The spectacular X-ray echos of a magnetar burst

Constraining the distance to the magnetar candidate 1E 1547.0-5408 and the properties of the interstellar dust thanks to three wonderful X-ray expanding rings

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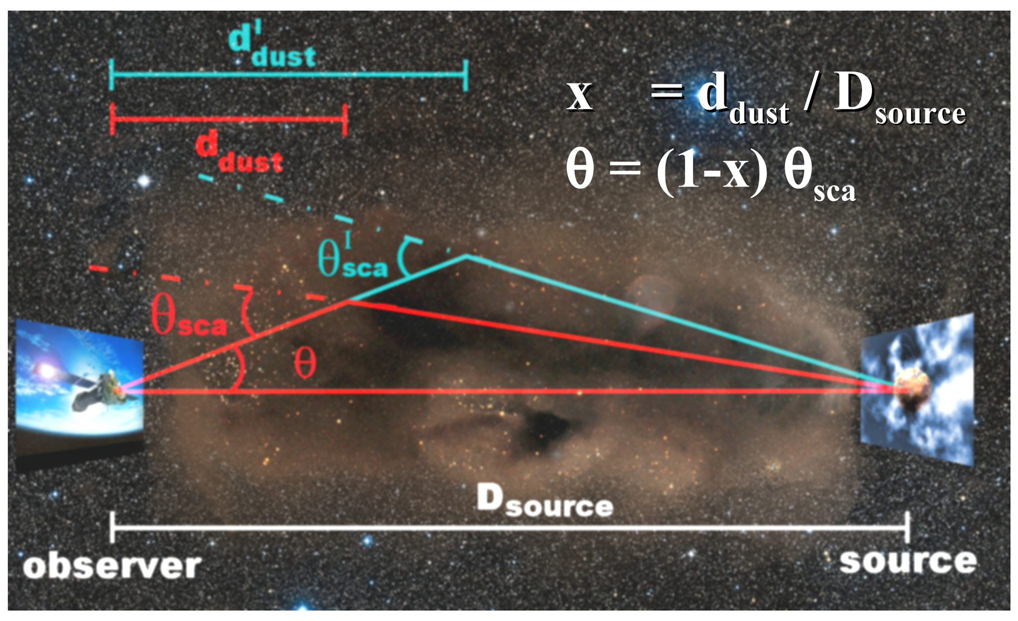
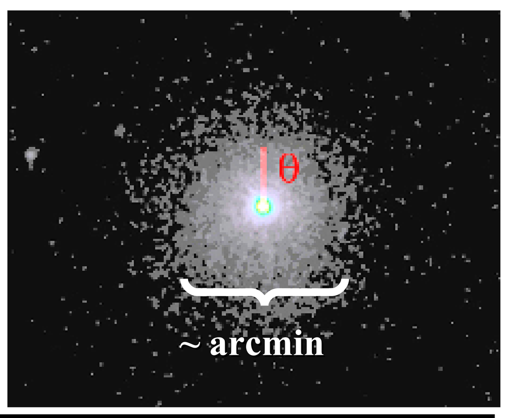
INTRODUCTION - On 2009 January 22 a series of extremely strong bursts from the anomalous X-ray pulsar 1E 1547.0 5408 were detected. We report on the discovery of three concentric X-ray rings observed with Swift/XRT and XMM-Newton/EPIC in the following two weeks. The ring radii increased with time following the expansion law expected for a short impulse of X-rays being scattered by three dust clouds. Assuming different models for the dust composition and grain size distribution, we fit the intensity decay of each ring as a function of time at different energies, obtaining tight constrains on the distance of the X-ray source. Although the distance strongly depends on dust models, some models are incompatible with our X-ray data, restricting to d ~ 4-8 kpc the range of possible distances for 1E 1547.0-5408. The best-fitting dust model provides a source distance of 3.91 +/- 0.07 kpc, which is compatible with the proposed association with the supernova remnant G327.24-0.13, and implies distances of 2.2 kpc, 2.6 kpc and 3.4 kpc for the dust clouds, in good agreement with the dust distribution inferred by CO line observations towards 1E 1547.0-5408. However, the same arguments are also valid for a set of similarly well fitting models that imply a source distance of ~ 5 kpc. A distance of ~ 4-5 kpc is also favored by the fact that these dust models had already shown to provide good fits to the dust-scattering halos of bright X-ray binaries.

Dust scattering rings

X-ray scattering by dust grains (typical dimension a ~ 0.1 μm) is in the Mie regime (λ < a), and is anisotropic in the forward direction. Typical scattering angles are of the order of few arcmin. The shape of the halo depends critically on the grain size distribution, thus it can be used to verify dust models.

Classical X-ray halo:





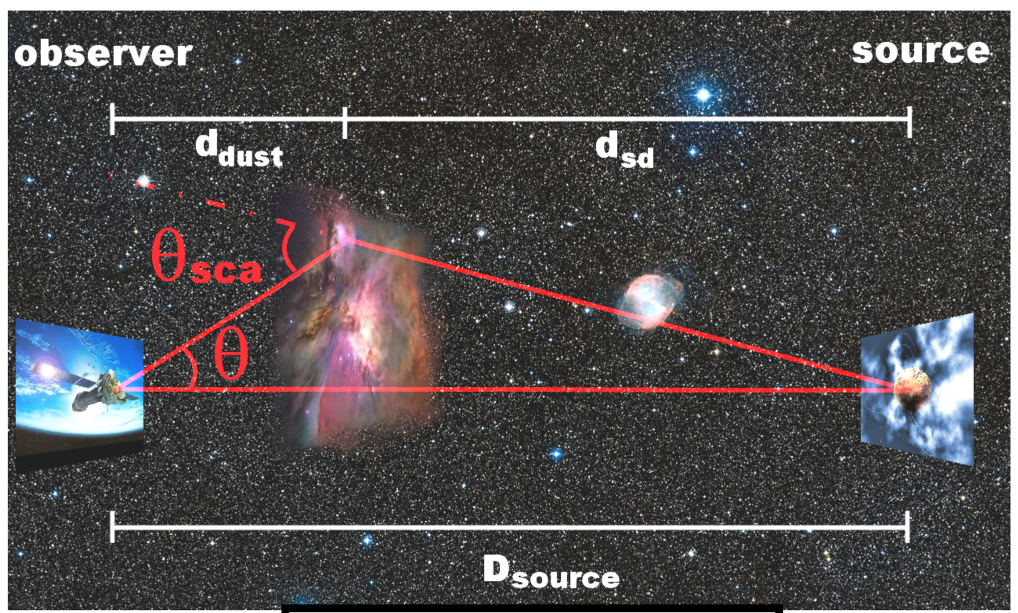
Intensity profile depends on:
- Dust properties
- Dust spatial distribution (very difficult to know)
- Source spectrum

Different optical path → Time delay:

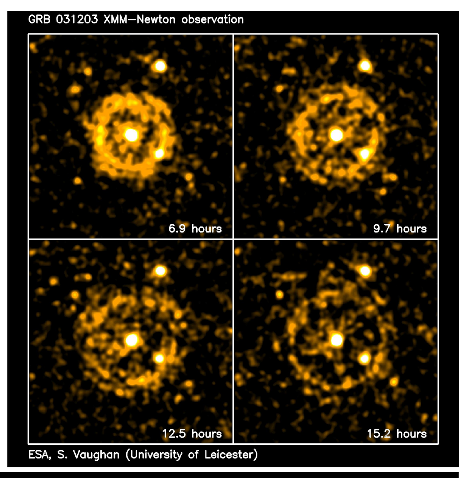
$$\theta(t)=\sqrt{\frac{1-x}{x}\frac{2c(t-t_0)}{d_{source}}}=K_i\sqrt{t-t_0} \quad (1)$$

(only geometry involved!)

Expanding rings:



$\theta \leftrightarrow \theta_{sca} \leftrightarrow t$



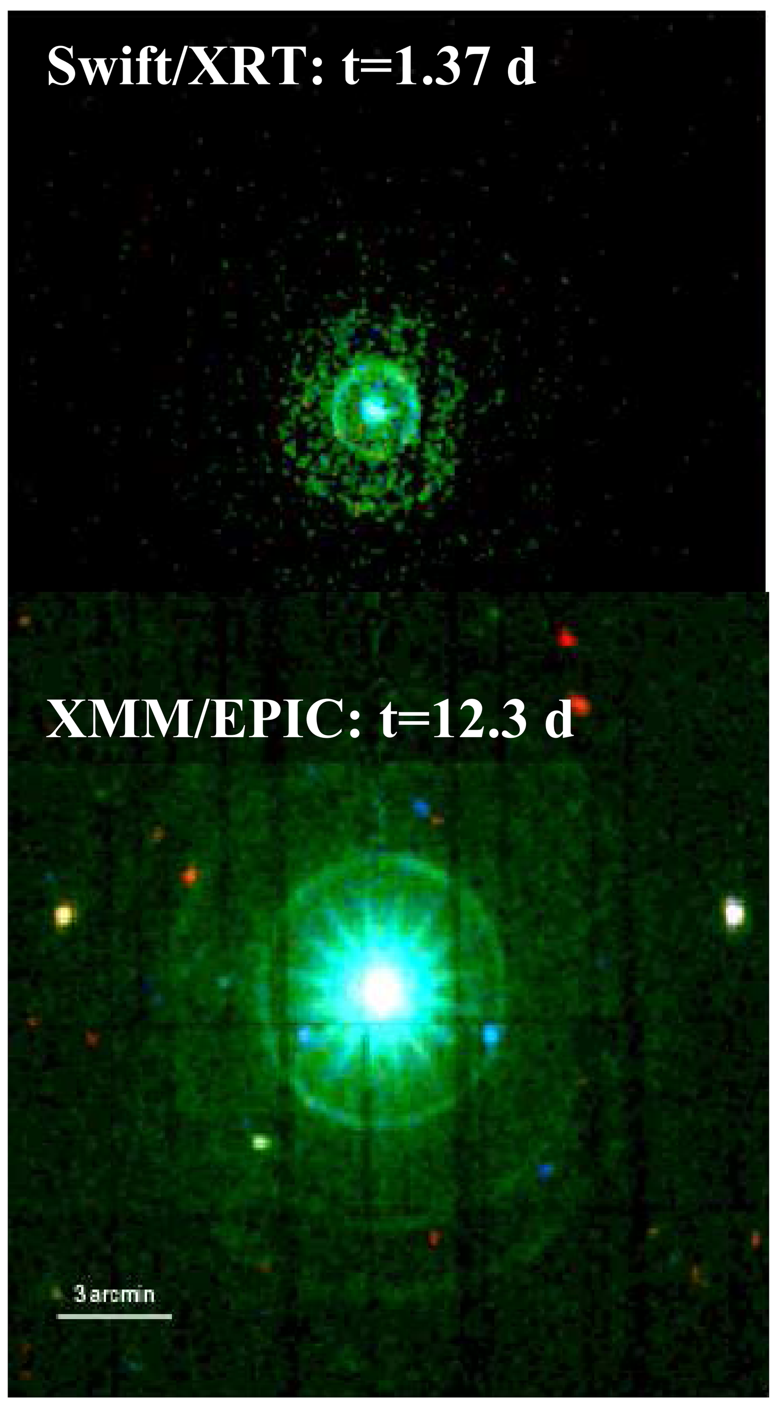
+
Short X-ray impulse

Intensity profile depends on:
- Dust properties
- Source spectrum

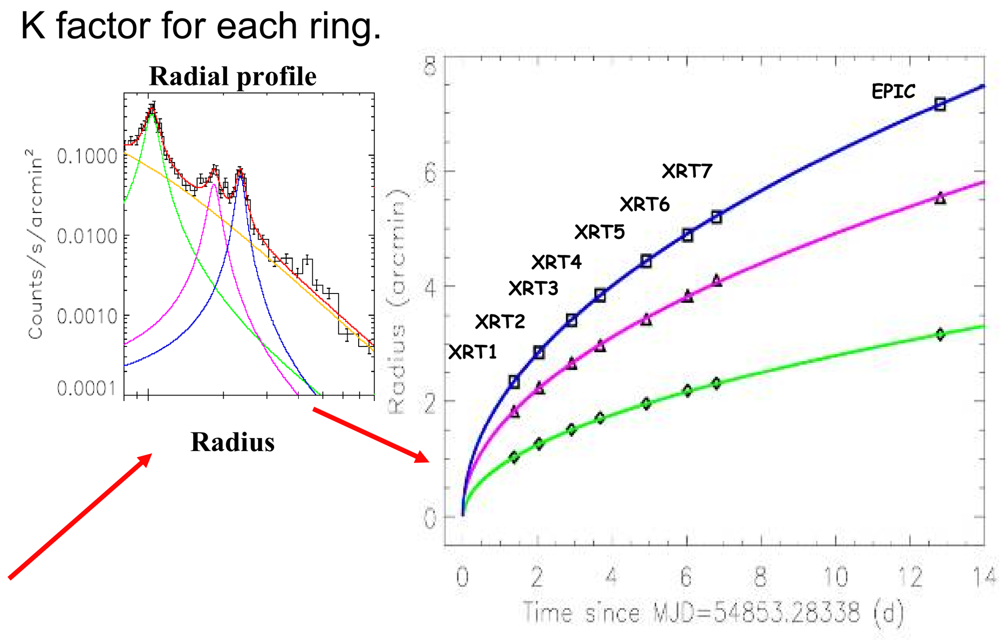
Ring expansion depends only on the geometry

Three rings around AXP 1E 1547.0-5408

On 22th, January 2009 the AXP 1E 1547.0-5408 emitted a lot of bursts, with two strong events around 06:45 a.m. Swift/XRT observations started few hours later revealed three brightl expanding rings around the source.

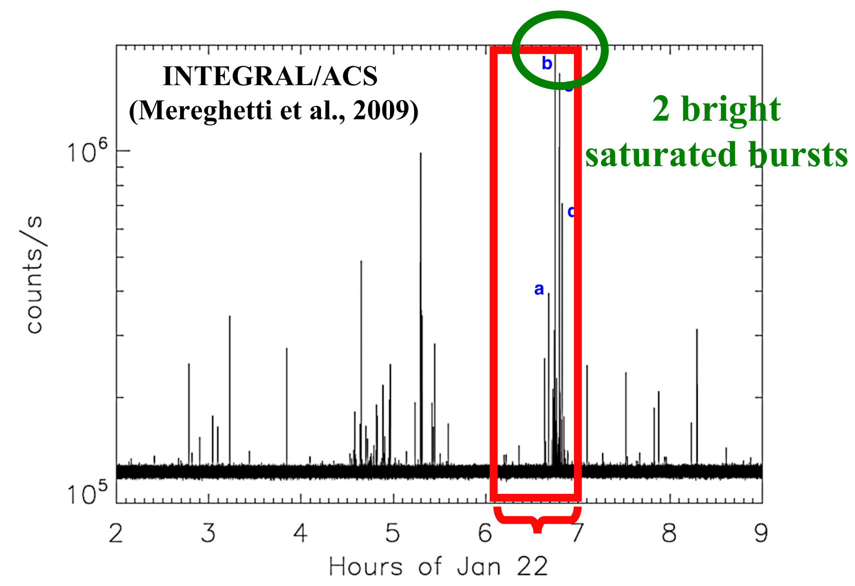


For every observation we extracted a radial profile, then we fitted it with 3 Lorentzian plus a continuum to measure the position of each ring. Then we fitted the expansion with the time-delay law (eq. 1). We have obtained a t_0 compatible with the two bright bursts, and a K factor for each ring.



1 burst, 3 dust layers | ~~3 bursts, 1 dust layer~~

Swift/XRT: 5x 2ks WT mode
7x 4 ks PC mode
XMM/Epic: 1x 50 Ks Full frame



Allowed t_0

How to determine the distance?

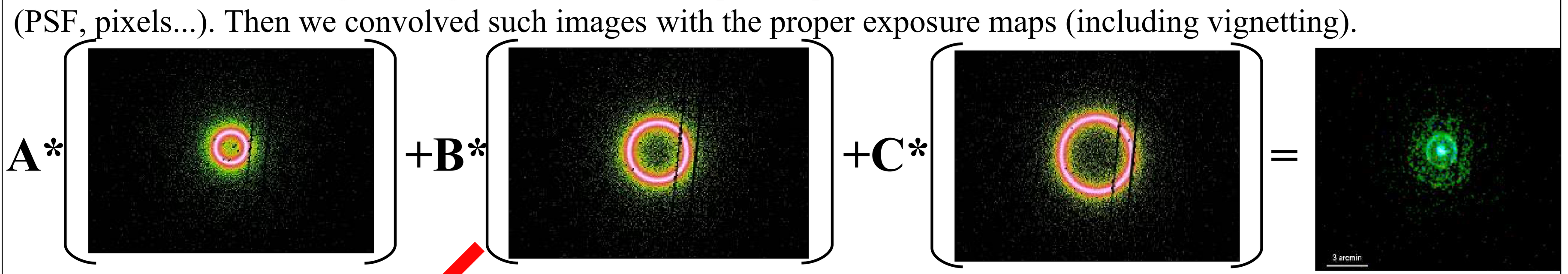
The study of the expansion of the three rings lead to determine a ratio between the distance of the source and that of each of the 3 dust sheets. How to resolve the degeneracy? We need an independent estimate of at least one of that ratios.

Fitting energy-resolved halo profiles:
- **Input: dust model, dynamic (k-factor)**
- **Output: distance, spectrum of the burst(s)**

$$I^i_{sca}(\theta(t),E)=c_1N_H\left(\frac{Dk^2+2c}{Dk}\right)^2 F_X\,S(E)\int_{a_{min}}^{a_{max}}da\,n(a)\frac{d\sigma_{sca}}{d\Omega}(a,E,K_i\sqrt{t-t_0})$$

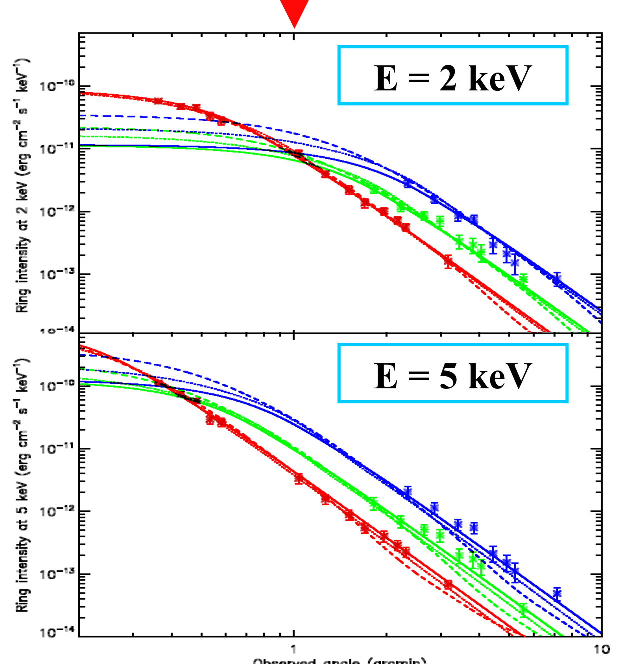
→ **Distance depends on dust model**

We generated simulated images of the three rings for each observation, using the information obtained with the study of the dynamic of the rings, taking into account the exposure plan (with occultations), and instrument characteristics (PSF, pixels...). Then we convolved such images with the proper exposure maps (including vignetting).



Ring 1 Ring 2 Ring 3 Observation

We fitted energy-.resolved radial profiles extracted from the observations with only the normalization of the rings profiles (extracted from simulations) free to vary.

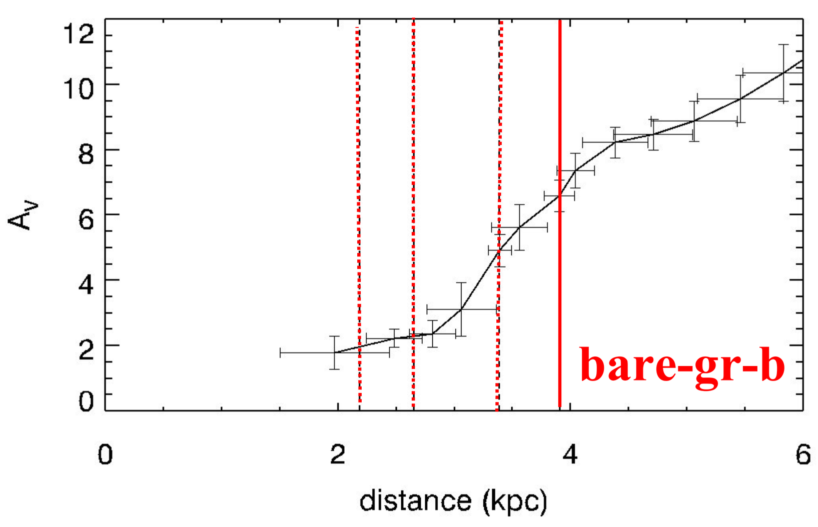


We repeated the process for a number of dust models (Zubko et al. 2004, Weingartdner & Draine 2001), obtaining different distances and different quality of the fit:

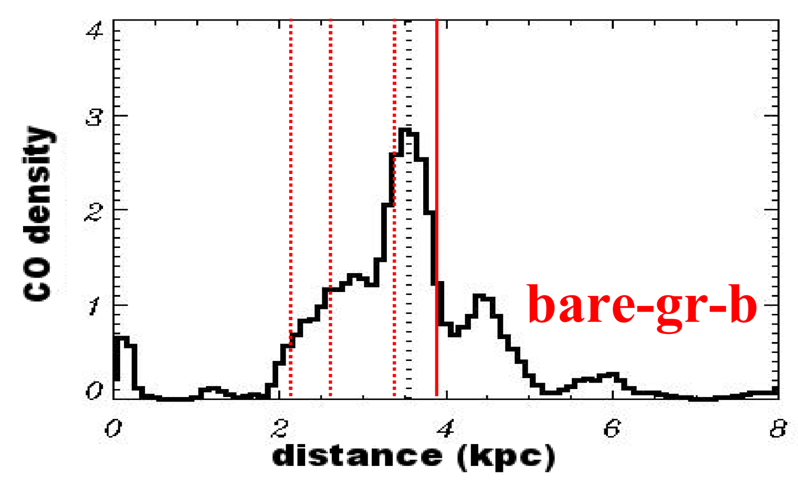
Dust models	Chisq.	D_{source} kpc	$D_{dust\ 1}$ kpc	$D_{dust\ 2}$ kpc	$D_{dust\ 3}$ kpc
bare-gr-b	0.77	3.91	3.39	2.65	2.19
bare-gr-s	0.79	4.76	4.00	3.01	2.43
bare-gr-fg	0.81	4.87	4.08	3.06	2.46
comp-gr-b	0.85	5.21	4.32	3.19	2.54
bare-dr-1	0.86	6.07	4.89	3.49	2.73
comp-gr-fg	1.06	6.94	5.45	3.76	2.89
comp-gr-s	1.10	7.71	5.91	3.98	3.02
bare-dr-7	1.27	6.91	5.43	3.75	2.89
comp-nc-b	1.35	11.86	8.08	4.86	3.50
bare-ac-s	1.37	5.74	4.68	3.38	2.66
bare-ac-b	1.43	4.85	4.07	3.05	2.45
bare-ac-fg	1.44	5.85	4.75	3.42	2.68
comp-ac-b	1.51	8.36	6.29	4.15	3.11
comp-ac-s	1.55	9.24	6.77	4.35	3.23
comp-ac-fg	1.73	8.15	6.16	4.09	3.08
comp-nc-s	1.81	10.16	7.25	4.55	3.33
comp-nc-fg	1.94	10.43	7.39	4.60	3.36
bare-dr-12	2.26	8.84	6.55	4.26	3.18

Results

In order to decide which is the best estimate of the distance to the source we used also independent information.



This plot of extinction vs distance (Marshall et al, 2006) shows that there is a jump in the extinction near 3.5 kpc.



Also this plot of CO density Vs distance (Dame et al., 2001) confirm that the denser dust sheet is near 3.5 kpc.

We slightly favor the bare-gr-b model because:
- Best fit quality
- Most dense layer (corresponding to the inner brighter ring) in the right place: $D_{dust\ 1}$ = 3.4 kpc
- Gelfand & Gaensler (2007), based on association with supernova remnant, gave an estimate of D_{source} ~ 4 kpc

However similar arguments are valid also for a set of similarly well fitting models with D ~ 5 kpc. Other classic halos are well described by these models (Smith 2006, Smith 2008, Valencic 2009)

Our best estimate for the distance of AXP 1E 1547.0-5408 is D~ 4-5 kpc

Our results is model dependent, although strengthened by independent measurements.