Completely random reactor model

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- Model concept
- Simplified model assumptions
- Equation
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- Monte Carlo simulation results
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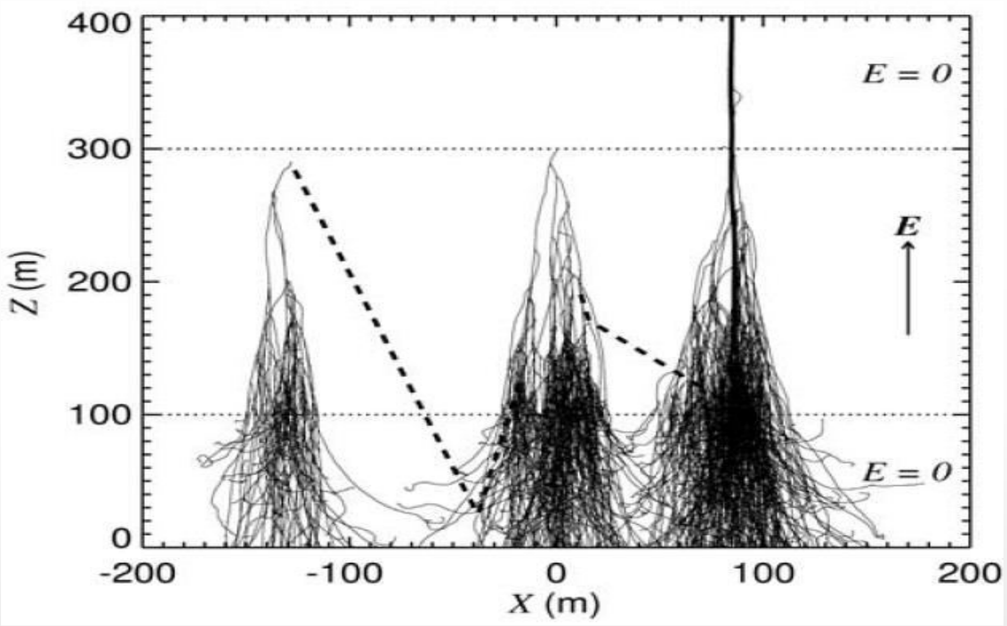
Dwyer RFDM

RREA reproduce themselves by positron and gamma feedback mechanisms.

Positrons are created by RREA bremsstrahlung and propagate in direction opposite to RREA propagation. Consequently, positrons create secondary avalanches at the beginning of the cell.

Does not work in observable conditions.



R. Dwyer J. A fundamental limit on electric fields in air // Geophysical Research Letters. — Vol. 30, no. 20. — URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2003GL017781.

RL-TGE model concept

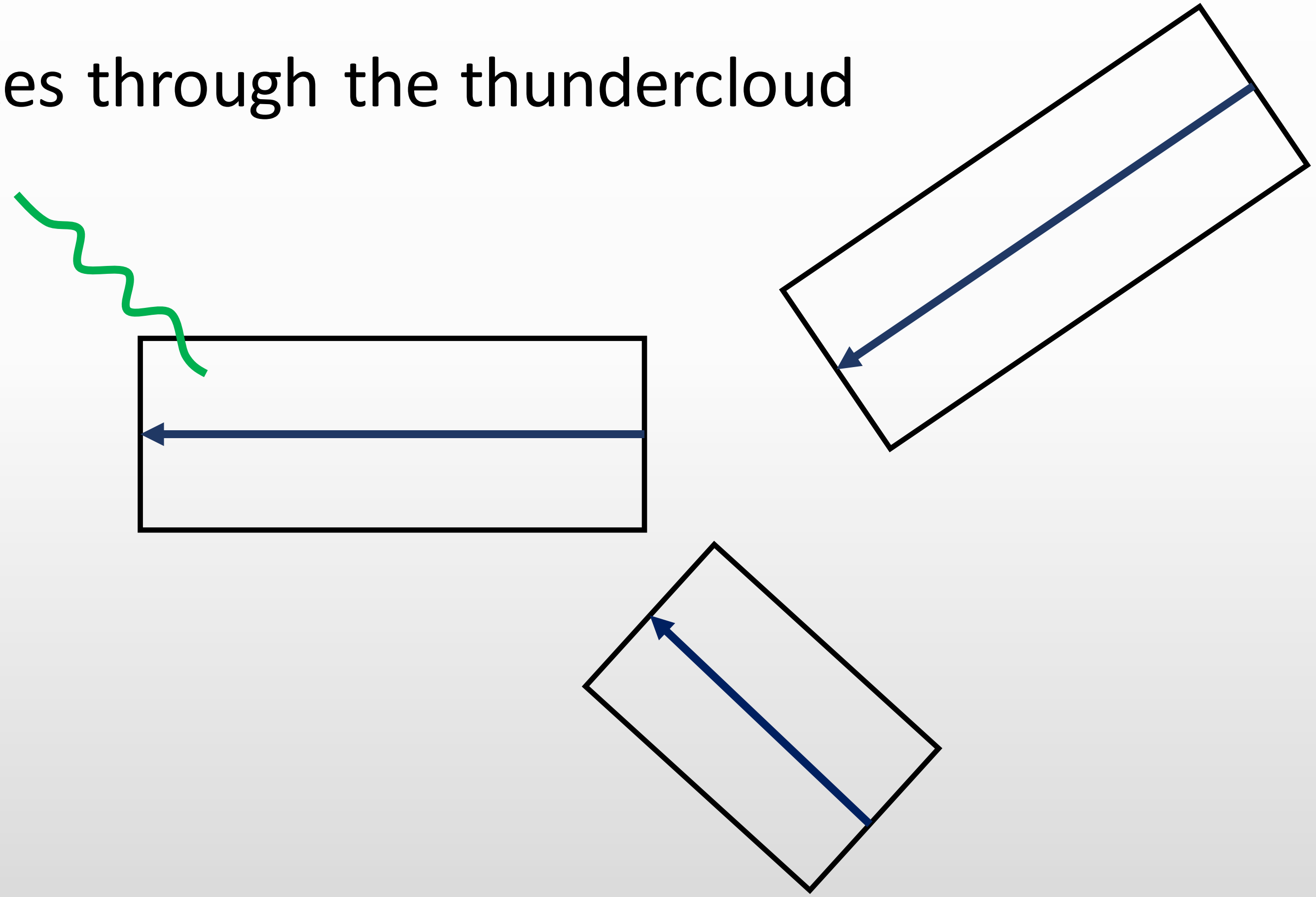
- Thundercloud electric field structure is considered to be complex:

  There are a lot of cells with critical electric field and different electric field direction

- Gamma dynamics is similar to neutron dynamics in nuclear reactor:
  - ✓ A gamma propagates through the thundercloud
  - ✓ It gives birth to a runaway electron within a cell
  - ✓ Runaway electron produces RREA
  - ✓ RREA radiates new gammas
  - ✓ These gammas propagate through the thundercloud

RL-TGE model concept

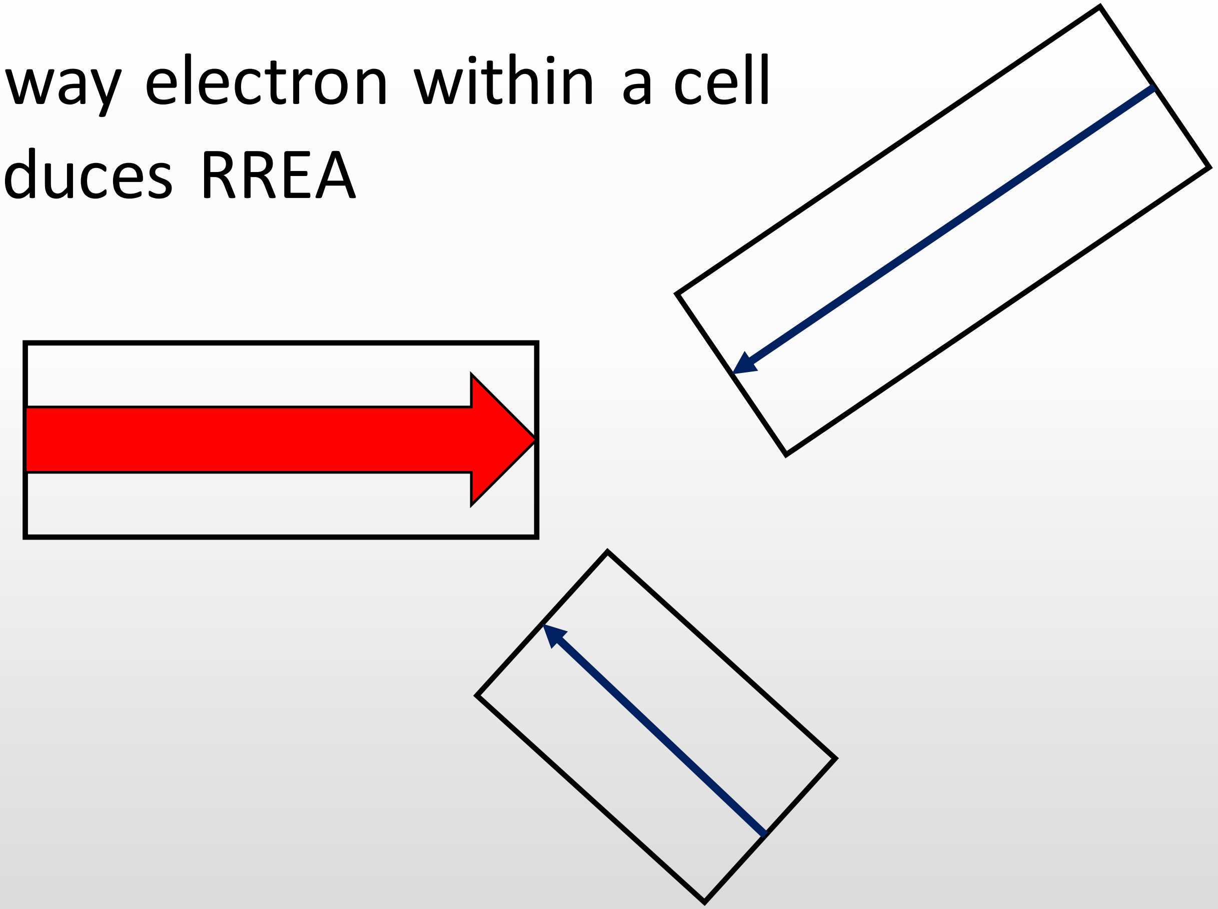
A gamma propagates through the thundercloud



RL-TGE model concept

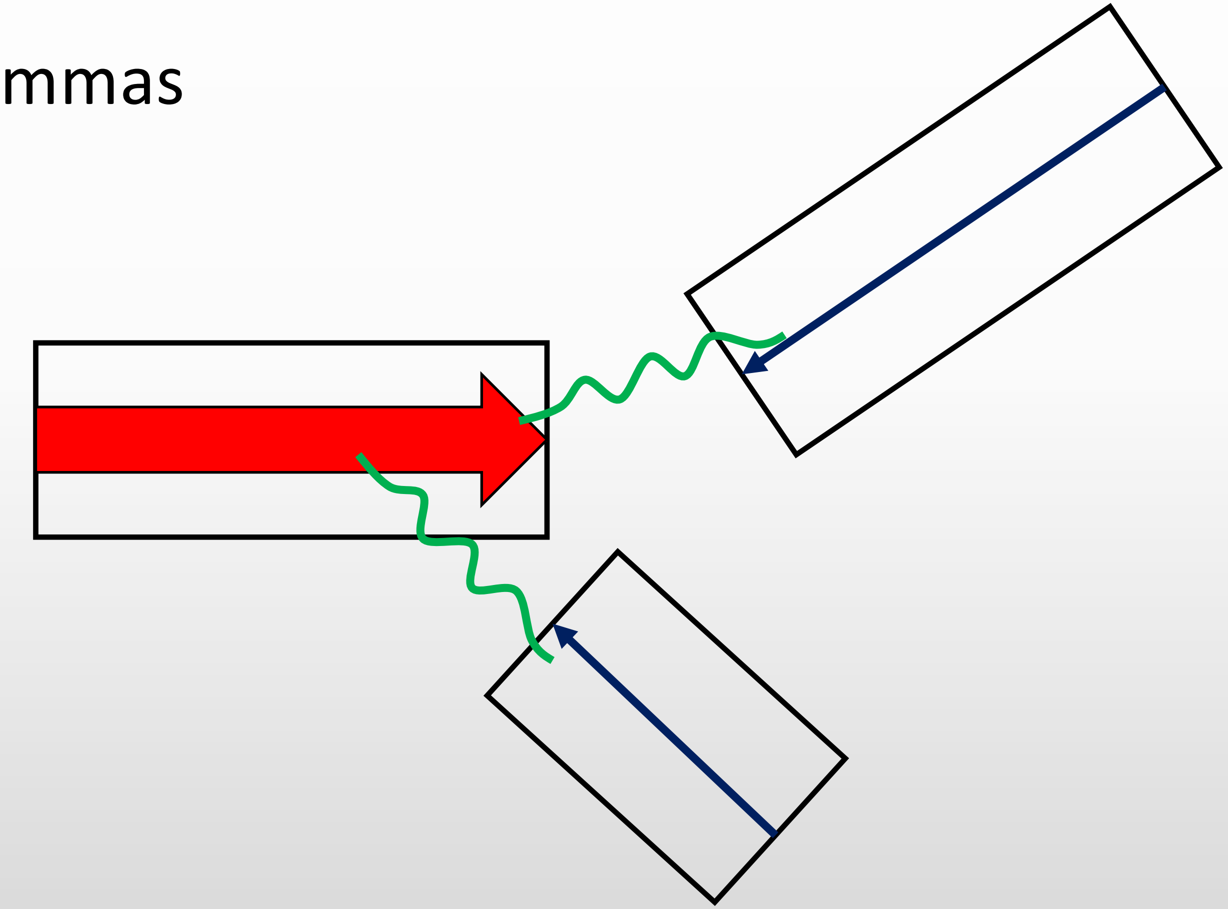
It gives birth to a runaway electron within a cell

Runaway electron produces RREA



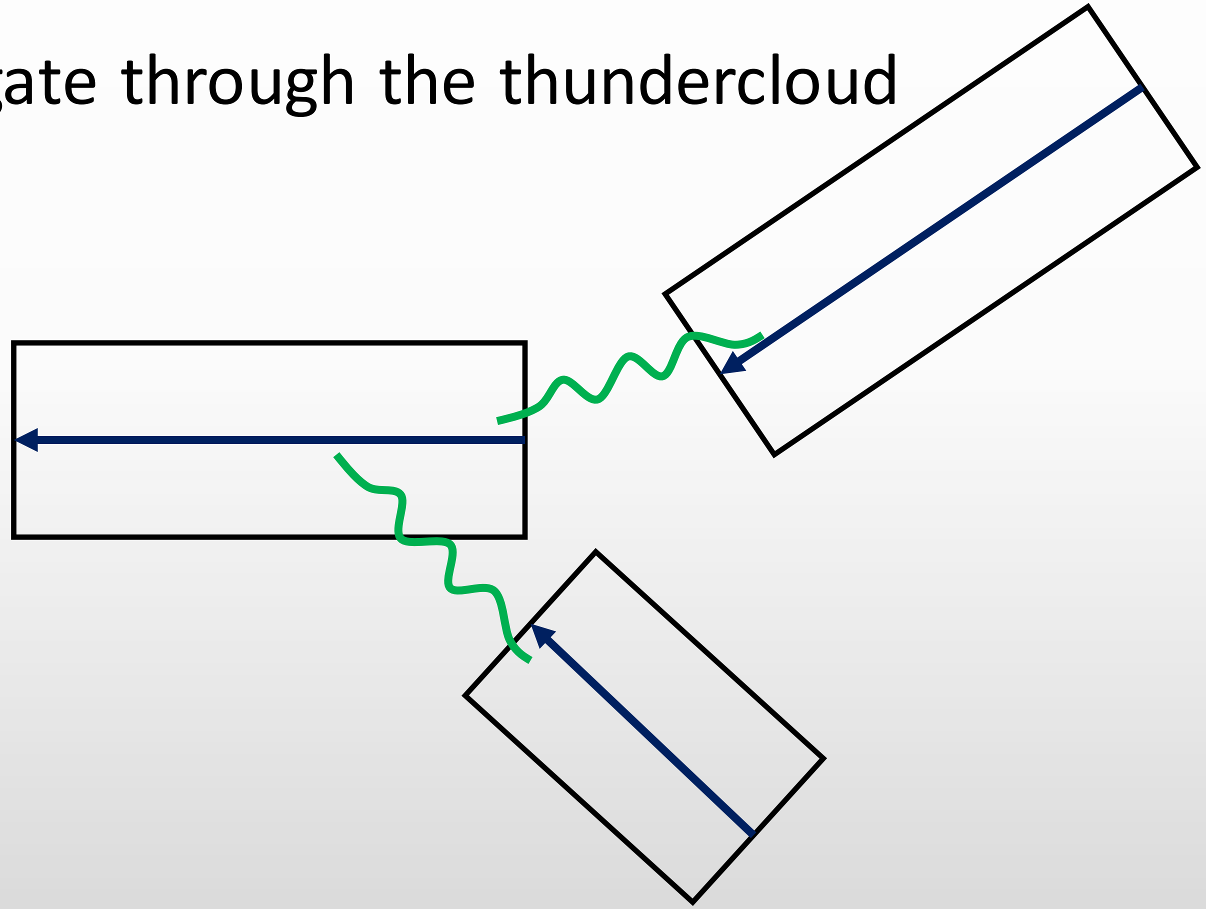
RL-TGE model concept

RREA radiates new gammas



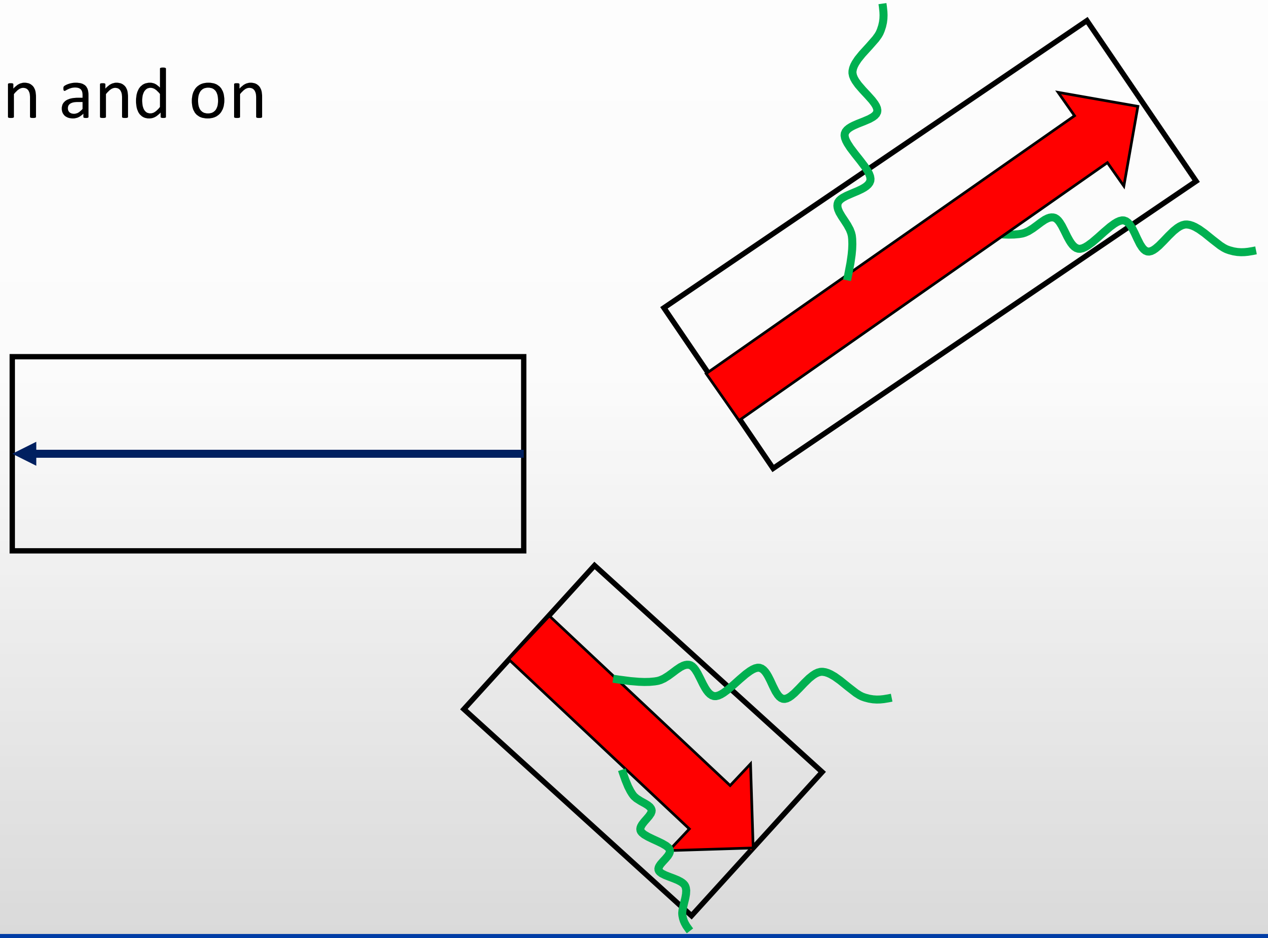
RL-TGE model concept

These gammas propagate through the thundercloud

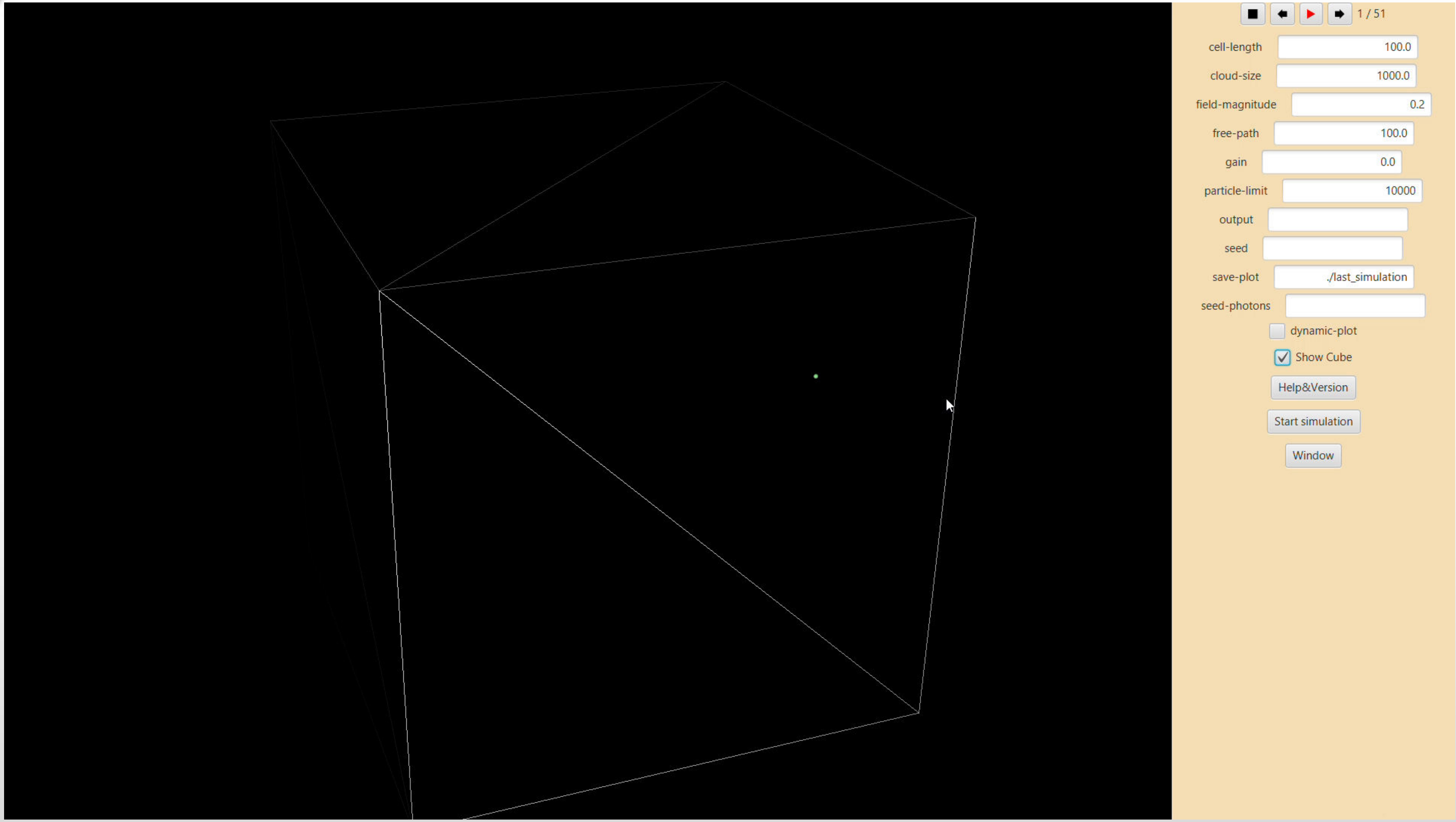


RL-TGE model concept

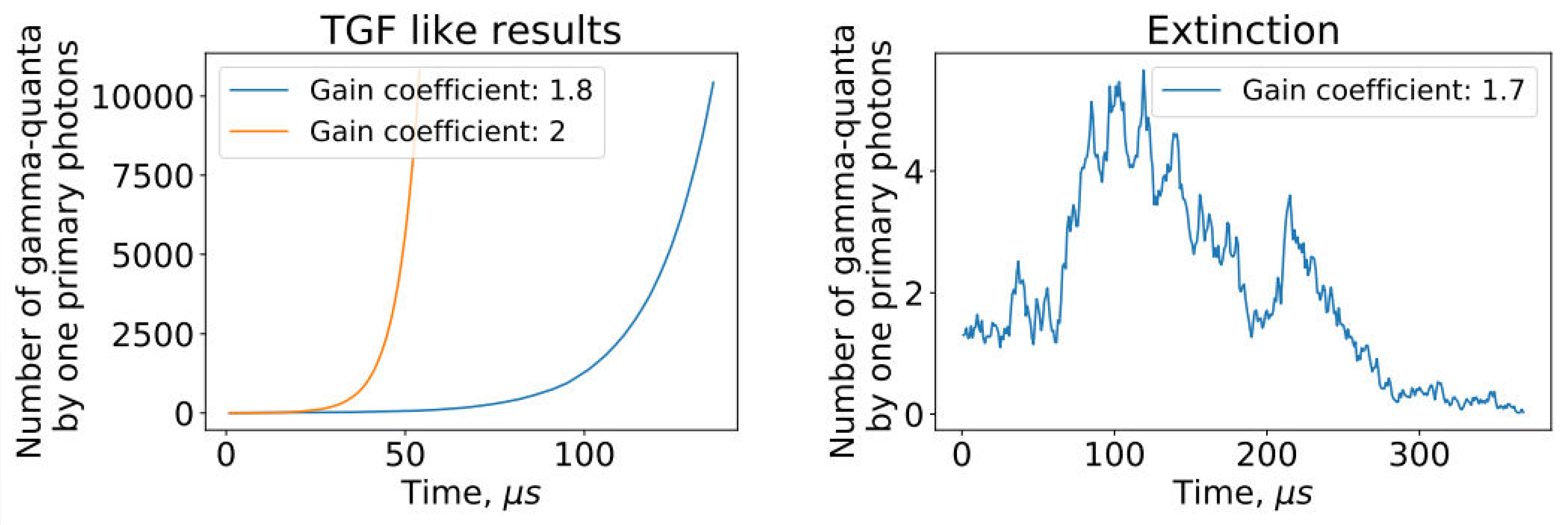
And everything goes on and on



Reactor model simplified simulation



Monte Carlo simulation results



Gain coefficient = local multiplication factor

Completely random reactor model assumptions

- The electric filed is completely random, which makes gamma production isotropic.
- There is noncritical electric field between critical cells, consequently, there is only gamma exchange between cells.
- Critical electric field is the same everywhere in the cloud.
- All gammas have the same energy.
- Runaway electrons have the same energy.
- Air density is the same throughout the cloud.
- Gammas leave the system in two ways: fly out of the thundercloud or produce a runaway electron.

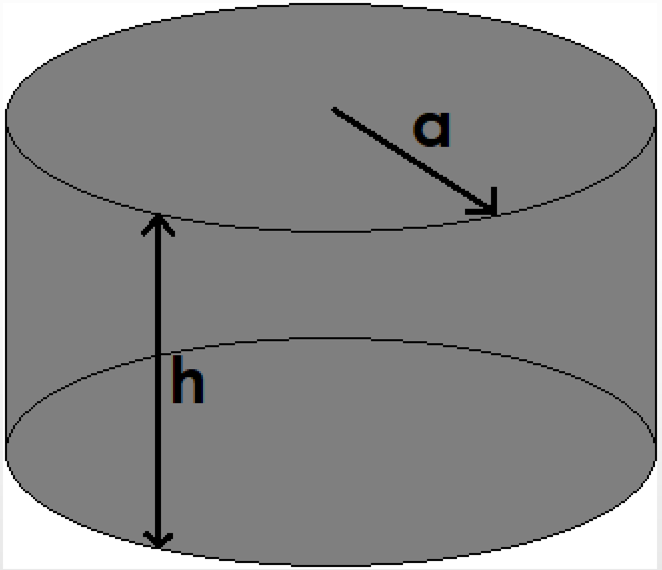
Equation

Under such assumptions gamma dynamics can be described with the following equation:

$$D\Delta n - c\Sigma n + \nu c\Sigma n = \frac{\partial n}{\partial t}$$

$$n|_{z=0,h} = 0$$

$$n|_{r=a} = 0$$



Here $n(\vec{r},t)$ –gamma concentration, $D = \frac{c\lambda}{3}$ – diffusion coefficient, λ–mean free path length for gammas, $\Sigma = \frac{1}{\lambda_{\gamma \to e-}}$ – mean macroscopic cross-section of runaway electron production by gamma, ν – local multiplication factor.

Local multiplication factor

Local multiplication factor is mean number of gammas generated by one gamma in a cell:

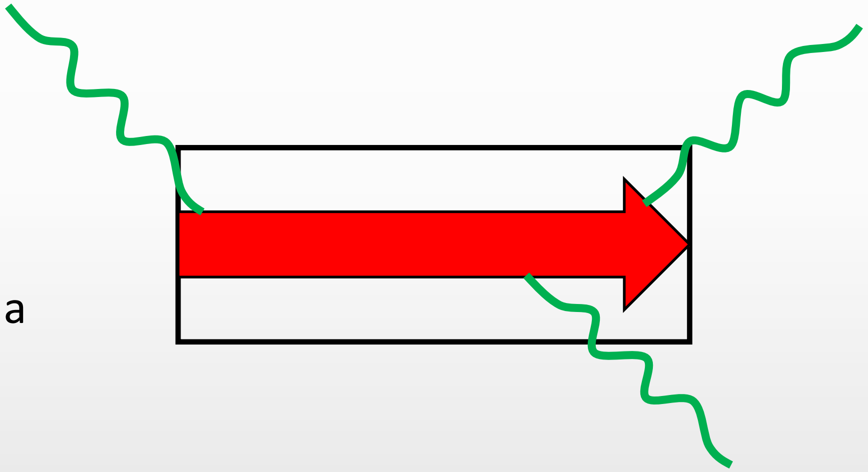
$$\nu = \text{RREA FORMATION PROBABILITY} \cdot \frac{\lambda_{RREA}}{\lambda_{e-\to\gamma}} \cdot \left(\exp\left(\frac{L}{\lambda_{RREA}}\right) - 1\right)$$

L – cell length.

RREA FORMATION PROBABILITY – average probability of RREA creation in a critical cell by gamma, also considering electric field geometry.

$\lambda_{RREA} = \frac{22mc^2}{eE}$ - Gurevich characteristic length of avalanche exponential growth (m, e – electron mass and charge, E – mean critical electric field).

$\lambda_{e-\to\gamma}$ - gamma production by runaway electrons length.



The equation solution

The first member of the equation solution dominates:

$$n(r,z,t) = n_0 \cdot J_0\left(\frac{2.405 \cdot r}{a}\right) sin\left(\frac{\pi z}{h}\right) \cdot e^{\varepsilon t},$$

where $\varepsilon = \frac{\lambda c}{3}\left(\frac{3(\nu-1)}{\lambda\lambda_{\gamma\rightarrow e-}} - \left(\frac{2.405}{a}\right)^2 - \left(\frac{\pi}{h}\right)^2\right)$ - global multiplication factor.

Consequently, thunderstorm gamma flux comes out as follows:

$$|\Phi(r,t)|\Big|_{z=0,h} = \frac{\lambda c}{3}\frac{\partial n(r,z,t)}{\partial z}\Big|_{z=0,h} = \frac{\pi\lambda c}{h} \quad {}_0 \cdot J_0\left(\frac{2.405 \cdot r}{a}\right) \cdot e^{\varepsilon t}$$

Reactor explosion criteria

Reactor becomes critical when number of gammas grows exponentially, or in other words, when $\varepsilon > 0$. Consequently, there is a following **reactor explosion criteria**:

$$\nu > \frac{\lambda\lambda_{\gamma\to e-}}{3}\left(\left(\frac{2.405}{a}\right)^2 + \left(\frac{\pi}{h}\right)^2\right) + 1$$

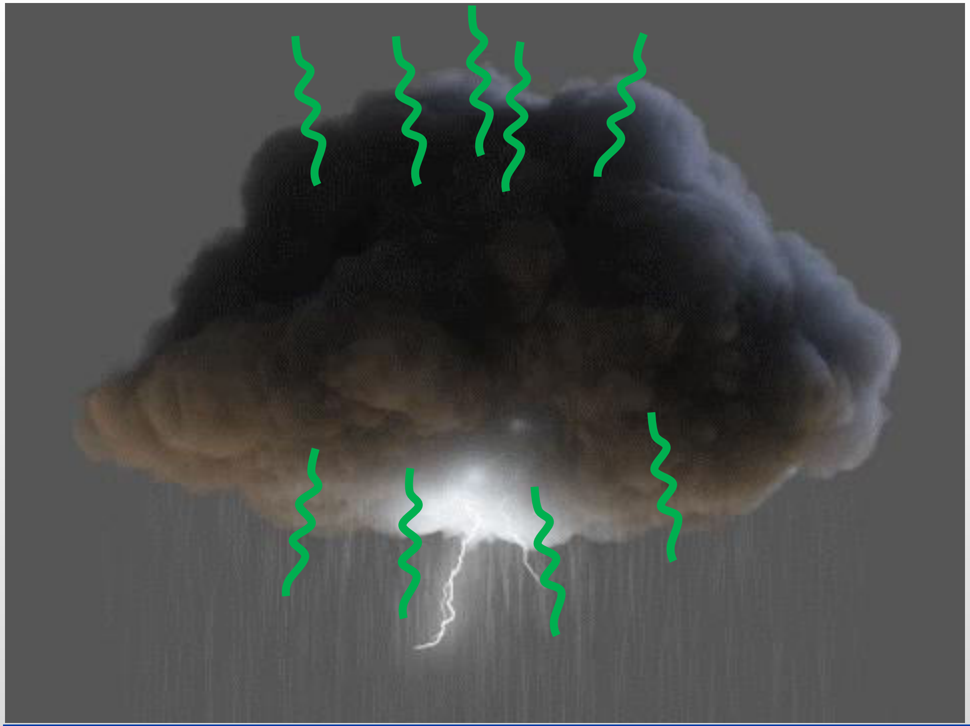
Or, considering the formula for local multiplication factor:

$$\text{RREA FORMATION PROBABILITY} \cdot \frac{22mc^2}{eE\lambda_{e-\to\gamma}} \cdot \left(\exp\left(\frac{L}{\lambda_{\text{RREA}}}\right) - 1\right) > \frac{\lambda\lambda_{\gamma\to e-}}{3}\left(\left(\frac{2.405}{a}\right)^2 + \left(\frac{\pi}{h}\right)^2\right) + 1$$

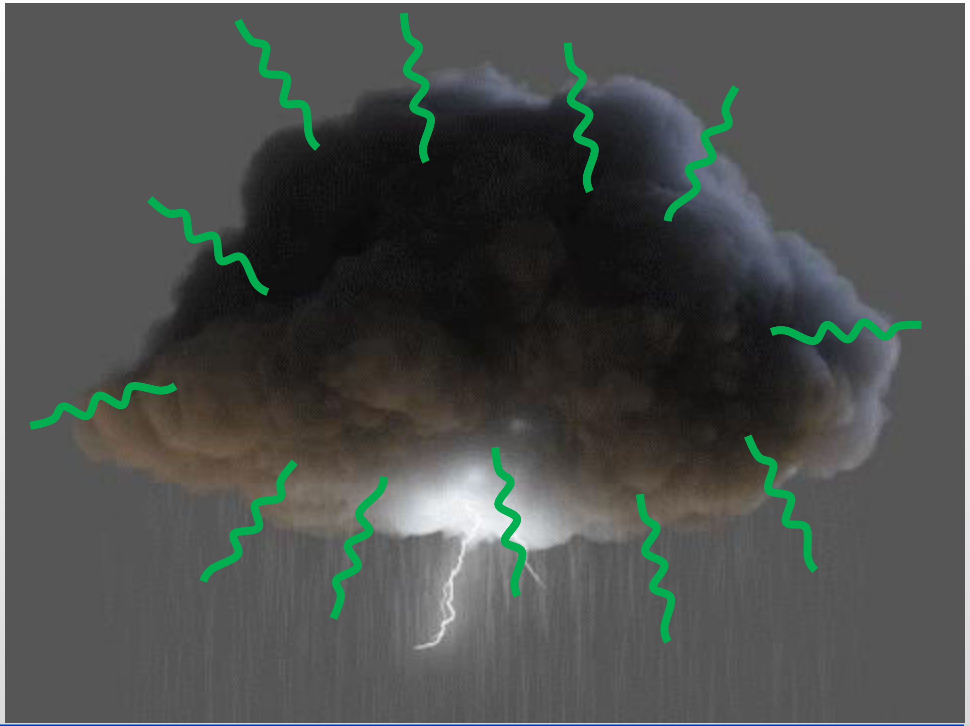
Reactor thundercloud gamma radiation

Reactor thundercloud gamma radiation is quasi-isotropic

Gurevich or Dwyer thundercloud



Reactor thundercloud



Gamma flux dependence on time

Considering cosmic ray flux gamma concentration dynamics is following:

$$dn = \frac{\partial n_{cosmic}}{\partial t} dt + n \cdot \varepsilon \cdot dt$$

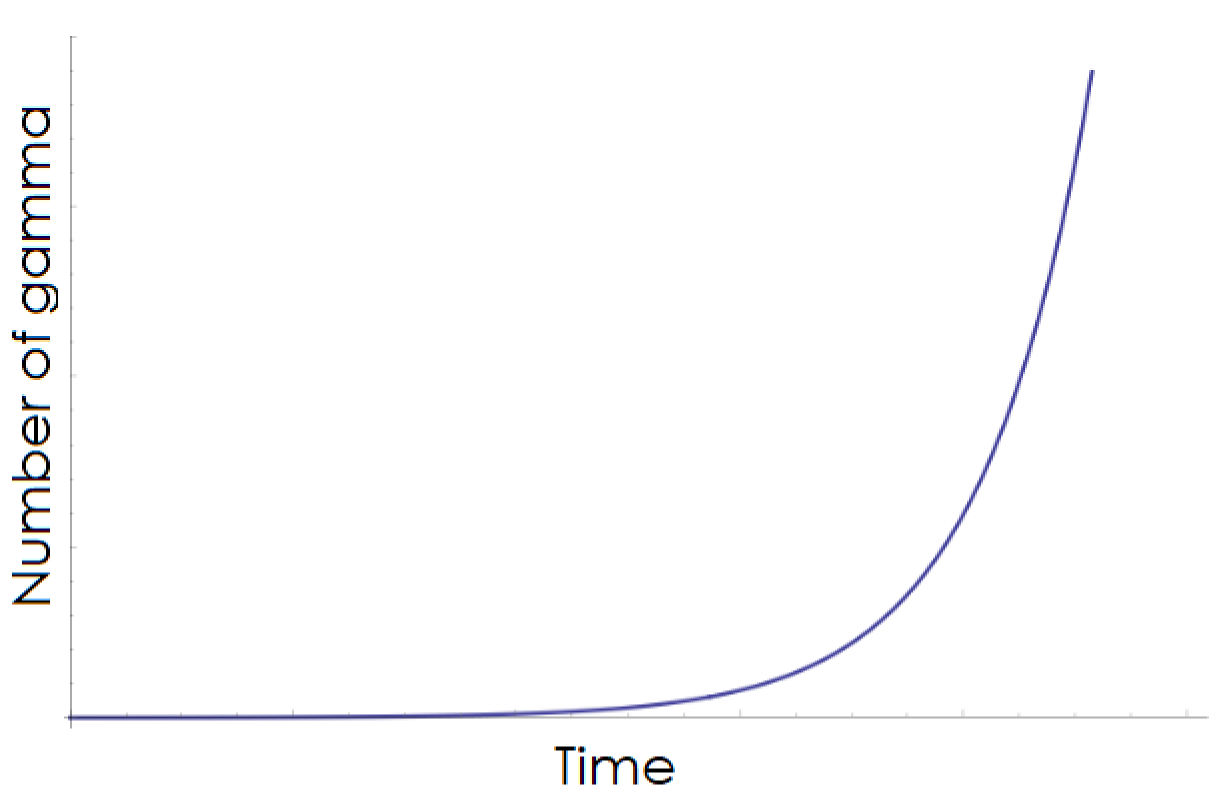
$$n(0) = n_0$$

Here n – gamma concentration, ε – global multiplication factor. Consequently:

$$n(t) = n_0 e^{\varepsilon t} + \frac{\partial n_{cosmic}}{\partial t} \frac{e^{\varepsilon t} - 1}{\varepsilon}$$

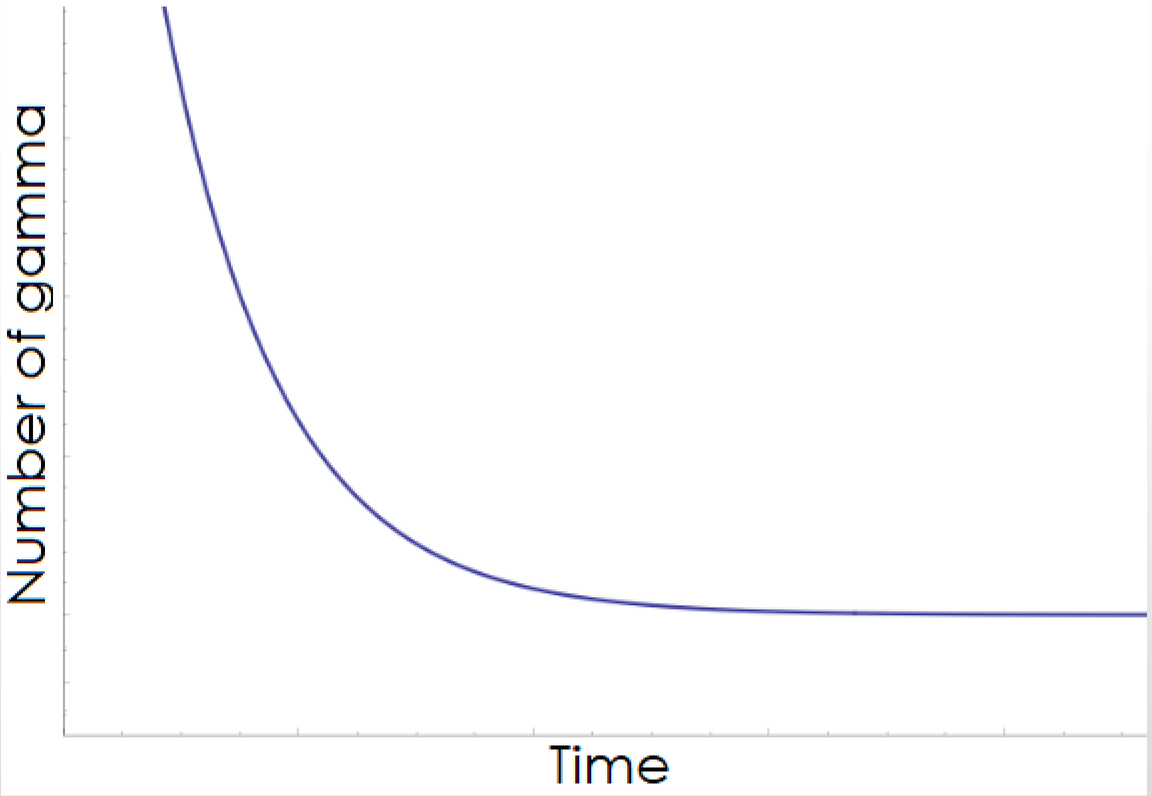
Gamma flux dependence on time

If $\varepsilon > 0$ then there is the following time dependence:



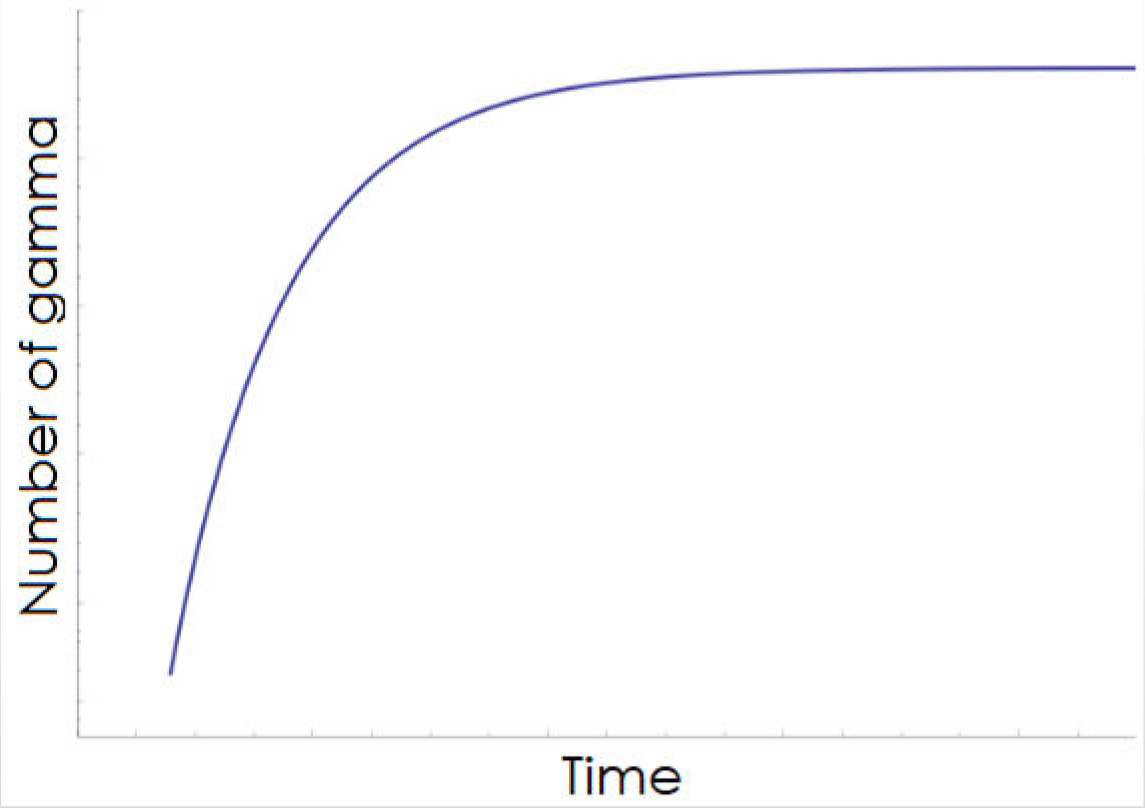
Gamma flux dependence on time

If $\varepsilon < 0, \frac{\partial n_{cosmic}}{\partial t} < \varepsilon n_0$ then there is the following time dependence:



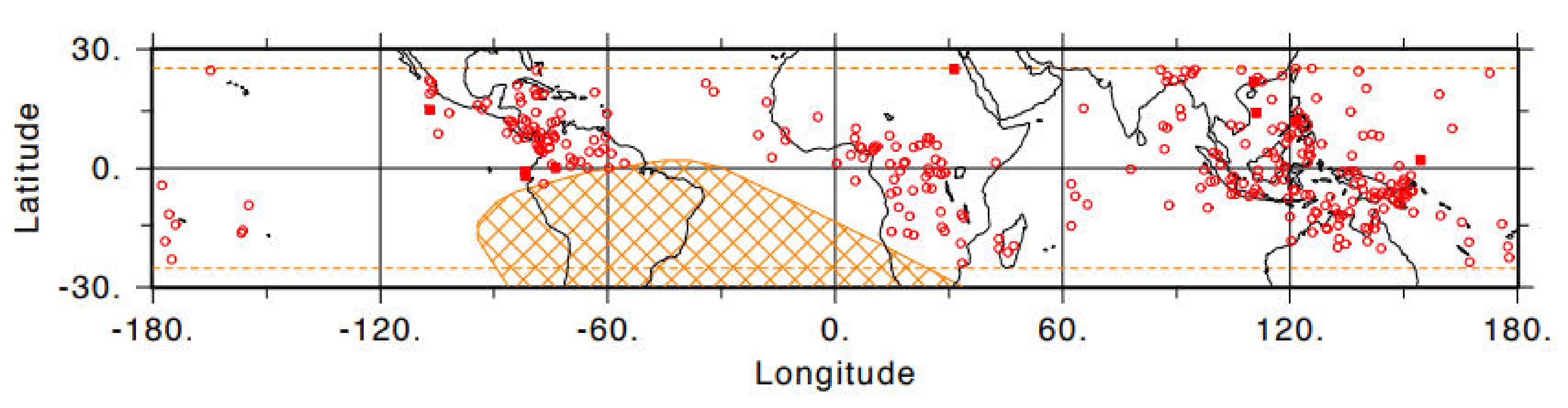
Gamma flux dependence on time

If $\varepsilon < 0$, $\frac{\partial n_{cosmic}}{\partial t} > \varepsilon n_0$ then there is the following time dependence:



TGF geography

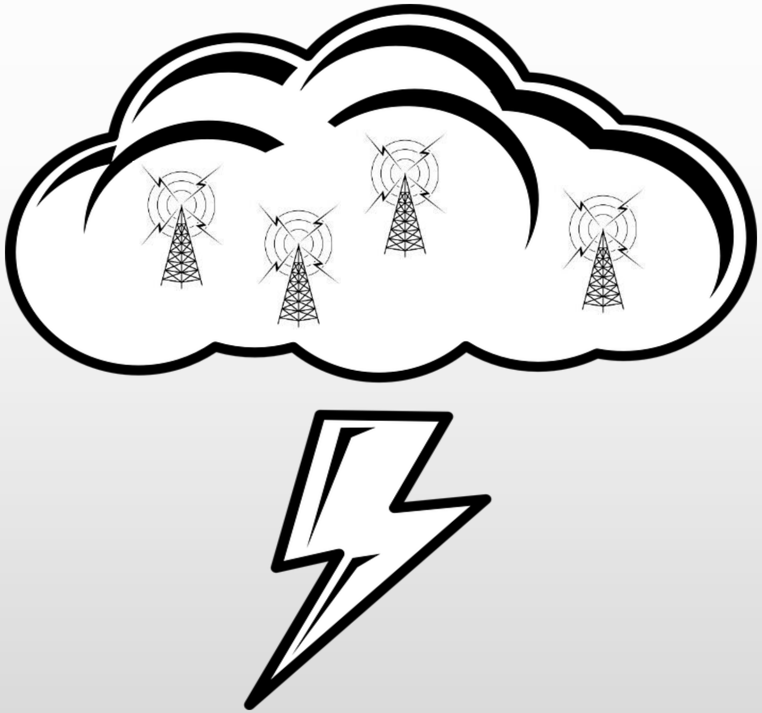
In reactor model gamma dynamics depends on thundercloud size and electric field value. Consequently, TGF requires huge thunderclouds.



[Briggs - 2013 - Fermi GBM Observations of Terrestrial Gamma-ray Flashes (TGFs)]

Reactor radio signal

RREA radio signal generation is quasi-uniform throughout the thundercloud in reactor thundercloud.

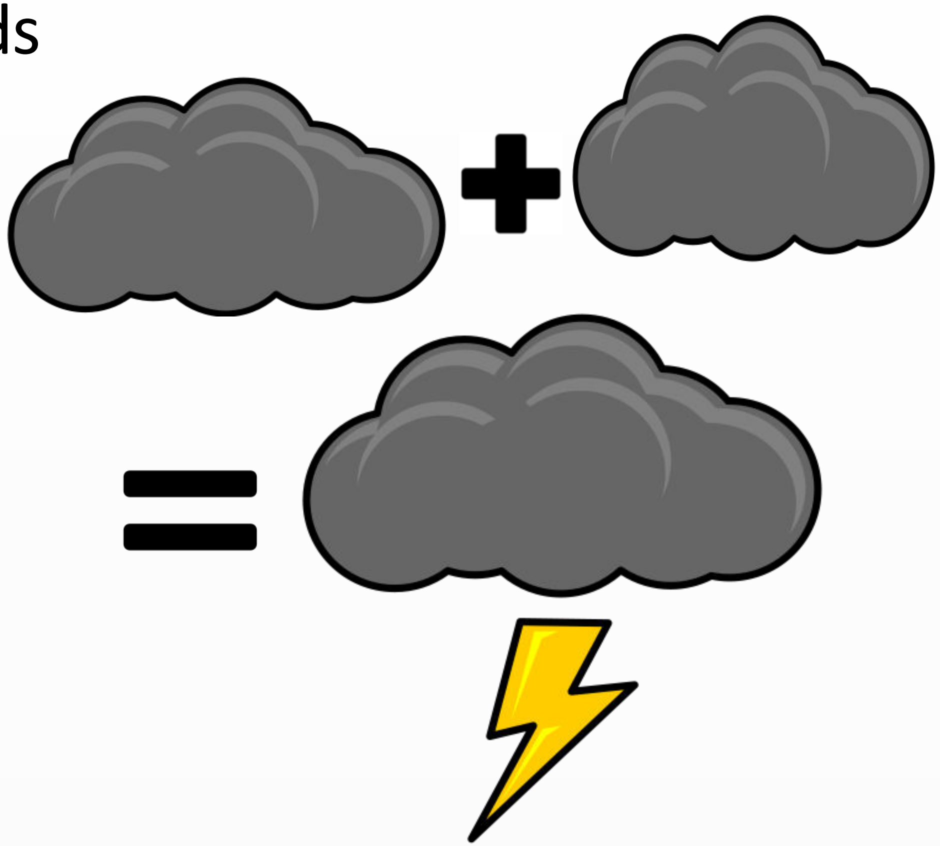


How to trigger TGF?

To burn only during hundreds of microseconds reactor explosion should be started initially with significant positive global multiplication factor.

List of TGF triggering hypothesizes:

- Undercritical thunderclouds collision
- Charge layers mixing by lightning
- Or simply low gamma fluxes are invisible from space.



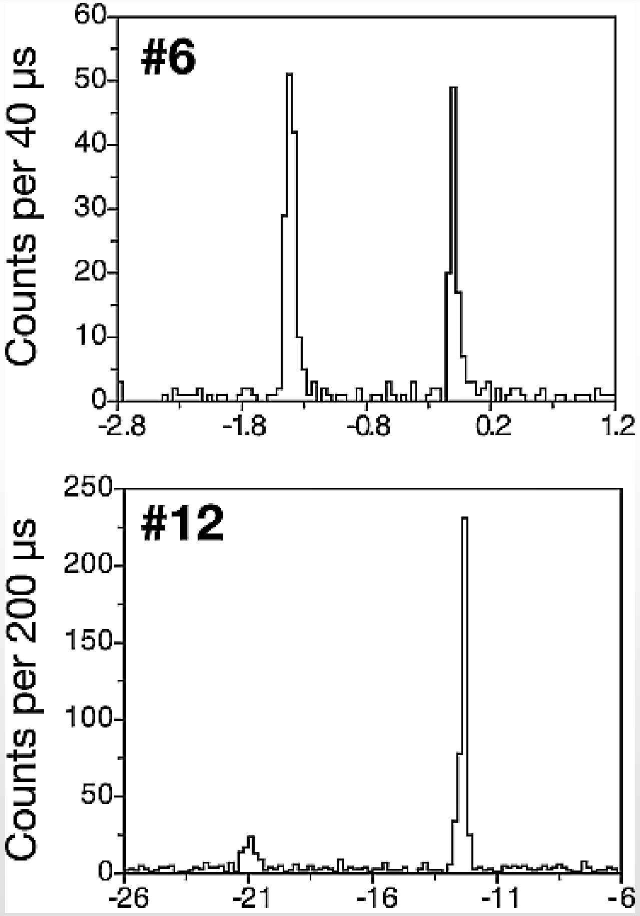
TGF dynamics in reactor model

TGF triggers discharges in cells.

Discharge at some cell can stop TGF making $\varepsilon < 0$.

That cell recharge can launch TGF again.

Consequently, multi-TGF is possible in reactor model.



https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010JA016084

Which came first: TGF or lightning?

<u>In reactor model</u> (hypothetically):

- TGF can cause lightning by triggering discharges.
- TGF can be terminated by lightning.
- Lightning can cause TGF by mixing cloud layers.

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MIPT at a glance

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THE Physics

#67 ★

THE Computer Science

#42 ★

QS Physics & Astronomy

Alumni

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Pilot astronaut, Hero of the Russian Federation

Alexander Kaleri
Pilot astronaut, Hero of the Russian Federation

Konstantin Novoselov
Nobel prizeman

Andrei Geim
Nobel prizeman

David Yan
Founder and Director of the board of ABBYY

Sergey Belousov
Founder and CEO of Acronis

Numbers

Founded in **1951**

10 Nobel prizemen among professors and alumni

80 Labs on campus

7132 Students

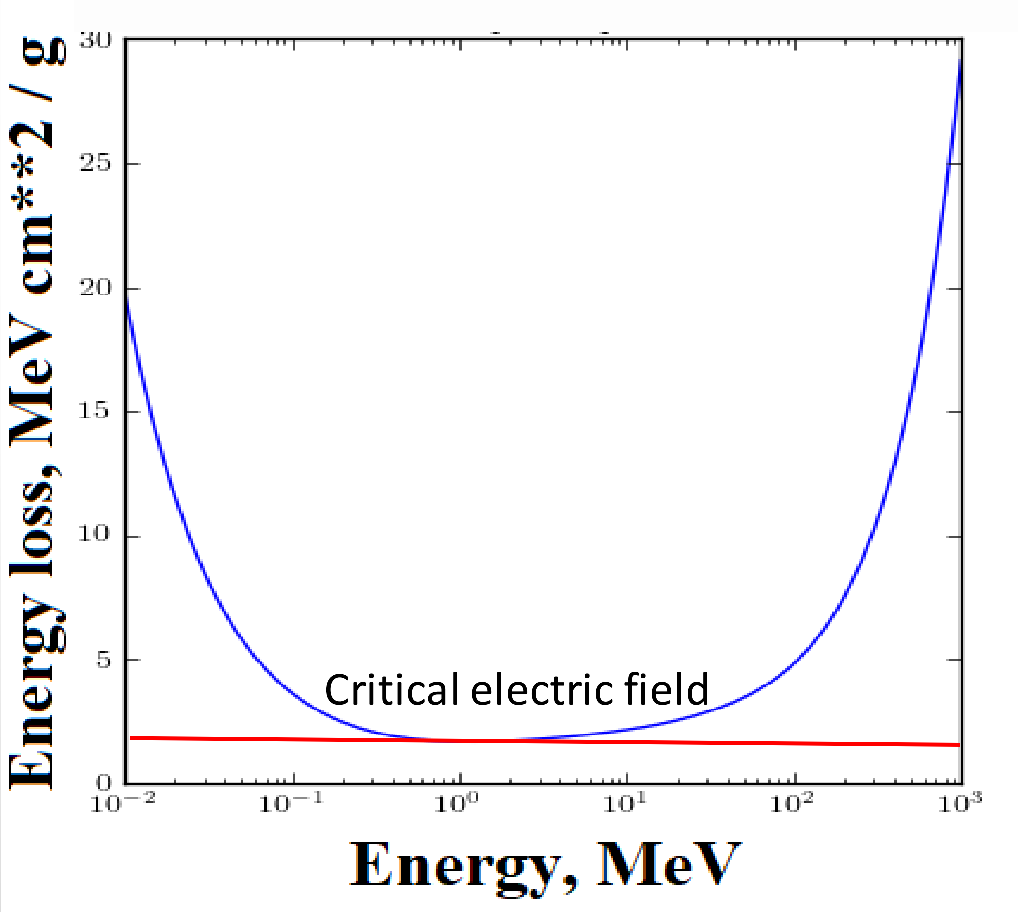
Phystech Schools

- Radio Engineering and Computer Technology
- Fundamental and Applied Physics
- Aerospace Technology
- Applied Mathematics and Informatics
- Biological and Medical Physics
- Electronics, Photonics and Molecular Physics

Runaway breakdown (Gurevich 1992)

Electric field might give to relativistic electron more energy than it wastes on interaction with air.

Such electric field is called **critical electric field**, accelerated electrons are called **runaway electrons**.



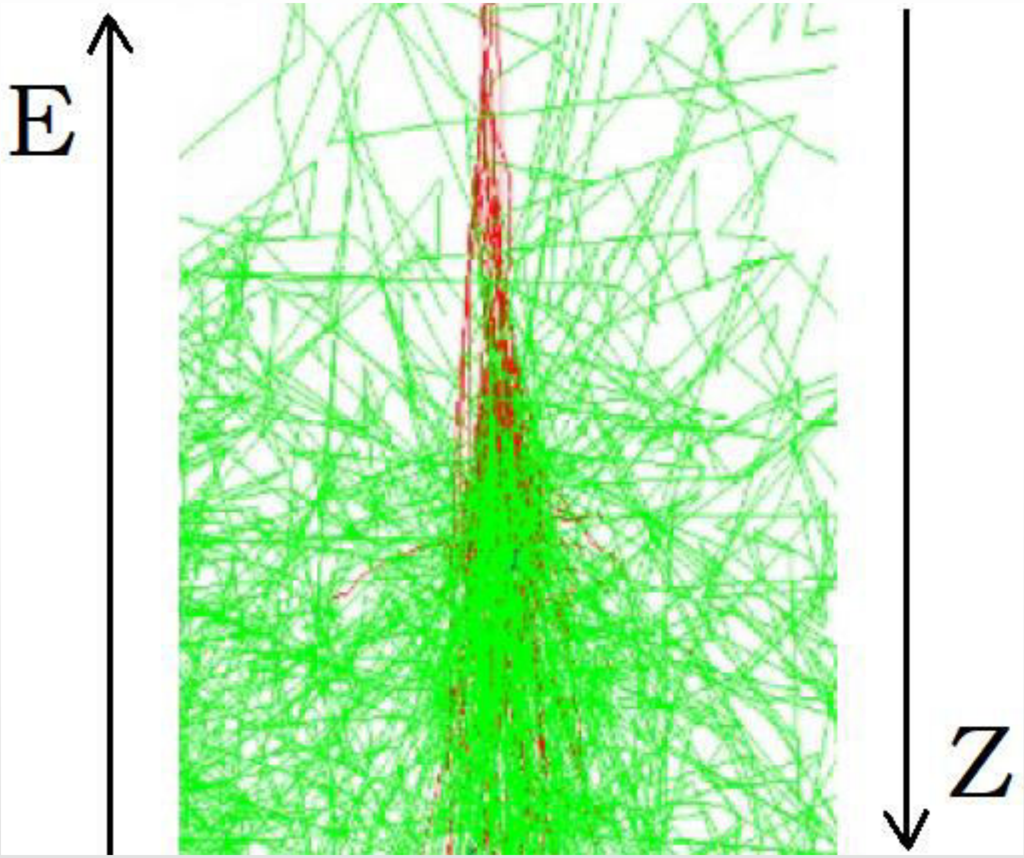
Relativistic runaway electron avalanche

Runaway electrons produce new runaway electrons by collision with air molecules' electrons.

The law of the **RREA** growth:

$$N(\mathbf{z}) = N_0 \cdot e^{\frac{\mathbf{z}}{l_a}}$$

l_a ~ 50 m

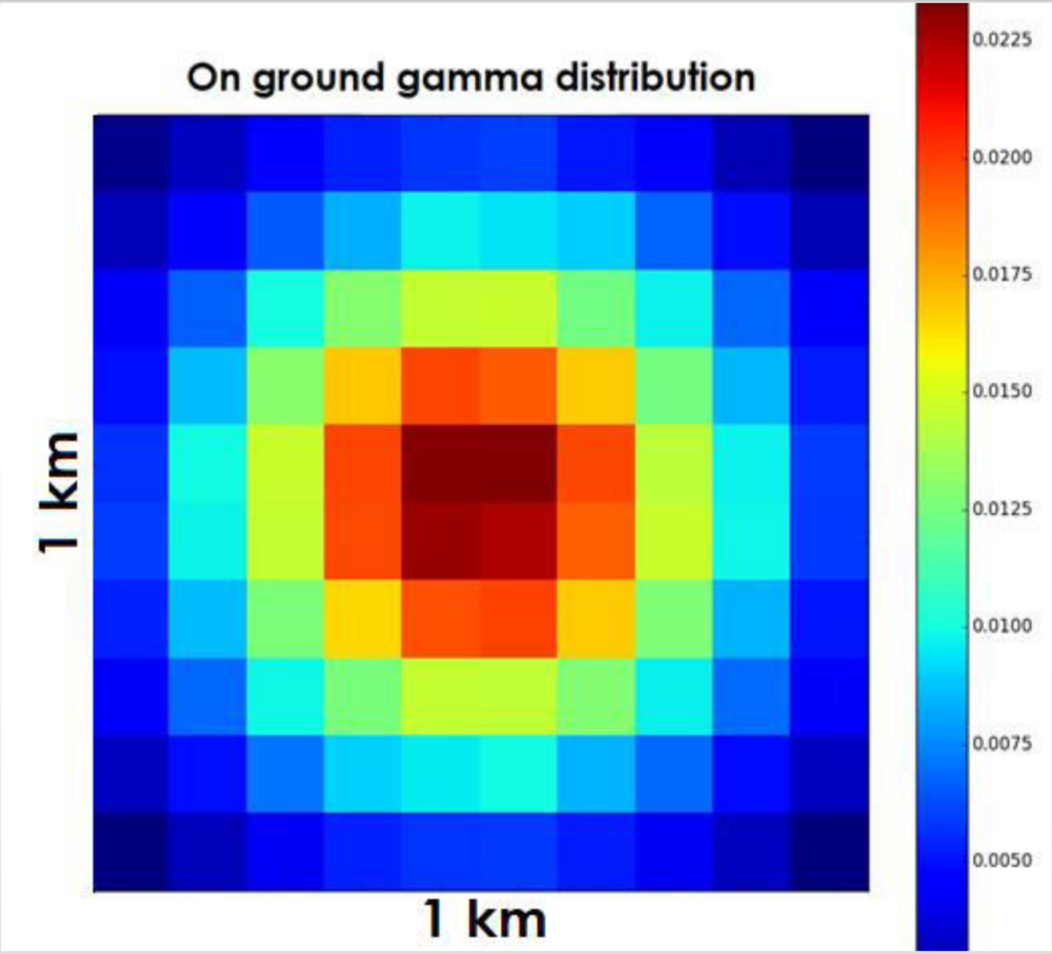


Geant4 simulation of RREA. Green – gammas, red – electrons.

Reactor thundercloud gamma radiation

On-ground quasi-isotropy hypothesis experimental observation is complicated due to air attenuation.

From 1 km isotropic gamma source looks like looks like directed source with Compton scattering.



Isotropic source Geant4 simulation

Reactor thundercloud gamma radiation