X-ray observations of interstellar dust and gas

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6th Institute of Space Sciences Summer School: Life Cycle of Dust

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11/07/2023

The X-rays and the interstellar medium

- X-ray astronomy: a brief overview
- X-ray observatories
- X-ray sources to study the interstellar medium

- Phases in the interstellar medium
- The Interstellar medium and the X-rays: gas and dust
- Hands-on session

X-ray missions and X-ray spectroscopy

X- ray astronomy is a relatively new field! -> Impossible from Earth

Light behaves more like particles -> Not your standard telescope!

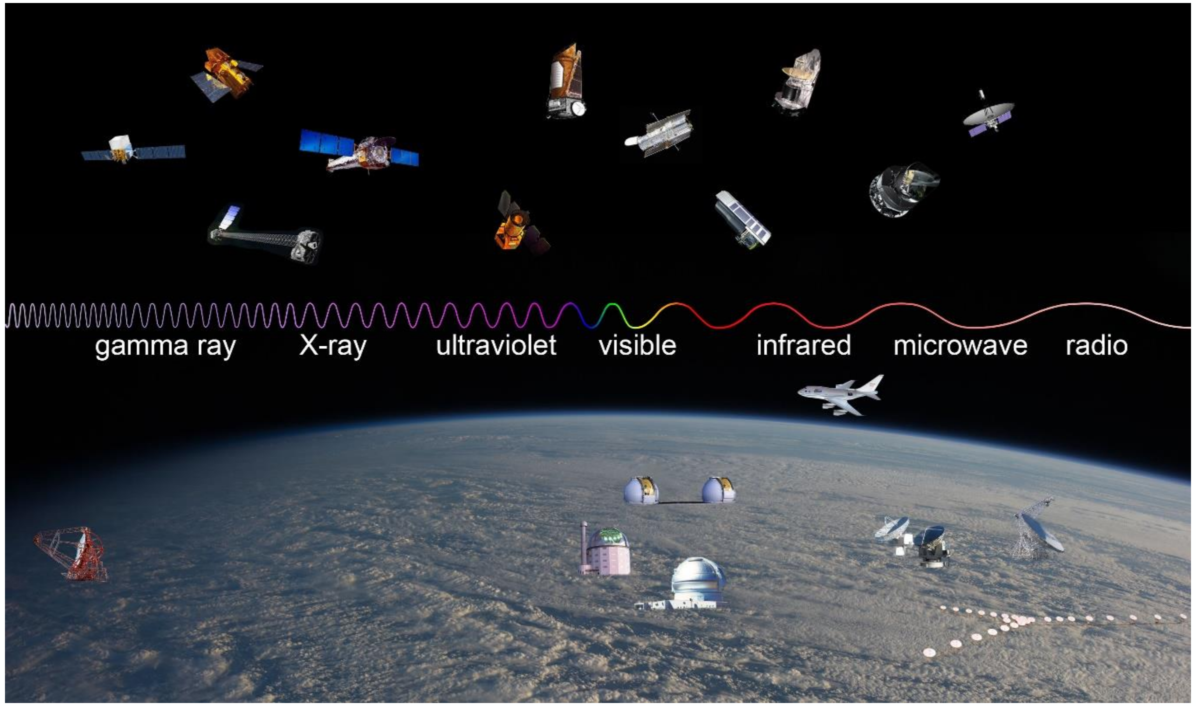


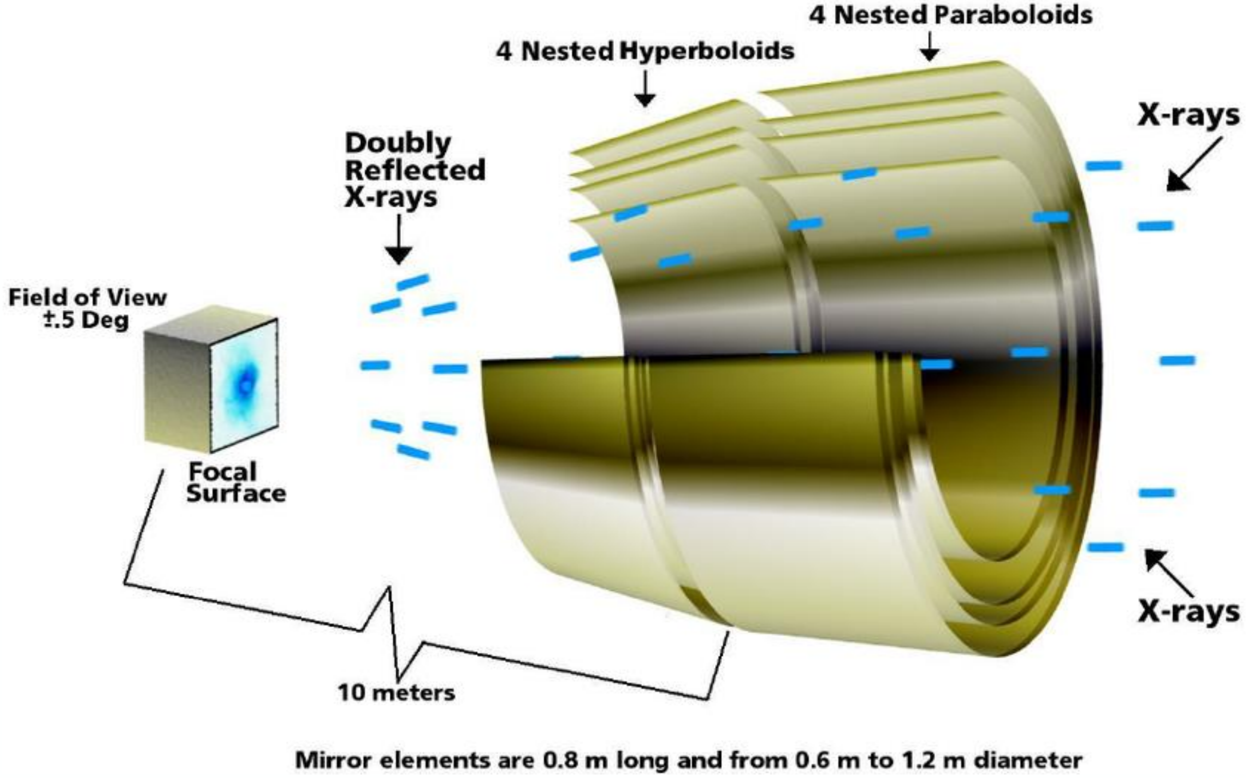
Image credit: OBSERVATORY IMAGES FROM NASA, ESA (HERSCHEL AND PLANCK), LAVOCHKIN ASSOCIATION (SPECKTR-R), HESS COLLABORATION (HESS), SALT FOUNDATION (SALT), RICK PETERSON/WMKO (KECK), GERMINI OBSERVATORY/AURA (GEMINI), CARMA TEAM (CARMA), AND NRAO/AUI (GREENBANK AND VLA); BACKGROUND IMAGE FROM NASA)

X-ray missions and X-ray spectroscopy

X- ray astronomy is a relatively new field! -> Impossible from Earth

Light behaves more like particles -> Not your standard telescope!

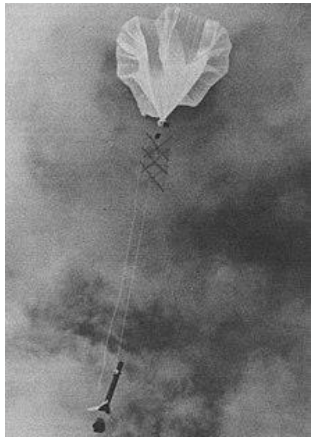
Detector: CCD or Calorimeter



Credit: NASA/CXC/ D. Berry

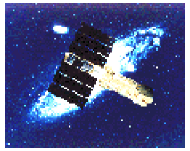
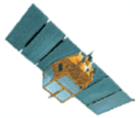
Discovering the ISM from the X-ray perspective

First X-ray missions in 1960s and 1970s, and many since









1960

First "X-ray telescope" rocket experiment By Giacconi

1970

Uhuru (1970)

Einstein First imaging (1978)

1980

EXOSAT (1983)

ROSAT (1990)

1990

ASCA

RXTE

BeppoSAX

2000

Chandra (1999)
XMM Newton (1999)
Hitomi (2016)
eROSITA (2019)

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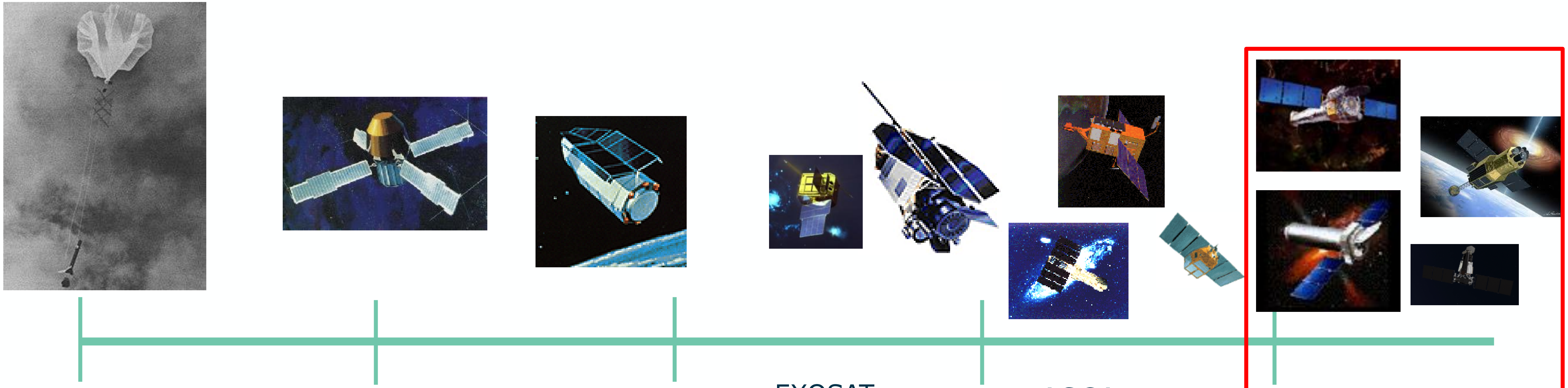

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X-ray spectroscopy: units and other jargon

eV and keV : used sometimes instead of Angstrom

Conversion factor: $E_{photon} = h\nu = hc/\lambda$

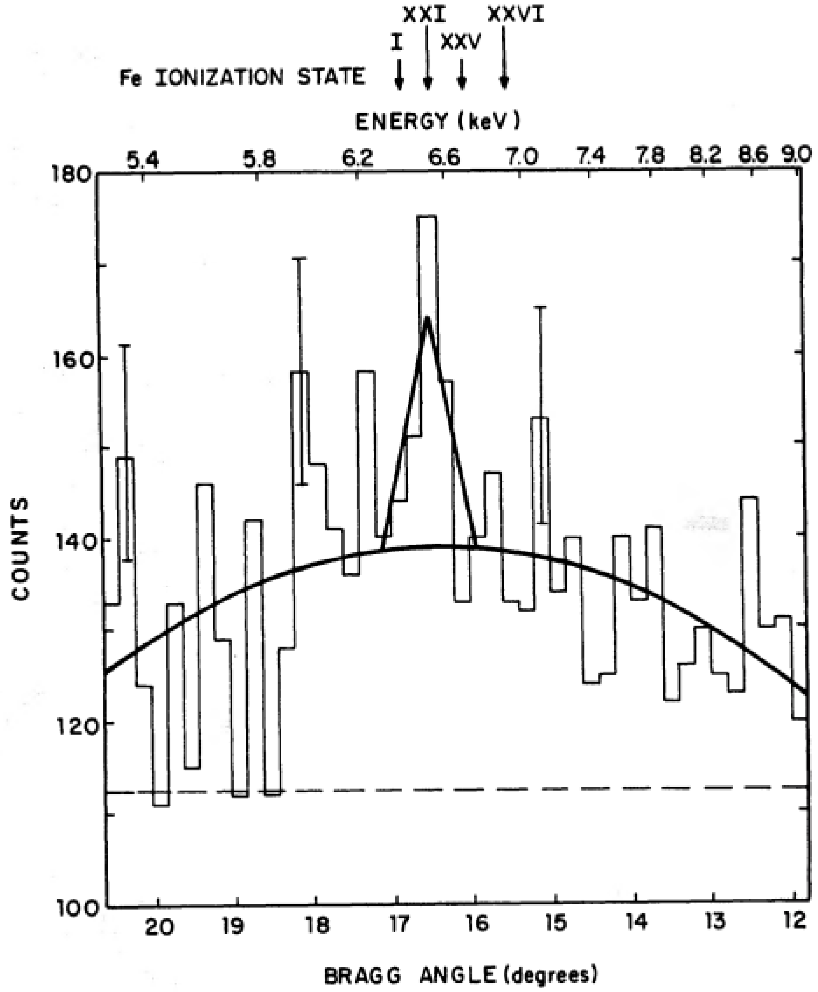
and 1 Angstrom (A) corresponds to 12398 eV (or 12.398 keV)

Soft X-rays: 0.1 – 10 keV

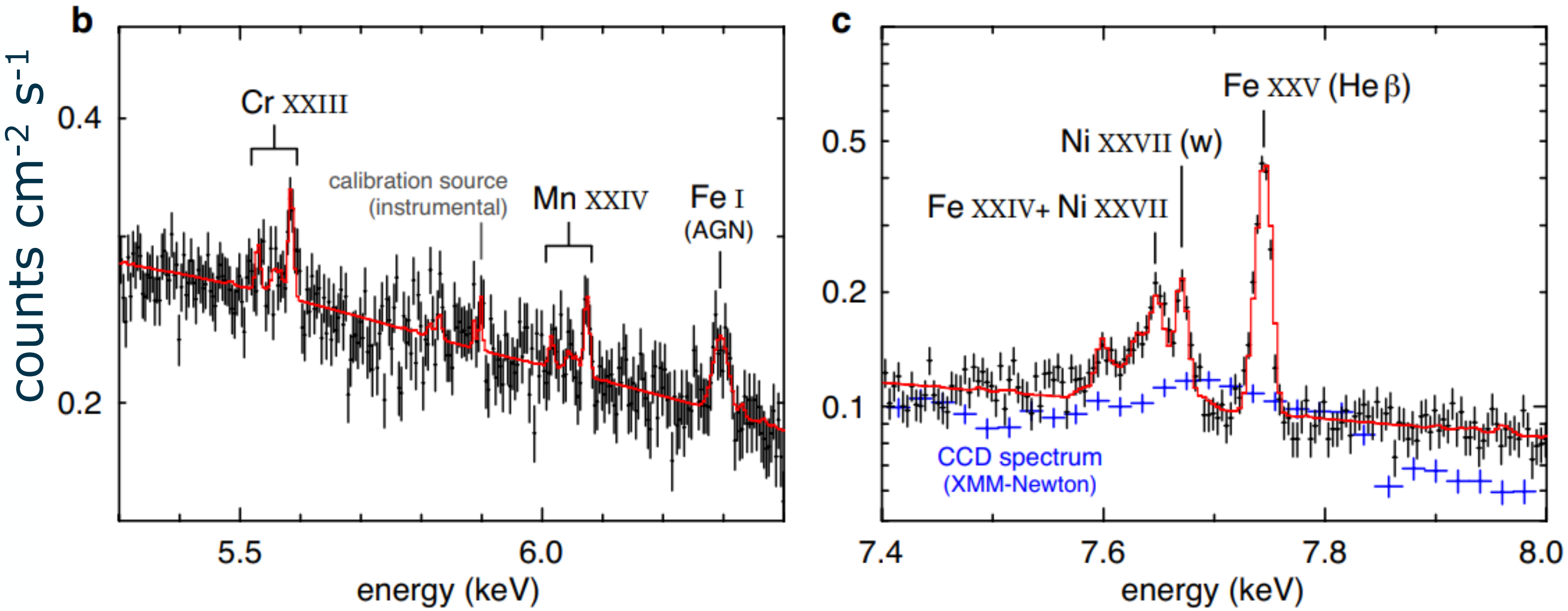
Hard X-rays: > 10 keV

Counts on the y-axis: yes, we are counting photons!

X-ray spectroscopy: OSO-8 (1978) vs Hitomi (2016)

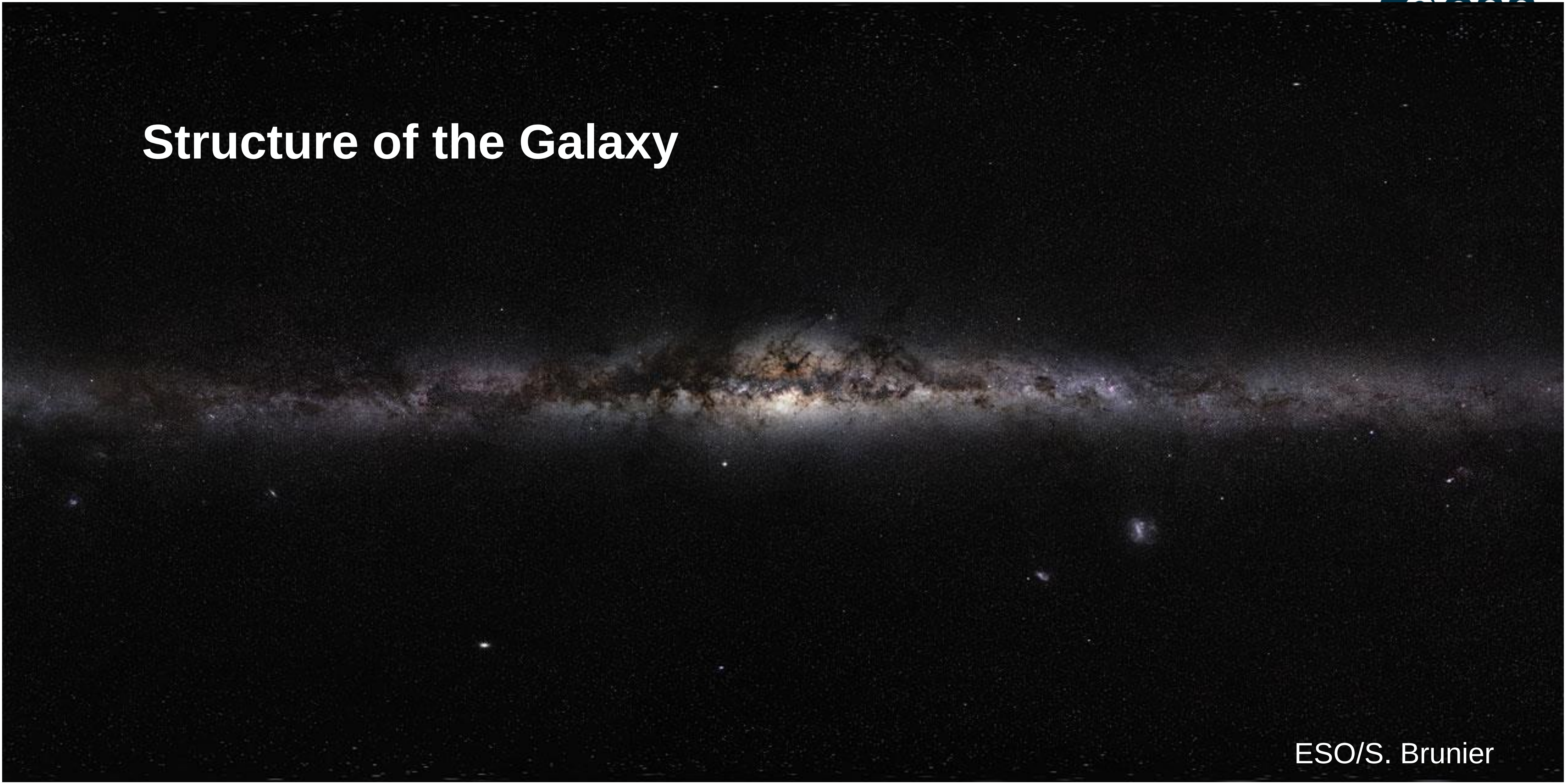


Cygnus X-3: Kestenbaum 1978

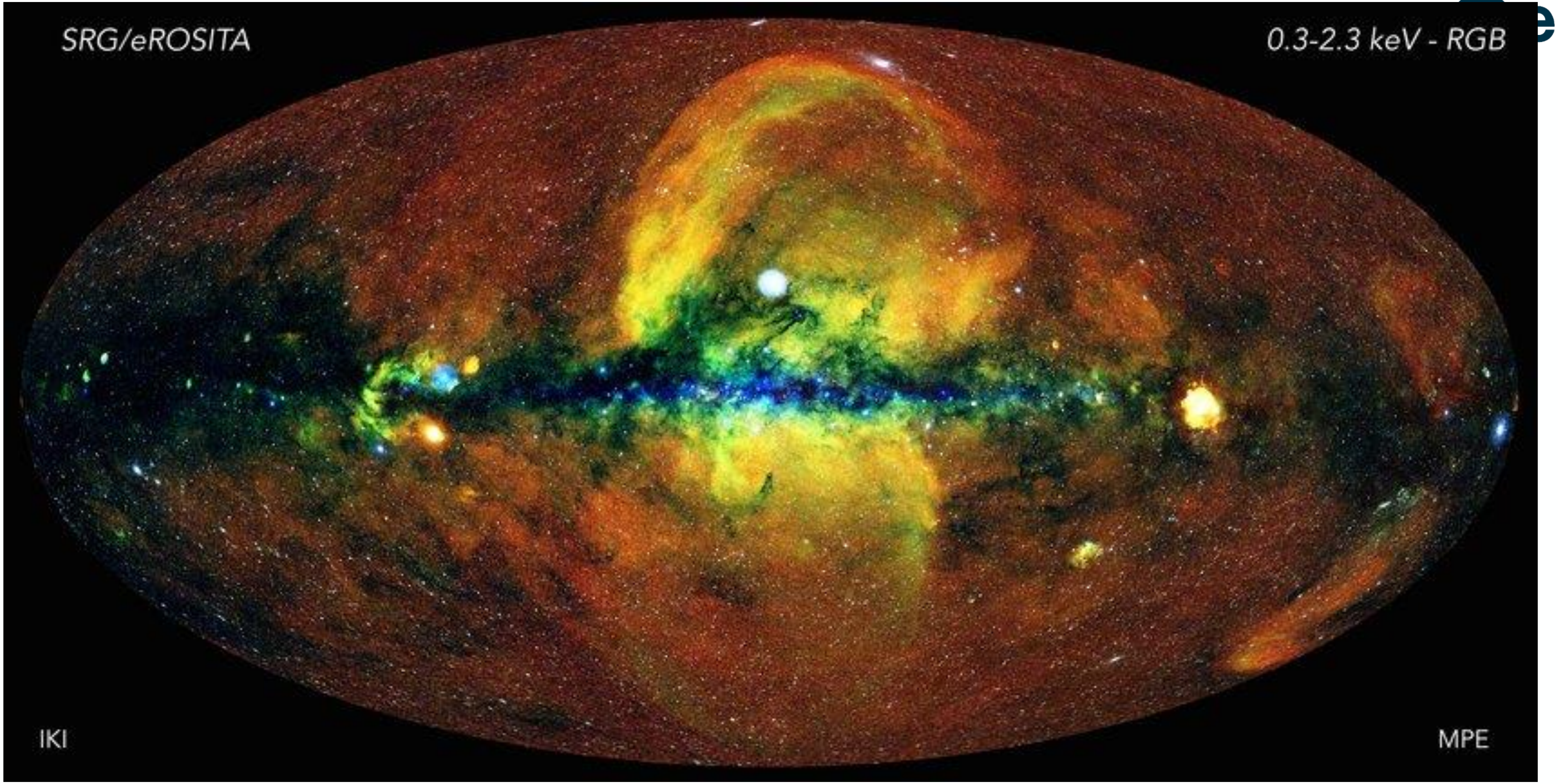


Perseus cluster : Hitomi collaboration 2017

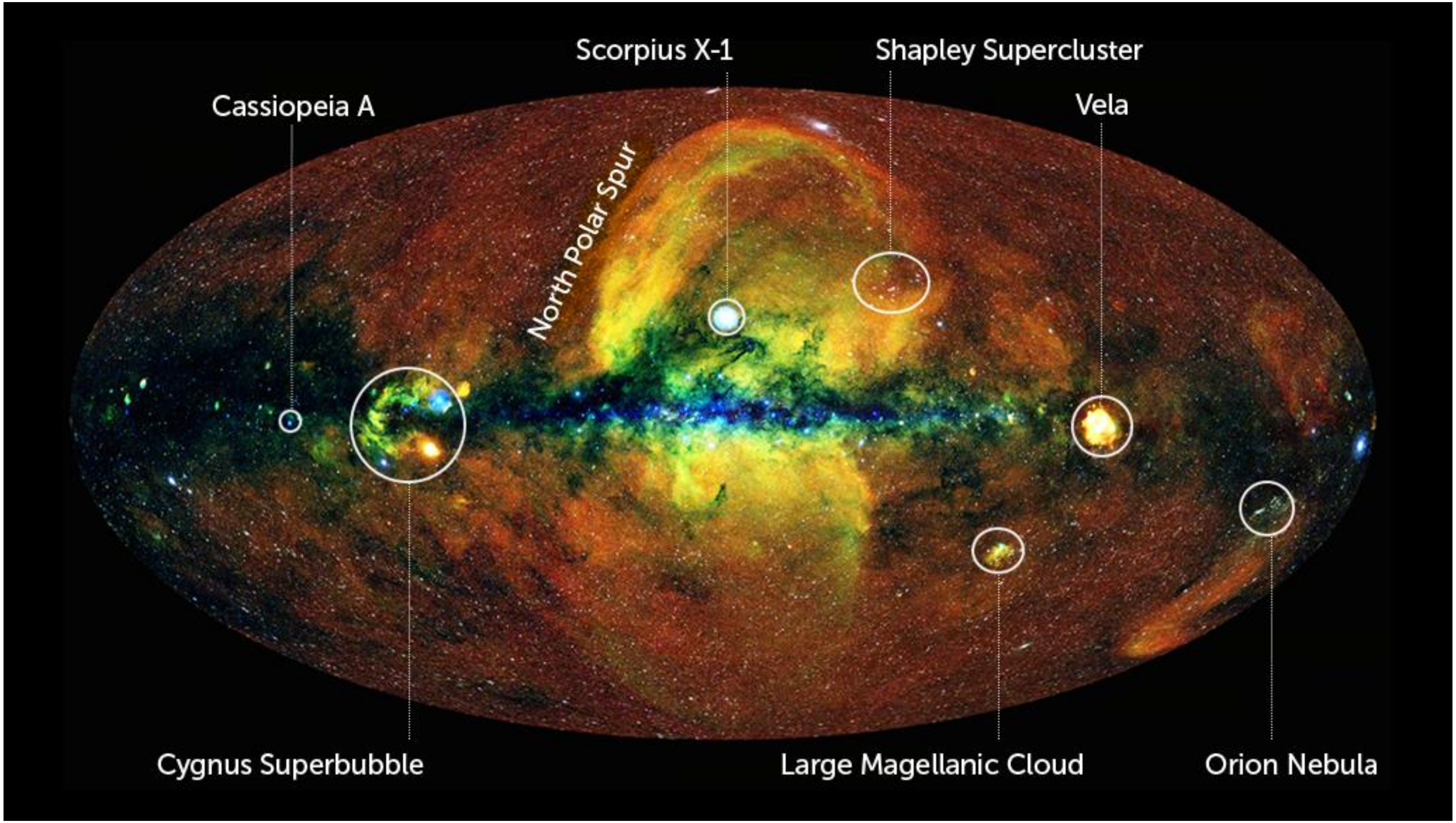
Structure of the Galaxy



ESO/S. Brunier



SOFT X-RAY MAP: compact object population (NS), diffuse emission (shocked gas), scattering and absorption by interstellar dust



SOFT X-RAY MAP: compact object population (NS), diffuse emission (shocked gas), scattering and absorption by interstellar dust

Phases of the ISM

	Phase	Density nH (cm -3)	Temperature (K)	Total mass (10^9 Msun)
Hot	Hot intercloud medium	0.003	10^6	-
Warm	Warm neutral medium	0.5	8000	2.8
Warm	Warm ionized medium	0.1	8000	1.0
Cold	Cold neutral medium (diffuse clouds)	50.0	80	2.2
Cold	Molecular clouds	>200.0	10	1.3
Cold	H II regions	$1 - 10^5$	10^4	0.05

Tielens 2005

Phases of the ISM

Tielens 2005

	Phase	Density nH (cm -3)	Temperature (K)	Total mass (10^9 Msun)	Heating/ ionizing source
Hot	Hot intercloud medium	0.003	10^6	-	Shockwaves from SNe
Warm	Warm neutral medium	0.5	8000	2.8	UV photons from hot stars
	Warm ionized medium	0.1	8000	1.0	Dust, stellar radiation, cosmic rays
Cold	Cold neutral medium (diffuse clouds)	50.0	80	2.2	Dust, stellar radiation, cosmic rays
	Molecular clouds	>200.0	10	1.3	Dust, stellar radiation, cosmic rays

Phases of the ISM

We can use the X-rays to detect these phases

	Phase	Density nH (cm -3)	Temperature (K)	Total mass (10^9 Msun)	indicator
Hot	Hot intercloud medium	0.003	10^6	-	O VI–VIII, ...
Warm	Warm neutral medium	0.5	8000	2.8	H I, O I, ...
	Warm ionized medium	0.1	8000	1.0	H II, O II–III, ...
Cold	Cold neutral medium (diffuse clouds)	50.0	80	2.2	H I, O I, ...
	Molecular clouds	>200.0	10	1.3	H2, CO, ...

Tielens 2005, Pinto 2013

Discovering the ISM from the X-ray perspective

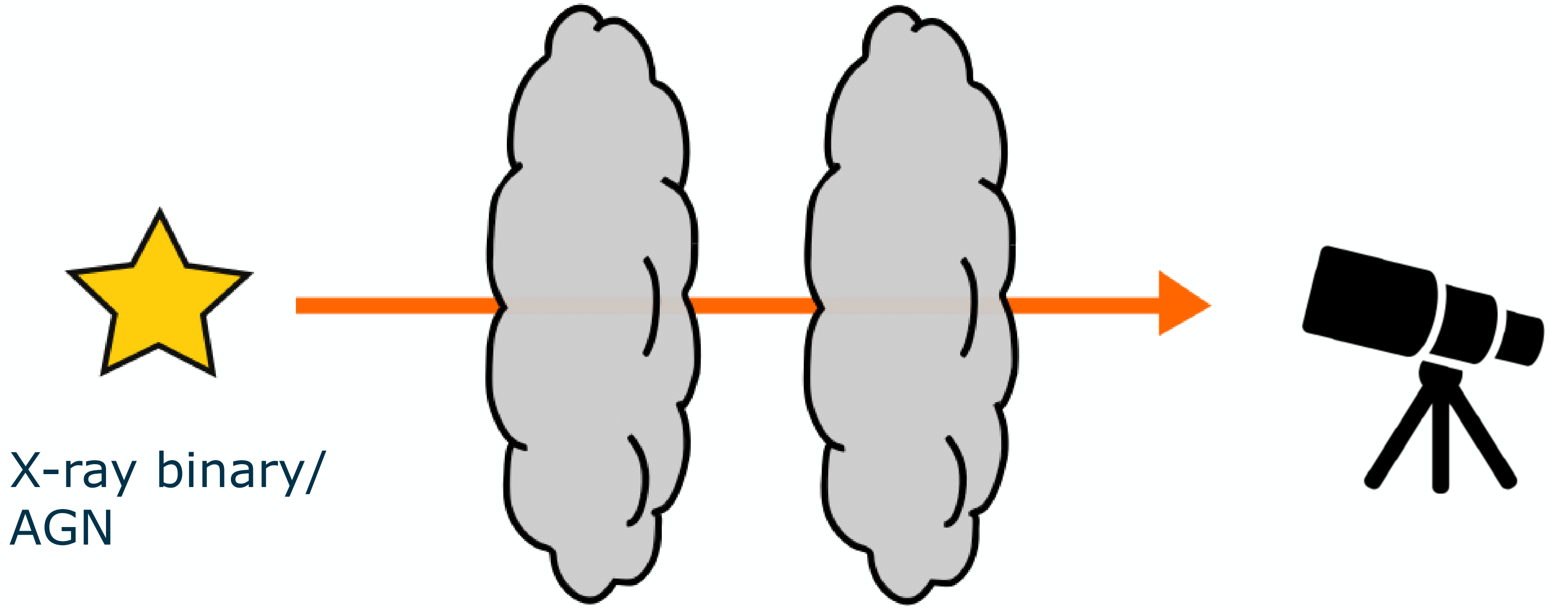
The X-rays provide important advantages to study the ISM

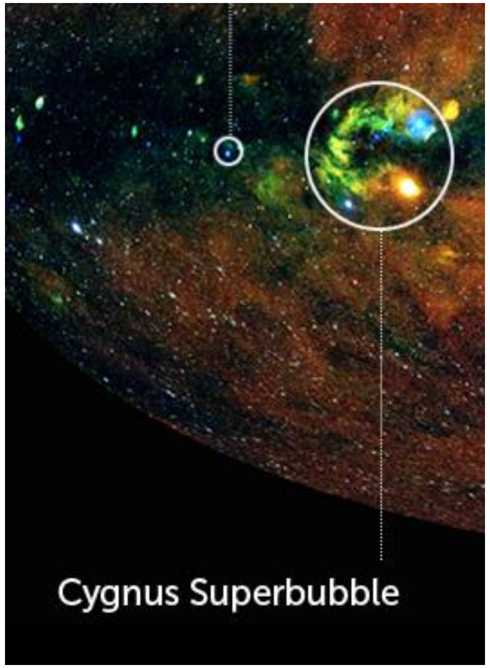
- **The broad band energy coverage (0.1–10 keV)** encompasses a variety of transitions, from neutral to highly ionized gas, of the **fundamental metals in the Universe**: C, N, O, Ne and Fe, among others.
- **Provides the possibility to measure hydrogen column densities**
- **Sensitive to a wide range of column density** → study various regions in the Galaxy
- **Absorption and scattering of dust can be simultaneously studied** → only X-rays can do this
- **Easy to determine the depletion from the gas phase**

Discovering the ISM from the X-ray perspective

1) Observing emission in X-rays from the ISM

2) Observing ISM in absorption with backlight source





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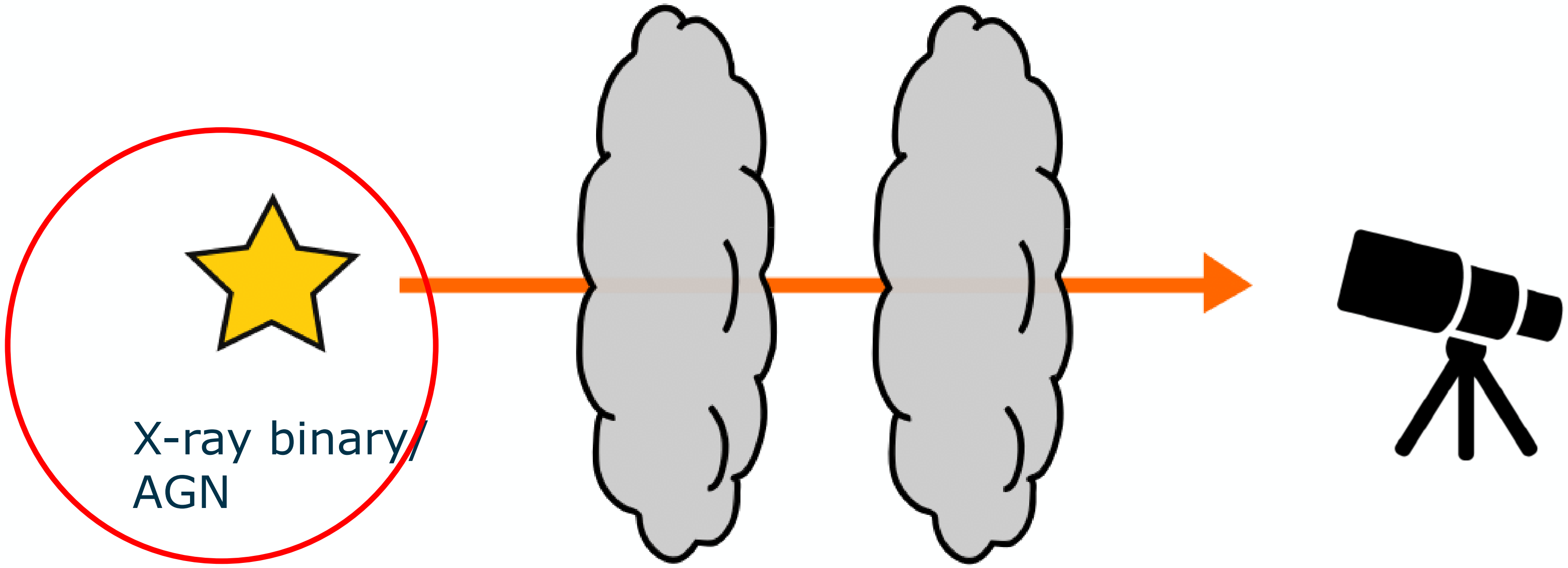
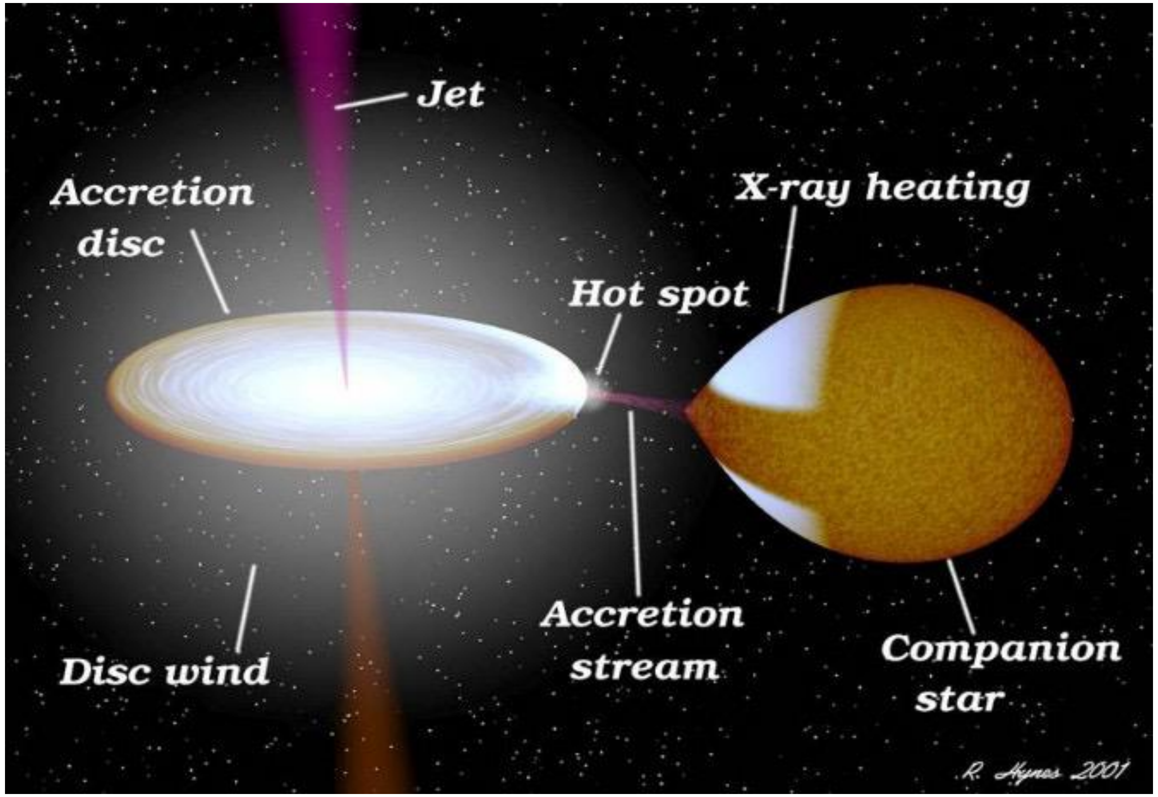


X-ray binaries

Binary star system:

Neutron star, Blackhole or white dwarf accreting mass from a less evolved companion



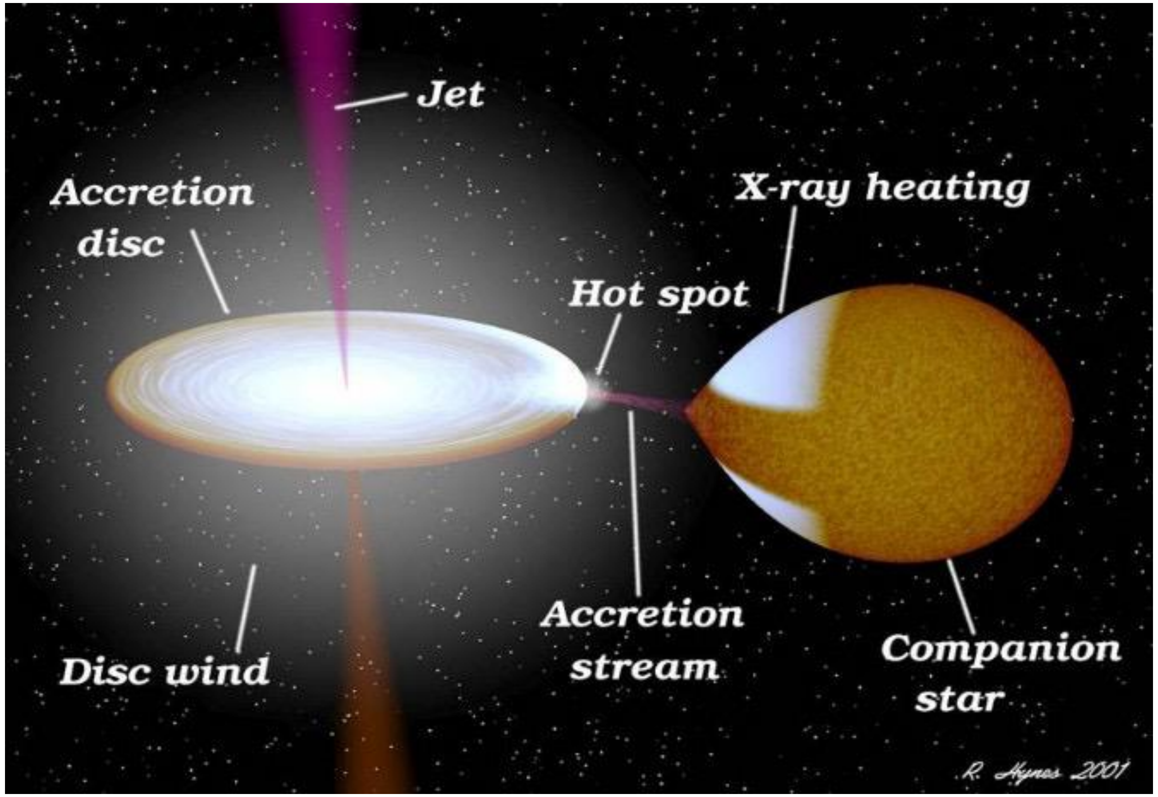
Why are X-ray binaries bright in X-rays?

Binary star system:

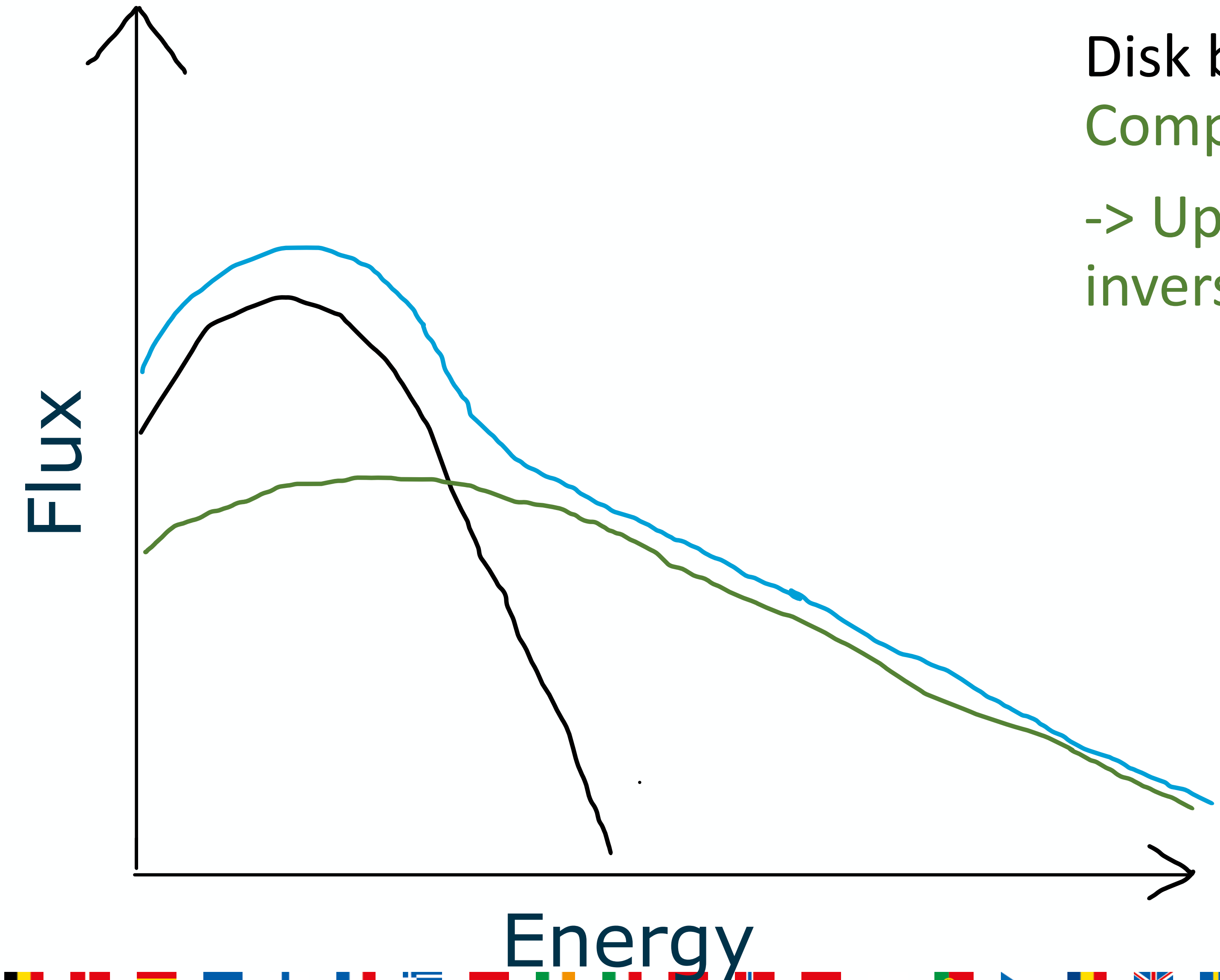
X-rays originate from the **gravitational potential energy** of the infalling matter.

<ins>Soft X-rays</ins>: accretion disc

<ins>Hard X-rays</ins>: from thin-hot plasmas above or inside the optically thick disk

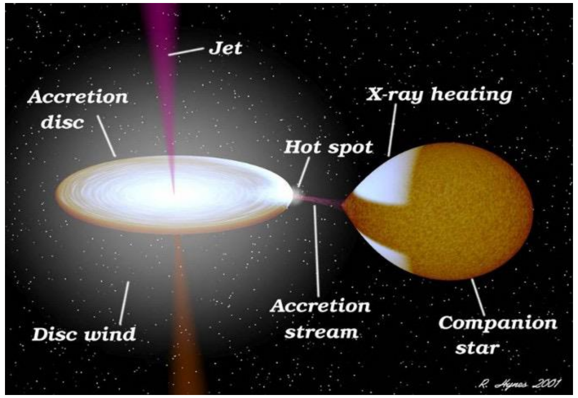


Why are X-ray binaries bright in the X-rays?



Disk black body model +
Compton component = Total

-> Upscattered photons:
inverse Compton scattering



Low and High mass X-ray binaries

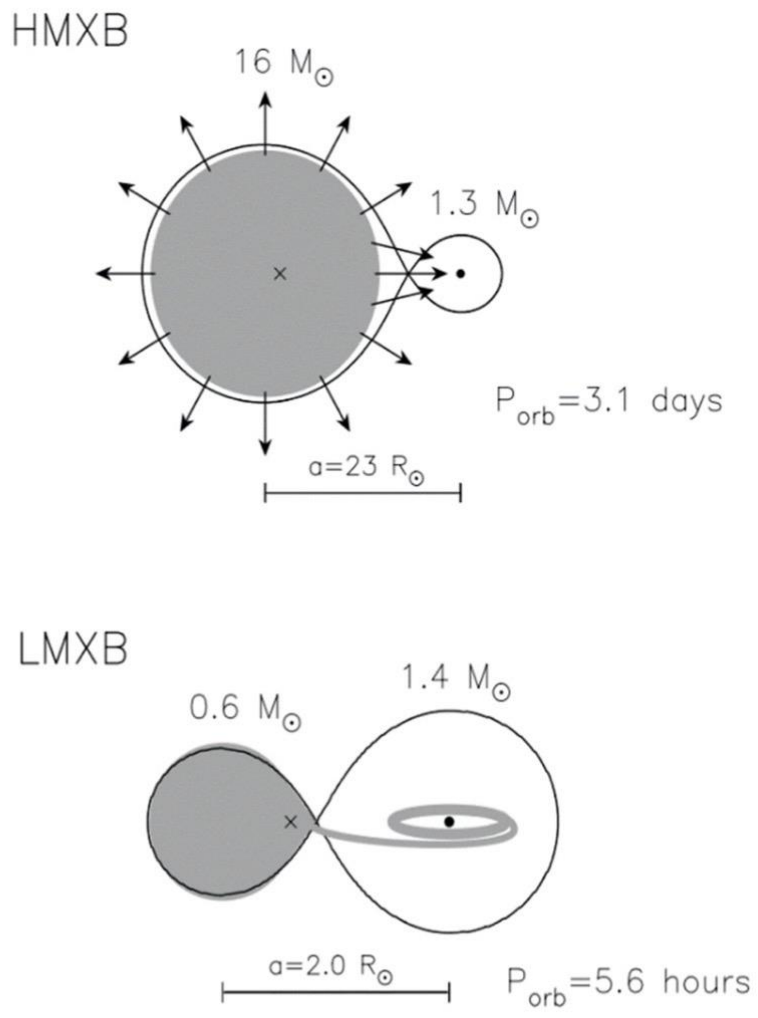
There are two types of X-ray binaries:

1) **Low mass x-ray binaries** companion star has a low mass:

$< 1.5\ M_{sun}$ + spectral type A or later

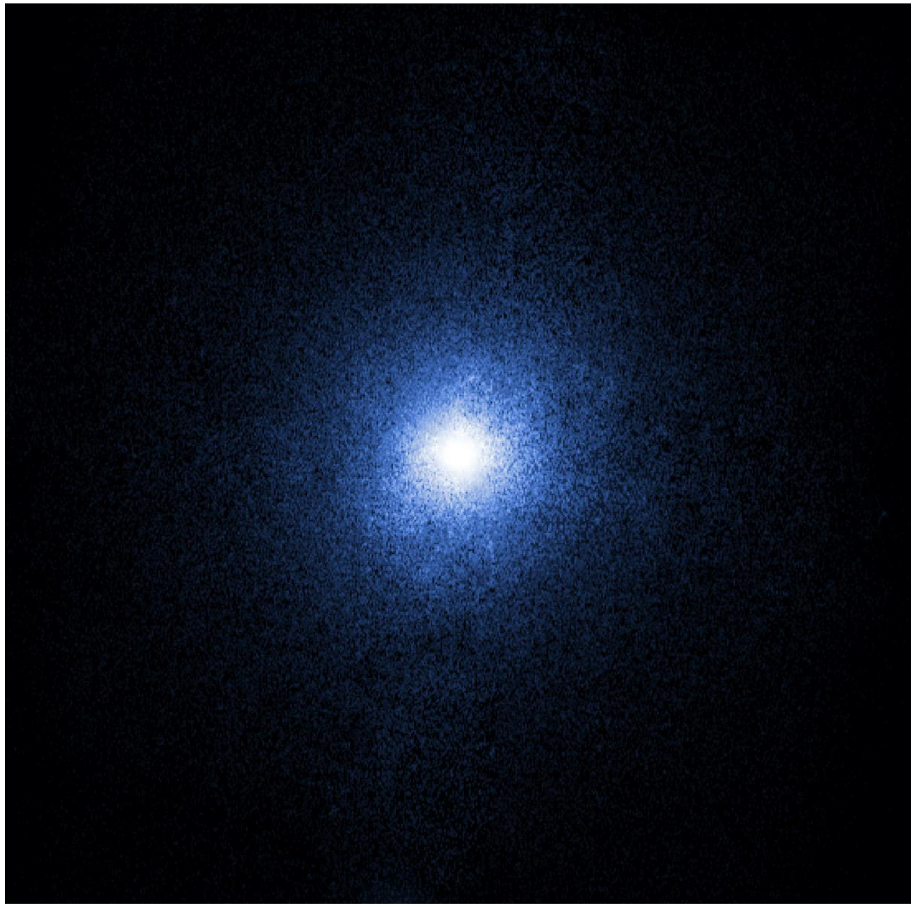
2) **High mass X-ray binaries** companion star has high mass:

$> 10\ M_{sun}$ + spectral type O or B star



Source: Tan 2012

X-ray binaries and scattering haloes



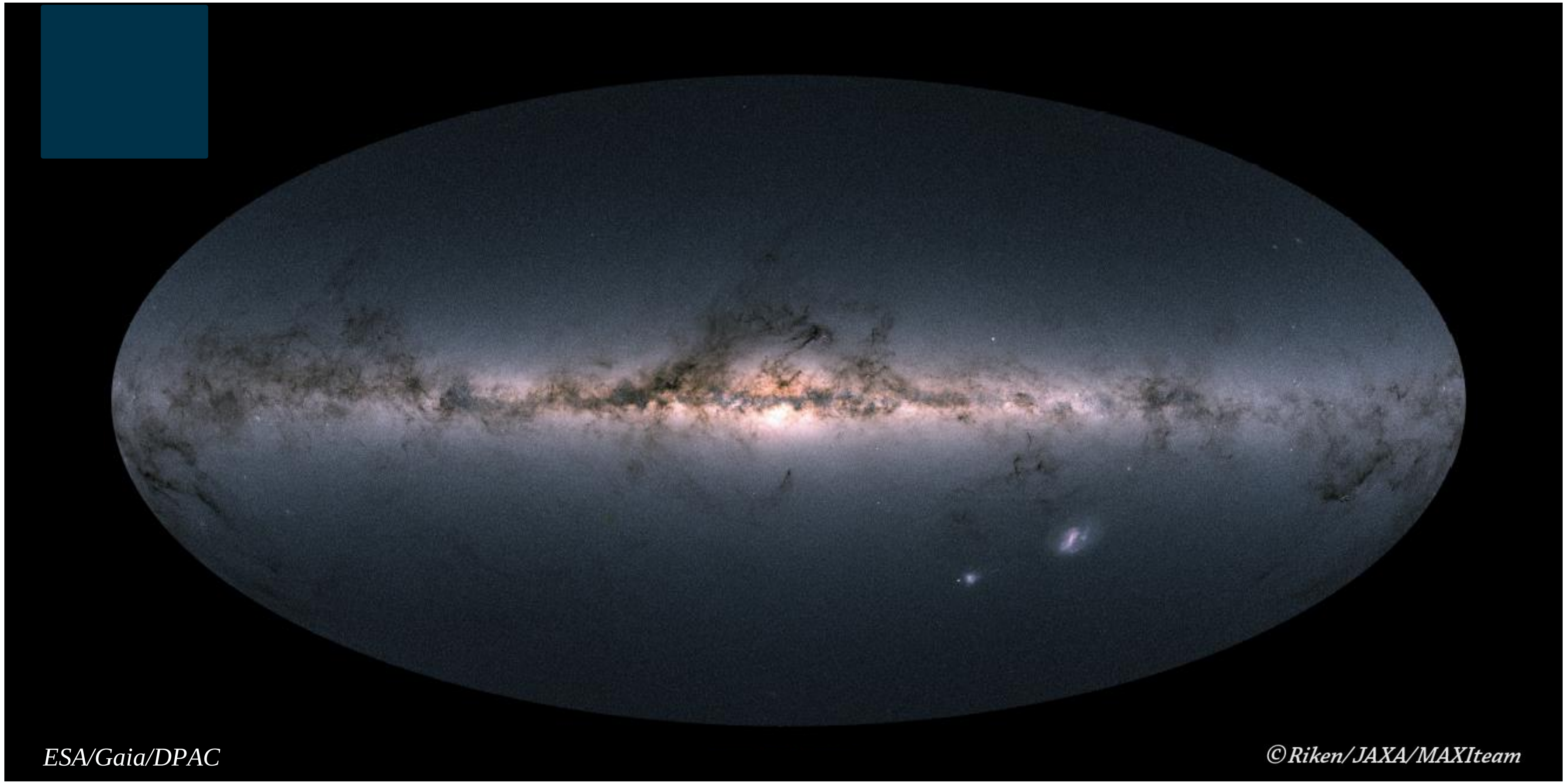
(Credit: X-ray: NASA/CXC; Optical: DSS; Illustration:NASA/CXC/M.Weiss)

X-rays are extremely forward scattered.
Scattering angles ~ 3^o (max)

When observing bright X-ray binaries we can detect a narrow scattering halo around the source

Observed here: Cygnus X-1 by the Chandra Observatory

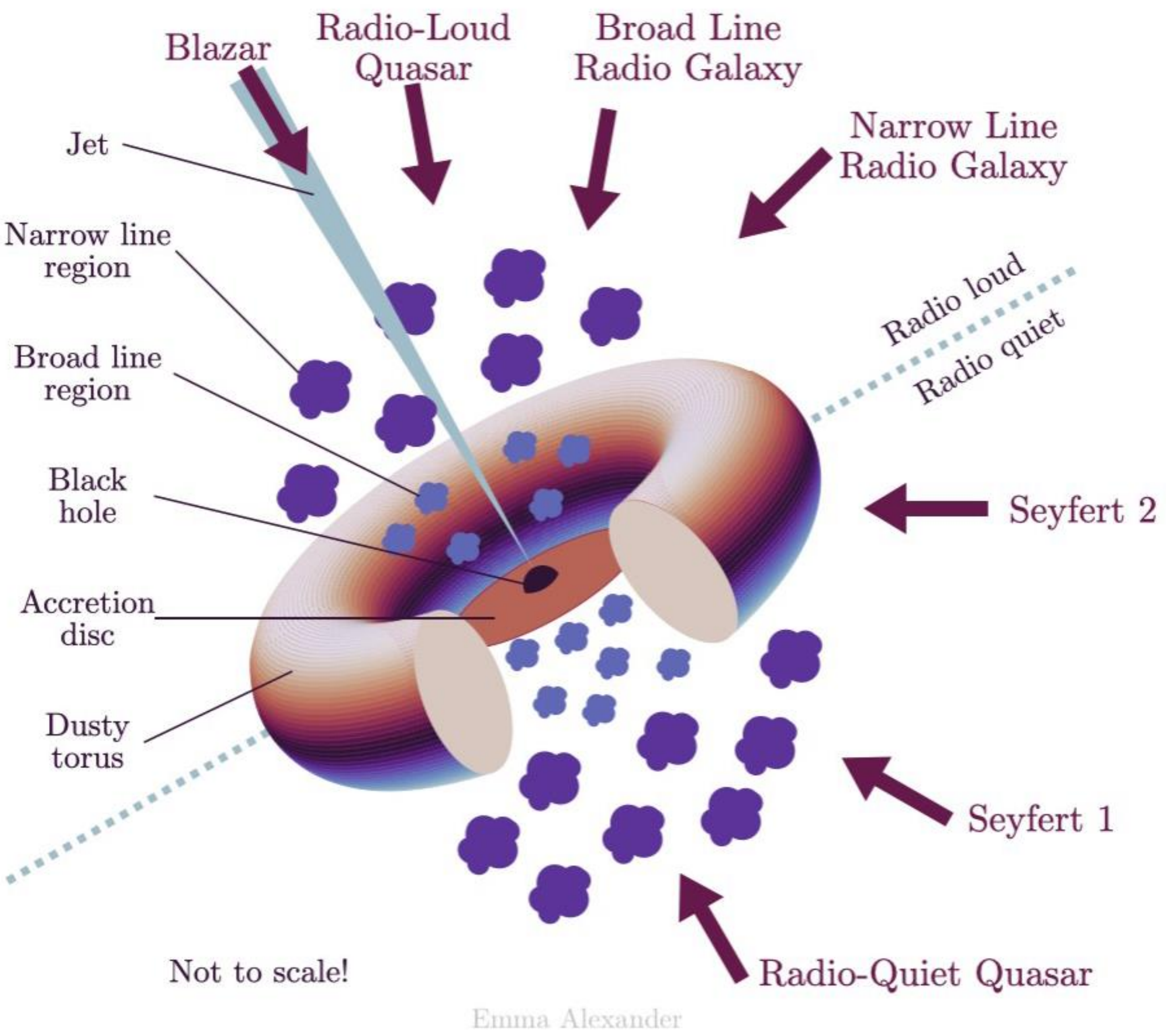
Sightlines towards the Galactic Plane



We can probe different lines of sight along the Galactic Plane

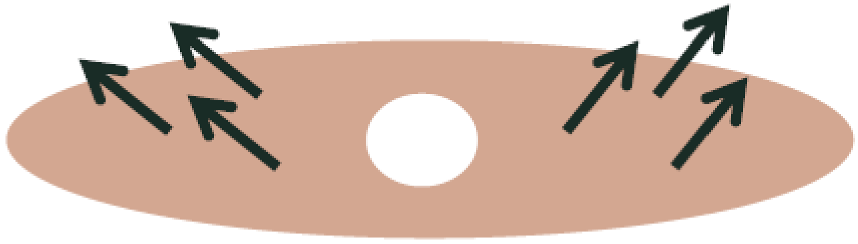
AGN: Active Galactic Nuclei

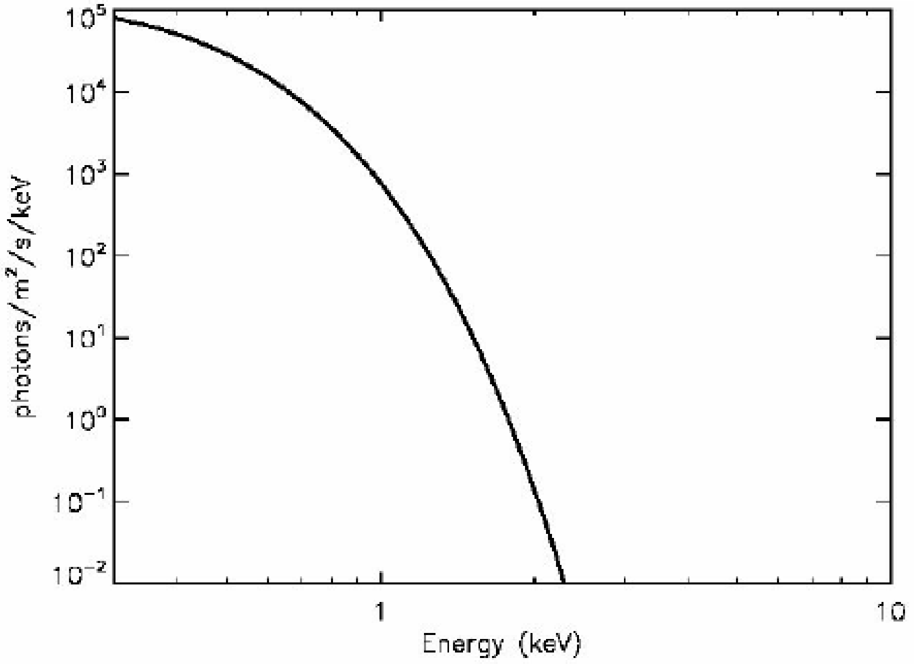
AGN galaxies appear different depending on the observing angle



Why are AGN bright in the X-rays?

$$F_\nu = \frac{2\pi h \nu^3 / c^2}{e^{h\nu / KT} - 1}$$



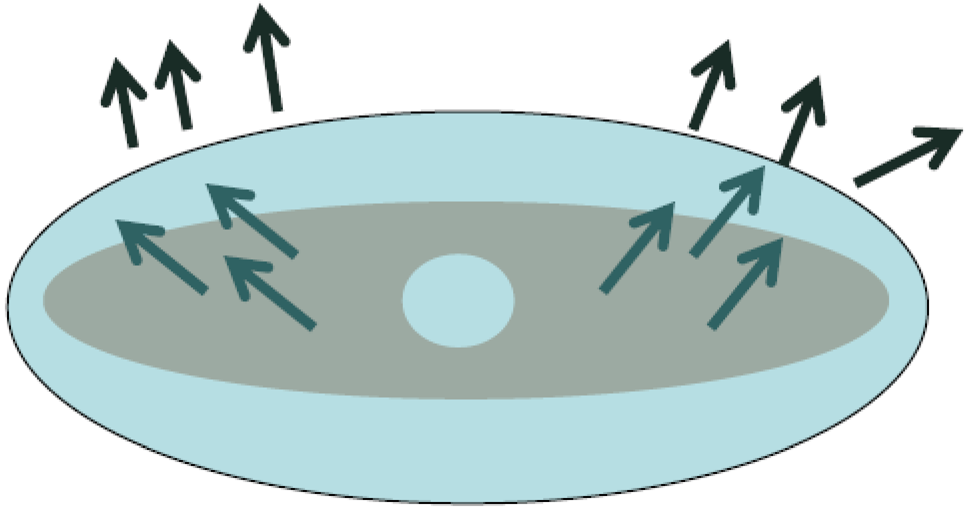


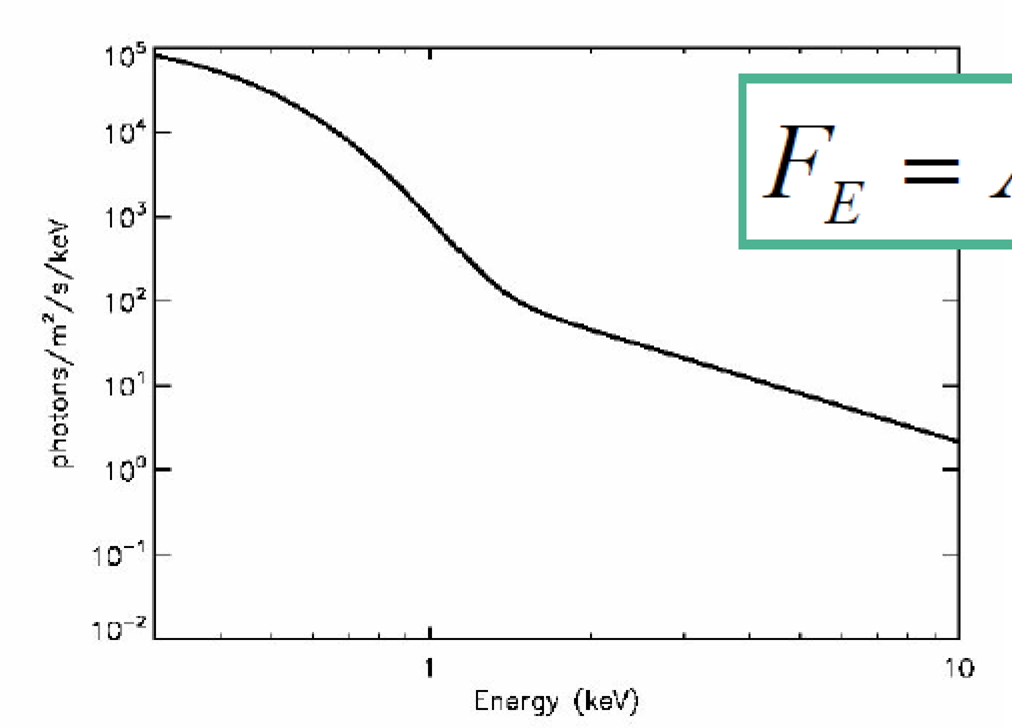
Blackbody emission from the accretion disc

Credit: E. Costantini

Why are AGN bright in the X-rays?

- Corona of hot electrons: inverse Compton effect with the photons of the disk



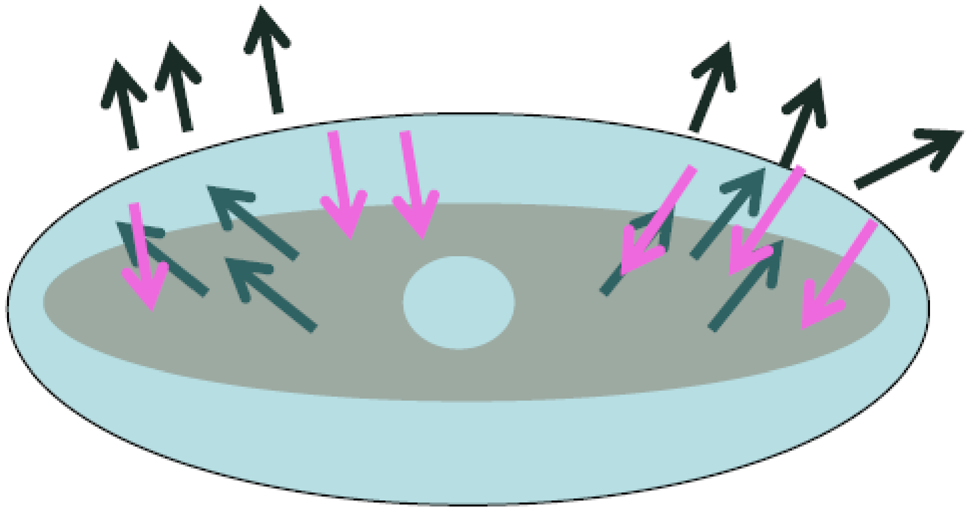


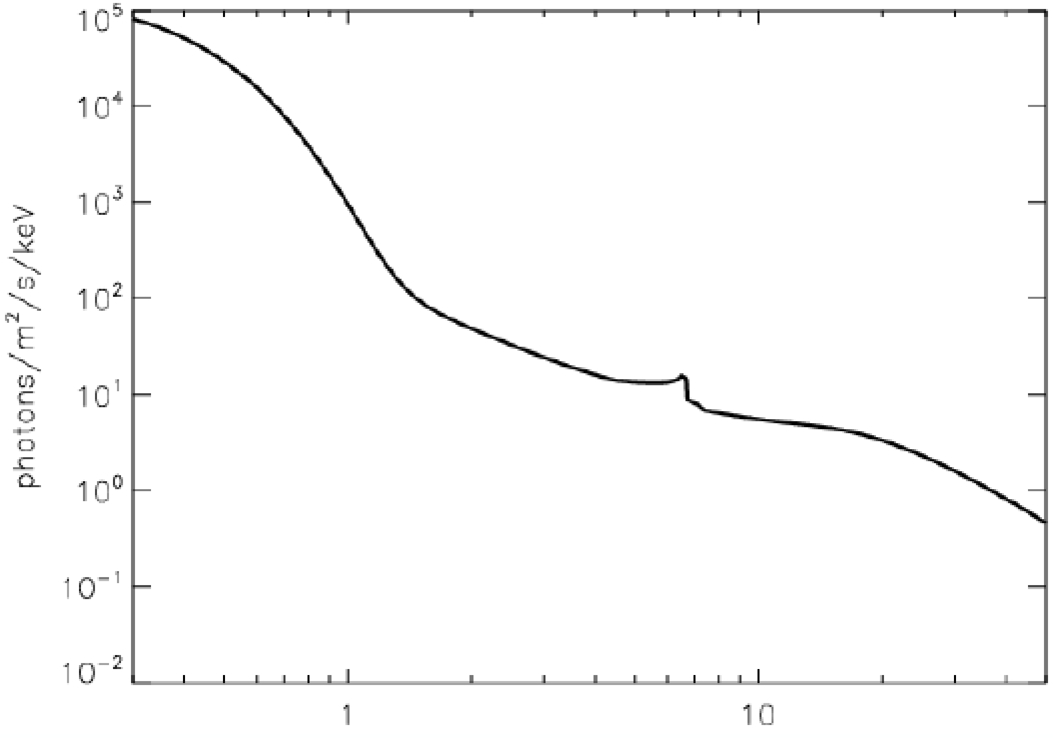
$$F_E = AE^{-\Gamma}$$

Credit: E. Costantini

Why are AGN bright in the X-rays?

Fluorescence Iron K α line at 6.4 keV from reflected photons on the disk





Credit: E. Costantini

Why are AGN bright in the X-rays?

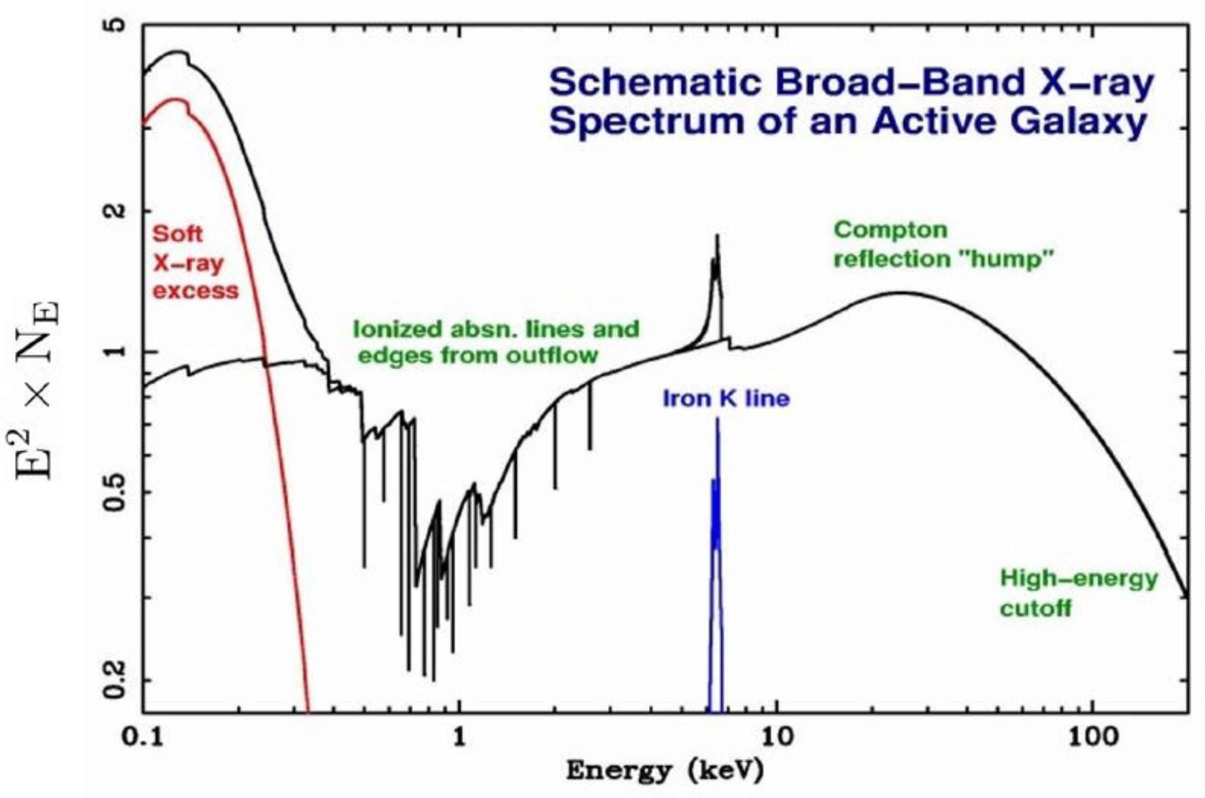
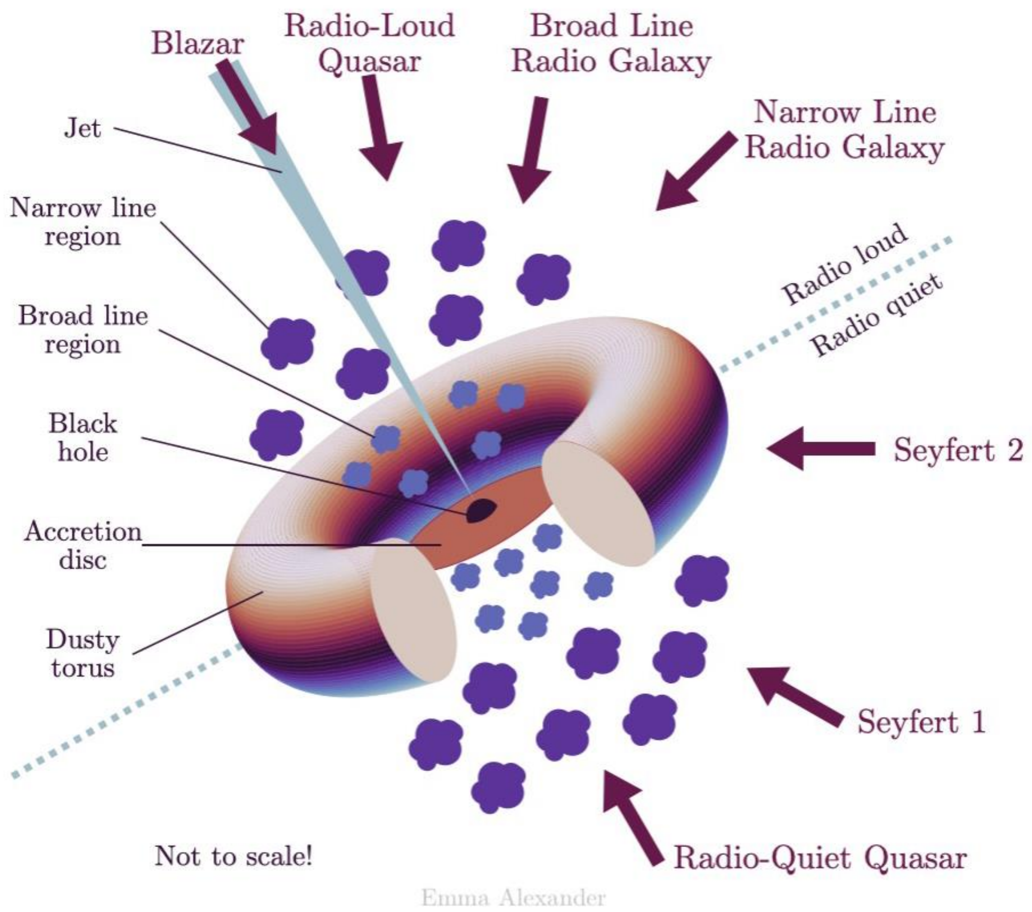


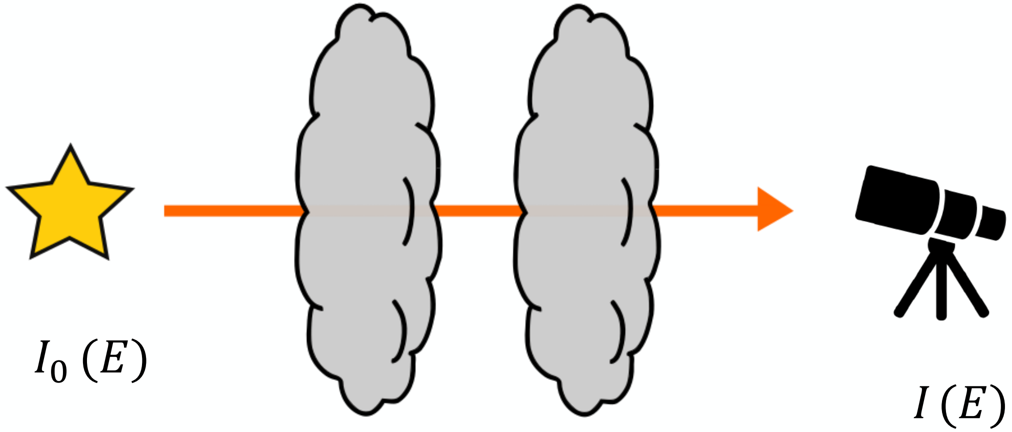
Figure: W. Brandt



→ THE EUROPEAN SPACE AGENCY

MODELING THE X-RAY ABSORPTION IN THE ISM: X-ray edges

Extinction: $\frac{I(E)}{I_0(E)} = e^{-\tau}$



τ: optical depth

$\tau = \sigma_{ISM} N(H)$

defined as the cross section times the number of particles, (N(H) is number of Hydrogen particles)

Cross sections: $\sigma_{ISM} = \sigma_{gas} + \sigma_{dust}$

MODELING THE X-RAY ABSORPTION IN THE ISM: X-ray edges

Cross sections

$$\sigma_{ISM} = \sigma_{gas} + \sigma_{dust}$$

$$\sigma_{\mathrm{gas}} = \sum_{Z,i} A_Z \times a_{Z,i} \times (1 - \beta_{Z,i}) \times \sigma_{\mathrm{bf}}(Z,i)$$

Reference: Wilms et al. 2000

Abundance of element Z:

$$A_Z = \frac{N(Z)}{N(H)}$$

Fraction of ions of element Z in ionization state i:

$$a_{Z,i} = \frac{N(Z,i)}{N(Z)}$$

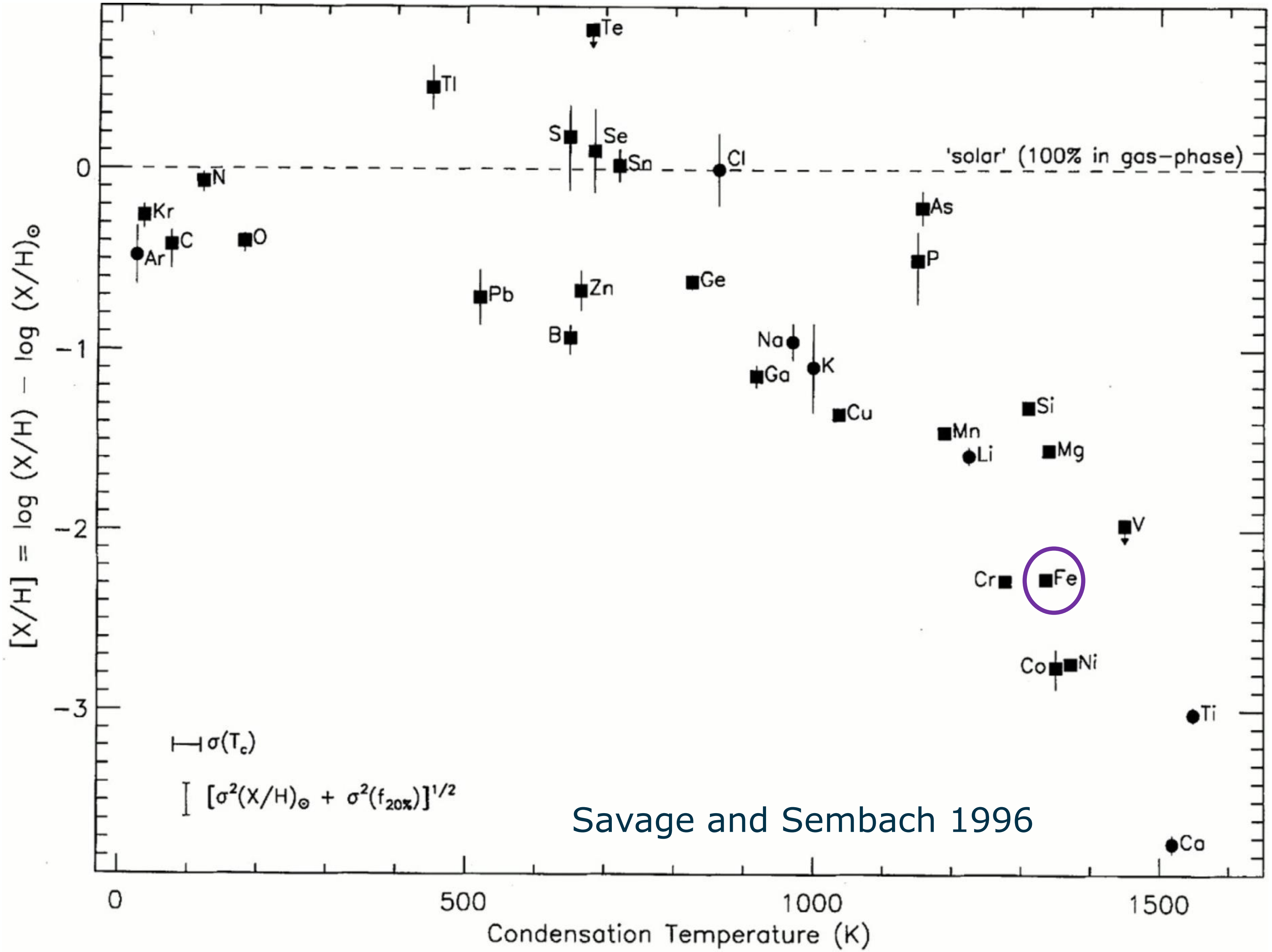
Depletion factor: $1 - \beta_{Z,i}$

Total photoionization crossection of elements : $\sigma_{bf}(Z,i)$

Elemental abundances and depletion

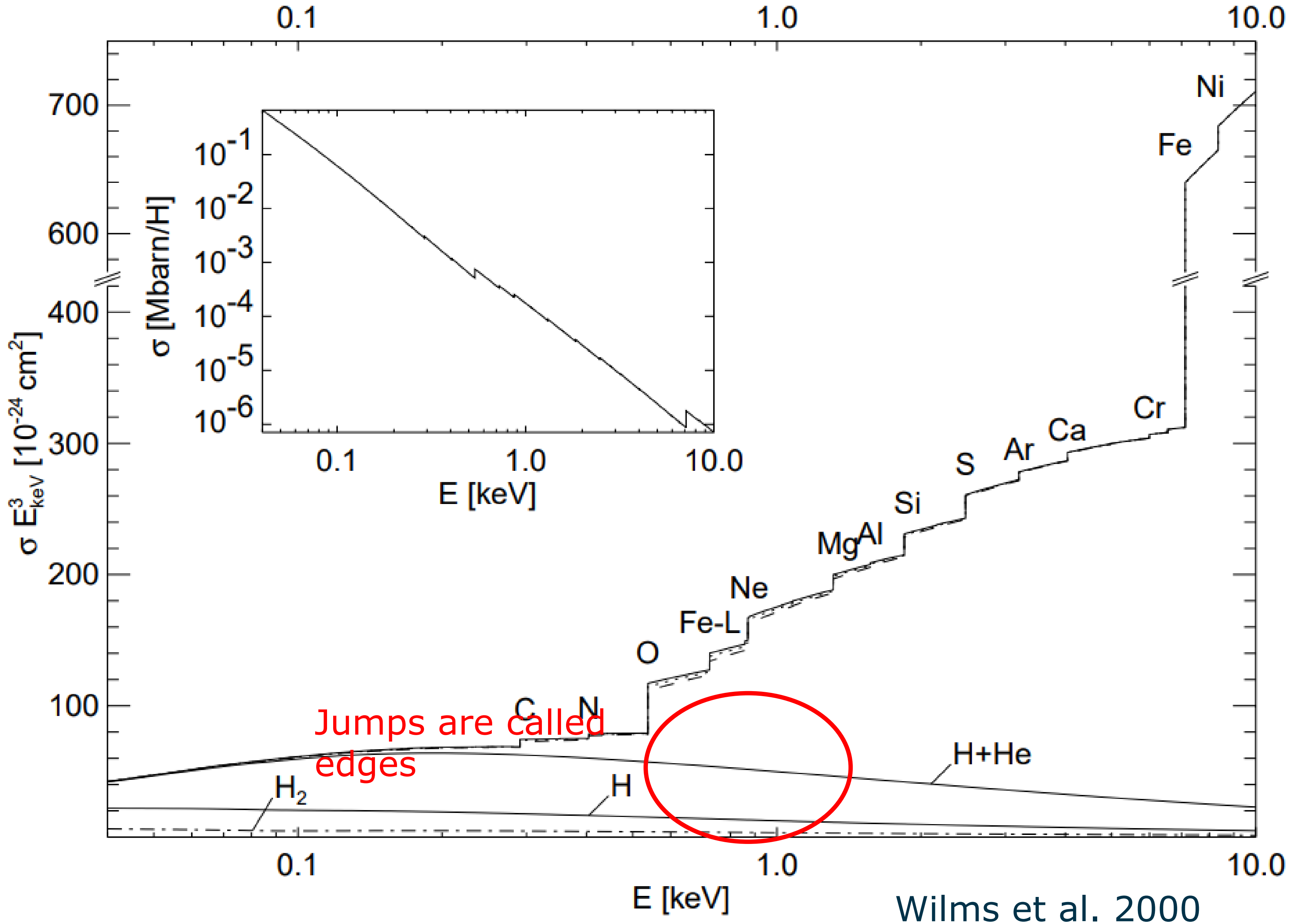
$$D(x) = log\left[\frac{N_x}{N_H}\right] - log\left[\frac{N_X}{N_H}\right]_{\odot}.$$

$$\delta(x) = 1 - 10^{D(x)}.$$



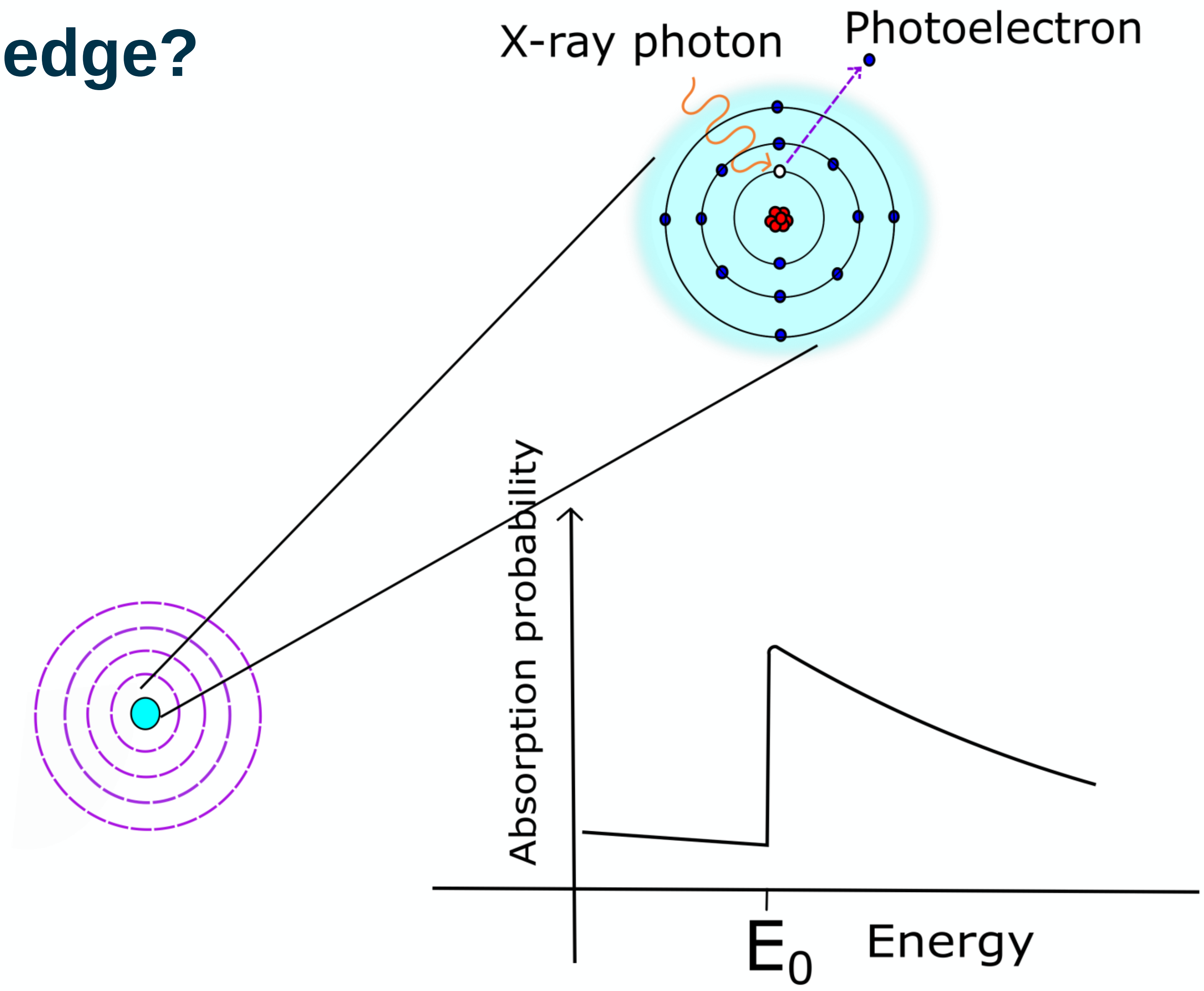
Savage and Sembach 1996

Cross sections



Wilms et al. 2000

What is an edge?



Credit: S. Zeegers

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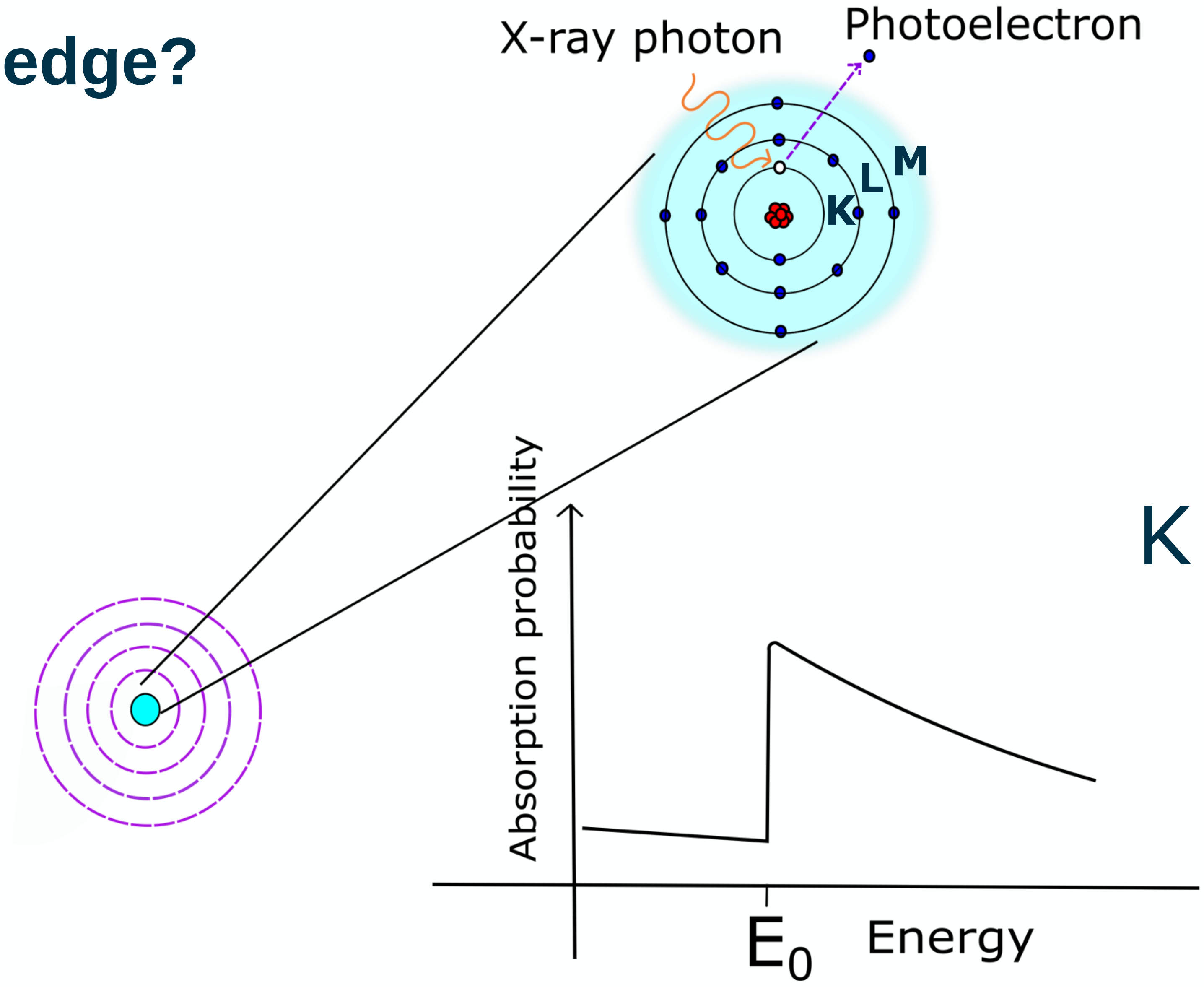


K edge

Credit: S. Zeegers

Exploring different environments in the Galaxy

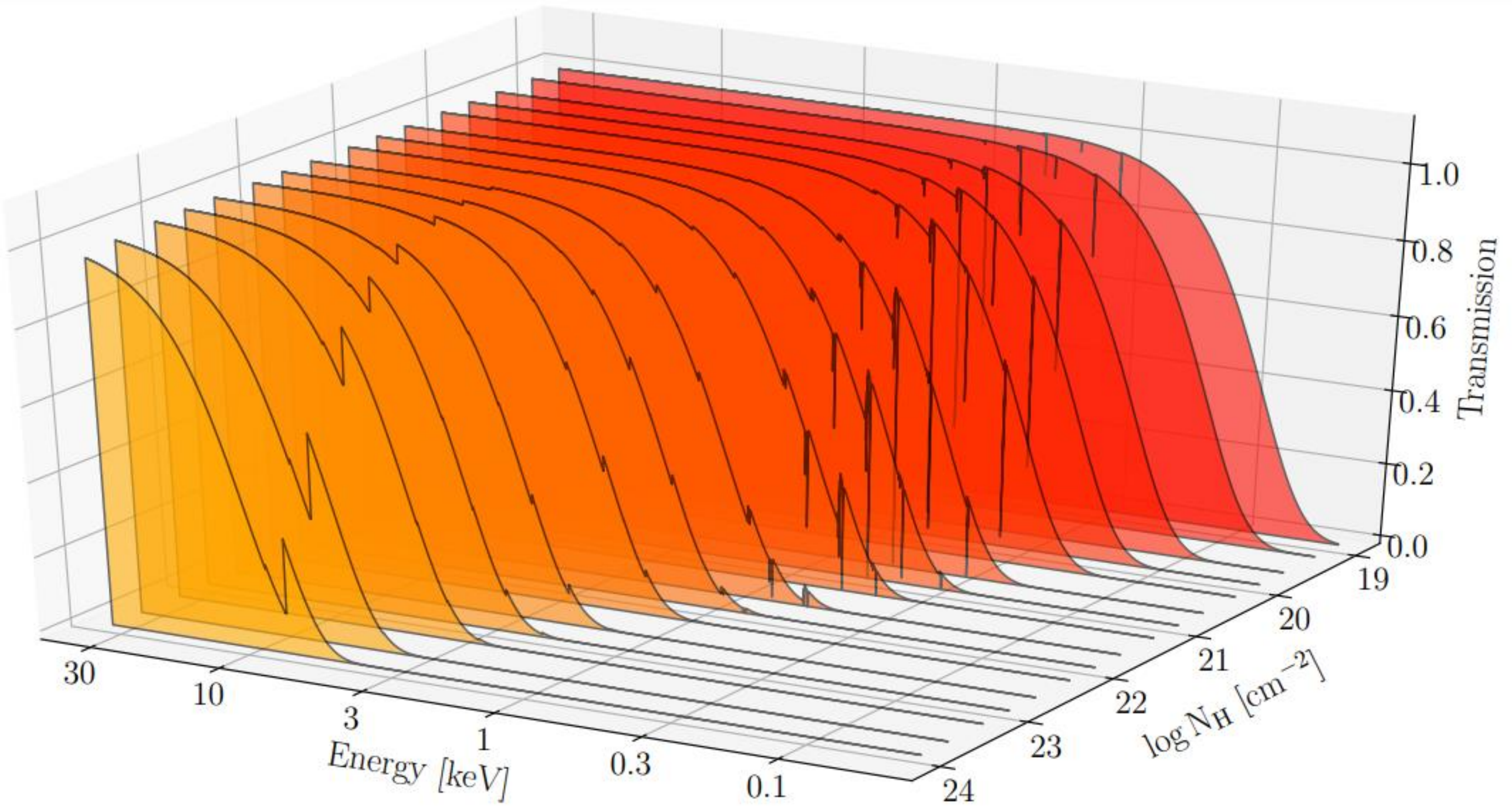


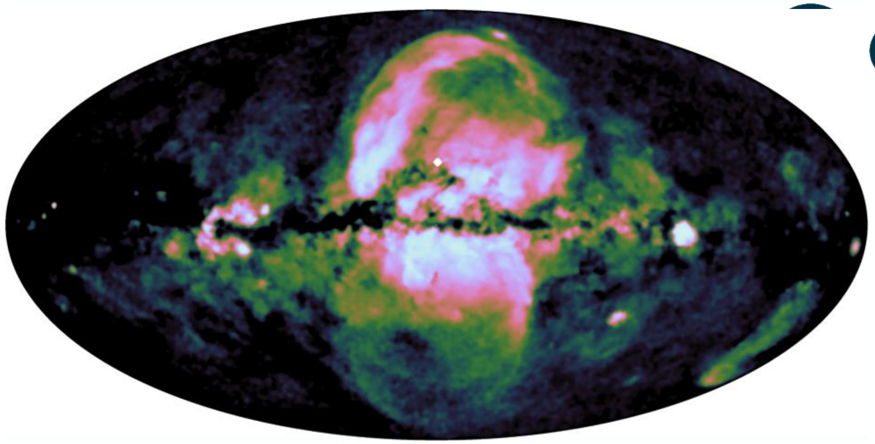
Figure: D. Rogantini 2020

Warm and hot gas

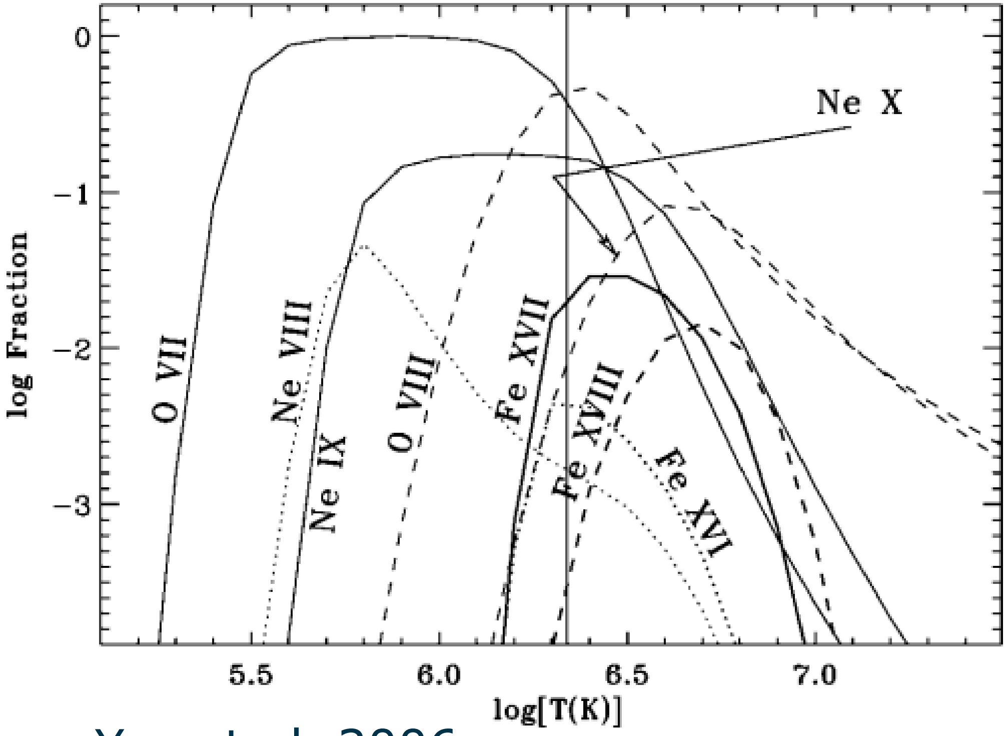
- 1965 Spitzer predicts hot gas
- First evidence from UV (Copernicus): hot gas (10^6 K) in the local bubble.
- ROSAT satellite: emission outside local bubble

Chandra and XMM Newton -> new possibilities!

- Yao and Wang (2005) studied 12 X-ray sources in the Galaxy: 2×10^6 K and a scaleheight of about 1 kpc

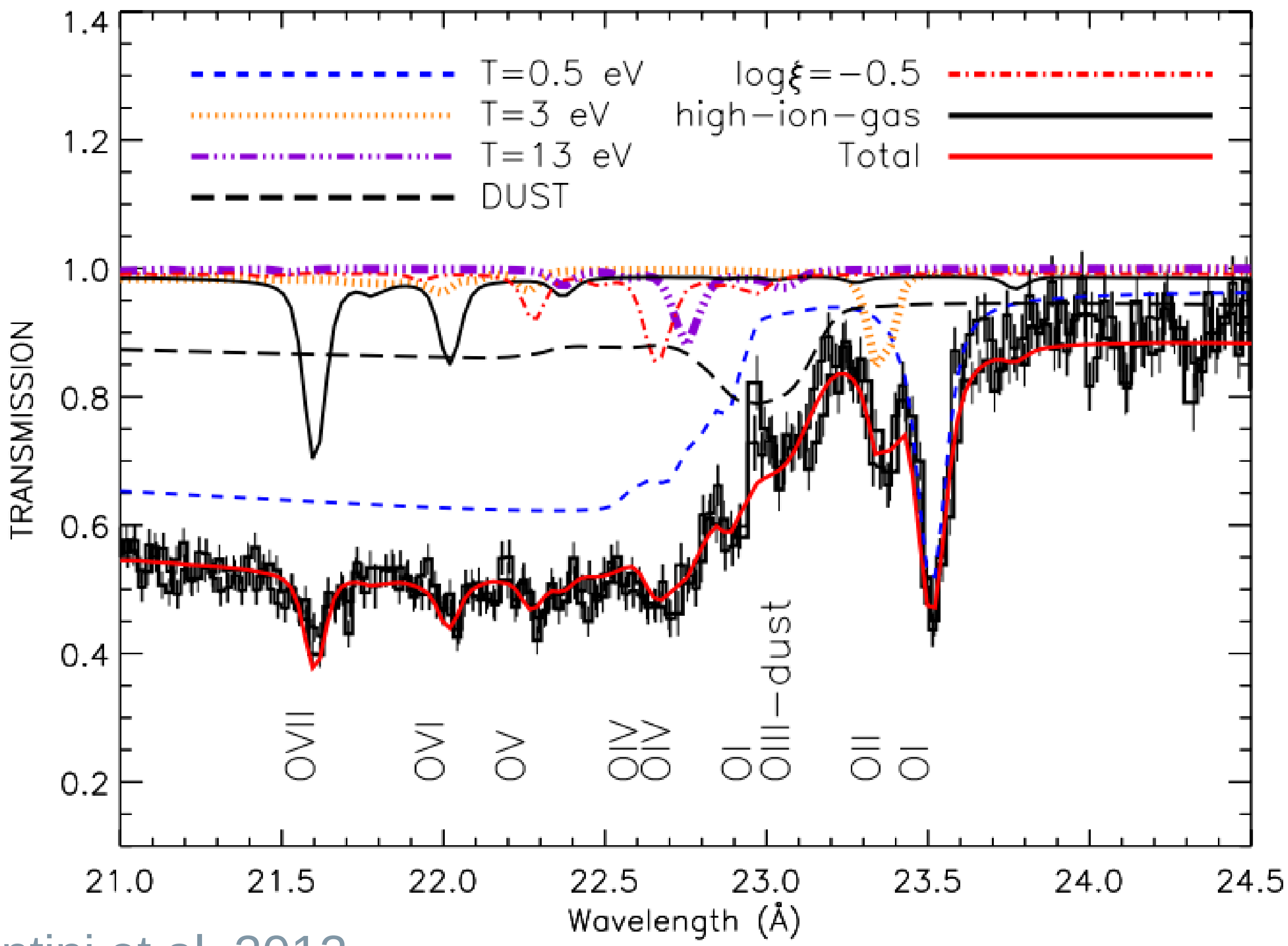


eROSITA bubbles hot gas: energies of 0.6-1.0 keV (image credit: MPE/IKI)



Yao et al. 2006

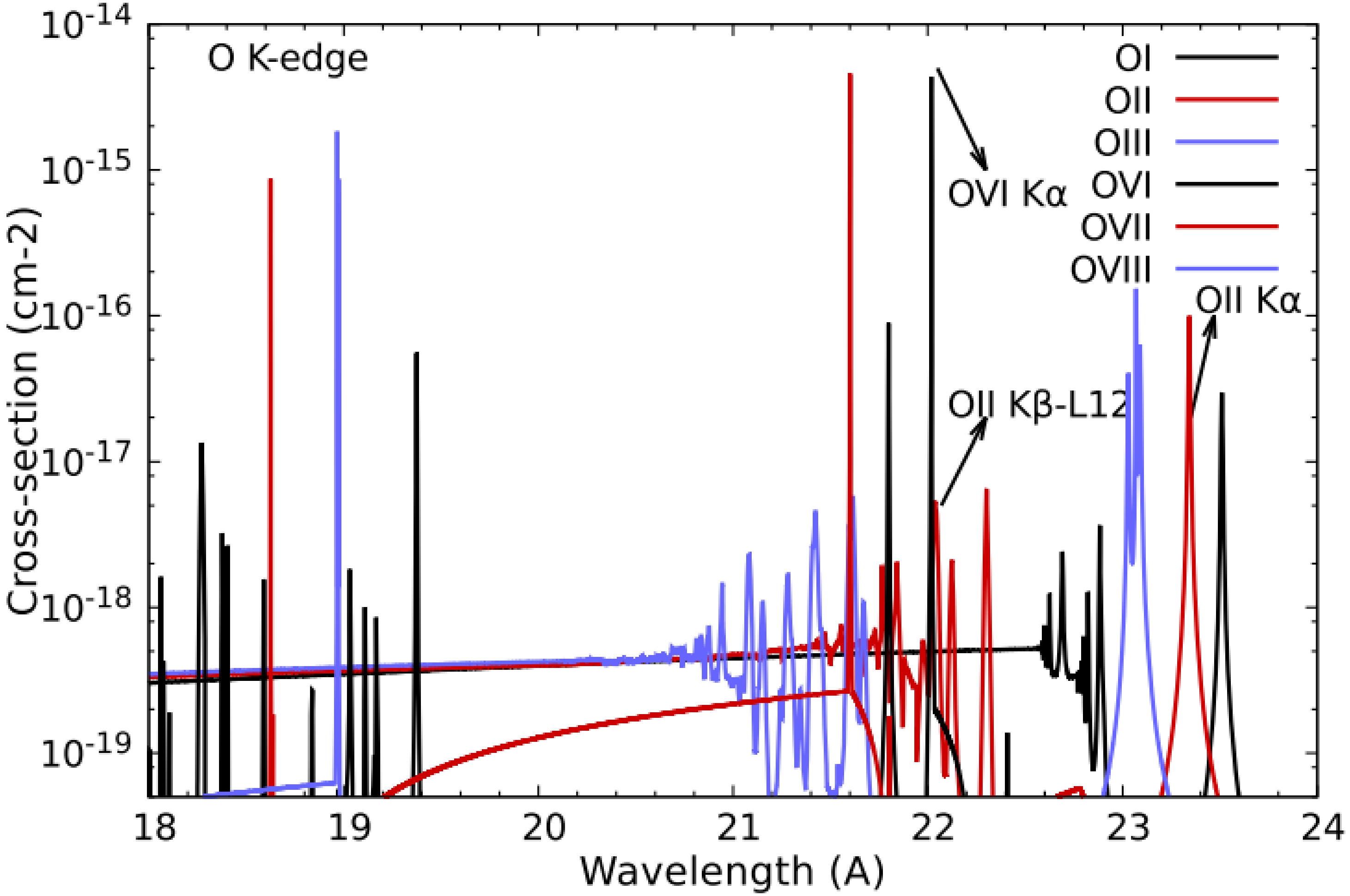
Warm and hot gas: clouds with different temperatures along the sightline of 4U 1820-30



Costantini et al. 2012

O K edge

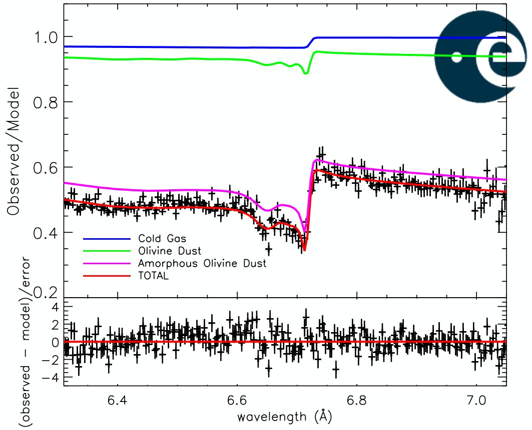
Gas edges: more complex

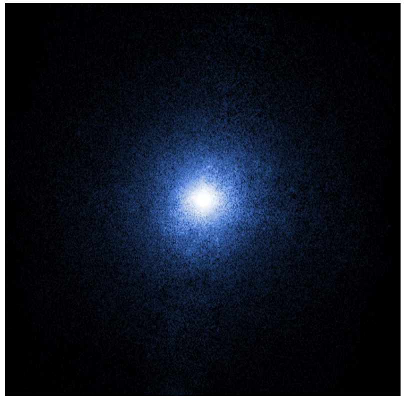


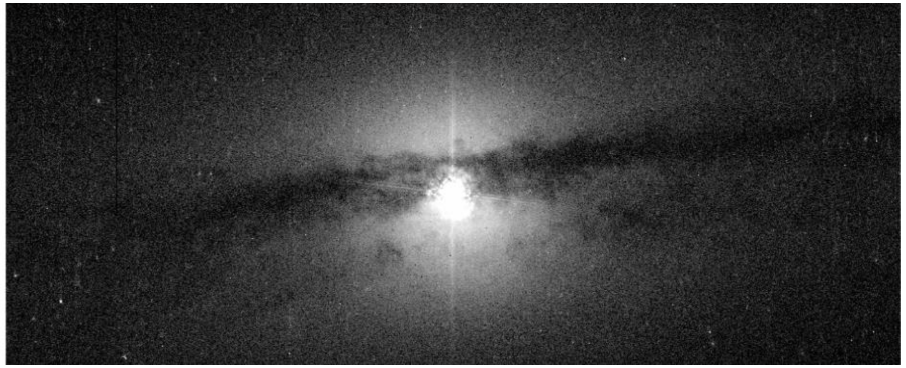
Gatuzz et al. 2018

X-rays and interstellar dust

- Dust in the diffuse ISM: Studying X-ray edges
- Scattering haloes
- Dust in other galaxies





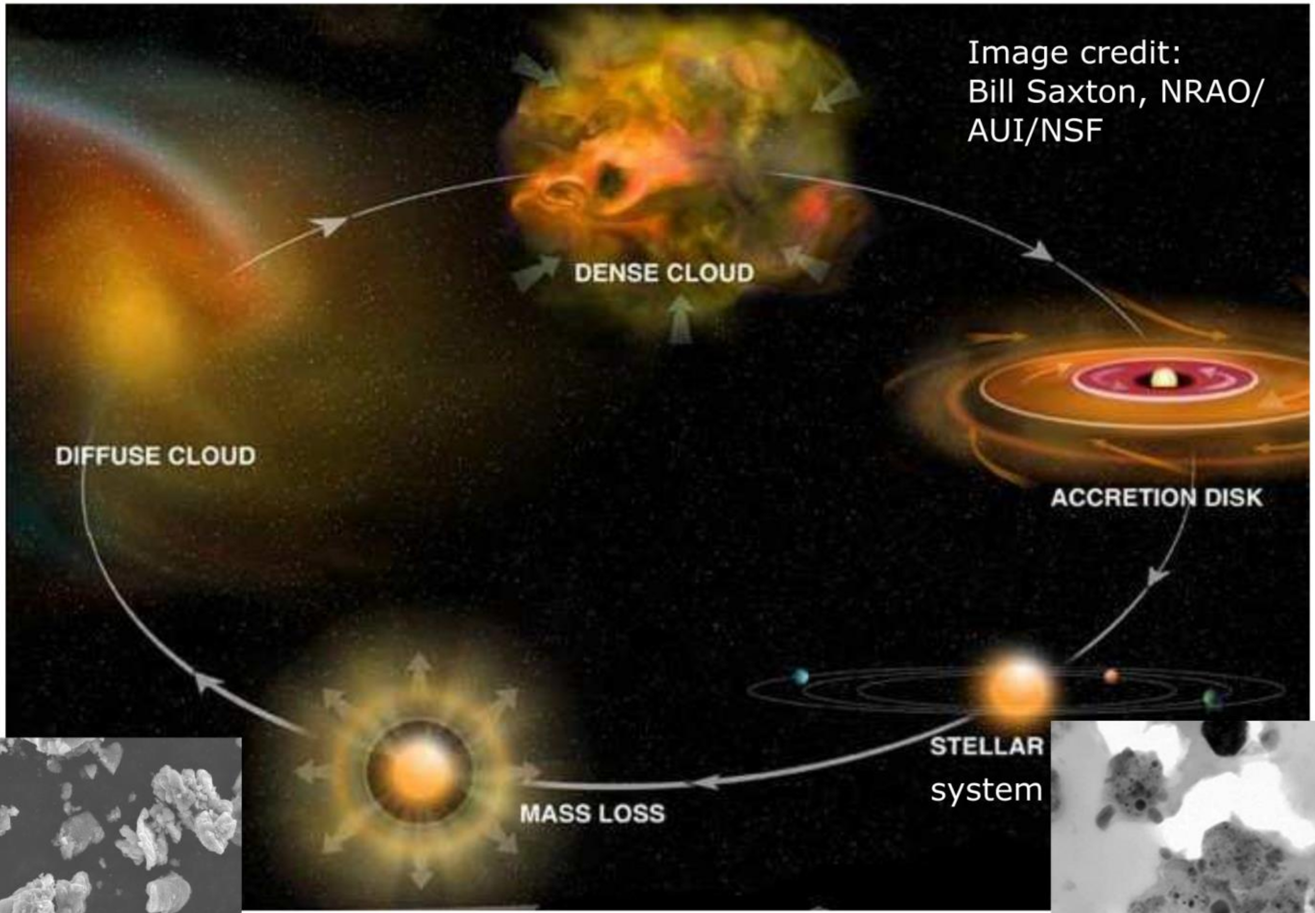


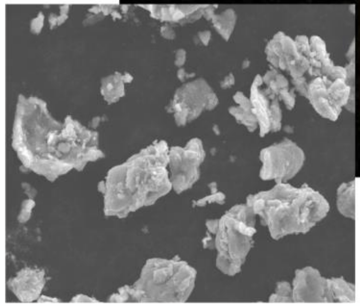
Why study the dust in X-rays ?

- **Sensitive to a wide range of column density** → study various regions in the Galaxy
- **Absorption and scattering of dust can be simultaneously studied** → only X-rays can do this
- **Easy to determine the depletion from the gas phase**
- **We can detect the properties of dust** and compare observations with longer wavelengths

Artist impression of an X-ray binary
Credits: David A. Hardy/PPARC

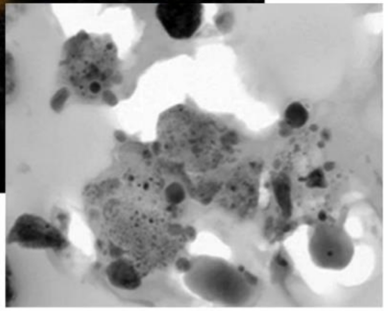
Why do we need to study the properties of interstellar dust?





Stardust (Artist impression Zeegers & Wang):
Fe, Mg rich silicates
~ 15% crystalline

Interplanetary dust particle: amorphous silicates with iron inclusions



Keller & Messenger 2013

How to study the properties of Interstellar Dust?

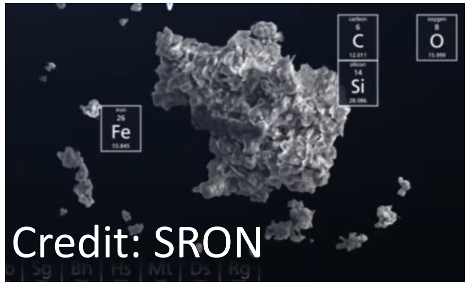
- Properties reveal what happened to grains in the Interstellar Medium

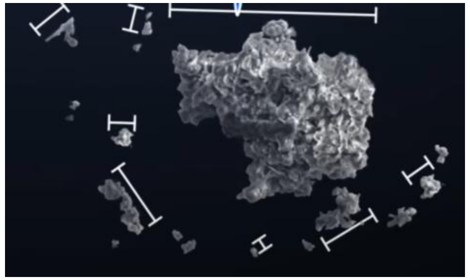
Imprint of dust features on spectra gives us information about:

chemical composition

crystallinity

grain size





Most ISM dust features are extremely weak and difficult to observe!

→ **We can find these ISM features in X-ray stellar spectra!**

Observational constraints on Dust properties

- **What is the composition of the dust? How much iron, sulfur, oxygen etc. is depleted from the gas phase in dust?**

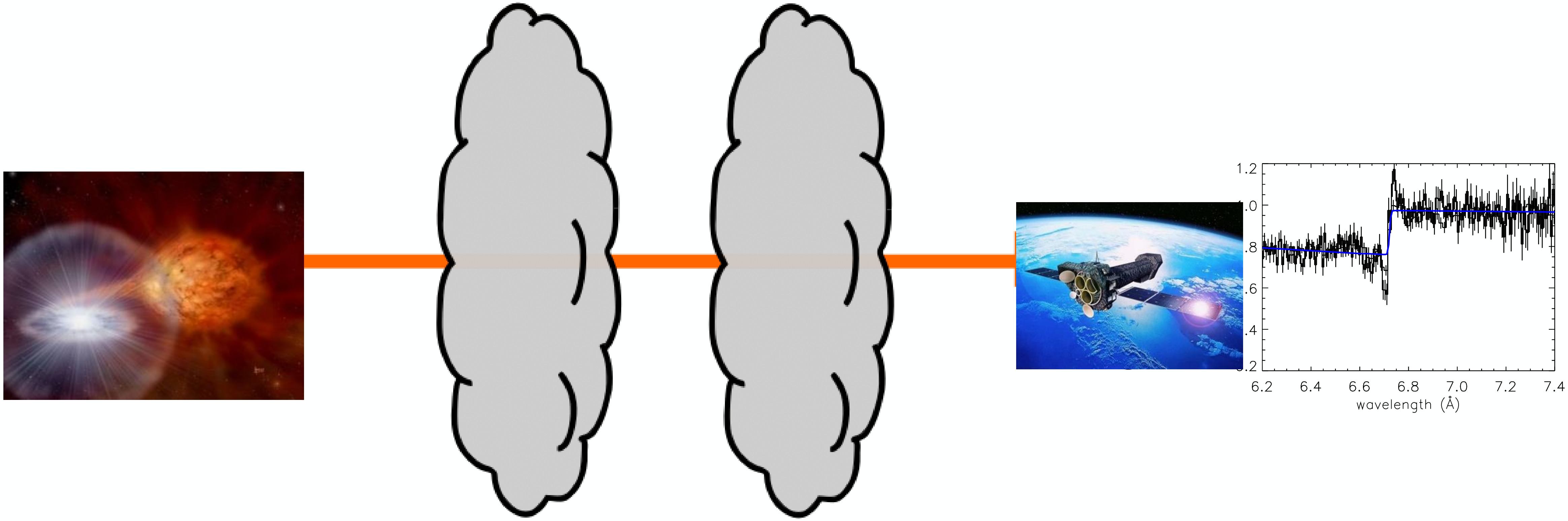
- **What is the ratio of crystalline/amorphous dust?**

- **What is the size distribution of dust in the ISM?**

- **Do the properties of dust vary in different environments?**

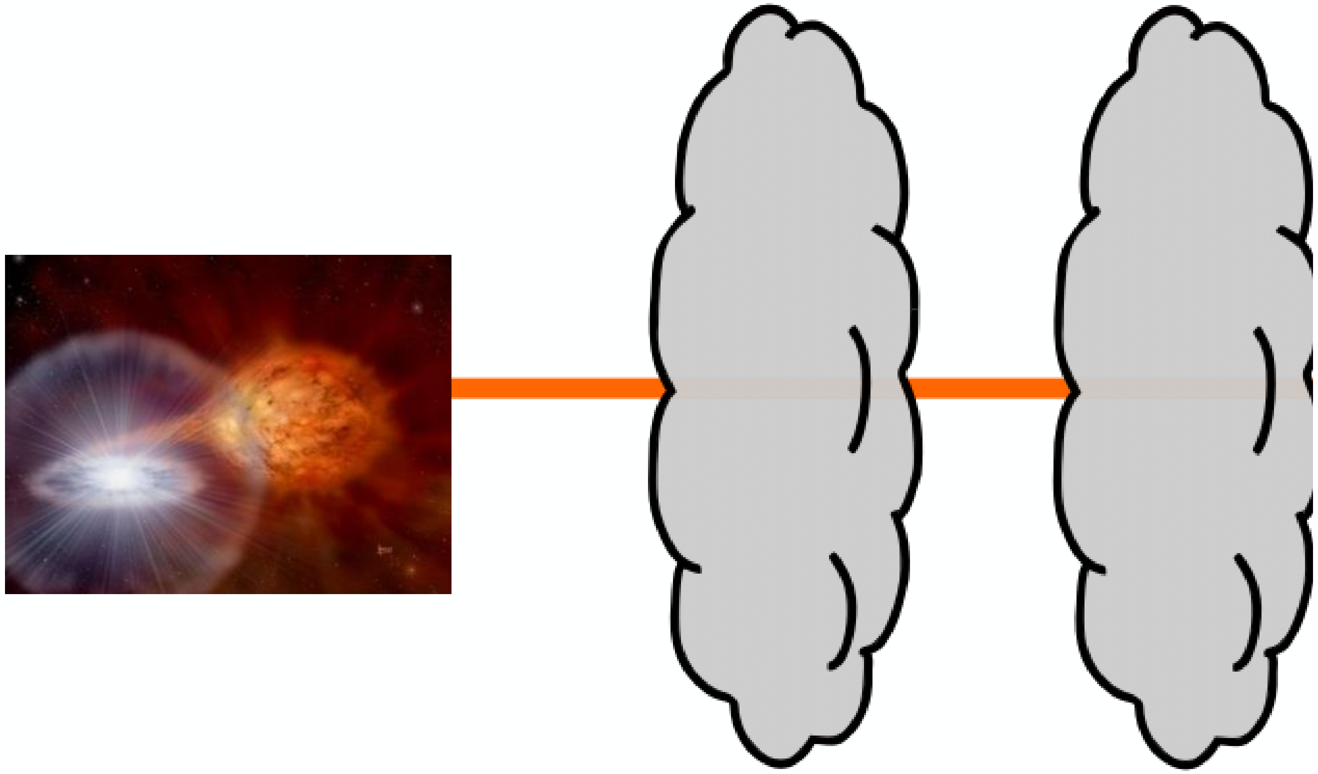
X-rays can provide an answer!

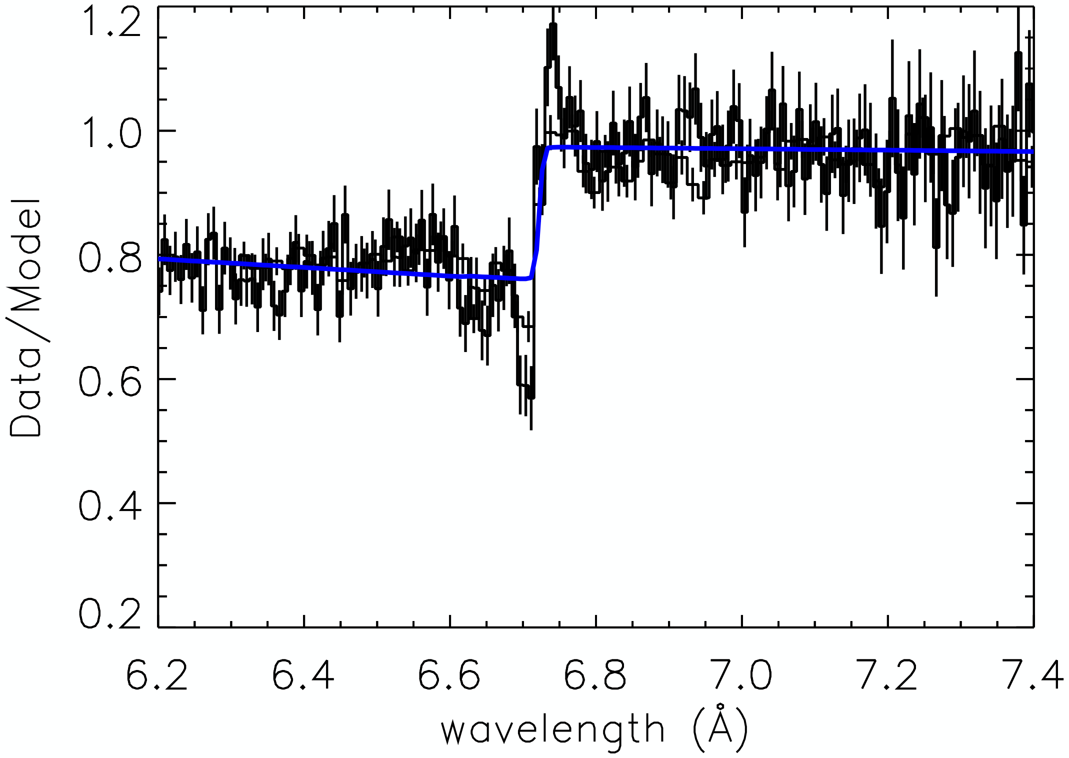
Observing dust in the X-rays



e.g. Lee 05,09, Costantini 12, Pinto 10,13, Corrales 16, Zeegers 17, 19, Rogantini 20, Psaradaki 21

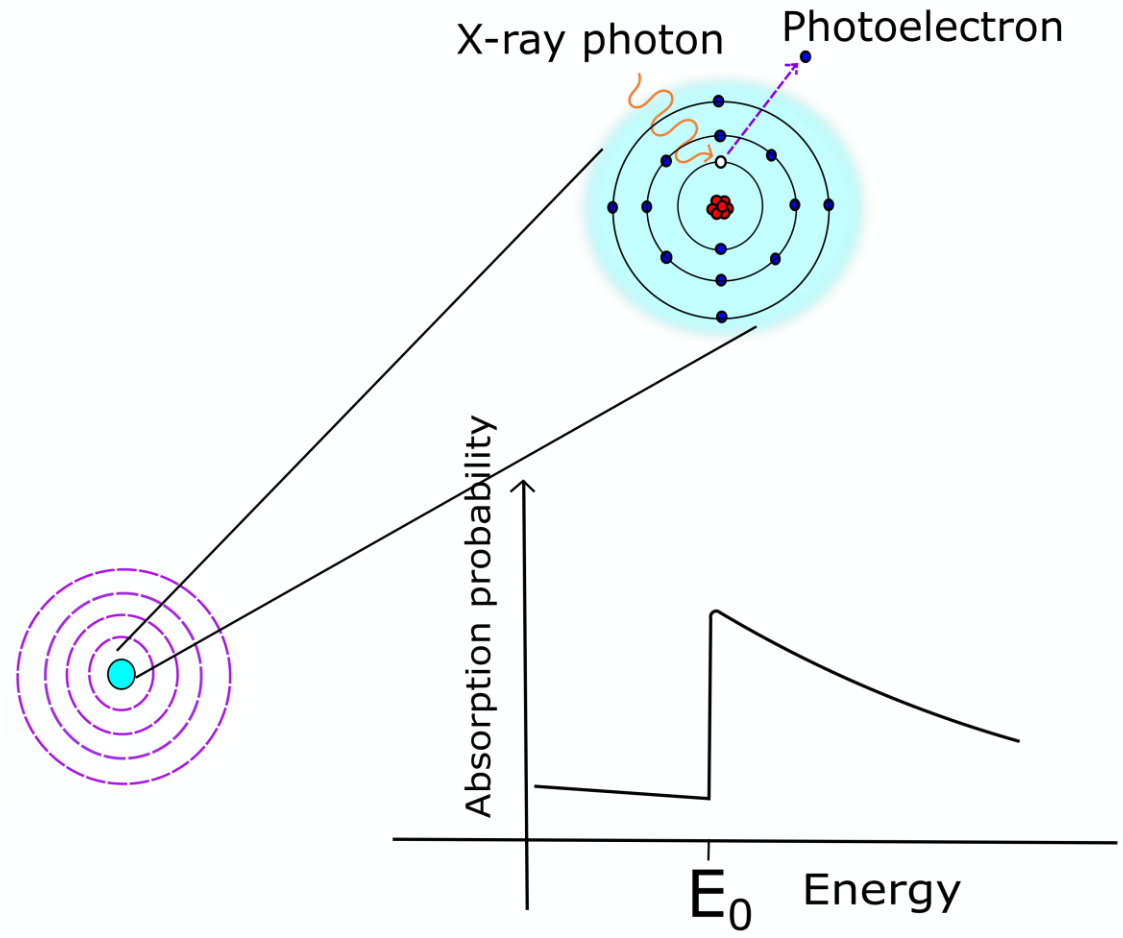
Observing dust in the X-rays



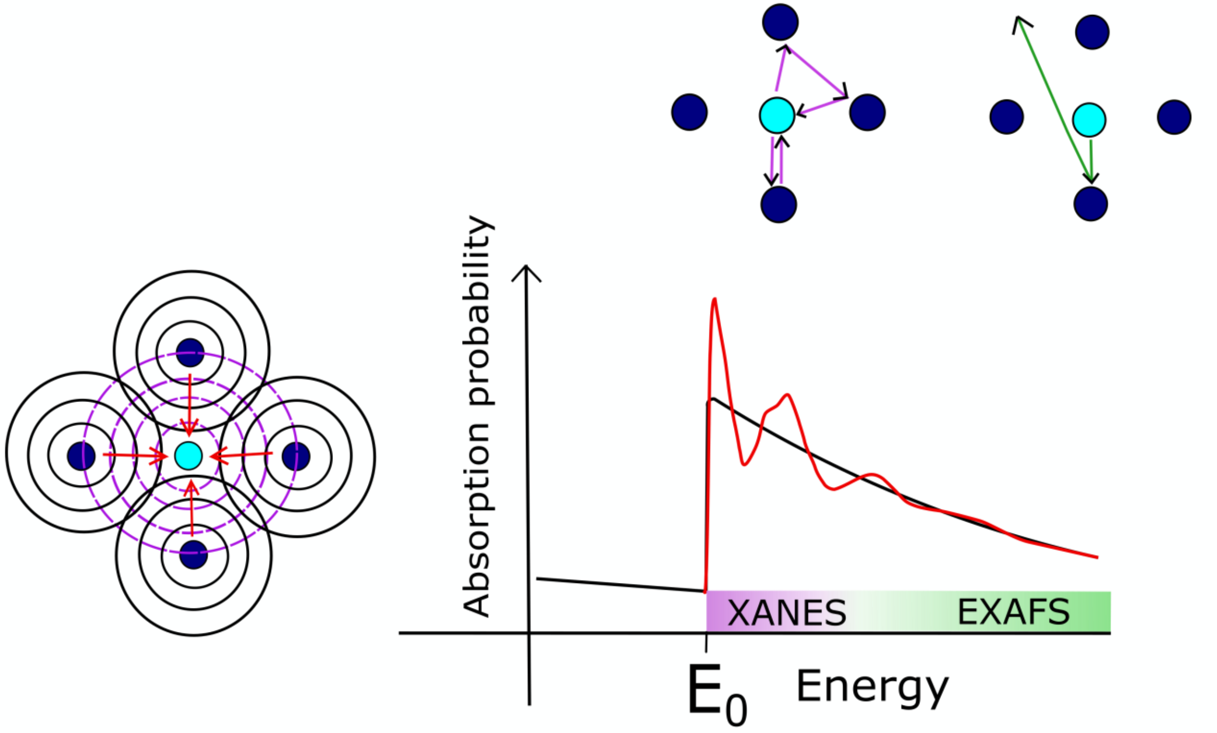


e.g. Lee 05,09, Costantini 12, Pinto 10,13, Corrales 16, Zeegers 17, 19, Rogantini 20, Psaradaki 21

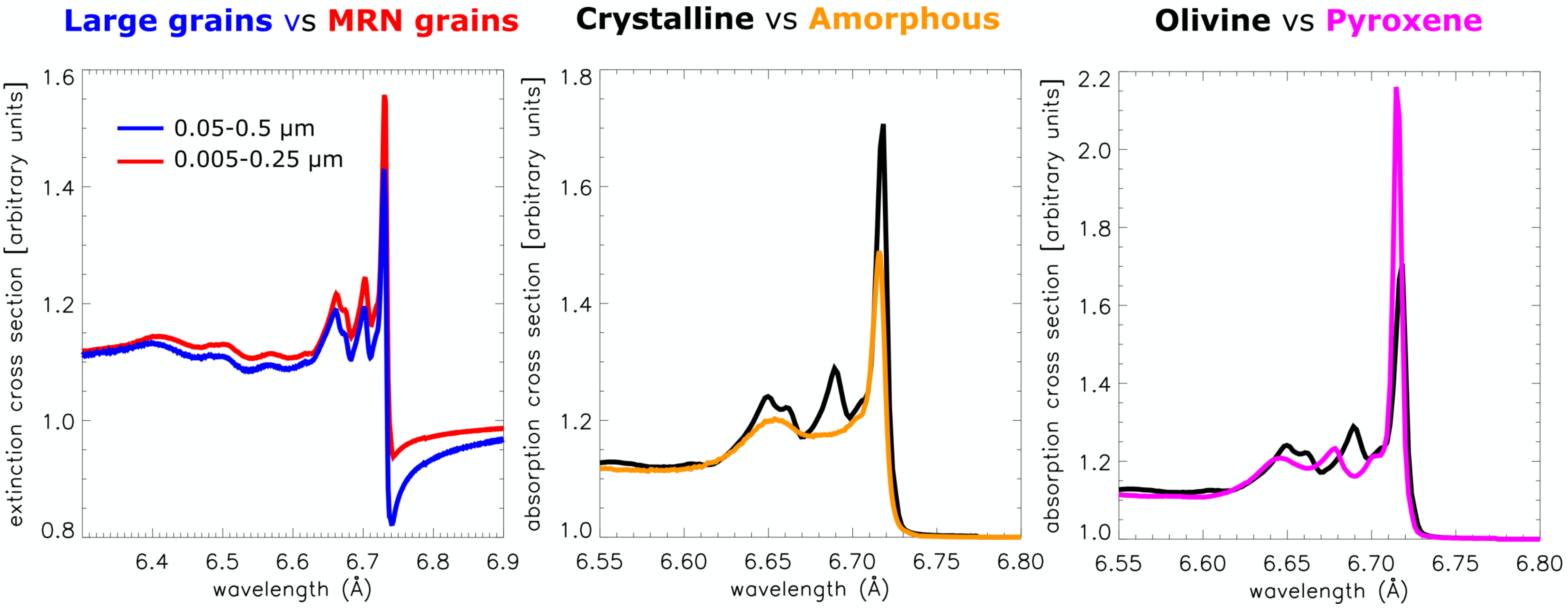
X-ray absorption fine structures (XAFS)



Costantini, Corrales 2022: Figure by S. Zeegers



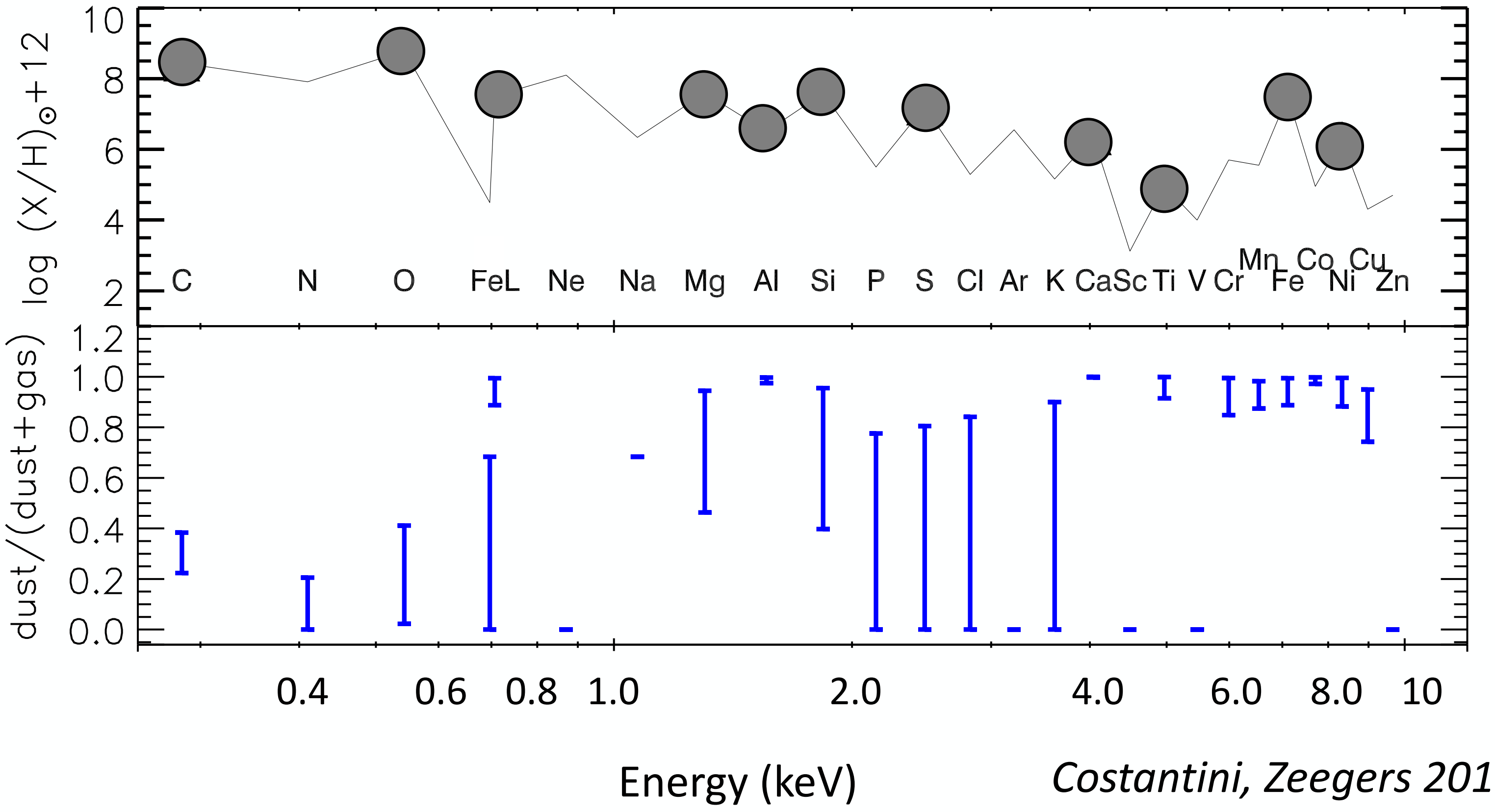
What can we learn from X-ray spectra?



Costantini, Corrales 2022: Figure by S. Zeegers

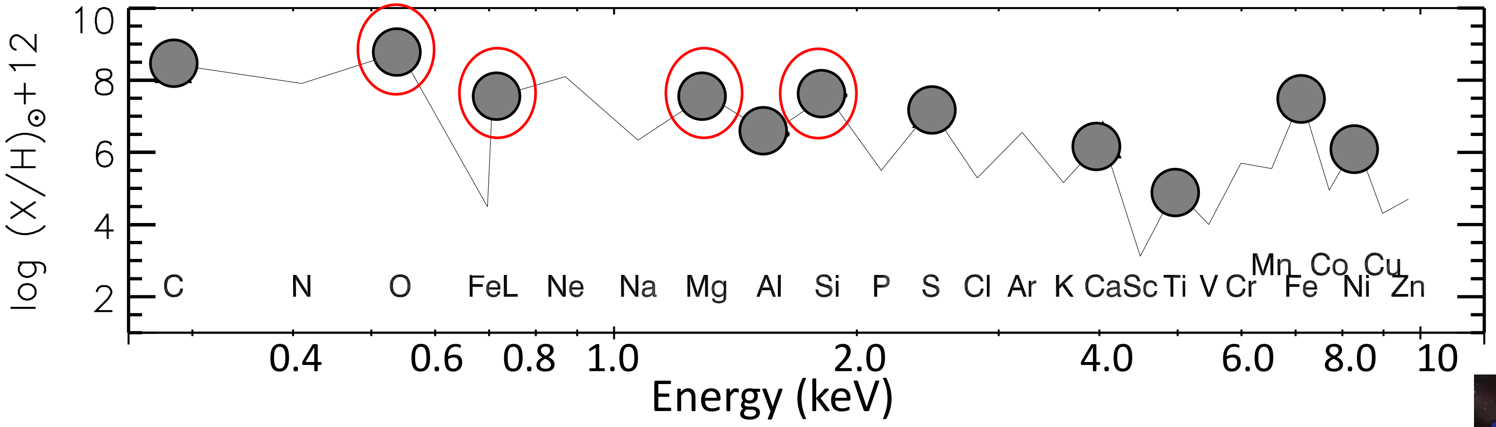
→ THE EUROPEAN SPACE AGENCY

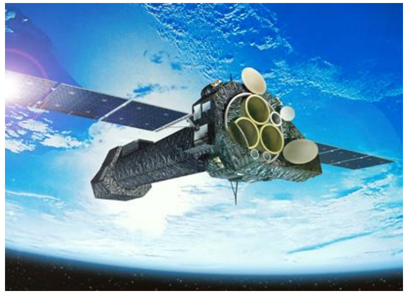
The soft X-ray band



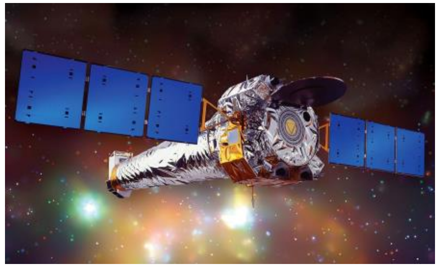
Costantini, Zeegers 2019

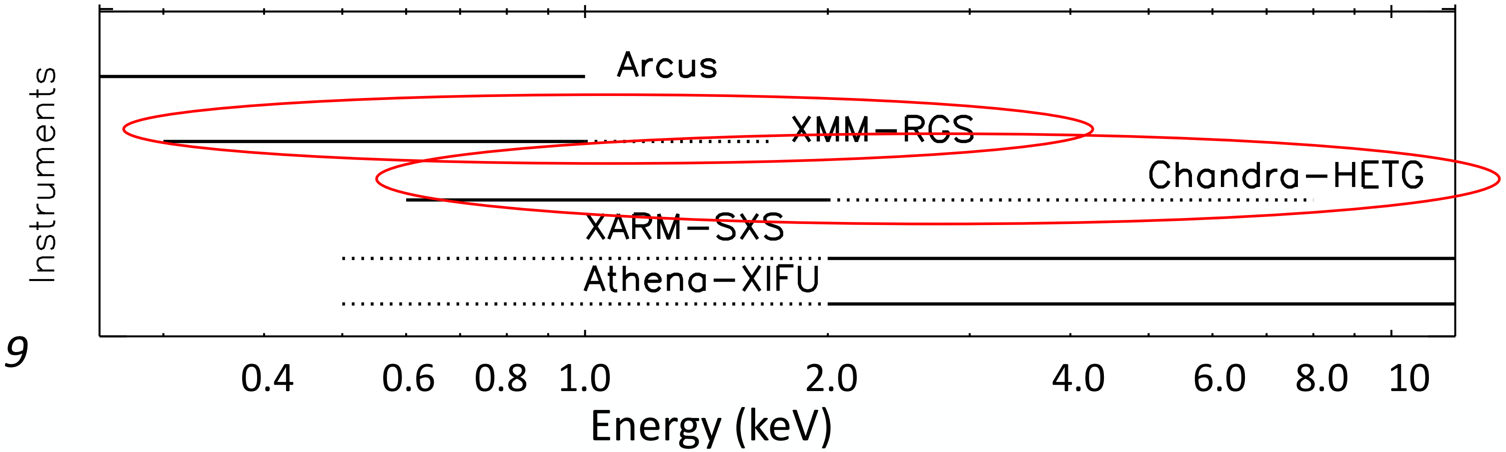
The soft X-ray band





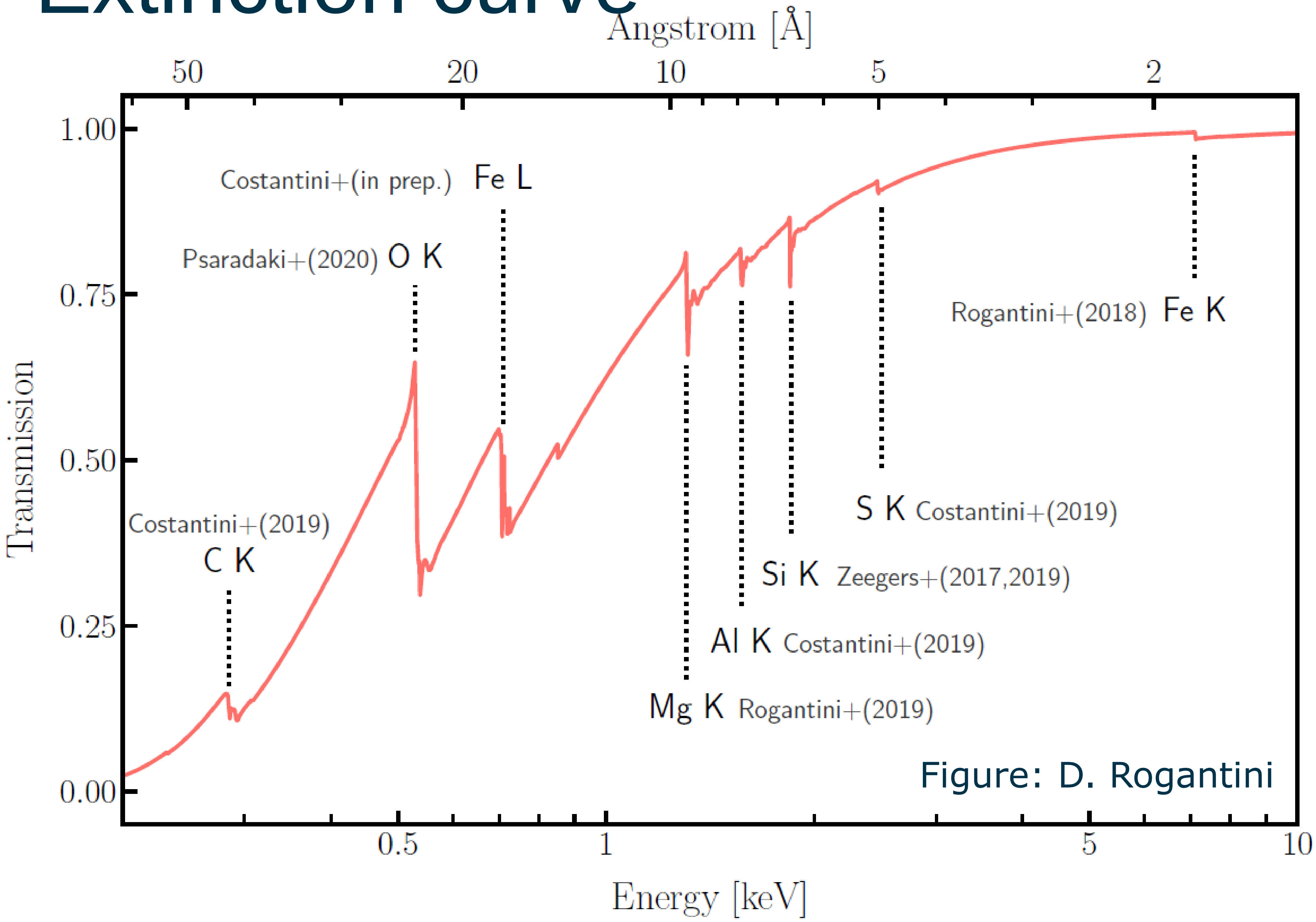
With Chandra and XMM we can explore Silicates

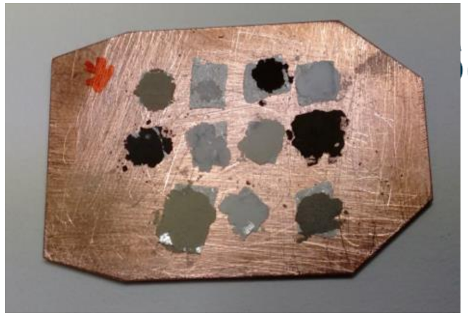




Costantini, Zeegers 2019

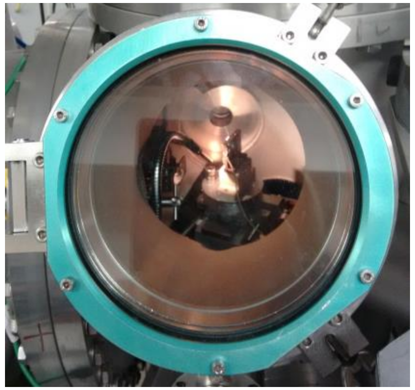
Extinction curve

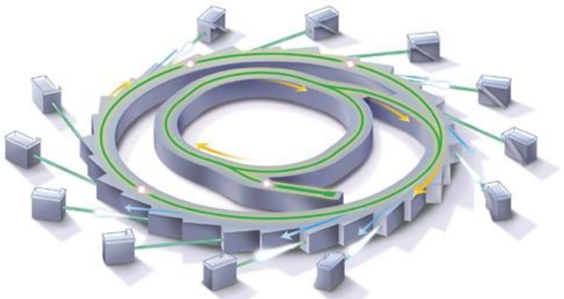




Laboratory Campaigns

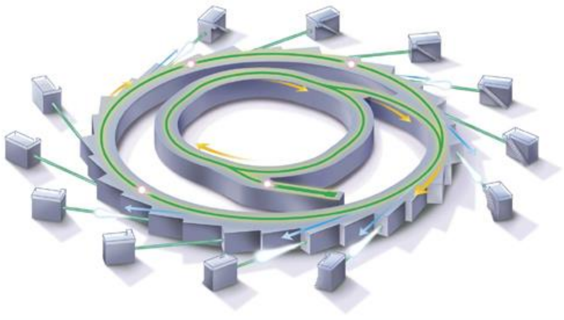
E. Costantini 2012





Laboratory dust measurements

Dust samples → Synchrotron measurements → Data analysis → Fitting Spectra



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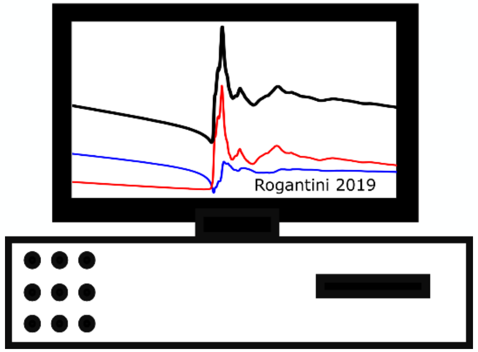

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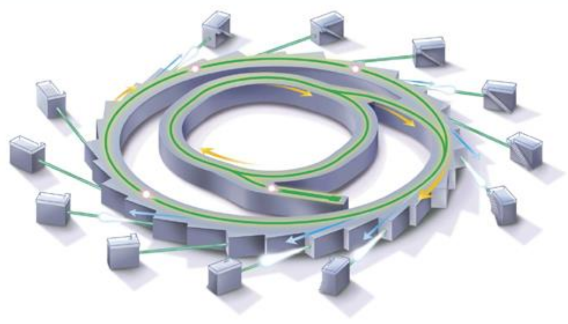

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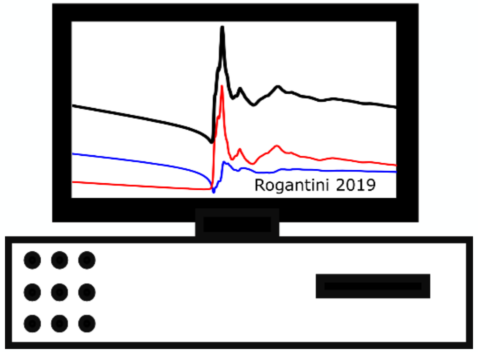


Conversion from lab absorption spectra to extinction models

From lab measurements to ID Models

calculated

From the lab

m = n - ik

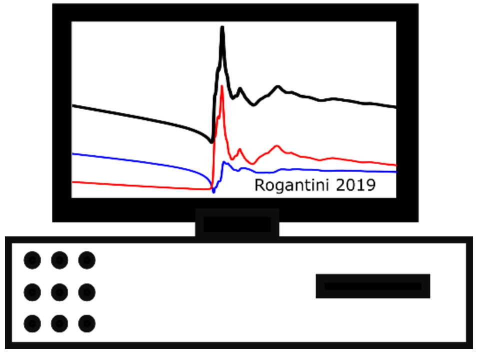
Refractive index

Energy

Size distribution

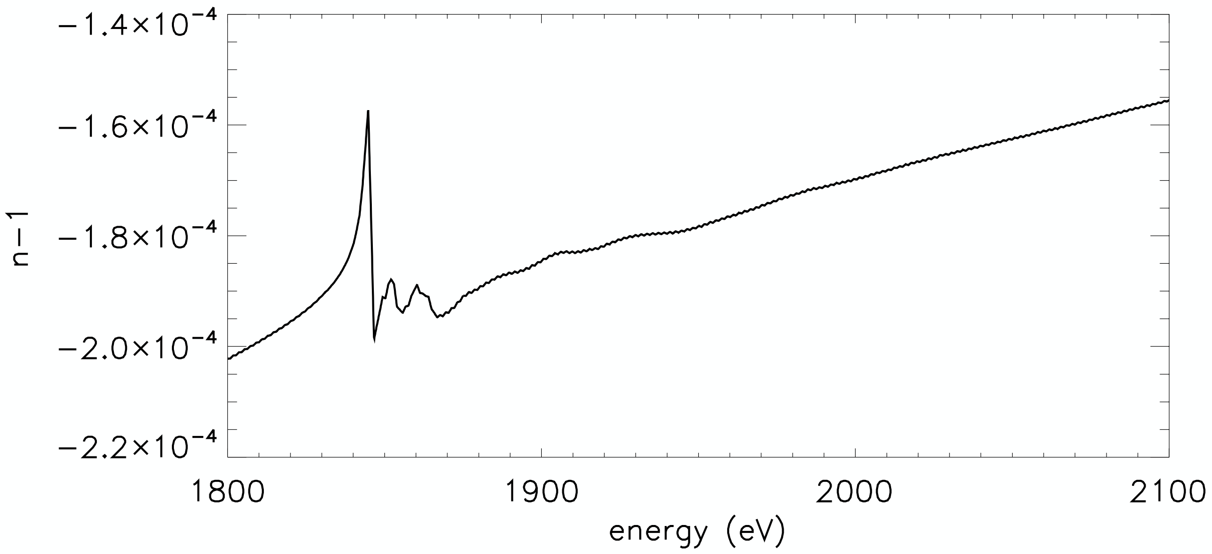
Dust

Mie scattering code

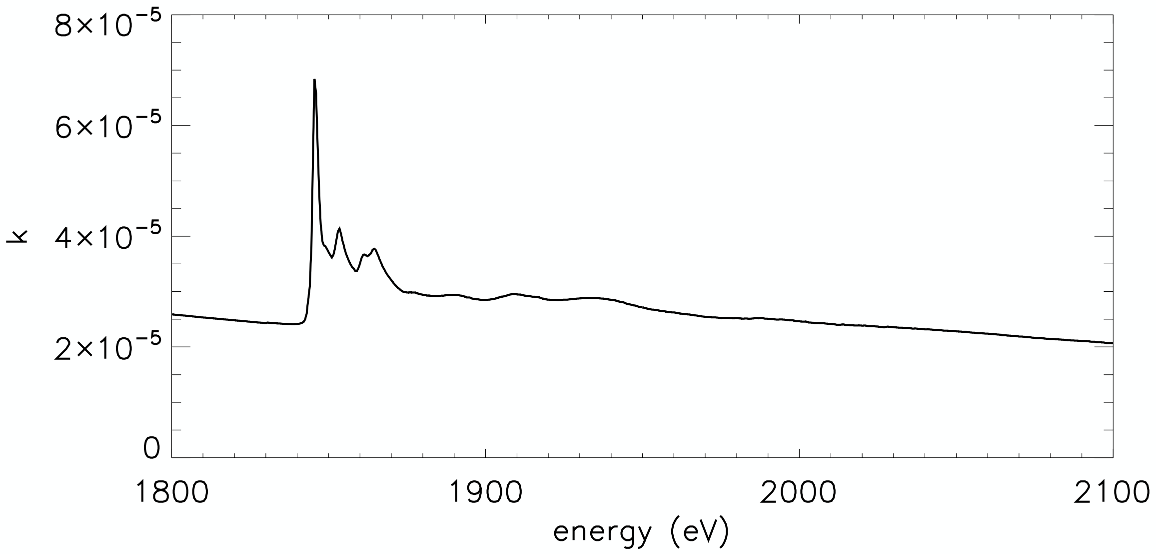


References for further reading:
Zeegers 2017 and Rogantini 2018

N and K



-1.4×10^{-4}
-1.6×10^{-4}
-1.8×10^{-4}
-2.0×10^{-4}
-2.2×10^{-4}
n−1
1800
1900
2000
2100
energy (eV)

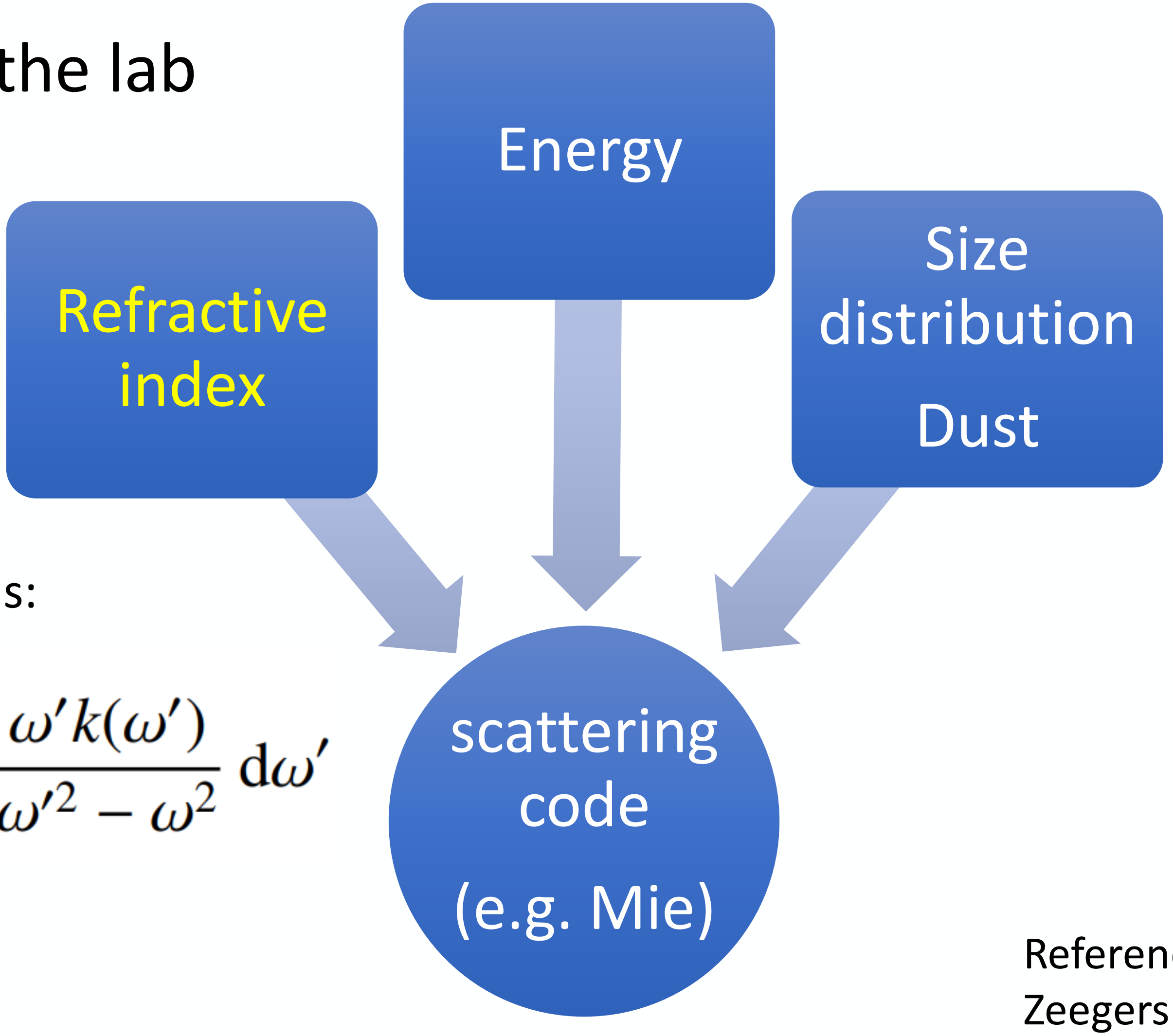


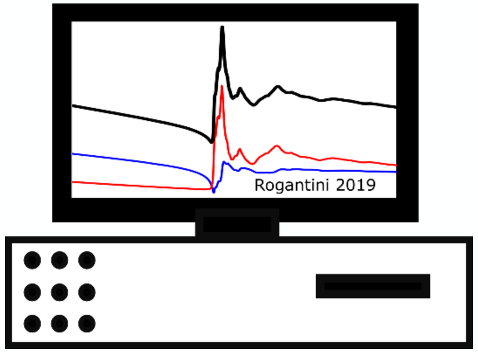
8×10^{-5}
6×10^{-5}
4×10^{-5}
2×10^{-5}
0
k
1800
1900
2000
2100
energy (eV)

From lab measurements to ID Models

calculated   From the lab

$$\mathbf{m} = \mathbf{n} - \mathbf{i}\mathbf{k}$$





Kramers Kronig relations:

$$n(\omega) = 1 + \frac{2}{\pi} P \int_0^{\infty} \frac{\omega' k(\omega')}{\omega'^2 - \omega^2} \, d\omega'$$

References for further reading:
Zeegers 2017 and Rogantini 2018

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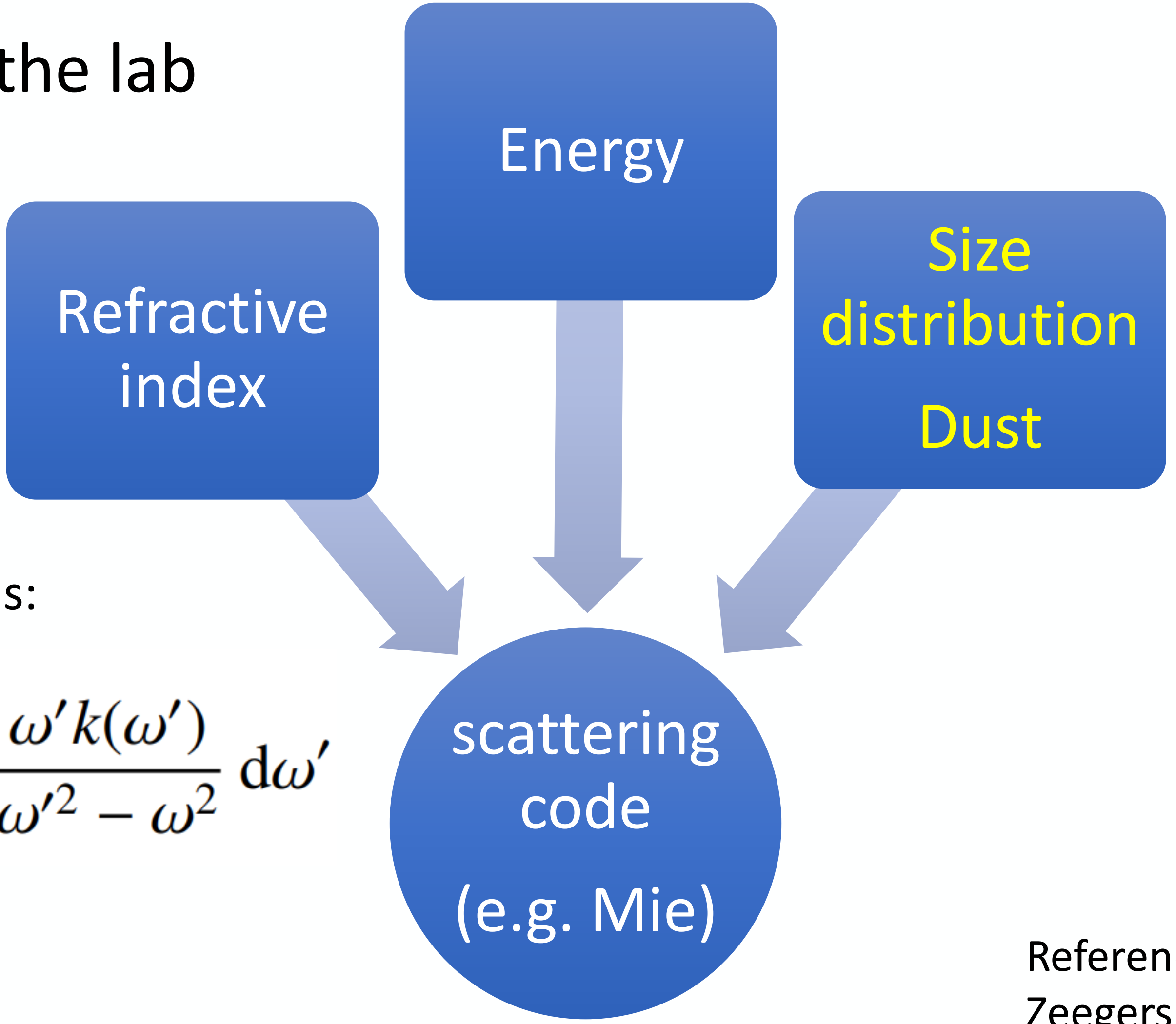

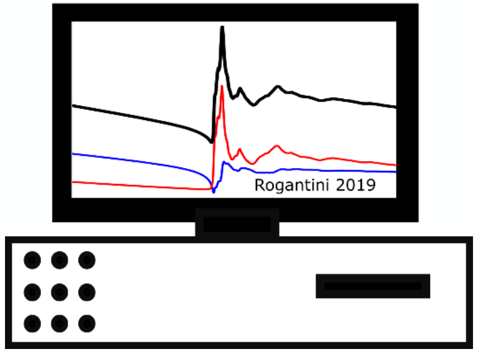

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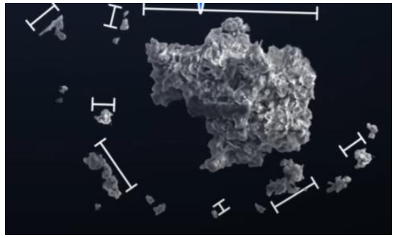
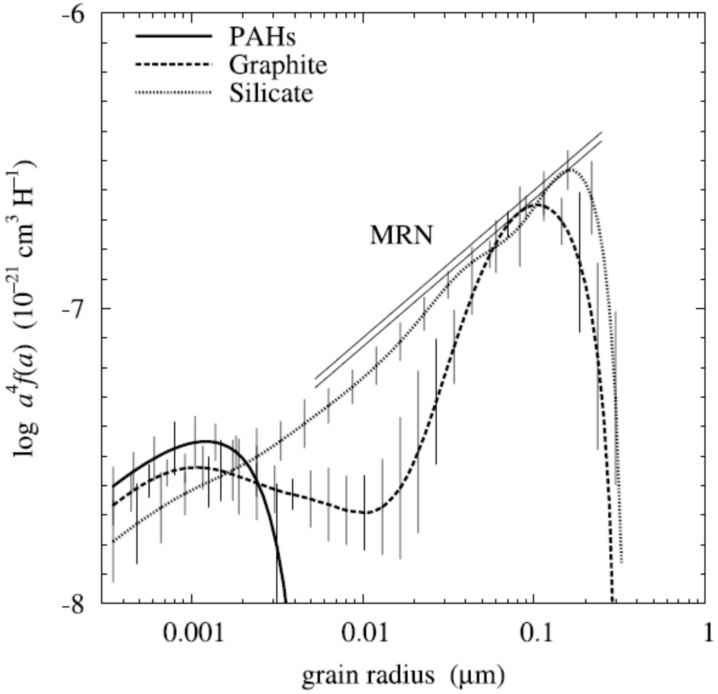
Grain Size

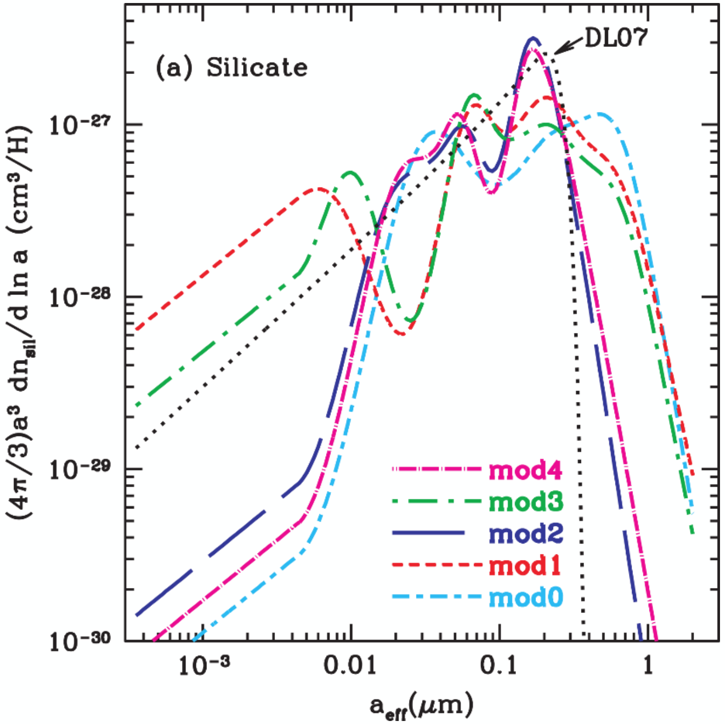


The sizes of the dust particles range from small molecular size to micron size dust

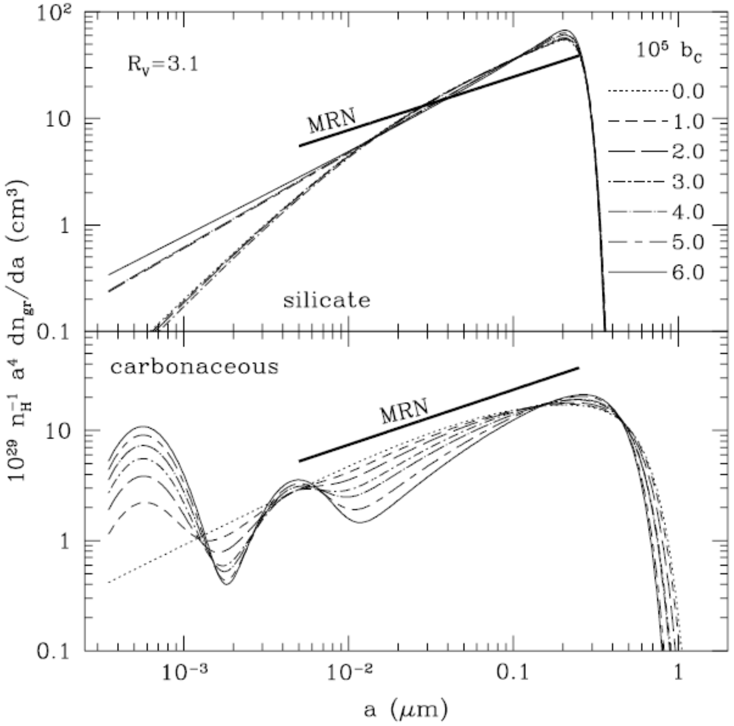
Many different size distribution models



Zubko et al. 2004, Mathis 1977 et al.



Draine & Fraisse 2009



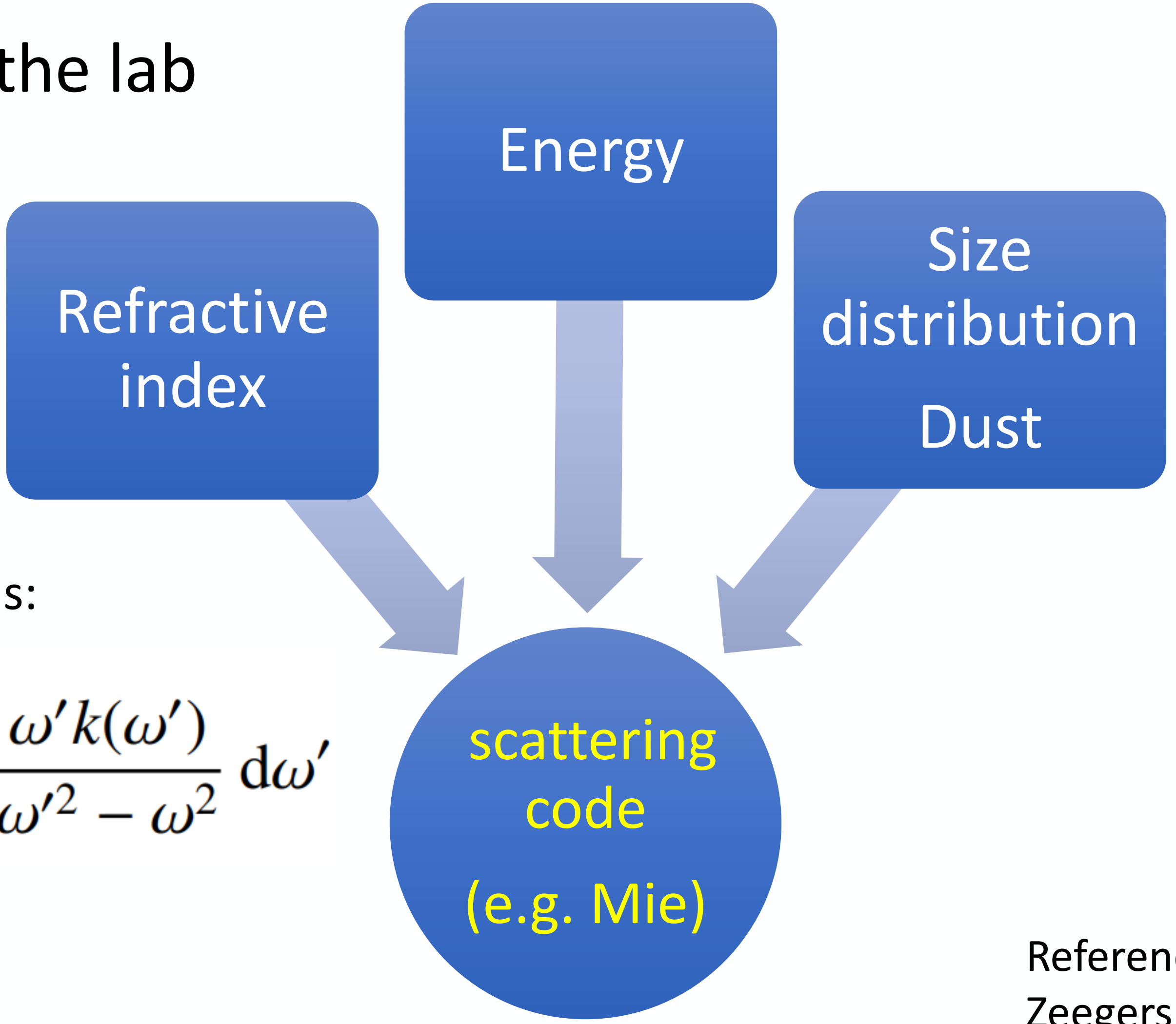
Weingartner & Draine 2001

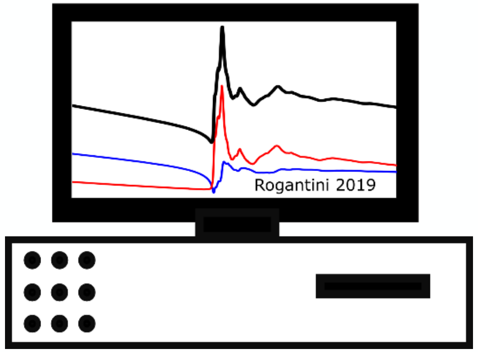
From lab measurements to ID Models

calculated

From the lab

m = n - ik





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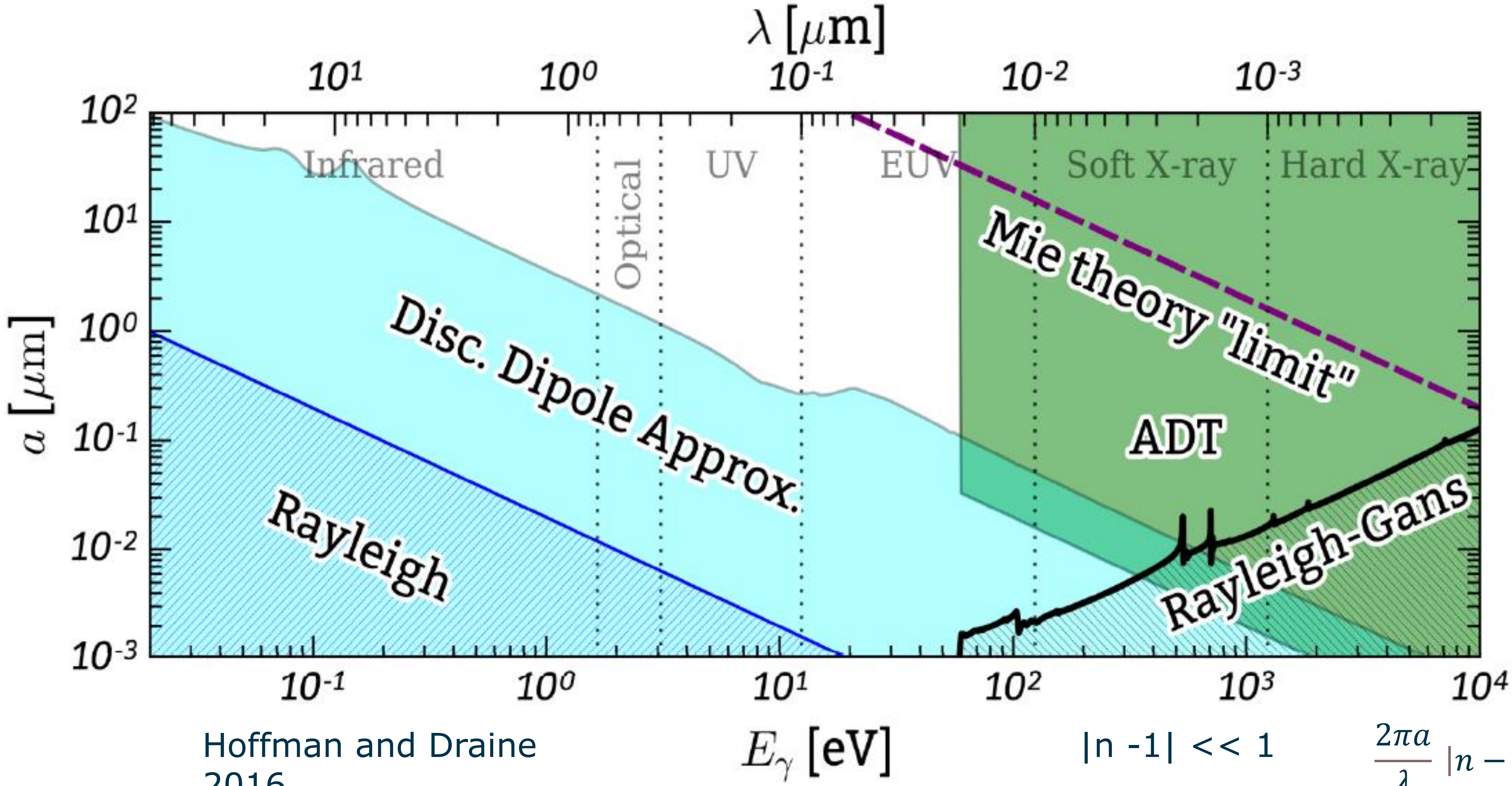
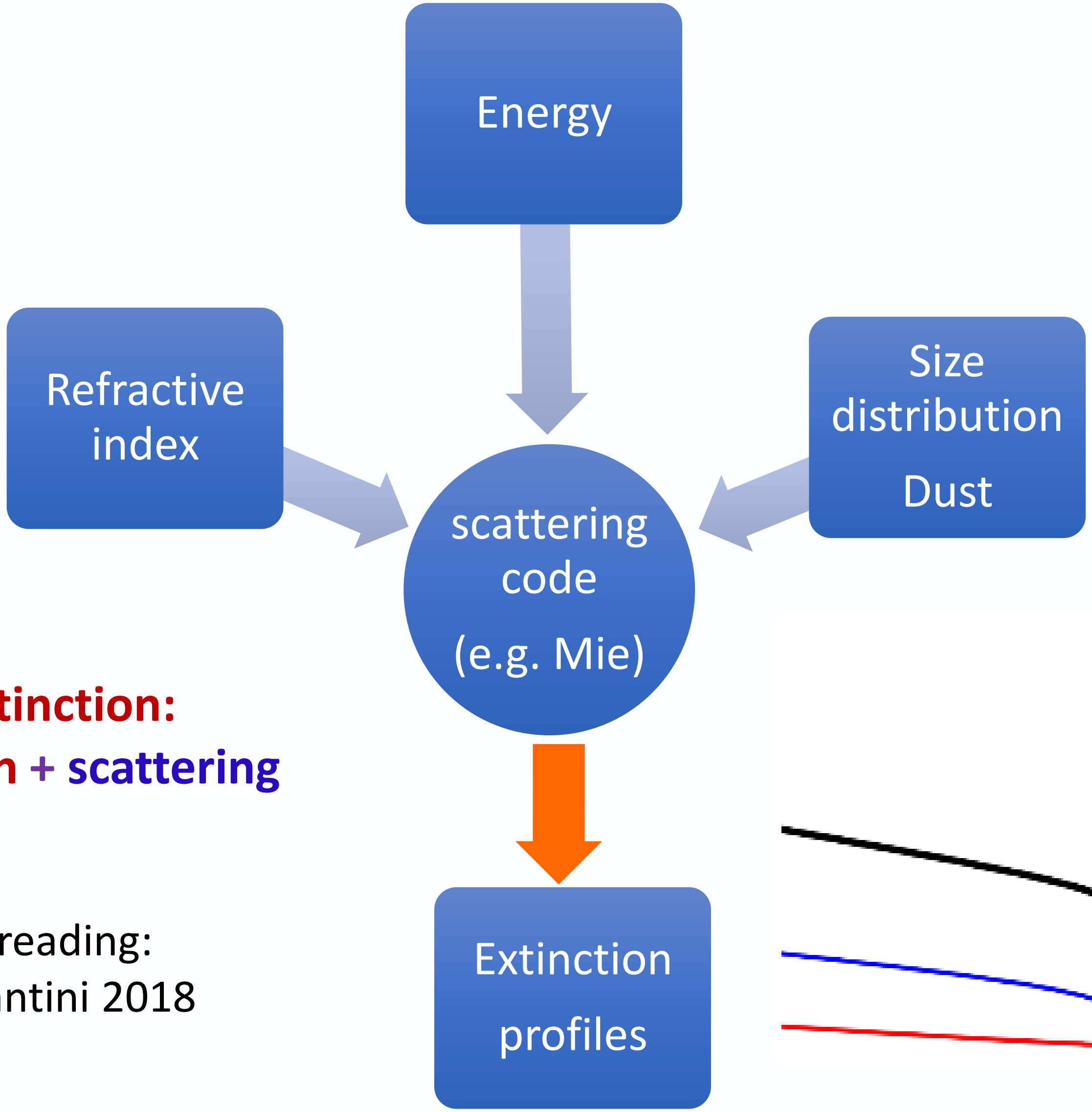


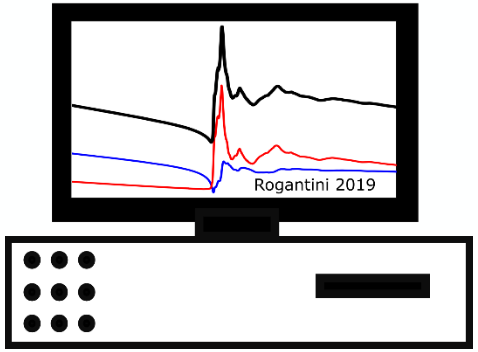
Hoffman and Draine 2016

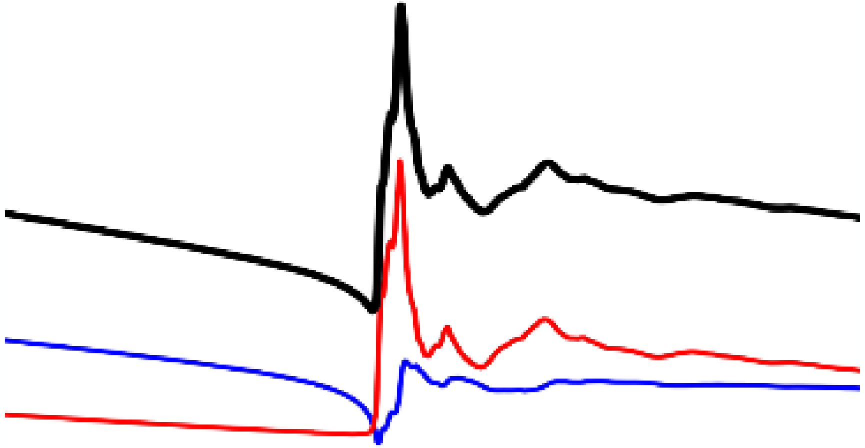
$|n - 1| << 1$

$$\frac{2\pi a}{\lambda} |n-1| \ll 1$$

From lab measurements to ID Models







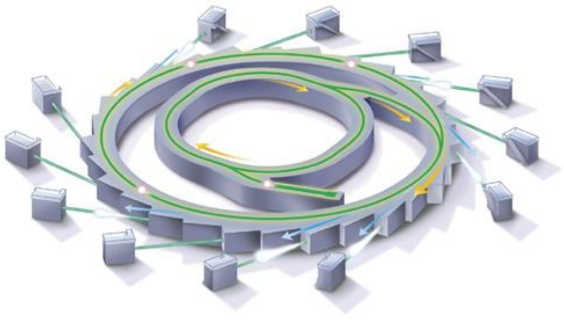
From absorption to Extinction:

Extinction = absorption + scattering

References for further reading:
Zeegers 2017 and Rogantini 2018

Laboratory dust measurements

Dust samples → Synchrotron measurements → Data analysis → Fitting Spectra



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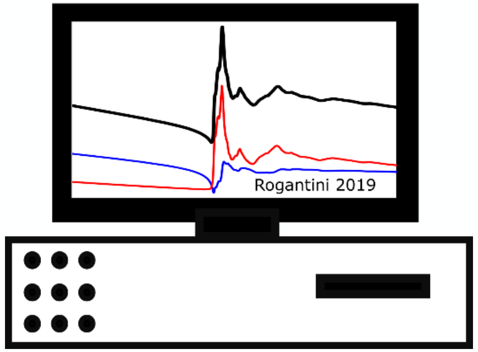
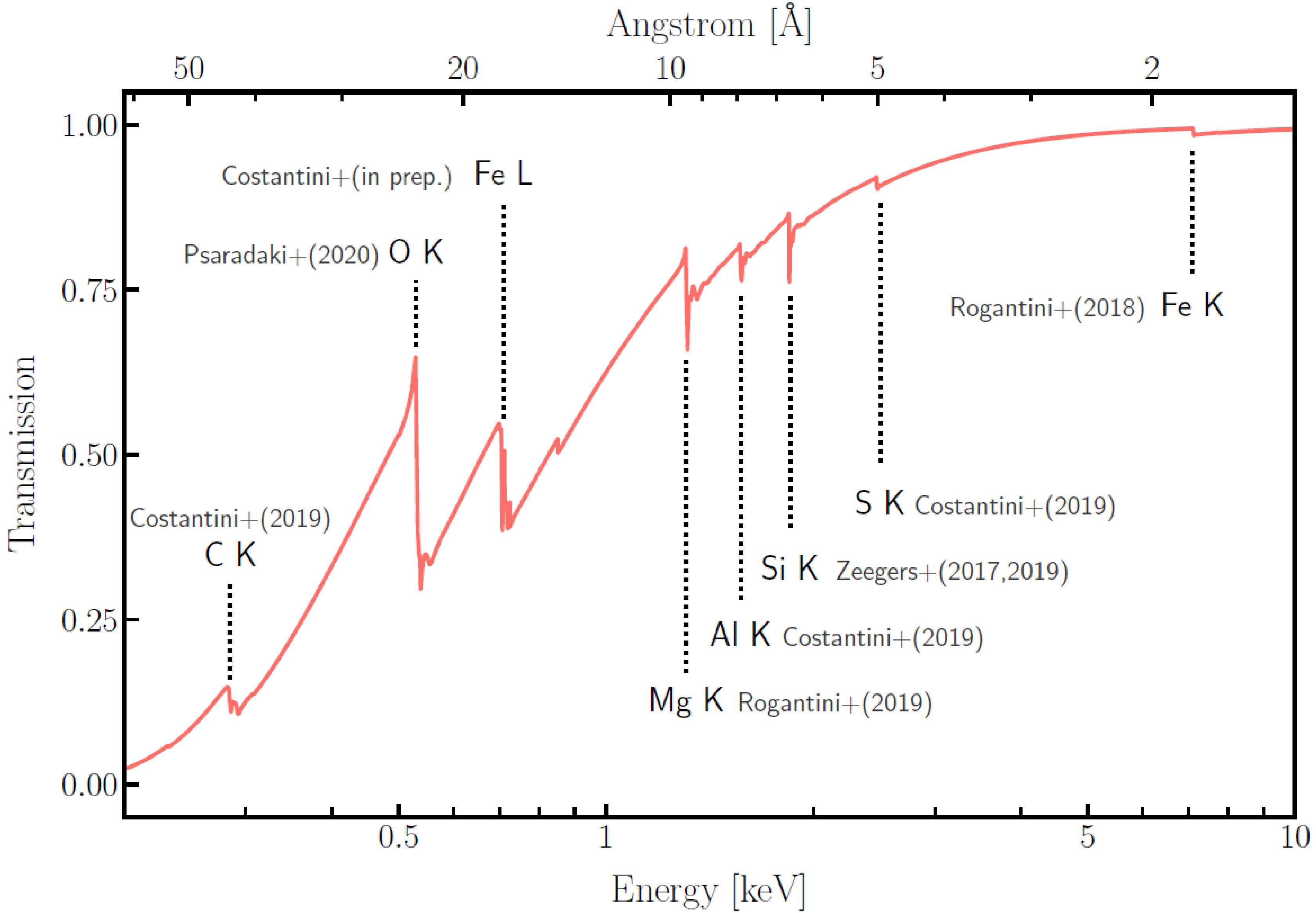
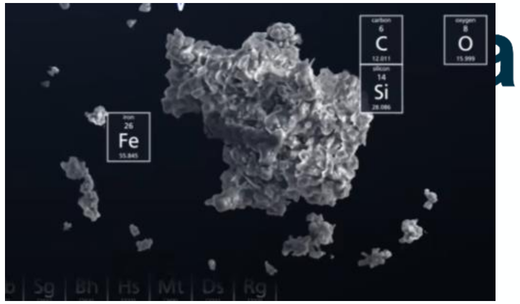


Conversion from lab absorption spectra to extinction models

Extinction curve

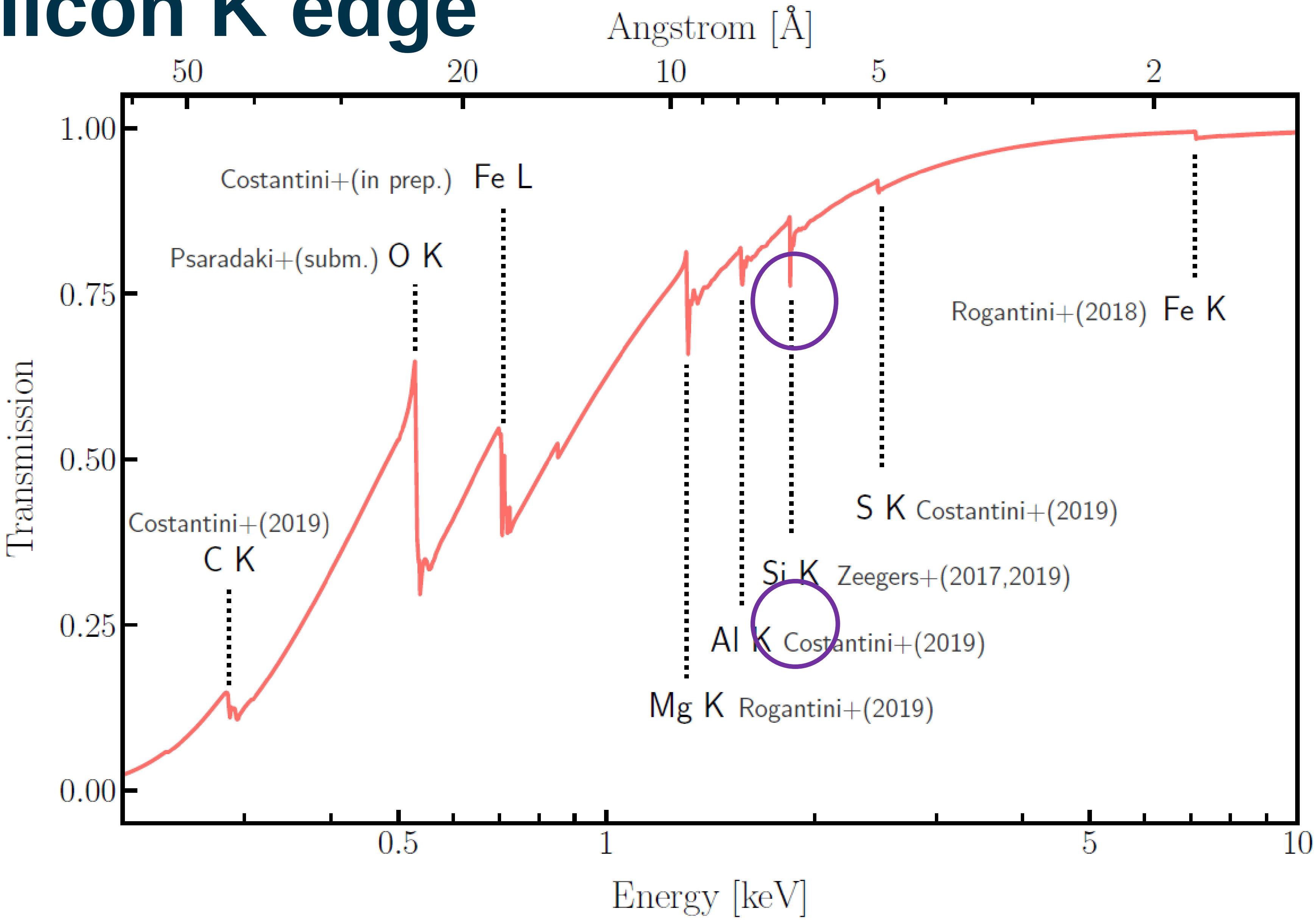




Amol model in SPEX

Figure: D. Rogantini

The Silicon K edge



Credit:
D. Rogantini

GX5-1 X-ray binary

- Bright X-ray binary
- Column density: $n_H = 3.52 \times 10^{22}\ cm^{-2}$
- Assumed distance: 9 kpc (Smith et al. 2006)

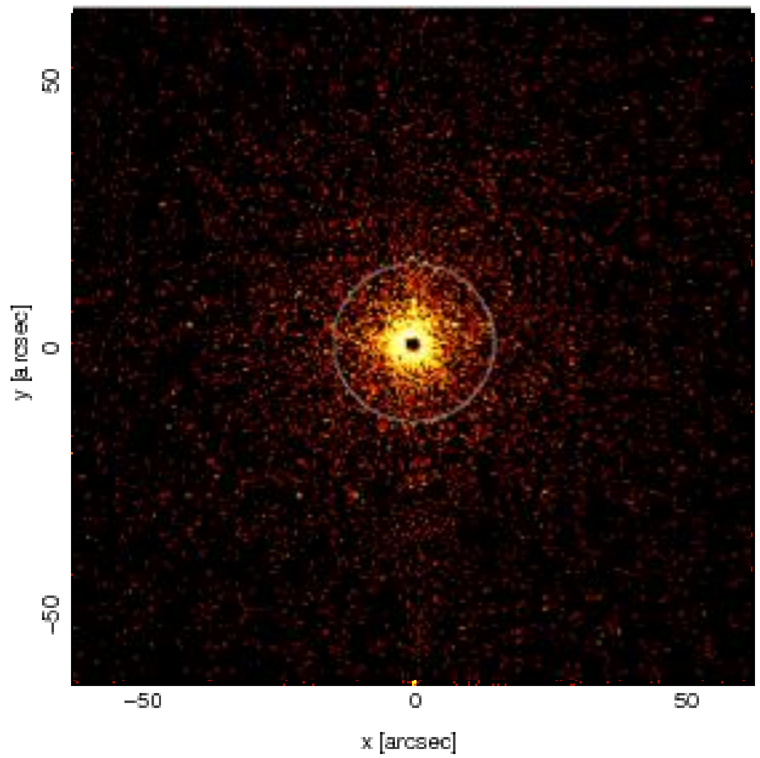


Image credit: Chandra, Tgcat

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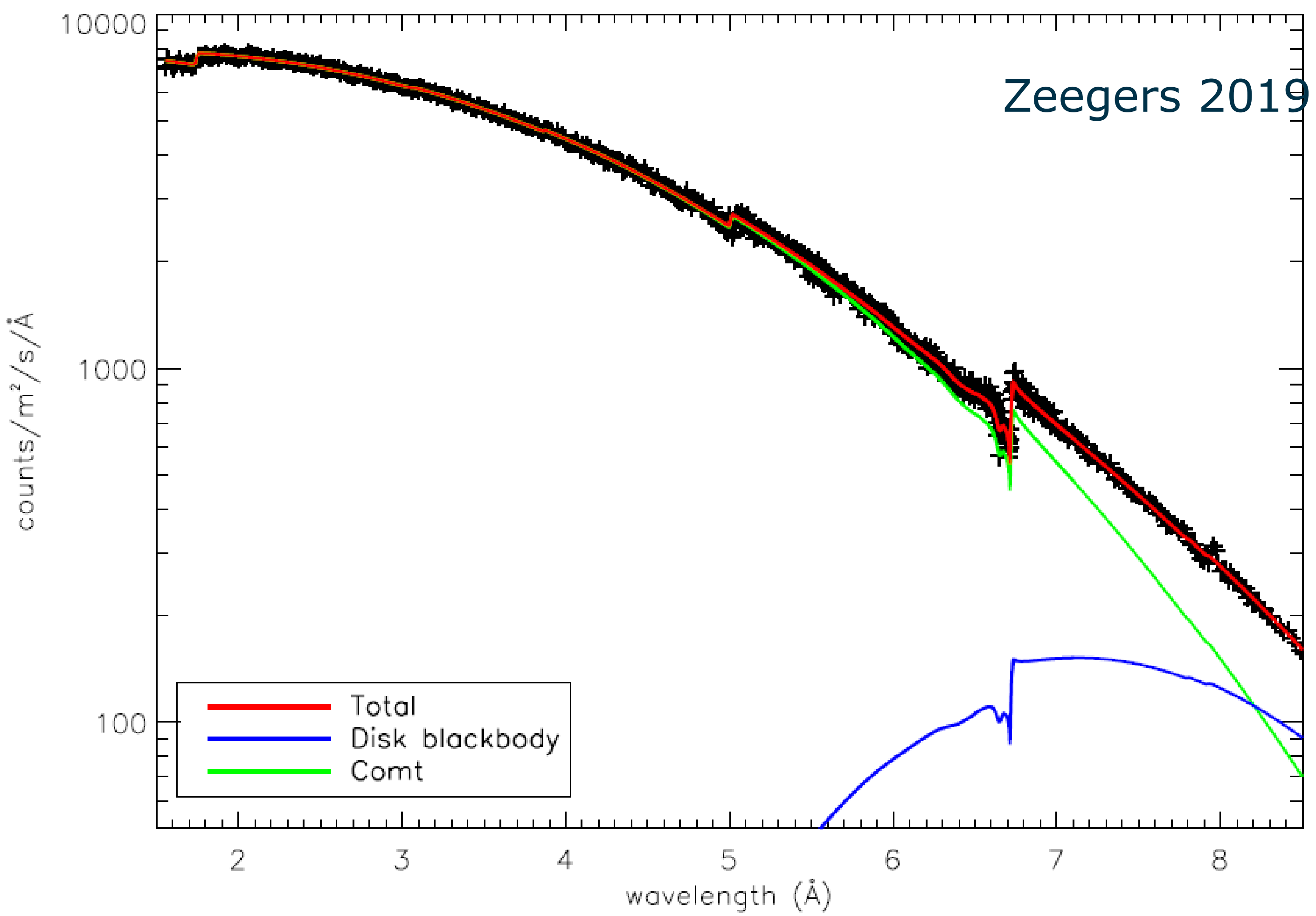
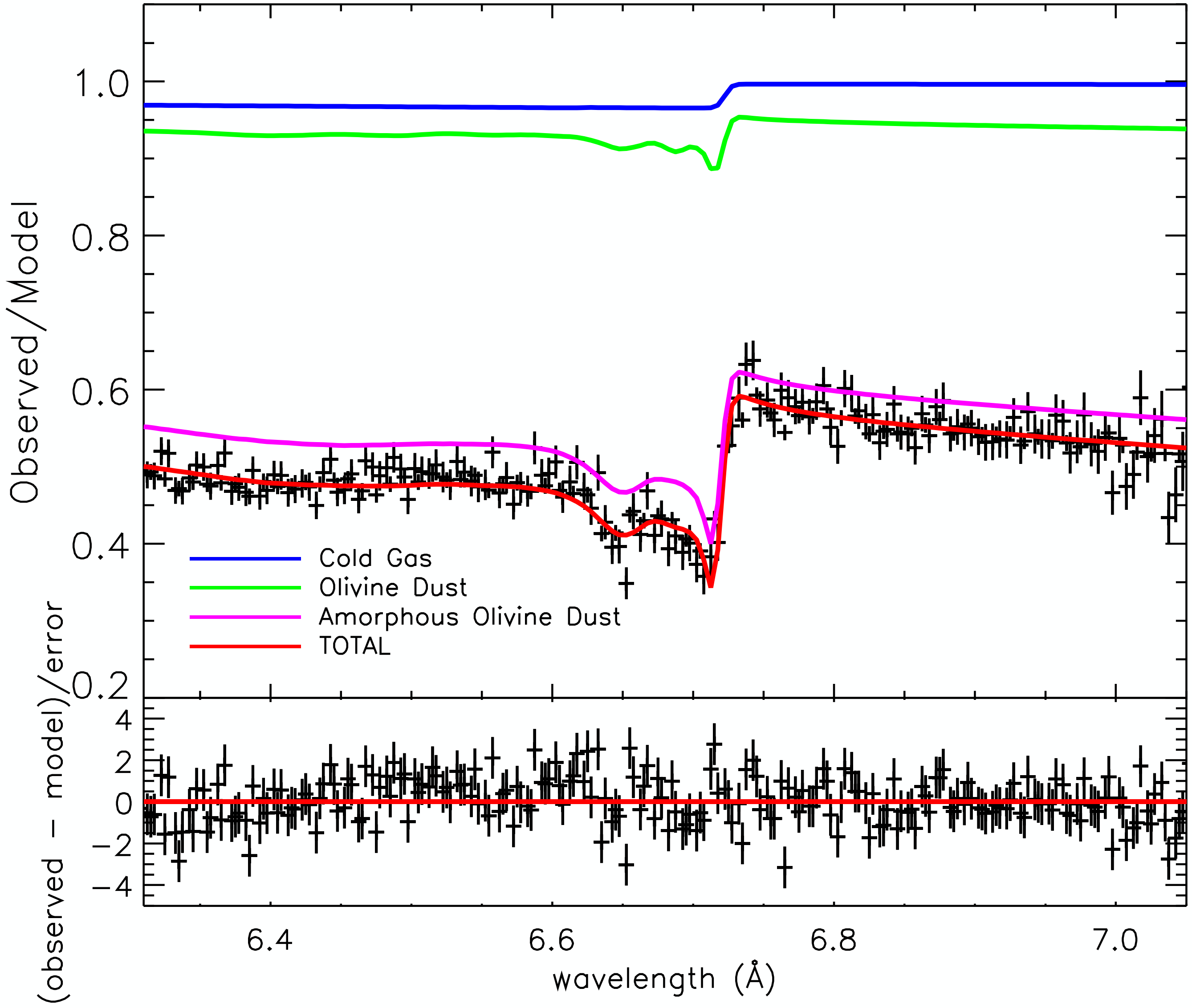


Dust along the line of sight of GX 5-1



Best fit:

Mix of amorphous Olivine

($[Mg_{0.5}Fe_{0.5}]_2SiO_4$)

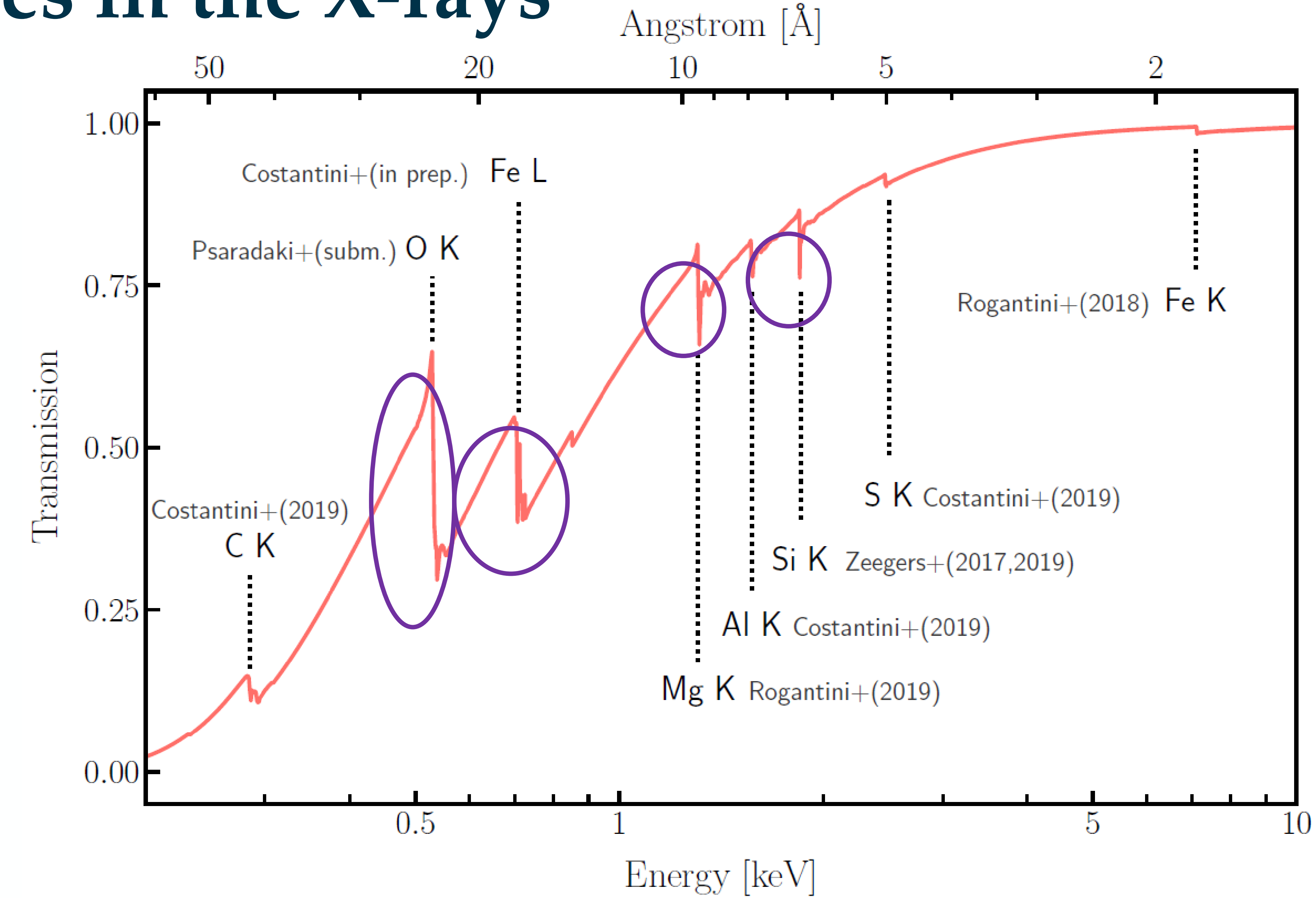
and

Crystalline Olivine

($Mg_{1.56}Fe_{0.4}Si_{0.91}O_4$)

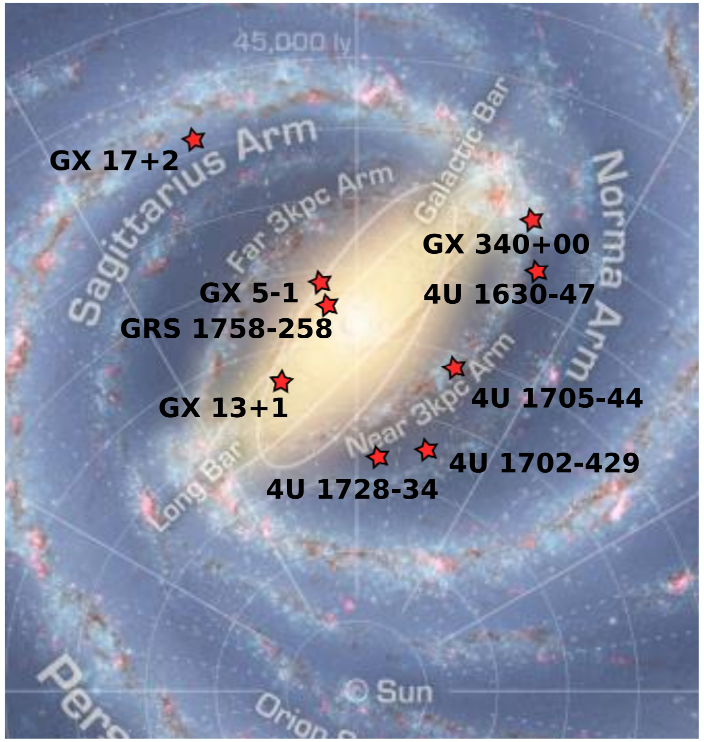
(*Zeegers et al.2017, Zeegers et al. 2019*)

Silicates in the X-rays



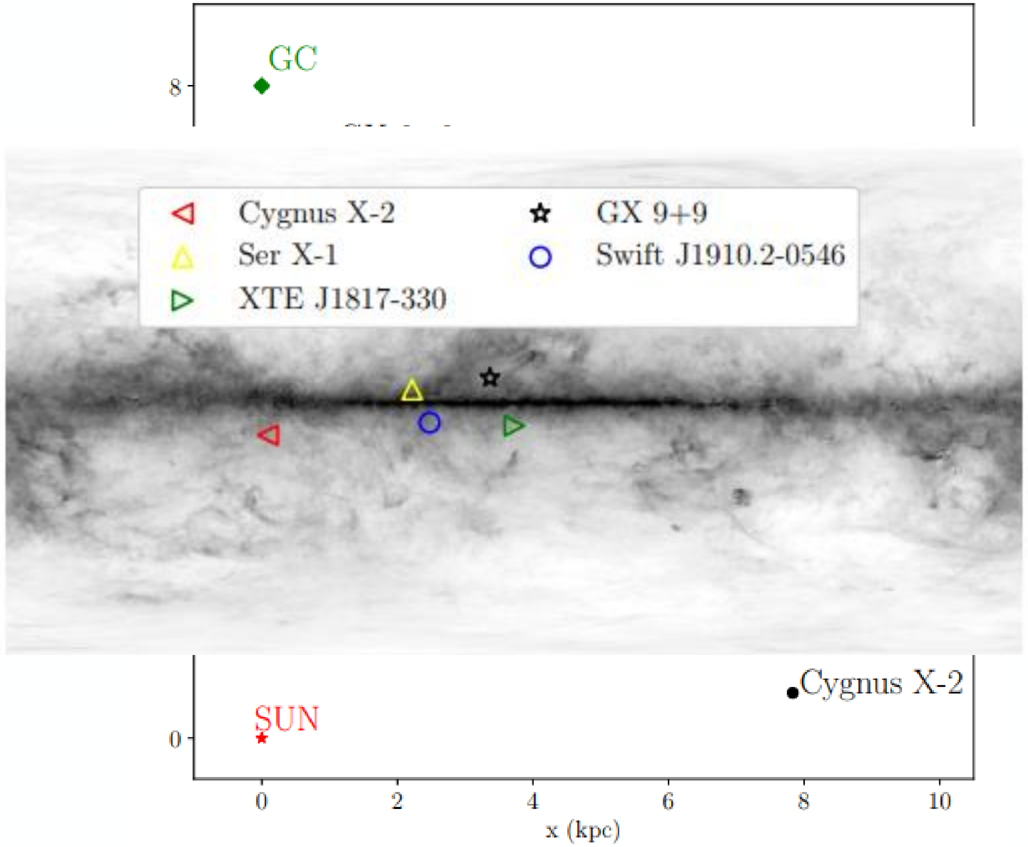
Credit:
D. Rogantini

Dense regions



Mg K edge + Si K edge
9 sources
Zeegers et al 2019, Rogantini et al 2020

Diffuse regions



O K edge + Fe L edge
5 sources
Psaradaki et al. 2023

Dense regions

<u>Conclusions:</u>

Mg K edge + Si K edge

- Crystallinity of 11%
- Dominant component:
  Amorphous $[Mg,Fe]_2SiO_4$
  Mg-rich dust not preferred in fits
- No preference for pyroxene dust

Zeegers et al 2019, Rogantini et al 2020

Diffuse regions

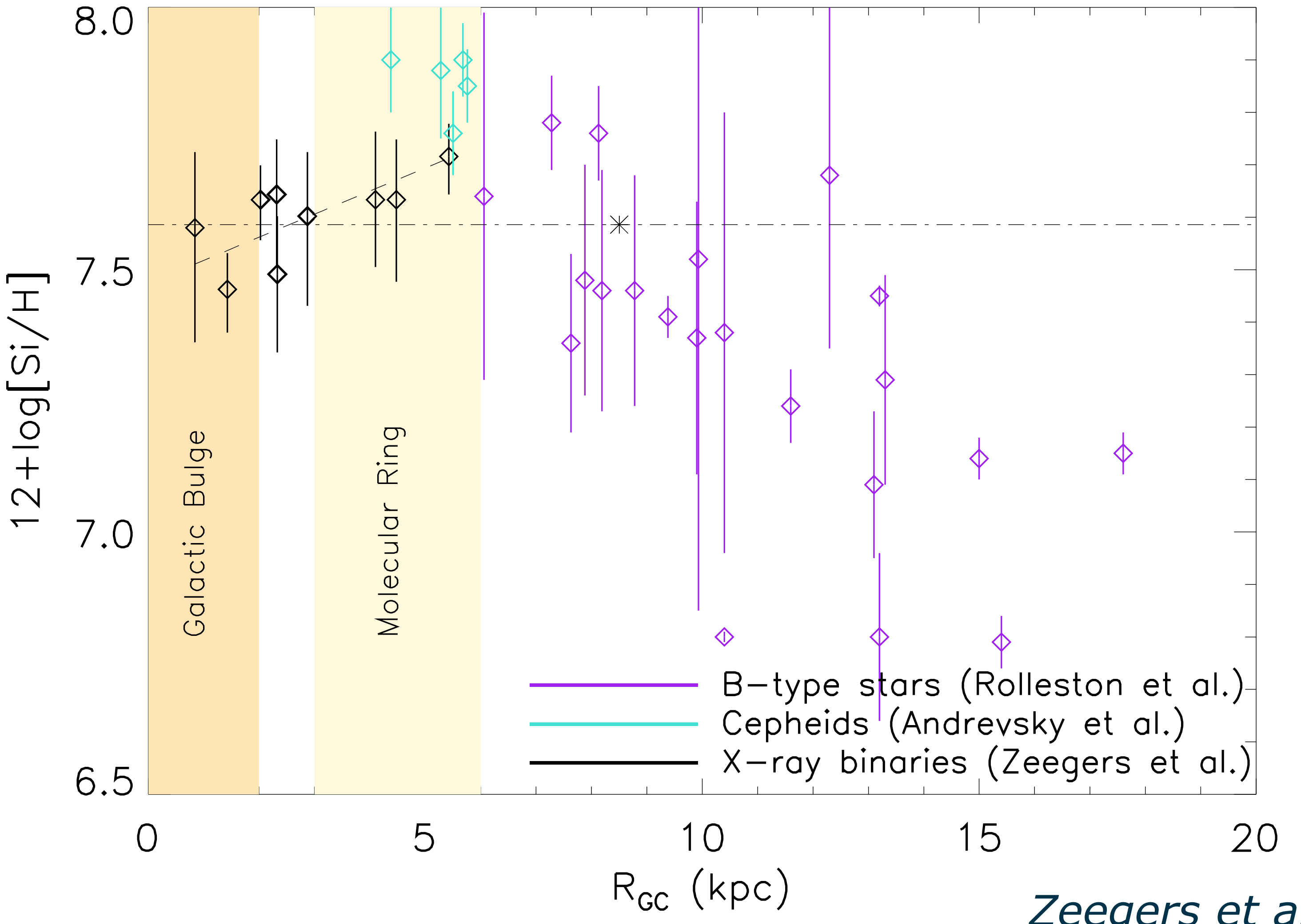
<u>Conclusions</u>:

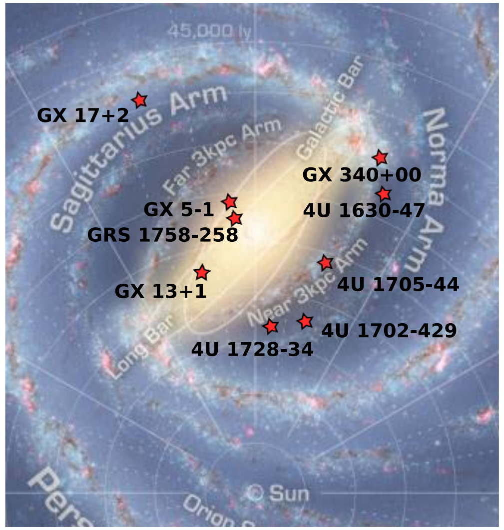
O K edge + Fe L edge

- upper limit silicate crystallinity of 15%
- Dominant component:
  Mg-rich amorphous pyroxene dust
- Metallic iron detected

Psaradaki et al. 2023
Costantini 2012

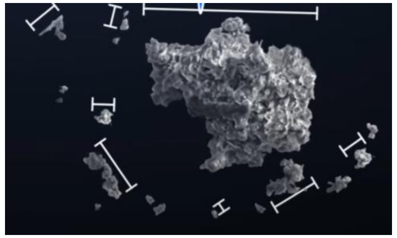
Si Abundances toward the GC





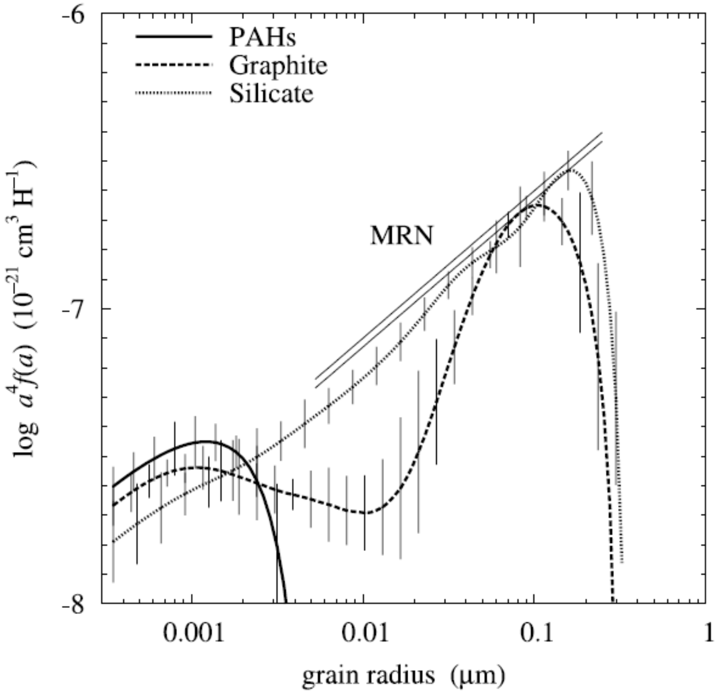
Zeegers et al. 2019

Grain Size

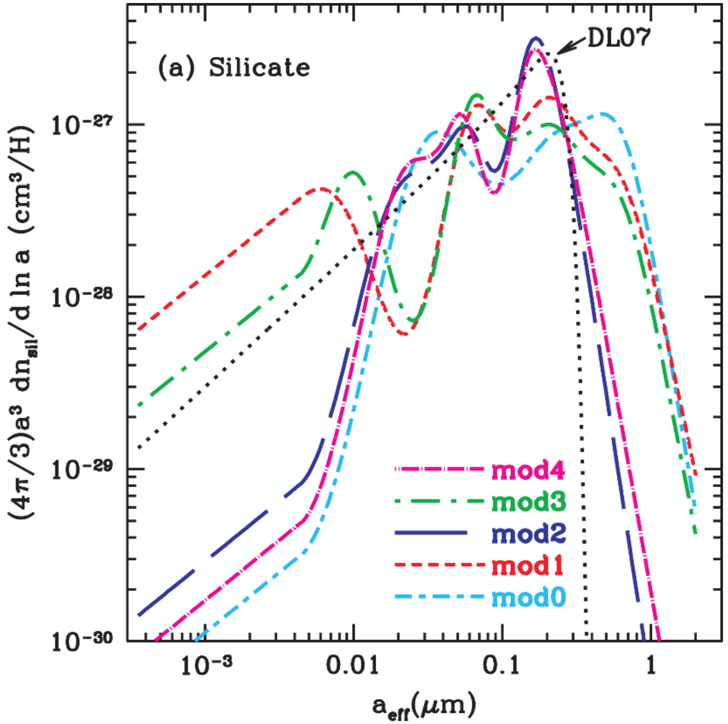


The sizes of the dust particles range from small molecular size to micron size dust

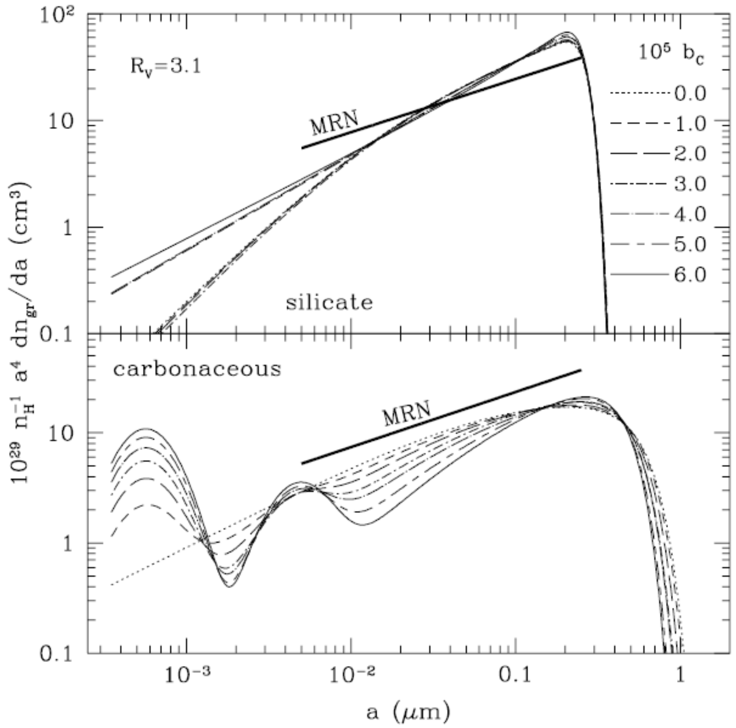
Many different size distribution models



Zubko et al. 2004, Mathis 1977 et al.

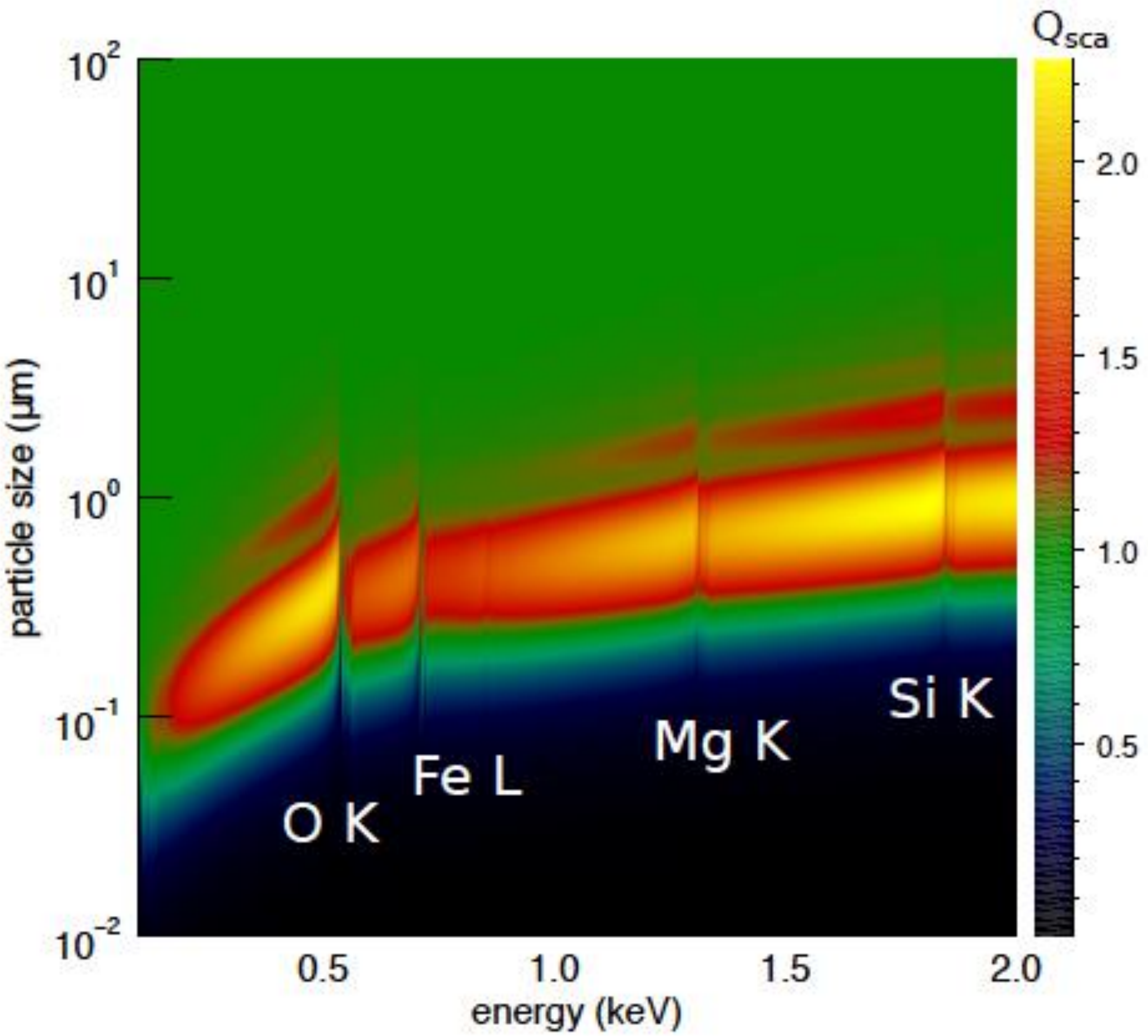


Draine & Fraisse 2009



Weingartner & Draine 2001

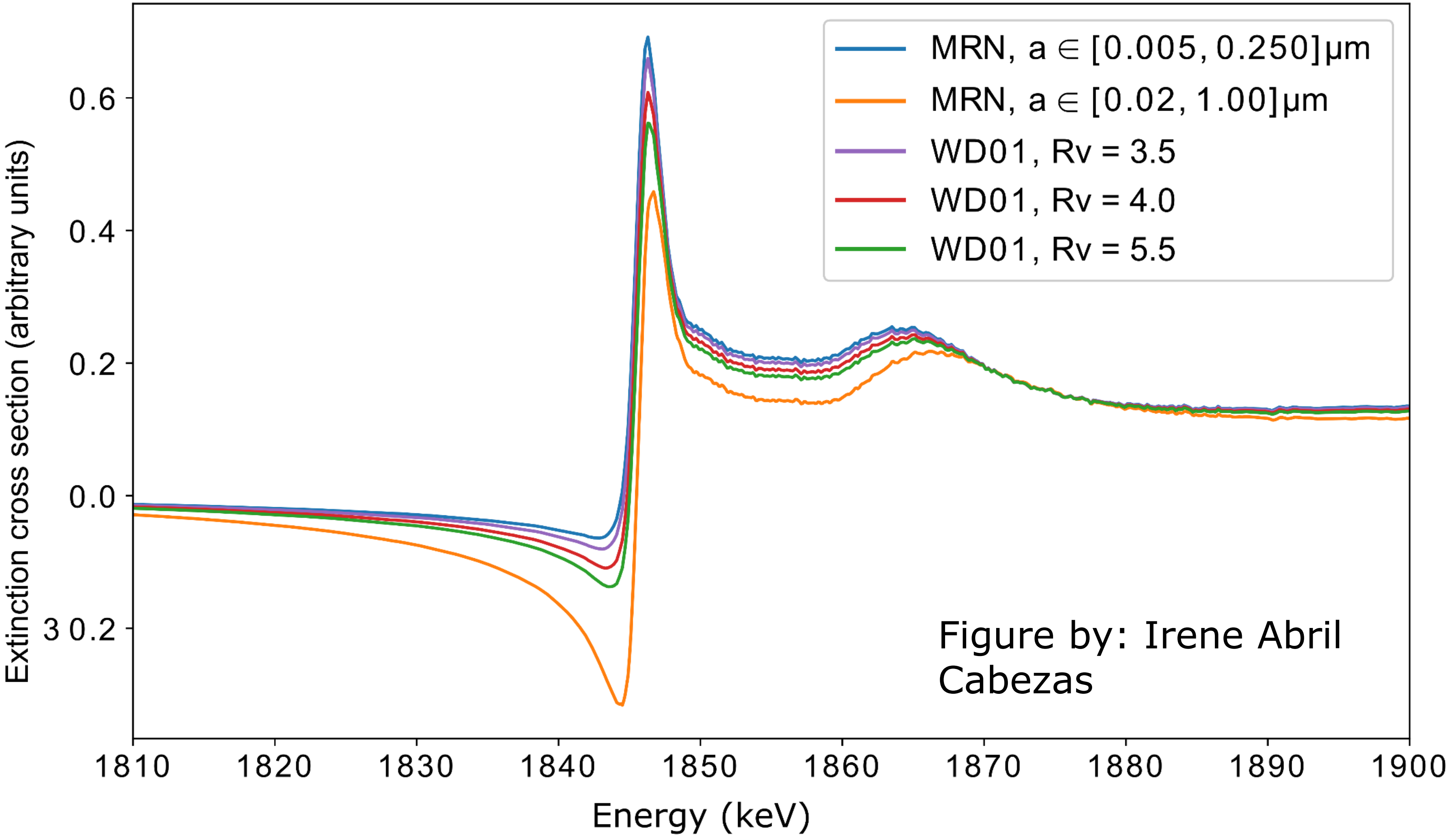
Particle sizes and scattering efficiency



Zeegers 2018

Grain size distribution

New method to investigate grain sizes of interstellar dust



Grain size distribution

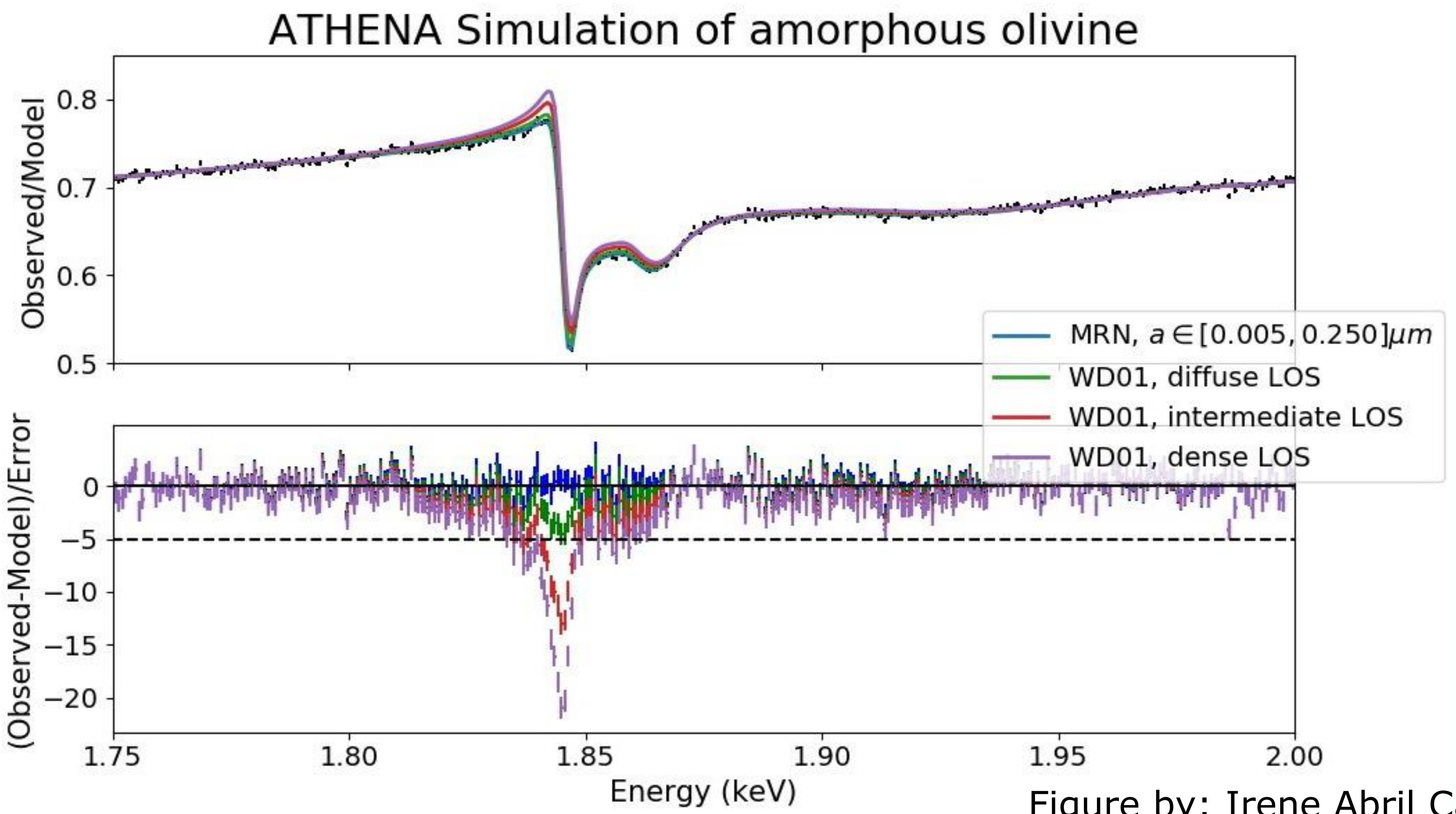
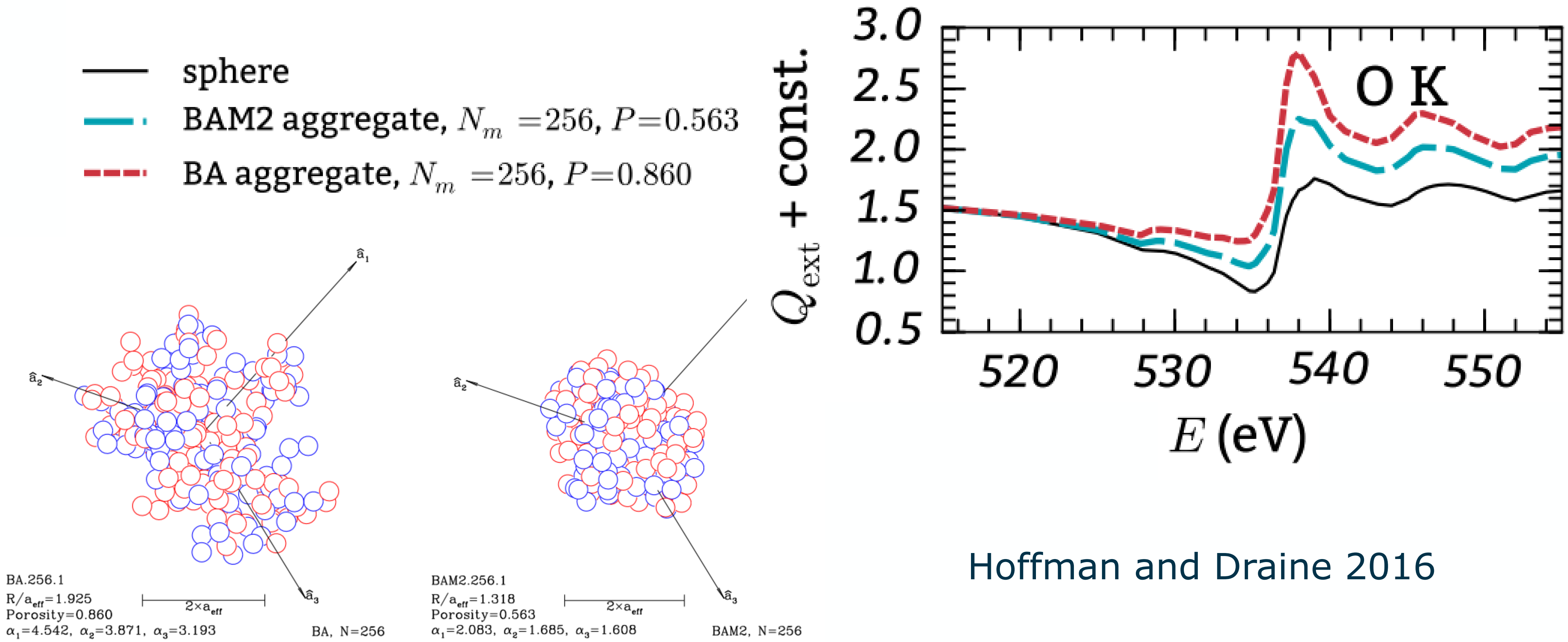


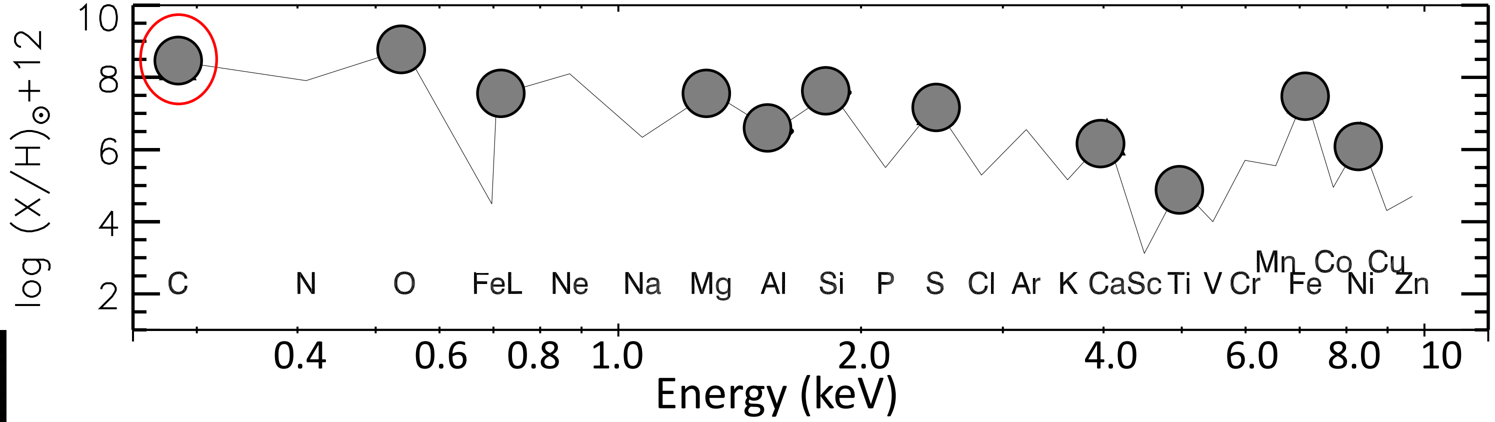
Figure by: Irene Abril Cabezas

Grain porosity

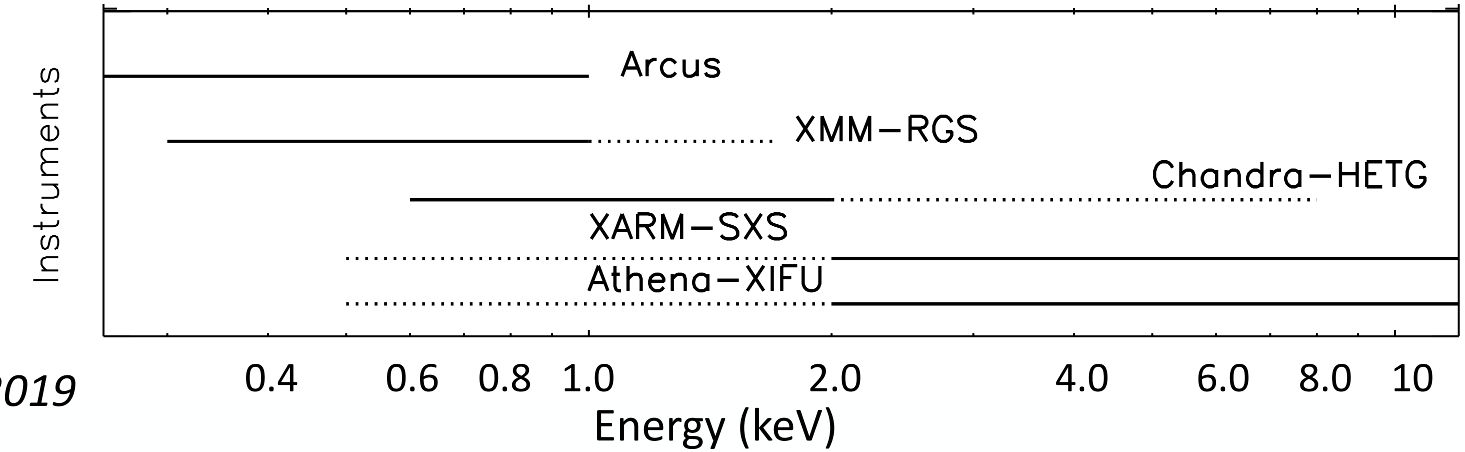


Hoffman and Draine 2016

Carbon in the X-rays

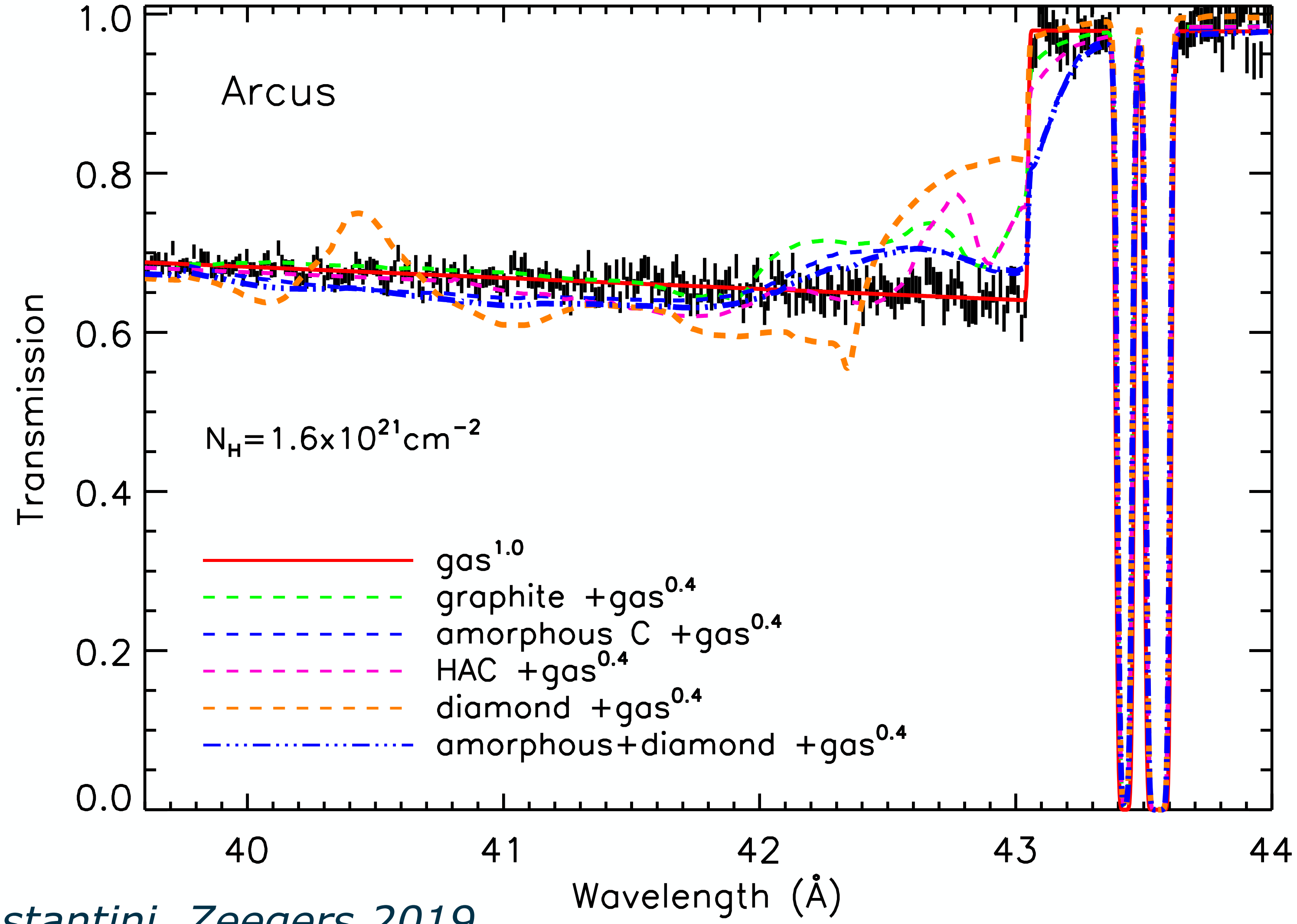


Carbon K edge may be explored with Arcus



Costantini, Zeegers 2019

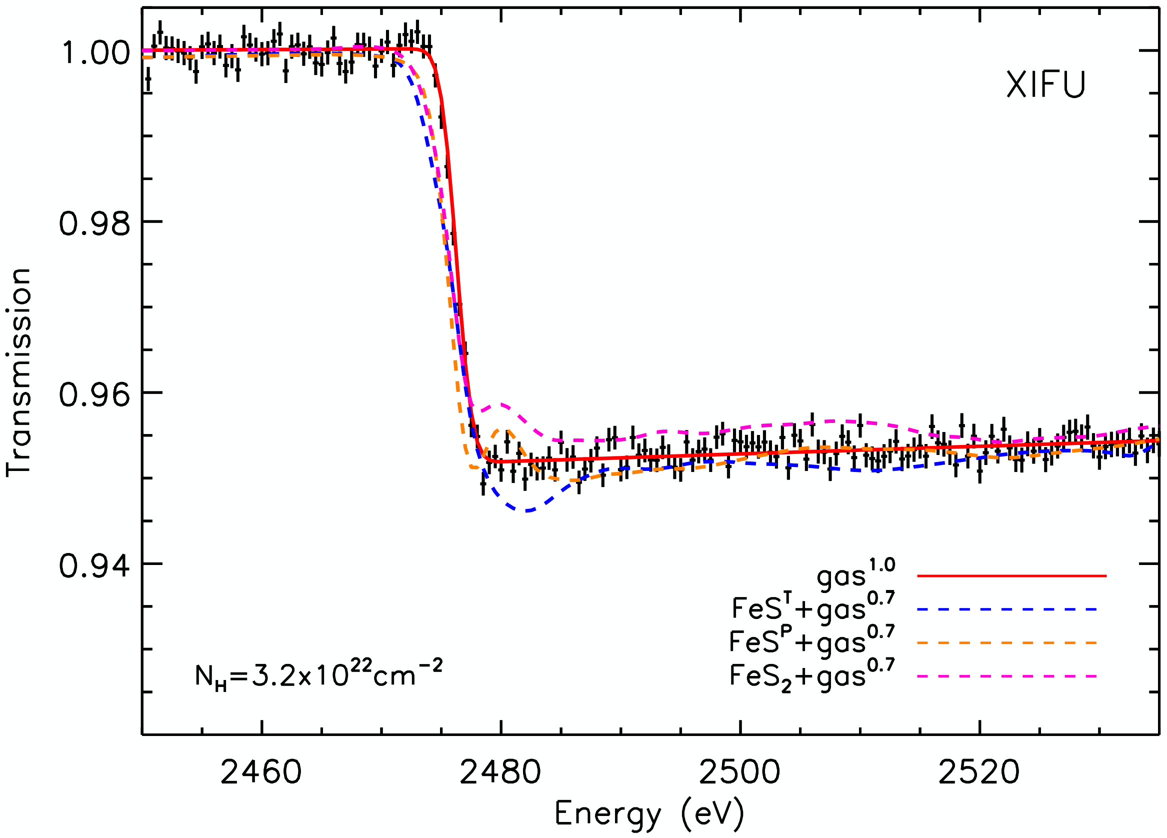
Carbon in the ISM: Carbon K edge



Costantini, Zeegers 2019

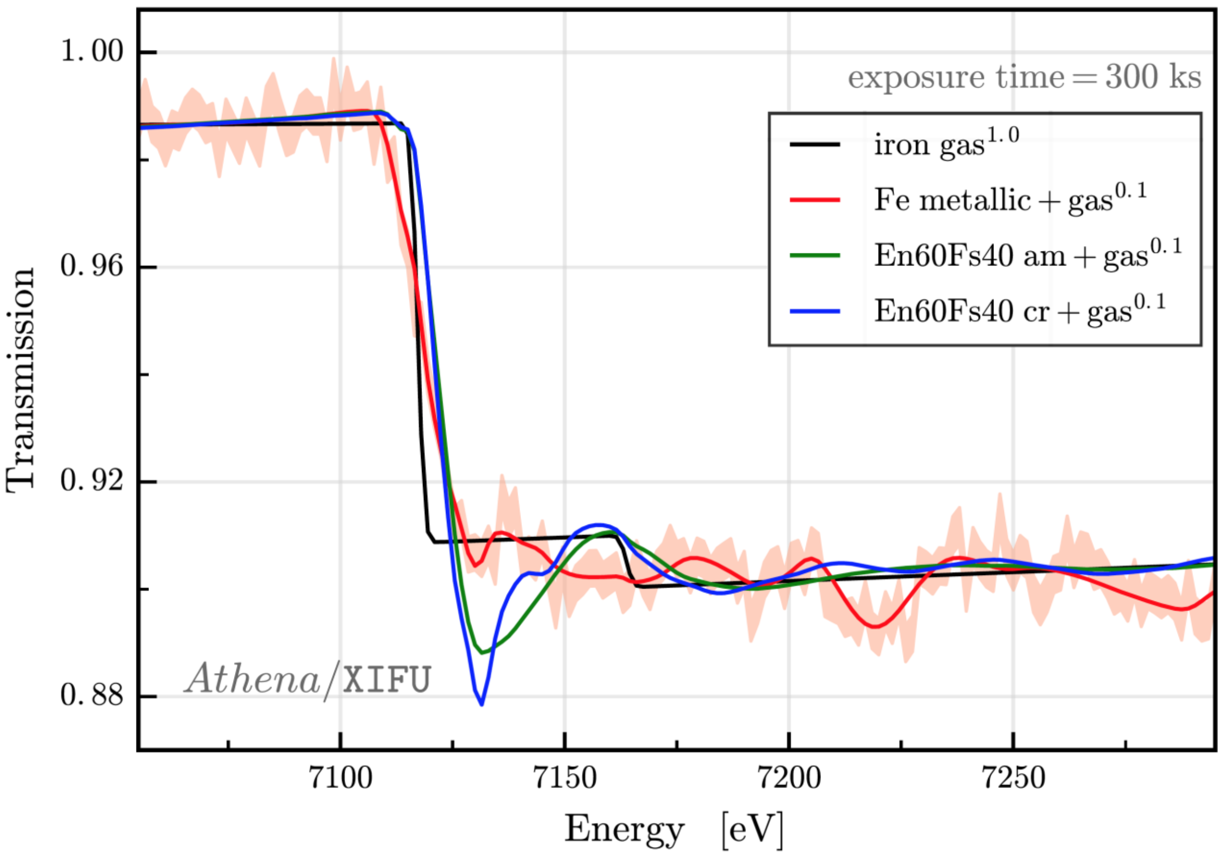
Sulfur and iron in the ISM

Sulfur K-edge



Costantini, Zeegers 2019

Iron K-edge



Rogantini et al. 2018

X-rays and dust: where is the dust?

Light echoes:

Light scatters on dust particles along the line of sight

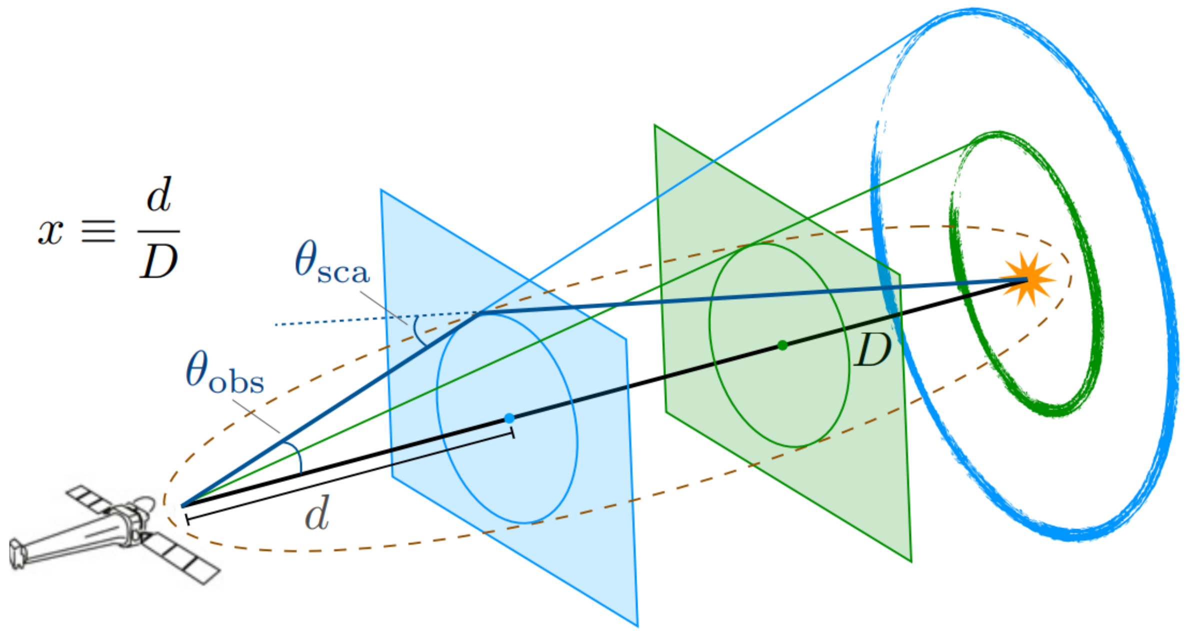
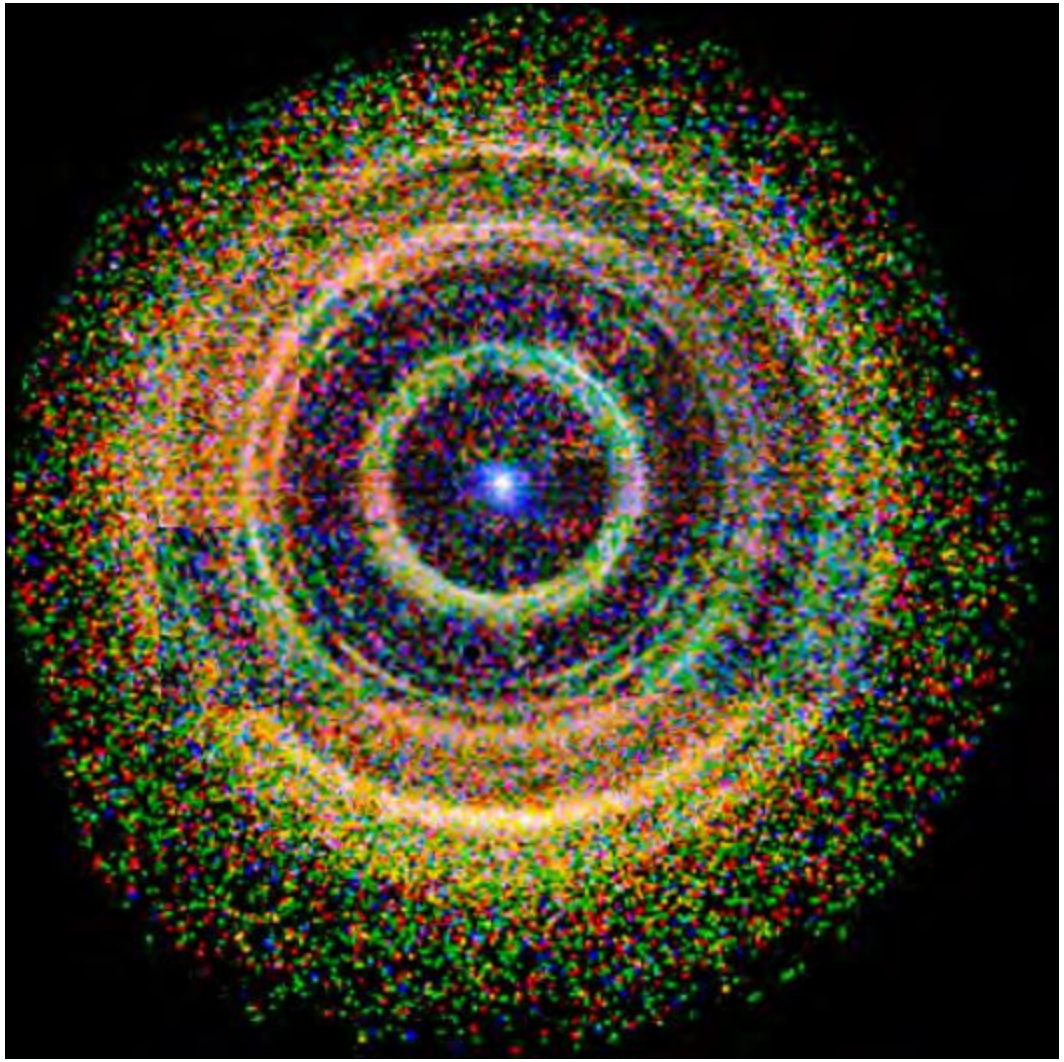


Image: Costantini & Corrales 2022

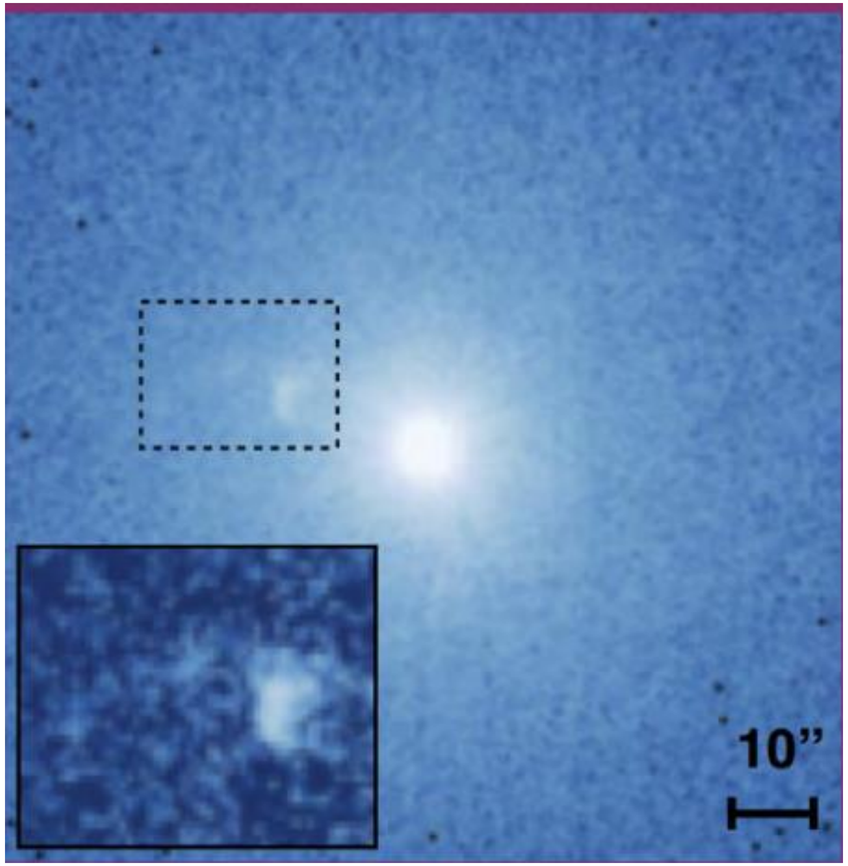


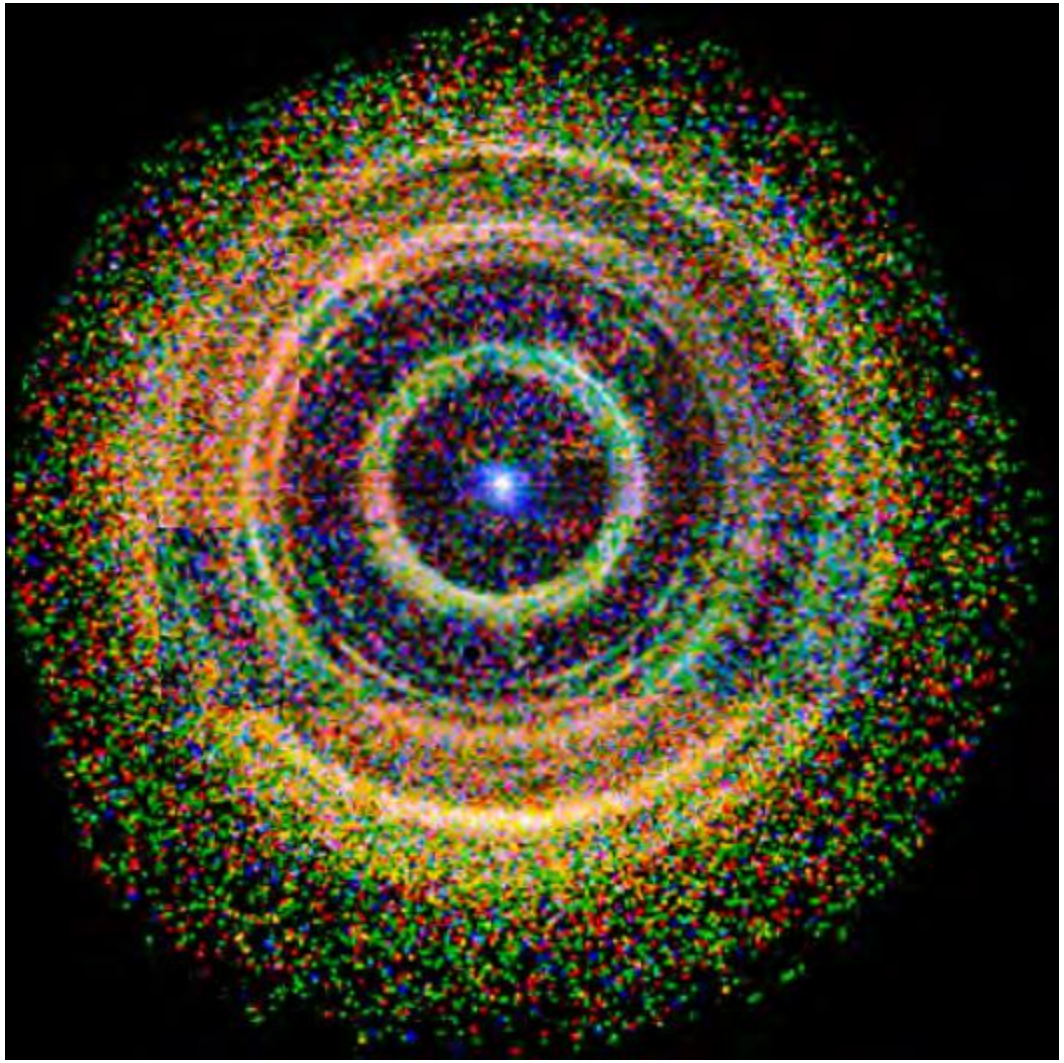
X-rays and dust: where is the dust?

Heinz 2021

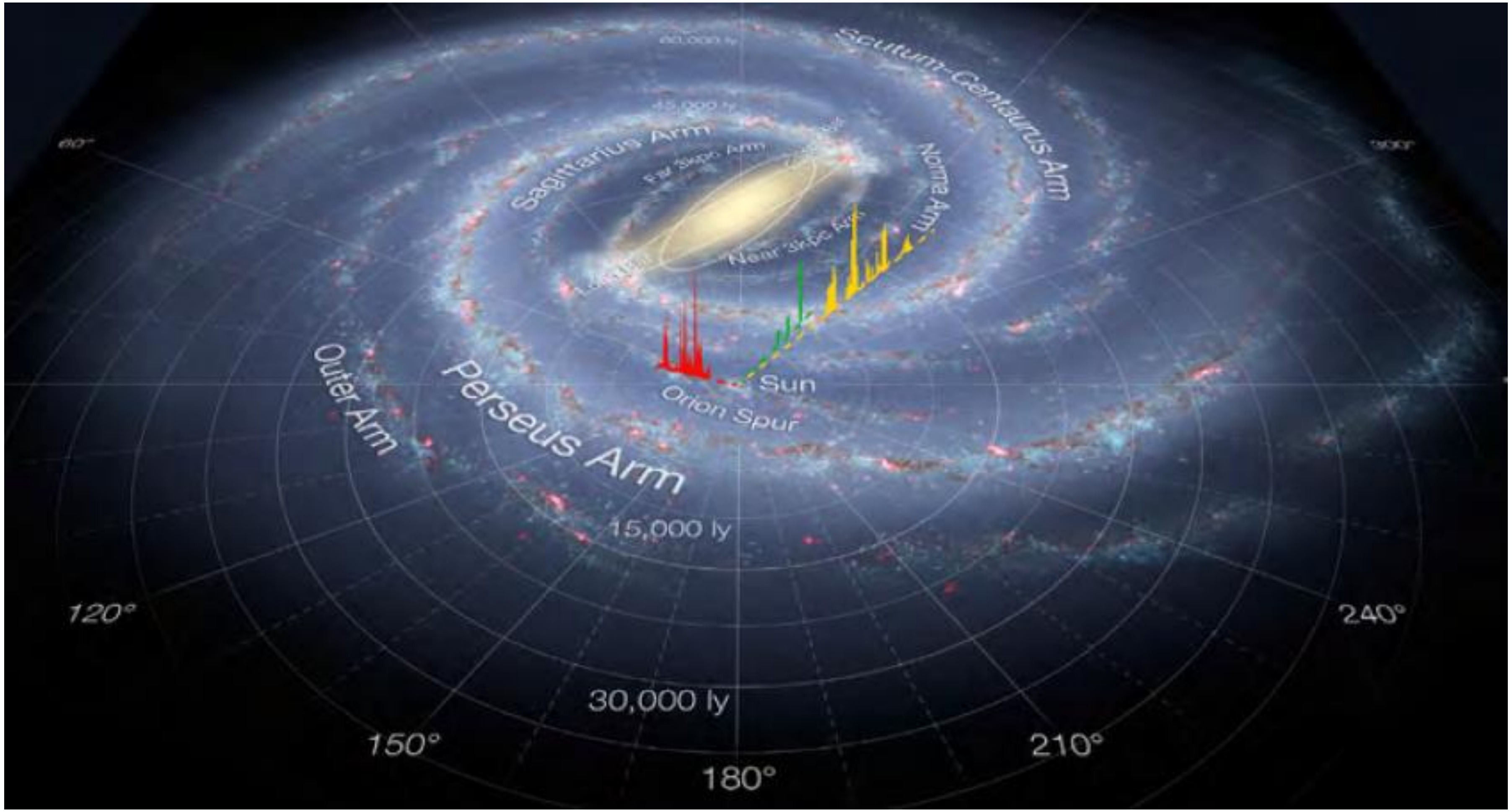
Light echoes:

Light scatters on dust particles along the line of sight



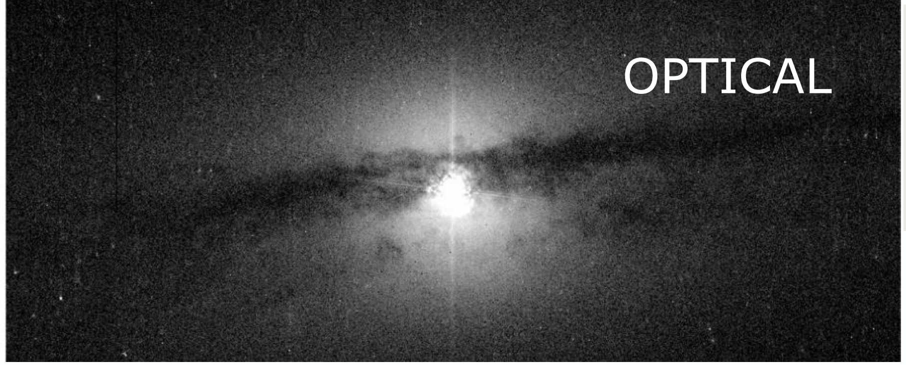


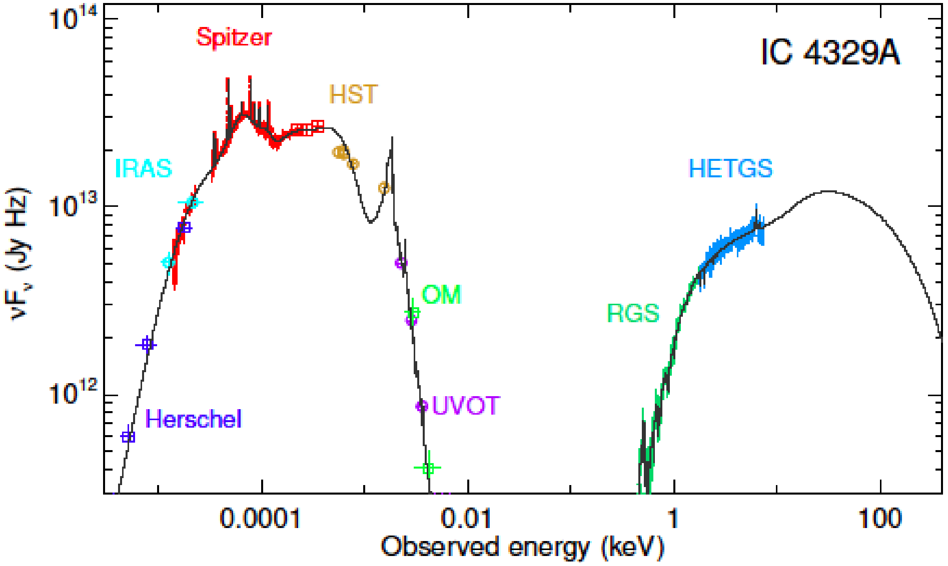
X-rays and dust: where is the dust?



Dust distributions towards V404 Cygni (red; Heinz et al. 2016), Circinus X-1 (yellow; Heinz et al. 2015), and 1E1547.0-54.08 (green, from Tiengo et al. 2010

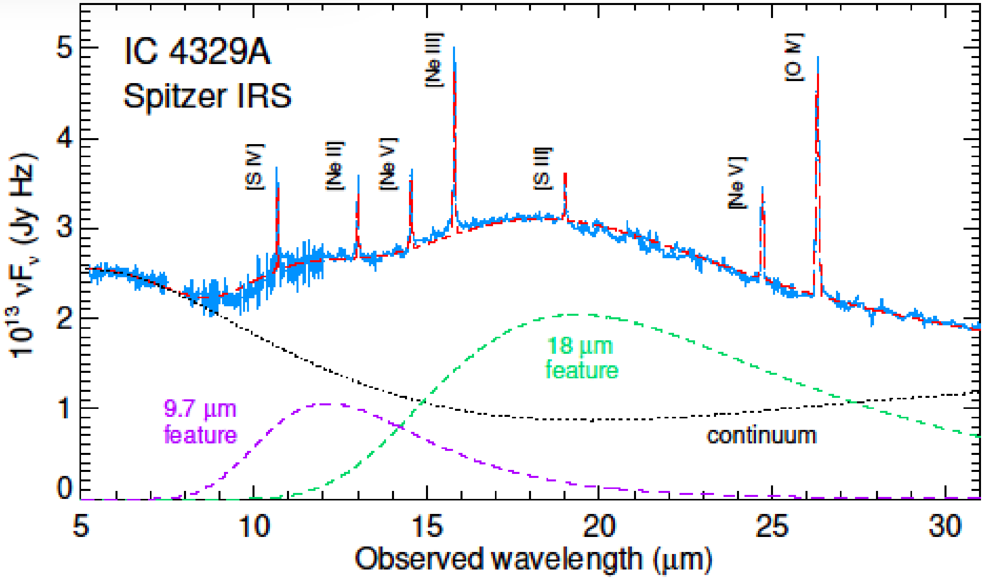
DUST in AGN: QSO IC4329a

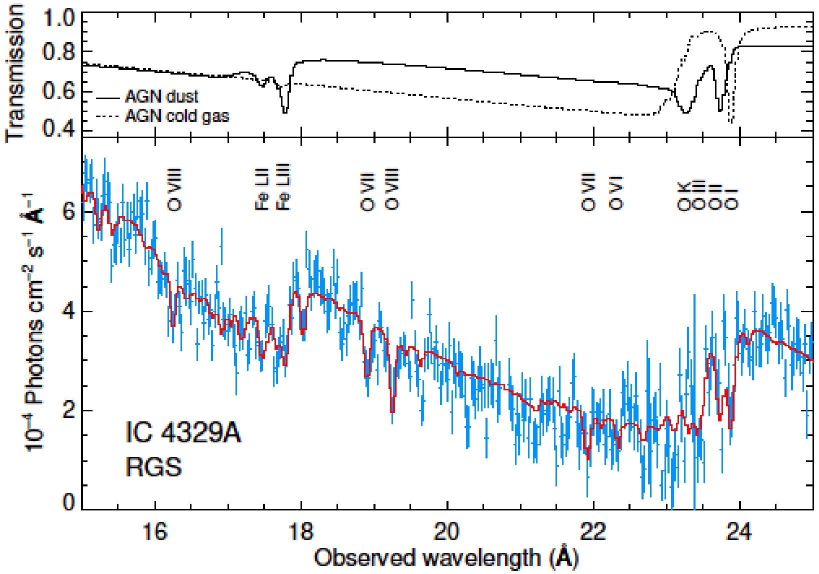




- Negligible NH from MW
- Host galaxy
- Huge absorption in the SED
- Cold Absorption in the X-ray band
- Ionized Absorption in the X-ray band
- Emission in the Spitzer band

(Mehdipour & Costantini 18)

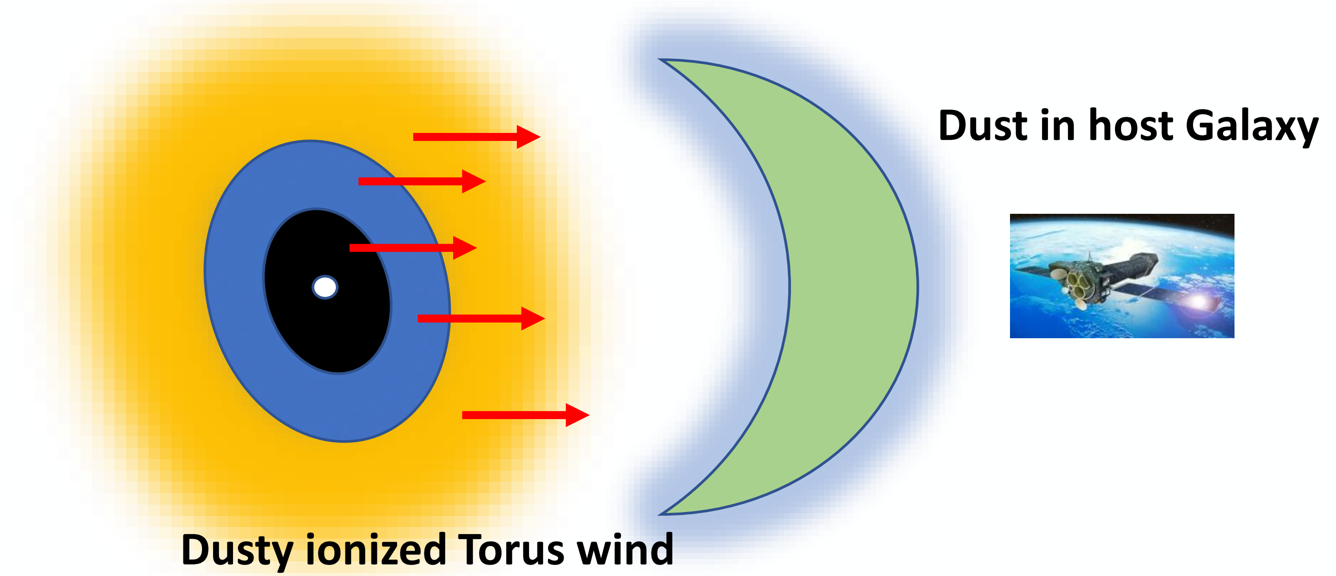




DUST in AGN:
QSO IC4329a

- The X-ray cold absorption can be explained by the sum of:
  - Host galaxy (edge on)
  - Ionized wind (dusty warm absorber!)
- The SED is obscured by:
  - Host galaxy (Cardelli +89 extinction law, MW)
  - Dust intrinsic to AGN (Czerny+ 04 extinction law, grey)
- Emission from dusty torus: amorphous and porous silicates (Li+ 08)

(Mehdipour & Costantini 18)

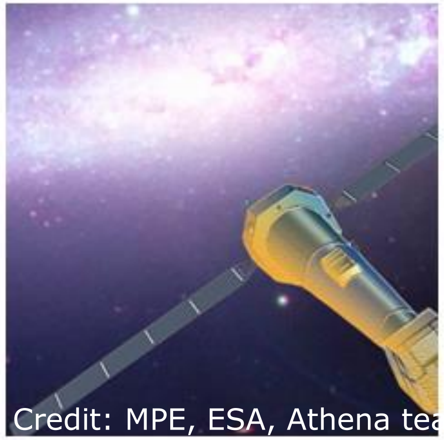


New missions to study the interstellar medium dust in the X-rays

XRISM: launch later this year!

image credit: NASA

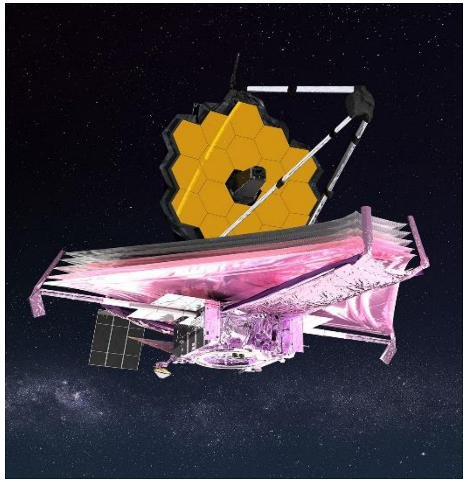
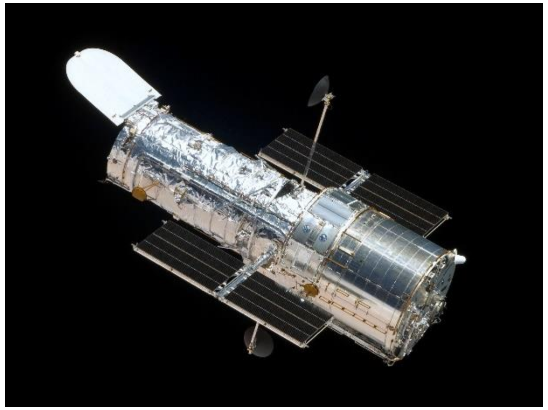
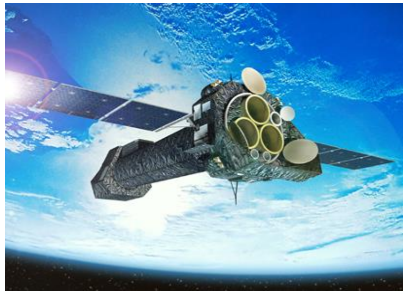
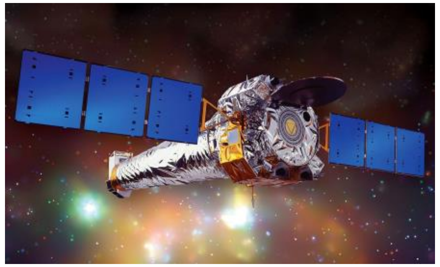
NEW ATHENA



Credit: MPE, ESA, Athena tea

Bright future with upcoming observatories and new dust models!

Multi wavelength studies are important!


From the infrared

To the X-rays!

Bright future with upcoming observatories and new ISM models!

SPEX Models ISM

Gas models:

Hot cold model: neutral gas

Hot model: neutral gas

Xabs model: slab of ionized gas

Dust models:

Amol

Summary and conclusion

The X-ray window provides us unique insights in the properties of the Interstellar medium:

- **The broad band energy coverage (0.1–10 keV)** encompasses a variety of transitions, from neutral to highly ionized gas, of the **fundamental metals in the Universe**: C, N, O, Ne and Fe, among others.
- **Provides the possibility to measure hydrogen column densities**
- **Sensitive to a wide range of column density** → study various regions in the Galaxy
- **Absorption and scattering of dust can be simultaneously studied** → only X-rays can do this
- **Easy to determine the depletion from the gas phase**

Exercises

1) Properties of interstellar dust, depletion of gas into dust and hydrogen column densities

2) Determine temperature and ionization of gas in the ISM