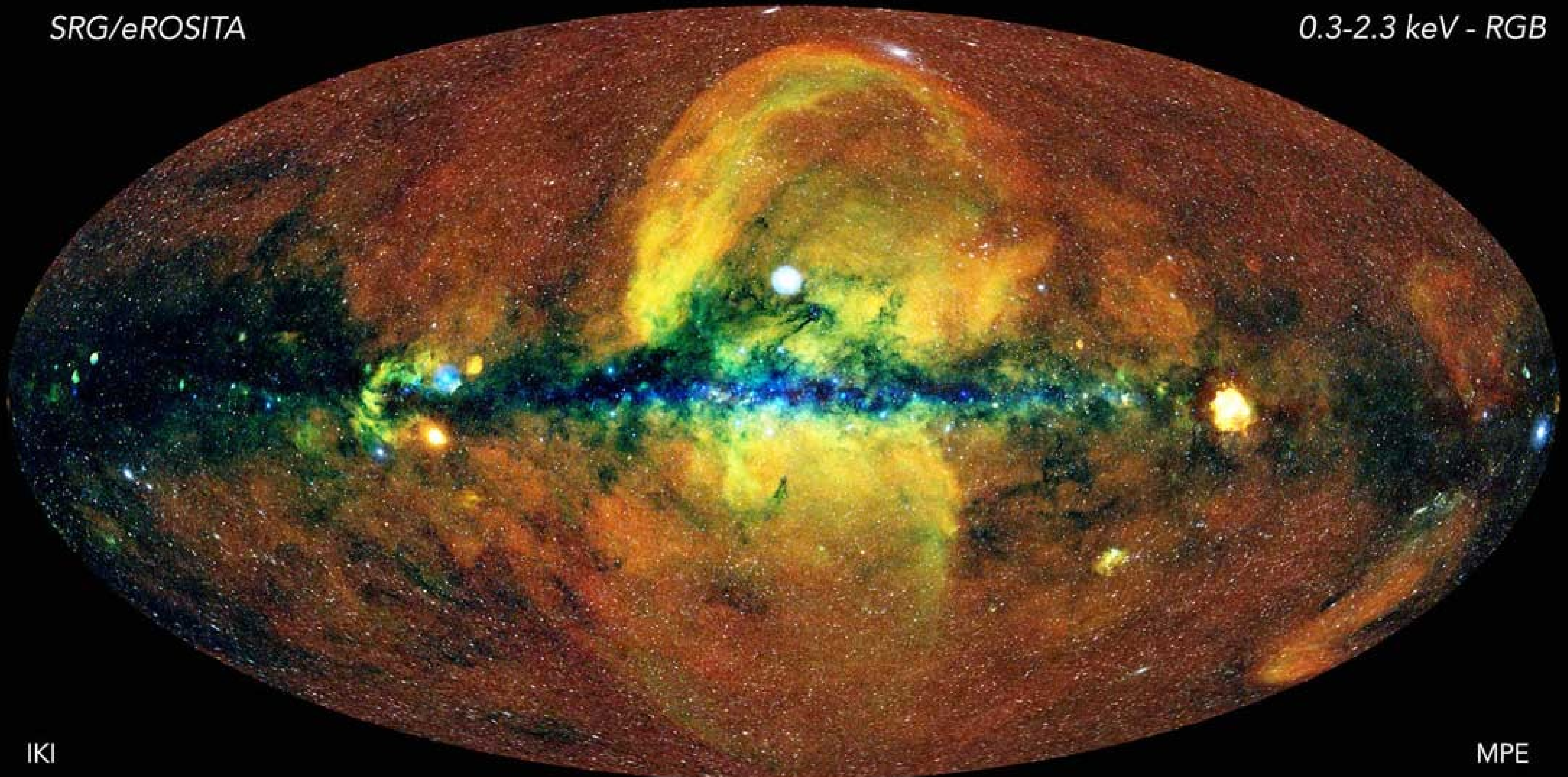


Probing the ISM in X-rays

Efrain Gatuzz (MPE)

X-RAY VISION 2023

TABLE OF CONTENTS:

The Interstellar Medium (ISM)

WHAT IS THE ISM?

"Everything that is between stars and around galaxies"
Physics of the interstellar and intergalactic medium – Bruce Draine

Including:
Gas, dust, electromagnetic radiation, cosmic rays and magnetic fields.

WHY IS THE ISM IMPORTANT?

- Stellar formation processes.

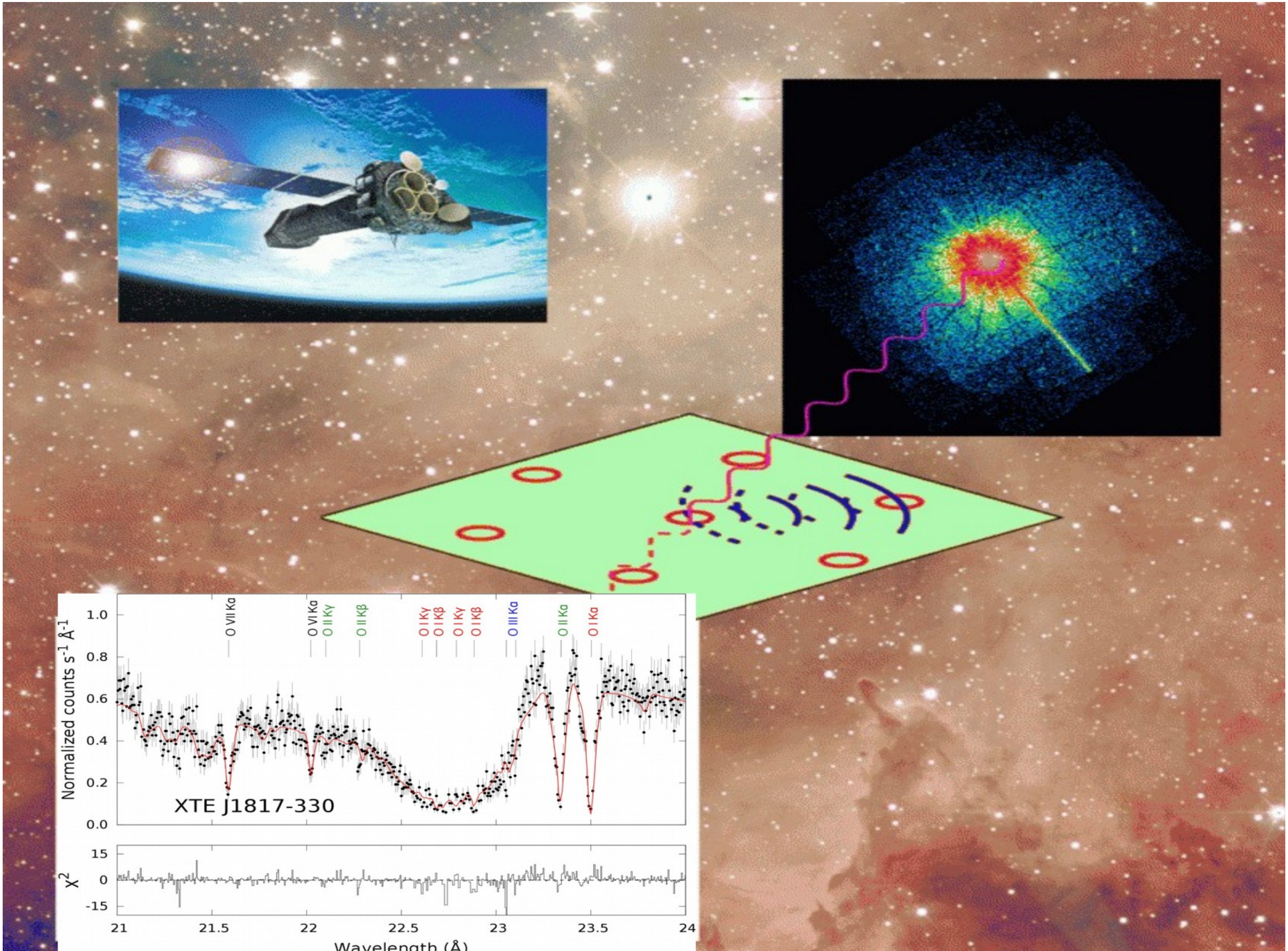
- Stellar evolution processes.

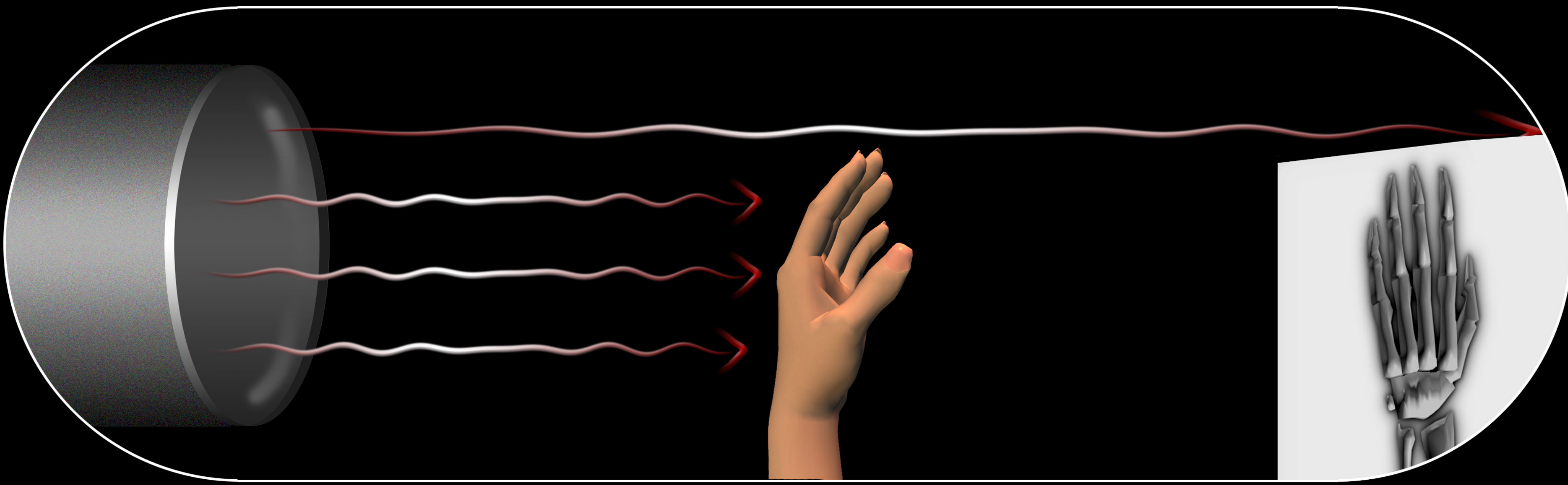
The Interstellar Medium (ISM)

Phase	Component	Temp. (K)	Constituents
Cold	Dust	~ 10 - 20	$MgSiO_3$,...
	Molecules	~ 10 - 20	H_2, CO, ...
	Neutral Gas	~ 50 - 100	H I, O I, ...
Warm	Neutral Gas	$\leq 10^4$	H I, O I, ...
	Ionized Gas	$\sim 10^4$	H II, O II-V, ...
Hot	Ionized Gas	$\sim 10^6$	O VI-VIII, Ne IX, ...

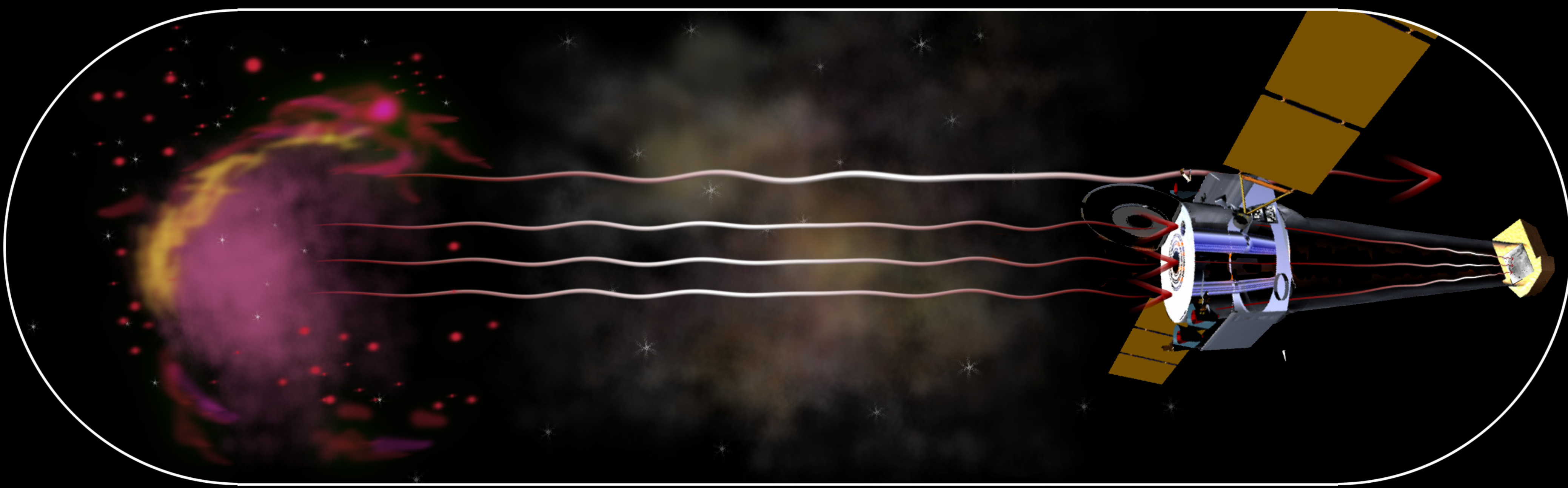
High-resolution X-ray spectroscopy allows the direct measurement of spectral features such as absorption lines and edges that lead to the identification of multiple atomic ionization species, molecules and solid components (e.g. Juett+05, Yao+09, Pinto+11, Costantini+12, Pinto+13)

X-ray absorption spectroscopy





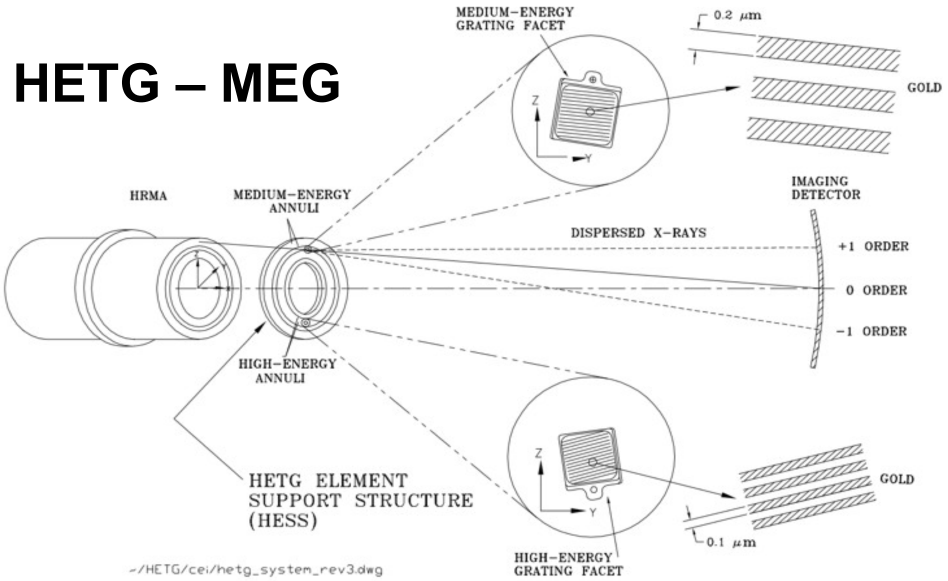
X-Ray Source Hand Film in Camera



Galaxy Gas Cloud Chandra

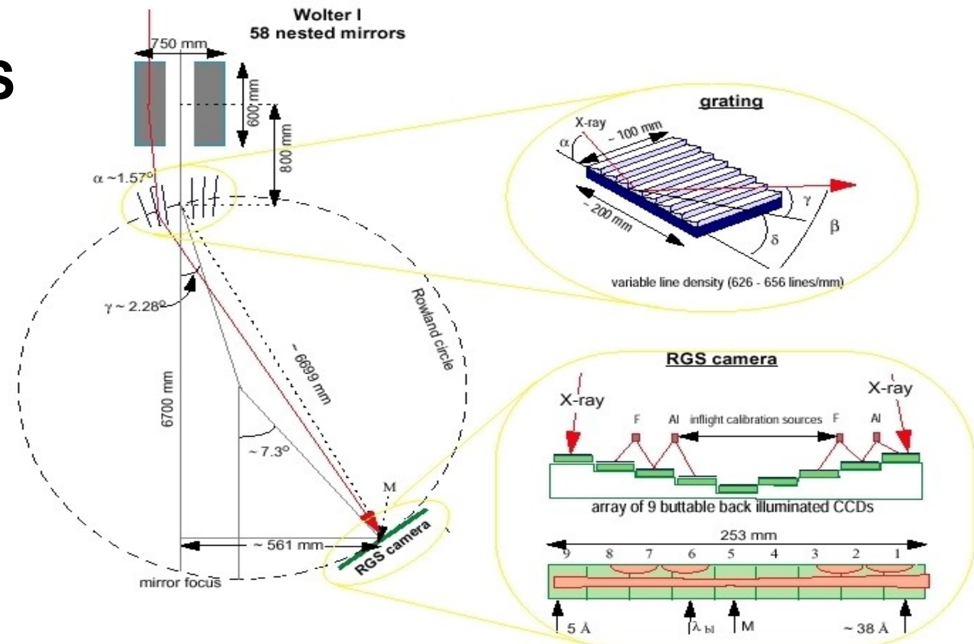
Chandra X-ray Observatory

HETG – MEG



X-ray Multi-Mirror Mission (XMM-Newton)

RGS



Chandra X-ray Observatory

HETG – MEG

Bandpass:	1.2 – 30 Å
Effective Area:	35 cm^2 (10 Å)
	10 cm^2 (20 Å)
Resolution (ΔÅ):	0.012 Å FWHM

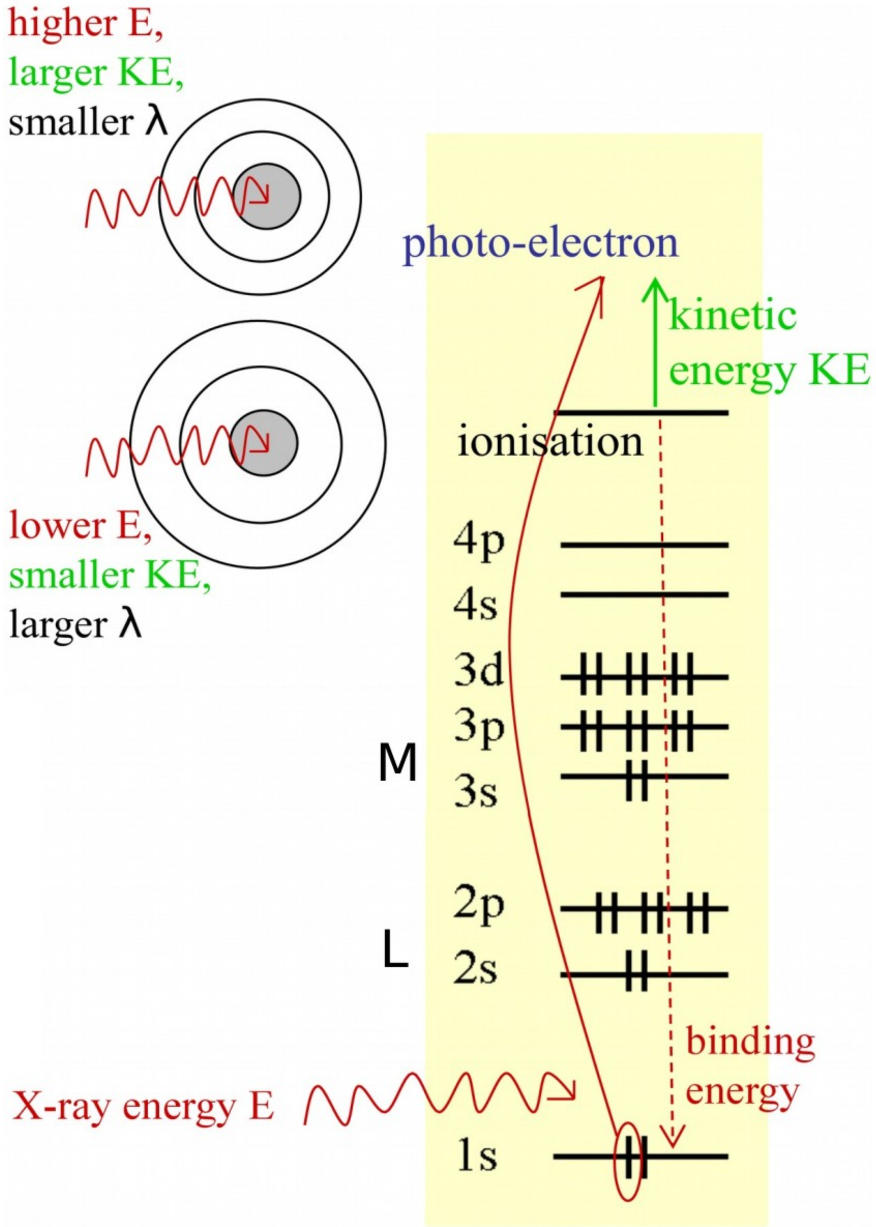
X-ray Multi-Mirror Mission (XMM-Newton)

RGS

Bandpass:	10 – 35 Å
Effective Area:	59 cm^2 (10 Å)
	50 cm^2 (20 Å)
	70 cm^2 (30 Å)
Resolution (ΔÅ):	0.035 Å FWHM

X-ray photoabsorption and photoionization

- The atom is excited by a photon.
- There is one **photoabsorption cross-section** for each ion.
- There are two decay processes:
  - X-ray fluorescence
  - Auger effect



ISM absorption affects all X-ray spectra!

Atomic data

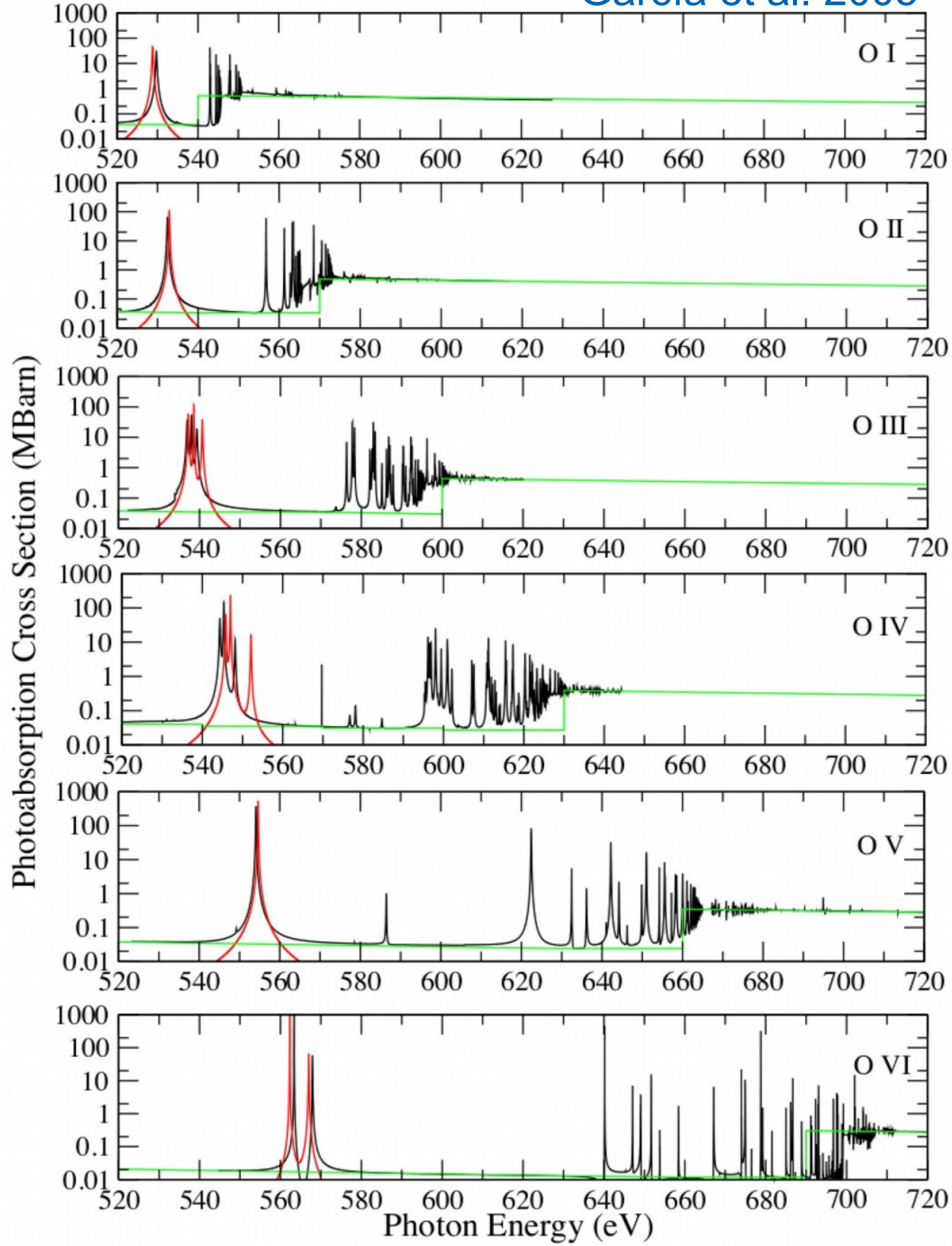
High-energy photoabsorption cross-sections for O ions:

Green lines:
Reilman+Manson+79

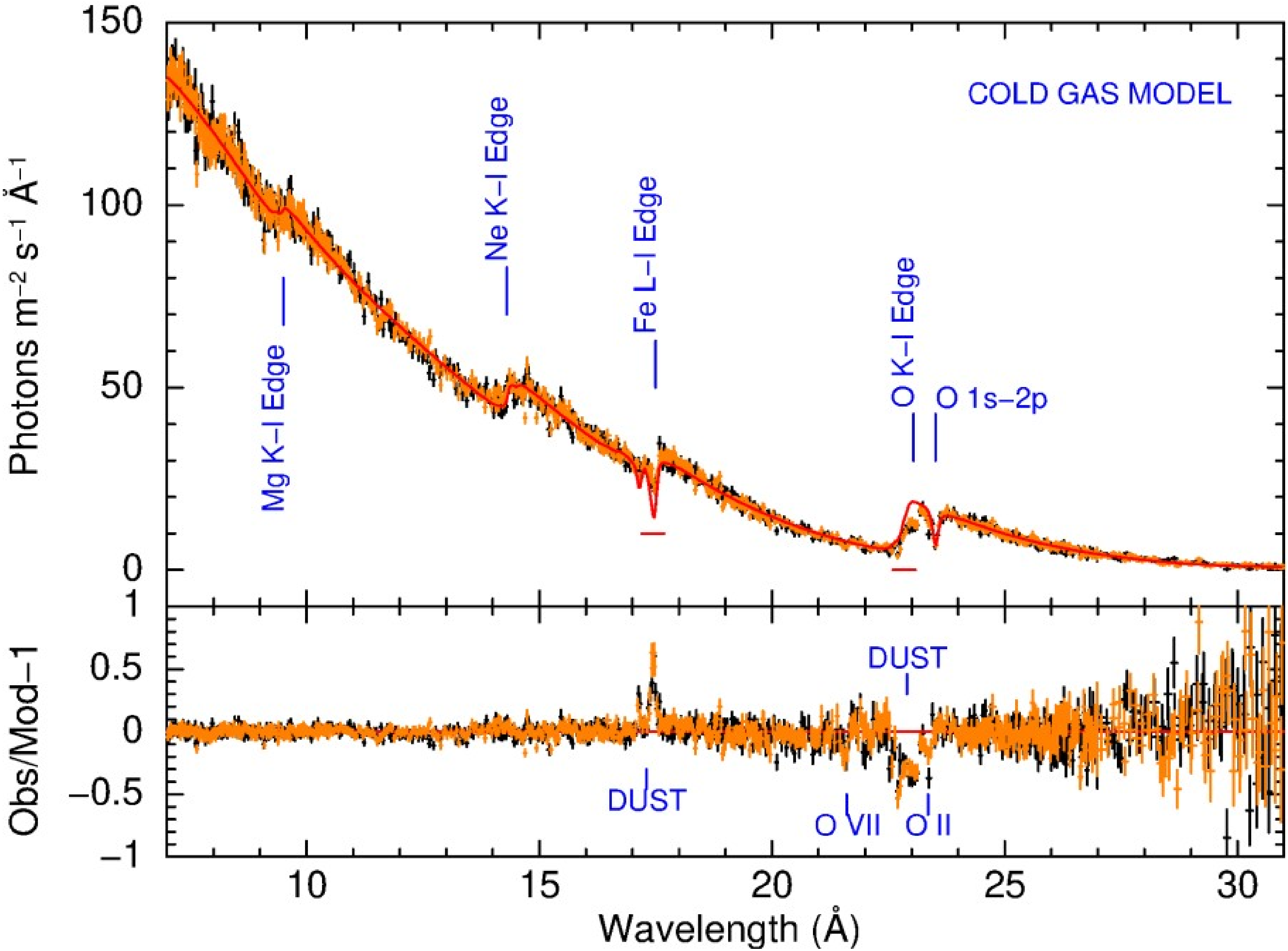
Red lines:
Pradhan+03

Black lines:
García+05

García et al. 2005

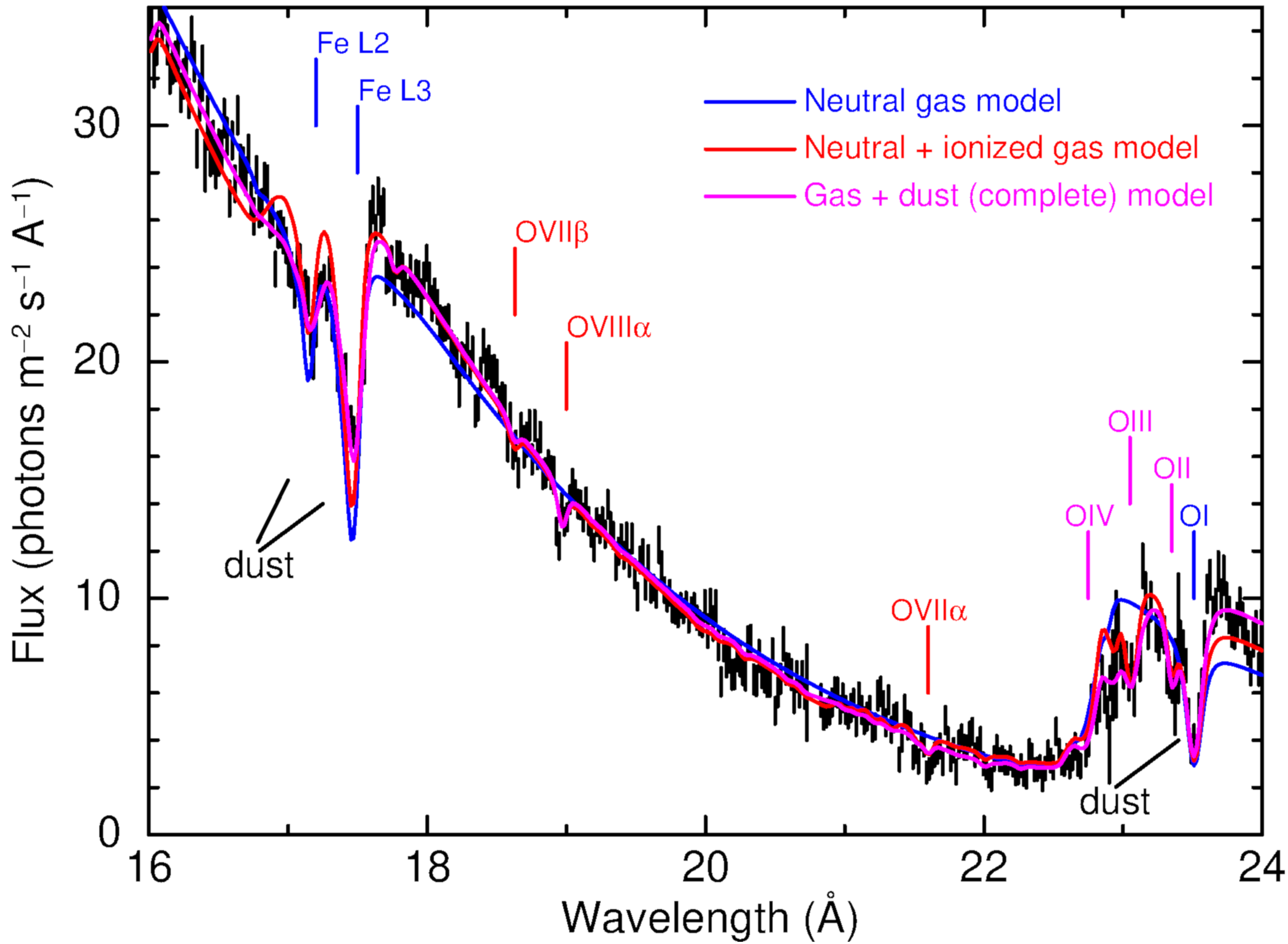


GS 1816-238 spectrum



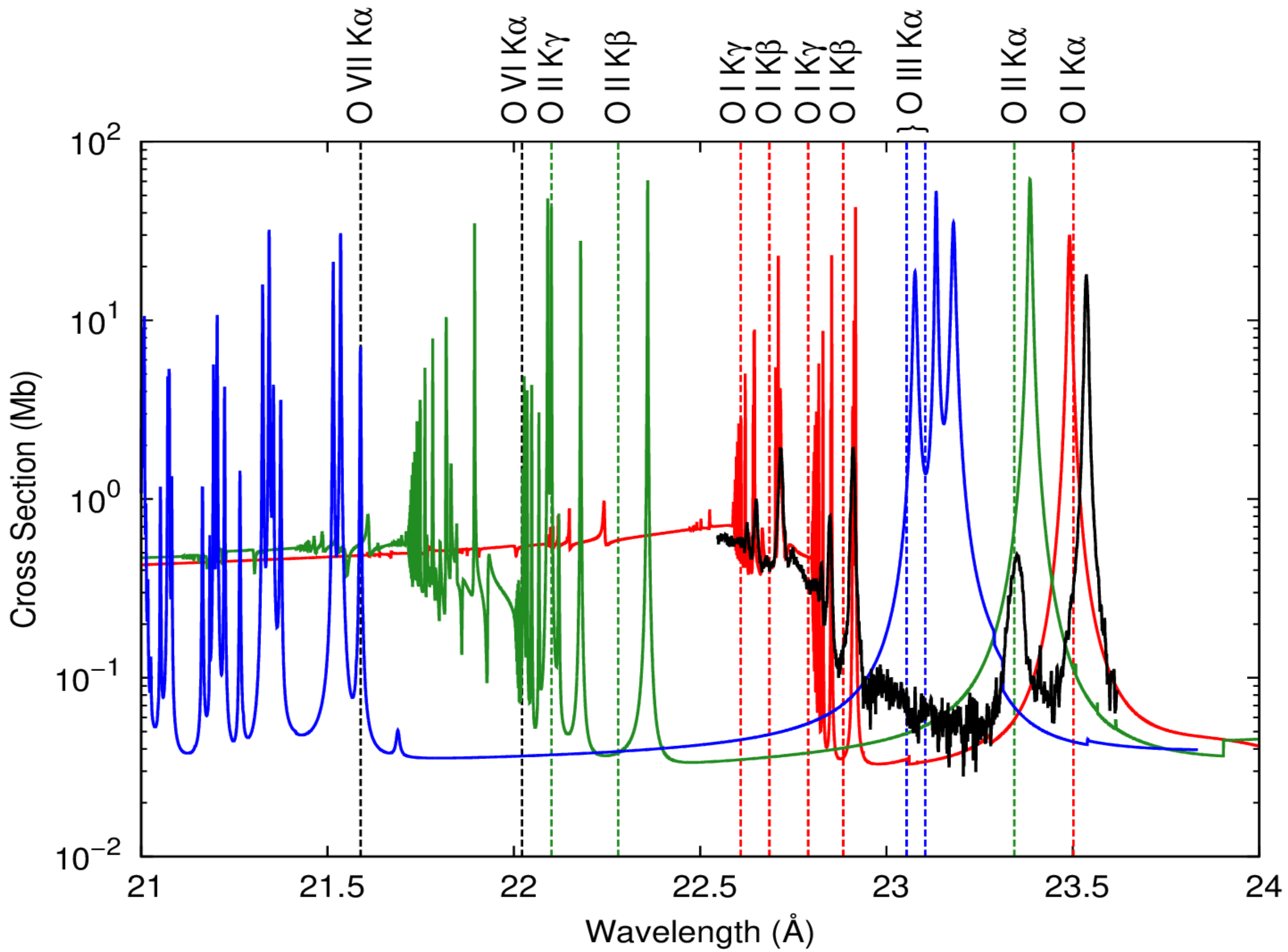
Pinto+10

GS 1816-238 spectrum



Pinto+13

Benchmarking of Atomic Data: Oxygen



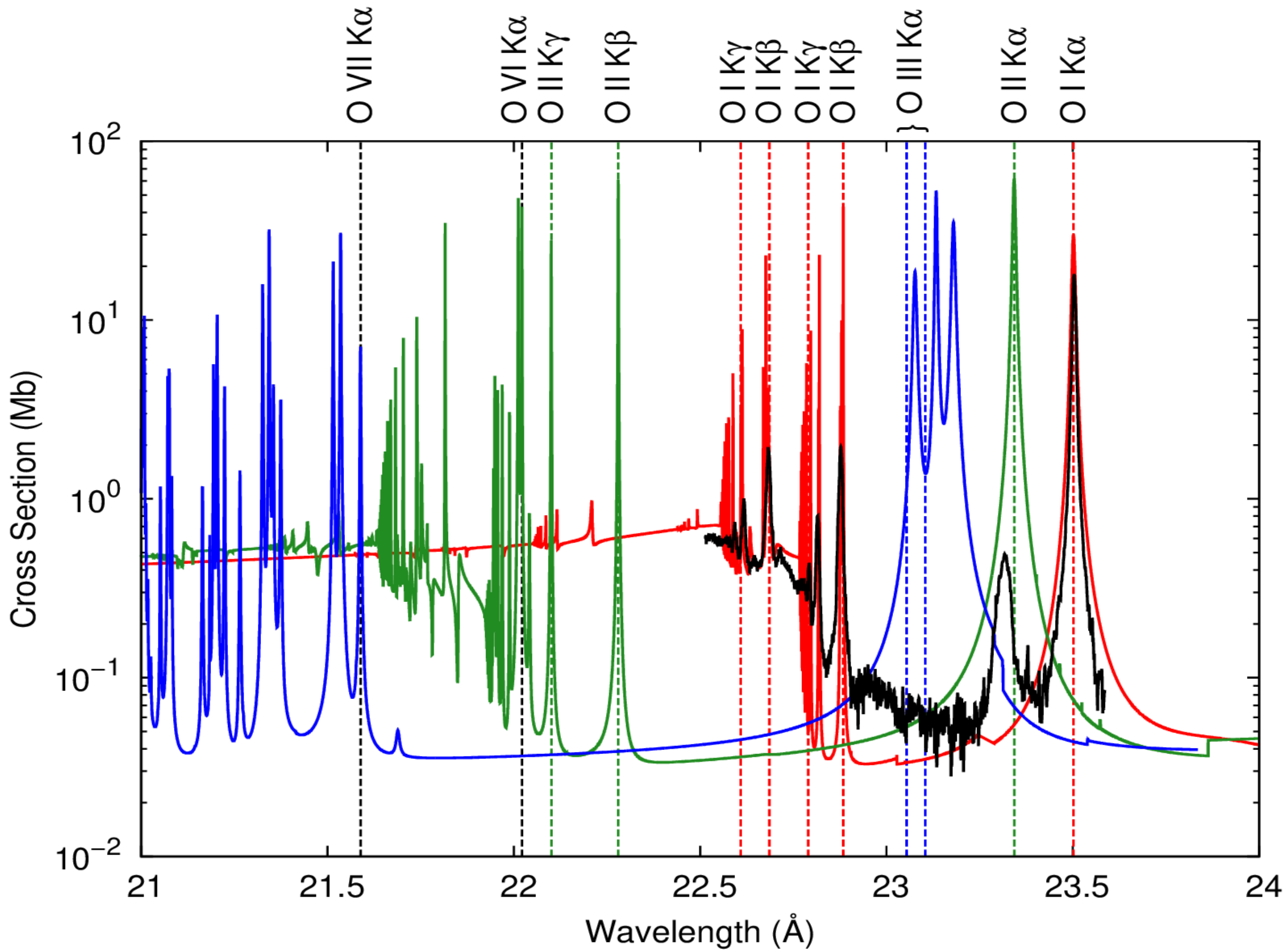
Gatuzz+13

Theoretical photoabsorption cross sections for **O I**, **O II** and **O III** computed by Garcia+05

Experimental photoabsorption cross section for **O I** measured by Stolte+97

O I shift: 29 mÅ
O II shift: 75 mÅ

Benchmarking of Atomic Data: Oxygen



Gatuzz+13

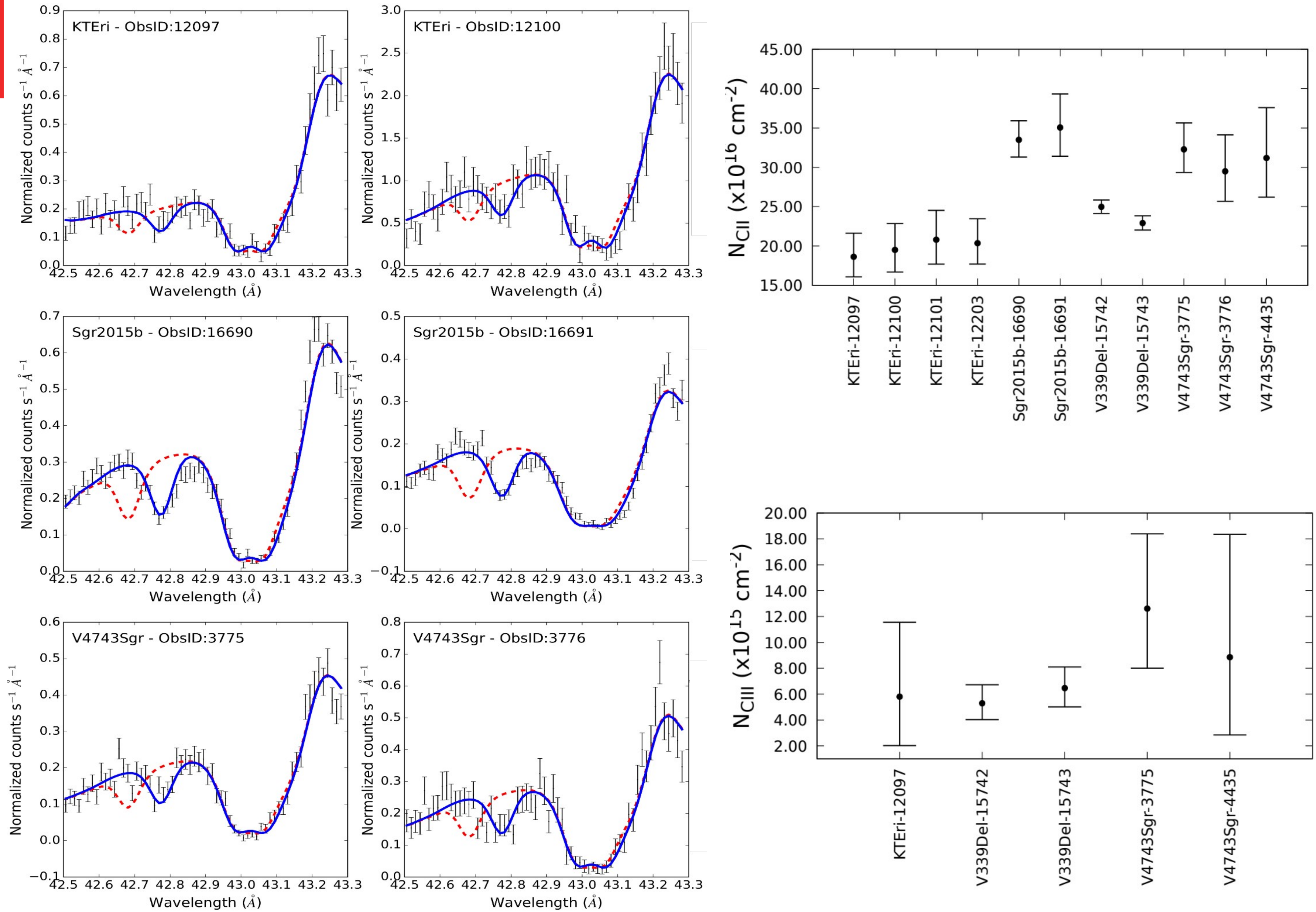
Theoretical photoabsorption cross sections for **O I**, **O II** and **O III** computed by Garcia+05

Experimental photoabsorption cross section for **O I** measured by Stolte+97

O I shift: 29 mÅ
O II shift: 75 mÅ

Lab measurement also needs to be shifted!
(Stolte+13,McLaughlin+13,Bizau+15)

X-raying the ISM: X-ray Novae



Gatuzz et al. (2018b)

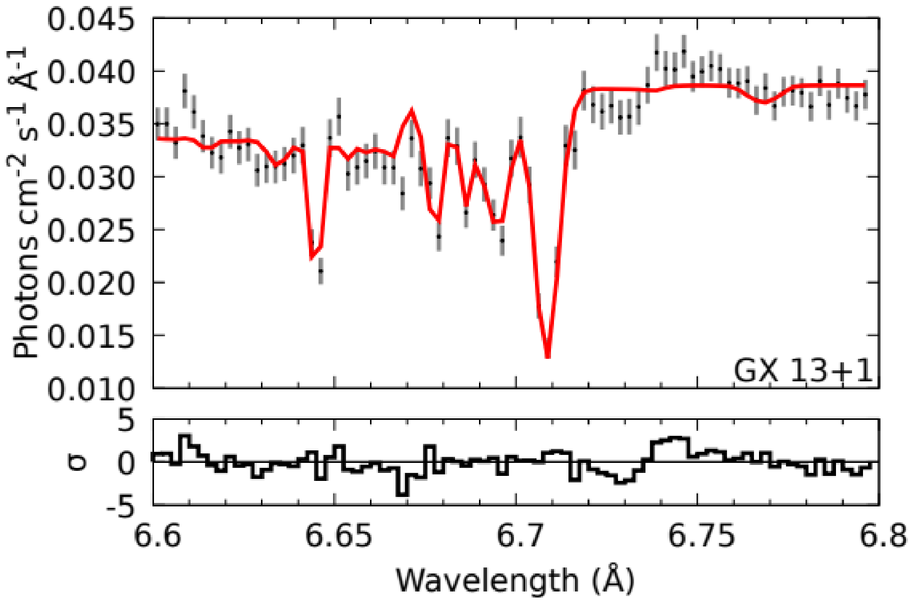
X-raying the ISM: the Si K-edge

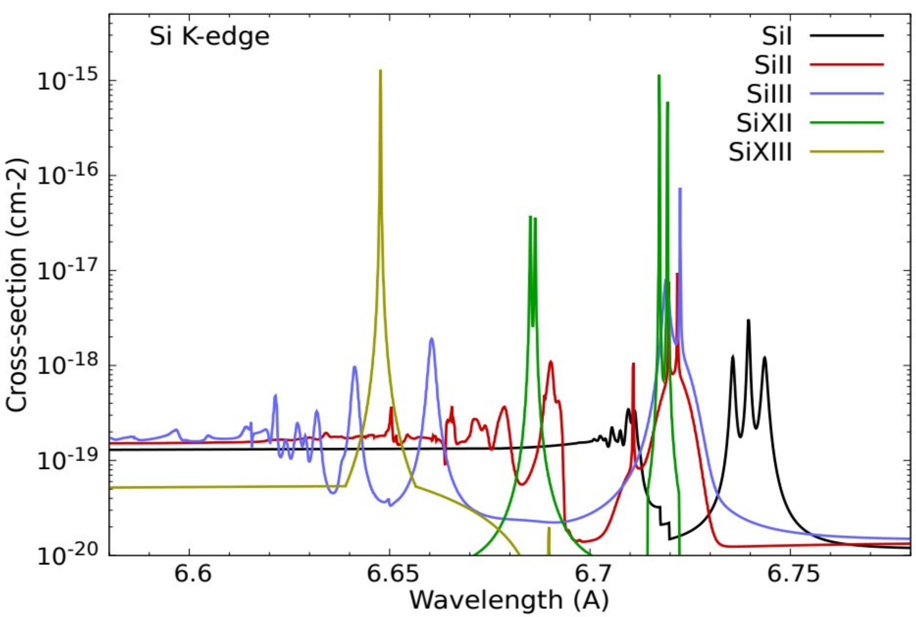
16 Chandra LMXBs analyzed

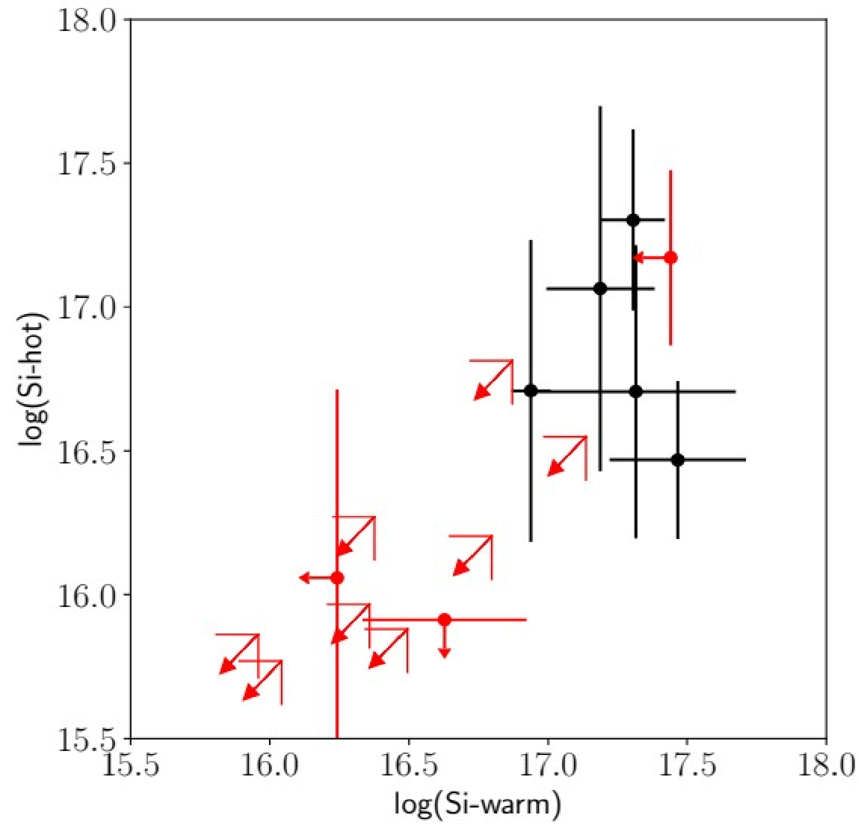
Si I from Gorczyca et al (2020)
Ionic species from Witthoeft et al. (2009)

Good agreeement between theoretical atomic data and X-ray observations.

We estimated ionic column densities corresponding to the cold (Si I), warm (Si II, Si III) and hot (Si XII, Si XIII) phases of the gaseous ISM







Gatuzz et al. (2020b)

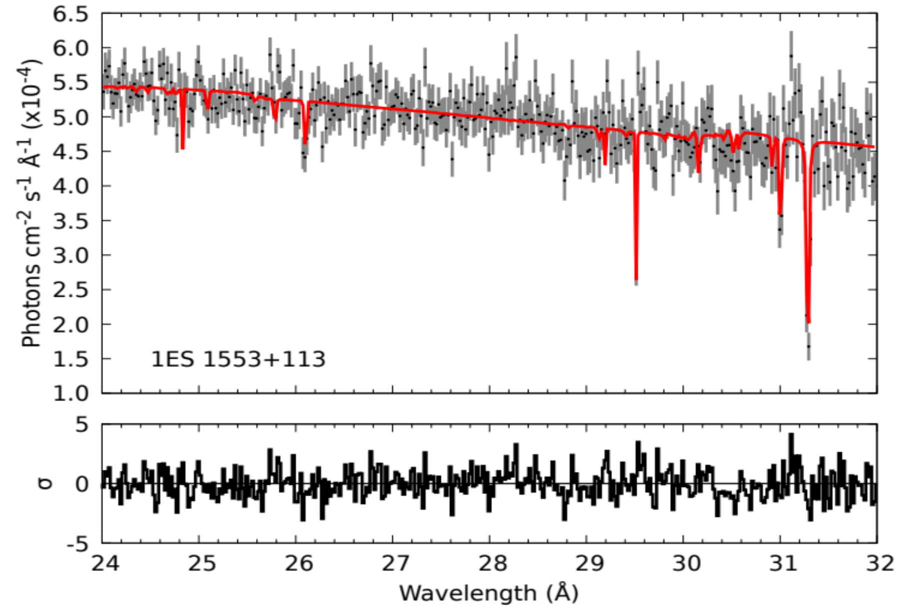
X-raying the ISM: the N K-edge

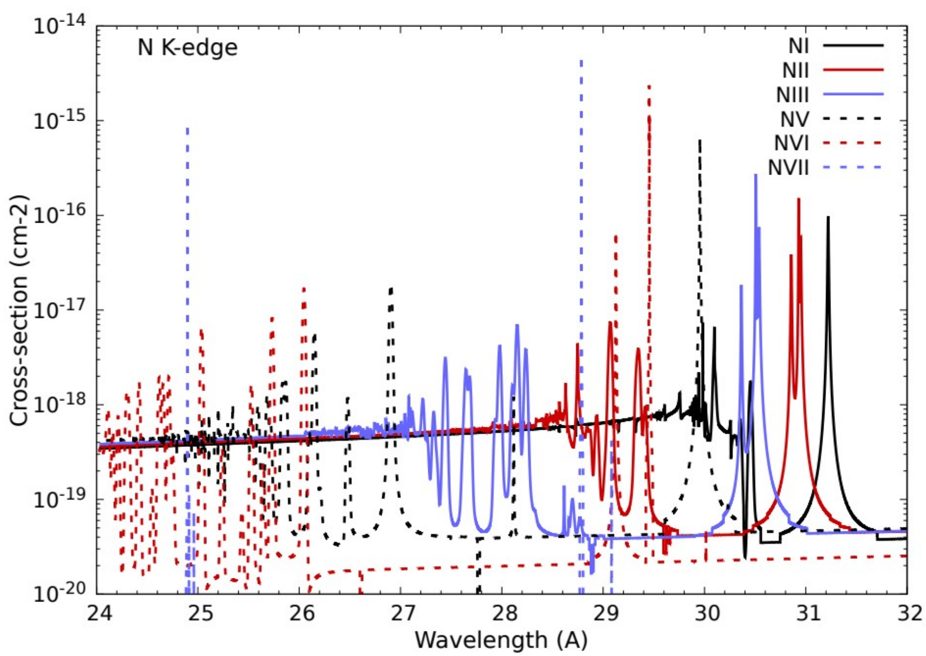
XMM-Newton data sample:
12 LMXBs
40 extragalactic sources

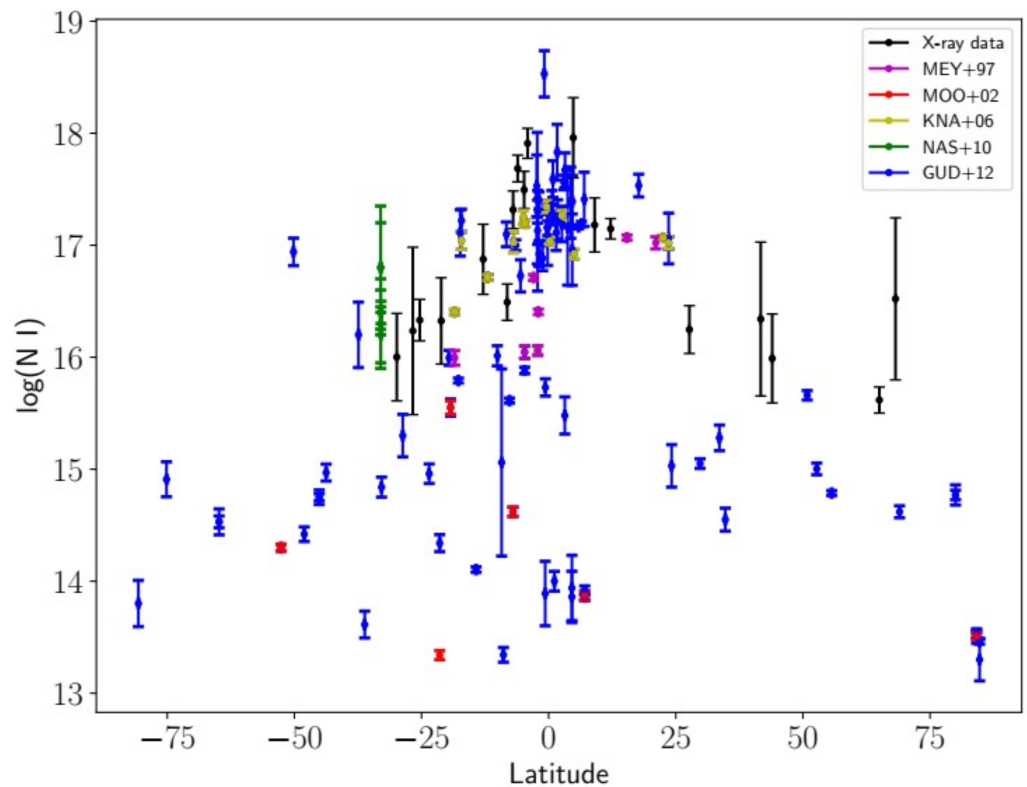
Atomic data from García et al (2009)

<u>Results:</u> column densities for cold (N I), Warm (N II, N III), hot (N V, NVI, NVII) phases of the ISM

Good agreement with UV observations for the cold component!







Gatuzz et al. (2020c)

X-ray absorption models

Model name (xspec)	**Reference**	**Parameters**
wabs	Morrison & McCammon (1983)	N_h,z
phabs	Arnaud et al. (1996)	N_h,z, Z_i
Tbabs *(tbnew, tbgrain, etc.)*	Wilms et al. (2000)	N_h, z, Z_i Grain density and size
ISMabs	Gatuzz et al. (2015)	N_h, N_i (for single and double ionized species)
IGMabs	Gatuzz et al. (2018)	N_i (highly ionized species)
IONeq	Gatuzz & Churazov (2018)	N_h, T, Z_i, v, z

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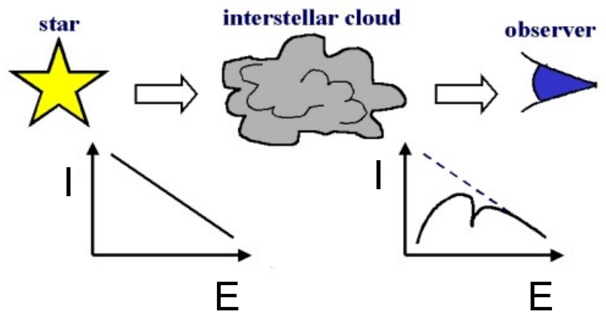

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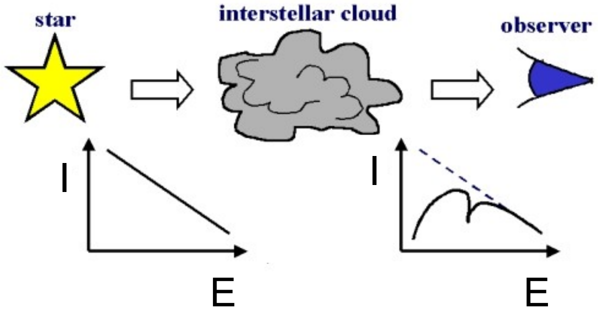

$$I_{obs}(E) = e^{-\sigma_{ISM}(E)\, N_H} I_{source}(E)$$

$$\sigma_{ISM} = \sigma_{gas} + \sigma_{molecules} + \sigma_{grains}$$

X-ray absorption models

Model name (xspec)	Reference	Parameters
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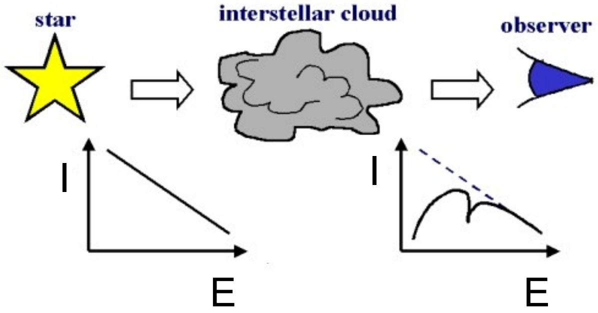

$$I_{obs}(E) = e^{-\sigma_{ISM}(E) N_H} I_{source}(E)$$

$$\sigma_{ISM} = \sigma_{gas} + \sigma_{molecules} + \sigma_{grains}$$

$$\sigma_{gas} = \sum_{Z,i} A_z \xi_{Z,i} (1 - \beta_{Z,i}) \sigma_{Z,i}(E)$$

$$\sigma_{molecules} = A_{H_2} \sigma_{bf}(H_2)$$

$$\sigma_{grains} = \xi_g \int_0^\infty \frac{d\eta_{gr}(a)}{da} \sigma_{geom} \times (1 - \exp(-\langle\sigma\rangle\langle N\rangle)) \, da$$

X-ray absorption models

Model name (xspec)	Reference	Parameters
Tbabs (tbnew, tbgrain, etc.)	Wilms et al. (2000)	N_h, z, Z_i Grain density and size (only neutral gas)
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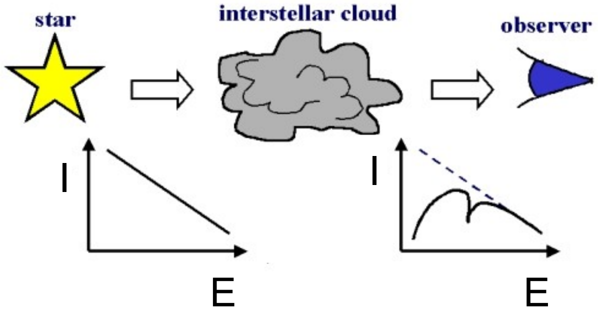

$$I_{obs}(E) = e^{-\sigma_{ISM}(E)\,N_H}\, I_{source}(E)$$

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

Tbabs

$$\sigma_{gas} = \sum_{Z,\,i} A_Z\, \xi_{Z,\,i}\,(1-\beta_{Z,\,i})\,\sigma_{Z,\,i}(E)$$

ISMabs (IGMabs)

$$\sigma_{gas}\, N_H = \sum_i \sigma_i(E)\, N_i$$

X-ray absorption models

Model name (xspec)	Reference	Parameters
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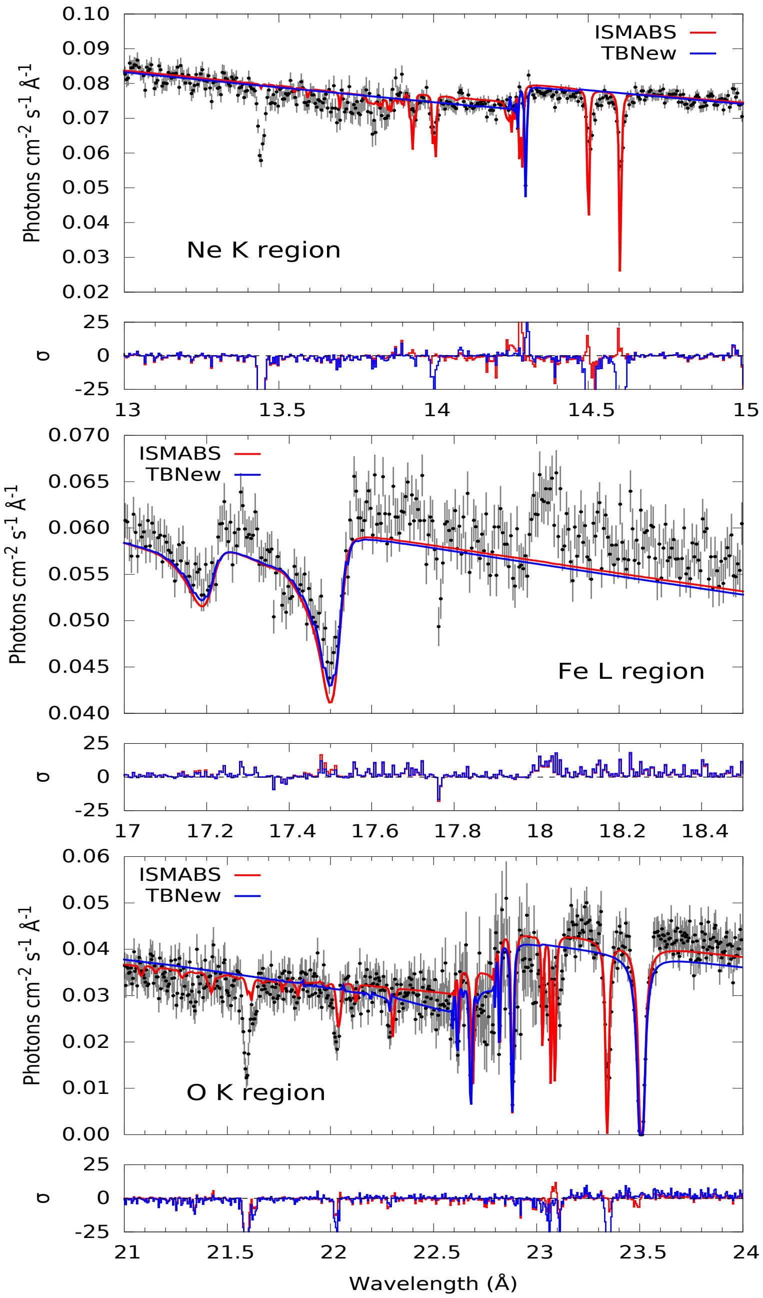

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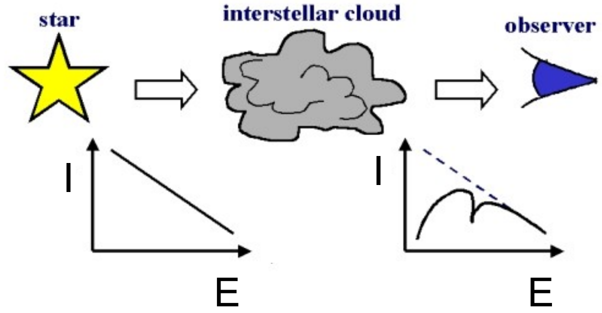


$$I_{obs}(E) = e^{-\sigma_{ISM}(E) N_H} I_{source}(E)$$

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

IONeq

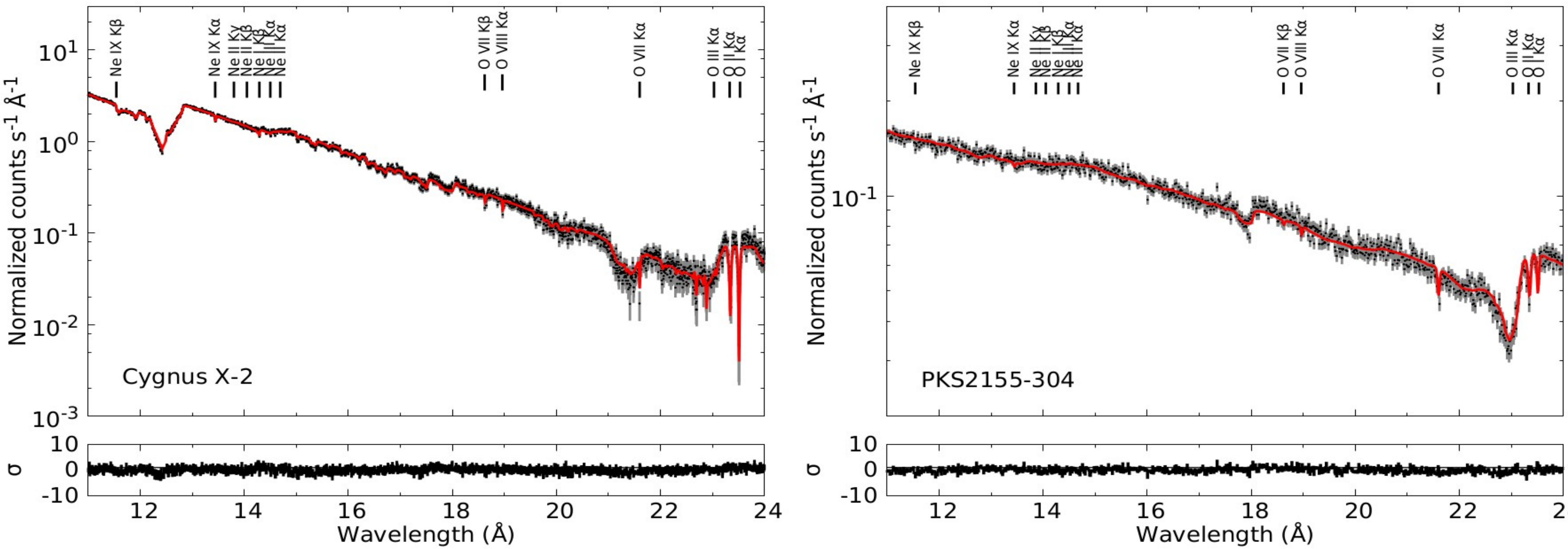
$$\sigma_{gas} = \sum_{Z,i} A_z \xi_{Z,i} \sigma_{Z,i}(E)$$

$$\xi_{Z,i} = \frac{\eta_{Z,i}}{\sum_{Z,i} \eta_{Z,i}}$$

$$0 = \sum_{i' \neq i} \eta_{Z,i'} R_{Z,i' \to i} - \eta_{Z,i} \sum_{i' \neq i} R_{Z,i \to i'}$$

The physical processes included in the creation and destruction rates are: photoionization, auger ionization, direct collisional ionization, radiative recombination and dielectronic recombination

Ionization Equilibrium model (IONeq)



COLD COMPONENT (Te ~ 10000 K): O I, Ne I, Fe I, Metallic Fe

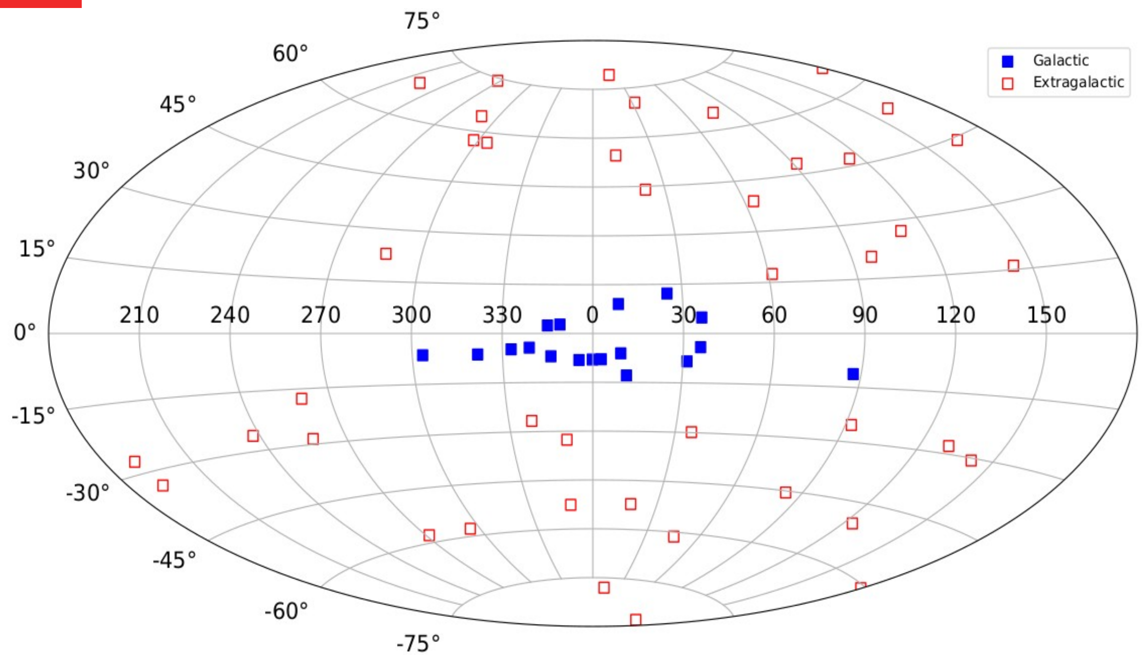
WARM COMPONENT (Te ~ 51000 K): O II, O III, Ne II, Ne III

HOT COMPONENT (Te ~ 1.9 MK): Ne IX, O VII, O VIII

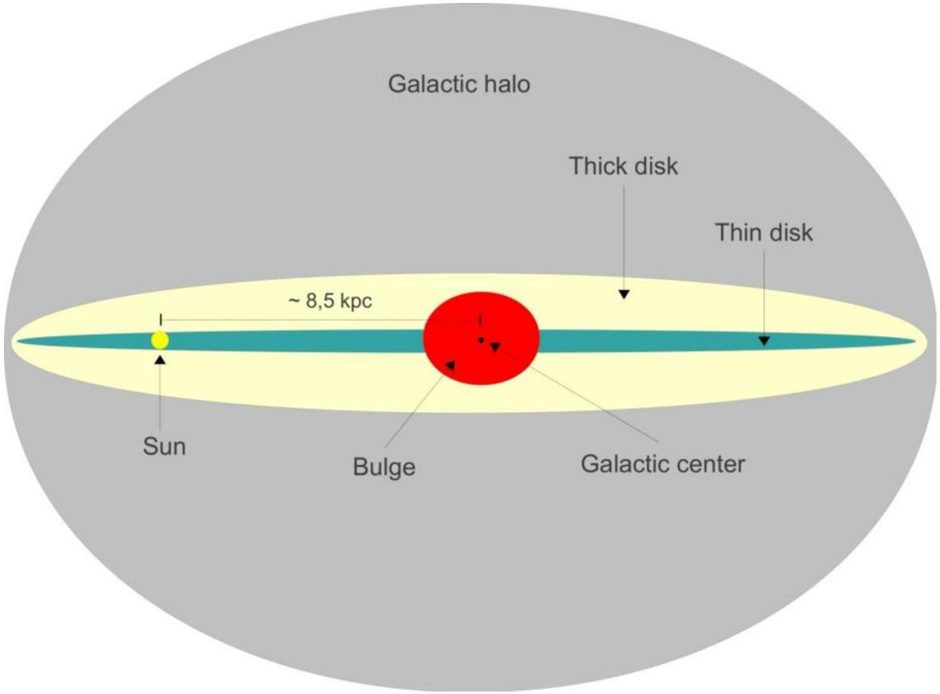
Gatuzz & Churazov (2018)

https://github.com/efraingatuzz

X-raying the ISM: cold, neutral and hot gas



Galactic: 18 Extragalactic: 42
165 observations from Chandra
257 observations from XMM-Newton



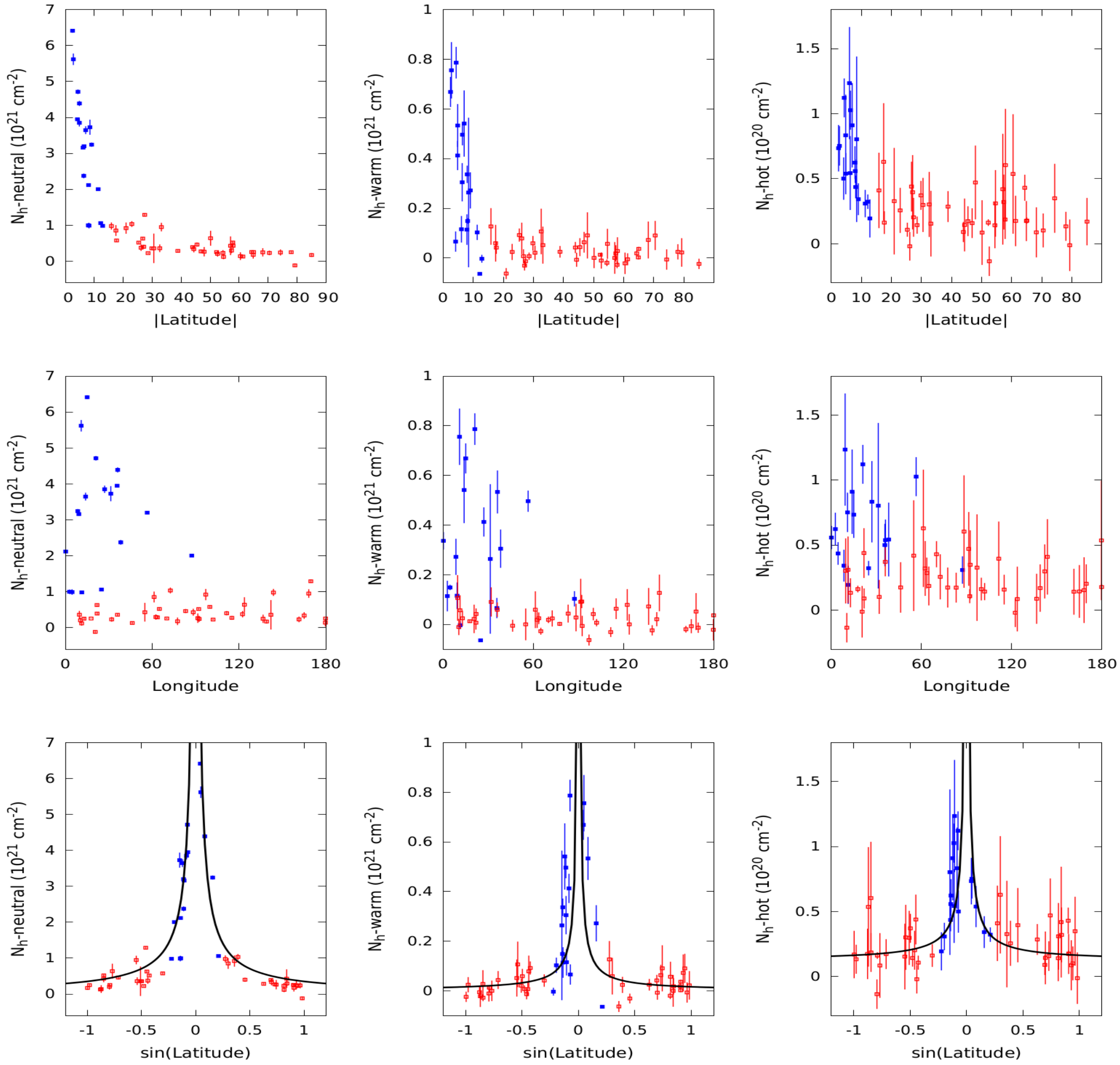
Galactic Sources → LMXB
Extragalactic Sources → Blazars

> 1000 counts in the 21-24 A wavelength region

We did not impose additional constrains! (e.g. O VII Ka detection)

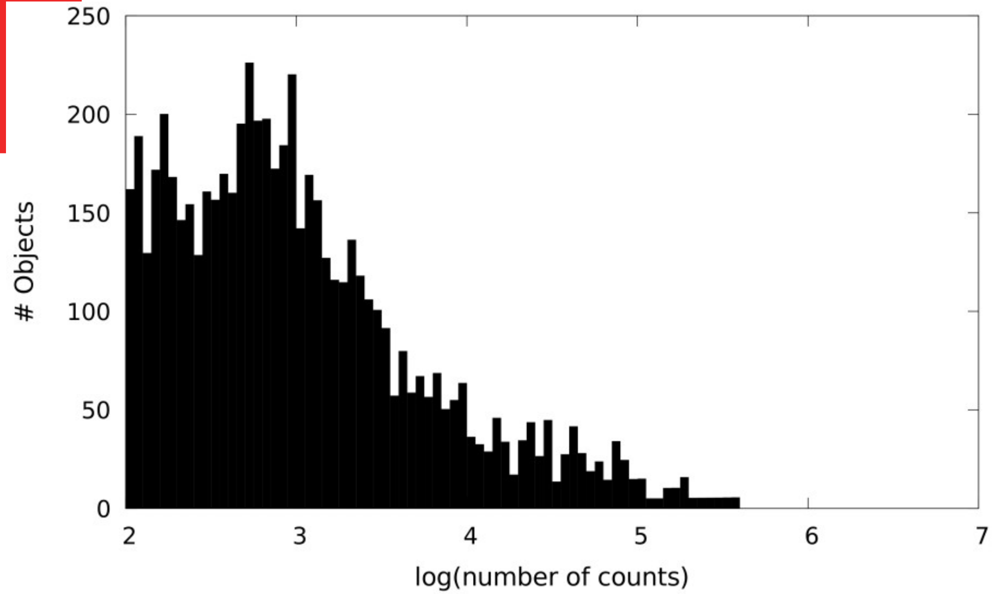
Gatuzz & Churazov (2018)

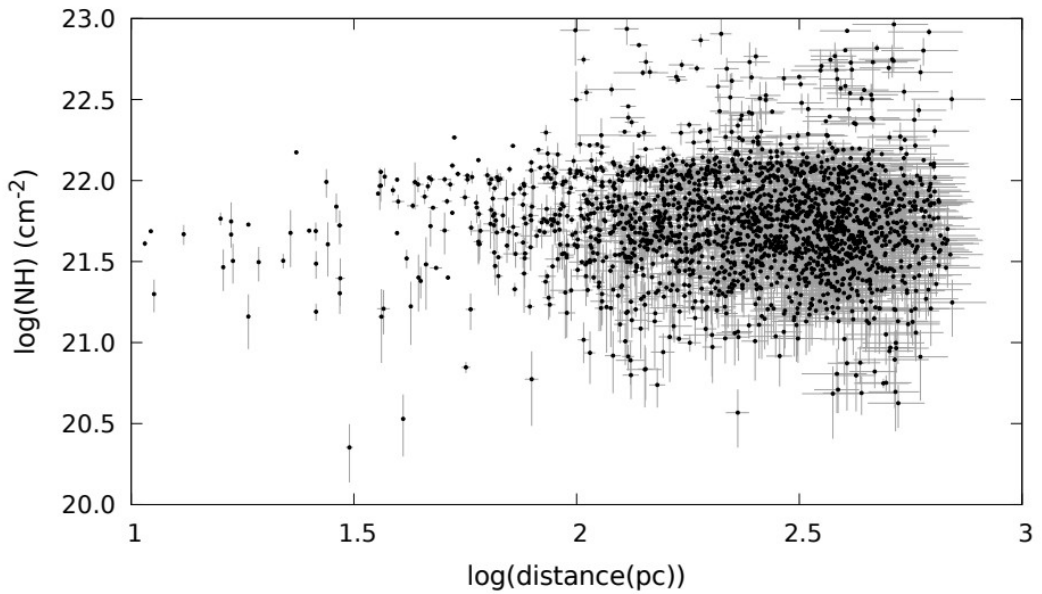
X-raying the ISM: cold, neutral and hot gas

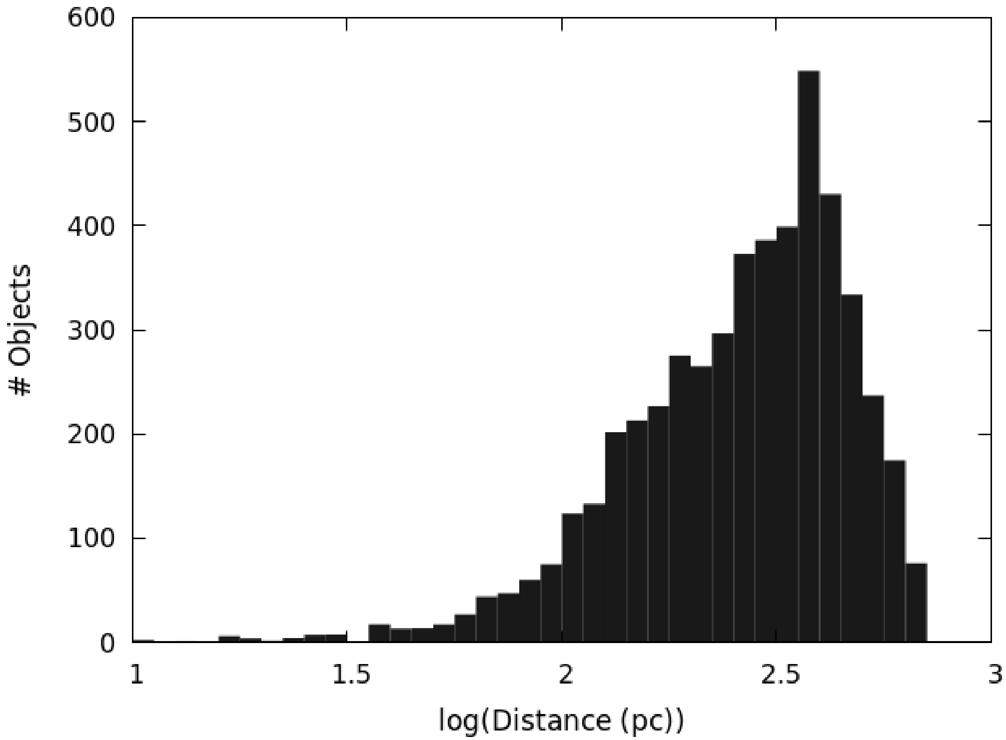


Gatuzz & Churazov (2018)

X-raying the ISM: synergy with GAIA DR1







Spectral fits and classification obtained from *Exploring the X-ray Transient and Variable Sky* (ExTRAS)

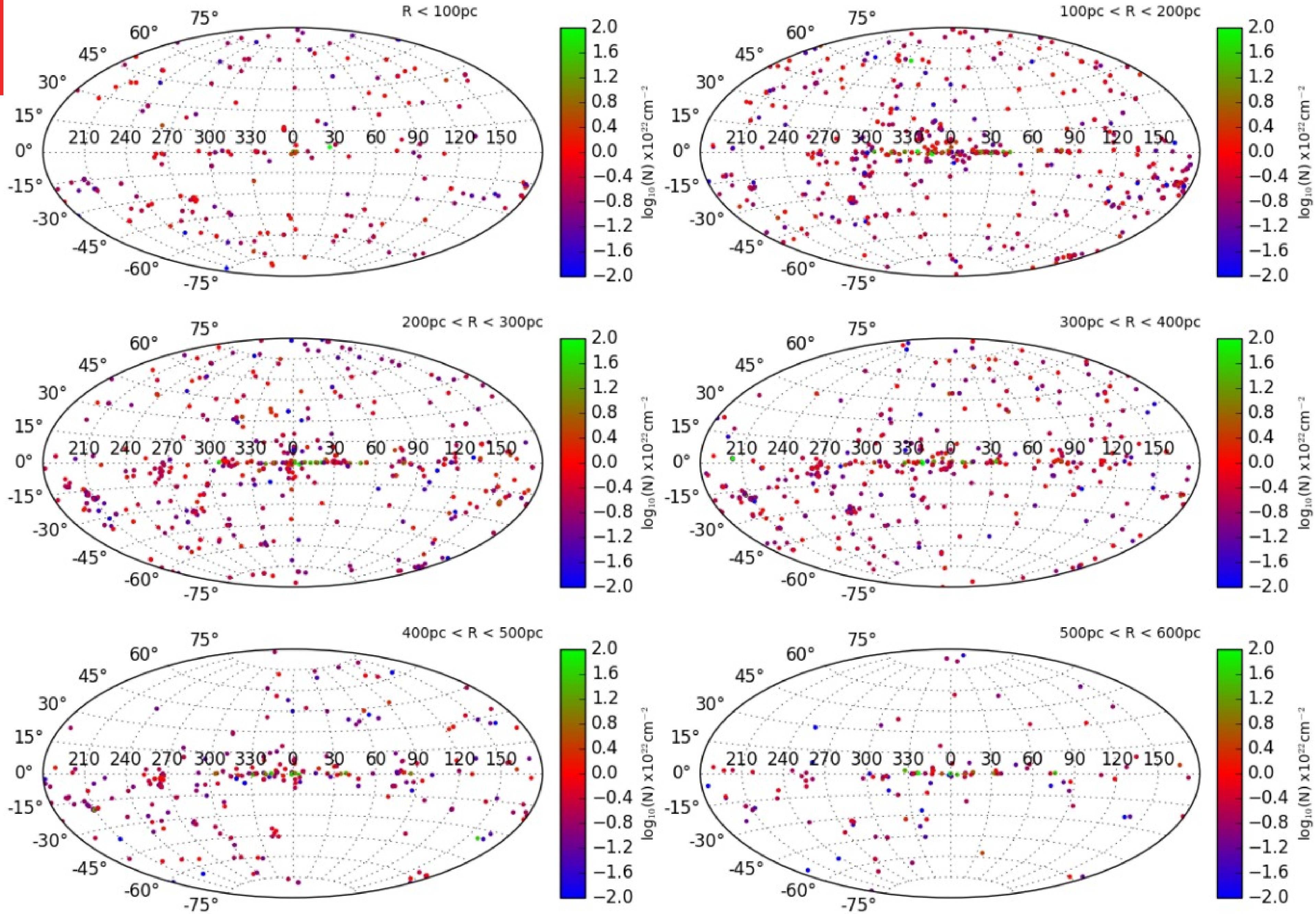
Six phenomenological models:
- tbabs*pow
- tbabs*bbody
- tbabs*apec
- tbabs*(apec+tbabs2*pow)
- tbabs*(pow+tbabs2*pow)
- tbabs*(bbody+tbabs2*pow)

Nh from best fit model

<u>Final sample:</u> 2800 sources

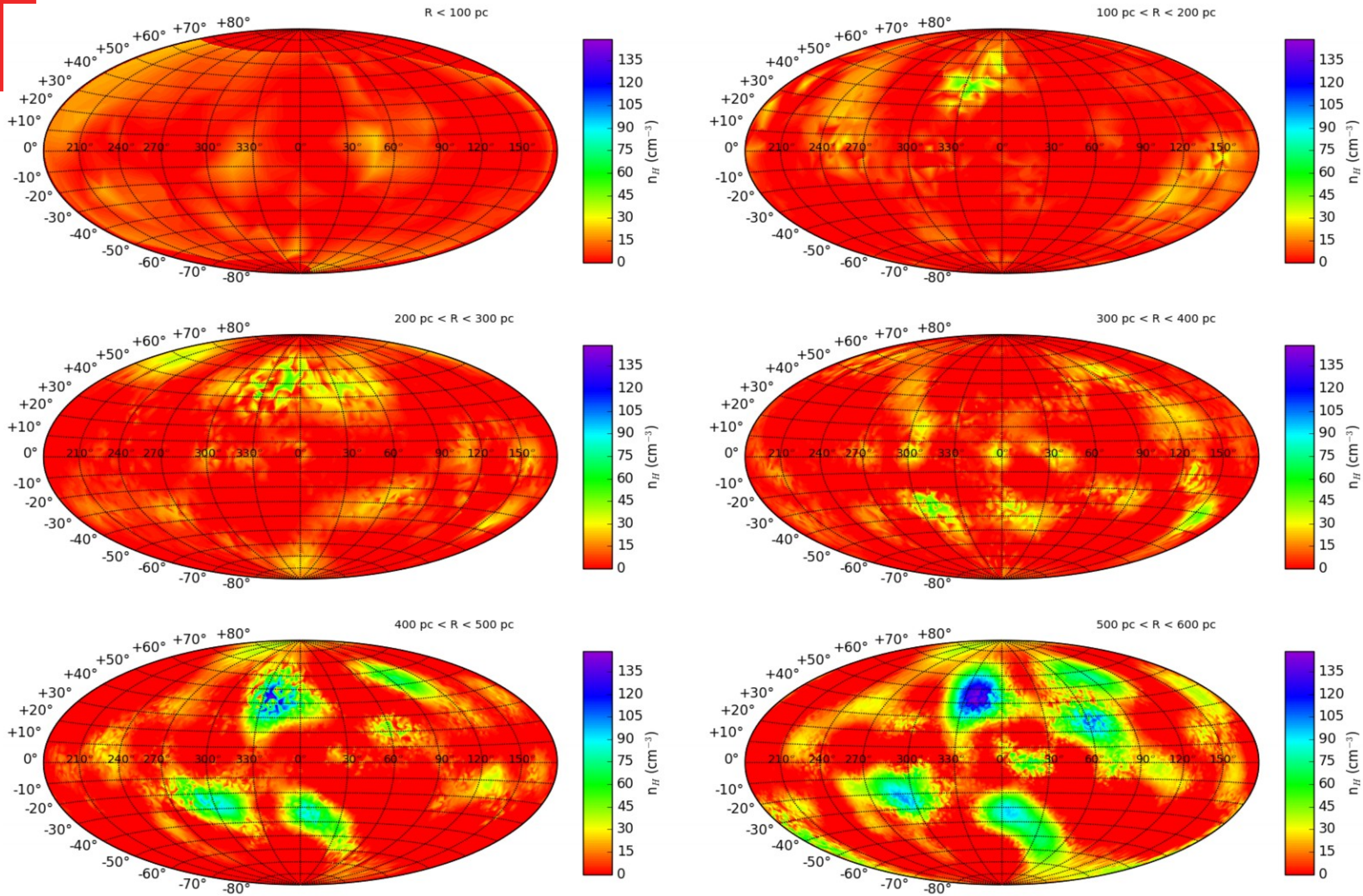
Gatuzz et al. (2018c)

X-raying the ISM: synergy with GAIA DR1



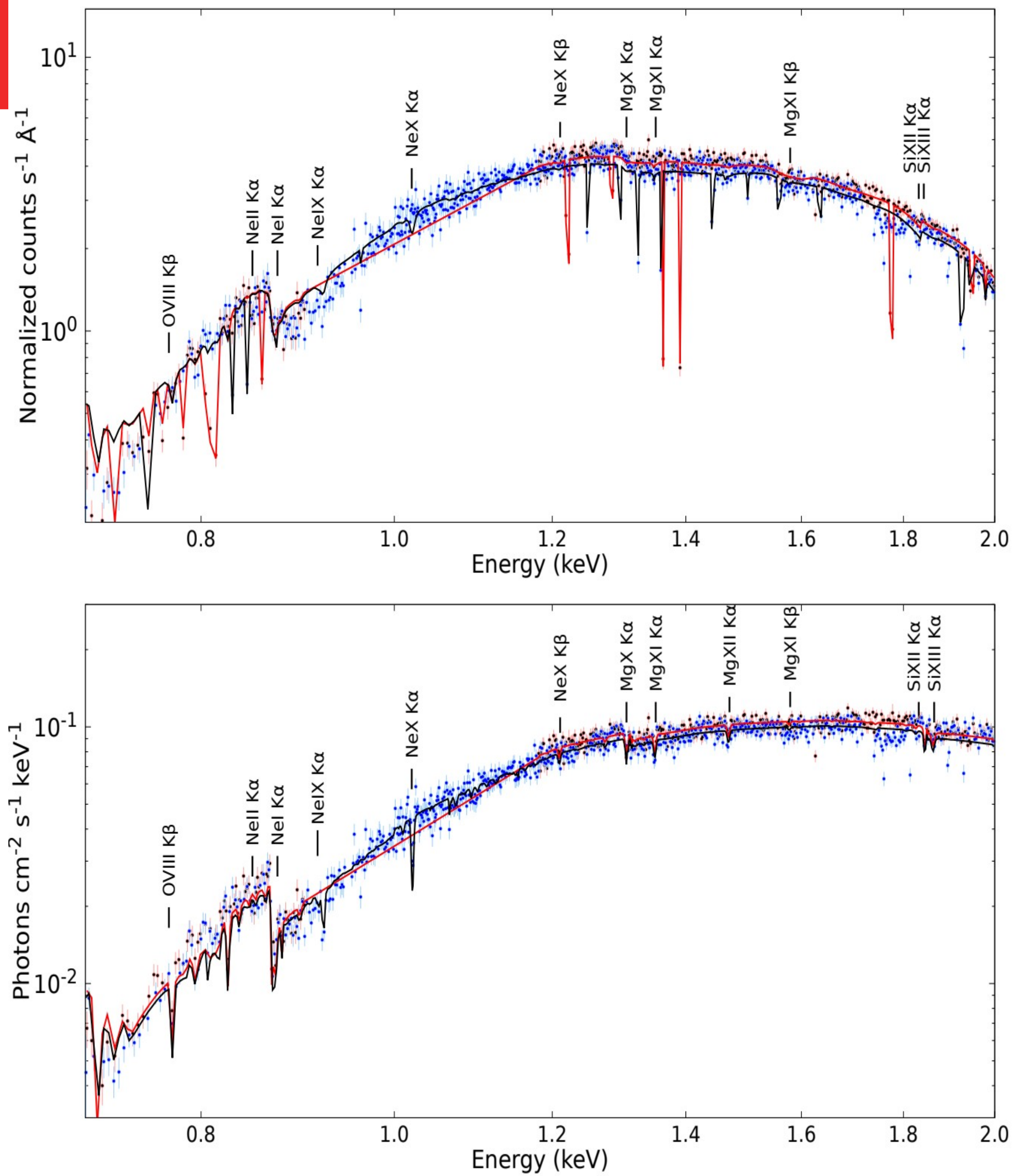
Gatuzz et al. (2018c)

X-raying the ISM: synergy with GAIA DR1



Gatuzz et al. (2018c)

X-ray absorption features: ISM or LMXB origin?



The LMXB *IGRJ17091-3624* analyzed

The model:

Two flavours for the continuum:
powerlaw+diskbb
nthcomp+diskbb

Cold-Warm-Hot ISM:
IONeq

Photoionized absorber:
Warmabs

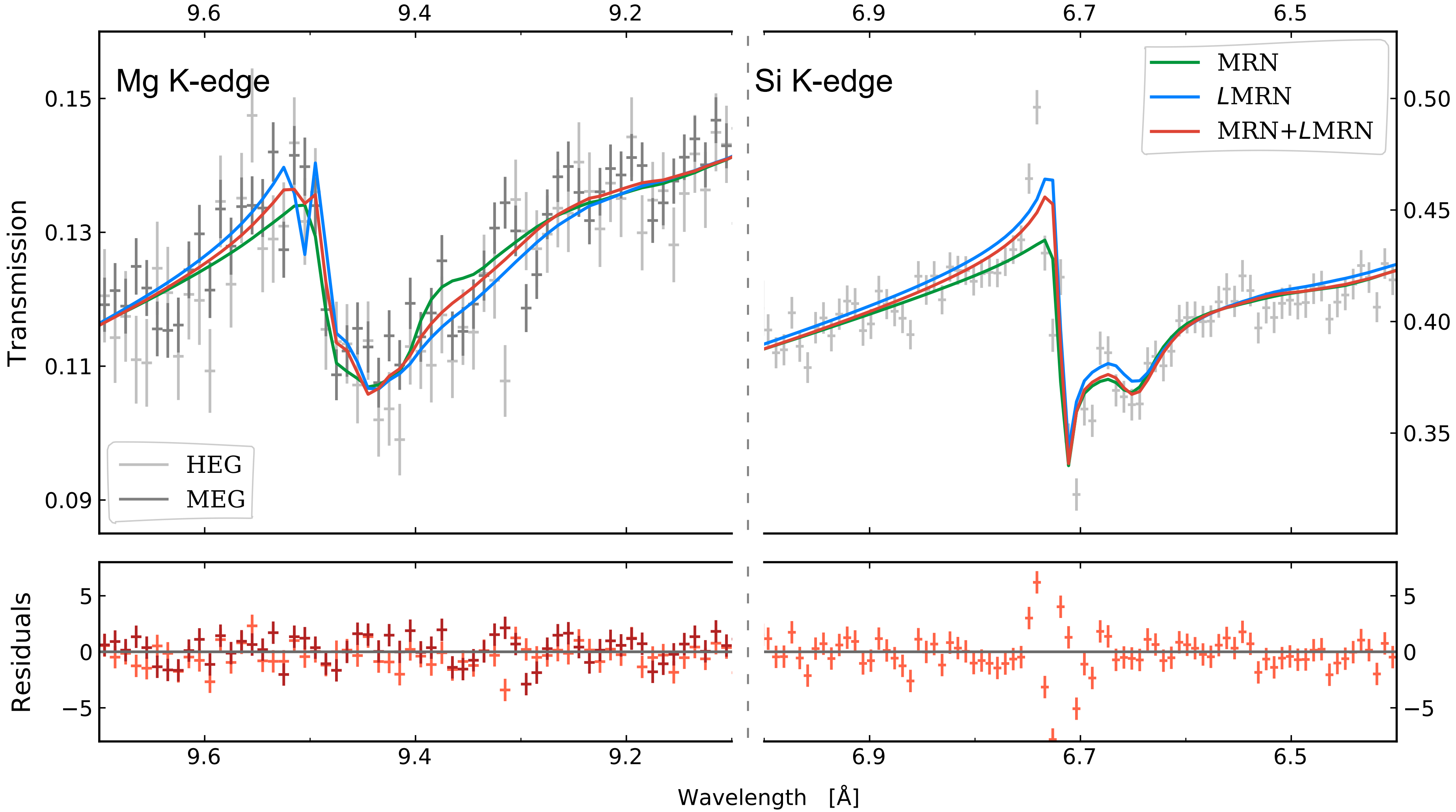
We were able to distinguish hot gas from two sources:

The ISM
(e.g. Ne VIII, NeIX, Mg X)

The LXMB
(e.g. NeX, MgXII, Si XIII, Fe XIX)

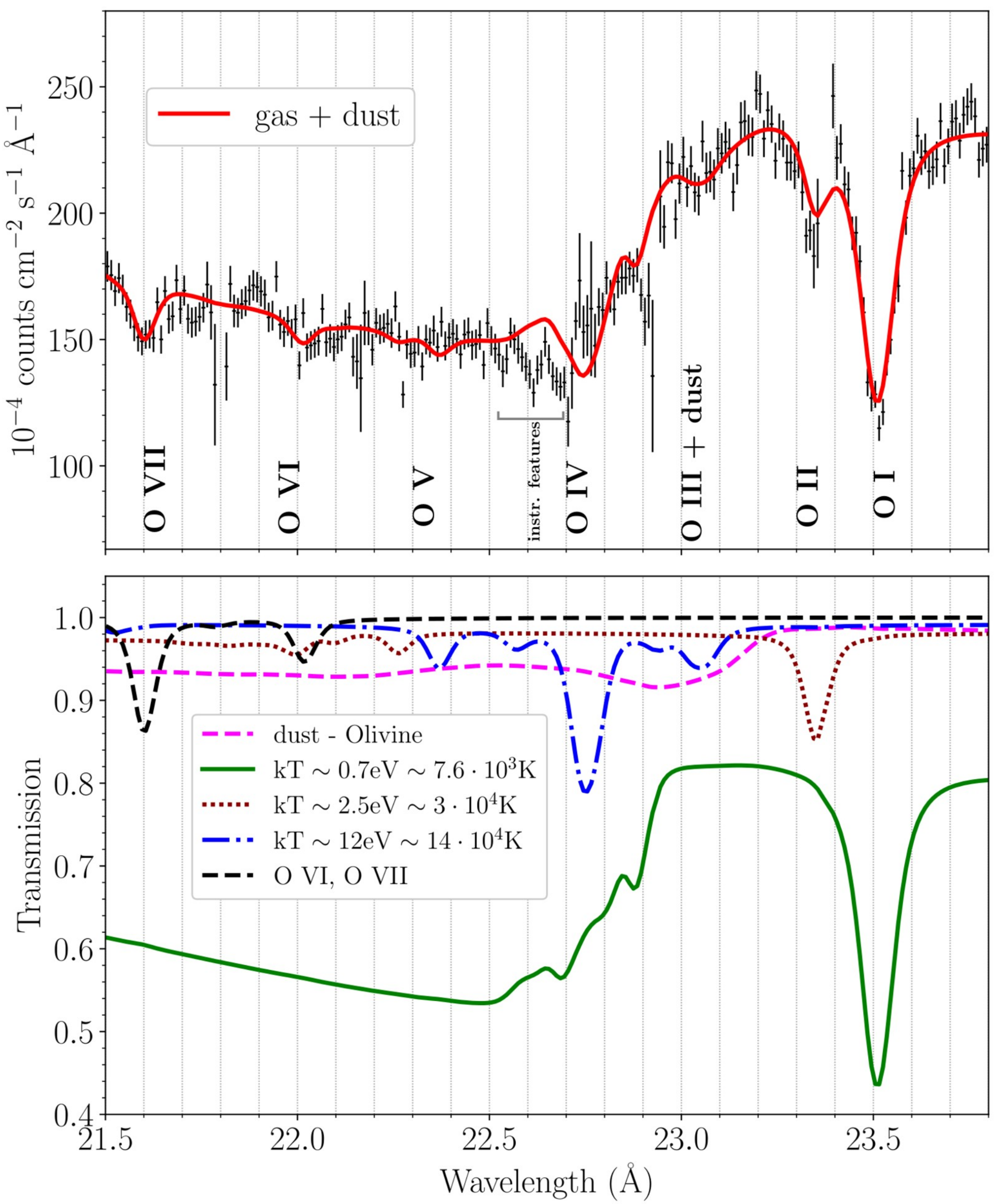
Gatuzz et al. (2020a)

X-ray ISM absorption: dust component

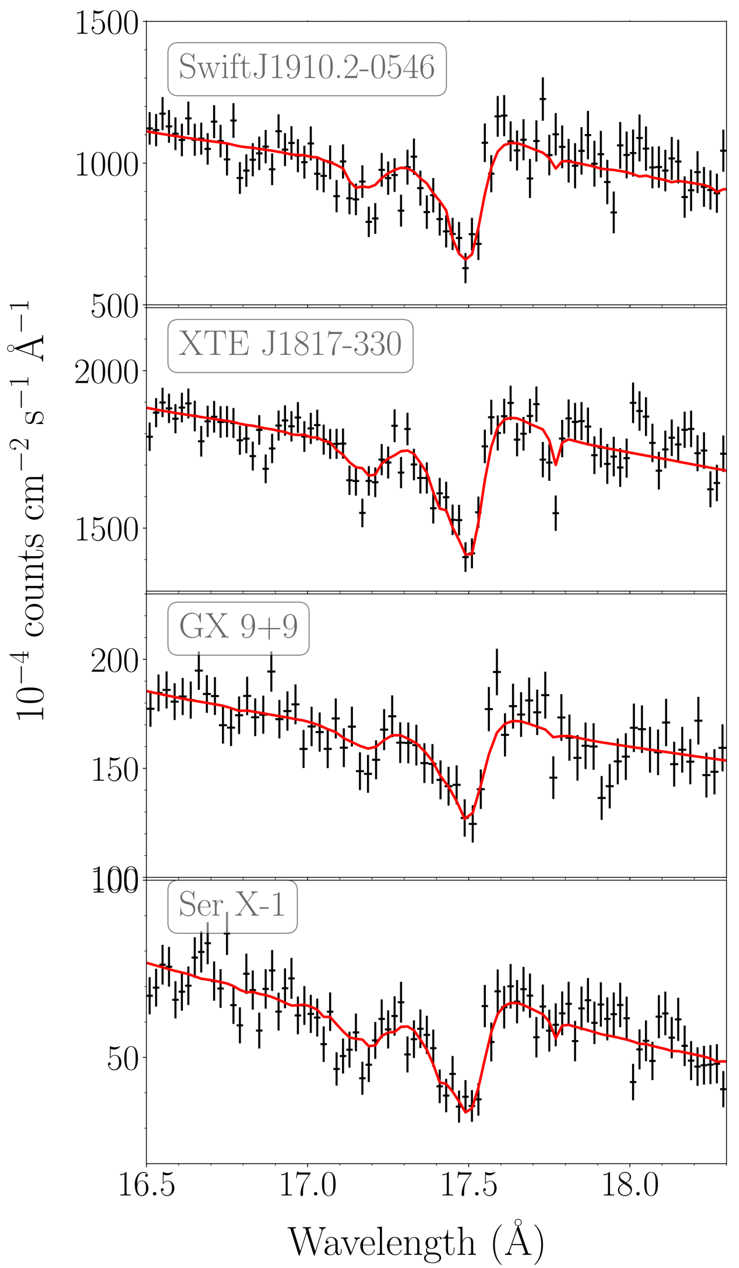


Rogantini et al. (2019)

X-ray ISM absorption: dust component



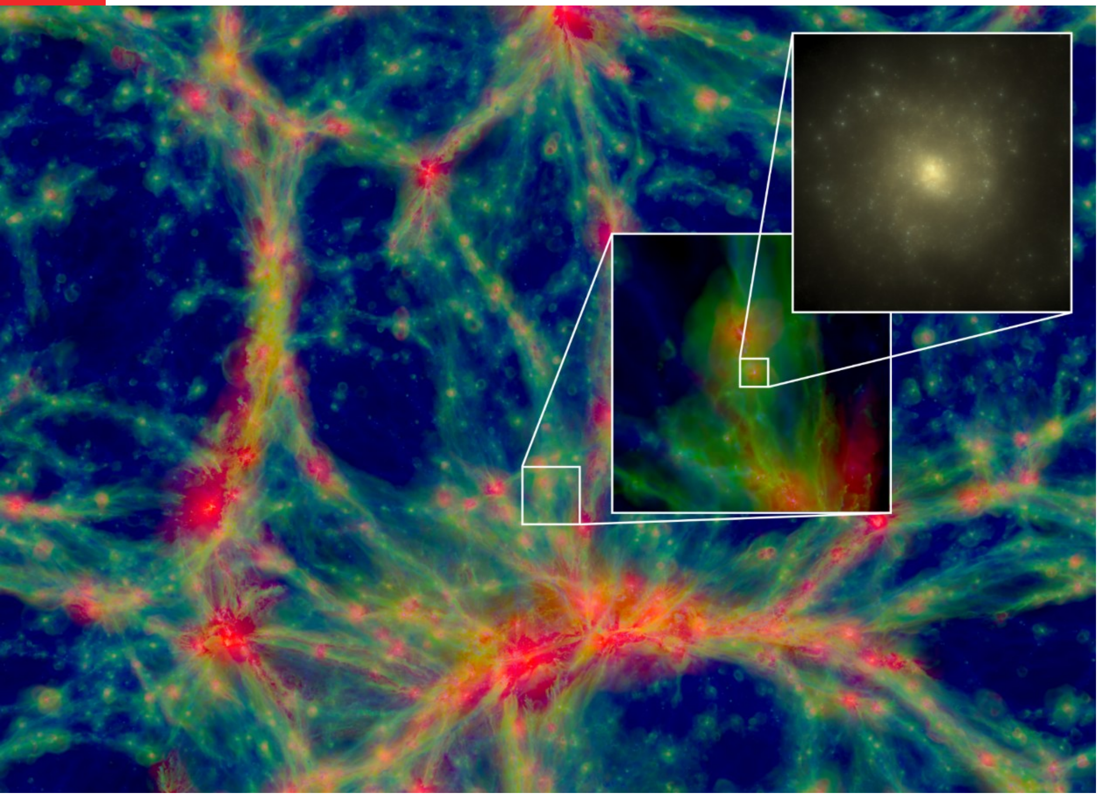
Psaradaki et al. (2022a)



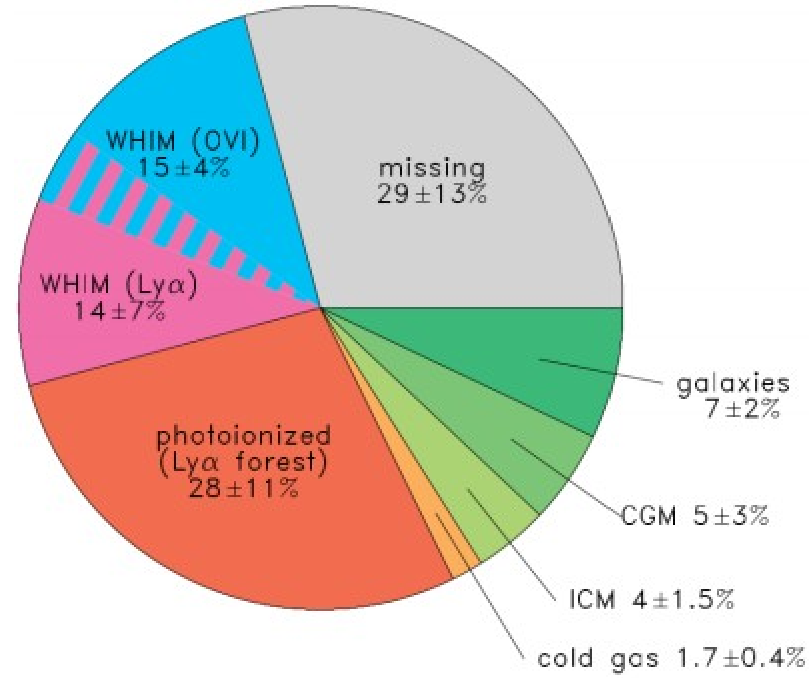
Psaradaki et al. (2022b)

WARNING!

The warm-hot intergalactic medium (WHIM)

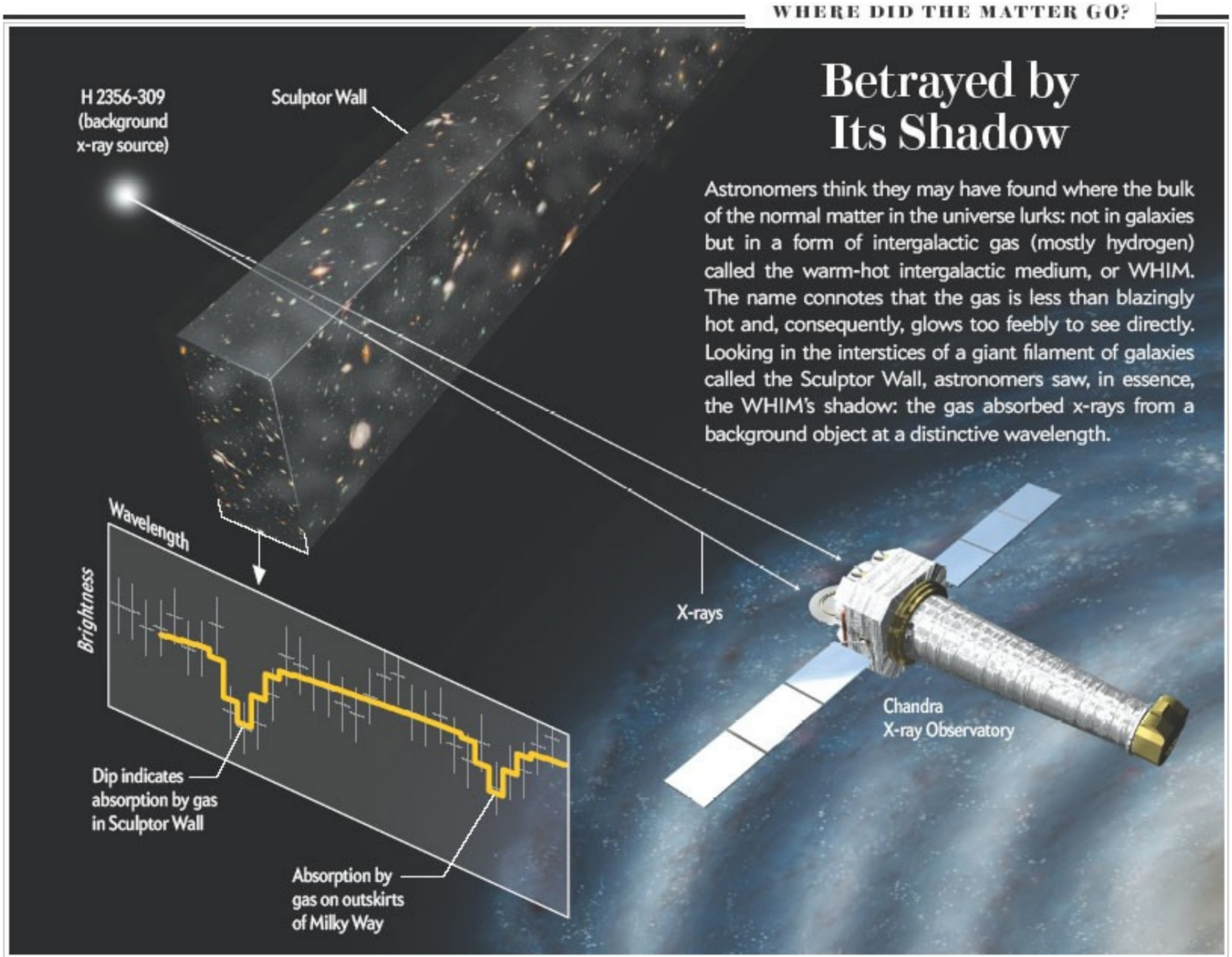


Schaye et al. (2015)



Shull et al. (2012)

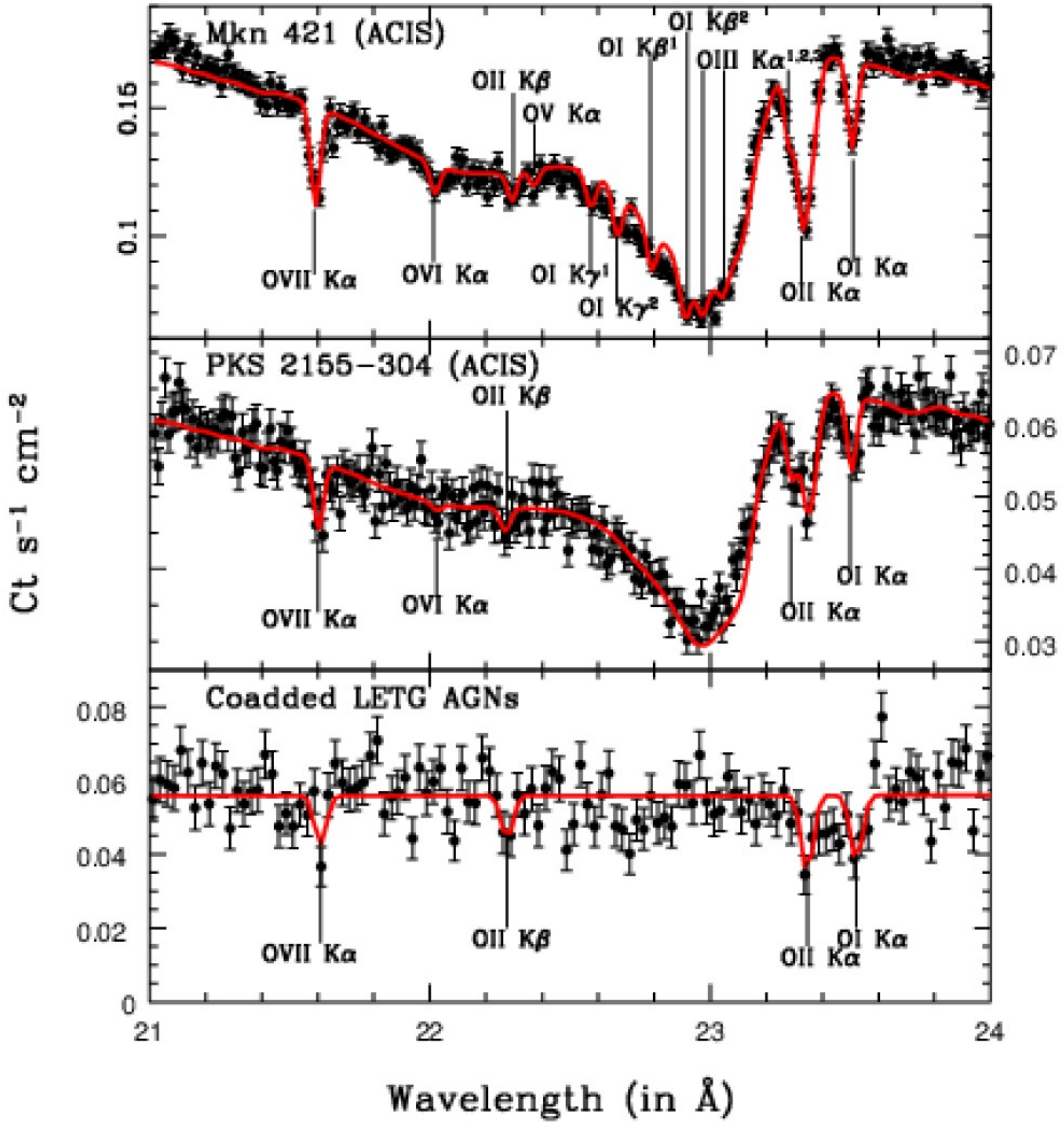
Phase	Temp. (K)	Tracers	Wavelength
Warm	10^{5} - $10^{5.7}$	O VI, C V	Far UV, soft X-rays
Warm-hot	$10^{5.7}$ - $10^{6.3}$	O VII	Soft X-rays
Hot	$10^{6.3}$ - 10^{7}	H-like metals	Soft/Hard X-rays



Buote+09, Fang+10, Zappacosta+10, Fang+11, Zappacosta+12

The local ISM is important!

O VII Ka at z≃0.03 from WHIM (Buote et al. 2009, Fang et al. 2010, Ren et al. 2014)

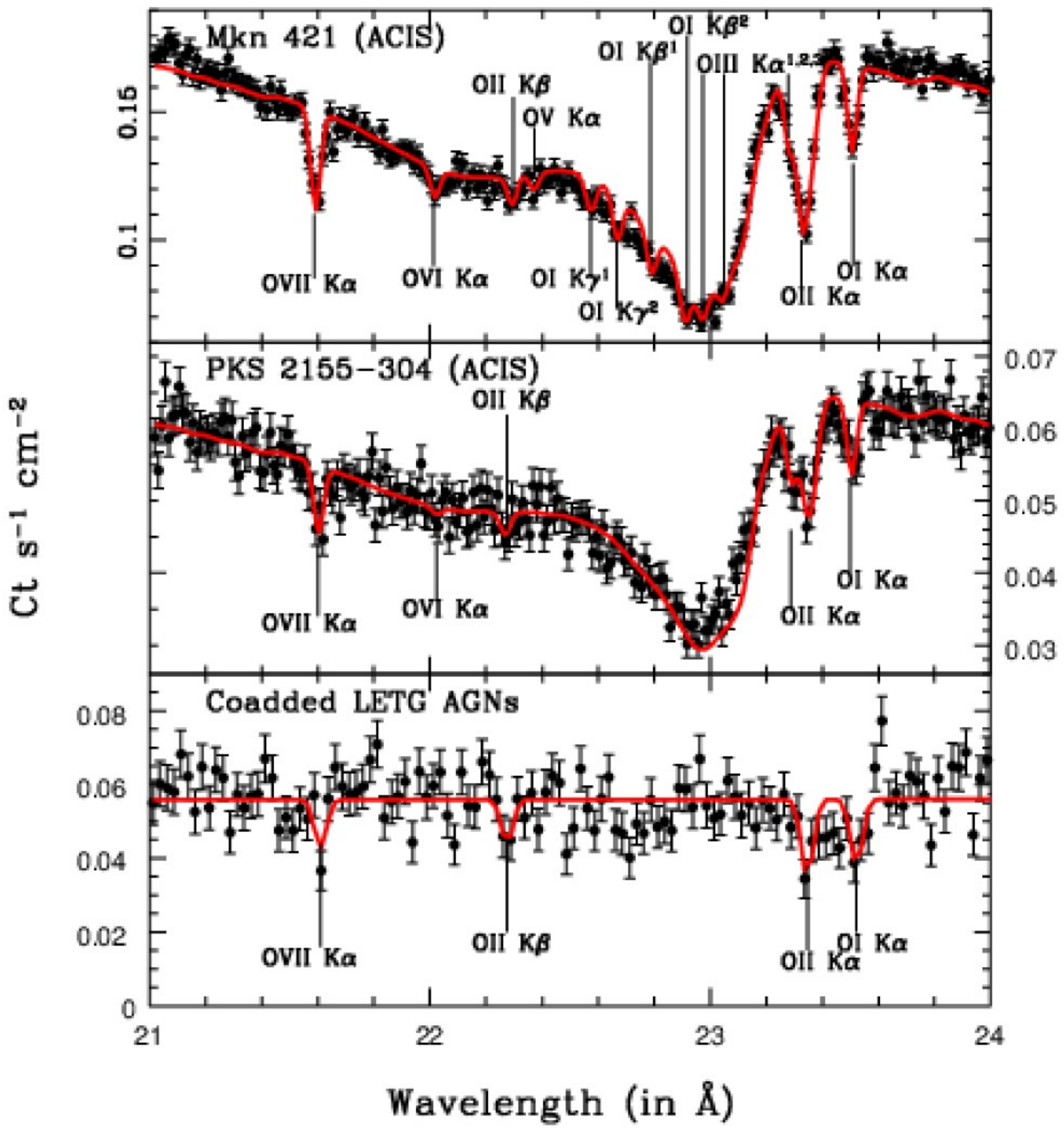


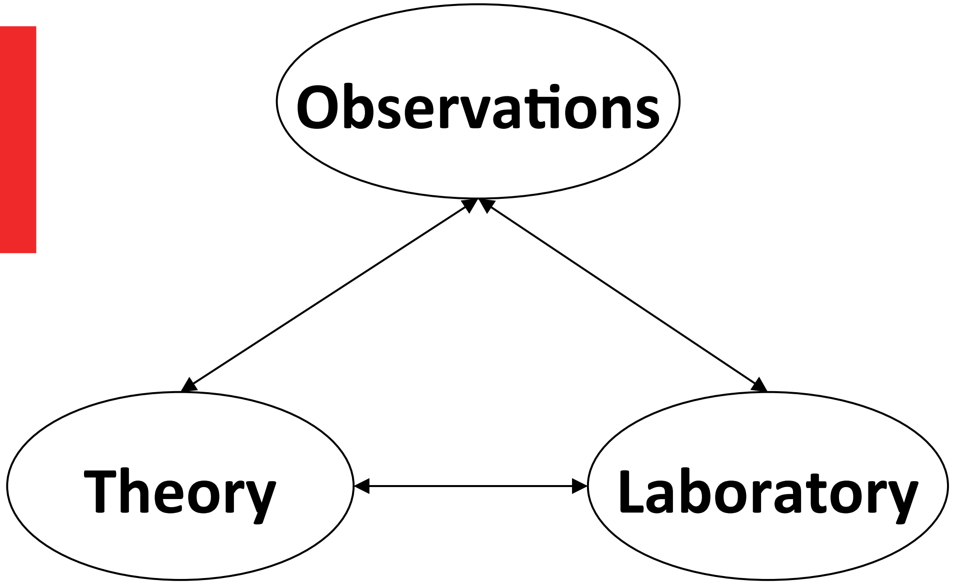
The local ISM is important!

O VII Ka at z≃0.03 from WHIM
(Buote et al. 2009, Fang et al. 2010, Ren et al. 2014)

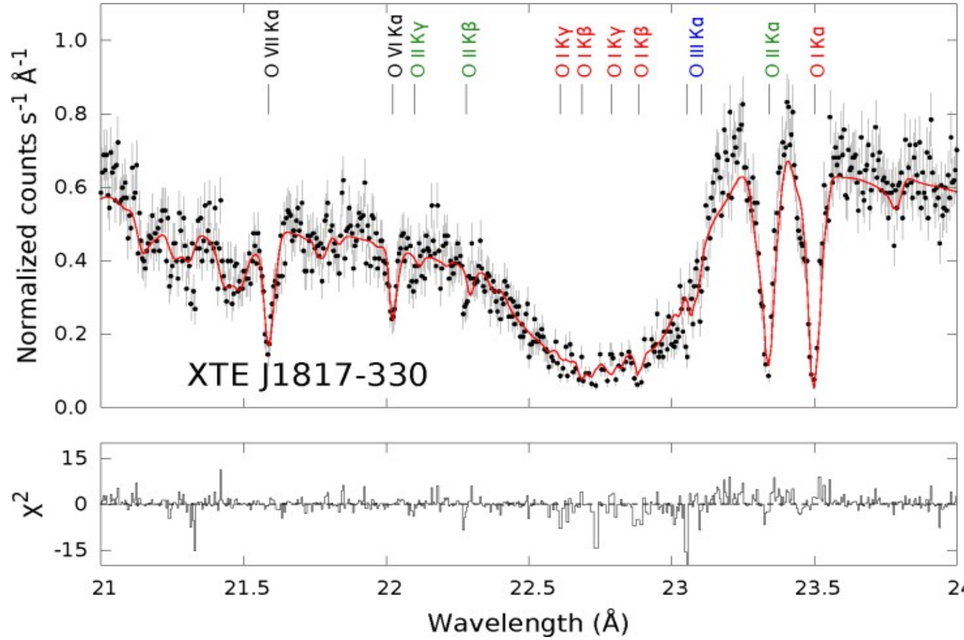
OR

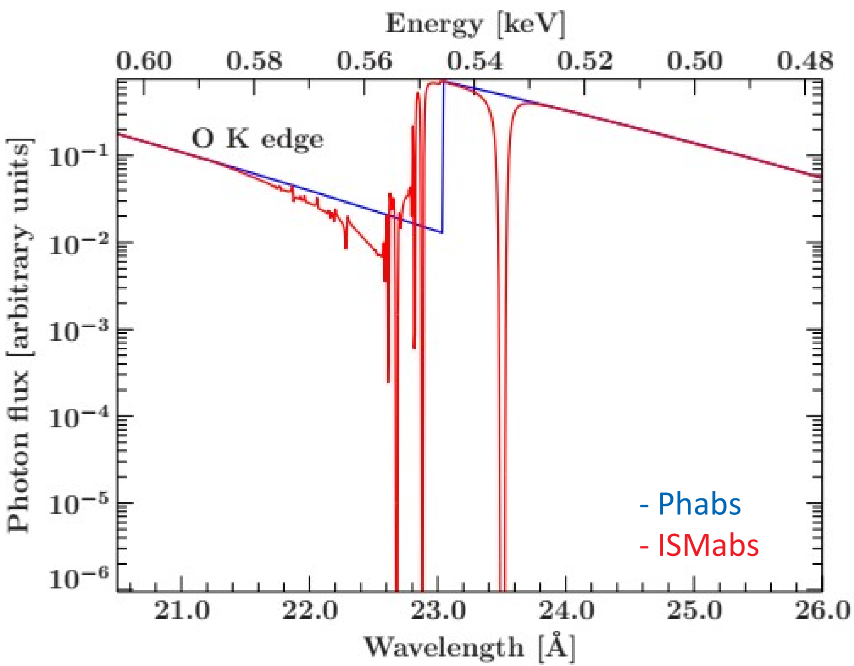
O II Kβ at z = 0 from ISM
(Nicastro et al. 2016)

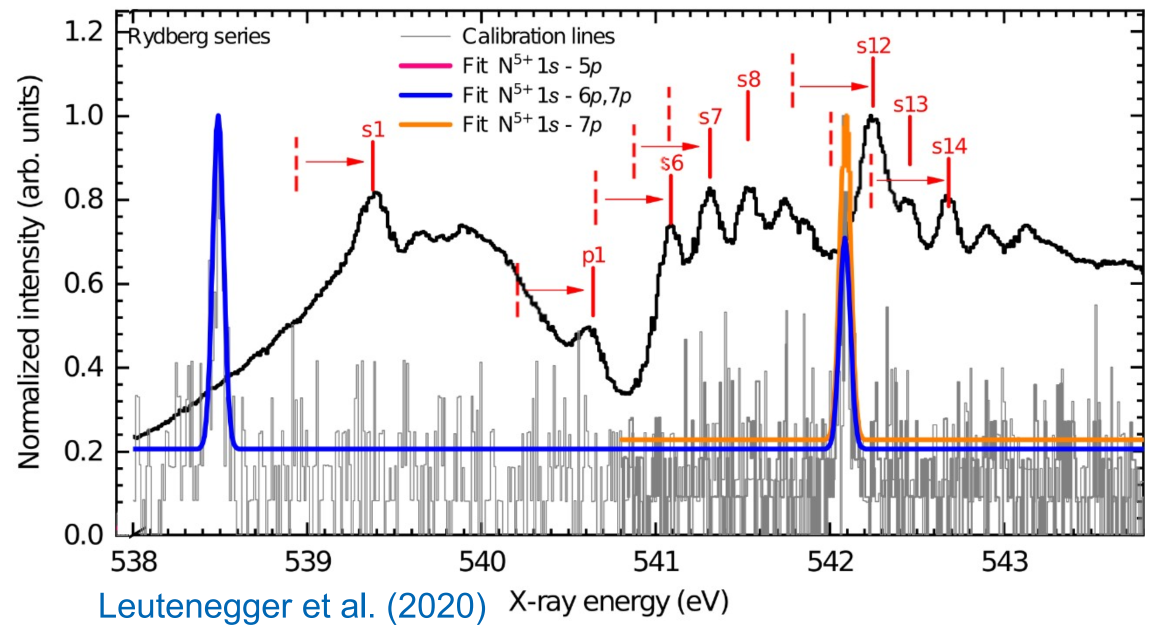




Gatuzz et al. (2013), Gorczyca et al. (2013)







Leutenegger et al. (2020)

What atomic data are you using?

Conclusions

- ISM absorption affects all X-ray spectra and needs to be modeled carefully.
- X-ray observations provides constrains for the neutral, warm and hot components of the ISM.
- Accurate atomic data is crucial in order to avoid misidentification of the spectral features observed. **What atomic data are you using?**
- The gas component needs to be accurately modeled (very important for dust analysis!)
- We can distinguish between the ISM and the absorption intrinsic to the sources

Thank you!