Interpretation of Voyager 1 data on low energy cosmic rays in galactic wind model

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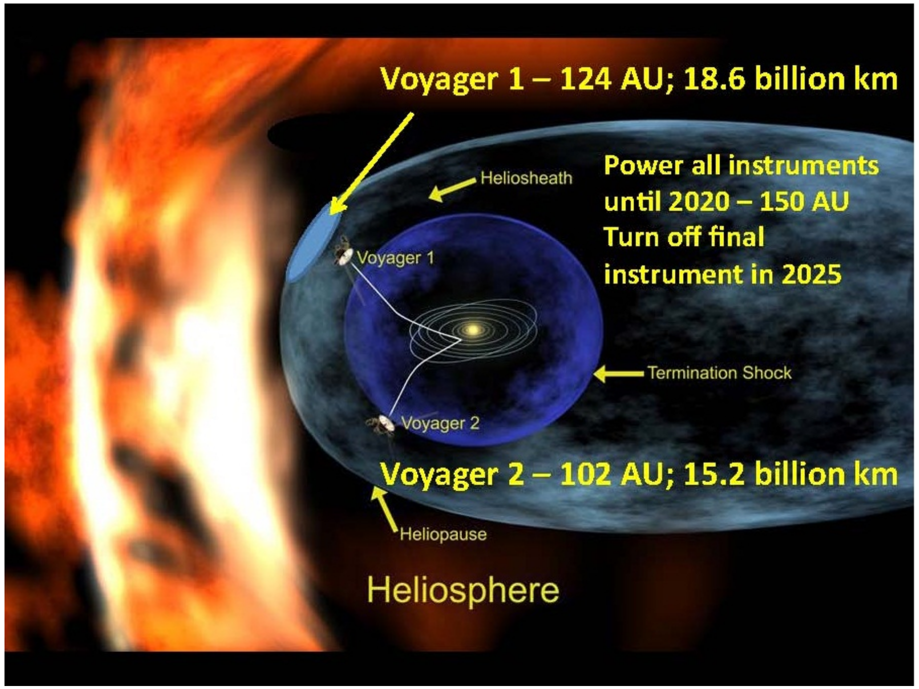
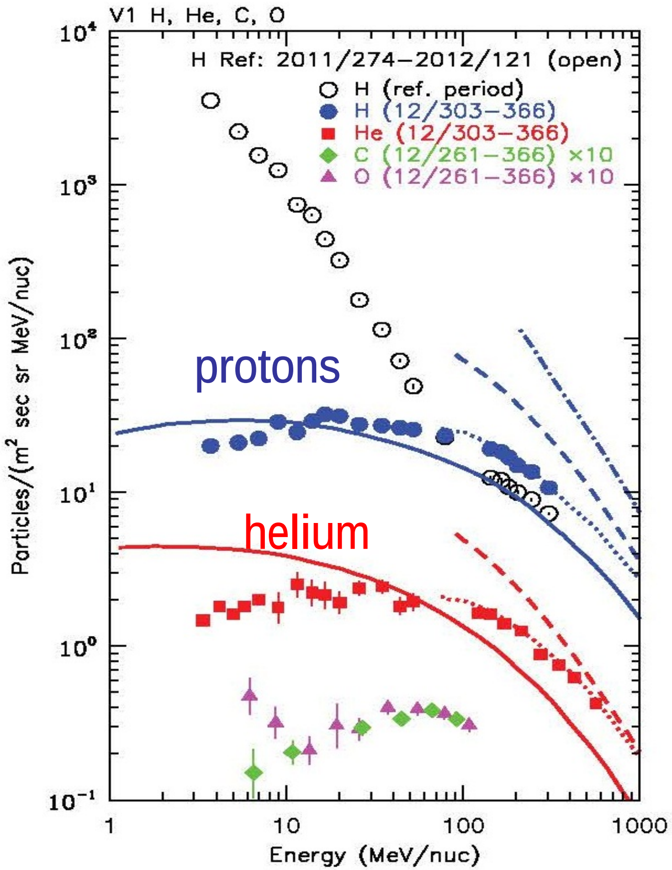
Abstract

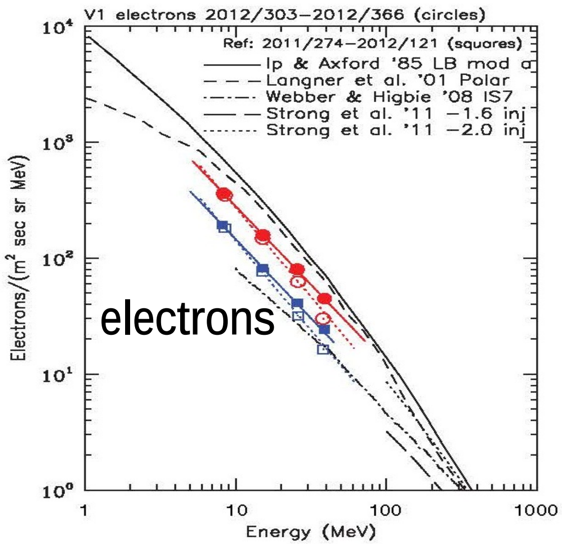
The local interstellar energy spectra of galactic cosmic ray protons, nuclei and electrons down to a few MeV/nucleon were directly measured in the experiment on the board of the Voyager 1 spacecraft. We suggest interpretation of these data based on our models of cosmic ray acceleration in supernova remnants and propagation in galactic wind selfconsistently driven by cosmic rays.

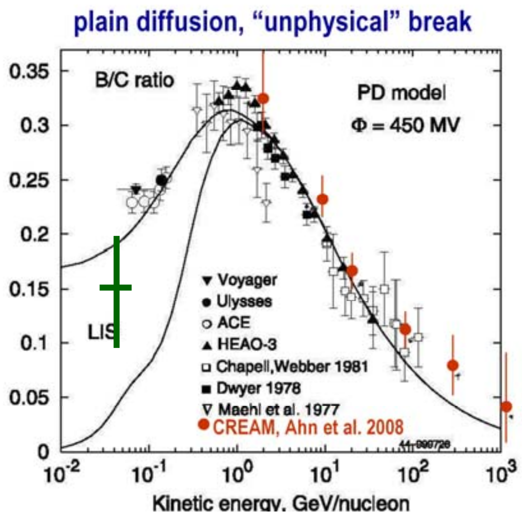
Voyager direct measurements of interstellar CR spectra at low energies

Stone et al. 2013









suggested interpretations of Voyager data

plane diffusion model Webber, Higbie, McDonald 2013

H, He, C/O, electrons; no B/C

low rigidities: $D \sim v/R^2$ for nuclei; $D \sim v/R$ for electrons

high rigidities: $D \sim vR^{0.5}$

source: $q \sim R^{-2.24}$

diffusion with reacceleration Lave et al 2013

H, He and other nuclei including B and C; no electrons

$D \sim vR^{1/3}$

$q \sim R^{-2.4}$ with flattening to small rigidities

diffusion + adiabatic deceleration without convective transport

Schlickeiser, Webber, Kempf 2014

H nuclei only

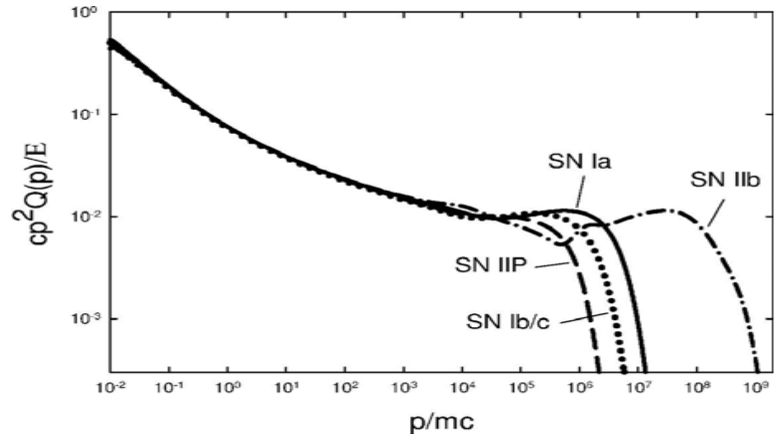
$D \sim v$ at nonrelativistic energies

$q \sim R^{-2.24}$

present calculations

- source spectrum:
modelling of CR acceleration in SNRs VP, Seo, Zirakashvili 2010

$q \sim R^{-2.28}[1+0.07\log(R/0.7)\log(R/100)]$,

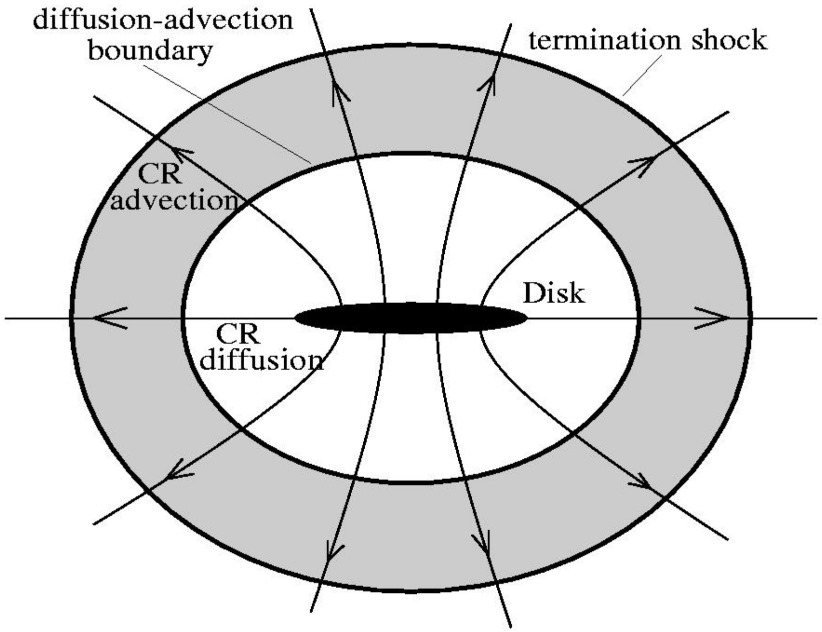


- propagation model:
Galactic wind model with CR streaming instability
Zirakashvili, et al. 1996, VP et al. 1997,

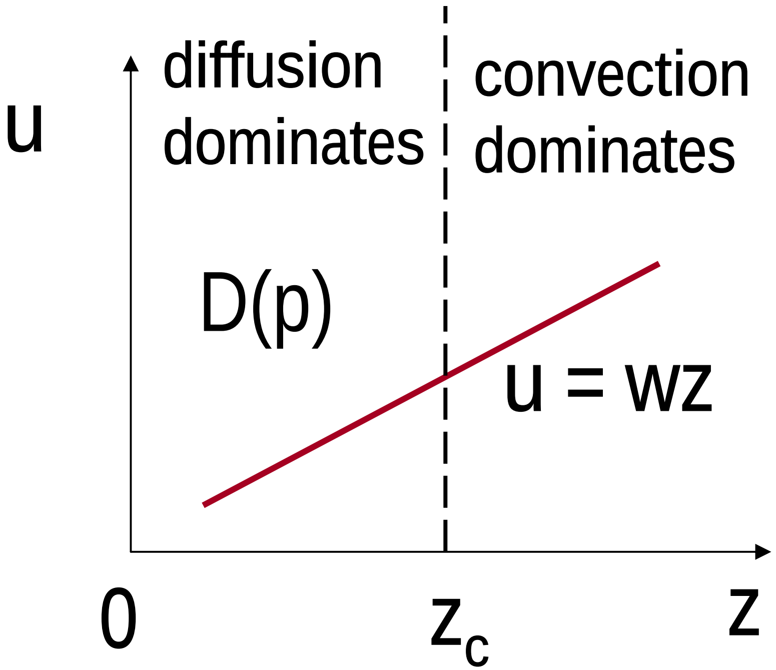
$D \sim v(qR)^{-1}$

(without ionization losses;
exact for a power law source function)

adjustment of wind velocity u(z) at small z Soutoul & VP 1999



diffusion – convection model



$$\frac{z_c}{u(z_c)} \approx \frac{z_c^2}{D(p,z_c)} \quad \Rightarrow \quad \boxed{z_c(p) = \frac{D(p,z_c)}{u(z_c)}}$$

$$z_c(p) = \sqrt{D(p)/w} \quad \text{if} \quad u = wz$$

$$\boxed{X \approx \frac{\mu v z_c(p)}{2D(p)}} = \frac{\mu v}{2\sqrt{wD(p)}} = \boxed{\frac{\mu v}{2u_c(z_c(p))}}.$$

$$X \propto p^{-0.6} \quad \text{requiers} \quad D \propto p^{1.2} \quad \text{at v} \approx c$$

Soutoul & VP 1999:

empirically from B/C data

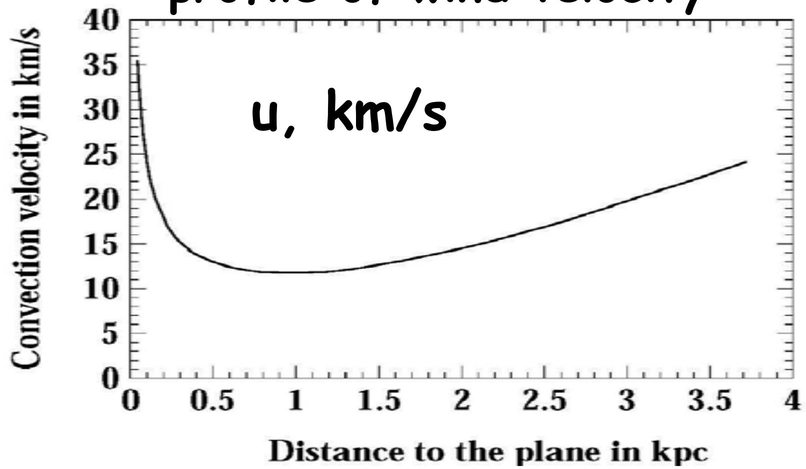
$$X = \frac{37.5\beta}{(\beta R)^{0.6} + (\beta R/2.4)^{-1.4}} \ \frac{g}{cm^2}$$

$$R = p/Z \text{ in GV}$$

maximum in X(p) can be explained by minimum in u(z)

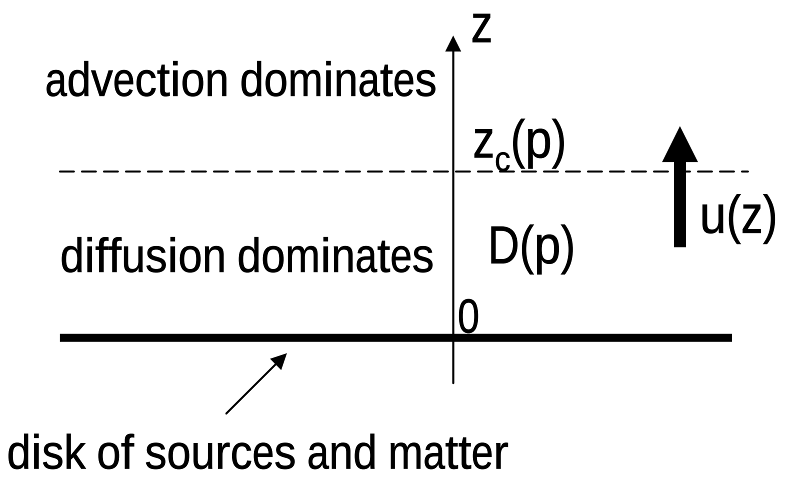
$\Rightarrow$

profile of wind velocity



NL leaky box approximation for 1D wind model with galactic disk of infinitesimal thickness

Seo & VP 1994, Jones et al. 2001



$z_c = D/u(z_c)$

$$-D(p)\frac{\partial^2 f(p,z)}{\partial z^2} + u(z)\frac{\partial f(p,z)}{\partial z} - \frac{p}{3}\frac{du(z)}{dz}\frac{\partial f(p,z)}{\partial p} + \frac{\mathrm{v}\sigma\mu}{m}\delta(z) f(p,z) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{ion} f(p,z)\right] = s(p)\delta(z) \quad (*)$$

surface gas density

surface source density

$$\left(dp/dt\right)_{ion} = b_0(p)\mu\delta(z)/m < 0$$

integration of (*) $\lim \int_{-\varepsilon}^{\varepsilon} \ldots dz$ at $\varepsilon \to 0$ gives the boundary condition at $z = 0 + \varepsilon$;

solution of (*) at $0 < z < z_c$ and $z > z_c$ with continuity of flux $-D\frac{\partial f}{\partial z} - \frac{u}{3}p\frac{\partial f}{\partial p}$ at $z = z_c$ leads to eq. for $J_0(E)$:

$$\boxed{\frac{J_0}{X} + \frac{d}{d\varepsilon}\left[\left(\frac{d\varepsilon}{dx}\right)_{ion} J_0\right] + \frac{\sigma}{m_{ism}} J_0 = \frac{Q(\varepsilon)}{\rho_0},}$$

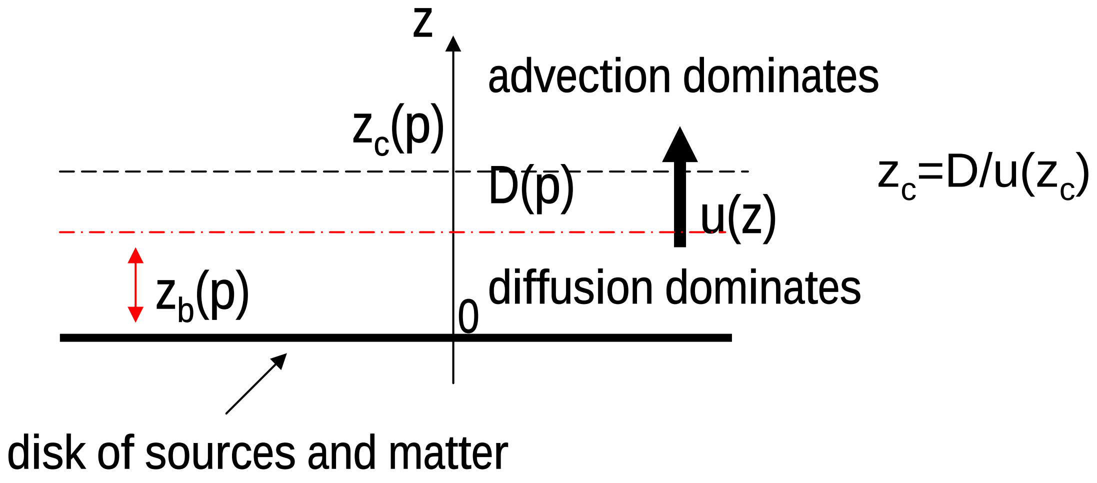
where $\varepsilon = E/A$, $Q = \frac{Ap^2}{\mathrm{v}} q_0(p)$, $dx = \mathrm{v}\rho_0 dt$,

$$\boxed{X = \frac{\mu \mathrm{v}}{2u_c}\left[1 - 3\int_p^{\infty}\frac{dp_1}{p_1}\left(\frac{p}{p_1}\right)^5 \frac{J(\varepsilon(p_1))}{J(\varepsilon(p))}\right]^{-1}}$$

- effective escape length.

the case of electrons:

NL leaky box approximation works at energies E < 1 GeV when synchrotron and inverse Compton energy losses of electrons are small on the time z_c^2/D.



$dE/dt = - b\,E^2$

$$\mathbf{b = \gamma_s + (1+a)/2 \quad \text{at } z_b < z_c}$$

$z_b = (D/bE)^{1/2}$

in our case 2.2 + (1+1.2)/2 = 3.3

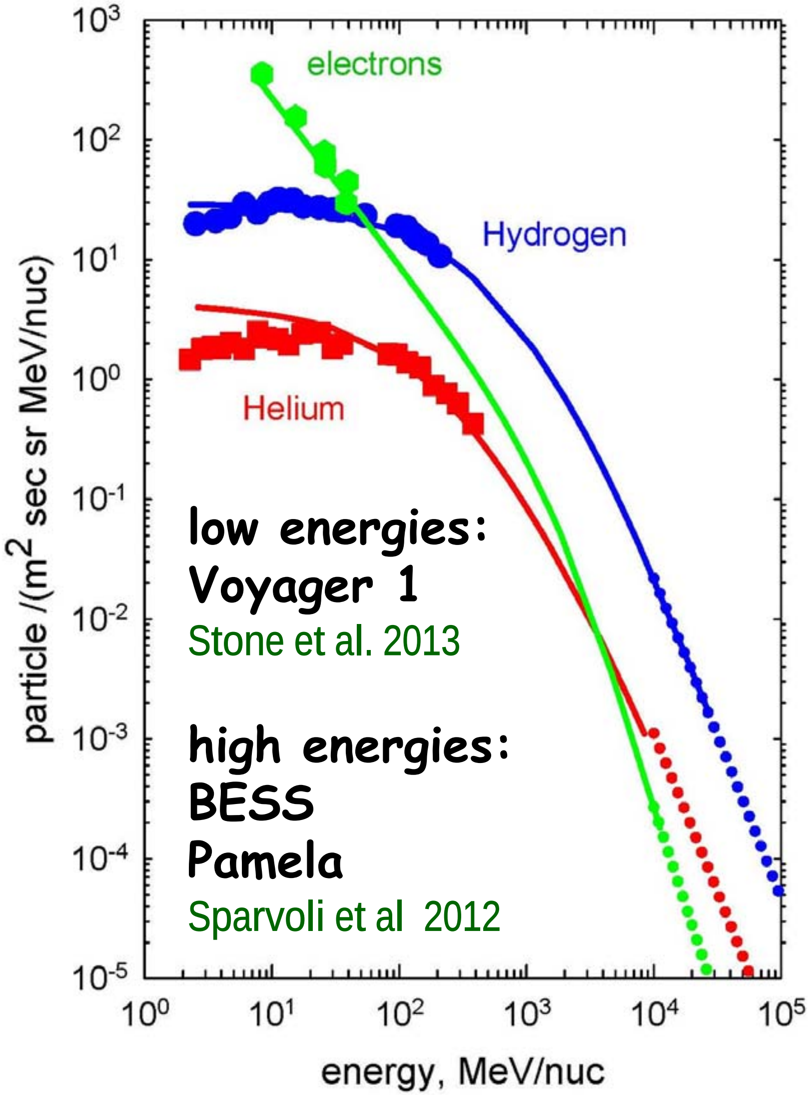
$J \sim E^{-b}$

solution of diffusion equation

$$J_0(E) = \frac{1}{z_c b E^2} \int_E^\infty dE_2 s(E_2) \sum_{n=1}^{\infty} \exp\left[-\frac{(2n-1)^2 \pi^2}{4 z_c^2} \mu(E_2, E) \right],$$

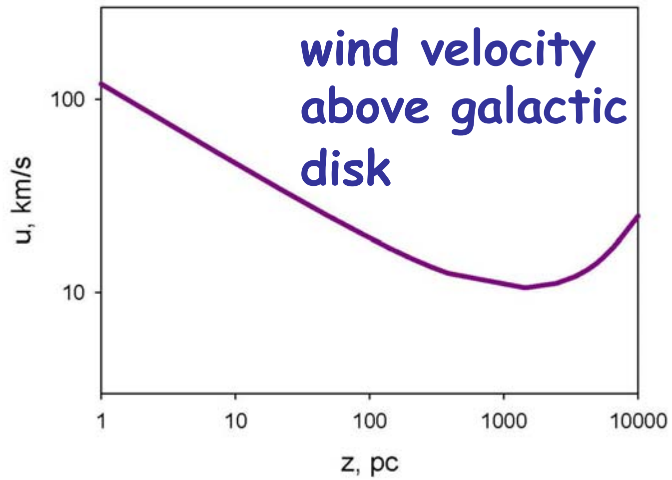
$$\text{where } \mu(E_2, E) = \int_E^{E_2} dE_1 \frac{D(E_1)}{bE_1^2}.$$

results of calculations



low energies:
Voyager 1
Stone et al. 2013

high energies:
BESS
Pamela
Sparvoli et al 2012



B/C (70MeV/n) =
0.14 calc.; 0.15+-0.06 obs V1

$$X = \frac{34\beta}{D_0^{0.5} + \left(D_0 / 1.3\right)^{-0.71}} \times \varphi_{ad} \;\; g/cm^2,$$

$$D = 2 \times 10^{27} \times D_0 \; cm^2/s,$$

$$D_0 = \beta R^{1.28} / \left(1 + 0.07\log(R/0.7)\log(R/100)\right)$$

$$R = pc/Z$$

problem: no theoretical justification of the model for electrons at E < 100 MeV

conclusions

Considered galactic wind model with depending on distance convection velocity may explain cosmic ray spectra at energies from few MeV to more than 10 GeV.

Refinement of the model is needed for low energy electrons.