Search for X-ray emission from coronal electron beams associated with type III radio bursts

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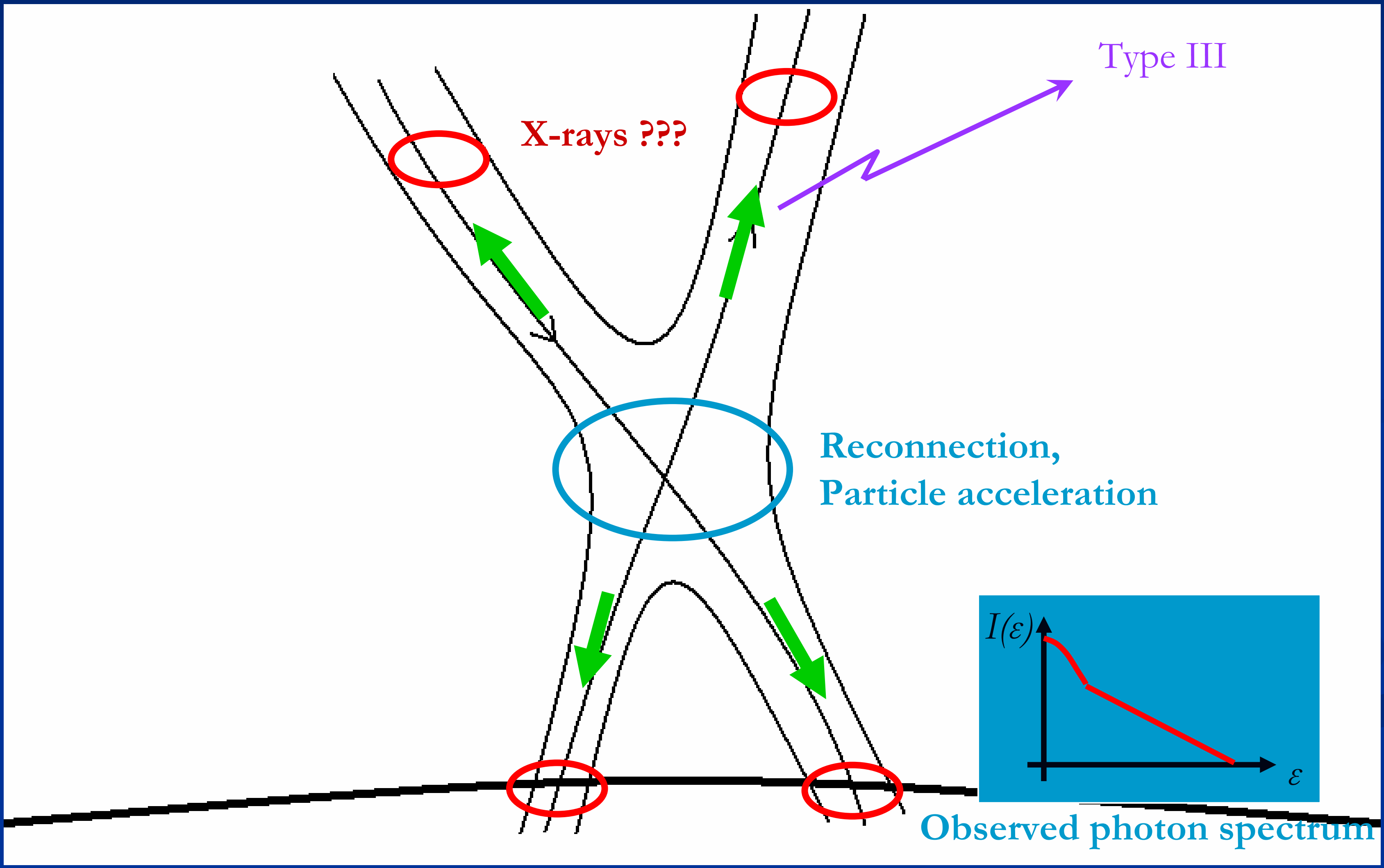
- X-rays from electron beams in the upper corona have never been observed.
- RHESSI should be able to observe them ***<u>if</u>*** they are similar in characteristics to the downward going beams usually observed in flares

Standard flare scenario:



Outline:

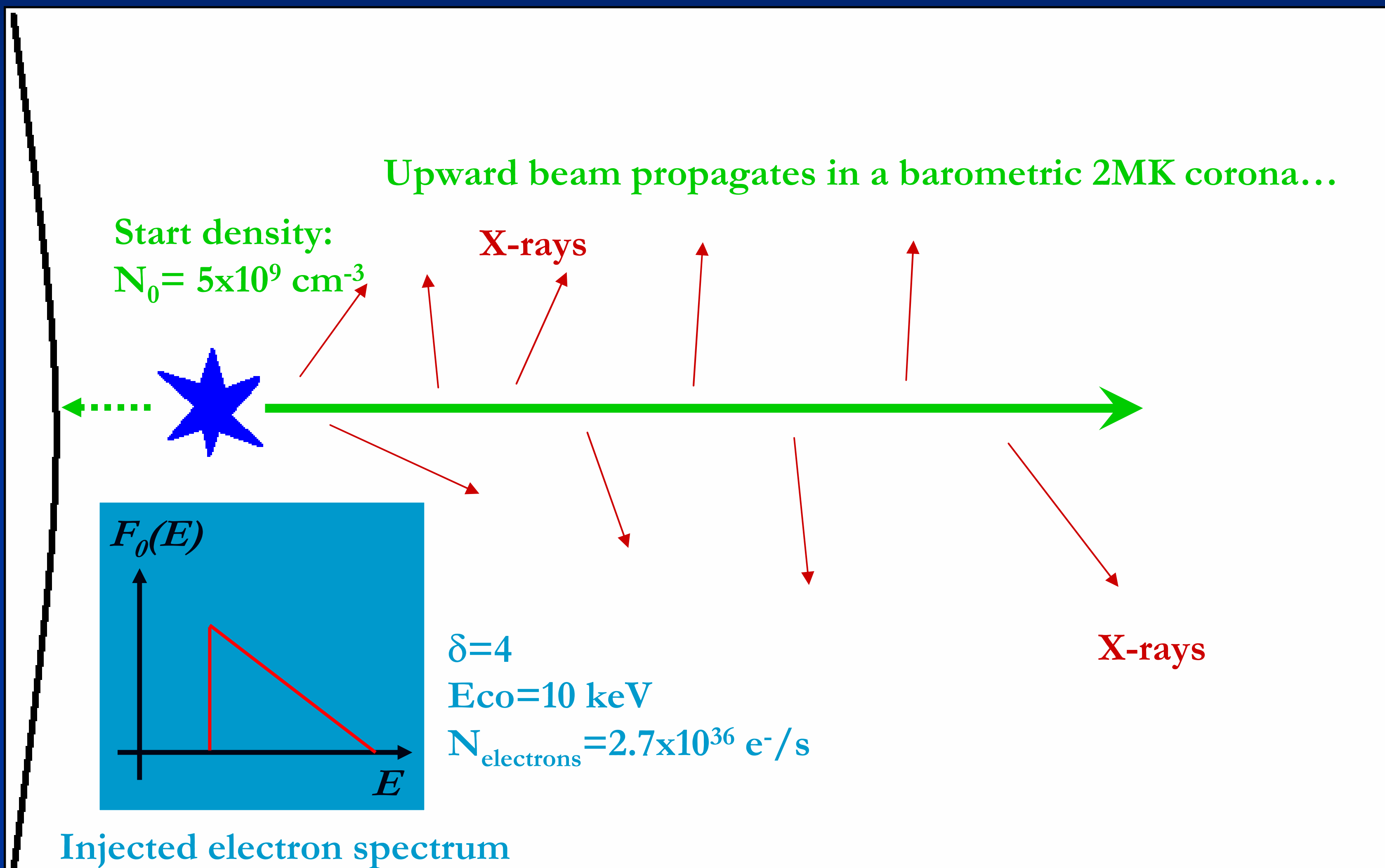
- Can we find and characterize propagating electron beams in the solar corona that emit both in radio (as type IIIs) and in X-rays?

  → numerical modeling

  → RHESSI simulations

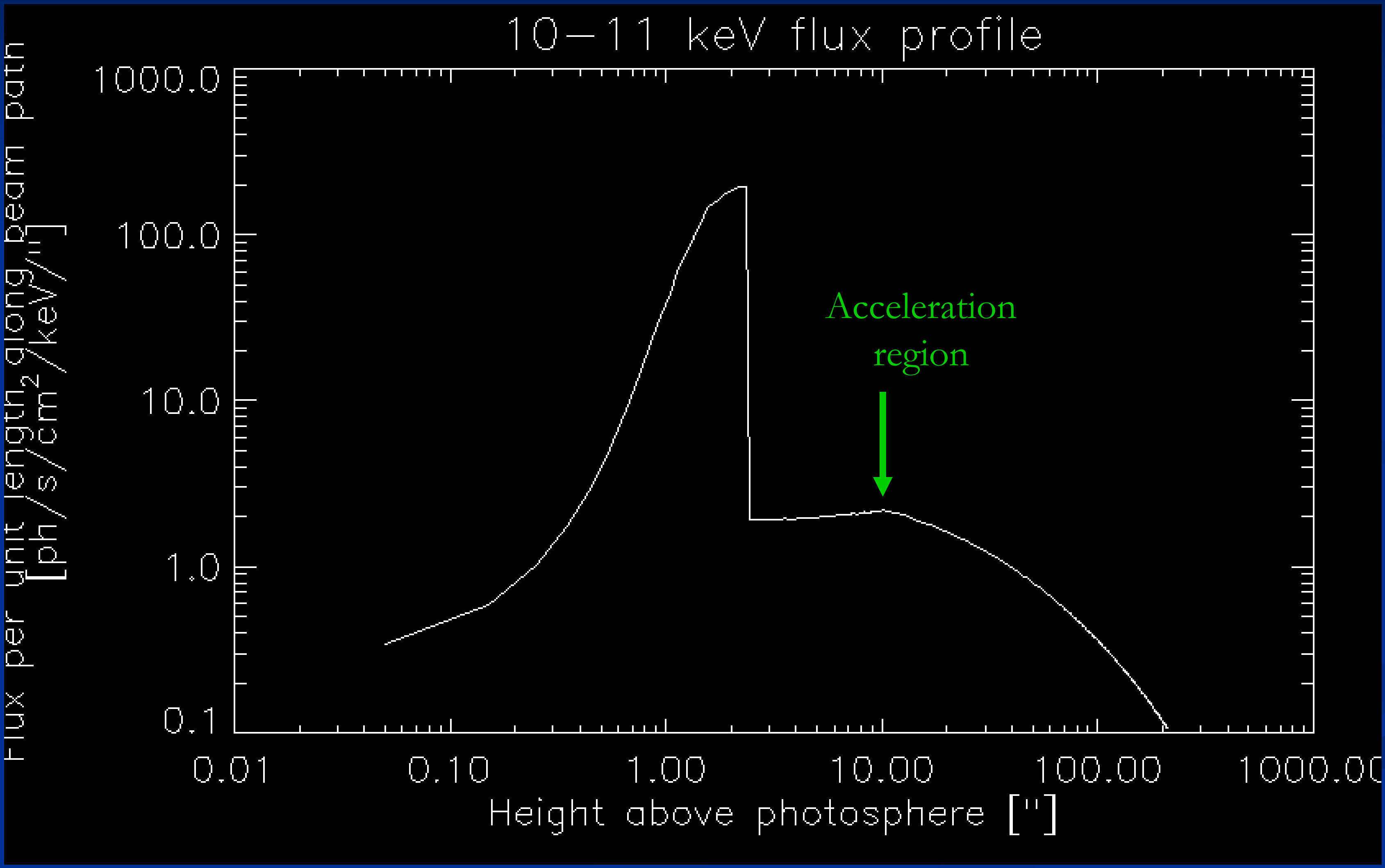
- What do observations tell us?

Model:



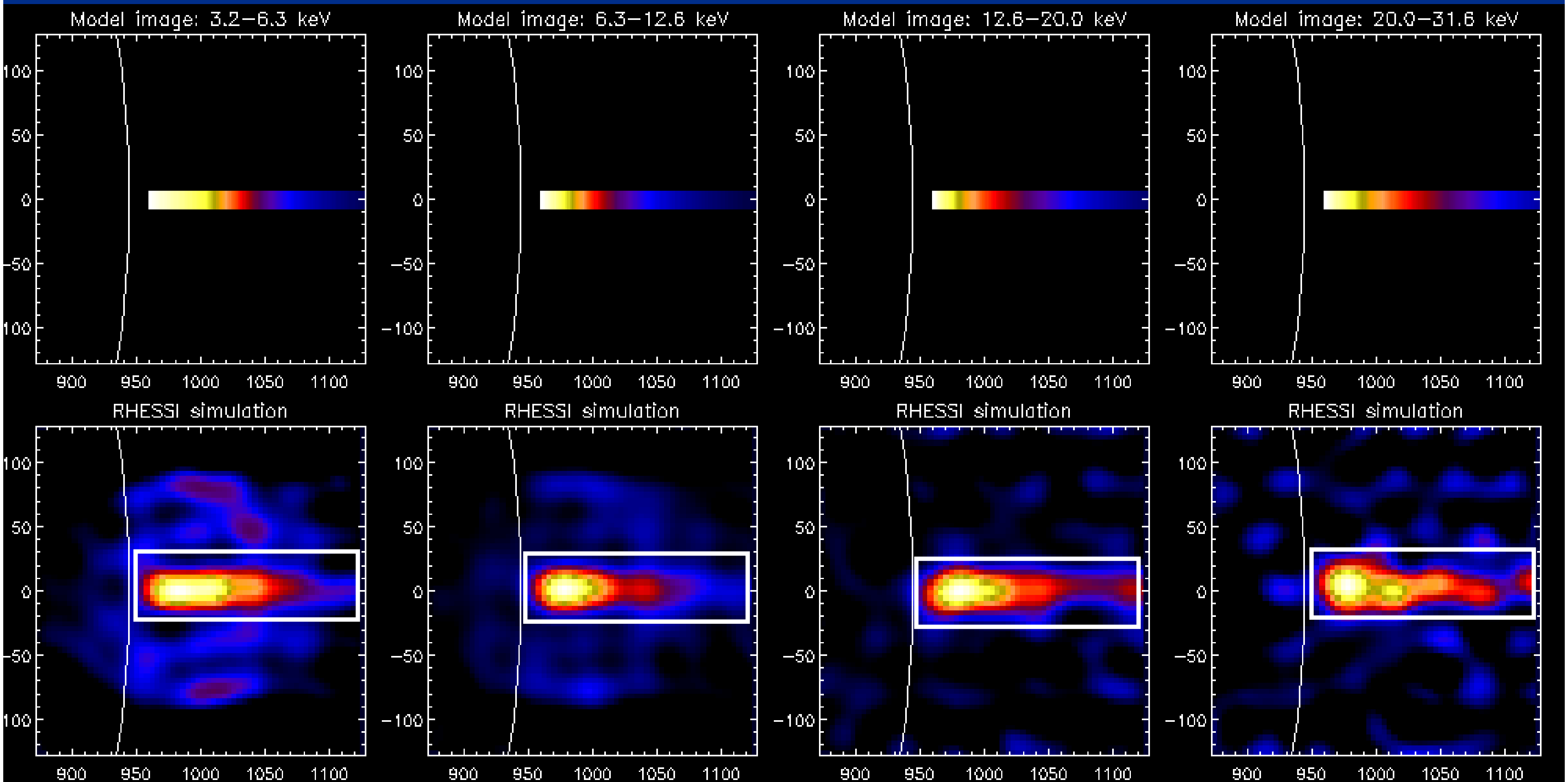
Upward beam propagates in a barometric 2MK corona…
Start density:
$N_0 = 5 \times 10^9$ cm^{-3}
X-rays
$F_0(E)$
E
$\delta=4$
Eco=10 keV
$N_{electrons} = 2.7 \times 10^{36}$ e$^-$/s
X-rays
Injected electron spectrum

Combined, symmetric downward and upward beam:

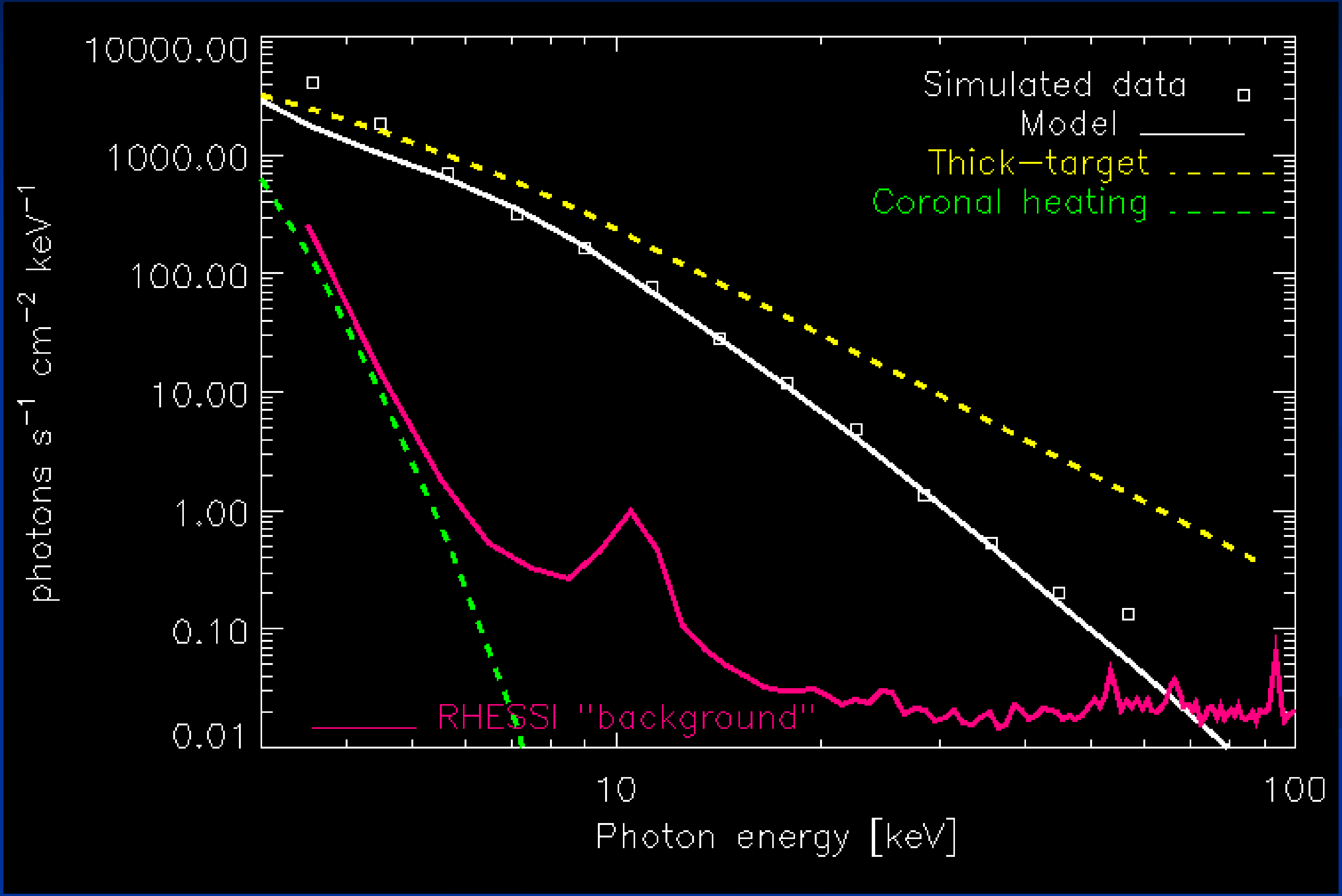


→ Need flares with occulted footpoints!

N_0=5x10^9 cm^{-3}, δ=4, Eco=10 keV, N_{beam}=2.7x10^{36} electrons/s, dt=4s



Imaging spectroscopy:



The simplest model to estimate thermal emission (coronal heating by propagating electron beam):

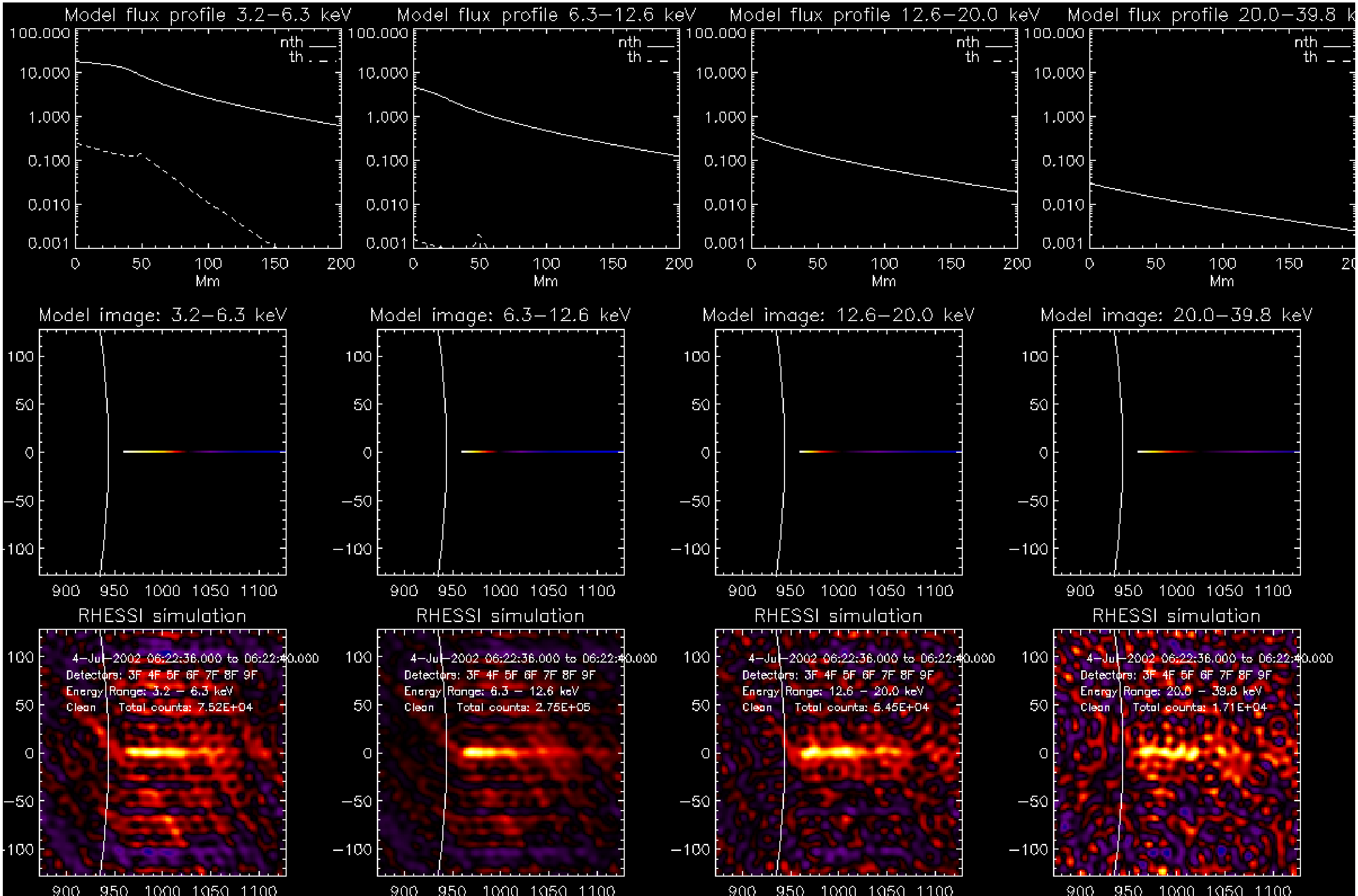
- At equilibrium, in a volume element:

$$P_{nth} = E_{th} / \tau_{cond}$$

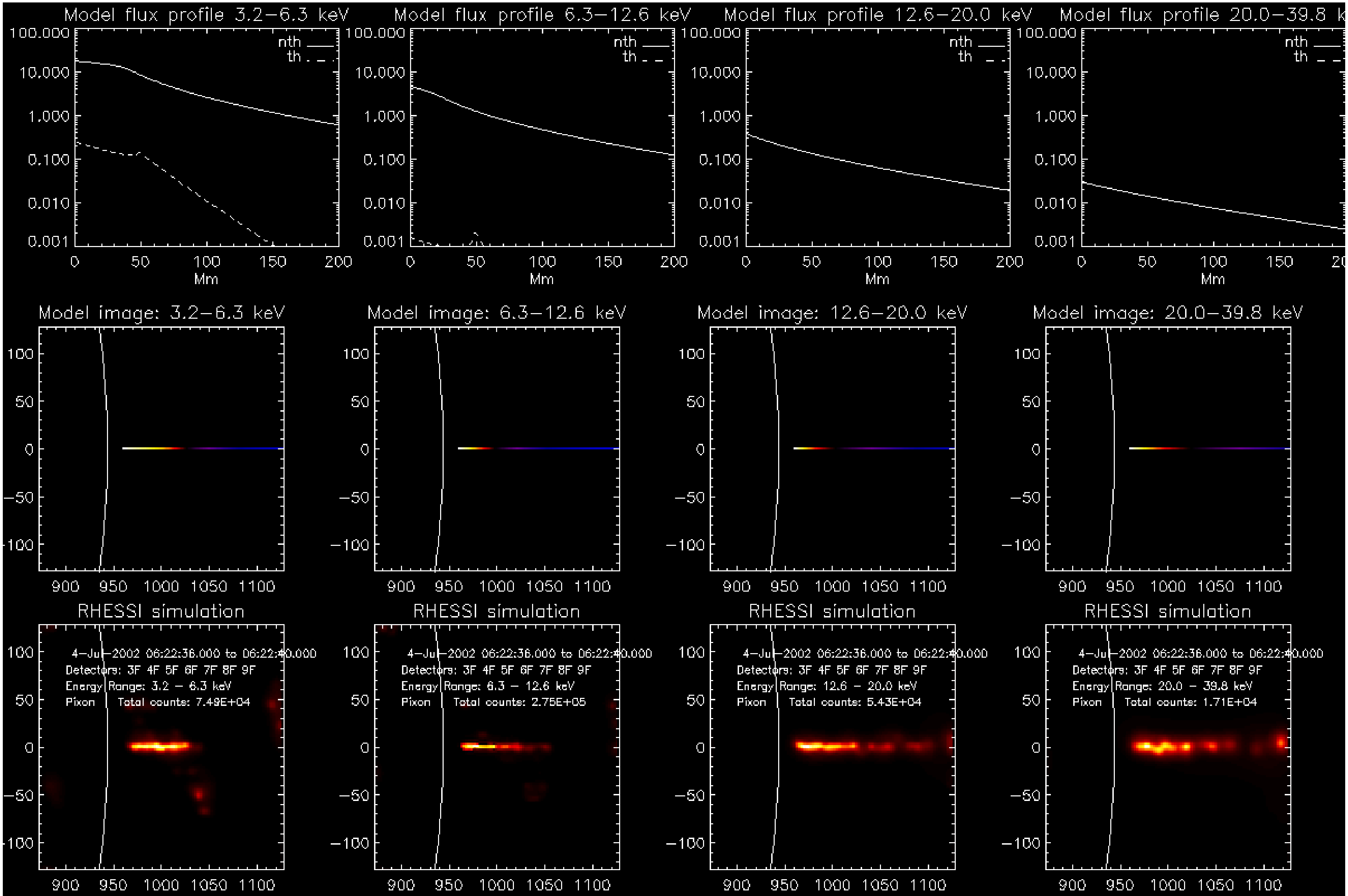
- $E_{th} = 3\, k_B T\, n V$
- $\tau_{cond} \sim 3\, k_B\, n\, L^2\, T^{-5/2}$
- $(\;\; \tau_{rad} = 3 k_B T / n / \Lambda(T) \;\;)$

$$T_{eq} \propto \left(\frac{P_{nth}}{L} \right)^{2/7}$$

L = heat conductivity scale length for losses
~ height above photosphere for "down" beam
~ coronal density scale height for "up" beam
→ upper limit for T

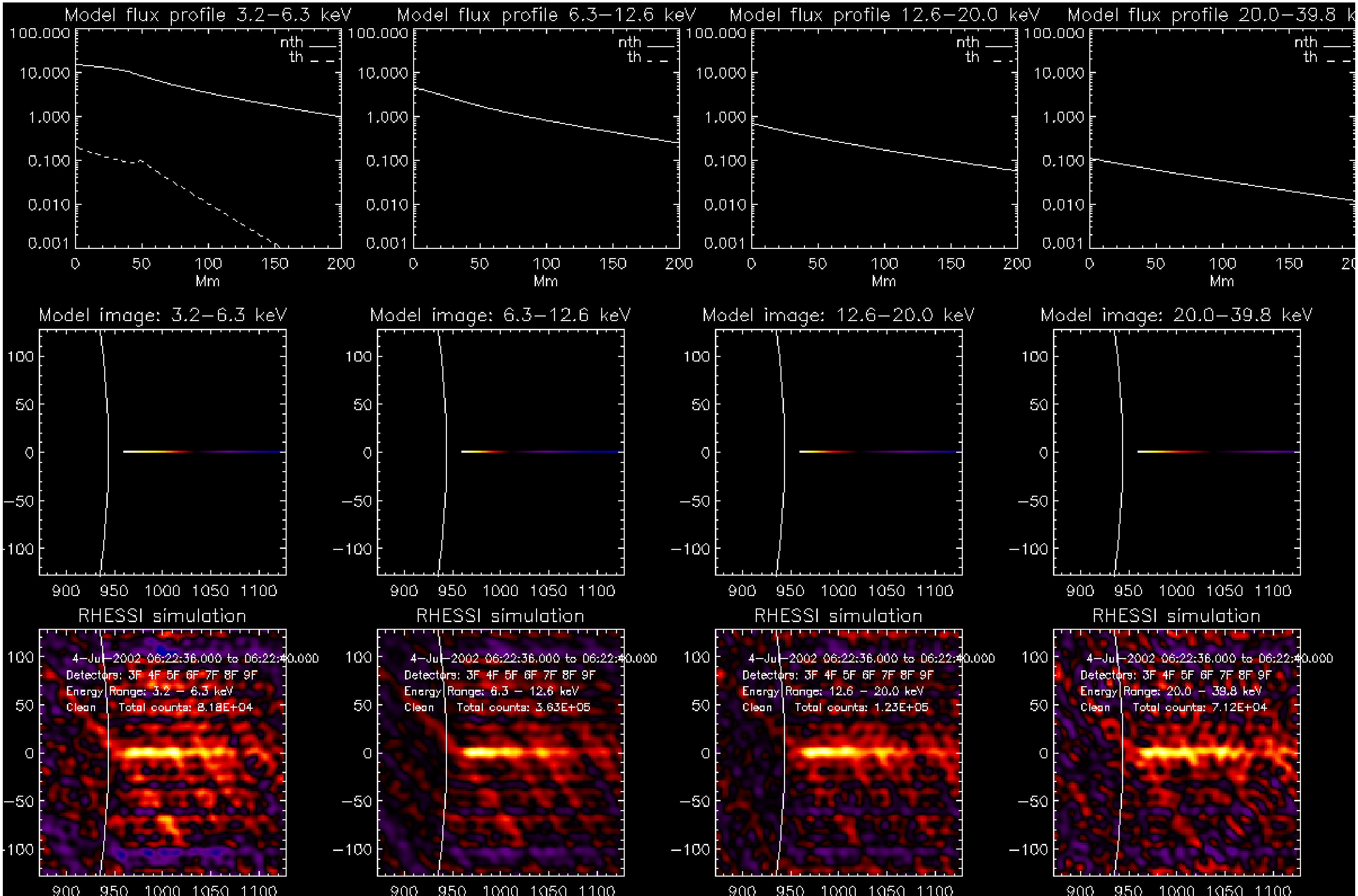


Electron beam propagates radially outward, in a barometric atmosphere, starting at n_0=5 ·10^9 cm^{-3}.
A_{50}=1.3x10^{33} (50-keV electrons)/s/keV, δ=4, Eco=10 keV → $N_{>Eco}$= 2.7x10^{36} electrons/s

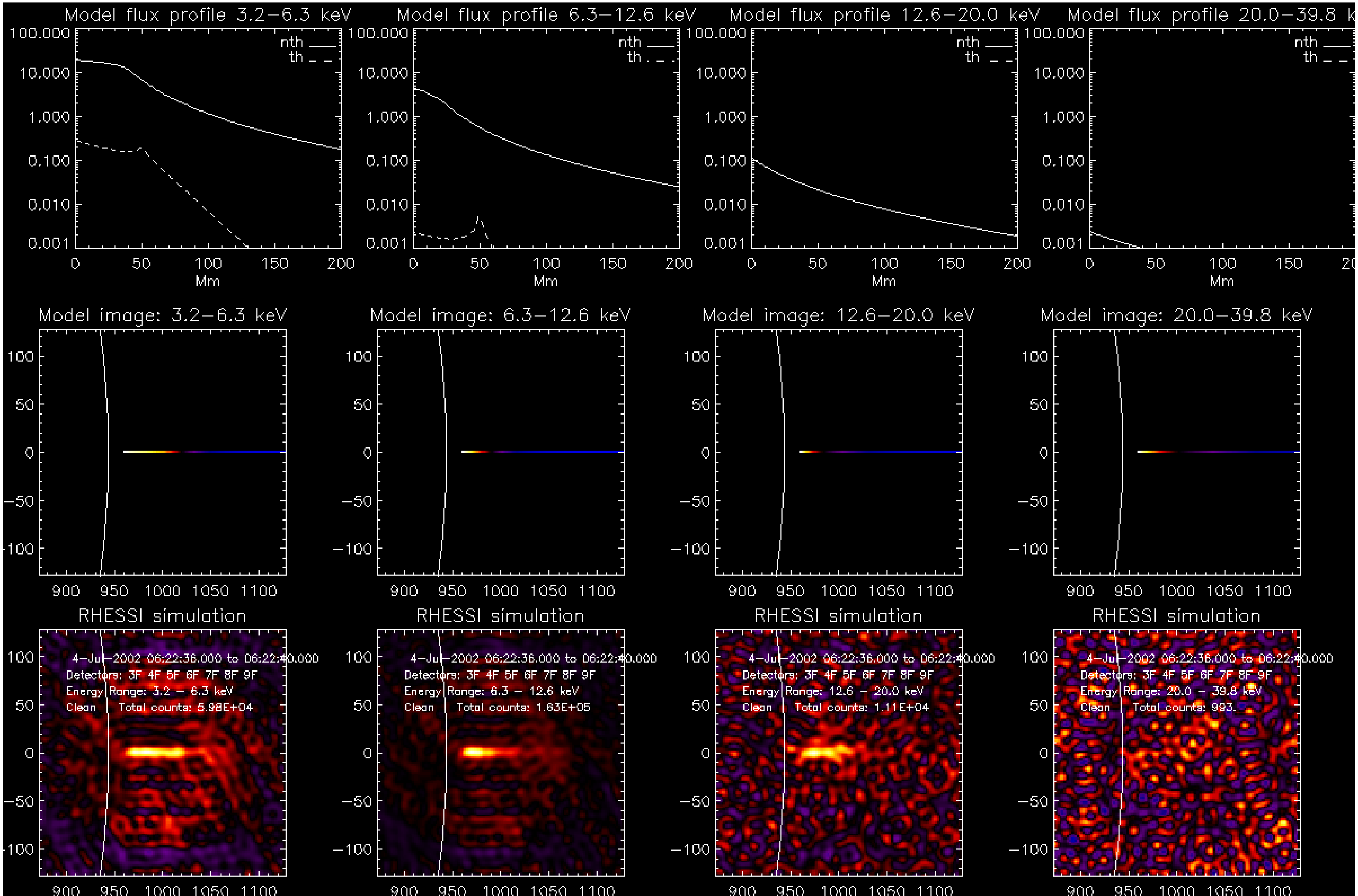


Model flux profile 3.2–6.3 keV
Model flux profile 6.3–12.6 keV
Model flux profile 12.6–20.0 keV
Model flux profile 20.0–39.8 keV
nth
th
Mm
Model image: 3.2–6.3 keV
Model image: 6.3–12.6 keV
Model image: 12.6–20.0 keV
Model image: 20.0–39.8 keV
RHESSI simulation
4-Jul-2002 06:22:36.000 to 06:22:40.000
Detectors: 3F 4F 5F 6F 7F 8F 9F
Energy Range: 3.2 – 6.3 keV
Pixon Total counts: 7.49E+04
Energy Range: 6.3 – 12.6 keV
Pixon Total counts: 2.75E+05
Energy Range: 12.6 – 20.0 keV
Pixon Total counts: 5.43E+04
Energy Range: 20.0 – 39.8 keV
Pixon Total counts: 1.71E+04

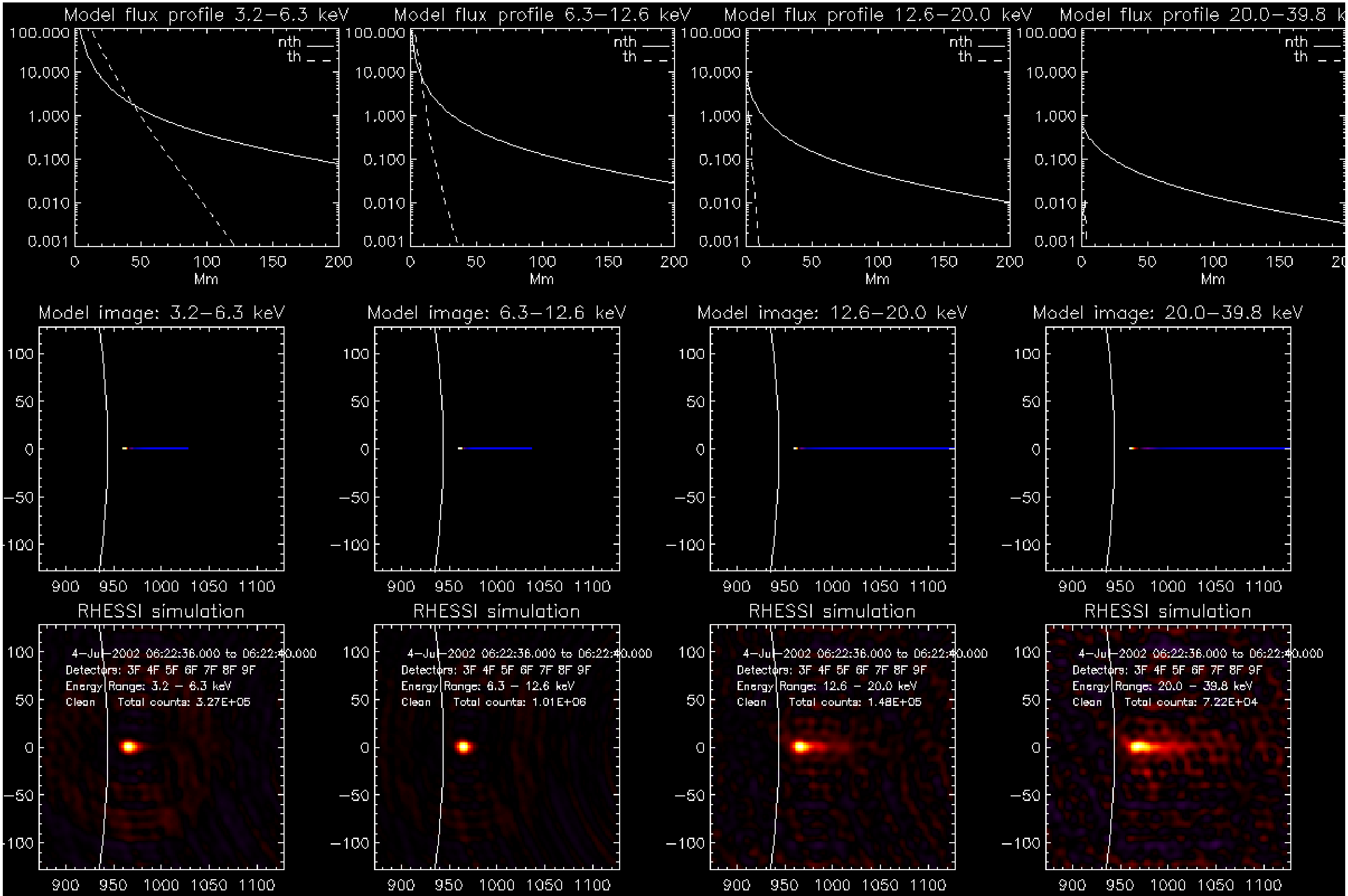
Pixon…



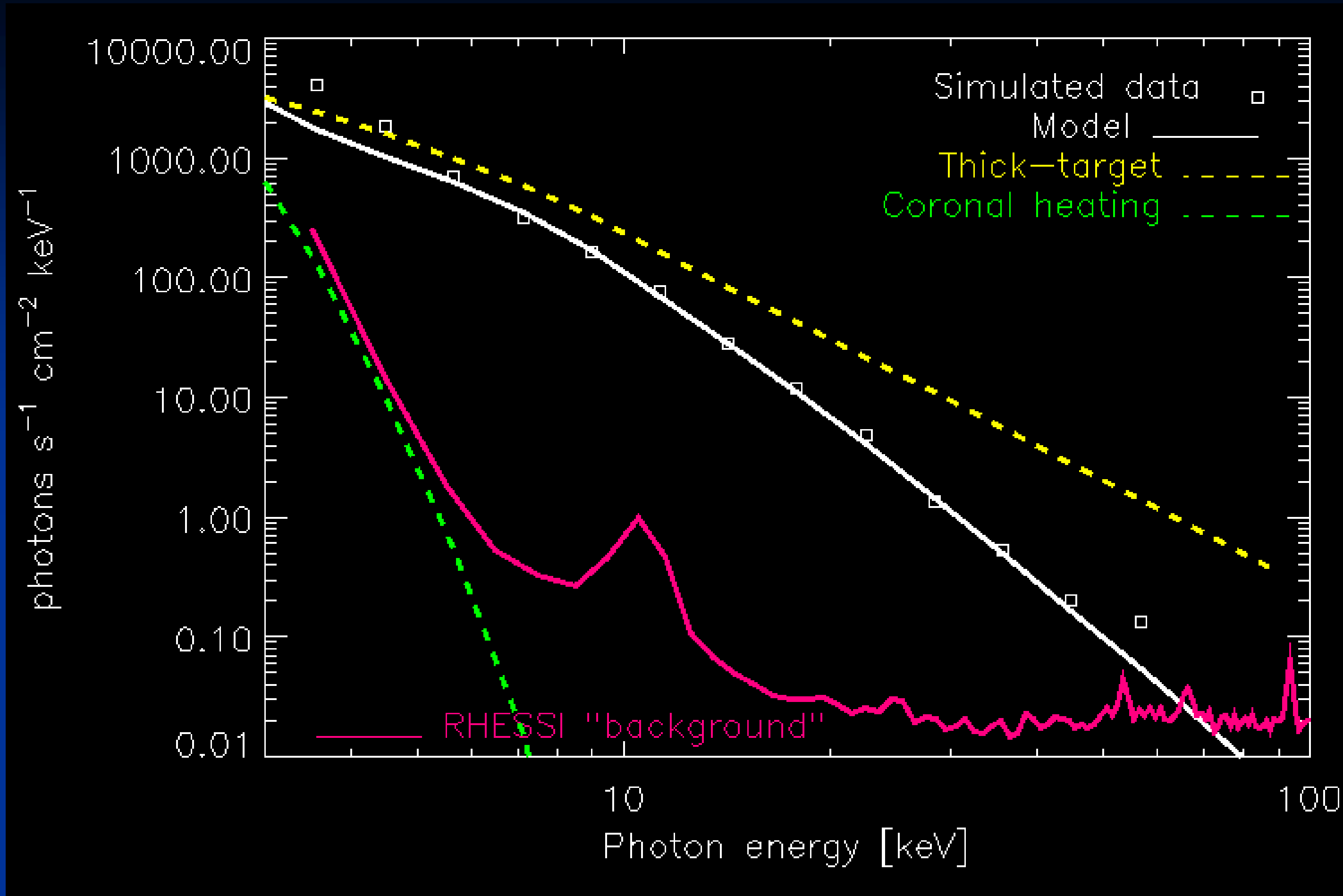
$\delta=2.5$ (same Eco, same $N_{>Eco}$)



$\delta=7$ (→ elongated structure less obvious)



$N_0=10^{11}$ cm^{-3} (→ elongated structure less obvious)



RHESSI Countrates:

$\delta=4$

Eco=10keV

$N_{>Eco} = 2.7x10^{36}$ e/s

Energy band	*[cts/s/det] above background*	
	Atten. State 0	*Atten. State 1*
3-6 keV	*578*	*0.3*
6-12 keV	*3291*	*101*
12-25 keV	*843*	*347*
25-50 keV	*80.3*	*70*
50-100 keV	*6.5*	*6.3*

Summary 1: Modeling

- Flare-like "upwards-going" coronal electron beams should be observable
- Coronal beam heating due to beam only observable when local densities are high (10^{11} cm^{-3})
- Best candidates are occulted flares (→ limb)
- At limb, elongated structures are expected (best: small δ)

Observations:

- Start point: list of decimetric radio bursts from Phoenix-2 spectrometer (ETH Zurich)
- → 867 type III bursts between RHESSI launch and June 2005.
- 326 were also observed by RHESSI, with attenuator state 0.
- Take the ones that have X-ray sources above the solar limb

→ 29 candidates

Some ancillary results:

- From 2003/04/10 to 2004/01/11
- Out of 62 Type III bursts, 60 occurred during HXR peaks:

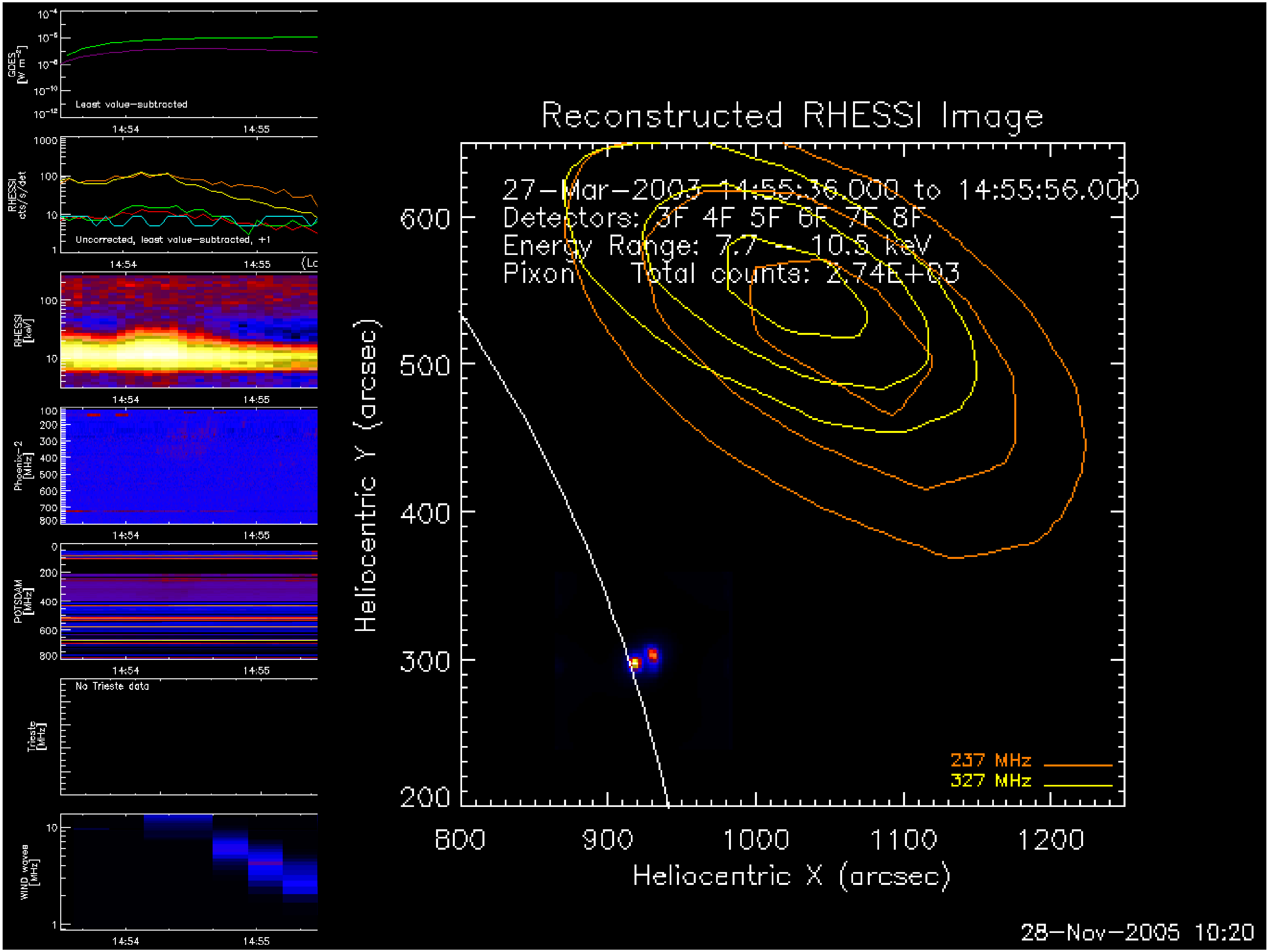
  24 occur within +/-30 degrees longitude

  24 between [30,60] and [-30,-60] degrees

  12 beyond +/-60 degrees

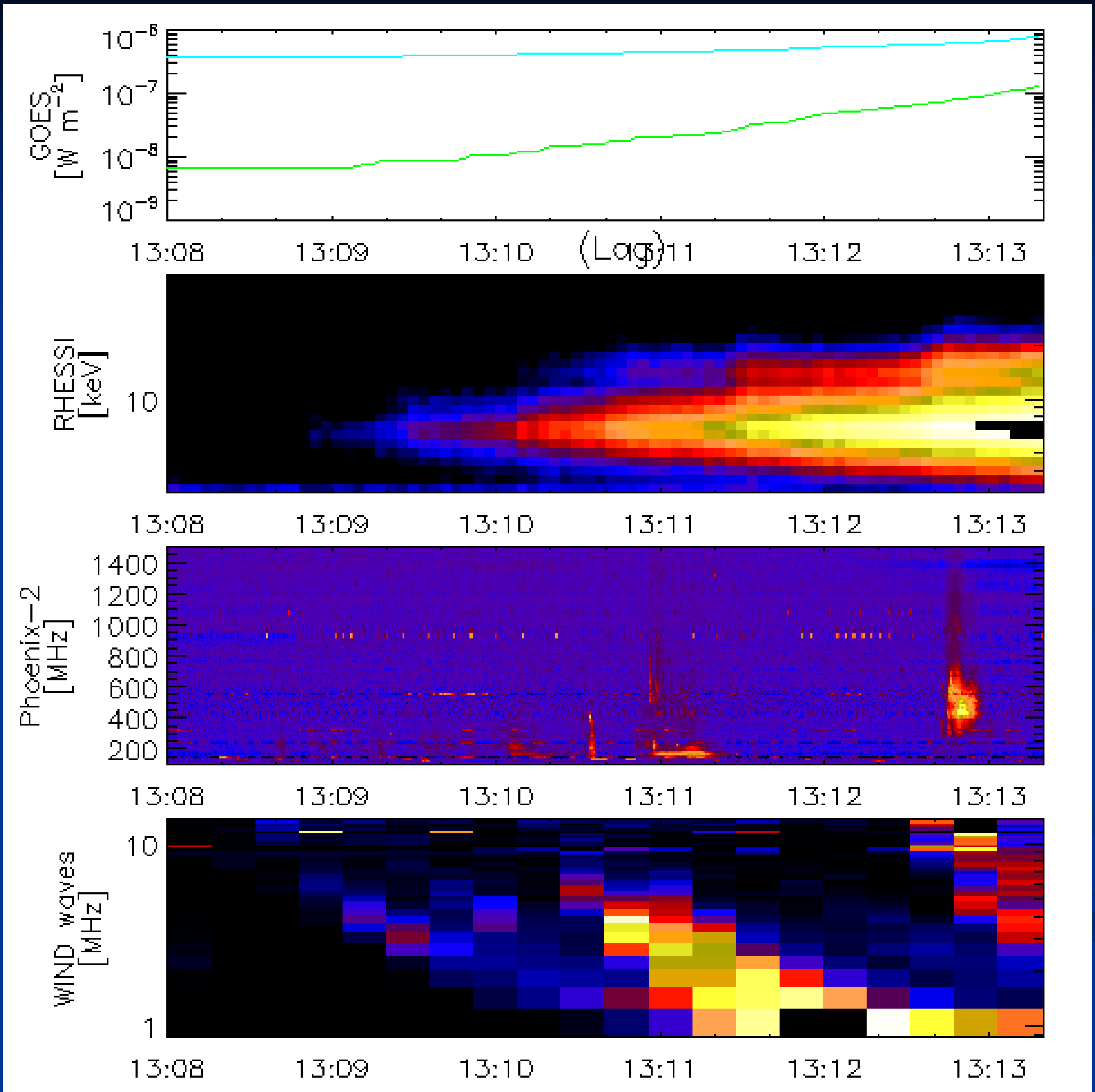
  2 have no RHESSI flare associated

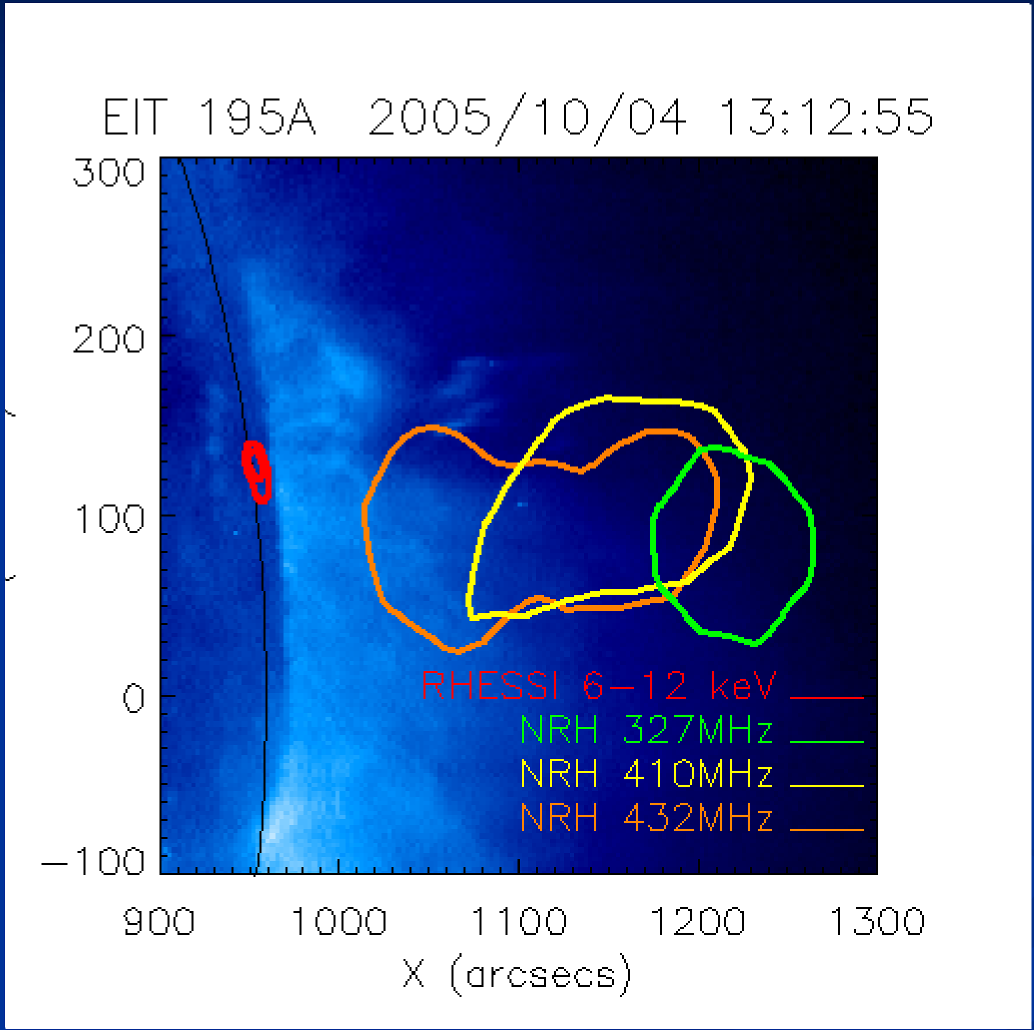
  (positions determined by X-ray sources!)
- Most Type IIIs are well correlated with HXR peaks: they occur ***roughly*** at same time.
- Type III burst simultaneous with “above the limb” flares occur seldom (directivity effects?).



Reconstructed RHESSI Image
27-Mar-2003 14:55:36.000 to 14:55:56.000
Detectors: 3F 4F 5F 6F 7F 8F
Energy Range: 7.7 - 10.5 keV
Pixon Total counts: 2.74E+03
Heliocentric Y (arcsec)
Heliocentric X (arcsec)
237 MHz
327 MHz
28-Nov-2005 10:20
GOES [W m⁻²]
Least value-subtracted
RHESSI cts/s/det
Uncorrected, least value-subtracted, +1
RHESSI [keV]
Phoenix-2 [MHz]
POTSDAM [MHz]
No Trieste data
Trieste [MHz]
WIND waves [MHz]
14:54
14:55

2003/10/04 13:16




EIT 195A 2005/10/04 13:12:55
300
200
100
0
−100
900
1000
1100
1200
1300
X (arcsecs)
RHESSI 6−12 keV
NRH 327MHz
NRH 410MHz
NRH 432MHz

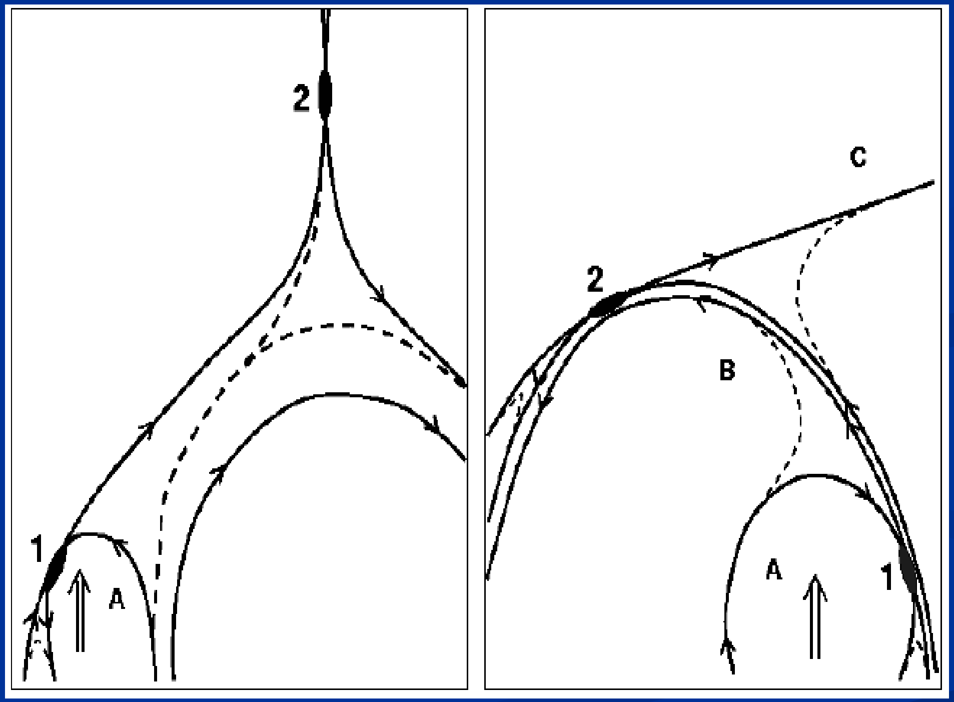
Conclusion so far…

- No clear Type IIIs associated with limbic electron beams propagating outwards (using X-rays as proxy) have been found so far. Statistically, a few were expected. Will use NRH 900ms data…
- RHESSI imaging requires ~10^{35} electrons/s
- For detection, about 5×10^{33} electrons/s [above 10 keV] are needed. Just the fact that Type IIIs and HXR lightcurves are *rarely* time-correlated means we rarely have that many electrons in the Type III-producing beam…
- In agreement with previous estimations: interplanetary Type III-emitting electron beams contain only ~10^{31} electrons/s (Lin, 1973) : product of a (secondary) reconnection process higher up in the corona?

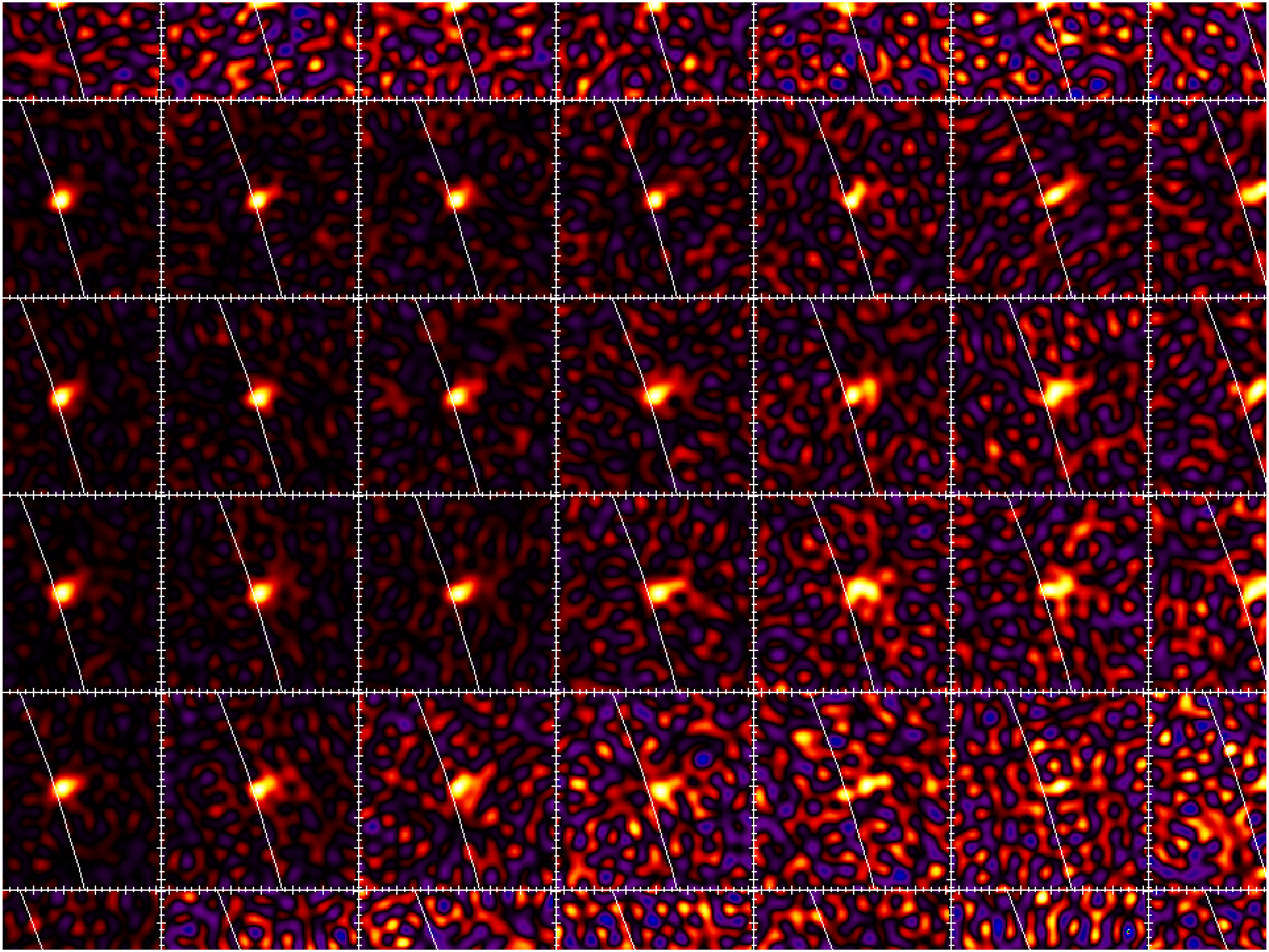
Two (simultaneous) reconnection sites?

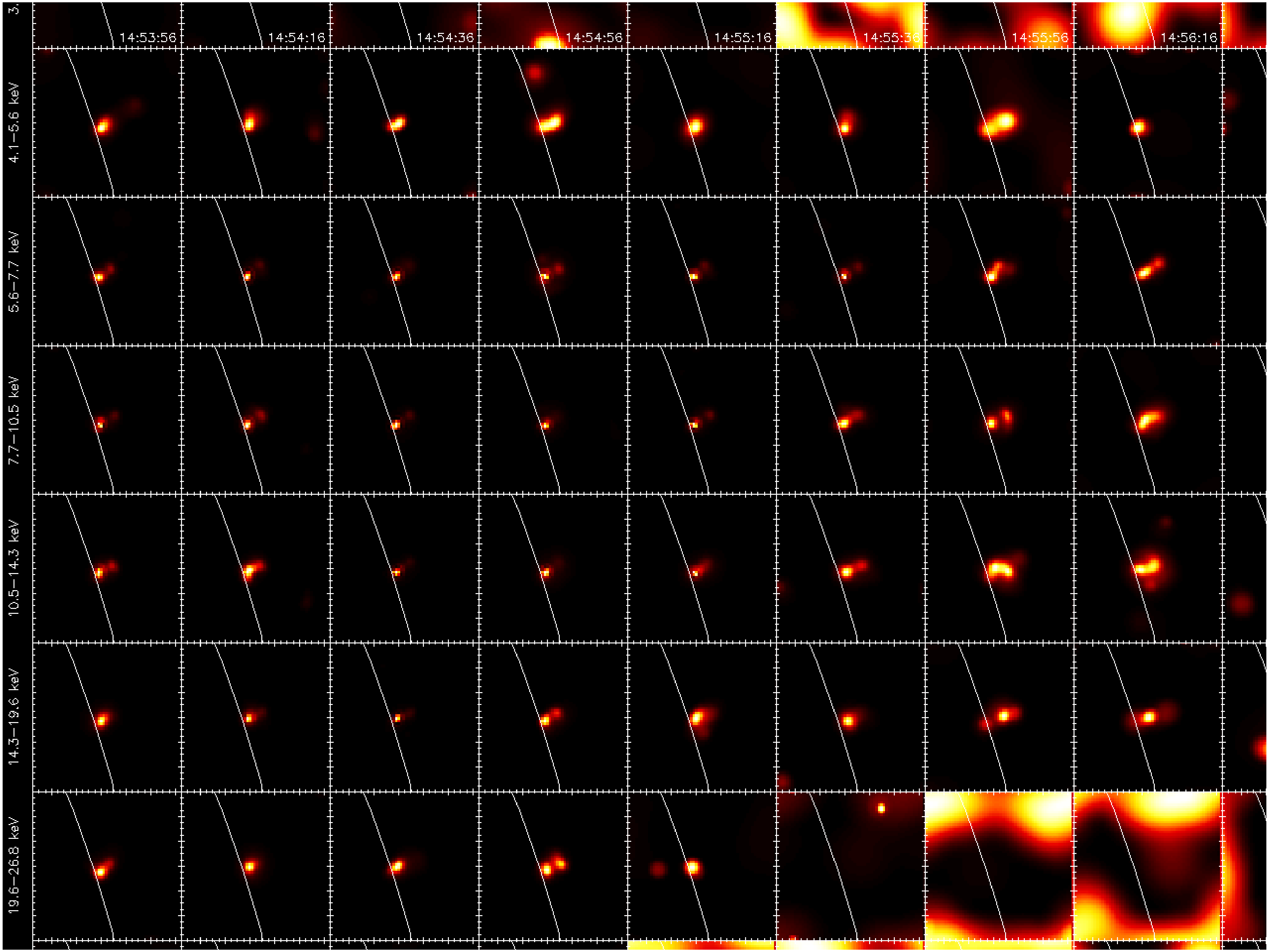
2: Secondary reconnection site:
~10^{31} electrons/s

1: Main energy release site
(main driver):
$10^{35\text{-}36}$ electrons/s

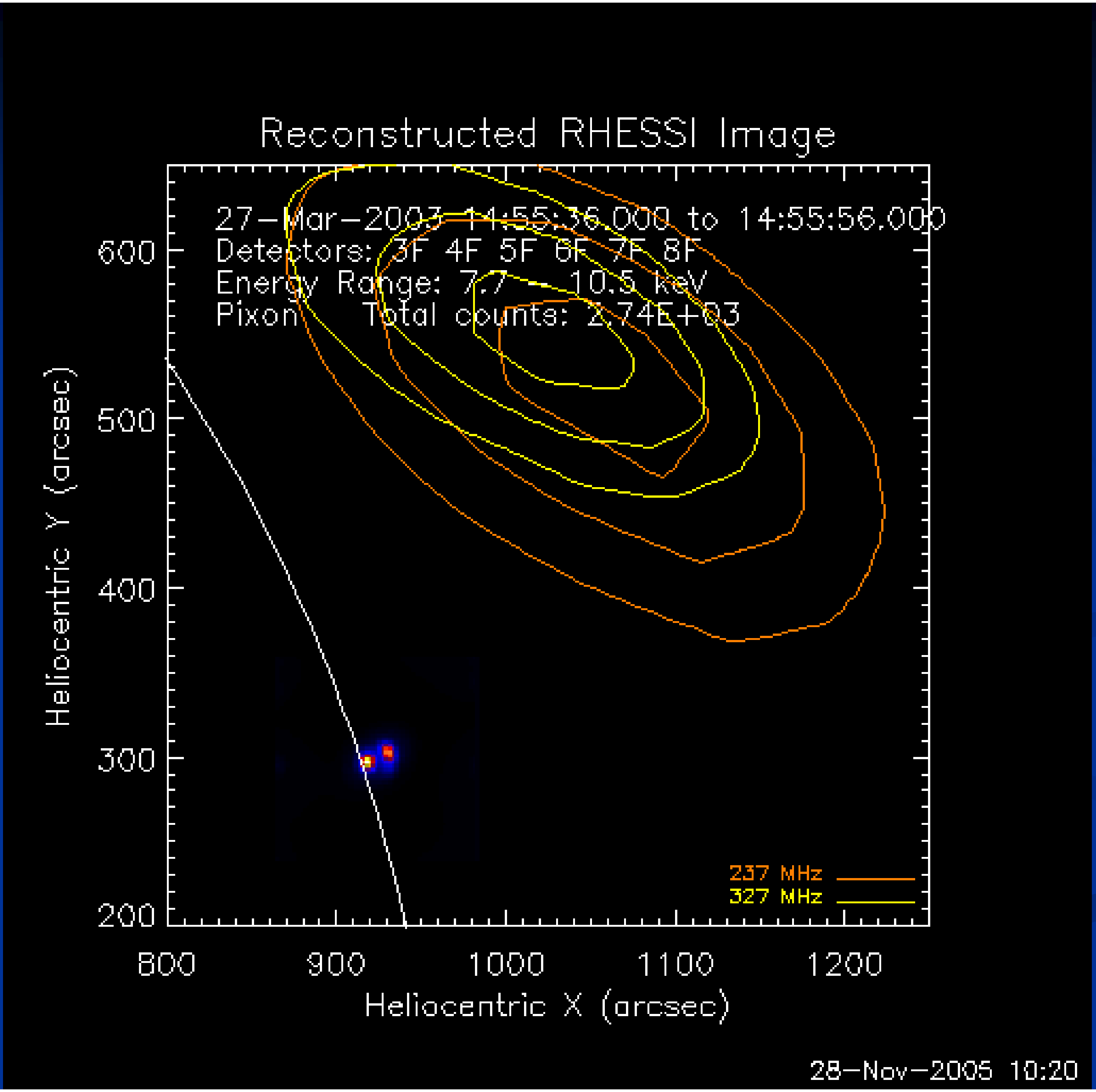


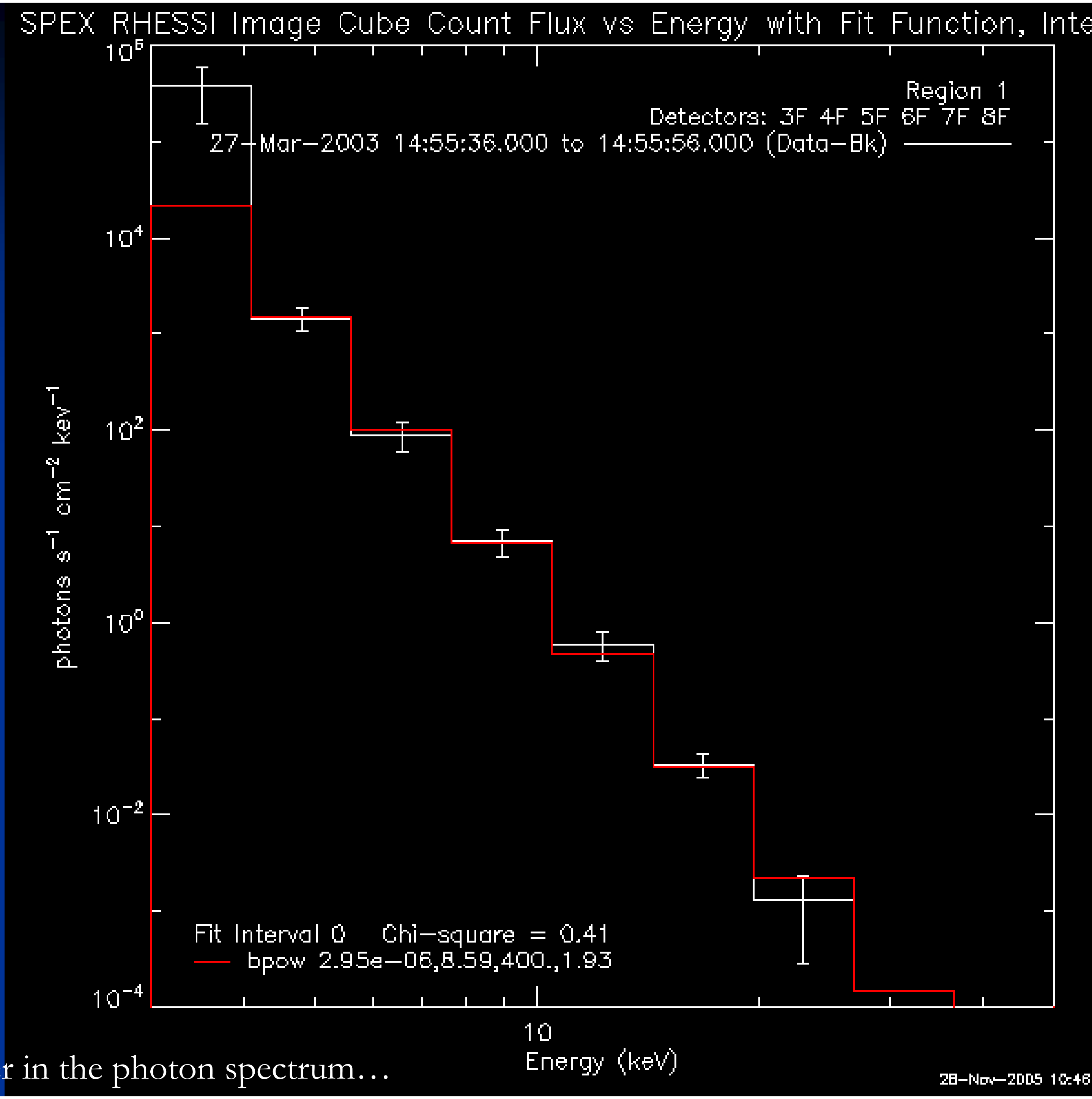
Benz et al., 2005



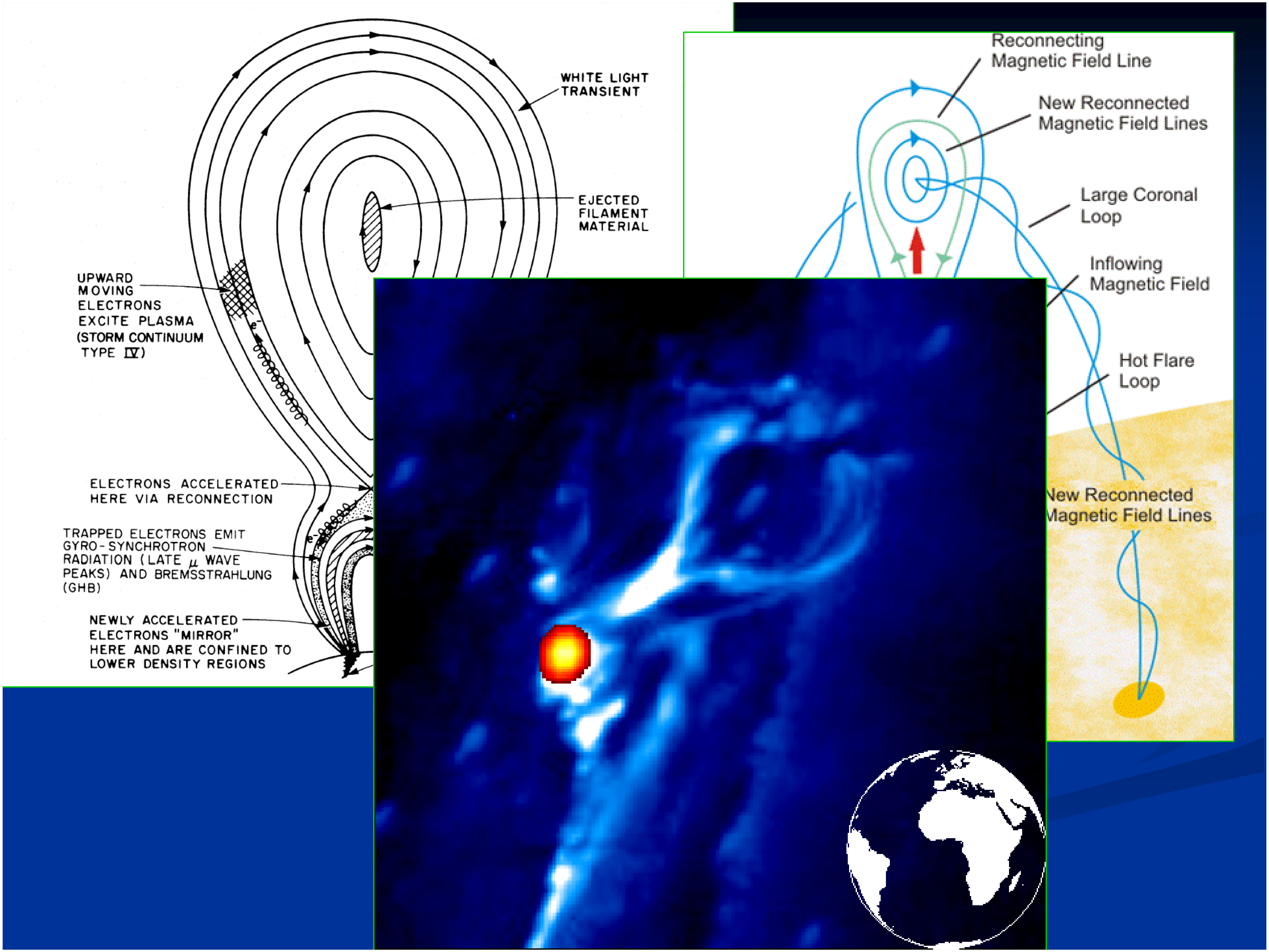


3.
4.1–5.6 keV
5.6–7.7 keV
7.7–10.5 keV
10.5–14.3 keV
14.3–19.6 keV
19.6–26.8 keV
14:53:56
14:54:16
14:54:36
14:54:56
14:55:16
14:55:36
14:55:56
14:56:16

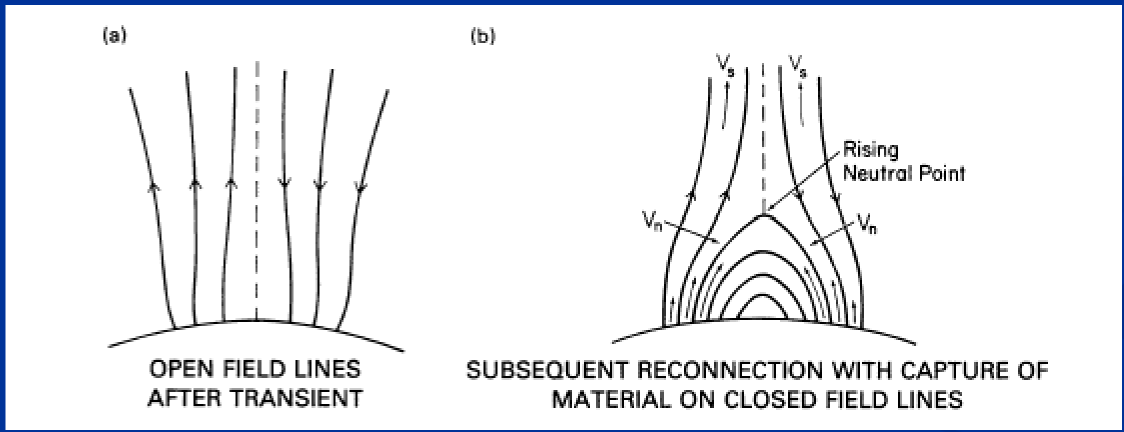

Reconstructed RHESSI Image
27-Mar-2003 14:55:36.000 to 14:55:56.000
Detectors: 3F 4F 5F 6F 7F 8F
Energy Range: 7.7 - 10.5 keV
Pixon Total counts: 2.74E+03
Heliocentric Y (arcsec)
600
500
400
300
200
800
900
1000
1100
1200
Heliocentric X (arcsec)
237 MHz
327 MHz
28-Nov-2005 10:20

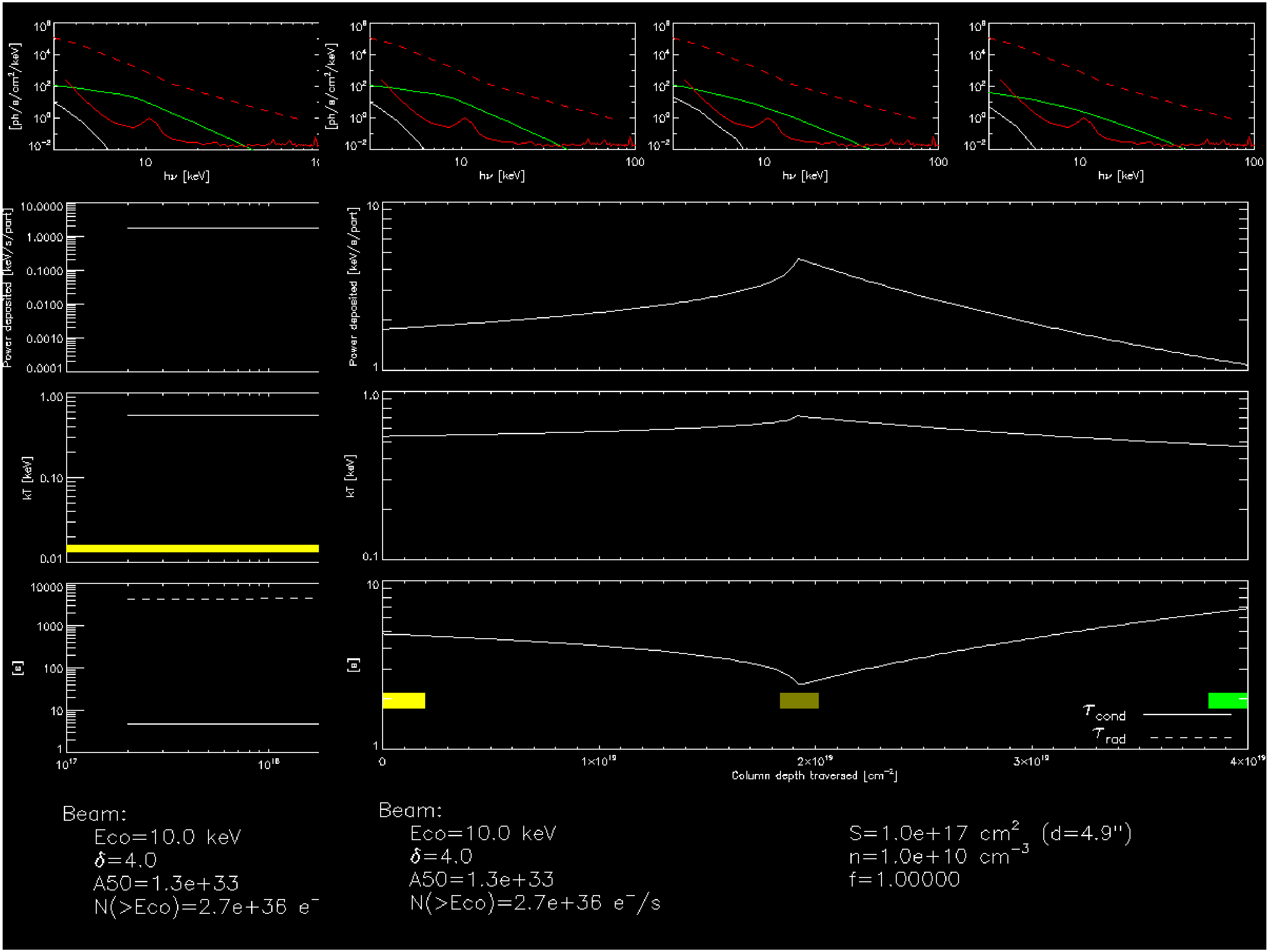


No turnover in the photon spectrum…

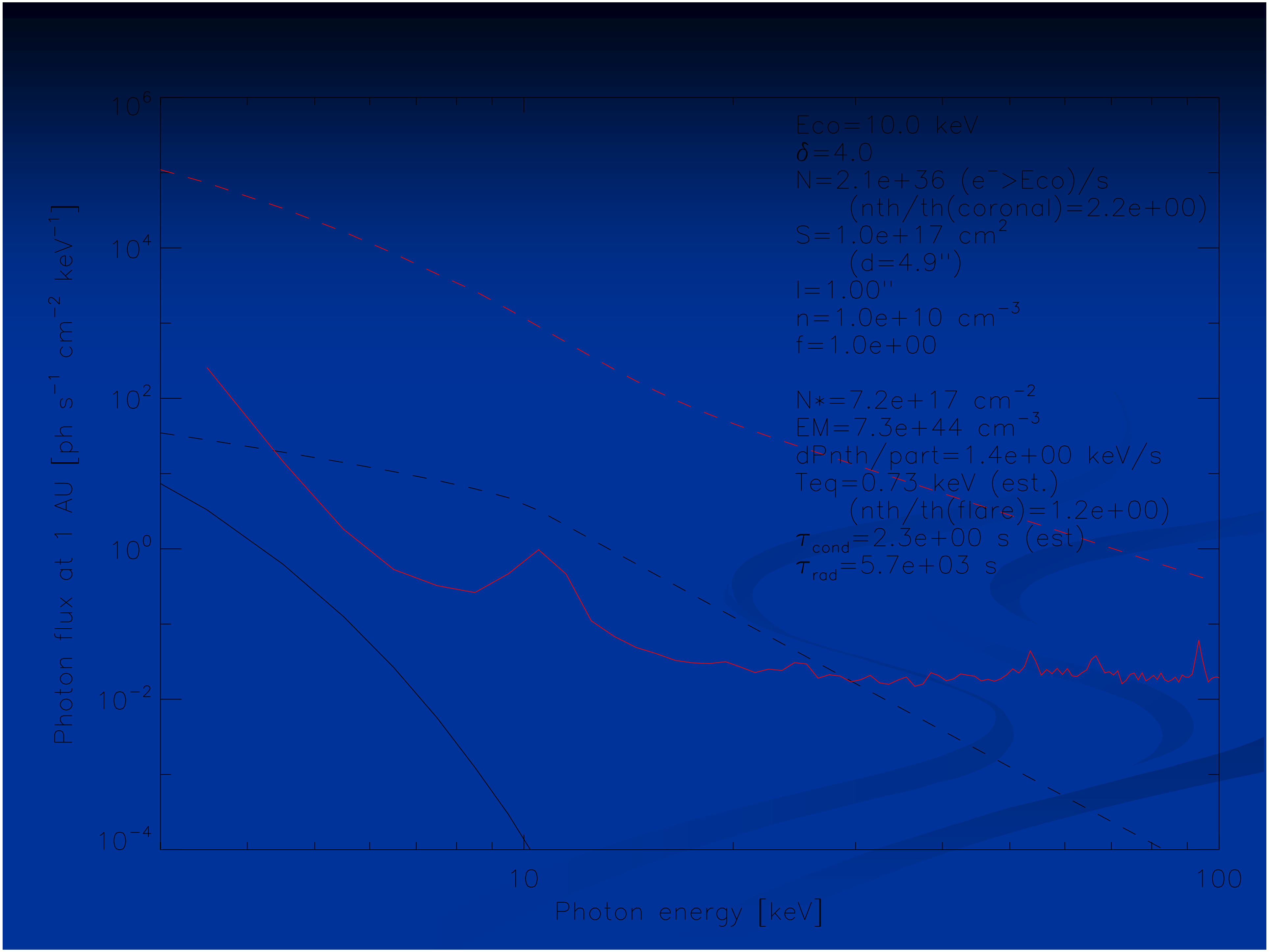

WHITE LIGHT TRANSIENT
EJECTED FILAMENT MATERIAL
UPWARD MOVING ELECTRONS EXCITE PLASMA (STORM CONTINUUM TYPE IV)
ELECTRONS ACCELERATED HERE VIA RECONNECTION
TRAPPED ELECTRONS EMIT GYRO-SYNCHROTRON RADIATION (LATE μ WAVE PEAKS) AND BREMSSTRAHLUNG (GHB)
NEWLY ACCELERATED ELECTRONS "MIRROR" HERE AND ARE CONFINED TO LOWER DENSITY REGIONS
Reconnecting Magnetic Field Line
New Reconnected Magnetic Field Lines
Large Coronal Loop
Inflowing Magnetic Field
Hot Flare Loop
New Reconnected Magnetic Field Lines

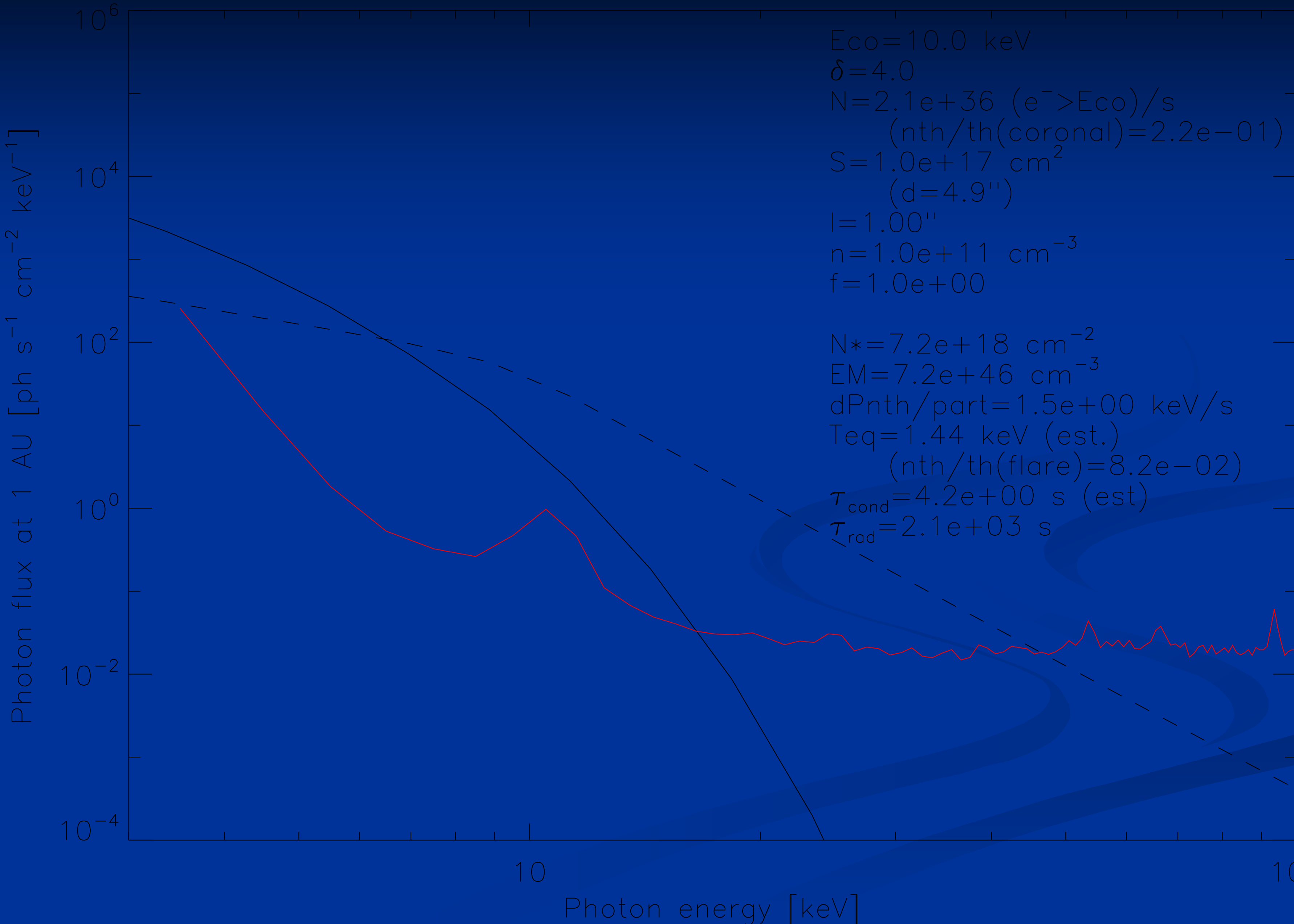
Simplest reconnection model is probably wrong:



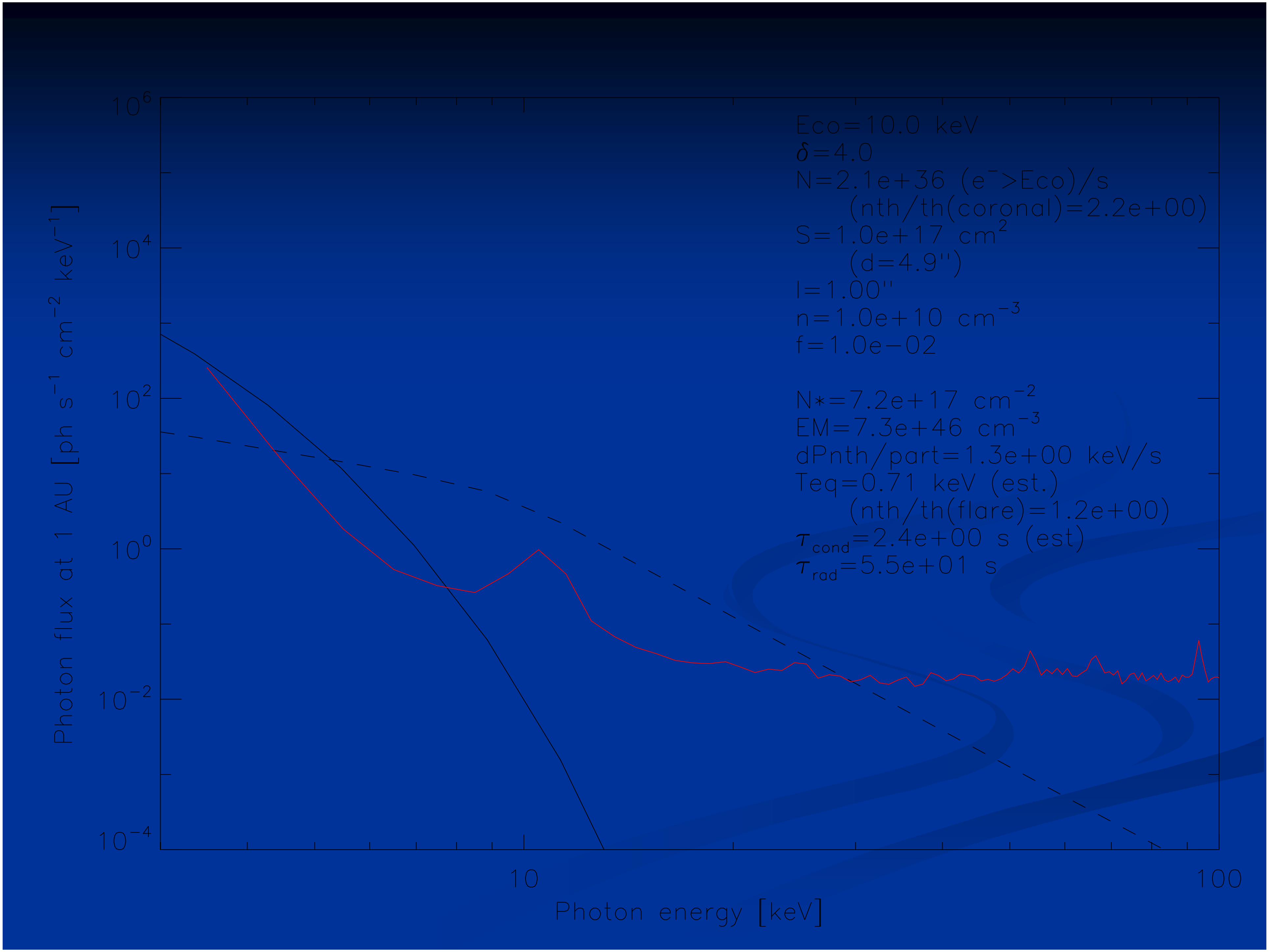


[ph/s/cm^2/keV]
hν [keV]
Power deposited [keV/s/part]
kT [keV]
[s]
Column depth traversed [cm^{-2}]
τ_{cond}
τ_{rad}
Beam:
Eco=10.0 keV
δ=4.0
A50=1.3e+33
N(>Eco)=2.7e+36 e$^-$
Beam:
Eco=10.0 keV
δ=4.0
A50=1.3e+33
N(>Eco)=2.7e+36 e$^-$/s
S=1.0e+17 cm^2 (d=4.9")
n=1.0e+10 cm^{-3}
f=1.00000

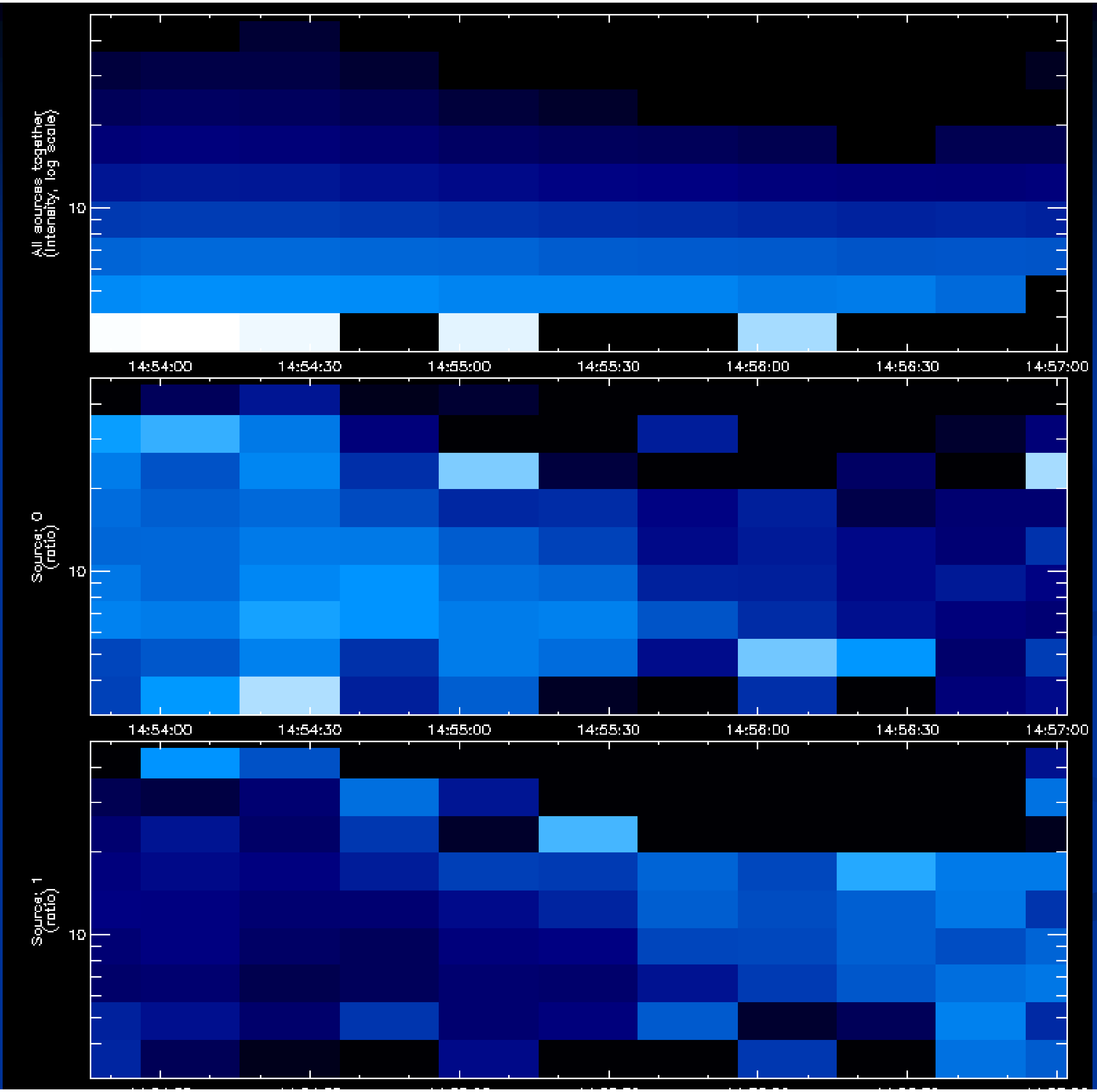

Eco=10.0 keV
δ=4.0
N=2.1e+36 (e⁻>Eco)/s
(nth/th(coronal)=2.2e+00)
S=1.0e+17 cm²
(d=4.9'')
l=1.00''
n=1.0e+10 cm⁻³
f=1.0e+00
N*=7.2e+17 cm⁻²
EM=7.3e+44 cm⁻³
dPnth/part=1.4e+00 keV/s
Teq=0.73 keV (est.)
(nth/th(flare)=1.2e+00)
τcond=2.3e+00 s (est)
τrad=5.7e+03 s
Photon flux at 1 AU [ph s⁻¹ cm⁻² keV⁻¹]
Photon energy [keV]
10⁶
10⁴
10²
10⁰
10⁻²
10⁻⁴
10
100

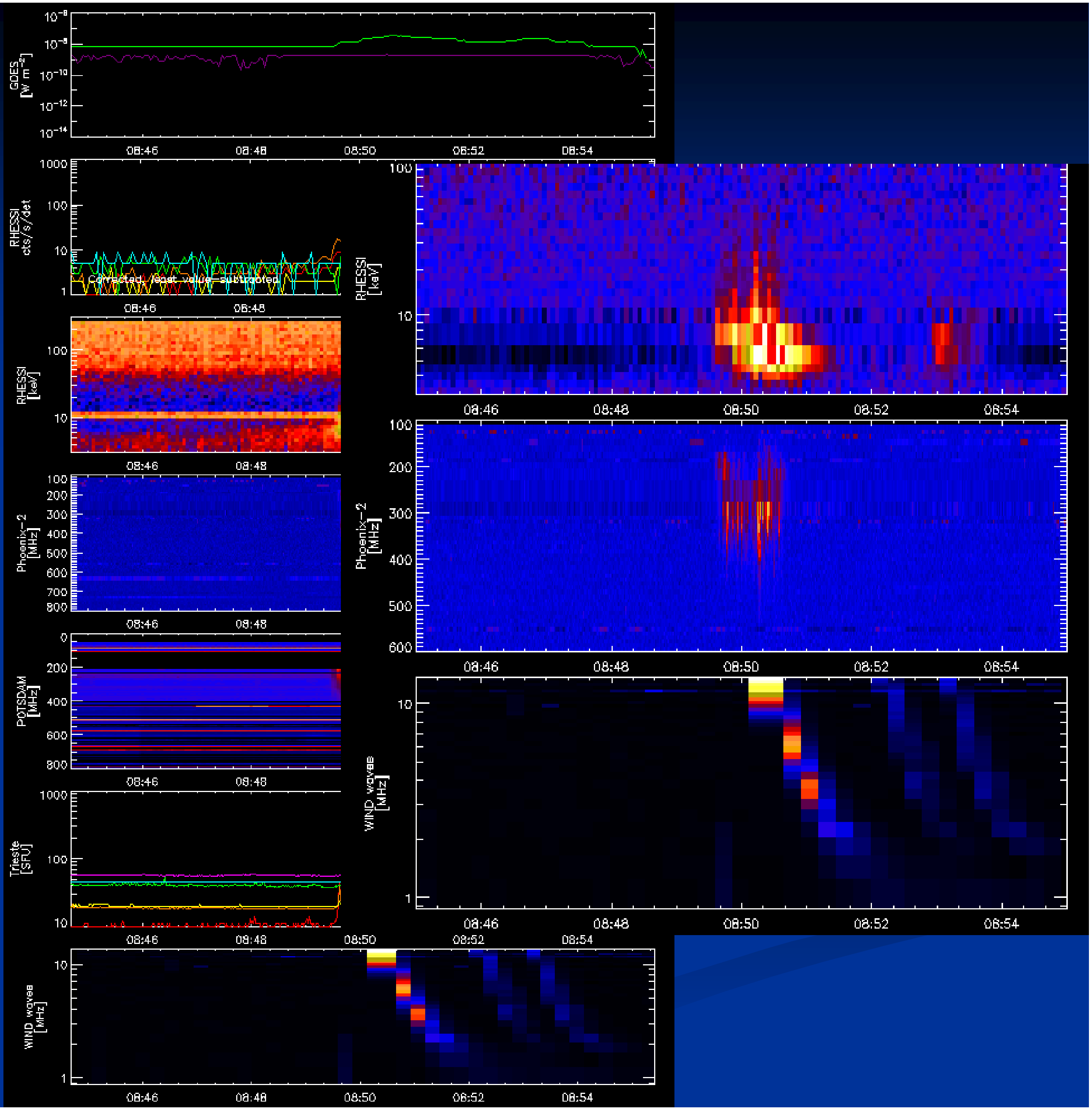


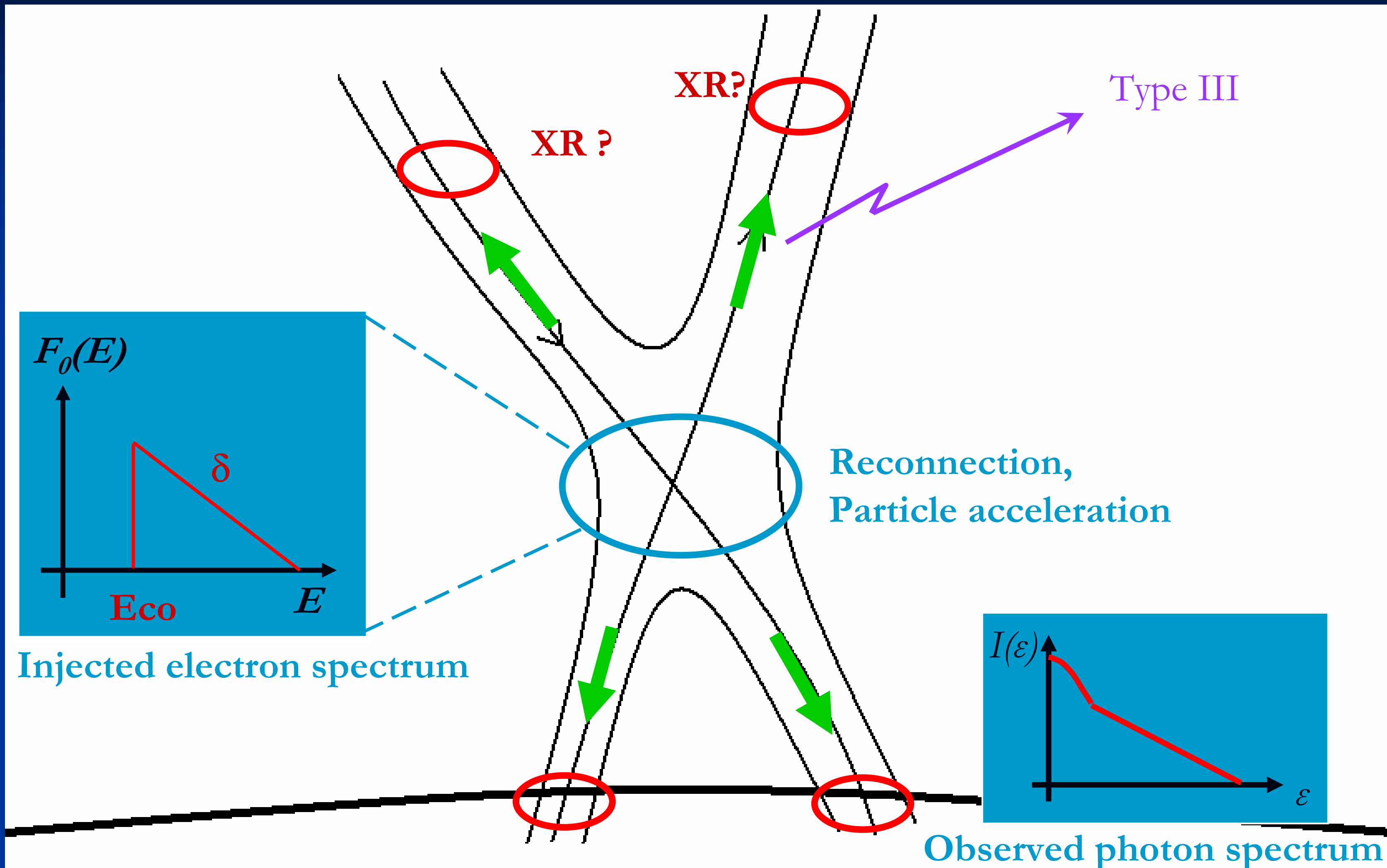
Eco=10.0 keV
δ=4.0
N=2.1e+36 (e⁻>Eco)/s
(nth/th(coronal)=2.2e−01)
S=1.0e+17 cm²
(d=4.9")
l=1.00"
n=1.0e+11 cm⁻³
f=1.0e+00
N*=7.2e+18 cm⁻²
EM=7.2e+46 cm⁻³
dPnth/part=1.5e+00 keV/s
Teq=1.44 keV (est.)
(nth/th(flare)=8.2e−02)
τcond=4.2e+00 s (est)
τrad=2.1e+03 s
Photon flux at 1 AU [ph s⁻¹ cm⁻² keV⁻¹]
Photon energy [keV]
10⁶
10⁴
10²
10⁰
10⁻²
10⁻⁴
10
100



Eco=10.0 keV
δ=4.0
N=2.1e+36 (e⁻>Eco)/s
(nth/th(coronal)=2.2e+00)
S=1.0e+17 cm²
(d=4.9'')
l=1.00''
n=1.0e+10 cm⁻³
f=1.0e−02
N*=7.2e+17 cm⁻²
EM=7.3e+46 cm⁻³
dPnth/part=1.3e+00 keV/s
Teq=0.71 keV (est.)
(nth/th(flare)=1.2e+00)
τcond=2.4e+00 s (est)
τrad=5.5e+01 s
Photon flux at 1 AU [ph s⁻¹ cm⁻² keV⁻¹]
Photon energy [keV]
10
100


All sources together
(intensity, log scale)
10
14:54:00
14:54:30
14:55:00
14:55:30
14:56:00
14:56:30
14:57:00
Source: 0
(ratio)
10
14:54:00
14:54:30
14:55:00
14:55:30
14:56:00
14:56:30
14:57:00
Source: 1
(ratio)
10


GOES [W m^-2]
RHESSI cts/s/det
Corrected, least value subtracted
RHESSI [keV]
Phoenix-2 [MHz]
POTSDAM [MHz]
Trieste [SFU]
WIND waves [MHz]
08:46
08:48
08:50
08:52
08:54


XR?
XR ?
Type III
$F_0(E)$
δ
Eco
E
Reconnection,
Particle acceleration
Injected electron spectrum
$I(\varepsilon)$
ε
Observed photon spectrum

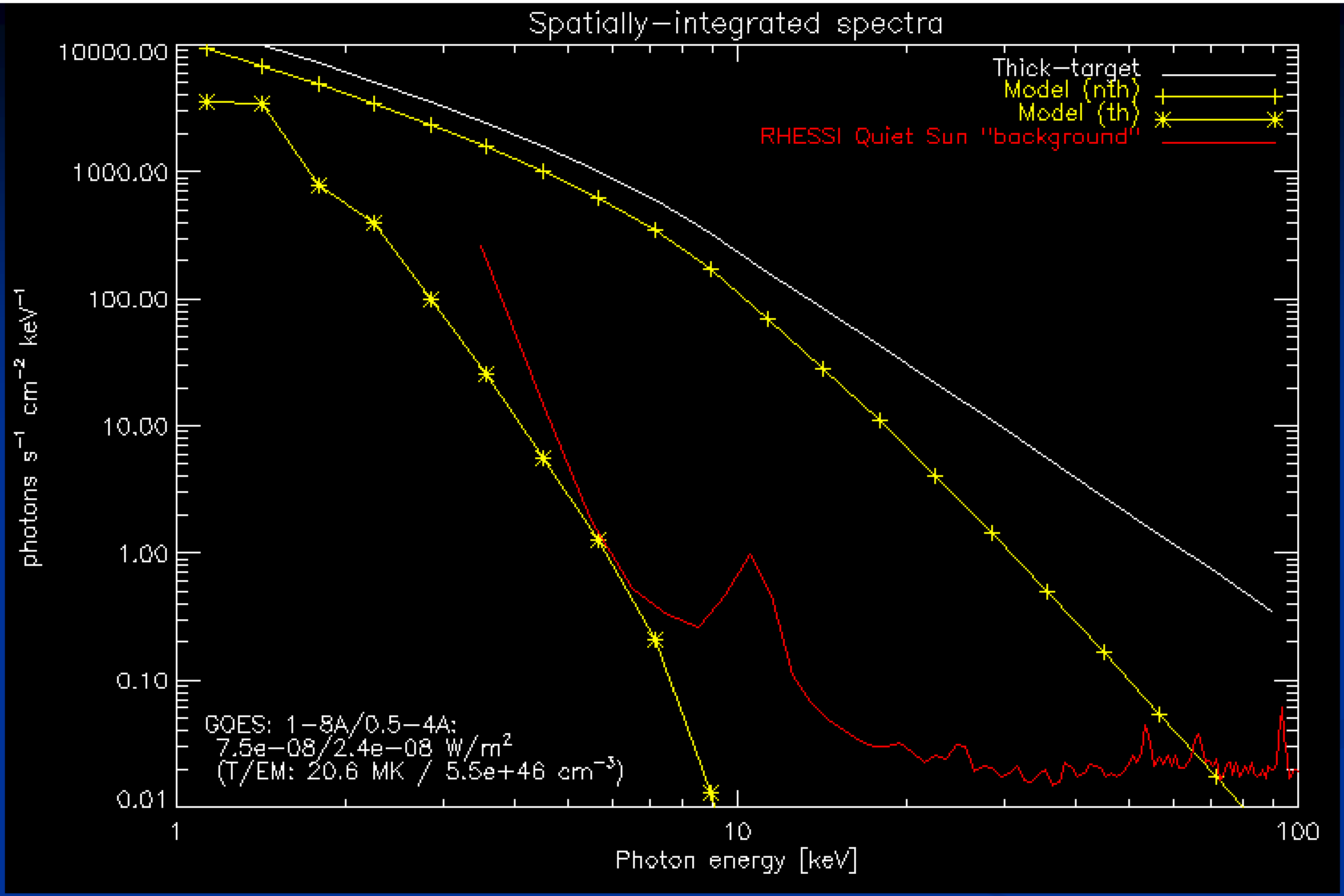
Non-thermal emission:

$$F_0(E) = \begin{cases} A \cdot E^{-\delta} & E > E_{CO} \\ 0 & E < E_{CO} \end{cases}$$

$$F(E,N) = \frac{E}{\sqrt{E^2 + 2KN}} F_0\left(\sqrt{E^2 + 2KN}\right)$$

Partial thick-target bremsstrahlung emission from every dV along the way (numerically)

P_{nth} : non-thermal power dumped in every dV along the way (numerically)



RHESSI Countrates:

$\delta=4$

Eco=10keV

$N_{>Eco} = 2.7\text{x}10^{36}$ e/s

Energy band	*[cts/s/det] above background* Atten. State 0	Atten. State 1
3-6 keV	*578*	*0.3*
6-12 keV	*3291*	*101*
12-25 keV	*843*	*347*
25-50 keV	*80.3*	*70*
50-100 keV	*6.5*	*6.3*

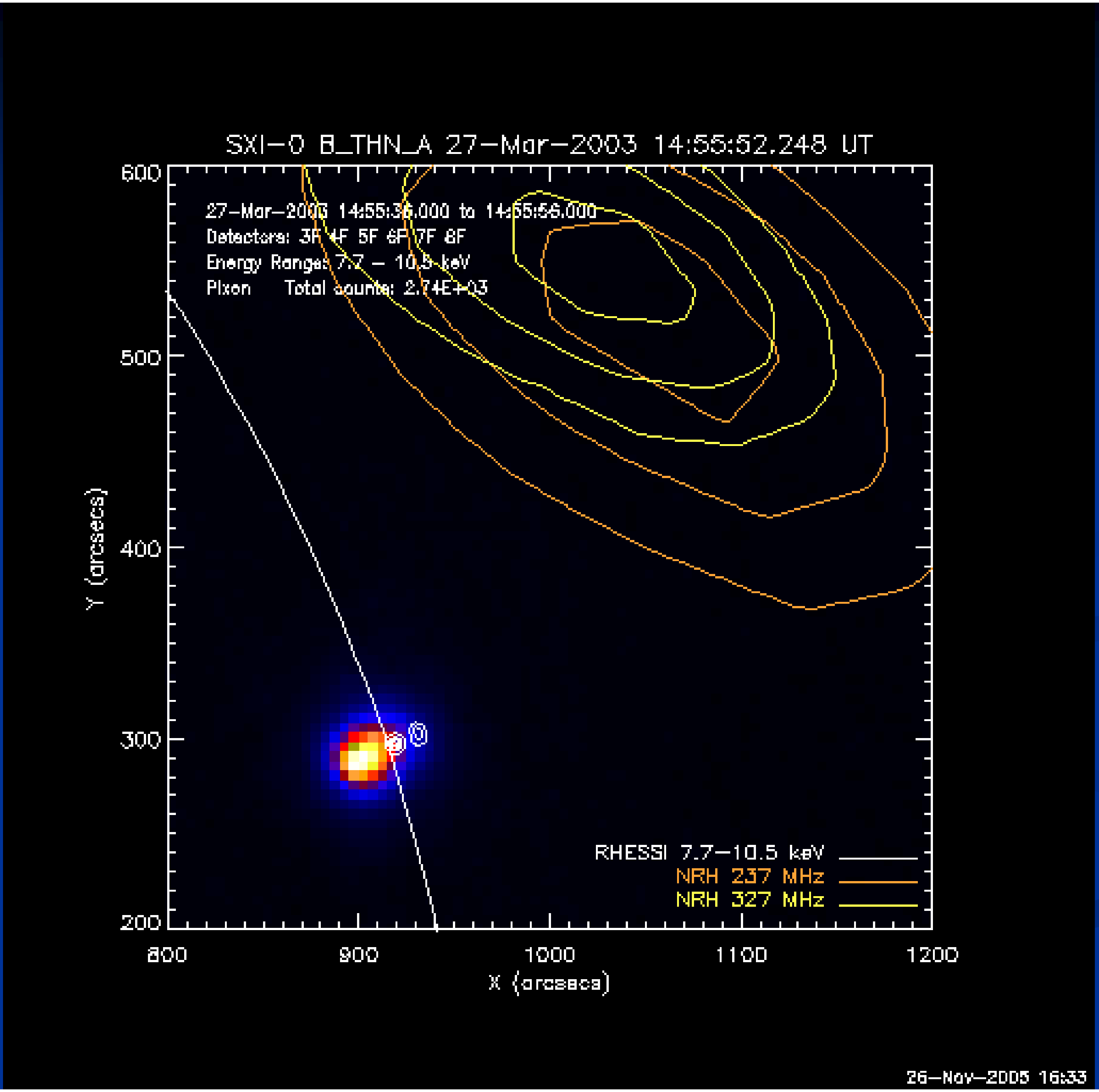
RHESSI 6-12 keV detection (attenuator state 0; typical δ=4, Eco=10 keV, $N_{>Eco}$=2.7x10^{36} e$^-$/s):

- Lightcurves, 5-sigma detection, 1-s integration:

  $N_{>Eco} \geq 5\text{x}10^{33}$ electrons/s [above 10 keV]

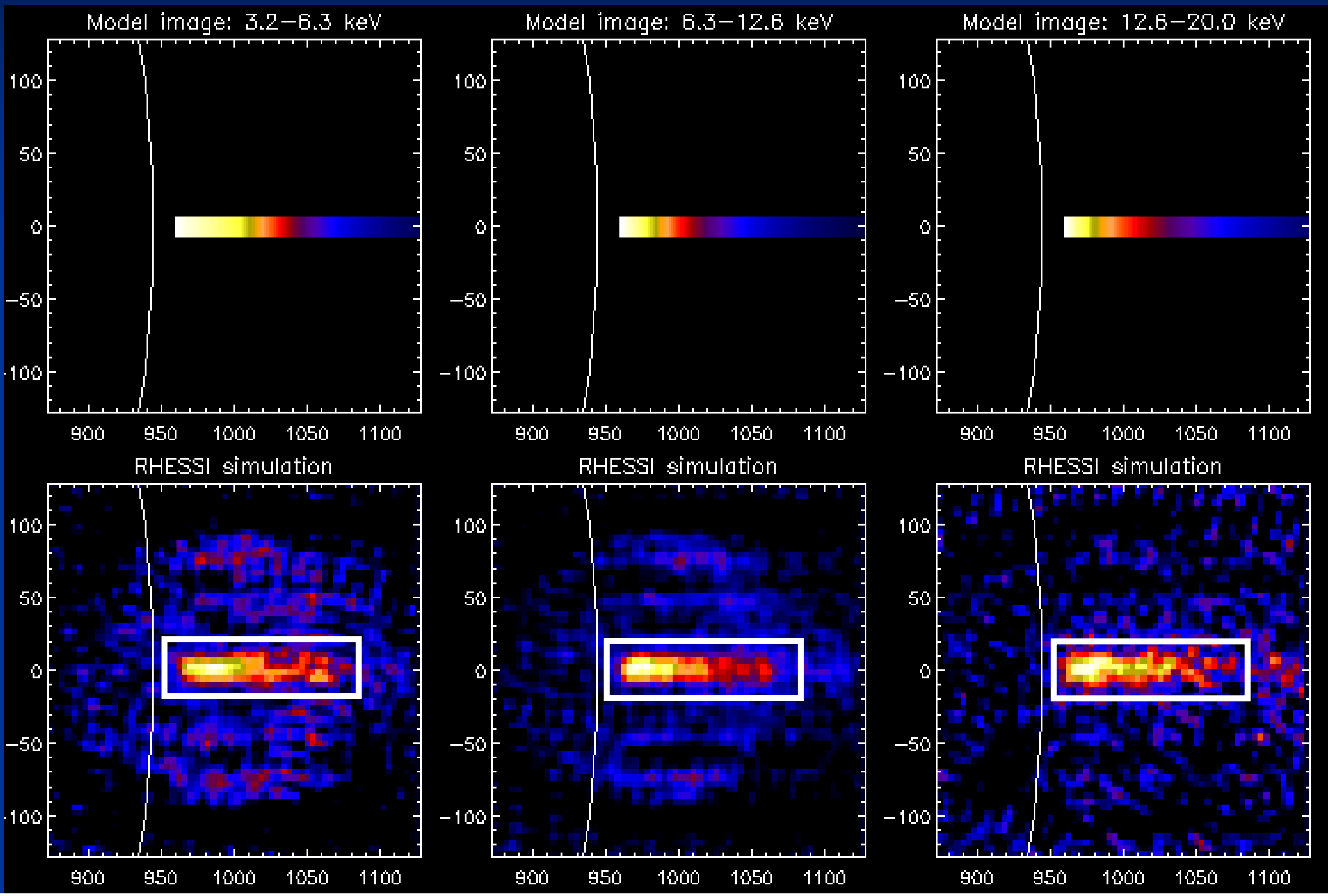
  (increases noticeably when both δ and Eco increase)
- Lin, 1974: ~10^31 electrons/s in Type IIIs…→ could detect them if a group,… but looks like we will never image them…
- Imaging, ~1000 cts/det over 4 seconds:

  $N_{>Eco} \geq 2\text{x}10^{35}$ electrons/s [what is seen in flares…]

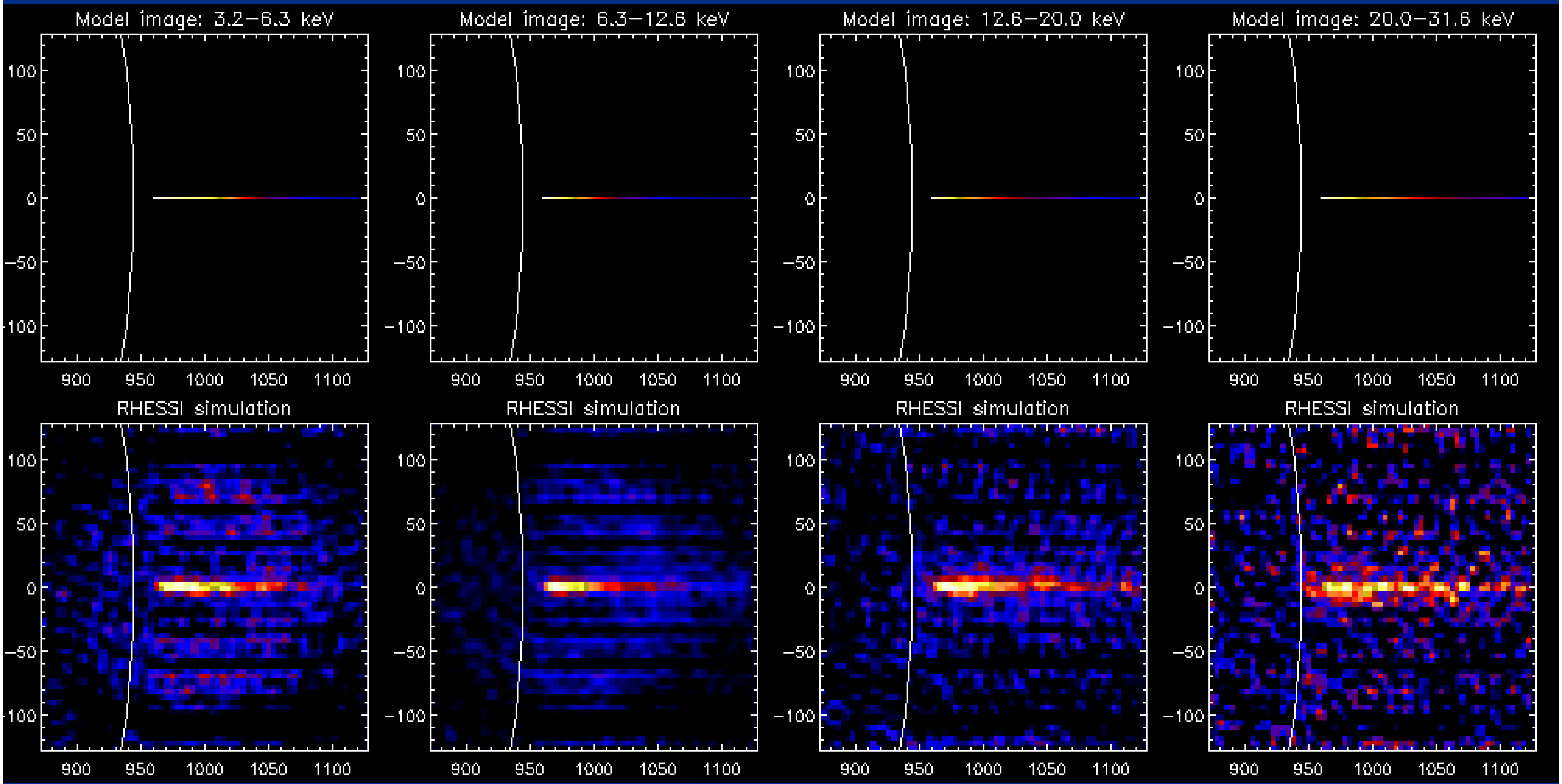


SXI-0 B_THN_A 27-Mar-2003 14:55:52.248 UT
27-Mar-2003 14:55:36.000 to 14:55:56.000
Detectors: 3F 4F 5F 6F 7F 8F
Energy Range: 7.7 - 10.5 keV
Pixon Total counts: 2.74E+03
RHESSI 7.7-10.5 keV
NRH 237 MHz
NRH 327 MHz
Y (arcsecs)
X (arcsecs)
600
500
400
300
200
800
900
1000
1100
1200
26-Nov-2005 16:33

$N_0 = 5 \times 10^9$ cm^{-3}, $\delta = 4$, Eco=10 keV, $N_{beam} = 2.7 \times 10^{36}$ electrons/s, dt=4s



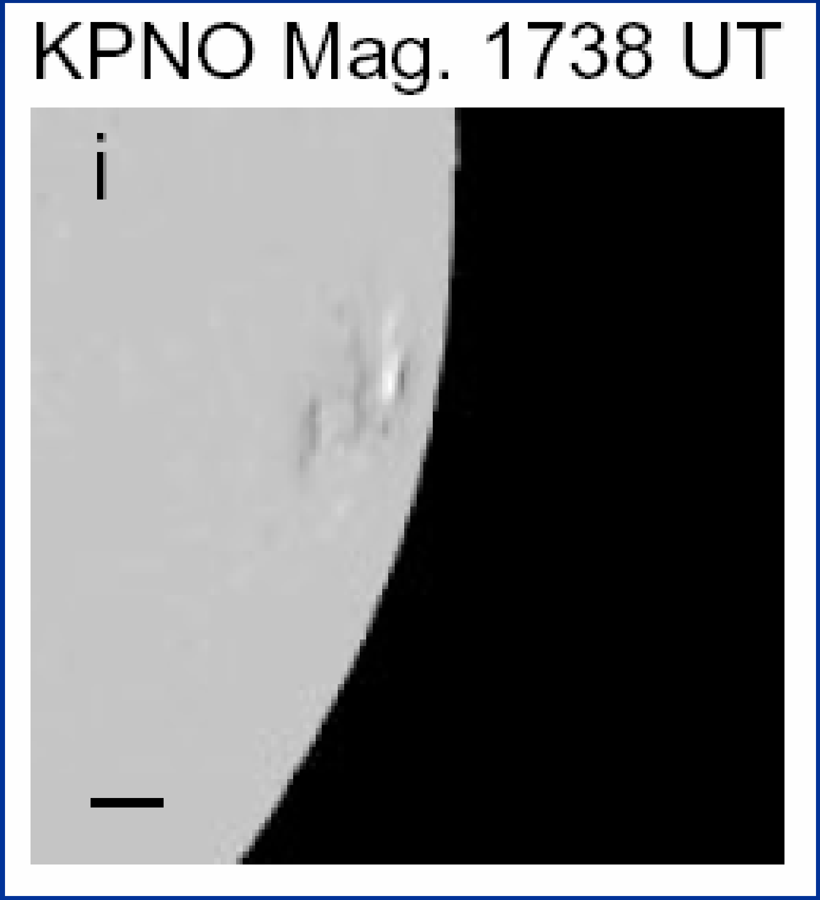
1 Mm wide beam
(≈ TRACE loop diameter)

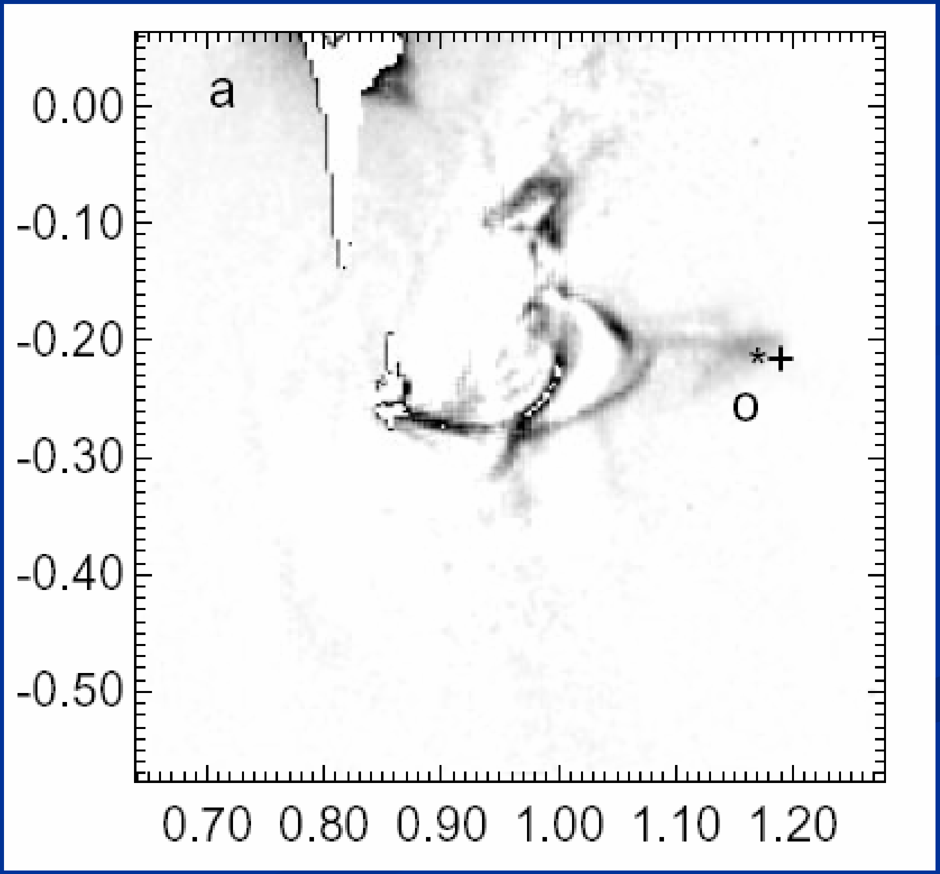


Some previous related work:

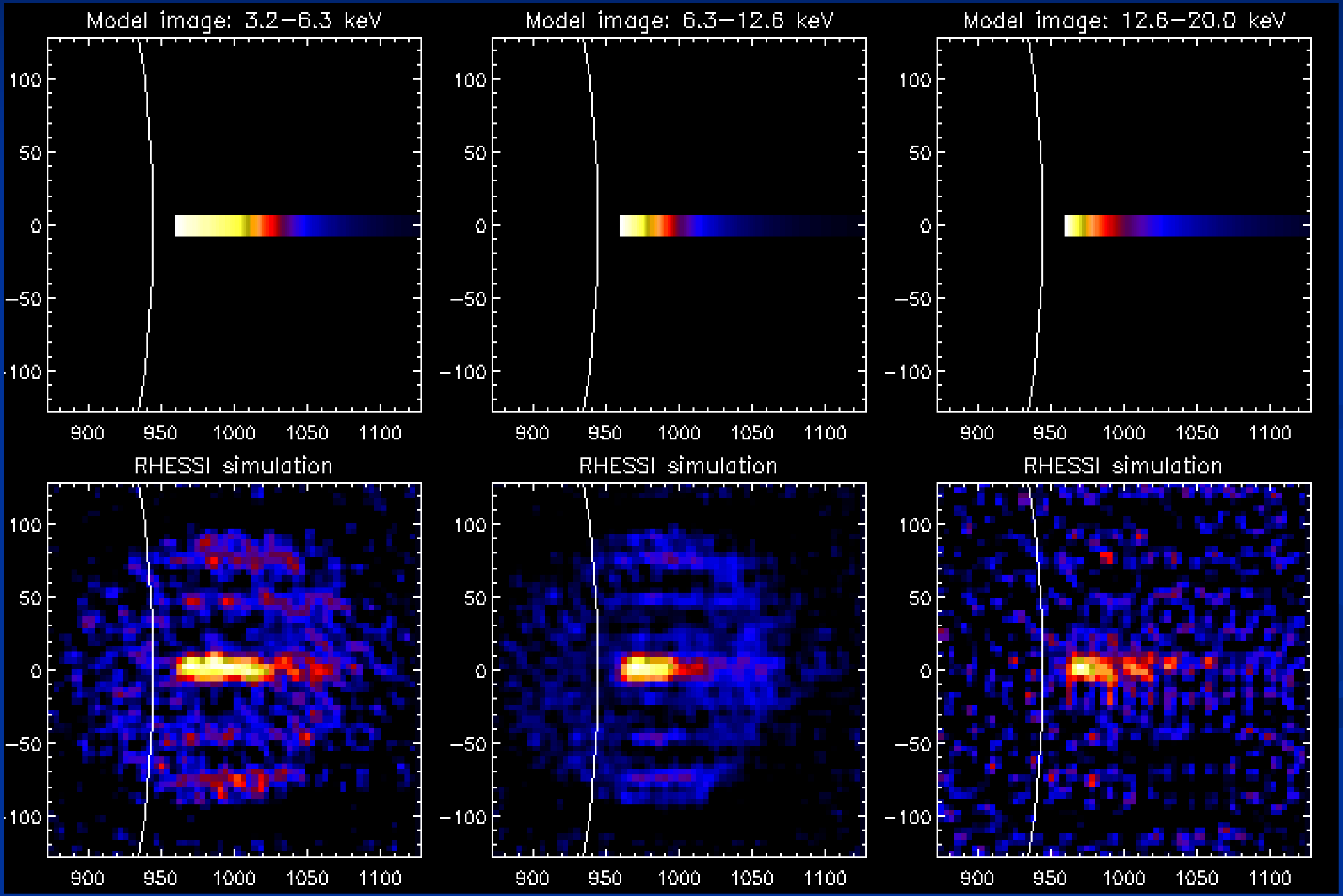
- Type III radio bursts and HXR *can* be extremely well *time*-correlated (down to ~0.2s, Aschwanden et al., 1995)
- Some Type III radio bursts have been *spatially* associated with some SXR jets above flare loops (Raulin et al., 1996)
- Yet, interplanetary electrons beams, which clearly seem to be the cause of type IIIs (decimetric, interplanetary), seem to have particle numbers (and energies) orders of magnitude less than what is needed for flare X-ray emission.

Previous SXR/Type III association: Raulin et al., 1996

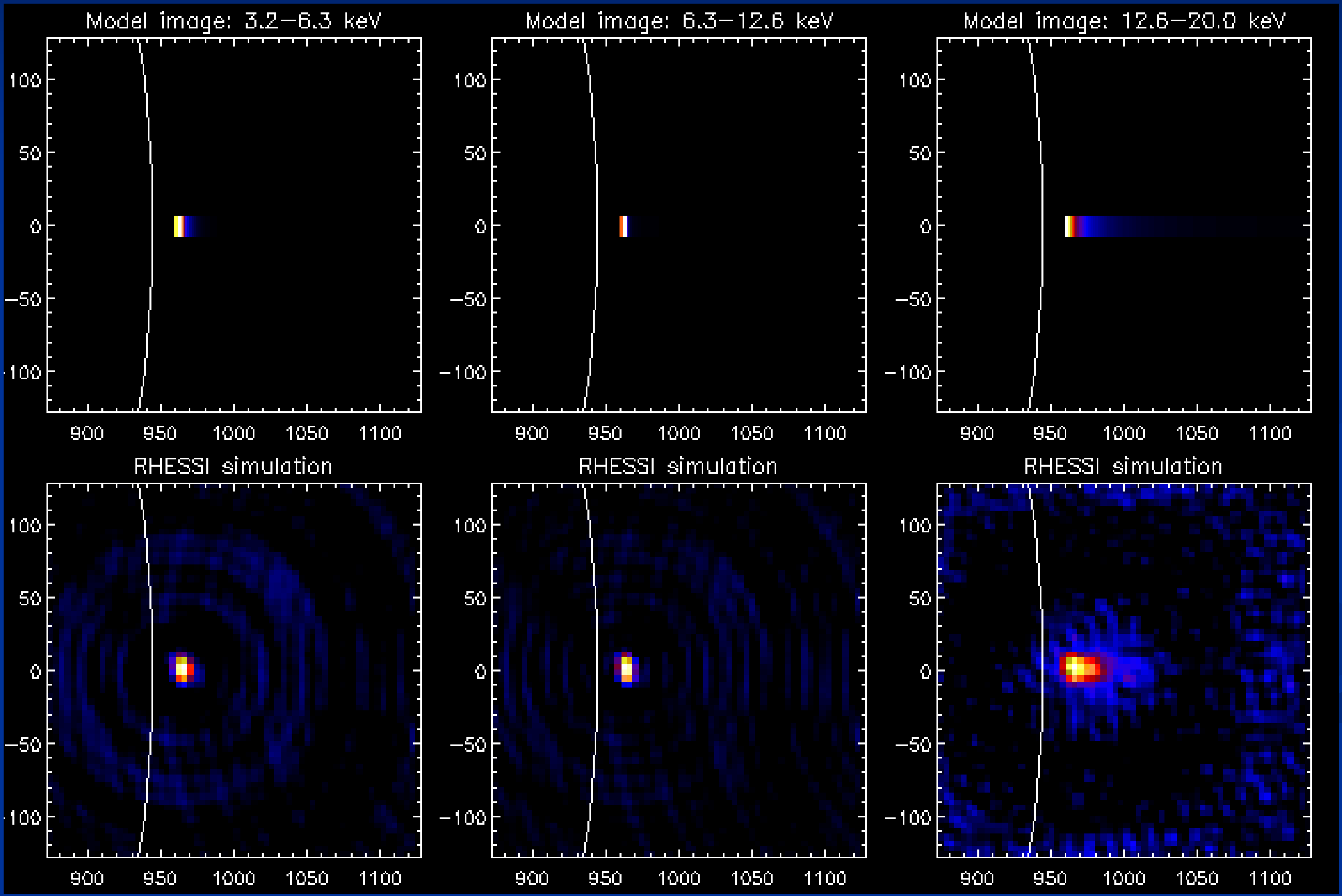


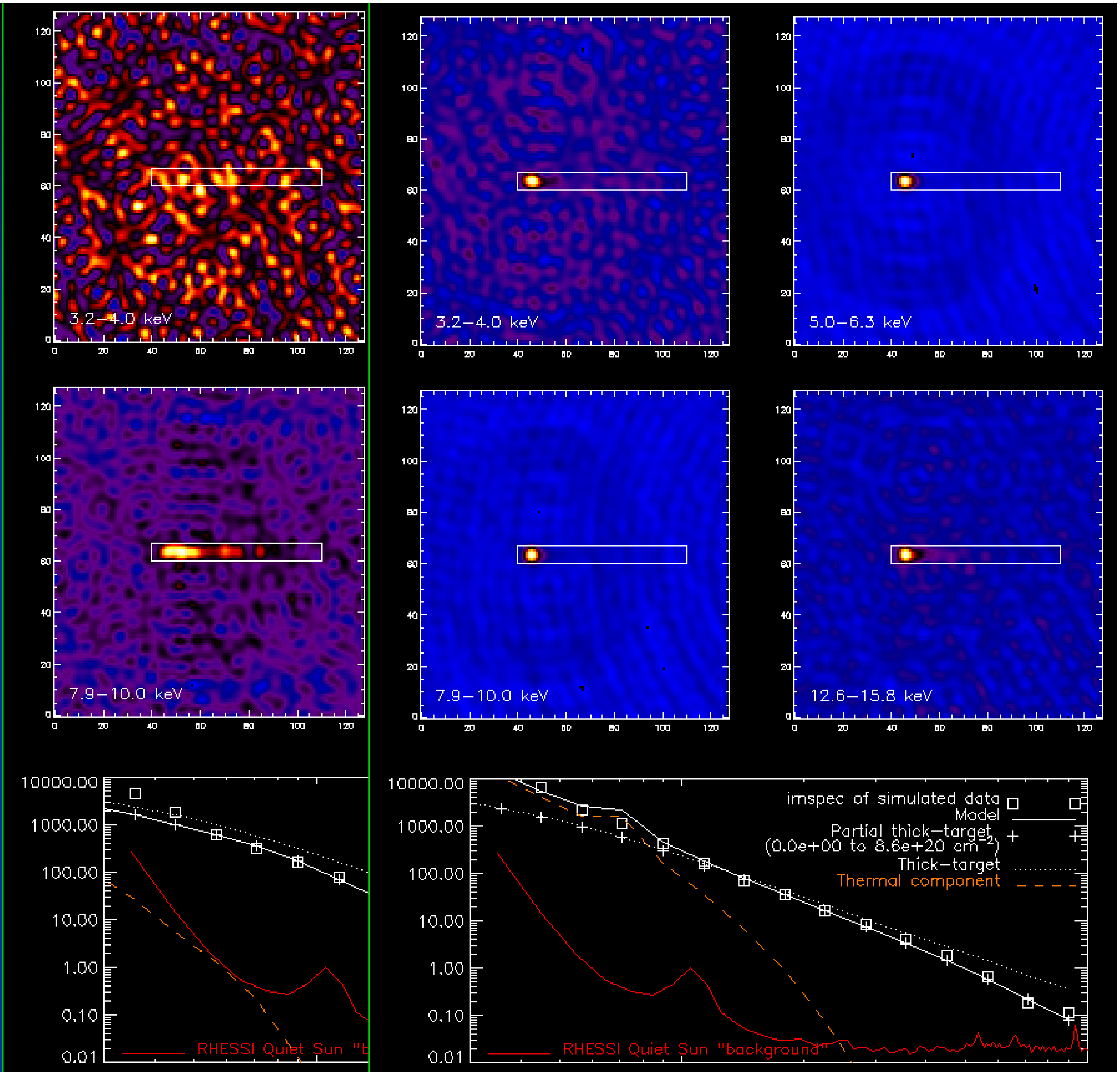


$N_0 = 5x10^9$ cm^{-3}, $\delta = 7$, Eco=10 keV, N=$2.7x10^{36}$ electrons/s , dt=4s



$N_0=10^{11}$ cm^{-3}, $\delta=4$, Eco=10 keV, N=2.7×10^{36} electrons/s , dt=4s





E_{co}=10 keV, n_0=5x10^9 cm^{-3} n_0=10^{11} cm^{-3}