Monte Carlo model of the transport in the atmosphere of relativistic electrons and gamma rays associated with TGFs

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Outline

What are TGFs?

The TARANIS mission

Building and validating the Monte-Carlo model

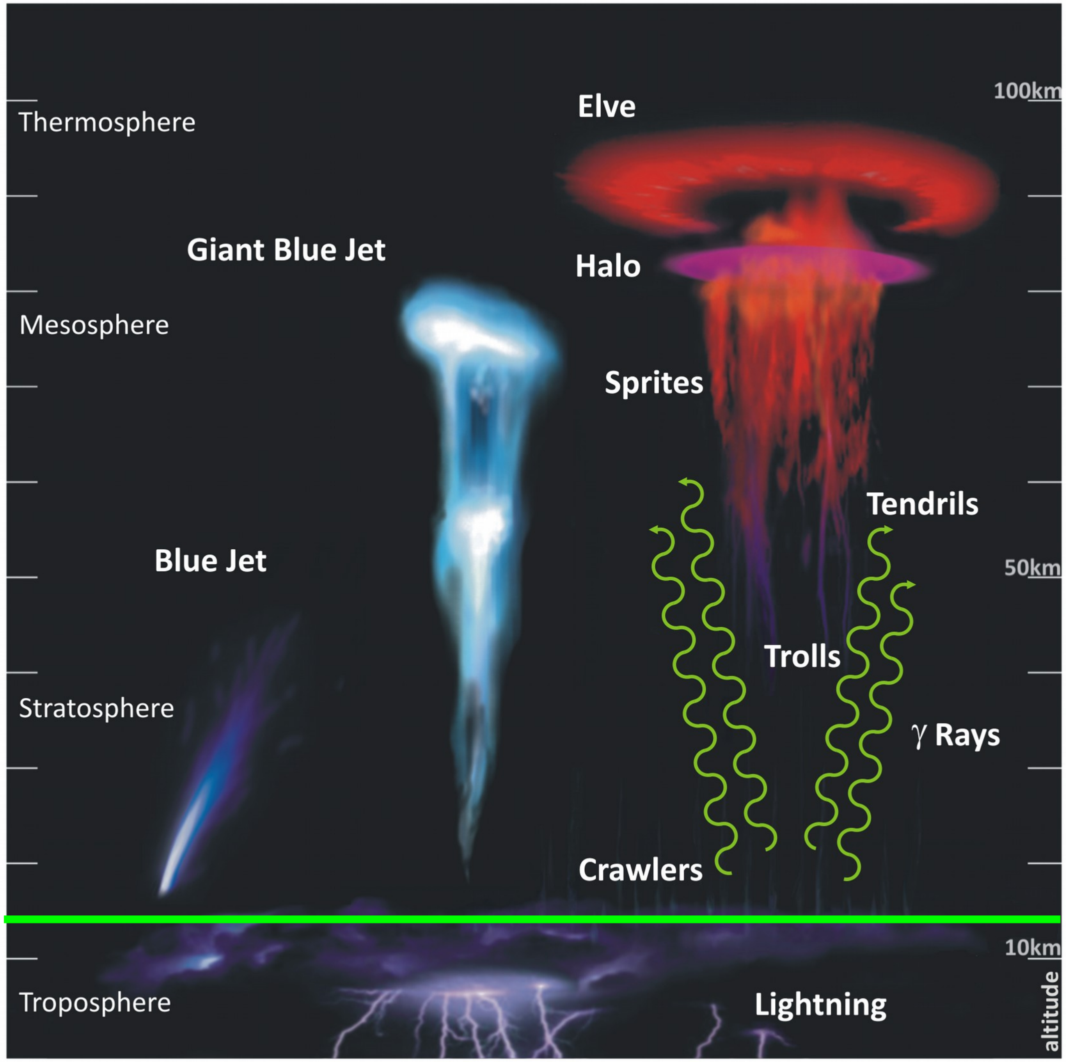
Application of the model

What are TGFs?

What are TGFs?

→ What are TLEs?

TLEs and TGFs



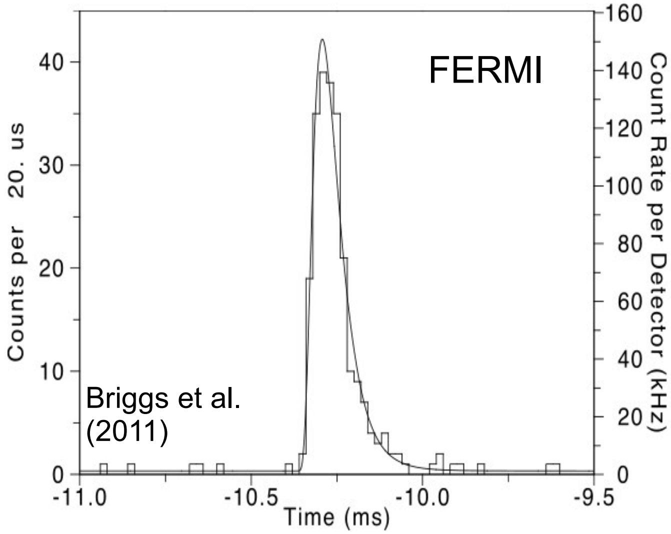
15 km

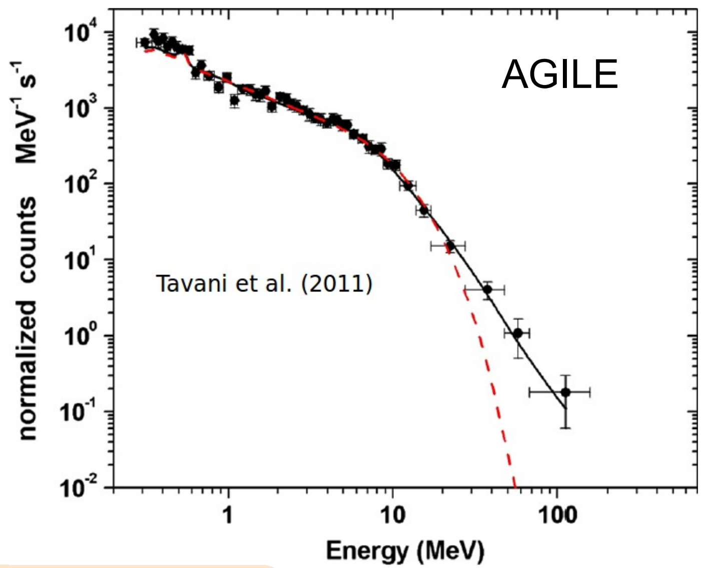
TLE = Transient Luminous Event
TGF = Terrestrial Gamma-Ray Flash

TGFs : observations

Discovered by BATSE (CGRO) in 1992, published in Fishman et al. 1994

Then, observed mostly by RHESSI, FERMI and AGILE





About 400 μs duration, and some multiple pulse events

Bremsstrahlung spectrum ~ 1/E * exp(-E/ϵ), ϵ~7.3 MeV
(red curve only!)

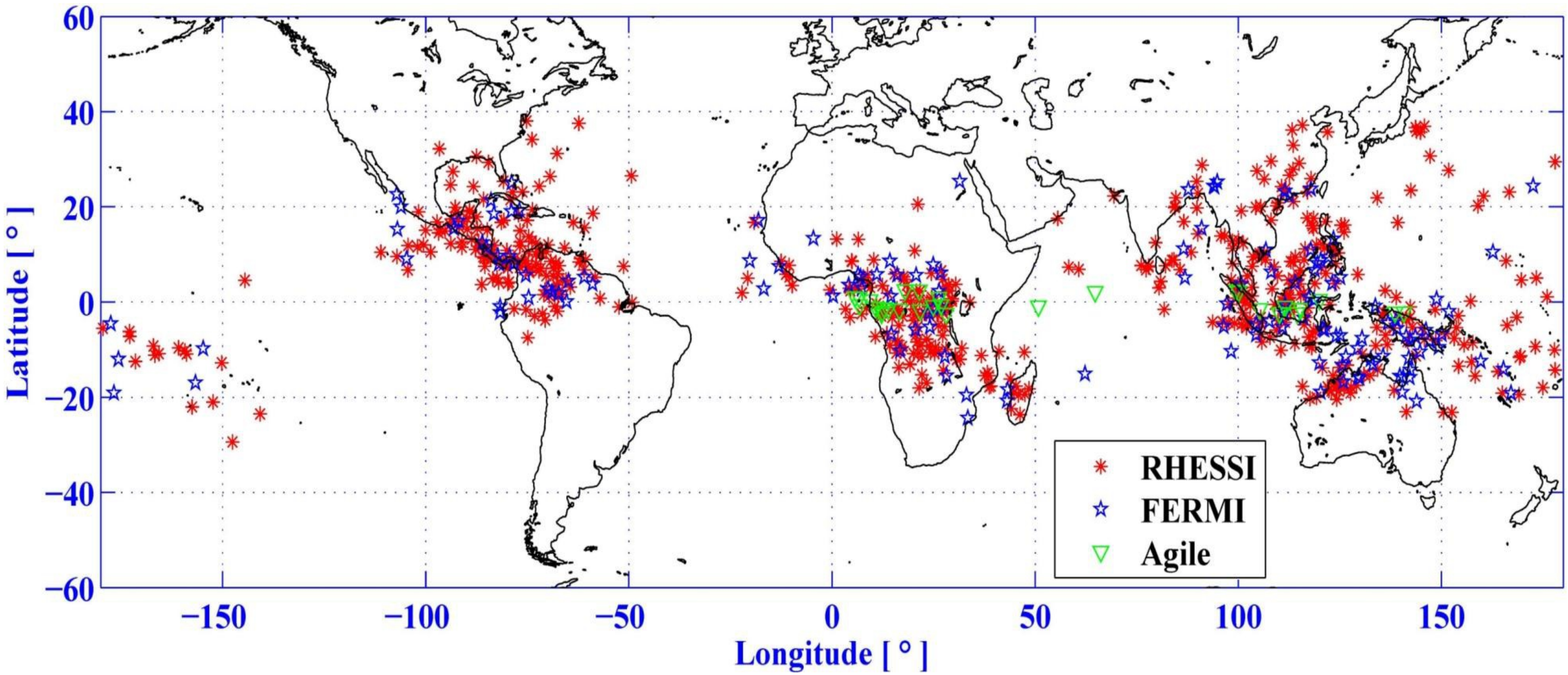
Maximum energies ~ 40 MeV, up to 100 MeV ? (AGILE)

Production altitude ~10-15 km, zenith half-angle emission >30°

~ 1 photon/cm² at satellite altitude

~ 400 TGF/day

TGFs : observations



→ Strong correlation between TGF and thunderstorm activity

Secondary electron Beams

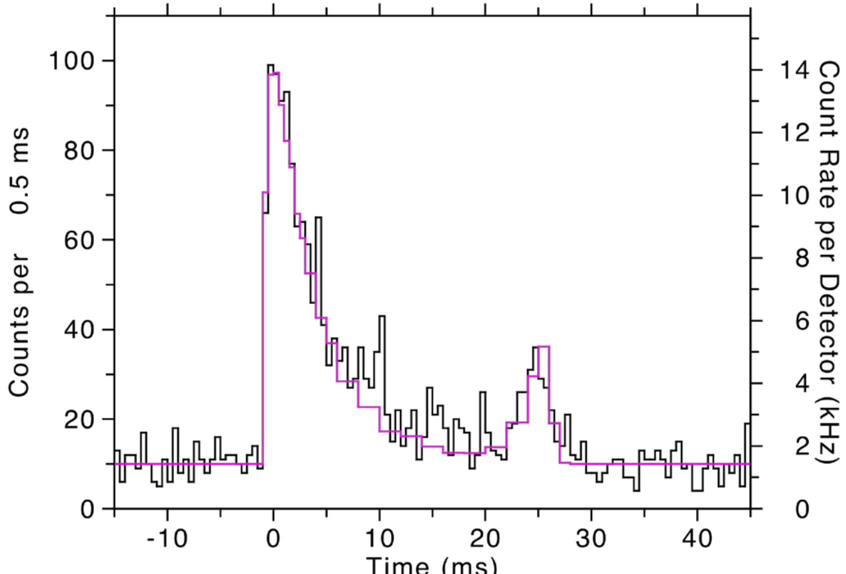
- Primary electrons : no chance of escaping the atmosphere
- Photons produce secondary electrons at higher altitude (> 30 km) that can reach satellite altitude.
- This population of electrons will be confined by the magnetic field of the Earth,

  ➔ ***Terrestrial Electrons Beams (TEBs)***

➔ **Responsible for « TGF » detections above deserts**

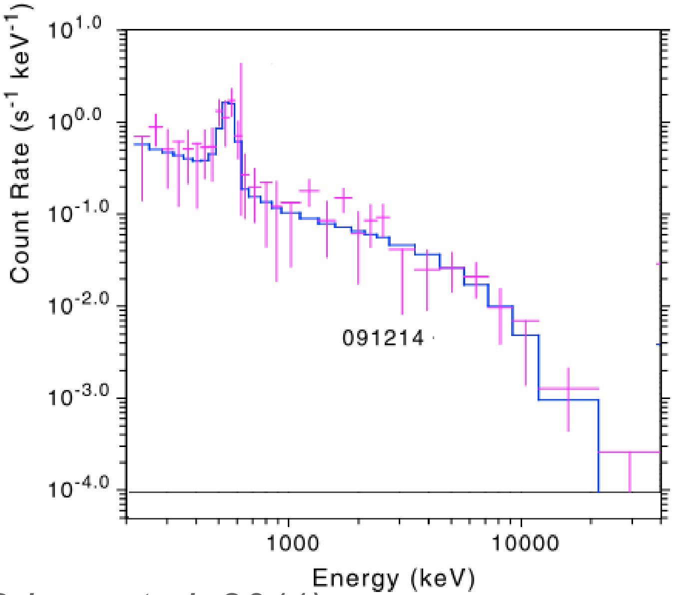
1/100 TEB/TGF ratio

(estimated from detections of instruments primarily designed to detect photons + models)



TEB fluence > TGF fluence

(particules/cm²)

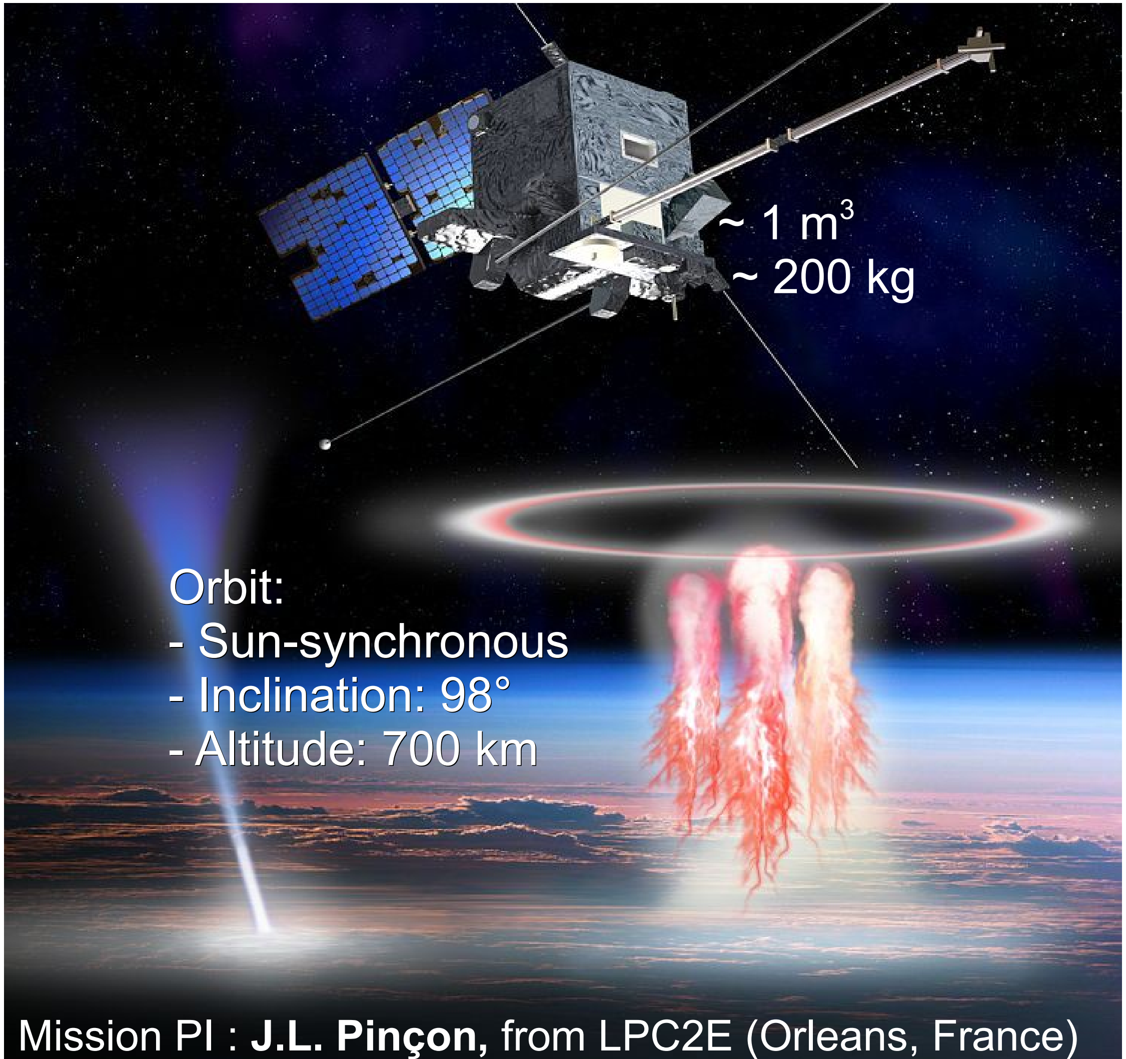


FERMI event 091214 (Briggs et al. 2011)

The TARANIS mission

Taranis : general information

Tool for the Analysis of RAdiation from lightNIng and Sprites



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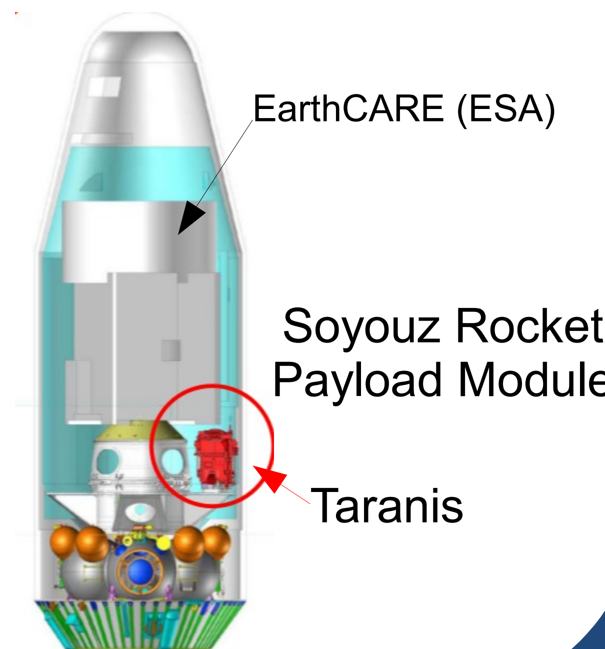
Expected launch : spring 2017



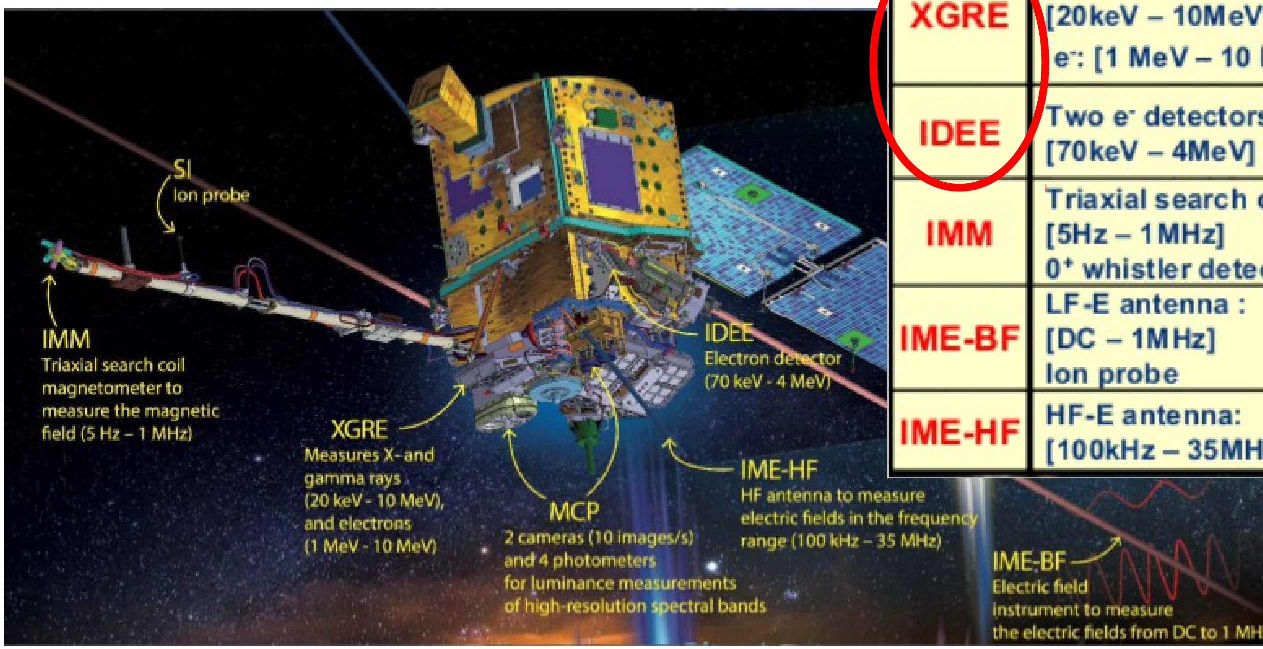
Taranis : scientific objectives

- **Physical understanding of the links between TLEs, TGFs and environmental conditions**

- **Identify the signatures associated with these phenomena and to provide inputs to test generation mechanisms.**

- **To provide inputs for the modelling of the effects of TLEs, TGFs and bursts of precipitated and accelerated electrons on the Earth's atmosphere.**

Taranis : instruments



MCP	Lightning micro-camera TLE micro-camera 4 Photometers	PI: E. Blanc, CEA (F) and Th. Farges (CEA)
XGRE	X and γ detectors: [20keV – 10MeV] e⁻: [1 MeV – 10 MeV]	PI: P-L. Blelly, IRAP (F) and F. Lebrun, APC (F)
IDEE	Two e⁻ detectors: [70keV – 4MeV]	PI: J-A. Sauvaud, IRAP (F) + Univ. Prague (Cz)
IMM	Triaxial search coil : [5Hz – 1MHz] 0^+ whistler detector	PI: J-L. Pinçon, LPC2E (F) + Univ. Stanford (USA)
IME-BF	LF-E antenna : [DC – 1MHz] Ion probe	PI: E. Seran, LATMOS (F) + GSFC (USA)
IME-HF	HF-E antenna: [100kHz – 35MHz]	PI: J-L. Rauch, LPC2E (F) + Univ. Prague, IAP (Cz)

When a priority event is detected (TLE, TGF, electron beam, burst of electromagnetic waves), then all instruments record and transmit to ground high resolution data.

Taranis : motivations for this work

Different TGF production models are available
(Relativistic feedback and Cold Runaway)

→ • Constraints of the TGF source mechanisms and properties?

• Multiple pulsed TGFs?

• Ability to detect electron and photons: XGRE and IDEE

• What is the link between TLEs and TGFs?
• Do TGFs produce visible light?

→ Taranis will provide a lot of information to answer to all these questions

To prepare for TARANIS, focusing on XGRE and IDEE, simulating the physics of the propagation of high energy photons and electrons, in the earth environment, from the TGF source (~ 10-15 km) **to the satellite** (500-700 km) **is necessary**

→ Monte-Carlo model

Generalities about the model

3D

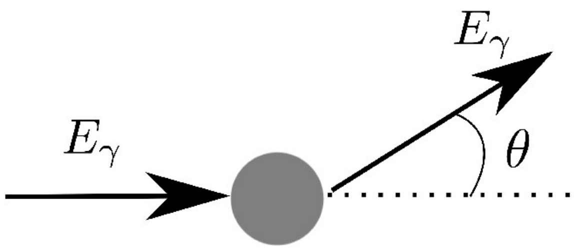
Involved particules :

Photons Electrons Positrons

- N_{proc} = 11 processes involved
- 1 keV to 100 MeV energy range
- Propagation in the atmosphere (M-SIS)
And magnetic field of the Earth (IGRF-11)
- For 10^7 initial photons ~10 hours to compete

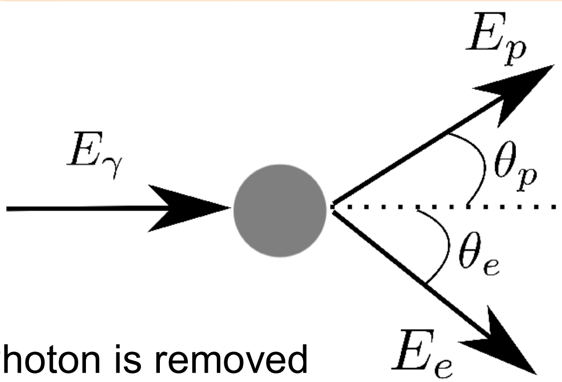
Involved interactions : photons

Coherent (Rayleigh) scattering



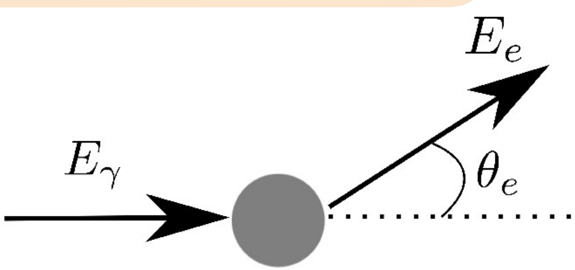
- Only deviation, no energy change

Electron/positron pair production



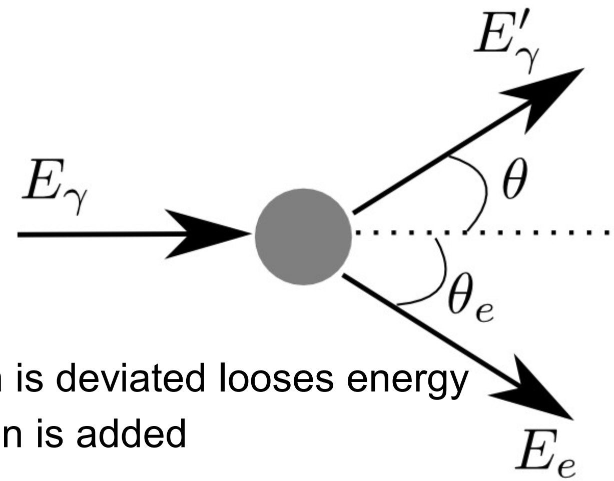
- Photon is removed
- Electron and positron are added

Photo-electric absorption



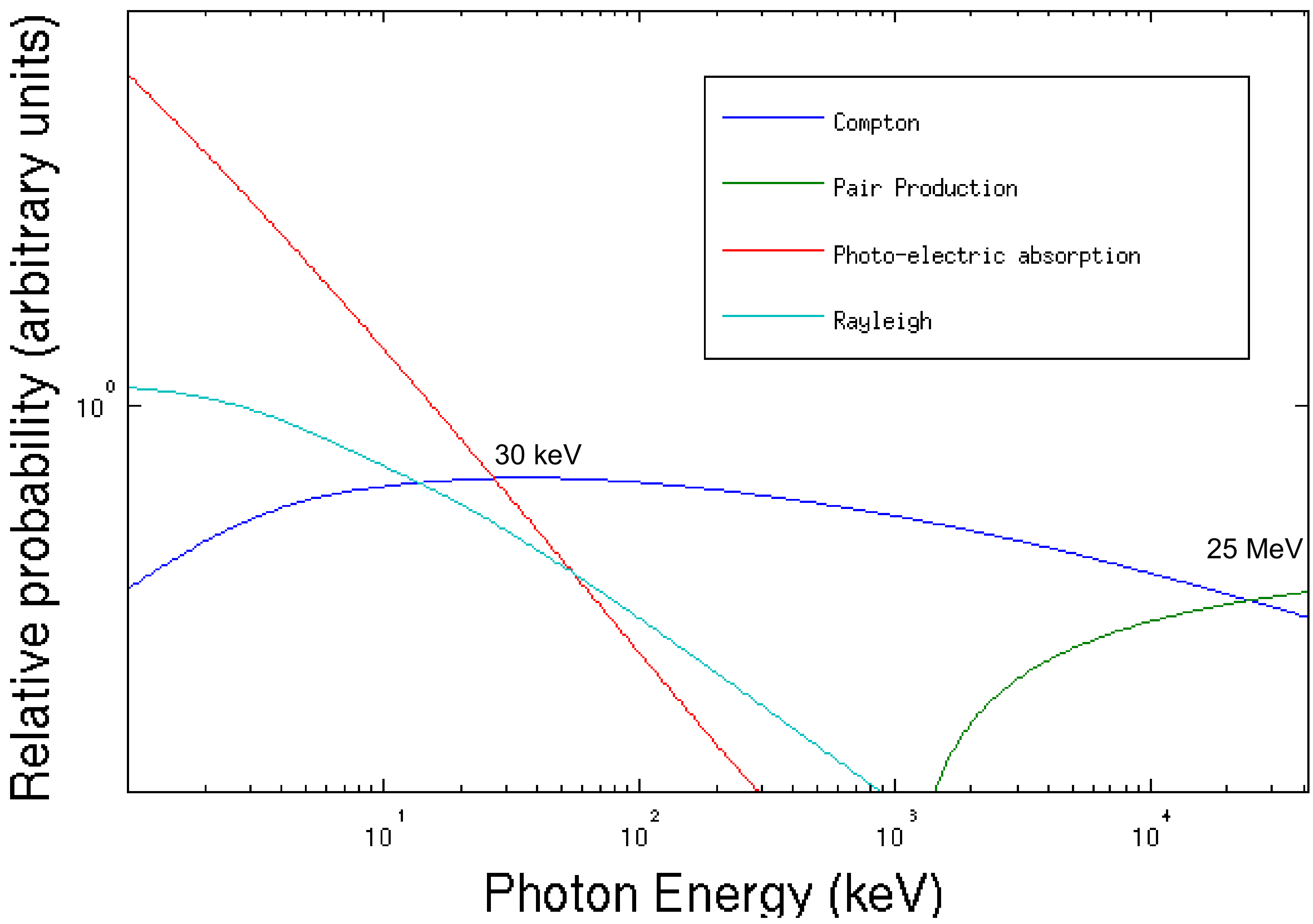
- Photon is removed
- Electron is added

Incoherent (Compton) scattering



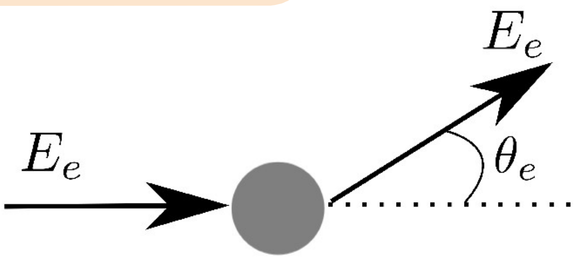
- Photon is deviated looses energy
- Electron is added

Photon interactions probabilities



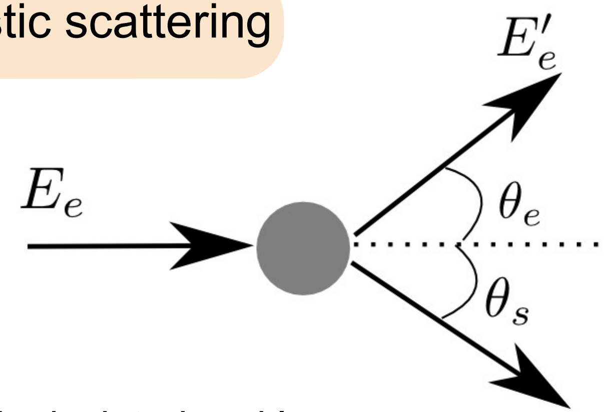
Involved interactions : electrons and positrons

Elastic scattering



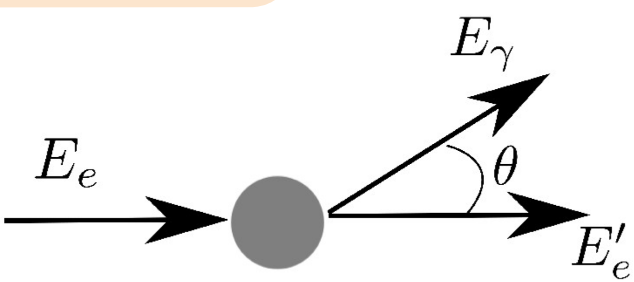
- Only deviation, no energy change

Inelastic scattering



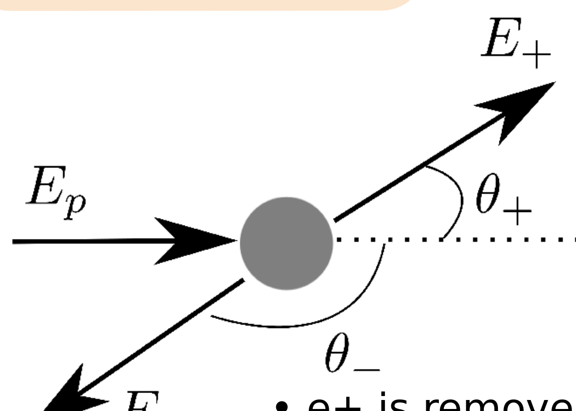
- e-/e+ is deviated and looses energy
- Electron is added

Bremsstrahlung



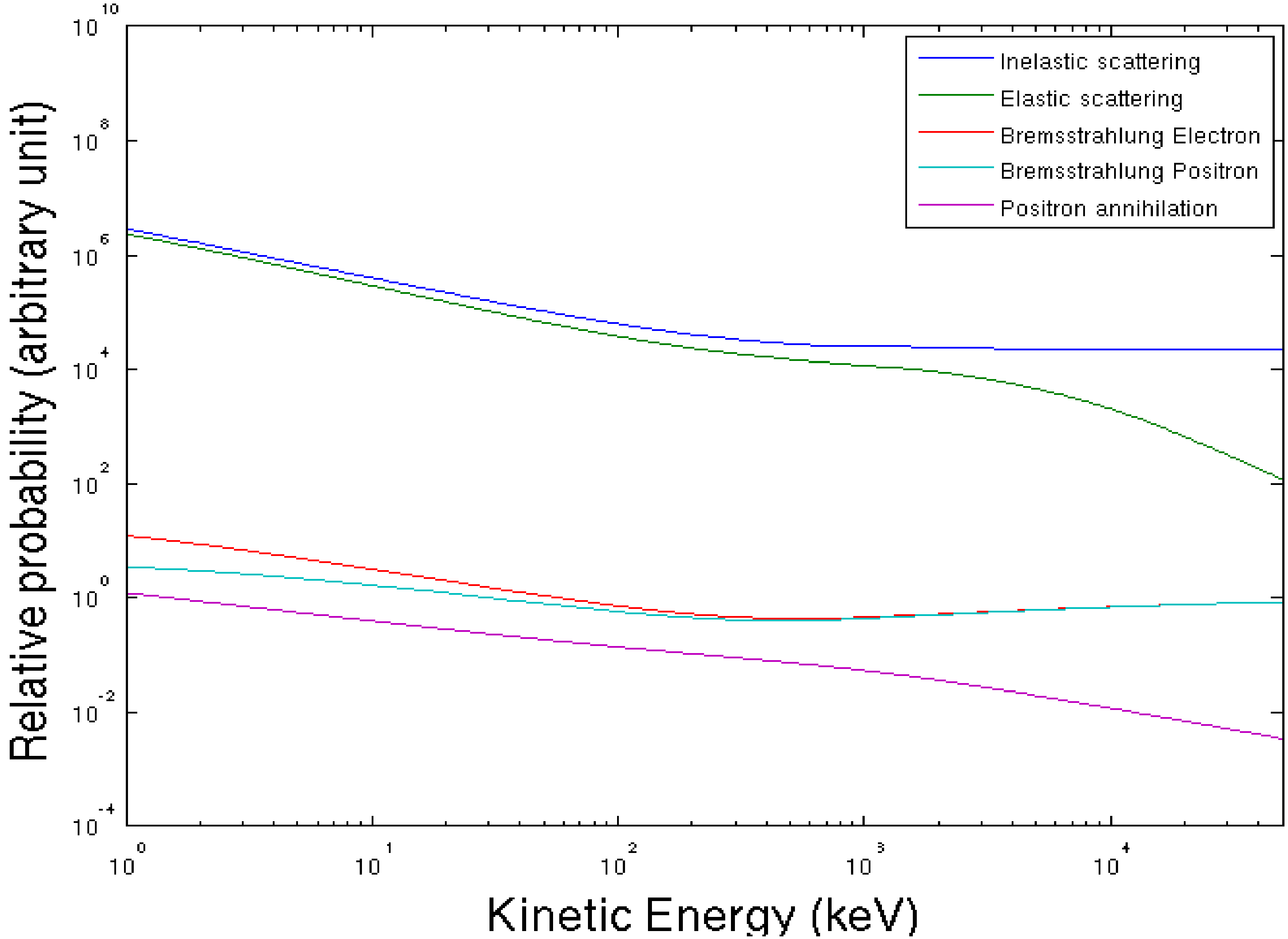
- e-/e+ looses energy
- Photon is added

Positron annihilation



- e+ is removed
- Two photons are added

Electron/positron interactions probabilities



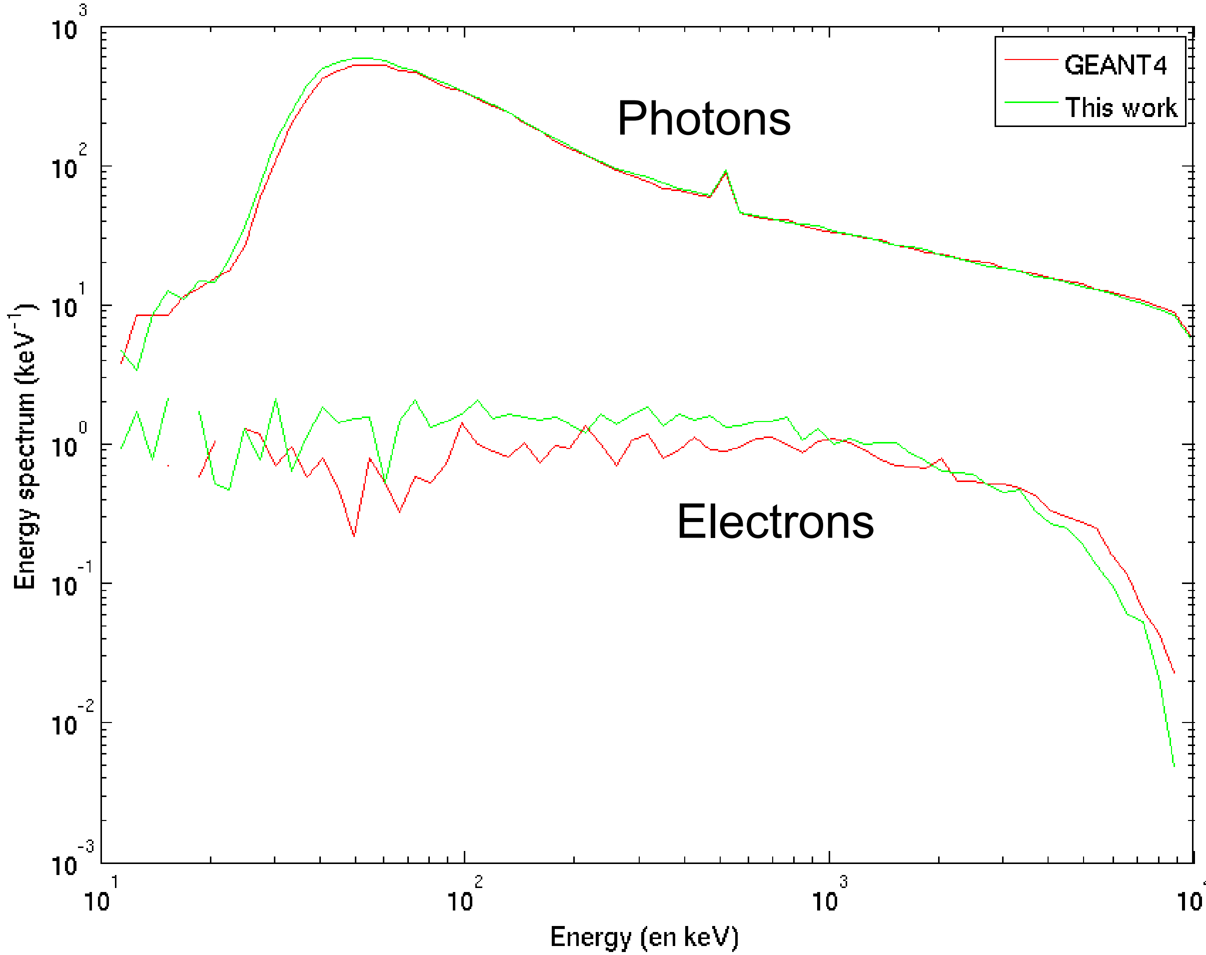
GEANT4 Comparison

Monte-Carlo code developed by an international collaboration lead by CERN.

Used to validate our model

GEANT4 Comparison

- Source of photons with 1/E spectrum at 15 km altitude
- Detection set to 100 km altitude



+ Radial distance distribution with ~perfect agreement

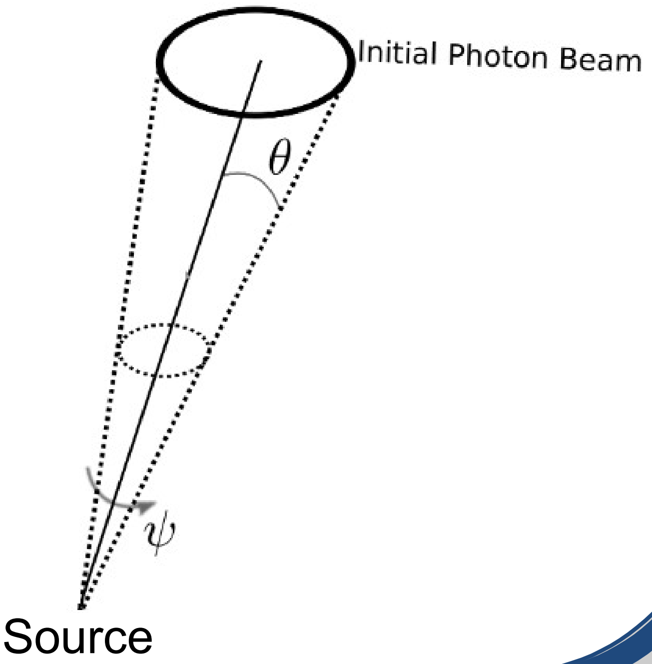
Application of the model

Simulation parameters

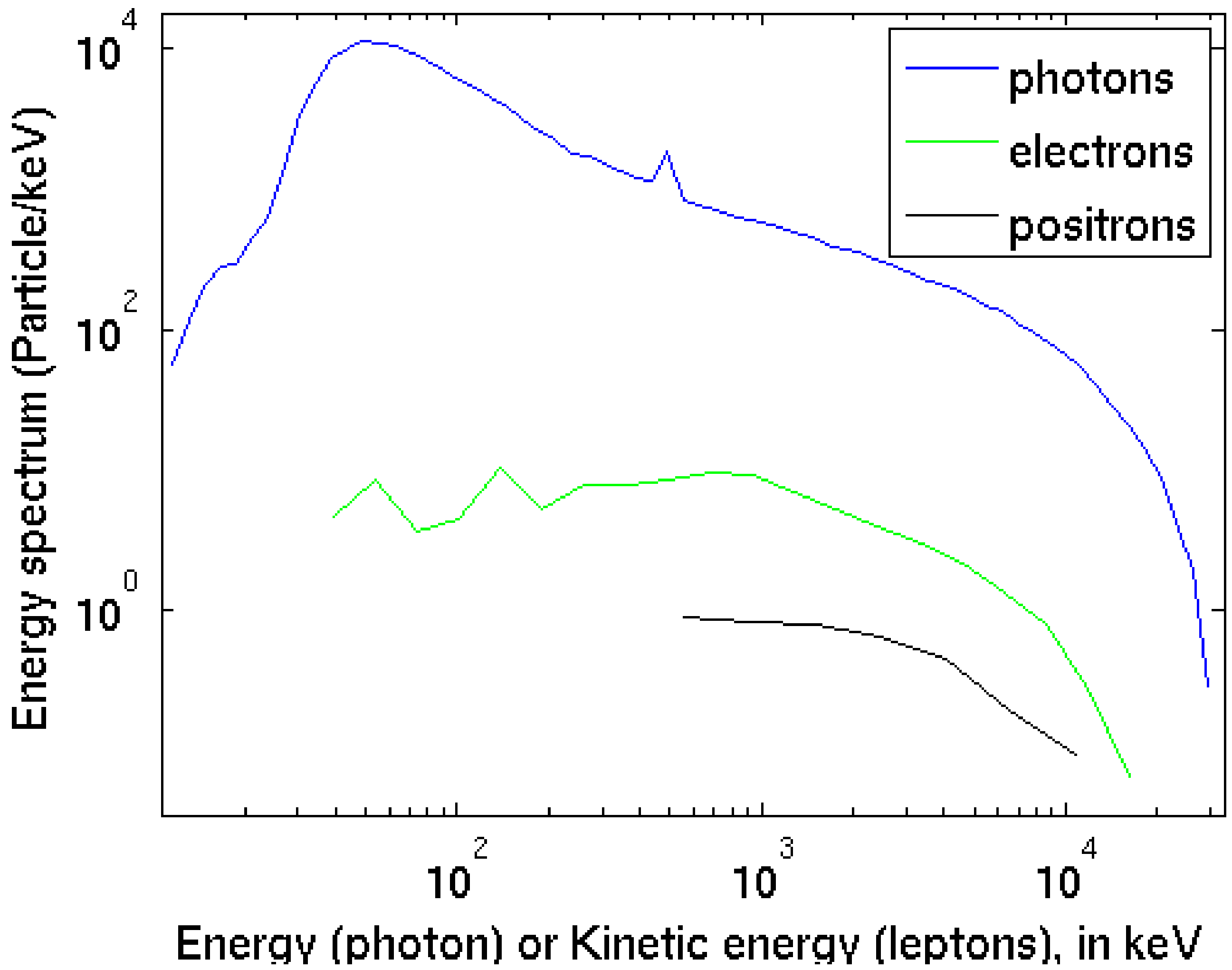
Source :

- Altitude = 15 km, southern hemisphere, equatorial region
- Point source, gaussian distributed opening angle σ=35°
- Initial energies : Bremsstrahlung, E=[10 keV, 30 MeV]
- 10^7 initial photons (real TGF is ~10^{16} photons)

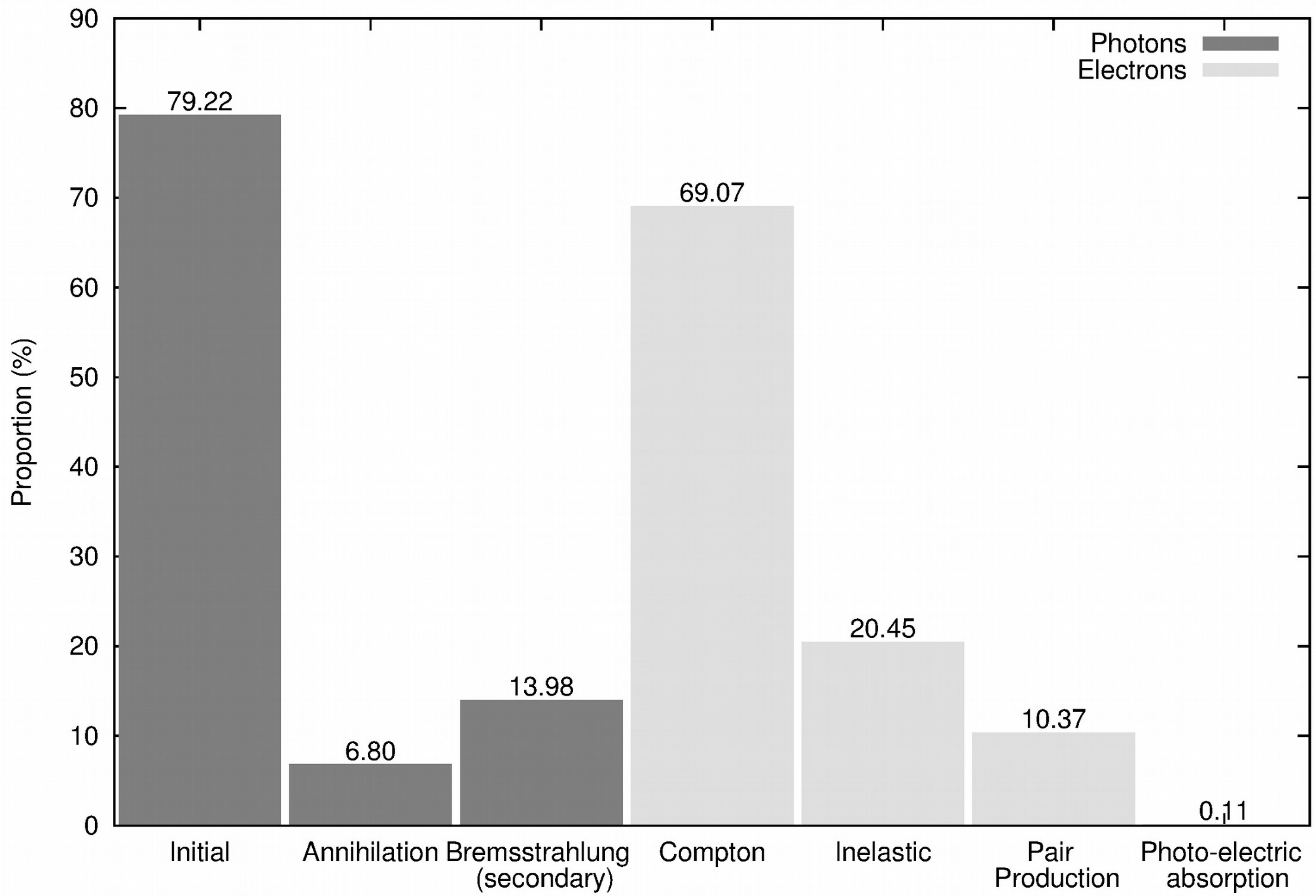
Fermi event 091214 ?



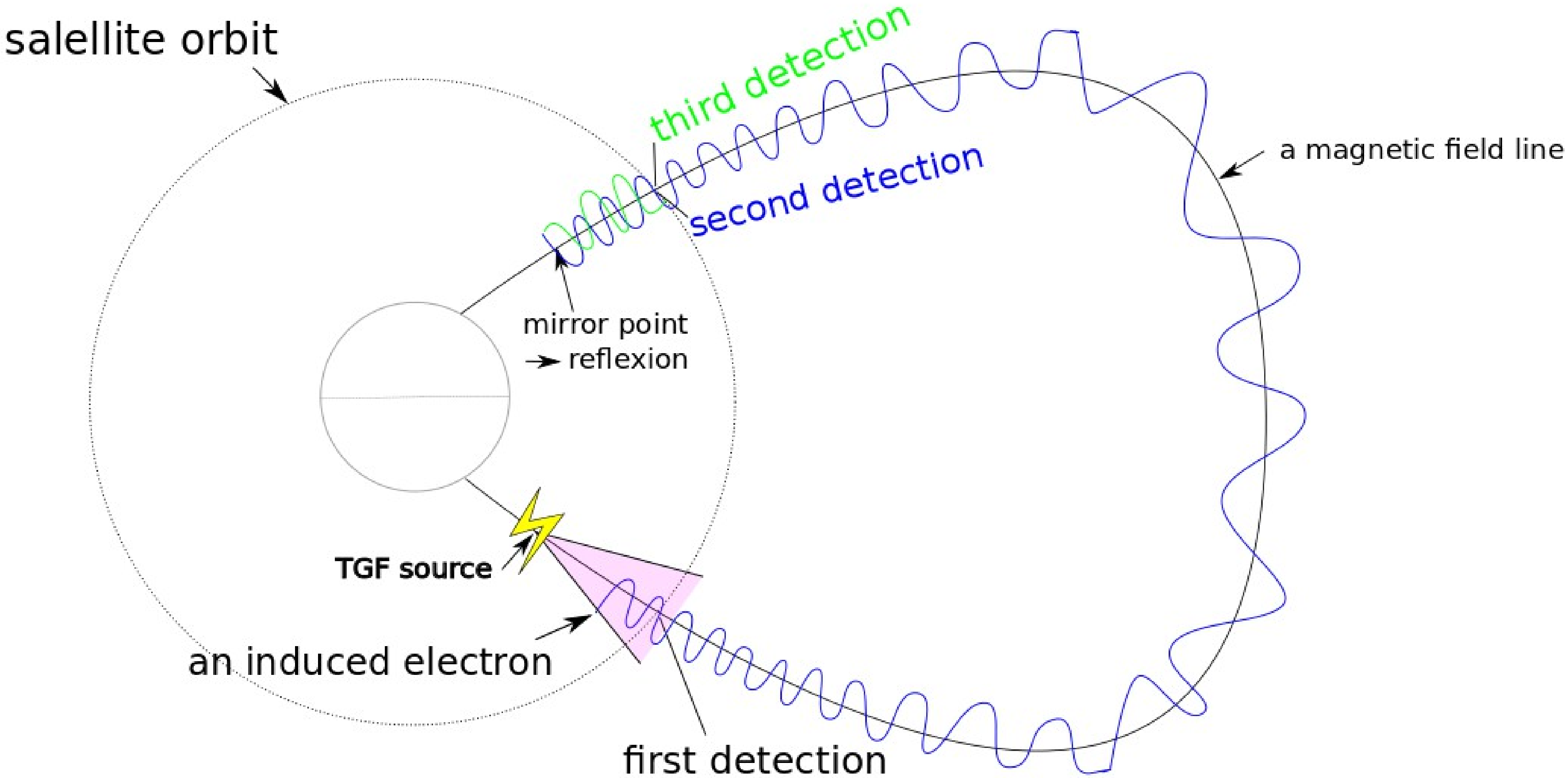
Particules detected: Energy spectra



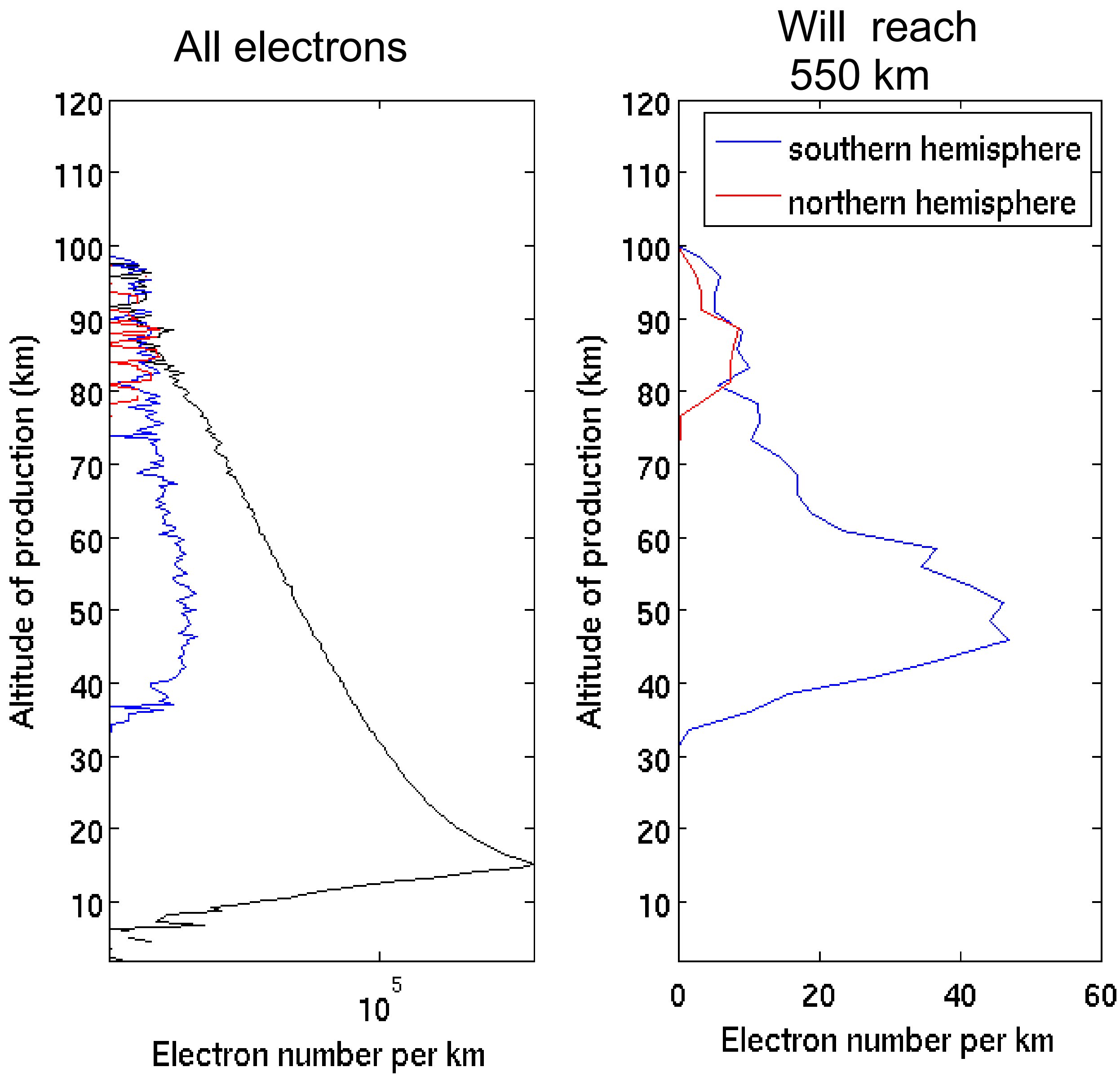
Particules detected: production processes



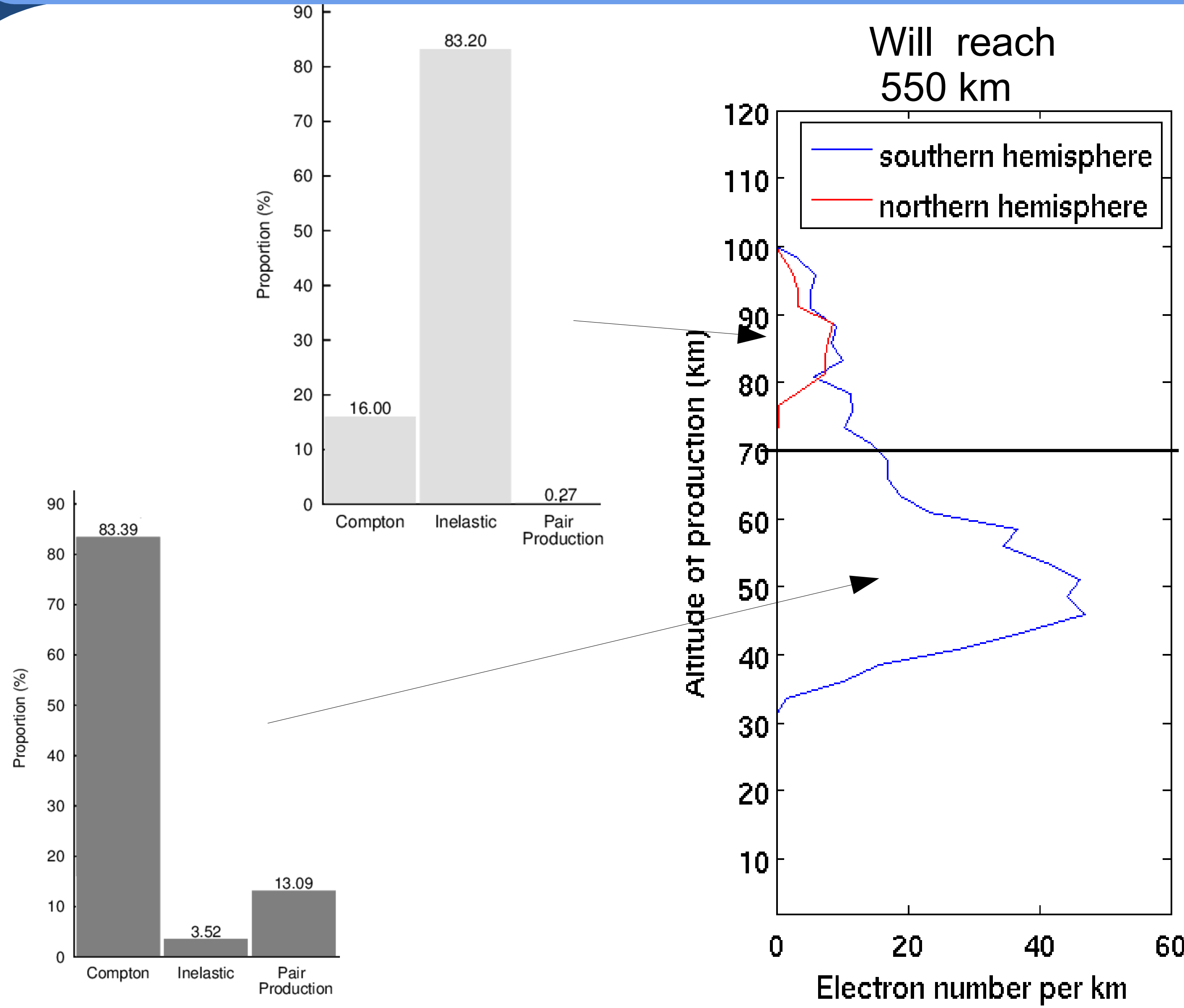
Geometry


salellite orbit
third detection
second detection
a magnetic field line
mirror point
reflexion
TGF source
an induced electron
first detection

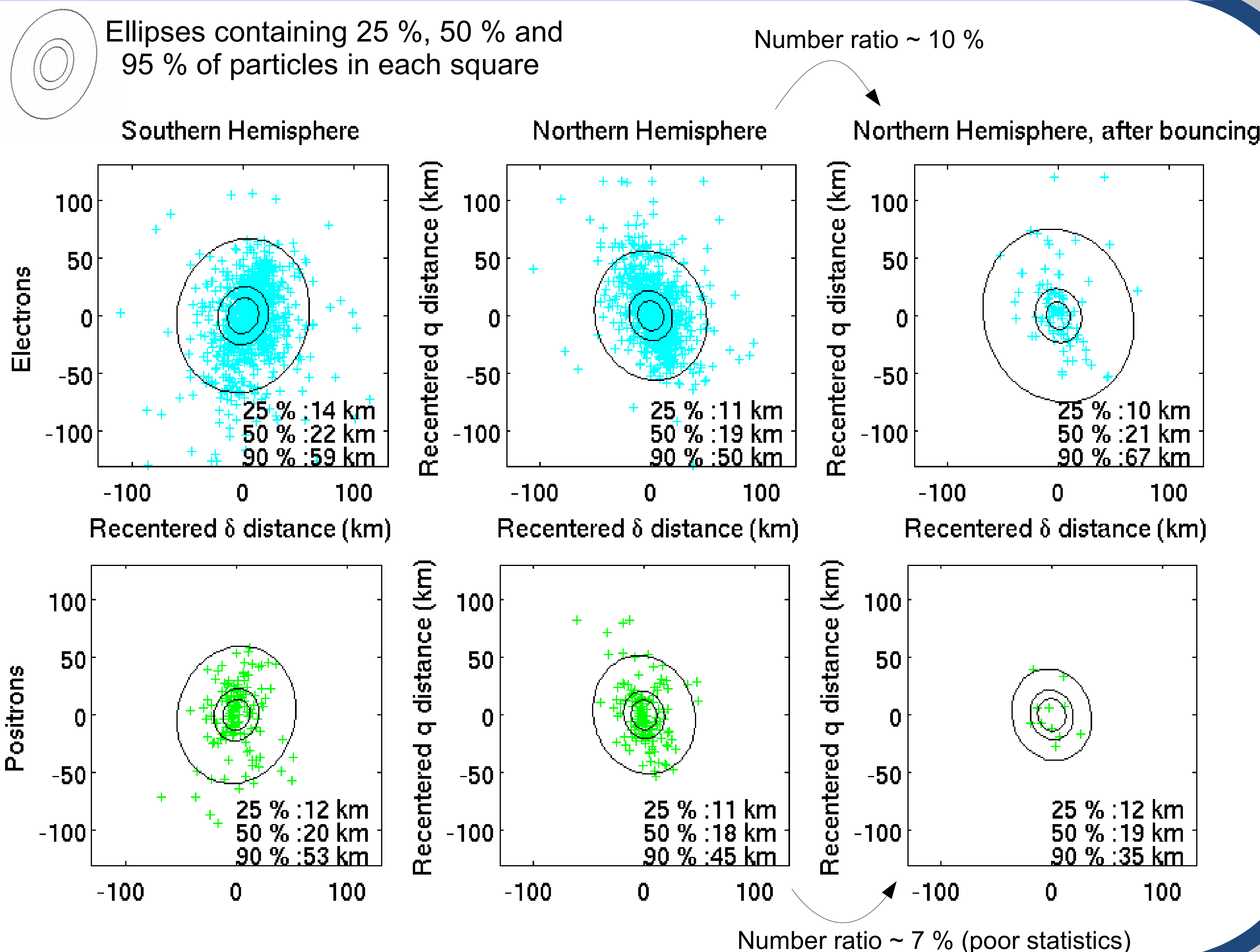
Production altitudes



Production altitudes



Particules detected at 550 km : electron/positron beam



Conclusions : some simulation results

Monte-Carlo model for photon/electron/positron transport in Earth atmosphere, and magnetic field, taking into account 11 processes.

Photons detected:

- primary source ~79 %, annihilation ~7%, bremsstrahlung ~14%

Electrons detected:

- compton ~70 %, inelastic scattering ~20 %, pair production ~10 %

Production altitudes of electrons :

- 30-70 km : dominated by compton scattering
- 70-100 km : dominated by inelastic scattering

→ Electron beams r~20 km, ~2 times higher than *Dwyer et al. But source altitude lower and opening angle of the source probably wider.*

Bouncing ratio ~10 % for electrons, ~7 % for positrons.

Is it highly dependent on some properties of the source?

What about time distributions? Positron/Electron ratio?

THANK YOU FOR YOUR ATTENTION

Questions are very welcome

Production theory

Main theories at present :

Relativistic feedback from cosmic ray seed particles

- Strong large scale electric potentials (> 100 MV over >100 m) :
- RREA + Feedback mechanism is enough to account for observed TGFs
- Timescale ~ 10-100 µs
- Narrow TGF beams

Lightning current pulse (LCP)

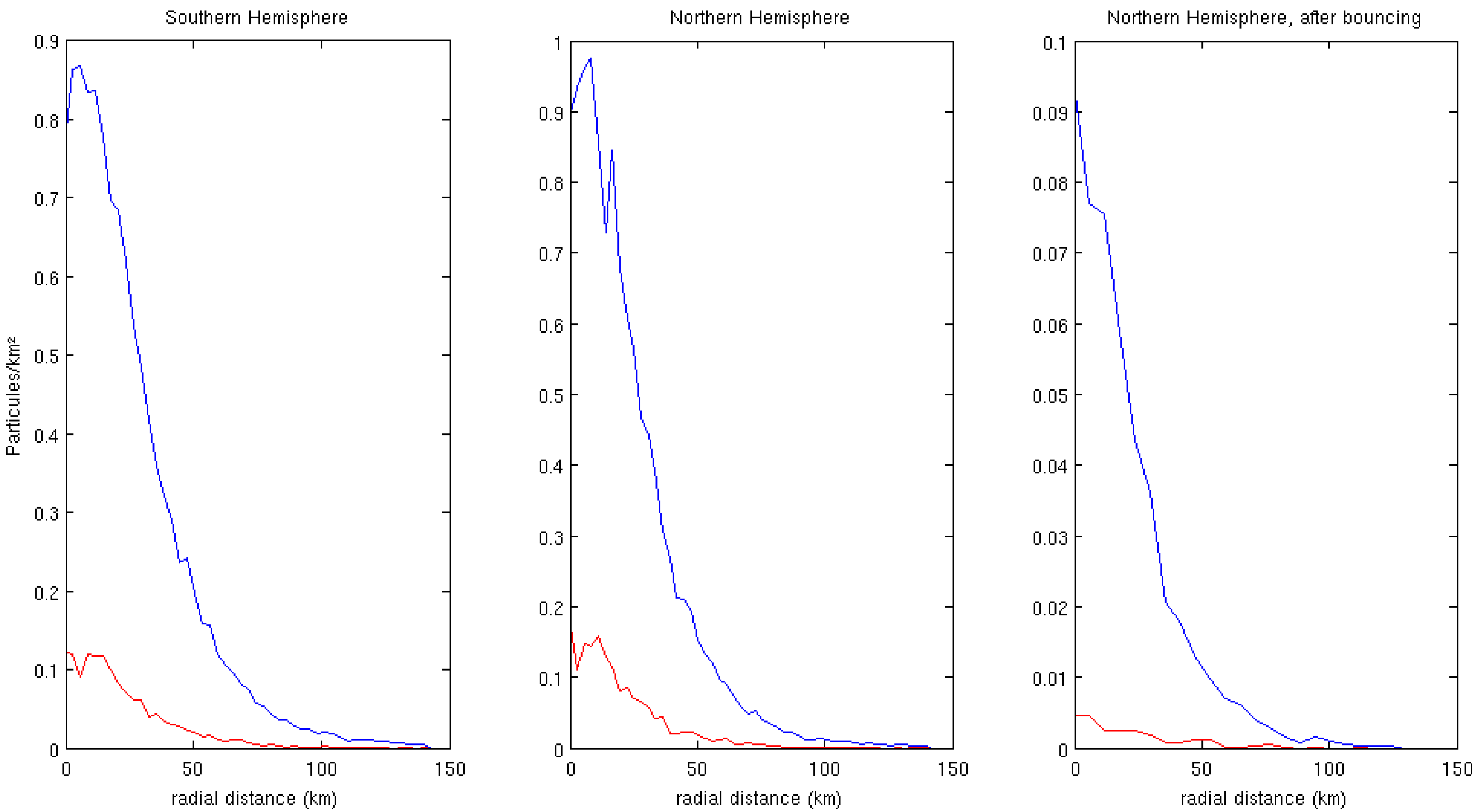
- Very strong small scale potential that can make run-away thermal electrons
- Negative leaders required
- Lightning must be associated to TGF
- Feedback negligible
- Broad TGF beams
- Timescale ~ 400 µs

Relativistic feedback in non-uniform fields

- Positive leaders more likely
- TGF can be produce without lightning (« dark lightning »)

Particules detected at 550 km : electron/positron beam profiles

Electrons
Positrons



Random sampling interactions

- How to choose an interaction ?

Cross-sections are used as point probabilities :

$$P_{i_{proc}} = \frac{\sigma_{i_{proc}}}{\sum_{i=1}^{i=N_{proc}^{i_{type}}} \sigma_i}$$

Cross section sets used

Particle	Processes	Total Cross-section source
Photon	Compton Scattering Photo-electric Absorption Rayleigh Scattering e-/e+ Pair Production	EPDL[1]
Electron	Inelastic scattering Bremsstrahlung Elastic Scattering	EEDL[4] Seltzer-Berger[3] EEDL[4]
Positron	Inelastic scattering Bremsstrahlung Elastic Scattering Annihilation	EEDL[4] Seltzer-Berger[3] with an analytical correction[2] ELSEPA[2] and EEDL[4] Analytical formula[2]

1 : Ref. *Cullen et al.* [1997]
2 : Ref. *Salvat et al.* [2011]
3 : Ref. *Seltzer and Berger* [1986]
4 : Ref. *Perkins et al.* [1991]

Random sampling the path-lengths

Between two interactions, the particle follows straight lines.
Applying the inverse transform method to U(s) gives :

$$s = \frac{-1}{a\ \cos(\alpha)} ln \left(1 + \frac{ln(\xi)\ a\ \cos(\alpha)}{\mu_{att,i_{par}}\ \rho(h_1)}\right)$$

- α is the angle between particle direction and local vertical.
- ξ is a random number between 0 and 1
- ρ is the density of the atmosphère
- μ_{att} is calculated from cross-sections and specie densities
- h_1 is the altitude of the particle before moving

- Used for photons at any altitude

For h_1=15 km and E=10 keV :

s ~ 2 km for photons
s ~ 2 cm for electrons

- Used (with different μ_{att}) for electrons/positrons if the collision frequency dominates the gyration frequency
- If the gyration frequency dominates, electrons/positrons are propagated solving the relativistic Lorentz equation with a 4th order Runge kutta

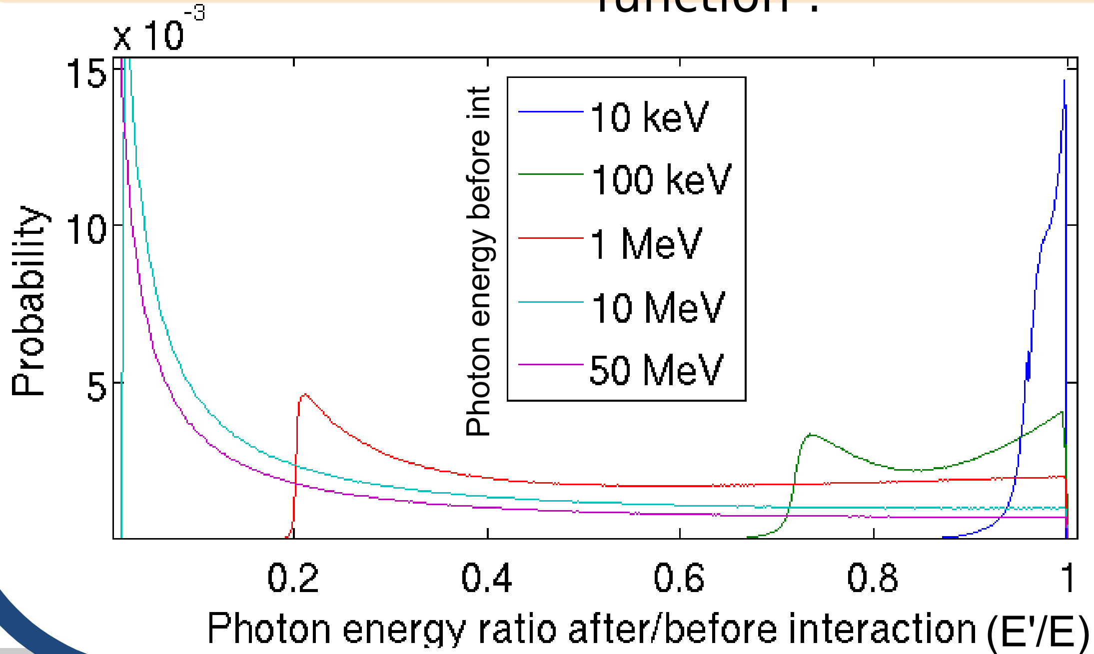
Random sampling interactions

Different for each interaction, but always the same general method :

A differential cross section in ***energy*** or ***angle*** can be computed analytically
or from tabulated values. For example, for Compton scattering :

$$\frac{\mathrm{d}\sigma_{\mathrm{Co}}}{\mathrm{d}E'} = \frac{\pi r_{\mathrm{e}}^2}{E}\kappa^{-3}\left(\frac{E^2}{E'^2} + \frac{(\kappa^2-2\kappa-2)E}{E'} + (2\kappa+1) + \frac{\kappa^2 E'}{E}\right) S_{\mathrm{WH}}(q_{\mathrm{C}})$$

Normalizing it to unity gives a probability density function :



Then, the remaining unknowns are deduced using conservation of momentum and energy.

Conclusions

TLEs, TGFs and TEBs are fascinating, recently discovered phenomena.

Observations lead to **some important constraints** :

- Correlated to thunderstorms
- Altitude of production 10-20 km
- 1 photon/cm² at satellite
- ~400 μs duration
- Bremsstrahlung spectrum
- Max energies 40 MeV (100 MeV ??)
- Induced Electron beams
- Fairly Common phenomena (~400 TGF/day)

A good theoretical work as been done, and two theories are still defended :
Cold Runaway and **Relativistic feedback**

TARANIS is designed to detect TGFs, TLEs and TEBs, **with simultaneous high resolution measurements of X/gamma rays, electrons, radio waves and optical emissions** (TARANIS launch is expected in the end of 2016).

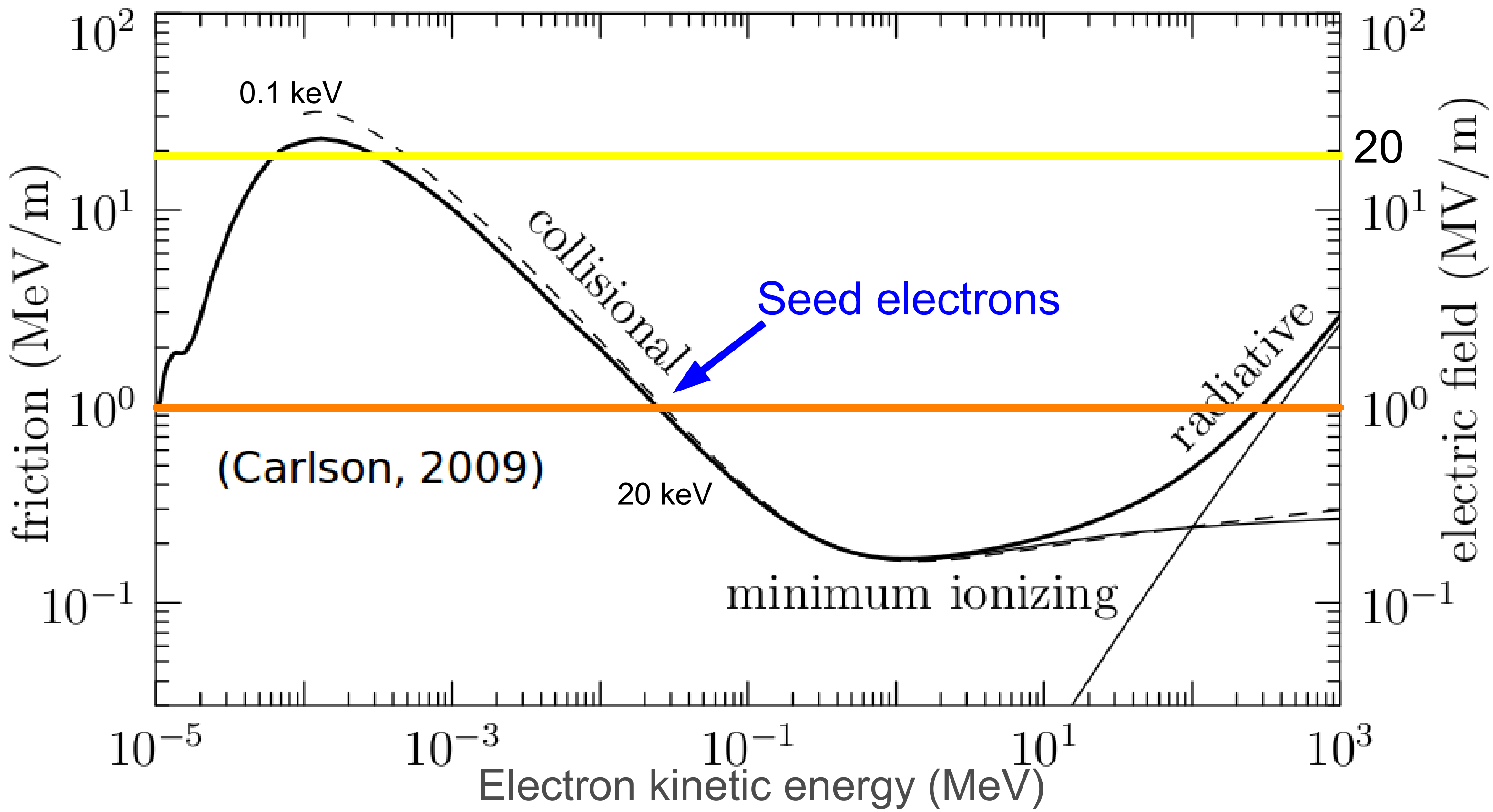
In preparation of TARANIS data analysis, **we build a complete Monte Carlo model of the transport of photons, electrons and positrons in the atmosphere** :

- 3D, including atmosphere (MSIS) and magnetic field model (IGRF-11)
- Follows photons, electron and positrons and includes N_{proc}=11 in total.
- It is in very good agreement with Geant4.

Production theory

During a lightning event

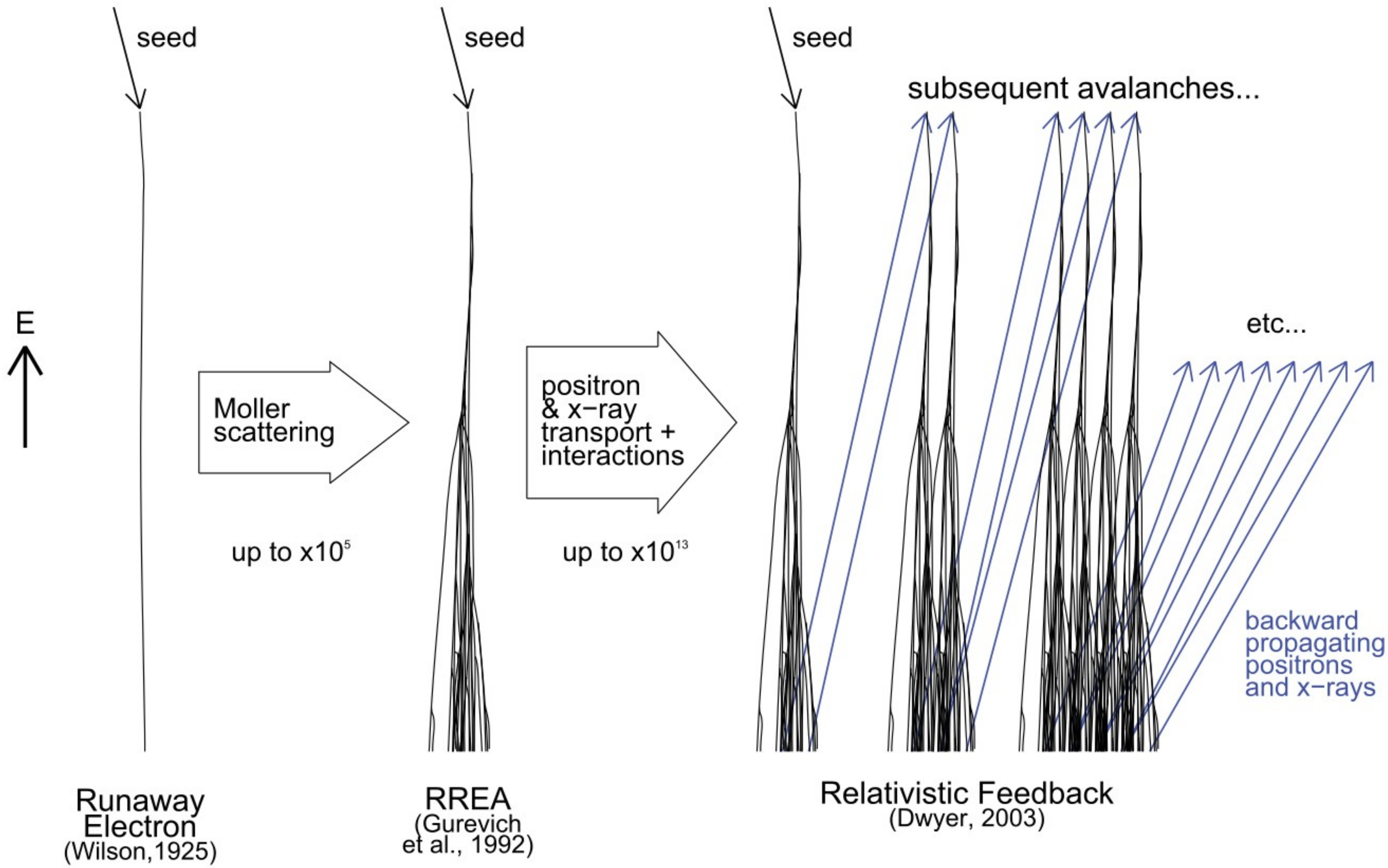
Electric field induced acceleration VS Air friction



Relativistic feedback and **cold runaway** are possible mechanisms

Production theory

From J.R Dwyer et al. review (2012)



Bremsstrahlung emission

Random sampling

s = path-length = distance between two interactions.

P(s) = probability of not interaction after reaching a distance s

$$P(s) = 1 - exp\left[-\int_0^s \frac{ds'}{\lambda(s')}\right]$$

λ = « local mean free path »

$$\lambda^{-1} = \sigma\left(E, Z\right)\rho\left(h\left(s'\right)\right)$$

Important assumption : $\rho\left(h\right) = \rho_0 e^{-\frac{h}{H}}$

H ~ 7 km

GEANT4 Comparison

Monte-Carlo code developed by an international collaboration lead by CERN.

Used to validate our model

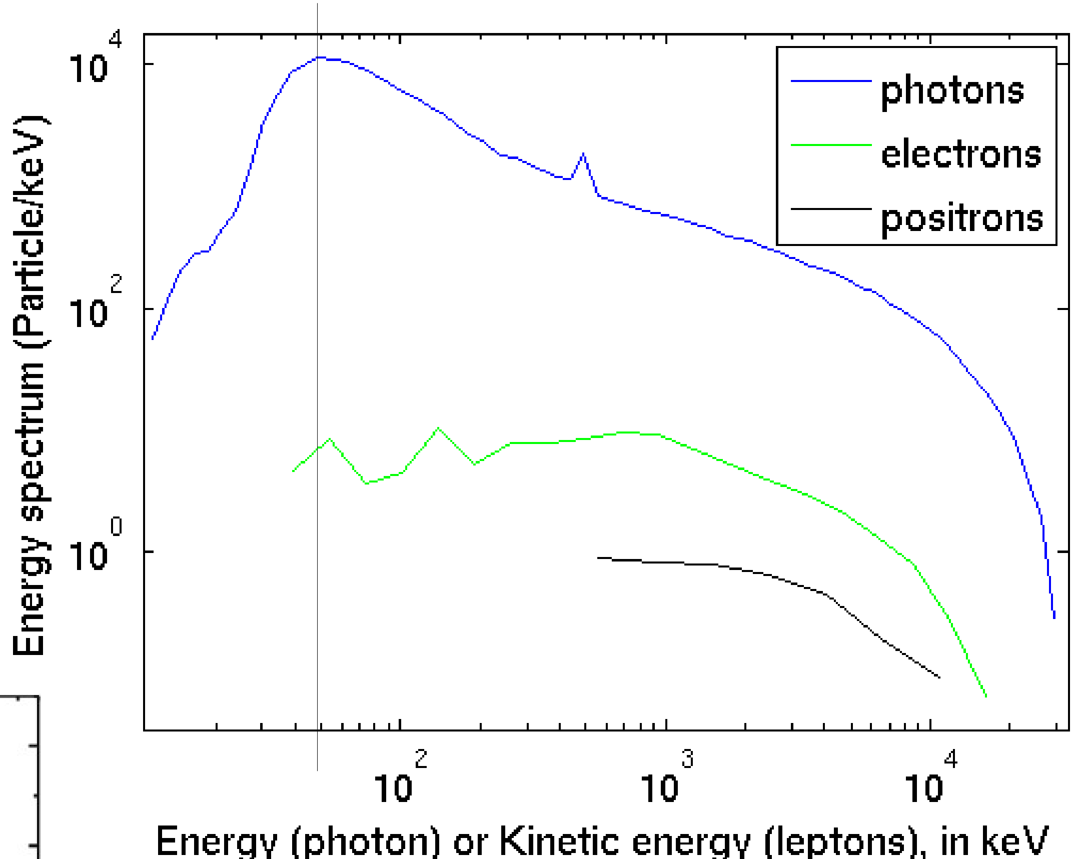
G4 Primarily designed to simulate detectors : can only handle constant density layers

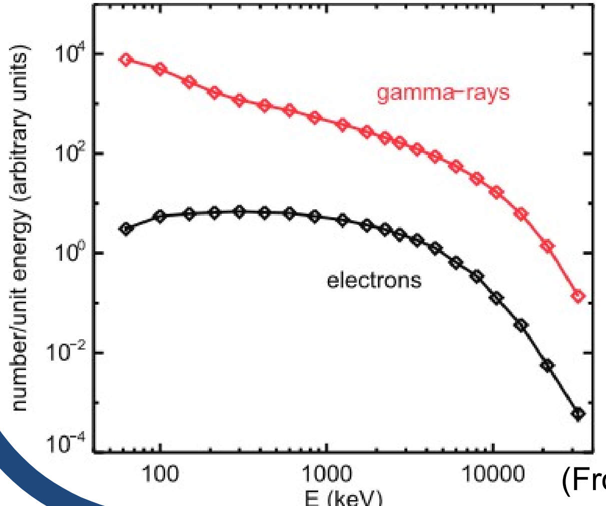
→ Atmosphere = 500 exponentially spaced layers ∈ [0 100] km

Different physics lists are used.

→ Most relevant : LHEP and LBE, no change in practice (for this problem)

Particules detected: Energy spectra





(source at 15 km altitude)

(Source at 21 km altitude)

(From Dwyer et al. 2008b)