Energy deposition by flare accelerated electrons in seismically active solar flares

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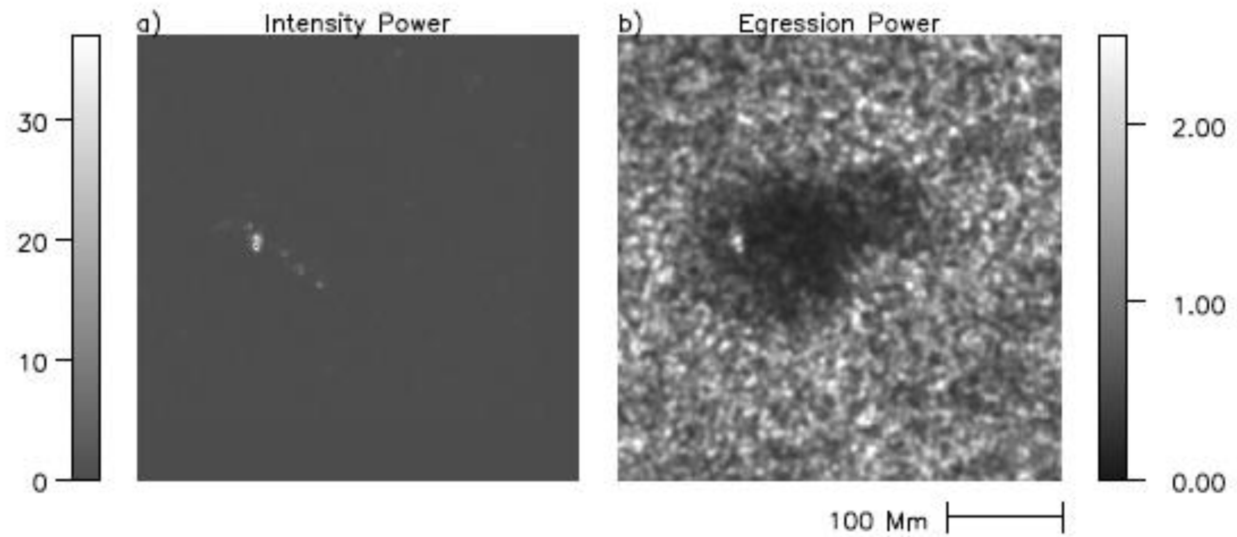
Introduction

- Sunquake: seismic transient that propagates below the photosphere which usually occurs during the impulsive phase of solar flares in a small localized region.

- Predicted to occur as part of the solar flare process by Wolff (1972) but first report of an observed sunquake not until Kosovichev & Zharkova (1998)
  - X2.6 class flare on the 9 July 1996.

- Can be observed on the solar surface as a ripple which is detected through helioseismology.



Lindsey & Donea (2008)

GONG white light intensity

Egression power (acoustic source)

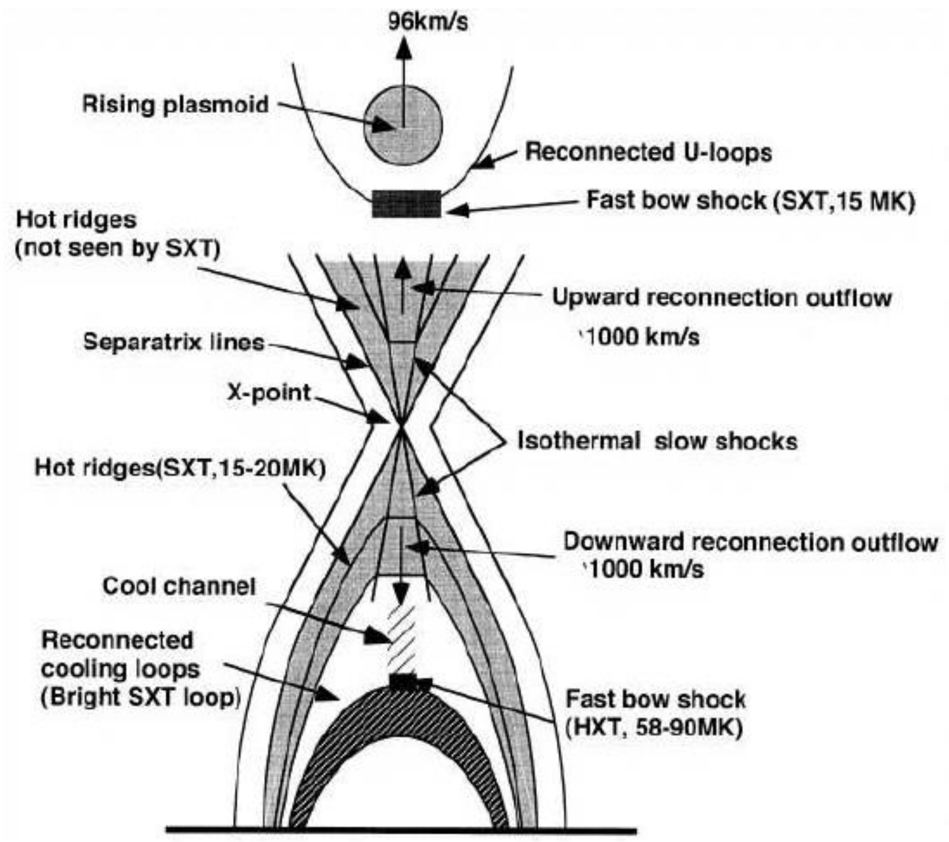
Introduction

- Challenges the “Standard Flare Model”, where energy is released in the solar corona through magnetic reconnection and results in plasma heating and particle acceleration.

- How is the energy and momentum for a sunquake transported from the corona to the photosphere?

- Not all flares produce a sunquake, so what makes these events special? Does current instrument sensitivity and detection techniques prevent use finding more events?

- Several competing mechanisms…



Tsuneta (1997) – “Standard flare model”

Possible mechanisms

Chromospheric shocks:

Particles accelerated to high energies during the impulsive phase of the flare, deposit their energy in the chromosphere and heat the surrounding region (thick-target model). The intense heating and the resulting dynamic effects could excite shock waves that penetrate downwards into the photosphere triggering a seismic event (Kosovichev and Zharkova (1998).

- Hydrodynamic models have suggested radiative losses might be too great for sufficient amounts of energy to reach the photosphere.

Photospheric heating:

Sunquakes are highly correlated with white light flares.

Downward propagating radiation, specifically from the visible continuum, as a result of an impulsively heated chromosphere could penetrate into the photosphere and be absorbed (Hudson 1972) i.e. back warming (Emslie 1986). If sufficiently impulsive this could drive and acoustic transient.

Possible mechanisms

Lorentz Force:

During the flare, the coronal magnetic field undergoes large scale restructuring. The lorentz force associated with this restructuring could provide the energy required to initiate a sunquake (Hudson 2008, Donea 2006, Oliveros 2009). i.e. the “McClymont jerk” (A. N. McClymont, Anwar et al., 1993)

Accelerated particle:

Direct heating of the low photosphere by accelerated particles (Najita and Orrall (1970). Requires large beams of high energy particles i.e. 100 MeV protons (ˇSvestka, 1970, Hudson 2011).

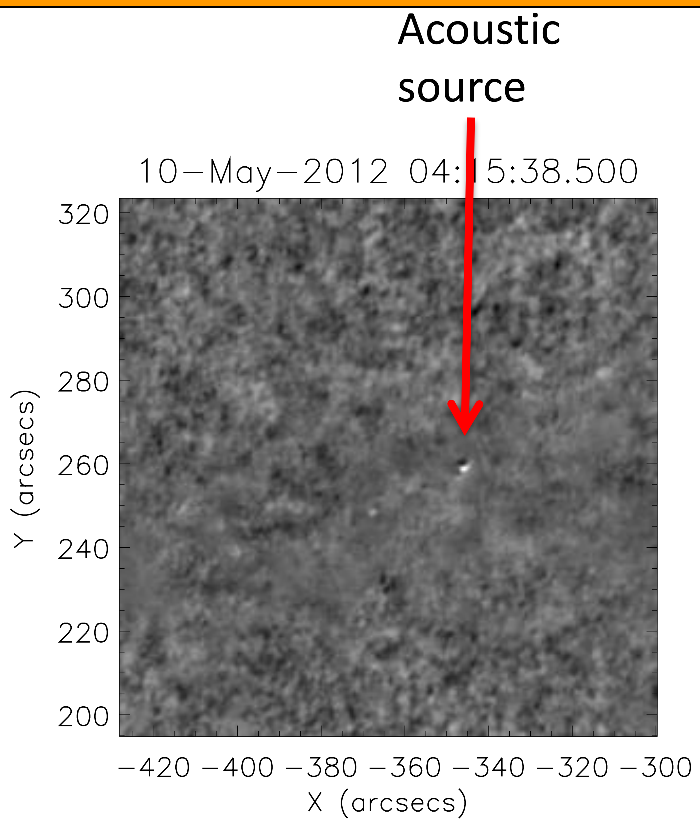
- Gamma-ray emission not always detected. Moradi et al. (2007) found a seismically active flare without gamma-ray emission.

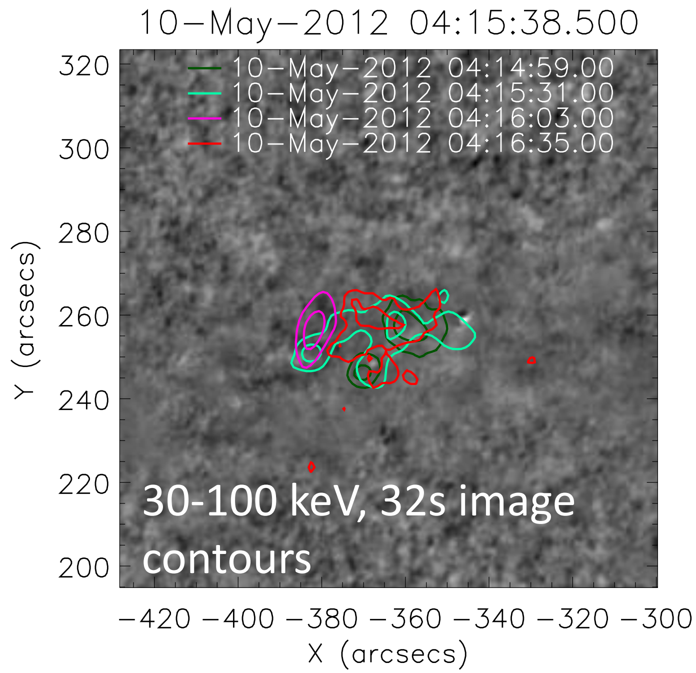
In practice, there may be a combination of several mechanisms.

The plan!

- Juan Carlos Martinez Oliveros is preparing a paper comparing the energetics associated with different competing mechanisms potentially responsible for the sunquake.
- Comparing the energy from white light emission, energy deposition by particles (HXR and gamma-ray emission) and from magnetic field with acoustic energy.
- In this talk I'm presenting the RHESSI analysis.
- For investigating energy deposition from accelerated electrons, imaging spectroscopy is important tool – The acoustic source is often a compact and localized to a small region within the flare.
- In many events, there is HXR emission from parts of the flare that are not associated with the acoustic source. What is different about these regions?

Imaging spectroscopy





- May 10th, 2012 event is an example of why using imaging spectroscopy is important.

Event selection

- To search for new sunquake events, Buitrago-Casas 2015 looked for RHESSI HXR events with >50 keV emission that also had enhanced flaring white light emission observed with SDO HMI. – found 18 sunquakes out of the 75 flares investigated.

- Starting with this list of sunquake events observed with SDO HMI (for doppler and white light observations) and RHESSI (for imaging spectroscopy capability)....plus a few extra events.

Table 1. Times and locations of the seismically active solar flares found in this survey. Some of these have been reported by other authors before, e.g., Kosovichev (2011, 2014); Zharkov *et al.* (2013a); Sharykin, Kosovichev, and Zimovets (2014). Peak times and positions were taken from the RHESSI flare list.

#	Date	Peak time	X (arcsec)	Y (arcsec)	GOES
1	2011-02-15	1:55:30	205	-222	X2.2
2	2011-07-30	2:09:10	-526	170	M9.3
3	2011-09-26	5:07:58	-519	116	M4.0
4	2012-03-09	3:34:52	0	389	M6.3
5	2012-05-10	4:17:42	-364	259	M5.7
6	2012-07-04	9:54:26	289	-343	M5.3
7	2012-07-05	3:35:50	417	-338	M4.7
8	2012-07-05	11:44:14	495	-332	M6.1
9	2012-07-06	1:39:38	585	-322	M2.9
10	2012-10-23	3:17:22	-795	-272	X1.8
11	2013-02-17	15:50:22	-338	307	M1.9
12	2013-07-08	1:22:10	75	-217	C9.7
13	2013-11-06	13:48:42	-549	-267	M3.8
14	2013-11-07	3:39:38	-450	-272	M2.3
15	2013-11-07	14:28:22	-363	-263	M2.4
16	2014-01-07	10:16:14	-228	-168	M7.2
17	2014-02-02	6:33:54	-300	314	M2.6
18	2014-02-07	10:28:38	764	270	M1.9

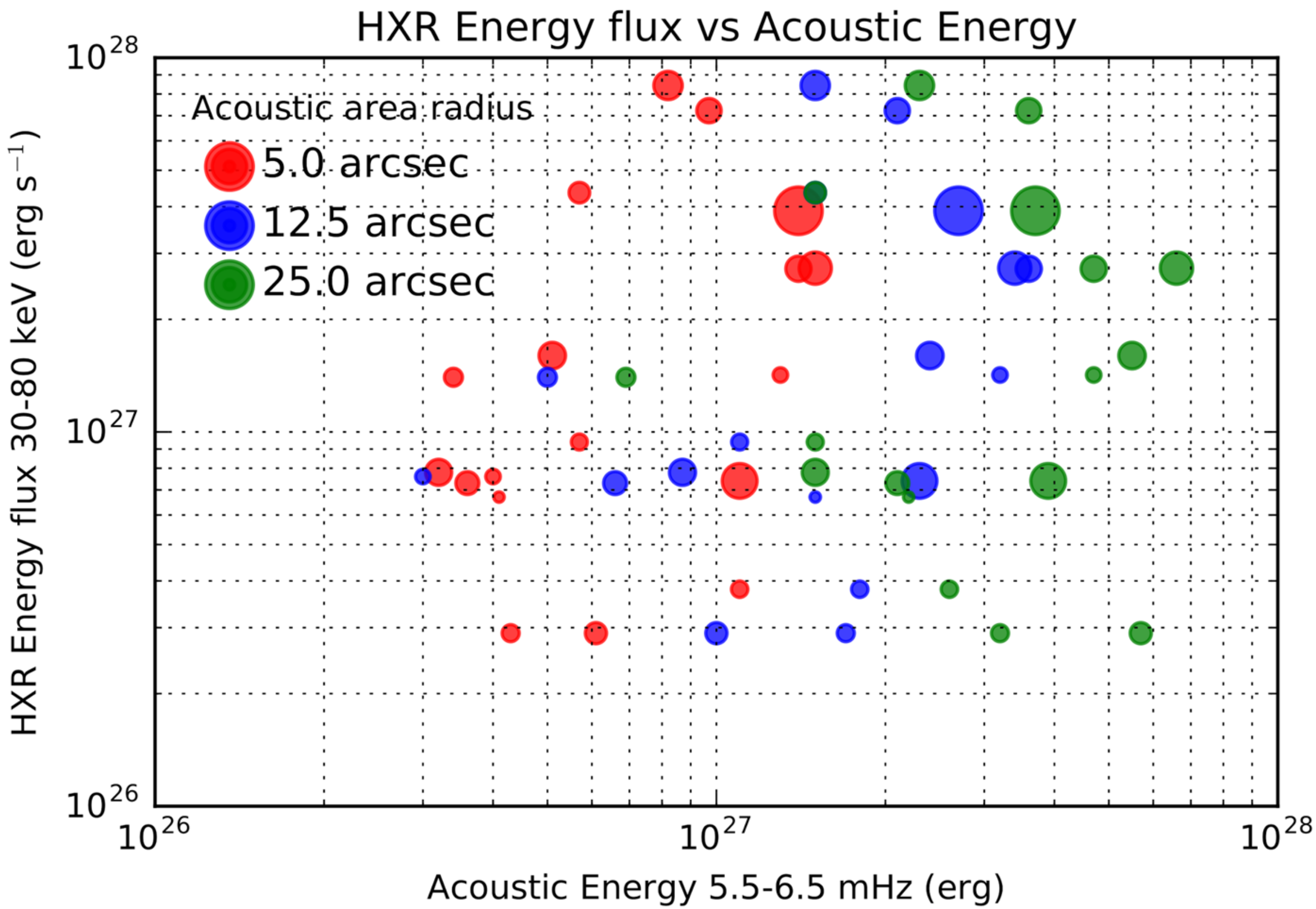
Event table from Buitrago-Casas 2015

Energetics

Date	Acoustic Energy	HXR energy [10^{27} erg s^{-1}]	Error (krupar 2016)	WL	Error
2011-02-15T01:51:00	1.40E+27	3.9	0.72	5.00E+30	8.40E+29
2011-07-30T02:13:30	1.50E+27	2.74	0.66	2.98E+30	8.90E+29
2011-08-03T04:36:45	6.10E+26	0.29	0.15	9.73E+29	6.45E+29
2011-09-26T05:10:30	5.10E+26	1.6	0.4	1.07E+30	4.60E+29
2012-03-09T03:28:30	1.40E+27	2.73	0.85	8.22E+28	3.15E+28
2012-05-10T04:18:45	9.70E+26	7.22	1.71	3.26E+29	2.88E+29
2012-07-04T09:57:00	3.60E+26	0.73	0.71	9.84E+29	3.67E+29
2012-07-05T03:36:45	3.20E+26	0.78	0.16	2.80E+30	1.02E+30
2012-07-05T11:45:45	3.40E+26	1.4	0.14	2.37E+30	1.64E+30
2012-07-06T01:41:15	1.10E+27	0.74	0.25	1.81E+30	5.80E+29
2013-02-17T15:51:45	1.30E+27	1.42	0.14	1.92E+29	8.08E+30
2013-07-08T01:23:15	4.10E+26	0.67	0.07	4.78E+29	3.36E+29
2013-11-06T13:42:45	5.70E+26	4.36	0.44	9.79E+29	5.29E+29
2013-11-07T03:41:15	5.70E+26	0.94	0.09	2.57E+30	1.50E+30
2013-11-07T14:31:30	1.10E+27	0.38	0.04	7.79E+29	6.02E+29
2014-01-07T10:15:00	8.20E+26	8.43	1.72	2.15E+30	1.04E+30
2014-02-02T06:34:30	4.30E+26	0.29	0.03	9.40E+29	2.30E+29
2014-02-07T10:24:00	4.00E+26	0.76	0.21	8.16E+29	6.63E+29

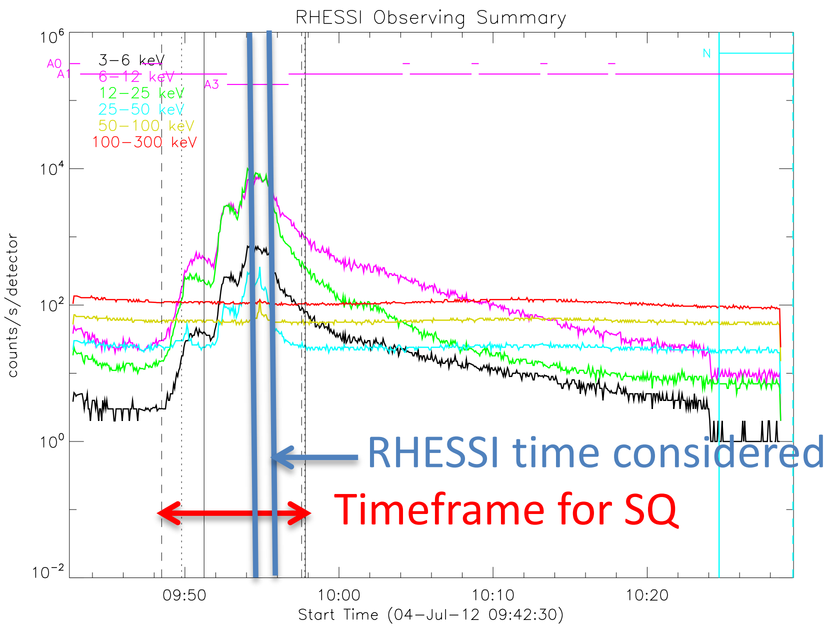
- Kuhar et al. 2016 – study of white light and HXR flares to investigate link between flare accelerated electrons and white light emission.
- Almost all of the sunquake events were included in that study.
- HXR energy estimates from spatially integrated RHESSI spectroscopy (45s time int. around peak).

HXR vs Acoustic



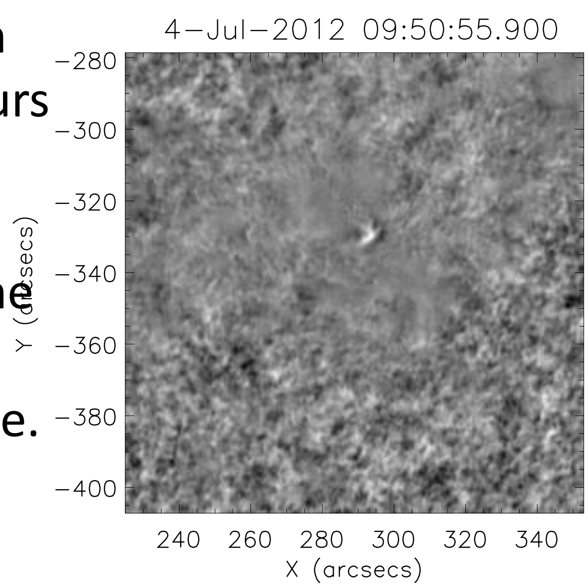
Comparison of HXR energy flux from Kuhar 2016. Credit Juan Carlos Martinez Oliveros

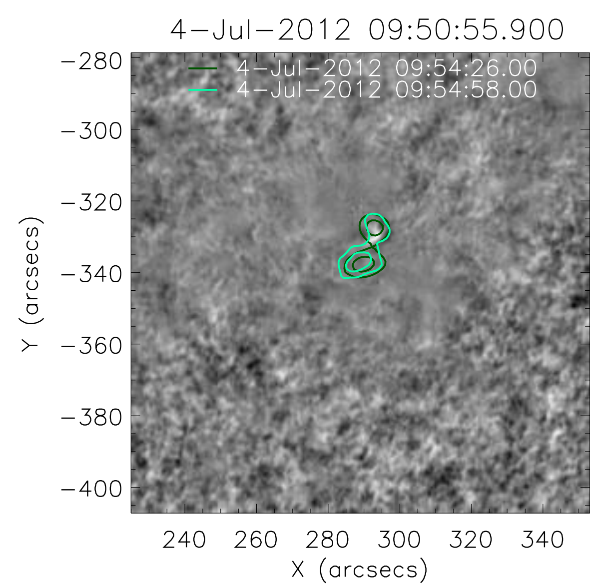
Comparison with acoustic source



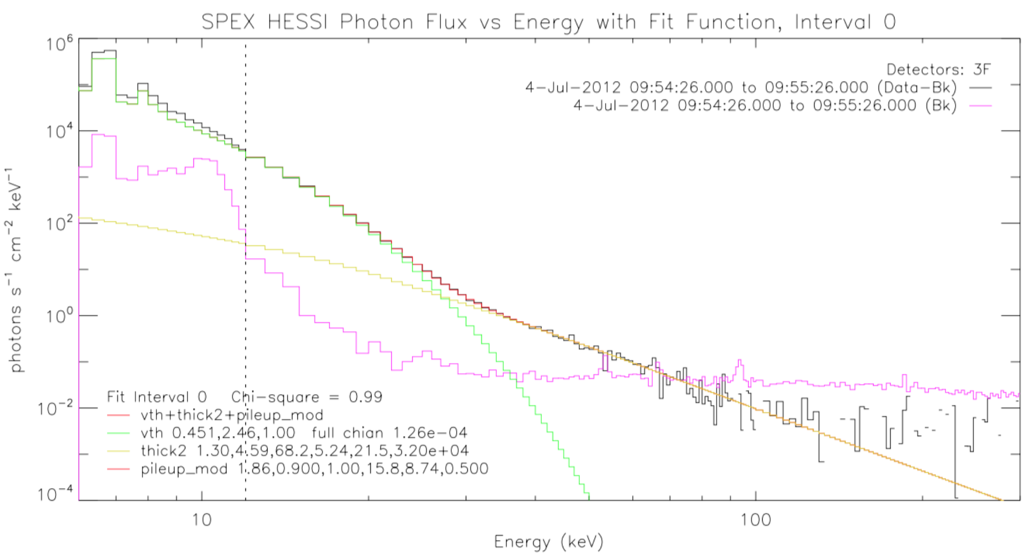
- Uncertainty in the SQ onset time of about +/- 4 minutes from the heliospheric holography.
- RHESSI intervals chosen around the peak of the flare.

- Acoustic source (left) with RHESSI 30-100 keV contours (right).
- Note: Only a fraction of the HXR source is associated with the acoustic signature. Also not the strongest source of HXR emission.





4-July-2012 SQ event

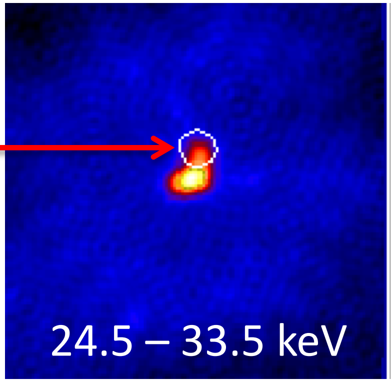


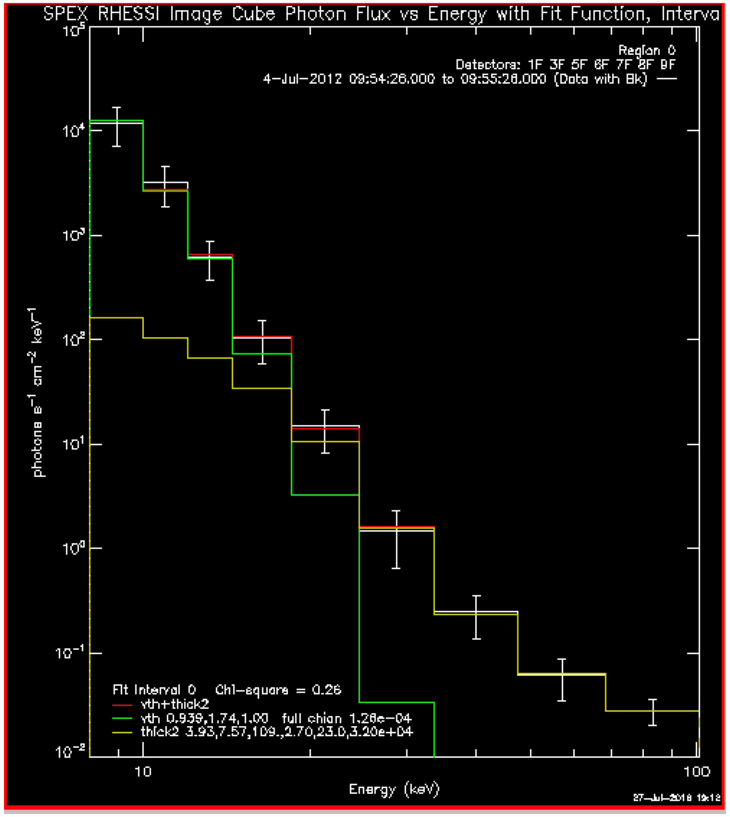
- **Spatially integrated spectrum** fitted with vth + thick2 + pileupmod

Energy bins (keV):
8.0 – 10.0
10.0 – 12.0
12.0 – 14.5
14.5 – 18.5
18.5 – 24.5
24.5 – 33.5
33.5 – 47.5
47.5 – 68.5
68.5 – 101.0

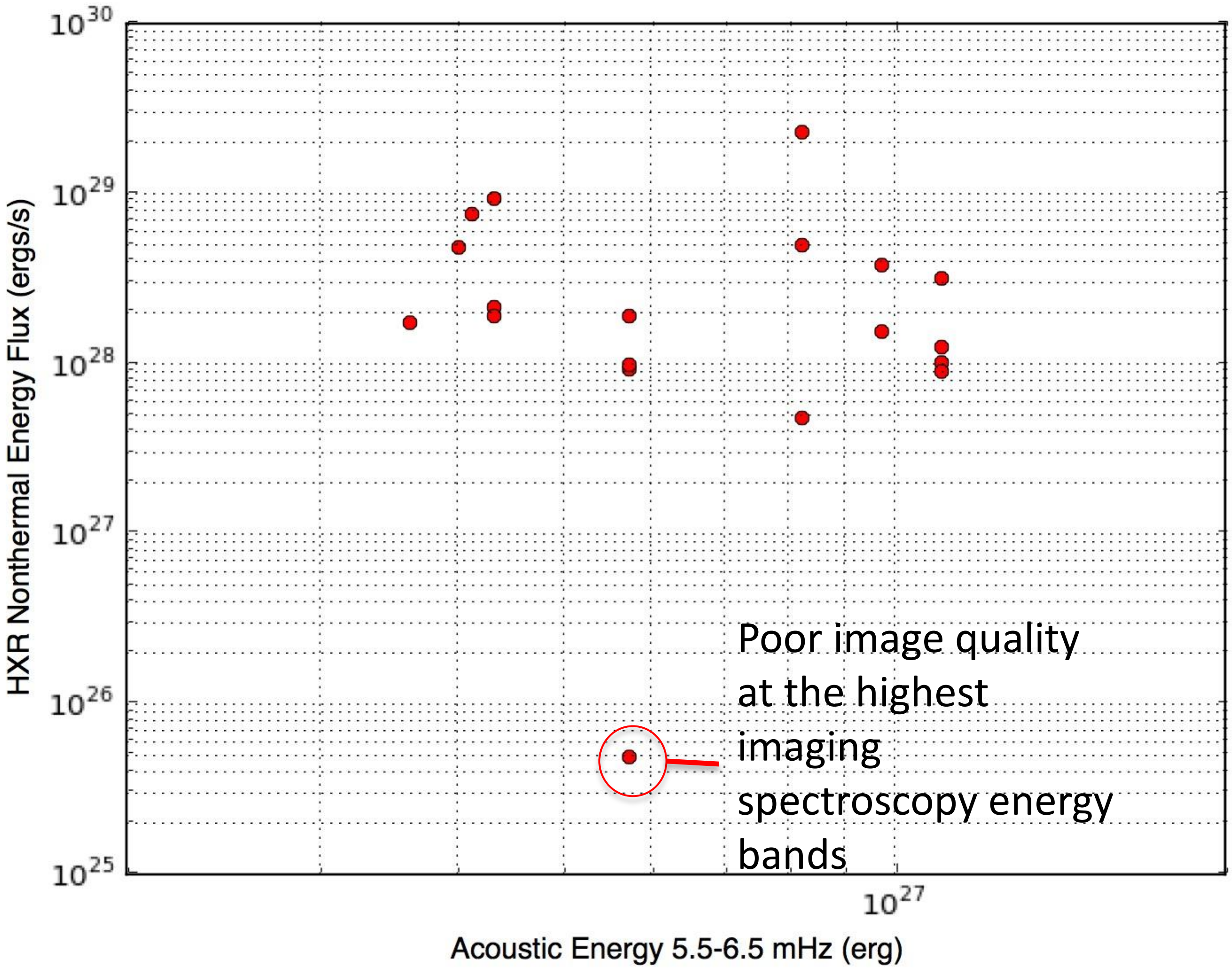
- **Imaging spectroscopy** fit with vth + thick2

RHESSI region of interest

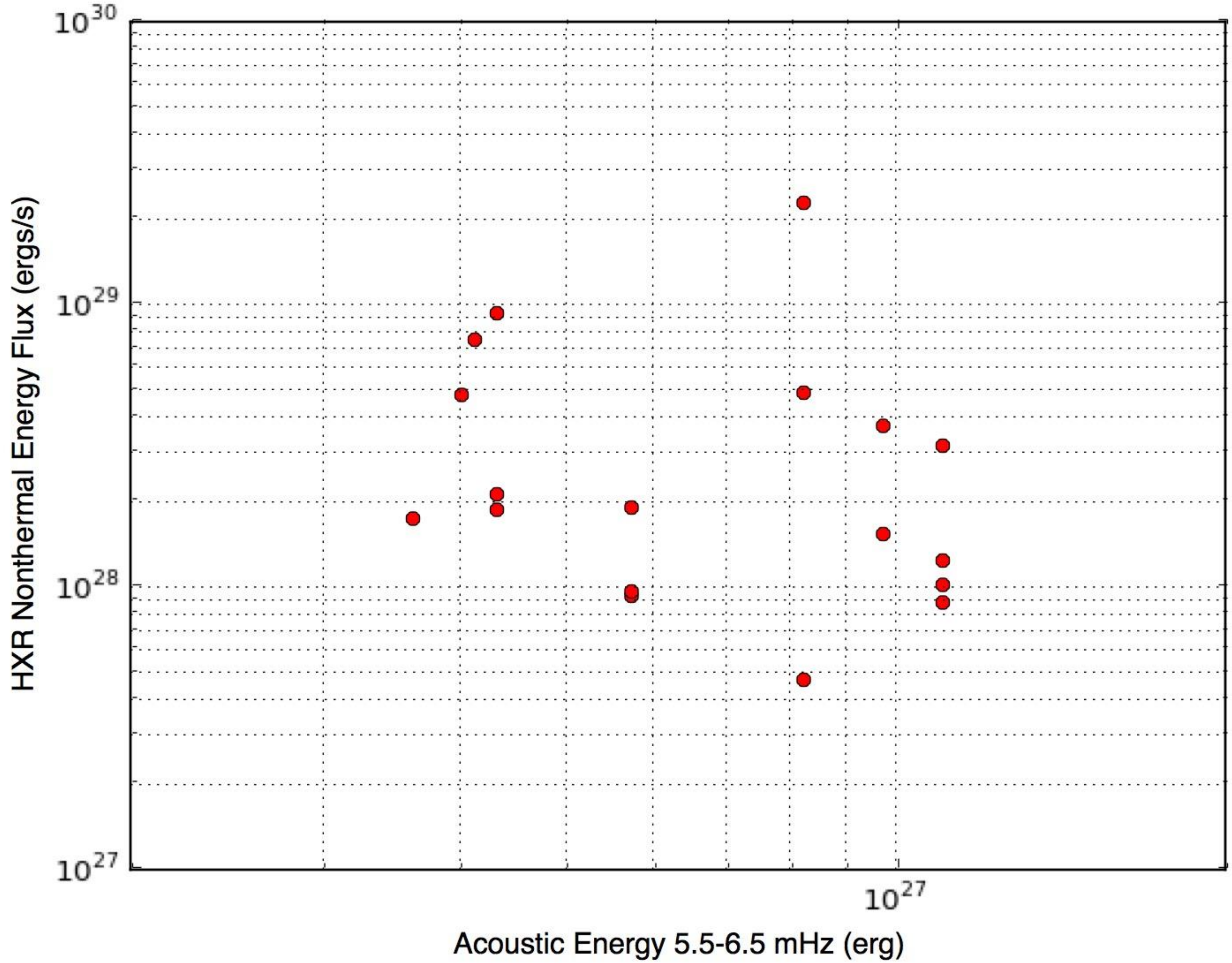




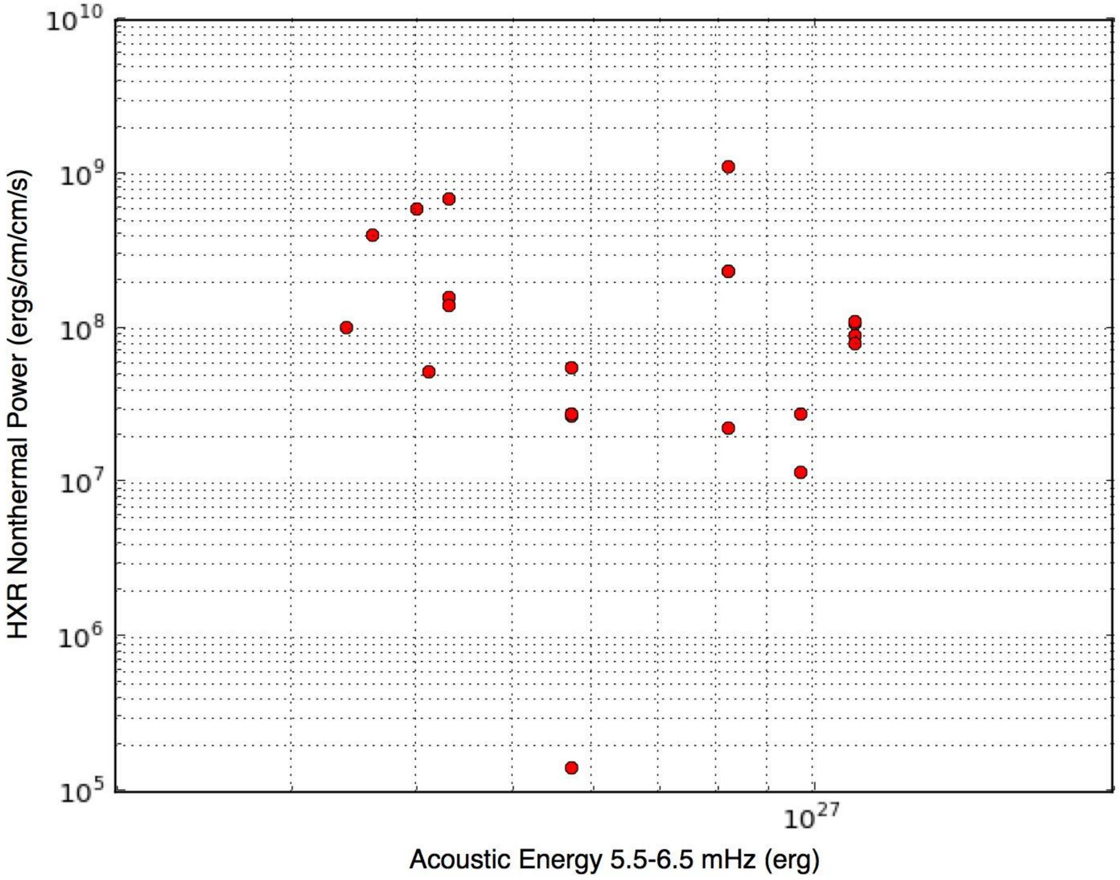
Acoustic vs HXR nonthermal energy flux



Acoustic vs HXR nonthermal energy flux



Acoustic vs HXR power



- Values are rather lower than expected. F = 10^{10} ergs cm^{-2} s^{-1} in Allred et al (2005) find that the energy deposited is balanced by radiative losses for ~1 min before triggering explosive temperature increase.
- However the area is probably overestimated for these results. Need to determine the area more carefully.

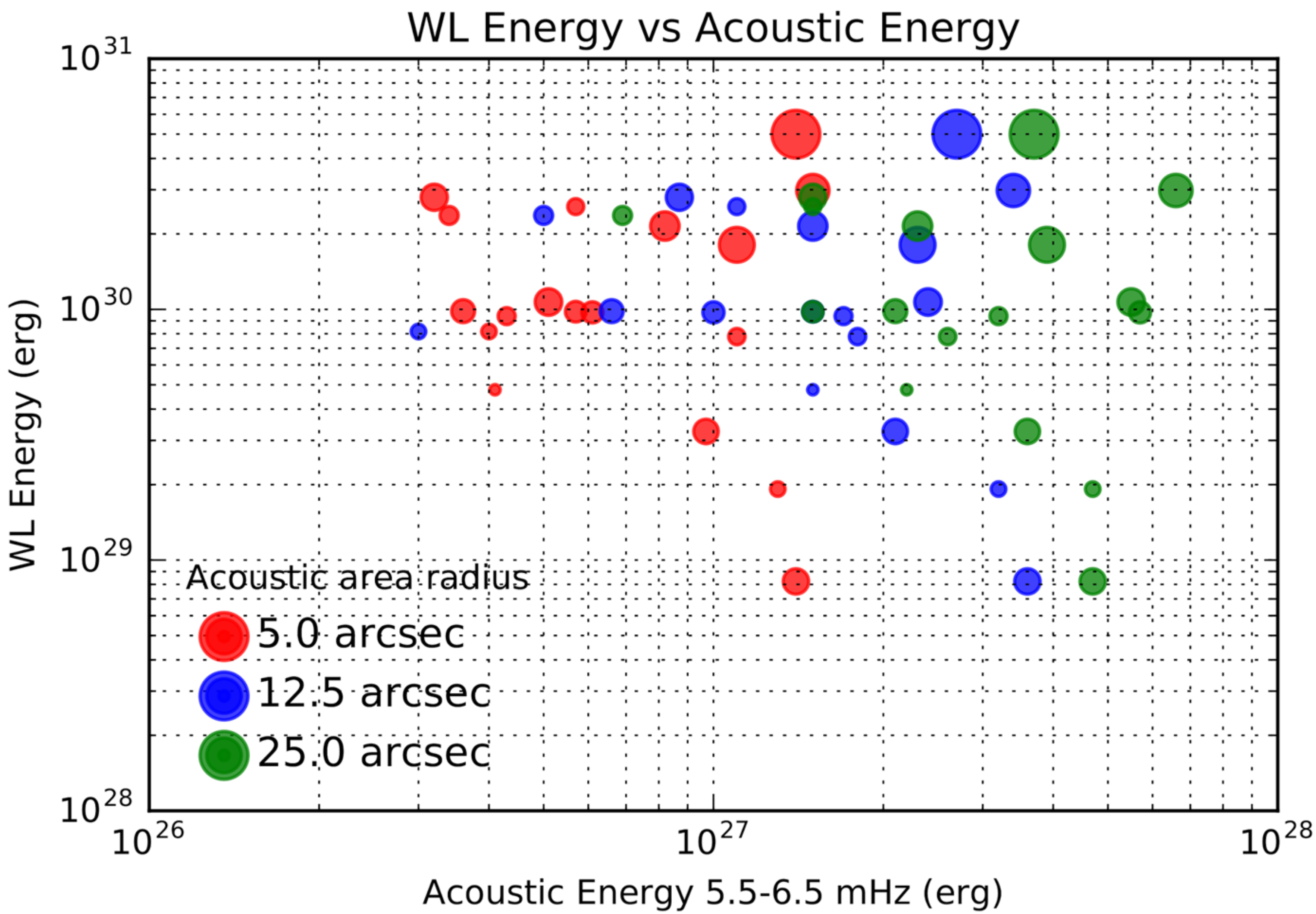
Conclusions

- No obvious correlation between HXR nonthermal energy flux and acoustic energy – similar result for WL and Ion energetics.

- HXR footpoints move with time and the electron distribution defining parameters may change rapidly during the onset of the flare, so we'll push the imaging spectroscopy down to shorter timescales to try and catch some of this behavior
  - how the rate of energy deposition changes
  - how the spectral hardness evolves
  - footpoint motions
  - the effect of multiple bursts.

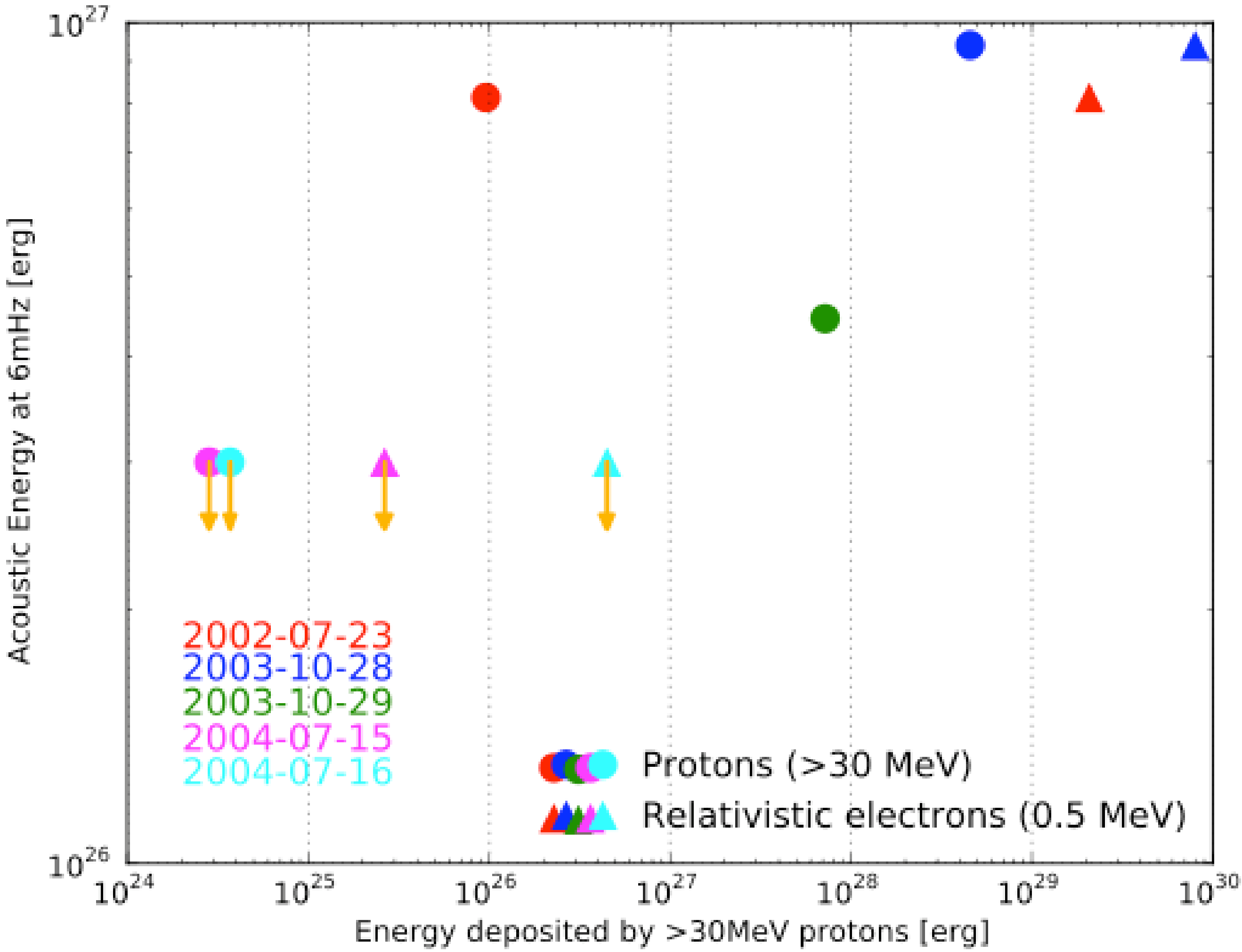
- We plan to compare our energetic budgets with flares that are not seismically active to see if there is a statistical difference between these different populations.

Acoustic vs WL



- **From Juan's talk at the RAS 2016**

Acoustic vs Ion Energies



- **From Juan's talk at the RAS 2016**