Transport of *high energy photons* in the *atmosphere*

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Atmospheric Electricity and Hard Radiation from Thunderclouds
Research School
May 23rd, 2019

Suggested reads

- *Article:* Dwyer, J. R. (2003), **A fundamental limit on electric fields in air** (Geophysical Research Letters)
- *Article:* Dwyer, J. R., Smith D. M. (2005) **A comparison between Monte Carlo simulations of runaway breakdown and terrestrial gamma-ray flash observations** (Geophysical Research Letters)
- *Article:* Østgaard, N., Gjesteland, T., Stadsnes, J., Connell, P. H. and Carlson B. (2008), **Production altitude and time delays of the terrestrial gamma flashes : Revisiting the BATSE spectra** (Journal of Geophysical Research)
- *Article:* Sarria, D., Blelly, P.-L. and Forme, F. (2015), **MC-PEPTITA: a monte carlo model for photon, electron and positron tracking in terrestrial atmosphere. Application for a terrestrial gamma-ray flash** (Journal of Geophysical Research)
- *PhD Thesis:* Lehtinen, N. G. (2000), **Relativistic Runaway Electrons Above Thunderstorms**
  - in particular, section 3.2
- *PhD Thesis:* Xu, W. (2015), **Monte Carlo Simulation of Terrestrial Gamma-ray Flashes Produced By Stepping Lightning Leaders**
  - in particular, section 2.3
- *PhD Thesis:* Carlson, B.E. (2009), **Terrestrial Gamma-ray Flash Production By Lightning**
  - in particular, chapter 3
- *Book:* Kalos, M. H., Whitlock, P. A. (2008), **Monte Carlo methods.**
- *Book:* Salvat, F., Fernández-Varea J. M. , and Sempau J. (2011), **PENELOPE-2011 : A Code System for Monte Carlo Simulation of Electron and Photon Transport**
- *You can also check and try a freely available Geant4-based model of TGF/TEB propagation in Earth's atmosphere here:* https://doi.org/10.5281/zenodo.2597039

Outline

1. Introduction:
    - motivation
    - the atmosphere

2. High energy particle transport in the atmosphere
    - the Monte-Carlo approach
    - processes
    - path sampling
3. Results :
    - TGF duration
    - Terrestrial Electron Beams

Motivation

Why modeling transport of high energy γ, (and e-, e+) in the atmosphere ?

1. **Terrestrial Gamma-Ray Flash** (TGF) propagation
    - detected from space (or ground), but altered
    - constraints from spectral fit (production altitude, beaming)
    - time scattering, infer TGF intrinsic duration
    - energy deposition
    - radioactive dose (airplanes)
    - production of isotopes
    - input for models of optical emissions

2. **Gamma-ray glows** (GRG)
    - energy deposition
    - constraints

The protagonists

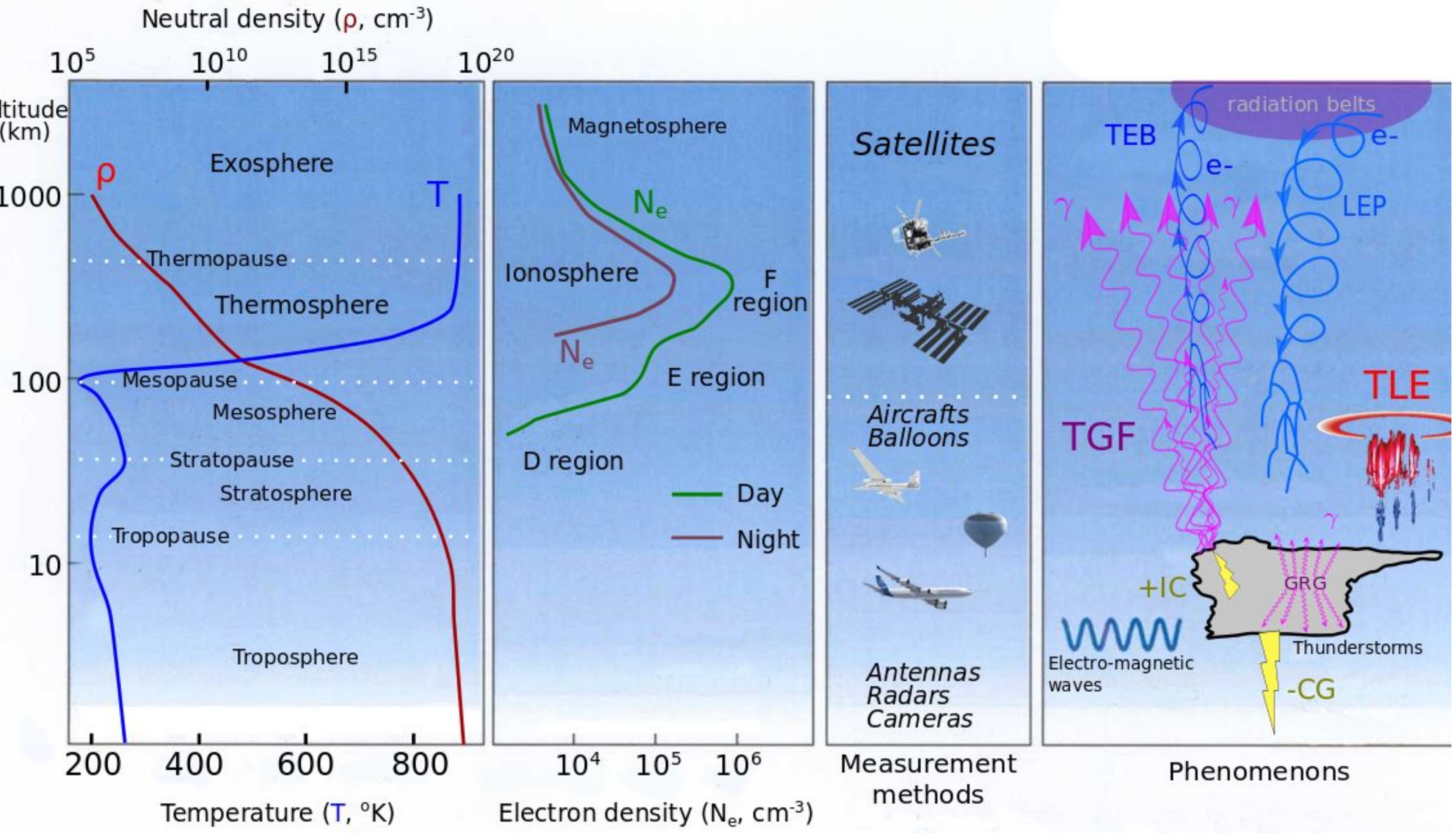
γ = high energy (>10 keV) photon

- no charge
- no mass

+ electron (e-) and positron (e+)

- ***Electro-magnetic particles***
  - e- or e+ can produce γ (bremsstrahlung)
  - γ can "kick-out" e- from molecules (Compton, Photo-electric)
  - γ can be converted to a e- e+ pair ($E=mc^2$) (pair production)

The stage



~80% N_2 and ~20% O_2

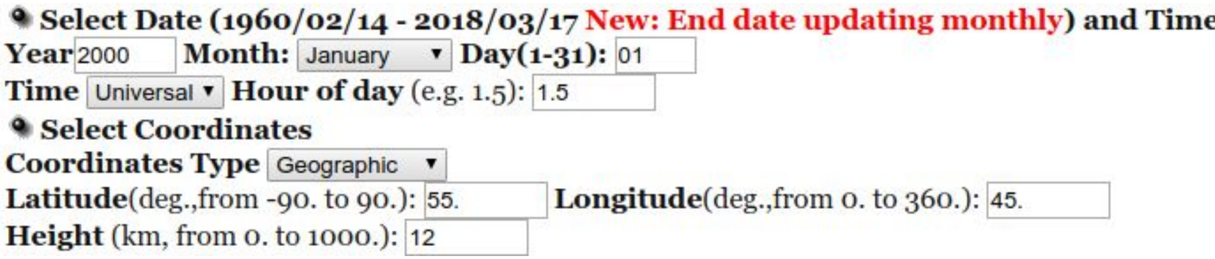
Atmosphere: **NRL-MSISE-00** model

- To get compositions, temperature, as function of altitude
- **NRL-MSISE-00** is reference, state-of-the-art atmospheric model
- From NRL (Naval Research Lab.), *[Picone, J. M. et al., 2002]*
- MSIS = **M**ass **S**pectrometer and **I**ncoherent **S**catter radar
    - two primary data sources of earlier versions
- **Empirical** (=based on measurement data), from:
    - mass spectrometers
    - incoherent scatter radar
    - satellite missions
    - balloon sounding
    - some measurement from Space Shuttle

The NRL-MSISE-00 model

How to *quickly* get *atmosphere's composition and density* ?

- Go to https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php
  (alternatively, type *"NRL MSISE 00"* on google")
- Choose time, coordinates:



Select Date (1960/02/14 - 2018/03/17 New: End date updating monthly) and Tim

Year 2000 **Month:** January ▾ **Day(1-31):** 01

Time Universal ▾ **Hour of day** (e.g. 1.5): 1.5

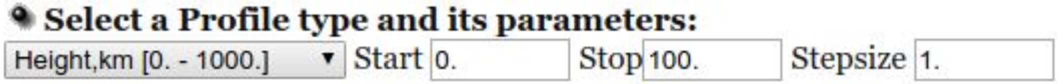
Select Coordinates

Coordinates Type Geographic ▾

Latitude(deg.,from -90. to 90.): 55. **Longitude**(deg.,from 0. to 360.): 45.

Height (km, from 0. to 1000.): 12

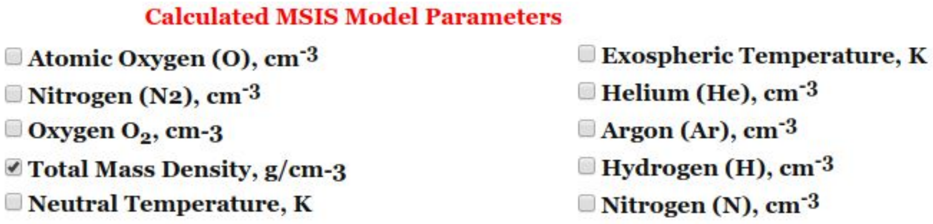
- Choose height (~altitude) grid: range and step:



Select a Profile type and its parameters:

Height,km [0. - 1000.] ▾ Start 0. Stop 100. Stepsize 1.

- Let height as the only independent variable
- Choose which quantity you want as function of height, and press enter.



Calculated MSIS Model Parameters

☐ **Atomic Oxygen (O), cm^{-3}**
☐ **Nitrogen (N2), cm^{-3}**
☐ **Oxygen O_2, cm-3**
☑ **Total Mass Density, g/cm-3**
☐ **Neutral Temperature, K**
☐ **Exospheric Temperature, K**
☐ **Helium (He), cm^{-3}**
☐ **Argon (Ar), cm^{-3}**
☐ **Hydrogen (H), cm^{-3}**
☐ **Nitrogen (N), cm^{-3}**

The NRL-MSISE-00 model

Disclaimer:

- this is "quick and dirty" use.
- Python, Matlab, Fortran and C implementation are available for more serious use. See:
  https://github.com/scivision/msise00

The NRL-MSISE-00 model

Using online run of NRL-MSISE-00:

Altitude (km)	Air density (g/m^3)
~0	1200
~20	92.47
~80	0.01678

10^6 g/m^3 = 1 g/cm^3

(latitude = 25 deg, longitude = 0 deg)

- **<u>Question :</u>** Which one of these functions is a good approximation for the air density as function of altitude ?
  - Linear : $\rho(h) = b*h + a$
  - Power law : $\rho(h) = b*h^a$
  - Exponential : $\rho(h) = b*\exp(-h/a)$

b, a = parameters
h = altitude
d = air mass density

Remark : convenient to use the column density of air to cross from a given altitude before reaching space (in g/cm^2)

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Tutorial: the NRL-MSISE-00 model

$a \approx$ 7.6 km

- a is the characteristic height scale ("scale height") of the atmosphere density:
  - each time altitude is increase by a, density is decreased by a factor of $e \approx 2.7$
  - **>90% of the atmosphere is contained within 80 km**

- Alternatively : $a = \dfrac{RT}{Mg}$,can be found assuming:
  - *air is an ideal gas*
  - *a local hydrostatic equilibrium*

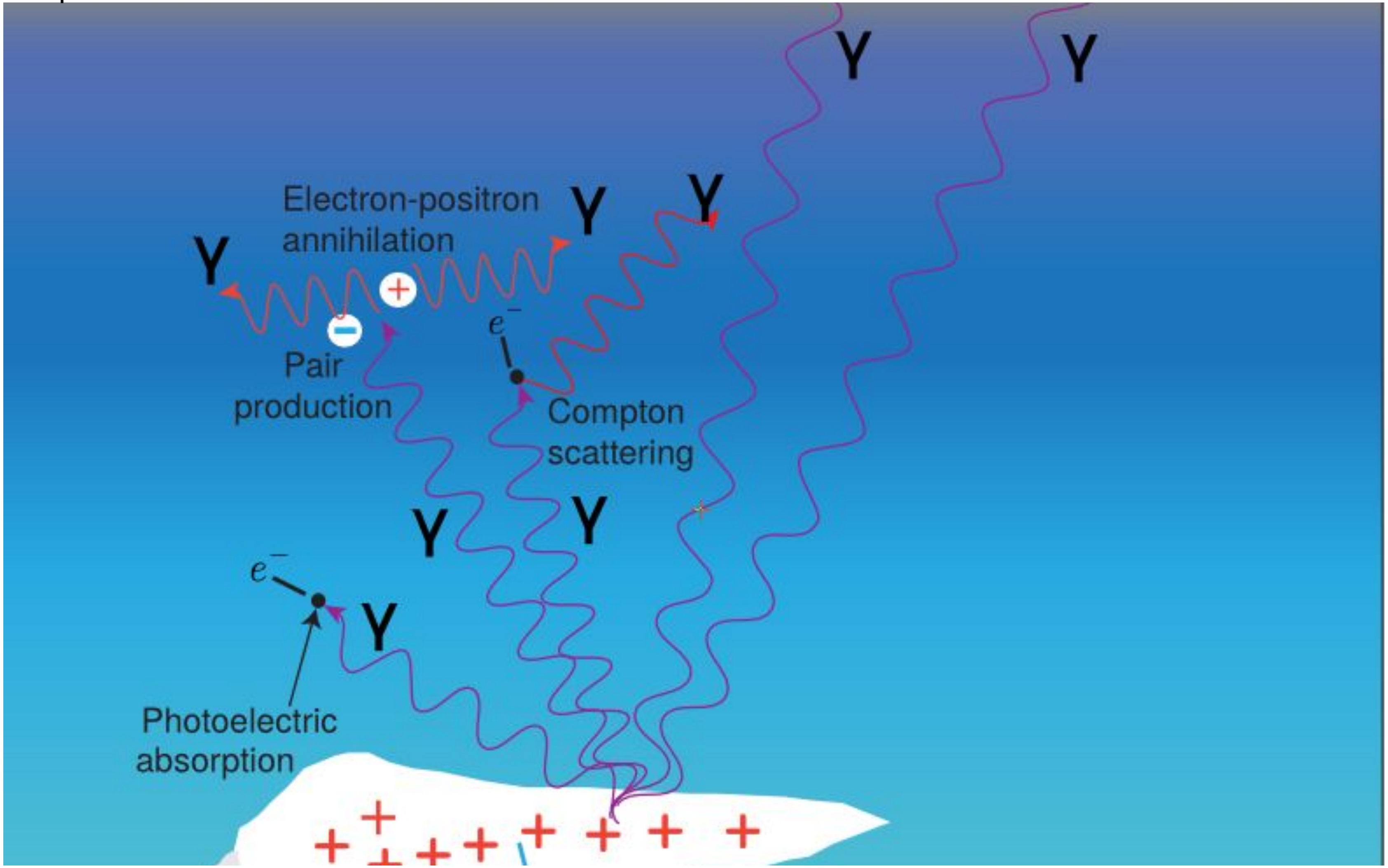
  - T = average neutral air temperature ≈ 260 K, below 80 km altitude
  - R = ideal gas constant = 8.314 SI
  - M = molar mass of air = 0.0290 kg/mol
  - g = gravitational acceleration = 9.81 m/s^2

- **Photons: atmosphere** is **negligible above ~80-100 km**
- **Electrons: atmosphere** is **negligible above ~120-150 km**

The Monte-Carlo approach

High energy Photon propagation in atmosphere

adapted from W. Xu dissertation



Particle transport: Monte-Carlo approach

- **Monte-Carlo dominates the works done for high energy particle transport in this atmosphere**

- **each interaction is random, based on probability distributions**

- **Each process has his own Total Cross Section** (function of energy and target material), that can be **interpreted as probability distribution** if normalized:

Notation: $\sigma_i(E_1)$

primary particle energy

unit of area (e.g., m^2 , barn)
1 Barn = 10^{-28} m^2

- Concept inherits from classical physics (e.g. Thomson scattering ≈ low energy Compton)

- Each process has one or several ***Differential* Cross Sections** (in angle and in energy of secondary, primary, ...) **interpreted as a probability** of scattering at given angle, of losing a given amount of energy, etc...

secondary particle energy

scattering angle

Examples:

$$\frac{d\sigma_i\left(E_1, E_2\right)}{dE_2} \qquad \frac{d\sigma_i\left(E_1, \theta\right)}{d\theta} \qquad \frac{d^2\sigma_i\left(E_1, E_2, \theta\right)}{d\theta dE_2}$$

Particle transport: Monte-Carlo approach

- **Fully analytical models available** for some processes (e.g. Compton scattering, pair production) **under some assumptions**,
    - usually valid for energies above ~10 keV
    - usually only DCS formula is known, total DC from numerical integration
    - usually fast and good enough

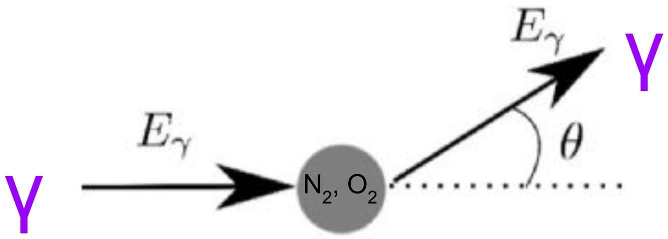
- **The most precise cross-sections** are **based on experimental databases**
    - Good reference for electro-magnetic particles are
        - **EPDL: E**valuated **P**hoton **D**ata **L**ibrary
        - **EEDL**: **E**valuated **E**lectron **D**ata **L**ibrary
            - from Lawrence Livermore national laboratory

Sophisticated numerical techniques to sample accurately and quickly from tabulated probability densities:

- e.g., Rational Inverse Transform with Aliasing *[PENELOPE, Salvat, F. et al., 2011]*

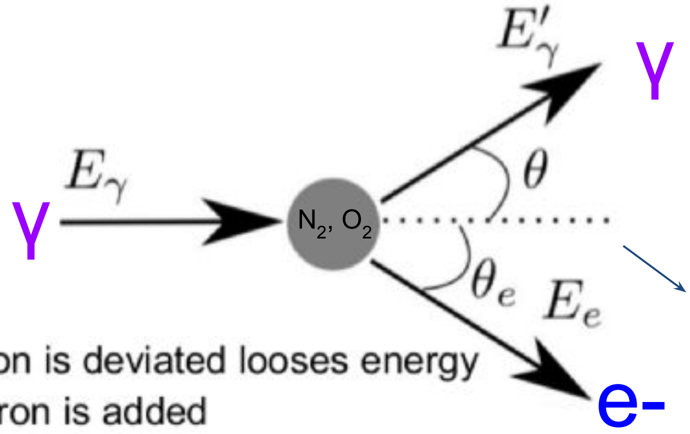
Processes : photons

Coherent (Rayleigh) scattering



- Only deviation, no energy change

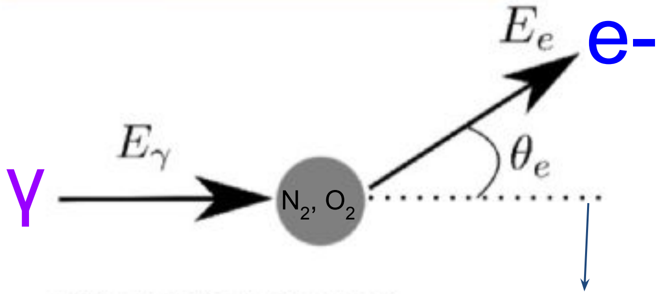
Incoherent (Compton) scattering



ionization

- Photon is deviated looses energy
- Electron is added

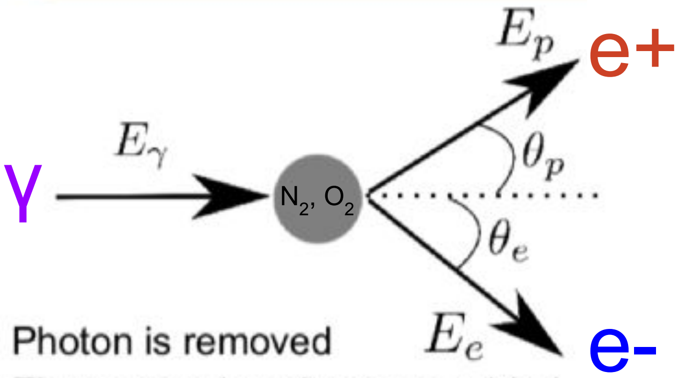
Photo-electric absorption



ionization

- Photon is removed
- Electron is added

Electron/positron pair production



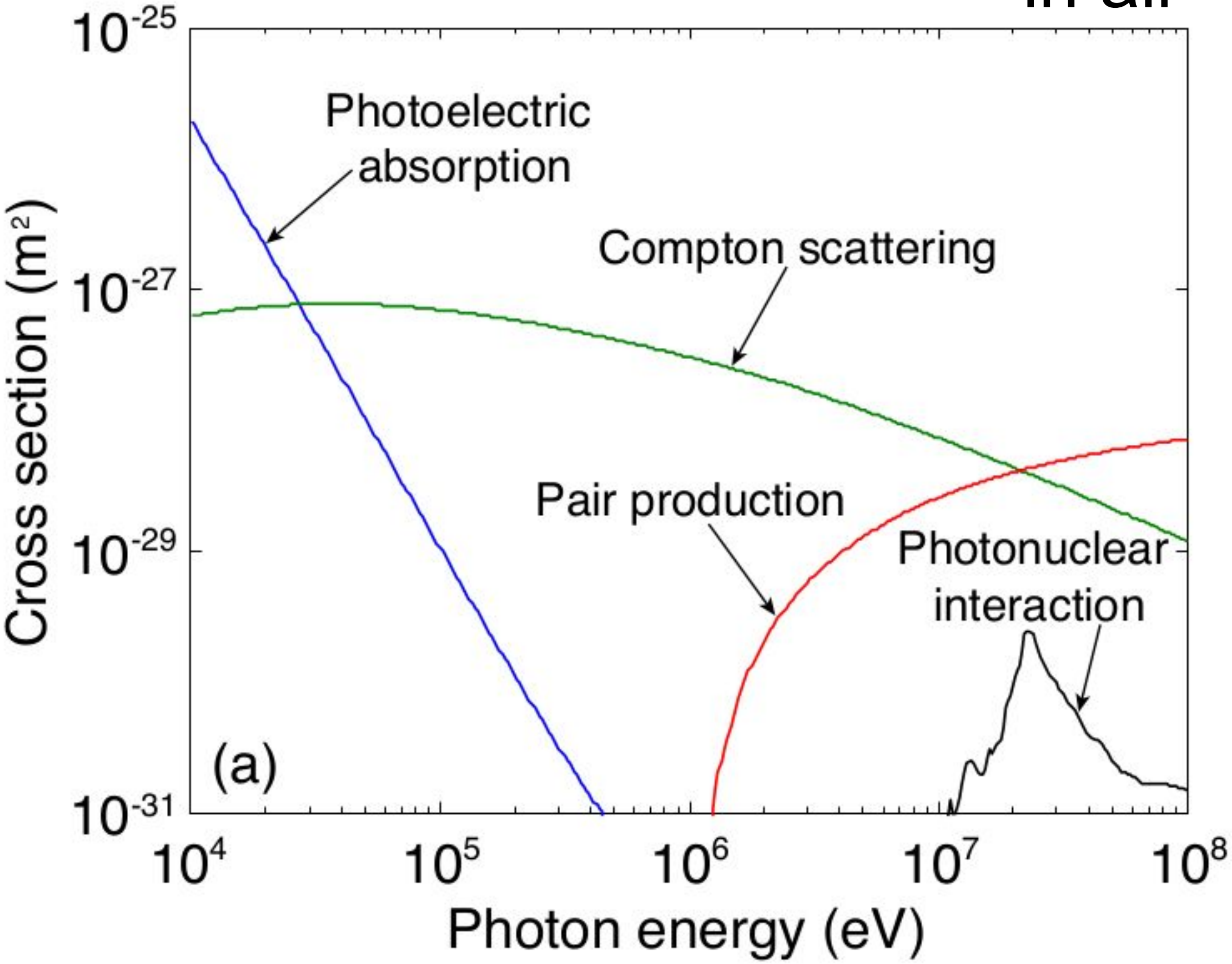
- Photon is removed
- Electron and positron are added

- Photonuclear reactions may also be considered, but attenuation to flux is negligible
- photon "breaks" atomic nuclei -> production of neutrons and isotopes

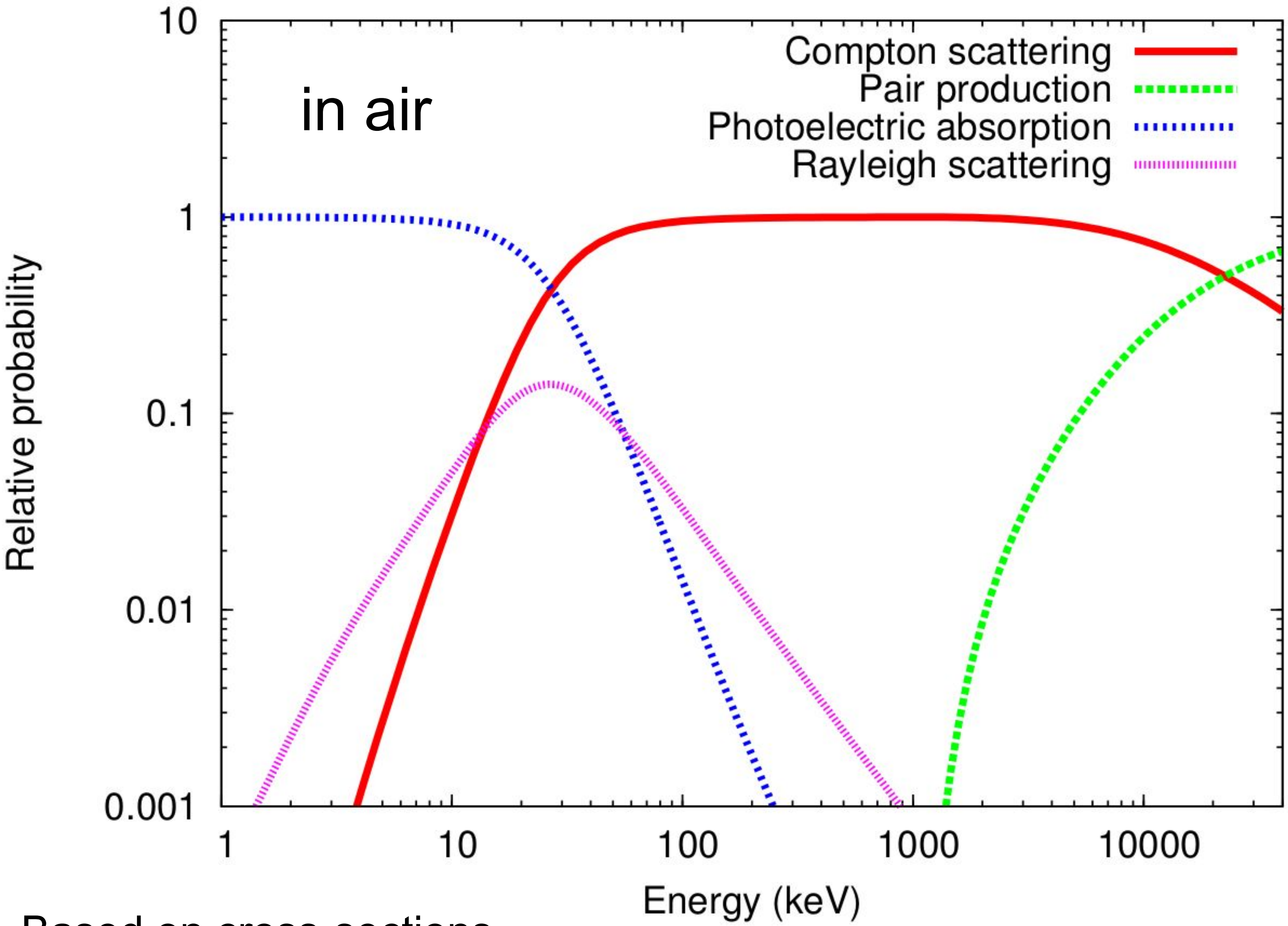
Processes : photons, relative probability

(adapted from W. Xu Phd thesis)

in air



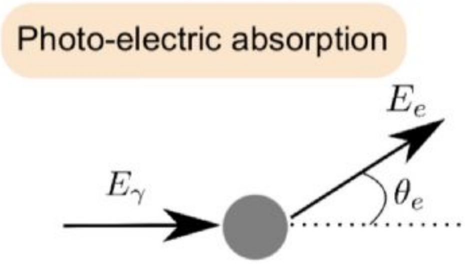
Processes : photons, relative probability



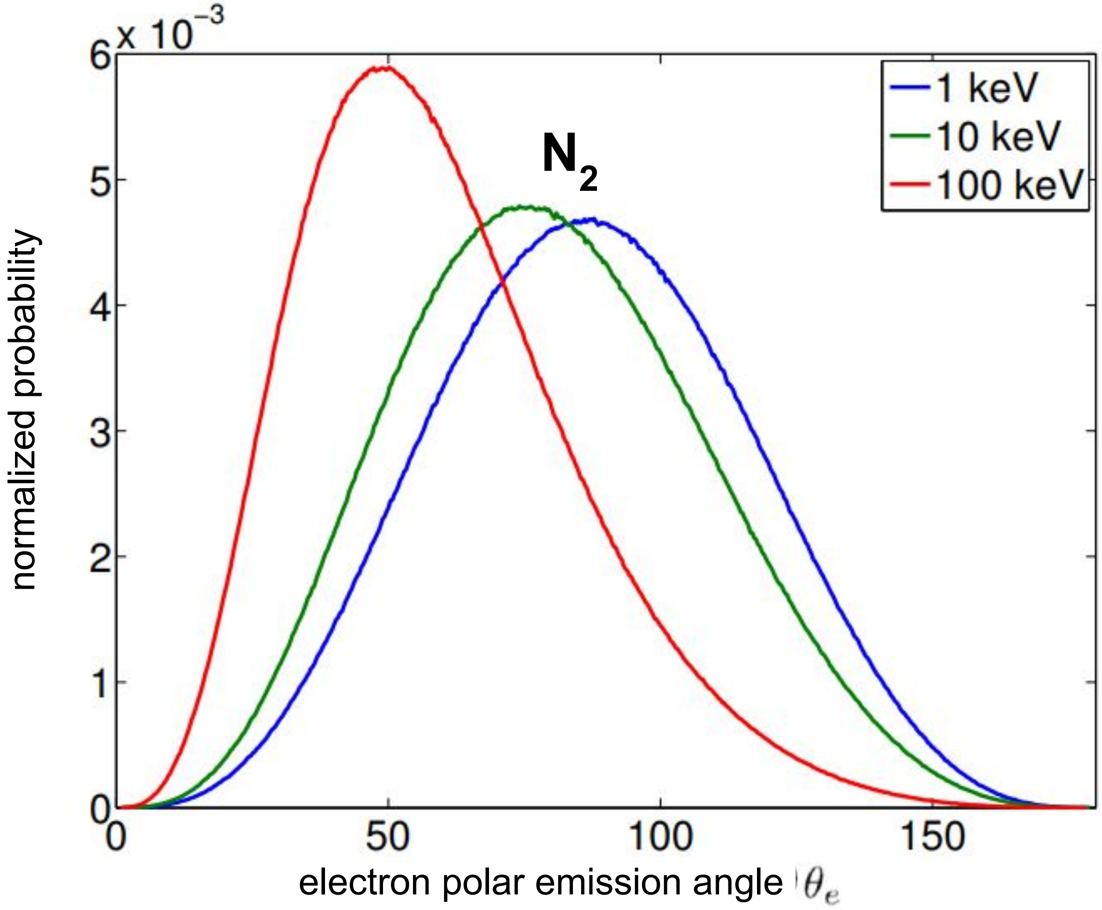
- Based on cross-sections
- Rayleigh scattering is usually neglected

Photo-electric absorption

- Negligible above ~200 keV in air (higher energies for heavier materials, depends on atomic number)



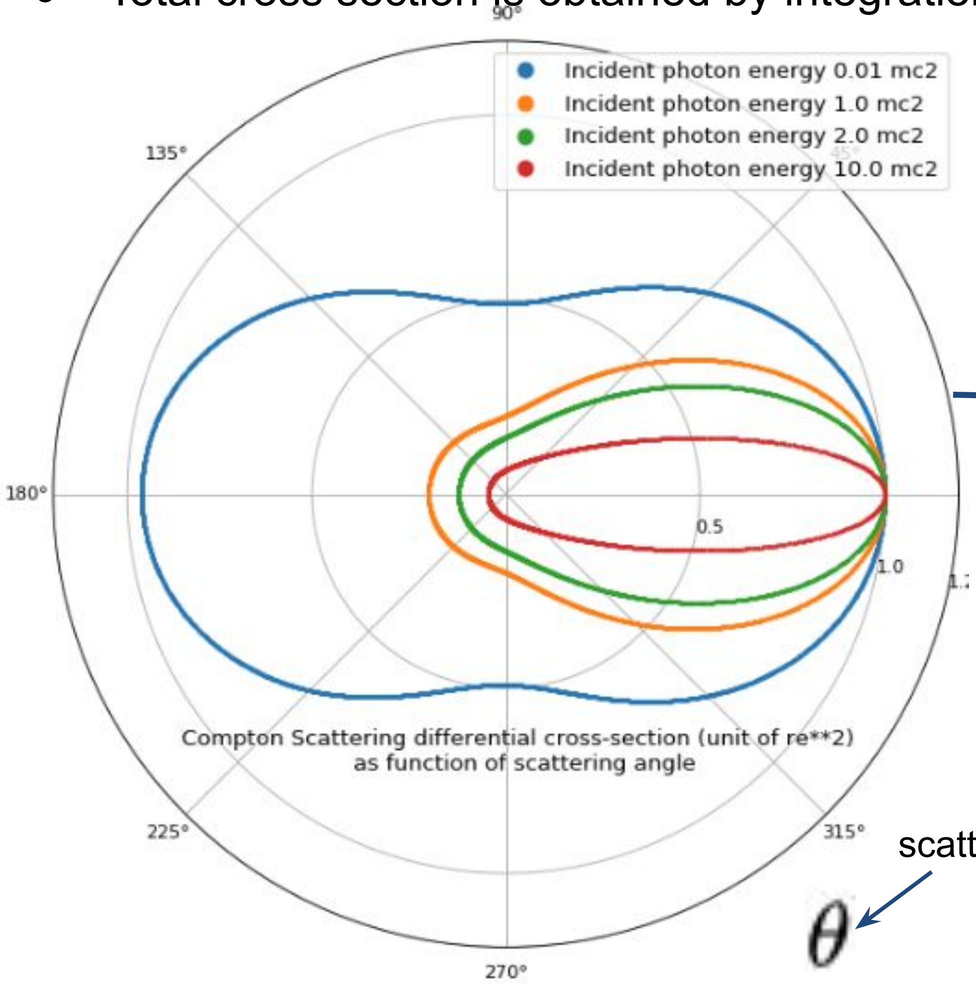
- Photon is removed
- Electron is added

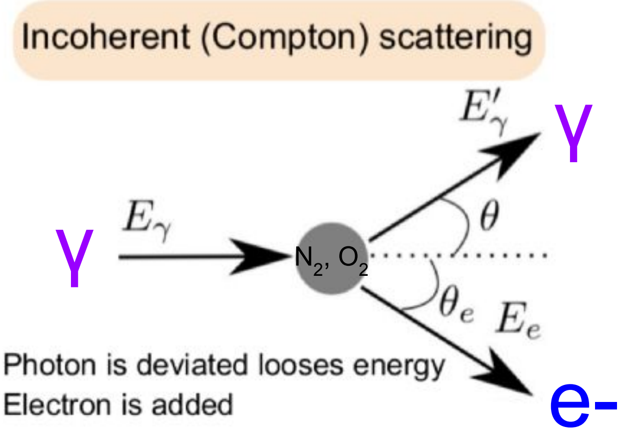


Uses Cross-section from PENELOPE model

Compton scattering

- **Klein-Nishina** Differential cross section (QED) [*Heitler, 1954, p. 219 or N. Lehtinen PhD thesis, p. 52, for a description in this context*]
- Assumes free electron at rest (ok if E > ~300 keV)
- Total cross section is obtained by integration





- Photon is deviated looses energy
- Electron is added

→ More energy, more forward scattering

Strategy to simulate:

- Use DCS to sample an angle
- Ratio of γ energy after/before scattering:

$$P(E_\gamma, \theta) = \frac{1}{1 + (E_\gamma / m_e c^2)(1 - \cos\theta)}$$

scattering angle

θ

- Electron angle and energy deduced from **conservation of energy and momentum**

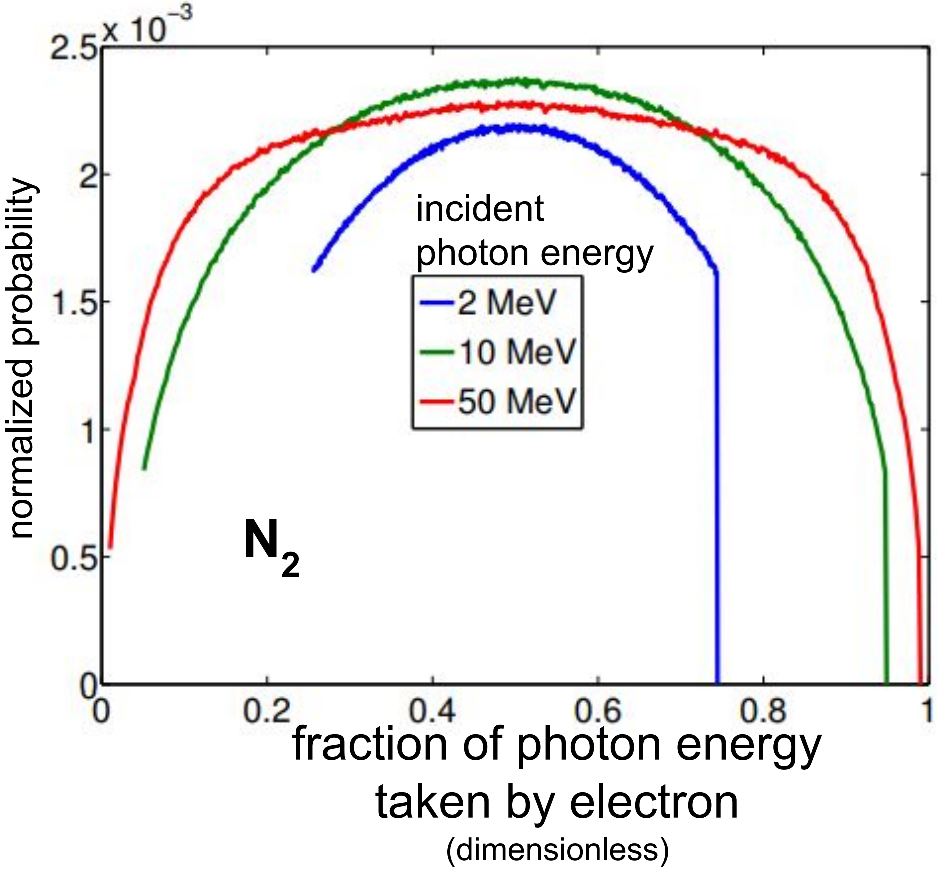
Compton scattering

Interactive visualisation of the Klein-Nishina cross section and photon/electron scattering angles:

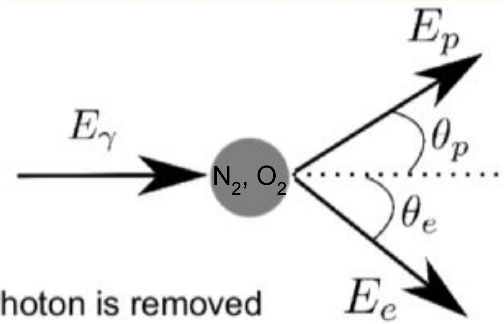
https://demonstrations.wolfram.com/KleinNishinaFormulaForComptonEffect/

Electron/positron pair production

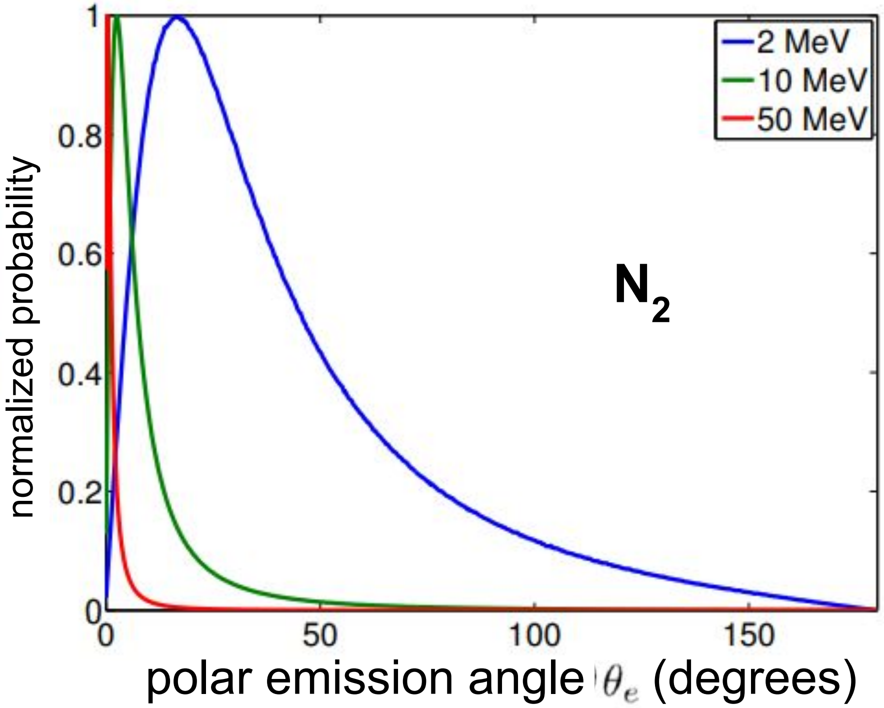
Example with PENELOPE model cross-sections:



Electron/positron pair production

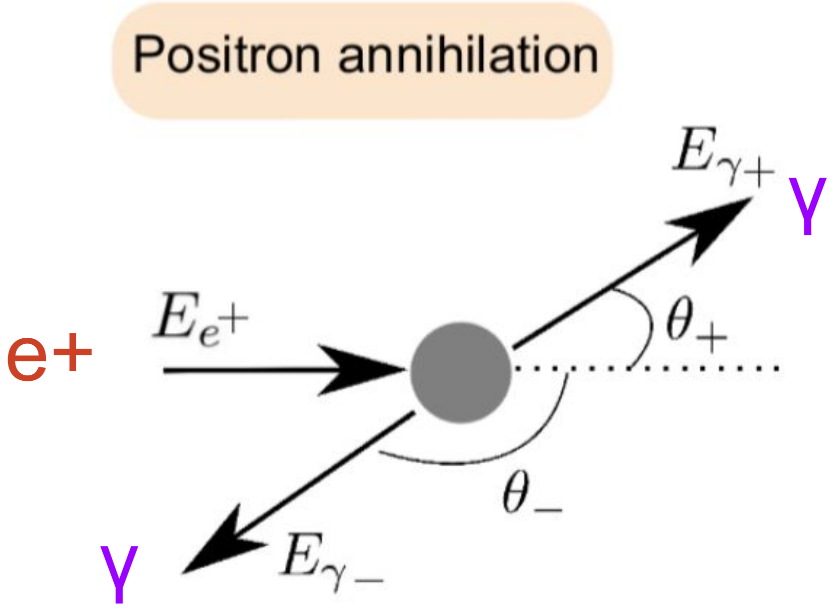


- Photon is removed
- Electron and positron are added



- *The positron will then annihilate !*

Extra process for e+

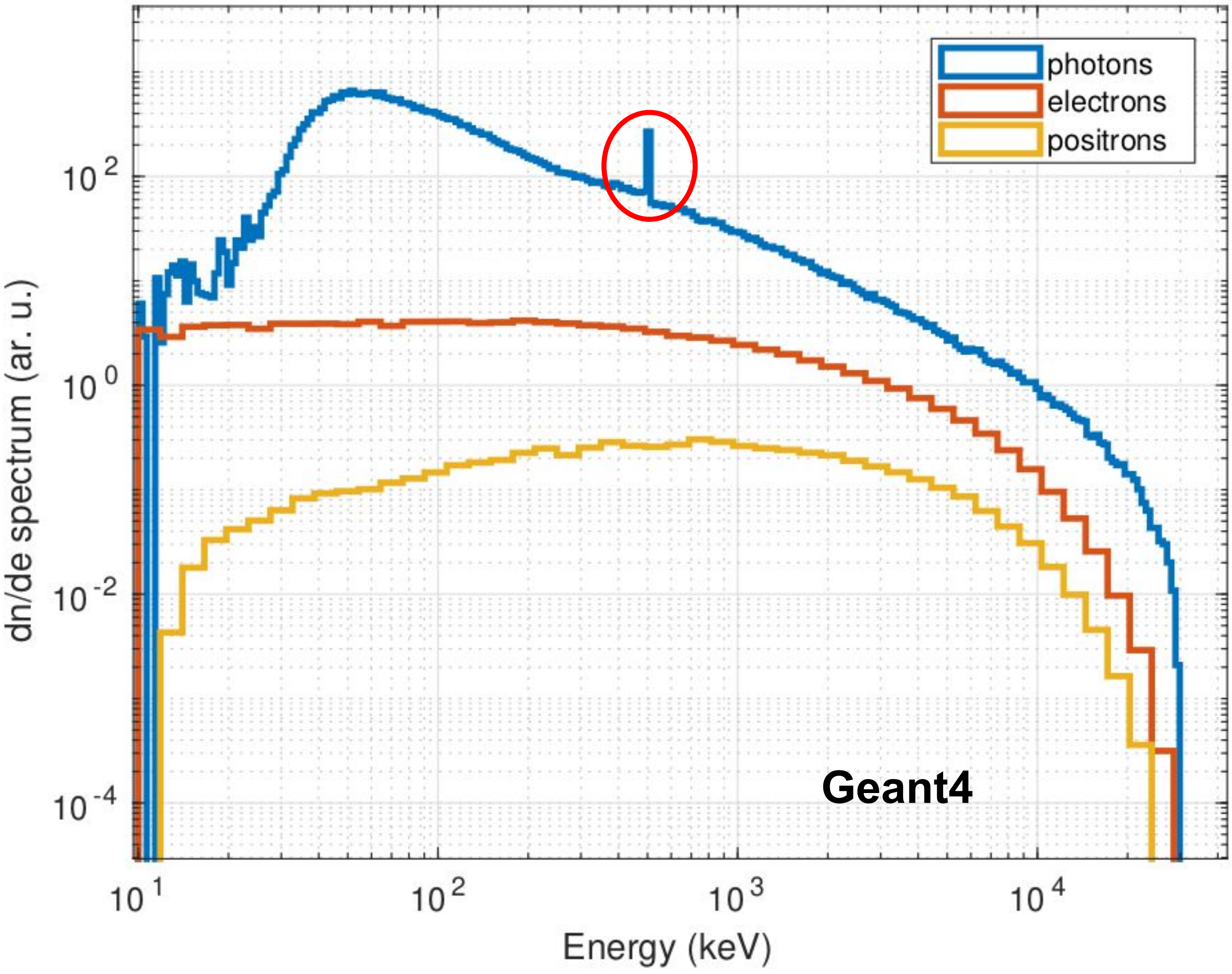


- "In-flight" (i.e. with kinetic energy > keV) annihilation is very unlikely
- **first, the positron has to lose almost all its kinetic energy**
- then encounters an electron and enters in a positronium phase
- In a dense medium, annihilation only after para-positronium phase

$\rightarrow$ e^-/e^+ annihilation into 2 photons with $E_{\gamma+} \approx E_{\gamma-} \approx 511$ keV

with opposite momentums

Typical spectra after escaping atmosphere



Average effect

- **Exponential attenuation** of the γ flux of energy *E* along path

actual position

initial position

$$I(\mathbf{r}) = I(\mathbf{r} = \mathbf{r_0}) \boxed{\exp\left(-\delta_{opt}\right)}$$

optical depth

$$\delta_{opt} = \int_{\mathbf{r_0}}^{\mathbf{r}} \Lambda\left(E, \mathbf{r}'\right) d\mathbf{r}'$$

Total nitrogen cross-section

Total oxygen cross-section

linear attenuation coefficient

$$\Lambda\left(E, \mathbf{r}'\right) = 2\, N_{N_2}\left(\mathbf{r}'\right)\, \sigma_N^{tot}\left(E\right) + 2\, N_{O_2}\left(\mathbf{r}'\right)\, \sigma_O^{tot}\left(E\right)$$

N_2 number density

O_2 number density

- Argon is neglected here
- At high altitudes, other elements can be added (atomic)
- **γ go through air much more easily than e-/e+** (i.e. γ has lower cross-sections)
  - Typically, **γ can travel ~100 times farther in air than e-/e+ before absorption**

Moving particles between collisions

- **Two different techniques :**
  - **fixed time steps** (small enough, usually nanosecond scale)
    - null collisions, time synchronous
    - better for simulations including electric field
    - mandatory if one want to include the effect of electrons on electric field (space charge)
    - See e.g. open source code from A. Luque
      - GRanada Relativistic Runaway (GRRR)
      - https://github.com/aluque/grrr
  - **direct calculation of distance between interactions**
    - non-time synchronous, higher energies first
    - cheaper in CPU
    - more efficient for atmospheric propagation (no E-field)
    - **presented next**

Sampling path length between collisions

- **Particles are moved step by step, and do interaction at end of each step**

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

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

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

↙

Between 0 and 1

- A **key** of Monte-Carlo modeling is to **inverse this function** in order **to find a formula to sample a particle's path length between two collisions**

Exercice

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

probability of not
interacting after distance *s*

A particle has a mean free path λ in air
Let ξ be a random number between 0 and 1, representing P(s)

Find a formula to sample a path length between two interaction, for two cases:

a) Assuming the density is constant.

b) Assuming the density follows an exponential evolution with altitude (like in the atmosphere) : $n(h) = n_0 * \exp(-h/a)$

Exercice: solutions

a) $$s = -\lambda \ln\left(\xi\right)$$

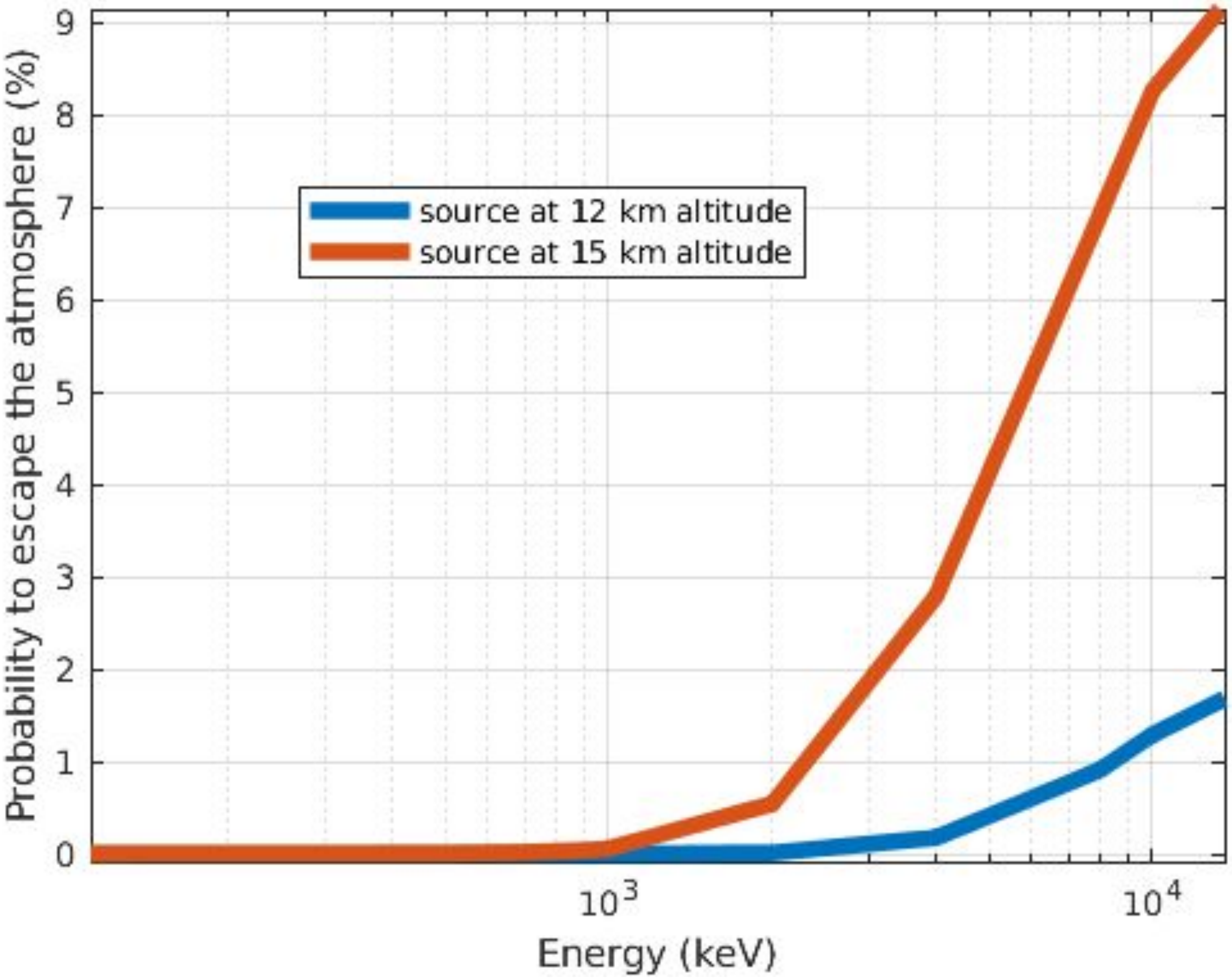
b) $$s = \frac{-a}{\cos\left(\alpha\right)} \ln\left(1 + \lambda_0 \ln\left(\xi\right) \frac{\cos\left(\alpha\right)}{a}\right)$$

α = angle between particle's direction and zenith's direction

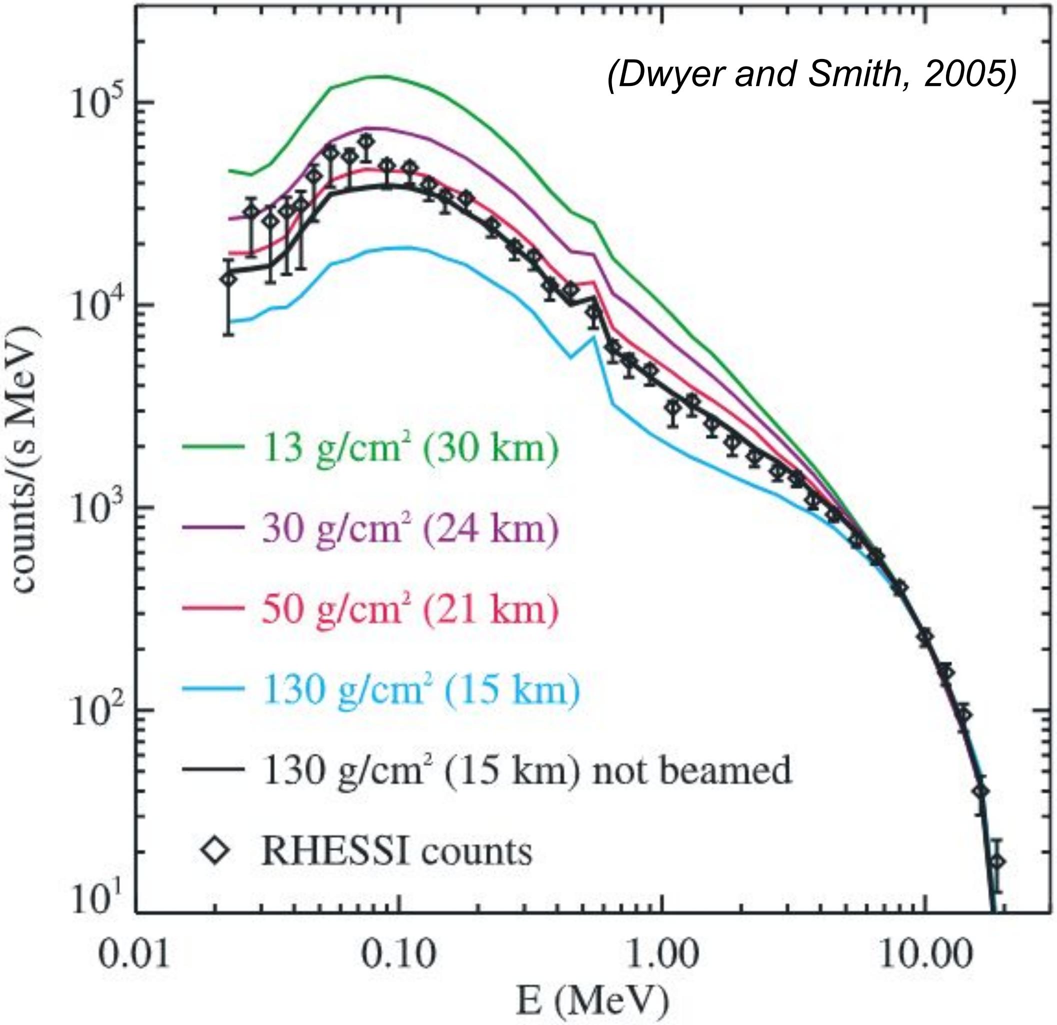
- **This formula permits to *quickly* compute the distance between collisions in the atmosphere**
  (Østgaard et al., 2008)

Some Results

Probability of HE photons to reach space



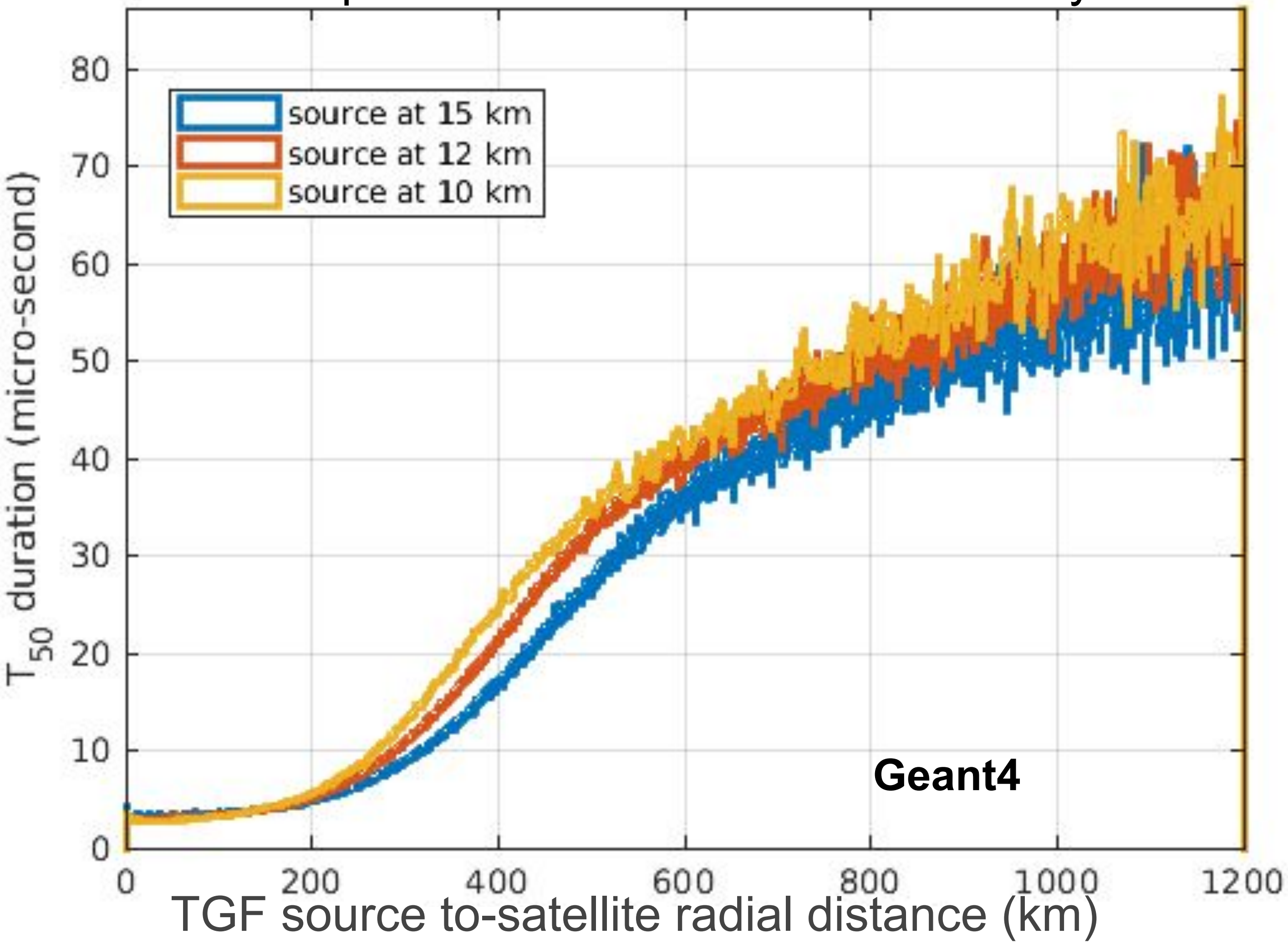
TGF production altitude



- Forward modeling
- Later, down to **10-15 km** (updated RHESSI, AGILE, Fermi)

TGF duration and Compton scattering

- assumption: TGF emitted instantaneously



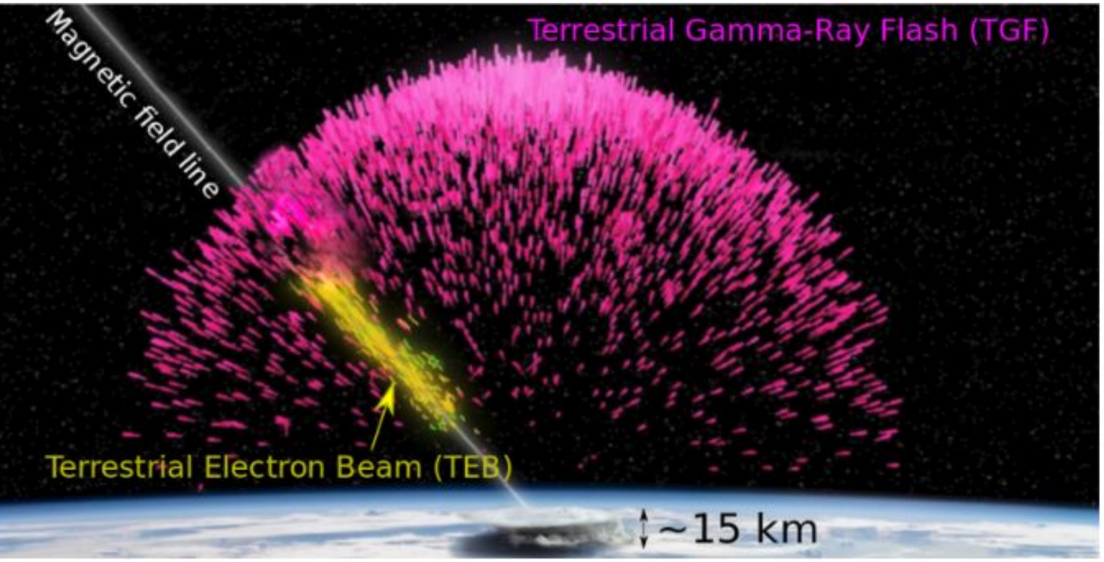
Observed TGF T_{50} ~ 40 us to 2 ms

-> TGFs must have intrinsic duration

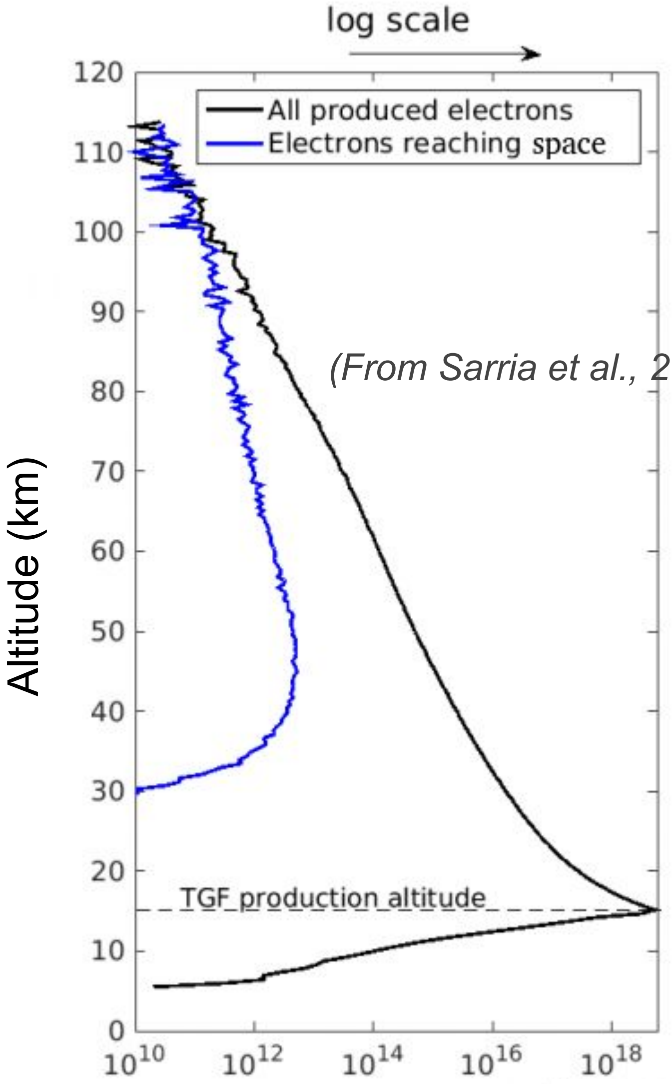
Introduction : Terrestrial Electron Beam

- Production of large amounts of
  - electrons (Compton scattering + pair production)
  - positrons (pair production)

- A small fraction can reach space : propagation in ionosphere, magnetosphere
  - **"beamed" by Earth's magnetic field**
  -> **T**errestrial **E**lectron **B**eam (**TEB**)
  - First report using BATSE data (*Dwyer et al., 2008*)
  - Then detected by Fermi, BeppoSAX, AGILE?, ASIM



Production rate altitude profile

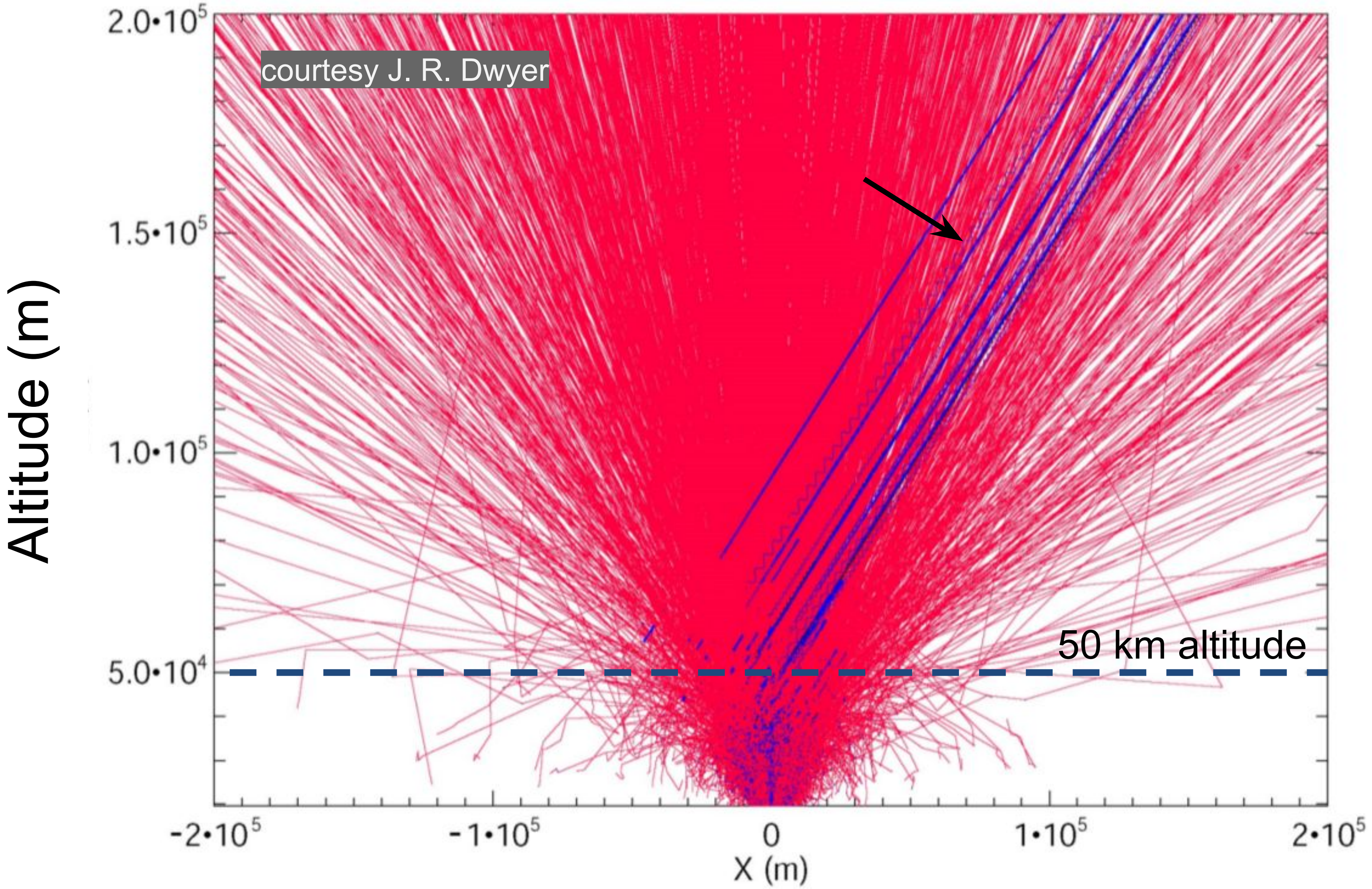


(From Sarria et al., 2015)

Electron number per km (>1 keV)
source of 10^{17} photons

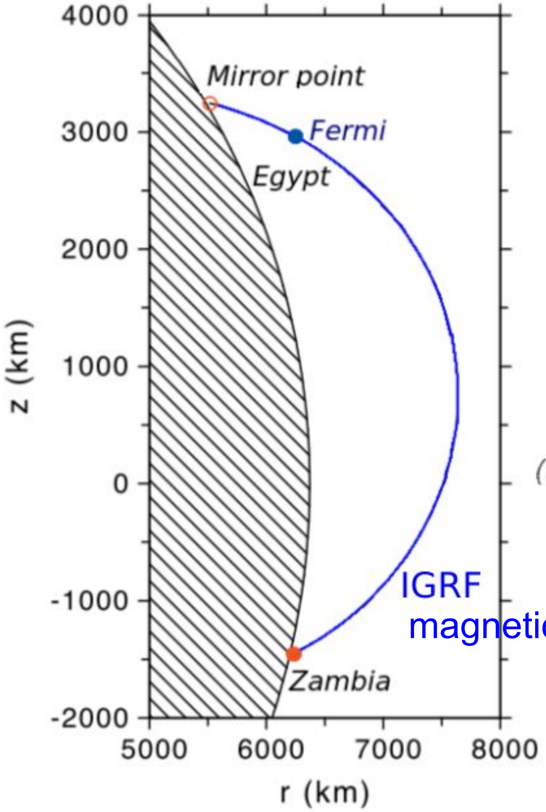
Photon and electron/positron trajectories

Photons in red, electrons in blue

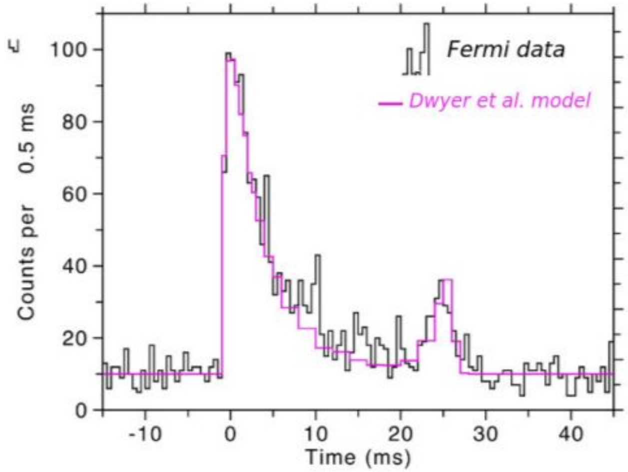


TEB example (Fermi)

TEB = Terrestrial Electron Beams (usually ~ 10% positron from pair production)

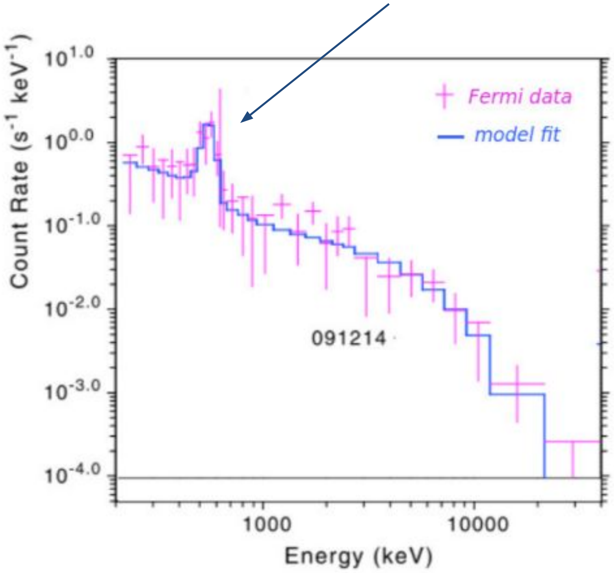


IGRF magnetic field line



(Briggs et al., 2011)

511 keV line !



- 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

Summary

- Simulating High energy particle transport in the atmosphere is useful to
    - interpret/analyse TGF detection by instruments from space (e.g. ASIM, Fermi), air or ground
    - Compute quantities for other models (optical emissions, chemistry) to estimate TGF effects on atmosphere, ionosphere and magnetosphere

- Monte-Carlo approach :
    - stochastic processes
    - cross-sections -> attenuation coefficients -> probability of interaction with path
    - differential cross-sections -> probabilities: scattering angle, energy loss, ...

- Results:
    - TGF production altitude (10-15 km)
    - TGFs must have intrinsic duration
    - Terrestrial Electron Beams, work to be done

Suggested reads

- *Article:* Dwyer, J. R. (2003), **A fundamental limit on electric fields in air** (Geophysical Research Letters)
- *Article:* Dwyer, J. R., Smith D. M. (2005) **A comparison between Monte Carlo simulations of runaway breakdown and terrestrial gamma-ray flash observations** (Geophysical Research Letters)
- *Article:* Østgaard, N., Gjesteland, T., Stadsnes, J., Connell, P. H. and Carlson B. (2008), **Production altitude and time delays of the terrestrial gamma flashes : Revisiting the BATSE spectra** (Journal of Geophysical Research)
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    - in particular, chapter 3
- *Book:* Kalos, M. H., Whitlock, P. A. (2008), **Monte Carlo methods.**
- *Book:* Salvat, F., Fernández-Varea J. M. , and Sempau J. (2011), **PENELOPE-2011 : A Code System for Monte Carlo Simulation of Electron and Photon Transport**
- *You can also check and try a freely available Geant4-based model of TGF/TEB propagation in Earth's atmosphere here:* https://doi.org/10.5281/zenodo.2597039

Thank you for your attention

Pitch angles / time distribution

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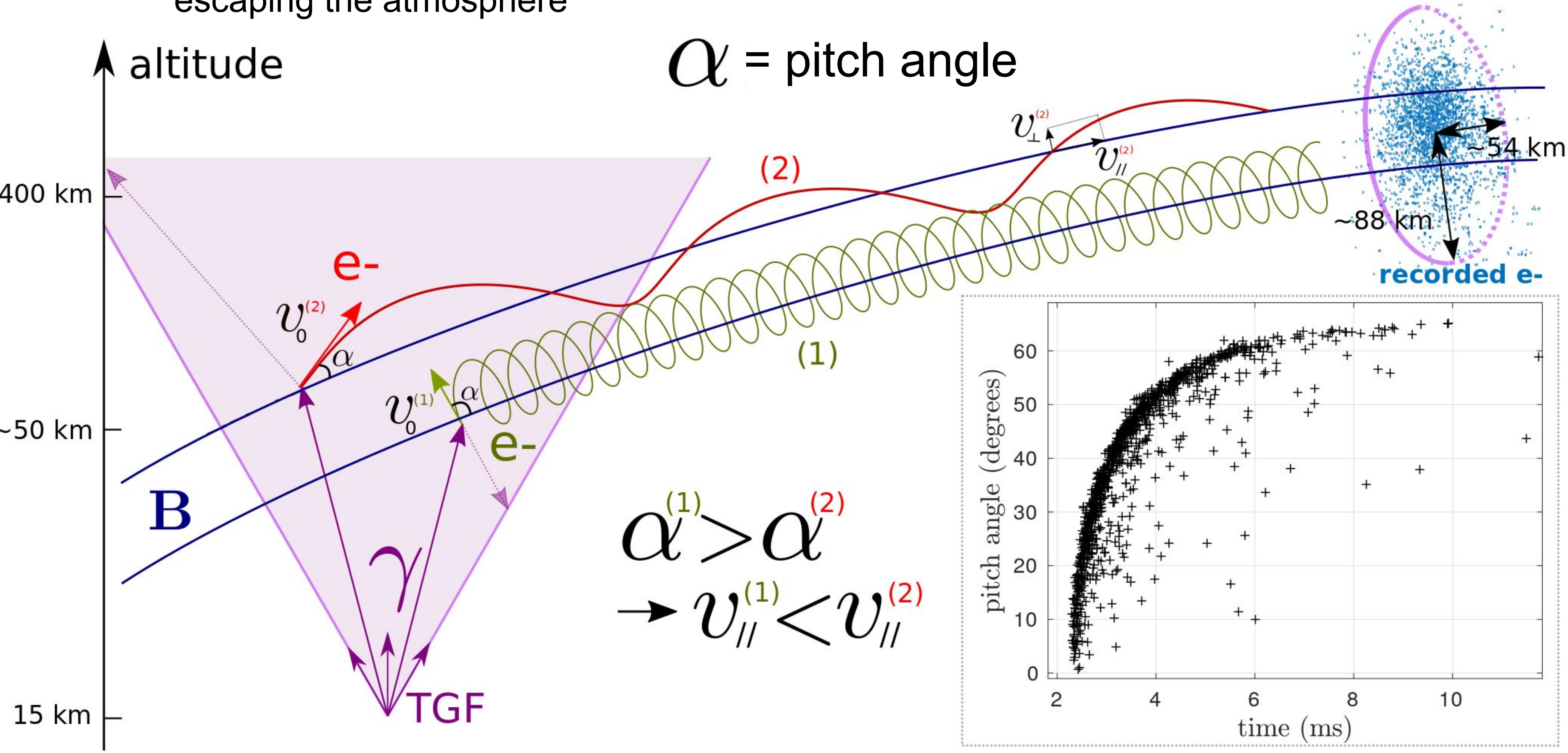
- **TEB much longer than TGFs (~2 to ~20 times)**
- TEB time duration is affected by the distribution of electrons' pitch angles when escaping the atmosphere



- 400 km altitude : Electrons/positrons are spread inside an ellipse, that is typically ~50 km (95% content)

Grammage

Remark : can be convenient to use "g/cm^2", that in the integrated quantity of atmosphere the photons have to cross before reaching space

- **30 g/cm^2 -> ~24 km altitude**
- **50 g/cm^2 -> ~21 km altitude**
- **130 g/cm^2 -> ~15 km altitude**