Modèle Monte Carlo du transport dans l'atmosphère des électrons relativistes et des photons gamma en relation avec les Flashs Gamma Terrestres (TGF)

Soutenance de thèse

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Sous la direction de Pierre-Louis Blelly

14 Septembre 2015

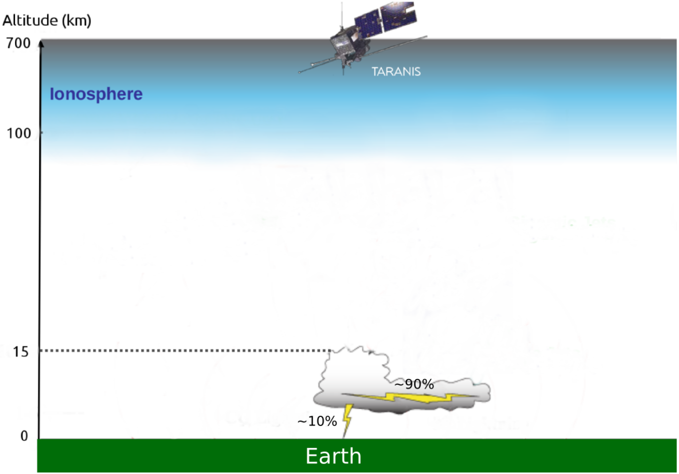
En vue de l'obtention du grade de docteur de l'Université Paul Sabatier

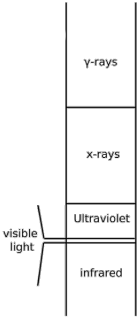
Outline

Introduction

- Transient events from thunderstorms, environment

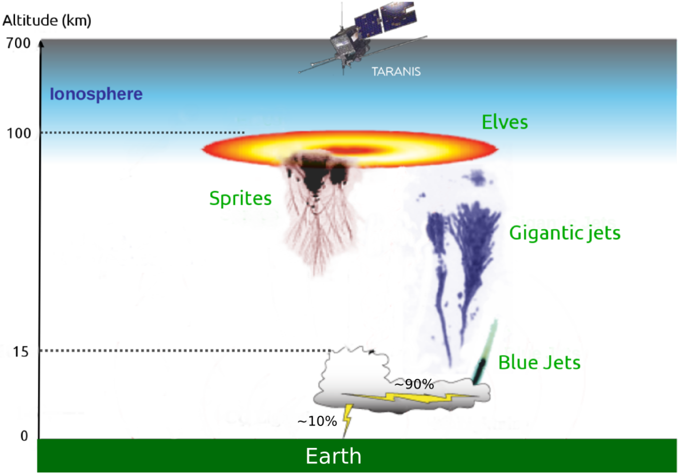
TLE and TGF

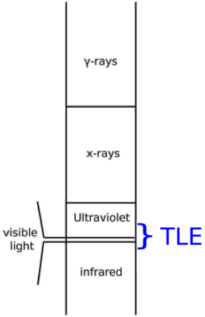

Altitude (km)
700
100
15
0
TARANIS
Ionosphere
~90%
~10%
Earth


γ-rays
x-rays
Ultraviolet
visible light
infrared

TLE and TGF

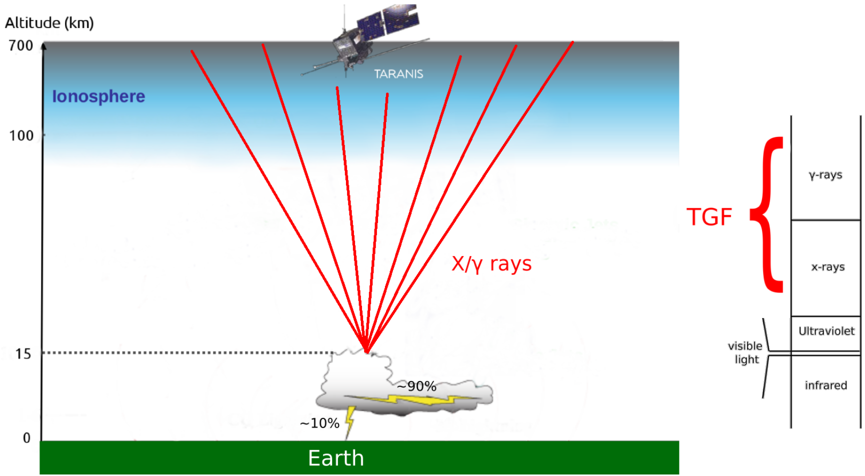
TLE = **T**ransient **L**uminous **E**vent (1990)
= Sprites, Elves, Jets, etc ...



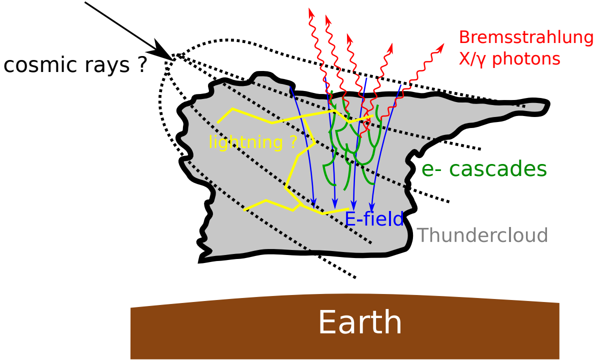


TLE and TGF

TGF = **T**errestrial **G**amma-ray **F**lash (1994)

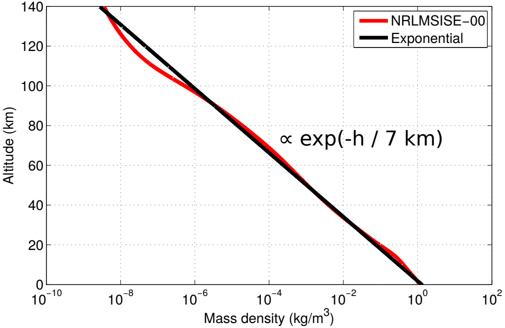


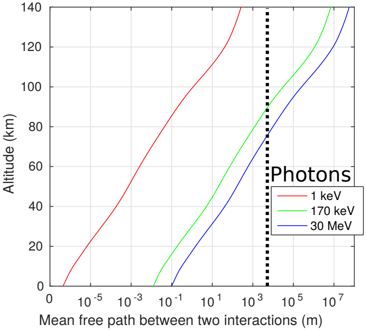
TGF : Production sketch



- Ingredients : high energy electrons ("seeds"), strong electric field
- Relativistic electron avalanche
- Bremsstrahlung radiation
- Cold Runaway VS Relativistic Feedback

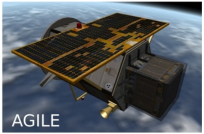
TGF : atmospheric filtering

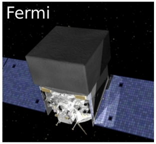




- Reference model : MSIS (empirical)
- Density falls exponentially with increasing altitude, scale height $\sim$7 km
- Gamma ray flux too faint to be detected from ground $\rightarrow$ detected from space

TGF : detections



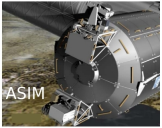


First detections by BATSE on-board NASA-CGRO, published in Science *(Fishman et al., 1994)*

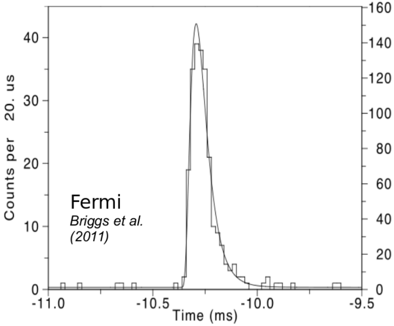
Also detected by RHESSI, Fermi and AGILE (Not their primary goal)

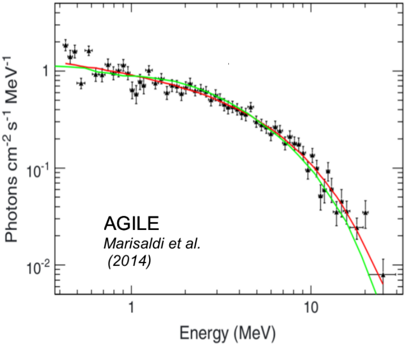
Fermi : > 400 TGF/day (*Briggs et al.*). Maybe 50,000 TGF/day ! (*Ostgaard et al.*)

Primary objective of TARANIS and ASIM



TGF : morphology

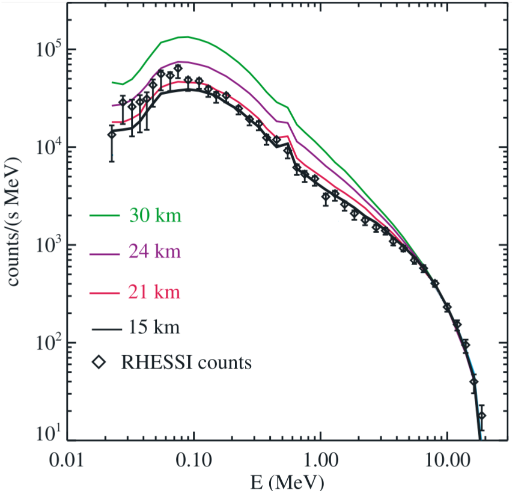




- Typical duration of $\sim$ 0.5 ms
- Bremsstrahlung energy spectrum filtered by the atmosphere.
- $\sim$ 1 photon/cm^2 at satellite's altitude ($\sim$ 600 km)
- Simulations $\rightarrow \gtrsim 10^{16}$ photons at source ($\sim$ 15 km)

TGF : source altitude

(Dwyer and Smith, 2005)



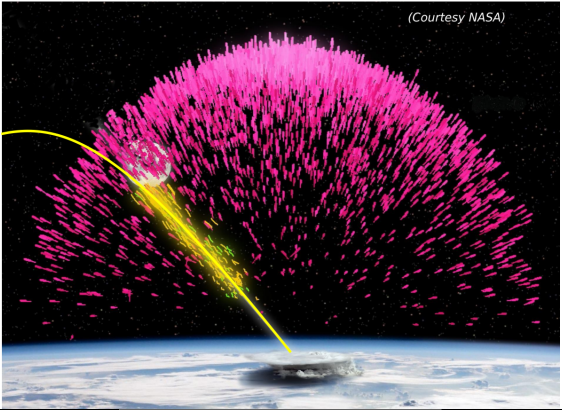
- The energy spectrum seen at satellite altitude is changed if the photons are emitted at different altitudes
- Monte-Carlo simulations for different source altitudes
- Comparison with satellite data
- Early estimation : 15-21 km
- Later estimation : 12-15 km

TEB

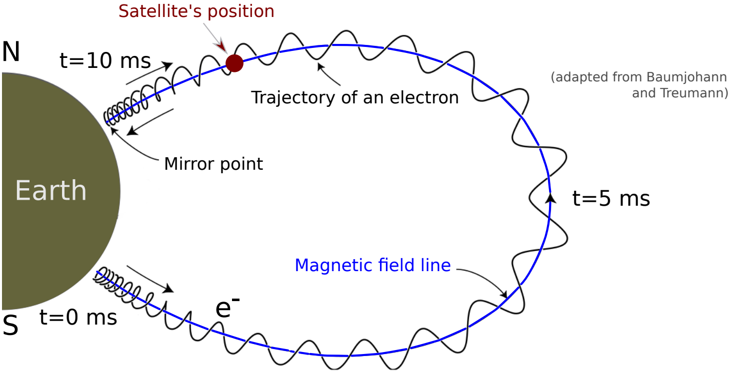
- During their propagation in the atmosphere, photons will produce a lot of electrons and positrons.

Once escaping the atmosphere :

- Electrons and Positrons are guided by magnetic field lines
  $\rightarrow$**T**errestrial **E**lectron **B**eam (**TEB**)
- TGF (=photons) follow straight trajectories



TEBs : Electron motion

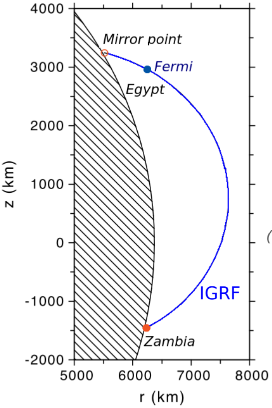


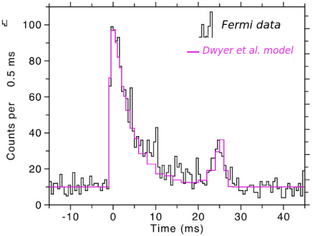
Conservation of the first adiabatic invariant

→ Magnetic mirror

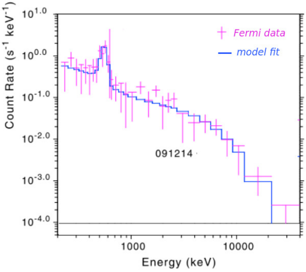
→ Possible detection of electrons on both sides

TEB example : 091214 Fermi event





(Briggs et al., 2011)



- Double peaked
- Much longer than a TGF
- TGF detection above the egyptian desert ?
- 511 keV line : positron annihilation
- Electrons/positron beams ! TGF was actually over Zambia

Monte-Carlo model

Generalities

MC-PEPTITA = **M**onte-**C**arlo **P**hoton **E**lectron **P**ositron **T**racking **I**n **T**errestrial **A**tmosphere

3D

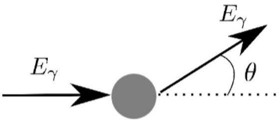
Involved particles:

Photons Electrons Positrons

- Energy range : 10 keV to 100 MeV
- External models :
  - MSIS for the atmosphere
  - IGRF-12 for the magnetic field
- 11 processes included

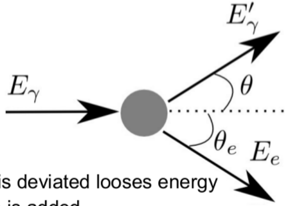
Processes : photons

Coherent (Rayleigh) scattering



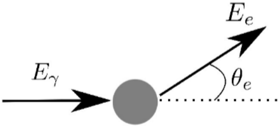
- Only deviation, no energy change

Incoherent (Compton) scattering



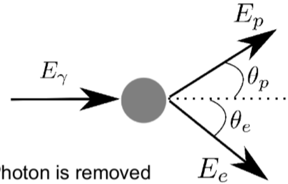
- Photon is deviated looses energy
- Electron is added

Photo-electric absorption



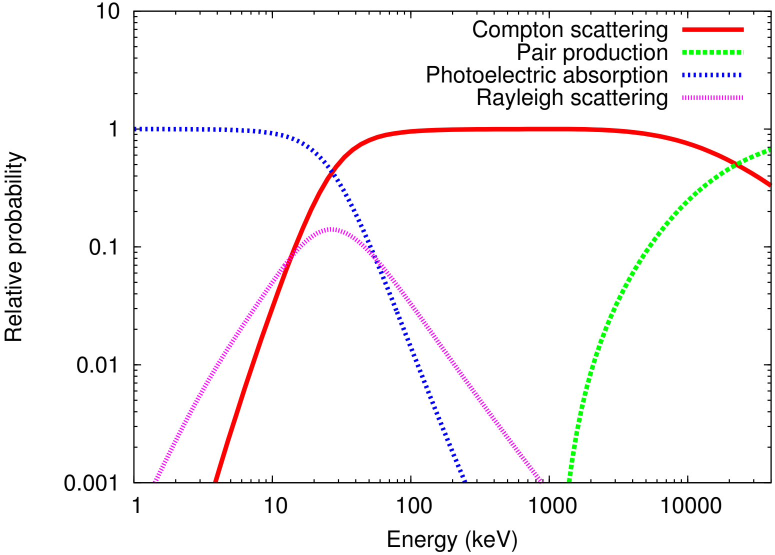
- Photon is removed
- Electron is added

Electron/positron pair production



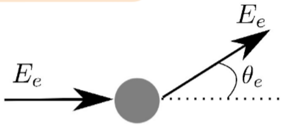
- Photon is removed
- Electron and positron are added

Processes : photons, relative probability



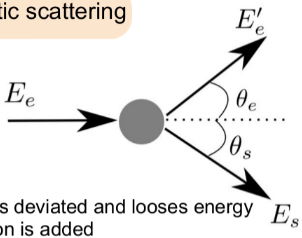
Processes : Electrons and positrons

Elastic scattering



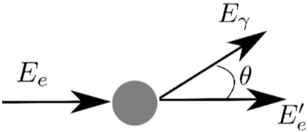
- Only deviation, no energy change

Inelastic scattering



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

Bremsstrahlung

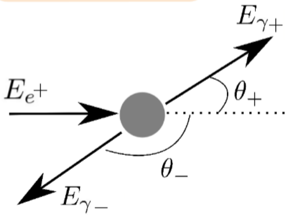


- e-/e+ looses energy
- Photon is added

Processes : Positrons

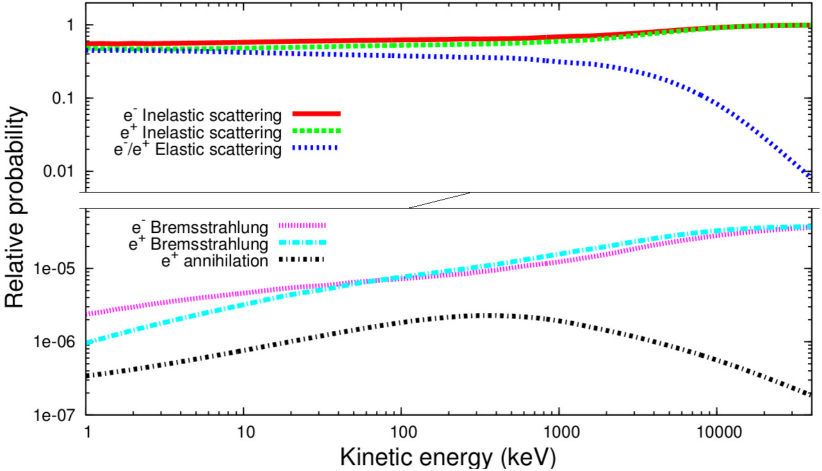
One extra process :

Positron annihilation



In a dense medium, annihilation only after para-positronium phase
$\rightarrow$ **e^-/e^+ annihilation into 2 photons with $E_{\gamma+} \approx E_{\gamma-} \approx$ 511 keV**

Processes : Electrons/Positrons, relative probability



Particles' displacement

- $s =$ distance between 2 interactions
- σ = total cross section, ρ = number density, λ = mean free path
- $P(s)$ = probability of not interacting after reaching a distance s

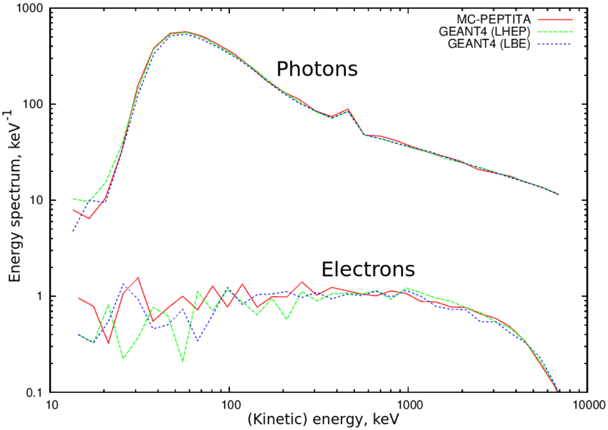
$$\lambda^{-1} = \sigma(E)\,\rho(h)$$

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

- γ trajectories : straight lines between two interactions
- $\mathrm{e}^-/\mathrm{e}^+$ trajectories :
  - Solving $\frac{d\vec{p}}{ds} = \frac{\vec{v}\times\vec{\Omega}}{v} - \nu\frac{\vec{v}}{v}$
  - Different regimes function of ν/Ω, a lot of care taken

Validation : Comparison with GEANT4

- GEANT4 is a reference Monte-Carlo code developped by CERN
- Testing similar set-ups with GEANT4 and MC-PEPTITA
- Test of the collision model



- Excellent agreement between GEANT4 and MC-PEPTITA

MC-PEPTITA : assets

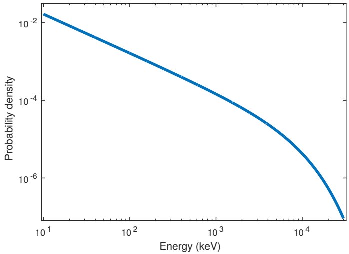
- Full tracking of all the particle
- Particle's outputs with new information, including :
  - Process of production (see next)
  - Production altitude (see next)
  - Pitch angles of $\mathrm{e}^-, \mathrm{e}^+$ (see next)
  - Larmor radii of $\mathrm{e}^-, \mathrm{e}^+$
  - Number of interactions
- Accurate resolution of $\mathrm{e}^-, \mathrm{e}^+$ transport
- Fast (e.g. compared to G4), optimized for Earth's environment
- Parallelized, with very good scalability

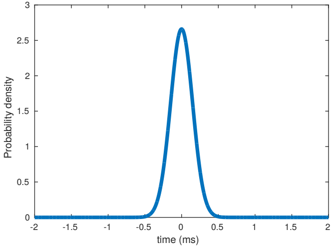
Applications of the model

1. Simulation of a typical TGF : γ and $\mathrm{e}^{-}\mathrm{e}^{+}$
2. Simulation of Fermi $\mathrm{e}^{-}\mathrm{e}^{+}$ events, focus on 091214

Initial conditions for a typical TGF

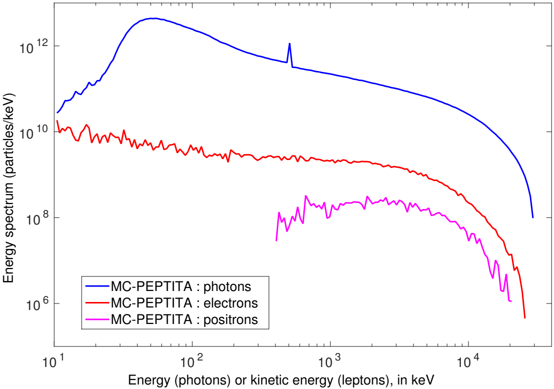
- Source at 15 km altitude, southern hemisphere.
- Energy spectrum $\propto \frac{1}{E} exp\left(\frac{-E}{\epsilon}\right)$, $\epsilon = 7.3$ MeV.
- Time distribution $\propto exp\left(\frac{-t^2}{2\sigma_{t,src}^2}\right)$, $\sigma_{t,src} = 0.15$ ms.
- Angle beaming $\propto exp\left(\frac{-\theta^2}{2\sigma_\theta^2}\right)$, $\sigma_\theta = 35^o$.





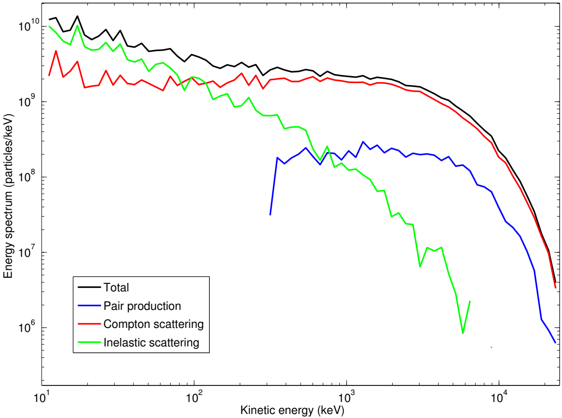
- Every particle crossing satellite's altitude is saved.

γ, e^-, e^+ energy spectra at satellite altitude



- Photon spectrum roughly agree with previous works (e.g. *Dwyer et al.*)
- e^-, e^+ more noisy than γ (Monte-Carlo), $\frac{N(\gamma)}{N(e^-)} \sim 100$; $\frac{N(e^-)}{N(e^+)} \sim 8$
- Positron spectrum determined for the first time.
- MC-PEPTITA permits to decompose these spectra : focus on electrons

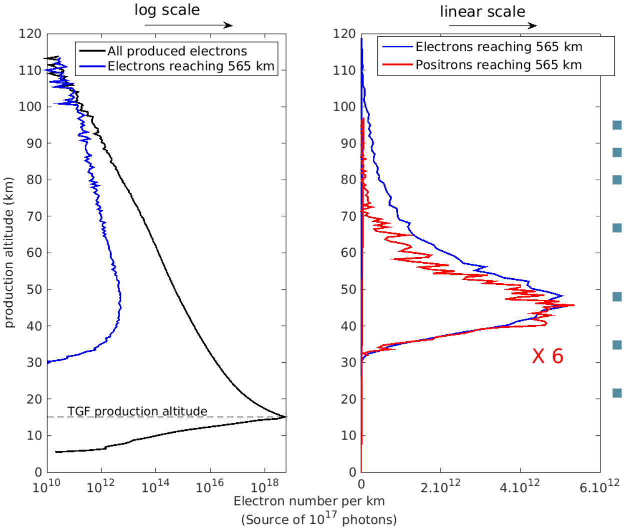
e^- energy spectra decomposition



- > 100 keV : domination of Compton, < 100 keV : domination of inelastic
- Pair production : same spectrum as positrons, not dominant, but $\sim$ 12% of total

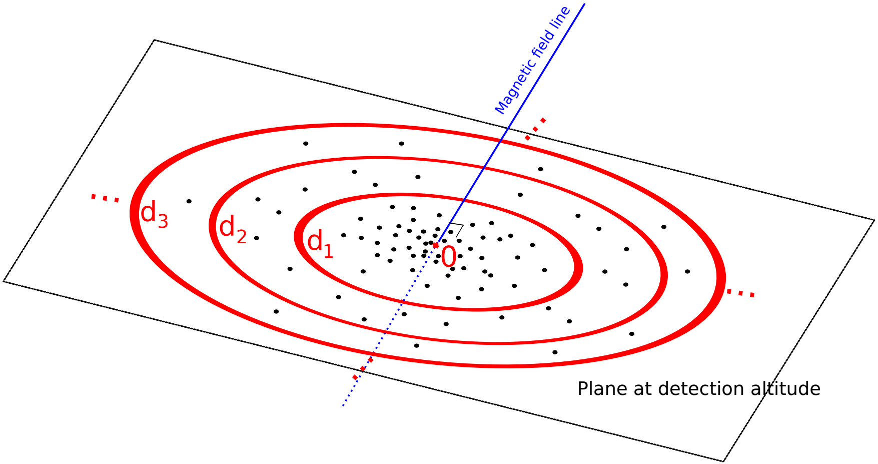
e^-, e^+ : production profile

- Determined for the first time with MC-PEPTITA.

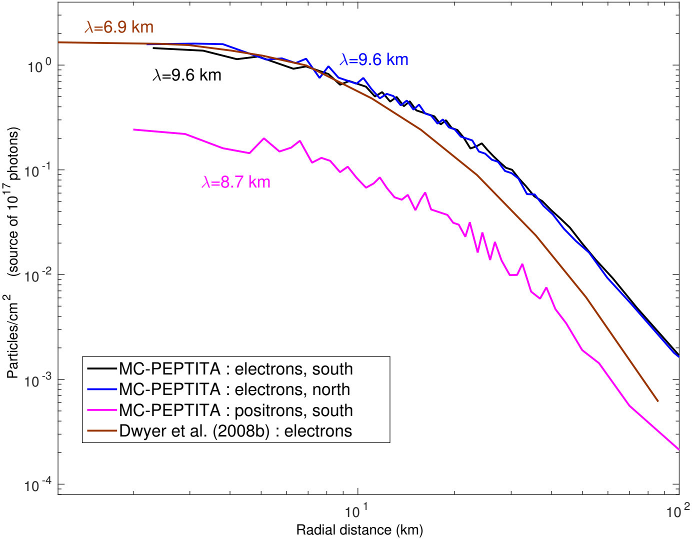


- $\sim 10^{19}$ e^- produced (above 10 keV),
- Effects of this massive production ?
- $\sim 10^{14}$ can escape, all produced above $\approx$ 30 km
- e^- production non-negligible up to 100 km, neglected above 60 km in previous works.
- Below 70 km, e^- production dominated by Compton scattering
- Above 70 km : 50% Compton scattering, 50% inelastic scattering
- e^+ lower average production altitude ($\approx$48 km vs $\approx$53 km)

e^-, e^+ fluxes at satellite altitude : definition



e^-, e^+ fluxes at satellite altitude



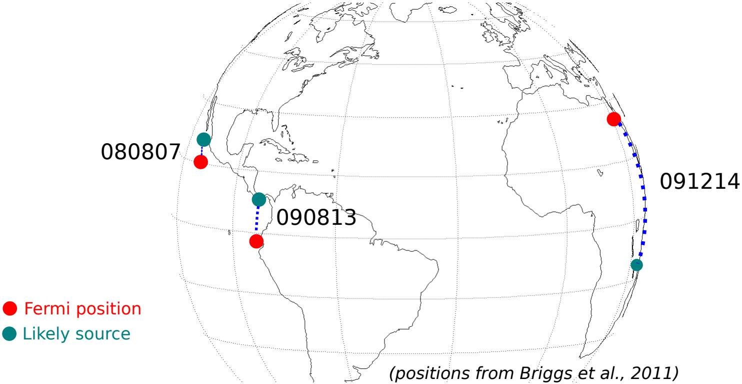
- All e^-, e^+ fluences well fit by $\propto \exp\left(-\frac{d}{\lambda}\right)$
- e^- beam stays similar after travelling between hemispheres
- e^+ beam $\approx$ 10% smaller than e^- beam
- e^+/e^- fraction $\approx$ 12%
- e^- beam $\approx$ 40% wider than previous models

Applications of the model

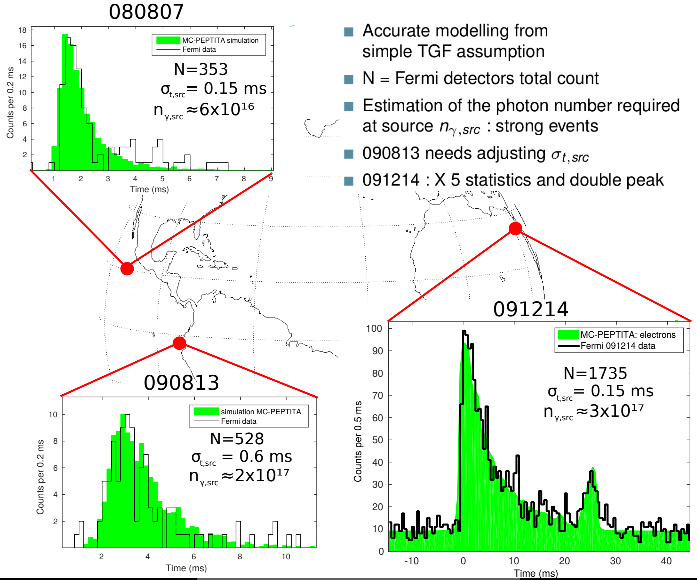
1. Simulation of a typical TGF : γ and $\mathrm{e}^{-}\mathrm{e}^{+}$
2. Simulation of Fermi $\mathrm{e}^{-}\mathrm{e}^{+}$ events, focus on 091214

Simulating 3 Fermi e^-e^+ events (1/2)

- *Briggs et al. (2011)* : Three e^-e^+ events detected by Fermi-GBM

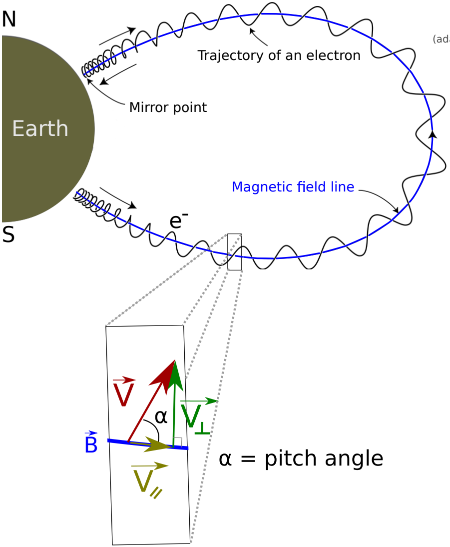


Simulating 3 Fermi e^-e^+ events (2/2)



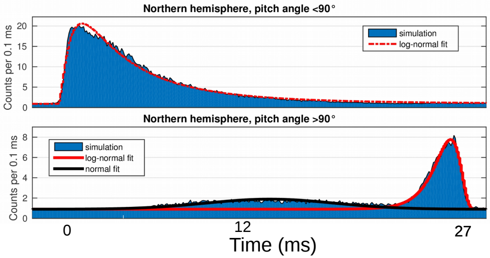
- Accurate modelling from simple TGF assumption
- N = Fermi detectors total count
- Estimation of the photon number required at source $n_{\gamma,src}$: strong events
- 090813 needs adjusting $\sigma_{t,src}$
- 091214 : X 5 statistics and double peak

Fermi 091214 event : pitch angle definition



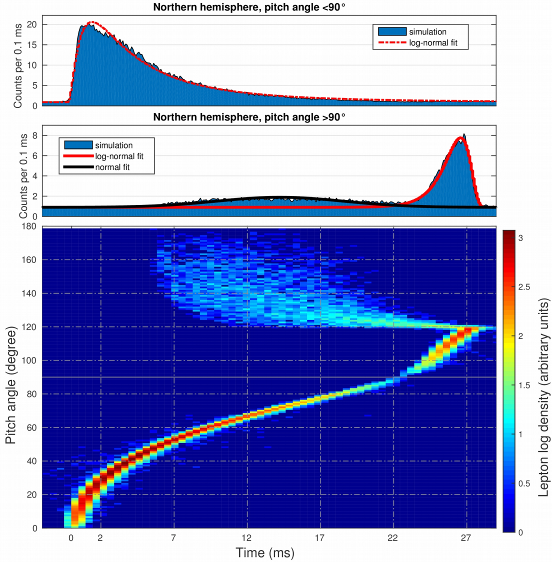
(adapted from Baumjohann and Treumann)

Fermi 091214 event : pitch angle time decomposition



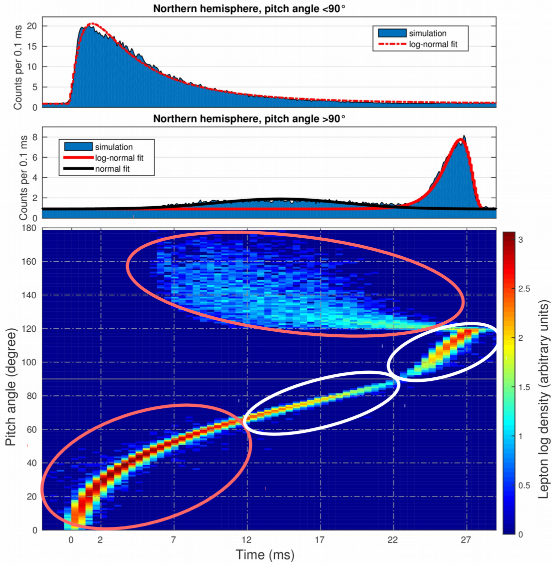
Fermi 091214 event : pitch angle time decomposition

- Full TEB pitch angle distribution resolved for the first time !



Fermi 091214 event : pitch angle time decomposition

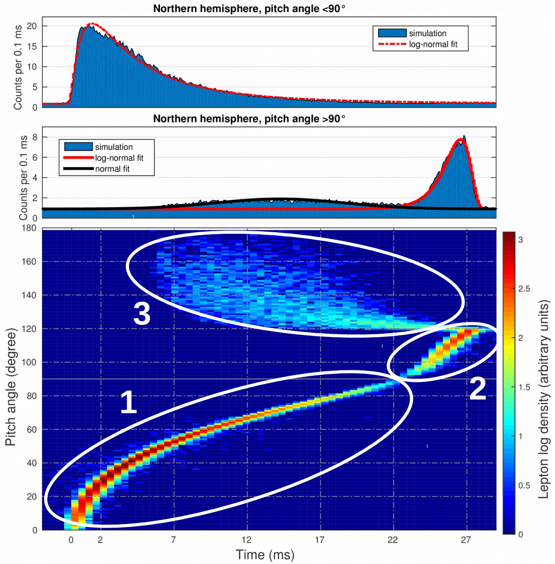
Pitch angle of ~120°
⟶ Had mirroring altitude of ~100 km



Fermi 091214 event : pitch angle time decomposition

Three populations :

1. Coming from south
2. Mirroring with negligible interactions
3. Mirroring with non-negligible interactions



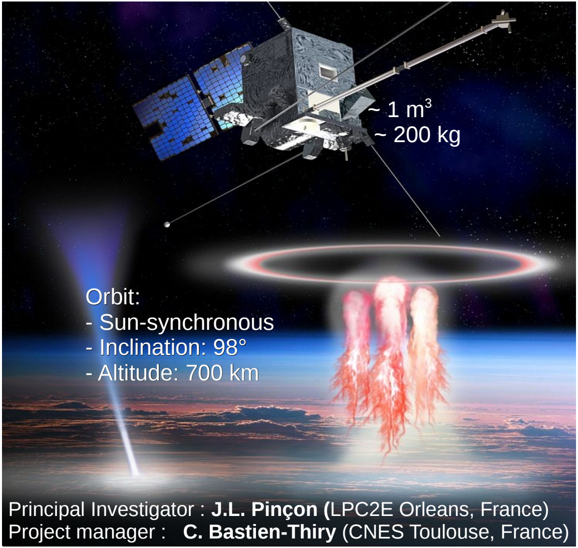
Applications of the model : summary

- e^{+} spectrum (new).
- Decomposition of e^{-} spectrum (new).
- Production profile of e^{-}, e^{+} (new).
- Spatial properties of e^{-}, e^{+} beams, $\sim$ 40% wider than previously expected.
- Accurate simulation of Fermi events.
- Pitch angle decomposition of e^{-}/e^{+} time histogram (new).
- Method for estimating the satellite's position within the TEB (not discussed).
- Determining geographical positions for mirror pulse of TEBs (not discussed).

- Gives important information for understanding the data of the TARANIS XGRE and IDEE instruments, and makes predictions

TARANIS

General features



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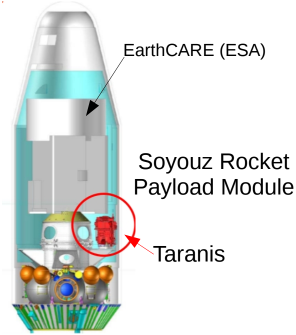
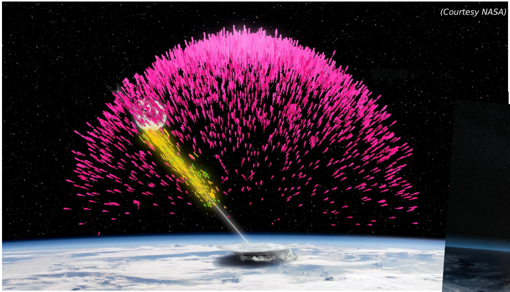


Expected launch : 2018

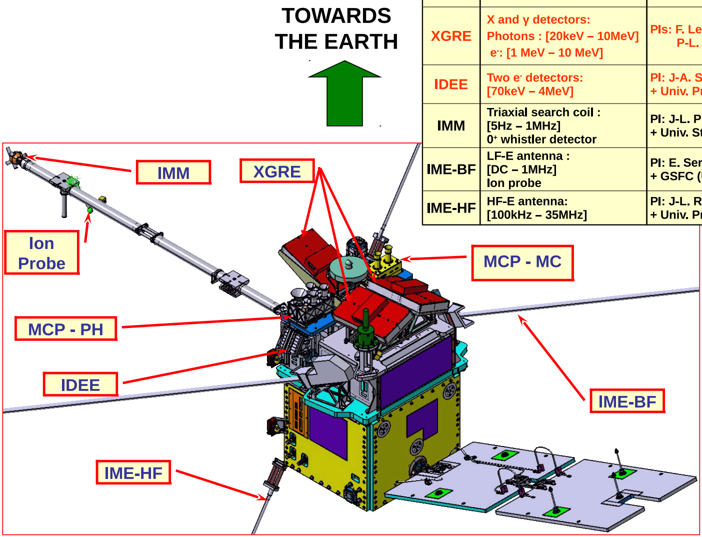
TARANIS : Main scientific objectives



- To advance the physical understanding of the links between TLEs, TGFs and environmental conditions
- To 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.

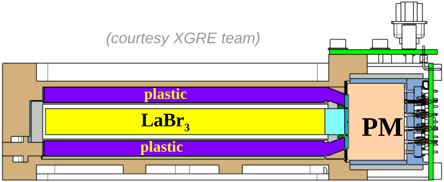
TARANIS : Instrumentation

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



TARANIS : XGRE

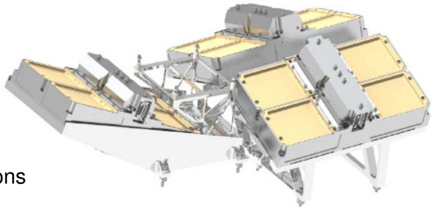
(courtesy XGRE team)



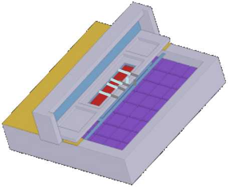
Rough estimation :

~ 850 TGF/year
each with ~ 280 counts

- Sandwich design of plastic/crystal scintillators
- Photons : 20 keV to 10 MeV (LaBr3)
- Electrons : 1 MeV to 10 MeV (plastic)
- Dead time < 350 ns
- Total detection area $\sim$800 cm^2
- 3 detectors, 20^o tilts
  $\rightarrow$ Estimation of the direction of photons

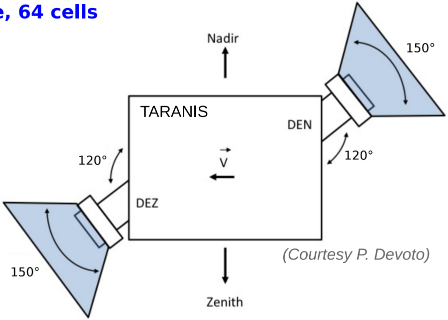


TARANIS : IDEE



Silicium, 5 cells

CdTe, 64 cells



(Courtesy P. Devoto)

- 2 detectors
- Electrons : 60 keV to 5 MeV
- $<$ 2 ms time resolution
- Pitch angle estimated from coincidence between Si and CdTe cells.

Conclusions

- Transient events related to thunderstorms, including TGFs and associated electron and positron emissions :
  - Recently discovered (1990+)
  - Generation mechanism not well understood
  - as well as their effects on the environment
- We built a model of propagation of $\gamma, \mathrm{e}^-, \mathrm{e}^+$ on Earth :
  - Accounts for all the relevant physics.
  - Accurate, fast.
  - Access to a lot of new information.
- Will be helpfull for the TARANIS data analysis (2018), in particular :
  - XGRE : X/γ photons and high-energy electrons.
  - IDEE : Electrons on a large energy range, with pitch angle estimation.

Future work

- Applying our model to other events (Fermi,TARANIS,ASIM ?).
- Collaboration with *M.S. Briggs* at Univ. of Alabama :
  - Effects of pitch angles of the $\mathrm{e}^-/\mathrm{e}^+$, interactions with satellite and detectors.
  - Important for TARANIS' IDEE and XGRE data.
- Coupling MC-PEPTITA with others models
  - Ionospheric models : effects of TGF, e.g. production of excited states and optical emissions.
  - Radio emission
- Spectral response of the XGRE detector (Post-doc at APC).
- 2018 : TARANIS data analysis.

Merci pour votre attention

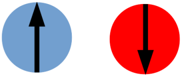
Un grand merci à mon directeur de thèse et à tous mes collègues, ma famille et mes amis pour leur soutien durant ces trois ans

Extra slides

Process : Positron annihilation

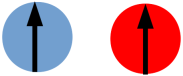
- In-flight annihilation is very unlikely
- Positrons will loose most of their energy (=slow down) catch an electron to form a positronium

Two ways of annihilation :



Para-Positronium

$\longrightarrow$ 2 photons,
each at 511 keV

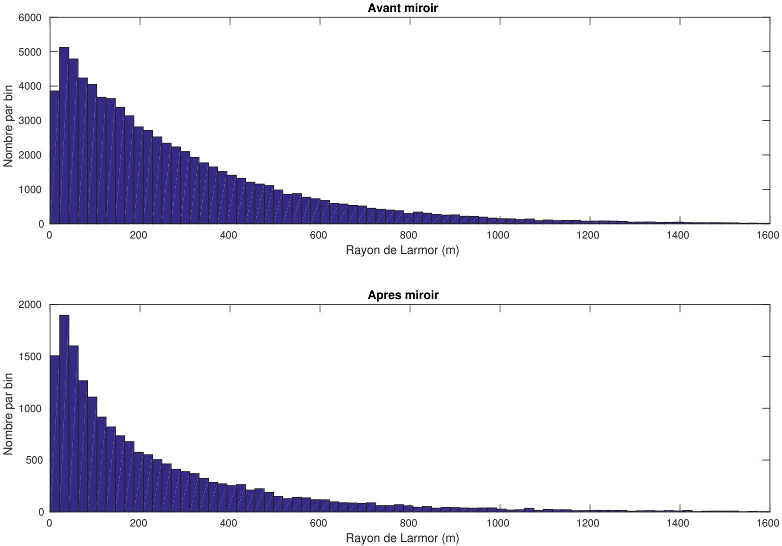


Ortho-Positronium

$\longrightarrow$ 3 photons

- InterStellar Medium density $\sim$ 30 cm^{-3} , Air density at 40 km altitude $\sim 7 \times 10^{16}$ cm^{-3}
- PP lifetime = 1.2×10^{-10} s $<<$ OP lifetime = 1.4×10^{-7} s
- In ISM, if any of these two state forms, it will annihilate a long time before encountering another electron from the medium.
- In a dense medium, if OP forms, its long lived lifetime permits "pick-off" annihilation where an opposite spin electron from some surrounding material will annihilate in para-orientation before the ortho-bound electron can collapse and annihilate with the positron.

091214 : Larmor radii



- Full TEB pitch angle distribution resolved for the first time !

Three populations :

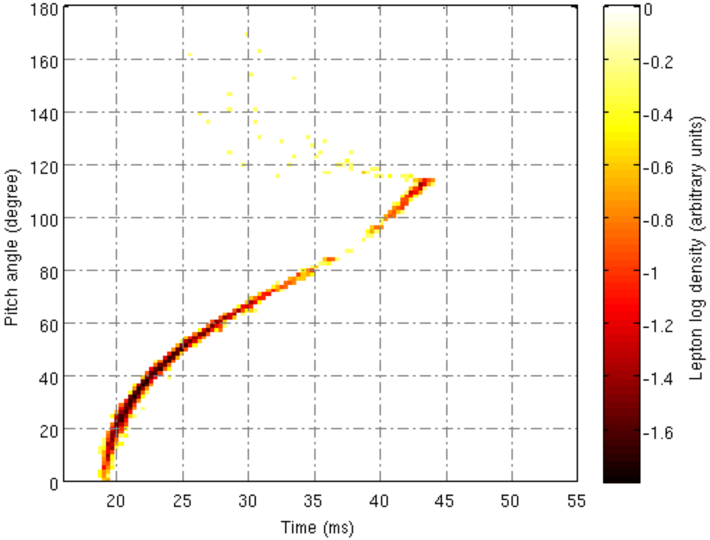
1. Coming from south
2. Mirroring with negligible interactions
3. Mirroring with non-negligible interactions

- Accurate analytical model for the corresponding time distributions
  - Permits estimation of position of the satellite within the TEB

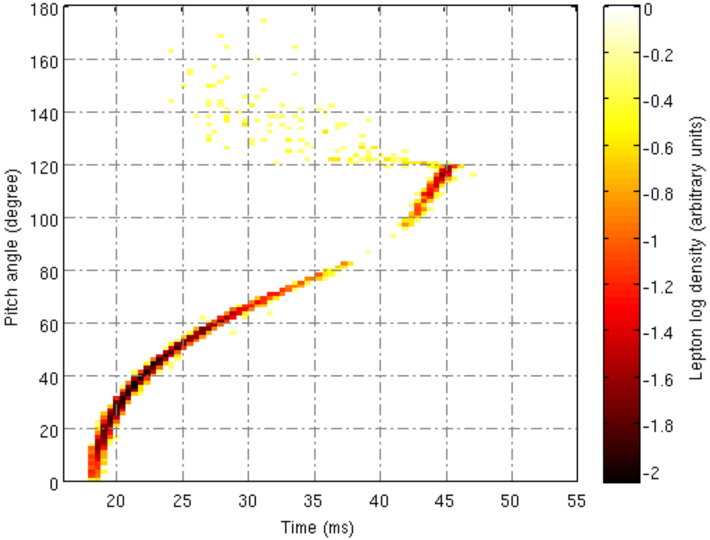
- Both time and pitch angle will be estimated by TARANIS-IDEE

- Accurate modelling from simple TGF assumption
- N = Fermi detectors total count
- Estimation of the photon number required at source $n_{\gamma,src}$: strong events
- 090813 needs adjusting $\sigma_{t,src}$
- 091214 : X 5 statistics and double peak

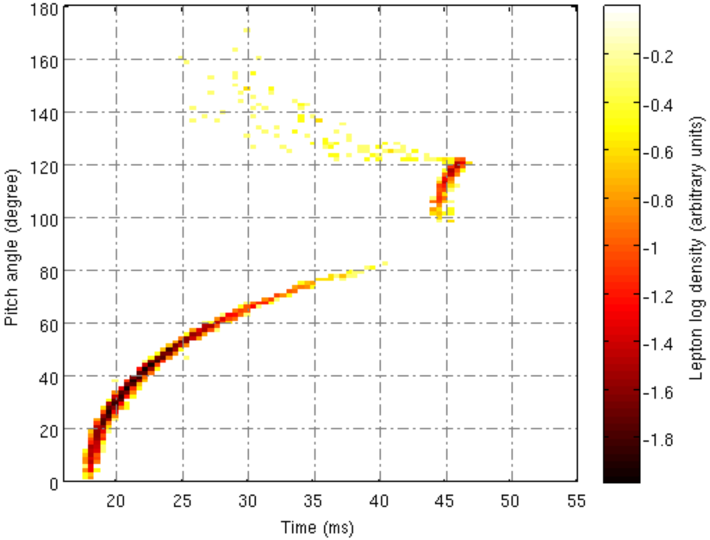
Detection at 400 km



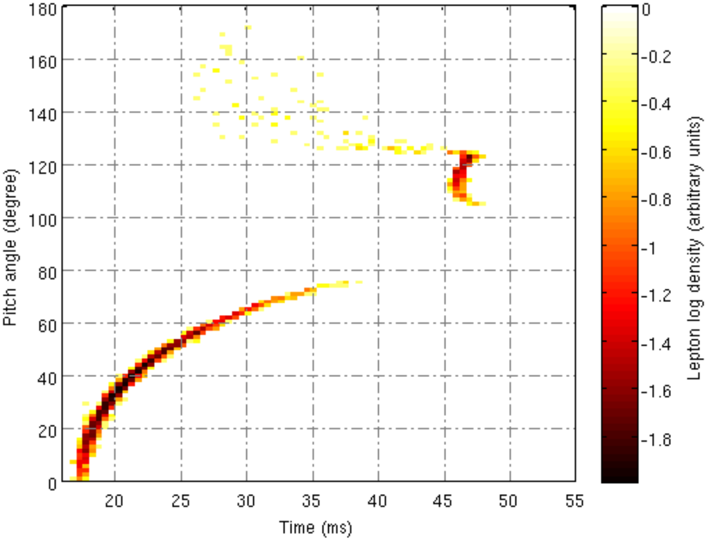
Detection at 550 km



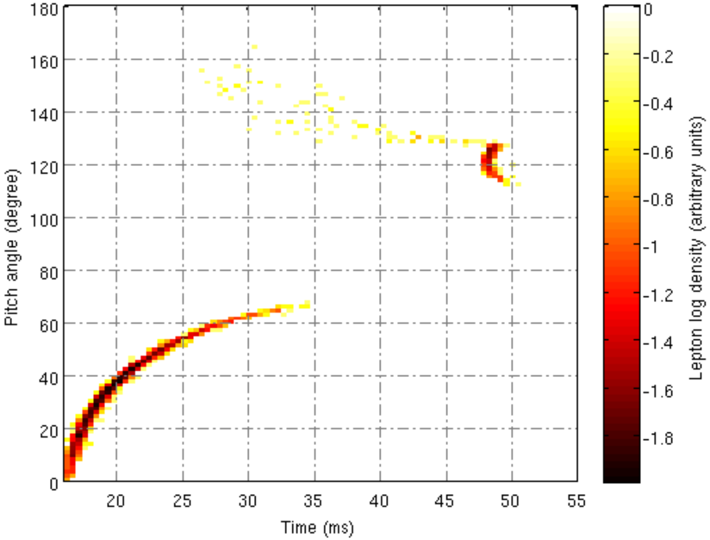
Detection at 620 km



Detection at 700 km

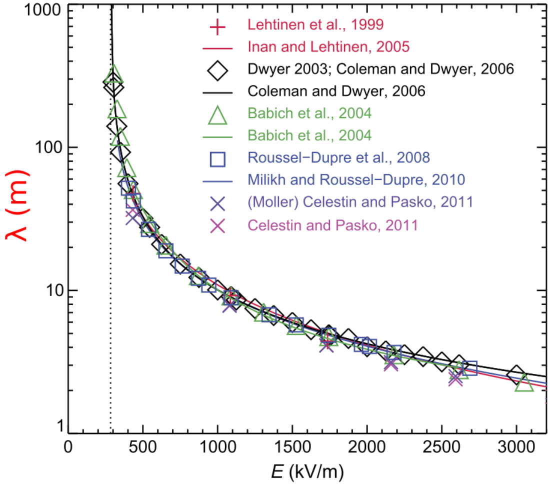


Detection at 850 km



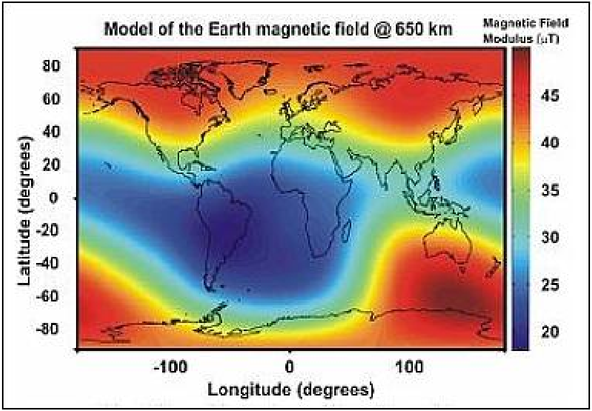
- $\sim 10^{19}$ e^- produced (above 10 keV),
- Effects of this massive production ?
- $\sim 10^{14}$ can escape, all produced above $\approx$ 30 km
- e^- production non-negligible up to 100 km, neglected above 60 km in previous works.
- Below 70 km, e^- production dominated by Compton scattering
- Above 70 km : 50% Compton scattering, 50% inelastic scattering
- e^+ lower average production altitude ($\approx$48 km vs $\approx$53 km)

RREA : Relativistic Runaway Electron Avalanche (2/2)

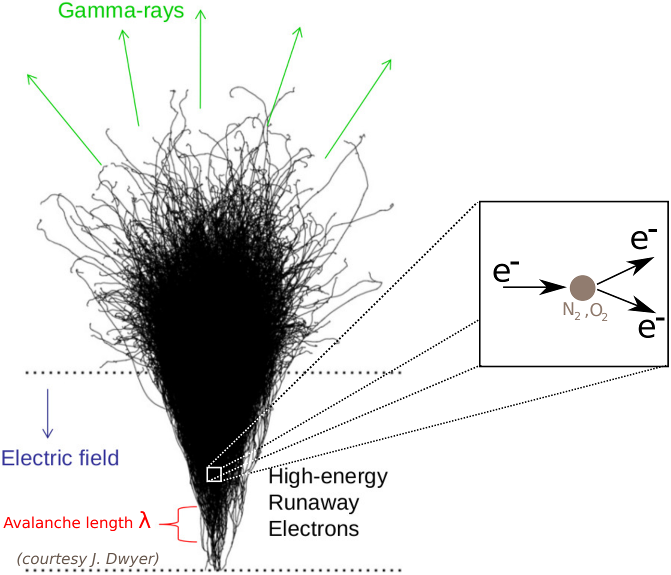


(adapted from Dwyer et al, 2012)

RREA : Relativistic Runaway Electron Avalanche (2/2)



RREA : Relativistic Runaway Electron Avalanche (1/2)



Conclusions

- We built the MC-PEPTITA model of propagation of $\gamma, \mathrm{e}^-, \mathrm{e}^+$ on Earth :
  - Accounts for all the relevant physics
  - Access to a lot of new information
  - Accurate, fast
- Applications of the model :
  - Energetic decomposition of $\gamma, \mathrm{e}^-, \mathrm{e}^+$
  - Spatial properties of $\mathrm{e}^-, \mathrm{e}^+$ beams
  - Simulation of Fermi events
  - Pitch angle decomposition of $\mathrm{e}^-, \mathrm{e}^+$ time histogram.
  - Method of estimating the satellite's position within the TEB (not discussed here).
  - Determining geographical positions where we may or may not see the mirror pulse for TEBs (not discussed here).
- Made in preparation for the TARANIS mission, featuring :
  - Simultaneous measurement of transient events in X/γ, optical, and radio.
  - X/γ photons and high-energy electrons (XGRE)
  - Electrons on a large energy range, with pitch angle estimation (IDEE).