Revisiting Dust Scattering Halos from X-ray Surveys with eROSITA

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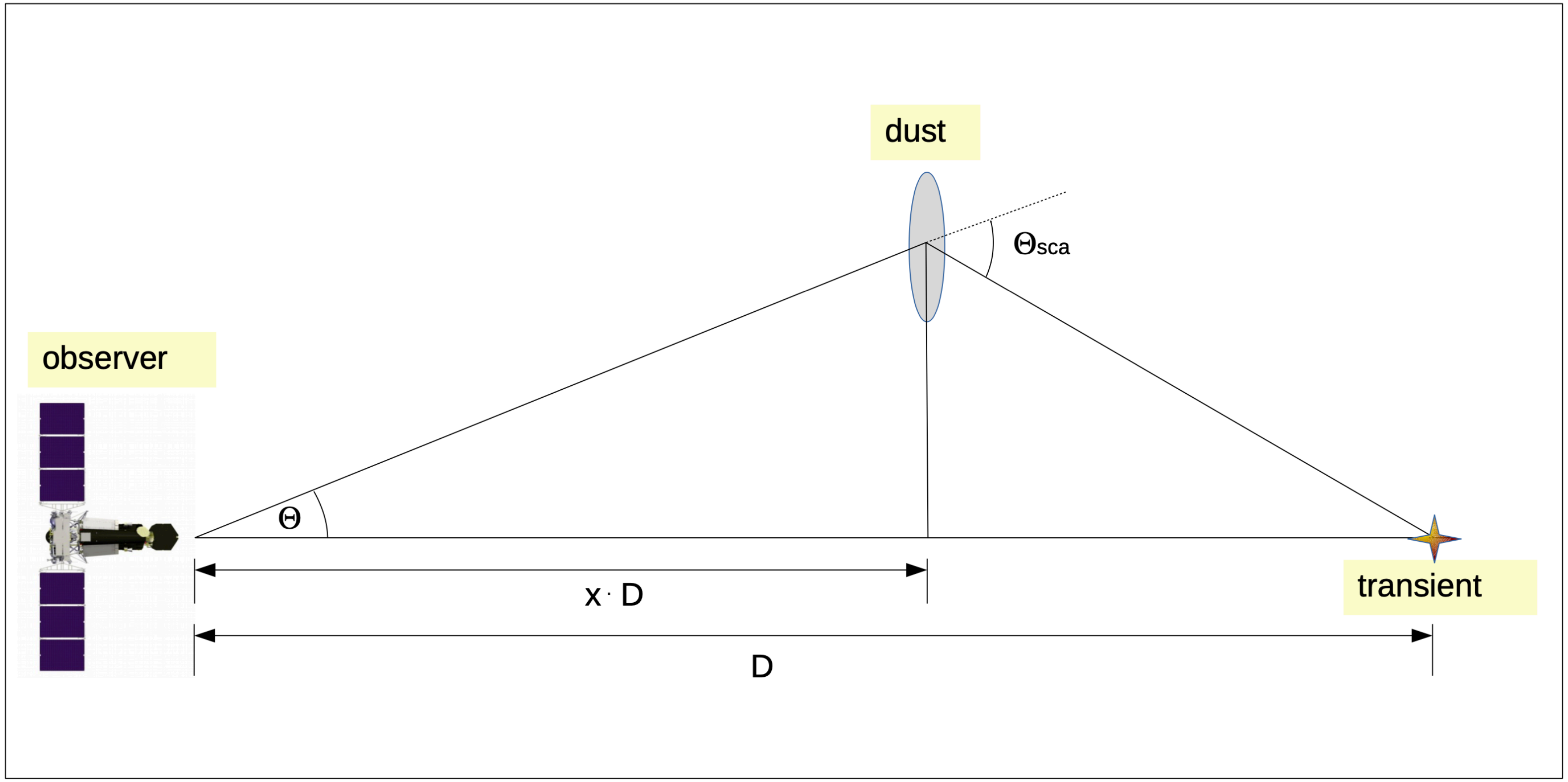
Scattering Halos – formation

Dust along line of sight can both **absorb** and **scatter** X-ray photons.

Scattering has two effects:

- Photons scattered out of direct path
- Photons scattered into extraction region

Second effect causes formation of diffuse halo around the source.



Lamer et al., 2021

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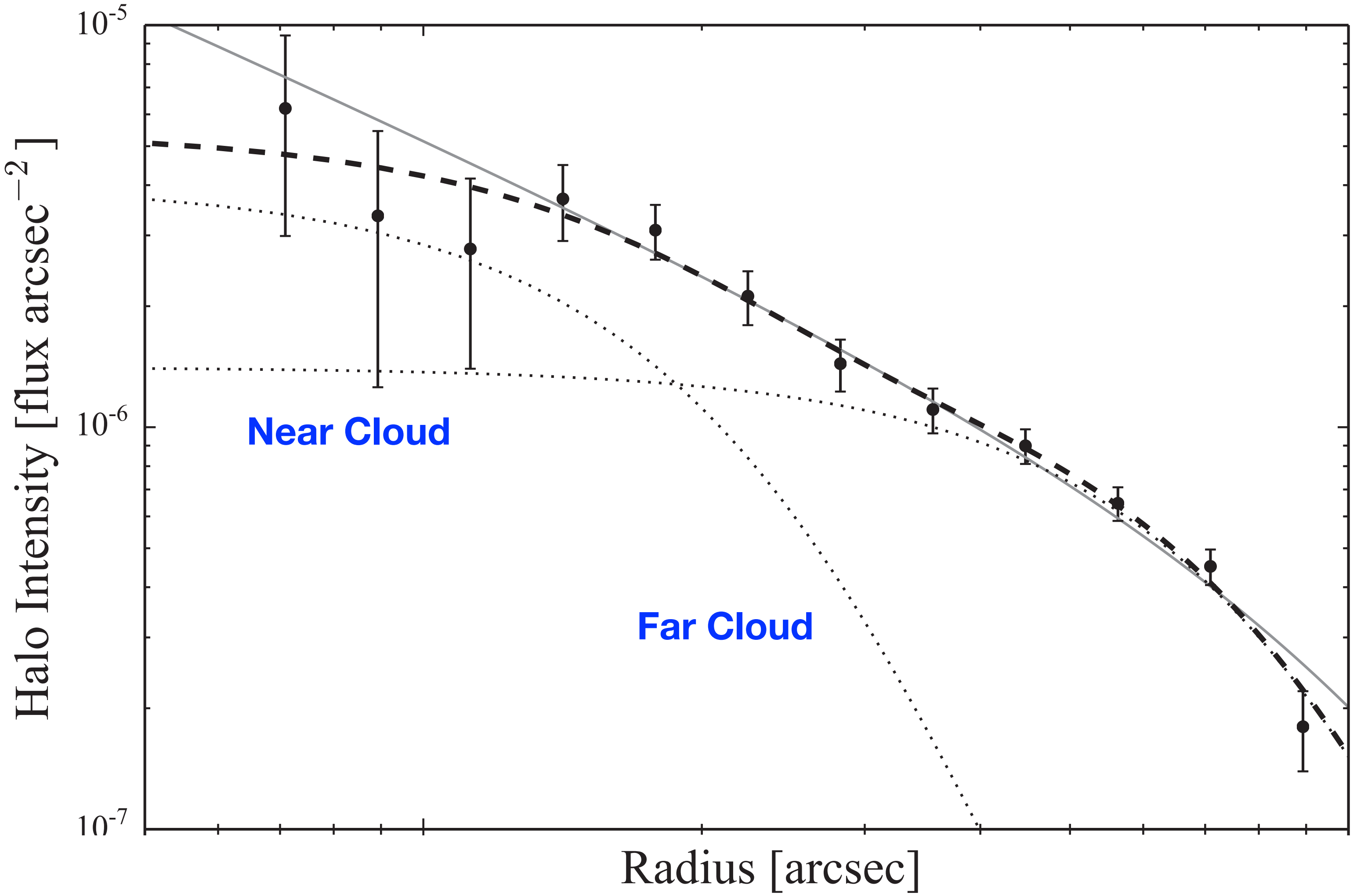


Costantini and Corrales, 2023

Scattering Halos – previous studies

Scattering halos are present around most galactic X-ray sources

Study of halos allows

- Separate analysis of line-of-sight dust (absorption includes dust and gas)
- Test of different dust population models
- Estimation of distance to sources (with known dust locations from e.g. spiral arms)

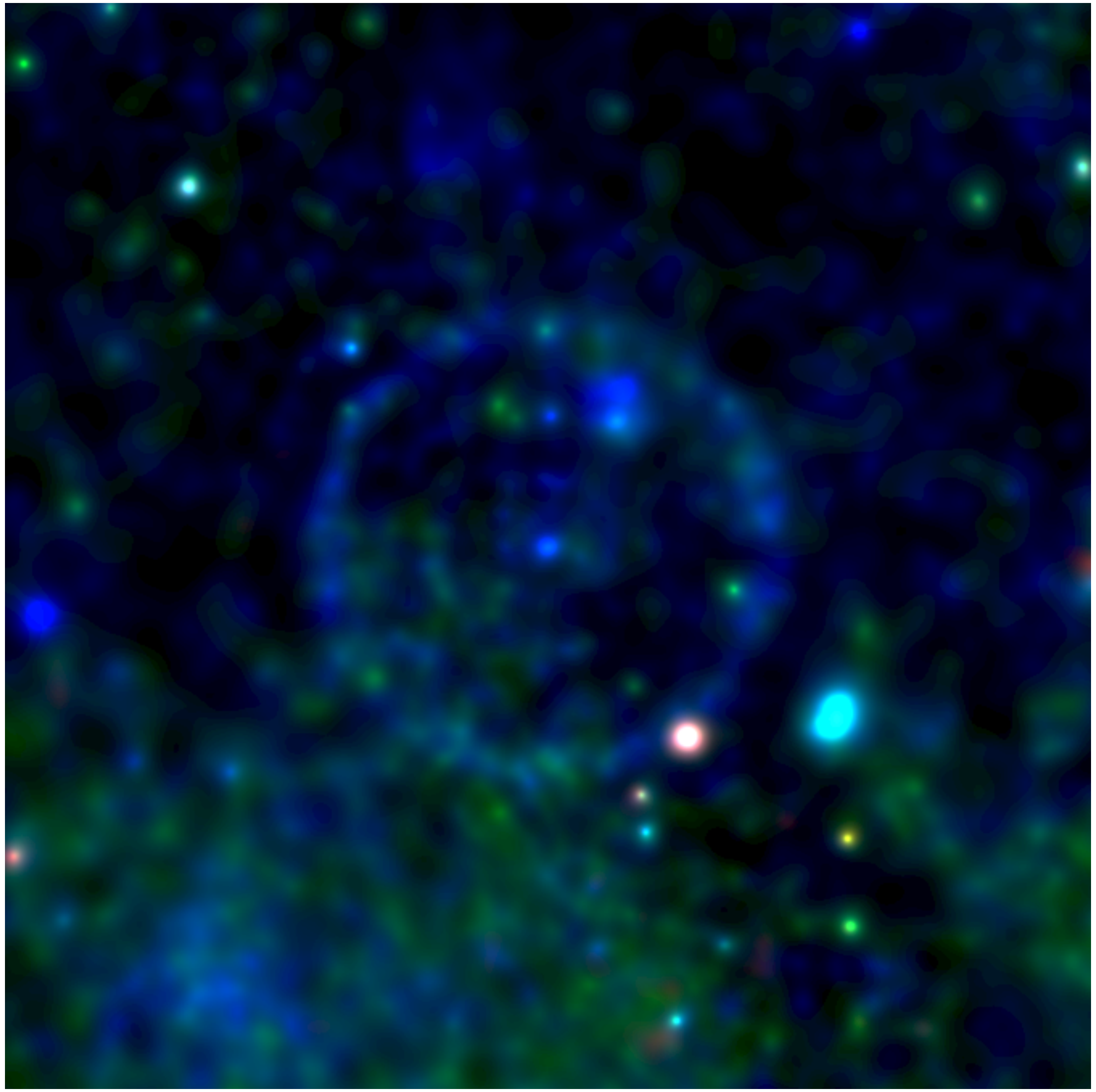
Scattering halos were previously studied in dedicated obserations, but also in surveys, e.g.

- *ROSAT* (Predehl & Schmitt, 1995)
- Archival *Chandra* and *XMM Newton* observations (Valencic & Smith, 2015)

Halos in *eROSITA*

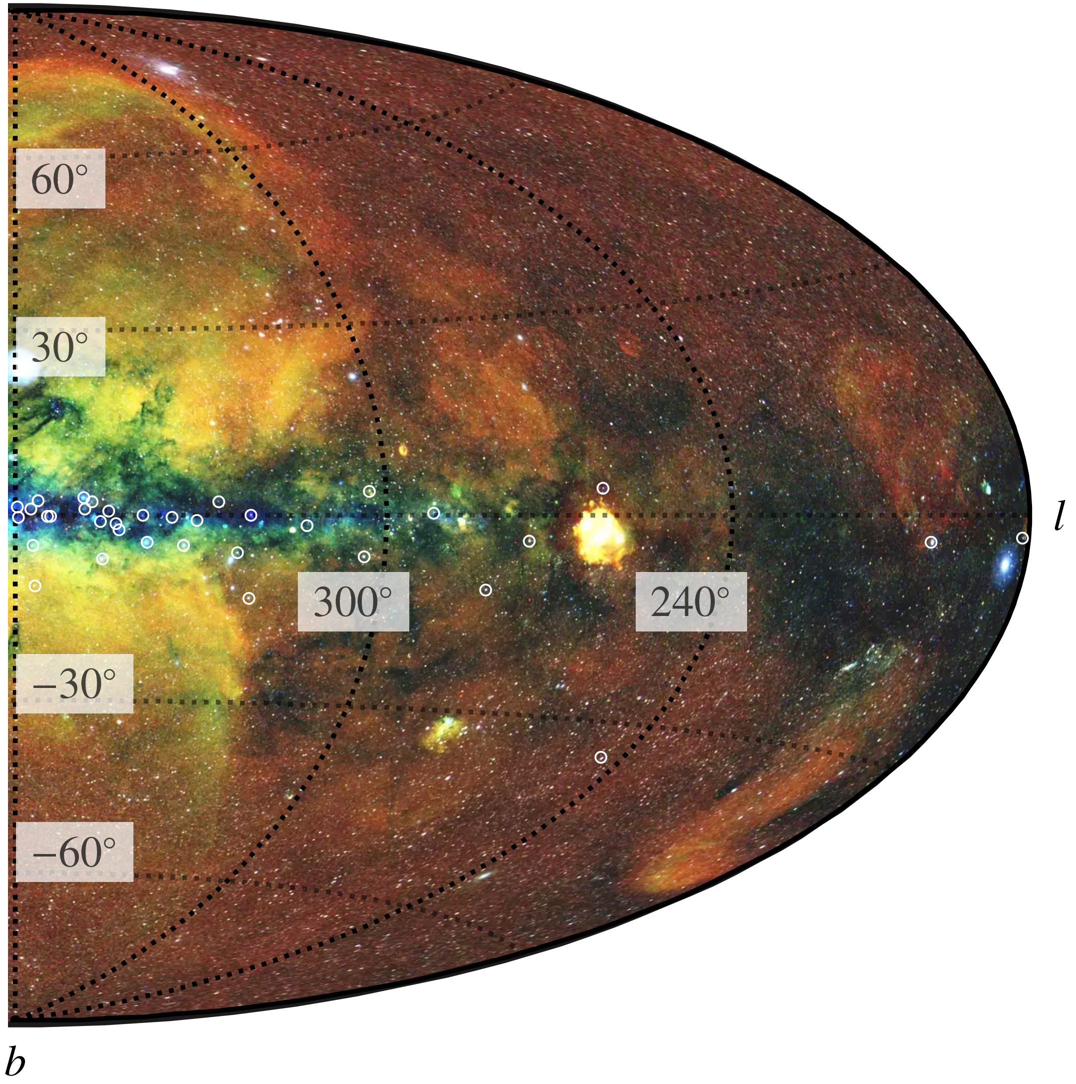
As a survey telescope, *eROSITA* observes many scattering halos.

Lamer et al., 2021 reported a dust scattering echo around a black hole transient in eRASS 1:



Halos in *eROSITA*

We selected 35 sources that are sufficiently bright for halo extraction.
Mostly known XRBs in the galactic plane.



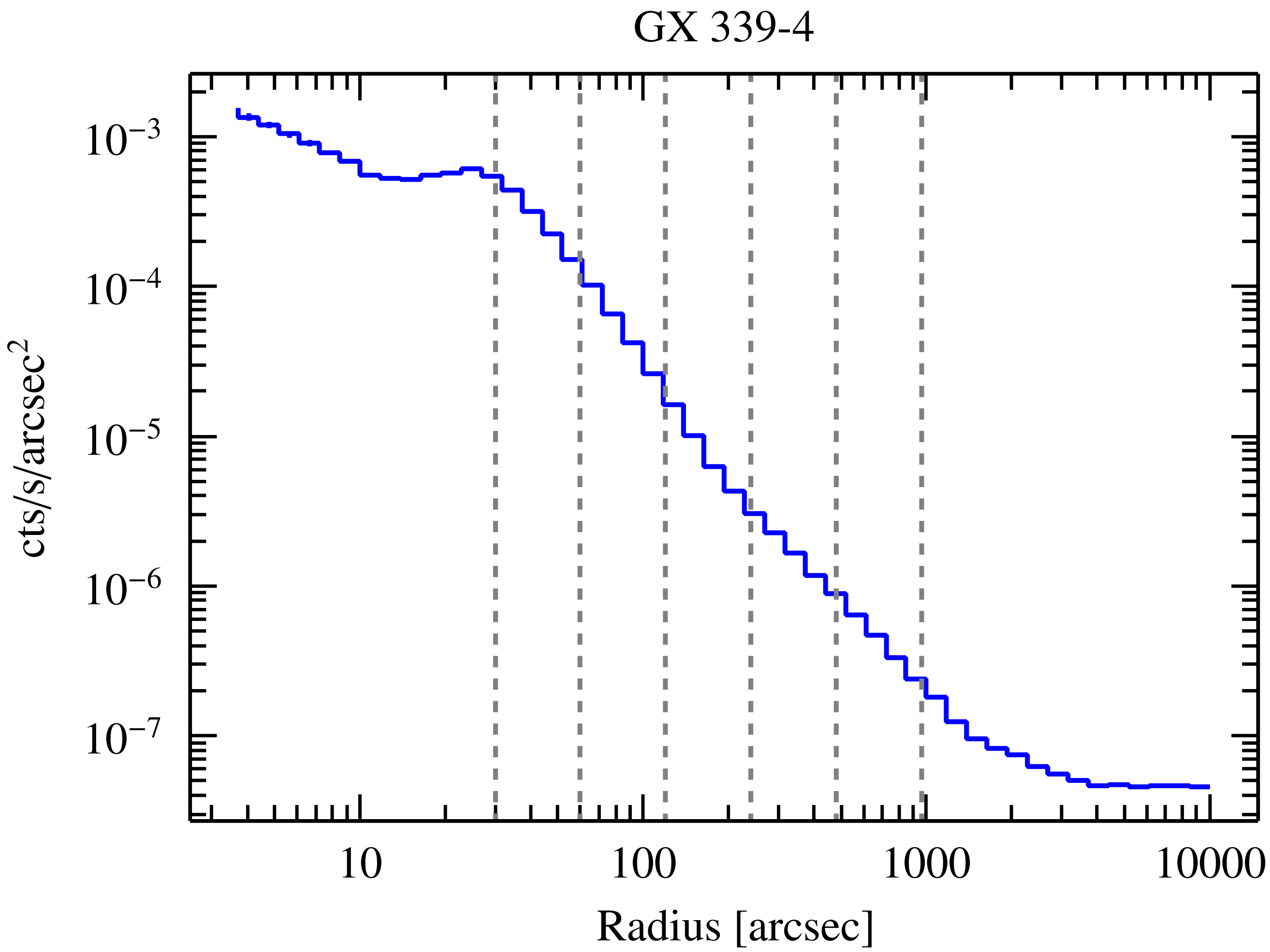
Spectral Extraction

Radial surface brightness distribution shows pile-up, especially for very bright sources.

Use SIXTE (Dauser et al., 2019) simulations to determine which surface brightnesses are safe from pile-up ($< 1\%$).

Here: Count rates
below $\sim 10^{-4}\,\mathrm{cts/sec/arcsec^{-2}}$

Extract spectra from predefined annuli for fitting



`xscat` model and fitting

In a given annulus, extracted photons come from **two components**:

Direct point source and scattered into annulus

Use the `xscat` model (Smith, Valencic, & Corrales, 2016) to fit both components:
For given radius R, `xscat` calculates **fraction of source flux within a circular region**

So for a given source model:

- $\texttt{xscat}(R = 0) * \texttt{source\_model}$ = Direct point source
- $(\texttt{xscat}(R = R_{\text{out}}) - \texttt{xscat}(R = R_{\text{in}})) * \texttt{source\_model}$ = scattered into annulus

Then, per annulus, fit measured counts as **combination of both components**, and fit all annuli **simultaneously**

Note: Need to extract separate ARFs for each component: scattered flux is an extended source, direct flux is a point source

Example Spectrum

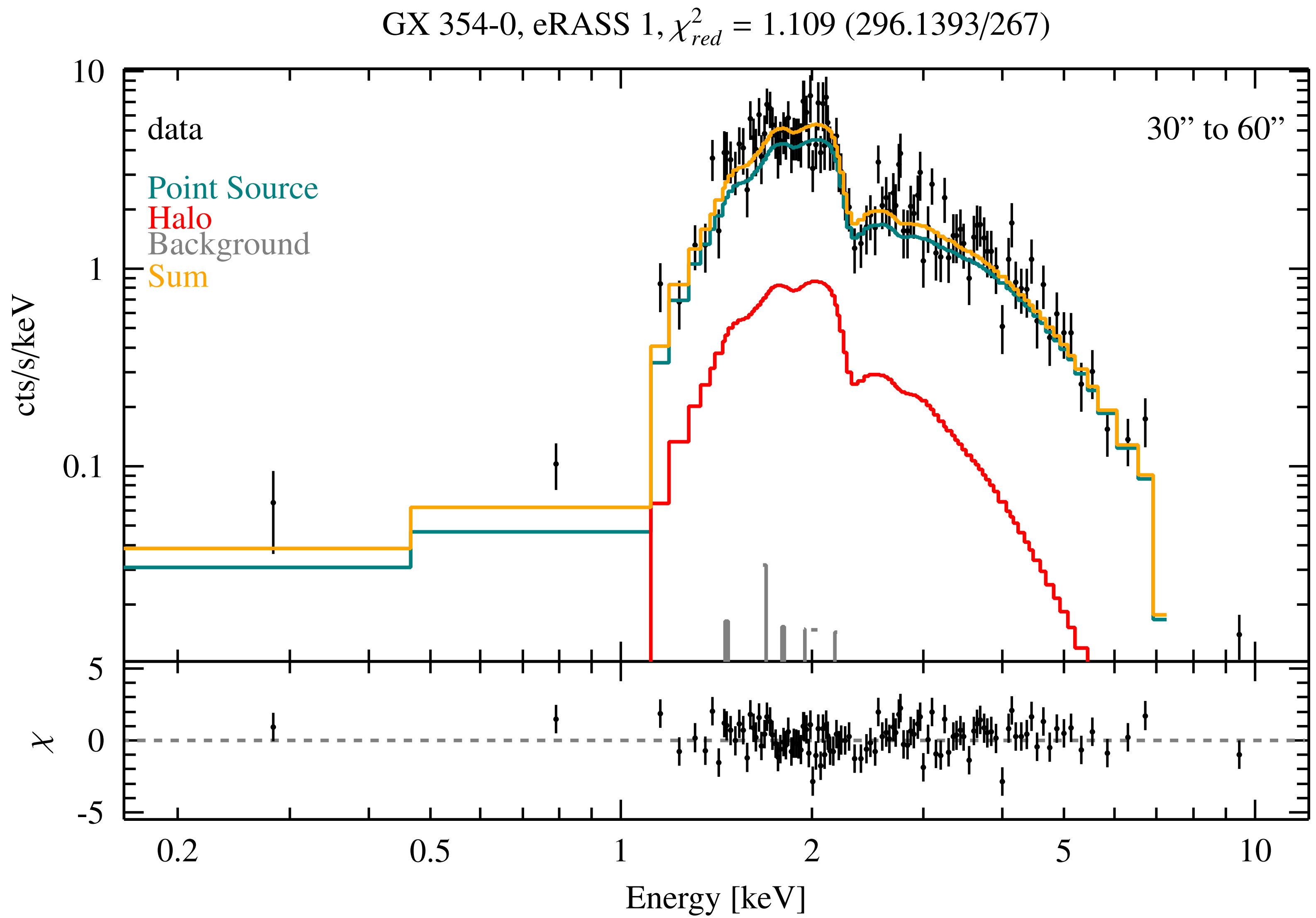
Example Source: GX 354-0

Model:
`xscat * (tbabs * powerlaw)`

$N_{\mathrm{H,abs}} = 4.29^{+0.27}_{-0.25} \cdot 10^{22}\,\mathrm{cm}^{-2}$

$\Gamma = 2.29^{+0.14}_{-0.14}$
norm $= 0.79^{+0.17}_{-0.14}$

$N_{\mathrm{H,sca}} = 2.42^{+0.39}_{-0.27} \cdot 10^{22}\,\mathrm{cm}^{-2}$
$x_{\mathrm{sca}} = 0.50^{+0.06}_{-0.06}$



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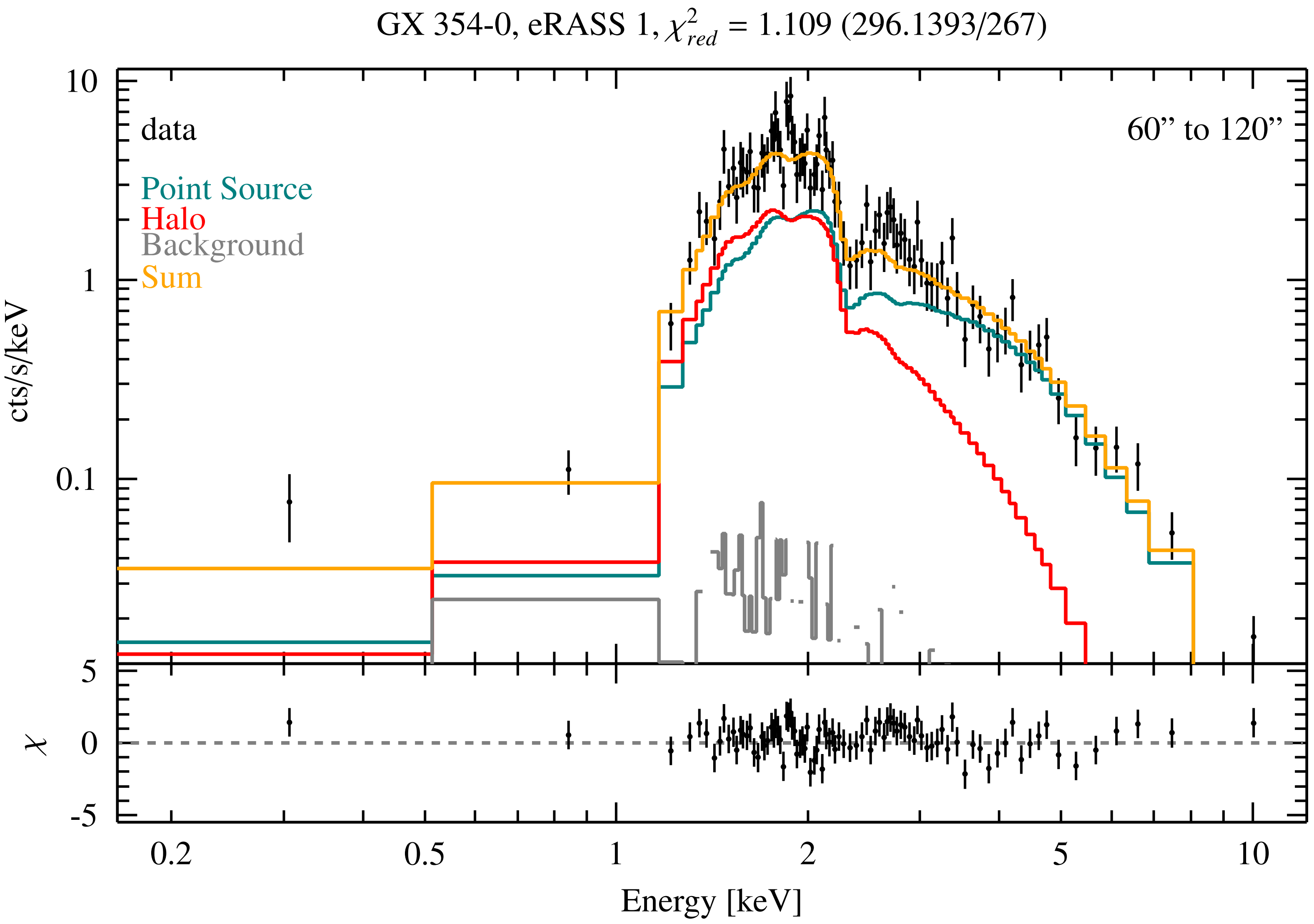

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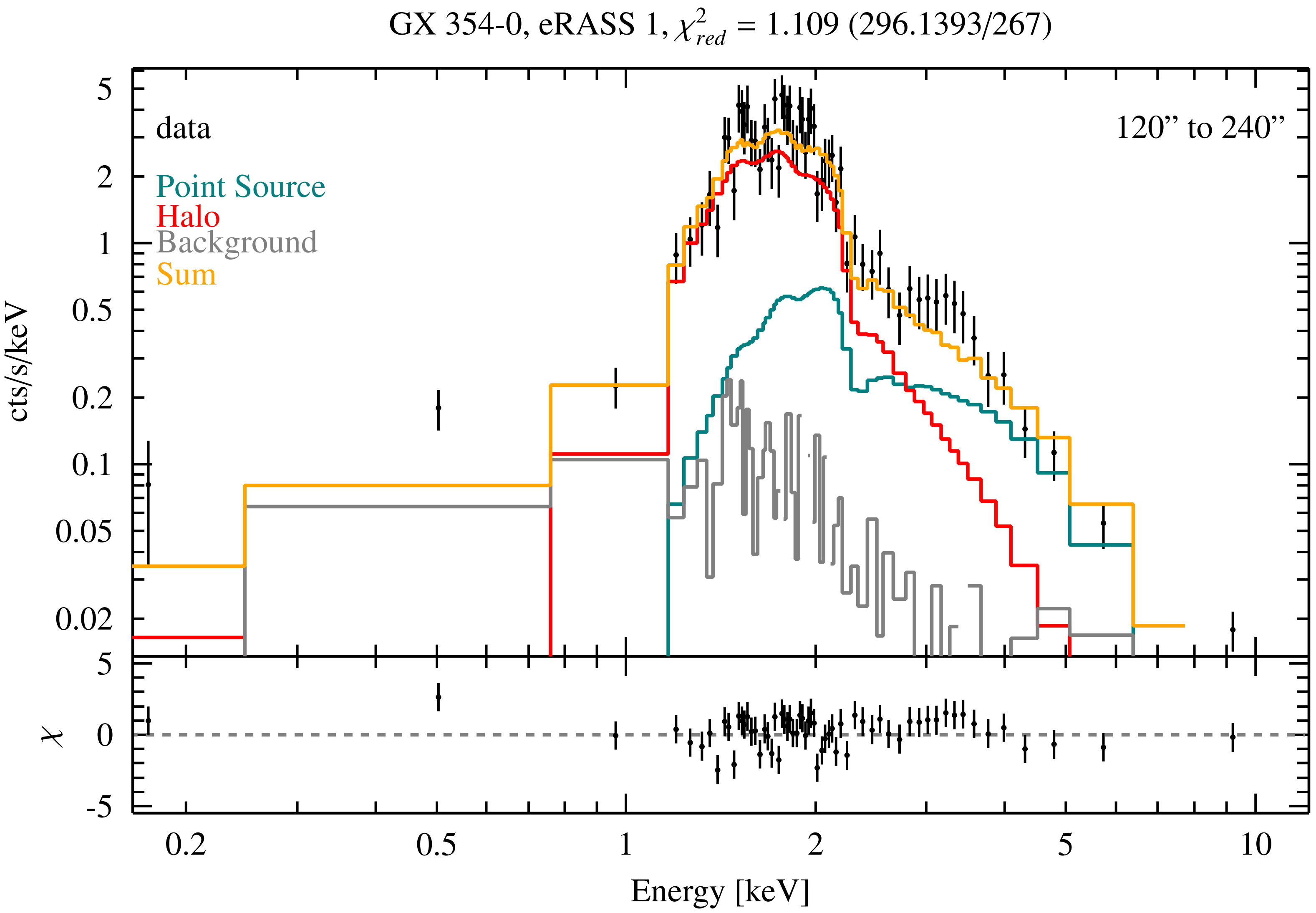
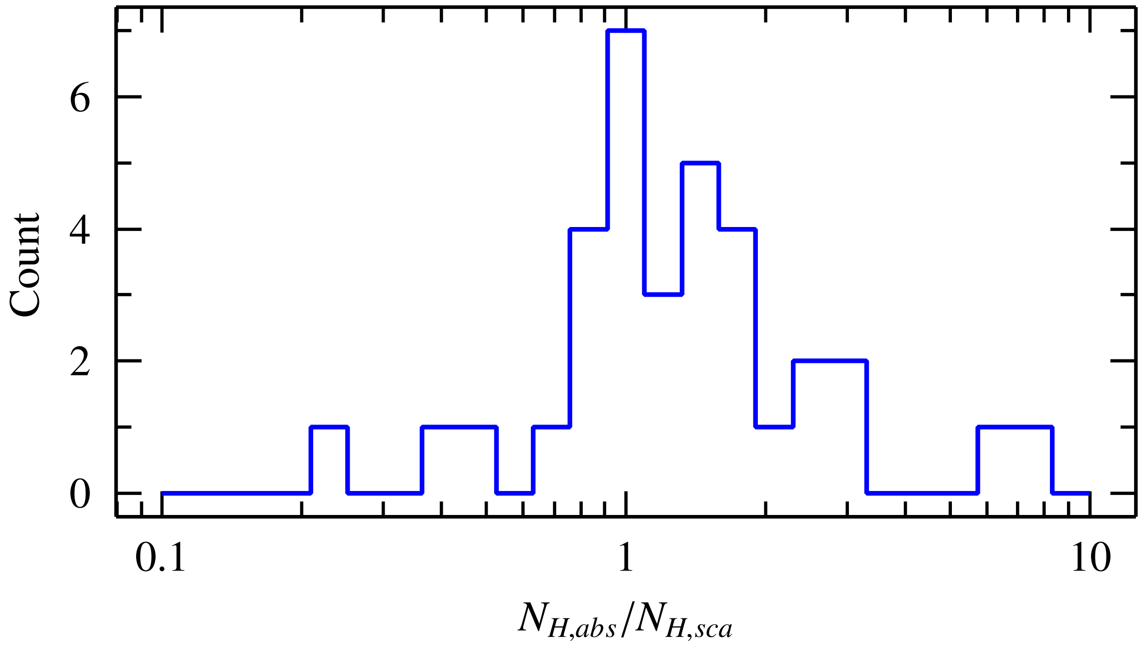
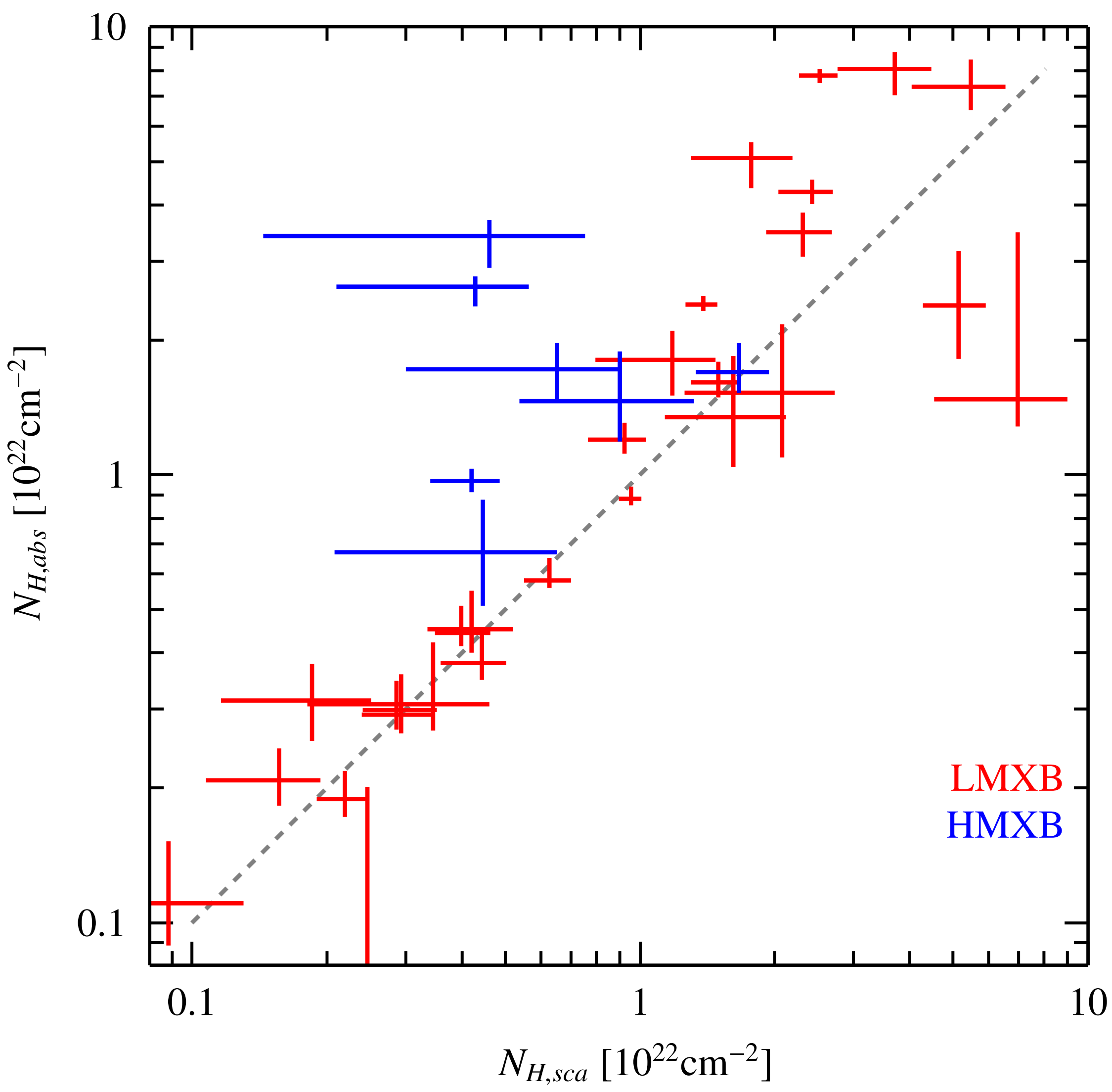


Results: $N_{H,abs}$ vs $N_{H,sca}$

Using all sources, can plot the ratio of N_H in absorption compared with N_H in scattering



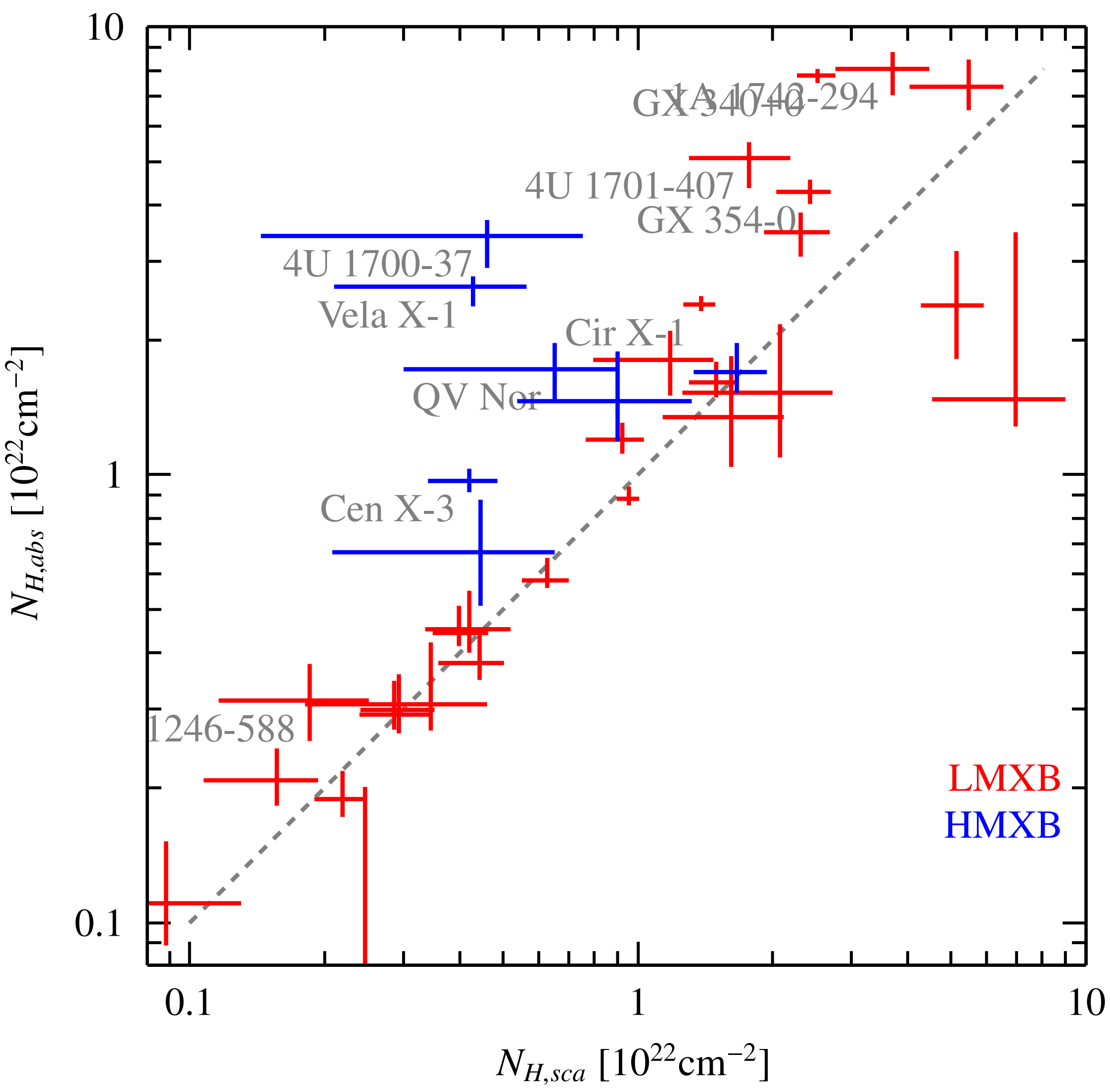


Results: Local absorption

Several sources have an excess of N_H in scattering.

Most of these sources are known to have local absorption, due to stellar wind or viewing angle through accretion disc.

$\Longrightarrow$ separate local N_H from interstellar N_H!



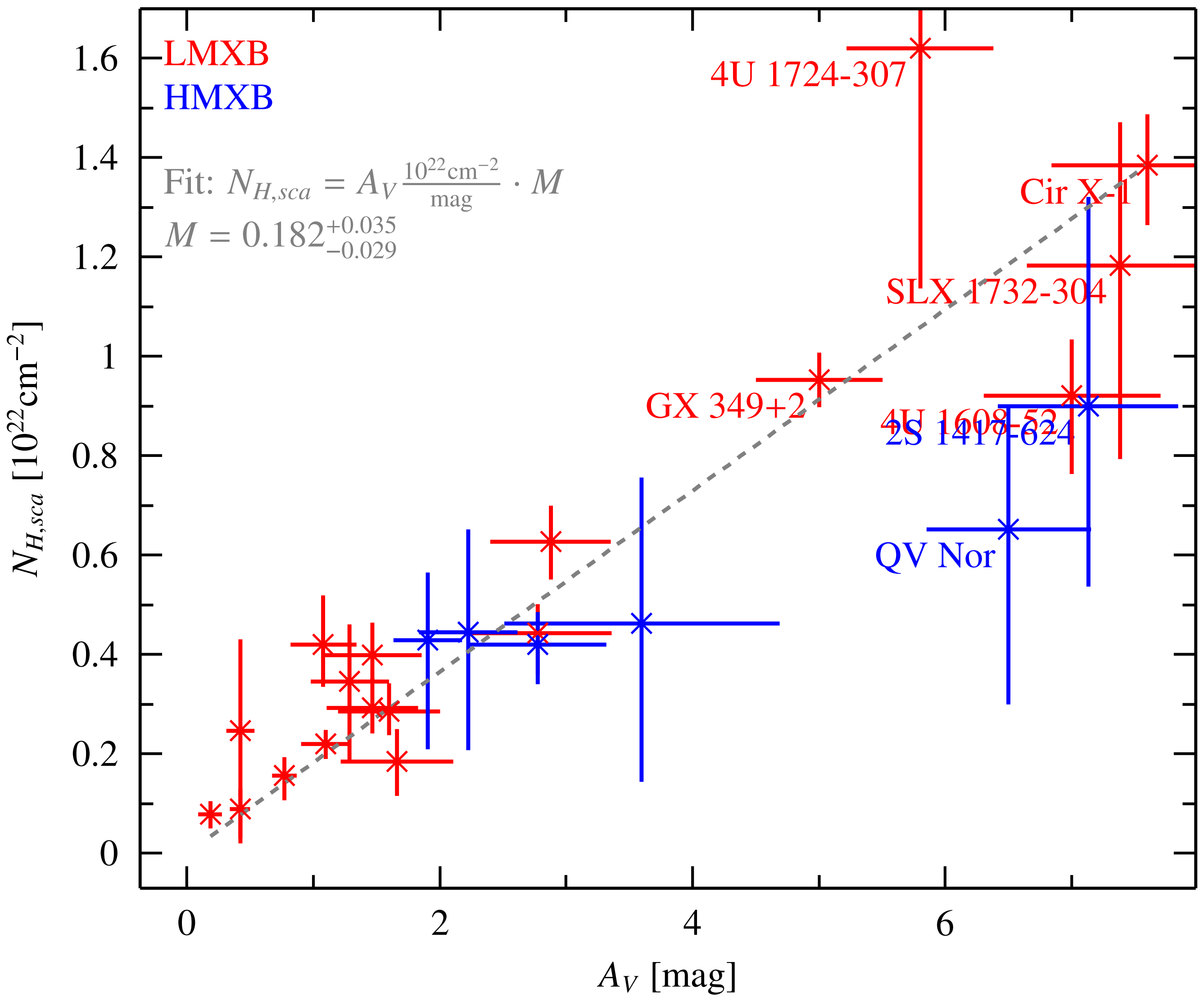
Results: A_V vs $N_{H,sca}$

Use this dataset to re-determine the A_V to N_H ratio from Predehl and Schmitt, 1995

Below $A_V = 4$ mag, values are extracted from Gaia using StarHorse (Queiroz et al., 2023).
Above, values are taken from the literature where available.

Fitted relation:
$N_{H,sca}/A_V = 0.182^{+0.035}_{-0.029}\ 10^{22}\,\mathrm{cm}^{-2}\,\mathrm{mag}^{-1}$

Very similar to value of 0.179 ± 0.003 from Predehl and Schmitt, 1995



Results: A_V vs $N_{\mathrm{H,sca}}$

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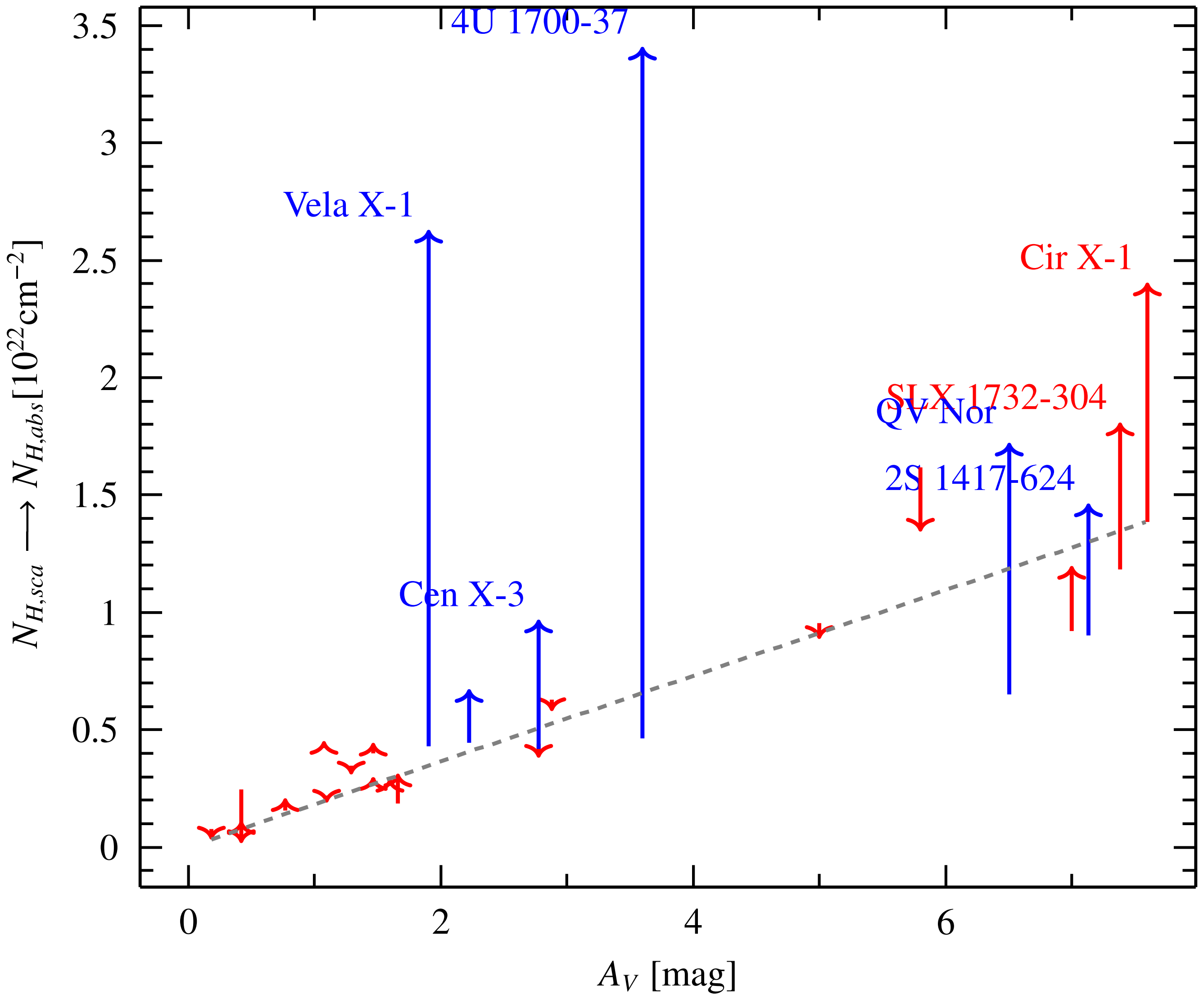
However, N_{H} corresponds only to interstellar absorption!

Local absorption must be removed, either extracted from the scattering halo or by estimation with, e.g., variability.



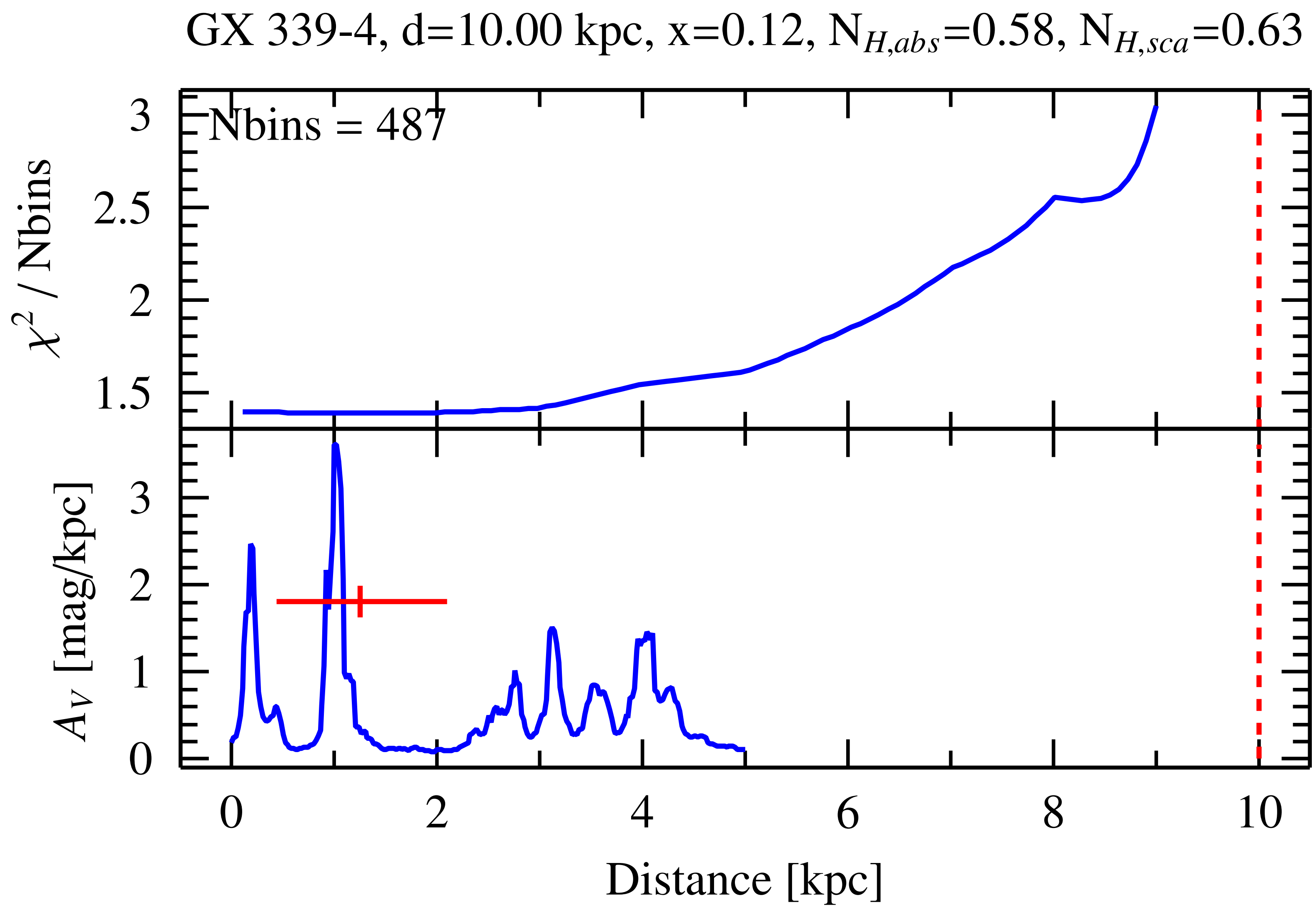
Results: Location of dust

`xscat` fits also include fractional distance x to scattering screen

$\Longrightarrow$ with estimate of distance to source, can estimate distance to dust screen

Compare to 3D optical extinction maps (Vergely, Lallement, & Cox, 2022)

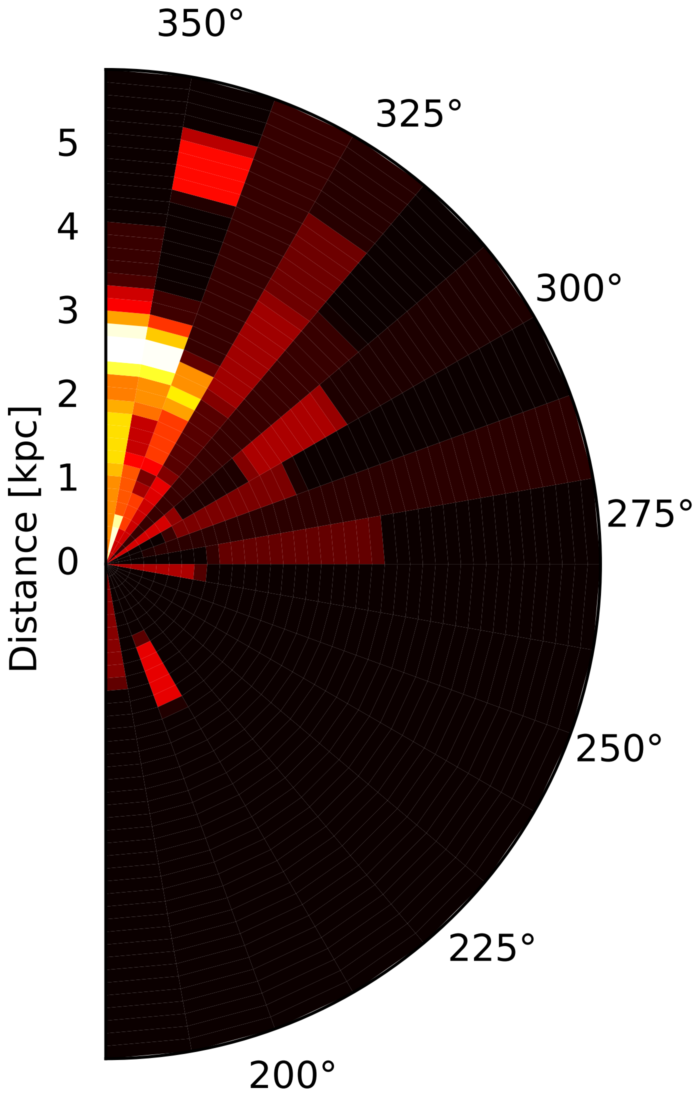
Note: Distance to X-ray sources is often quite uncertain!



Results: Location of dust

Adding all sources together, we find a concentration of dust at 2 to 3 kpc towards galactic center

⟹ Scutum-Centaurus Arm?



Summary and further steps

Summary

- Analyze dust scattering halos in *eROSITA* by simultaneously fitting unscattered and scattered photons
- Fitting approach allows separation between local and interstellar N_H
- N_H in scattering correlates to optical extinction
- Fitted dust locations correspond to nearby spiral arms

Further Steps

- Fit spectra to farther annuli
  Currently restricted by *eROSITA* PSF only being known out to 240"
- Compare different dust models
  Currently using Zubko, Dwek, and Arendt, 2004 with bare grains and graphite, solar abundances

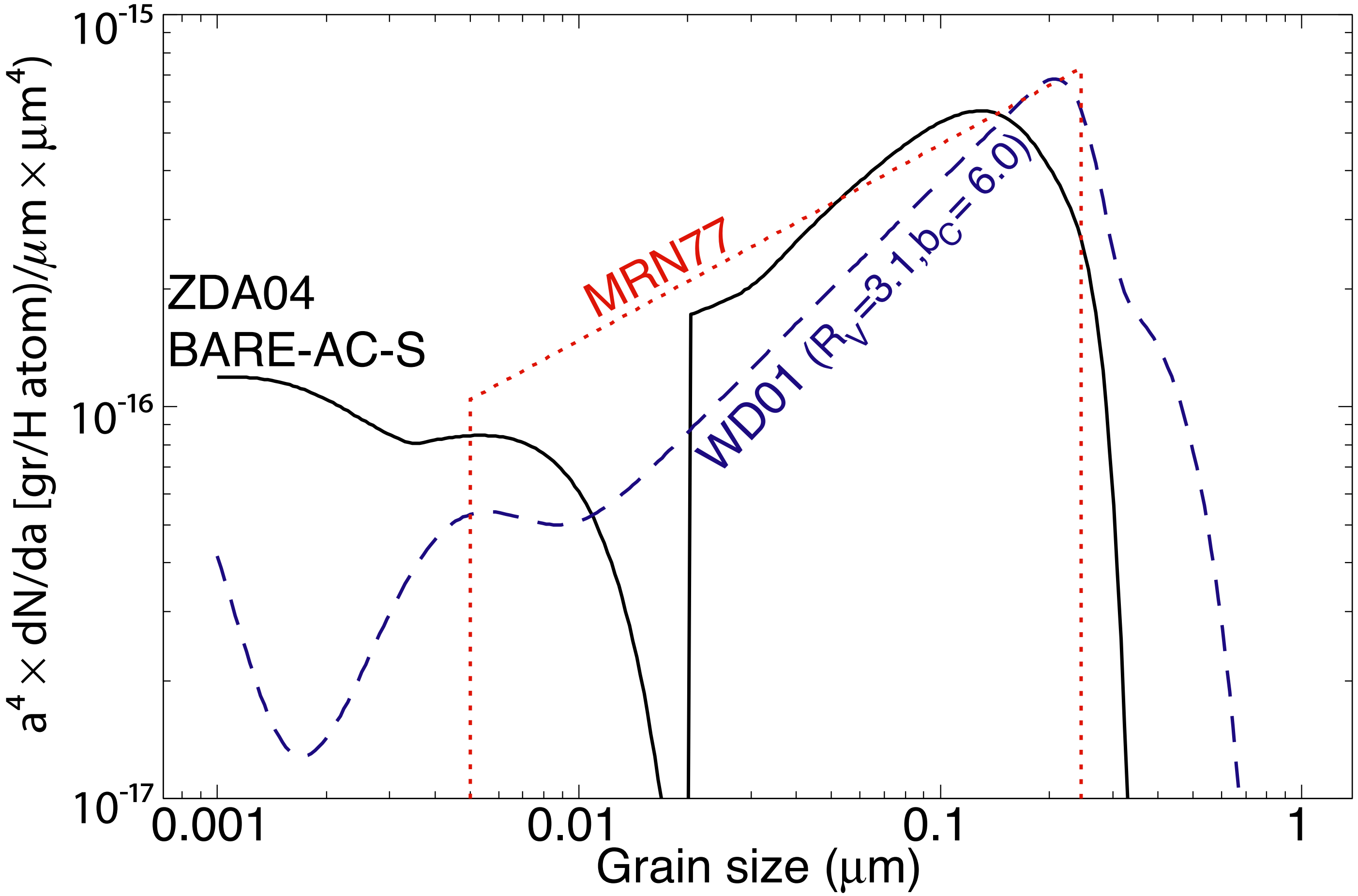
Thank you for your attention!

Backup – Dust models

`xscat` includes multiple dust models

- Mathis, Rumpl, and Nordsieck, 1977
- Zubko, Dwek, and Arendt, 2004 families
- Weingartner and Draine, 2001 families

This varies grain size distribution (right) and grain composition



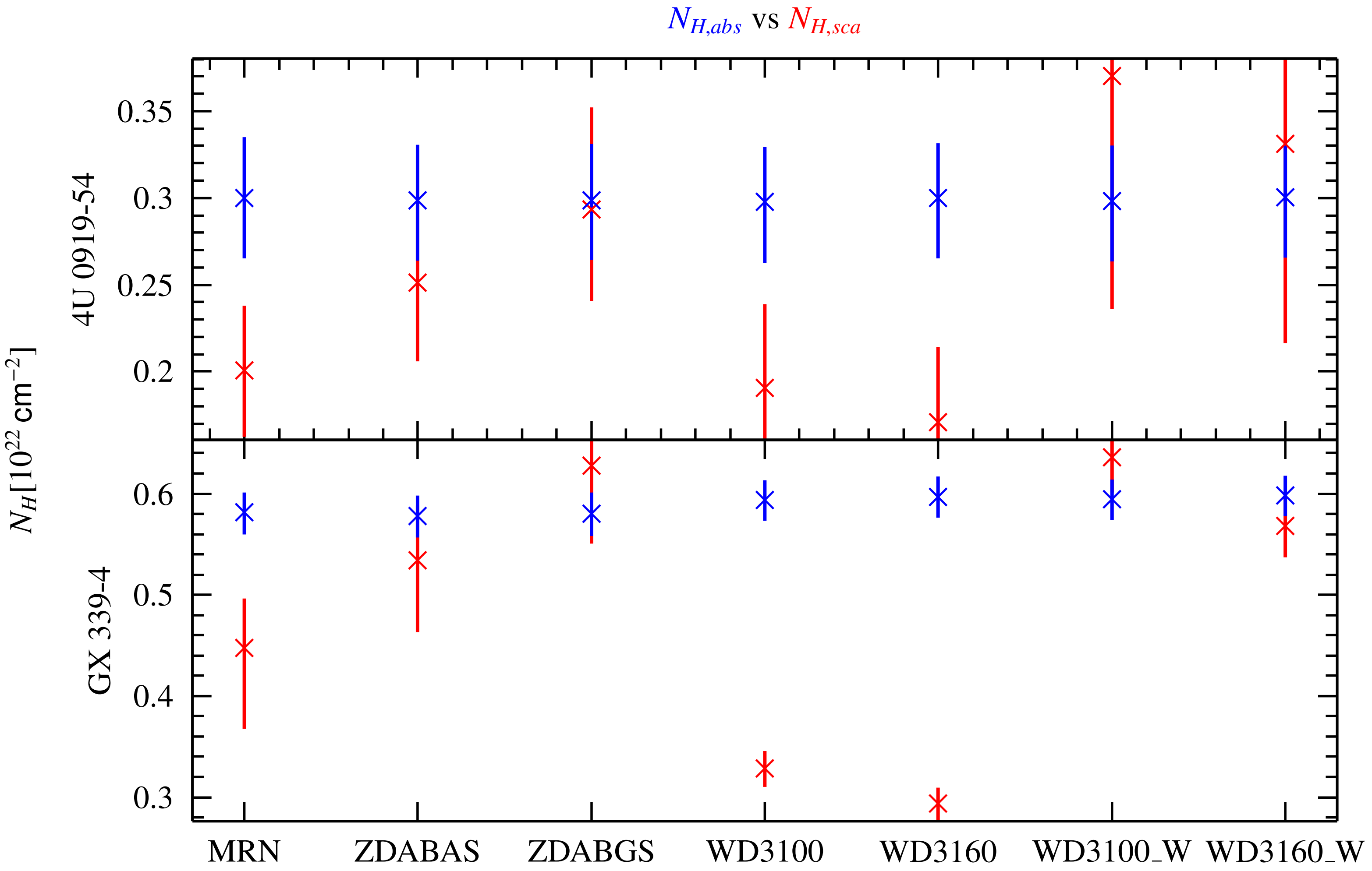
Smith, Valencic, and Corrales, 2016

Backup – Dust models

Different models yield different $N_{\mathrm{H,sca}}$

However, $N_{\mathrm{H,abs}}$ and other source parameters don't change significantly

Results in this presentation use ZDABGS, which was also favored by Xiang, Lee, Nowak, and Wilms, 2011



_W models have abundances internally adjusted to `wilm`

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