# Search for TNO Occultation in X-rays

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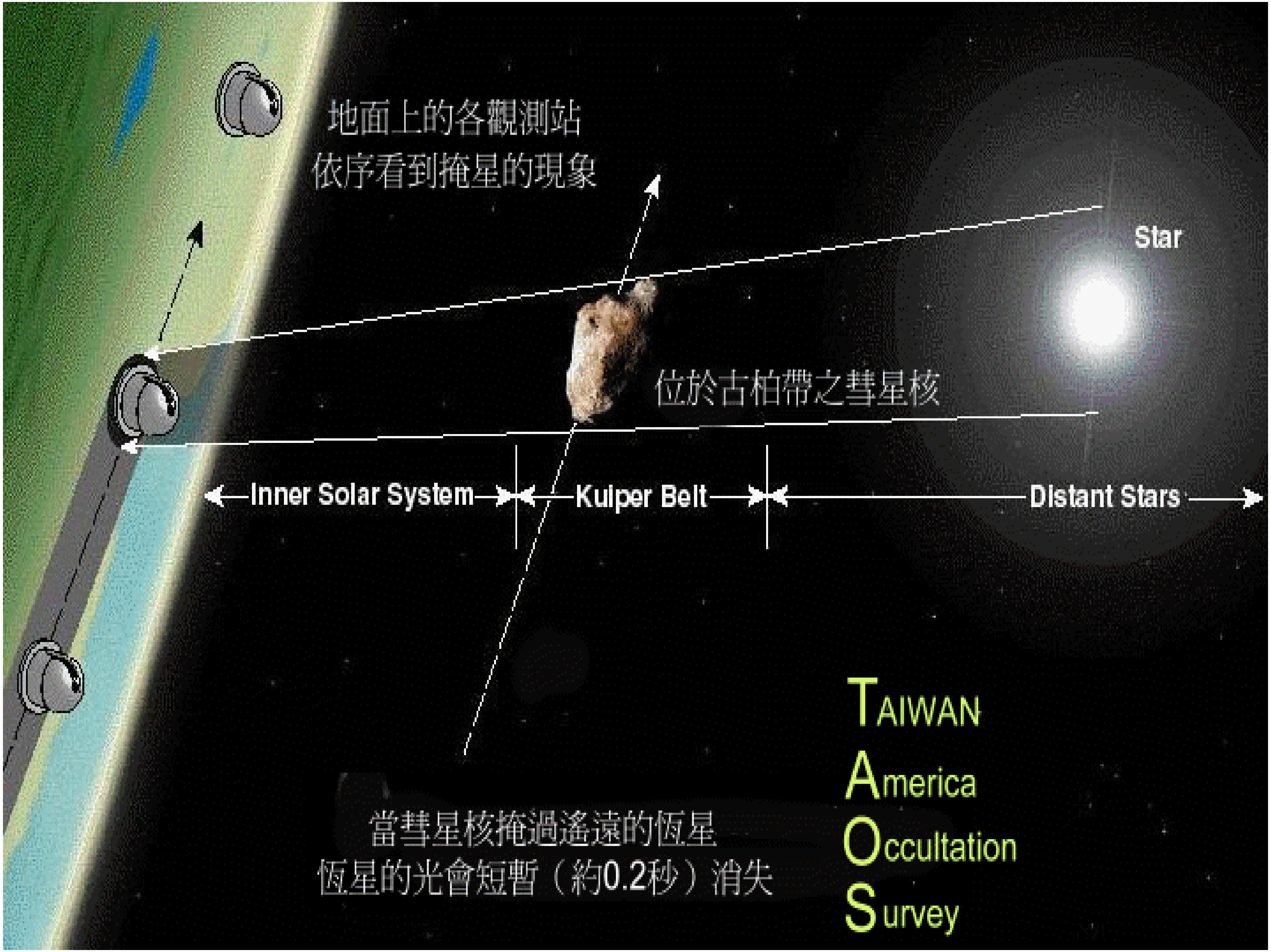
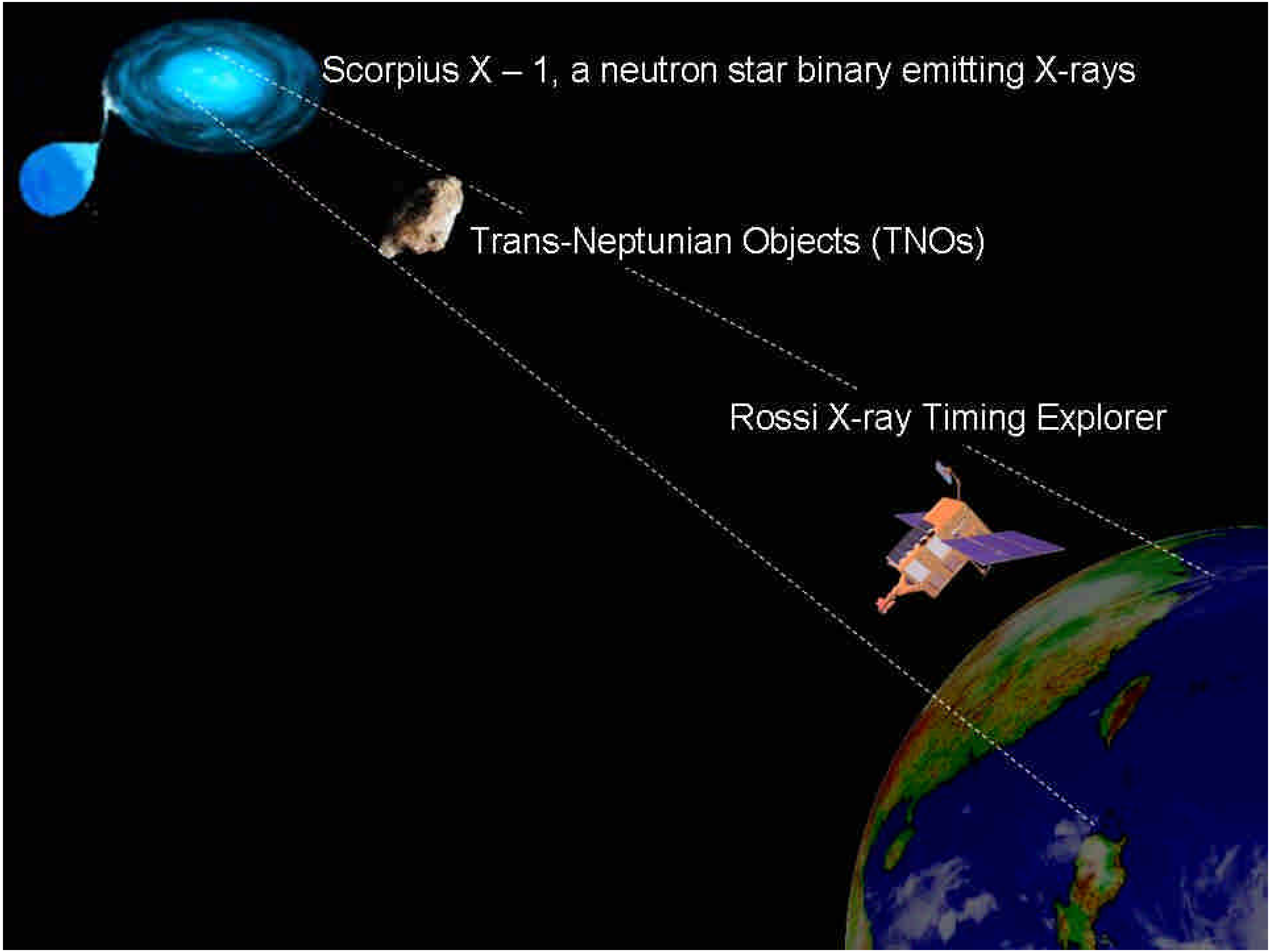

地面上的各觀測站
依序看到掩星的現象
Star
位於古柏帶之彗星核
Inner Solar System
Kuiper Belt
Distant Stars
當彗星核掩過遙遠的恆星
恆星的光會短暫（約0.2秒）消失
TAIWAN
America
Occultation
Survey


Scorpius X – 1, a neutron star binary emitting X-rays
Trans-Neptunian Objects (TNOs)
Rossi X-ray Timing Explorer

# Why X-ray occultation?

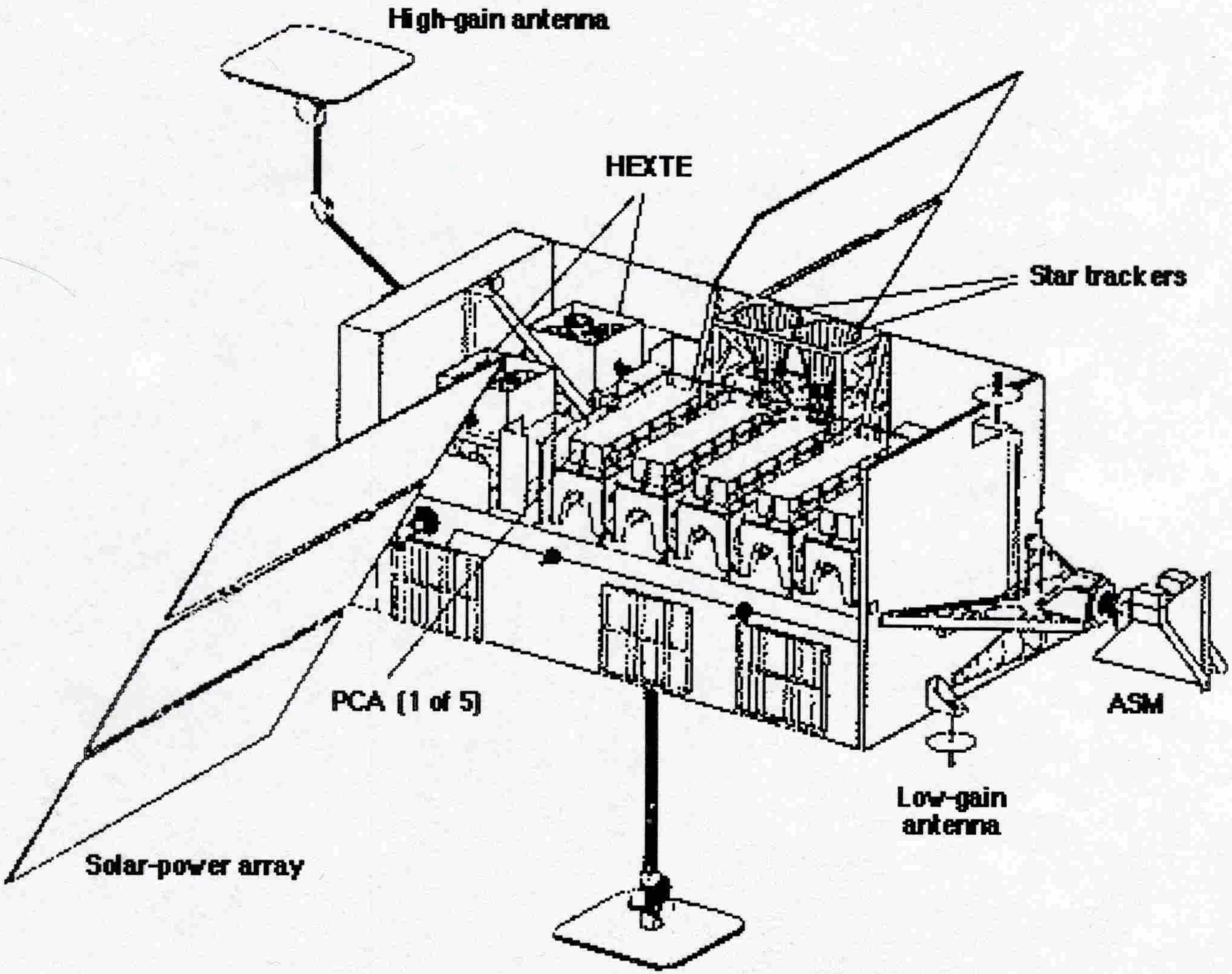
faster photometry
less diffraction → shorter events → smaller bodies → better chance to detect

* The background X-ray source needs to be bright enough.

* Sco X-1 is the brightest in the Sky.
* RXTE/PCA has the largest effective area.

* The typical PCA count rate of Sco X-1 is $10^5$ cps.
* Detection of msec time-scale occultation is possible.

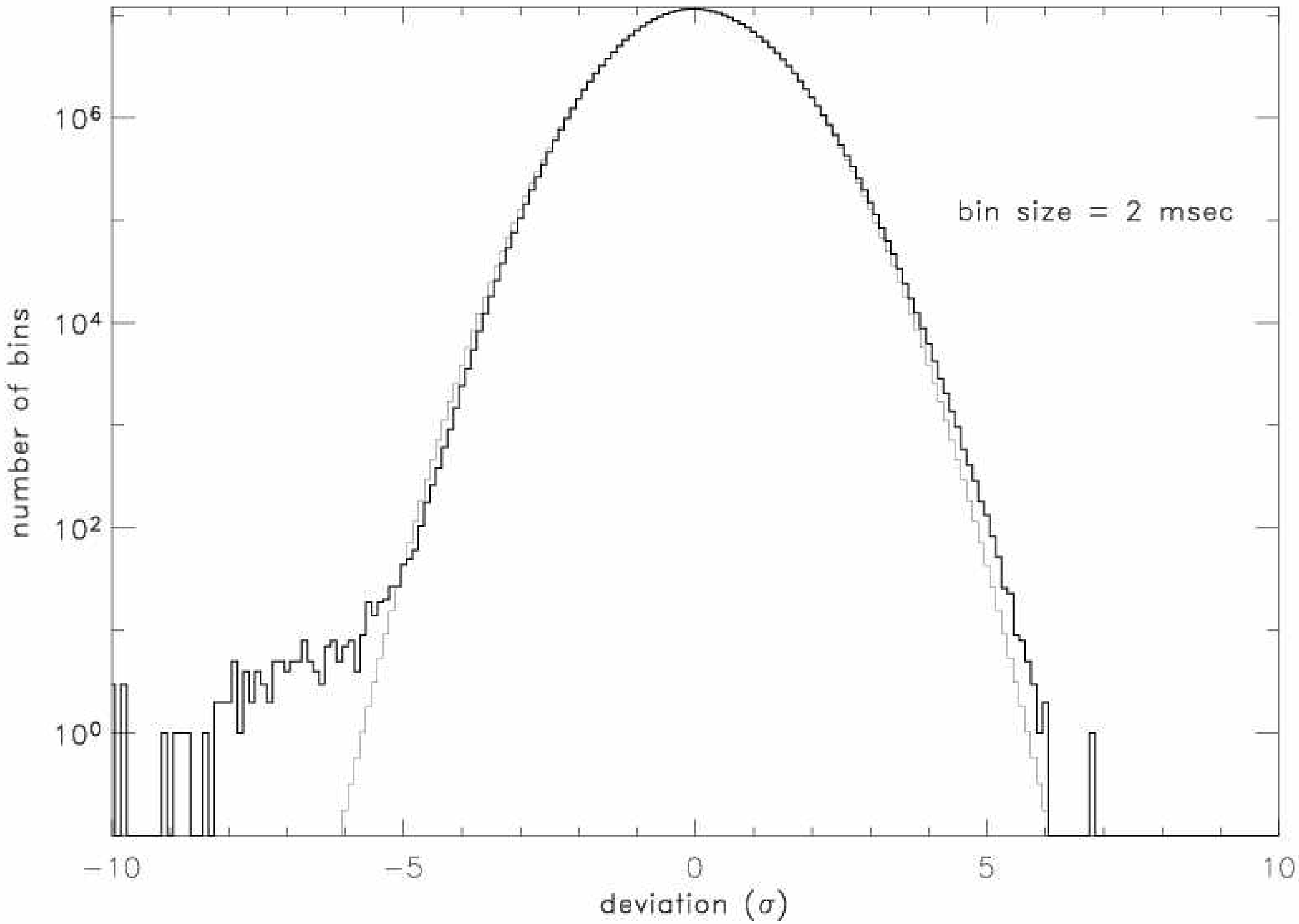
# XTE Spacecraft



# In the first attempt……

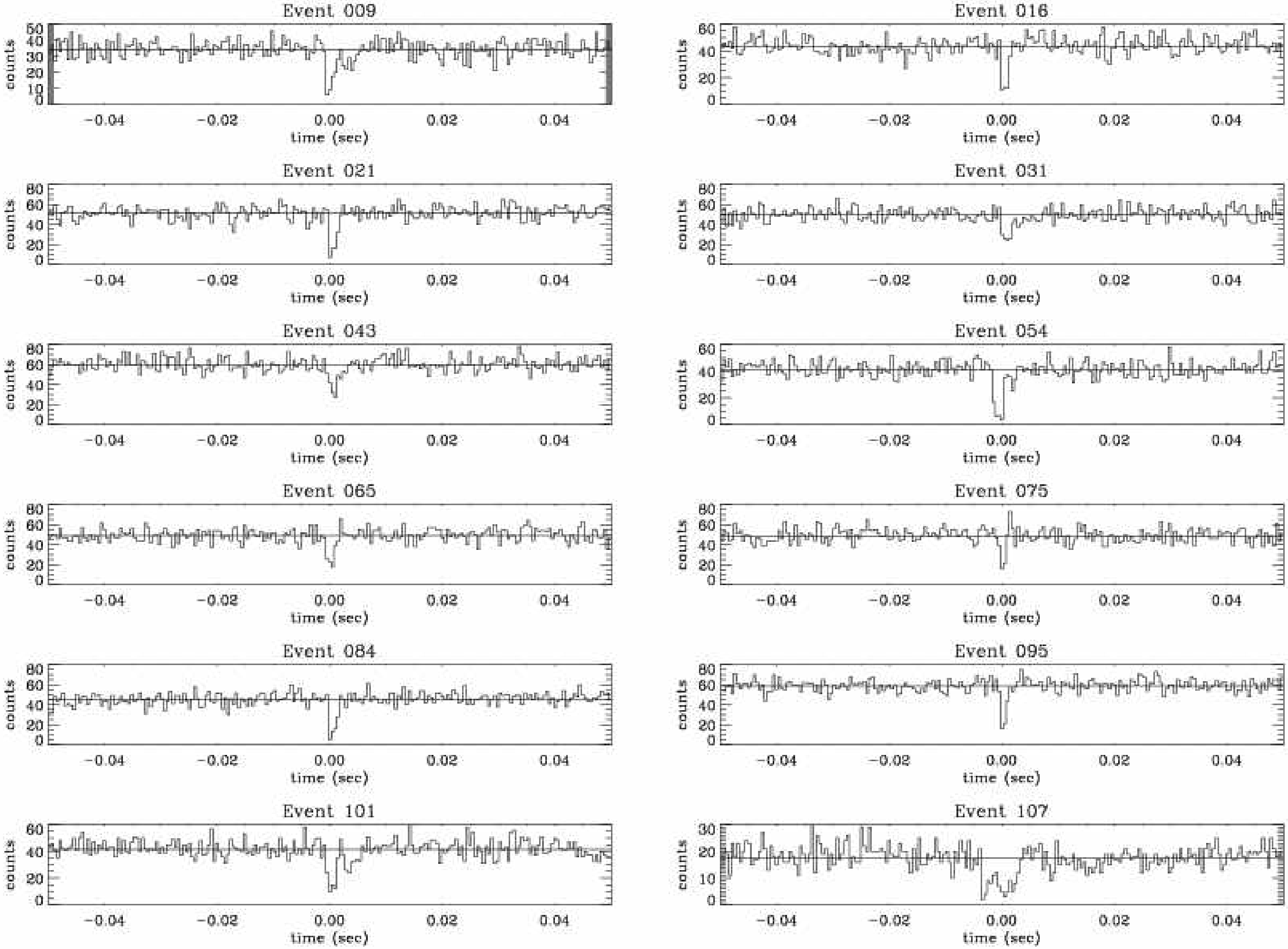
RXTE/PCA data of Sco X-1, 1996-2002, 564 ksec
(Chang et al. 2006, Nature 442, 660;
Chang et al. 2007, MNRAS 378, 1287;
Jones et al. 2008, ApJ 677, 1241)

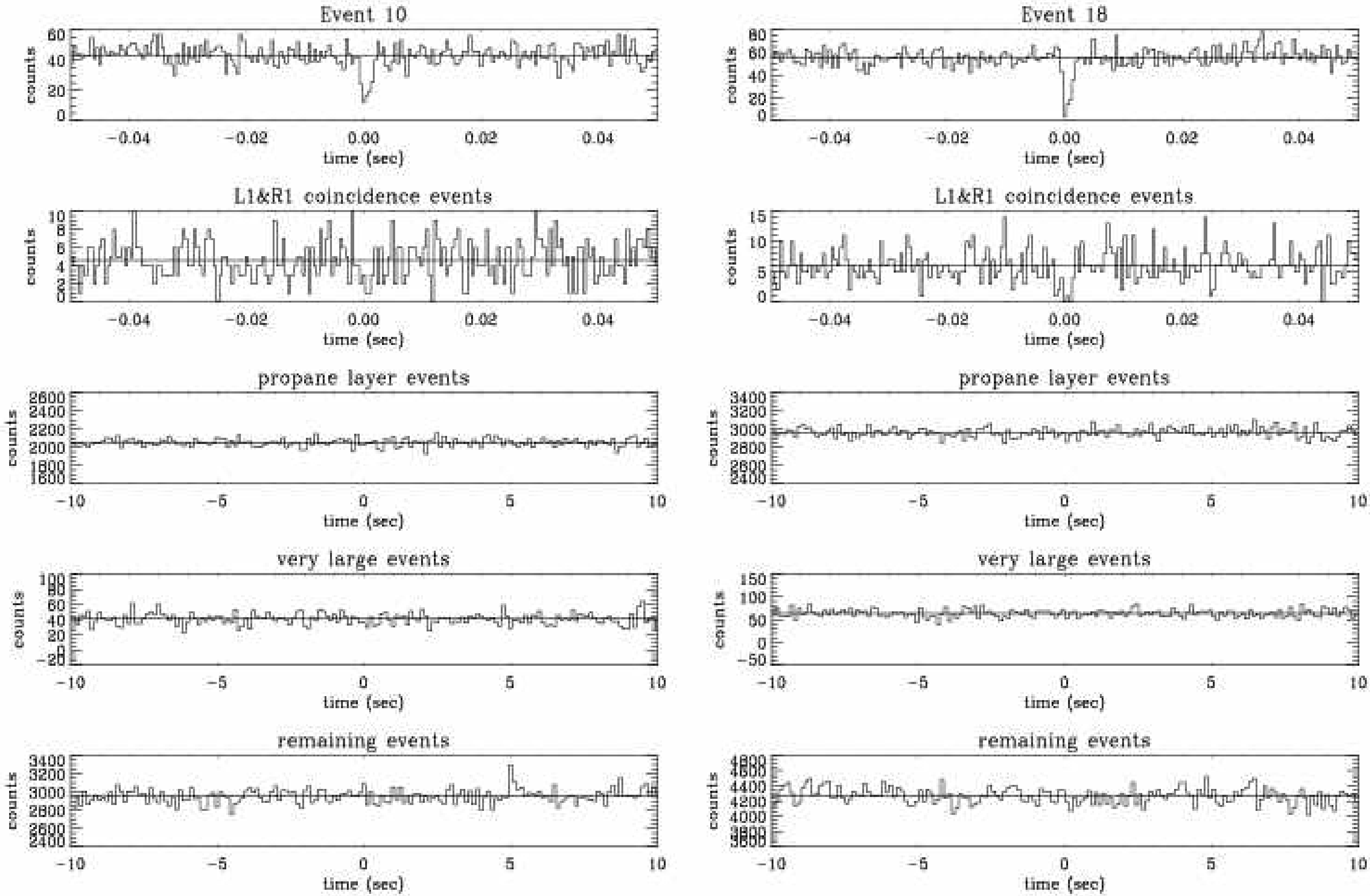
* 107 significant dips were found.
* There are signatures indicating that most, if not all, of them could be due to some possible instrumental effects, which are previously unknown.
* Those signatures allow 10% of the dip events to be non-instrumental.




* The RXTE/PCA data used in this search spans over 7 years from 1996 to 2002. The total exposure is 564.3 ksec.

In the 564-ksec data, 107 events were found.


Event 009
Event 016
Event 021
Event 031
Event 043
Event 054
Event 065
Event 075
Event 084
Event 095
Event 101
Event 107
counts
time (sec)
-0.04
-0.02
0.00
0.02
0.04


Event 10
counts
time (sec)
L1&R1 coincidence events
counts
time (sec)
propane layer events
counts
time (sec)
very large events
counts
time (sec)
remaining events
counts
time (sec)
Event 18
counts
time (sec)
L1&R1 coincidence events
counts
time (sec)
propane layer events
counts
time (sec)
very large events
counts
time (sec)
remaining events
counts
time (sec)

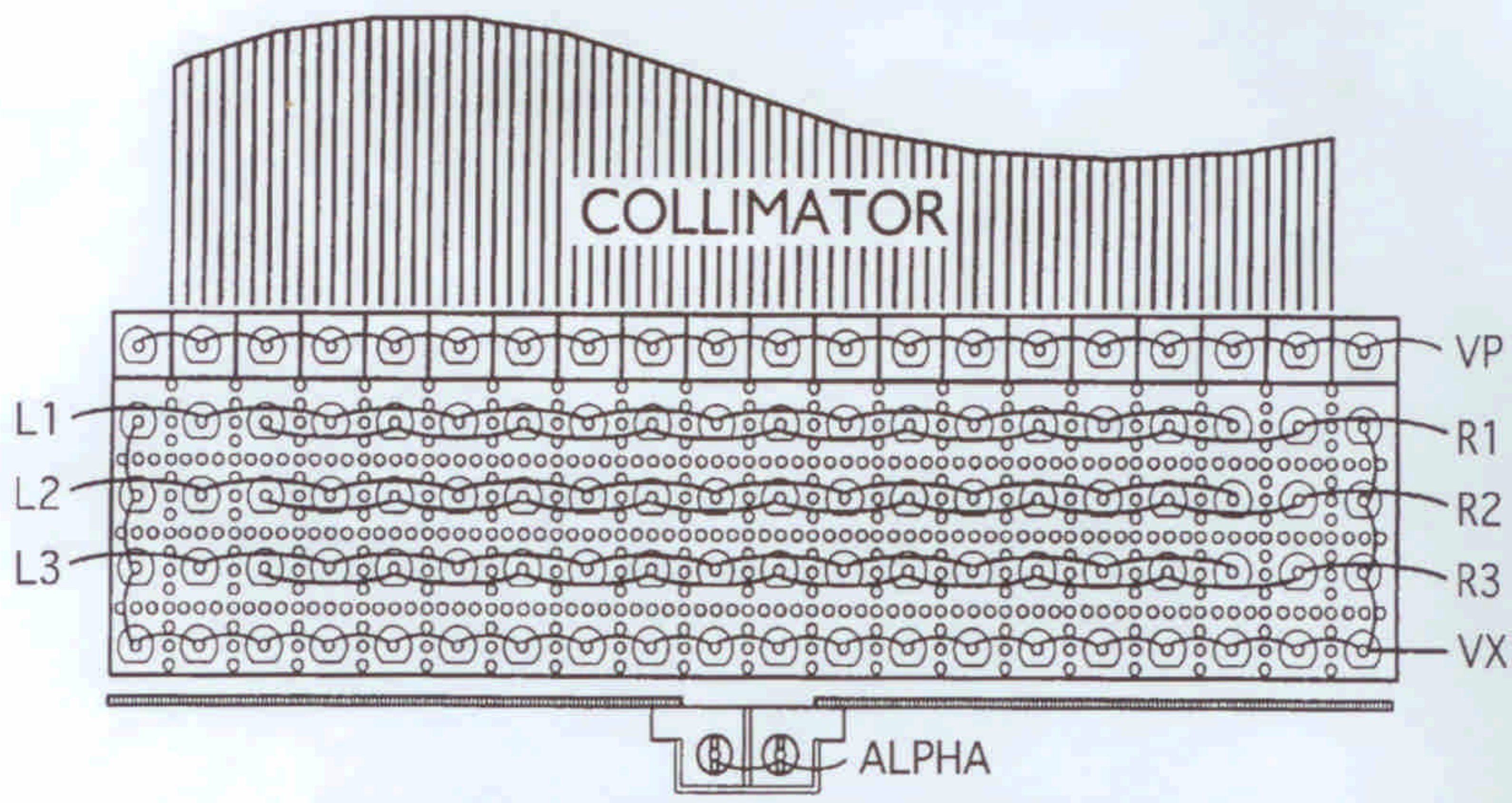
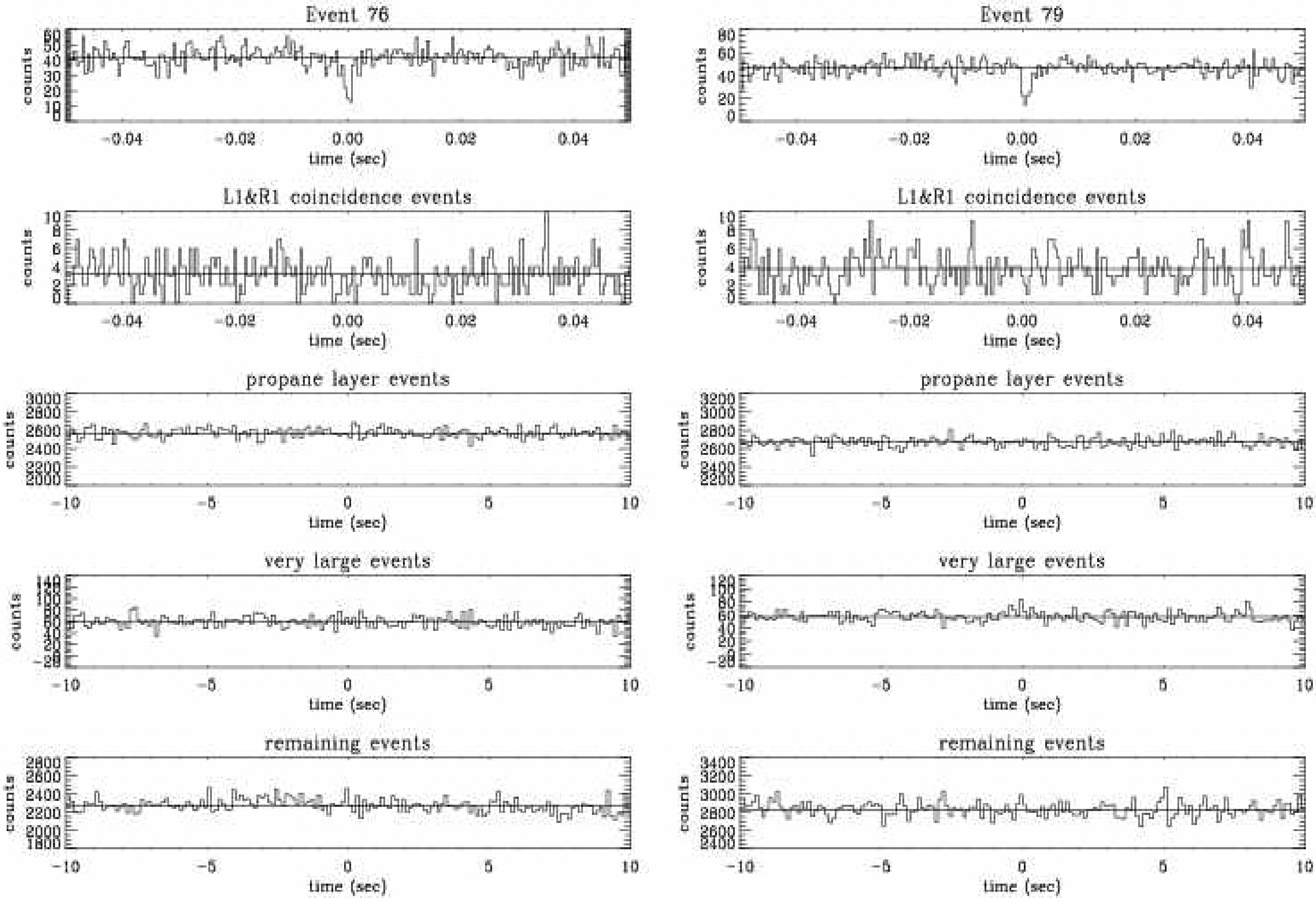
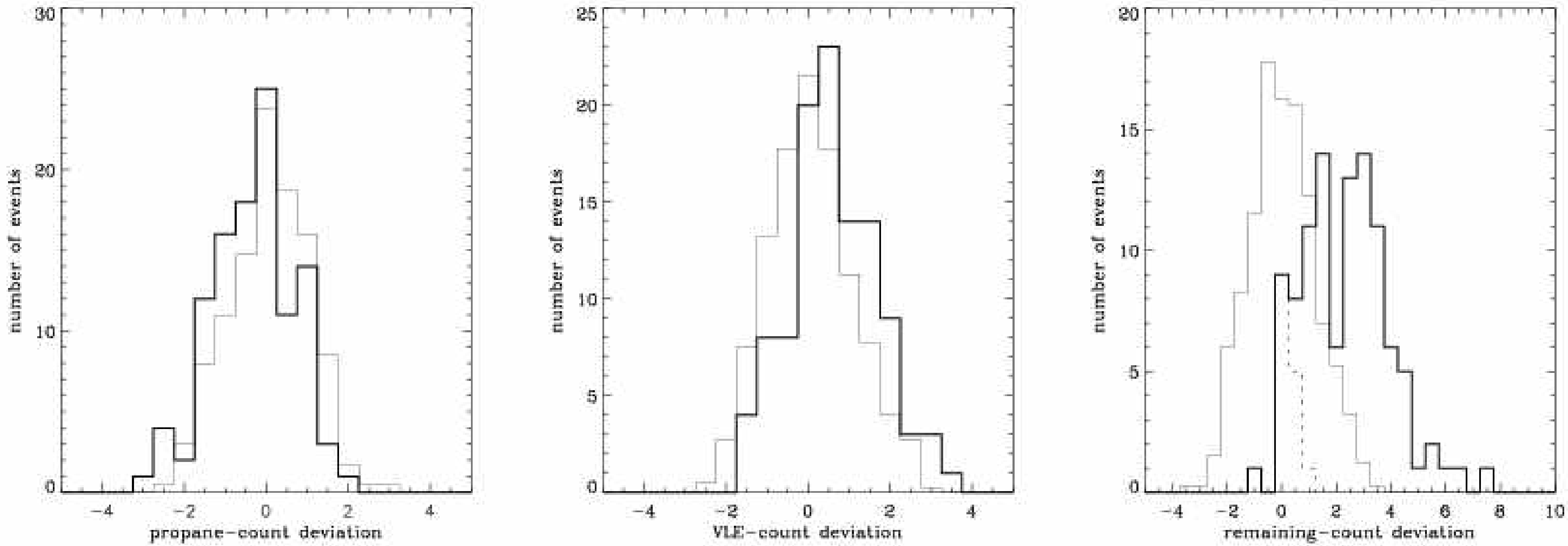



Fig. 4.2 The anode and signal connections for the 9 independent channels of analog electronics. The interleaved anodes provide rejection of charged particle background.

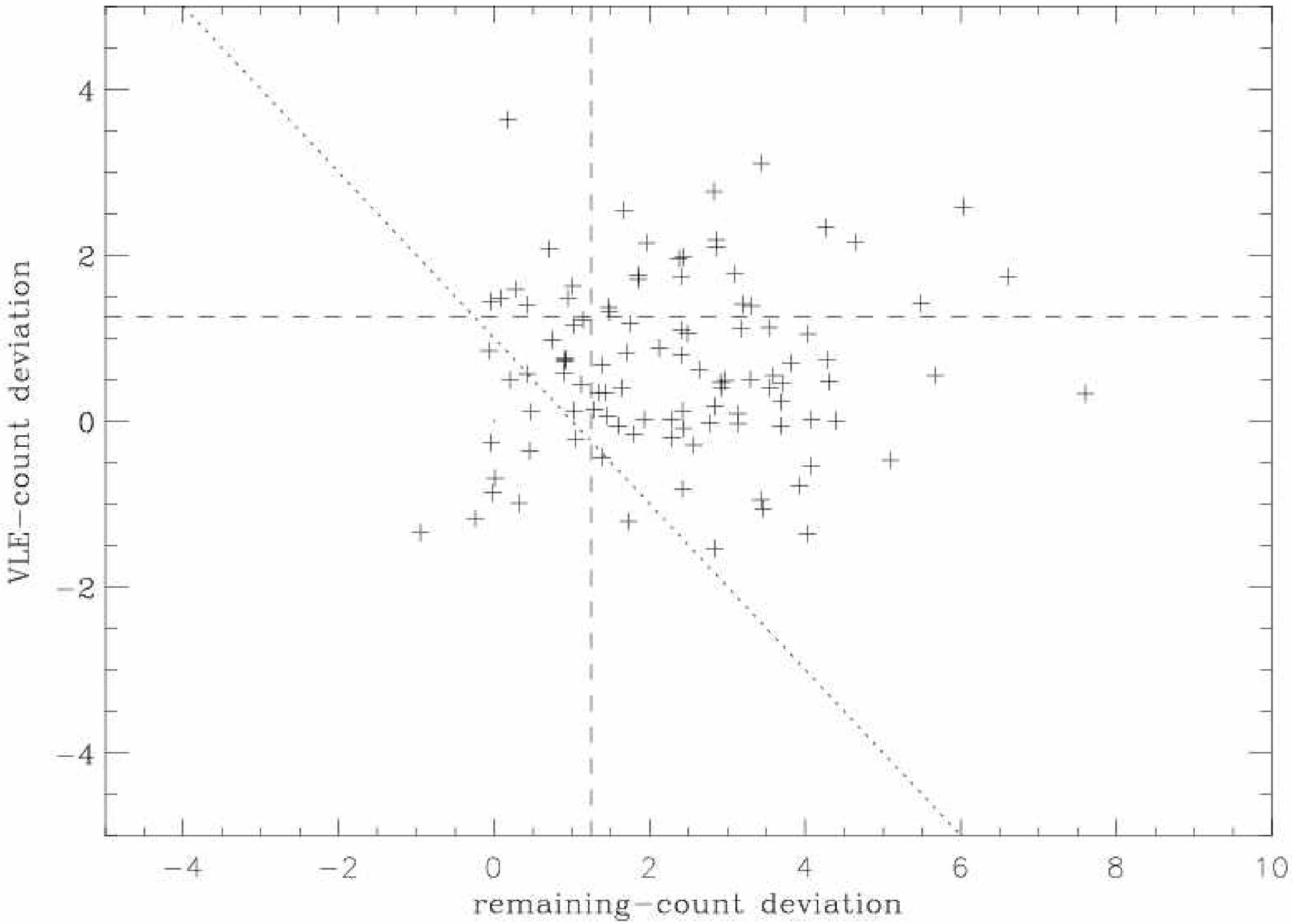
RXTE PCA Very Large Events (VLEs) are those events which deposit more than 100 keV in any one of the 6 active xenon layers or the propane layer.



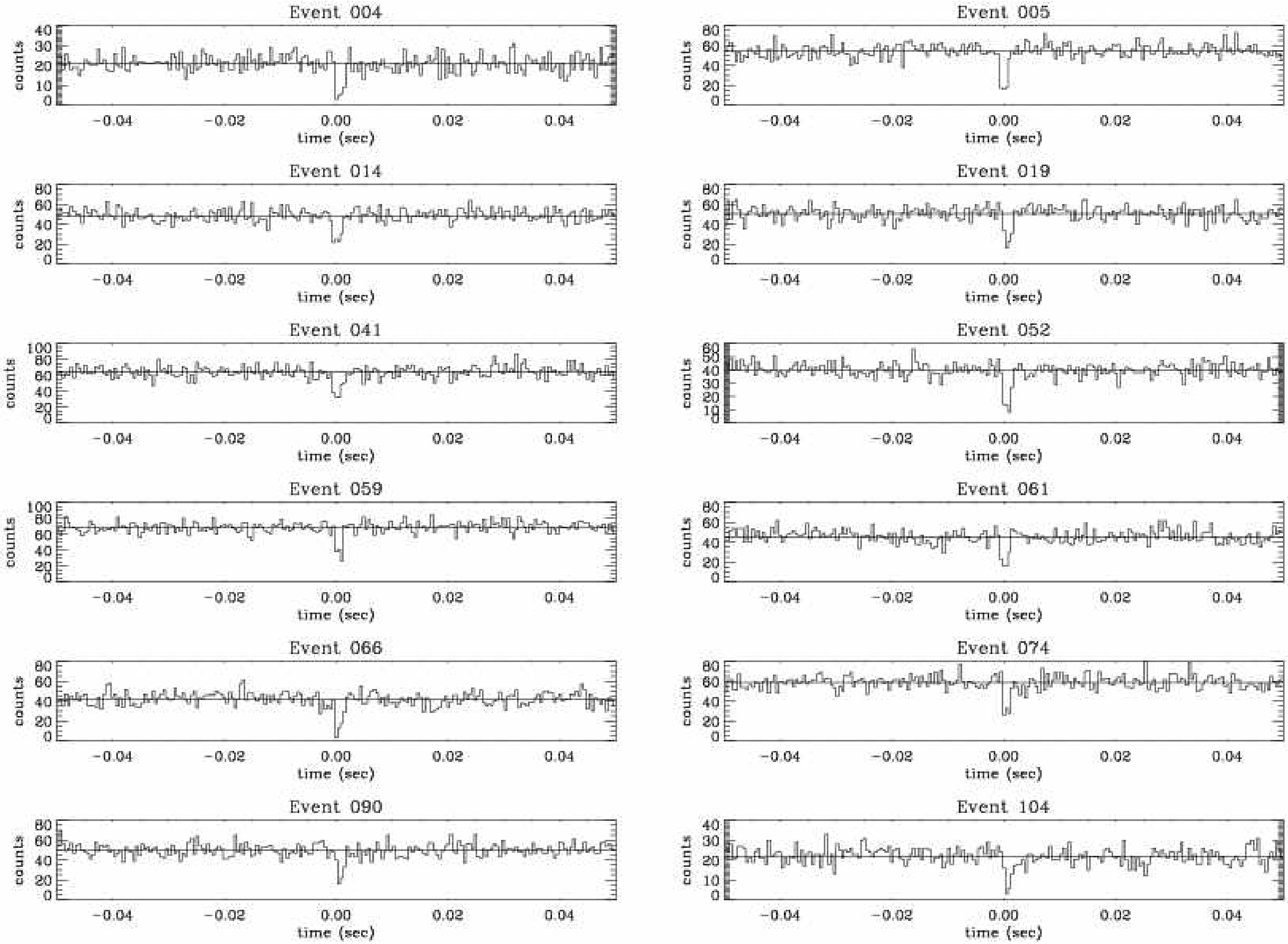
Event 76
Event 79
L1&R1 coincidence events
L1&R1 coincidence events
propane layer events
propane layer events
very large events
very large events
remaining events
remaining events
counts
time (sec)
-0.04
-0.02
0.00
0.02
0.04
-10
-5
0
5
10



30
20
10
0
number of events
-4
-2
0
2
4
propane-count deviation
25
20
15
10
5
0
number of events
-4
-2
0
2
4
VLE-count deviation
20
15
10
5
0
number of events
-4
-2
0
2
4
6
8
10
remaining-count deviation



VLE-count deviation
remaining-count deviation
4
2
0
−2
−4
−4
−2
0
2
4
6
8
10




Light curves of the 12 probable non-instrumental events
(no anomaly in ‘remaining’ and ‘VLE’ counts)

To pin down the distance and the size of each occulting body more accurately for all the events is an important issue but requires further analysis on the dead-time-corrected light curves, diffraction patterns and different orbital inclinations and eccentricities.

For an approximate estimation of the occulting-object sizes at this stage, we contend ourselves by considering a typical relative speed of 30 km $s^{-1}$ between the occulting TNOs and *RXTE* and a random crossing through the shadow. The average crossing length of a random crossing is $\pi/4$ times that of a central crossing, assuming a circular shadow.

We therefore set the size range of these 12 objects to be from 60 to 100 m for durations from 1.5 to 2.5 ms.

For a background point source, the event rate is

$$\frac{N}{T} = \frac{\int_{s_1}^{s_2} \left(\frac{\mathrm{d}N}{\mathrm{d}s}\right) sv \, \mathrm{d}s}{d^2 \Omega_{\mathrm{A}}} \quad , \tag{1}$$

where $N$ is the number of detected events (assuming a 100% detection efficiency), $T$ the total exposure time, $\left(\frac{\mathrm{d}N}{\mathrm{d}s}\right)$ the differential size distribution, $v$ the typical relative speed, $d$ the typical distance to the TNOs, and $\Omega_{\mathrm{A}}$ the total solid angle of the sky distributed with TNOs. To derive $\left(\frac{\mathrm{d}N}{\mathrm{d}s}\right)$ from the event rate, a function form of the distribution needs to be assumed. On the other hand, if the integration is only over a small range of the size, we may consider to derive an average value at that size. Noting that $\frac{\mathrm{d}N}{\mathrm{d}\log s} = \frac{\mathrm{d}N}{\mathrm{d}s}\, s \ln 10$, we have

$$\int_{s_1}^{s_2} \left(\frac{\mathrm{d}N}{\mathrm{d}s}\right) sv \, \mathrm{d}s = \left(\frac{\mathrm{d}N}{\mathrm{d}\log s}\right)_{s_1 < s < s_2} \frac{v(s_2 - s_1)}{\ln 10} \quad , \tag{2}$$

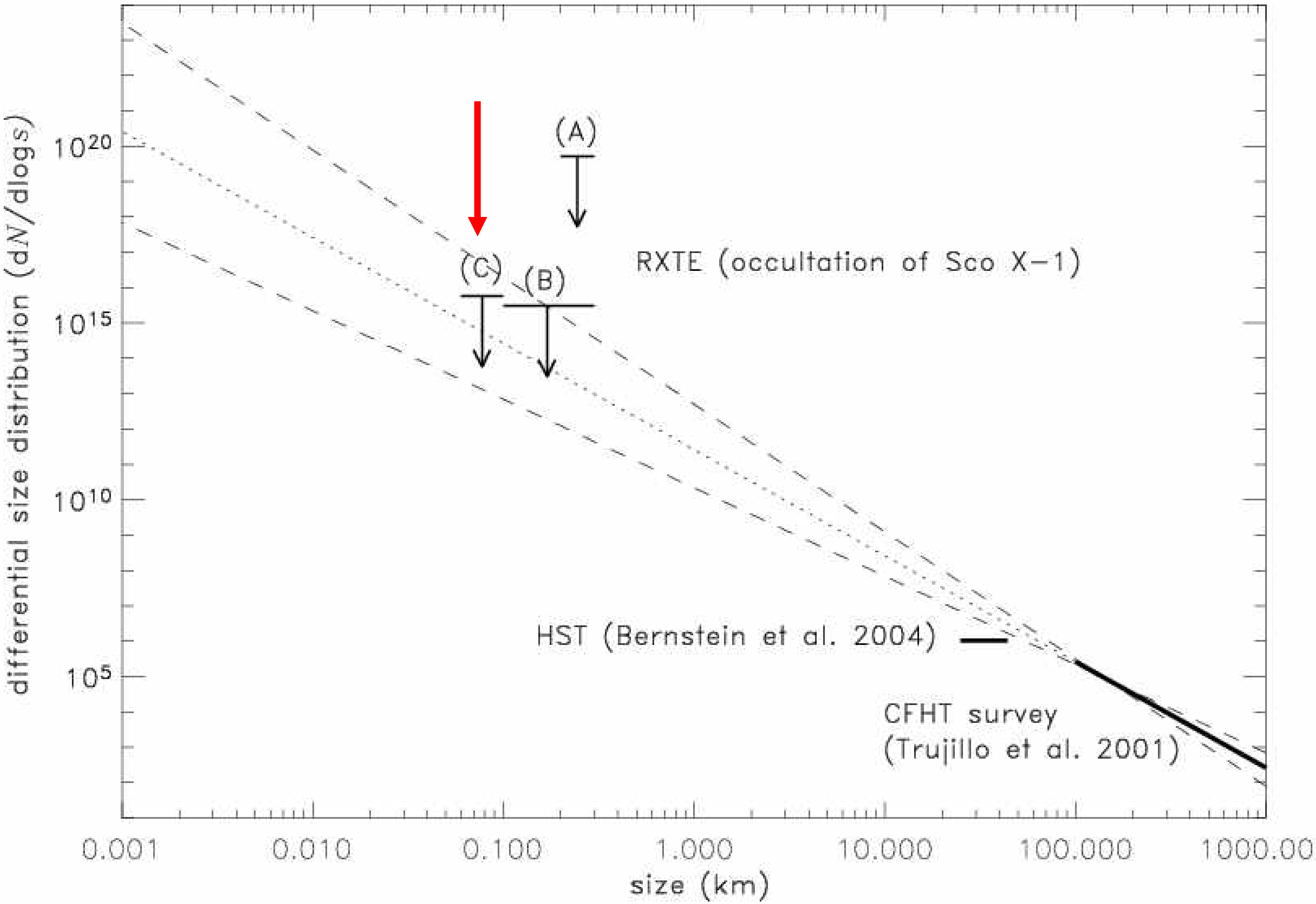
and

$$\left(\frac{\mathrm{d}N}{\mathrm{d}\log s}\right)_{s_1 < s < s_2} = \frac{d^2 \Omega_{\mathrm{A}}}{v(s_2 - s_1)} \frac{N}{T} \ln 10 \quad . \tag{3}$$

We can estimate $\Omega_{\mathrm{A}}$ with the inclination distribution obtained from the CFHT survey (Trujillo et al. 2001), which reported a 20° half-angle of an assumed gaussian distribution. This half-angle in the inclination distribution translates to about 12.8° for a corresponding half-angle in the apparent ecliptic latitude distribution, assuming circular orbits. Sco X-1 is 5.5° north of the ecliptic. To use the detection rate in the direction toward Sco X-1 to represent the whole TNO population, the equivalent sky area is a zone occupying ±15.5° in latitude. Therefore, $\Omega_{\mathrm{A}} = 360 \times 31 \times (\frac{\pi}{180})^2 = 3.4$. Assuming a typical distance $d = 43$ AU, a typical relative sky-projection speed $v = 30$ km/s, and $T = 564.3$ ks, we have in the size range from 60 m to 100 m

$$\left(\frac{\mathrm{d}N}{\mathrm{d}\log s}\right) \approx 5.7 \times 10^{15} \quad . \tag{4}$$

The total number of TNOs in that size range is about $1.3 \times 10^{15}$.



differential size distribution (dN/dlogs)
10^20
10^15
10^10
10^5
(A)
(C)
(B)
RXTE (occultation of Sco X−1)
HST (Bernstein et al. 2004)
CFHT survey
(Trujillo et al. 2001)
0.001
0.010
0.100
1.000
10.000
100.000
1000.00
size (km)

# In the second attempt ……

RXTE/PCA data of Sco X-1, 2007/2008/2009, 240 ksec
(Liu et al. 2008, MNRAS 388, L44;
Chang et al. 2009, in preparation)

* New event modes for recording the so-called 'very large events' (VLEs) were designed, in the hope to identify clearly the instrumental effect associated with dip events.

* The arrival time of each VLE is recorded with 125-$\mu$s resolution. The identification of anodes which detect the recorded VLE is also known.

## The RXTE/PCA VLE types

According to the number of anodes triggered, we classify VLEs as the following:

RXTE PCA Very Large Events (VLEs) are those events which deposit more than 100 keV in any one of the 6 active xenon layers or the propane layer.

Type A: no anodes are triggered!!!
Type B: all anodes are triggered.
Type C: more than one but not all are triggered.
Type D: only one anode is triggered.

The average count rate is

| | |
|---|---|
| for all VLEs | $90.5 \pm 19.2$ counts per sec per PCU; |
| for Type A | $1.73 \pm 0.29$ counts per sec per PCU; |
| for Type B | $34.5 \pm 11.2$ counts per sec per PCU; |
| for Type C | $44.8 \pm 9.80$ counts per sec per PCU; |
| for Type D | $9.44 \pm 2.27$ counts per sec per PCU. |

# The RXTE/PCA dip events

39 'significant' dips are found in the 240-ks data (June 2007 – Oct 2009).

According to the types of VLEs detected 'near' the dip event epoch, we classify dip events as the following:

| | |
|---|---|
| Group A: with Type A VLE | 34 |
| Group B: with Type B VLE | 2 |
| Group C: with Type C VLE | 2 |
| Group D: with Type D VLE | 0 |
| Group E: no VLE | 1 |

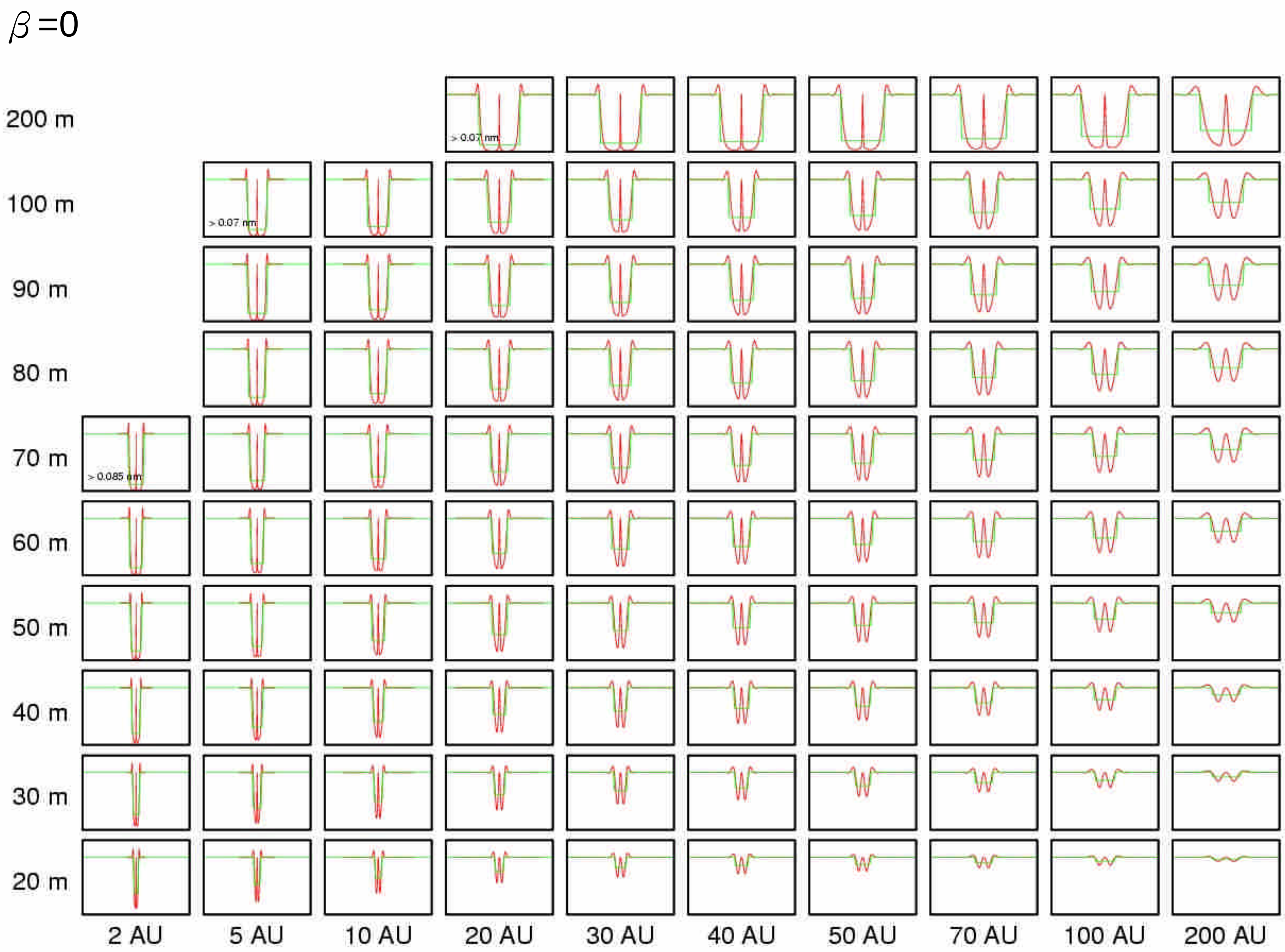
## The RXTE/PCA dip events

253 'less significant' dips are found in the 240-ks data (June 2007 – Oct 2009).

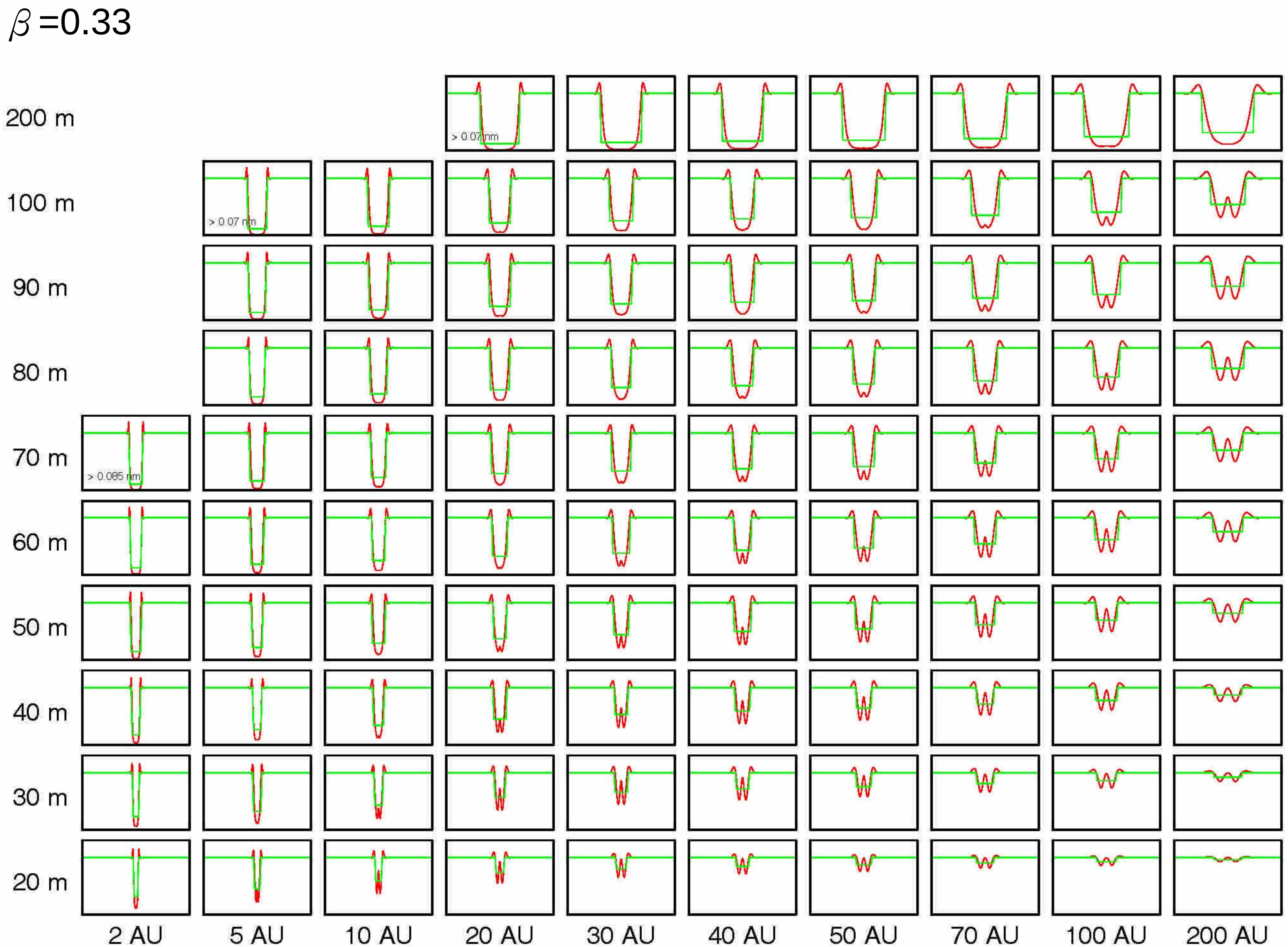
According to the types of VLEs detected 'near' the dip event epoch, we classify dip events as the following:

| | | |
|---|---|---|
| Group A: with Type A VLE | 34 | 125 |
| Group B: with Type B VLE | 2 | 94 |
| Group C: with Type C VLE | 2 | 23 |
| Group D: with Type D VLE | 0 | 3 |
| Group E: no VLE | 1 | 8 |

Assuming a Gaussian distribution, the number of bins with counts less than 5 $\sigma$ below the average is about 34.4, for 2-ms bins in 240-ks data.



β =0
200 m
100 m
90 m
80 m
70 m
60 m
50 m
40 m
30 m
20 m
> 0.07 nm
> 0.07 nm
> 0.085 nm
2 AU
5 AU
10 AU
20 AU
30 AU
40 AU
50 AU
70 AU
100 AU
200 AU



$\beta$ =0.33
200 m
100 m
90 m
80 m
70 m
60 m
50 m
40 m
30 m
20 m
2 AU
5 AU
10 AU
20 AU
30 AU
40 AU
50 AU
70 AU
100 AU
200 AU
> 0.07 nm
> 0.07 nm
> 0.085 nm

# The most recent result is like this …

From RXTE/PCA data of Sco X-1, 2007/2008/2009, 240 ksec

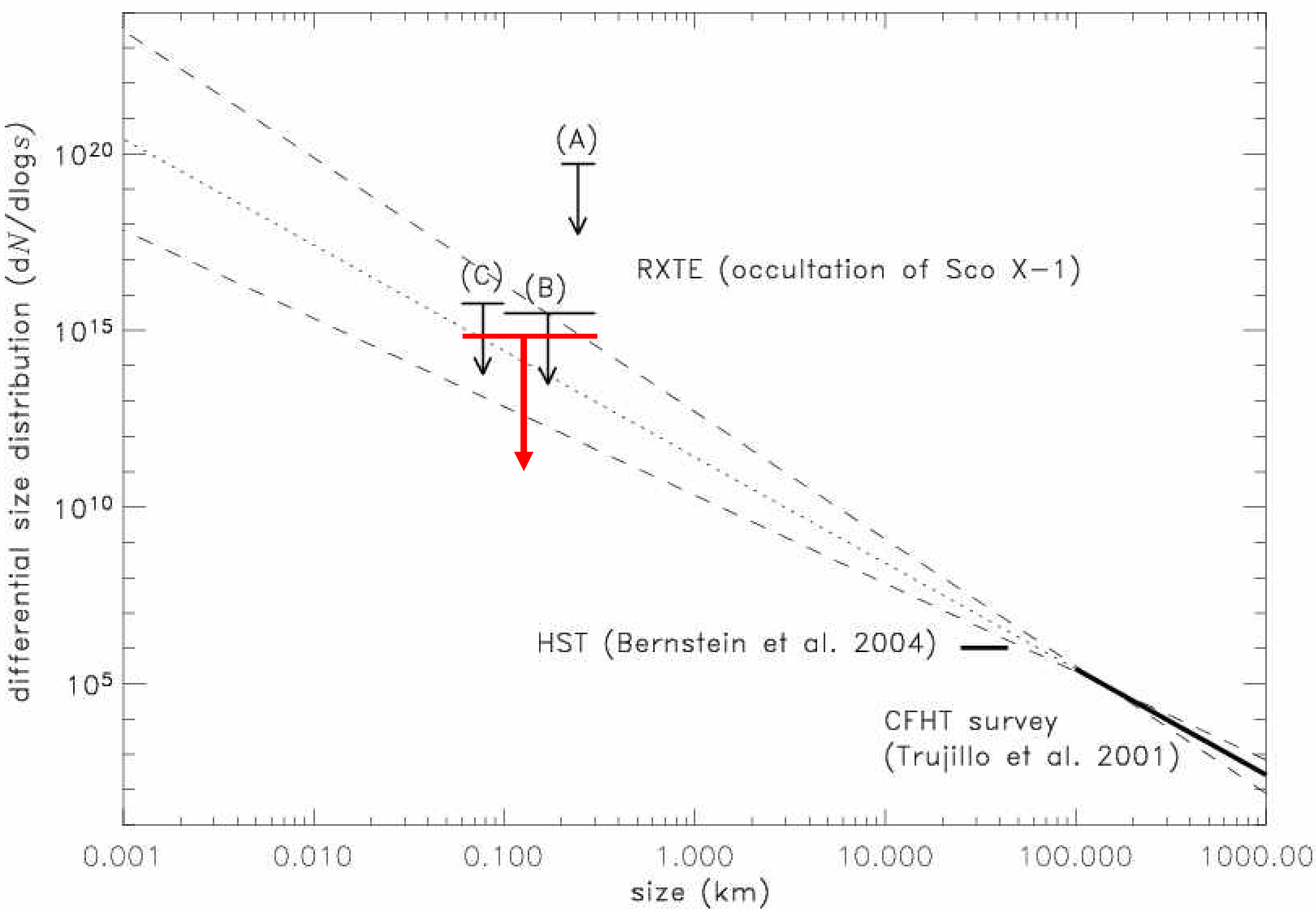
(Liu et al. 2008, MNRAS 388, L44; Chang et al. 2009, in preparation)

* 39 significant dips were found, but 36 of them are associated with some particular types of VLEs, whose presence indicates instrumental effects. The remaining 3 deserve further investigation.

* 253 less-significant dips were identified, 219 of which are associated with those particular VLEs. The remaining 34 are consistent with random fluctuations.

In the future

ASTROSAT/LAXPC observation of Sco X-1 ???
AXTAR, 10 times more sensitive than RXTE ???



(A)
RXTE (occultation of Sco X-1)
(C)
(B)
HST (Bernstein et al. 2004)
CFHT survey
(Trujillo et al. 2001)
differential size distribution (dN/dlogs)
$10^{20}$
$10^{15}$
$10^{10}$
$10^{5}$
0.001
0.010
0.100
1.000
10.000
100.000
1000.00
size (km)