Constraining the chemistry, turbulence, and more in the multi-phase "hot" circumgalactic medium

High-resolution X-ray Spectroscopy: A Chandra workshop

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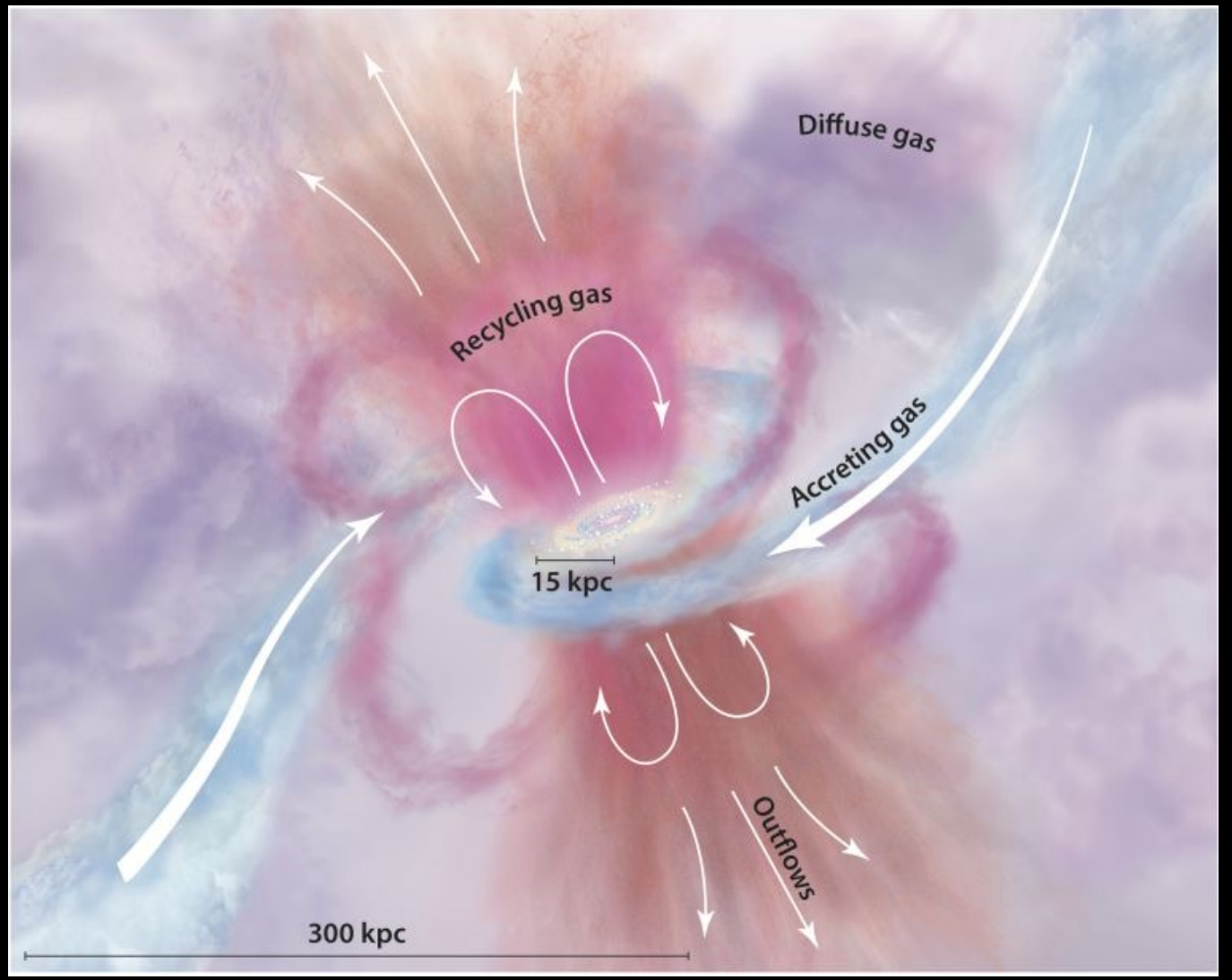
Introduction

"**Hot**" and highly ionized circumgalactic medium (**CGM**)

- is the most massive and volume-filling component of the multi-phase CGM
- traces the pristine gas from the IGM as well as galactic outflows/winds/feedback, and
- its physical and chemical properties are crucial to the coevolution of the disk and the halo of a galaxy

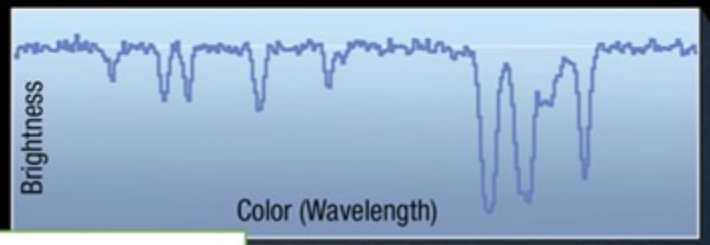


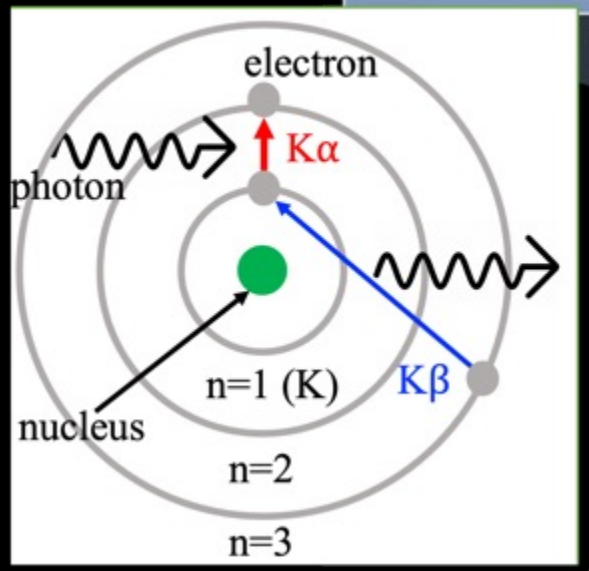
Tumlinson et al 2017, ARA&A

Methods to observe >10^5K gas

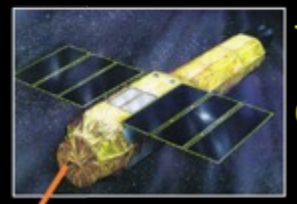
Quasar

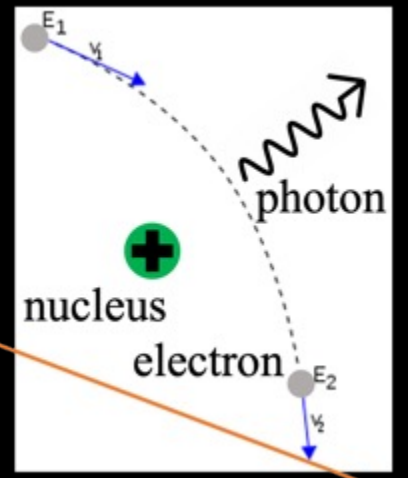
Absorption lines

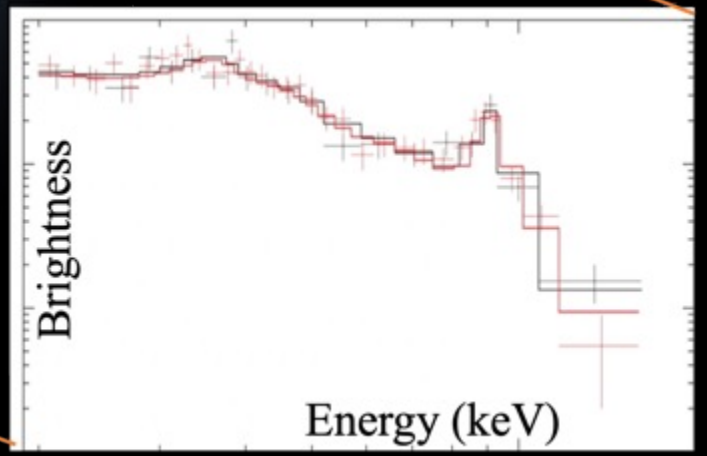




Emission lines + free-free continuum







Absorption

Con:

1. Limited by X-ray bright quasars intervening the CGM
2. Samples small areas in the sky
3. Probed by only metal ions (no absolute metallicity)

Pro:

1. No density bias: $\int ndl$
2. No emissivity bias: broader range of temperature
3. Continuum is well-described
4. Grating spectra can resolve transitions of different metals

Emission

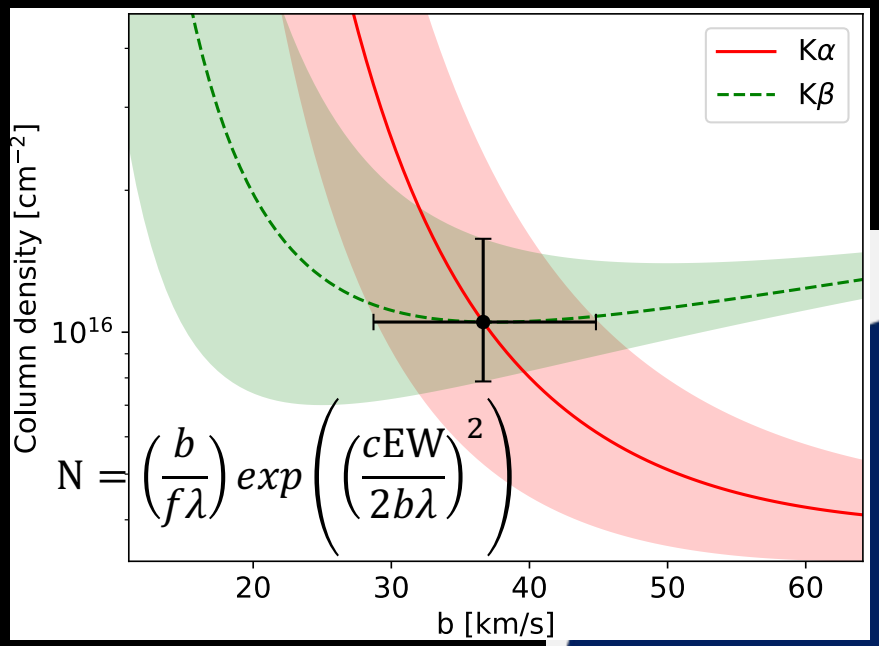
Pro:

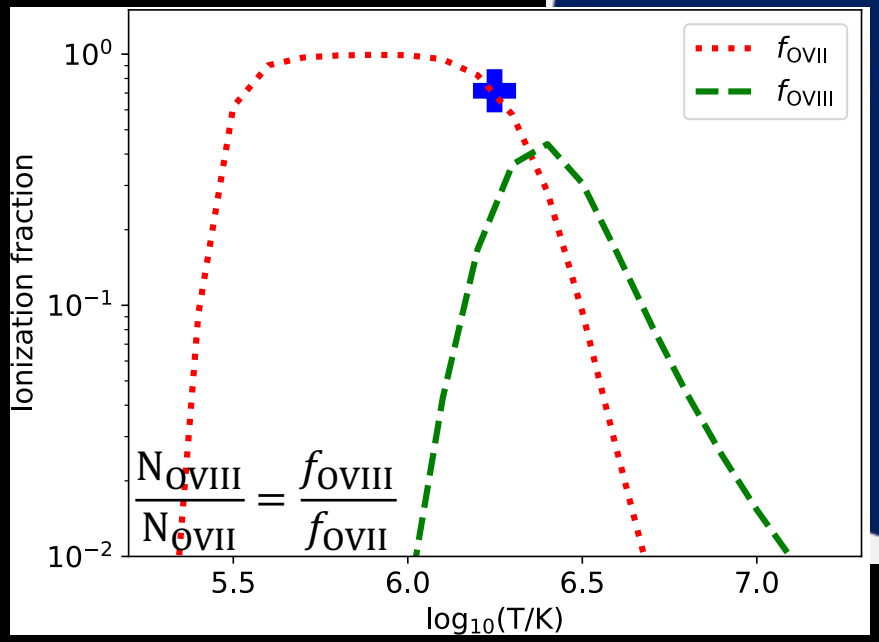
1. Plenty of blank-sky fields, not dependent on quasars
2. Samples large areas in the sky
3. Probed by continuum as well as metal ions

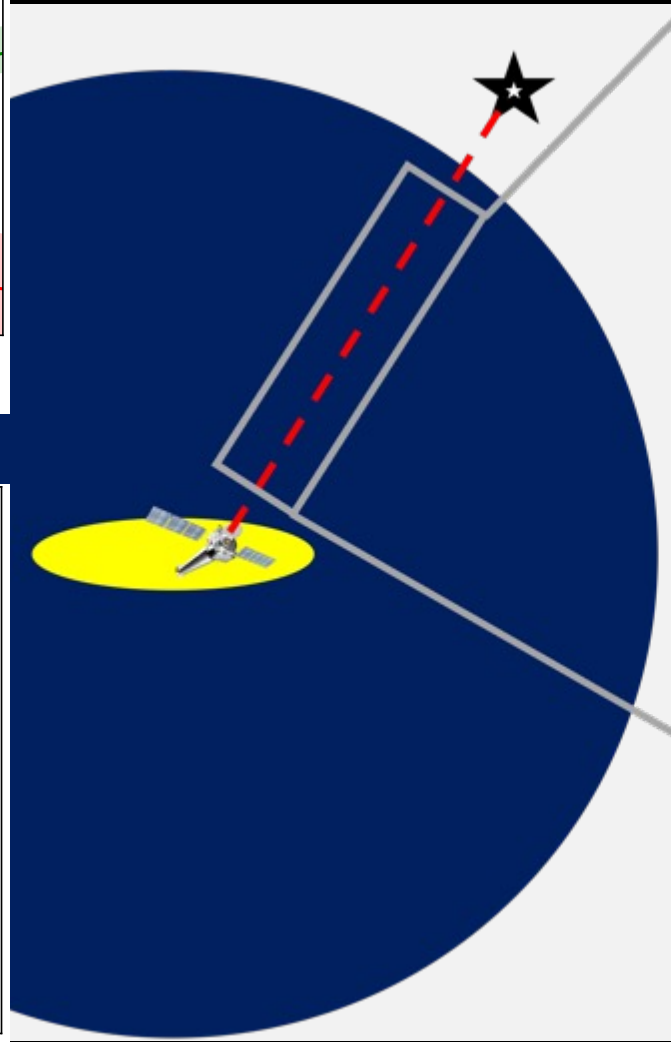
Con:

1. Biased to denser gas: $\int n^2 dl$
2. Biased to higher emissivity: limited temperature range
3. Background-dominated
4. CCD spectra cannot resolve transitions of different metals

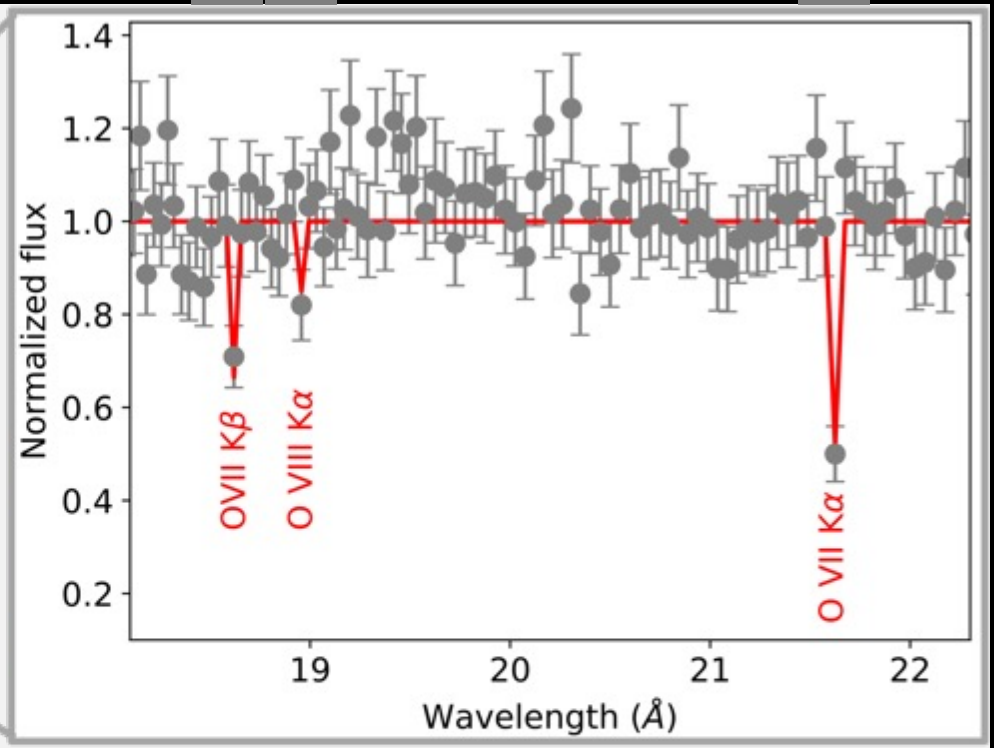
Methods







0.664 keV | 0.653 keV | 0.575 keV

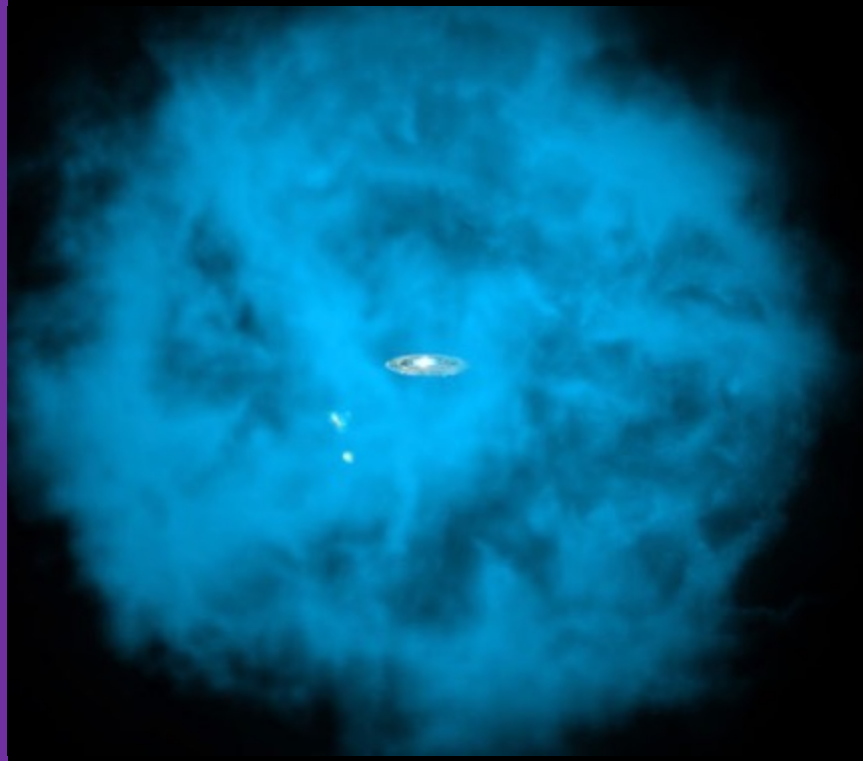


He-like and H-like ions of oxygen are the main tracer

Nicastro+2002, Williams+05, Gupta+12, Gupta+14, Fang+15, Nicastro+16, Gupta+17, Gatuzz+18...

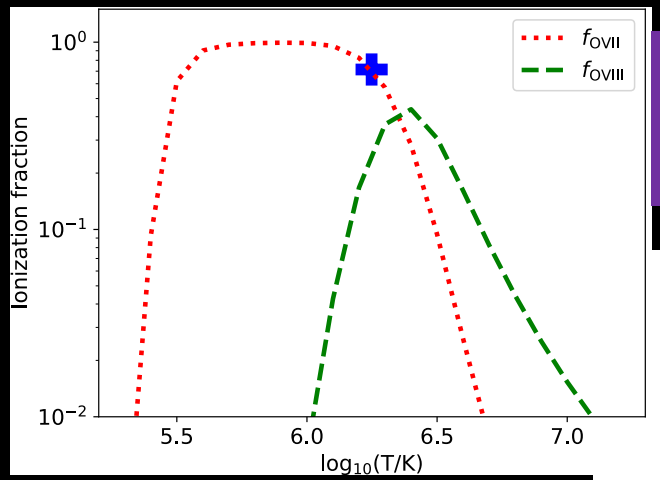
Summary of previous studies

1. The "hot" CGM of the Milky Way probed in X-ray absorption is at the ≈**virial temperature** of the Galaxy
2. The spatial distribution of the oxygen column density across the sky is consistent with a **spherical halo**
3. Combined with X-ray emission studies,
    1. The halo is extended out to **>200 kpc**
    2. The halo is **massive** enough to account for the missing Galactic baryons



Chandra News (Gupta et al. 2012, ApJL)

Nicastro+2002, Williams+05, Gupta+12, Gupta+14, Fang+15, Nicastro+16, Gupta+17, Gatuzz+18...

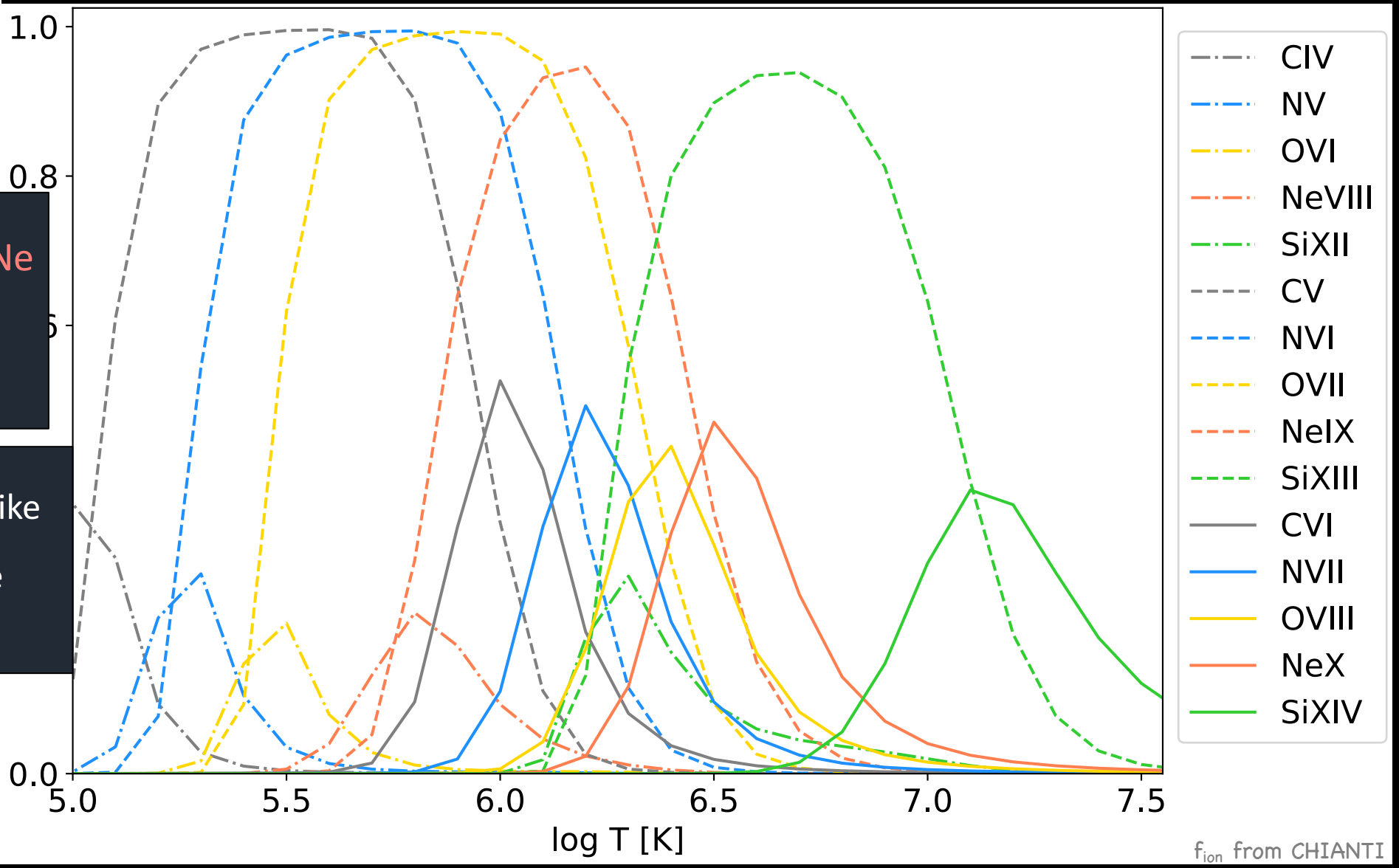


1. Do all OVII and OVIII come from the same phase?
2. Are Oxygen and other metals in solar chemical composition?

1. Ne X/Ne IX → T_{Ne}
O VIII/O VII → T_O
Is $T_{Ne} == T_O$?

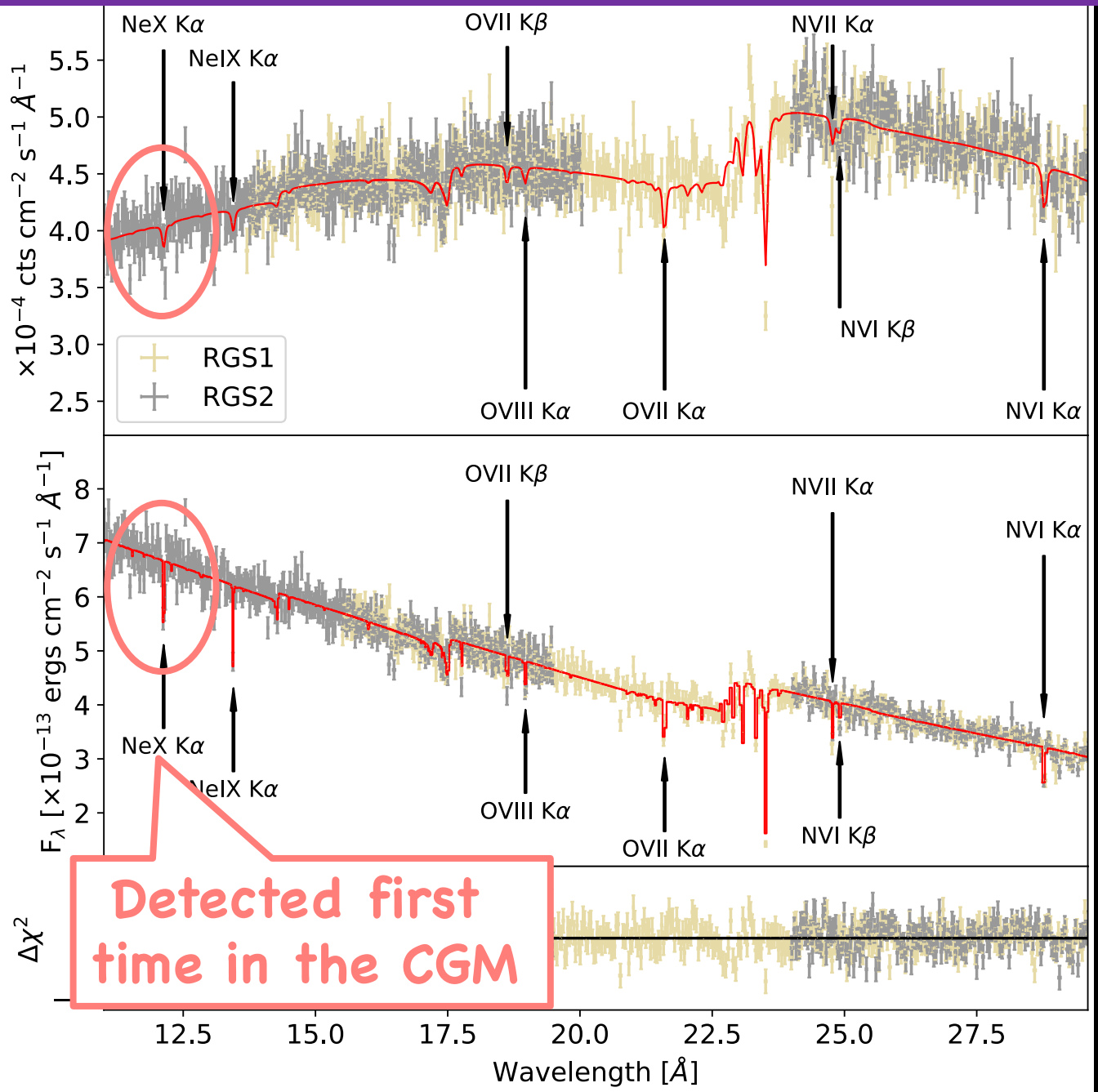
2. Ne X/O VIII → $T_{H\text{-}like}$
Ne IX/O VII → $T_{He\text{-}like}$
Is $T_{He\text{-}like} == T_{H\text{-}like}$?

3. Is (Ne/O) == $(Ne/O)_\odot$?



f_{ion} from CHIANTI

1.86 Ms XMM/RGS data toward the blazar 1ES1553+113 (l=22, b=41)



1. $T_{Ne} \neq T_O \neq T_N$
2. $T_{NeX/OVIII} \neq T_{NeIX/OVII}$
3. $N(Ne) \cong N(O) \cong N(N)$

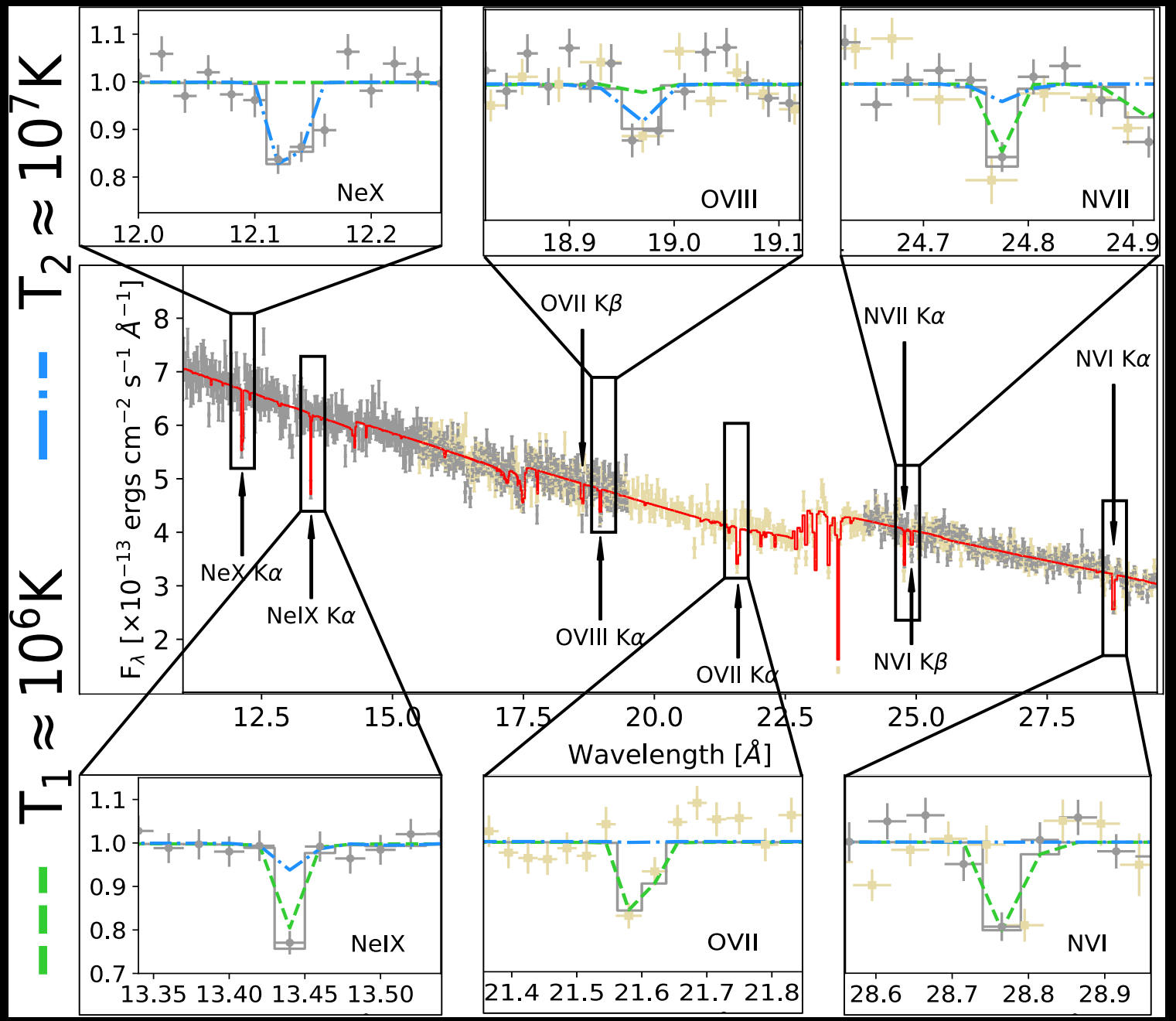
PHASE (Hybrid-ionization) modeling
[Krongold+2003, ApJ]

Detected first time in the CGM

Das, Mathur, Nicastro, Krongold, 2019, ApJL, 882, 23

1.86 Ms XMM/RGS data toward the blazar 1ES1553+113 (l=22, b=41)

1. ≈10^7 K super-virial phase coexists with the ≈10^6 K virial phase
2. OVII and OVIII do NOT come from the same phase (same for NeIX and NeX)
3. Baryon and metal content of the virial phase need to be revised



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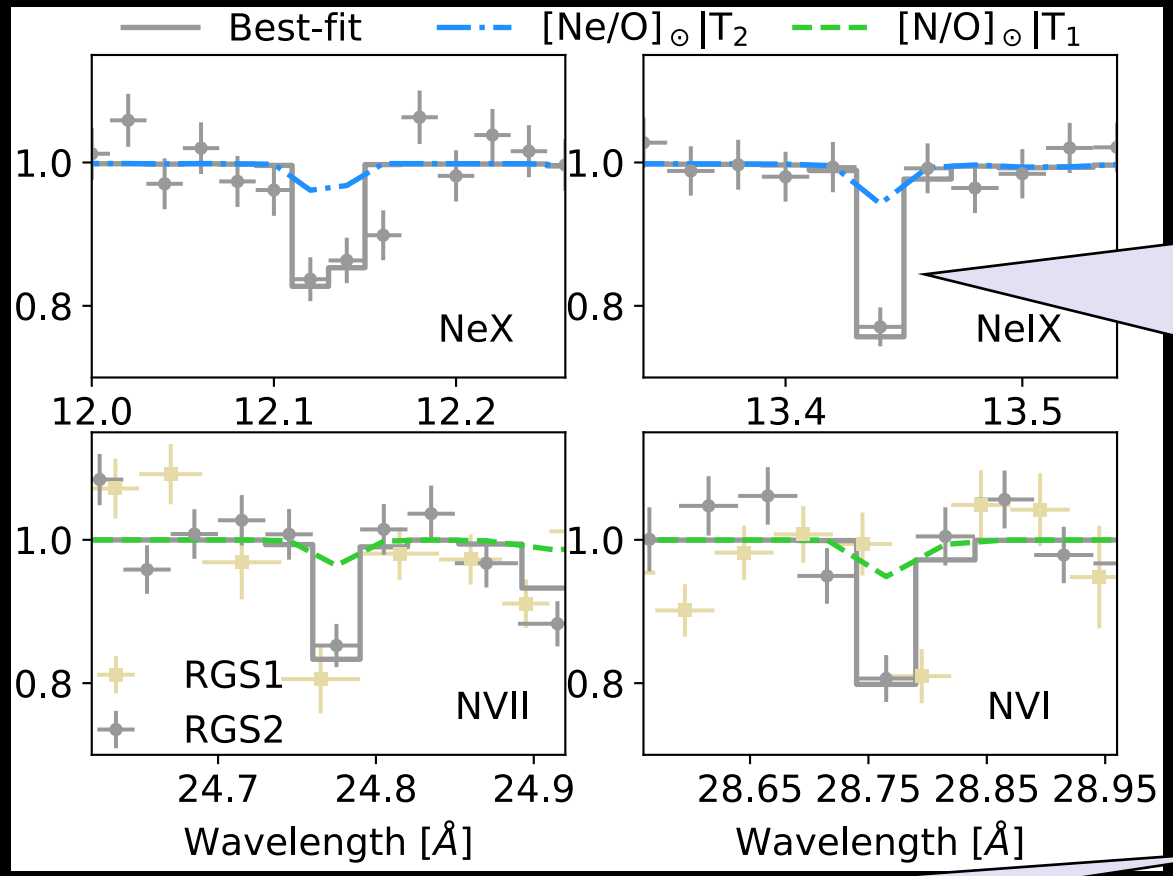
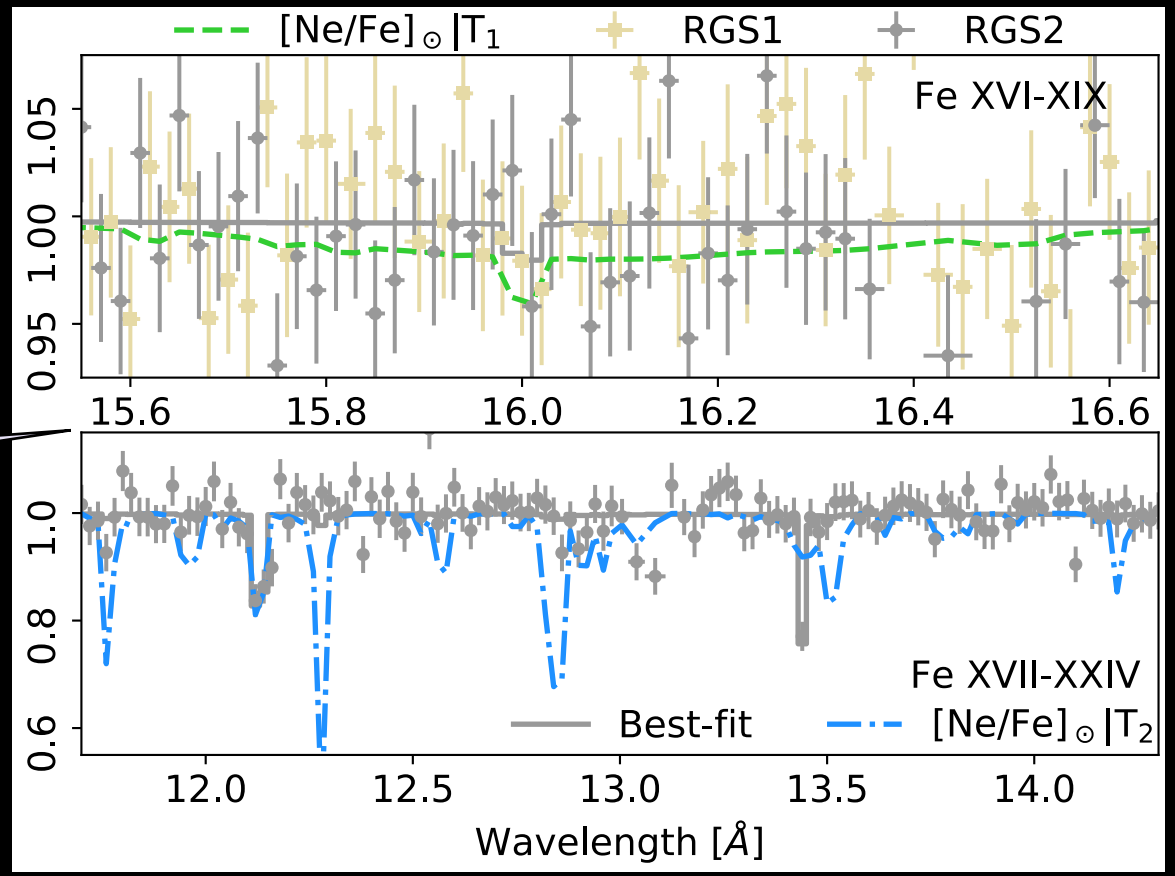


4. Neon & nitrogen are **super-solar** than oxygen

☞ Enrichment of Neon and Nitrogen from CCSNe and AGB winds and/or depletion of oxygen onto dust?

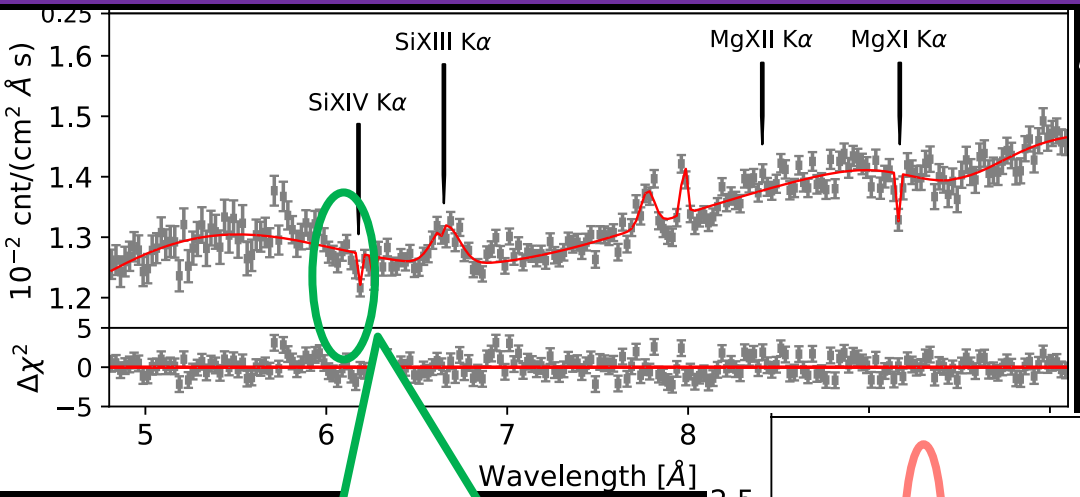


5. Neon & oxygen are super-solar than Fe (i.e., **α-enhancement**)

☞ Enrichment from CCSNe and/or depletion of Fe onto dust?

Das, Mathur, Nicastro, Krongold, 2019, ApJL, 882, 23

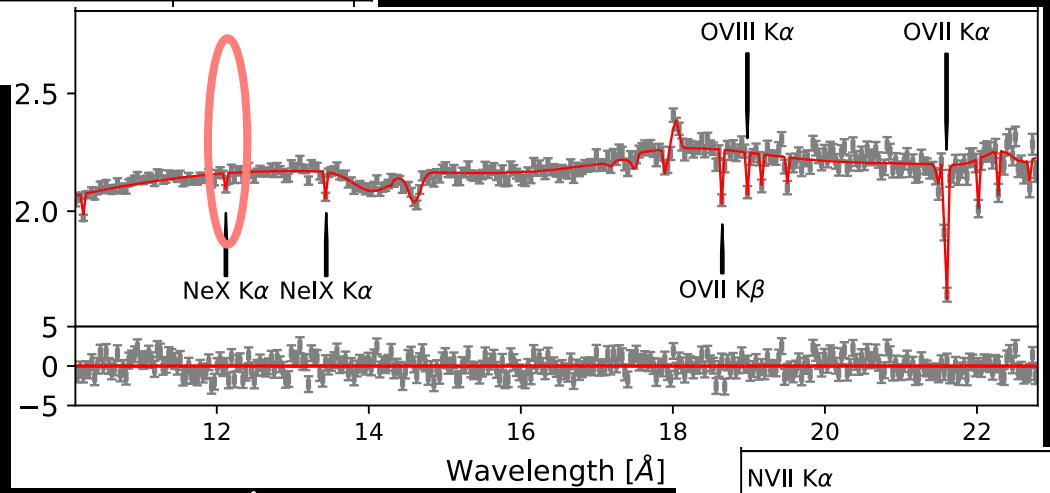
1.51 Ms Chandra/TG data toward the blazar Mrk421 (l=180, b=64)



ACIS-S/HETG

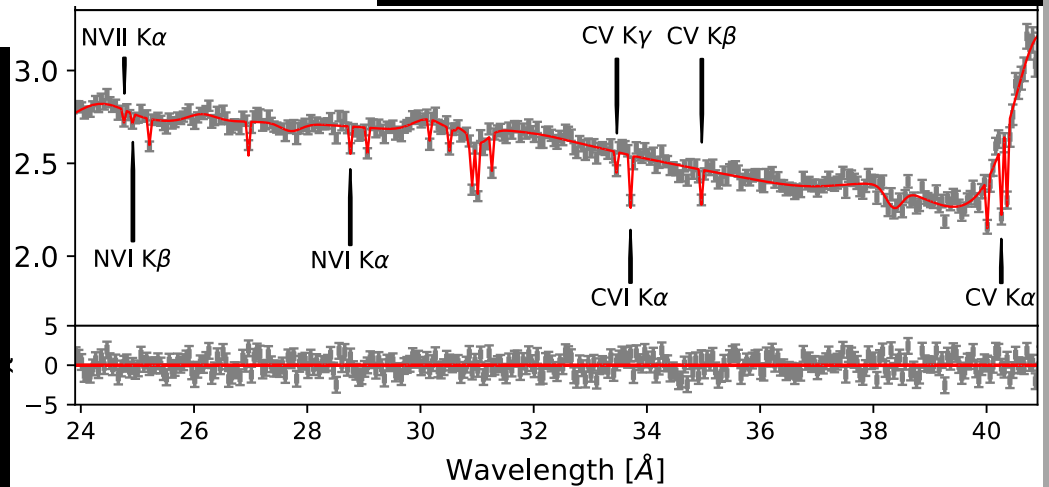
Larger wavelength coverage, more metal tracers, broader temperature range

Detected first time in the CGM



ACIS-S/LETG

HRC-S/LETG



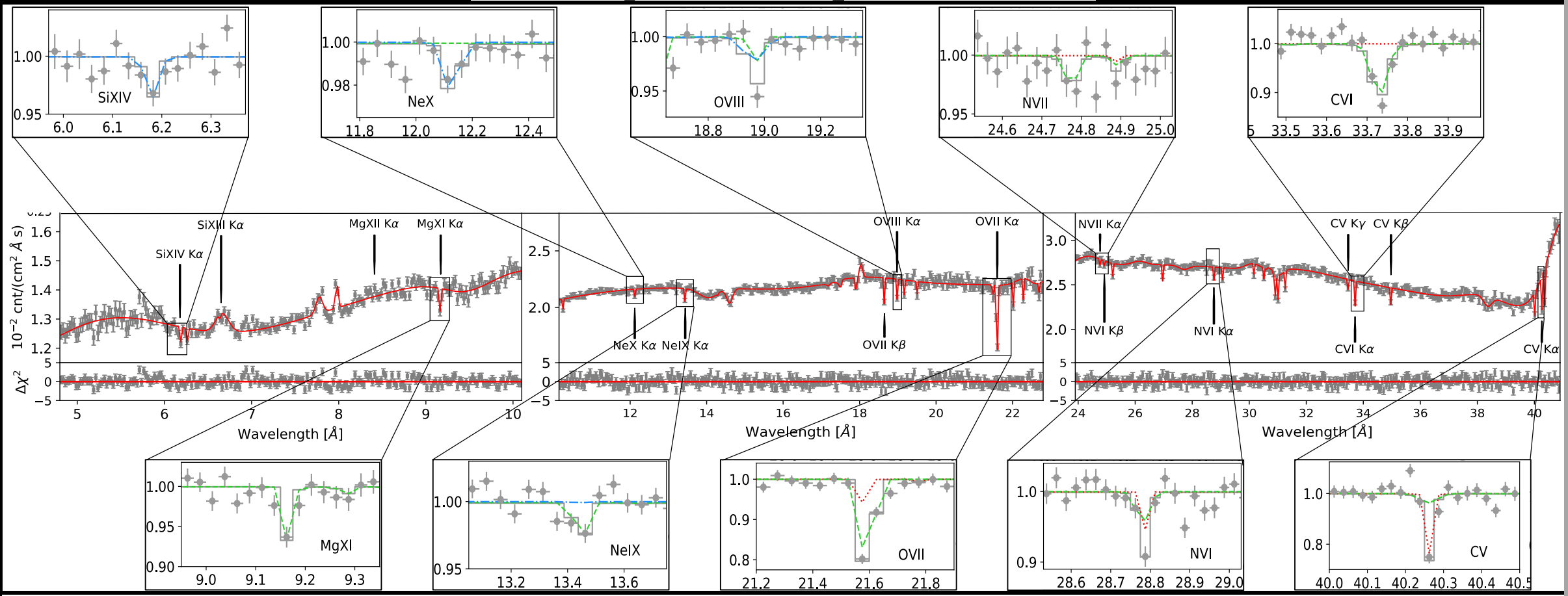
Sightline away from Galactic center; likely unaffected by past nuclear outflows

Das, Mathur, Gupta, Krongold, 2021, ApJ, 918, 83

1.51 Ms Chandra/TG data toward the blazar Mrk421 (l=180, b=64)

Sub-virial | Virial | Super-virial

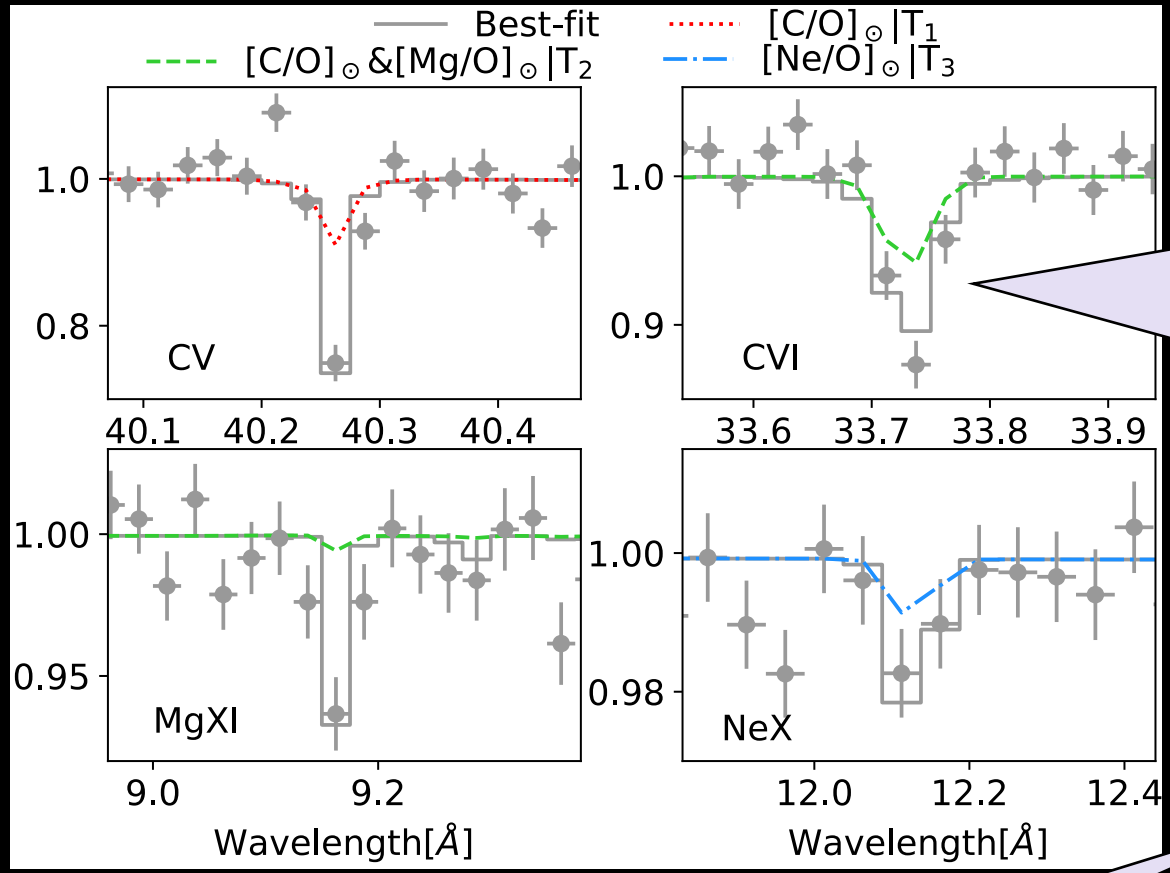
T_1 T_2 T_3



1. $10^{7.5}$ K super-virial phase and $10^{5.5}$ K sub-virial phase coexist with the 10^6 K virial phase
2. Some ions (NVI, OVII, OVIII) reside in multiple phases
3. Different ions of the same metal (C, N, O, Ne) reside in different phases

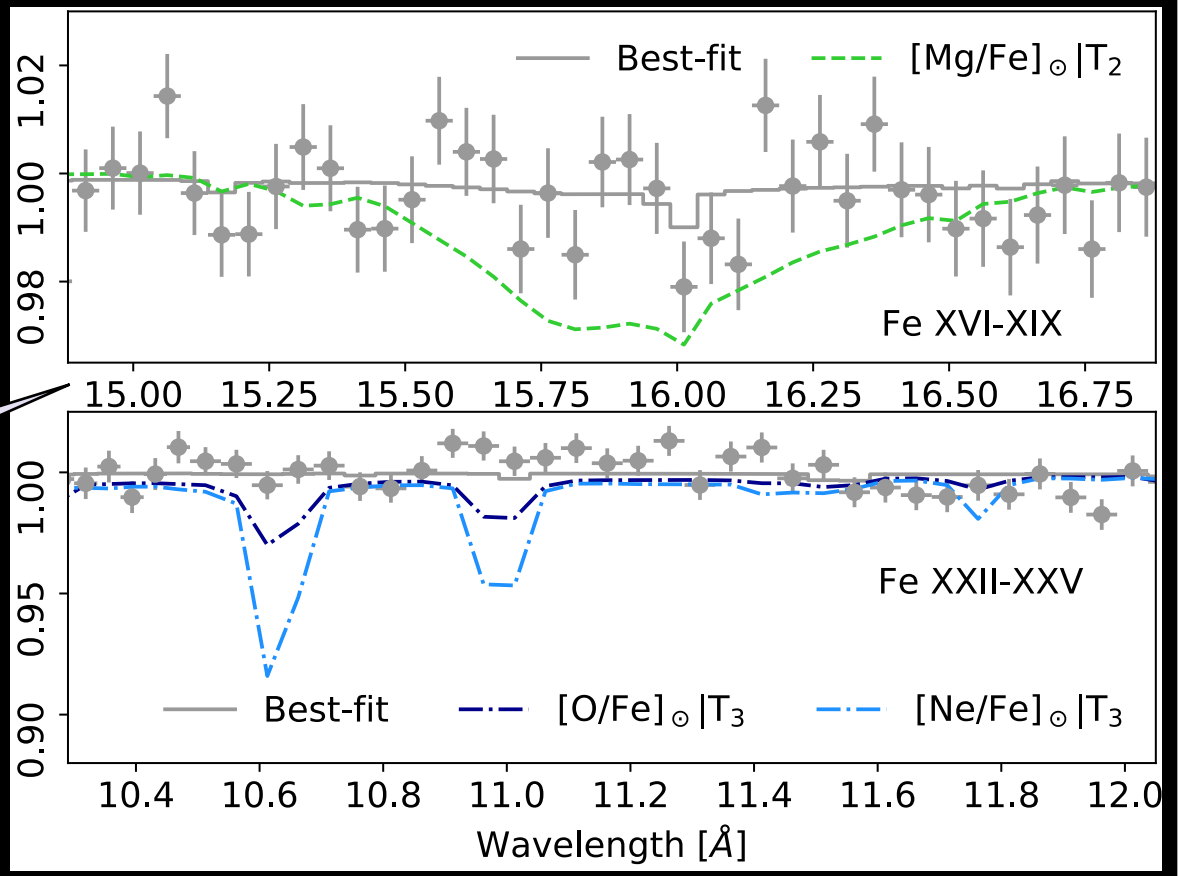
Das, Mathur, Gupta, Krongold, 2021, ApJ, 918, 83

1.51 Ms Chandra/TG data toward the blazar Mrk421 (l=180, b=64)



4. Some metals are **super-solar** than oxygen in some phases but solar in other phases

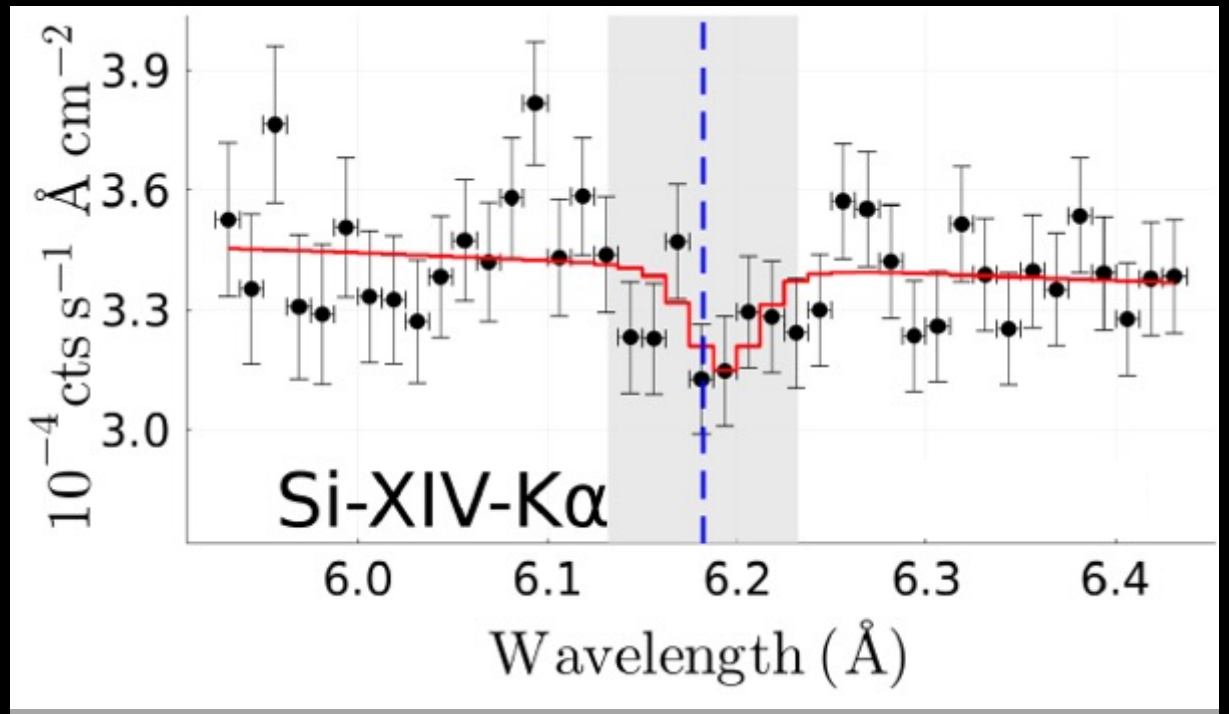
☞ Enrichment + depletion + inhomogeneous mixing?



5. **α-enhancement**

Das, Mathur, Gupta, Krongold, 2021, ApJ, 918, 83

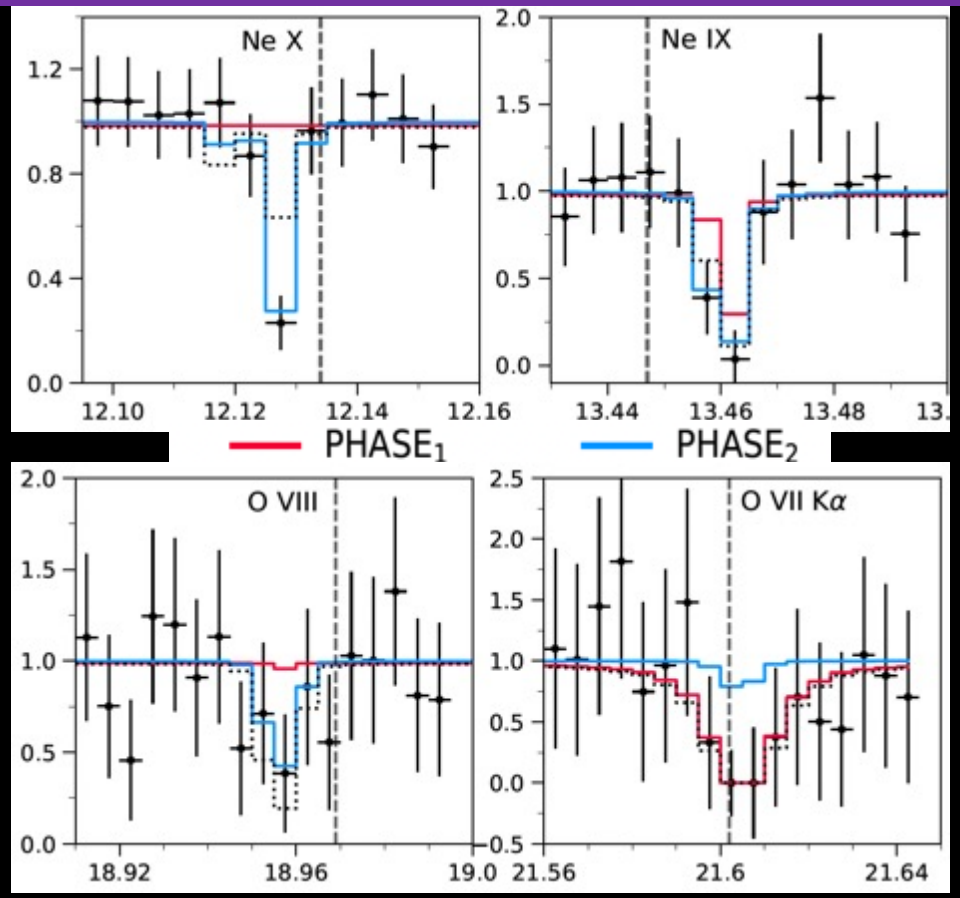
Evidence of super-virial hot CGM from **stacked** 10 Ms ACIS-S/HETG and 1 Ms ACIS-S/LETG data across the sky + first detection of S XVI Kα absorption in the CGM (not shown here)



Lara-DI et al. (incl. **Das**) 2023, ApJ

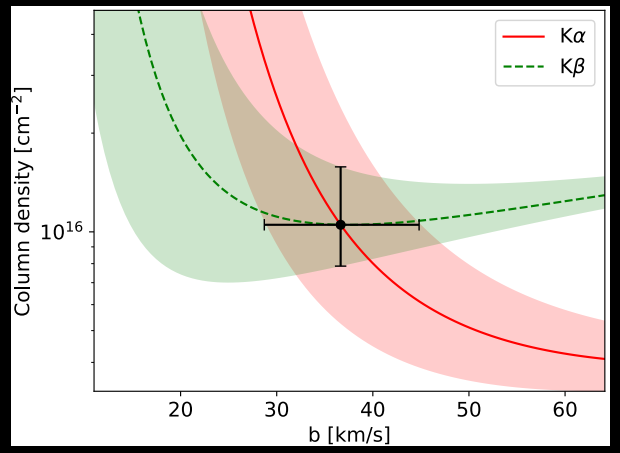
(More details in the next talk by Armando)

Further evidence of coexisting virial and super-virial phases and super-solar Ne/O toward another **individual** quasar sightline

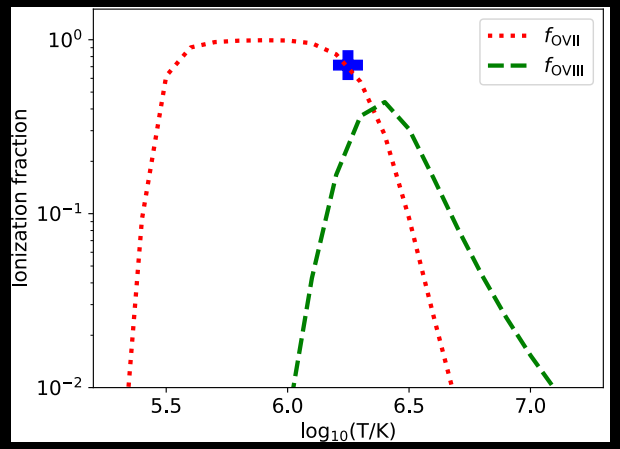


McClain, Mathur, **Das** et al., 2023 (to be submitted soon!)

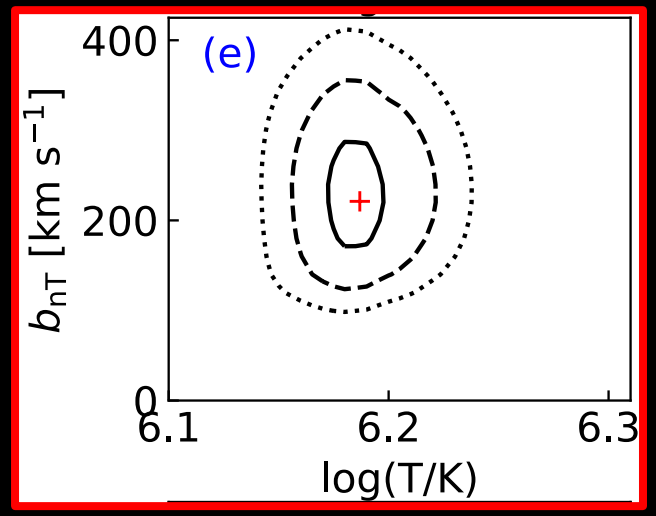
Non-thermal (turbulent) line broadening



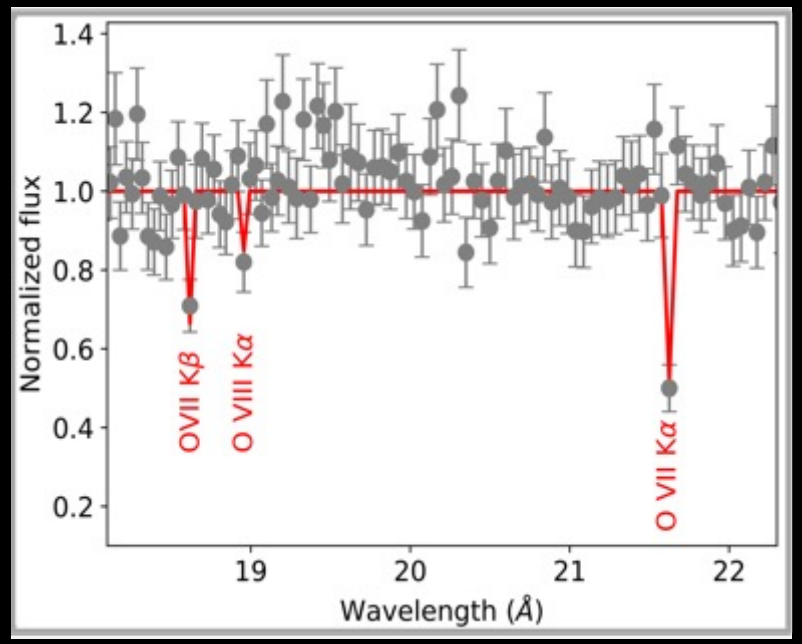
Total line broadening

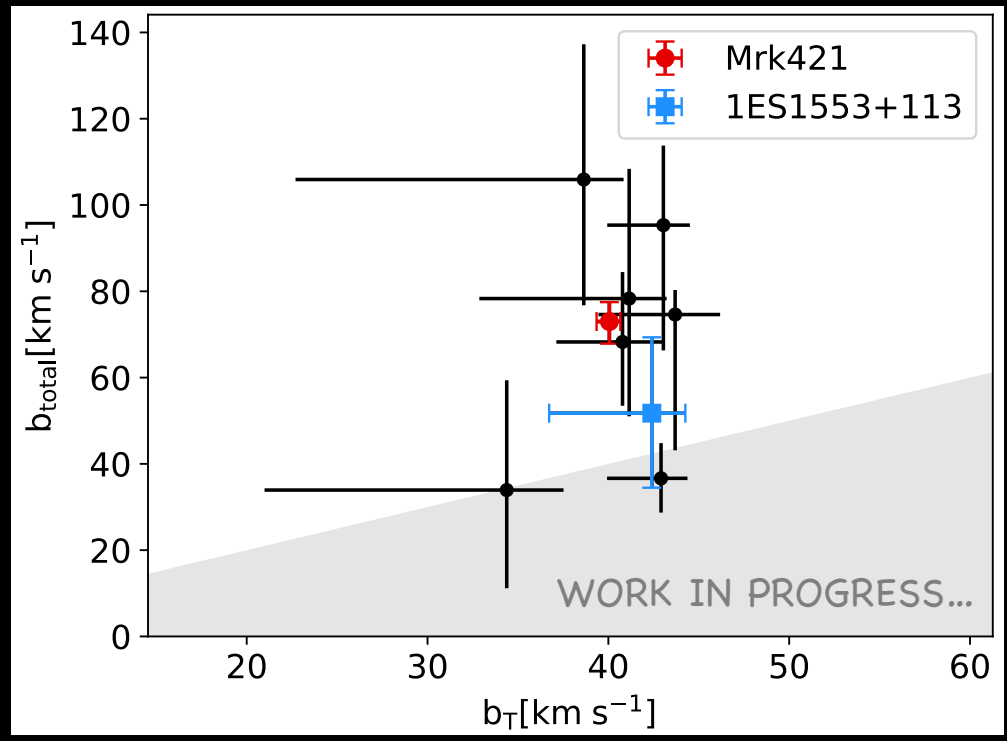


Thermal line broadening



Das et al., 2021, ApJ, 918, 83 (toward Mrk 421)



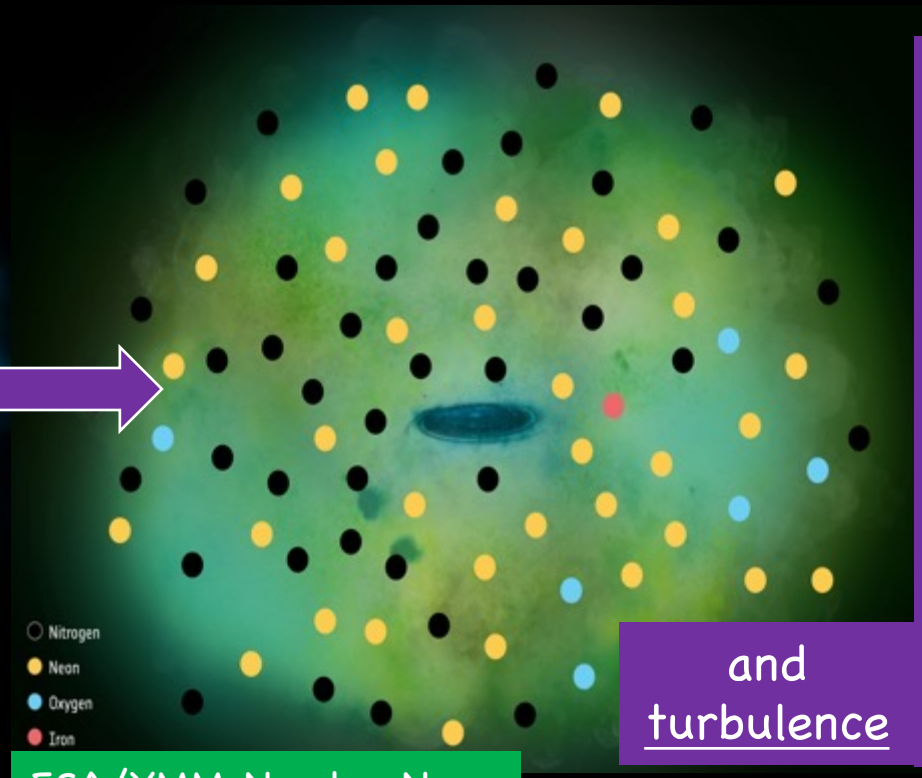


Summary

Thermal, non-thermal & chemical properties of the "hot" CGM are yet to be understood

Only oxygen: Virialized "hot" CGM in solar chemical composition

Chandra News



ESA/XMM-Newton News

and turbulence

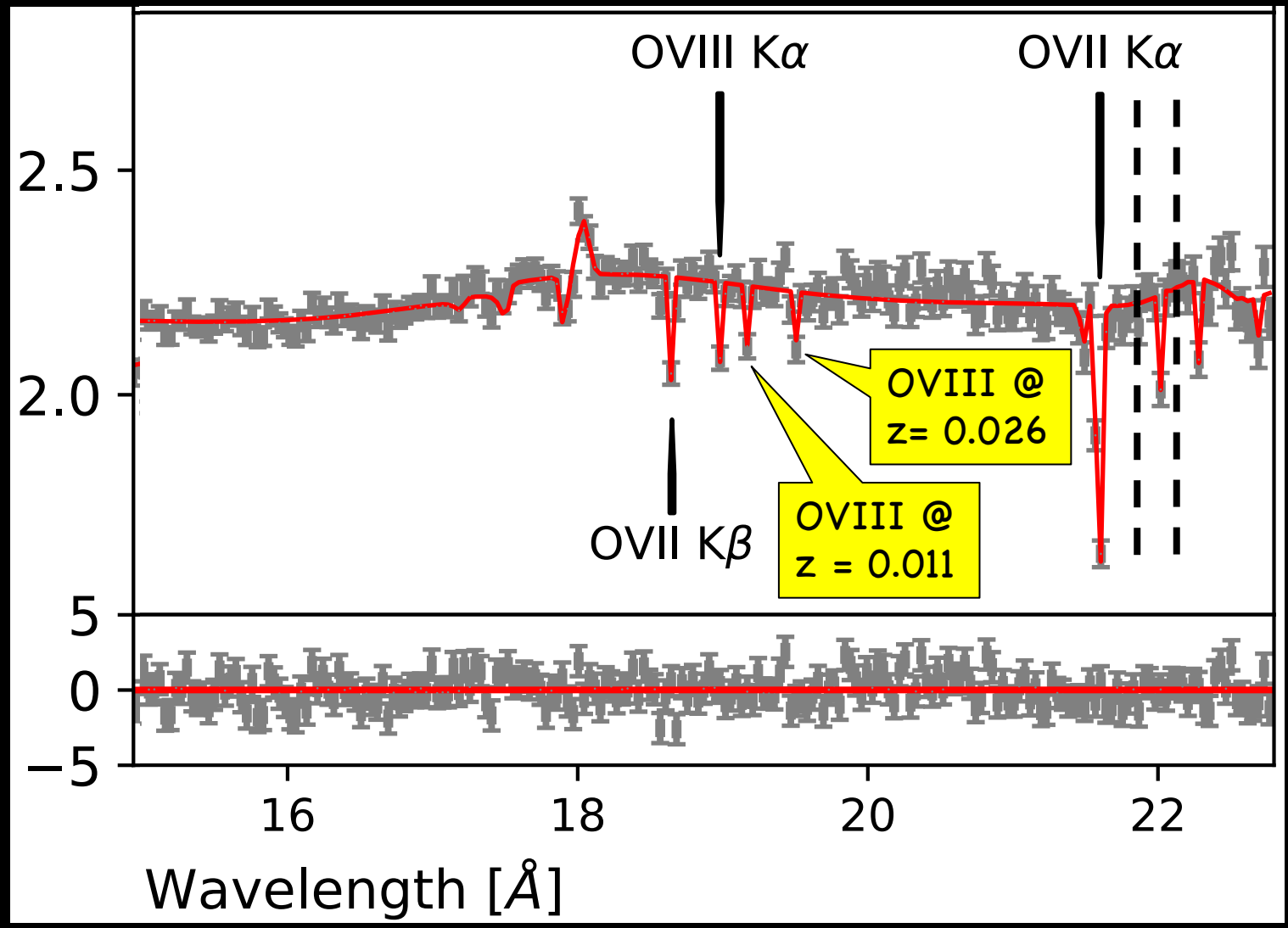
Oxygen and other metals:

1. multi-phase (super-virial, virial, and sub-virial) "hot" CGM
2. Non-solar chemical composition
3. Inhomogeneous mixing of metals

Future X-ray missions should aim for kinematically resolving the metal ions in the CGM.
Microcalorimeter: $E/\Delta E$ better at higher energy. Good for metals heavier than oxygen (Ne, Mg, Si, S).
Grating: $\lambda/\Delta\lambda$ better at higher wavelength (lower energy). Good for lighter metals (C, N, O).

Intervening lines: warm-hot IGM or CGM of external galaxies

OVII is not detected.
OVIII is detected.
Hotter IGM/CGM
than expected?



Also see Nicastro+2005, ApJ

Das, Mathur, Gupta, Krongold, 2021, ApJ, 918, 83