Studying Interstellar Dust Grain Composition

with X-ray spectroscopic imaging

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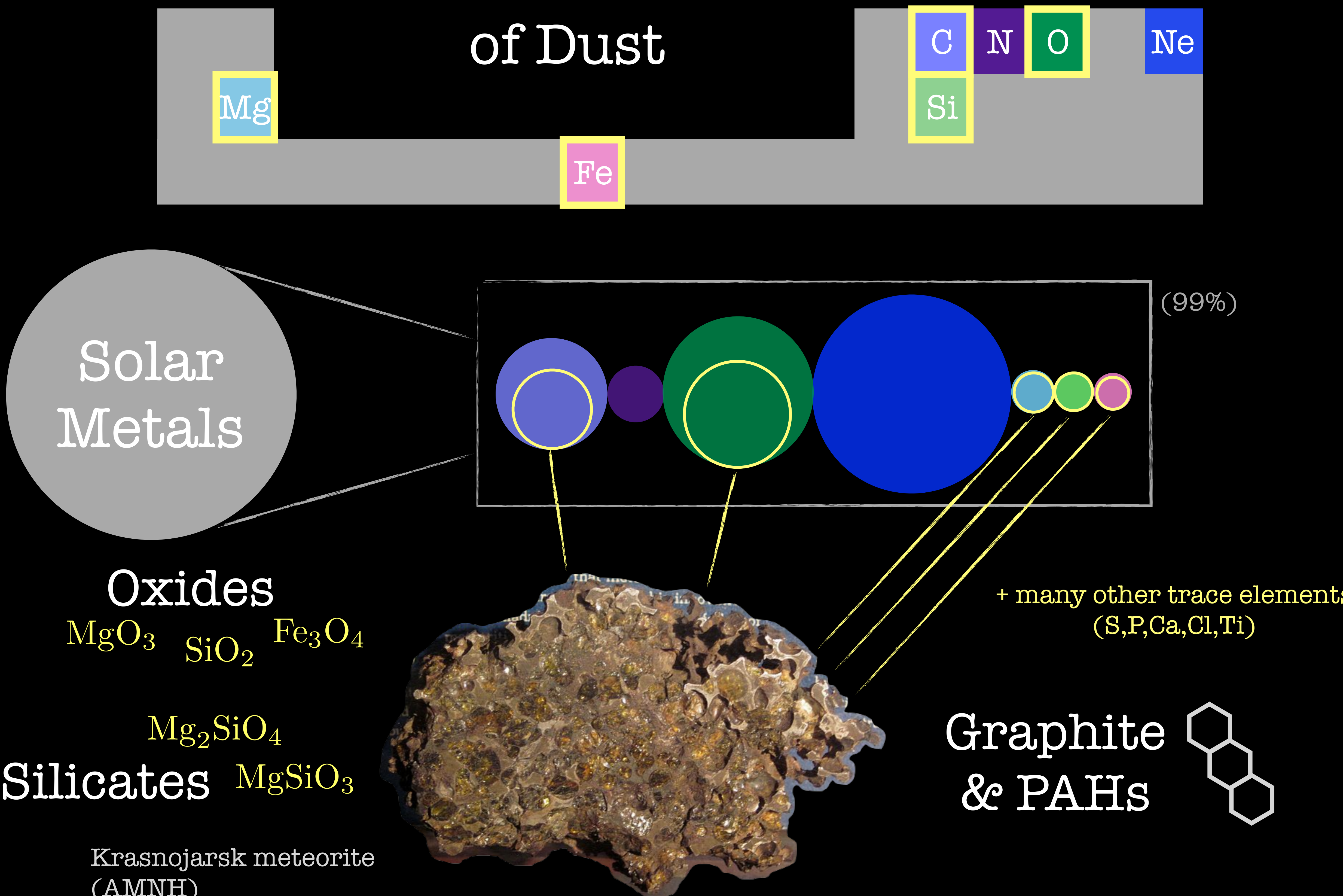
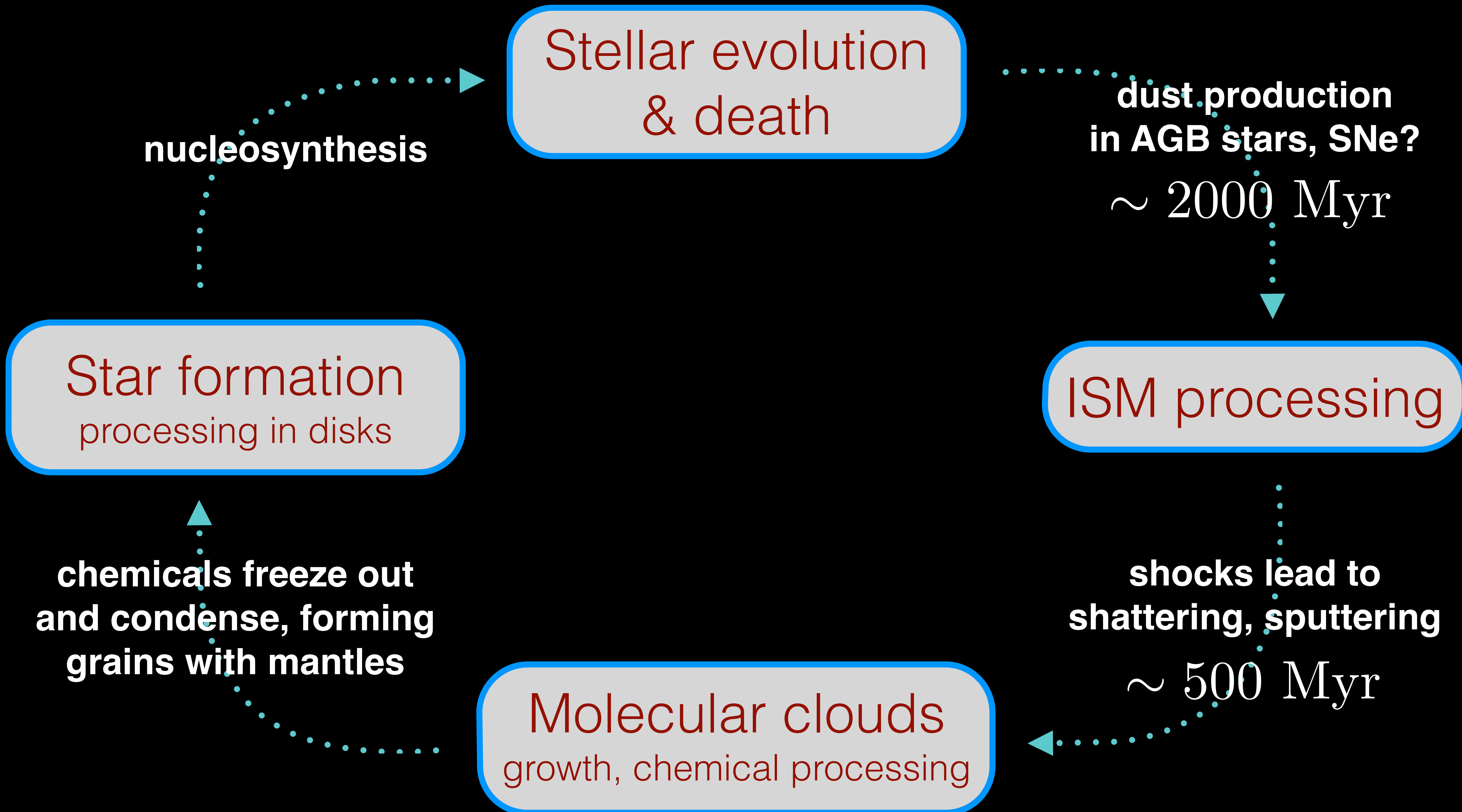
Periodic Elements of Dust



Dust Life Cycle



Tielens
Jones & Tielens 1994, 1996

Big questions

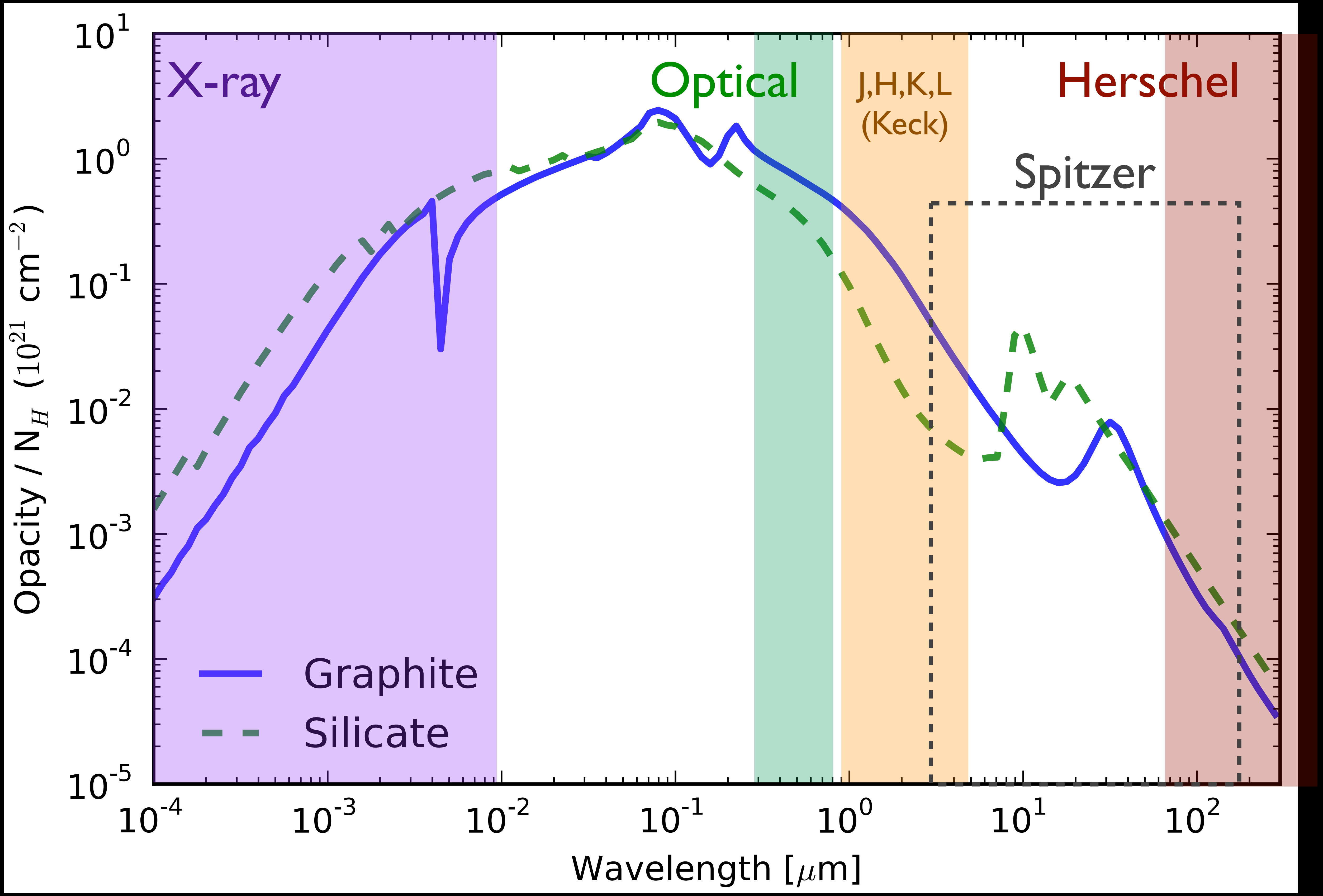
1. What is **dust grain composition** in diffuse ISM?
2. **Where does dust grow** and **how big can it get**?
3. How does dust influence the **physics of the ISM**: star formation, feedback, and galaxy evolution?

Using bright X-ray point sources as beacons,
we can **probe the dust and gas** properties
of the **cool phase Universe**.

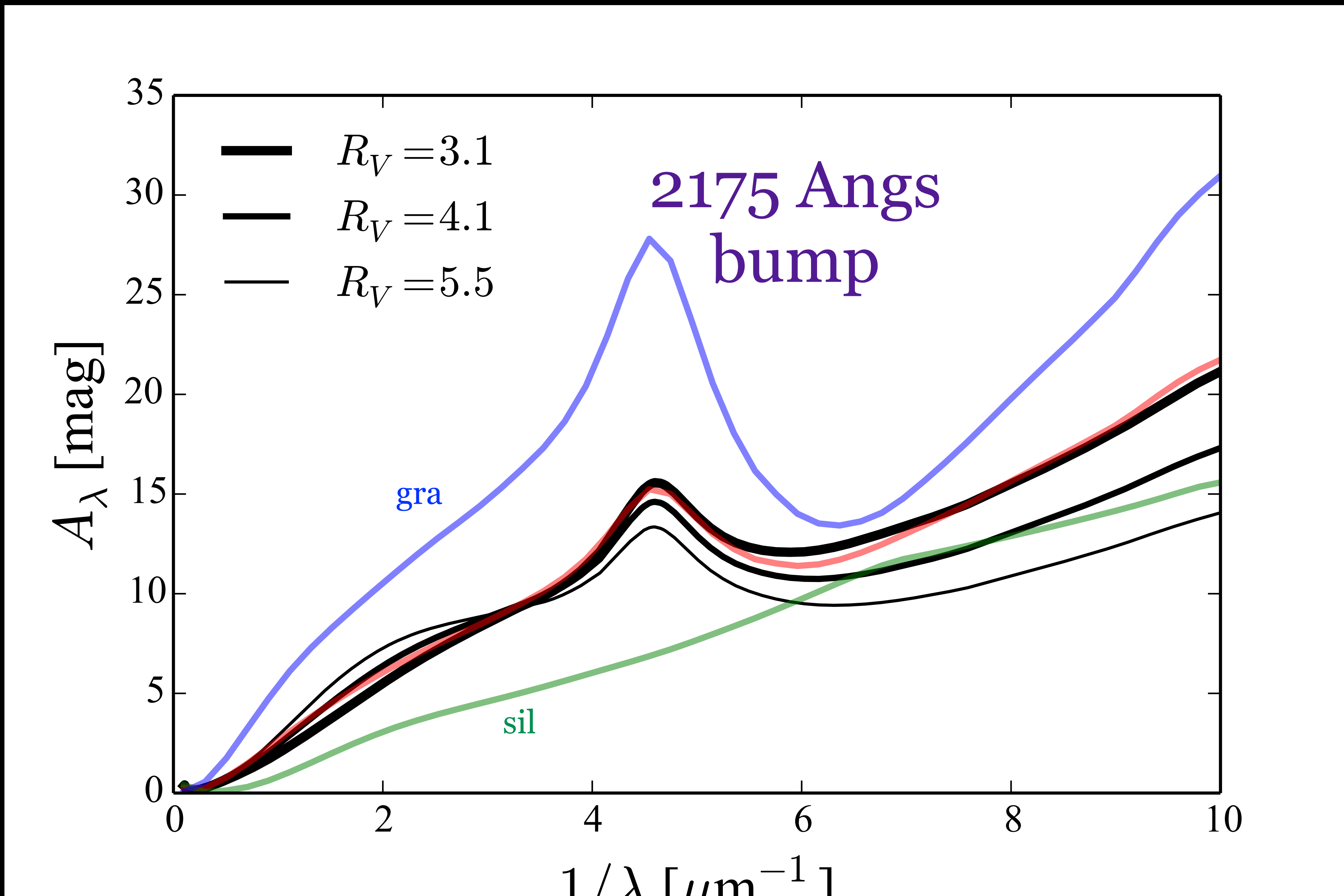
absorption
probes total metal column (dust + gas)

scattering
probes large end of the grain size distribution

Milky Way optical depth due to dust



Dust model used in this talk



MRN 1977

$$\frac{dn_d}{da} \propto a^{-3.5}$$

$$0.005\mu\text{m} \leq a \leq 0.3\mu\text{m}$$

Astrosilicate and **Graphite** optical constants from Draine (2003)

60% silicate
40% graphite

no amorphous, iron needles,
or low-filling factor ("fluffy") dust

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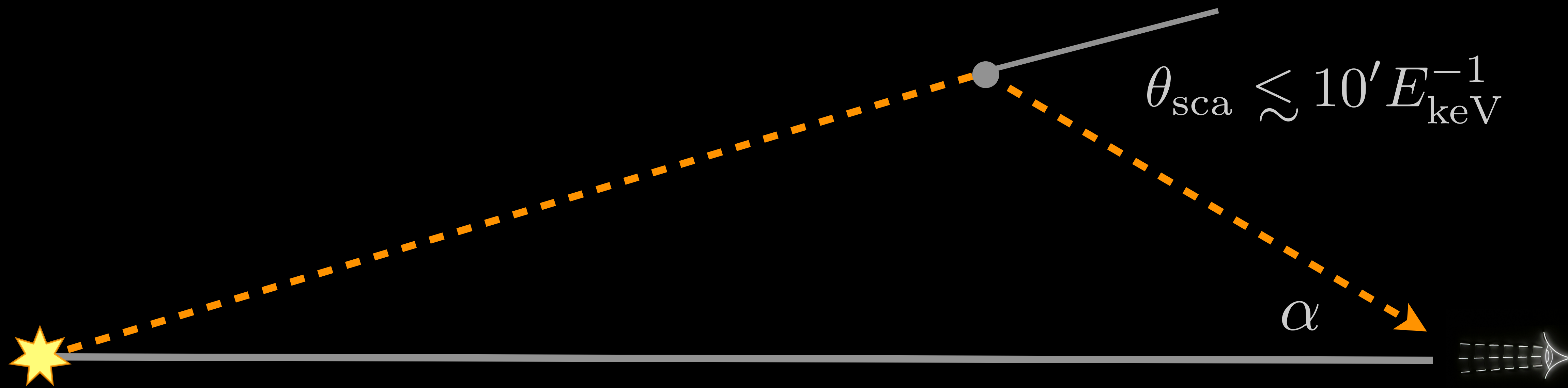
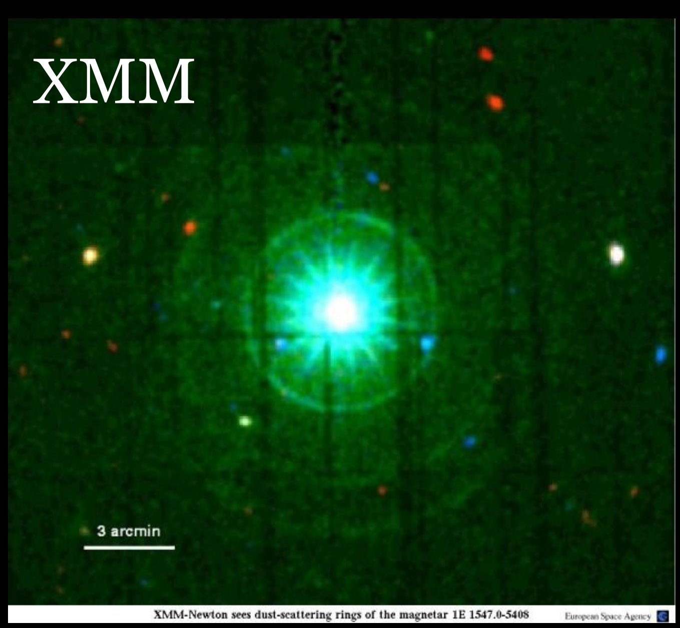
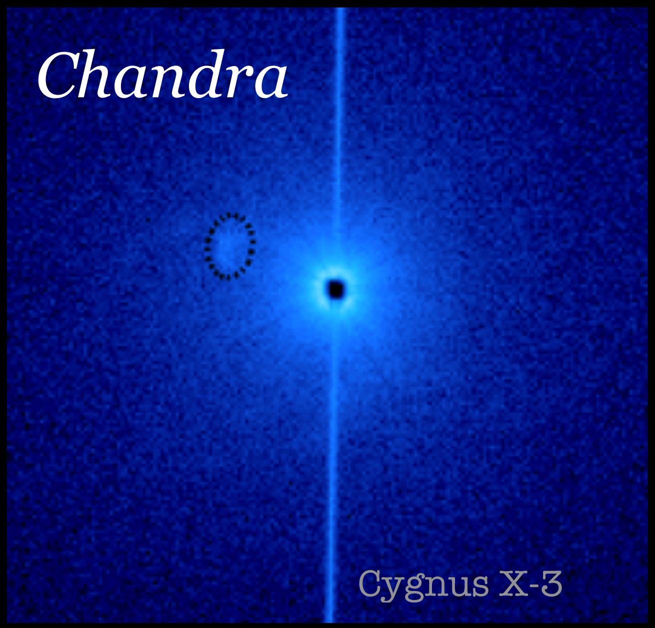
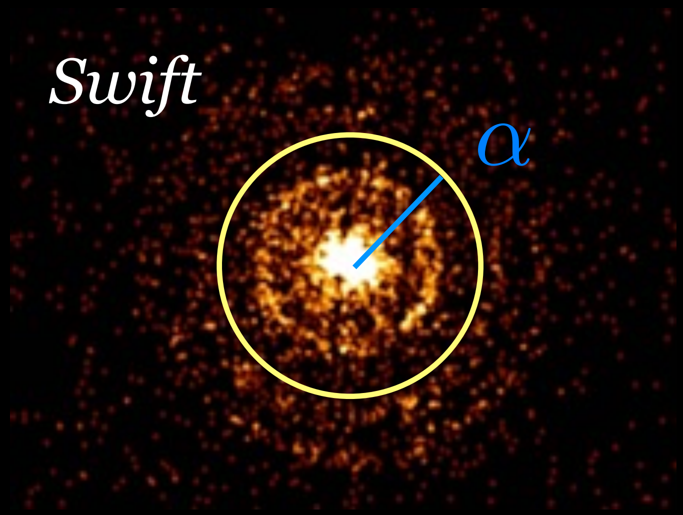
light scattered by dust **intermediate in line of sight** produces a scattering **halo image**





IE 1547.0-5408 (ESA)

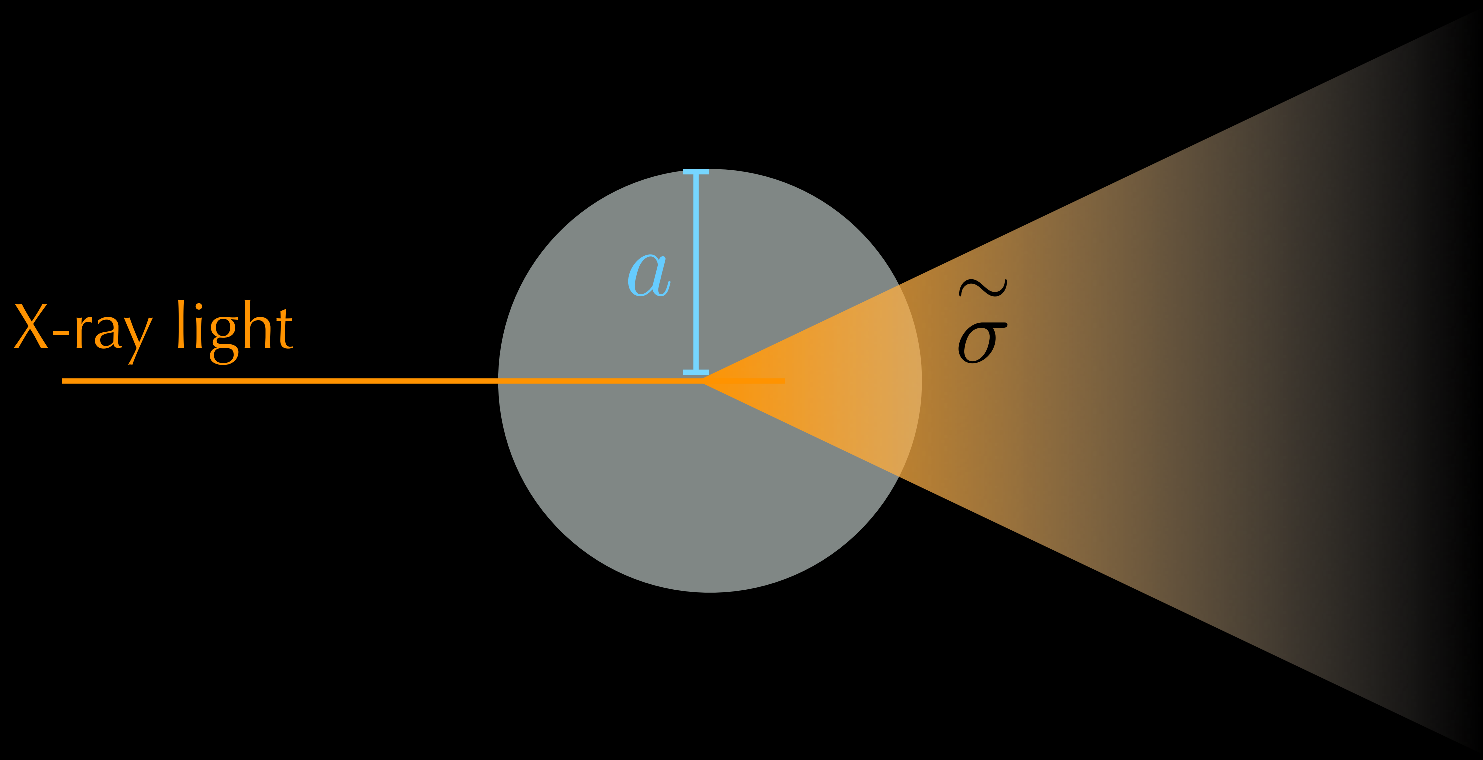


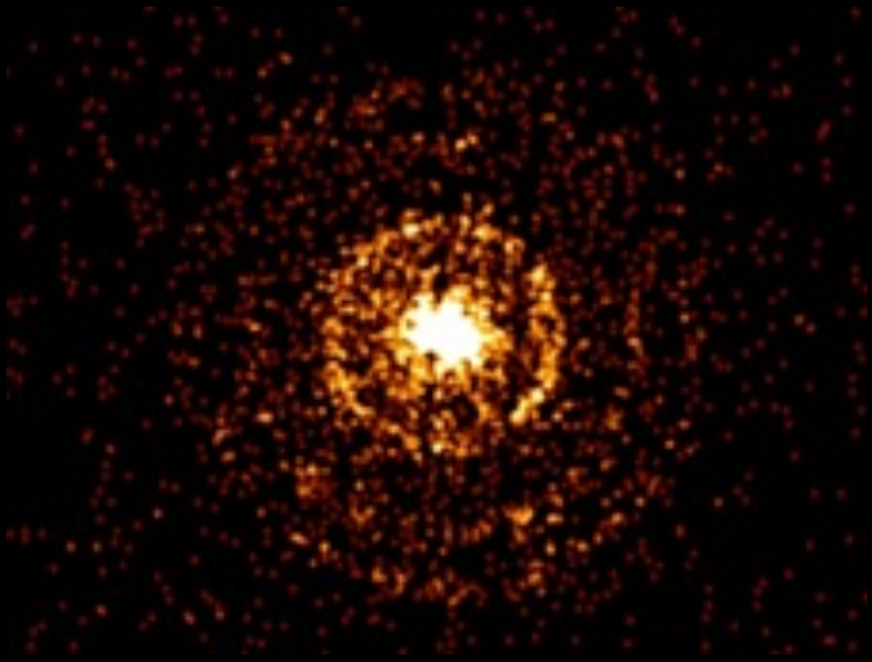


SGR J1550-5418
(NASA/Swift/Halpern)

dust scattering mainly affects
sub-arcmin resolution instruments

X-ray scattering is a diagnostic tool for ISM grain sizes





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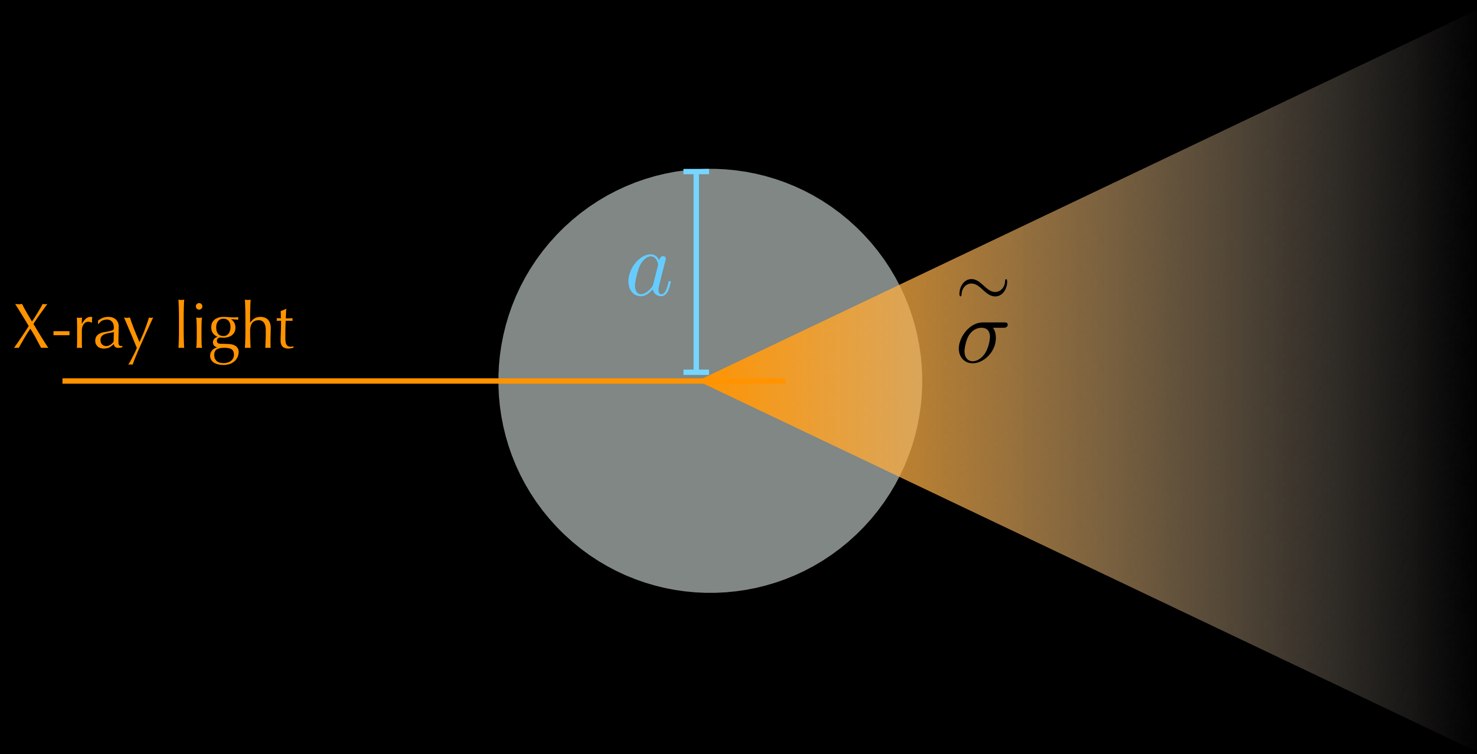

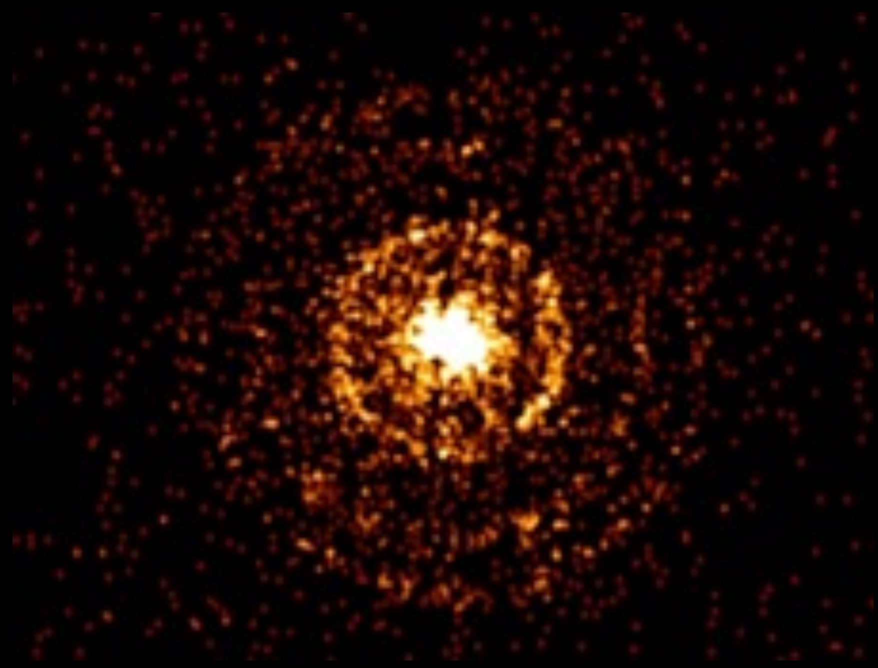

SGR J1550-5418
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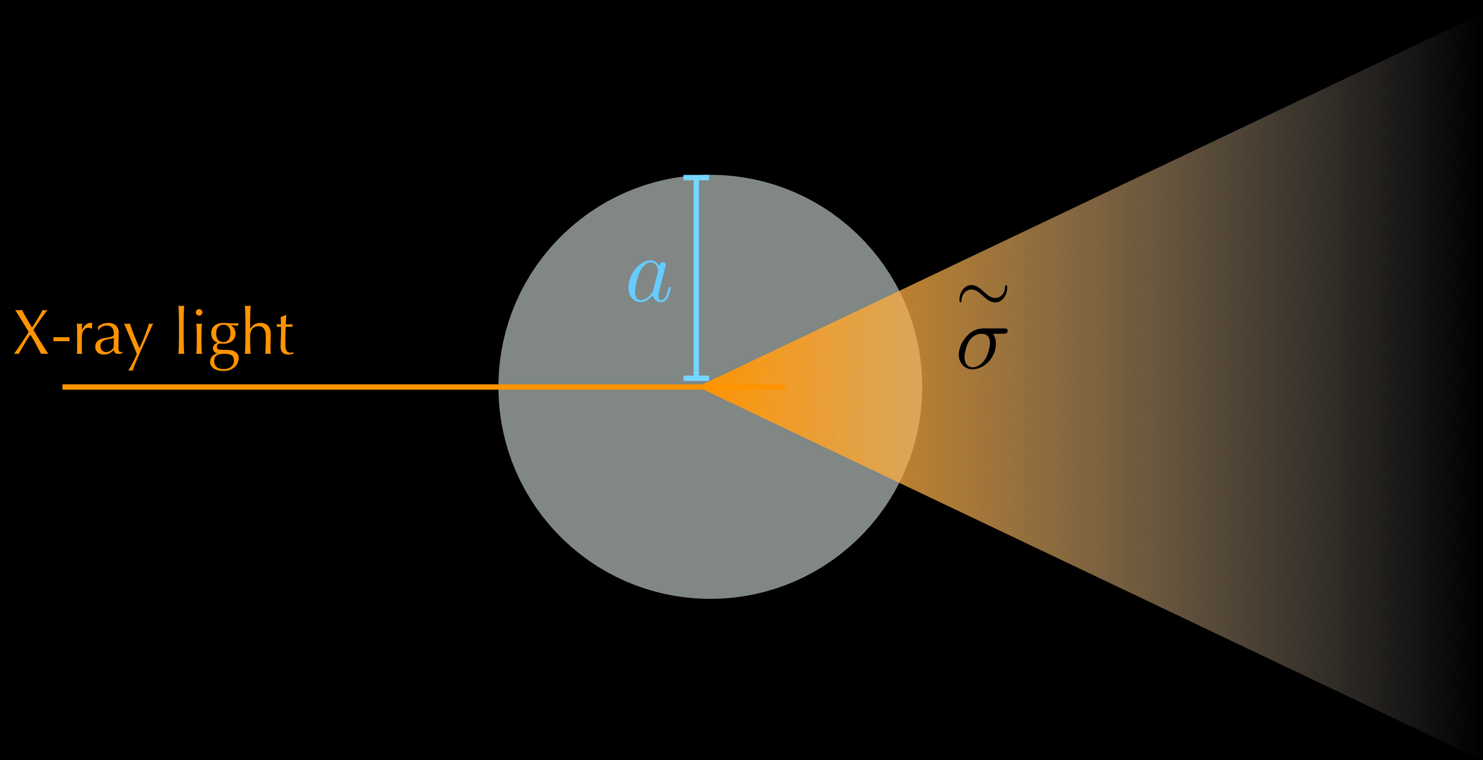
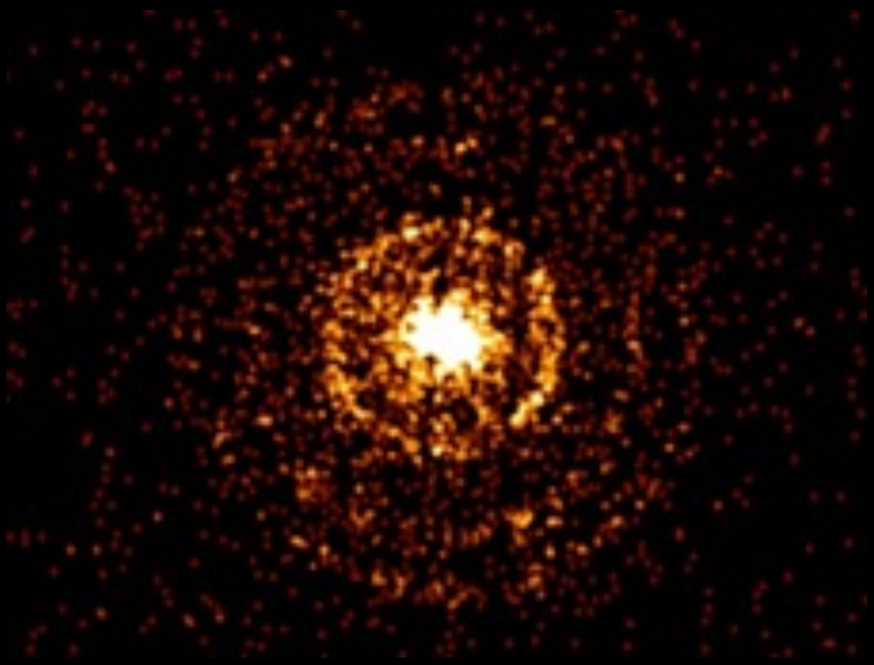
Strongly forward
(small angle) scattering → $\tilde{\sigma} \approx \dfrac{1'}{a(\mu\mathrm{m})\ E(\mathrm{keV})}$

X-ray scattering is a diagnostic tool for ISM grain sizes





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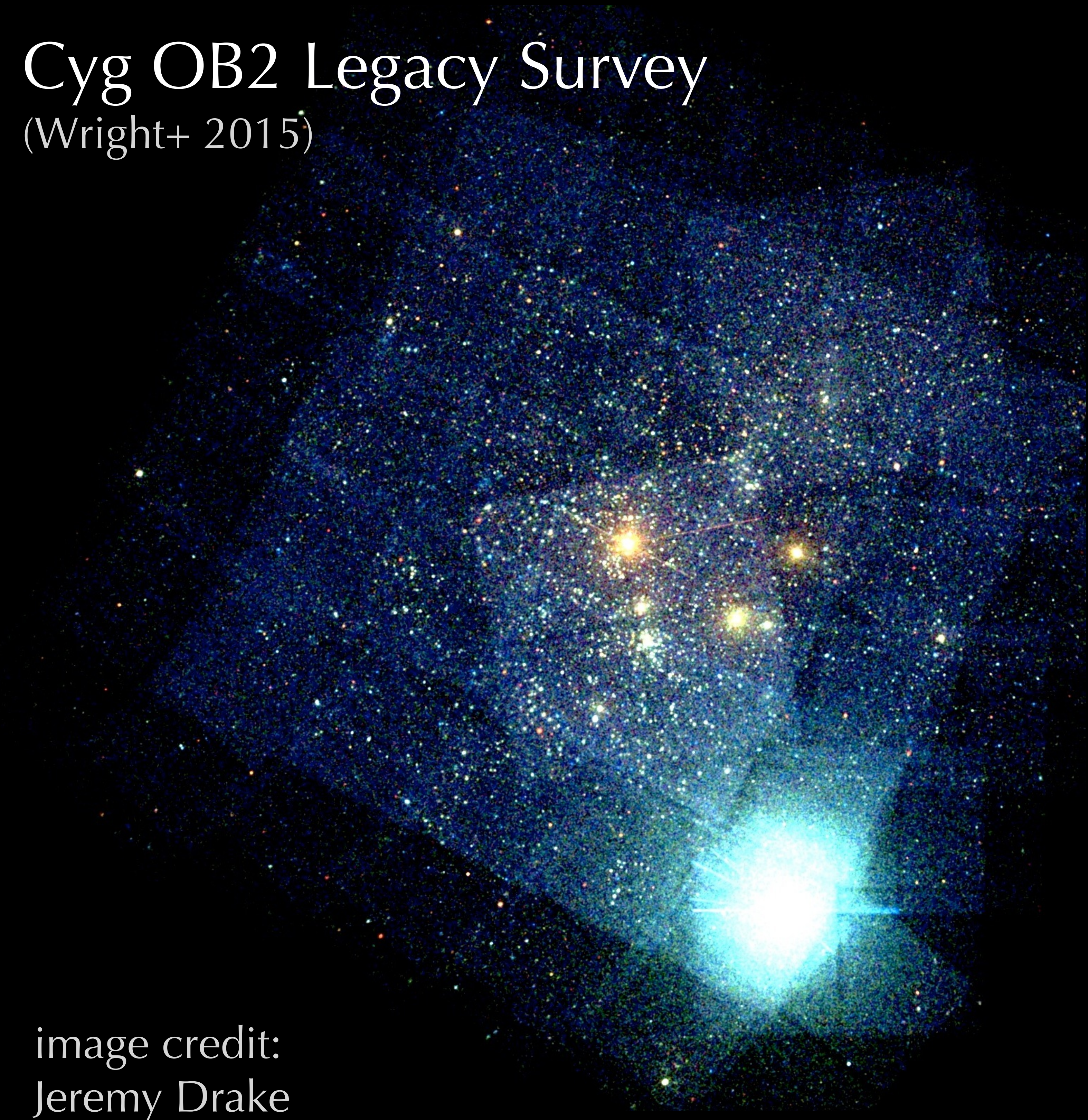
Strongly forward
(small angle) scattering → $\tilde{\sigma} \approx \frac{1'}{a(\mu\mathrm{m})\ E(\mathrm{keV})}$

Strongly **sensitive**
to grain size → $\sigma_{\mathrm{sca}} \propto a^4 E^{-2}$

Scattering halo flux yields **direct measurement of scattering cross-section**

Cyg OB2 Legacy Survey
(Wright+ 2015)



$$\frac{F_h}{F_{ps}} = e^{\tau_{\mathrm{sca}}} - 1$$

Cyg X-3 (HETG)

image credit: Jeremy Drake

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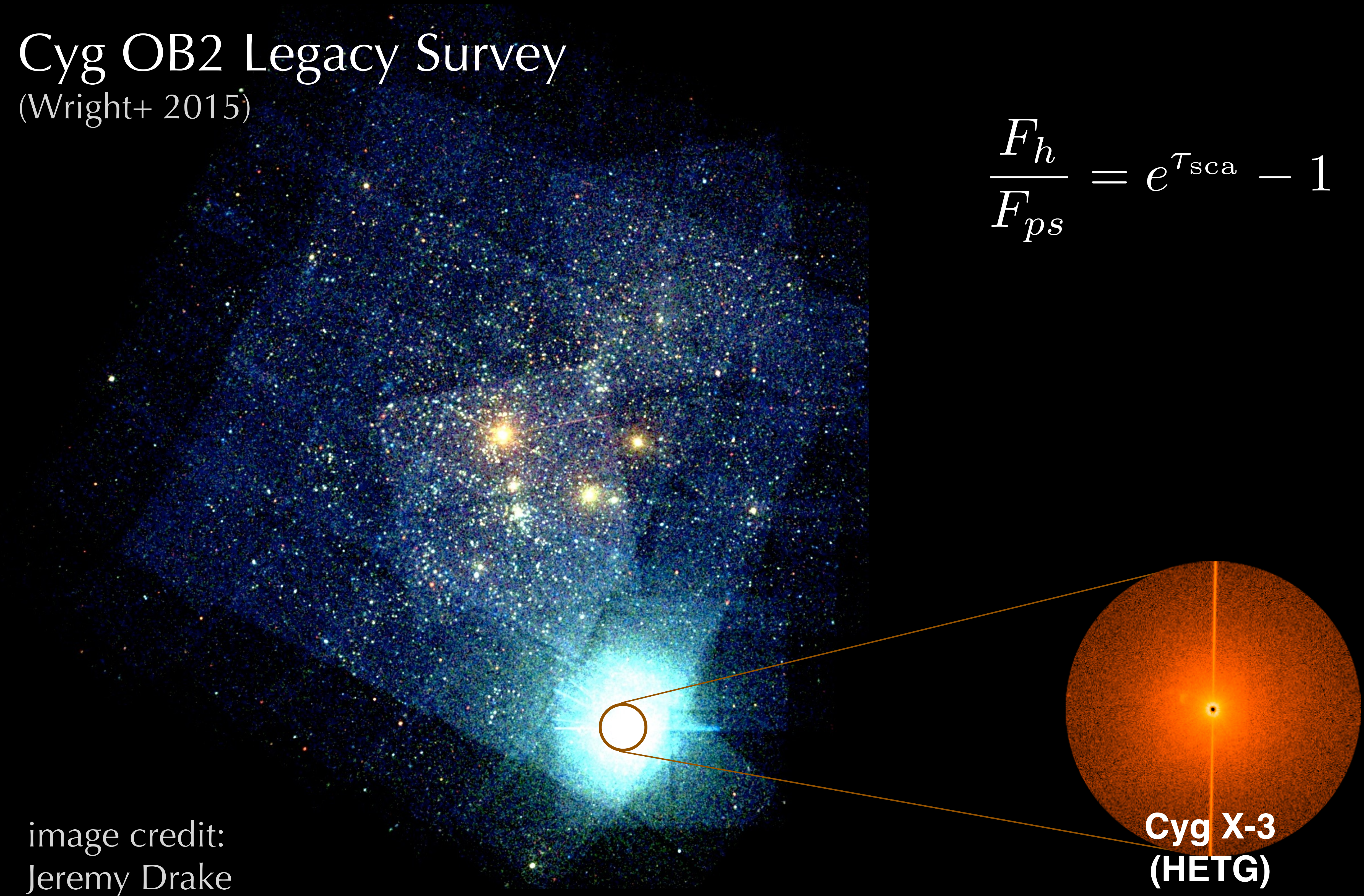

image credit:
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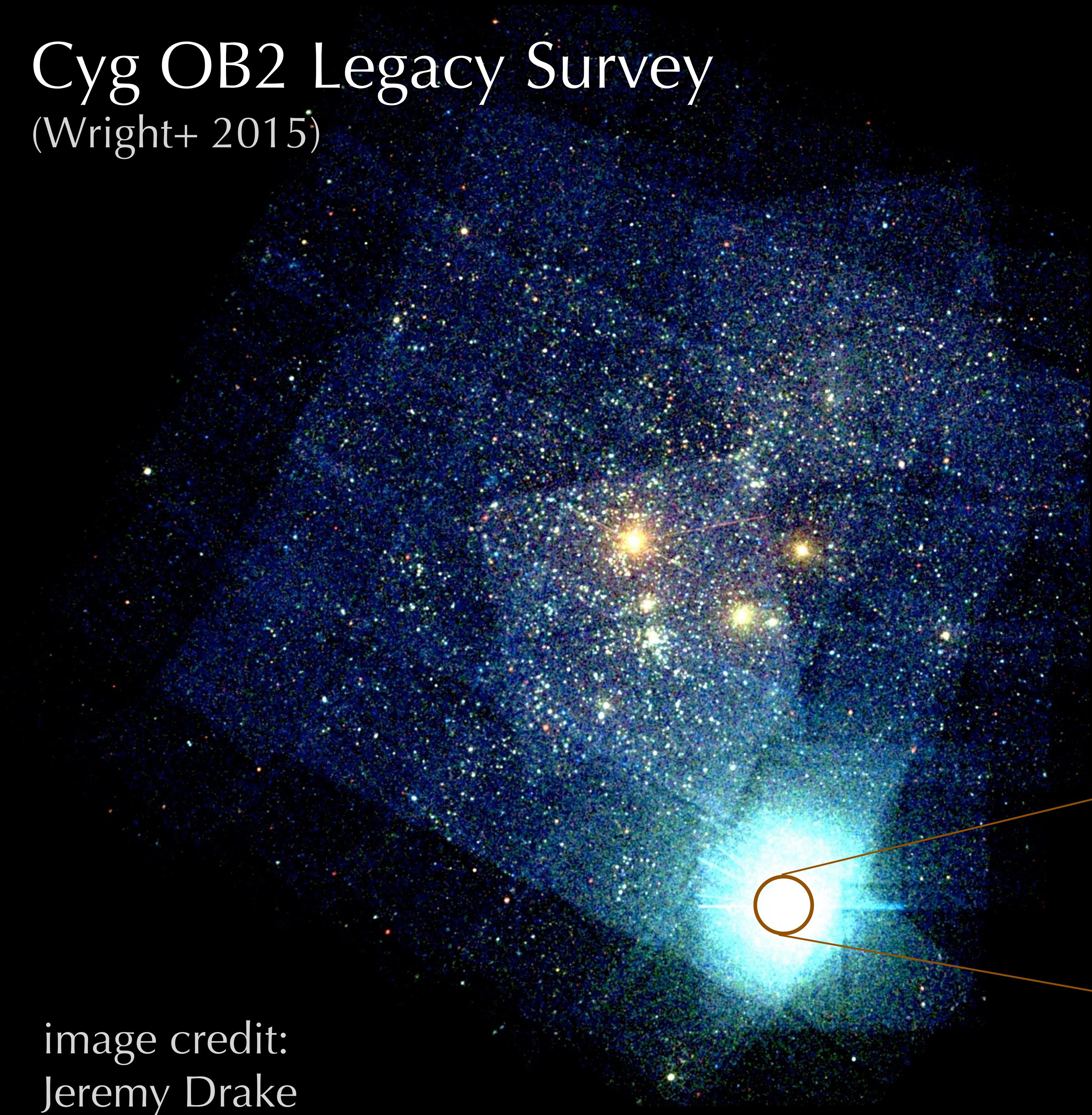


$$\frac{F_h}{F_{ps}} = e^{\tau_{\rm sca}} - 1$$

$$\frac{F_h^{obs}}{F_{ps}} = f_{cap}\ \left(e^{\tau_{\rm sca}} - 1\right)$$

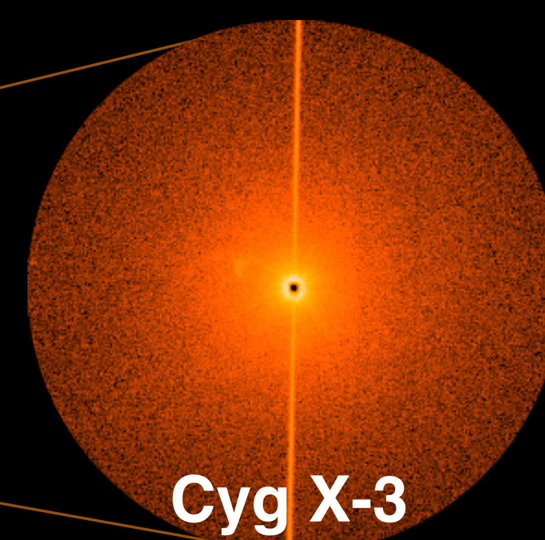
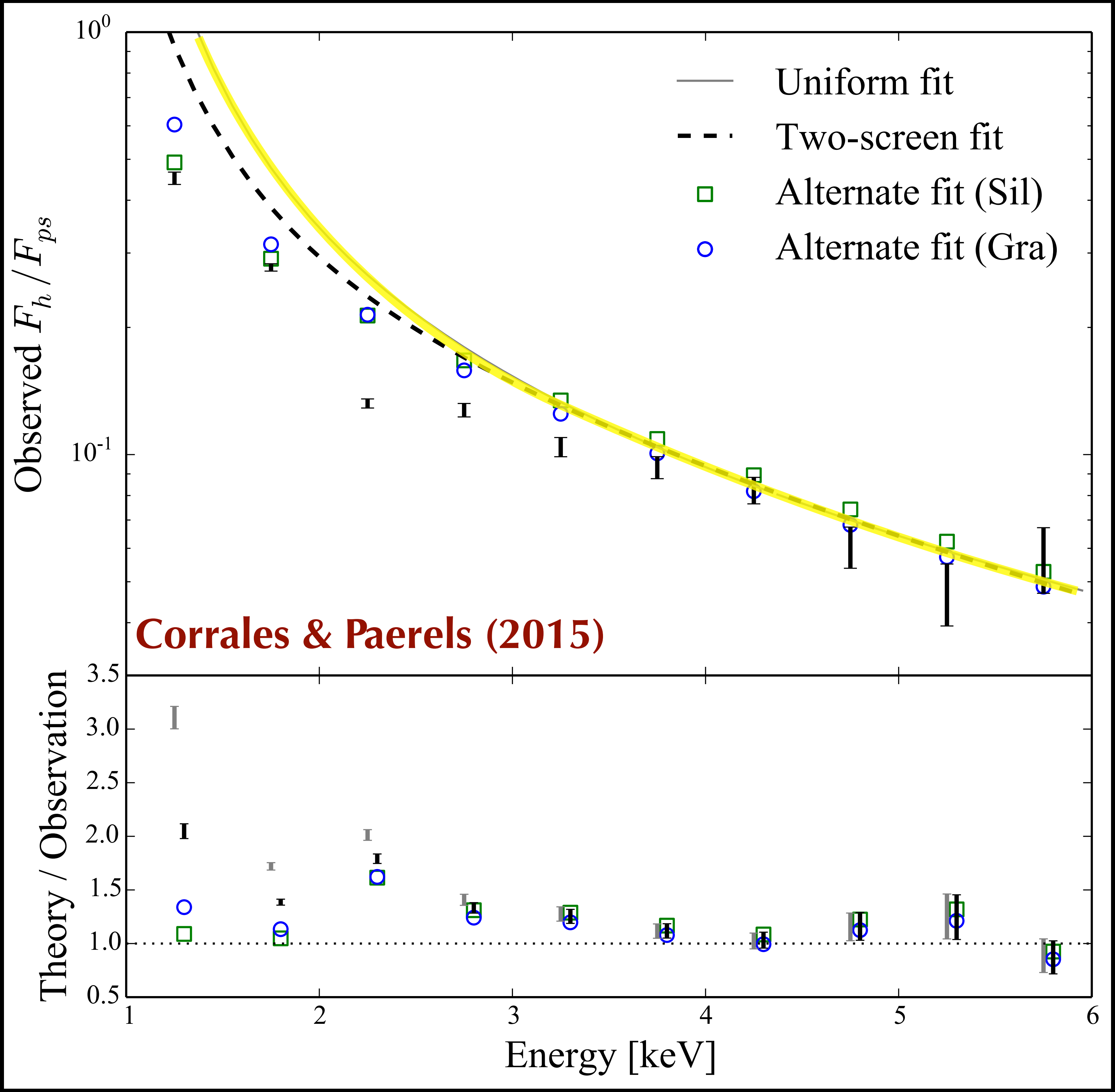
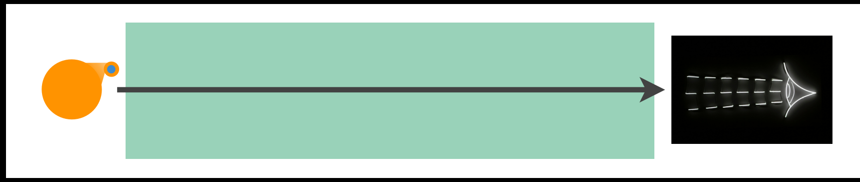
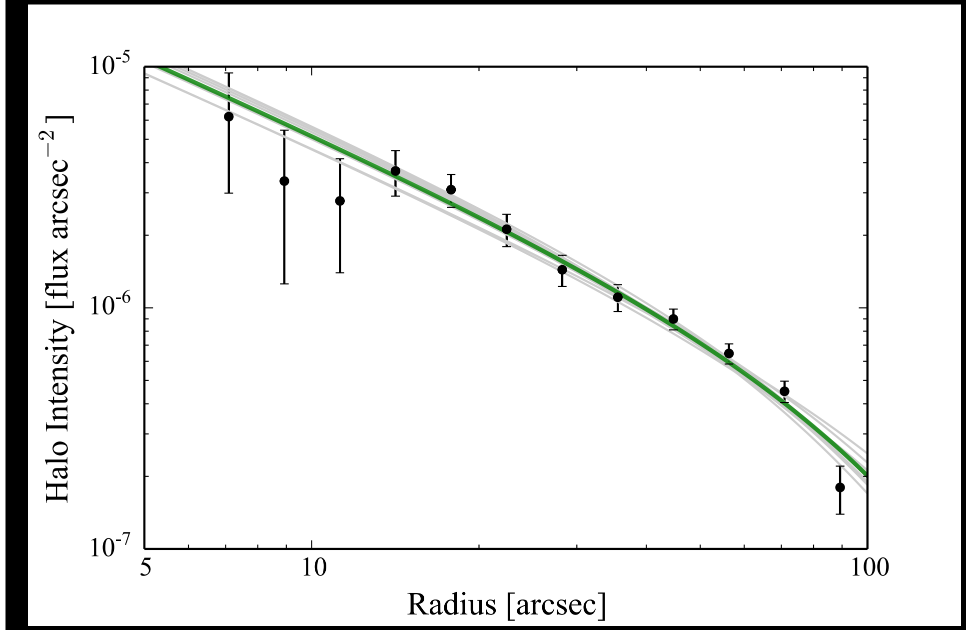


image credit:
Jeremy Drake

The scattering halo of Cyg X-3 supports several solutions, degeneracy might be broken with **energy resolved scattering halos**







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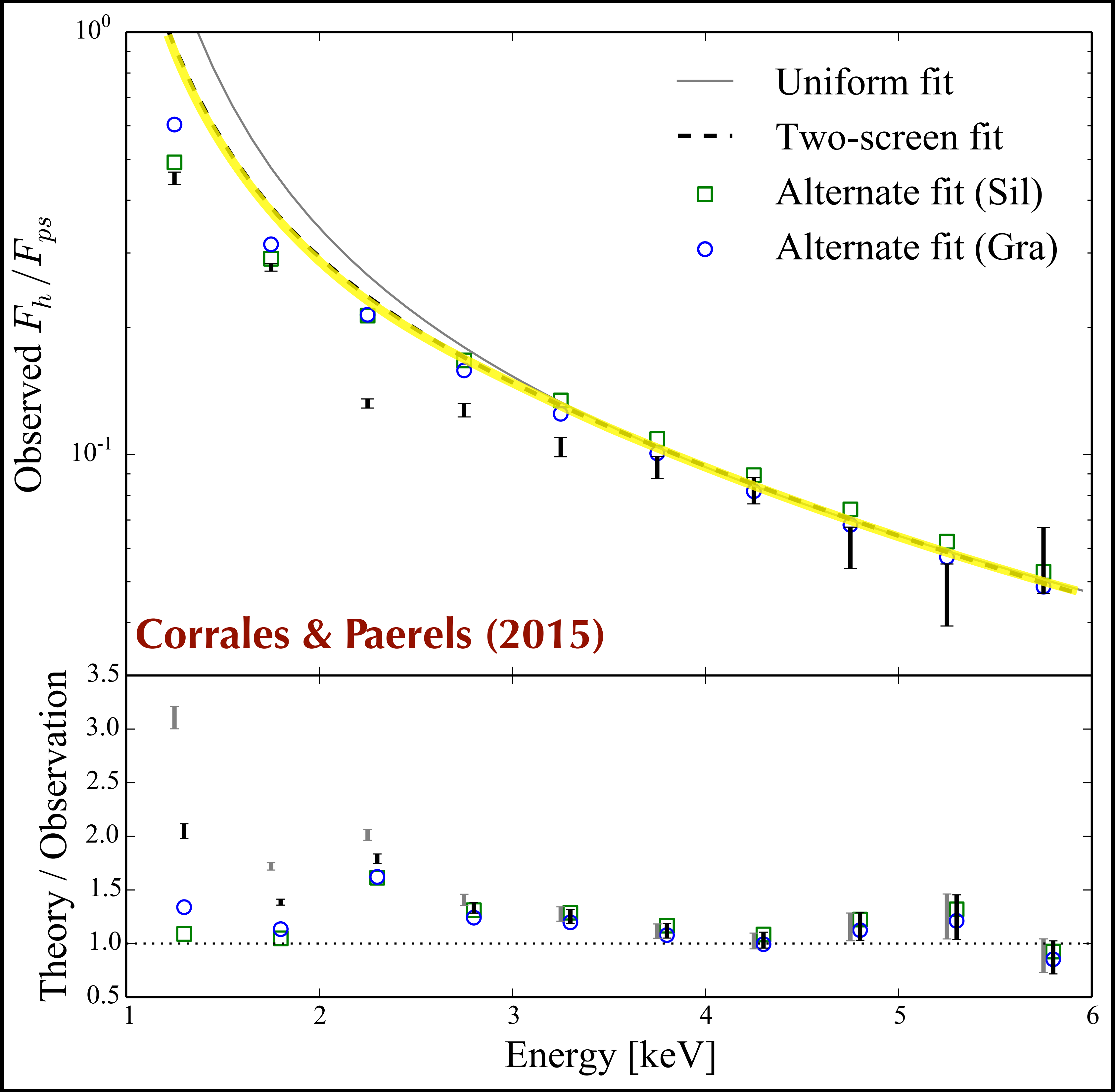

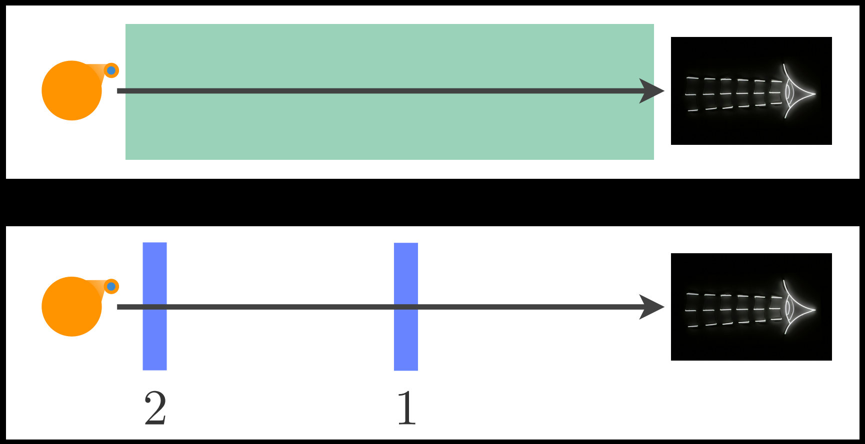

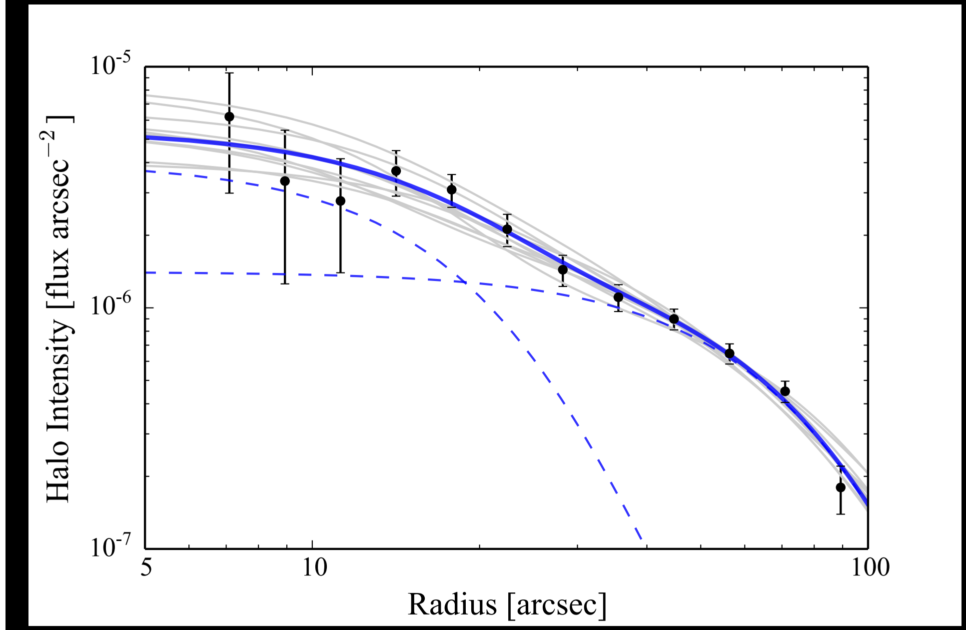

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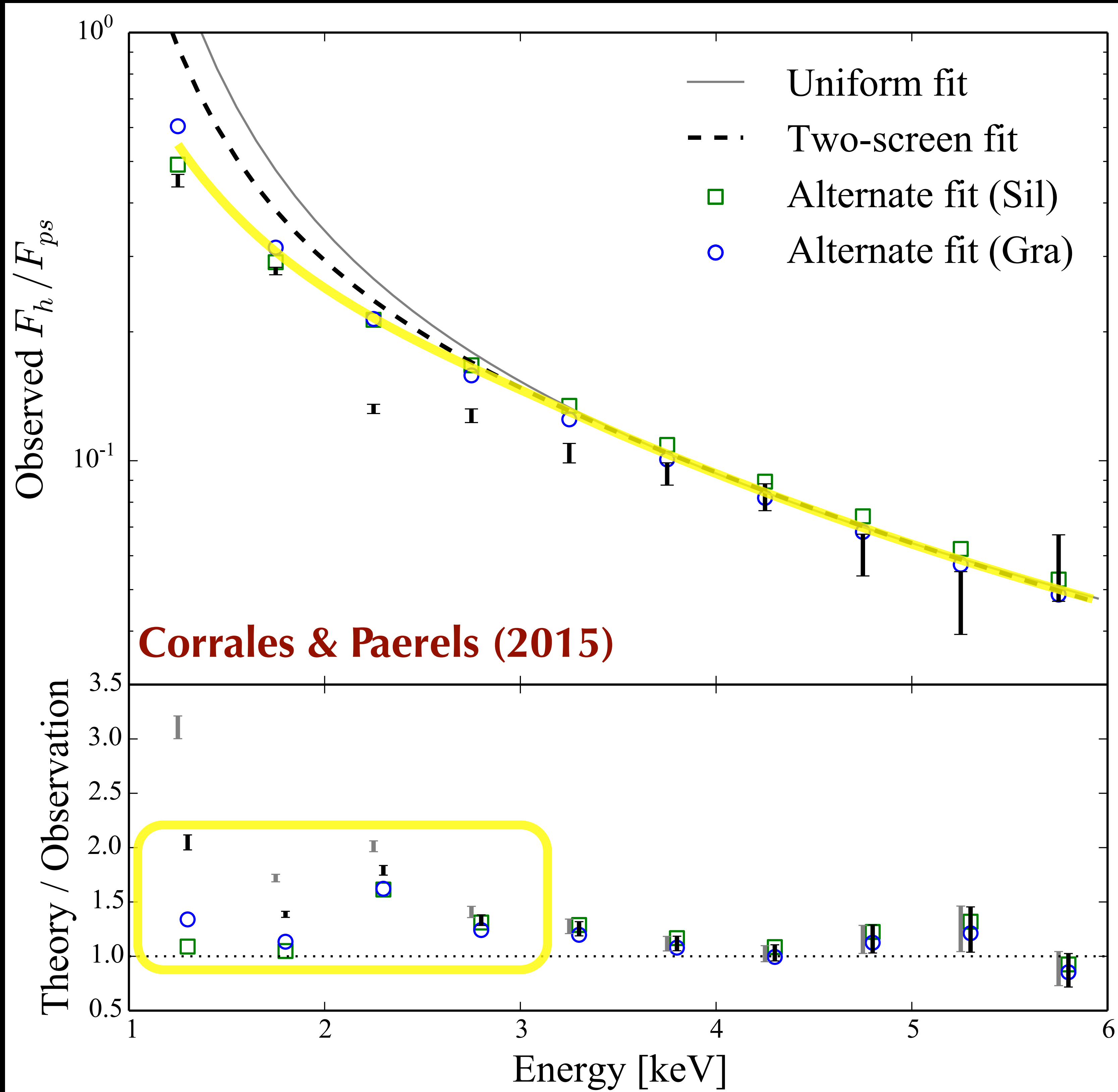
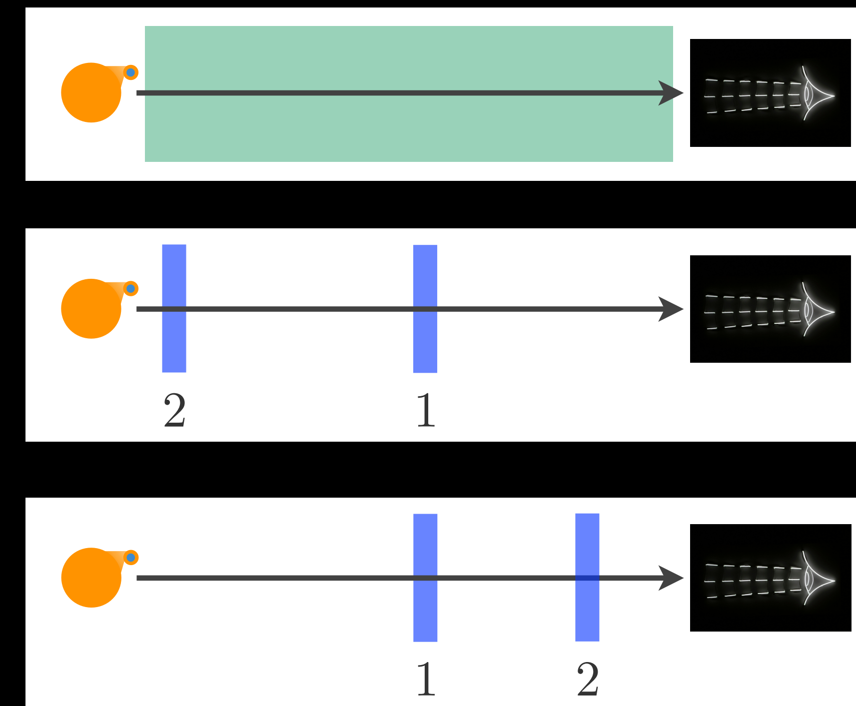
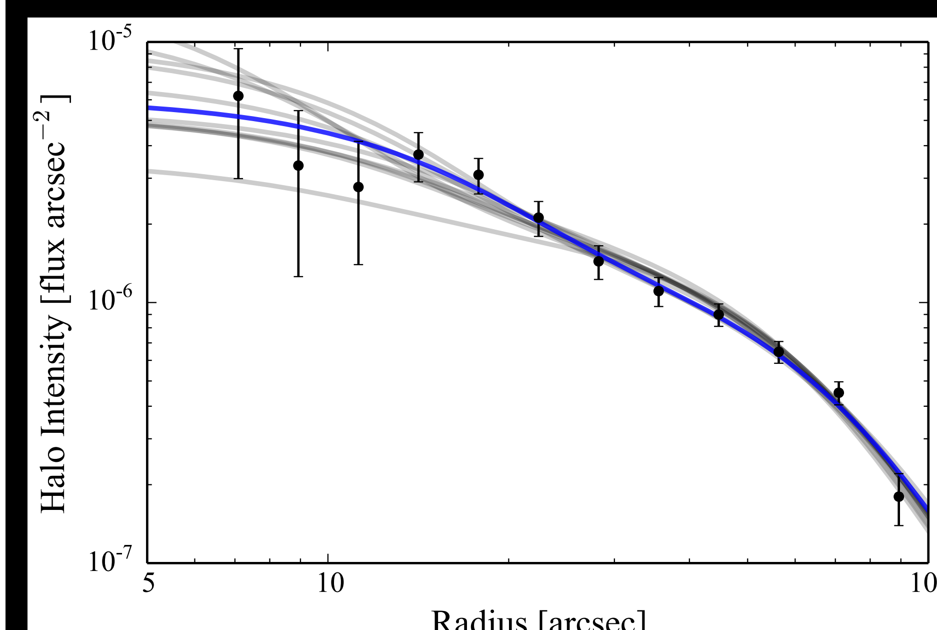




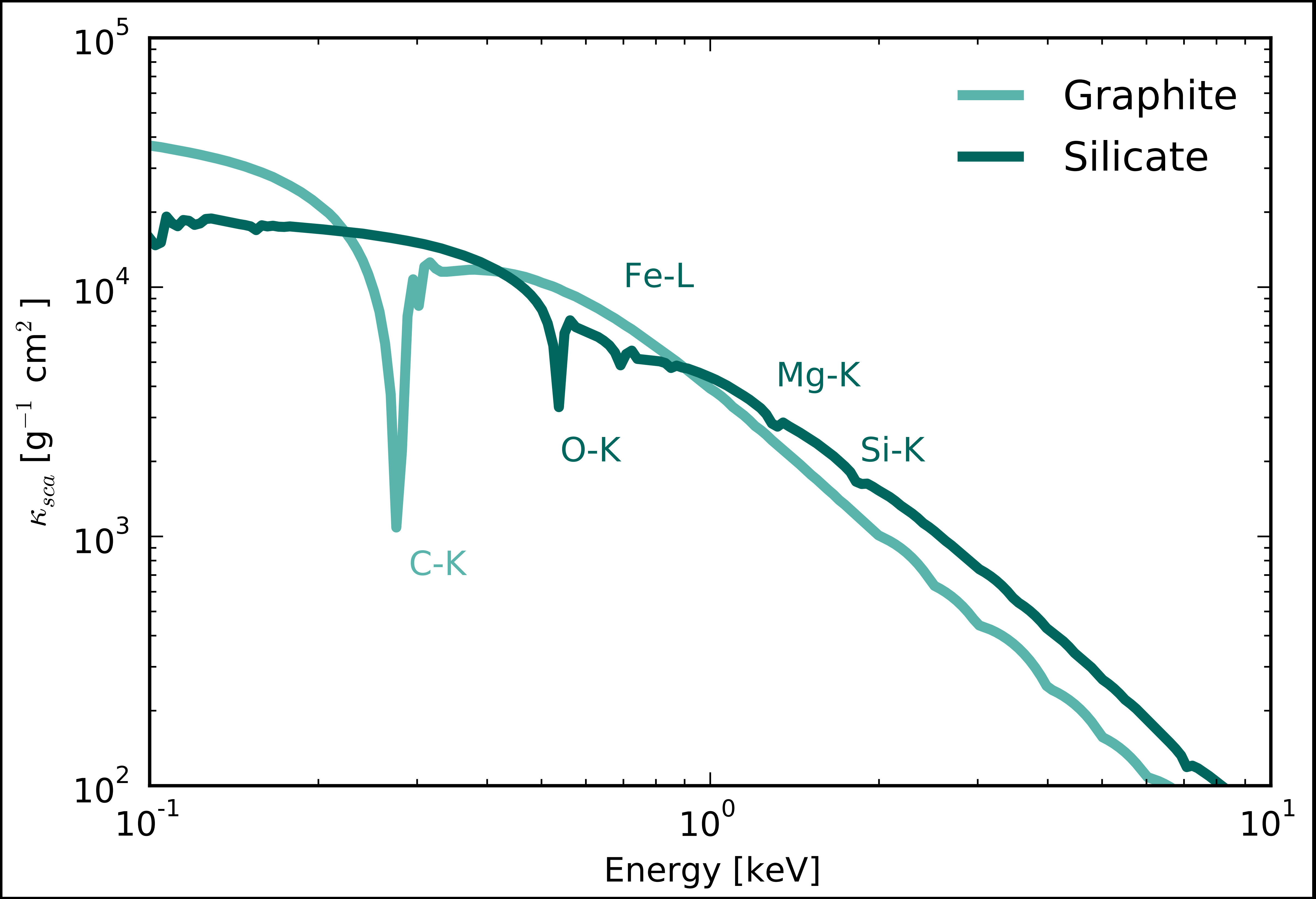
same as before

$a_{\mathrm{max}} = 1.5\ \mu\mathrm{m}$

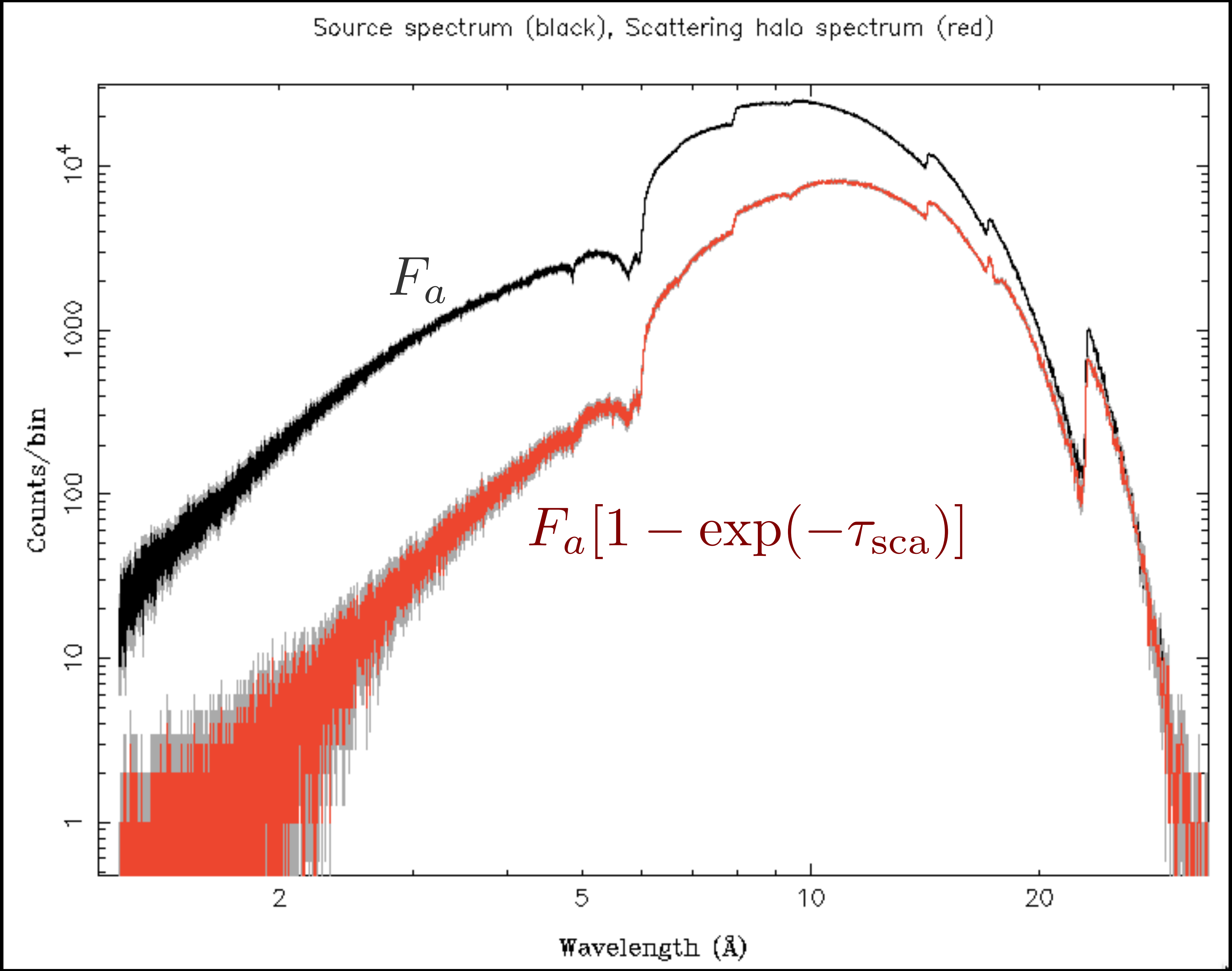
$p = 3.6$



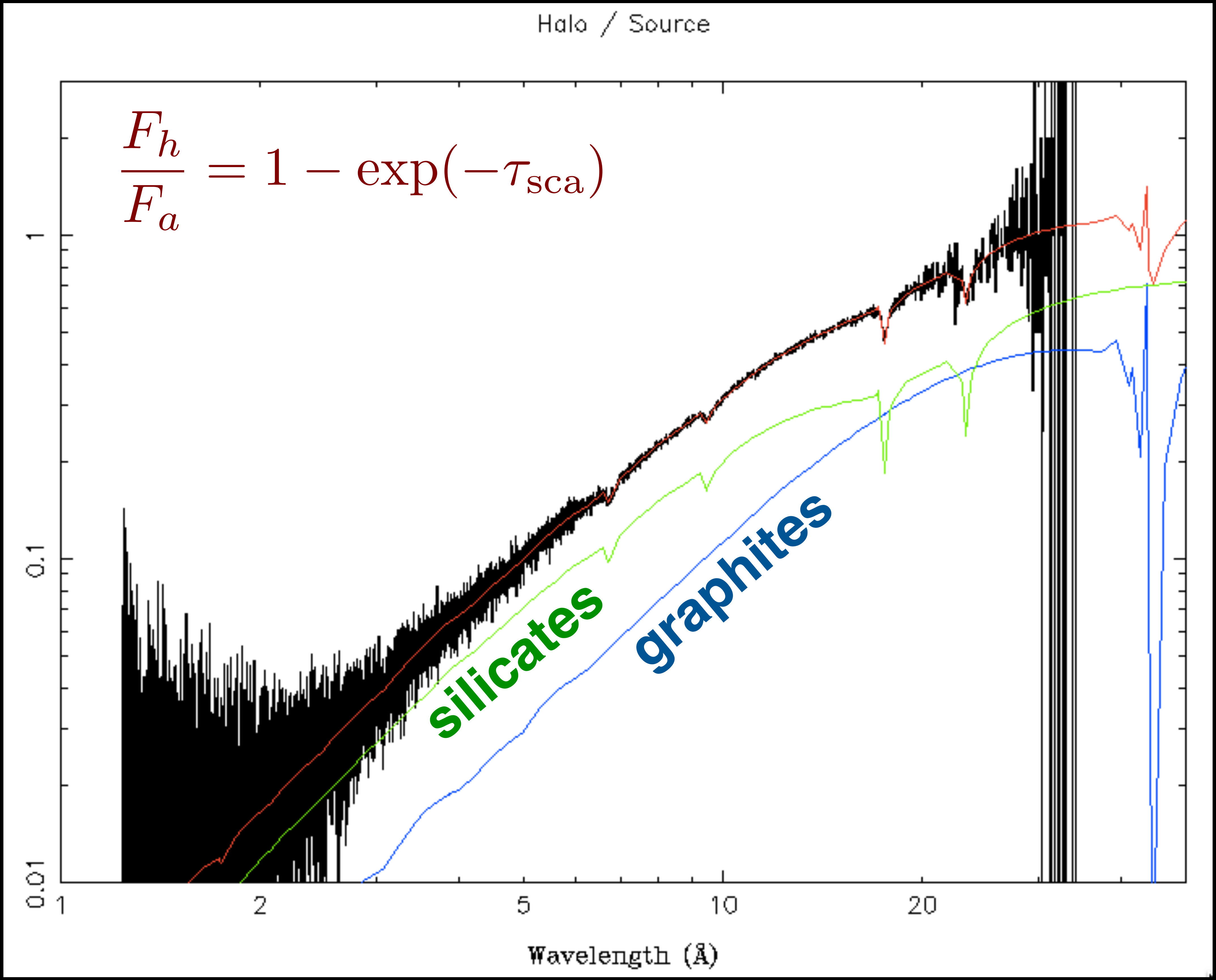
Spectrum of dust scattered light should have features coincident with **absorption edge structure** from **constituent elements**



Simulated spectrum (micro-calorimeter)



Ratio of halo to source reveals **dust spectral features**



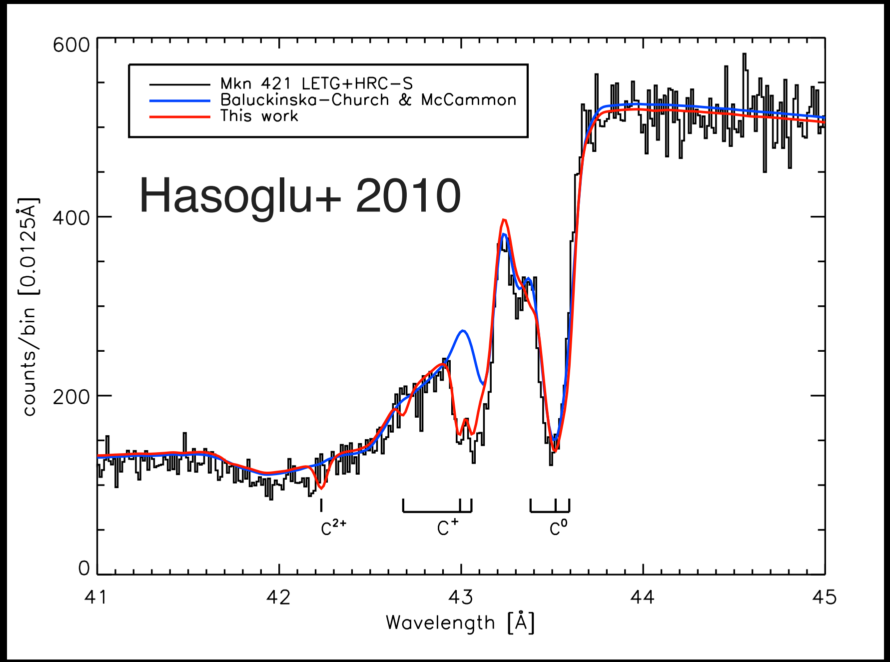
Approach 1: X-ray Scattering

1. Wide **field of view is important**

2. Need to image SB over several orders of magnitude

3. **High resolution imaging**
   — avoid confusion (point source vs halo)
   — probe deeper into sight line (dust closer to source)
   — image fainter scattering echoes

4. **Can we push to C-K edge**?
   — PAHs (2175 Angs) are
   lever-arm for many dust models



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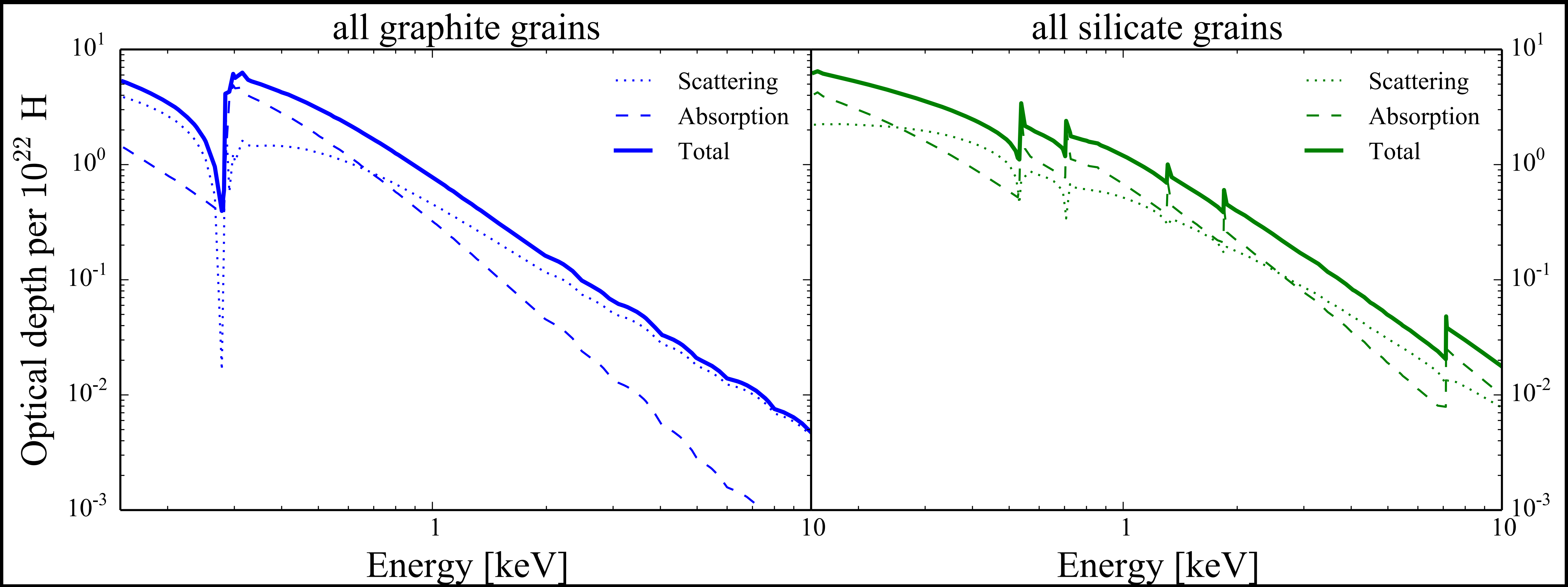
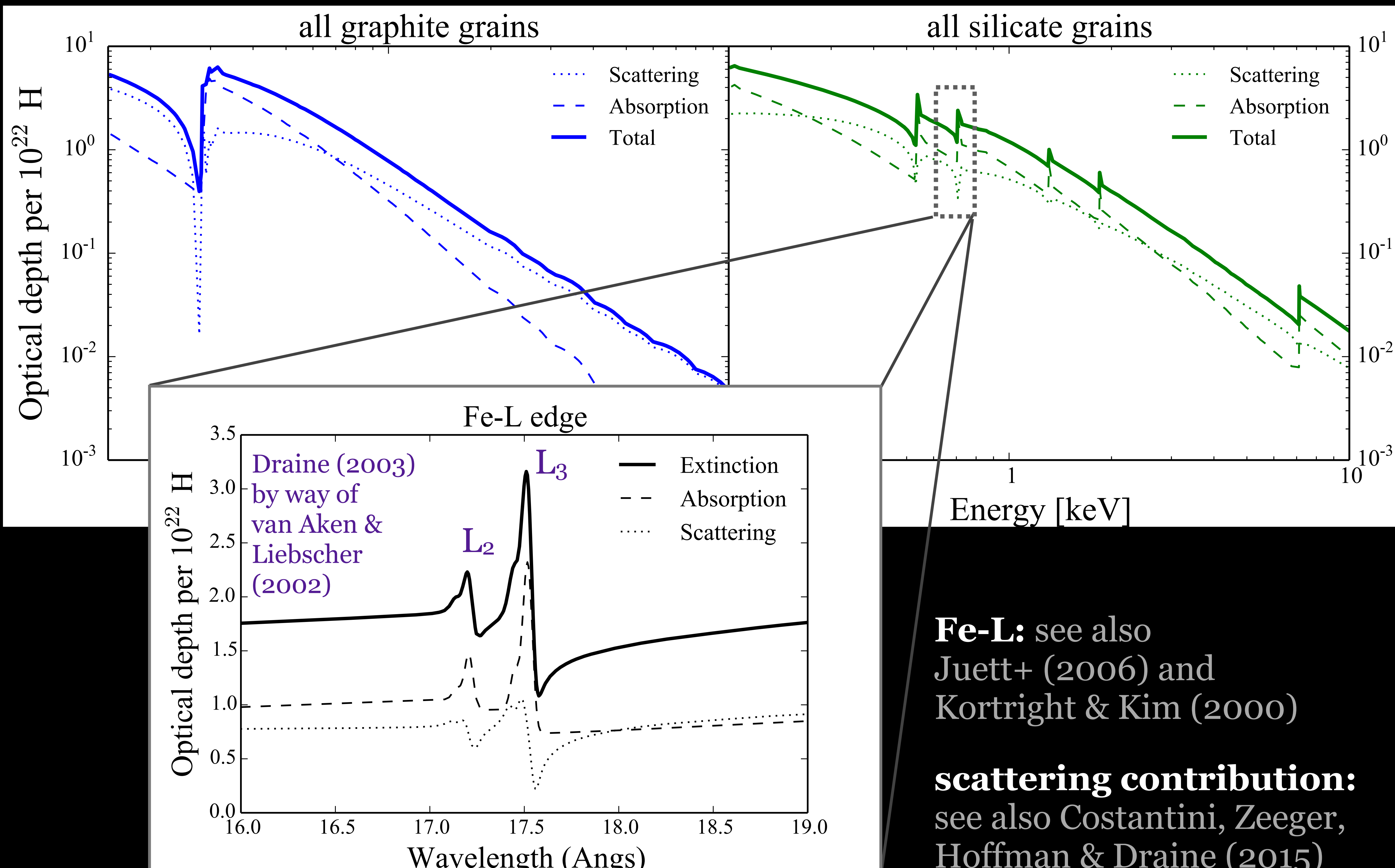
X-ray Absorption Fine Structure (XAFS)

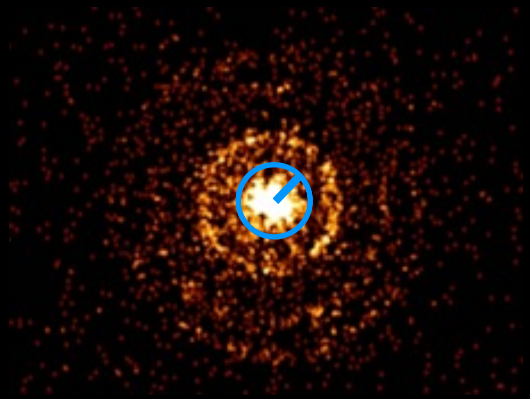


X-ray Absorption Fine Structure (XAFS)

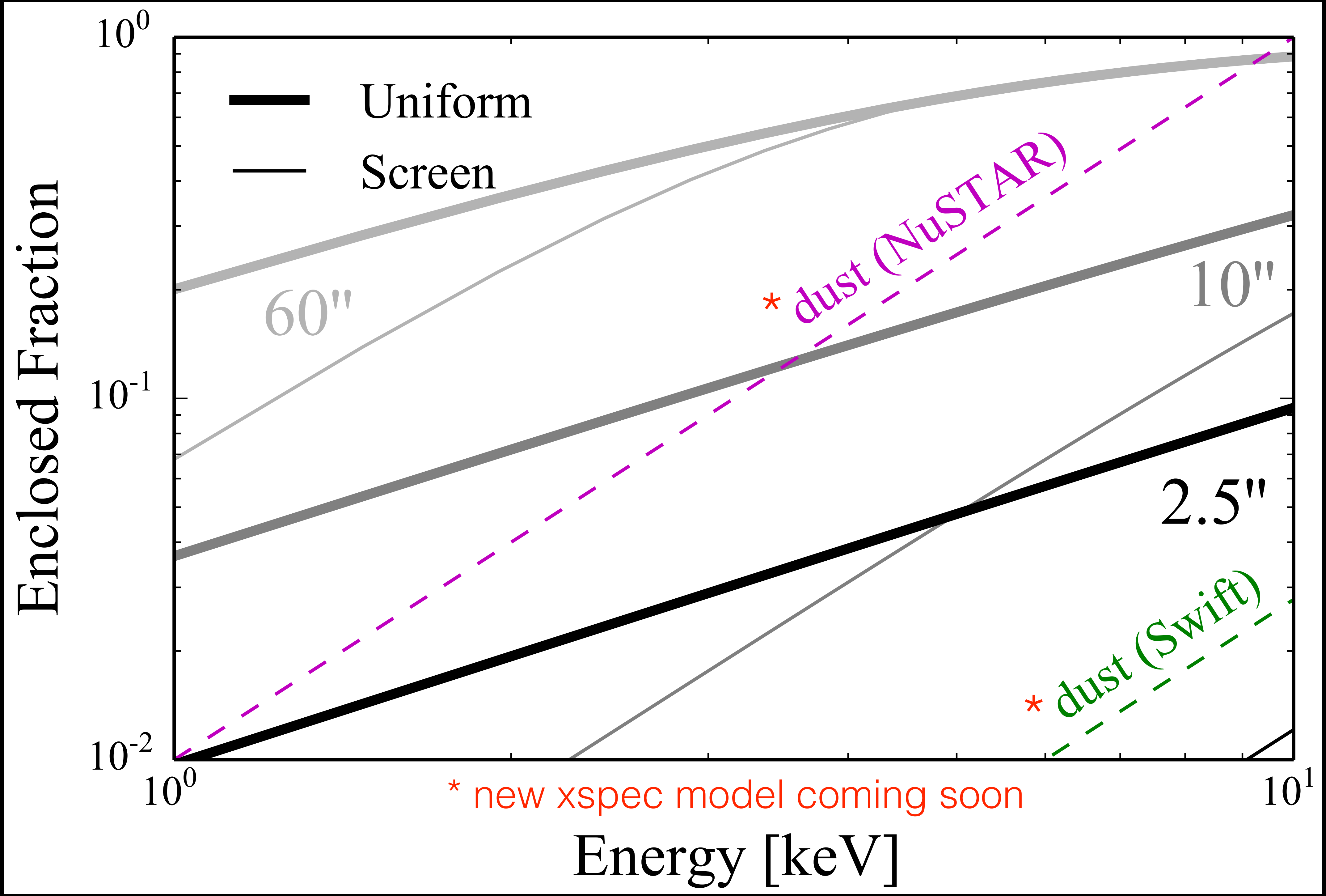


Fe-L: see also Juett+ (2006) and Kortright & Kim (2000)

scattering contribution: see also Costantini, Zeeger, Hoffman & Draine (2015)



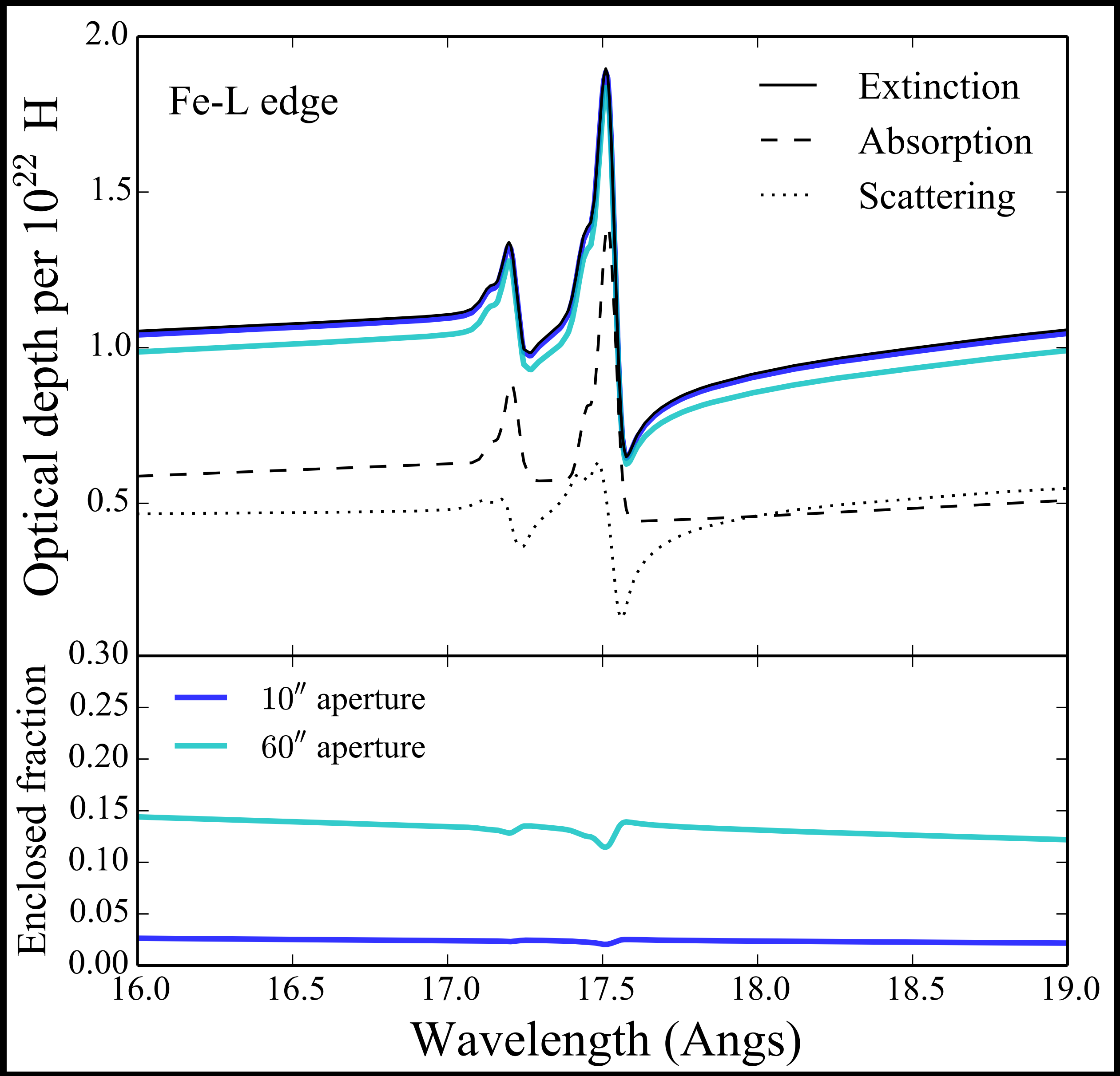
Fraction of dust scattering halo captured within source extraction region (PSF)



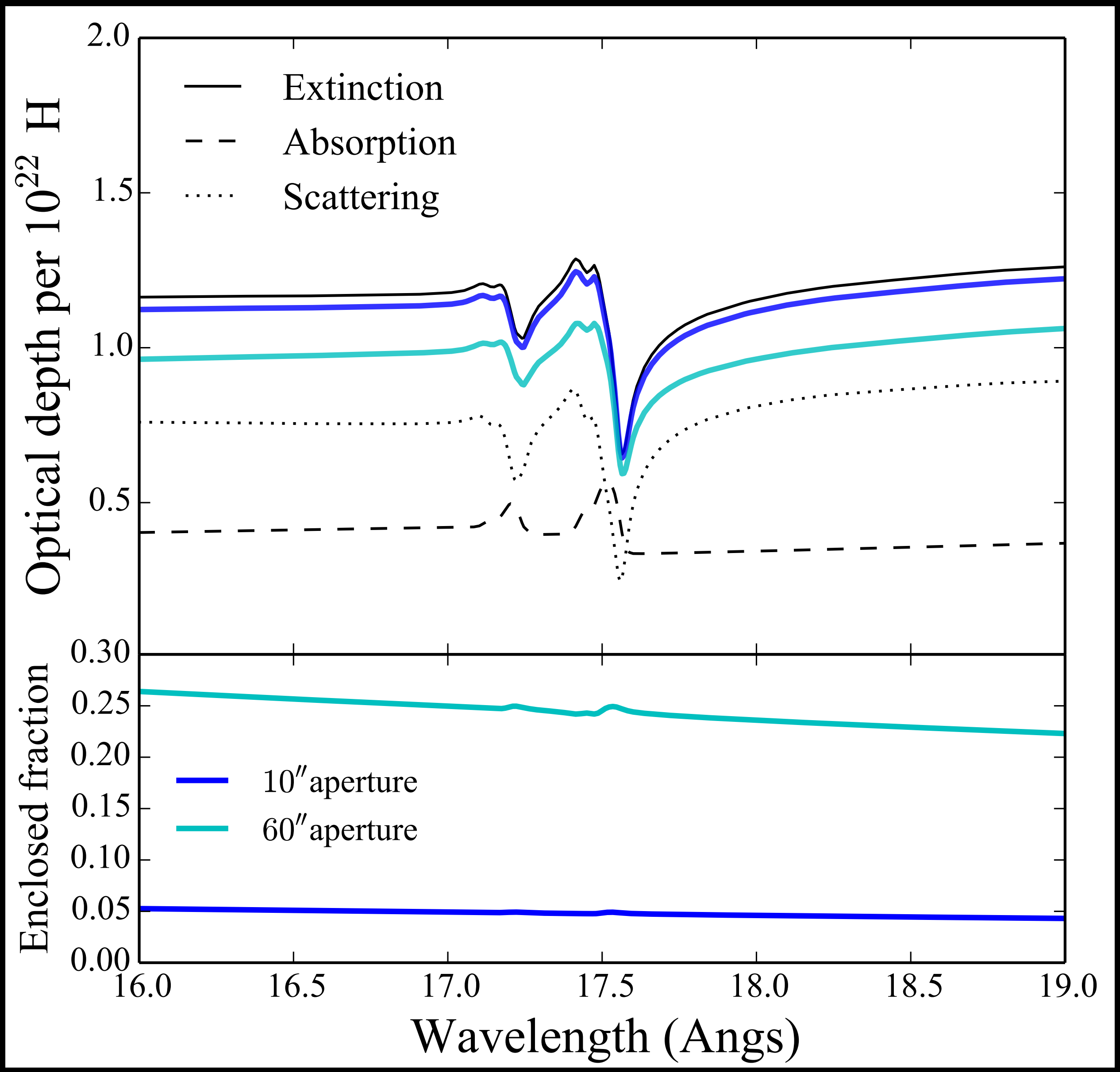
* new xspec model coming soon

Absorption edge fine structure is also **dependent on imaging resolution and grain size**

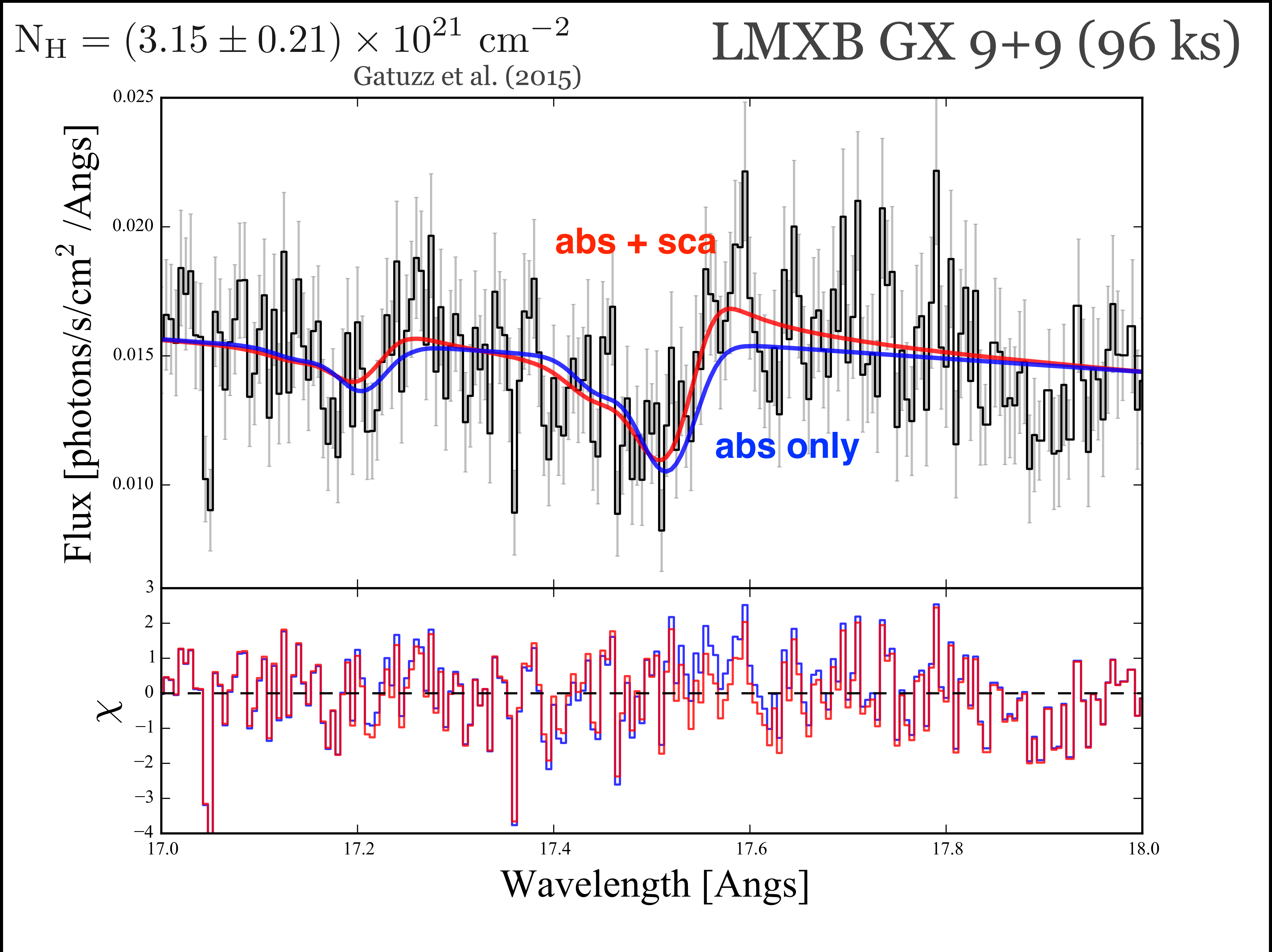
MRN dust

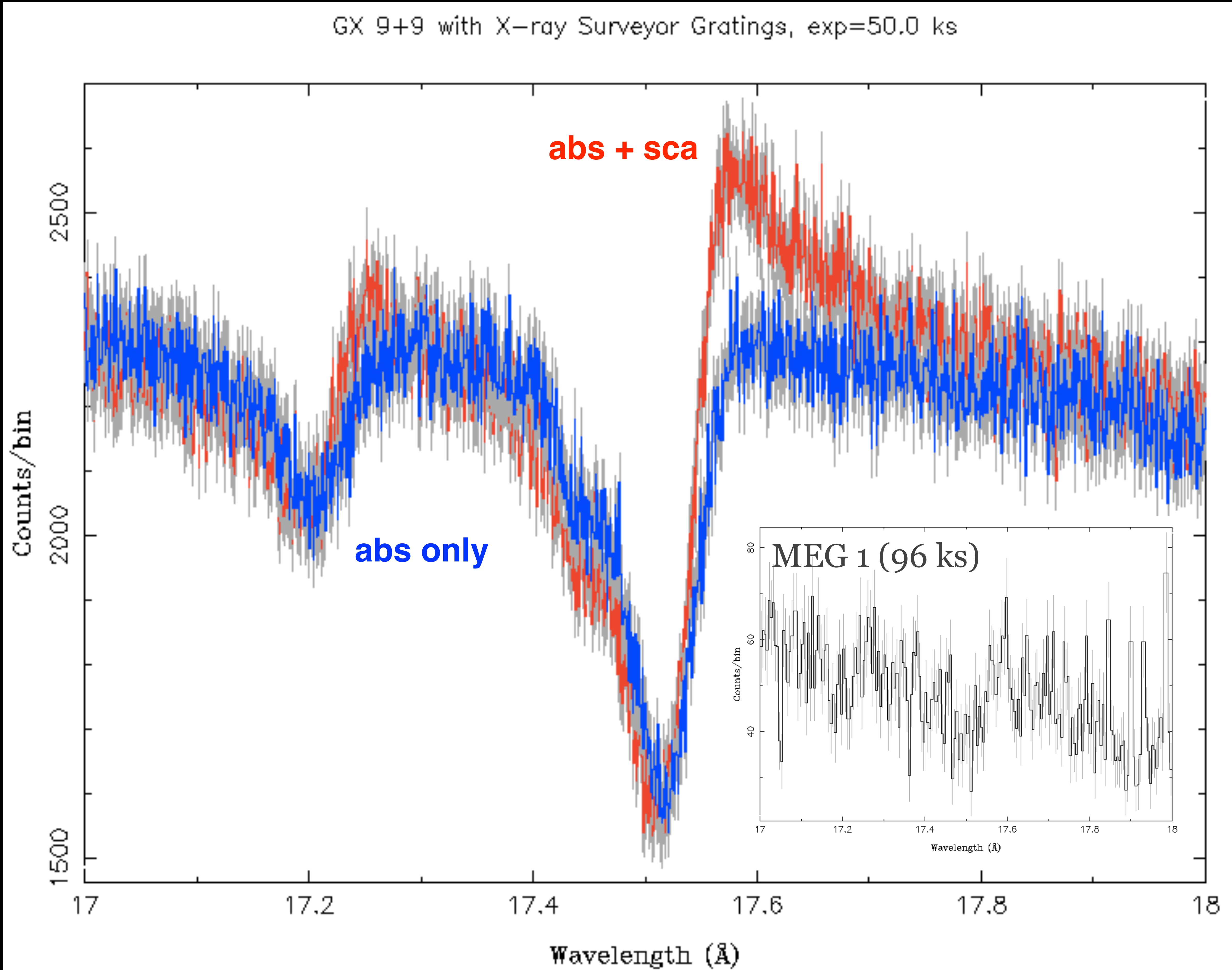


0.3 micron grains



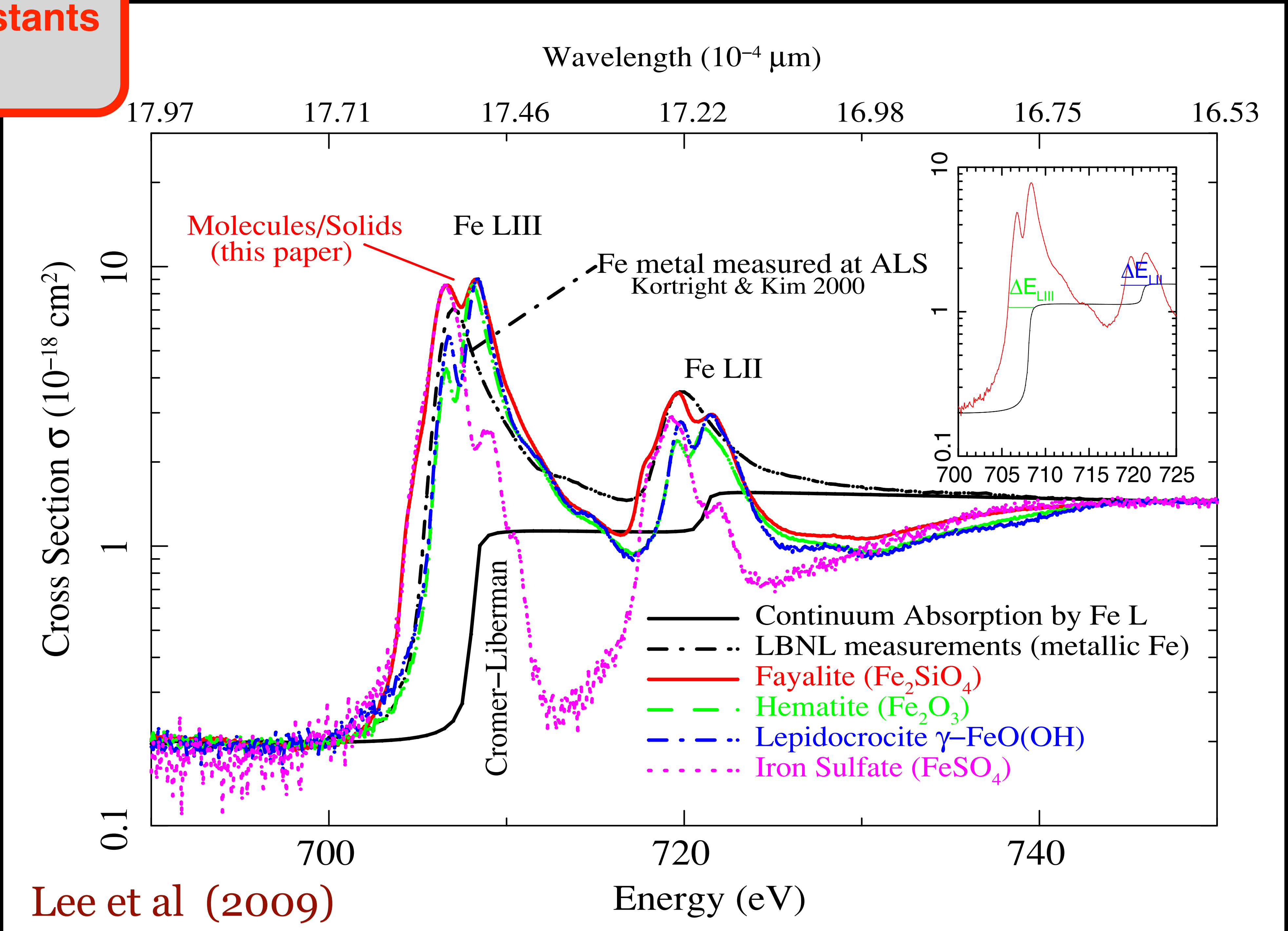
Fe-L edge


$N_H = (3.15 \pm 0.21) \times 10^{21}$ cm^{-2}
Gatuzz et al. (2015)
LMXB GX 9+9 (96 ks)
abs + sca
abs only
Flux [photons/s/cm^2 /Angs]
0.025
0.020
0.015
0.010
χ
3
2
1
0
−1
−2
−3
−4
17.0
17.2
17.4
17.6
17.8
18.0
Wavelength [Angs]


GX 9+9 with X-ray Surveyor Gratings, exp=50.0 ks
abs + sca
abs only
Counts/bin
2500
2000
1500
17
17.2
17.4
17.6
17.8
18
Wavelength (Å)
MEG 1 (96 ks)
80
60
40
Counts/bin
Wavelength (Å)

We need lab astrophysics and scattering models

Use absorption cross-section to measure optical constants —> compute extinction



LAB
Kortright & Kim (2000)
van Aken & Liebscher (2002)
Lee et al. (2009)
Lee (2010)
Costantini (e.g. 2013)

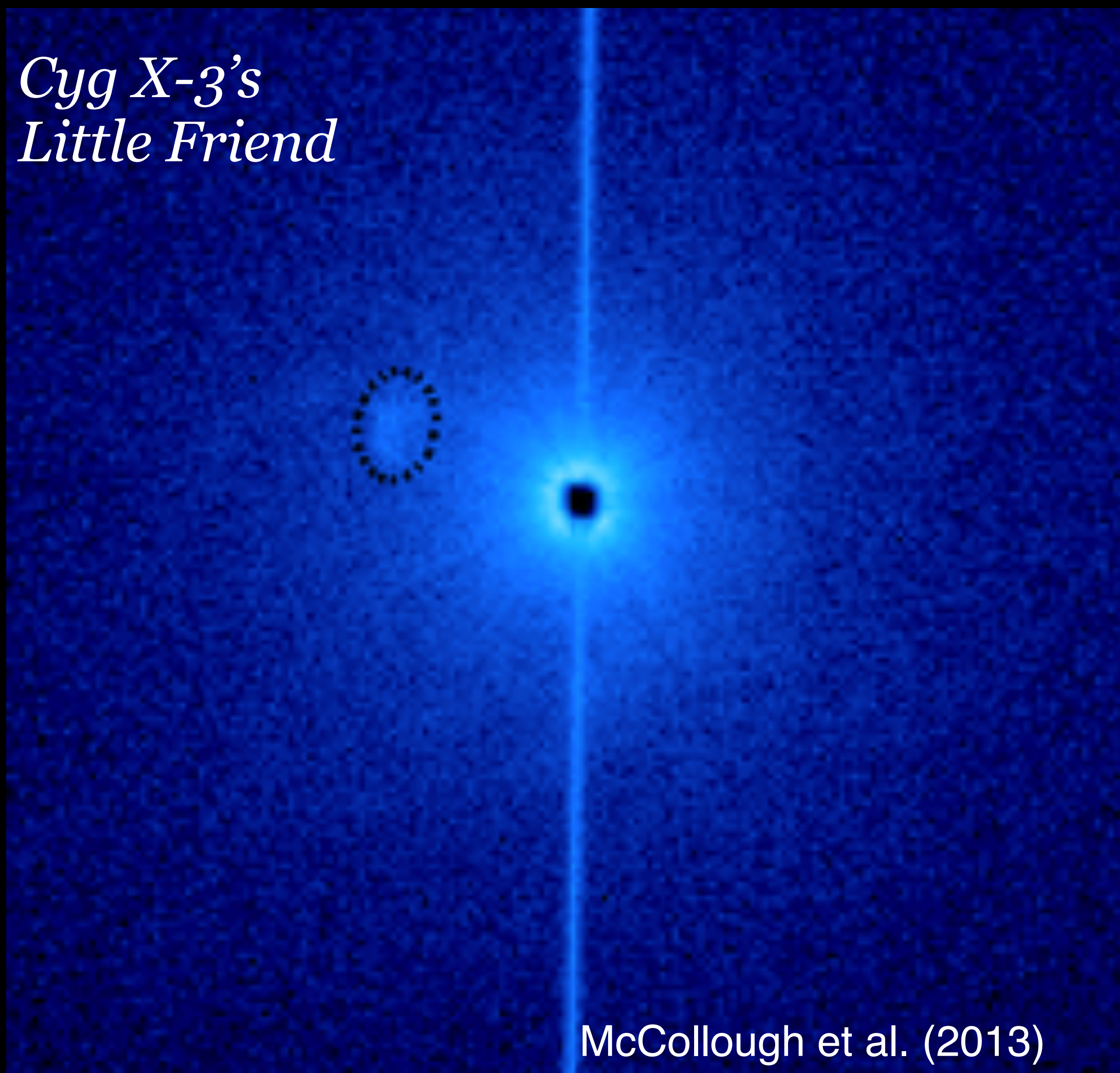
MODELS
Draine (2003)
Hoffman & Draine (2015)
Smith, Valencic, Corrales (in prep)

Approach 2: X-ray Absorption Fine Structure

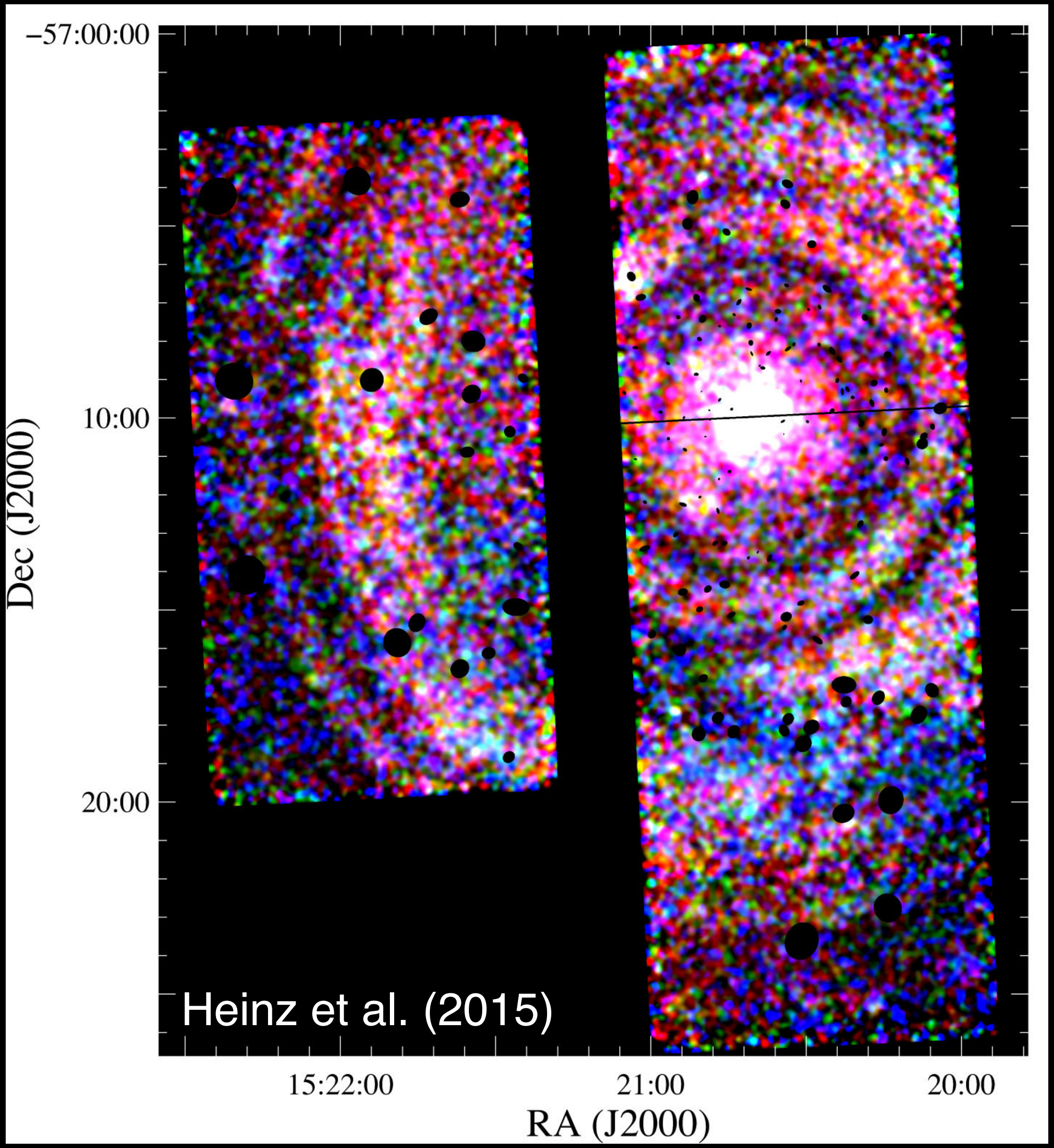
1. We need to be able to observe **bright objects!!**

2. **Gratings**
   — mitigate pileup
   — **high-resolution spectroscopy in the soft X-ray**

3. Need high S/N, high resolution spectroscopy



Cir X-1 dust scattering echoes



What can X-ray scattering do for you?

1. **Distance measurements to X-ray binaries**
   — variability
   — CO and IR measurements will help

   see Tiengo et al. (2010), Mao et al. (2014), Heinz et al. (2015),

2. **Trace the metals** (neutral vs hot phase)
   — measure depletion
   — determine metallicity in your plasma / gas of interest

   see Gatuzz et al. (2014)

Fantasy questions

Dust absorption features from obscured, moderately redshifted AGN?

need high resolution soft X-ray spectroscopy

Absorption or scattering features from CGM?

need quasar-galaxy pairs or lensed quasars,
larger effective area for dimmer objects, low NH

Scattering echoes from diffuse CGM or IGM dust?

need larger effective area, low background, high resolution
see Corrales & Paerels (2012), Corrales (2015)

Summary

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Distance measurements to X-ray binaries

Trace the metals