Search For Sub-Kilometre Sized Trans-Neptunian Objects Using CoRoT Asteroseismology N1 Data

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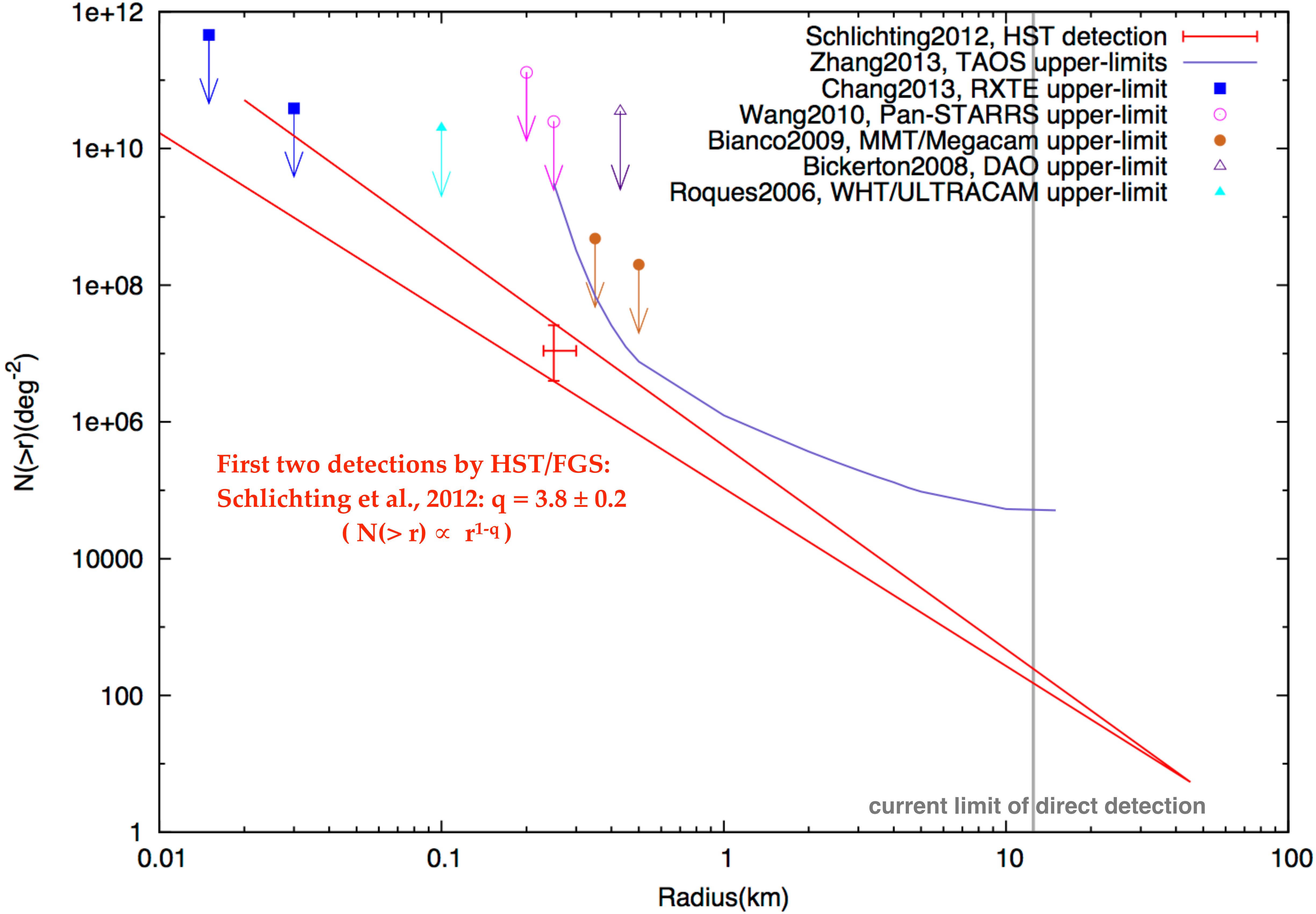
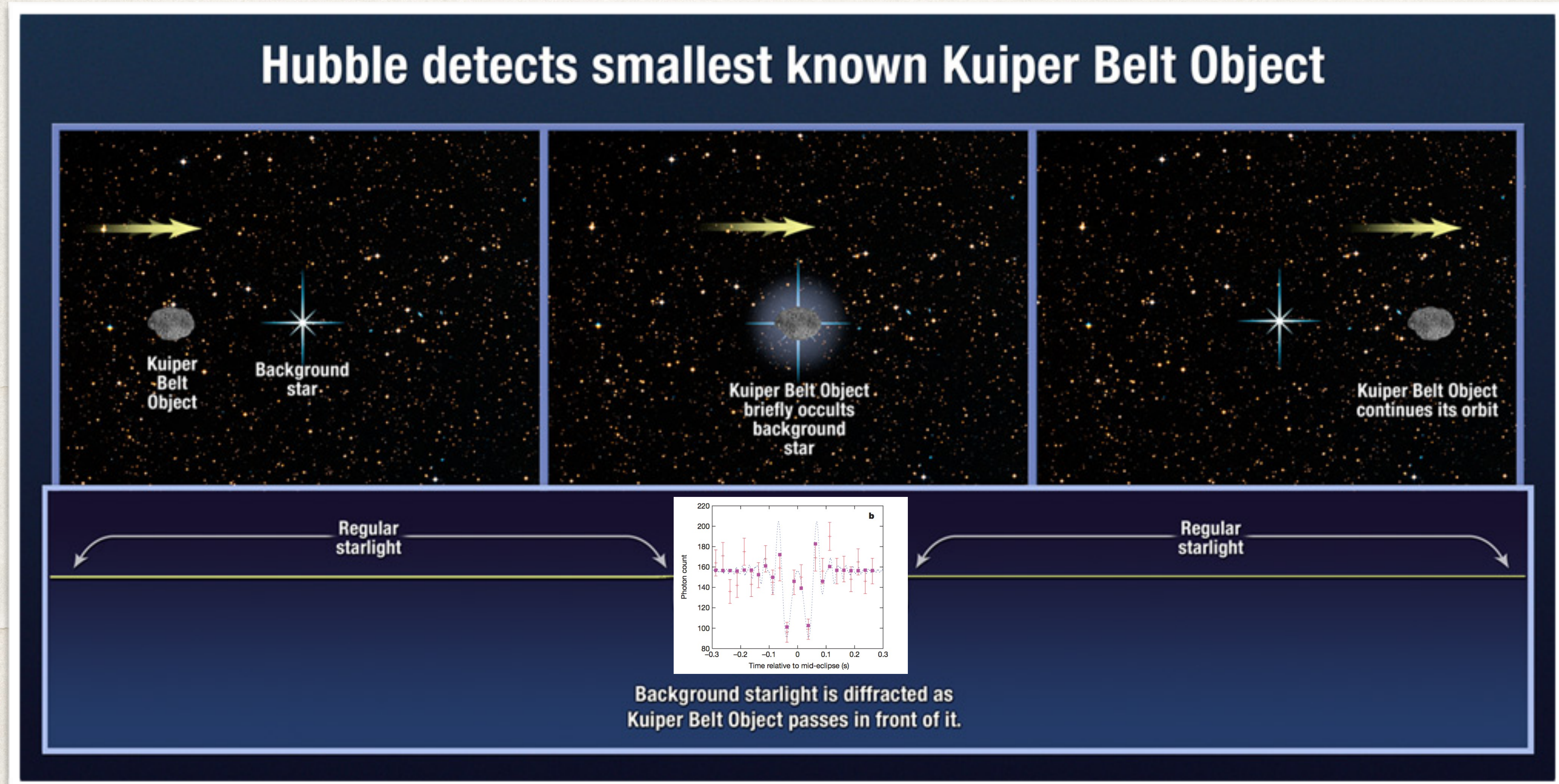
[Cumulative KBO size distribution as a function of TNO radius]

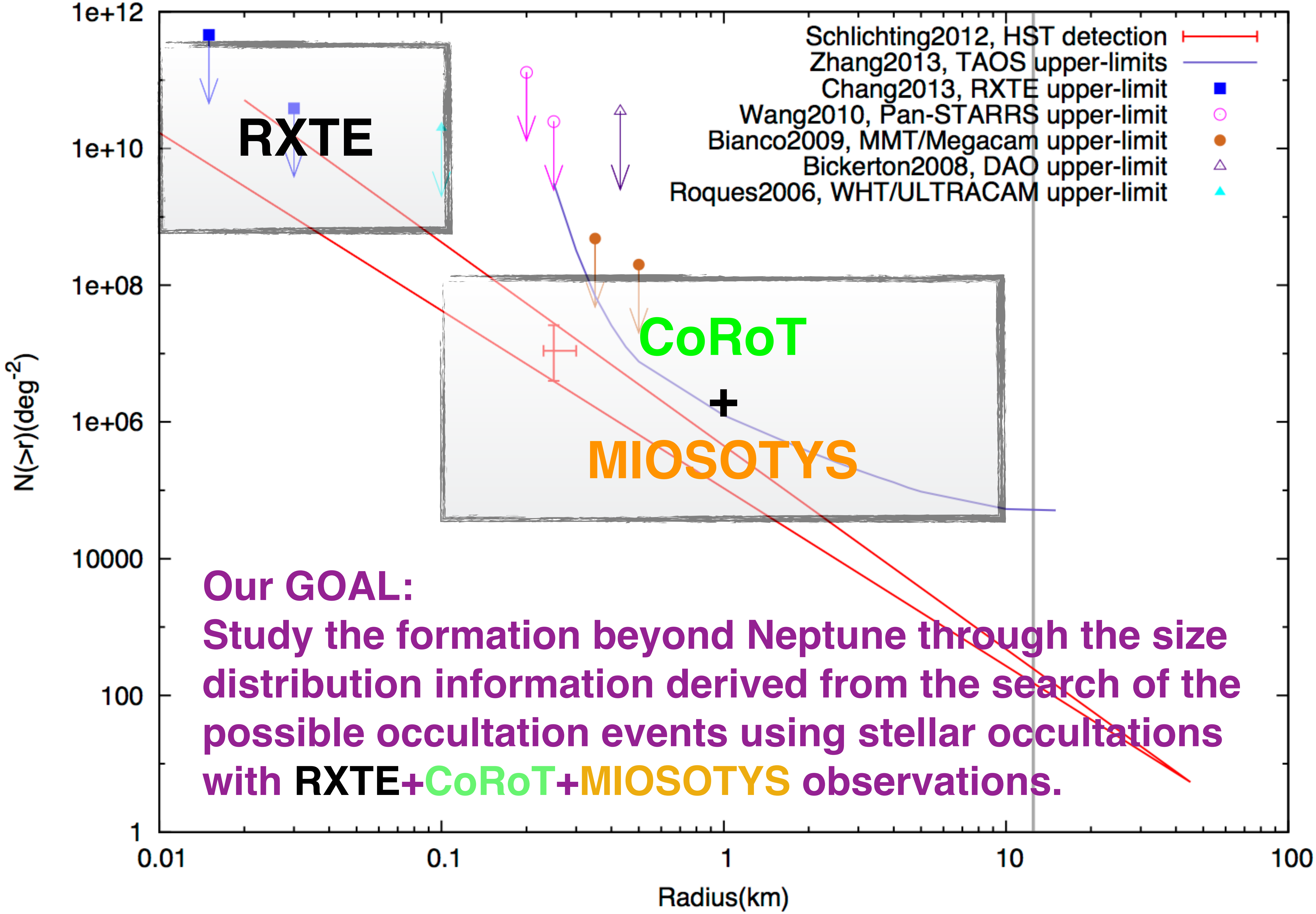


First TNO Occultation Event!



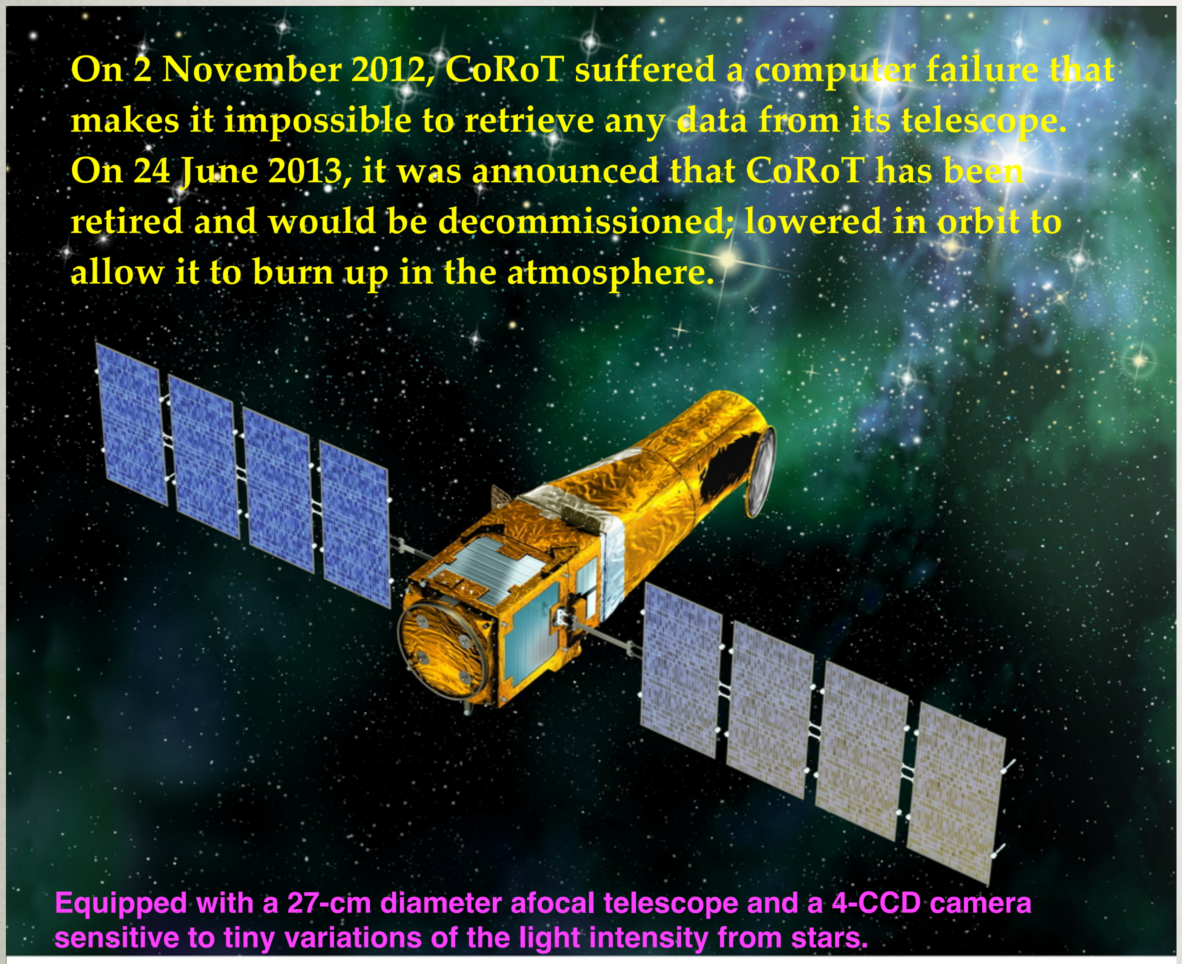
Schlichting et al., Nature (2009) 462, 895

HST/FGS (40-Hz; 1.2×10^4 star hours) found an occultation
by a body with an approximately 500-metre radius at a distance of 45 AU



Schlichting2012, HST detection
Zhang2013, TAOS upper-limits
Chang2013, RXTE upper-limit
Wang2010, Pan-STARRS upper-limit
Bianco2009, MMT/Megacam upper-limit
Bickerton2008, DAO upper-limit
Roques2006, WHT/ULTRACAM upper-limit
RXTE
CoRoT
+
MIOSOTYS
Our GOAL:
Study the formation beyond Neptune through the size distribution information derived from the search of the possible occultation events using stellar occultations with RXTE+CoRoT+MIOSOTYS observations.
1e+12
1e+10
1e+08
1e+06
10000
100
1
0.01
0.1
1
10
100
Radius(km)
N(>r)(deg-2)

CONVECTION, ROTATION & PLANETARY TRANSITS



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The Fresnel Scale $F_s = (\lambda D/2)^{1/2}$	
For λ = 550 nm (Visible)	
D (AU)	F_s (m)
43	1331.8

- **Launched on 2006 December 27,**
- It was developed and is operated by the CNES
- It has a polar inertial circular orbit (***90***-degree inclination) at an altitude of ***896*** kilometers.
- The orbital period : ***6184*** seconds.

TABLE Ia

Observing run duration	150 days
Number of stars	10
Magnitude	between 6 and 9
Number of observing runs	5
Total number of targets	50
Spectral types	mostly A, F, G

TABLE Ib

Observing run duration	20-30 days
Number of stars	10
Magnitude	between 6 and 9
Number of observing runs	between 5 and 10
Total number of targets	between 50 and 100
Spectral types	all types

COROT ASTEROSEISMOLOGY OBSERVATION PROPERTIES

Credit to http://smsc.cnes.fr/COROT/sismologie.htm

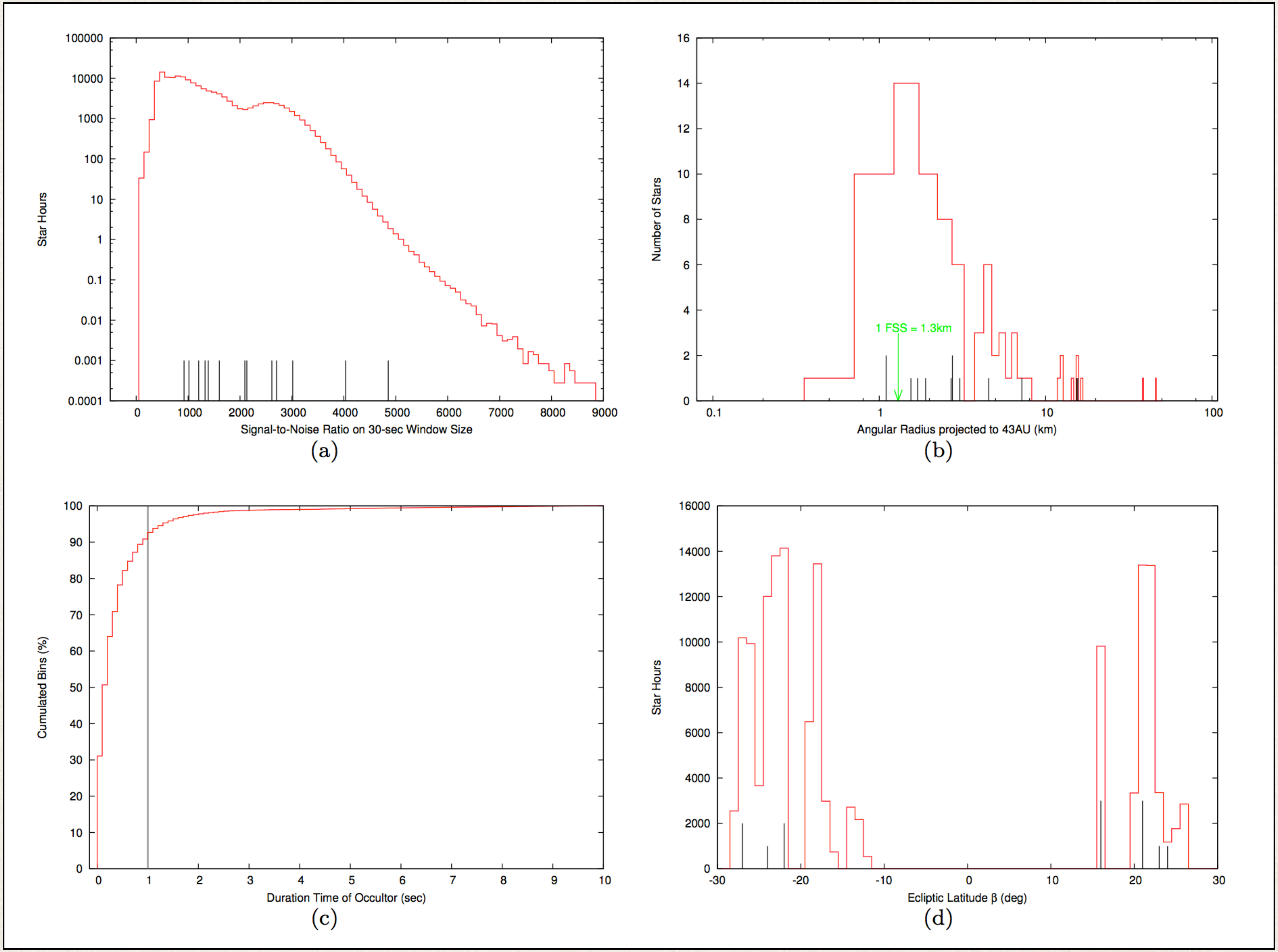
COROT AN1 Data Sets

(PART I)

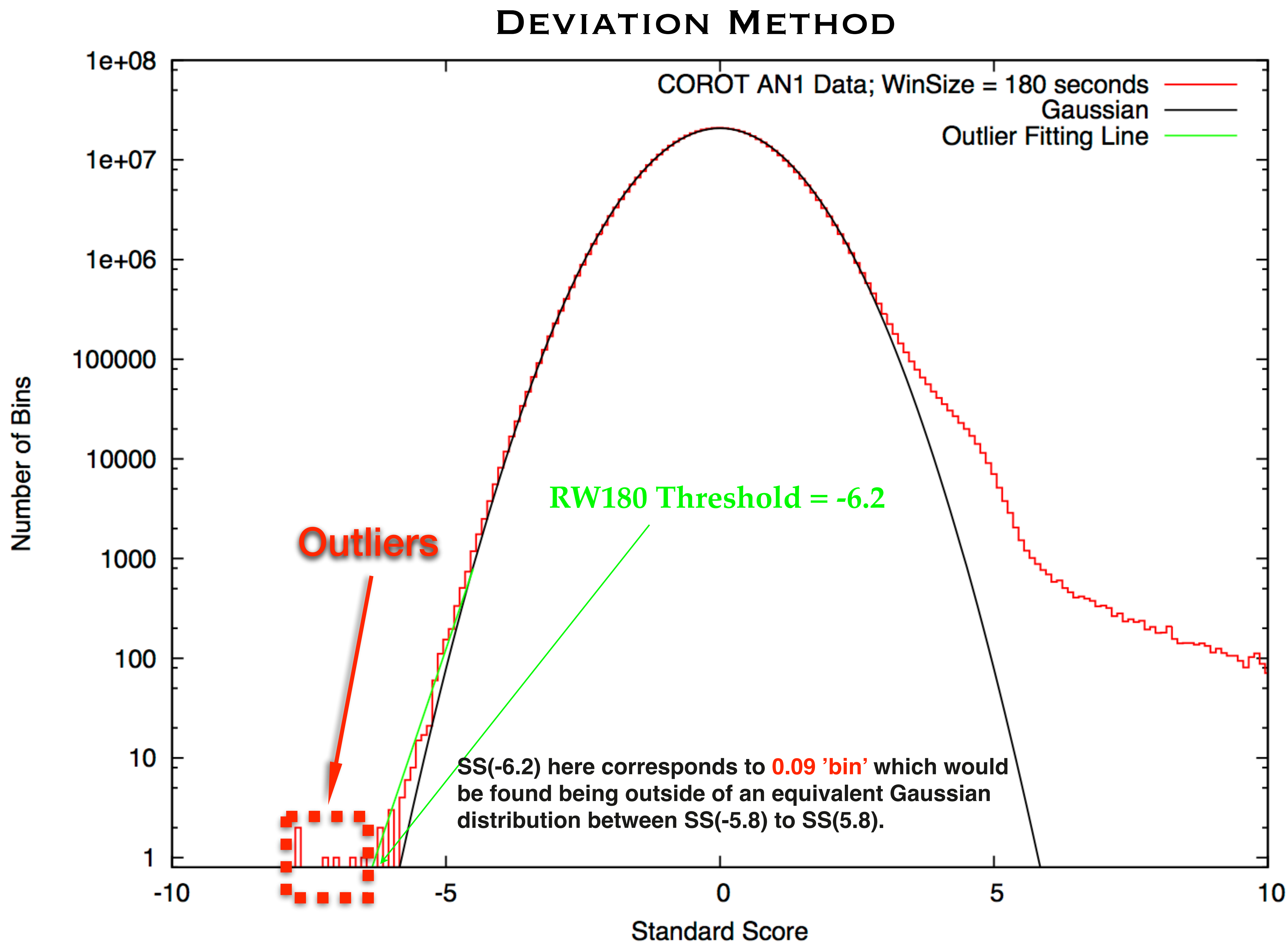
TABLE1: COROT ASTEROSEISMOLOGY N1 DATA EMPLOYED				
SEGMENT	RUN CODE	DATE BEGIN	DATE END	ACCUMULATED OBSERVING TIME (HOURS)
1	IRa01	1/31/07 11:06 AM	4/2/07 7:12 AM	12455.77
2	SRc01	4/11/07 3:07 PM	5/9/07 7:13 AM	5799.25
3	LRc01	5/11/07 1:10 PM	10/14/07 11:59 PM	33460.73
4	LRa01	10/18/07 8:57 AM	3/3/08 9:49 AM	28665.71
5	SRa01	3/5/08 10:34 PM	3/31/08 7:43 AM	5422.20
6	SRa02	10/8/08 10:44 PM	11/12/08 8:29 AM	7450.72
7	LRa02	11/13/08 10:49 PM	3/11/09 10:31 AM	25137.60
8	LRc03	4/1/09 8:49 PM	7/2/09 3:53 AM	9813.25
9	LRa03	10/1/09 8:57 PM	3/1/10 8:37 AM	16203.11
		TOTAL STAR HOURS		144,408.34

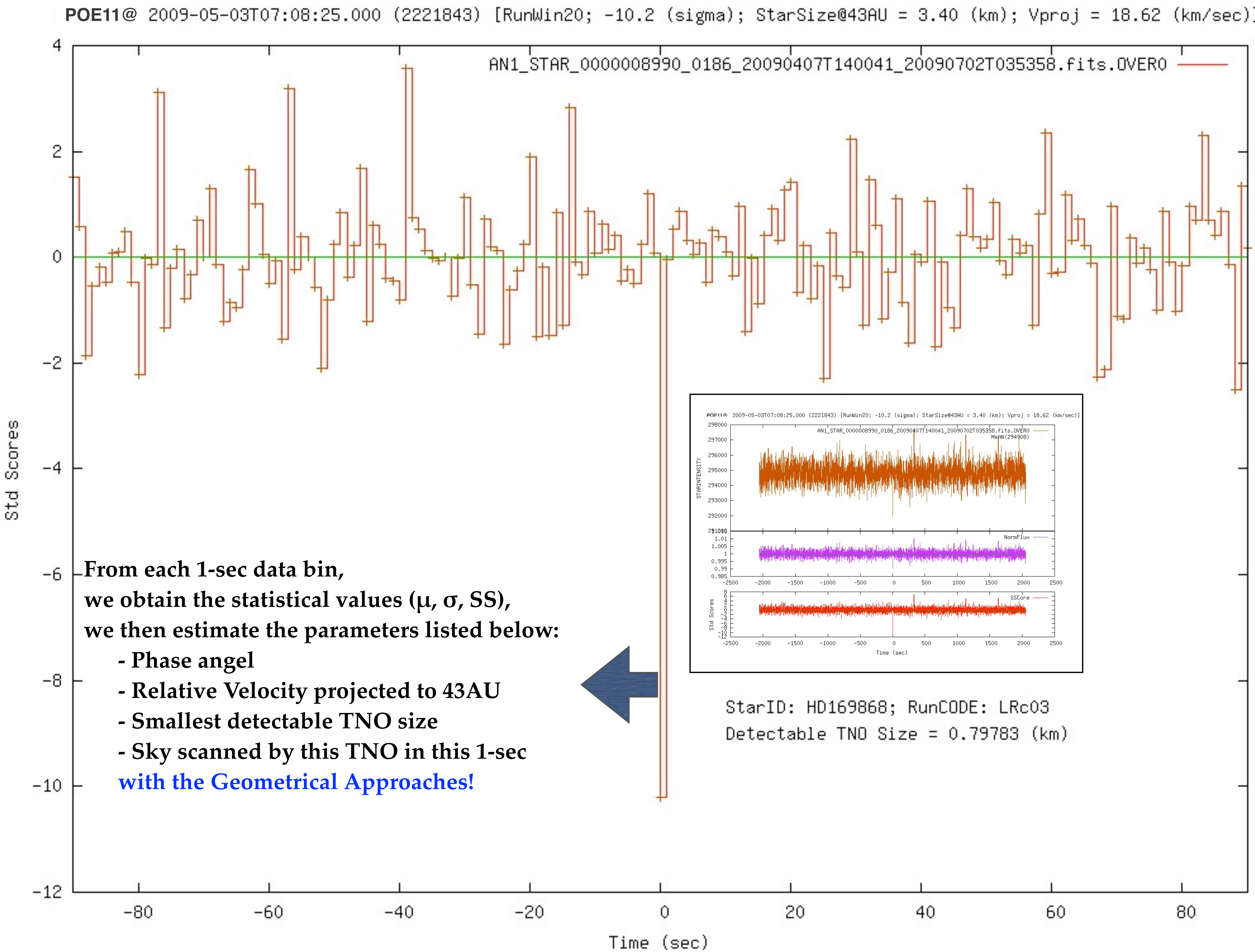
Properties of Data Sets

- Asteroseismology Level-1 data
- Time resolution == **1** Hz
- **165** light-curves from **79** stars
- Vmag: **4.8 ~ 9.5**
- **S/N ~ 360** for a **V=7.36** star (for a whole light-curve)
- Star sizes @ 43AU: 1.47 ~91.65 km
- Longest light-curve ~ **131.5** days
- Shortest light-curve ~ **411** seconds



Liu et al., MNRAS 446, 932–940 (2015)


Deviation Method
COROT AN1 Data; WinSize = 180 seconds
Gaussian
Outlier Fitting Line
RW180 Threshold = -6.2
Outliers
SS(-6.2) here corresponds to 0.09 'bin' which would be found being outside of an equivalent Gaussian distribution between SS(-5.8) to SS(5.8).
Number of Bins
1e+08
1e+07
1e+06
100000
10000
1000
100
10
1
-10
-5
0
5
10
Standard Score



StarID: HD169868; RunCODE: LRc03
Detectable TNO Size = 0.79783 (km)

From each 1-sec data bin,
we obtain the statistical values (μ, σ, SS),
we then estimate the parameters listed below:

- **Phase angel**
- **Relative Velocity projected to 43AU**
- **Smallest detectable TNO size**
- **Sky scanned by this TNO in this 1-sec**

with the Geometrical Approaches!

Table 2. 13 Possible Occultation Events and 7 Instrumental Effect Events

$N°$	*RunCode*	WinSize† (sec)	MJD (day)	Depth (σ)	FluxDrop (%)	StarID	V_{mag}	$\beta*$ (deg)	$\omega*$ (deg)	$R_s^{\ddagger}$ (km)	V_{rel} (km/s)	SNR	R_{ogeom} ♯ (km)
POE01	SRc01	20	54208.482227	-10.2	0.39	HD175272	7.40	+24.63	78.16	3.06	13.94	2613	0.29
POE02	LRc01	35	54244.415845	-7.8	0.16	HD181440	5.46	+21.05	52.05	4.55	21.36	4854	0.28
POE03	LRc01	25	54326.764120	-9.1	0.57	HD182198	7.94	+21.28	35.49	1.91	26.74	1601	0.38
POE04	**LRc01**	**70**	**54352.408877**	**-6.6**	**0.16**	**HD181907**	**5.83**	**+21.61**	**56.98**	**15.39**	**19.73**	**4032**	**0.62**
POE05	LRc01	30	54376.565587	-8.3	0.63	HD180642	8.27	+23.10	79.79	1.57	12.91	1326	0.25
POE06	LRa01	20	54408.387337	-9.3	1.01	HD49862	9.47	−24.06	64.85	1.08	17.67	921	0.31
POE07	**LRa01**	**30**	**54472.189174**	**-8.4**	**0.76**	**HD49330**	**8.88**	**−22.13**	**22.36**	**1.12**	**29.96**	**1106**	**0.35**
POE08	LRa01	20	54505.935521	-9.3	0.34	HD49294	7.00	−22.56	42.97	2.71	24.79	2703	0.34
POE09	LRa02	30	54785.312491	-8.1	0.39	HD51722	7.53	−27.14	57.70	2.73	21.08	2093	0.34
POE10	LRa02	50	54828.166559	-7.2	0.52	HD51722	7.53	−27.14	28.67	2.73	29.67	1388	0.46
POE11	LRc03	20	54953.297340	-10.2	1.00	HD169868	9.28	+16.76	56.66	1.70	18.62	1016	0.40
POE12	LRc03	20	54986.009771	-9.9	0.47	HD169751	8.37	+16.16	28.10	7.18	27.75	2131	0.68
POE13	LRc03	60	55011.518949	-6.7	0.22	HD169370	6.30	+16.23	16.30	15.62	29.99	3014	0.73
IEE01	IRa01	180	54143.848821	-6.4	1.79	HD50844	9.10	−23.80	44.46	1.30	24.60	356	0.54
IEE02	SRc01	20	54205.229091	-10.4	0.40	HD175272	7.40	+24.63	81.04	3.06	13.35	2632	0.28
IEE03	LRc01	180	54293.734927	-6.0	1.41	HD180642	8.27	+23.10	23.12	1.57	30.00	428	0.57
IEE04	LRc01	85	54310.990668	-6.5	1.40	HD180642	8.27	+23.10	27.53	1.57	29.09	461	0.56
IEE05	LRa03	180	55107.750660	-6.2	0.86	HD43587	5.70	−18.27	84.18	12.74	9.89	722	1.18
IEE06	LRa03	180	55110.305301	-6.2	0.56	HD43587	5.70	−18.27	81.79	12.74	10.33	1096	0.95
IEE07	LRa03	180	55110.810865	-6.5	2.01	HD43823	7.35	−18.85	81.68	12.56	10.62	323	1.78

†The running-window sizes applied to the search for the events.
‡The radii projected at 43AU of the background stars.
♯The smallest detectable radii projected at 43AU of the occultators.
∗Ecliptic latitude and Opposition angle respectively.

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Table 3. 15 Running Window Sizes

N°	$RW_{20_{sec}}$	$RW_{25_{sec}}$	$RW_{30_{sec}}$	$RW_{35_{sec}}$	$RW_{40_{sec}}$	$RW_{45_{sec}}$	$RW_{50_{sec}}$	$RW_{55_{sec}}$	$RW_{60_{sec}}$	$RW_{65_{sec}}$	$RW_{70_{sec}}$	$RW_{75_{sec}}$	$RW_{80_{sec}}$	$RW_{85_{sec}}$	$RW_{180_{sec}}$
POE01	⋆														
POE02				⋆											
POE03		⋆													
POE04											⋆	⋆	⋆	⋆	
POE05			⋆												
POE06	⋆														
POE07			⋆	⋆	⋆	⋆									
POE08	⋆														
POE09			⋆												
POE10							⋆								
POE11	⋆														
POE12	⋆														
POE13									⋆						
IEE01															⋆
IEE02	⋆	⋆	⋆	⋆			⋆								
IEE03															⋆
IEE04														⋆	⋆
IEE05															⋆
IEE06															⋆
IEE07															⋆

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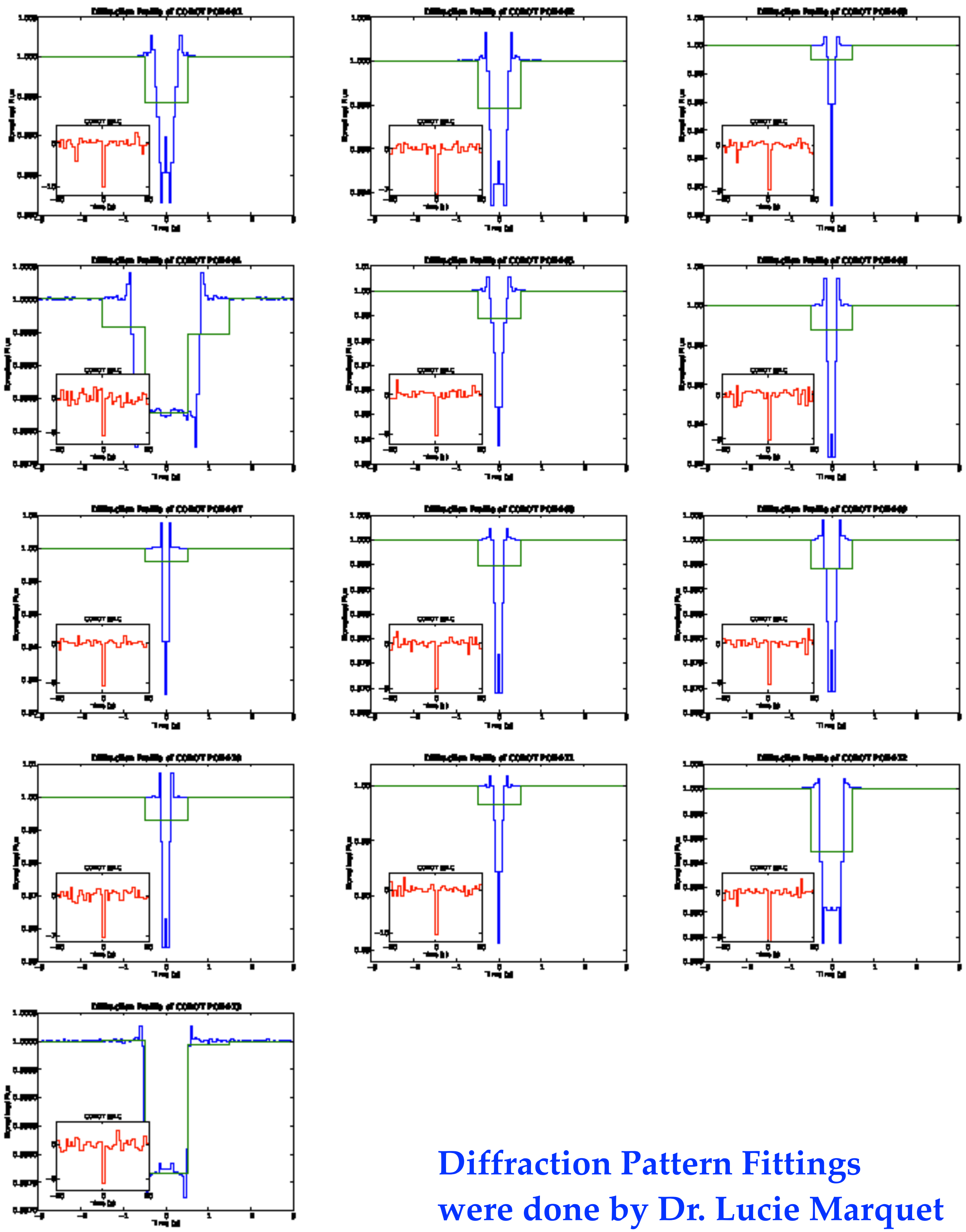
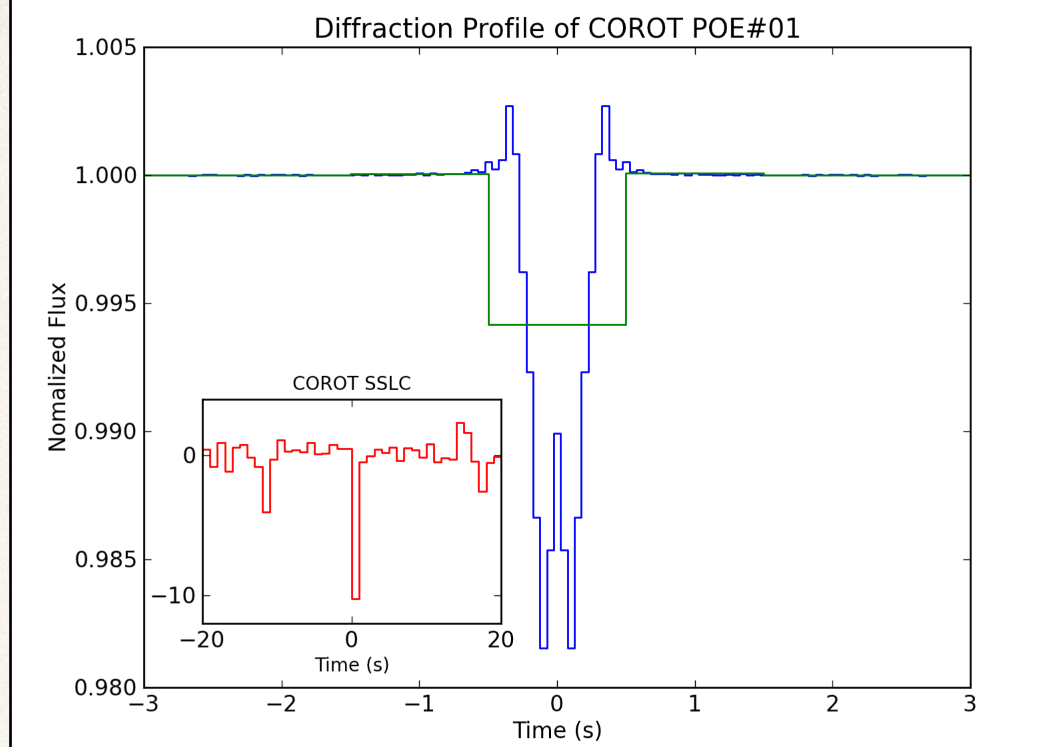
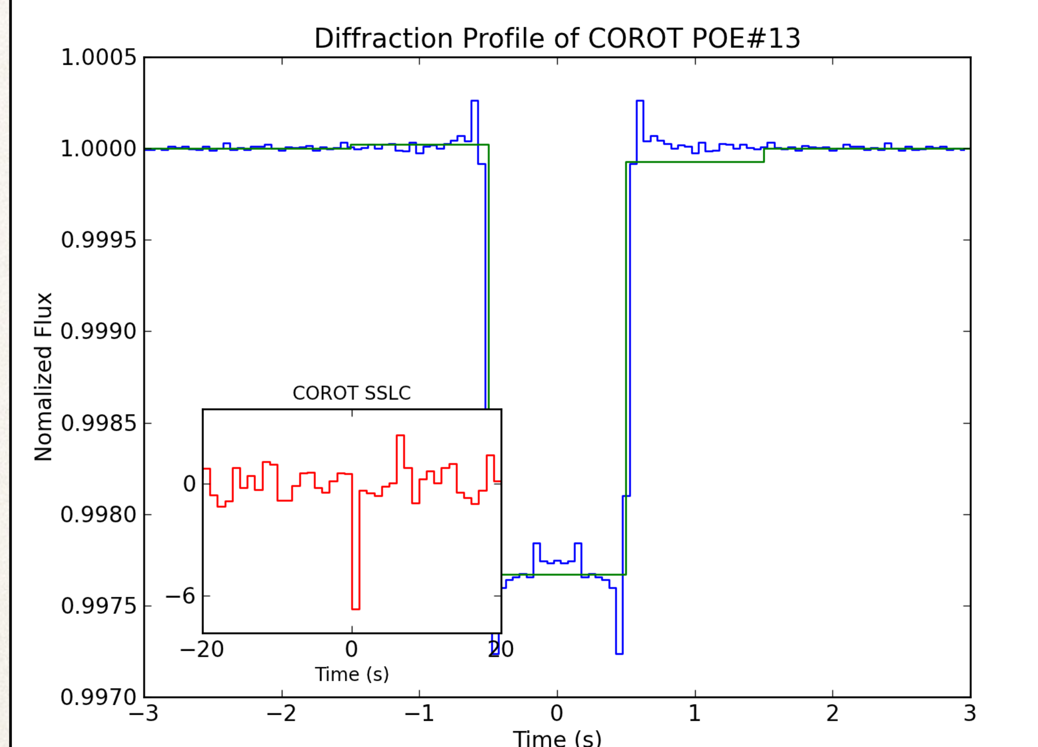
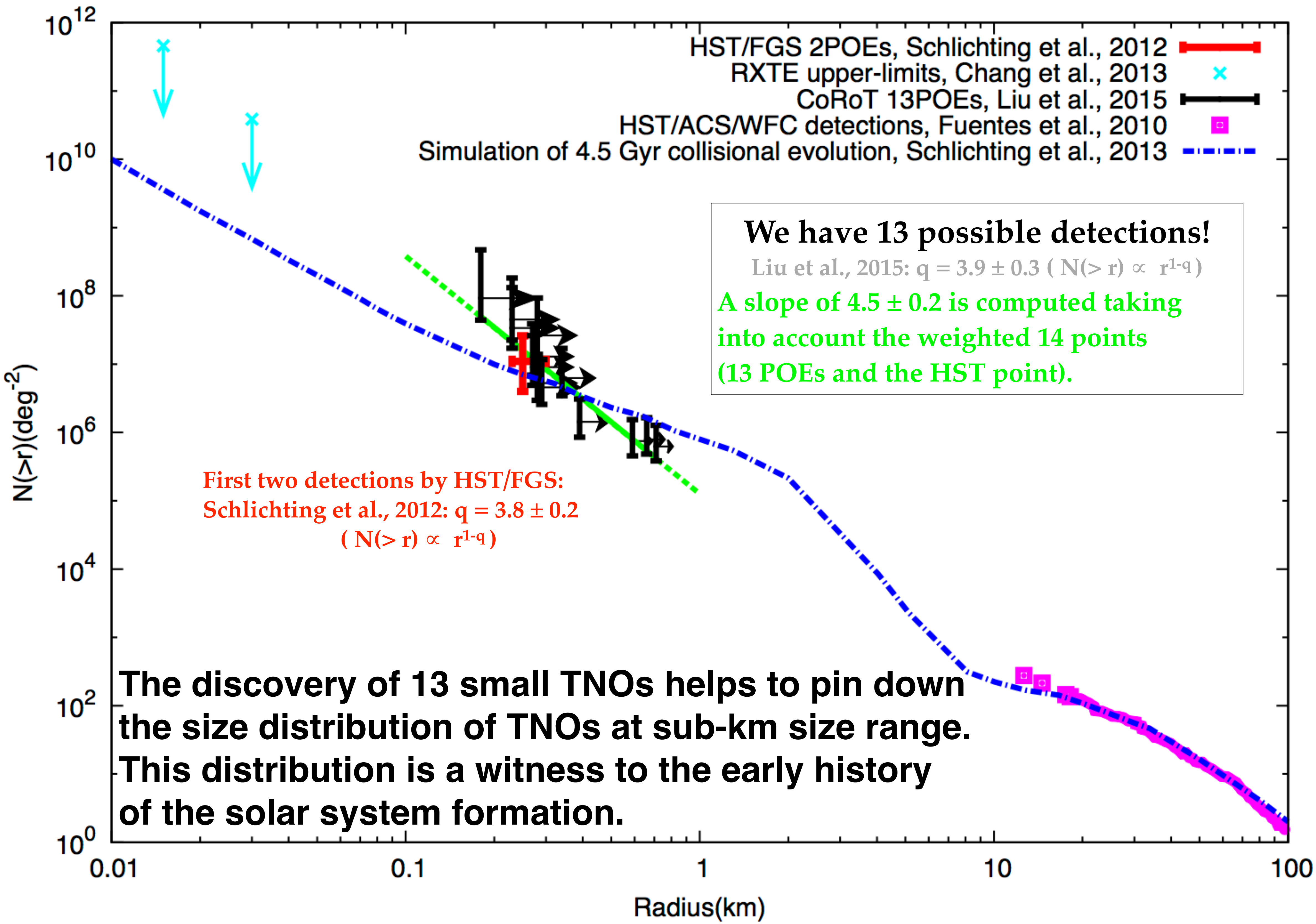


Diffraction Pattern Fittings were done by Dr. Lucie Marquet





Liu et al., MNRAS 446, 932–940 (2015)


HST/FGS 2POEs, Schlichting et al., 2012
RXTE upper-limits, Chang et al., 2013
CoRoT 13POEs, Liu et al., 2015
HST/ACS/WFC detections, Fuentes et al., 2010
Simulation of 4.5 Gyr collisional evolution, Schlichting et al., 2013
We have 13 possible detections!
Liu et al., 2015: q = 3.9 ± 0.3 (N(> r) ∝ r^(1-q))
A slope of 4.5 ± 0.2 is computed taking
into account the weighted 14 points
(13 POEs and the HST point).
First two detections by HST/FGS:
Schlichting et al., 2012: q = 3.8 ± 0.2
(N(> r) ∝ r^(1-q))
The discovery of 13 small TNOs helps to pin down
the size distribution of TNOs at sub-km size range.
This distribution is a witness to the early history
of the solar system formation.
N(>r)(deg^-2)
Radius(km)
10^12
10^10
10^8
10^6
10^4
10^2
10^0
0.01
0.1
1
10
100

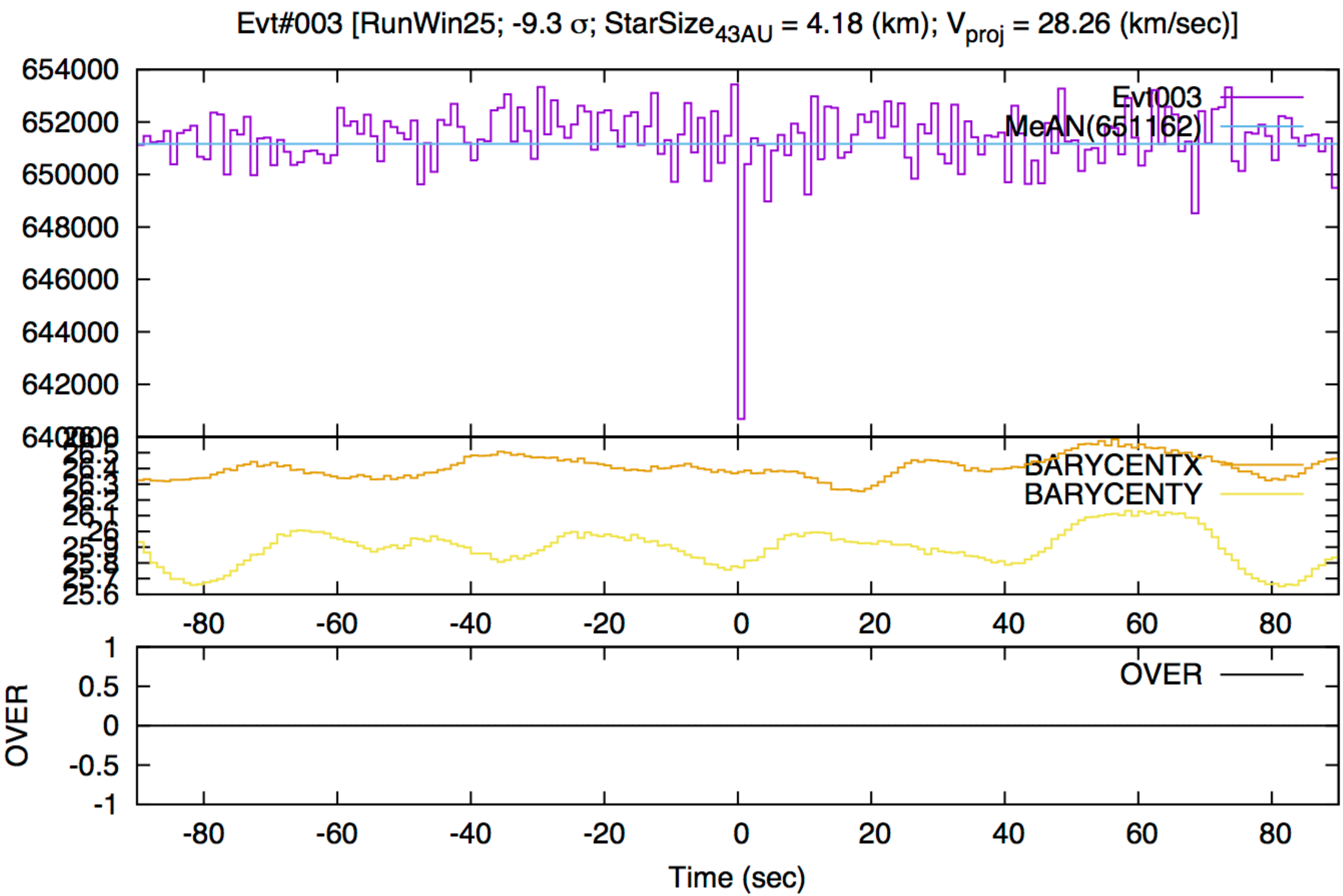
CoRoT AN1 Data: Part II

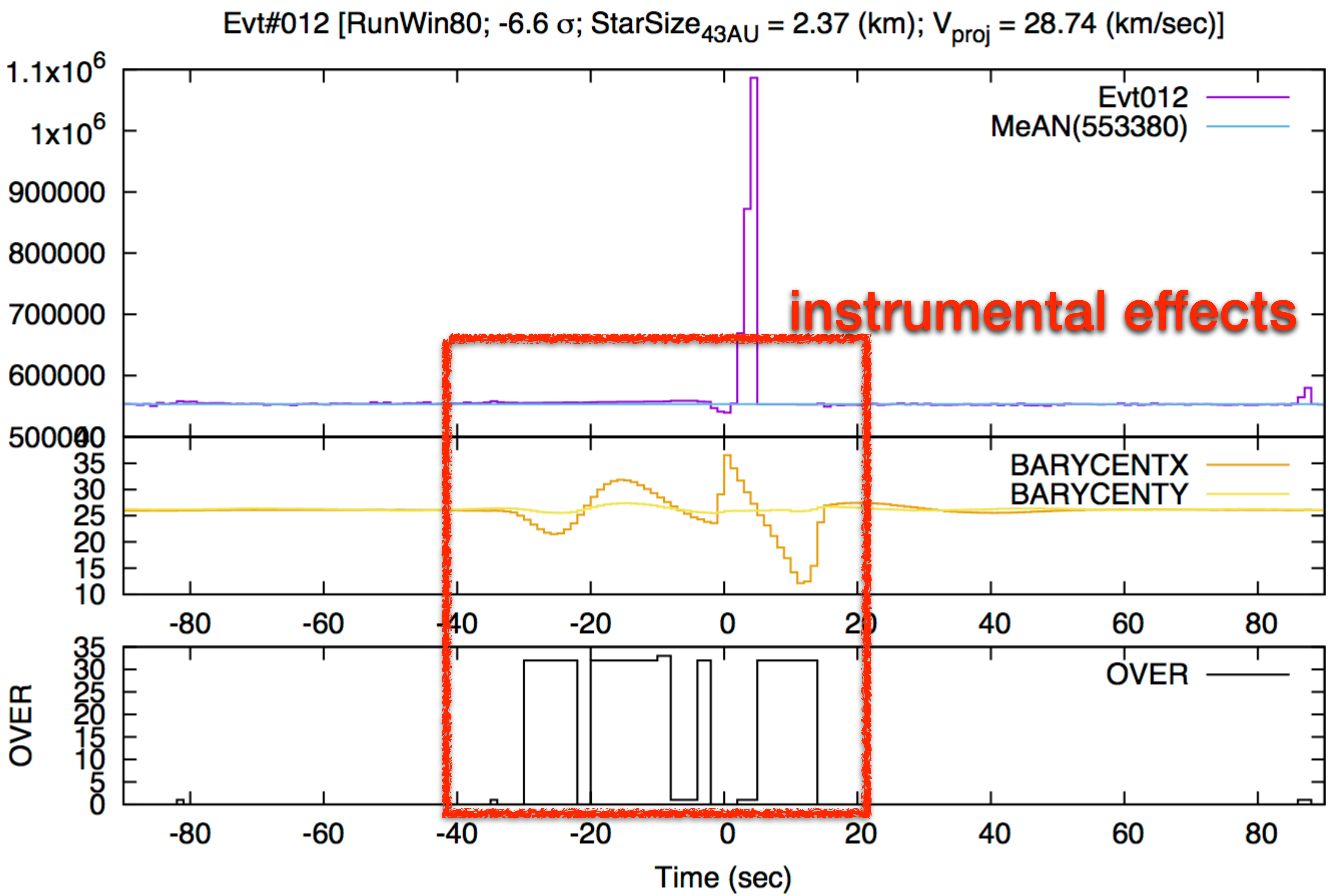
(N0-N1 Pipeline Version 3.0)

COROT AN1 DATA	PART I	PART II	TOTAL
# 0F 1-SEC BINS	519869933	469411359	989281292
EXPOSURE (STAR HOURS)	144.4×10^3	130.4×10^3	274.8×10^3
# OF RUNCODES	9	16	25
# OF AN1 LCS	165	188	353
BACKGROUND STARS	79	77	143
# OF POES / OUTLIERS	13 / 20	TBD / 12	TBD / 32

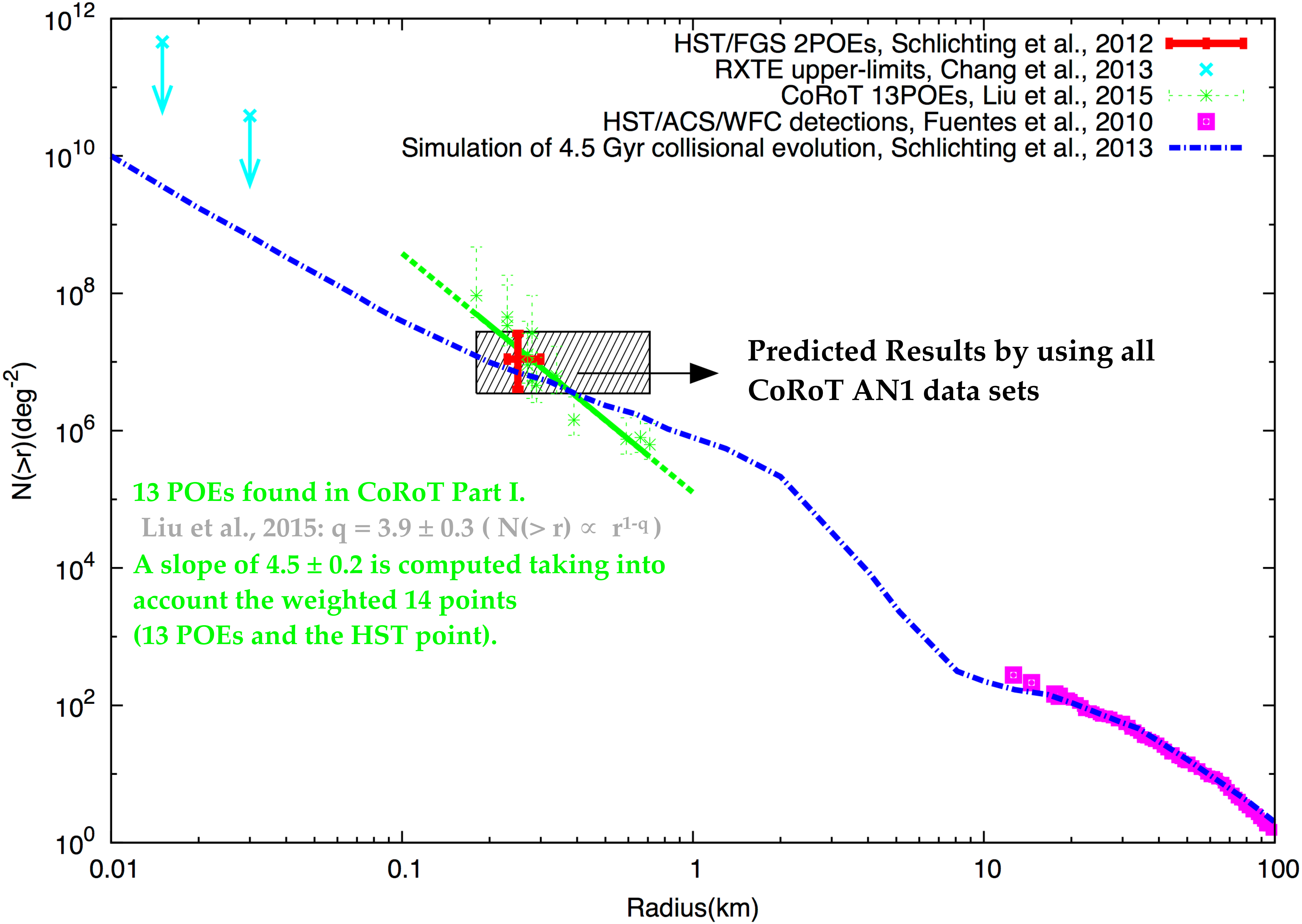
NewOUT#	$RW20_{-9.3}$	$RW25_{-8.7}$	$RW30_{-7.9}$	$RW35_{-7.7}$	$RW40_{-7.2}$	$RW45_{-7.1}$	$RW50_{-7.0}$	$RW55_{-6.9}$	$RW60_{-6.7}$	$RW65_{-6.7}$	$RW70_{-6.6}$	$RW75_{-6.6}$	$RW80_{-6.6}$	$RW85_{-6.5}$	$RW180_{-6.2}$
01	-9.4														
02	-10.1														
03		-9.3	-9.4	-9.8	-10.4	-10.6	-10.9	-10.9	-10.9	-10.9	-11.0	-11.1	-11.1	-11.3	-11.6
04			-7.9												
05			-8.2		-7.6	-8.0									
06			-7.9												
07					-7.2	-7.1	-7.1			-6.7					
08					-7.2										
09						-7.1									
10						-7.4	-7.0								
11										-6.8	-7.0	-6.9	-6.6	-6.5	-7.0
12													-6.6	-6.7	-8.6

NewOUT#	RunCode	WinSize	MJD	Depth	$Flux_{Drop}$	StarID	V_{mag}	β	ω	D_s	V_{rel}	SNR	$D_{o_{geom}}$
01	LRc05	20	55307.556956	-9.4	0.25	HD_170580	6.68	+27.28	69.78	5.73	17.22	3734	0.50
02	LRc02	20	54591.253796	-10.1	1.18	HD_170987	7.55	+29.96	59.44	6.86	21.38	862	1.31
03	LRc09	25	56097.031262	-9.3	1.61	HD_179192	8.29	+19.20	28.03	4.18	28.26	579	1.38
04	LRa05	30	55586.178264	-7.9	0.24	HD_42089	6.65	-15.91	35.78	22.56	25.69	3306	1.18
05	LRc09	30	56028.291574	-8.2	0.24	HD_178484	6.59	+20.06	86.77	31.63	10.43	3481	1.54
06	LRc02	30	54589.509375	-7.9	0.29	HD_171427	7.22	+29.61	61.28	17.79	20.68	2756	1.03
07	SRa05	40	55913.169838	-7.2	0.26	HD_48977	5.90	-14.37	21.39	5.56	28.91	2742	0.65
08	LRc09	40	56037.147037	-7.2	0.60	HD_179192	8.29	+19.20	79.17	4.18	11.36	1192	0.54
09	SRa04	45	55884.808542	-7.1	0.45	HD_45975	7.46	-27.91	48.55	3.32	24.32	1589	0.60
10	LRc05	45	55338.222072	-7.4	0.24	HD_170973	6.41	+26.85	45.29	5.53	25.08	3040	0.58
11	LRc02	65	54636.313993	-6.8	1.51	HD_171218	9.12	+29.65	31.49	3.45	29.57	449	1.24
12	SRa05	80	55911.660127	-6.6	2.54	HD_48752	8.36	-13.30	21.56	2.37	28.74	260	1.32


Evt#003 [RunWin25; -9.3 σ; StarSize43AU = 4.18 (km); Vproj = 28.26 (km/sec)]
654000
652000
650000
648000
646000
644000
642000
640000
Evt003
MeAN(651162)
BARYCENTX
BARYCENTY
25.6
25.7
25.8
25.9
26
26.1
26.2
26.3
26.4
26.5
-80
-60
-40
-20
0
20
40
60
80
OVER
1
0.5
0
-0.5
-1
Time (sec)



Evt#012 [RunWin80; -6.6 σ; StarSize43AU = 2.37 (km); Vproj = 28.74 (km/sec)]
Evt012
MeAN(553380)
instrumental effects
BARYCENTX
BARYCENTY
OVER
Time (sec)


HST/FGS 2POEs, Schlichting et al., 2012
RXTE upper-limits, Chang et al., 2013
CoRoT 13POEs, Liu et al., 2015
HST/ACS/WFC detections, Fuentes et al., 2010
Simulation of 4.5 Gyr collisional evolution, Schlichting et al., 2013
Predicted Results by using all
CoRoT AN1 data sets
13 POEs found in CoRoT Part I.
Liu et al., 2015: q = 3.9 ± 0.3 (N(> r) ∝ r^(1-q))
A slope of 4.5 ± 0.2 is computed taking into
account the weighted 14 points
(13 POEs and the HST point).
N(>r)(deg^-2)
Radius(km)
10^12
10^10
10^8
10^6
10^4
10^2
10^0
0.01
0.1
1
10
100

Thank you for your attention!

Estimation of Stellar Angular Radius

StarName	Radius ($R_\odot$)	Parallax (mas)	θ_{CoRoT} (mas)	$\theta_{Nordgren}$ (mas)	Reference
HD46375	0.74	28.72	0.098923	0.138634	Mosser et al. 2013
HD49385	1.92	13.91	0.124311	0.130695	Mosser et al. 2013
HD49933	1.55	33.69	0.243060	0.232071	Mosser et al. 2013
HD52265	1.34	34.53	0.215368	0.209255	Mosser et al. 2013
HD175272	1.63	11.30	0.085733	0.097920	Ozel et al. 2013
HD175726	1.01	37.73	0.177373	0.179885	Bruntt 2009
HD181420	1.60	21.05	0.156766	0.157914	Ozel et al. 2013
HD181906	1.39	14.72	0.095236	0.103657	Bruntt 2009

The ERROR of the CoRoT results is ~ 15%

The Barnes-Evans Relation:
F_{K_0} = 4.227 -0.1K_0 - 0.5log(2 × θ)

From the fitting of 57 NPOI giants, Nordgren(2002) found:
F_{K_0} = (3.942 ± 0.006) – (0.095 ± 0.007)(J_0 – K_0),

Liu et al., MNRAS 446, 932–940 (2015)

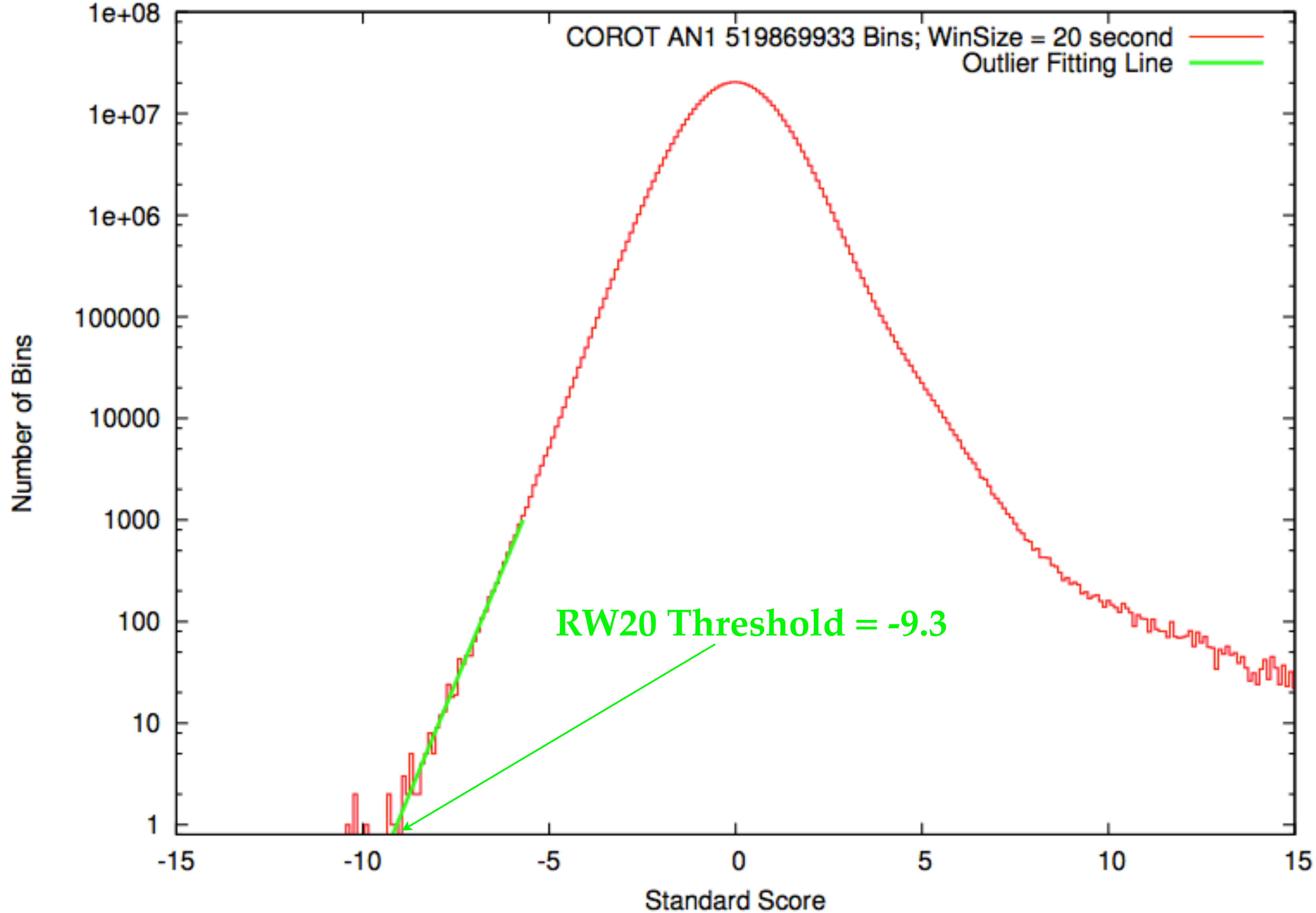
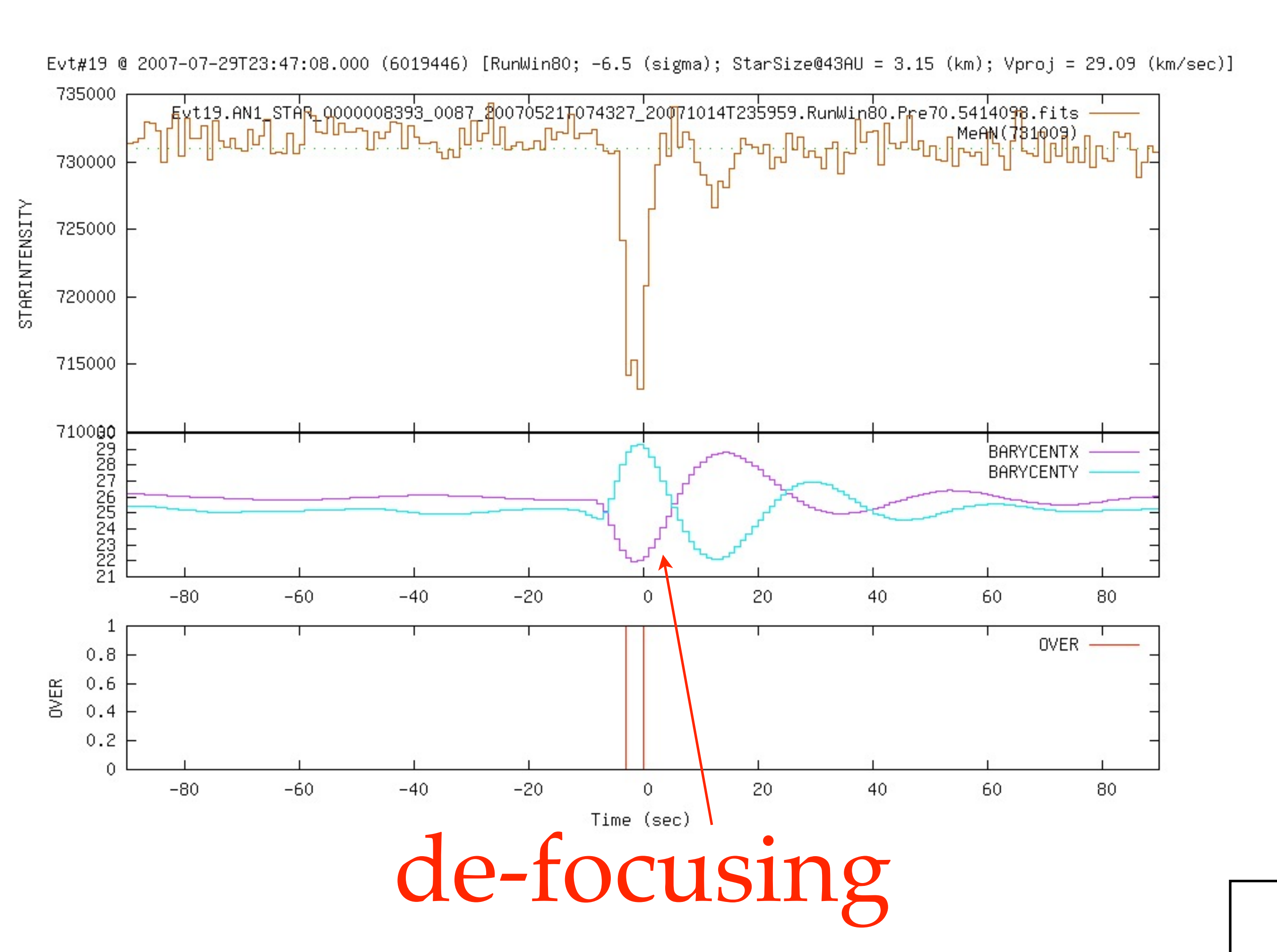


Figure 2. The red curve is the deviation distribution of all COROT data bins by using the 20-sec running window. The green line is the linear fitting result from number of bins 1000 to 3. The bins on the left-hand side of the green line are potential outliers.

False Events



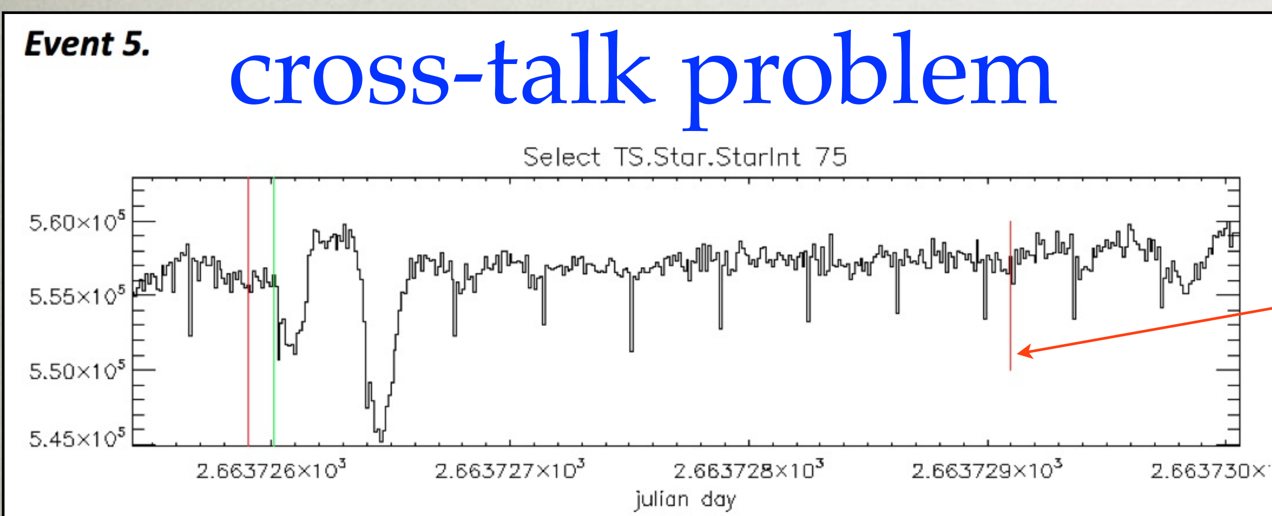
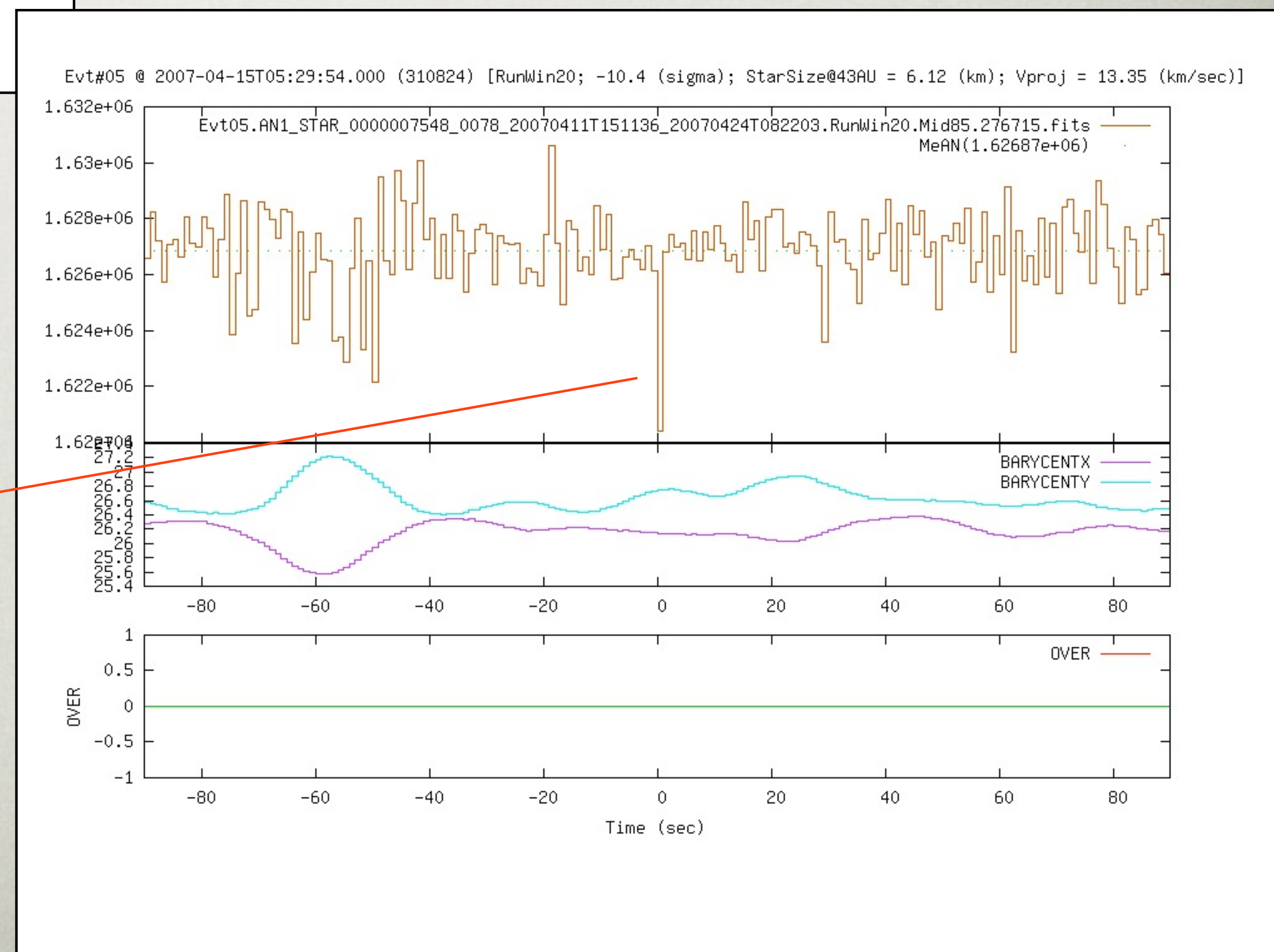
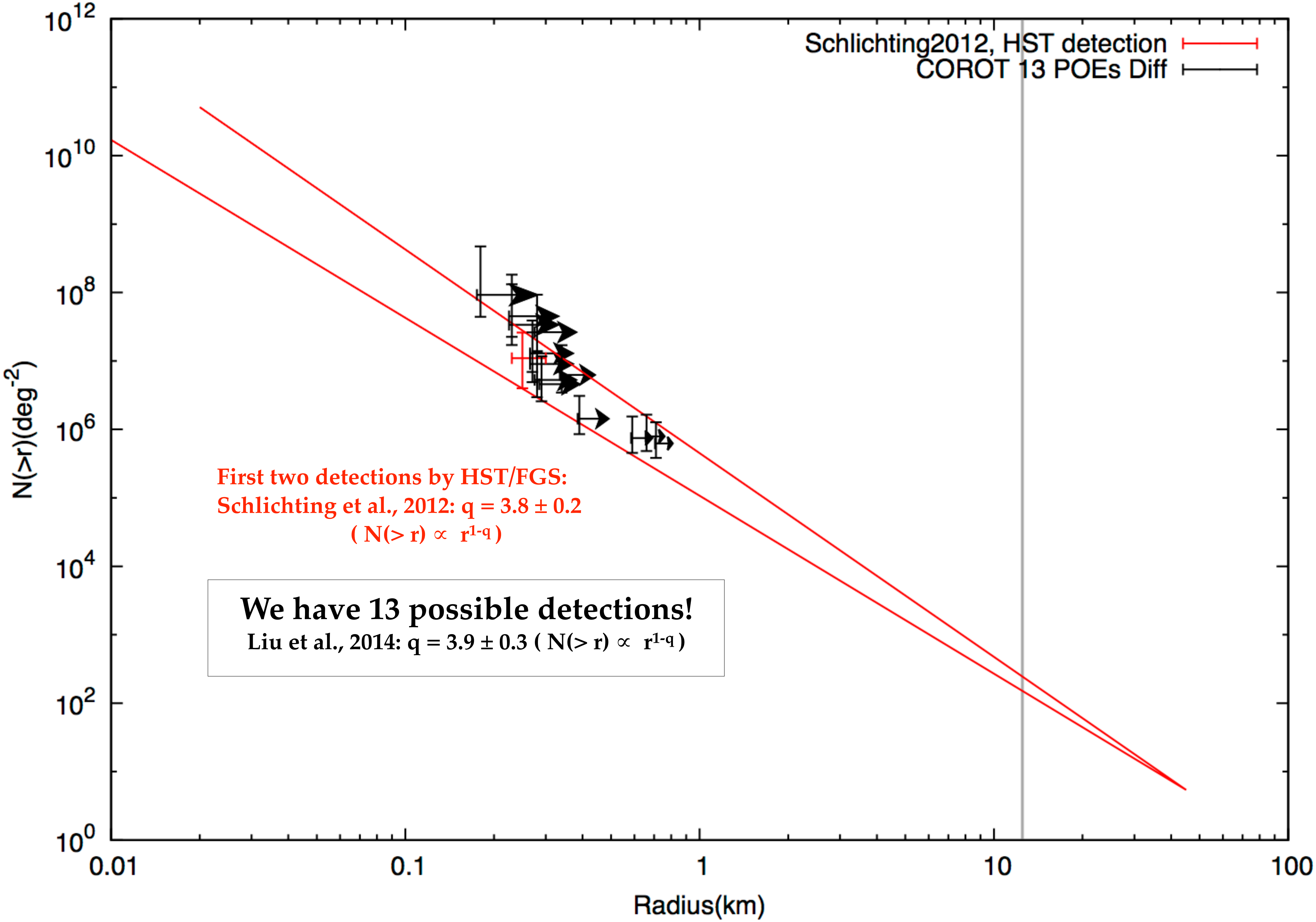


Figure 11. N0 data of the star 7548. We can see on the figure 10 an eclipse ingress and the delayed flux perturbation, a dip each 32 seconds, due to the cross-talk between the exoplanet and seismo CCDs, and the event itself (red vertical segment).

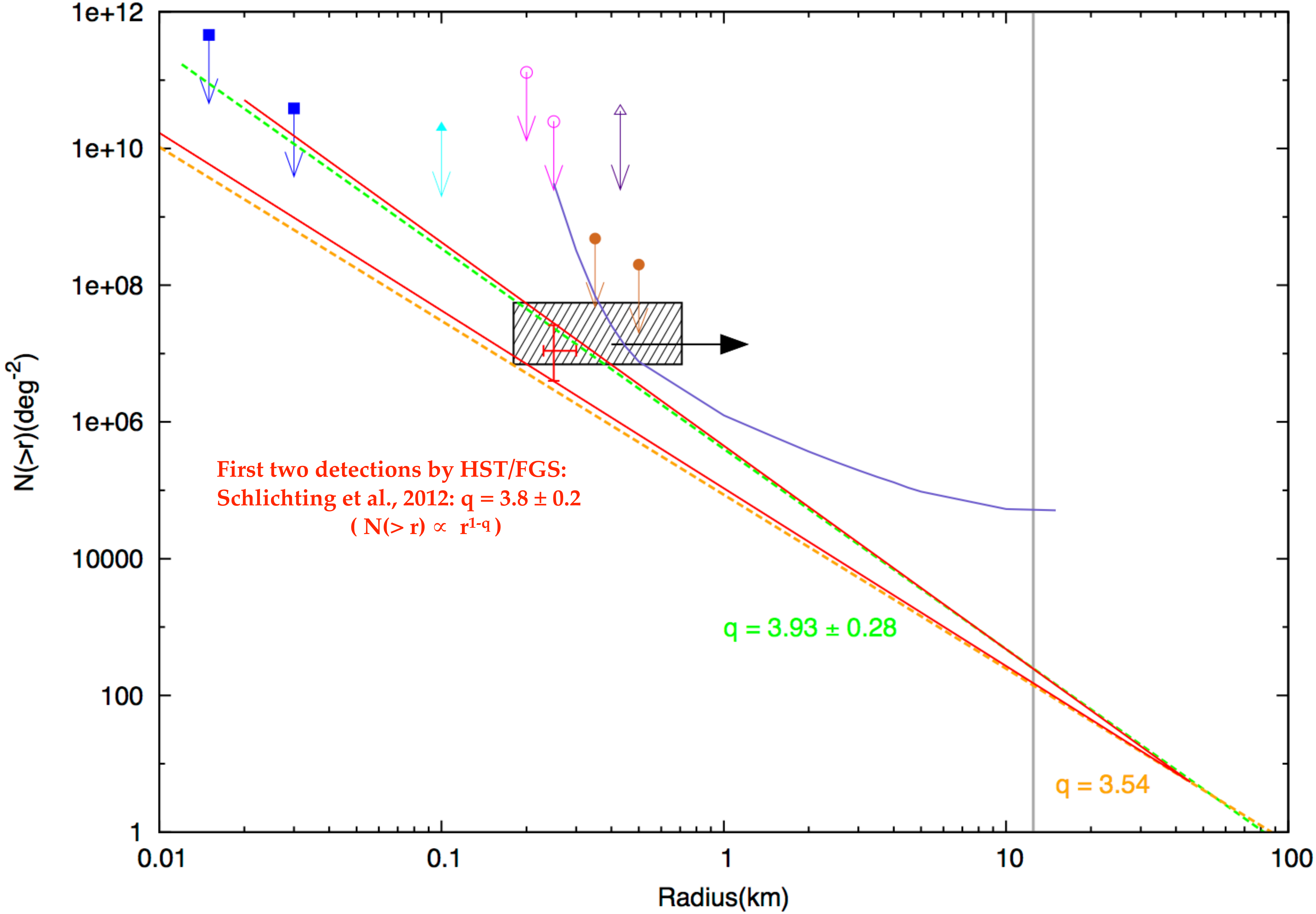


COROT 13 Possible Detections; ~144k star-hours data



Liu et al., MNRAS 446, 932–940 (2015)

COROT 13 Possible Detections; ~144k star-hours data



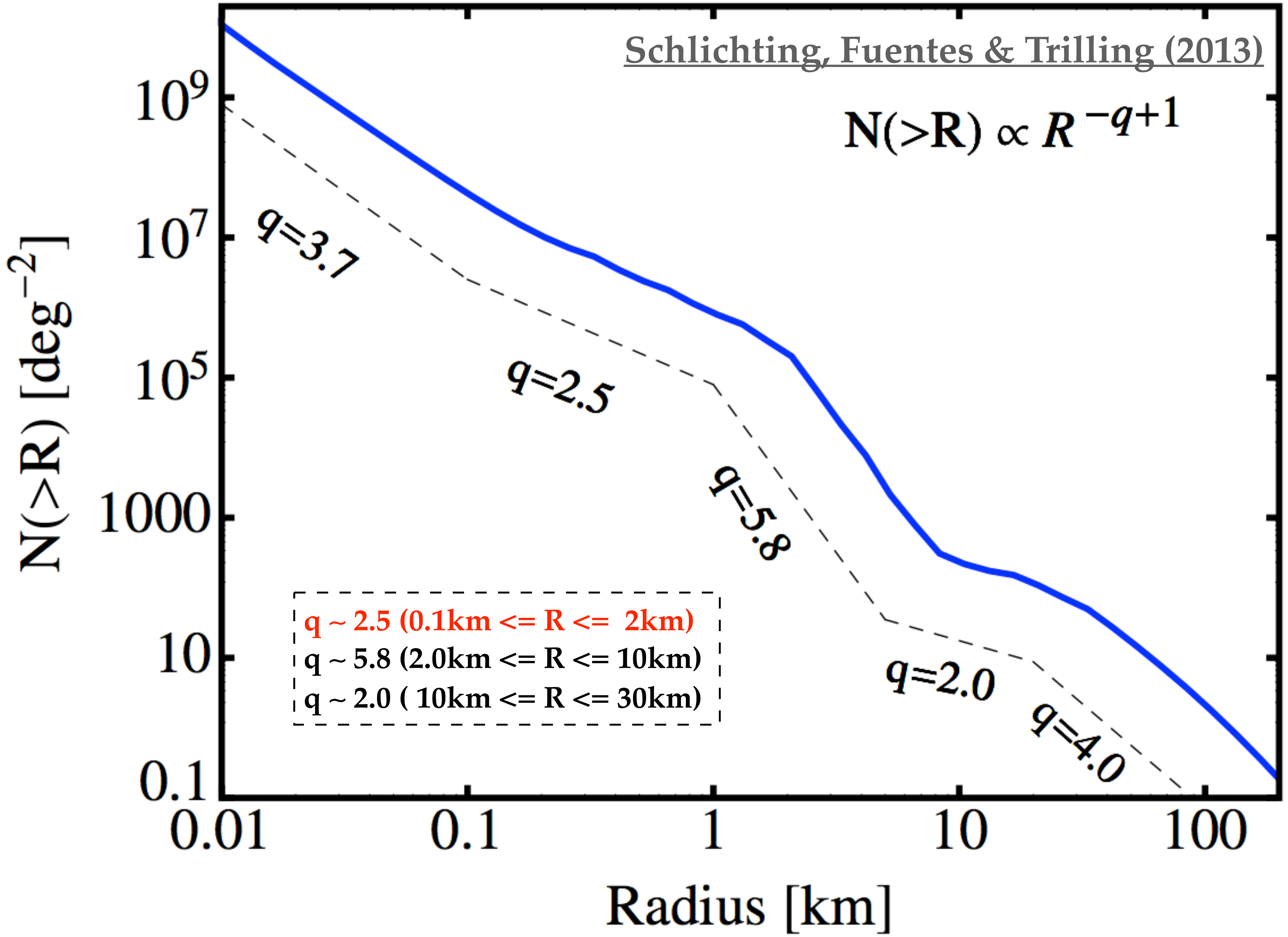


Figure 7. Same small KBO size distribution after 4.5 Gyr of collisional evolution as shown in Figure 6 but plotted with the corresponding differential power-law indices for the different segments of the size distribution. The deficit around 10 km results from an excess of ∼1 km planetesimals at the onset of the collisional evolution. The size distribution for $R \lesssim 0.1$ km takes on the expected equilibrium value for material strength dominated bodies as calculated in Section 2.2. The size distribution above $R \sim 30$ km remains unchanged by collisional evolution over the age of the solar system and is therefore primordial.

miosotys

Multi-object Instrument for Occultations in the SOlar system and TransitorY Systems

- CAHA 2.2m, 1.23m; OHP1.93m
- Time Resolution: 20 Hz
- Selected Stars:
  - V_{mag} = 9~11 ; AngSize ≤ 2 F_S
  - near Opposition
- ~119 nights; (ExpTime ≥ 4.4×10^{7} sec)