Terrestrial gamma-ray flashes, antimatter and hadrons correlated to lightning events

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11 January 2011 Last updated at 08:34

Antimatter caught streaming from thunderstorms on Earth

By Jason Palmer
Science and technology reporter, BBC News, Seattle

Electrons racing up electric field lines give rise to light, then particles, then light

A space telescope has accidentally spotted thunderstorms on Earth producing beams of antimatter.

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Antimatter caught streaming from thunderstorms on Earth

Other species?

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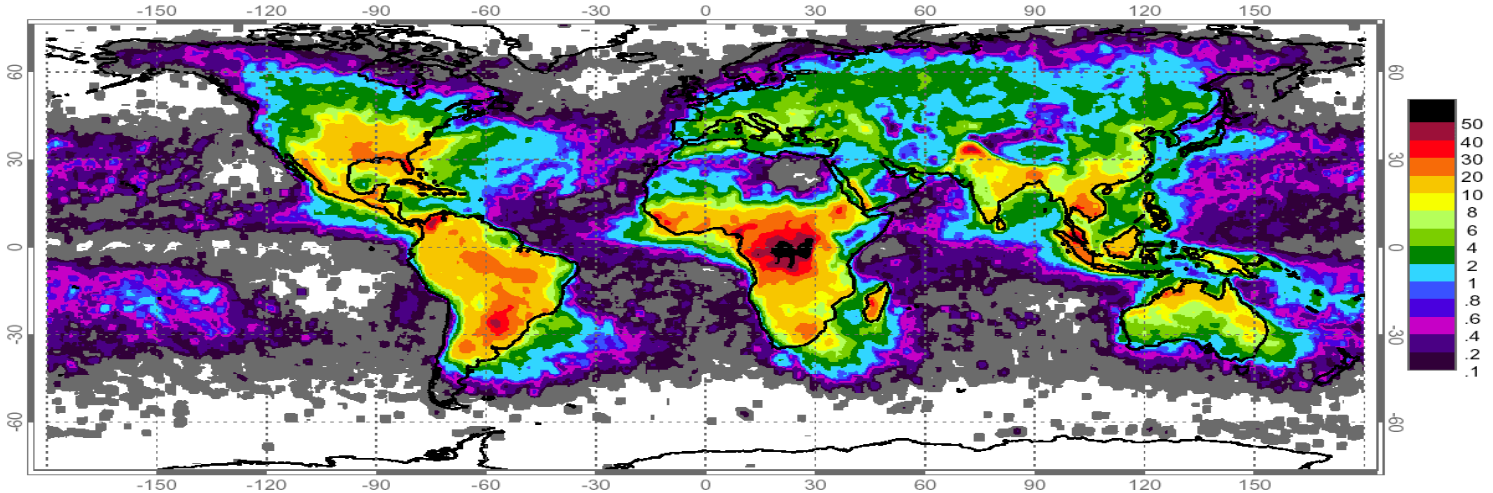
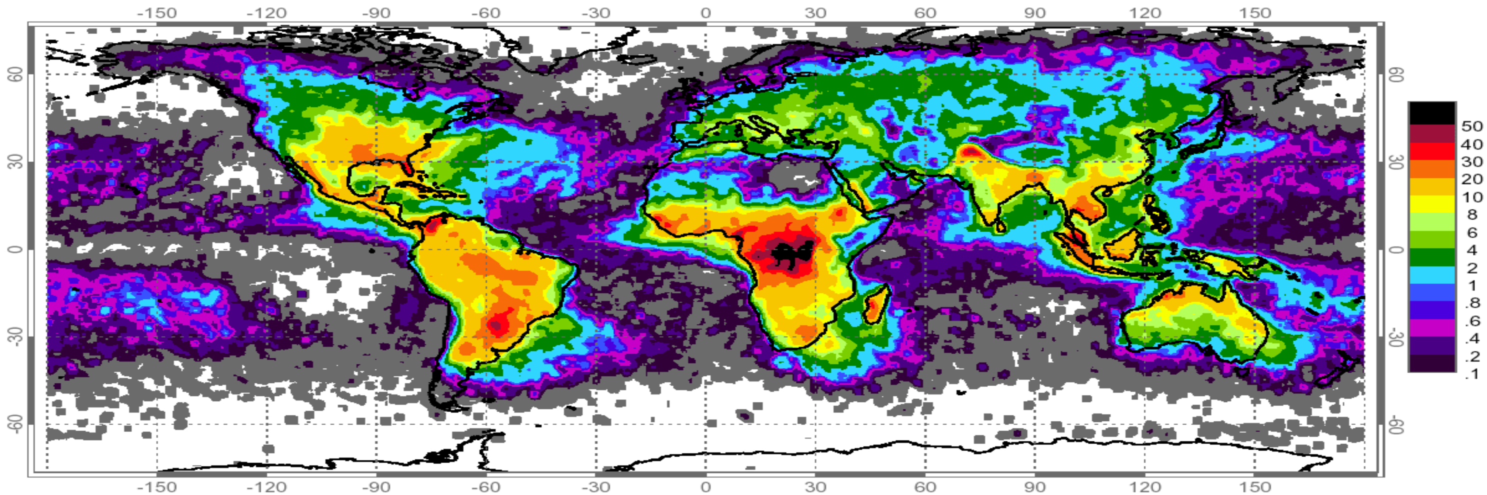


Lightning per year and km²

Lightning and gamma-rays



Lightning
per year
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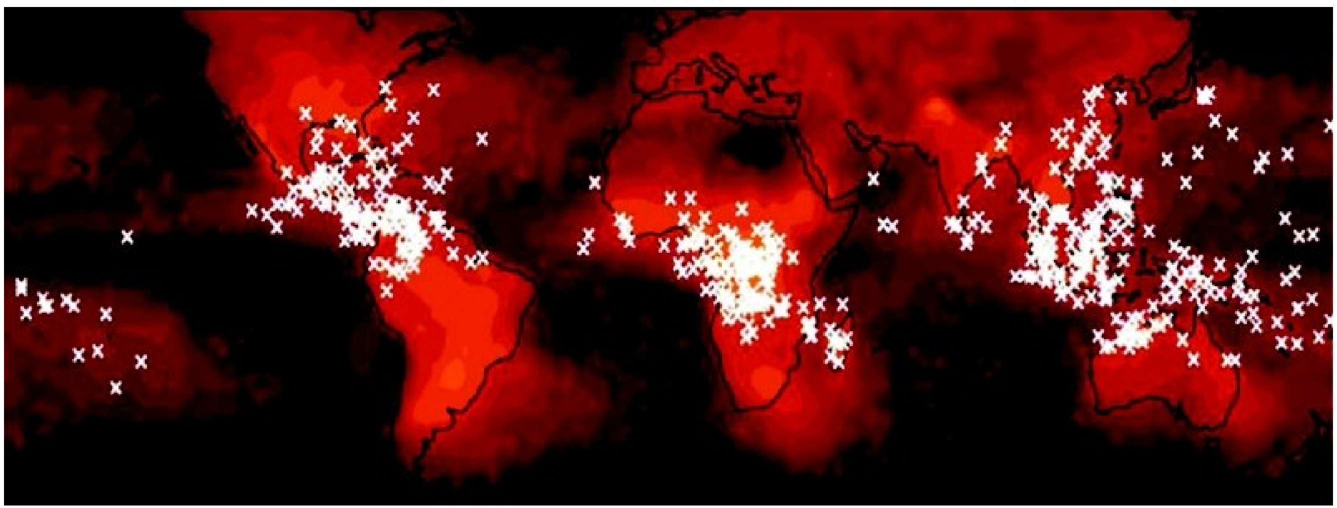
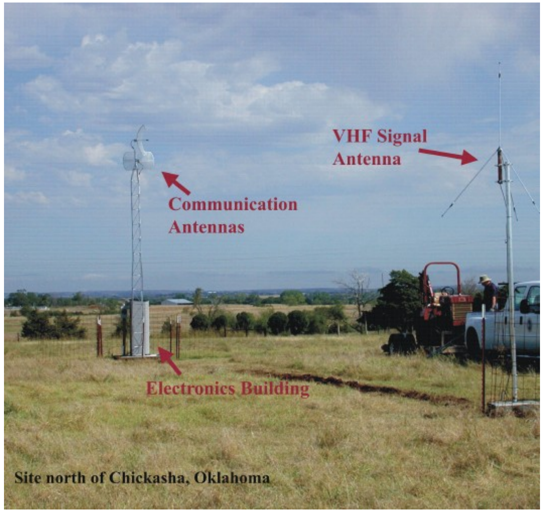
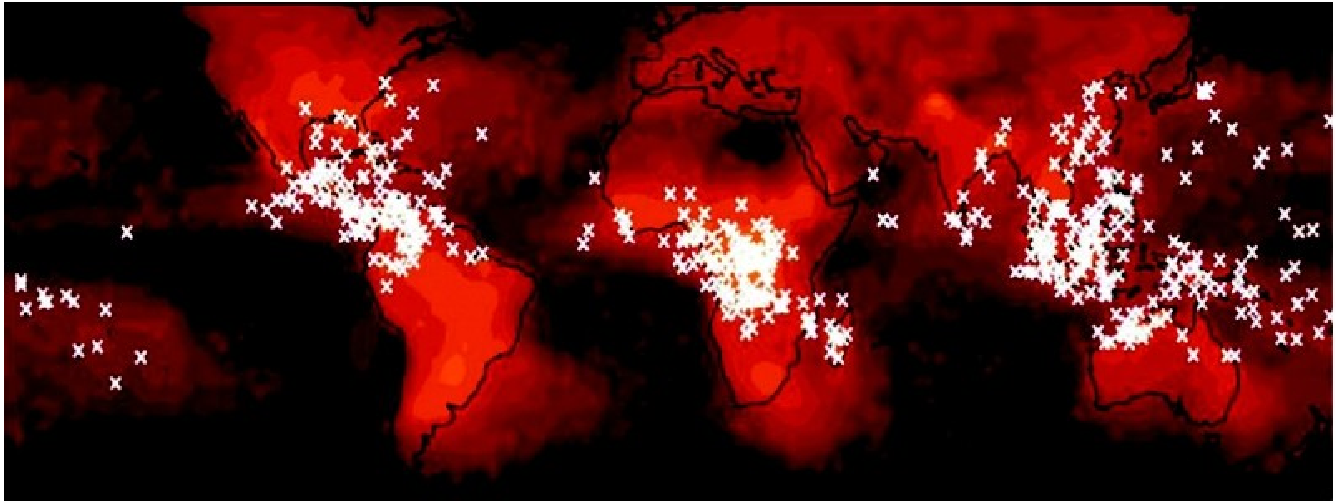


Gamma-rays measured
by RHESSI (2006)

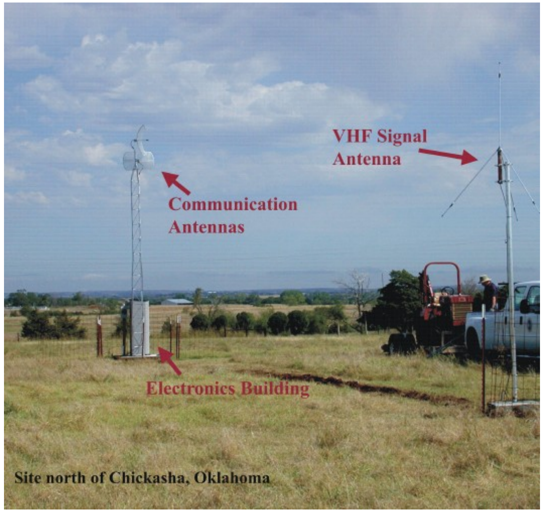
=> **Terrestrial gamma-ray flashes (TGFs)**

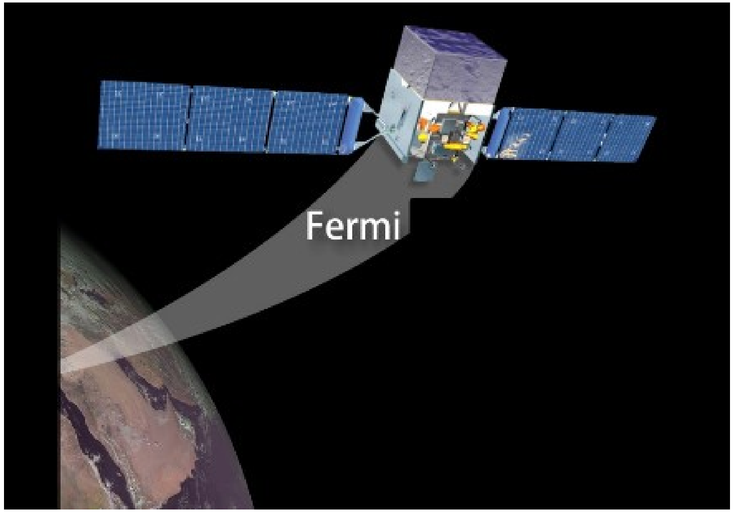
Lightning and gamma-rays

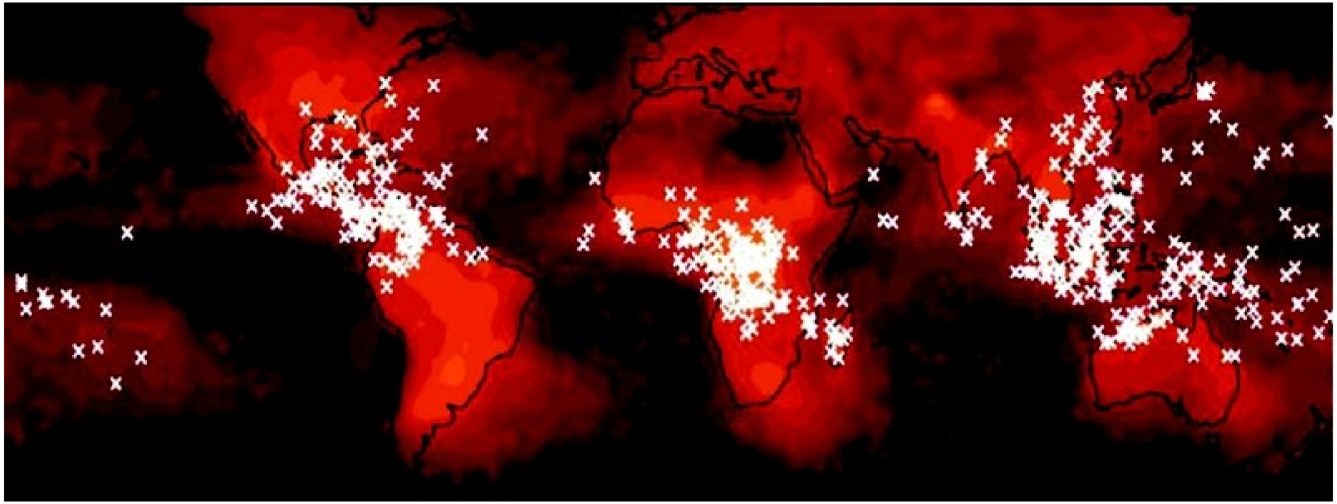




Lightning and gamma-rays





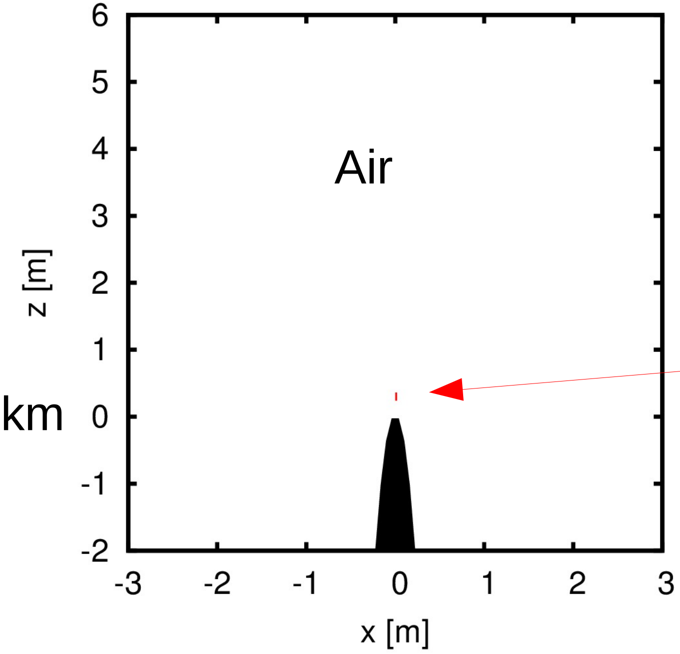


E_γ to 40 MeV (Fermi)

E_γ to 100 MeV (Agile)

Stepping lightning leader

Test case: Negative stepped lightning leader



16 km

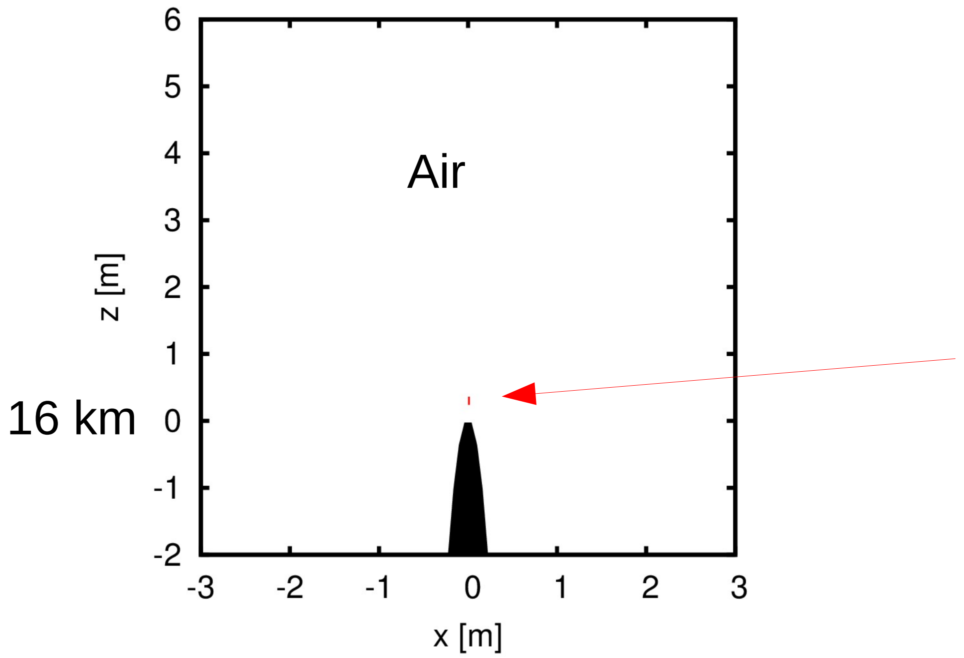
A hot, propagating and stepping plasma channel transporting charge through air

Here: L = 4 km, r = 1 cm

- Test electron(s) 30 cm ahead of leader tip

[Xu, Celestin and Pasko, Geophys. Res. Let., vol. 39, L08801, 2012]

Test case: Negative stepped lightning leader



A hot, propagating and stepping plasma channel transporting charge through air

Here: L = 4 km, r = 1 cm

- Test electron(s) 30 cm ahead of leader tip
- Calculate electric field of leader

[Xu, Celestin and Pasko, Geophys. Res. Let., vol. 39, L08801, 2012]

Electric field of a leader

Simulate negative leader as an ellipsoid

$$E_0 = 0.5\,\mathrm{kV/cm}$$
$$L = 4\,\mathrm{km}$$
$$r_C = 1\,\mathrm{cm}$$

Potential of a charged ellipsoid in an ambient field:

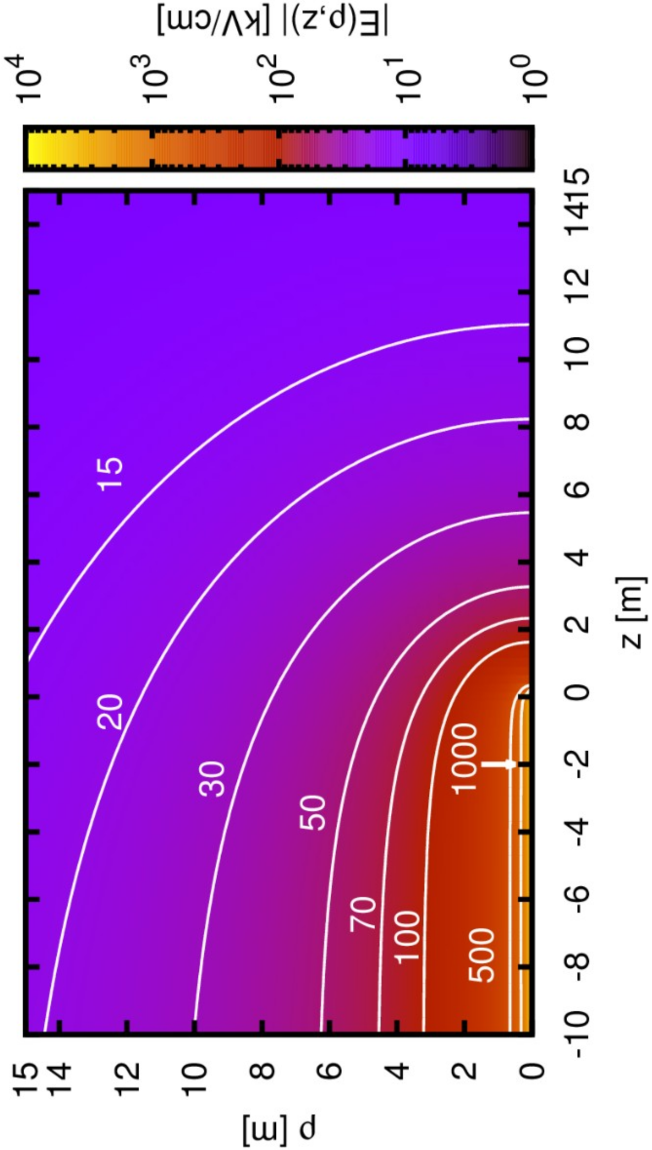
$$\Phi(\vec{r}) = -E_0 z \left[1 - \frac{\int_{\xi(\vec{r})}^{\infty} \frac{ds}{(s+L^2)^{3/2}(s+a^2)}}{\int_{0}^{\infty} \frac{ds}{(s+L^2)^{3/2}(s+a^2)}} \right]$$

where $\xi(\vec{r})$ is one of the ellipsoidal coordinates

[Landau and Lifschitz, Electrodynamics of Continuous Media, 1984]

=> Large field enhancement close to the leader tip

Electric field of a leader



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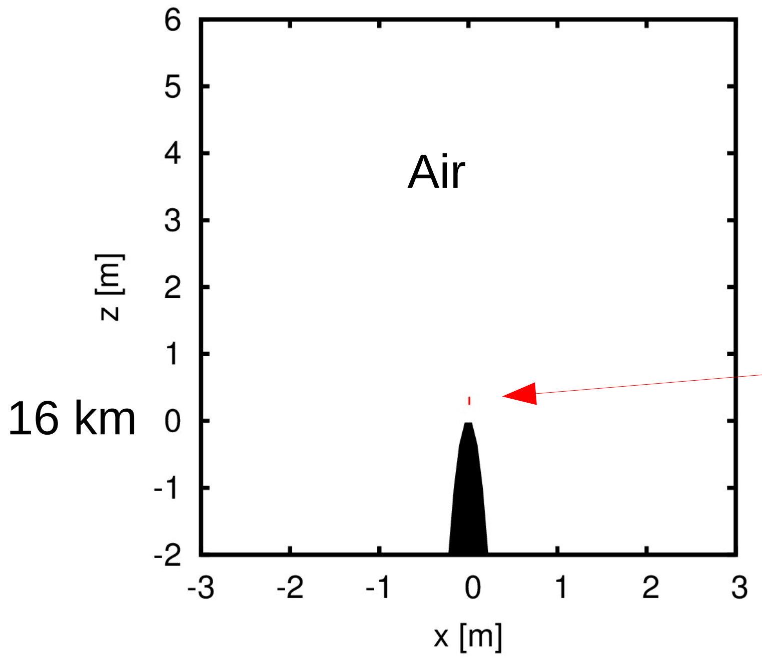


A hot, propagating and stepping plasma channel transporting charge through air

Here: L = 4 km, r = 1 cm

- Test electron(s) 30 cm ahead of leader tip
- Calculate electric field of leader
- Accelerate electrons in this field

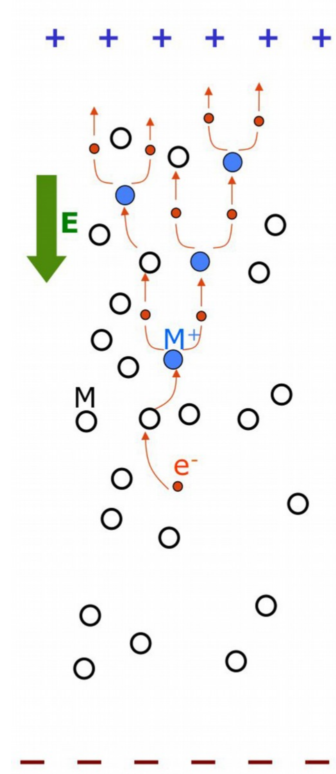
[Xu, Celestin and Pasko, Geophys. Res. Let., vol. 39, L08801, 2012]

3D relativistic MC Code

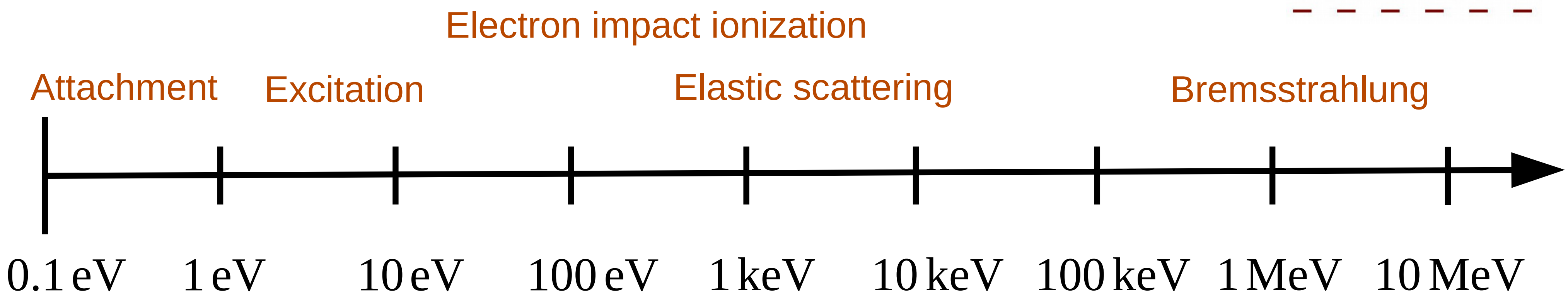
- Relativistic leap-frog between two collisions:

$$\vec{r}_{n+1} = \vec{r}_n + \Delta t\, \vec{v}_{n+\frac{1}{2}} \quad \text{with} \quad \vec{p}_{n+\frac{1}{2}} = \vec{p}_{n-\frac{1}{2}} + q\,\Delta t\, \vec{E}(\vec{r}_n, t_n)$$

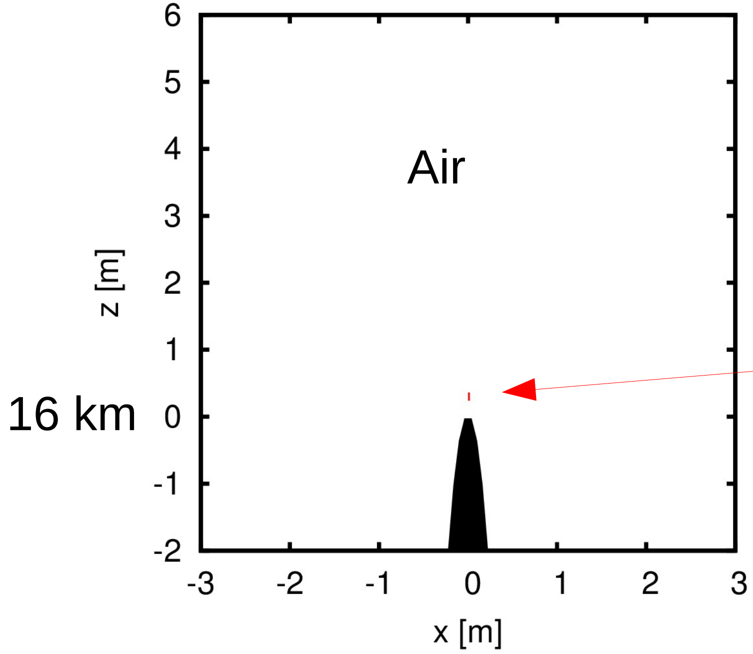
$$\vec{v}_{n+\frac{1}{2}} = \frac{c^2}{E_{n+\frac{1}{2}}} \cdot \vec{p}_{n+\frac{1}{2}} \qquad E_{n+\frac{1}{2}} = \sqrt{c^2 \left|\vec{p}_{n+\frac{1}{2}}\right|^2 + m^2 c^4}$$



Collisions of electrons with air molecules:



Test case: Negative stepped lightning leader



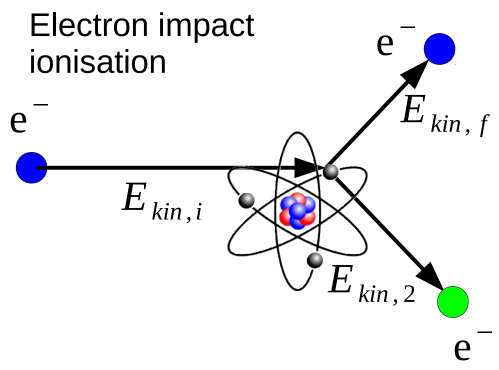
A hot, propagating and stepping plasma channel transporting charge through air

Here: L = 4 km, r = 1 cm

- Test electron(s) 30 cm ahead of leader tip
- Calculate electric field of leader
- Accelerate electrons in this field
- Create new electrons and Bremsstrahlung photons

[Xu, Celestin and Pasko, Geophys. Res. Let., vol. 39, L08801, 2012]

Source of electrons and photons

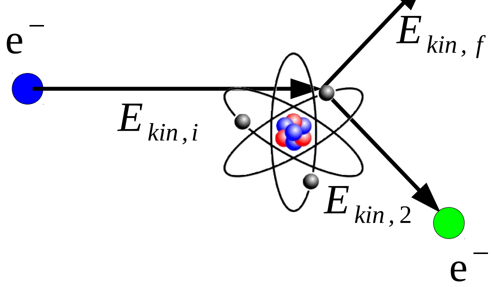


$$e^- + A \rightarrow e^- + A^+ + e^-$$

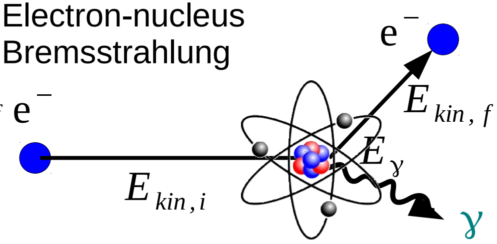
[Y. K. Kim, J. Paulo Santos, 2000.
Phys. Rev. A, vol. 62, 052710]

Source of electrons and photons

Electron impact ionisation



Electron-nucleus Bremsstrahlung

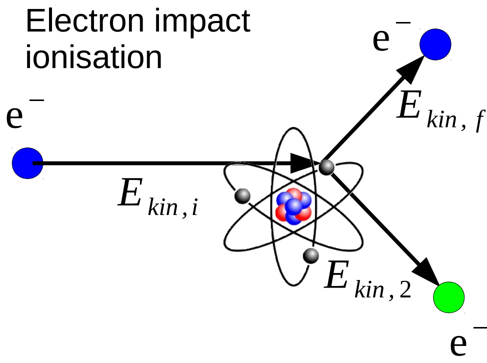


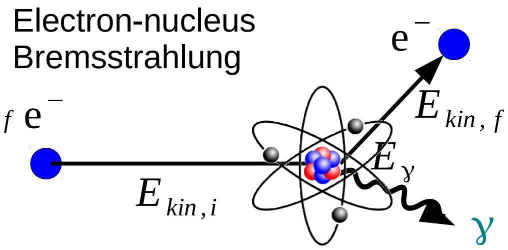
$$e^- + A \rightarrow e^- + A^+ + e^- \qquad e^- + A \rightarrow e^- + A + \gamma$$

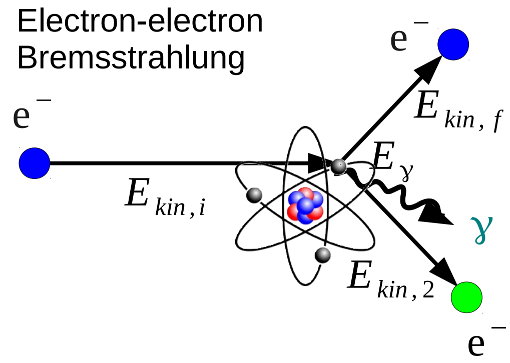
[Y. K. Kim, J. Paulo Santos, 2000. Phys. Rev. A, vol. 62, 052710]

[C. Köhn and. U. Ebert, 2014. Atmos. Res., vol. 135-136, pp. 432-465]

Source of electrons and photons







$e^- + A \rightarrow e^- + A^+ + e^-$ $e^- + A \rightarrow e^- + A + \gamma$ $e^- + A \rightarrow e^- + A^+ + e^- + \gamma$

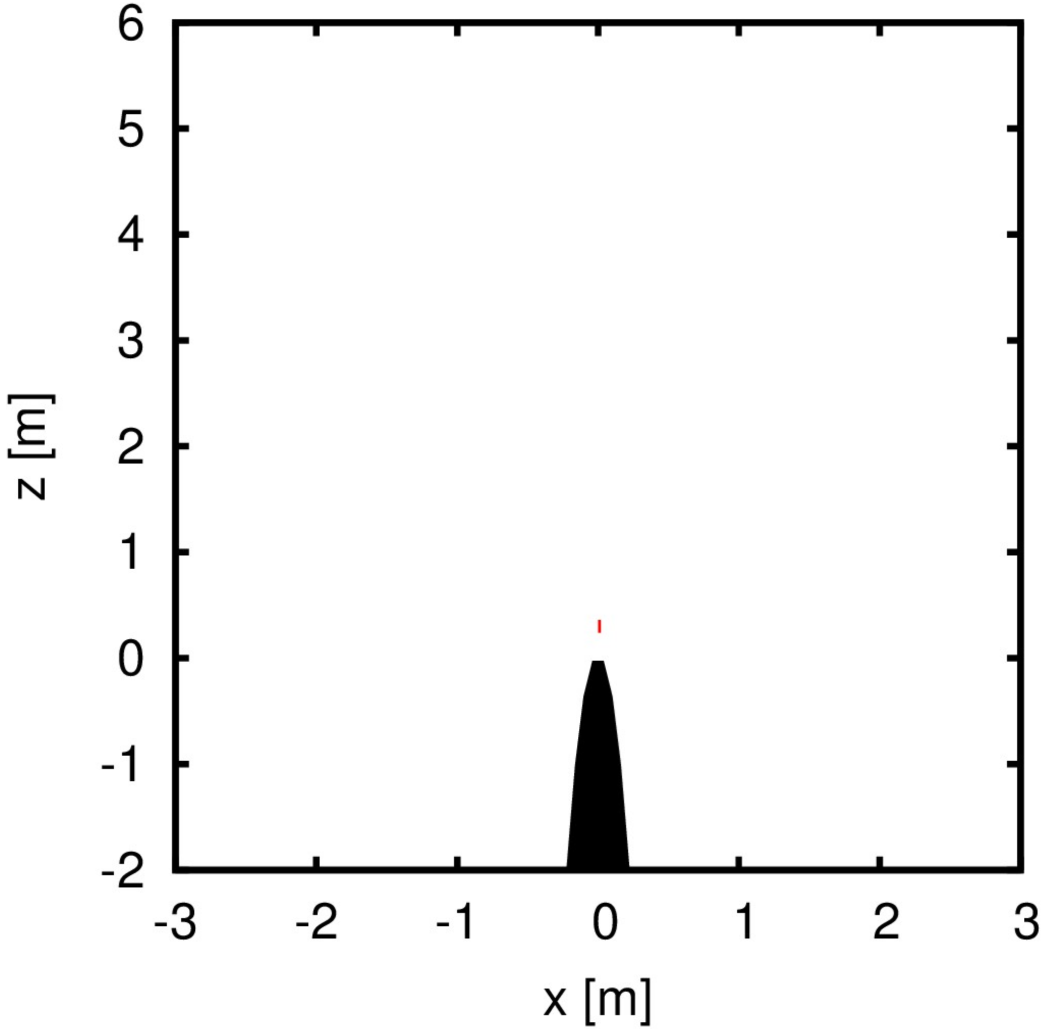
[Y. K. Kim, J. Paulo Santos, 2000. Phys. Rev. A, vol. 62, 052710]

[C. Köhn and. U. Ebert, 2014. Atmos. Res., vol. 135-136, pp. 432-465]

[F. Tessier and I. Kawrakow, 2007. NIM Phys. Res. B, vol. 266, pp. 625-634]

Dominant for energies above 1 MeV
=> Enrichment of high-energy electrons
=> More high-energy photons

Temporal evolution of electrons

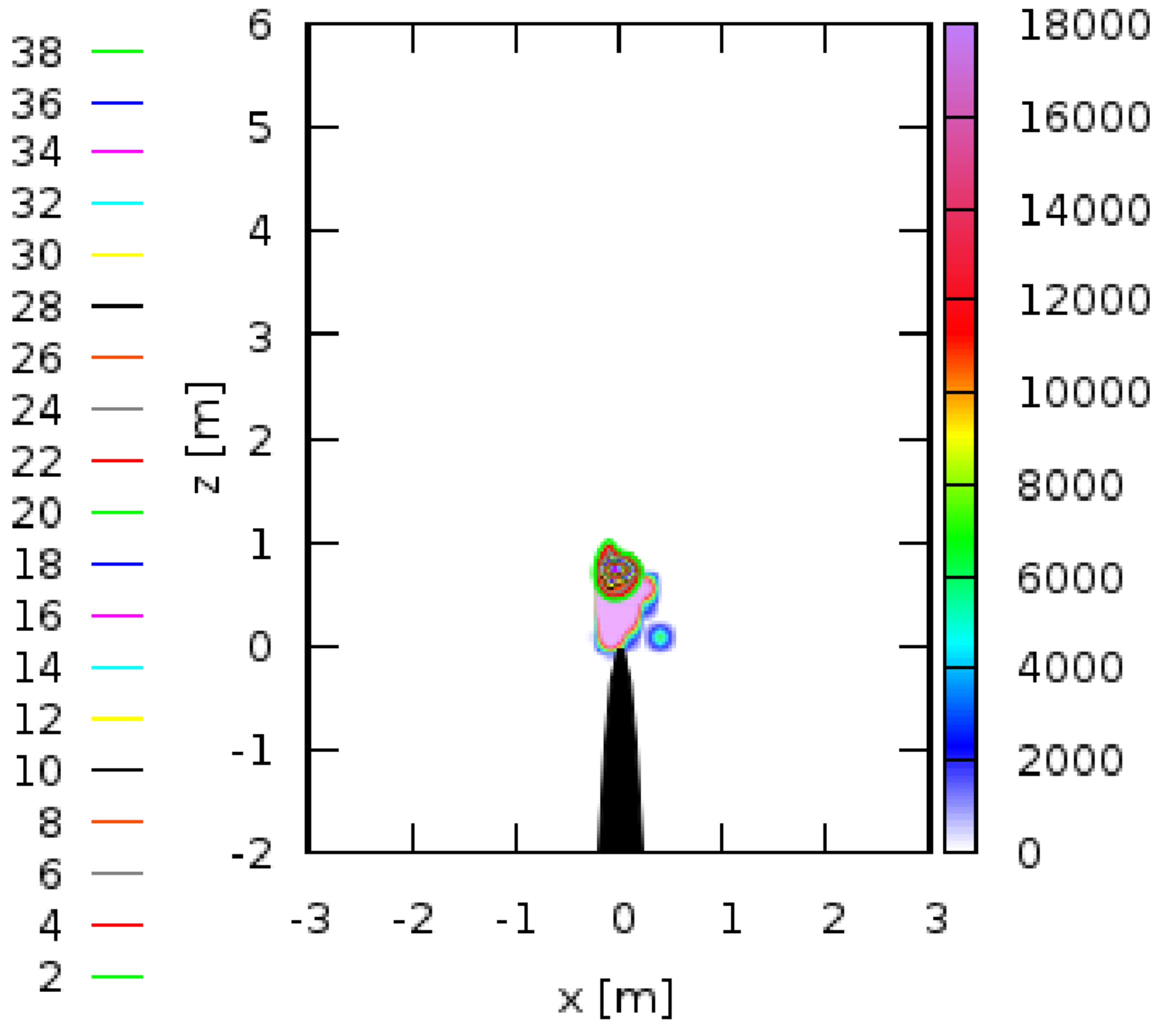


t = 0 ns

[C. Köhn et al., 2014. The importance of electron-electron Bremsstrahlung for terrestrial gamma-ray flashes, electron beams and electron-positron beams. J. Phys. D.: Appl. Phys., vol. 47, 252001]

Temporal evolution of electrons

Electron density > 1 MeV [1/m³]



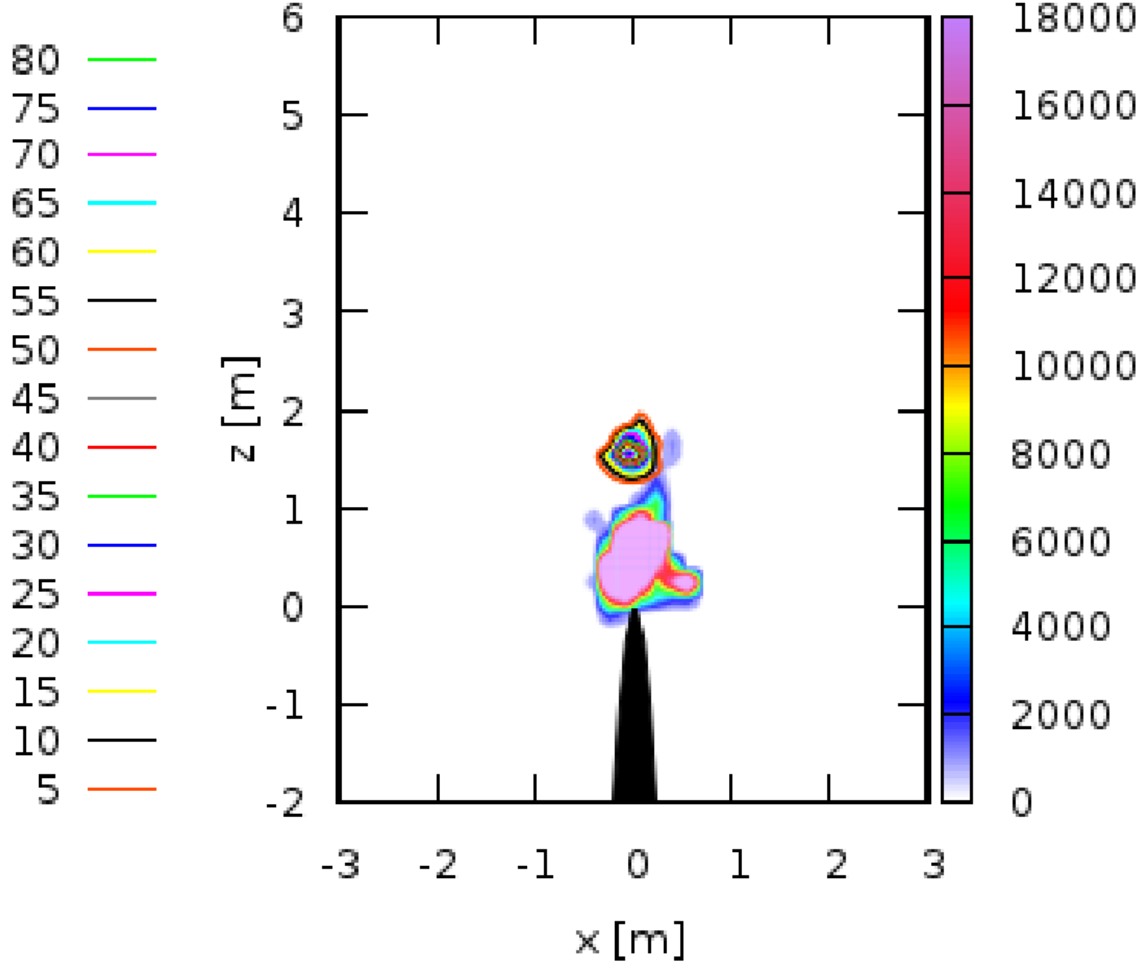
t = 5 ns

Electron density < 1 MeV [1/m³]

[C. Köhn et al., 2014. The importance of electron-electron Bremsstrahlung for terrestrial gamma-ray flashes, electron beams and electron-positron beams. J. Phys. D.: Appl. Phys., vol. 47, 252001]

Temporal evolution of electrons

Electron density > 1 MeV [1/m³]

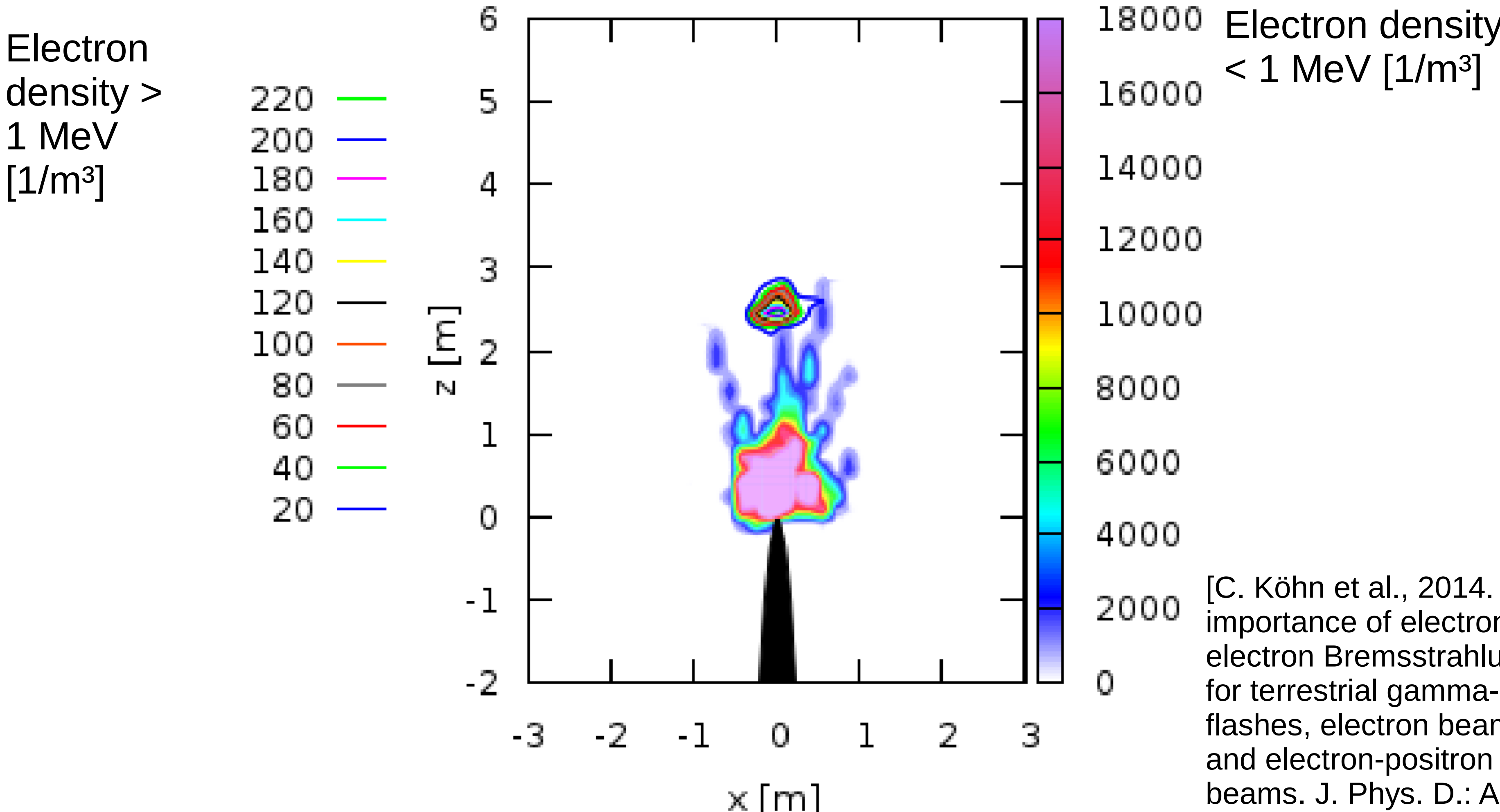


t = 10 ns

Electron density < 1 MeV [1/m³]

[C. Köhn et al., 2014. The importance of electron-electron Bremsstrahlung for terrestrial gamma-ray flashes, electron beams and electron-positron beams. J. Phys. D.: Appl. Phys., vol. 47, 252001]

Temporal evolution of electrons

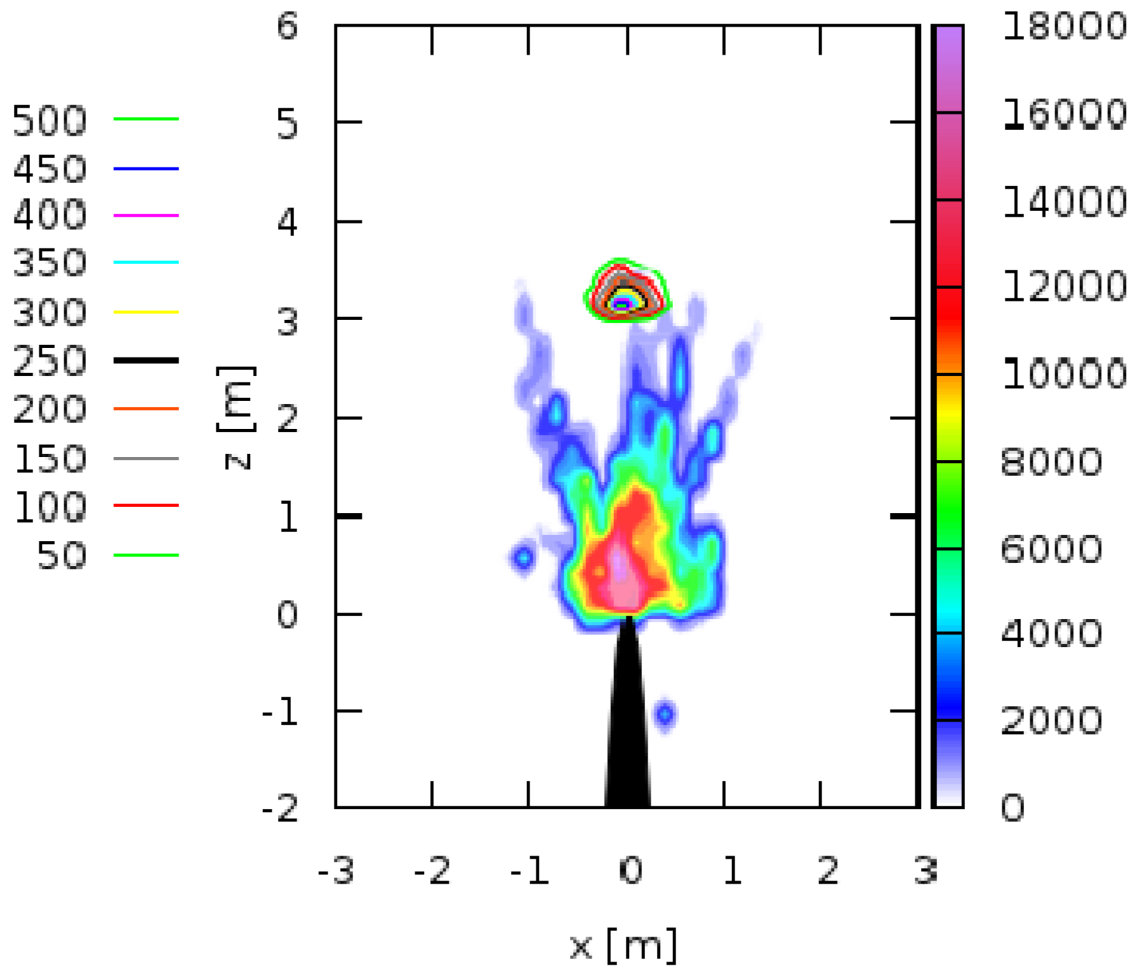


t = 15 ns

[C. Köhn et al., 2014. The importance of electron-electron Bremsstrahlung for terrestrial gamma-ray flashes, electron beams and electron-positron beams. J. Phys. D.: Appl. Phys., vol. 47, 252001]

Temporal evolution of electrons

Electron density > 1 MeV [1/m³]



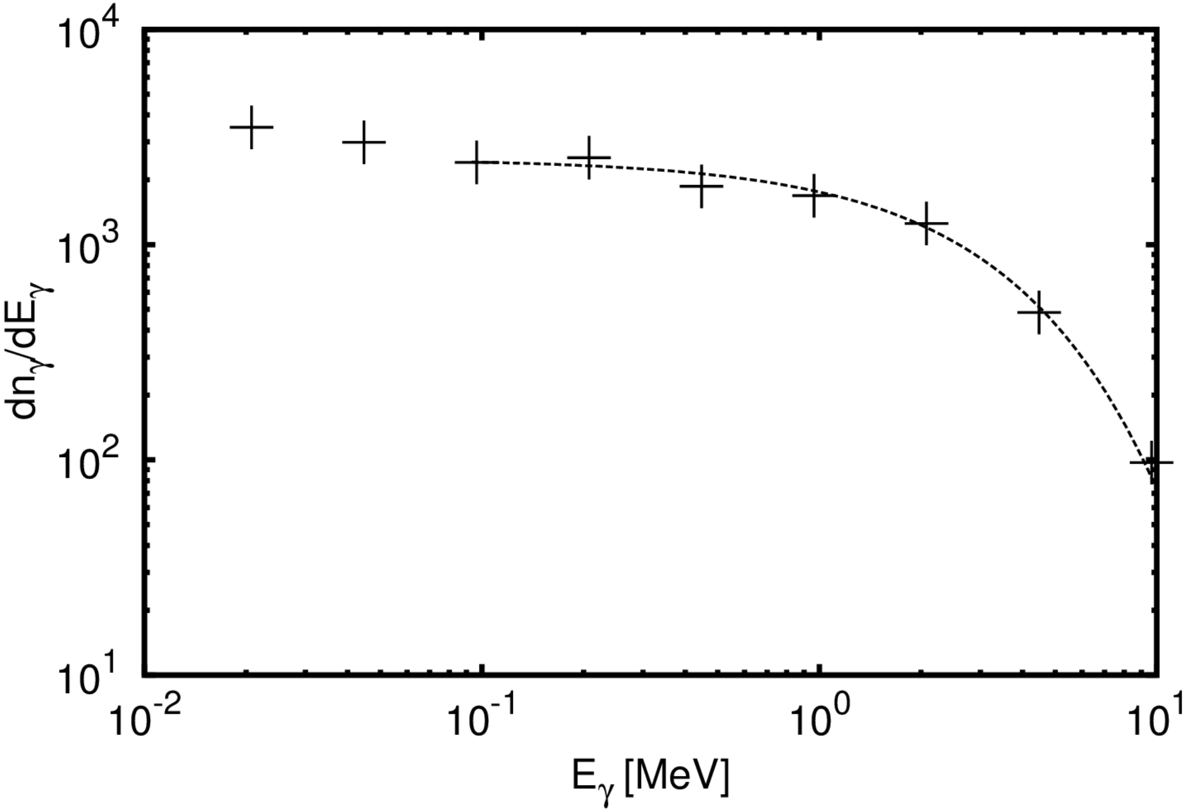
t = 20 ns

Electron density < 1 MeV [1/m³]

[C. Köhn et al., 2014. The importance of electron-electron Bremsstrahlung for terrestrial gamma-ray flashes, electron beams and electron-positron beams. J. Phys. D.: Appl. Phys., vol. 47, 252001]

From photons to other species

Starting with a spectrum $\frac{dn_\gamma}{dE_\gamma} \sim e^{-E_\gamma/3\,\mathrm{MeV}}$ with energies <= 40 MeV from stepped lightning leader



Motion of photons

3D Monte Carlo code

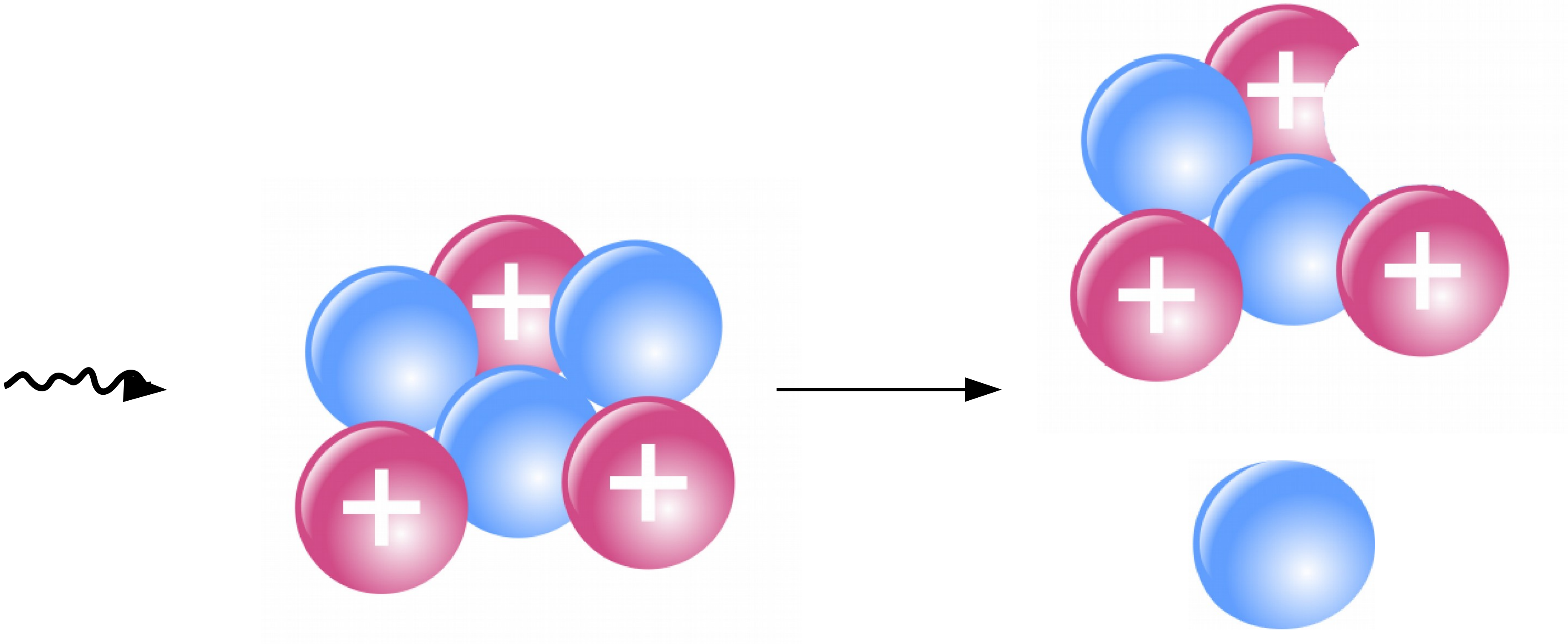
- Free motion between collisions

Motion of photons

3D Monte Carlo code

- Free motion between collisions
- Differential cross sections to model collisions:
  - Photo ionization (Photons disappear)
  - Compton scattering
  - Pair production (Photons disappear)
  - Neutron production (Photons disappear)
  - Proton production (Photons disappear)

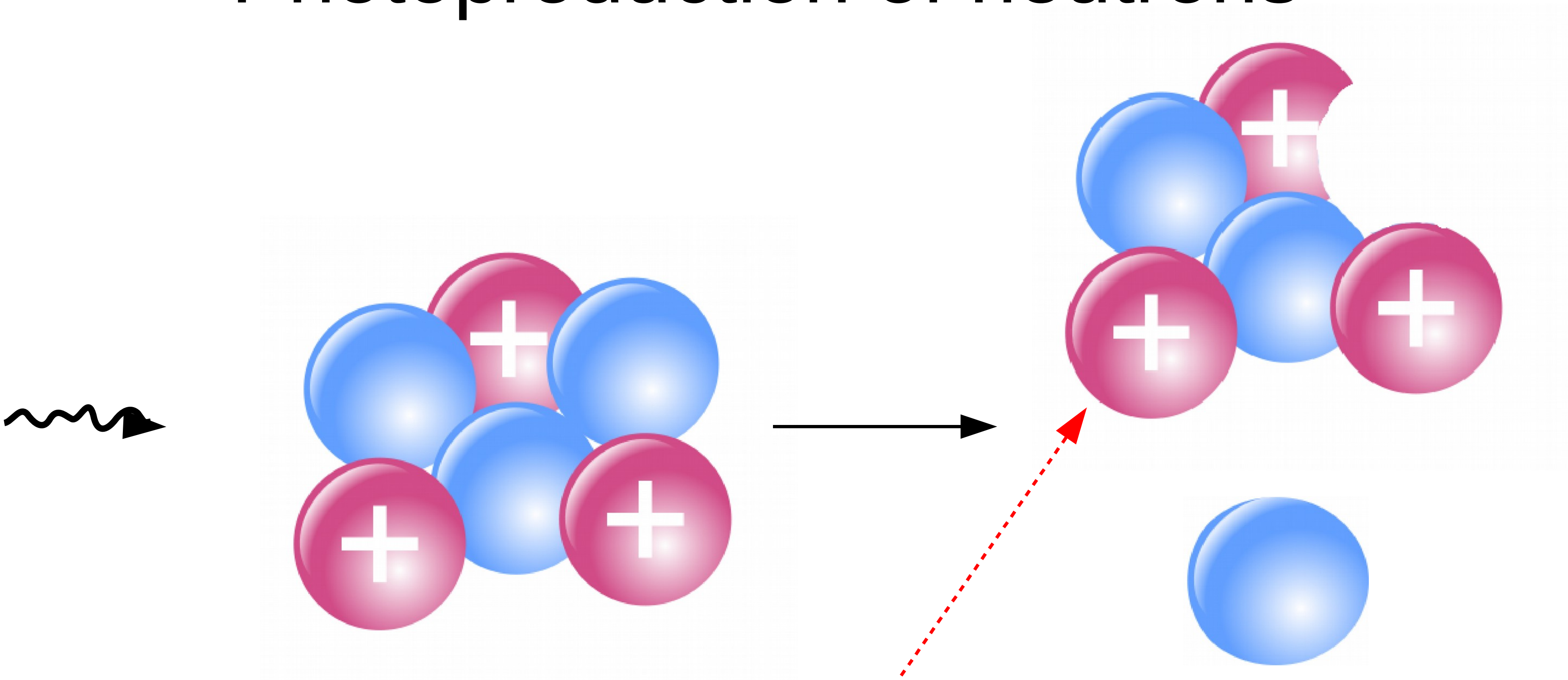
Photoproduction of neutrons



Binding energy of a nucleon approx. 8 MeV

[E.G. Fuller, 1985. Photonuclear reaction cross sections for C, N and O. Physics reports, vol. 127, pp. 185-231]

Photoproduction of neutrons

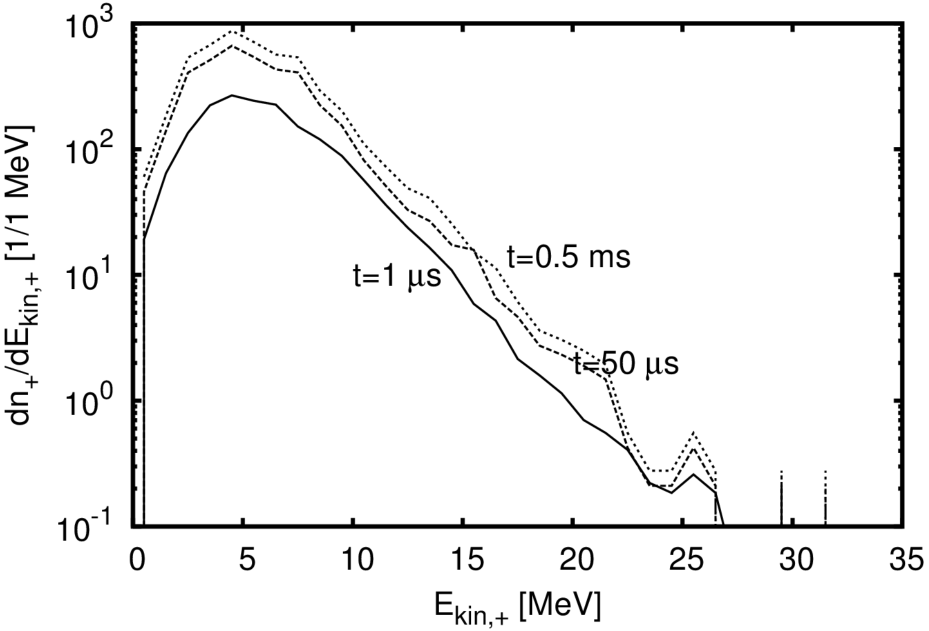


Binding energy of a nucleon approx. 8 MeV

Likewise for protons

[E.G. Fuller, 1985. Photonuclear reaction cross sections for C, N and O. Physics reports, vol. 127, pp. 185-231]

Generation and propagation of positrons

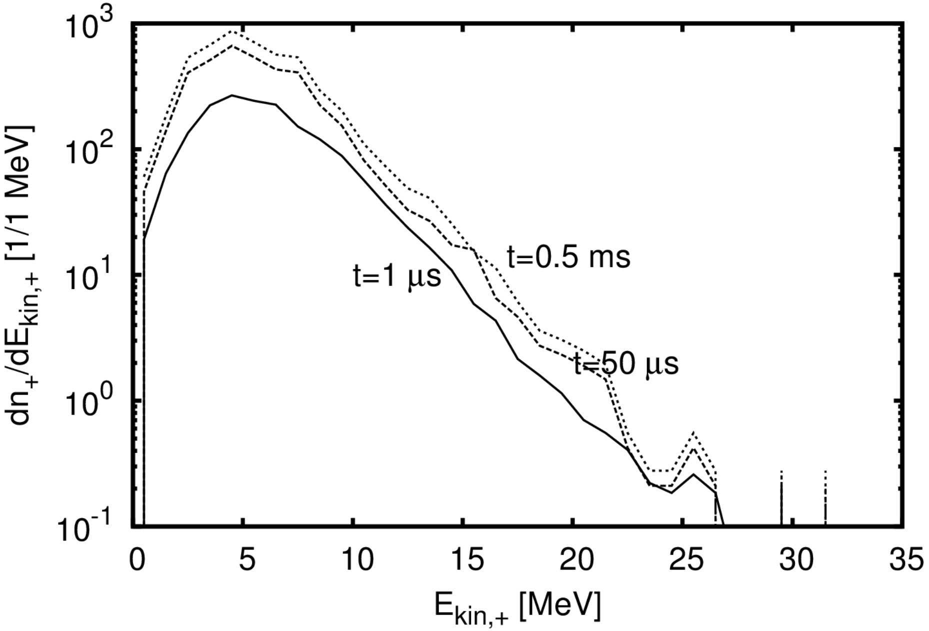


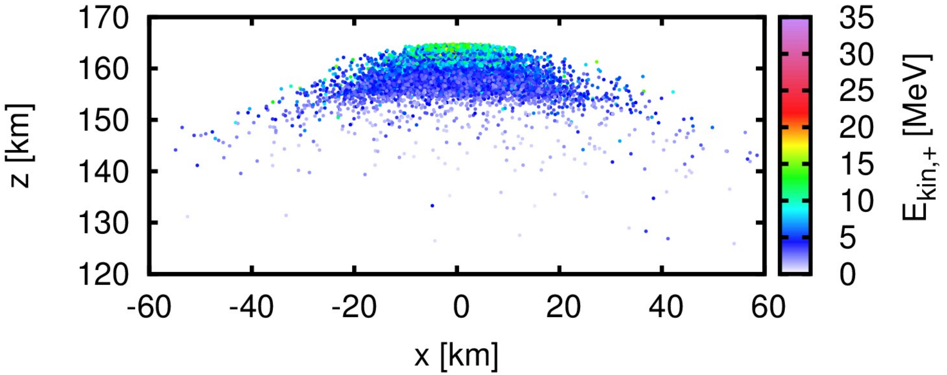
Maximum of energy distribution at approx 7 MeV

Energies of up to 30 MeV

[C. Köhn and U. Ebert., 2015. Calculation of beams of positrons, neutrons and protons associated with terrestrial gamma-ray flashes. J. Geophys. Res., vol. 120, doi:10.1002/2014JD022229]

Generation and propagation of positrons





Positron beam limited by relativistic positrons

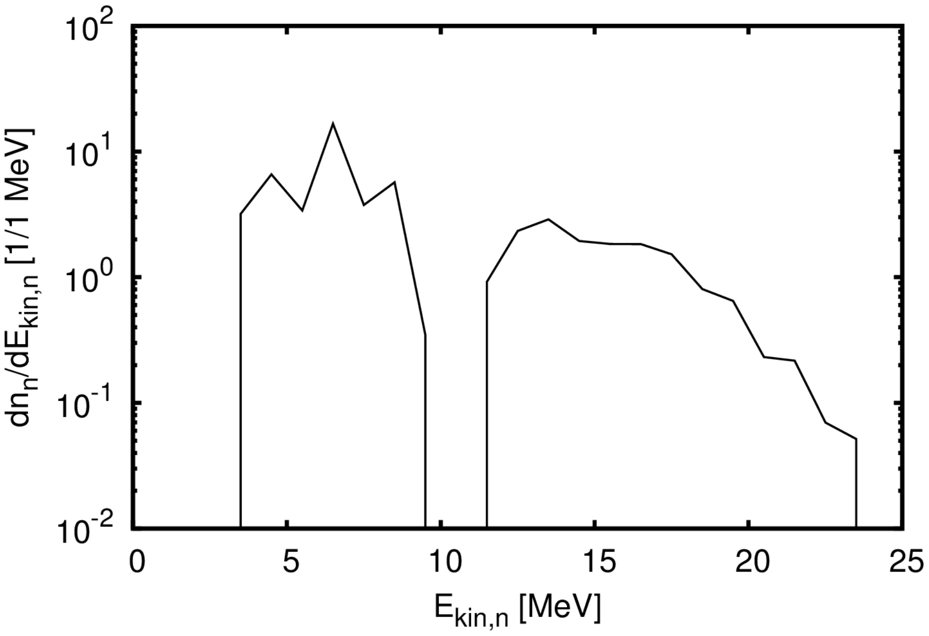
Maximum of energy distribution at approx 7 MeV

Energies of up to 30 MeV

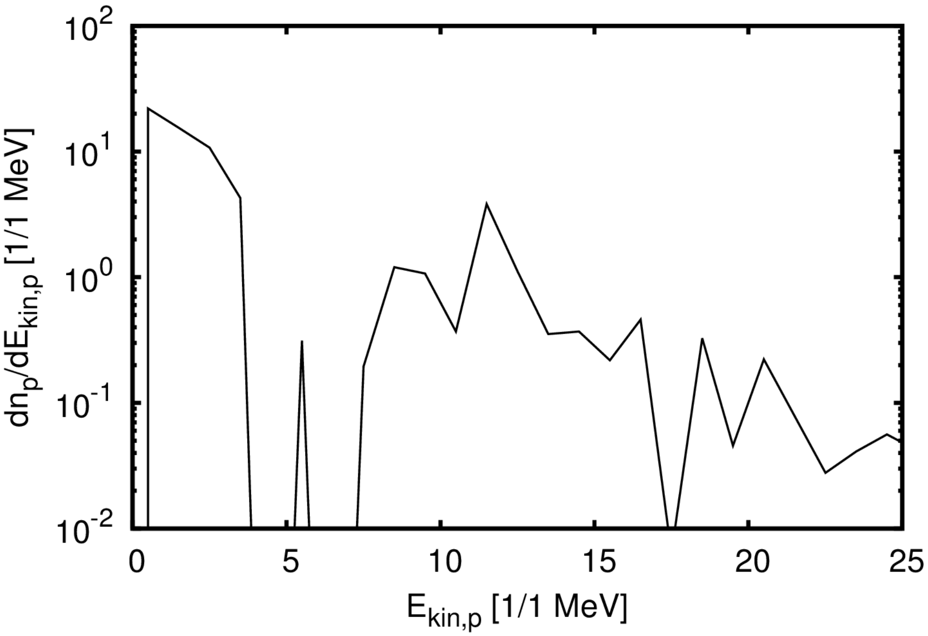
[C. Köhn and U. Ebert., 2015. Calculation of beams of positrons, neutrons and protons associated with terrestrial gamma-ray flashes. J. Geophys. Res., vol. 120, doi:10.1002/2014JD022229]

Hadron energy distributions

Neutrons:



Protons:



Energies of up to tens of MeV

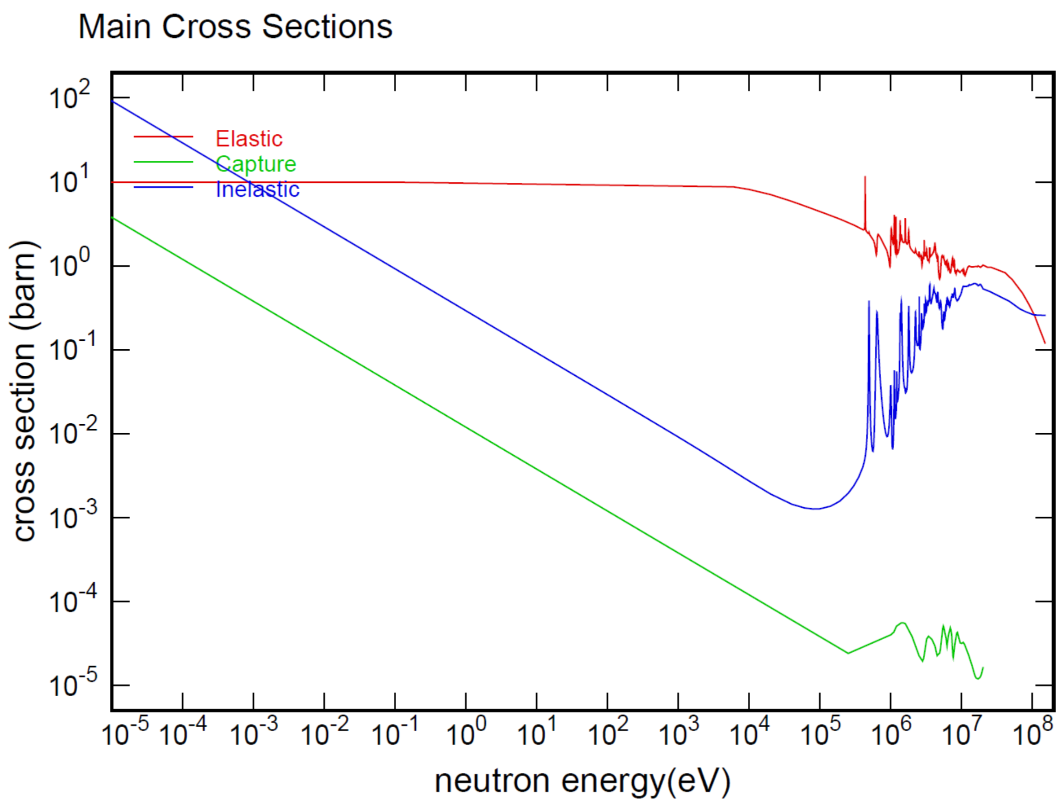
Resonances because of cross sections

Propagation of hadrons through the atmosphere?

[C. Köhn and U. Ebert., 2015. Calculation of beams of positrons, neutrons and protons associated with terrestrial gamma-ray flashes. J. Geophys. Res., vol. 120, doi:10.1002/2014JD022229]

Neutron cross sections

for nitrogen

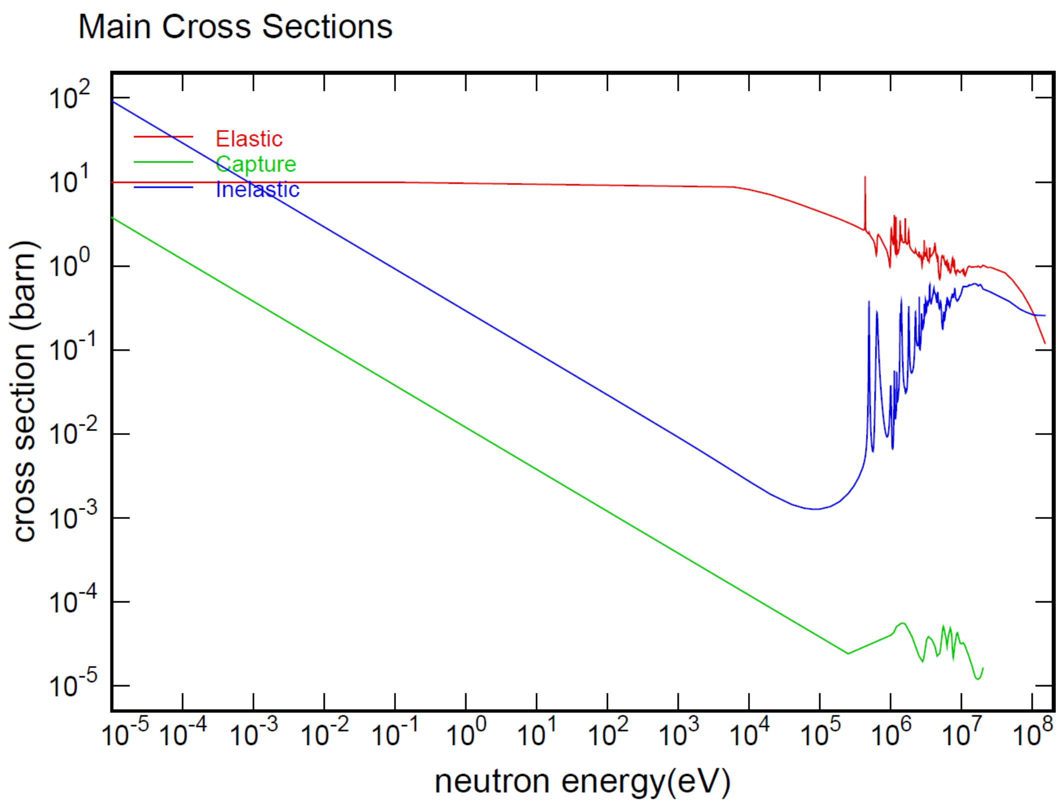


Elastic scattering:
- Energy transfer to air nulcei (recoil)
- Change of direction

[https://www-nds.iaea.org/geant4/]

Neutron cross sections

for nitrogen



Elastic scattering:
- Energy transfer to air nulcei (recoil)
- Change of direction

Inelastic scattering:
- Energy transfer to nuclei (excitations) in MeV range
- Change of direction
- Loss of neutrons, e.g.

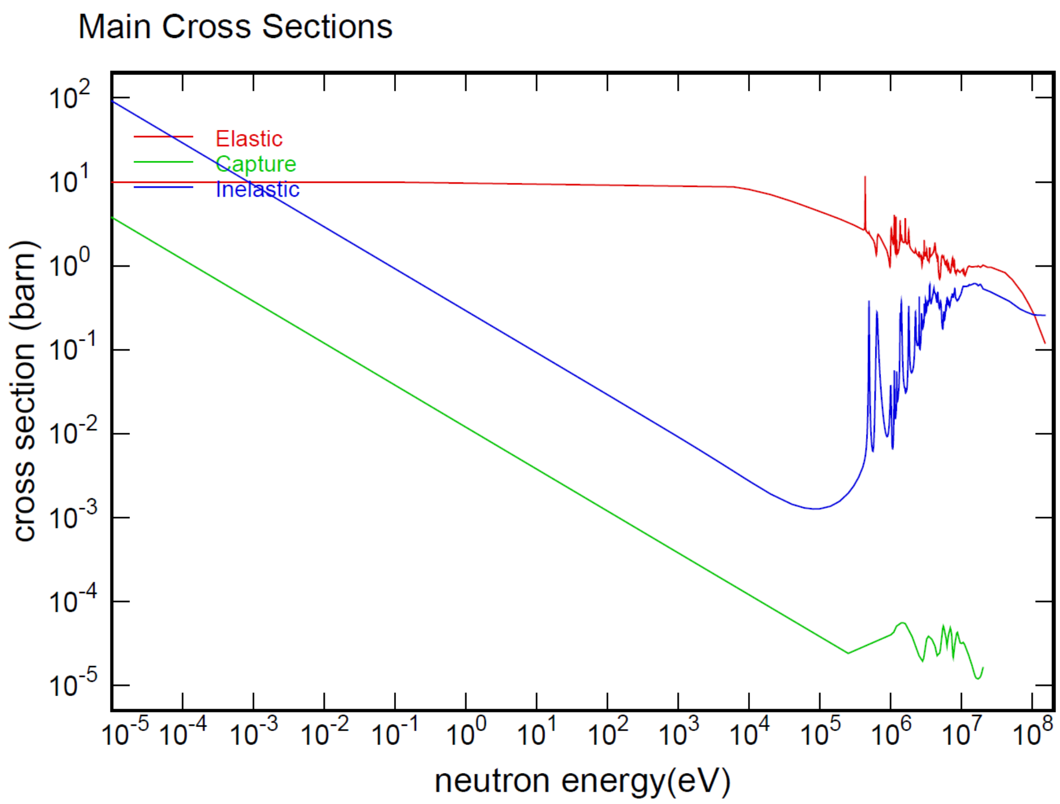
$$A + n \rightarrow B^{-} + p^{+}$$

- Changes constitution of atmosphere

[https://www-nds.iaea.org/geant4/]

Neutron cross sections

for nitrogen



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- Energy transfer to nuclei (excitations) in MeV range
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- Loss of neutrons, e.g.

$$A + n \rightarrow B^{-} + p^{+}$$

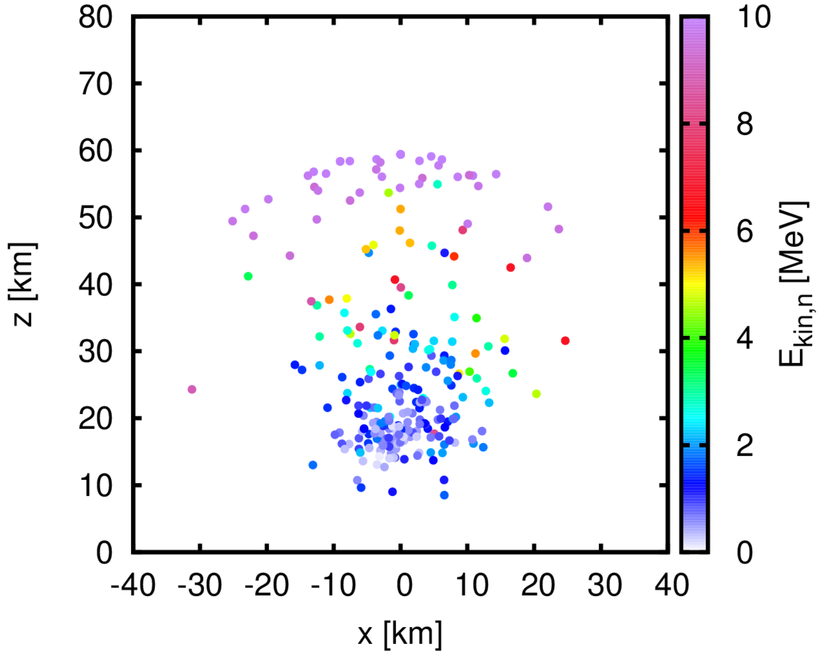
- Changes constitution of atmosphere

Capture:
- Loss of neutrons

[https://www-nds.iaea.org/geant4/]

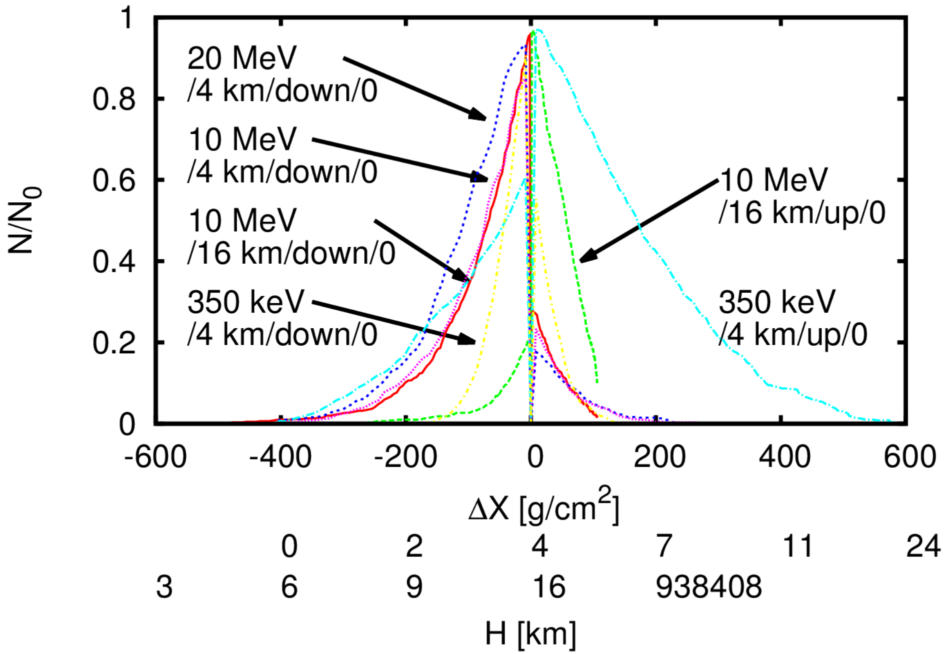
Temporal evolution of neutron beam

Beam of monoenergetic test neutrons



Neutron characteristics

Start with different monoenergetic
neutron beams at different altitudes

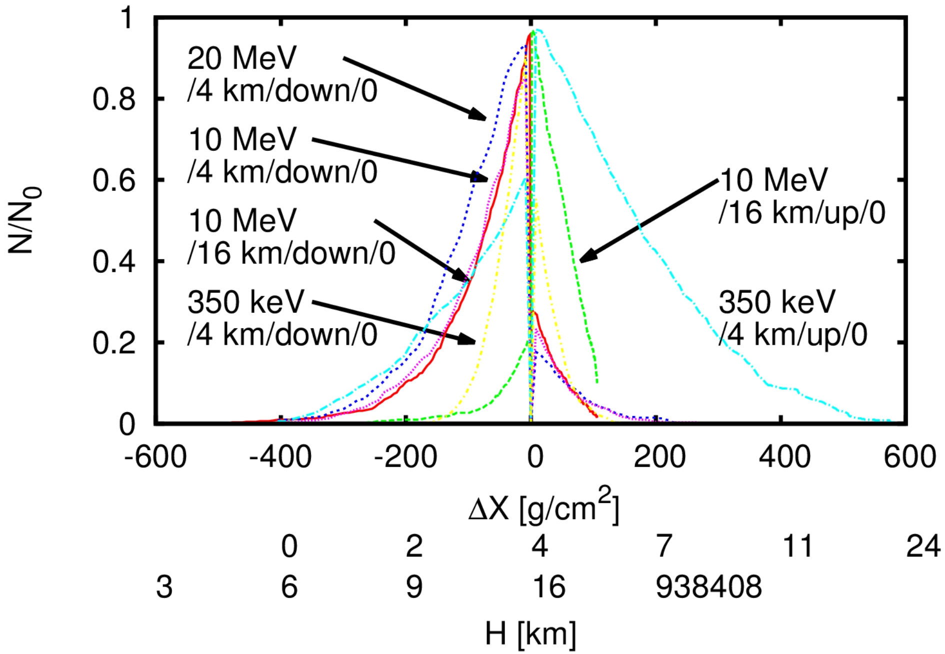


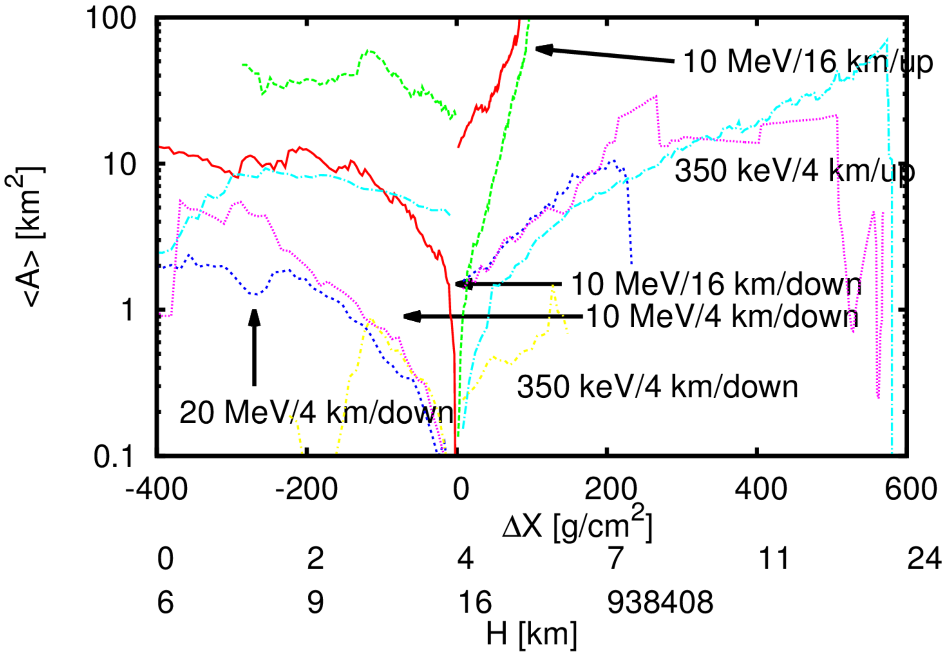
- Small probability of detecting neutrons at ground for all simulated cases
- For upward beams satellite detection possible

[In prep.]

Neutron characteristics

Start with different monoenergetic
neutron beams at different altitudes





- Small probability of detecting neutrons at ground for all simulated cases
- For upward beams satellite detection possible

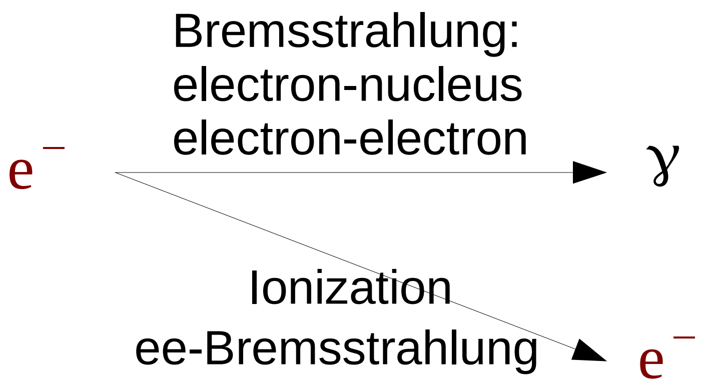
However: Mean cross sections of areas of tens of km^2

[In prep.]

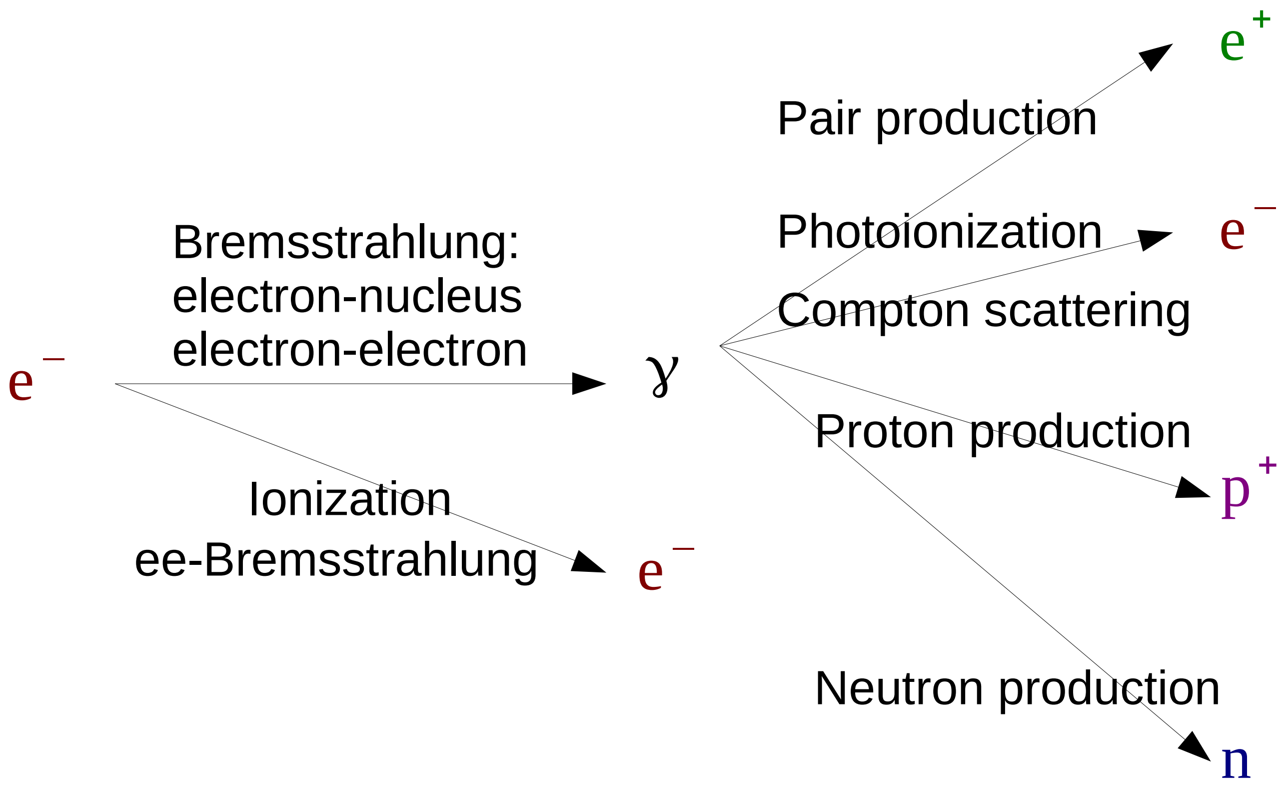
Towards a full feedback model

e^-

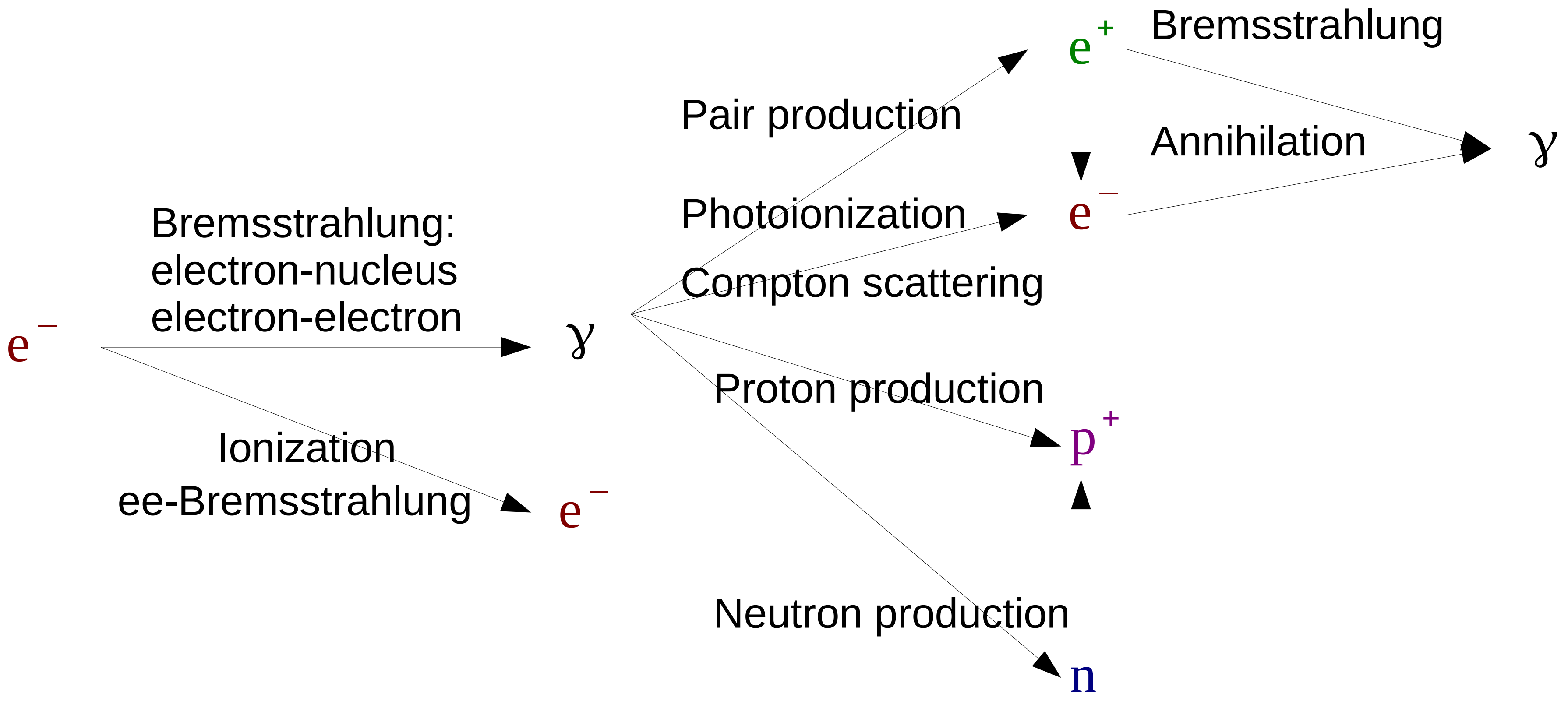
Conversion from electrons to different species



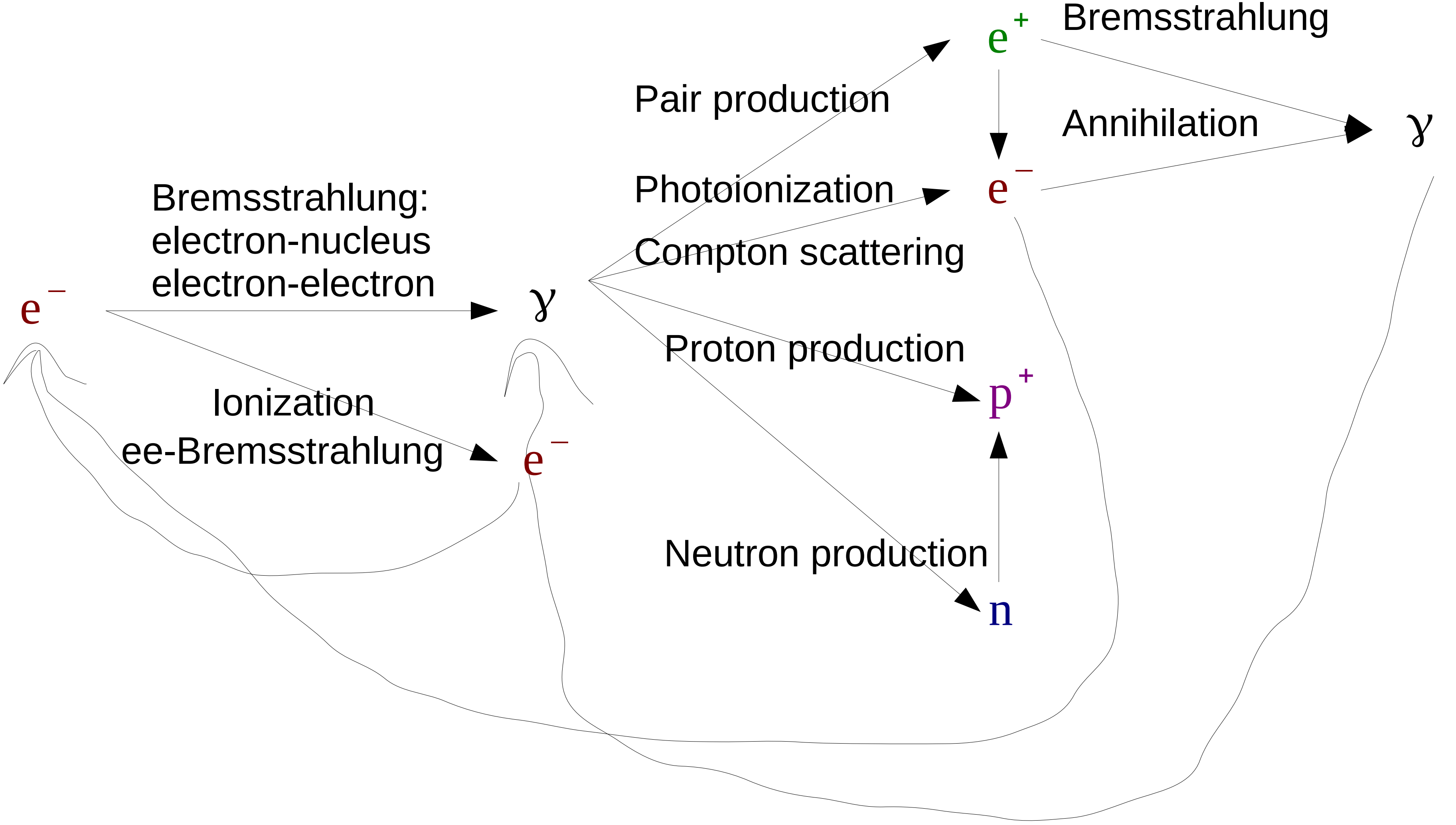
Conversion from electrons to different species



Conversion from electrons to different species



Conversion from electrons to different species



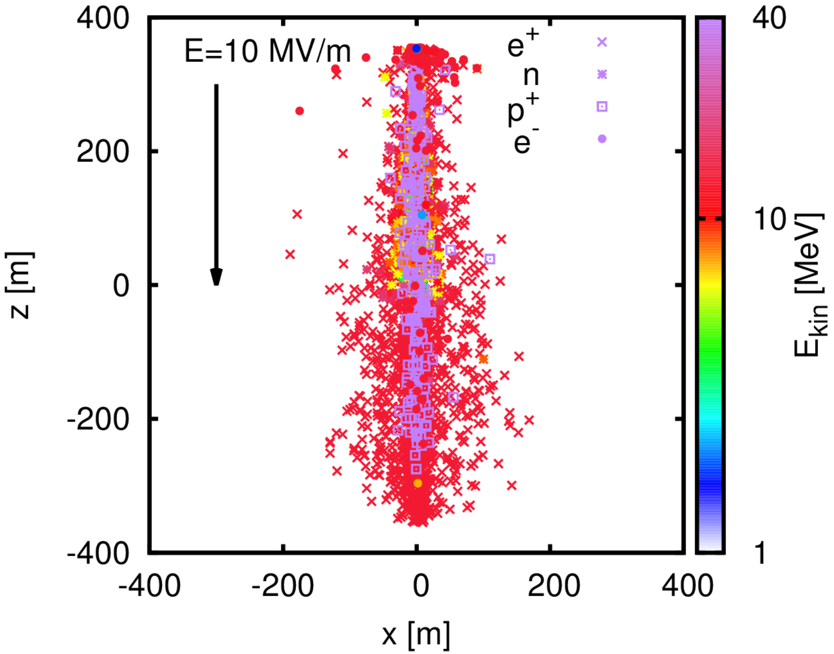
Example: Motion in a constant field

Start with upwards photon beam $$\frac{dn_\gamma}{dE_\gamma} \sim e^{-E_\gamma/3\,\mathrm{MeV}}$$

[In prep.]

Example: Motion in a constant field

Start with upwards photon beam $\frac{dn_\gamma}{dE_\gamma} \sim e^{-E_\gamma/3\,\mathrm{MeV}}$



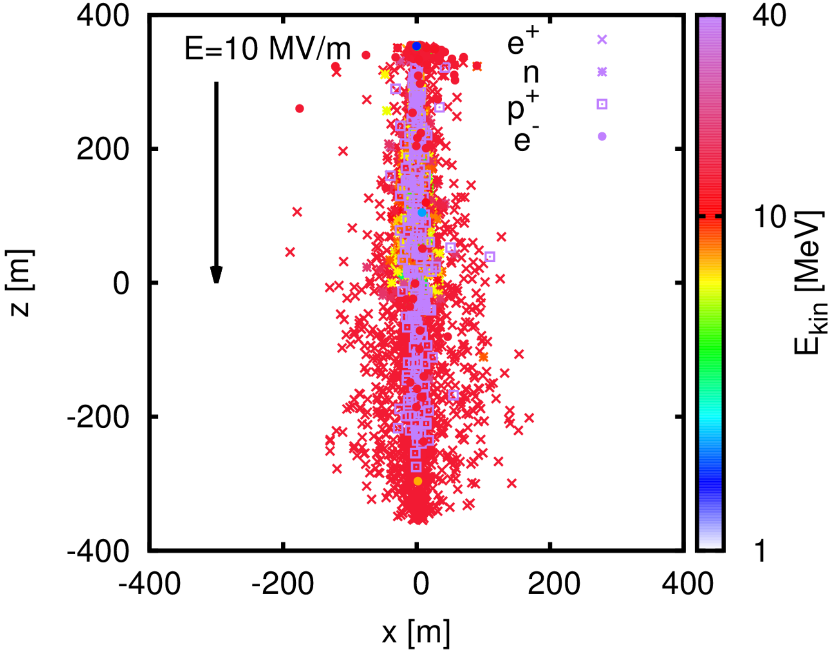
Position and energy of different species after 1 μs

i) photon produce leptons and hadrons along their path

[In prep.]

Example: Motion in a constant field

Start with upwards photon beam $$\frac{dn_\gamma}{dE_\gamma} \sim e^{-E_\gamma/3\,\mathrm{MeV}}$$



Position and energy of different species after 1 μs

i) photon produce leptons and hadrons along their path
ii) electrons move against the electric field

[In prep.]

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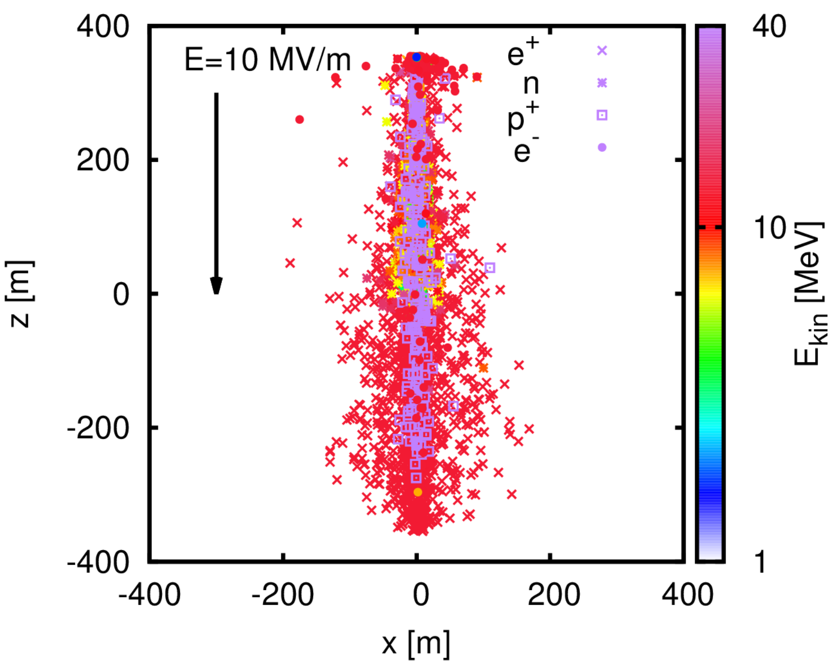

Position and energy of different species after 1 μs

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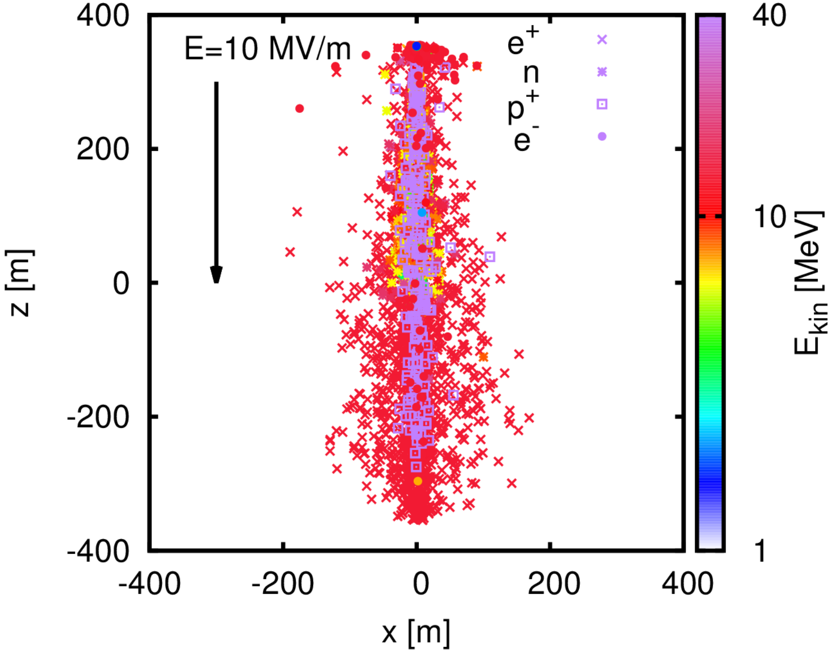
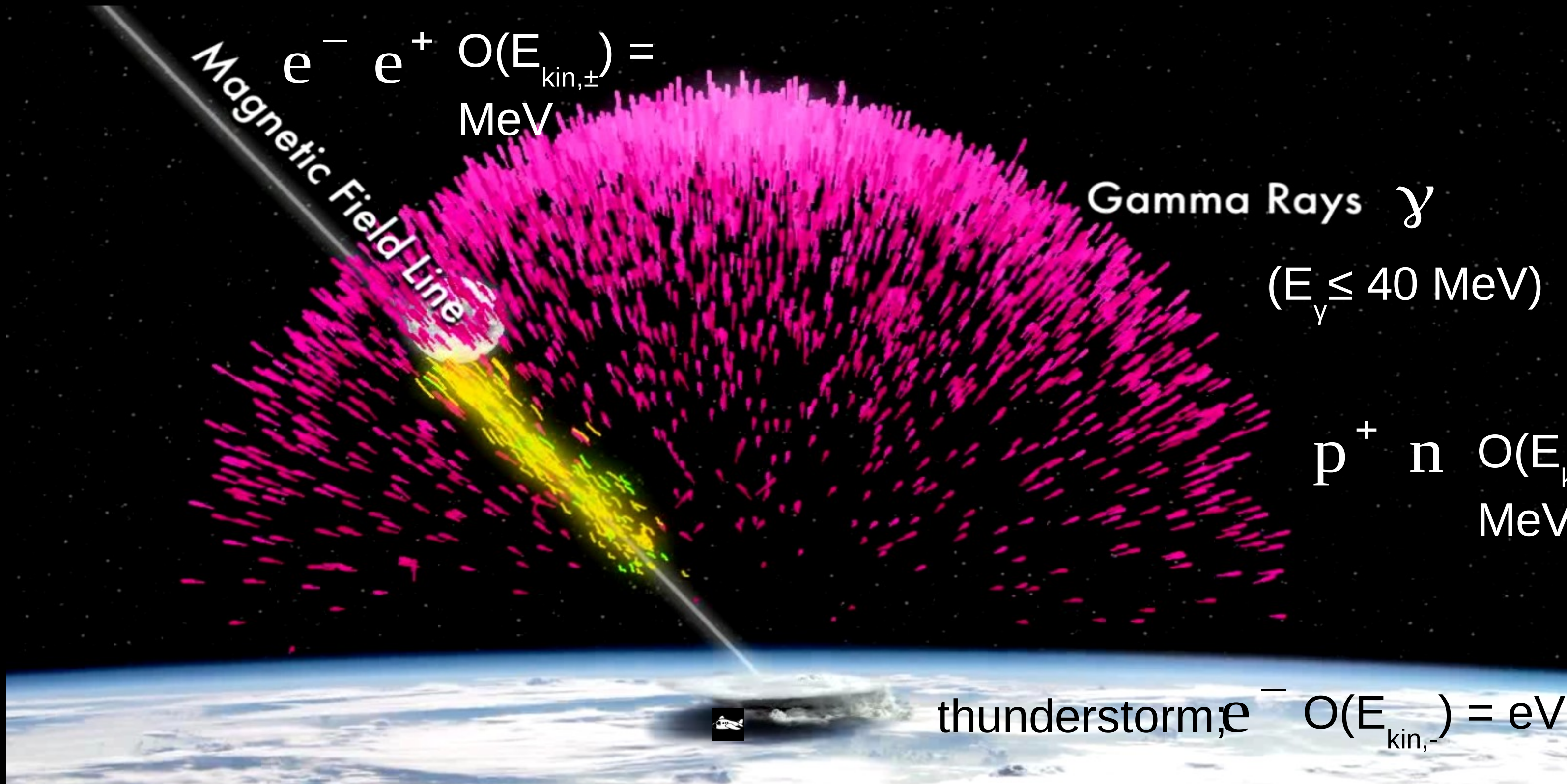


Position and energy of different species after 1 μs

i) photon produce leptons and hadrons along their path
ii) electrons move against the electric field
iii) positrons in the opposite direction
iv) protons and neutrons much more slower than leptons

[In prep.]

Conclusion



[http://www.nasa.gov/mission_pages/GLAST/news/vision-improve_prt.htm]