Hybrid Simulations of Chromospheric Flare HXR Sources

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Motivation

Recent RHESSI measurements of vertical extent of HXR footpoint sources are inconsistent with predictions given by CTTM (Brown, 1971).

RHESSI observations:

- energy dependent size typically 2 - 6 arcsec
  i.e. 1.5 - 4.5 Mm (Kontar et al. 2008, 2010, Battaglia et al. 2011)

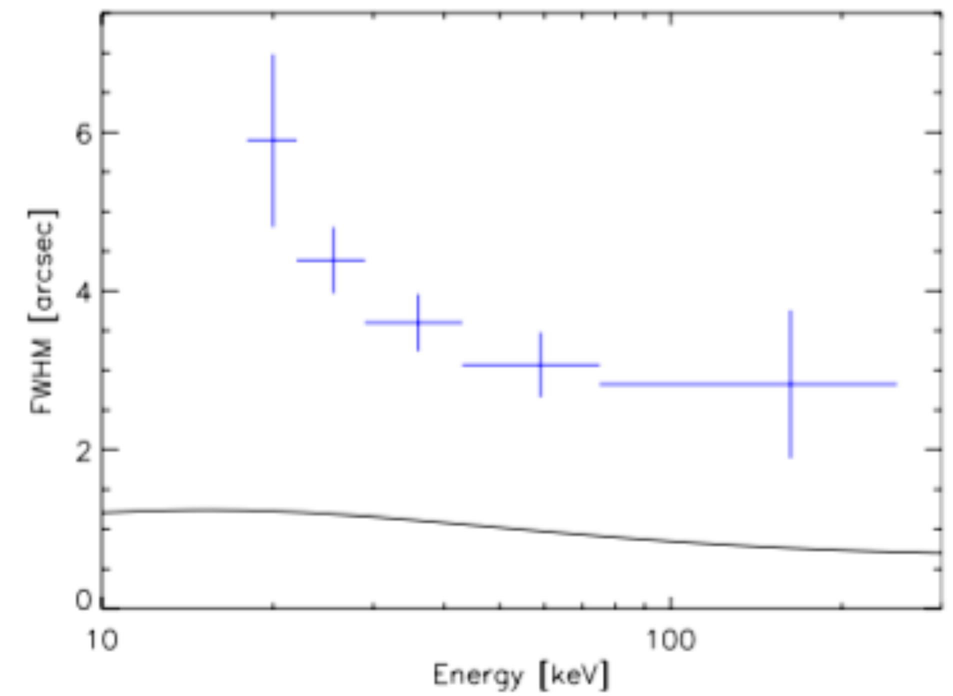
Theory (CTTM):

- ~ 1 arcsec and smaller (under ~1 Mm)

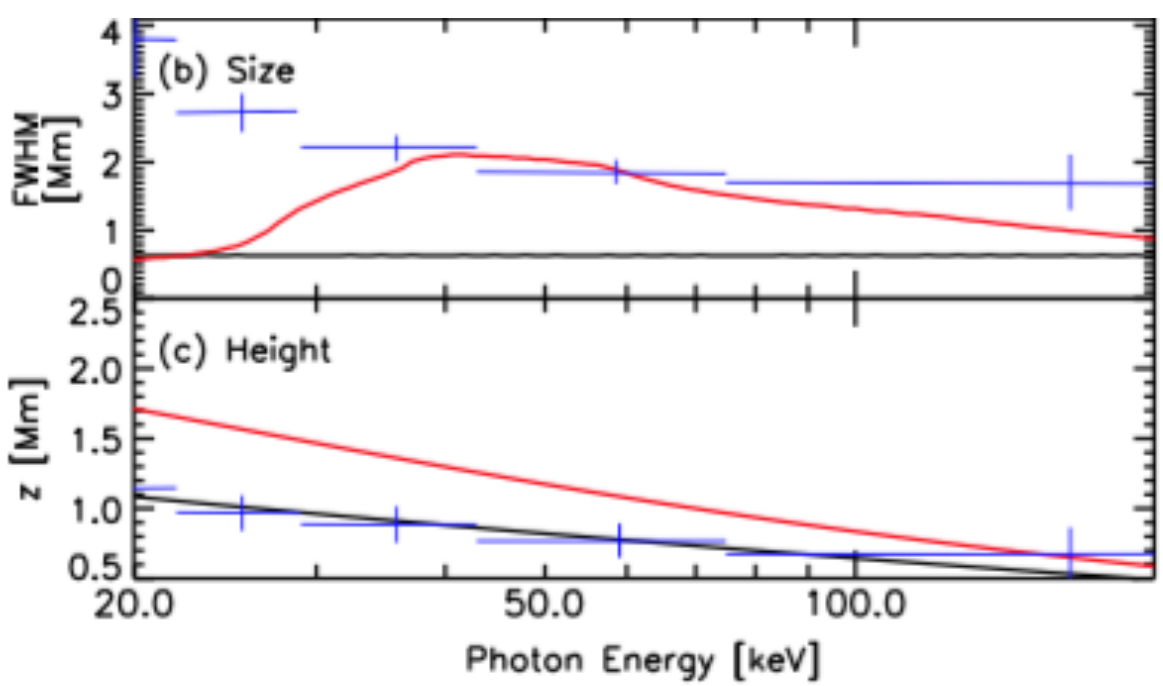
Attempts to model HXR source sizes:

- Battaglia et al. (2012):
  HXR sizes modelled for prescribed density structures and various μ_0 distributions
  - sources under ~1.5 arcsec

- O'Flannagain et al. (2015)
  accounting for NUI effects of target plasma - prescribed artificially
  - sources up to ~ 2.3 arcsec at 40 keV



Observed FWHM of HXR vertical source size for 6th January, 2004 event (Battaglia et al. 2012)



(O'Flannagain et al. 2015)

Chromospheric HXR source vertical sizes

The key factors influencing the HXR vertical source sizes:

- electron beam parameters: $F(t)$, E_0, δ and initial pitch angle distribution $M(\mu_0)$
- target atmosphere: $T(s)$, $n_H(s)$ (or distribution of the column density) and H ionisation structure $x(s)$
- magnetic structure of the loop (mirroring)

Observations done by RHESSI:

- typical accumulation time for a RHESSI image is 20 - 60 s

Substantial changes occur in the flaring atmosphere within the first several tens of seconds -> vertical evolution of the column density within the HXR source is expected. How will it influence the HXR vertical source size in a single flare loop during the flare evolution?

Initial setup

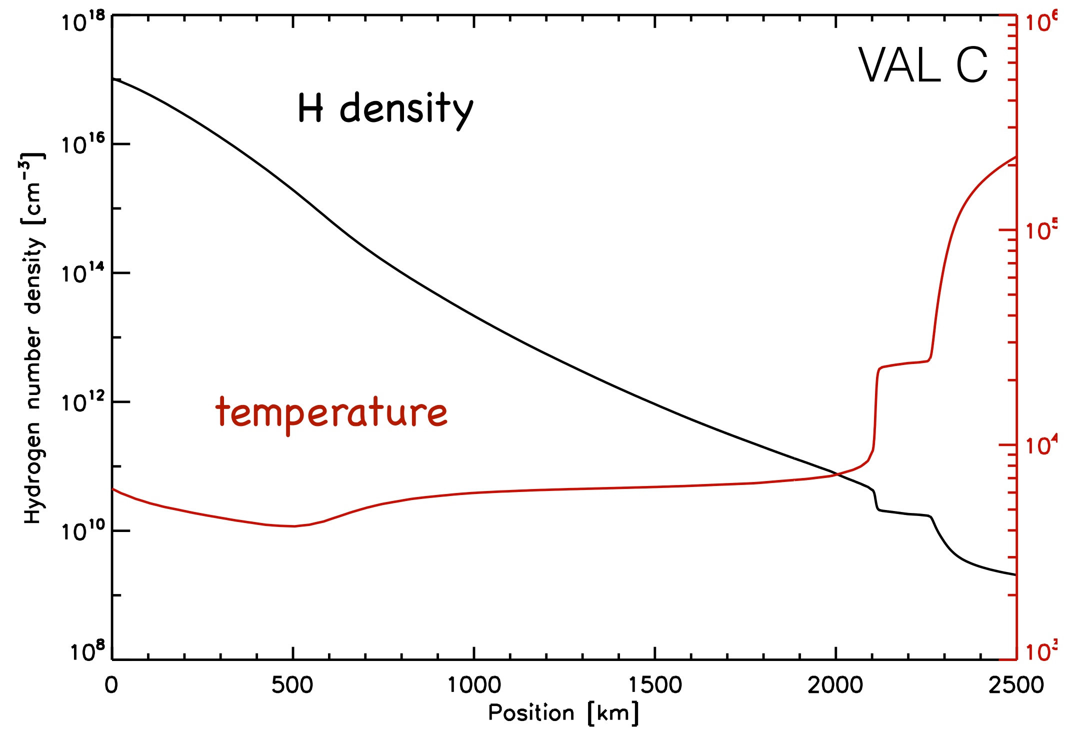
Parameters:

- semicircular single flare loop L = 15 Mm, constant B
- HS VAL C initial atmosphere (Vernazza et al., 1981)
- power-law beam generated at the apex

$$F(E, \mu_0, z_0 = 0) = M(\mu_0)(\delta_p - 2)\frac{F_0}{E_0^2}\left(\frac{E}{E_0}\right)^{-\delta_p}$$

- initial pitch angle distribution

$$M(\mu_0) = \begin{cases} 1, & \mu_0 \in (-1, -0.5) \cup (0.5, 1) \\ 0, & \mu_0 \in (-0.5, 0.5) \,. \end{cases}$$



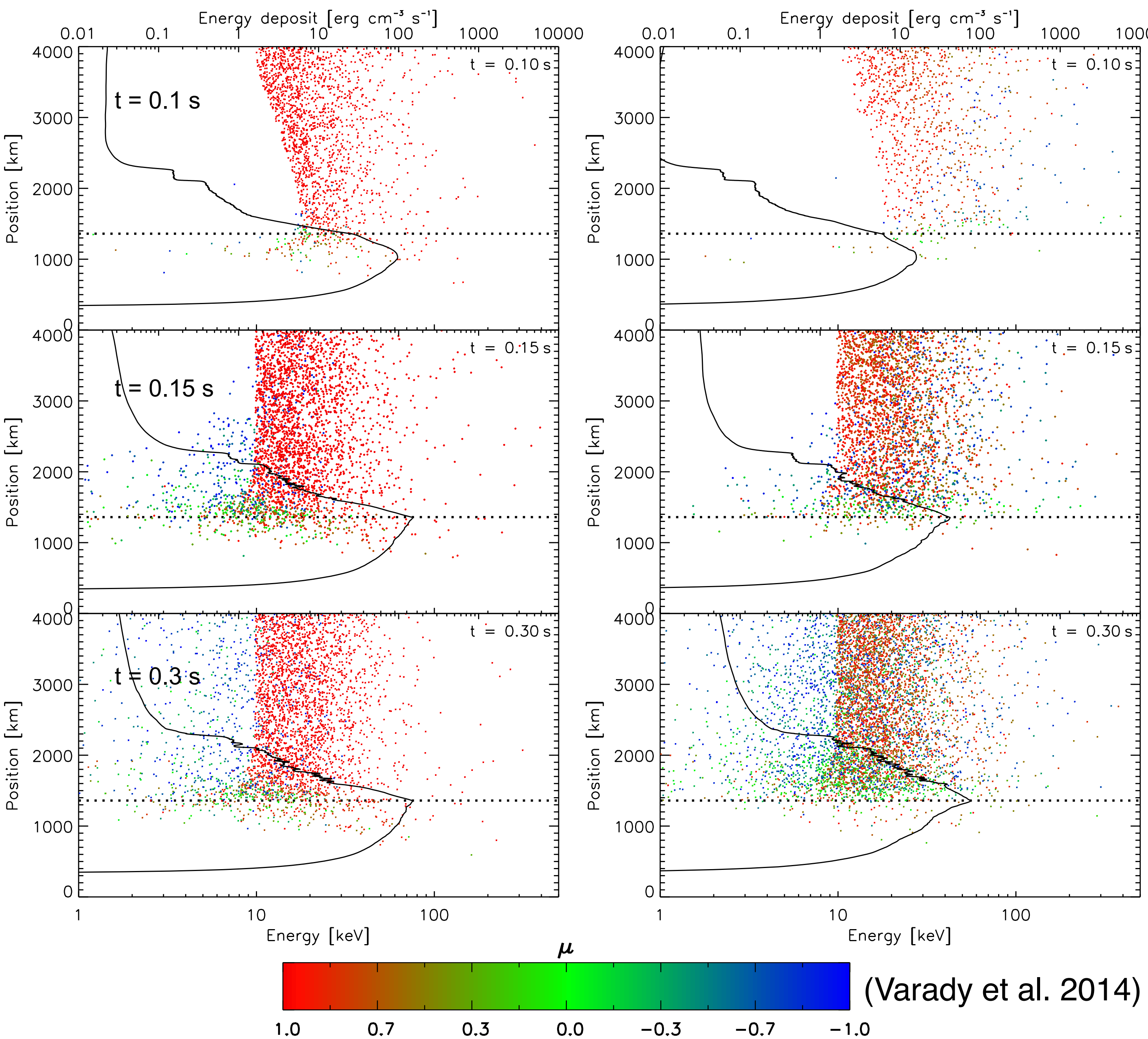
- E_0 = 20 keV, E_1 = 150 keV, δ = 3, 5, 7, F_0 = 1 and 2x10^{10} erg cm^{-2} s^{-1}
  $F_0(t)$ = F_0 for t > 2.5 s, for lower times linear increase

Hybrid code Flarix (described by Jana Kašparová yesterday)

- RHD code involving - test particle code + 1D HD + nonLTE (Kašparová et al. 2009, Varady et al. 2010, Varady et al. 2014)
- self-consistent modelling of time evolution of chromospheric HXR sources -> source sizes (methodology of HXR sources measurement corresponding to Battaglia et al., 2012)

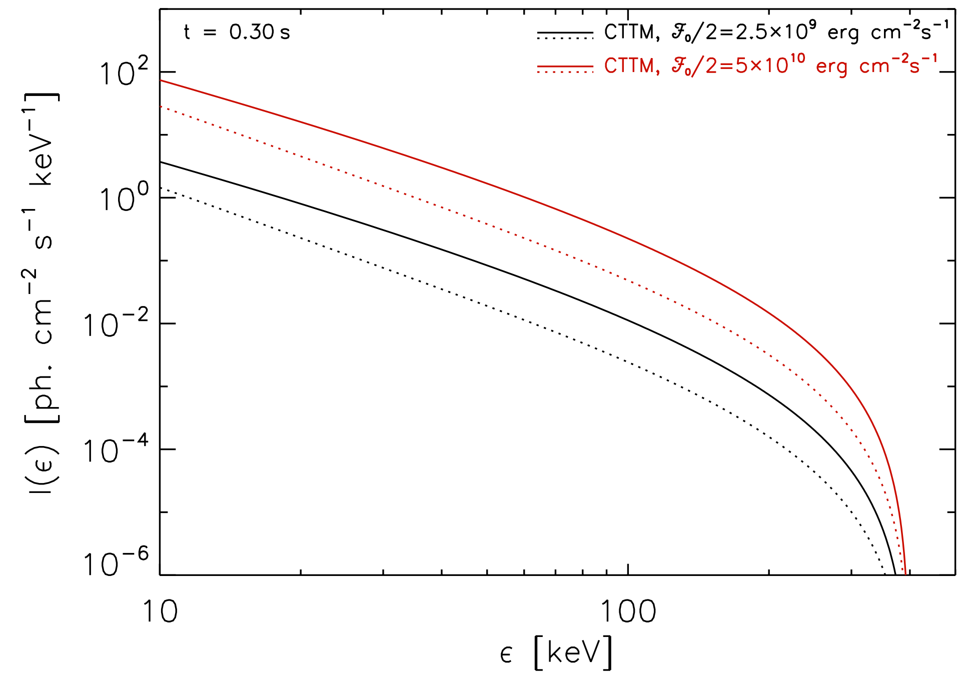
TP code - CTTM approximation

Fully focused beam: Semi-uniform distribution:

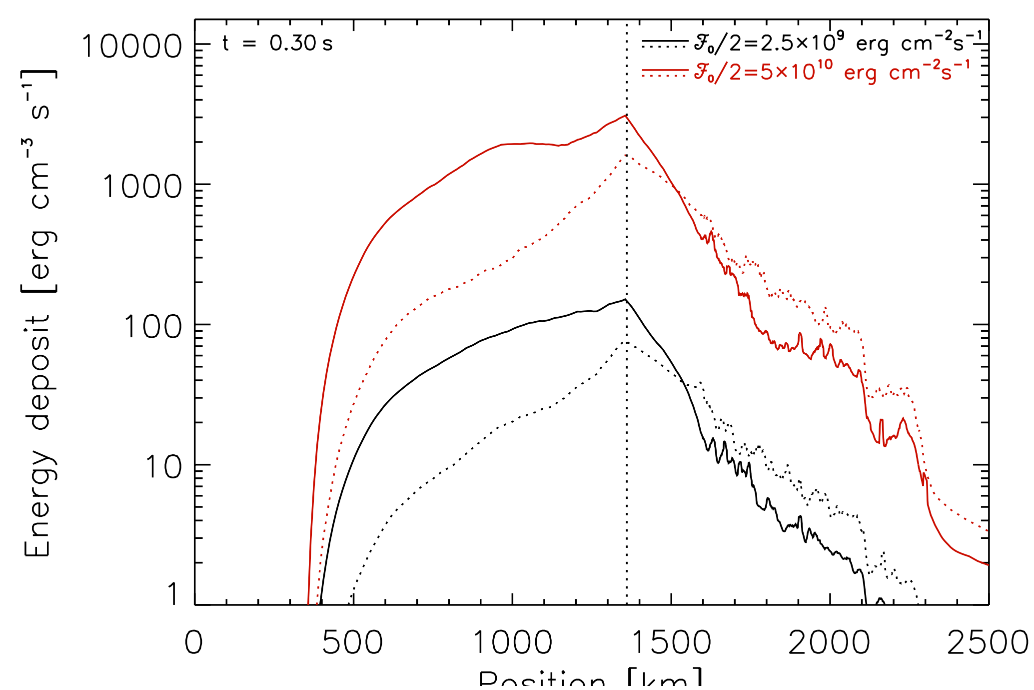


(Varady et al. 2014)

HXR spectra:



Beam energy deposit:

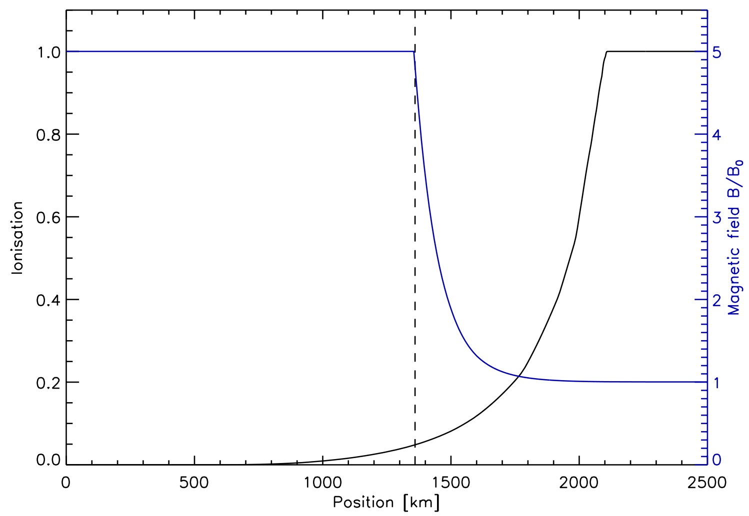


- kinematics of non-thermal e$^-$ $\delta = 3$ for VAL C atmosphere with magnetic mirror $R_m = 5$ (bottom of the mirror - dotted line)
- energy deposits for $F_0 = 2.5\times10^9$ erg cm^{-2} s^{-1} (solid line)

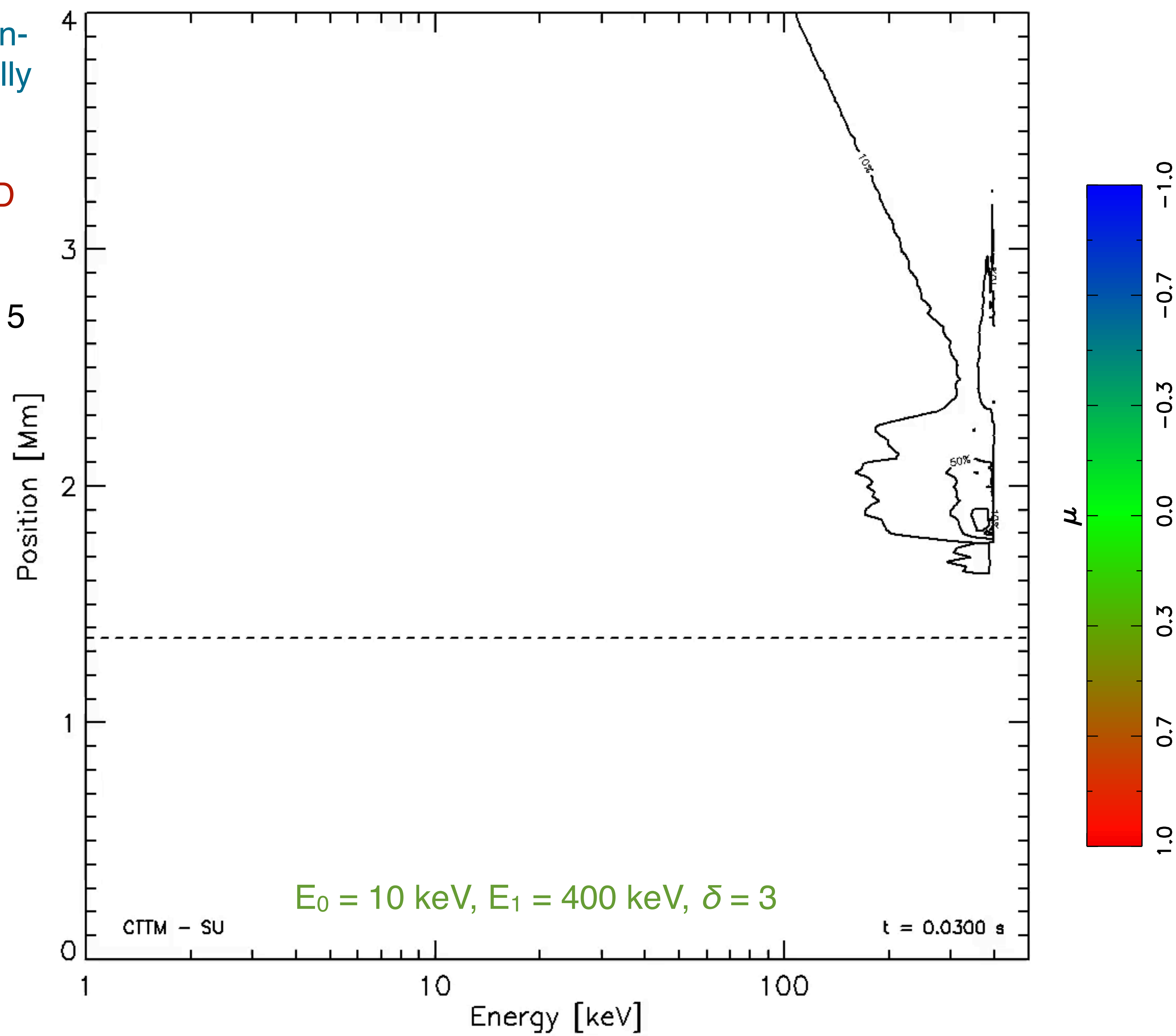
TP model of e⁻ beam propagation and HXR emission

Purely collisional interaction of non-thermal electrons with cold, partially ionised target atmosphere.

- VAL C atmosphere - here no HD response to the beam heating
- convergent magnetic field $R_m = 5$



- initial (coronal) μ_0 distribution uniform for $\mu_0 = (0.5, 1)$
- CTTM approximation
- HXR emission calculated according to Haug (1997)



Flarix: 1D HD

Evolution of low beta plasma along magnetic field lines in one fluid approximation (Kašparová et al. 2009, Varady et al. 2010).

Physics:

- flare heating - calculated by the test particle code
- thermal conduction - classical Spitzer formula (along field lines)
- H ionisation - H ionisation modified Saha eq. (Brown 1973)
- RL optically thin - corona and TR
- RL optically thick – analytic approximation of RL from VAL (Peres, 1982) - no radiative transfer

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v_s) = 0$$

$$\frac{\partial \rho v_s}{\partial t} + \frac{\partial}{\partial s}(\rho v_s^2) = -\frac{\partial P}{\partial s} + F_g + F_\nu$$

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial s}(E v_s) = -\frac{\partial}{\partial s}(v_s P) + \frac{\partial}{\partial s}\mathcal{F}_c + \Delta\mathcal{E}_p - \mathcal{R} + \mathcal{I} + \mathcal{S}$$

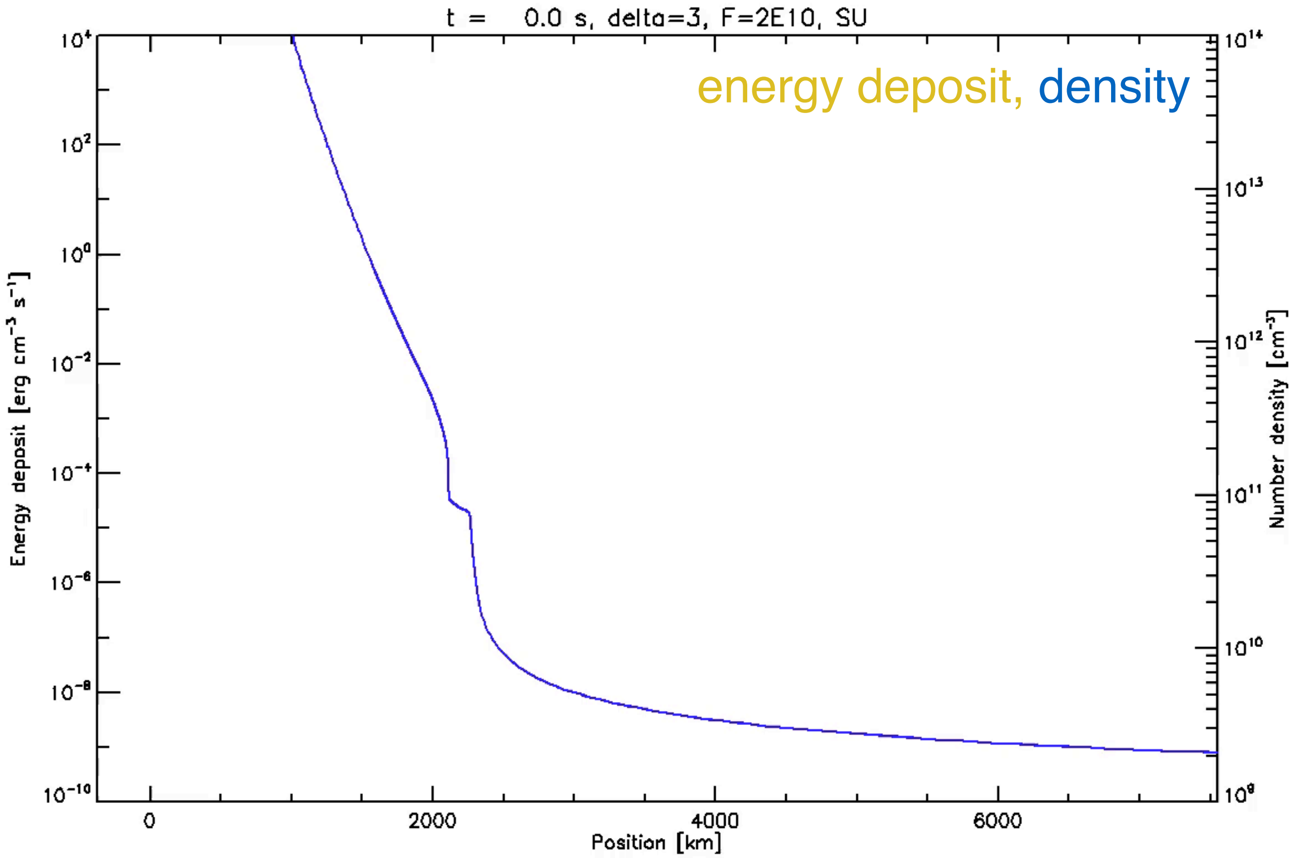
$$P = n_H k_B(\vartheta + x + \varepsilon)T \qquad E = U + \frac{1}{2}\rho v_s^2$$

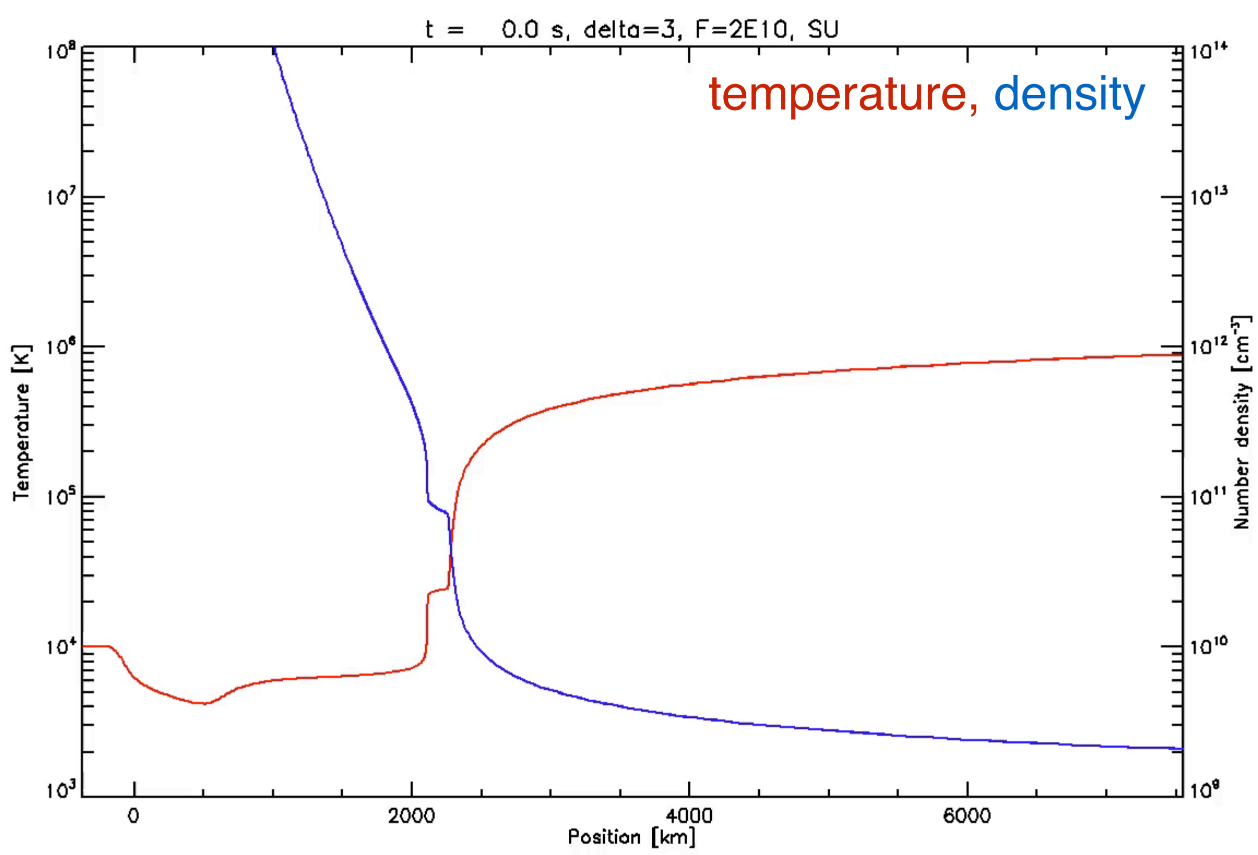
Numerical methods:

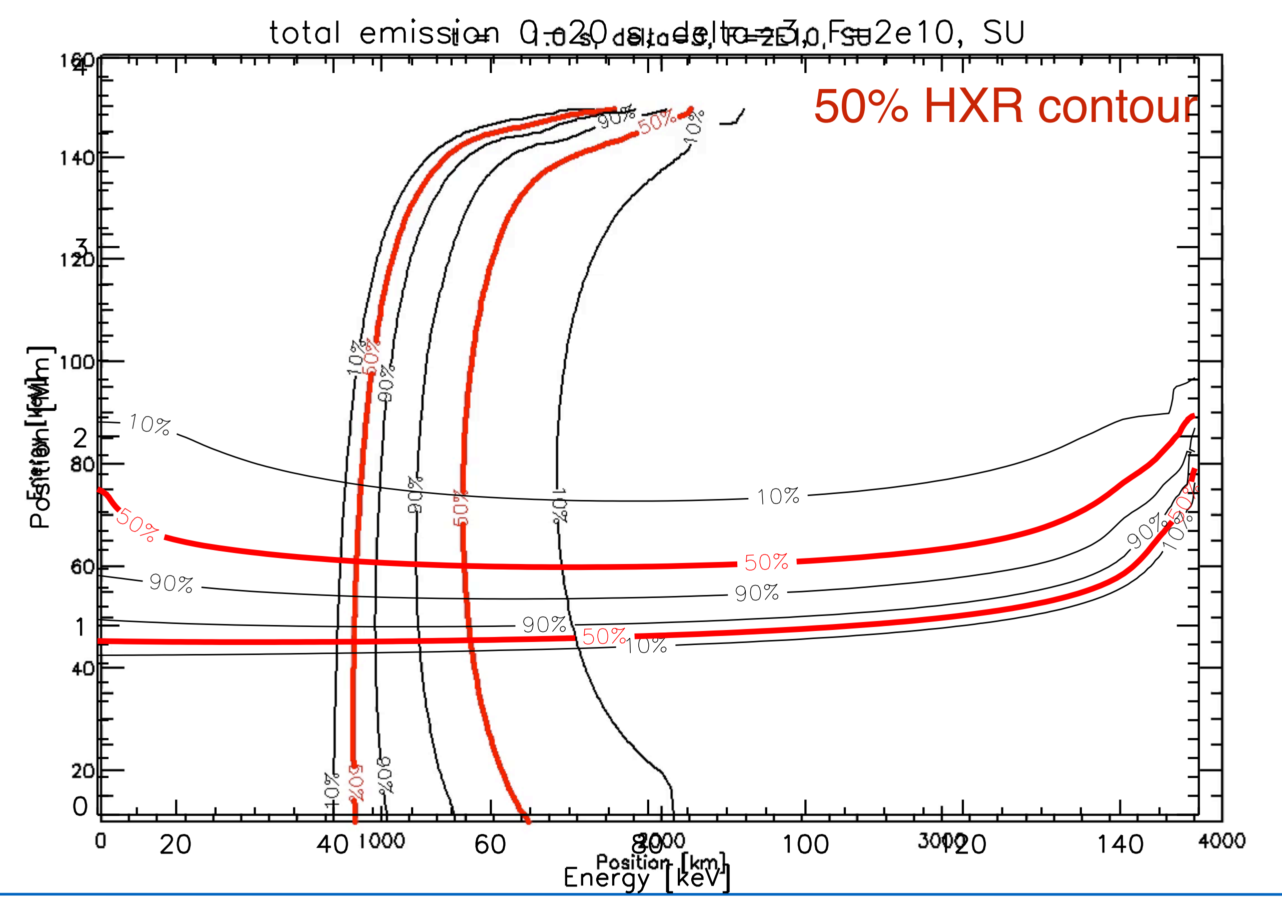
- convection - LCPFCT algorithm for solving generalised continuity equations (NRL)
- explicit algorithm time-step splitting method
- thermal conduction in flare loop - centred algorithm (Crank-Nicholson)

Results (F_0 = 2x10^{10}, delta = 3)

- F_0 = 2x10^{10} erg cm^{-2} s^{-1}
- E_0 = 20 keV
- E_1 = 150 keV
- δ = 3
- evolution 20 s

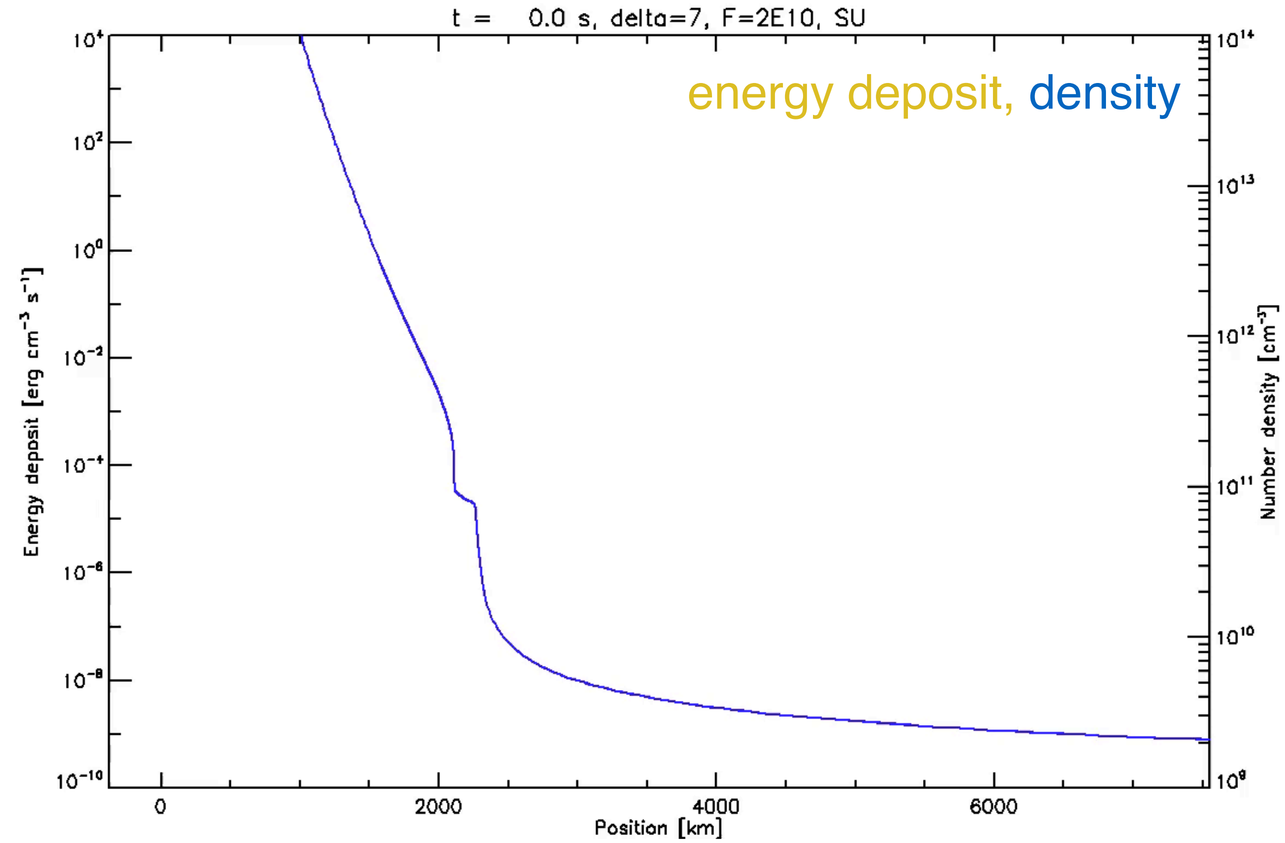


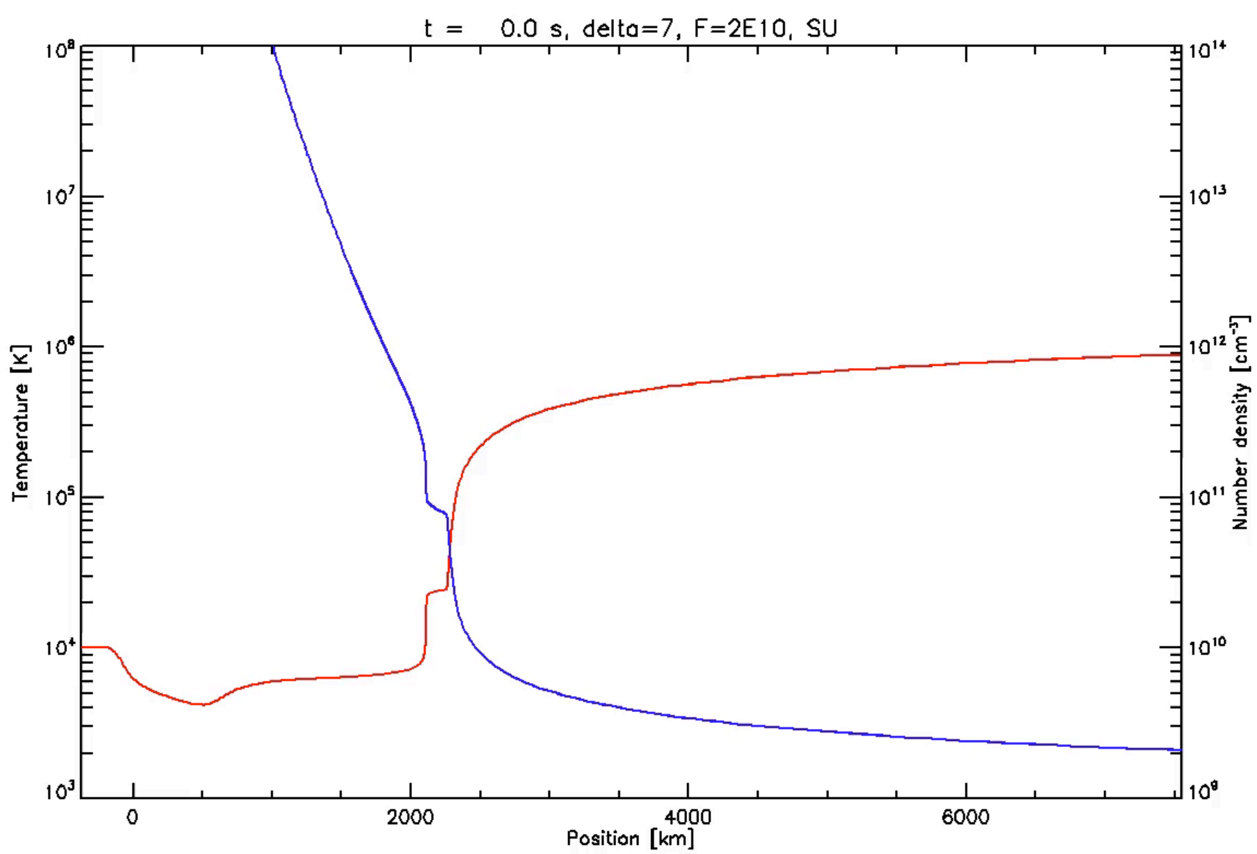


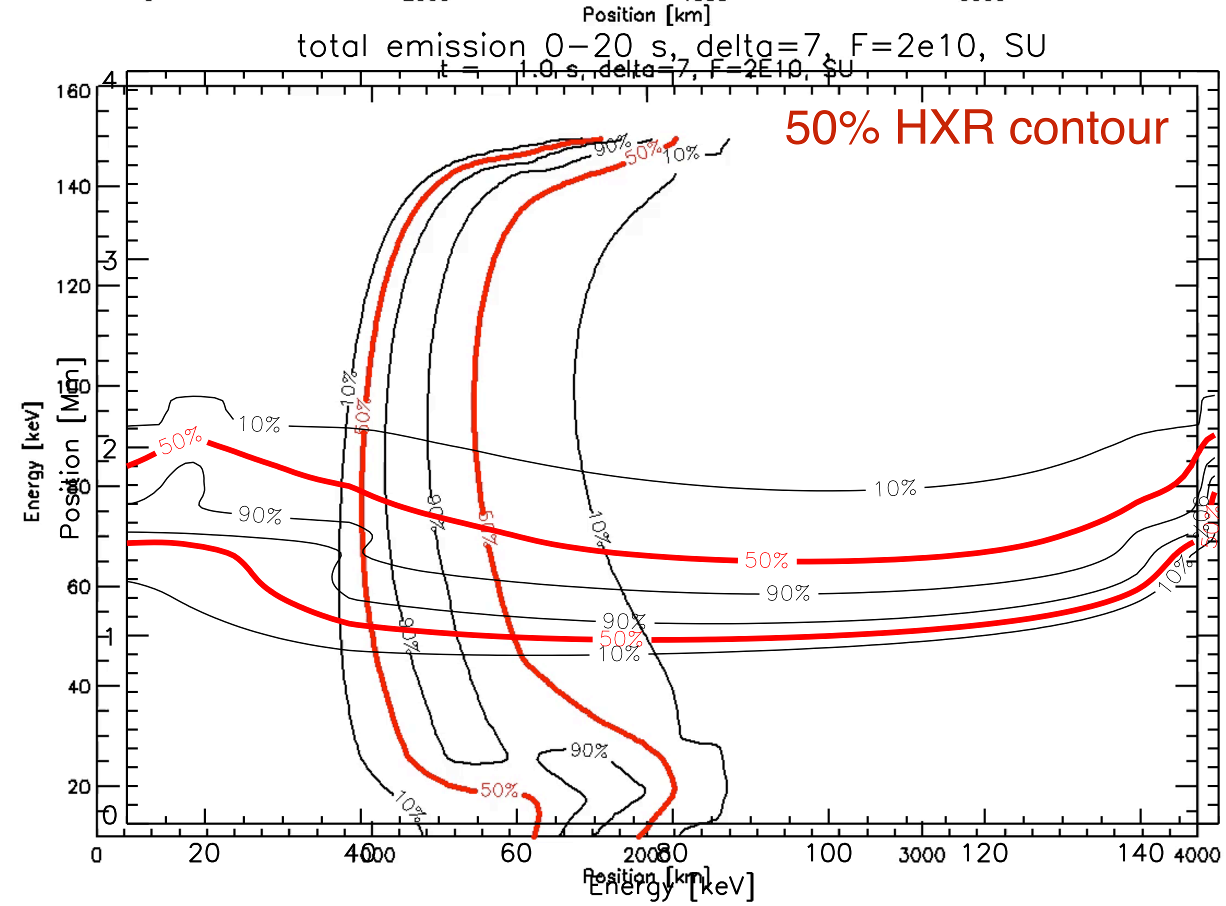


Results (F_0 = $2x10^{10}$, delta = 7)

- $F_0 = 2x10^{10}$ erg cm^{-2} s^{-1}
- E_0 = 20 keV
- E_1 = 150 keV
- $\delta = 7$
- evolution 20 s
- most extreme case (out of all studied cases)



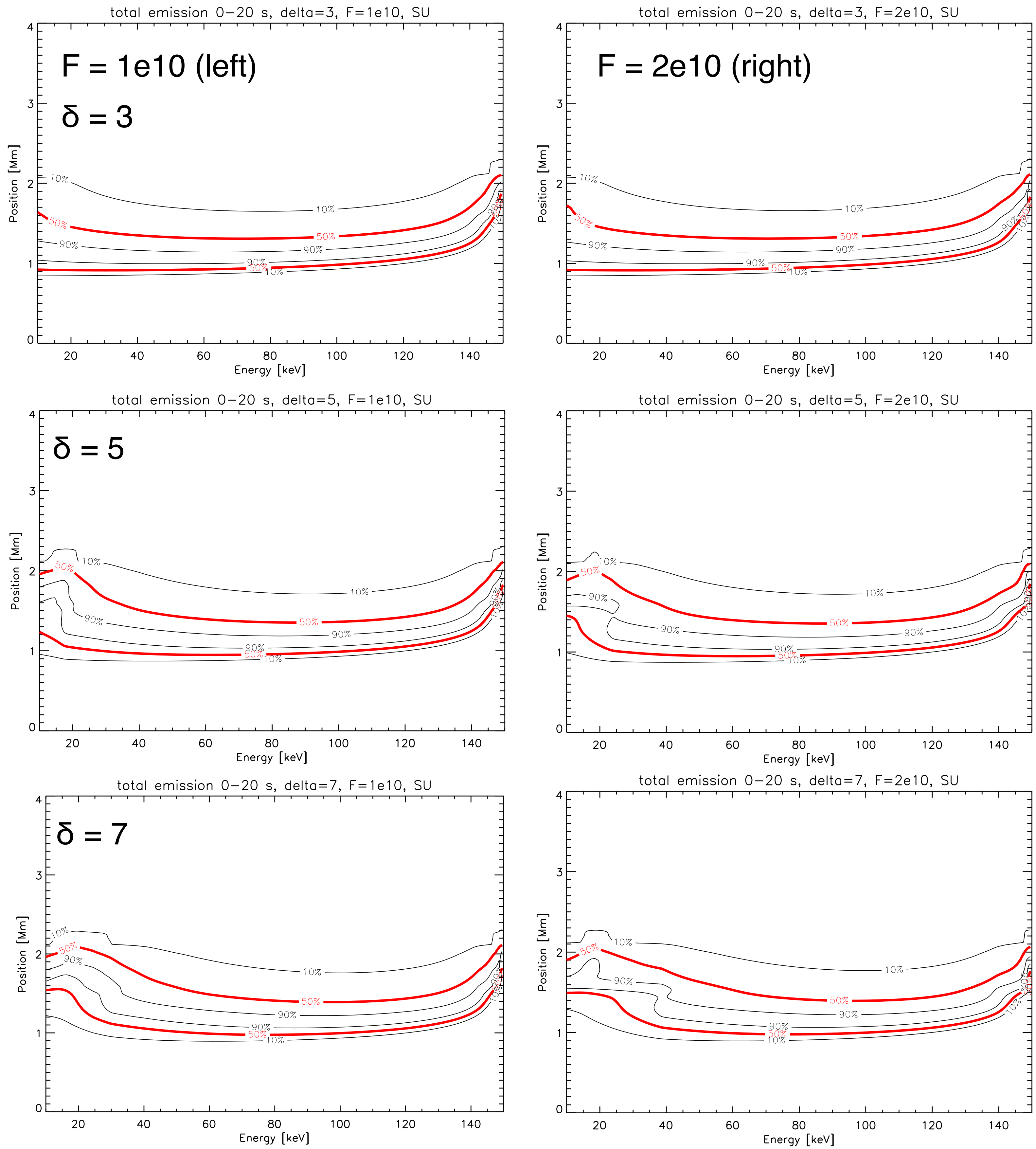




Results - energy dependent HXR source sizes

Energy dependent HXR vertical source sizes integrated over 20s of evolution:

- maximum source sizes on small or medium energies 20-30 keV < 1.5 arcsec
- at high energies sources size tends to decrease
- relatively week dependence of the source size on initial energy flux and δ



Conclusions

Using Flarix (combined TPC and 1D HD approach) we modelled chromospheric HXR source sizes using the CTTM for a single flare loop $L = 15$ Mm and 20 s heating corresponding to RHESSI data acquisition time for imaging.

- all models exhibit significant changes in density, temperature and ionisation structure along the loop during the evolution, but only minor changes in the corresponding HXR footpoint source sizes and positions were obtained
- HXR source sizes integrated over 20 s of evolution are under 1.5 arcsec - thus inconsistent with RHESSI observations (correspond to results obtained by Battaglia et al. 2012)
- observed vertical sizes of HXR chromospheric sources can not be explained by the time evolution of flaring atmosphere taking the CTTM and a single flare loop

For details see: Moravec, Varady, Kašparová et al., 2016, Astron. Nachr., in print (arxive)

Work on extension of the model from single compact loops to a multi-threaded flare loop composed of a bunch of magnetically convergent single threads in progress.

F-CHROMA

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Outline

1. Motivation
2. Propagation and thermalisation of non-thermal electrons
3. HD of flare plasma
4. Results
5. Conclusions

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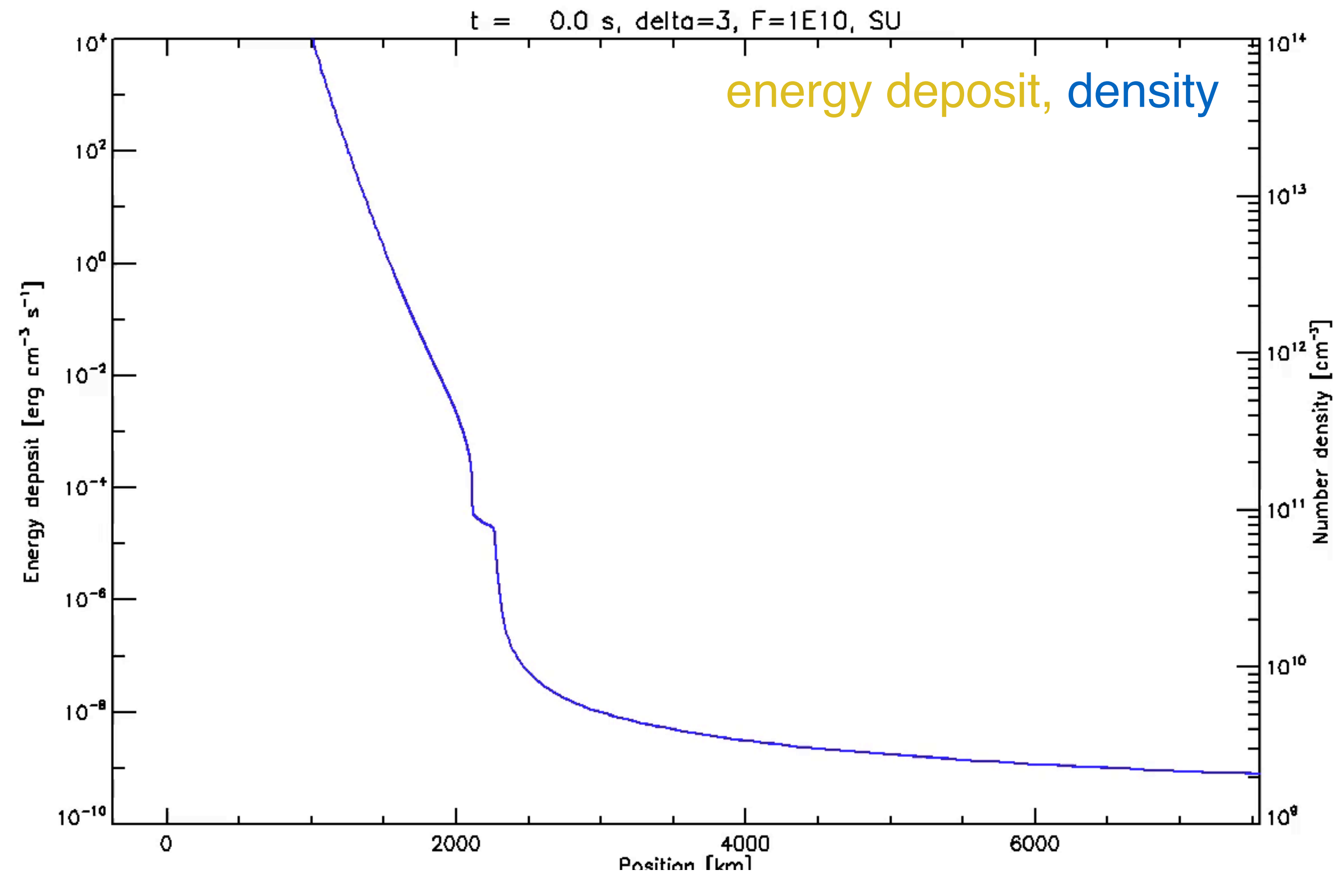
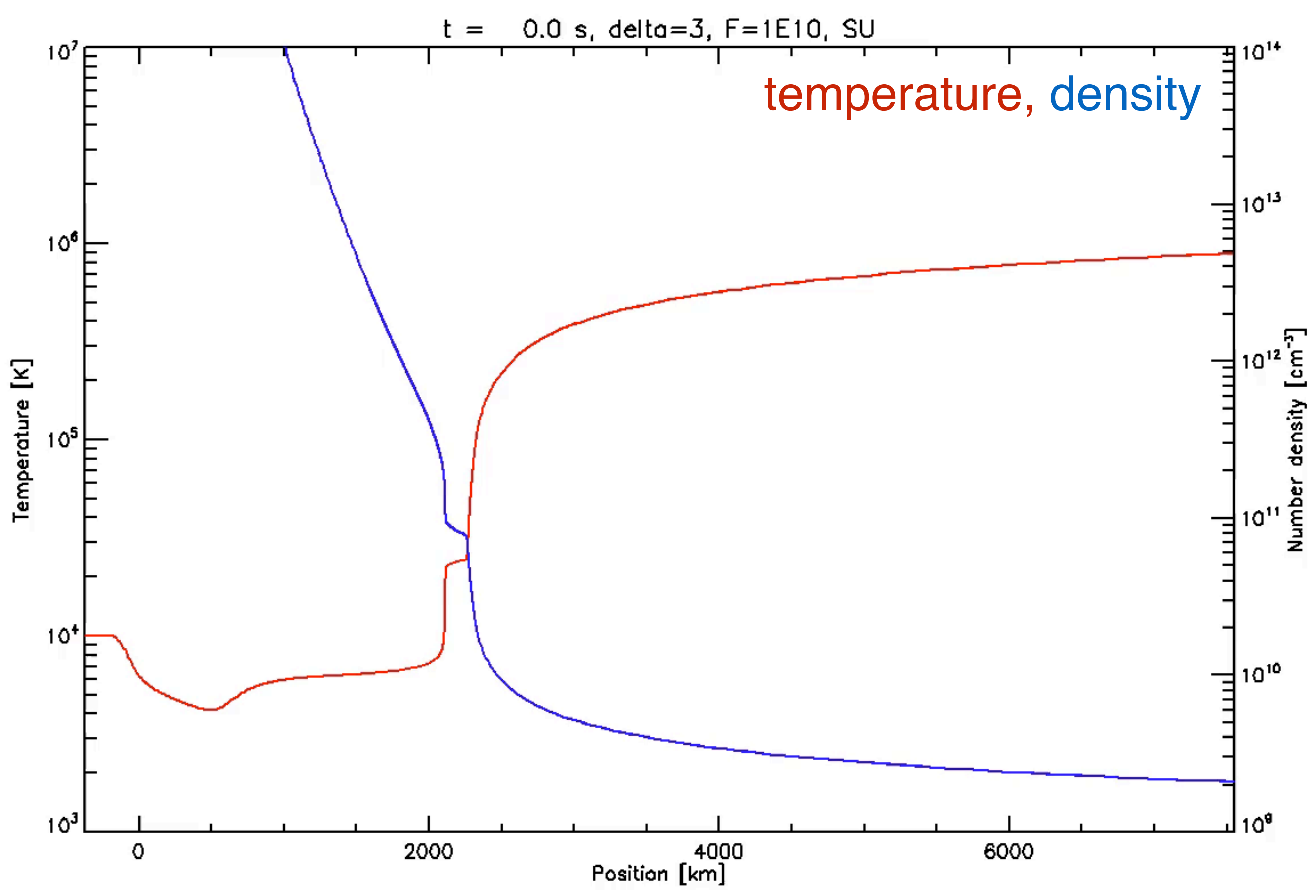
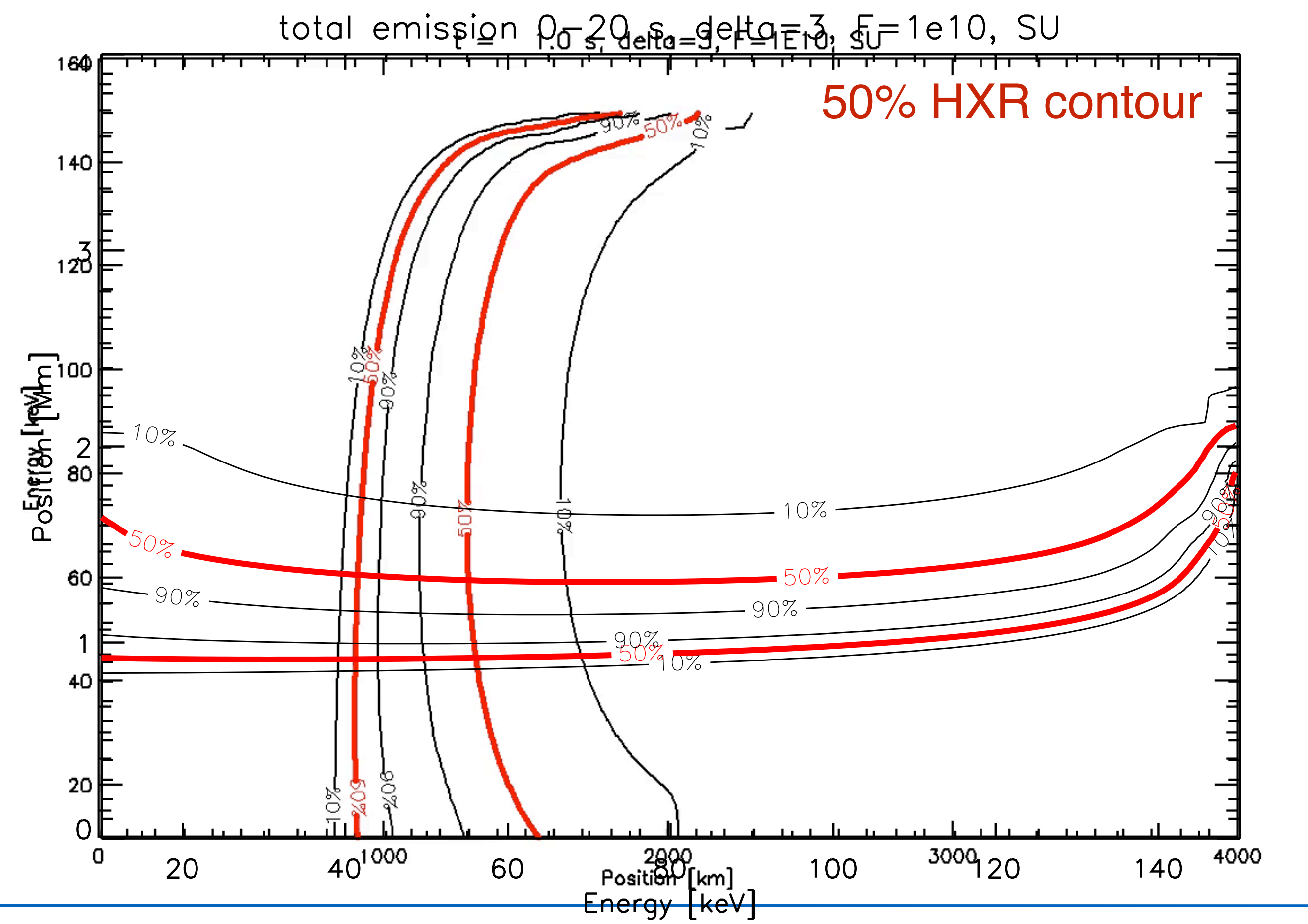
- $\delta = 3$
- evolution 20 s

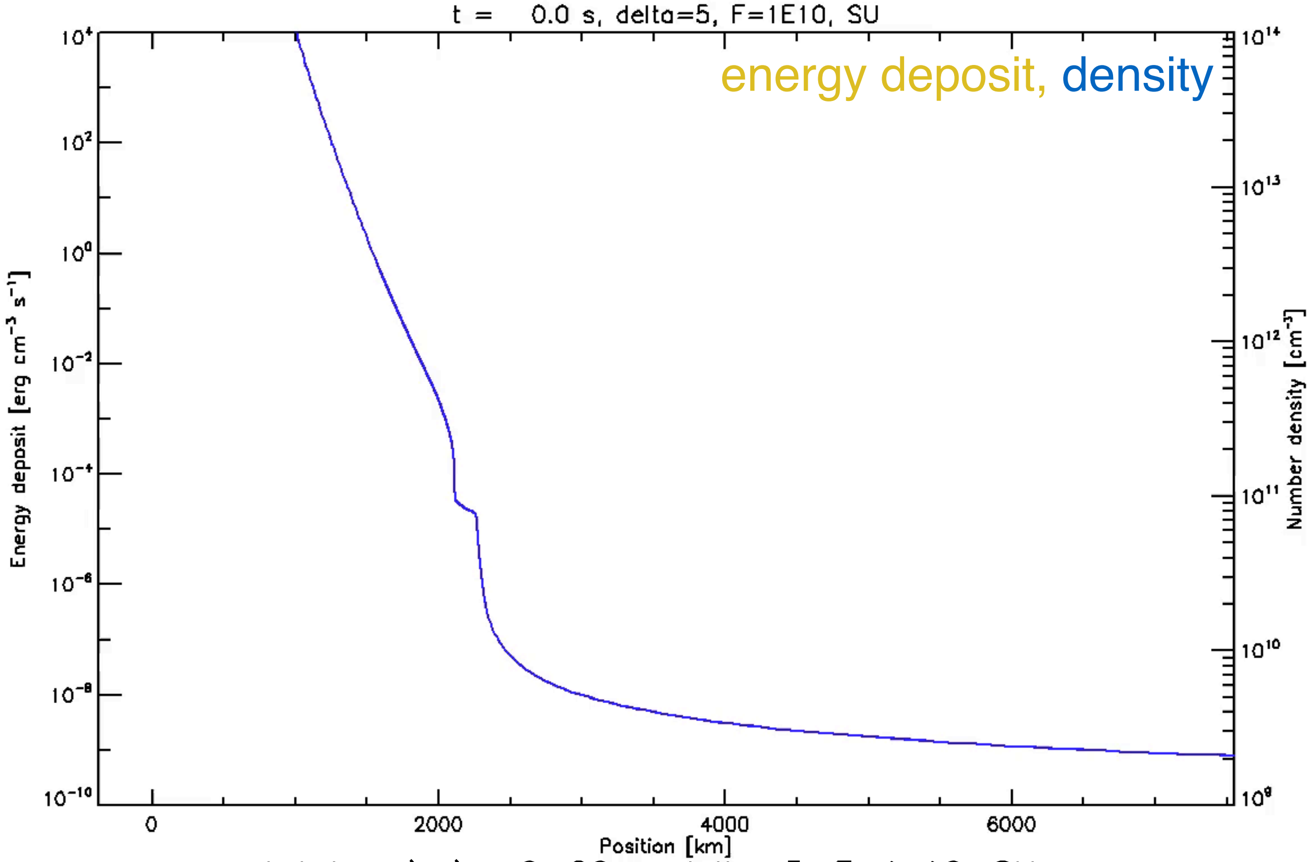


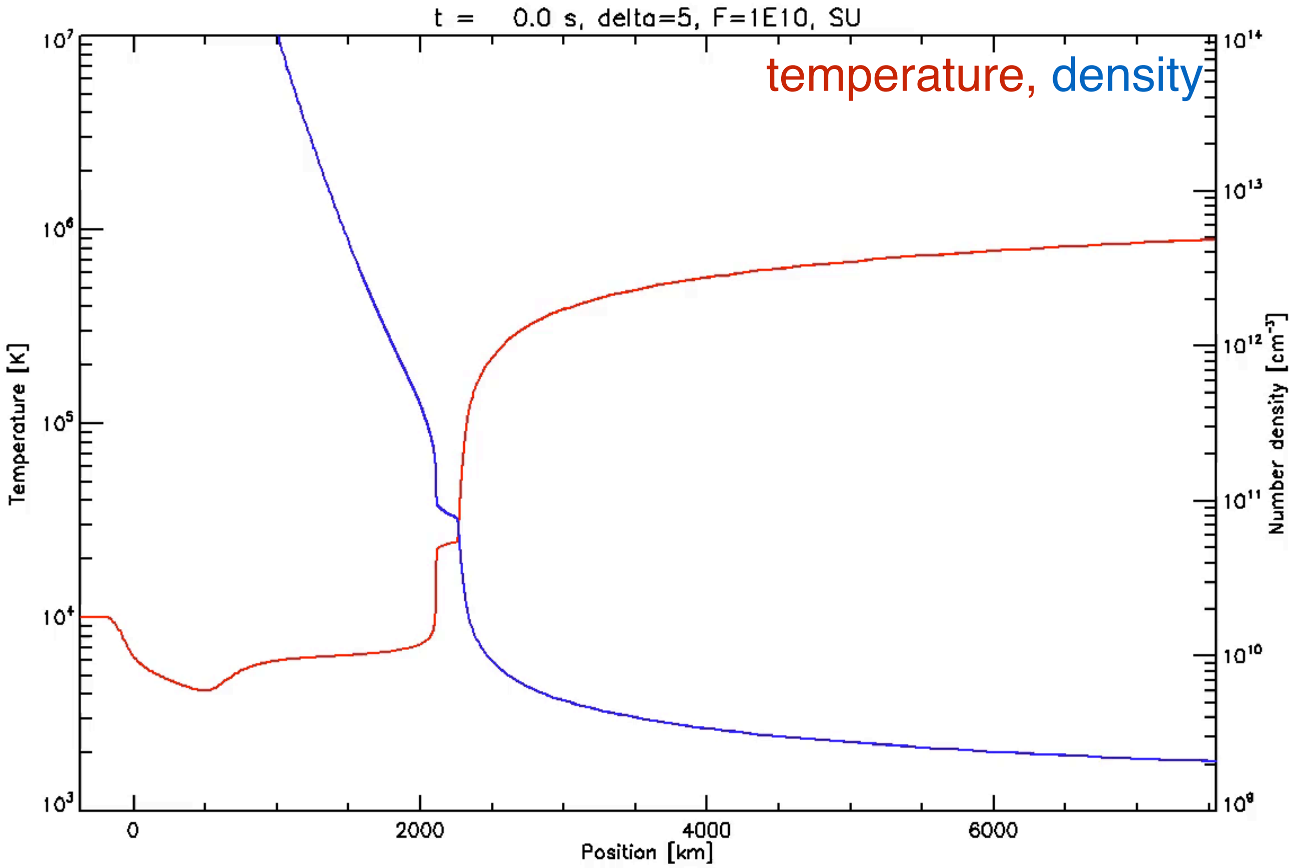


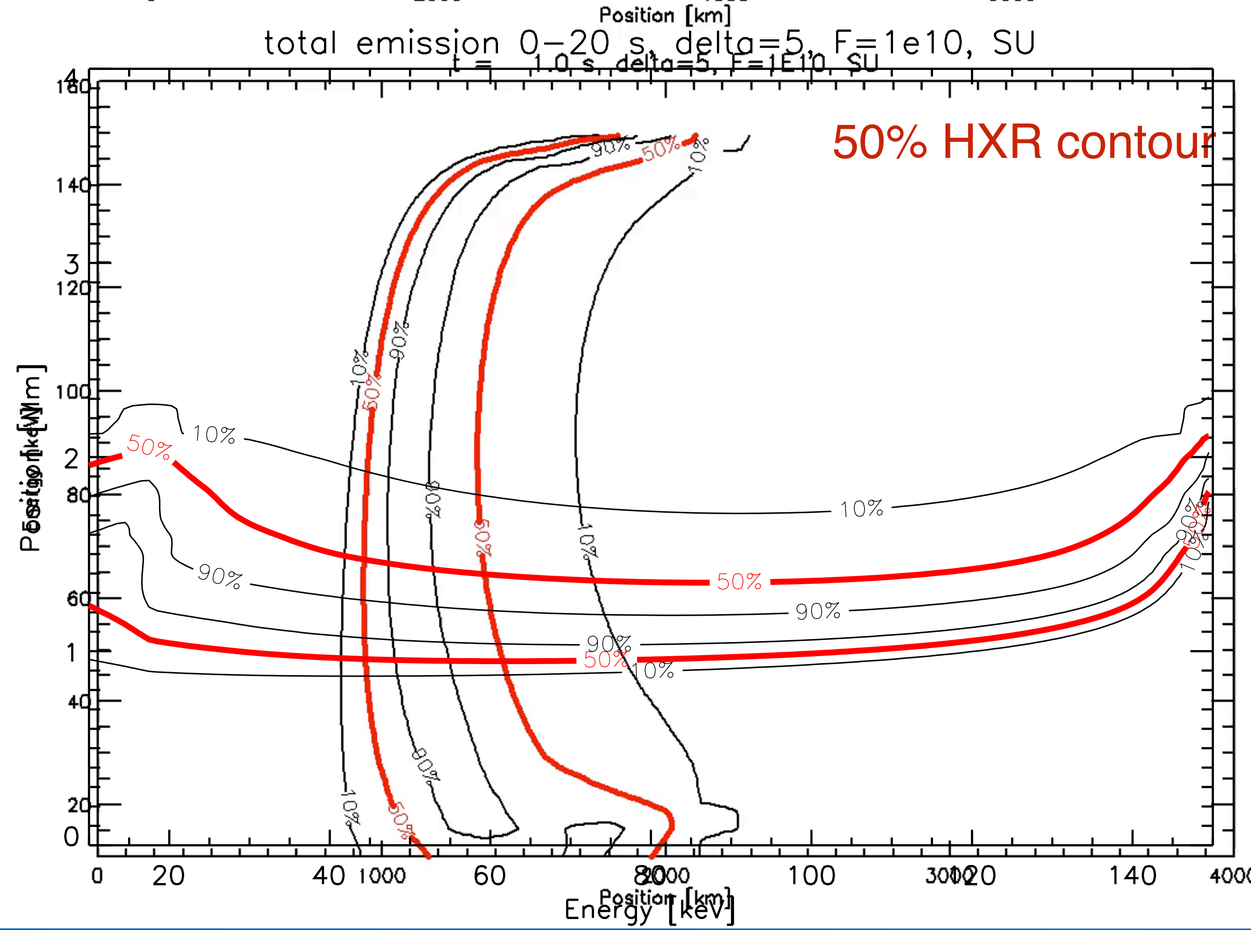


Results ($F_0 = 1 \times 10^{10}$, delta = 5)

- $F_0 = 1 \times 10^{10}$ erg cm^{-2} s^{-1}
- E_0 = 20 keV
- E_1 = 150 keV
- δ = 5
- evolution 20 s

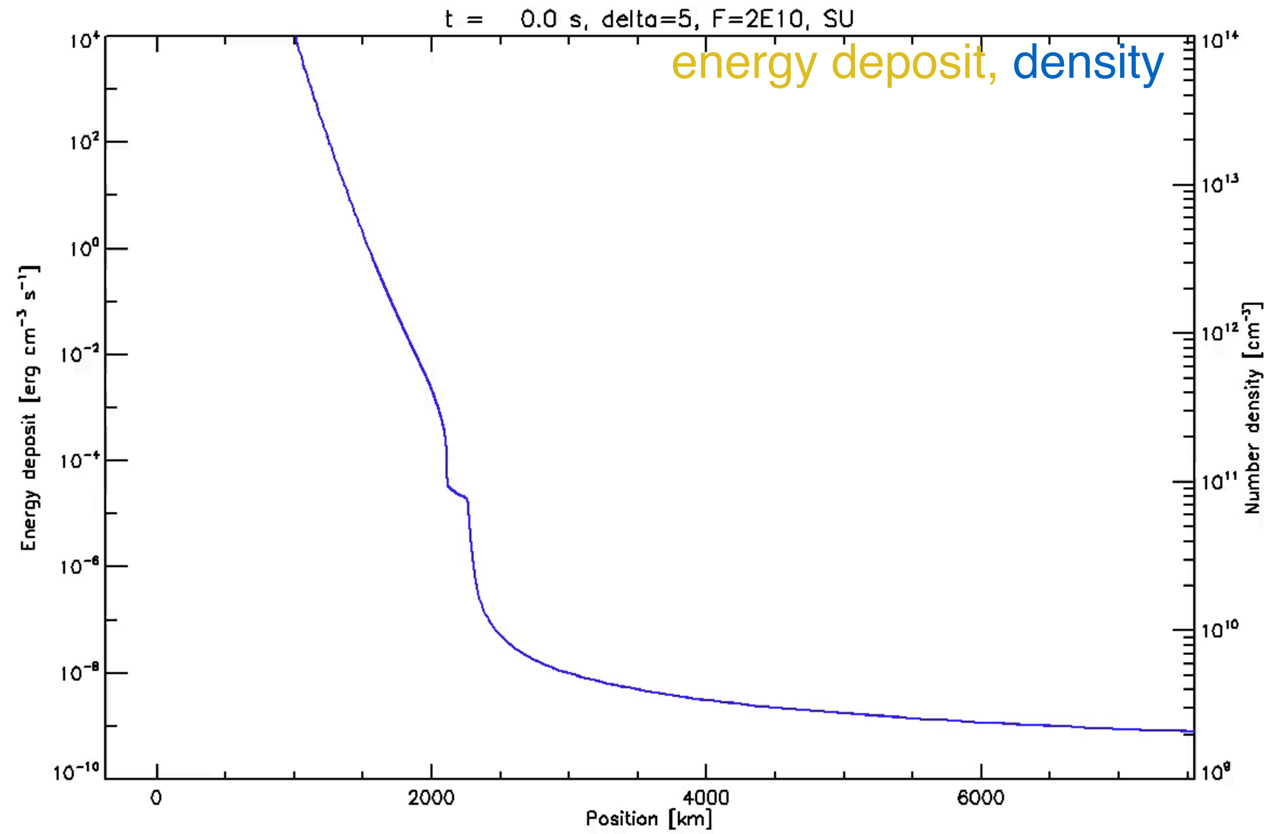


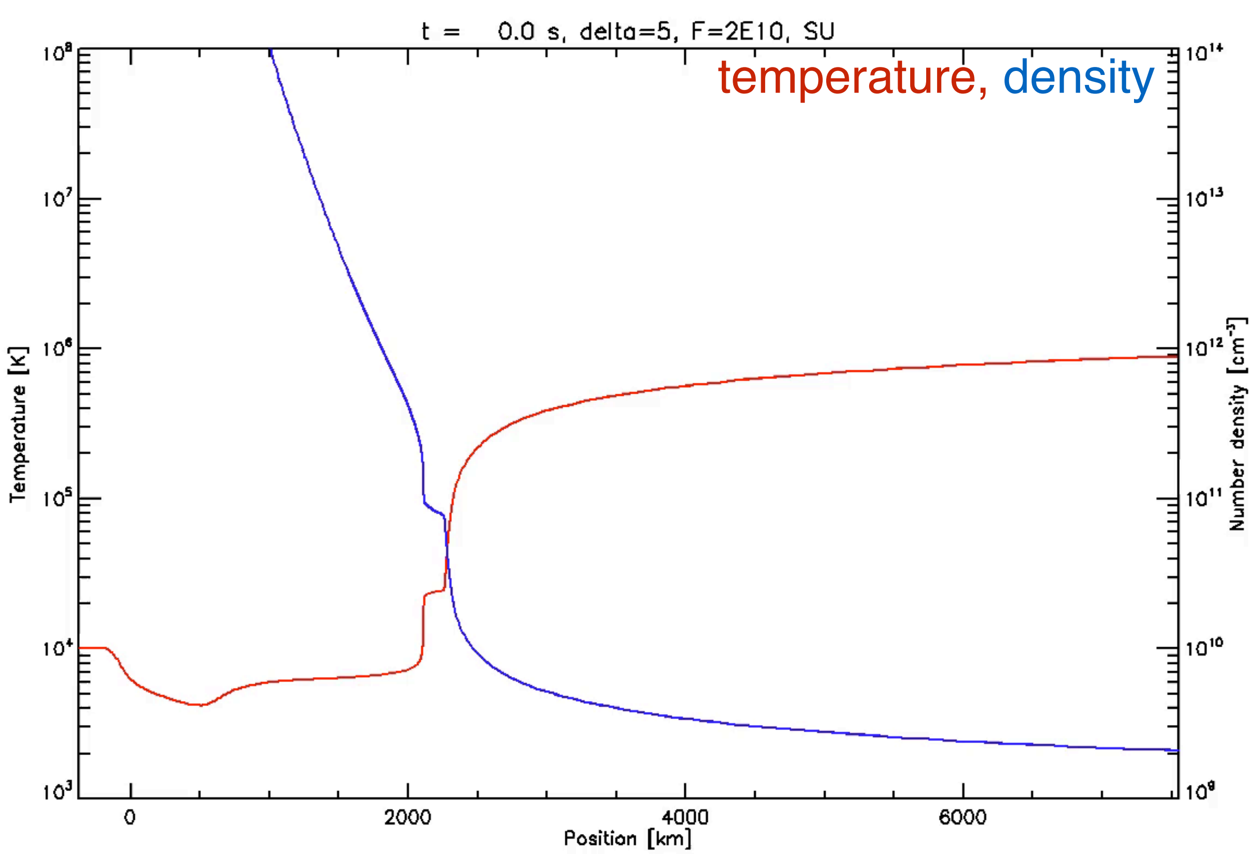


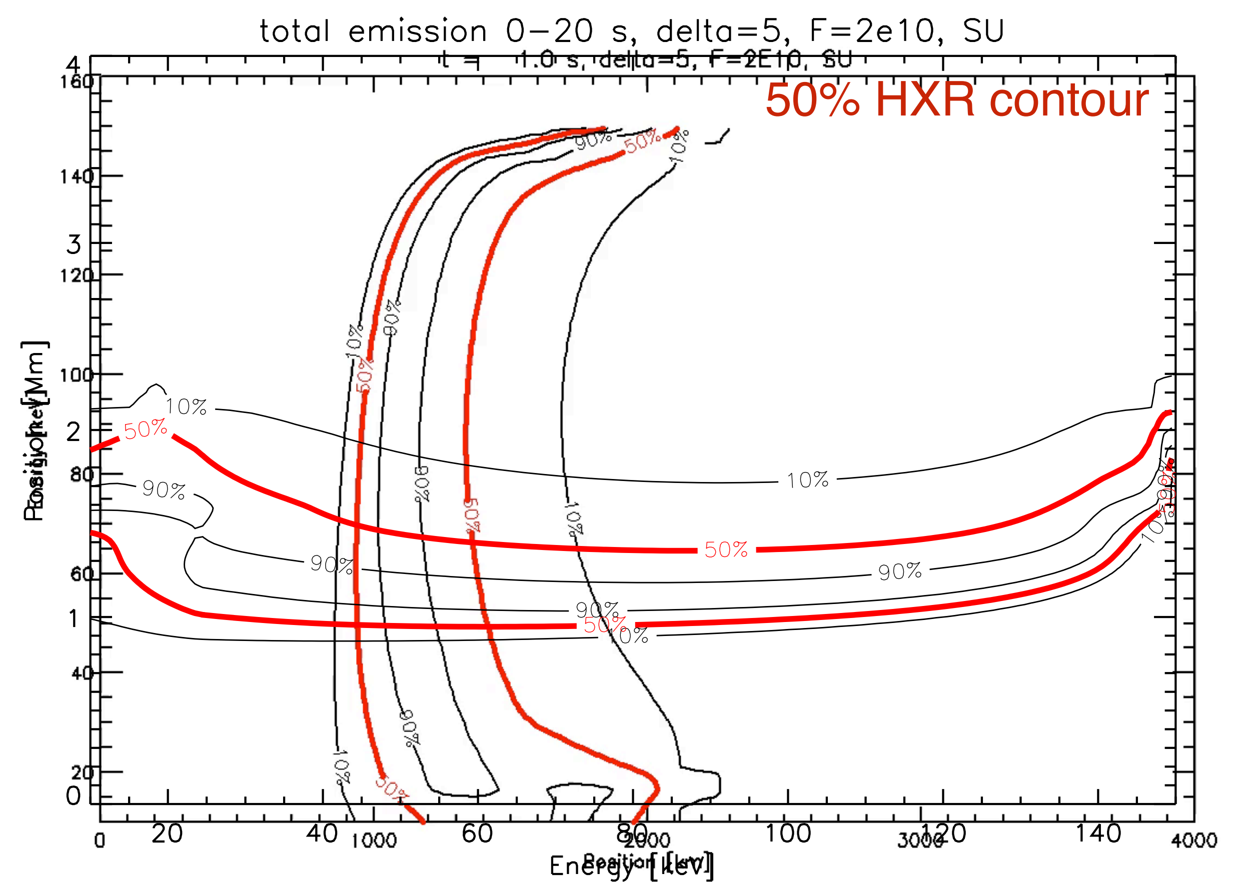


Results (F_0 = 2x10^{10}, delta = 5)

- $F_0 = 2 \times 10^{10}$ erg cm^{-2} s^{-1}
- E_0 = 20 keV
- E_1 = 150 keV
- $\delta = 5$
- evolution 20 s







Results ($F_0 = 1x10^{10}$, delta = 7)

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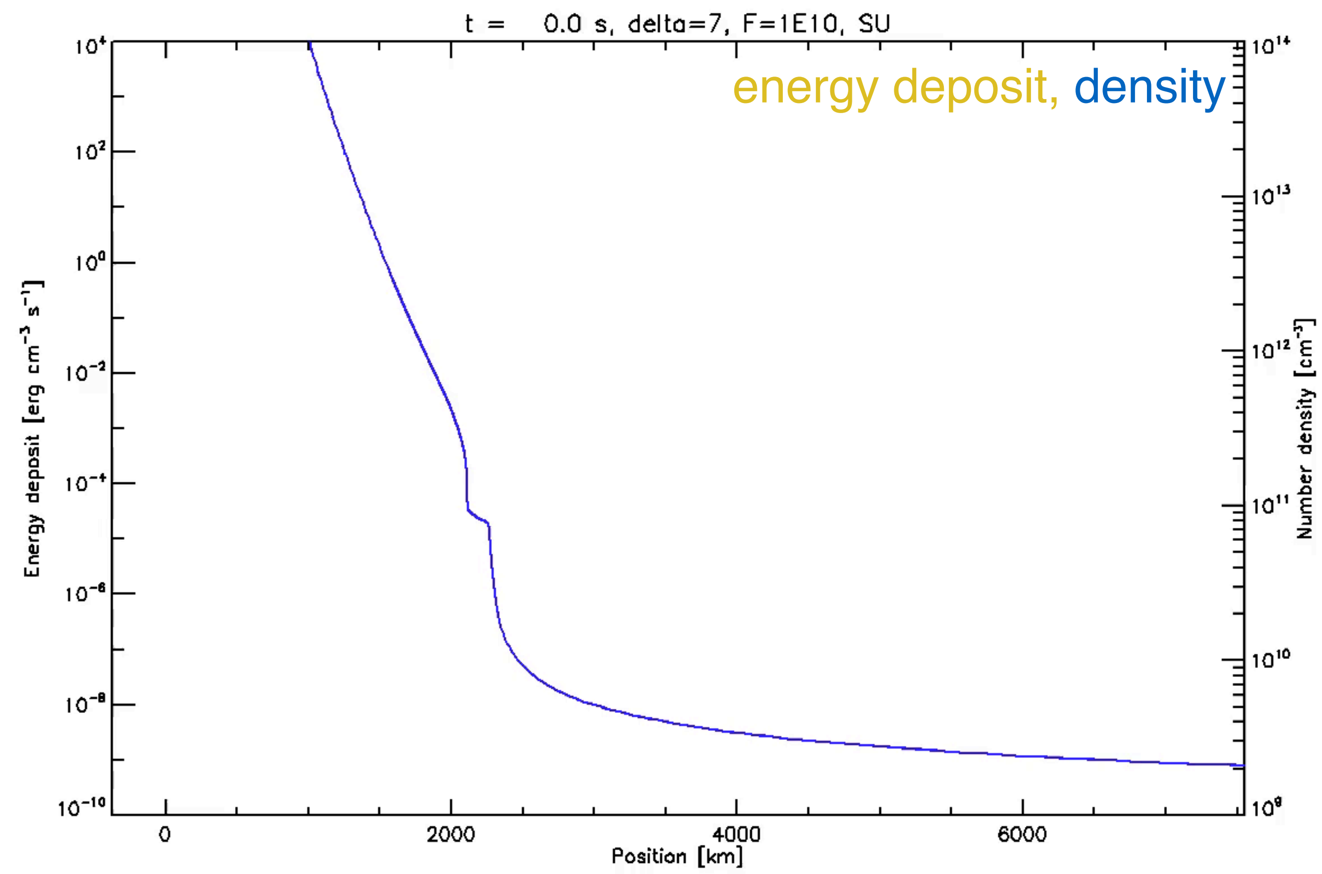
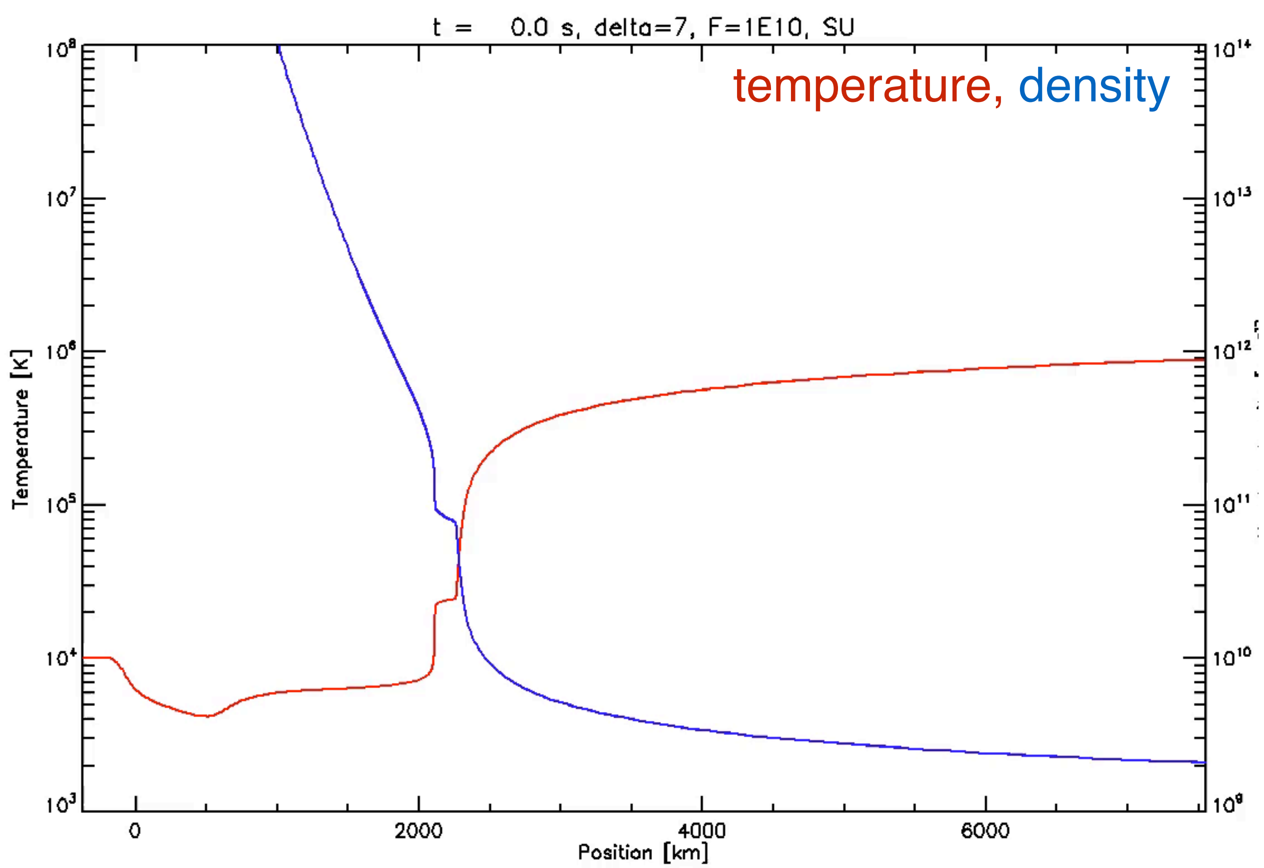
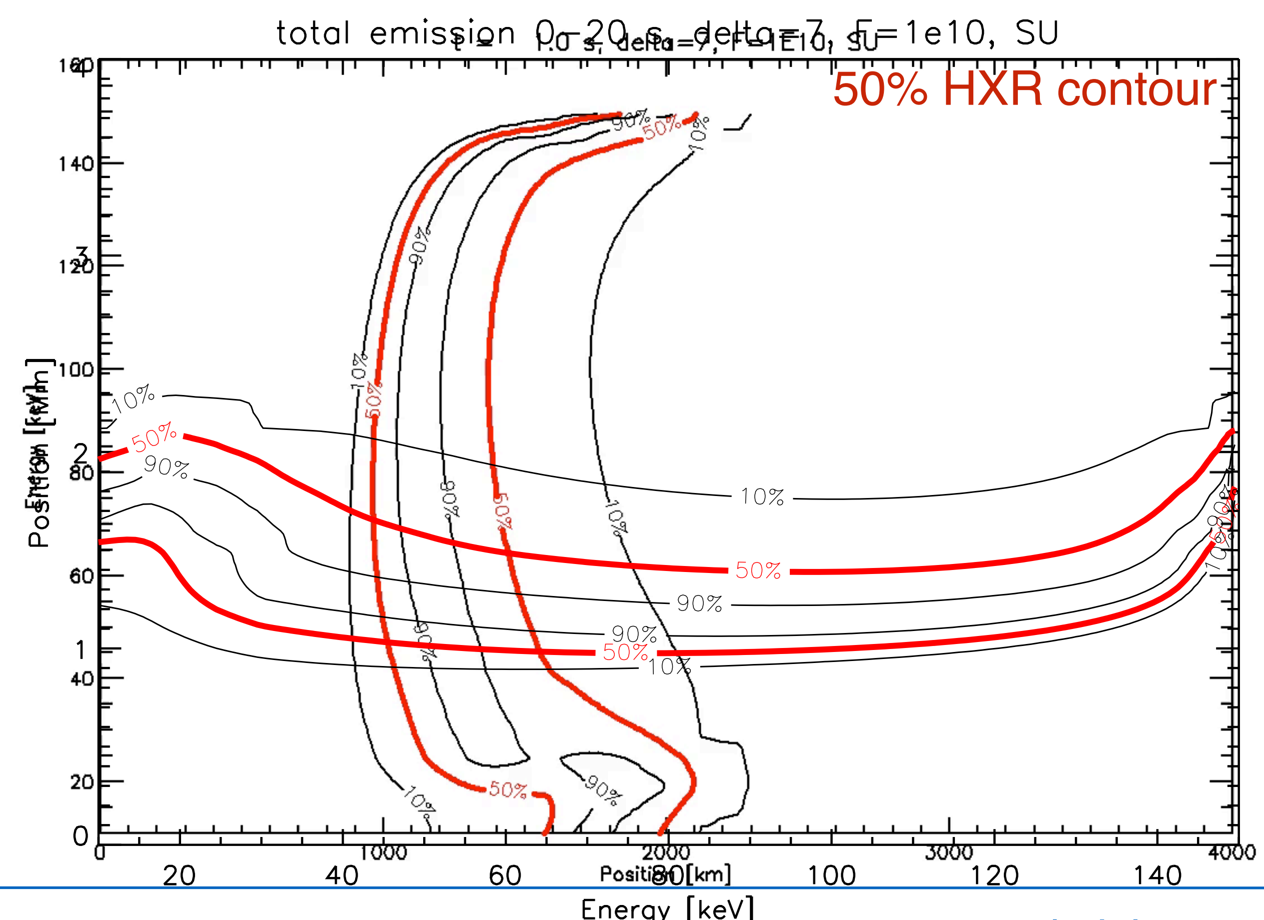
- E_0 = 20 keV
- E_1 = 150 keV
- $\delta = 7$
- evolution 20 s







Typical results ($F_0 = 2x10^{10}$, delta = 7)

- $F_0 = 2x10^{10}$ erg cm^{-2} s^{-1}
- E_0 = 20 keV
- E_1 = 150 keV
- δ = 7
- evolution 20 s
- most extreme case (6 cases in total)