What is known and what is not about Terrestrial Gamma-ray Flash

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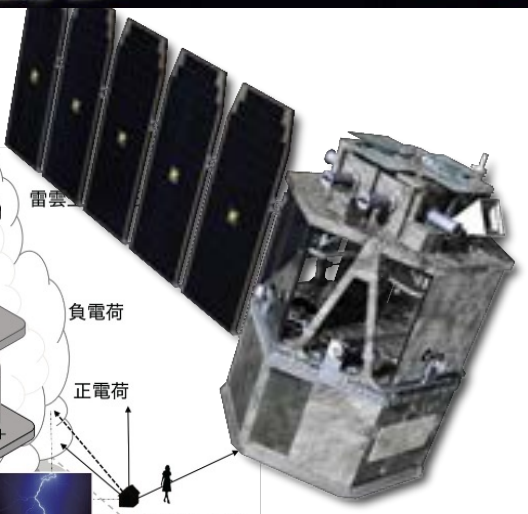
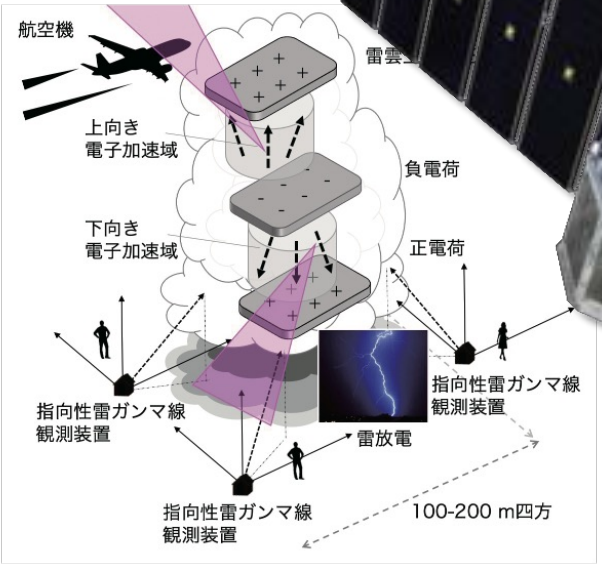
and the GROWTH-collaboration

Nagoya-U[A], RIKEN[B], Osaka-U[C], JAEA[D]

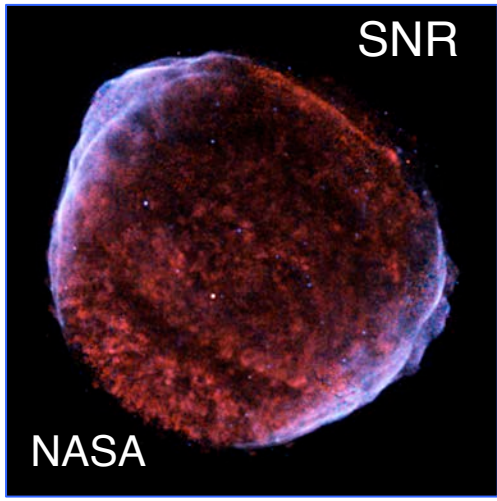




1: Scientific importance of Thunderstorm Gamm-ray emission

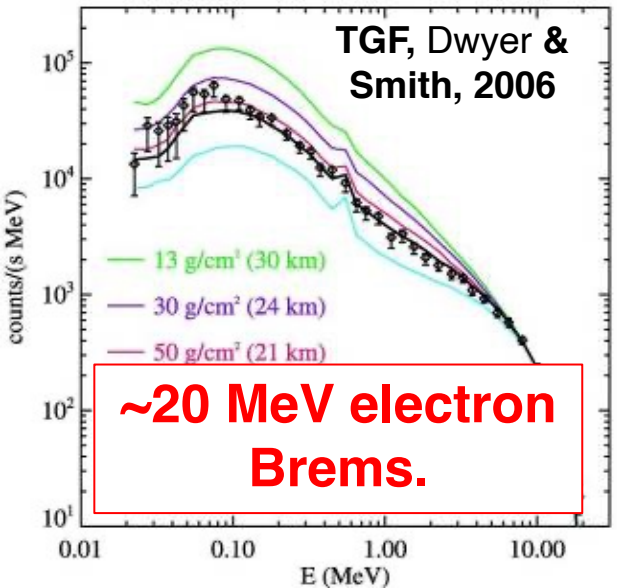
- **New particle-acceleration mechanism**

- Solar flare (GeV), SNR blast wave (PeV)＝ magnetic field
- Thunder. gamma rays = electrostatic 30 ~MeV electron acceleration (without magnetism) ← missing link?



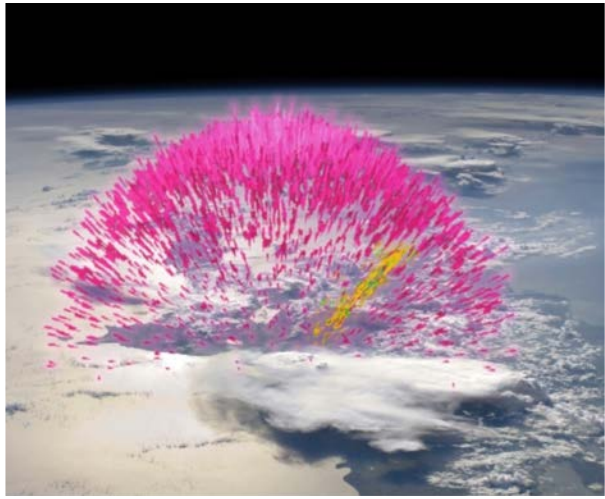
- **Hot and emerging science**

TGF spectra



- Came to be "well-known" only after 1990s. (original finding around 1980s).
- Electro-static acceleration was deemed to be "impossible" until this findings. Was a big surprise.
- Emerging science → HOT

Phenomenologically new and Physically Important



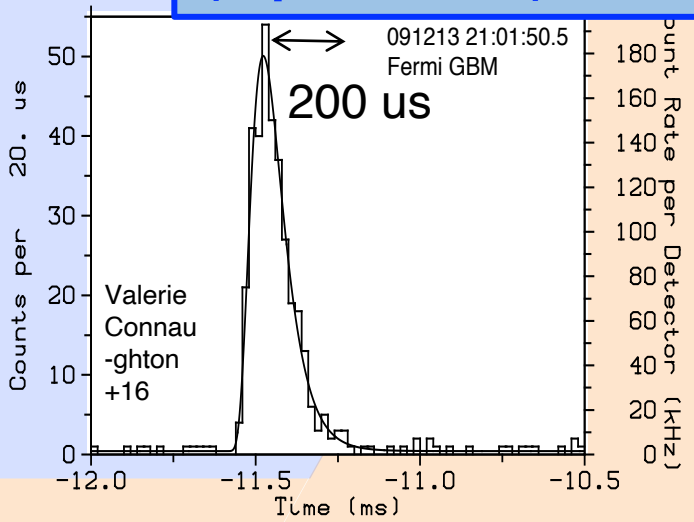
2: Two distinct types of events

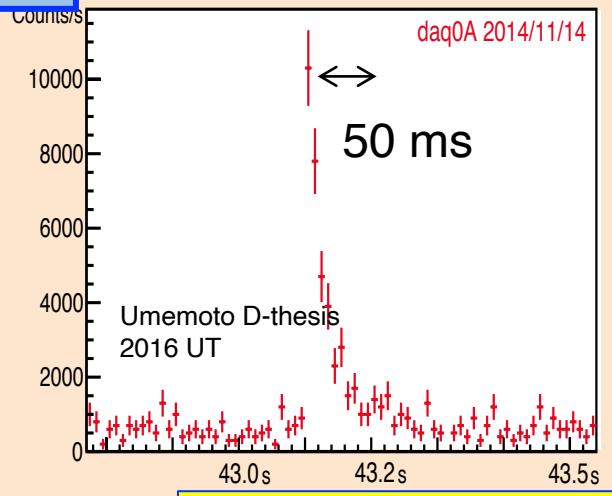
from space

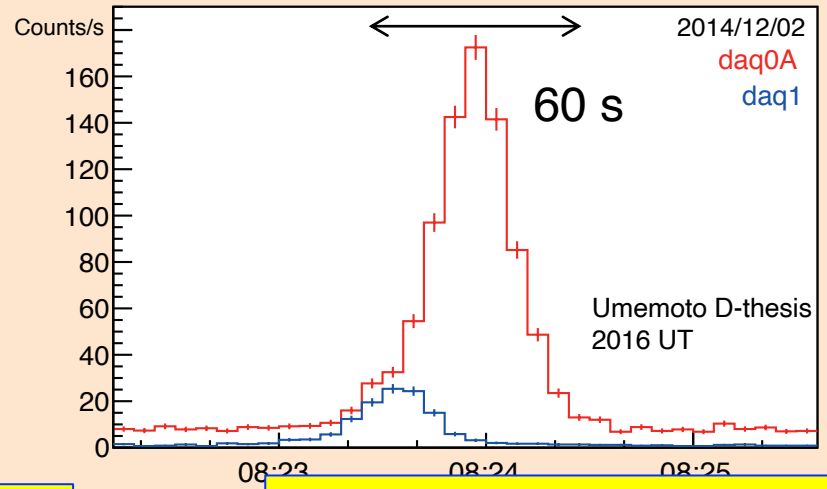
(upward-) TGF

bursts" (100 ms)

2: Long burst (100 s)







from ground

with lightning discha

e.g. Fishman+94, Smith+05, Briggs+1

downward-TGF

neutrons from photo-nuclear reactions

continuous gam-ma-ray generation in cloud

- Winter th… w a… r → pr…
- On-ground gamma-ray observations

→ GROWTH collaboration leading on-ground measurements

(Gamma-Ray Observation of Winter Thunderclouds)

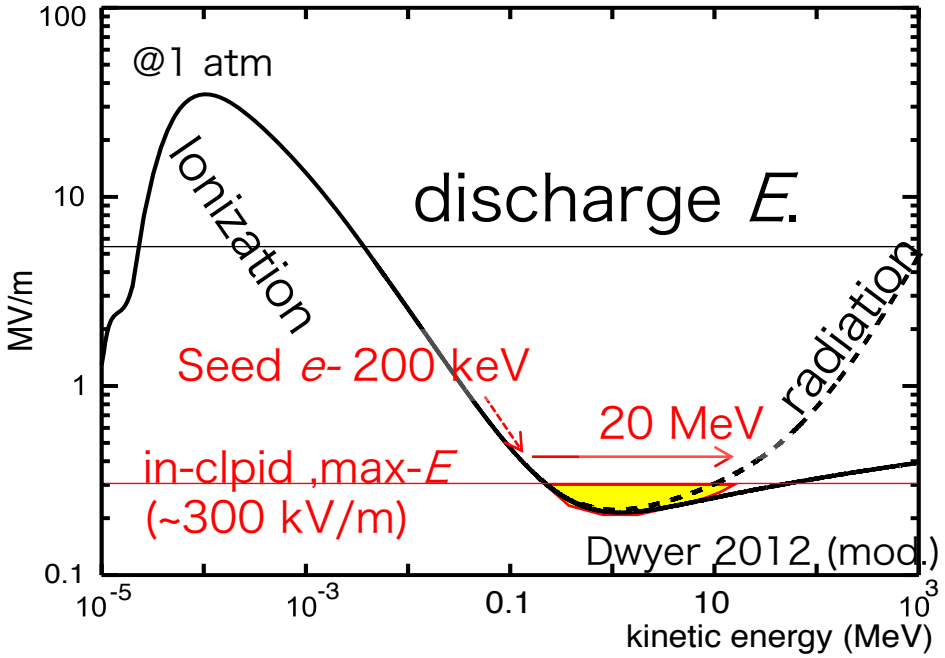
e.g. Torii +02, Kuroda+ PLB 2016

e.g. Tsuchiya PRL+07, Tsuchiya+ JGR 2011, Tsuchiya+ PRD 2012, Umemoto+2016 PRE

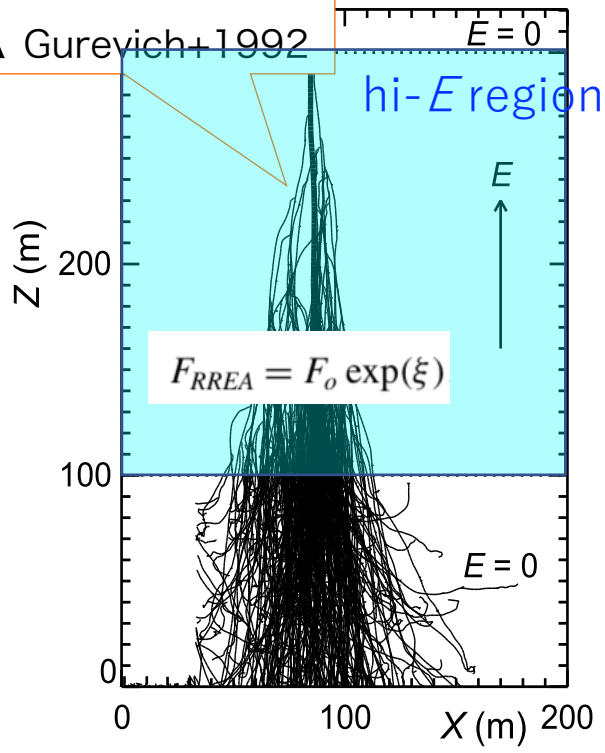
3 : Physics of electron acceleration: Relativistic Runaway Electron Avalanche

- **Basics**

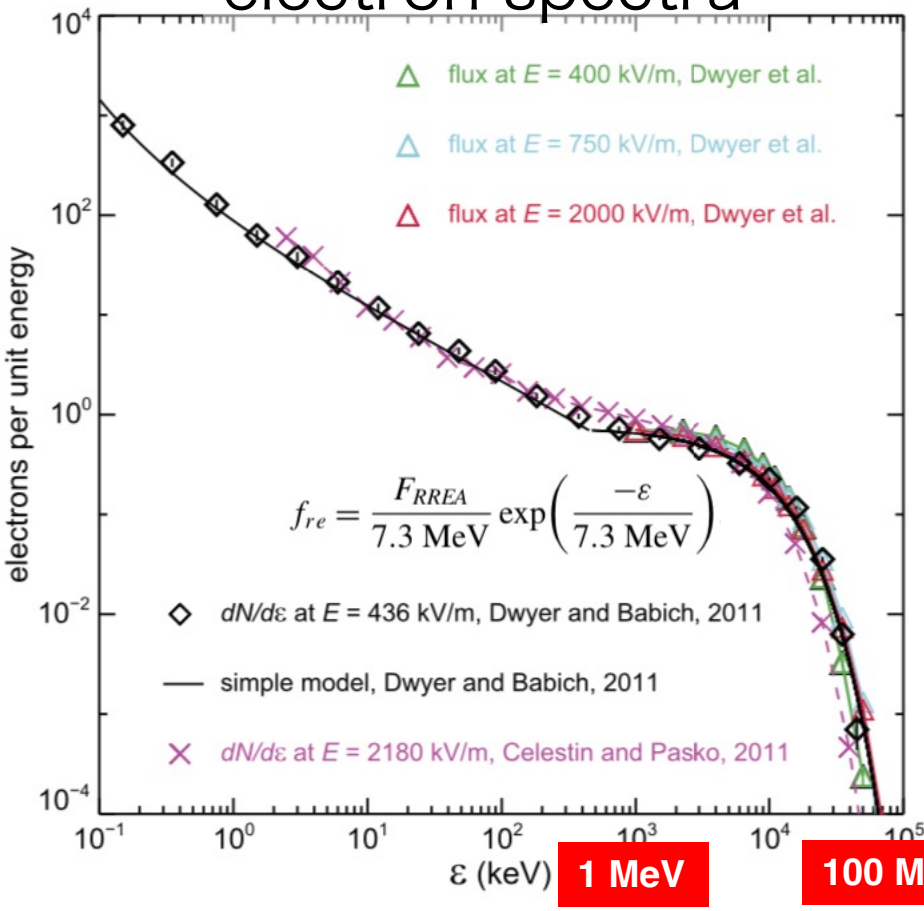
(Wilson 1925)
Relativistic Runaway ele.



＋ avalanche
RREA Gurevich+1992



electron spectra



accelerated 10-30 MeV electrons with ~7.3 MeV cutoff

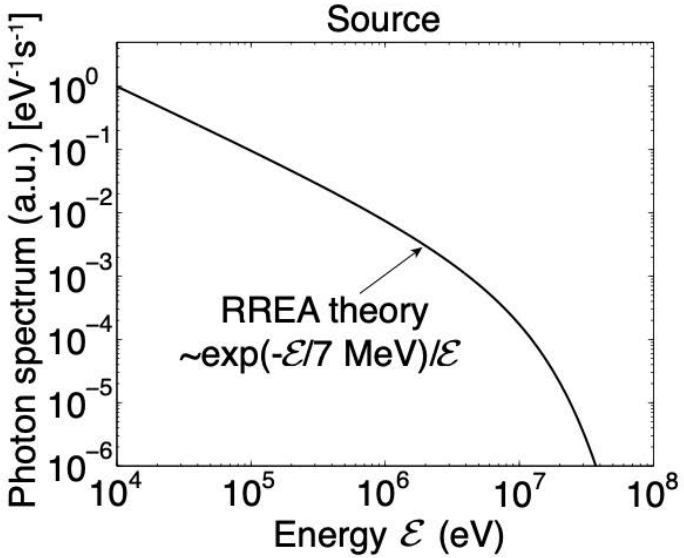
5 : upward-TGF: what is known? (1)

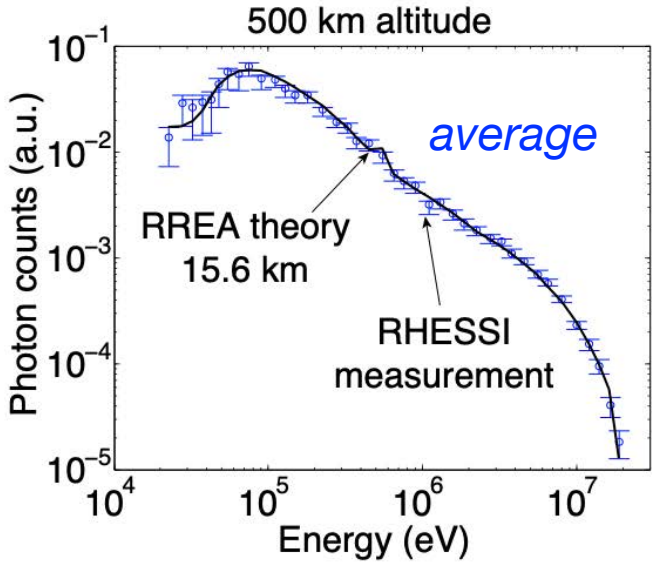
from Celestin (2016)

- **parameters of TGFs**
  - Typical max energy ~30 MeV
    - reports up to 100 MeV? (pile up?) [Tavani+ 2011]
  - Duration t_{50} ~ 100 μs [Fishman+ 2011, Marisaldi+ 2015]
  - Fluence ~> 0.5 pts/cm^2 in 50 μs

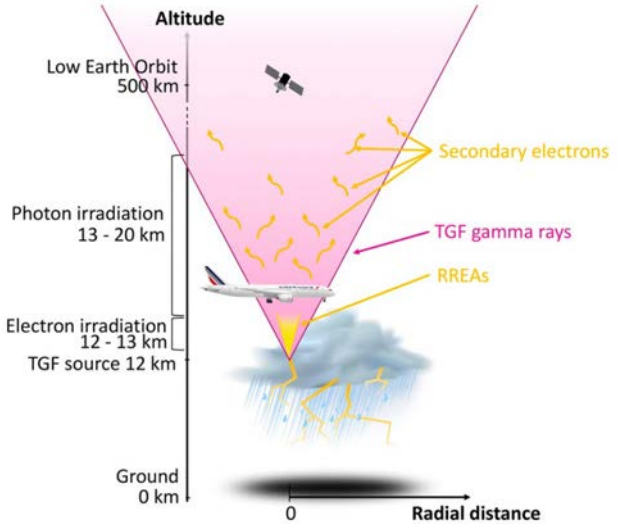
Illustration of a TGF. Credit: NASA/Goddard Space Flight Center.

- **altitude (ave.) =15 km**





Assuming a TGF source at 15 km, the RREA spectra at satellite altitude matches RHESSE averaged TGF spectra [Dwyer and Smith, 2005]

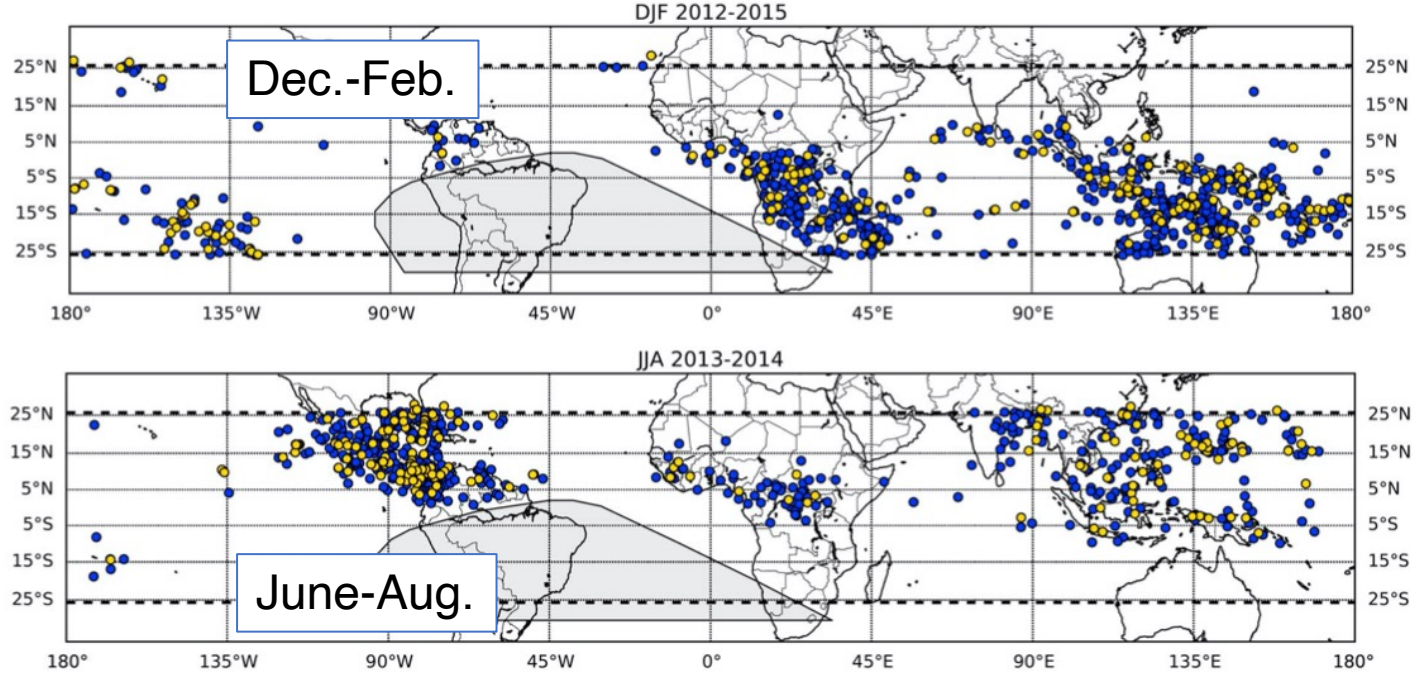


5 : upward-TGF: what is known? (2)

from Celestin (2016)

- frequent around equator

Fermi



- ~2 TGFs/day

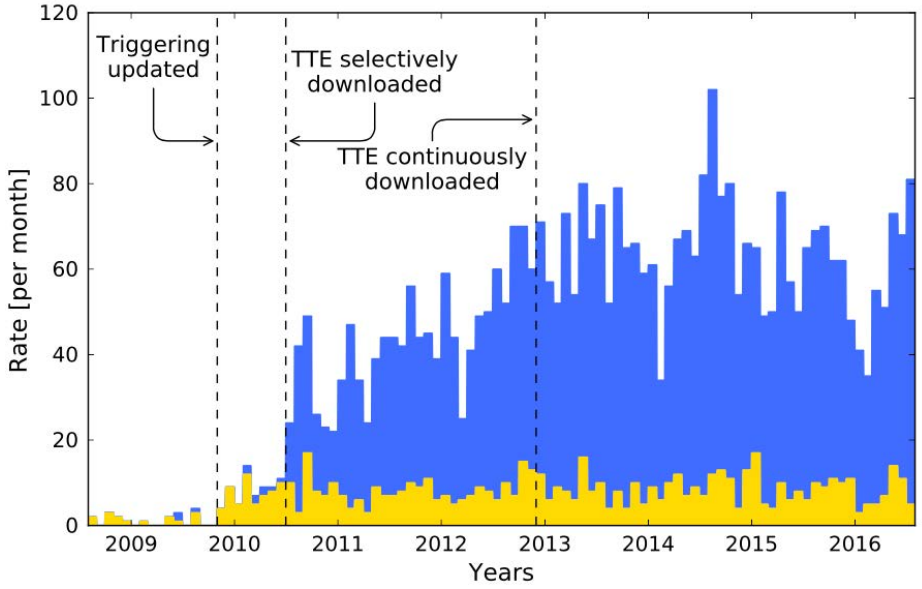


Figure 12. (Top) Three years of terrestrial gamma ray flash (TGF) data from the months of December, January, and February (DJF). (Bottom) Two years of TGF data from the months of June, July, and August (JJA). (Both plots) Blue markers are TGFs without a very low frequency association; yellow markers denote TGFs with a very low frequency association. The SAA region (gray shaded region) and inclination of *Fermi* are also shown. On average, about 30 to 50 TGFs are detected by Gamma-ray Burst Monitor during DJF and 70 to 100 during the northern hemisphere summer months of JJA.

Roberts+ 2017

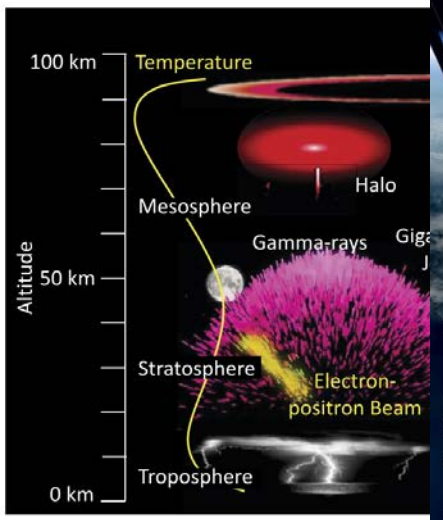
- Similar results from *AGILE*/MCAL [Marisaldi+ 2016]

なお、短時間現象なのでpile-up/dead-time 補正に注意が必要

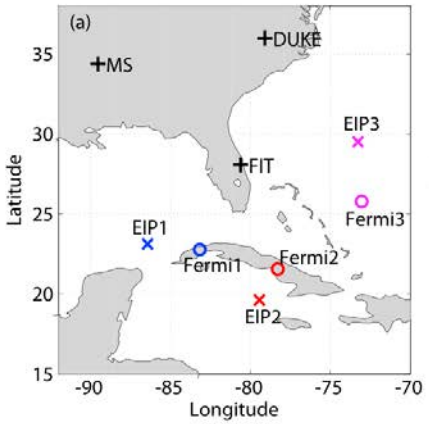
5 : upward-TGF: what is known? (3)

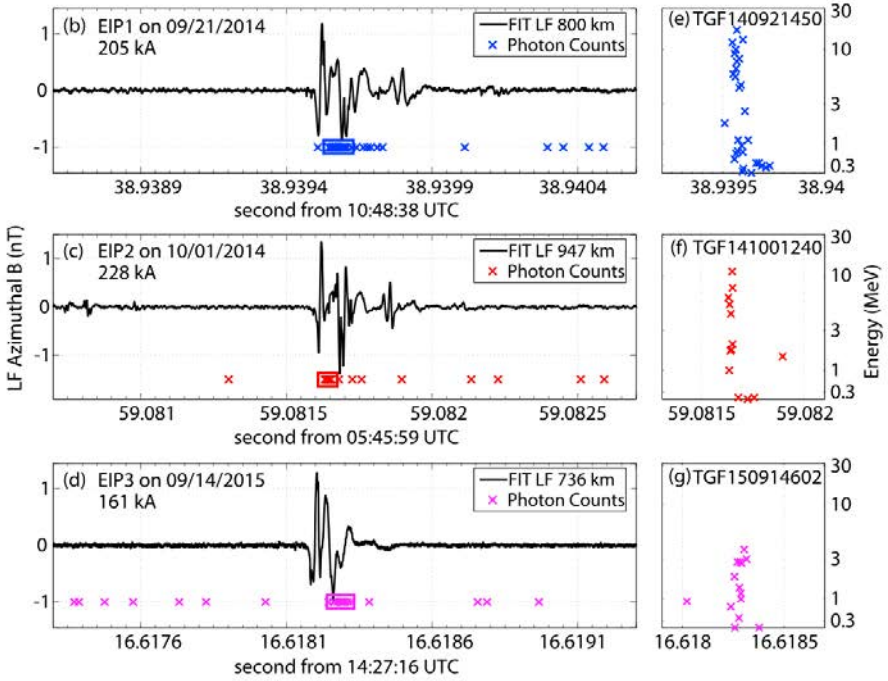
- **Relation with TLE (*ASIM* on ISS)**
  - ASIM = CdTe coded-mask + BGO + Optical
    - + ground radio obs.

→ Coincidence of, TGF and Elves confirmed.



- **Radio signal "Energetic In-cloud Pulse" and "Narrow Bipolar Event"**
  - Lyu+ 2011,2016
  - Mailyan+ 2018





- *AGILE/RHESSI/Fermi*-GBM + on-ground radio

→ TGF and EIP (or NBE) coincide frequently

- downward-TGF + radio obs (Japan, our group)

→ EIP/NBE radio pulses are associated with TGF, but "not always" → **Related, but not identical**

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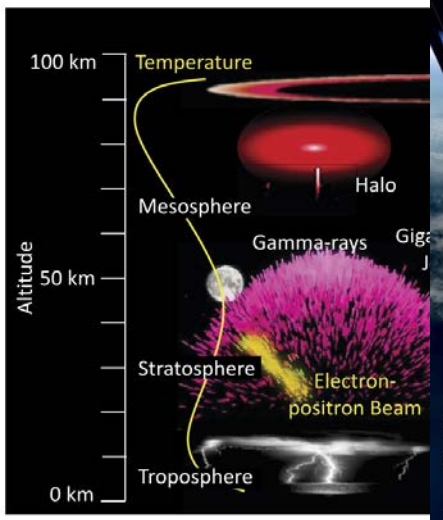
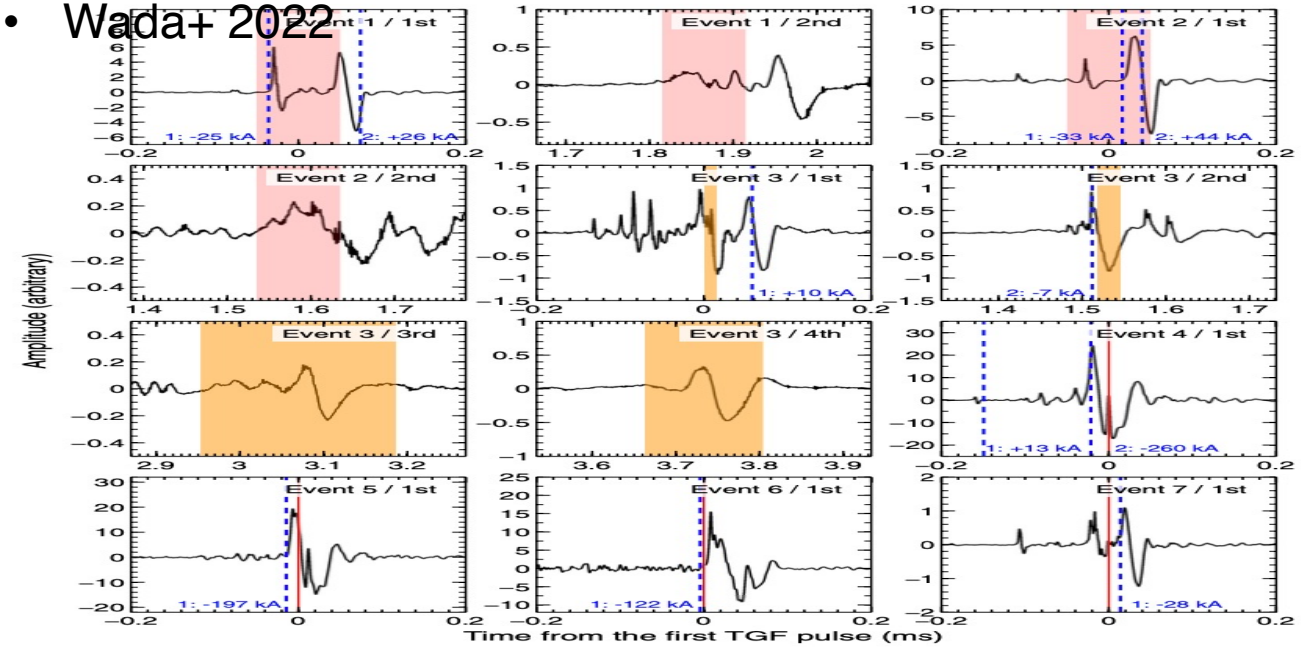


- **Radio signal "Energetic In-cloud Pulse" and "Narrow Bipolar Event"**
  - Wada+ 2022



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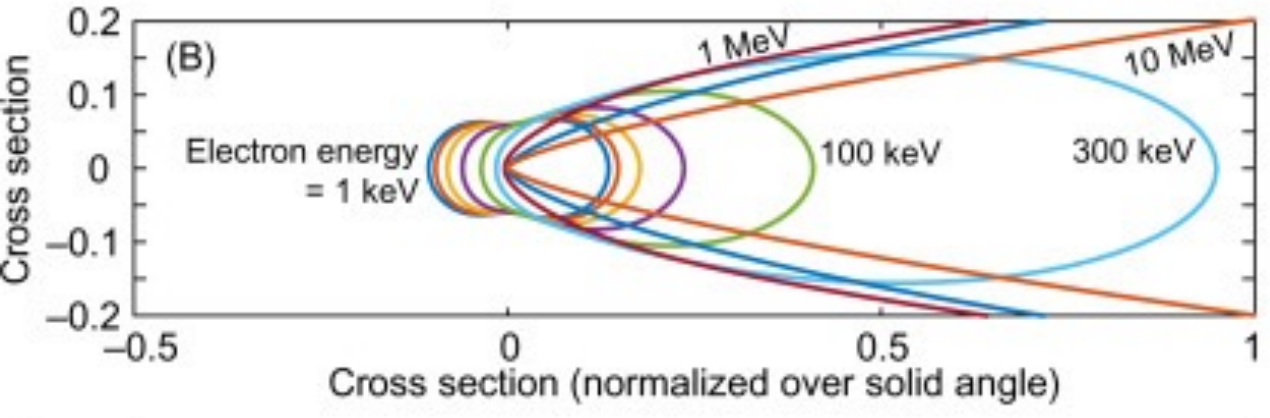
6 : Remaining issue (1): ビーミング/開口角 of TGF

- relativistic beaming of Bremss.



Science Direct
Atmospheric effects and signatures of high-energy electron precipitation
Robert A. Marshall, Chris M. Cully, in The Dynamic Loss of Earth's Radiation Belts, 2020, 7.2.2 Bremsstrahlung

- beaming of TGFs

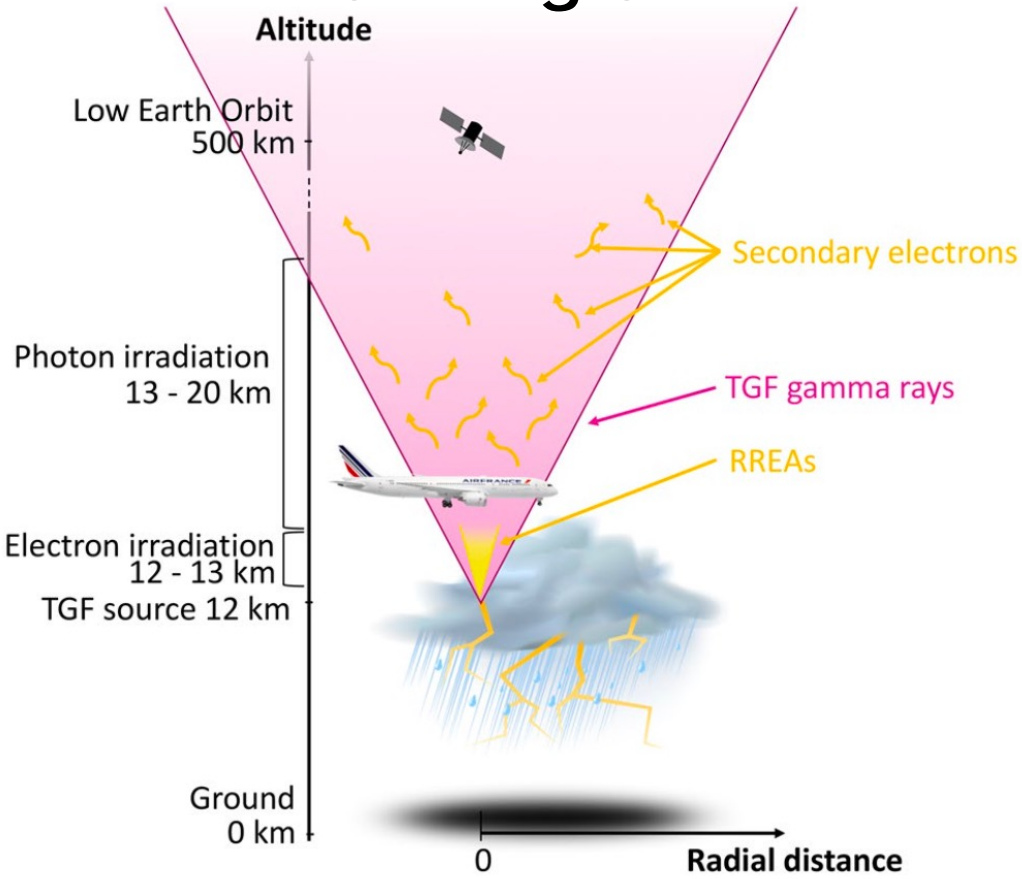
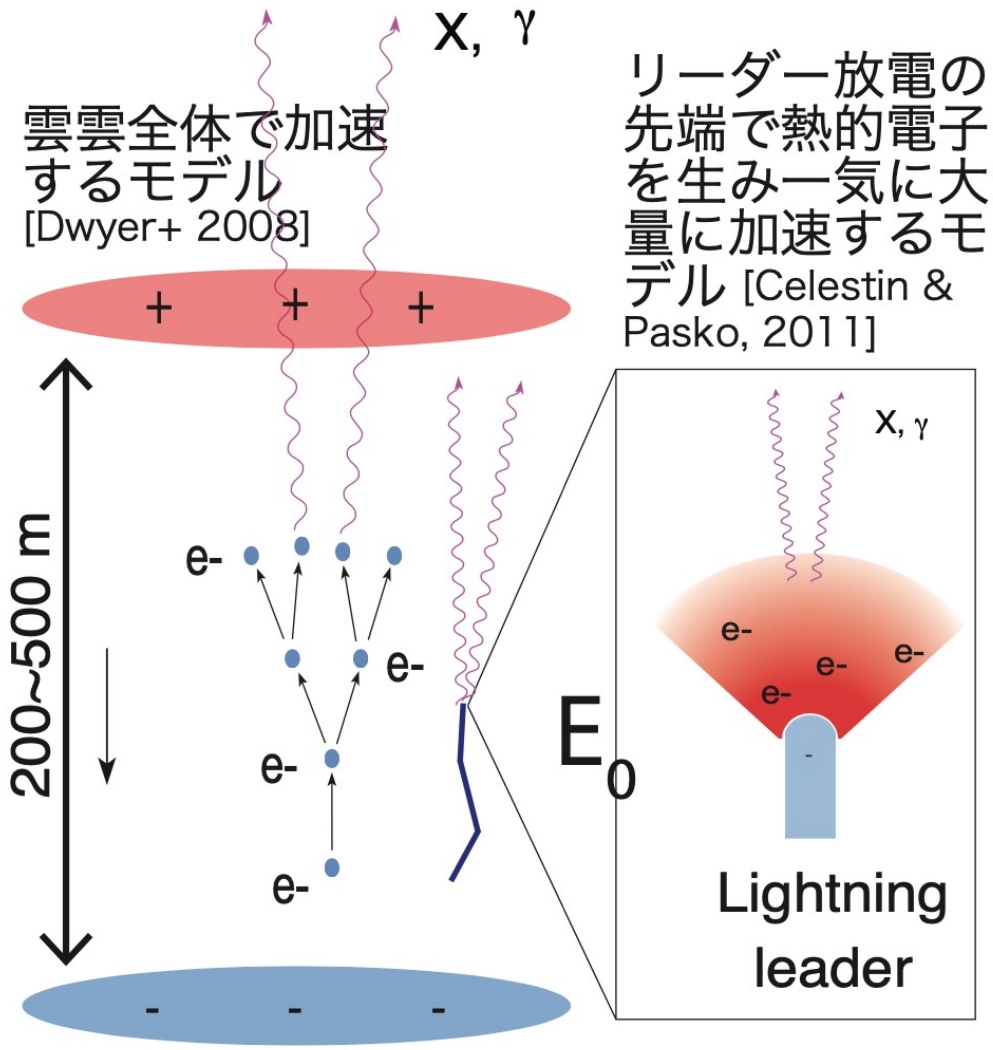
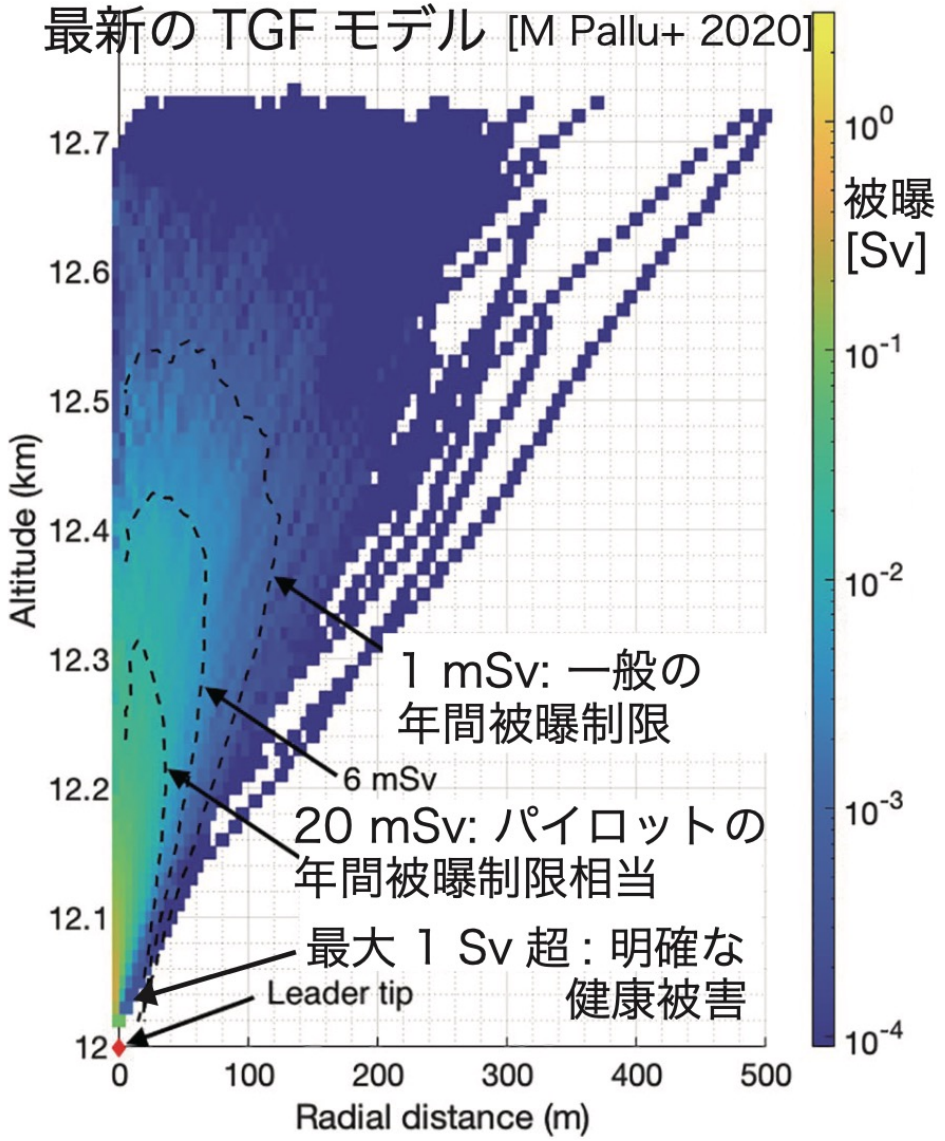


Figure 1. Representation of the situation studied in this work. The pink area represents the TGF, while the yellow area is the location of causative RREAs. Secondary electrons are electrons produced by collisions between TGF photons and air molecules. RREA, relativistic runaway electron avalanches; TGF, terrestrial gamma ray flashes.

6 : Remaining issue (2): 1シーベルトに達する強い被曝量？

TGF = leader-tip phenomena?
→ Compact and very high dose





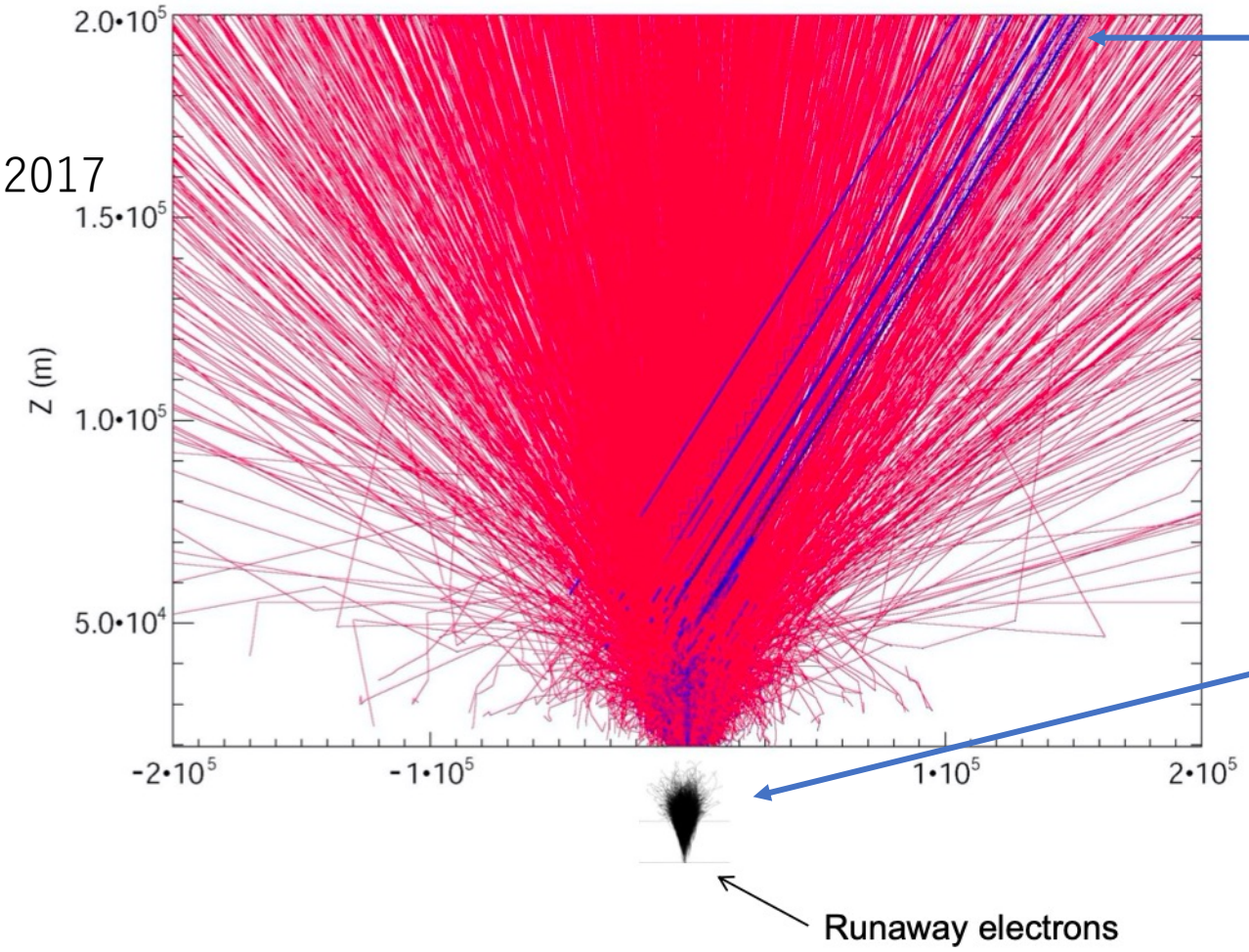
1 Sv @ 100 m → dangerous dose level

6：強い被曝量とビーミング/開口角の関係は？

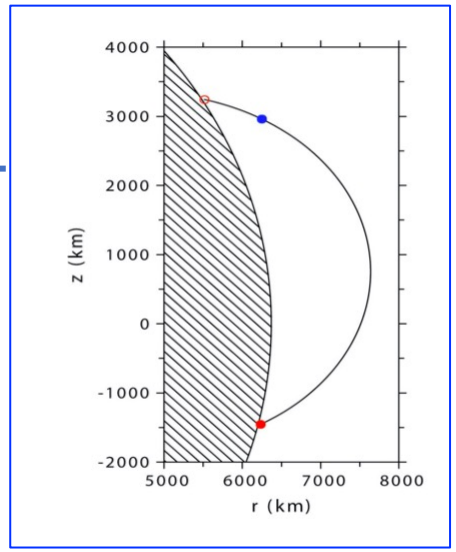
- Opening angle is not measured → total fluence not known

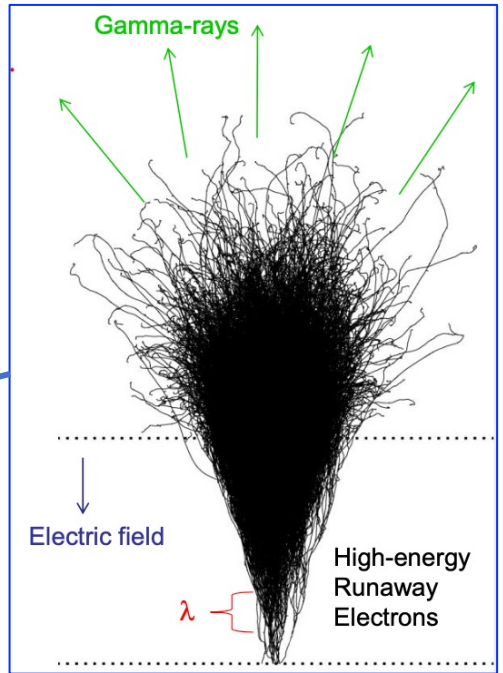
As the TGF gamma-rays (red) propagate to space they create electrons and positrons (blue) that also propagate to space, following the geomagnetic field line.

Dwyer 2017



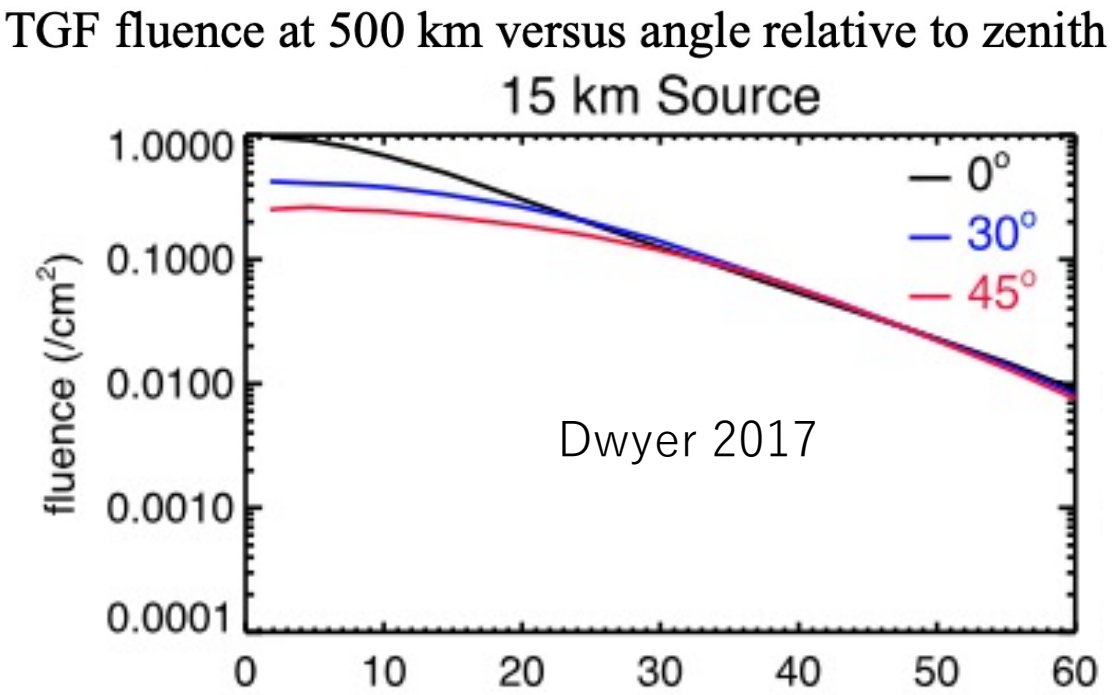
electron/positron beam





7-1: 開口角の推定の現状

- **Opening angle is not measured → total fluence not known**

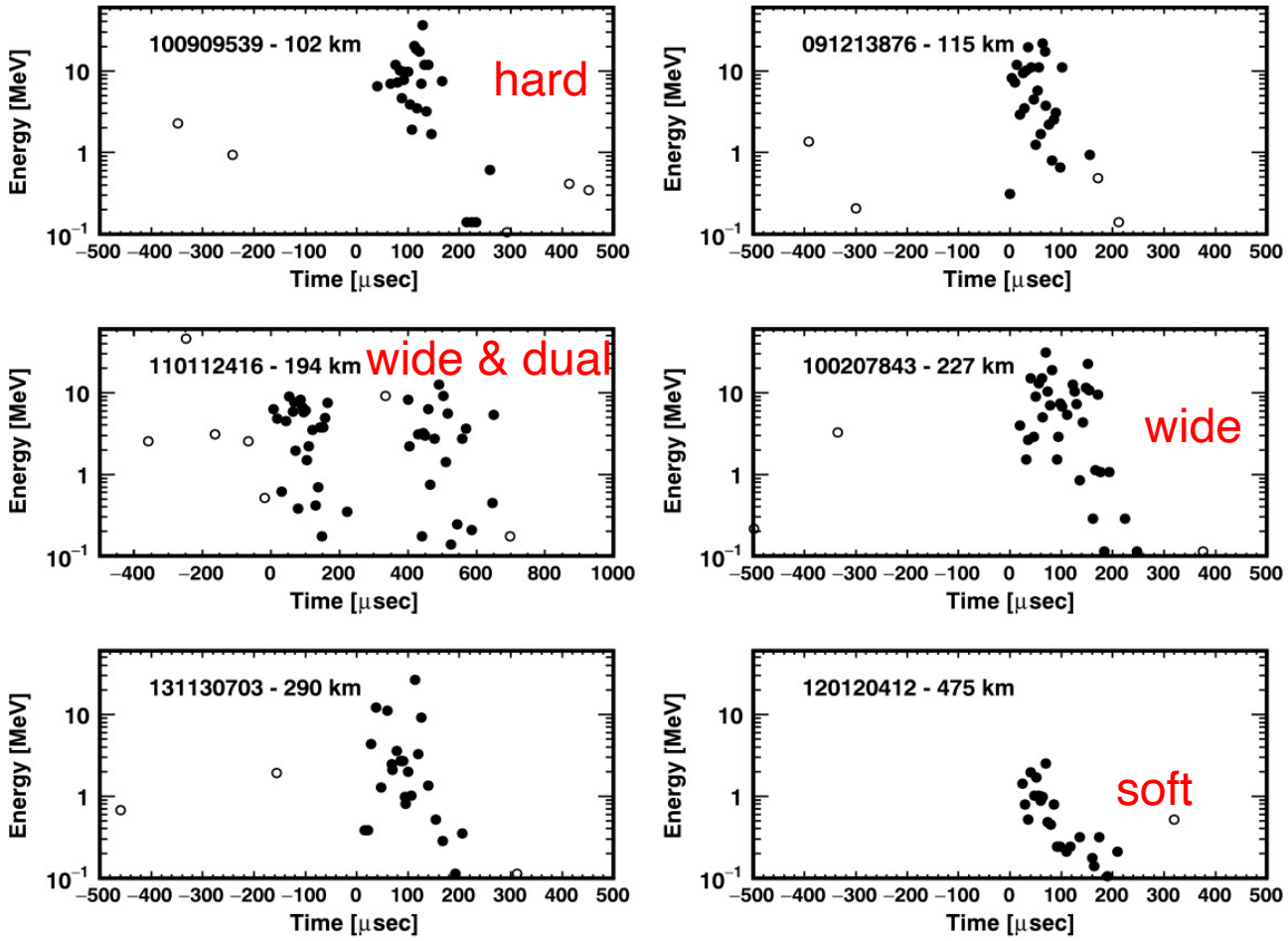


consistent with summed TGF spectra, but...

Opening angle is large, but not well constrained by theory

- **Diversity in spectra**

hard and soft ....



Mailyan+ 2016

7-2: 傾斜角の分布も重要では？

- ビームの傾斜角は分かっていない

Xu+ 2019

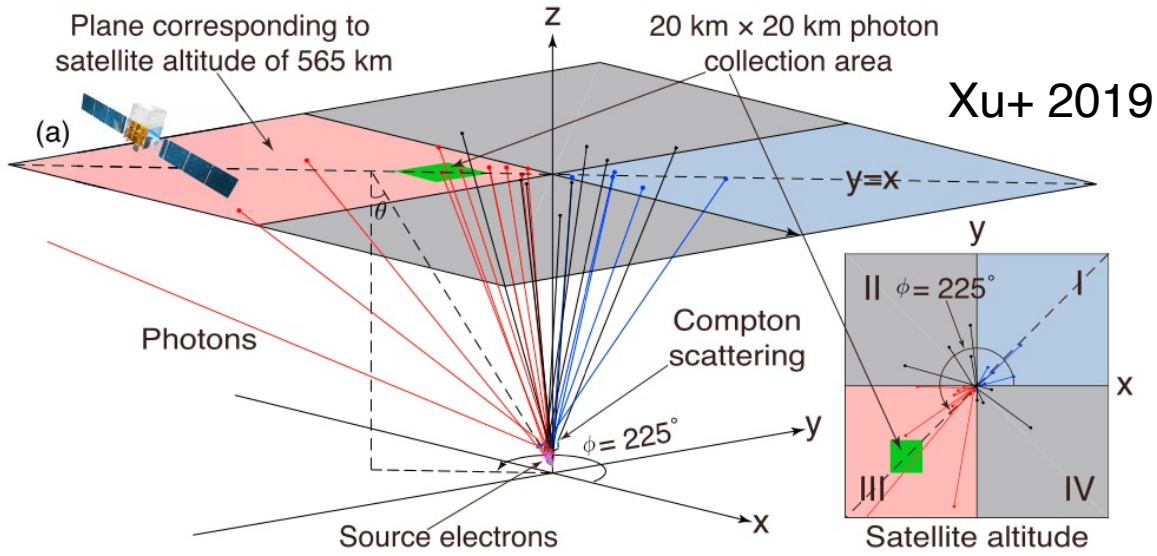
Despite the increased emphasis, the tilted TGF geometry still remains poorly understood and has not been investigated in detail ... Critical to the accurate interpretation of satellite measurements ....Three-dimensional (radio) *interferometric images have shown that initial leader steps are mostly tilted away from the zenith direction with an angle between 6 deg and 38 deg (Lyu et al., 2016). ...*

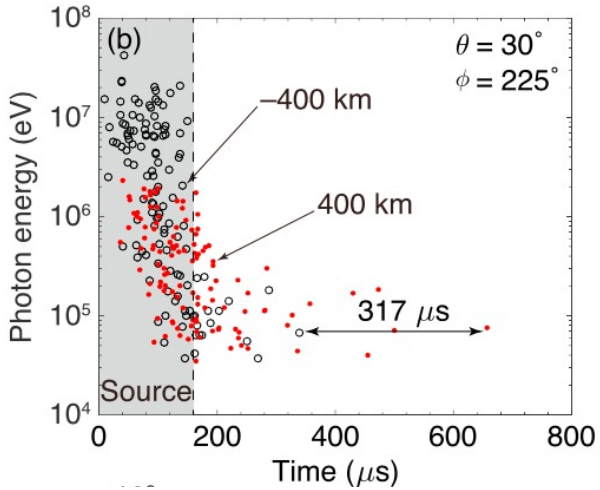
加速原理からして傾斜しても全くおかしくない

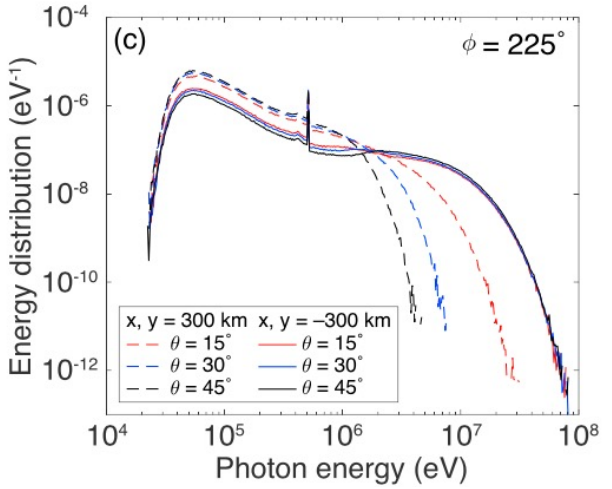
However, "leader steps = TGF origin" NOT confirmed yet (actually, NOT ALL leader steps generate TGFs)

model of inclined and wide-opening TGF

Xu+ 2019



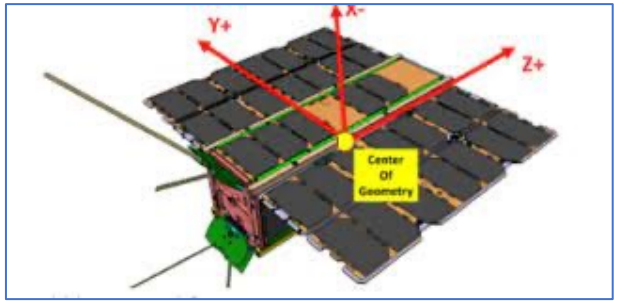


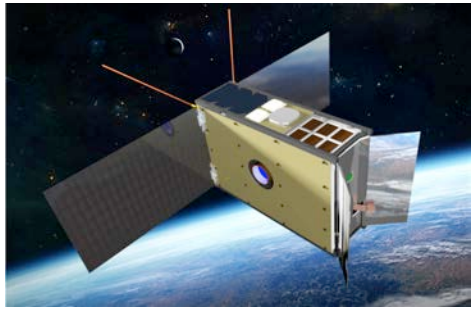


8：ビーミング/傾斜/開口角問題を解くには？

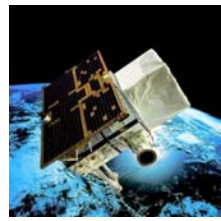
1: ガンマ線で傾斜角と開口角を見るTGFの多点観測があれば良い

赤道軌道に複数のガンマ線衛星があるといいなぁ。。
例えば AGILE (incl. 2 deg)、 Fermi (21 deg)に
COSI (0 deg)が加わると？
COSI - AGILE の"two-satellite simultaneous
TGFs" は 10-20 per year 期待される

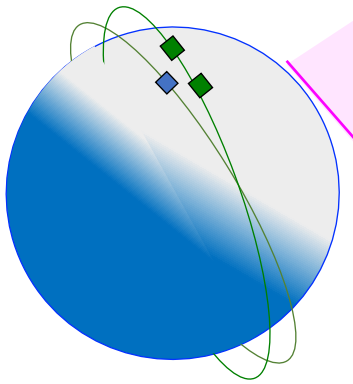




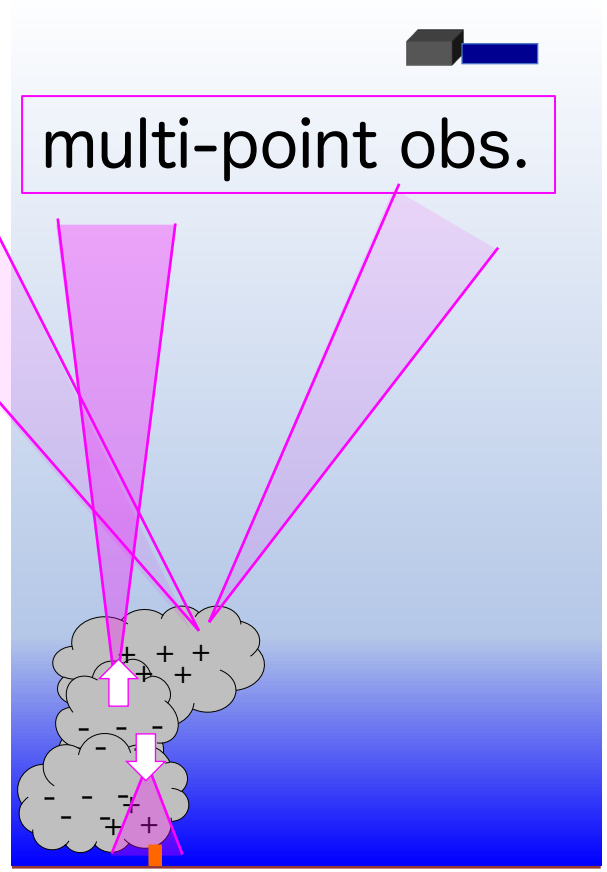
GRB/TGF cubesats? CAMELOT
and HERMES and many others



multi-point obs.



better be 3-4 points



8：ビーミング/傾斜/開口角問題を解くには？

2: 上層大気がTGFを受けてX線で輝くか？

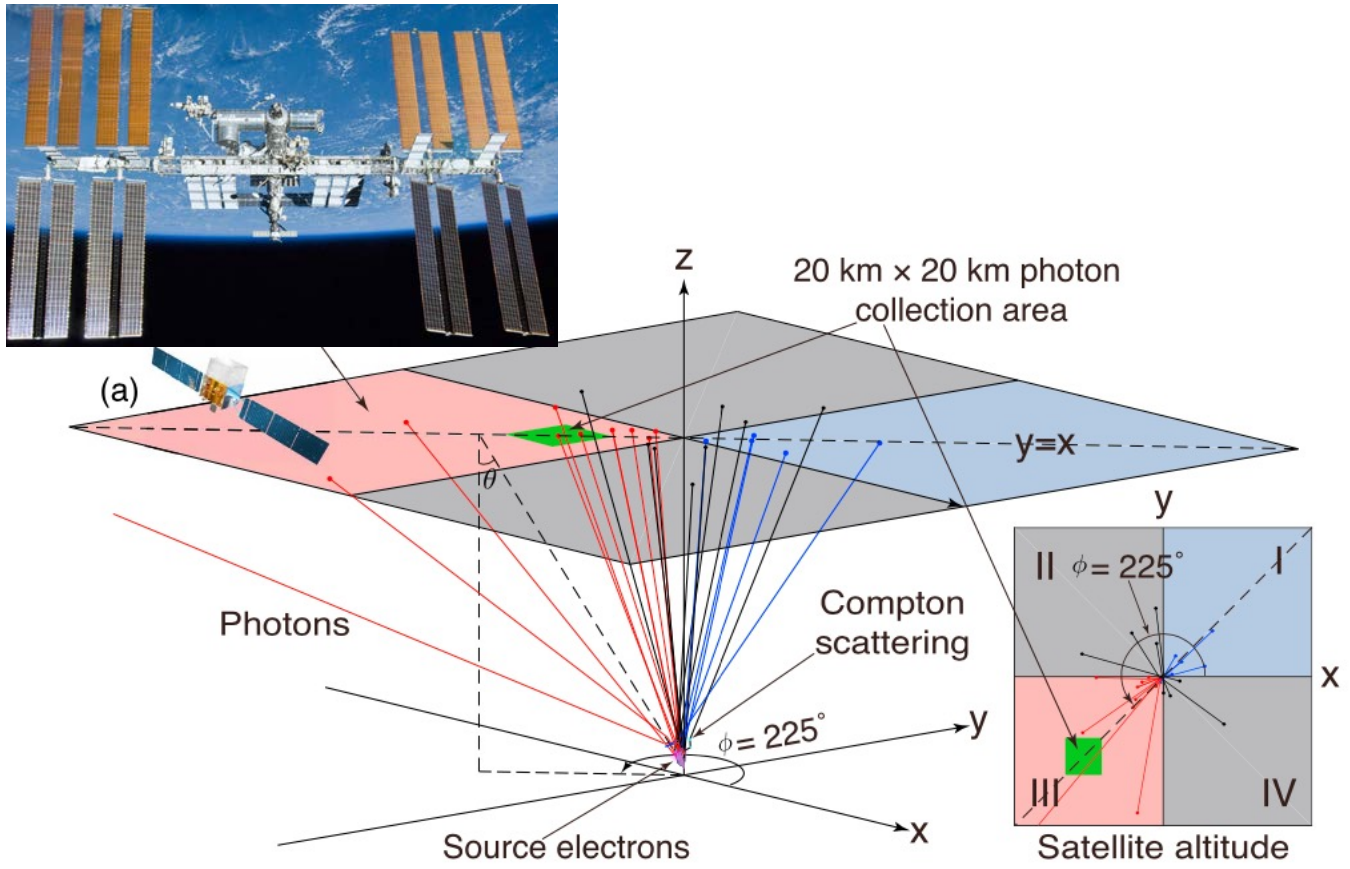
Xu+ 2019

１：観測できるのか？

- 発光と吸収の戦い
- フラックスは足りるか？
- 0.1-30 MeVのガンマ線が100こ/cm2。継続時間は100-200 us

２：何がわかるのか？

- 広い視野での被曝量（カロリーメータ）がわかる？（ただし誰かがTGFを観測しないと難しい）
- ビームの傾斜角と開口角が見える？もし水平方向に少しでも角分解できれば、放電位置よりずれたところから２次X線 & コンプトンX線が出ている？



Summary

- TGF science includes Electric field direct acceleration of 10-30 MeV electrons, potentially has wide application region (e.g. stellar dust disk, Muranishi+ 2015)
- Basic mechanism is RREA. But location, occurrence, amplitude not known. Potentially a high dose as much as 1 Sv.
- Opening angle and tilt of the TGF beam is not known yet → multi-point satellite obs. can do. Radio coincidence obs. is on-going, but not yet clear. MeV gamma-ray missions, incl. COSI can contribute, especially around equator
- 上層大気のTGF由来のX線２次放射って見えるだろうか？広視野で、1-10 degree の角分解能があれば十分。