2.3 Cosmic ray Electrons

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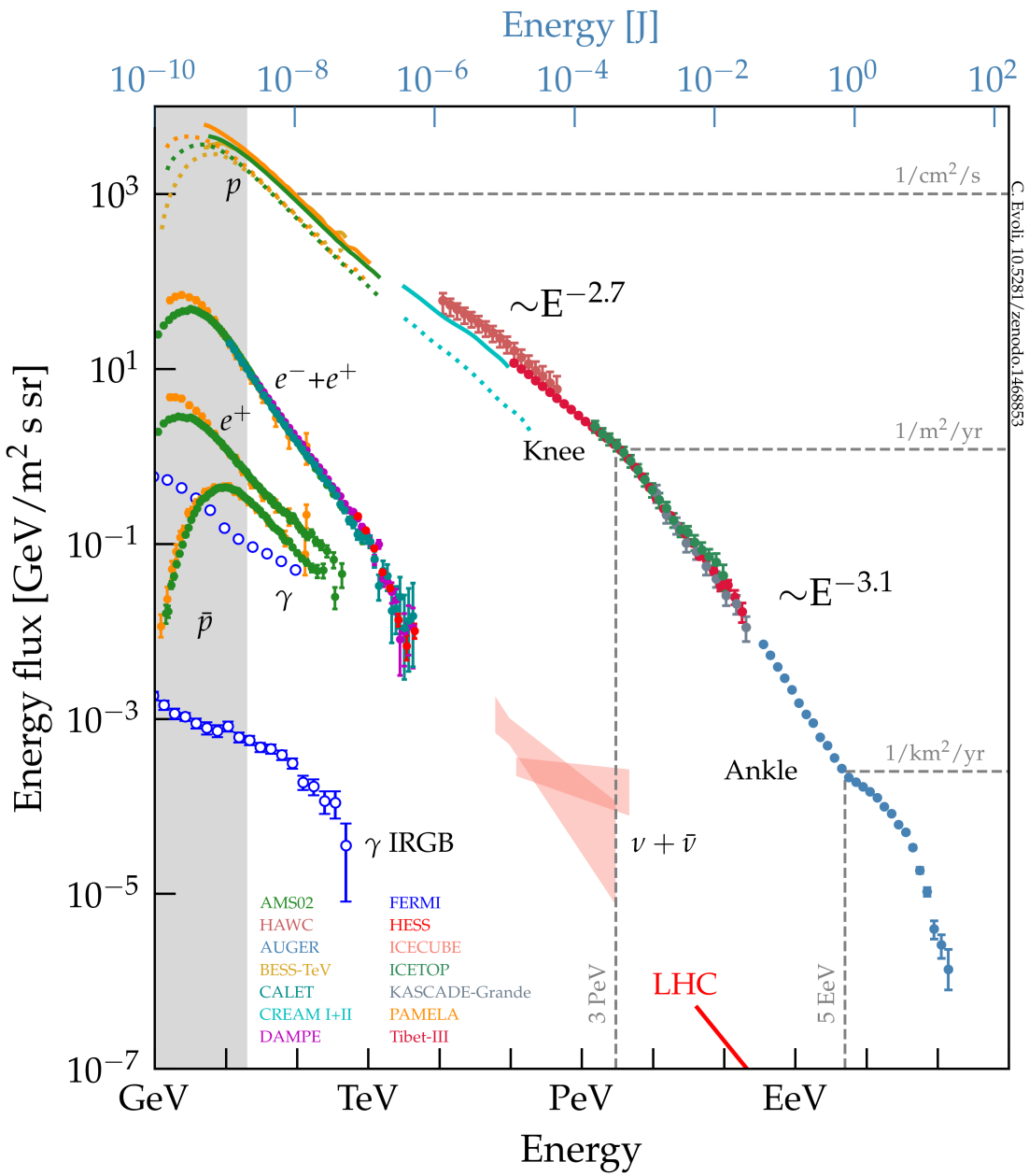
Cosmic ray electrons

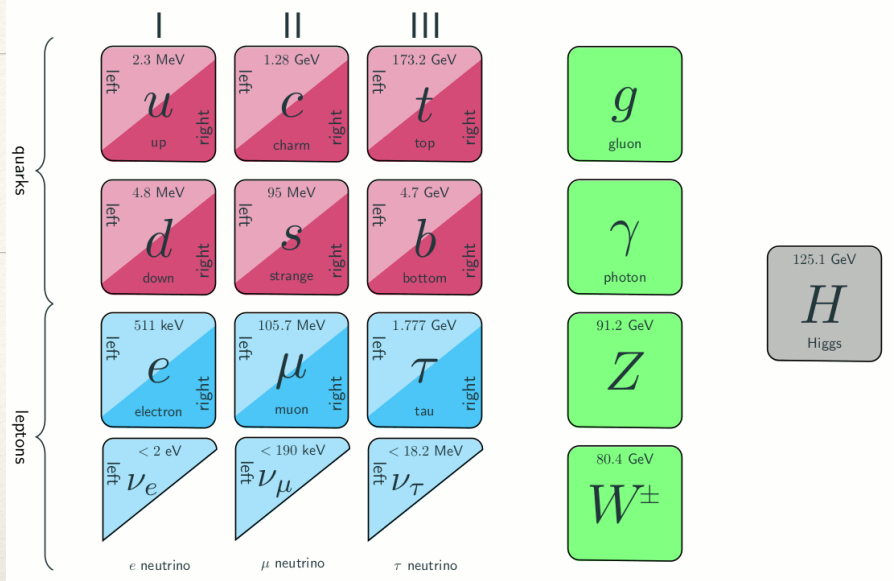
- If cosmic rays are normal stuff accelerated to high energies
- Electrons can also be accelerated

- Observation
  - Electrons has smaller flux than protons
  - The spectral index is softer



Cosmic ray electrons

- We need to be more careful for electrons
- It is lighter than protons about 2000 times



Electron mass ~ 511 keV
Proton mass ~ 1 GeV

- Consider electron-photon scattering
- Classically/historically:
  - Thompson scattering
  - $$\sigma_t = \frac{8\pi}{3}\left(\frac{q^2}{4\pi\varepsilon_0 mc^2}\right)^2$$
  - For photon-proton elastic scattering, it is weaker by $\left(\frac{m_e}{m_p}\right)^2 \sim 2\times 10^{-7}$
  - Proton energy loss have been ignored.
  - **Electron energy loss during propagation cannot be ignored**

Electron-Matter interactions

- If a particle interacts with stuff lower energy than itself => energy loss

- Ionization
  - Kicking electrons off atoms
- Moller/Bhabba scattering
  - e^-/e^+ + electron scattering
- Positron annihilation
  - $e^+ + e^- \rightarrow \gamma + \gamma$

- Bremsstrahlung

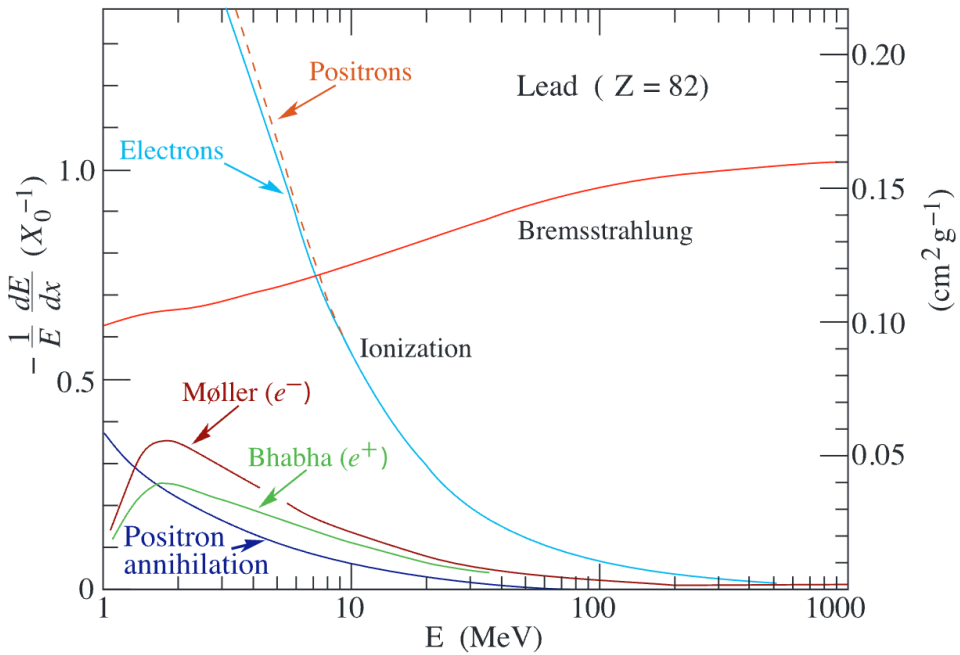
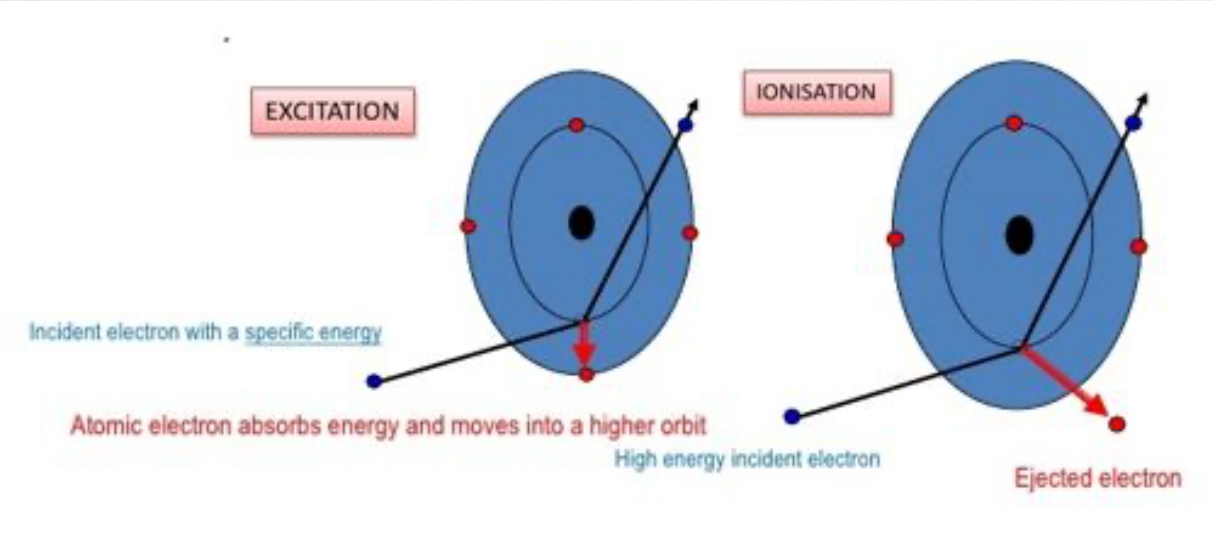
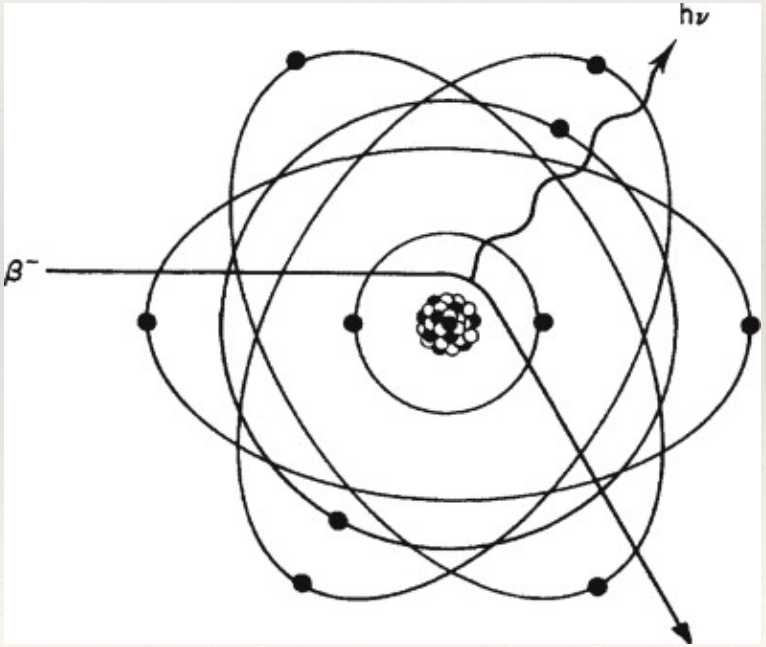


Figure 34.11: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Møller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use $X_0(\text{Pb}) = 5.82$ g/cm^2, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials ($X_0(\text{Pb}) = 6.37$ g/cm^2).

Electron energy loss process in matter

- Ionization energy loss
  - Atomic electrons being kicked off
- Bremsstrahlung
  - Electrons deflected by electric fields of a nuclei

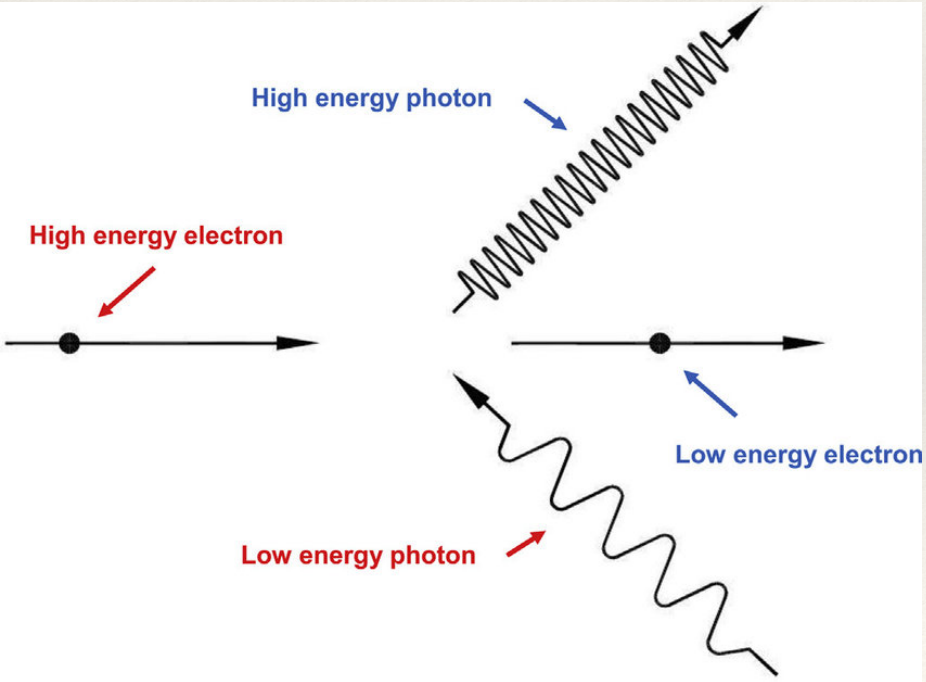




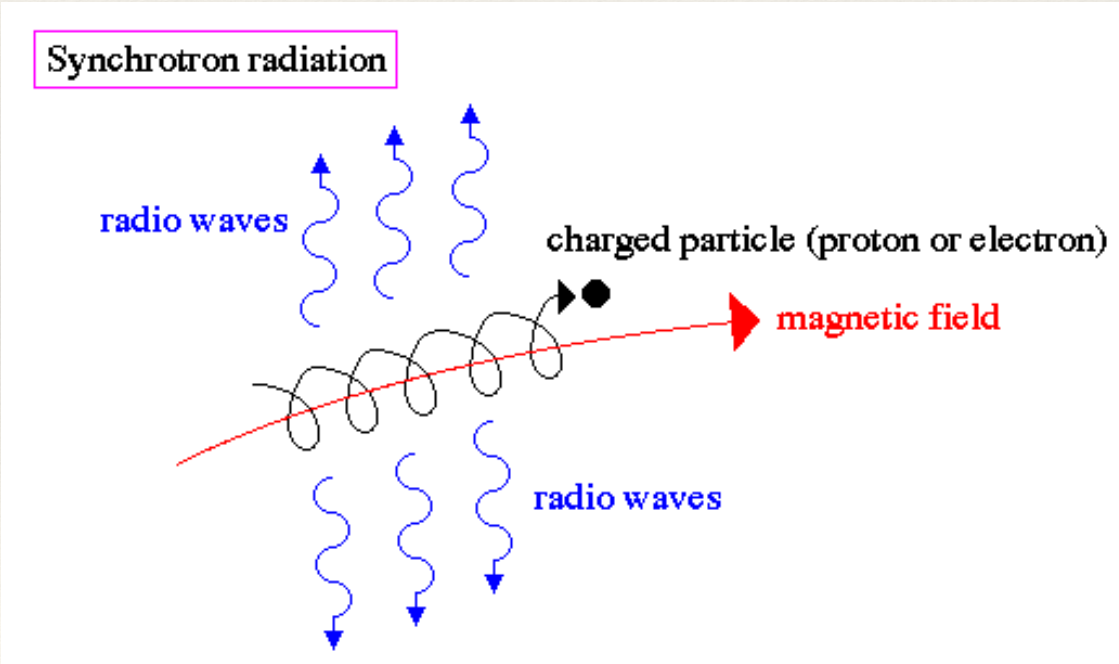
However, there are not much matter in space
There are additional energy loss processes

Electron energy loss in space

- Inverse-Compton scattering
  - Low energy photon up-scattered by electrons

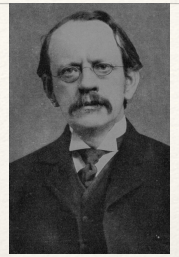


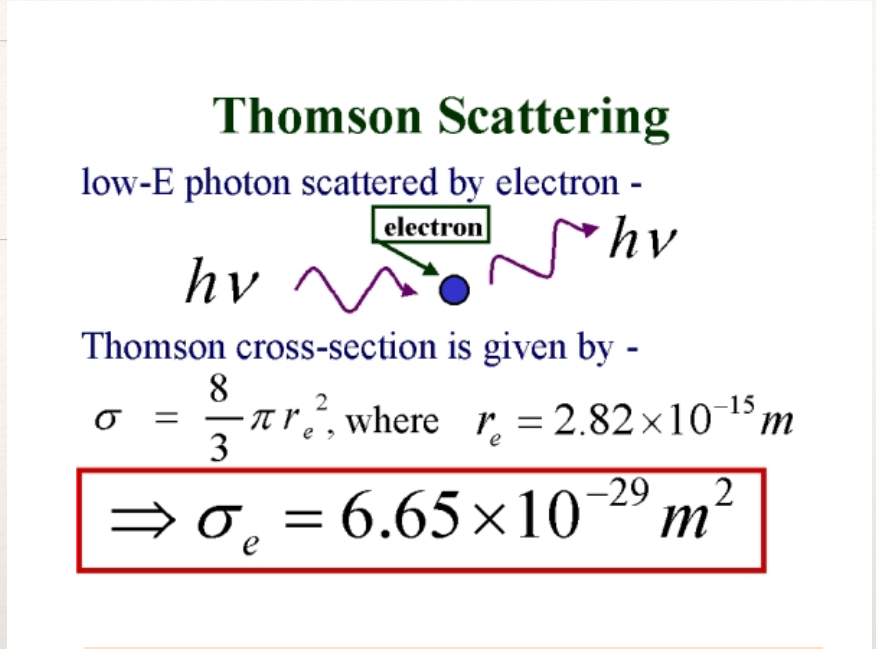
- Synchrotron radiation
  - Curved motion in magnetic field -> radiation



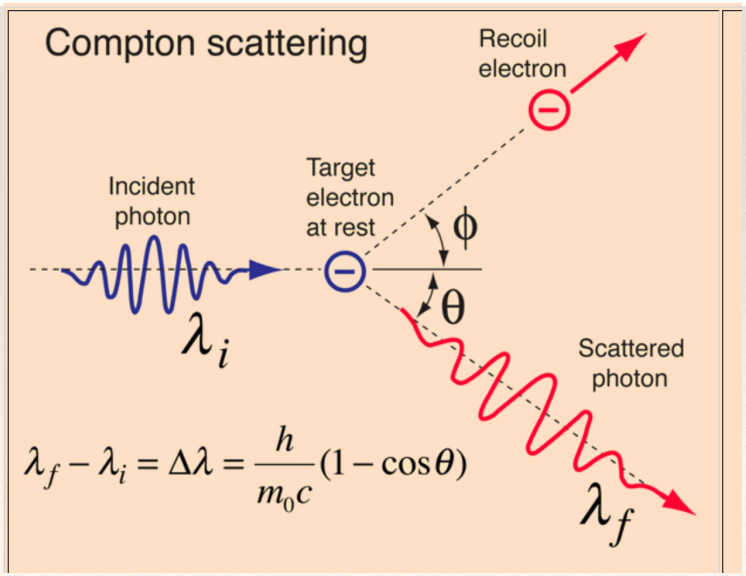
Electron photon interaction

- Thomson scattering
  - Photon electron **elastic** scattering
  - Photon energy doesnt change





- Compton scattering
  - Photon electron **inelastic** scattering
  - Photon energy **changed**

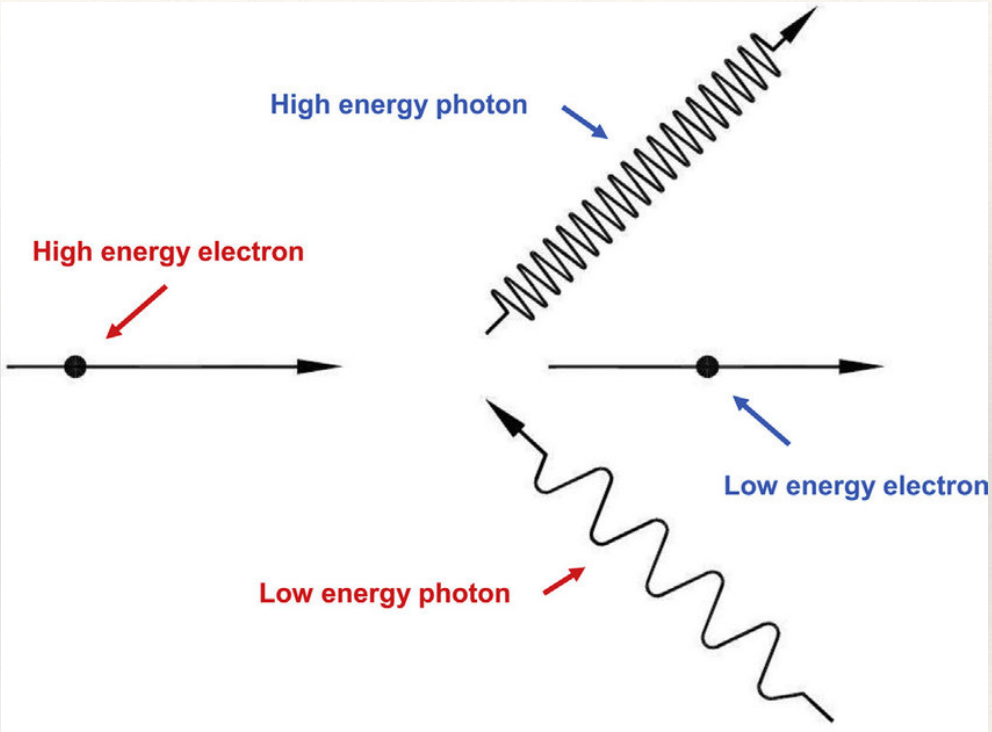


This depends whether the incoming
Photon energy is comparable with rest mass of electrons

Inverse Compton Scattering

Inverse Compton Scattering

- Exercise
- Let's consider TeV CR electron, scattering on CMB photons (2.7K thermal distribution)
- Photon energy in CR frame E_{ph} ~ kT ~ 10^{-4}eV
- What is the the CMB photon energy in electron rest frame?
- What is the maximum up-scatter photon energy in observer frame?



Inverse Compton Scattering

- Transformation from CR frame to Electron Rest frame
  - headon scattering, boost along the electron direction
- $$\begin{bmatrix} E'_{ph} \\ E'_{ph} \end{bmatrix} = \begin{bmatrix} \gamma & \gamma\beta \\ \gamma\beta & \gamma \end{bmatrix} \begin{bmatrix} E_{ph} \\ E_{ph} \end{bmatrix}$$
- $E'_{ph} = \gamma(1+\beta)E_{ph} \simeq 2\gamma E_{ph}$
- We are in Thomson regime,
- So after scattering in CM frame, the outgoing photon energy
  - $E'_{\gamma} = E'_{ph} = 2\gamma E_{ph}$ [This is only true for Thomson]

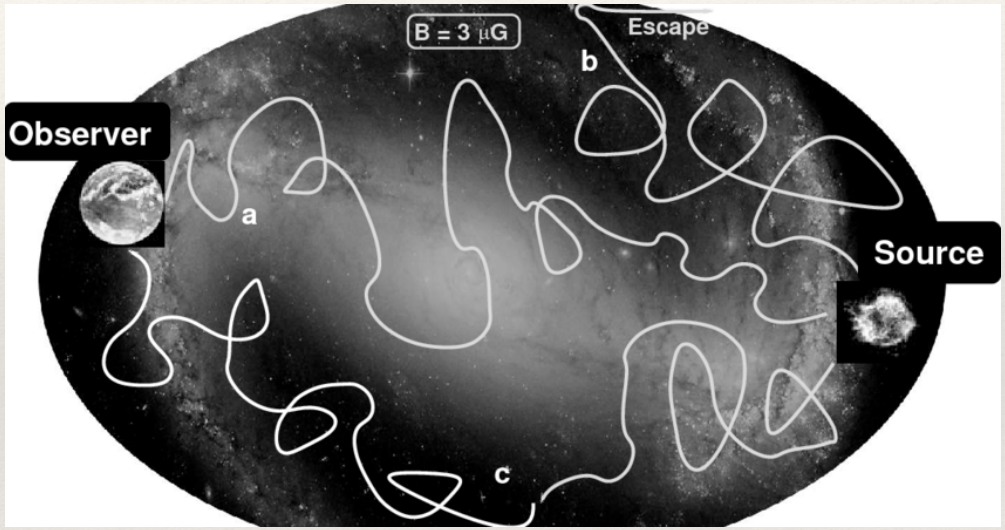
Inverse Compton Scattering

- So after scattering in ERS frame, the outgoing photon energy
  - $E'_\gamma = E'_{ph} = 2\gamma E_{ph}$
- Now boost back to the CR frame
- Notice that the boost direction is again along the direction of photon
- $\begin{bmatrix} E_\gamma \\ E_\gamma \end{bmatrix} = \begin{bmatrix} \gamma & \gamma\beta \\ \gamma\beta & \gamma \end{bmatrix} \begin{bmatrix} E'_\gamma \\ E'_\gamma \end{bmatrix}$
- $E_\gamma \simeq 2\gamma E'_\gamma \simeq 4\gamma^2 E_{ph}$
  - What is wrong with this, how to fix it?

IC energy loss <–>. IC photon emission

- So, significant amount of energy can be transfer from electrons to low-energy photon field
- Contributes to electron energy loss
- IC photon emission: one way of gamma-ray production

- ***We need the rate of energy loss for electrons when traveling in the galaxy, encountering photons***



Blumenthal & Gould 1970 Or Longair, Rybicki&Lightman

IC energy loss

In the CR frame, electron energy loss = photon energy gain

$$-\frac{dE_e}{dt} = \frac{dE_\gamma}{dt}$$

And we will use that in the energy change rate is the same in ERS and CR frame:

$$\frac{dE'_\gamma}{dt'} = \frac{dE_\gamma}{dt}$$

As

$$dE' = \gamma(1 - \beta\cos\theta)dE \rightarrow \gamma dE$$

$$dt' \rightarrow \gamma dt$$

Both energy and time are the first component of a 4-vector

Blumenthal & Gould 1970 Or Longair, Rybicki&Lightman

IC energy loss

In the CR frame, electron energy loss = photon energy gain

$$-\frac{dE_e}{dt} = \frac{dE_\gamma}{dt}$$

And we will use that in the energy change rate is the same in CM and CR frame:

$$\frac{dE'_\gamma}{dt'} = \frac{dE_\gamma}{dt}$$

——— in the ERS frame——

$$\frac{dE'_\gamma}{dt'} = \text{power emitted by the electron}$$

IC energy loss

——— in the ERS frame——

$$\frac{dE'_\gamma}{dt'} = \text{power emitted by the electron}$$

= number of electron-photon scattering x outgoing photon energy

We will short-hand the notation of

$$\int dn_{ph} = \int \frac{dn_{ph}}{dE_{ph}d\Omega} dE_{ph} d\Omega \quad [n_{ph} \text{ is number density}]$$

$$\frac{dE'_\gamma}{dt'} = \int E'_\gamma \frac{cd\sigma}{dE'_\gamma} dE'_\gamma dn'_{ph}$$

IC energy loss

Re-call scattering rates, and the production of photons

$$\frac{dE'_\gamma}{dt'} = \int E'_\gamma \frac{c d\sigma}{dE'_\gamma} dE'_\gamma dn'_{ph}$$

Let's work in Thomson limit in the ERS frame, what is the differential cross section?

$$\frac{d\sigma}{dE'_\gamma} = \sigma_t \delta(E'_{ph} - E'_\gamma)$$

Introduce the Dirac Delta function

$$\frac{dE'_\gamma}{dt'} = \int E'_\gamma c \ \sigma_t \delta(E'_{ph} - E'_\gamma) dE'_\gamma dn'_{ph} = \int E'_{ph} c \ \sigma_t \delta(E'_{ph} - E'_\gamma) dE'_\gamma dn'_{ph}$$

$$\frac{dE'_\gamma}{dt'} = \int E'_{ph} c \ \sigma_t dn'_{ph} = c \ \sigma_t U'_{ph}$$

U'_{ph} **is the photon energy density (in ERS)**

IC energy loss

$$\frac{dE'_\gamma}{dt'} = \int E'_{ph} c\ \sigma_t dn'_{ph} = c\ \sigma_t U'_{ph}$$

U'_{ph} **is the photon energy density (in ERS)**

$$U'_{ph} = \int E'_{ph} dn'_{ph} = \int E'^2_{ph} \frac{dn'_{ph}}{E'_{ph}}$$

$$U'_{ph} = \int E'^2_{ph} \frac{dn'_{ph}}{E'_{ph}} = \int E'^2_{ph} \frac{dn_{ph}}{E_{ph}}$$

The combination $\frac{dn'_{ph}}{E'_{ph}} \sim \frac{N}{VE}$

Volume and energy transform in opposite way in Lorentz transformation.

$\left(\frac{dn_{ph}}{E_{ph}}\right)$ is Lorentz invariant

IC energy loss

$$U'_{ph} = \int E'^2_{ph} \frac{dn'_{ph}}{E'_{ph}} = \int E'^2_{ph} \frac{dn_{ph}}{E_{ph}}$$

$$E'_{ph} = E_{ph}\gamma(1 - \beta\cos\theta)$$

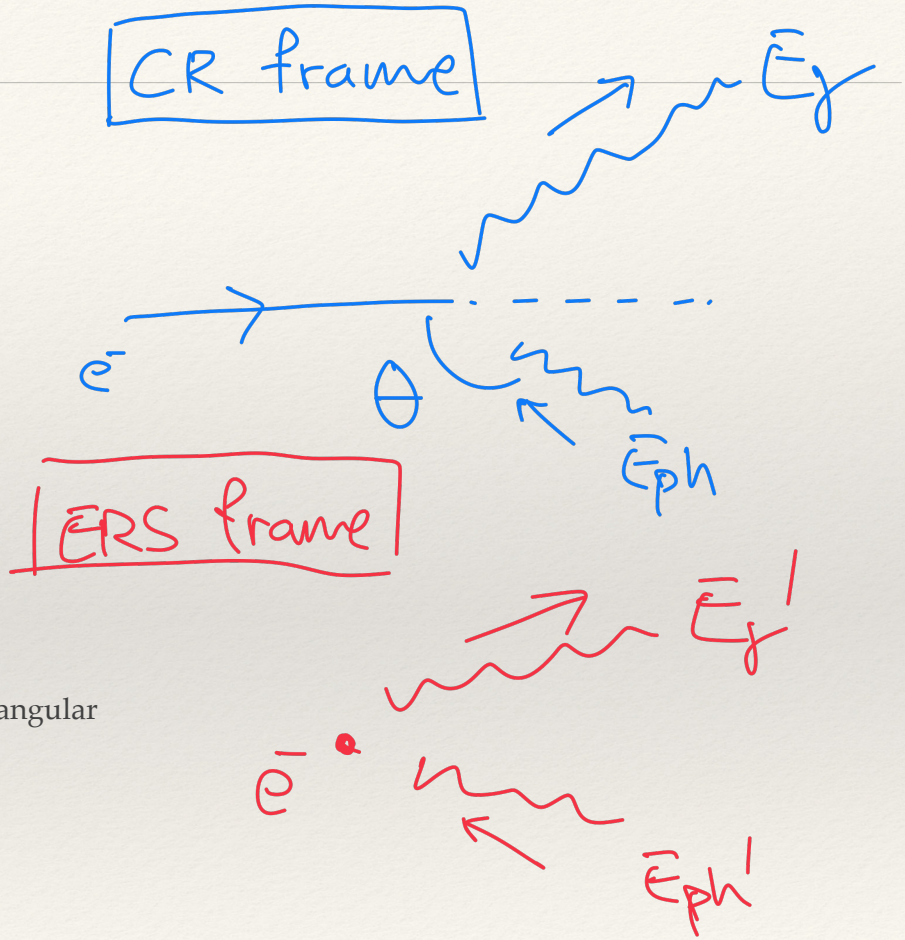
$$U'_{ph} = \int E_{ph}\gamma^2(1 - \beta\cos\theta)^2 dn_{ph}$$

$$U'_{ph} = \gamma^2 \int E_{ph}(1 - \beta\cos\theta)^2 \frac{dn_{ph}}{dE_{ph}d\Omega} dE_{ph}d\Omega$$

$$U'_{ph} = \gamma^2 \int E_{ph} \frac{dn_{ph}}{dE_{ph}} dE_{ph} 4\pi(1 + \frac{\beta^2}{3}) \frac{1}{4\pi}$$

We will assume that the photon distribution in [CR frame] is isotropic, so $\frac{dn_{ph}}{dE_{ph}d\Omega}$ has no angular dependence , $\frac{dn_{ph}}{dE_{ph}d\Omega} = \frac{1}{4\pi}\frac{dn_{ph}}{dE_{ph}}$

Then we need to do $\int (1 - \beta\cos\theta)^2 2\pi d\cos\theta = 2\pi(2 + \beta^2\frac{2}{3}) = 4\pi(1 + \frac{\beta^2}{3})$



IC energy loss

- $U'_{ph} = (1 + \frac{\beta^2}{3})\gamma^2 U_{ph}$
- $\frac{dE}{dt} = \frac{dE'_\gamma}{dt'} = \int E'_{ph} c\ \sigma_t dn'_{ph} = c\ \sigma_t U'_{ph} = c\sigma_t(1 + \frac{\beta^2}{3})\gamma^2 U_{ph}$
- This "dE/dt" is the energy gained in the photon field from up scattering the low energy photons
- The actual change in energy in the whole system need to minus a factor of ("dE/dt" $= c\ \sigma_t U_{ph}$)
- $\frac{dE}{dt} = c\sigma_t(1 + \frac{\beta^2}{3})\gamma^2 U_{ph} - c\ \sigma_t U_{ph} = c\sigma_t \frac{4\beta^2}{3}\gamma^2 U_{ph}$
- $\frac{dE_e}{dt} = -\frac{4}{3} c\sigma_t U_{ph} \left(\frac{\beta E_e}{m_e c^2}\right)^2 \simeq -\frac{4}{3} c\sigma_t U_{ph} \left(\frac{E_e}{m_e c^2}\right)^2$
  - we are going to set $\beta \sim 1$, as our electrons are very relativistic.

Energy loss rate proportional to [cross section] x [photon energy density] x [energy squared.]

Beyond Thomson

The full photon-electron scattering is described by the Klein-Nishina formula (~1928)

In the ERS frame

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(\frac{\lambda}{\lambda'}\right)^2 \left[\frac{\lambda}{\lambda'} + \frac{\lambda'}{\lambda} - \sin^2(\theta)\right]$$

λ, λ' are the wavelengths of incident and outgoing photons

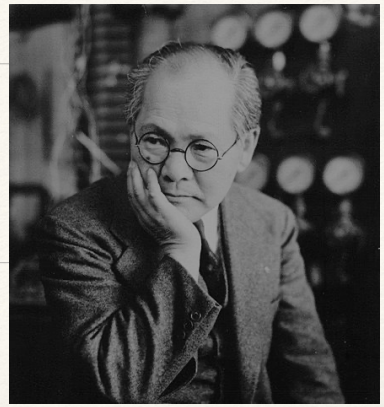
($\lambda = \lambda'$ for Thomson scattering)

Yoshio Nishina

Article Talk

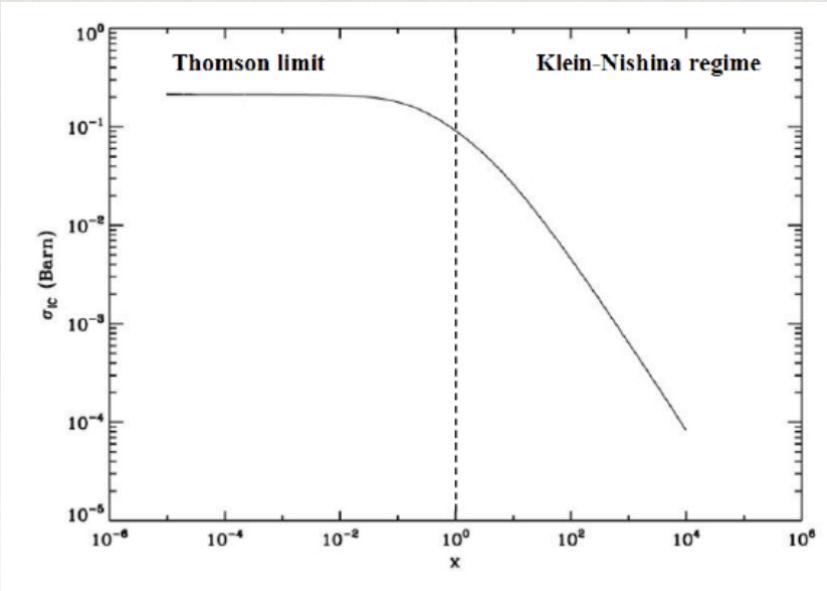
From Wikipedia, the free encyclopedia

Yoshio Nishina (仁科 芳雄, *Nishina Yoshio*, December 6, 1890 – January 10, 1951) was a Japanese physicist who was called "the founding father of modern physics research in Japan". He led the efforts of Japan to develop an atomic bomb during World War II.[1]



Compton's forumla

$$\frac{\lambda}{\lambda'} = \frac{E_\gamma}{E_{ph}} = \frac{1}{1 + \frac{E_{ph}}{m_e c^2}(1 - \cos\theta)}$$

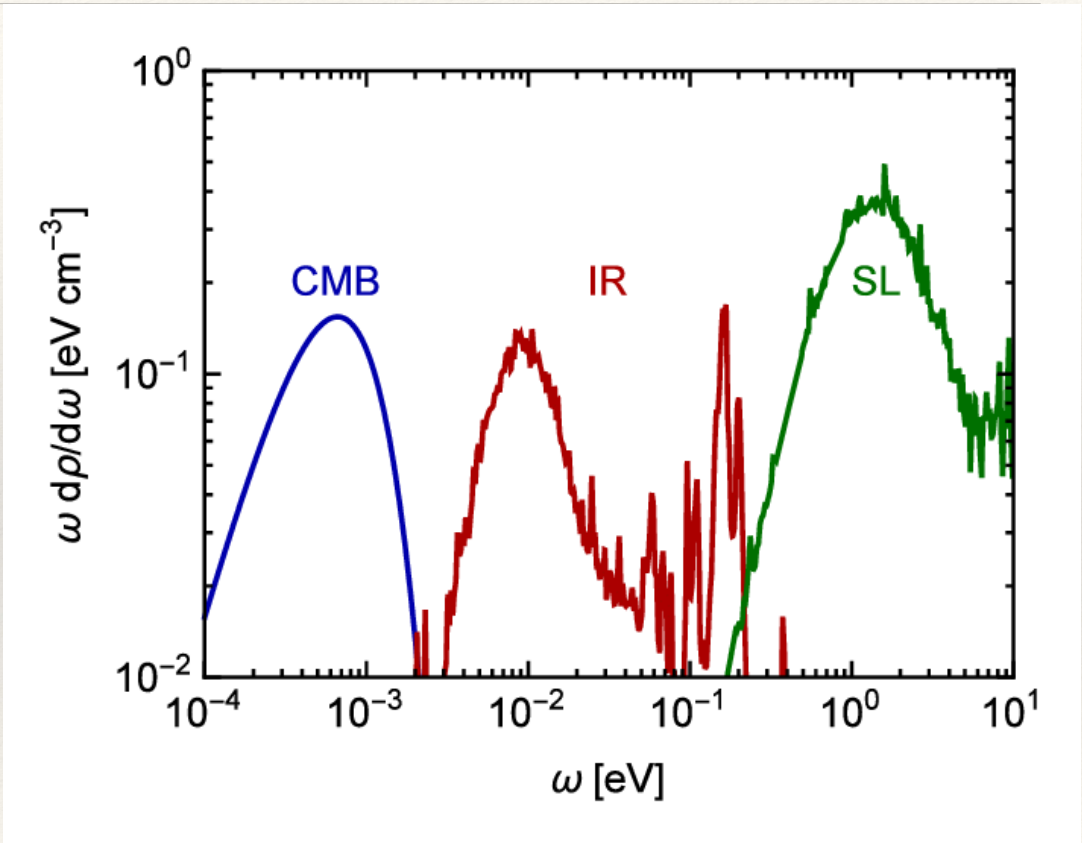


$$x = \frac{E_{ph}}{m_e c^2}$$

IC energy loss

- $$\frac{dE}{dt} = -\frac{4}{3} c\sigma_t U_{ph} f_{KN}(E) \left(\frac{E}{m_e c^2}\right)^2$$
- Where U_{ph} is the photon energy density
- $f_{KN}(E)$ takes into account the difference between Thomson regime and Klein-Nishina, the full expression.

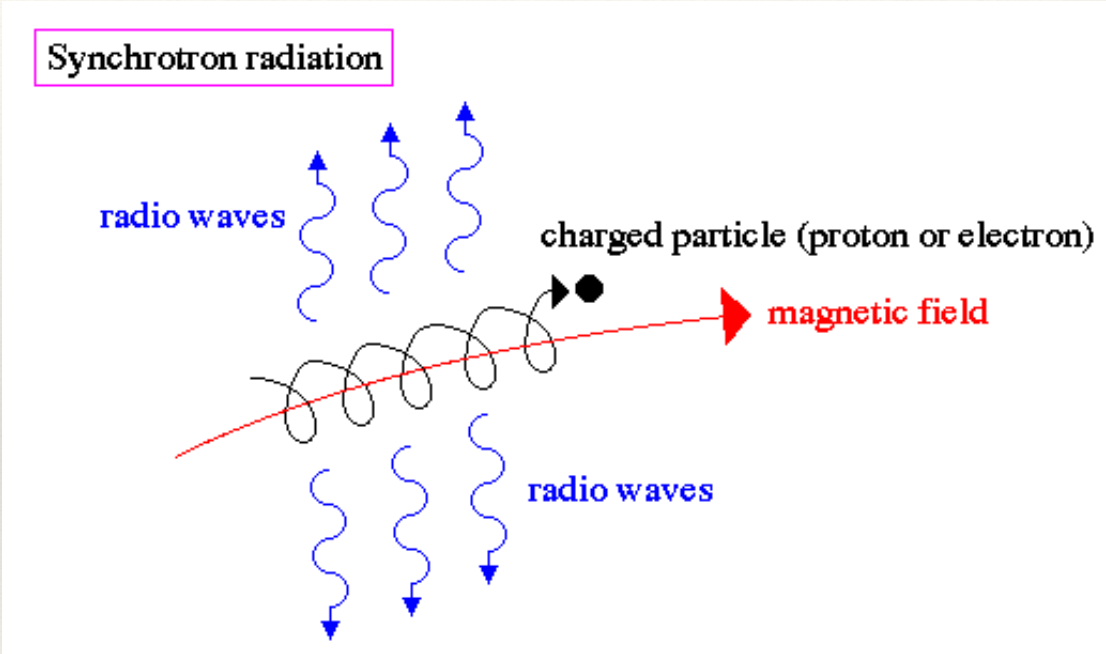
- Which source of photon determines whether we need to worry about KN?
- What CR electron energy we need to start worry about KN?



Synchrotron Energy loss

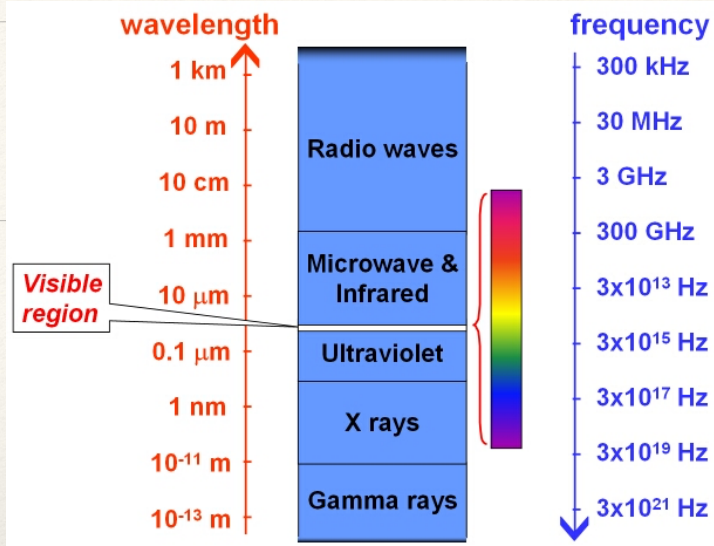
Synchotron energy loss

- Let's cheat to get this
- IC = electron + photon
- Syn = electron + Magnetic fields (EM field~ photons)



Synchotron energy loss

- $$\frac{dE}{dt} = -\frac{4}{3} c\sigma_t U_B \left(\frac{E}{m_e c^2}\right)^2$$
- Same mathematical structure
- U_B the magnetic field energy density
  - $\frac{B^2}{2\mu_0}$ in SI unit.
- Typical "photon energy" in the magnetic field ~ Cyclotron frequency~ $(\frac{1}{L_R}) \sim \frac{eB}{mc}$



- From IC: $E_\gamma \simeq 2\gamma E'_\gamma \simeq 4\gamma^2 E_{ph}$

Synchrotron radiation frequency

$$\nu_c \sim \gamma^2 \frac{eB}{mc} \sim (\frac{E}{m})^2 \frac{eB}{mc}$$

$$\nu_c = \frac{3eE^2B}{4\pi m_e^3 c^4} = 16\,\mathrm{MHz}\left(\frac{E}{\mathrm{GeV}}\right)^2\left(\frac{B}{\mu\mathrm{G}}\right)$$

Synchrotron and IC emission [a peep into γ-astrophysics]

- Both IC and Syn are electron energy loss mechanism.
- That means the presence of high-energy electrons can produce radio and gamma-ray emission through these processes.

- Rate of IC photon production for each electron, at some electron energy E_e
- $\frac{dN}{dE_\gamma dt} = \int \frac{dn_{ph}}{dE_{ph} d\Omega} \frac{d\sigma}{dE_\gamma} c \, dE_{ph} d\Omega$ (Note that this is written in CR frame, not ERS frame as before)
- (What we did before was $\frac{dE_\gamma}{dt} = \int E_\gamma \frac{dN}{dE_\gamma dt} dE_\gamma$)
- Rate of IC photon production per volume
- $\frac{dn}{dE_\gamma dt} = \int \frac{dn_e}{dE_e d\Omega_e} \frac{dN}{dE_\gamma dt} dE_e d\Omega_e$ It is somewhat complicated.

Synchrotron and IC emission [a peep into γ-astrophysics]

- $$\frac{dn}{dE_\gamma dt} = \int \frac{dn_e}{dE_e d\Omega_e} \frac{dN}{dE_\gamma dt} dE_e d\Omega_e$$

- Can be analytically done assuming isotropic electron and photons
- $$P = E_\gamma \frac{dN}{dE_\gamma dt}$$

$$\mathcal{P}(\epsilon_1, E, r) = \frac{3\sigma_{\rm T}}{4\gamma^2}\epsilon_1 \int_0^1 dy \frac{n(\epsilon(y), r)}{y} \left[2y \ln y + y + 1 - 2y^2\right] \qquad \text{[Thomson limit]}.$$

$\epsilon_1 = E_\gamma$

- Or in KN

$$\mathcal{P}(\epsilon_1, E, r) = \frac{3\sigma_{\rm T}}{4\gamma^2}\epsilon_1 \int_{1/4\gamma^2}^1 dq \left(1 - \frac{1}{4q\gamma^2(1-\tilde{\epsilon}_1)}\right) \frac{n(\epsilon(q), r)}{q} \left[2q \ln q + q + 1 - 2q^2 + \frac{1}{2}\frac{\tilde{\epsilon}_1^2}{1-\tilde{\epsilon}_1}(1-q)\right]$$

- More work to take into account the angular distributions.

IC flux in our galaxy

The spectrum of isotropic diffuse gamma-ray emission between 100 MeV and 820 GeV

Fermi-LAT Collaboration • M. Ackermann (DESY) Show All(144)

Oct 14, 2014

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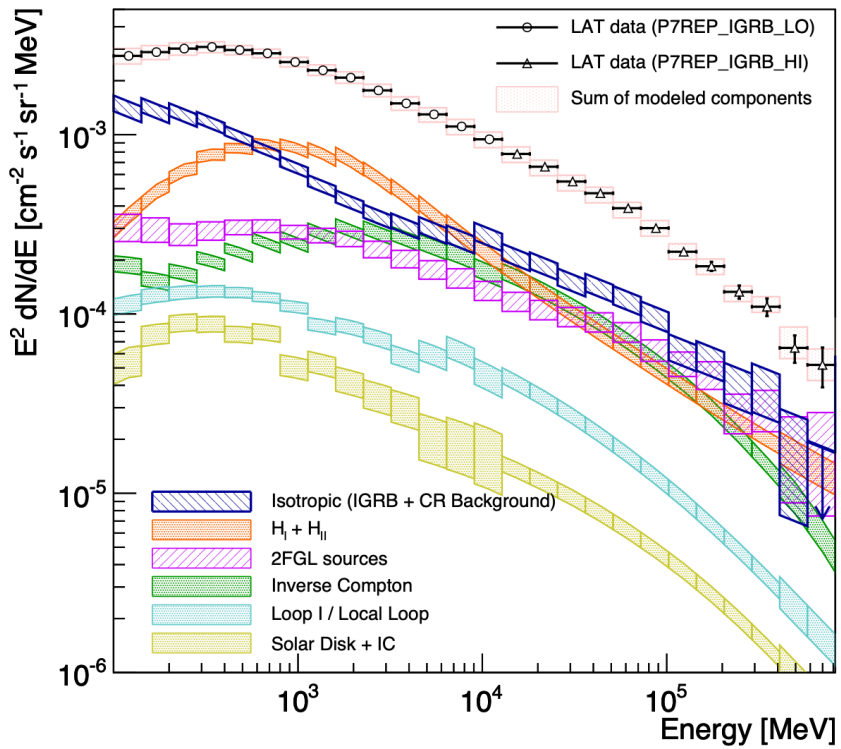
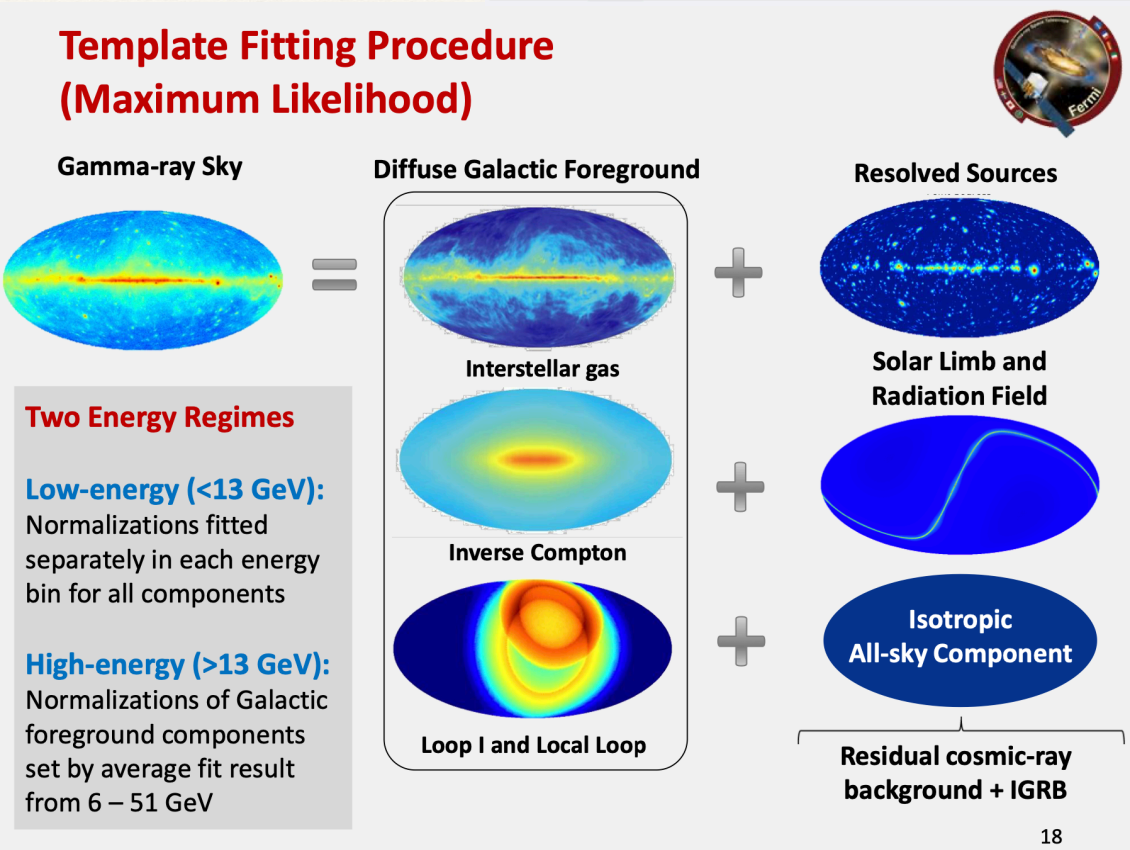


Fig. 4.— Results of the IGRB fit for foreground
tudes $|b| > 20°$ are shown. *Left:* Intensities attril



Cosmic Ray Propagation with energy loss

Leaky Box Model

- By aggressively simplify the problem.
- $\frac{\partial}{\partial t} n = D \nabla^2 n - \frac{\partial}{\partial E}\left(n\dot{E}\right) + Q$
- $\frac{n}{T_{esc}}$
- With energy loss
- $\frac{n}{T_{esc}} + \frac{\partial}{\partial E}\left(n\frac{dE}{dt}\right) = Q$

- We can define the characteristic energy loss time scale

$$T_{loss} = \frac{E}{|dE/dt|}$$

It is then helpful to compare

$$\frac{1}{T_{esc}} \text{ vs } \frac{1}{T_{loss}}$$

Tloss vs Tesc

- Now that we know $\frac{dE}{dt} \propto E^2$

$$T_{loss} = \frac{E}{|dE/dt|} \sim \text{E}$$

It is then helpful to compare

$$\frac{1}{T_{esc}} \propto E^{0.3}$$

$$\frac{1}{T_{loss}} \propto E$$

Go to high enough energy, it must be E_loss dominated

C/B ratio

- $T(E) \propto E^{-\delta}$
  - $\delta \sim [0.3, 0.4]$
- Recall that CR spectrum $E^{-2.7}$
- That means $Q(E) \sim E^{-2.3}$ or $E^{-2.4}$

Rigidity

$$R = \frac{pc}{q} \simeq E/q$$

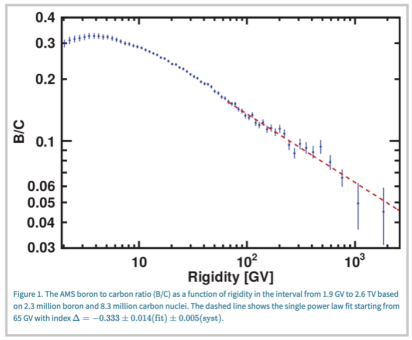
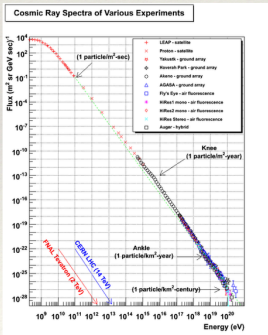
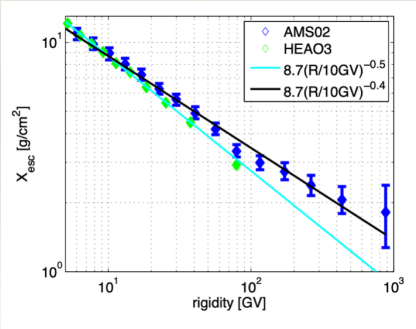


Figure 1. The AMS boron to carbon ratio (B/C) as a function of rigidity in the interval from 1.9 GV to 2.6 TV based on 2.3 million boron and 8.3 million carbon nuclei. The dashed line shows the single power law fit starting from 65 GV with index $\Delta = -0.333 \pm 0.014(\text{fit}) \pm 0.005(\text{syst})$.



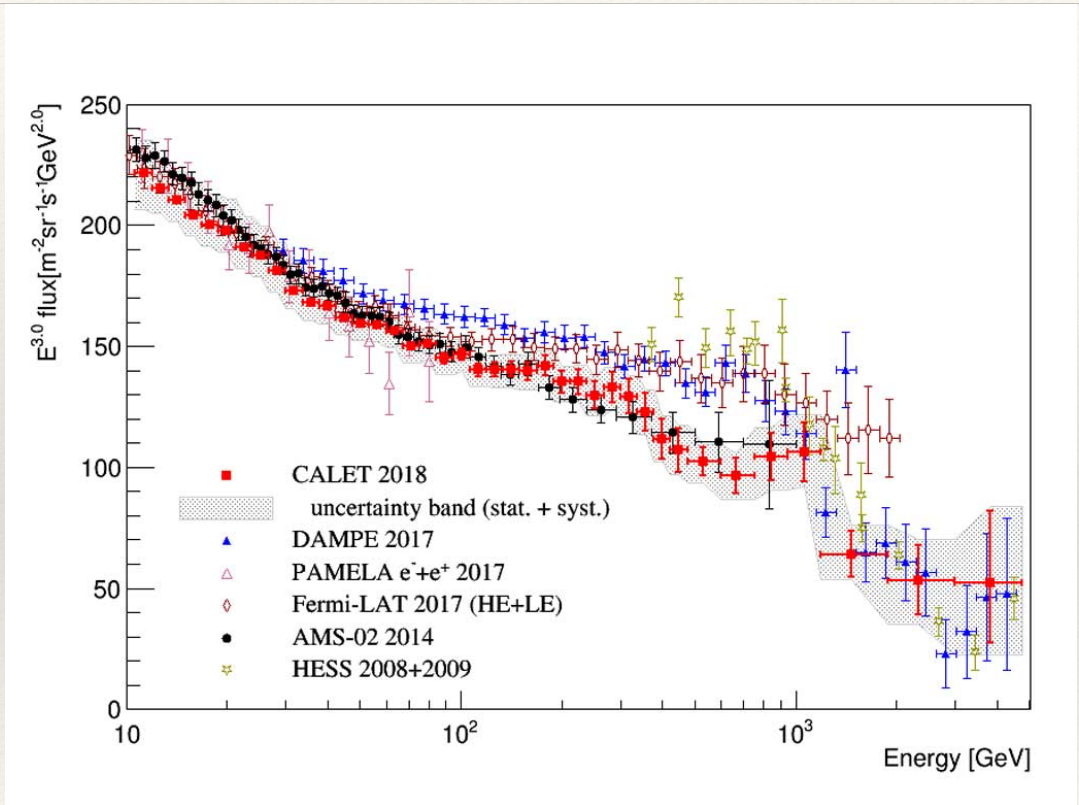


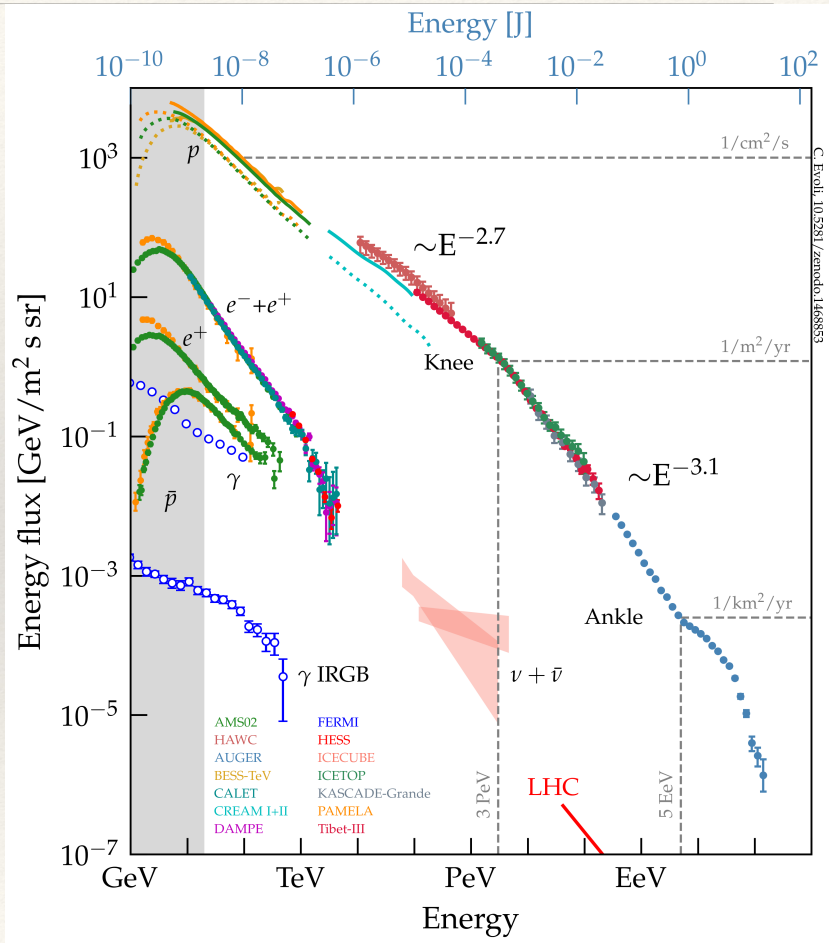
- $\frac{\partial}{\partial t} n = D \nabla^2 n - \frac{\partial}{\partial E}\left(n\dot{E}\right) + Q$
- $\rightarrow -\frac{\partial}{\partial E}\left(n\dot{E}\right) + Q = 0$
- Without the need for Leaky box assumption!
- Solution?

Tloss vs Tesc

- For an $Q \propto E^{-2.3}$
- $n \sim QT_{loss} \sim E^{-3.3}$

Cosmic-ray electrons ($e^+ + e^-$)

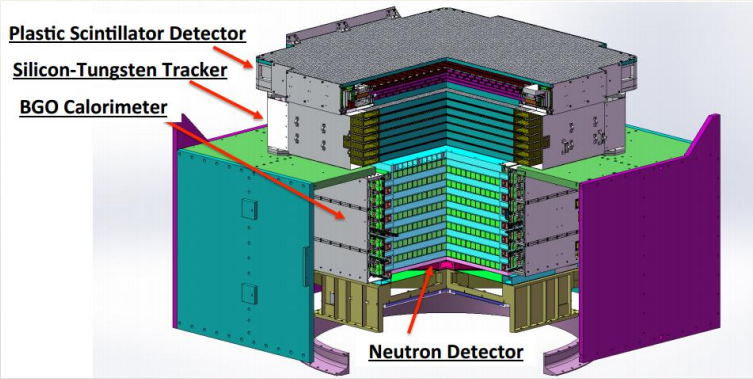


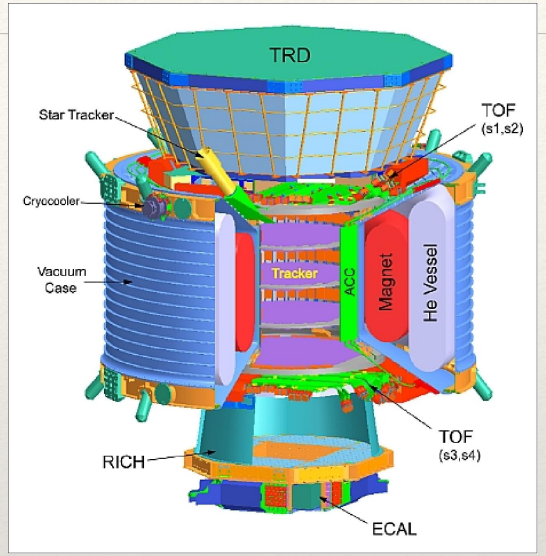


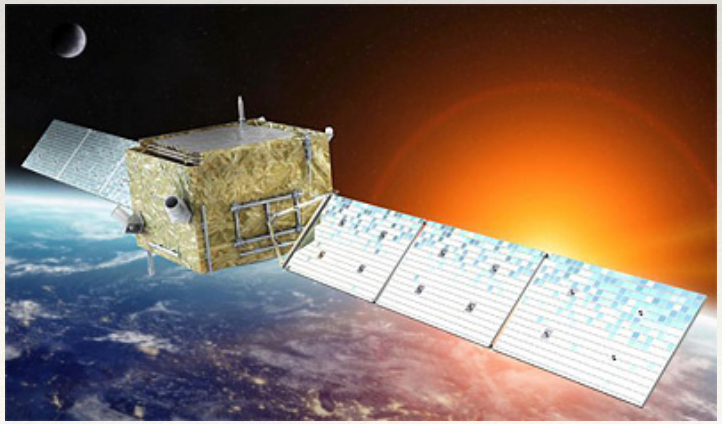
- Satellite measurements

Cosmic ray electron measurement

- Dampe/Fermi (no magnets)
- AMS-2, with magnets







Electron detection

- When electrons enter the detector, they loss energy following the plot in RHS
-

- Electron energy loss

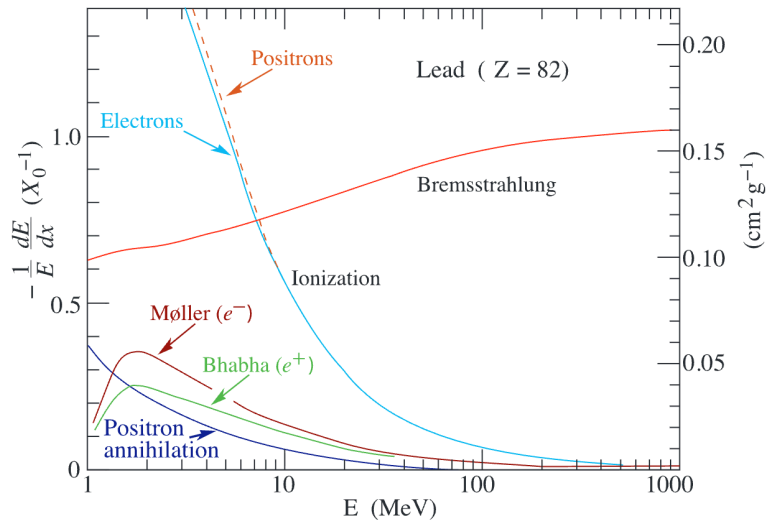
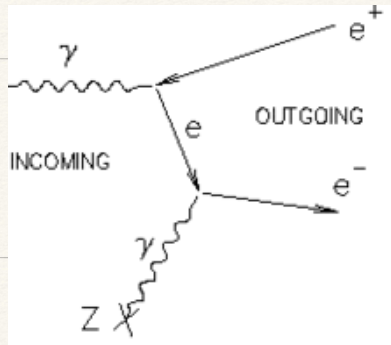
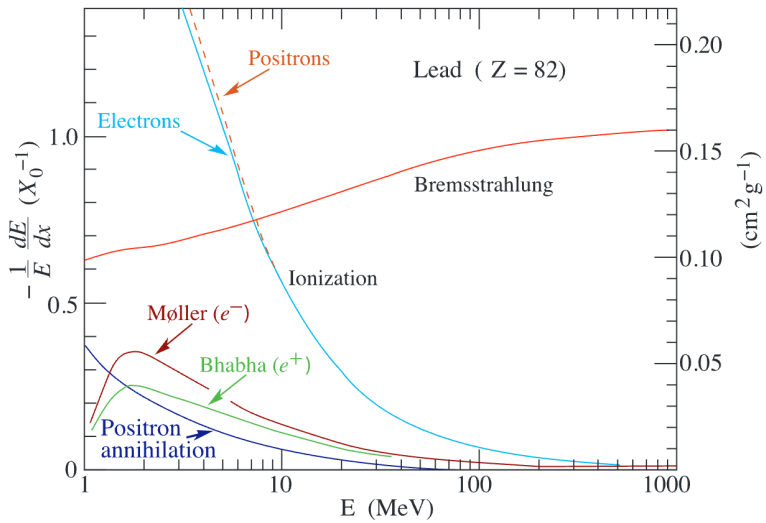


Figure 34.11: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Møller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use $X_0(\mathrm{Pb}) = 5.82$ g/cm^2, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials ($X_0(\mathrm{Pb}) = 6.37$ g/cm^2).

Electron detection in Matter



- Electron energy loss



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- Photon energy loss

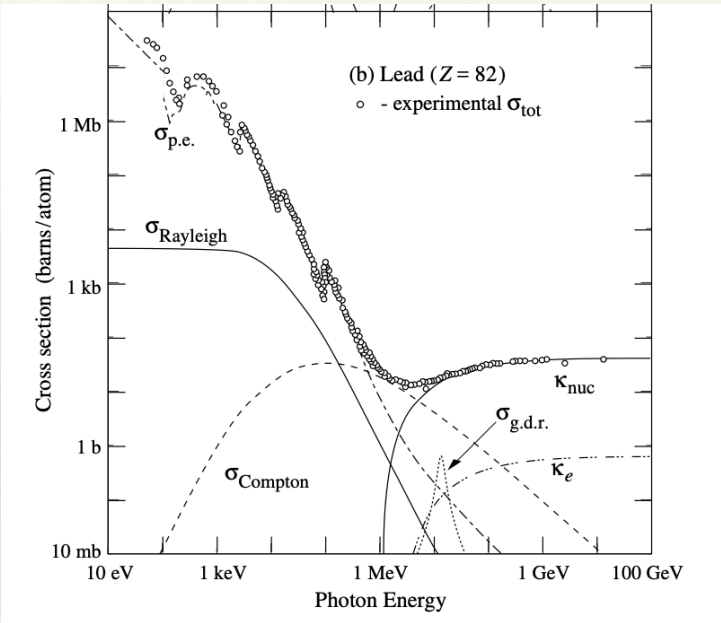


Figure 34.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [50]:

$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [51]. In these interactions, the target nucleus is usually broken up.

Electron -> Photons

- At high energies, above about 10 MeV
- Bremsstrahlung dominates electron energy loss
  - Production of photons
  - $e + A \rightarrow e + \gamma + A$
- Pair production dominates photon energy loss
  - Production of electrons(+positrons)
  - $\gamma + A \rightarrow A + e^{+} + e^{-}$
- Electrons/photons create each other!
  - Cascade/showers

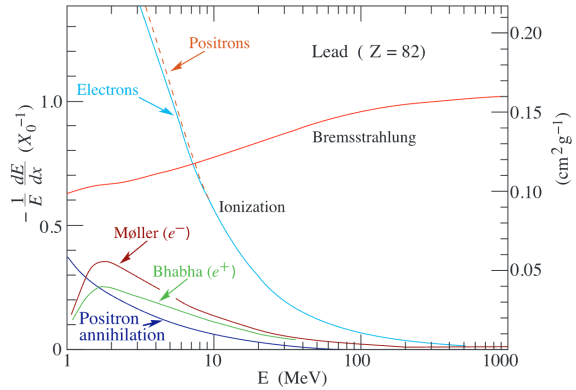
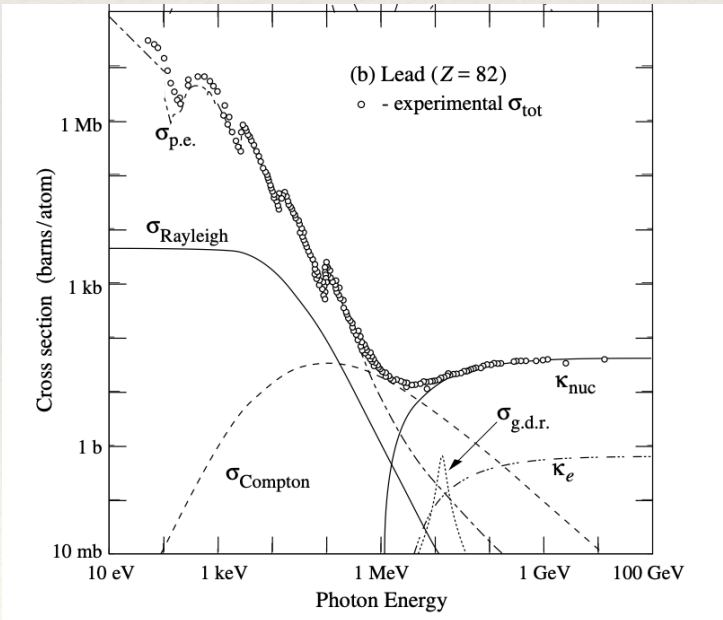
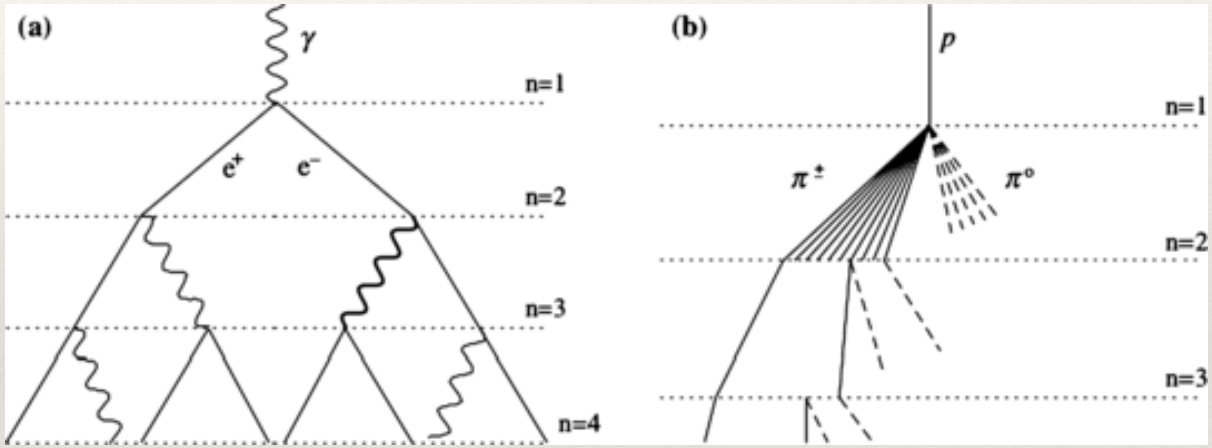


Figure 34.11: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Møller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use $X_0(\mathrm{Pb}) = 5.82$ g/cm^2, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials ($X_0(\mathrm{Pb}) = 6.37$ g/cm^2).



Electromagnetic cascade/showers

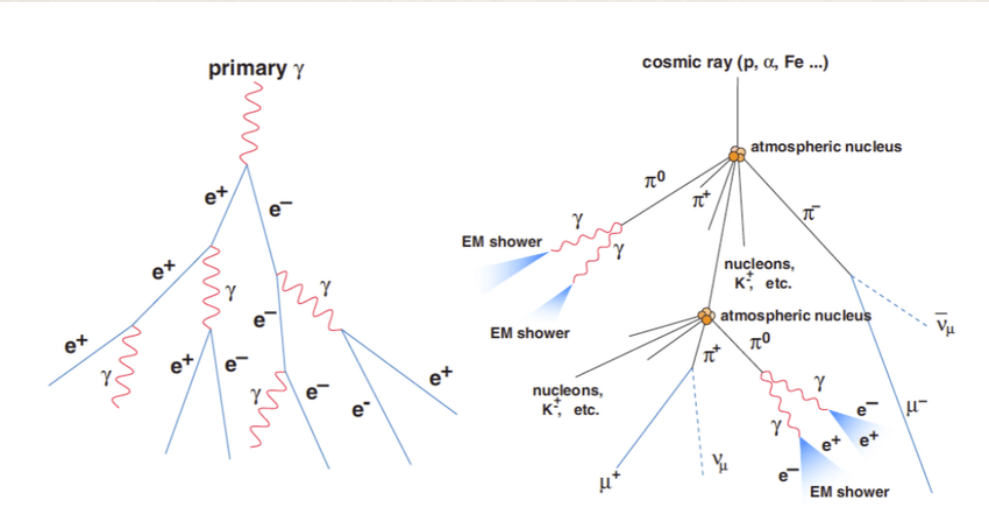
- When high-energy electron/photons enter a detector (some matter stuff)
- Energy loss means they quickly become a cascade of lower energy electron/positrons and photons

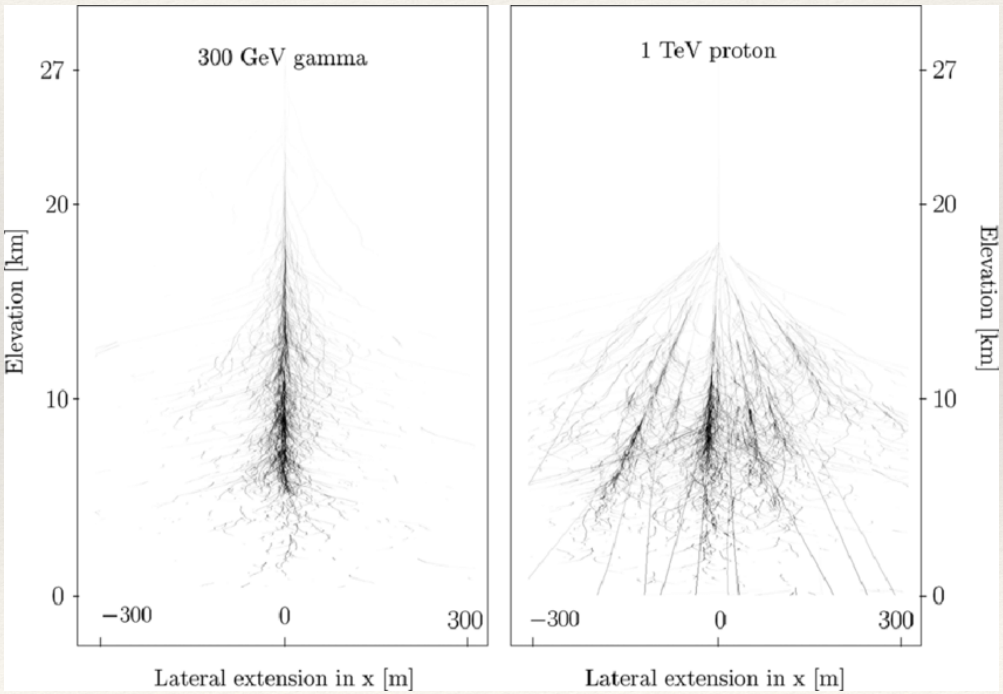


- Space detectors can use this property to detect EM particles with high efficiency
  - VS Hadronic particles would create a lot of other stuff

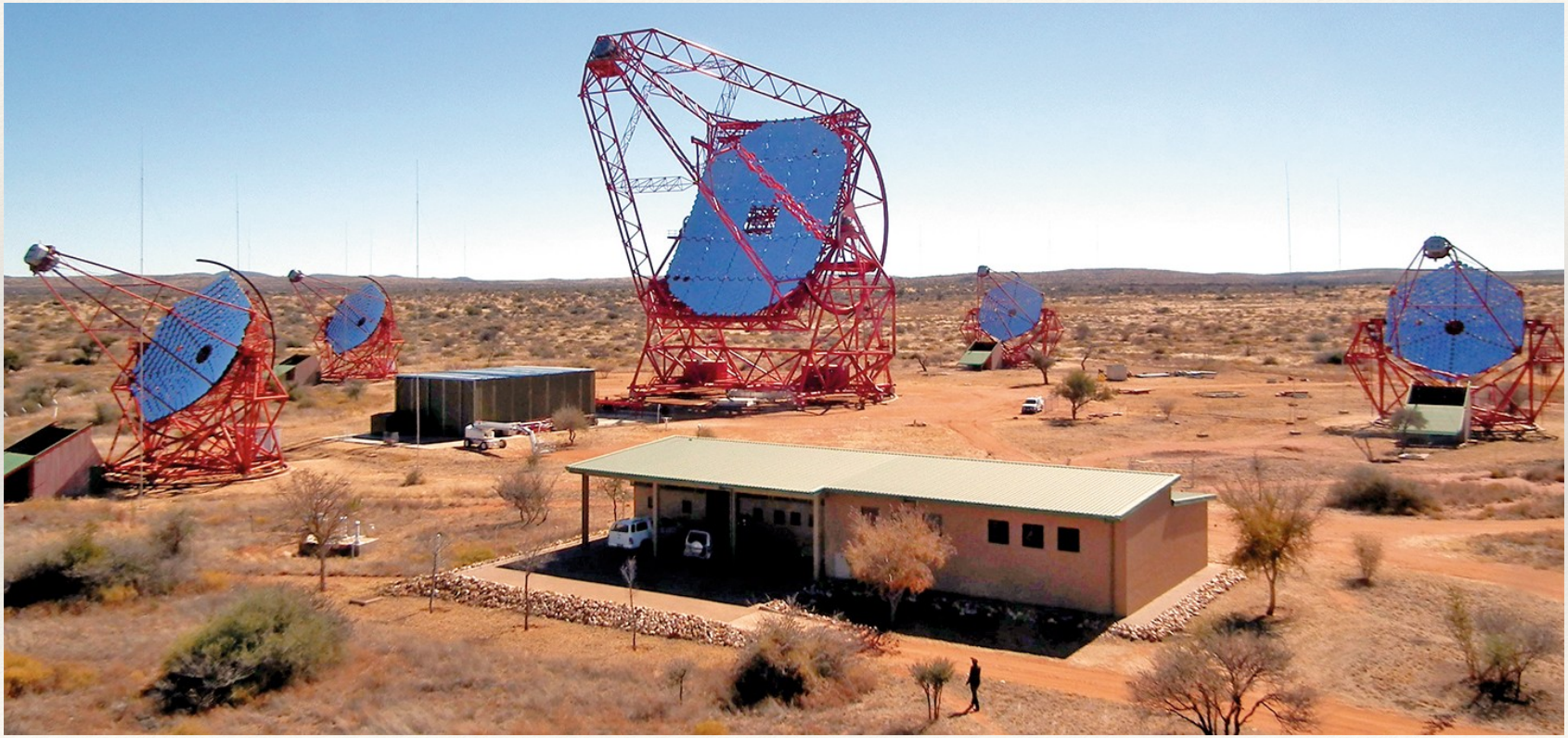
Showers in atmosphere

- Ground based experiments?



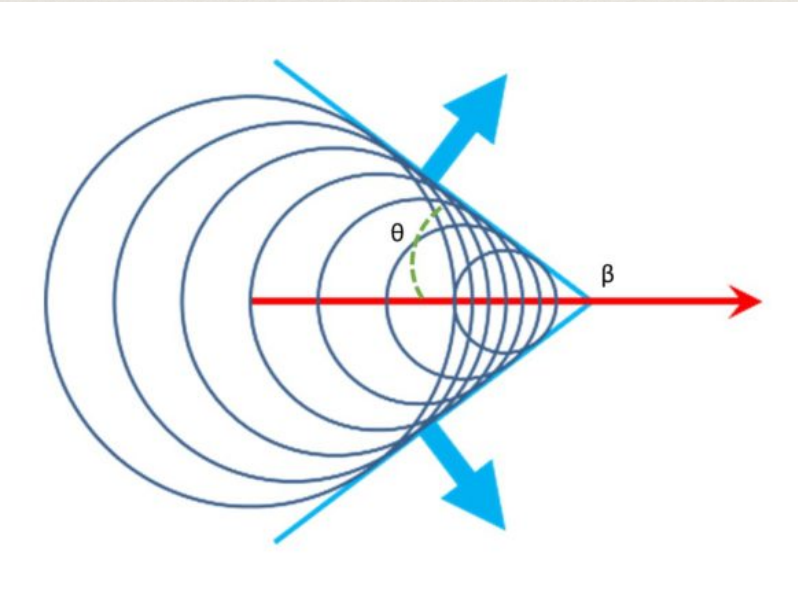


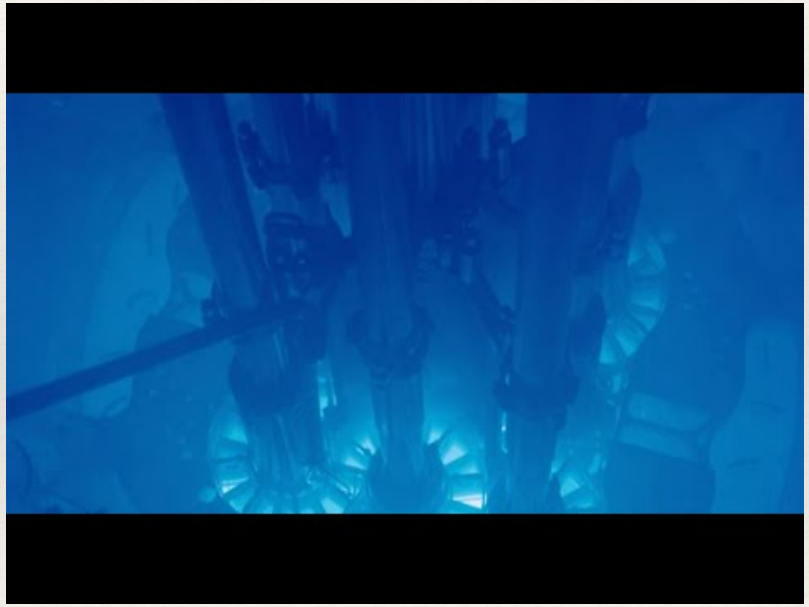
Air Cherenkov Telescopes



Cherenkov radiation

- When charged particles travels in a dielectric medium faster than the speed of light in that medium
- An emission cone is emitted





Pavel Cherenkov

Павел Черенков

Cherenkov in 1958

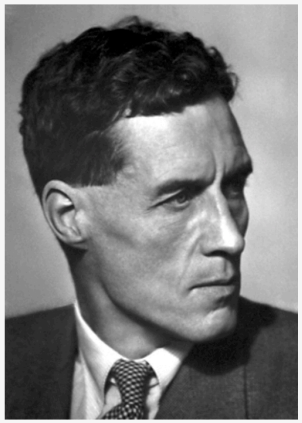
Born	Pavel Alekseyevich Cherenkov 28 July 1904 Novaya Chigla, Voronezh Governorate, Russian Empire
Died	6 January 1990 (aged 85) Moscow, Soviet Union
Resting place	Novodevichy Cemetery, Moscow
Alma mater	Voronezh State University
Known for	Discovering Cherenkov radiation (1934)

Air Cherenkov effect

- Cherenkov radiation in air first proposed by Blackett

https://arxiv.org/pdf/1101.4535

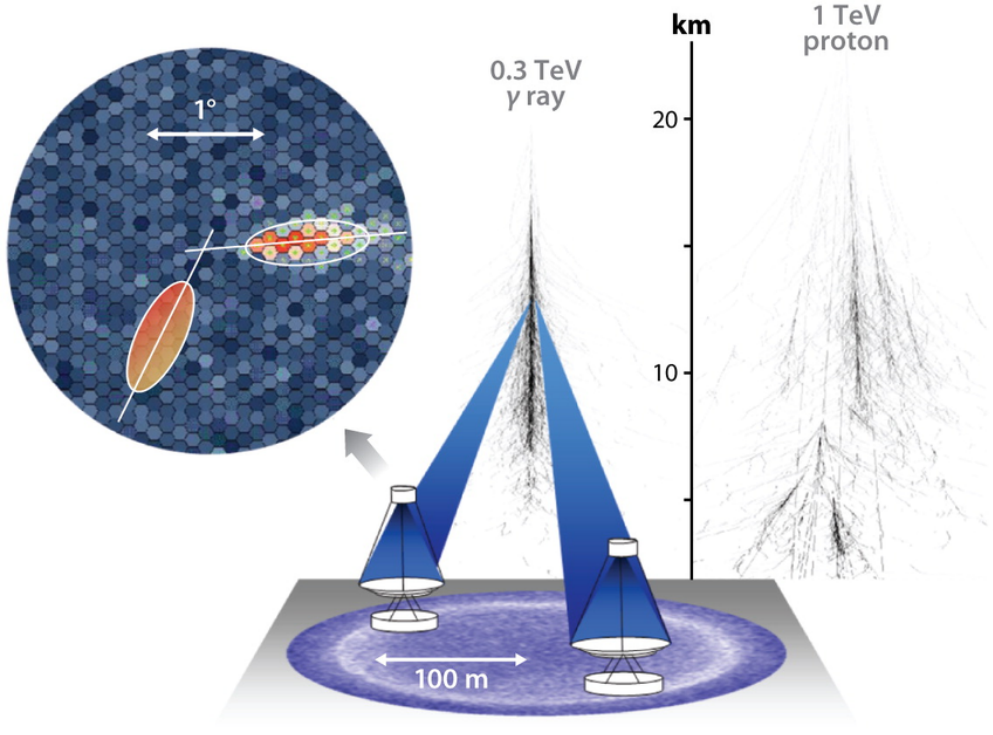
The Right Honourable
The Lord Blackett
OM CH FRS



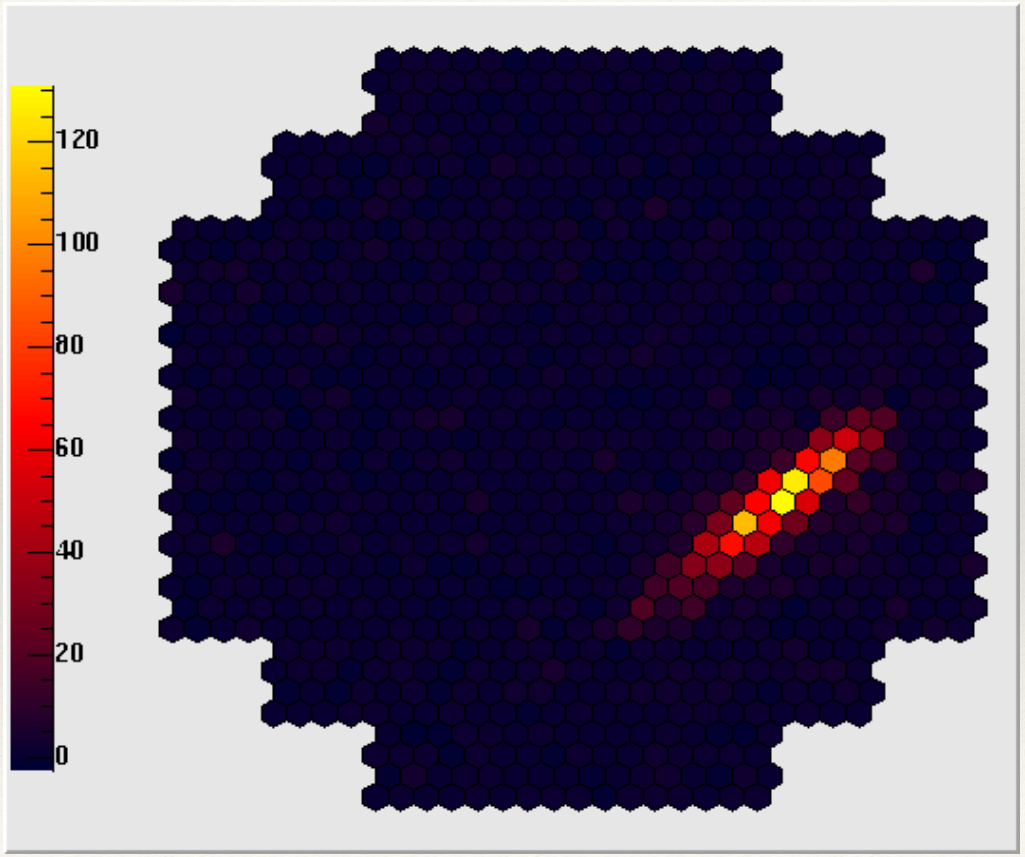
Blackett in 1948

In 1948, Blackett was awarded the Nobel Prize in Physics "for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation".[19]

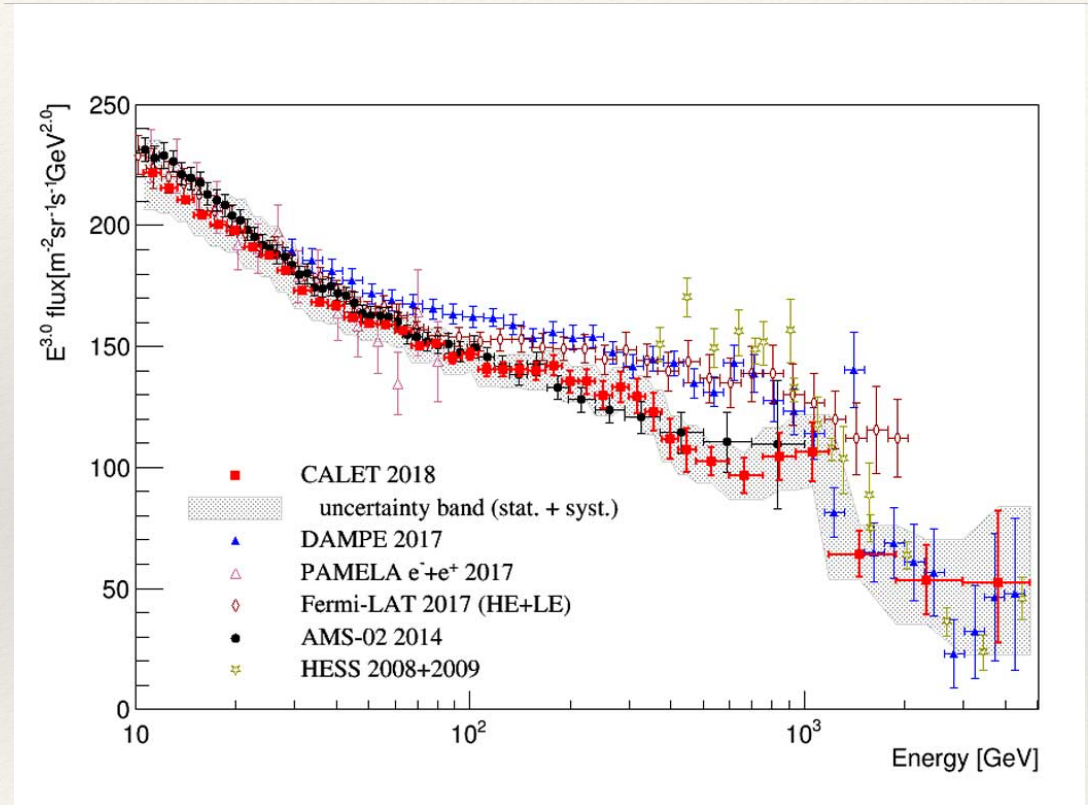
Air Cherenkov Telescopes



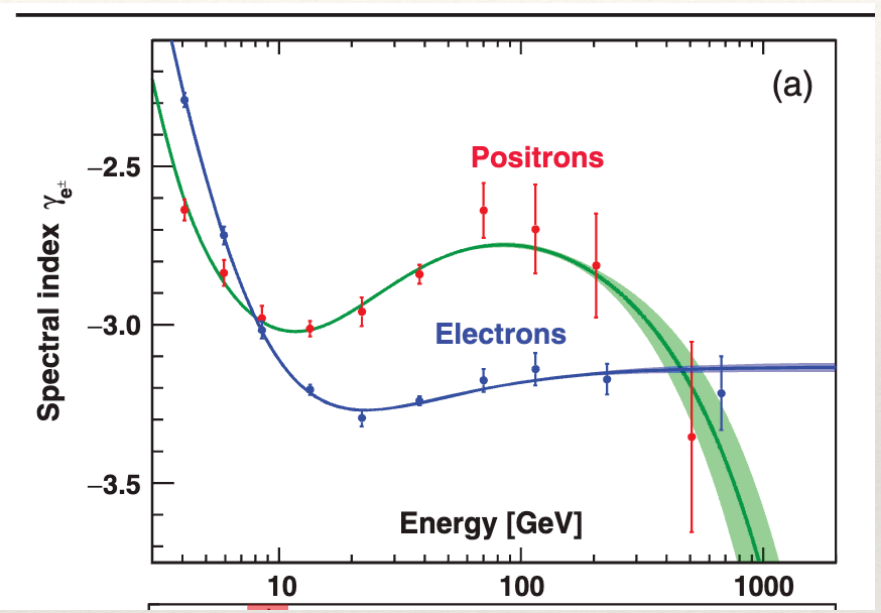
Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65



Cosmic-ray electrons ($e^+ + e^-$)

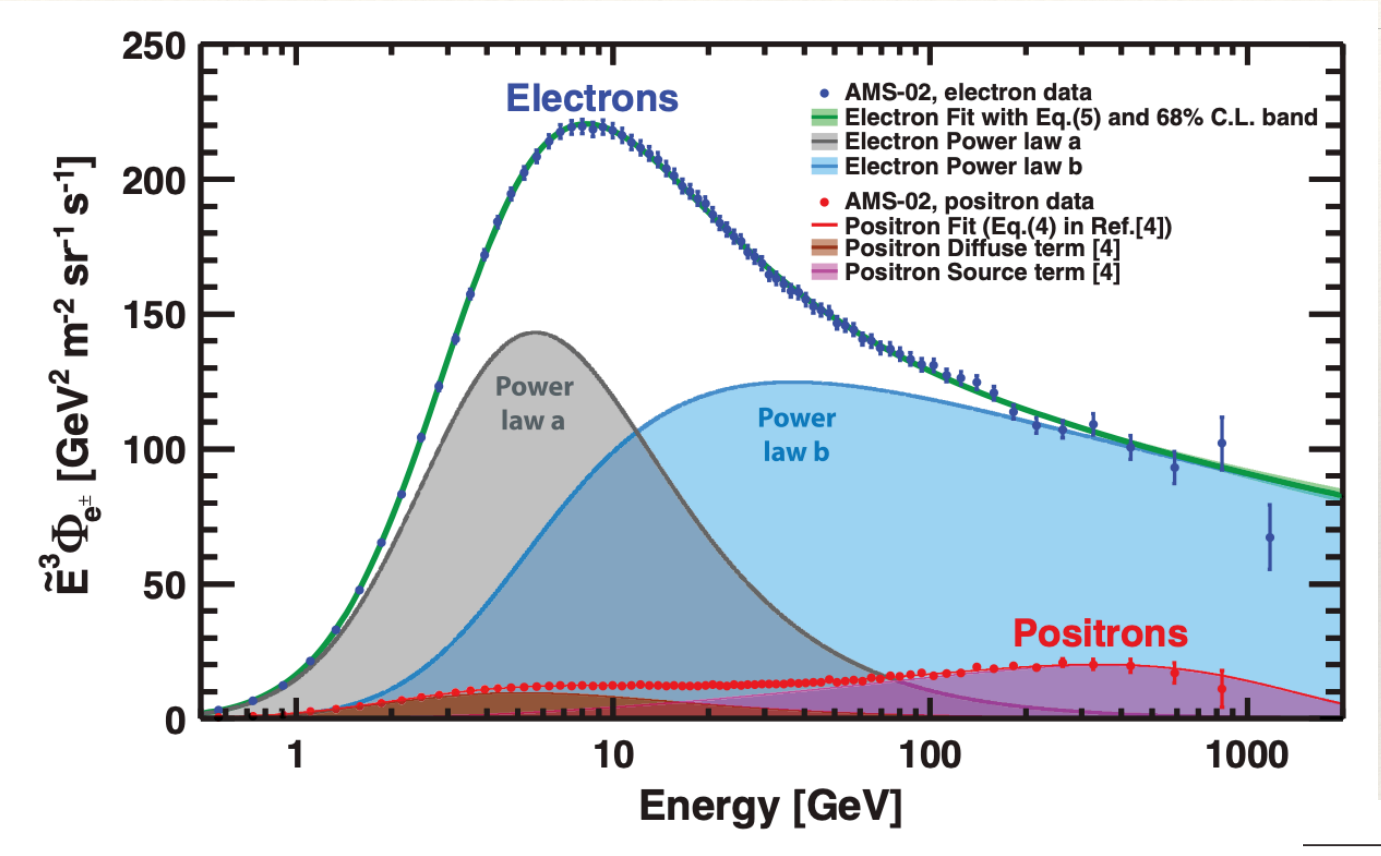


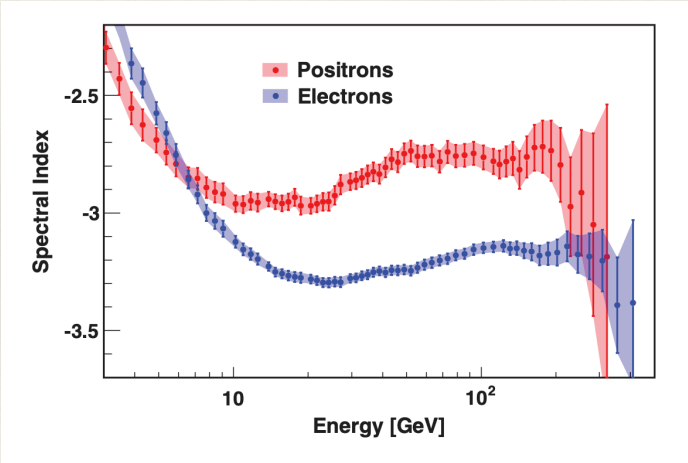
- Satellite measurements



- For an $Q \propto E^{-2.3}$
- $n \sim QT_{loss} \sim E^{-3.3}$
- Roughly works!!

Low energy behaviour: Multiple-source interpretation



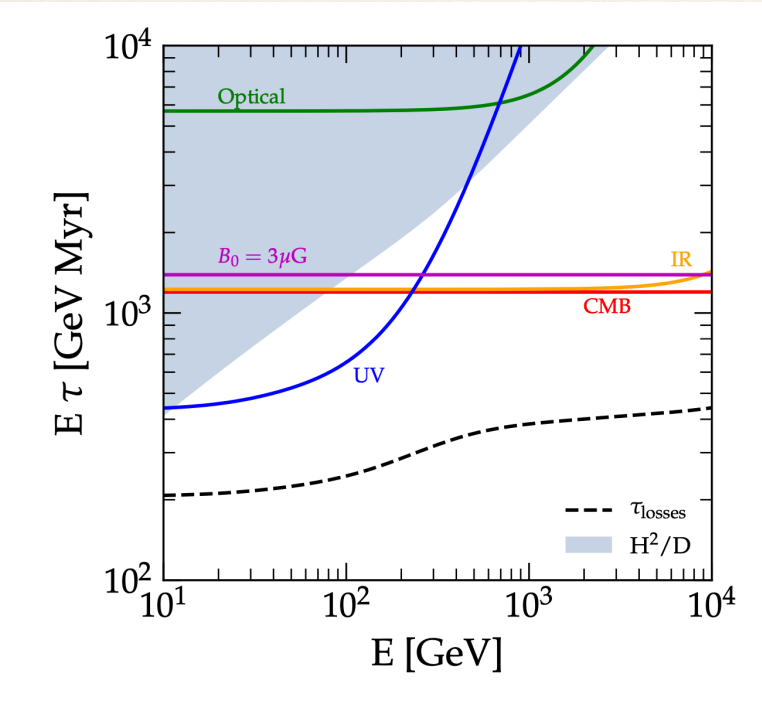


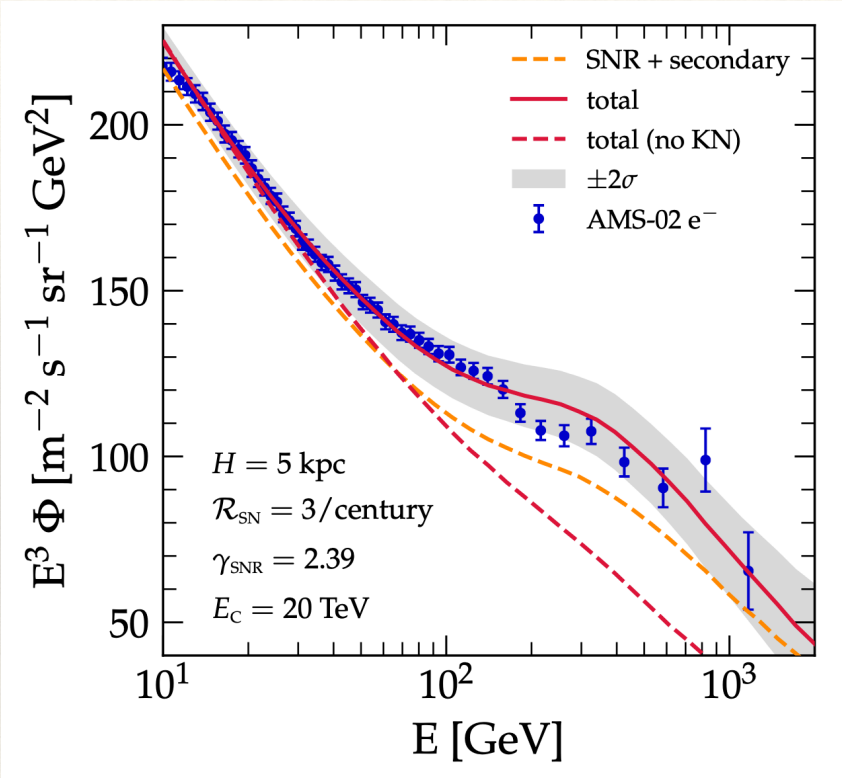
PHYSICAL REVIEW LETTERS **122,** 101101 (2019)

Towards Understanding the Origin of Cosmic-Ray Electrons

Energy loss interpretation

- Why plot. (E T_{loss})



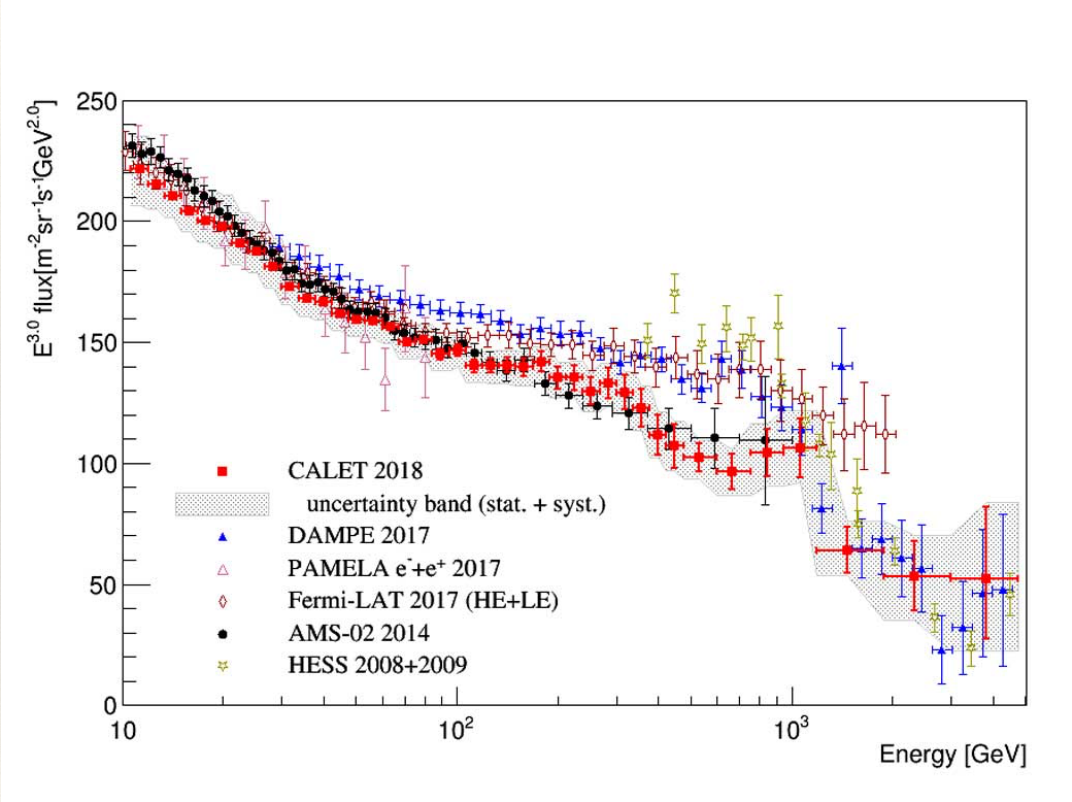


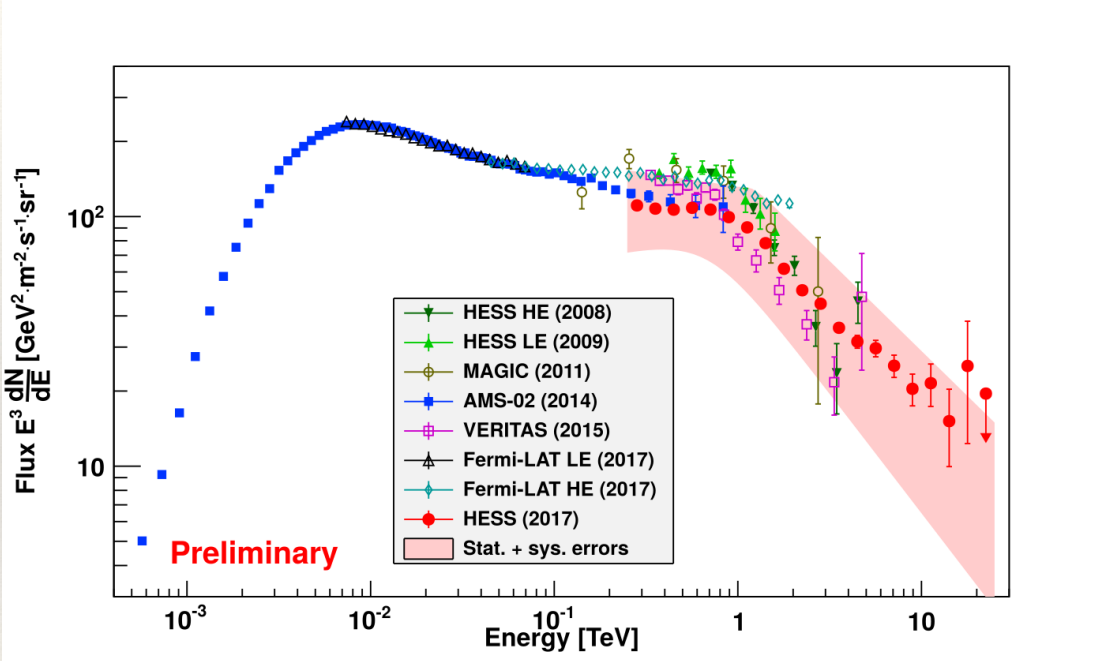
Signature of Energy Losses on the Cosmic Ray Electron Spectrum

Carmelo Evoli [1,2,*] Pasquale Blasi [1,2,†] Elena Amato [3,‡] and Roberto Aloisio [1,2,§]

[1] Gran Sasso Science Institute (GSSI), Viale Francesco Crispi 7, 67100 L'Aquila, Italy

High-energy Cosmic-ray electrons ($e^+ + e^-$)

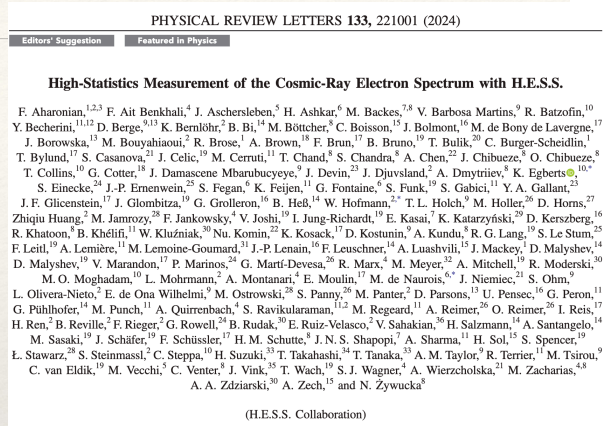




- Satellite measurements
- + ground based measurement

Cosmic-ray electrons ($e^+ + e^-$) > TeV

- A break at 1 TeV
- - possibly running out of sources
  - (Higher energy, more nearby)
- Intrinsic properties of the CR source
- ???



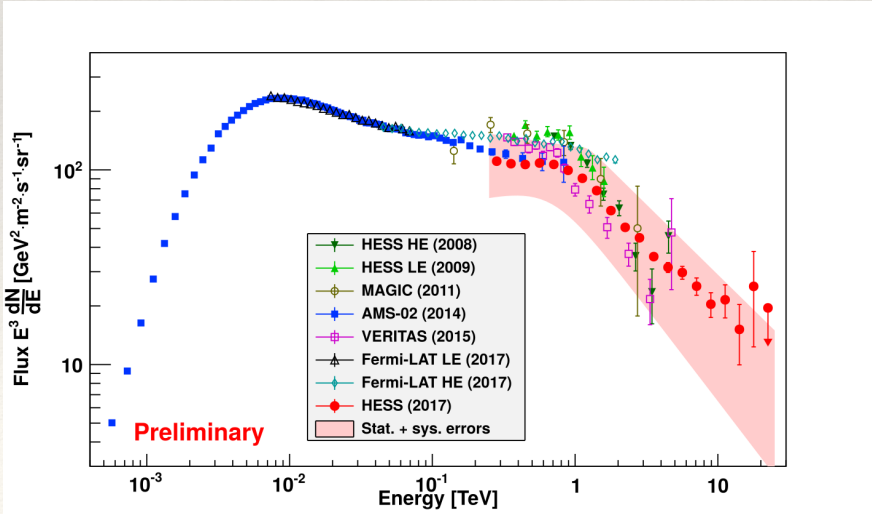
PHYSICAL REVIEW LETTERS **133,** 221001 (2024)

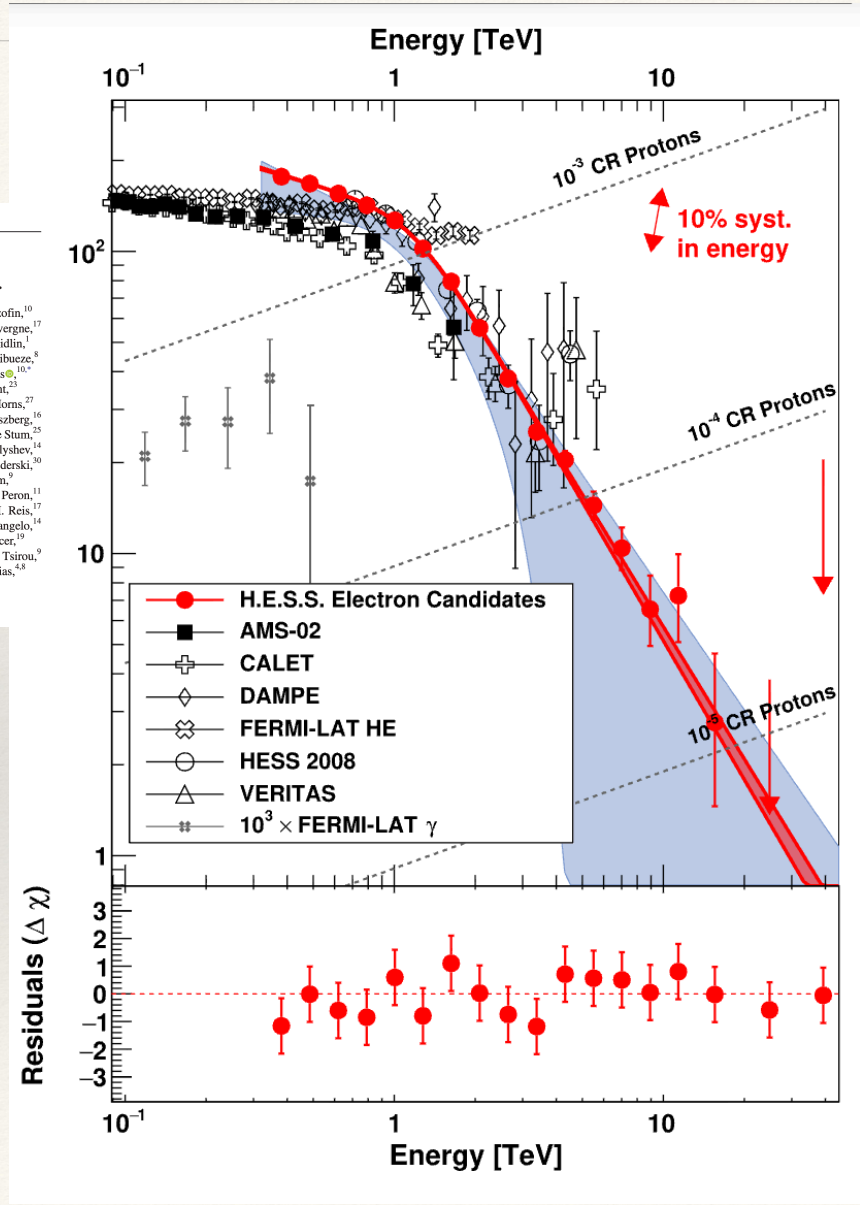
Editors' Suggestion | Featured in Physics

High-Statistics Measurement of the Cosmic-Ray Electron Spectrum with H.E.S.S.

F. Aharonian,[1,2,3] F. Ait Benkhali,[4] J. Aschersleben,[5] H. Ashkar,[6] M. Backes,[7,8] V. Barbosa Martins,[9] R. Batzofin,[10] Y. Becherini,[11,12] D. Berge,[9,13] K. Bernlöhr,[2] B. Bi,[14] M. Böttcher,[8] C. Boisson,[15] J. Bolmont,[16] M. de Bony de Lavergne,[17] J. Borowska,[13] M. Bouyahiaoui,[2] R. Brose,[1] A. Brown,[18] F. Brun,[17] B. Bruno,[19] T. Bulik,[20] C. Burger-Scheidlin,[1] T. Bylund,[17] S. Casanova,[21] J. Celic,[19] M. Cerruti,[11] T. Chand,[8] S. Chandra,[8] A. Chen,[22] J. Chibueze,[8] O. Chibueze,[8] T. Collins,[10] G. Cotter,[18] J. Damascene Mbarubucyeye,[9] J. Devin,[23] J. Djuvsland,[2] A. Dmytriiev,[8] K. Egberts,[10,*] S. Einecke,[24] J.-P. Ernenwein,[25] S. Fegan,[6] K. Feijen,[11] G. Fontaine,[6] S. Funk,[19] S. Gabici,[11] Y. A. Gallant,[23] J. F. Glicenstein,[17] J. Glombitza,[19] G. Grolleron,[16] B. Heß,[14] W. Hofmann,[2,*] T. L. Holch,[9] M. Holler,[26] D. Horns,[27] Zhiqiu Huang,[2] M. Jamrozy,[28] F. Jankowsky,[4] V. Joshi,[19] I. Jung-Richardt,[19] E. Kasai,[7] K. Katarzyński,[29] D. Kerszberg,[16] R. Khatoon,[8] B. Khélifi,[11] W. Kluźniak,[30] Nu. Komin,[22] K. Kosack,[17] D. Kostunin,[9] A. Kundu,[8] R. G. Lang,[19] S. Le Stum,[25] F. Leitl,[19] A. Lemière,[11] M. Lemoine-Goumard,[31] J.-P. Lenain,[16] F. Leuschner,[14] A. Luashvili,[15] J. Mackey,[1] D. Malyshev,[14] D. Malyshev,[19] V. Marandon,[17] P. Marinos,[24] G. Martí-Devesa,[26] R. Marx,[4] M. Meyer,[32] A. Mitchell,[19] R. Moderski,[30] M. O. Moghadam,[10] L. Mohrmann,[2] A. Montanari,[4] E. Moulin,[17] M. de Naurois,[6,*] J. Niemiec,[21] S. Ohm,[9] L. Olivera-Nieto,[2] E. de Ona Wilhelmi,[9] M. Ostrowski,[28] S. Panny,[26] M. Panter,[2] D. Parsons,[13] U. Pensec,[16] G. Peron,[11] G. Pühlhofer,[14] M. Punch,[11] A. Quirrenbach,[4] S. Ravikularaman,[11,2] M. Regeard,[11] A. Reimer,[26] O. Reimer,[26] I. Reis,[17] H. Ren,[2] B. Reville,[2] F. Rieger,[2] G. Rowell,[24] B. Rudak,[30] E. Ruiz-Velasco,[2] V. Sahakian,[36] H. Salzmann,[14] A. Santangelo,[14] M. Sasaki,[19] J. Schäfer,[19] F. Schüssler,[17] H. M. Schutte,[8] J. N. S. Shapopi,[7] A. Sharma,[11] H. Sol,[15] S. Spencer,[19] Ł. Stawarz,[28] S. Steinmassl,[2] C. Steppa,[10] H. Suzuki,[33] T. Takahashi,[34] T. Tanaka,[33] A. M. Taylor,[9] R. Terrier,[11] M. Tsirou,[9] C. van Eldik,[19] M. Vecchi,[5] C. Venter,[8] J. Vink,[35] T. Wach,[19] S. J. Wagner,[4] A. Wierzcholska,[21] M. Zacharias,[4,8] A. A. Zdziarski,[30] A. Zech,[15] and N. Żywucka[8]

(H.E.S.S. Collaboration)





Where do CR electrons come from?

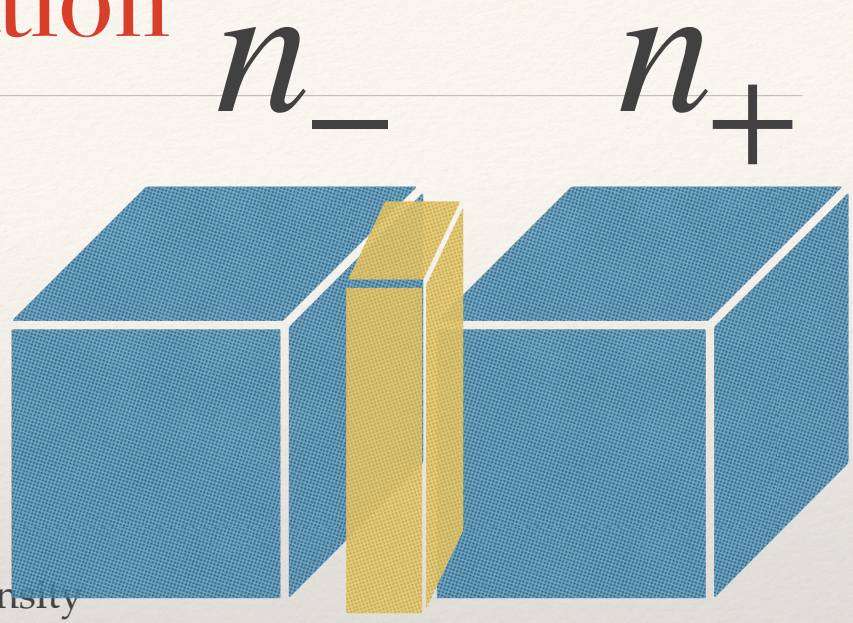
- If you forgot about random walk, read Feynman or wiki

Cosmic-ray electron sources are nearby

- Diffusions are random walk (each step with one mean free path)
- Mean traveled distance $= \langle x \rangle = 0$
- Root mean distance squared $= \sqrt{< x^2 >} = R = \ell\sqrt{N}$
-

Recall from Diffusion

Diffusion equation



- ϕ_x , ϕ_y , ϕ_z

- Now goes to microscopic picture
  - (Feynman lecture: diffusion)
- Particles travel a **"mean free path [l]"**, then scatter
- There can only be non-zero ϕ_x , when there is a difference in number density
- Net flow of particles $\phi_x = \left(n_- - n_+\right) v$
  - "v" is the microscopic particle velocity
- $\phi_x = -\dfrac{dn}{dx}\Delta x\, v \;\simeq -\dfrac{dn}{dx}\ell v \;\equiv -D\dfrac{dn}{dx}$, *Phenomenologically, Fick's law*
- $\vec{\phi} = -D\vec{\nabla} n$

- If you forgot about random walk, read Feynman or wiki

Cosmic-ray electron sources are nearby

- Diffusions are random walk (each step with one mean free path)
- Mean traveled distance = <x> = 0
- Root mean square (rms) distance = $\sqrt{< x^2 >}$ = R = $\ell\sqrt{N}$

- Diffusion constant = mean free path x particle speed = lc
- Given the cosmic ray life time, T

$$D \simeq lv \simeq l\frac{Nl}{T}$$

$$\sqrt{N} \simeq \sqrt{DT}l^{-1}$$

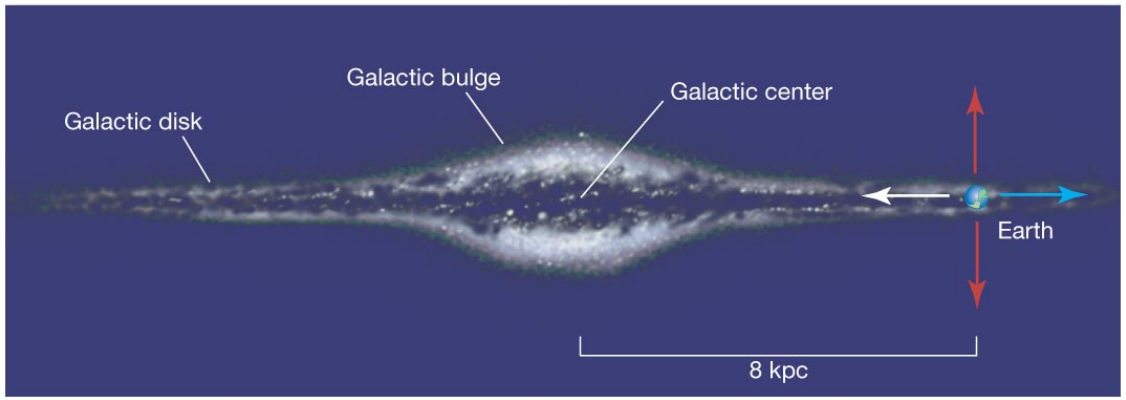
$$R \simeq \sqrt{DT}$$

- How can we find the rms distance?

- If you forgot about random walk, read Feynman or wiki

Cosmic-ray electron sources are nearby

- Cosmic-ray electron lifetime (when energy loss dominated)
- $T \sim 10^5 yr \left(\frac{E}{\mathrm{TeV}}\right)^{-1}$
- The observed high-energy CR e^+e^- are dominated by a few sources



(a) Artist's view of Milky Way from afar

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- Exercise to show that electron sources are nearby
  - How nearby?