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Interstellar dust at X-rays

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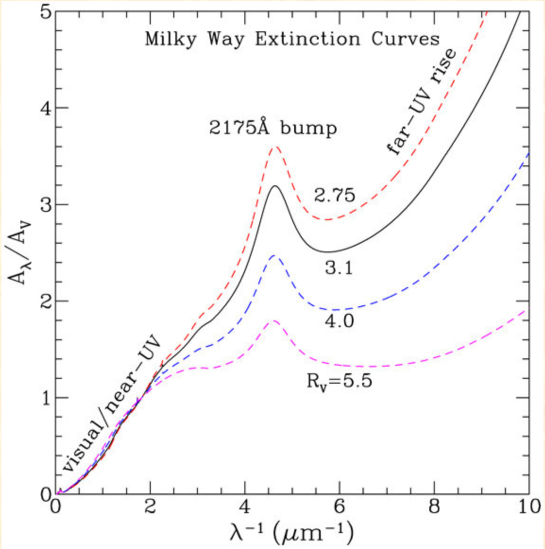
Why should we study dust?

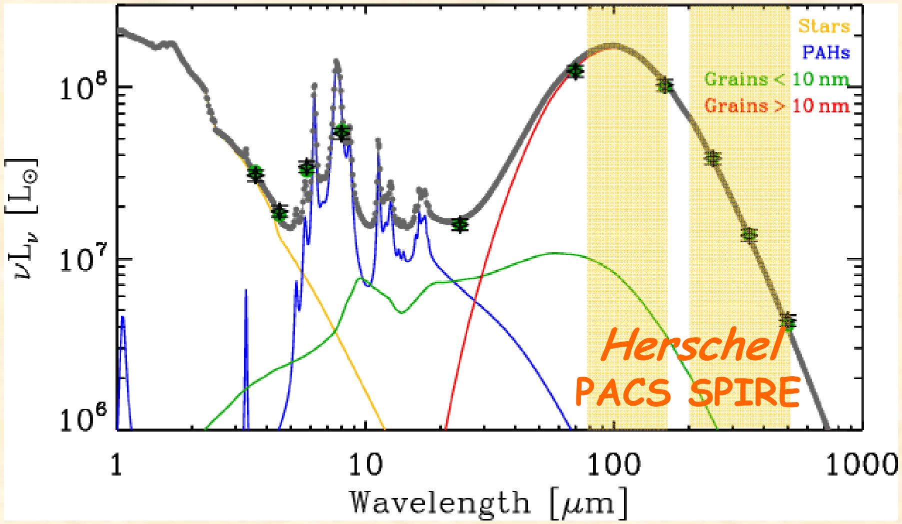
- A trouble in astronomical observations (mainly optical/UV):
  - **Dust extinction**: e.g., extinction correction in host galaxy for SN Ia (discovery of cosmic acceleration, Nobel Prize 2011, *Perlmutter et al. 1999, ApJ 517, 565*)
  - **Dust emission**: e.g., foreground component in CMB (Nobel Prize 2006; *Smoot et al. 1992, ApJ 396, L1*)
- Essential for **star formation**: dust is the main cooling factor leading to molecular cloud collapse
- Screening from stellar UV radiation allows formation of molecules in space: is dust a fundamental ingredient for the **origin of life** in the universe?
- **Dust production** (in AGB stars and/or SNe) **and evolution** (in diffuse ISM and/or dense clouds) are still open questions to explain large dust amounts in early universe (e.g., high redshift quasars)

How can we study dust?

- Dust extinction:
  stars reddening from NIR to FUV



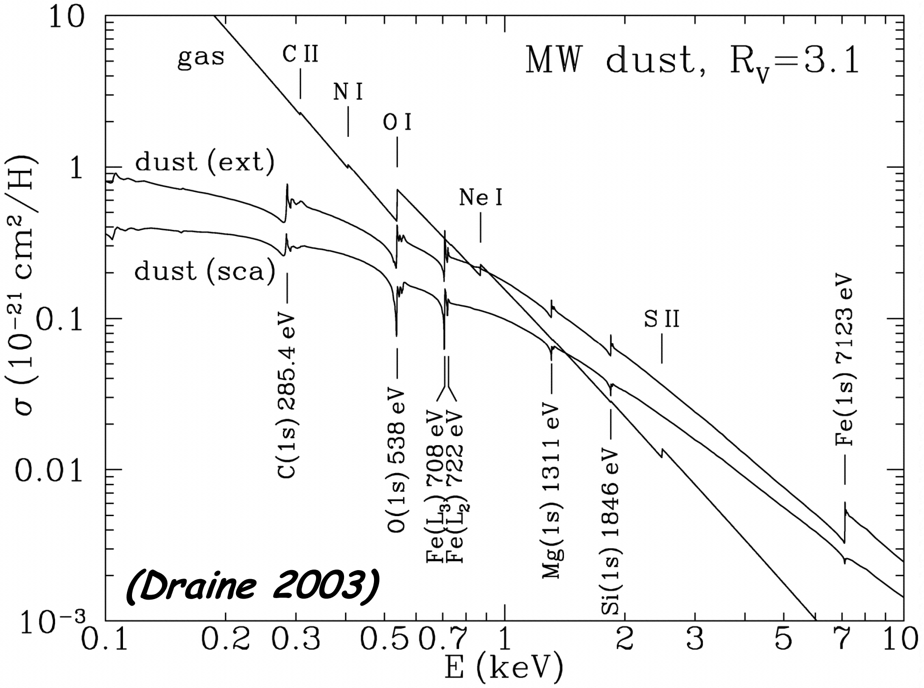
- Dust emission:
  from microwaves to midIR



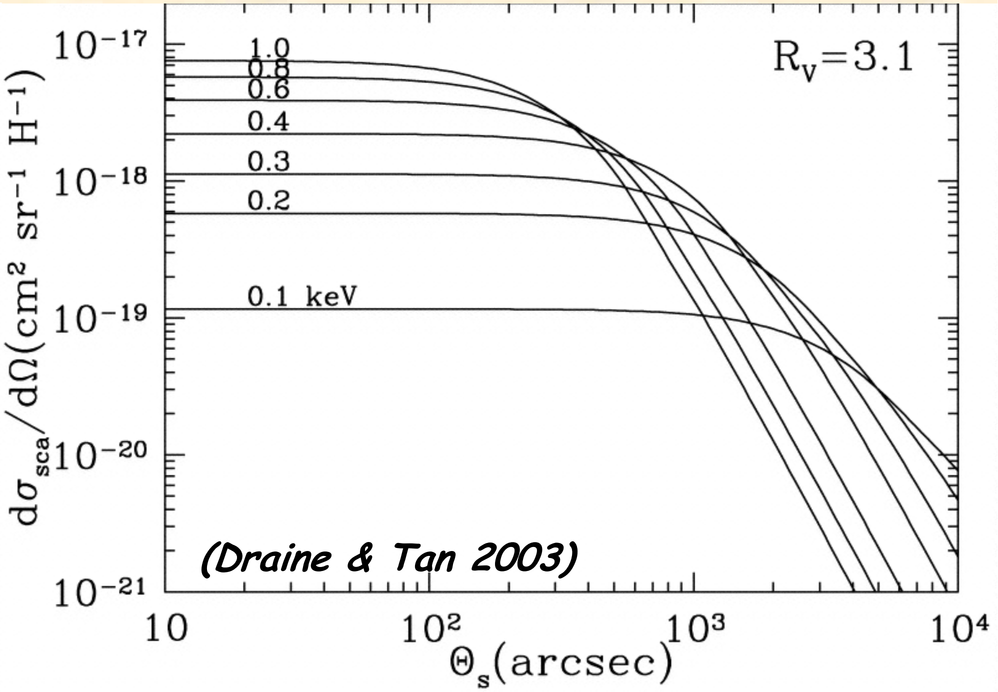
- Dust scattering (and absorption) at X-rays

Dust and X-rays

Soft X-rays **(E < few keV)** are scattered at small angles **(θ ~ few arcmin)** by interstellar dust (*big dust grains*, **a ≈ 0.1 μm**)



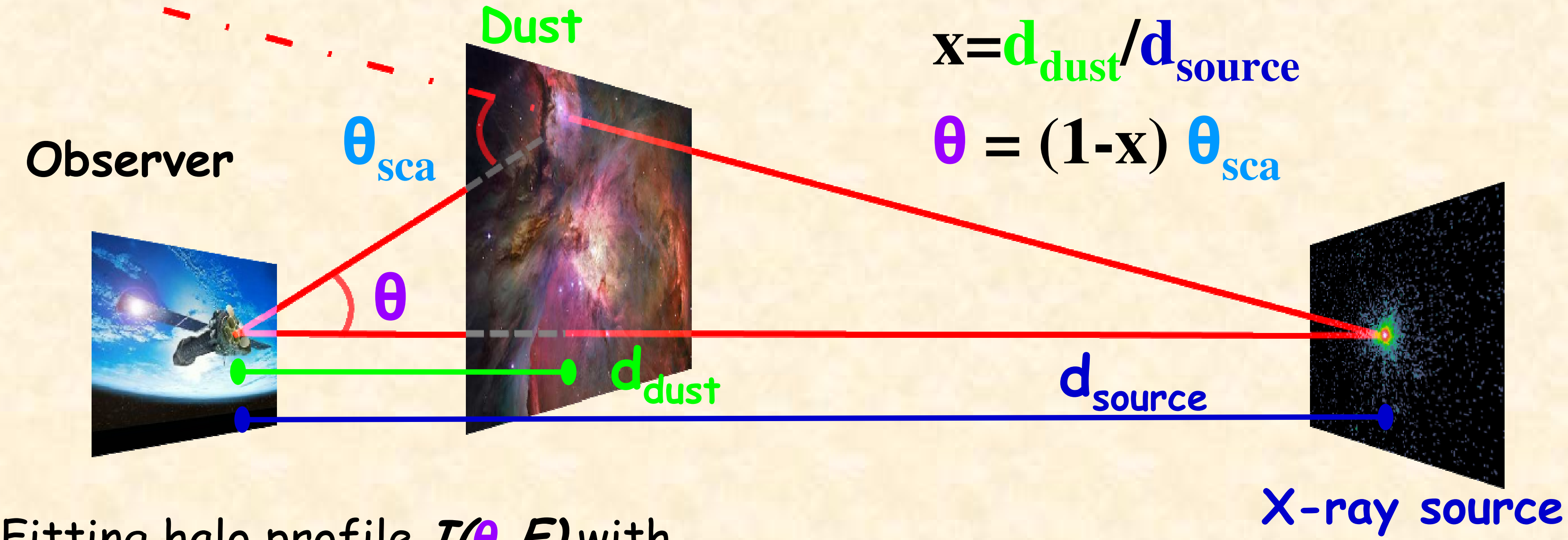
(Draine 2003)



(Draine & Tan 2003)

As predicted by *Overbeck* ***(1965, ApJ 141, 864)*** and firstly observed with *Einstein* ***(Rolf 1983, Nature 302, 46; Catura 1983 ApJ 275, 645)***, due to dust scattering, point X-ray sources are surrounded by **diffuse emission** ⇒ X-ray dust halos

Scattering geometry

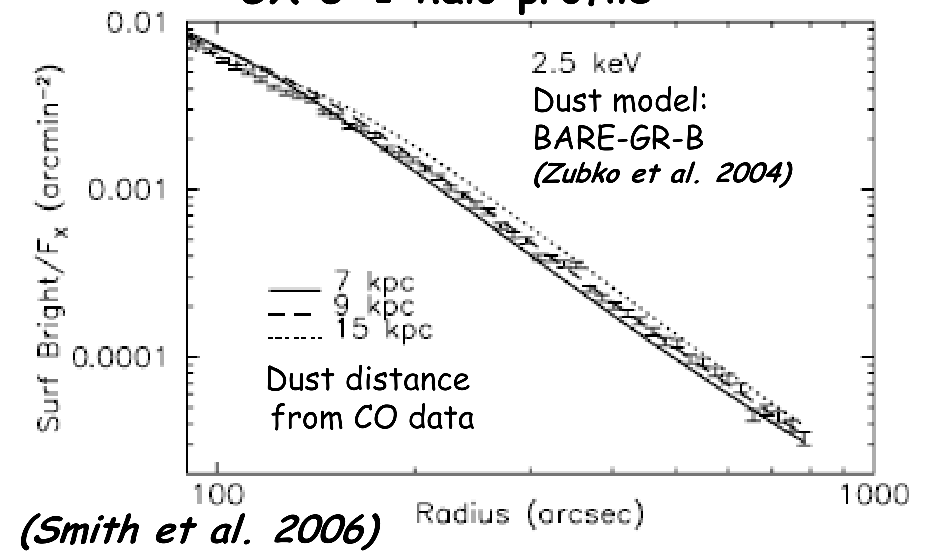


$$x = d_{dust} / d_{source}$$

$$\theta = (1-x)\,\theta_{sca}$$

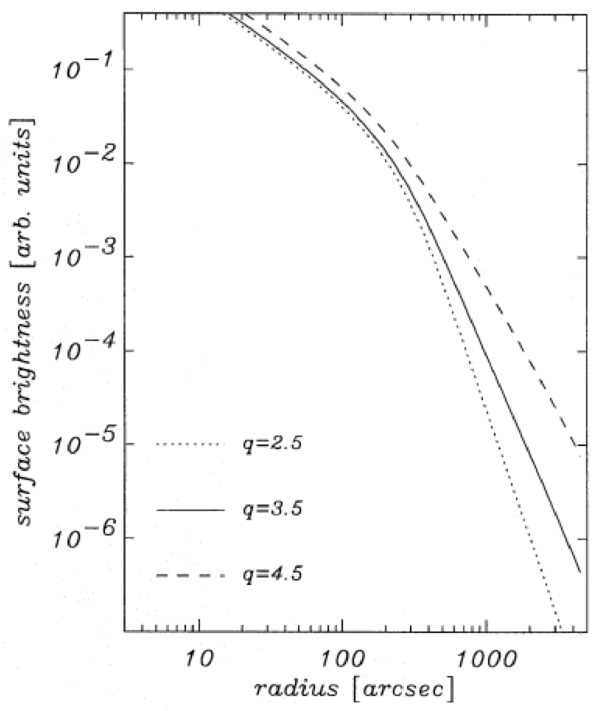
Fitting halo profile *$I(\theta, E)$* with scattering cross-section *$\sigma(\theta_{sca}, E)$*, which depends on **dust grain composition and size distribution**, the **source distance** can be derived, if ***dust distance distribution*** is known.
Vice versa, if **source AND dust distances** are known, **dust models** can be tested

GX 5-1 halo profile



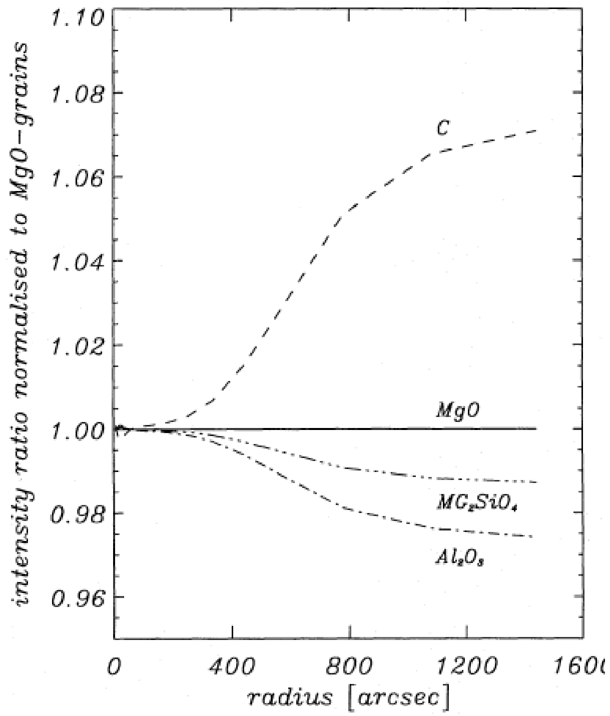
(Smith et al. 2006)

Halo profiles *(Predehl & Klose 1996)*



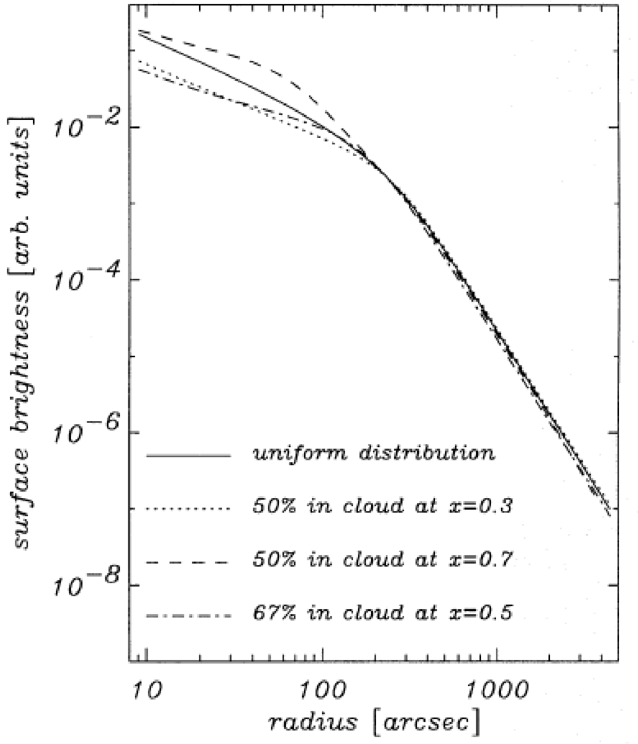
Uniform dust, E=1.5 keV, $n(a) \propto a^{-q}$, a_{max}=0.25 μm

⇒ larger grains produce a narrower halo



Uniform dust, $n(a) \propto a^{-3.5}$

⇒ halo profile only marginally depends on dust composition



Identical dust model

⇒ more distant dust produces a narrower halo

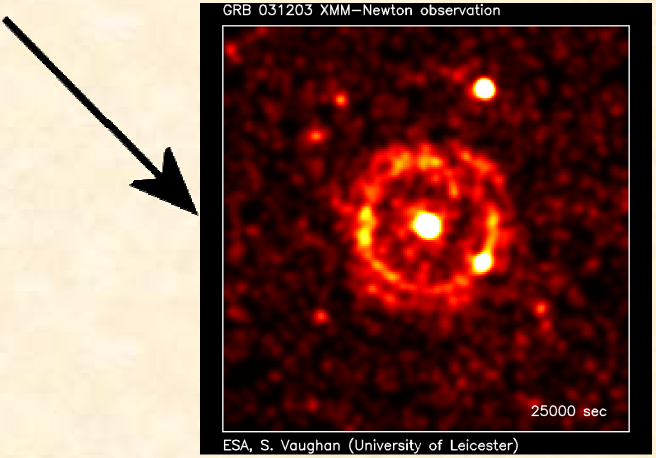
X-ray scattering is sensitive to dust distance and grain size distribution, but not to temperature and composition ⇒ complementary to long wavelengths observations

Time delay ⇒ distance estimate

(Trumper & Schonfelder 1973, A&A 25, 445)

$x = d_{dust}/d_{source}$

$\theta = (1-x)\,\theta_{sca}$


GRB 031203 XMM–Newton observation

25000 sec

ESA, S. Vaughan (University of Leicester)

Dust-scattered X-rays detected at off-axis angle θ ($\approx \theta_{sca}$ if $d_{dust} << d_{source}$) will have a time delay:

$$(t - t_0) = \frac{x}{1-x}\,\frac{d_{source}\,\theta^2}{2c}$$

$$\Rightarrow \theta(t) = \sqrt{\frac{1-x}{x}\,\frac{2c(t-t_0)}{d_{source}}} \approx \sqrt{\frac{2c(t-t_0)}{d_{dust}}}$$

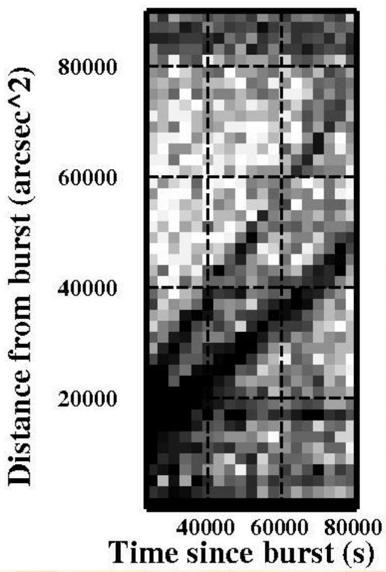
if $d_{dust} << d_{source}$

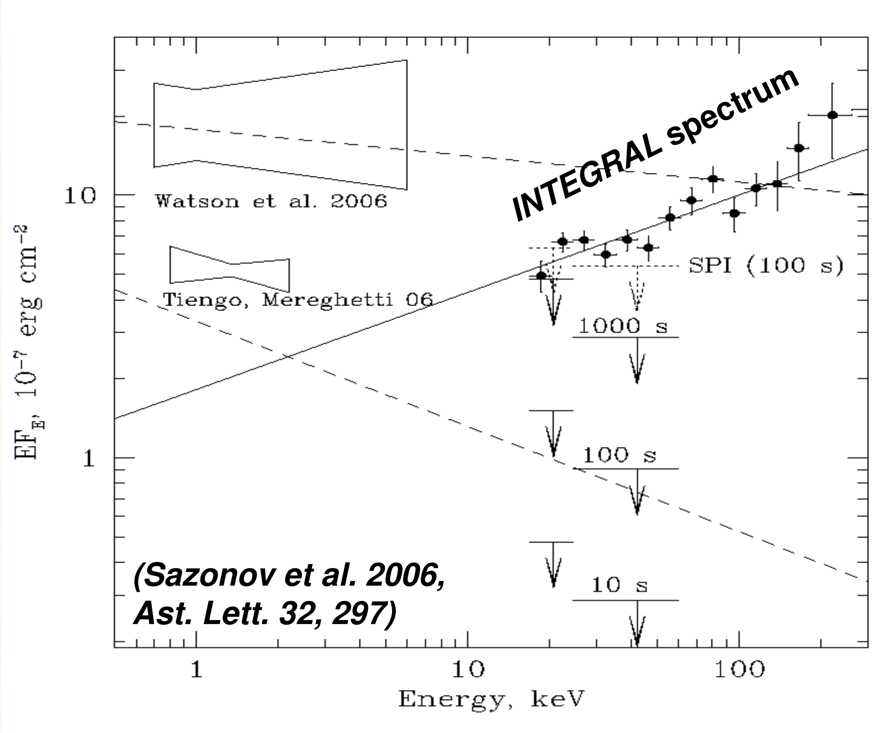
Thin dust layer AND X-ray impulse ⇒ X-ray expanding ring

GRB031203: the first and the brightest

(Vaughan et al. 2004, ApJ 603, L5)

- *INTEGRAL* GRB followed-up by *XMM-Newton*
- Low latitude: **b=-5°** (N_H~10^{21} cm^{-2}; **A_V~2**)
- Nearby: **z=0.1055**
- Spectroscopically associated with **SN** 2003dh
- Underluminous (below **E_{peak}-E_{iso}** relation)
- 2 bright (and 1 dim, **Feng & Fox 2010**) **X-ray rings**





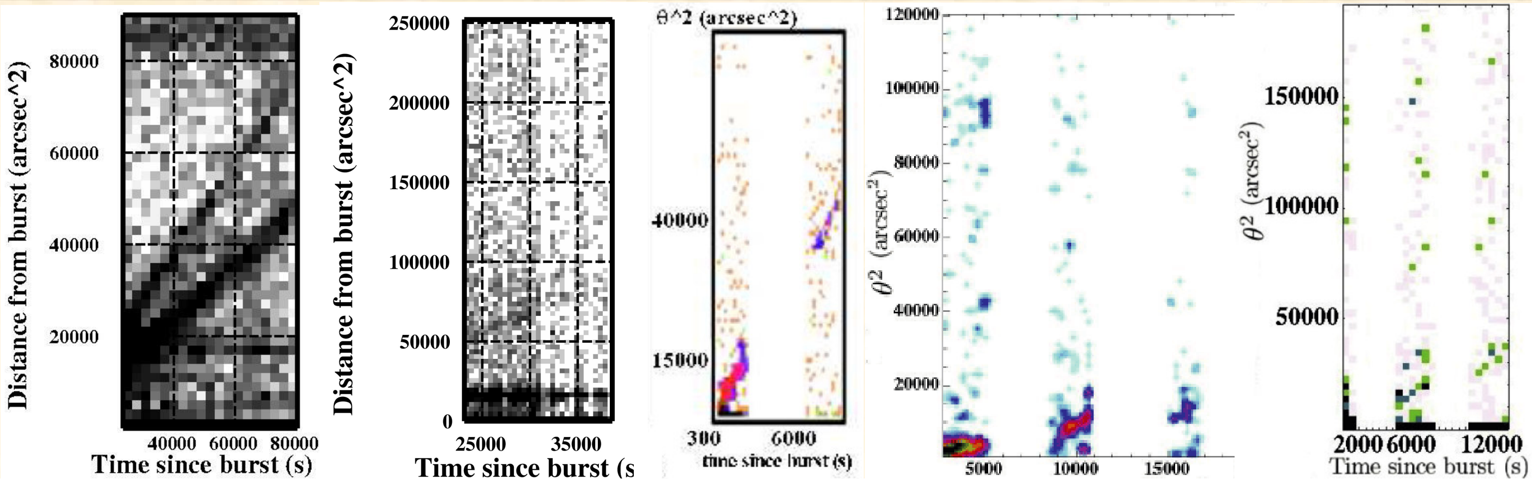
(Sazonov et al. 2006, Ast. Lett. 32, 297)

- From ring expansion law, accurate **dust distance**: d_1=870±10 pc, d_2=1390±10 pc, d_3=9.9±0.4 kpc
- Ring flux decay consistent with expected **halo profile**
- From ring flux and assuming different dust models, GRB **soft X-ray fluence >> hard X-ray extrapolation** ⇒ compatible with **E_{peak}-E_{iso}** relation

5 GRBs with X-rays rings

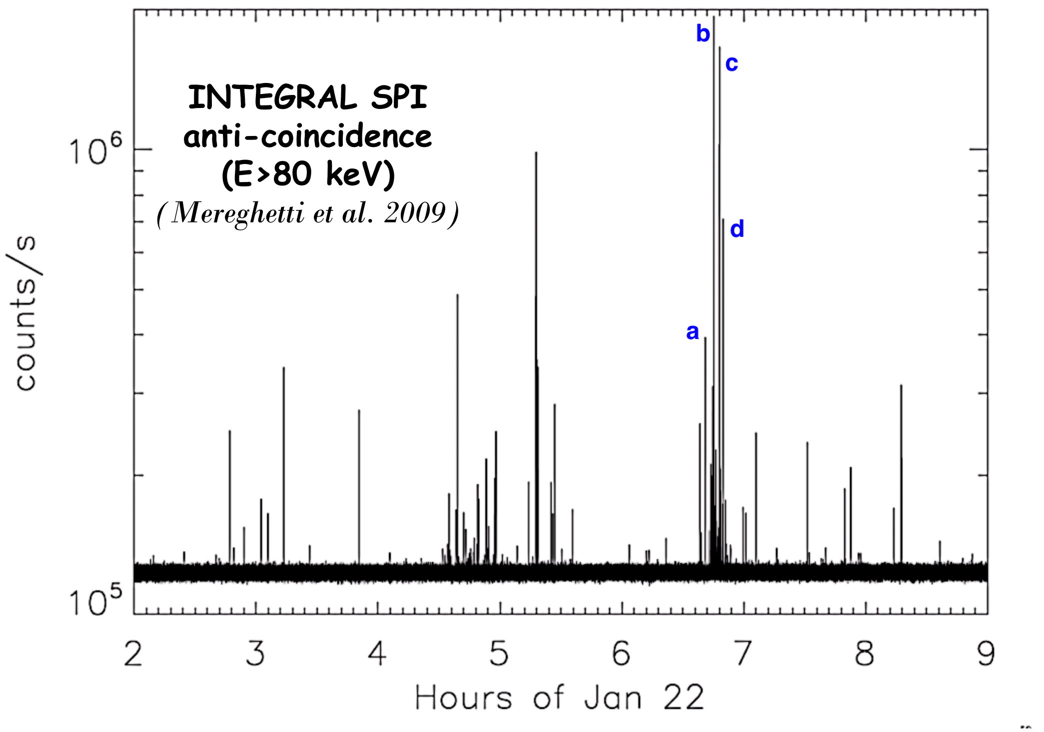
	031203	050713A	050724	061019	070129
GRB discovery	*Integral*/IBIS	*Swift*/BAT	*Swift*/BAT	*Swift*/BAT	*Swift*/BAT
Rings discovery	*XMM*/EPIC *Vaughan et al. 2003*	*XMM*/EPIC *Tiengo&Mereghetti 2006*	*Swift*/XRT *Vaughan et al. 2006*	*Swift*/XRT *Romano et al. 2006*	*Swift*/XRT *Vianello et al. 2007*
A_V	2	0.5	1.5	**3.4**	**0.4**
Dust dist.(pc)	870±5; 1384±9	364±7	**144 ±3**	940 ±40	(150); 290
Ring photons	**840; 1740**	190	150	180	**32**
Notes	Nearby; with SN Ibc; X-ray excess	Ring flux ≤ expected	z=0.258; **short with 200 s tail**	Identified with MC; **$\Delta D_{MC} \geq 150$ pc**	Partial ring; **prompt X observed**

"Dynamical images"
(Tiengo & Mereghetti 2006, A&A 449, 203)

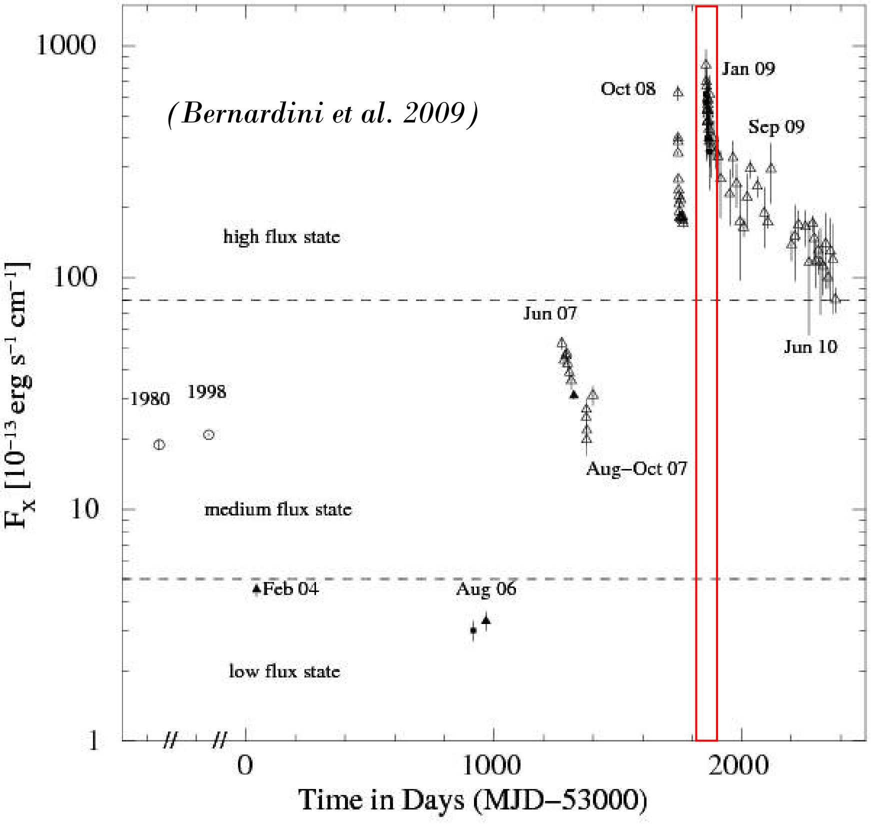


The magnetar 1E 1547.0-5408

- On 22 January 2009, the magnetar 1E1547 emits **many bright bursts** *(Mereghetti et al. 2009, ApJ 696, L74; Savchenko et al. 2010, A&A 510, A77; Kaneko et al. 2010, ApJ 710, 1335)*
- From follow-up X-ray observations: large **flux increase** *(Bernardini et al. 2011, A&A 529, A19)* and **X-ray rings** *(Tiengo et al. 2010, ApJ 710, 227)*

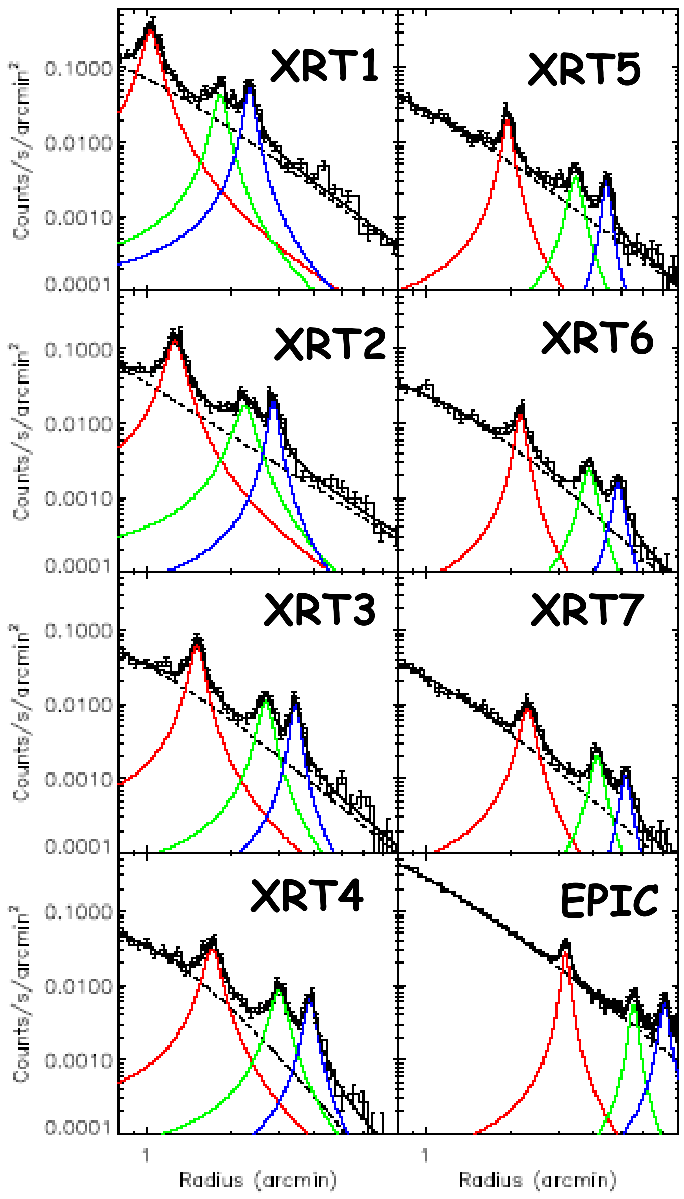


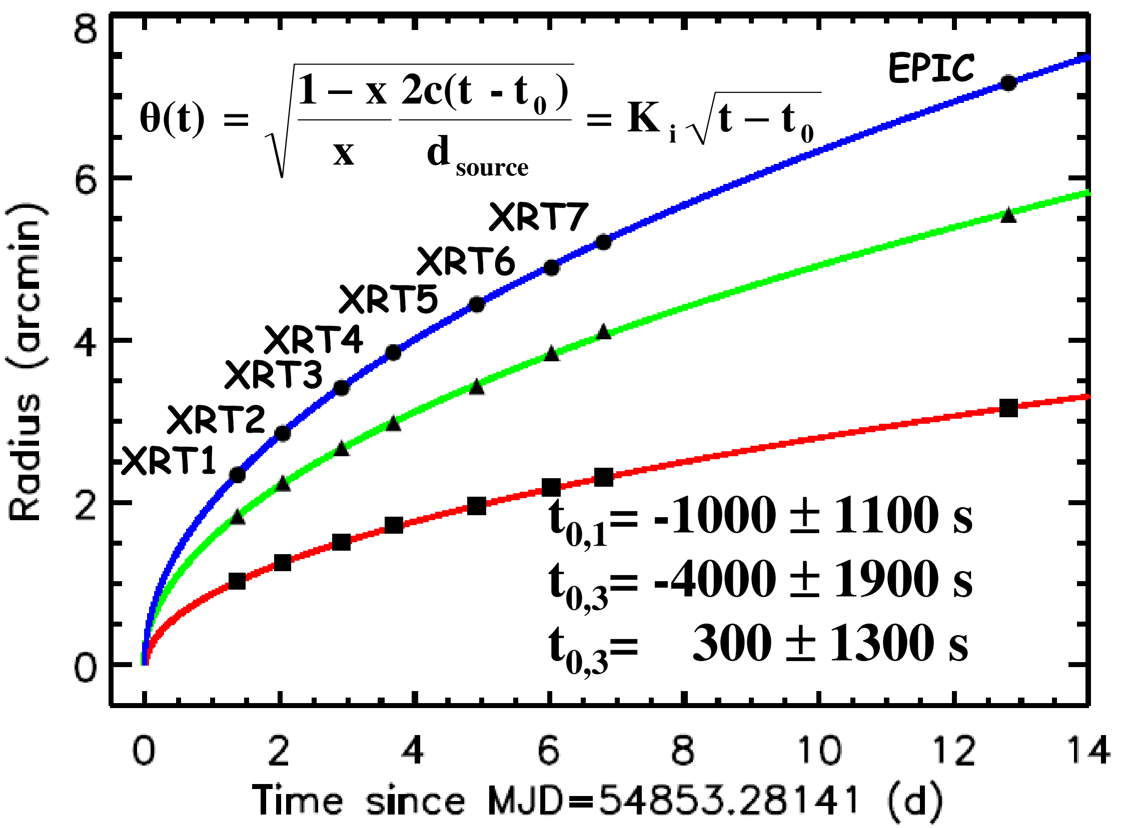
(Mereghetti et al. 2009)



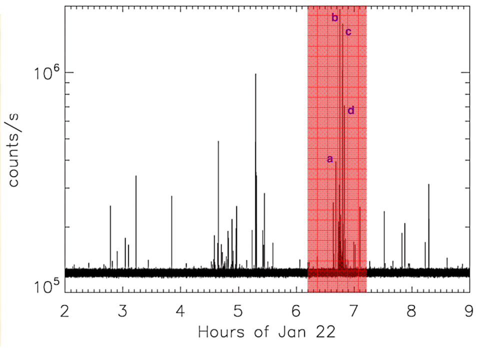
(Bernardini et al. 2009)

Radial profiles and rings expansion

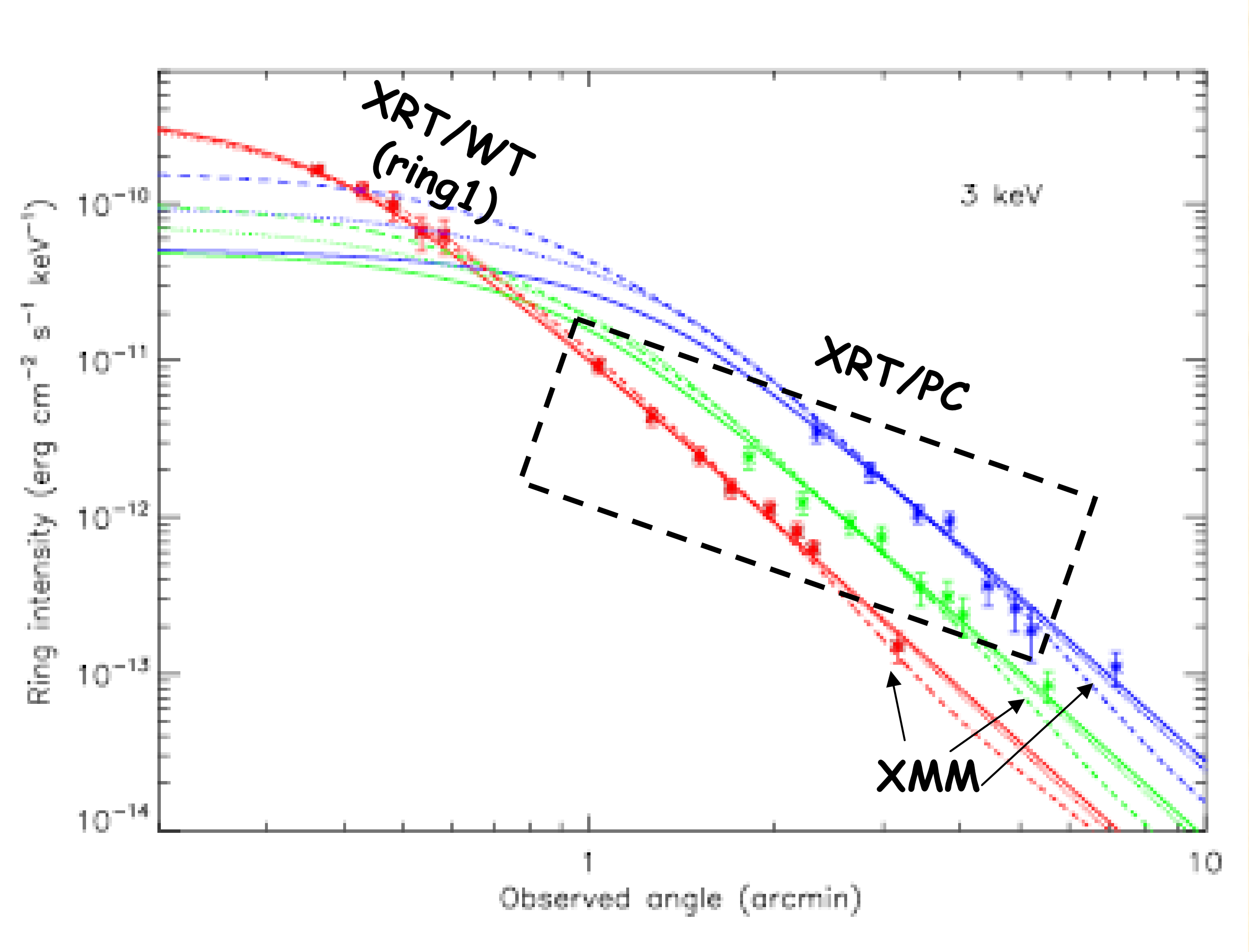




t_0 consistent with period of maximum bursting activity (including **Intermediate Flares**)



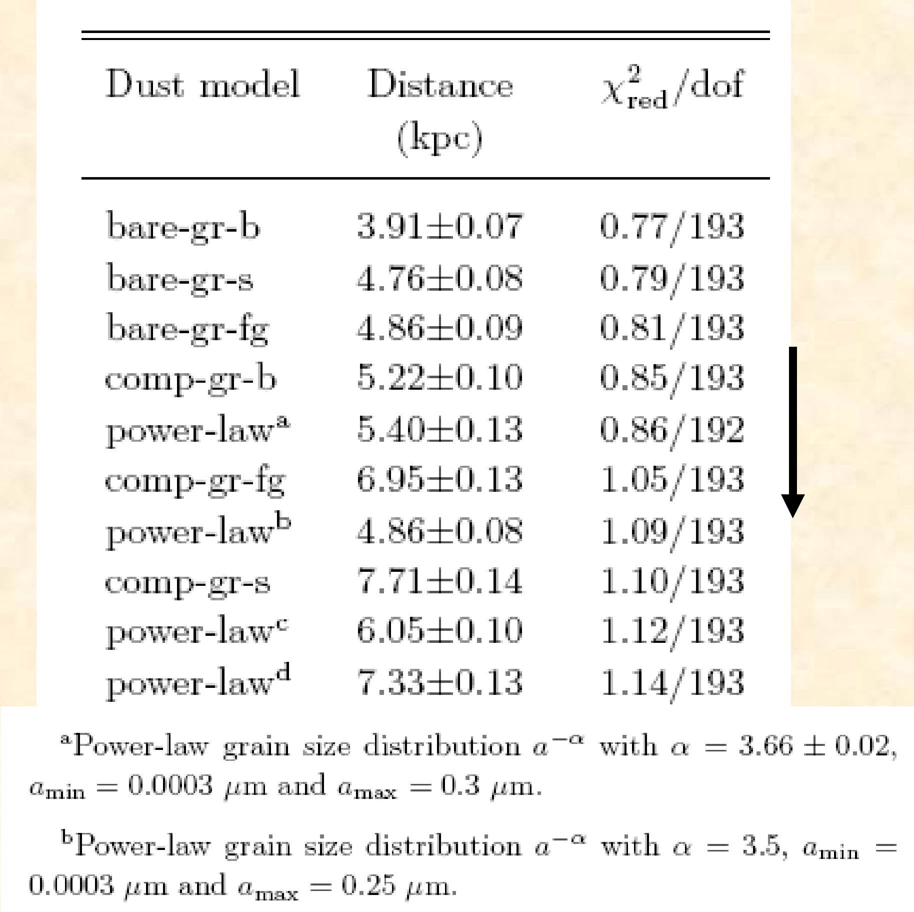
Ring intensities = halo profile



Assuming 17 different dust models (⇒ **cross-sections**), we get source and dust clouds **distances** by fitting energy-resolved halo profiles

Dust models (grain composition and size)

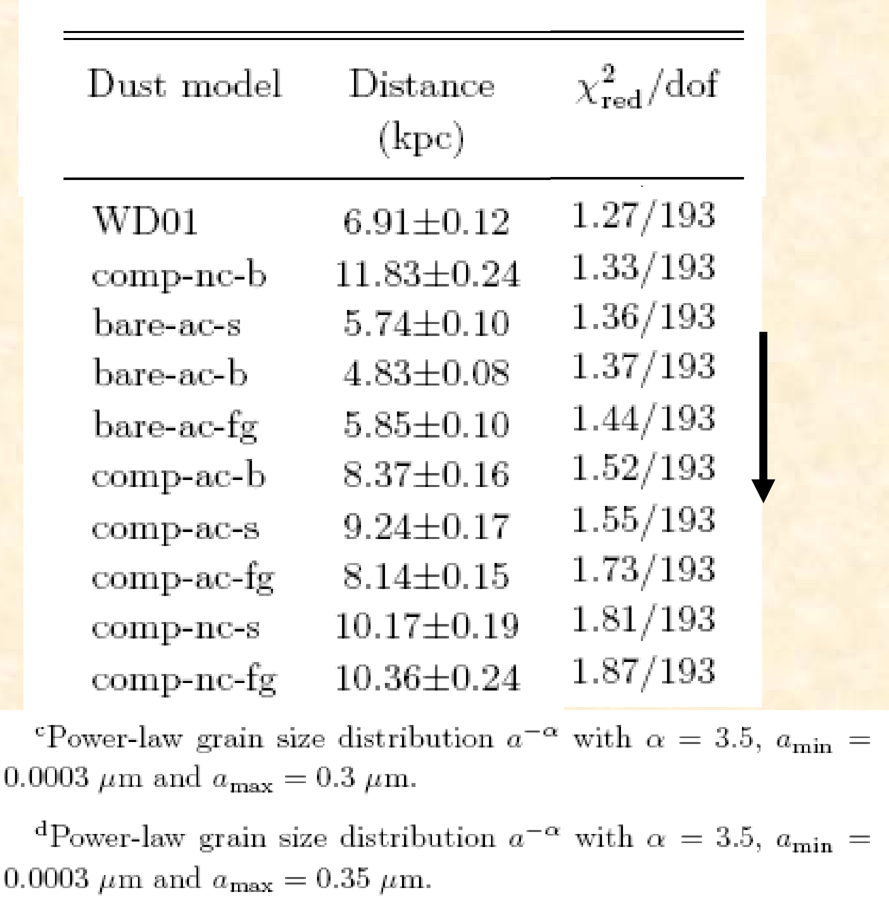
(Zubko et al. 2004, ApJS 152, 211; Mathis et al. 1977, ApJ 217, 425; Weingartner & Draine 2001, ApJ 548, 296)



Dust model	Distance (kpc)	$\chi^2_{\rm red}$/dof
bare-gr-b	3.91±0.07	0.77/193
bare-gr-s	4.76±0.08	0.79/193
bare-gr-fg	4.86±0.09	0.81/193
comp-gr-b	5.22±0.10	0.85/193
power-law[a]	5.40±0.13	0.86/192
comp-gr-fg	6.95±0.13	1.05/193
power-law[b]	4.86±0.08	1.09/193
comp-gr-s	7.71±0.14	1.10/193
power-law[c]	6.05±0.10	1.12/193
power-law[d]	7.33±0.13	1.14/193

[a] Power-law grain size distribution $a^{-\alpha}$ with $\alpha = 3.66 \pm 0.02$, $a_{\rm min} = 0.0003$ μm and $a_{\rm max} = 0.3$ μm.

[b] Power-law grain size distribution $a^{-\alpha}$ with $\alpha = 3.5$, $a_{\rm min} = 0.0003$ μm and $a_{\rm max} = 0.25$ μm.



Dust model	Distance (kpc)	$\chi^2_{\rm red}$/dof
WD01	6.91±0.12	1.27/193
comp-nc-b	11.83±0.24	1.33/193
bare-ac-s	5.74±0.10	1.36/193
bare-ac-b	4.83±0.08	1.37/193
bare-ac-fg	5.85±0.10	1.44/193
comp-ac-b	8.37±0.16	1.52/193
comp-ac-s	9.24±0.17	1.55/193
comp-ac-fg	8.14±0.15	1.73/193
comp-nc-s	10.17±0.19	1.81/193
comp-nc-fg	10.36±0.24	1.87/193

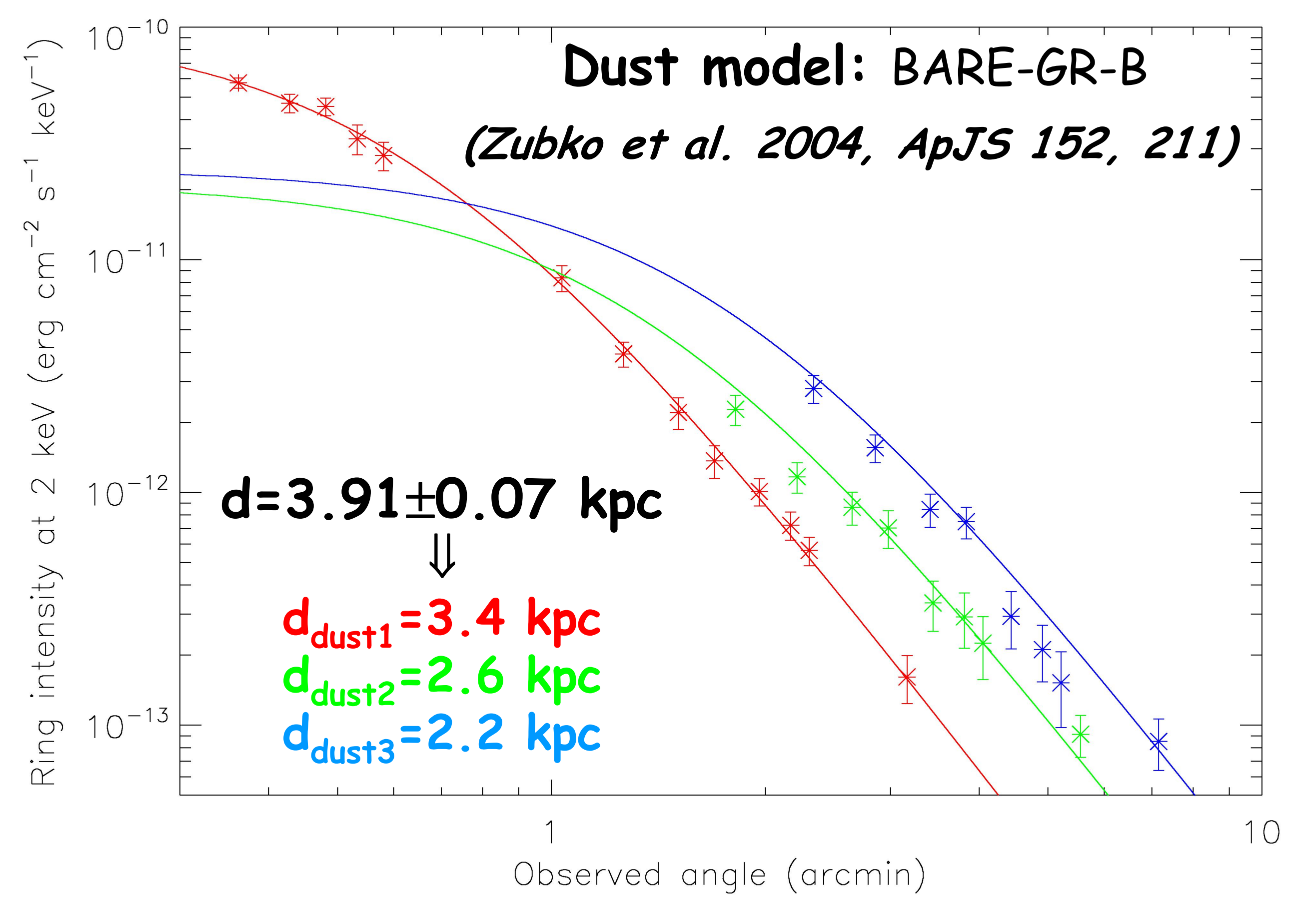
[c] Power-law grain size distribution $a^{-\alpha}$ with $\alpha = 3.5$, $a_{\rm min} = 0.0003$ μm and $a_{\rm max} = 0.3$ μm.

[d] Power-law grain size distribution $a^{-\alpha}$ with $\alpha = 3.5$, $a_{\rm min} = 0.0003$ μm and $a_{\rm max} = 0.35$ μm.

Precise magnetar's distance from each model, but large scatter

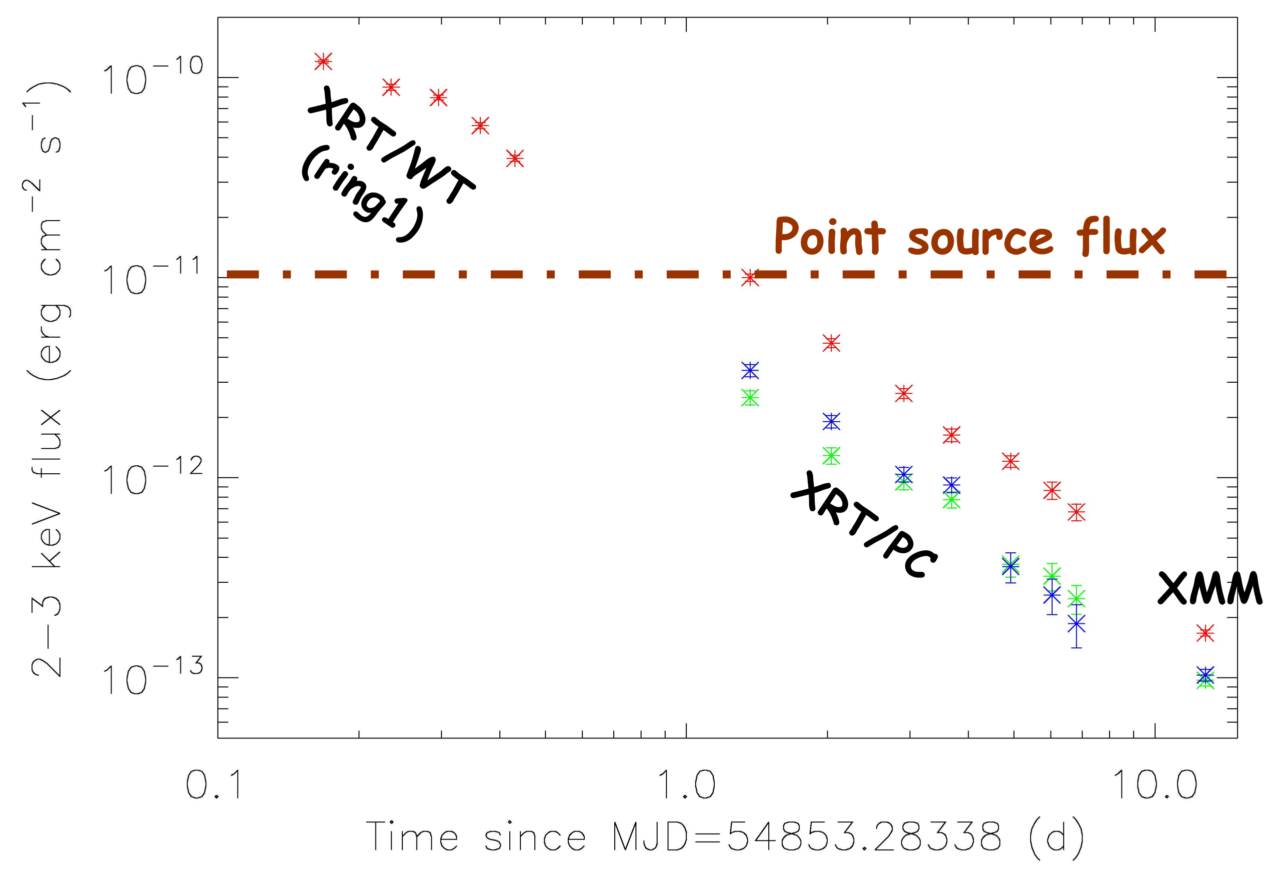
Best-fit models give d~4-6 kpc

The best-fit dust model



Cloud distances compatible with CO data *(Dame et al 2001, ApJ 547, 792)* and 1E1547 distance consistent with possibly associated SNR (d~4 kpc; *Gelfand & Gaensler 2007, ApJ 667, 1111*)

Ring lightcurve



For ~1 day the flux of the innermost ring was brighter than the persistent X-ray emission of the magnetar

⇒ if ring emission not spatially resolved, it looks like an afterglow!

Analogue to gravitational micro-lensing ⇒ micro-echo **(Tiengo et al. in prep)**

3 ways of studying interstellar dust through X-ray sources, and vice versa

1) X-ray dust halos *(persistent, or variable, extended halos):*

easy to observe (bright, possibly variable, source behind dusty regions), but **difficult to interpret** (results depend on dust distance distribution, poorly calibrated PSF wings and photon pile-up)

⇒ Observations of bright (or many) targets behind dust

2) X-ray dust echoes *(expanding rings):*

very rare (bright and short burst behind thin dust layer), but provide **robust results on dust and X-ray source** (dust distance distribution is derived from ring expansion law and ring profile is shaped by well calibrated PSF core)

⇒ Rapid follow-up observations of bright bursts behind dust clouds

3) X-ray dust micro-echoes *(burst tails):*

easier to observe (relatively bright burst behind rather concentrated dust) but **more difficult to interpret** (results depend on dust distance distribution and possible afterglow-like emission)

⇒ Bright and/or many bursts during pointed observations of active SGRs

Other wavelengths (IR, radio…) can make this tool much more powerful