Generation of Nonthermal Electons in the Quiet Solar Corona

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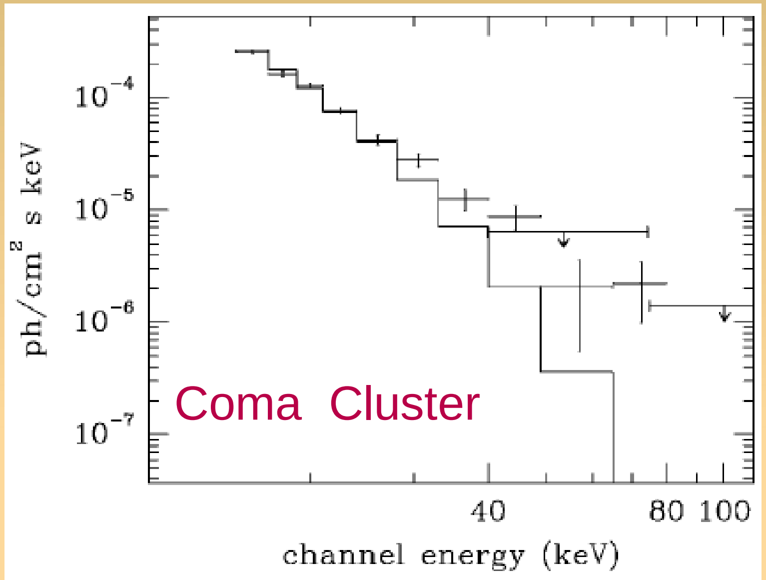
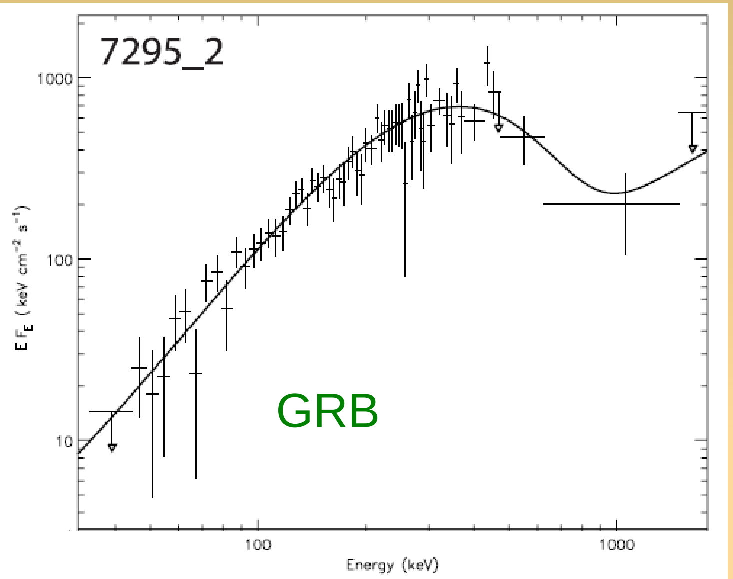
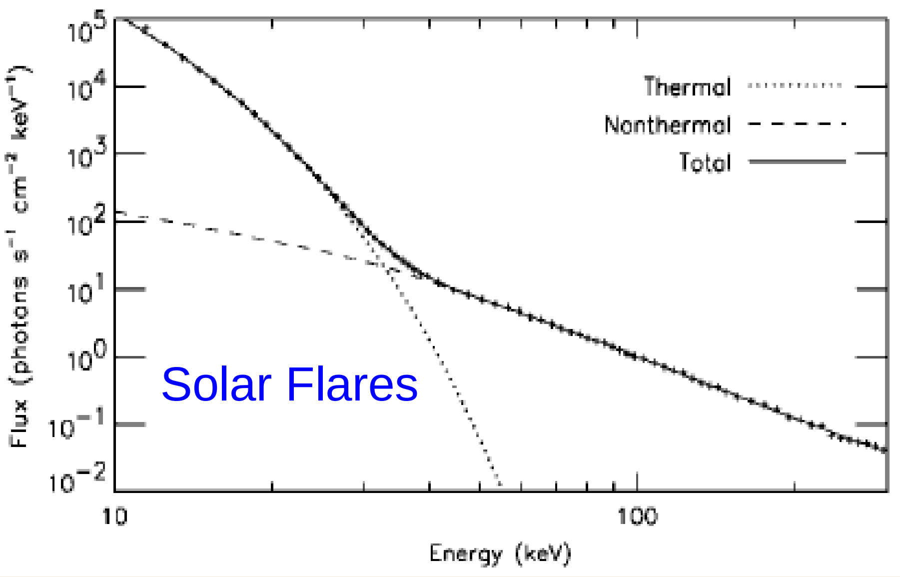
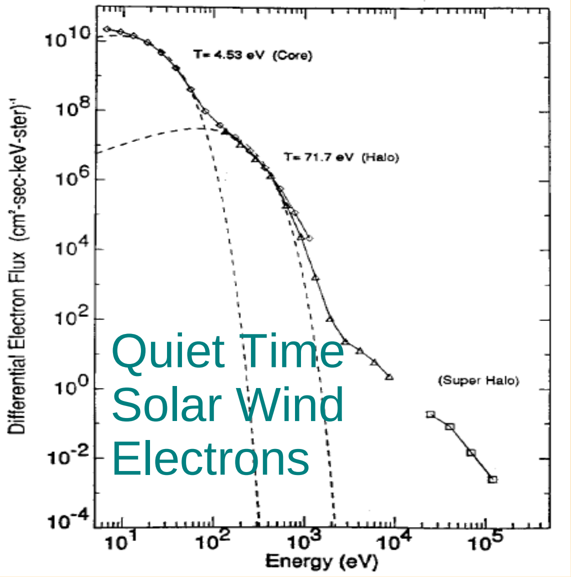
Non-thermal (NT) Tails

- Frequently observed in many astrophysical situations









Even in the Quiet Solar Corona?

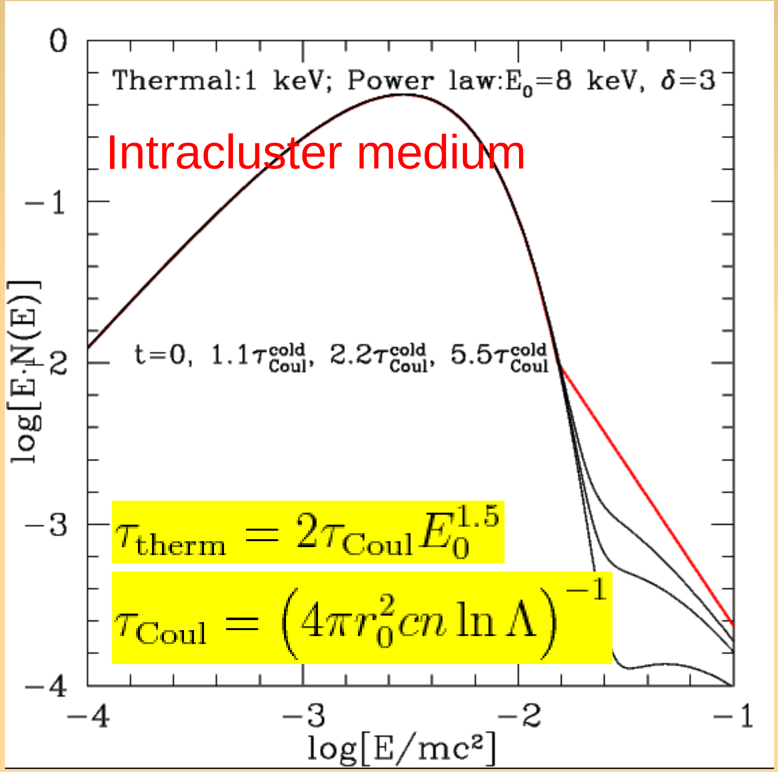
Ion (1)	λ (Å) (2)	Transition (3)	T_e^{max} (K) (4)	I_{ij}^{meas} (5)	$I_{ij}^{CHIANTI}$ (6)	I_{ij}^{NOMAD} (7)	I_{ij}^{T2} (8)
Ar XI	745.80	$2s^22p^4\ {}^3P_1$–$2s^22p^4\ {}^1S_0$	1.8×10^6	0.047	0.051	0.058	0.095
Ar XI	1392.10	$2s^22p^4\ {}^3P_2$–$2s^22p^4\ {}^1D_2$	1.8×10^6	0.53	0.44	0.41	0.61
Ar XII	649.09	$2s^22p^3\ {}^4S_{3/2}$–$2s^22p^3\ {}^2P_{3/2}$	2.6×10^6		0.013	0.016	0.053
Ar XII	670.31	$2s^22p^3\ {}^4S_{3/2}$–$2s^22p^3\ {}^2P_{1/2}$	2.6×10^6		7.2×10^{-3}	8.4×10^{-3}	0.027
Ar XII	1018.75	$2s^22p^3\ {}^4S_{3/2}$–$2s^22p^3\ {}^2D_{5/2}$	2.6×10^6	0.11	0.046	0.049	0.157
Ar XII	1054.59	$2s^22p^3\ {}^4S_{3/2}$–$2s^22p^3\ {}^2D_{3/2}$	2.6×10^6	0.19	0.052	0.057	0.182
Ar XIII	656.69	$2s^22p^2\ {}^3P_1$–$2s^22p^2\ {}^1S_0$	3.3×10^6		2.1×10^{-4}	2.0×10^{-4}	0.0019
Ar XIII	1330.53	$2s^22p^2\ {}^3P_1$–$2s^22p^2\ {}^1D_2$	3.3×10^6		6.0×10^{-4}	5.5×10^{-4}	0.0049
Ca XIII	648.68	$2s^22p^4\ {}^3P_1$–$2s^22p^4\ {}^1S_0$	2.6×10^6		2.5×10^{-3}	3.3×10^{-3}	0.022
Ca XIII	1133.76	$2s^22p^4\ {}^3P_2$–$2s^22p^4\ {}^1D_2$	2.6×10^6	0.25	0.023	0.028	0.168
Ca XIV	545.23	$2s^22p^3\ {}^4S_{3/2}$–$2s^22p^3\ {}^2P_{3/2}$	3.3×10^6		9.2×10^{-5}	1.4×10^{-4}	0.004
Ca XIV	579.85	$2s^22p^3\ {}^4S_{3/2}$–$2s^22p^3\ {}^2P_{1/2}$	3.3×10^6		6.4×10^{-5}	9.3×10^{-5}	0.0025
Ca XIV	880.40	$2s^22p^3\ {}^4S_{3/2}$–$2s^22p^3\ {}^2D_{5/2}$	3.3×10^6		3.6×10^{-4}	5.4×10^{-4}	0.015
Ca XIV	943.63	$2s^22p^3\ {}^4S_{3/2}$–$2s^22p^3\ {}^2D_{3/2}$	3.3×10^6	0.024	4.8×10^{-4}	7.5×10^{-4}	0.021
Ca XV	555.38	$2s^22p^2\ {}^3P_1$–$2s^22p^2\ {}^1S_0$	4.0×10^6		2.1×10^{-7}	2.1×10^{-7}	3.9×10^{-5}
Ca XV	1098.48	$2s^22p^2\ {}^3P_1$–$2s^22p^2\ {}^1D_2$	4.0×10^6		6.8×10^{-7}	6.6×10^{-7}	1.2×10^{-4}
Ca XV	1375.95	$2s^22p^2\ {}^3P_2$–$2s^22p^2\ {}^1D_2$	4.0×10^6		1.0×10^{-6}	9.8×10^{-7}	1.8×10^{-4}

NOTES.— The last column contains line intensities calculated with $T_2 = 300$ eV and $f_2 = 5\%$ and bulk electron temperature of 108 eV.

- Ralchenko et al. (2007) find that a secondary 5% suprathermal electrons of 3-4 MK can account for the unexpected brightness excess of a number of hot lines in the ~1MK quiet solar corona observed by *SOHO*/SUMER.

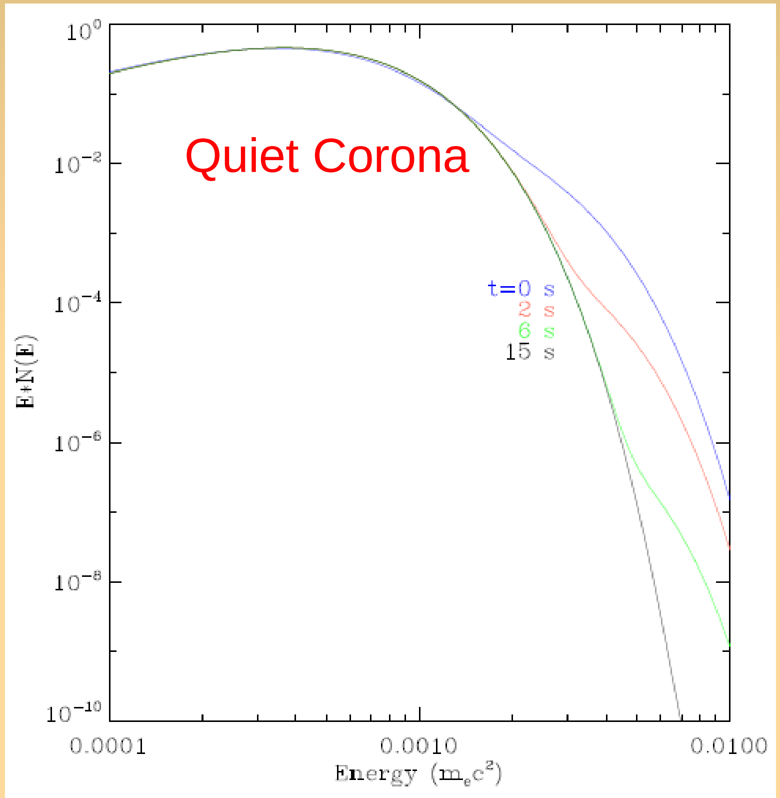
Problems with NT Tail Generation

- Thermalization of NT Tails by Coulomb collision is fast, usually within a few thermalization timescales (see Petrosian & East 2008)



$$\tau_{\rm therm} = 2\tau_{\rm Coul} E_0^{1.5}$$

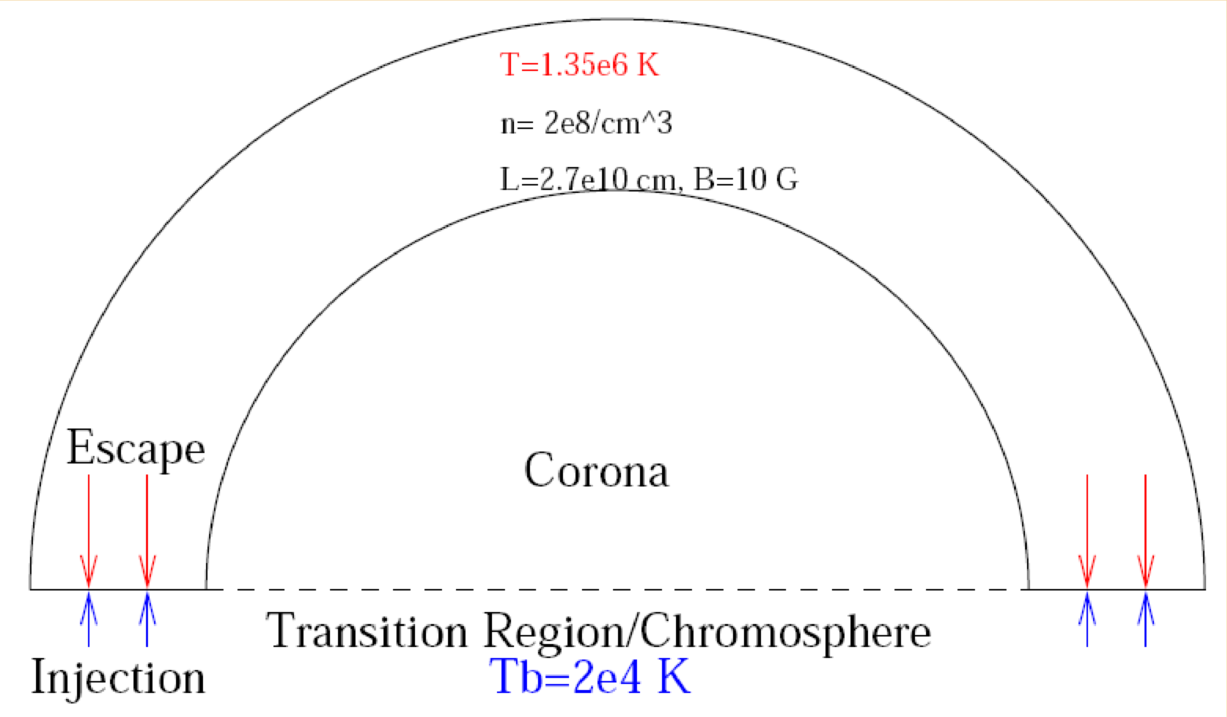
$$\tau_{\rm Coul} = \left(4\pi r_0^2 c n \ln\Lambda\right)^{-1}$$



- To produce and maintain non-Maxw dsitribution $\tau_{\rm acc} \leq \tau_{\rm therm}$
- But usually, in steady state situations $\frac{1}{\tau_{\rm acc}} = \frac{1}{\tau_{\rm rad}} + \frac{1}{\tau_{\rm cond}} \ll \frac{1}{\tau_{\rm therm}}$

Model Coronal Loop

- Coulomb collision
- Radiation cooling
- Conduction loss
- Turbulence



Kinetic Modeling

- To obtain particle velocity or energy distribution, we need to use the kinetic approach by solving the Fokker-Planck transfer equation; we need to know the energy rates for relevant processes.

$$\frac{\partial N}{\partial t} = \frac{\partial^2}{\partial E^2}\left[D(E)N\right] - \frac{\partial}{\partial E}\left[\left(A(E) - \dot{E}_{\rm L}\right)N\right] - \frac{N}{T_{\rm esc}(E)} + \dot{Q}(E)$$

Diffusion Convection Escape Injection

$D_{\rm Coul} + D_{\rm turb}$ Sys. Acce. $\dot{E}_{\rm Coul} + \dot{E}_{\rm Rad}$ Conduction

- Coulomb Collision

$$\dot{E}^{\rm hot}_{\rm Coul} = \dot{E}^{\rm cold}_{\rm Coul}\left[{\rm erf}(\sqrt{x}) - 4\sqrt{\frac{x}{\pi}}e^{-x}\right] \qquad D_{\rm Coul} = \dot{E}^{\rm cold}_{\rm Coul}\,(kT)\left[{\rm erf}(\sqrt{x}) - 2\sqrt{\frac{x}{\pi}}e^{-x}\right]$$

where $\dot{E}^{\rm cold}_{\rm Coul} = 4\pi r_0^2 cn \ln\Lambda/\beta$ $\quad x = E/kT$

- Stochastic acceleration by turbulence

$$D_{\rm turb}(E) = \frac{E^2}{\zeta(E)\tau_0(1+E_c/E)^q}$$

$$A(E) = \frac{D_{\rm turb}(E)\zeta(E)}{E} + \frac{d}{dE}D_{\rm turb} \qquad \zeta(E) = (2-\gamma^{-2})/(1+\gamma^{-1})$$

Continued

- Radiation (from CHIANTI)

  $n\Lambda(T)$ with $T \to 2E/3$

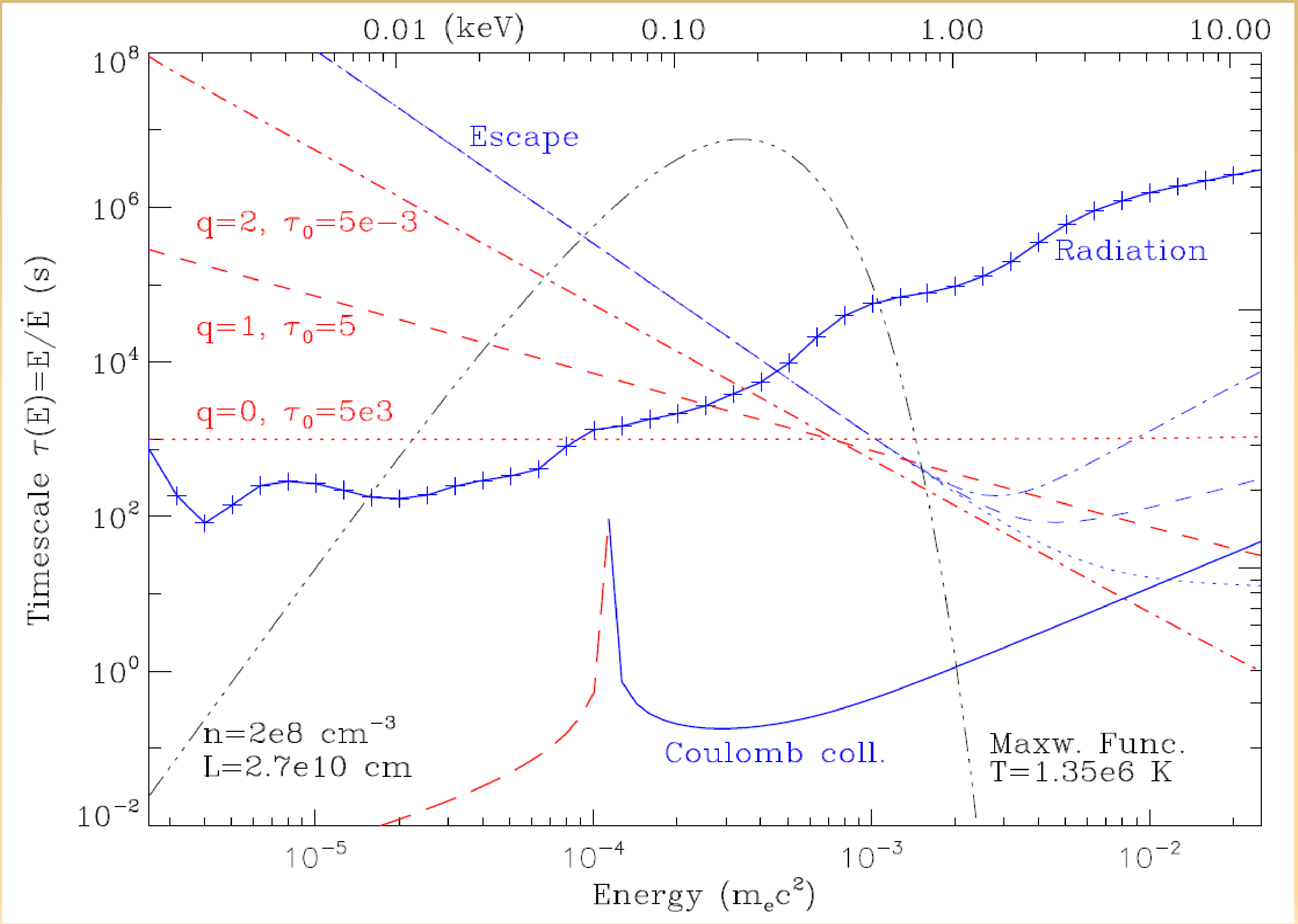
- Conduction modeled by Escape & Injection terms, also suppressed by turbulence; Conduction flux is roughly twice radiation flux in the quiet corona (Withbroe & Noyes 1977)

$$T_{\mathrm{esc}} = \frac{L^2}{v^2 \tau_{\mathrm{sc}}}, \text{ with } \frac{1}{\tau_{\mathrm{sc}}} = \frac{1}{\tau_{\mathrm{sc}}^{\mathrm{Coul}}} + \frac{1}{\tau_{\mathrm{sc}}^{\mathrm{turb}}}$$

$$\tau_{\mathrm{sc}}^{\mathrm{turb}} = \frac{E^2}{D_{\mathrm{turb}}(E)} \left(\frac{\beta_{\mathrm{A}}}{\beta} \right)^2$$

$$\tau_{\mathrm{sc}}^{\mathrm{Coul}} = E\beta / (4\pi r_0^2 c n \ln \Lambda)$$

Timescales in Quiet Corona



Solving FP Equation

- We start with a Maxwellian function of typical coronal temperature and include the processes mentioned above.
- At each time step, we evalute the energy loss rate and adjust the level of turbulence to achieve the steady state condition.

Adjust Turbulence Acceleration Rate

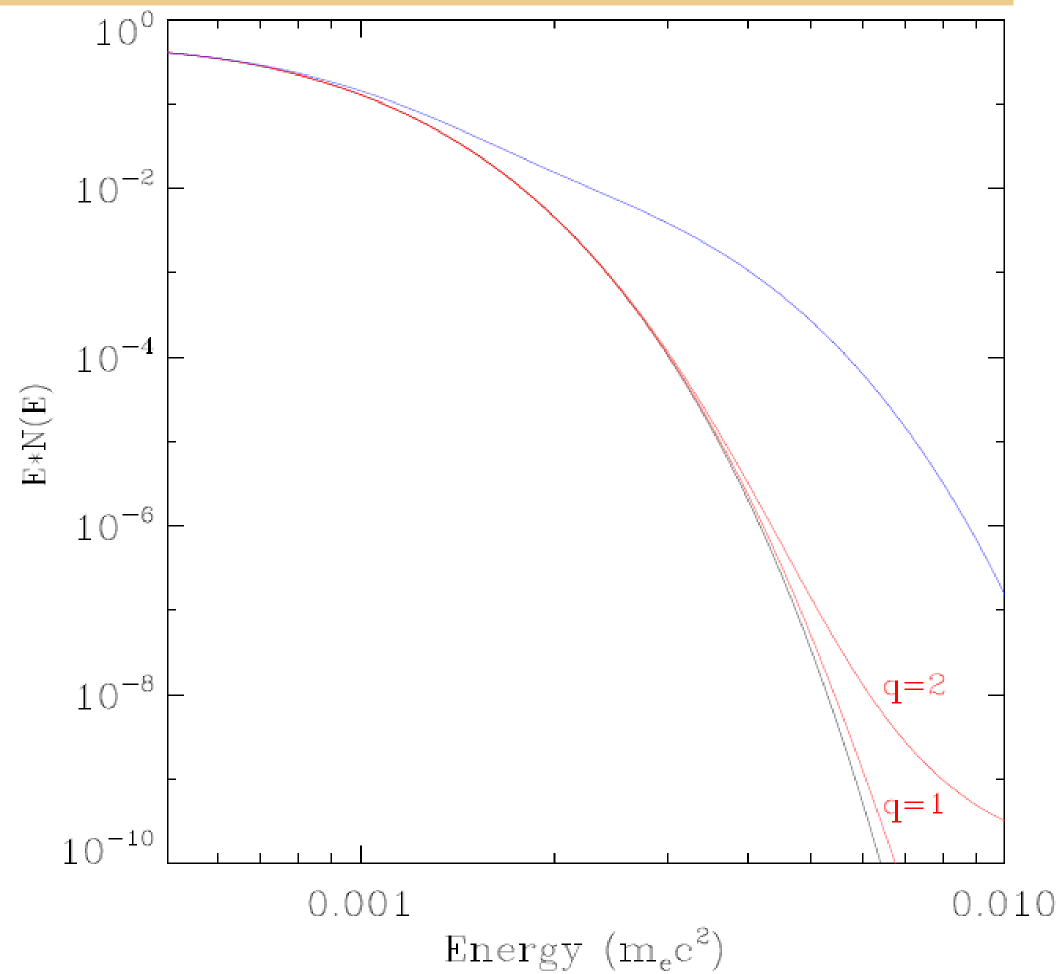
$$\int A(E)N(E)dE = \int \left(\frac{E}{T_{\rm esc}(E)} + \dot{E}_{\rm R}\right) N(E)dE - \left(\frac{3}{2}kT_{\rm b}\right)\dot{Q}$$

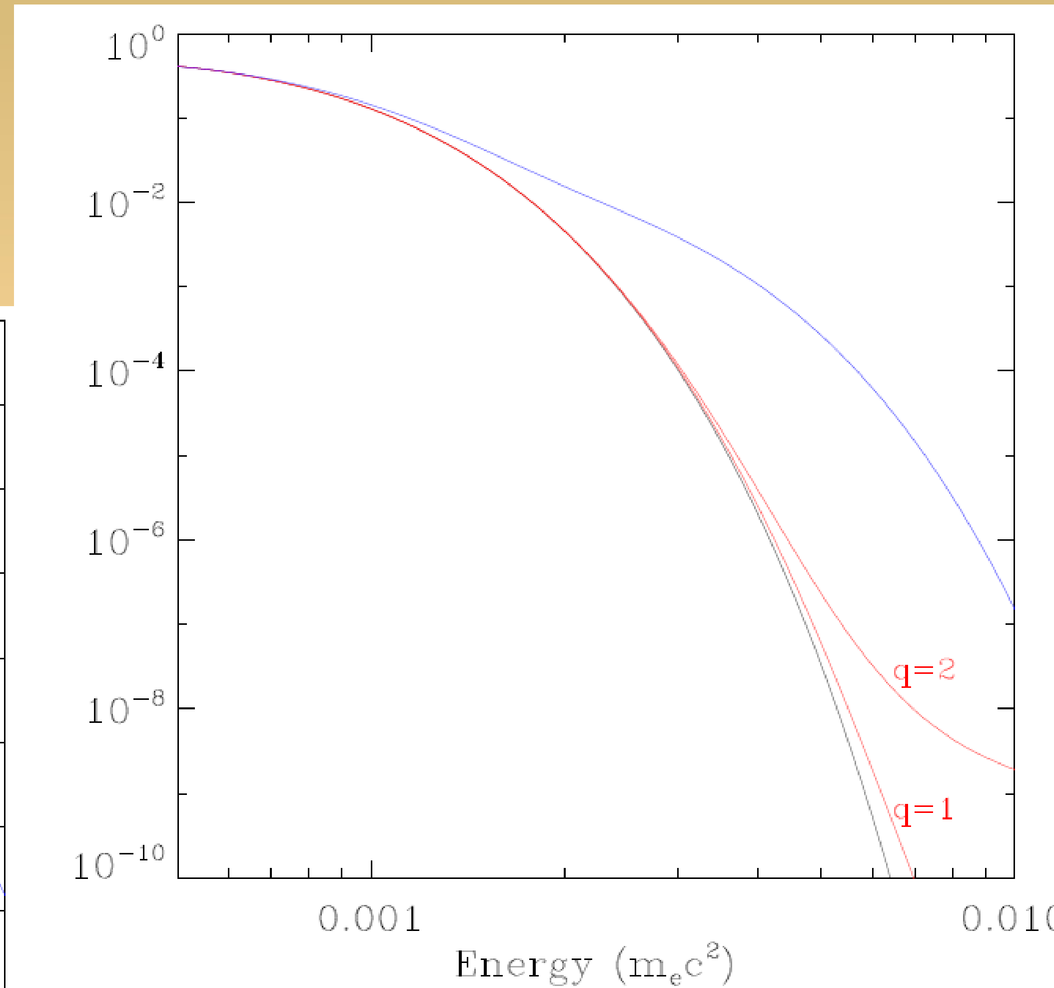
Adjust Number of Injected Electrons

$$\dot{Q} = \int \dot{Q}(E)dE = \int \frac{N(E)}{T_{\rm esc}(E)}dE = \dot{N}_{\rm esc}$$

Steady State Spectrum

Energy loss including
only conduction





Energy loss including
both conduction and radiation

Conclusion

- In collisonal plasma, generation of significant nonthermal tails is very difficult; Only a very weak tail is present in the steady state spetrum under the quiet solar corona condition.
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- The observed brightness excess of hot lines may probably be the superposition of emission from two physically separated regions of different temperatures along the line of sight.