Modeling Terrestrial Gamma-ray Flashes

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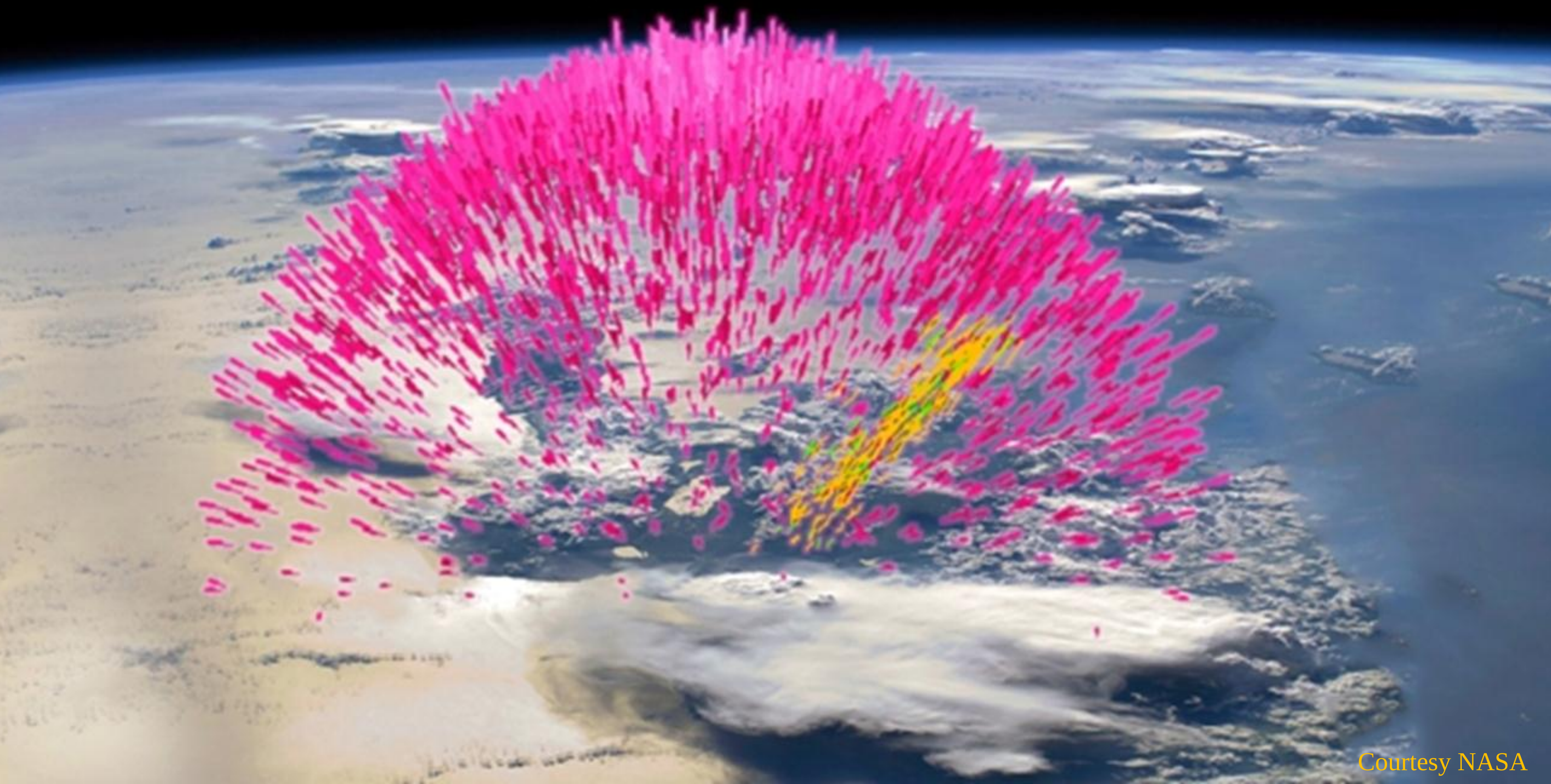
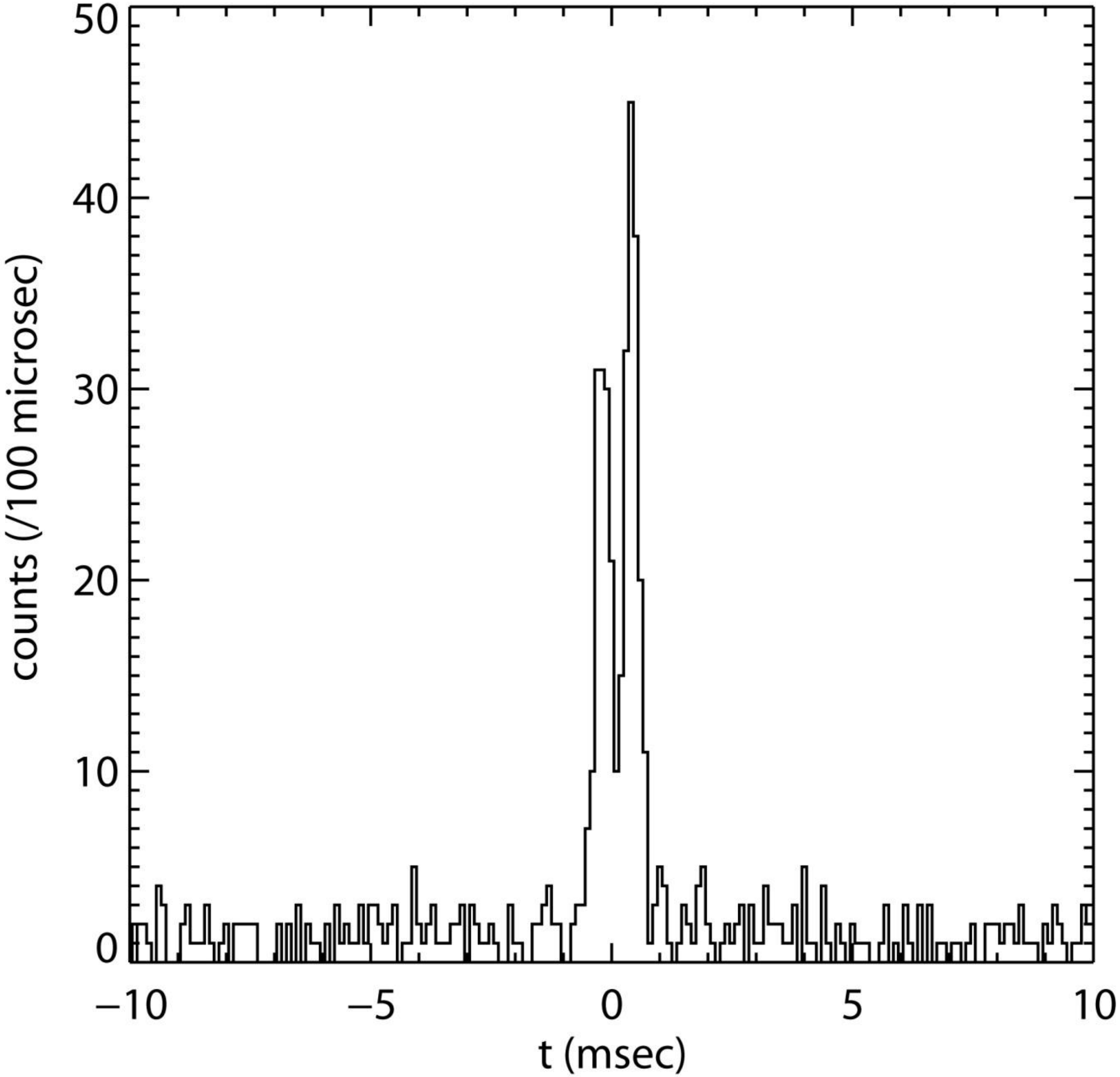


Courtesy NASA

CGRO/BATSE Terrestrial Gamma-ray Flash (TGF)
(Fishman *et al*. 1994)



http://www.batse.msfc.nasa.gov/batse/tgf/

TGF summary

- ~200 μsec bursts of MeV gamma-rays (not 1 msec as originally described using BATSE data). This is also the timescale of the runaway electron source.

- TGFs longer than 1 msec appear to be mostly terrestrial electron beams or normal TGFs suffering large instrumental saturation effects along with Compton scattering.

- ~10^{17} runaway electrons produced at the source.

- Nearly all TGFs appear to originate from < 21 km, i.e. thundercloud altitudes, with little evidence of an additional high altitude source.

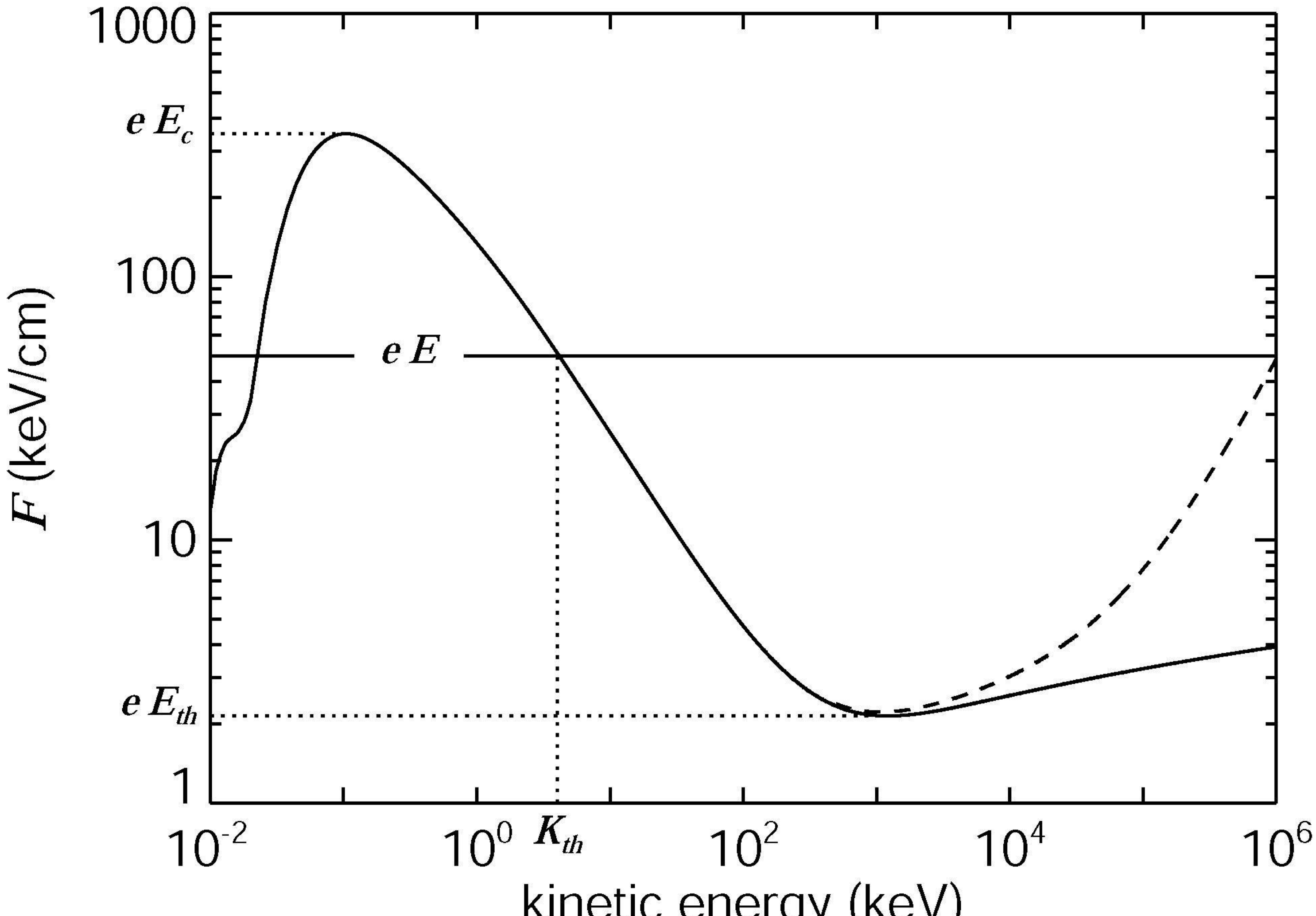
- The energy spectrum is consistent with RREA up to at least ~20 MeV, but there may be a problem with the RREA spectrum at higher energies (AGILE observations)

- The lightning associated with TGFs are typically strong +IC flashes that transfer too little charge to cause sprites. The TGFs occur at the early stages of the IC flash when the upward leader is still moving between the negative and positive charge regions, *i.e*. before most of the charge is transferred.

Relativistic Runaway Electron Avalanches (RREAs)

(Wilson 1925; Gurevich *et al.* 1992)

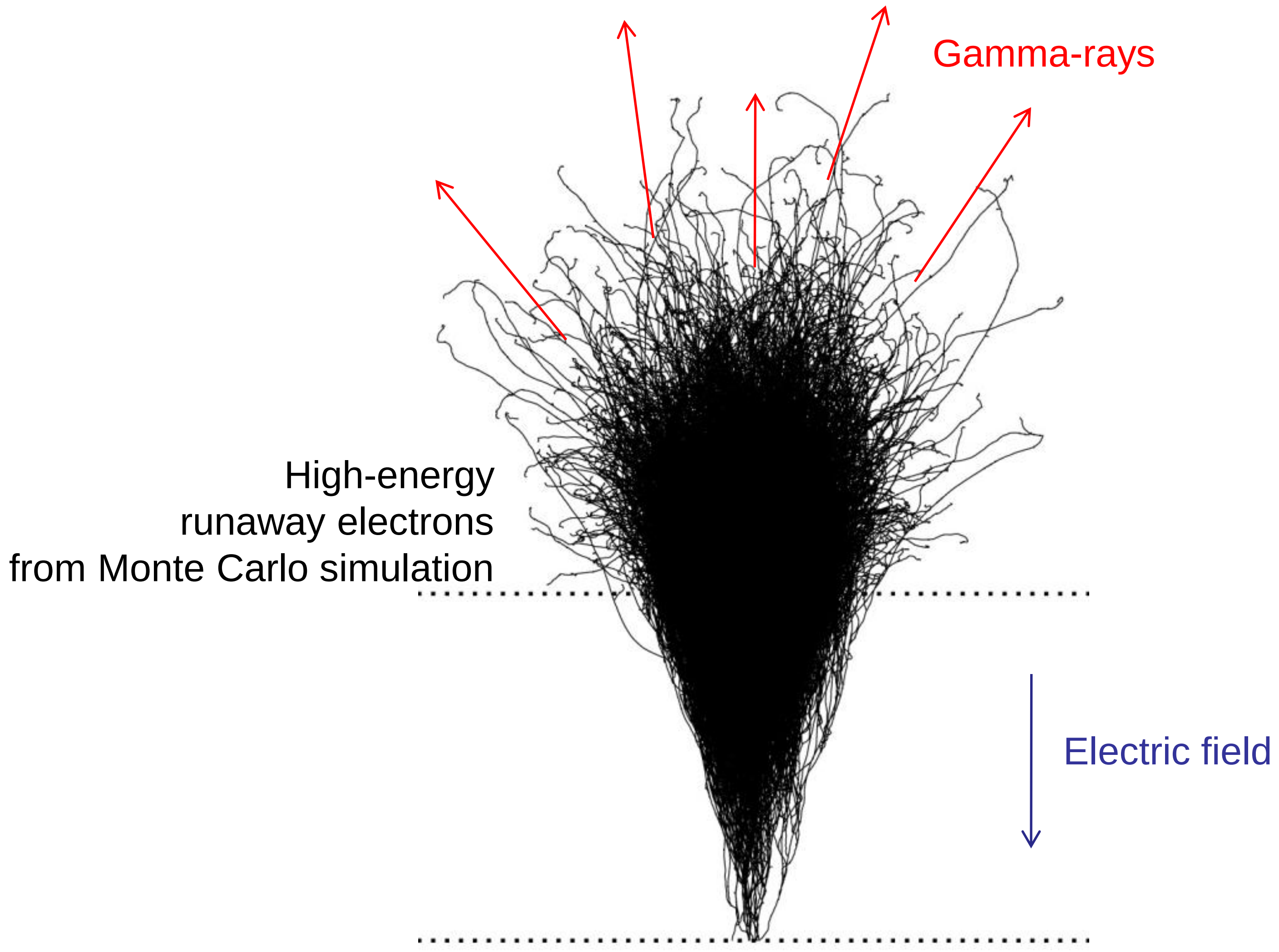
Energy loss and gain experienced by an electron in air (Bethe Equation)



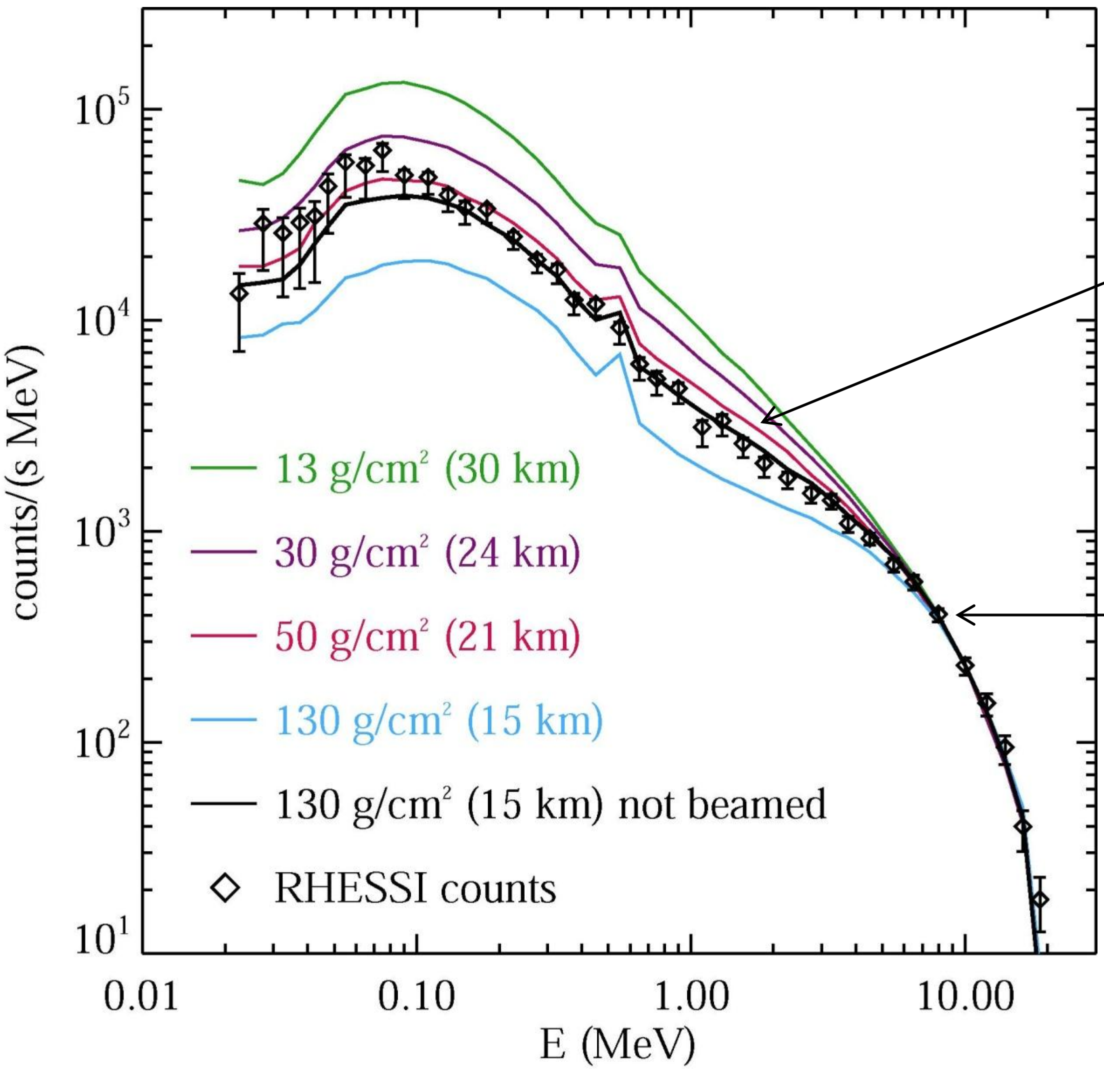
From Dwyer (2004)

Inside a thundercloud:

Strong electric fields accelerate electrons to nearly the speed of light.
These electrons emit gamma-rays via bremsstrahlung interactions with air.



Terrestrial Gamma-Ray Flash (TGF) spectrum and results of Monte Carlo simulation for different source altitudes



TGF spectrum too flat >1 MeV to be from a high source altitude

TGF spectrum fits RREA model well up to 20 MeV

From Dwyer and Smith (2005)

Possible mechanisms

- RREAs acting on background cosmic-rays or extensive air showers cannot explain TGFs (Dwyer 2008).
- TGFs could be produced by runaway electron production (cold runaway) in the high fields associated with leaders.
- TGFs could be produced by the relativistic feedback mechanism.

Does cold runaway from lightning inside thunderclouds make TGFs?

- Cold runaway + Wilson runaway = energetic radiation from lightning

- If instead we have cold runaway + RREA we would get enough runaway electrons to make a TGF: 10^{17} sec^{-1} $\times 10^{4} \times 0.0001$ sec = 10^{17} runaway electrons (Dwyer *et al*. 2010).

Challenges:

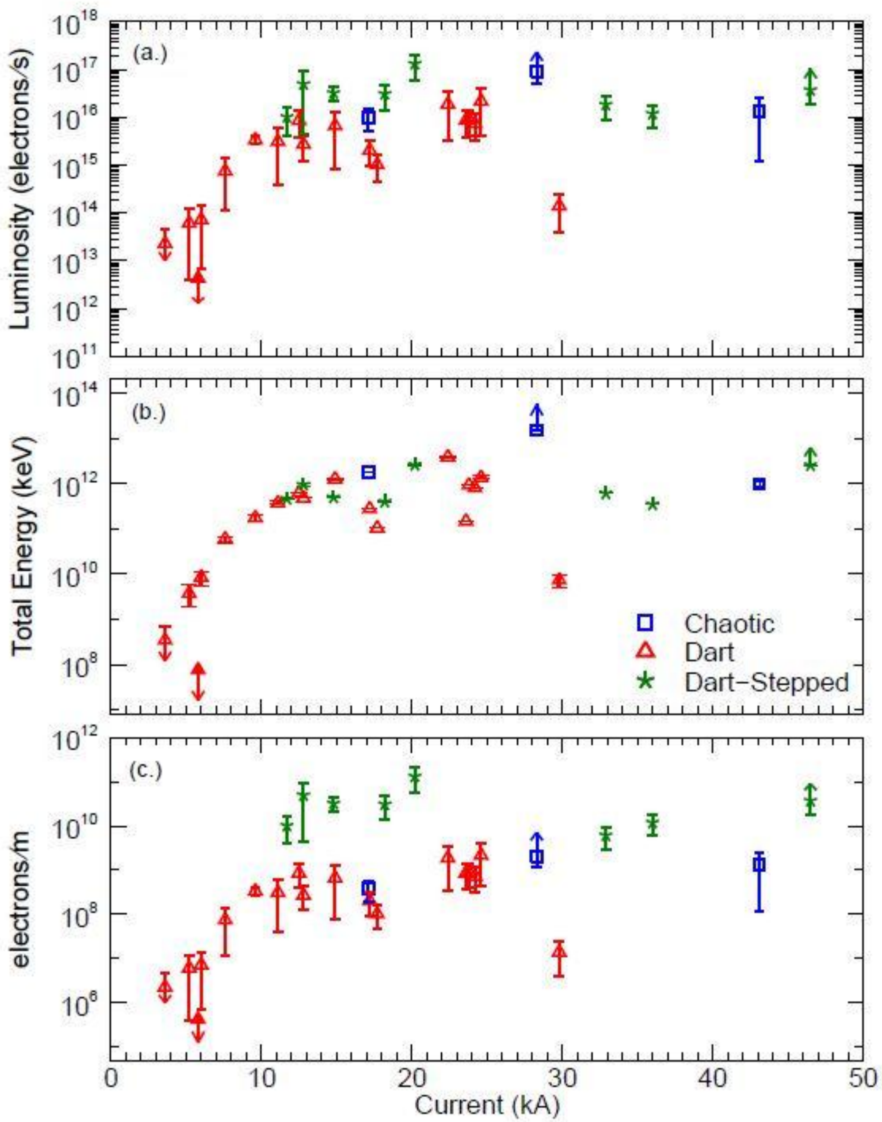
- Even though lightning probably has larger potentials then a few MeV in the high field region in front of the leader, the energy of the runaway electrons has never been observed to exceed a few MeV, *i.e*. RREA never observed.

- The time scale for the x-ray emission from lightning ~0.5 μsec. Not obvious how to get the 100 μsec timescales of TGFs.

- X-rays from natural lightning occur during the step formation. How are steps related to TGFs?

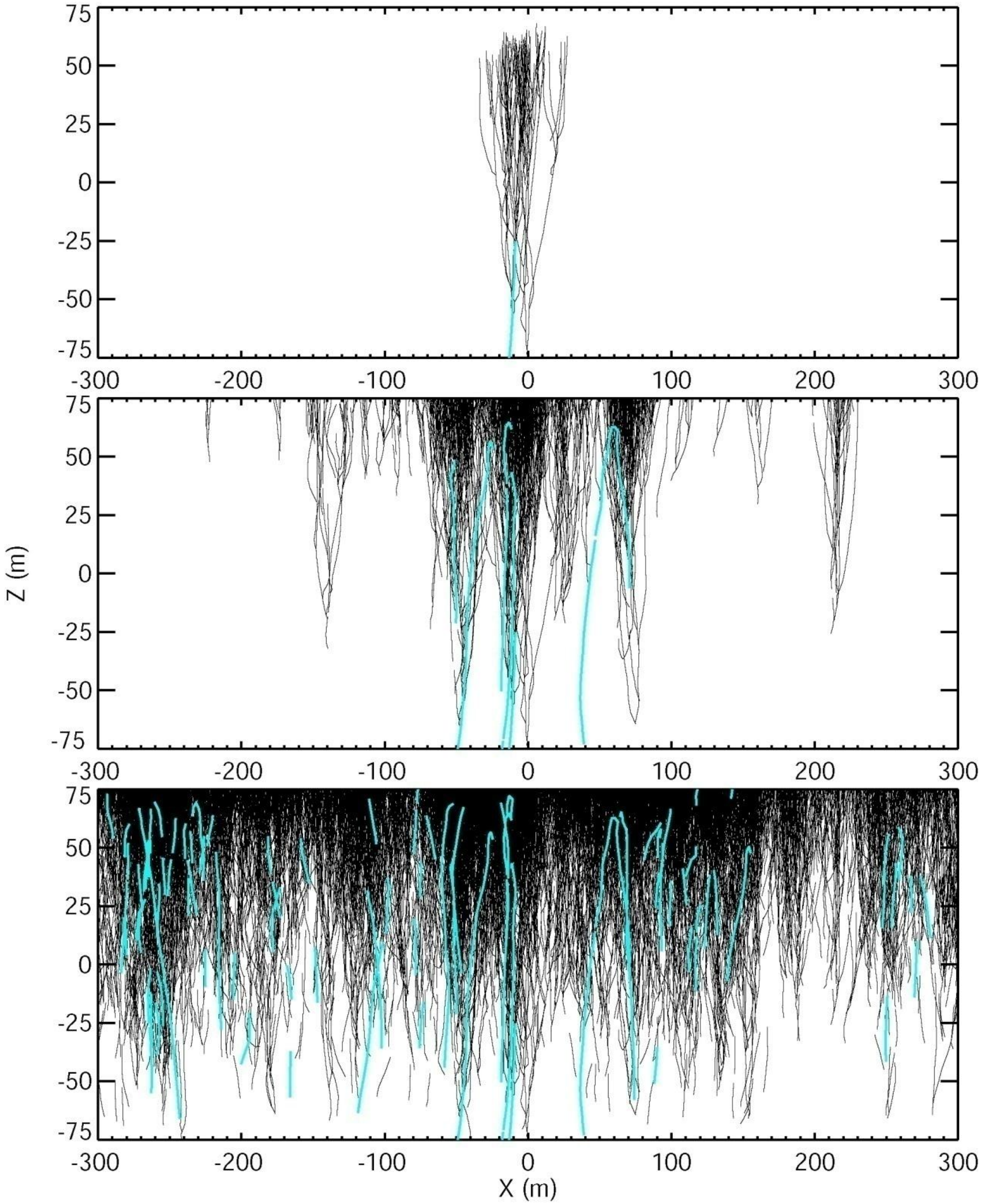
Final problem:

The runaway electron production by lightning near the ground appears to saturate (Schaal *et al*. 2012)



Relativistic Feedback Discharge
due to backward propagating x-rays and positrons.

The central avalanche is due to the injection of a single, 1 MeV seed electron. All the other avalanches are produced by x-ray and positron feedback. The top panel is for times, t < 0.5 μs. The middle panel is for t < 2 μs, and the bottom panel is for t < 10 μs.

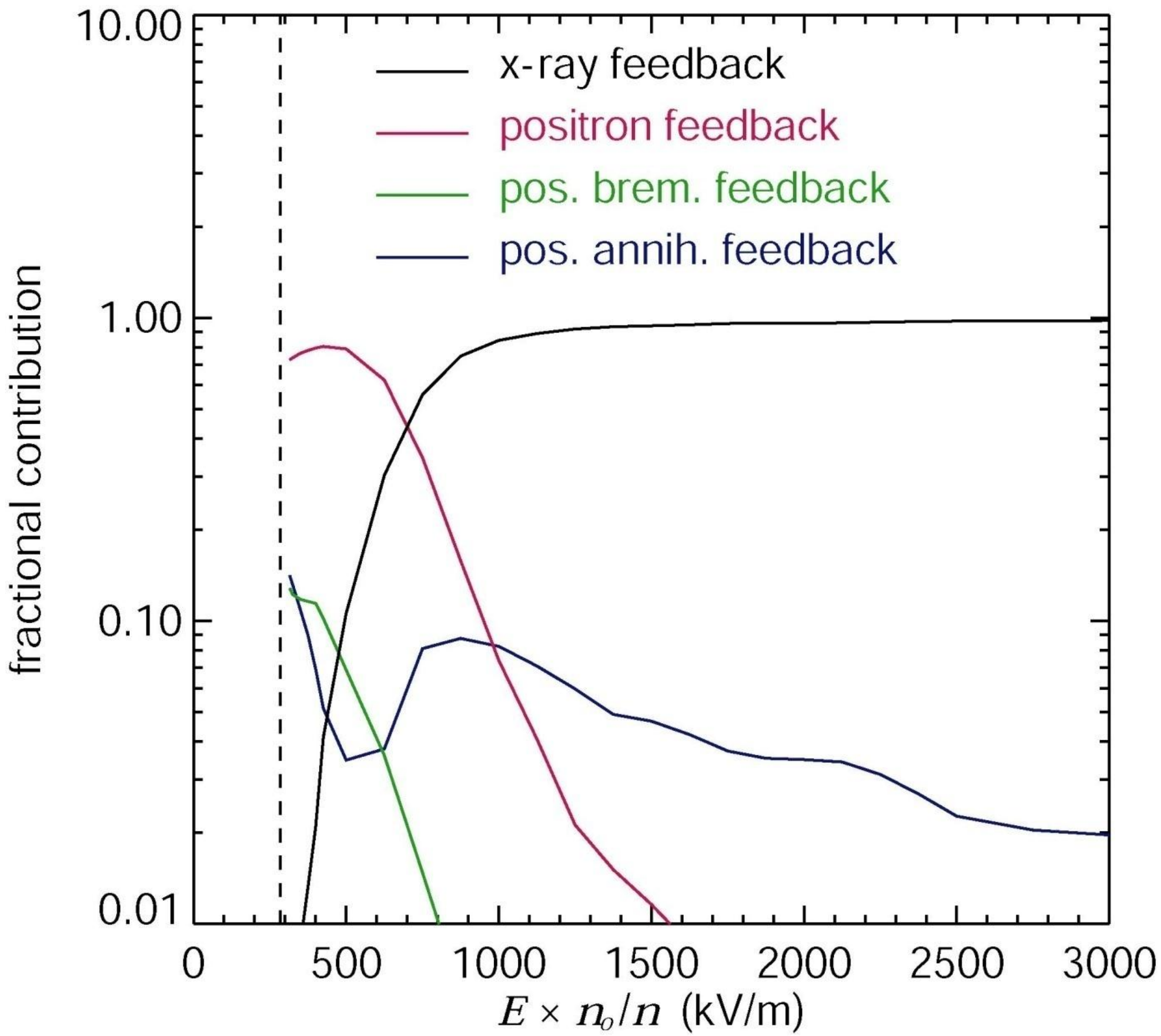


From Dwyer (2007)

Runaway positrons

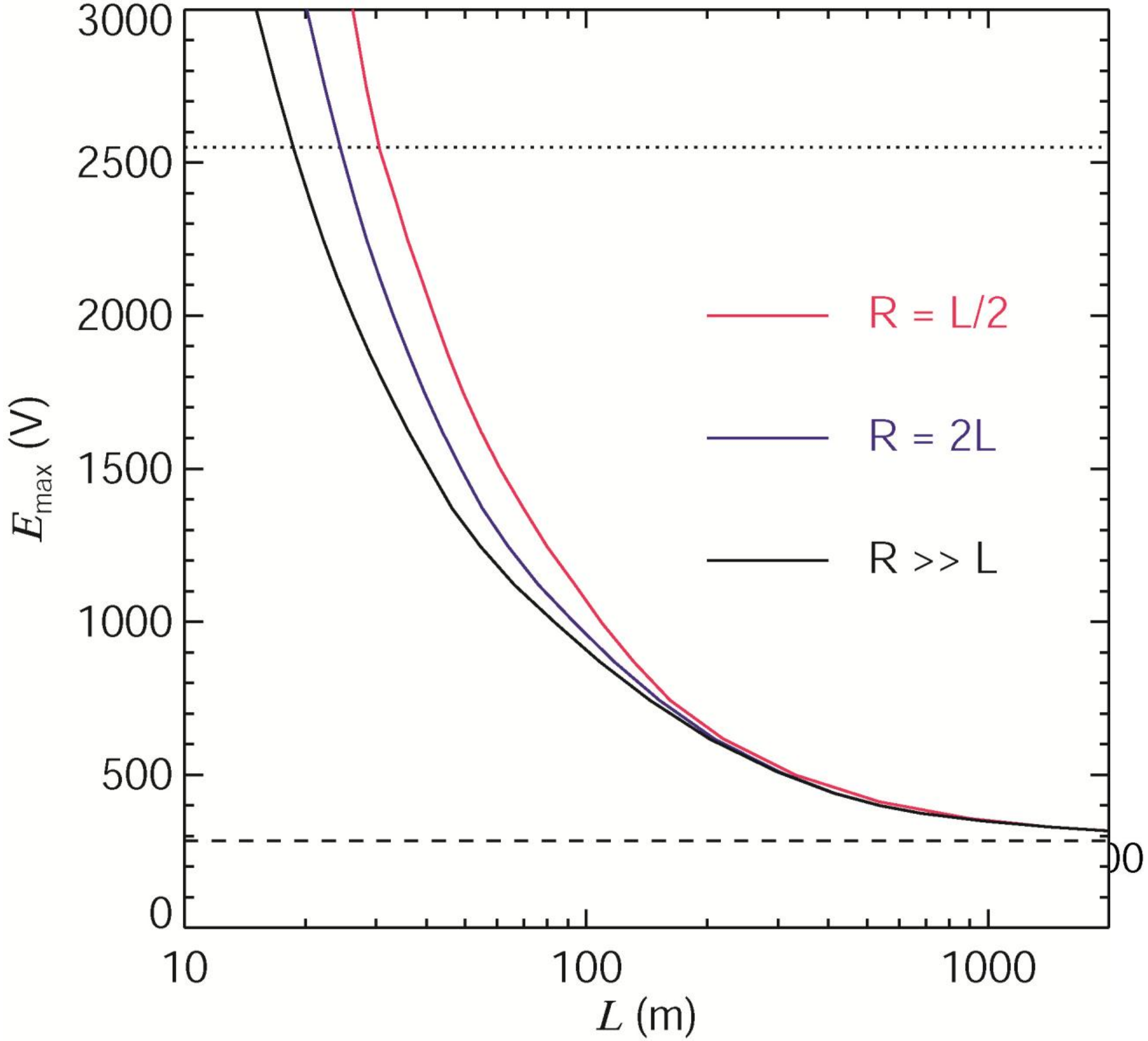
- The average energy of runaway electrons is about 7 MeV and the energy spectrum is exponential.
- The average energy of the runaway positrons could, in principle, approach 100 MeV, resulting in a 1/E power law gamma-ray spectrum that extends to very high energies.
- Such a “positron” TGF could be produced between the upper negative and main positive charge layers inside a thundercloud.

Contributions to relativistic feedback



From Dwyer (2007)

Positron and x-ray feedback limit the electric field that can be achieved in air on timescales longer than a few tens of microseconds



From Dwyer (2007)

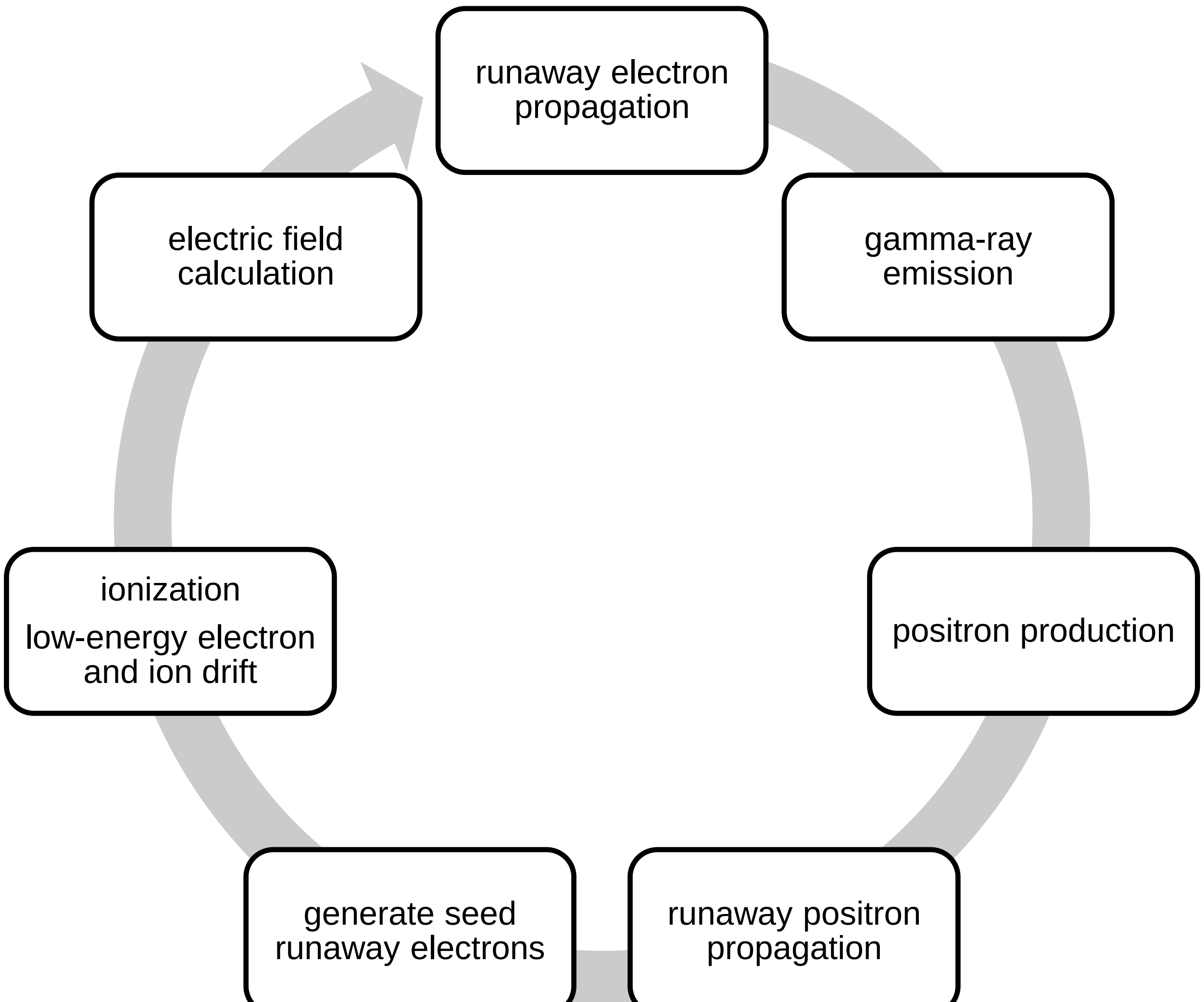
Relativistic Feedback Discharge Model

Transport code for runaway electrons and positrons

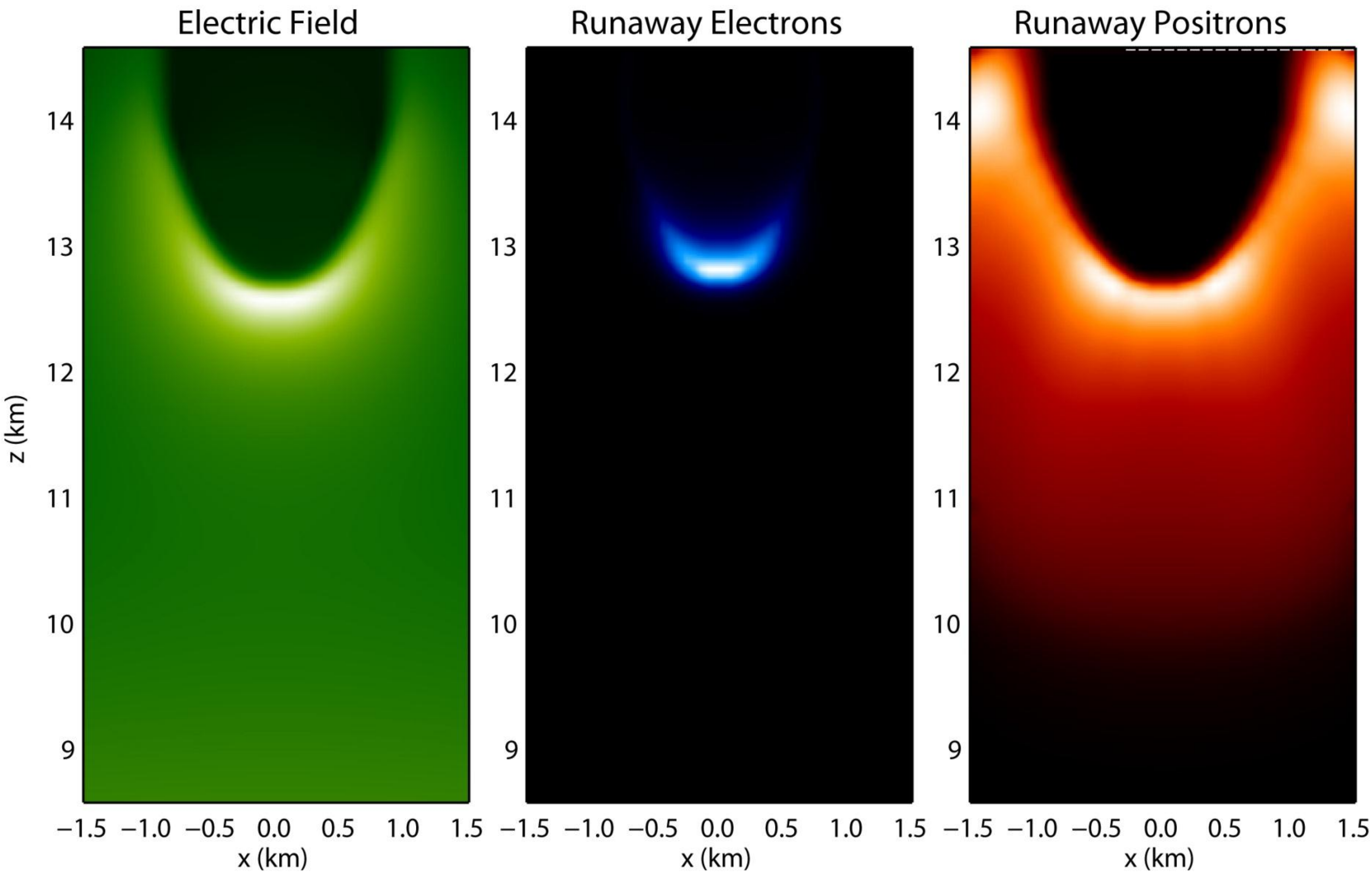
Time-dependent transport equation:
$$\frac{\partial n_r}{\partial t} + \vec{\nabla} \cdot (\vec{v} n_r) - \vec{\nabla} \cdot \left(\hat{D} \vec{\nabla} n_r \right) - \frac{n_r}{\tau} = S$$

$\vec{v}$ is the velocity of the energetic particles in the electric field.
$\hat{D}$ is the diffusion coefficient.
τ is the avalanche time for the electrons and annihilation time for the positrons.
S is the source function of energetic particles.

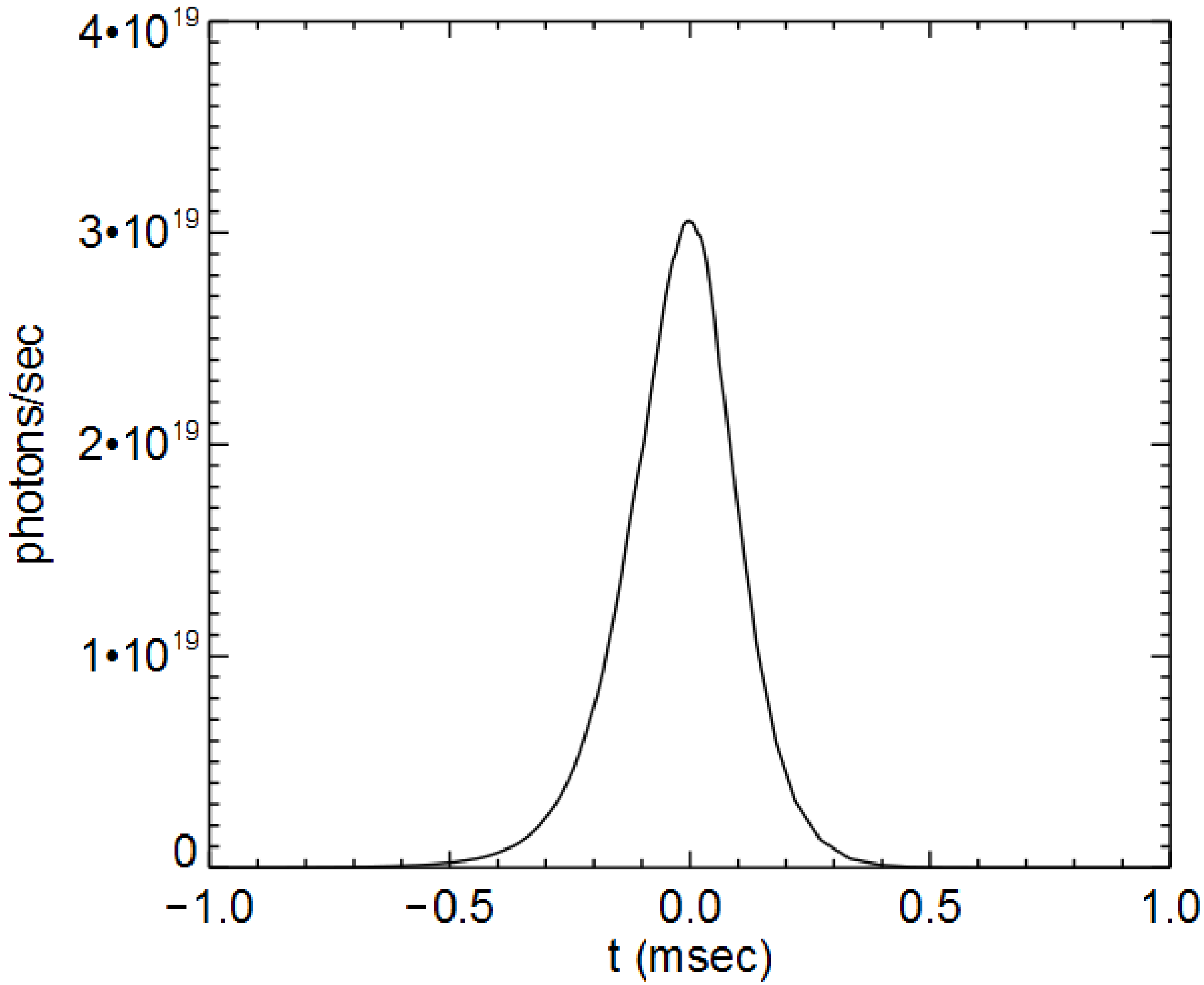
Relativistic Feedback Discharge Model



Simulation results



Resulting gamma-ray emission has same pulse shape, duration and intensity as observed TGFs



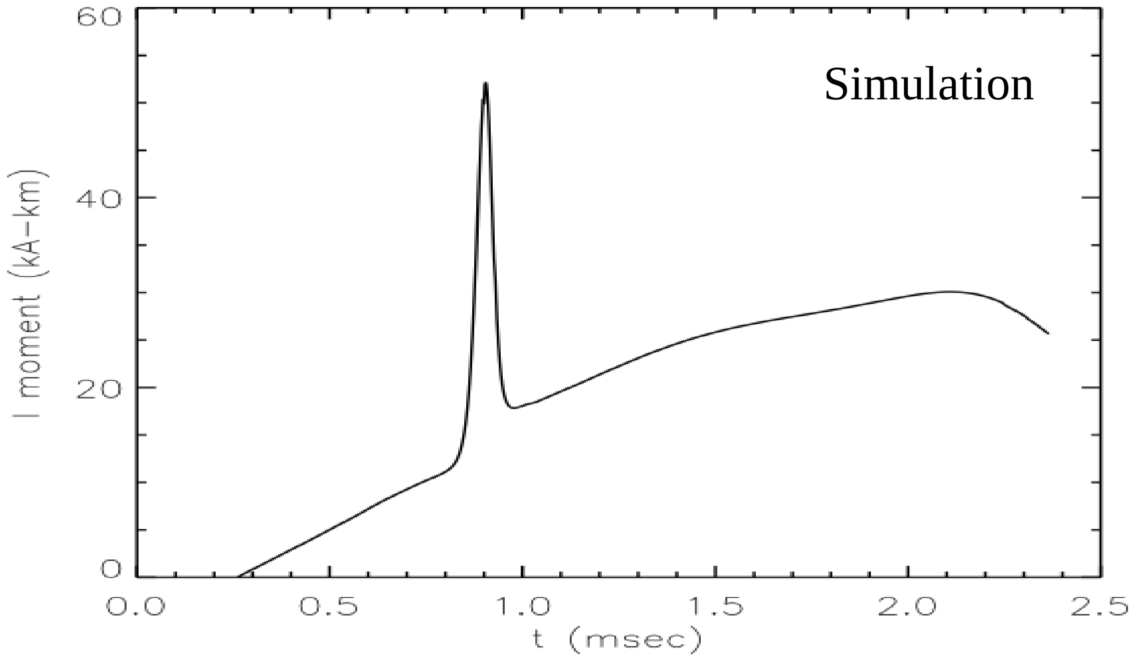
Dwyer (2012)

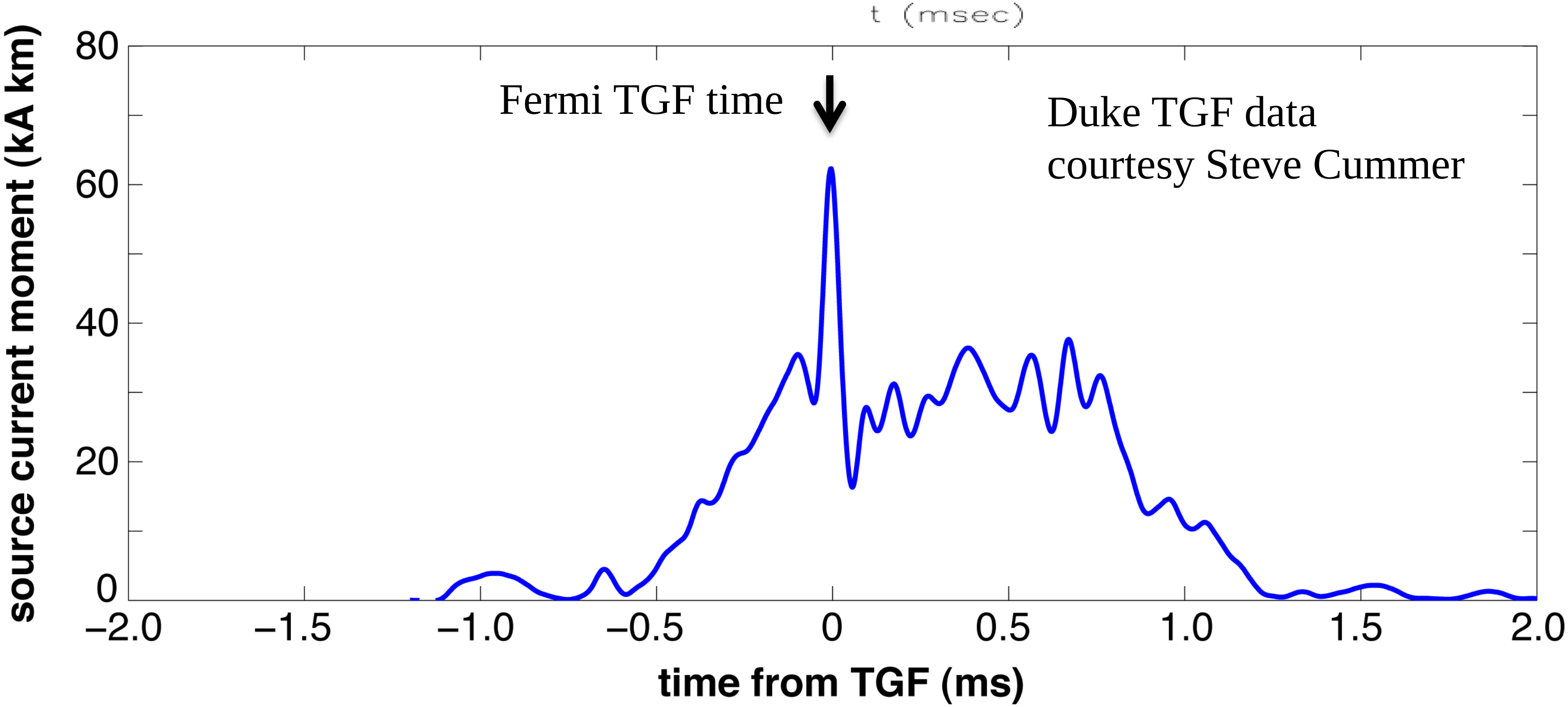
TGFs and Lightning

The TGF produces

40 kA peak current

3×10^{12} W peak power

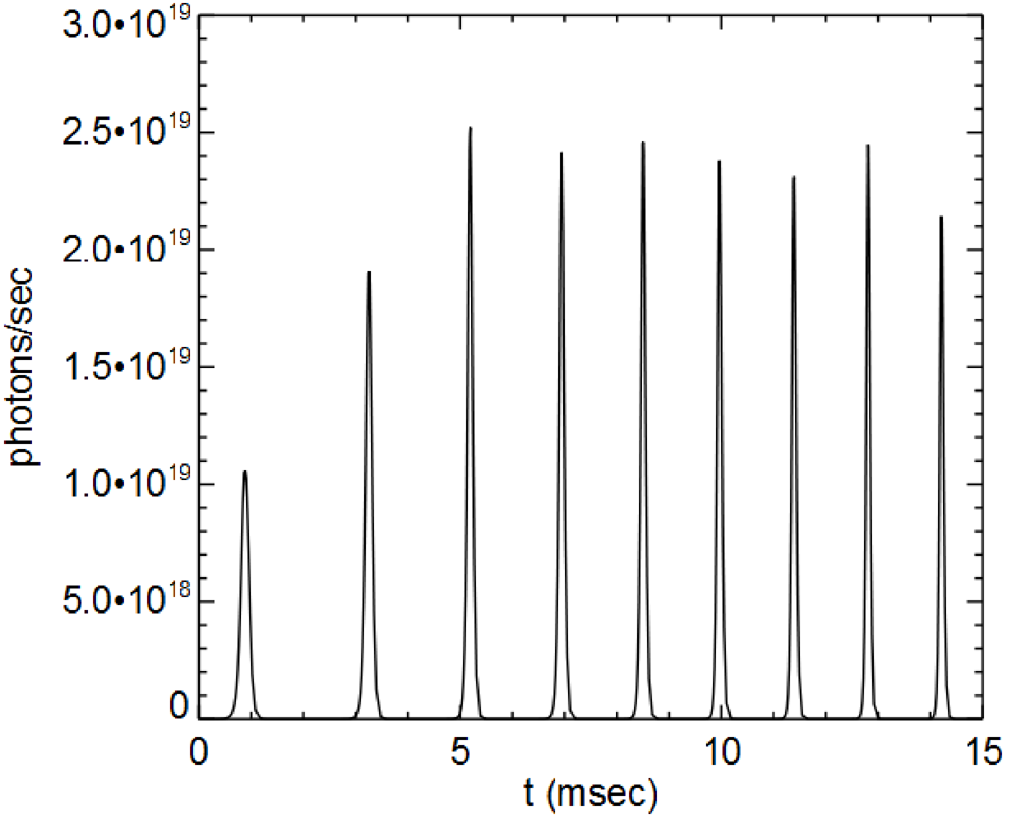




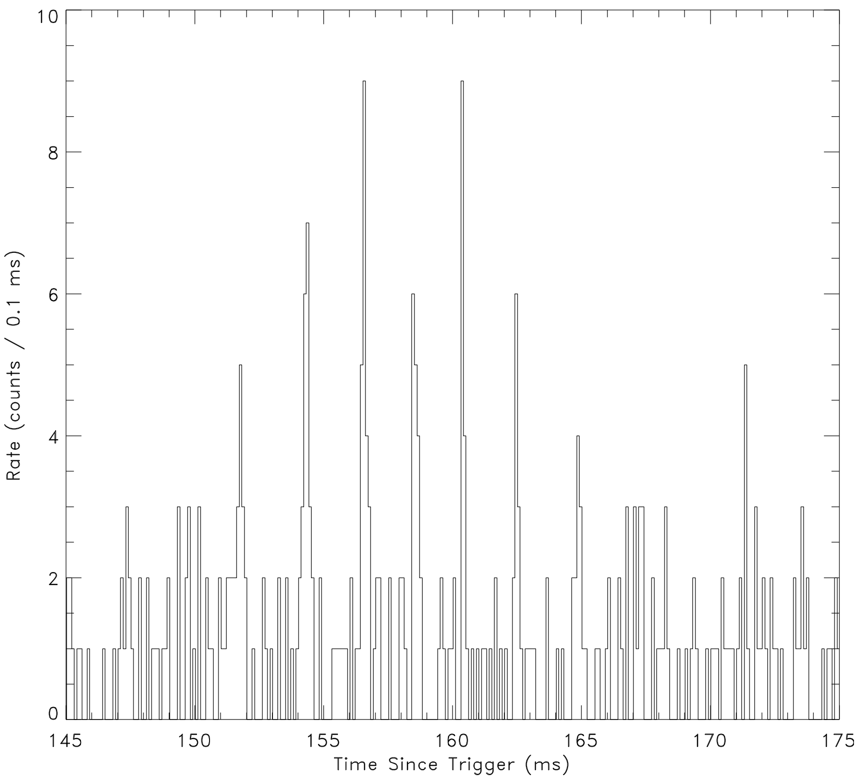
Example of gamma-ray pulses emitted by a relativistic feedback discharge

Note the correct pulse widths and spacing as observed TGF

Model result



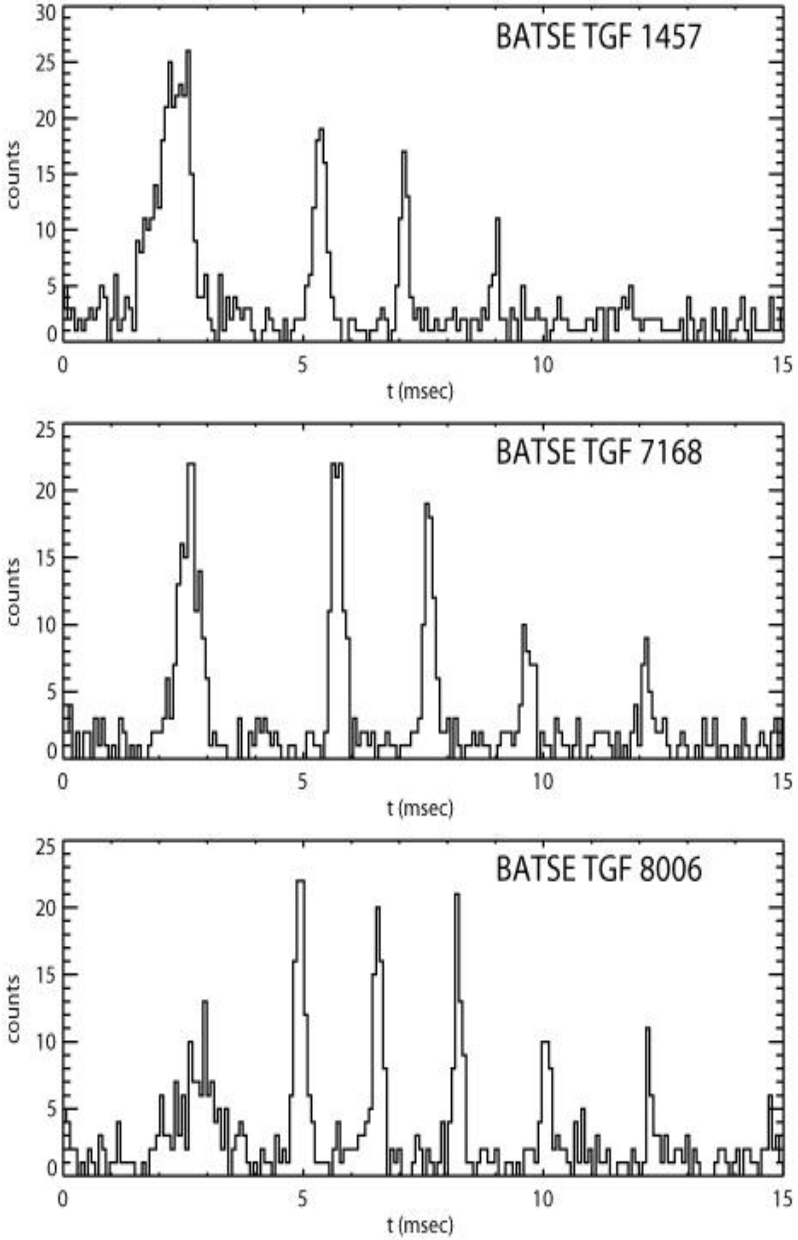
CGRO/BATSE TGF



Dwyer (2012)

CGRO/BATSE TGFs

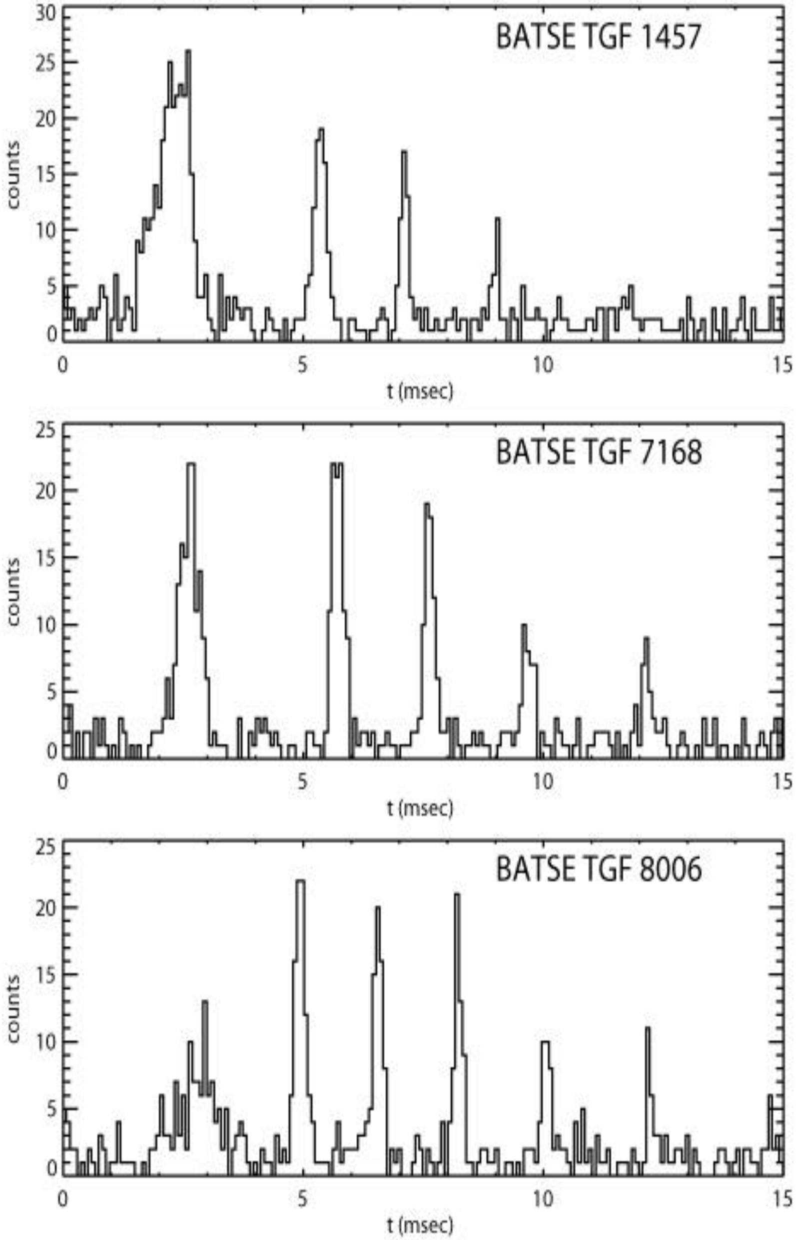
More multi-pulsed TGFs



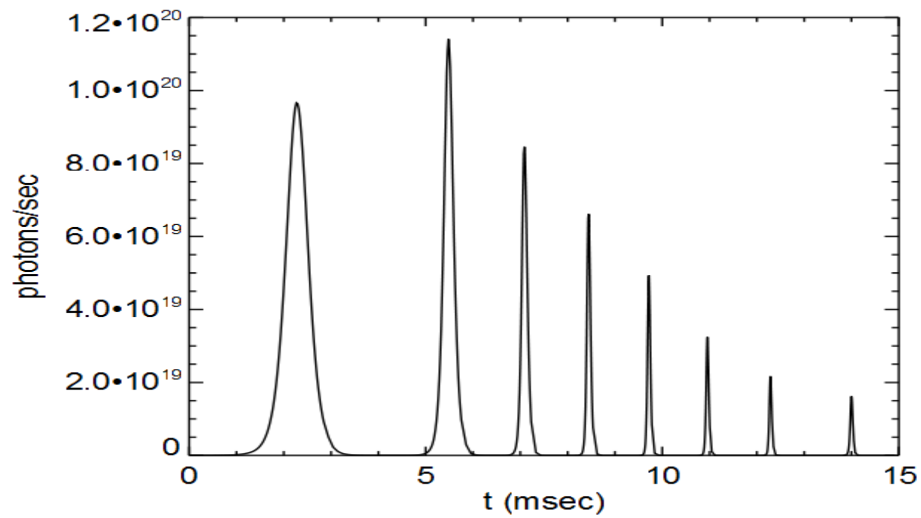
Dwyer (2012)

More multi-pulsed TGFs

CGRO/BATSE TGFs

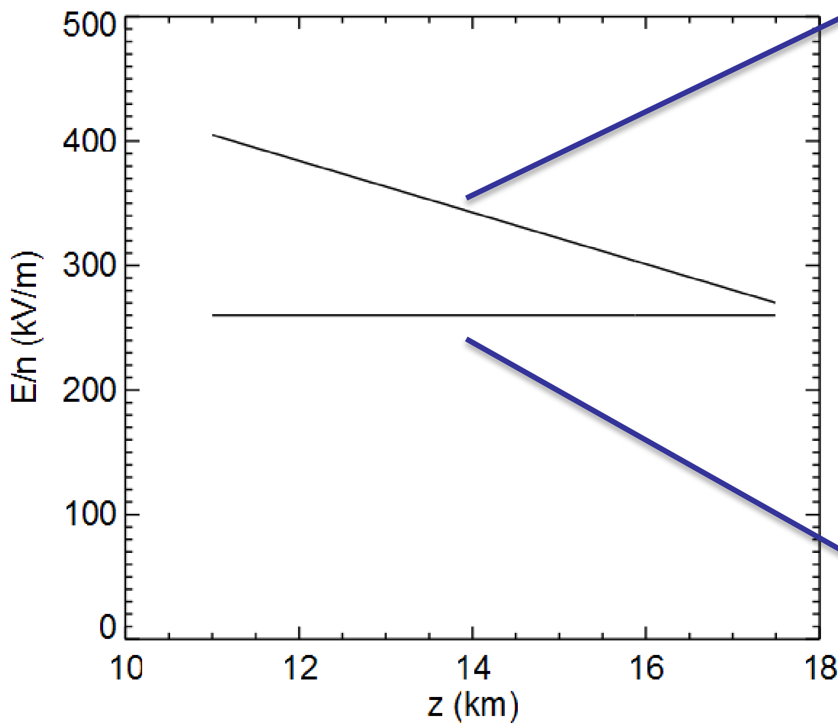


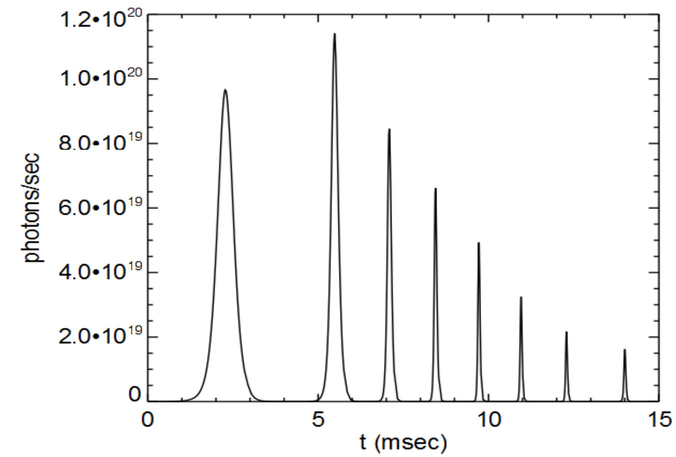
Model result

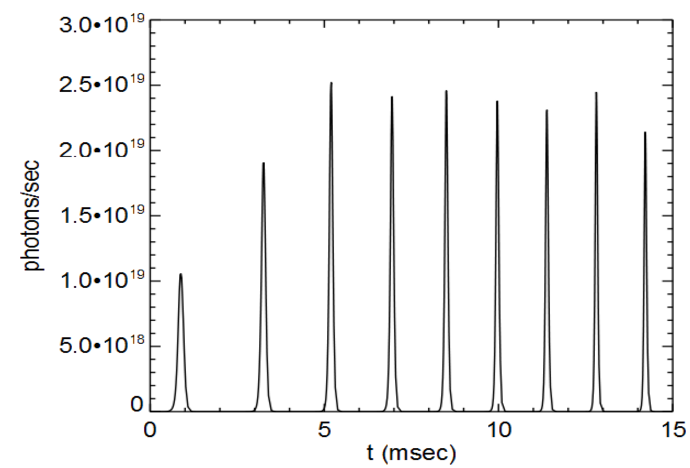


Dwyer (2012)

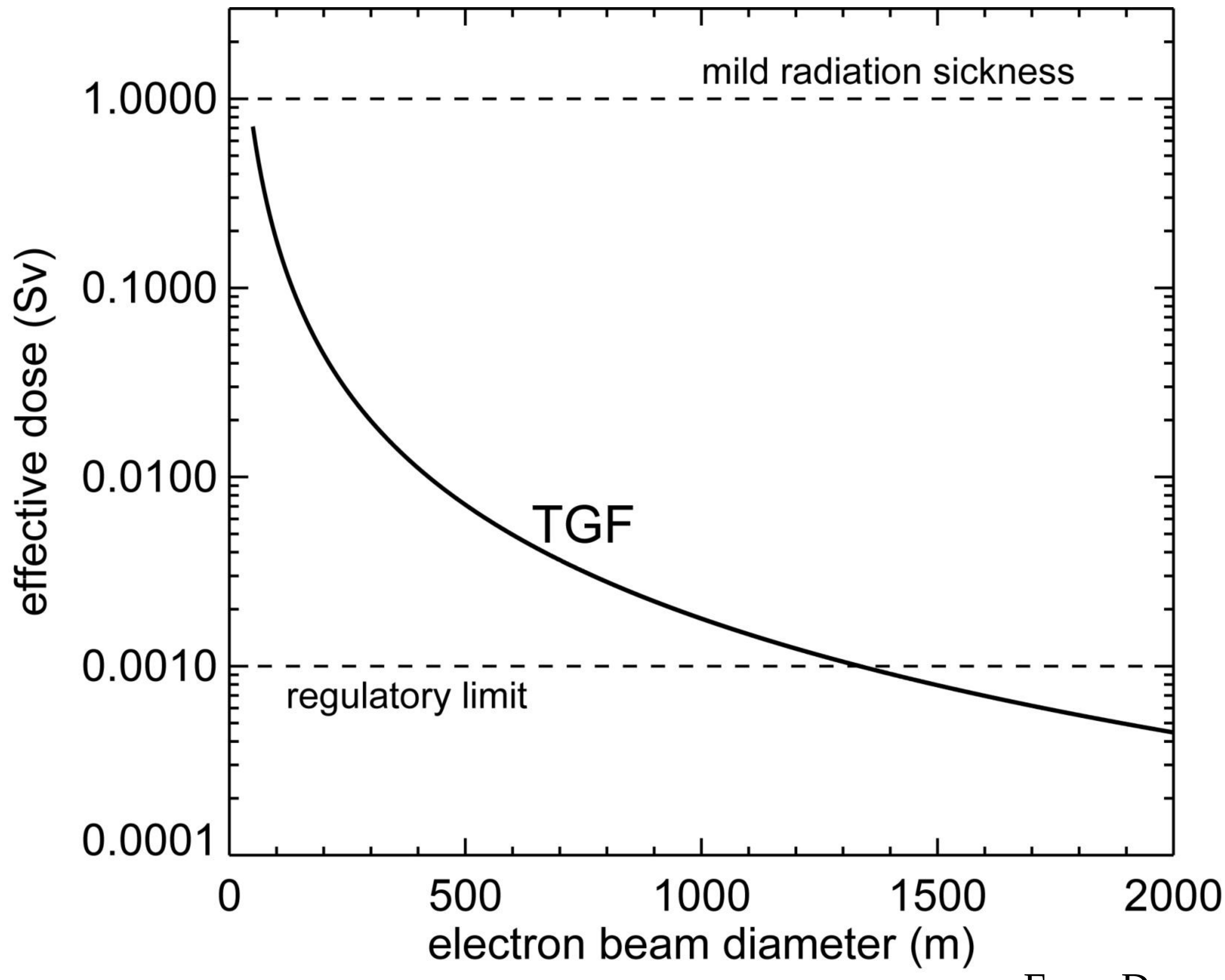
Electric field configuration explains TGF morphology







Radiation doses received by individuals inside aircraft struck by a TGF

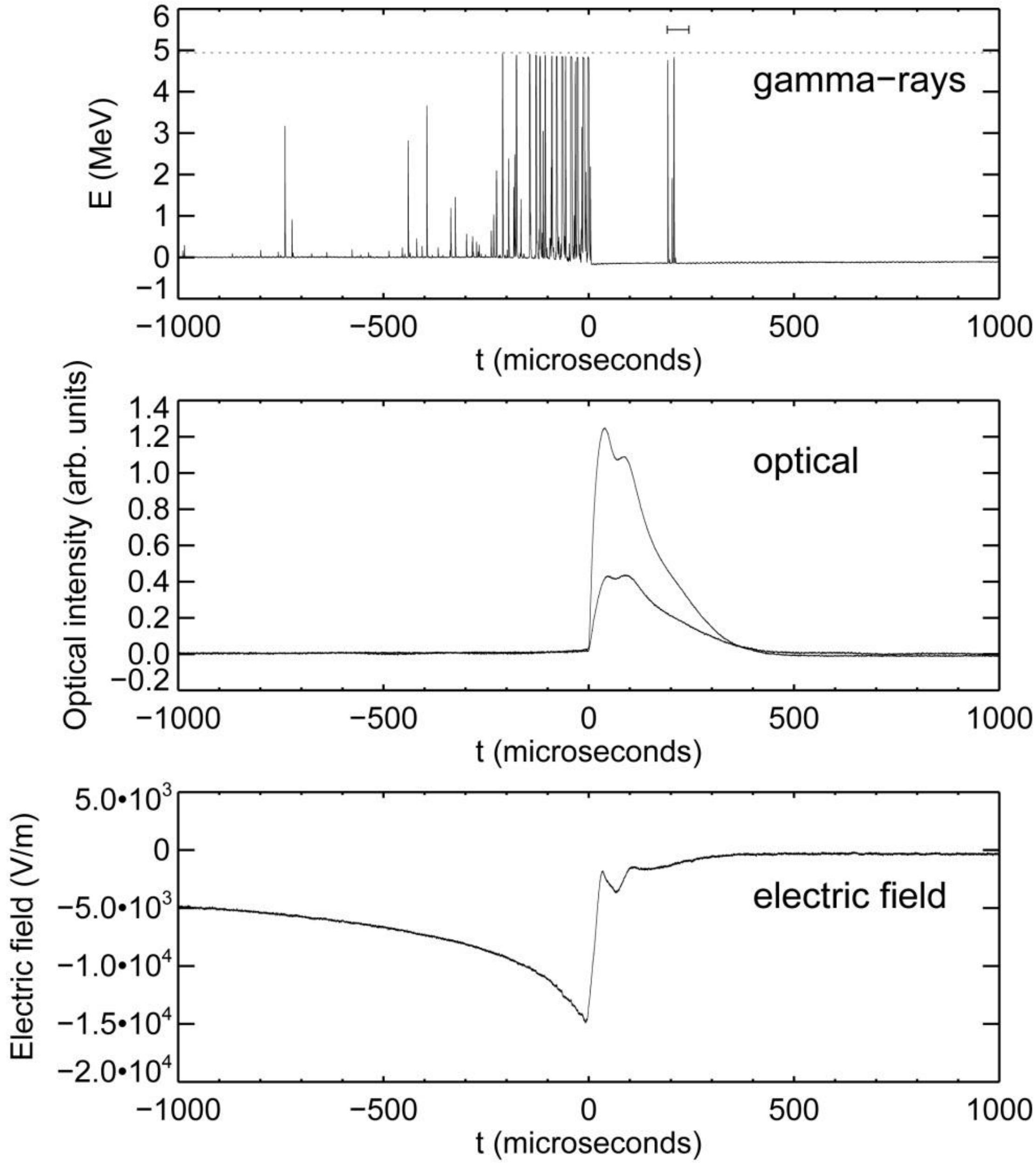


From Dwyer et al. (2010)

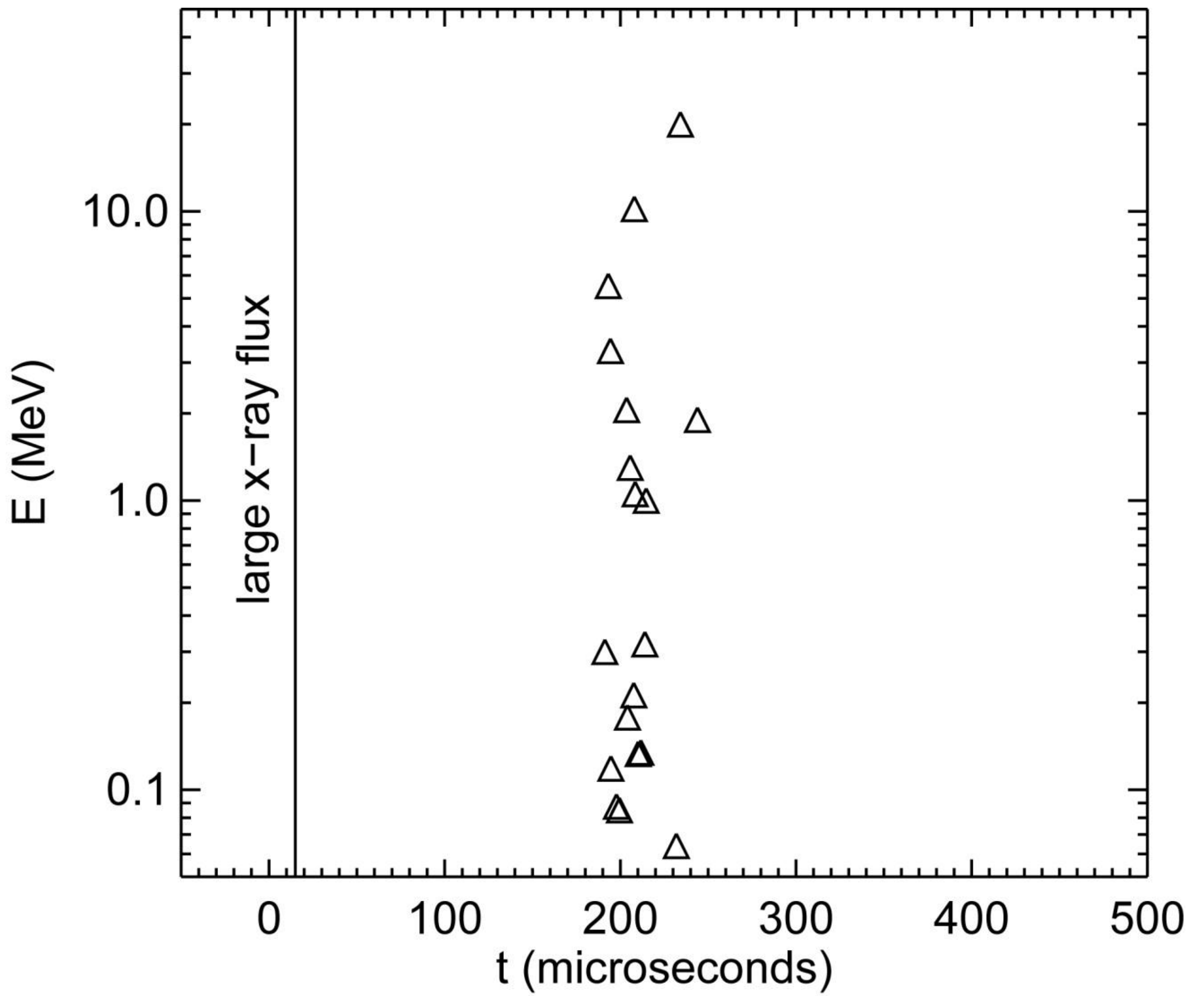
Relativistic feedback discharge model summary
(Dwyer 2012)

- Simulations typically produce TGFs with 10^{17} runaway electrons, exactly the right value.
- Gives the correct TGF energy spectrum as measured by RHESSI.
- Pulses are usually symmetrical (Gaussian) with a width ~200 μsec, similar to real TGFs.
- Predicts a rich variety of phenomena that have much overlap with the observed TGFs, e.g. gives both single and multi-pulsed TGFs with correct pulse spacing and morphology.
- Current moments for both the causative lightning and the TGF agree with Duke observations, i.e. TGF occurs at the right place and time.
- The runaway electrons and resulting ionization during a TGF can produce very largest current pulses that might be mistaken for lightning.
- An inverted discharge could produce a “positron” TGF with a very high energy power law gamma-ray spectrum.

New ground level TGF observed at the ICLRT at Camp Blanding, FL (Dwyer *et al*. 2012)



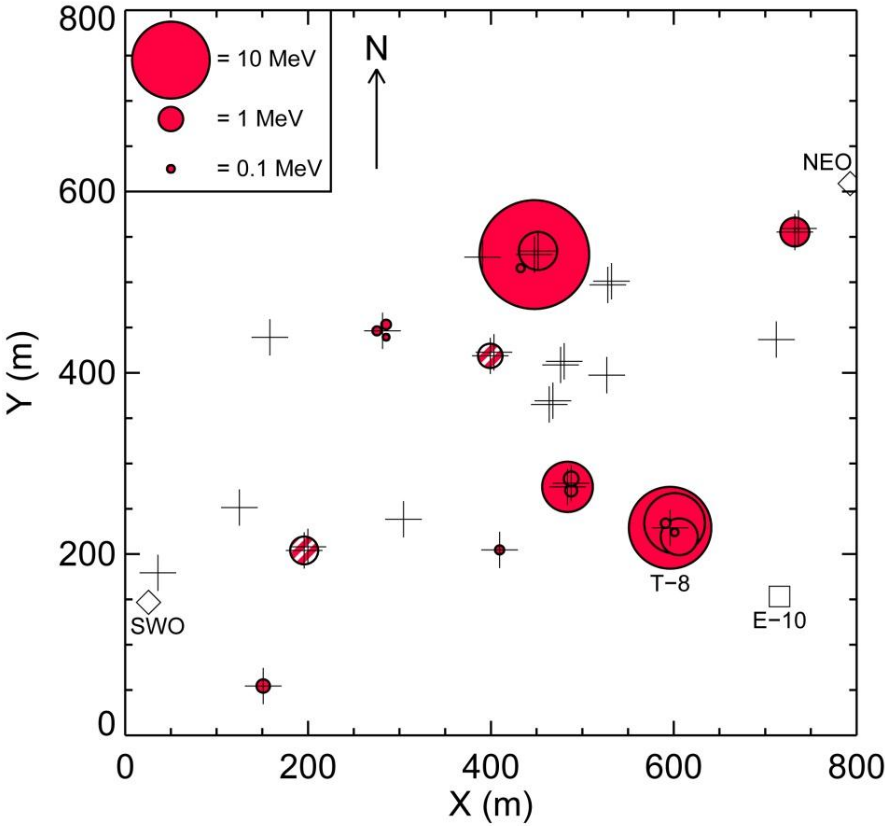
Energy versus time for ground level TGF



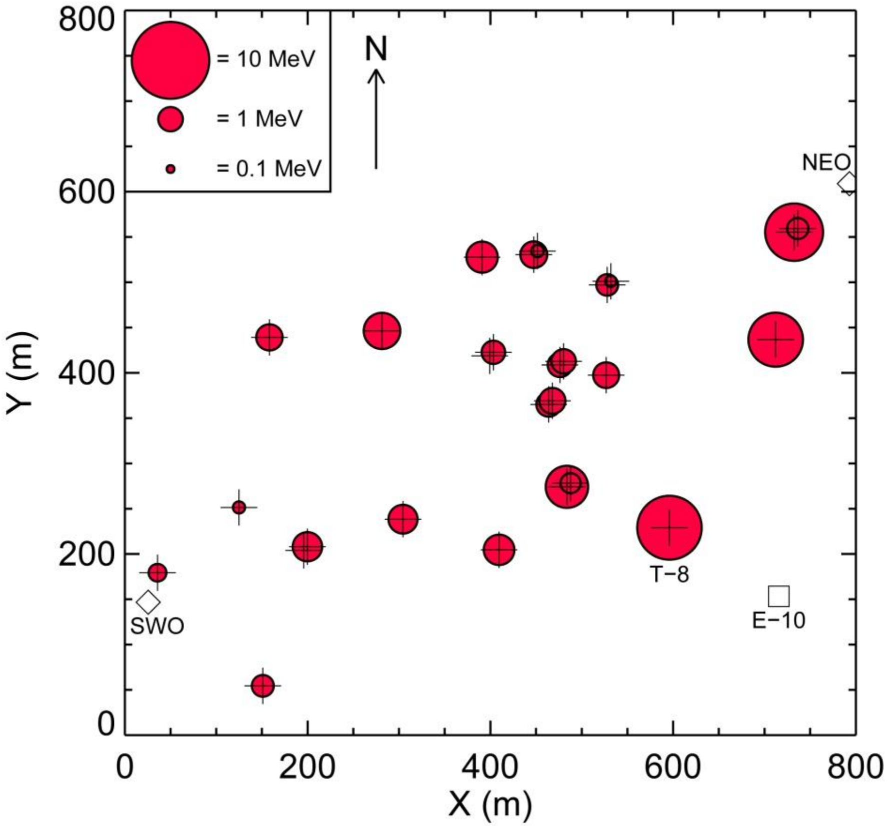
(Dwyer *et al*. 2012)

Spatial distribution of ground level TGF compared with x-rays from lightning

Ground level TGF

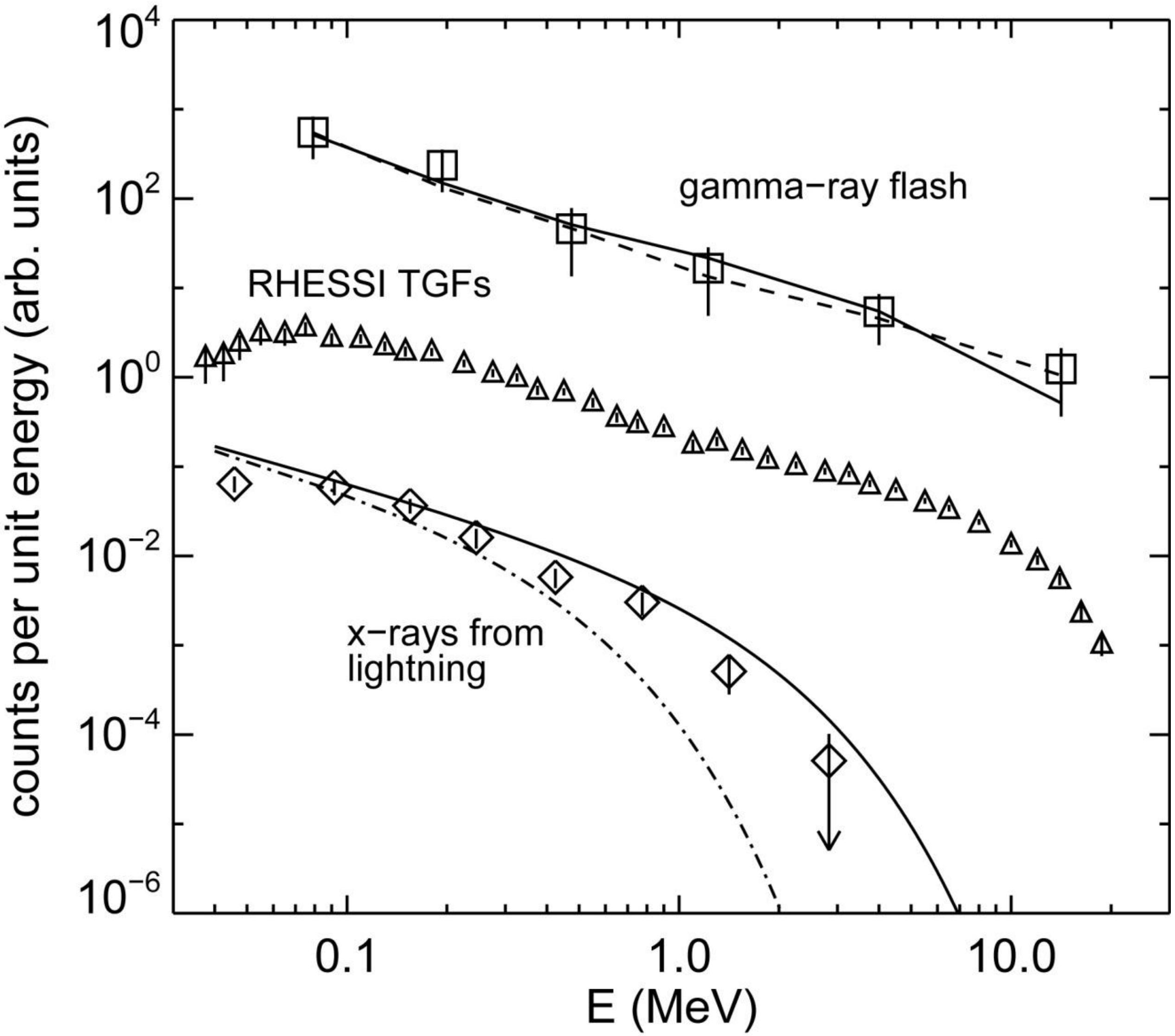


X-rays from lightning



(Dwyer *et al*. 2012)

Energy spectrum of ground level TGF



(Dwyer *et al*. 2012)

Summary

- The relativistic feedback discharge model is able to explain many observed features of TGFs.
- Qualitatively, the lightning leader model can also explain some features of TGFs.
- It is possible that TGFs are produce by both mechanisms.
- However, even if TGFs are produced by lightning leaders, the limits on the electric field resulting from relativistic feedback still need to be taken into account.
- A new ground level TGF was seen at the ICLRT during a CG return stroke. More modeling is needed to understand this event.