IMPLICATIONS OF ELECTRON BEAM PROPAGATION ON SOLAR FLARE ENERGETICS

Meriem Alaoui (UMD)
alaoui@umd.edu

Joel Allred (NASA/GSFC)
Gordon Holman (NASA/GSFC)
Rafael Eufrasio (UARK)
Tünde Fülöp (Chalmers)
Brian Dennis(NASA/GSFC)

New collaborators: J. Drake, M. Swisdak

Institute for Research in Electronics & Applied Physics

Outline

Standard and extended models of solar eruptive events

Standard model with return currents and open questions

How do return currents affect HXR observations?

Motivation for developing RunawayRC

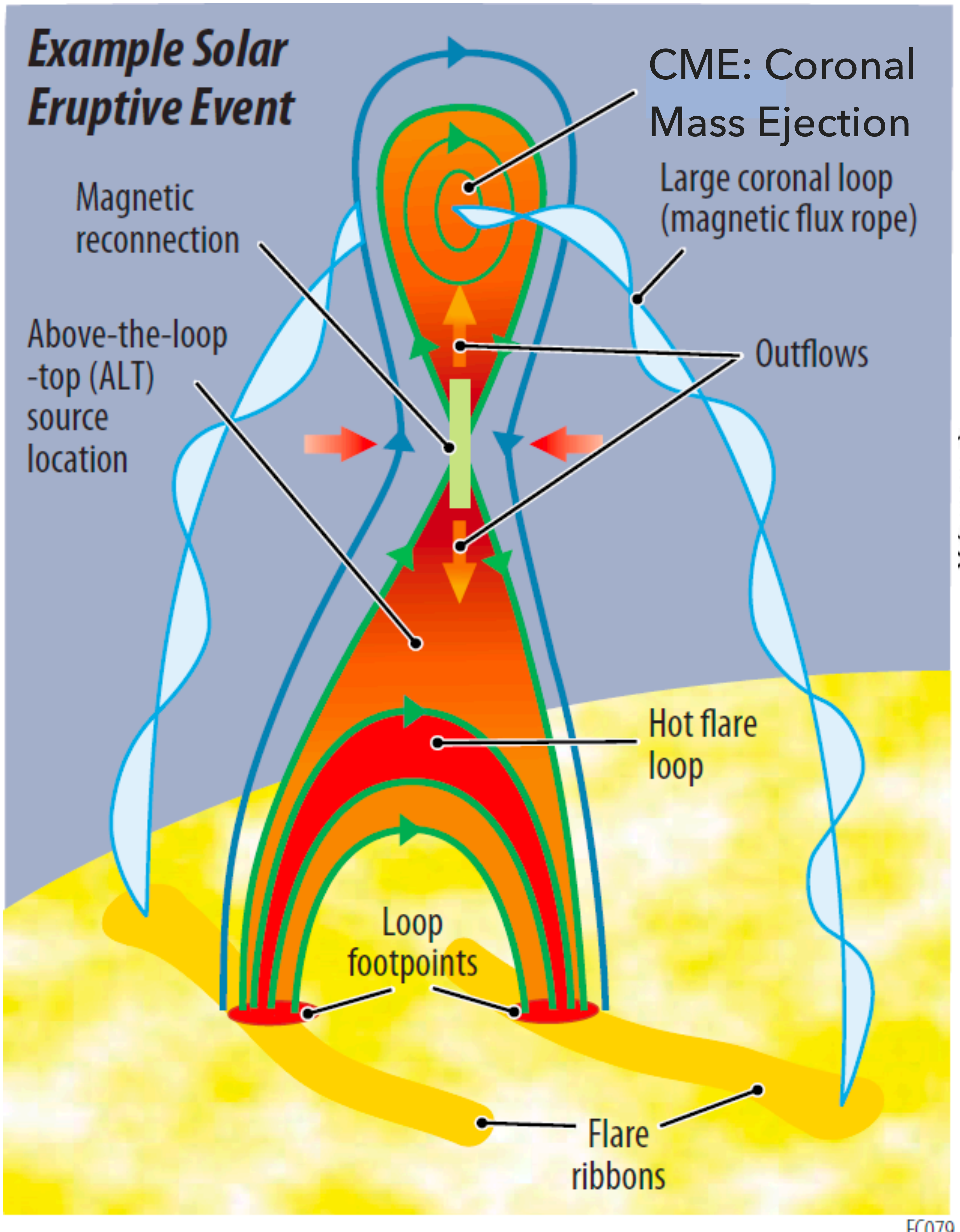
Recent advances in modeling the beam/return current propagation

Beam/return current model which neglects runaway electrons Allred+20 (FP)
and which includes runaway electrons Alaoui+21 (RunawayRC)

Thermal response to the injection of an electron beam including return currents

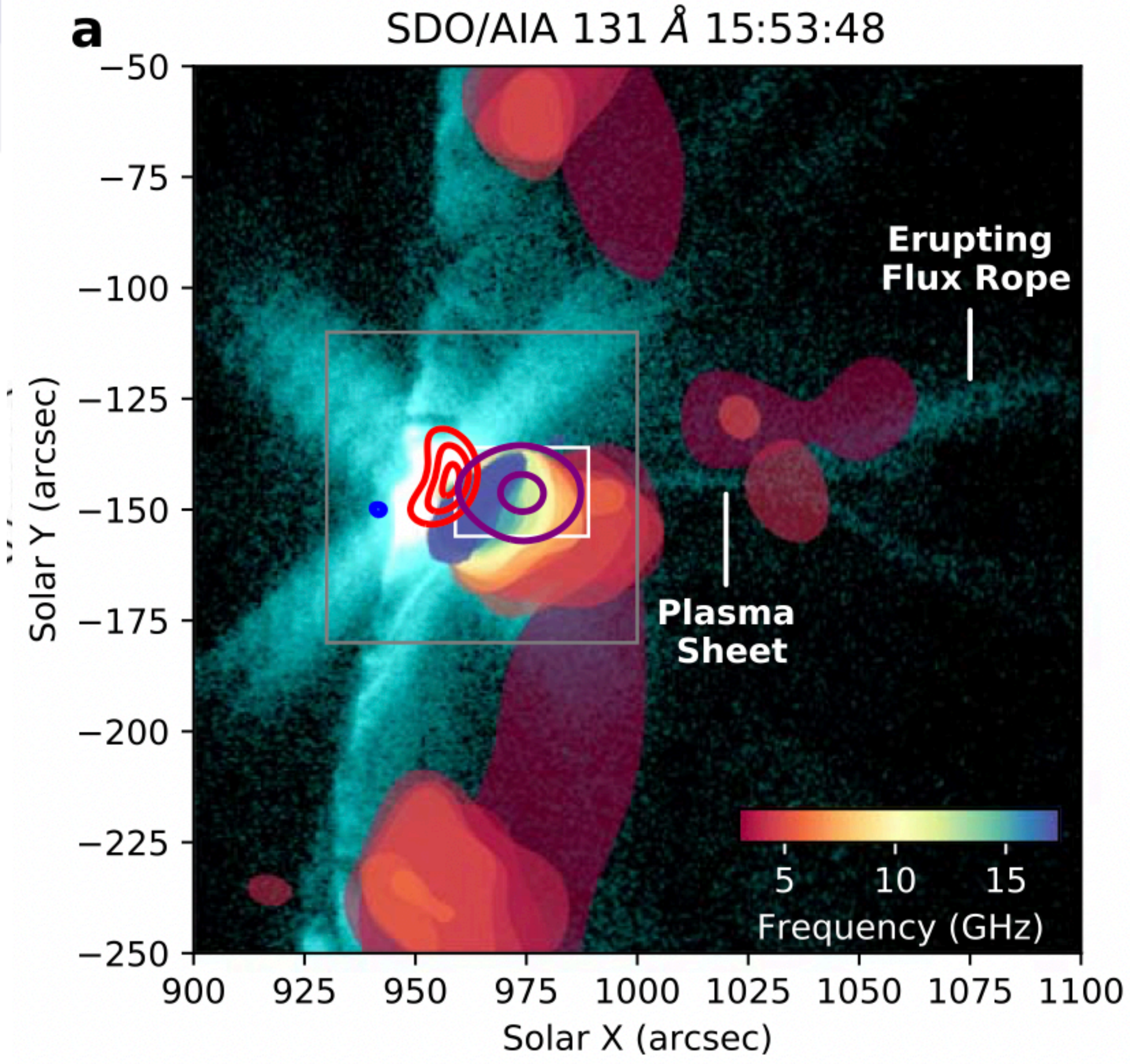
STANDARD MODEL FOR SOLAR ERUPTIVE EVENTS

Cartoon of 2D standard model



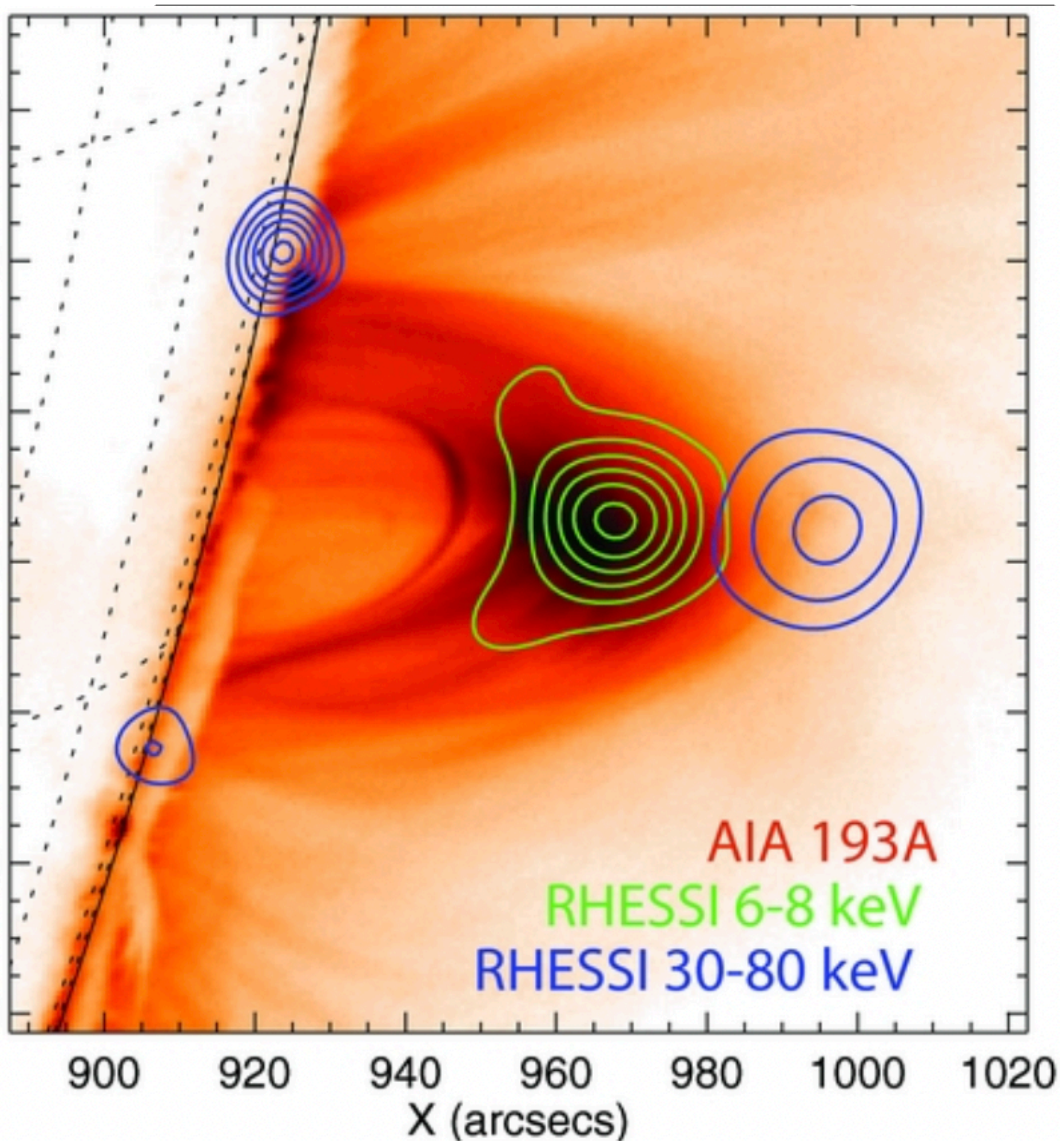
Real observations

Microwave (1-18 GHz); X-ray and EUV emissions



Gary et al. 2018

X-ray and EUV emission



Krucker & Battaglia 2014

"PROBLEMS" WITH STANDARD MODEL

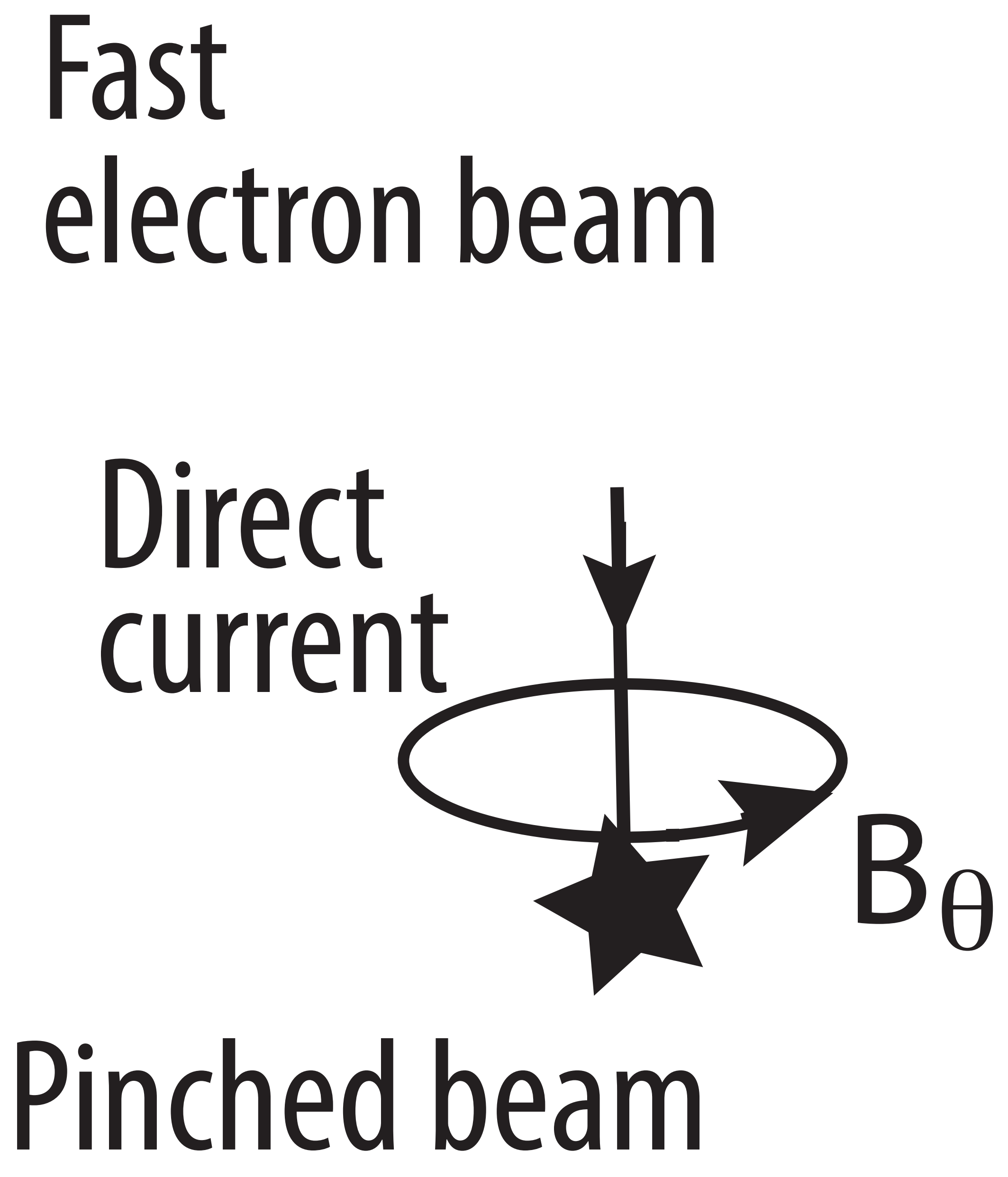
NUMBER "PROBLEM"

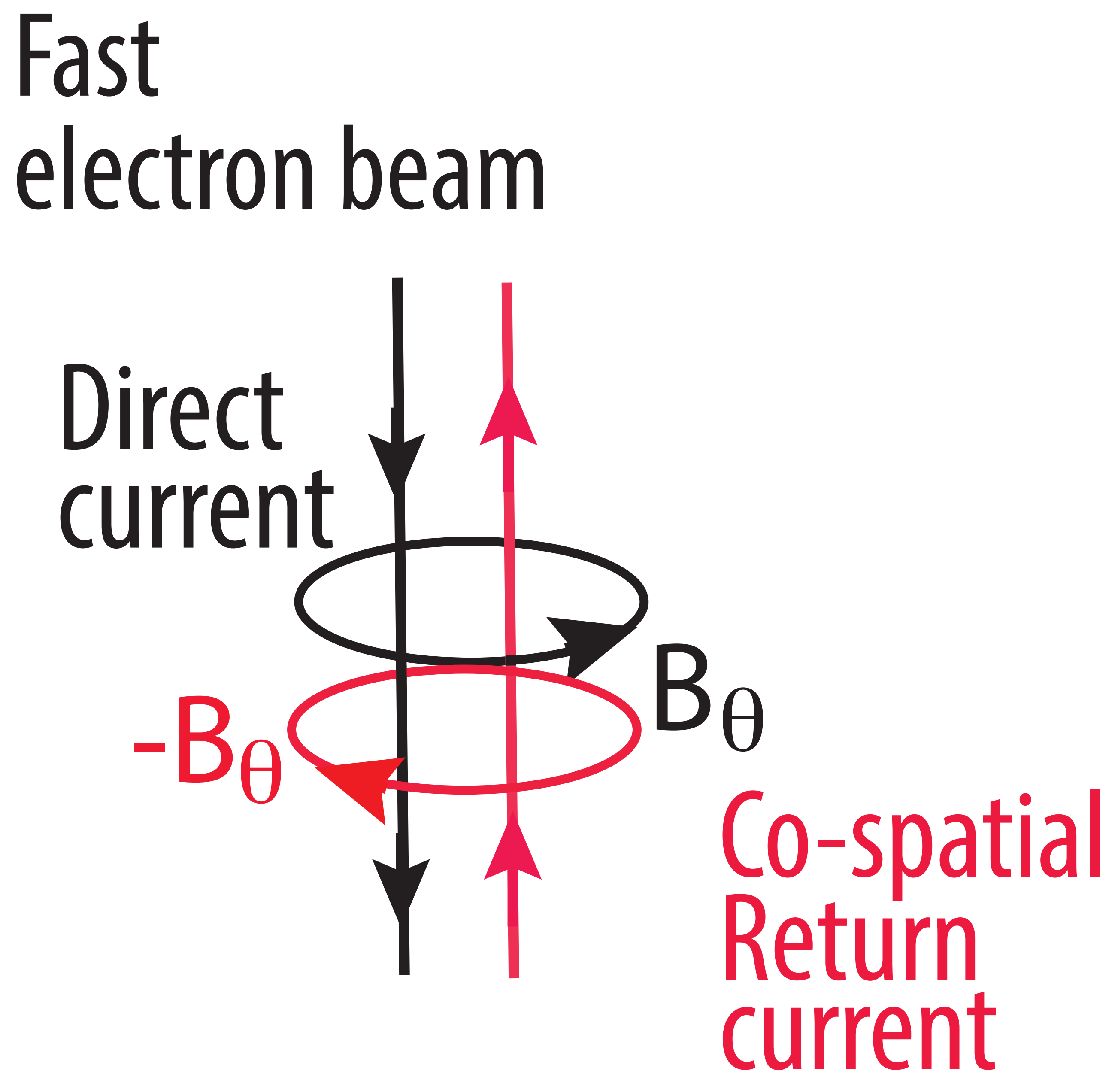
Electron flux required to produce observed X-ray emission is $\sim 10^{36}$ electrons/s. (Hoyng et al 1976, 1978)

Number of electrons in typical flaring region $nV \sim 10^{37}$
=> evacuation of the flaring region in seconds

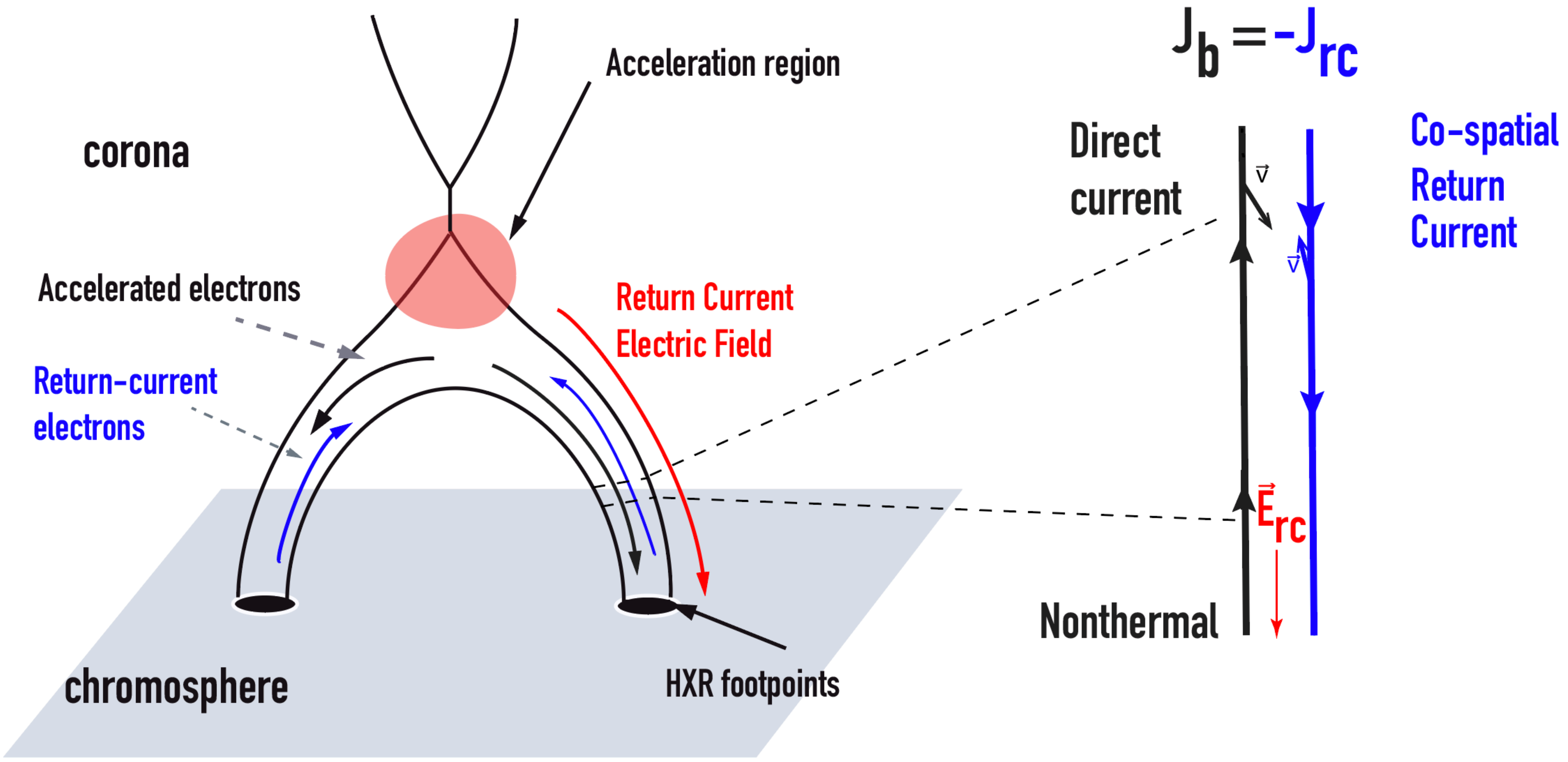
CURRENT STABILITY "PROBLEM"

Currents 10^{17} Amps
Induced magnetic field 10^5 G
=> pinched beam (Bennet 1934, 1955)

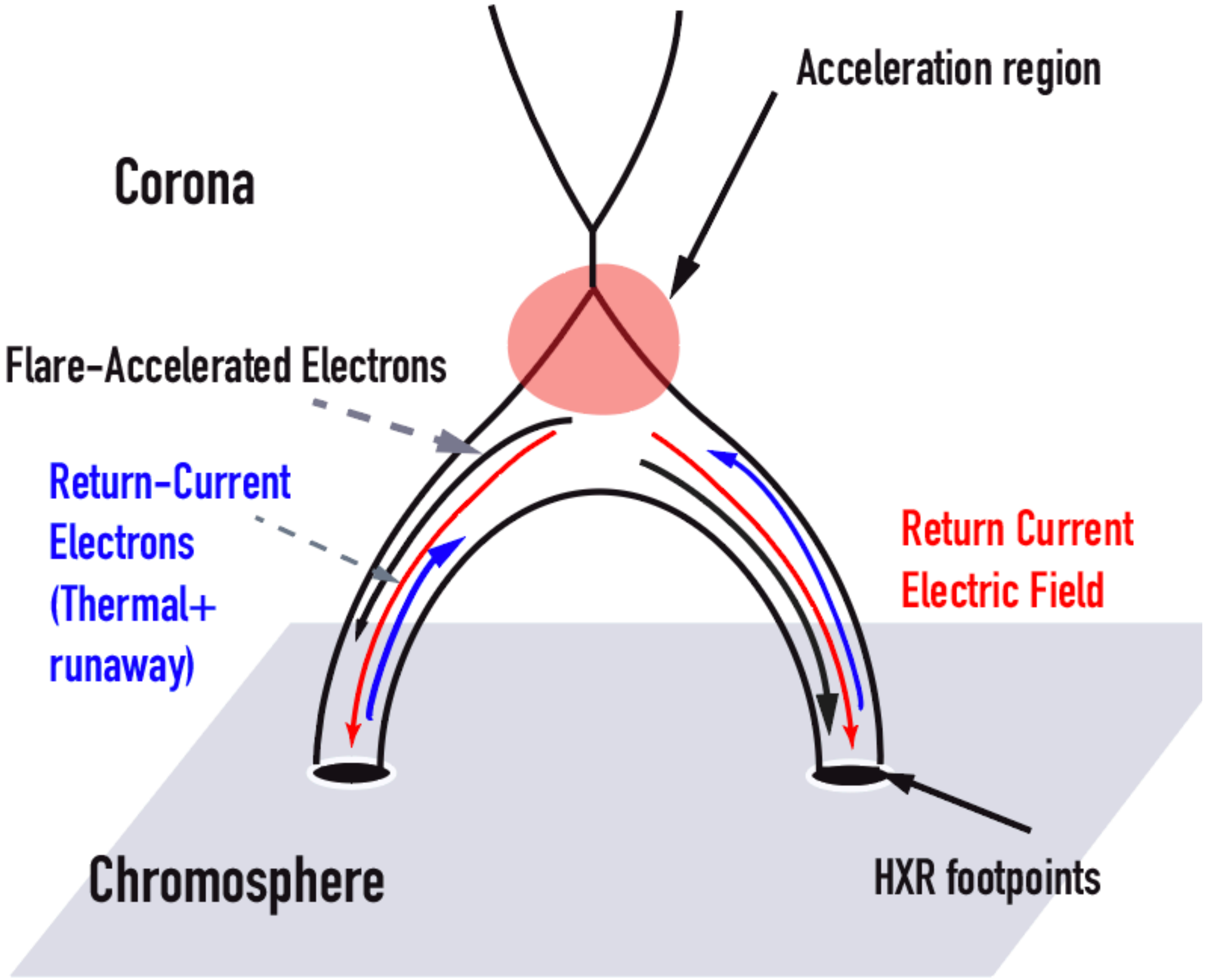




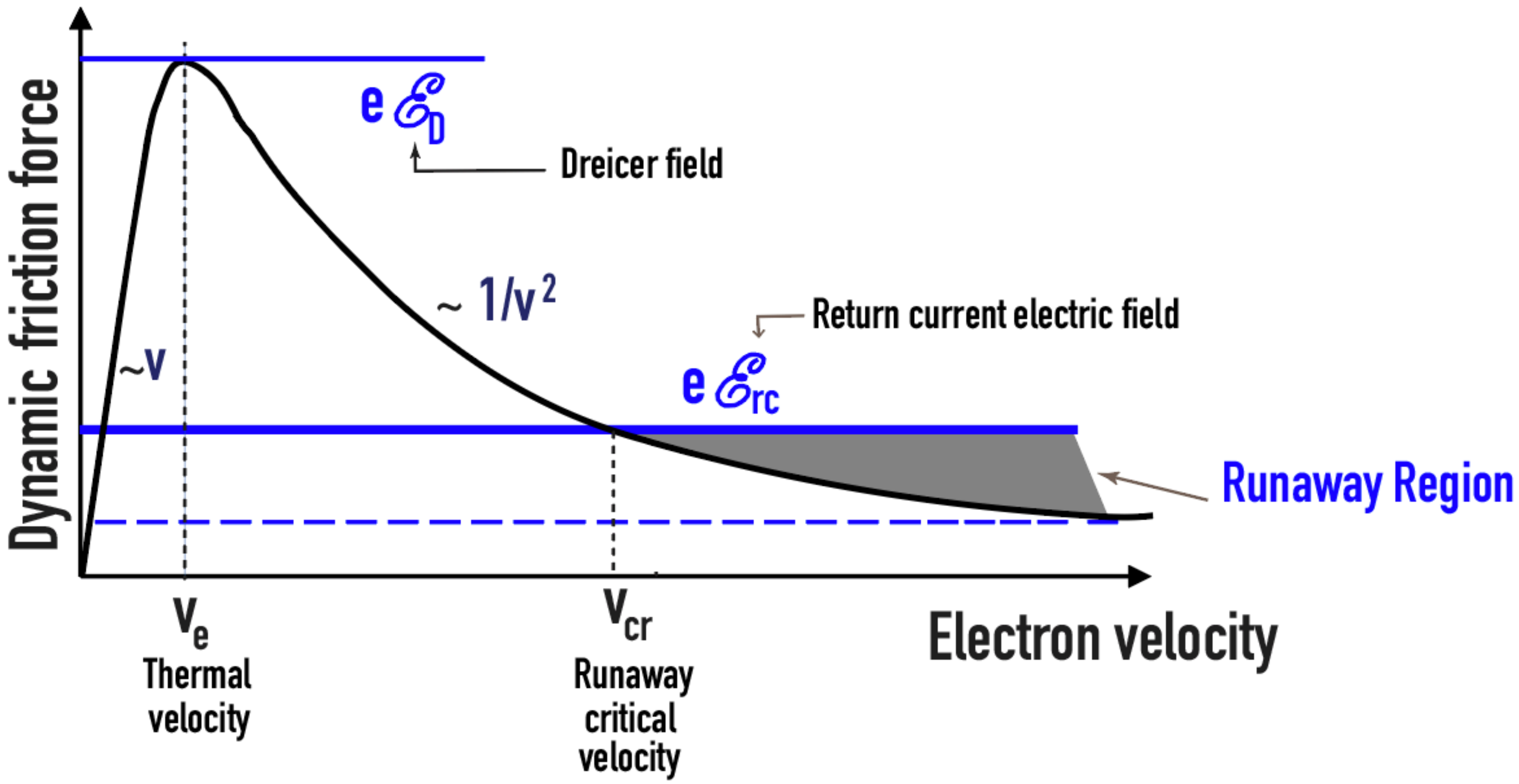
Extended Standard model for electron propagation with return currents



Which electrons carry the return current?



(1) Thermal
(2) Suprathermal Runaway Electrons
(3) Nonthermal beam electrons scattered backwards



Outstanding questions

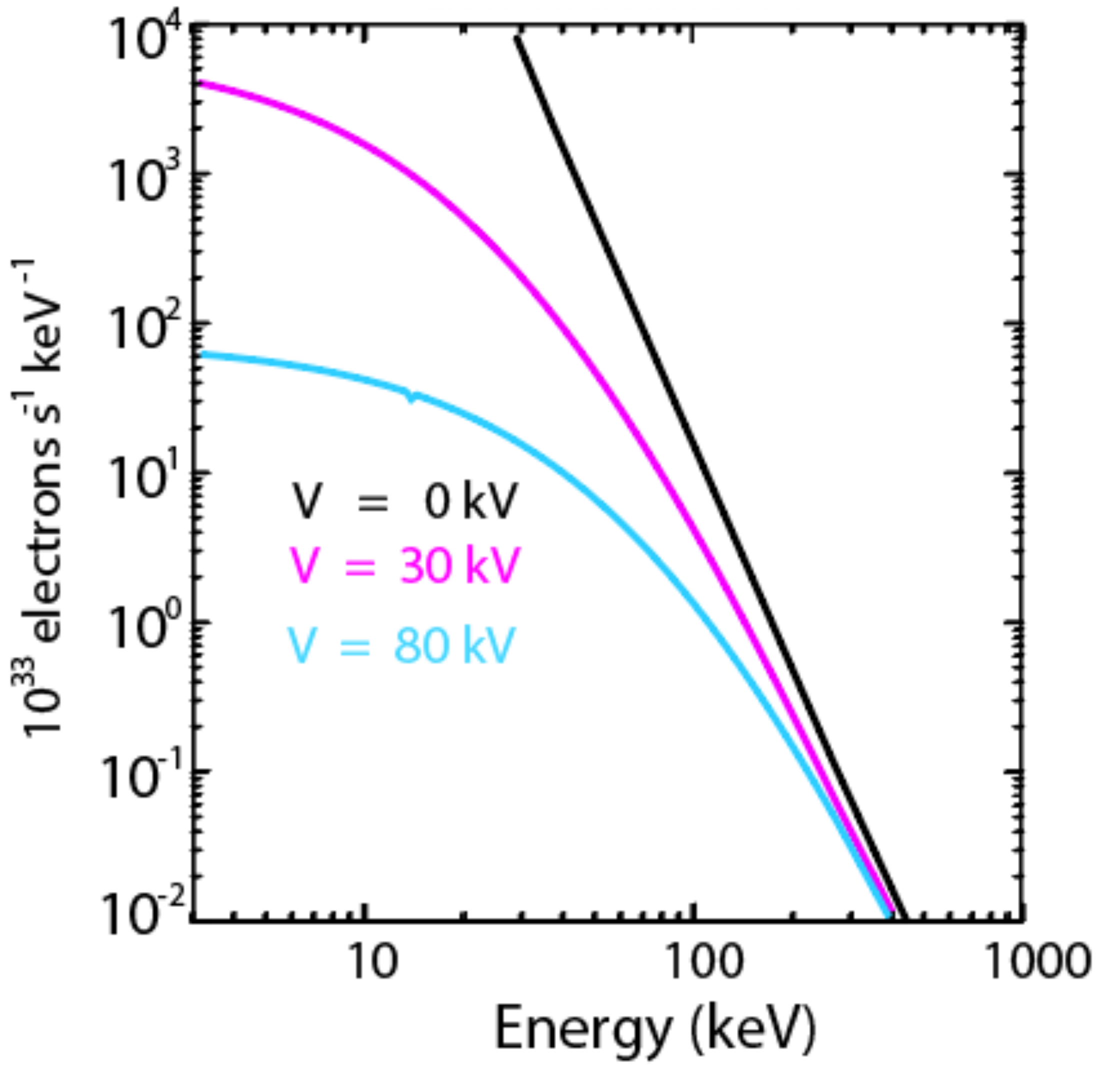
Is there a feedback between the large scale propagation effects and the acceleration process itself?

How much and where is the electrons energy dissipated?

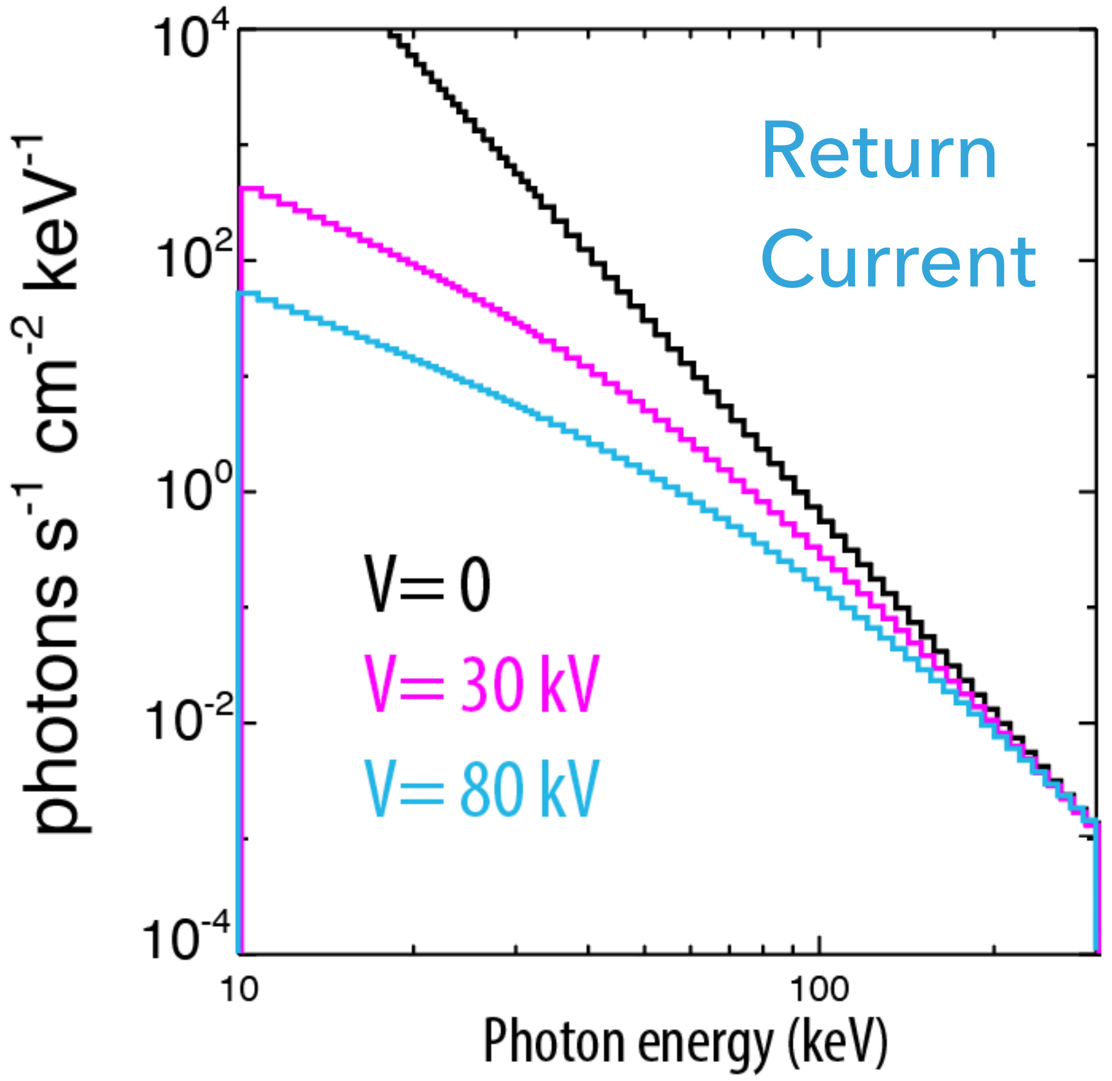
Do electron beams accelerated in the solar corona produce the observed spectral properties?

How do return current losses affect X-ray spectra?

Electron distribution (**modeled**)



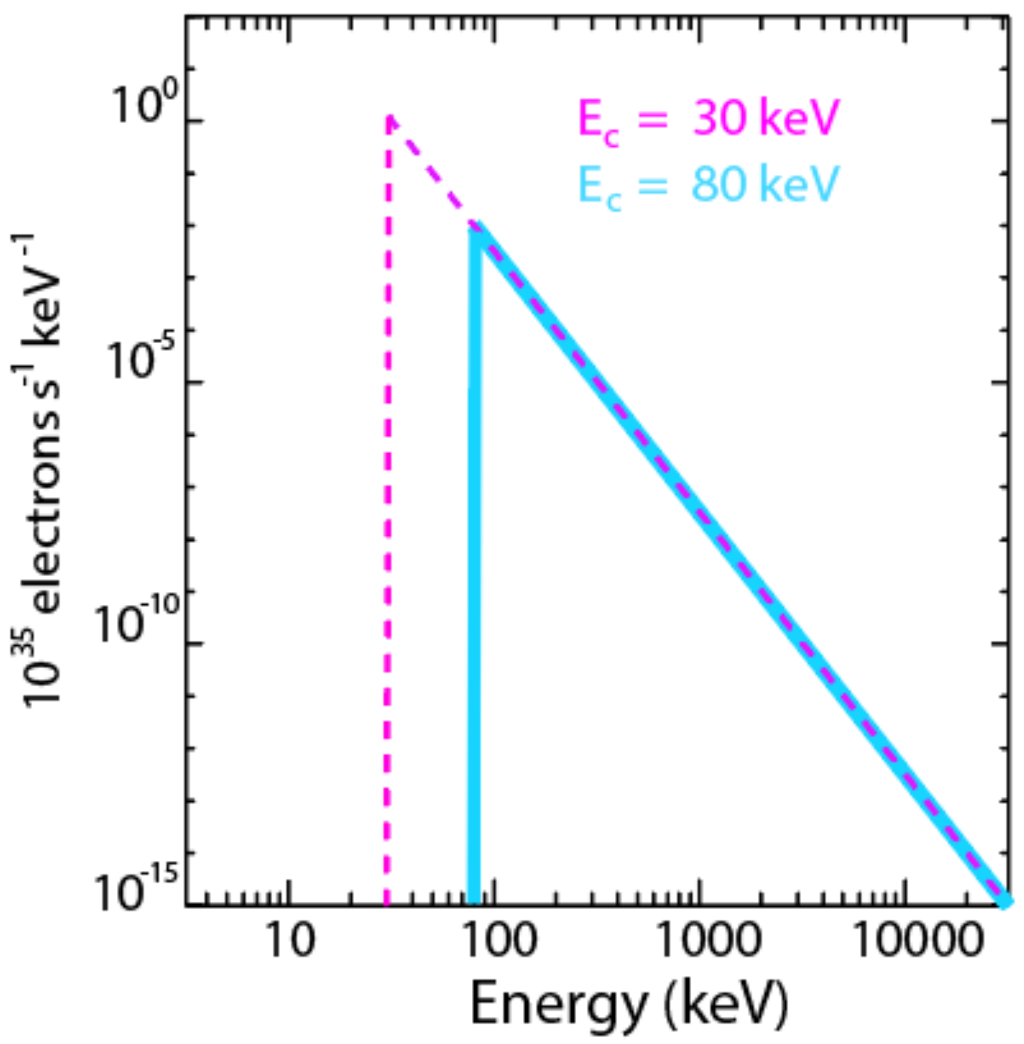
Photon spectrum (**observed**)



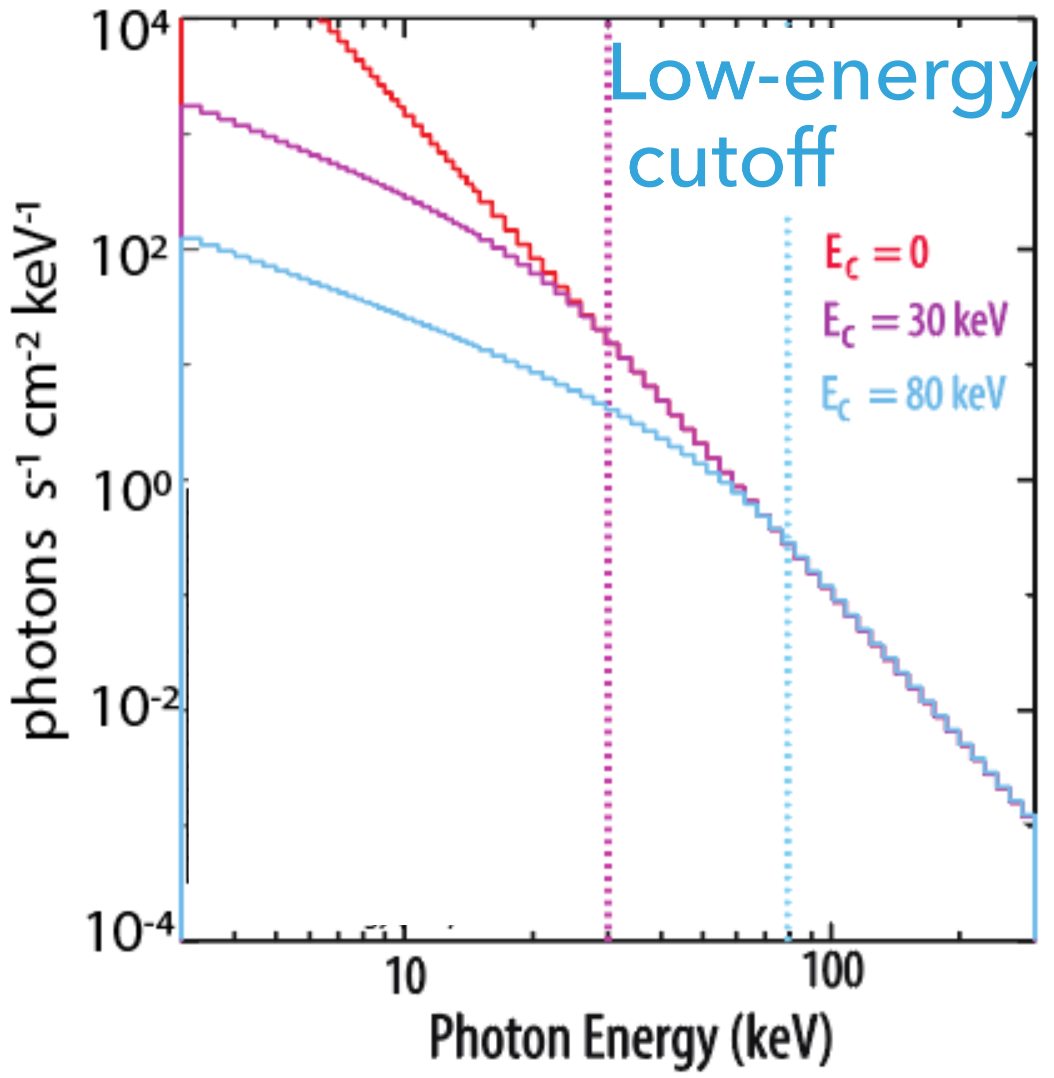
Lowest energy electrons lose the highest *fraction* of their energy

Flatten electron distribution at low-energies

Electron distribution (**modeled**)



Photon spectrum (**observed**)

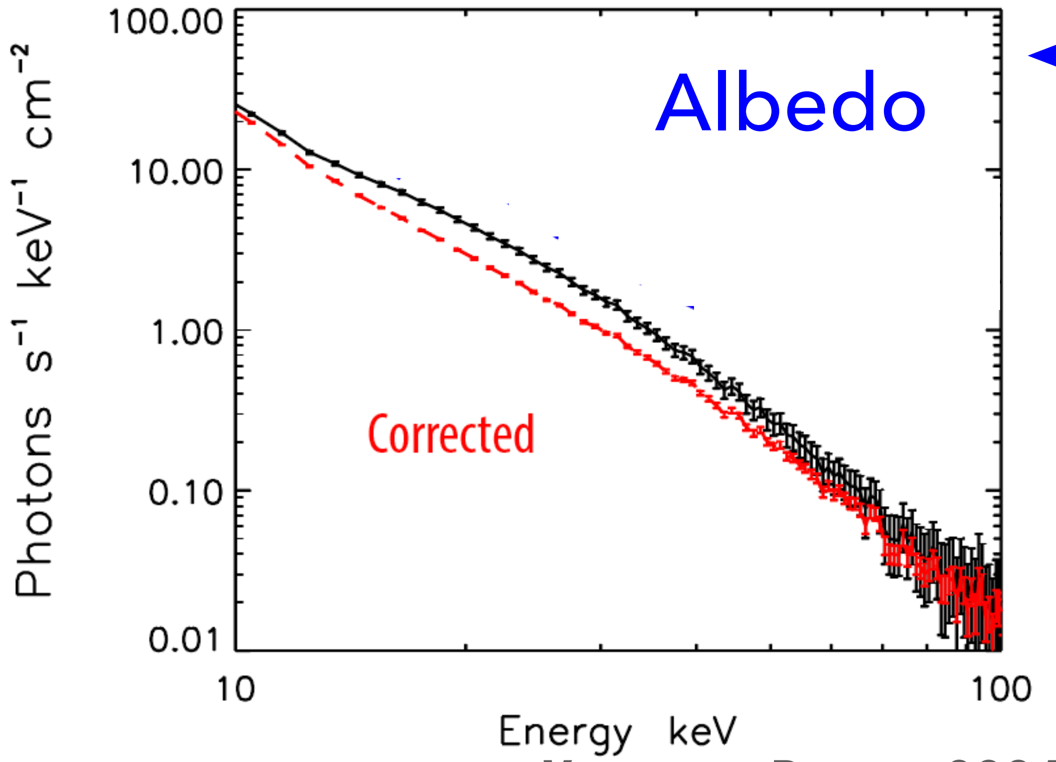


A large enough value of the low energy cutoff is also observed as a flattening in the X-ray spectrum

Question

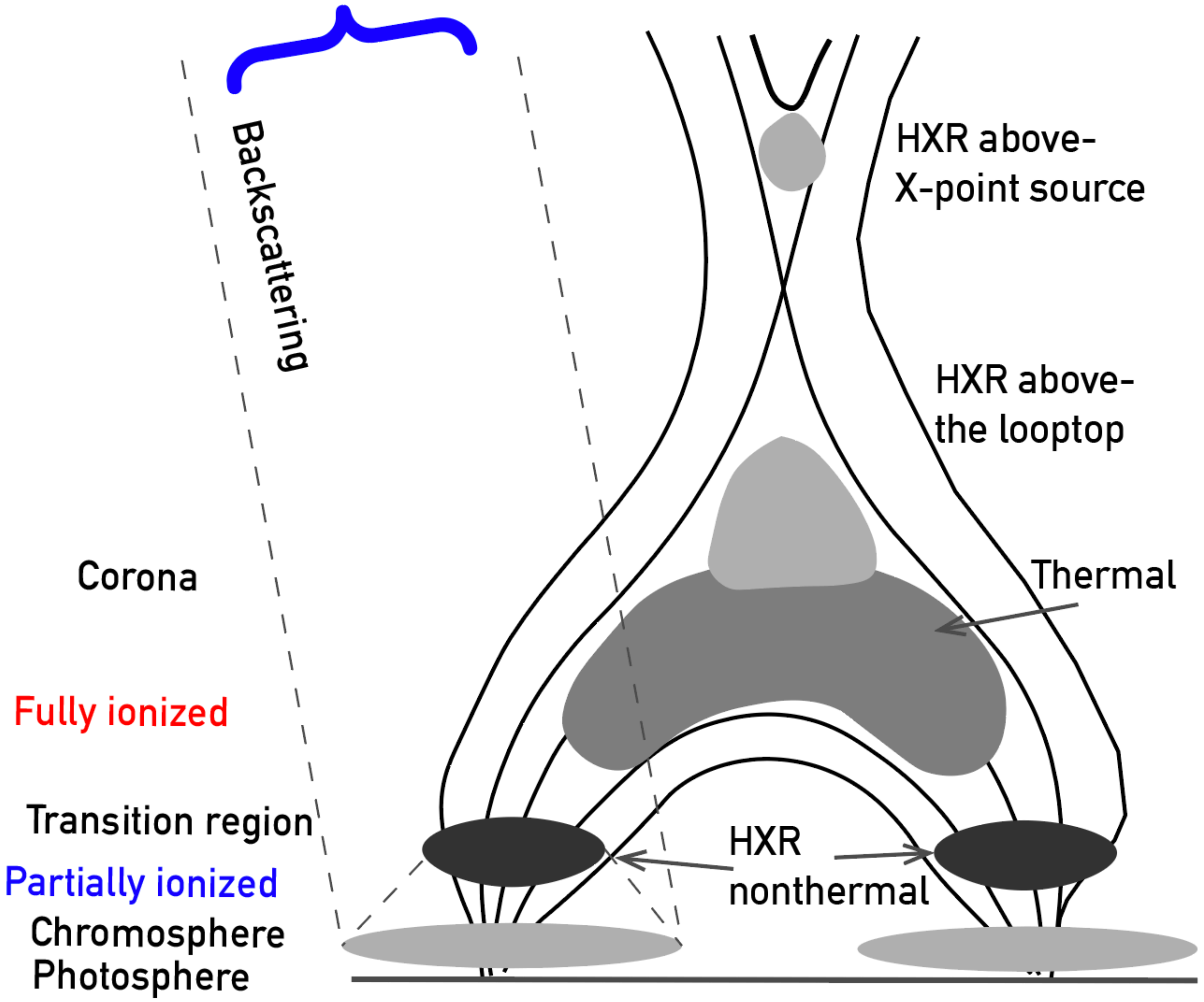
To what extent is the shape of X-ray spectra a consequence of the acceleration mechanism or beam propagation?

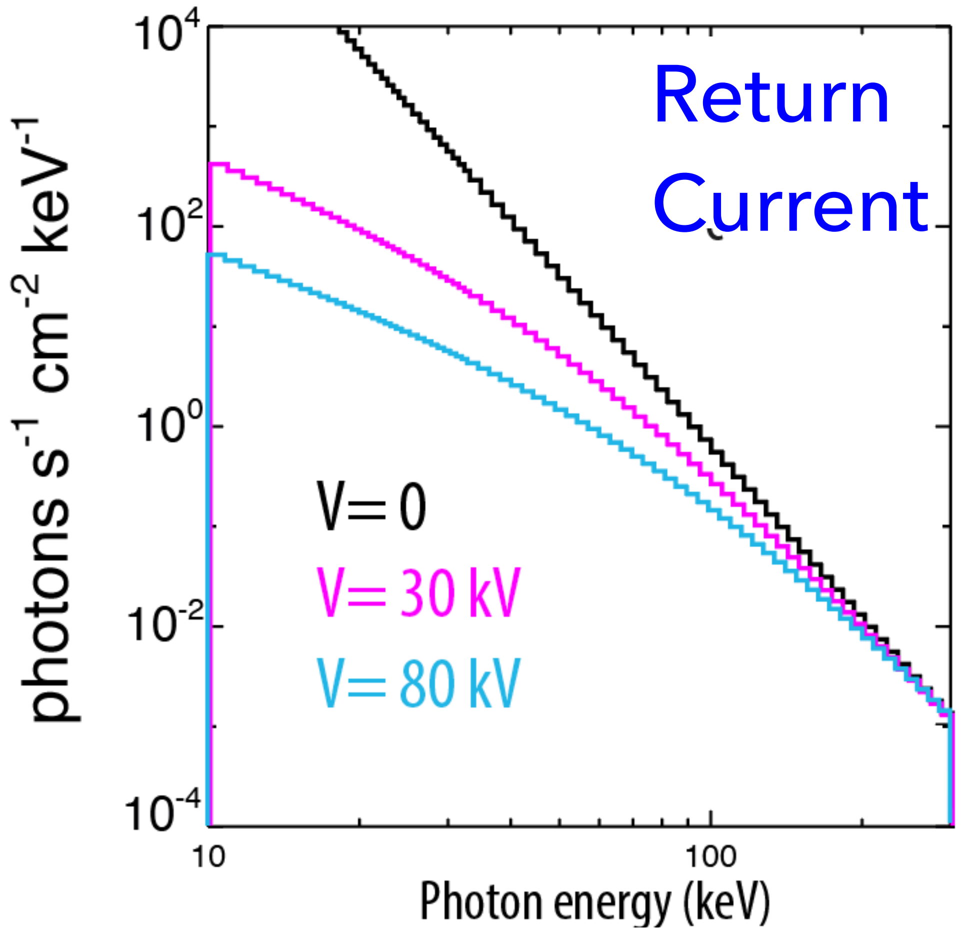
Mechanisms which affect the HXR emission

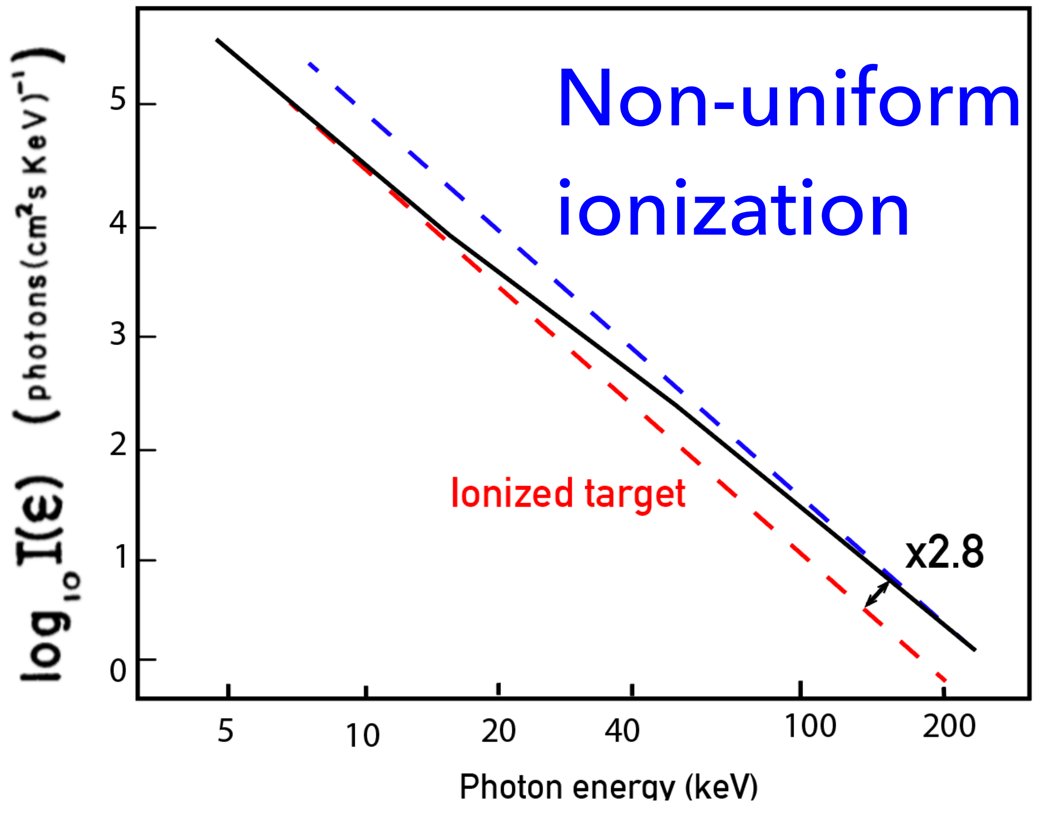


Kontar & Brown 2006

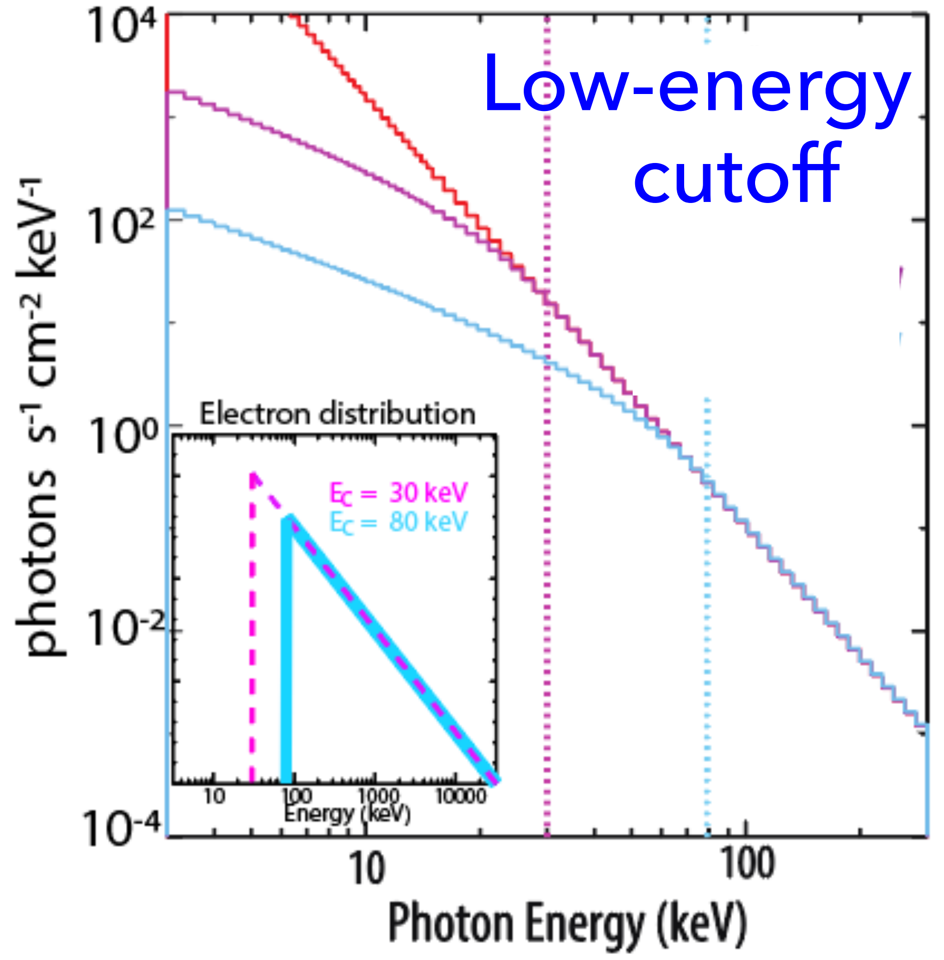
Not included in latest beam propagation models





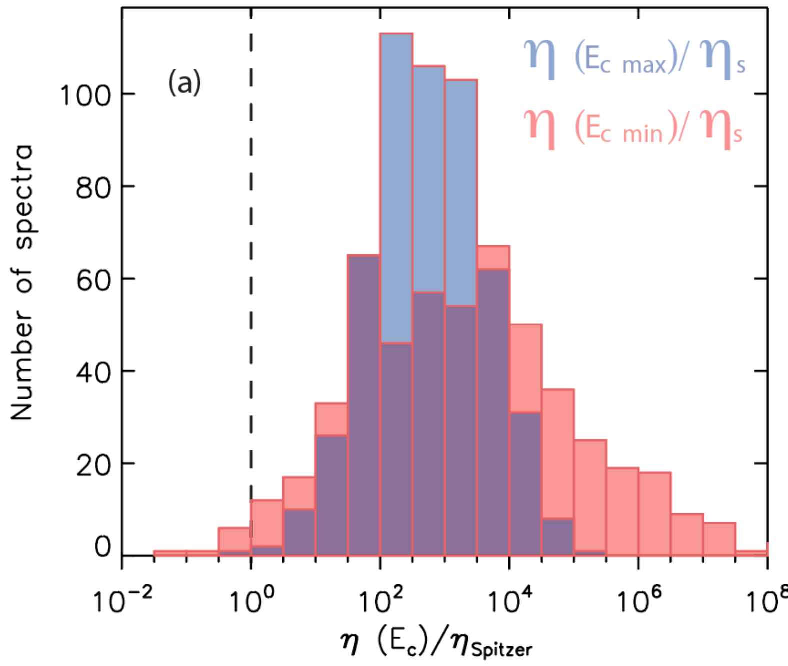


Brown 1973; Su et al. 2011



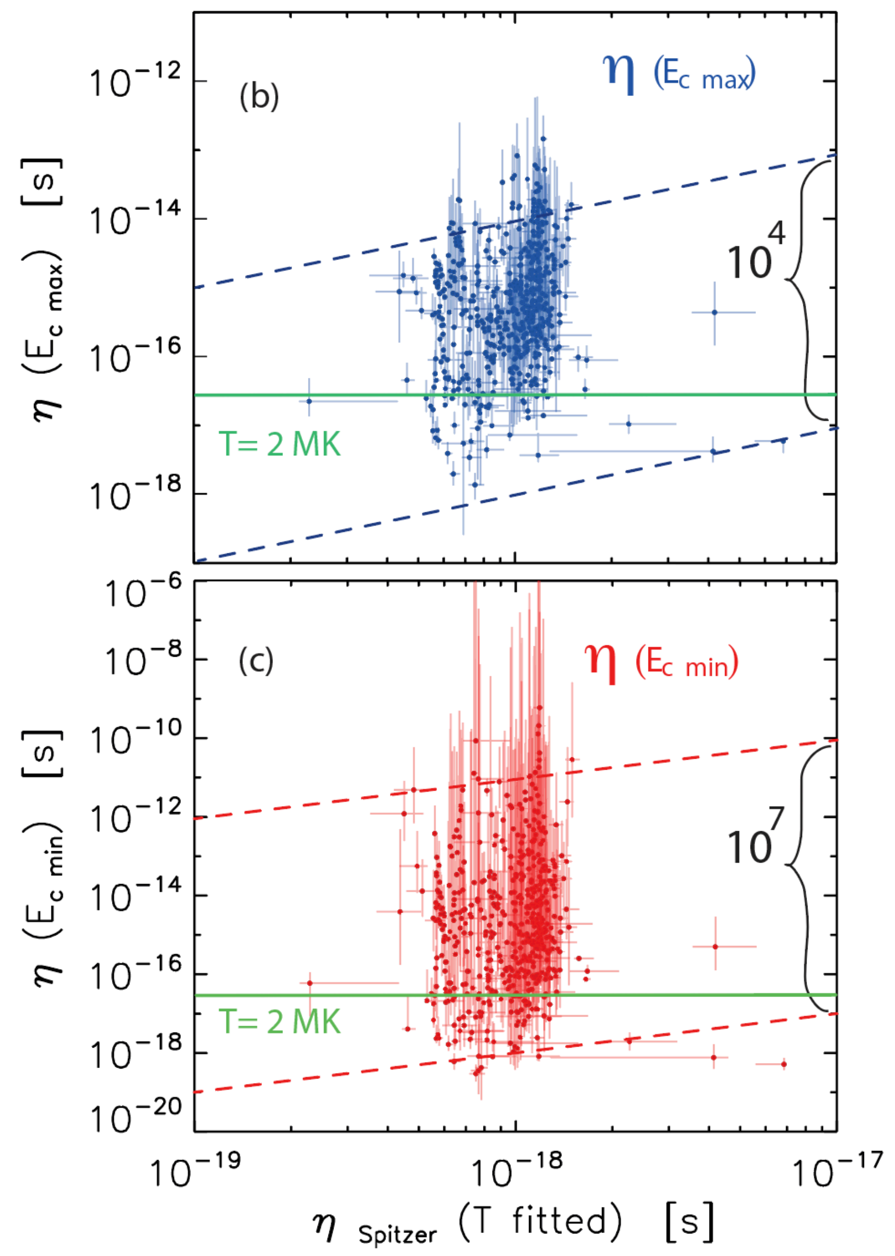
With imaging spectroscopy with higher range of sensitivity (dynamic range), high spatial and temporal resolution: can differentiate between these effects

Are current-driven instabilities responsible for X-ray flattening?

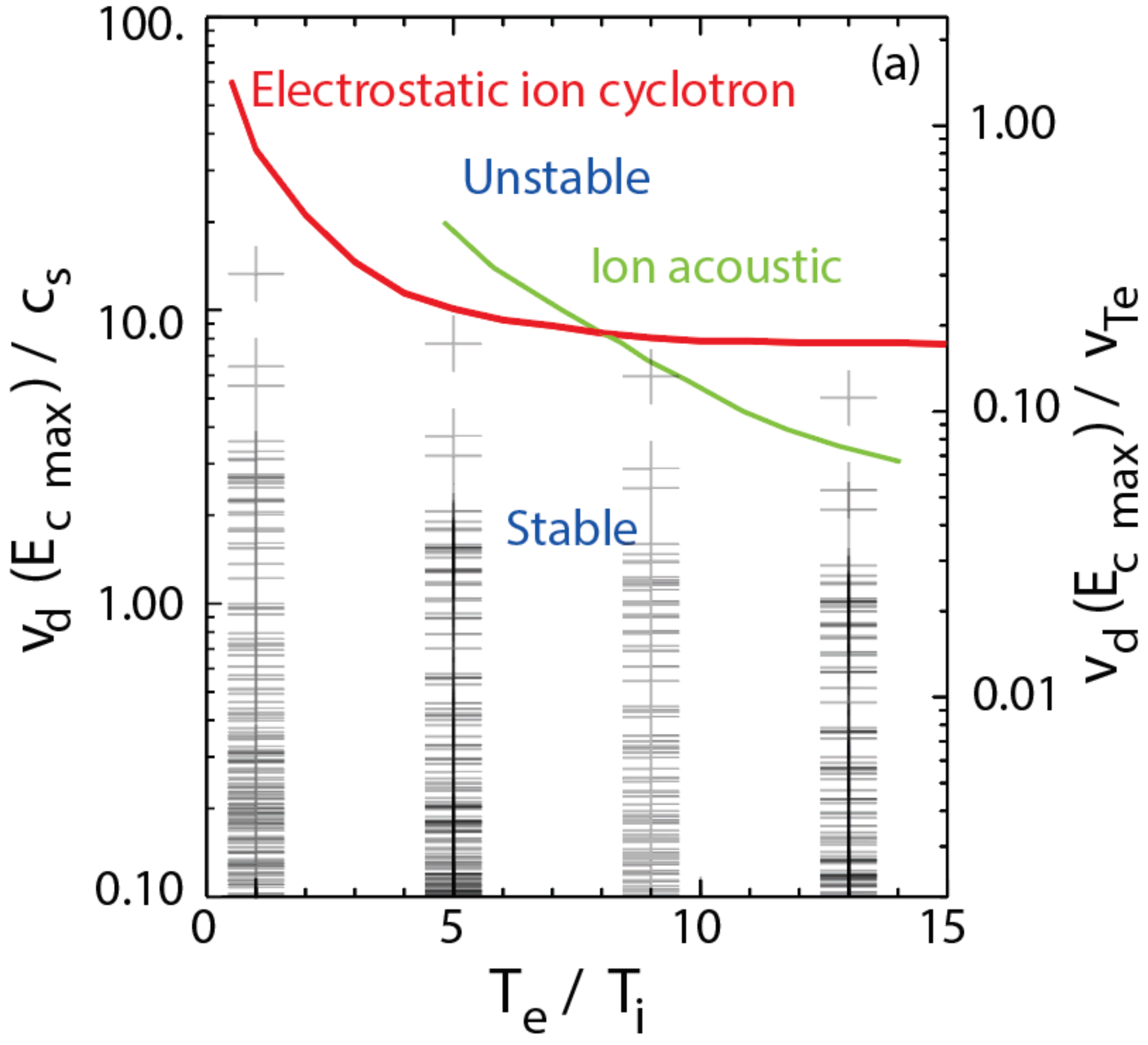


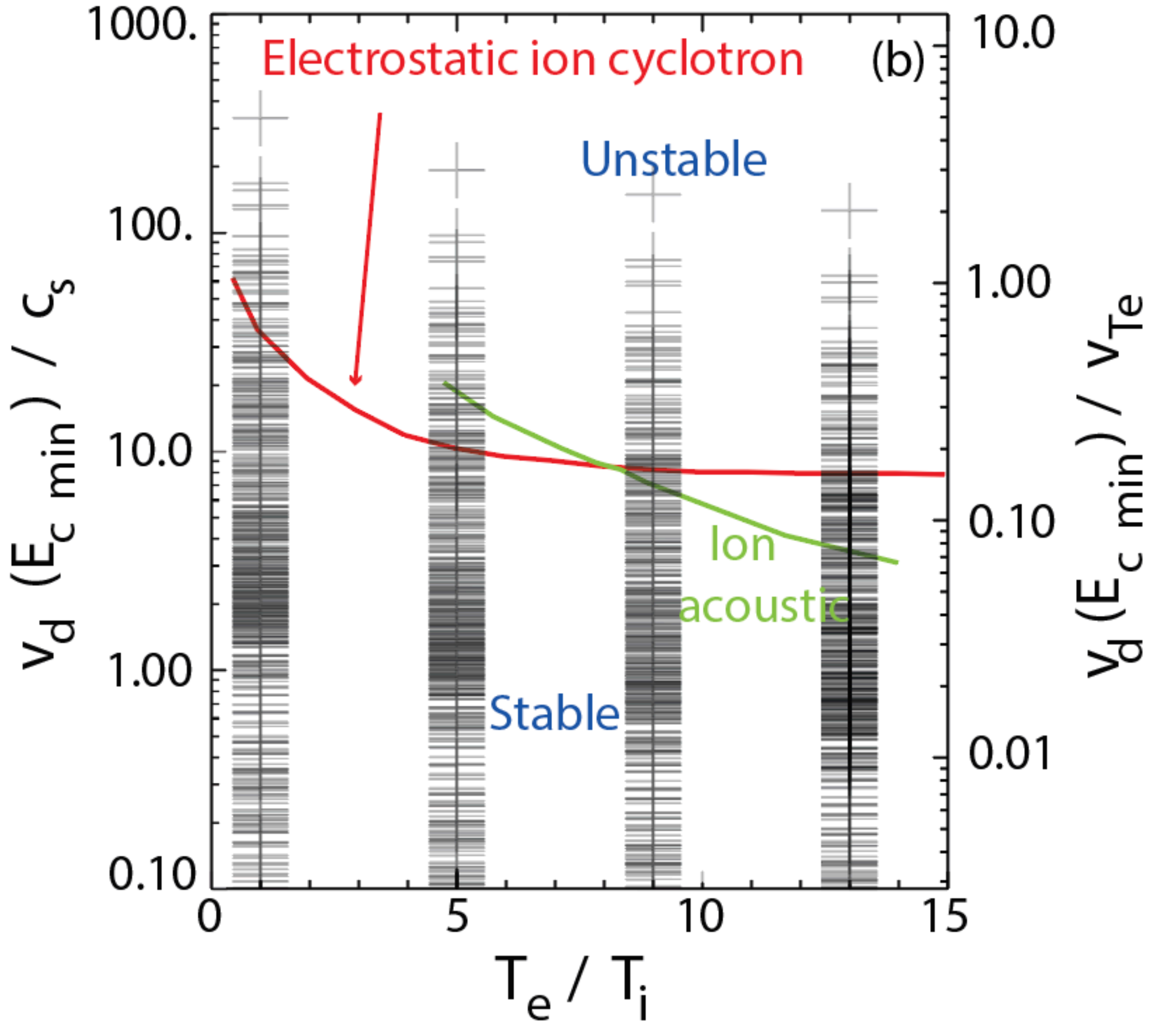
Classical (Spitzer) resistivity proportional to $T^{-3/2}$

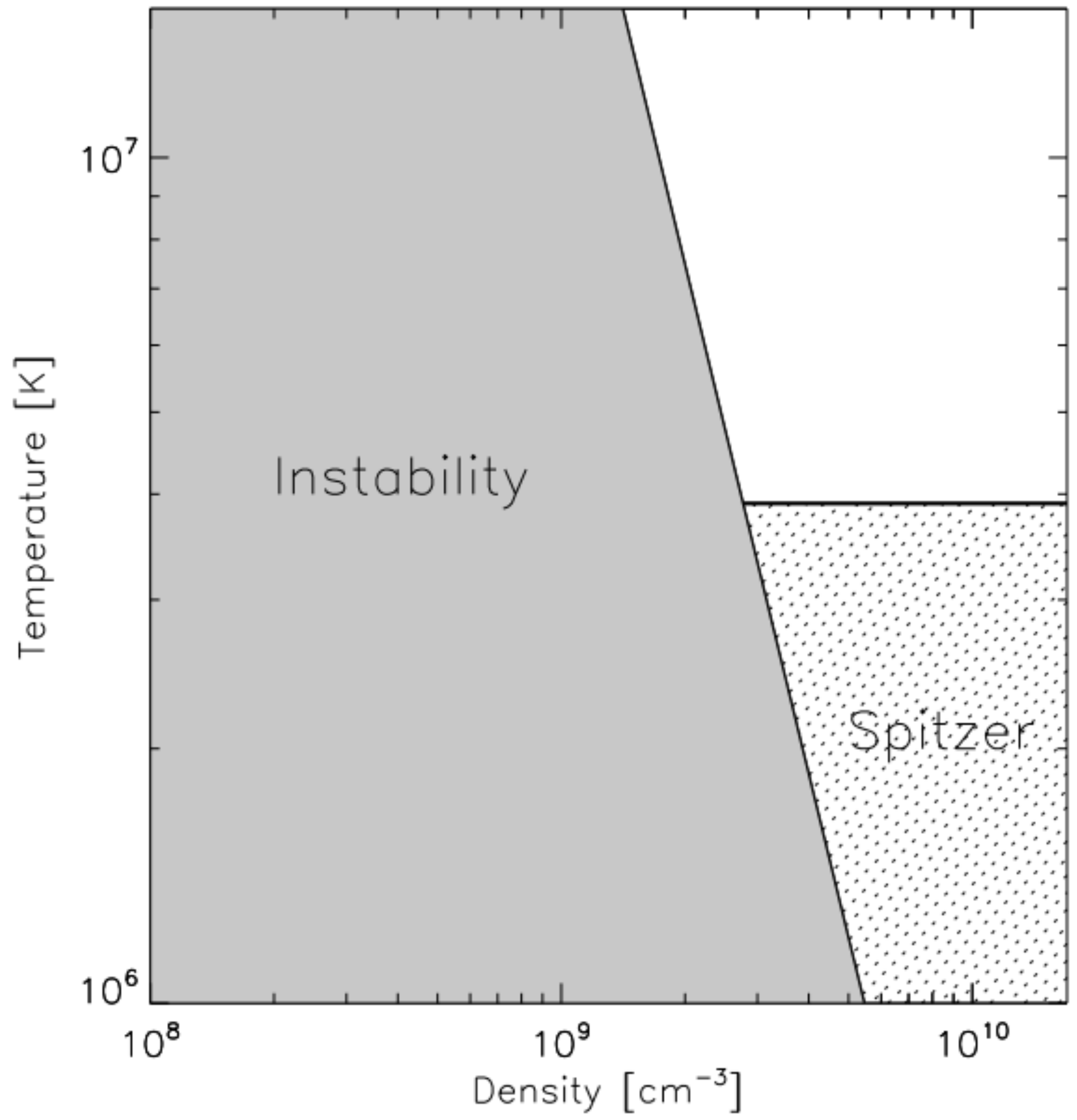
Resistivity up to 7 orders of magnitude higher than Spitzer



Alaoui & Holman 2017







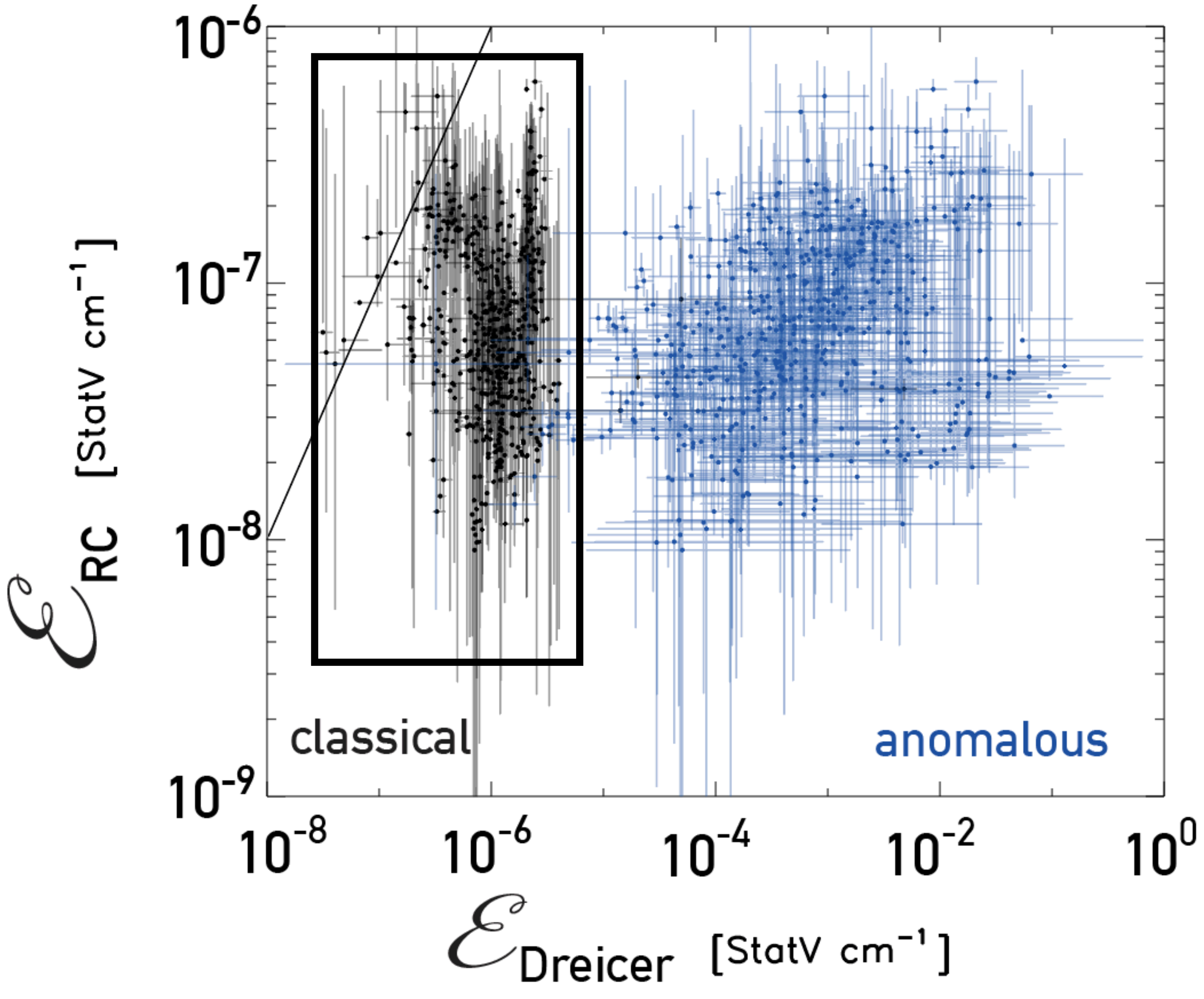
Battaglia & Benz 2008

RC driven instabilities can occur in solar flare conditions but they are not sufficient to explain the flattening at lower energies in X-ray spectra in most cases

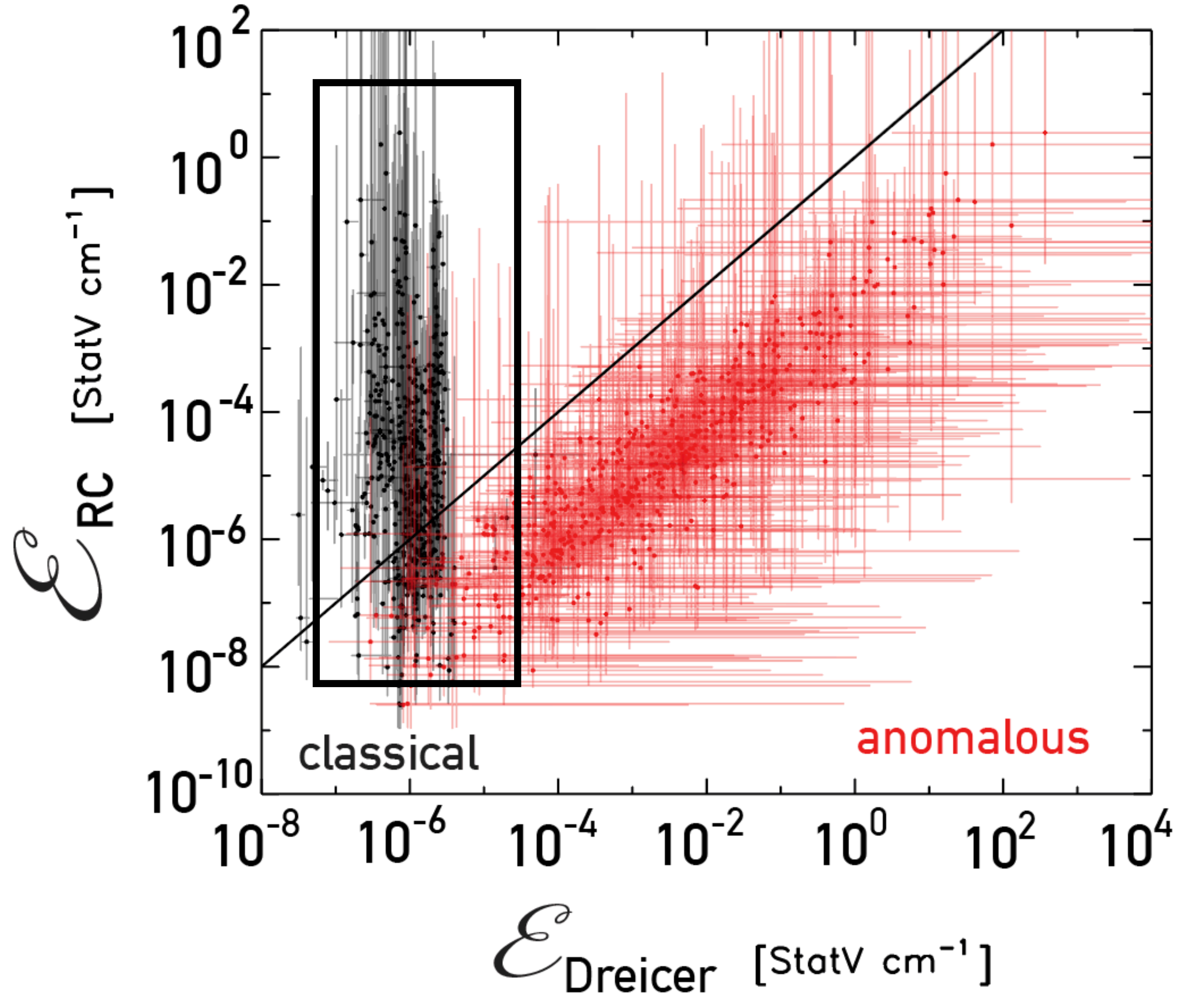
Observational and theoretical motivation for runaway model

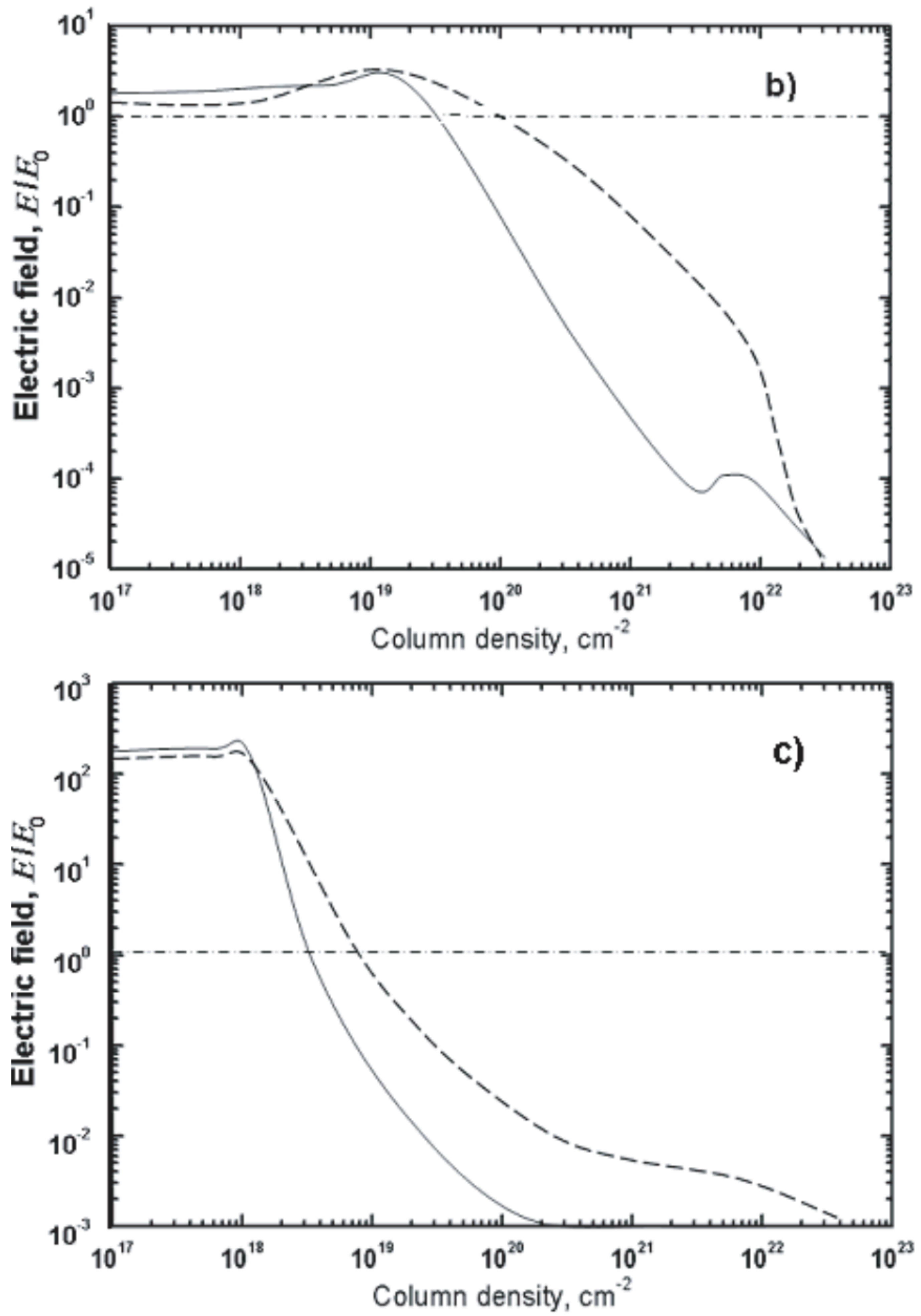
Electric field strength from models without runaways

Lower limit of flux density



Upper limit of flux density





$E_{RC} \in [0.01, 10]\ E_{Dreicer}$

Mostly super-Dreicer

Zharkova & Gordovskyy 2006

Alaoui & Holman 2017

=> Runaway electrons cannot be neglected

Kinetic modeling of electron beam propagation in flares

Injected electron flux density at looptop ↓

	Model description	Applicability conditions		References
RC losses negligible	‘Standard model’ Collisions in **cold** target	High value of low energy cutoff	Hot plasma	Brown 71, 73; Emslie 78
	Collisions and scattering but no return currents (**Warm** target)	Any low energy cutoff		Jeffrey+2014, 2019; Kontar+ 2015, Emslie 2003
RC losses significant runaways negligible	Return currents and collisions in **cold** target	High value of low energy cutoff	Any temperature	Zharkova et al 95, 10; Zharkova & Gordovsky 05,06 Siversky & Zharkova 2009 Knight & Sturrock 1977
	Return currents in **warm** target Ohm’s law assumed (no runaways)	Any low energy cutoff		Holman 2012 Allred, Alaoui, Kowalski, Kerr 2020
Both RC & runaways significant	Return currents in **warm** target Ohm’s law not assumed			Alaoui, Holman, Allred, Eufrasio 2021
Fully runaway regime	Return currents in **warm** target Co-spatial plasma fully running away		Any plasma co-spatial	Not modeled self-consistently yet

Cold target: Energy of the beam electrons>> energy of plasma with which they interact:
It does not mean that the plasma has a low T

Model Description: Alaoui et al. 2021

POWER-LAW INJECTED accelerated electrons continuously injected at apex of 1D loop model

CURRENT BALANCE $J_{beam}(x) = J_{RC}(x)$

Ohm's law Runaway growth rate from Landreman et al. (2014)

$\rightarrow J_{drift}(x) + J_{runaway}(x)$

STEADY-STATE Time scales >> than electron-ion collision time, i.e., return current/beam system reached steady-state (Van den Oord 1990, Siversky & Zharkova 2009)

BOUNDARY CONDITION No runaway electrons at the footpoints. $J_{runaway}(x = L) = 0$

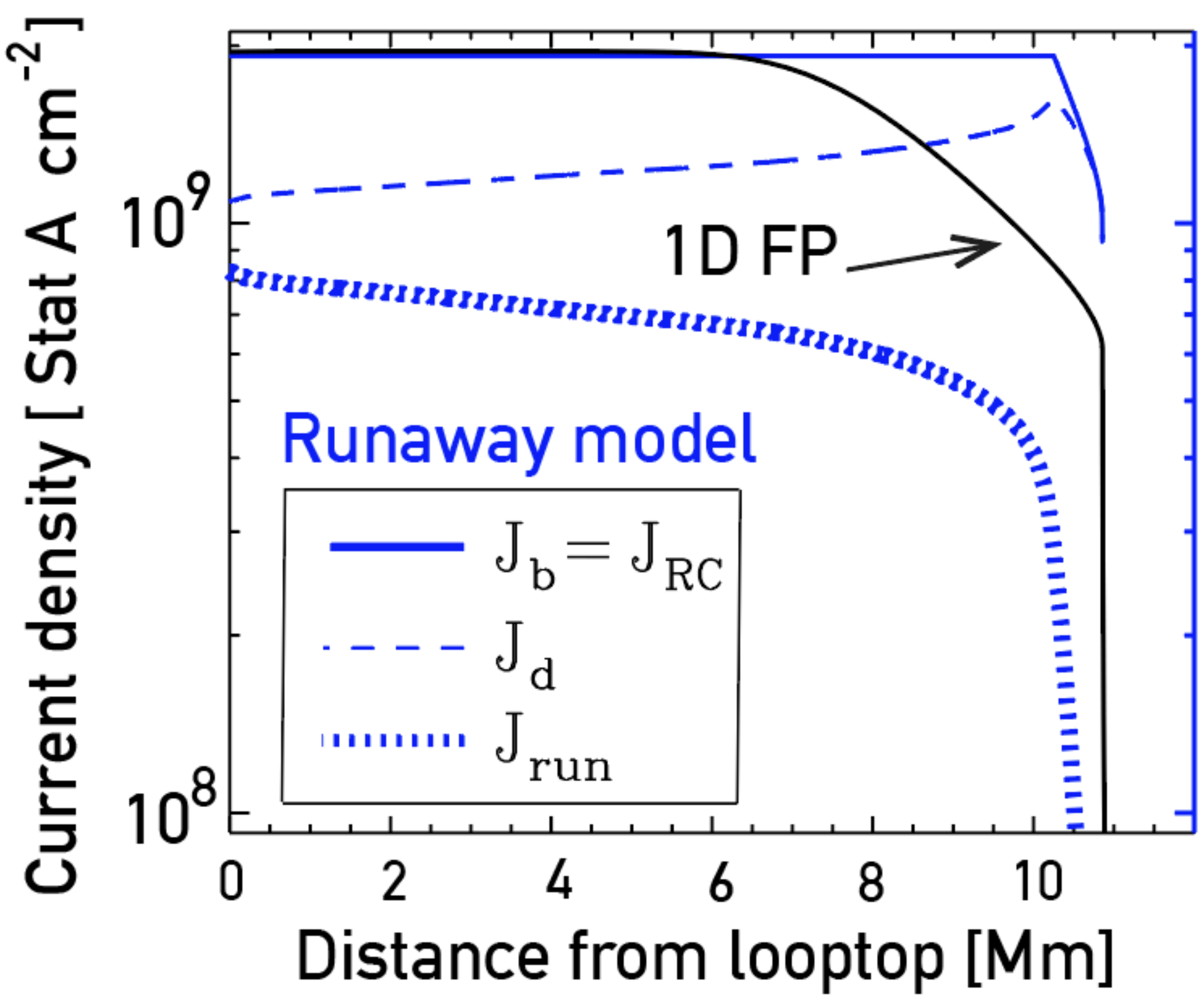
STABLE RETURN CURRENT No current-driven instabilities. Resistivity is Spitzer

SUB-DREICER ELECTRIC FIELD $E_{RC} < 0.11 E_D$ everywhere along the electrons' path

We use higher values for E_{RC} but the accuracy of the solution decreases with increasing E_{RC}

THERMALIZATION OF ELECTRONS If energy of direct beam electrons reaches thermal energy, electrons lost from beam

Return current affects acceleration region and chromosphere



Current density linearly proportional to flux density

INPUT PARAMETERS

T=3.2 MK $n_e = 7.5 \times 10^9 cm^{-3}$

BEAM FLUX DENSITY

$F_{e0} = 4 \times 10^{18} e^- cm^{-2} s^{-1}$; $2.4F11$

$E_{c0} = 25$ keV $\delta = 4$

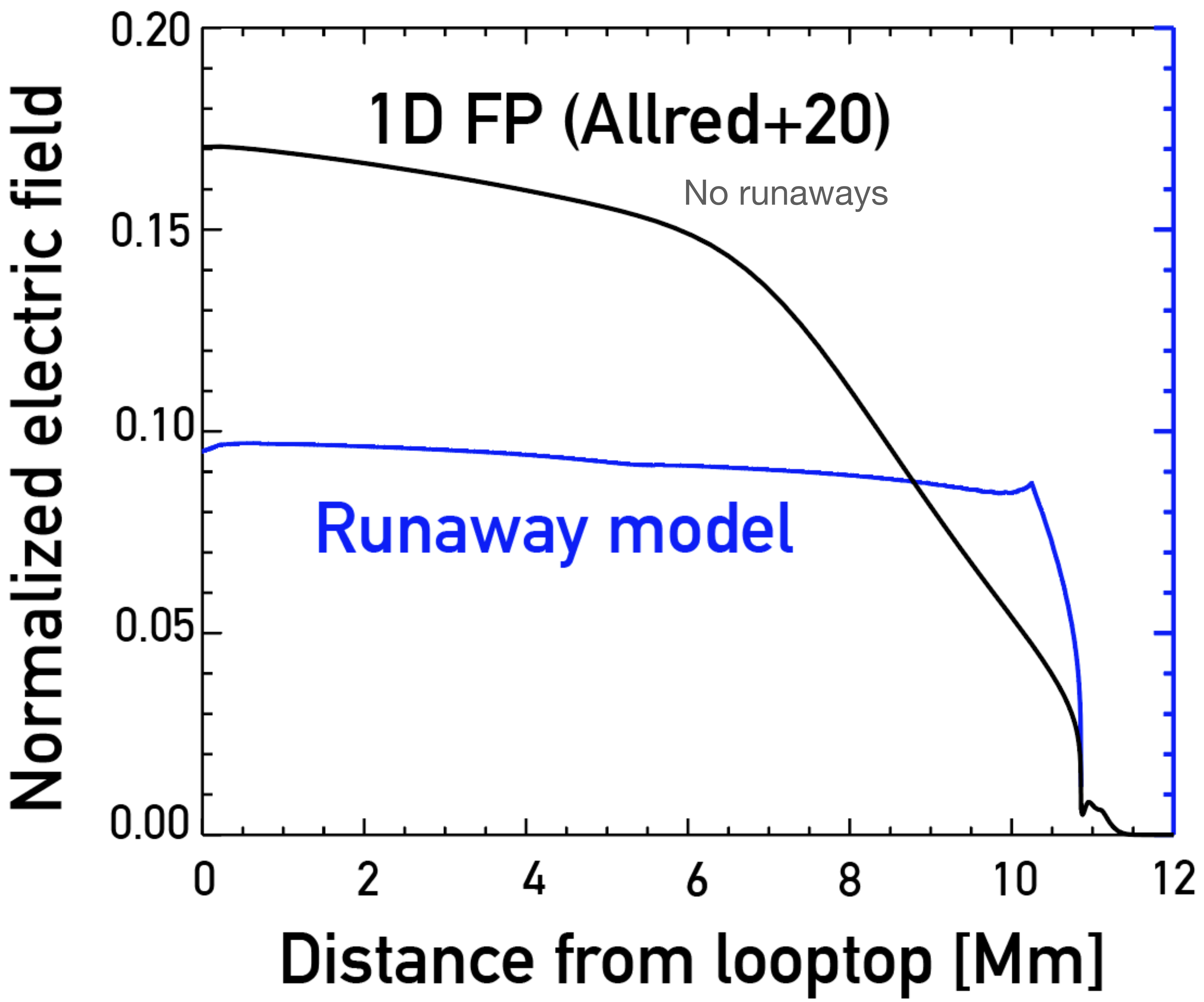
Main implications

(1) 43% of flux returning to acceleration region is suprathermal (energy gain 21 keV)

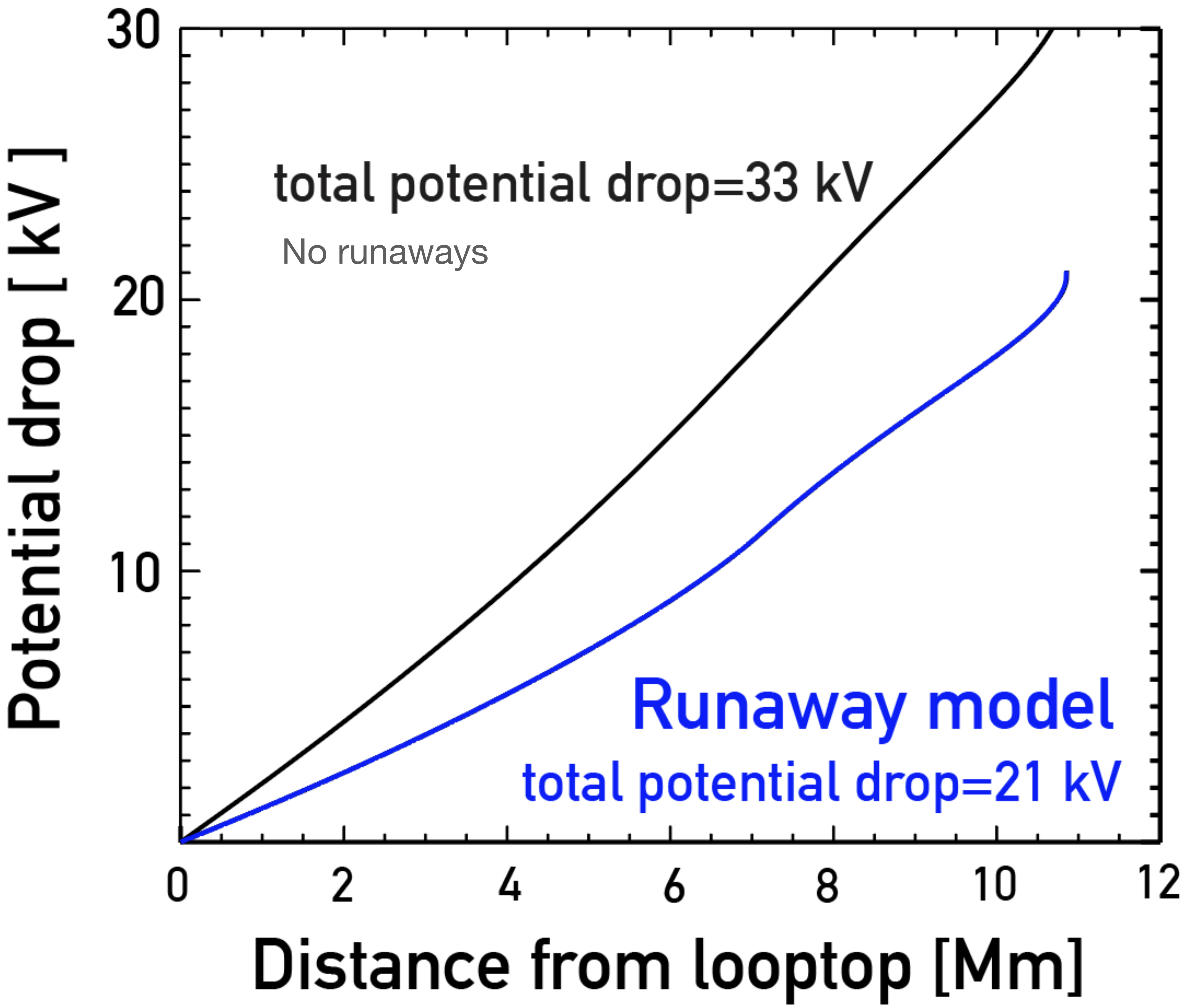
(2) Electron flux injected into chromosphere reduced due to thermalization by the return current

Electric field & potential drop spatial evolution

ELECTRIC FIELD EVOLUTION



POTENTIAL DROP

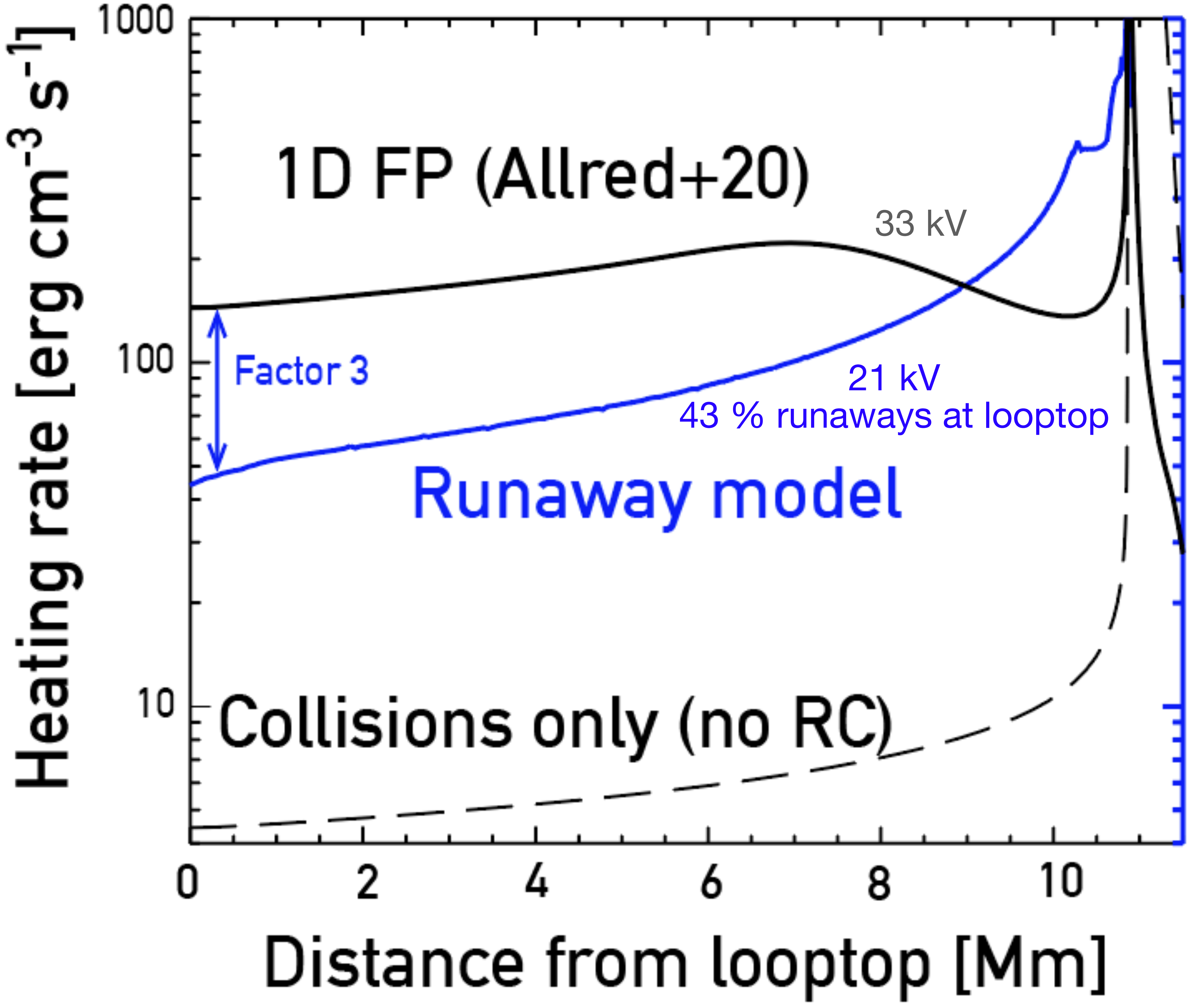


Energy of runaway electrons at looptop (gain of 21 keV) >> thermal energy

Electrons returning to the acceleration region are already suprathermal=> further accelerated to keep acceleration ongoing

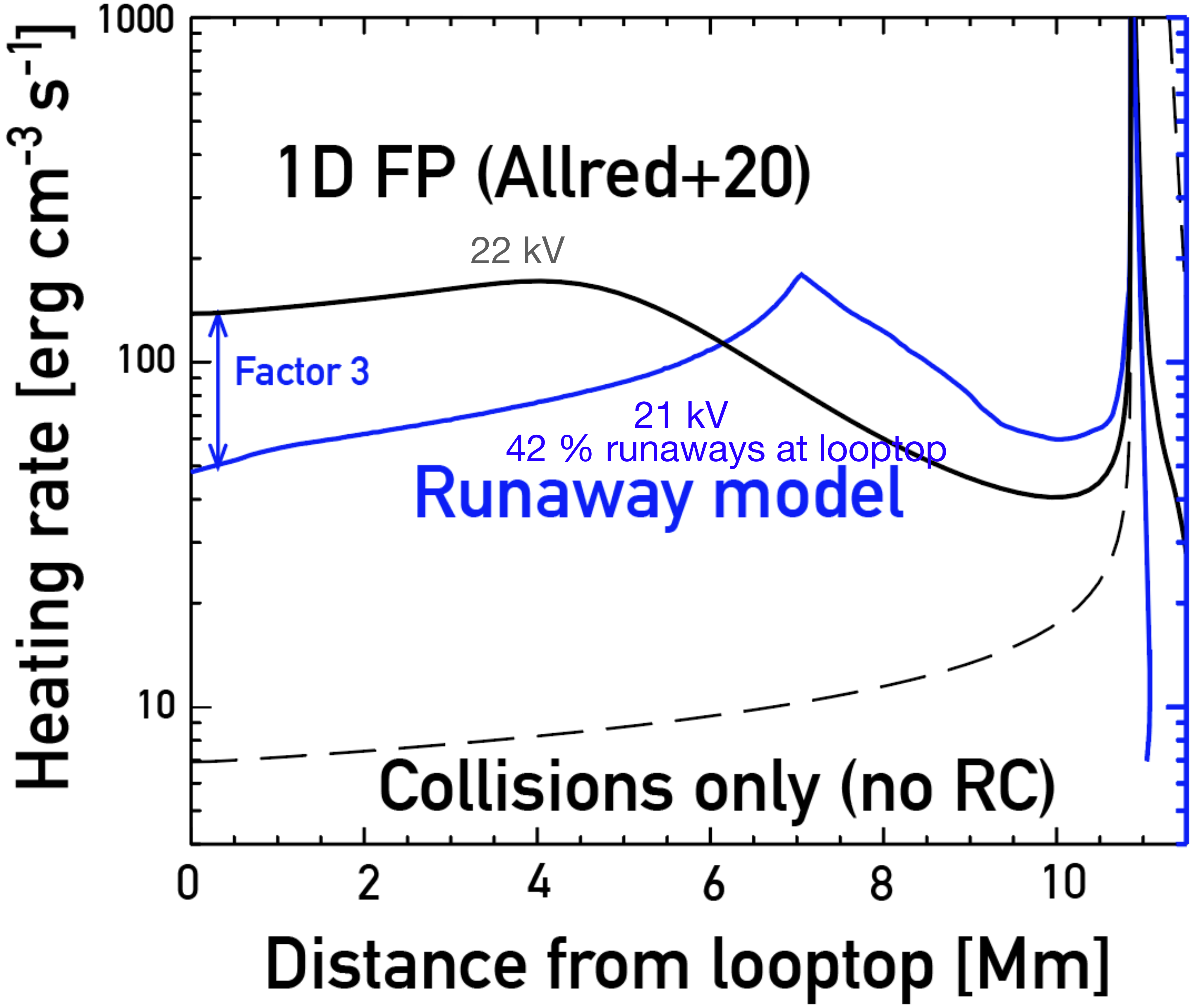
Return current energy losses dominate over Coulomb collisions

Low-energy cutoff 25 keV



Same parameters (number flux density)

Except low-energy cutoff 15 keV

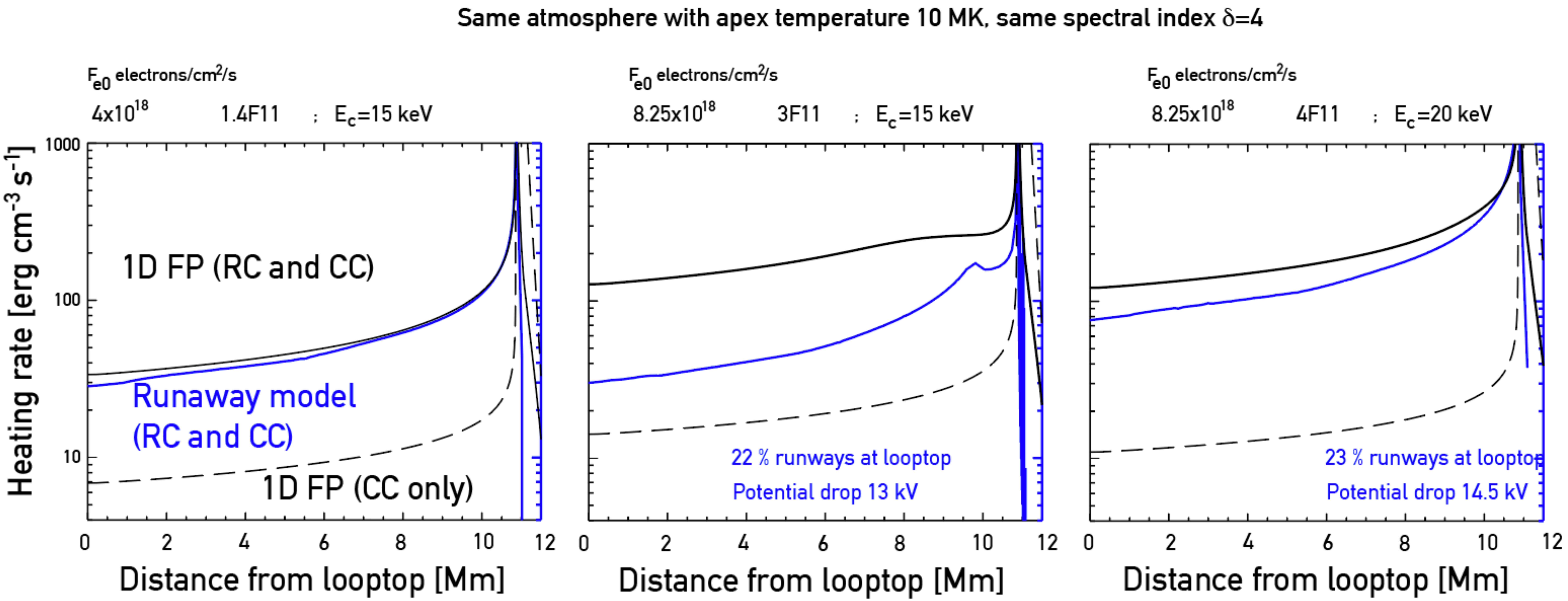


Return currents cannot be neglected

Even when considering heating reduction due to presence of runaways

Lower low-energy cutoff results in thermalization of more beam electrons in the corona=>reduced electron flux into chromosphere

In hotter plasmas return currents are still significant



Same beam parameters as example 1 but hotter atmosphere

RC significant but runaways negligible (5% at LT)

Higher injected flux density compared to example on left

Higher injected flux=> higher runaways and higher reduction of heating +Coulomb collisions contribute to reducing the heating especially in runaway case

Same injected flux density compared to example in the middle, higher low-energy cutoff

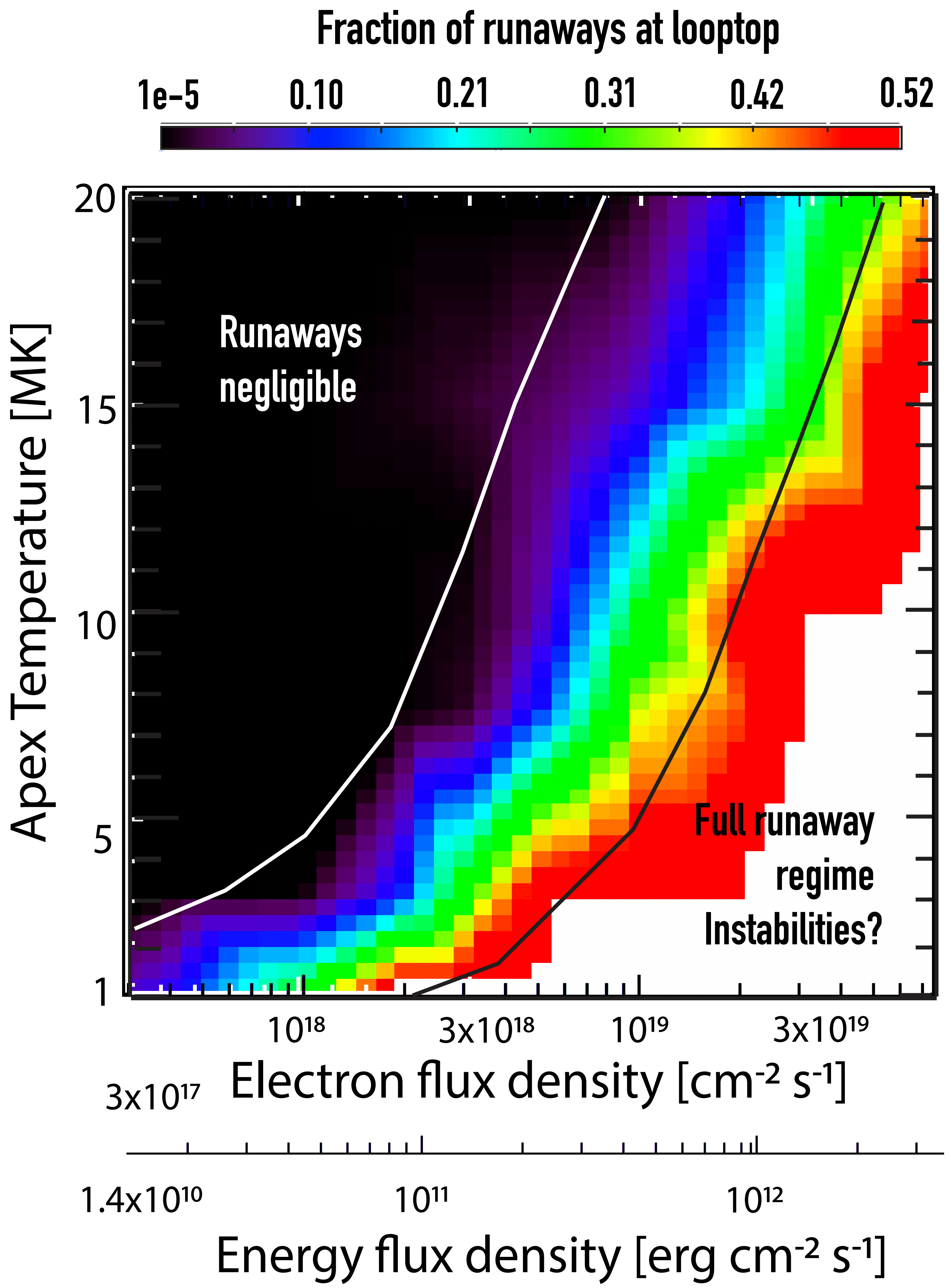
Beam electrons thermalized below transition region

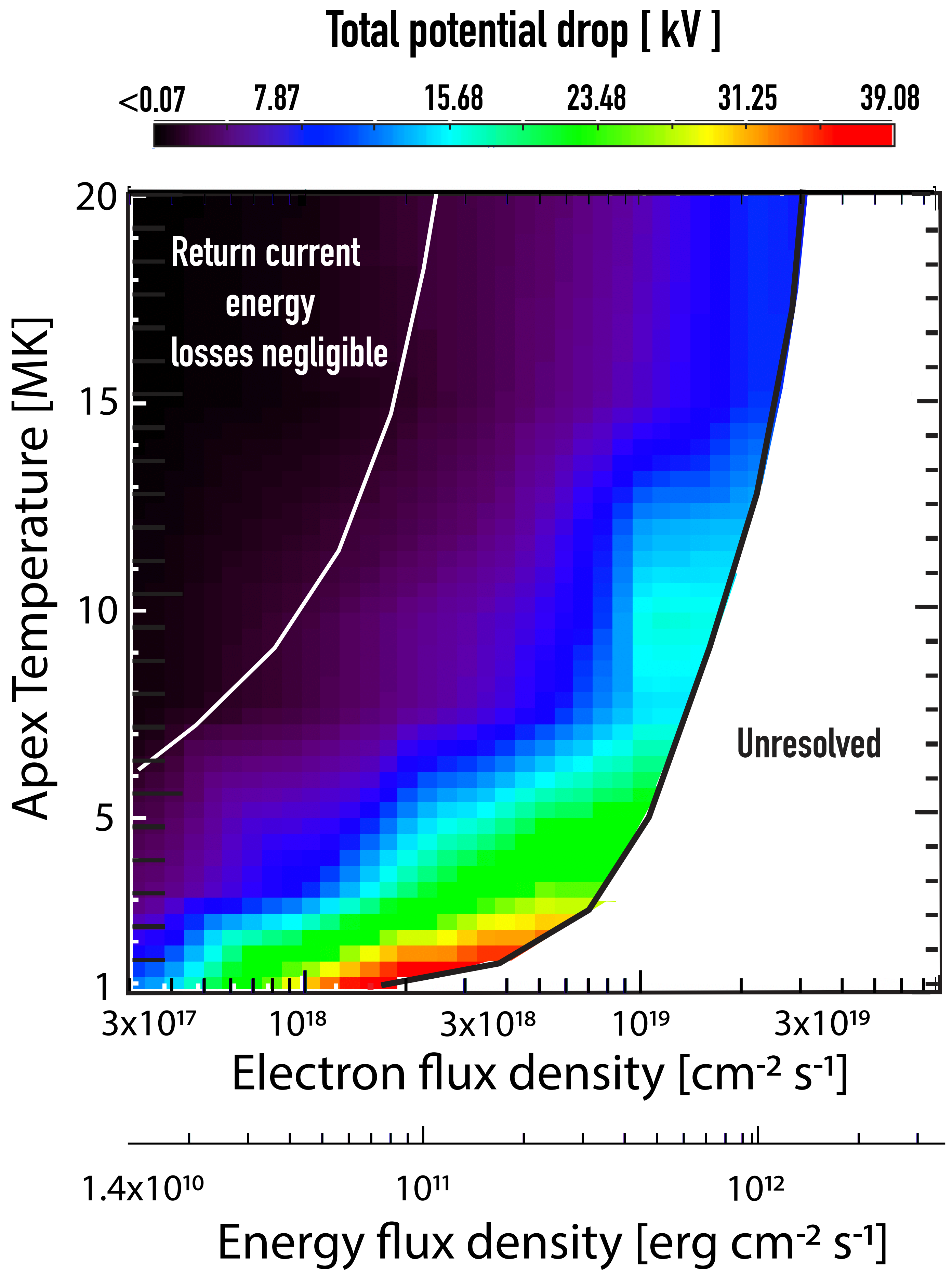
Fraction of runaways at the looptop: Various regimes for propagation

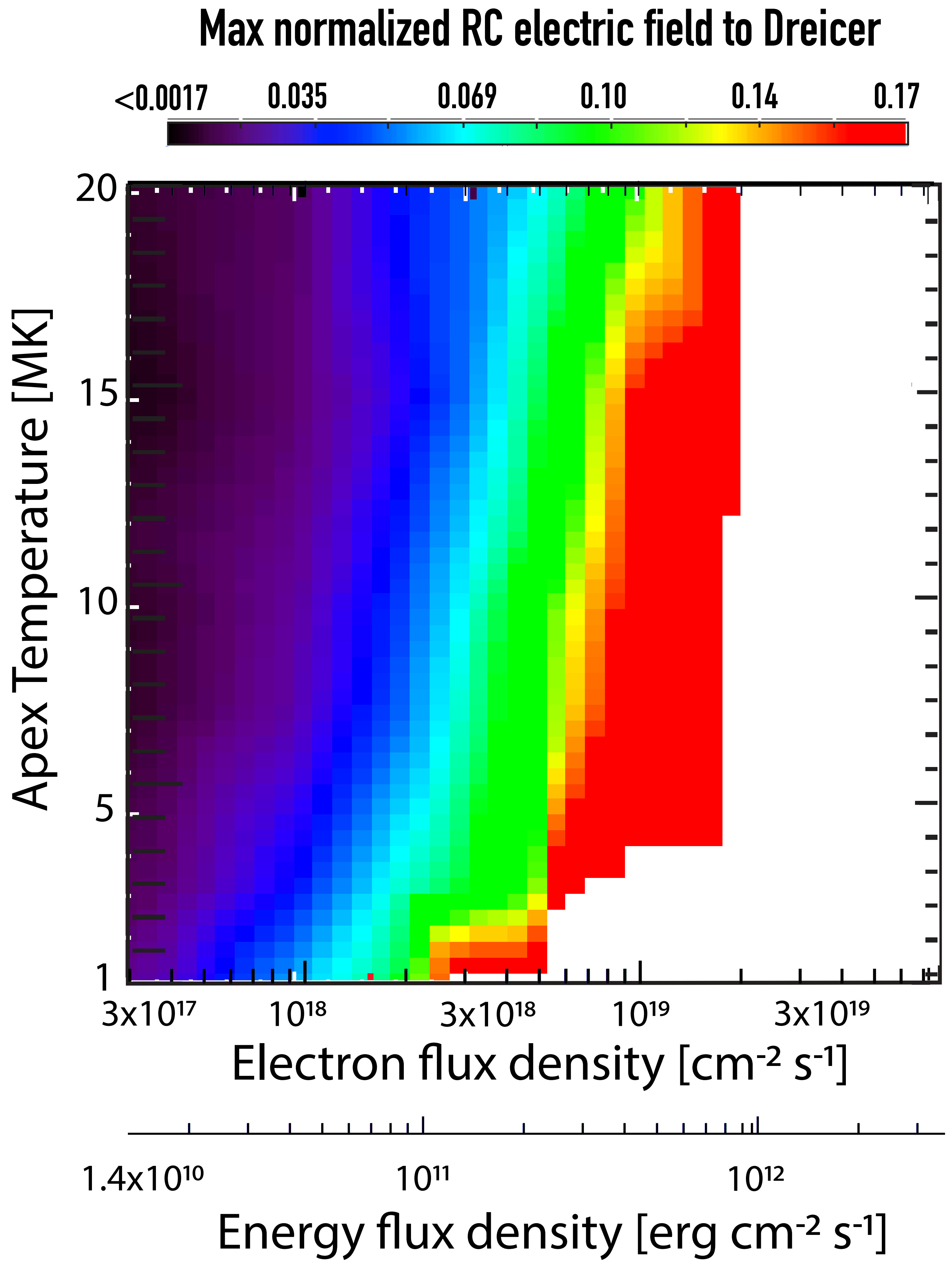
Apex density $n_e = 8 \times 10^9 \ cm^{-3}$

$\delta = 4 \quad ; E_c = 20 \ keV$

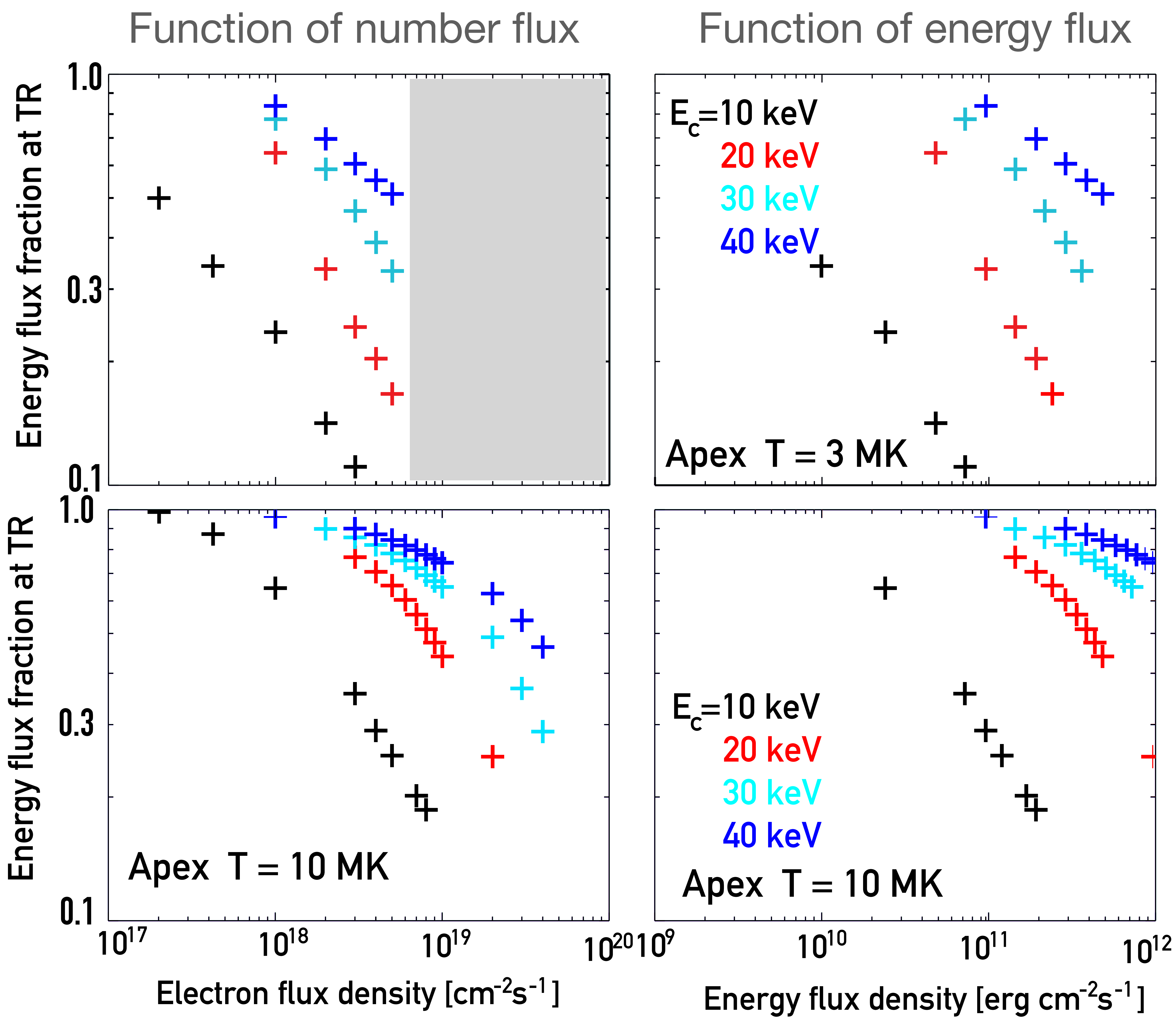
Under which conditions are the return current losses negligible?
Under which conditions are runaways significant?







Fraction of injected energy flux reaching the transition region is reduced by the return current



How much of the injected energy flux density at the corona reaches the top of the transition region?

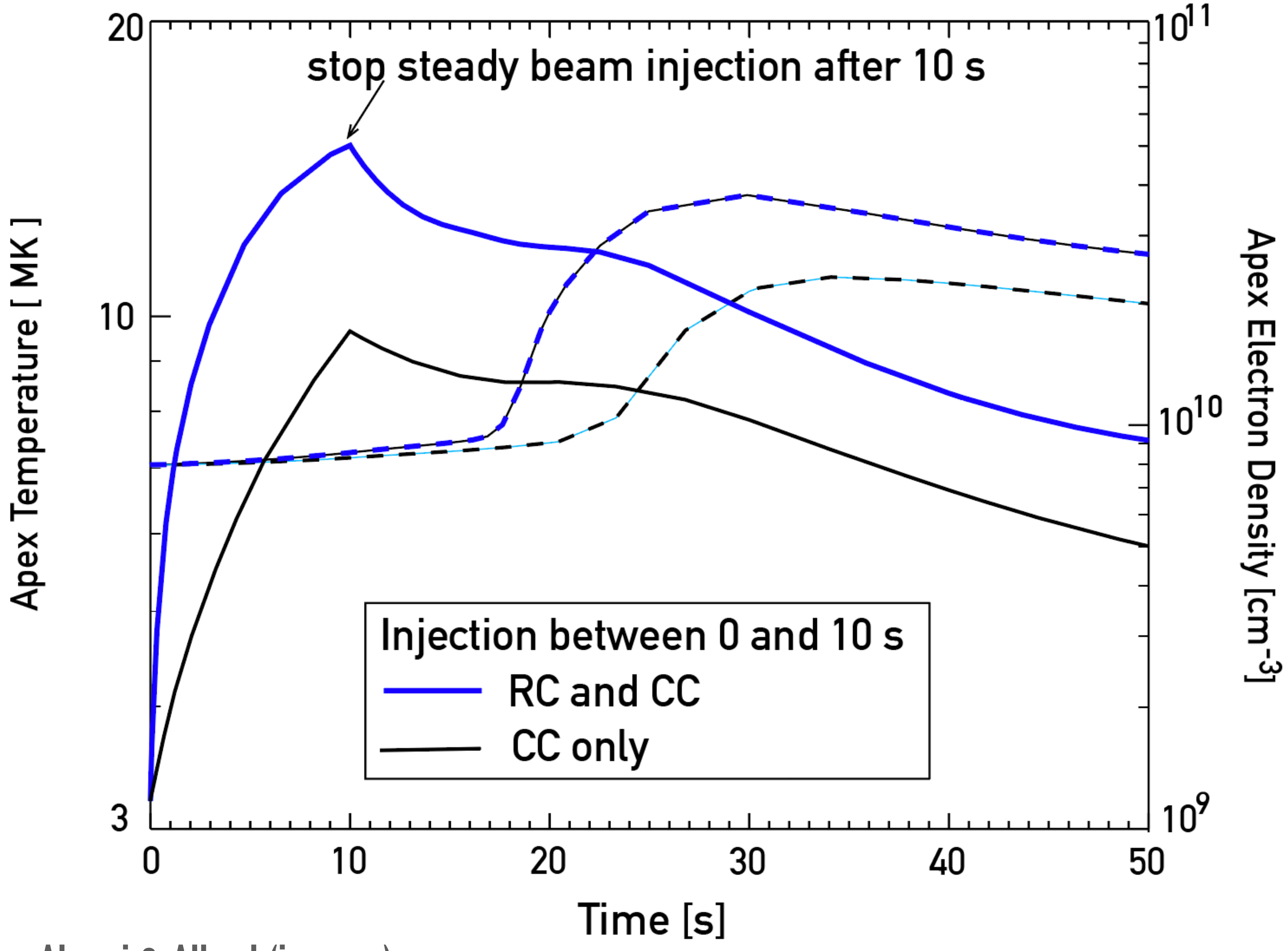
Initial apex temperature

Top panels: 3 MK

Lower panels: 10 MK

Misinterpretation of the energy flux injected into the transition region and therefore also the accelerated flux density injected at the top of the loop

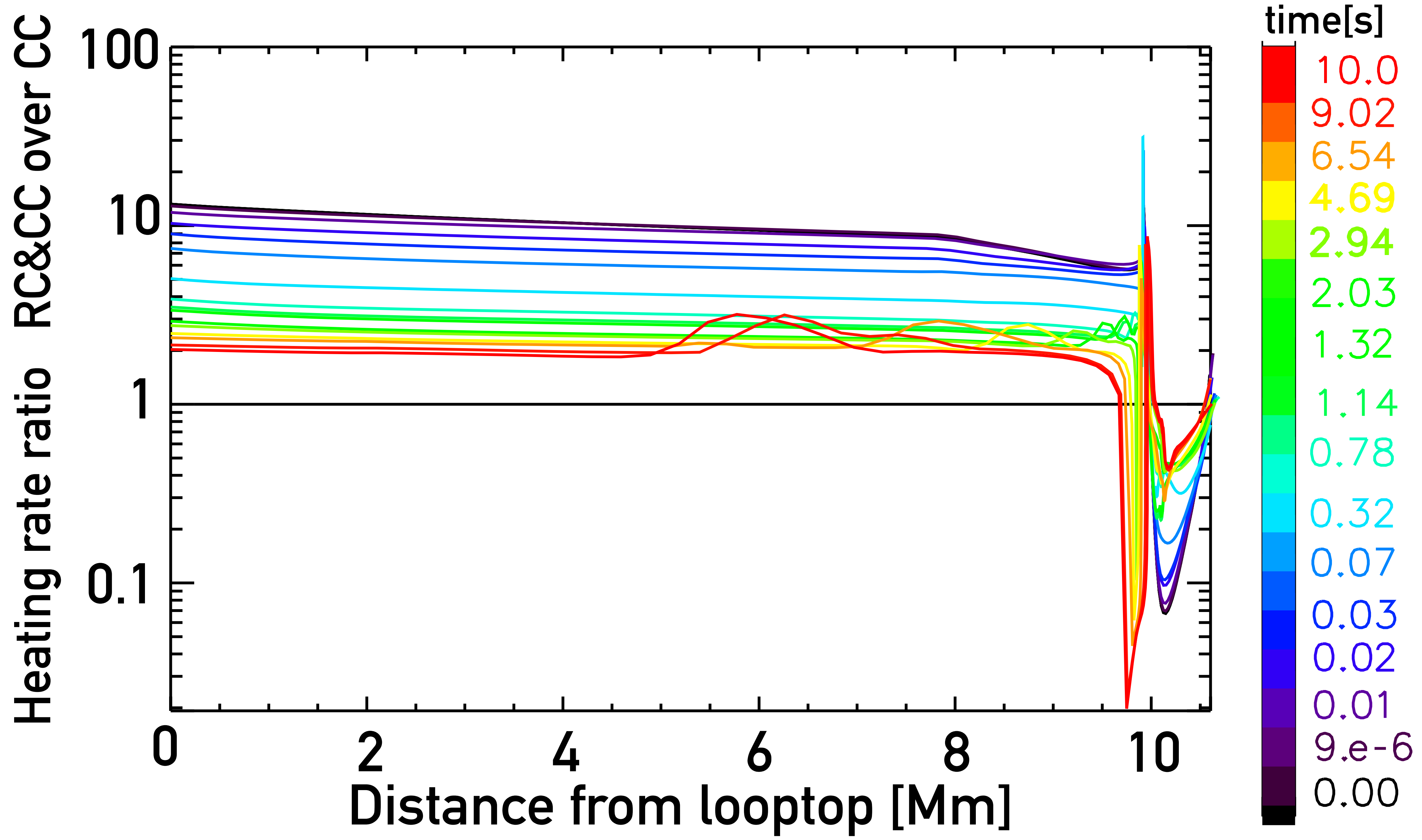
How neglecting return current losses affects the thermal response



Alaoui & Allred (in prep)

Injected energy flux density 8.5×10^{10} erg $cm^{-2}\, s^{-1}$

Low energy cutoff 20 keV
Electron spectral index $\delta = 4$



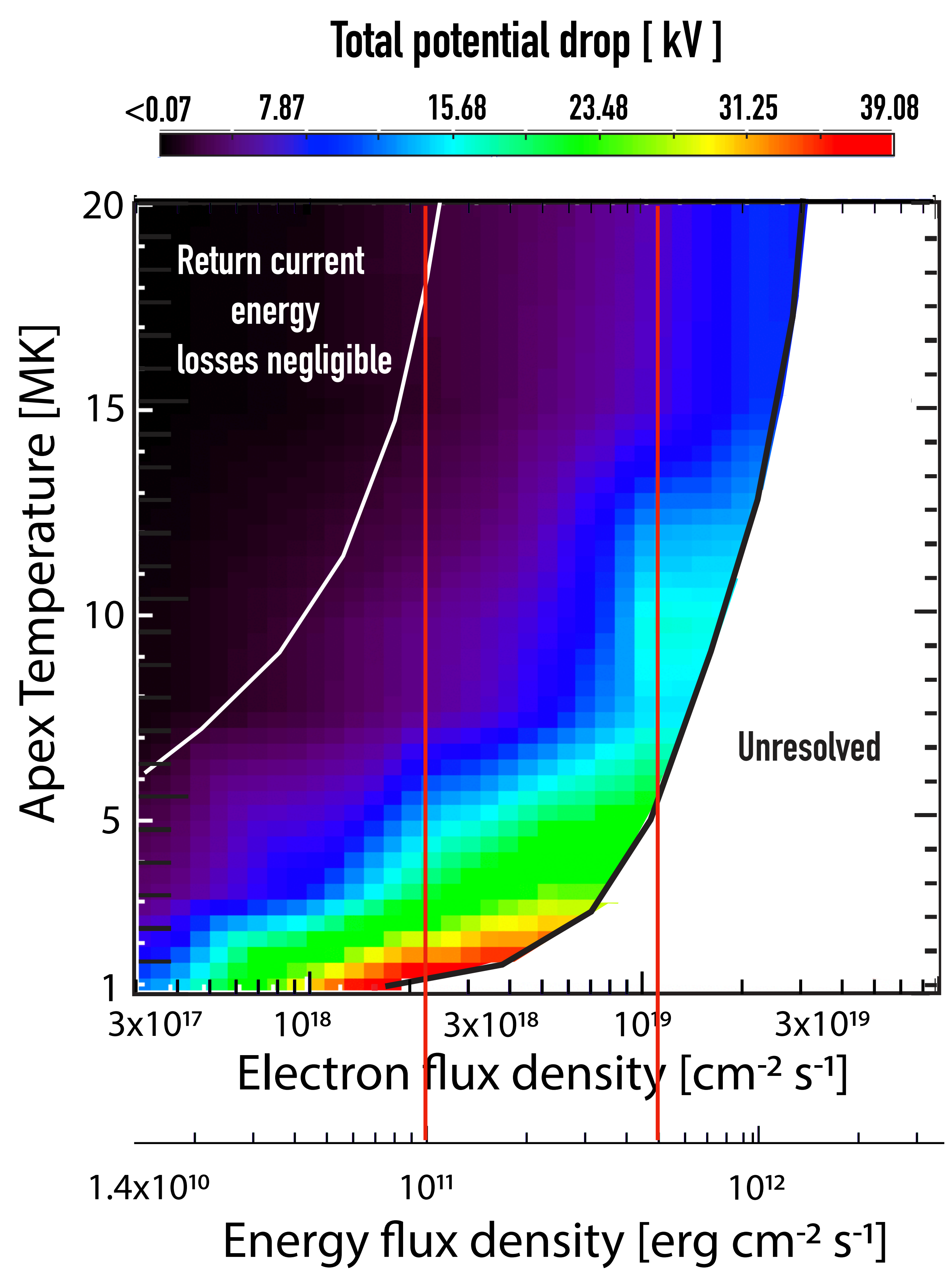
The heating in the chromosphere is overestimated when return currents are not considered

Many large flares are associated with higher flux densities than previous examples

Recent modeling which requires accounting for the return current energy losses

Kowalski et al 2022 Range of injected fluxes between vertical red lines

model ID	Beam Flux [erg s^{-1} cm^{-2}]	δ	E_c [keV]	μ_o	Beam Duration [s]	Comment
c15s-5F11-25-4.2	5×10^{11} (5F11)	4.2	25	0.1	15	"Extended heating" 5F11 in Paper I.
c20s-F11-25-4	10^{11} (F11)	4	25	0.1	20	Published in Kuridze et al. (2020).
c20s-F11-15-5	10^{11} (F11)	5	15	0.1	20	Published in Graham et al. (2020).



Graham et al 2020 Only lower energy cutoffs are consistent with observations BUT the chromosphere gets heated faster in the simulations

Because the return current results in a significant energy deposition in the corona, can timing inconsistencies between models and observations be resolved simply by including them in the simulations?

What constraints on the beam energy distribution and the initial atmosphere can be deduced?

Do electron beams accelerated in the solar corona produce the observed spectral properties?

Summary

Understanding electron beam/return current propagation is important for:

THERMAL RESPONSE

(1) Corona is heated faster and to higher temperatures; below TR stays cooler for longer

(2) The injected energy (and flux) at the looptop is significantly different from that injected into the chromosphere

Flares with high injected flux densities should be reanalyzed to include the return current effects

ELECTRON BEAM ACCELERATION

Runaways provide suprathermal particles to the looptop. Are particles accelerated there? If so, the runaways are seed particles for continuing acceleration

Runaways energies ~10-50 keV; runaway fractions can be tens of % at the looptop