Quasi-periodic energy release in a three-ribbon solar flare

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Outline of the presentation

- Brief introduction to QPPs in solar flares
- General overview of a three-ribbon M1.1 flare studied (SOL2012-07-05T06:49)
- Spectral analysis of flare’s X-ray emission and founding of ‘hidden’ QPPs
- Energetics of QPPs
- Dynamics of QPP sources
- Comparison with a homologous M6.1 flare (SOL2012-07-05T11:39)
- Magnetic structure of the flare region and the QPP production site
- Discussion of possible mechanisms
- Summary
- Additional materials

QPP definition(s) & properties

There is no strict mathematical definition of QPPs

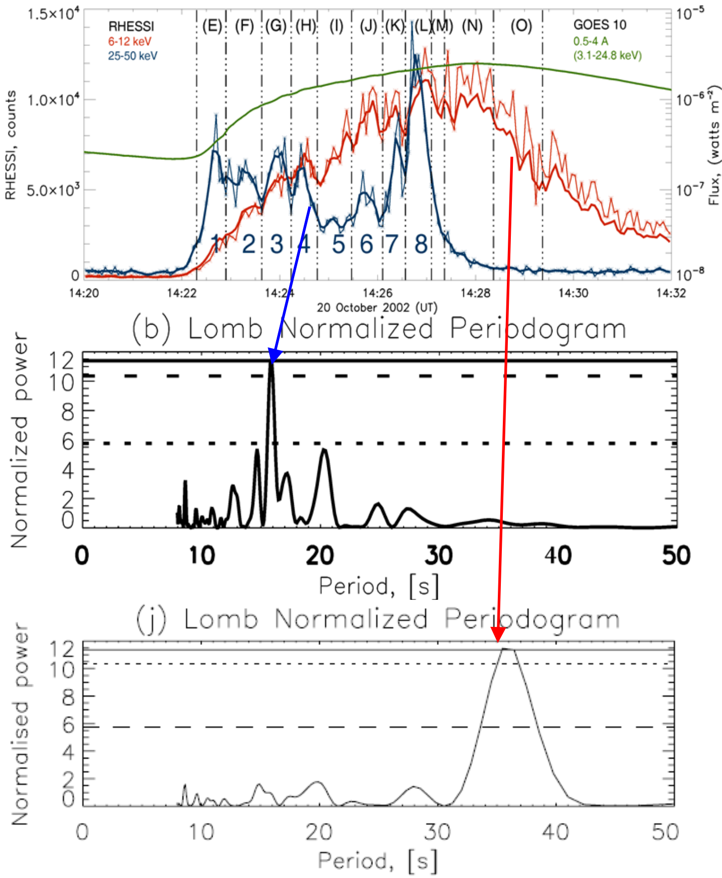
Definition A: a sequence of at least 3 emission intensity bursts with similar time intervals between successive peaks

Definition B: there's presence of a statistically-significant frequency peak above noise level (in Fourier, wavelet, EMD etc. spectra)

- **Occurrence:** in many (~30-90%) but not in all flares (technique, sensitivity matter?) – recent results
- **Flare types:** possibly all (impulsive, long-duration, microflare, confined, eruptive, two-ribbon, circular-ribbon, three-ribbon?)
- **Flare phases:** all (pre-flare, impulsive, decay)
- **Wavebands:** from radio emission (~MHz) up to gamma-rays (MeV)
- **Periods:** from milliseconds to tens of minutes
- **Number per flare:** from a few (3-4) to dozens (usually, ~4-10 in HXR & MW)
- **Modulation depths:** from a few % to almost 100%
- **Some special characteristics:** a) non-harmonicity
  b) non-regularity
  c) multi-periodicity
  d) multi-timescale

Especially for QPPs of non-thermal emissions

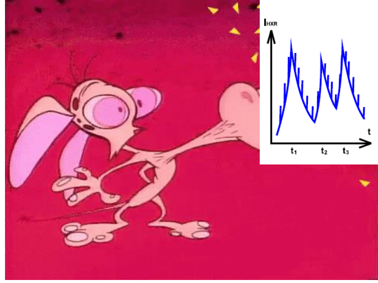
Mechanisms (are not defined yet): i) direct modulation by MHD and other waves
ii) modulation of energy efficiency by MHD waves
iii) spontaneous quasi-periodic energy release (DC-to-AC)



Zimovets & Struminsky (2010, SoPh)

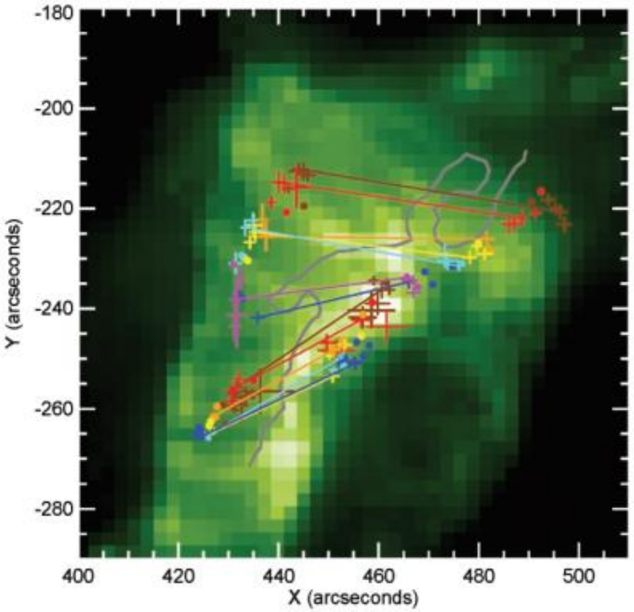
Van Doorsselaere+ (2016 SSR), McLaughlin+ (2018 SSR), Kupriyanova+ (2020 STP), Zimovets+ (2021 SSR, acc)

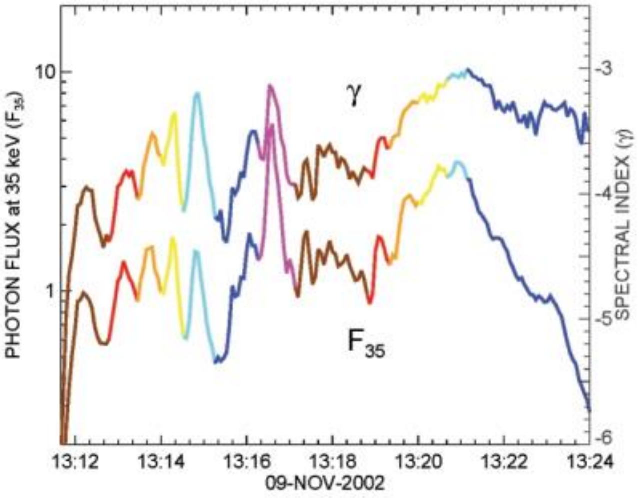
Why study QPPs?



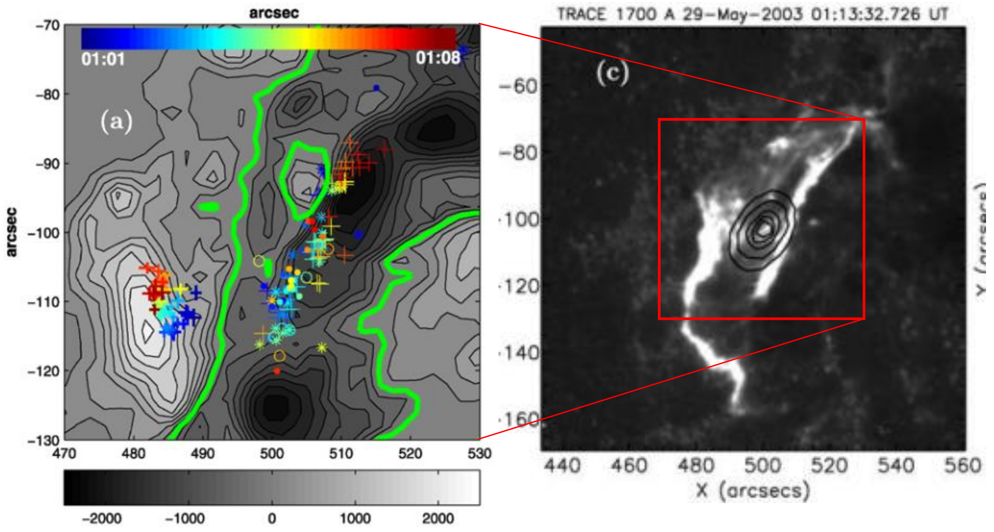
- Quasi-periodic (or oscillatory) processes are ubiquitous and always attractive
- The origin of QPPs is not known yet despite more than 10 mechanisms have been proposed
- Flare models should naturally explain the presence of QPPs and their properties, since QPPs accompany a large fraction (~30-90%) of solar flares (and are found in stellar flares too)
- QPPs can be used as a diagnostic tool for physical properties of solar flare regions if their mechanism is confidently identified
- One can diagnose stellar flare regions with QPPs relying on solar-stellar analogies (if proved)

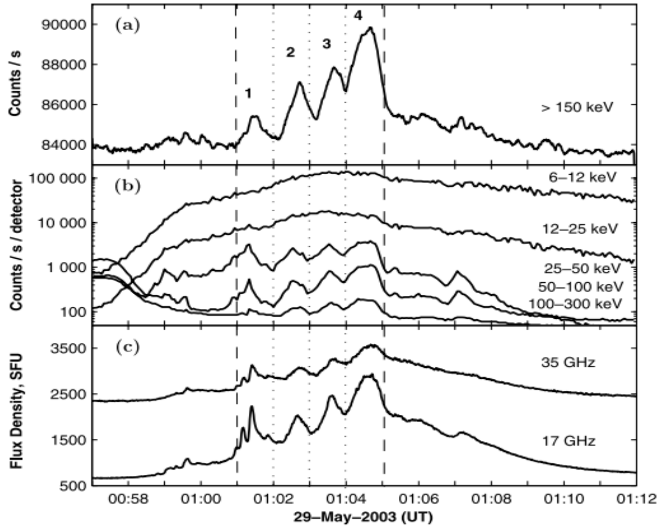
QPPs were found in two-ribbon & circular-ribbon flares



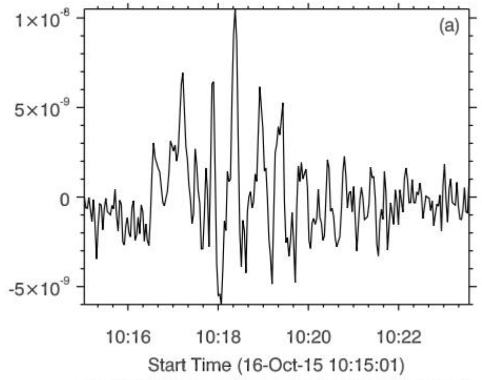


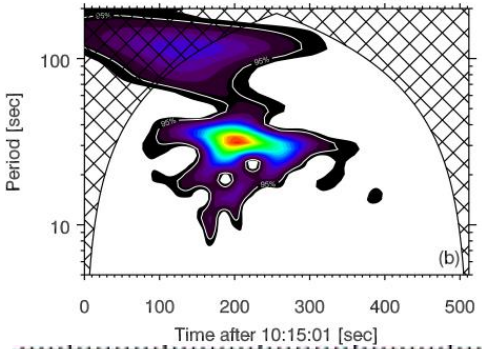
Grigis & Benz (2005, ApJL)

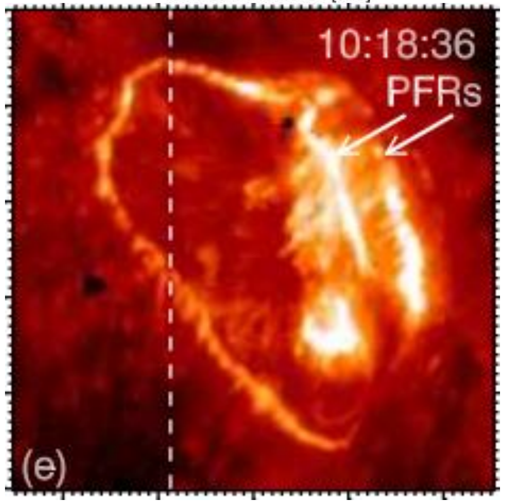




Zimovets & Struminsky (2009, SoPh)



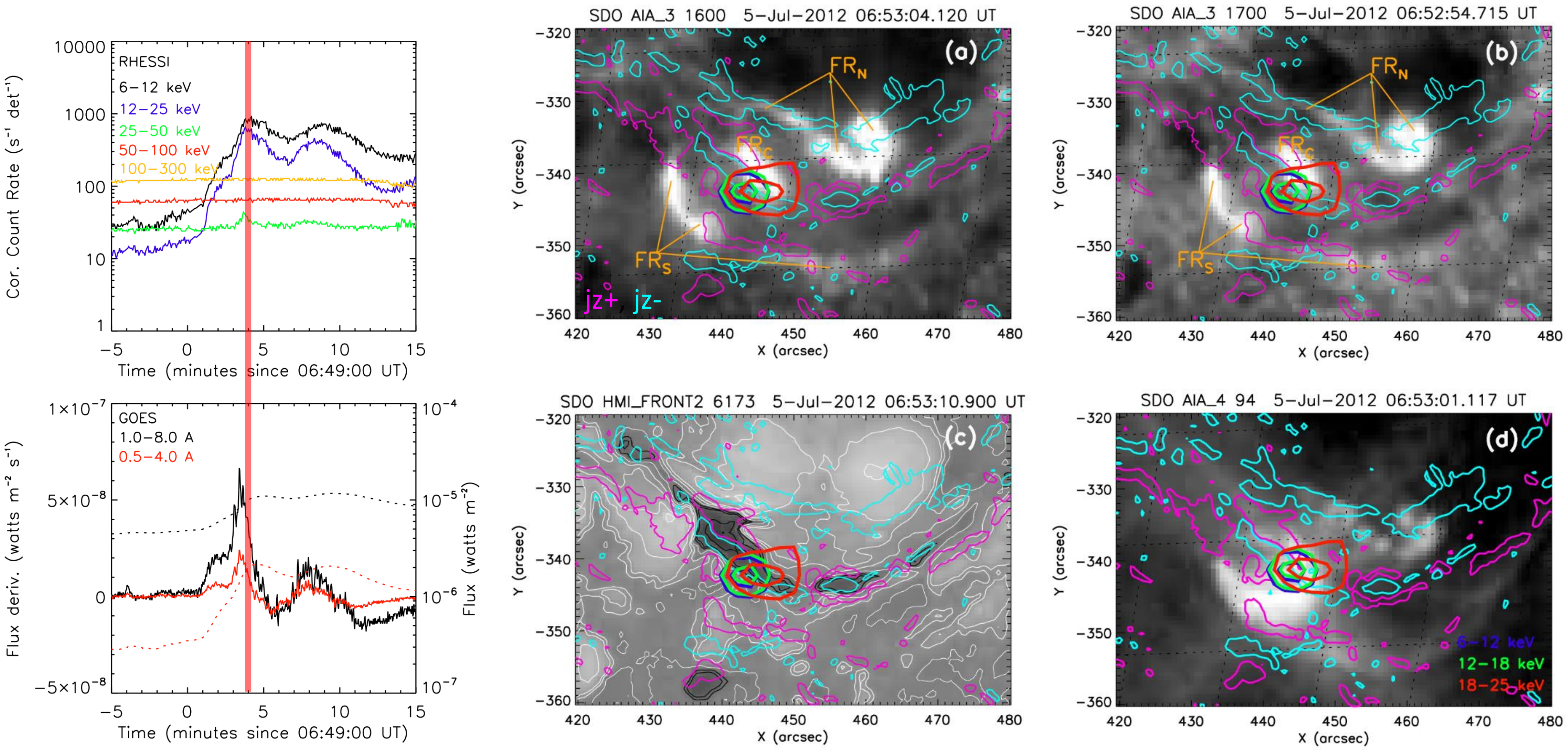




Zhang+ (ApJ, 2016)

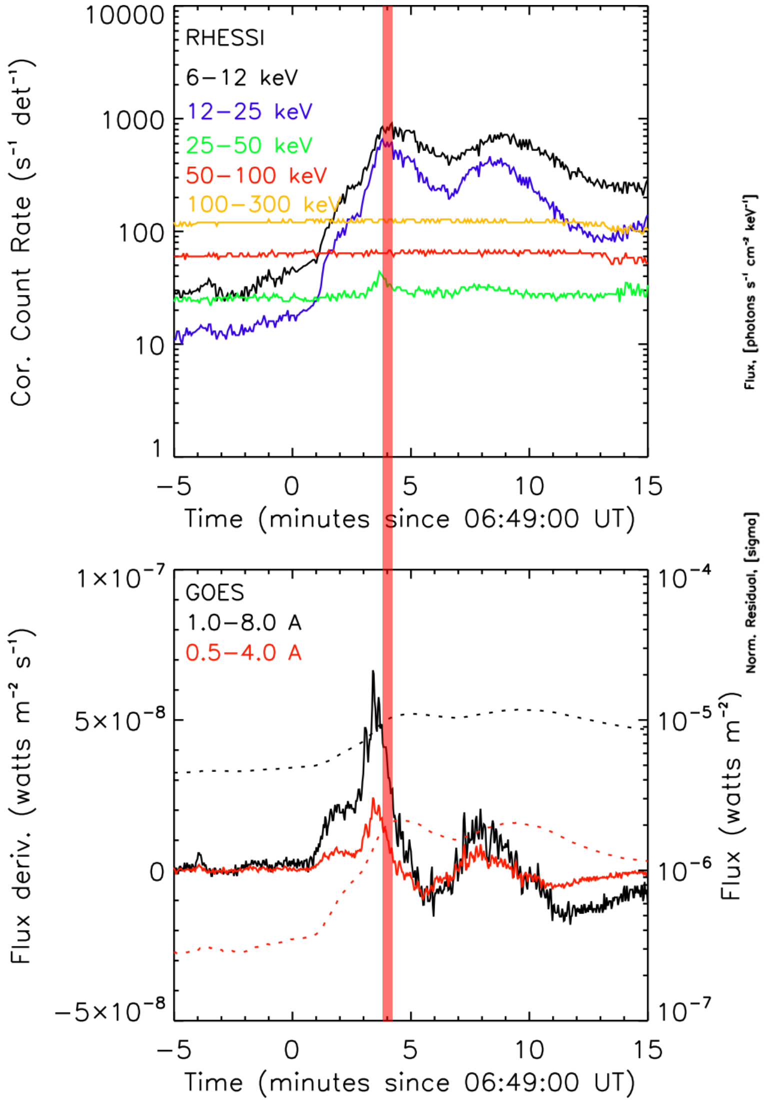
Below we present an example of QPPs in a three-ribbon flare

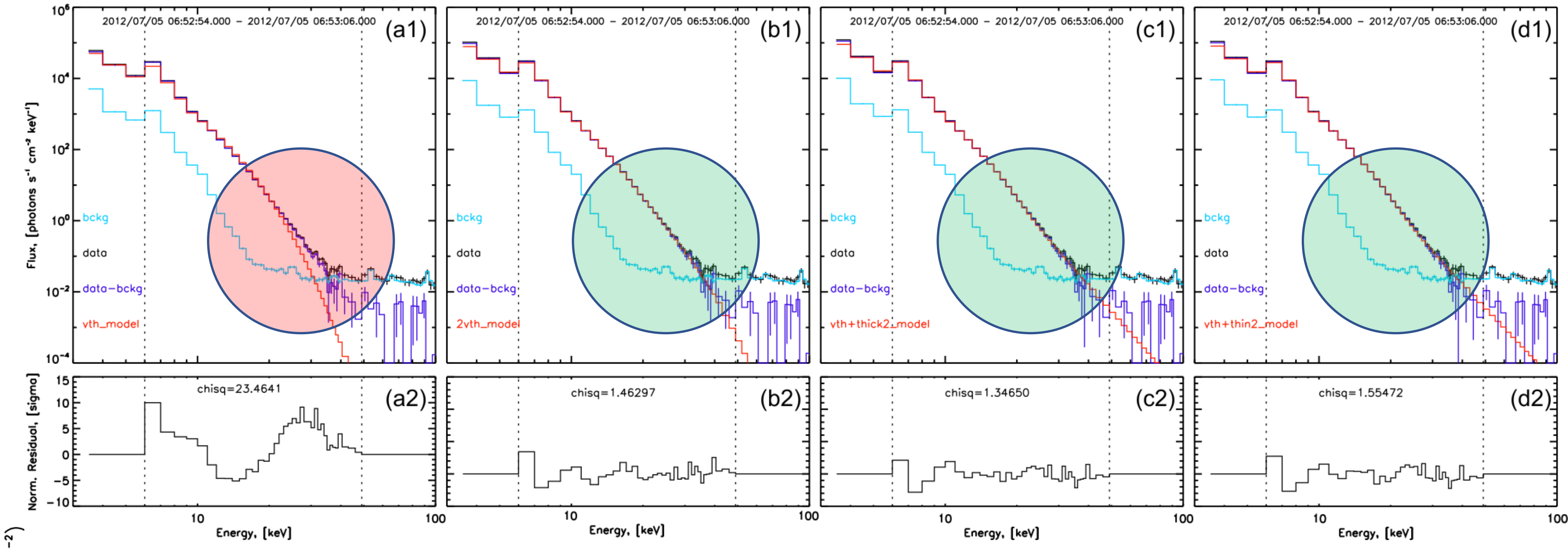
Here we analyze M1.1 three-ribbon solar flare on 5-Jul-2012, 06:49 UT



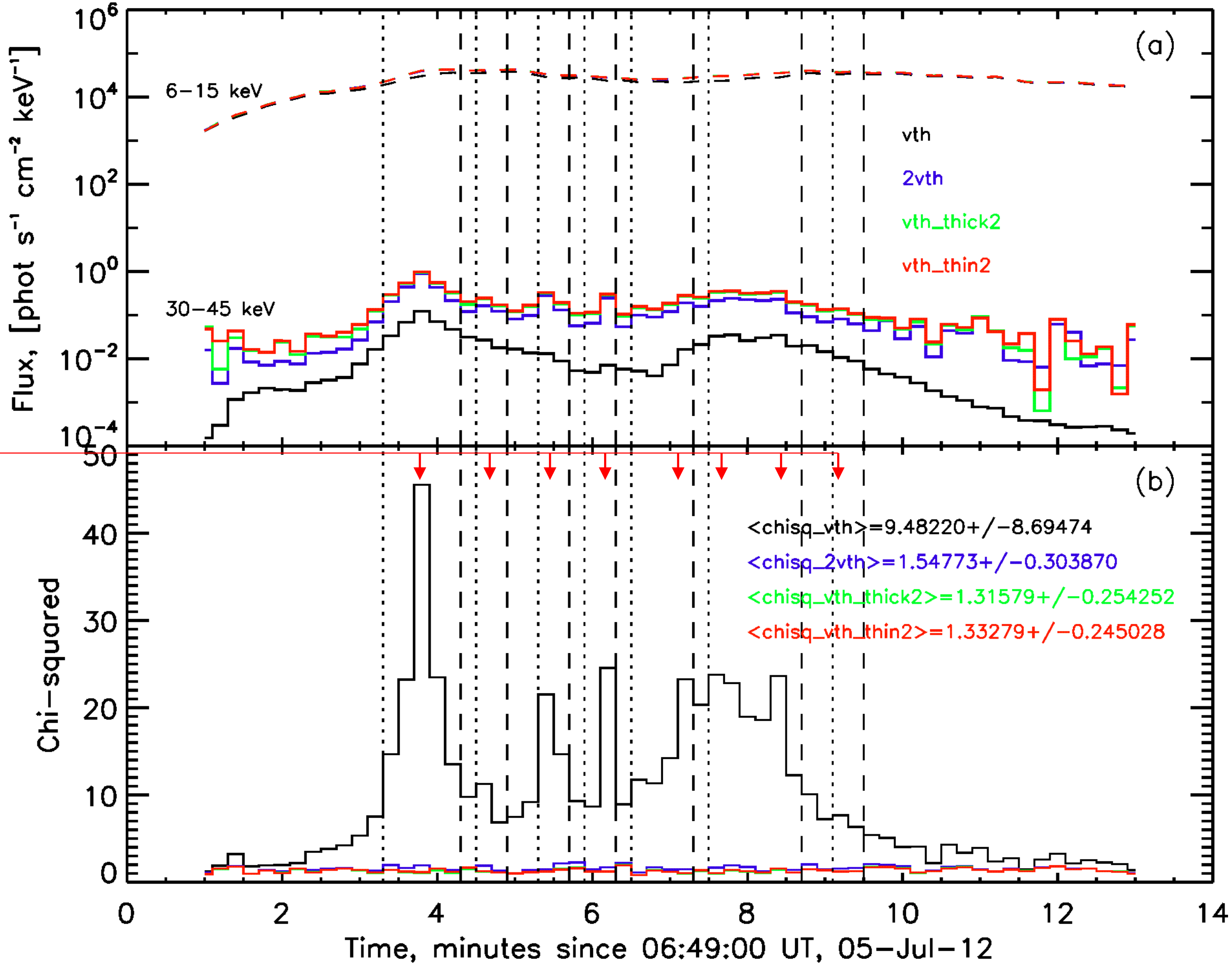
Fitting of flare X-ray spectrum with different models. I.

X-ray light curves	vth	2vth	vth+thick2	vth+thin2
	Doesn't fit well	Fits well	Fits well	Fits well





Model fit quality



QPPs

~~Vth~~

2Vth

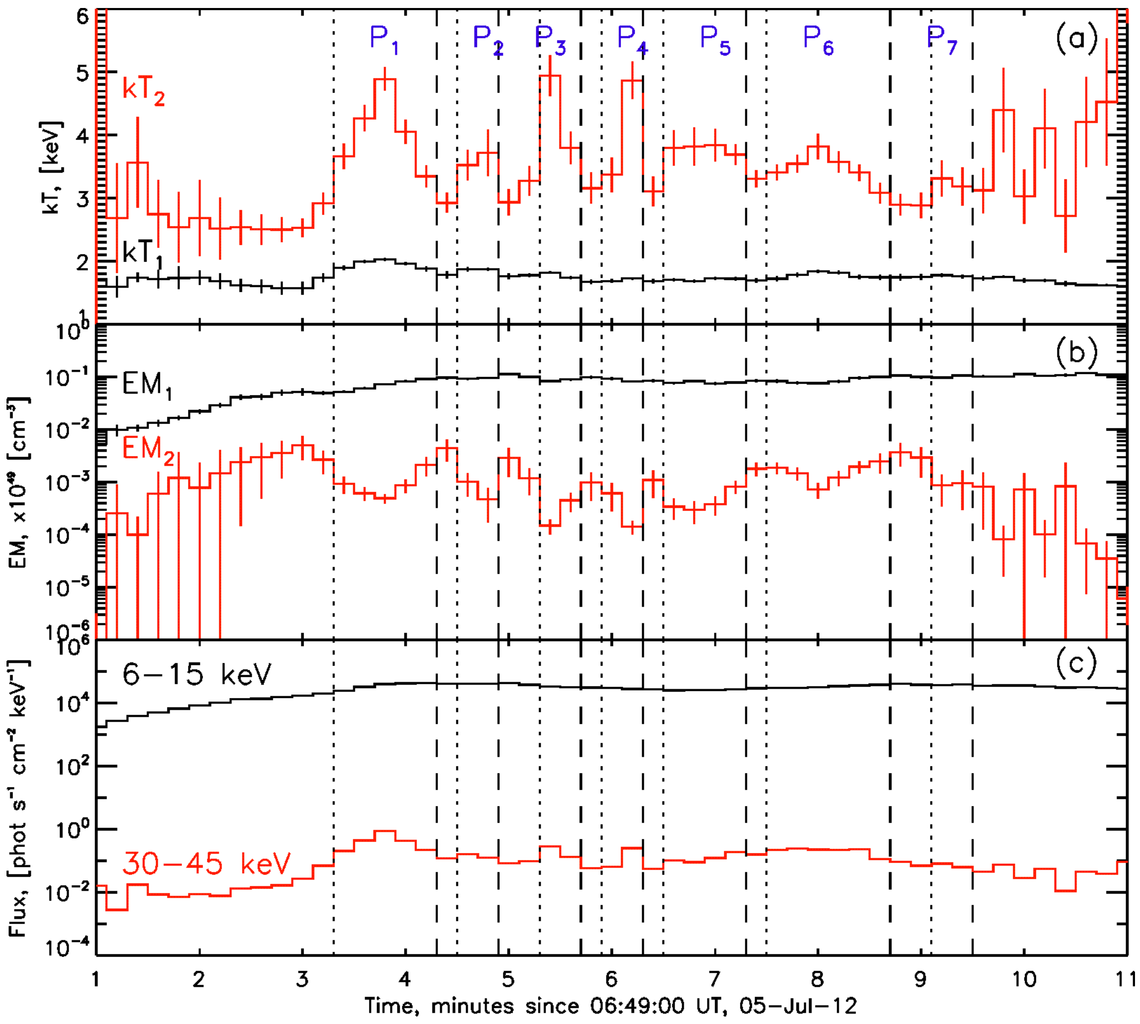
Vth+thick2

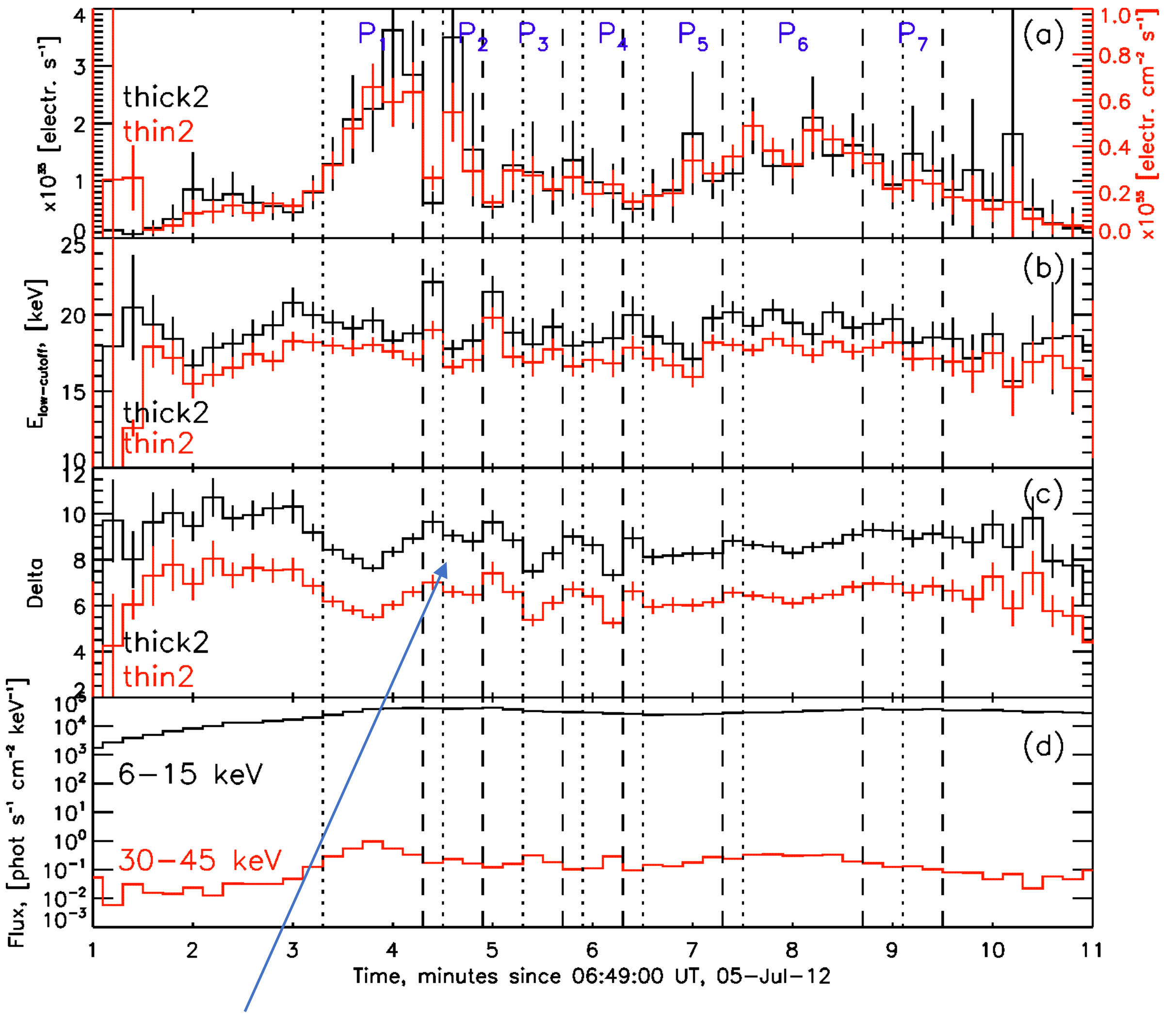
Vth+thin2

QPPs with P = 54 ± 13 s in T of "super-hot" (T~30-50 MK) plasma component

or

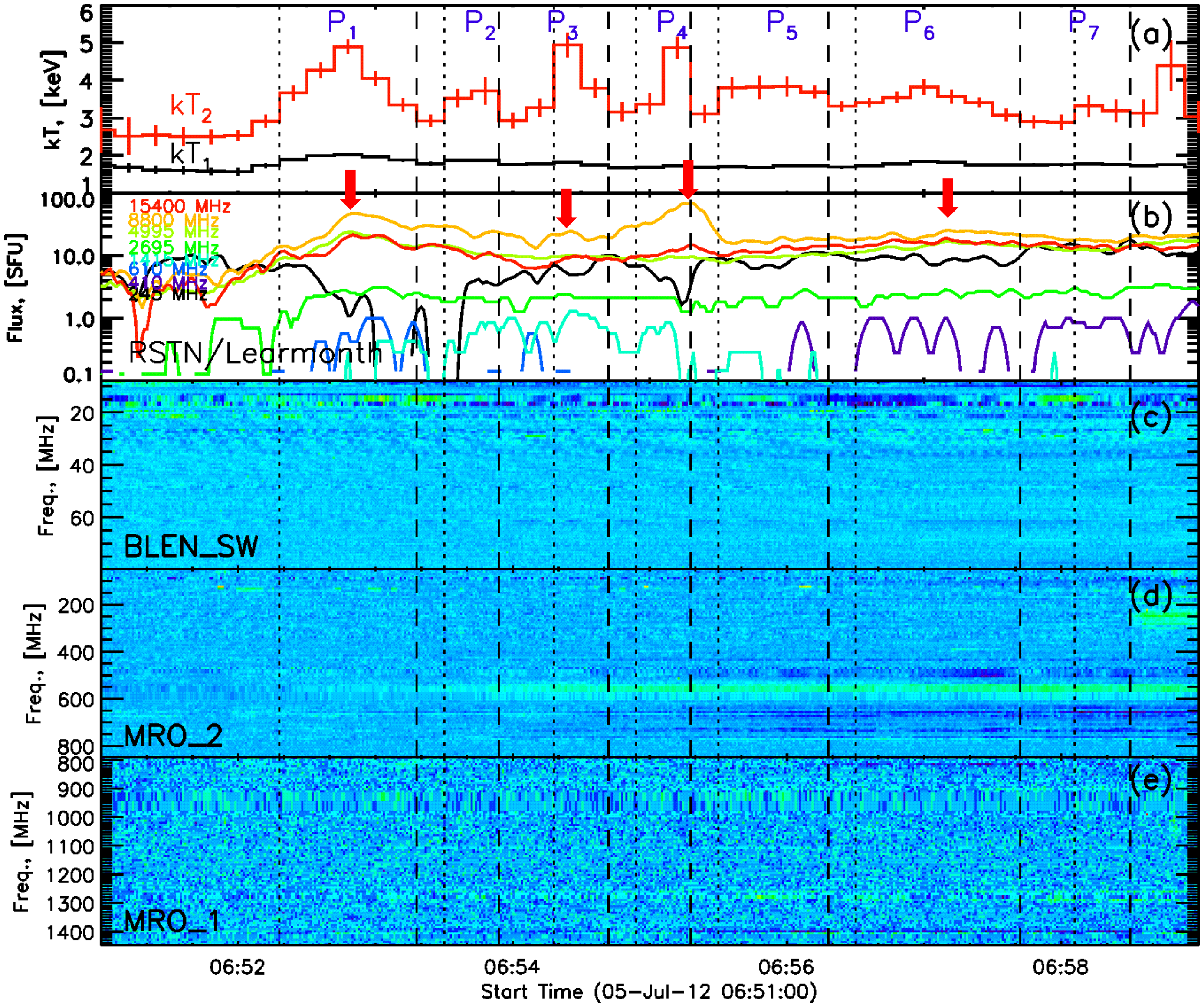
QPPs (less pronounced) in spectral parameters of non-thermal electrons





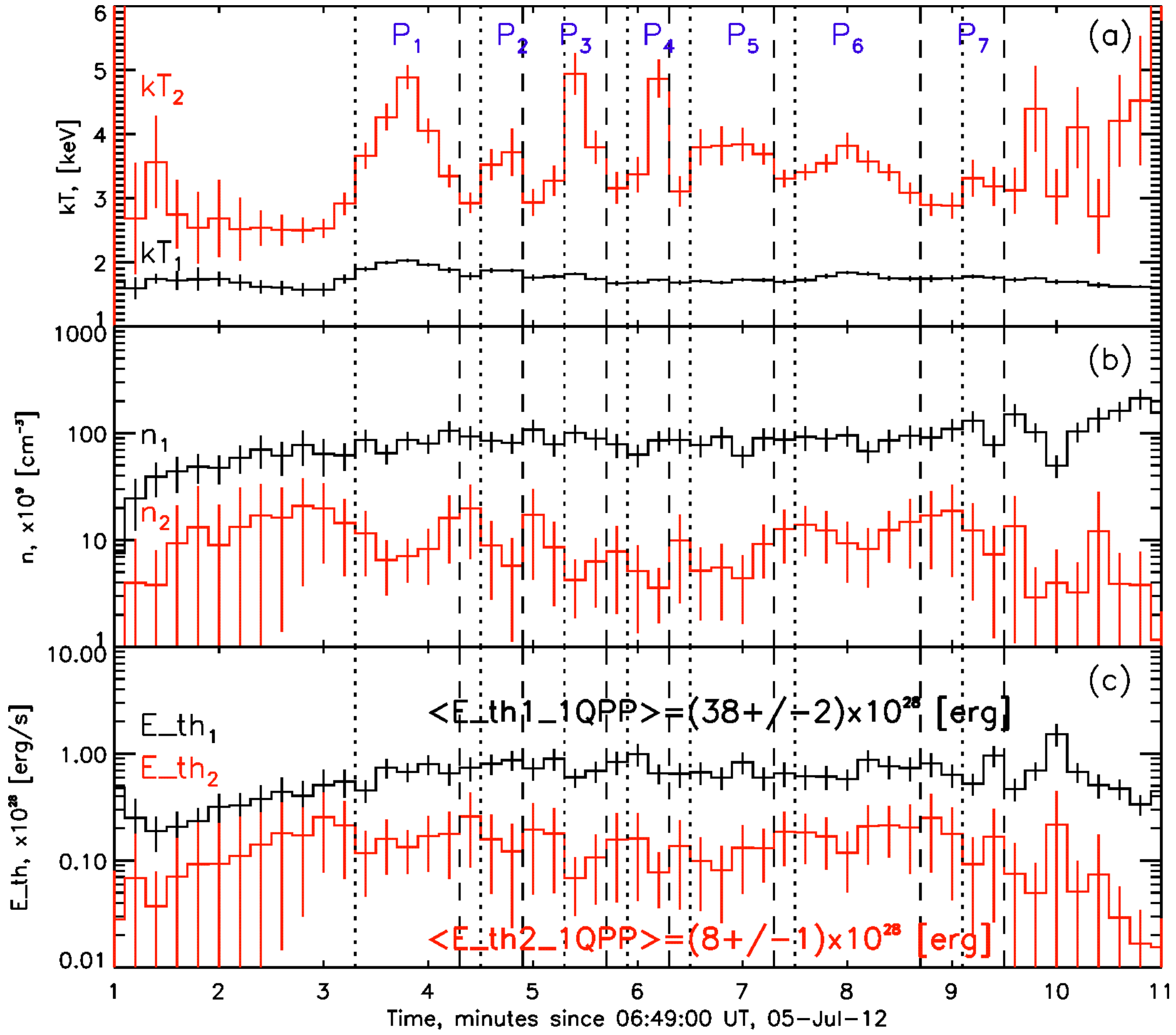
Note: non-thermal e- spectral index is very high, i.e. HXR spectrum is very soft - possibly it is too unrealistic (see also p. 9)

Check for presence of QPPs in radio emission



- There are some signatures of these QPPs in microwaves (although no peak-to-peak matching)
- There are no QPPs in decimeter-meter-decameter wavelength ranges, e.g. there are no type-III bursts – against presence of e-beams (no access to 'open' field lines or too weak?)

Parameters of hot and super-hot thermal plasmas



Total thermal energy during QPPs:
Tot(E_th1) ~ $(2.7\pm0.1)\times10^{30}$ erg
Tot(E_th2) ~ $(5.7\pm0.7)\times10^{29}$ erg

Total release of magnetic energy:
ΔTot(B) ~ $8\text{x}10^{30}$ erg

ΔTot(B) > Tot(E_th1) > Tot(E_th2)

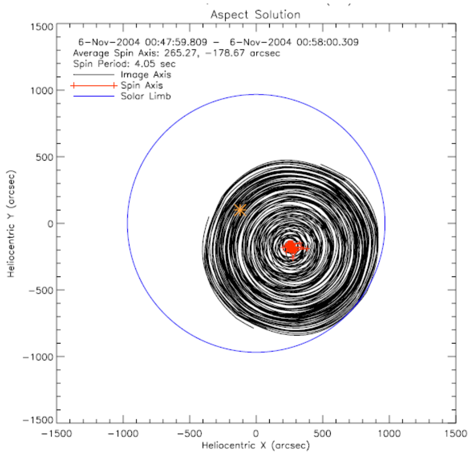
Thermal energy of one pulsation:
<E_th1_1QPP> ~ $(3.8\pm0.2)\times10^{29}$ erg
<E_th2_1QPP> ~ $(0.8\pm0.1)\times10^{29}$ erg
- comparable to energy of a microflare

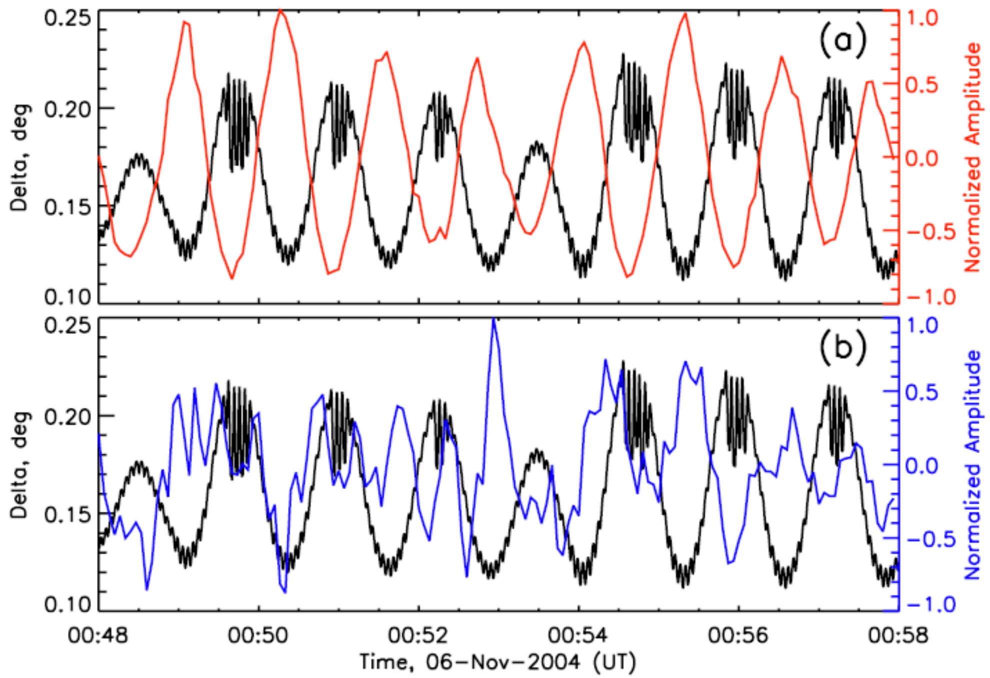
Energy loss by e- in X-ray sources:
<E_loss_th1_1QPP> ~19.2 $\pm$0.8 keV
<E_loss_th2_1QPP> ~6.3 $\pm$1.4 keV

Are these QPPs - RHESSI artifact? Most probably - no!

Inglis+ (2011, AA)

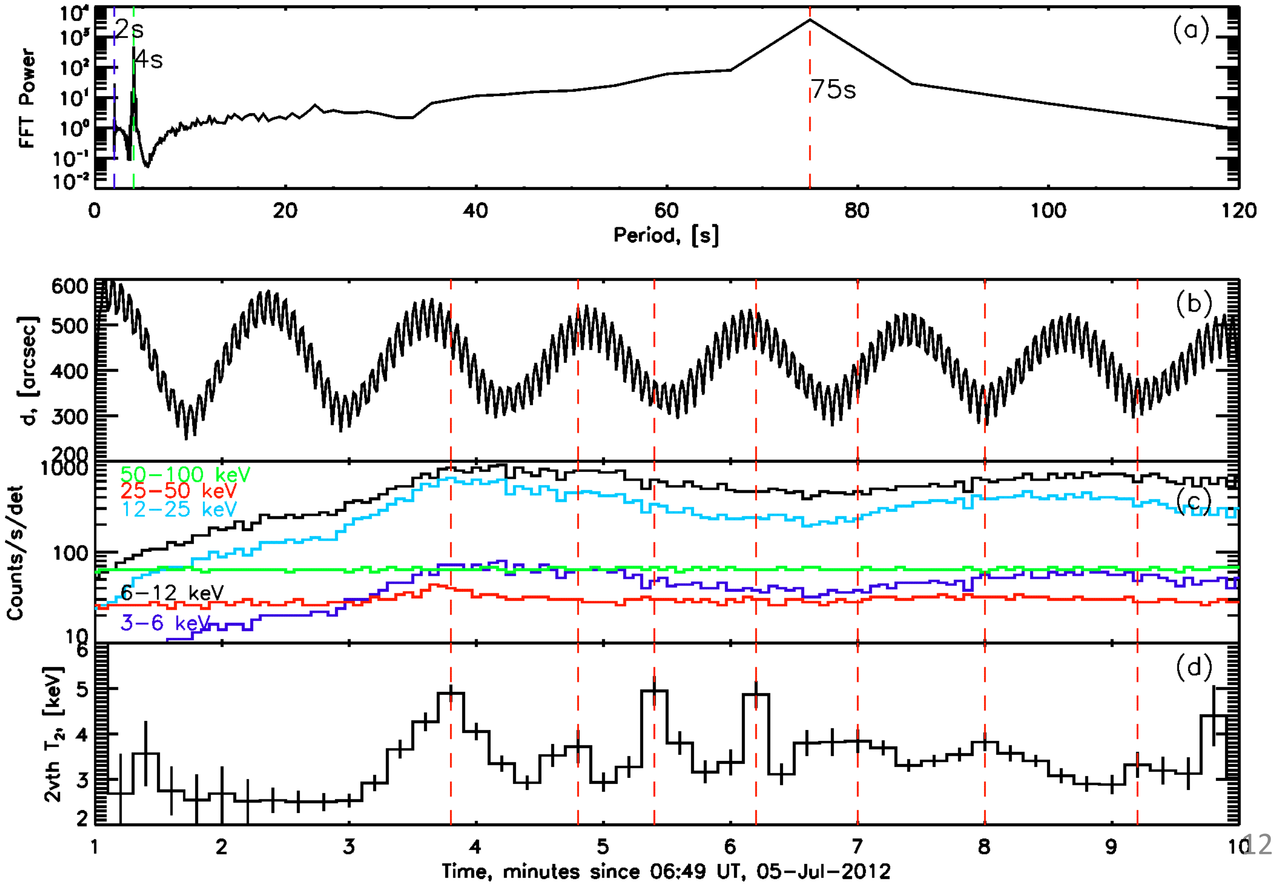
Nutation of rotating RHESSI SC can cause artificial QPPs with P~70-80 s





Properties of QPPs in the flare studied:

1) No visible QPPs in count rates *(as expected in case of the artifact)*
2) QPPs of T (EM or e- spectral index) don't have stable period opposite to pointing period *(mean periods differ: 75 s vs. 54 s)*
3) QPPs are out of phase with pointing of RHESSI imaging axis



Dynamics of X-ray source during the flare

1700 A 1600 A 94A

P1

P2

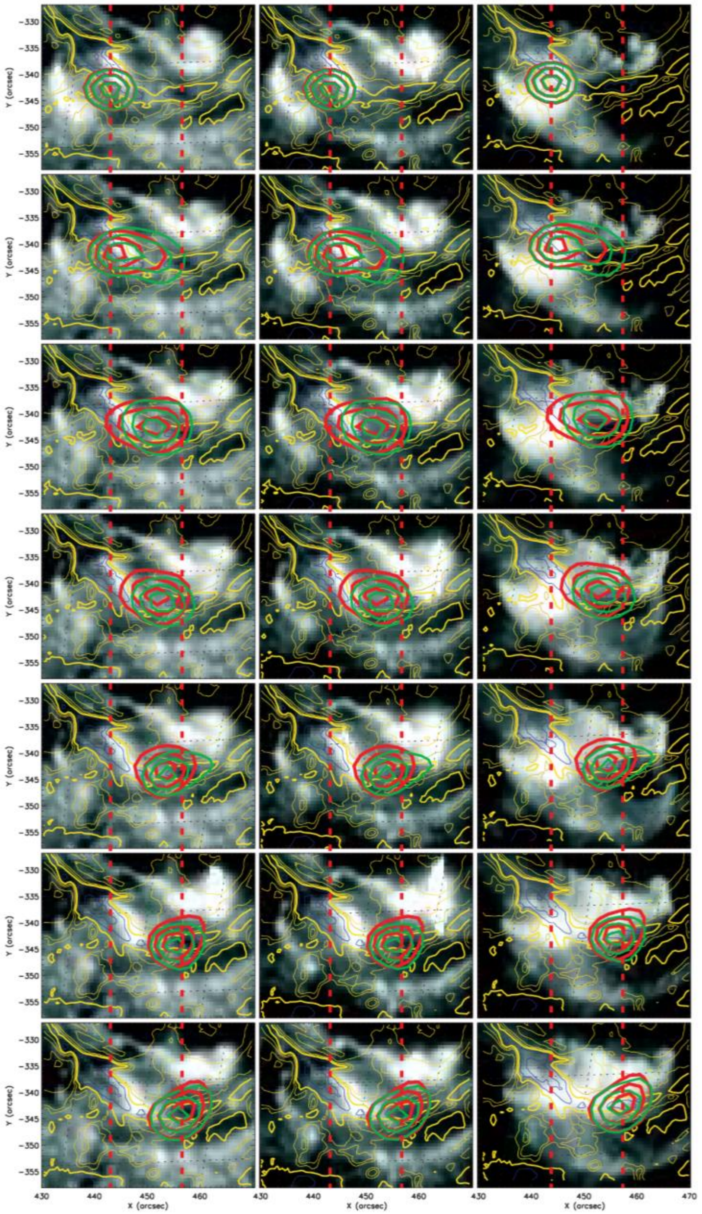
P3

P4

P5

P6

P7



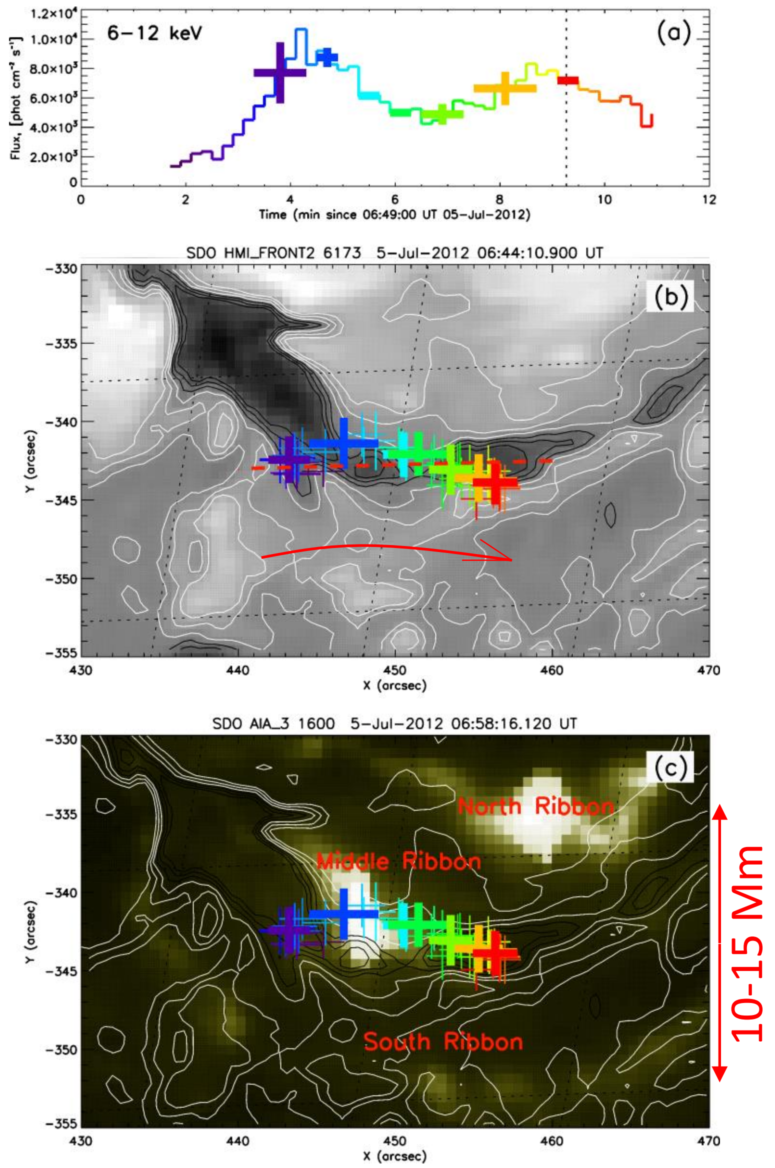
6-12 keV
12-18 keV

Systematic ‘displacement’ of X-ray source from East to West during QPPs

Spread of flare EUV loop system from East to West during QPPs

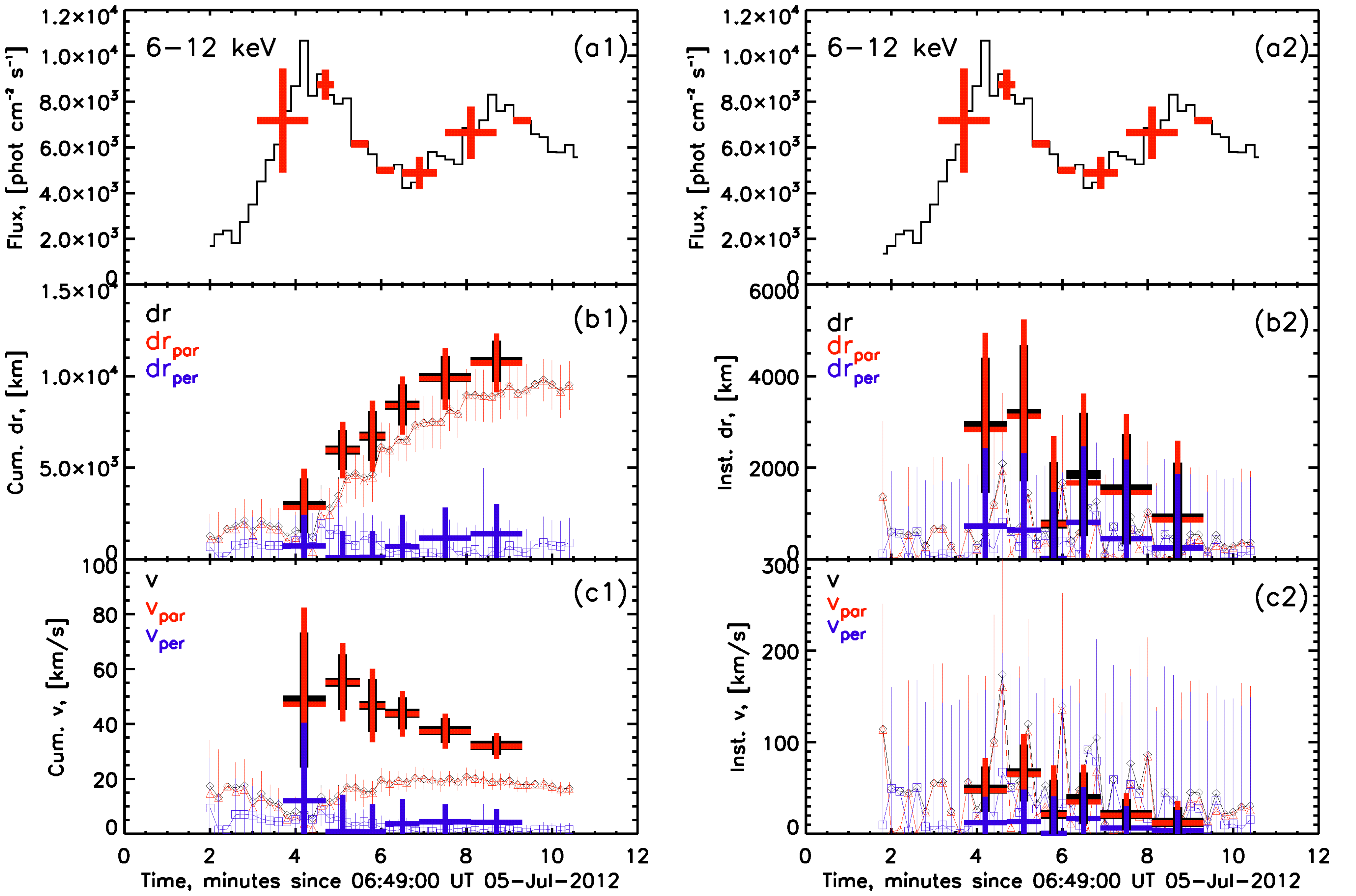
Dynamics of X-ray source during the flare

Source flux & position



Source cumulative dynamics (dr[i]-dr[0])

Source instantaneous dynamics (dr[i+1]-dr[i])



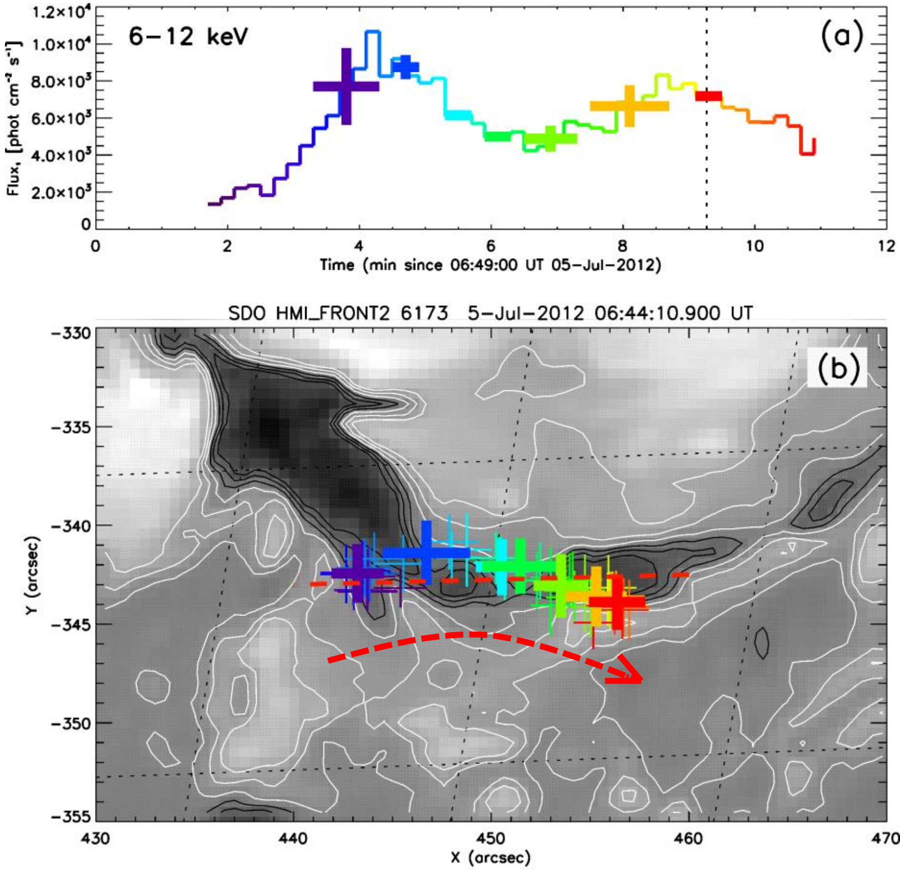
Dynamics of X-ray source during QPPs

Source displacement:
dr=1867±1021 km
dr_{par}=1793±997 km
dr_{per}=483±306 km/s

Source velocity:
v=36±21 km/s
v_{par}=34±21 km/s
v_{per}=9±7 km/s

Very slow displacement:
$v \ll v_s \ll v_A$ (as usual for flares)
see e.g. S.Kuznetsov+ (2016, SoPh)

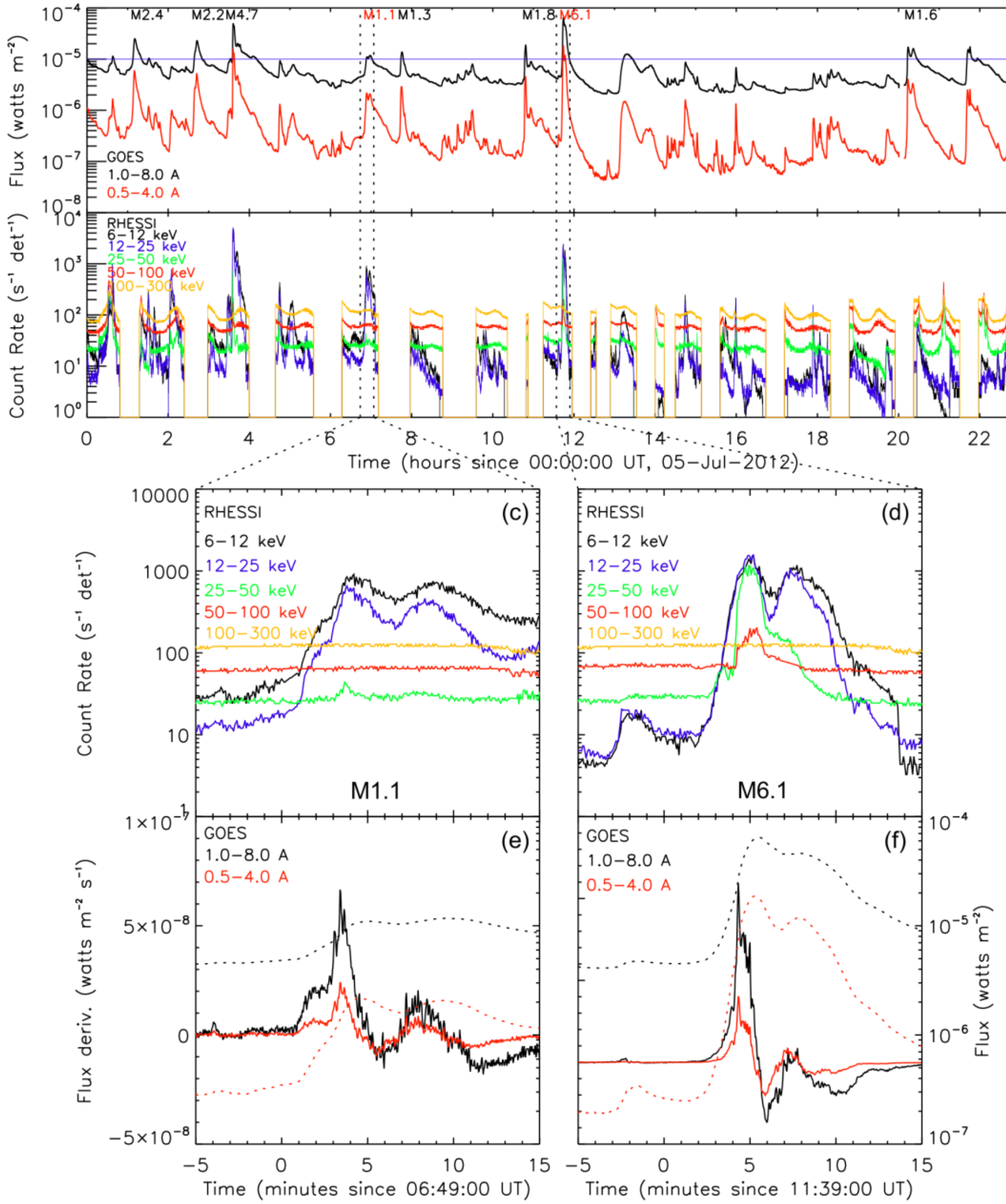
$V_s \sim 0.17 \times (T_{[K]})^{0.5} \sim 170\text{-}1320$ km/s
$v_A \sim 22 B_{[G]}/(n_{[10]})^{0.5} \sim 350\text{-}6600$ km/s
(T~1-60 MK, B~50-300 G, n~10^{10}-10^{11})

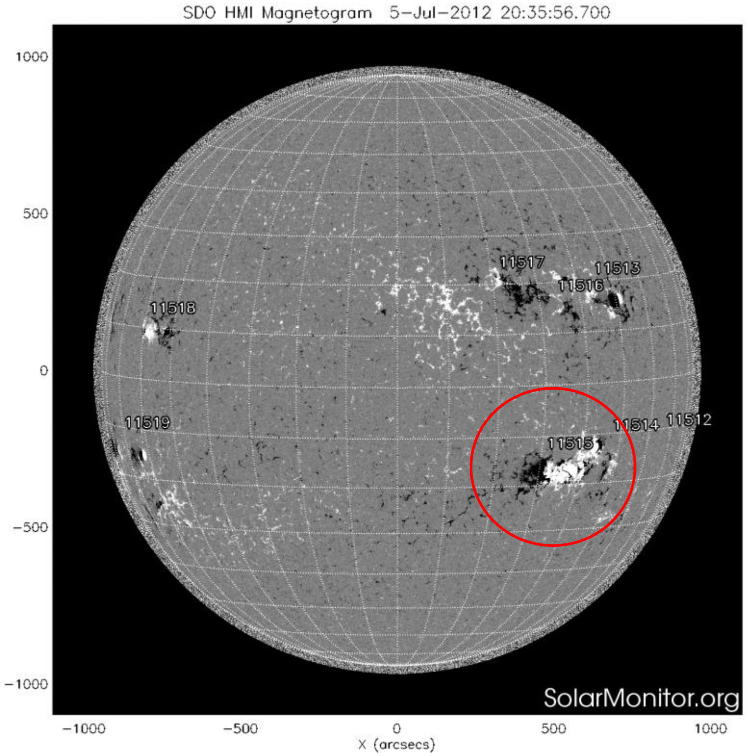


Comparison with homologous M6.1 flare (~5h after M1.1)

Time profiles

We compare the M1.1 flare with a homologous M6.1 flare happened ~5h later in the same NOAA AR 11515

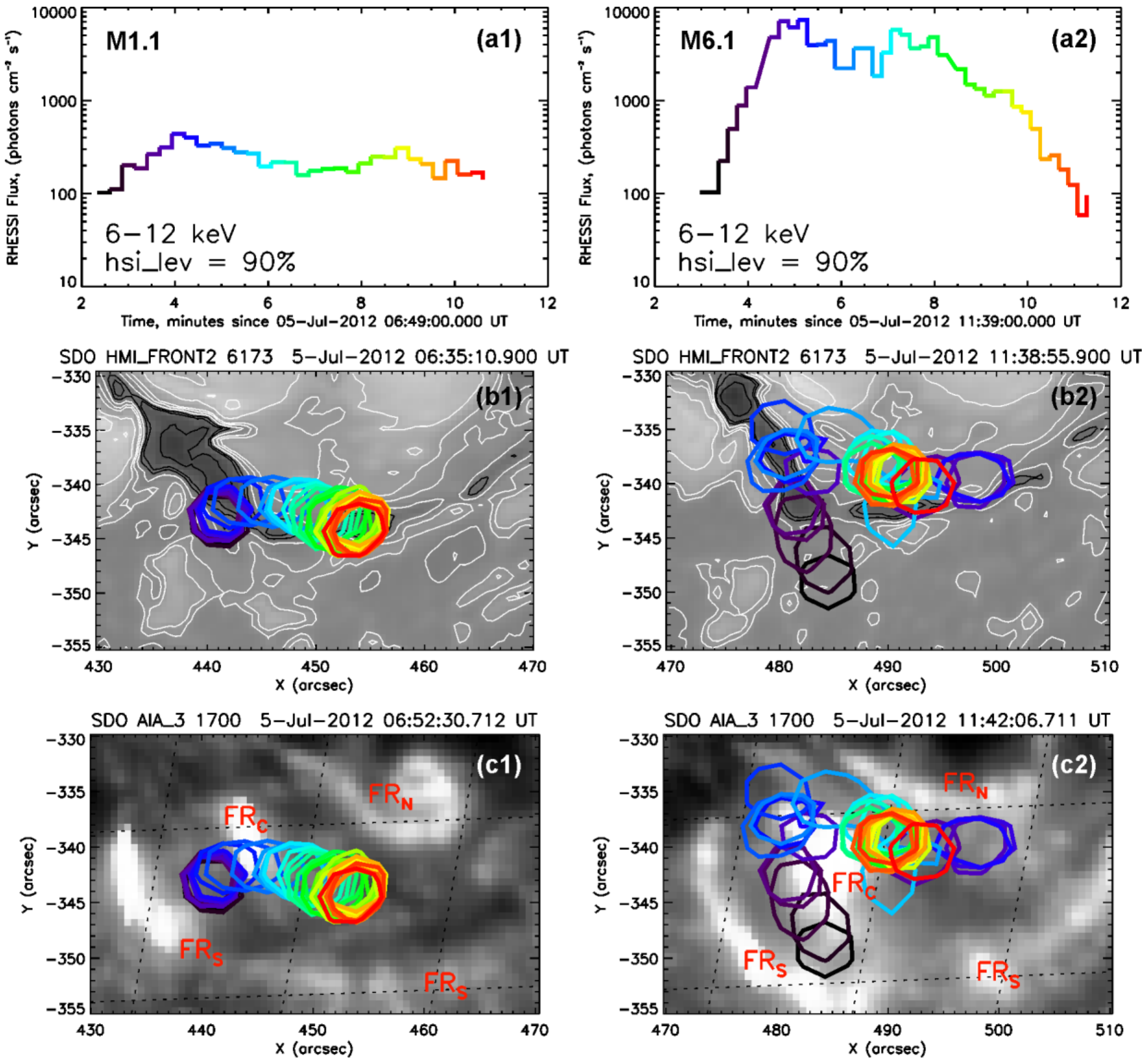




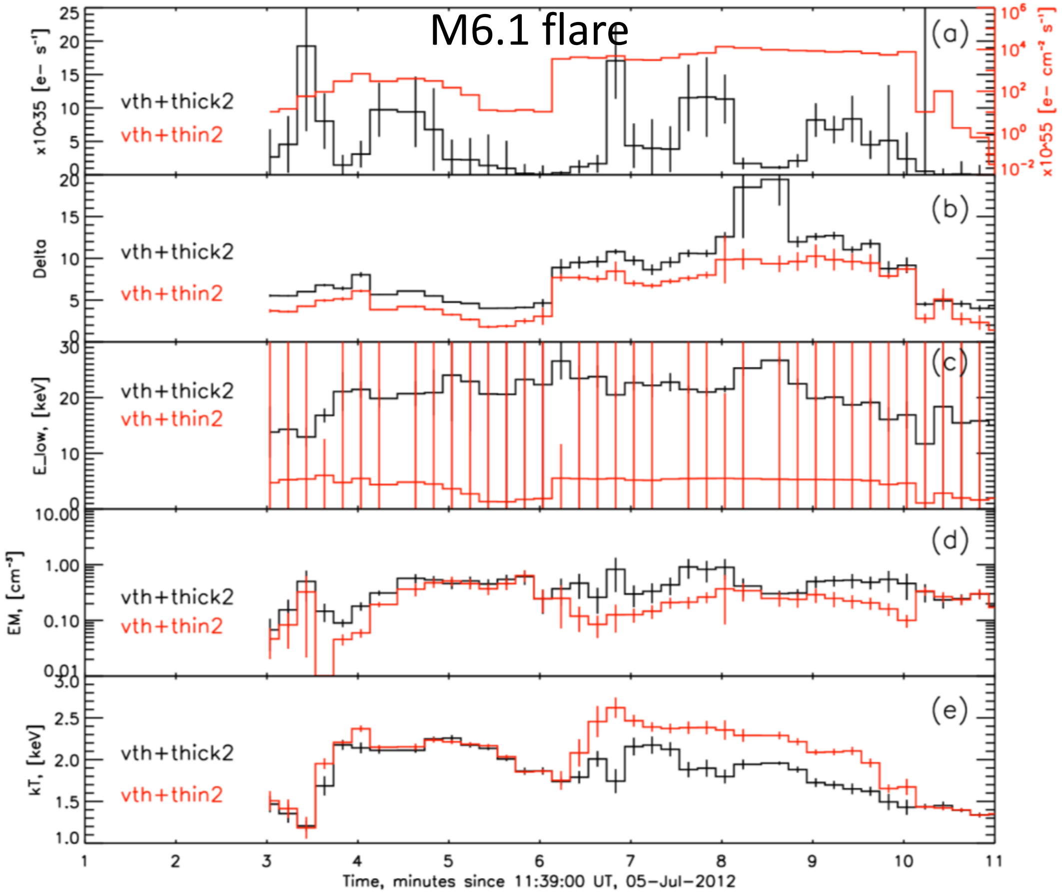
Comparison with homologous M6.1 flare

X-ray source dynamics

M1.1 M6.1

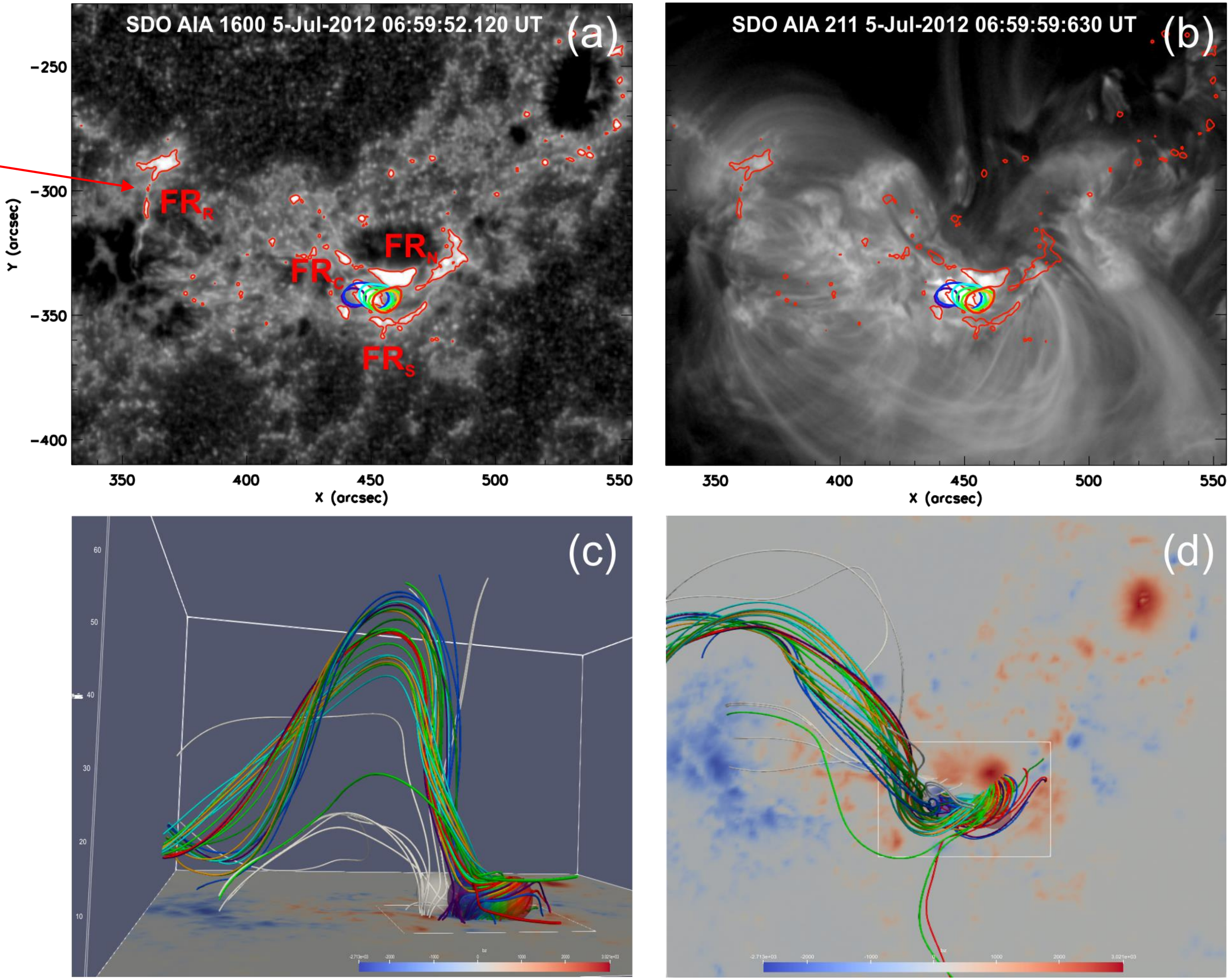


- SXR source dynamics in M6.1 flare is much less “systematic” than in M1.1 flare
- And we don’t see clear QPPs in fit spectral parameters of M6.1 flare
- Possibly, “systematicity” of motion along a particular direction (e.g. PILs) is an important factor for the quasi-periodicity to be observed



Magnetic structure of the flare region

Remote ribbon



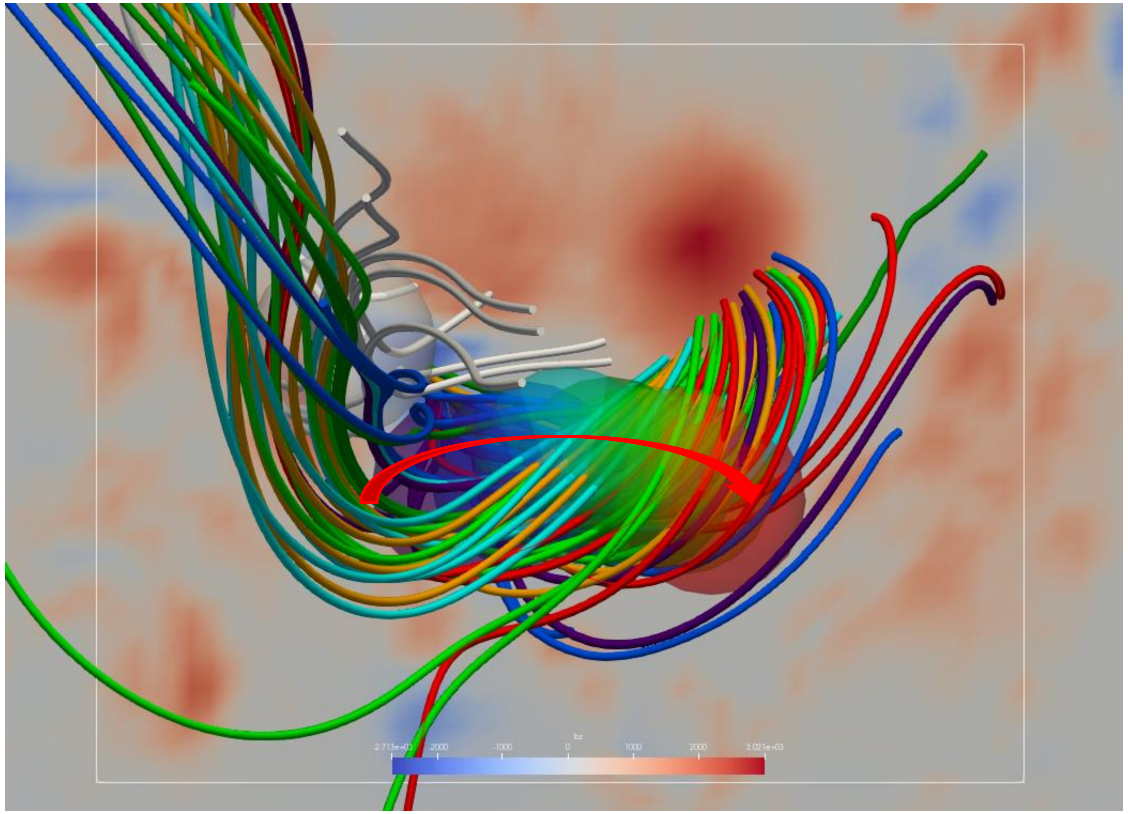
Observations

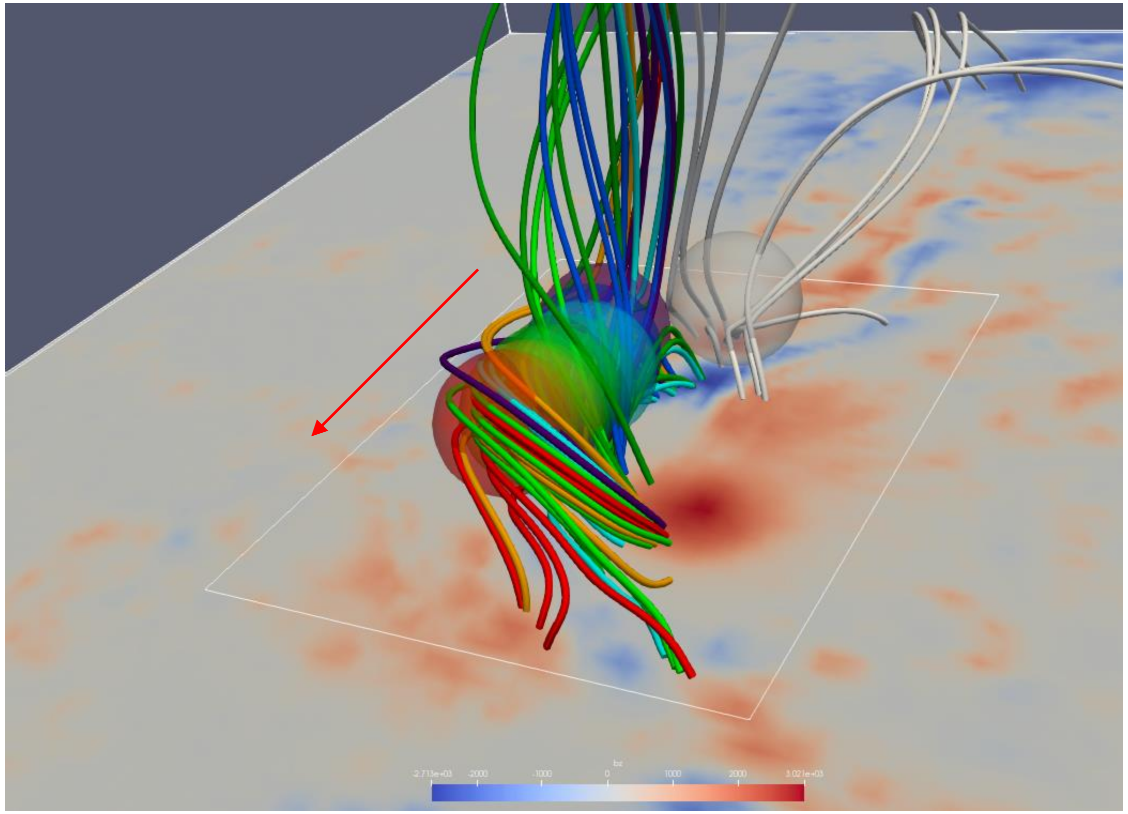
(SXR sources are shown by thick colored contours)

NLFFF extrapolation

(FL are started from SXR source locations)

Magnetic structure of the flare region: closer view

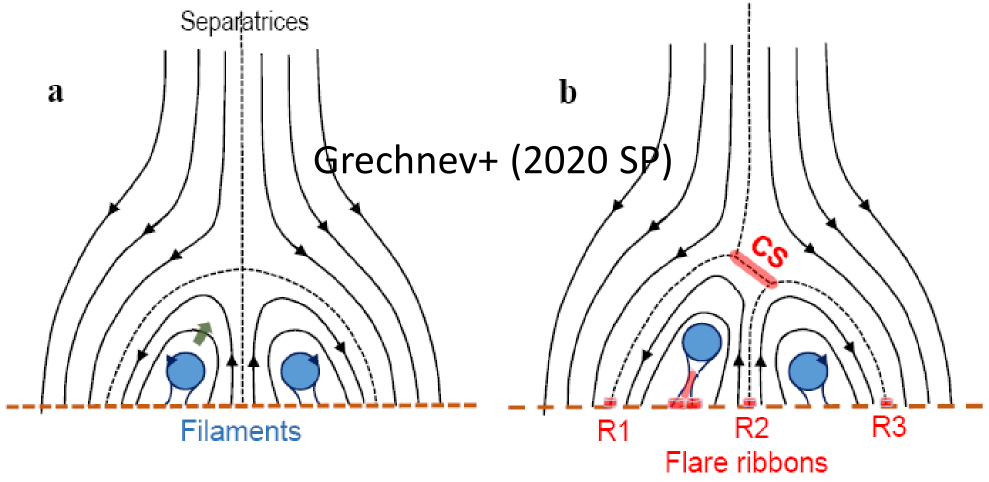




X-ray sources are shown by colored semi-transparent spheres

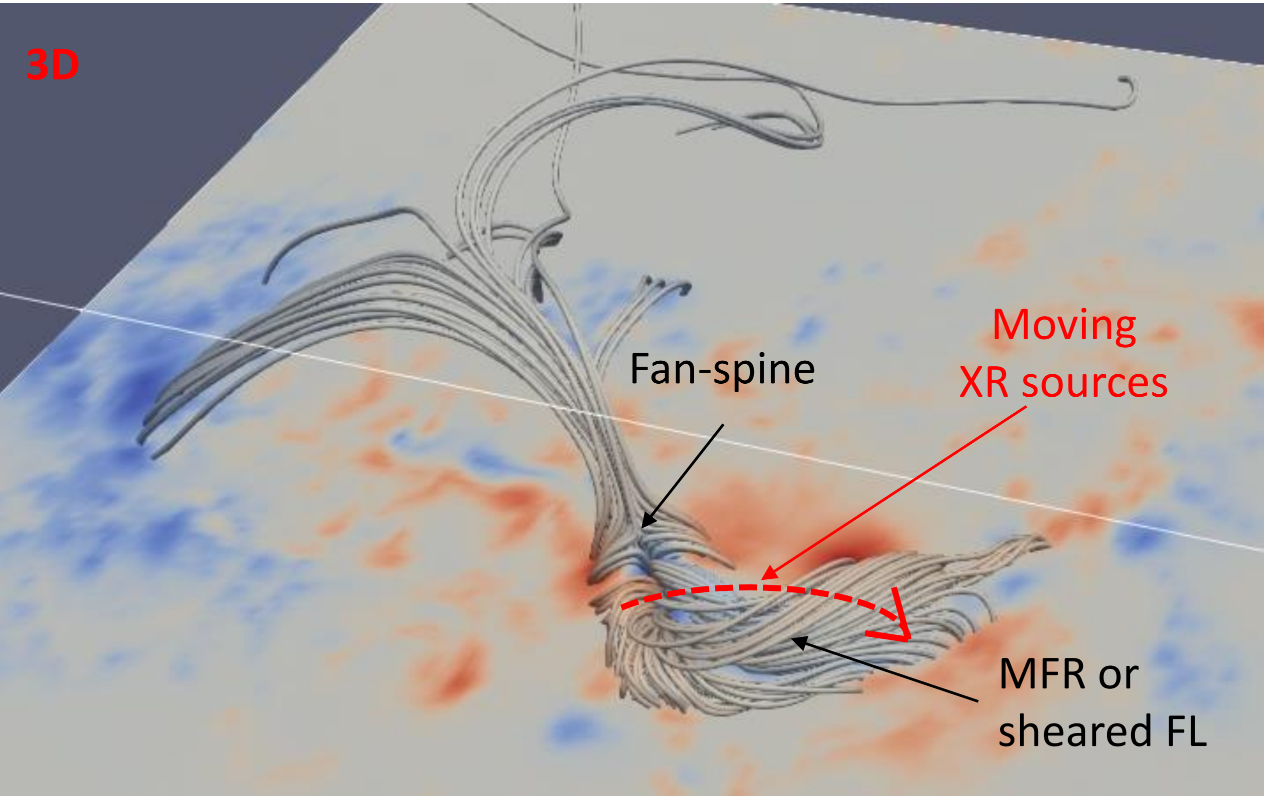
Magnetic structure of three-ribbon flares

2D



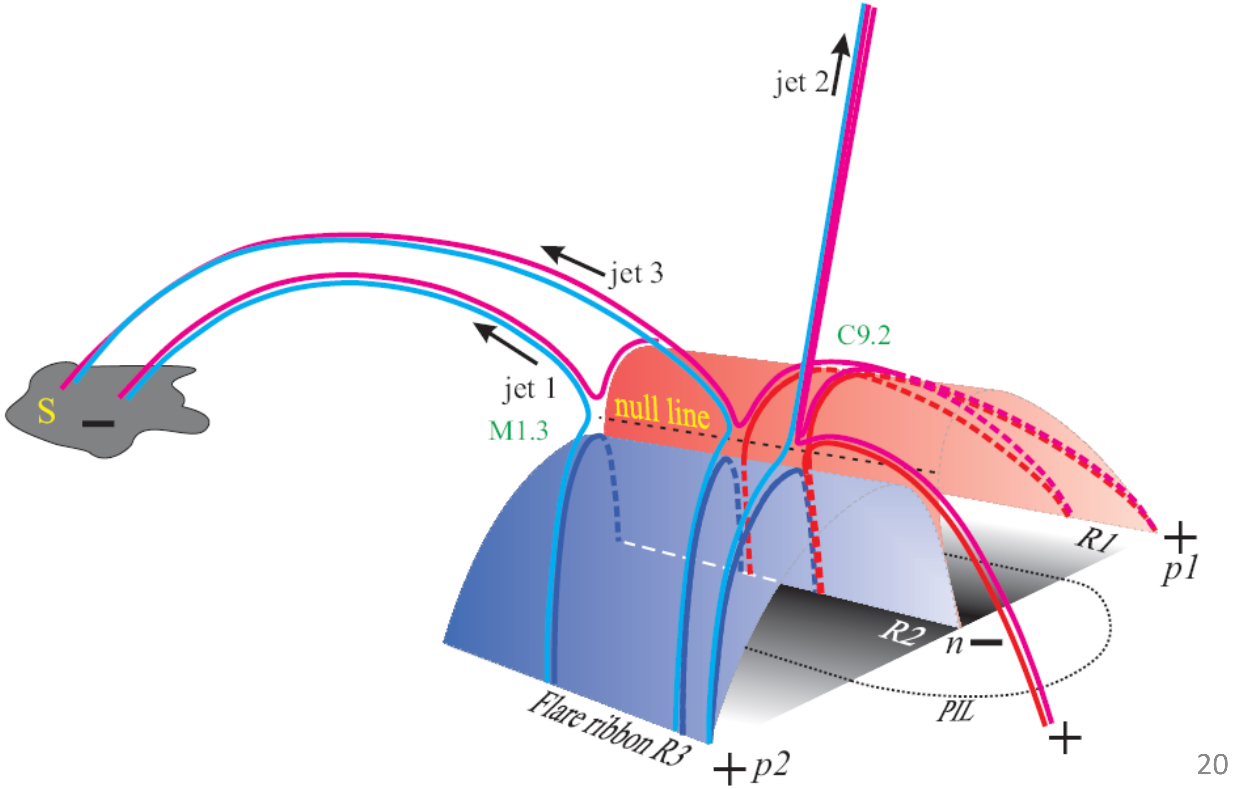
- **Magnetic field is not translationally symmetric along PILs (essentially 3D, not 2.5D)**
- **Very strong shear (up to ~85 deg);**
- **Flux rope is expected along PILs, rather than null line as in Wang+**

3D



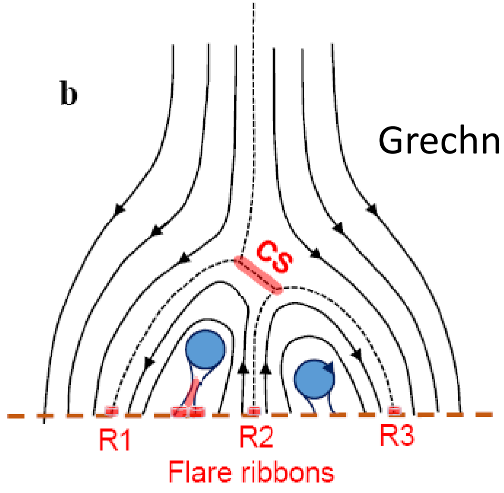
Schematic picture from Wang+ (2014, ApJ)

(for two others homologous (?) flares, M1.3 and C9.2, in the same active region, a day later, on 6 July 2012)



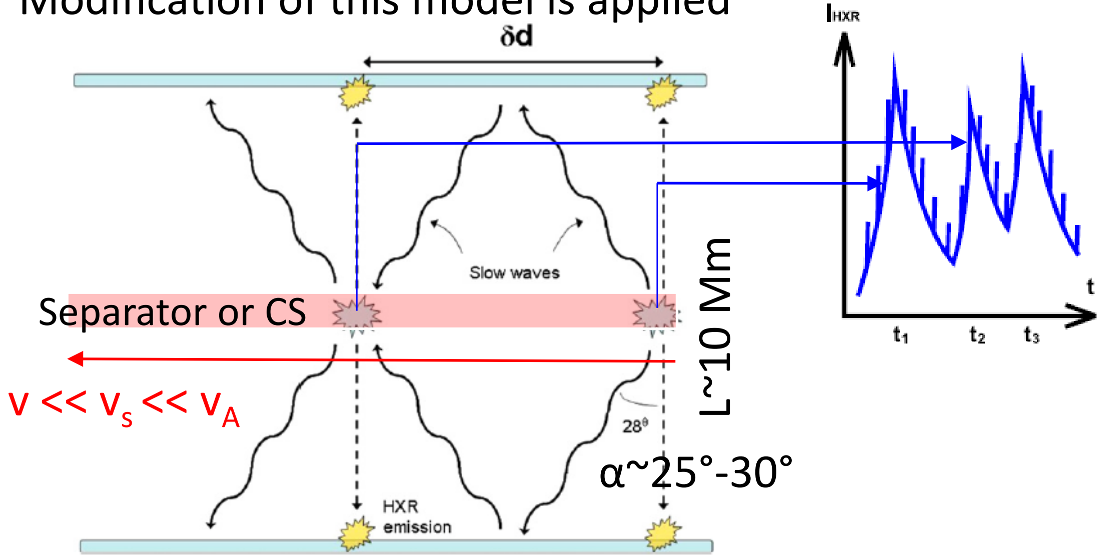
Why $v<v_s<v_A$?

Let's check one possible interpretation based on slow-mode waves as a trigger



Grechnev+ (2020 SP)

Modification of this model is applied



From Inglis & Dennis (2012, ApJ)
based on model by Nakariakov & Zimovets (2011, ApJL)

P_m~$(L/\cos\alpha)/v_s$

v_s~200 km/s (for T_b~1.5 MK, i.e. slow wave propagates on background pre-flare plasma)

P_m~56 s which is consistent with $P_{obs}=54\pm13$ s

δd~L*tgα~5 Mm - around 2-to-5 times larger than the observed one ($dr_{par}=1793\pm997$ km)

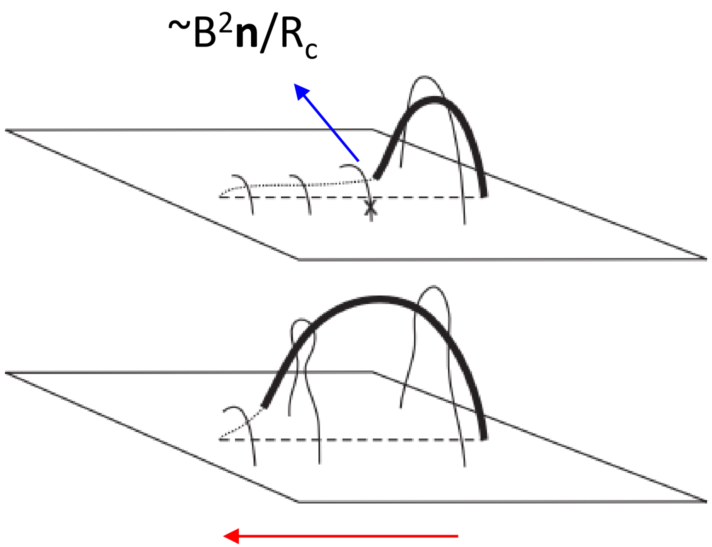
Incorporation of magnetic shear leads to higher δd, which makes the interpretation with this model even more difficult

One needs to suggest other mechanisms to satisfy available observations (see next page)

Other possible mechanisms of the observed QPPs (not all)

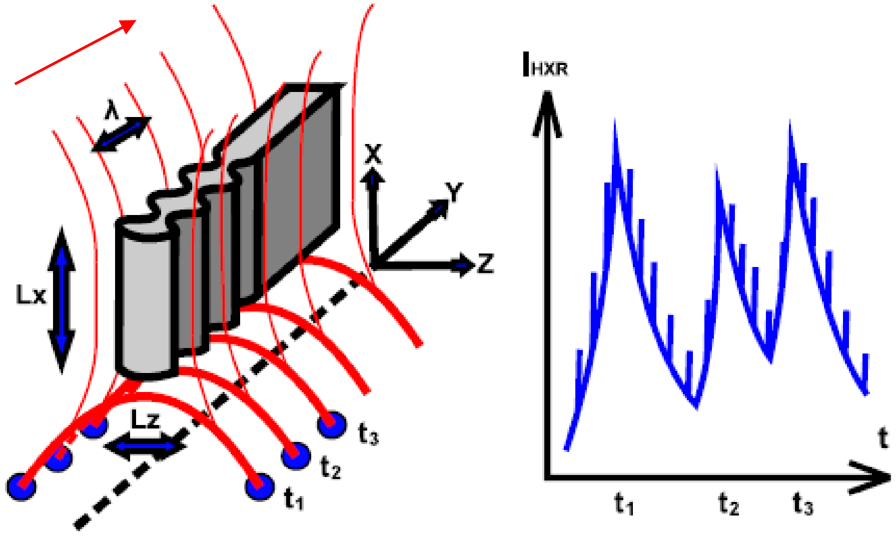
Proposed for 2-ribbon flares, but could be adopted for the 3-ribbon event

Asymmetric flux-rope eruption



Grigis & Benz (ApJL, 2005)
R.Liu+ (ApJ, 2009)
Zimovets+ (JASTP, 2018)

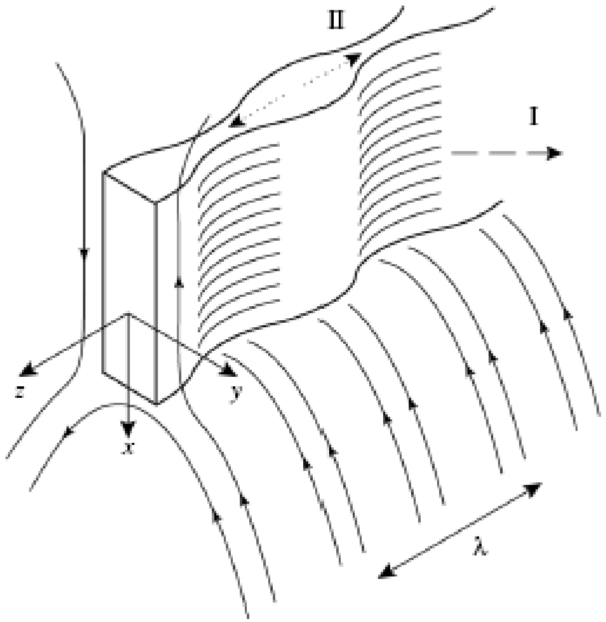
Flapping oscillations of current sheet



P ~ 0.1 - 1000 s
δd ~ 100 – 10000 km

Artemyev & Zimovets (SPh, 2012)

Thermal instability of current sheet

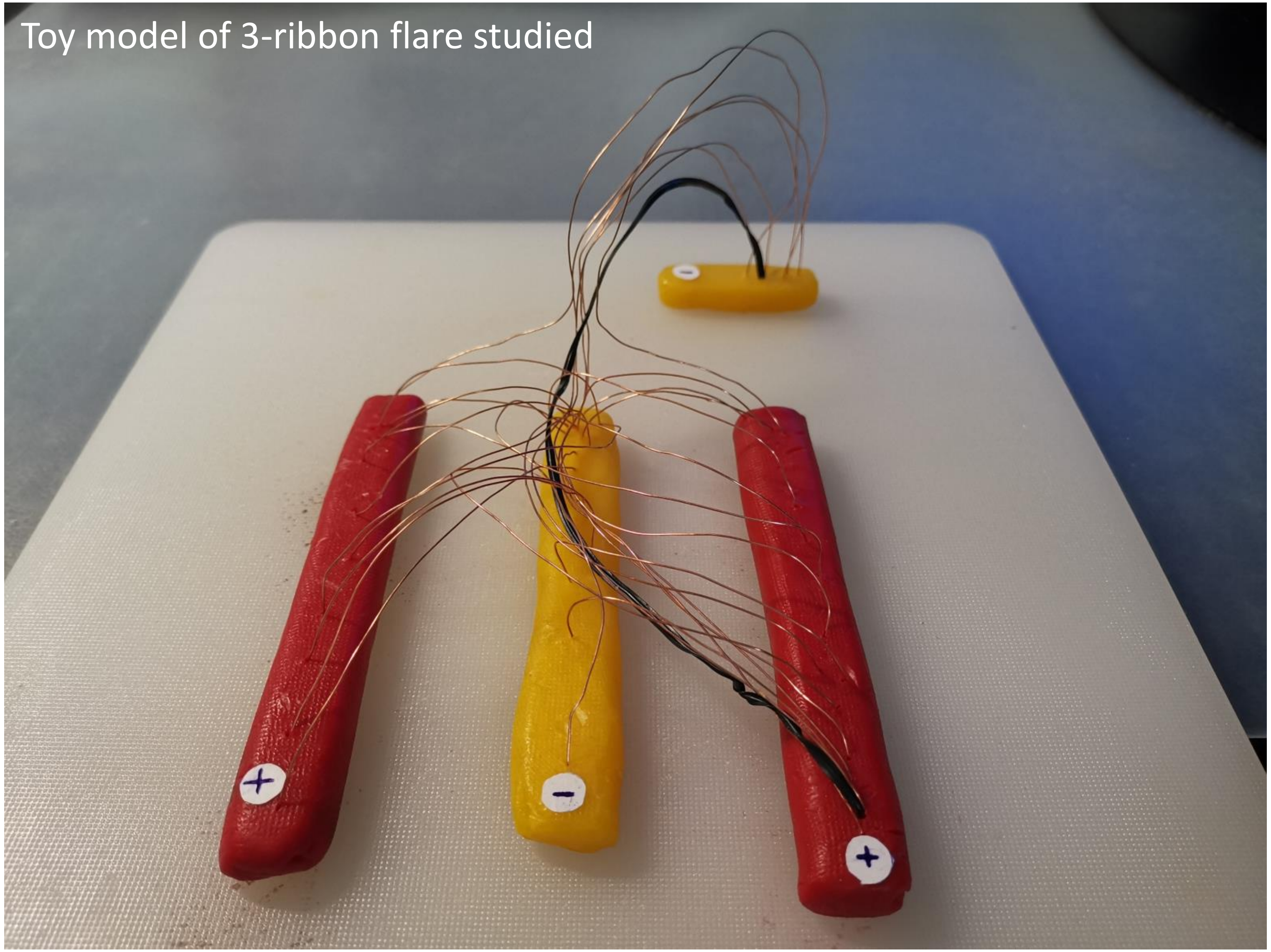


Ledentsov & Somov (AL, 2016)
Ledentsov (2021, SPh)

Summary

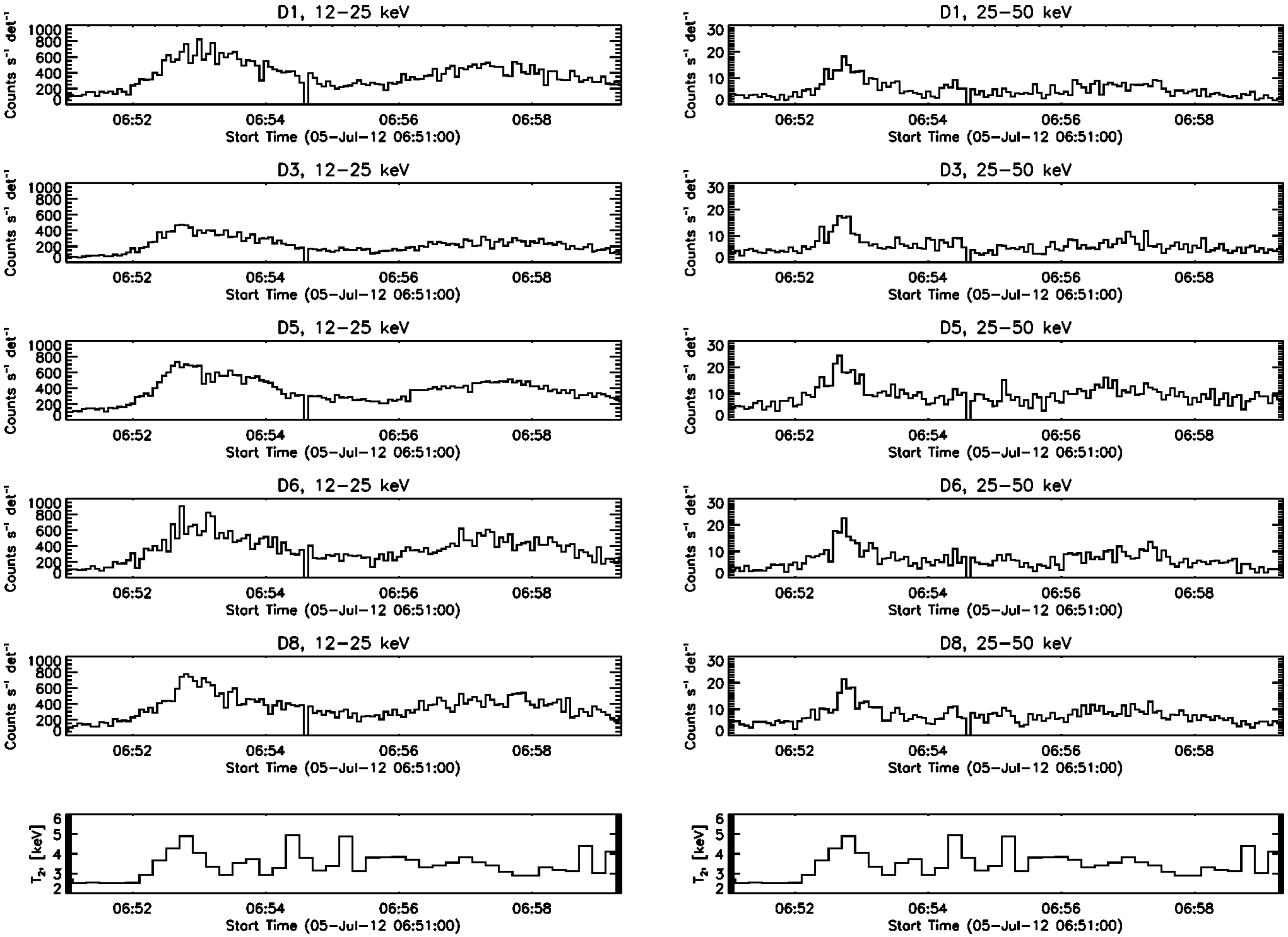
- We found QPPs (with $P = 54 \pm 13$ s) in parameters of super-hot plasma (T~30-50 MK) or non-thermal electrons (less probable) in a three-ribbon flare
- QPPs are not obvious in broad band count rates (or emission light curves) that could be due to much smaller ($\sim 10^2$ times) emission measure of super-hot plasma than of hot (T~16-20 MK) plasma
- There is systematic slow displacement of SXR source during QPPs along a separator or asymmetric MFR above a middle flare ribbon with $v<v_s<v_A$ (which is usual for solar flares, and yet not clear why)
- We can’t easily interpret the observations with modification of the slow-mode wave model in two-ribbon flares
- Other mechanisms are possible and awaiting verification (we are open for discussions)

Thank you!

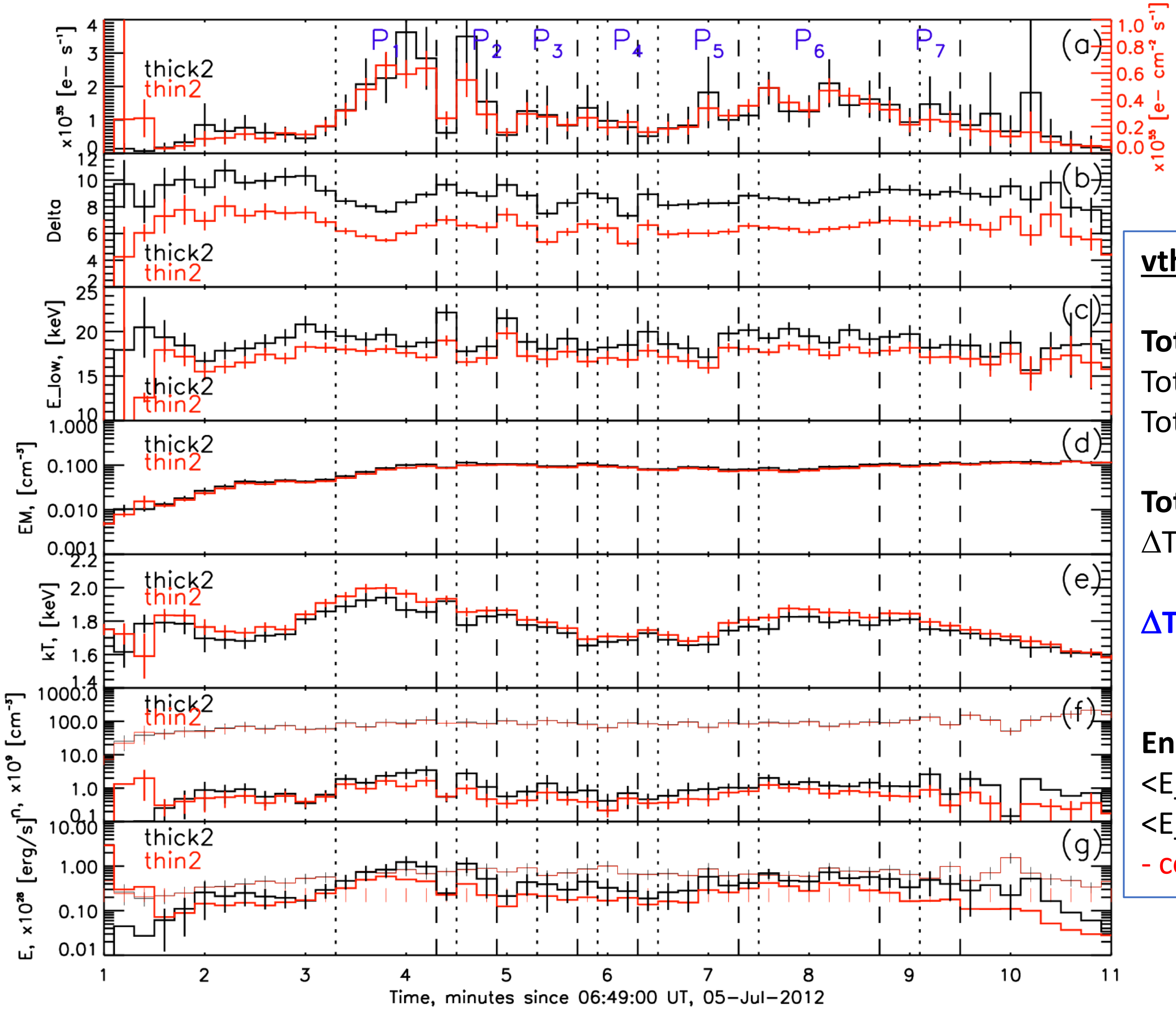


Additional materials

No pronounced QPPs in separate RHESSI detectors’ count rates



Energetics of thermal plasma and non-thermal electrons in vth + thick2 & thin2 model



vth + thick2	**vth + thin2**
Total thermal energy during QPPs:	**Total thermal energy during QPPs:**
Tot(E_th) ~ $(2.8\pm0.1)\times10^{30}$ erg	Tot(E_th) ~ $(2.7\pm0.1)\times10^{30}$ erg
Tot(E_nth) ~ $(1.9\pm0.2)\times10^{30}$ erg	Tot(E_nth) ~ $(1.1\pm0.02)\times10^{30}$ erg
Total release of magnetic energy:	**Total release of magnetic energy:**
ΔTot(B) ~ 8×10^{30} erg	ΔTot(B) ~ 8×10^{30} erg
ΔTot(B) > Tot(E_th) > Tot(E_nth)	**ΔTot(B) > Tot(E_th) > Tot(E_nth)**
Energy of one pulsation:	**Energy of one pulsation:**
<E_th_1QPP> ~ $(3.9\pm0.2)\times10^{29}$ erg	<E_th_1QPP> ~ $(3.9\pm0.2)\times10^{29}$ erg
<E_nth_1QPP> ~ $(2.7\pm0.2)\times10^{29}$ erg	<E_nth_1QPP> ~ $(1.5\pm0.03)\times10^{29}$ erg
- comparable to energy of a microflare	- comparable to energy of a microflare

2vth model parameters

Variable	Value	Error	Units
<EM1>	0.088	0.014	$x10^{49}$ cm^{-3}
<EM2>	0.0013	0.0012	$x10^{49}$ cm^{-3}
<EM1/EM2>	67.4	62.8	
<T1>	1.8	0.1	keV
<T2>	3.6	0.6	keV
<T1/T2>	0.5	0.1	
<S>	24.1	5.1	$x10^{16}$ cm^{2}
<N1>	87.6	19.9	$x10^{9}$ cm^{-3}
<N2>	10.2	6.4	$x10^{9}$ cm^{-3}
<N1/N2>	10.4	7.0	
<E1_stop>	19.2	0.8	keV
<E2_stop>	6.3	1.4	keV
<Eth1>	38.2	1.6	$x10^{28}$ erg
<Eth2>	8.2	1.0	$x10^{28}$ erg
<Eth1/Eth2>	4.7	0.6	
Tot_Eth1	267.1	11.1	$x10^{28}$ erg
Tot_Eth2	57.5	6.9	$x10^{28}$ erg
Tot_Eth1/ Tot_Eth2	4.7	0.6	

vth + thick2 model parameters

Variable	Value	Error	Units
<EM>	0.093	0.014	x10^{49} cm^{-3}
<T>	1.8	0.1	keV
<S>	24.1	5.1	x10^{16} cm^2
e- <flux>	1.46	0.98	x10^{35} e- s^{-1}
e- <low delta>	8.6	0.6	
e- <E_break> (fixed)	33000	0	keV
e- <high delta> (fixed)	6	0	
e- <lec>	19.1	1.4	keV
e- <hec> (fixed)	32000	0	keV
<Nth>	90.4	24.1	x10^9 cm^{-3}
<Nnth>	1.3	0.9	x10^9 cm^{-3}
<Nth/Nnth>	68.4	0.9	
<Eth_stop>	19.5	0.8	keV
<Enth_stop>	2.3	0.6	keV
<Eth>	39.3	1.9	x10^{28} erg
<Enth>	27.1	2.2	x10^{28} erg
<Eth/Enth>	1.5	0.1	
Tot_Eth	275.2	13.6	x10^{28} erg
Tot_Enth	189.6	15.5	x10^{28} erg
Tot_Eth/ Tot_Enth	1.5	0.1	

vth + thin2 model parameters

Variable	Value	Error	Units
<EM>	0.087	0.013	x10^{49} cm^{-3}
<T>	1.8	0.1	keV
<S>	24.1	5.1	x10^{16} cm^{2}
e- <norm factor>	0.34	0.16	x10^{35} e- cm^{-2} s^{-1}
e- <low delta>	6.4	0.6	
e- <E_break> (fixed)	33000	0	keV
e- <high delta> (fixed)	6	0	
e- <lec>	17.6	1.0	keV
e- <hec> (fixed)	32000	0	keV
<Nth>	87.1	19.1	x10^{9} cm^{-3}
<Nnth>	0.74	0.44	x10^{9} cm^{-3}
<Nth/Nnth>	118.4	0.4	
<Eth_stop>	19.1	0.8	keV
<Enth_stop>	1.7	0.4	keV
<Eth>	38.8	1.6	x10^{28} erg
<Enth>	15.0	0.3	x10^{28} erg
<Eth/Enth>	2.6	0.1	
Tot_Eth	271.5	11.2	x10^{28} erg
Tot_Enth	104.6	1.8	x10^{28} erg
Tot_Eth/ Tot_Enth	2.6	0.1	

Model fit quality for M6.1 flare