Flare Loops

1d gas dynamics

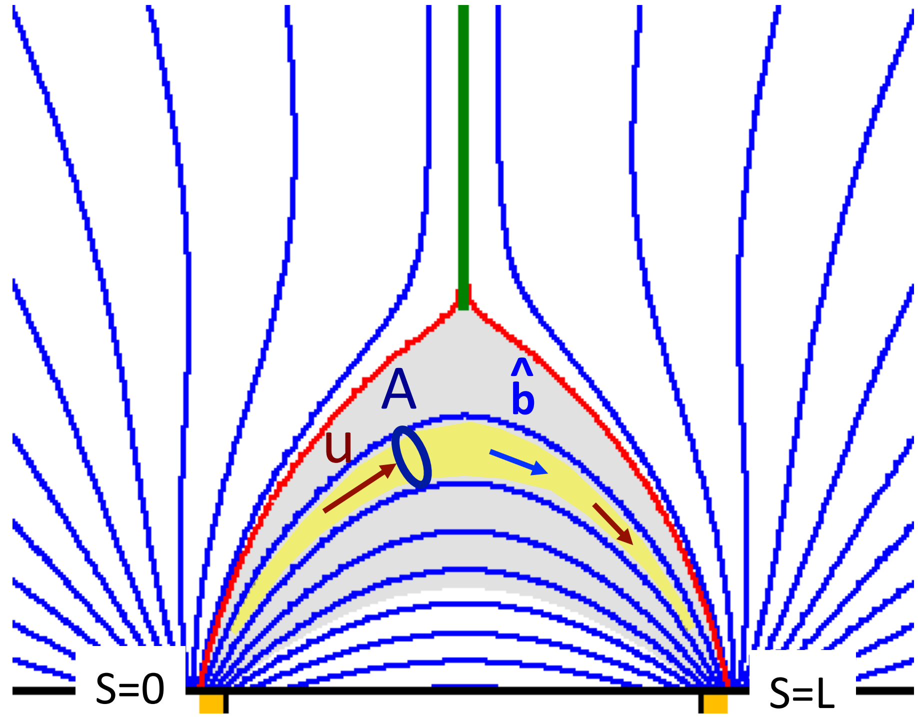
Lecture 10

Feb. 22, 2017

The 1d flare loop

ρ(s,t), u(s,t) & T(s,t)

Fixed A(s) & $g_{||}$(s)



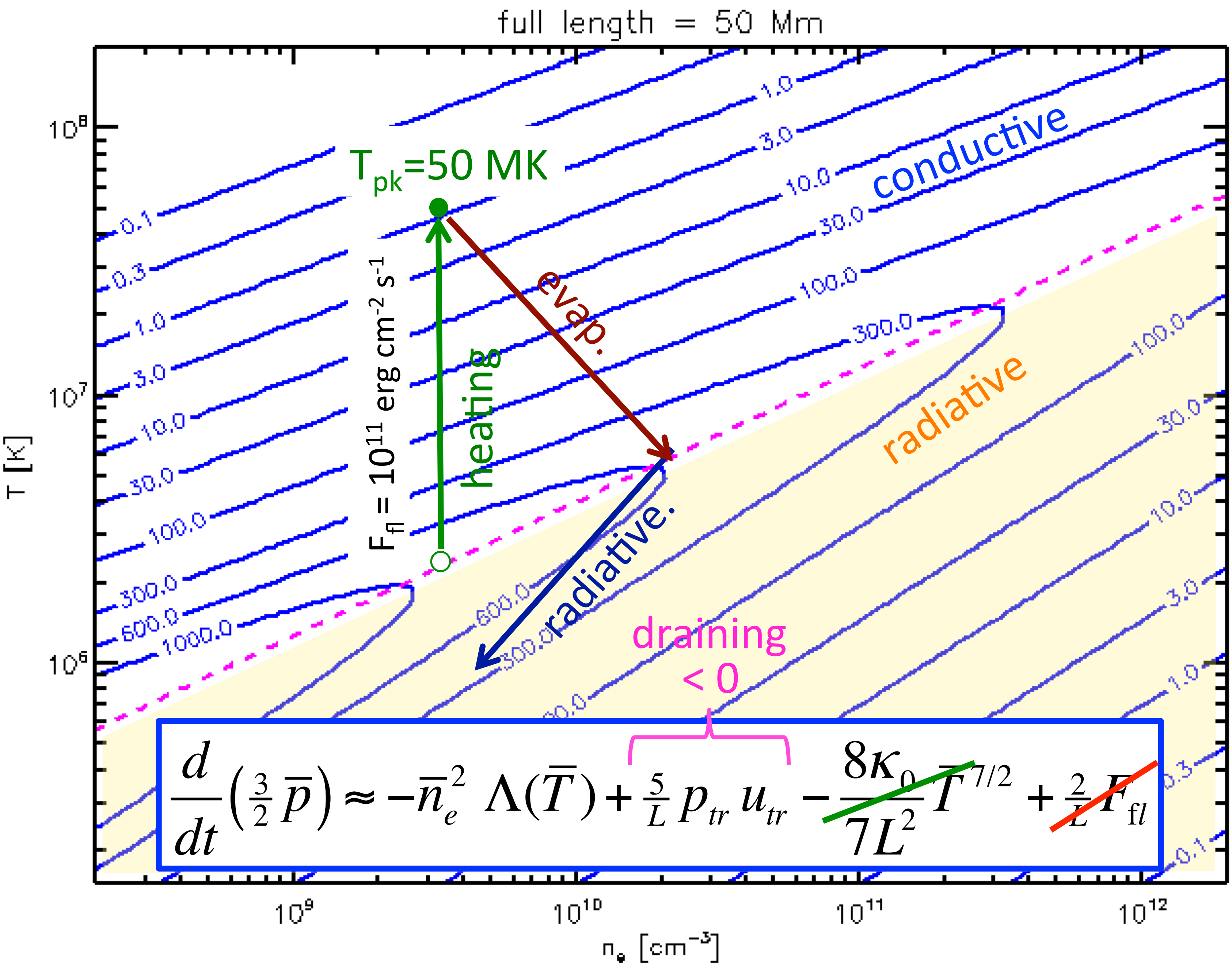
$$\frac{\partial \rho}{\partial t} = -\frac{1}{A}\frac{\partial}{\partial s}(A\rho u)$$

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial s}\right) = -\frac{\partial p}{\partial s} + \rho g_{\parallel} + \frac{\partial}{\partial s}\left(\tfrac{4}{3}\mu\frac{\partial u}{\partial s}\right)$$

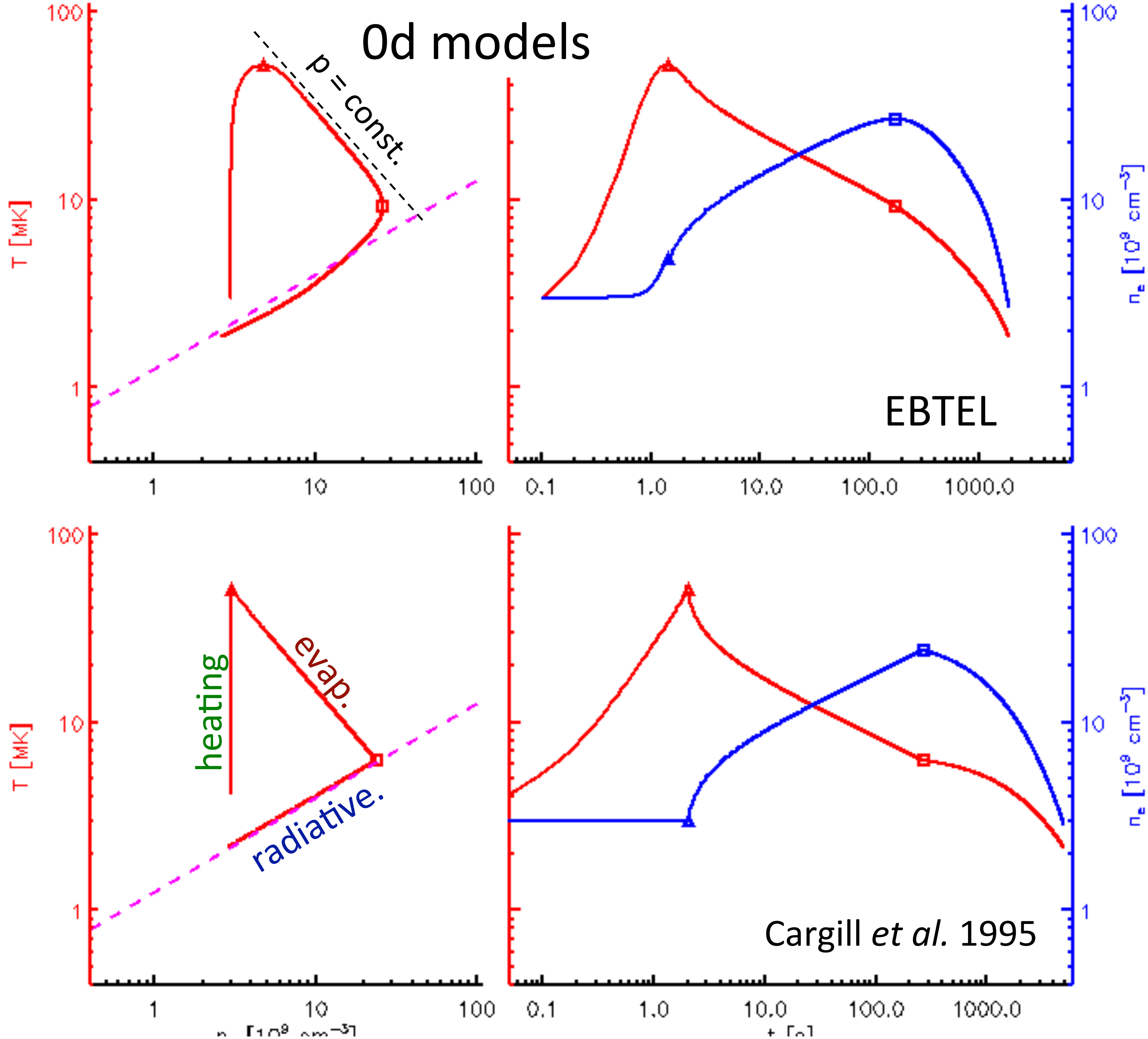
Source of flare energy

$$\rho c_v\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial s}\right) = -\frac{p}{A}\frac{\partial}{\partial s}(Au) + \tfrac{4}{3}\mu\left|\frac{\partial u}{\partial s}\right|^2 + \frac{1}{A}\frac{\partial}{\partial s}\left[A\kappa\frac{\partial T}{\partial s}\right] - n_e^2\Lambda(T) + h$$

$$p = \frac{k_b}{\bar{m}}\rho T \qquad c_v = \frac{3}{2}\frac{k_b}{\bar{m}}$$



$$\frac{d}{dt}\left(\tfrac{3}{2}\,\bar{p}\right) \approx -\bar{n}_e^{\,2}\ \Lambda(\bar{T}) + \underbrace{\tfrac{5}{L}\,p_{tr}\,u_{tr}}_{\text{draining}<0} - \frac{8\kappa_0}{7L^2}\bar{T}^{7/2} + \tfrac{2}{L}F_{\rm fl}$$


0d models
p = const.
EBTEL
heating
evap.
radiative.
Cargill et al. 1995
T [MK]
100
10
1
100
10
1
n_e [10^9 cm^{-3}]
0.1
1.0
10.0
100.0
1000.0

$$\bar{n}_{e,\max} = 2.6 \times 10^{12} \frac{E^{2/3}}{V^{2/3} L^{1/3}}$$

$$\bar{T}_{em,pk} = 930 \left(\frac{EL}{V} \right)^{1/3}$$

IF flare were a single loop

$$\max(EM) = V \bar{n}_{e,\max}^2 = 7 \times 10^{24} \frac{E^{4/3}}{V^{1/3} L^{2/3}} = 7 \times 10^{49} \, \mathrm{cm}^3 \frac{E_{30}^{4/3}}{V_{27}^{1/3} L_9^{2/3}}$$

$$\bar{T}_{em,pk} = 930 \left(\frac{EL}{V} \right)^{1/3} = 9 \times 10^6 K \left(\frac{E_{30} L_9}{V_{27}} \right)^{1/3}$$

$E_{30} = E/10^{30}$ ergs

$\sim E^{7/4}$

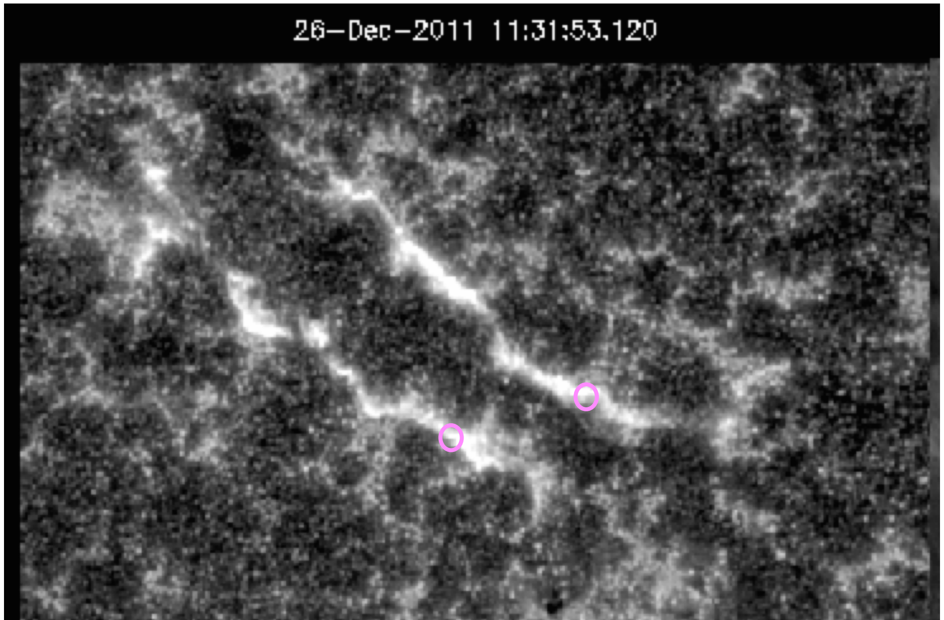
GOES peak:

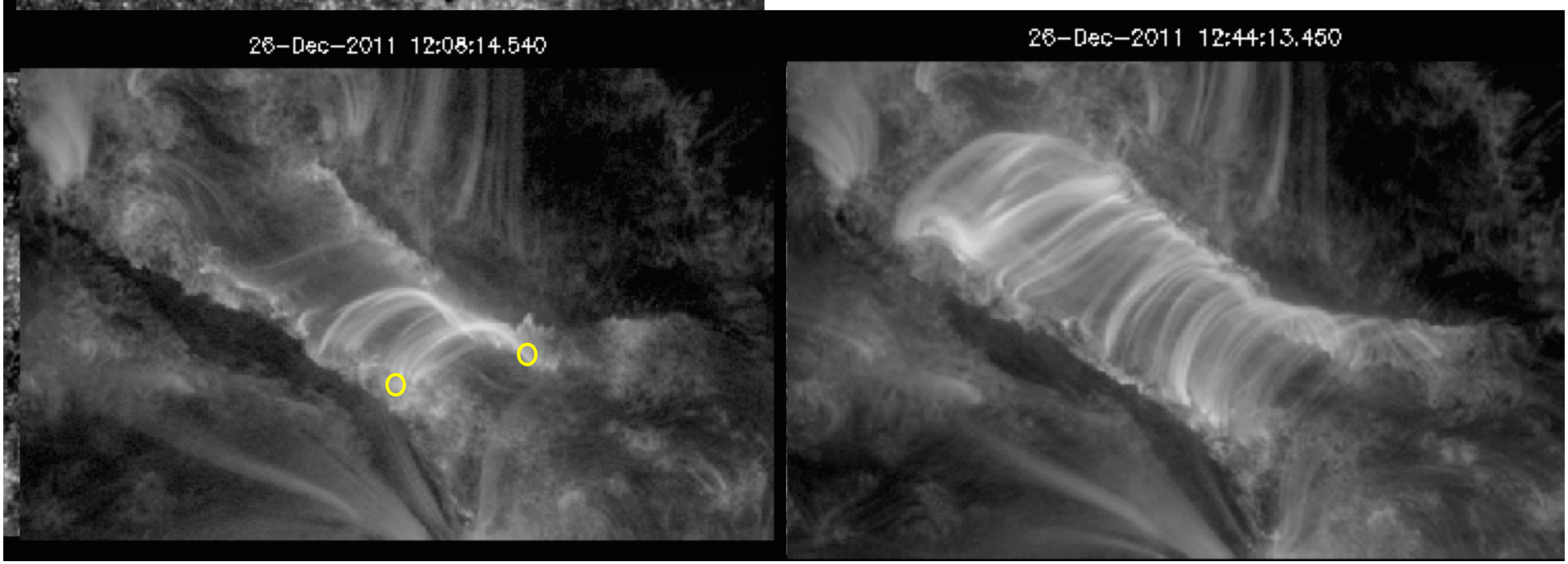
$$F_{1-8} \approx 10^{-63} \frac{\mathrm{W}}{\mathrm{m}^2} EM \; T^{5/4} = 4 \times 10^{-5} \frac{\mathrm{W}}{\mathrm{m}^2} \cdot \frac{E_{30}^{7/4}}{L_9^{1/4} V_{27}^{3/4}}$$

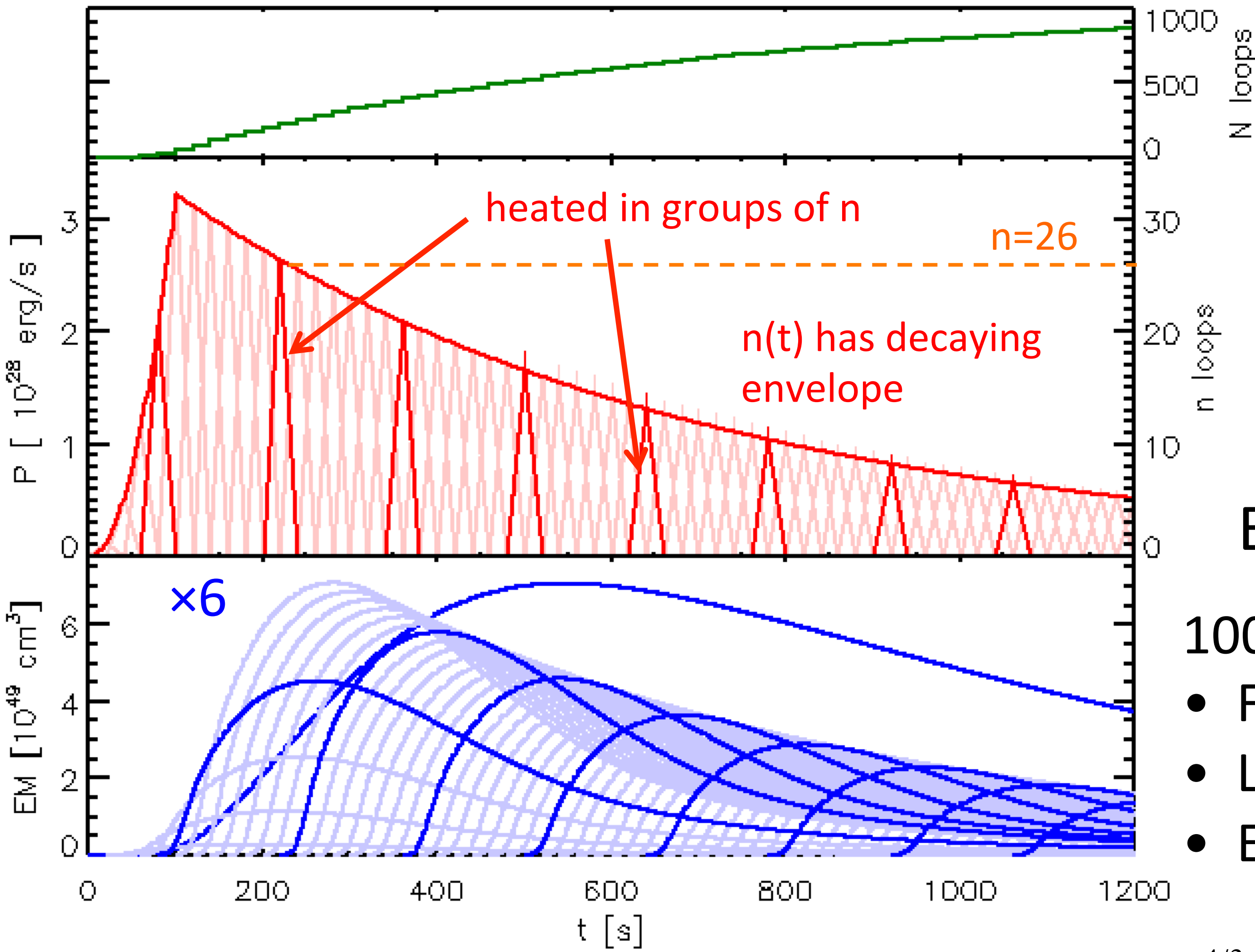
M4 flare

Warren & Antiochos 2004

BUT a real flare is built from many diff. loops – each evolving independently







Example model:

Hori et al. 1997, Warren et al. 2002, Reeves & Warren 2002, Qiu et al. 2012, 2013, …

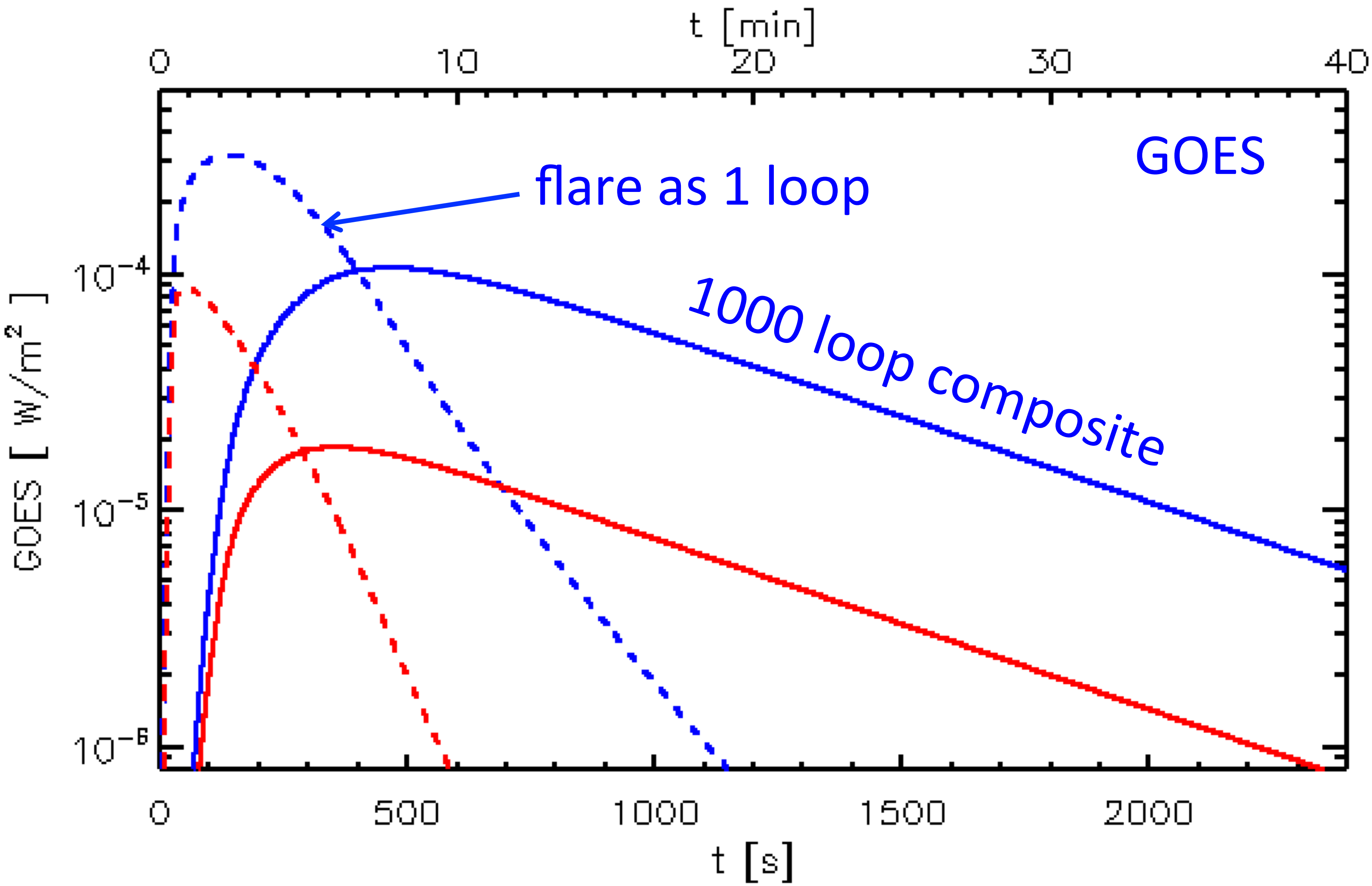
$E = 2 \times 10^{31}$ erg

1000 loops:

- $F_{fl} = 10^{11}$ erg/s/cm^2
- $L = 5 \times 10^9$ cm
- $E_i = 2 \times 10^{28}$ erg

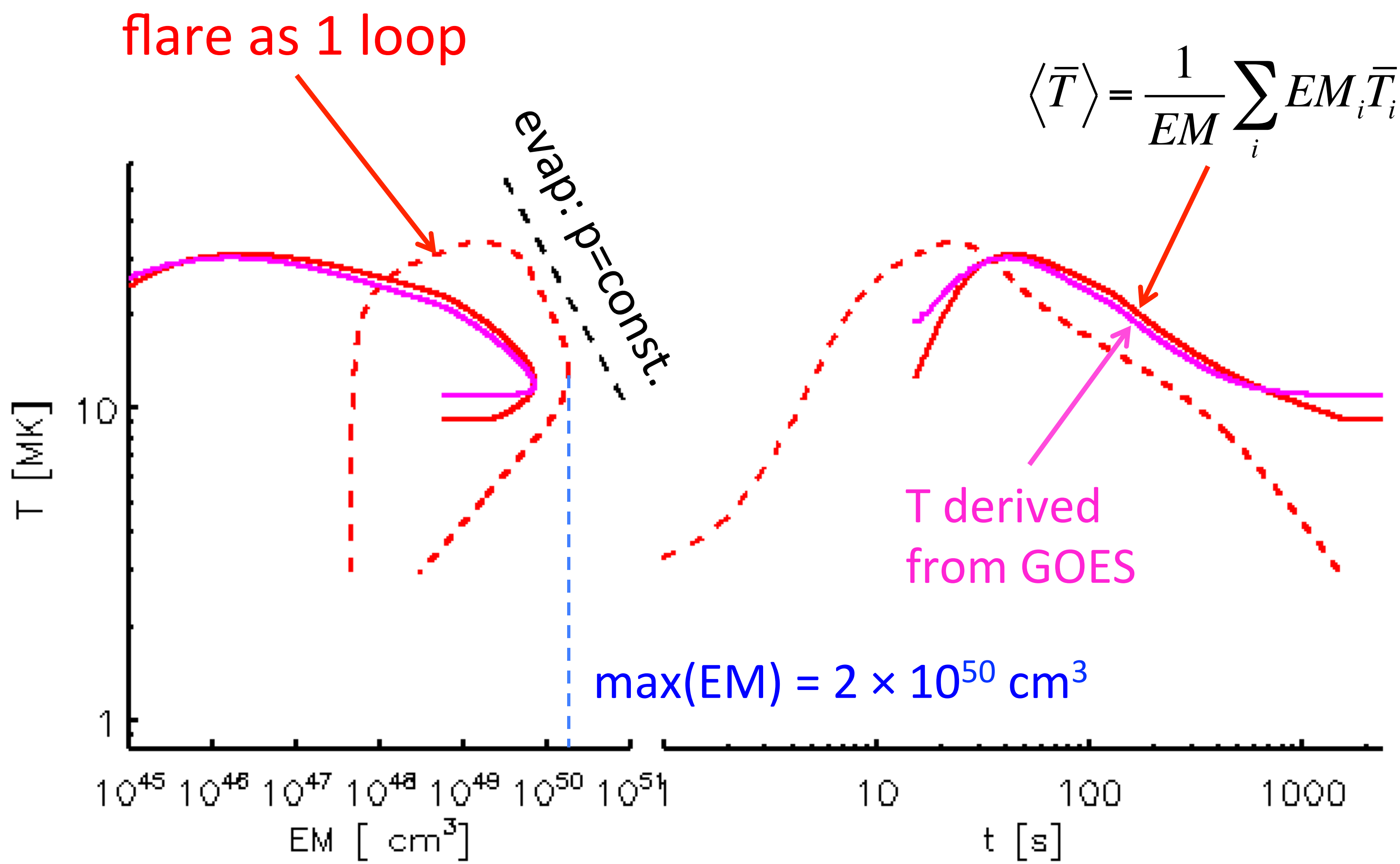
Each loop: $$\max(EM) = 7\times10^{49}\,\mathrm{cm}^3\,\frac{E_{30}^{4/3}}{V_{27}^{1/3}L_9^{2/3}} = 0.03\times10^{49}\,\mathrm{cm}^3$$

Flare as 1 loop: $$\max(EM) = 7\times10^{49}\,\mathrm{cm}^3\,\frac{E_{30}^{4/3}}{V_{27}^{1/3}L_9^{2/3}} = 30\times10^{49}\,\mathrm{cm}^3$$

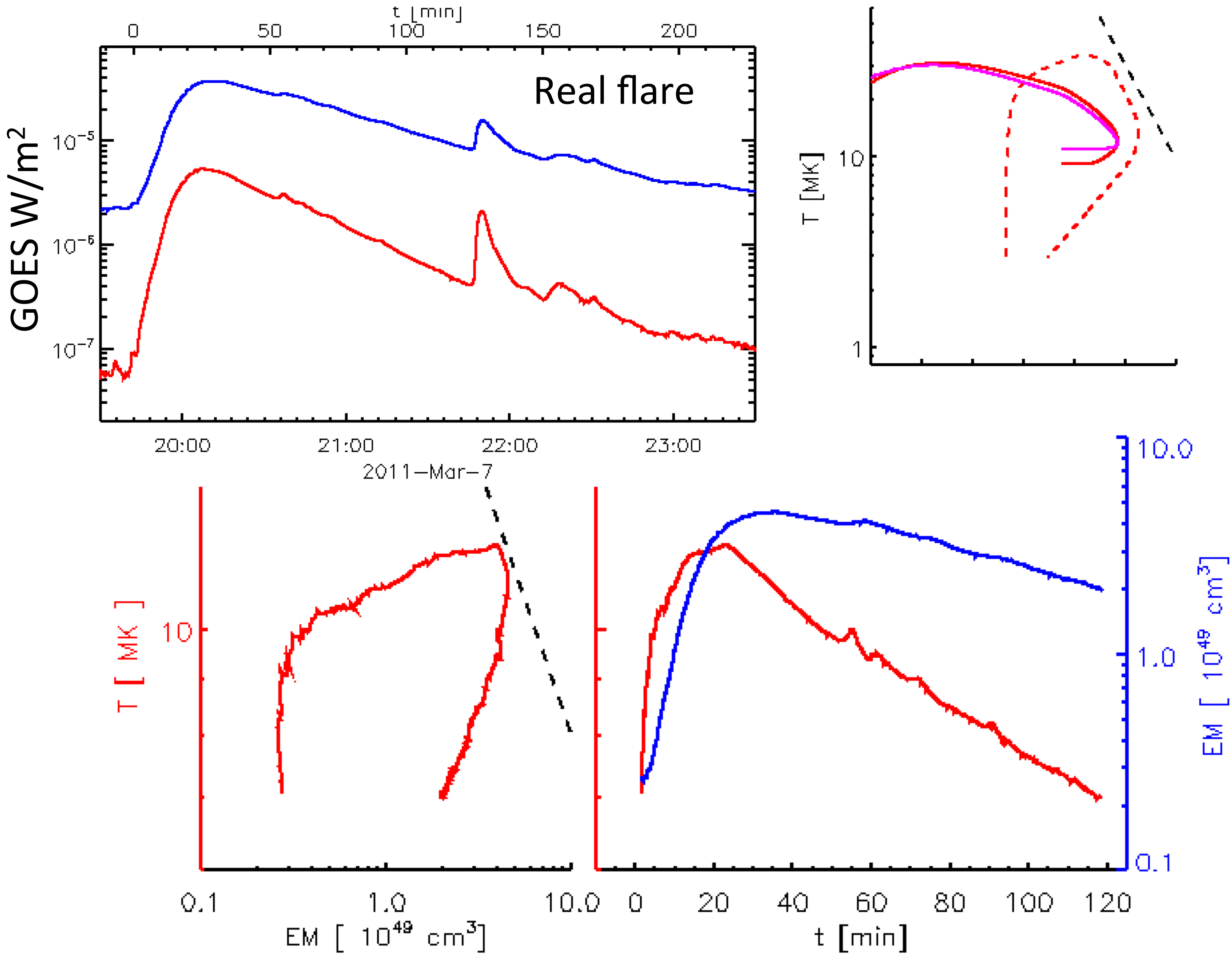


Flare as 1 loop:

$$F_{1-8} \approx 4\times10^{-5}\,\frac{\mathrm{W}}{\mathrm{m}^2}\cdot\frac{E_{30}^{7/4}}{L_9^{1/4}V_{27}^{3/4}} = 3\times10^{-4}\,\frac{\mathrm{W}}{\mathrm{m}^2}$$



flare as 1 loop
evap: p=const.
$\langle \bar{T} \rangle = \frac{1}{EM} \sum_i EM_i \bar{T}_i$
T derived
from GOES
max(EM) = 2 × 10^50 cm^3
T [MK]
10
1
10^45 10^46 10^47 10^48 10^49 10^50 10^51
EM [cm^3]
1
10
100
1000
t [s]



Real flare
GOES W/m²
t [min]
0
50
100
150
200
10⁻⁵
10⁻⁶
10⁻⁷
20:00
21:00
22:00
23:00
2011−Mar−7
T [MK]
10
1
EM [10⁴⁹ cm³]
0.1
1.0
10.0
t [min]
0
20
40
60
80
100
120
EM [10⁴⁹ cm³]

Solving the 1d problem

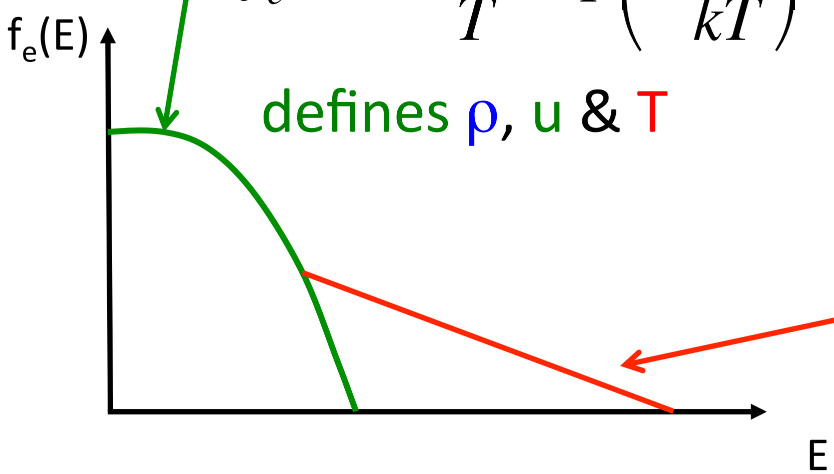
$$\frac{\partial \rho}{\partial t} = -\frac{1}{A}\frac{\partial}{\partial s}(A\rho u) \qquad \rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial s}\right) = -\frac{\partial p}{\partial s} + \rho g_{\parallel} + \frac{\partial}{\partial s}\left(\tfrac{4}{3}\mu\frac{\partial u}{\partial s}\right)$$

$$\rho c_v\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial s}\right) = -\frac{p}{A}\frac{\partial}{\partial s}(Au) + \tfrac{4}{3}\mu\left|\frac{\partial u}{\partial s}\right|^2 + \frac{1}{A}\frac{\partial}{\partial s}\left[A\kappa\frac{\partial T}{\partial s}\right] - n_e^2\Lambda(T) + \boxed{h(s,t)}$$

Maxwellian

$$f_e(E) \sim \frac{n_e}{T}\exp\left(-\frac{E}{kT}\right)$$

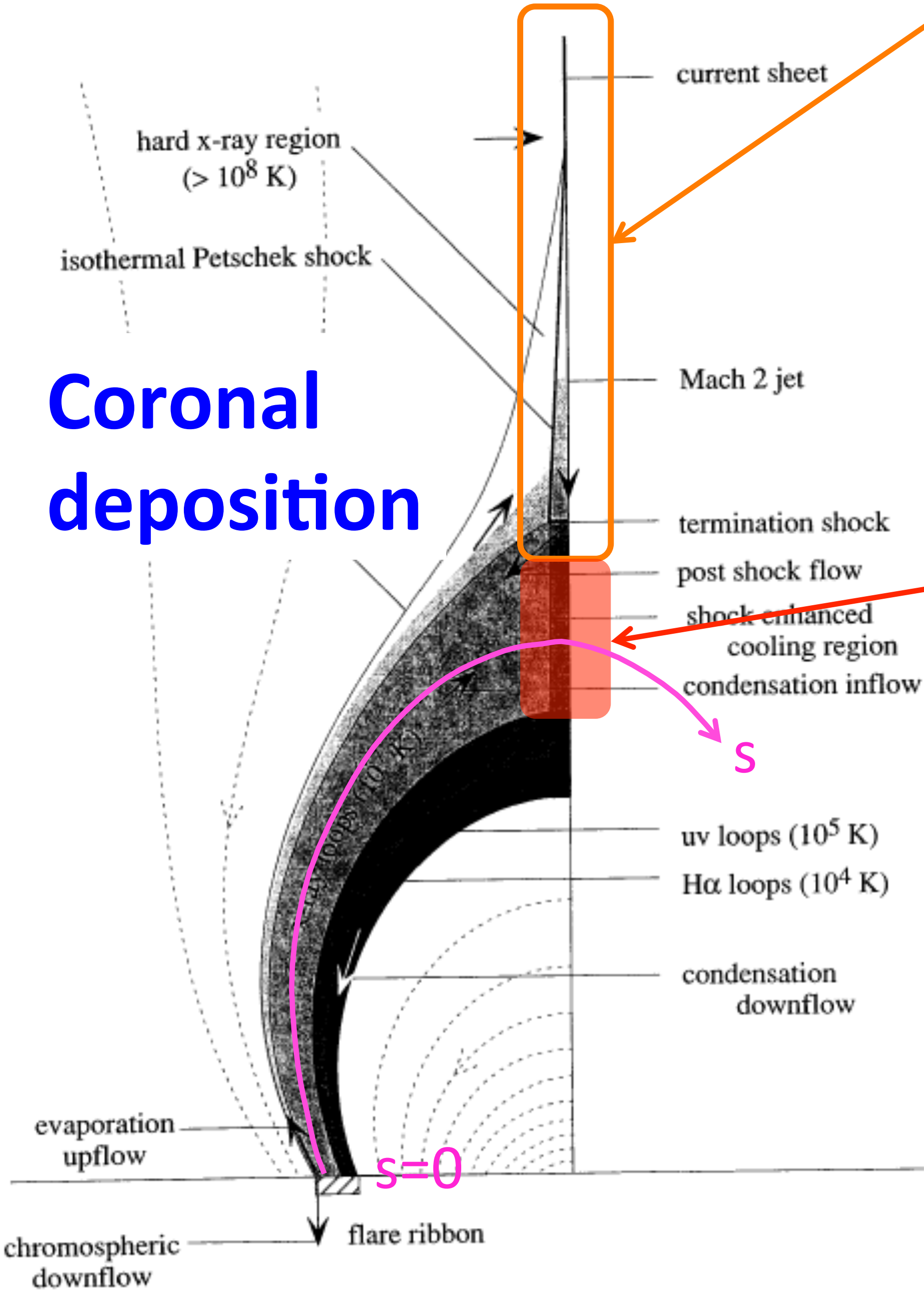
defines ρ, u & T



Source of flare energy:
heat originating in
magnetic energy,
kinetic energy, or
non-thermal electrons

$$F_{\rm fl}(t) = \int_0^{L/2} h(s,t)\, ds$$

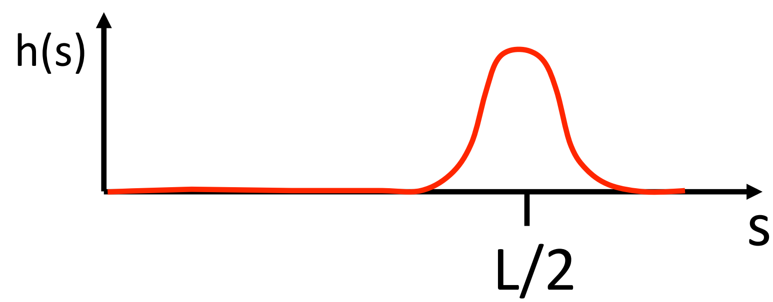
Coronal deposition



Petschek reconnection:

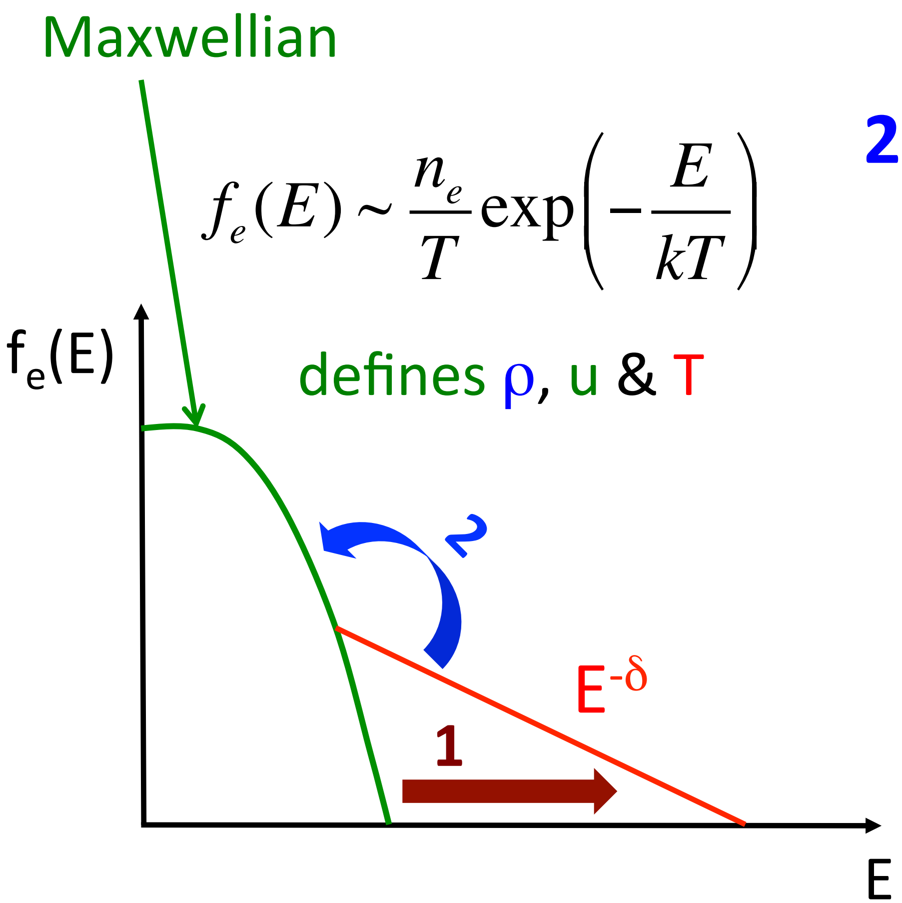
- converts magnetic energy to kinetic energy of outflow
- shocks convert KE to heat

h(s,t) localized to loop apex (s=L/2)



$$F_{\rm fl} = \varsigma \frac{B^2}{8\pi} v_A = \frac{\varsigma}{2\sqrt{\rho}} \left(\frac{B^2}{4\pi} \right)^{3/2}$$

Non-thermal electrons



$$f_e(E) \sim \frac{n_e}{T}\exp\left(-\frac{E}{kT}\right)$$

1. **Some process*** adds energy to subset of e^-s from Maxwellian — creates **NT tail.** Often a power law:

$$f_e(E) \sim E^{-\delta}$$

2. **Collisions** return NT e^-s to Maxwellian: **thermalization.** Adds energy to Maxwellian: heating **h**

Q: where does thermalization occur? i.e. what is h(s)?

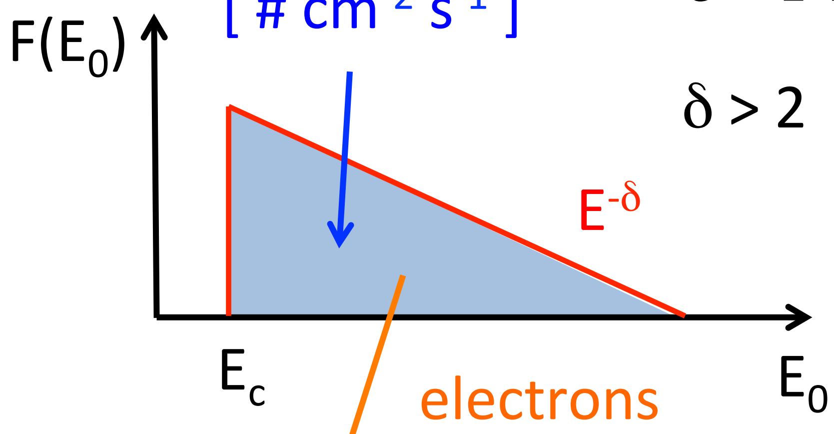
*acceleration – more later

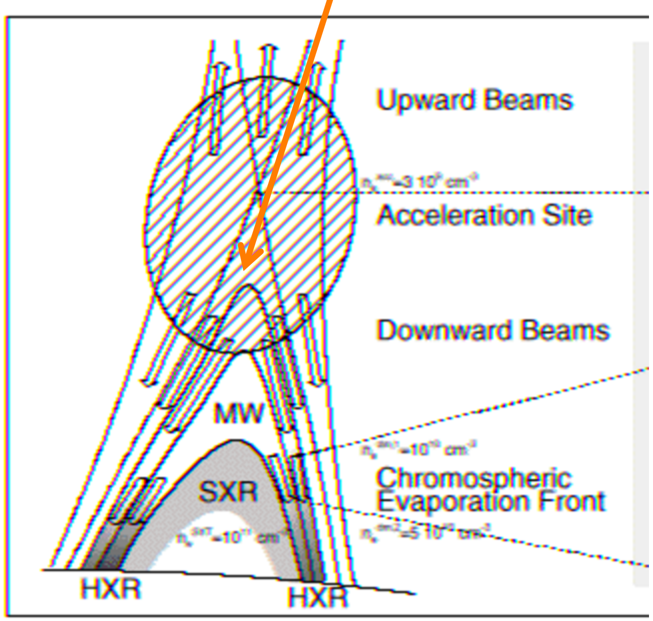
Non-thermal e^{-}s

flux of NT e^{-}s $= \frac{\delta-2}{\delta-1}\frac{F_{fl}}{E_c}$

[# cm^{-2} s^{-1}]

$\delta > 2$



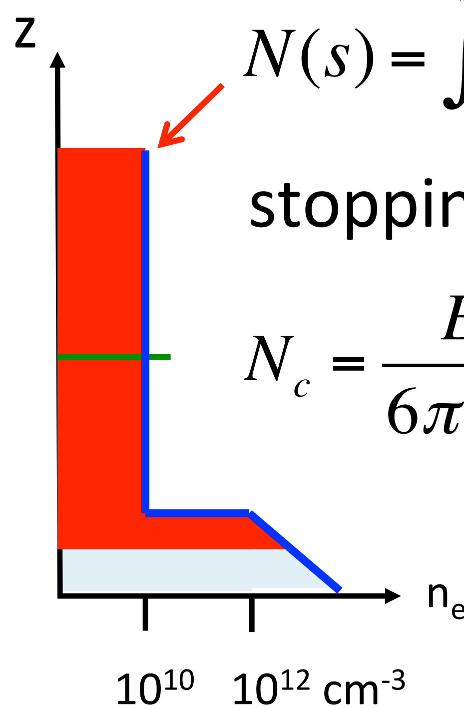


collision cross section

$$\sigma_e = 10^{-17}\ \mathrm{cm}^2 \times E_{\mathrm{keV}}^{-2}$$

column depth:

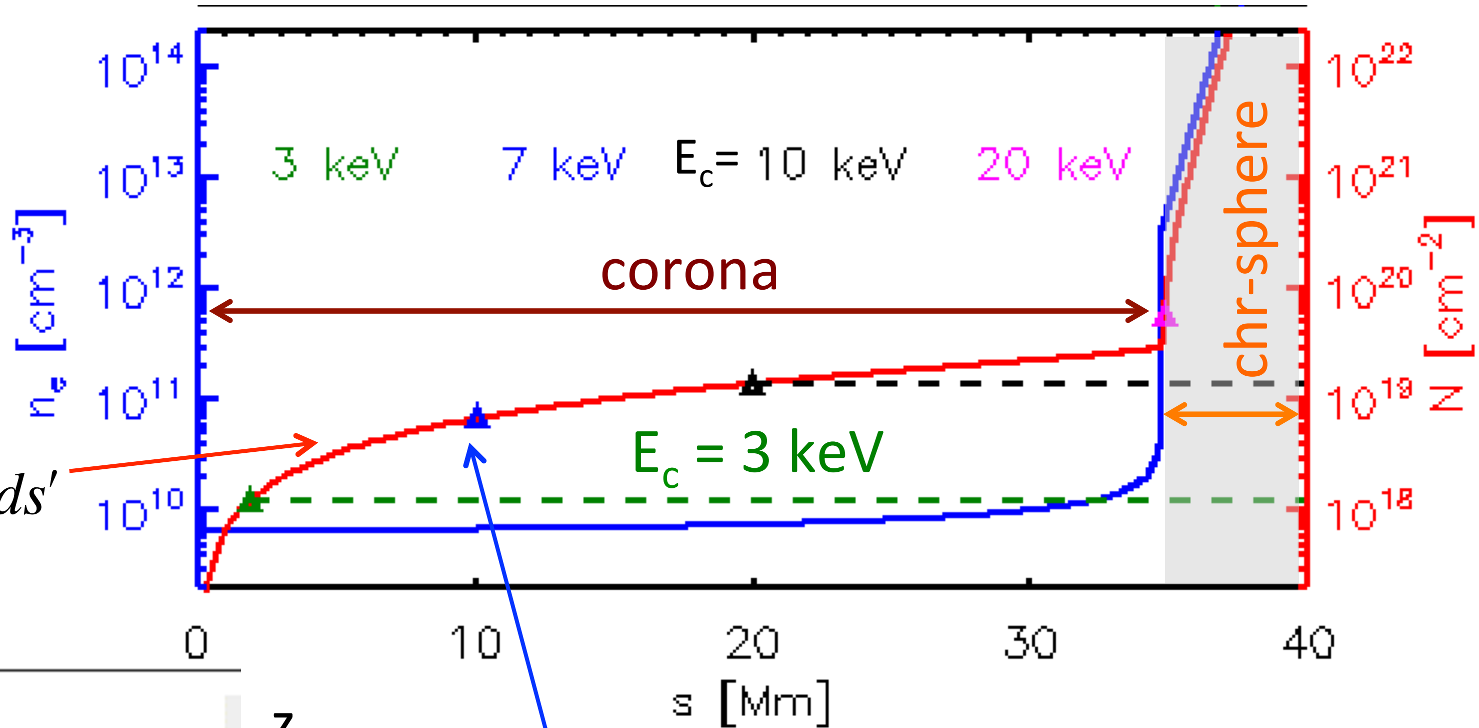
$$N(s) = \int^{s} n_e(s')\,ds' \quad [\mathrm{cm}^{-2}]$$



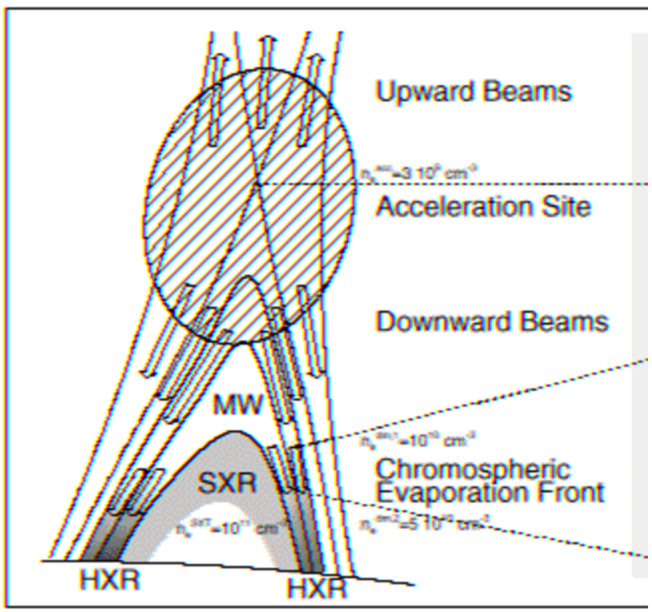
stopping column: $N\,\sigma_e = 1$

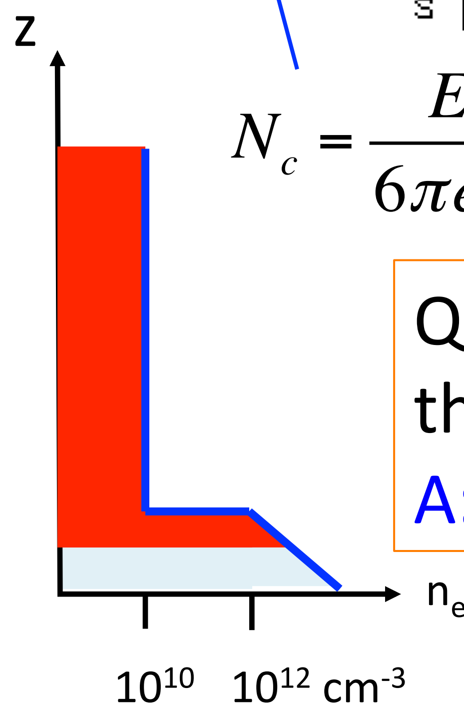
$$N_c = \frac{E_c^2}{6\pi e^4 \Lambda} = 1.4\times10^{17}\,\mathrm{cm}^{-2}\,E_{c,keV}^2$$

stop cut-off



$$N(s) = \int^{s} n_e(s')\,ds'$$





$$N_c = \frac{E_c^2}{6\pi e^4 \Lambda} = 1.4\times10^{17}\,\mathrm{cm}^{-2}\,E_{c,keV}^2$$

Q: where does thermalization occur?

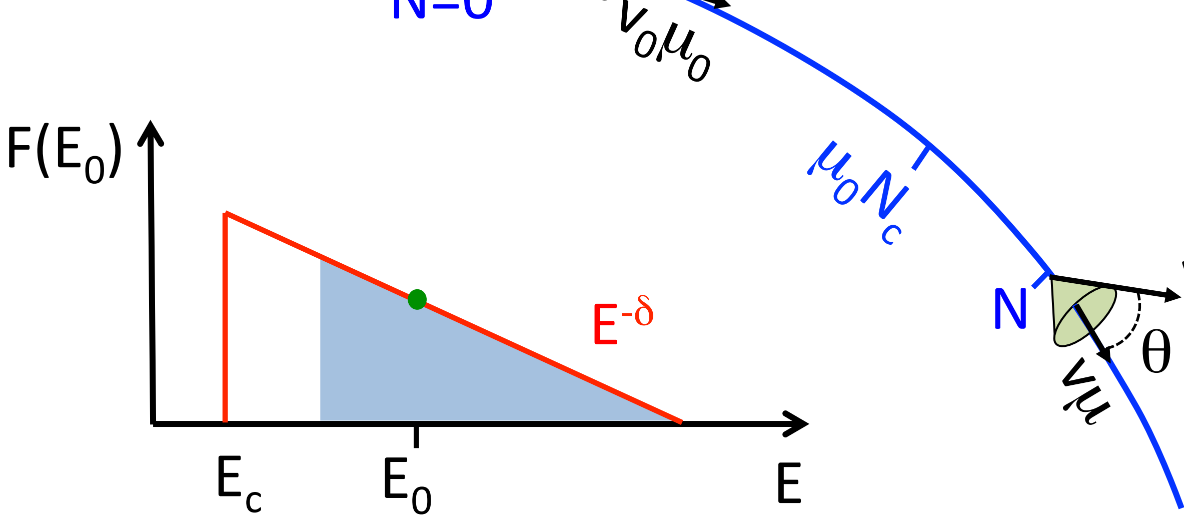
A: Where the e^-s stop

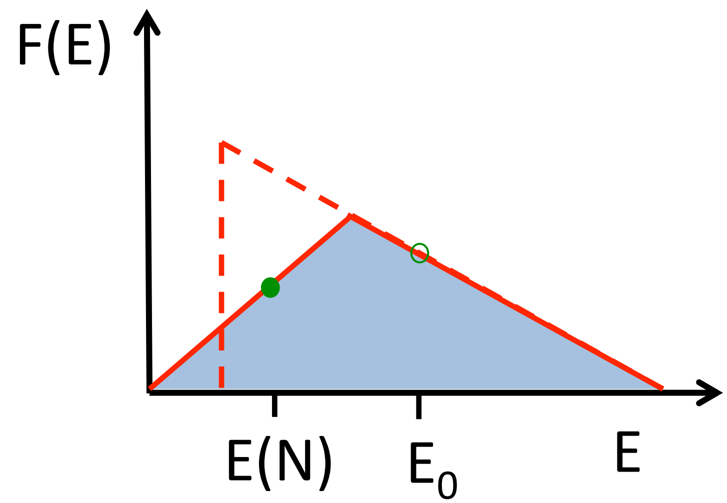
$$\frac{\mu}{\mu_0} = \frac{E}{E_0} \qquad \frac{dE}{dN} = -\frac{2\pi e^4 \Lambda}{\mu E} = -\frac{2\pi e^4 \Lambda}{\mu_0 E_0}\left(\frac{E_0}{E}\right)^2$$

$$\frac{E(N)}{E_0} = \left[1 - \frac{6\pi e^4 \Lambda}{\mu_0 E_0^2} N\right]^{1/3} = \left[1 - \frac{E_c^2}{E_0^2}\frac{N}{\mu_0 N_c}\right]^{1/3}$$

$$E = \tfrac{1}{2} m_e \mathrm{v}^2$$

$$\mu = \cos\theta$$



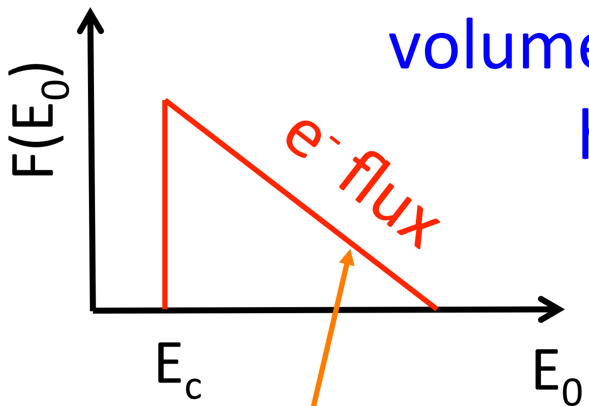


$$E(N) = E_0\left[1 - \frac{E_c^2}{E_0^2}\frac{N}{\mu_0 N_c}\right]^{1/3} \qquad \frac{dE}{dN} = -\frac{E_c^2}{3\mu_0 N_c E_0}\left(\frac{E_0}{E}\right)^2$$

loss per NT e^-

$$\frac{dE}{ds} = \frac{dN}{ds}\frac{dE}{dN} = -\frac{n_e E_c^2}{3\mu_0 N_c E_0}\left[1 - \frac{E_c^2}{E_0^2}\frac{N}{\mu_0 N_c}\right]^{-2/3}$$

gain by plasma: volumetric heat



$$h(N,\mu_0) = \int\left(-\frac{dE}{ds}\right)F(E_0)\,dE_0$$

$$= \frac{n_e E_c^2}{\mu_0 N_c}\int\left[1 - \frac{E_c^2}{\mu_0 E_0^2}\frac{N}{N_c}\right]^{-2/3} F(E_0)\frac{dE_0}{E_0}$$

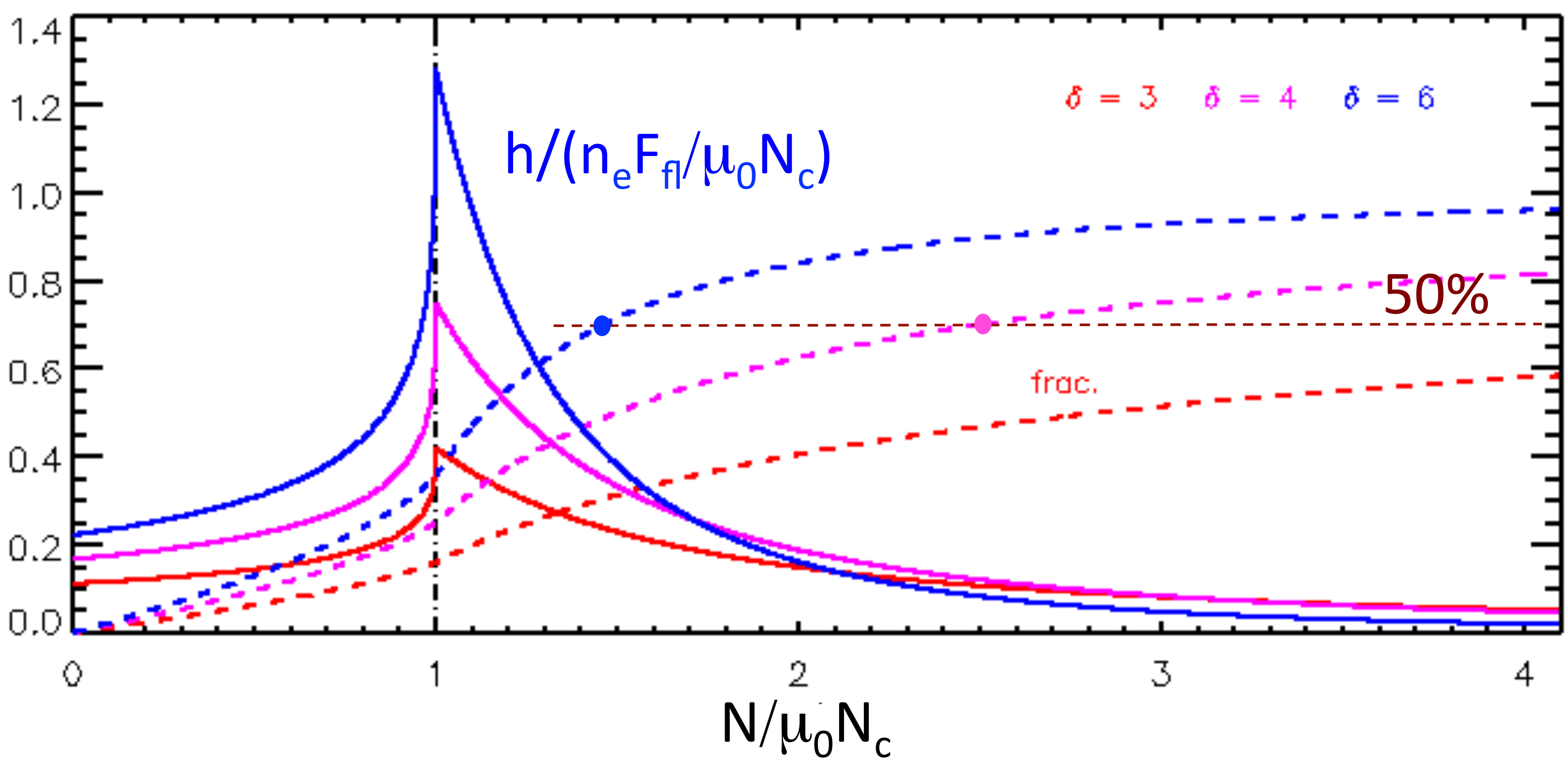
$$F(E_0) = (\delta - 2)\frac{F_{\mathrm{fl}}(t)}{E_c^2}\left(\frac{E_0}{E_c}\right)^{-\delta}$$

$\rightarrow$

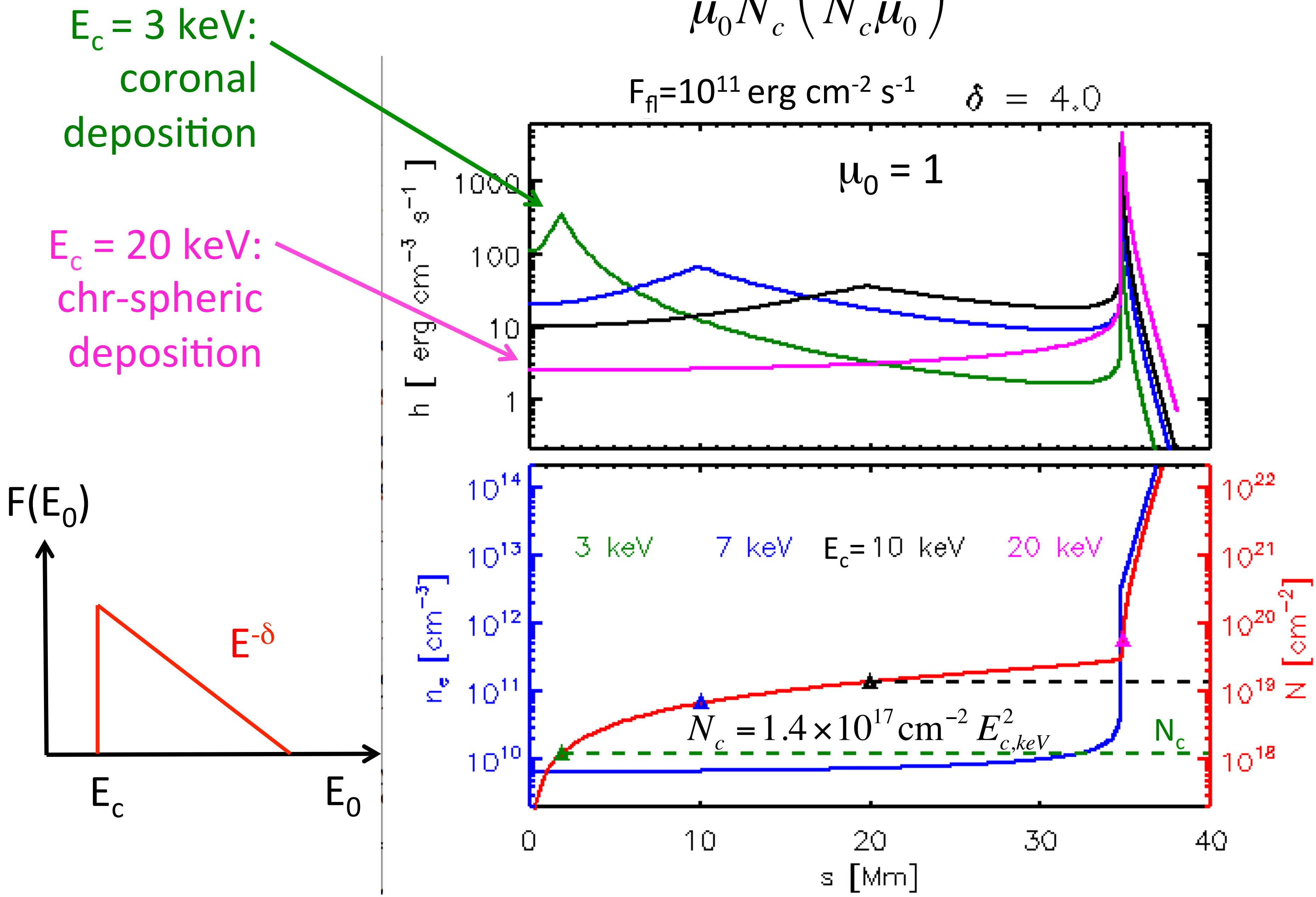
$$h \sim F_{\mathrm{fl}}(t)\frac{n_e(s)}{\mu_0 N_c}\left(\frac{N}{N_c \mu_0}\right)^{-\delta/2}$$

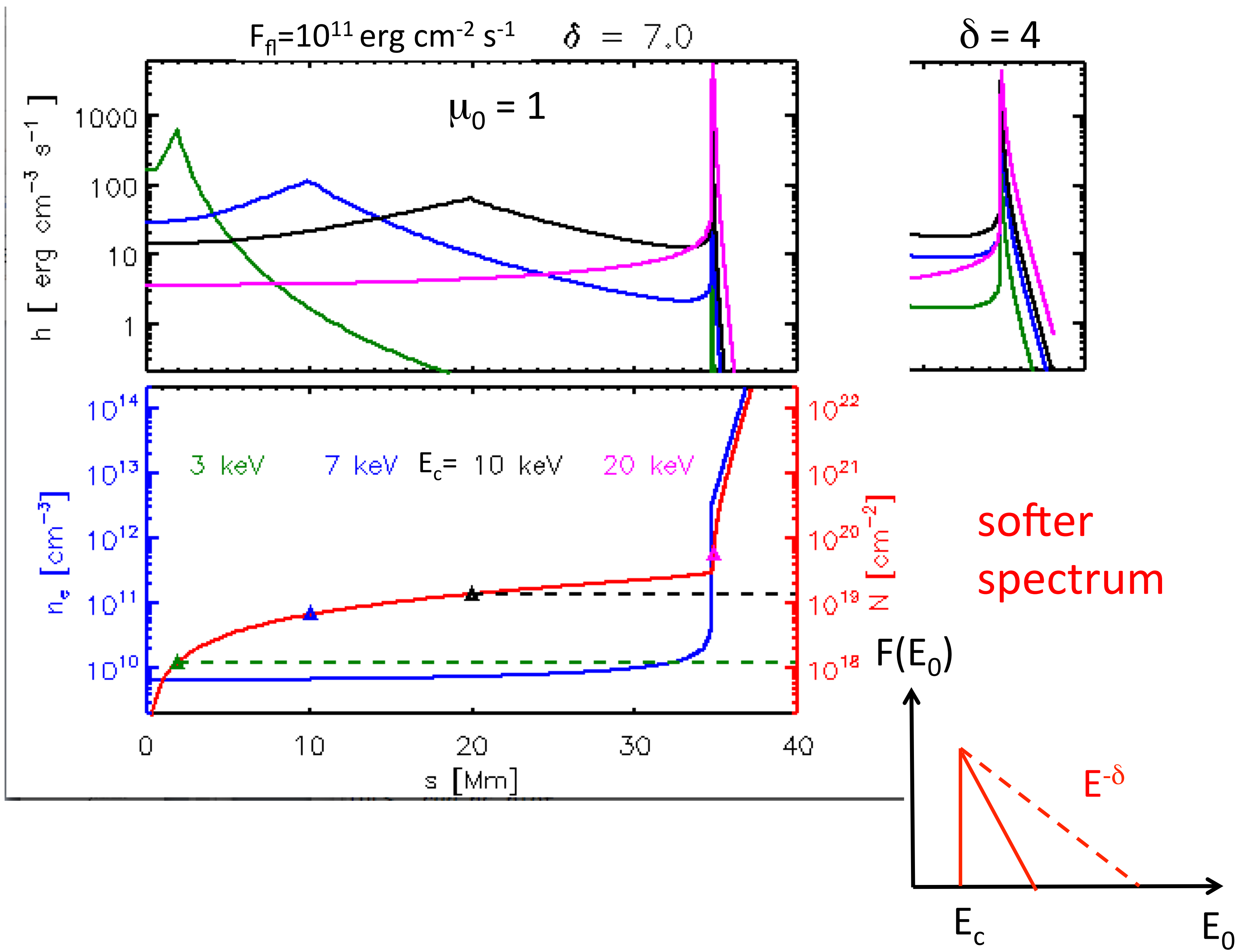
NT e⁻ heating

$$h = \frac{\delta - 2}{6}\left(\frac{n_e F_{\rm fl}}{\mu_0 N_c}\right)\left(\frac{N}{\mu_0 N_c}\right)^{-\delta/2} \begin{cases} B\left(\dfrac{N}{\mu_0 N_c}; \dfrac{\delta}{2}, \dfrac{1}{3}\right) & , \quad N < \mu_0 N_c \\ B\left(\dfrac{\delta}{2}, \dfrac{1}{3}\right) = \dfrac{\Gamma(\frac{1}{2}\delta + \frac{1}{3})}{\Gamma(\frac{1}{2}\delta)\Gamma(\frac{1}{3})} & , \quad N > \mu_0 N_c \end{cases}$$

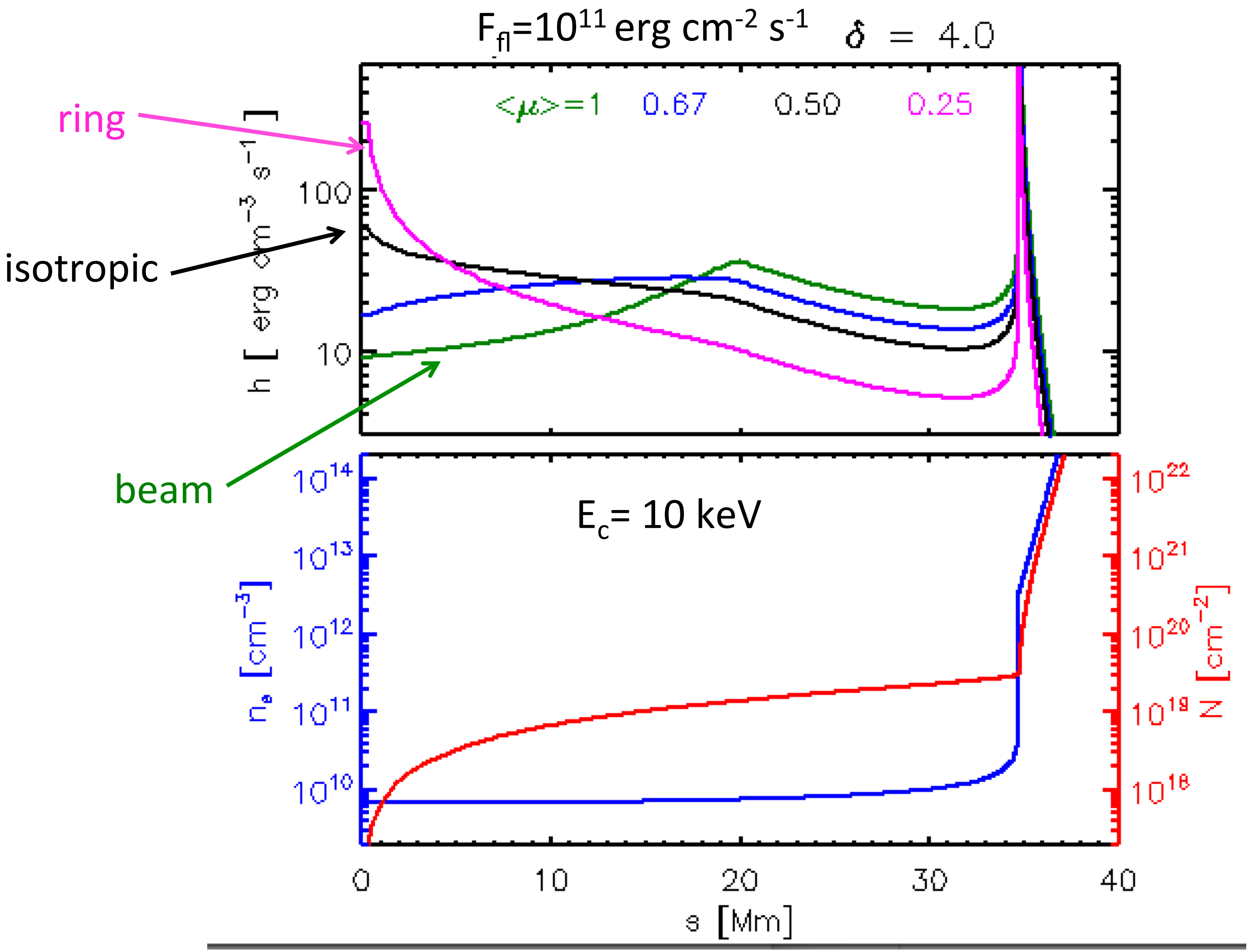


$$h \sim F_{\mathrm{fl}}(t)\frac{n_e(s)}{\mu_0 N_c}\left(\frac{N}{N_c\mu_0}\right)^{-\delta/2}$$



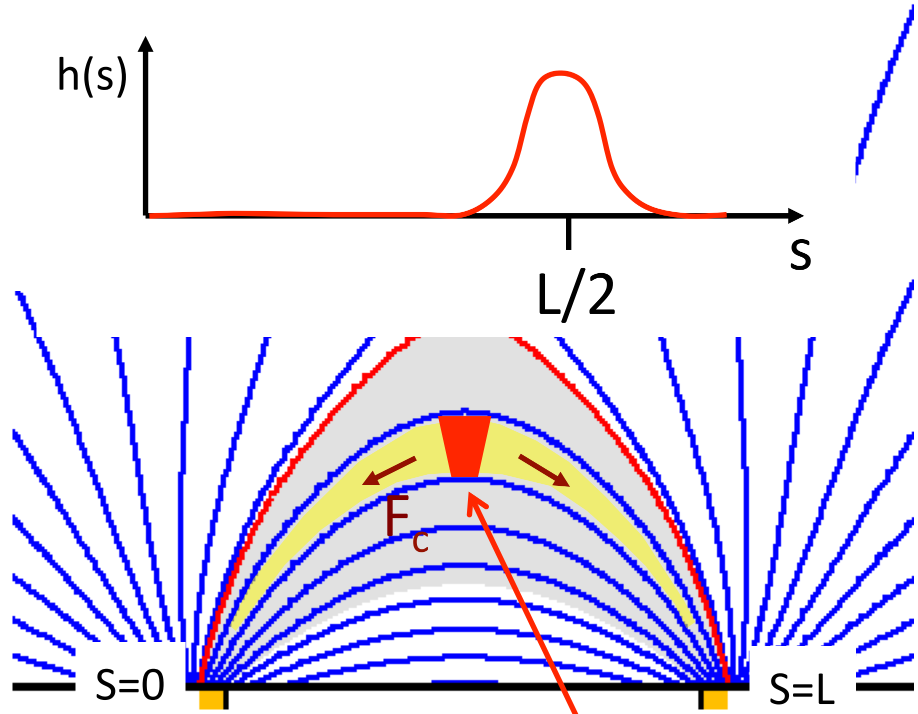


$F_{fl}=10^{11}$ erg cm^{-2} s^{-1} δ = 7.0
δ = 4
μ_0 = 1
h [erg cm^{-3} s^{-1}]
1000
100
10
1
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
n_e [cm^{-3}]
3 keV
7 keV
E_c= 10 keV
20 keV
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
N [cm^{-2}]
0
10
20
30
40
s [Mm]
softer spectrum
$F(E_0)$
$E^{-\delta}$
E_c
E_0



F_fl=10^11 erg cm^-2 s^-1 δ = 4.0
<μ>=1 0.67 0.50 0.25
ring
isotropic
beam
h [erg cm^-3 s^-1]
100
10
E_c= 10 keV
n_e [cm^-3]
N [cm^-2]
10^14
10^13
10^12
10^11
10^10
10^22
10^21
10^20
10^19
10^18
0
10
20
30
40
s [Mm]

Coronal deposition



Reconnection, or small E_c, or large δ, or small μ_0

source

$$\frac{\partial \rho}{\partial t} = -\frac{1}{A}\frac{\partial}{\partial s}(A\rho u)$$

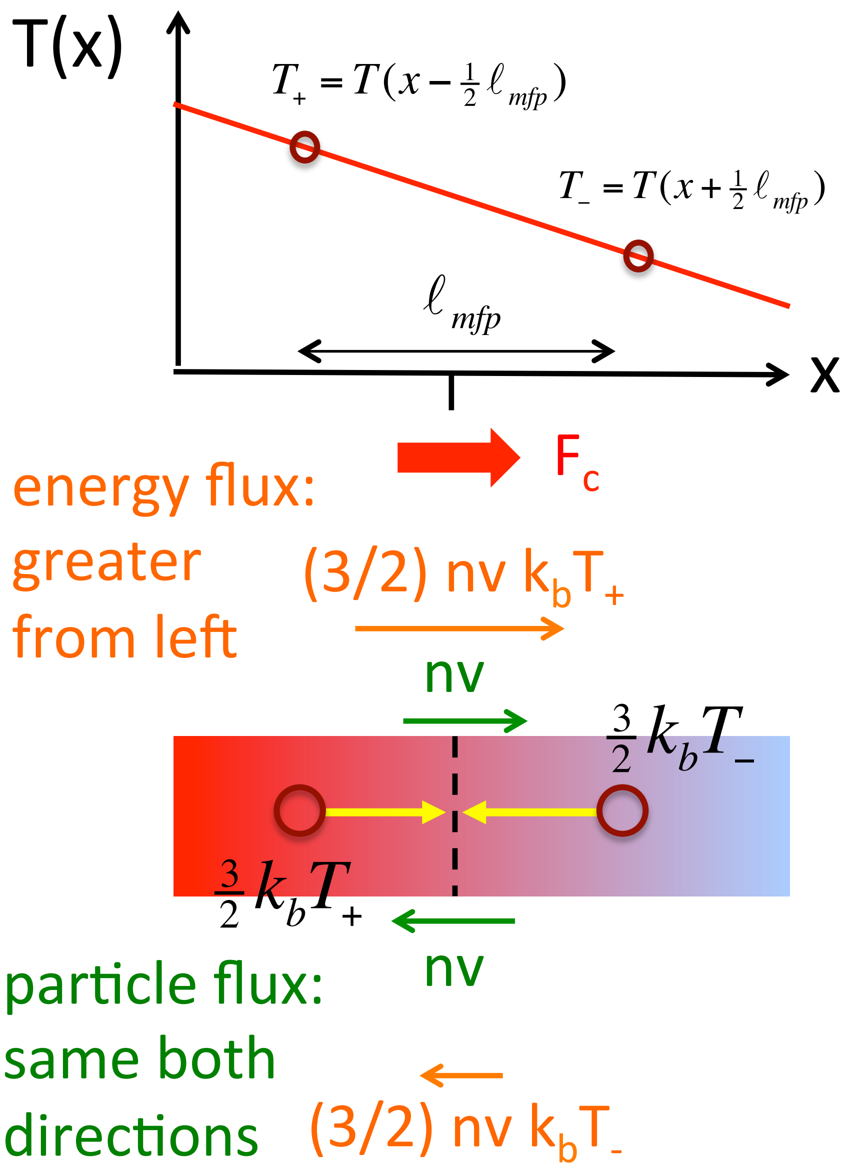
$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial s}\right) = -\frac{\partial p}{\partial s} + \rho g_{\parallel} + \frac{\partial}{\partial s}\left(\tfrac{4}{3}\mu\frac{\partial u}{\partial s}\right)$$

$$\rho c_v\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial s}\right) = -\frac{p}{A}\frac{\partial}{\partial s}(Au) + \tfrac{4}{3}\mu\left|\frac{\partial u}{\partial s}\right|^2 + \frac{1}{A}\frac{\partial}{\partial s}\left(A\boxed{\kappa\frac{\partial T}{\partial s}}\right) - n_e^2\Lambda(T) + h$$

F_c

$$p = \frac{k_b}{\bar{m}}\rho T \qquad c_v = \frac{3}{2}\frac{k_b}{\bar{m}}$$

Conductive flux



$$F_c = \tfrac{3}{2} n \mathrm{v}\, k_b \left(T_+ - T_-\right)$$

IF gradient is shallow or m.f.p. is small

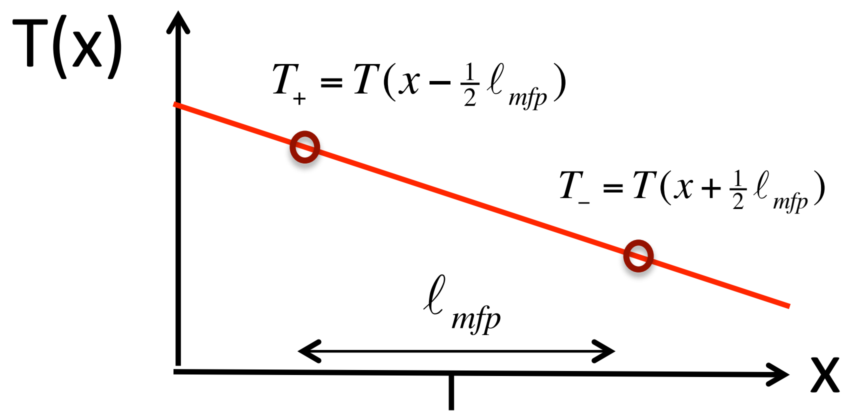
$$F_c \approx -\boxed{\tfrac{3}{2} n \mathrm{v}\, k_b \ell_{mfp}} \frac{\partial T}{\partial x}$$

$= \kappa$

$$\boxed{\vec{F}_c = -\kappa \nabla T}$$

Fourier's law – classical heat flux

Conductive flux



$$F_c = \tfrac{3}{2} n \mathrm{v} k_b \left(T_+ - T_-\right)$$

IF gradient is shallow or m.f.p. is small

$$F_c \approx -\tfrac{3}{2} n \mathrm{v} k_b \ell_{mfp} \frac{\partial T}{\partial x}$$

$= \kappa$

$$\kappa = \tfrac{3}{2} k_b \mathrm{v}_{th} n \ell_{mfp} = \frac{3}{2}\frac{k_b \mathrm{v}_{th}}{\sigma_{sc}}$$

$$\sigma_{sc} \sim \frac{q^4}{m^2 \mathrm{v}_{th}^4}$$ Rutherford scattering

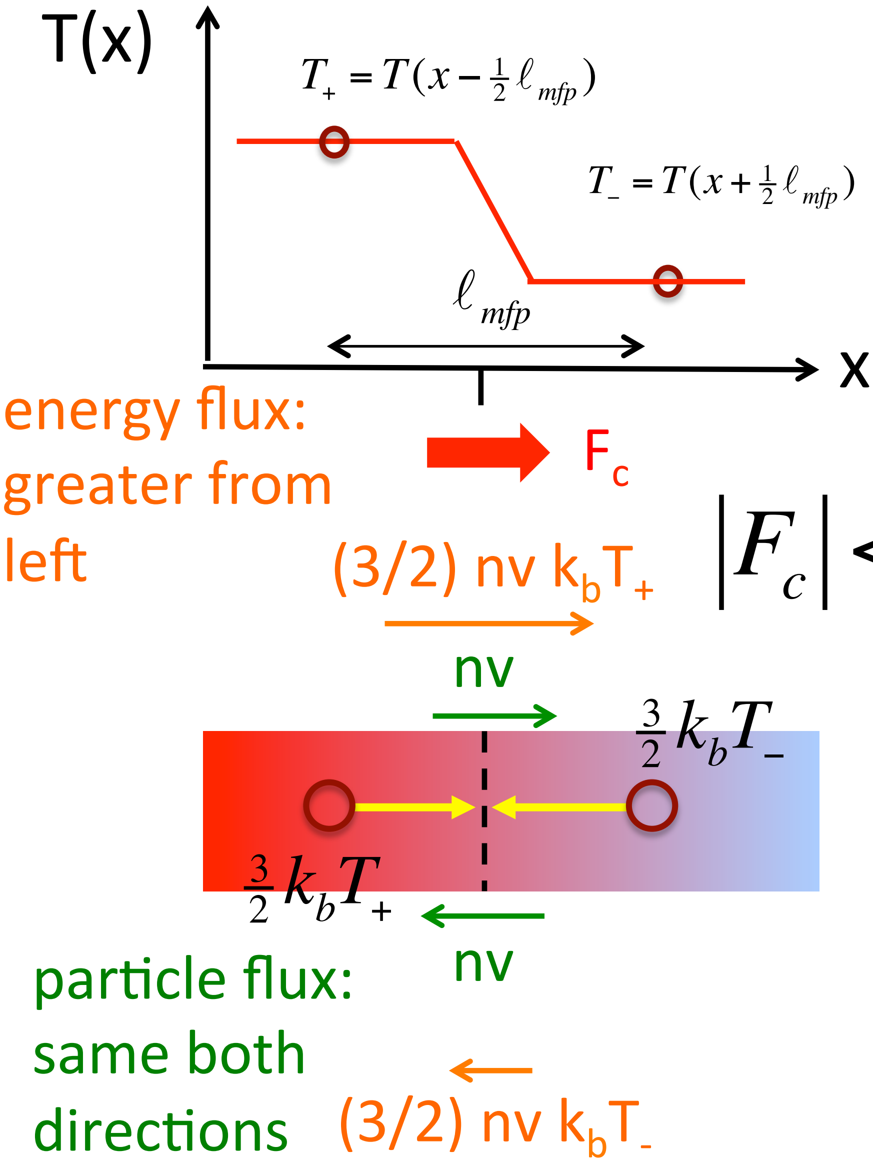
$$\kappa \sim \frac{k_b m^2 \mathrm{v}_{th}^5}{q^4} \sim \frac{k_b^{7/2}}{m^{1/2} q^4} T^{5/2}$$

e^-s : smallest m ➔ most heat flux

$\kappa = \kappa_0 T^{5/2}$ [erg cm^{-2} s^{-1} K^{-1}]

$\kappa_0 \simeq 10^{-6}$ erg cm^{-2} s^{-1} K$^{-7/2}$

Conductive flux



$$F_c = \tfrac{3}{2} n \mathrm{v}\, k_b \left(T_+ - T_-\right)$$

IF NOT

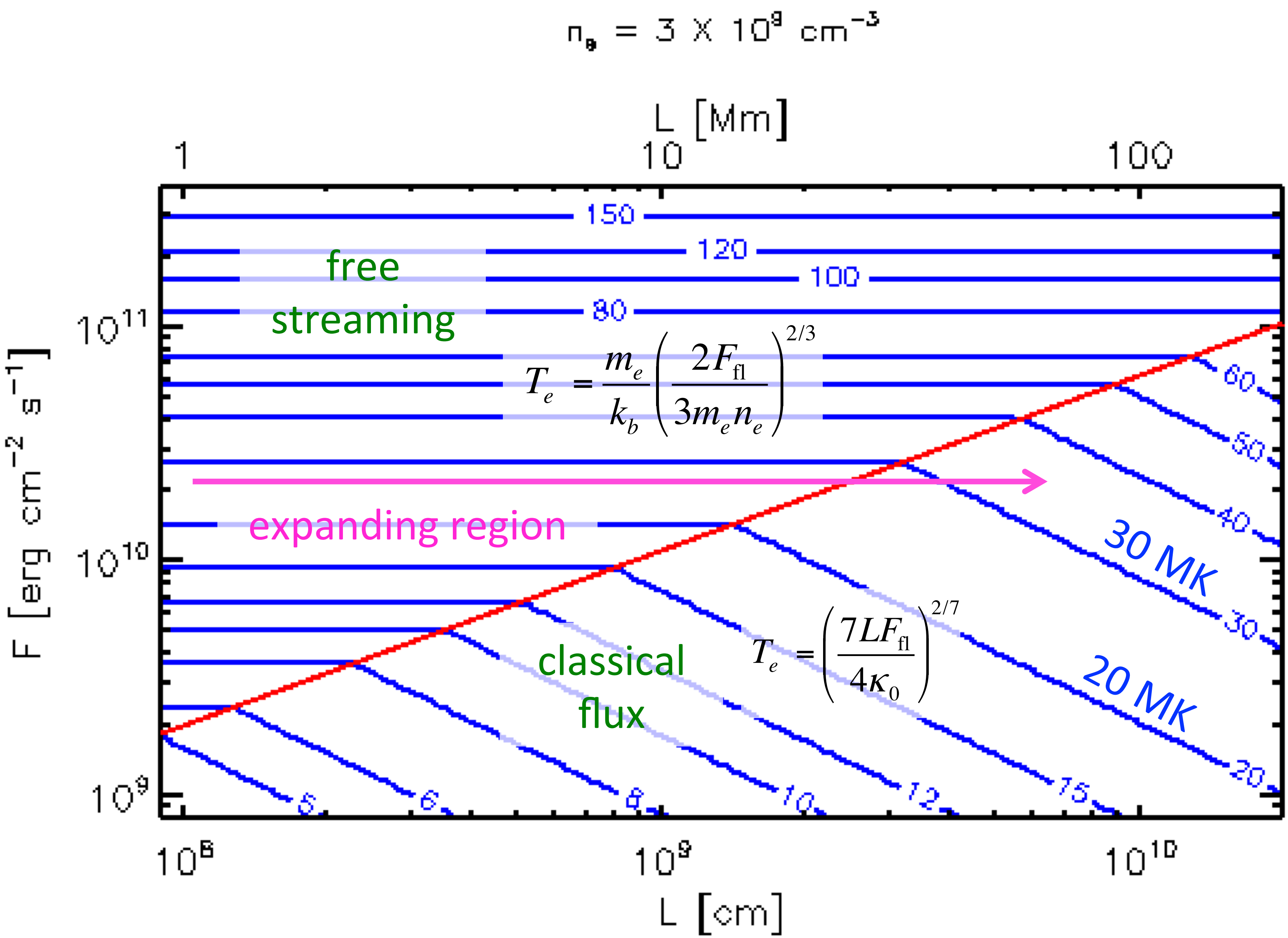
$$\left|F_c\right| < \tfrac{3}{2} n \mathrm{v}_{th} k_b T_+ = \boxed{\tfrac{3}{2} n_e \frac{k_b^{3/2}}{m_e^{1/2}} T_e^{3/2}}$$

$=F_{fs}$

Free-streaming

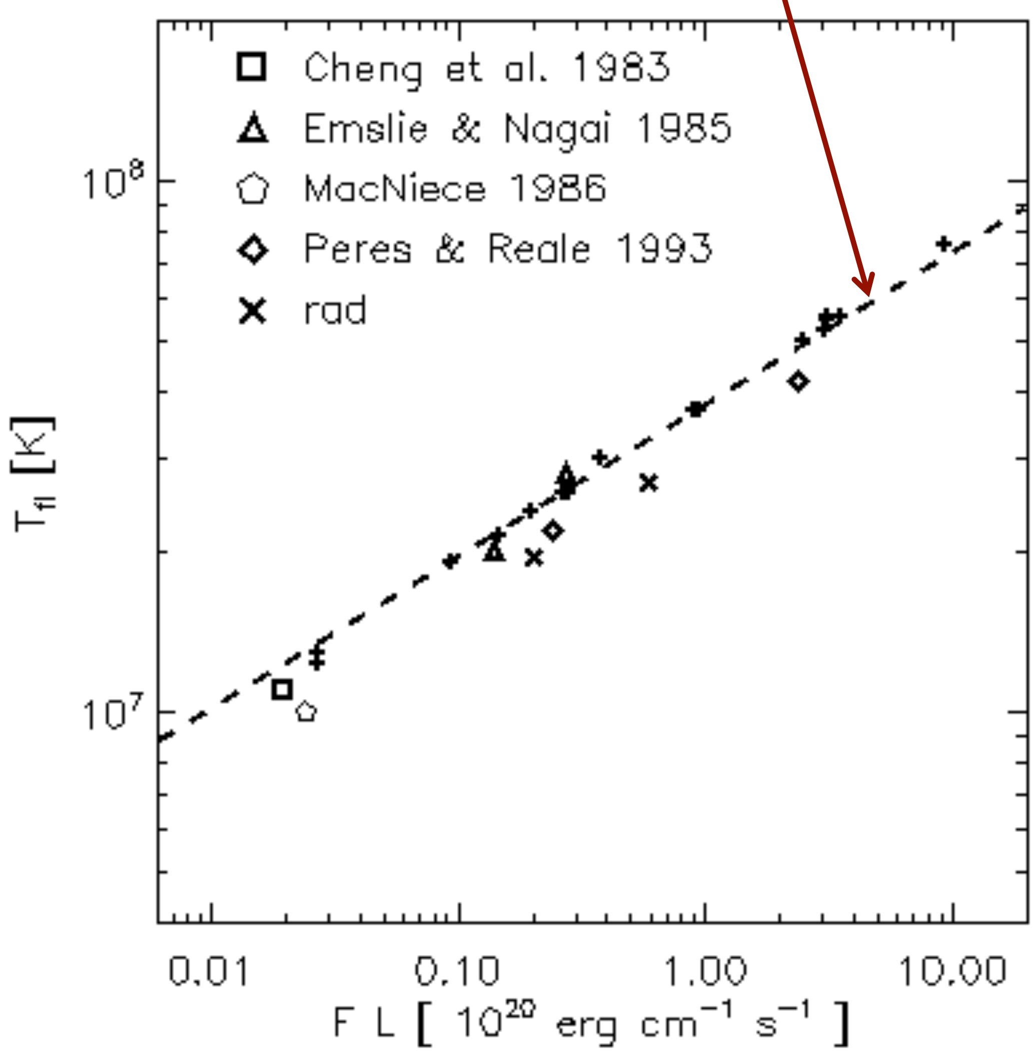
heat flux:

upper bound



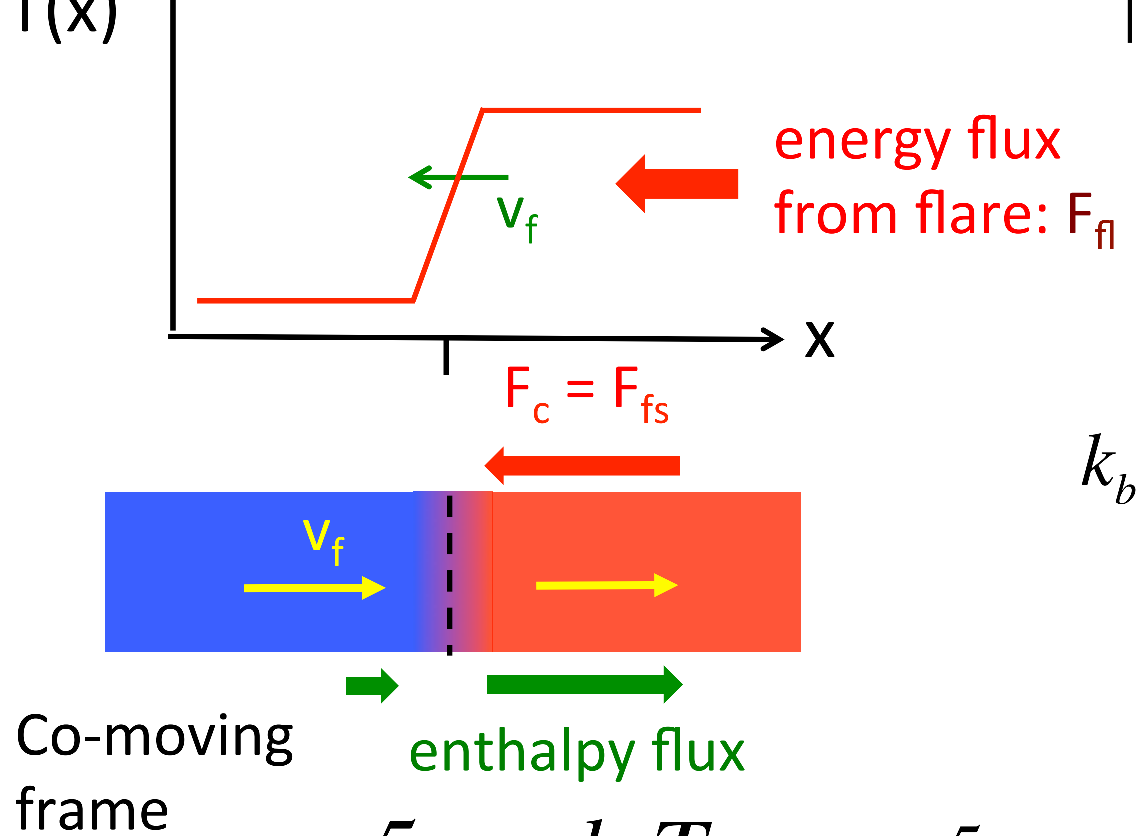
$n_e = 3 \times 10^9$ cm^{-3}
L [Mm]
1
10
100
F [erg cm^{-2} s^{-1}]
10^{11}
10^{10}
10^{9}
L [cm]
10^{8}
10^{9}
10^{10}
150
120
100
80
60
50
40
30
20
15
12
10
8
6
5
free streaming
$T_e = \frac{m_e}{k_b}\left(\frac{2F_{fl}}{3m_e n_e}\right)^{2/3}$
expanding region
30 MK
20 MK
classical flux
$T_e = \left(\frac{7LF_{fl}}{4\kappa_0}\right)^{2/7}$

$$T_{\rm fl} = C_T\,(FL/\kappa_0)^{2/7}, \quad C_T=1.46$$



Longcope 2014

Heat front



$$|F_c| = \tfrac{3}{2} n_e \frac{k_b^{3/2}}{m_e^{1/2}} T_e^{3/2}$$

free-streaming
heat flux

$$k_b T_e = m_e \left(\frac{2F_{\mathrm{fl}}}{3 m_e n_e} \right)^{2/3}$$

$$5 \mathrm{v}_{\mathrm{f}} n_e k_b T_e = 5 \mathrm{v}_{\mathrm{f}} n_e m_e \left(\frac{2F_{\mathrm{fl}}}{3 m_e n_e} \right)^{2/3} = F_{\mathrm{fl}}$$

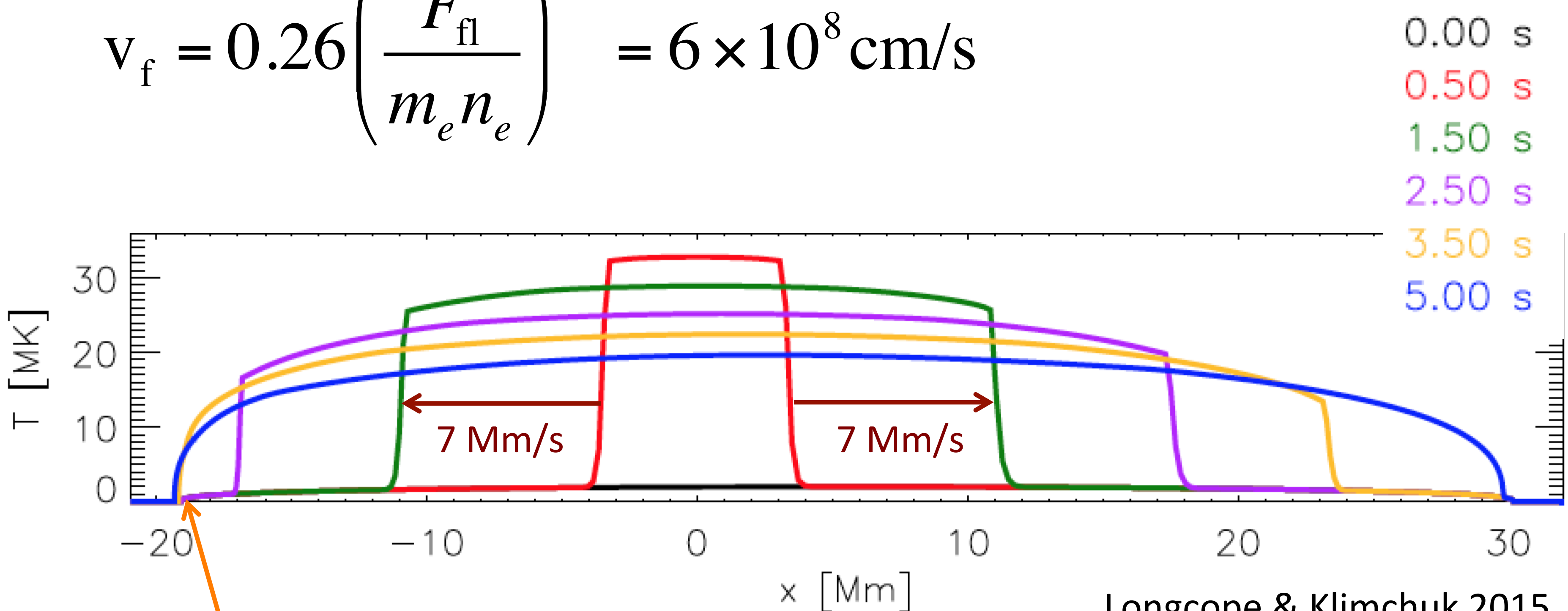
speed of
heat front

$$\mathrm{v}_{\mathrm{f}} = 0.26 \left(\frac{F_{\mathrm{fl}}}{m_e n_e} \right)^{1/3}$$

$F_{fl} = 1.2 \times 10^{10}$ erg cm^{-2} s^{-1} $n_e = 10^9$ cm^{-3} at first

$$T_e = \frac{m_e}{k_b}\left(\frac{2F_{fl}}{3m_e n_e}\right)^{2/3} = 2.8\times10^7\,\mathrm{K}$$

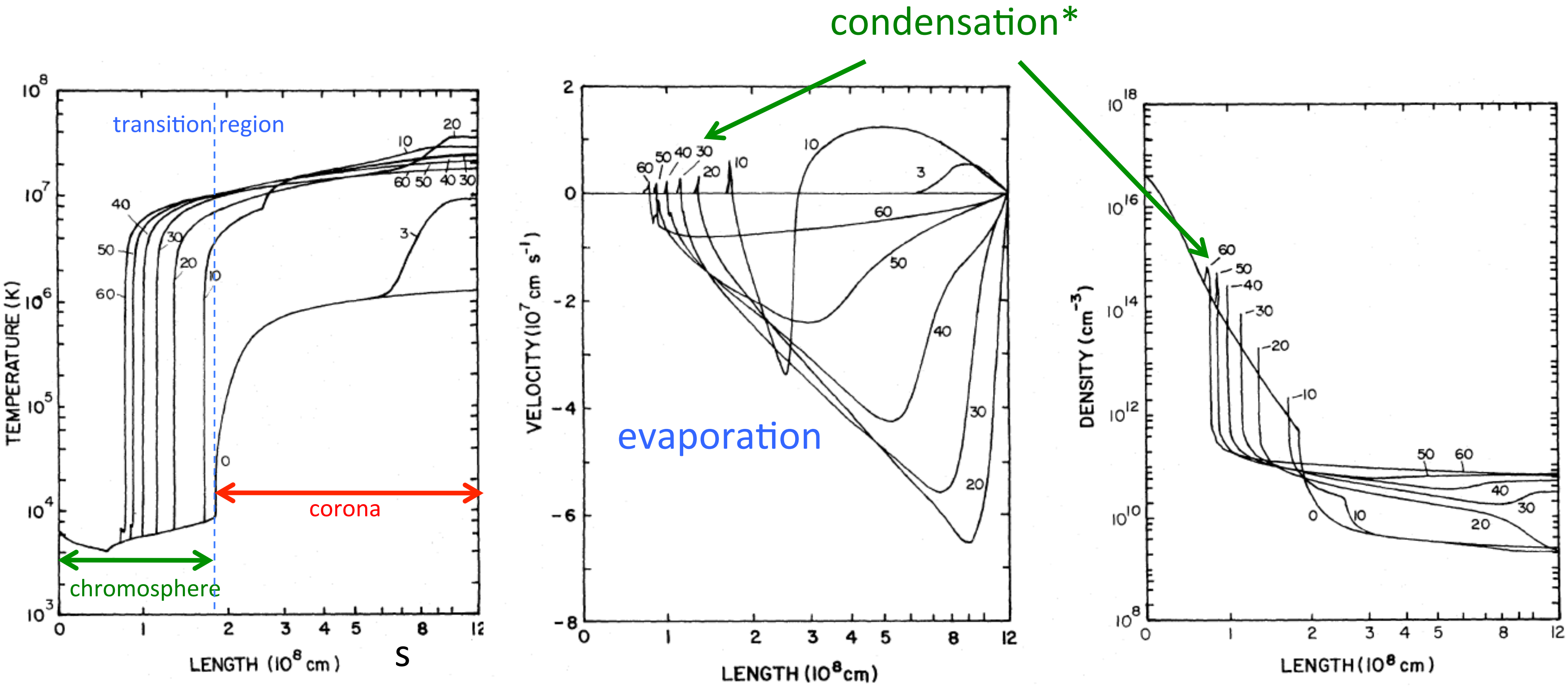
$$v_f = 0.26\left(\frac{F_{fl}}{m_e n_e}\right)^{1/3} = 6\times10^8\,\mathrm{cm/s}$$



Longcope & Klimchuk 2015

heat front reaches TR in ~ 3 sec.

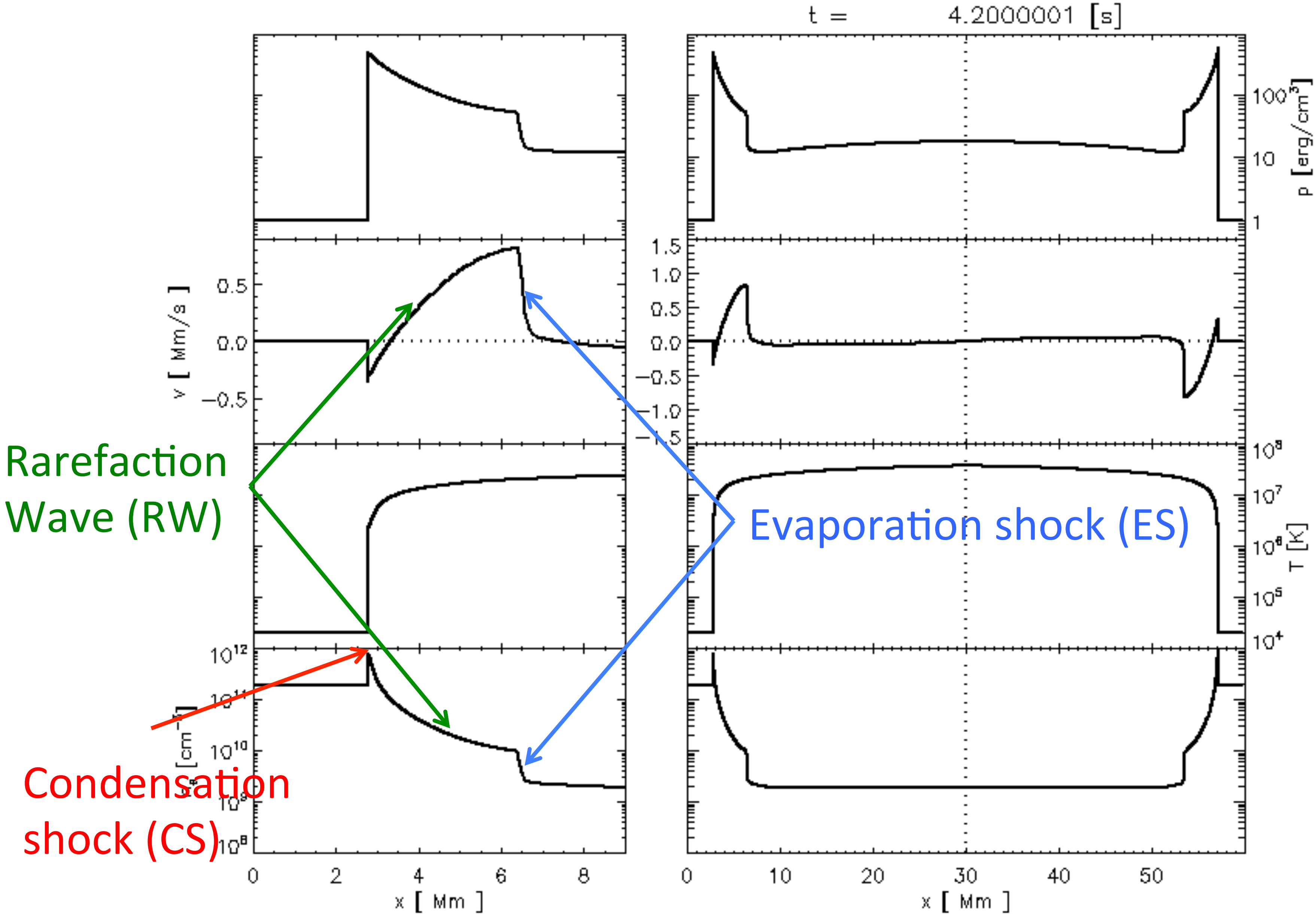
Conduction-driven evaporation

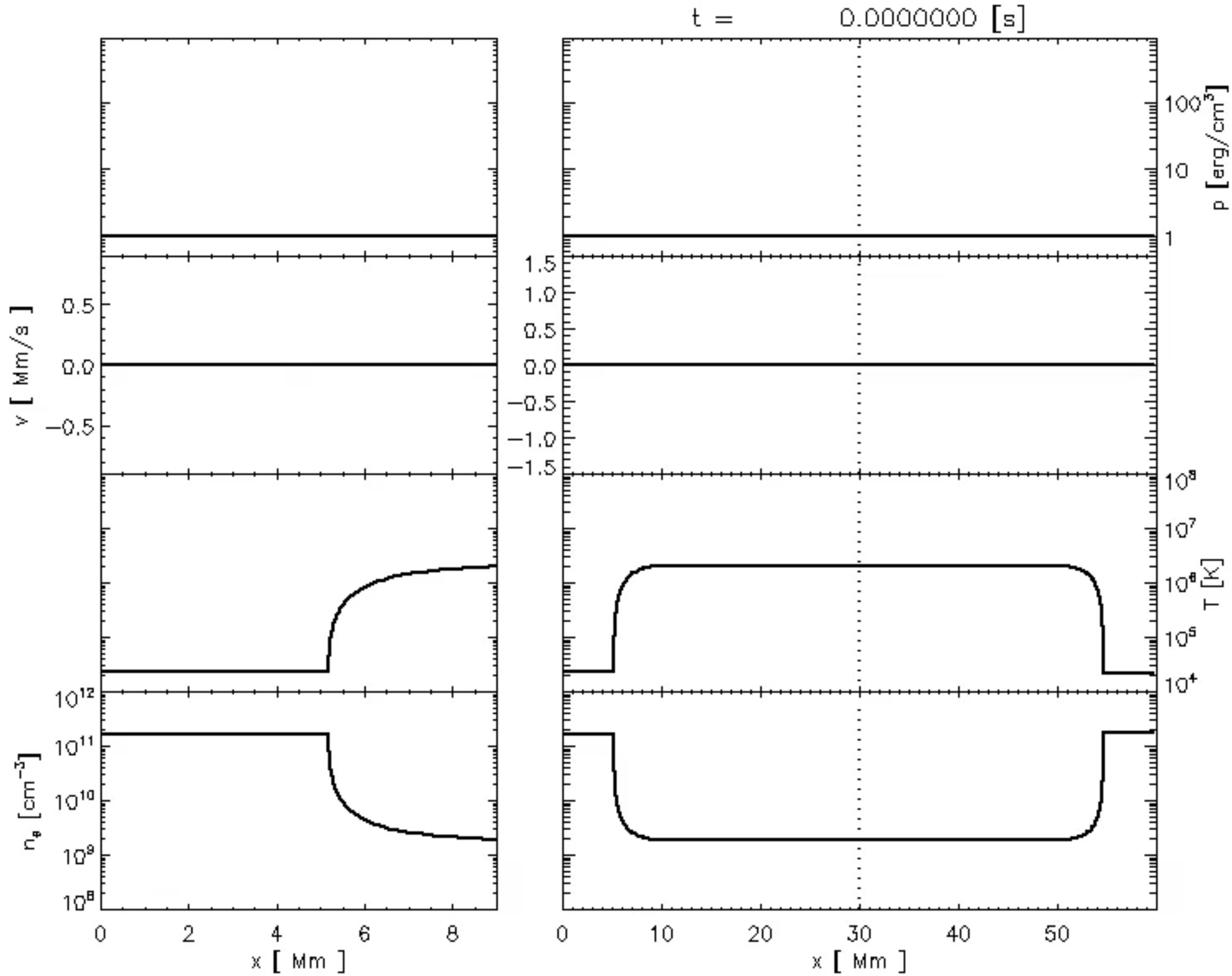


Emslie & Nagai 1985

* Another historical term

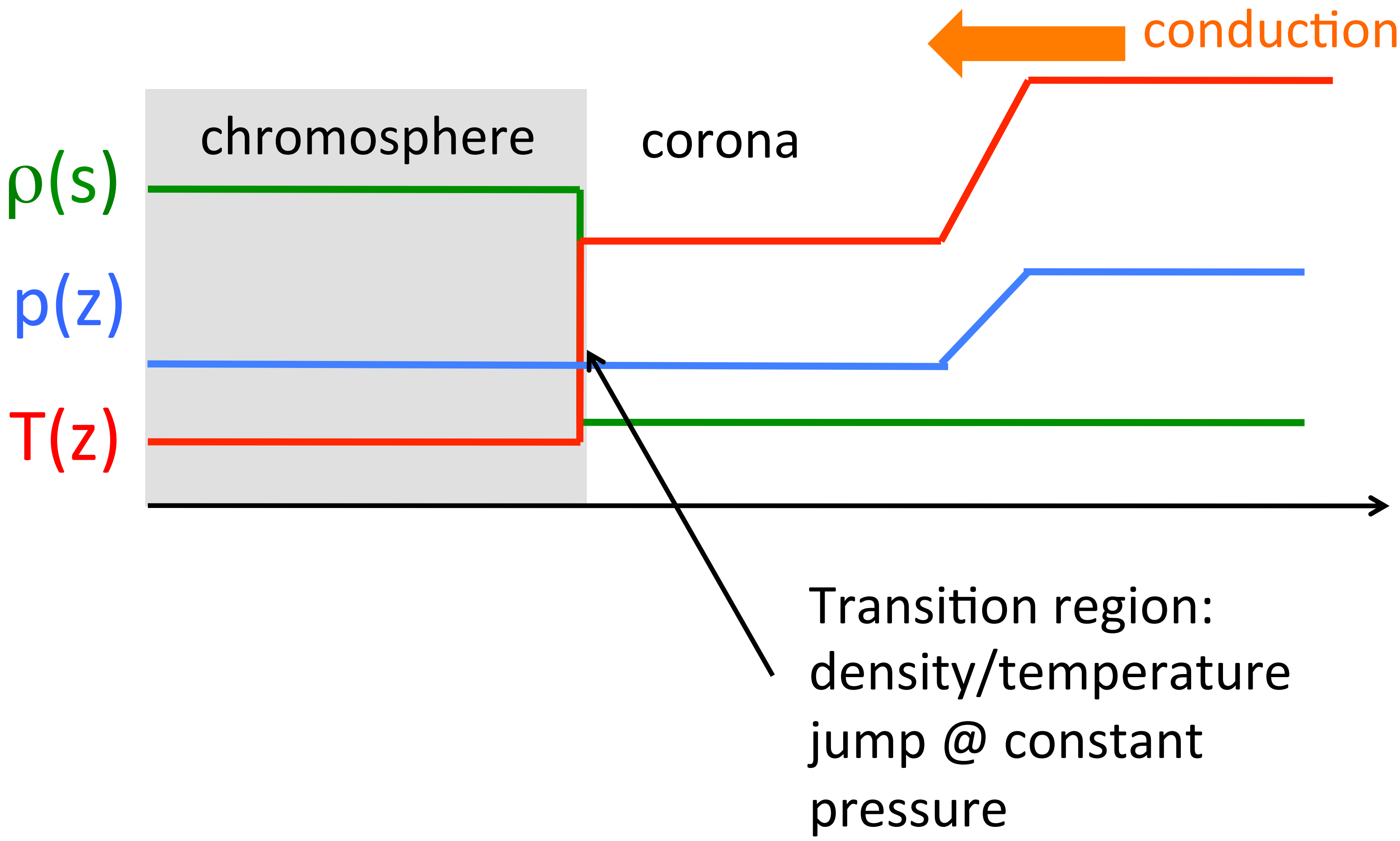
Evaporation





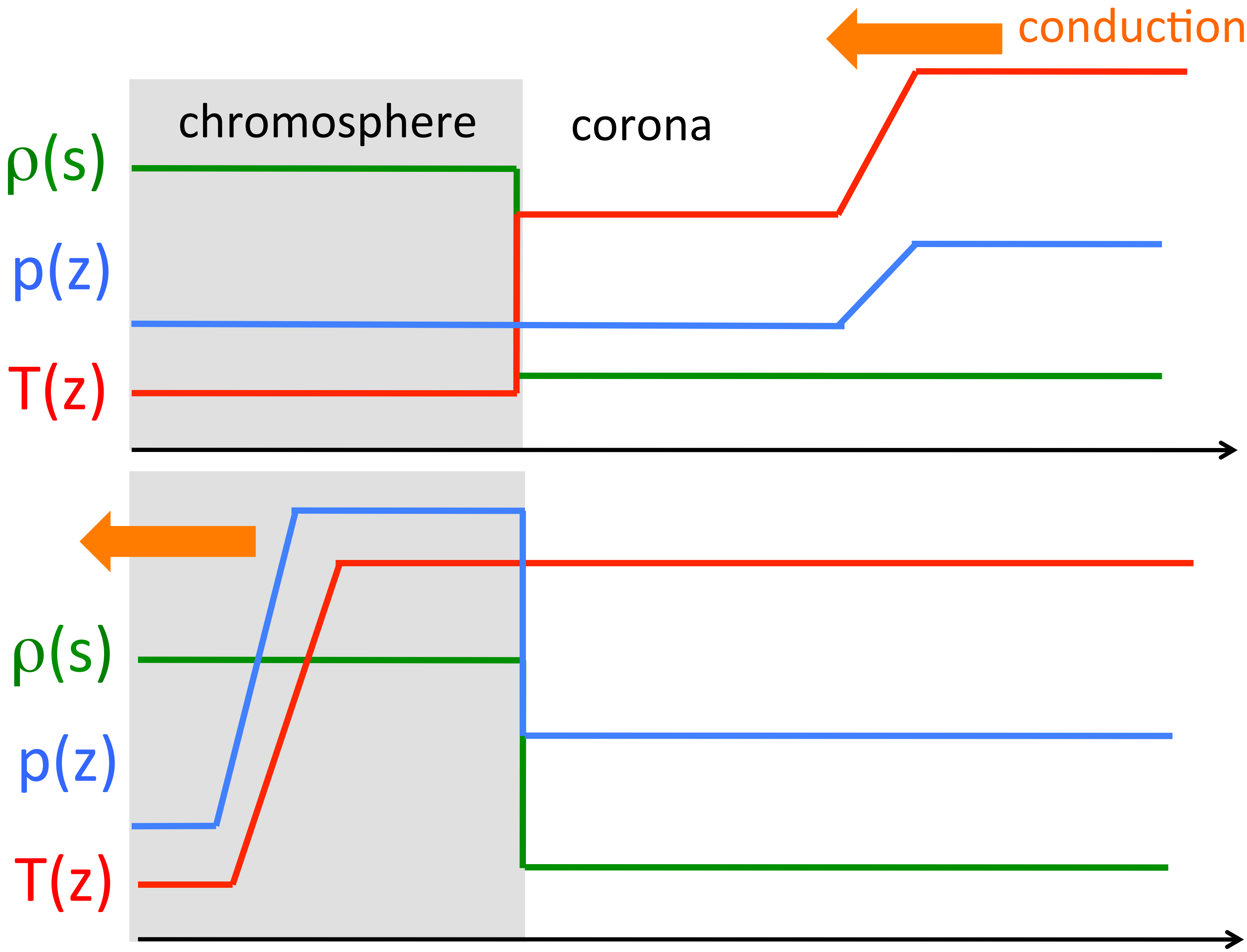
t = 0.0000000 [s]
p [erg/cm^3]
100
10
1
v [Mm/s]
0.5
0.0
-0.5
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
T [K]
10^8
10^7
10^6
10^5
10^4
n_e [cm^-3]
10^12
10^11
10^10
10^9
10^8
0
2
4
6
8
x [Mm]
0
10
20
30
40
50
x [Mm]

Conduction-driven evaporation

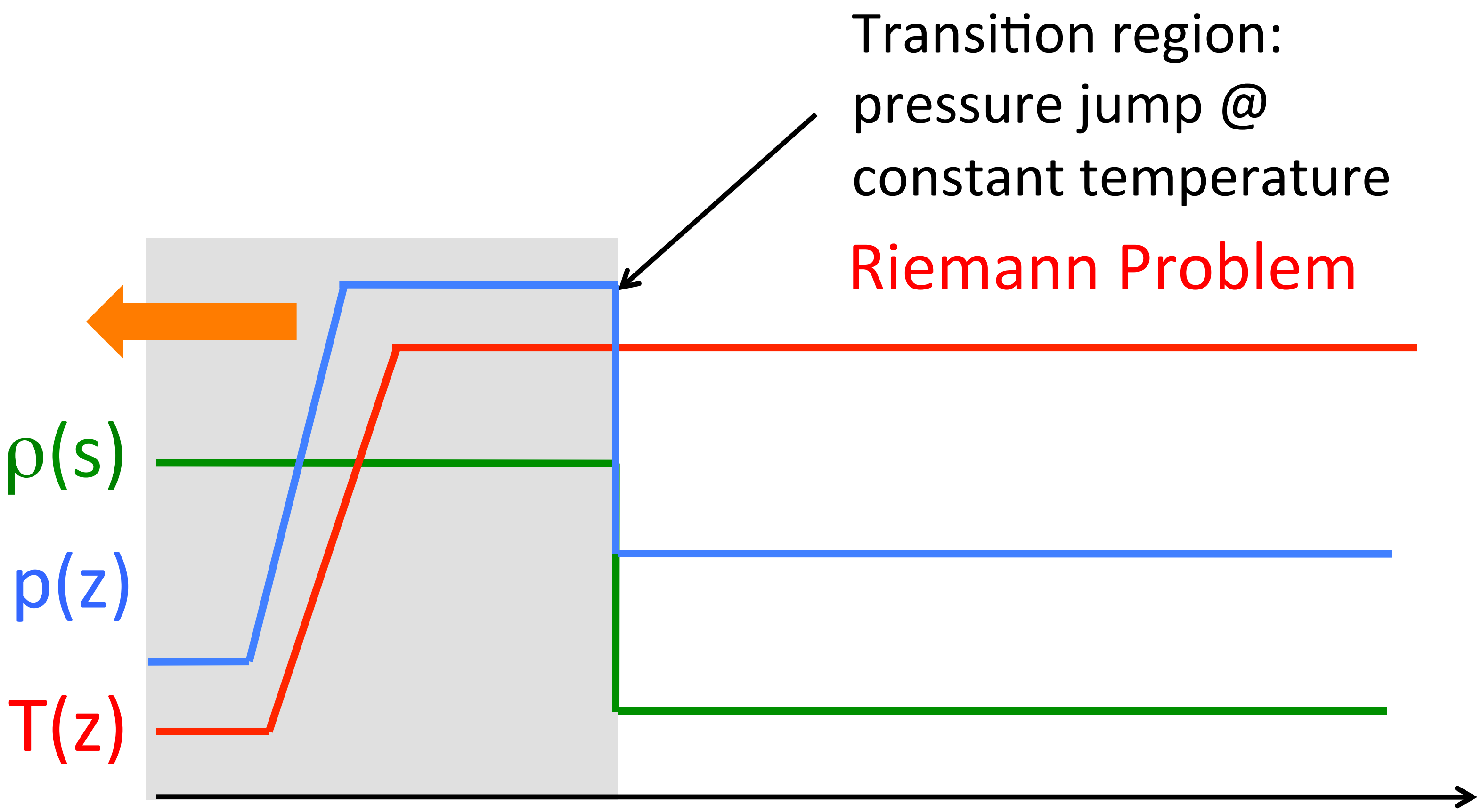


$$\frac{\rho_{\rm ch,0}}{\rho_{\rm co,0}} = \frac{T_{\rm co,0}}{T_{\rm ch,0}} = R_{\rm tr}.$$

Conduction-driven evaporation



Conduction-driven evaporation

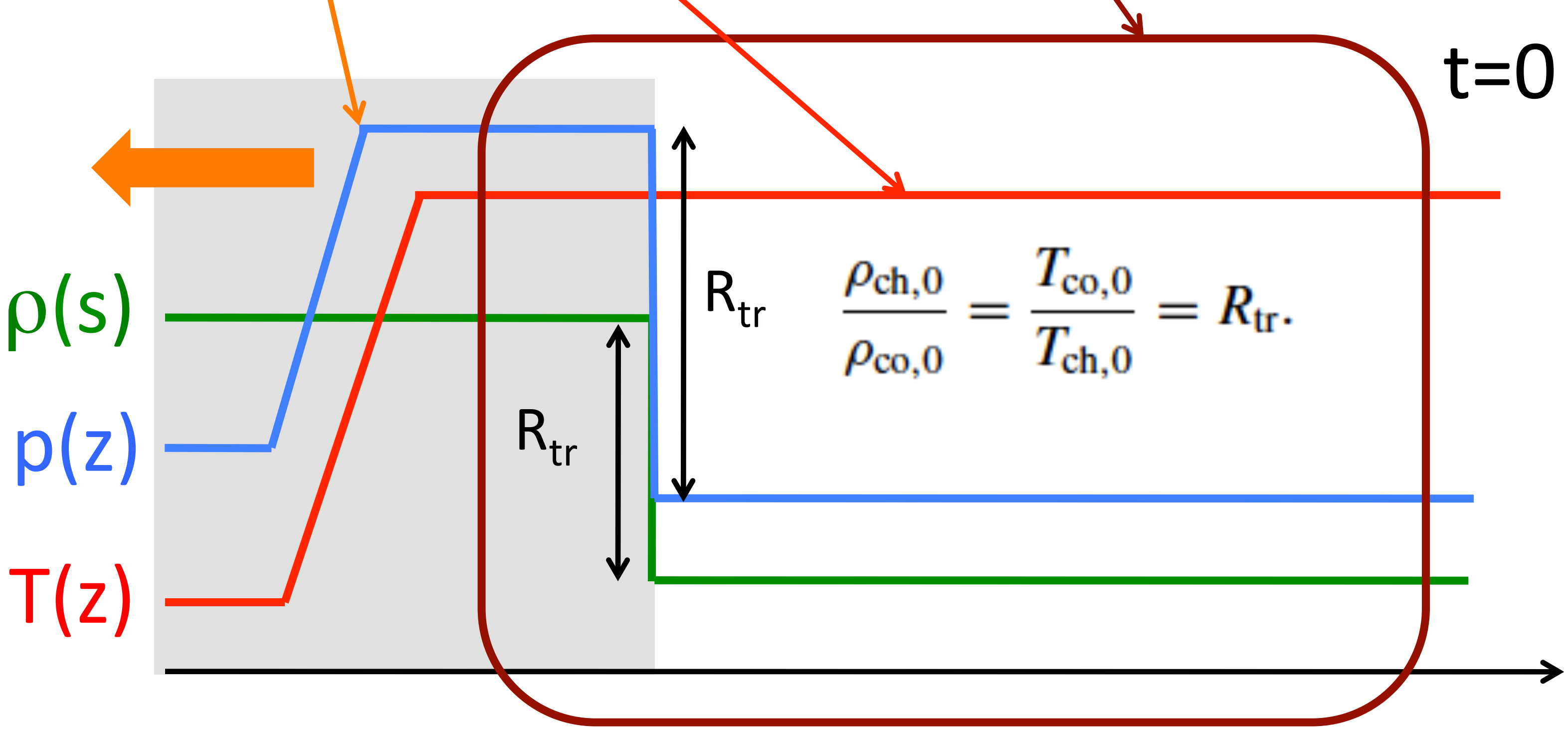


Evaporation as Riemann Problem

- conduction creates uniform high temp. around TR
- evaporation occurs @ constant T for t>0

Isothermal Riemann problem

- isothermal – sound speed a; iso-T Mach #: $v/a = M^{(it)}$
- condensation shock (hypersonic) propagates down



$$[M_{\rm es}^{(it)}]^2 = 4R_{\rm tr}\ \exp\left(-\sqrt{3} - M_{\rm es}^{(it)} + \frac{1}{M_{\rm es}^{(it)}}\right),$$

ES: $\frac{v_e}{a} = M_{\rm es}^{(it)} - \frac{1}{M_{\rm es}^{(it)}}.$

$$\frac{\rho_e}{\rho_{co,0}} = \left[M_{es}^{(it)}\right]^2$$

Condensation shock (CS): (hypersonic)

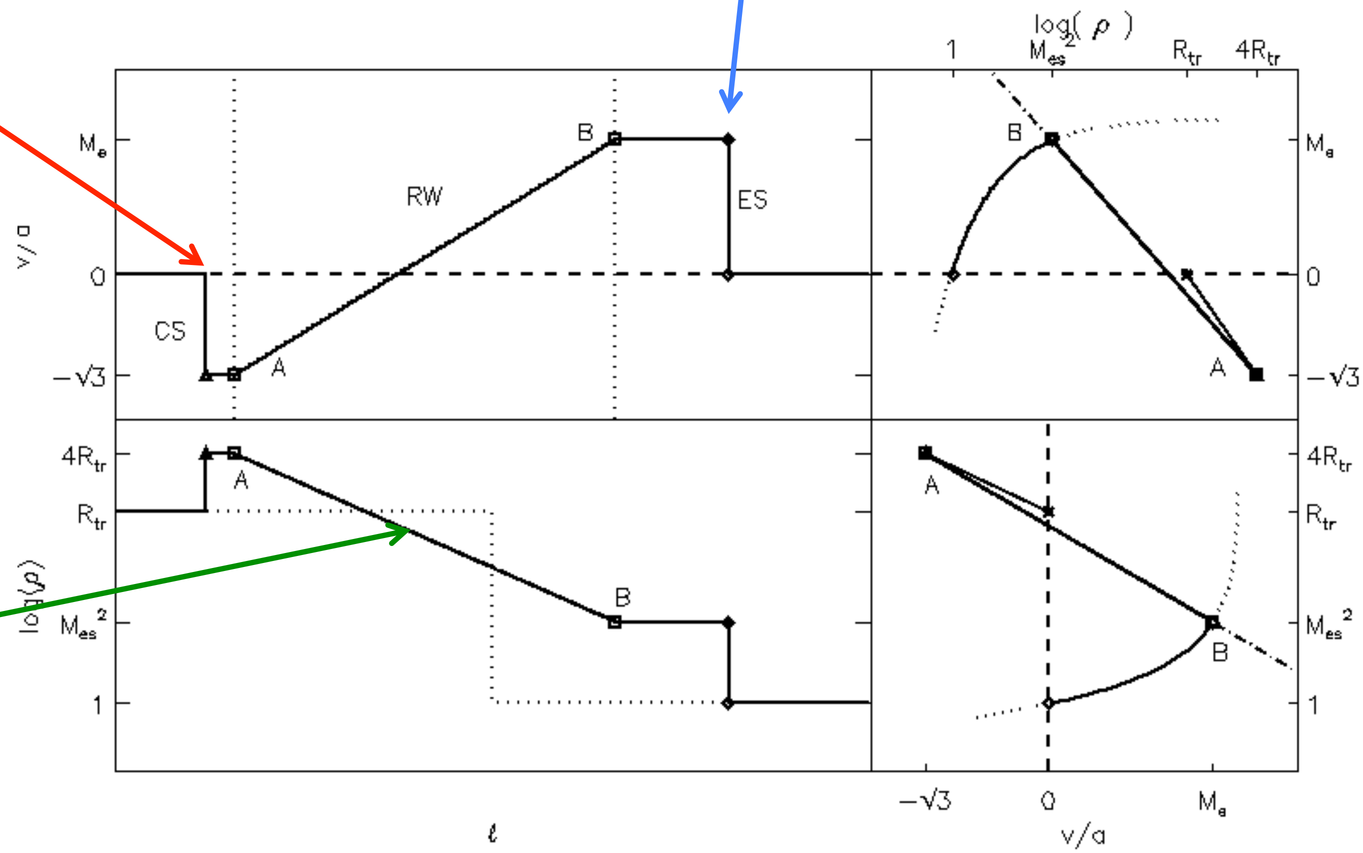
$$v_c = -\sqrt{3}\,a$$

$$\rho_c = 4\rho_{ch,0}$$

$$= 4R_{tr}\,\rho_{co,0}$$

Rarefaction Wave (RW):

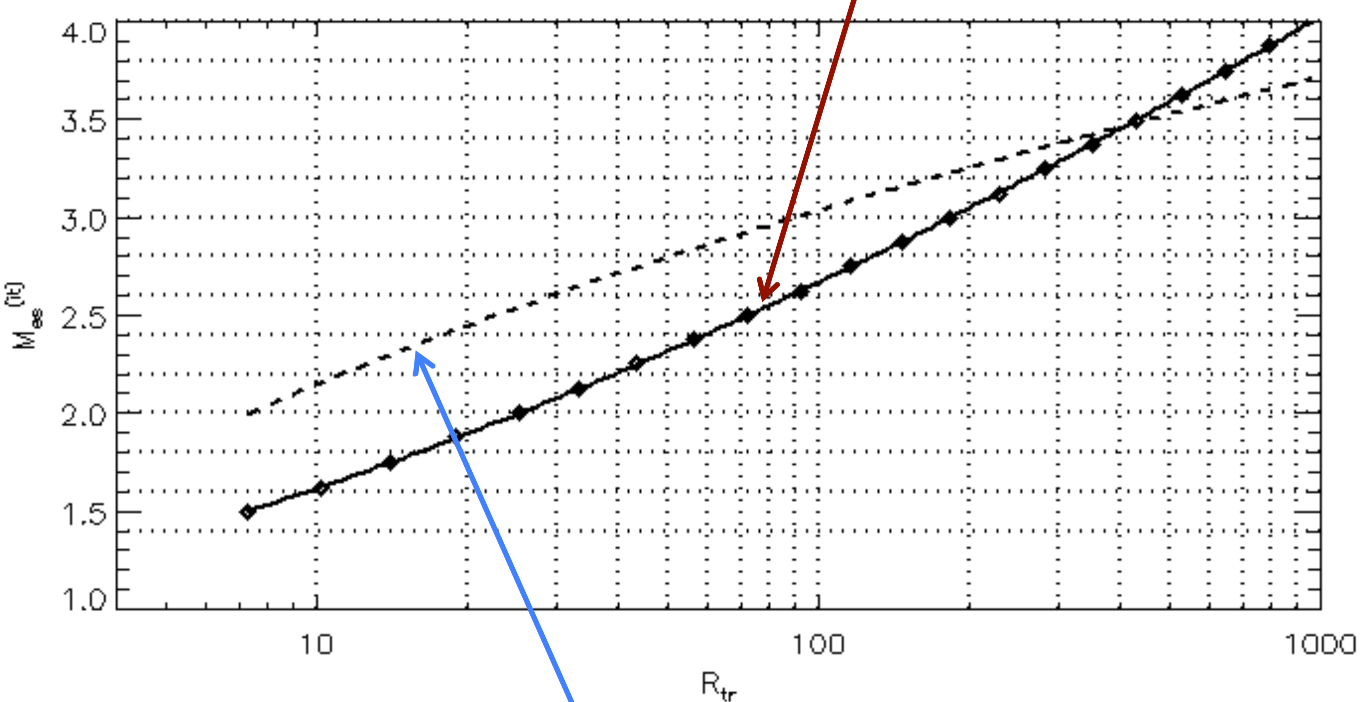
$$v(\ell, t) = \frac{\ell}{t} + a,$$



$$\rho(\ell, t) = \rho_0\ \exp\left(-\frac{\ell}{at}\right) = \rho_0\ \exp\left(1 - \frac{v}{a}\right) = 4R_{\rm tr}\ \exp\left(-\sqrt{3} - \frac{v}{a}\right)\ \rho_{\rm co,0}$$

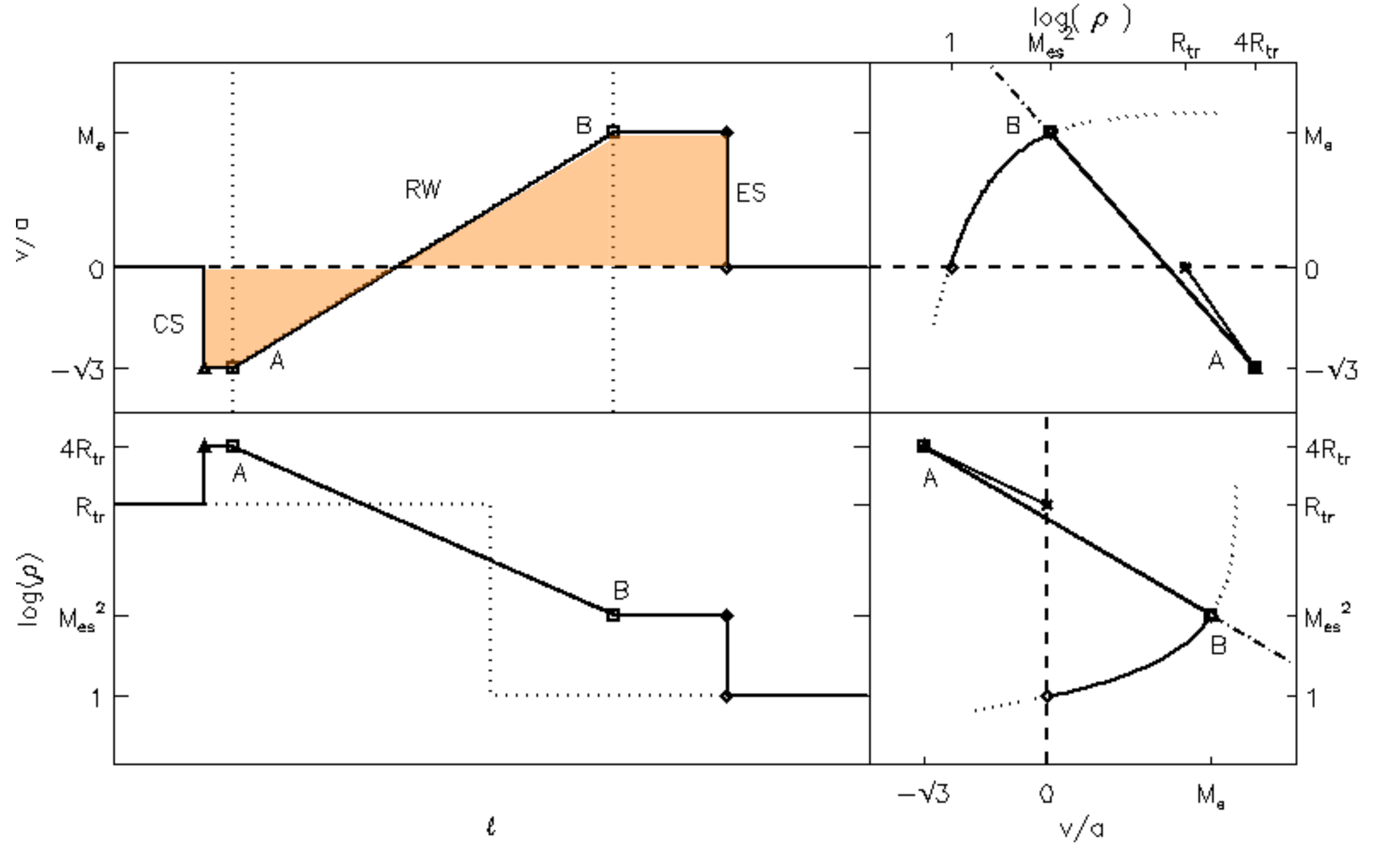
$$\left[M_{\rm es}^{(it)}\right]^2 = 4R_{\rm tr}\,\exp\left(-\sqrt{3} - M_{\rm es}^{(it)} + \frac{1}{M_{\rm es}^{(it)}}\right),$$

$$M_{\rm es}^{(it)} \simeq 2.670 + 1.209\,\log(R_{\rm tr}/100)\,[1 + 0.126\,\log(R_{\rm tr}/100)].$$



$$v_{\rm FCM} = \sqrt{(6/5)\,\ln R_{\rm tr}}\,c_{s,*} = \sqrt{2\ln R_{\rm tr}}\,a.$$

Fisher, Canfield & McClymont 1984



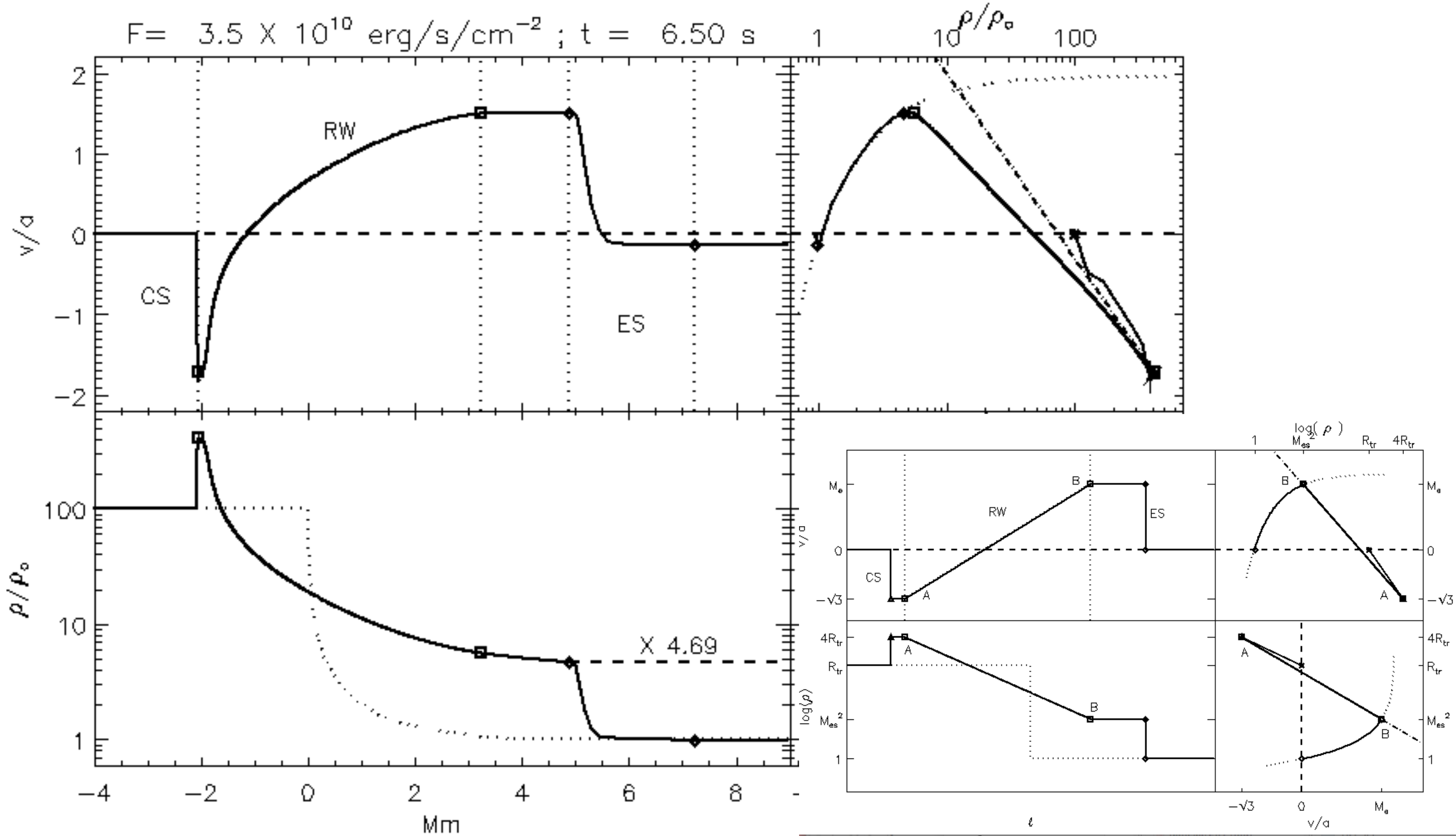
Longcope 2014

$$E_K = \int \frac{1}{2}\rho v^2\, d\ell = \frac{1}{2}\rho_{\rm co,0}\, a^3\, t \int \frac{\rho(\tilde{\ell})}{\rho_{\rm co,0}}\, [M^{(it)}(\tilde{\ell})]^2 d\tilde{\ell},$$

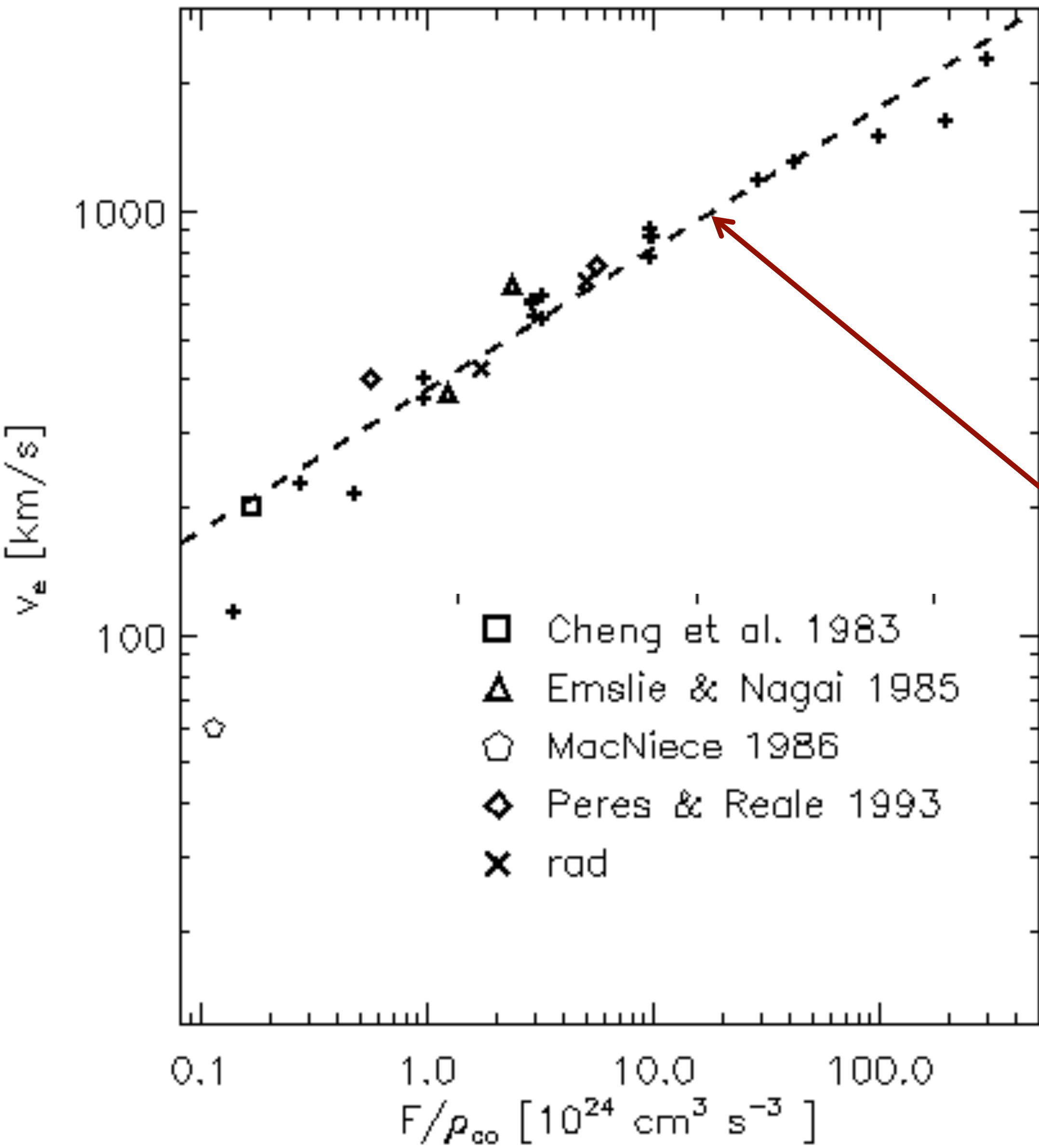
Flare energy flux

$$F = \frac{dE_K}{dt} \sim \rho_{co,0}\; a^3$$

$$v_e = aM_e^{(it)} \approx C_e \left(\frac{F}{\rho_{co,0}} \right)^{1/3}$$



F= 3.5 X 10^10 erg/s/cm^-2 ; t = 6.50 s
ρ/ρo
1
10
100
v/a
RW
CS
ES
ρ/ρo
X 4.69
Mm
log(ρ)
Mes^2
Rtr
4Rtr
Me
−√3
A
B
log(ρ)
ℓ
v/a

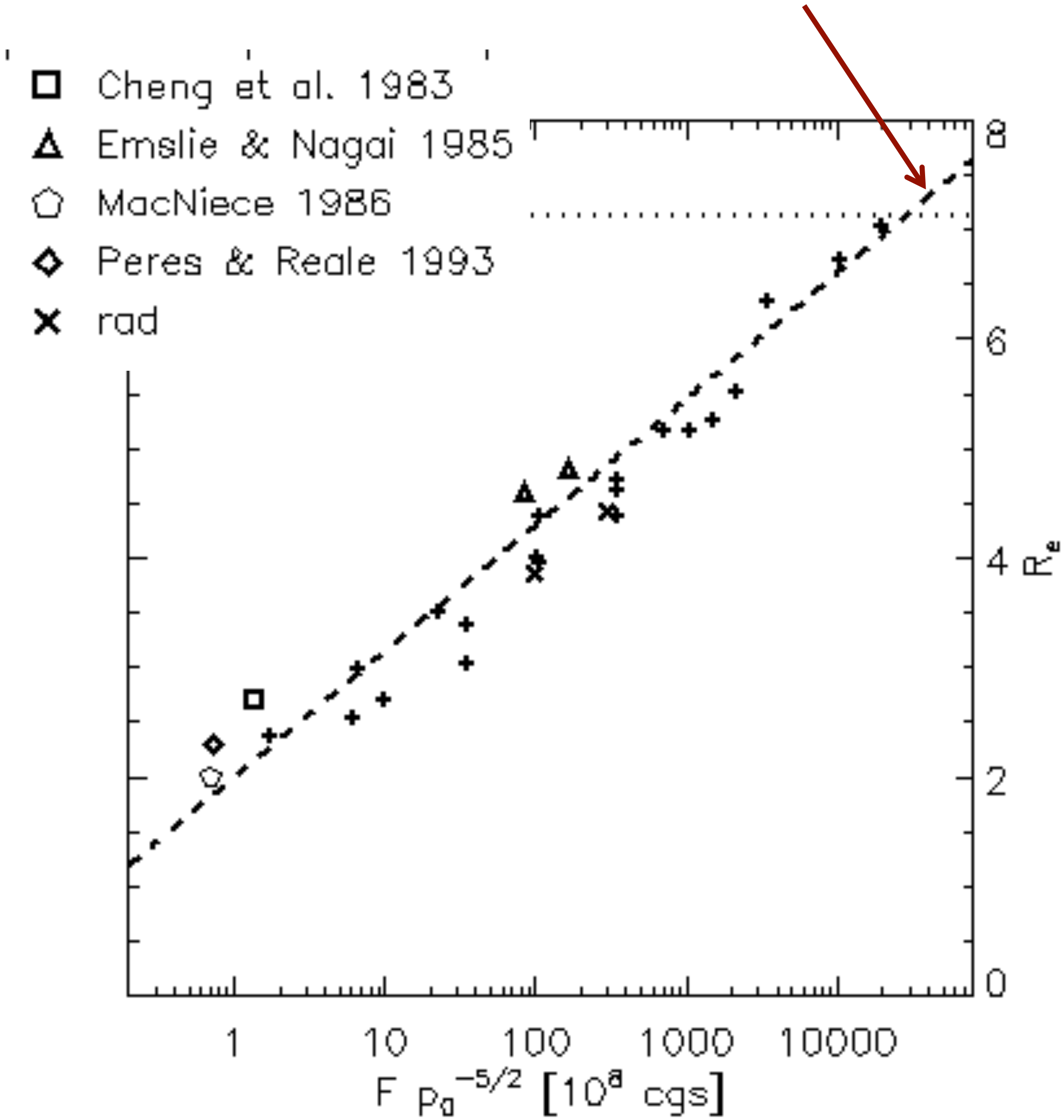


Simulations from the past

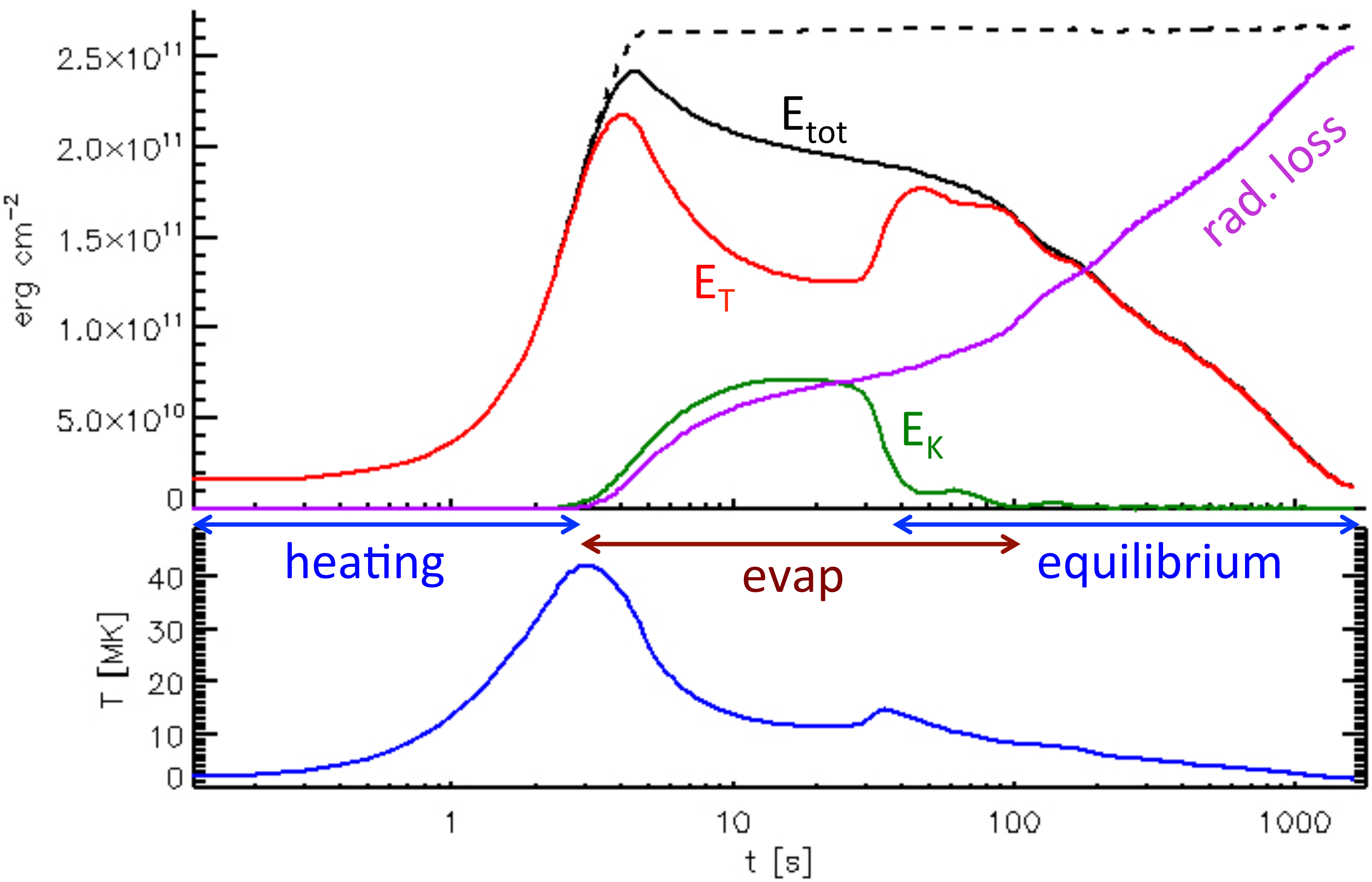
$$v_e = C_e \left(\frac{F}{\rho_{co,0}} \right)^{1/3}$$

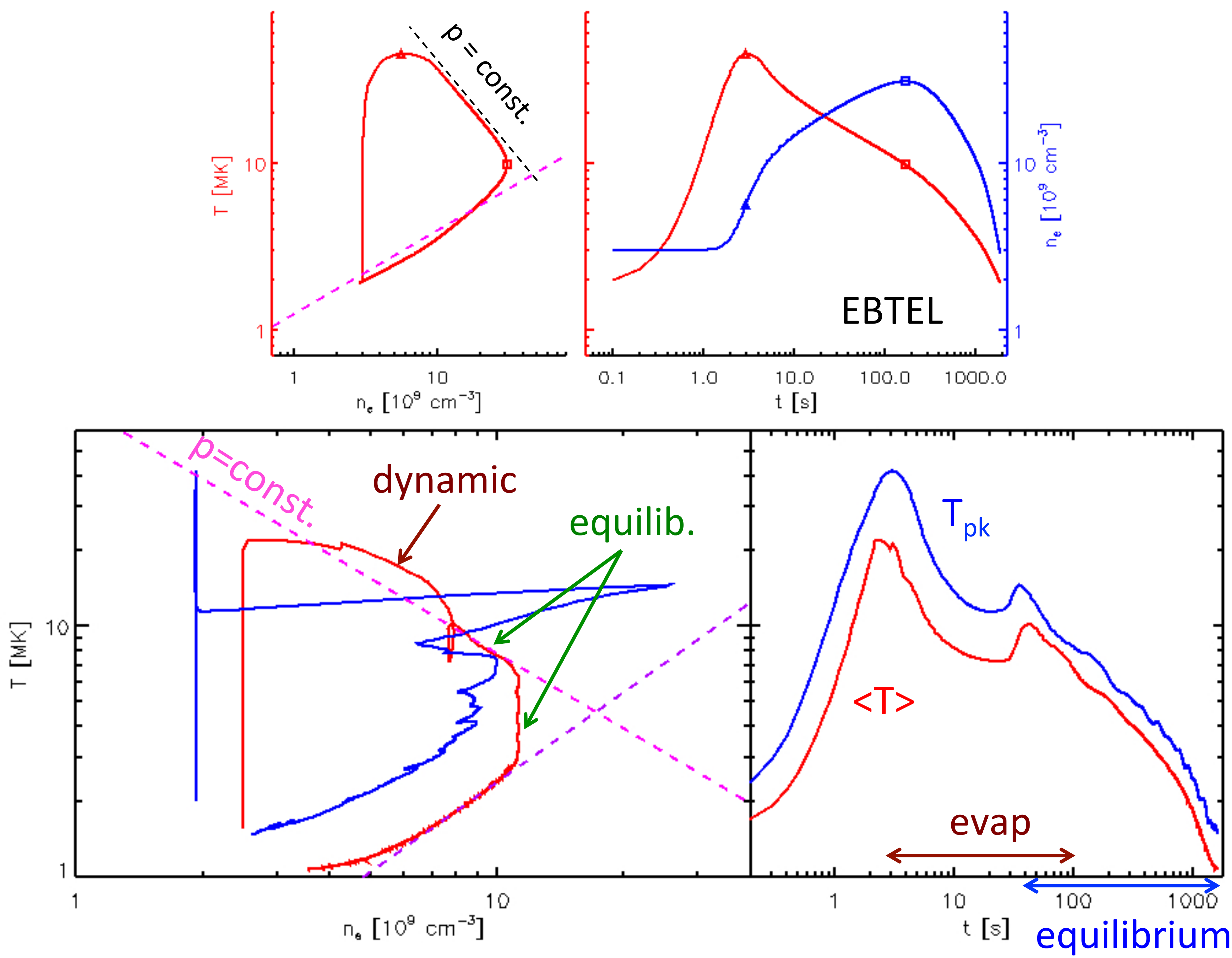
$C_e = 0.38$

$$R_{es} = \frac{1}{2} \ln\left(F\, p_0^{-5/2}/C_M\right) + 7.13,$$



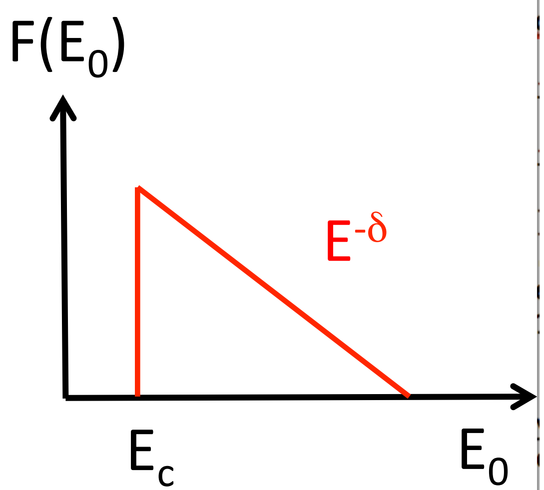
Comparison to 0d model

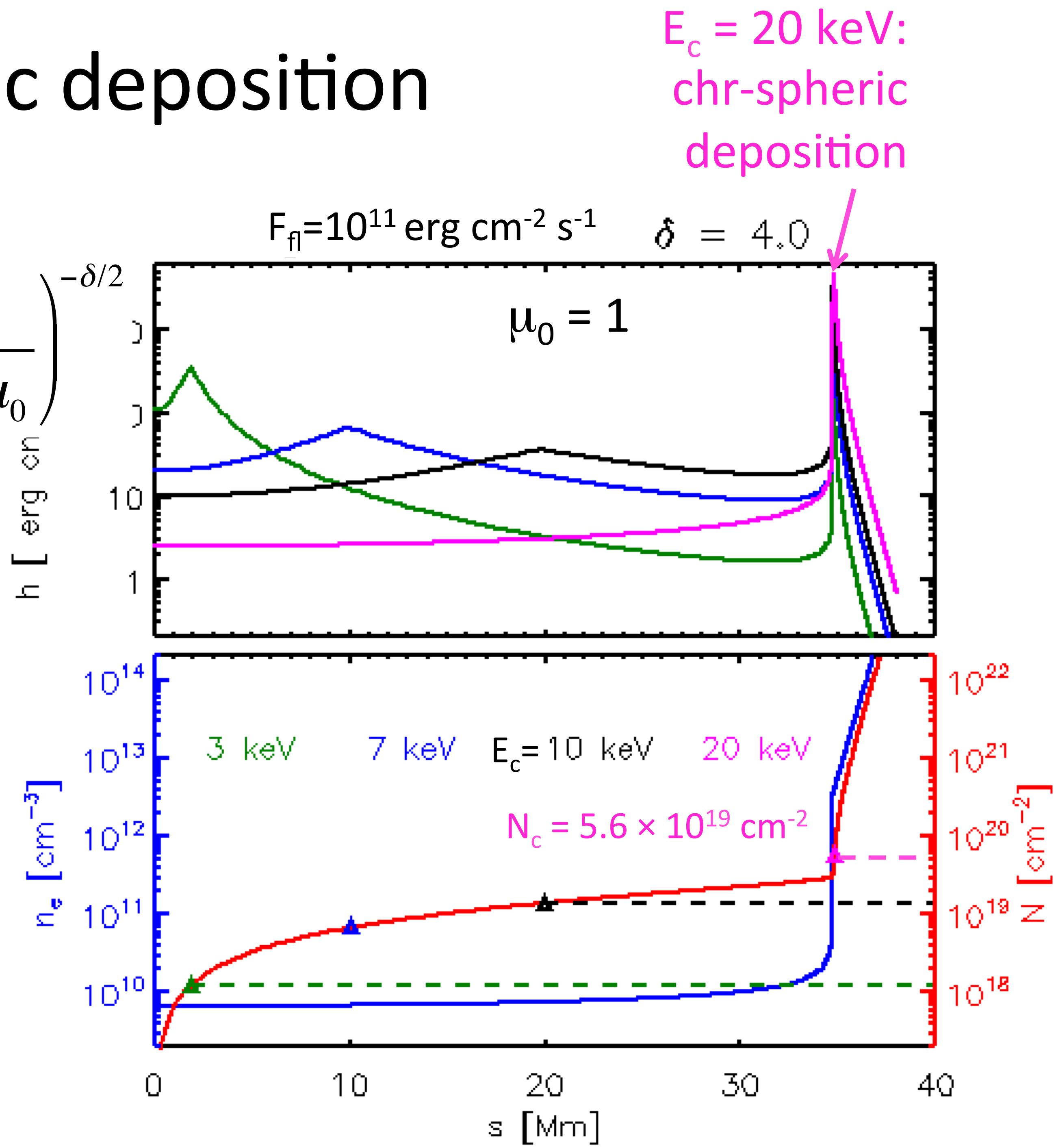



p = const.
T [MK]
n_e [10^9 cm^-3]
t [s]
n_e [10^9 cm^-3]
EBTEL
p=const.
dynamic
equilib.
T_pk
<T>
evap
equilibrium

Chr-spheric deposition

$$h \sim F_{\rm fl}(t)\frac{n_e(s)}{\mu_0 N_c}\left(\frac{N}{N_c\mu_0}\right)^{-\delta/2}$$





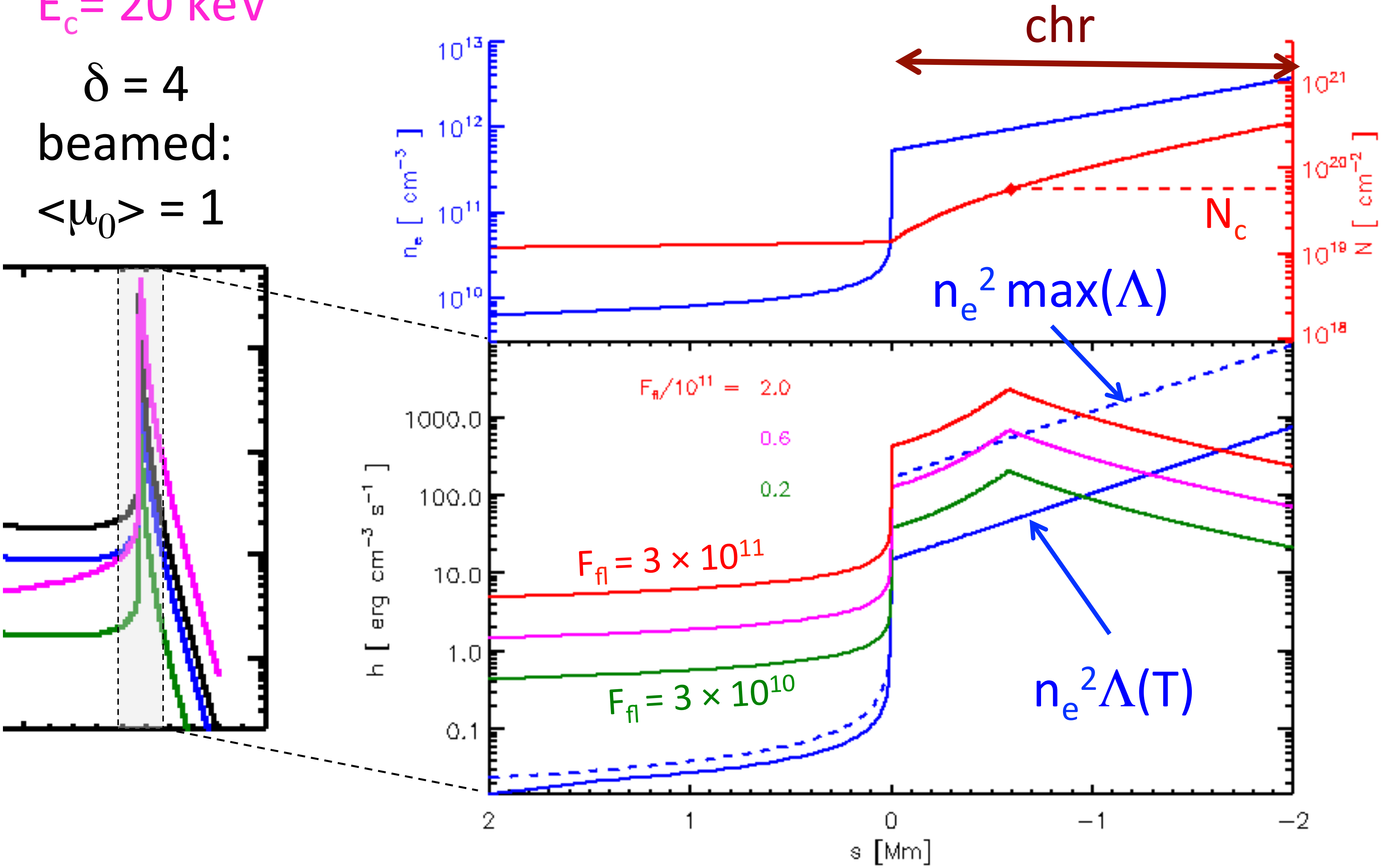
Chr-spheric deposition

E_c = 20 keV

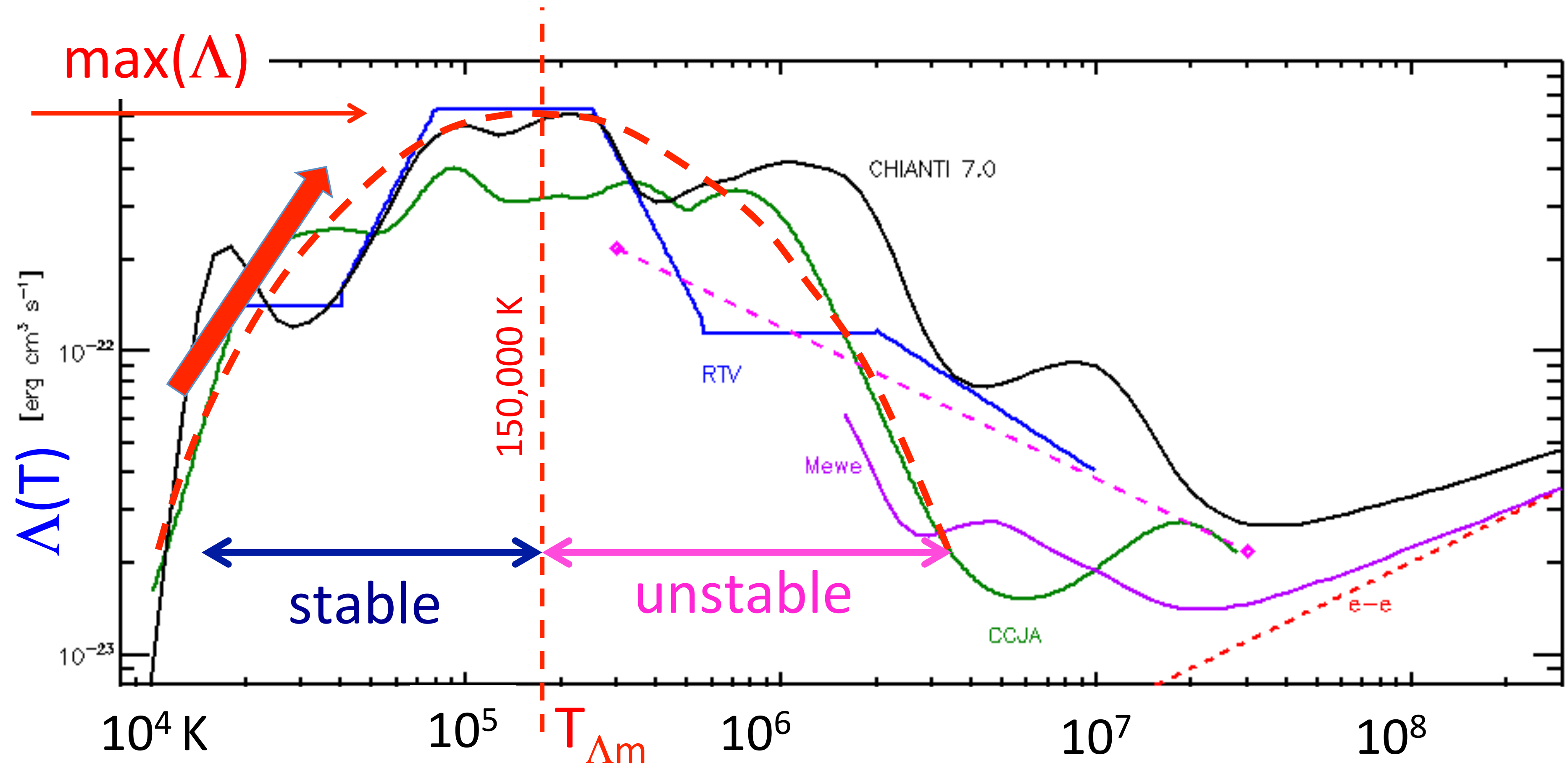
$\delta = 4$

beamed:

$<\mu_0> = 1$



Radiative instability (@ constant n_e)



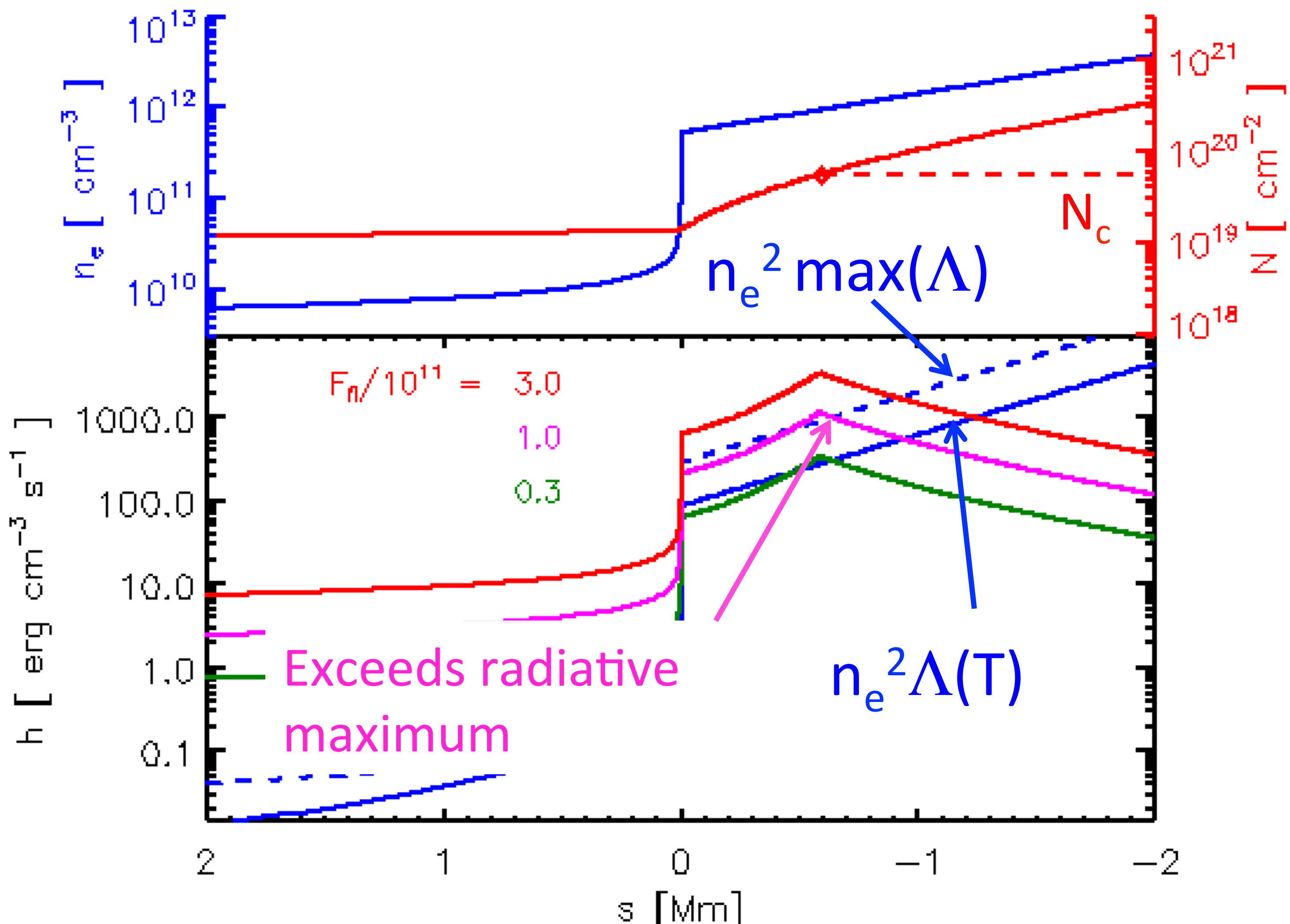
Chr-spheric deposition

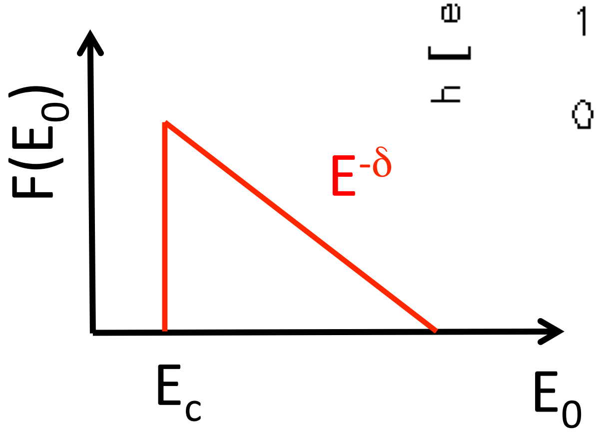
E_c= 20 keV

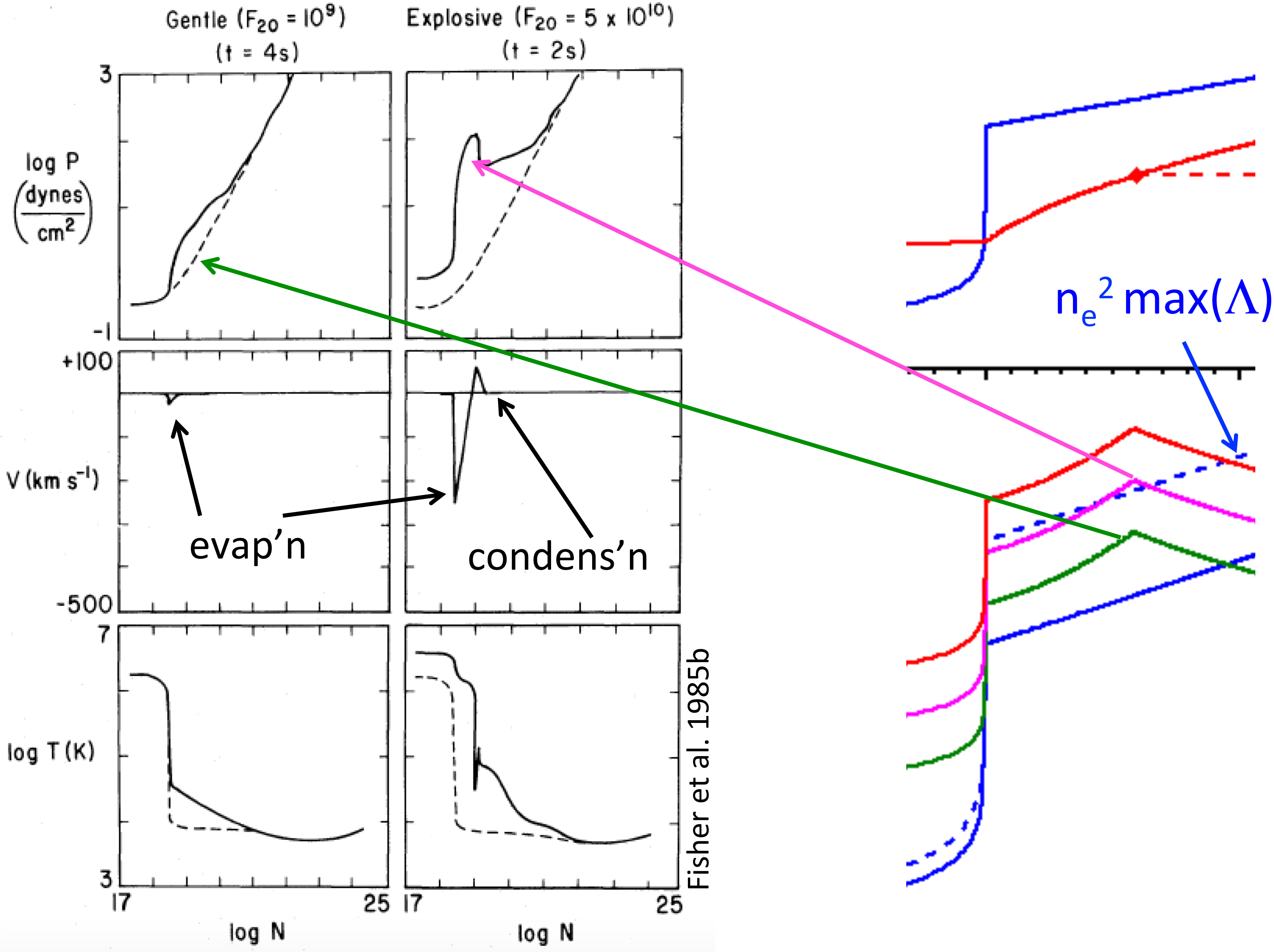
δ = 4

beamed:

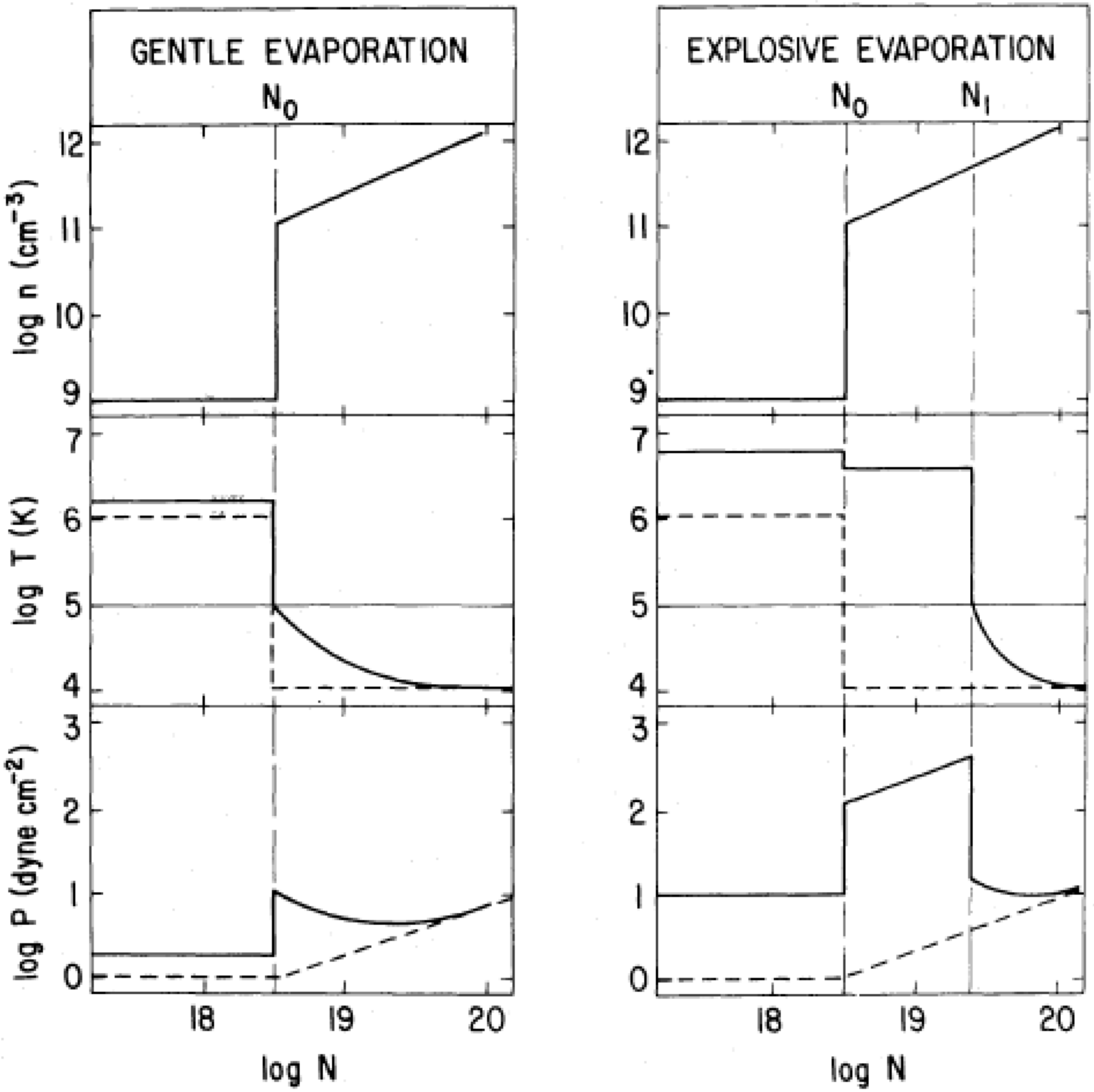
$\langle\mu_0\rangle$ = 1







Gentle ($F_{20} = 10^9$)
($t = 4s$)
Explosive ($F_{20} = 5 \times 10^{10}$)
($t = 2s$)
log P (dynes/cm²)
V (km s⁻¹)
log T (K)
log N
evap'n
condens'n
Fisher et al. 1985b
$n_e^2 \max(\Lambda)$



Fisher et al. 1985b

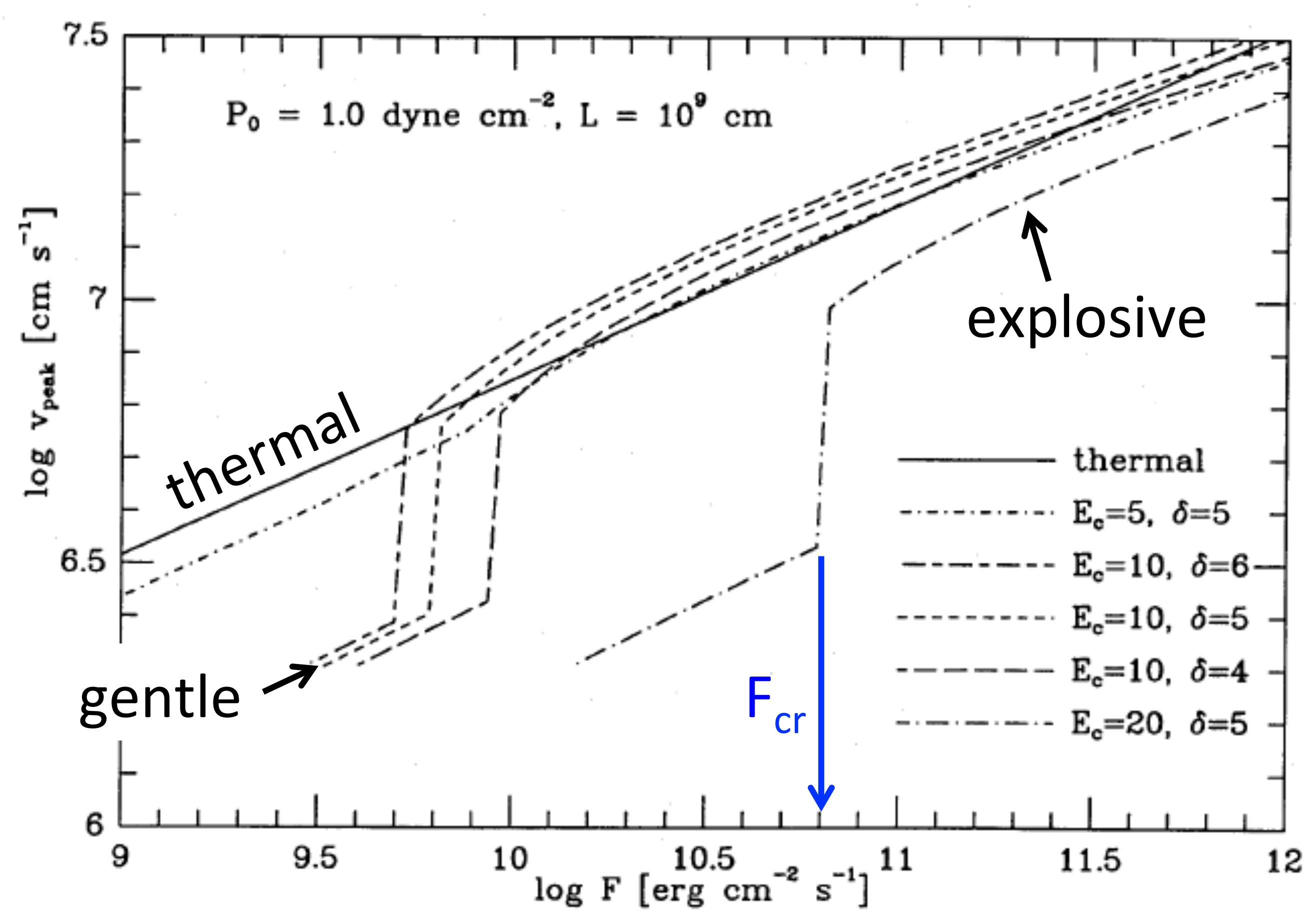
F_{cr}: local heating exceeds radiation

$F_{fl} < F_{cr}$: gentle evaporation

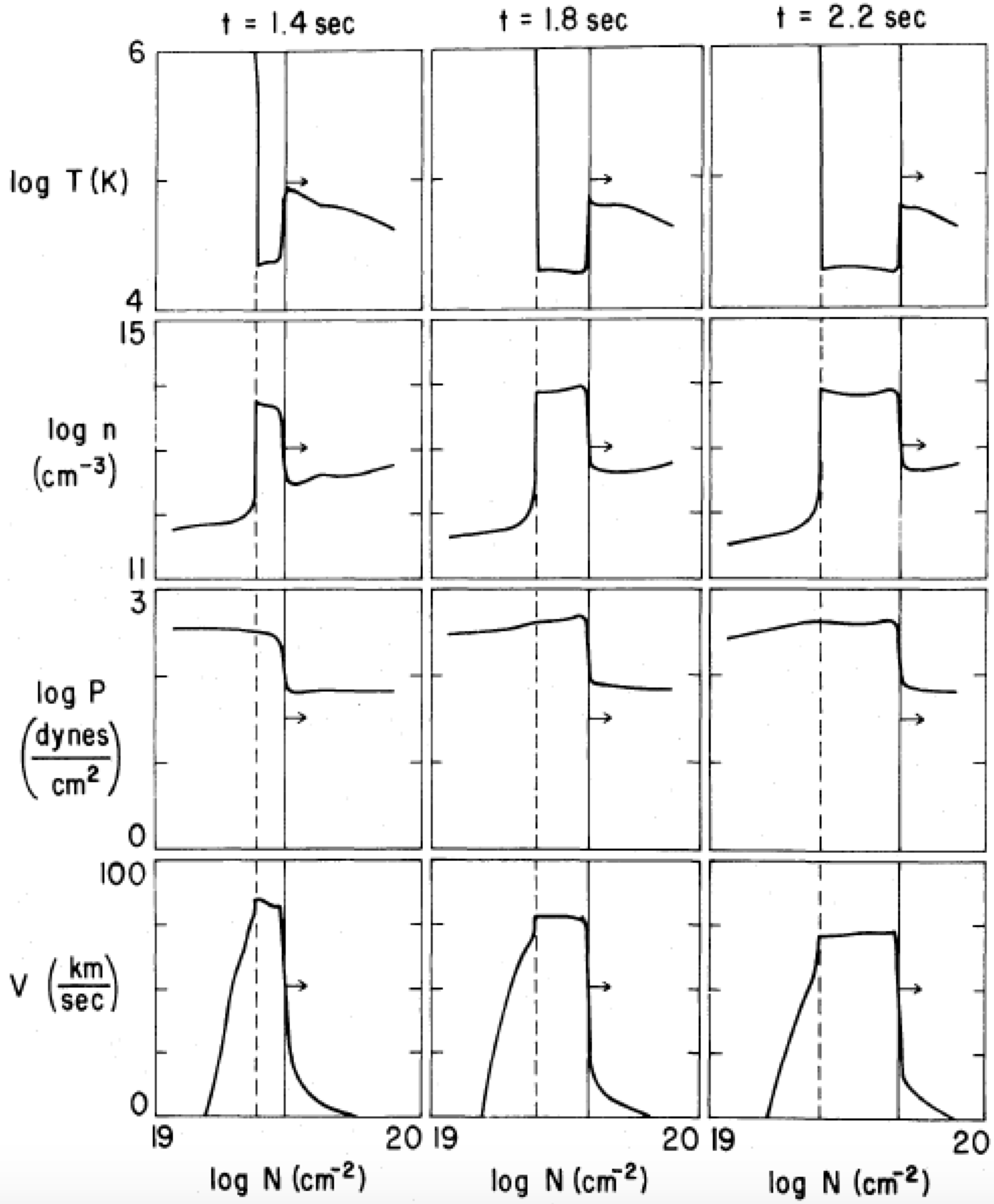
$F_{fl} > F_{cr}$: explosive evaporation

Fisher et al. 1985b

$$F_{\rm cr} \approx \frac{N_* \max(\Lambda)}{2k_b T_{ch}}\left(p_{cor} + m_p g N_c\right) = 2\times 10^{10}\,\mathrm{erg\,cm^{-2}s^{-1}}\left[p_{\rm cor,cgs} + 0.64\left(\frac{E_c}{10\,\mathrm{keV}}\right)^2\right]$$



Fisher 1989



Fisher et al. 1985b

Summary

- 1d dynamical evolution better models dynamics
  - Evaporation w/ significant KE
  - Chromospheric Energy Deposition by NT e^-
- 0d picture becomes accurate when KE has subsided – cooling phase