The highest energy cosmic rays: status and first results of the Pierre Auger Observatory

Where do UHECR come from ?

How can we observe them ?

What did Auger see ?

A brief historical overview

- ~1910 : evidence for excess of ionizing radiation compared to earth radioactivity
- Hess 1912-14 (balloon measurements) : radiation rate *increasing* with altitude → *extraterrestrial* origin
- -1930 (geomagnetic effects) : the cosmic rays are mainly *charged* particles
- Auger 1938 : evidence for *extensive* cascades of atmopheric interactions :

→ particles at ground level are *secondary*

→ the *primary* energy may be very large (up to 10^{15} eV)

1930-55 : discovery of new (unstable) particles in cosmic ray interactions (until the accelerator era)

1960-now : detection of atmospheric showers : the spectrum extends up to 10^{20} eV.

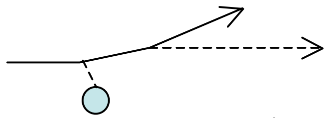
What are the cosmic rays ?

Must be *stable* objects (lifetime > travel time):

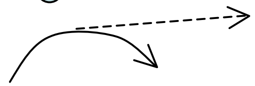
- protons, nuclei
- electrons
- photons, neutrinos
- unknown ?

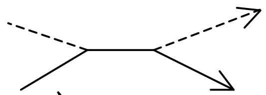
Electrons/positrons: low mass → undergo strong energy losses

- bremsstrahlung (in electric field of nuclei)



- synchrotron radiation (in magnetic fields)





- inverse Compton scattering (in photon fluxes)

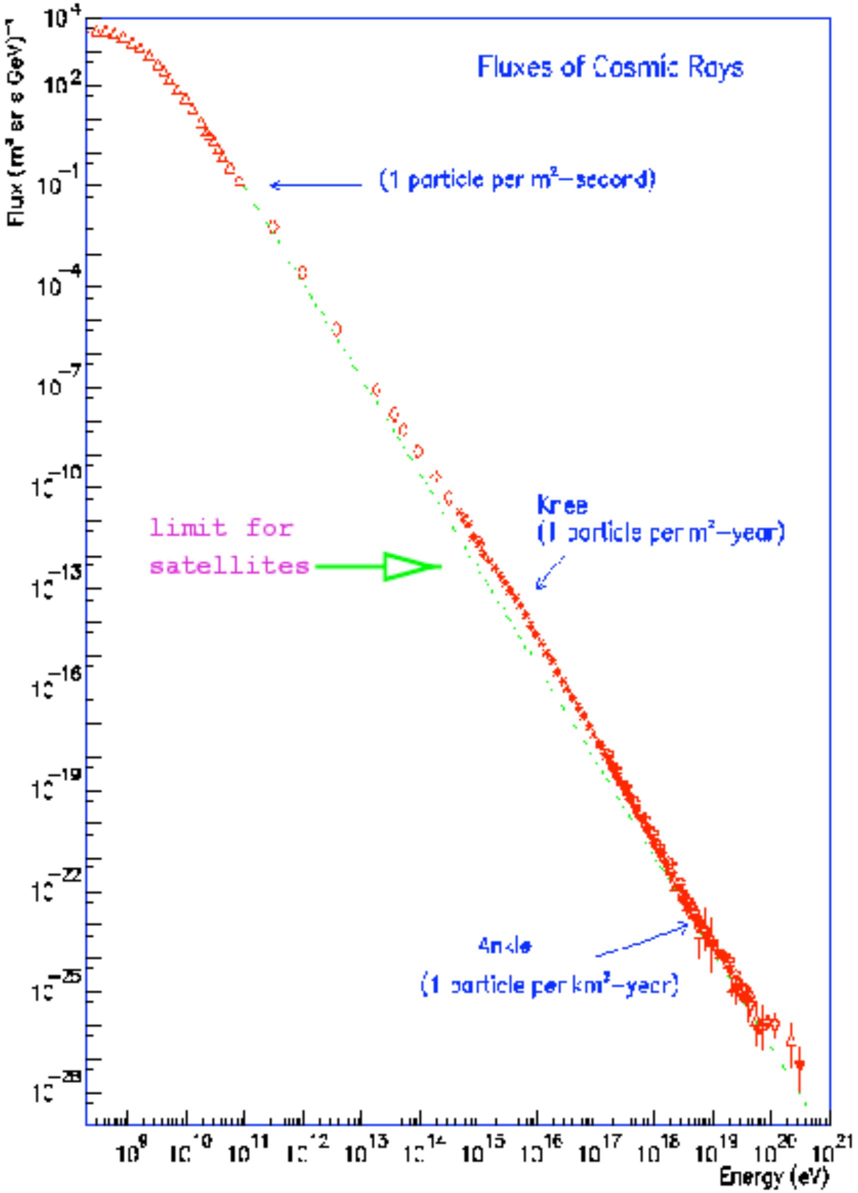
→ Cannot keep a large energy over long distances

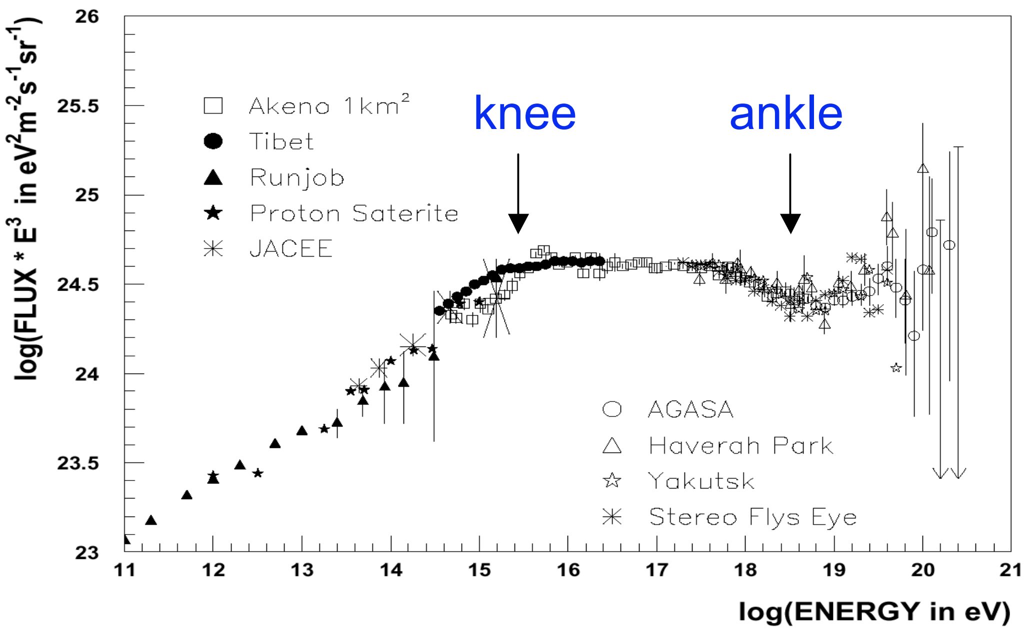
Photons, neutrinos: byproducts of other phenomena

- radiative processes (see above): photons
- decay of unstable particles (mainly mesons), e.g.

$\pi^0 \rightarrow \gamma\gamma$ $\pi \rightarrow \mu\nu$ $\mu \rightarrow e\nu\nu$

The spectrum of cosmic rays





Remarkable *power law* over 10 orders of magnitude !

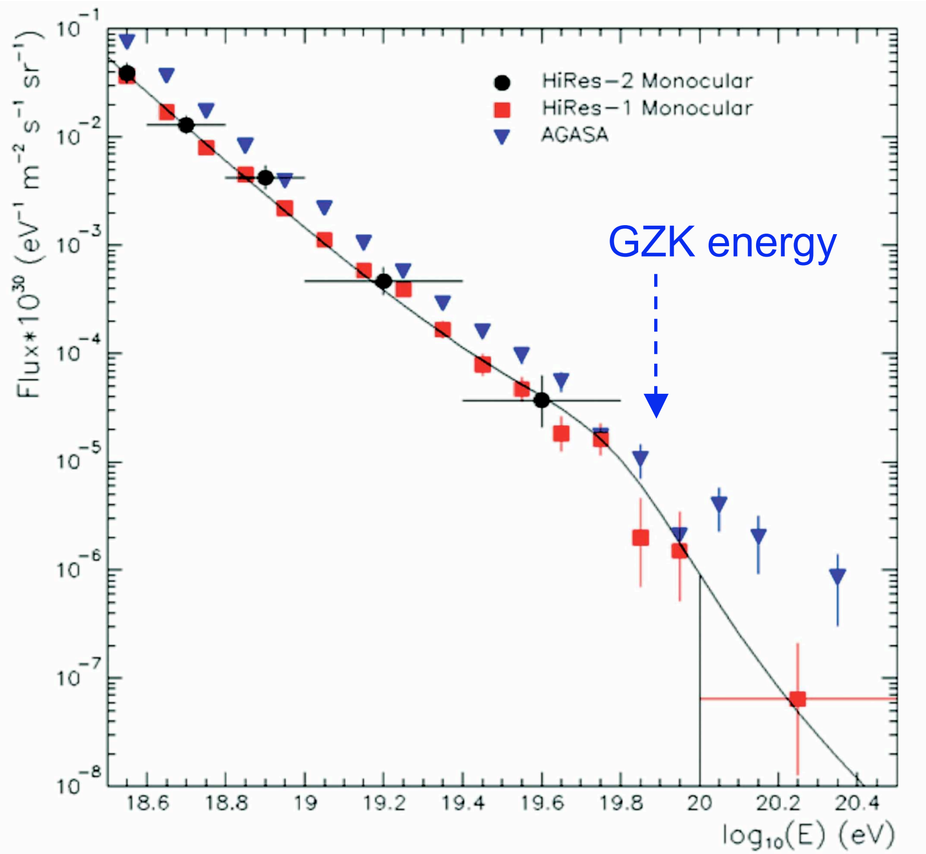
Two main *accidents*:

- the 'knee' at $10^{15\text{-}16}$ eV (probably: progressive escape of nuclei from galaxy, light ones first)

- the 'ankle' at $10^{18\text{-}19}$ eV (transition to extragalactic dominance ?)

The *nature* of CR above 10^{17}eV is difficult to establish

What at the end ?
(situation before Auger Observatory)



the *end* is not clear:

GZK cutoff expected at 5.10^{19} eV (limited propagation in cosmic background, see later)

- not seen by AGASA (ground array)

- seen by HIRES (fluorescence telescopes)

Discrepancy due to the observation technique ?

AUGER (hybrid detector, large area) should clarify…

other open questions:
nature (protons / nuclei / other ?)
origin (point sources ? large scale structures ? new physics ?)

The interstellar/intergalactic medium

• very low density of matter → very few direct collisions
interaction through electromagnetic fields

• no strong electrostatic fields at large scale

• persistent magnetic fields, amplified in condensed regions
(plasma: quasi 'superconducting' medium)

• radiation backgrounds (CMB, IR, radio) from Big Bang or galactic emissions

• still unknown objects, possibly supermassive ? (relics from the Big Bang ?)

How to accelerate charged particles ?

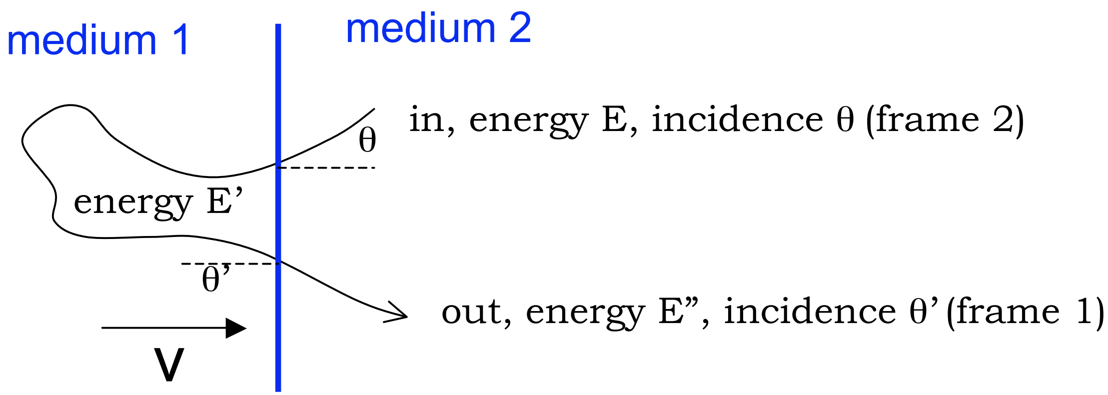
• thermal processes: low energies (10^6 K $\leftrightarrow$ 100 eV)

• stellar winds + flares (magnetic reconnection): up to 1 MeV
→ *Injection of high energy electrons, protons and nuclei into ISM*

• electrostatic fields: cannot be very large and persistent in the Universe

• electromotive fields: a magnetic field in a moving medium may produce an *acceleration*
(Lorentz transformation: B$\leftrightarrow$E)
main process (the only one ?) to obtain large energies
may occur on various sites, at various scales

The Fermi mechanism and its variants ("shock" acceleration)



non-relativistic shock: $\beta = v/c << 1$, $\gamma = 1$
ultrarelativistic approximation for particle (E=pc):

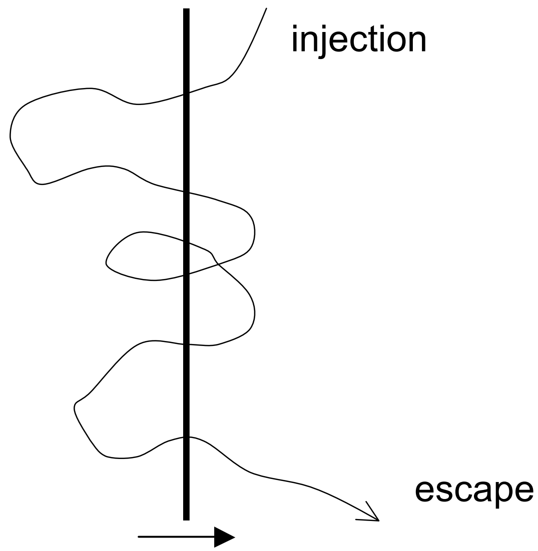
$E' = E(1+\beta\cos\theta)$

$E'' = E'(1+\beta\cos\theta') = E(1+\beta\cos\theta)(1+\beta\cos\theta')$

E">E if backscattering in medium 2 ($\Delta E/E \sim \beta$) (the shock acts as a "racket")

First possible scenario: multiple scattering on "clouds" with random speeds (positive and negative ΔE): positive average in β^2 (more frequent collisions with clouds coming towards the particle)
→ *Not enough efficient to explain highest energies*

Multistep acceleration

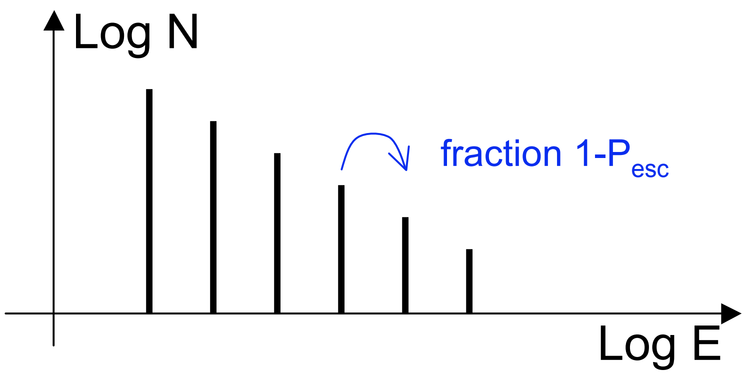


non-relativistic shock
(v << c)

Within media 1 and 2:
isotropisation w.r.t. local frame

at each step (2→1→2):
energy gain ~ v/c

escape probability ~ v/c



remarkable feature:
generation of a *power law* spectrum
(remains more or less true after accounting for realistic conditions)

One-step acceleration on ultrarelativistic shocks

Relativistic Lorentz formulae for the scattering of a shock with speed $v \approx c$ $(\gamma>1)$

$E' = E\,\gamma(1+\beta\cos\theta)$

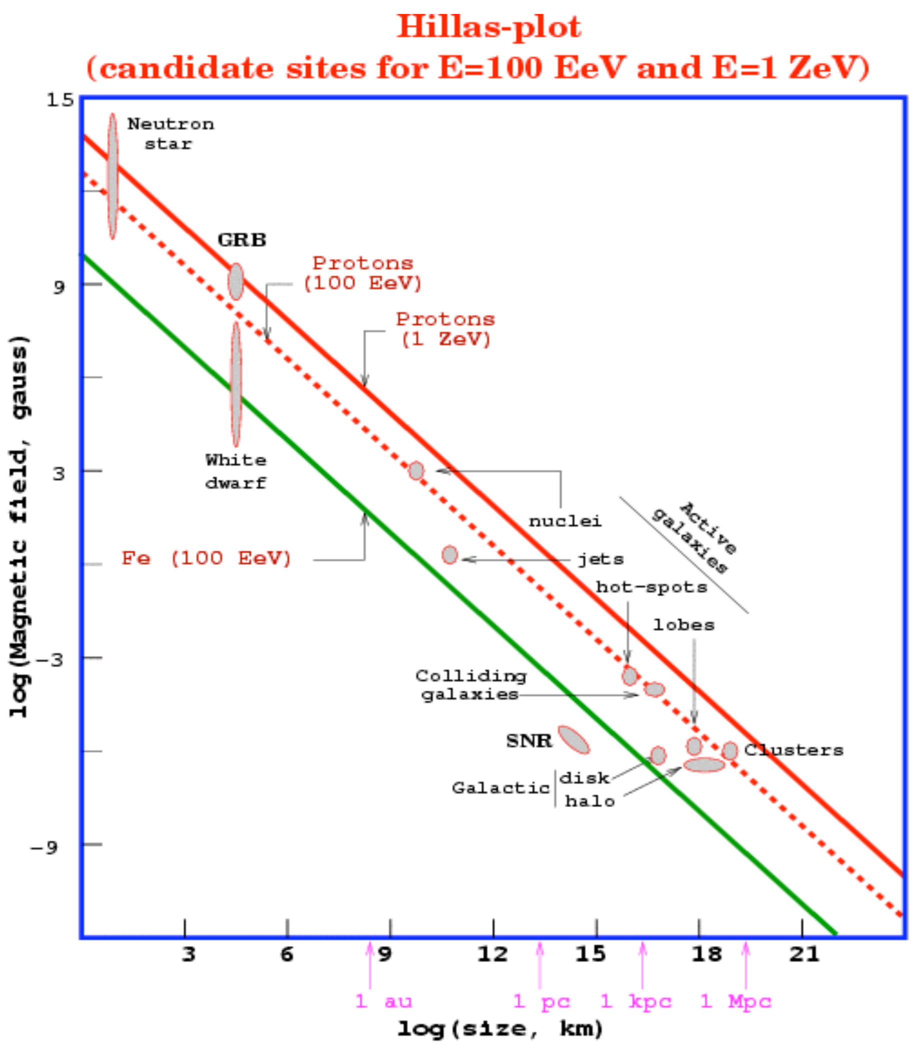
$E'' = E'\,\gamma(1+\beta\cos\theta') = E\,\gamma^2(1+\beta\cos\theta)(1+\beta\cos\theta')$

in an ultrarelativistic shock $(\gamma>>1)$ a particle can gain a large factor in E before escaping the magnetic confinment

Such shocks are expected in *fire ball* models (e.g. sources of GRB - gamma ray bursts): collapse/coalescence of very compact objects

Problem: charged cosmic rays arrive with a large delay (non straight line) → impossible to match with observed GRBs

The Hillas plot



$E_{max} \sim ZBL$ (Fermi)

$E_{max} \sim ZBL\Gamma$ (Ultra-relativistic shocks-GRB)

Necessary (not sufficient !) condition to accelerate particles up to energy E: *the Larmor radius (curvature in the magnetic field) must be less than the size of the structure*

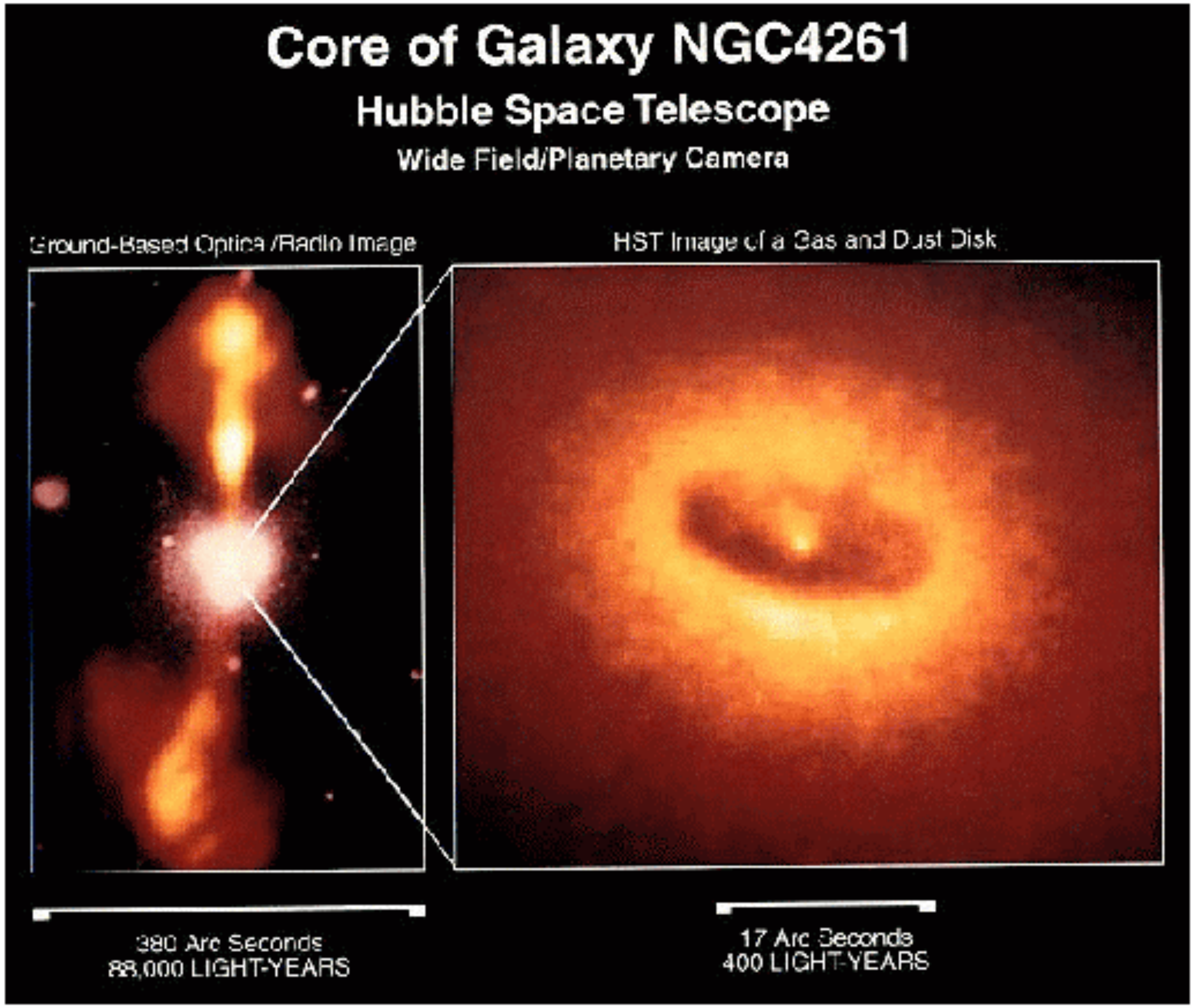
Possible exception: ultrarelativistic shock (large gain in the last crossing)
See later

Extreme cases:
- compact objects with high field (e.g. *neutron stars*)
- large structures with low fields

But: the particle has to escape the production region without interacting too much with the medium

Neuve

Active Galactic Nuclei

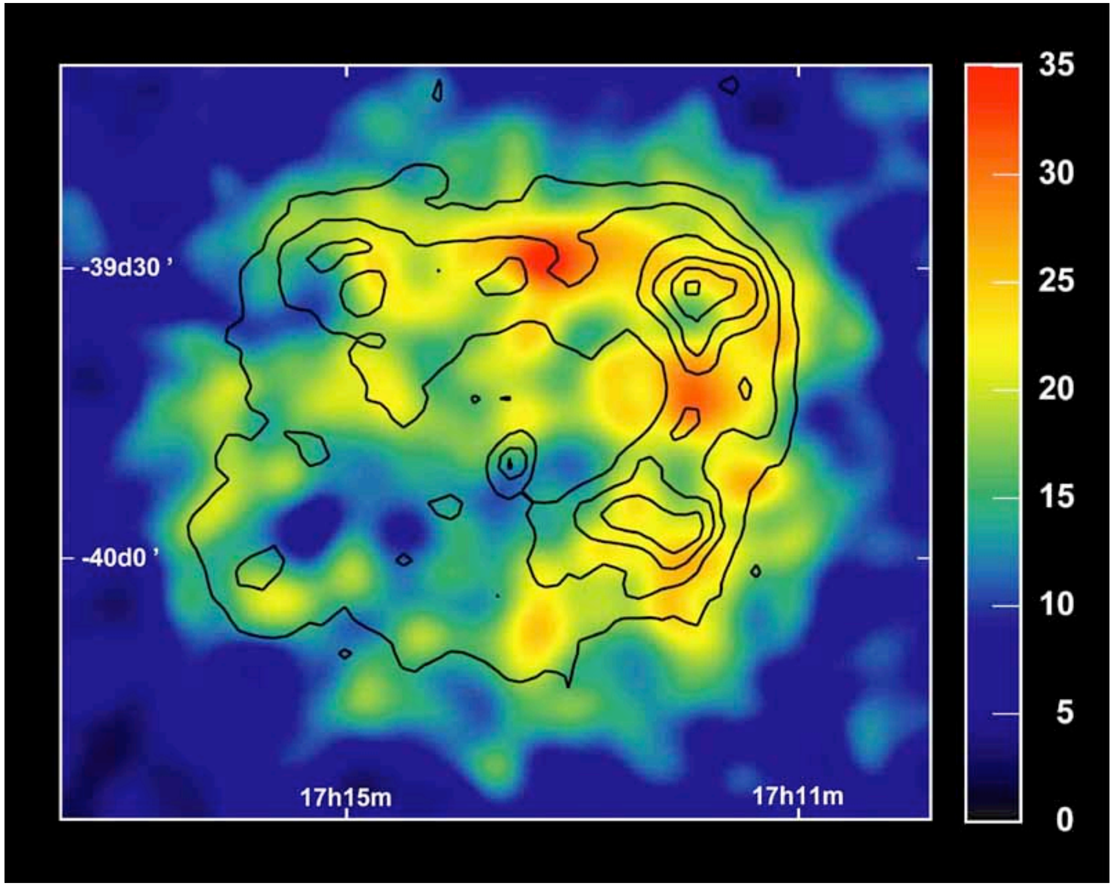


massive black hole ($\sim 10^6$ solar masses) accreting matter into a disk: two very fast jets are emitted (particles trapped in magnetic field lines)

→ two lobes (shock of the jets into the interstellar medium)

good candidate for CR acceleration site (low density,large size, large B)

First evidence for production of UHECR in supernova remnant



G347.3+0.5 (3000 l.y.)
(exploded in 393 ?)

Contours:
X-ray emission
(XMM-Newton)
Colors:
gamma 0.8→10 TeV
(HESS experiment)

clear correlation !

γ produced by particles accelerated up to ~ 100 TeV
p on matter; *e* on IR and vis. light

Open question: fraction of electron/proton

“top-down” models

General idea: hypermassive objects ($Mc^2 >> 10^{20}$ eV) decay into “normal” components: leptons (e,μ,τ) and quarks

leptons → electrons, photons, neutrinos

quarks → mesons (→ leptons , neutrinos) and baryons (→ protons)

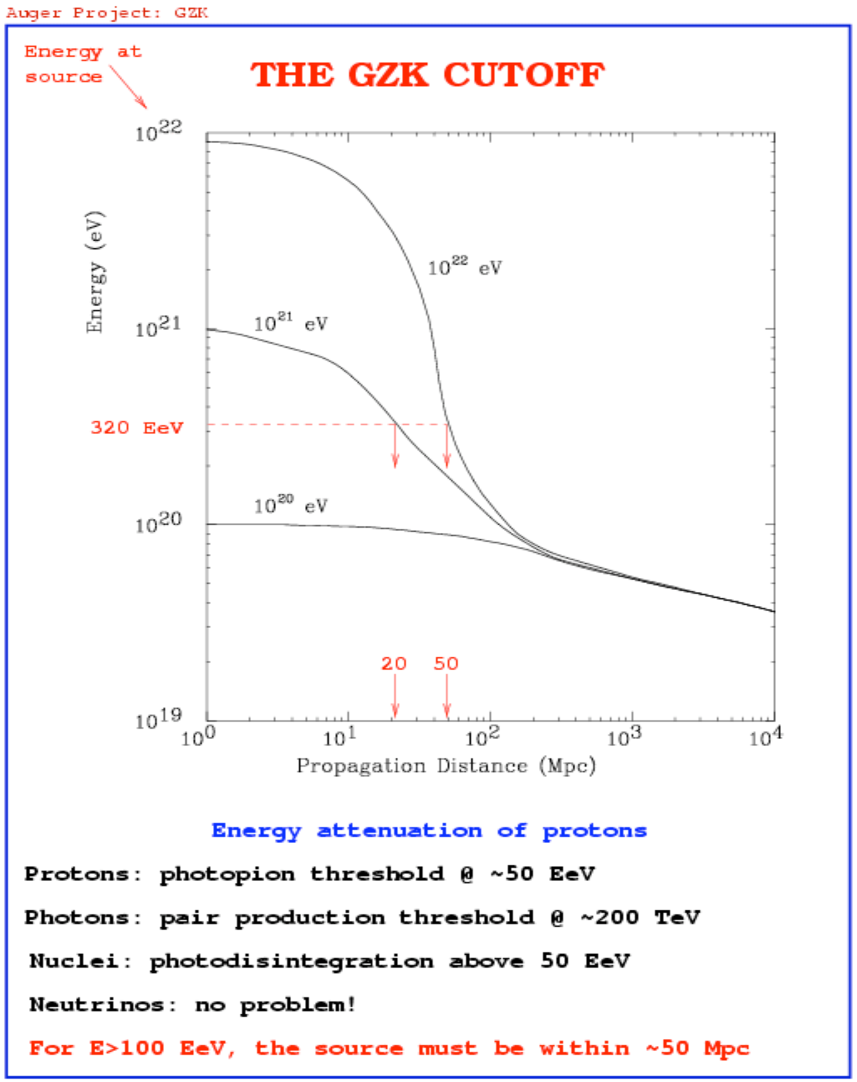
What objects ? Relics of Big Bang…

• topological defects (e.g. cosmic strings)
  disfavoured by cosmological parameters

• new particles, at the scale of Grand Unification (~10^{25} eV)
  e.g. scenario of Super Heavy Dark Matter

General features:
- hard spectrum, extending well above 10^{20} eV
- no nuclei; dominance of photons/neutrinos at highest energies

Propagation in ISM/IGM



Protons:
photoproduction of pions in CMB
$\gamma p \to \pi^0 p$ or $\pi^+ n$ (GZK effect)
not negligible if $E_p > E_{GZK}$ (5.10^{19} eV)
range bounded to a few ten Mpc
for protons above E_{GZK}
Nuclei: photodisintegration
similar limitations
Photons: range *increasing* with E
(but not too much: a few Mpc at 10^{20} eV)

Problem: no known sources in the 'neighbourhood' of our galaxy
possible solutions:

- *sources exist, not yet identified (too large magnetic deviations ?)*
- *exotic sources (top-down ?)*
- *violation of physical laws (e.g. Lorentz invariance) ?*

Still an open question…

Angular deviations

cause: galactic and intergalactic magnetic fields

radius of curvature for a particle of charge *Ze:*

$1/Z$ kpc/EeV/μG

galactic field ~ a few μG over a few kpc (?):

→ *large deviations for all nuclei up to 10^{19} eV at least*

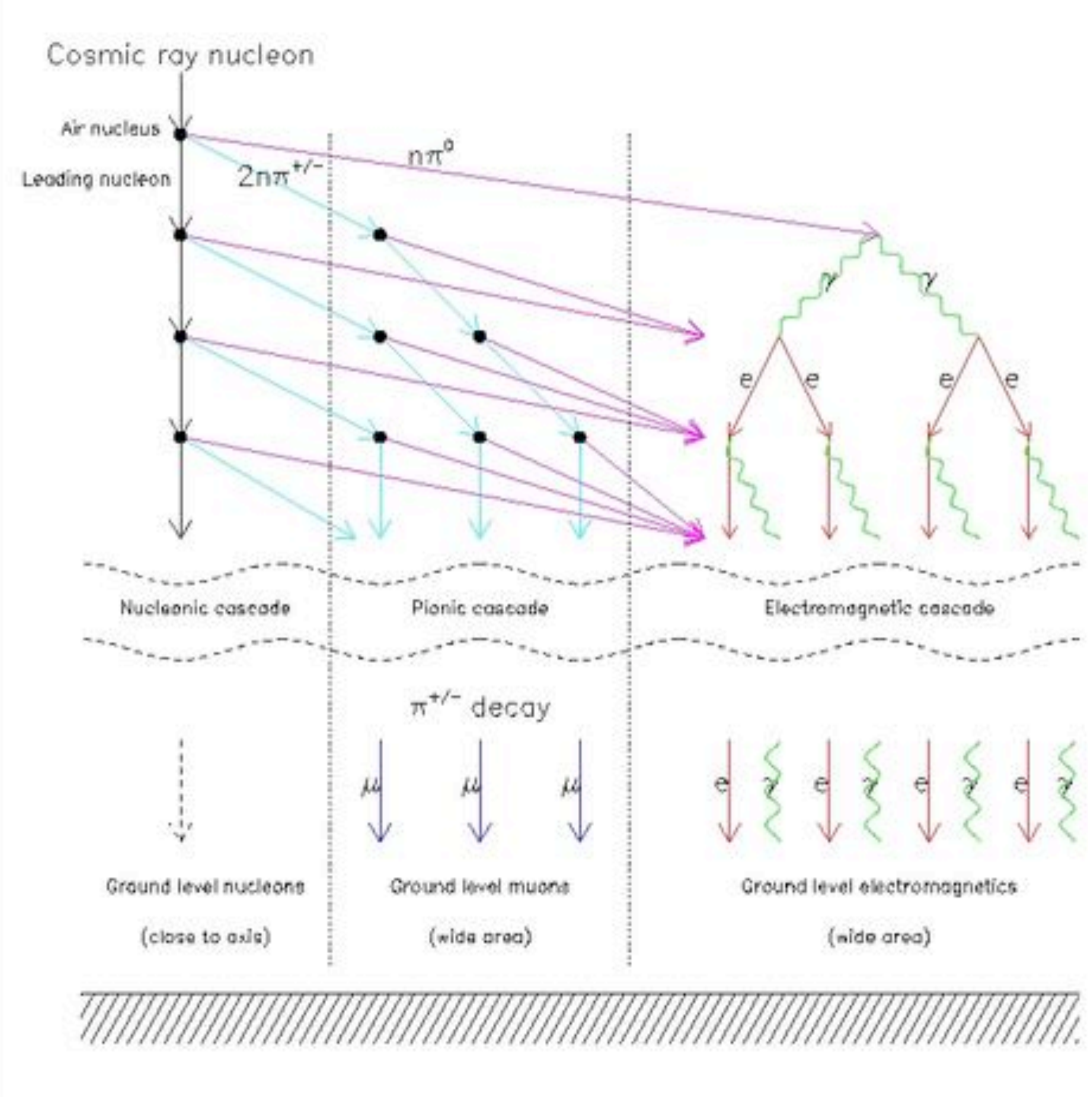
intergalactic ~ a few nG (??) with possible stronger structures (not well known)

hope to make "proton astronomy" above 10^{20} eV ?

neutrals (photons and neutrinos) point to the source

also: possible propagation of *neutrons* above 10^{18} eV within the galaxy

Atmospheric cascade



hadronic interactions:

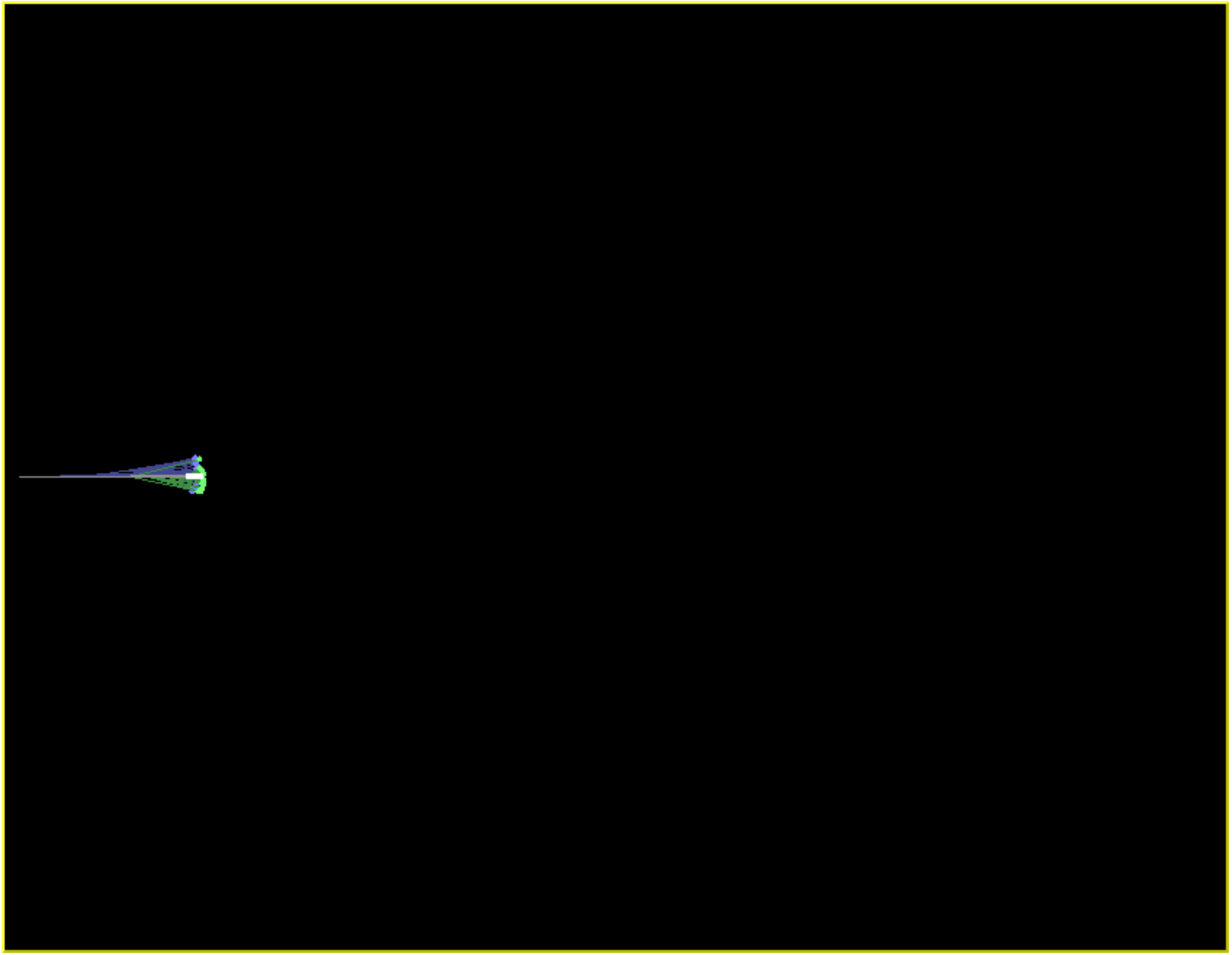
large multiplicity at high E
in average 1/3 of the energy goes into neutral mesons (mainly $\pi^0 \rightarrow \gamma\gamma$)
At the end: few GeV mesons decay before interacting → muons (propagating down to ground)

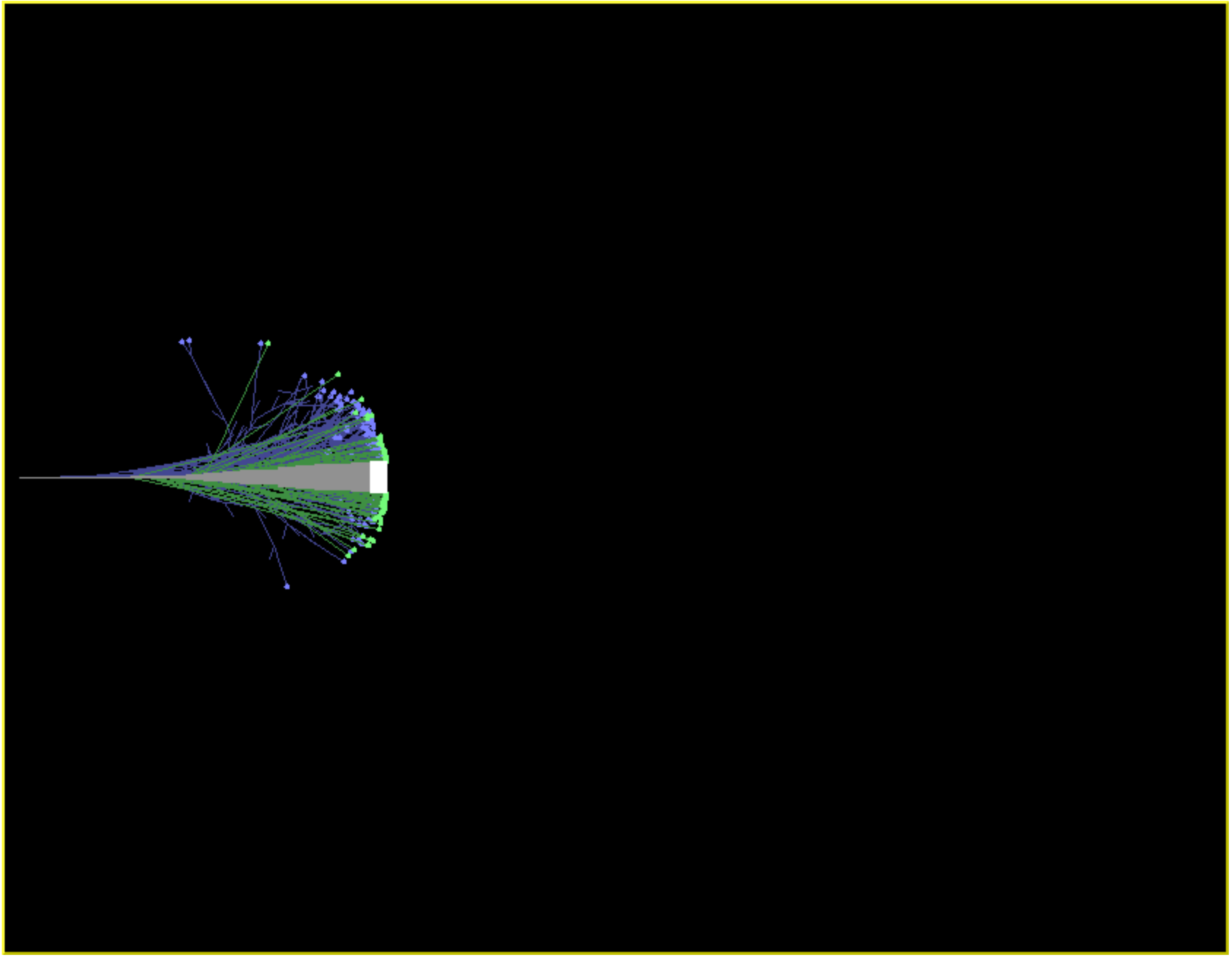
electromagnetic cascade:

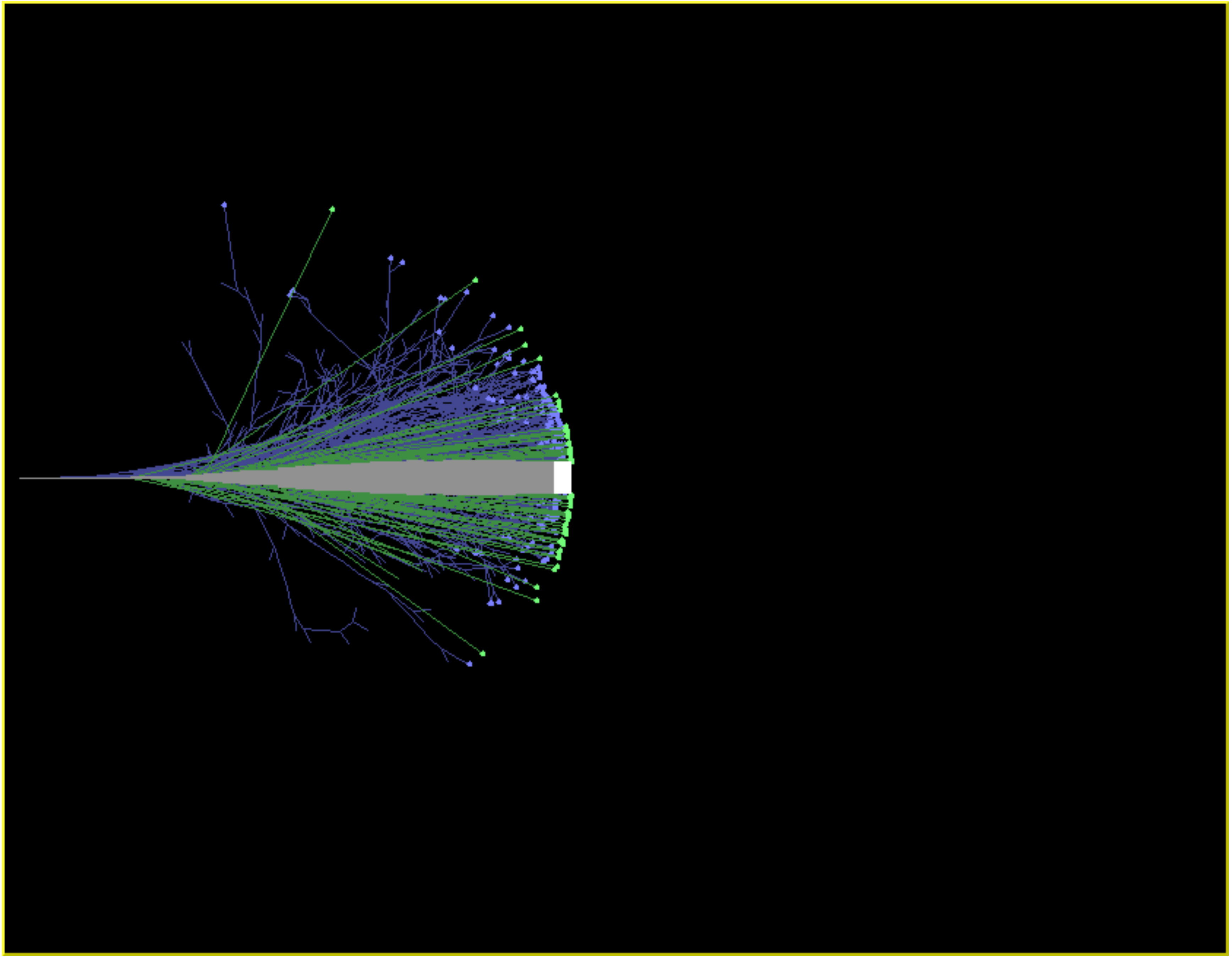
$\gamma \rightarrow e^+e^-$ (pair production)

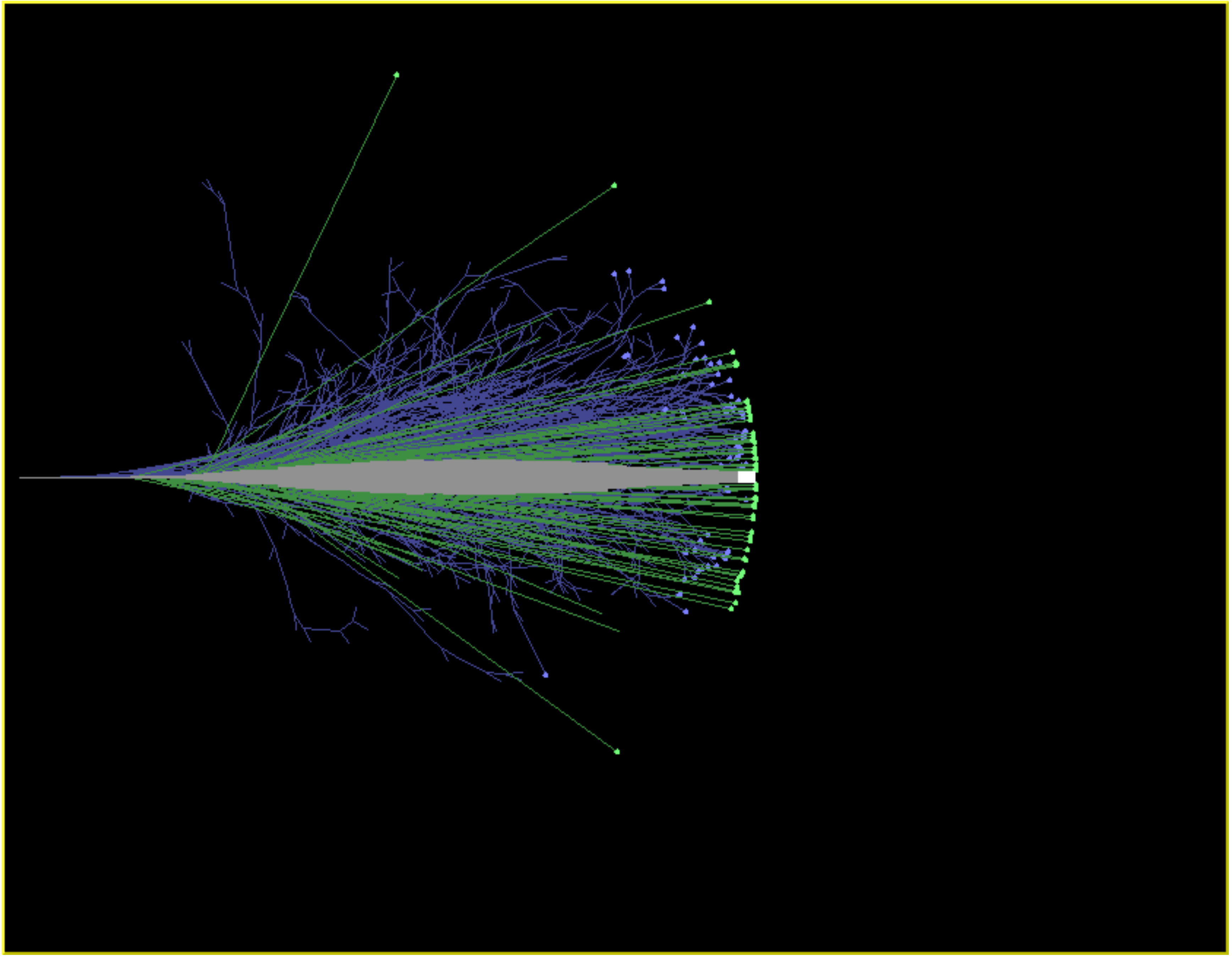
$e^\pm \rightarrow e^\pm \gamma$ (bremsstrahlung)

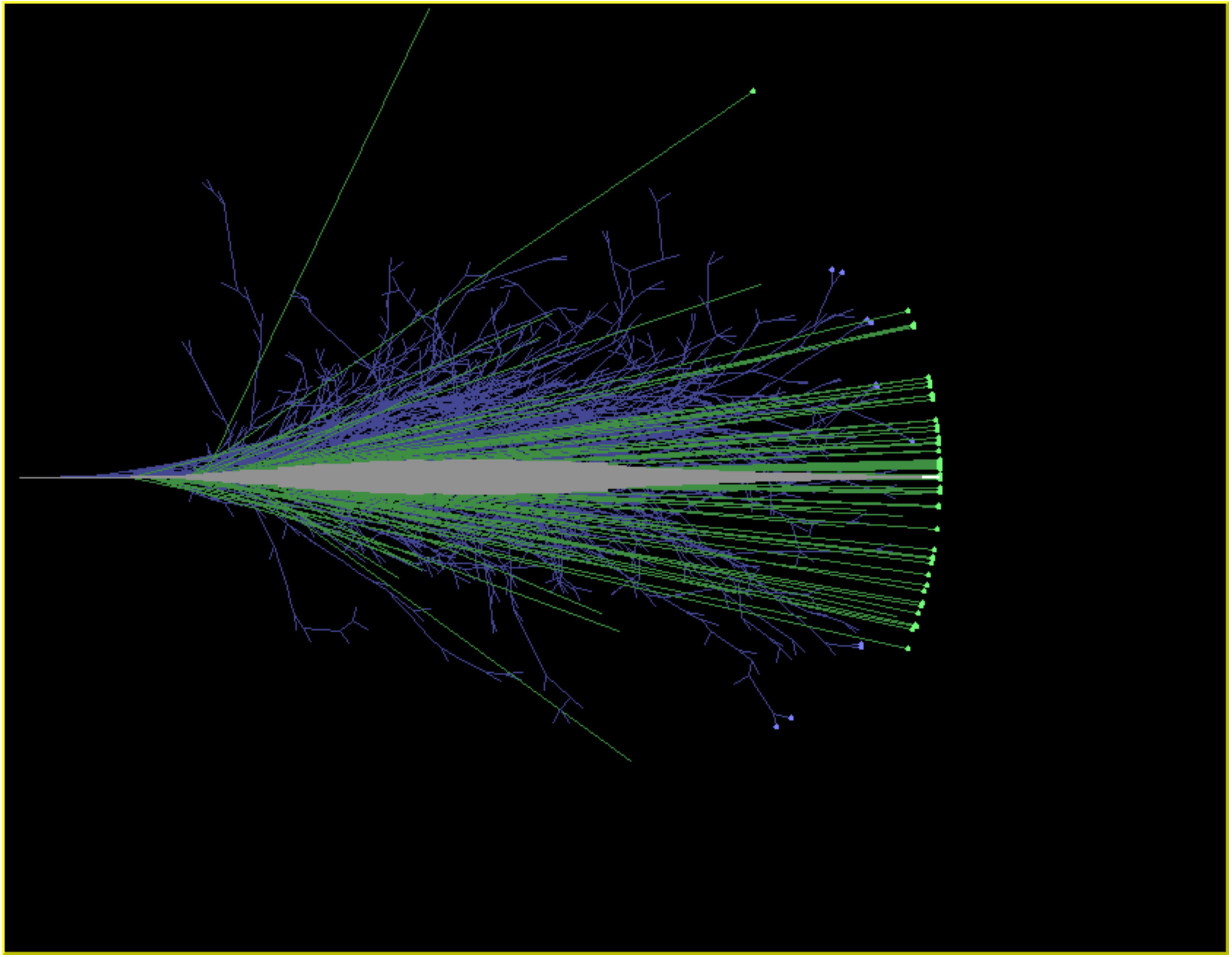
- in air (index n) charged particles produce **Cherenkov** light if $\beta n > 1$ (tightly collimated)
- excitation of nitrogen molecules: isotropic **fluorescence** light
- emission of **radio** waves

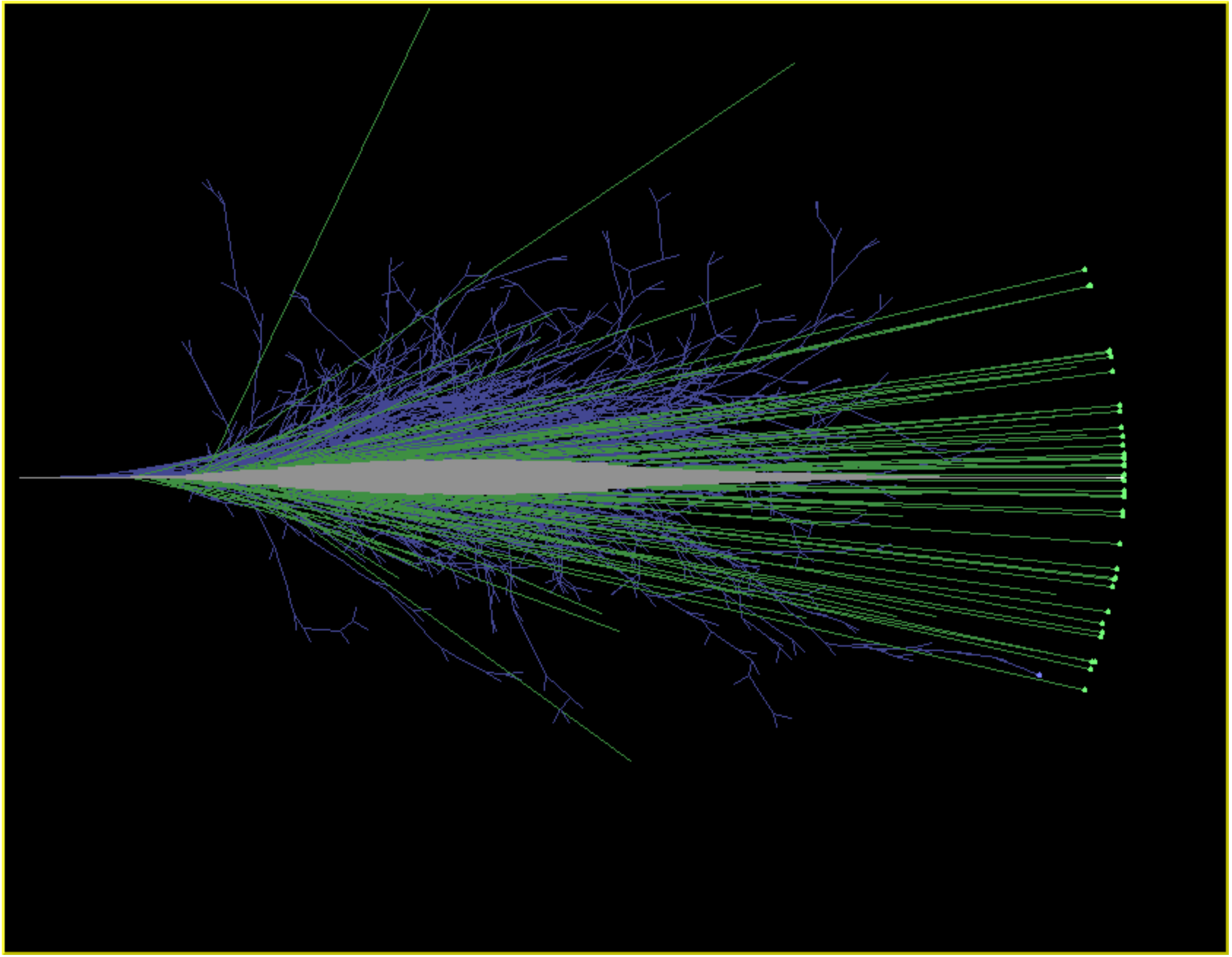












A simplistic model of cascade

- start with E_{prim}
- each step (1 interaction length): N particles with equal energies
- stopping energy: E_0

number of steps = $\log(E_{prim}/E_0) / \log(N)$

- *shower longitudinal extension increases logarithmically with E_{prim}*
- *maximum size (number of particles) proportional to E_{prim}*

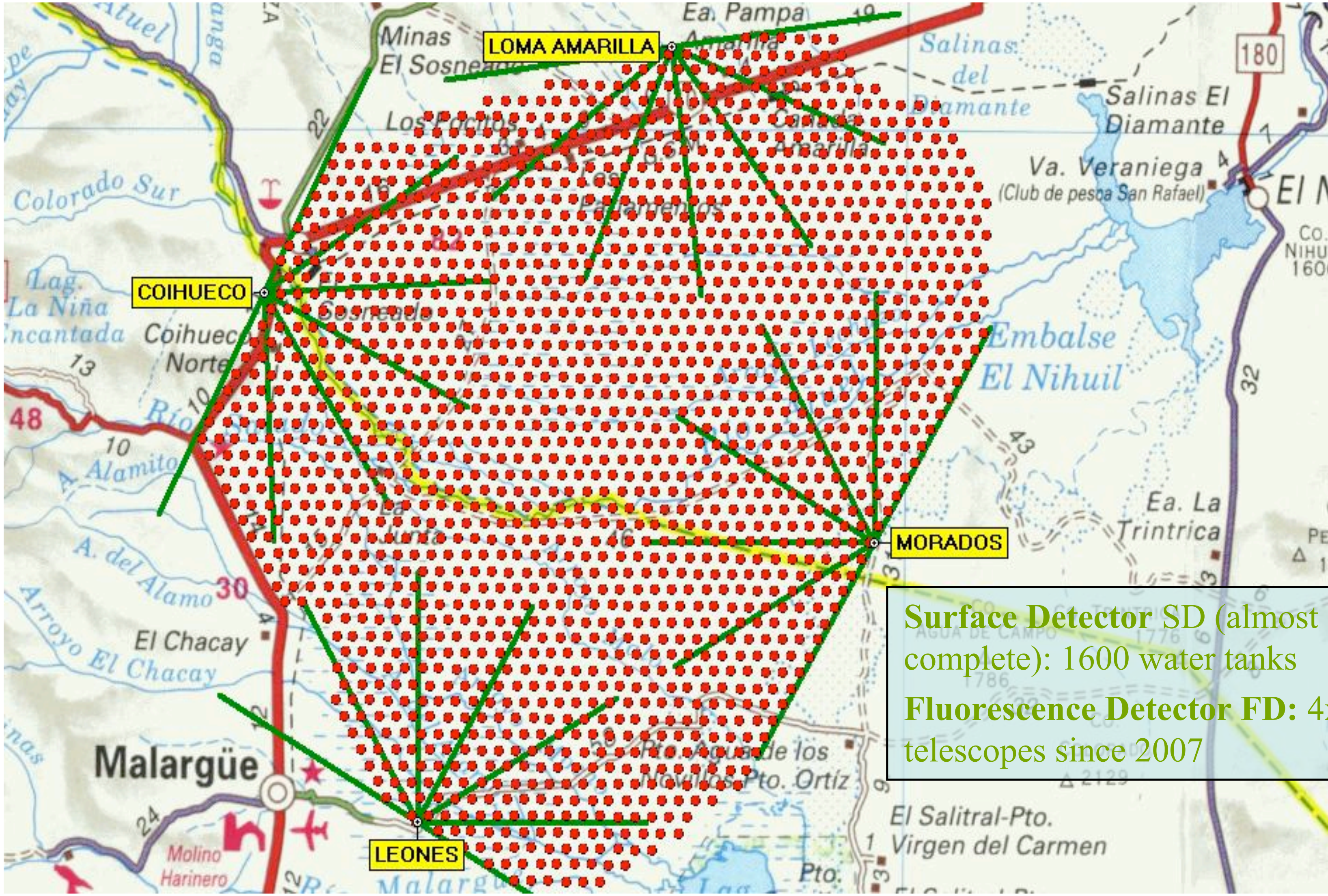
nucleus with A nucleons ⇔ A independent nucleons, energy E_{prim}/A

- *shorter extension for heavy nuclei*
- *less energy transfer from hadronic to electromagnetic cascade: more **muons** at the end*

in practice: step length and N variable, secondary energies spread, etc
increasing/decreasing profile (Gaisser-Hillas parametrization)

lateral extension: transverse momentum in hadronic interaction
multiple scattering of electrons/positrons

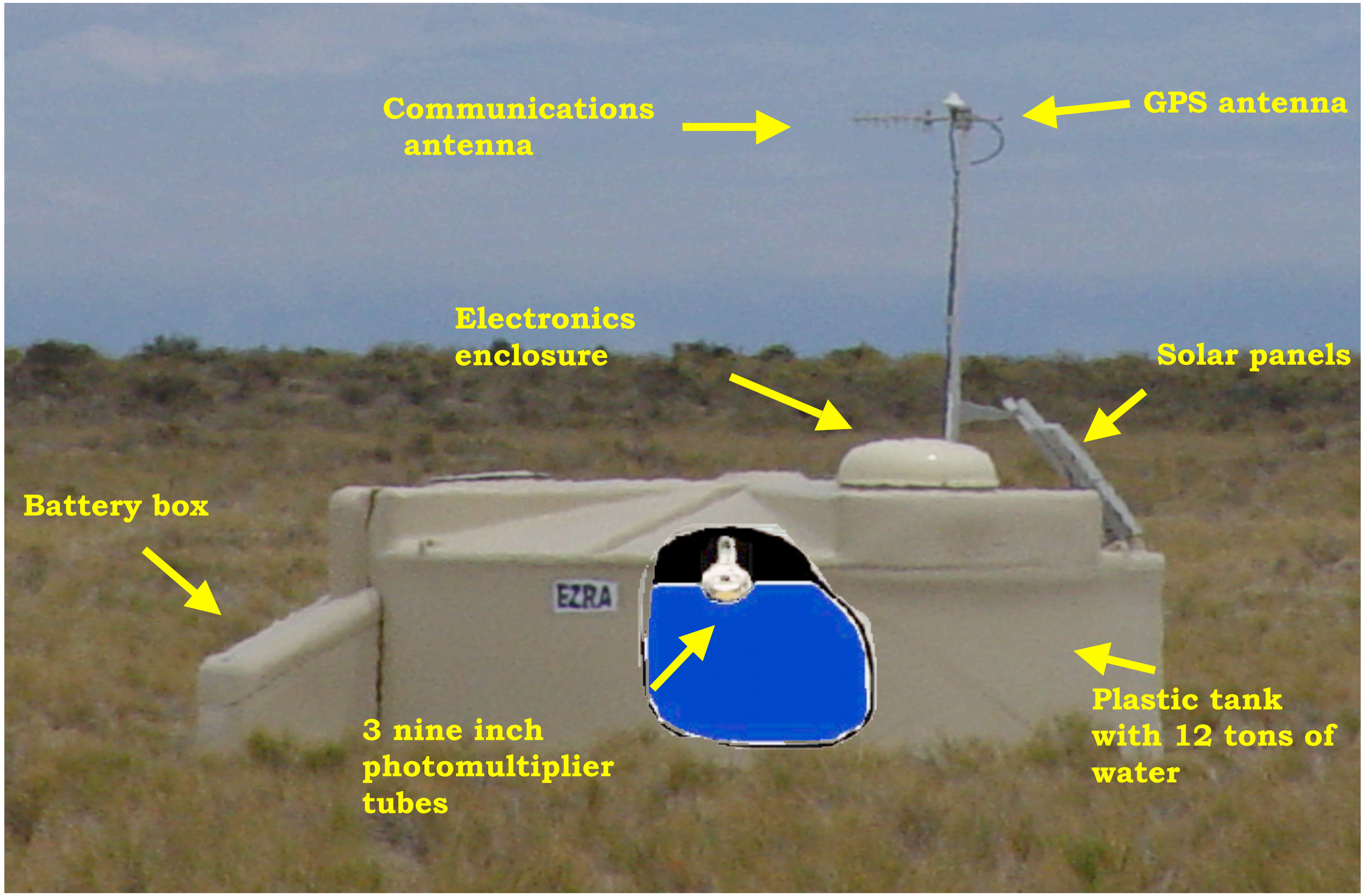
The Pierre Auger Observatory (3000 km²)



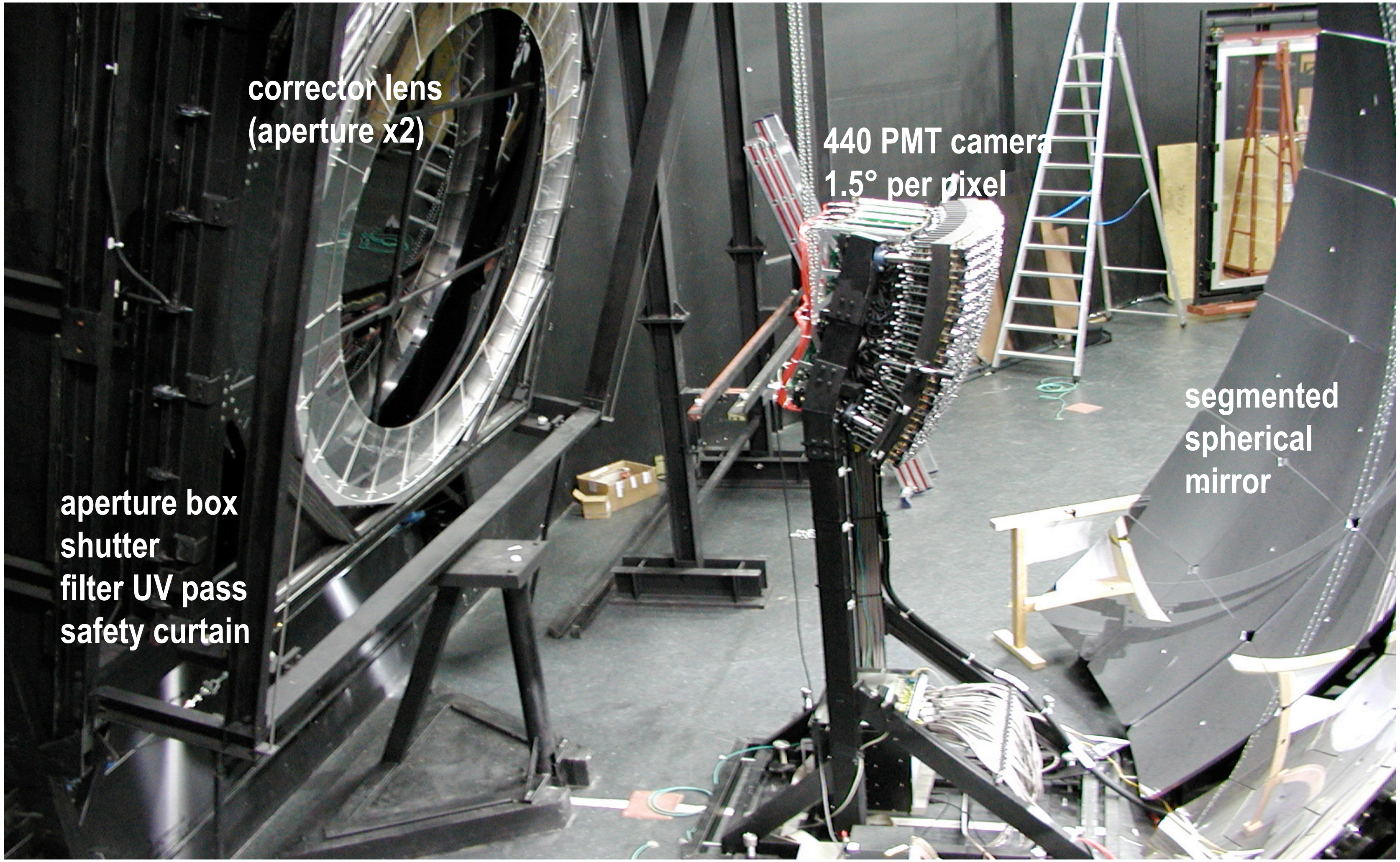
Surface Detector SD (almost complete): 1600 water tanks

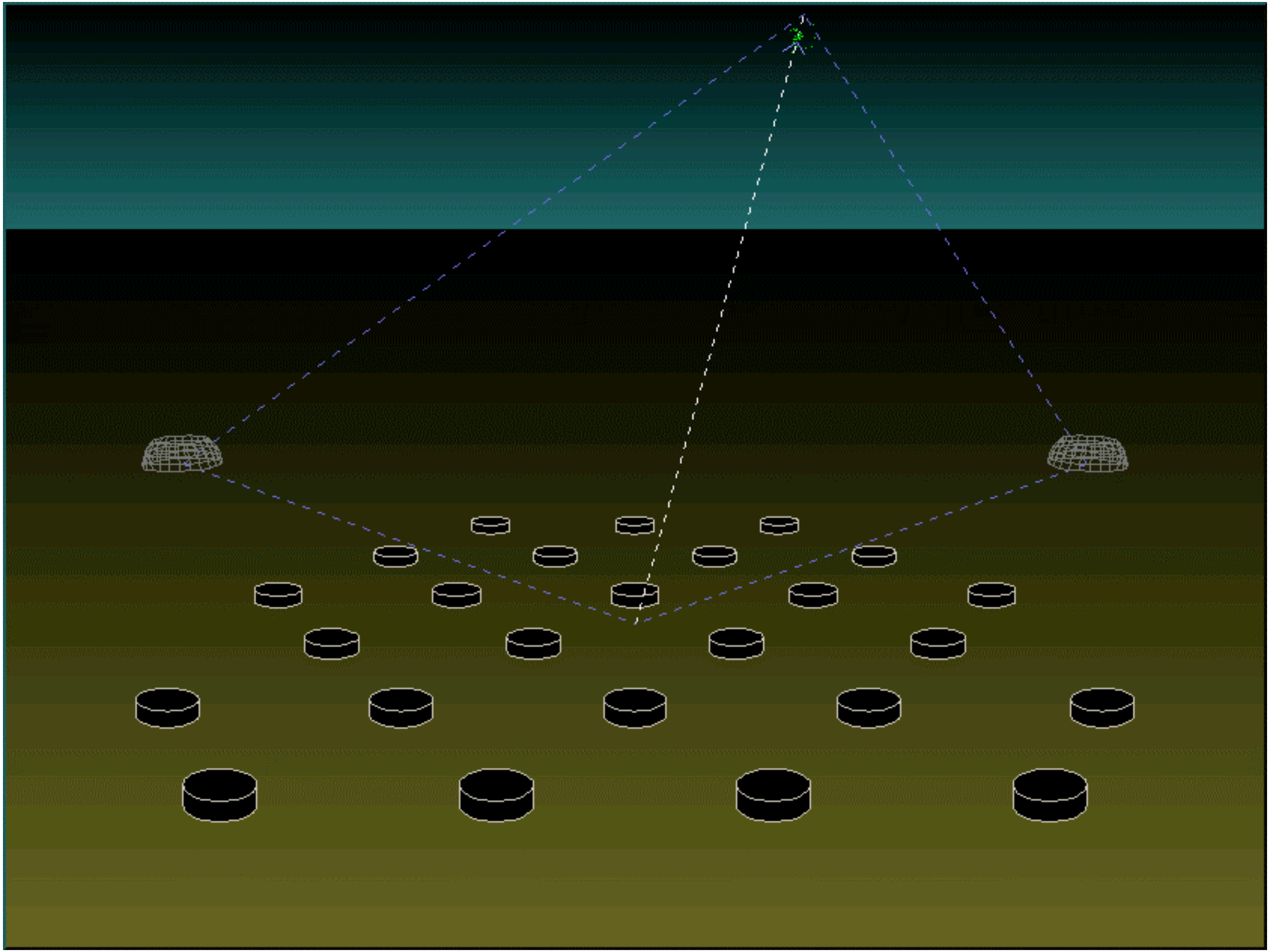
Fluorescence Detector FD: 4x6 telescopes since 2007

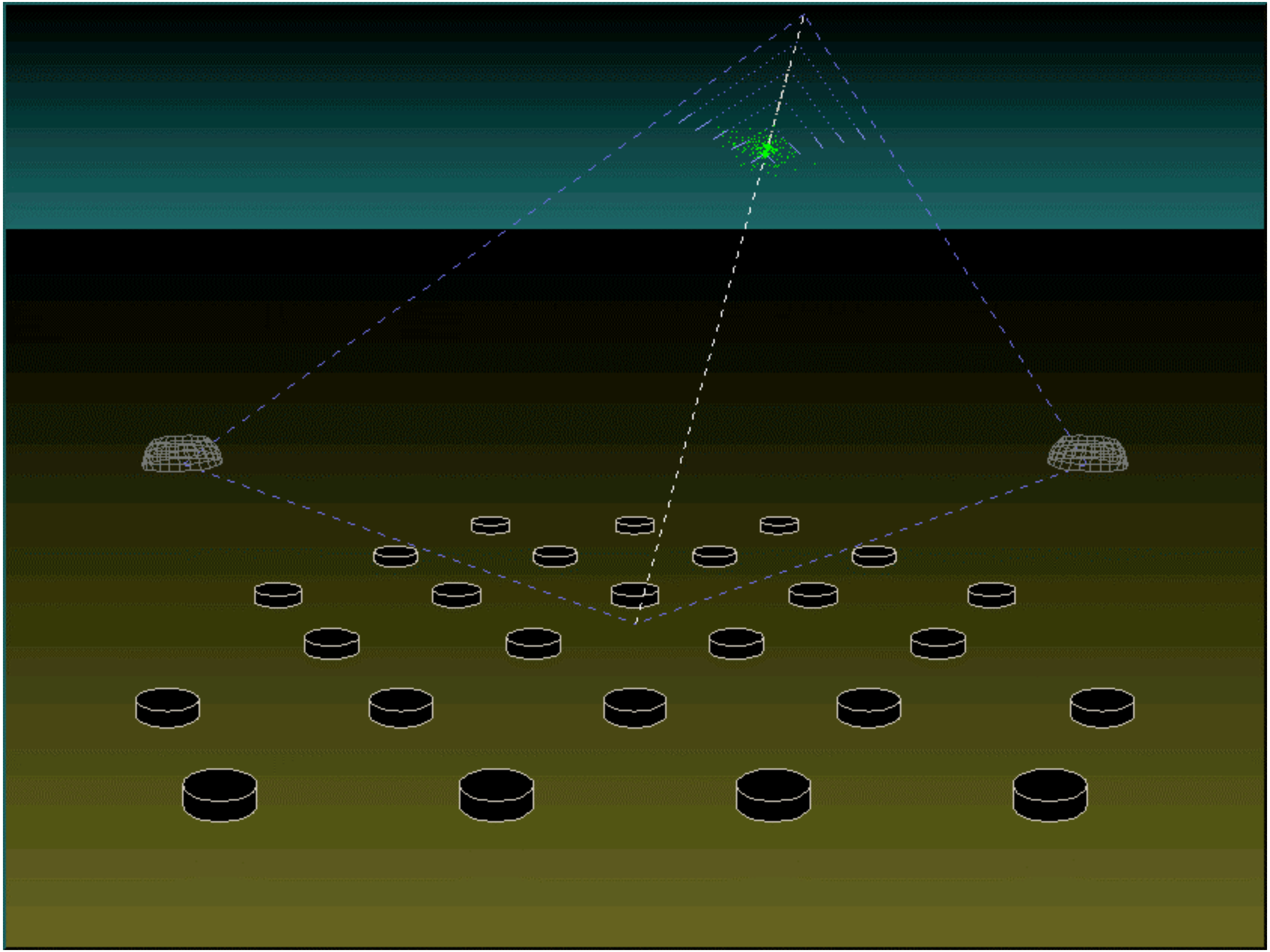
Water Cherenkov tanks

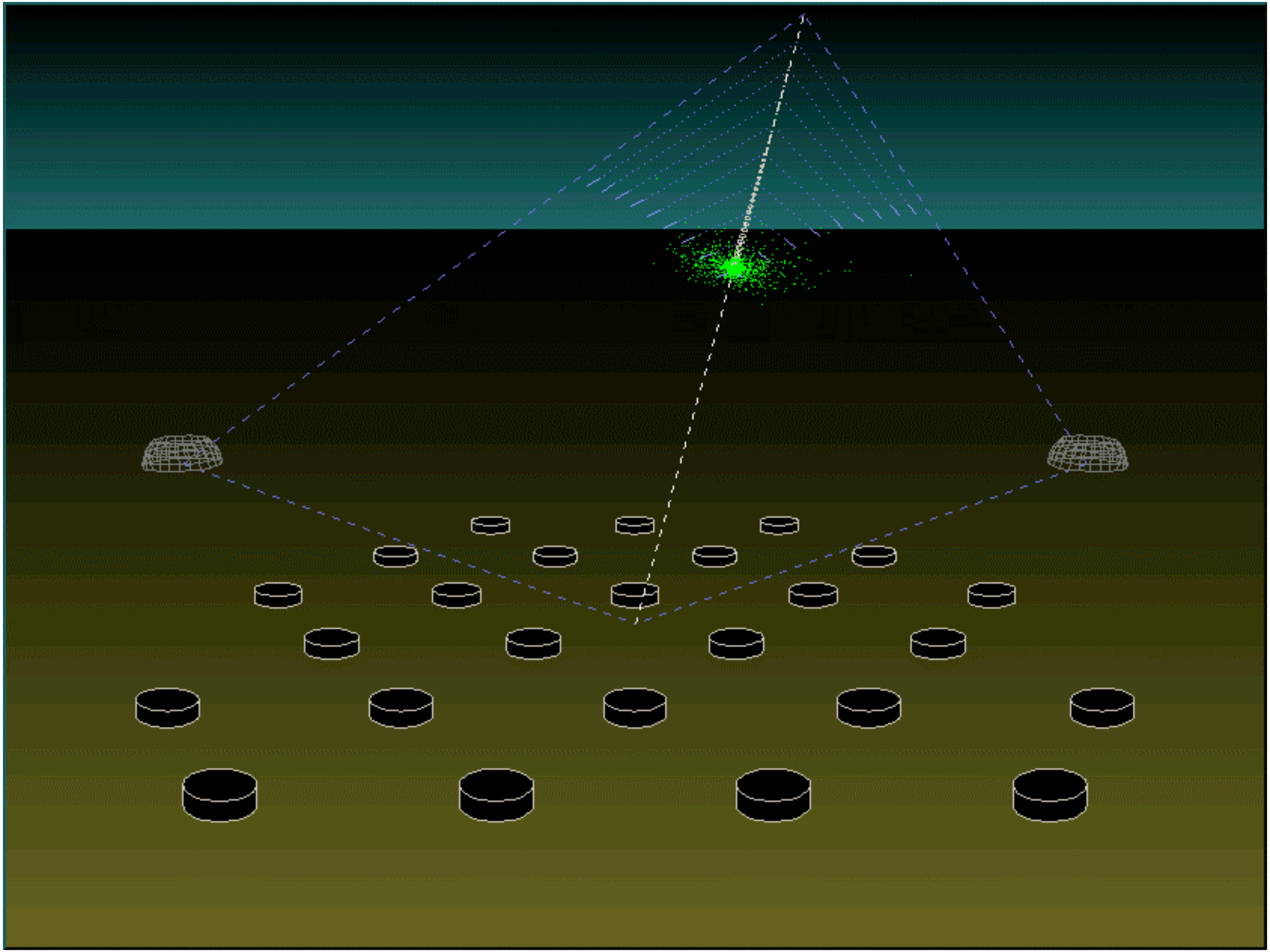


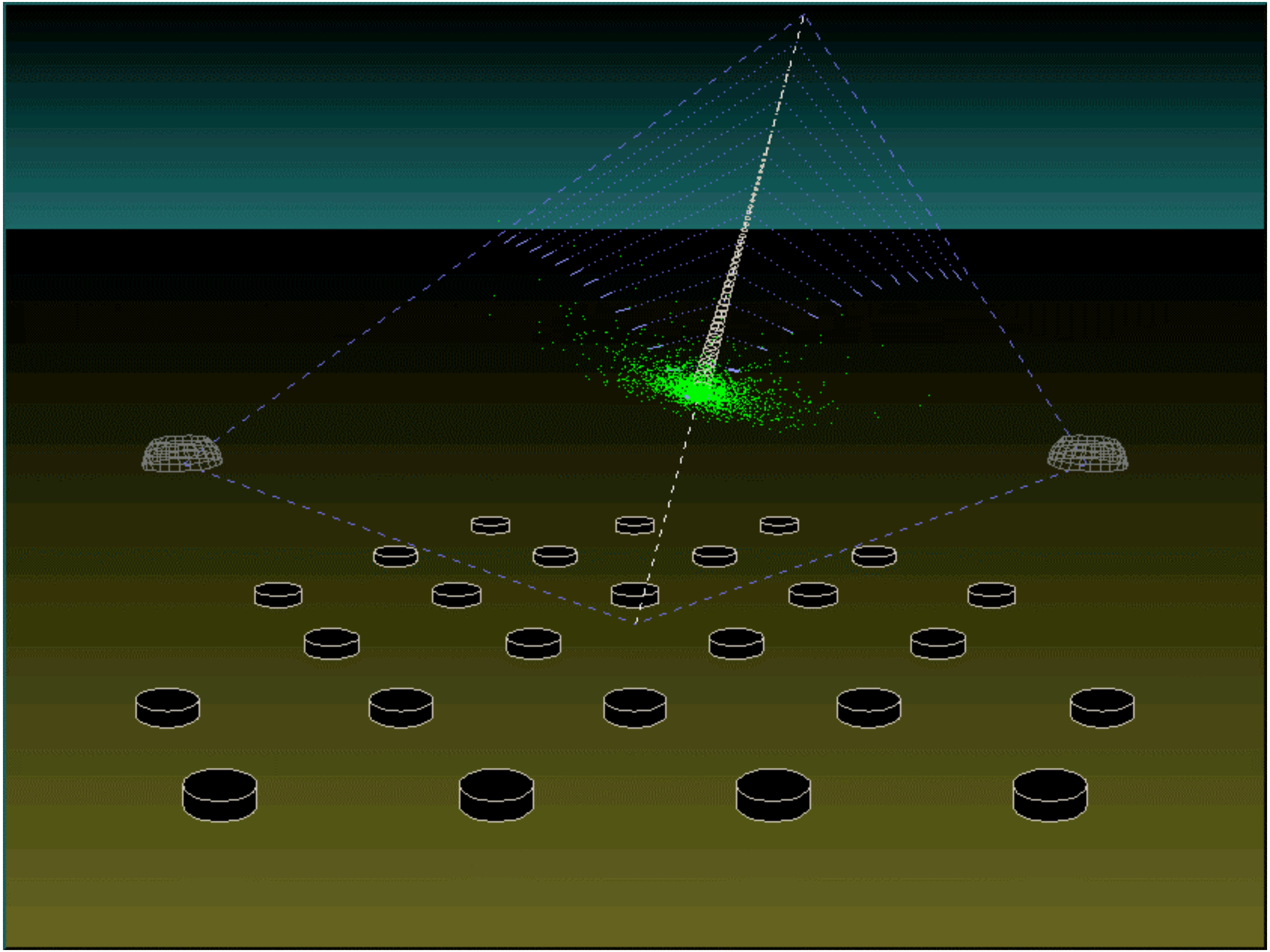
Optical system of fluorescence telescopes

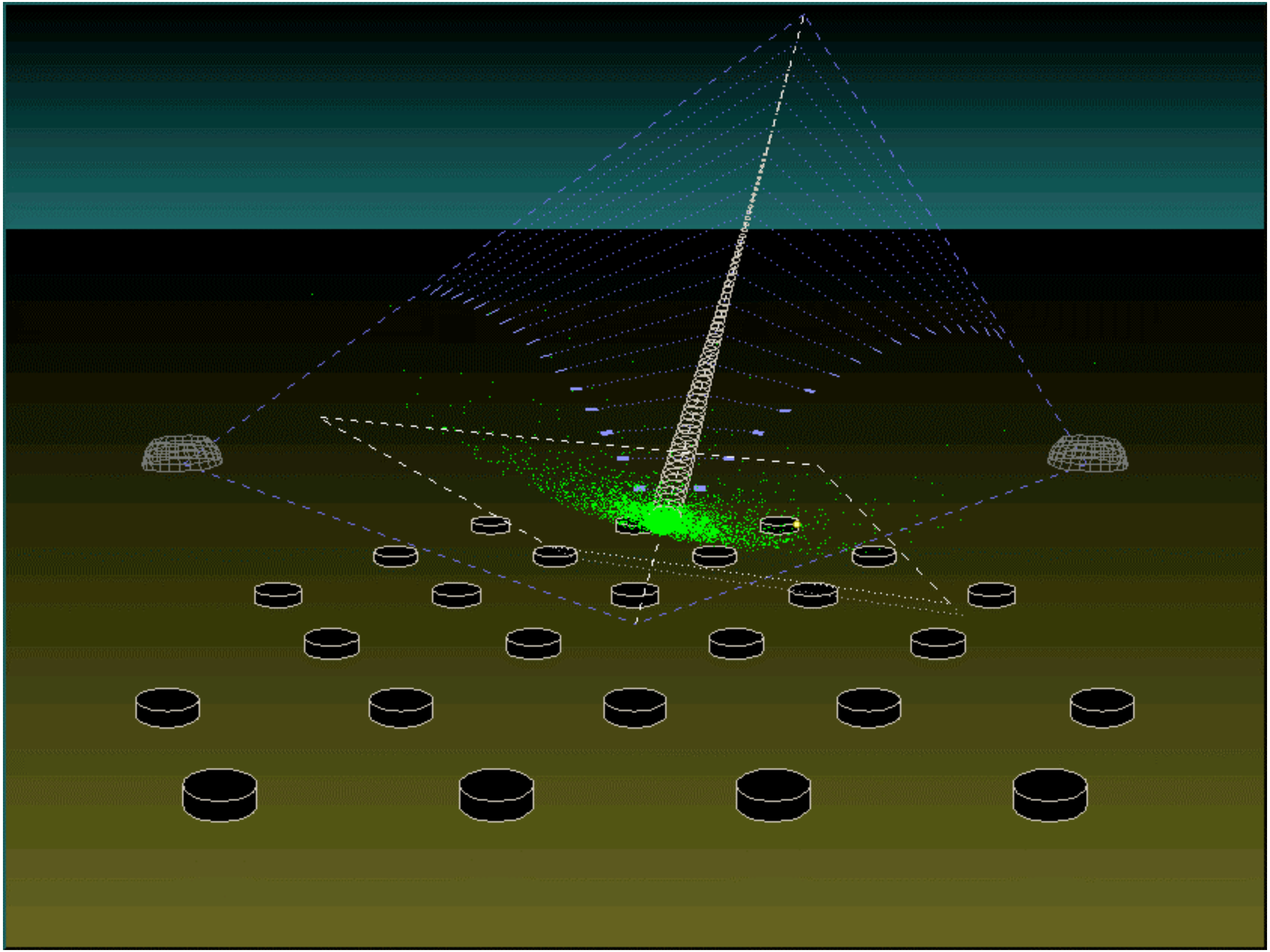


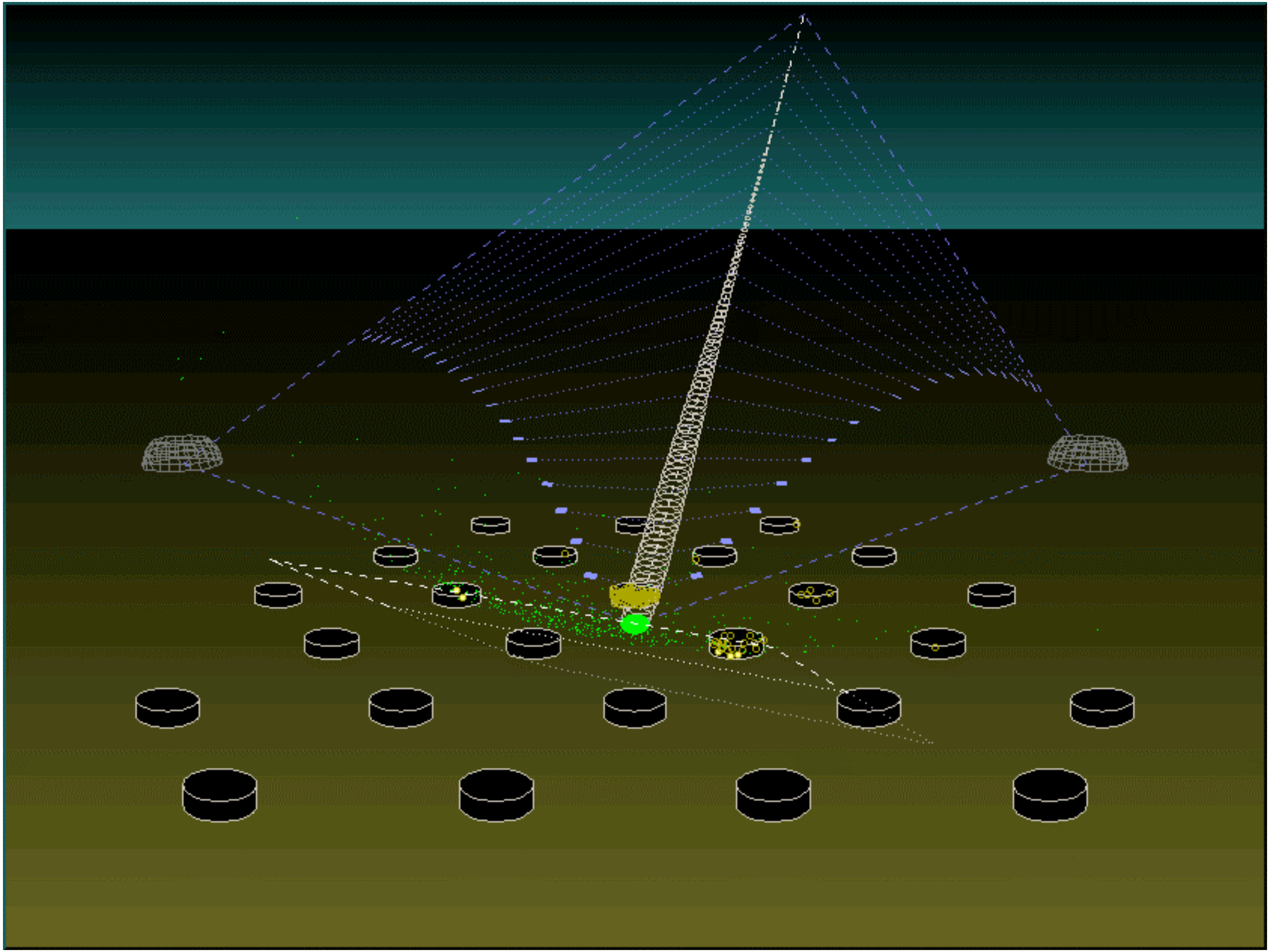


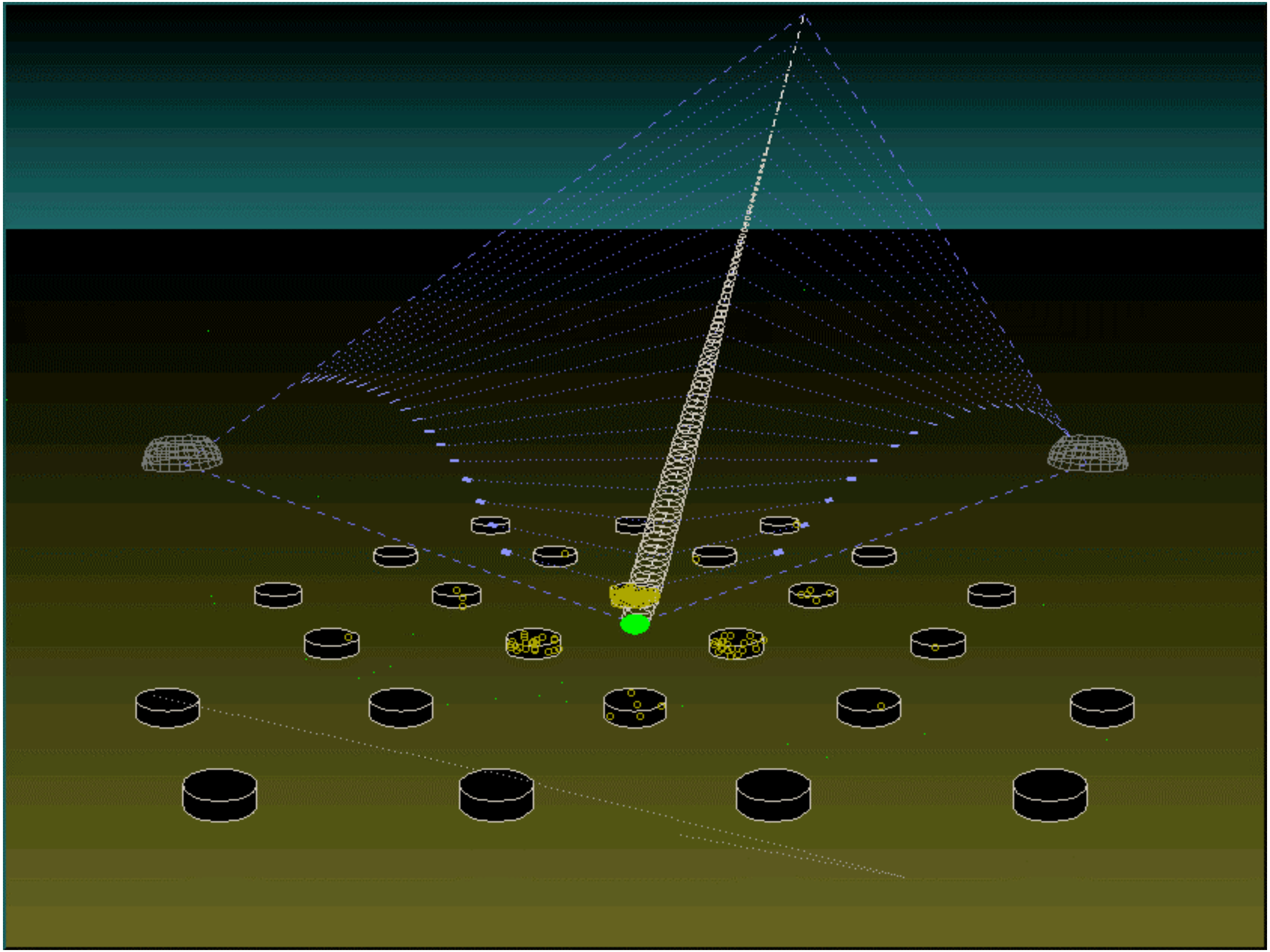


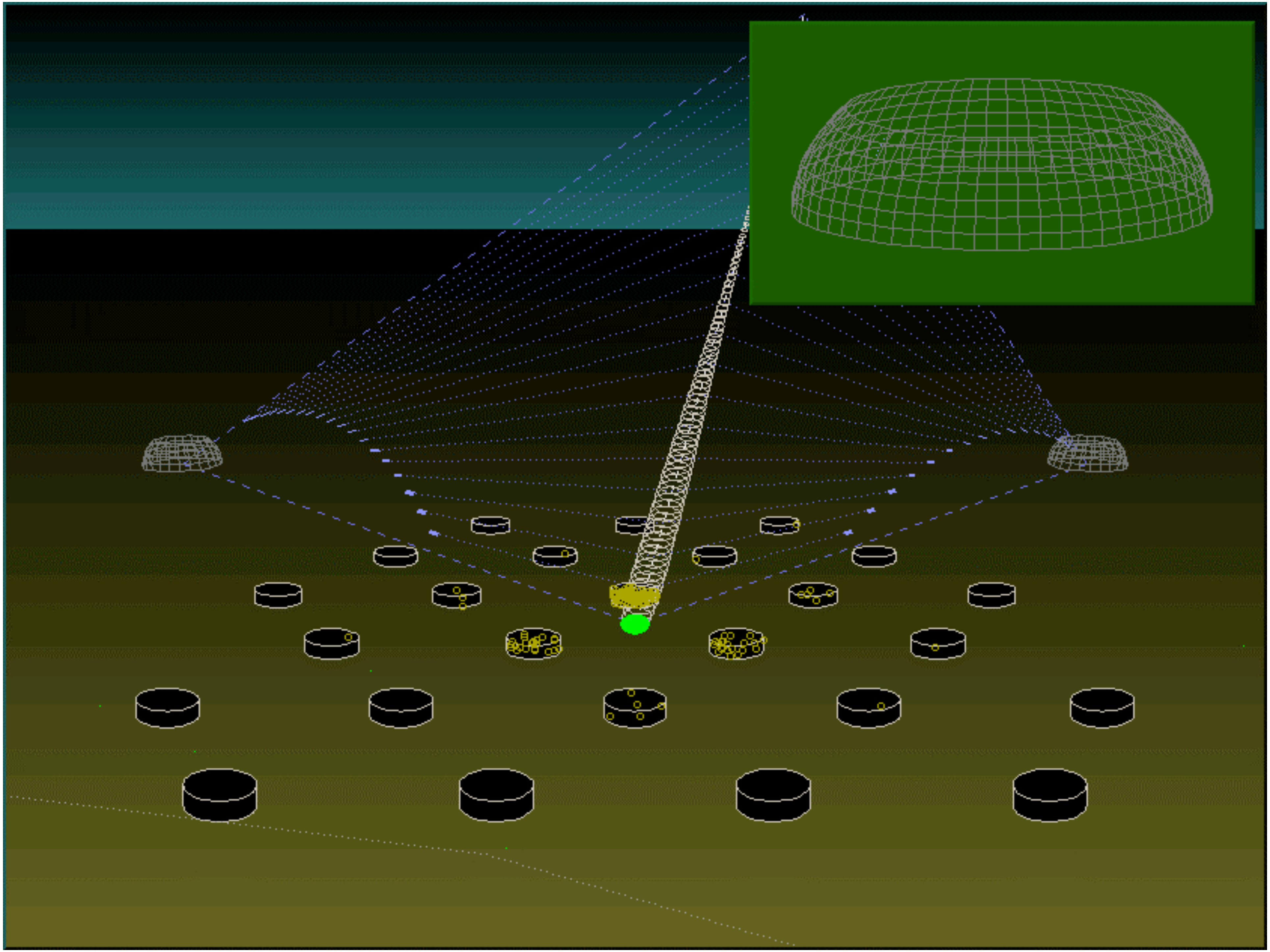


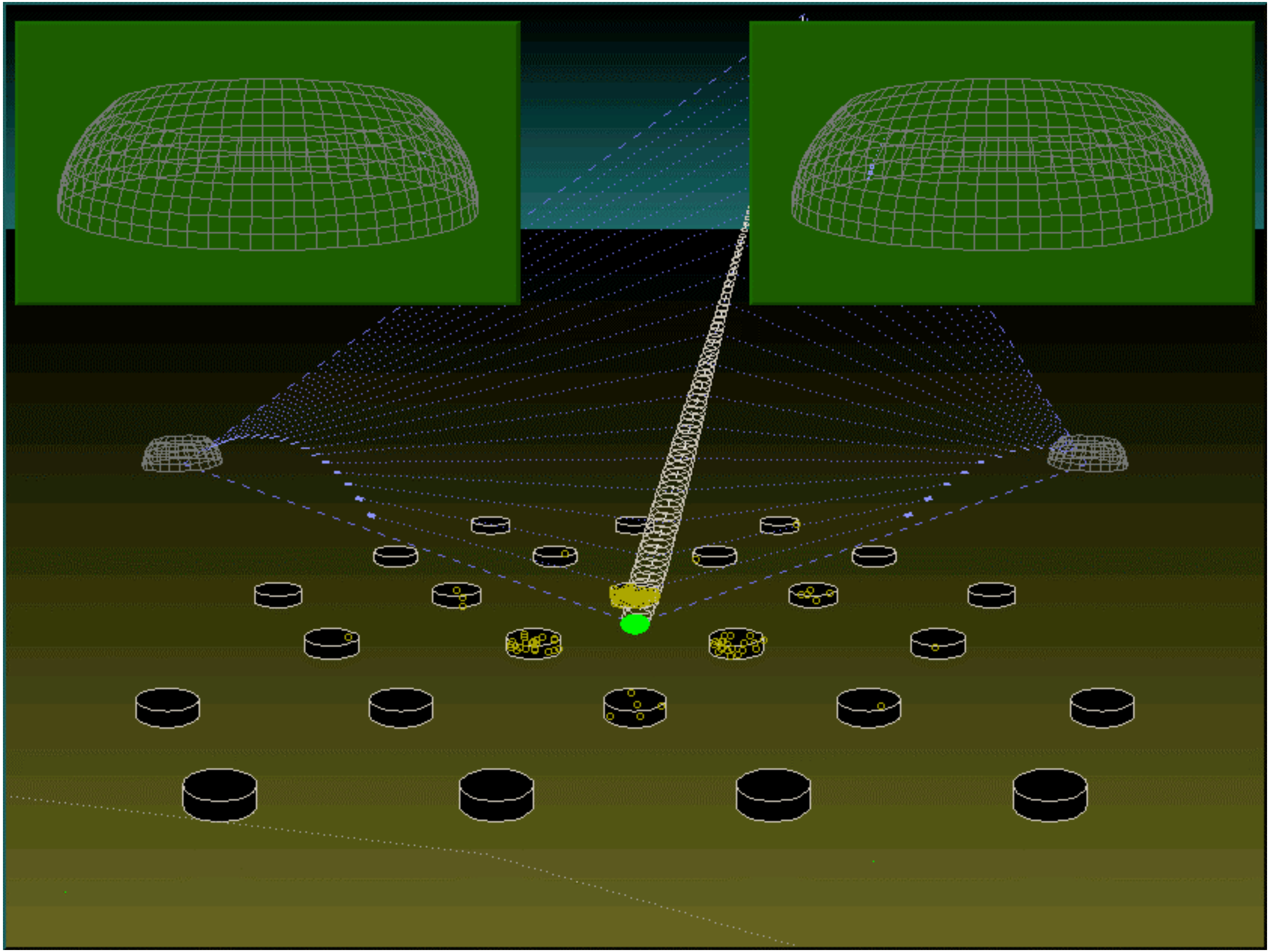


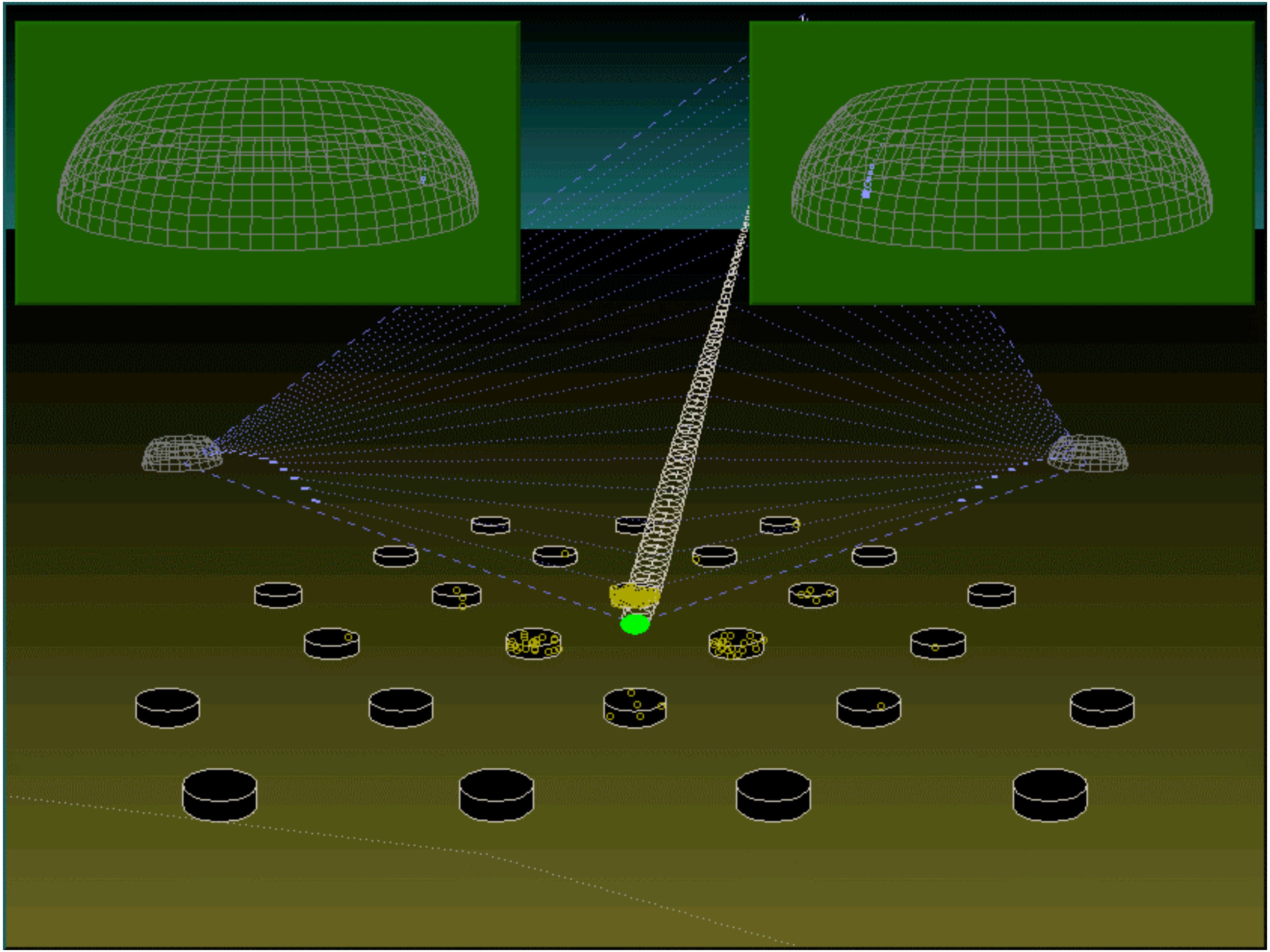


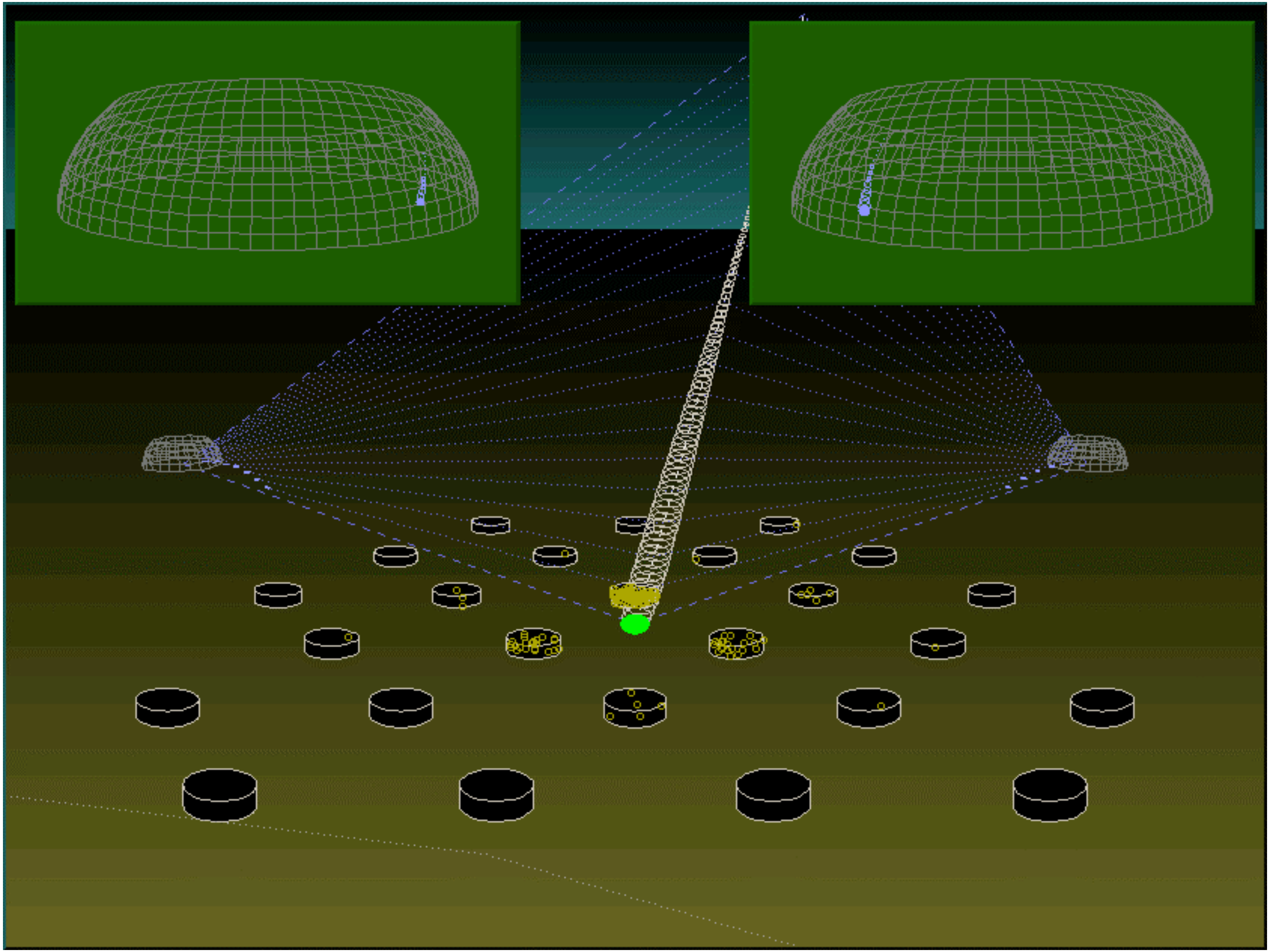


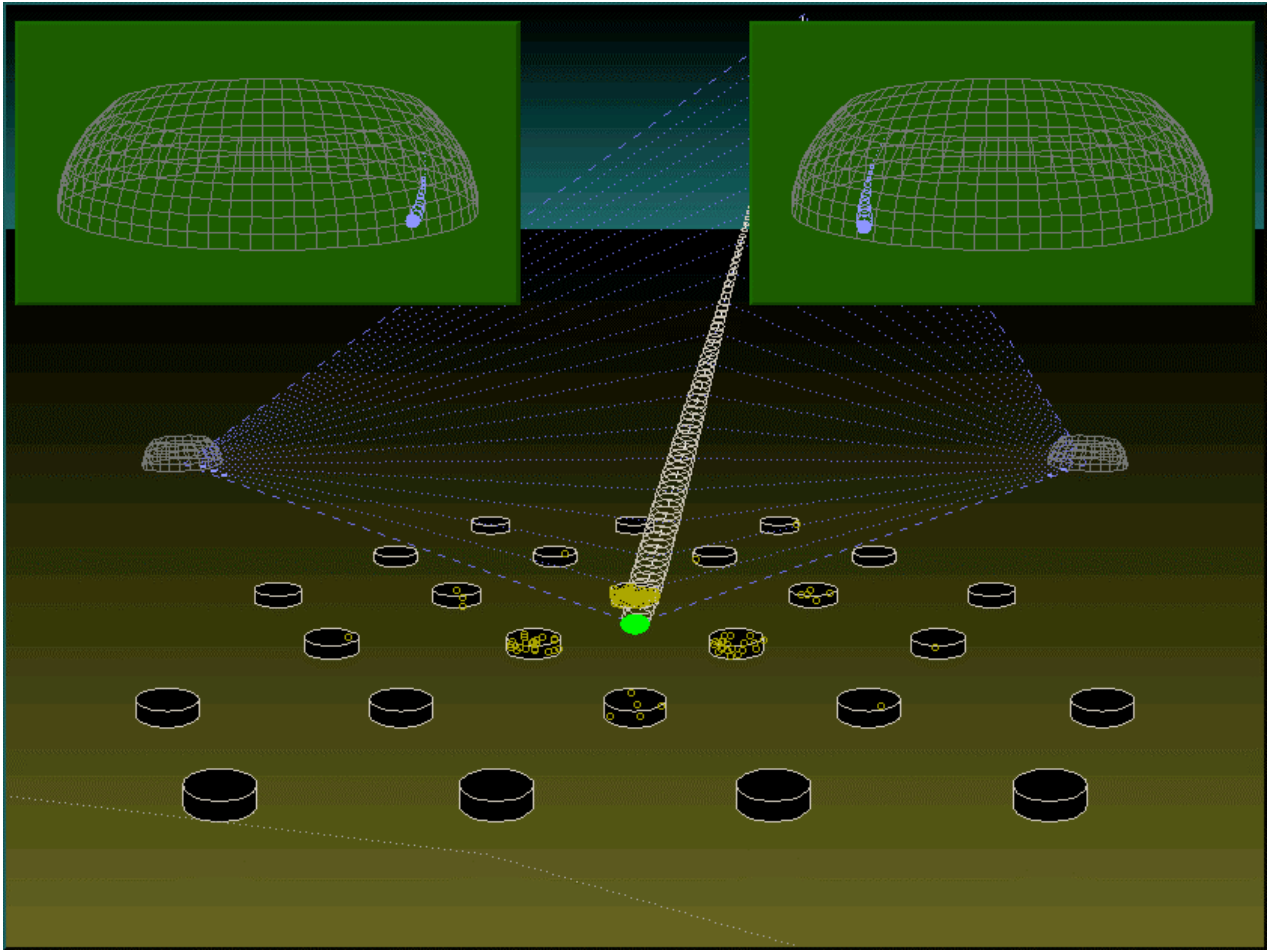


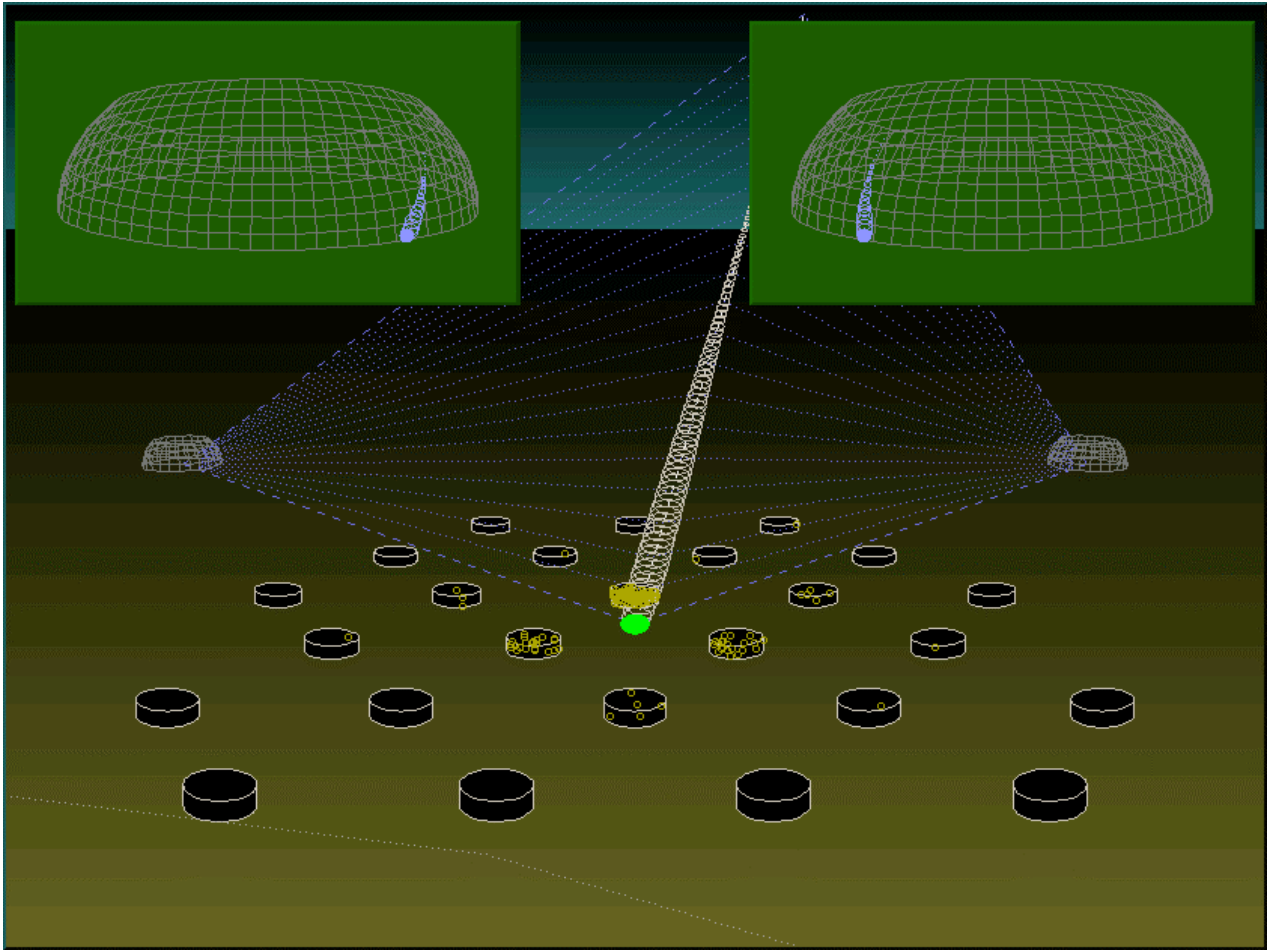




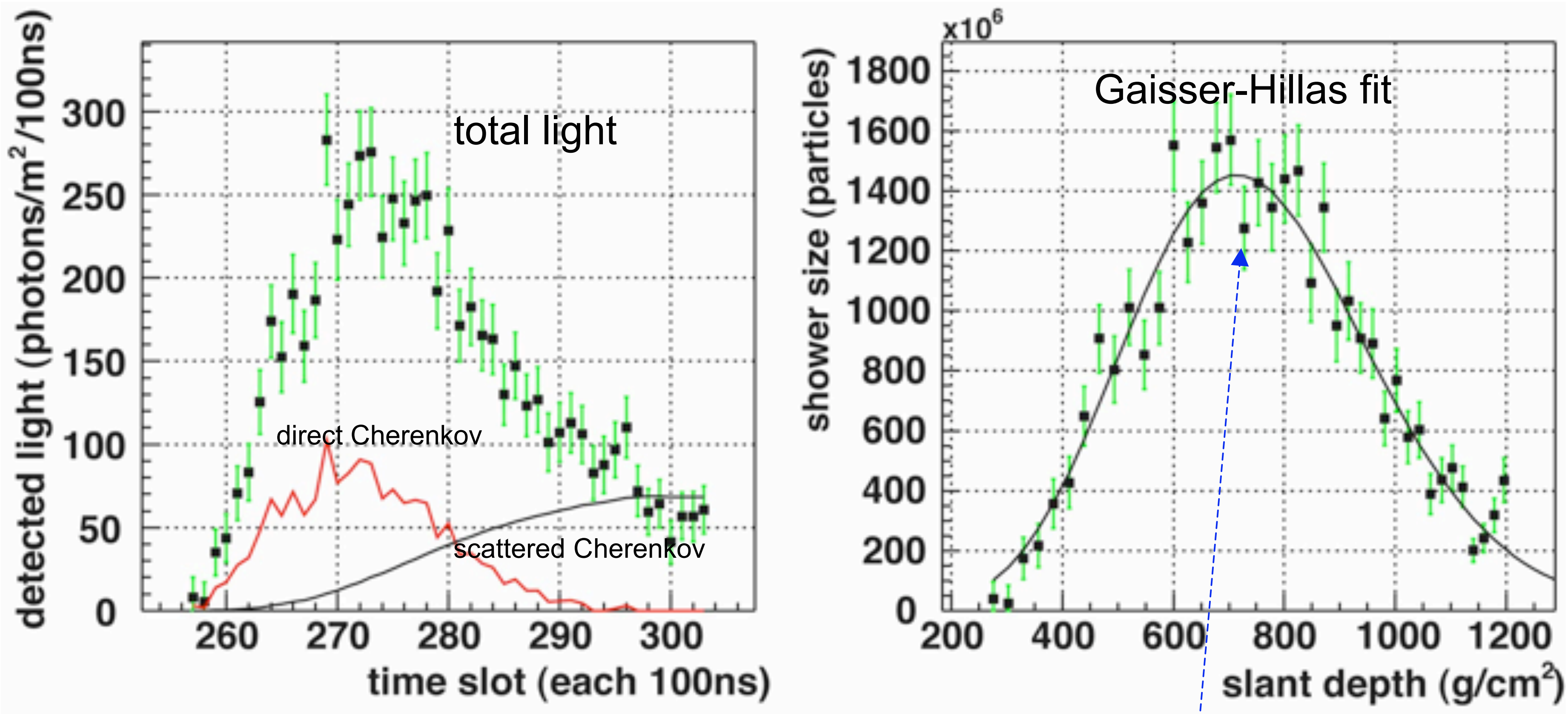








The longitudinal profile from fluorescence measurement



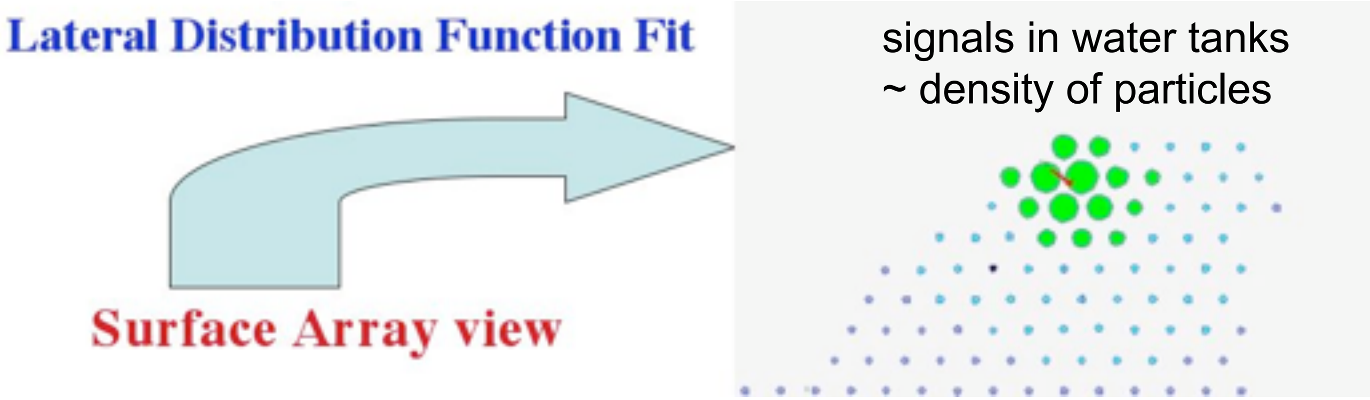
Size (X_{max}) → primary energy

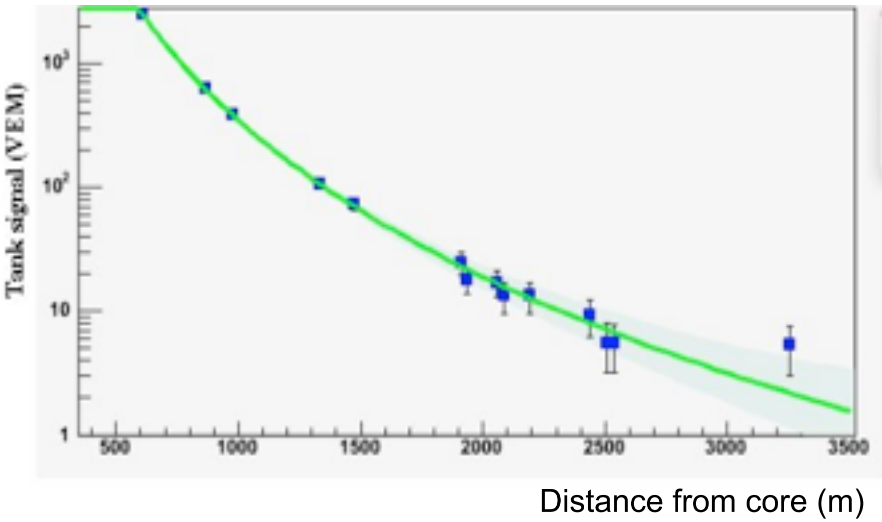
Position of X_{max} → nature (in principle…)

X_{max}

The lateral distribution

example of an Auger event





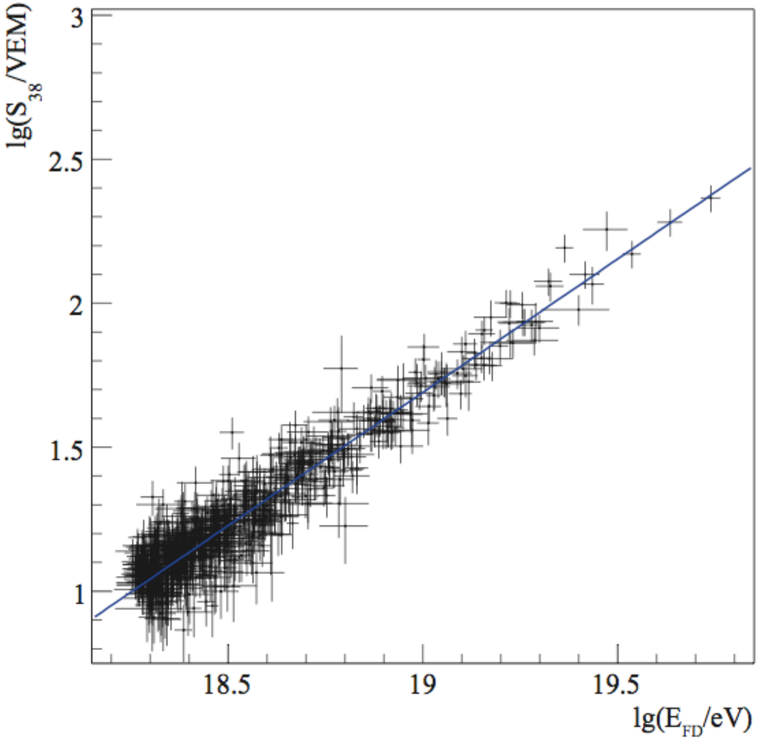
signal = K.f(r)
f : parametrized shape
K : fitted constant (→ energy)

K is expressed in terms of S_{1000}
(signal interpolated at 1 km from core)

SD calibration

• tank: use the "muon hump" (random cosmic muons) to define the VEM (vertical equivalent muon, measured in a tank with hodoscope)

• event: lateral distribution fit → S_{1000} **problem:** *the dependence of S_{1000} on E and θ is sensitive to shower modelling (longitudinal evolution) and primary composition*

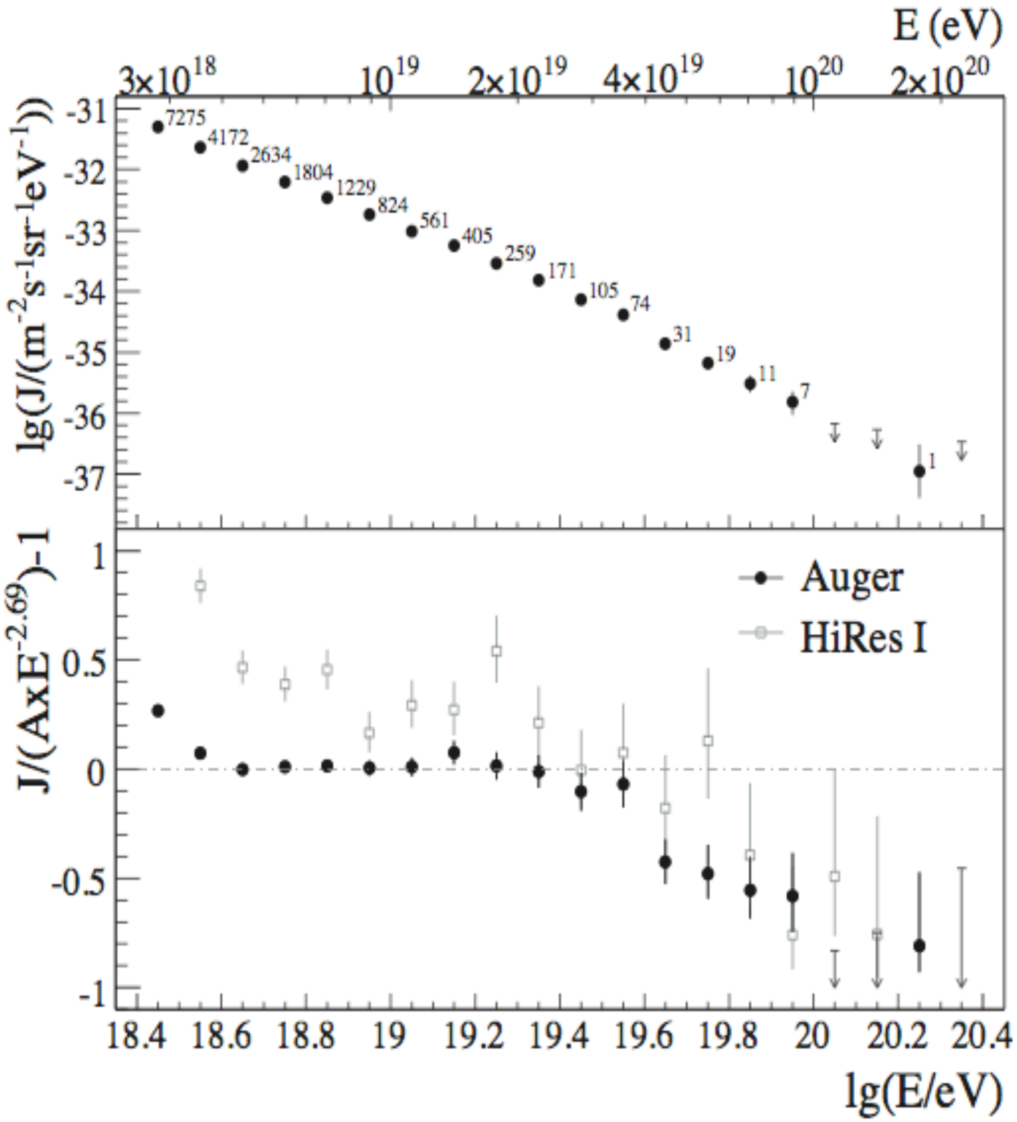


Present solution:

• apply "Constant Intensity Cut":
constrain θ dependence assuming zenithal distribution in $\cos\theta\, d(\cos\theta)$ up to a few 10 EeV
→ S_{38} = equivalent S_{1000} at 38 deg

• use hybrid events to find a relation between E_{FD} and S_{38}
good fit with a power law (dispersion 20%)

Spectrum



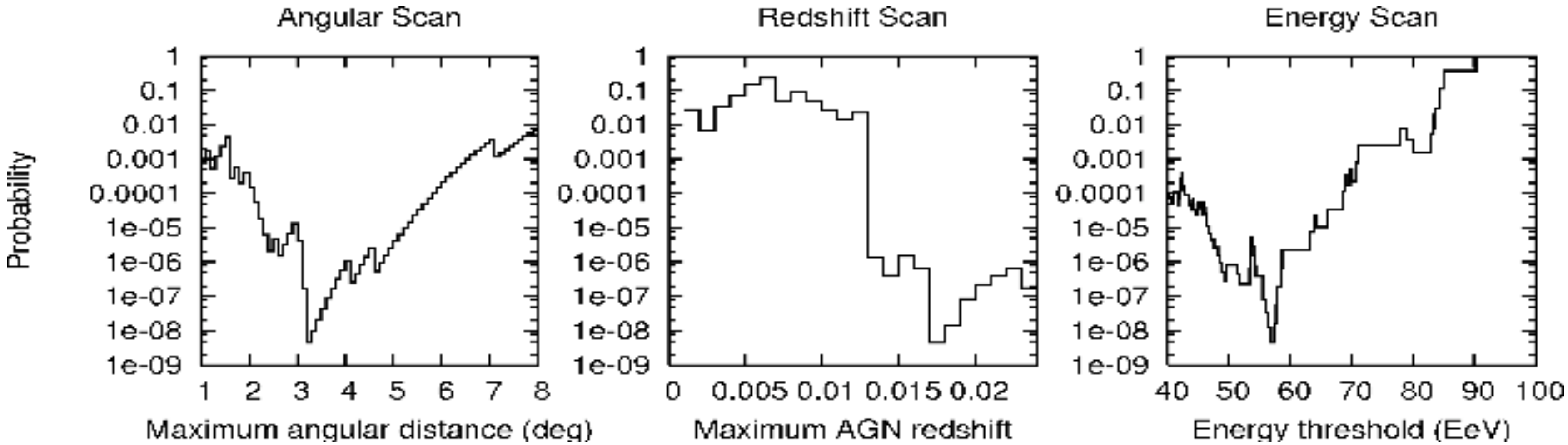
- compatible with HiRes
  within an energy shift
- "ankle" at lower edge
  (better seen with FD)
- clear break point around E_{GZK}

strong evidence for a suppression at highest E

Angular distribution (1)

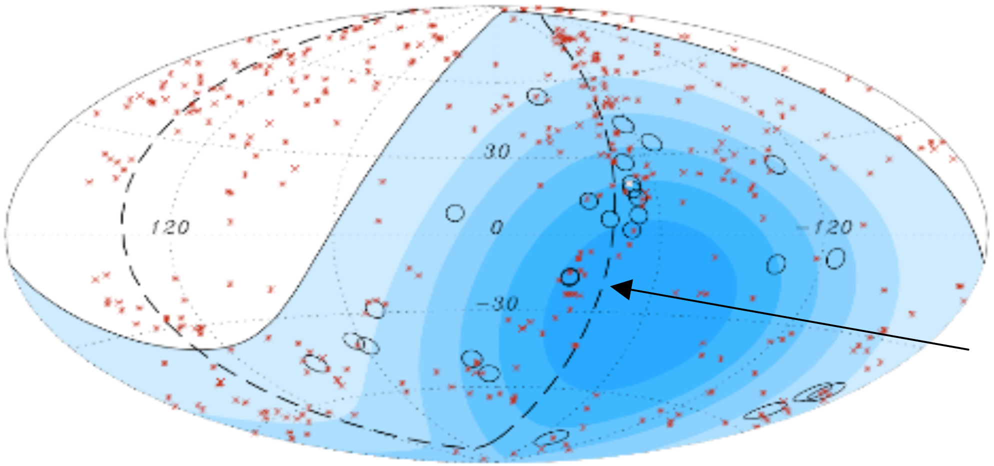
• **low energy:** no evidence for large or small scale anisotropy
(previous observations of ~ 4% excess around Galactic Center excluded)

• **high energy:** evidence for a correlation with “nearby” AGNs from Véron-Cetty catalog



• confirmation by subsequent data:
the hypothesis “isotropic flux” is excluded at 99% C.L.

Angular distribution (2)



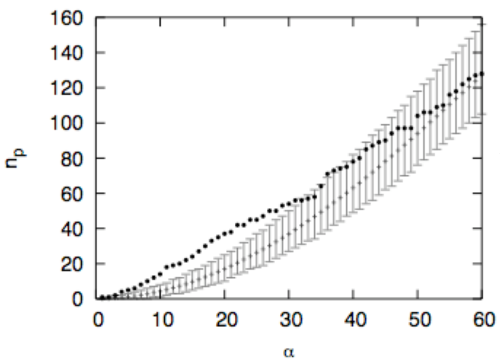
events E > 57 EeV
(galactic coordinates)
levels of blue = SD coverage
points: Veron-Cetty catalog
(z<0.018)

supergalactic plane

there is some correlation with the AGN distribution

(up to an horizon compatible with GZK within energy uncertainty), *but:*

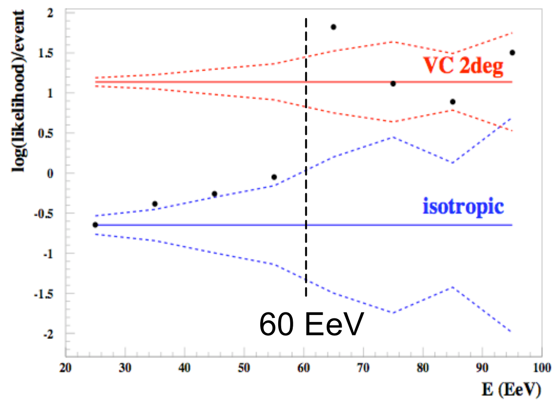
- it may be *partial* (events outside dense regions and/or dense regions not contributing)
- it may be *indirect* (the sources are just spatially correlated to AGN distribution)



autocorrelation function
(intrinsic test of anisotropy)

Transition from isotropy to
“VC-like” distribution

P. Billoir Louvain-la-Neuve



UHE neutrino telescopes

General principle: observe showers induced by (rare) weak interactions of *upgoing* neutrinos (to get rid of background from normal cosmic rays)

➞ Cherenkov light from charged secondaries in deep sea or ice

➞ coherent radio emission from moving accumulation of charges

Other possibility: use UHECR observatory (fluorescence telescope and/or ground array) to detect showers produced *deeply* in atmosphere by downgoing neutrinos, or by decay of tau leptons produced by quasi-horizontal nu_tau interactions in earth ("earth skimming")

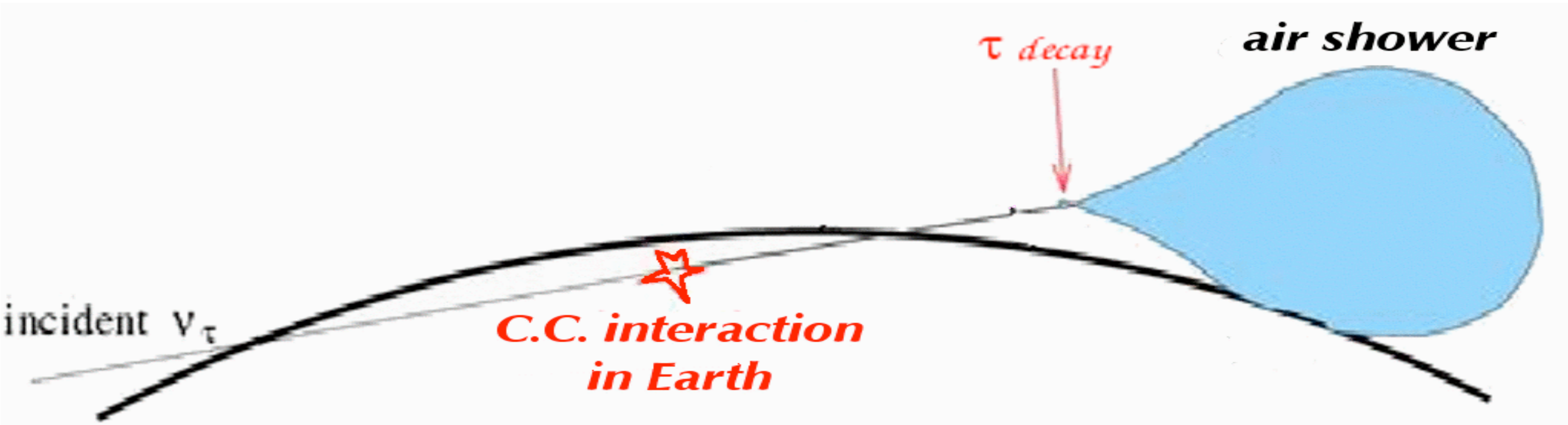
Not yet observed (upper limits, not yet constraining). More results within 5-10 years expected…

Earth skimming ν_τ scenario

sources of neutrinos: decay of mesons $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 2 : 0$

oscillations with full mixing 1 : 1 : 1

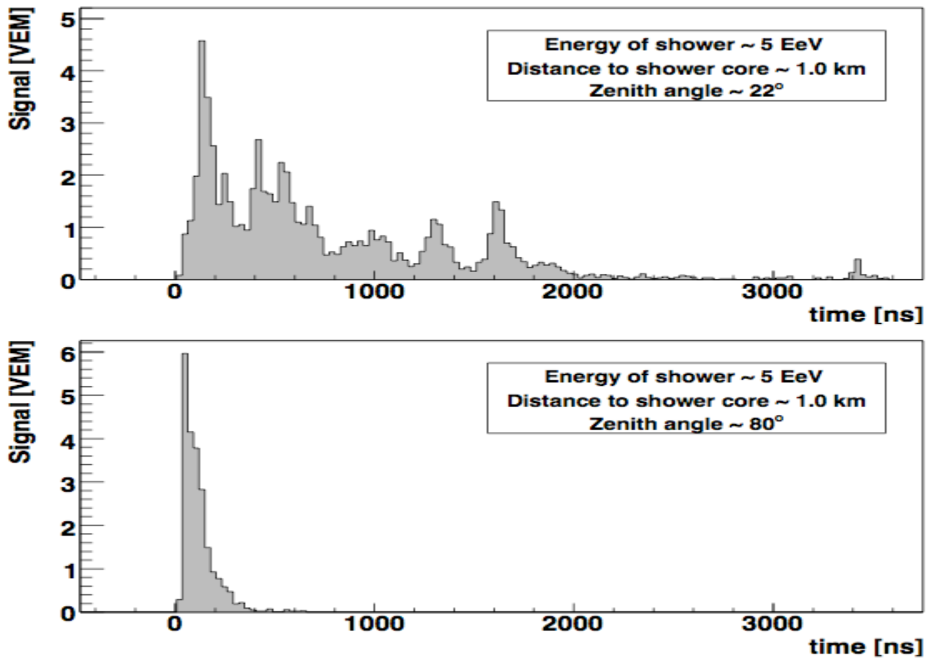
tau neutrino is abundant !



At 1 EeV: $L_{int}(\nu_\tau) = 500$ km $L_{dec}(\tau) = 50$ km L_{eloss}=10 km

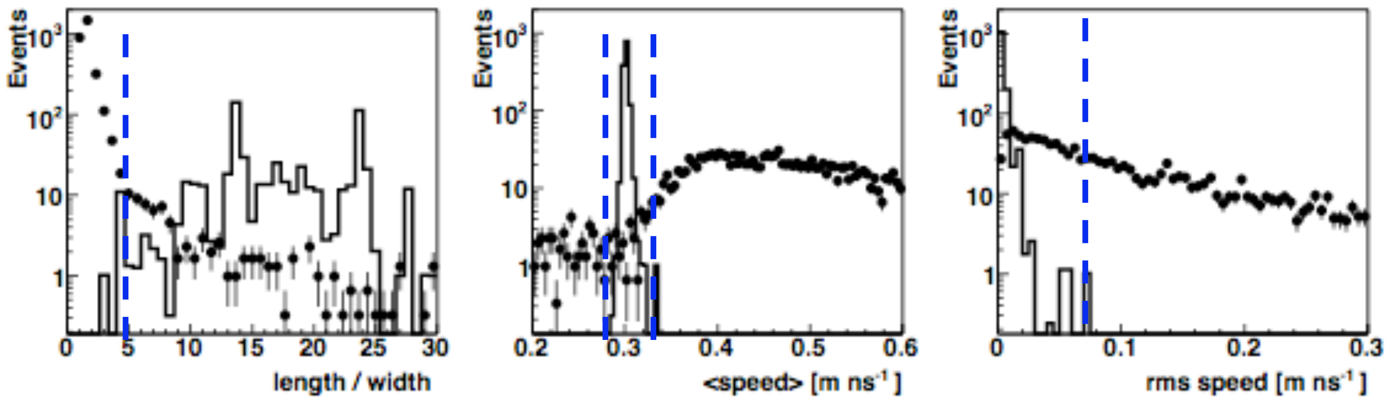
Auger (60x60 km^2) well adapted to detect tau neutrinos with an angle < 5 deg in this energy range (GZK neutrinos expected)

primary neutrino discrimination



Difference between “young” and “old” stage of a shower
(from real vertical/horizontal data)

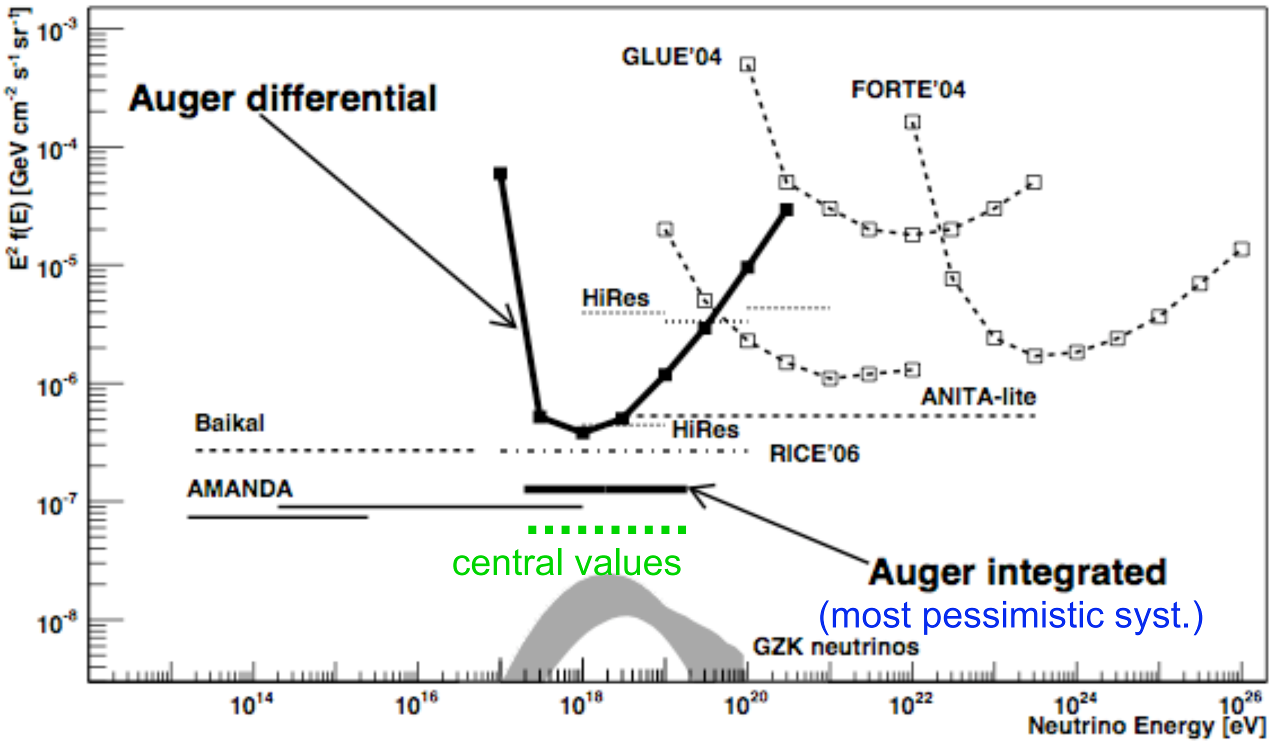
discriminating variables:
- *width of individual signals*
- *large length/width ratio*
- *times compatible with horizontal propagation at speed c*



comparison between simulated ν (histos) and 5% of real data (points)

tau neutrino upper limit

(no candidate up to 08/2007 ≈ 1 year of complete array)



best present limit in the range 1-10 EeV
severe constraint for "top-down" models
will be conclusive within 10 years (GZK n should be there)

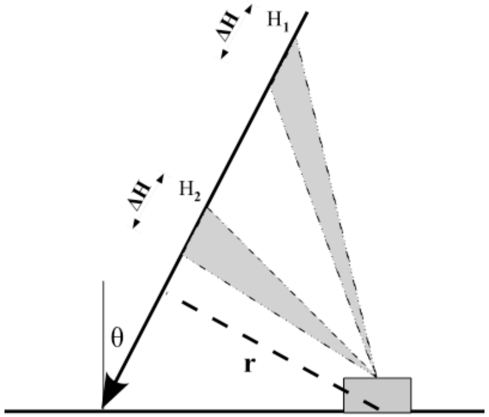
HE and UHE gamma telescopes

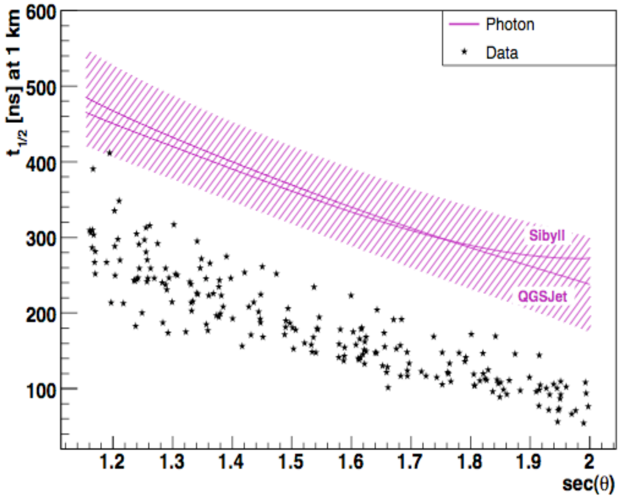
- up to 10^{14} eV : the universe is *transparent* to photons
detection of atmospheric showers developing at high altitude (collimated Cherenkov light detected at ground level)
rich observations of HE gamma sources

- from $\approx 10^{14}$ to $\approx 10^{19}$: absorption from interactions with radiation backgrounds (CMB,…) ➙ pair production

- at UHE : atmospheric showers *(pure electromagnetic cascade: slower development than from proton/nucleus primary)*
up to now: no evidence of UHE (upper limits soon going to be constraining)

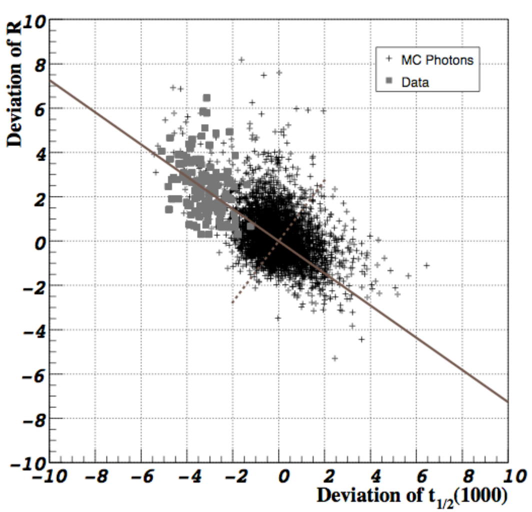
primary photon discrimination in SD

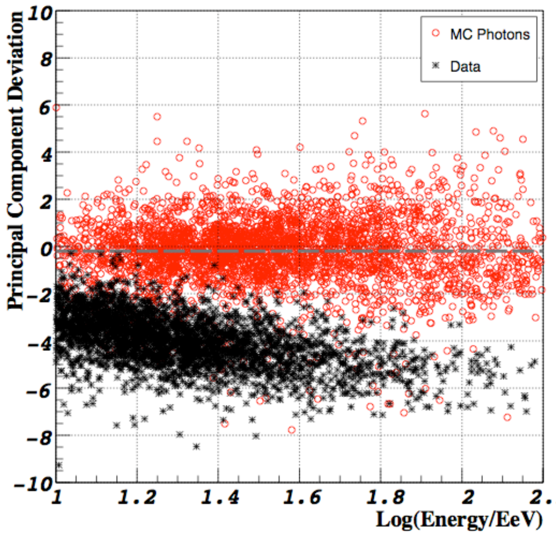




- compared to p/N showers:
  - *slower development*
  - *much less muons*

- discriminating variables:
  - *front curvature*
  - *rise time of signals*

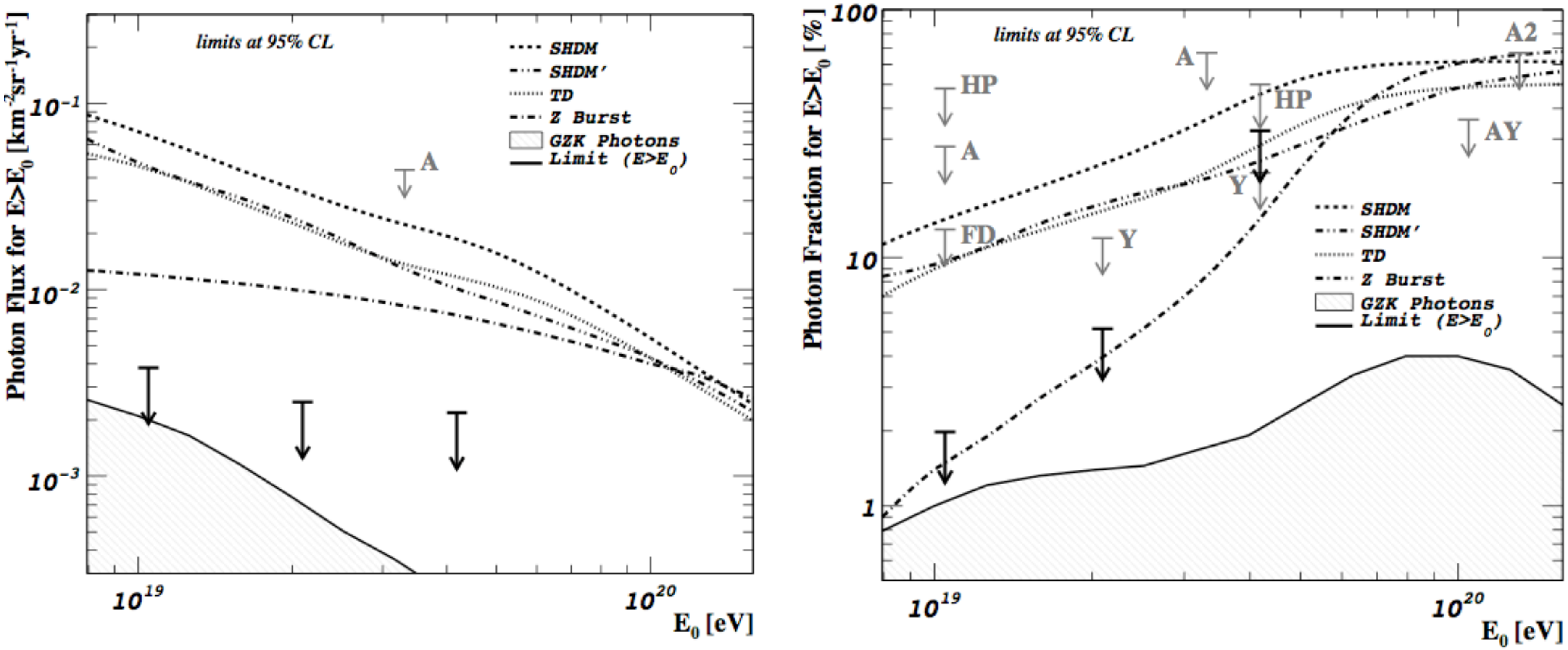




uve

- cut on a combined variable at medium photon value (MC)
  any event above the cut is a photon candidate
  (conservative approach)

upper limit on photon flux/fraction



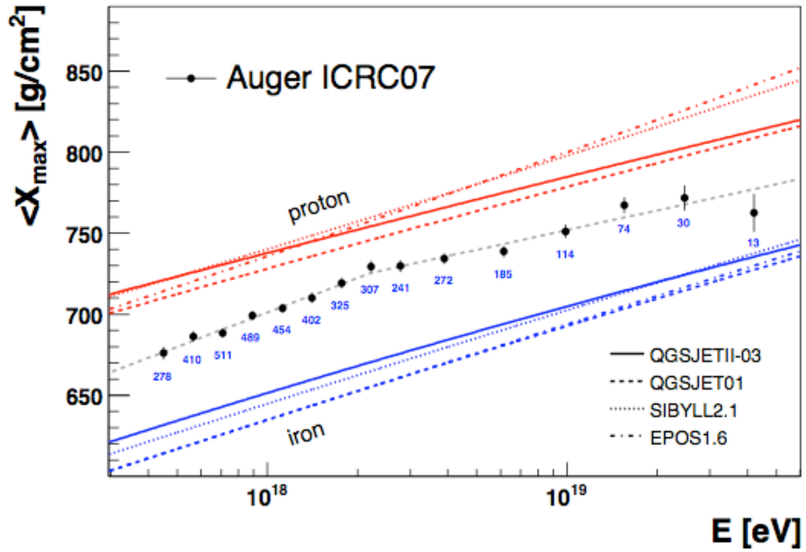
• greatly improved limits in the range 10 to 50 EeV

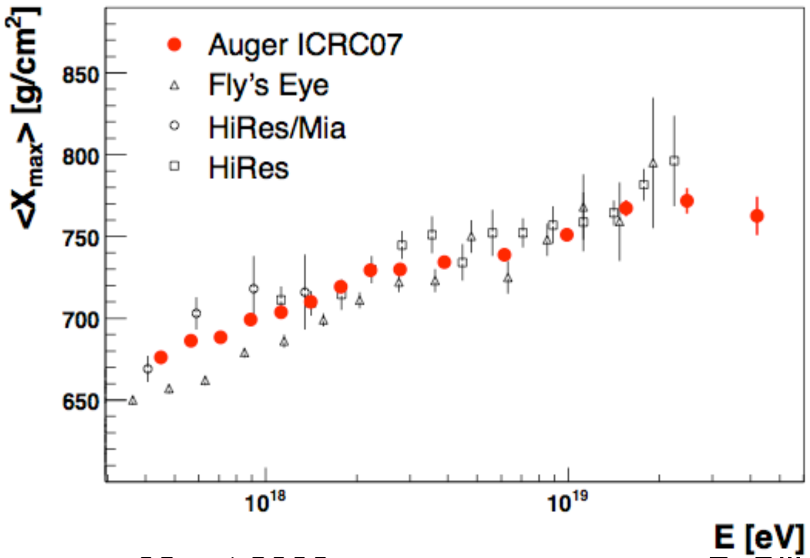
(poor SD acceptance at lower energy for photon showers)

• "top-down" models disfavoured or excluded

• no candidate with conservative cuts: room for future improvement !

Composition from X_{max} (FD)





careful selection needed to avoid biases (e.g. field of view) + various corrections

data suggest intermediate composition, with a kink at 20 EeV (~ the ankle ?)

hadronic model dependence to be understood

same global tendency, but systematic differences between experiments

not yet a clear conclusion about composition !

(further studies are underway…)

Conclusion

- The Auger Observatory works well and begins to solve the puzzle of UHECR: spectrum suppression, anisotropy, limits on "exotic" fluxes (neutrinos, photons)

  (at least: exclude some solutions)

- Nature seems to prefer old recipes (classical acceleration, GZK effect); exotic models (top-down) are disfavoured

- Still open questions: where are exactly the sources ? Are there structures at galactic level ? What is the *nature* of UHECR (protons, heavy nuclei, mixture ?)

- Future improvements:

  - extensions (infill array, radio detection; Auger North with a much larger area)

  - better understanding of shower physics and detector response, to exploit the sensitivity to *composition*