BIRKELAND CENTRE FOR SPACE SCIENCE

High-energy emission from Terrestrial Gamma-ray Flashes

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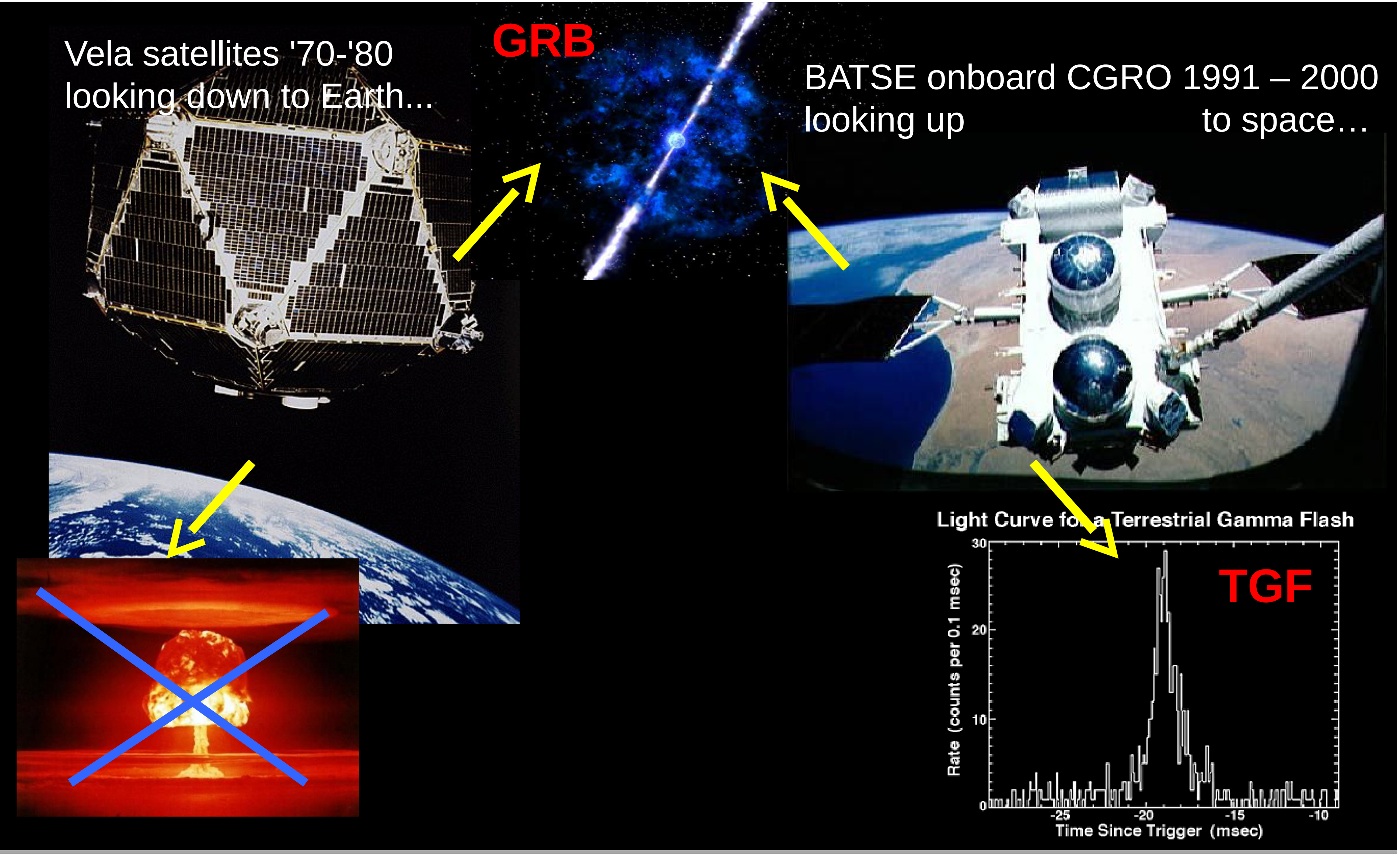
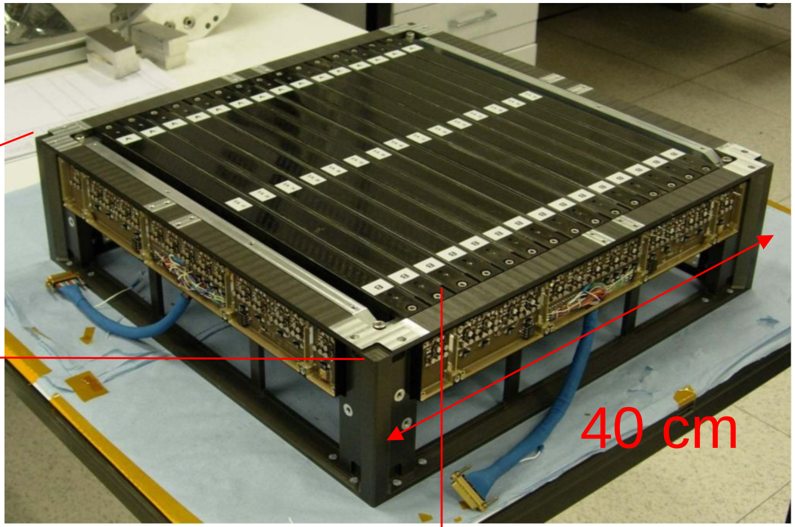
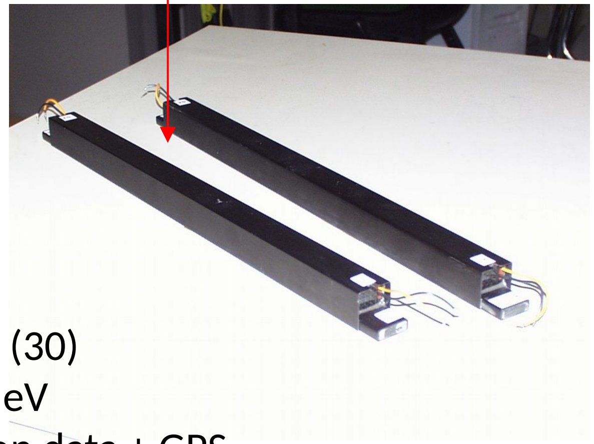
Serendipity at play



MCAL: do it as clever as possible!





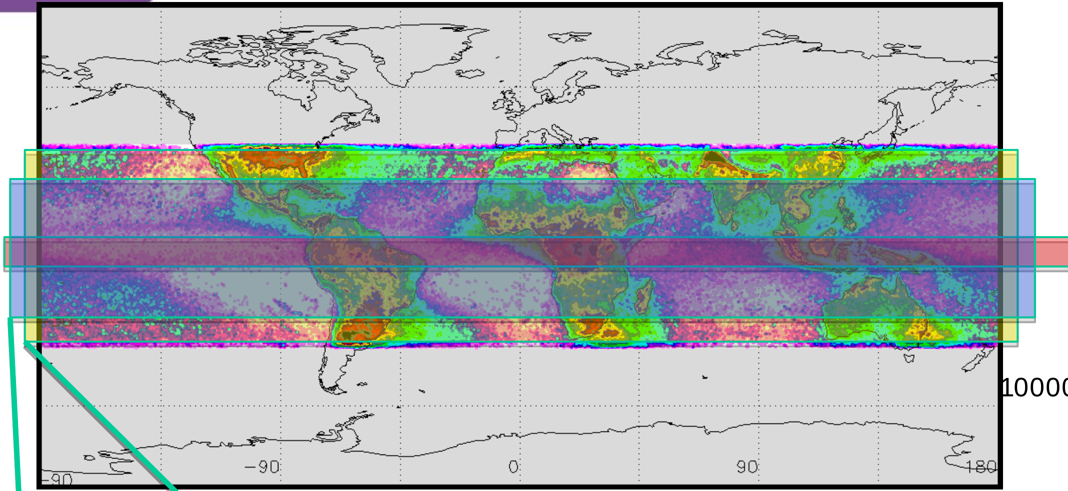
Constraints:

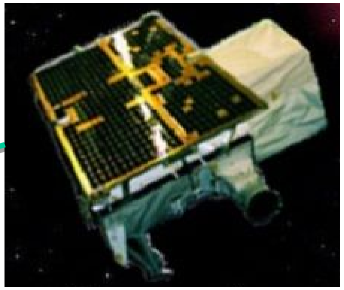
- Low weight
- Low power → few channels / solid state readout
- Low telemetry budget → on-board trigger logic

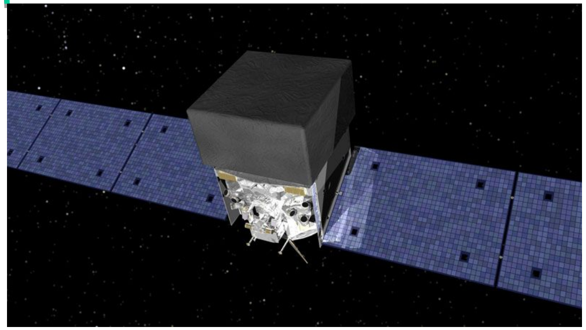
Design choices:

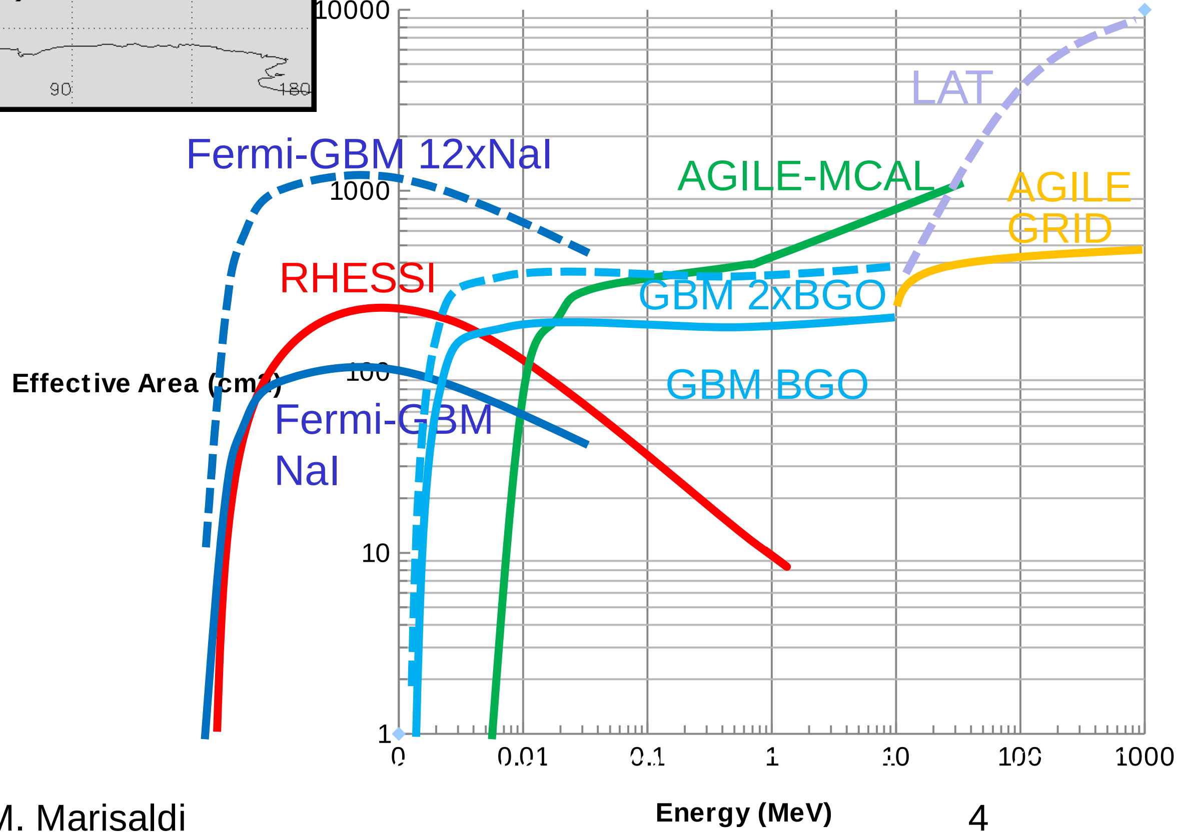
- Hodoscopic architecture → position reconstruction with few channels (30)
- PD readout: 350 keV threshold → energy range extended up to 100 MeV
- Trigger logic → very short time scales (300µs, 1ms) + photon-by-photon data + GPS

Operating TGF detectors









LUCK IS IMPORTANT

BUT YOU MUST BE PREPARED FOR IT

The top question

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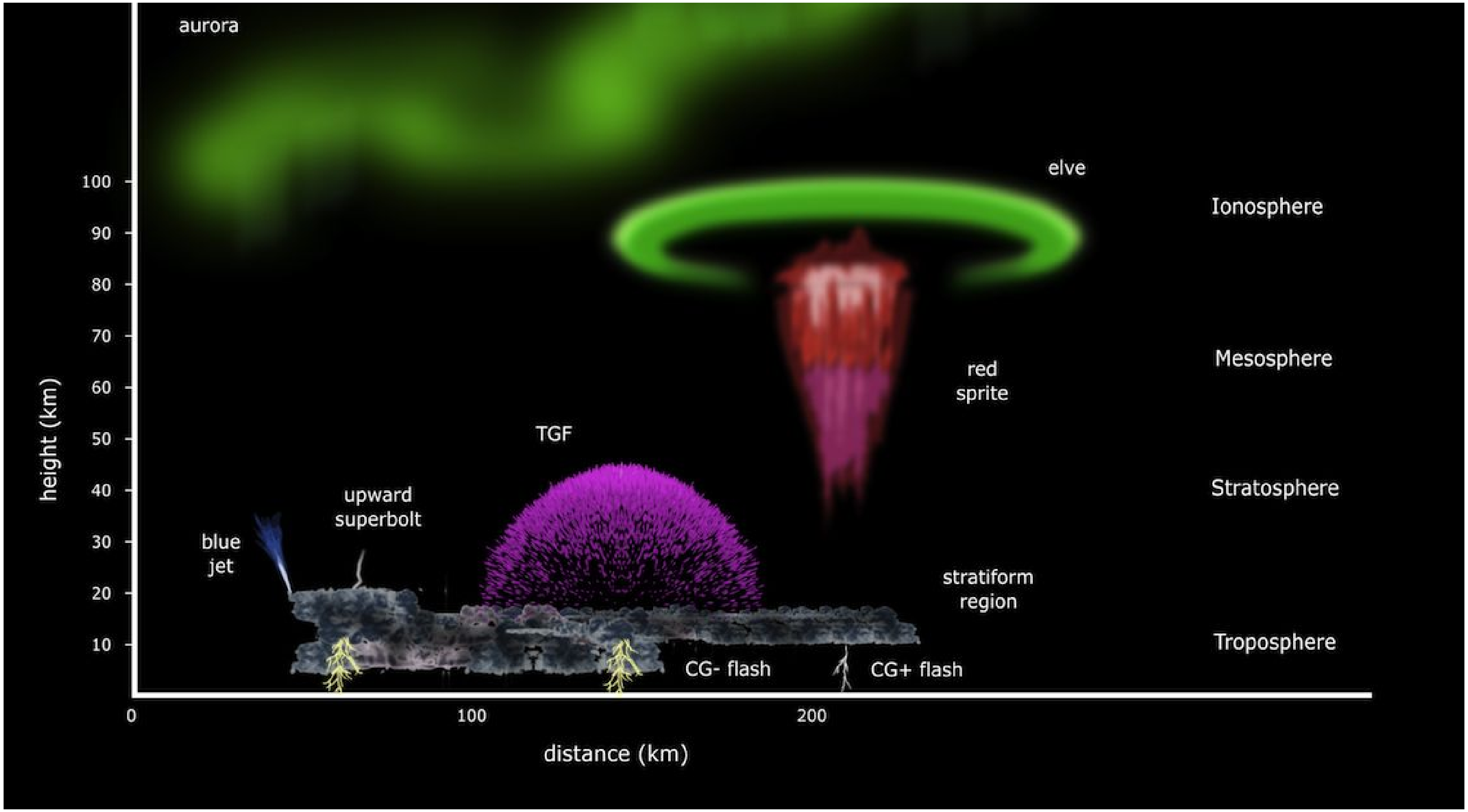
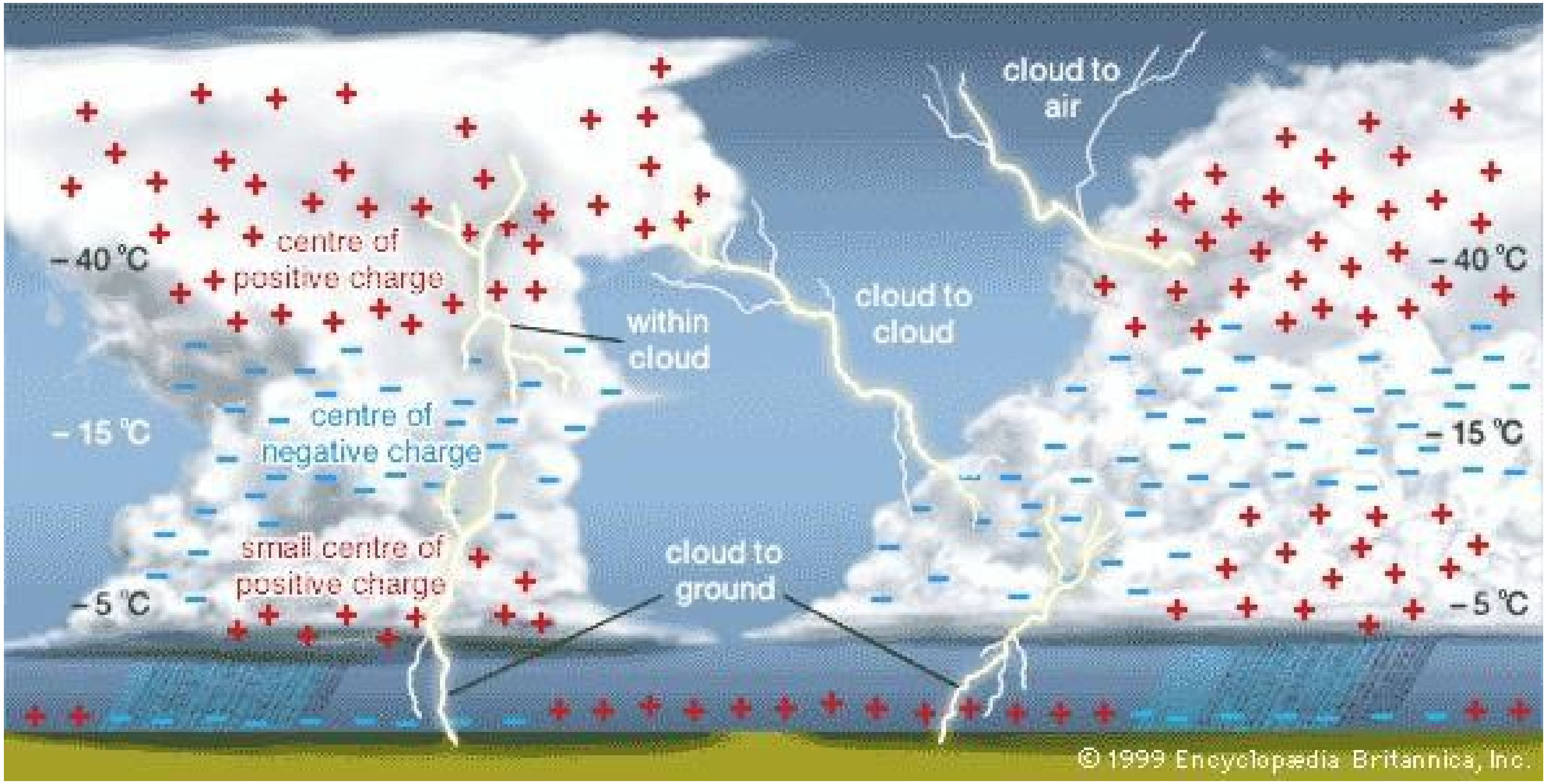


Credits: A. Ursi

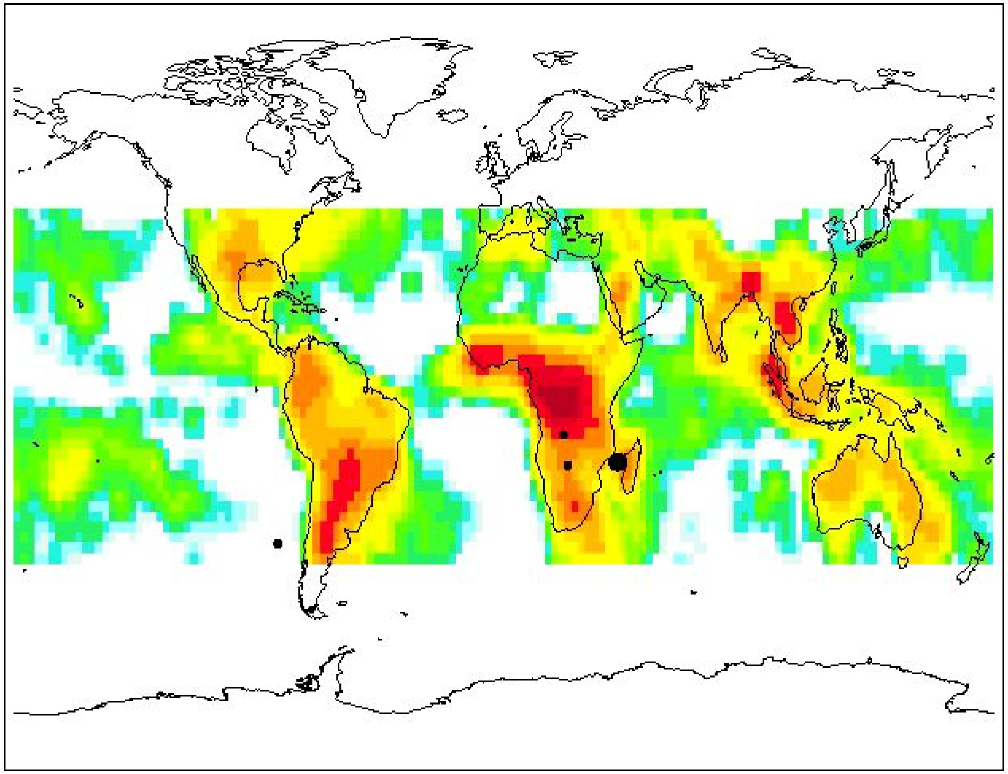
What is the role of energetic particles from thunderstorms on geospace?

The top question



- TGFs are closely associated to lightning activity.
- Lightning is a complex process, difficult to observe in situ and impossible to reproduce in the lab.
- What is the connection between energetic radiation production and the lightning process?

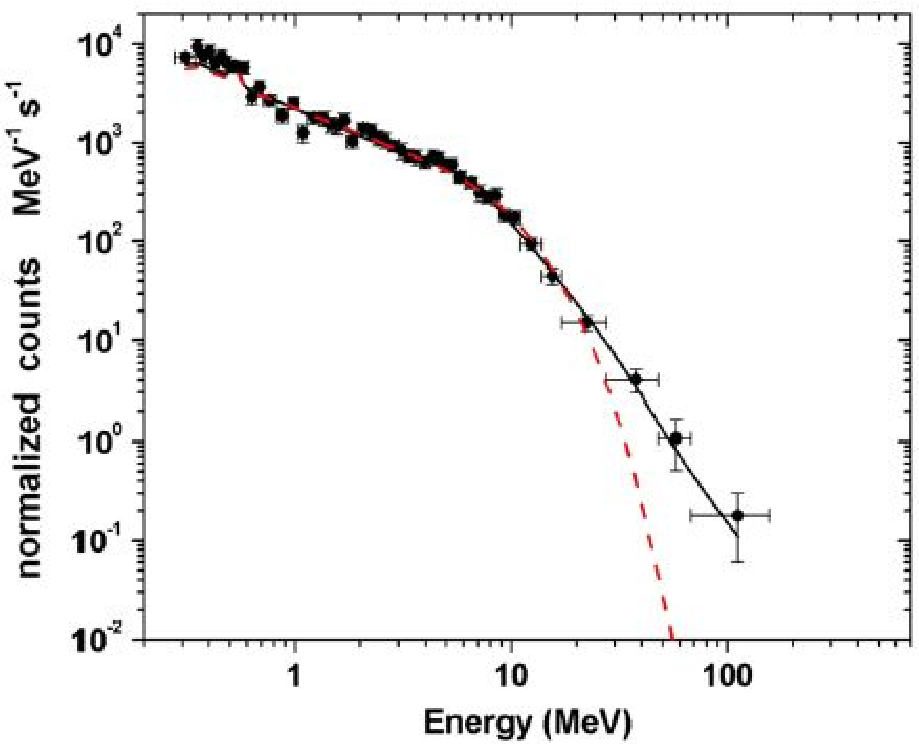
Why it is important



Gjesteland et al, 2012

- About 2000 thunderstorms active any moment.
- 45 lightning / second.
- Energy deposition very localized in space and time.
  Can it affect atmospheric chemistry and dynamics?

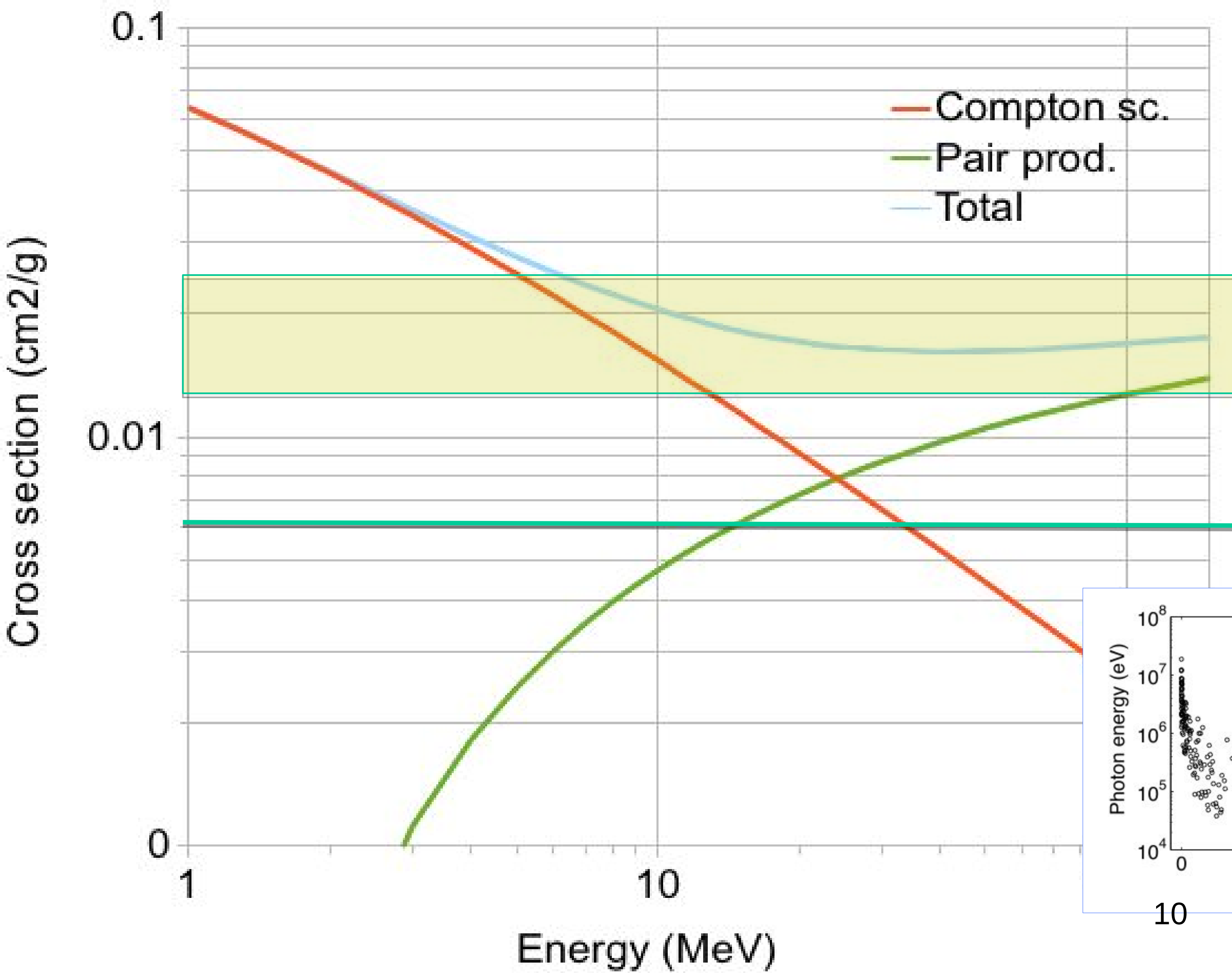
AGILE high-energy events



Tavani, MM+ 2011

- Can we reliably assess the highest photon energy in TGFs?
- High-energy (~30 MeV) photons are most likely the only photons that arrive to the detector without scattering in the atmosphere, due to the minimum in interaction cross section.
- Therefore they carry information on the energetics and timing of the production mechanism, without uncertainties introduced by transport in the atmosphere

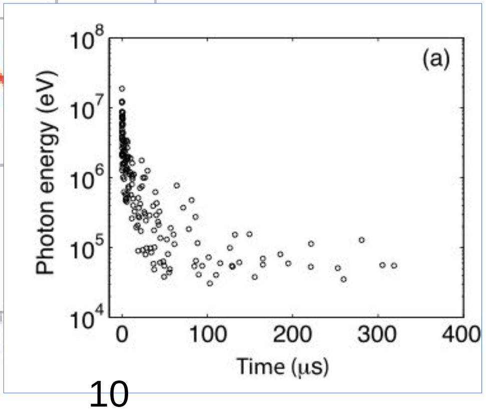
Photon cross section in air



20 km
0.025 cm²/g

15 km
0.012 cm²/g

10 km
0.006 cm²/g

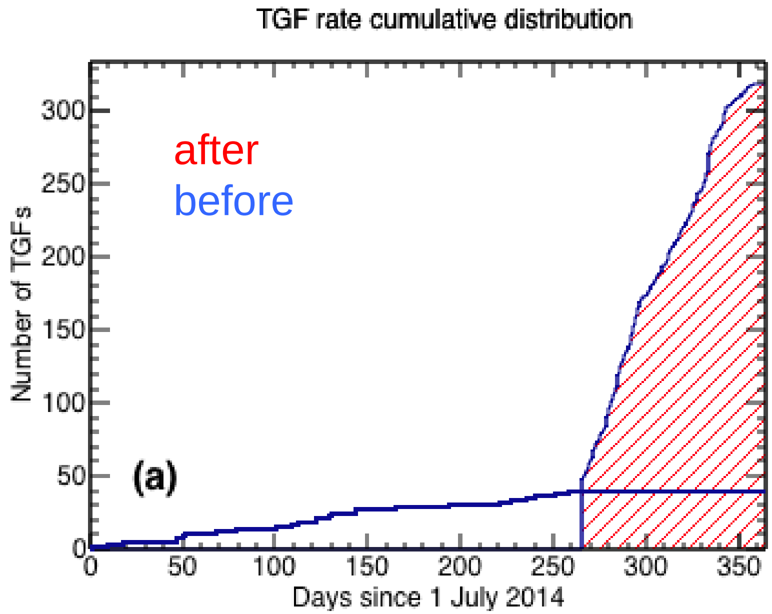


Celestin &Pasko 2011

AGILE contributions to TGF science

- ❑ AC disabled for MCAL: ten-fold increase in detection rate; ~700 TGFs/year; delivery of the 2nd AGILE TGF catalog (enhanced catalog):

Marisaldi et al., Geophys. Res. Lett. 42 (2015)

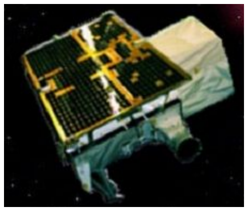


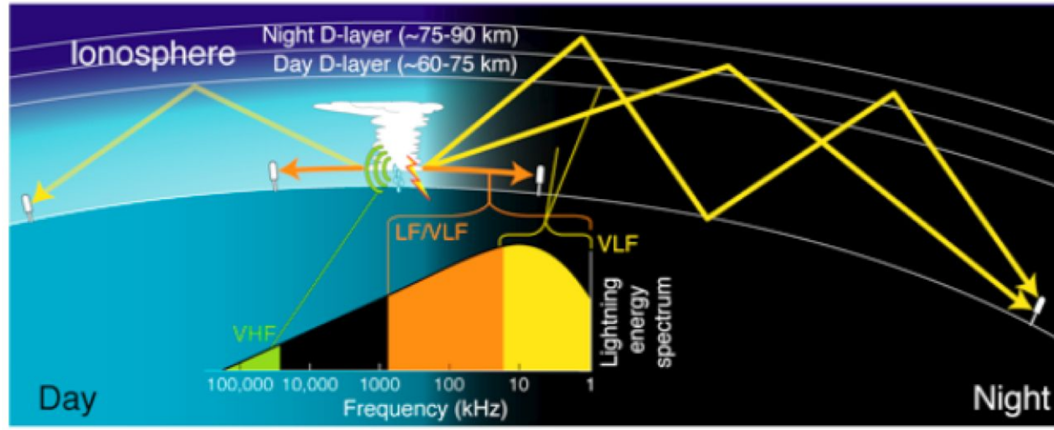
Results following configuration enhancements: see Alessandro Ursi presentation

AGILE TGF catalogs available online at ASI ASDC website: a tool for the community

Methodology: a multiwavelength approach

Gamma-rays from space



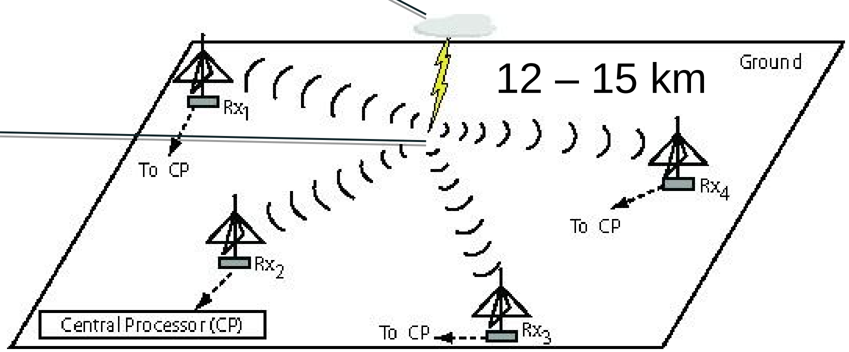


$\Delta t = L/c$

500 km

VLF lightning detection networks on ground

AGILE Footprint



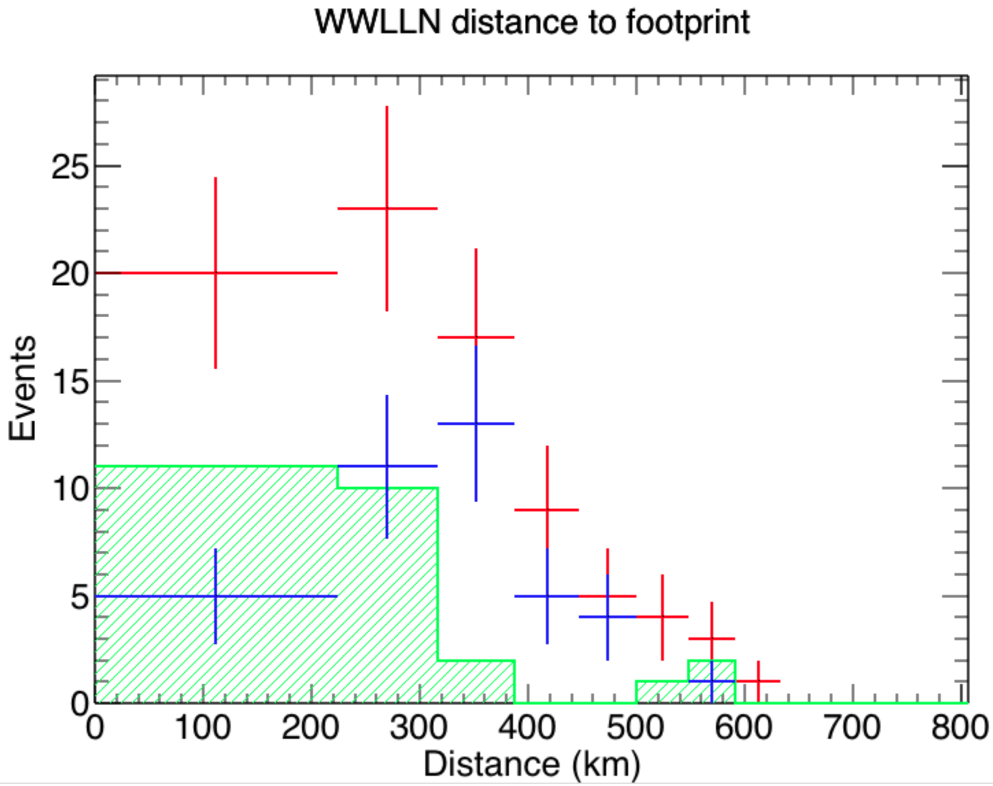
http://thunder.msfc.nasa.gov/

Dataset

Id	contact	trigger	TGF info							WWLLN data				Direction	
		id	date	time	longitude	latitude	n.counts	duration	E_max	longitude	latitude	Δt	distance	theta	phi
					(°)	(°)		(ms)	(MeV)	(°)	(°)	(ms)	(km)	(°)	(°)
1	42047	14	11/06/15	18:17.0	172.14	-2.3	6.8	0.108	**1879**	167.37	-3.39	0.164	**545**	120.6	337.8
2	41386	12	26/04/15	54:24.4	-7.71	-2.01	8.7	0.084	**1397**	-2.54	-1.64	0.291	**577**	133.4	202.5
3	41304	14	20/04/15	12:27.6	129.3	2.43	8.7	0.108	**697**	135.7	-4.89	-0.265	**1082**	85.2	2.9
4	41896	17	01/06/15	00:14.3	102.33	-1.95	9.7	0.084	**607**	98.89	-2.2	0.12	**384**	99.1	243.6
5	41561	13	08/05/15	47:59.9	23.86	0.99	12.9	0.062	**528**	24.25	-1.76	0.048	**310**	130	196.6
6	41194	3	12/04/15	50:36.5	73.73	2.08	8.7	0.151	**323**	88.58	9.95	0.201	**1857**	90.3	122.7
7	41813	27	26/05/15	15:27.3	141.29	-1.75	9.8	0.057	**173**	139.29	-2.95	0.064	**259**	21.6	129.6
8	41372	14	25/04/15	10:42.7	101.29	1.39	9	0.018	**159**	98.82	1.78	0.118	**278**	67.2	22.2
9	42047	4	11/06/15	04:14.7	122.16	-0.65	13	0.026	**159**	119.38	0.35	0.035	**329**	80.2	45.6
10	41313	25	21/04/15	21:58.1	132.11	-1.7	11	0.022	**113**	131.57	-1.74	0.107	**61**	47.3	289.9
11	41173	4	11/04/15	52:19.6	6.47	-0.34	13.7	0.085	**90**	8.81	1.17	0.225	**310**	134.8	247.8
12	41074	1	04/04/15	12:30.8	141.9	-2.46	11.8	0.051	**79**	140.43	-3.97	0.094	**235**	113.9	66.2
13	41020	1	31/03/15	35:18.9	130.78	-2.46	11.7	0.07	**70**	133.16	-2.54	0.102	**265**	102.4	55.8
14	41717	1	19/05/15	34:02.8	106.24	-2.11	10	0.026	**67**	104.49	-2.08	0.061	**195**	55	9.9
15	41454	13	01/05/15	29:30.5	108	-1.03	9	0.016	**62**	105.64	-1.5	-0.01	**268**	77.9	257.6
16	41586	7	10/05/15	26:51.0	4.11	2.47	12.8	0.057	**58**	3.98	4.42	0.004	**218**	79.1	228.9
17	41735	22	20/05/15	57:07.4	-84.94	1.61	8	0.018	**56**	-86.88	2.12	0.095	**223**	97.3	243.8
18	41749	1	21/05/15	06:31.0	112.71	0.79	8.9	0.031	**54**	111.07	0.74	0.031	**183**	96.2	43.9
19	41743	20	21/05/15	28:13.9	-81.94	2.26	11.5	0.112	**45**	-77.37	4.69	0.055	**575**	99.2	75.2
20	41766	11	23/05/15	02:07.9	105.87	1.51	11.9	0.026	**45**	104.61	1.17	0.018	**146**	128.7	297.4
21	41142	30	09/04/15	07:00.1	27.35	2.4	10	0.016	**43**	27.41	0.99	0.004	**157**	138.9	202.6
22	41955	1	05/06/15	12:20.0	94.69	-1.93	9	0.018	**41**	94.44	-2.22	0.224	**43**	75.2	249.7
23	41962	11	05/06/15	43:24.9	108.13	0.44	9	0.016	**41**	108.45	-1.52	-0.014	**222**	31.9	69.4
24	41515	2	05/05/15	12:52.0	127.93	1.8	15.8	0.061	**39**	129.49	2.08	0.17	**177**	27.4	216.7
25	41194	7	12/04/15	56:56.6	96.26	2.44	8	0.018	**38**	94.41	2.72	-0.018	**209**	167.1	120.5
26	41130	1	08/04/15	12:19.3	20.33	2.14	9	0.016	**36**	20.87	-0.41	-0.007	**290**	50.6	222.3
27	41820	10	26/05/15	52:37.2	107.78	2.43	12	0.026	**31**	105.73	0.82	0.041	**290**	54.6	183
28	41902	1	01/06/15	09:01.0	114.24	1.58	8.9	0.036	**30**	113.7	4.11	-0.023	**288**	129.3	116.1

- 84 events with WWLLN match and no other selection criteria (except >=6 counts in 300 µs)
- Includes the 39 TGFs with WWLLN match reported in MM+2015
- 28 events have counts with E>30 MeV (this work)

Distance to footprint distribution



Blue: MM+2015 sample (39 TGFs E_{MAX} <30 MeV with WWLLN match)

Red: this sample

Green: this sample, E_{MAX} > 30 MeV

- Radial bin size chosen to have equal subtended area: number of events is a proxy for the surface density, no need for normalization
- The E_{MAX}<30 MeV requirement (MM+ 2014 and 2015 samples) biases towards farer events
- E_{MAX}>30 MeV events are detected mostly closer than 400 km. Nearly compatible with previous findings: off-cone vs. in-cone observation geometry

E_{MAX} = 113 MeV, D_{WWLLN} = 61 km, θ = 47.3°

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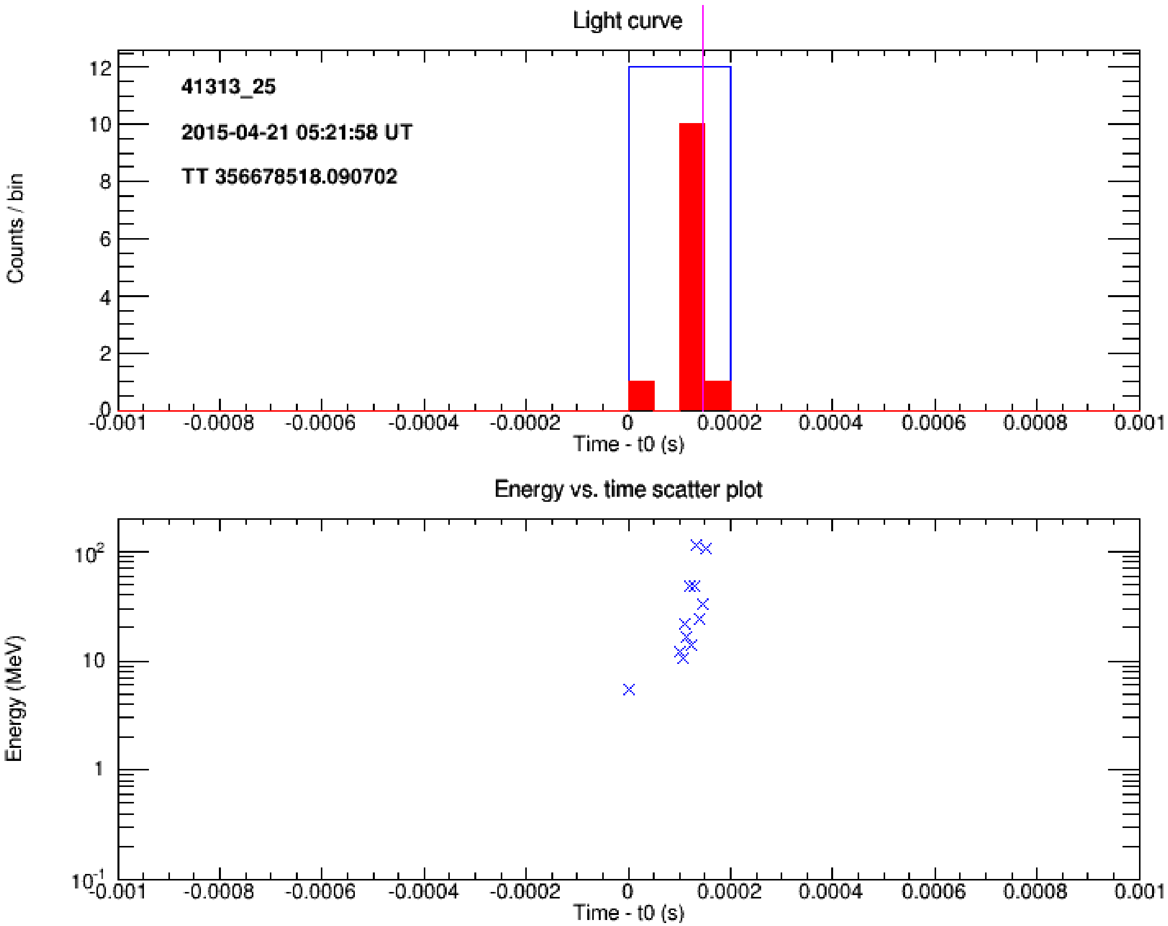

Energy (MeV)	Delta_t (s)
6	0.002747
12	0.0001
11	6.00E-06
22	4.00E-06
17	4.00E-06
49	5.00E-06
14	4.00E-06
49	6.00E-06
113	5.00E-06
24	4.00E-06
33	8.00E-06
107	6.00E-06

- Very energetic!
- Note the 'chirp' time structure.
- WWLLN matches high-energy counts
- But time structure is dominated by pile-up: energy measure is probably affected

MCAL dead-time and pile-up model

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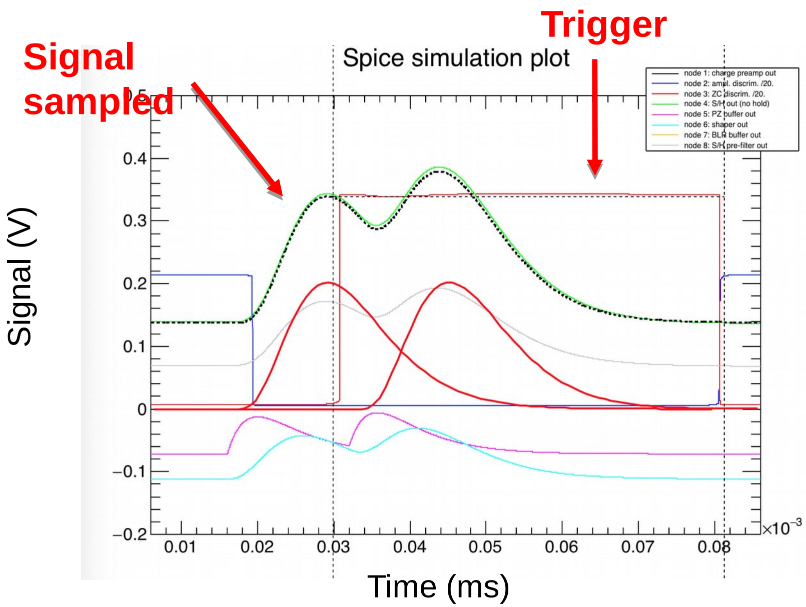

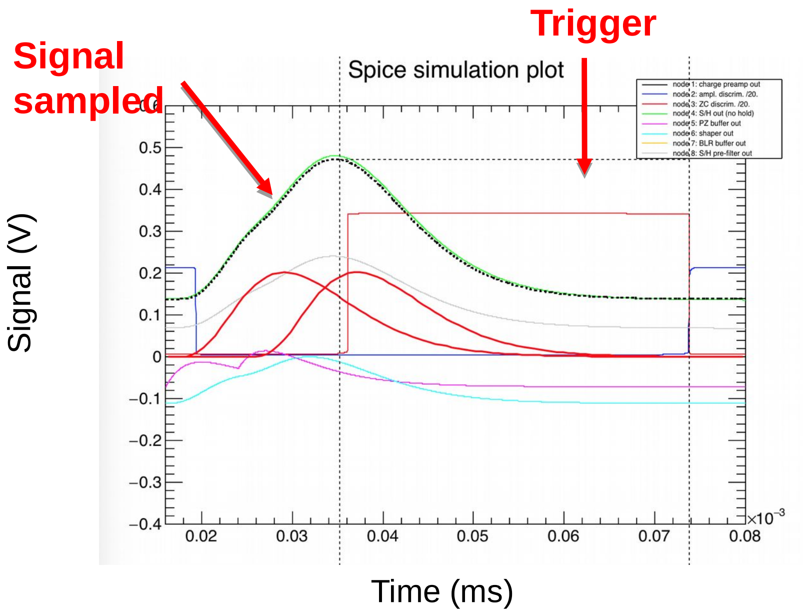

- PSPICE simulation of MCAL FEE thanks to P. Bastia – TASI
- There are three regimes depending on time separation between events
- Very complex behavior, MCAL was never tested in such high-flux conditions
- To do: Monte Carlo simulation of the full FEE (in progress)
- Still learning how MCAL works after 10 years in orbit! Lesson learnt: be humble and open minded even towards thing you think to know well!

The most important thing…