Downward Terrestrial Gamma Flashes Observed at the Telescope Array Surface Detector

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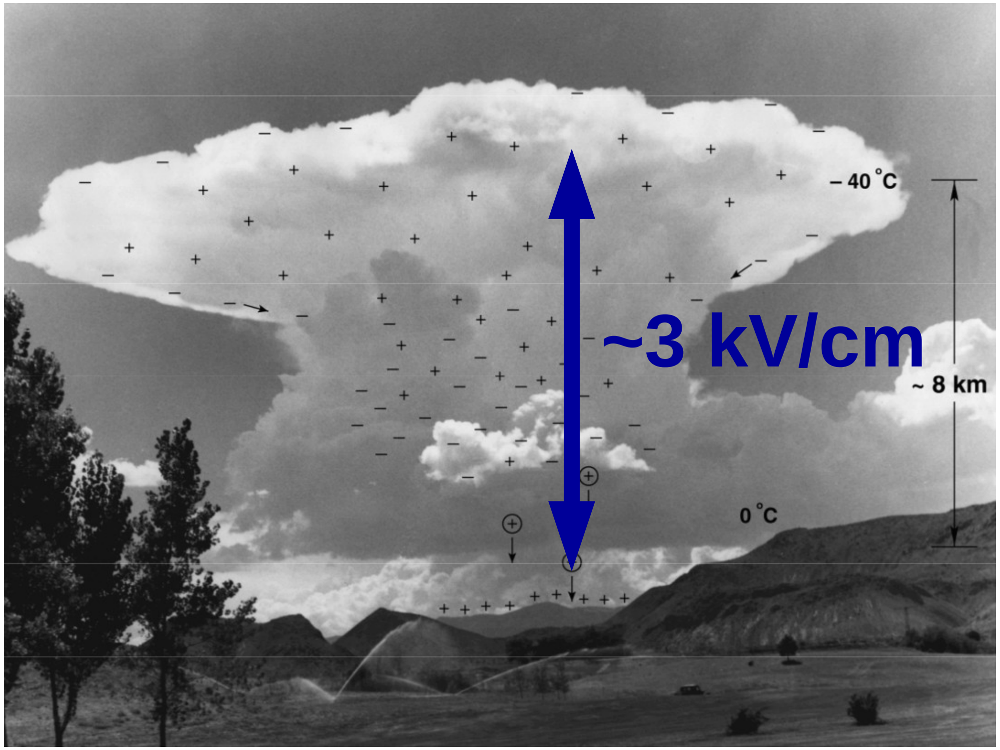
20180215

Unknowns In Lightning Production

- “When we consider how much we know about complex and exotic astrophysical objects half way across the universe, it is quite amazing that we do not understand the basics of how something as common as lightning gets started in clouds just a few miles above our heads.”
  - Dwyer & Uman, *Physics Reports* (2014)

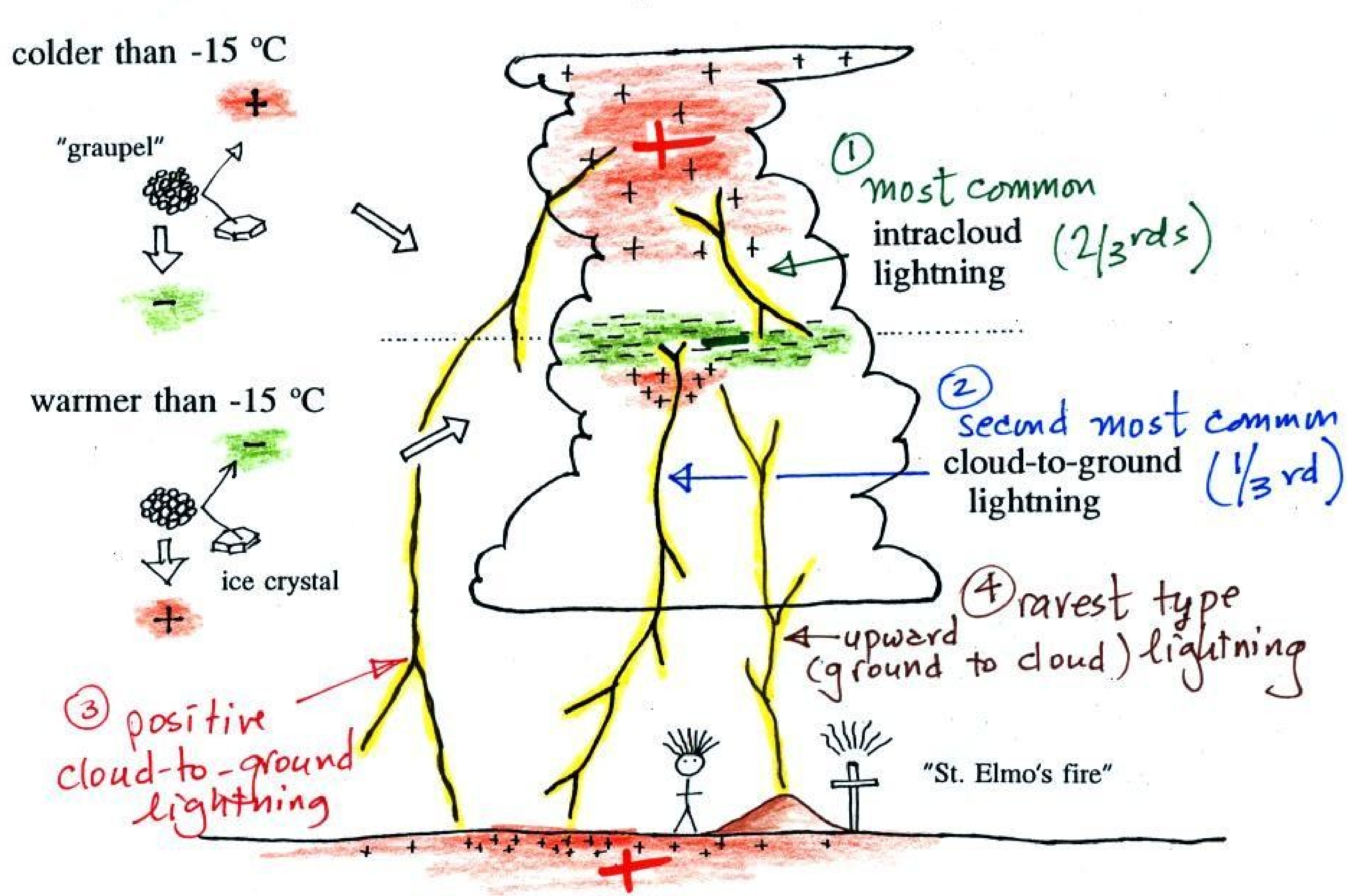
- **Basic Problem: Measured fields consistently too low by an order of magnitude.**

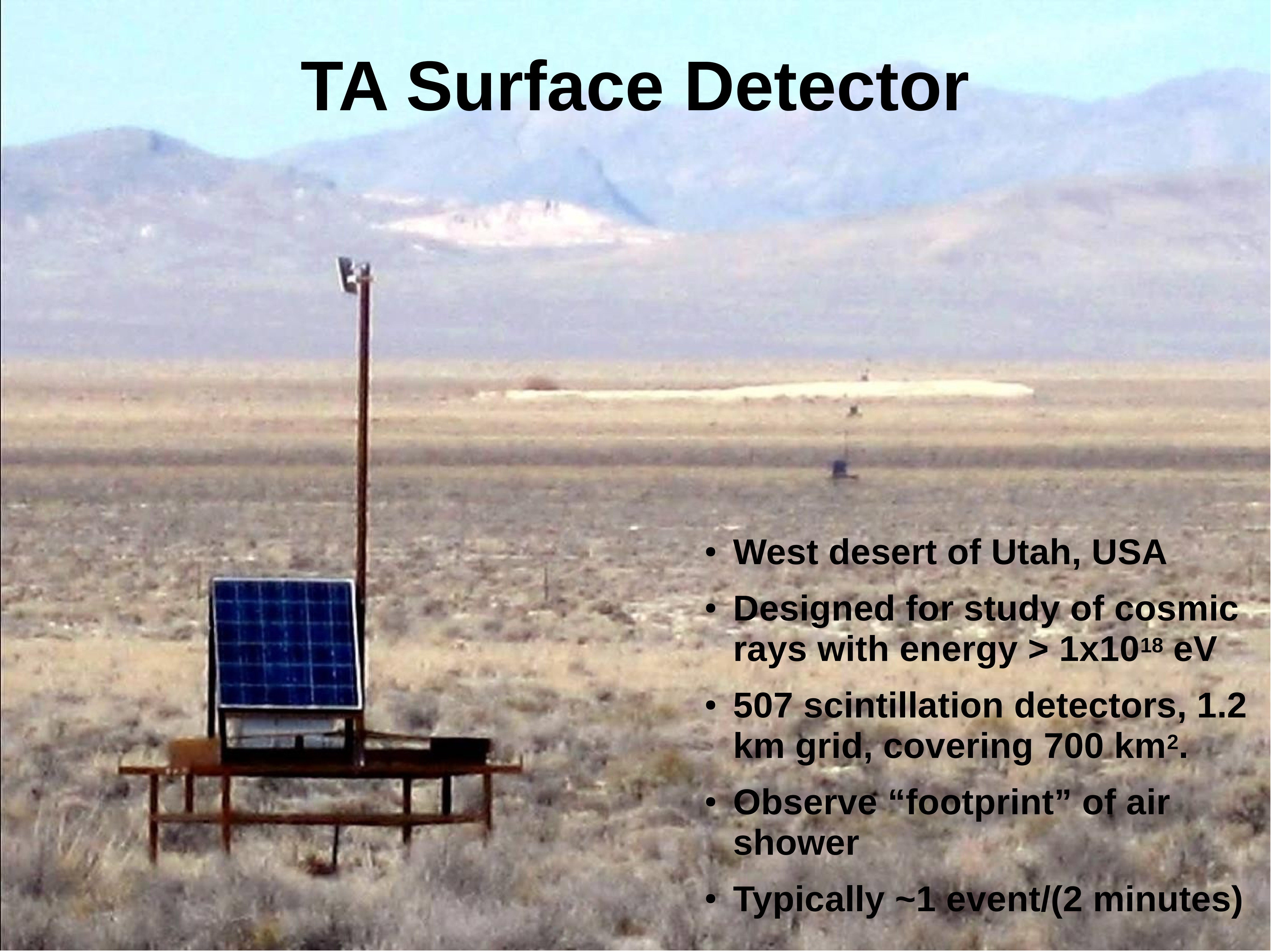
- Solutions
  - Mismeasurement of field?
  - Initiation from water or ice particles?
  - Energetic runaway electrons?



Lightning 101

“Graupel”



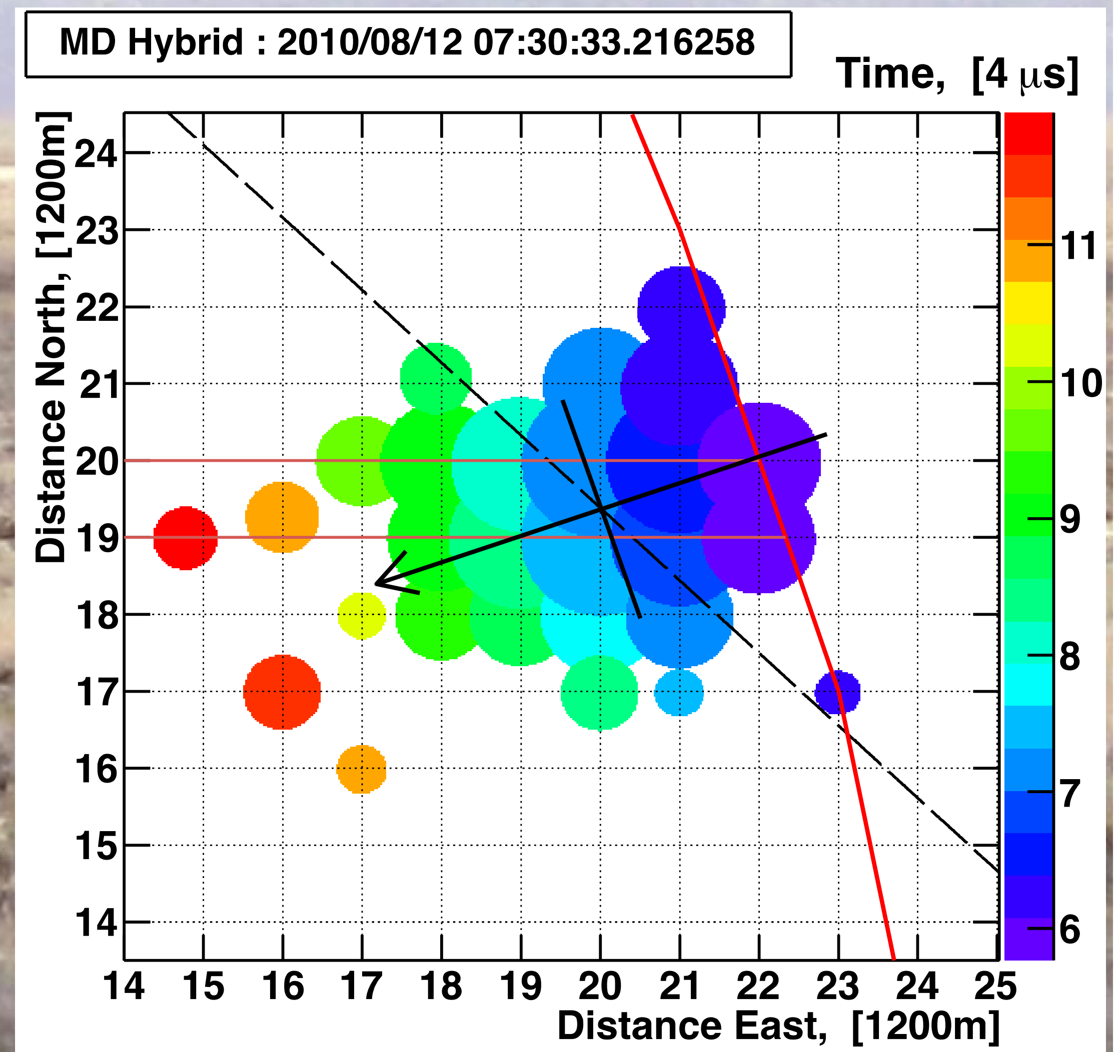


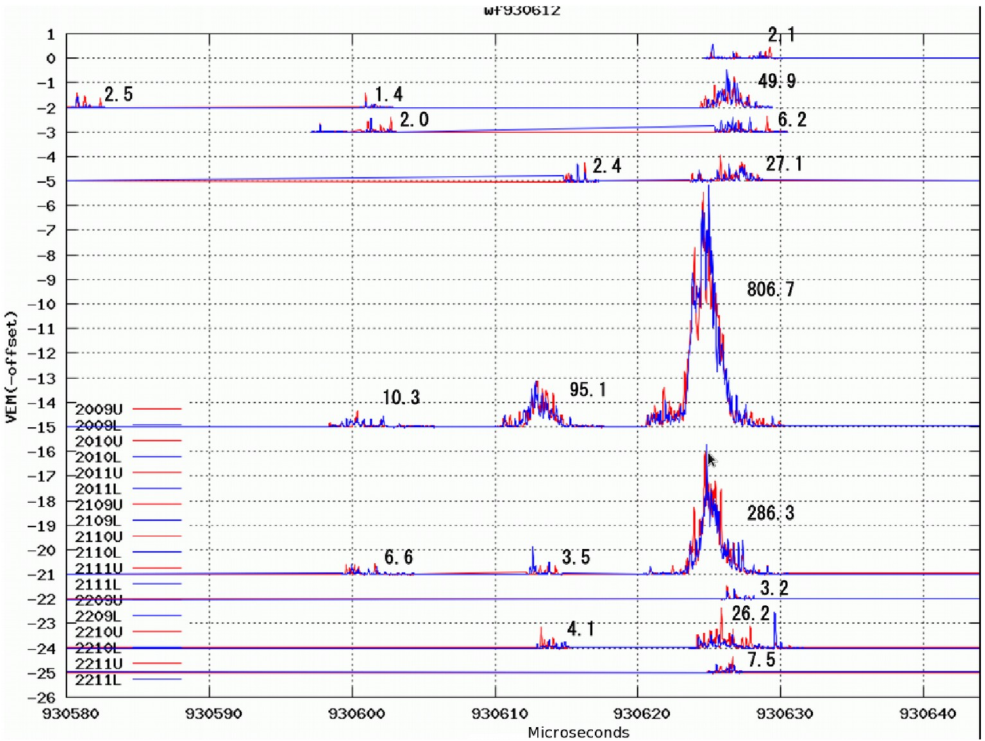
TA Surface Detector

- West desert of Utah, USA
- Designed for study of cosmic rays with energy > $1\text{x}10^{18}$ eV
- 507 scintillation detectors, 1.2 km grid, covering 700 km^2.
- Observe “footprint” of air shower
- Typically ~1 event/(2 minutes)

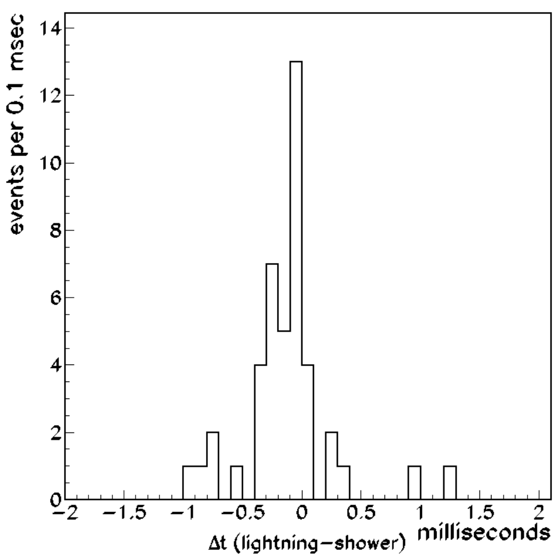
TA Surface Detector

- **E = 1.3 x 10^{20} eV**





Plot: T. Okuda

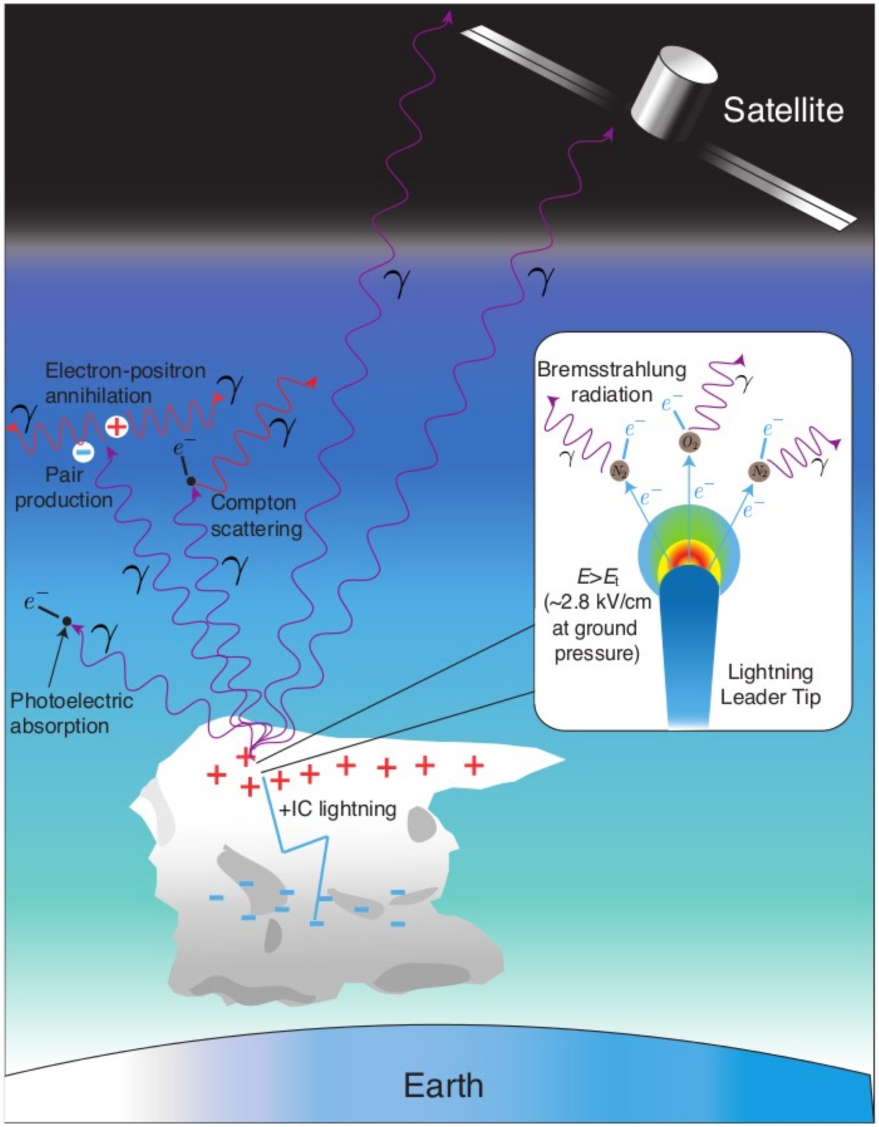


TA Observation: "Burst" Events

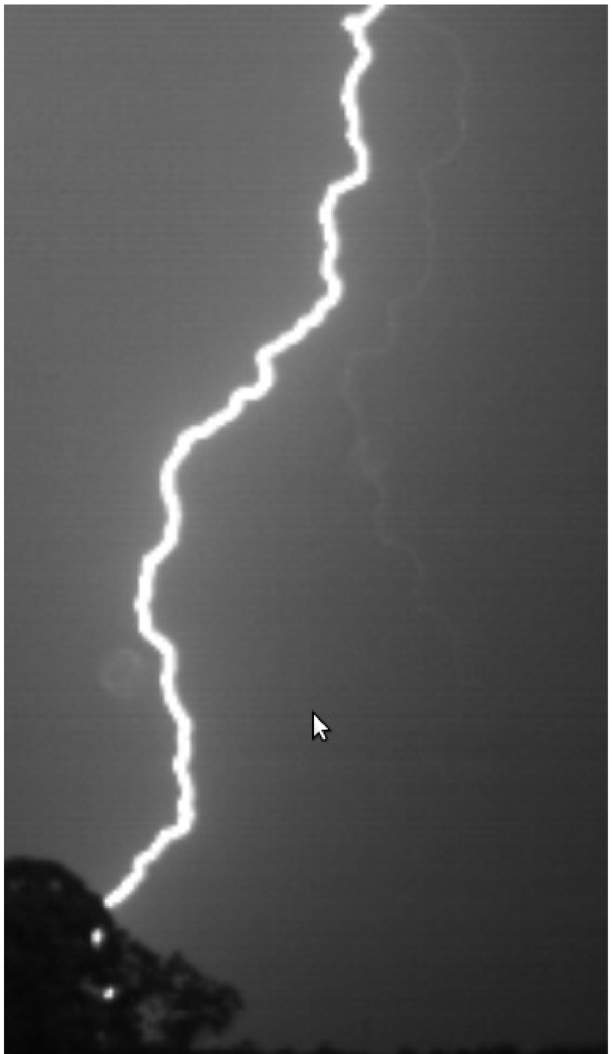
- 5 year data (2008-2013)
- 10 surface detector bursts seen
  - 3 or more SD triggers, $\Delta t < 1$ msec
  - Occasional $\Delta t \sim 10\ \mu$sec
- "Normal" SD trigger rate < 0.01 Hz. *These cannot be cosmic ray air showers*.
- Found to have close time/space coincidence with *U.S. National Lightning Detection Network* (NLDN) activity.
- Abbasi et al. *Phys. Lett.* **A 381** (2017)

Terrestrial Gamma Flashes

- Discovered with BATSE (CGRO) 1992
  - Assumed to arise from sprites
  - Now known to be associated with leader stage in intracloud discharges
- RHESSI (>2002) 805 TGFs
- Fermi Gamma Burst Monitor
- AGILE
- **Duration: 100 μsec → 1 msec**
- **Flux: estimates between 10^{12} → 10^{19} gammas above 100 keV. (Really!)**



Downward Leaders Followed by Cloud-to-Ground Stroke

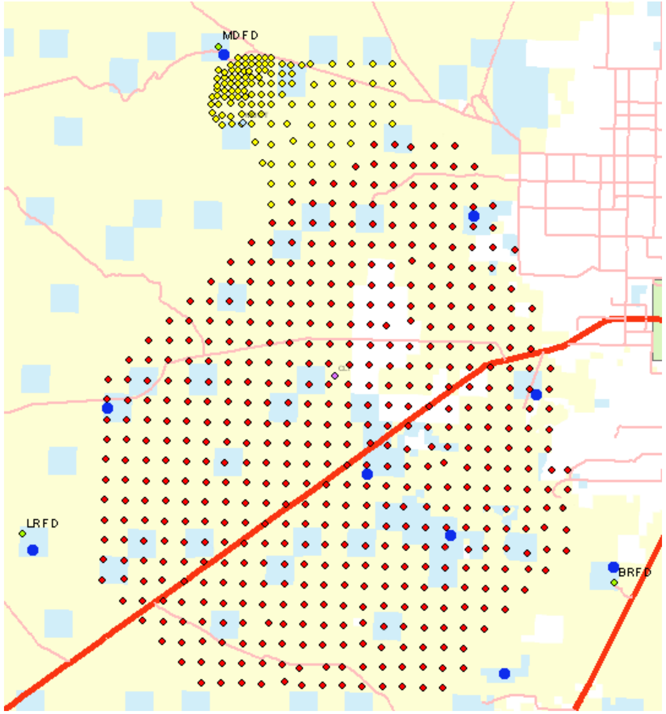


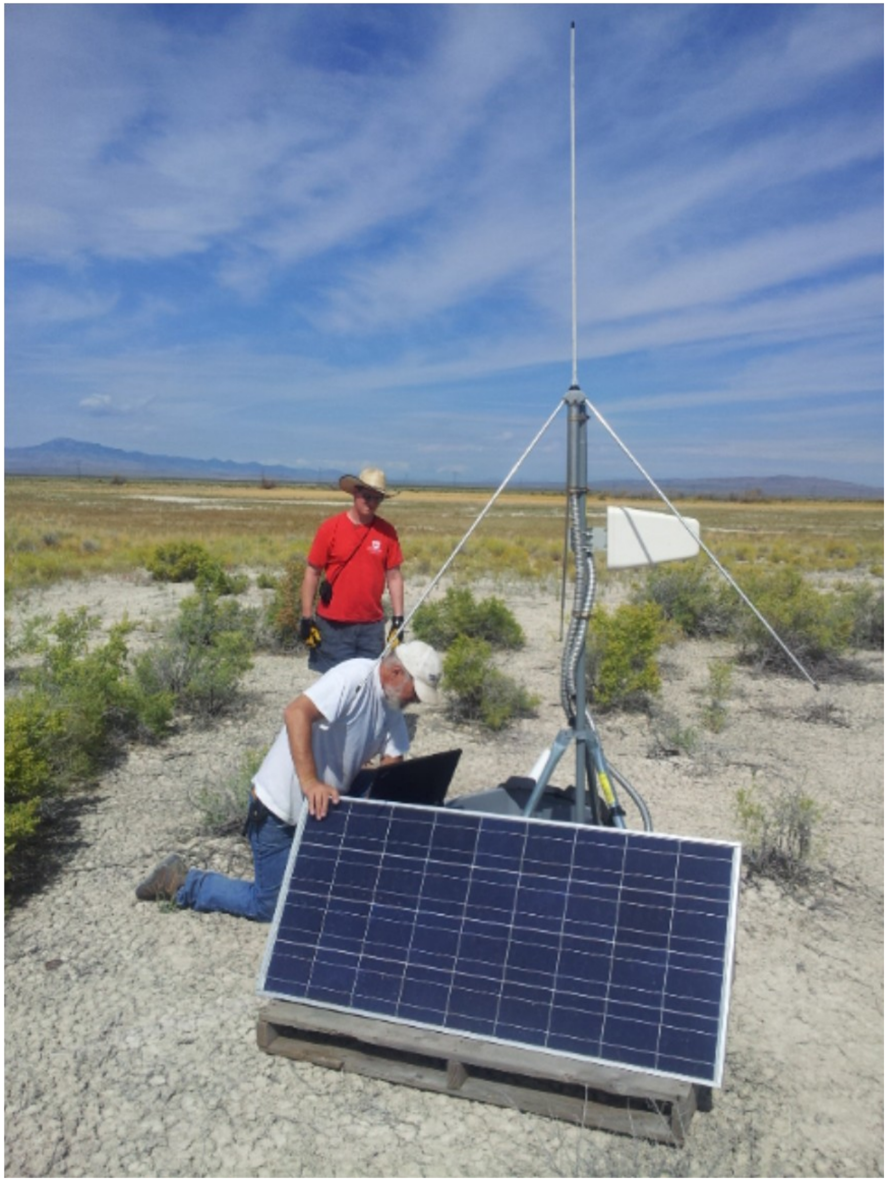
http://www.lightningsafety.noaa.gov/

- “Leaders” precede main flash.
- Responsible for current-carrying channel which is followed by flash.
- High potential gradients in ***upward*** leaders responsible for *Terrestrial Gamma Flashes* (TGFs)
- Probe of initial breakdown?

TA/LMA

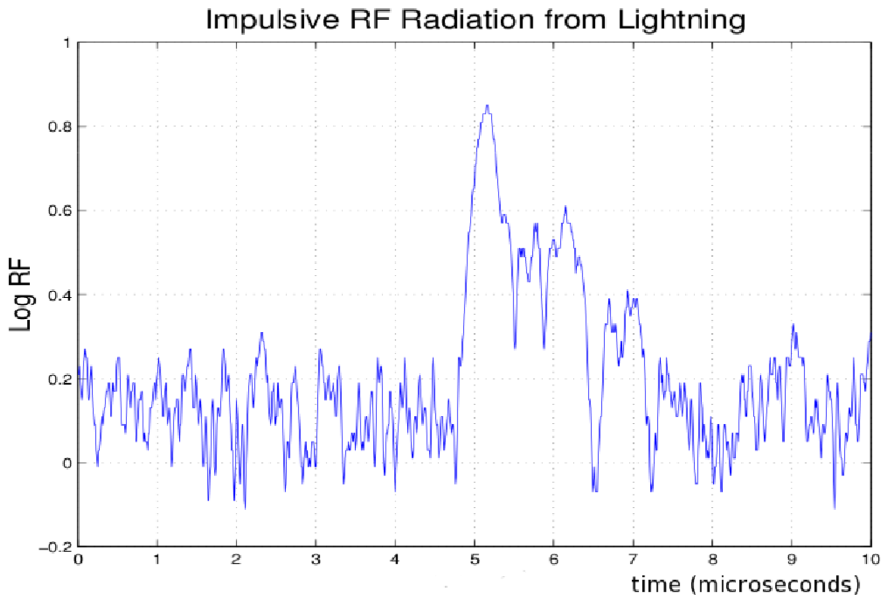
- 10/2013 – Installation
- 10/2013-08/2015 – Unstable operation. Only decimated data available for most detectors.
- 08/2015 – Visit, upgrade detector sites
- 08/2015-present – Optimal detector operation (see e.g. http://lightning.nmt.edu/talma)
- 04/2016 – Support awarded by US-NSF *Atmospheric and Geospace Sciences*



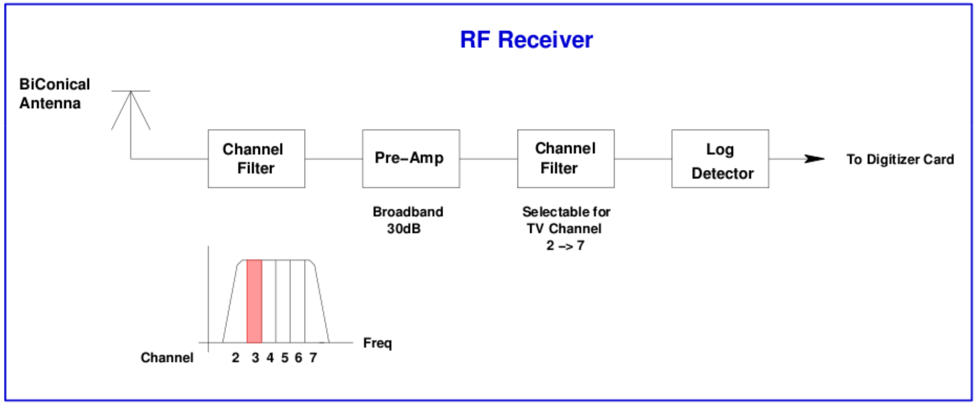


W. Hanlon (UU), W. Rison (NMTech)

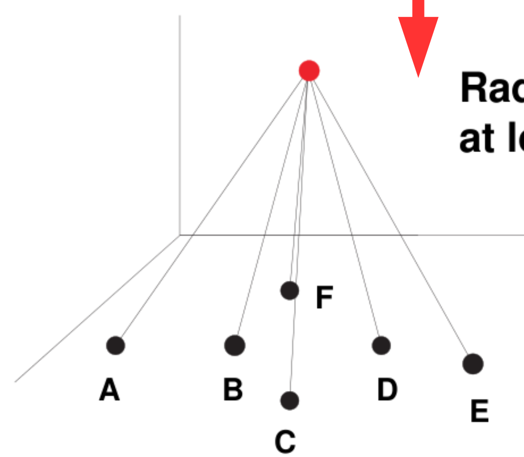
How is Lightning Mapped?



Impulsive radiation



VHF Receiver

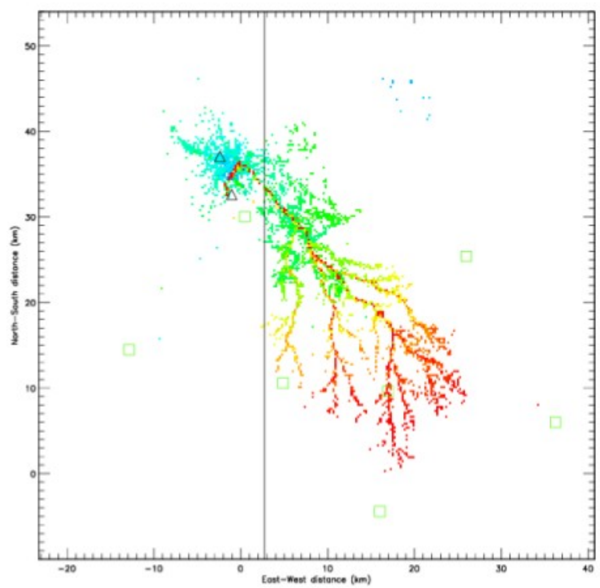


Radiation occurs at time t, at location (x, y, z)

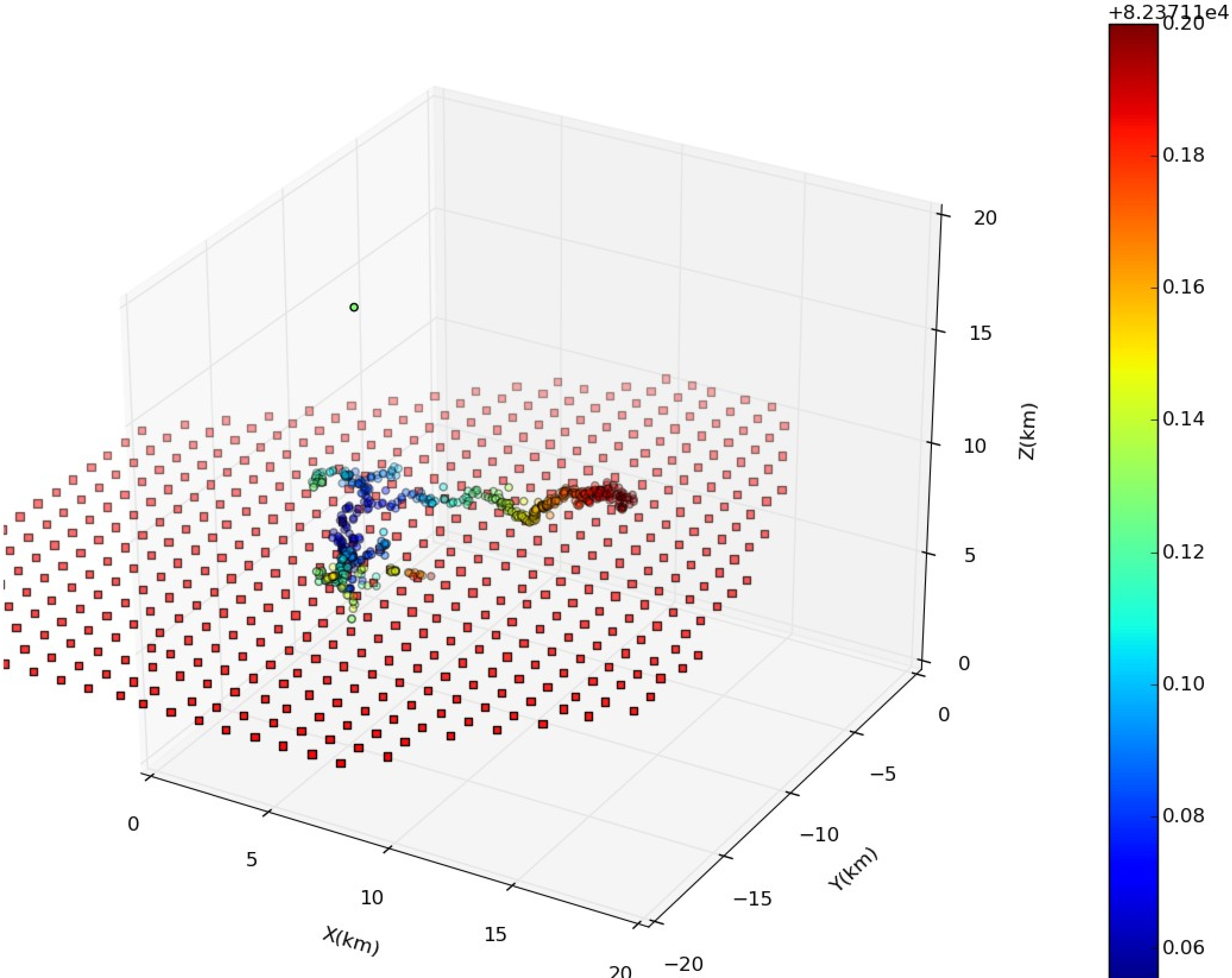
Radiation arrives at station i at time t_i, location (x_i, y_i, z_i)

$$t_i = t + \frac{\sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}}{c}$$

Fit to source x,y,z,t (offline)

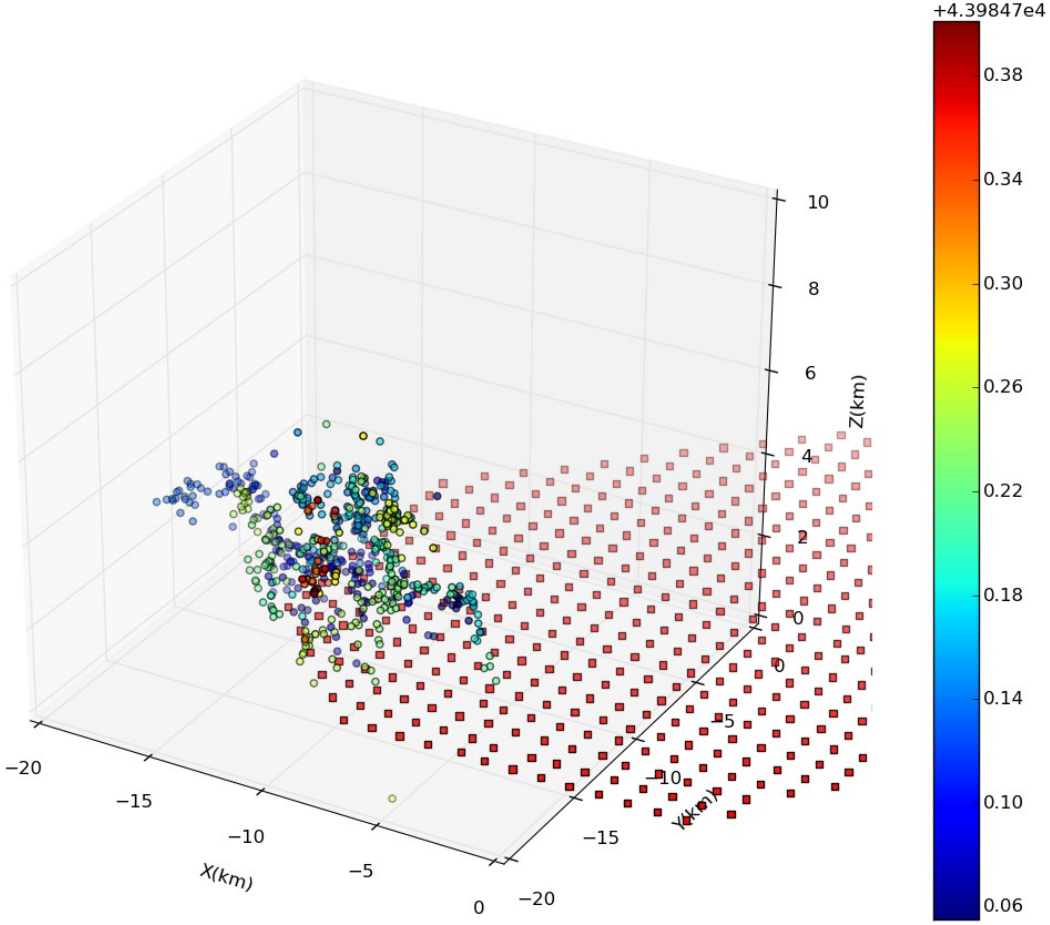


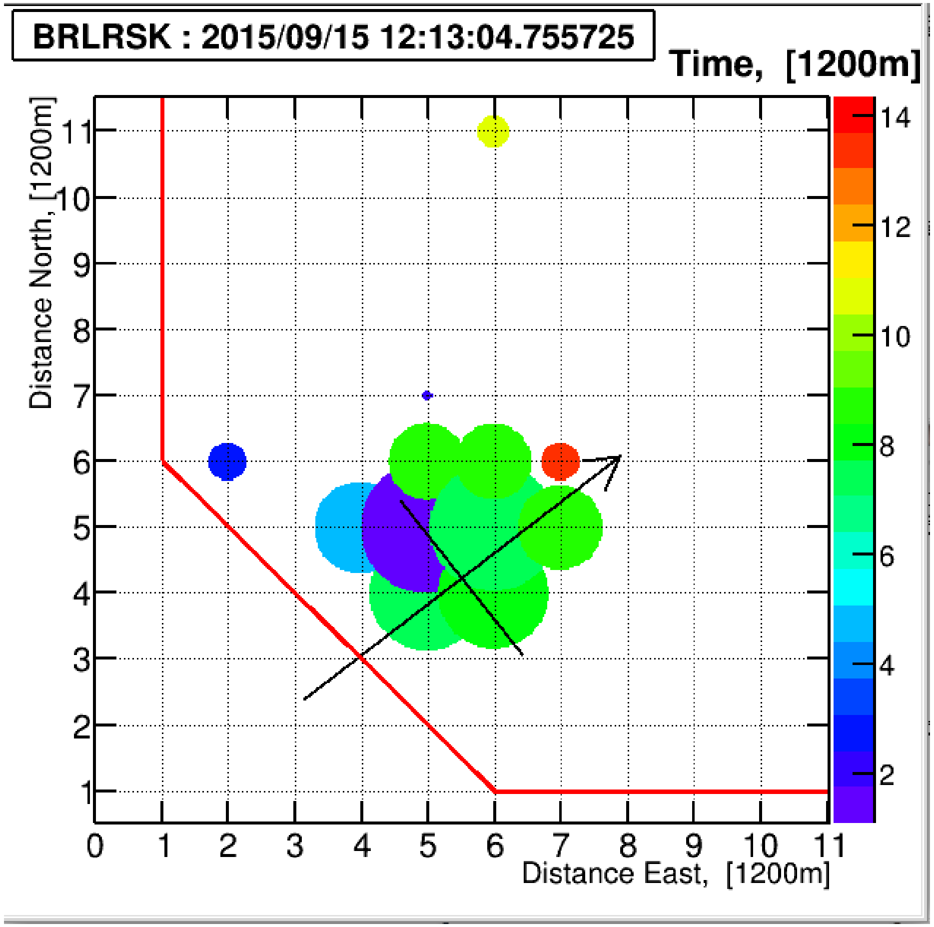
Combine to form map



X(km)
Y(km)
Z(km)
0
5
10
15
20
−5
−10
−15
−20
+8.23711e4
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06

TA/LMA Event 20150915-121304





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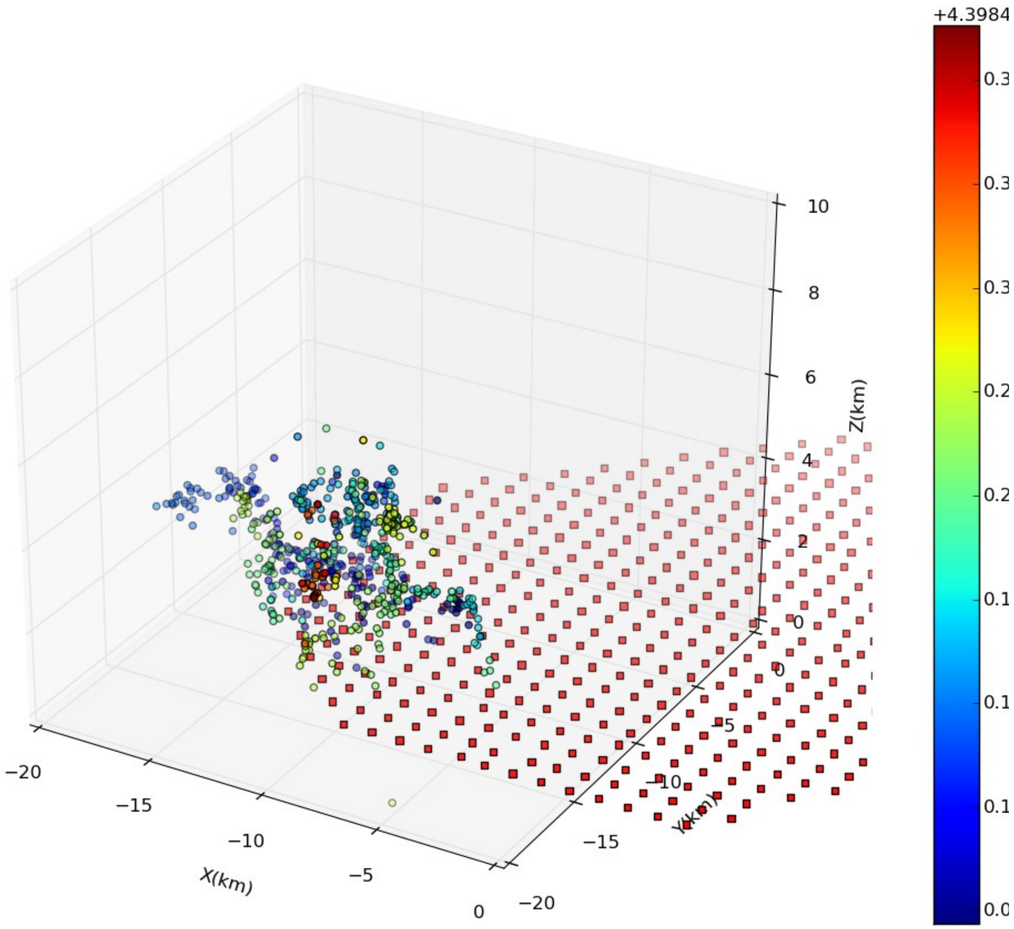
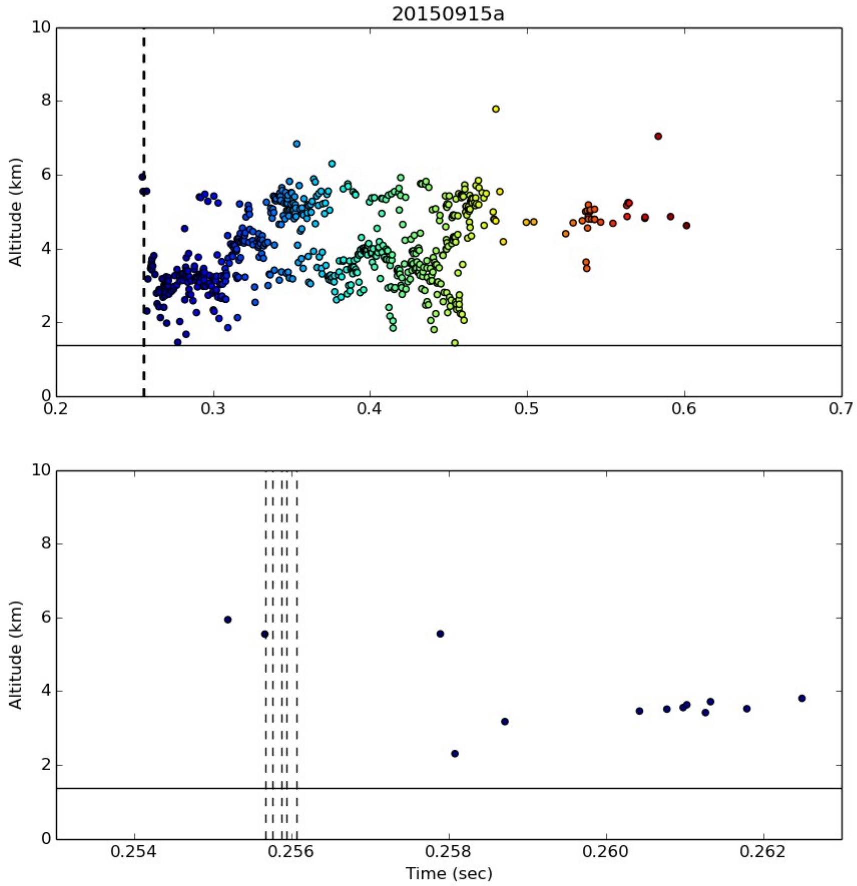
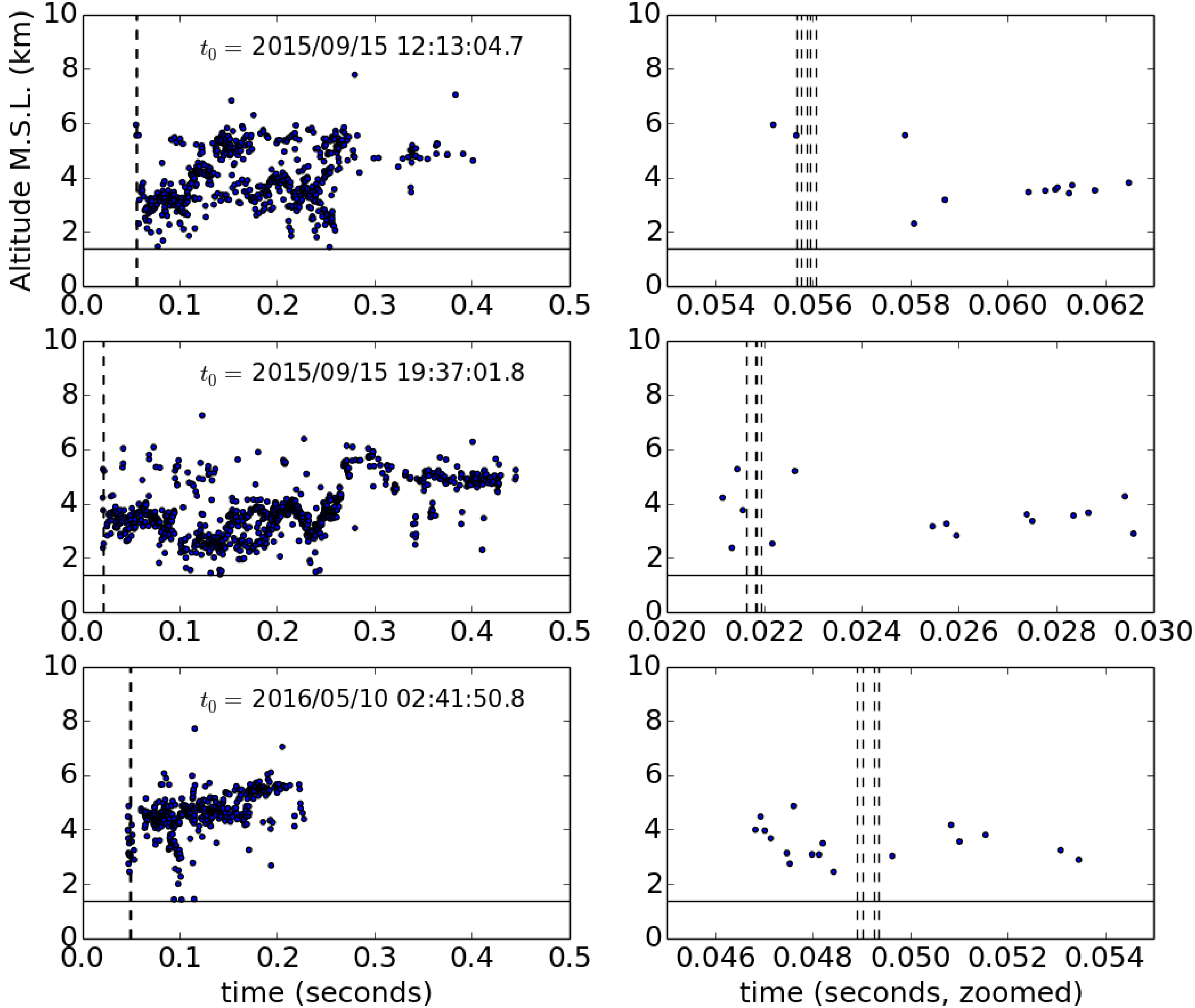




Dashed lines: TASD triggers

3 SD Bursts with Lightning Mapping Array



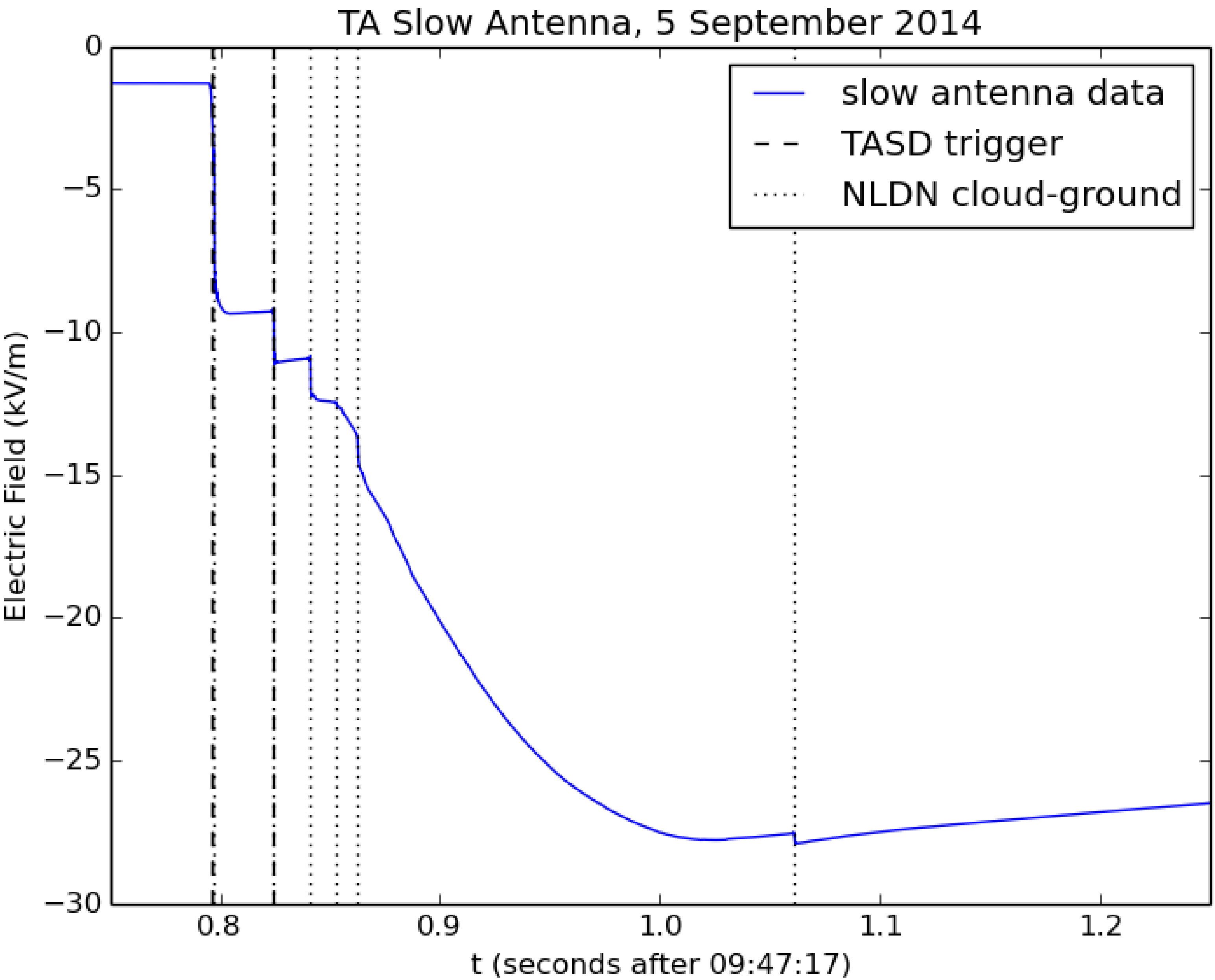
The "Slow Antenna"

- GPS-timed capacitor, read out with 4 s time constant.
- Record electric field
- (vs Fast antenna; RC ~ 50 μsec)

Active element; RC ~ 4 seconds

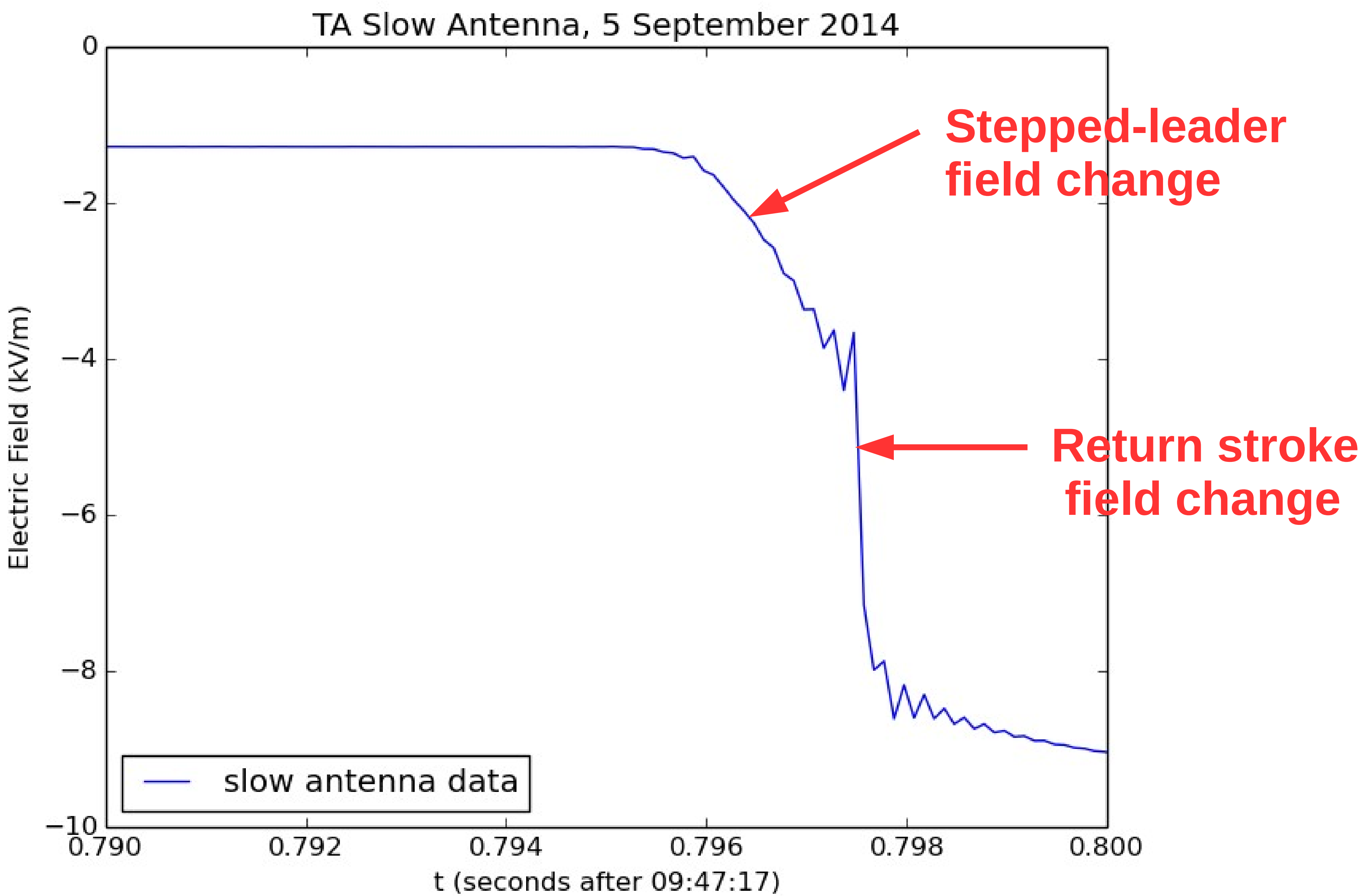
System Maintenance

SD Trigger Burst 20140905

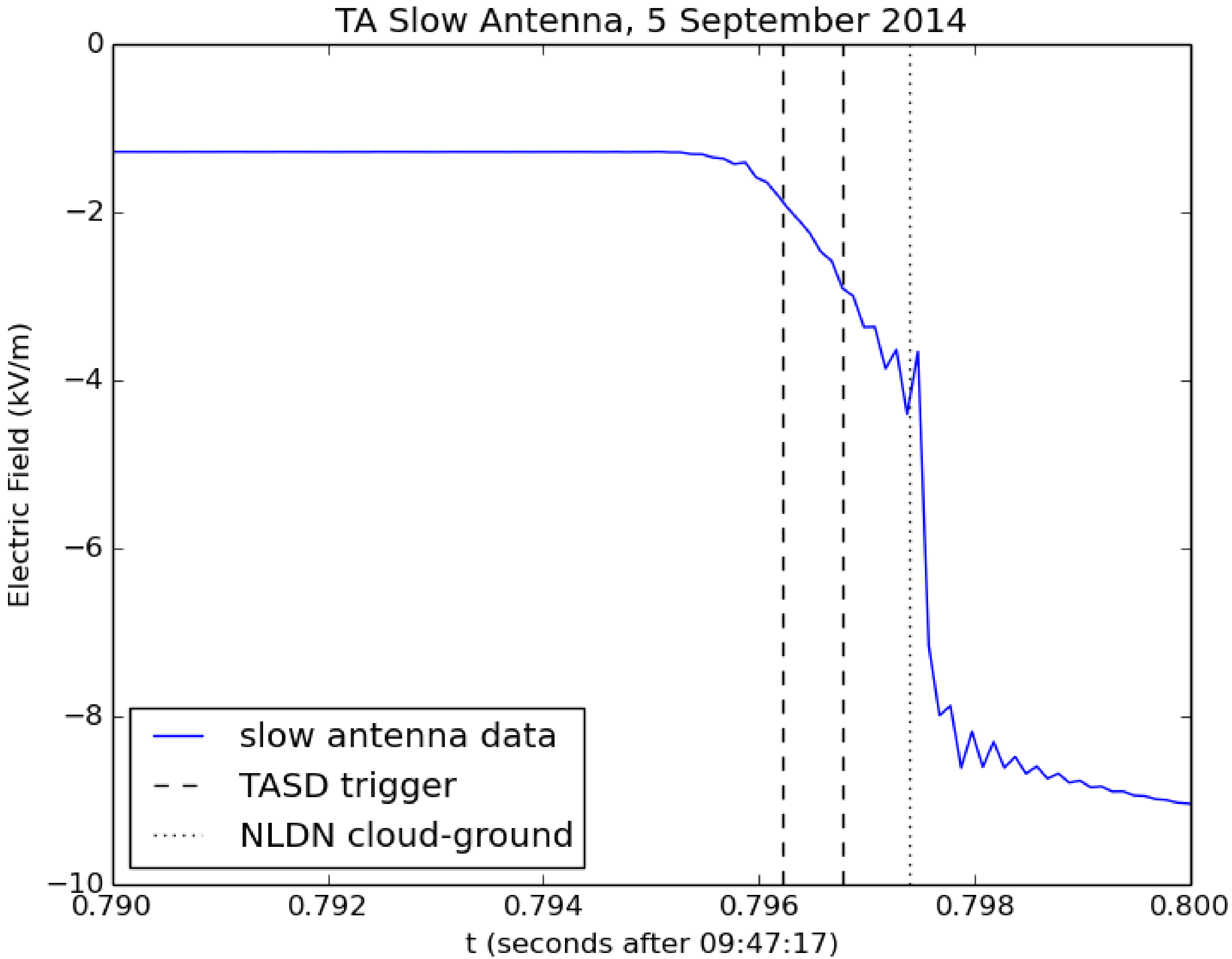


SD Trigger Burst 20140905

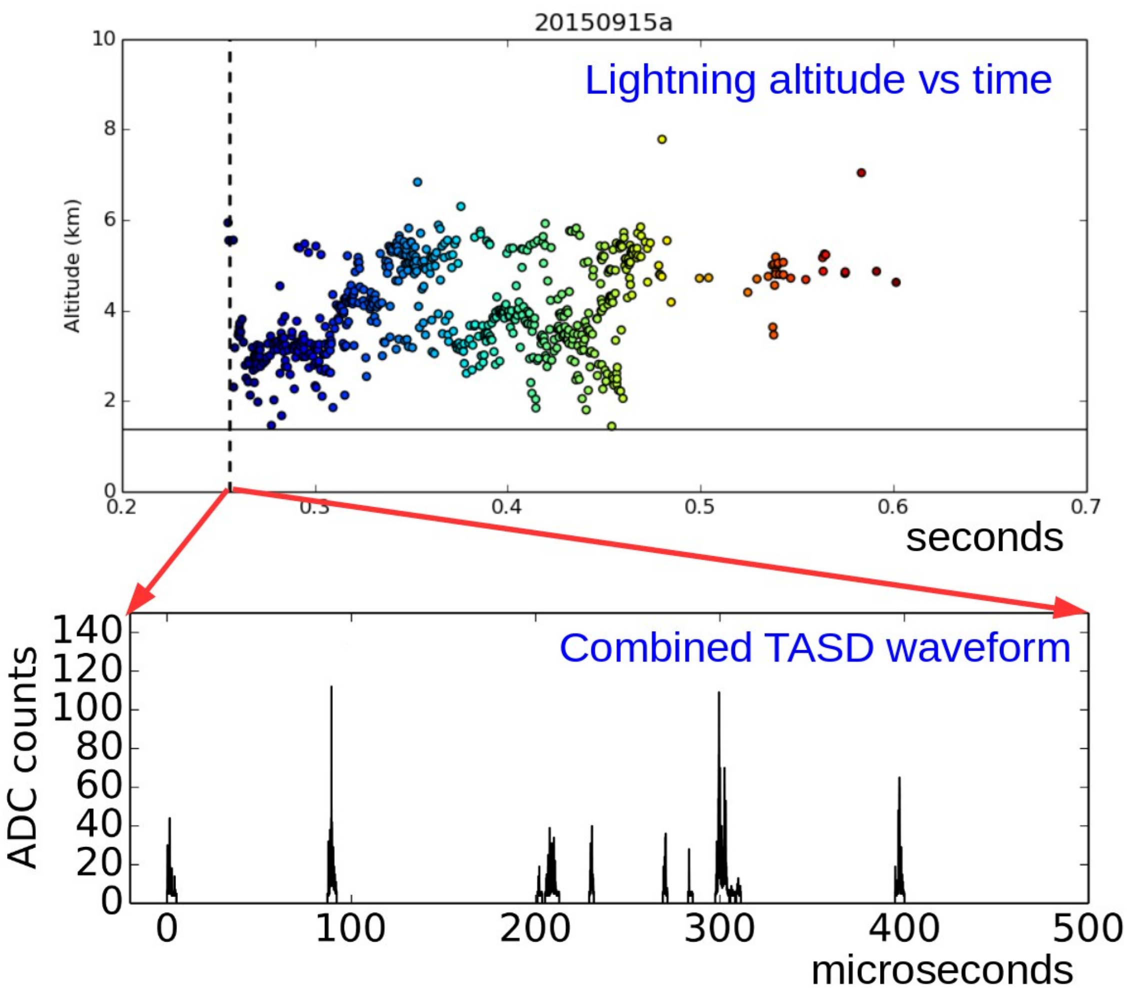
(first discharge)



SD Trigger Burst 20140905
(first discharge)



Are we seeing downward TGFs?



- Showers are gamma radiation: Overall size and nature of energy deposit in scintillator
- Overall duration of SD bursts comparable to observed TGF Δt
- Discrete subevents from few to few 10's of μsec.
  - We're viewing sources from ~1/100th the distance
  - Before Compton "smearing"
- Sources on "low end" of TGF estimates
  - Would be below satellite triggering threshold!

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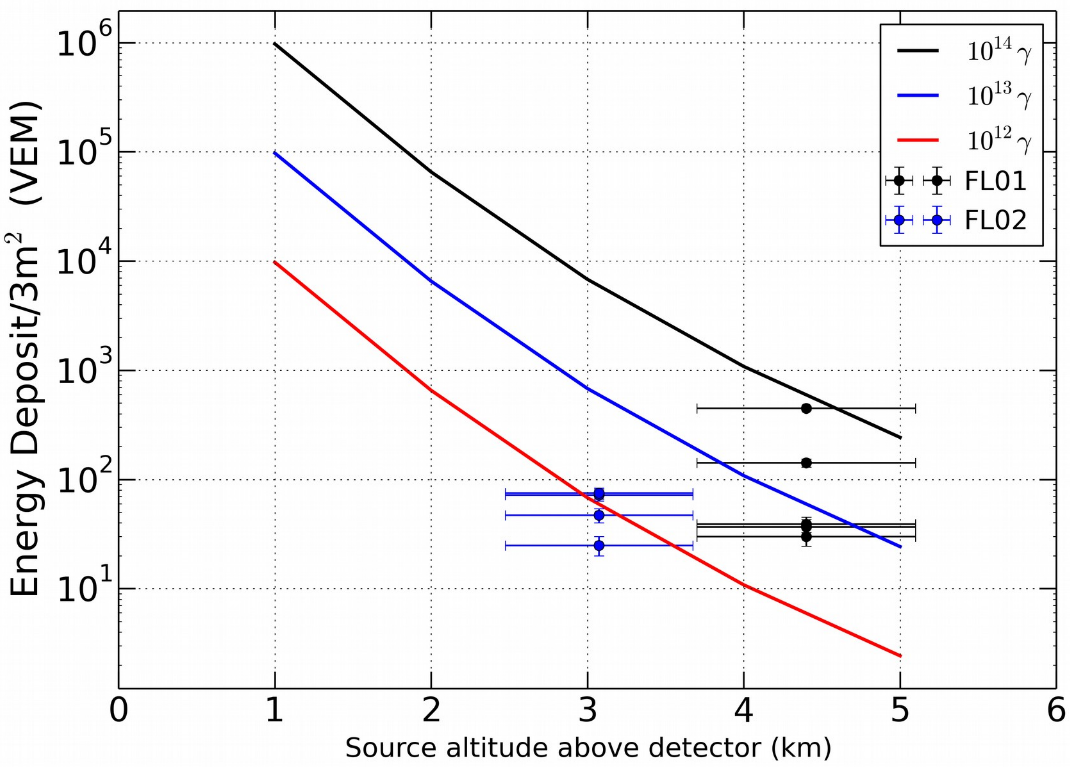

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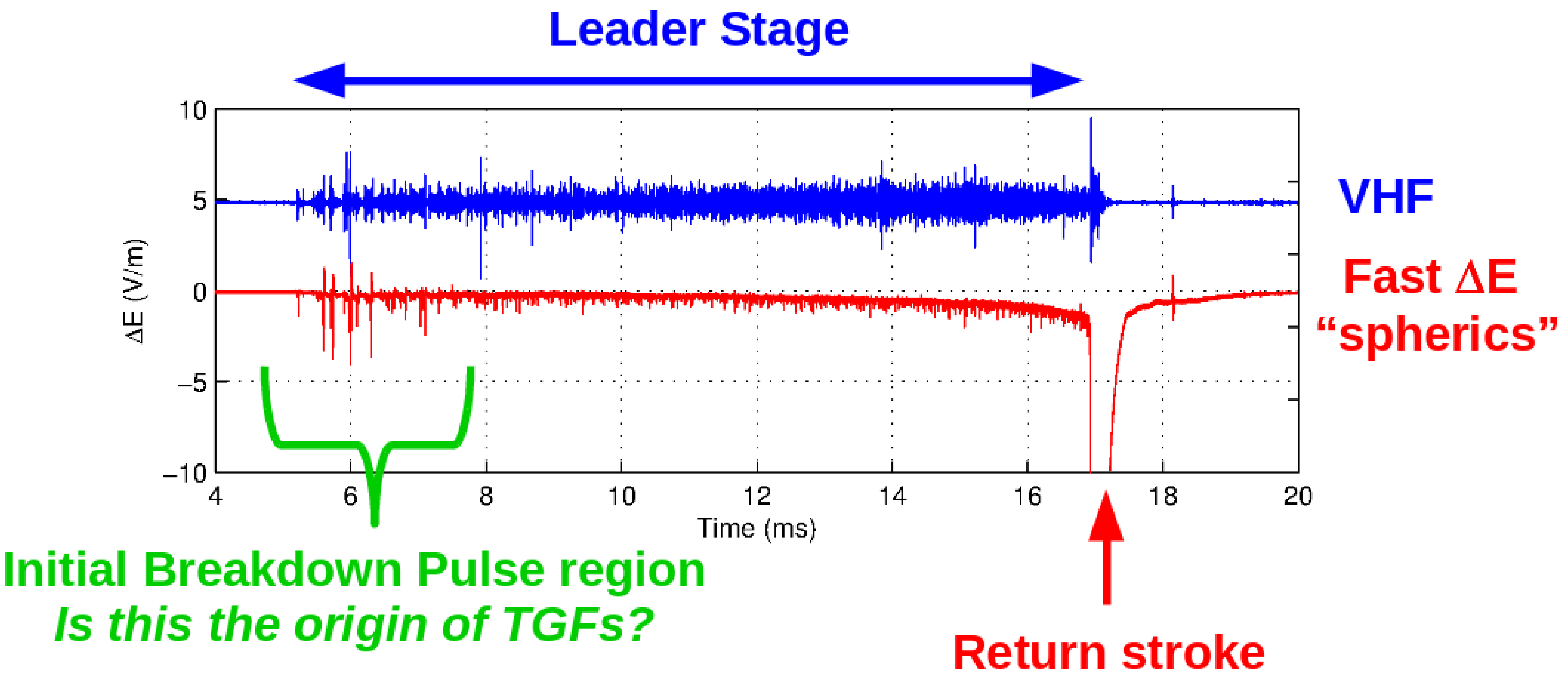
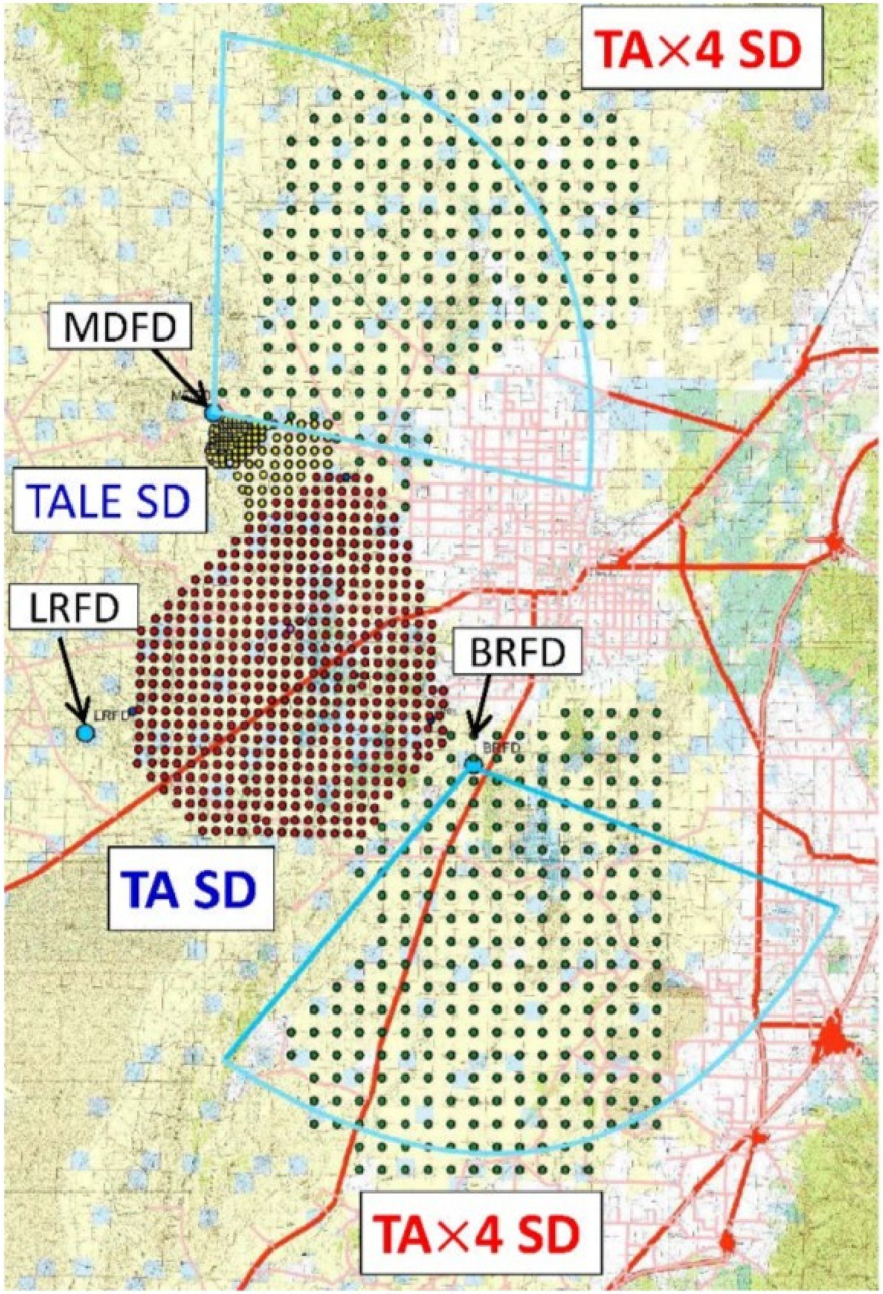
What's next?

Lightning flash recorded in New Mexico, associated with *fast positive breakdown* before -CG stroke



TA x 4 Project

- Quadruple TA SD (~3,000 km^2)
  - + 500 scintillator detectors
  - 2.08 km grid
- 2 new FD stations
- Funding
  - SD (Japan) Approved Summer 2015
  - FD (US) Approved Summer 2016
- Construction underway!

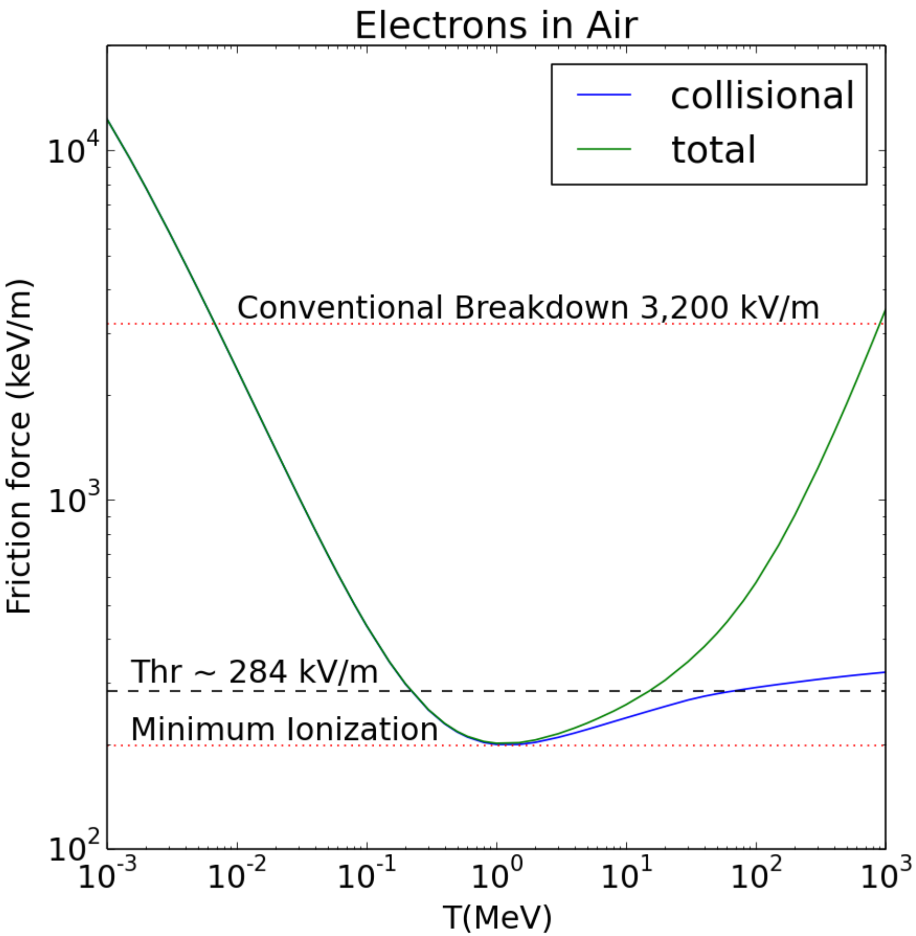


Summary

- Paying close attention to your data can lead to interesting surprises!
- TA/LMA in full operation since August 2015.
- Multiple events recorded in which TASD “trigger bursts” are coincident with LMA or slow antenna activity.
- Are we seeing downward TGF's?
  - Gamma radiation: Y
  - Lightning leaders: Y
  - Duration: Y
  - Some differences explained by proximity to sources… *Better than satellite measurements!*
- Insight into the lightning breakdown mechanism
- Paper submitted to *J. Geophys. Res.;* arXiv:1705.06258

Backup

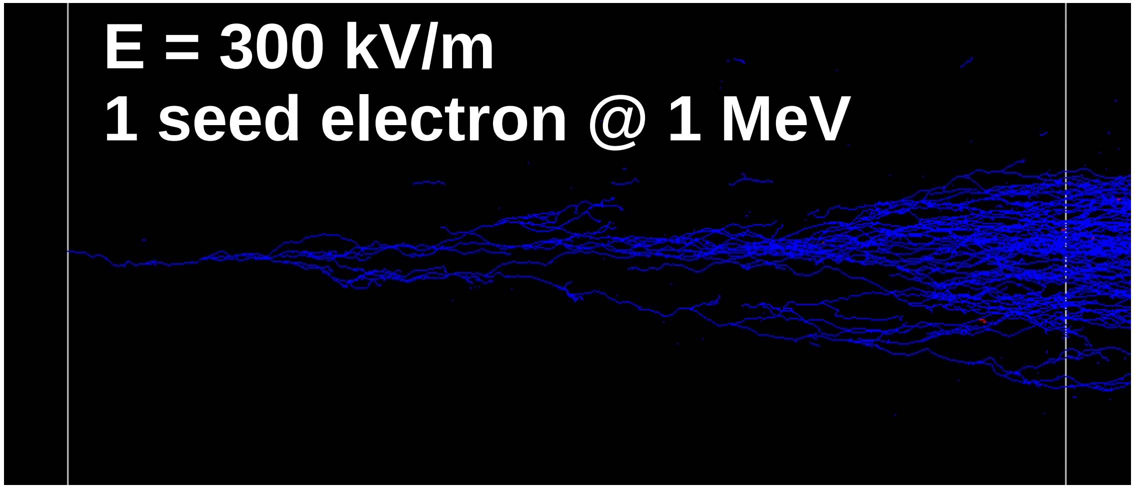
Relativistic Runaway Electron Avalanche



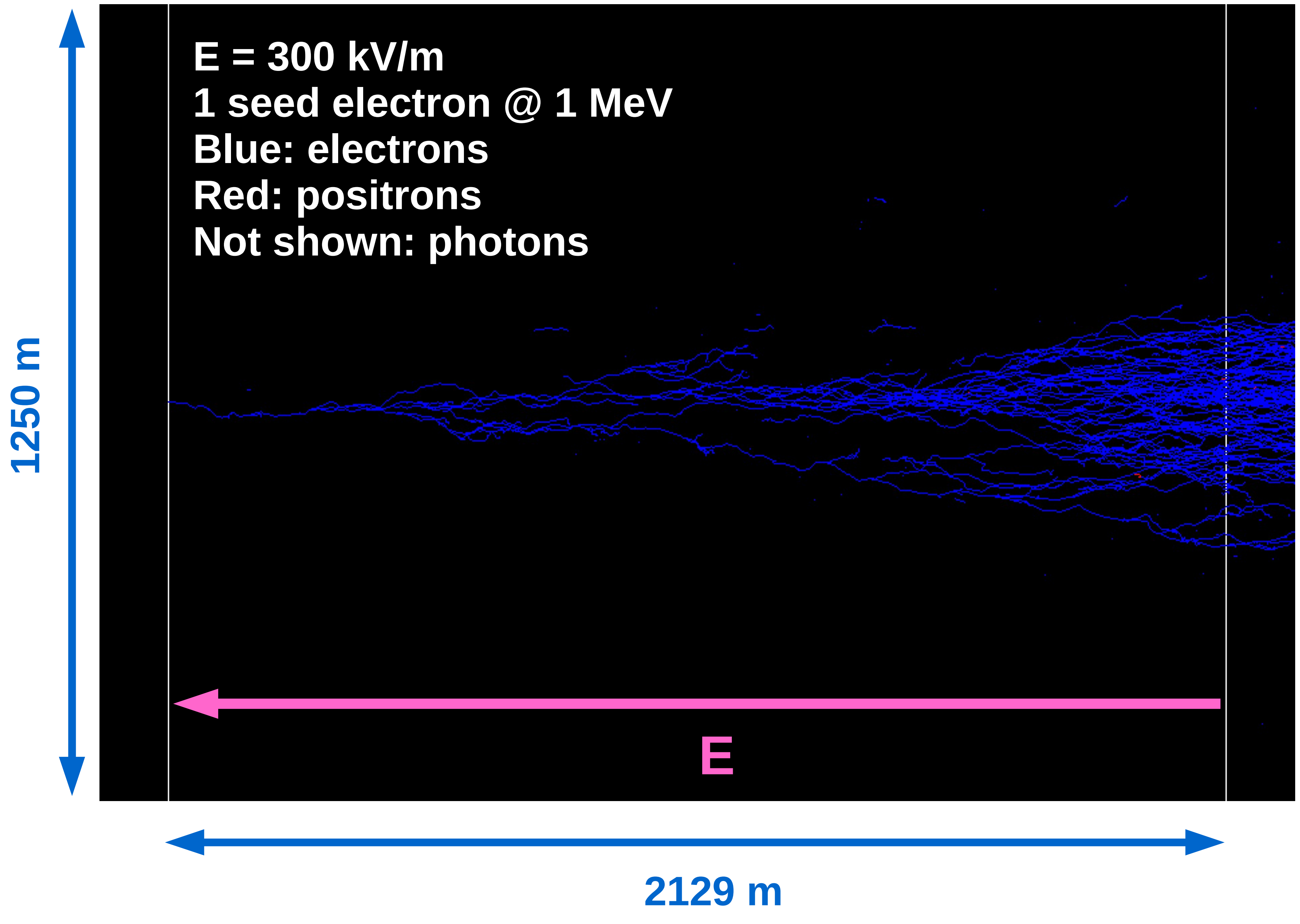
In RREA regime:
$dT = dz(eE - F_f)$

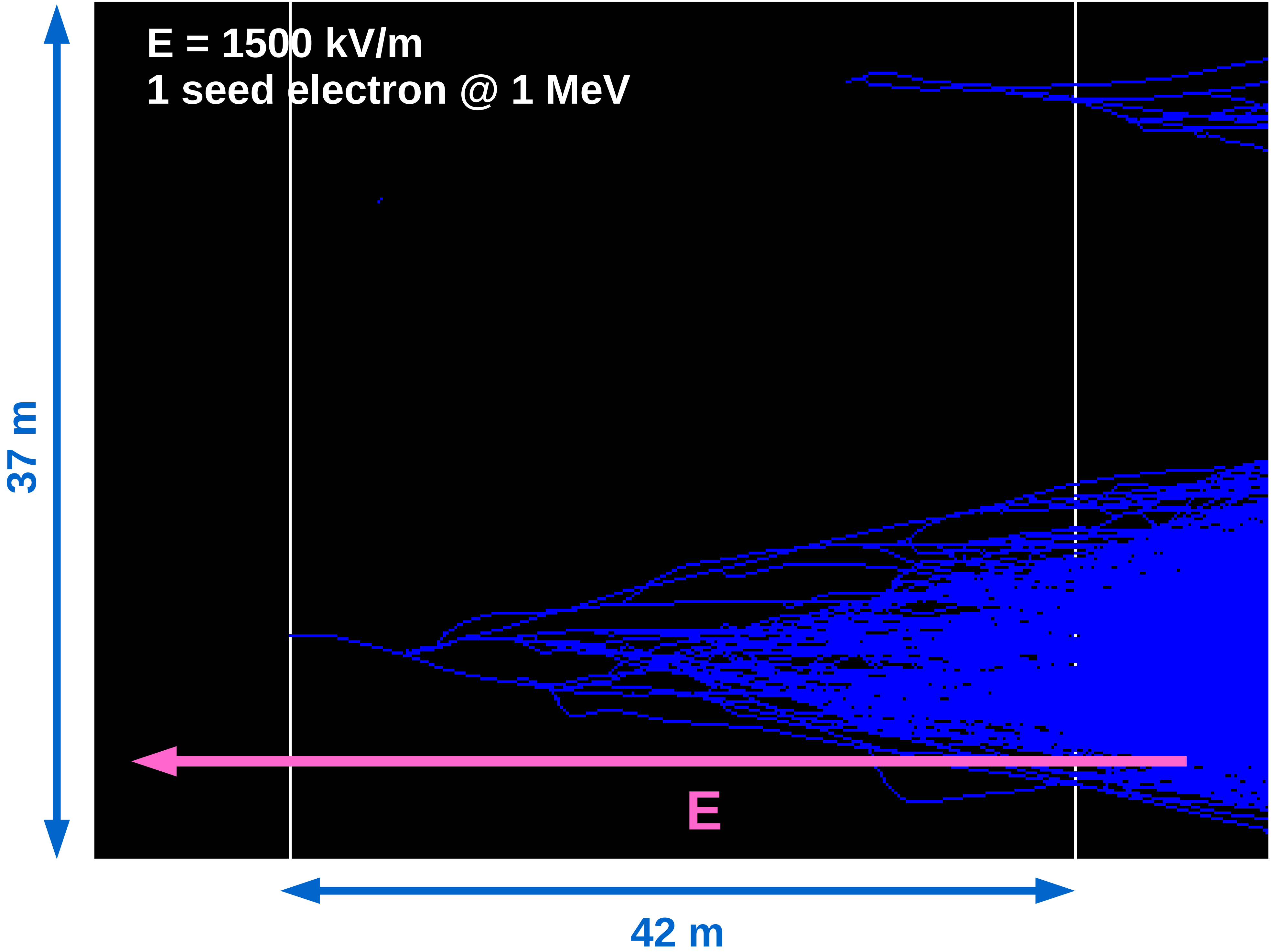
- Requires ~MeV seed electrons
- Present due to **cosmic rays** within 1 μsec in 100 m sphere at lightning initiation altitudes. (Carlson, 2008)
- **Basically always there!**
- Are rare effects (e.g. TGFs) due to large RREA–seeding events?

GEANT4 Simulation

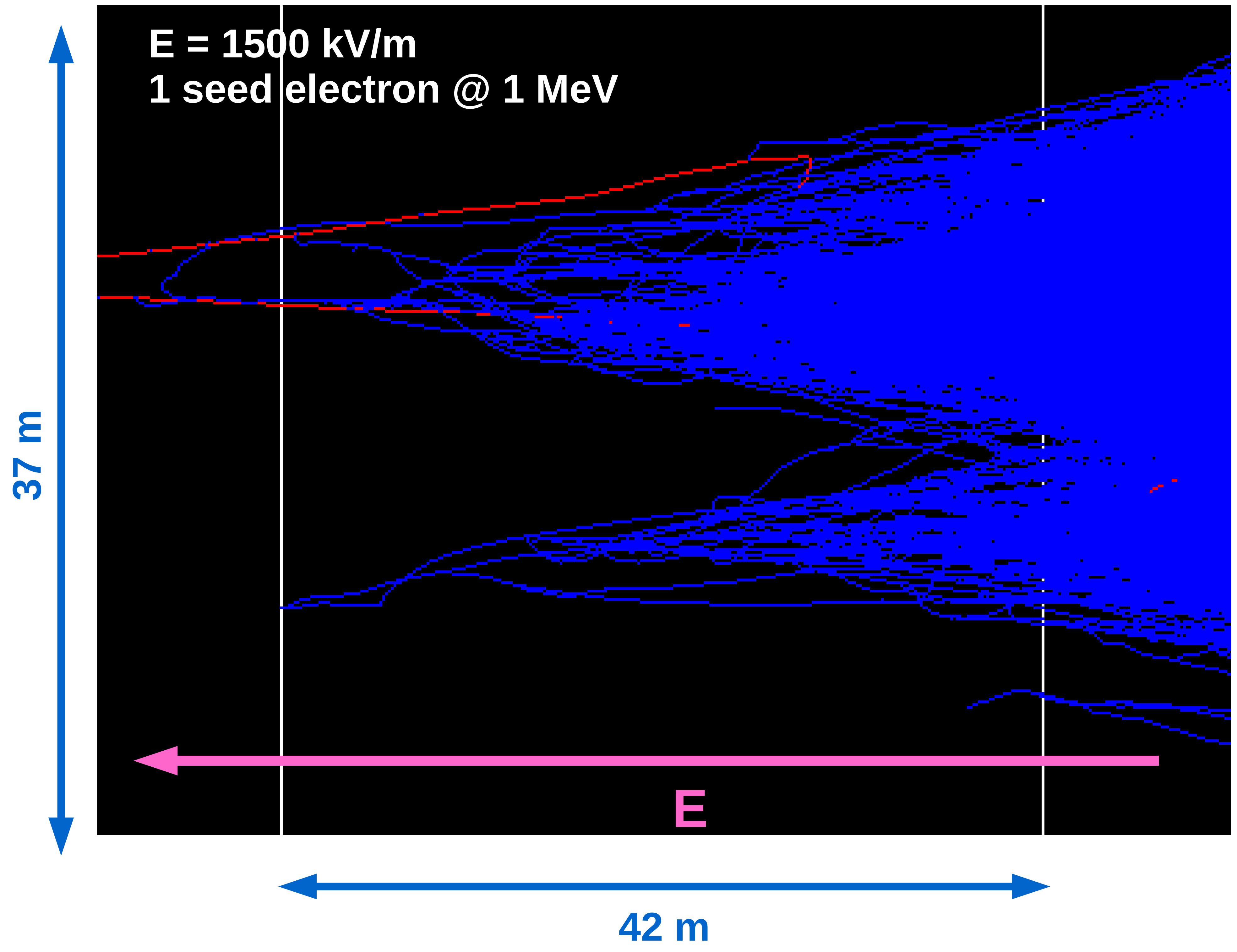


~2 km


E = 300 kV/m
1 seed electron @ 1 MeV
Blue: electrons
Red: positrons
Not shown: photons
E
1250 m
2129 m



E = 1500 kV/m
1 seed electron @ 1 MeV
37 m
E
42 m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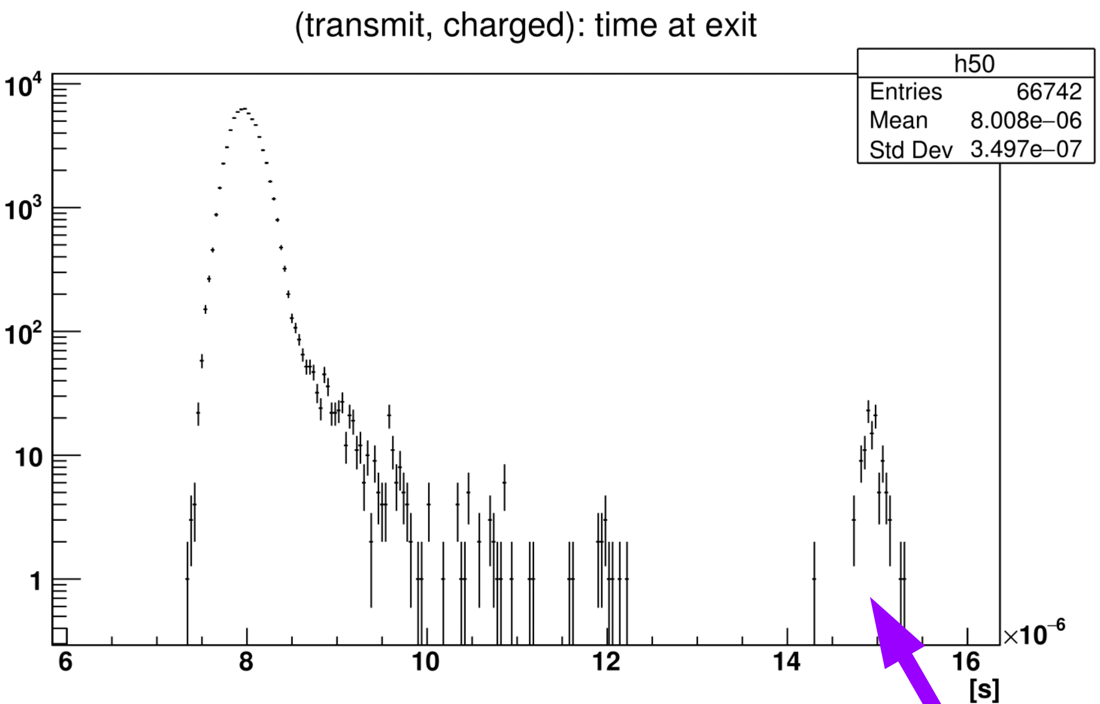
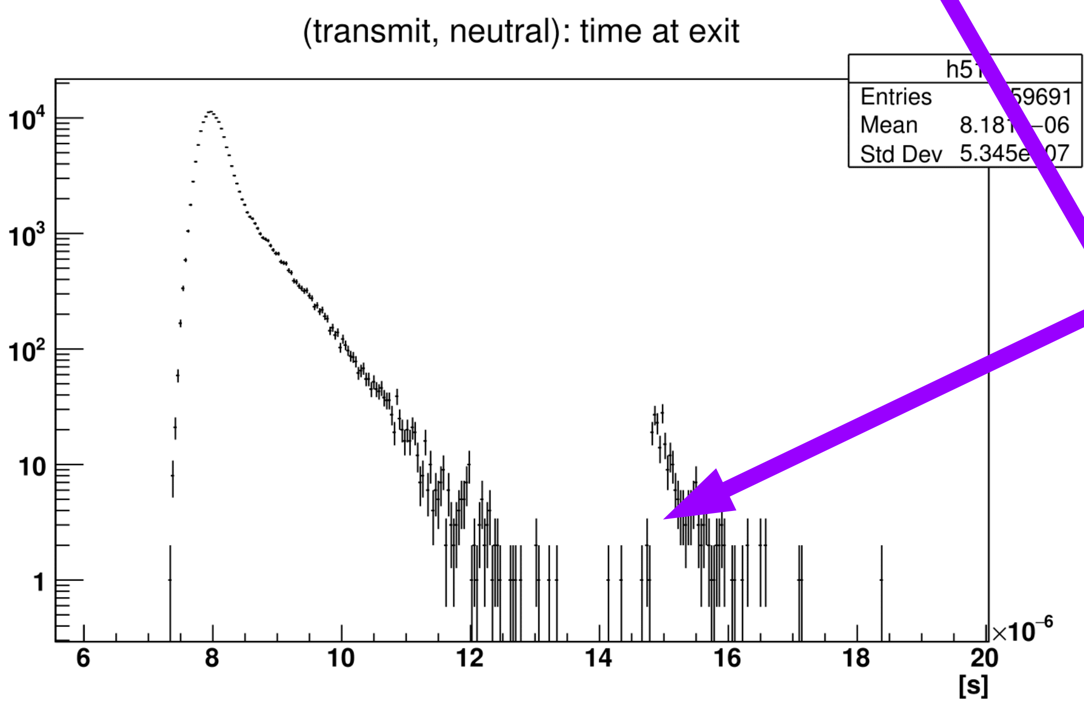
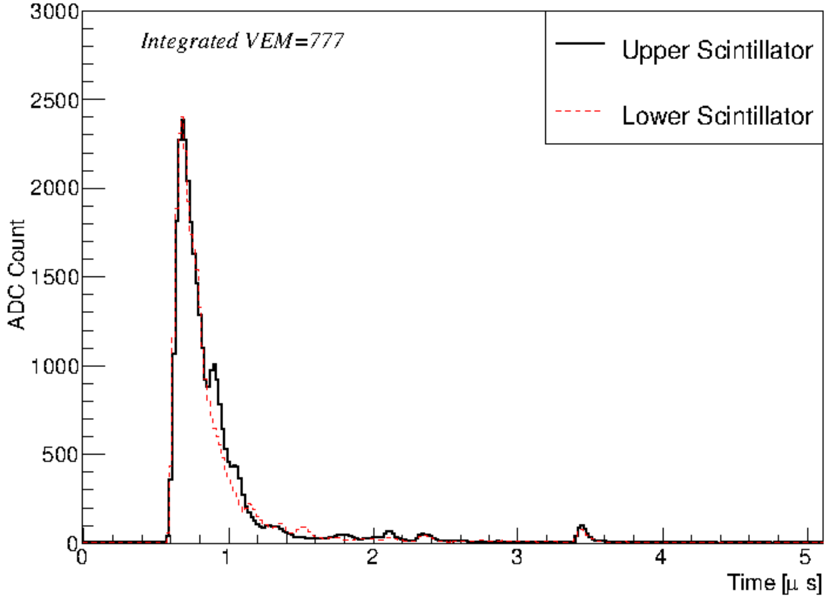
E
42 m



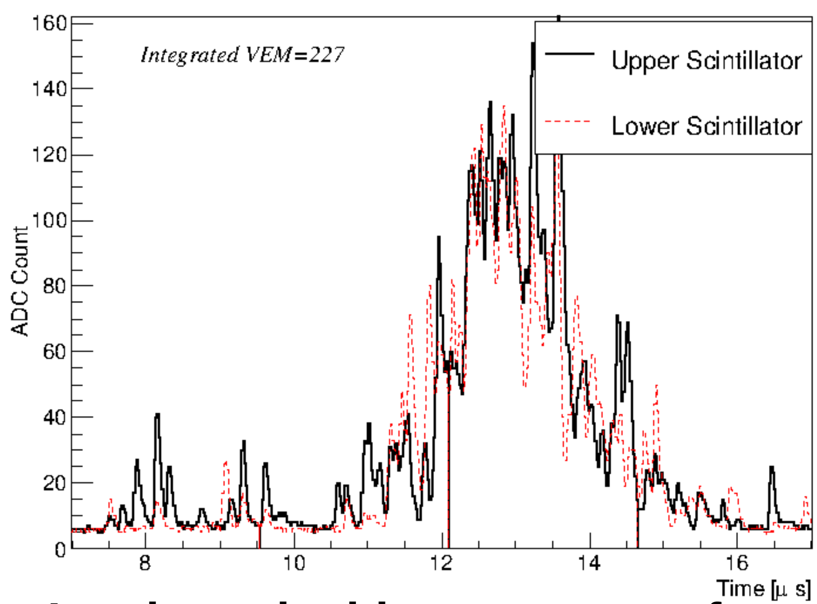


- 300 kV/m field in air
- "Arrival times" of charged (top) and neutral (bottom) RREA products.
- ~ µsec width of single avalanche
- ~7 µsec delayed "feedback" avalanche

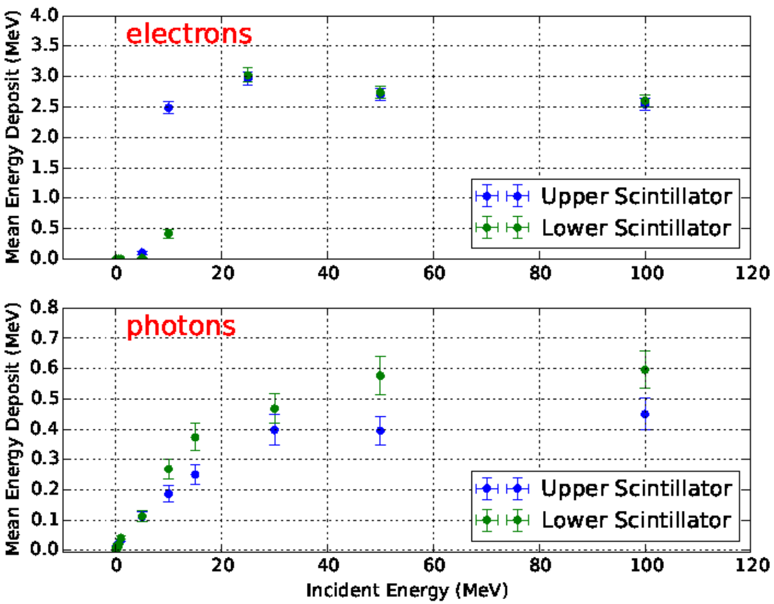
SD response: γ and $e^{\pm}$



Cosmic ray core waveform



Leader-coincident core waveform



GEANT4 simulation

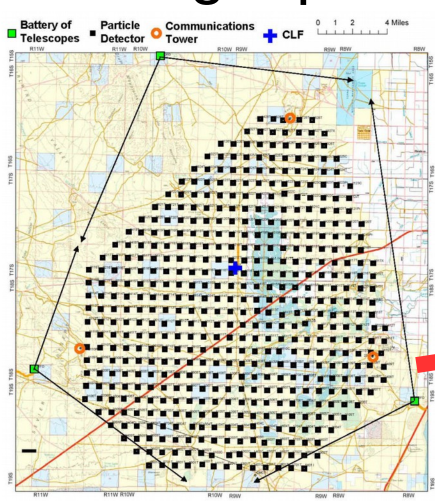
TASD is optimized for high-energy charged particles:

- inefficient for photons
- but this is what photons would look like!

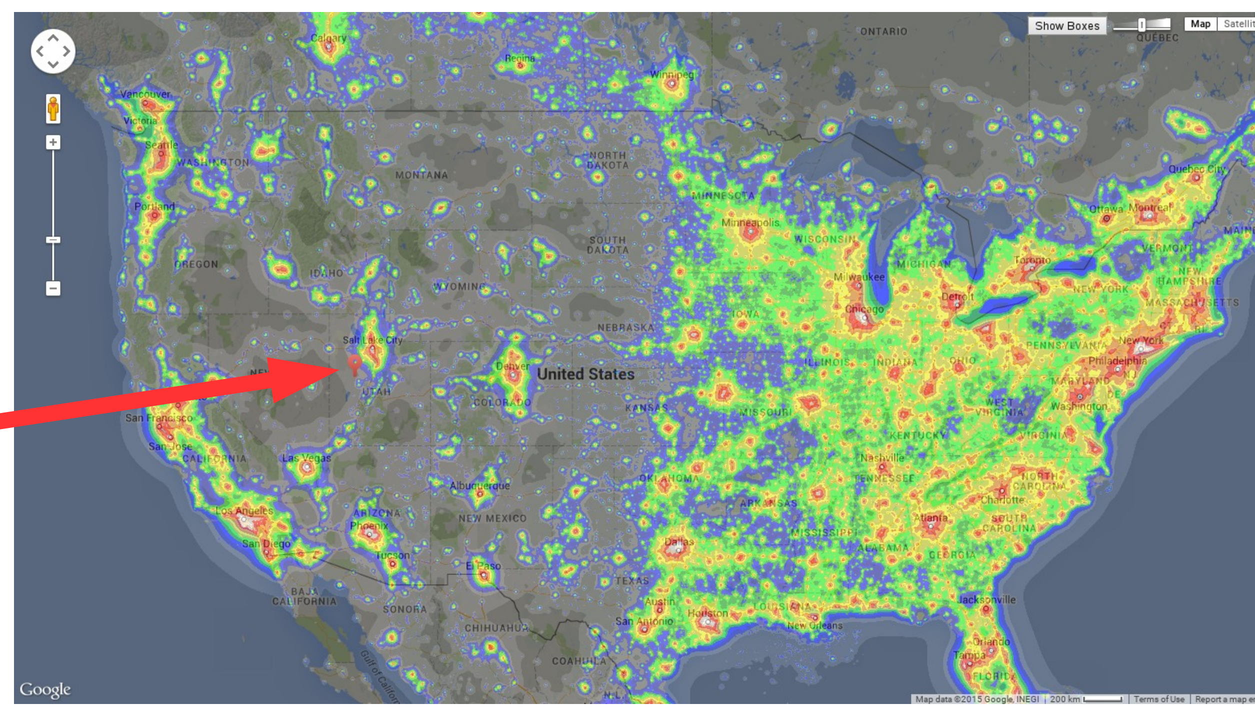
Why Utah?

- Geography!
  - Air parched by Sierras, Basin and Range.
  - Low-aerosol skies
  - Cleaner than U.S. “Standard Desert Atmosphere”

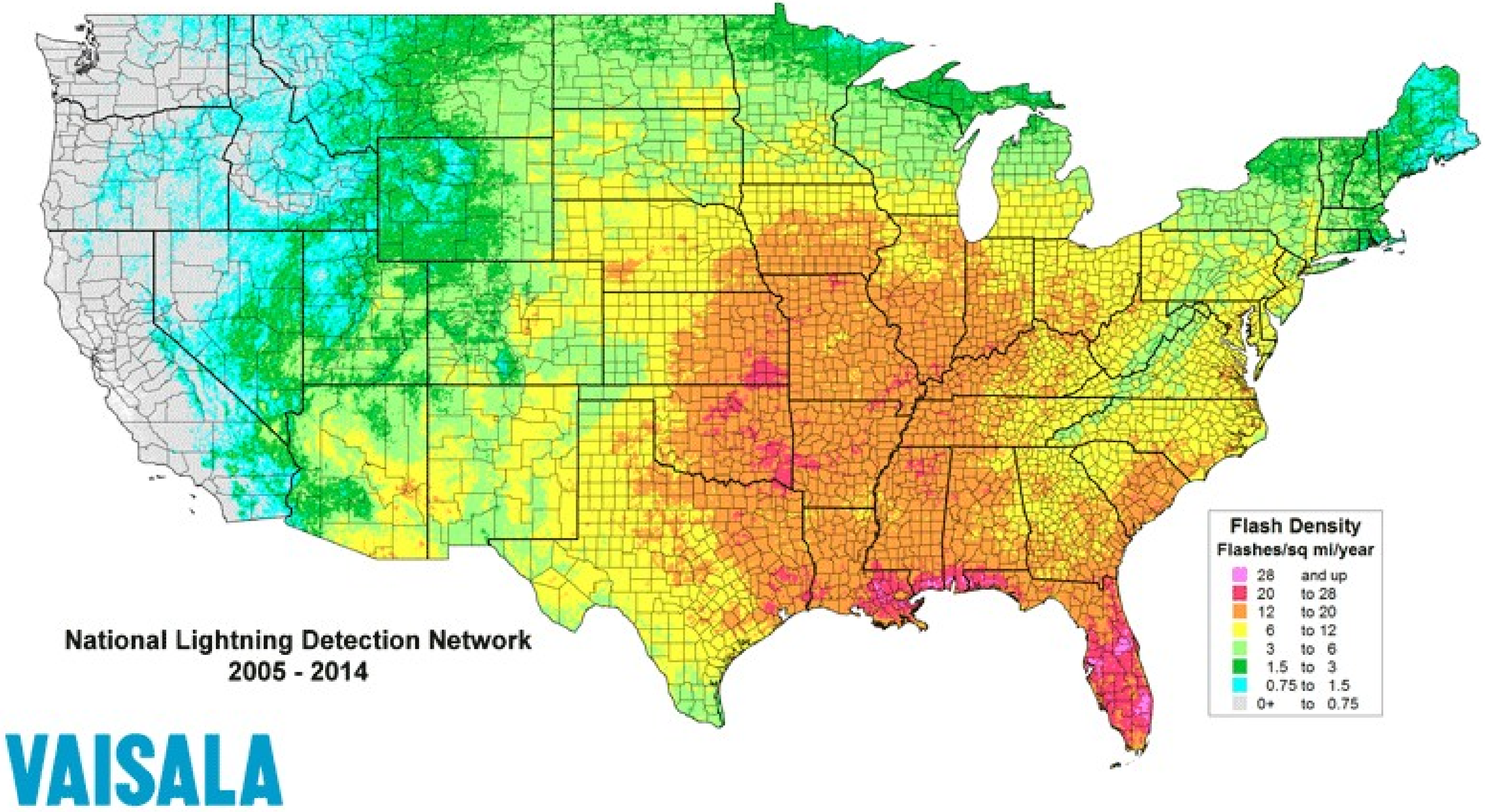
- Low light pollution!



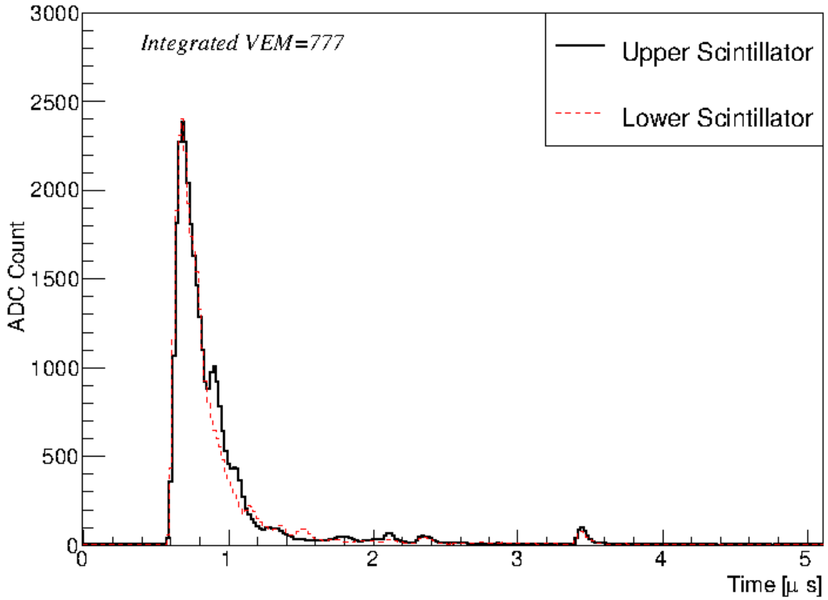
TA Observatory



Why *Not* Utah?


Flash Density
Flashes/sq mi/year
28 and up
20 to 28
12 to 20
6 to 12
3 to 6
1.5 to 3
0.75 to 1.5
0+ to 0.75
National Lightning Detection Network
2005 - 2014
VAISALA

SD response: γ and $e^{\pm}$



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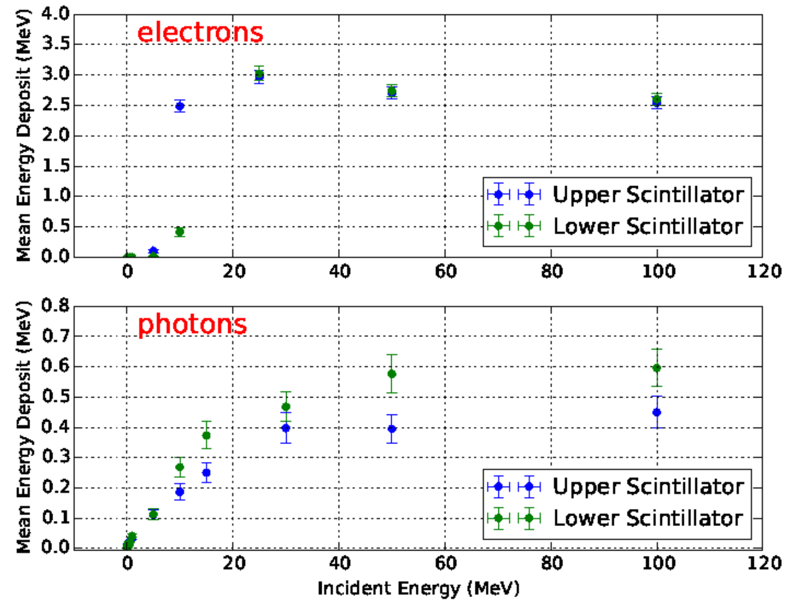

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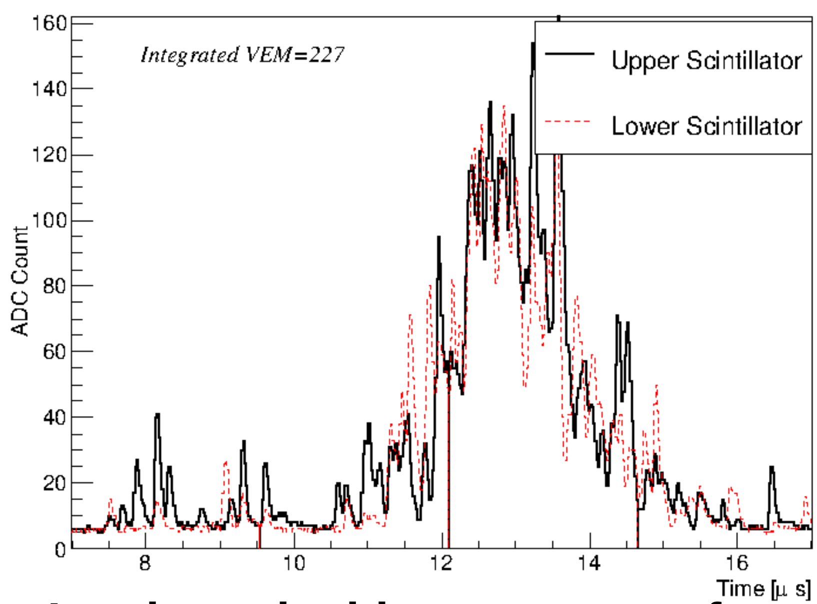

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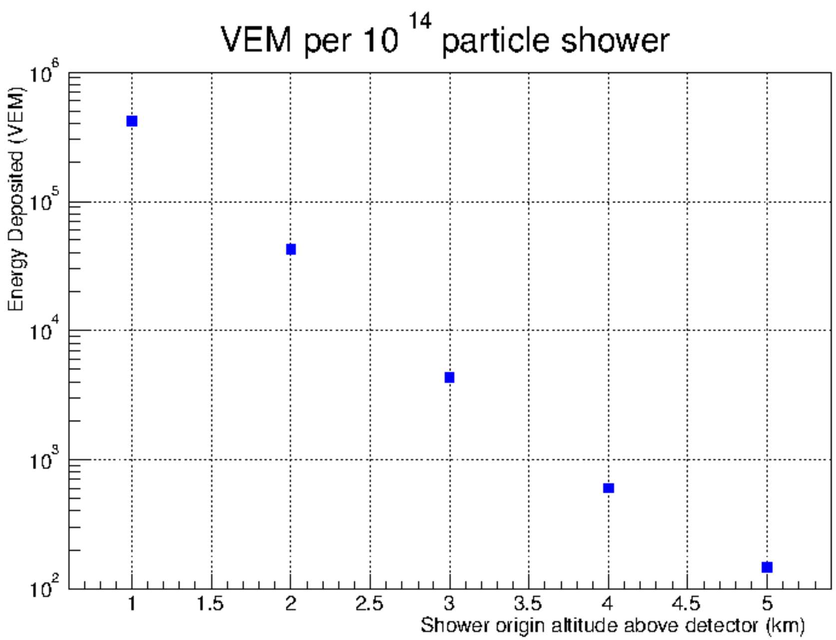

GEANT4 simulation

Simulation: R. LeVon

TA/LMA Project:

R. Abbasi, **J. Belz**, M. Byrne, R. LeVon,
W. Hanlon, P. Krehbiel,T. Okuda, J. Remington, W. Rison,
D. Rodeheffer, H. Takai, R. Thomas, G. Thomson

and the Telescope Array Collaboration

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RITSUMEIKAN

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