Frontier Objects
in Astrophysics and Particle Physics

Vulcano Workshop 2014

High-Energy Atmospheric Physics and Terrestrial Gamma-ray Flashes

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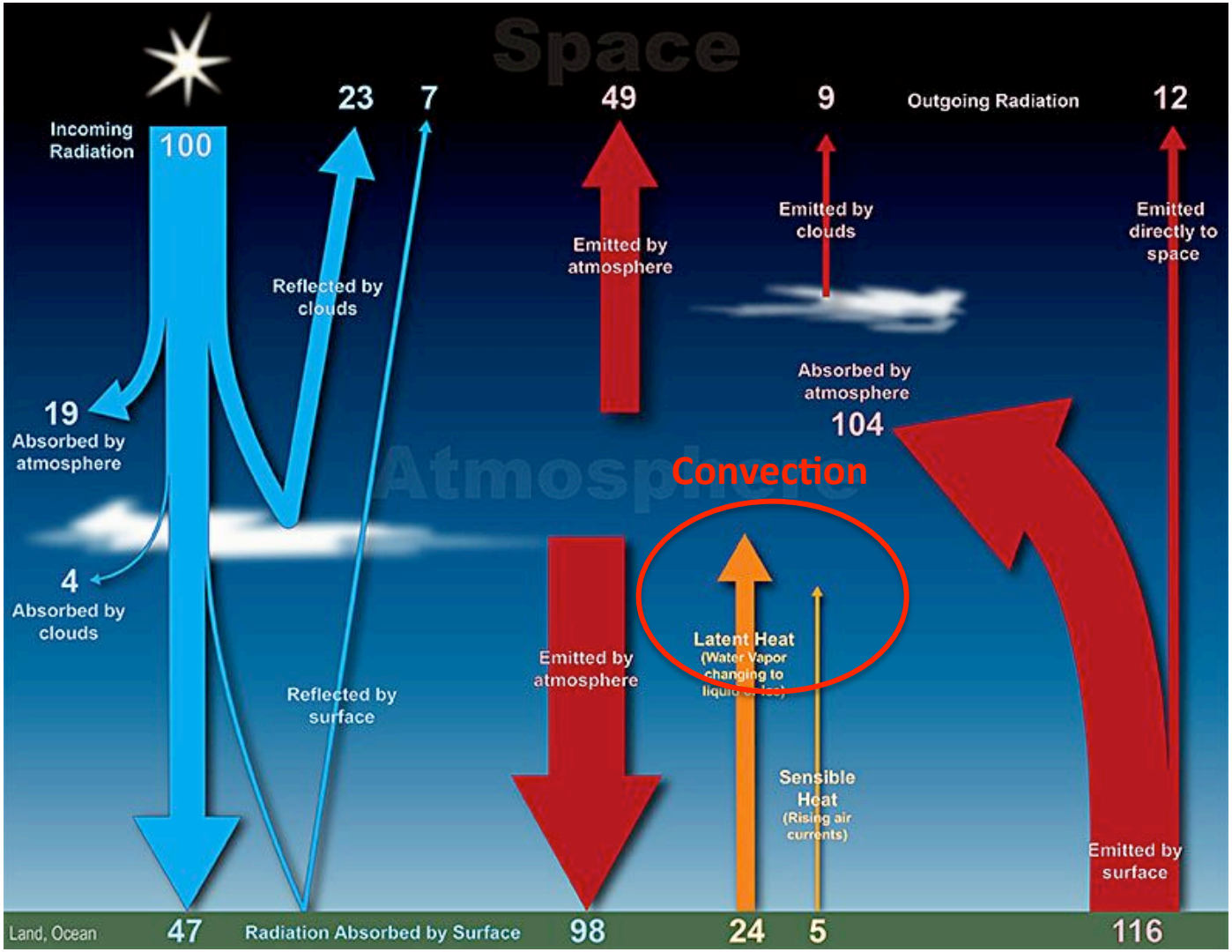
Take-home message:

Thunderstorms are the most powerful and energetic natural particle accelerators on Earth

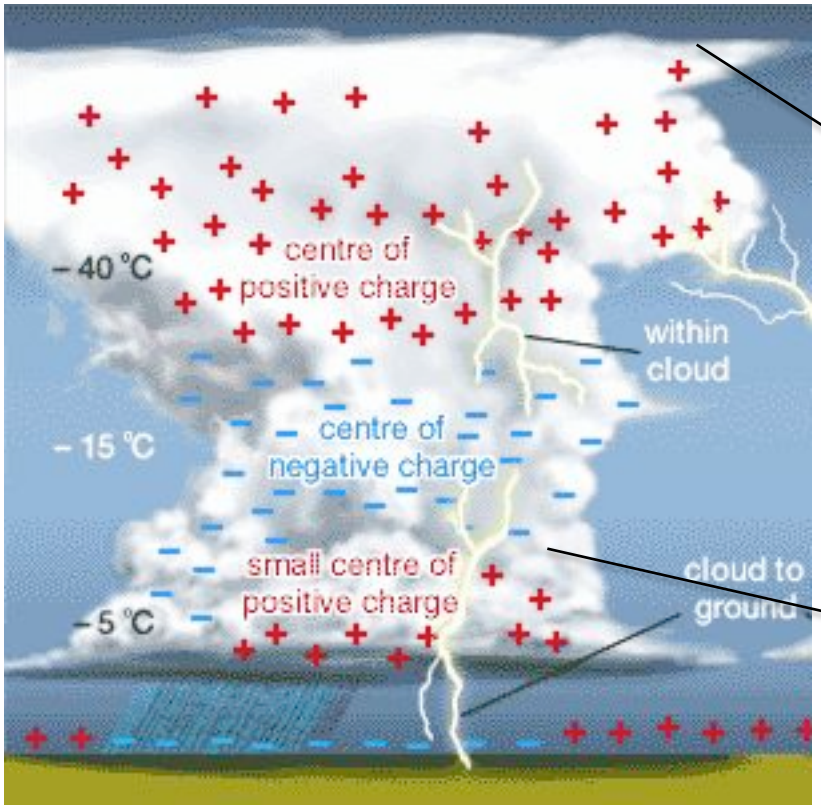
Earth atmosphere energy balance

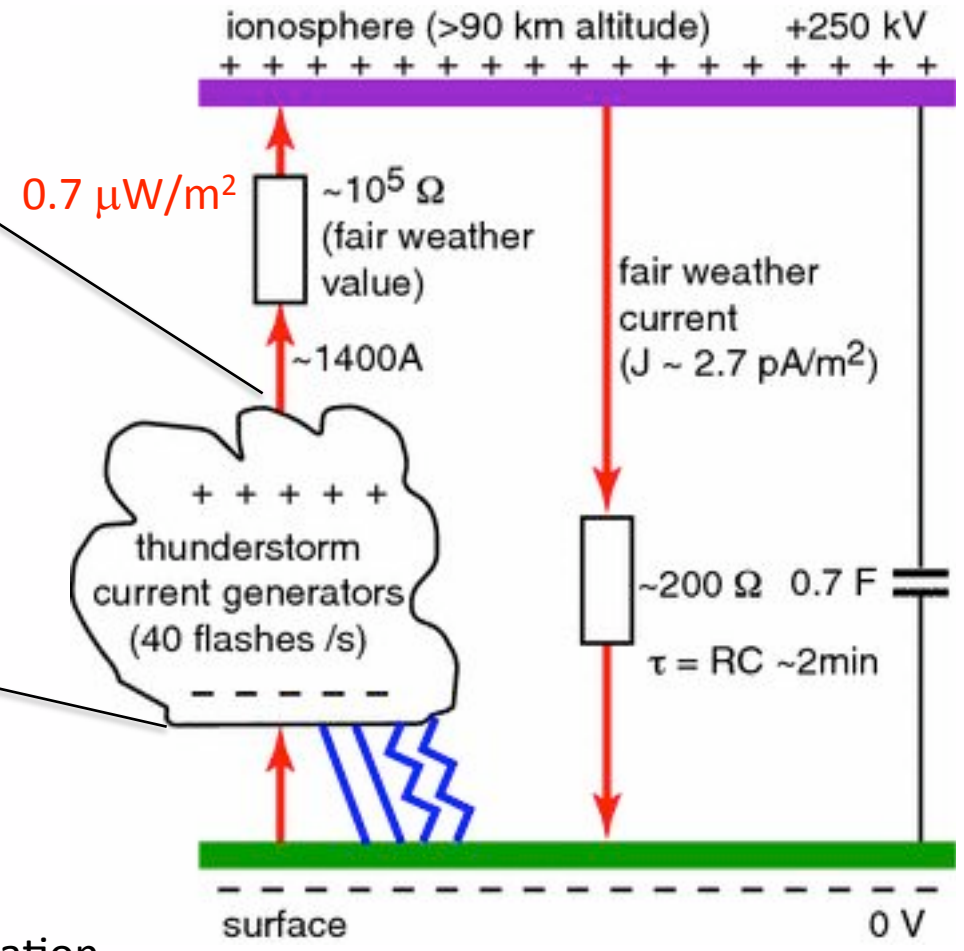
Average:
340 W/m^2



Credits: http://www.srh.noaa.gov/

The global electric circuit





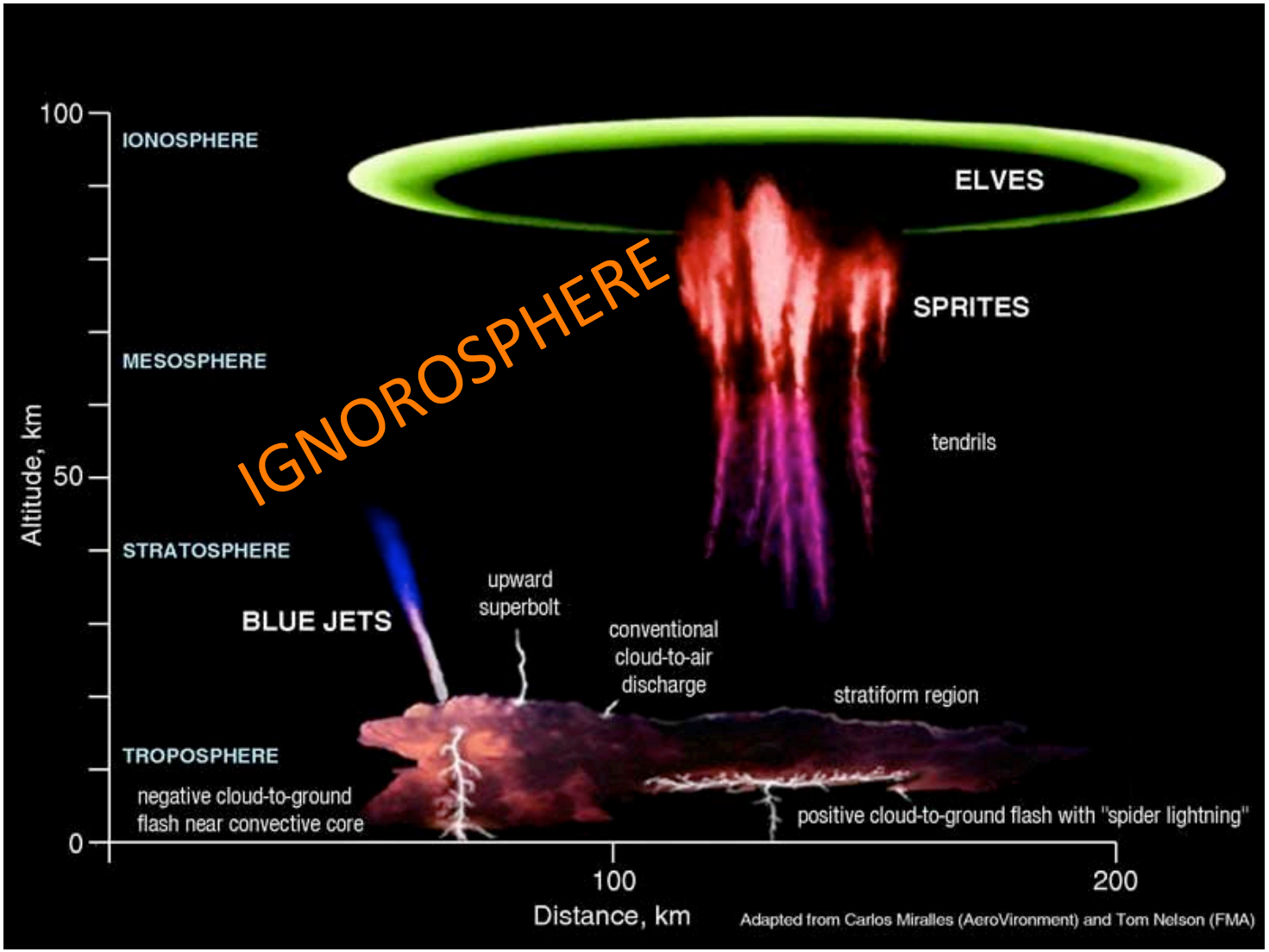
~100 W/m² available for atmospheric circulation

~40 lightning / s 10 MJ ÷ 10 GJ each ➔ <0.1mW/m²

mostly delivered as thermal energy and mechanical shock

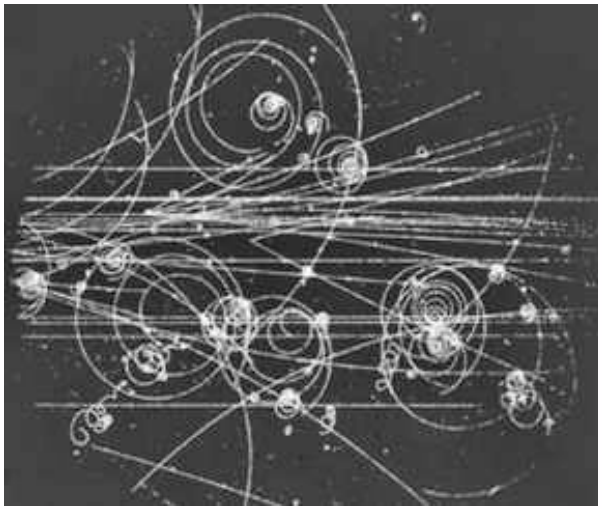
J. Kirkby, Surveys in Geophysics (2007)

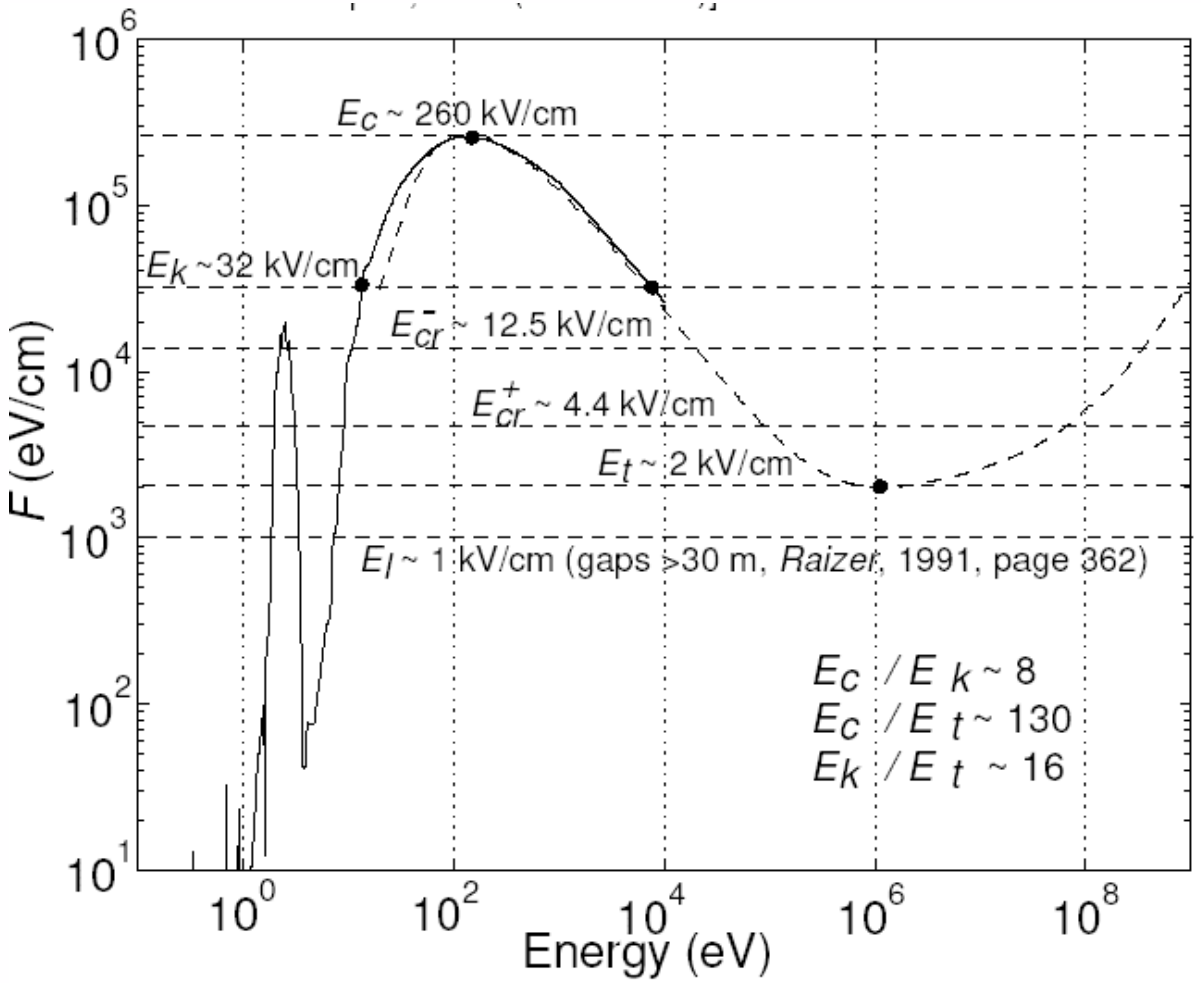
A more complicated picture



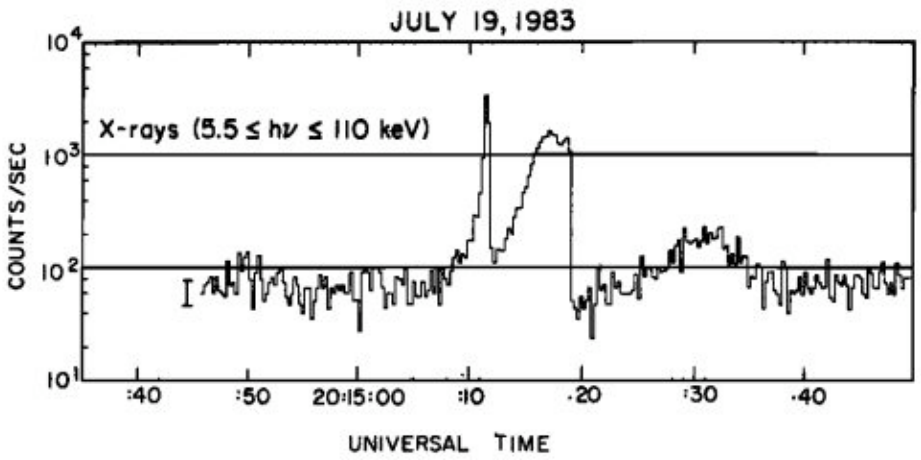
Theoretical prediction:

1925: C.T.R. Wilson and runaway electrons

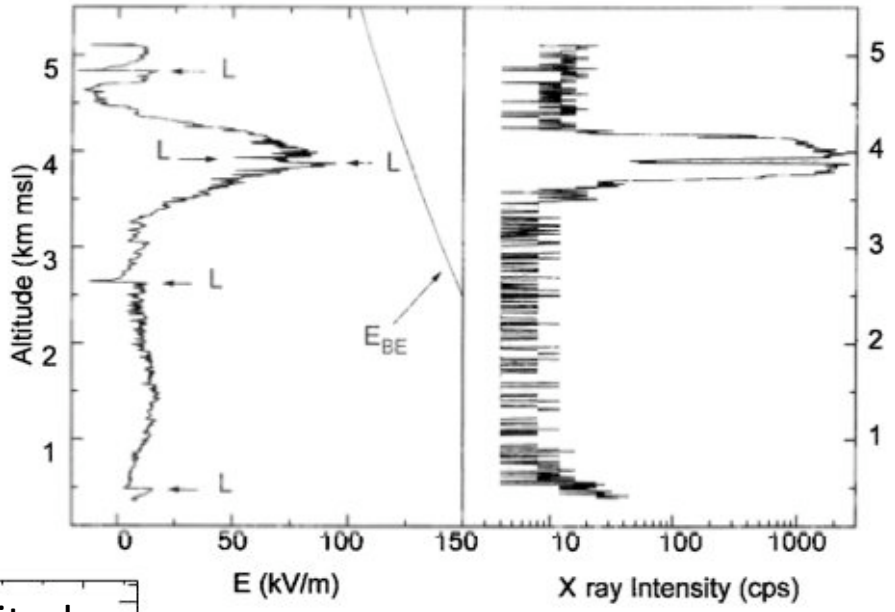




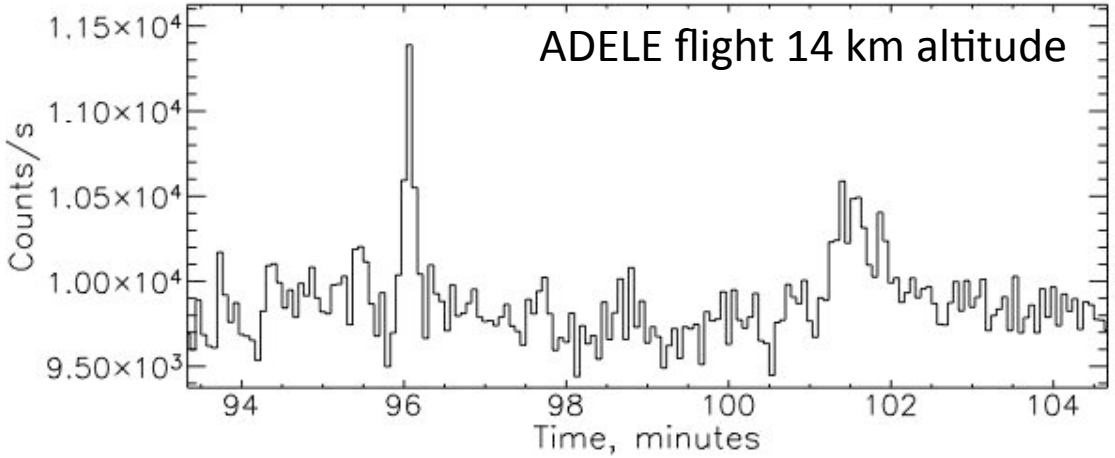
Aiplane and balloon observations



McCarty & Parks, GRL (1985)



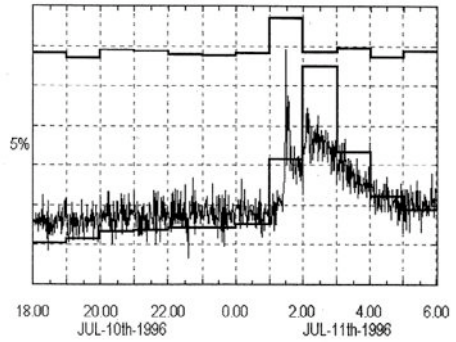
Eack et al., JGR (1996)



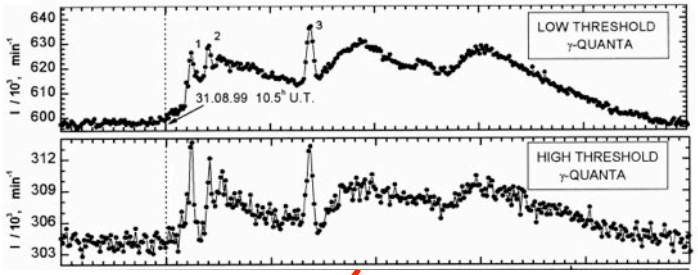
Dwyer Smith & Cummer, Sp. Sci. Rev. (2012)

Ground observations

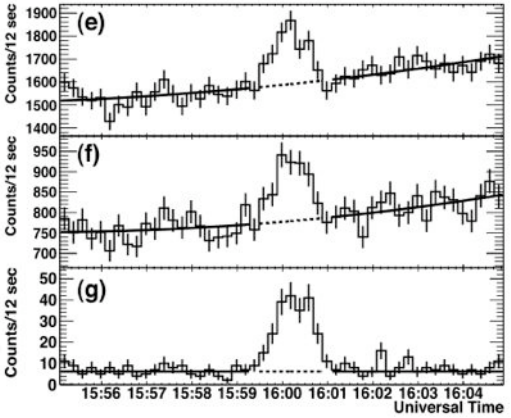
Italy, Gran sasso, 2005 m a.s.l.
(Brunetti+2000)

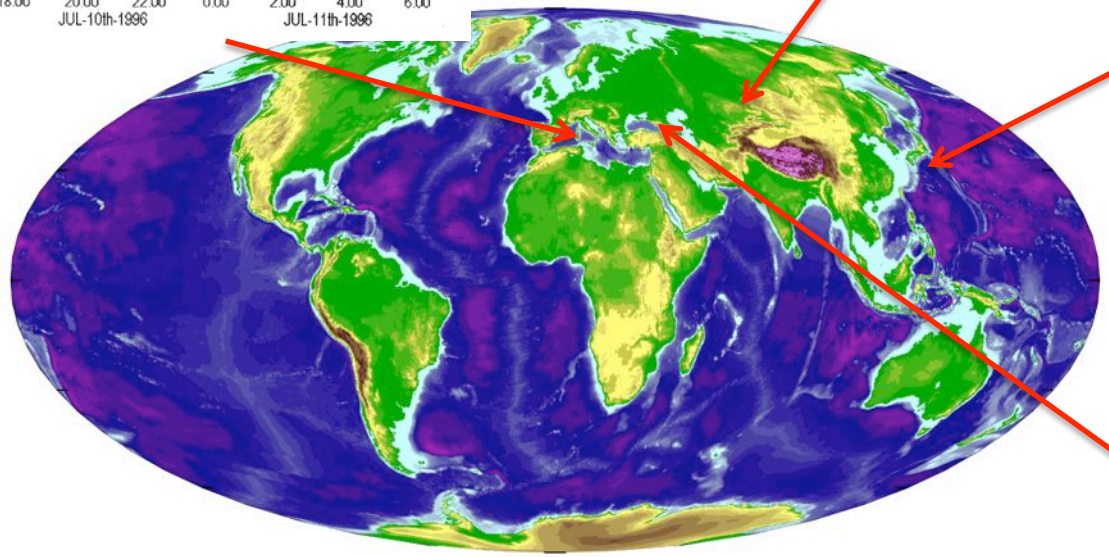


Russia / Kazakhstan, Tien-Shan, 3340 m a.s.l.
(Chubenko+2000)



Japan winter thunderstorms Sea level (Tsuchiya+2009, 2011)

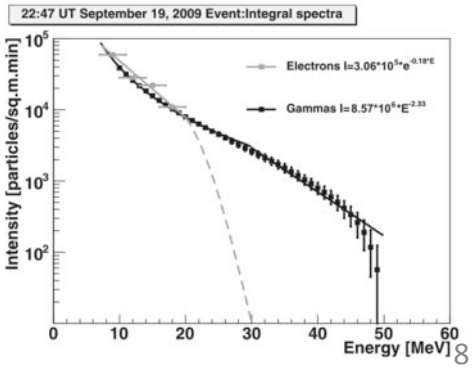




Present day Earth topography [m]

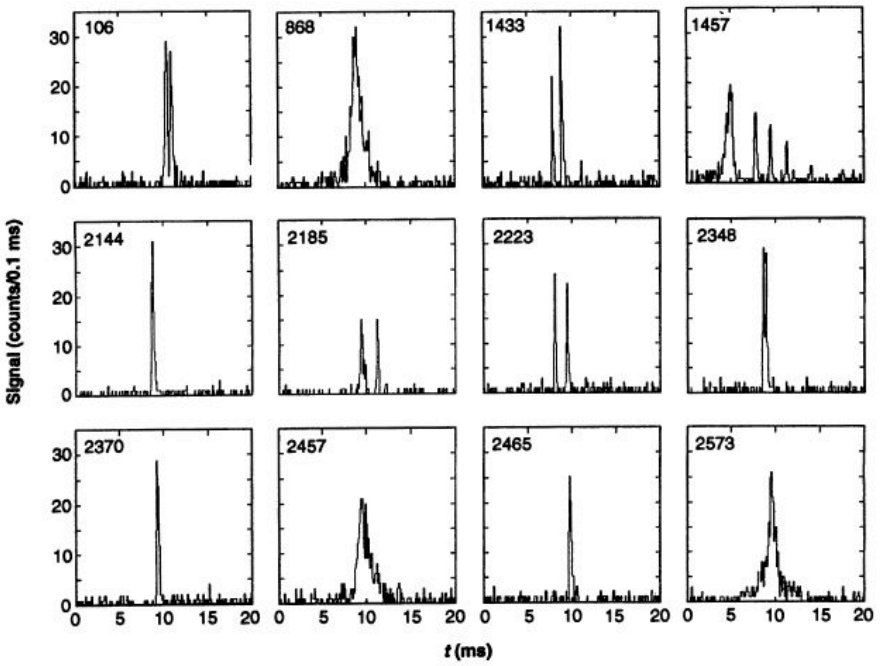
−6000 −4000 −2000 0 2000 4000 6000

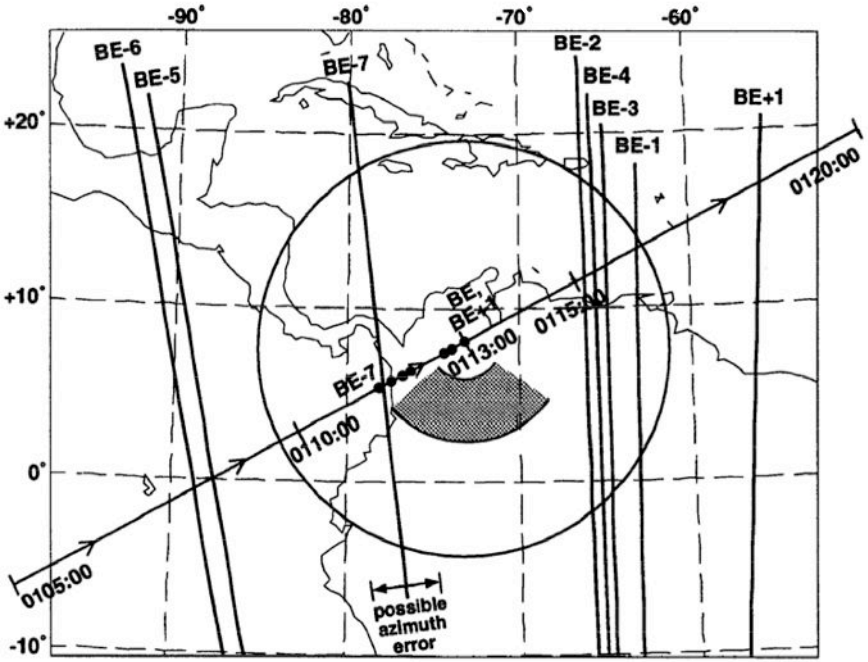
Armenia, Aragats 3250 m a.s.l.
(Chilingarian+ 2010,2011,2013)



Discovery of terrestrial gamma-ray flashes

Seminal paper by G.J. Fishman et al.,
"Discovery of Intense Gamma-Ray Flashes of Atmospheric Origin", Science (1994)



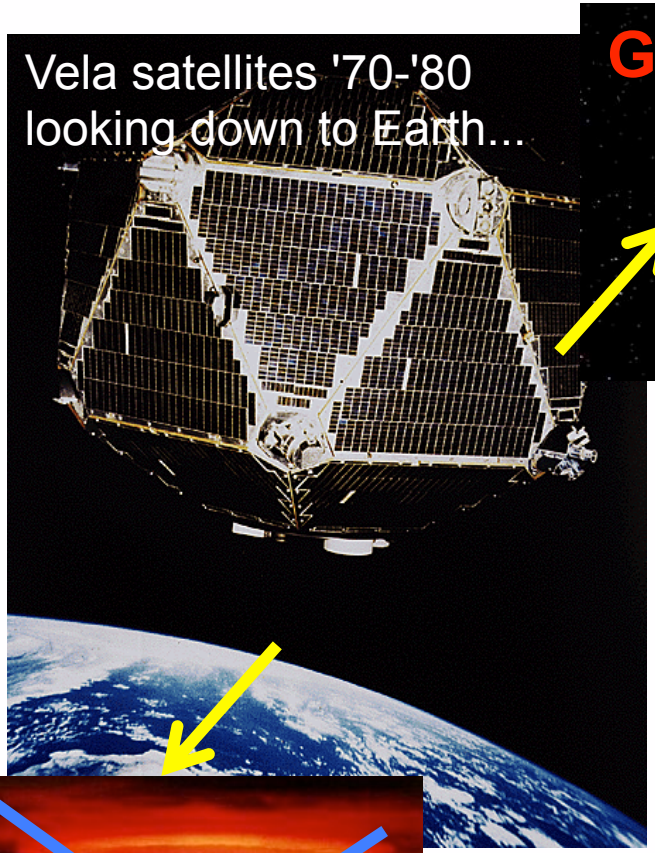


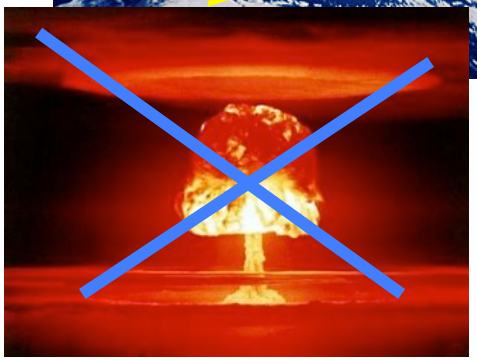
- Energy > 1MeV, harder than GRBs
- Very bright, ~1ms duration
- Associated to lightning

Accepted 19 April 1994.
Happy 20th birthday TGF!

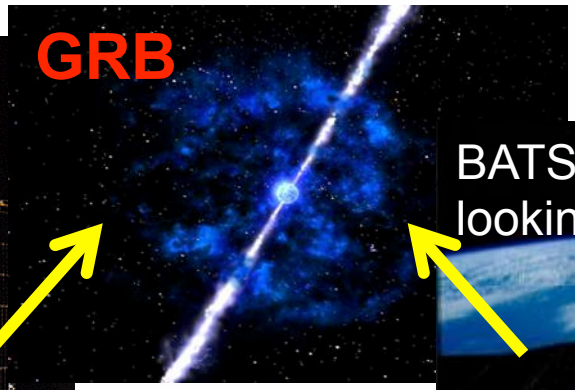
The discovery of TGFs: serendipity at play

Vela satellites '70-'80
looking down to Earth...

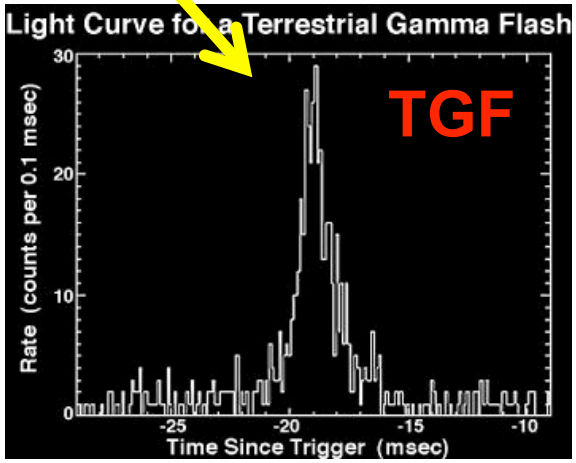




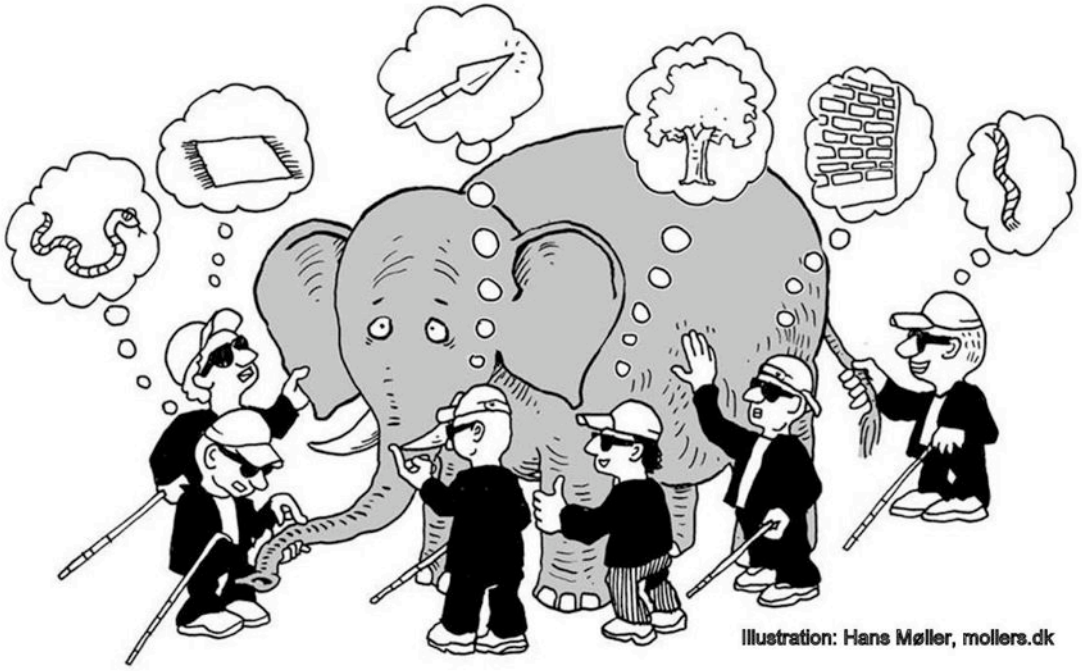
GRB



BATSE onboard CGRO 1991 – 2000
looking up to space...



What do we really know about TGFs?



Credits: Michael Briggs, EGU 2014

1. TGFs are short
Average duration ~0.1 ms
(direct observation)

2. TGFs are energetic
Average energy ~MeV
(direct observation)

3. TGFs are associated with lightning
(correlation studies)

4. TGFs are produced near thundercloud tops
(spectral modeling – sferics observation)

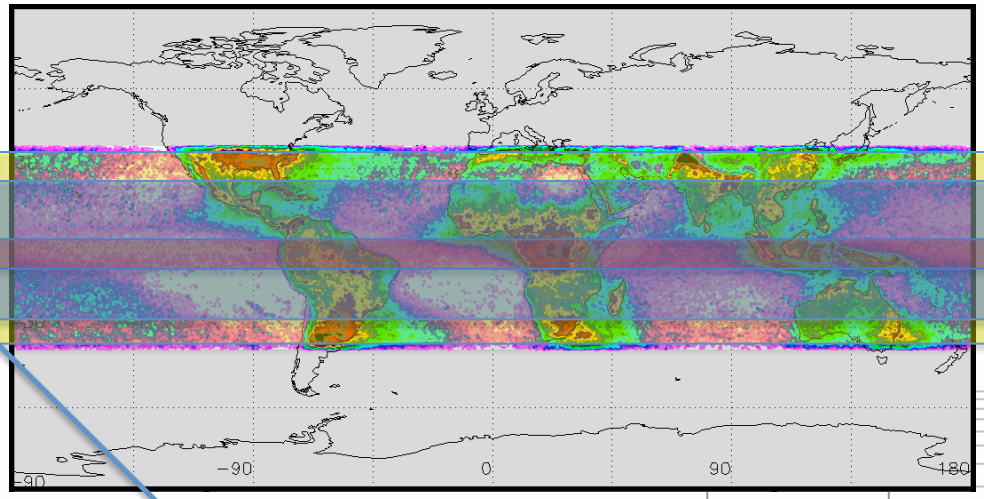
5. TGFs are bright
At least ~10^{17} energetic electrons – ~10 kJ
(flux observation and production altitude constraints)

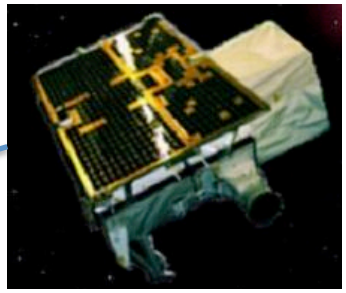
6. Intensity as a power law
(direct observation + dead time modeling)

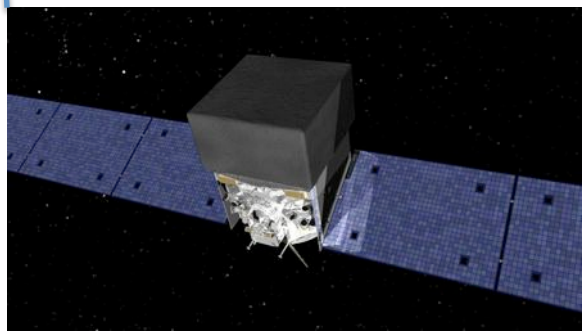
What we do not know about TGFs

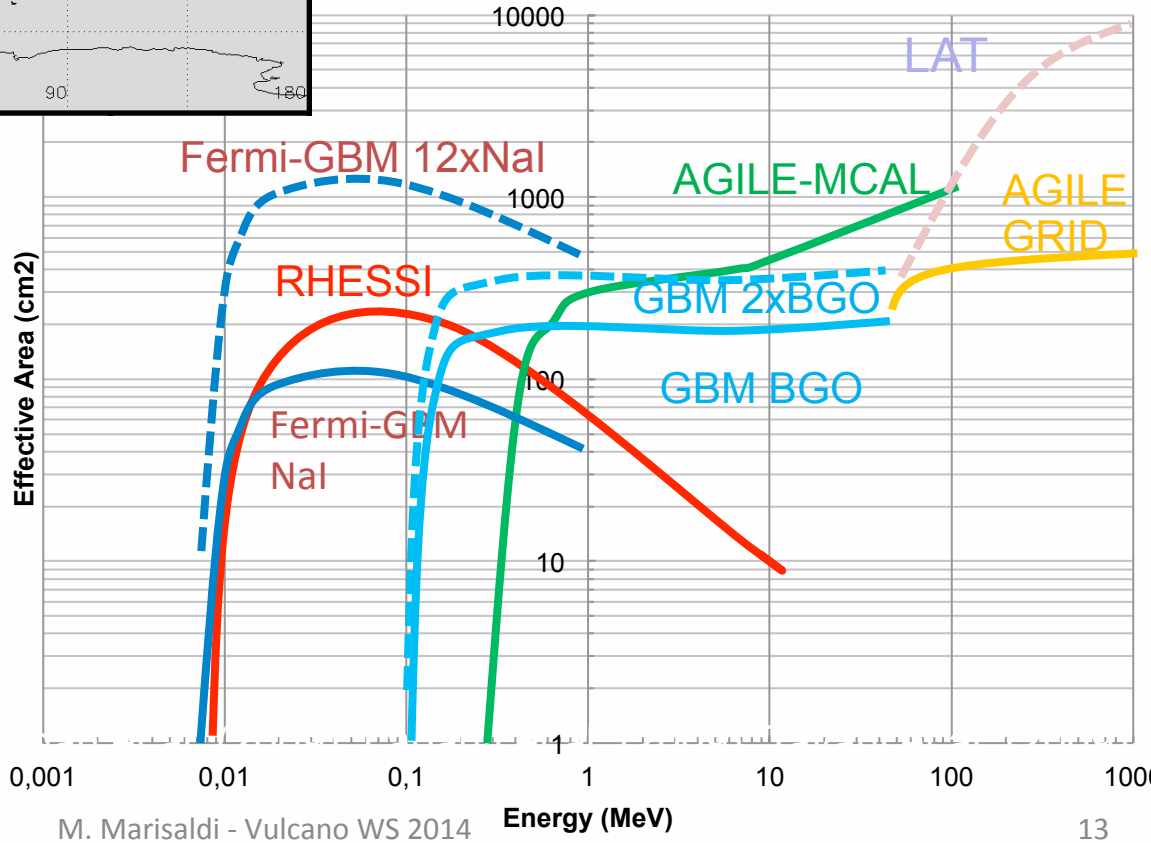
- What is the production model?
- Is there any type of thunderstorm / lightning / whether phenomenon preferentially conducive to TGF production?
- What is the contribution of cosmic rays to lightning and TGF initiation?
- How many TGFs are there?
- What is the maximum energy?
- What is the overall energy budget delivered by thunderstorms in the high-energy channel?
- What is the impact of this energy transfer to the dynamics of atmospheric layers and ultimately on climate?

Operating TGF detectors

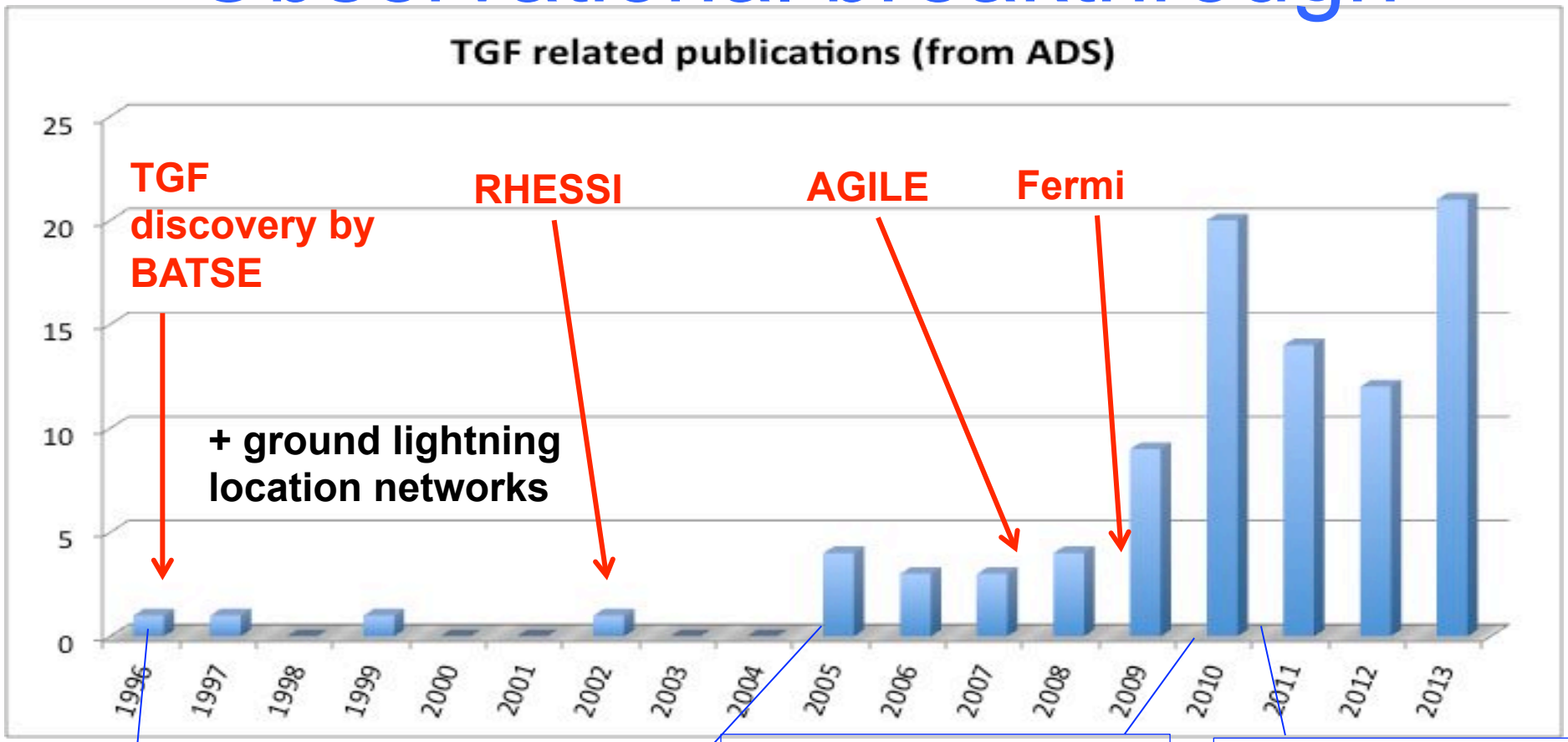








Observational breakthrough



Association to lightning

- Cumulative spectrum
- Energy up to 20 MeV
- production altitude < 20km

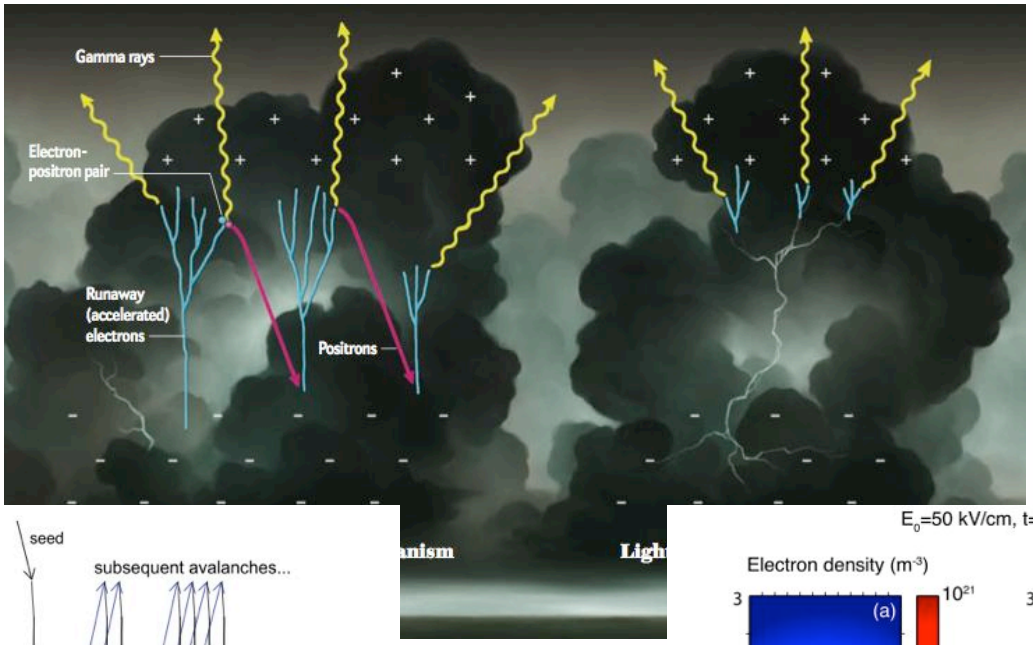
- Energy > 40 MeV up to ~ 100 MeV
- First localization in γ-rays from space
- TGF & global lightning activity
- 1st AGILE catalog

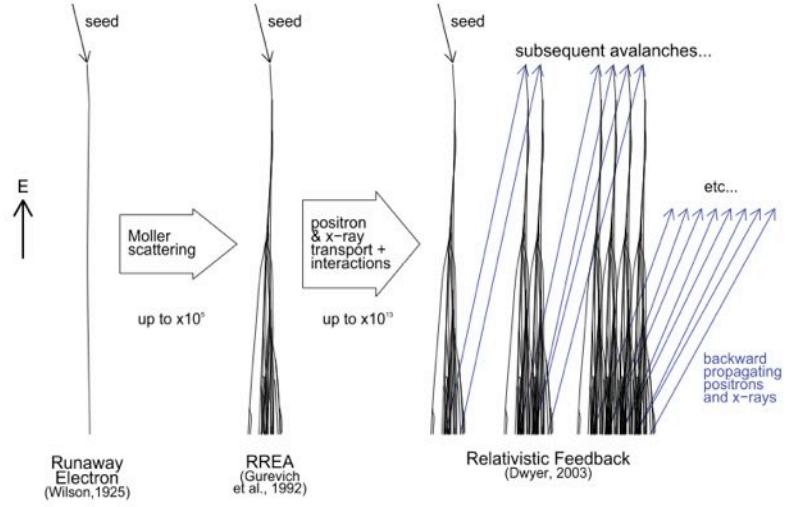
New!

- Discovery of e^+/e^- flashes
- Radio emission from TGFs
- Improved selection

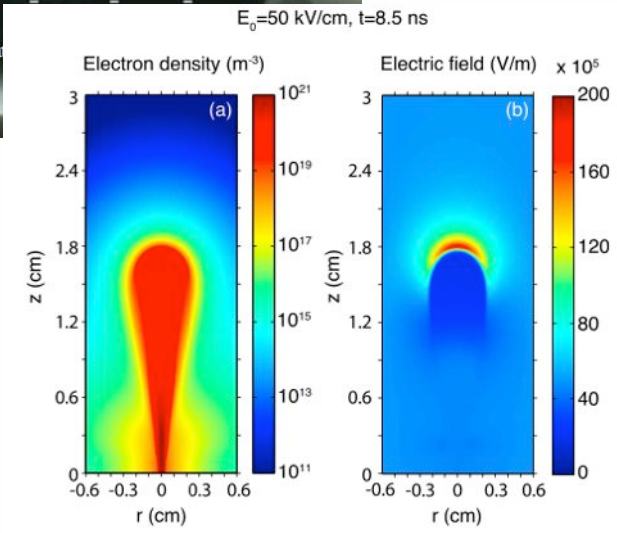
Two competing models

Dwyer and Smith, Scientific American (2012)





Dwyer, Smith & Cummer (2012)

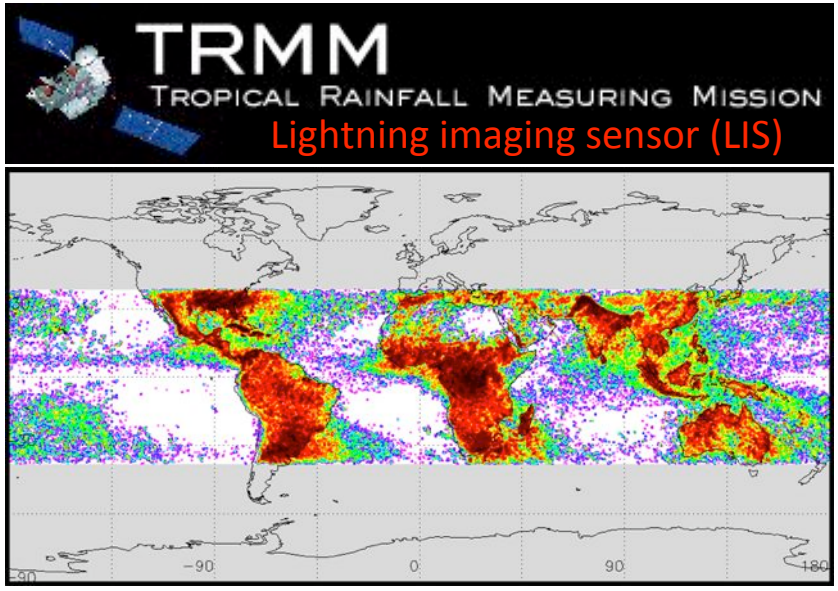


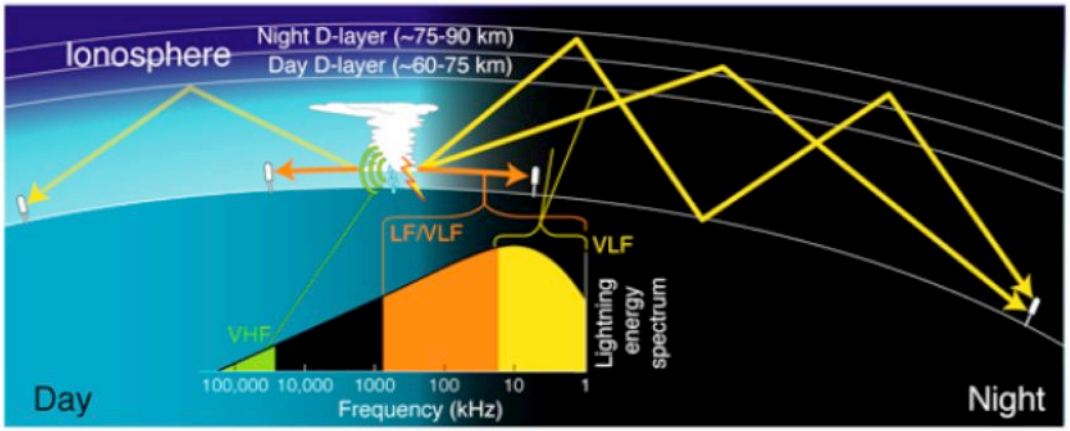
Celestin+ (2011)

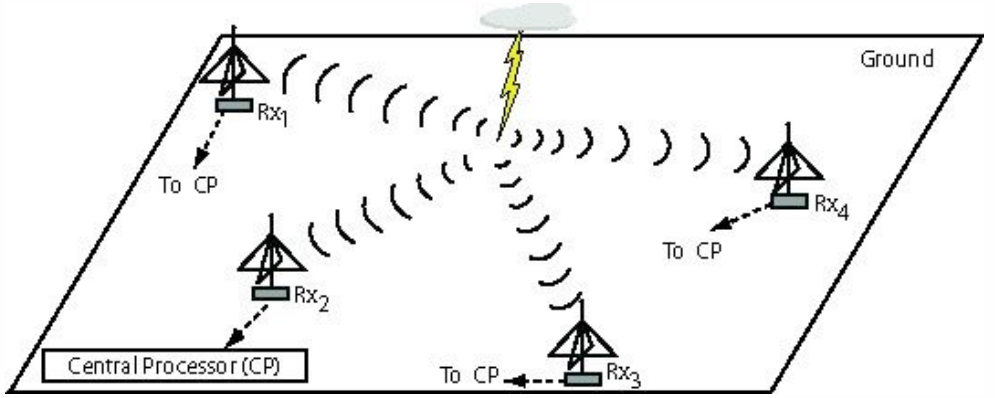
How to detect lightning

From space:

From the ground:

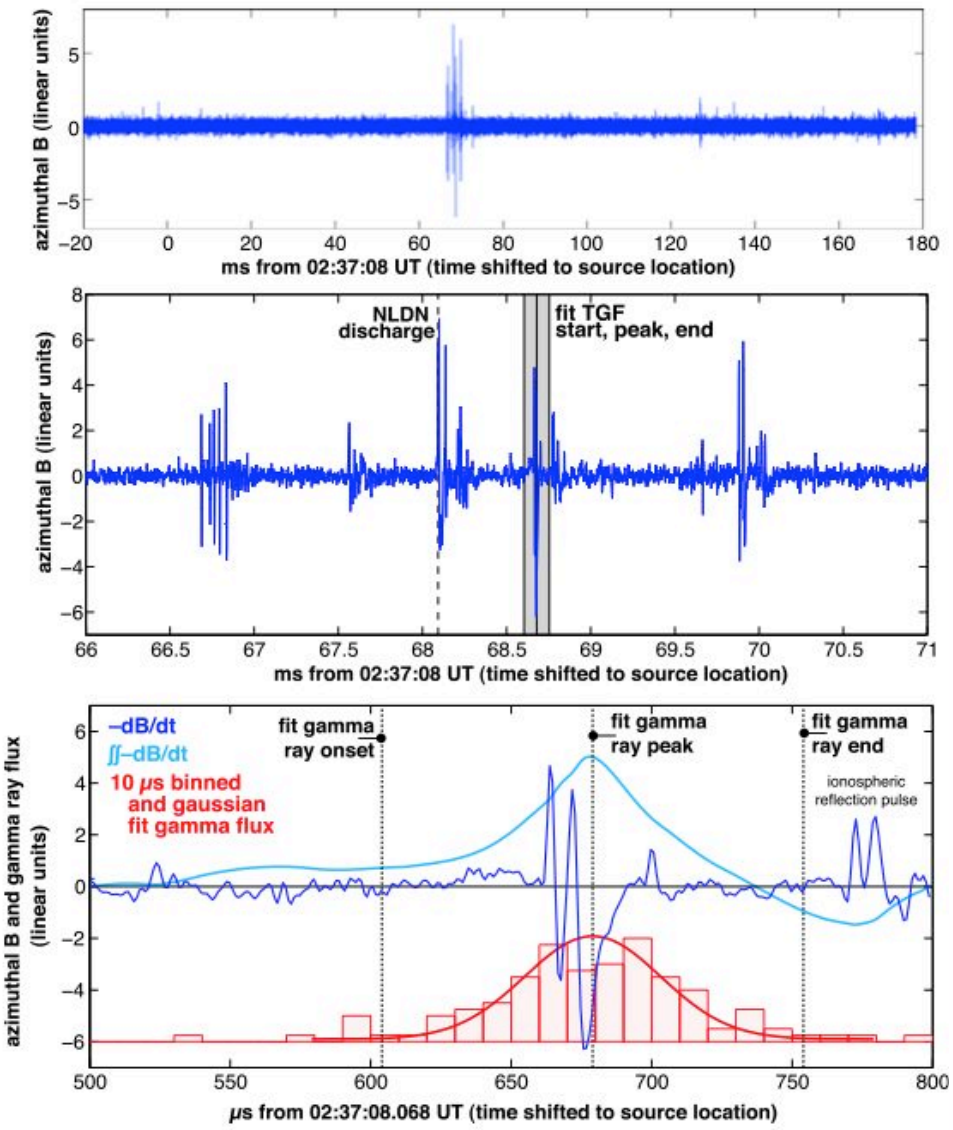




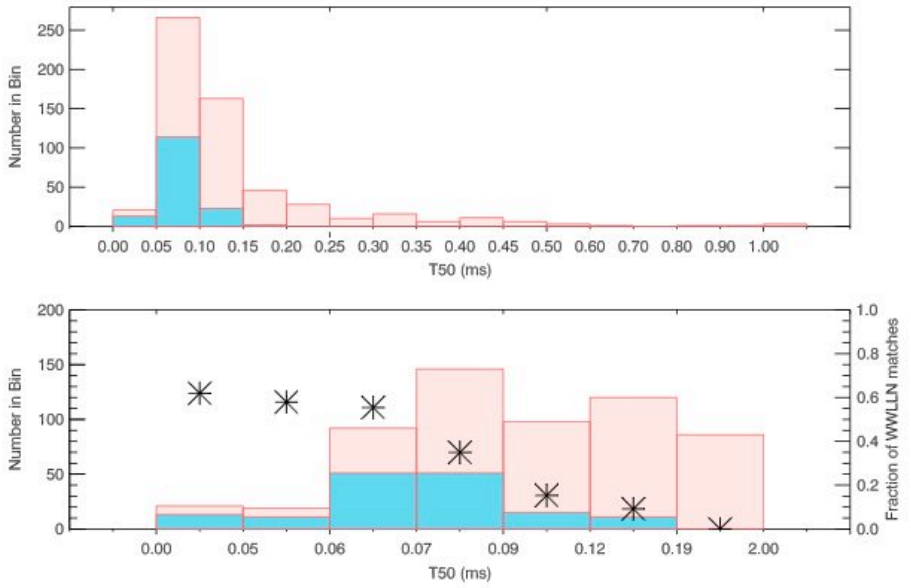


http://thunder.msfc.nasa.gov/

TGF / lightning connection

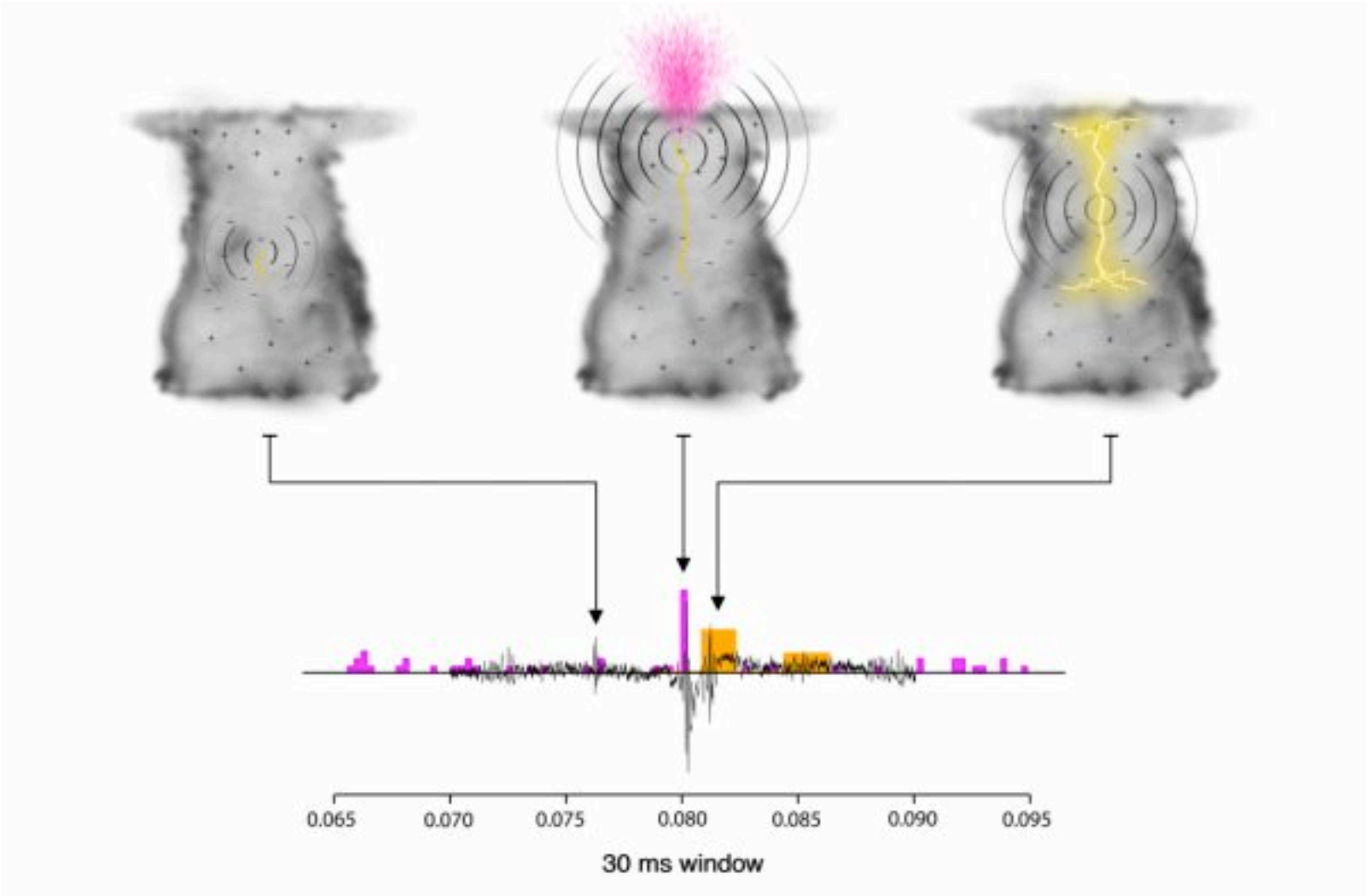


Cummer+ GRL (2011)



Connaughton+ JGR (2013)

TGF / lightning connection



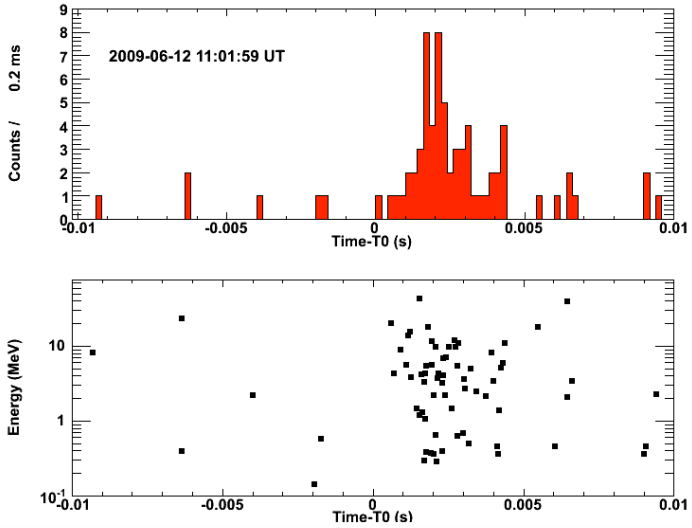
Ostgaard+2013

Credits: birkeland.uib.no

AGILE contributions to TGF science

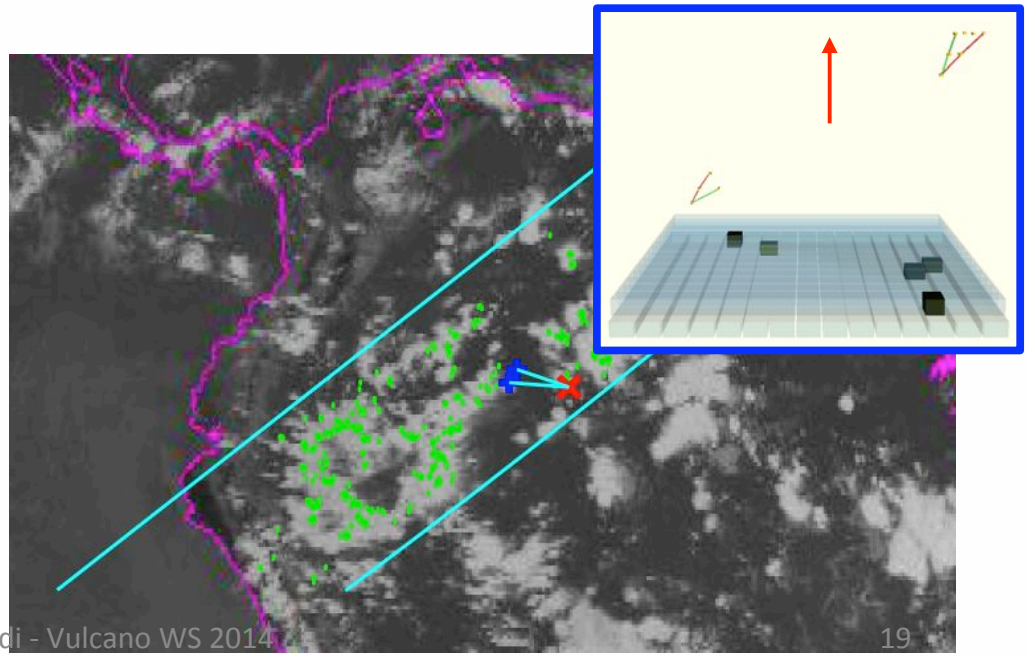
- TGF energy range extends at least to 40 MeV, doubling the previous range set by RHESSI:

Marisaldi et al., J. Geophys.Res. 115 (2010)



- TGFs can be localized from space directly in gamma-rays by the AGILE silicon tracker:

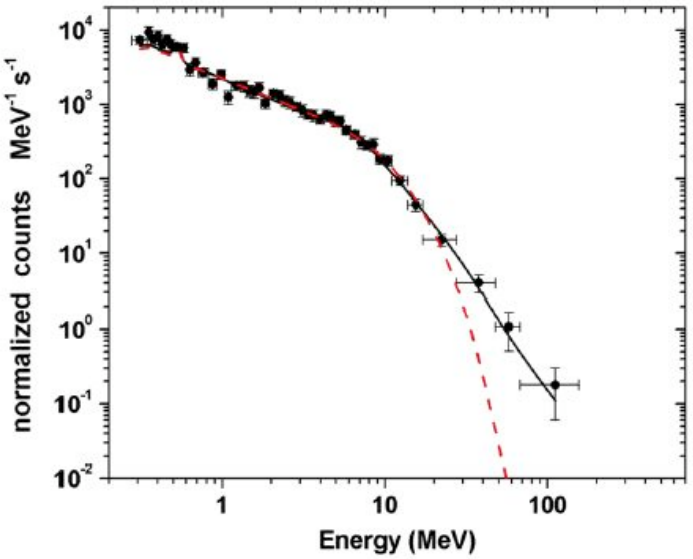
Marisaldi et al., Phys. Rev. Lett. 105 (2010)



AGILE contributions to TGF science

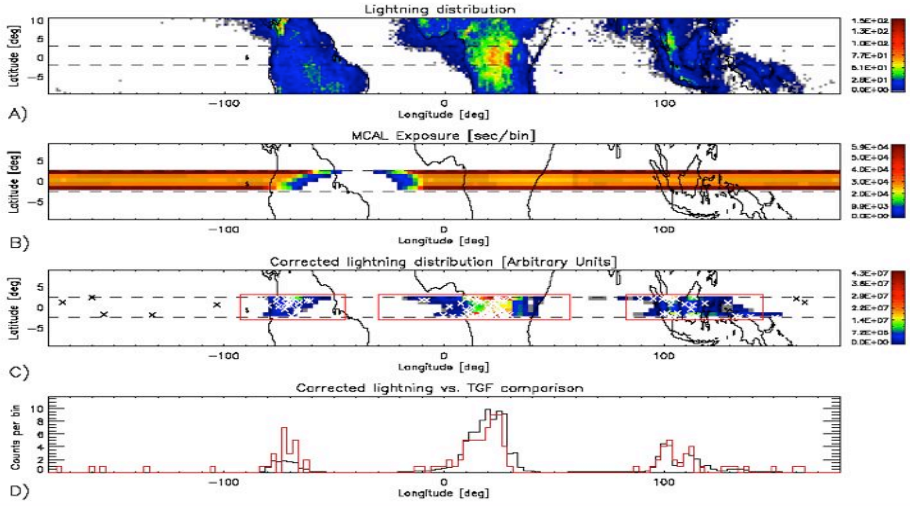
- TGFs high-energy spectrum extends up to ~100 MeV and challenges current models:

Tavani et al., Phys. Rev. Lett. 106 (2011)



- The TGF / lightning flash ratio is not constant over different geographical regions:

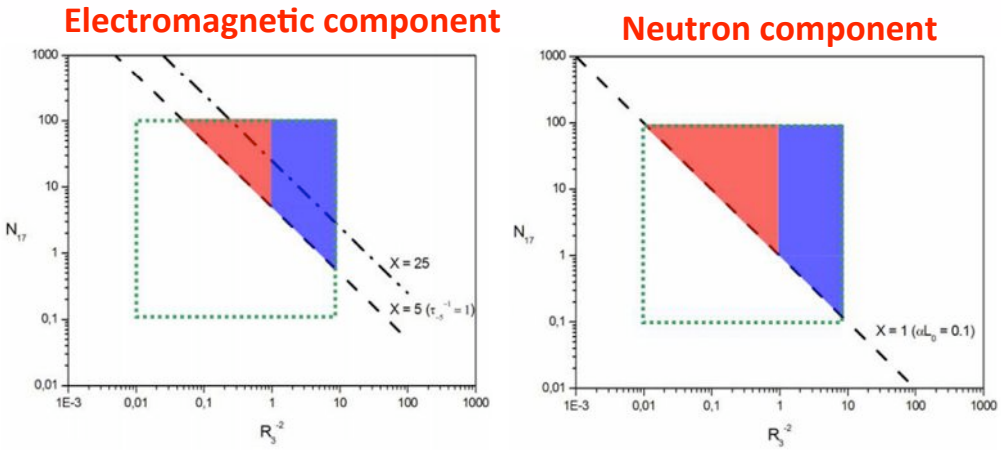
Fuschino et al., Geophys. Res. Lett. 38 (2011)



AGILE contributions to TGF science

- TGFs can potentially affect aircrafts avionics:

Tavani et al., NHESS 13 (2013)

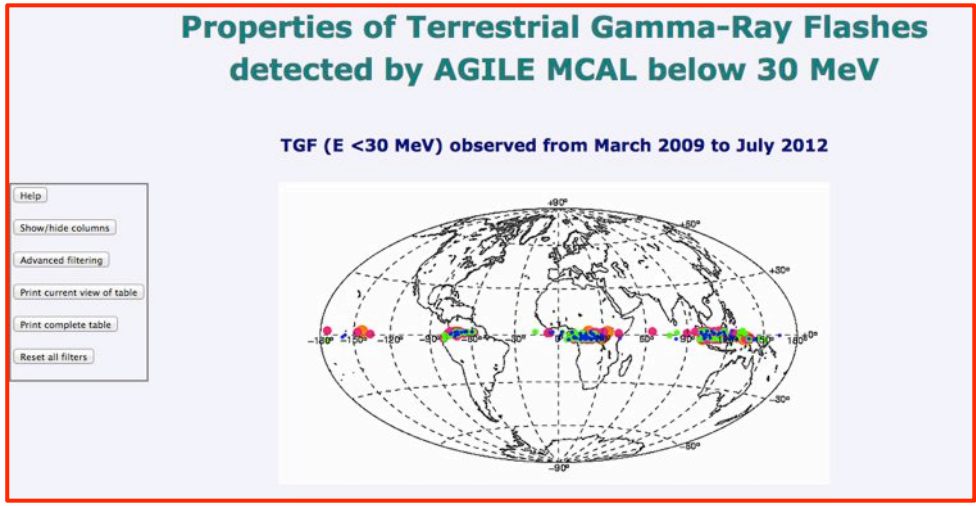


- AGILE TGFs in the frame of current observational framework; delivery of the 1st AGILE TGF catalog:

Marisaldi et al., J. Geophys. Res. 119 (2014)

Available at the ASI Science Data Center (ASDC) website:

www.asdc.asi.it/mcaltgfcat



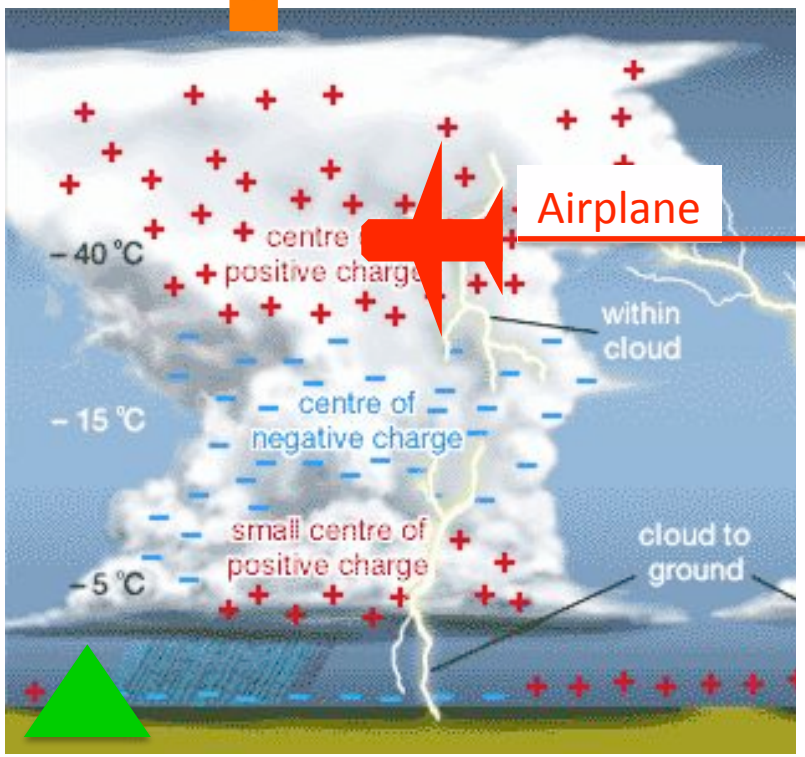
What is going on in the world?

Space

AGILE, RHESSI, Fermi
+
ASIM (ESA) - ISS
TARANIS (CNES)
Firefly (USA)
Firestation (USA) – ISS
GLIMS (JP) – ISS

Balloon

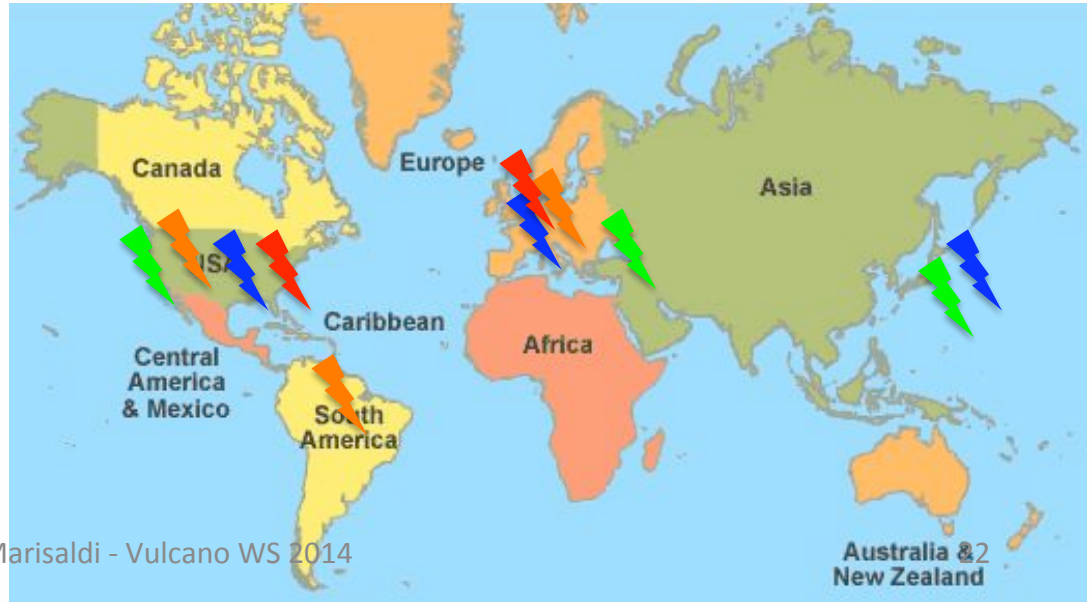
COBRAT (CNES+)
USA



ADELE (USA)
ILDAS (NL)
Air France + IRSN

Ground

USA
Japan
Armenia



What next?

AGILE, RHESSI and Fermi still have a lot more to say!

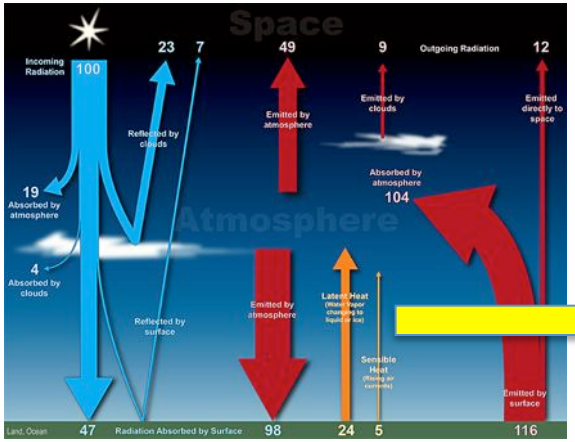
ASIM
ESA >= 2015

TARANIS
CNES >= 2015

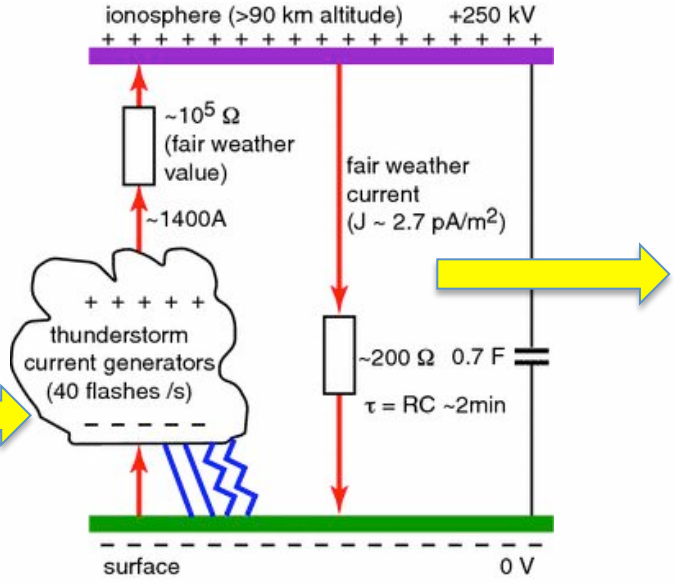
Why it is important

A global perspective

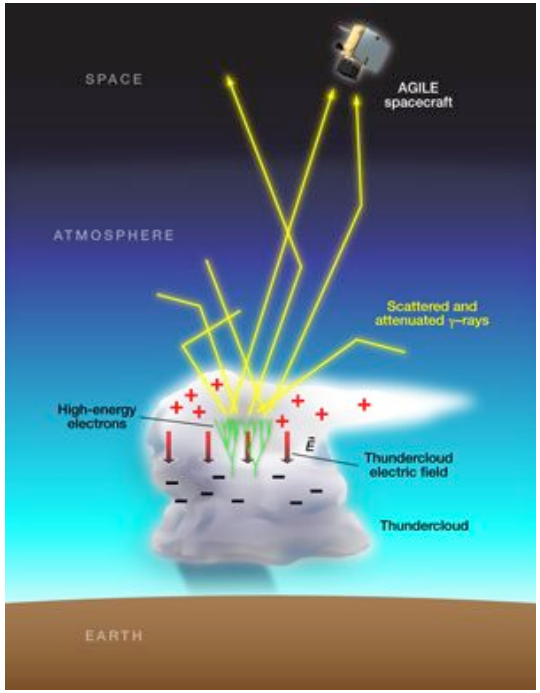
~100 W/m^2
available for convection



0.01 – 10 GJ / lightning
40 lightning / s
~100 μW/m^2
10^{-6} available energy



~10 kJ / TGF
If every lightning is associated to a TGF
10^{-11} available energy



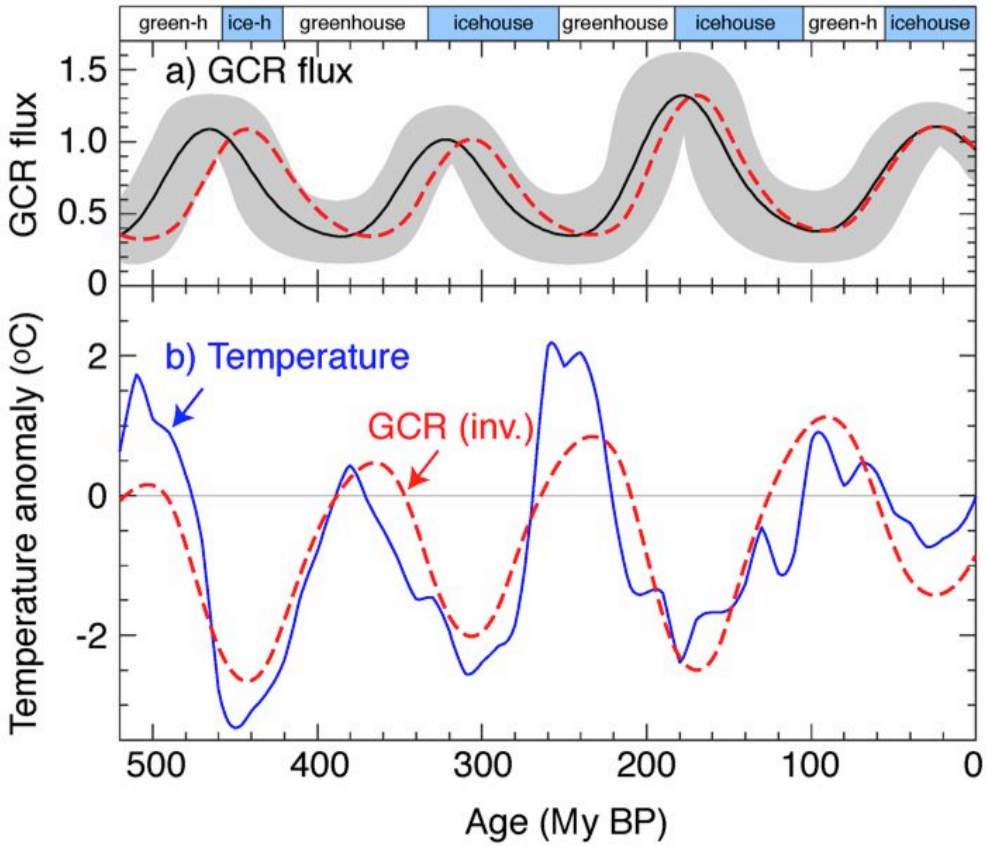
Credit: Alan Stonebraker

- Can such a tiny fraction of the energy budget have any significant impact?

Why it is important

A global perspective

- Example: galactic cosmic rays account for 10^{-9} of the total energy budget but their flux variation can potentially affect climate on the long term



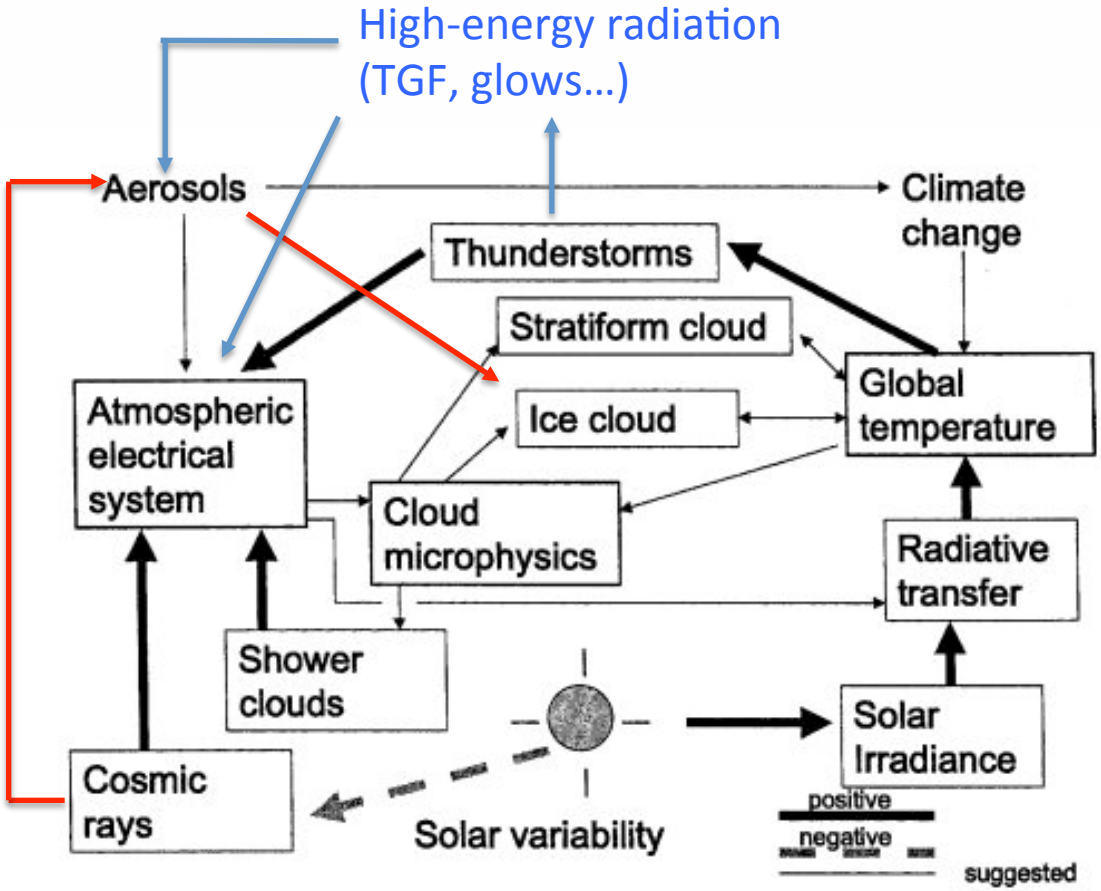
Kirkby 2008

Why it is important

A global perspective

- Relations between energetic radiation and climate is highly non-linear and mostly not understood

Cloud condensation nuclei enhancement (CLOUD experiment, Kirkby 2011)



Harrison 2004

Conclusions / outlook

- Energetic radiation production in thunderstorms is a piece of the puzzle of how the Earth is coupled to space
- TGFs are the manifestation of the most energetic natural particle accelerators on Earth
- After 20 years, lots of questions still do not have answers
- TGFs and radiation from atmospheric electricity is a fast growing scientific field
- European and American institutions are investing lots of efforts in this field
- The Italian AGILE mission is a player in the field and can still give significant contribution