Oxygen morphology and abundance in the interstellar medium through absorption line spectroscopy

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Interstellar medium (ISM)

homogeneous structure on large scales
cloudy structure on small scales

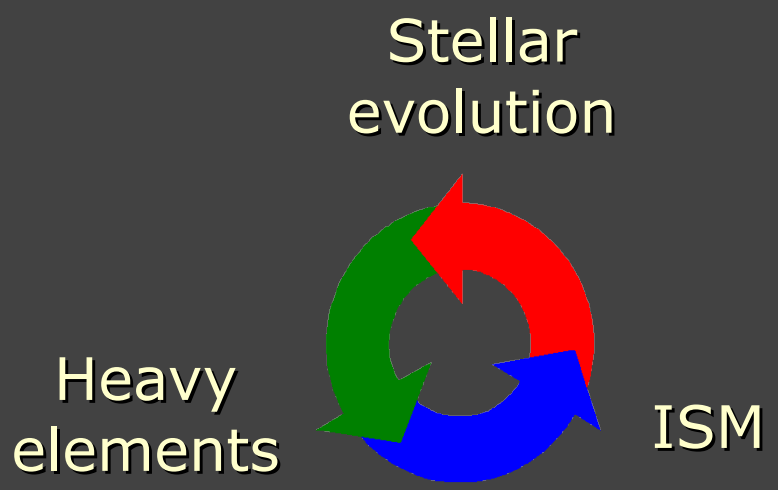
Diffuse ISM

- Structure
- Abundances
- Equilibrium

ISM clouds

- Kinematics
- Heating
- Location

ISM & Galactic ecology



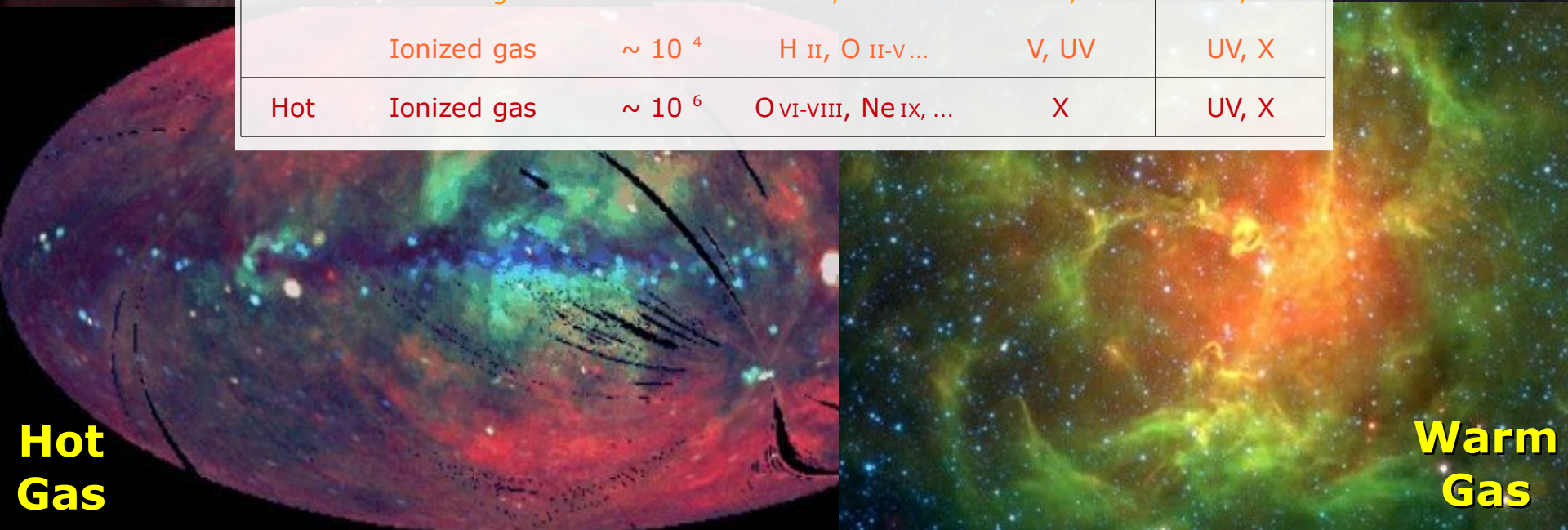
Oxygen - the most abundant heavy element & most direct testimony of stellar evolution

Interstellar medium: 3-phase structure

Dust

Molecular cloud

Phase	Component	Temp. (K)	Constituents	Primary band	This Work
	Dust	~ 10—20	$MgSiO_3$ ...	IR	UV, X
Cold	Molecules	~ 10—20	H_2, CO, ...	Radio, IR	UV, X
	Neutral gas	~ 50—100	H I, O I ...	Radio, UV	UV, X
Warm	Neutral gas	$\leq 10^4$	H I, O I ...	Radio, UV	UV, X
	Ionized gas	~ 10^4	H II, O II-V ...	V, UV	UV, X
Hot	Ionized gas	~ 10^6	O VI-VIII, Ne IX, ...	X	UV, X



Hot Gas

Warm Gas

Advantages in using FUV and X-ray

- FUV → HST / COS : λ 1150-1750 Å
- X-ray → XMM-Newton / RGS : λ 5-38 Å

  → ionization states (O I … VIII)

  → dust and molecules (H_2O ice … CO)

  → heavy elements (O, Mg, Si … Fe)

- Targets:

  → X-ray binaries (low latitudes: disk and bulge)
  → AGN (intermediate-high latitudes: disk and halo)

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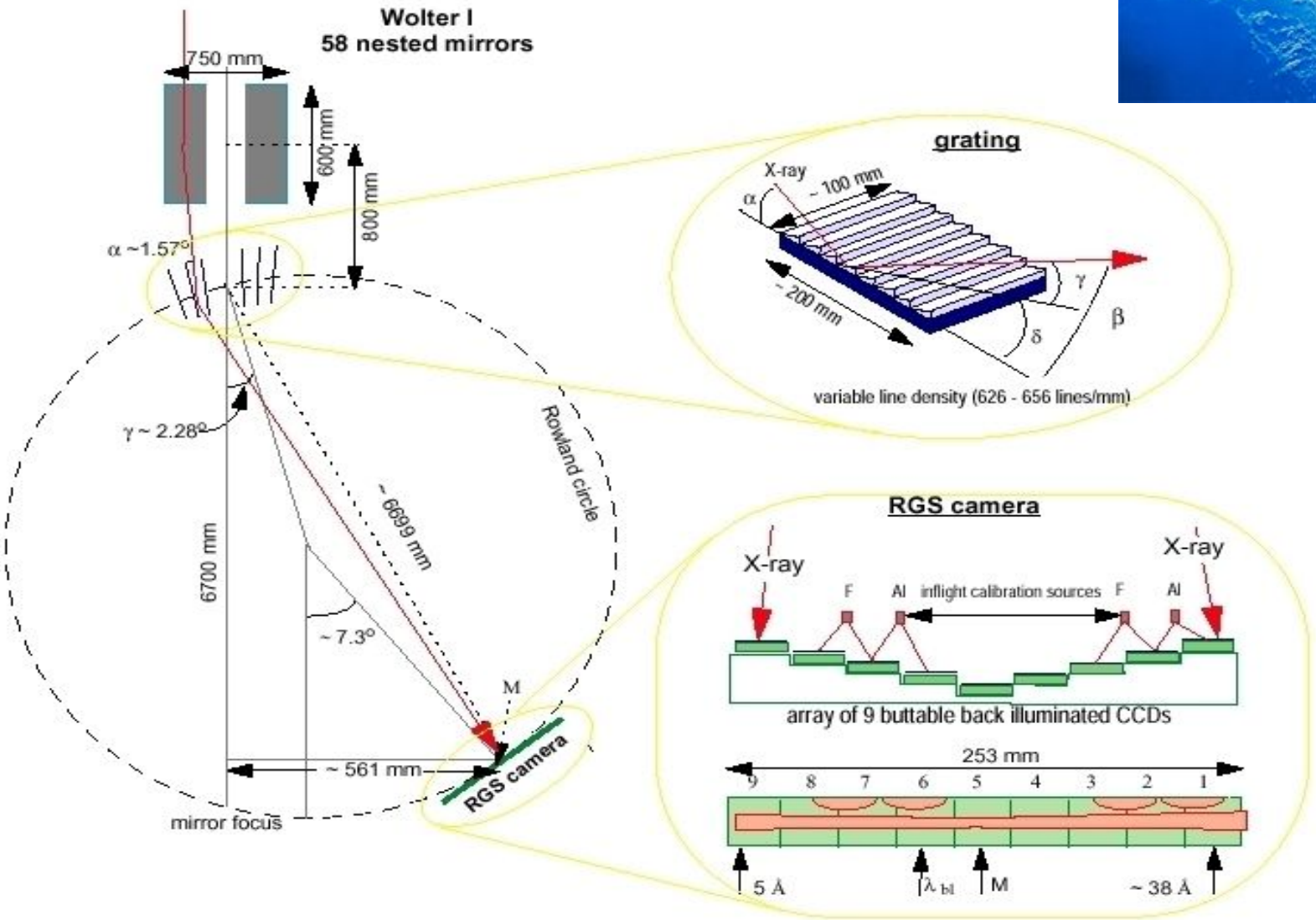
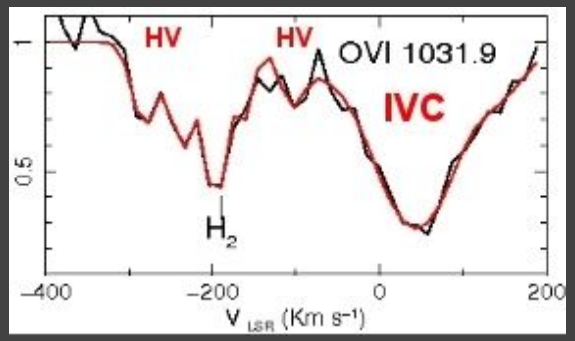
XMM-Newton Reflection Grating spectrometer (RGS)

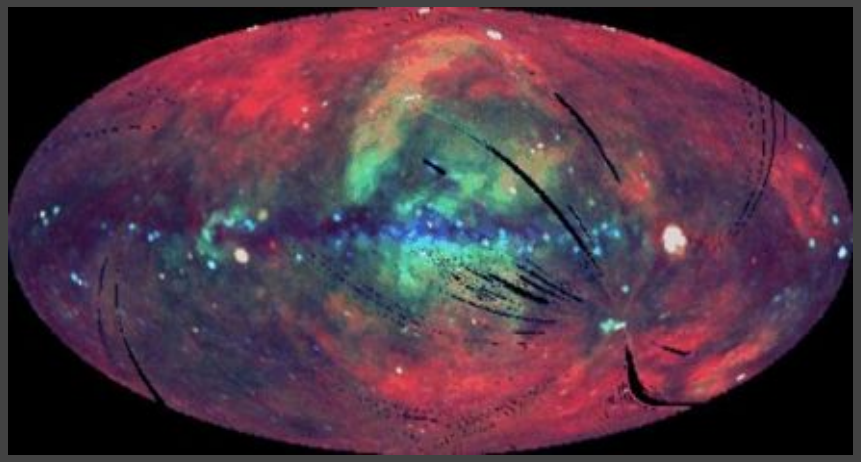


UV / X-ray Spectroscopy: method & highlights

Absorption edges & lines → Column densities & velocities



- ISM clouds kinematics, origin
- ISM Composition ~ Sun
- ISM Ne/O ≥ Sun
- Metals depletion
- Ionized gas ~ 10%



Galactic X-ray emission

Interstellar medium

homogeneous structure on large scales

- Multi-phase structure
- Dust depletion factor
- Abundance gradients

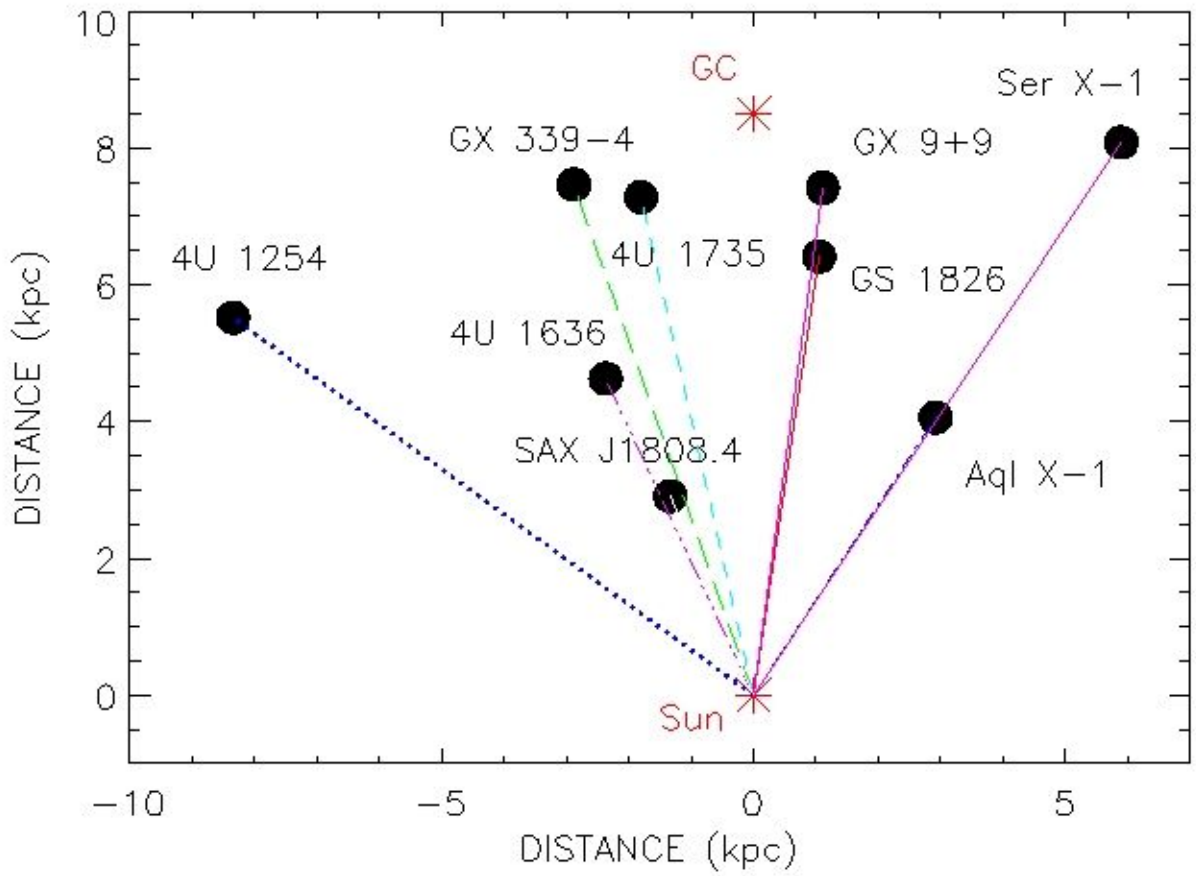
Abundances, depletion and structure of the ISM

X-ray spectroscopy of 9 low-mass X-ray binaries:

4U 1254-690, 4U 1636-536, 4U 1735-444, Aql X-1, Ser X-1, GS 1826-238, GX 339-4, GX 9+9, SAX J1808.4-3658

RGS Gratings

(*XMM-Newton*)



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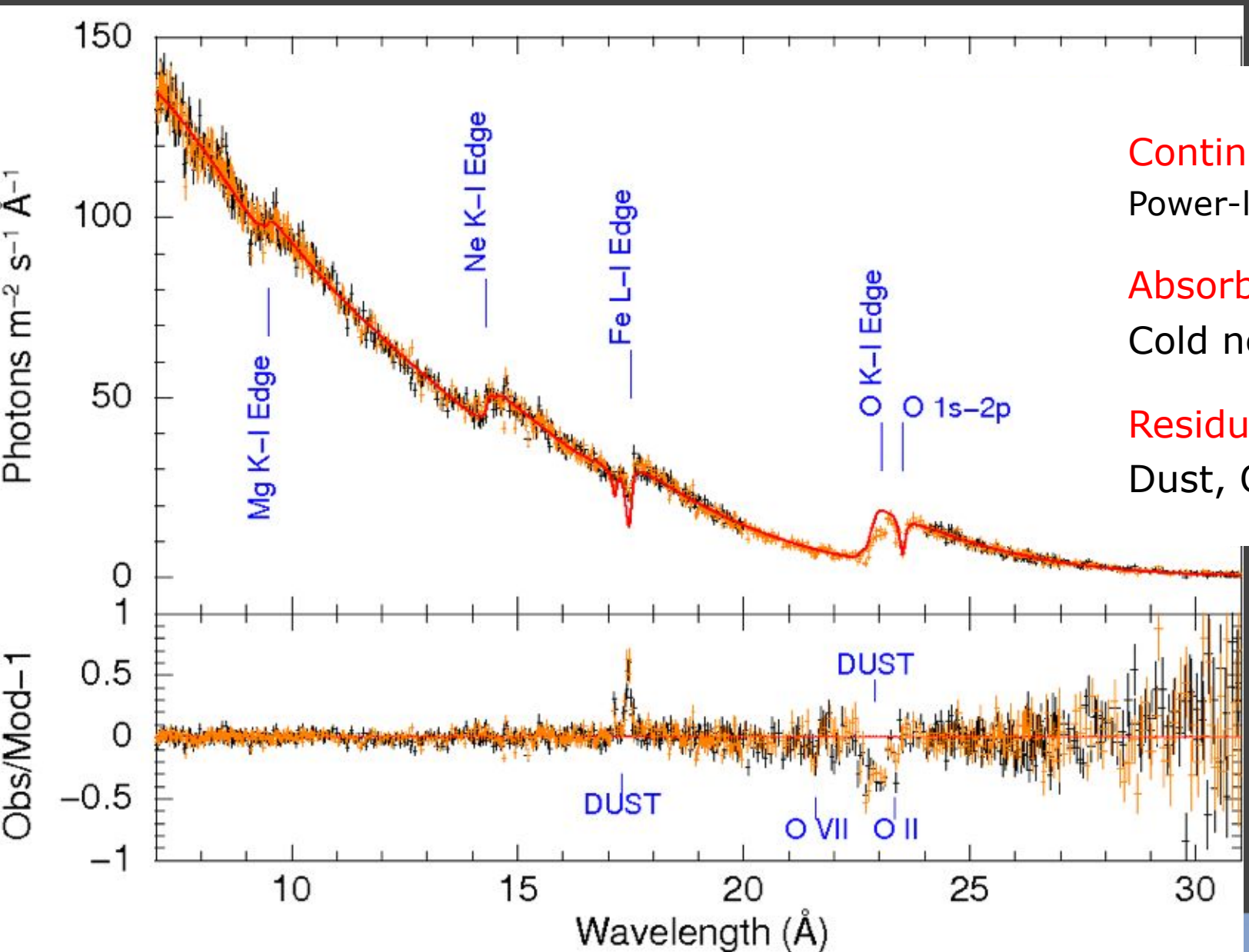
Example: GS 1826-238

SPEX UV / X-ray fitting package



Continuum:

Power-law

Absorber:

Cold neutral gas

Residuals:

Dust, O II-III, O VII

The ISM (empirical) model

- 3 (absorbing) ISM phases:

cold neutral gas + dust + molecules
warm mildly-ionized gas, e.g. O II-V
hot highly-ionized gas, e.g. O VI-VIII

- Column densities are empirical and model-independent

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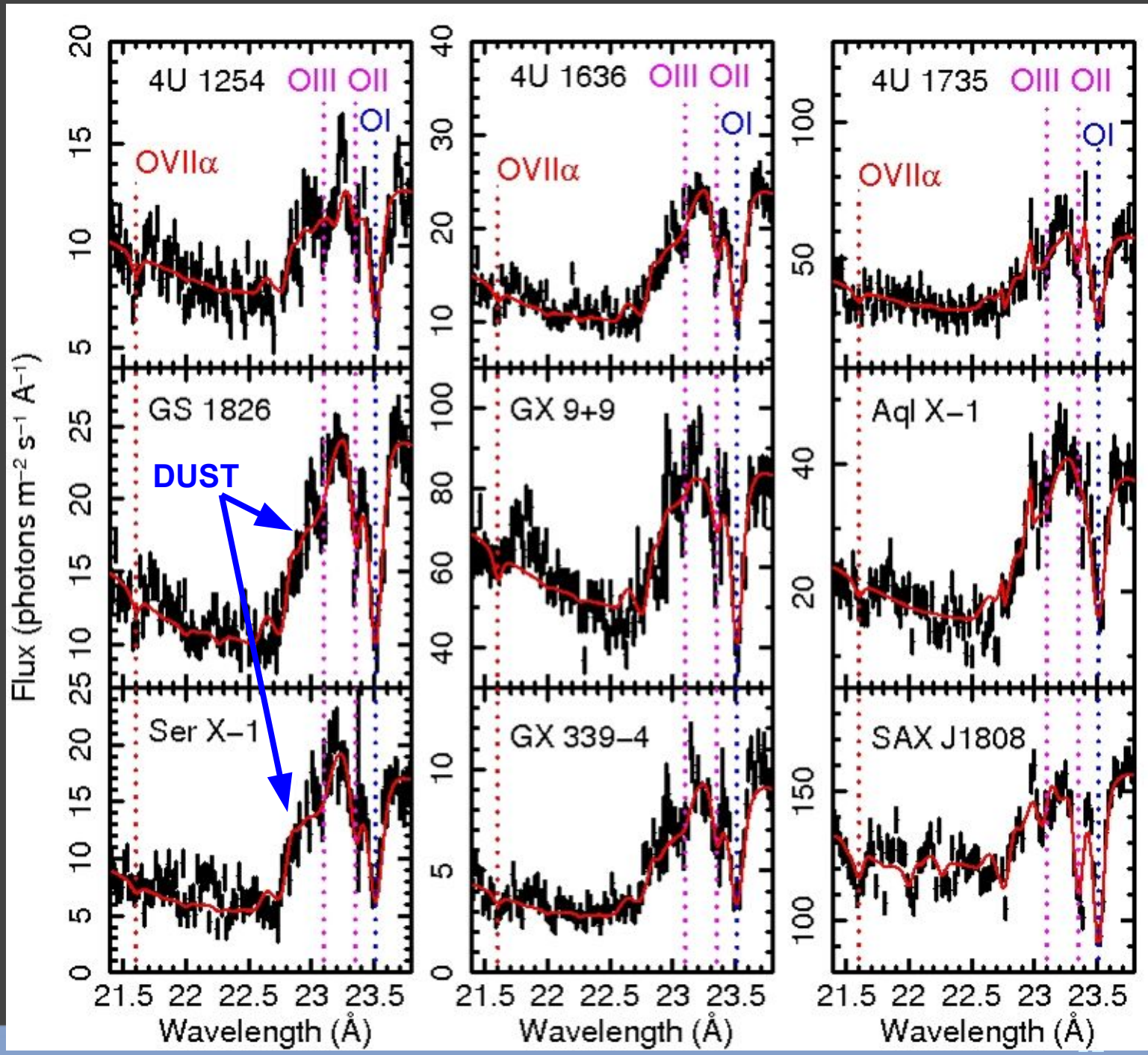
Oxygen edge



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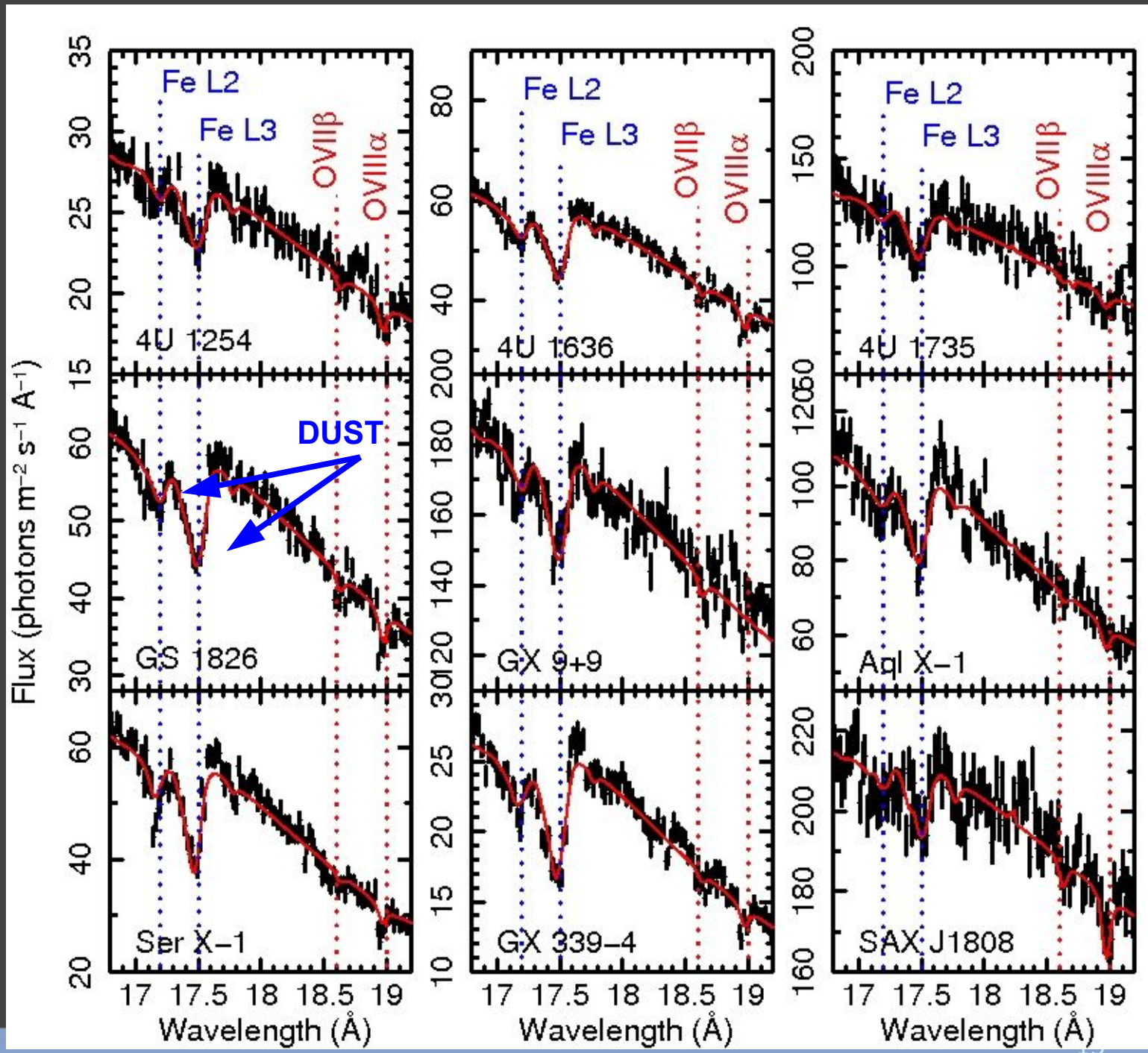
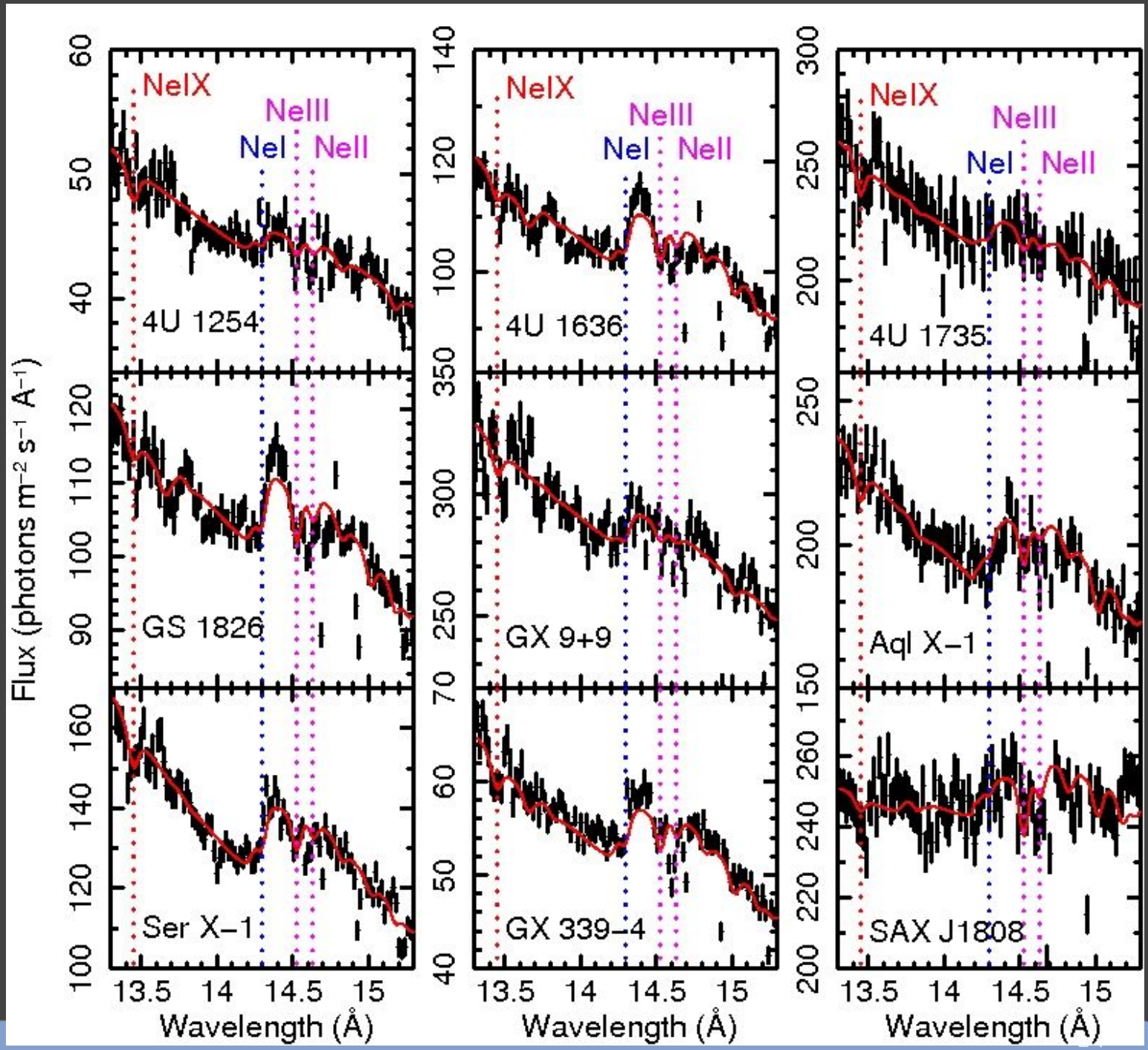
Iron edge


Fe L2
Fe L3
OVIIβ
OVIIIα
4U 1254
4U 1636
4U 1735
DUST
GS 1826
GX 9+9
Aql X−1
Ser X−1
GX 339−4
SAX J1808
Flux (photons m⁻² s⁻¹ A⁻¹)
Wavelength (Å)
17 17.5 18 18.5 19

Neon edge



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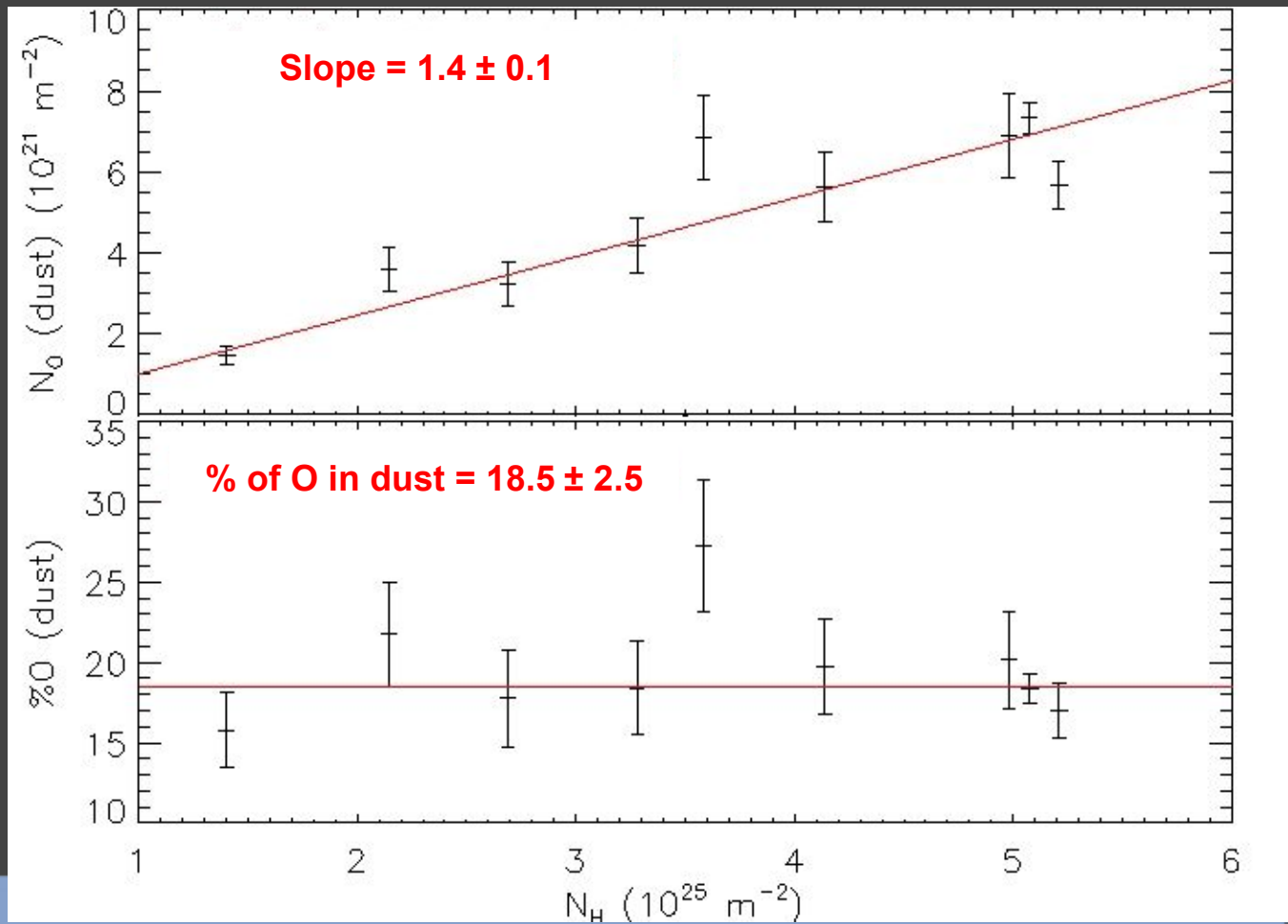
Oxygen: dust depletion

- Water ice and silicates
- $N_{DUST} \propto N_H$
- Oxygen ~ 15-20%
- Iron ~ 60-90%



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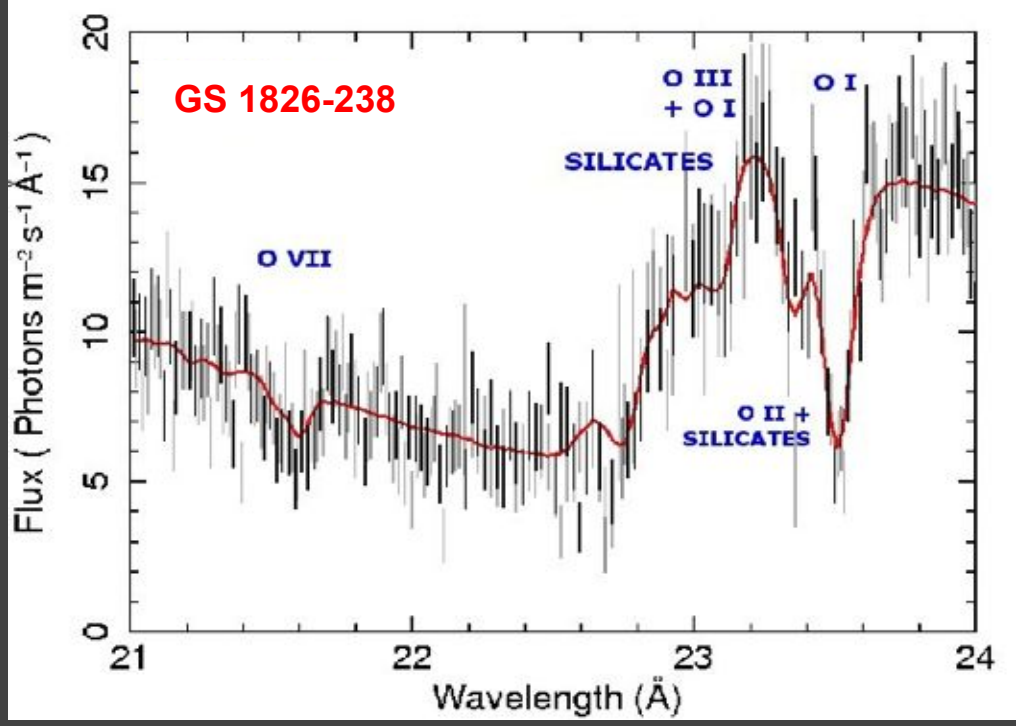
Oxygen: ionized gas

15-20 % oxygen : dust

70-80 % oxygen : neutral gas

5-10 % oxygen : ionized gas



- Warm ionized gas:

  O II + O III / O gas ~ 5%

  → Photo-ionized gas ~ 9 - 10 000 K

- Hot ionized gas

  O VII + O VIII / O gas ~ 5%

  → Collisionally-ionized gas with 1.5-2.5 mln K

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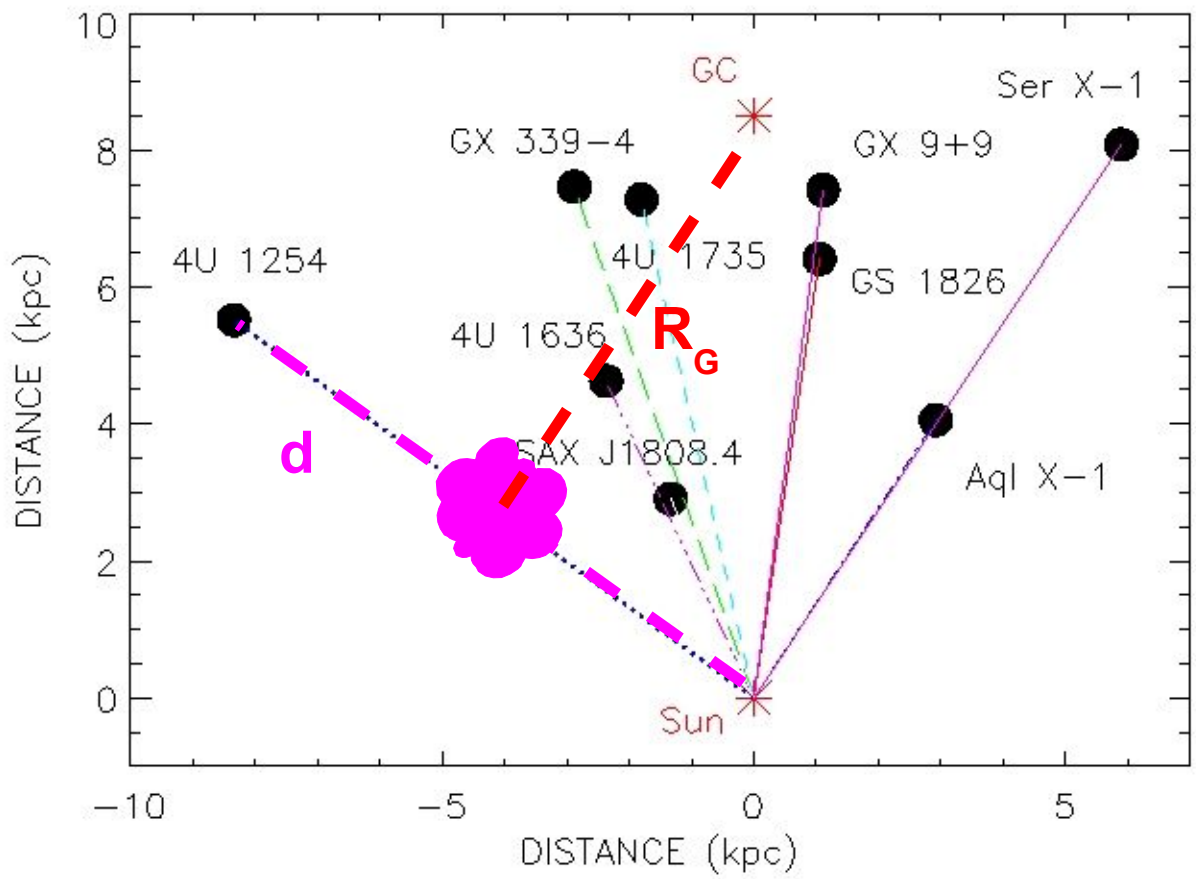
Abundance gradients of the cold phase (dust + gas)

Galactocentric distance R_G of the absorber

Distance from the GC to the midpoint of the L.O.S. towards the LMXB



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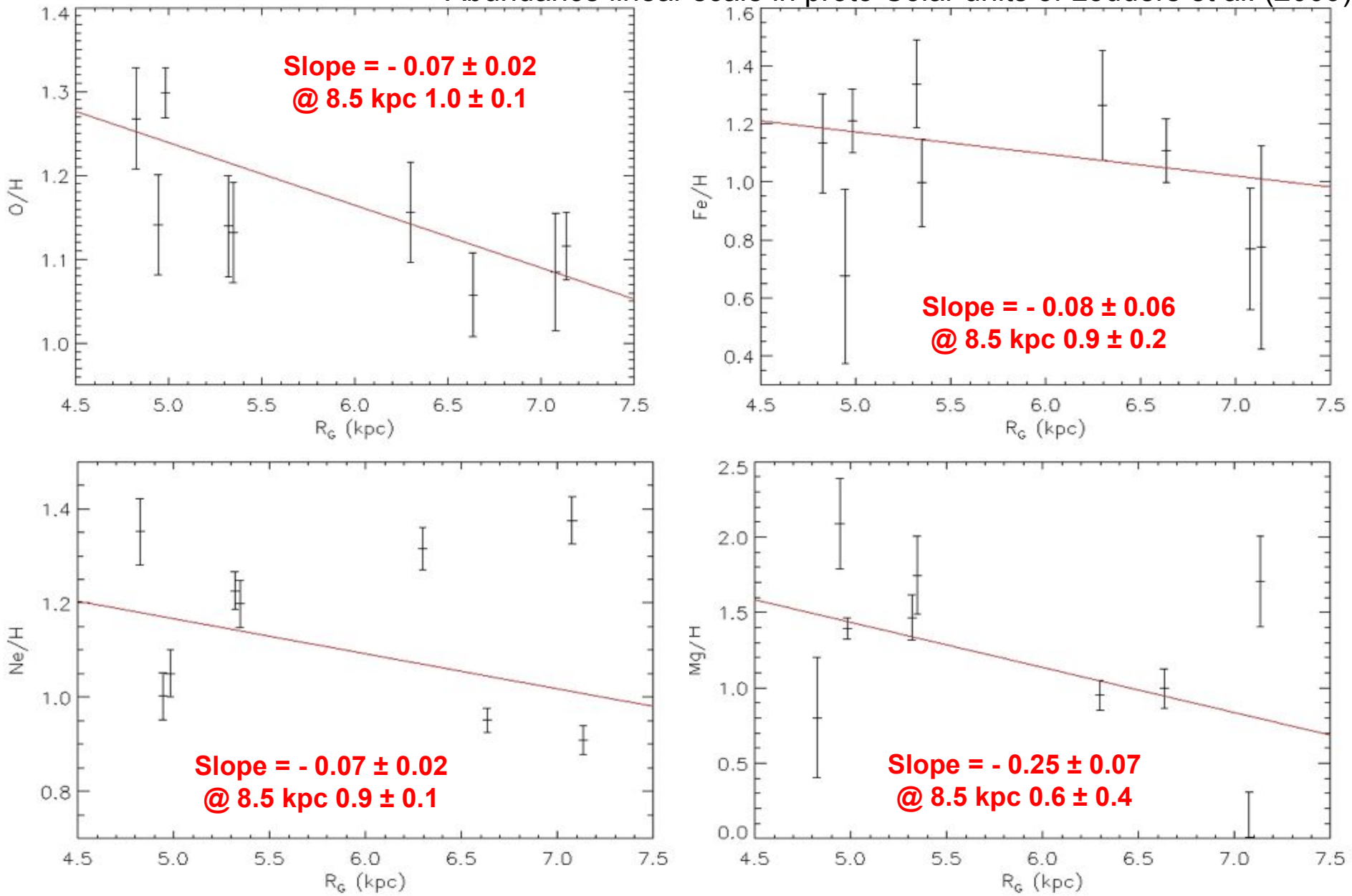
Abundance gradients of the cold neutral phase

Abundance linear scale in proto-Solar units of Lodders et al. (2009)

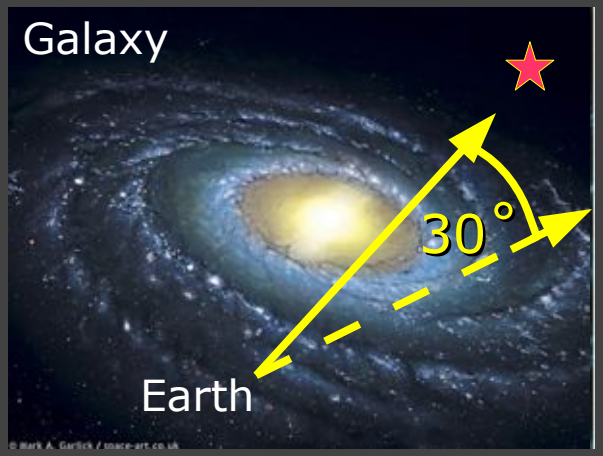


Interstellar medium

Cloudy / filamentary structure on small scales

- Kinematics
- Heating processes
- Location

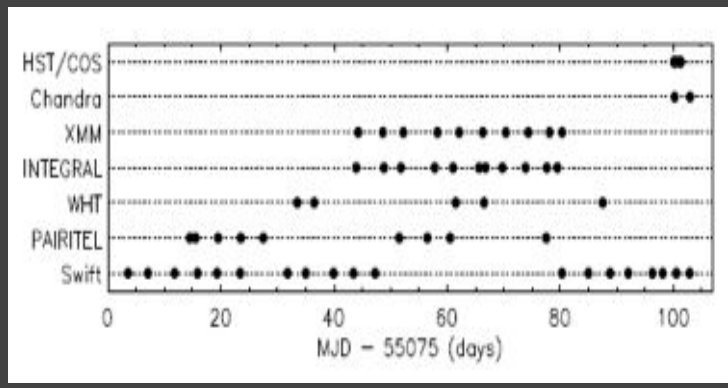
Mrk 509



The Mrk 509 Multi-wavelength Campaign

- Observations:

  600 ks XMM-Newton, 1.14 Gs INTEGRAL
  180 ks Chandra, 26 ks COS/HST
  7.2 ks PAIRITEL, 14.5 ks WHT, 20 ks SWIFT
  + archival FUSE data



Kaastra et al 2011a

- Aims & Contributions: 10+ papers

Campaign overview	→ Kaastra et al. 2011a
XMM-RGS new calibration	→ Kaastra et al. 2011b
AGN X-ray outflow structure	→ Detmers et al. 2011
AGN UV continuum & outflow	→ Kriss et al. 2011, Arav et al. 2012
AGN UV versus X-ray absorbers	→ Ebrero et al. 2011
Nature of Soft X-ray excess	→ Mehdipour et al. 2011
Abundances of absorbers	→ Steenbrugge et al. 2011
AGN Outflow location	→ Kaastra et al. 2011c
Galactic foreground	→ Pinto et al. 2012

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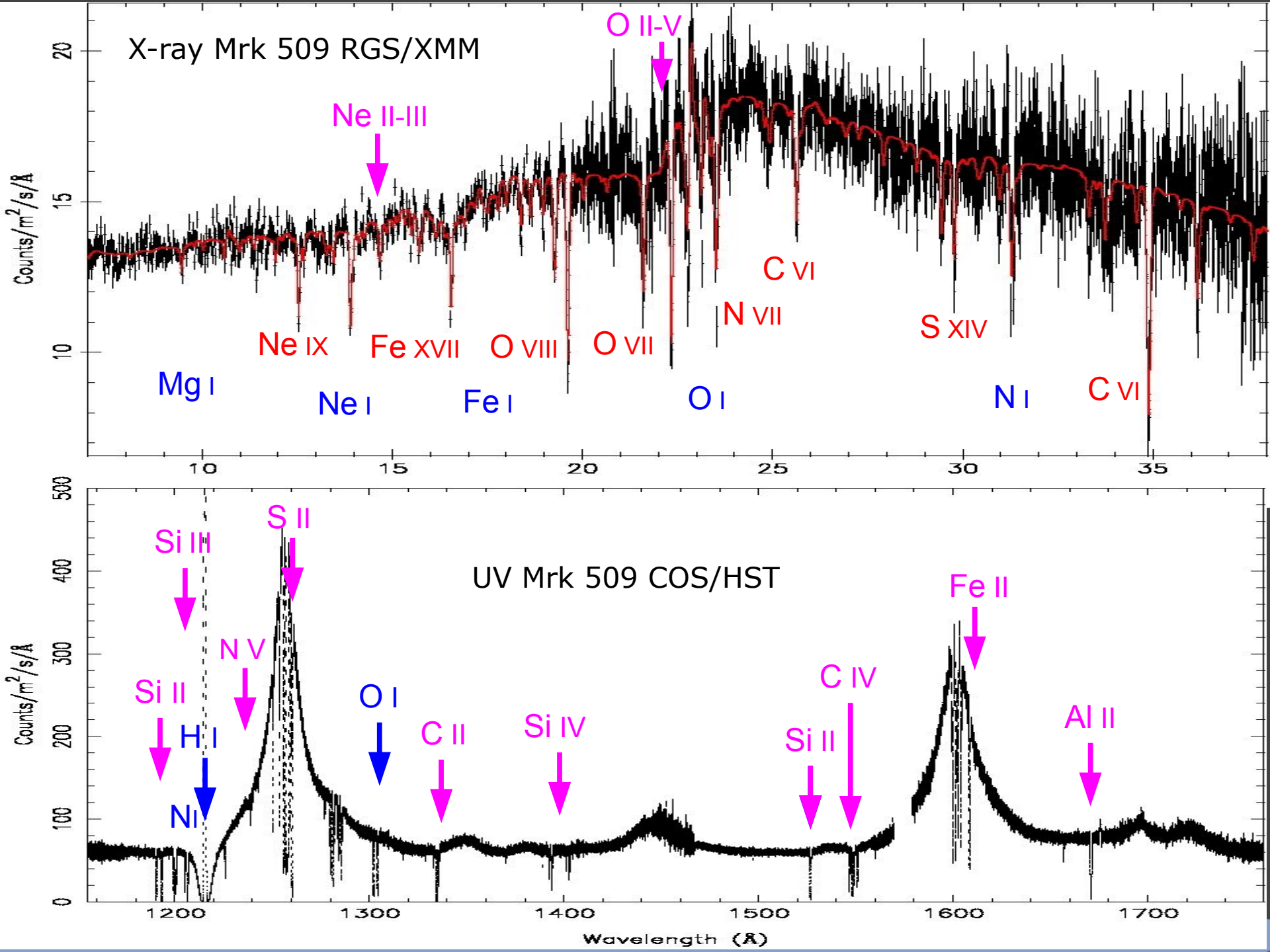
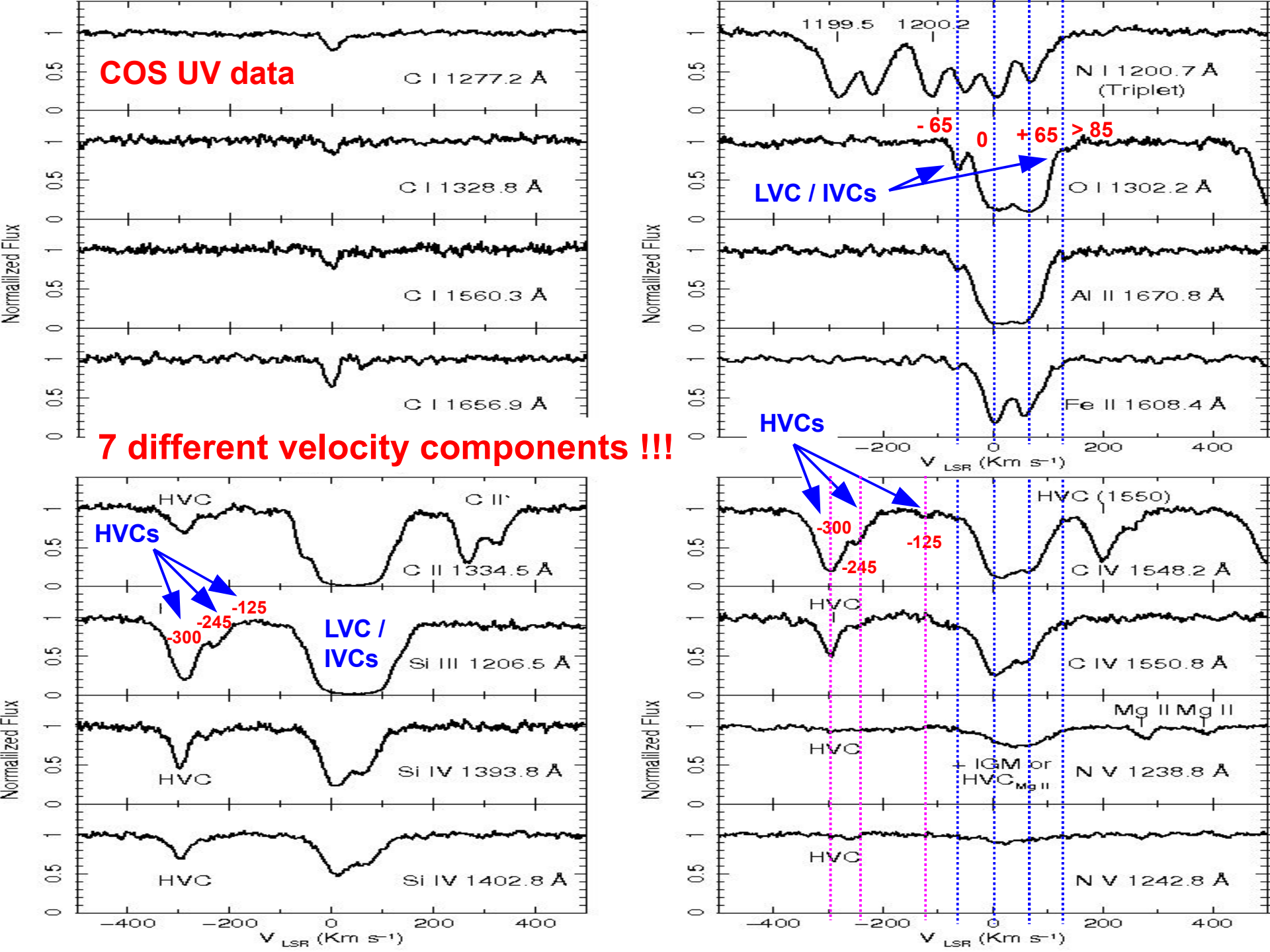

X-ray Mrk 509 RGS/XMM
O II-V
Ne II-III
C VI
N VII
S XIV
Ne IX
Fe XVII
O VIII
O VII
Mg I
Ne I
Fe I
O I
N I
C VI
Counts/m²/s/Å
UV Mrk 509 COS/HST
S II
Si III
Fe II
N V
Si II
O I
C IV
H I
C II
Si IV
Si II
Al II
N I
Wavelength (Å)


COS UV data
C I 1277.2 Å
C I 1328.8 Å
C I 1560.3 Å
C I 1656.9 Å
7 different velocity components !!!
1199.5
1200.2
N I 1200.7 Å
(Triplet)
- 65
0
+ 65
> 85
LVC / IVCs
O I 1302.2 Å
Al II 1670.8 Å
Fe II 1608.4 Å
HVCs
HVC
C II*
C II 1334.5 Å
-300
-245
-125
LVC /
IVCs
Si III 1206.5 Å
Si IV 1393.8 Å
Si IV 1402.8 Å
HVC (1550)
C IV 1548.2 Å
C IV 1550.8 Å
Mg II Mg II
+ IGM or
HVC Mg II
N V 1238.8 Å
N V 1242.8 Å
Normalized Flux
V LSR (Km s⁻¹)

The ISM (physical) model

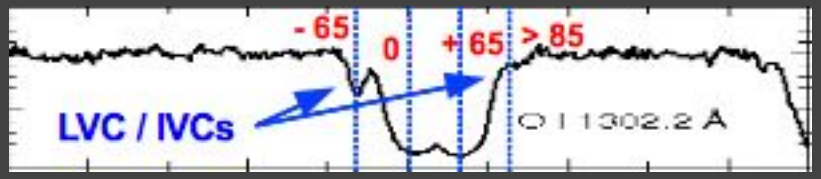
- 3 ISM phases:

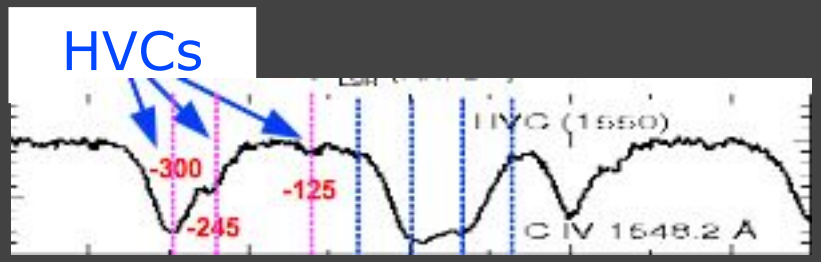
4 x cold neutral gas

7 x warm photoionized

7 x hot collisionally-ionized

O I absorption lines: 4 components





C IV absorption lines: 7 components

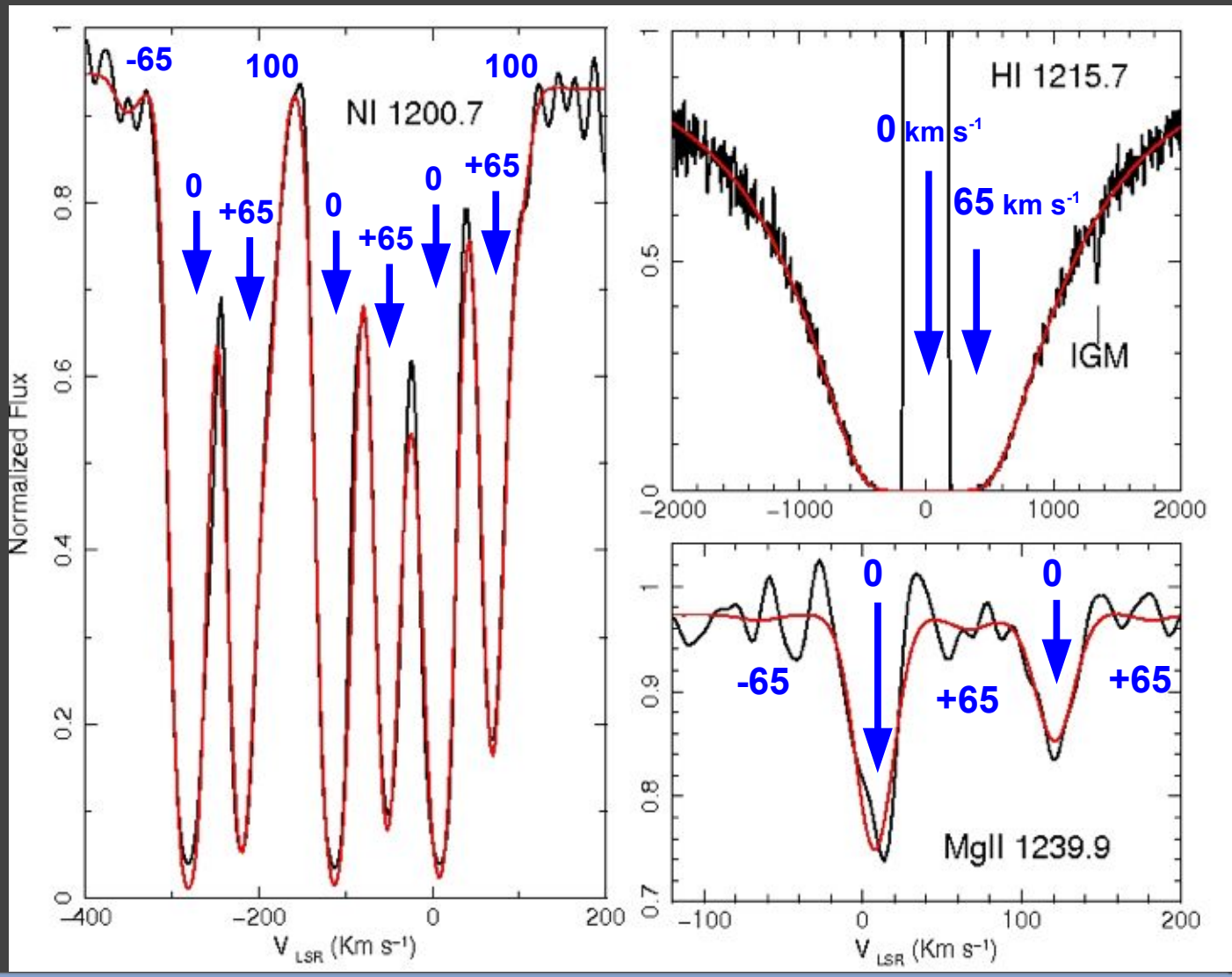
Cold gas: 1 LVC + 3 IVCs

Column density ratios

$N_{+0\ km/s}$ ~ 90%

$N_{+65\ km/s}$ ~ 7%

$N_{other\ IVCs}$ ~ 3%



Warm & hot gas: 1 LVC + 3 IVCs + 3 HVCs

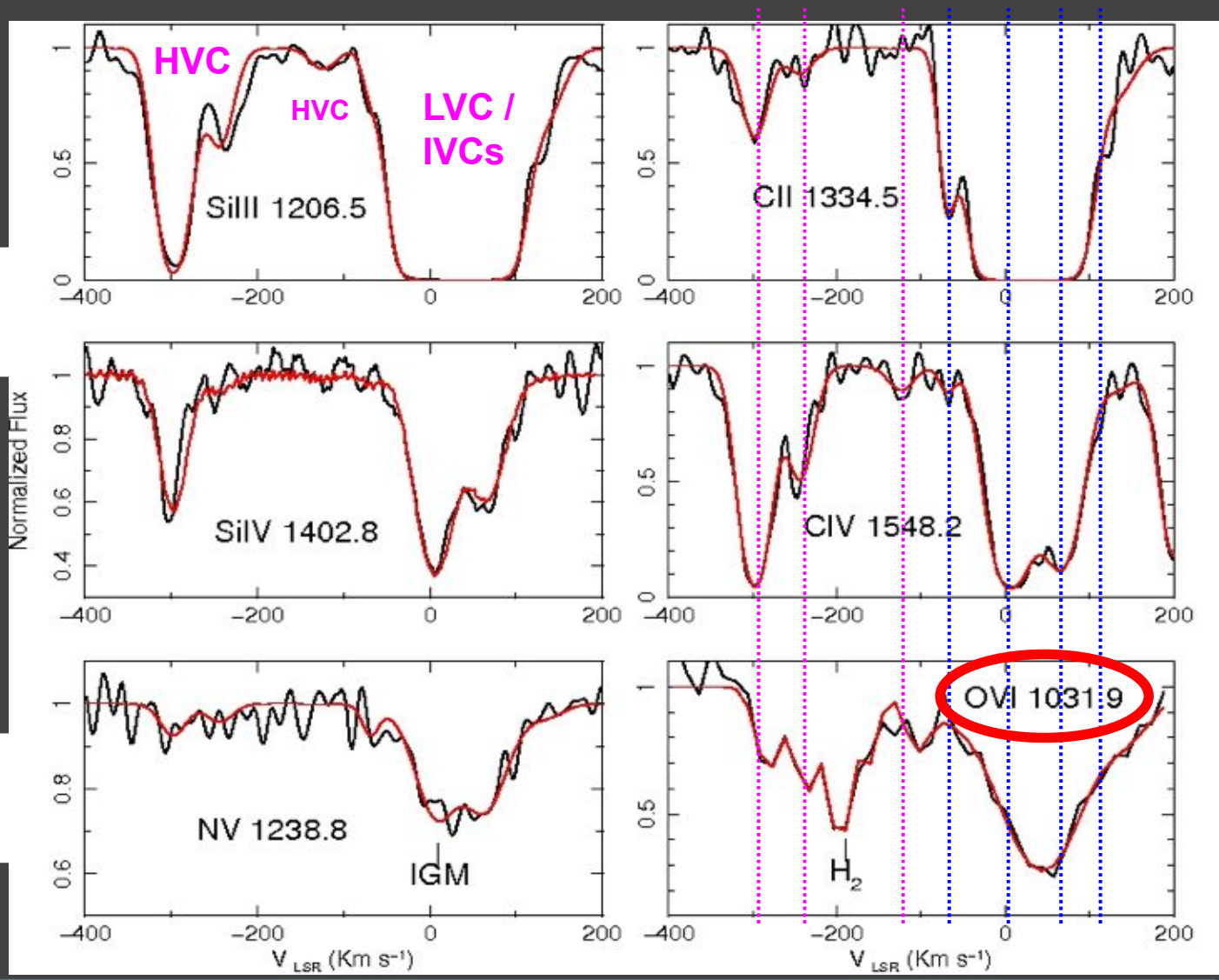
Photo-ionized

WARM GAS

++

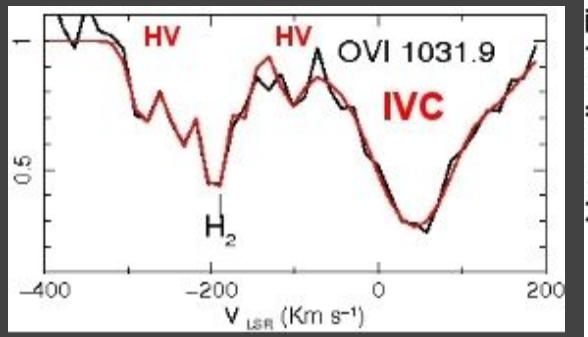
Collisionally-ionized

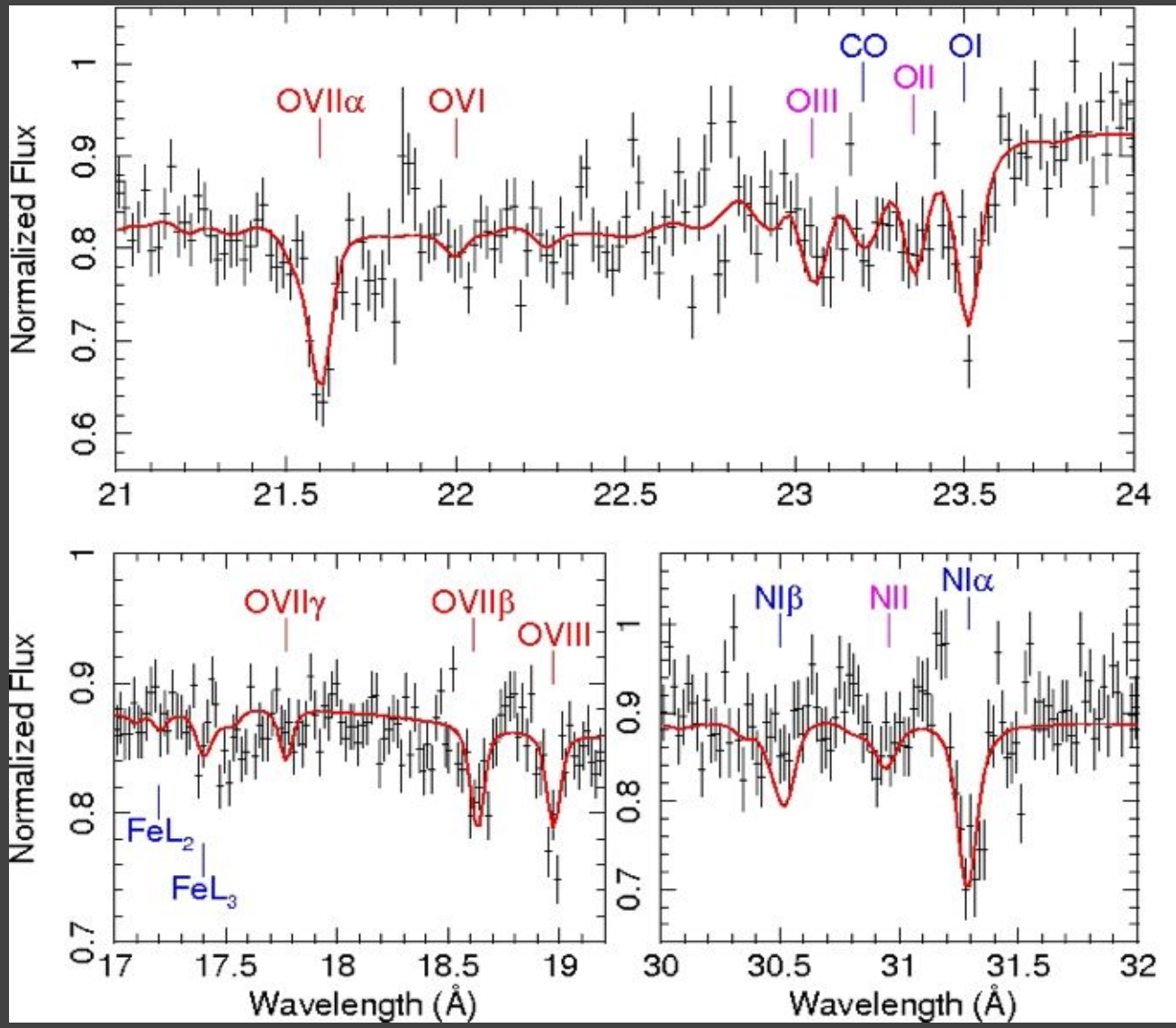
HOT GAS → O VI-VIII



ISM = Cold + Warm + Hot phases

Simultaneous UV / X-ray





Temperatures

$T_{cold} \leq 10\,000$ K

$T_{warm} \sim 10\,000$ K

$T_{hot} \sim 1\text{-}2$ mln K

% Dust in cold phase

O I ~ 20 %

C I > 50%

Fe I ≥ 90%

Abundances (SUN)

O = 0.7 ± 0.1 Fe = 0.9 ± 0.1

N = 0.8 ± 0.1 Ne = 1.3 ± 0.2

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Conclusion

- ISM UV / X-ray spectroscopy : powerful tool

  Multi-phase structure, abundances, heating, dust

  Dust depletion (ices and silicates)

  O ~ 15-20%, Fe ~ 60-90%

  Predicted Abundances near the Sun → ~ Lodders et al. (2009)

  Abundance gradients similar to those at longer λ

- Working in progress …

  → extend to more lines of sight

  → compare / update atomic data

  → compare with results at longer λ

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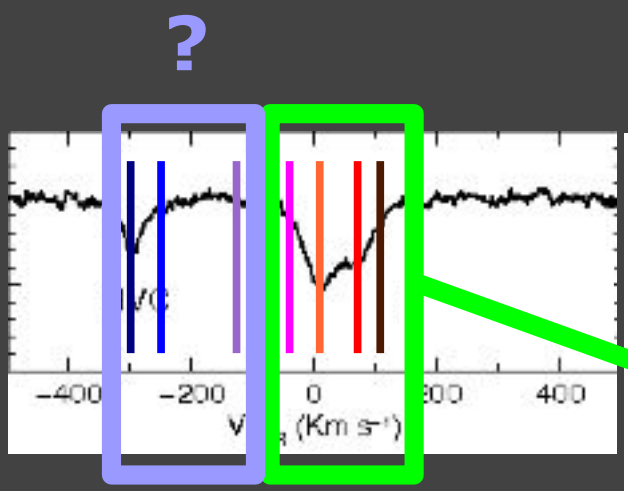
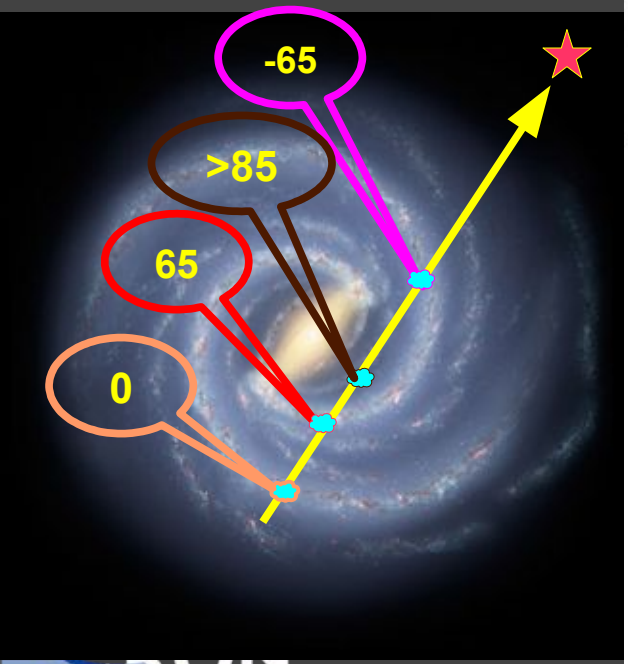
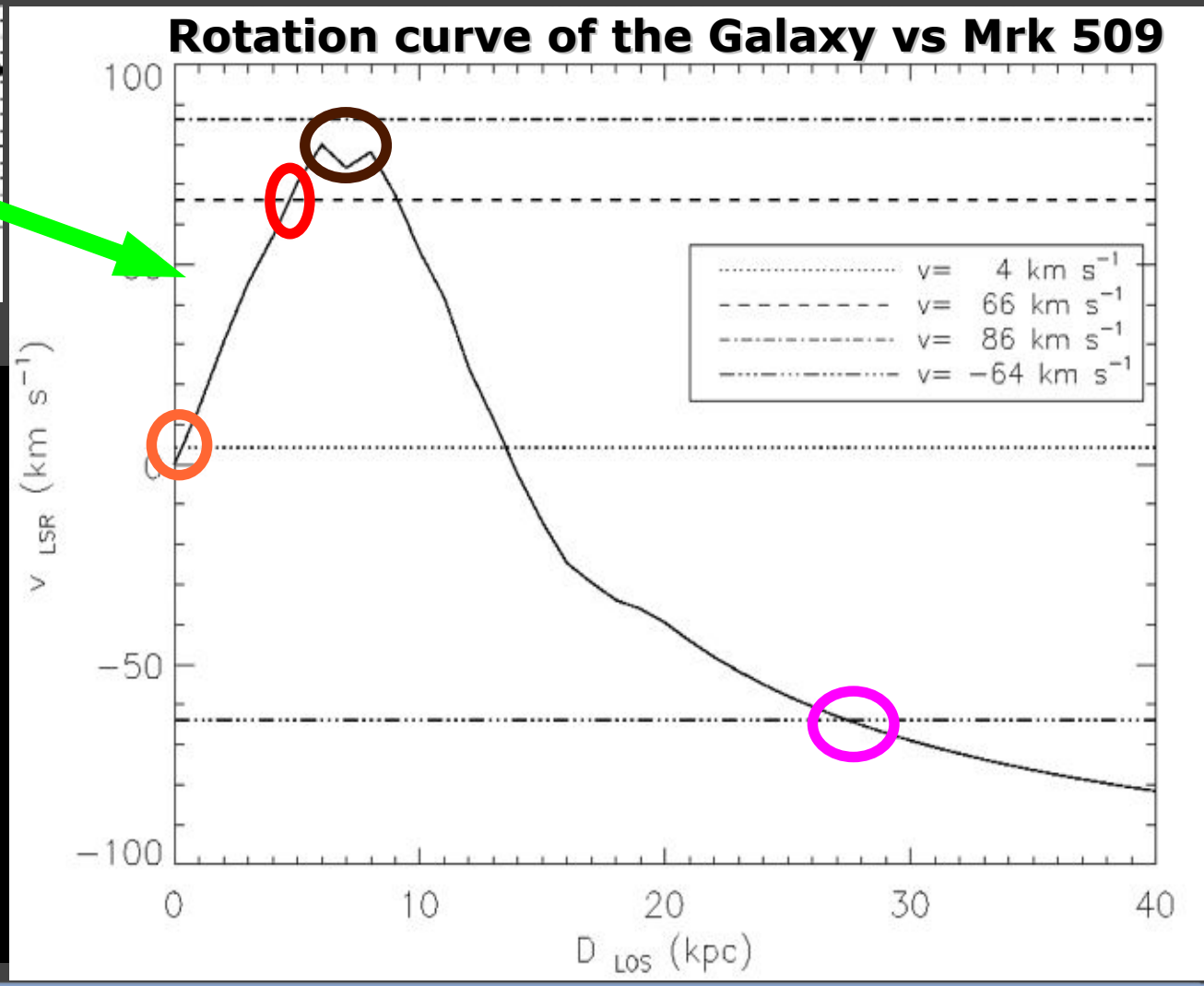
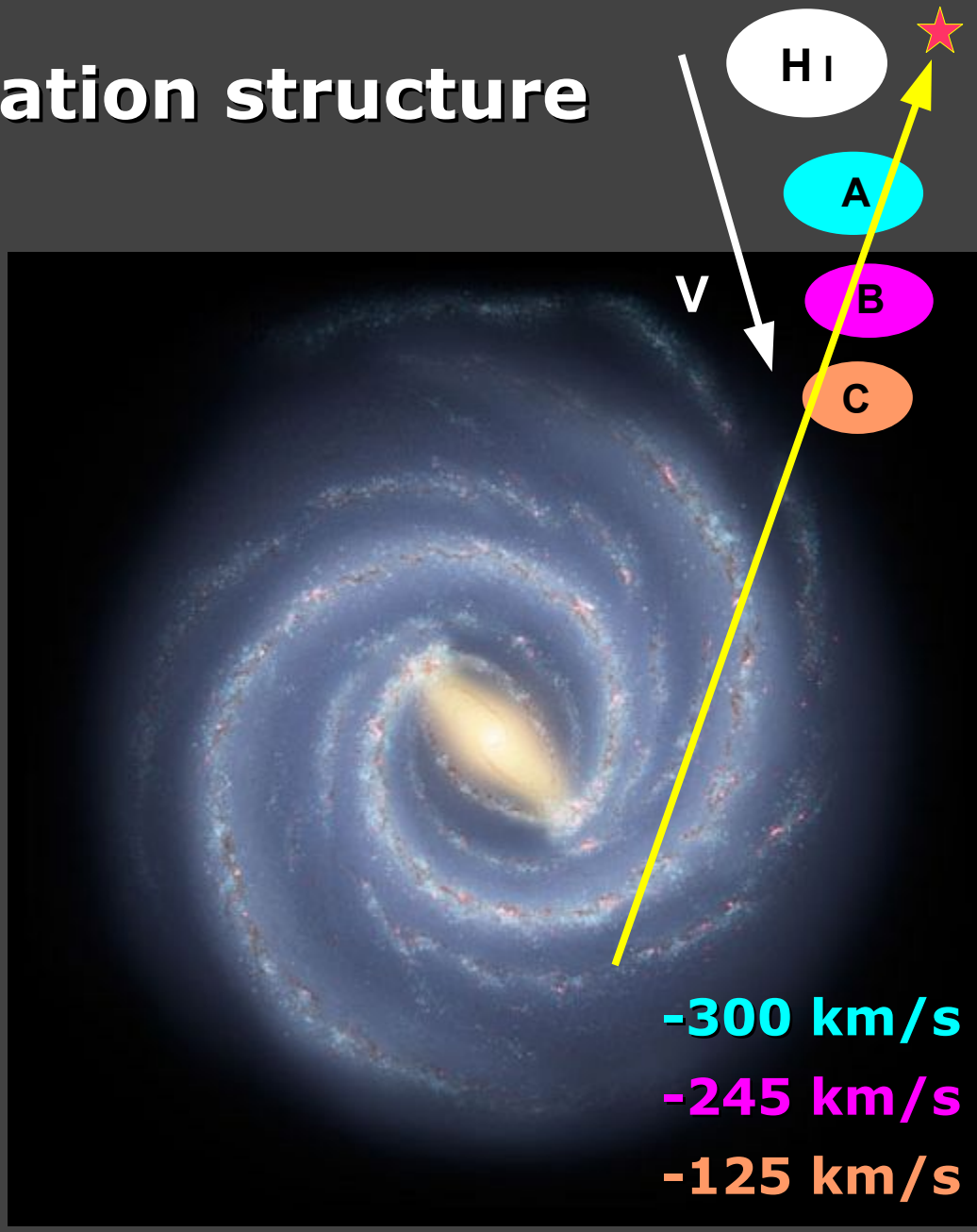
LVC / IVCs location: Galactic rotation







HVC location: ionization structure

- Fast H I only found at 2°
- Same (~ solar) abundances
- Same ionizing SED
- In pressure equilibrium
- + Collisional ionization
- Slower layer more ionized

→ <u>outskirt of 1 captured cloud</u>