Meter and Decimeter Wave Diagnostics of particle acceleration

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The Big Questions of Coronal Physics

- How do flares release magnetic energy?
- How do flares accelerate particles?
- How can the corona be destabilized and release a CME?
- How is the corona heated?

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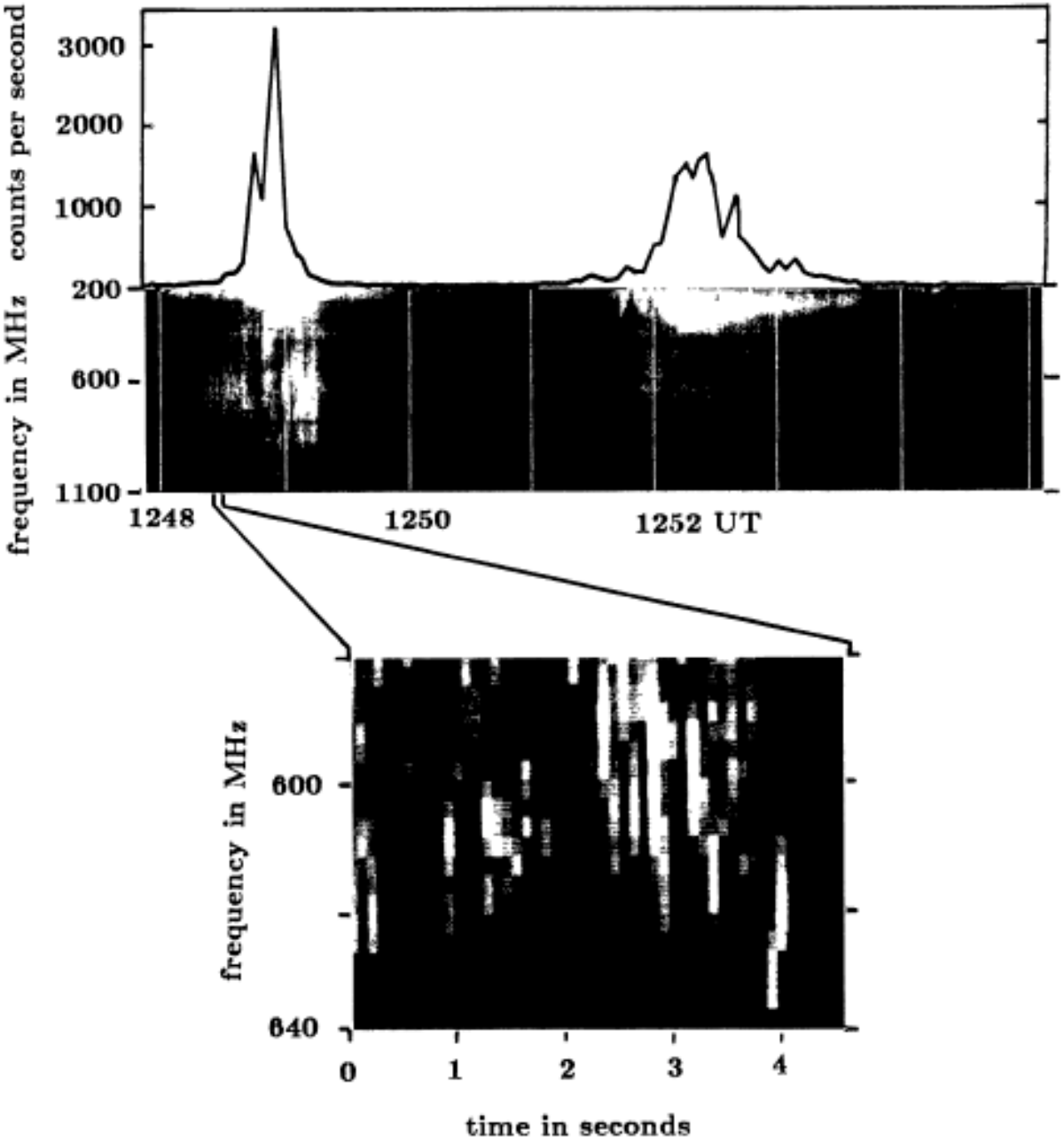
Non-thermal Electrons

Large flare	10^{39} (RHESSI)
Small microflare	10^{33} (RHESSI)
Large type III burst	10^{31} (Lin et al. 1986)

Are radio observations more sensitive than hard X-rays?

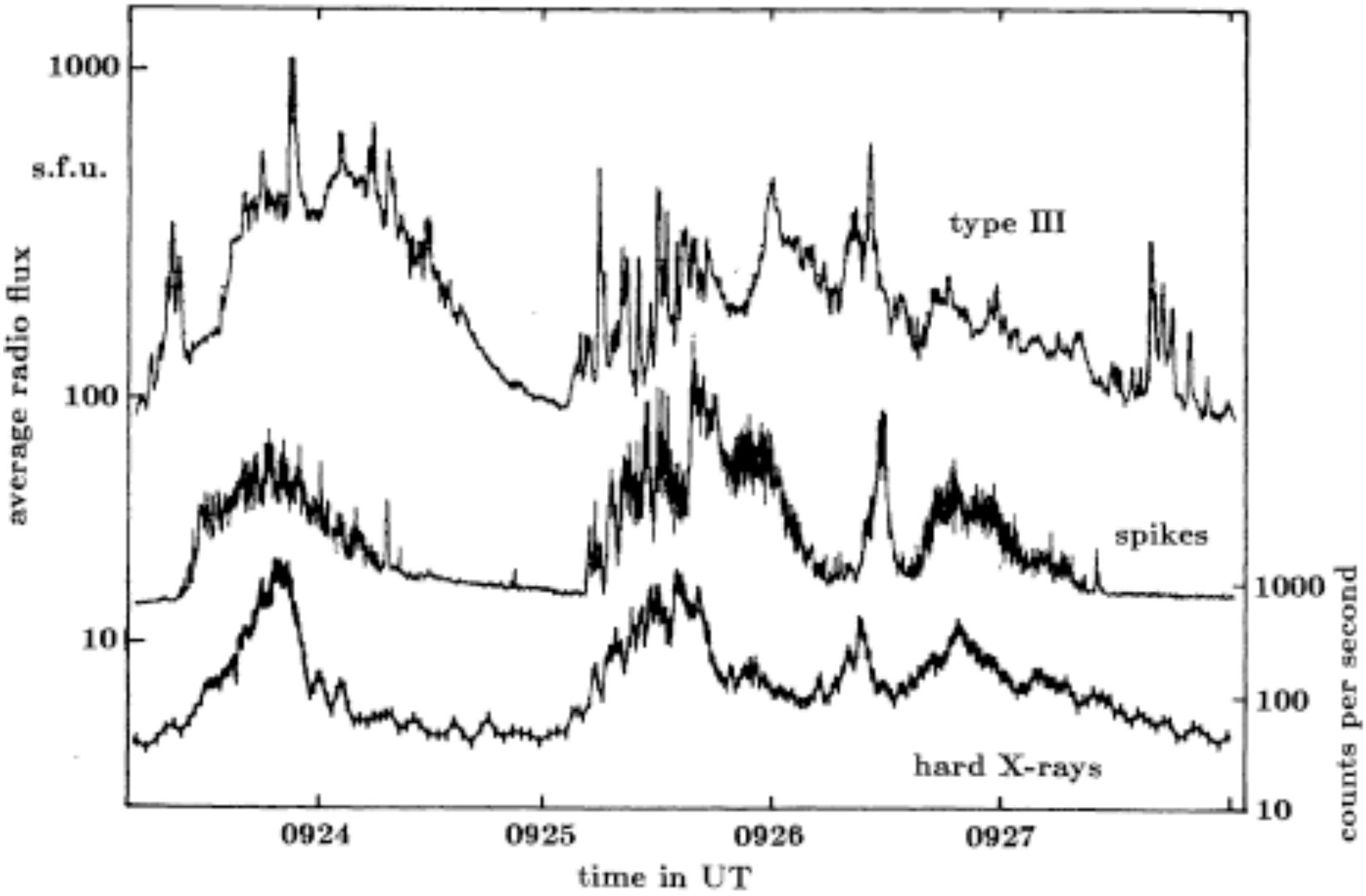
Part 1: Are radio and hard X-ray emissions of non-thermal electrons all the same?

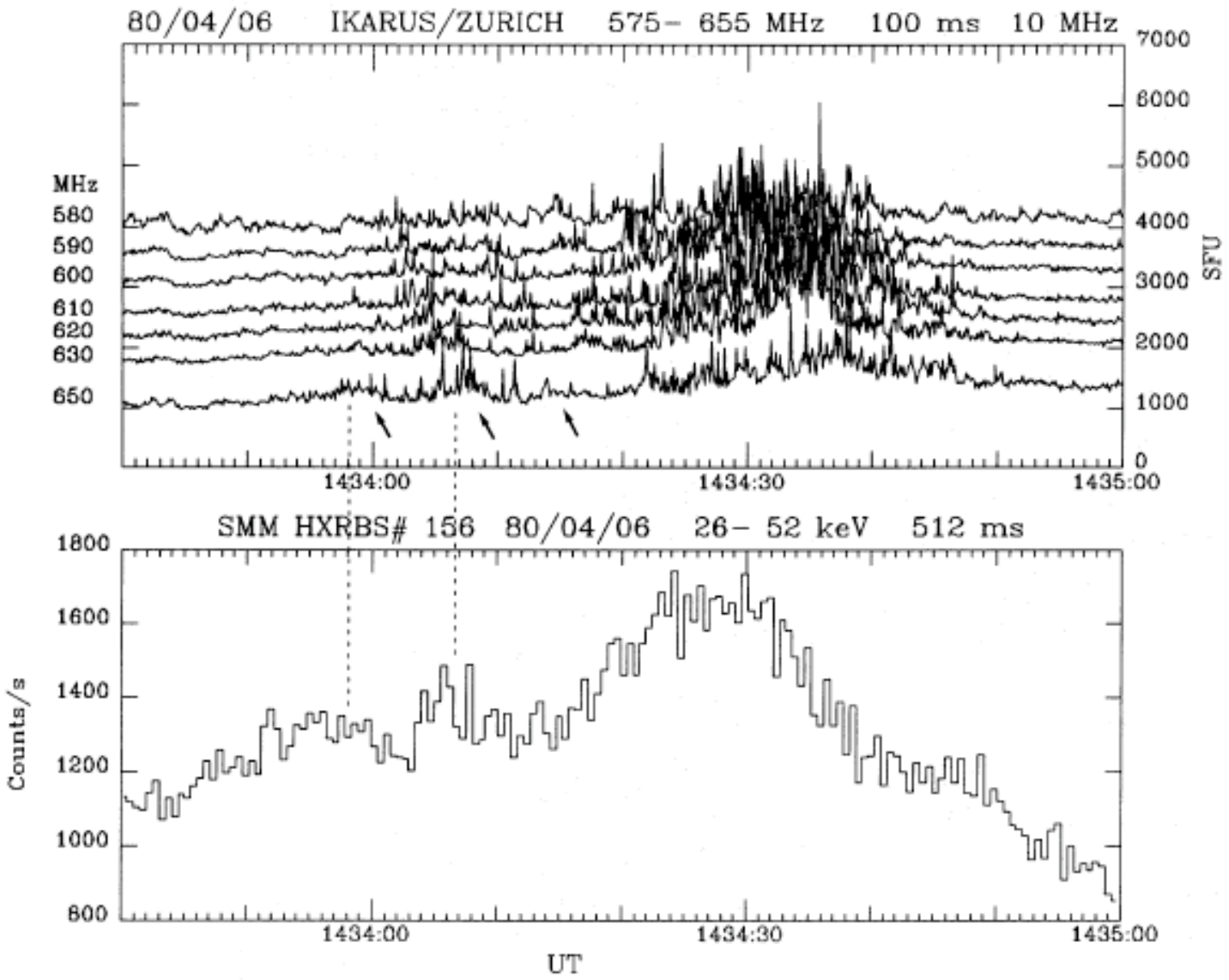
Radio Emissions of Acceleration Process?



decimetric narrowband spikes

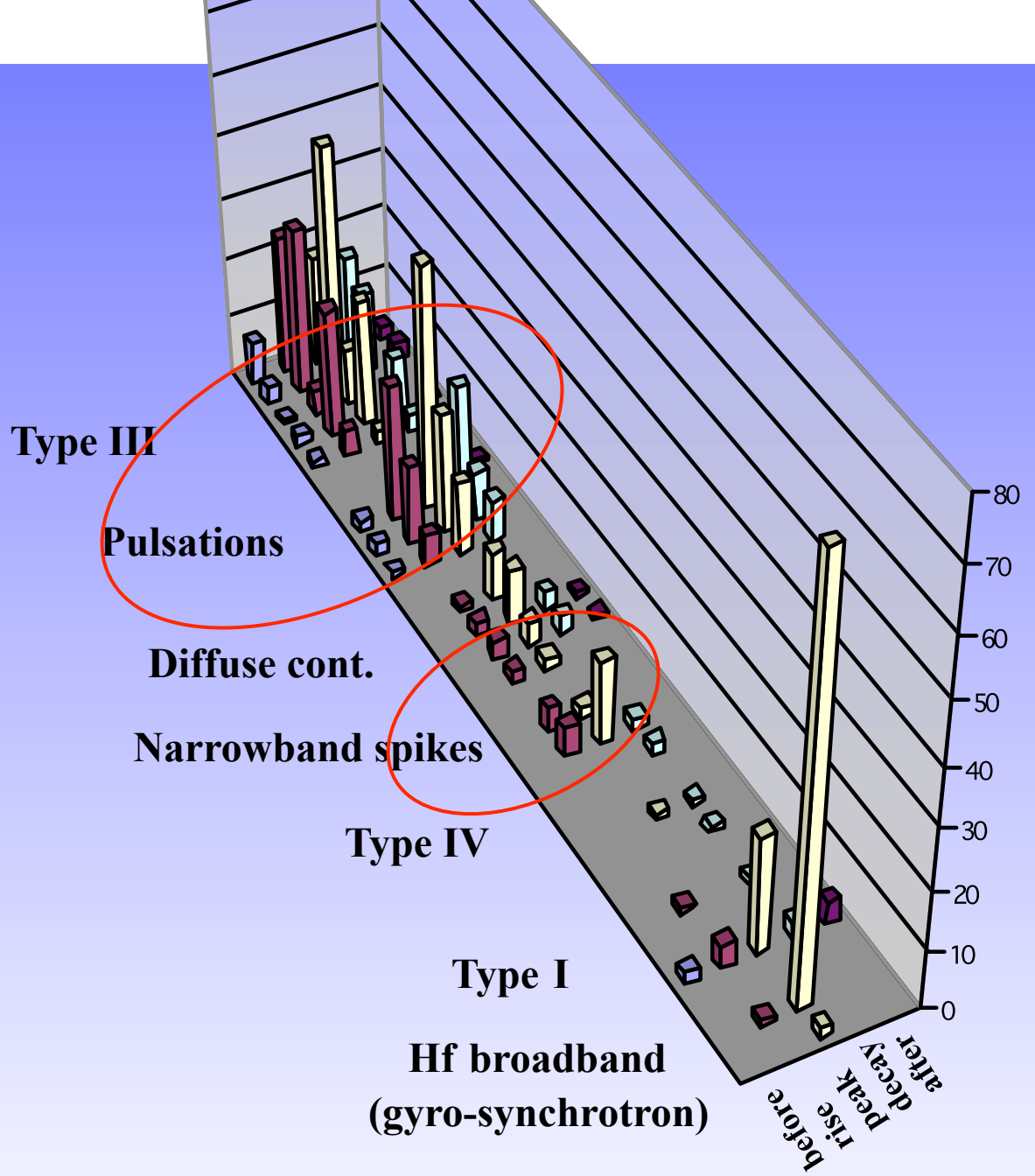
Benz, 1985


1000
s.f.u.
100
10
average radio flux
type III
spikes
hard X-rays
1000
100
10
counts per second
0924
0925
0926
0927
time in UT



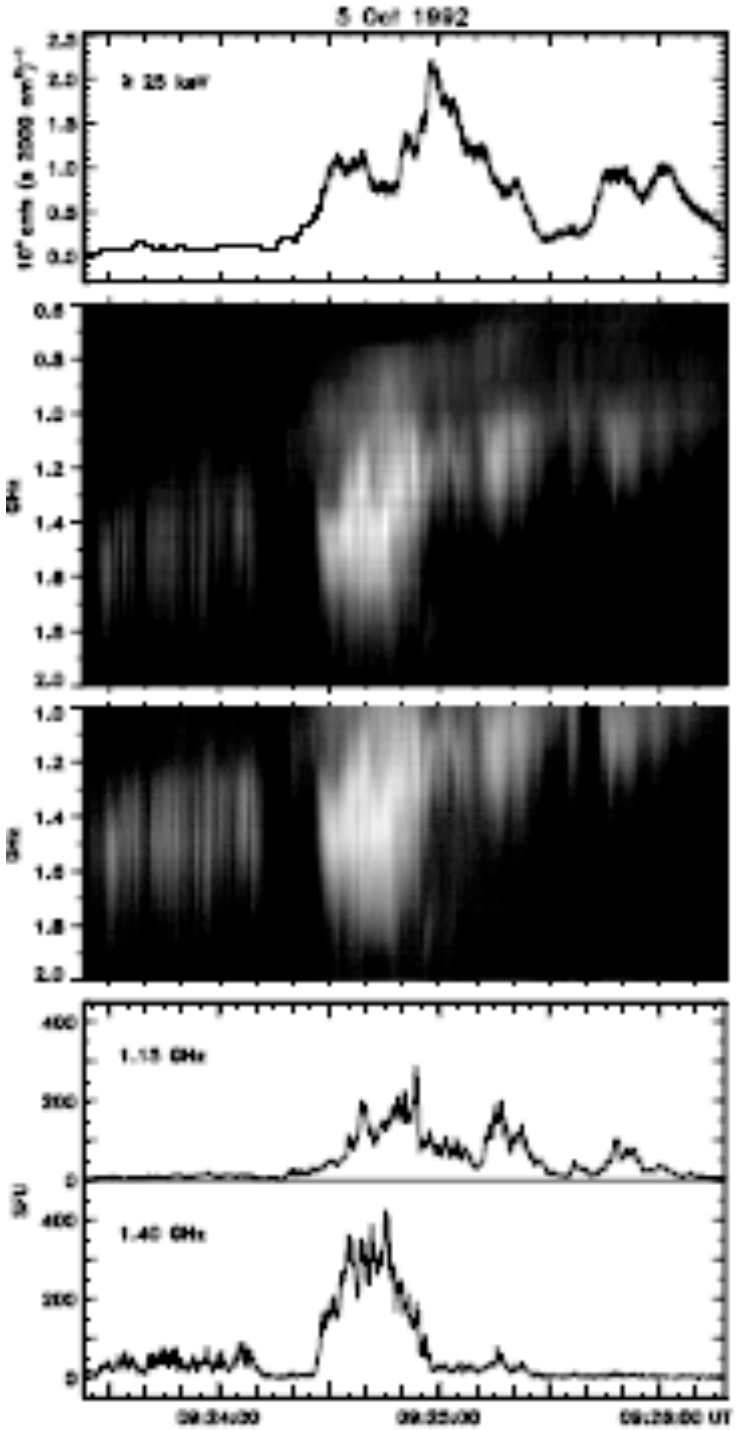
Decimteric narrowband spikes

Güdel et al., 1991



radio emission in 201 X-ray selected flares

Benz, Grigis, Saint-Hilaire, Csillaghy, 2005



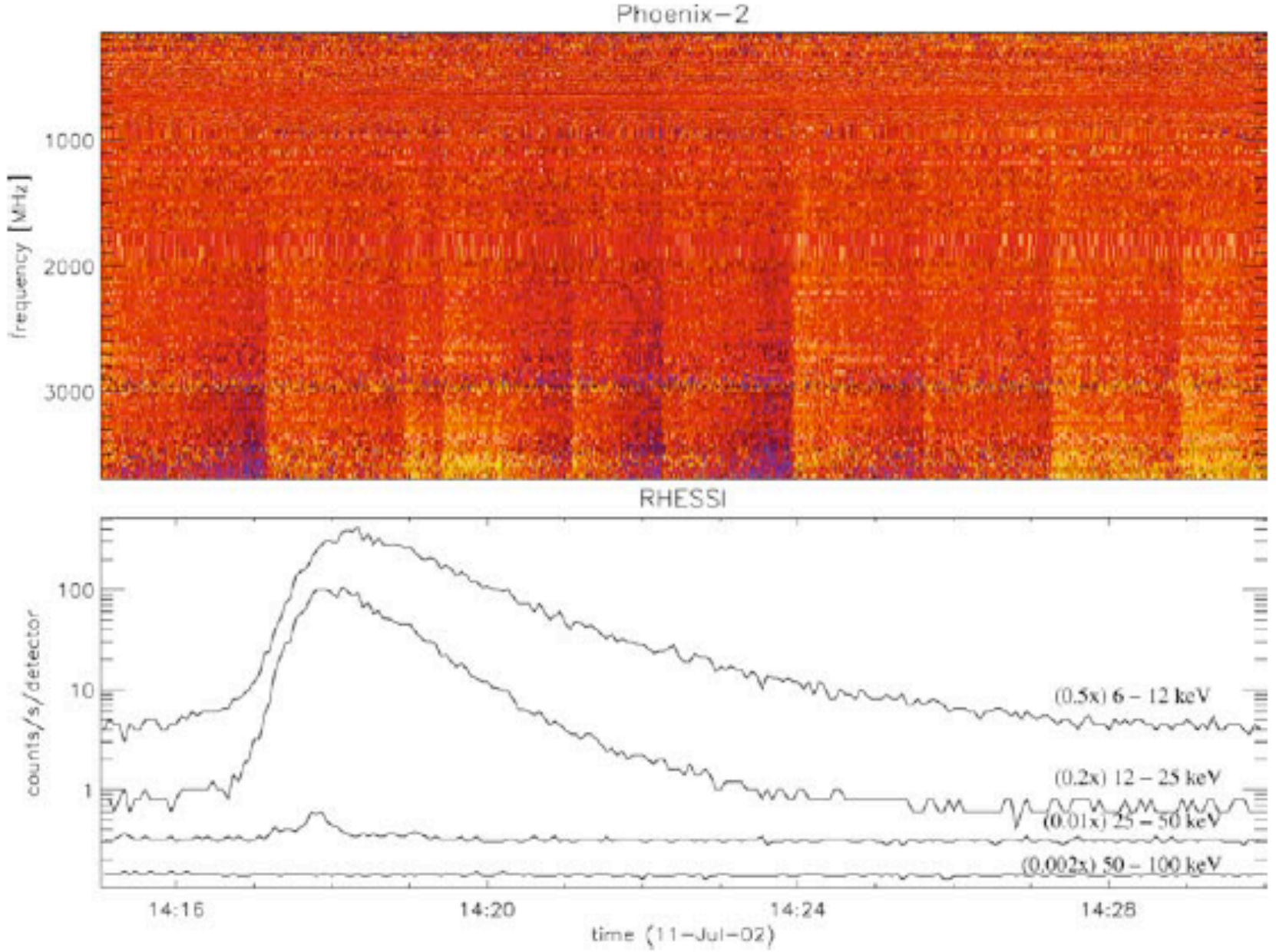
Hard X-rays BATSE

Decimetric pulsations

Kliem et al, 2000

But: only 30 % correlate well

M1 Class Flare



Benz et al. 2005

Standard Theory of Electron Acceleration in Flares:

Transit-time damping of fast mode waves

Wave-particle interactions of electrons and fast-mode waves at the Čerenkov resonance:

$$\omega \approx k_{\|} v_{\|} \qquad V_{ph} = \omega/k \approx V_A \approx v_{\|} \cos\theta$$

Requirement: electron velocity $v_{\|} > V_A$ ($< V_{th}^{e}$)

Physics: Electrons are mirrored at enhancements of the wave magnetic field, gain or lose energy.

On the average: gain more than lose (more head-on collisions).

Effect: Waves are damped,
thermal electrons are stochastically accelerated.

Evolution of the Electron Distribution

- Miller et al. have computed the diffusion (D_T) and convection (A_T) coefficients for the Fokker-Planck equation describing the transit-time damping energization of the electrons.

$$\frac{\partial N}{\partial t} = \frac{1}{2}\frac{\partial^2}{\partial E^2}\left[(D_C + D_T)\, N \right] - \frac{\partial}{\partial E}\left[(A_C + A_T)\, N \right]$$

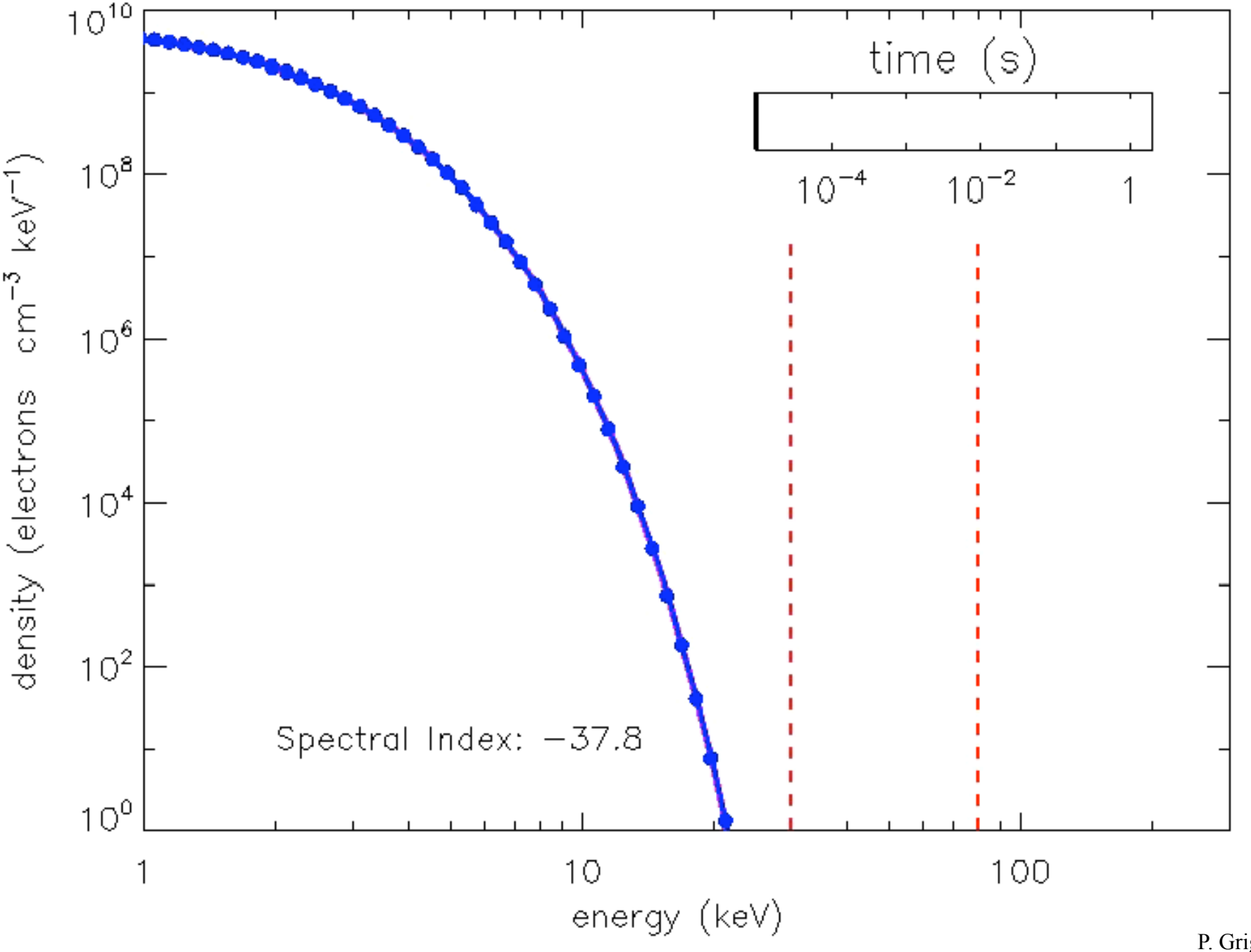
- The equation also contains the contribution to the coefficients due to Coulomb scattering with the ambient plasma (D_C, A_C).
- The TTD coefficients are proportional to the acceleration parameter:

$$I_{ACC} = \frac{U_T}{U_B} \cdot \frac{c\langle k \rangle}{\Omega_H}$$

added S(E) + Q(E)

S=escape Q=return current

(V. Petrosian, Stanford; J. Miller, Huntsville)


time (s)
10^{-4}
10^{-2}
1
density (electrons cm^{-3} keV^{-1})
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
Spectral Index: −37.8
1
10
100
energy (keV)

P. Grigis

Stochastic acceleration does not predict velocity space instabilitites,

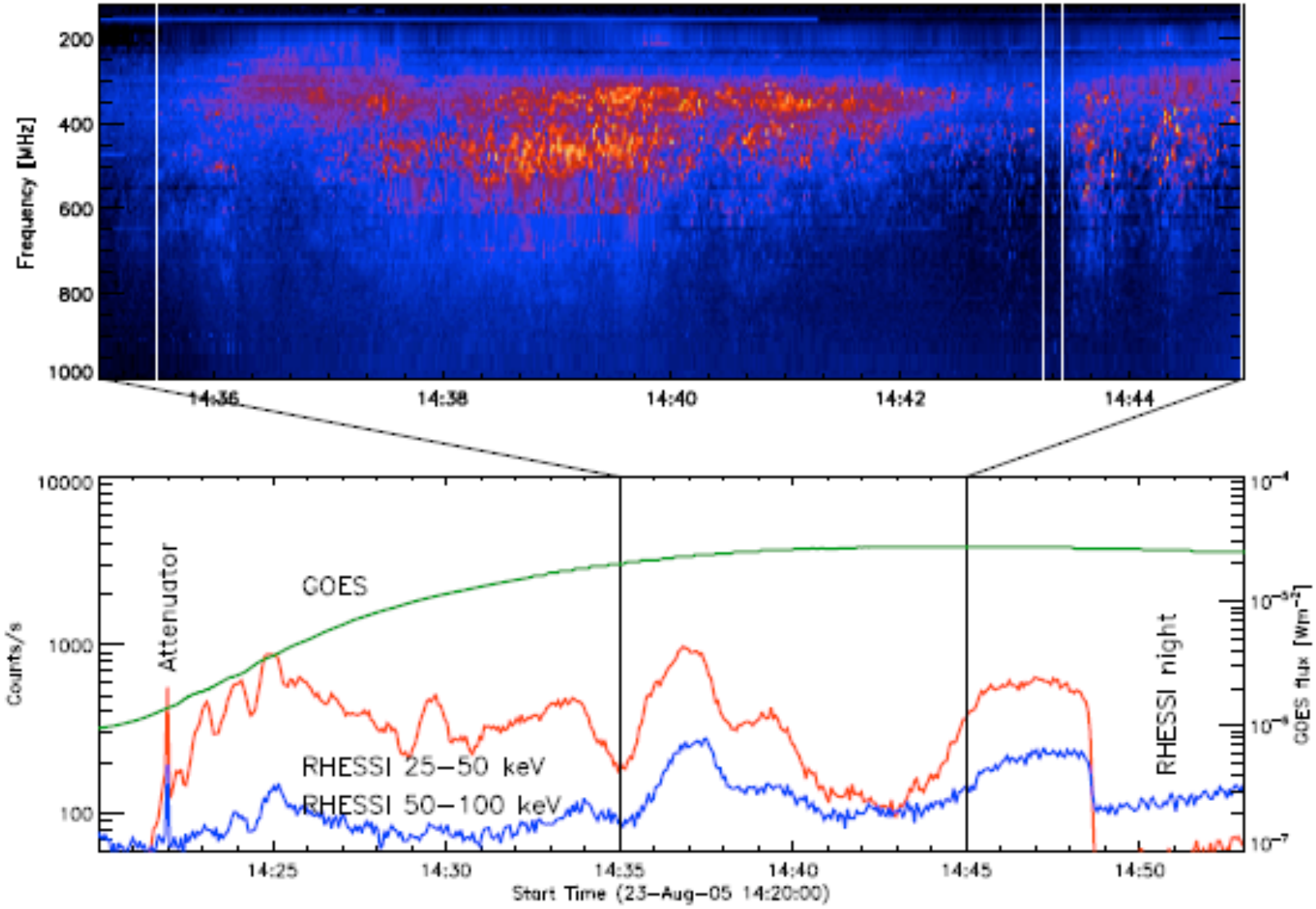
thus no radio emission expected.

Part 2: Why is there correlated decimetric emission at all?

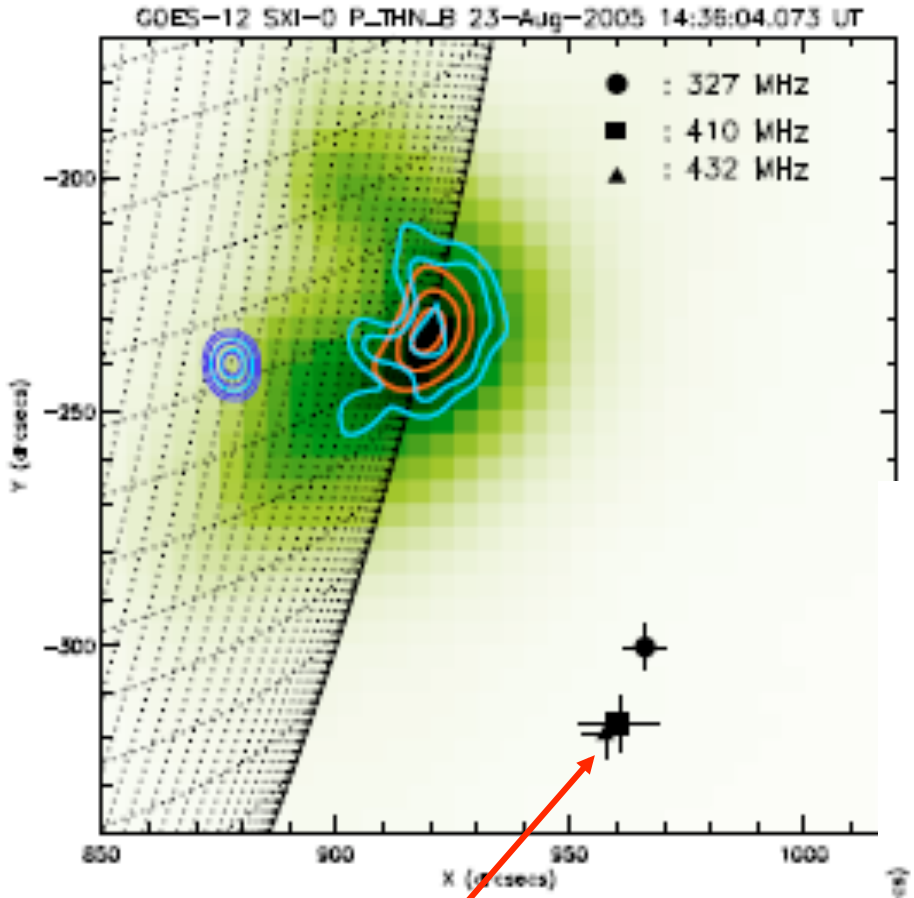
Velocity space instability in the coronal HXR source?

Prediction: Radio source coincides with coronal hard X-ray source

Decimetric narrowband spikes

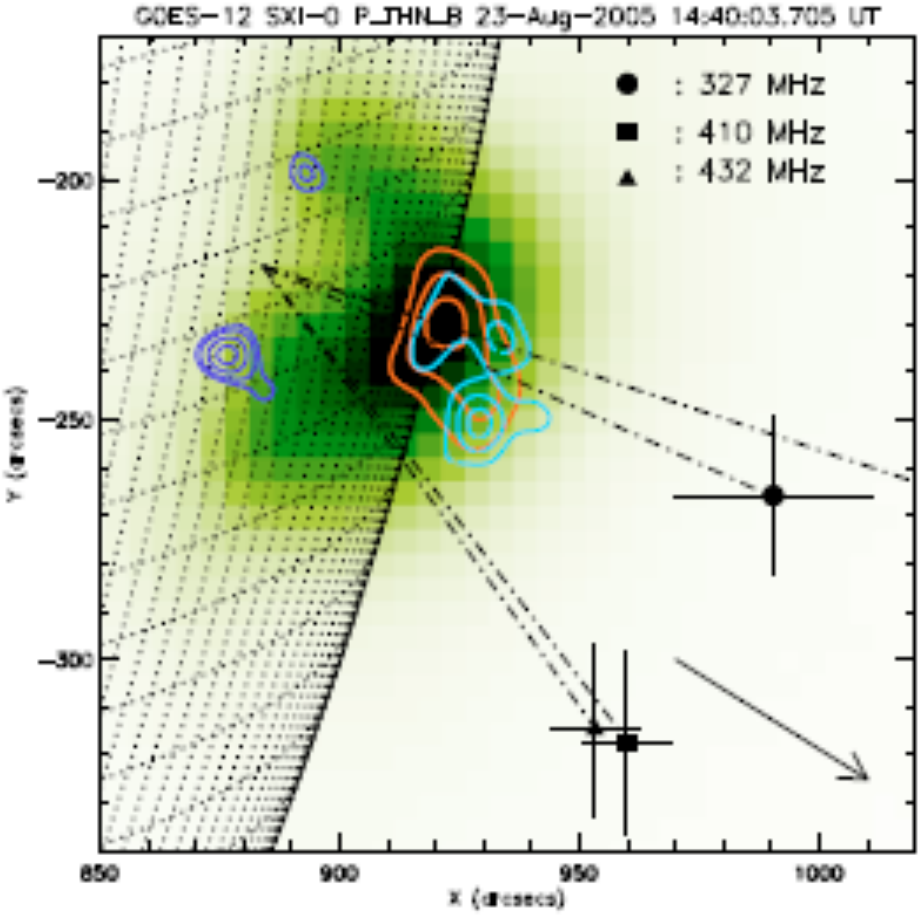


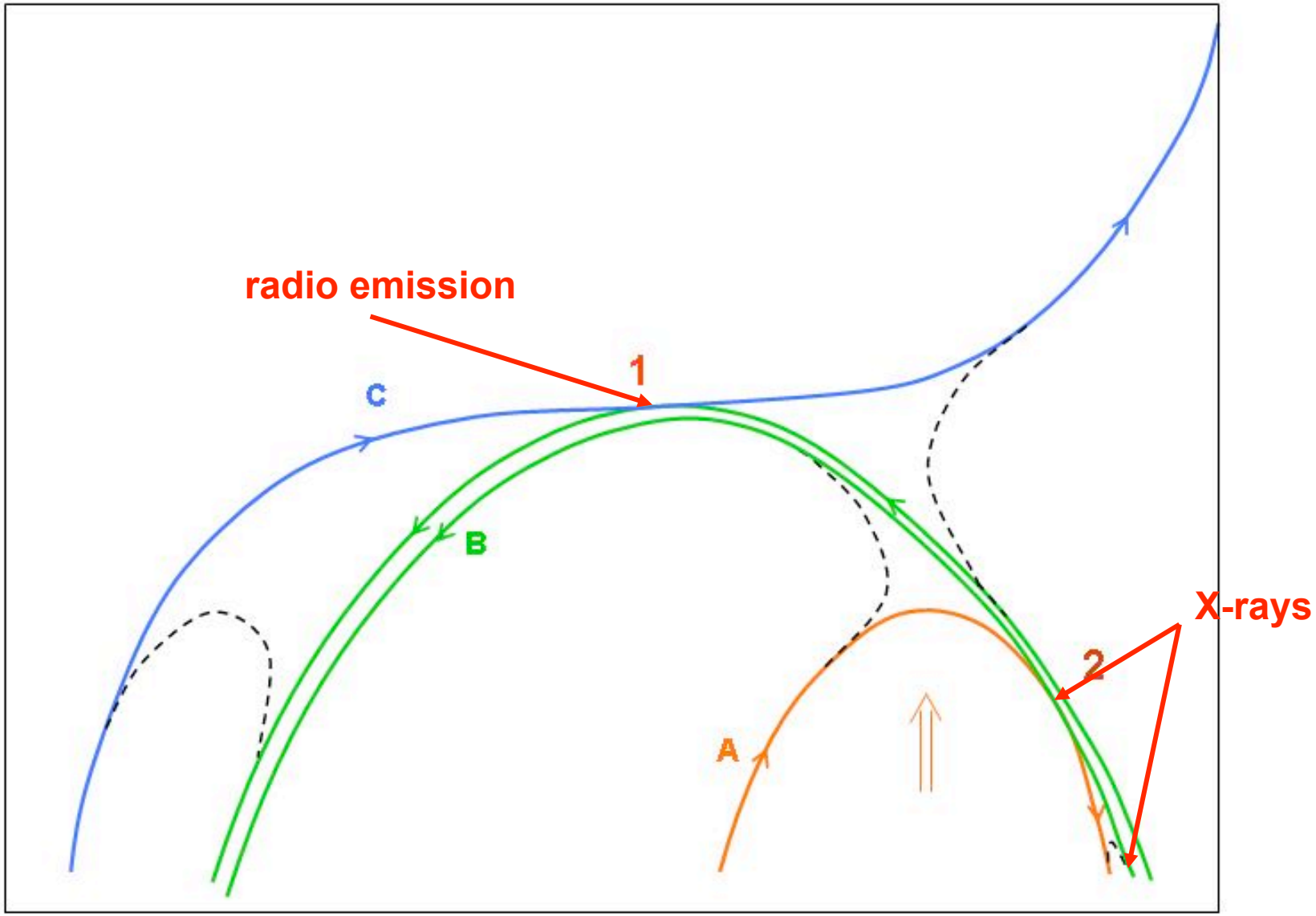
Battaglia & Benz, 2009

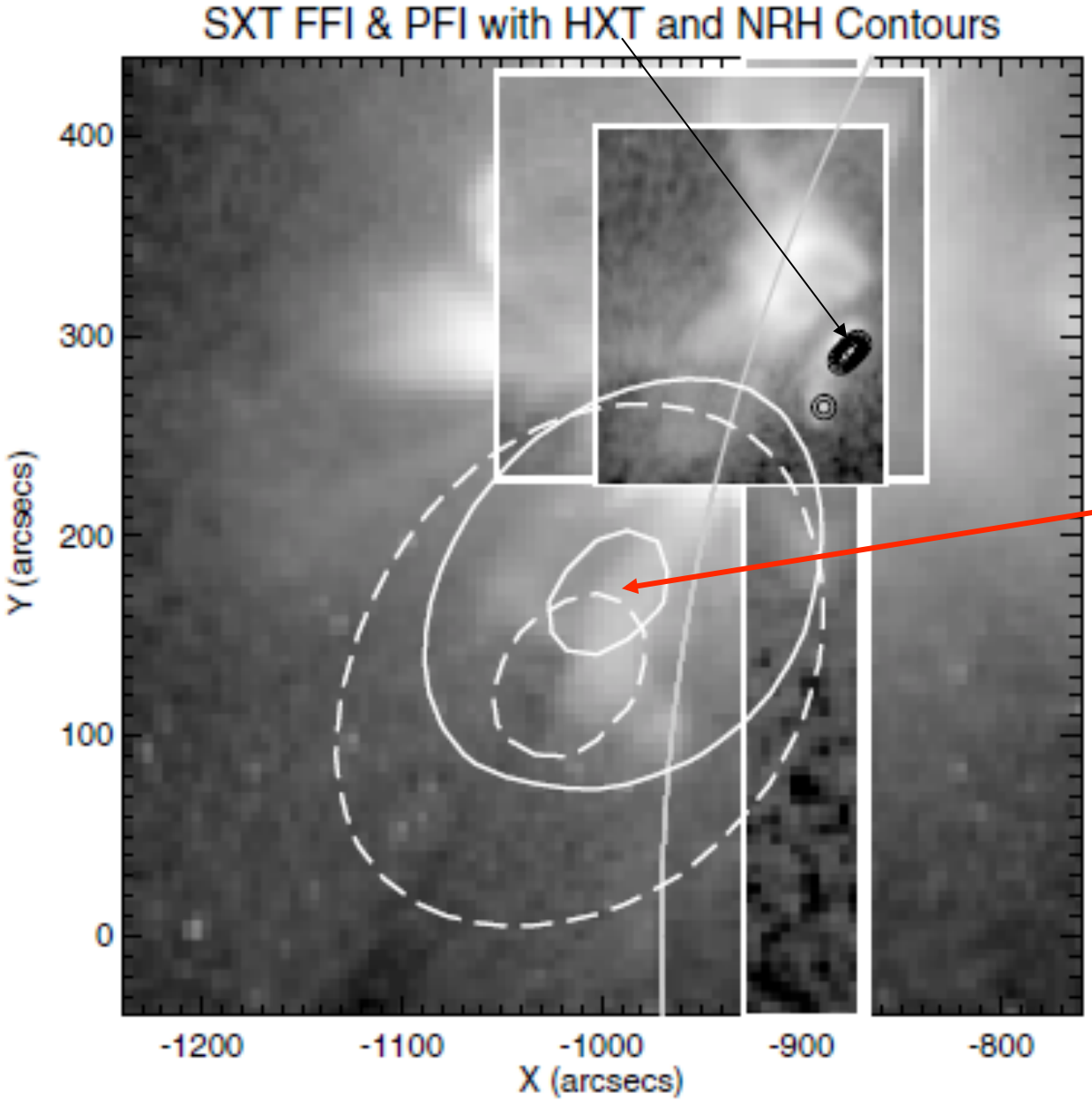


Decimetric narrowband spikes do not originate in the coronal HXR source

average spike centroids NRH



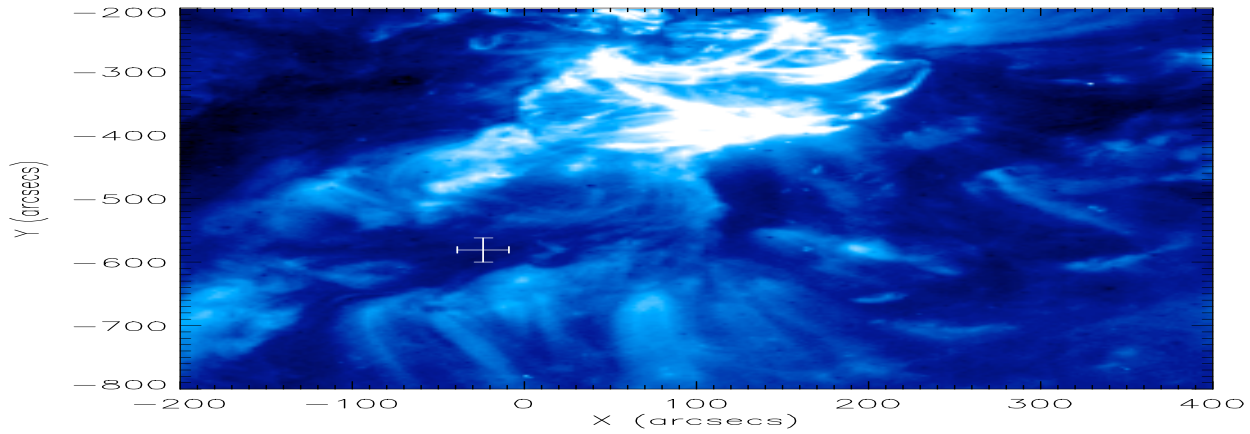

radio emission
1
C
B
A
2
X-rays



decimetric narrowband spikes

NRH

Khan & Aurass 2006



SOHO/EIT image at 195 Å

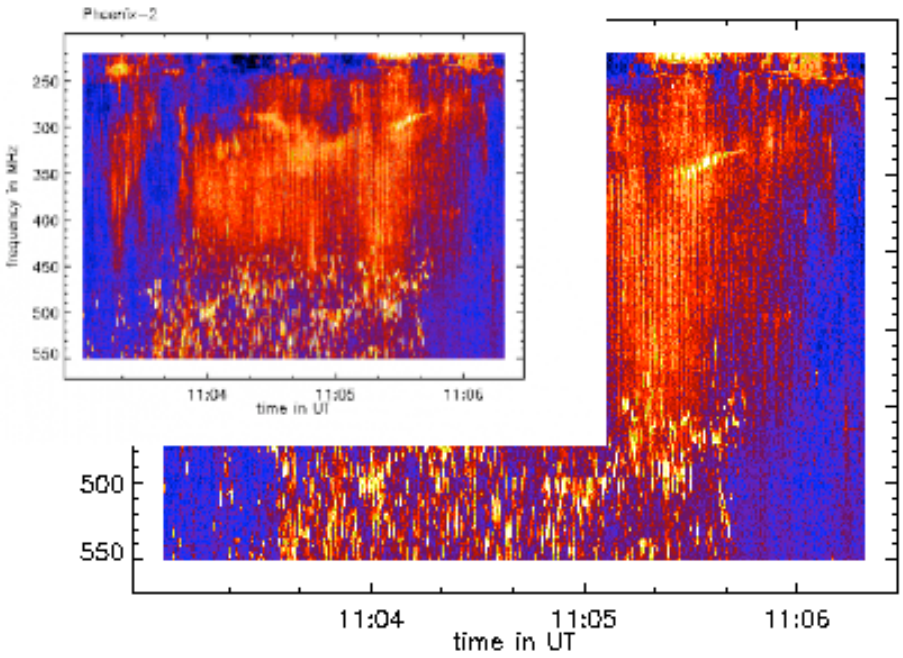
Flare loops

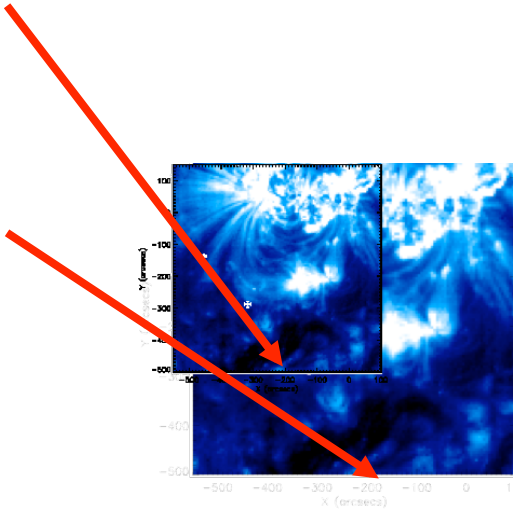
narrowband radio spikes

at 432 MHz
NRH

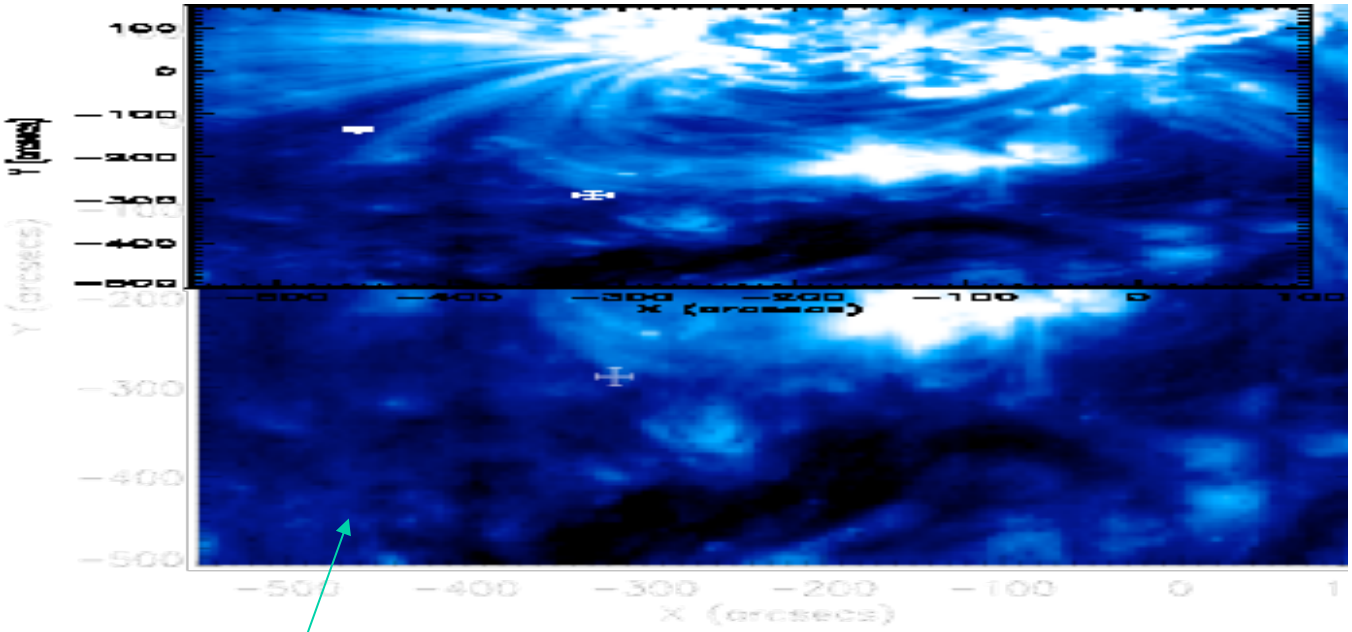
Benz, Saint-Hilaire, Vilmer, 2002

Narrowband spikes are not located at looptops of flare loops!


Phoenix-2
250
300
350
400
450
500
550
frequency in MHz
11:04
11:05
11:06
time in UT
500
550
11:04
11:05
11:06
time in UT



NRH and EIT



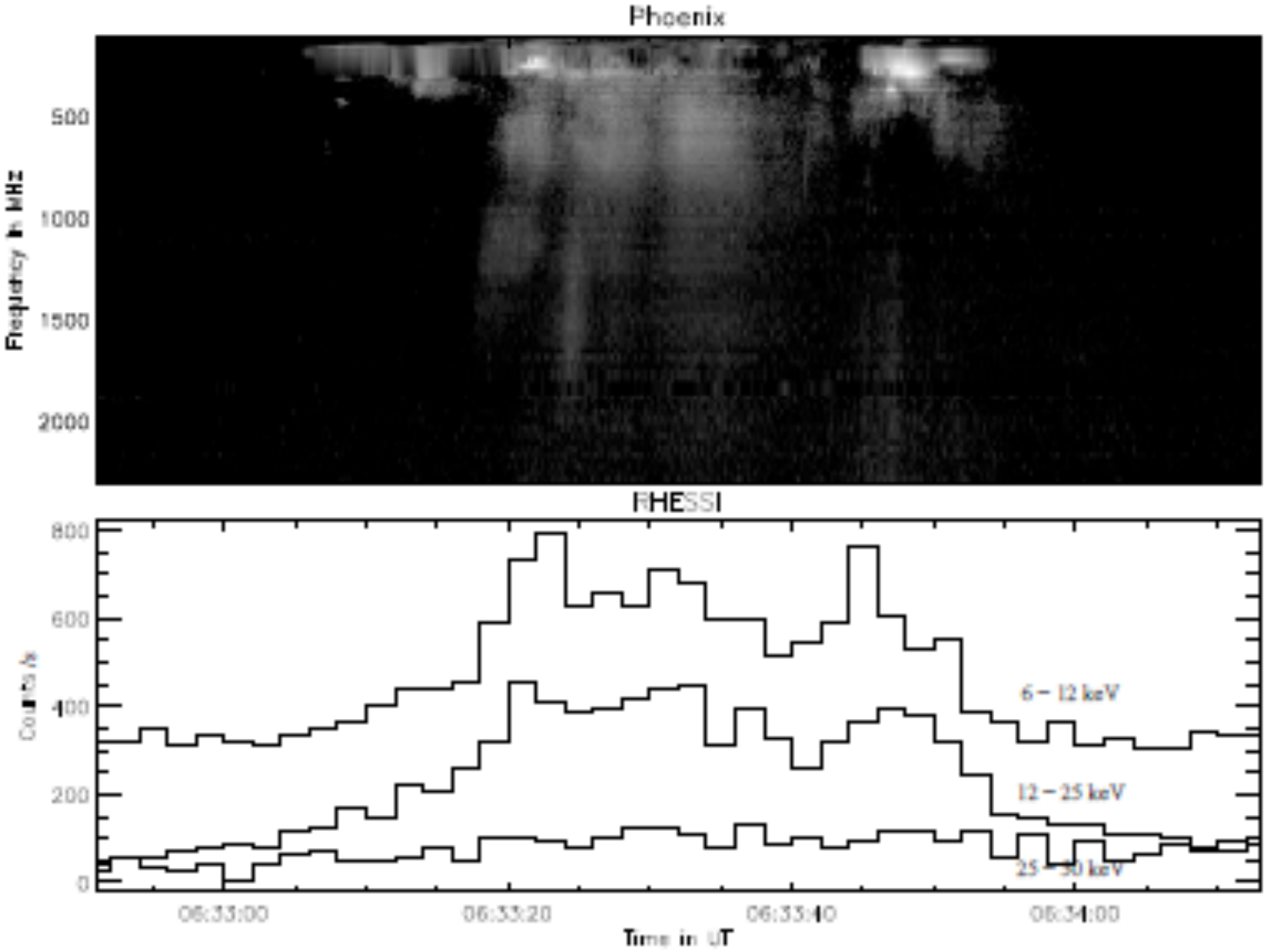
SOHO/EIT image
at 195 Å

narrowband radio spikes
at 432 MHz
NRH

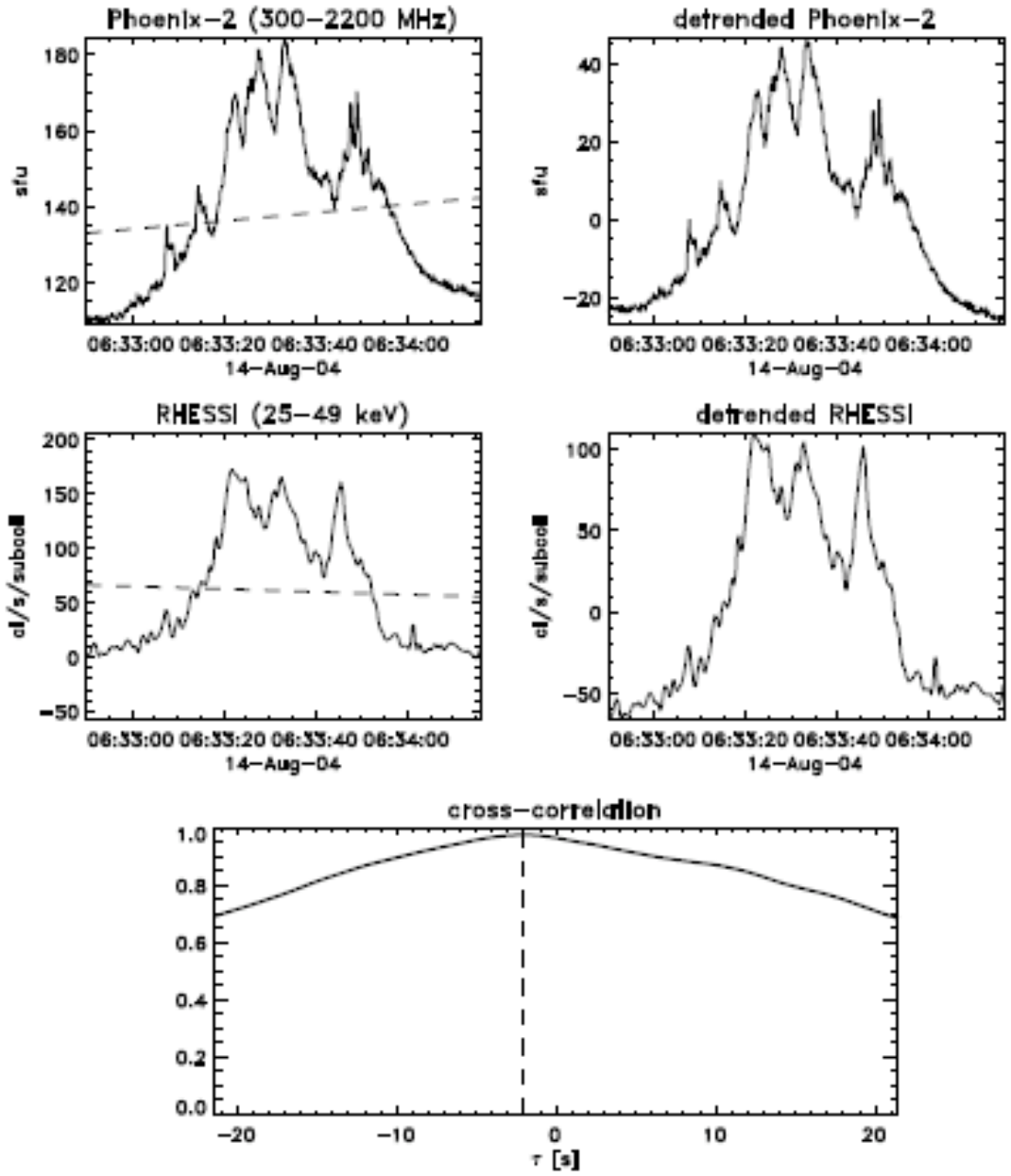
decimteric pulsations at 410 MHz, NRH

Decimetric narrowband Spikes do not originate in the coronal source.

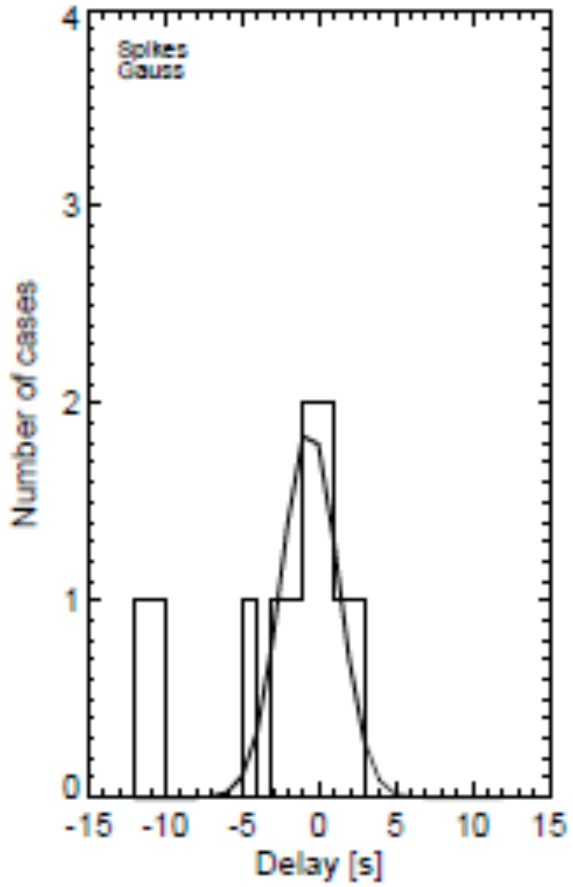
What about the events with good correlation between radio and hard X-rays?



Dabrowski & Benz, 2009

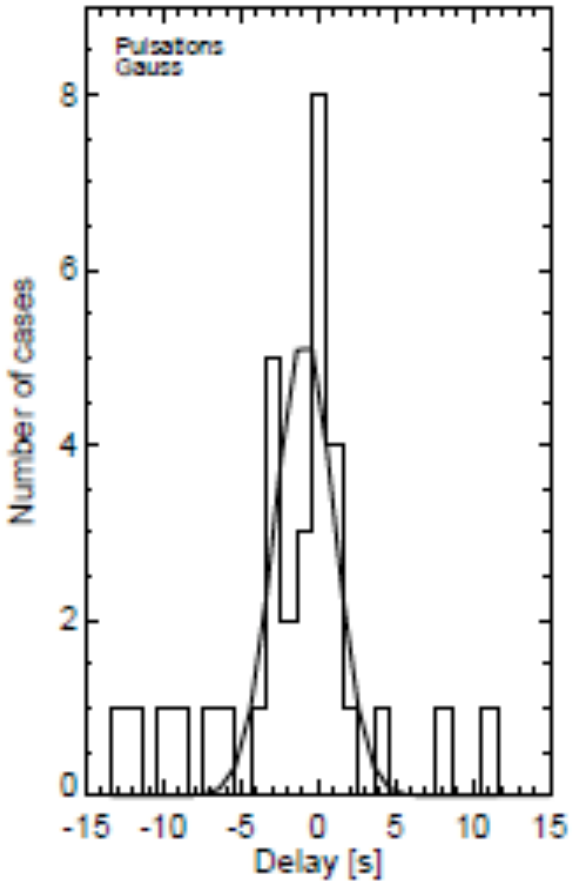

Phoenix-2 (300-2200 MHz)
sfu
180
160
140
120
06:33:00 06:33:20 06:33:40 06:34:00
14-Aug-04
detrended Phoenix-2
sfu
40
20
0
-20
06:33:00 06:33:20 06:33:40 06:34:00
14-Aug-04
RHESSI (25-49 keV)
cl/s/subcol
200
150
100
50
0
-50
06:33:00 06:33:20 06:33:40 06:34:00
14-Aug-04
detrended RHESSI
cl/s/subcol
100
50
0
-50
06:33:00 06:33:20 06:33:40 06:34:00
14-Aug-04
cross-correlation
1.0
0.8
0.6
0.4
0.2
0.0
-20
-10
0
10
20
τ [s]

Spikes



decimetric narrow-band spikes

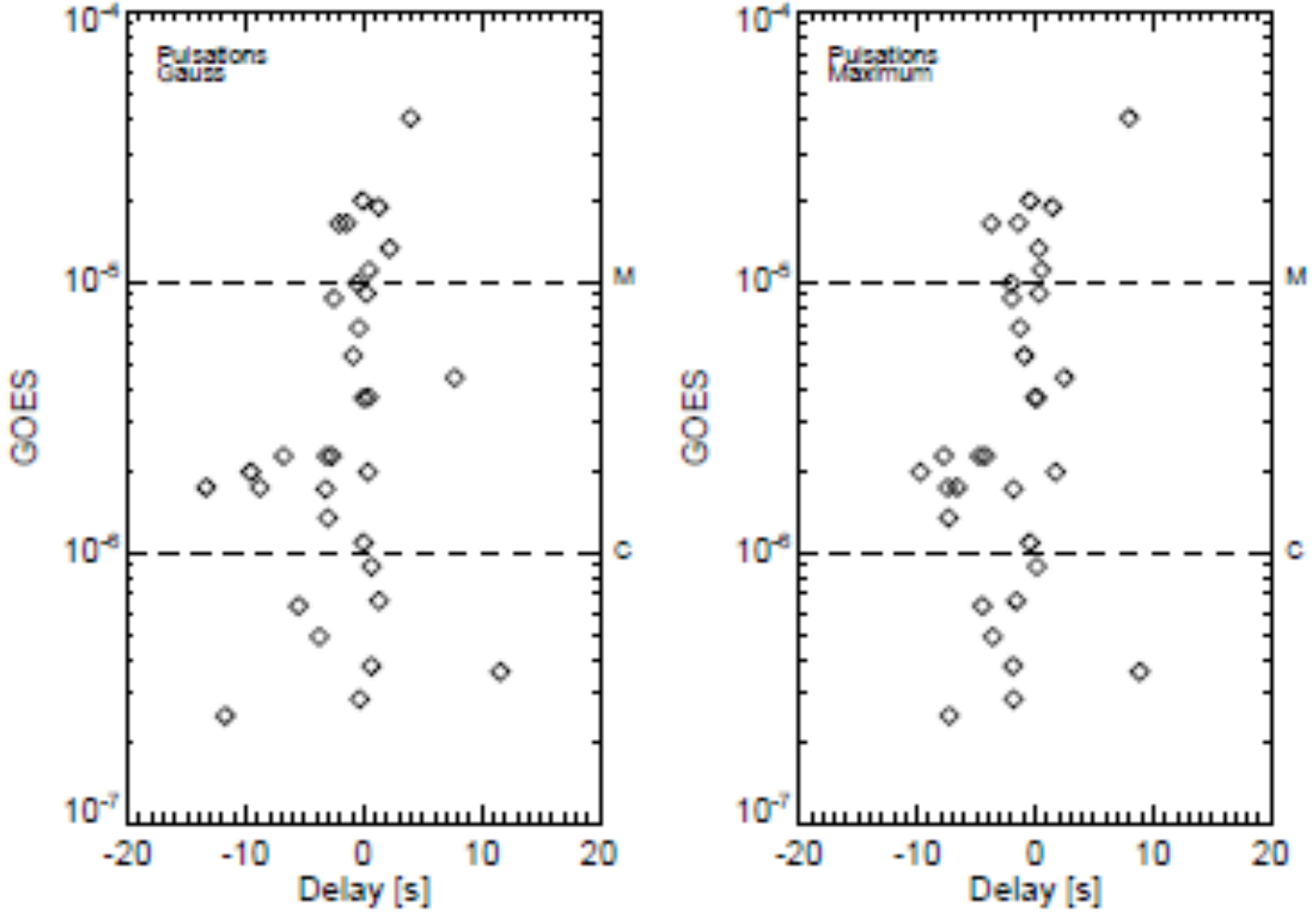
Pulsations



decimetric puls-ations

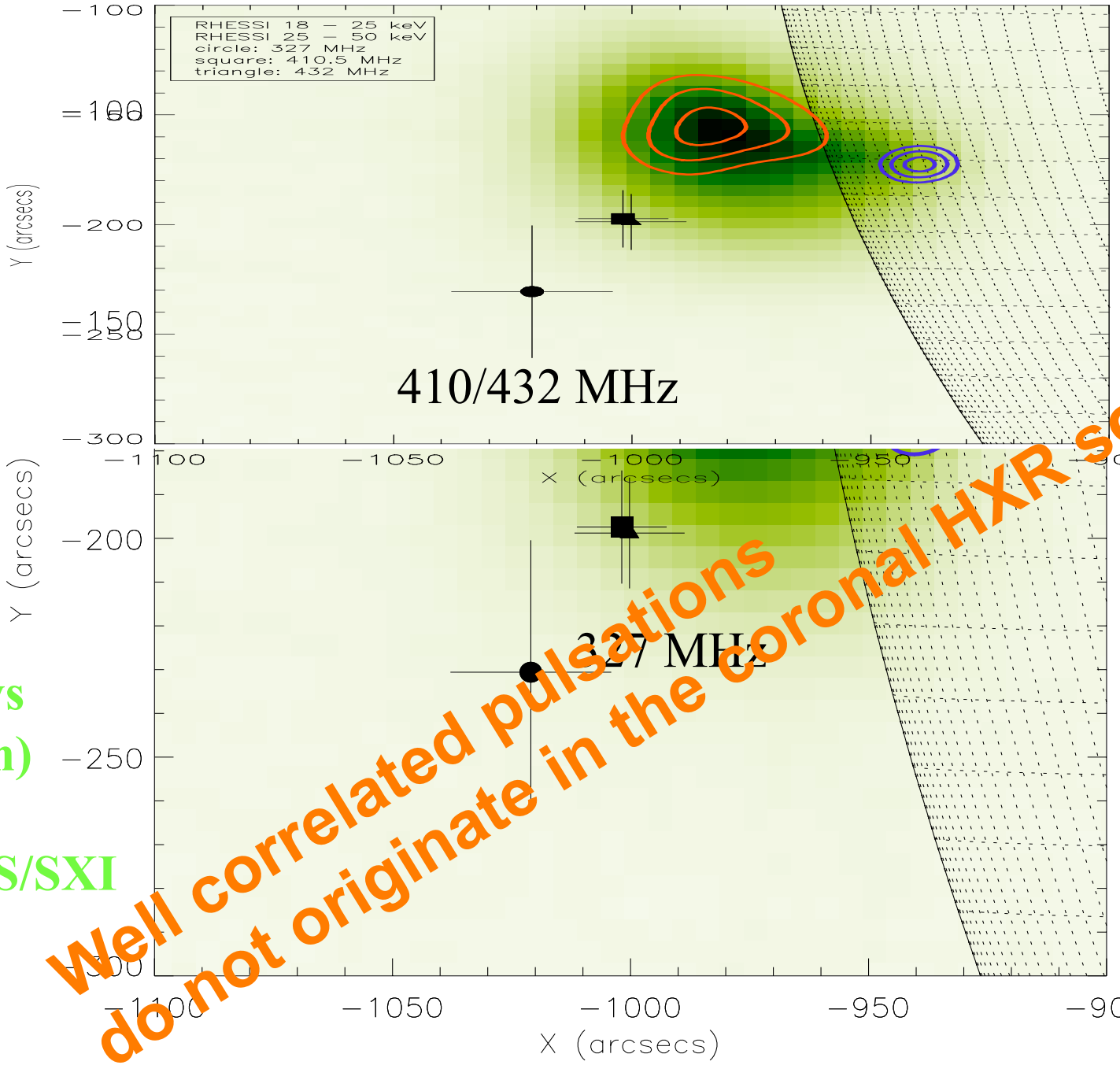
Dabrowski & Benz, 2009

Decimetric narrowband spikes



Delays are symmetric in positive and negative direction

Decimetric pulsation well correlated with HXR



RHESSI
thermal
non-thermal

Soft X-rays (green)

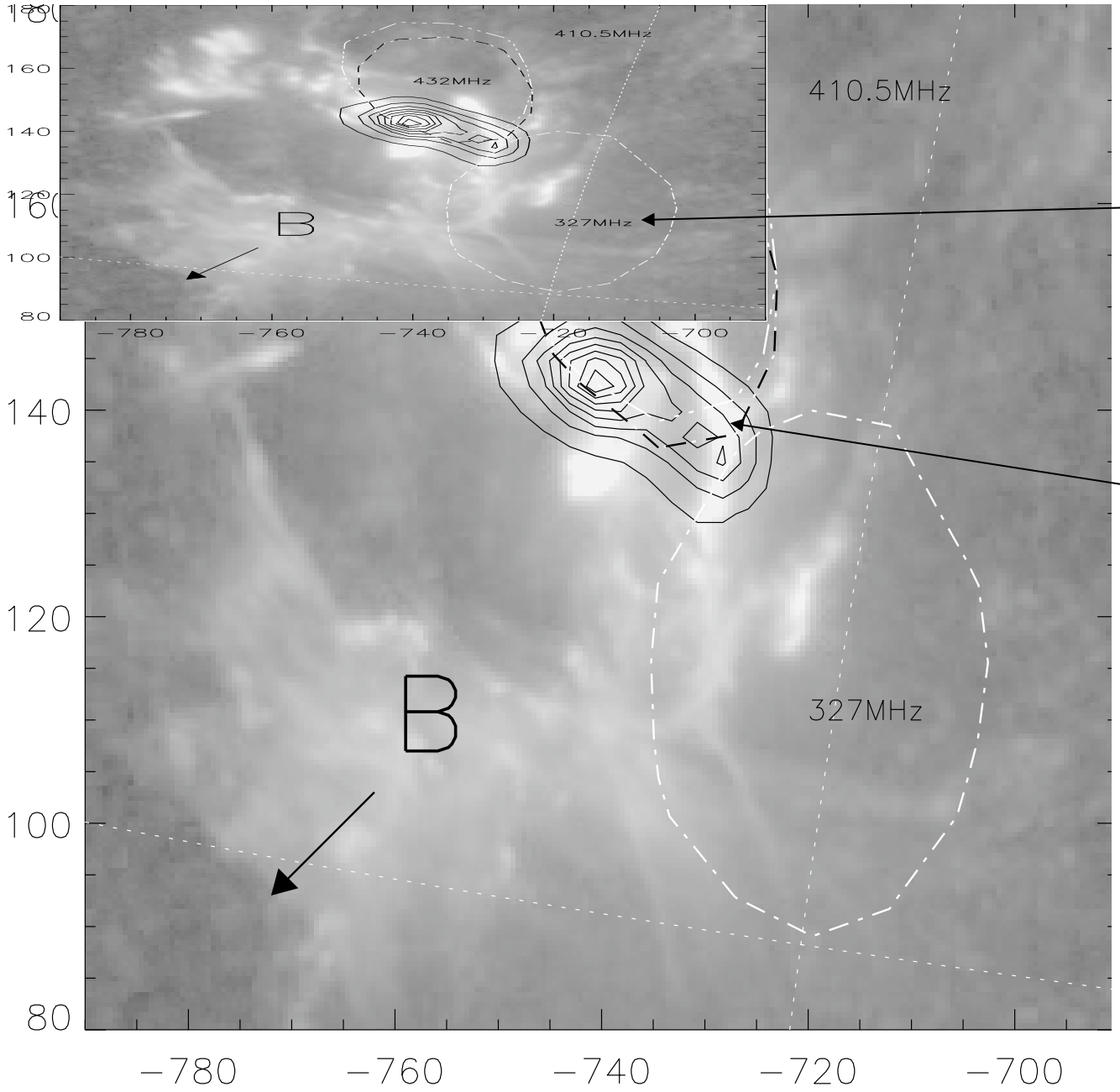
GOES/SXI

NRH
(black)

Well correlated pulsations do not originate in the coronal HXR source!

Benz & Battaglia, 2009

Flares are more complex than we ever dreamed.

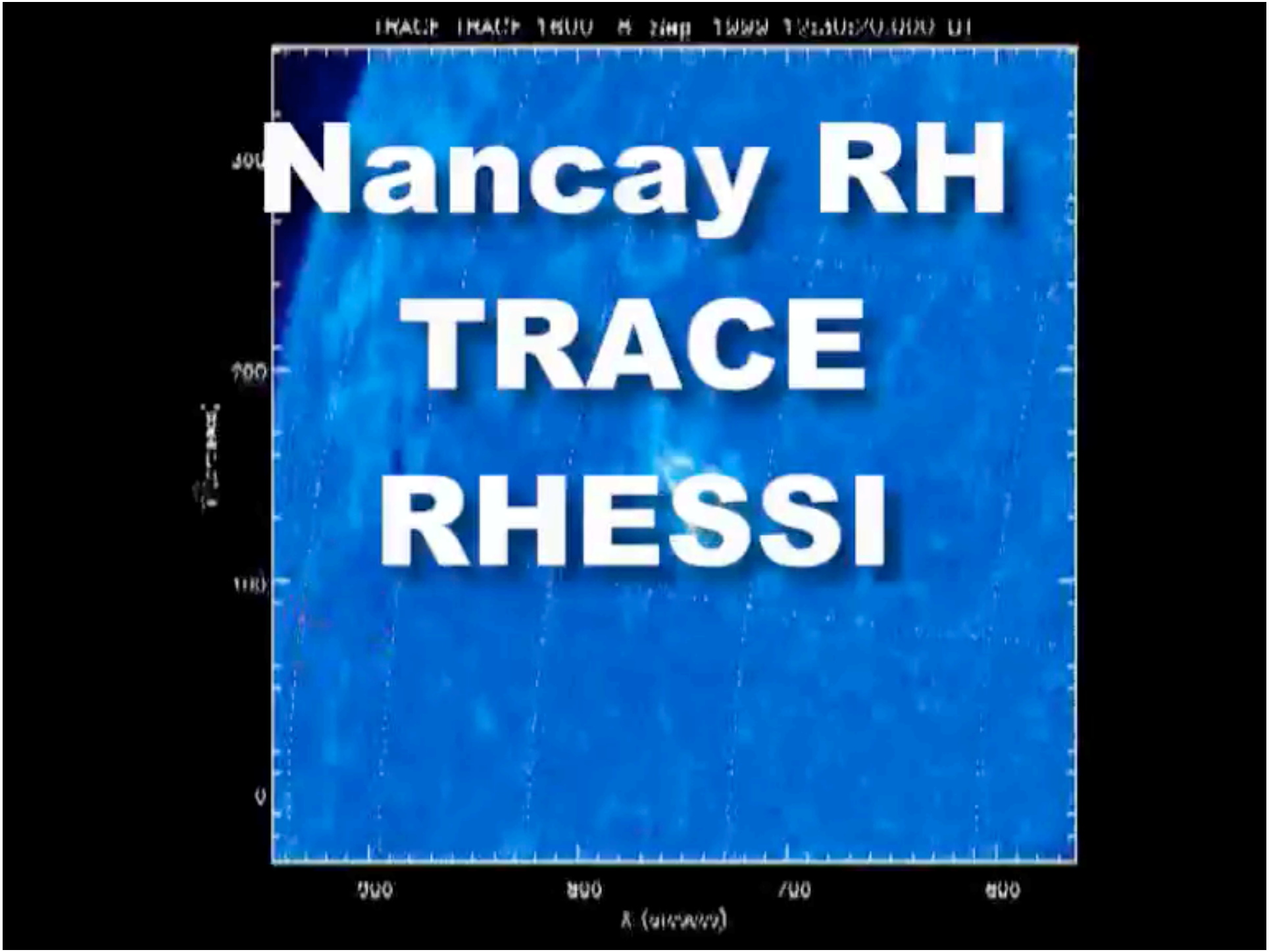


Decimeteric pulsations NRH

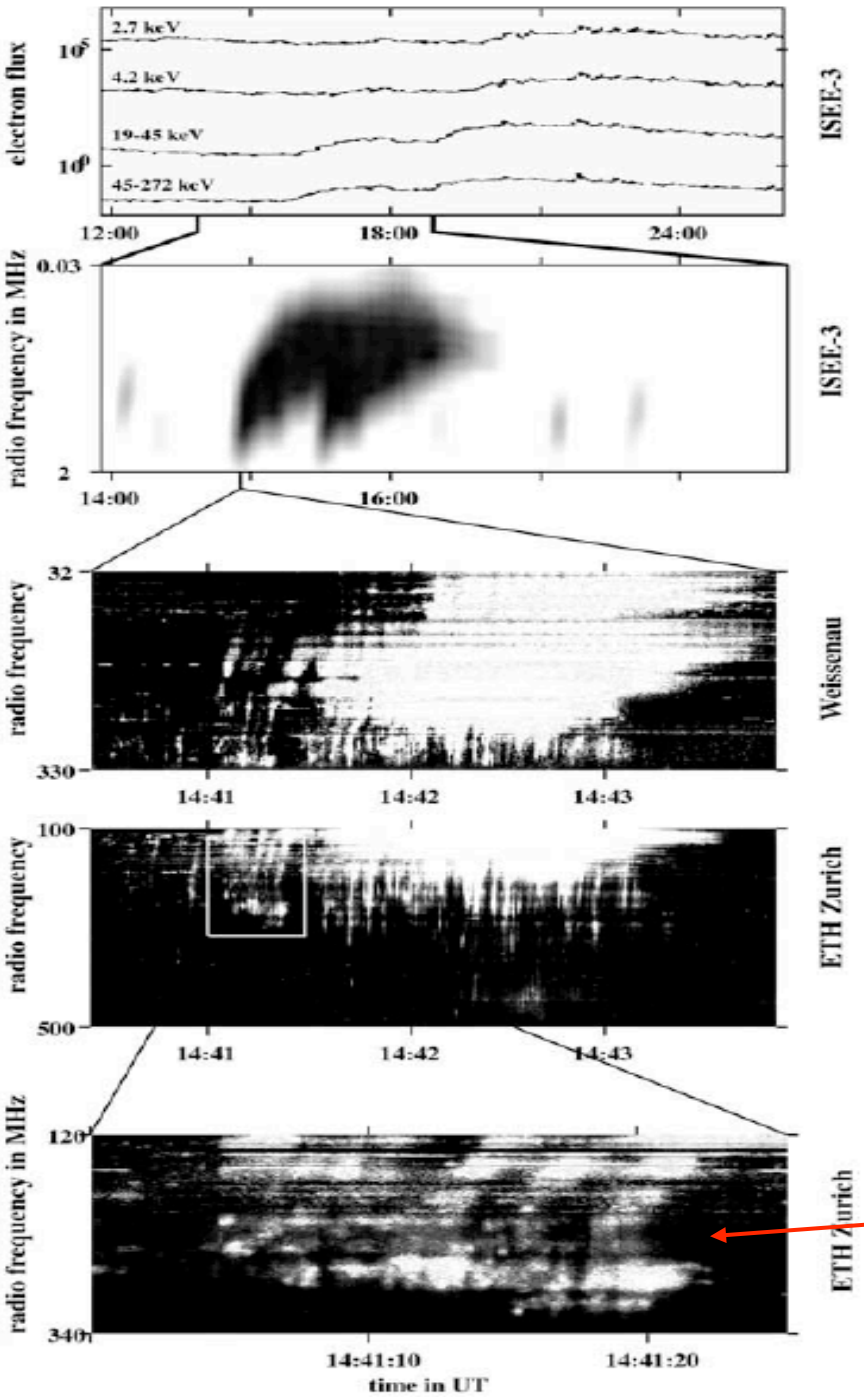
Hard X-rays 23 – 33 keV (RHESSI/HXR)

TRACE 1600 Å

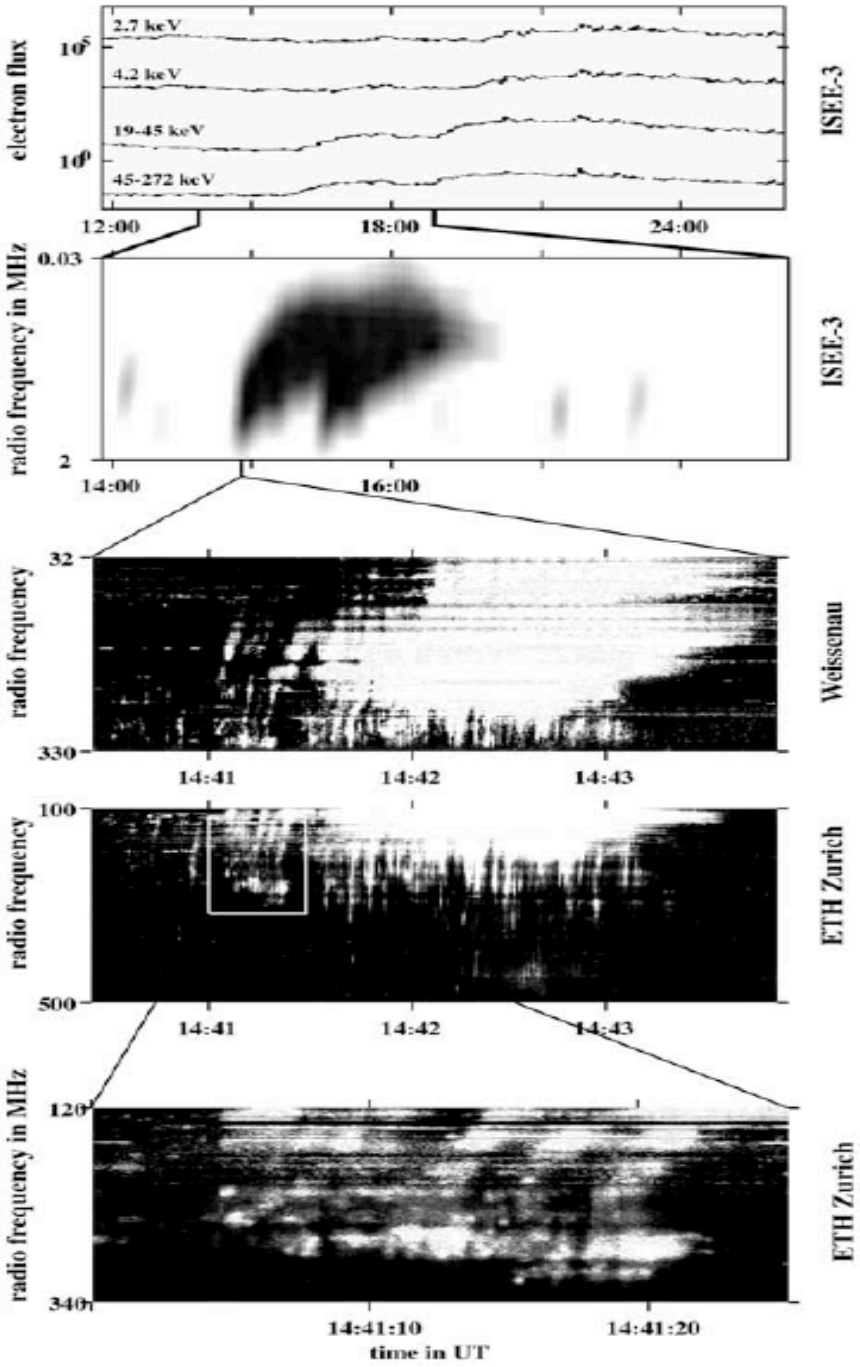
Saint-Hilaire et al. 2002

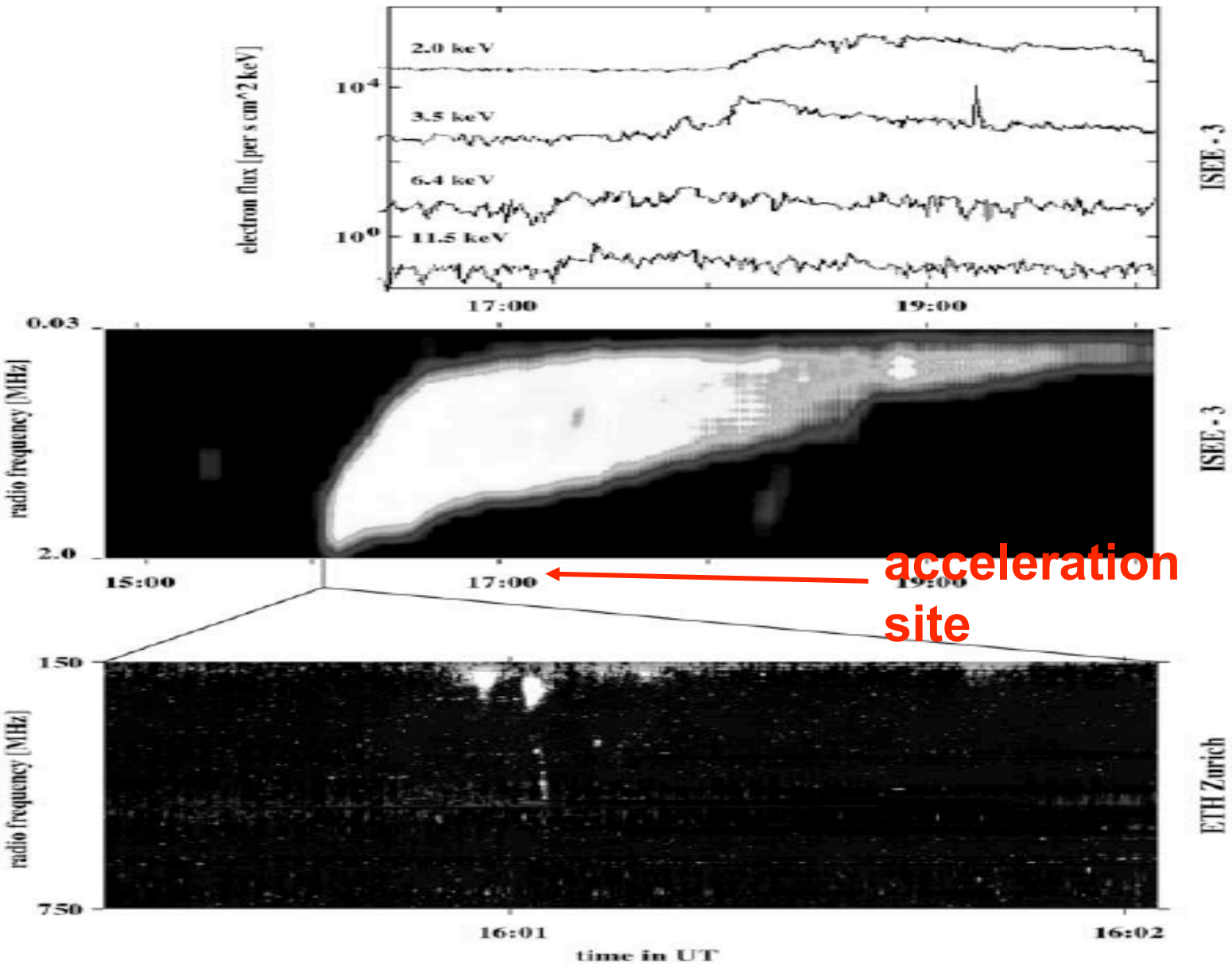

Nancay RH
TRACE
RHESSI

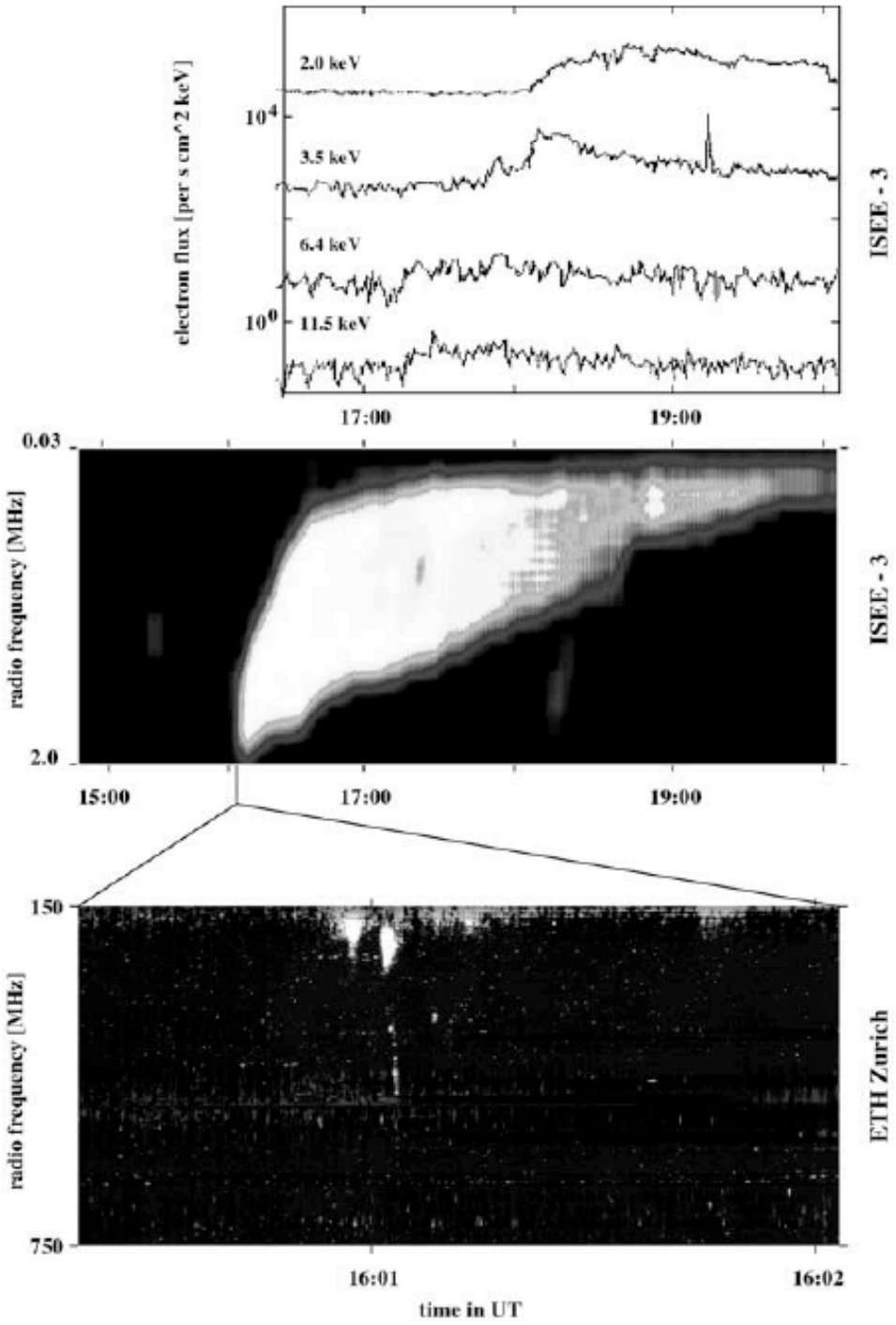
Part 3: The promise of meter and decimeter wave observations concerning acceleration in flares

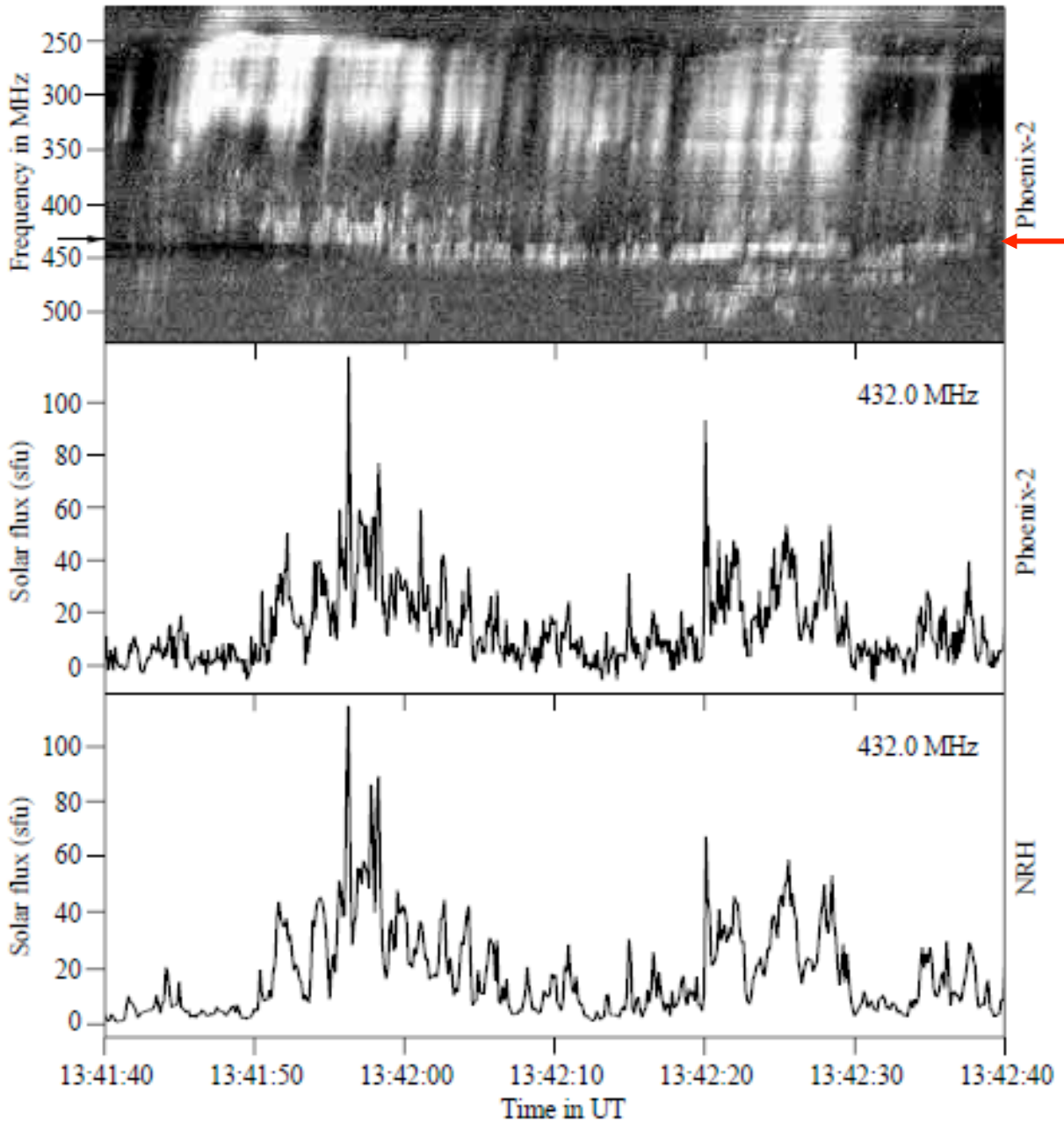


metric narrowband spikes

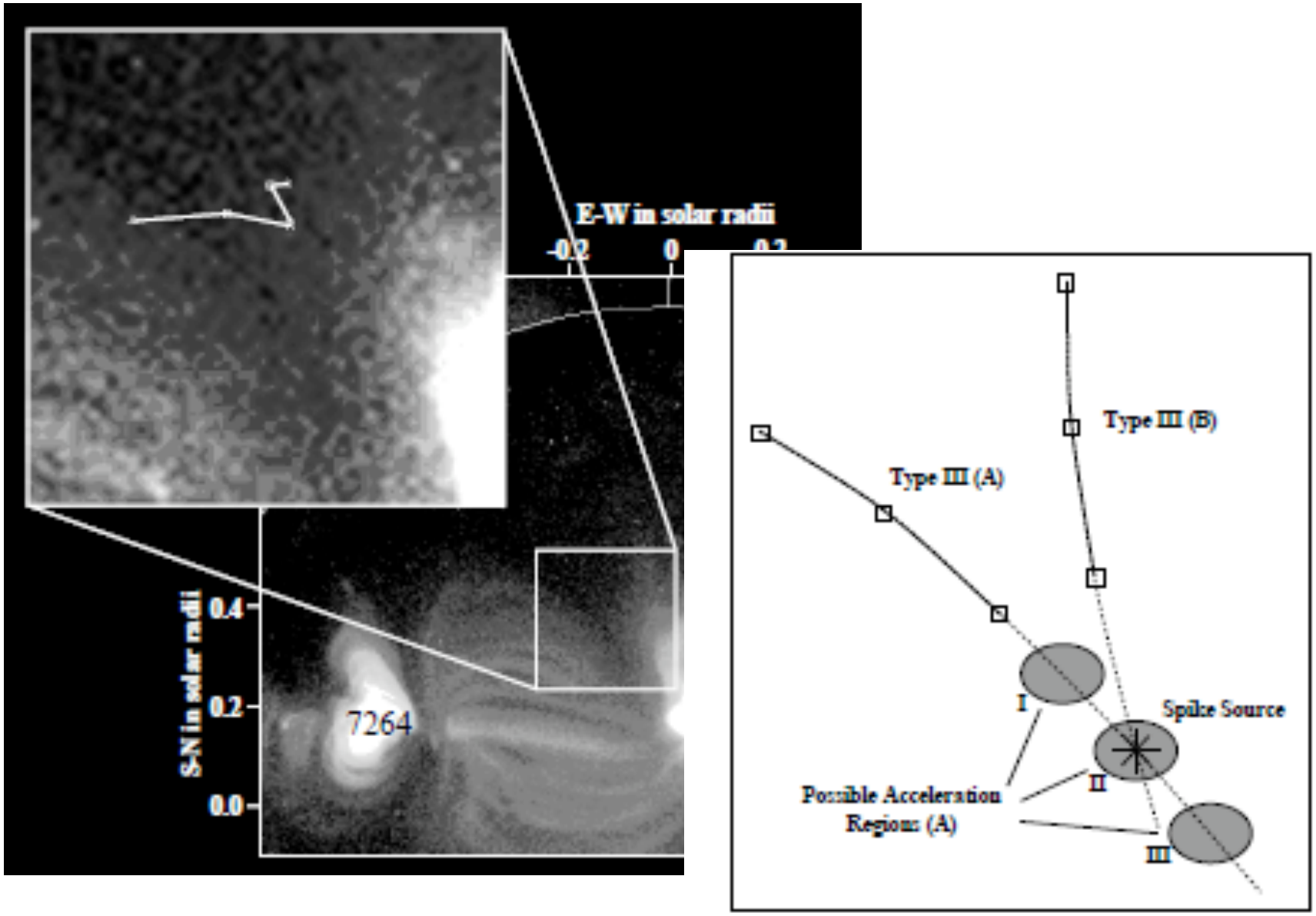

electron flux
2.7 keV
4.2 keV
19-45 keV
45-272 keV
ISEE-3
12:00
18:00
24:00
radio frequency in MHz
0.03
2
ISEE-3
14:00
16:00
radio frequency
32
330
Weissenau
14:41
14:42
14:43
radio frequency
100
500
ETH Zurich
14:41
14:42
14:43
radio frequency in MHz
120
340
ETH Zurich
14:41:10
14:41:20
time in UT


electron flux [per s cm^2 keV]
2.0 keV
3.5 keV
6.4 keV
11.5 keV
10^4
10^0
17:00
19:00
ISEE - 3
0.03
radio frequency [MHz]
2.0
15:00
17:00
19:00
ISEE - 3
acceleration site
150
radio frequency [MHz]
750
16:01
16:02
time in UT
ETH Zurich


2.0 keV
3.5 keV
6.4 keV
11.5 keV
electron flux [per s cm^2 keV]
10^4
10^0
17:00
19:00
ISEE - 3
0.03
2.0
radio frequency [MHz]
15:00
17:00
19:00
ISEE - 3
150
750
radio frequency [MHz]
16:01
16:02
time in UT
ETH Zurich



Paesold et al, 1992



NRH
Paesold et al, 1992

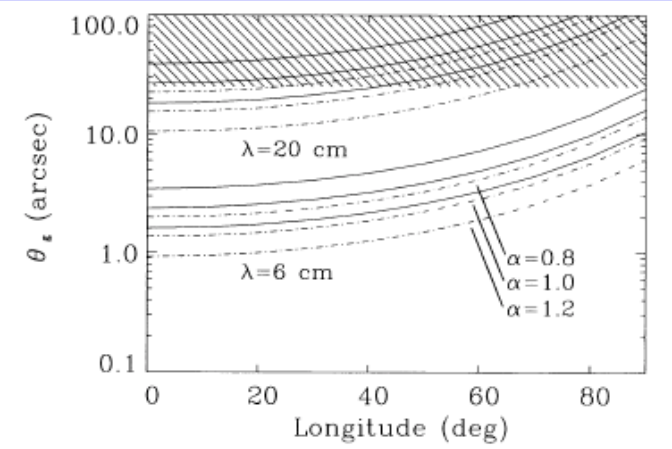
How accurate are radio positions?

- **Statistics of centroid position**

  $\Delta \approx$ beam width / signal-to-noise

  $\approx$ beam width / 20 ~ 10" (NRH)

- **Coronal scattering**

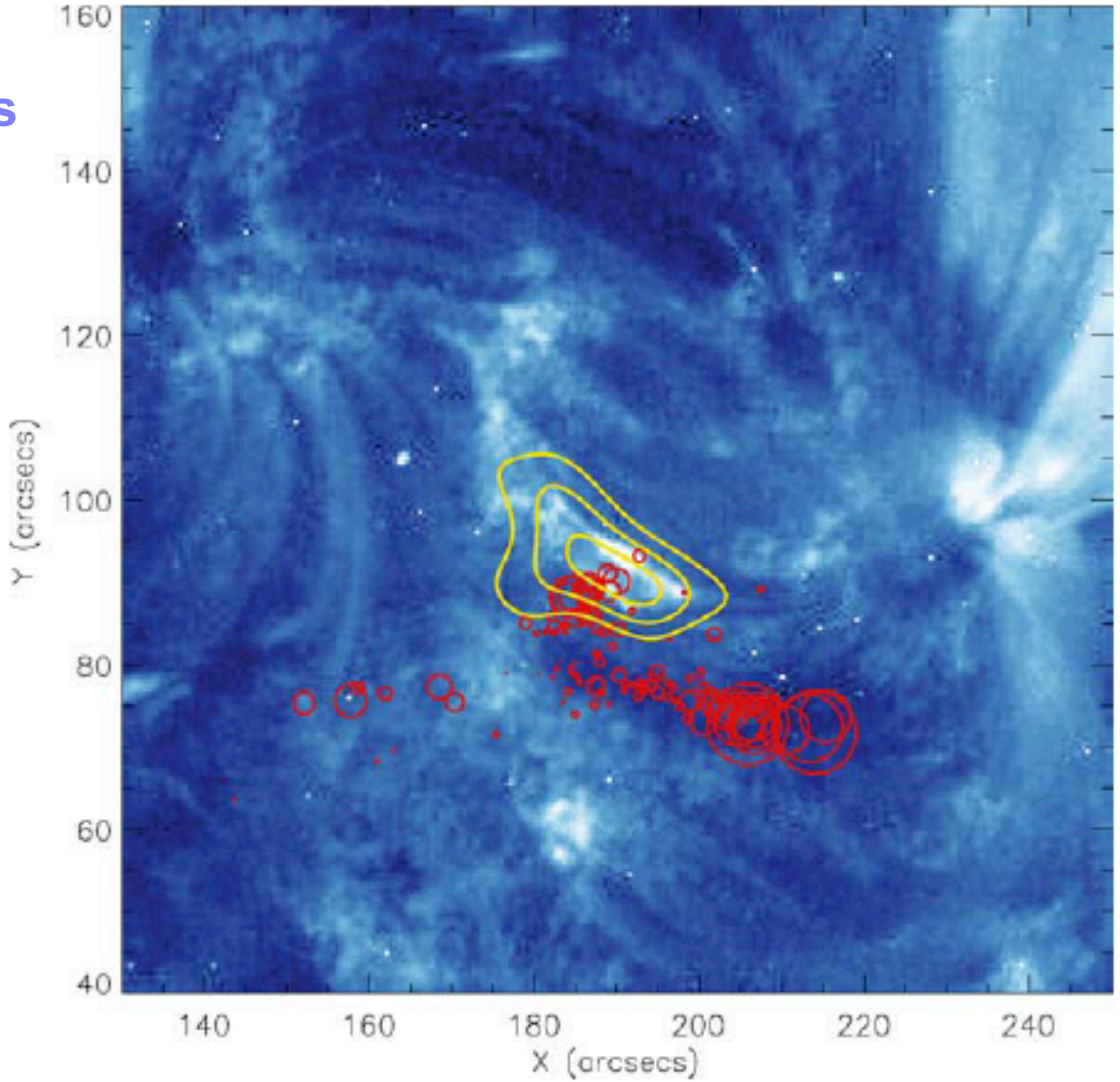


λ = 1 m

→ Θ is some arcmin

tian, 1994)

Metric Type I Bursts



TRACE
RHESSI
VLA

Are radio positions related to other features?

How accurate are radio positions?

- More serious: Scattering, refraction and ducting may shift the radio positions.
- Need to study the systematic shifts

Goal: 5 arsec accuracy of centroid

Conclusions

- **Part 1: Non-thermal radio and hard X-ray emissions don't tell the same story about acceleration.**
- **There are sometimes excellent correlations, and at other times no association at all.**
- **Part 2: The radio and HXR emissions often originate from different locations.**
- **Meter and decimeter waves explore parts of flare that do not show up in HXR.**
- **Flares are more complex than seen in HXR.**
- **Part 3: Metric radio spikes are possibly emitted from the acceleration site. Decimeter spikes and pulsations?**

Instrumental Possibilities at NRH Concerning Flares

- **Systematics of positional shifts by scattering, refraction and ducting in order to be compared to other wavelengths**
- **Add higher frequency channel to reach into the more energetic parts of the flare**
- **Improve positional accuracy (?)**