Observation of Ground Level Gamma-ray Showers in Coincidence with Downward Lightning Leader

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for the TA/LMA collaboration
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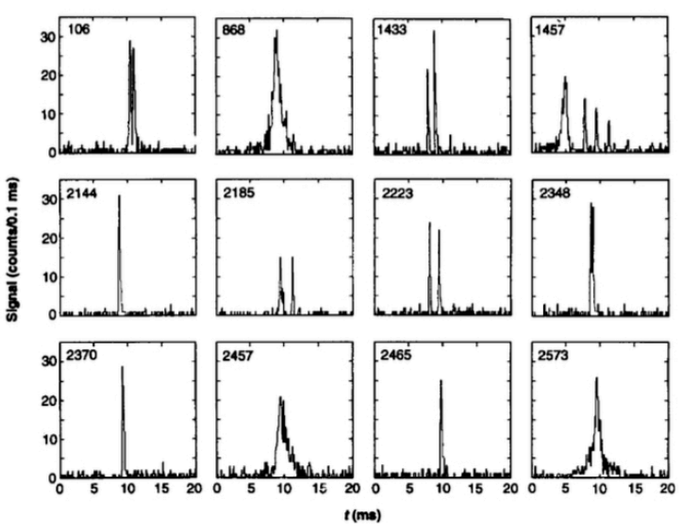
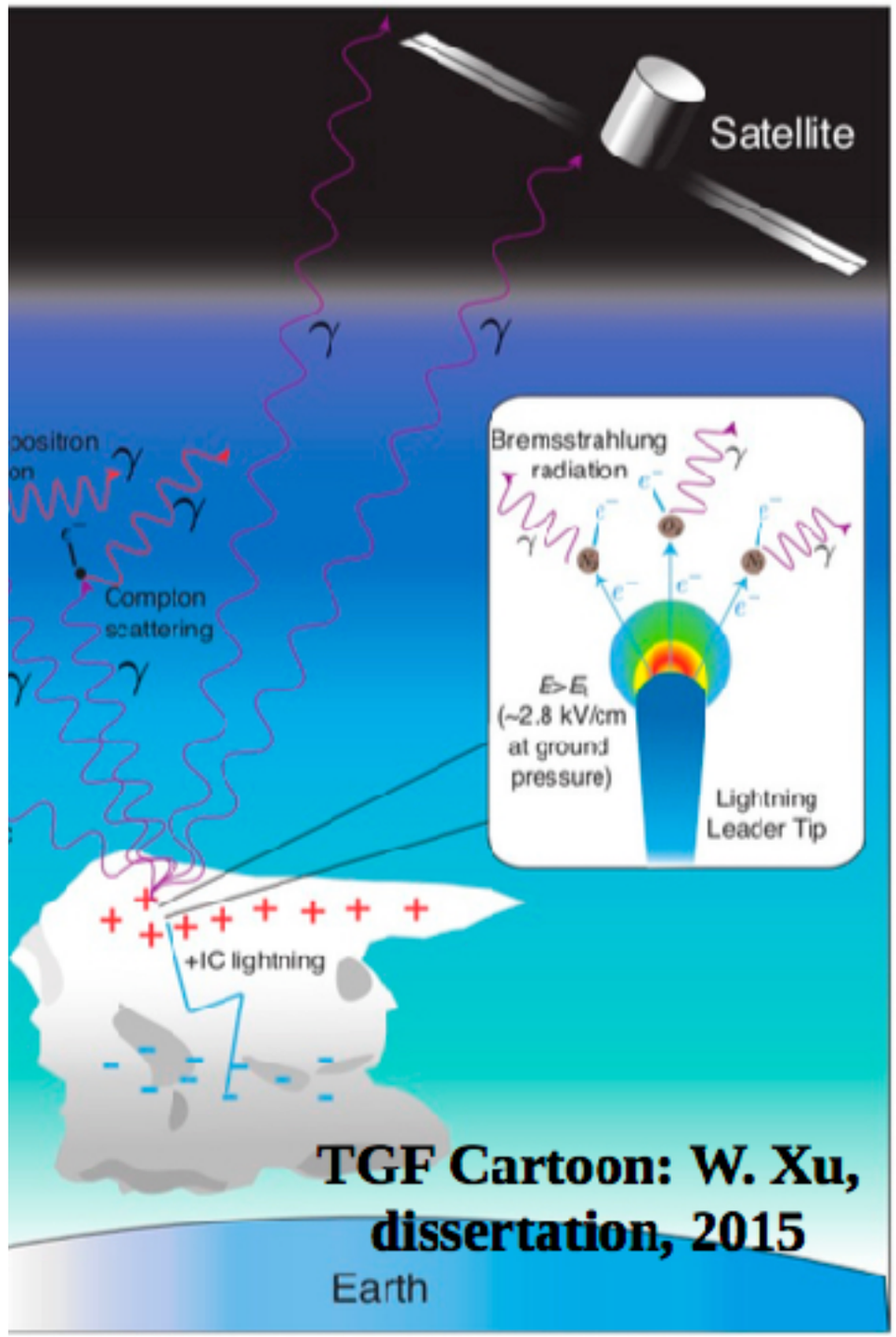
AtmoHead 2018
Capri, Italy

TERRSTIAL GAMMA RAY FLASHES

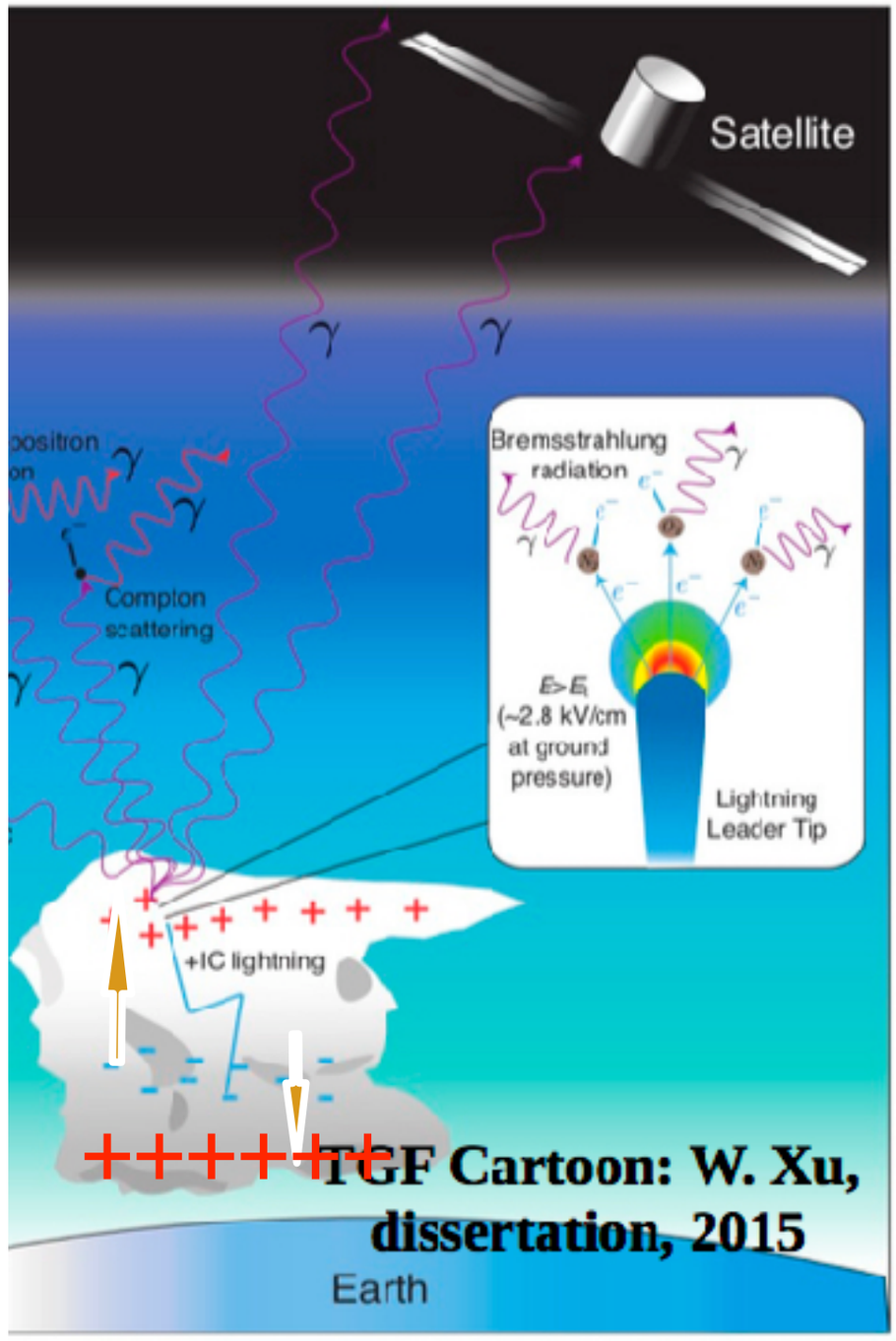
- Rare phenomenon that happens in ordinary thunderstorms.
- Observed by orbiting instruments (BATSE, RHESSI, FERMI, AGILE)
- Duration of tens of us to ms.
- generated during the initial negative breakdown stage of IC lightning
- 10^{14} –10^{19}, E>100KeV





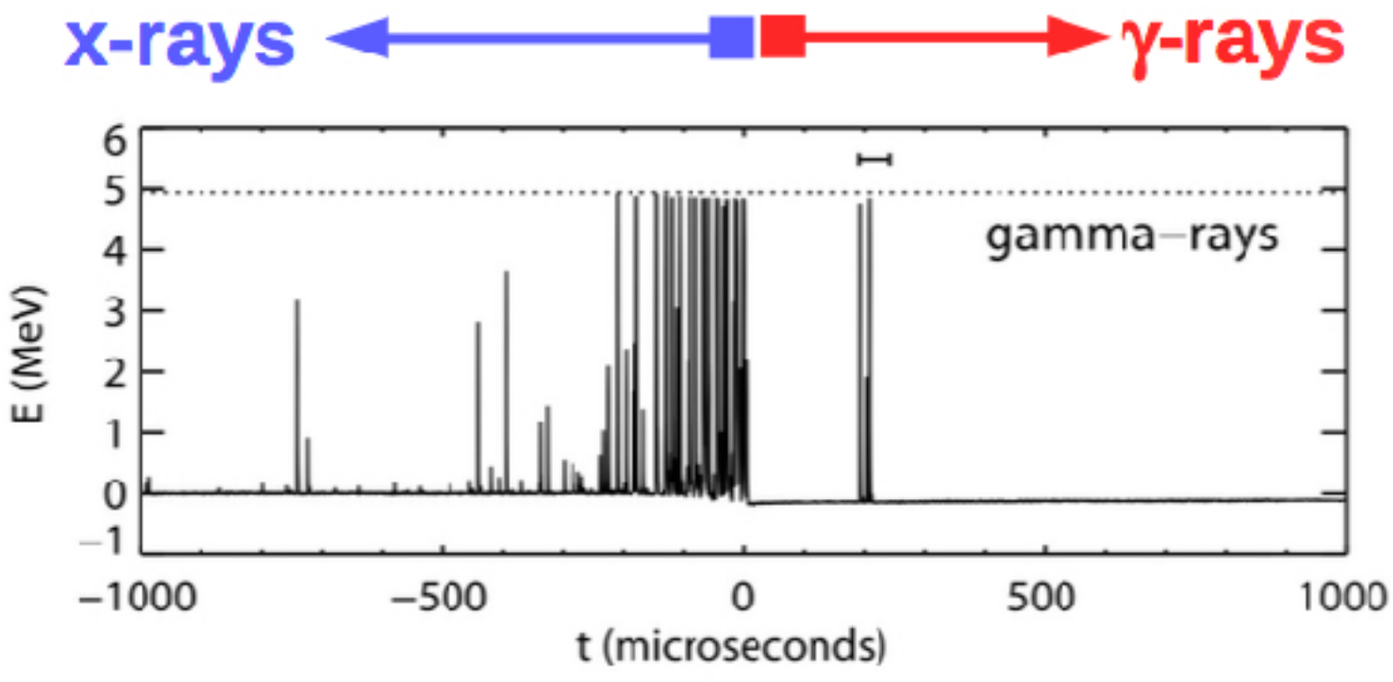
TERRSTIAL GAMMA RAY FLASHES

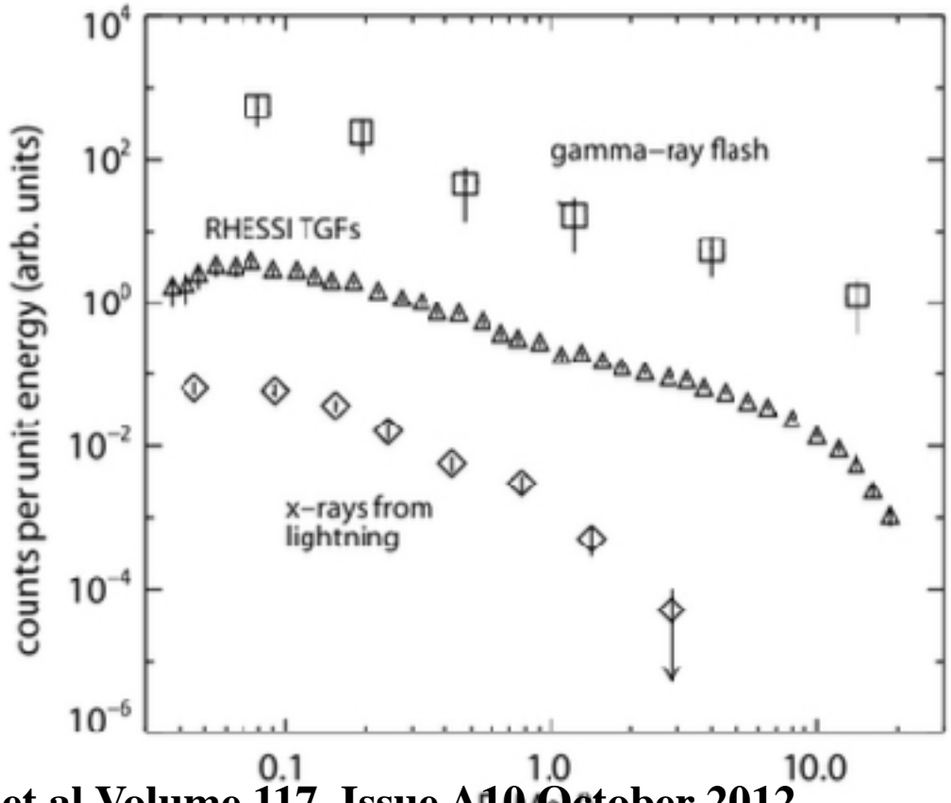
- **Is there a counterpart to this phenomenon?**
- **Can we obtain quantities at the generating TGF sources?**



Dwyer et al, JGR **117** A10303 (2012)

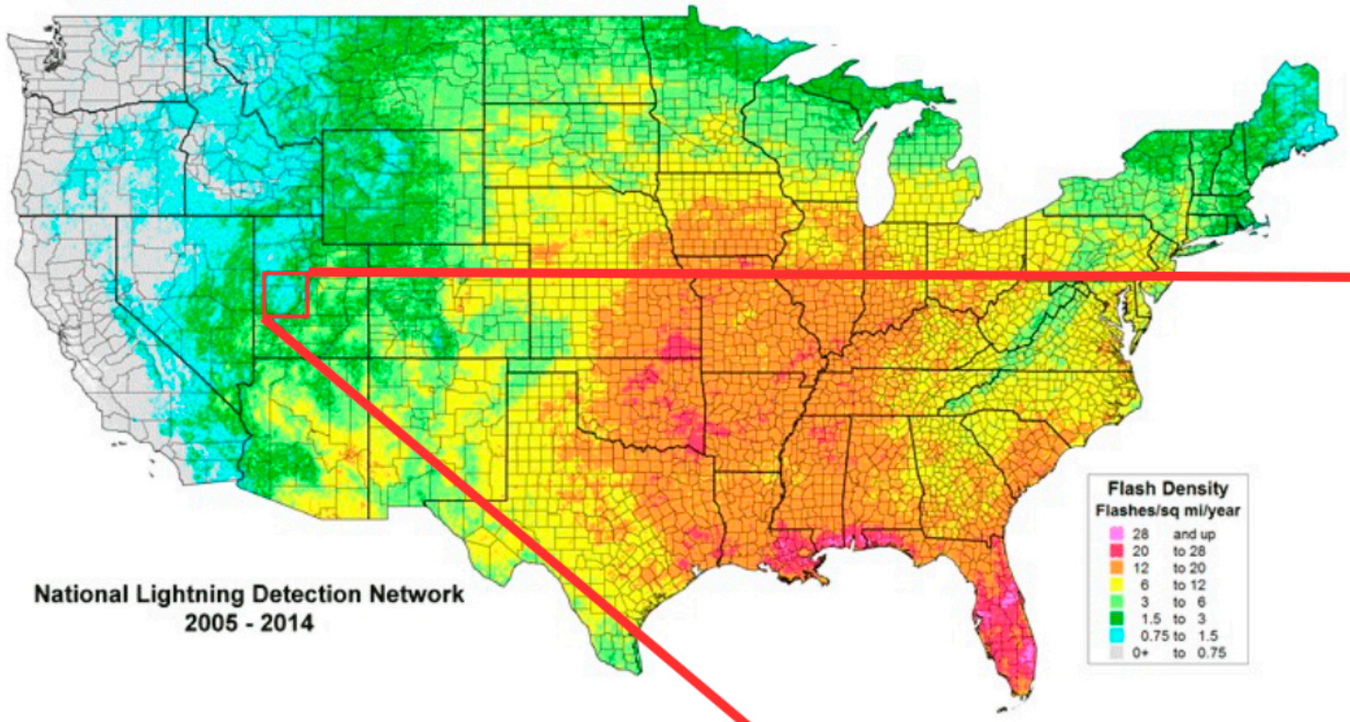
- Ground-Based TGF#1
- 20090630
- During natural 99kA –CG return stroke
- 191 μs after start of ground stroke
- 19 γ's, individual energy measurements
- *X-rays prior to ground stroke, TGF after.*

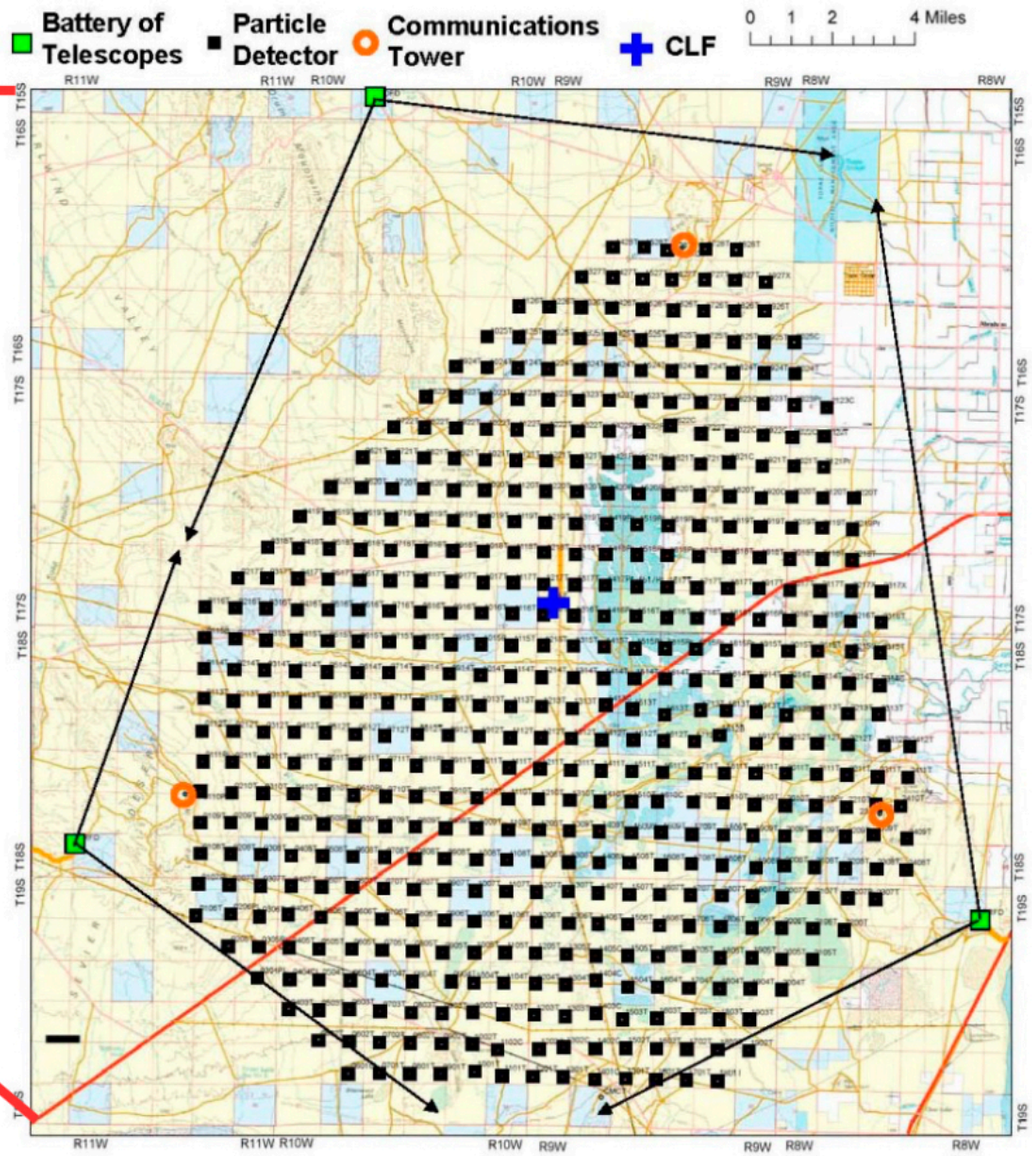




Dwyer et al Volume 117, Issue A10 October 2012

Telescope Array Observatory



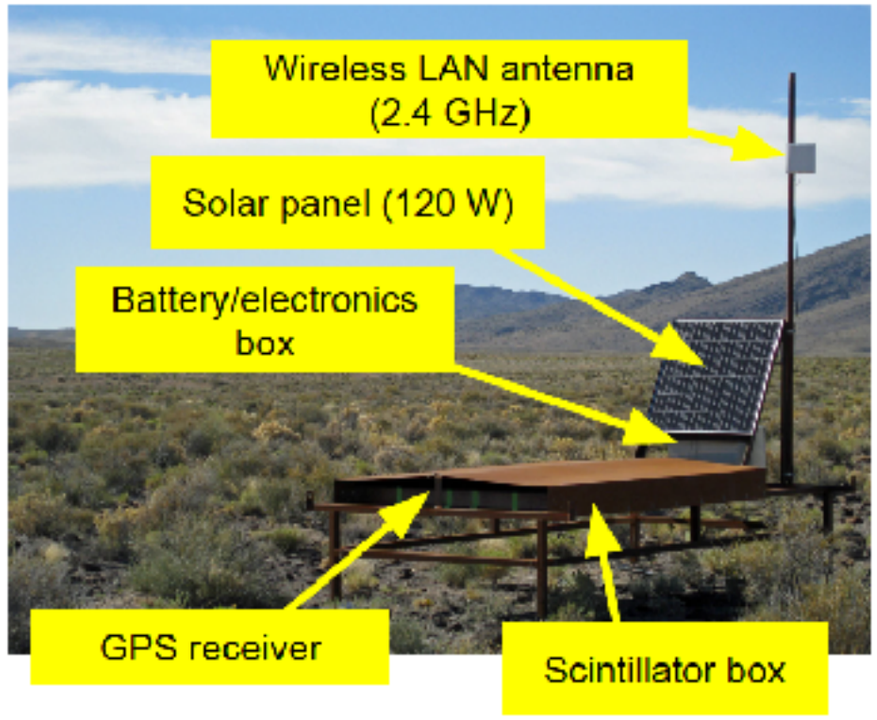


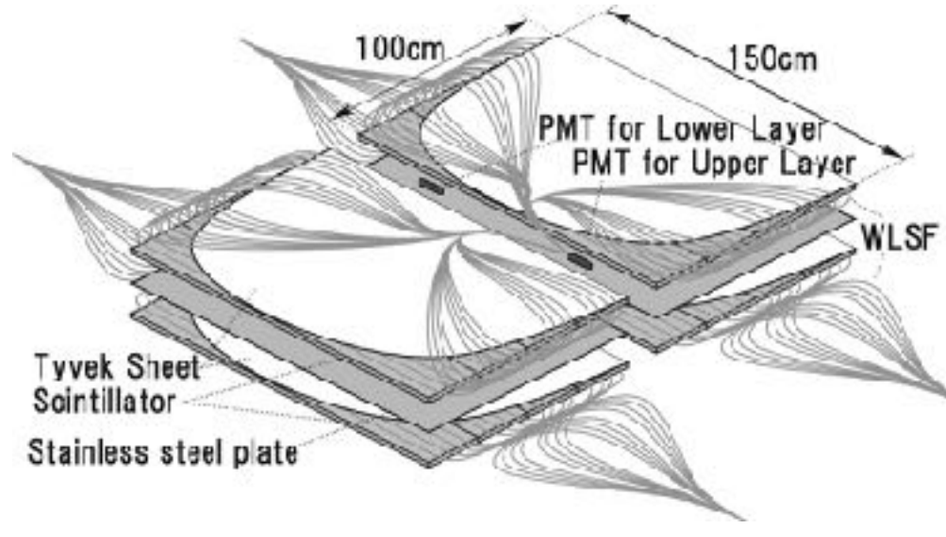
- **Ultra-High Energy Cosmic Ray** Detector; $10^{18} \rightarrow 10^{20}$ eV and higher
- TA Surface Detector (TASD): 507 scintillation detectors, 1.2 km grid, covering 700 km^2.
- Mean altitude 1400 meters MSL
- Operation since March 2008

Millard County, Utah U.S.A.

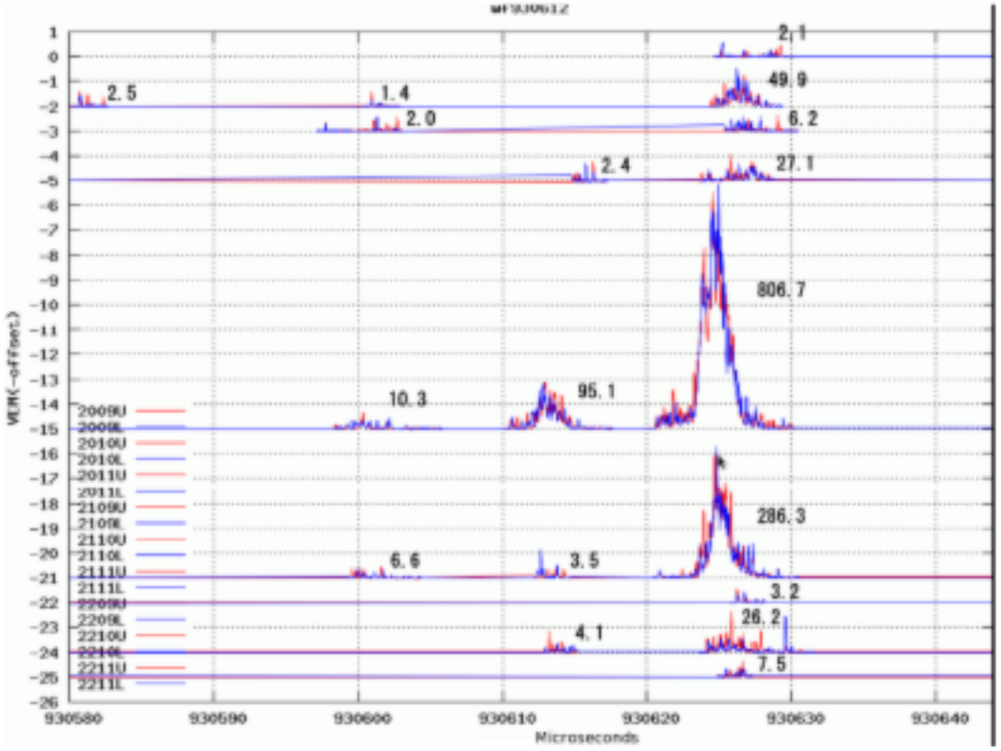
SCINTILLATION COUNTERS

- **2 layers of 3m² plastic scintillators, separated by steel sheet in ground steel box**
- **Autonomous, 24/7 operation**
- **GHz WLAN readout**
- **Typically 1 trigger/2 minutes**



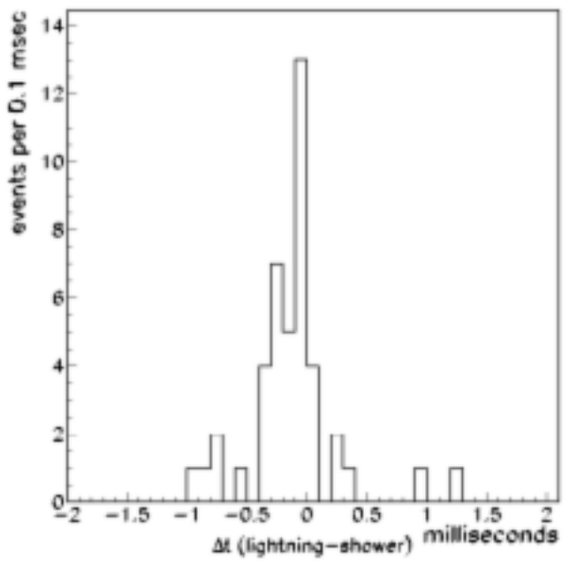


TA Observation: “Burst” Events



- 5 year data (2008-2013)
- 10 surface detector bursts seen
  - 3 or more SD triggers, < 1 msec
  - Occasional Dt ~ 10 msec

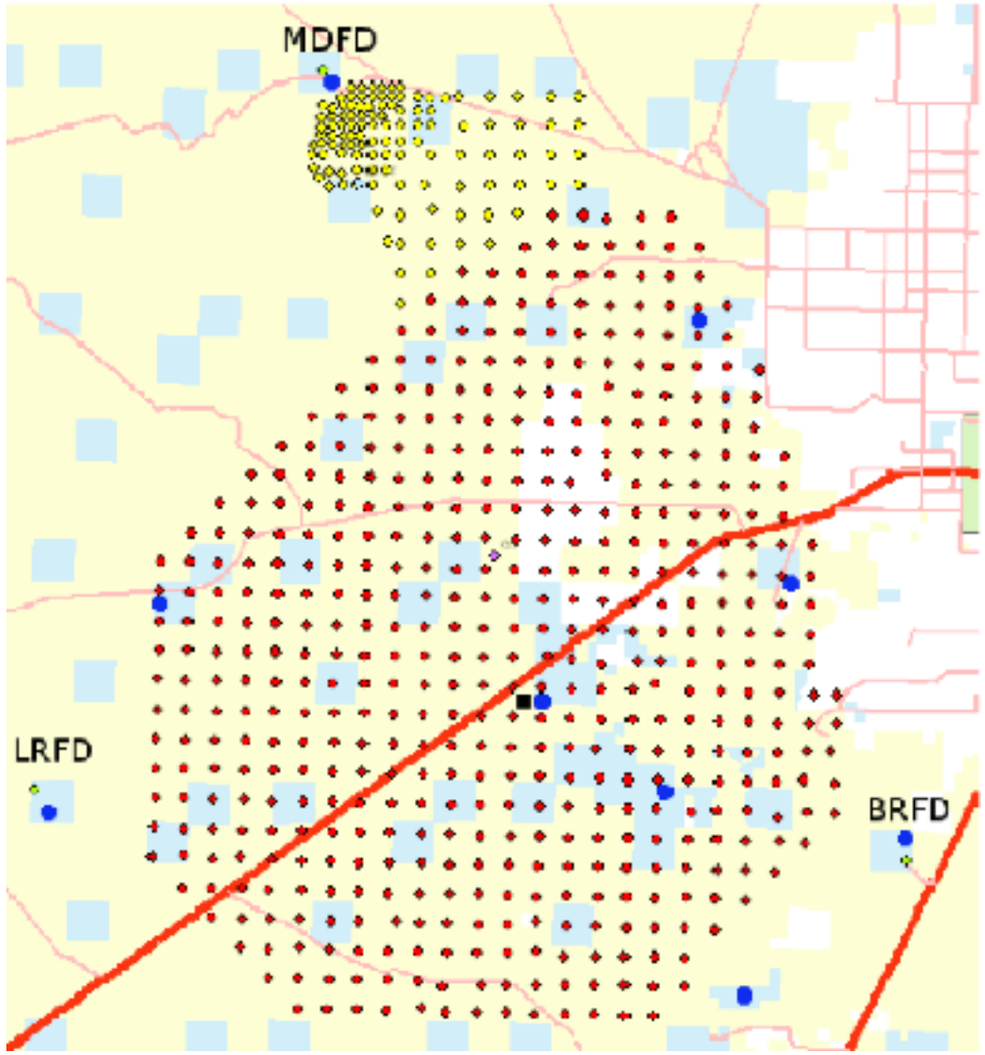
Plot: T. Okuda



- “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)

LMA, Slow antenna added (NM Tech 2013)

LIGHTNING MAPPING ARRAY

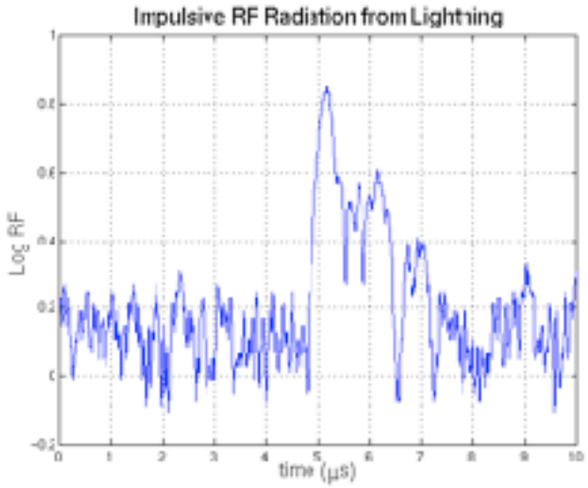


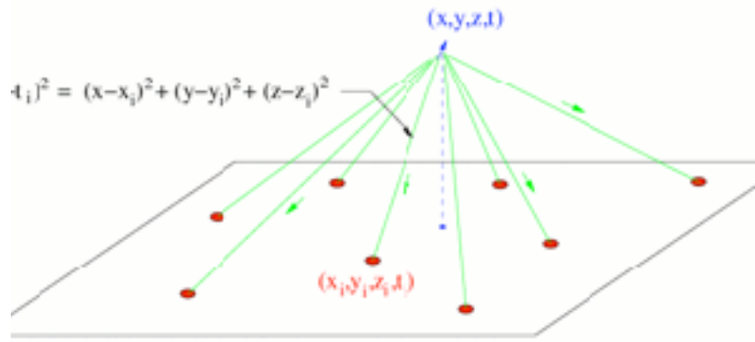
- **9 LMA Stations**
- **60 km in diameter**
- **RF quite locations**
- **Rural areas away from buildings**
- **E-measuring slow antenna.**

In operation since 2013

How Lightning Mapped

- Detect impulsive radiation within 80 us window in the band bet 60-66 MHZ.

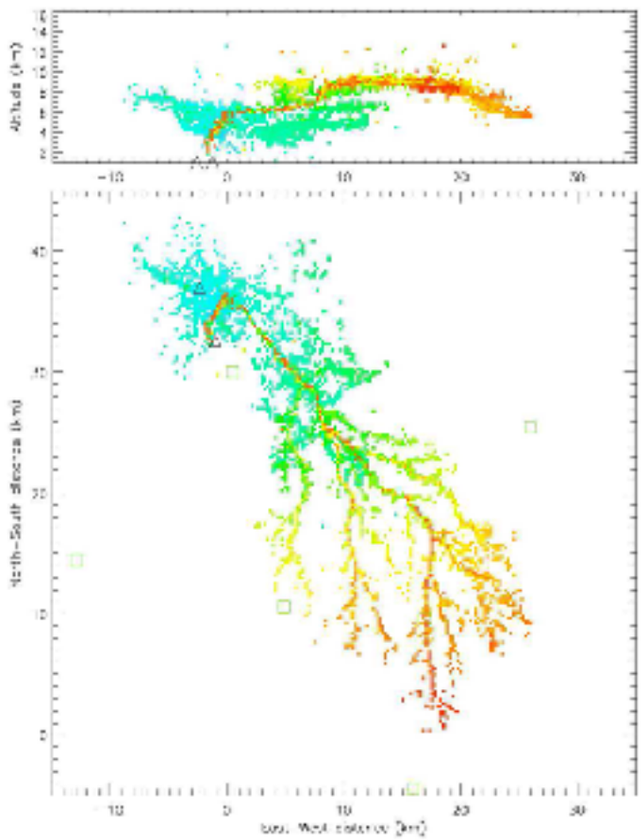




- multiple detectors to determine their x,y,z,t

- Avoid misconstruction >= 6 receivers are used.

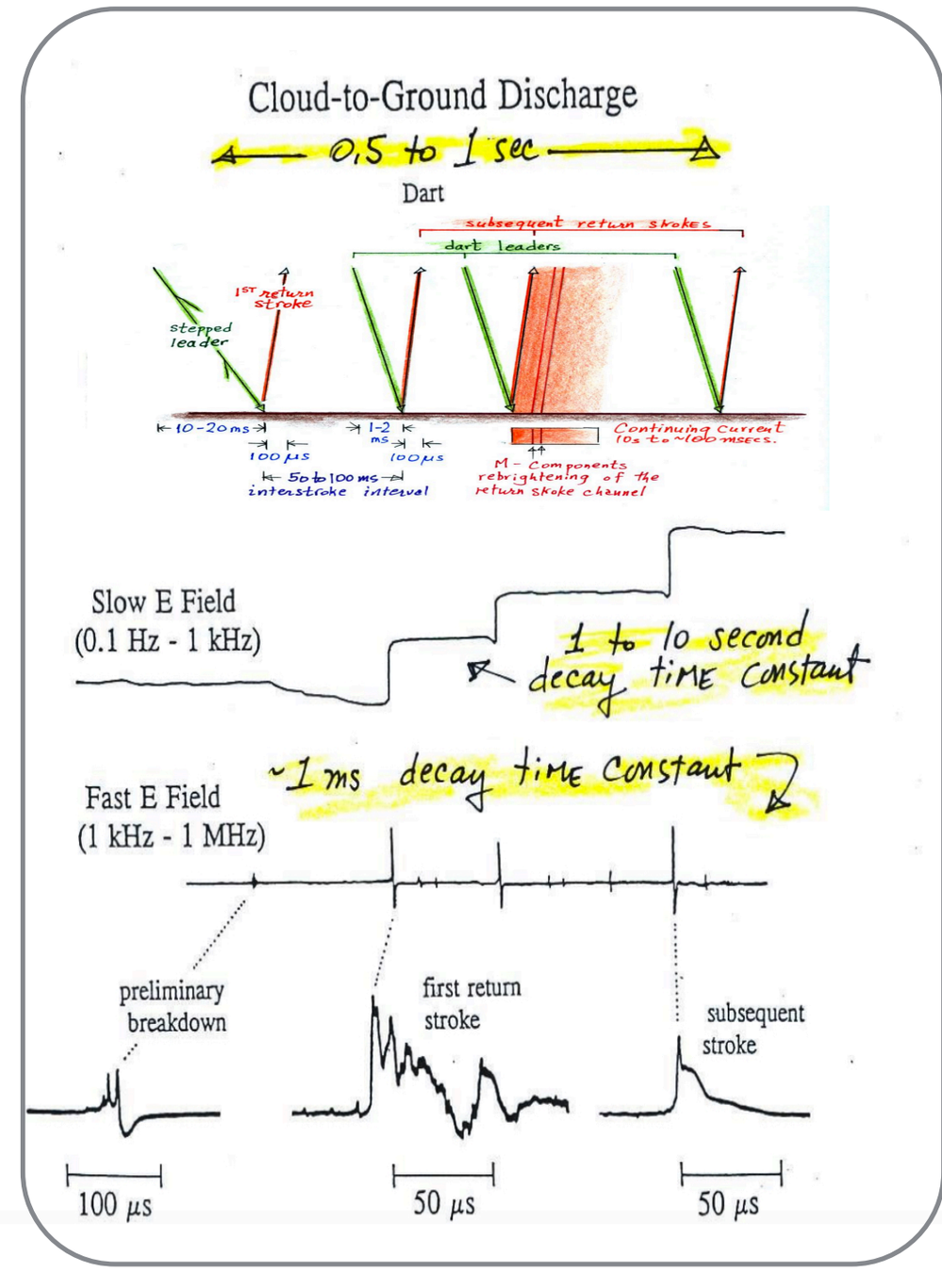
- Locate hunders to thousands of sources per flash



Slow antenna

- GPS-timed capacitor, read out with 10 s time constant.

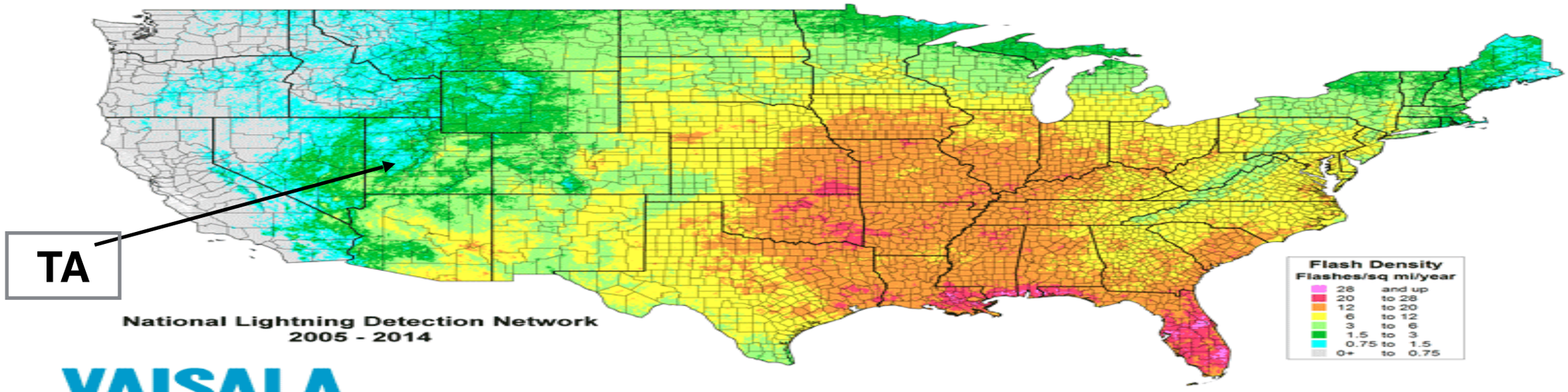
- Record electric field between 10 mV/m and 10 kV/m



Slow Antenna

Fast Antenna

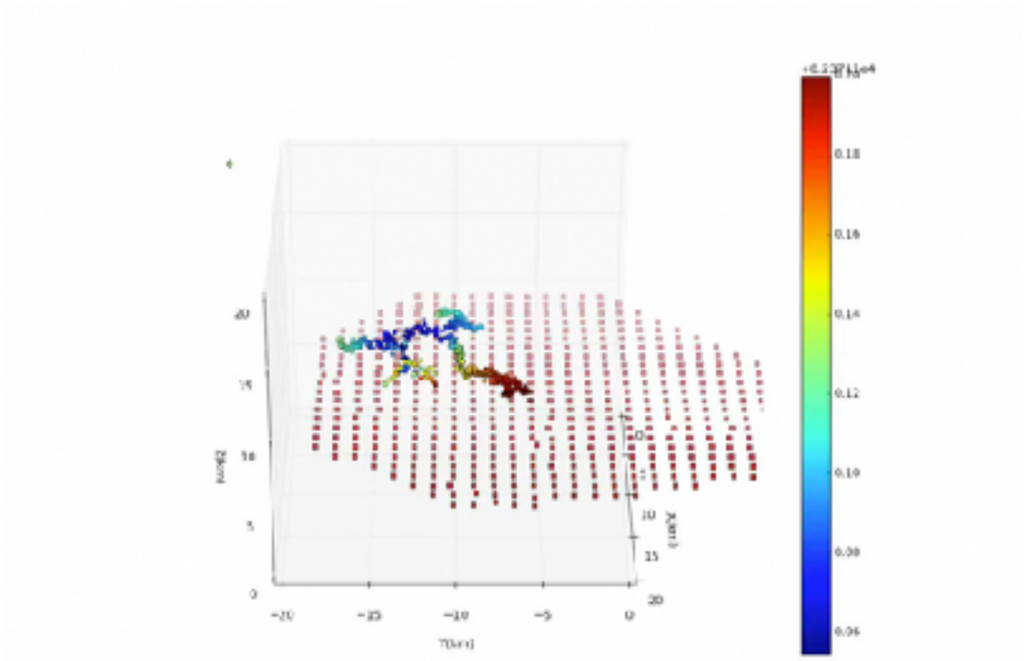
NATIONAL LIGHTNING DETECTION NETWORK (NLDN) DATA BASE

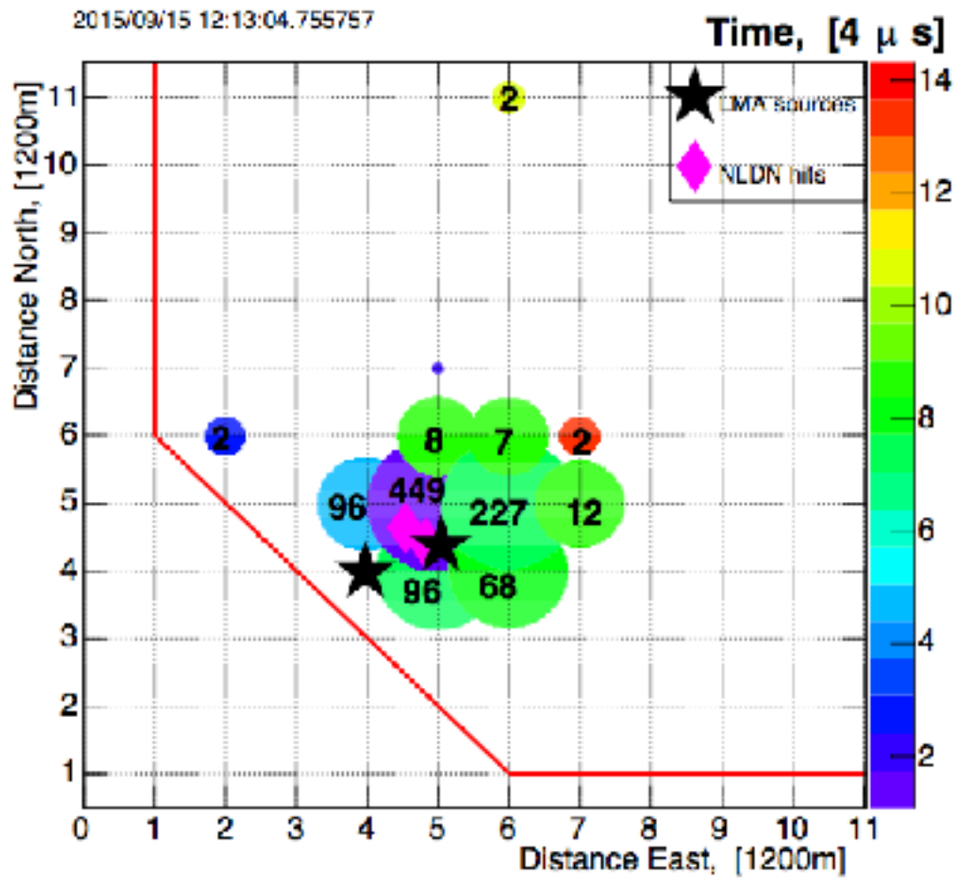


- Lightning time
- 2D Coordinates (Latitude and Longitude)
- Peak Current (kA)
- Polarity (+/-)
- Could-Cloud (50-60% efficiency)
- Cloud-Ground lightning (90% efficiency)

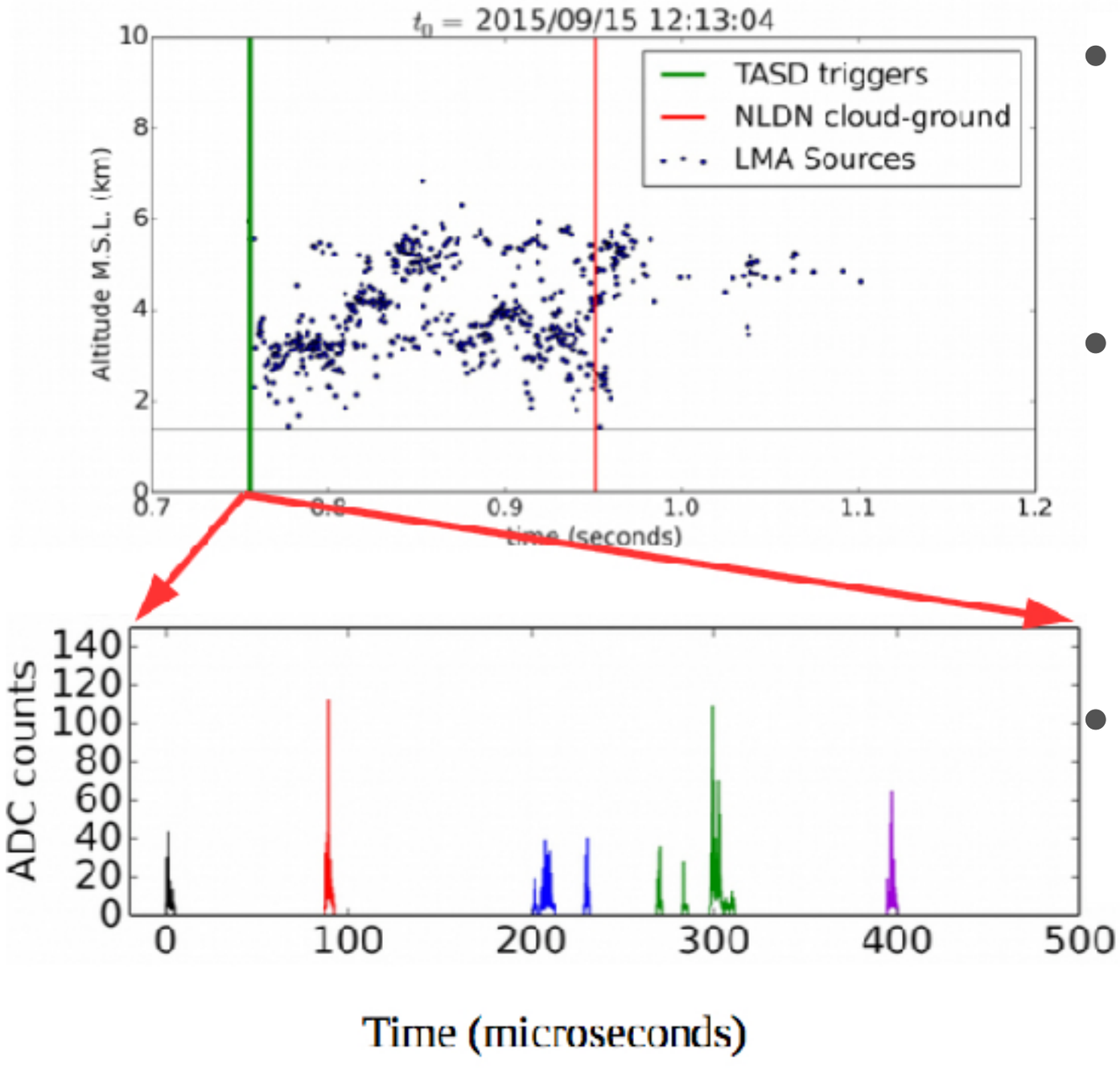
Observations

can we obtain quantities at the generating TGF source?



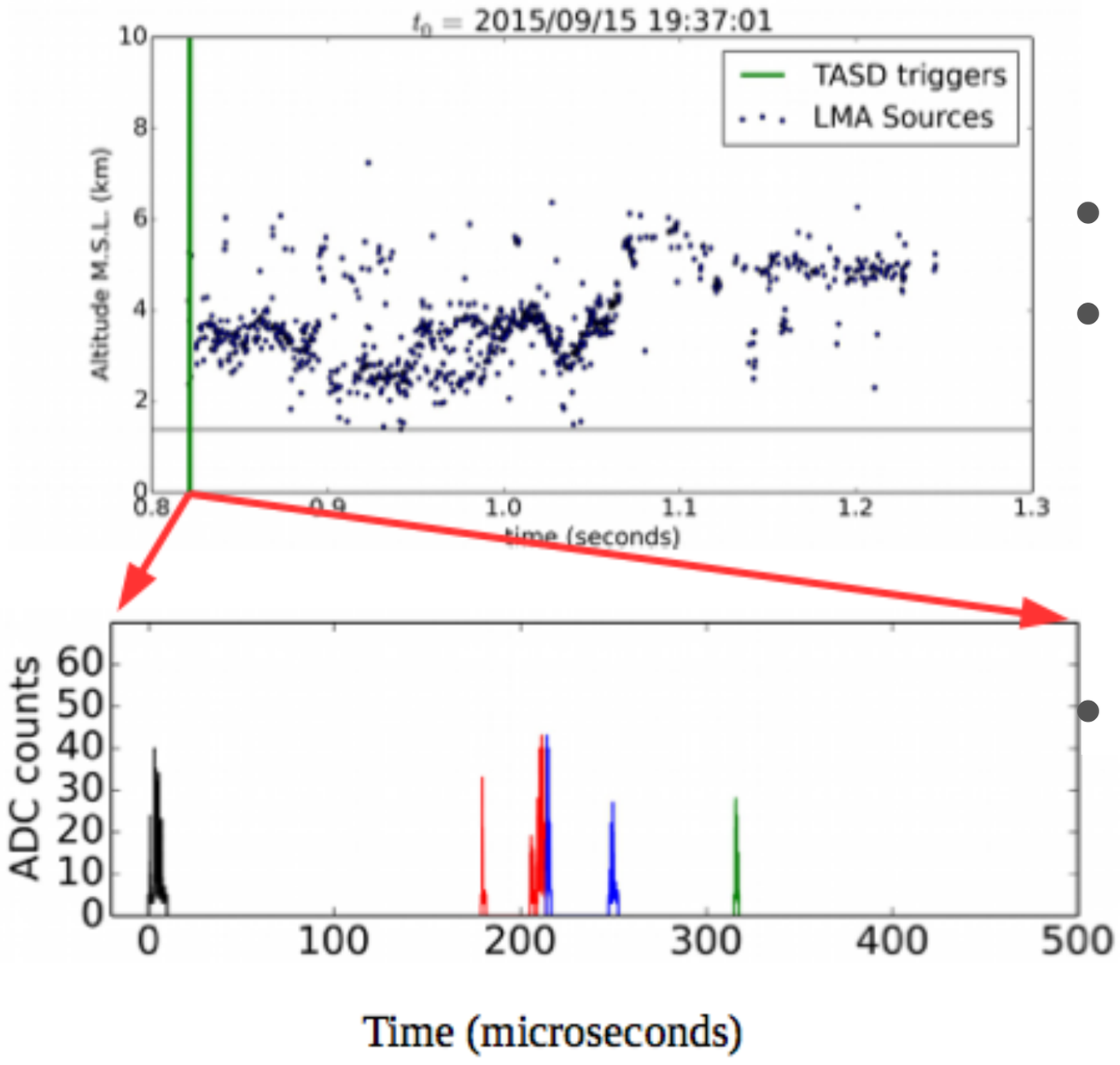


TA/LMA “Flash 1”



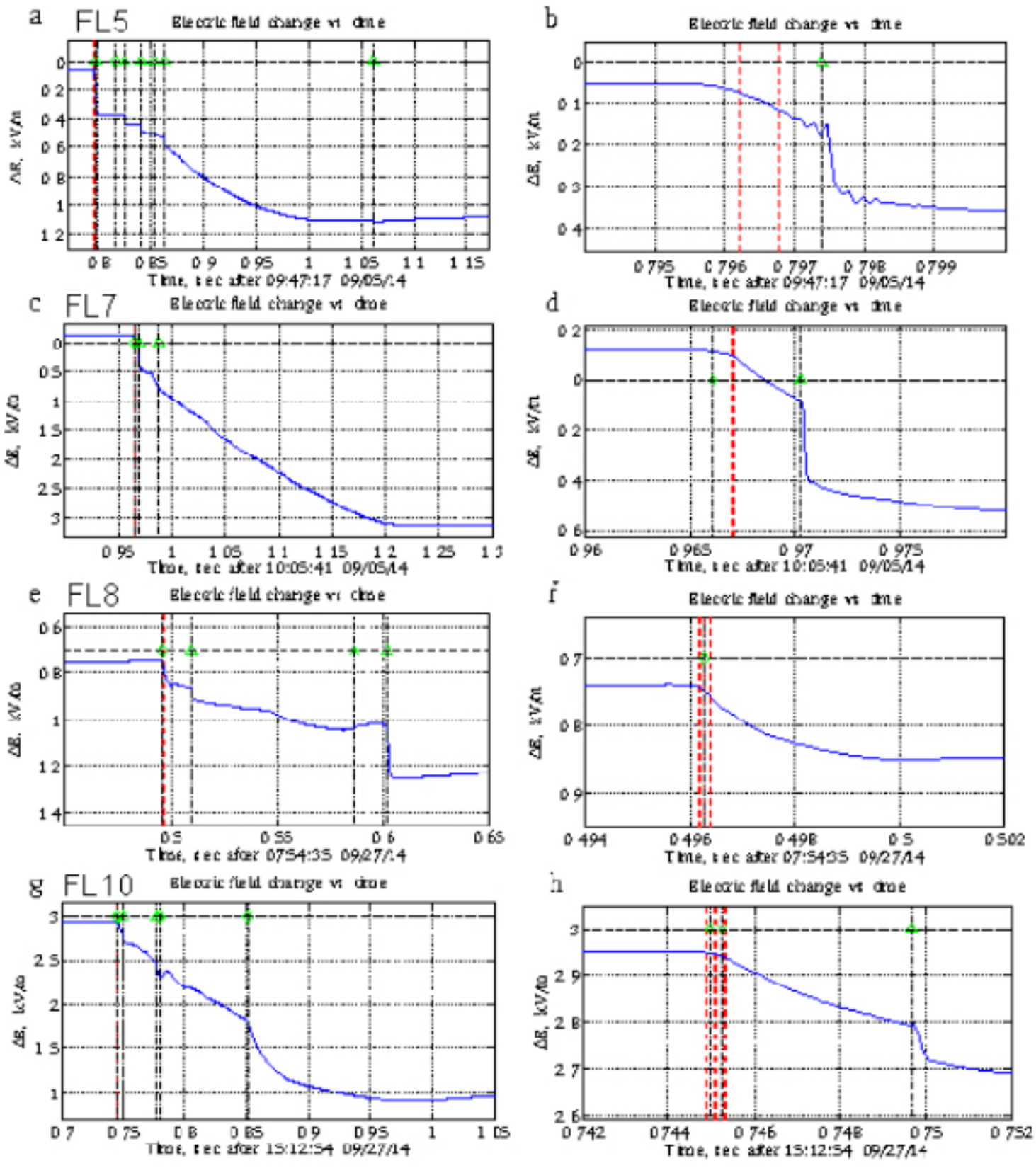
- occurred at the first 1 ms of the flash, ~200 ms before CG hit
- Occurred as a negative breakdown with a leader height between 4-5 km AGL
- TASD waveform has 400 μs duration with 10s of μs in sub-pluses

TA/LMA “Flash 2”



- Different Flash same day
- Occurred as a negative breakdown with a leader height between 3-4 km AGL
- TASD waveform has 400 μs duration with 10s of μs in sub-pluses

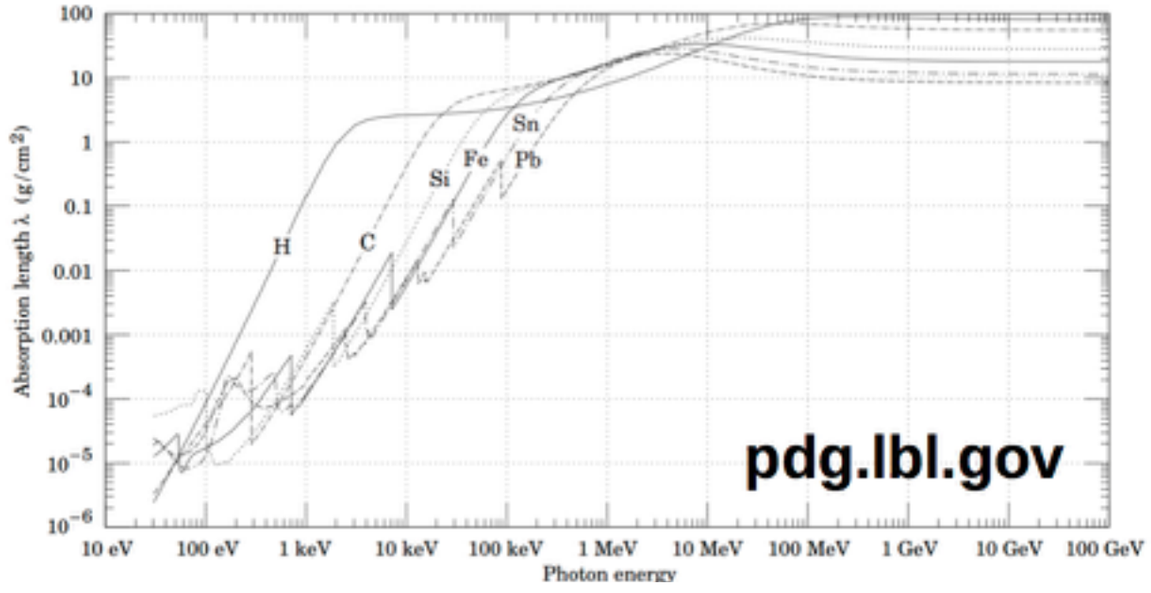
ΔE ("Slow Antenna") Measurements

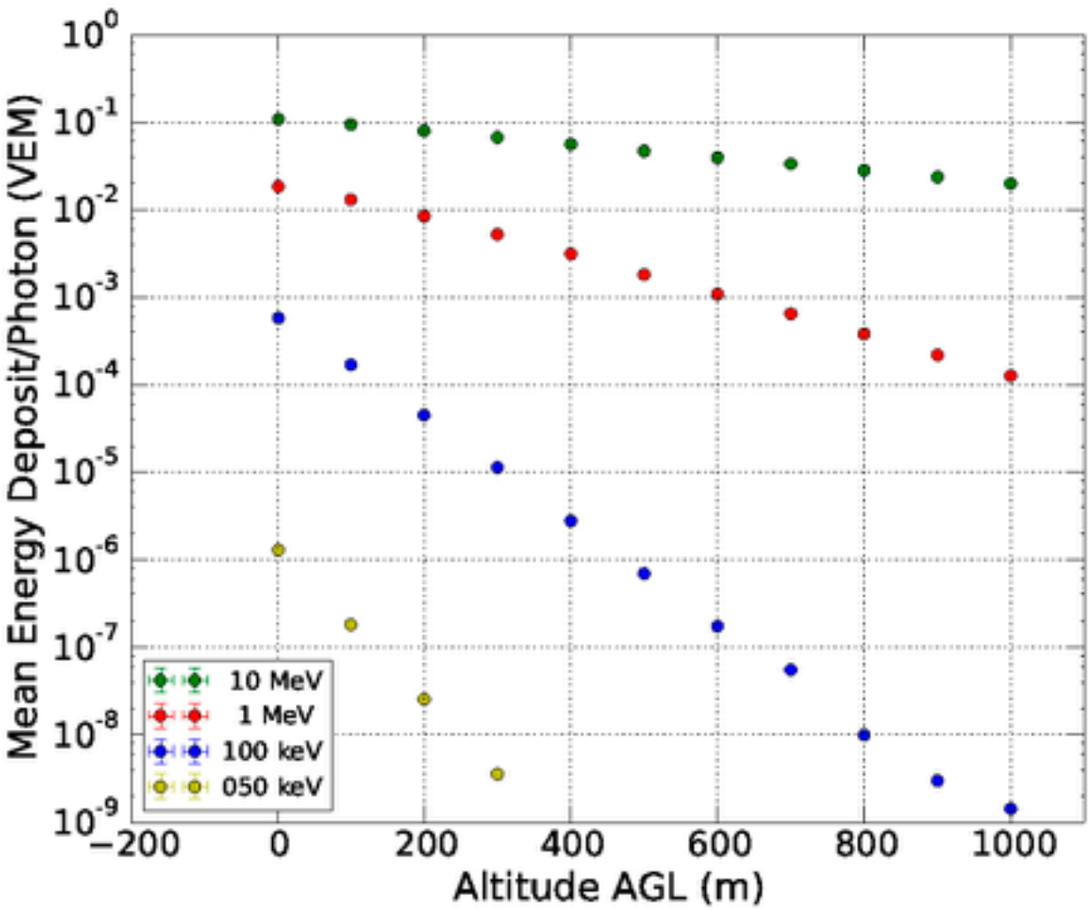


- (4/7 events shown here)
- Overall, similar "message" as LMA events
  - First ms of IC/CG flash
  - Moderate and energetic leaders

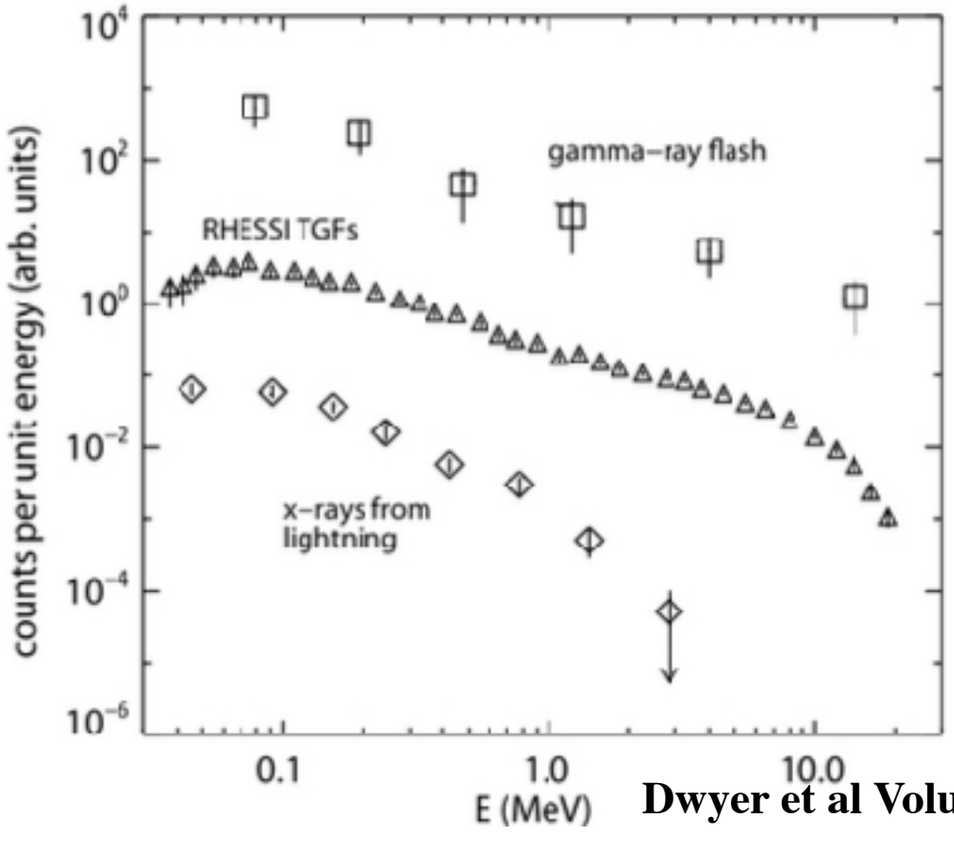
Are we seeing downward TGFs?

- Photon absorption length plateaus at few 10's g/cm² above ~100 keV.
- ~100's of meters @ TA elevations
- Few of the primary photons make it to the ground!





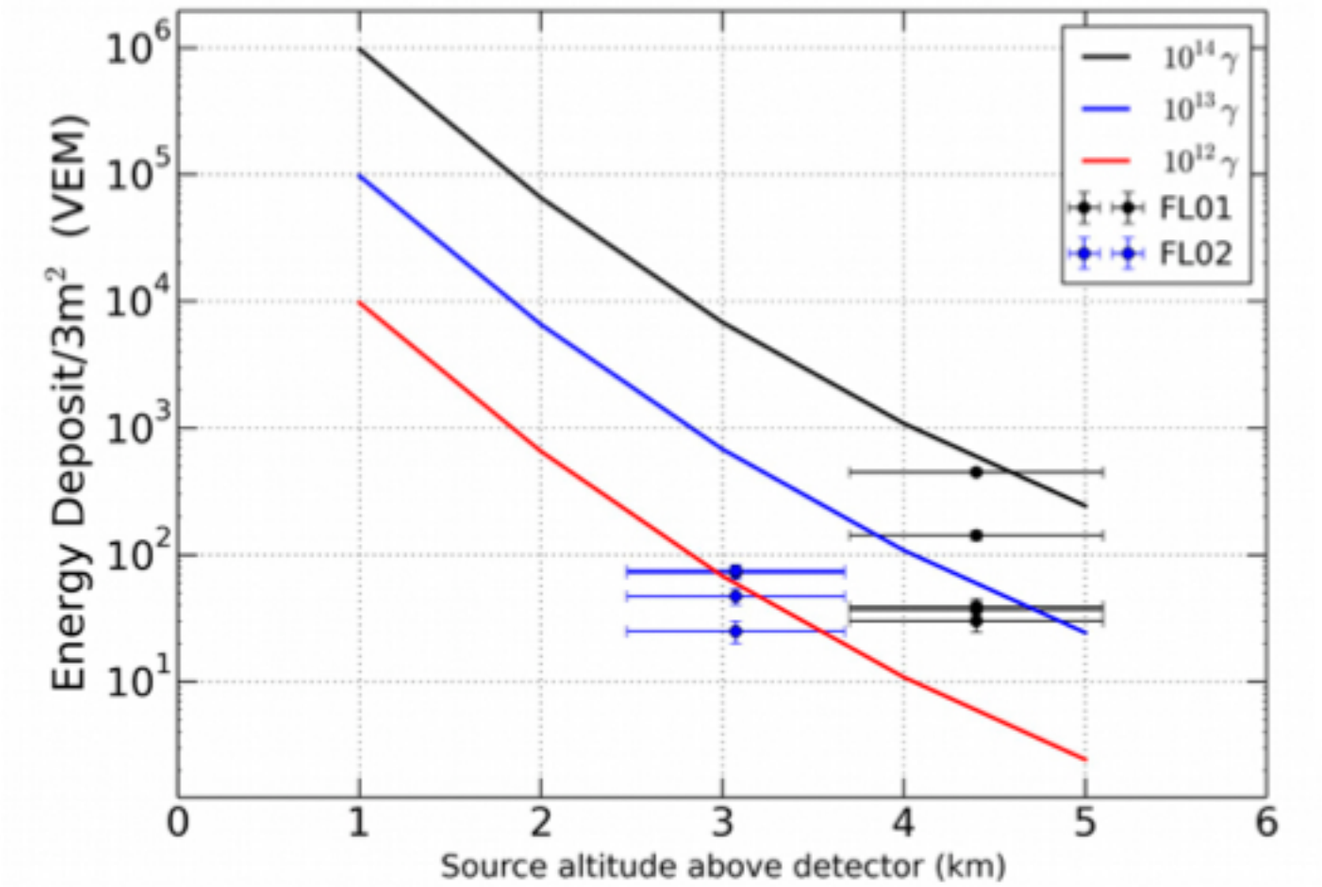
- GEANT4 Simulation: TASD response to RREA-Photon Spectrum at Altitude, including atmosphere.
- Mean energy deposit at low energy falls off much faster than reasonable spectra (i.e. RREA)
- *Conclude that primary photons responsible for TASD signal must be > 1 MeV at altitude.*



Dwyer et al Volume 117, Issue A10 October 2012

Comparison

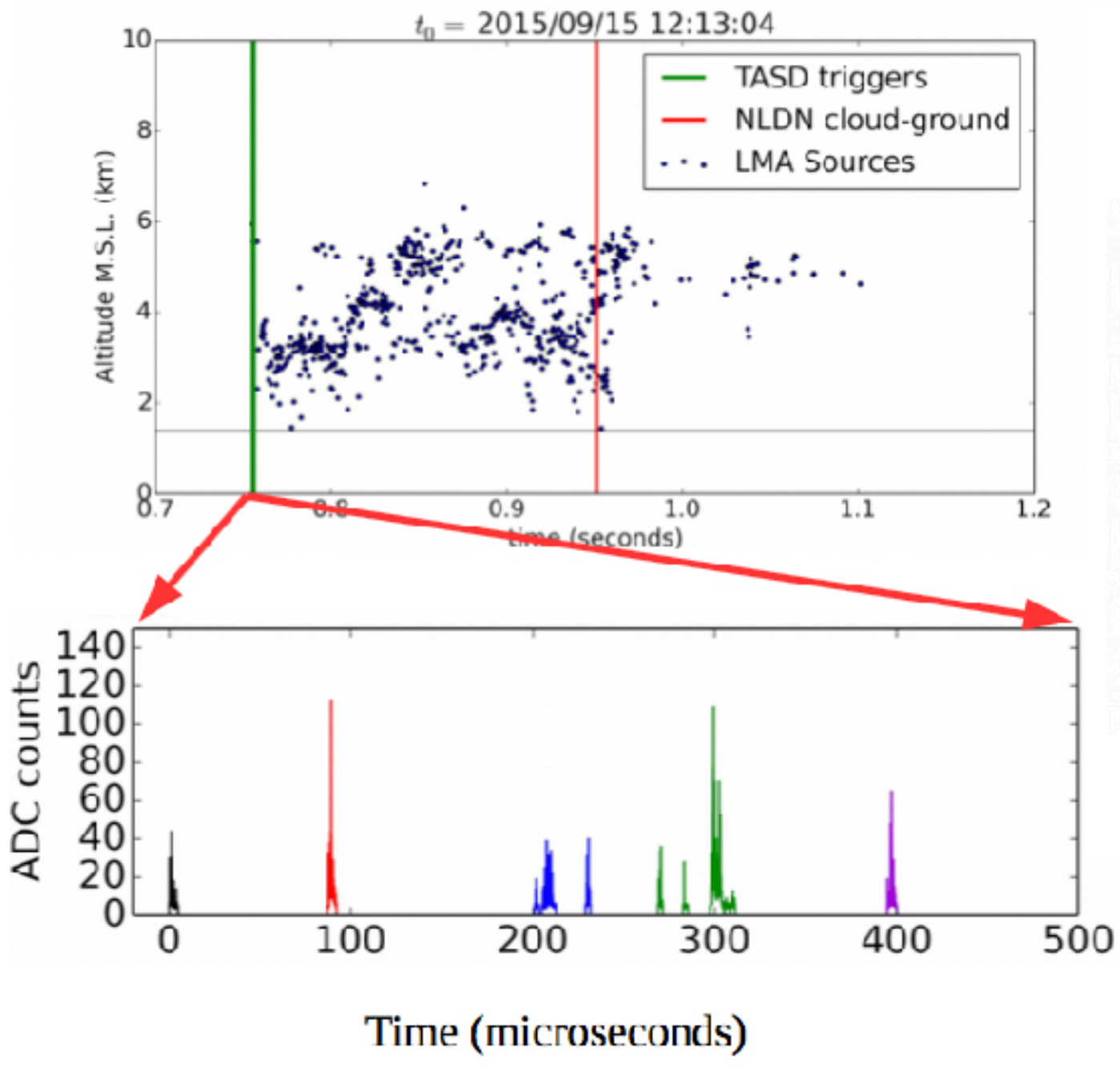
Number of photons



Sources on “low end” of TGF estimates

- Would be below satellite triggering threshold!

Comparison with other observations



- 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"

Celestian and pasko (2012)

Abbasi et al. Journal of Geophysical Research Atmosphere 123 p6864 (2018)

AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE
10.1029/2017JD027931

Gamma Ray Showers Observed at Ground Level in Coincidence With Downward Lightning Leaders

R. U. Abbasi[1], T. Abu-Zayyad[1], M. Allen[1], E. Barcikowski[1], J. W. Belz[1], D. R. Bergman[1], S. A. Blake[1], M. Byrne[1], R. Cady[1], B.G. Cheon[2], J. Chiba[3], M. Chikawa[4], T. Fujii[5], M. Fukushima[5,6], G. Furlich[1], T. Goto[7], W. Hanlon[1], Y. Hayashi[7], N. Hayashida[8], K. Hibino[8], K. Honda[9], D. Ikeda[5], N. Inoue[10], T. Ishii[9], H. Ito[11], D. Ivanov[1], S. Jeong[12], C. C. H. Jui[1], K. Kadota[13], F. Kakimoto[14], O. Kalashev[15], K. Kasahara[16], H. Kawai[17], S. Kawakami[7], K. Kawata[5], E. Kido[5], H. B. Kim[2], J. H. Kim[1], J. H. Kim[18], S. S. Kishigami[7], P. R. Krehbiel[19], V. Kuzmin[15], Y. J. Kwon[20], J. Lan[1], R. LeVon[1], J. P. Lundquist[1], K. Machida[9], K. Martens[6], T. Matuyama[7], J. N. Matthews[1], M. Minamino[7], K. Mukai[9], I. Myers[1], S. Nagataki[11], R. Nakamura[21], T. Nakamura[22], T. Nonaka[5], S. Ogio[7], M. Ohnishi[5], H. Ohoka[5], K. Oki[5], T. Okuda[23], M. Ono[24], R. Onogi[7], A. Oshima[25], S. Ozawa[16], I. H. Park[12], M. S. Pshirkov[13,26], J. Remington[1], W. Rison[19], D. Rodeheffer[19], D. C. Rodriguez[1], G. Rubtsov[15], D. Ryu[18], H. Sagawa[5], K. Saito[5], N. Sakaki[5], N. Sakurai[7], T. Seki[21], K. Sekino[5], P.D. Shah[1], F. Shibata[9], T. Shibata[5], H. Shimodaira[5], B. K. Shin[7], H. S. Shin[5], J. D. Smith[1], P. Sokolsky[1], R. W. Springer[1], B. T. Stokes[1], T. A. Stroman[1], H. Takai[27], M. Takeda[5], R. Takeishi[5], A. Taketa[28], M. Takita[5], Y. Tameda[29], H. Tanaka[7], K. Tanaka[30], M. Tanaka[31], R. J. Thomas[19], S. B. Thomas[1], G. B. Thomson[1], P. Tinyakov[15,32], I. Tkachev[15], H. Tokuno[14], T. Tomida[21], S. Troitsky[15], Y. Tsunesada[7], Y. Uchihori[33], S. Udo[8], F. Urban[32], G. Vasiloff[1], T. Wong[1], M. Yamamoto[21], R. Yamane[7], H. Yamaoka[31], K. Yamazaki[28], J. Yang[34], K. Yashiro[3], Y. Yoneda[7], S. Yoshida[17], H. Yoshii[35] and Z. Zundel[1]

[1]High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA, [2]Department of Physics and The Research Institute of Natural Science, Hanyang University, Seoul, Korea, [3]Department of Physics, Tokyo University of Science, Noda, Japan, [4]Department of Physics, Kinki University, Higashi-osaka, Japan, [5]Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Japan, [6]Kavli Institute for the Physics and Mathematics

Key Points:
- Gamma ray showers have been detected in a surface scintillator array coincident with lightning observed by a lightning mapping array or Delta *E* antenna
- The showers were produced less than 4–5 km above ground in the first 1–2 ms of downward negative breakdown during cloud-to-ground flashes
- The source durations are better resolved than for satellite observations and are consistent with being produced by stepping of the initial leader breakdown

Supporting Information:
- Supporting Information S1

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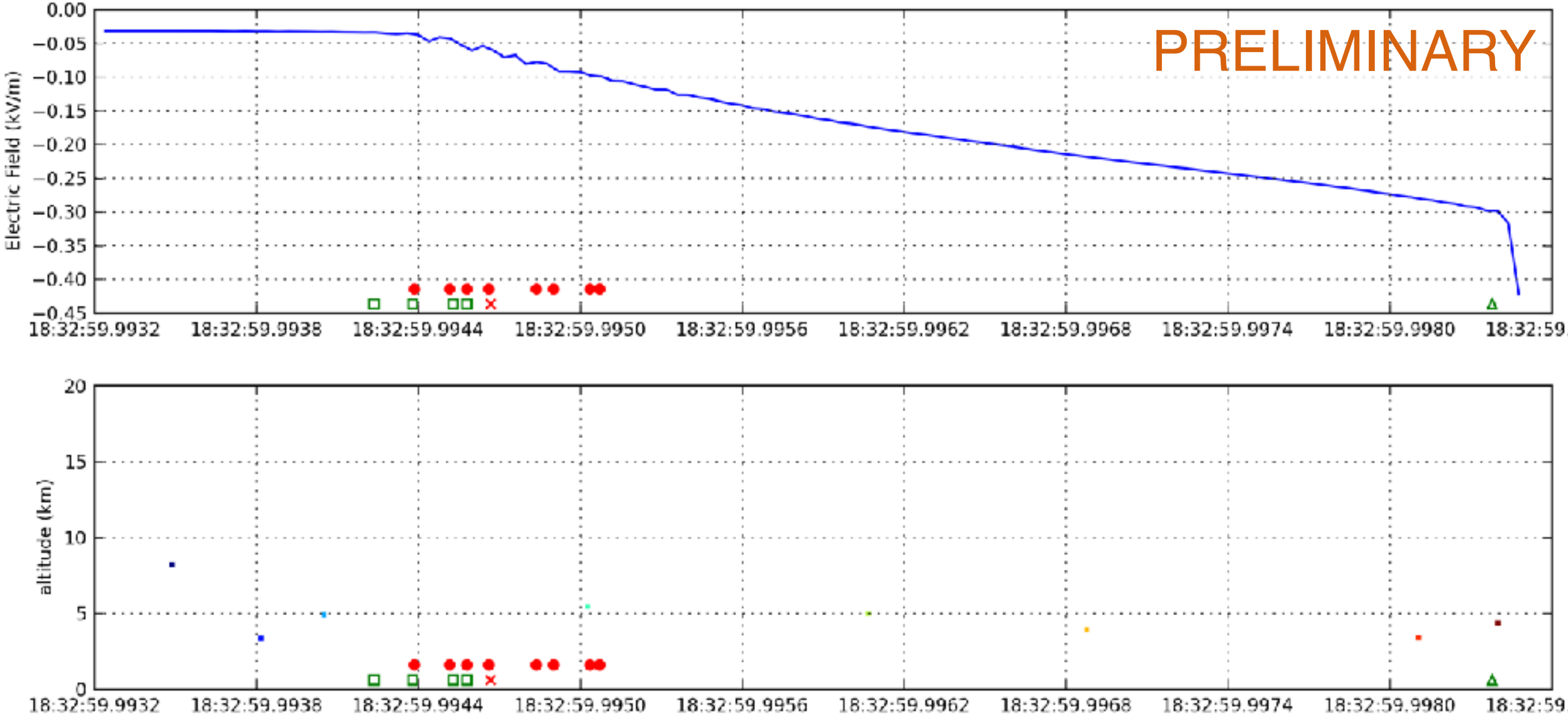
Abbasi, R. U., Abu-Zayyad, T., Allen, M., Barcikowski, E., Belz, J. W., Bergman, D. R., et al. (2018). Gamma

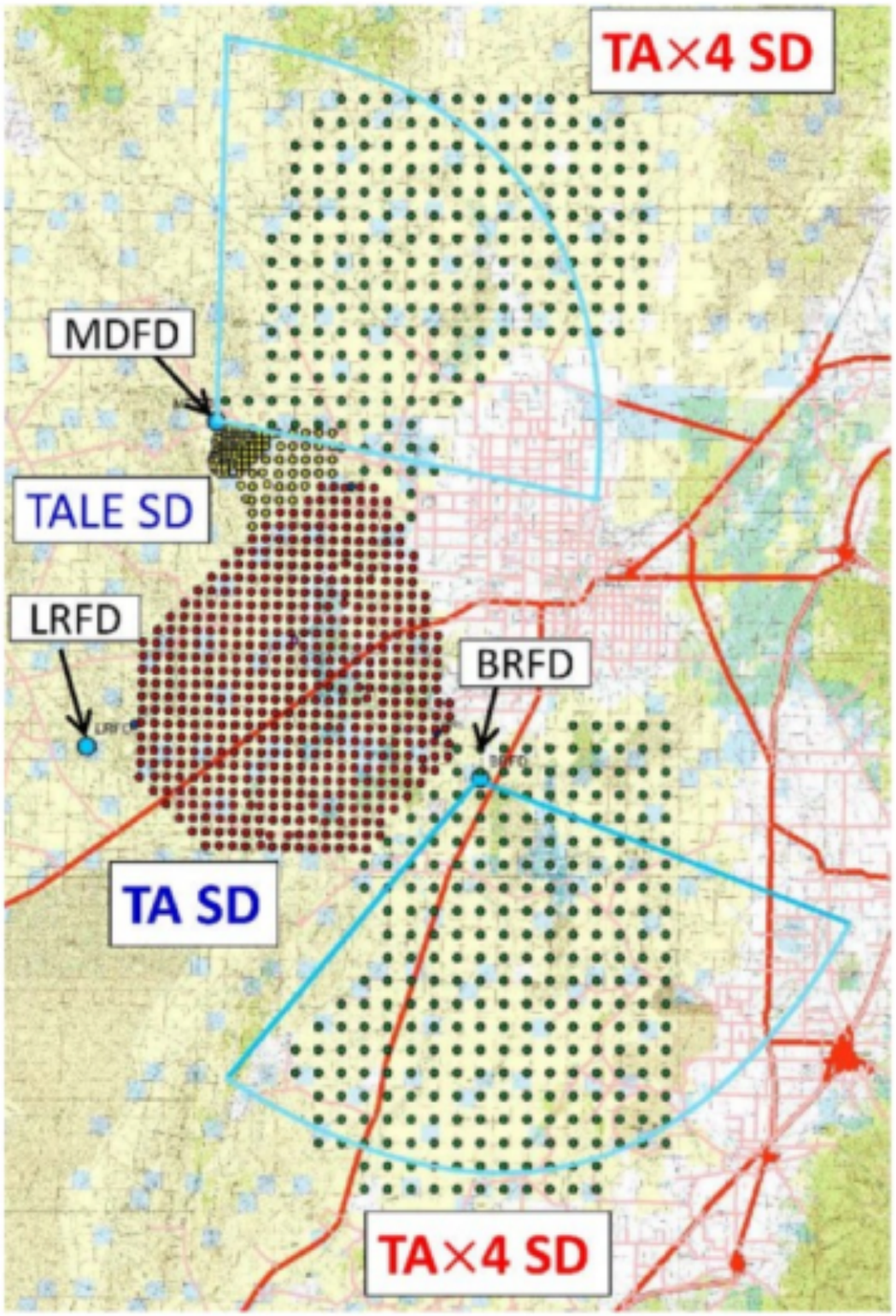
First observation of TGF with slow antenna, LMA, TASD, and NLDN



TGF observed on 2017 Sep 12th

- 9 10^5 m/s .
- Multiple IC observations followed by an energetic CG w/peak current of -113kA.

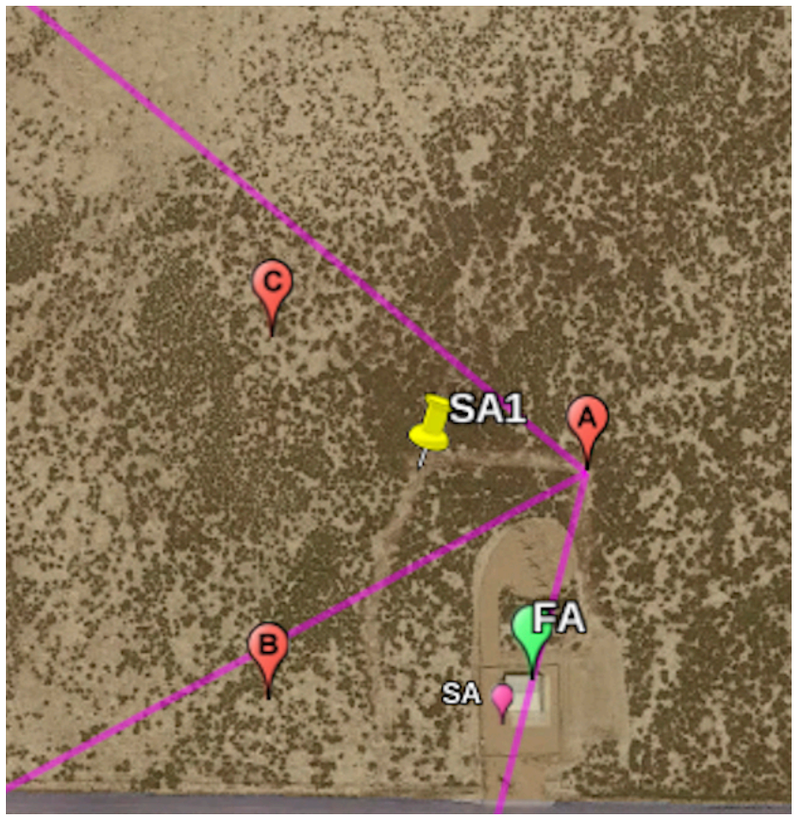
TA x 4 Project

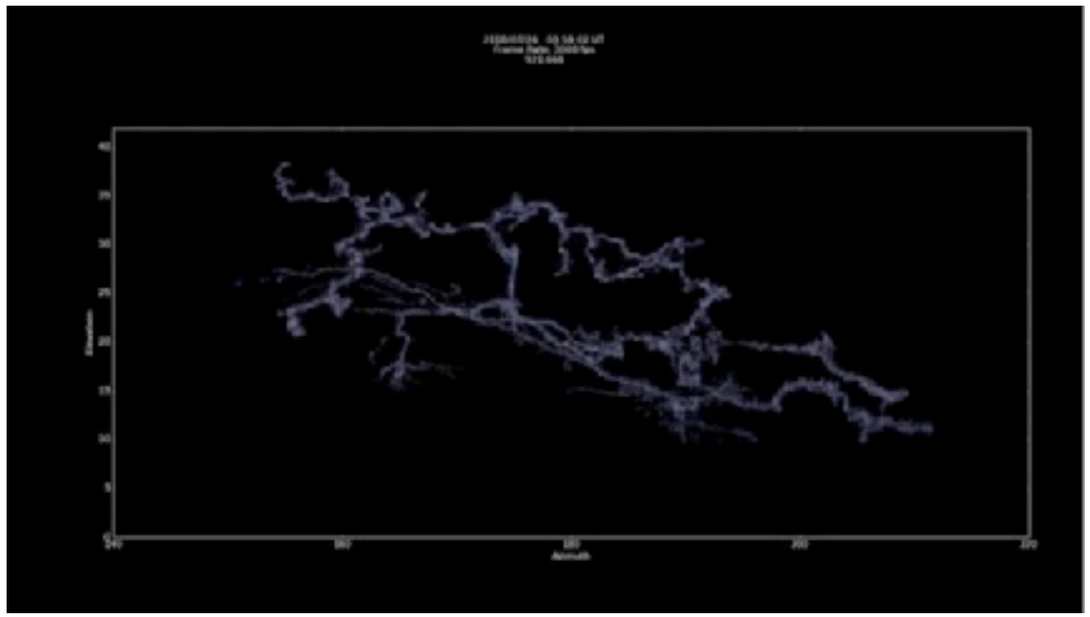


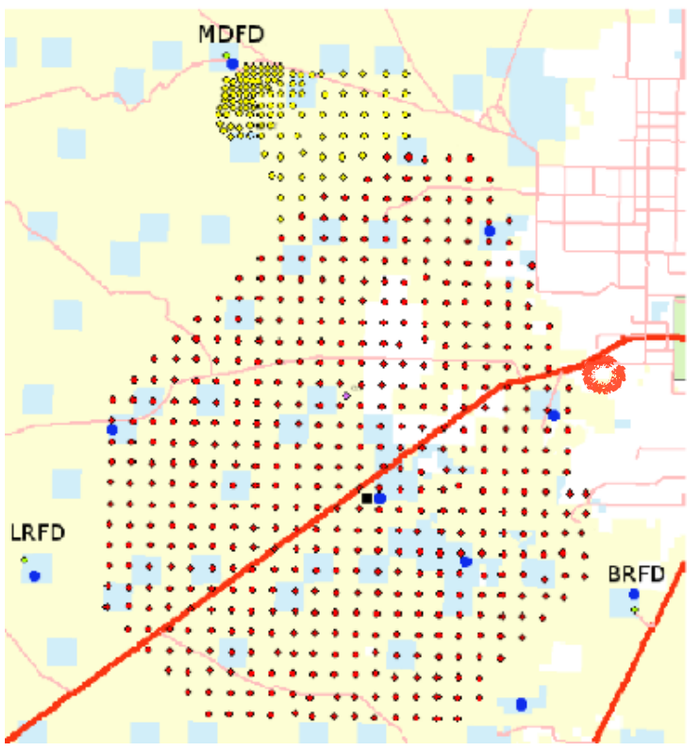
- world largest sample of downward observed gamma rays.
- we will have10 Events per year.

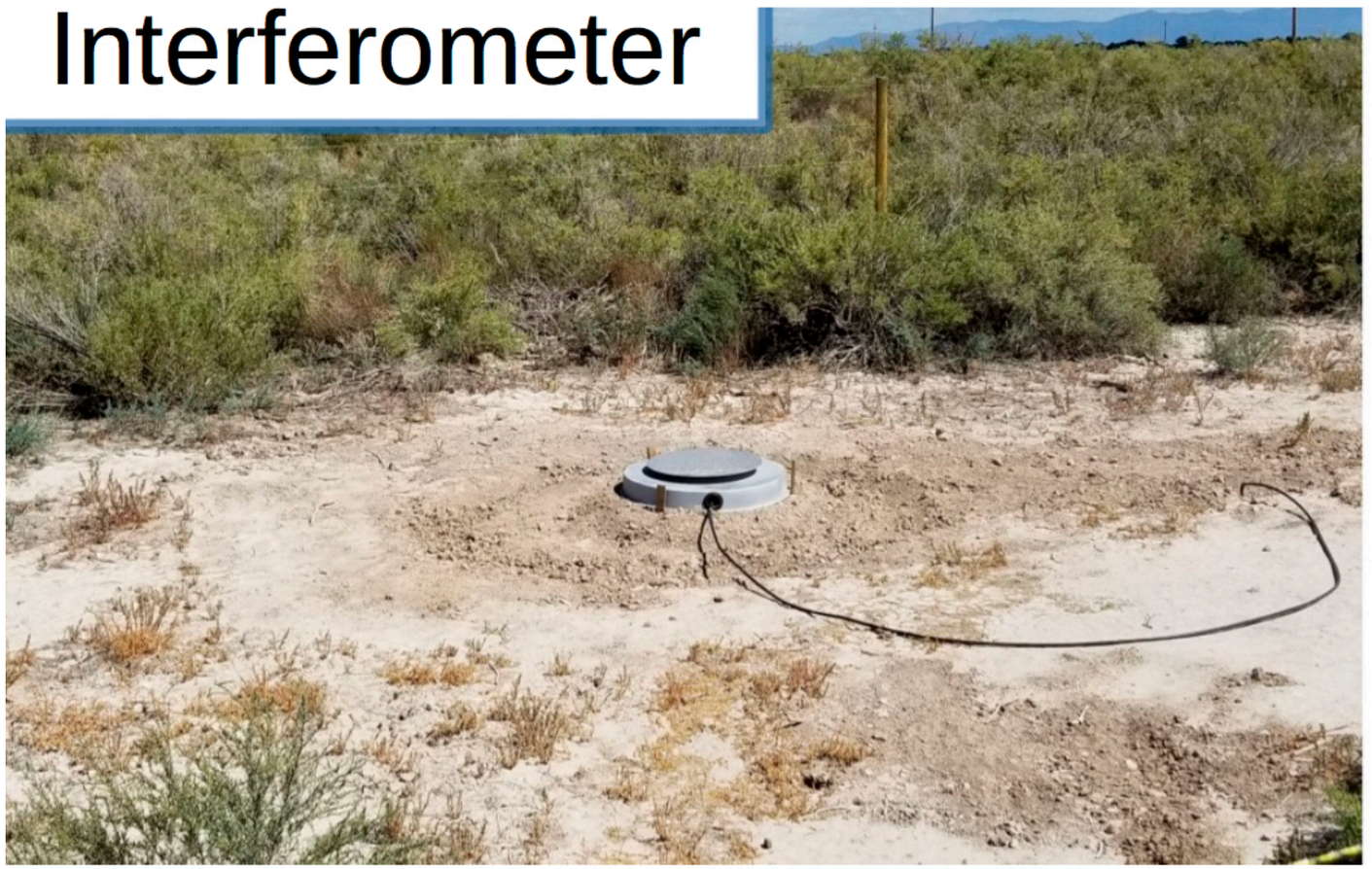
BREAKING NEWS!

Interferometer





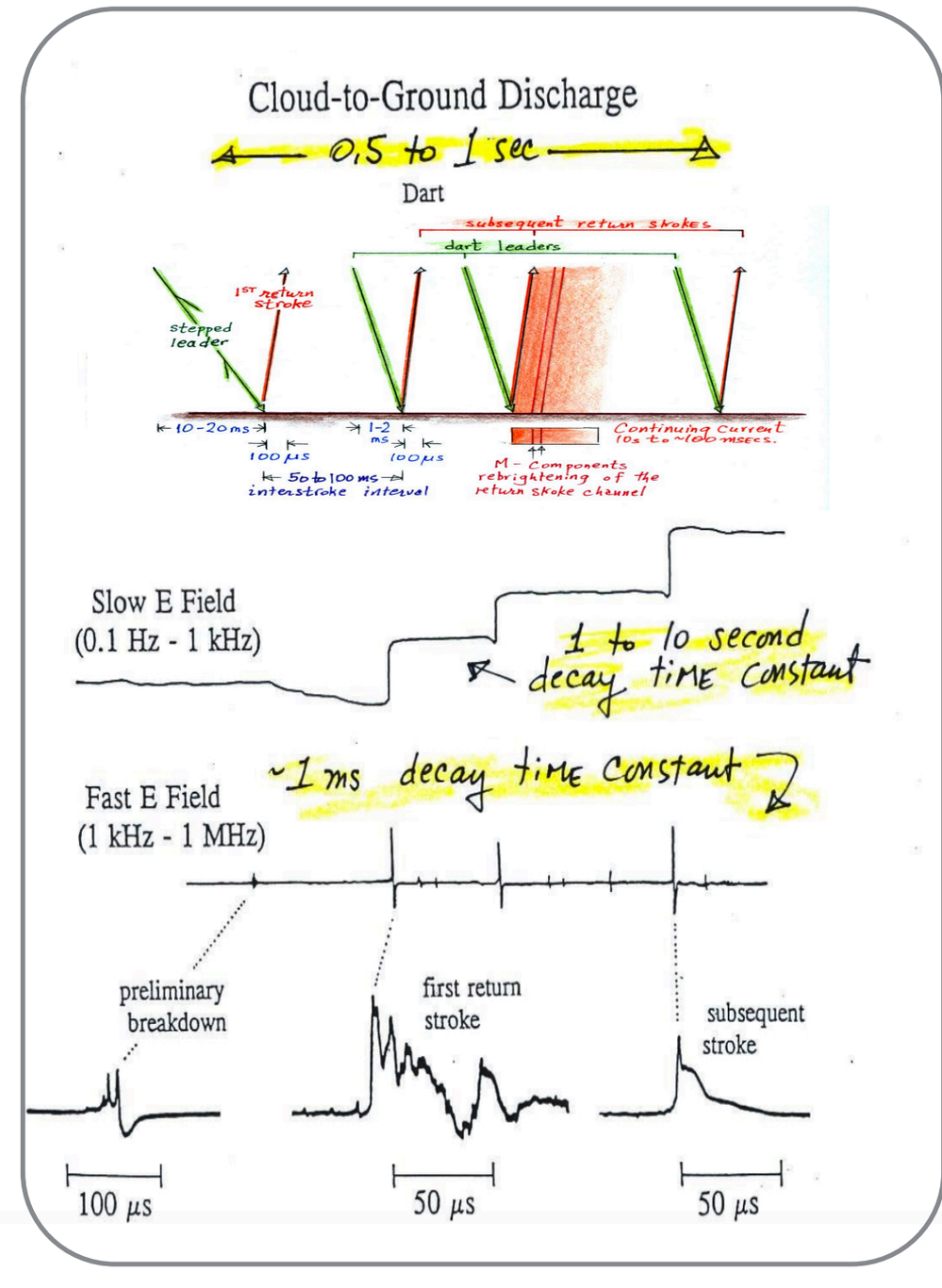




Slow antenna

- GPS-timed capacitor, read out with 10 s time constant.

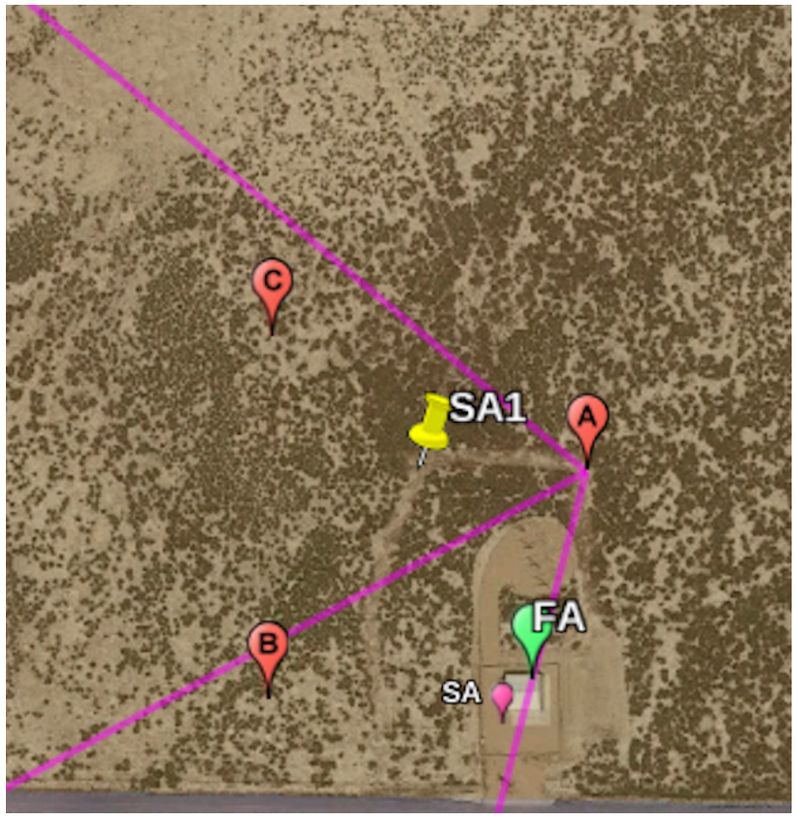
- Record electric field between 10 mV/m and 10 kV/m

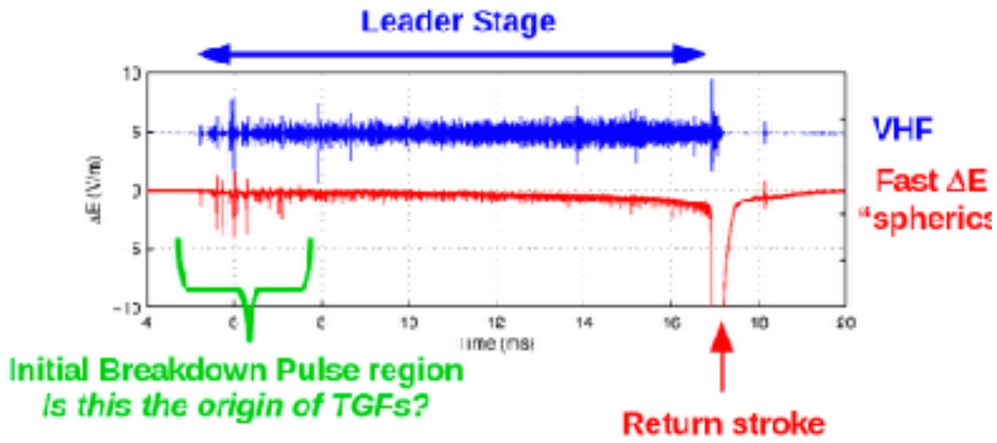


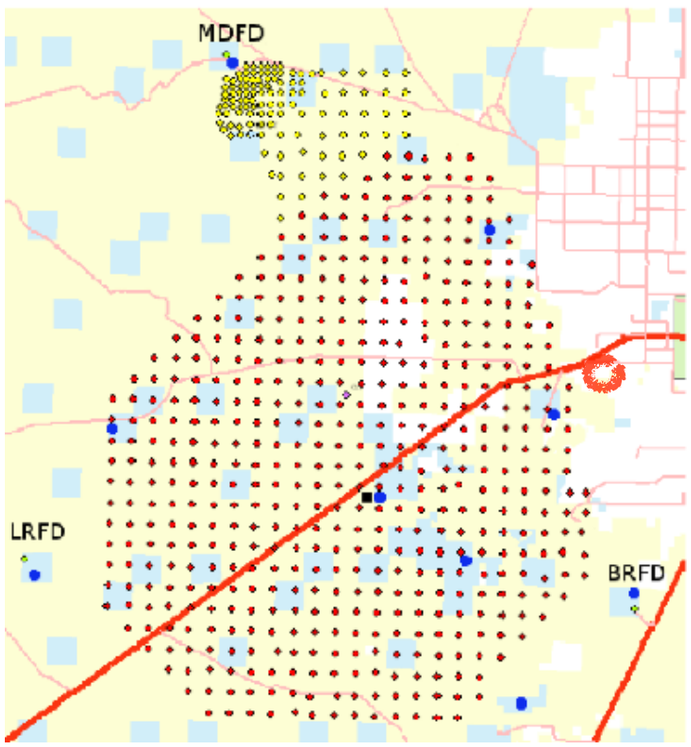
Slow Antenna

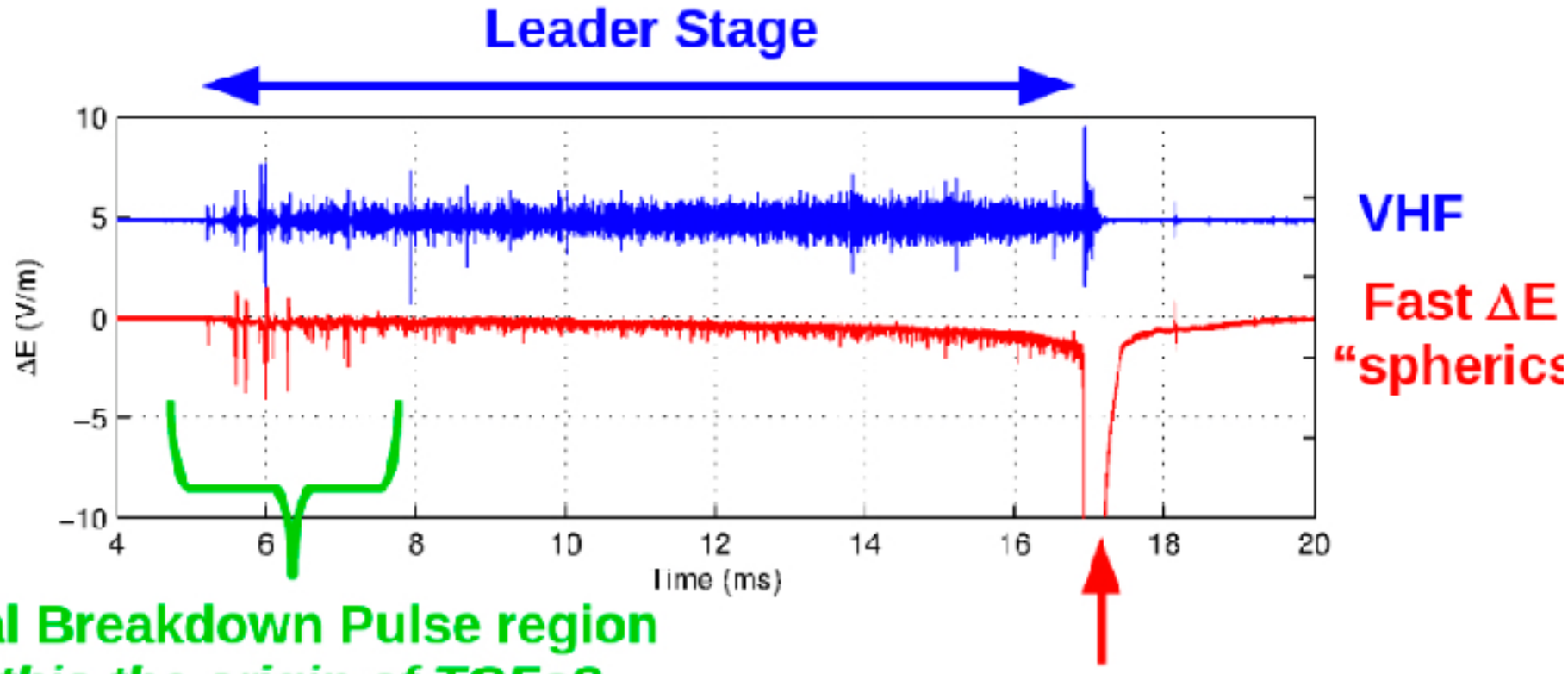
Fast Antenna

Fast Antenna

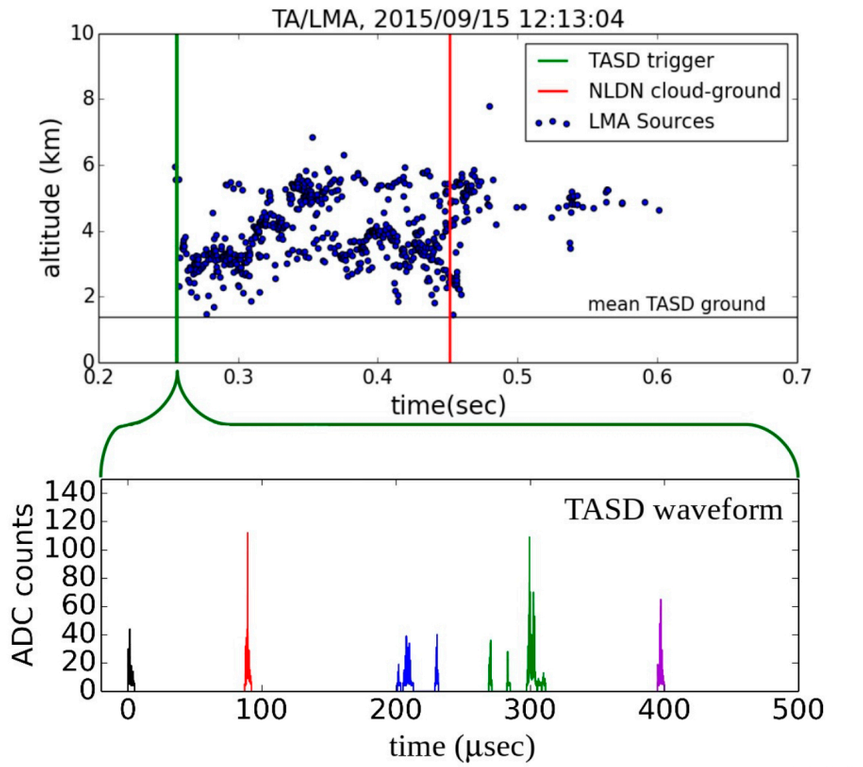


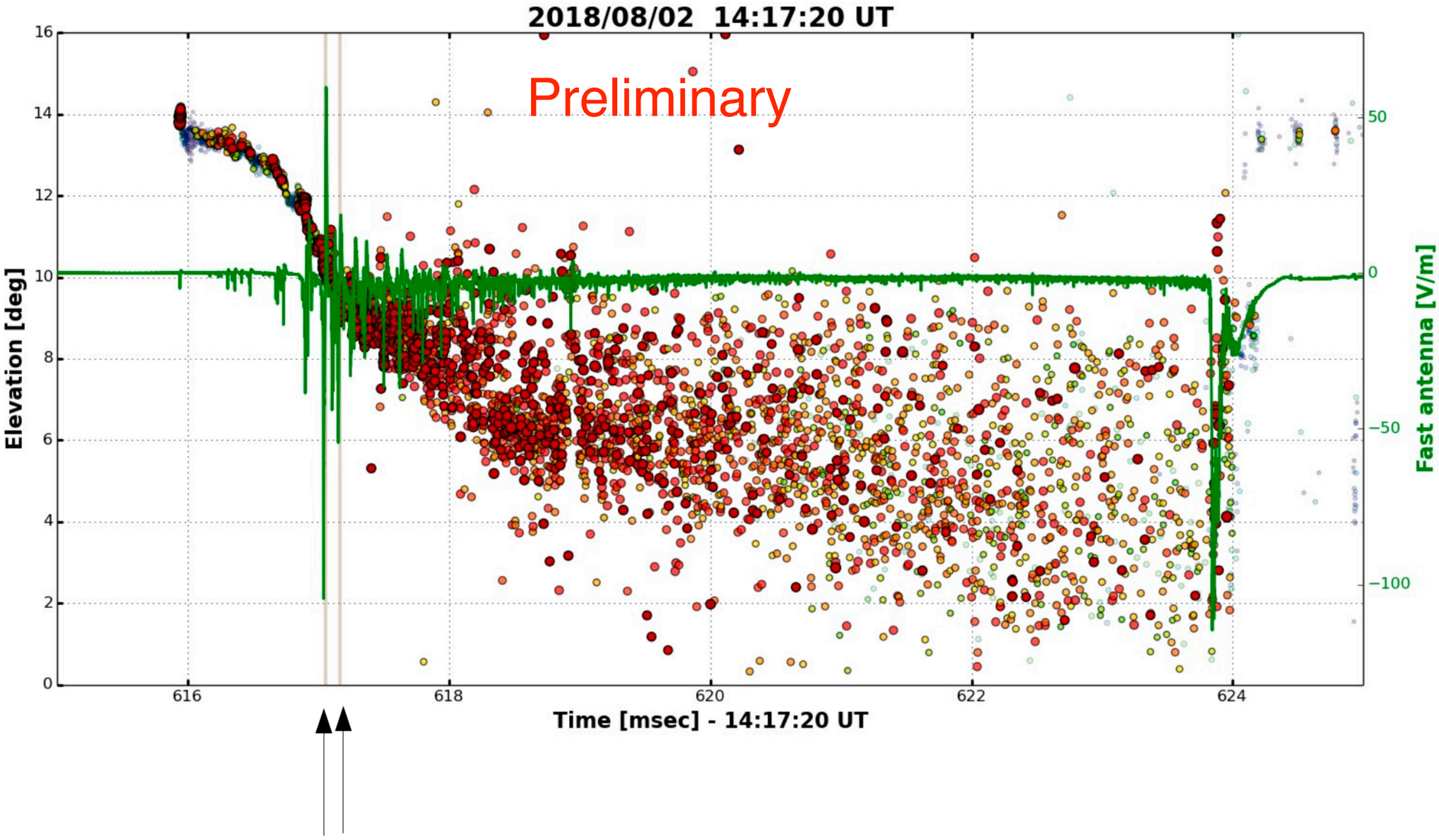




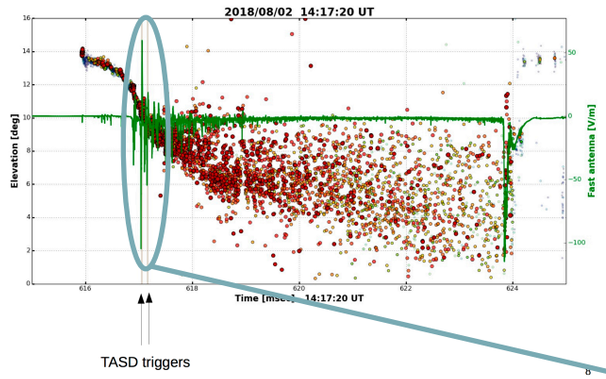


P.Krehbiel *et al*





TASD triggers



Preliminary

SUMMARY

- observed 25 TASD bursts in coincidence with lightning (world largest sample of downward observed gamma rays).

- 15 observed with LMA or slow antenna.

- Originate TGF observations to the **IBPs** of lightning.

- Forward-beamed showers of 10^{12}-10^{14} primary photons.

- First observed event with INTF and Fast antenna correlating observed TGF with two particularly energetic leader steps.

a FL1

Altitude vs. time

Altitude, km MSL

Time, sec after 12:13:04

b

Altitude vs. time

Time, sec after 12:13:04

c FL2

Altitude, km MSL

Time, sec after 19:37:01

d

Time, sec after 19:37:01

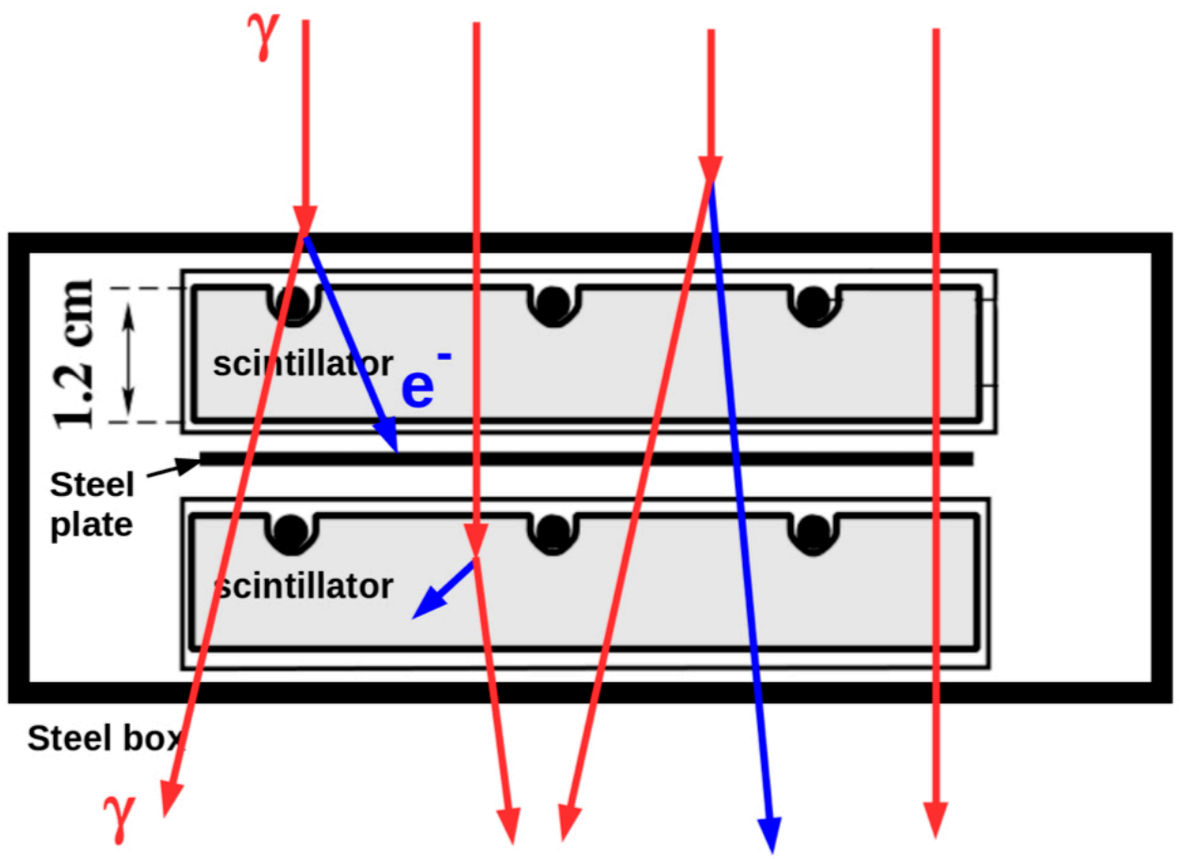
e FL3

Altitude, km MSL

Time, sec after 02:41:50

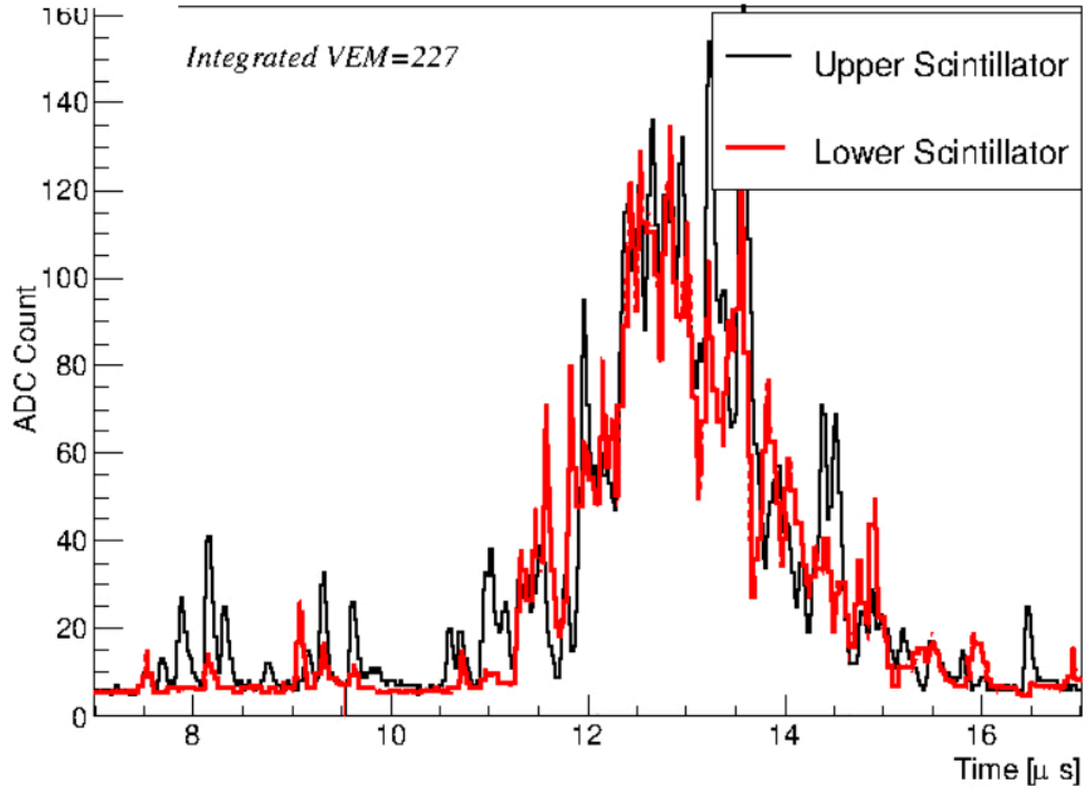
f

Time, sec after 02:41:50

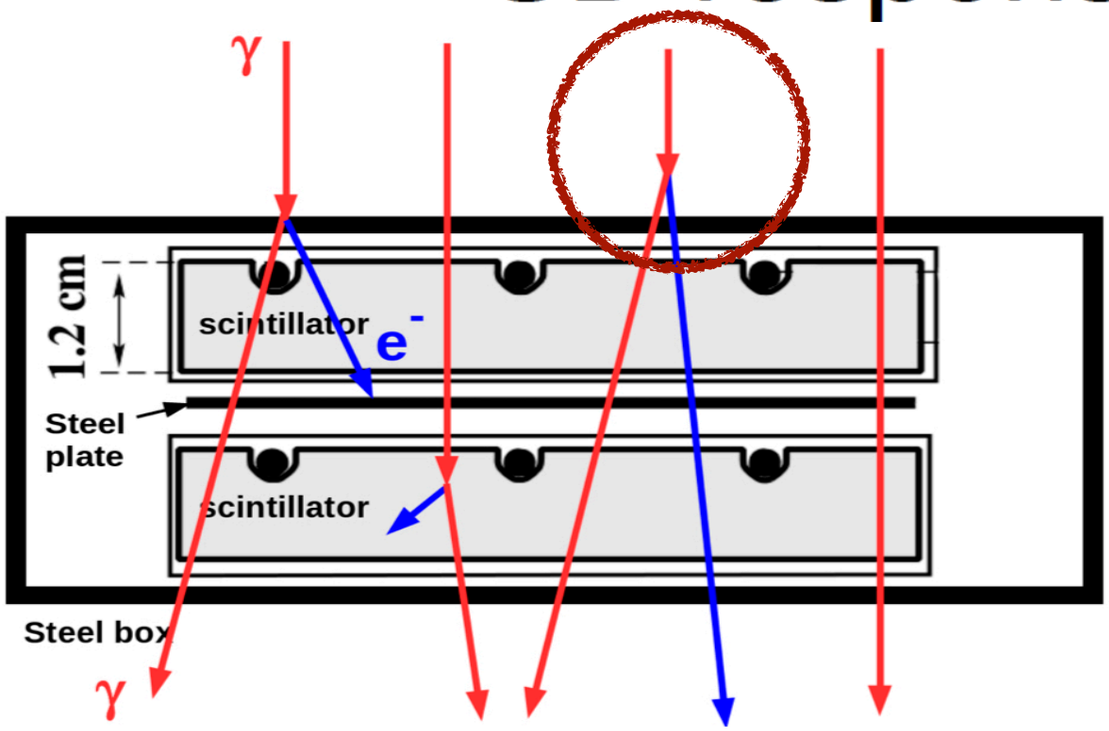


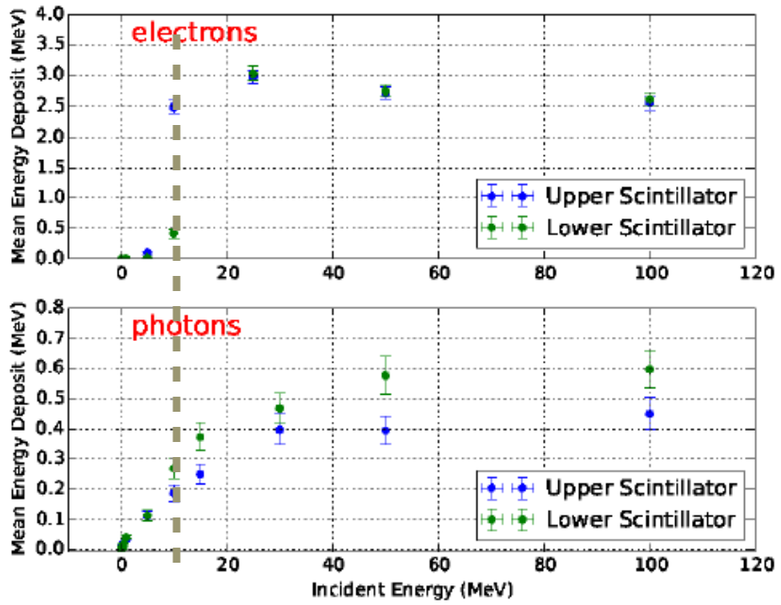
Are these
γ-ray showers?

- 1VEM ~ 30 ADC
- 1 ADC count ~ 70 keV
- Photon 170 keV

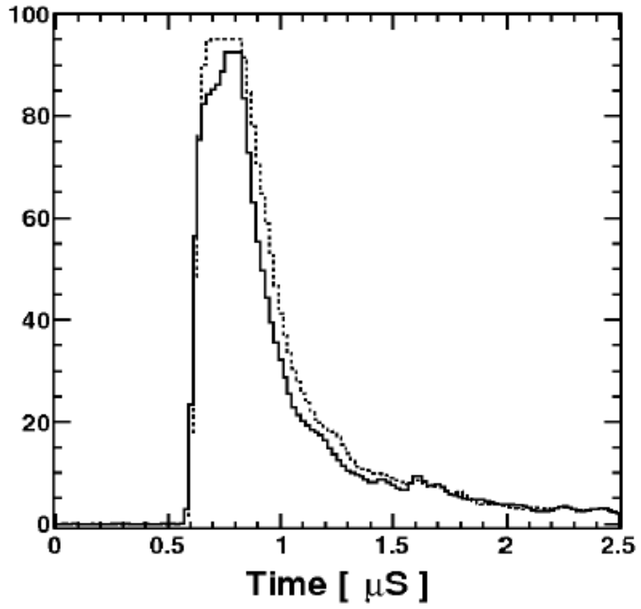


SD response: γ and $e^{\pm}$

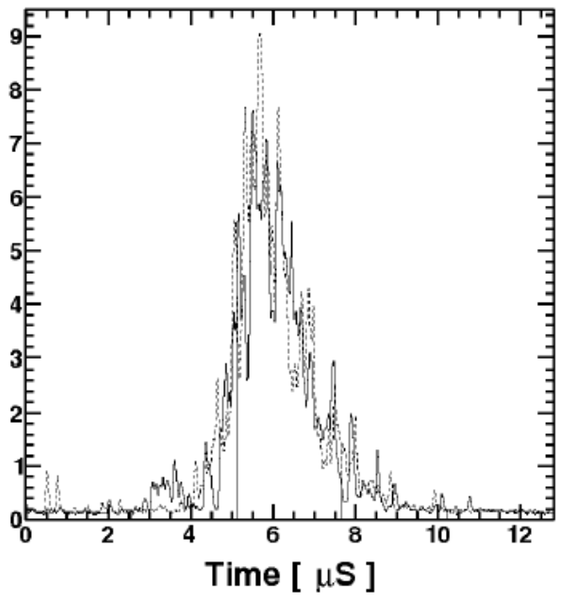




GEANT4 simulation



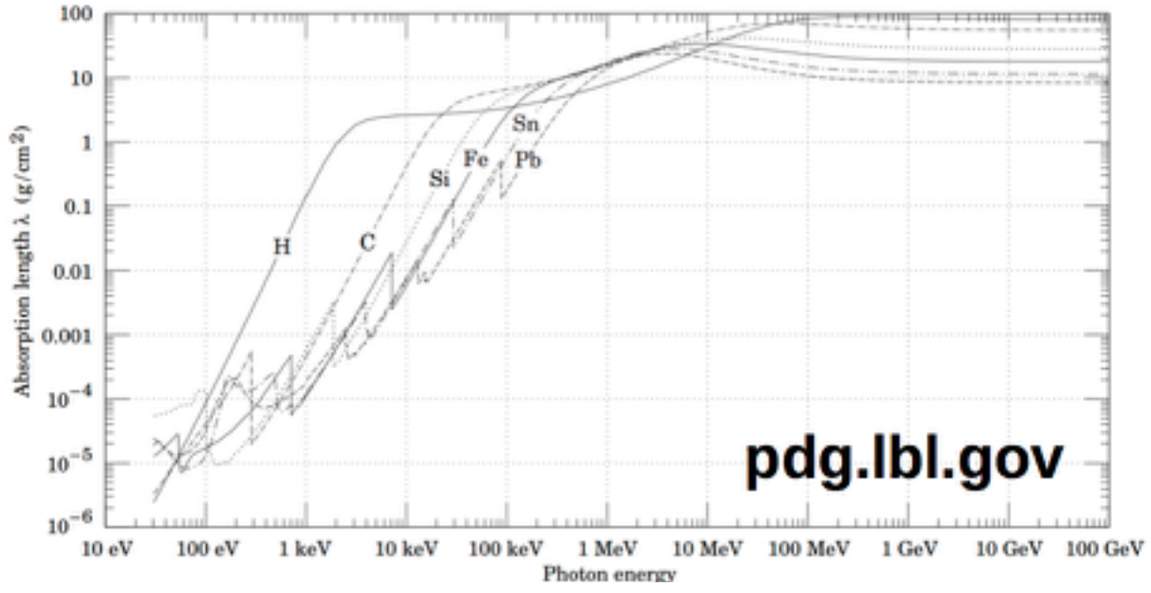
Cosmic ray core waveform



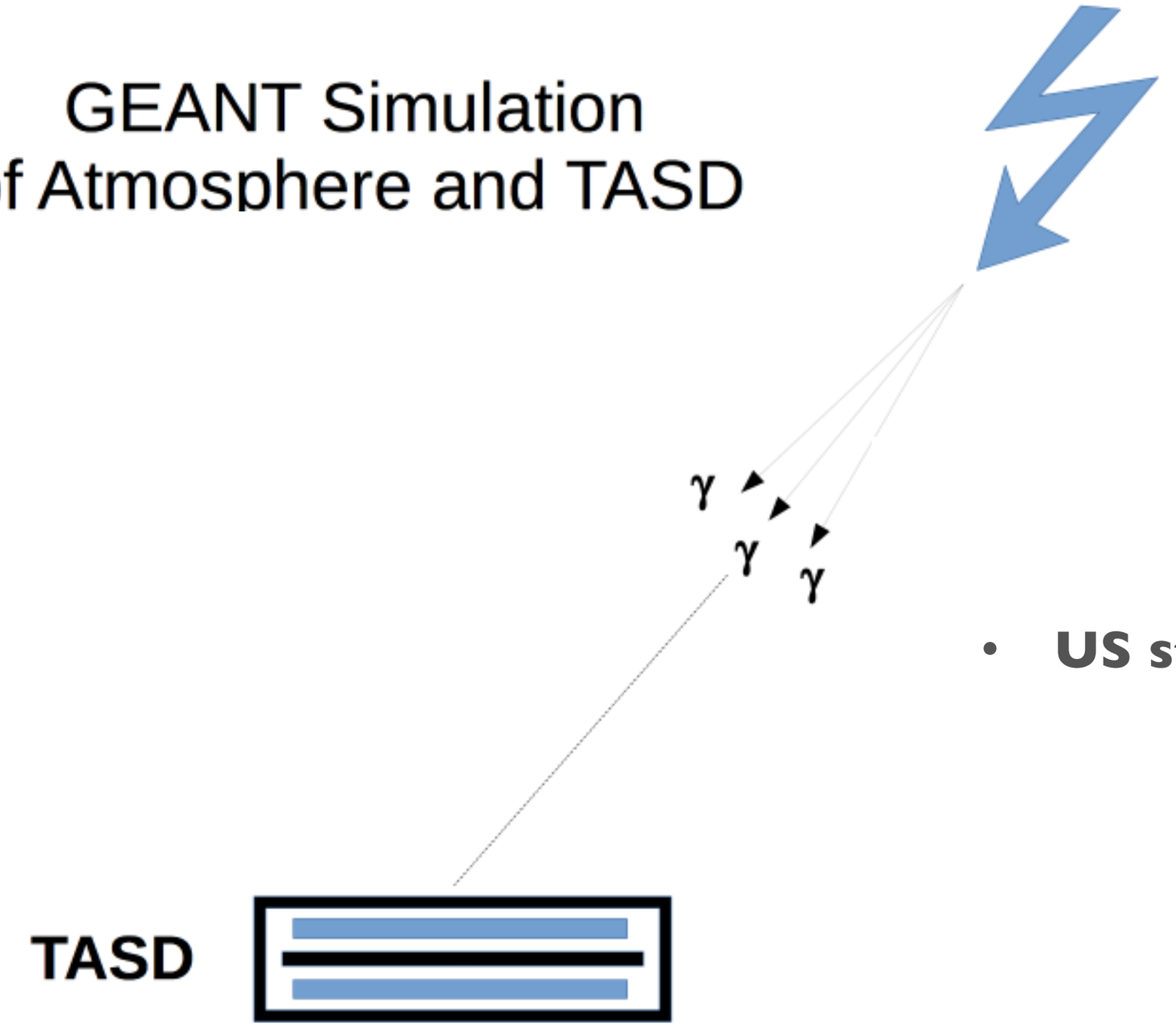
Leader-coincident core waveform

Are we seeing downward TGFs?

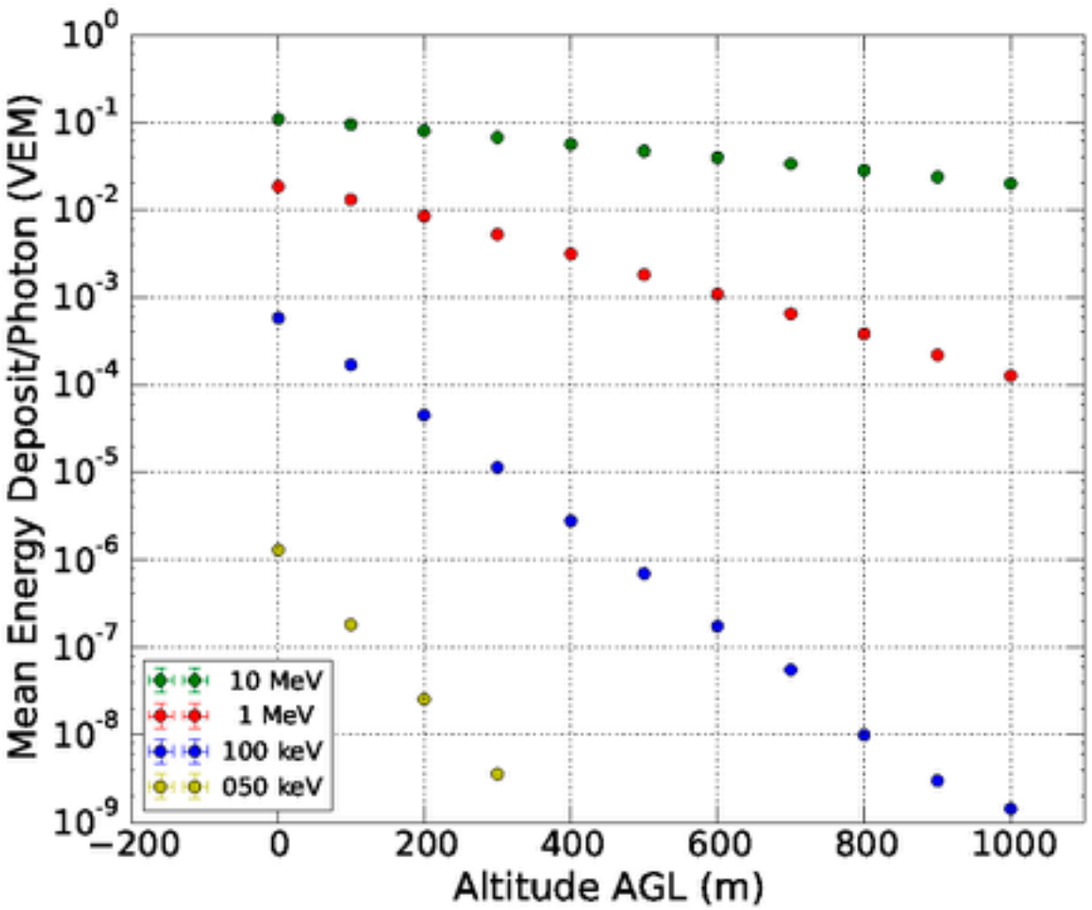
- Photon absorption length plateaus at few 10's g/cm² above ~100 keV.
- ~100's of meters @ TA elevations
- Few of the primary photons make it to the ground!



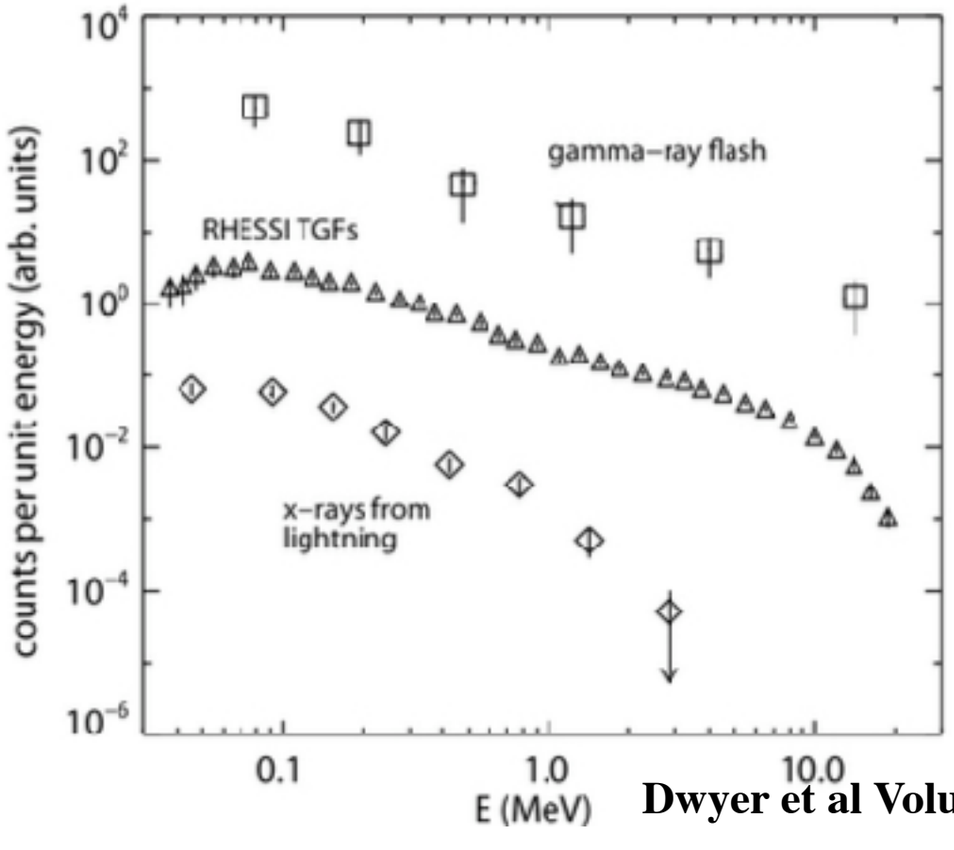
GEANT Simulation of Atmosphere and TASD



- **US standard atmosphere**



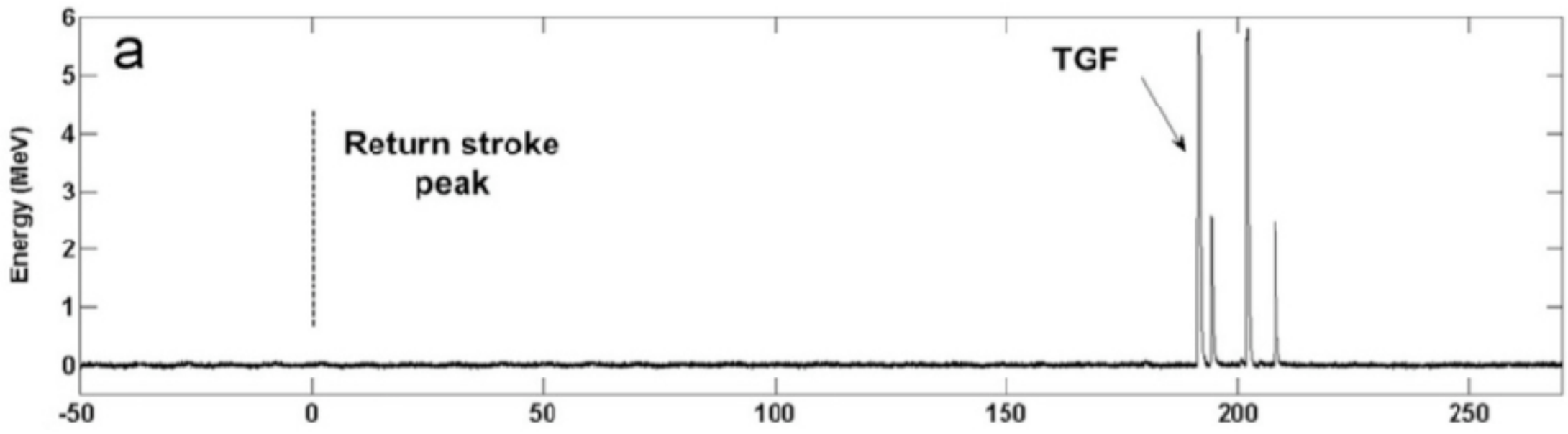
- GEANT4 Simulation: TASD response to RREA-Photon Spectrum at Altitude, including atmosphere.
- Mean energy deposit at low energy falls off much faster than reasonable spectra (i.e. RREA)
- *Conclude that primary photons responsible for TASD signal must be > 1 MeV at altitude.*



Dwyer et al Volume 117, Issue A10 October 2012

Tran et al, J. Atmos. & Solar-Terrestrial Phys **136** 86–93 (2015)

- Ground-Based TGF #2
- 20140613
- During natural 224 kA –CG return stroke
- 191 μs after peak of ground stroke
- 6 γ's ≤ 5.7 MeV
- *No radiation prior to ground stroke, TGF after.*



a FL1

Altitude vs. time

Altitude, km MSL

Time, sec after 12:13:04

b

Altitude vs. time

Time, sec after 12:13:04

c FL2

Altitude, km MSL

Time, sec after 19:37:01

d

Time, sec after 19:37:01

e FL3

Altitude, km MSL

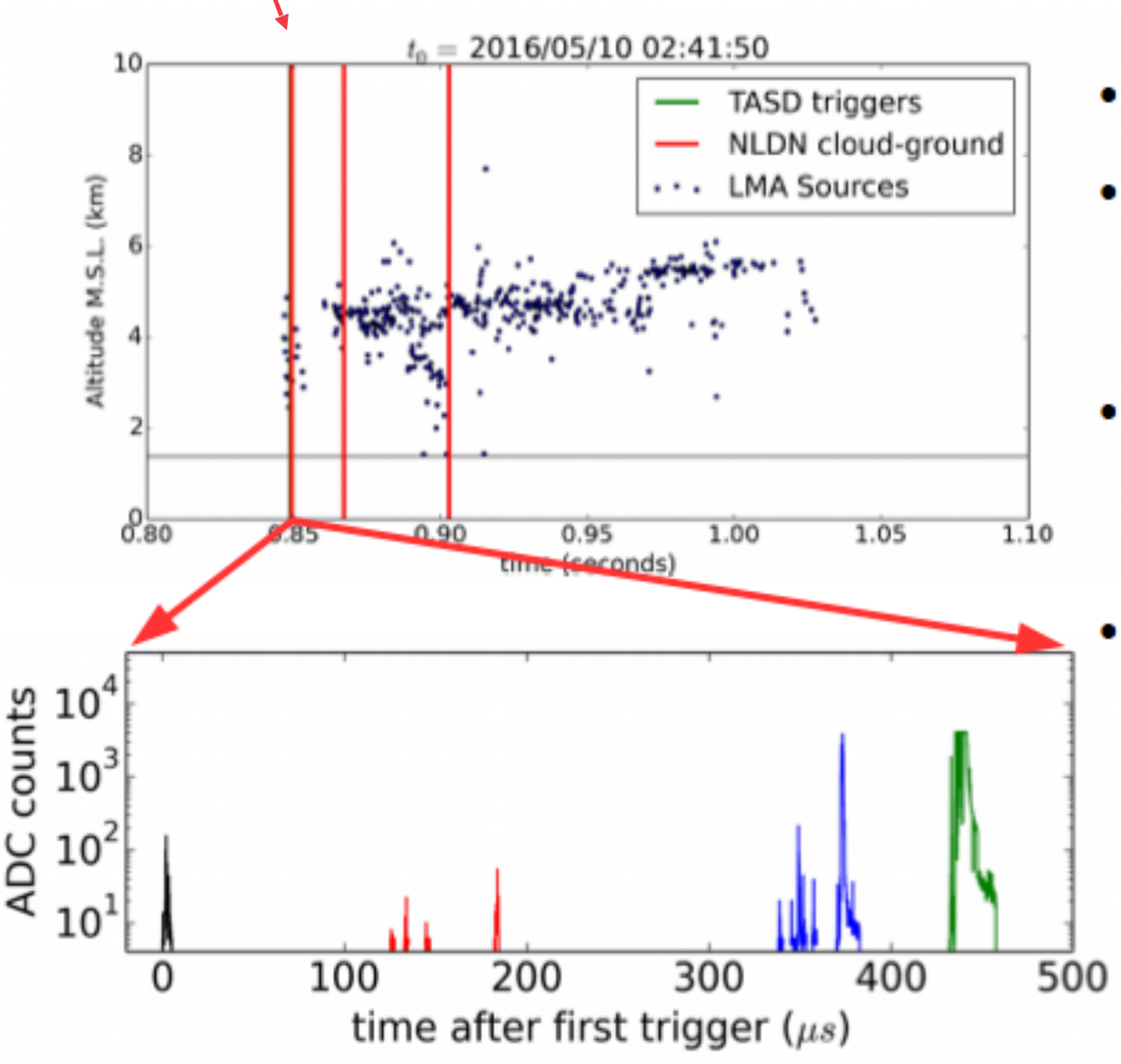
Time, sec after 02:41:50

f

Time, sec after 02:41:50

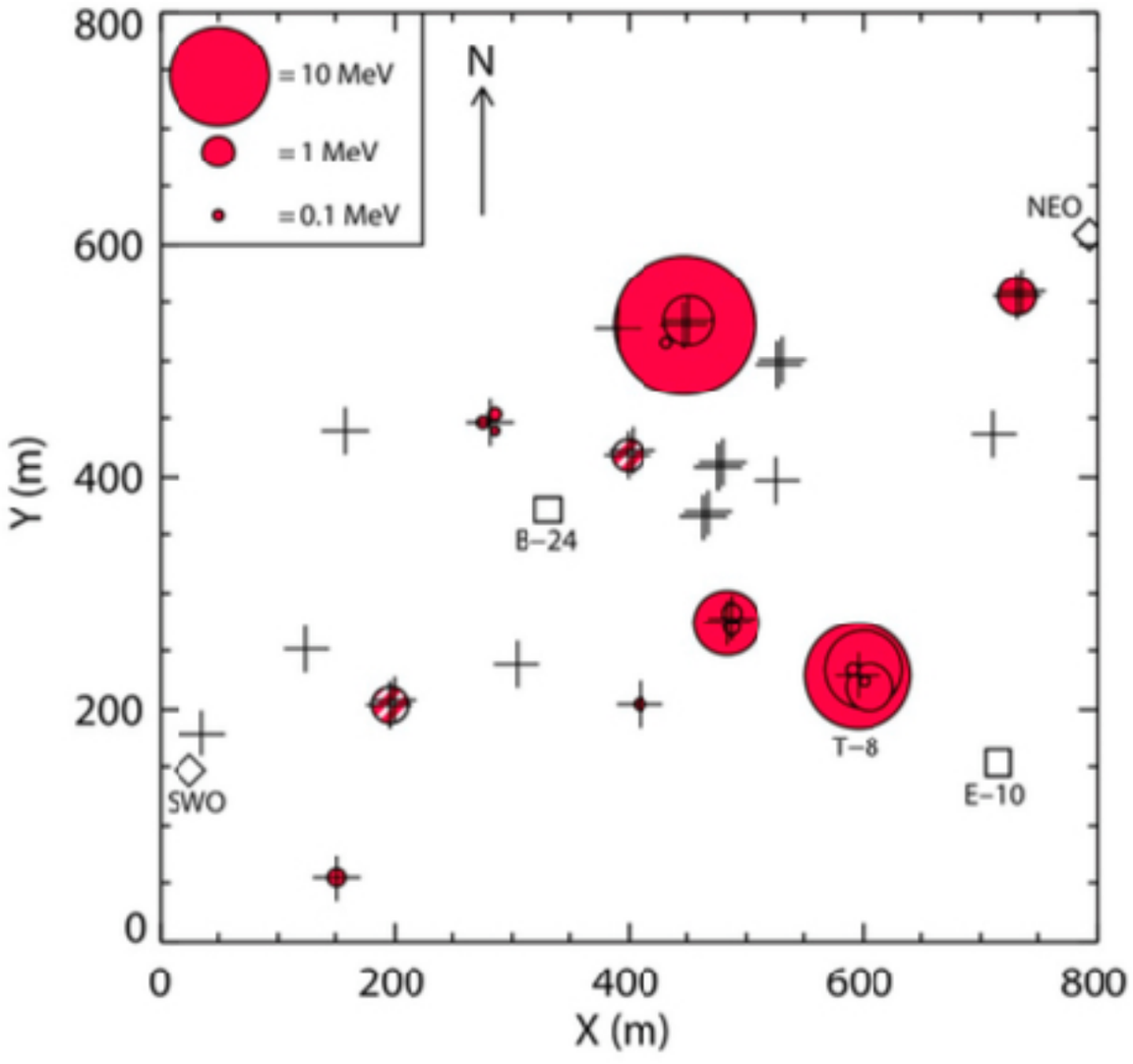
TA/LMA “Flash 3”

-94 kA

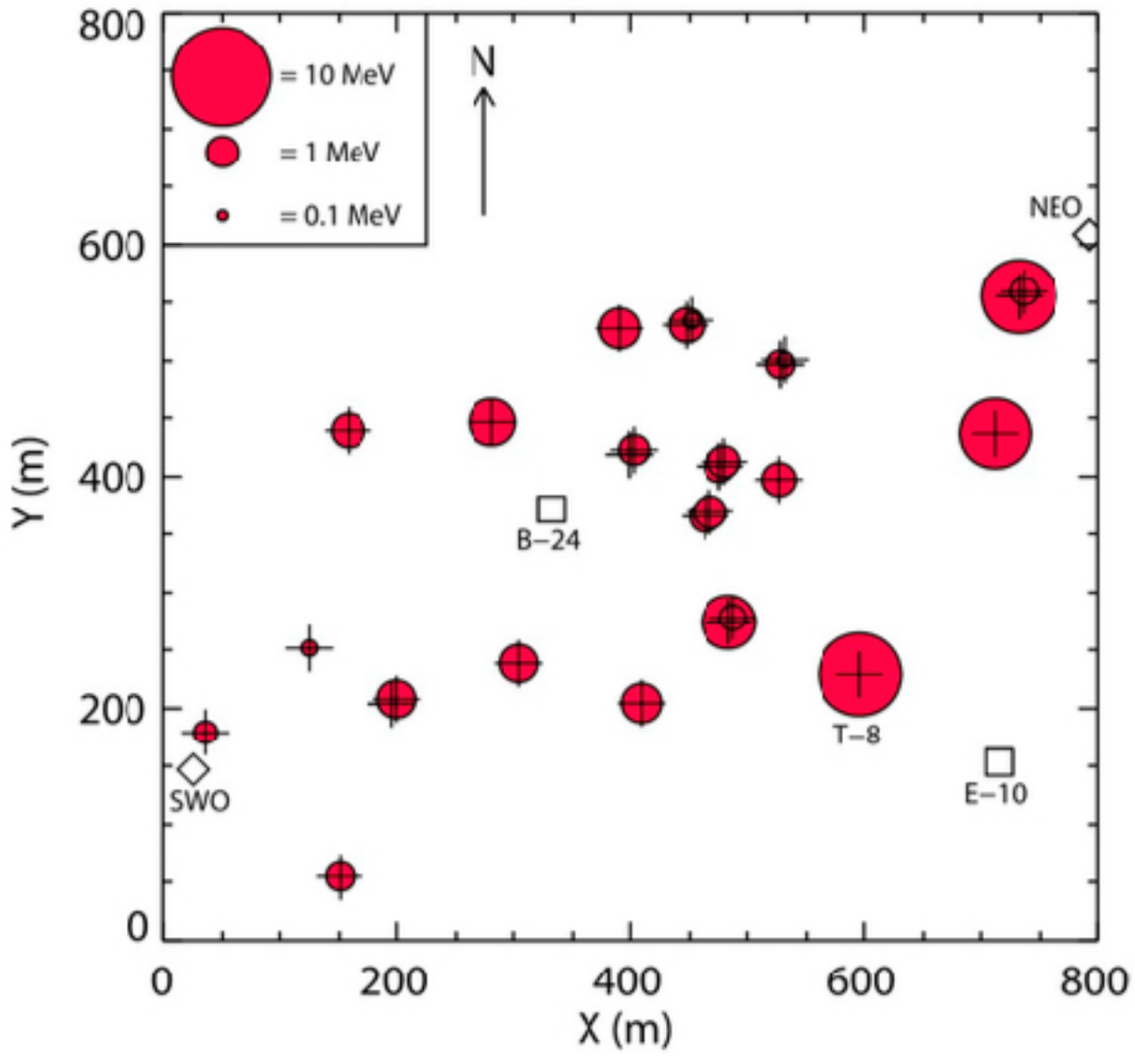


- Isolated event May 2016
- TASD triggers in 2nd ms of flash. Ground stroke occurs rapidly after.
- Suggests a somewhat different “energetic leader” event propagating rapidly to ground.
- Consistent with exponential growth of SD pulse heights with time.

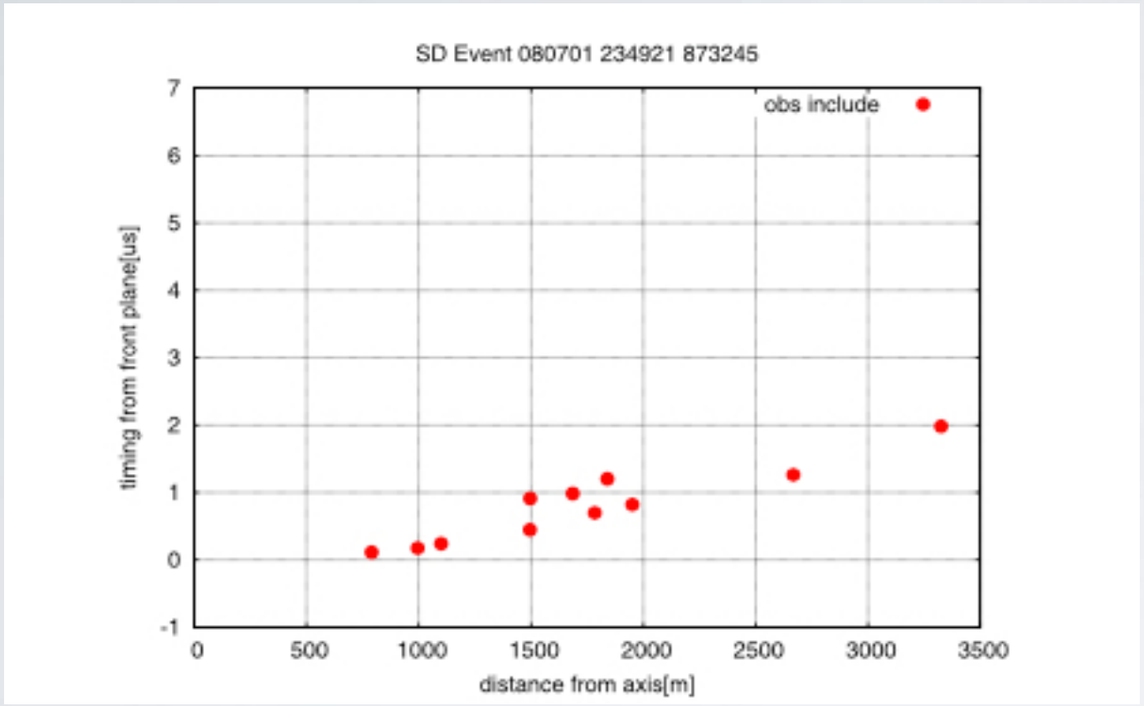
Dwyer et al, JGR **117** A10303 (2012)

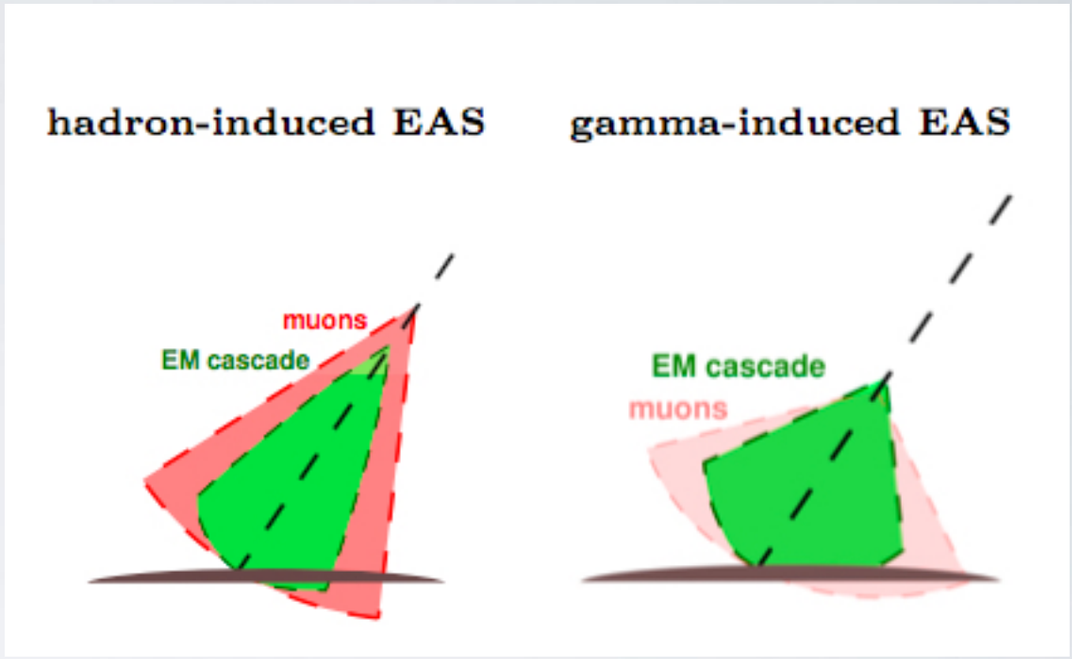


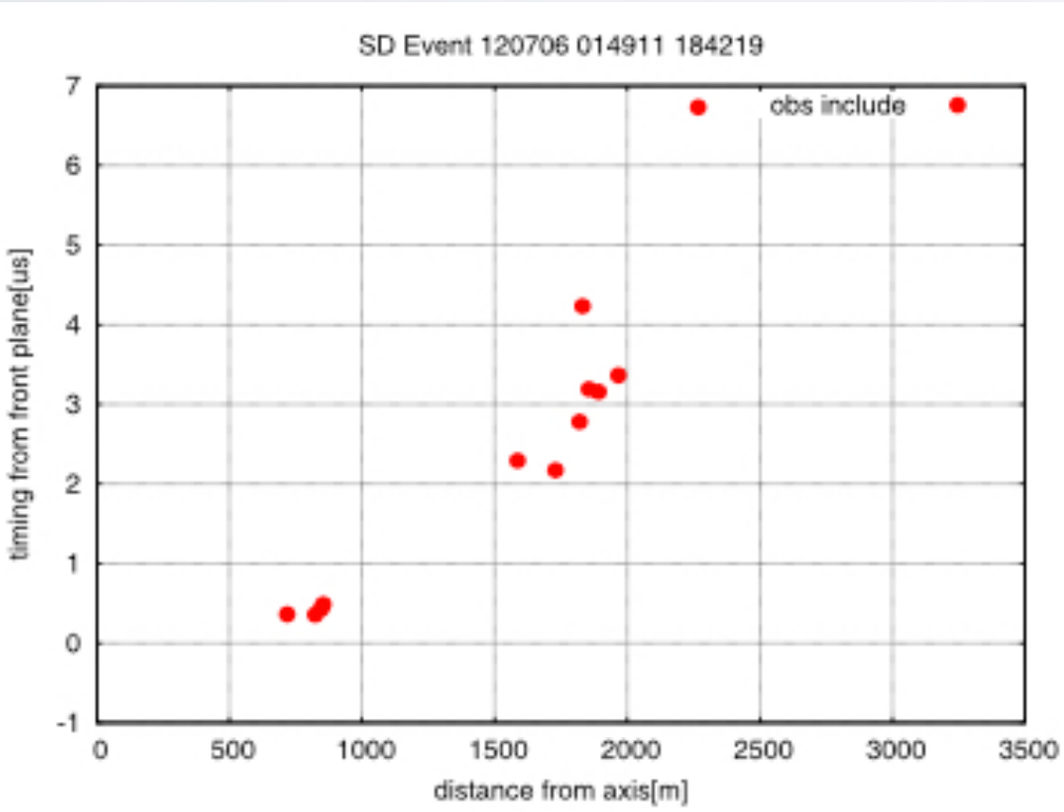
Gamma Rays

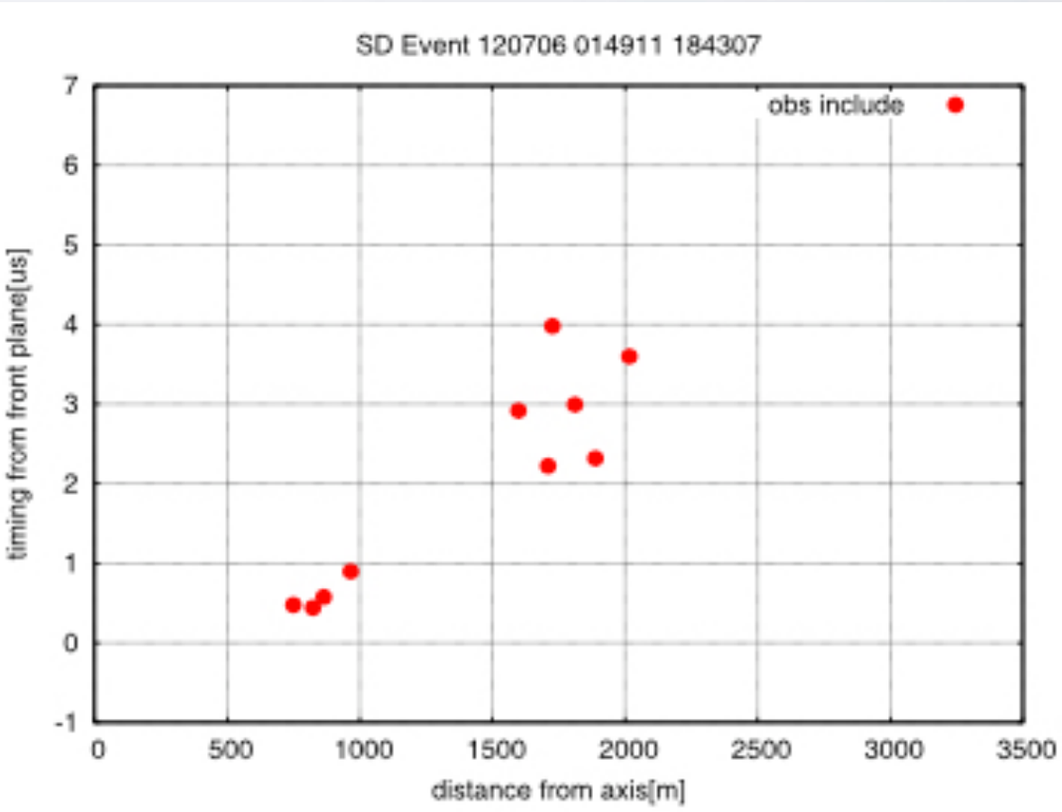


“x-rays from lightning”

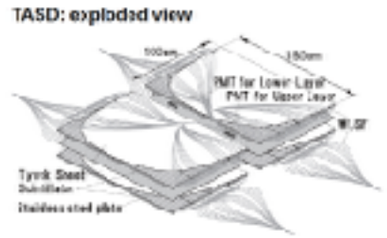

SD Event 080701 234921 873245
obs include
timing from front plane[us]
distance from axis[m]
7
6
5
4
3
2
1
0
-1
0
500
1000
1500
2000
2500
3000
3500

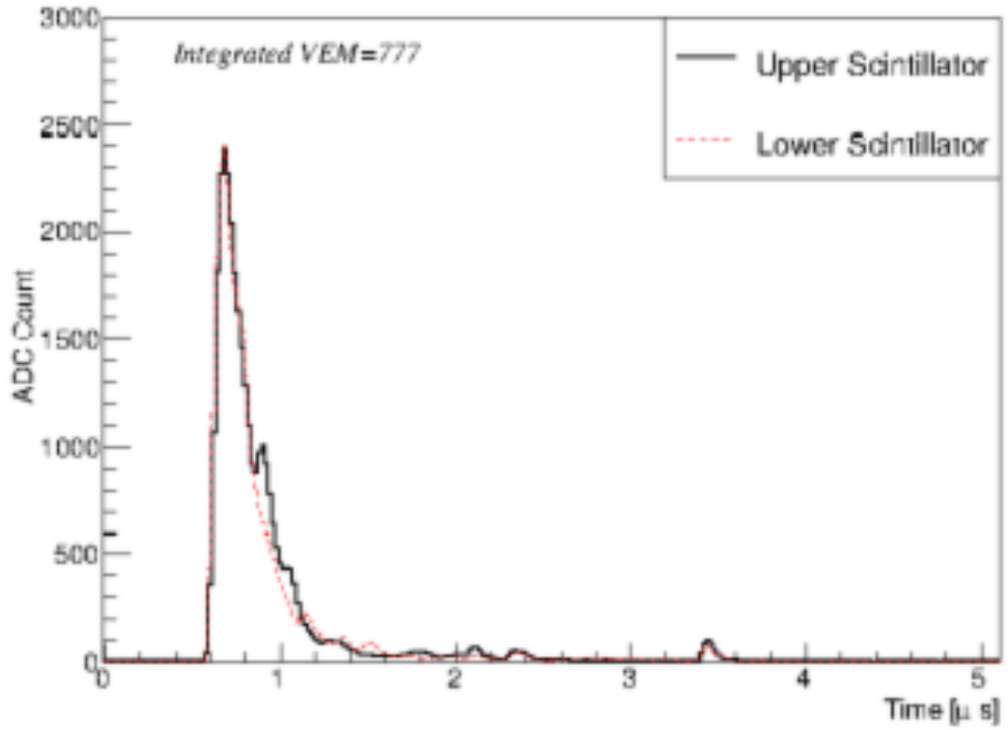

hadron-induced EAS
muons
EM cascade
gamma-induced EAS
EM cascade
muons


SD Event 120706 014911 184219
obs include
timing from front plane[us]
distance from axis[m]
7
6
5
4
3
2
1
0
-1
0
500
1000
1500
2000
2500
3000
3500

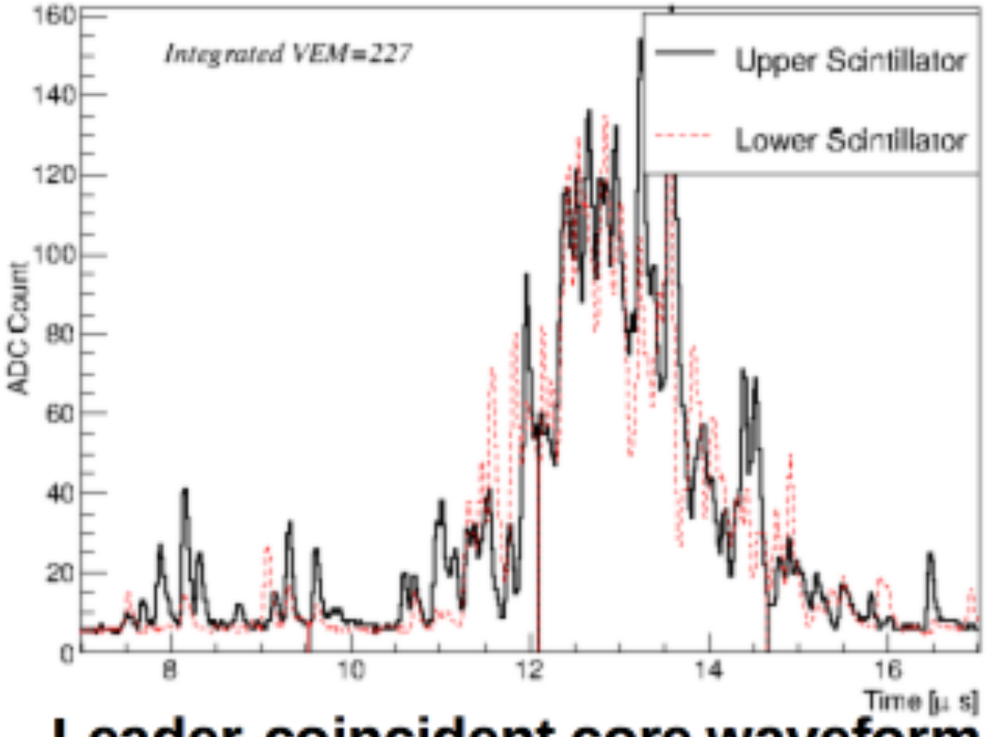

SD Event 120706 014911 184307
obs include
timing from front plane[us]
distance from axis[m]
7
6
5
4
3
2
1
0
-1
0
500
1000
1500
2000
2500
3000
3500

SD response: g and $e^{\pm}$

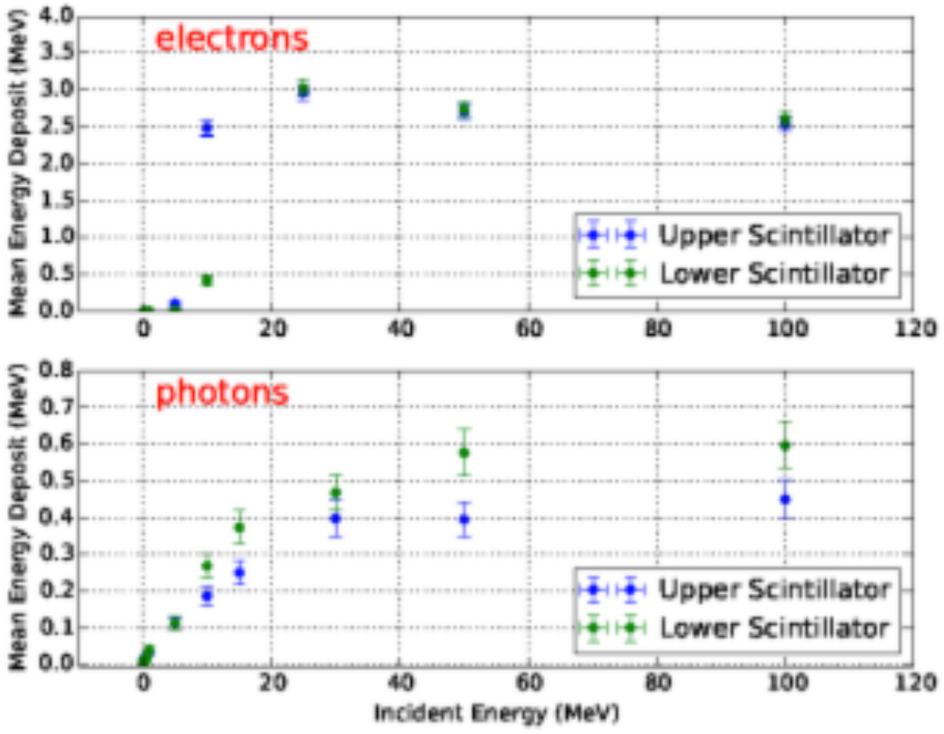




Cosmic ray core waveform



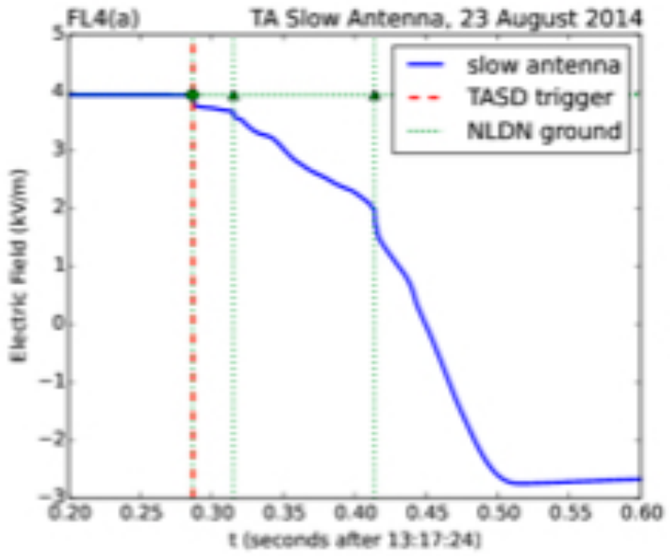
Leader-coincident core waveform

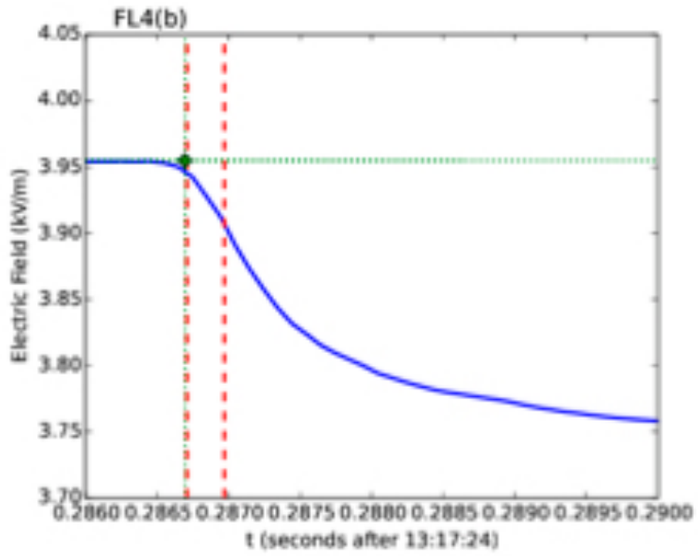


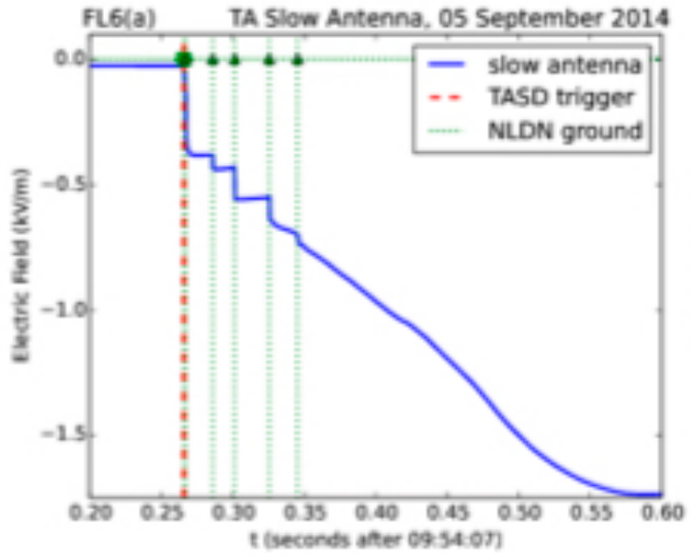
GEANT4 simulation

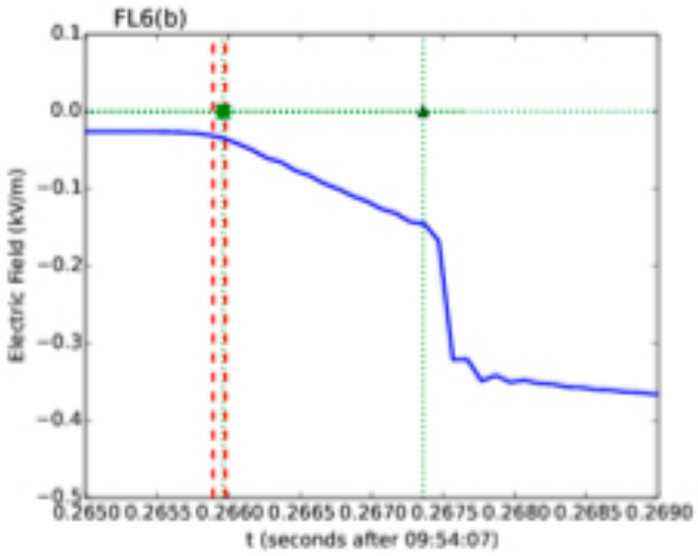
TASD is optimized for high-energy charged particles:

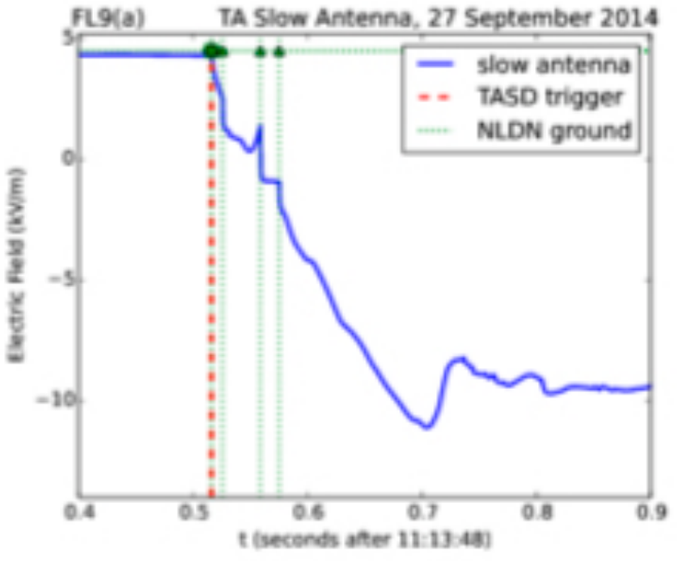
- inefficient for photons
- but this is what photons would look like!

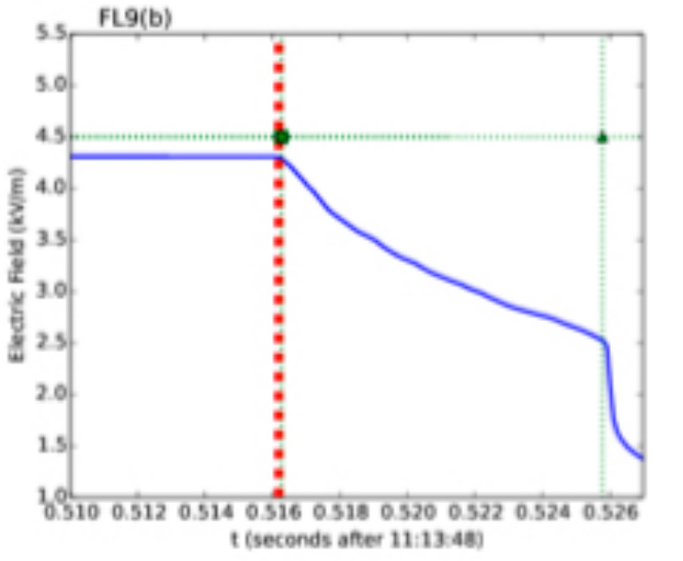

FL4(a)
TA Slow Antenna, 23 August 2014
slow antenna
TASD trigger
NLDN ground
Electric Field (kV/m)
t (seconds after 13:17:24)


FL4(b)
Electric Field (kV/m)
t (seconds after 13:17:24)

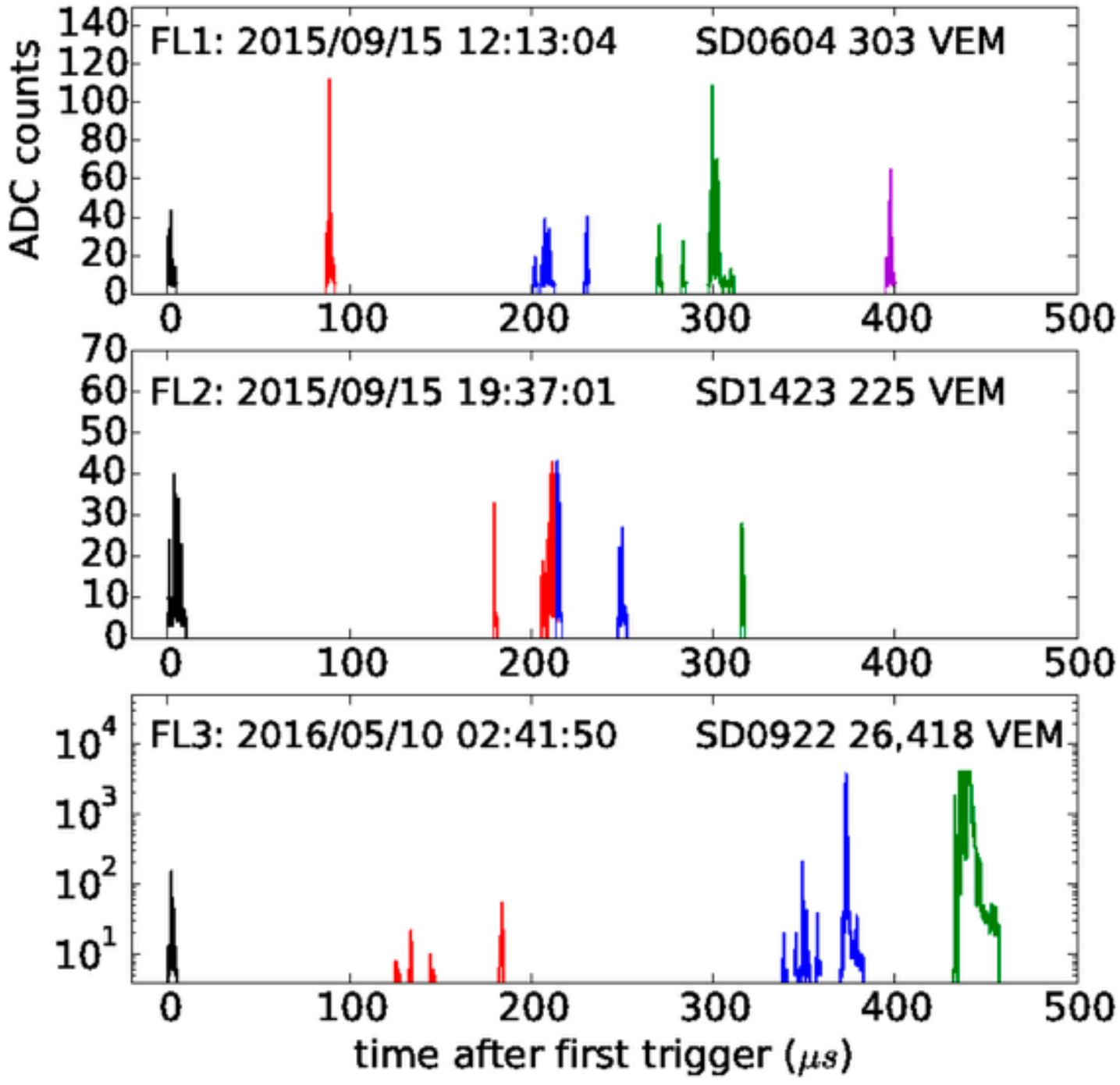

FL6(a)
TA Slow Antenna, 05 September 2014
slow antenna
TASD trigger
NLDN ground
Electric Field (kV/m)
t (seconds after 09:54:07)


FL6(b)
Electric Field (kV/m)
t (seconds after 09:54:07)


FL9(a)
TA Slow Antenna, 27 September 2014
slow antenna
TASD trigger
NLDN ground
Electric Field (kV/m)
t (seconds after 11:13:48)

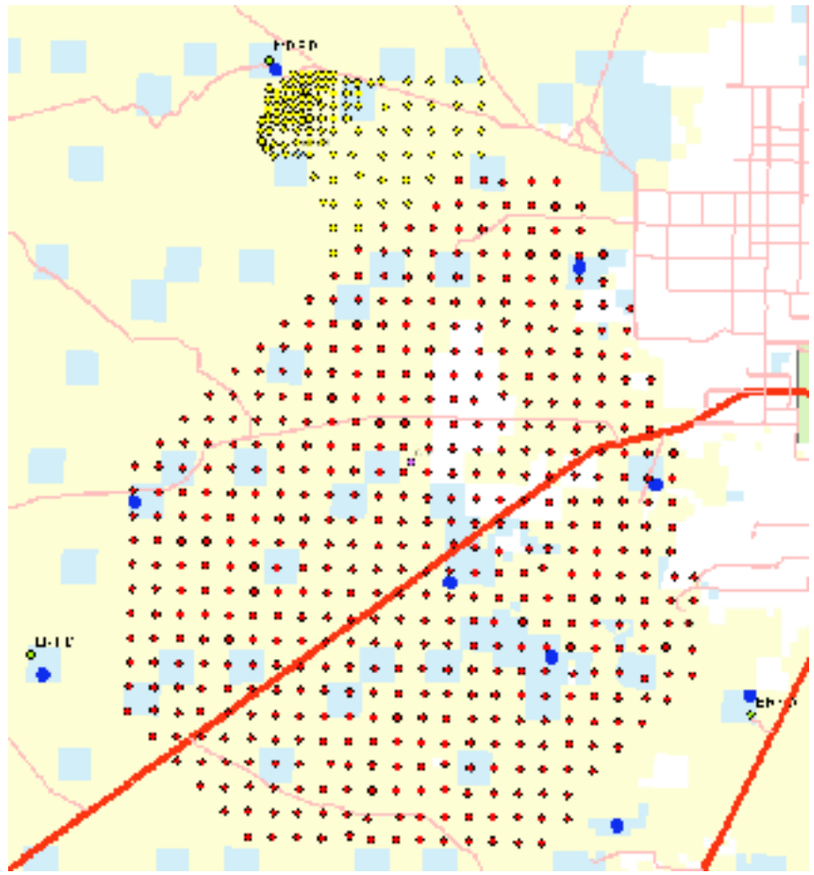

FL9(b)
Electric Field (kV/m)
t (seconds after 11:13:48)

TASD Waveforms, Flash 1, 2, 3

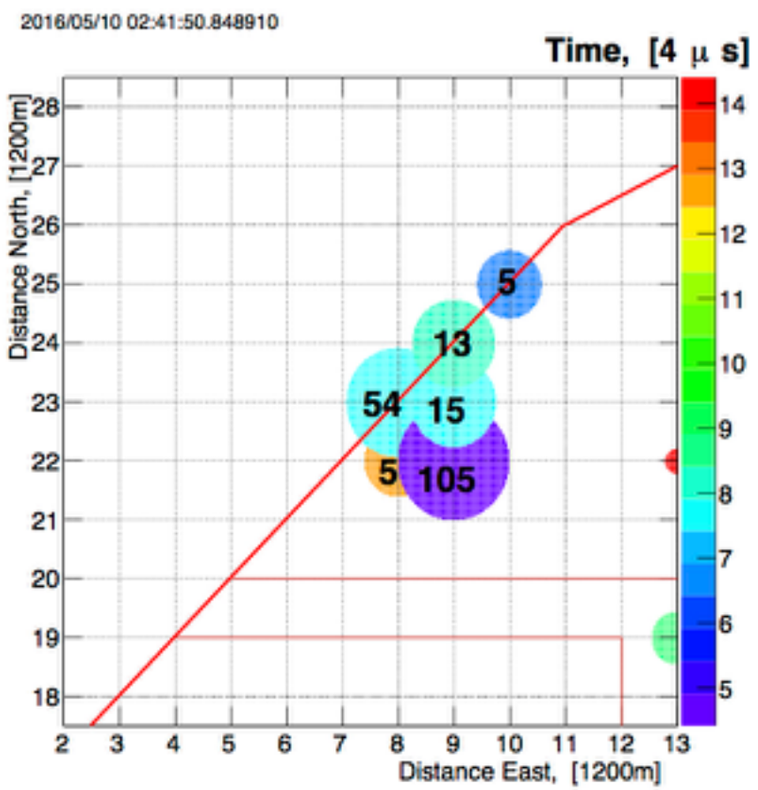


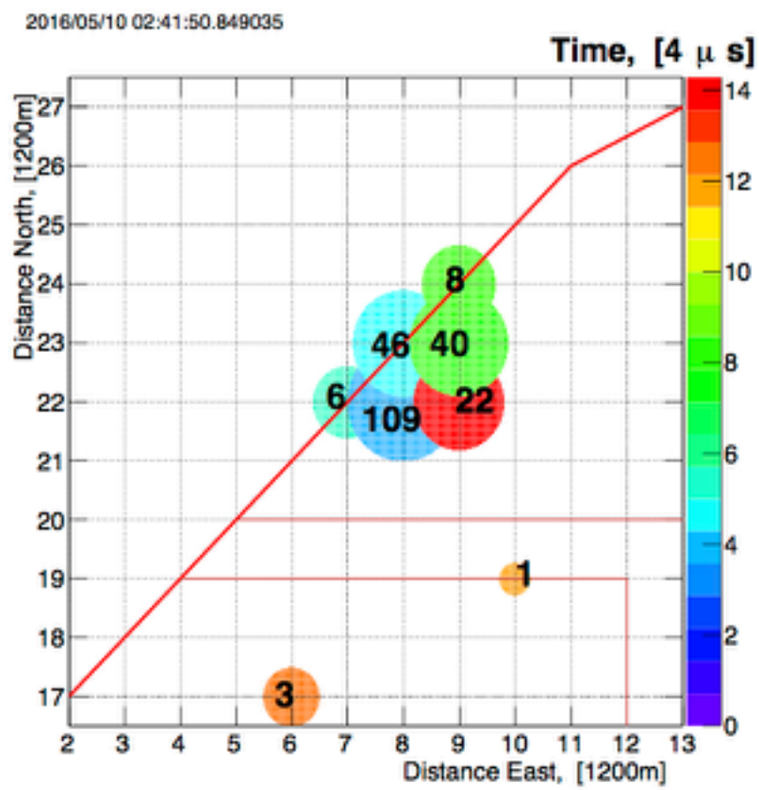
TELESCOPE ARRAY (TA/LMA)

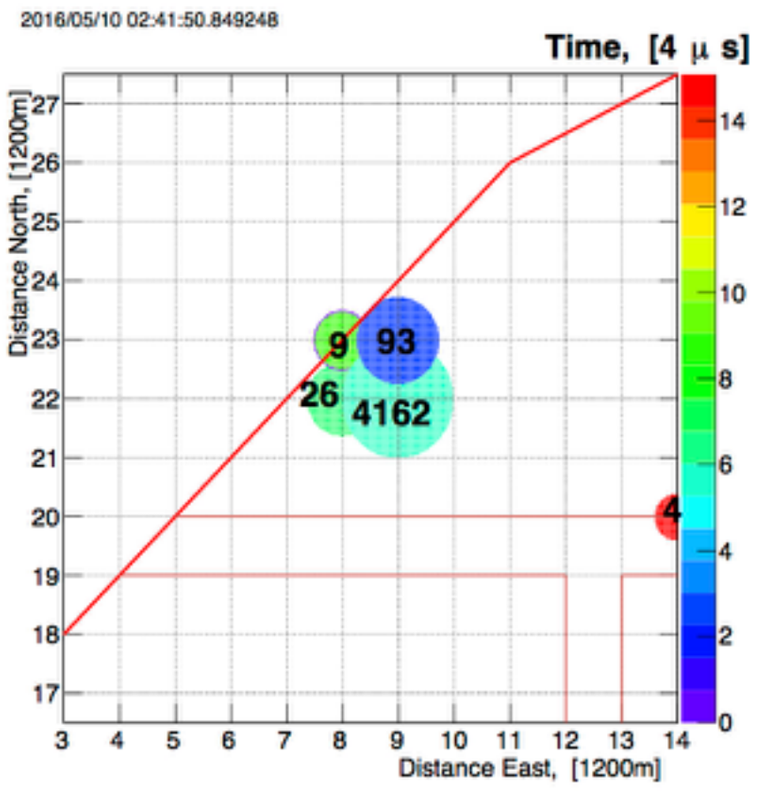
TASD	ɣ-ray SD
Plastic scintillaltor	Mainly NaI accompanied gas-counters
Lower SD number density	Higher SD number density
300 Times larger	Smaller in size
10 times faster response	Slower response

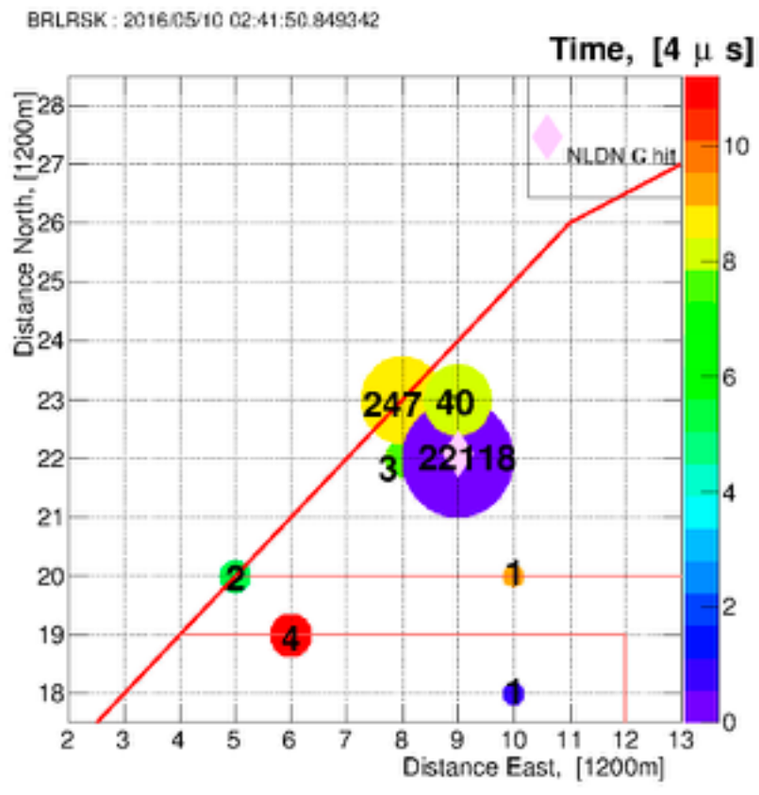


“Flash3” Event 20160510-024150

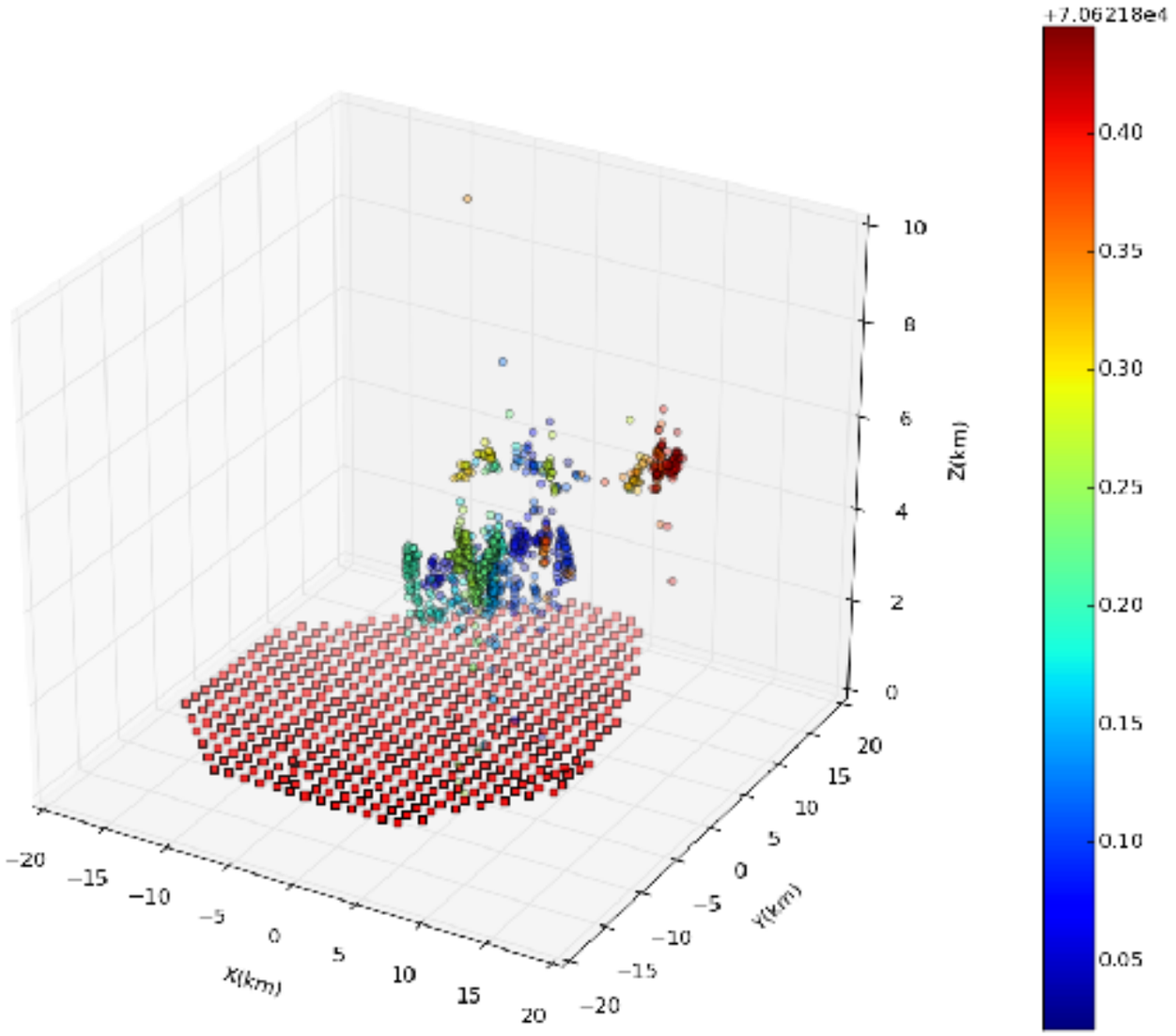


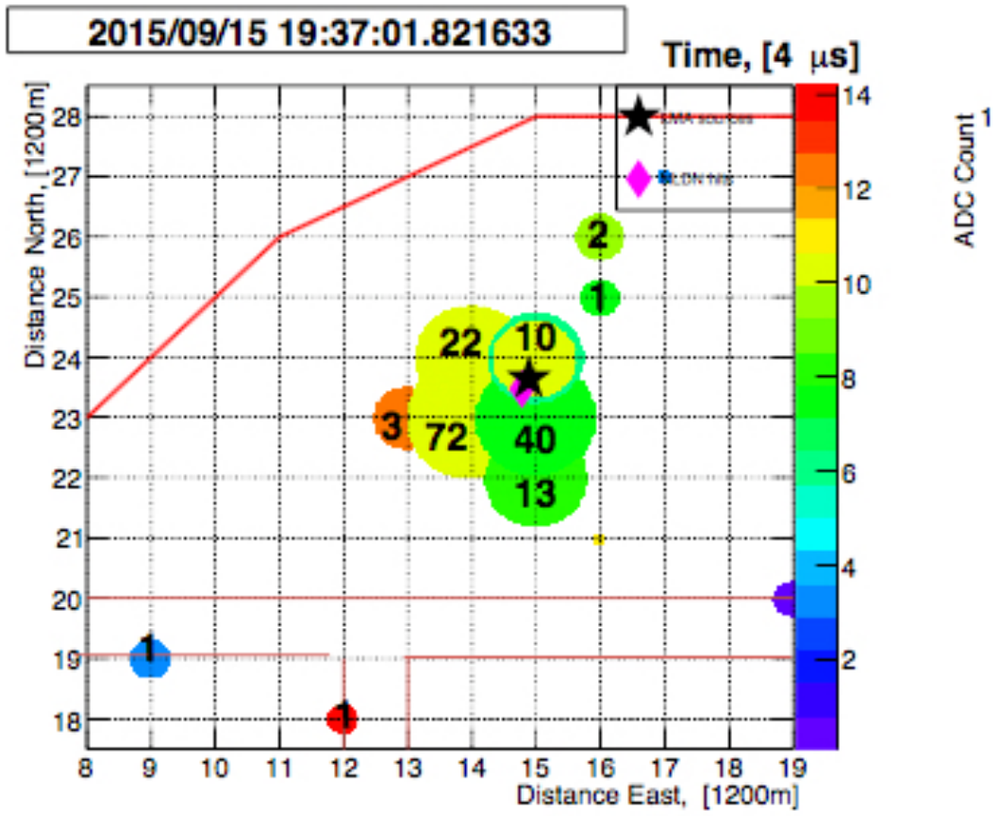






“Flash 2” Event 20150915-193701





NLDN - 12 kA IC

Date	Time	μsec	LMA dBW	NLDN I_{pk}	TASD VEM_{max}/MeV	Number of TASDs
2015/09/15	12:13:04	755191	16.2			
		293	18.0			
		343	15.6			
		413	13.3			
		422		-4.3 kA C		
		558	19.4			
		662	22.2			
		670			30/61	5
		672		-15.5 kA C		
		752	21.4			
		756		-17.5 kA C		
		757			449/920	9
		871			37/55	15
		873		-22.1 kA C		
		939			142/291	8
		950		-15.0 kA C		
		756035		-10.0 kA C		
		065			39/80	8
		260	18.6			
		855	18.6			
		951144		-7.1 kA G		
2015/09/15	19:37:01	821147	14.6			
		339	24.4			
		344		-12.3 kA C		
		450	17.4			
		451		-8.1 kA C		
		564	23.5			
		584		+17.1 kA G*		
		586		+18.4 kA G*		
		633			72/148	8
		643	23.2			
		759	16.6			
		812			75/154	6
		842		+9.3 kA C		
		847			47/96	6
		948			25/51.2	4
		822043	15.7			
		822094		-5.8 kA C		
		172	19.8			
		631	20.1			
2016/05/10	02:41:50	846823	-5.9			
		932	9.5			
		847017	19.1			
		141	15.1			
		257	15.1			
		467	22.8			
		527	20.8			
		606	25.2			
		706	17.2			
		713		-7.3 kA C		
		987	15.1			
		848132	19.0			
		208	20.0			
		299	13.8			
		434	15.4			
		643	16.8			
		708	11.8			
		761	16.5			
		910			105/215	6
		849035			109/223	6
		248			4,162/8,532	4
		342			22,118/45,342	4
		368		-94.1 kA G		
		637	14.9			

Cosmic Ray Shower (top) and “Burst” Event