Soft X-ray emission in kink-unstable coronal loops

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and

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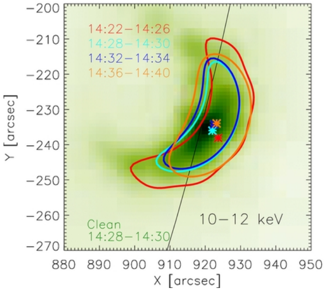
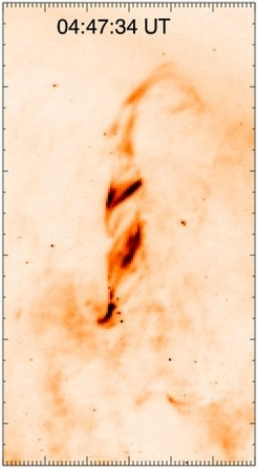
Flaring coronal loops



(RHESSI; Jeffrey and Kontar, 2013)

↑ Apparent **loop cross-section** ("corpulence") grows in time.

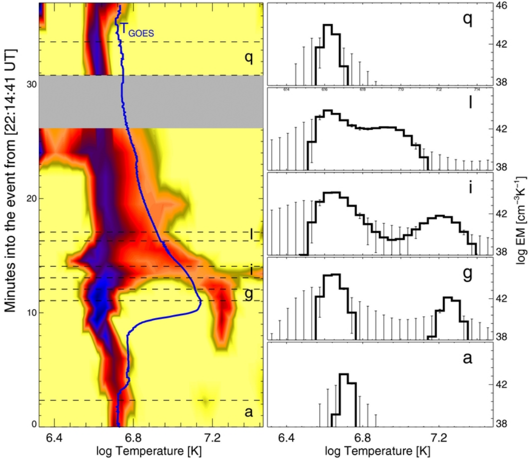
Magnetic twist visible in EUV →
But enough twist?
(This case: $L = 80$ Mm, $r = 4$ Mm, $\phi = 12\pi$)



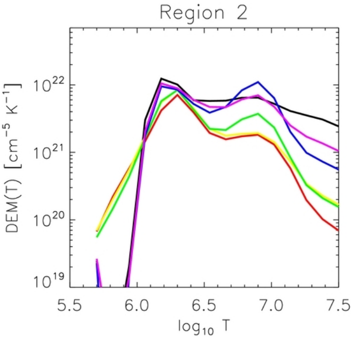
(TRACE 171;
Srivastava et al., 2010)

Multi-thermal flare plasma

Emission measure EM(T) vs. time



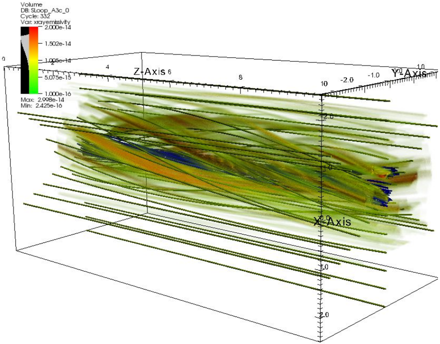
(Sylwester et al., 2014, RESIK)



(Battaglia and Kontar, 2012)

Two components in EM(T):
"cold" plasma
"hot" flare plasma

Overview



Thermal X-ray emissivity (5 keV),
Numerical simulation of kink-unstable flux-rope
Pinto, Vilmer, and Brun (2014)

Model:

Twisted flux-ropes,
uniform coronal background.

\+ simple, well-tested model
– no chromosphere

(cf. Bareford et al., 2013; Botha et al., 2011; Galsgaard and Nordlund, 1997; Gordovskyy and Browning, 2011; Hood and Priest, 1979; Hood et al., 2009; Linton et al., 1996; Lionello et al., 1998; Rappazzo et al., 2013; Török and Kliem, 2005)

Goals:

Soft X-ray emission properties (thermal continuum)
Morphological properties (twist)
Spectral properties and emission measures

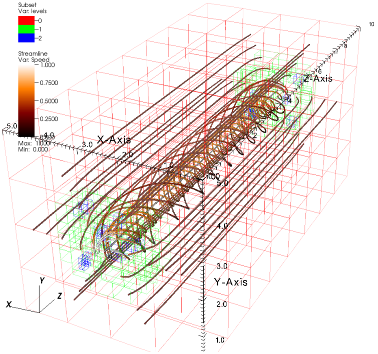
Code

PLUTO

MHD parallel code, good MPI scaling
(Mignone et al., 2007, 2012).

Resistive MHD, AMR, Spitzer-Härm thermal conduction.

Running on BlueGene/Q (Turing, IDRIS) and BullX (Curie, TGCC).



→ **Thermal X-ray emission**

$\rho\left(\mathbf{r},t\right), T\left(\mathbf{r},t\right)$

$\downarrow$

Thermal spectra (continuum), light-curves, emission measures

$$\mathrm{EM}\left(T_i, T_i+\delta T\right) = \sum_i n^2_{T_i,T_i+\delta T} \cdot \delta V_{T_i,T_i+\delta T}$$

$$I\left(h\nu, T\right) = I_0 \frac{\mathrm{EM}}{h\nu\sqrt{k_b T}} g_{ff}\left(h\nu, T\right) \exp\left(-\frac{h\nu}{k_b T}\right)$$

(Pinto, Vilmer, and Brun, 2014)

Initial conditions

Force-free twisted flux-rope, uniform background field.

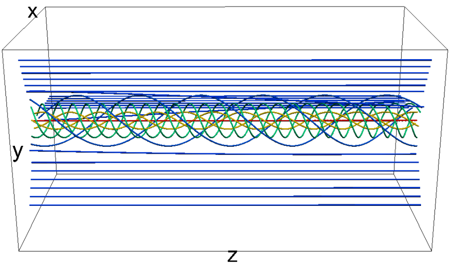
Parameters:

$L_0 = 50 - 100$ Mm, $T_{cor} = 0.9 - 1.25$ MK, $B_0 = 50 - 200$ G, $n_0 \approx .75 - 2 \times 10^{10}$ cm^{-3}, $\tau_A \approx 25$ s, $\tau_{cond} << \tau_{rad}$

boundary conditions:

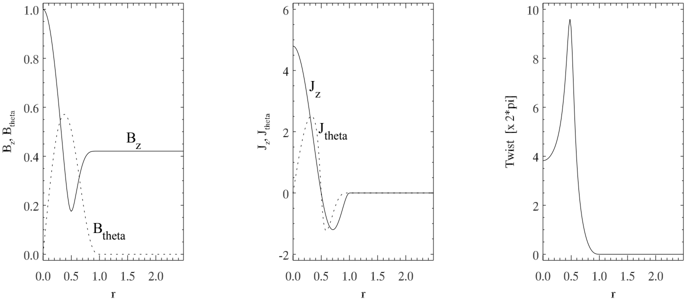
line-tied in z, periodic in the transverse directions, open to heat flux.

(*Similar models:* Botha et al., 2011; Gordovskyy and Browning, 2011; Hood et al., 2009)



Transverse profiles of:

B_z, B_θ,
J_z, J_θ,
$\Phi(r) = \frac{L_0}{r} \frac{B_\theta}{B_z}$.



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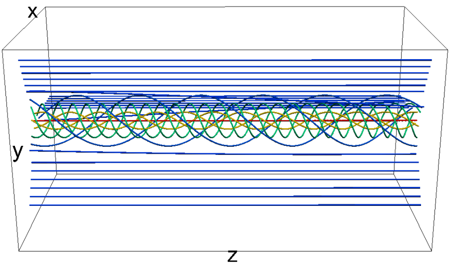

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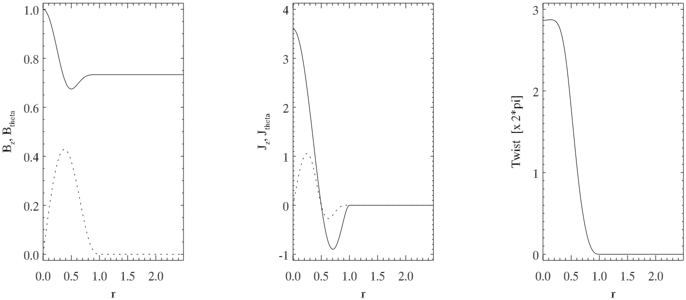
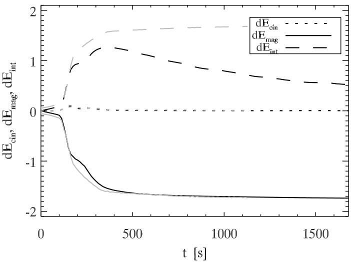


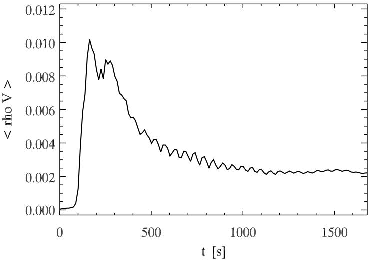
Energy budget



ΔE_{cin}, ΔE_{mag}, ΔE_{int}

ΔE_{cin} small
$\Delta E_{mag} \approx -\Delta E_{int}$ during the initial phases
ΔE_{int} decreases during the relaxation phase (conductive cooling)

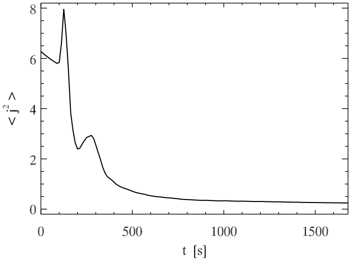
Grey lines: control case with no SH conduction



$\langle \rho v \rangle$

Strong peak, slow relaxation,
global oscillations (initially),
residual small scale flows

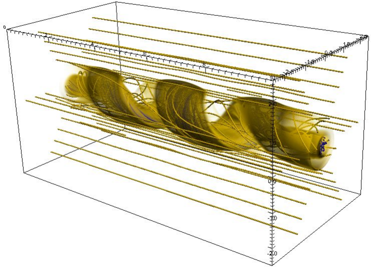
Currents

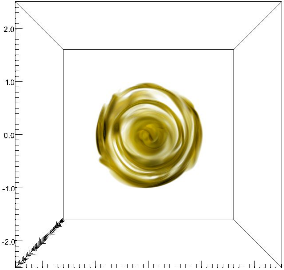


$\langle j^2 \rangle$

Strong peak at the saturation phase (strong ohmic heating)

Current vanishes as the magnetic field relaxes towards a potential-field state





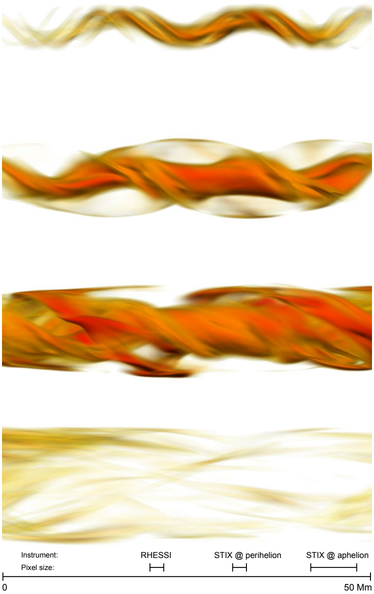
Emission morphology

105 s

125 s

155 s

350 s



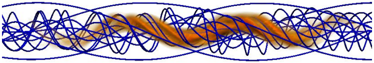
Emission patterns at 5 keV

Full resolution
(∼ 10× RHESSI or STIX@perihelion).

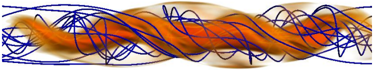
← **RHESSI and STIX pixel sizes.**

Emission morphology

105 s



125 s

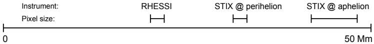


155 s

Emission patterns at 5 keV

"Emission" twist ≠ magnetic twist

350 s



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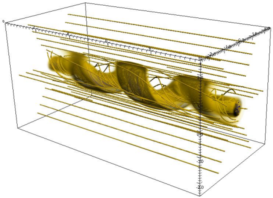
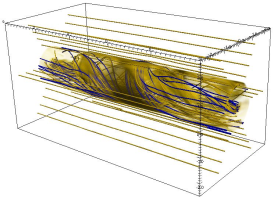
Current density **Emissivity (10 keV)** **Spectrum**

$t = 113$ s (linear phase)



$t = 153$ s (saturation phase)



Current density | **Emissivity (10 keV)** | **Spectrum**

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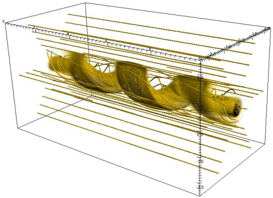

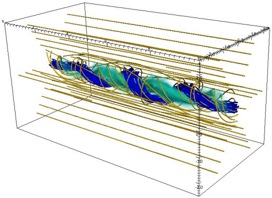

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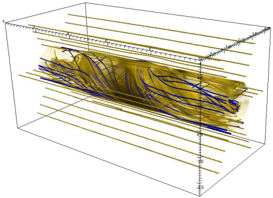

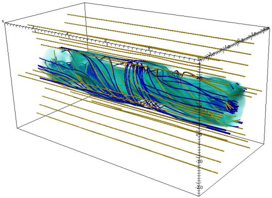

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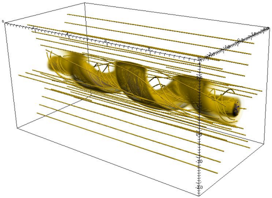

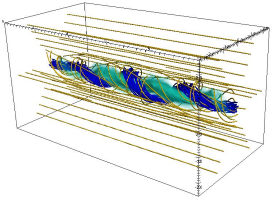

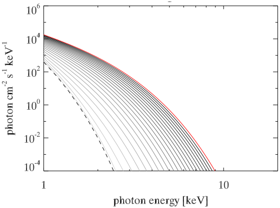

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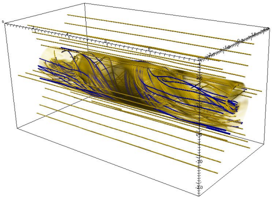
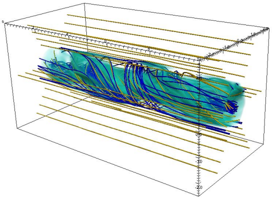
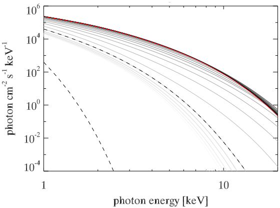
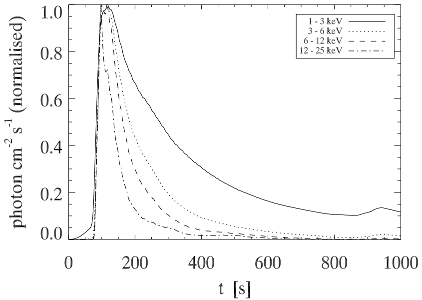






Light curves (normalised)

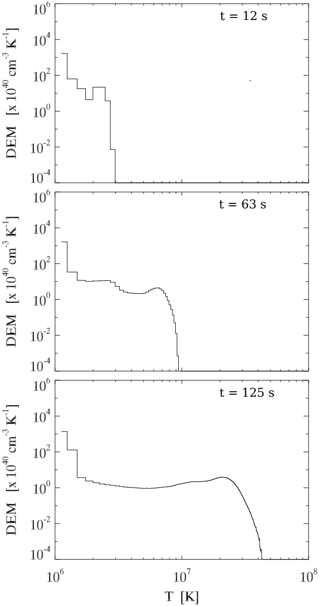


Lower energy bands $\Rightarrow$ **slow** decay;
Higher energy bands $\Rightarrow$ **fast** decay

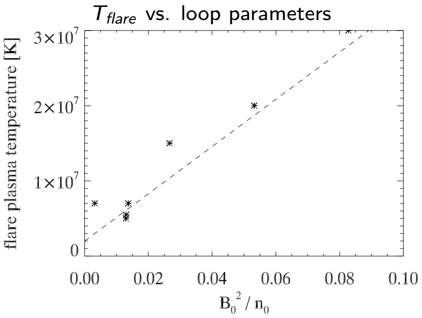
Flare plasma heating $\Rightarrow$ high temperature component in $EM(T)$ distribution

Total EM of hot flare plasma ($T > 9$ MK):
$EM_{hot} \sim 5 \times 10^{47}$ cm^{-3}

Emission measures $EM(T)$ vs. time



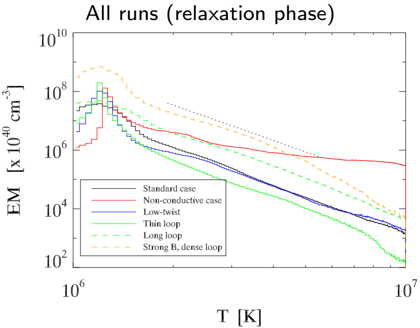
Flare plasma temperature



Flare temperature:
$T_{flare} \sim a \cdot B_0^2 / n_0 + T_0$

T_{flare} measured from $EM(T)$
T_0 is the background temperature

$EM(T)$ relaxation phase



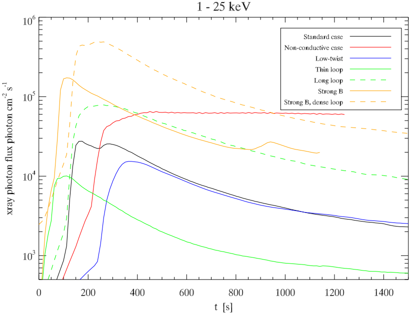
$t \geq 125$ s: Strong ohmic heating $\rightarrow$ Upper tail extending up to $T \sim 6 \times 10^7$ K

$t >> 500$ s: Power-law $EM \propto T^{-4.2}$

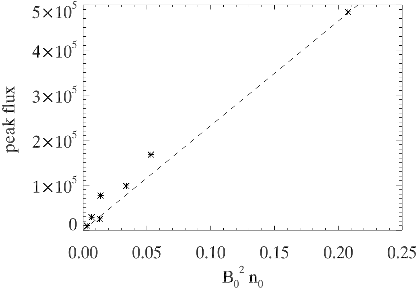
Similar behaviour for all runs performed.

Peak photon flux

Light-curves, different cases



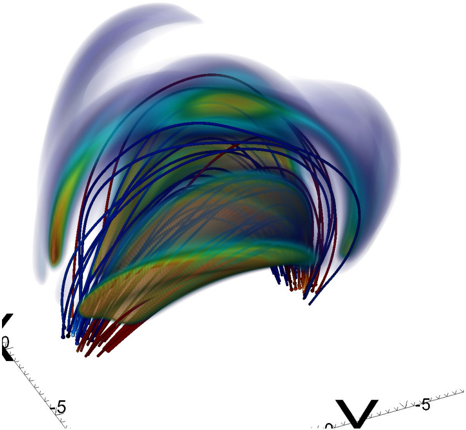
Peak flux vs. loop parameters

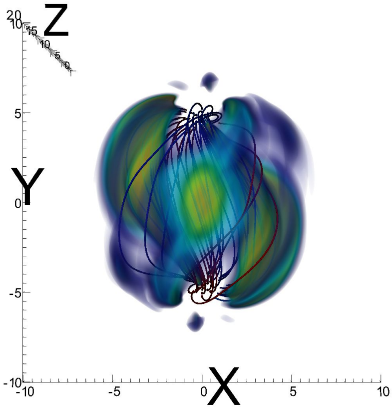


Peak amplitude:
$\max(I_{h\nu}) \propto B_0^2 n_0$

Peaking time-scale:
$\tau_{peak} \propto r_0 c_a^{-1}$

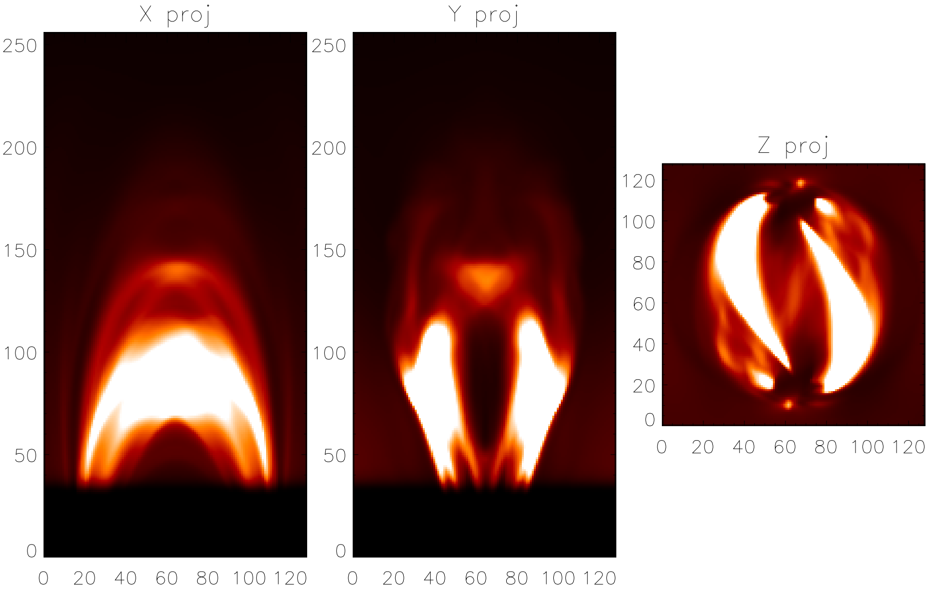
Perspectives





Curved loops + stratification, soft X-ray emission @ 2 keV
Hard X-ray emission (Gordovskyy, Pinto, et al, *in prep.*)

Perspectives



Conclusions

Thermal X-ray emission in flaring loops (Pinto et al., 2014)

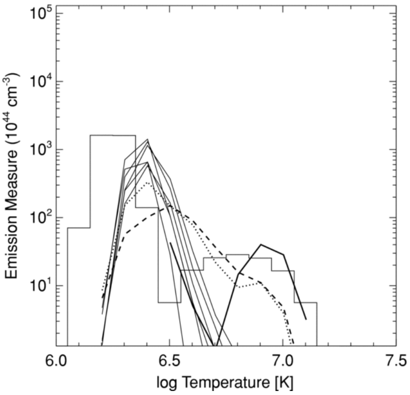
1. **Simple model** for the release of stored magnetic energy in flares
2. **Thermal conduction** (Spitzer-Härm) + **leakage** matters (filamentary emission, cooling)
3. Apparent twist underestimates actual magnetic twist?
4. Peak flux $\propto B_0^2 n_0$, flare temperature $\propto B_0^2 / n_0$
5. $EM \propto T^{-4.2}$ for $T > 2$ MK (asymptotically)

Perspectives

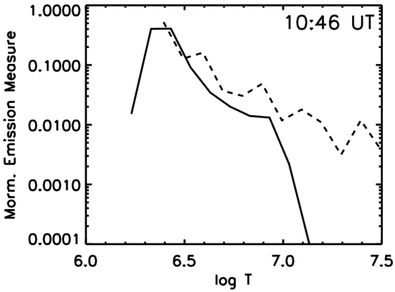
1. More complex models (curved loops, gravitational stratification, forcing mechanisms)
2. Chromospheric evaporation, magnetic funnels
3. Test-particles, hard X-ray spectra $\rightarrow$ **combined soft/hard X-ray** emission
4. **EUV, line-emission**

Thank you!

EM vs. T (observations)



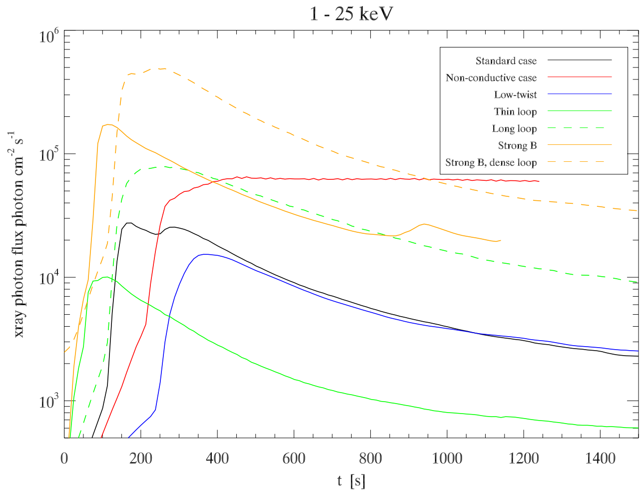
(Reale et al., 2009, Hinode/XRT)



(Parenti et al., 2010, Hinode/XRT; see also Battaglia & Kontar, 2012)

Peak photon flux

Light-curves, different cases

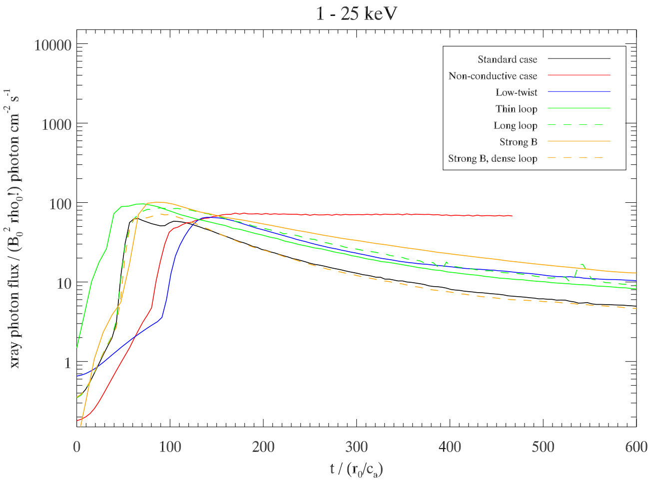


Peak amplitude:
$\max\left(I_{h\nu}\right) \propto B_0^2 n_0$

time of peak:
$\tau_{peak} \propto r_0 c_a^{-1}$

Peak photon flux

Light-curves, **re-scaled**



Peak amplitude:
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time of peak:
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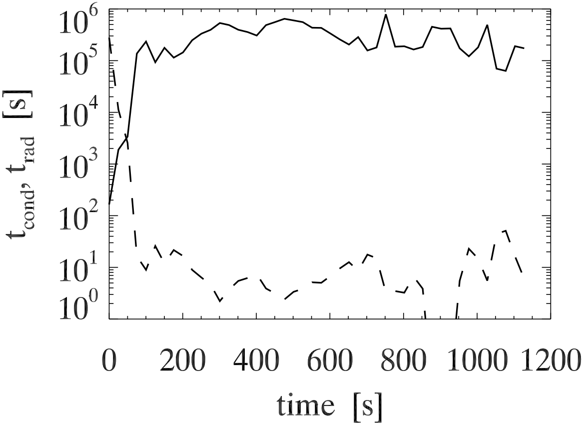
Cooling time-scales



Continuous line: τ_{rad}
Dashed line: τ_{cond}

Conductive cooling dominates

Radiative cooling time-scale **larger than** the simulated dynamical time-scales

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