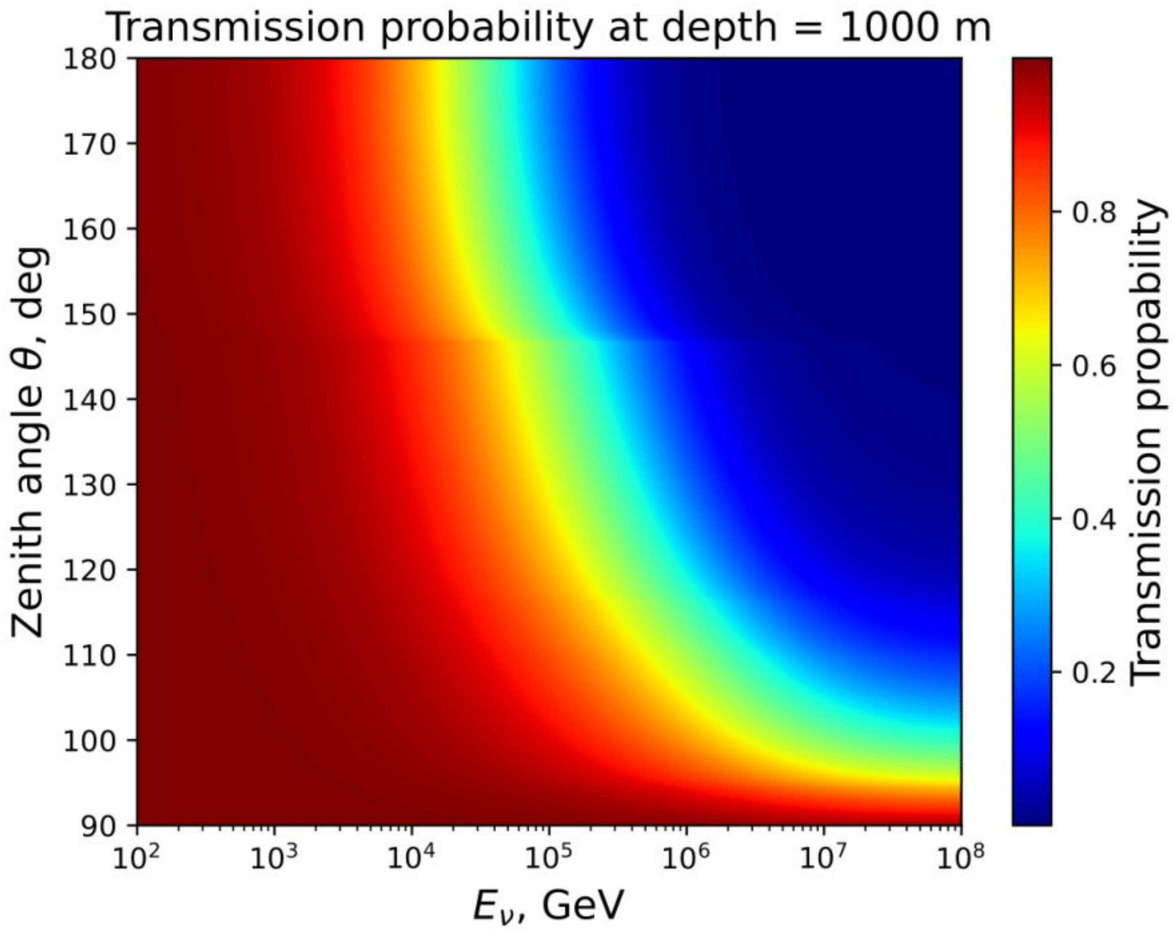
- Crust:

- Water:



NTSim Generators: NuGen

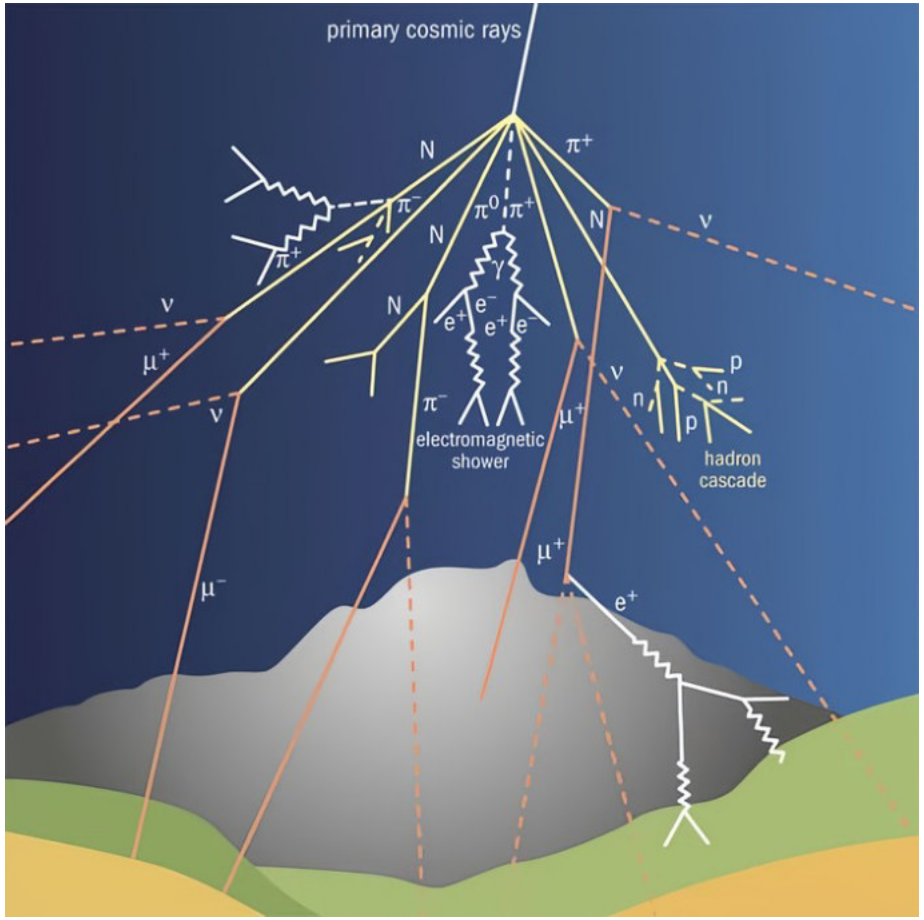




Why the upgoing flux?

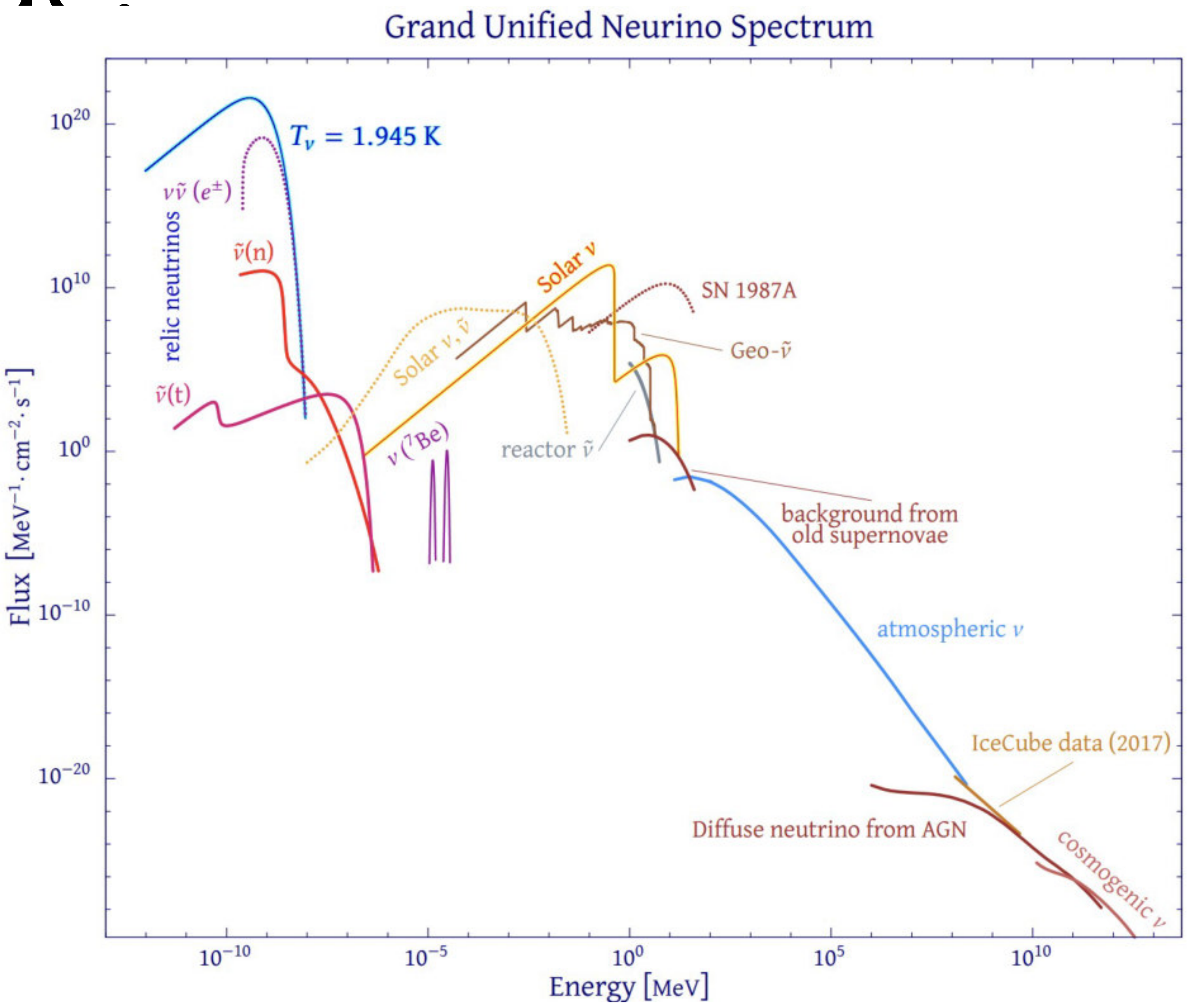
-
- sec
- km

Atmospheric neutrinos & muons are an unavoidable background for experiments to search for astrophysical neutrinos



Why the energy range?

- At TeV, we can distinguish between the atmospheric and astrophysical neutrino spectra (if we know well the processes occurring in atmospheric cascades)
- The identification of astrophysical neutrinos occurs based on the excess of the expected number of events for atmospheric neutrinos and muons

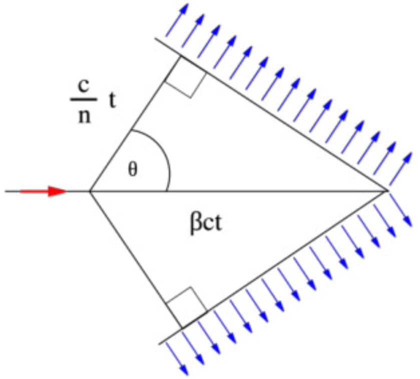


NTSim Structure: Propagators

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
- NuProp
  - 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 + Rayleigh)
- Radiative Transport Equation (under development) – (arXiv:2401.15698)

NTSim Structure:
Cherenkov Generator



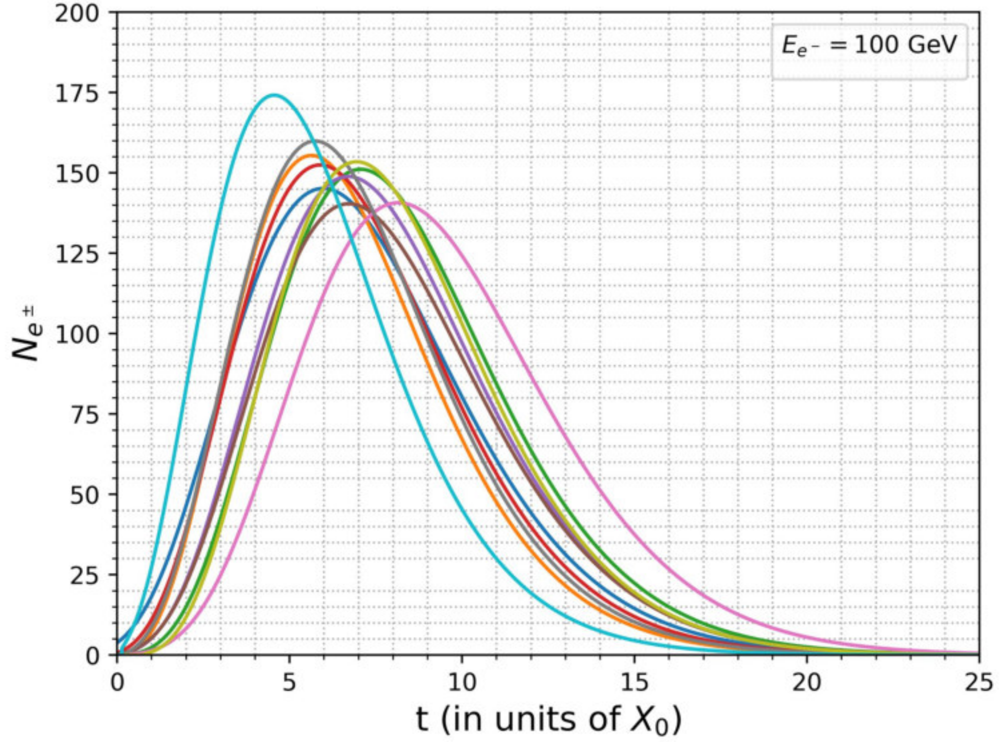
Cherenkov generator produce Cherenkov photons either from segments of charged particle tracks or from parameterization of e/m cascades.

- CherGen
  - Tracks
  - Cascades
    - longitudinal parameterization
    - – Greisen approximation

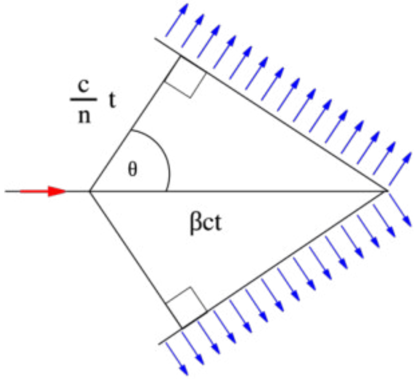
Frank-Tamm formula

$$N_{e^\pm}(t; N, t_{\max}, t_1) = \frac{0.31N}{\sqrt{y(t_{\max}, t_1)}} \cdot \exp\left\{t'\left[1 - \frac{3}{2}\ln s'(t', t_{\max})\right]\right\},$$

$$s'(t', t_{\max}) = \frac{3t'}{t' + 2y(t_{\max}, t_1)} \cdot \Theta(t'), \quad y(t_{\max}, t_1) = t_{\max} + t_1,$$



NTSim Structure:
Cherenkov Generator

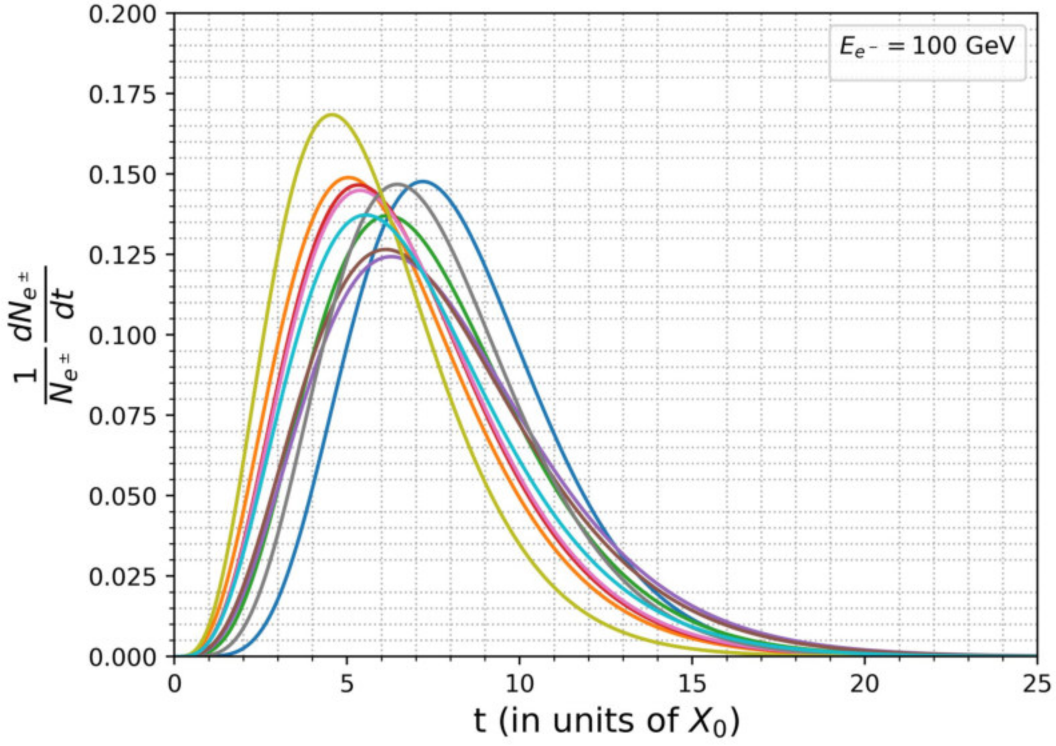


Cherenkov generator produce Cherenkov photons either from segments of charged particle tracks or from parameterization of e/m cascades.

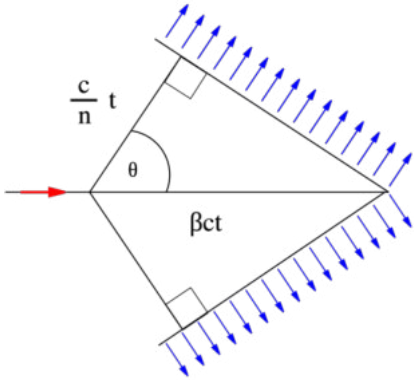
- CherGen
  - Tracks
  - Cascades
    - longitudinal parameterization
      - Gamma distribution

Frank-Tamm formula

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



NTSim Structure:
Cherenkov Generators

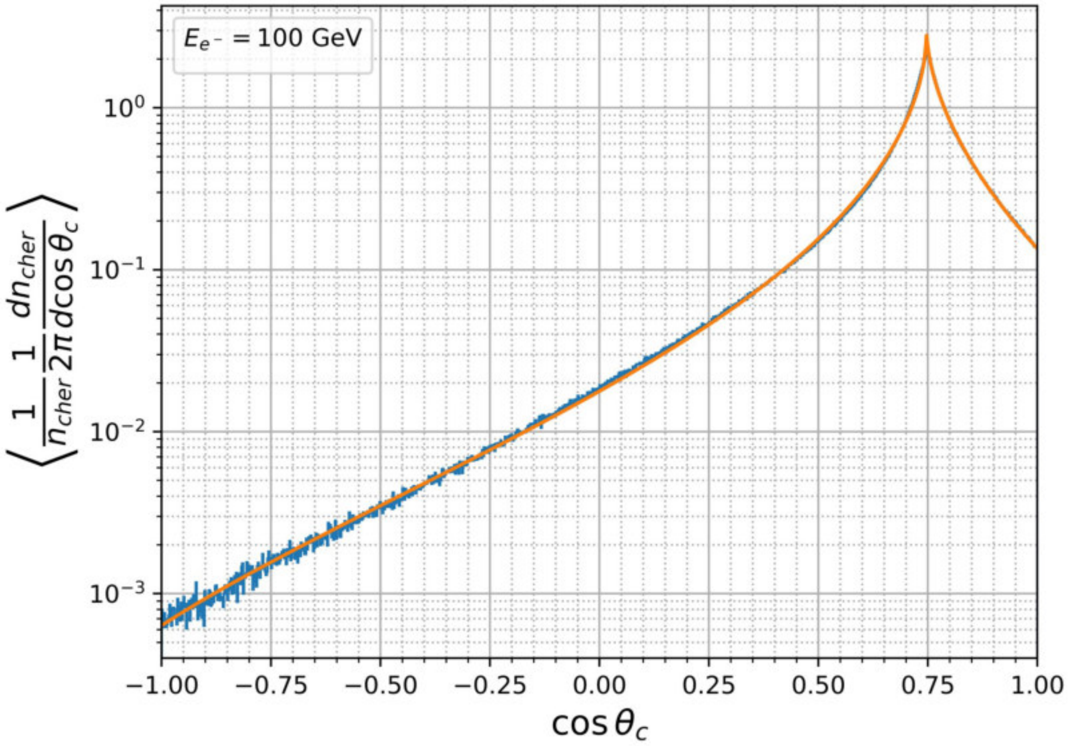


Cherenkov generators produce Cherenkov photons either from segments of charged particle tracks or from parameterization of e/m cascades.

- CherGen
  - Tracks
  - Cascades
    - angular parameterization

Frank-Tamm formula

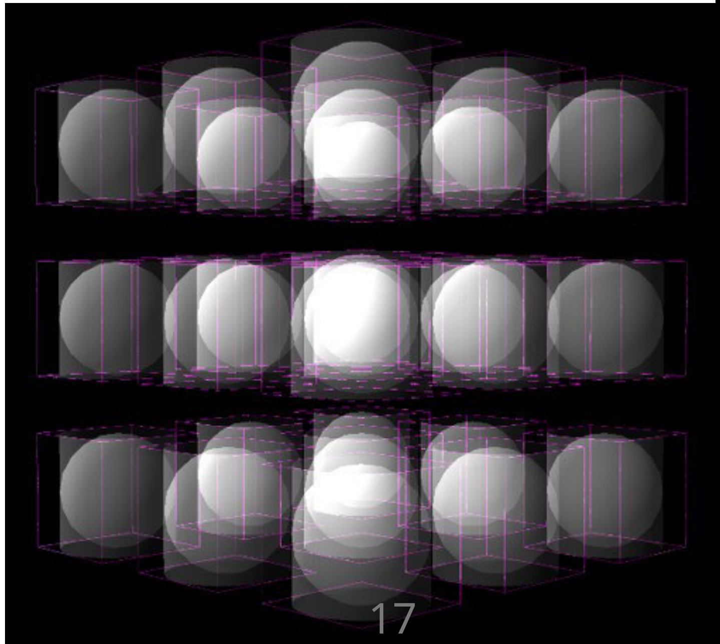
$$\left\langle \frac{1}{n_{\text{cher}}} \frac{1}{2\pi} \frac{\mathrm{d}n_{\text{cher}}\left(\cos\theta\right)}{\mathrm{d}\cos\theta} \right\rangle = a \cdot \exp\left\{ b \cdot \left| \cos\theta - \frac{1}{c} \right|^{d} - e \cdot \arctan\left(\cos\theta + f\right) \cdot \Theta\left(\frac{1}{c} - \cos\theta\right) \right\} + g$$

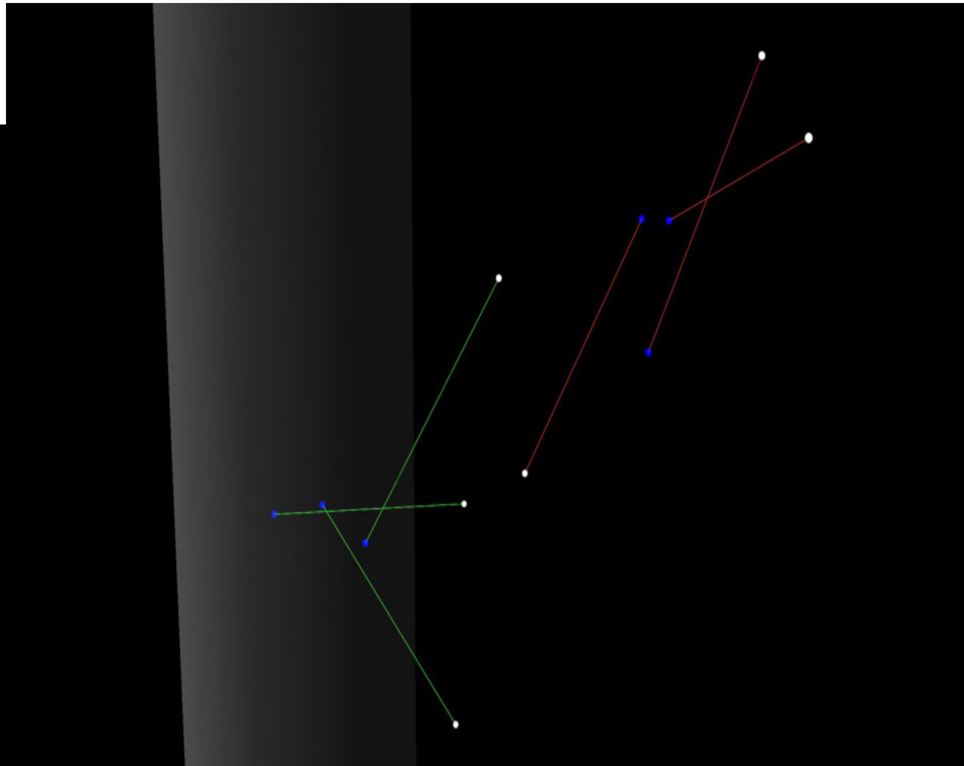


NTSim Structure: Ray Tracer

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

- SmartRayTracer

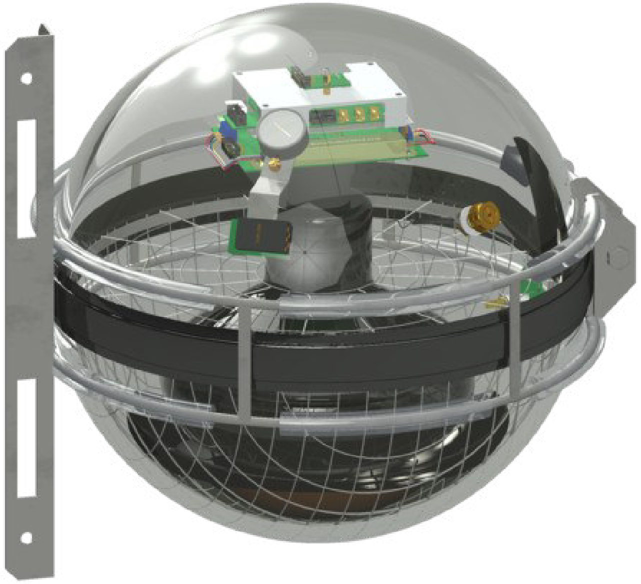


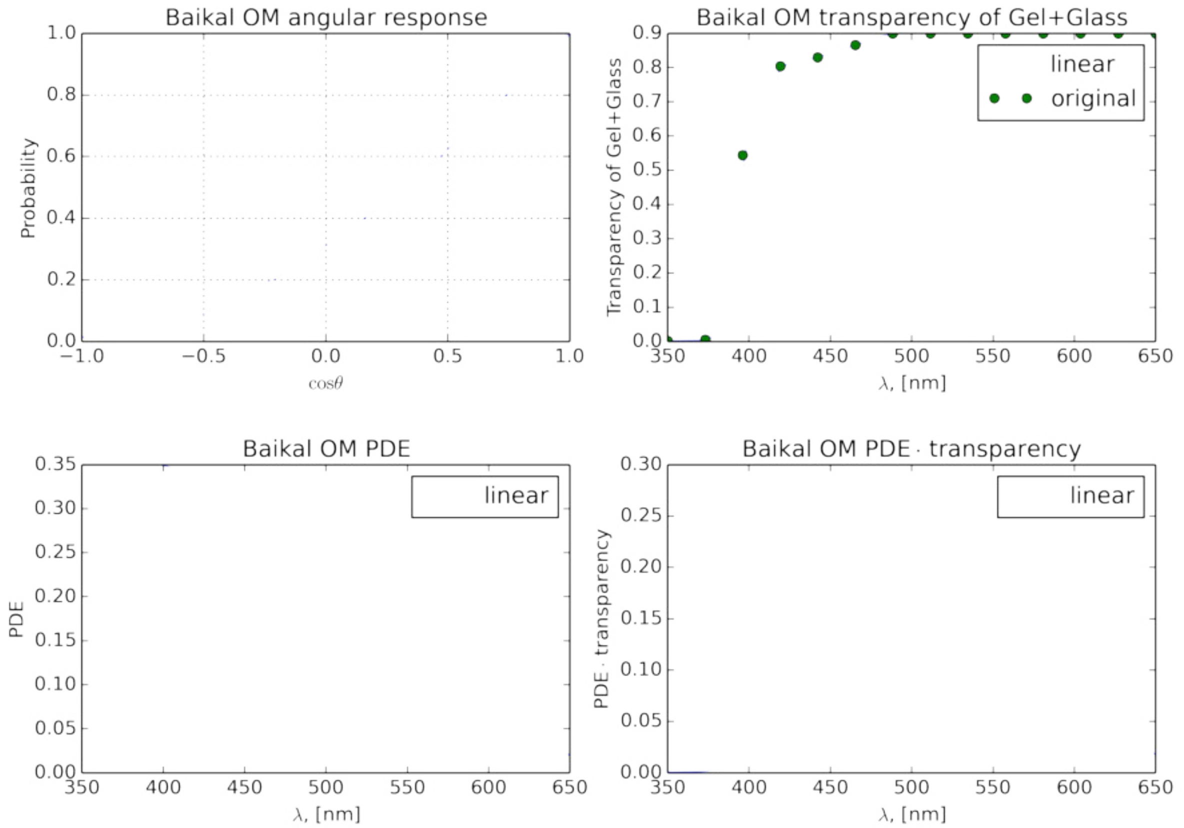


NTSim Structure:
Sensitive Detectors

Arbitrary optical detector with the wide range of detector parameters.

- BGVDSensitiveDetector

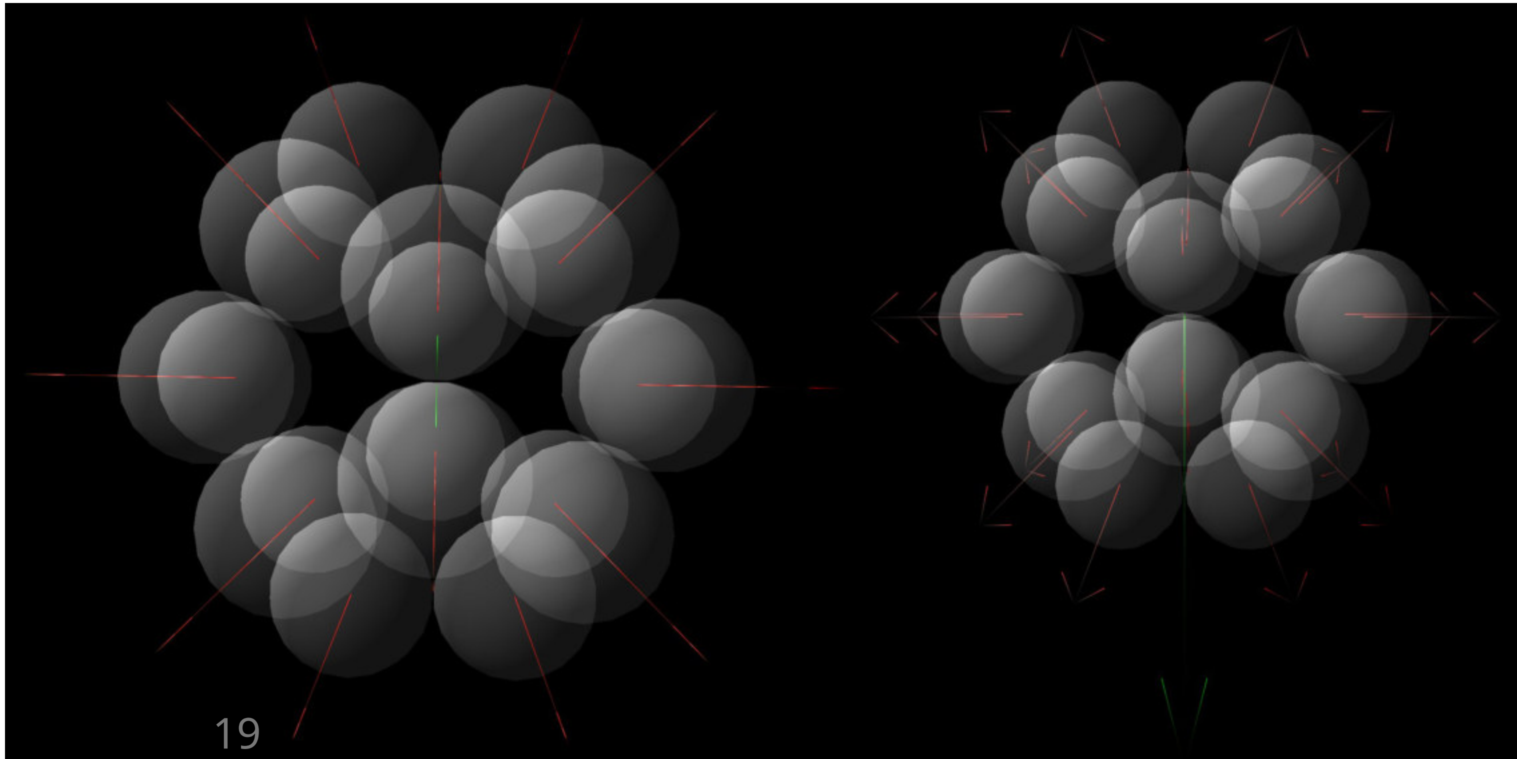




NTSim Structure:
Sensitive Detectors

Arbitrary optical detector with the wide range of detector parameters.

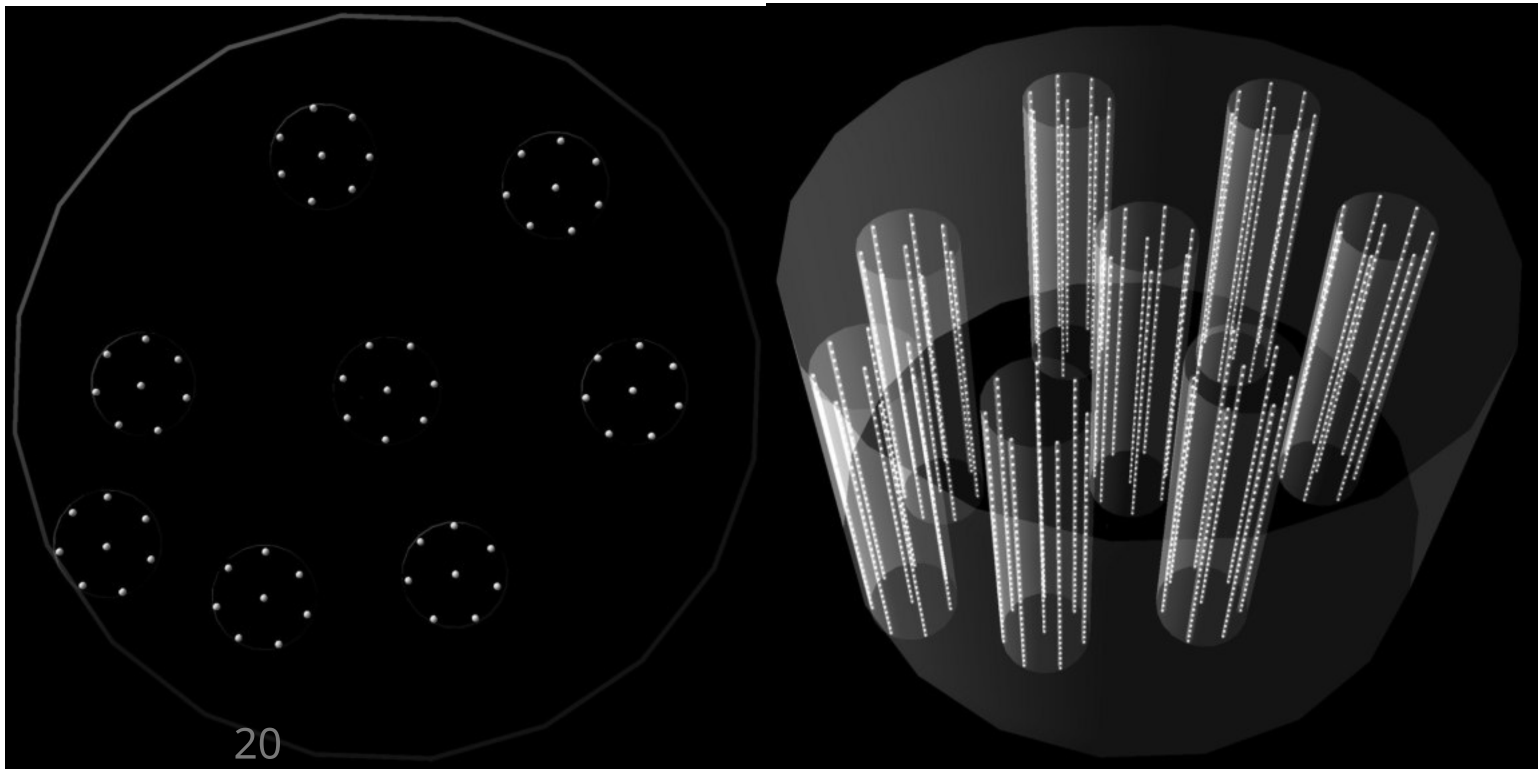
- BGVDSensitiveDetector
- FlyEyeSensitiveDetector
- …



NTSim Structure: Telescopes

Arbitrary geometry of a neutrino telescope in NTSim.

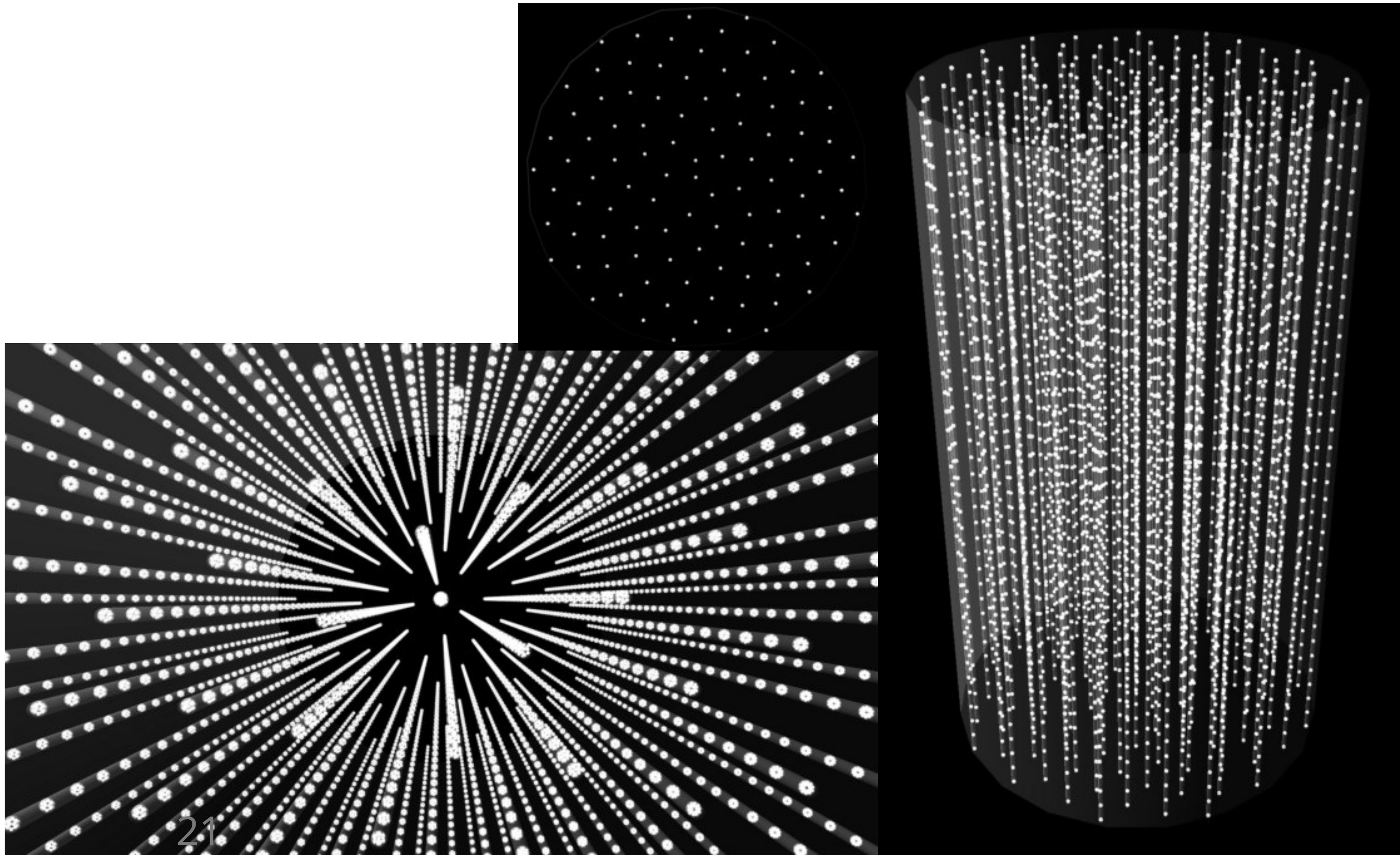
- BGVDTelescope



NTSim Structure: Telescopes

Arbitrary geometry of a neutrino telescope in NTSim.

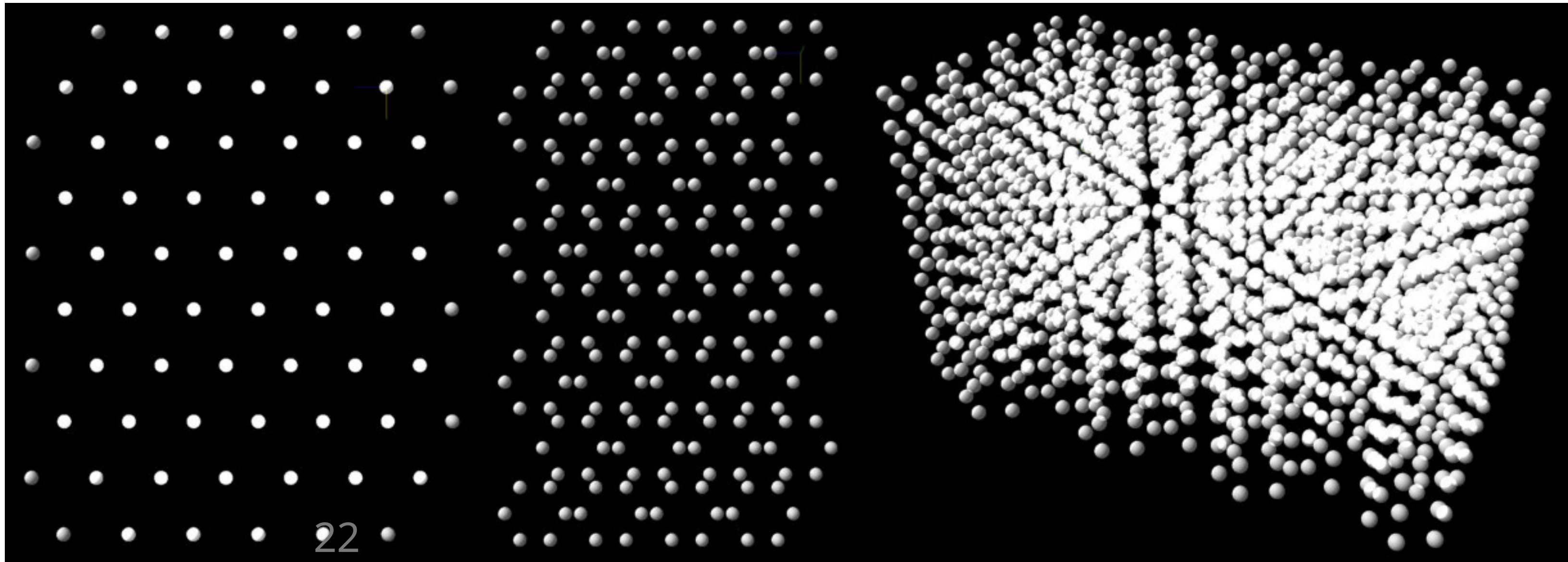
- BGVDTelescope
- SunflowerTelescope



NTSim Structure: Telescopes

Arbitrary geometry of a neutrino telescope in NTSim.

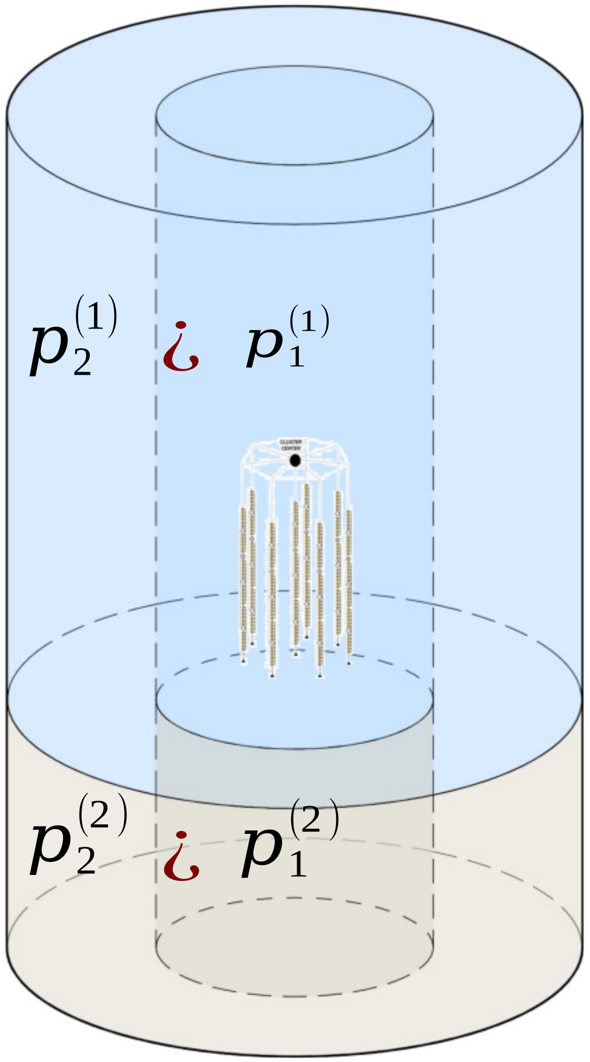
- BGVDTelescope
- SunflowerTelescope
- HoneycombTelescope
- …



Baikal-GVD Effective Volume

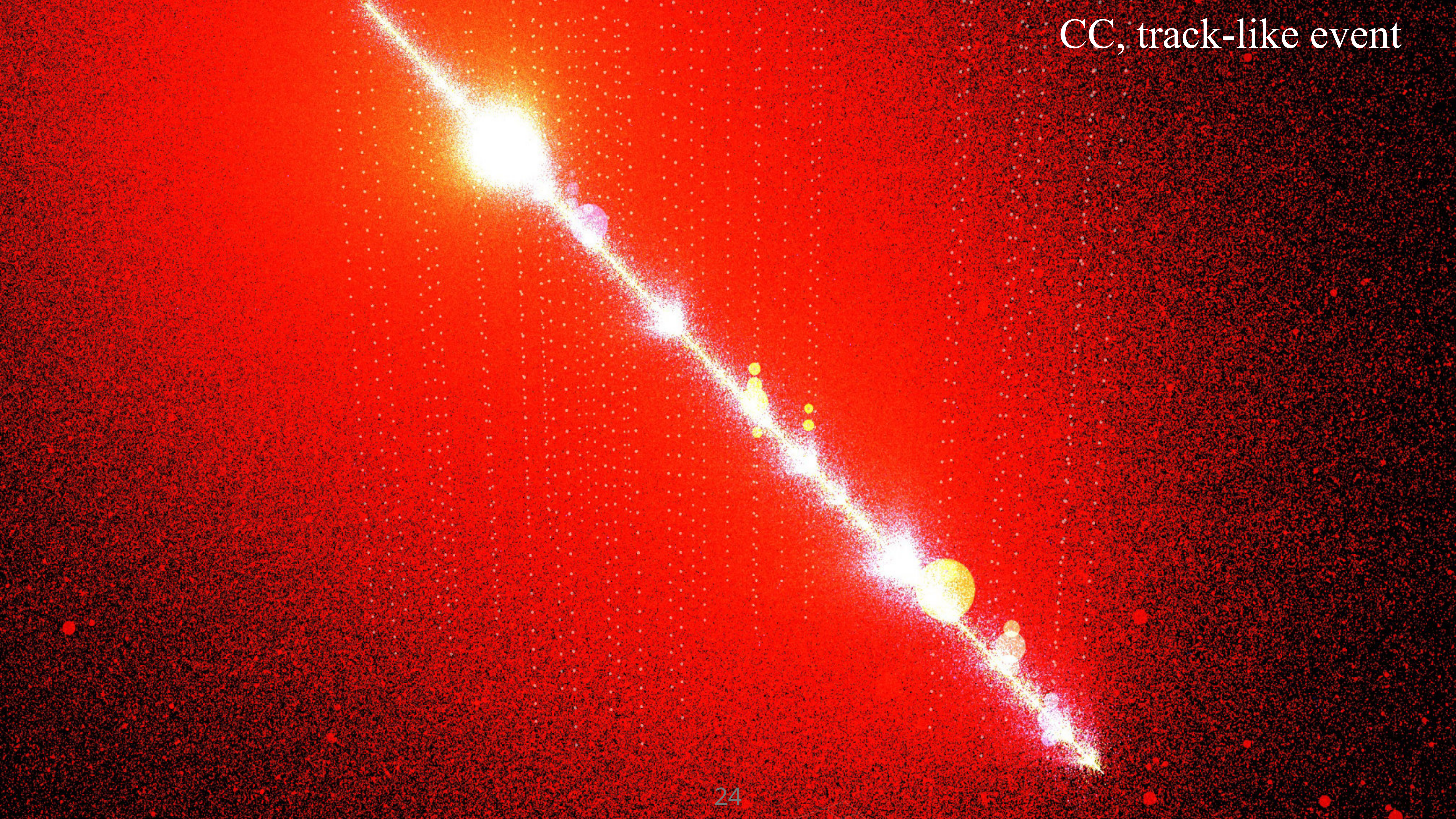
- - effective volume
- - event rate
- - interaction rate
- - bins of neutrino zenith angle and energy

$$I_{ij}=\frac{\rho N_A}{\mu}\int_{\theta_i}^{\theta_{i+1}} d\Omega \int_{E_j}^{E_{j+1}} dE \, \frac{d\Phi^{\nu,\bar{\nu}}_{astro}(E,\theta)}{dE\, d\Omega}\, \sigma_{\nu,\bar{\nu}}(E)$$

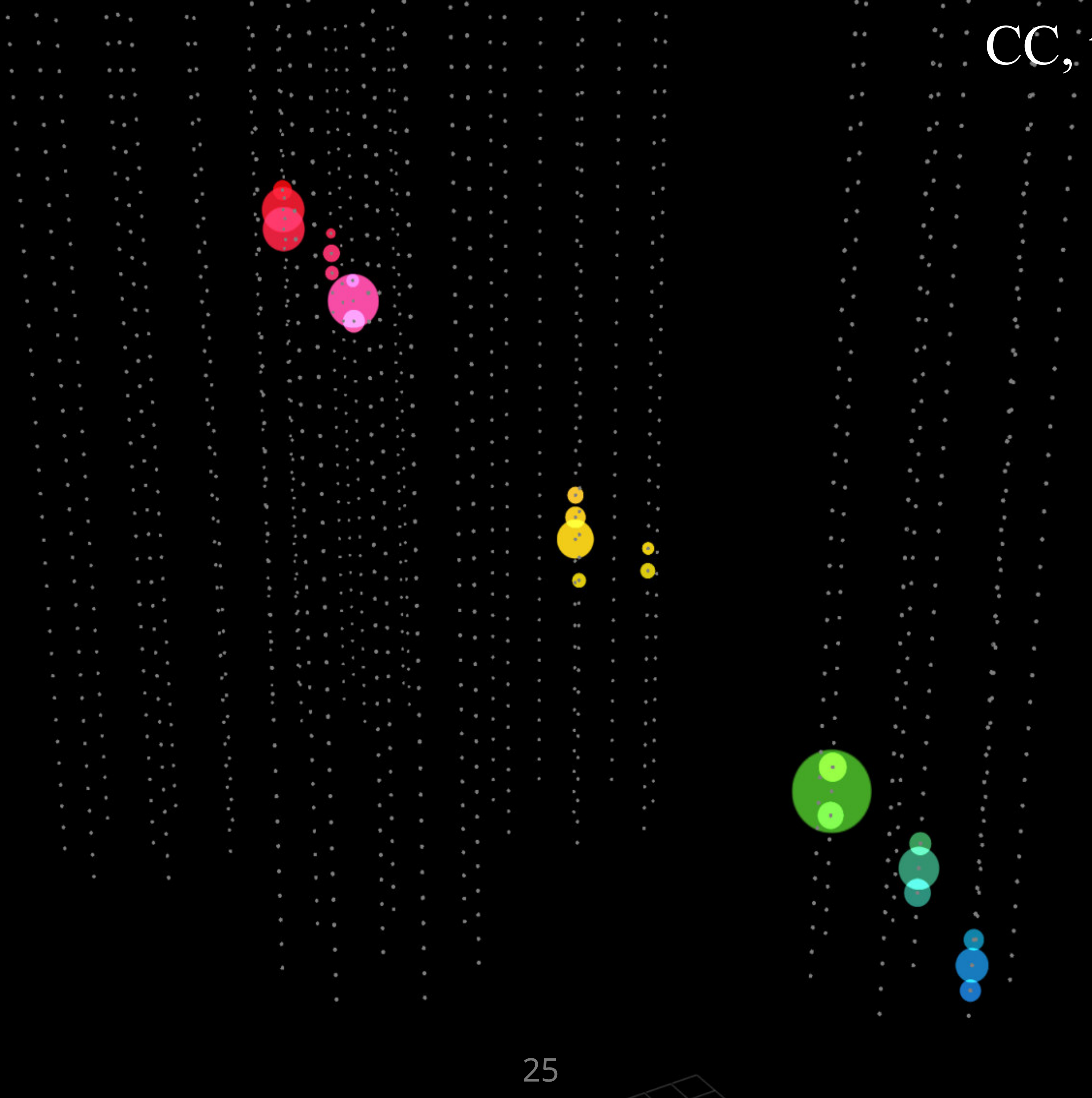


Volume importance sampling

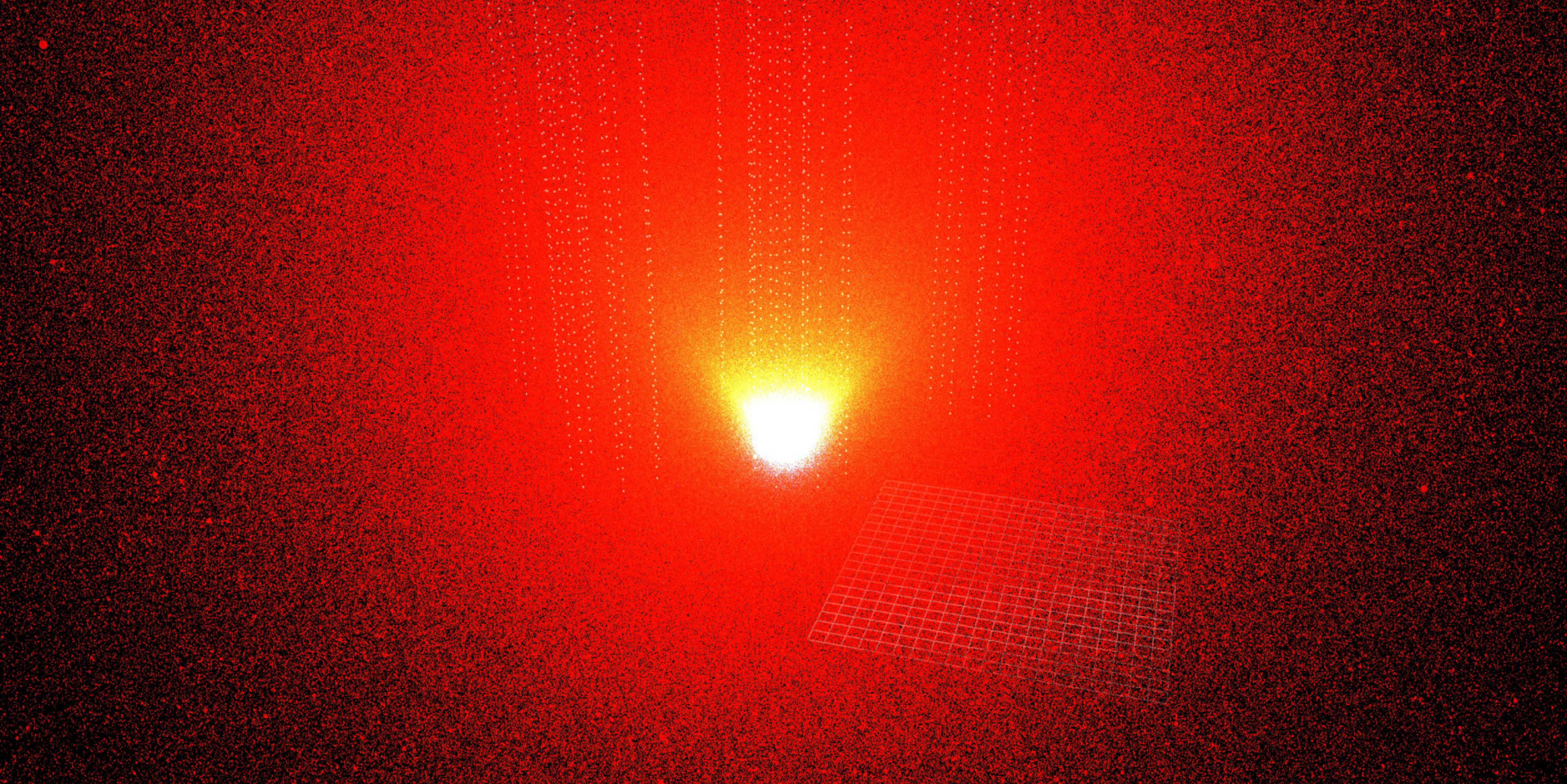
CC, track-like event



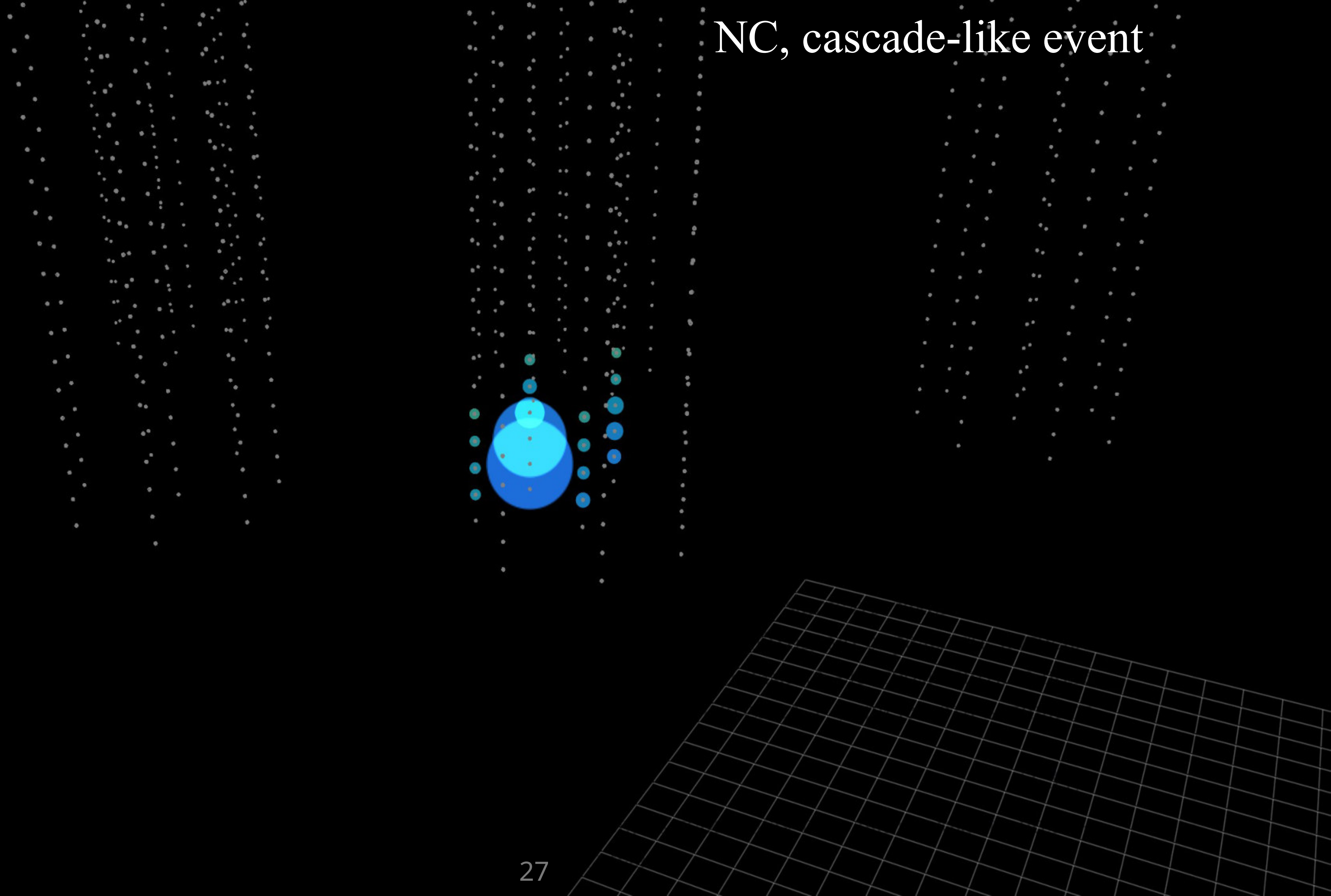
CC, track-like event



NC, cascade-like event



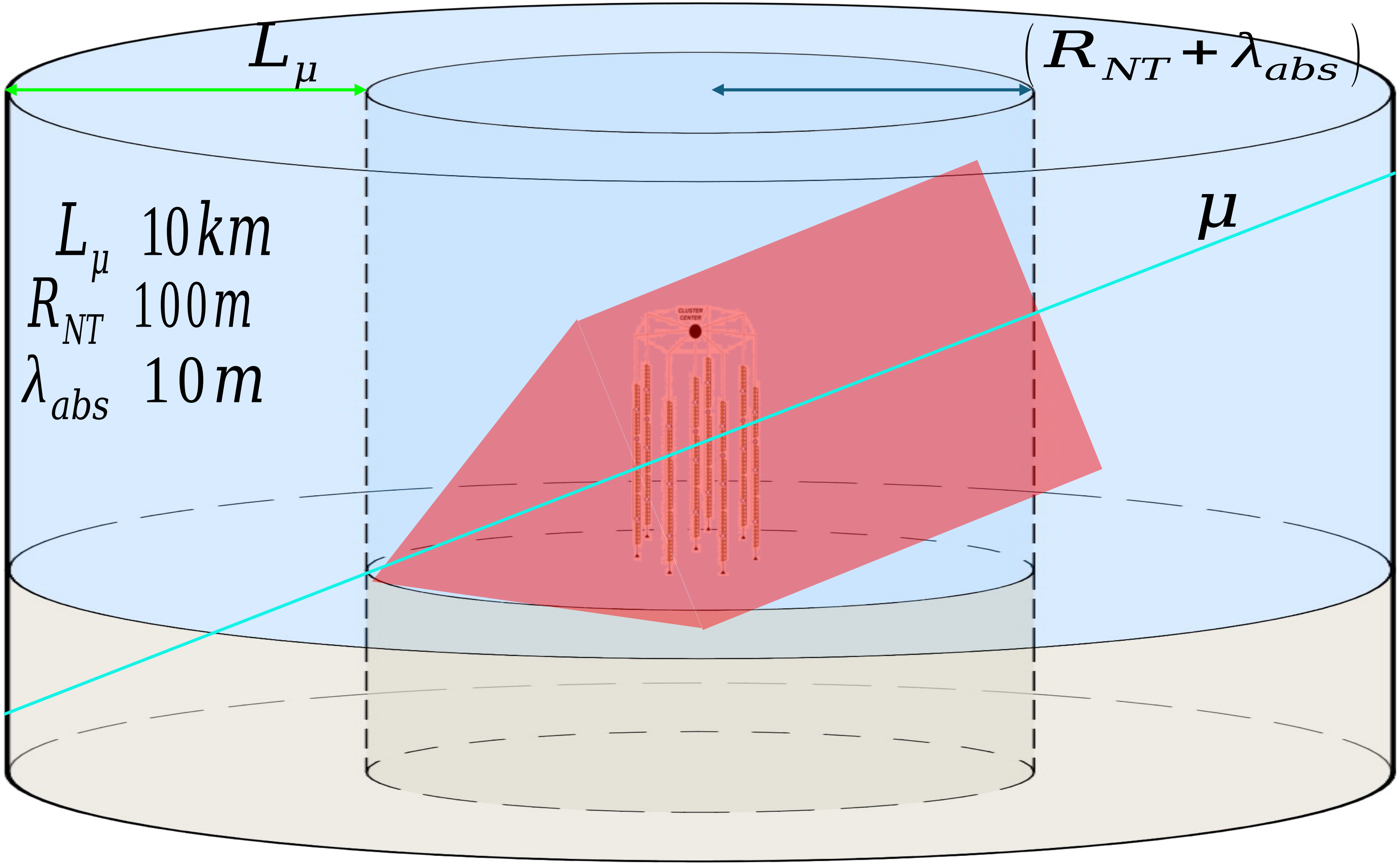
NC, cascade-like event



Baikal-GVD Effective Volume

Sensitive volume for track-like events

- - average muon path length
- - absorption length of optical photons
- - radius of the neutrino telescope



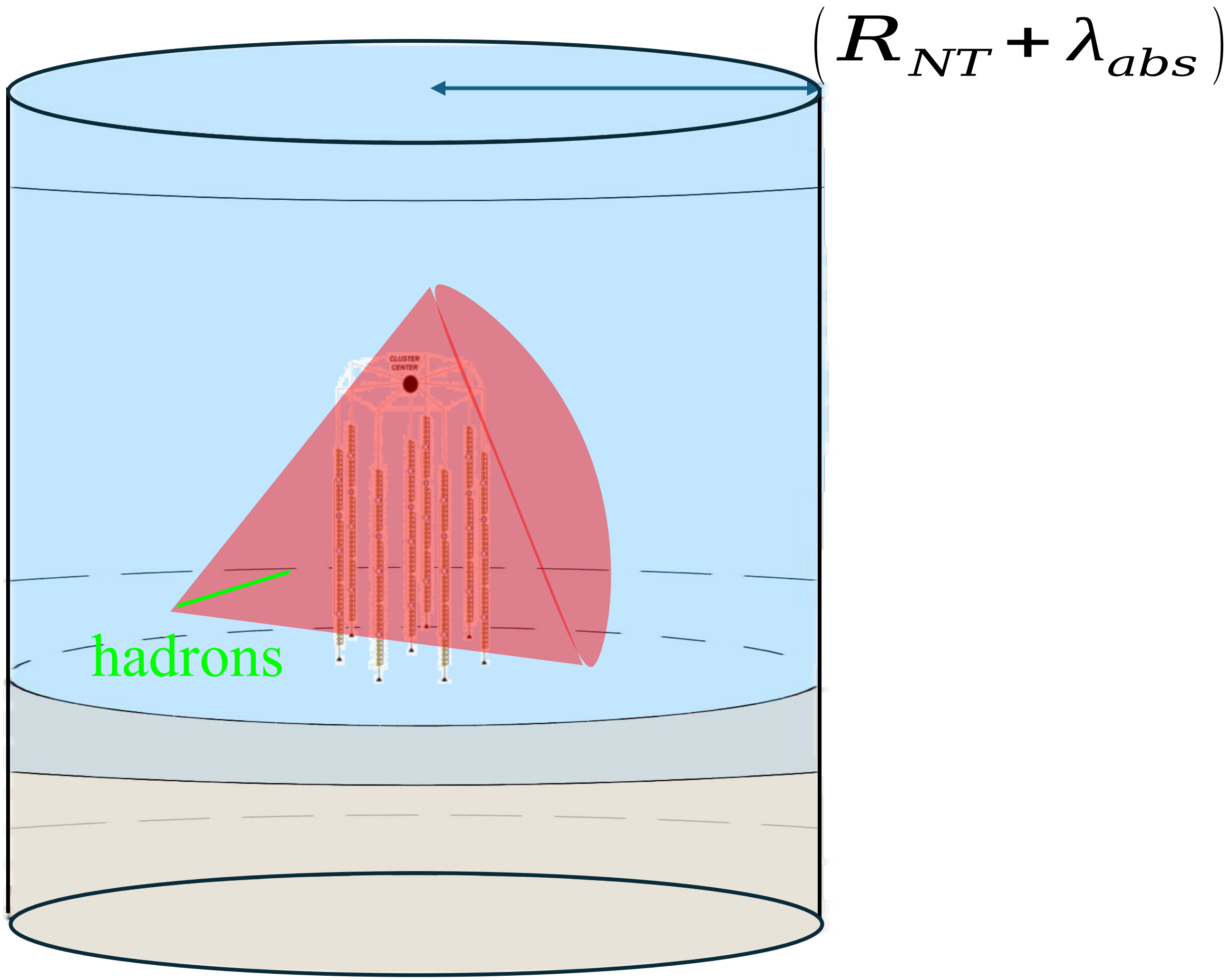
Baikal-GVD Effective Volume

Sensitive volume for cascade-like events

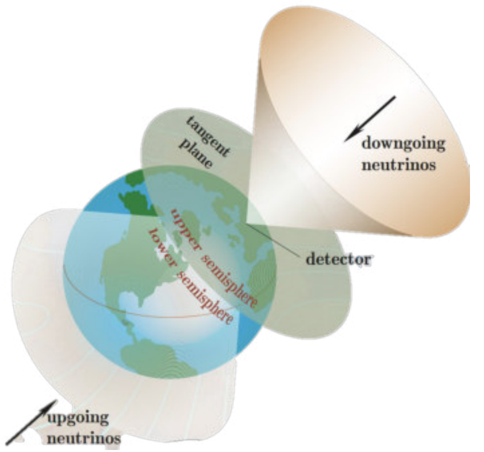
- - absorption length of optical photons
- - radius of the neutrino telescope

R_{NT} $100m$

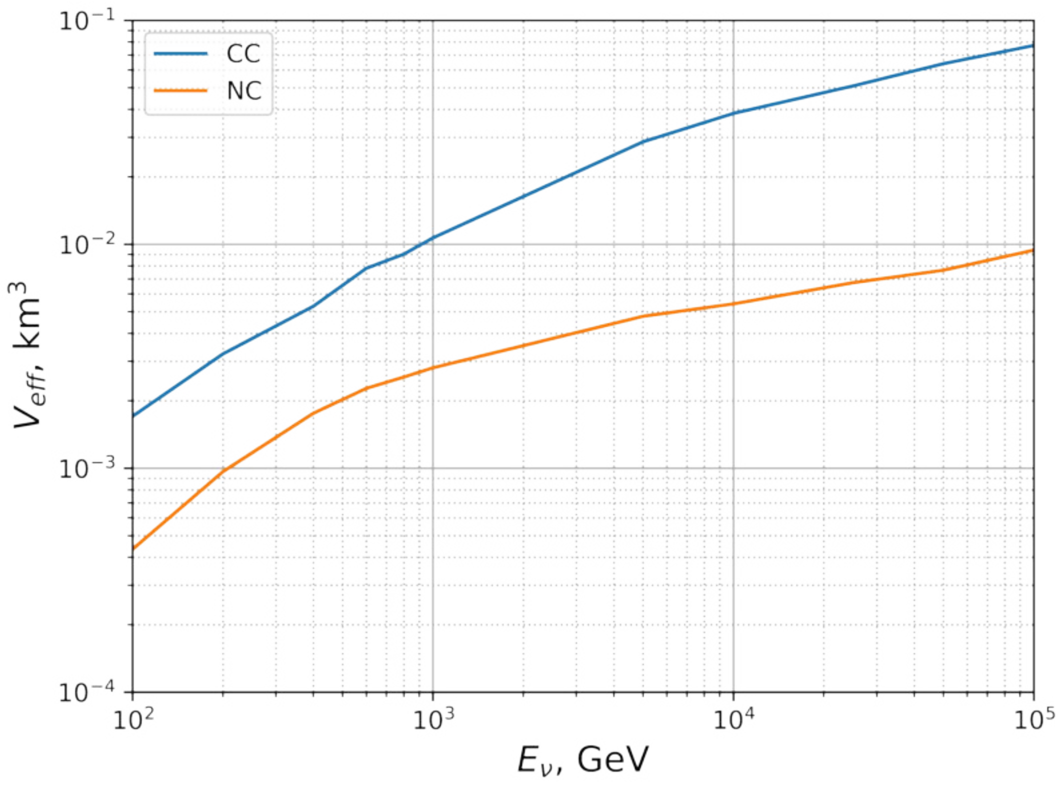
λ_{abs} $10m$



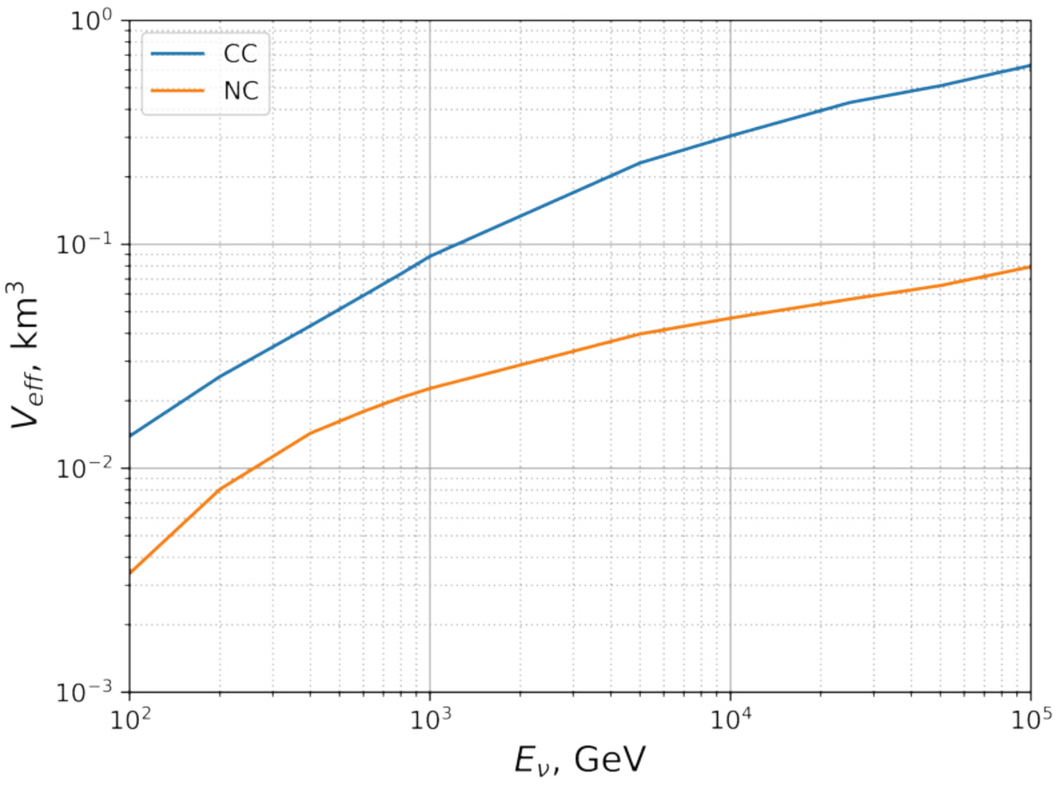
Baikal-GVD Effective Volume



flux,



Single cluster



Eight clusters (2021)

Summary

Key points:

- The NTSim provides a complete chain of neutrino event simulation and detector response.
- To enhance efficiency, we utilize different methods such as parameterizing e/m cascades, generating Cherenkov photons within the package, and fast searching for hits.
- The effectiveness of detecting neutrino events in the Baikal-GVD experiment was evaluated.
- 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:

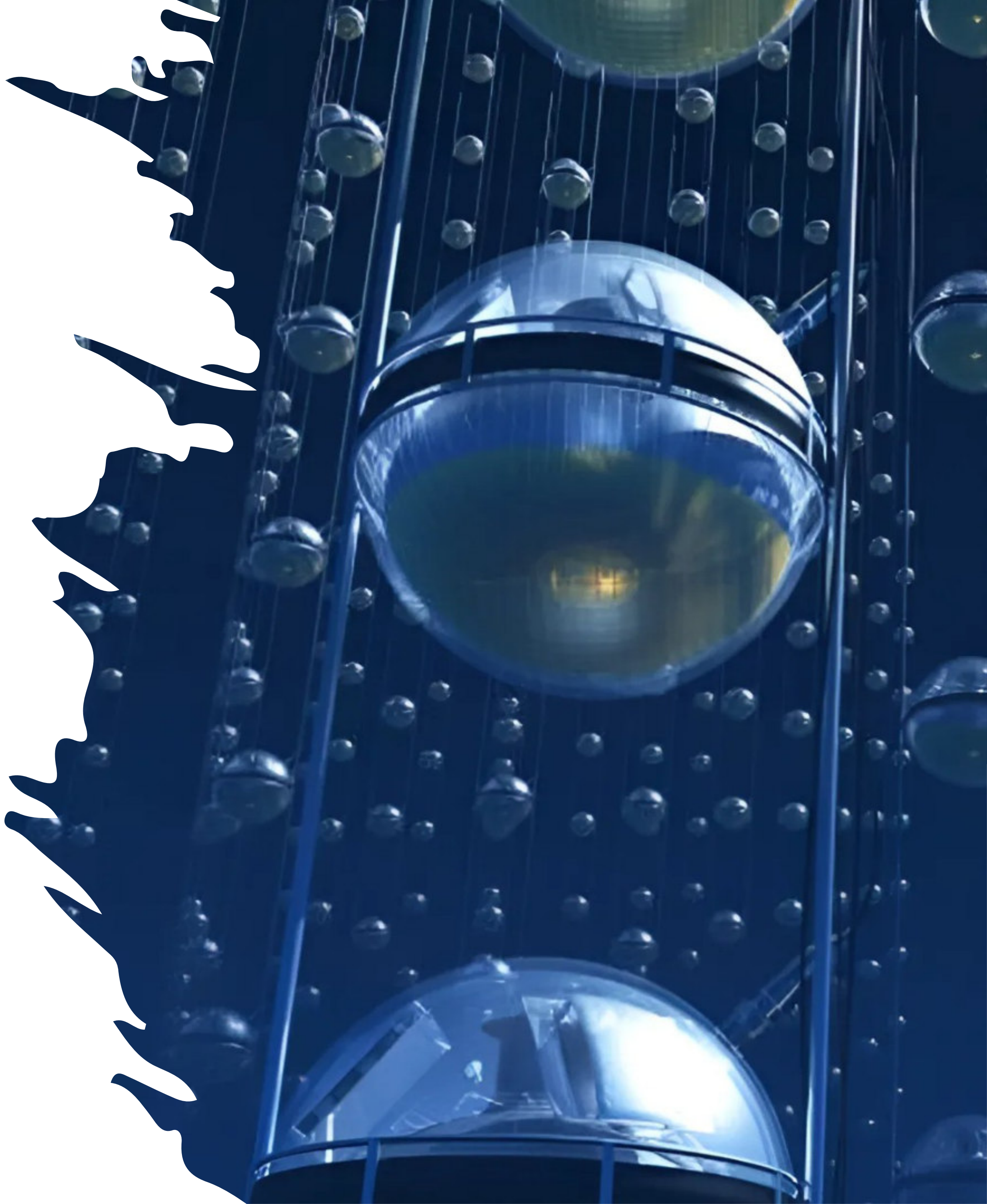
- PrimaryGenerator: Generates primary interaction vertex using NuGen/ToyGen.
- Propagator: Propagates particles through the medium using Particulerator and MCPhotonTransporter.
- CherenkovGenerator: Generates Cherenkov photons from charged particle tracks and e/m cascades.
- RayTracer: Searches for segments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

Personal contribution

- The NTSim software package for modeling neutrino telescopes has been advanced
- The Cherenkov photon generator CherGen has been developed and implemented into NTSim
- The method of longitudinal parameterization of individual electromagnetic cascades has been developed
- The concept of logical volumes has been integrated and a neutrino telescope in the shape of a sunflower flower has been created
- The NuGen neutrino generator has been improved
- The effective volume of the Baikal-GVD experiment has been estimated

Further steps

- Further work to improve and optimize NTSim.
- Including NTSim in the main data analysis process for the Baikal-GVD project.
- Analysis of experimental data on reconstructing the arrival direction and energy of astrophysical neutrinos using NTSim at the Baikal-GVD neutrino telescope.
- Implementing a semi-analytical method based on the RTE (Radiative Transfer Equation) solution to describe light propagation in the medium & different neutrino generators.
- Using NTSim as the primary simulation software for the HUNT (High-energy Underwater Neutrino Telescope) experiment.



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- D. N. Zaborov
- M. O. Gonchar
- S. S. Khokhlov
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- T. V. Yelzhov
- N. S. Bessonov
- E. K. Karkarian
- A. R. Popov
- N. A. Pozdnyakov
- A. G. Olshevsky
- The academic staff of the Department of Elementary Particle Physics

Publications

The work was presented:

- “Development of the NTSim Software Package for Designing Neutrino Telescopes and Evaluating Detection of Neutrino-Induced Events in the Baikal-GVD Experiment”, Moscow International School of Physics 2024, 05.03.2024
- “Разработка программного пакета NTSim для моделирования нейтринных телескопов и оценка эффективности регистрации нейтринных событий в эксперименте Baikal-GVD”, форум Ломоносов-2024, 16.04.2024
- Baikal-GVD Collaboration Meetings

Accepted for publication:

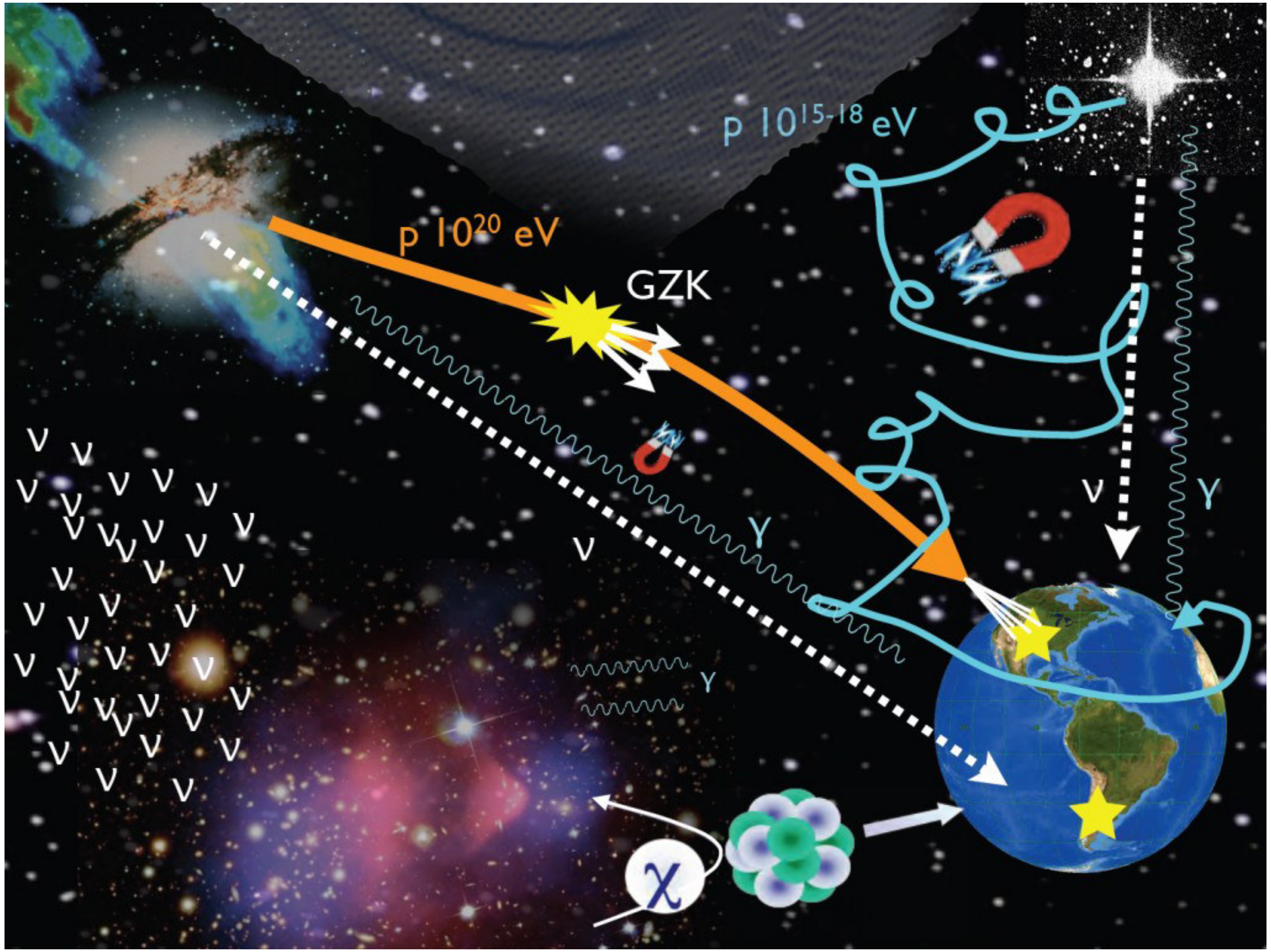
- “Baikal-GVD neutrino telescope: unlocking the secrets of the universe’s catastrophic events”, V. A. Allakhverdyan, D. V. Naumov and S. I. Zavyalov, Publications of the Astronomical Observatory of Belgrade
- “Optimization of cascade simulation process using spatial parametrization”, A. Belyakova, I. Chernousov, Y. Malyshkin, I. Perevalova and S. Zavyalov, Письма в ЭЧАЯ

Thank you for your attention

Back-Up

Astrophysical neutrino detection

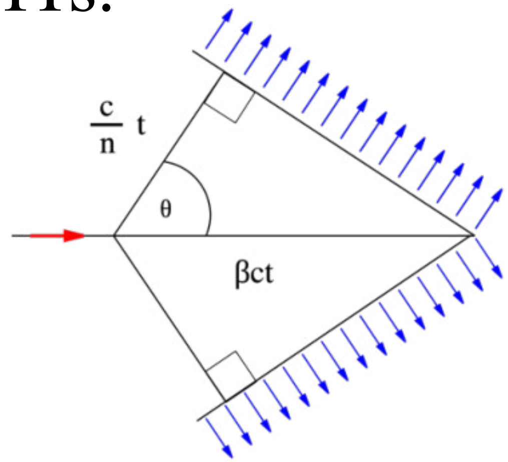
- **Principle 1:** Neutrinos interact very weakly with matter (via weak and gravitational forces) - they can propagate enormous large distances without changing their trajectory.
- **Sources:** AGNs, GRBs, SMBHs, etc. (arXiv:2311.00281)

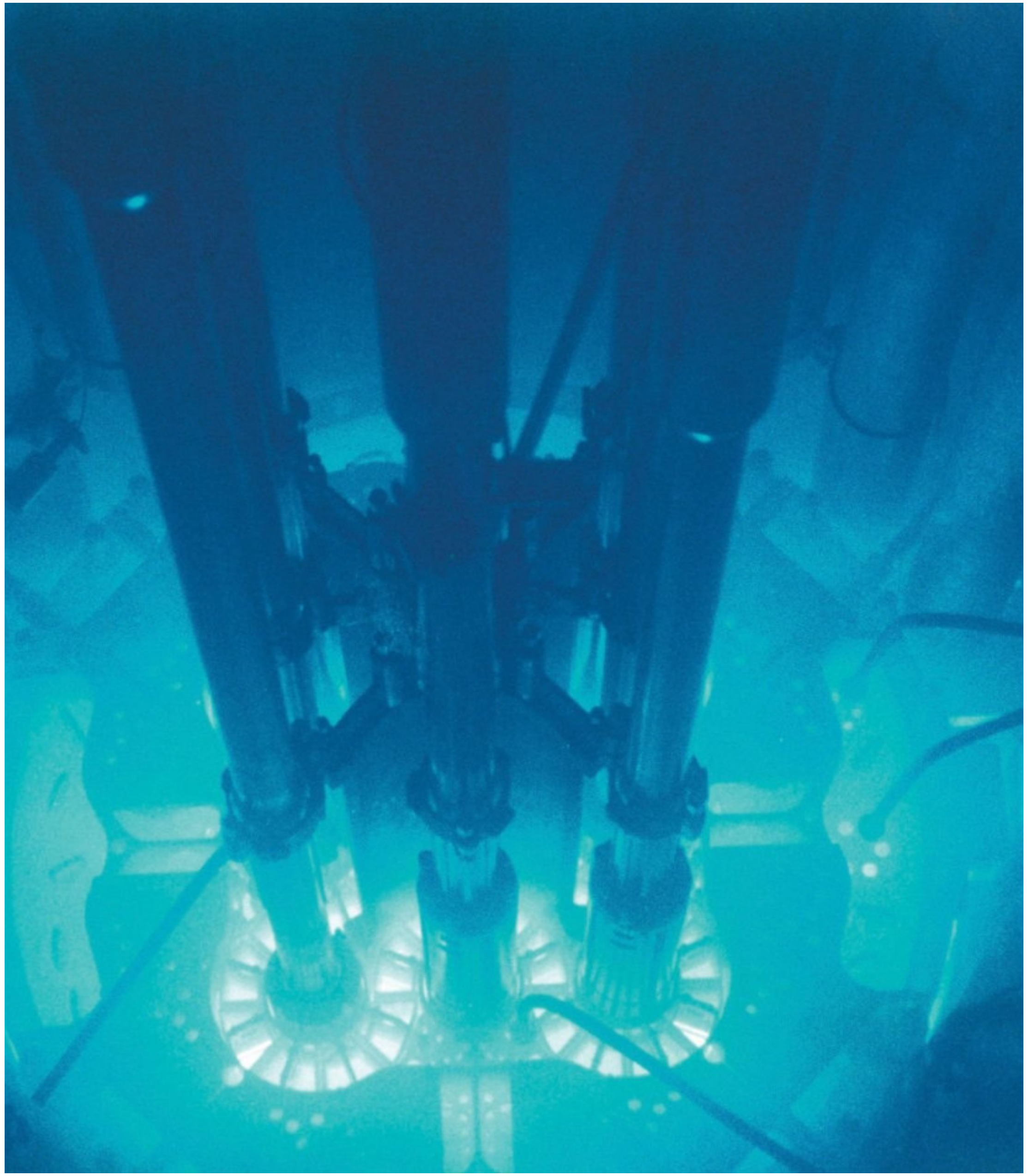


Astrophysical neutrino detection

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

Frank-Tamm formula





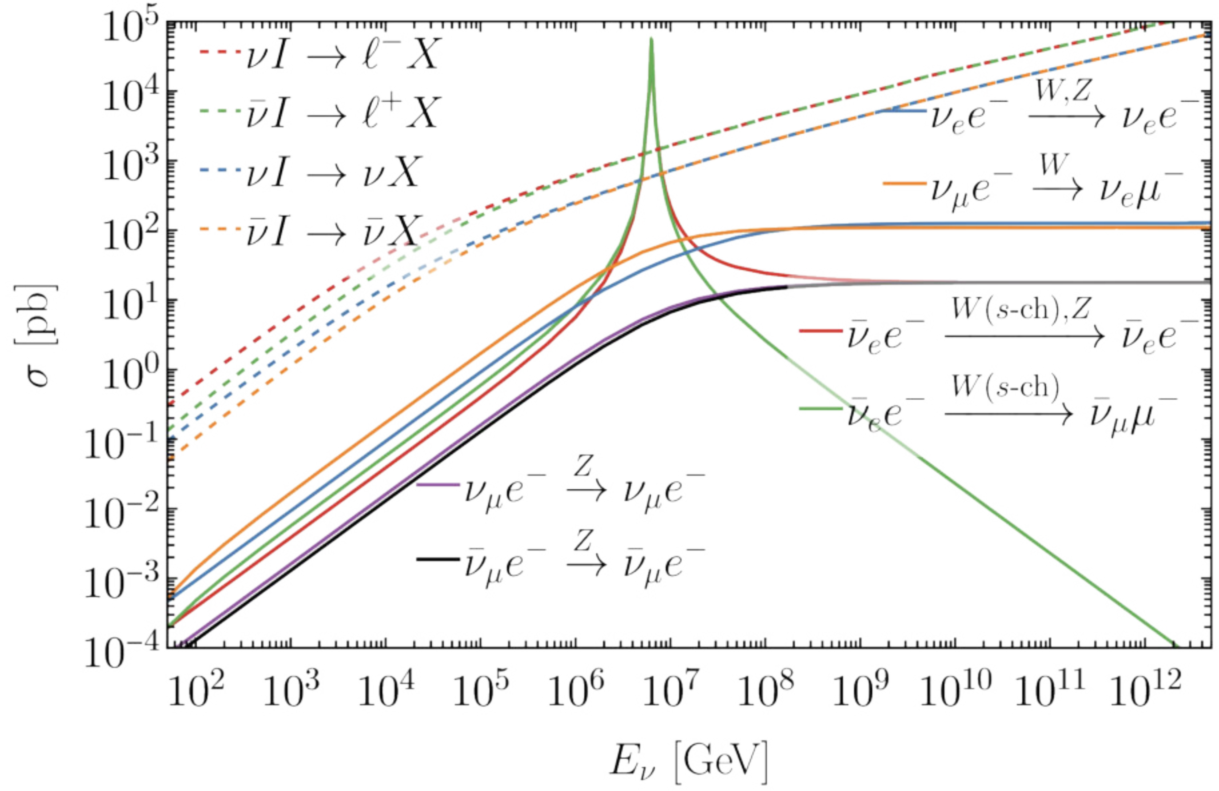
Baikal GVD 2024

Дневник Баира Шайдонова

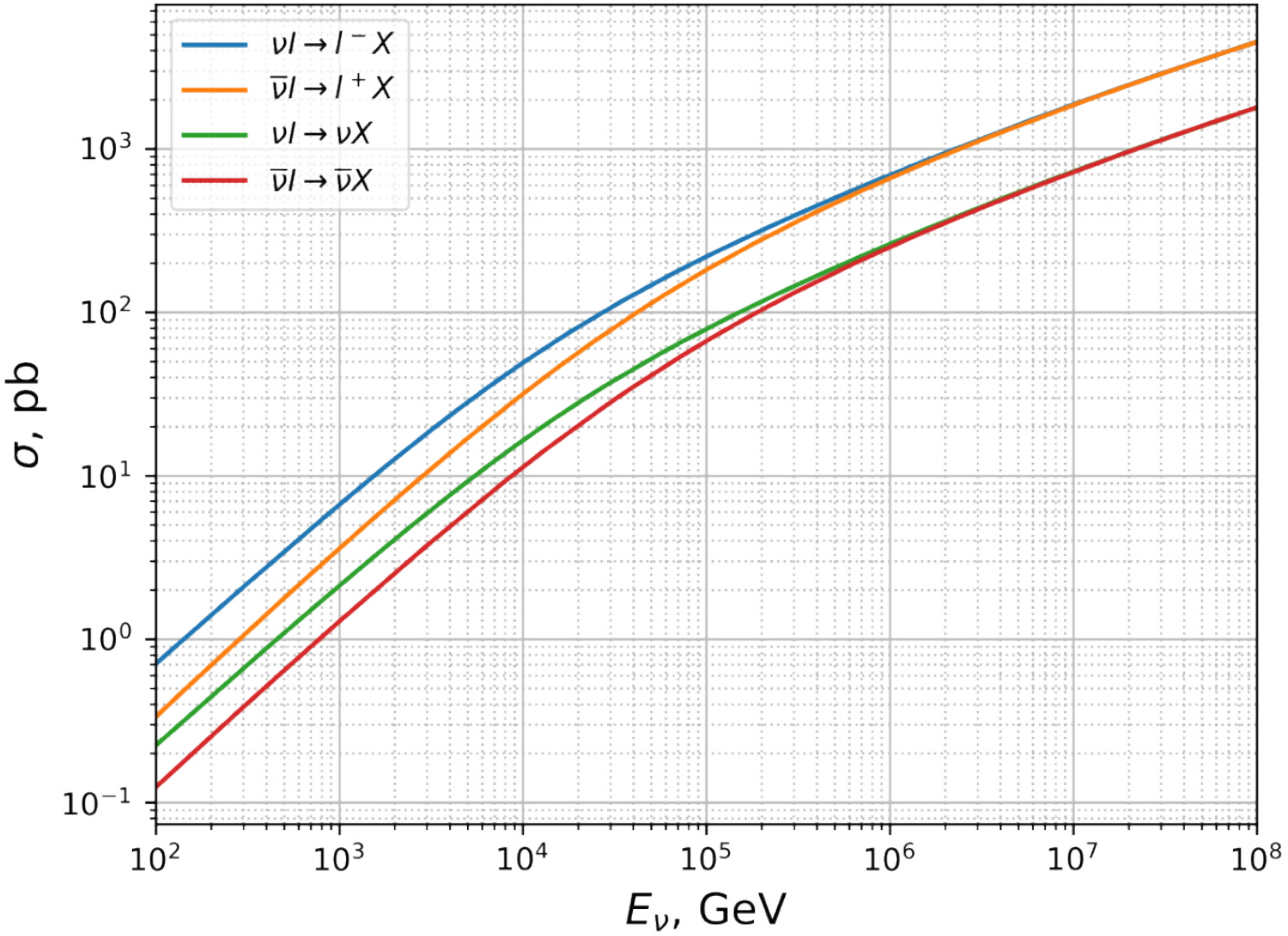
3 марта. День семнадцатый

Joint Institute
for Nuclear Research

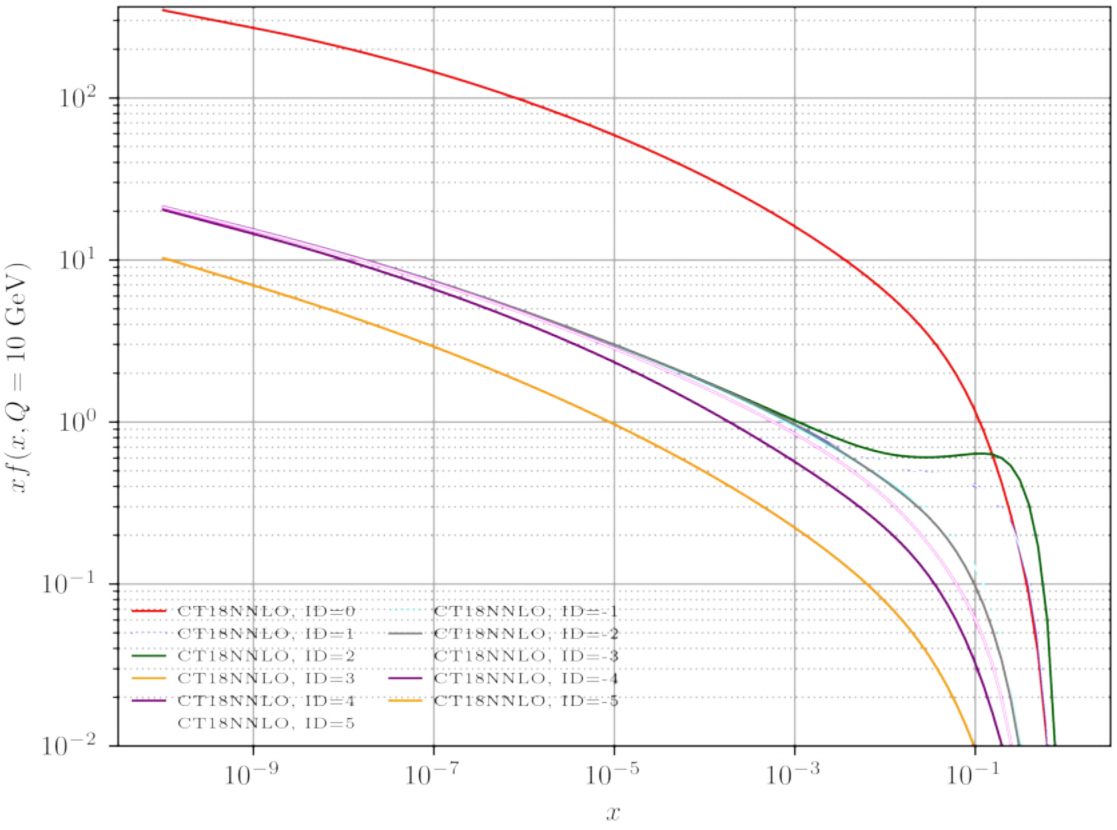
“Naive” parton model



Total cross section



CT18NNLO


$xf(x, Q = 10\ \mathrm{GeV})$
x
CT18NNLO, ID=0
CT18NNLO, ID=1
CT18NNLO, ID=2
CT18NNLO, ID=3
CT18NNLO, ID=4
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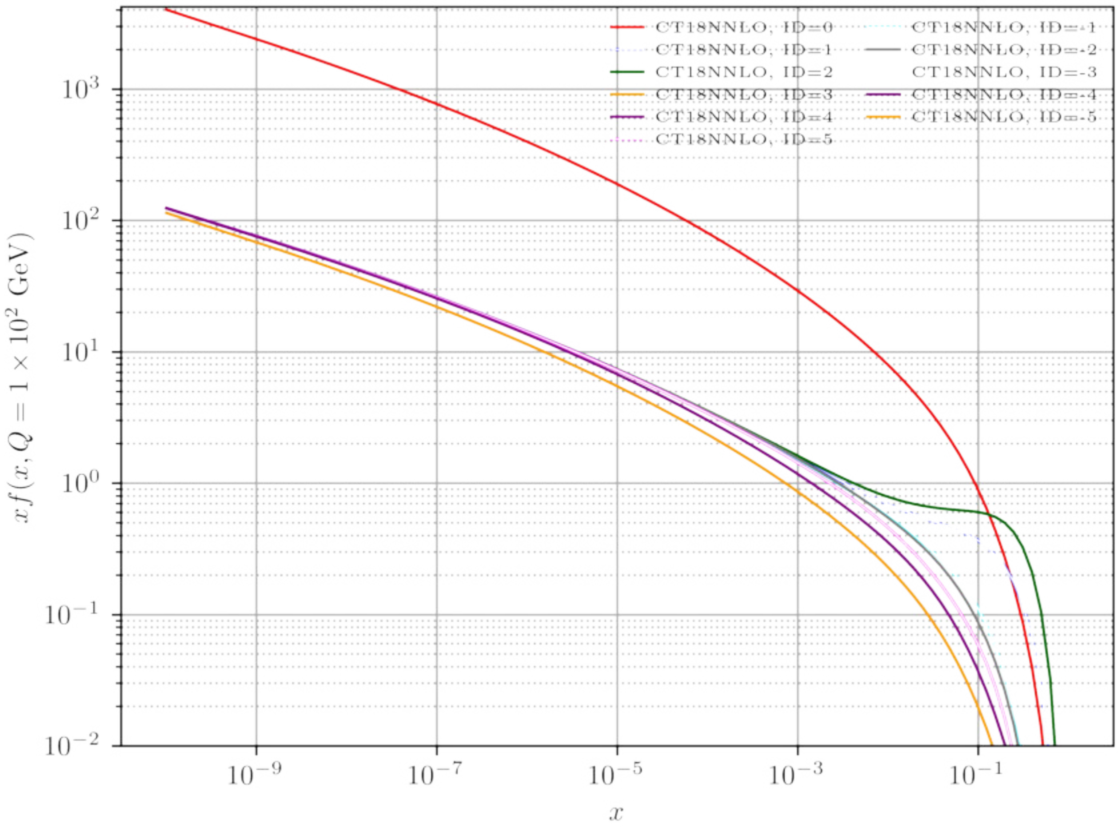
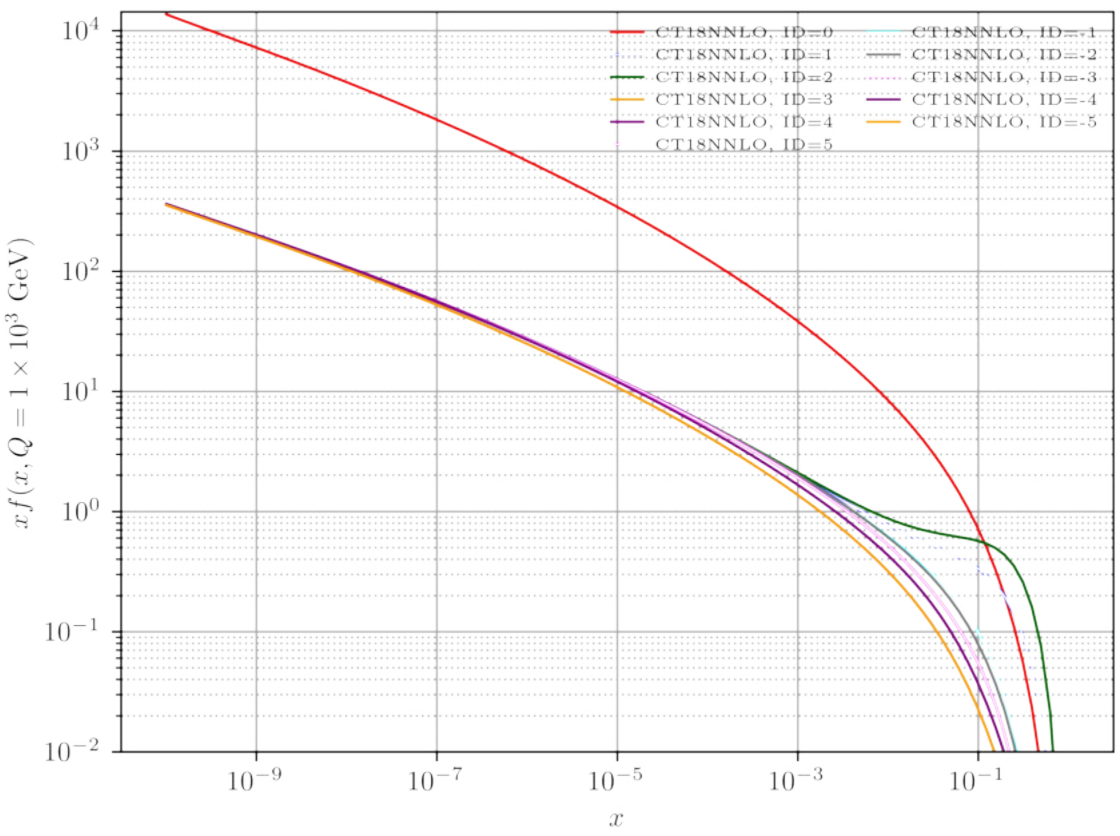
CT18NNLO, ID=-5


$xf(x, Q = 1 \times 10^2\ \mathrm{GeV})$
x
CT18NNLO, ID=0
CT18NNLO, ID=1
CT18NNLO, ID=2
CT18NNLO, ID=3
CT18NNLO, ID=4
CT18NNLO, ID=5
CT18NNLO, ID=-1
CT18NNLO, ID=-2
CT18NNLO, ID=-3
CT18NNLO, ID=-4
CT18NNLO, ID=-5

CT18NNLO


CT18NNLO, ID=0
CT18NNLO, ID=1
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CT18NNLO, ID=3
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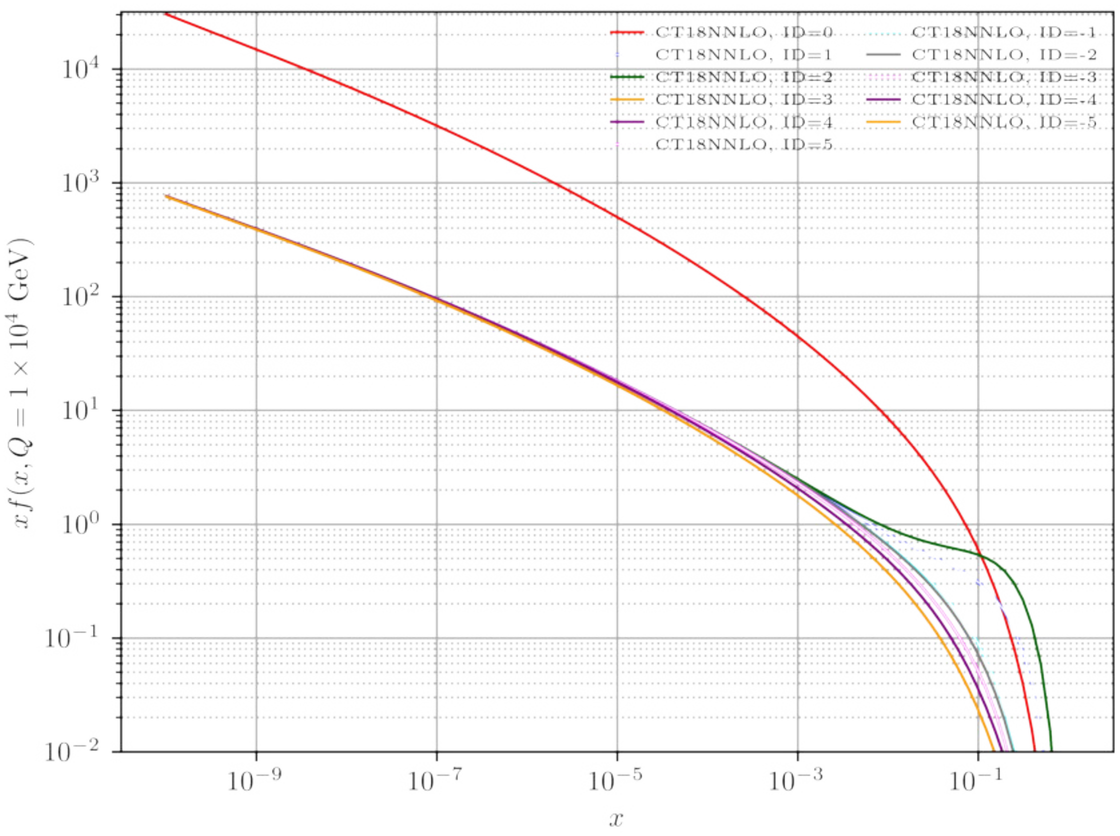
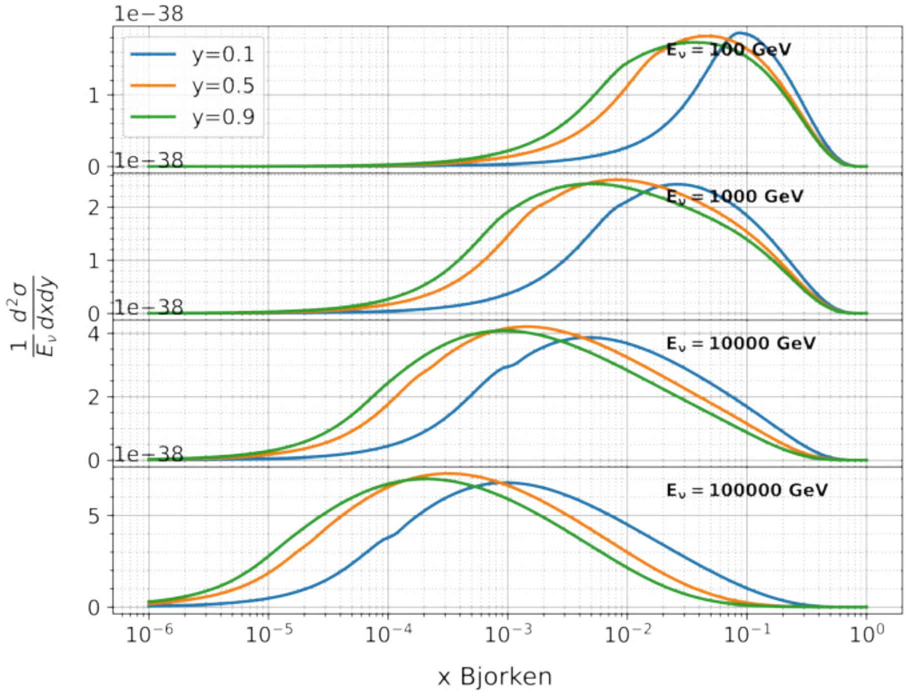
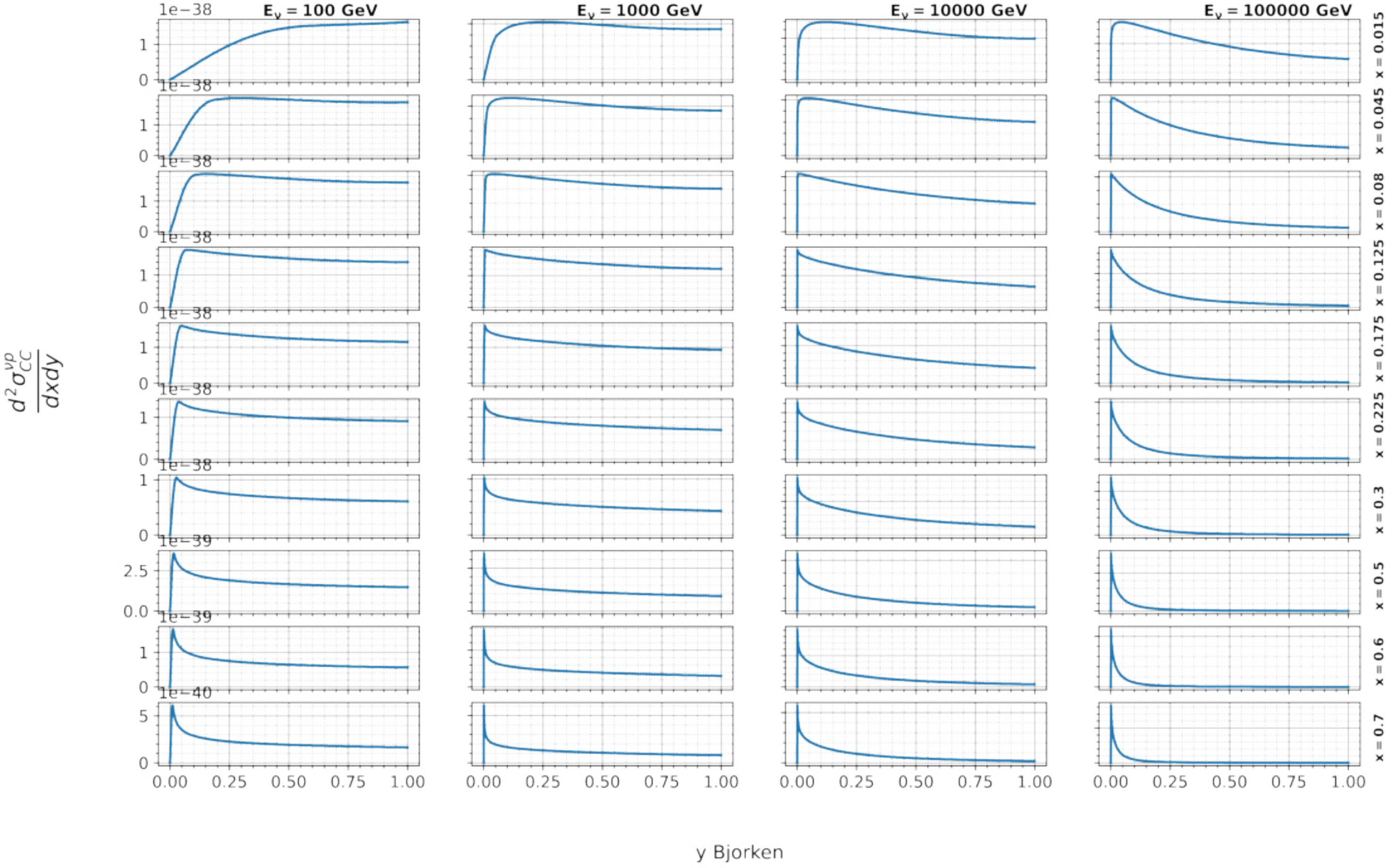
CT18NNLO, ID=5
CT18NNLO, ID=-1
CT18NNLO, ID=-2
CT18NNLO, ID=-3
CT18NNLO, ID=-4
CT18NNLO, ID=-5
$xf(x, Q = 1 \times 10^3$ GeV$)$
x


CT18NNLO, ID=0
CT18NNLO, ID=1
CT18NNLO, ID=2
CT18NNLO, ID=3
CT18NNLO, ID=4
CT18NNLO, ID=5
CT18NNLO, ID=-1
CT18NNLO, ID=-2
CT18NNLO, ID=-3
CT18NNLO, ID=-4
CT18NNLO, ID=-5
$xf(x, Q = 1 \times 10^4$ GeV$)$
x

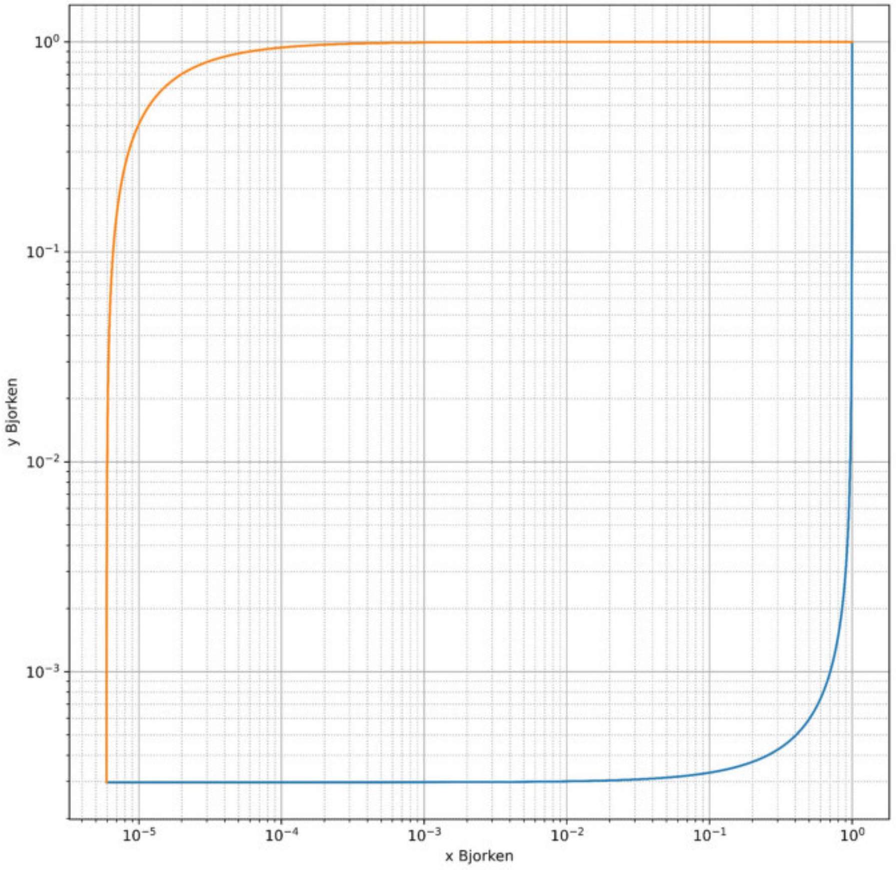
“Naive” parton model

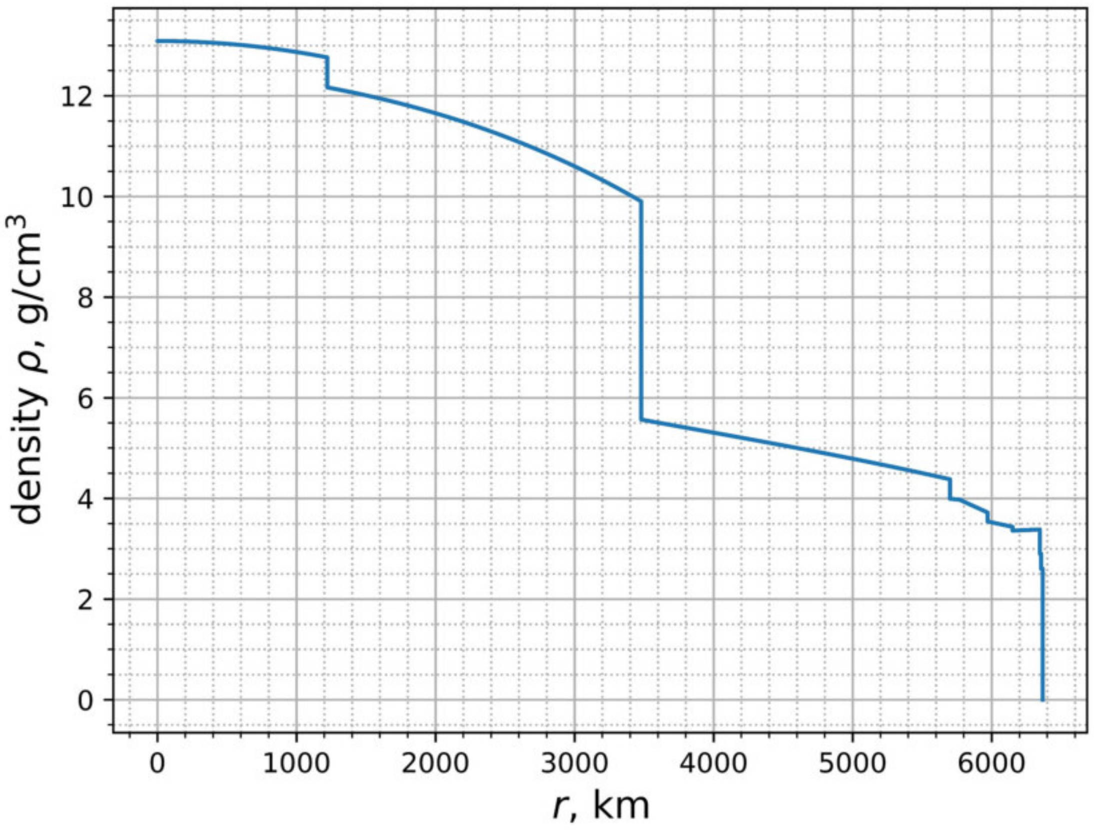




Kinematic boundaries & PREM

$$N_\alpha = \epsilon_{\alpha\beta\gamma\delta} p^\beta k^\gamma q^\delta$$





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

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

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

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

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

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

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

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

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

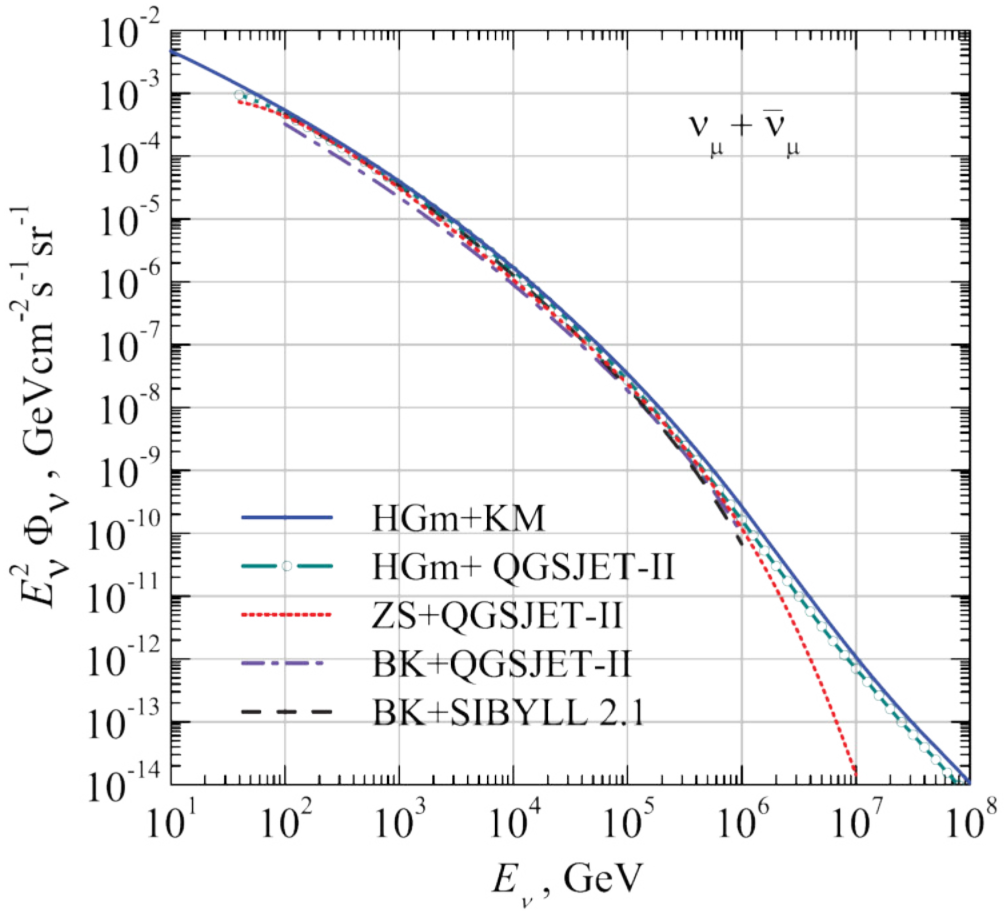
$$W_1^{\rm DIS}(x,Q^2) = F_1(x,Q^2), \quad W_n^{\rm DIS}(x,Q^2) = w^{-1}F_n(x,Q^2)$$

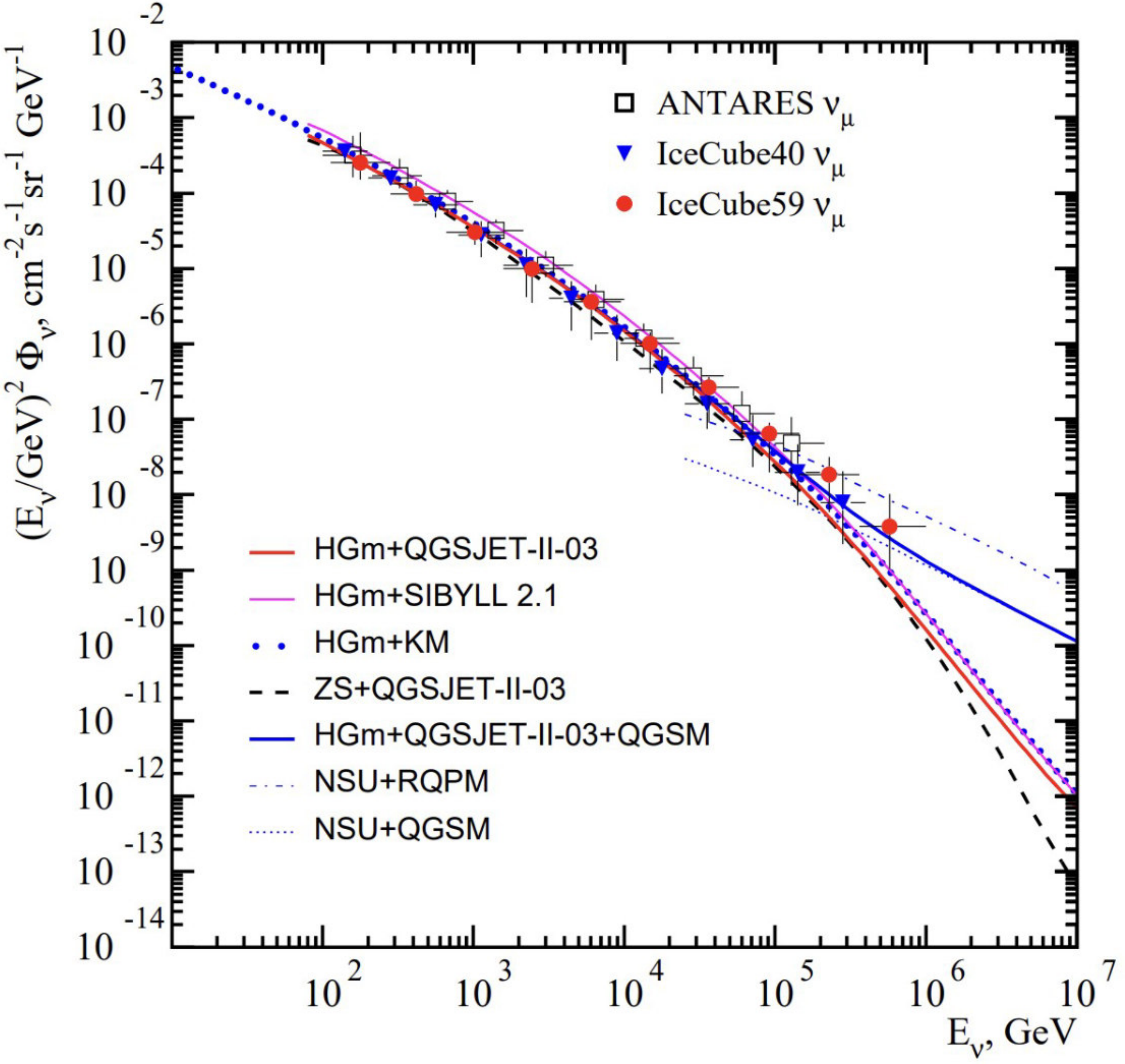
$$n = 2,\ldots,6,\ Q^2 = -q^2,\ x = Q^2/2(pq),\ w = (pq)/M^2.$$

NTSim Generators: NuGen

- Neutrino flux: atmospheric (conventional & prompt)

(arXiv:1407.3591)

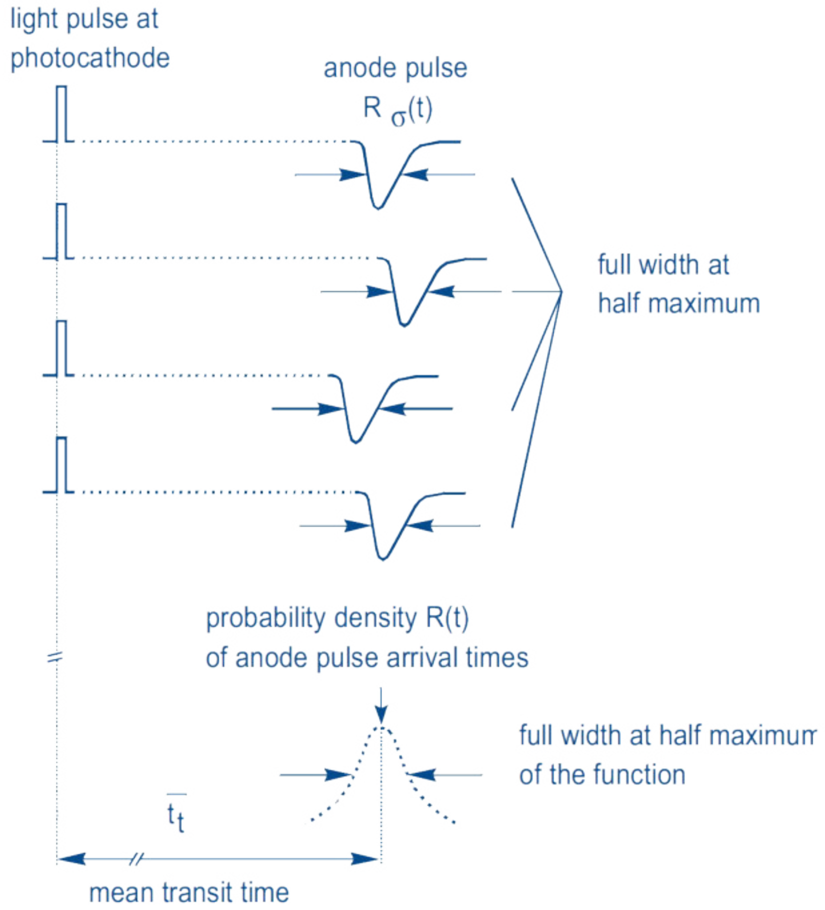



ANTARES ν_μ
IceCube40 ν_μ
IceCube59 ν_μ
HGm+QGSJET-II-03
HGm+SIBYLL 2.1
HGm+KM
ZS+QGSJET-II-03
HGm+QGSJET-II-03+QGSM
NSU+RQPM
NSU+QGSM
$(E_\nu/GeV)^2\ \Phi_\nu$, $cm^{-2}s^{-1}sr^{-1}\ GeV^{-1}$
E_ν, GeV

NTSim Structure: Triggers

Triggers allow to perform an initial analysis of MC data before converting to BARS

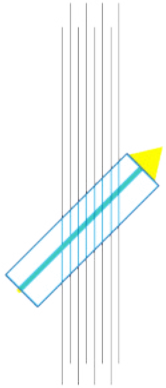
- BGVDTrigger
  - Transit time spread
  - Single-cluster trigger (arXiv:2106.06288)
    - two neighboring OMs within the same section
    - time window
    - hits magnitude: , p.e.
    - event time frame



Baikal-GVD

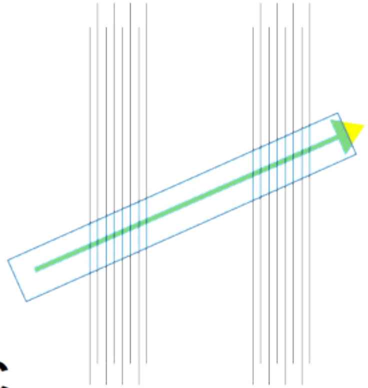
Event types

Single-cluster tracks



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

Multi-cluster tracks

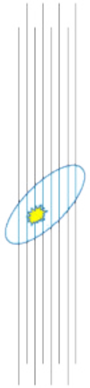


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- Best angular resolution

ν_μ CC

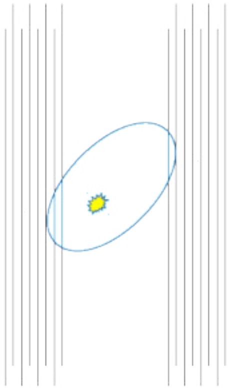
NC, ν_e ν_τ CC

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

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