Are Metals in the Intergalactic Medium Out of Equilibrium?

Benjamin Oppenheimer
Leiden University

Edinburgh Intergalactic Interactions

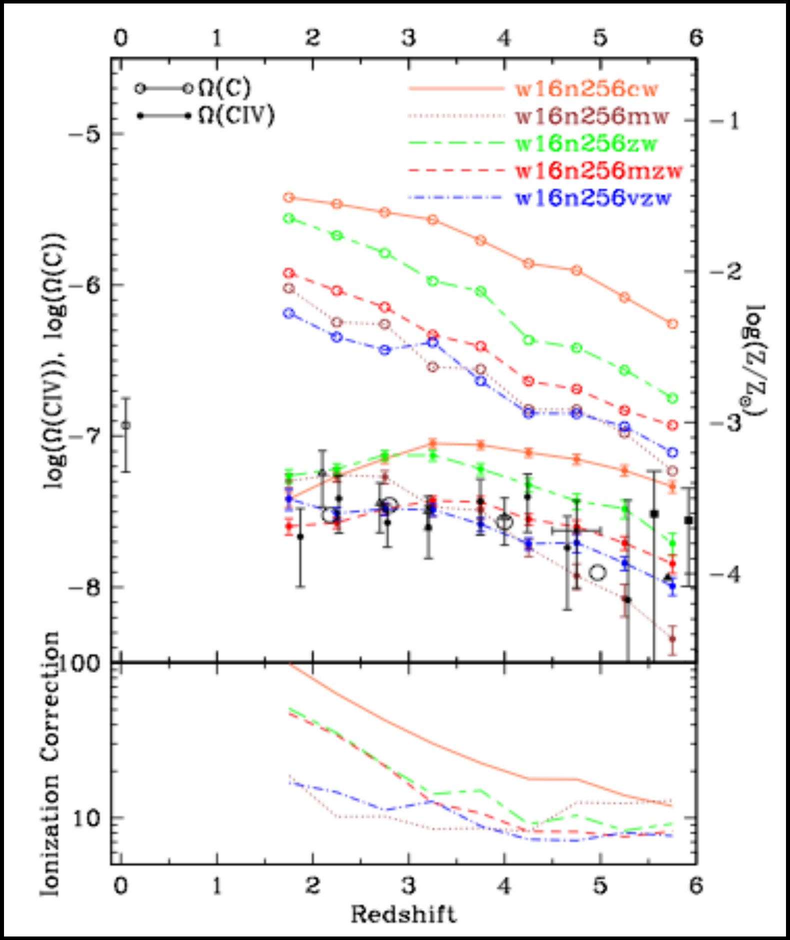
With Joop Schaye (Leiden)

Reason 1 to Care about Metals in the IGM/ CGM: Constraints on Galaxy Formation

The enrichment of the IGM/CGM by galactic superwinds is a key constraint of how galaxies form, grow, and evolve.

Reproducing C IV statistics from z=6->2 using cosmological hydrodynamic simulations allowed us to choose our momentum-driven wind model.

This model also fits many things about galaxies (many papers by Opp., Dave, Finlator, & others).

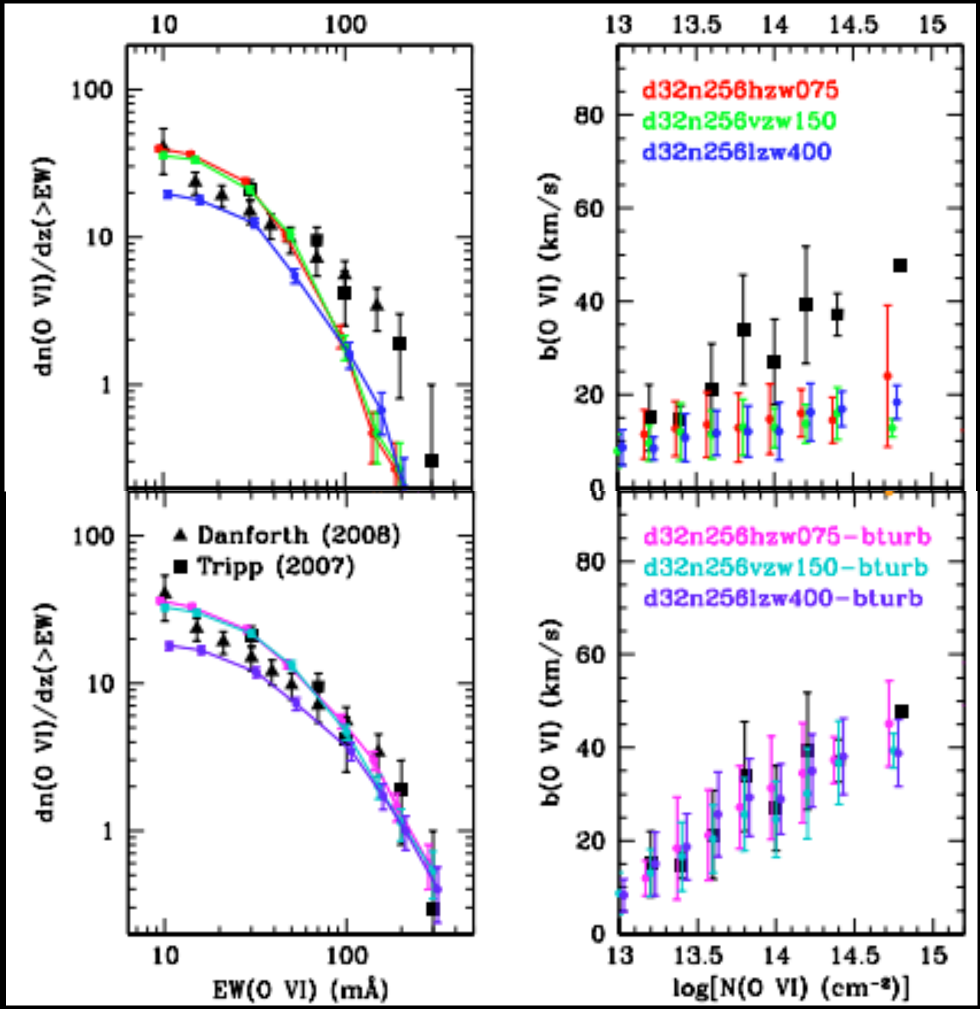


Opp/Dave (2006)

Reason 2 to Care about Metals in the IGM/CGM: Physical Conditions of Diffuse Gas

We can fit the observed column density distribution of O VI, but not the equivalent width distribution. Line widths are too thin in a cosmological SPH simulation.

Solution (Opp./Dave 2009) is to add sub-SPH turbulence, which is based on lensed CIV in quasar pair statistics (Rauch+, 2001) that find the metal-enriched IGM is turbulent.

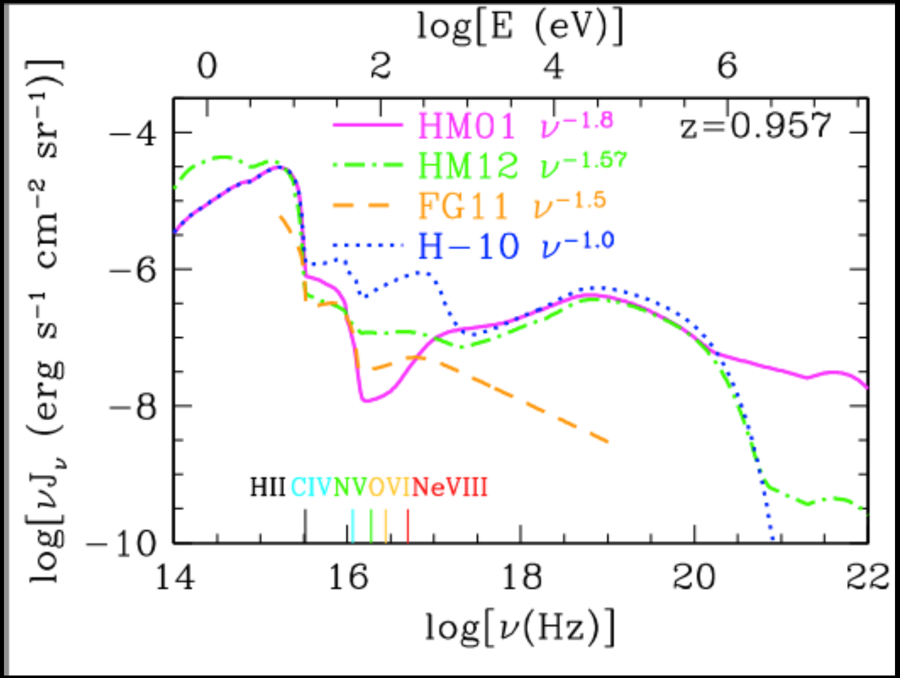


Opp./Dave (2009)

An Inherent Assumption in Such Modelling: Metals are in Equilibrium with the Extra-Galactic Background.

One usually assumes an ionizing extra-galactic background (EGB) that is completely uniform (eg. Haardt & Madau 2001 or 2012).

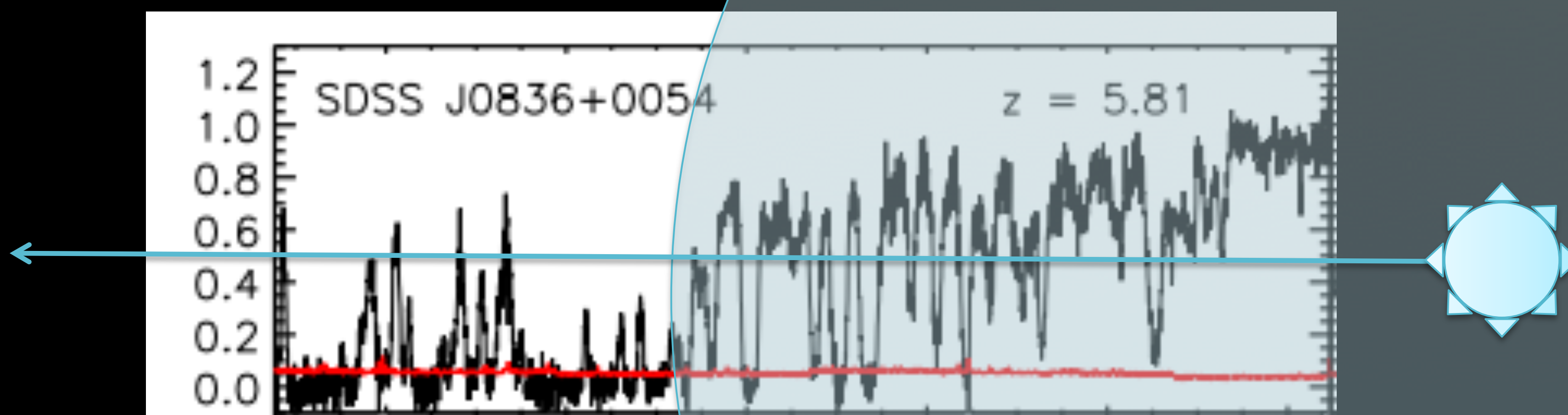
This is a valid assumption if the IGM is optically thin and photons have long mean free paths.



From Oppenheimer & Schaye (2013a)

However, Deviations from a Uniform Ionizing EGB Are Known to Exist

A very obvious example is the proximity zone of a quasar where the ionizing flux is increased by a significant factor.



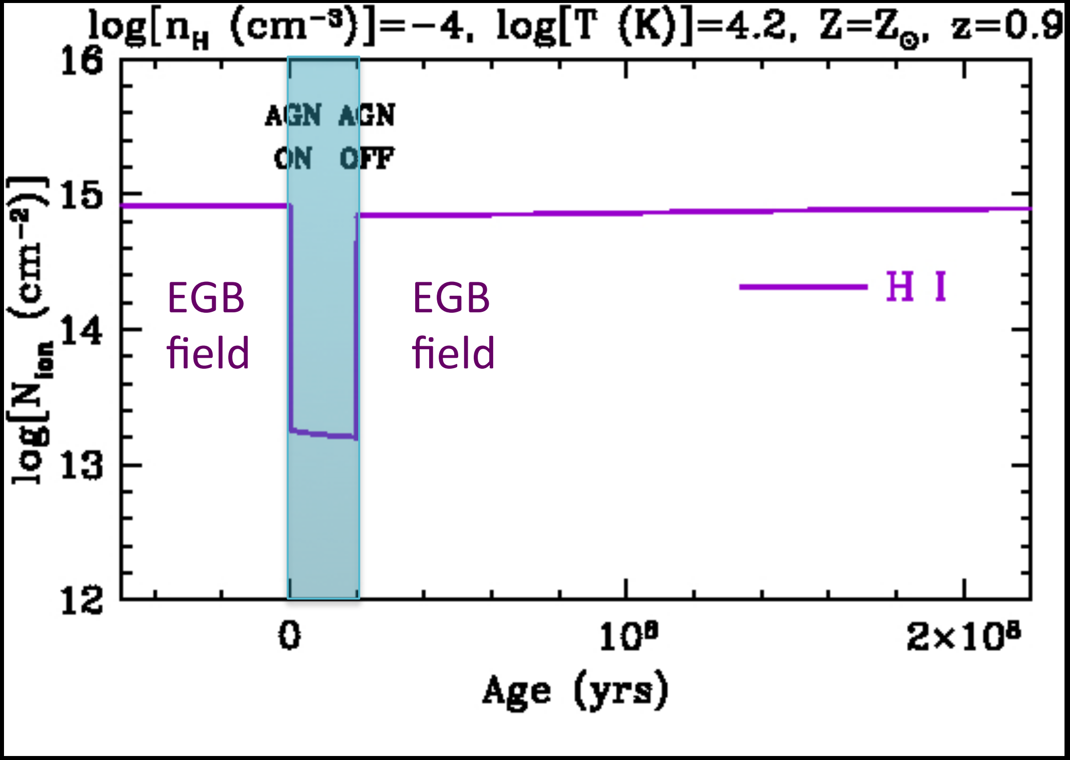
Lyman-alpha forest from Calverley et al. (2011)

Consider CGM Gas Exposed to the Changing Field Strength of an AGN

Applying our non-equilibrium calculations, we (Opp. & Schaye, 2013ab) consider cases where a QSO turns on for 20 Myrs and then off.

N(HI) is reduced by the increase in the 1 Ryd radiation: 50-fold in this example: $n_H=10^{-4}$ cm^{-3} cool (~10^4 K) gas.

However, HII recombines rapidly when the field returns to the ionizing background level.



Opp./JS (2013b)

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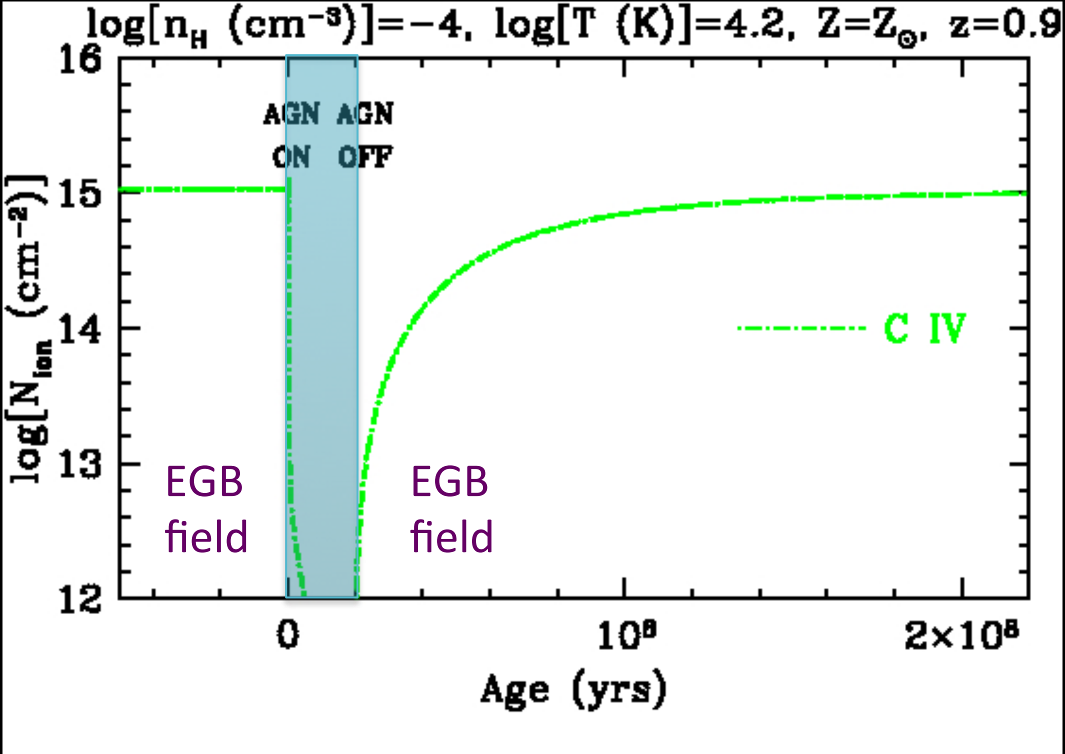

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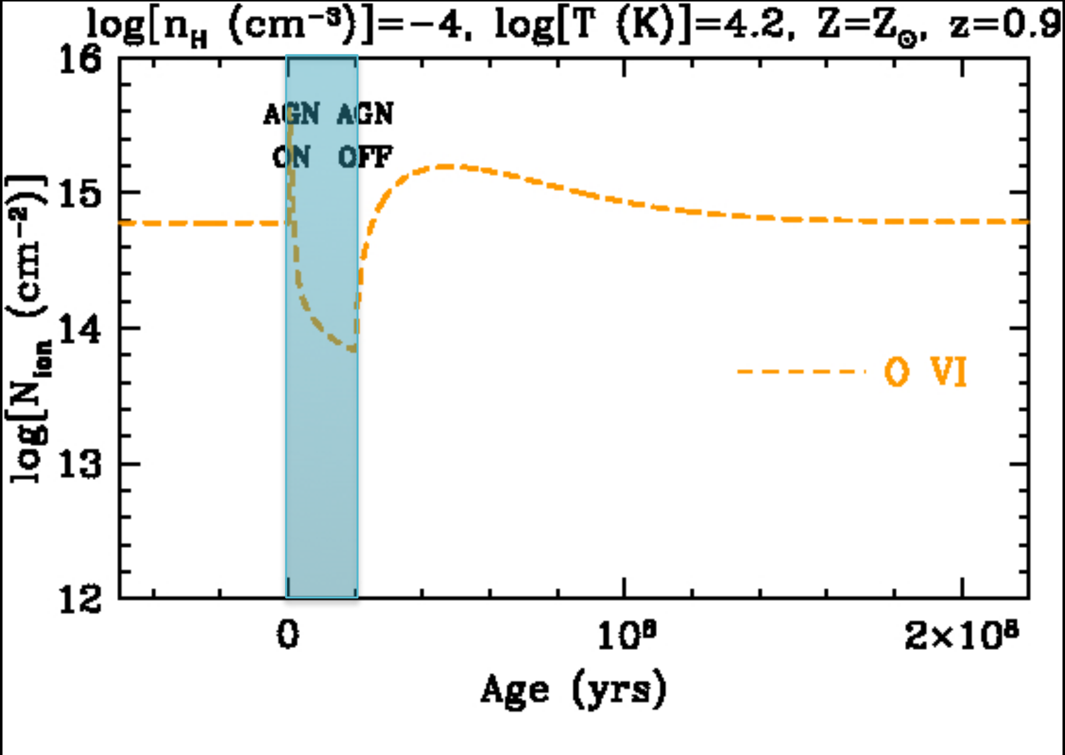

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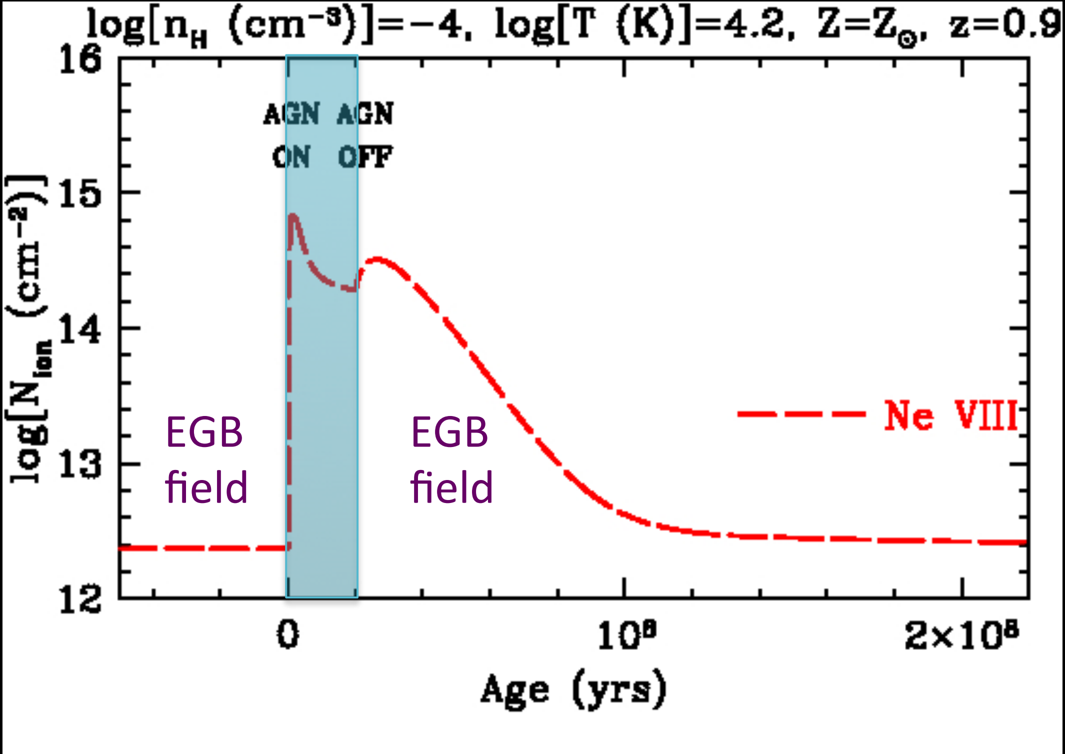


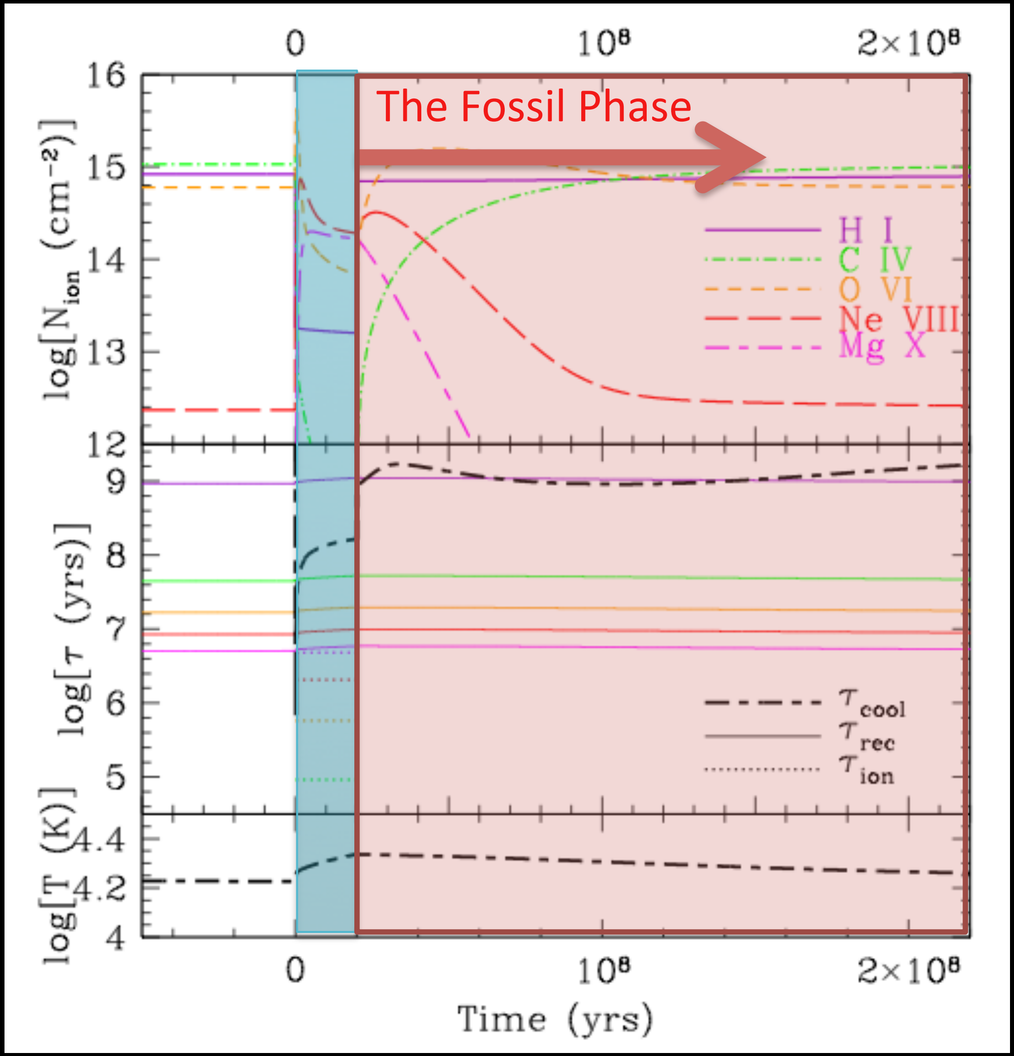
Opp./JS (2013b)

Metal Lines in AGN Proximity Zone *Fossils* Recombine Slowly

Metals have recombination timescales of 5-40 Myrs at the density we are exploring: comparable to or more than τ_{AGN}.

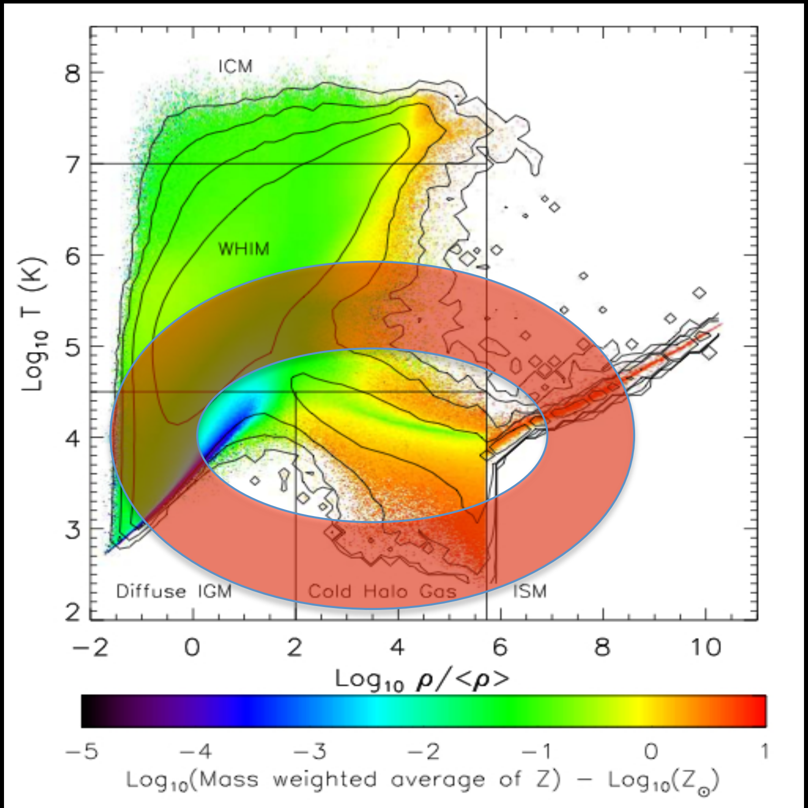
But… HII-> HI has a recombination timescale of 1 Gyr at the same density! However, it has to only recombine to f_{HI}~10^{-4}: τ_{rec}~10^5 yrs

The difference: metals have ion fraction of order unity so the entire τ_{rec} matters. Plus they have multiple states and τ_{rec}'s.

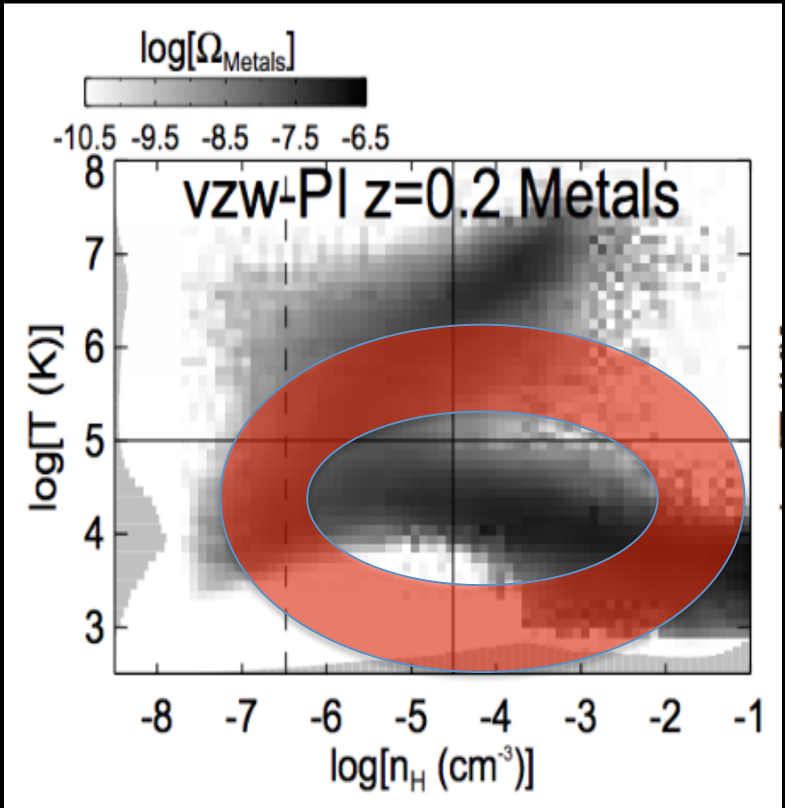


Opp./JS (2013b)

Metals Are Common in Cool CGM Gas



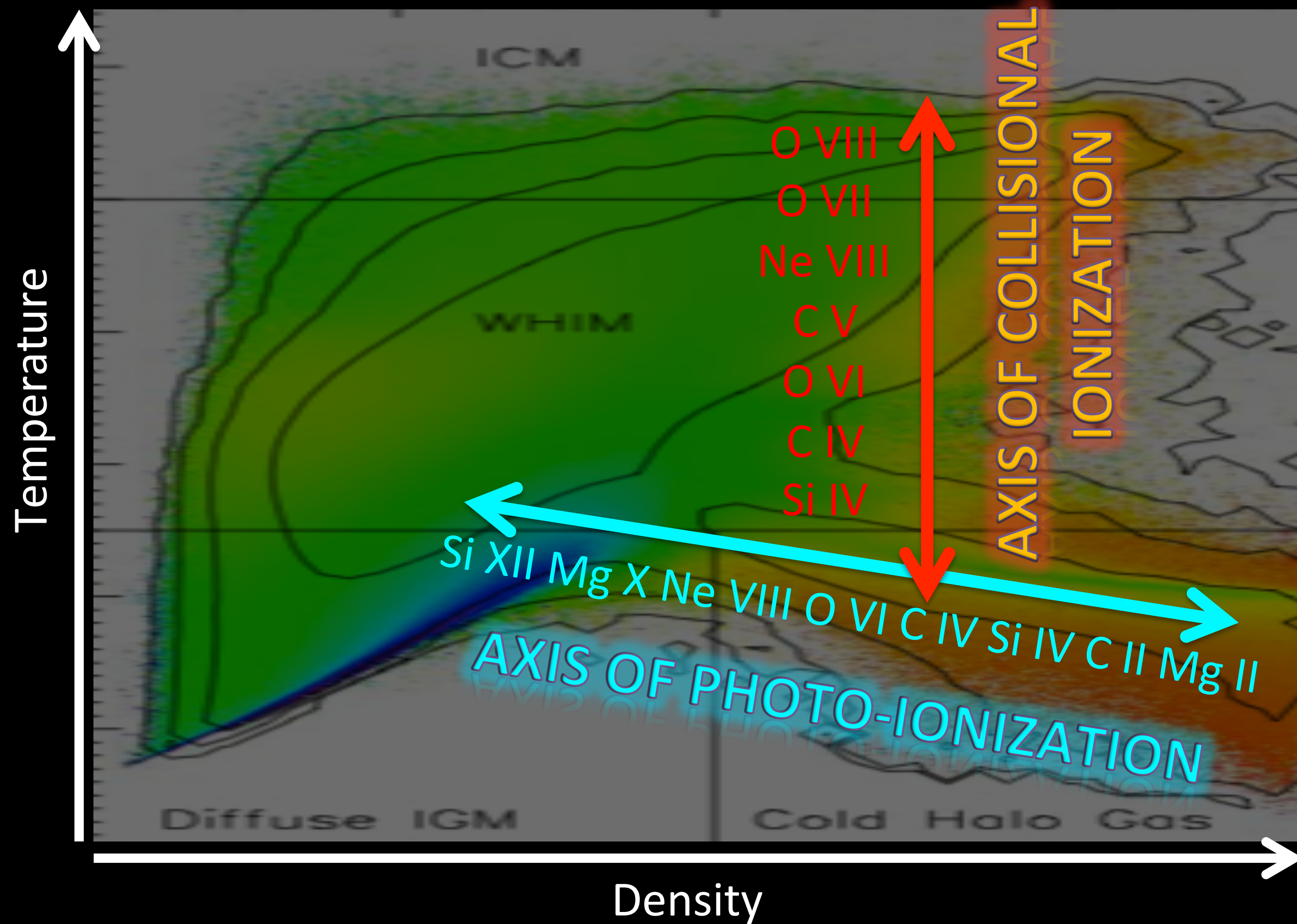
Wiersma et al. (2010)



Opp. et al. (2012)

Multiple simulations find a significant fraction of metal-enriched diffuse gas at cool ($T \sim 10^4$ K) circumgalactic densities ($\delta \sim 30$-10,000). These simulations argue observed metal absorbers often arise from this gas.

The Axes of Diffuse Metal Ions

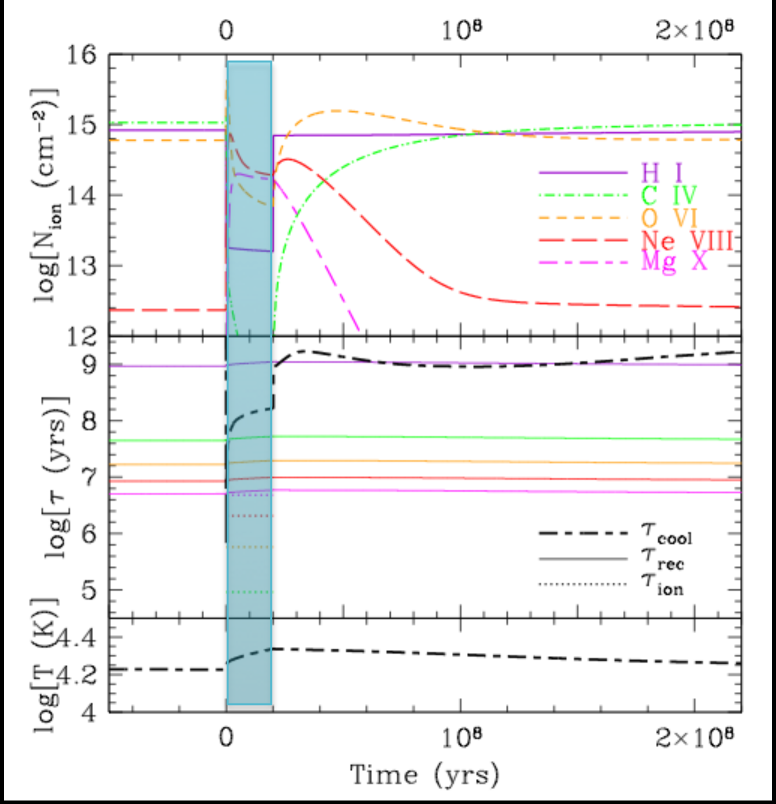


AGN Proximity Fossil Variations: Metallicity

The proximity zone effect is the same if you change the metallicity, except:

1) Your metal columns scale by Z, making them different relative to HI.

2) Photo-heating depends on metallicity with higher Z leading to greater photo-heating, but this effect even at $Z_\odot$ is minor.



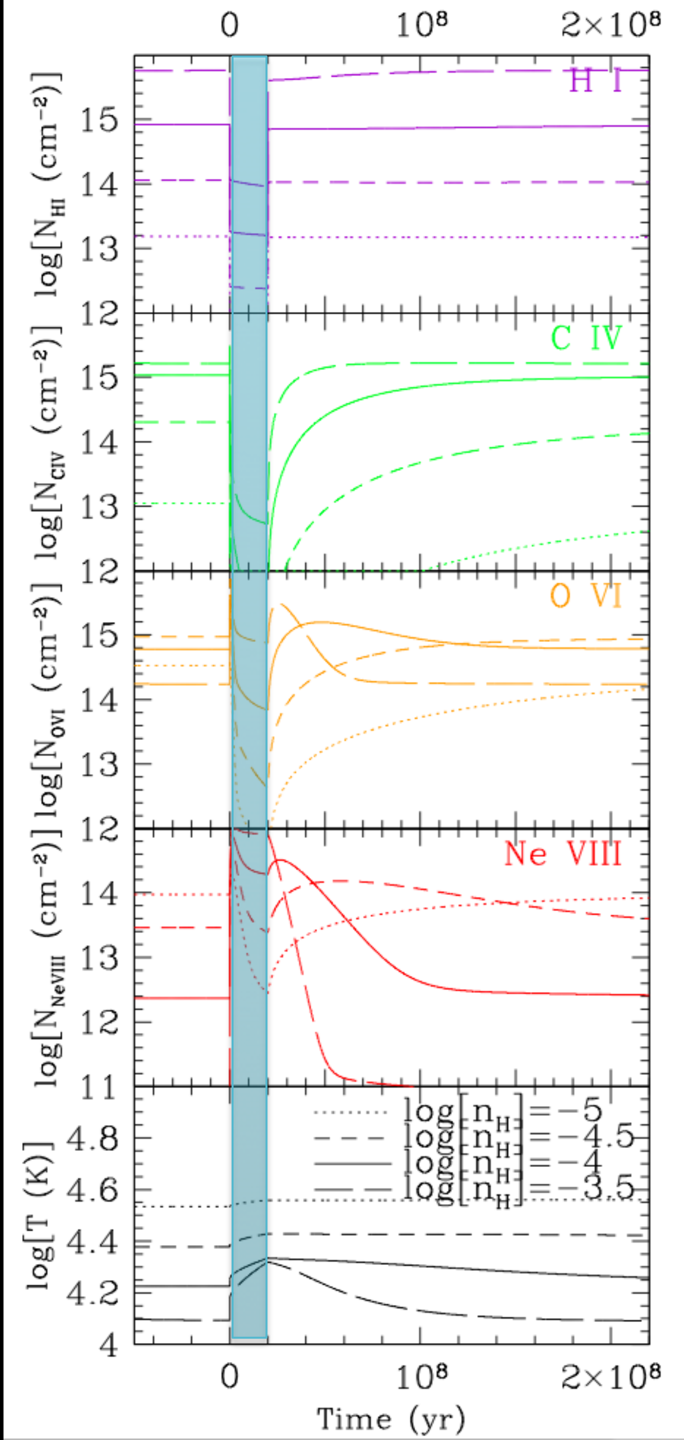
Opp./JS (2013b)

AGN Proximity Fossil Variations: Density

Fiducial case where $n_H=10^{-4}$ cm^{-3} because it is a typical enriched density in the CGM/IGM.

Lower density: $\tau_{rec} \sim 1/n_H$, so the recombination delay is even longer.

Higher density: it is still a significant effect for a shorter time scale, however the differences can be even more dramatic depending on the metal ion.



Opp./JS (2013b)

AGN Proximity Fossil Variations: AGN Intensity

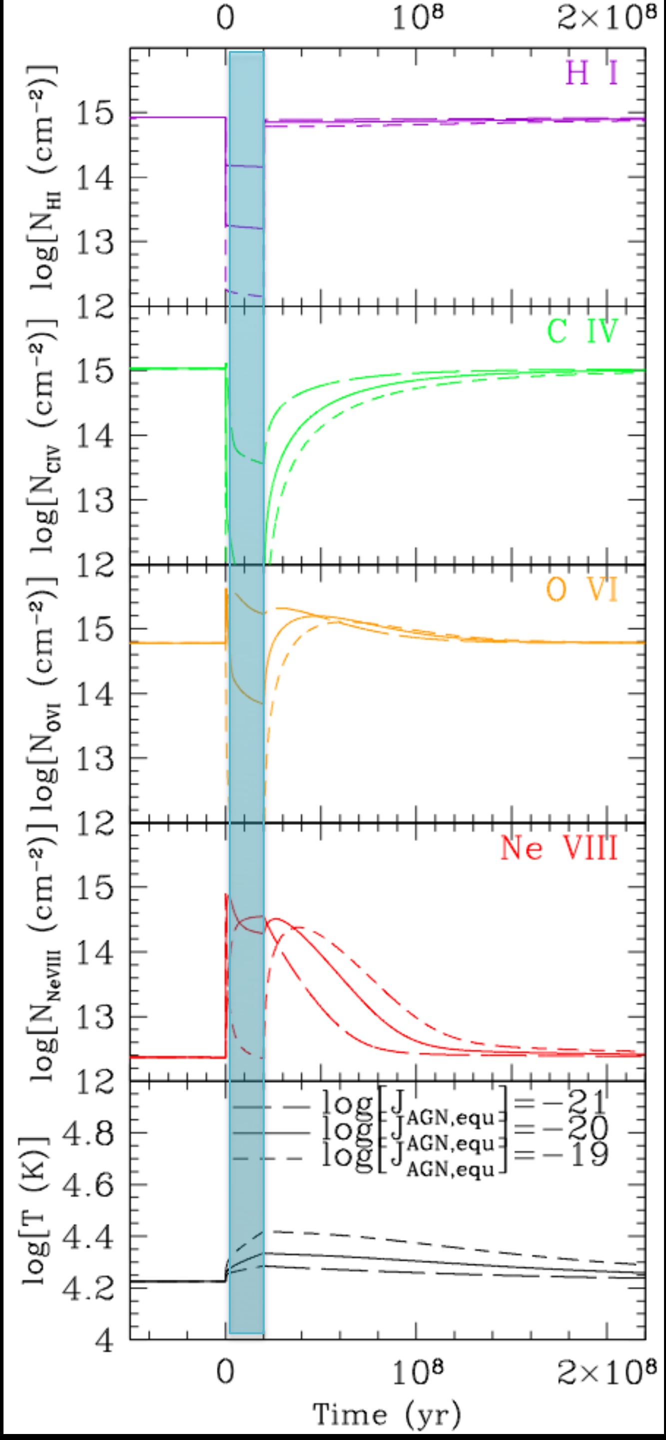
Fiducial case assumes 50-fold increase at Lyman limit corresponding to a $L_{0.5\text{-}2.0keV}$= $10^{44.1}$ erg/s AGN at 100 kpc.

Increasing or decreasing the field by a factor of 10 doesn't fundamentally change the behavior:

1) Weaker AGNs ionize to a lower state than stronger AGNs. $\tau_{ion} \sim 1/f_{AGN}$ means it takes longer to reach ionization equilibrium during the AGN-on phase.

2) Nevertheless, τ_{rec} during fossil phase is the same.

Opp./JS (2013b)



How Common Are AGN Proximity Zone Fossils? Perhaps Pretty Common

We show average column density changes in proximity zone fossils on grids of density and AGN intensity for individual ions: CIV, NV, OVI, NeVIII.

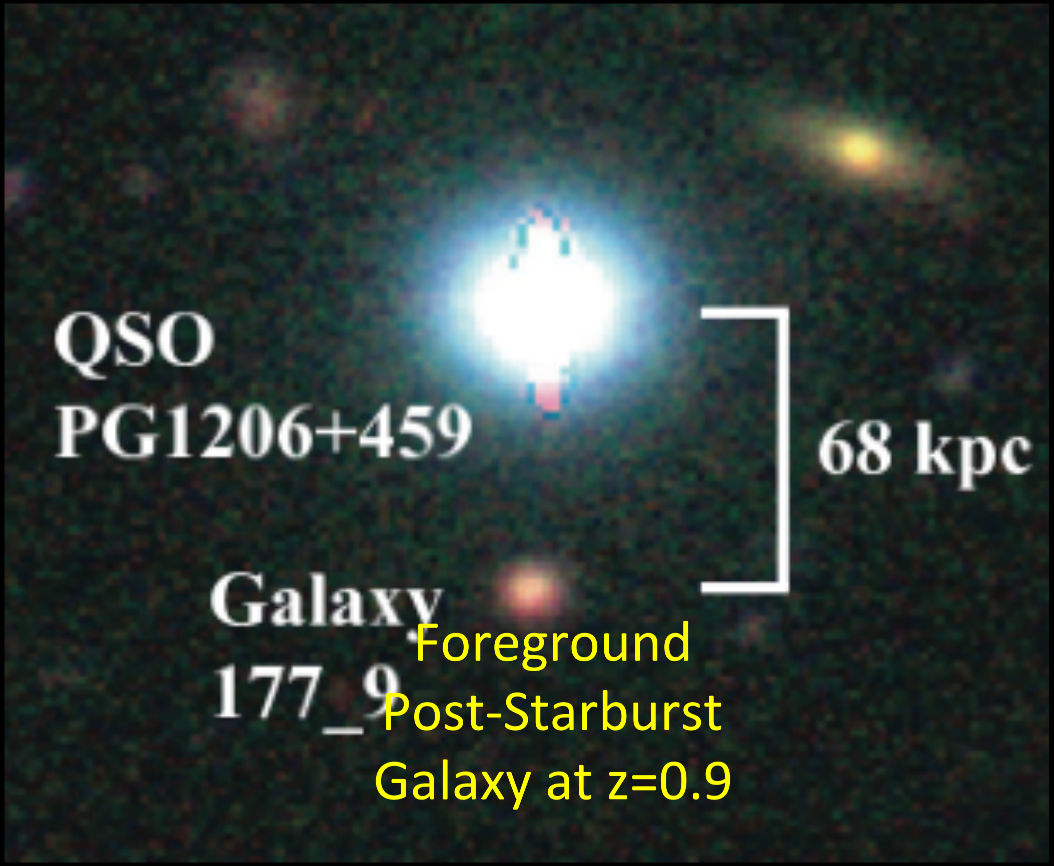
The effect is common for a variety of metal-enriched diffuse gas densities and AGN strengths.

O VI CGM
at z=0.25

$\log[n_H]$	HM01	-22.5	-22.0	-21.5	-21.0	-20.5	-20.0
-5.0	14.7	+0.0	+0.1	+0.1	+0.0	-0.4	-1.0
-4.5	14.6	+0.1	+0.3	+0.5	+0.6	+0.4	-0.1
-4.0	14.0	+0.2	+0.5	+0.9	+1.3	+1.4	+1.2
-3.5	13.2	+0.3	+0.7	+1.3	+1.9	+2.3	+2.3
-3.0	12.2	+0.4	+1.0	+1.8	+2.6	+3.1	+3.3

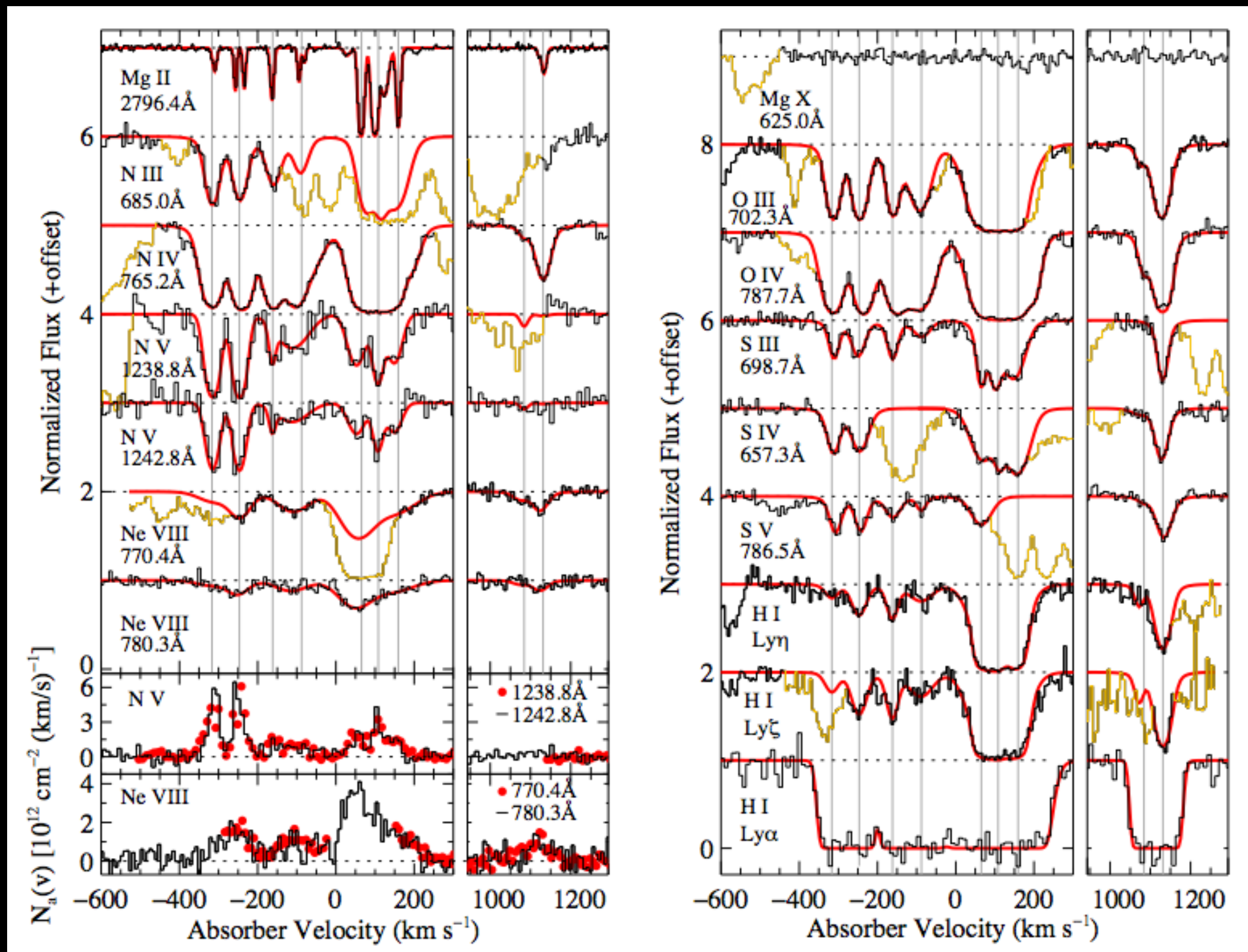
Opp./JS (2013b)

Linking Gas to Galaxies: Probing the Circumgalactic Medium of a 1.8 L* Post-Starburst Galaxy toward the PG1206+459 QSO



Observations by Tripp et al. 2011

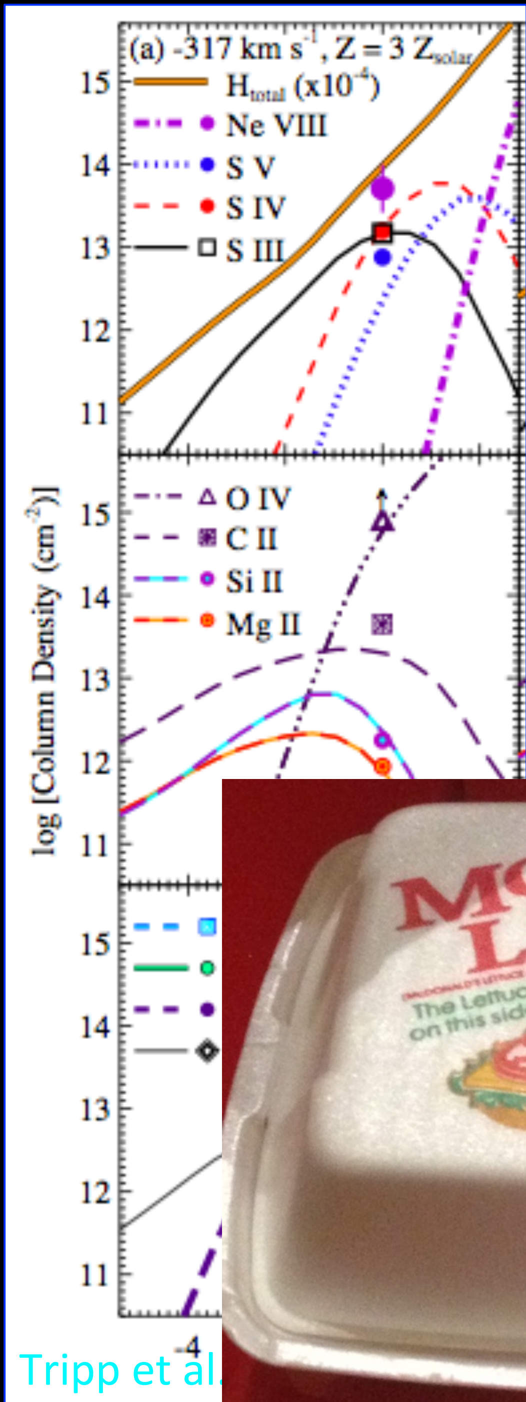
Tripp et al. (2011): Fifteen detected ion species in aligned components at the redshift of the post-starburst galaxy, including Ne VIII aligned with Mg II.

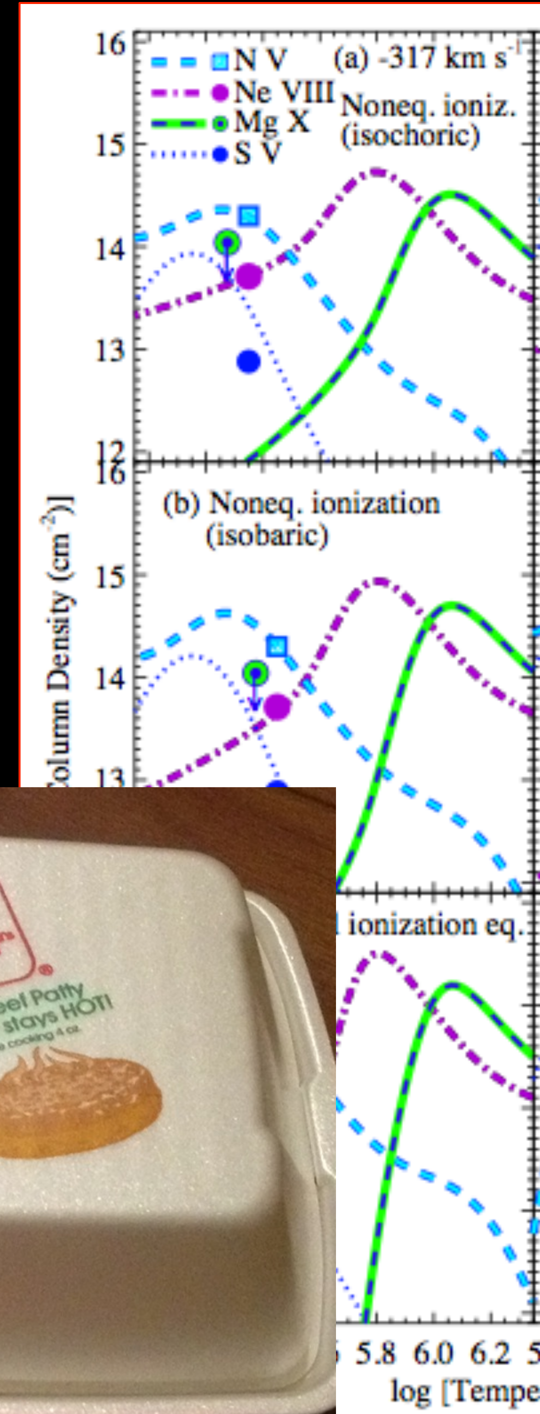


Tripp et al. (2011)

Tripp et al. (2011): No Single-Phase Model Fits All Absorbers.

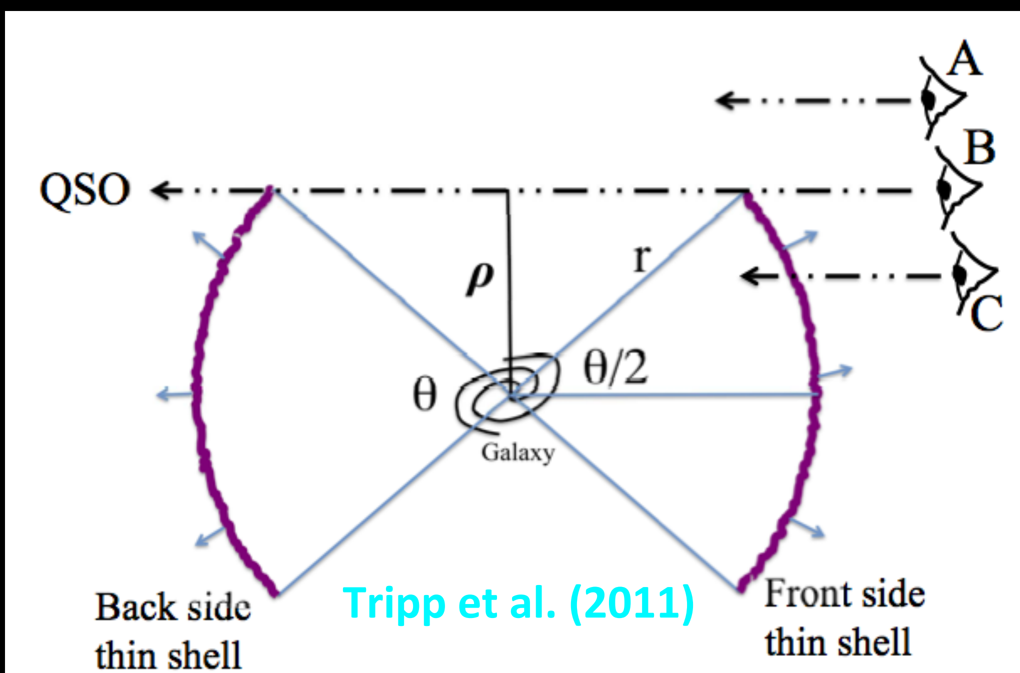
Their model has separate parts cold and hot. Just like the:



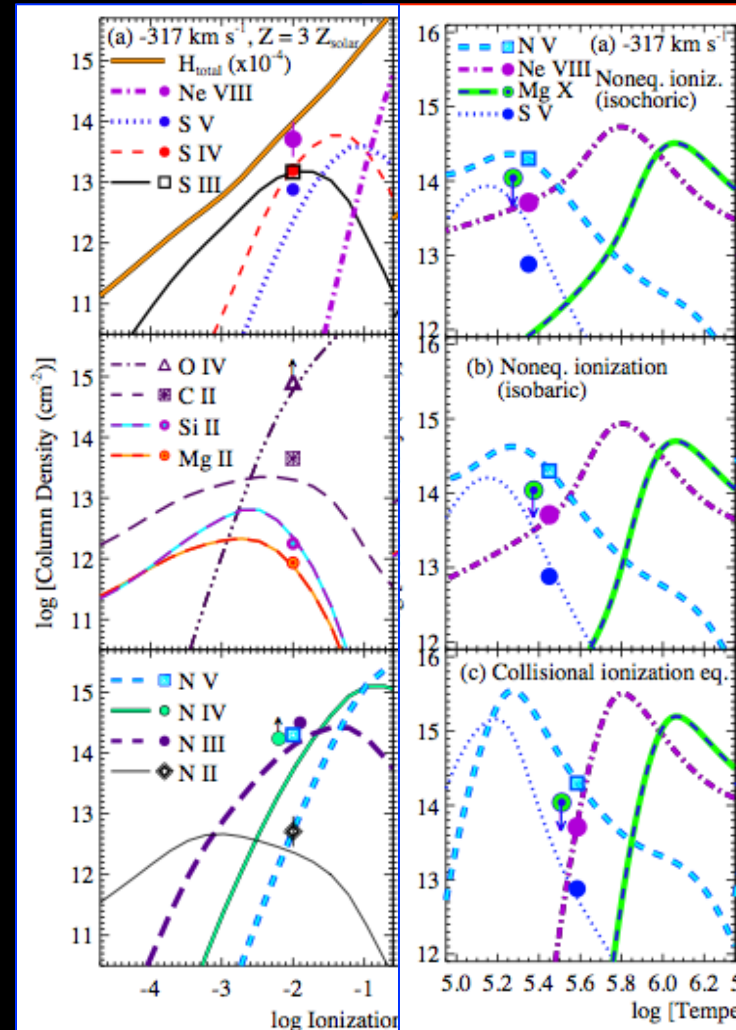


Tripp et al.

Signatures of a Galactic Superwind Tripp et al. model this as a biconical outflow!



Tripp et al. (2011)

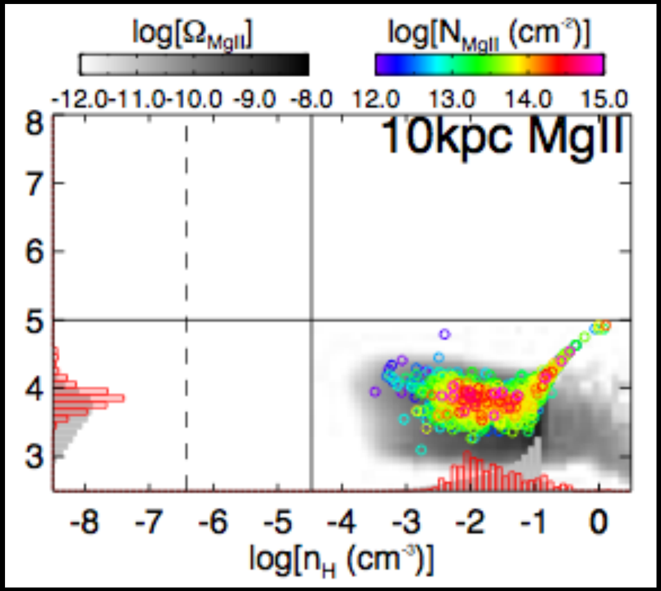


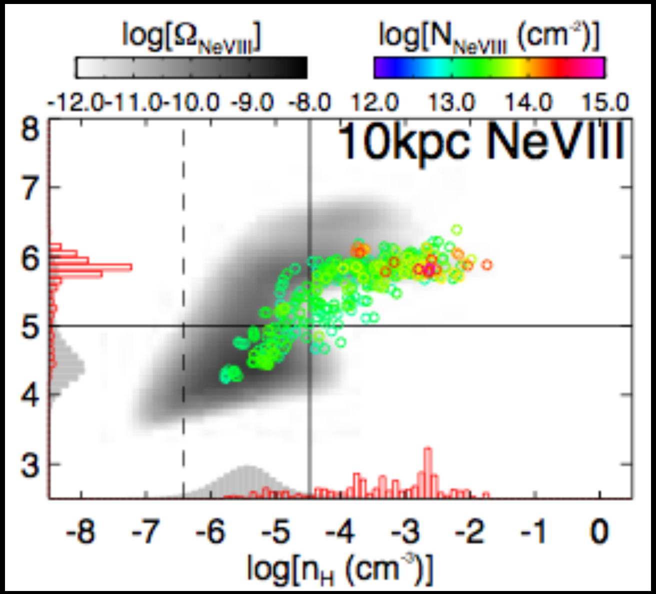
Tripp et al. (2011)

Their model is multi-phase: separate parts cold, T~10^4 K and hot, T>10^5 K.

Alignment of low metal ions and high metal ions is a challenge.

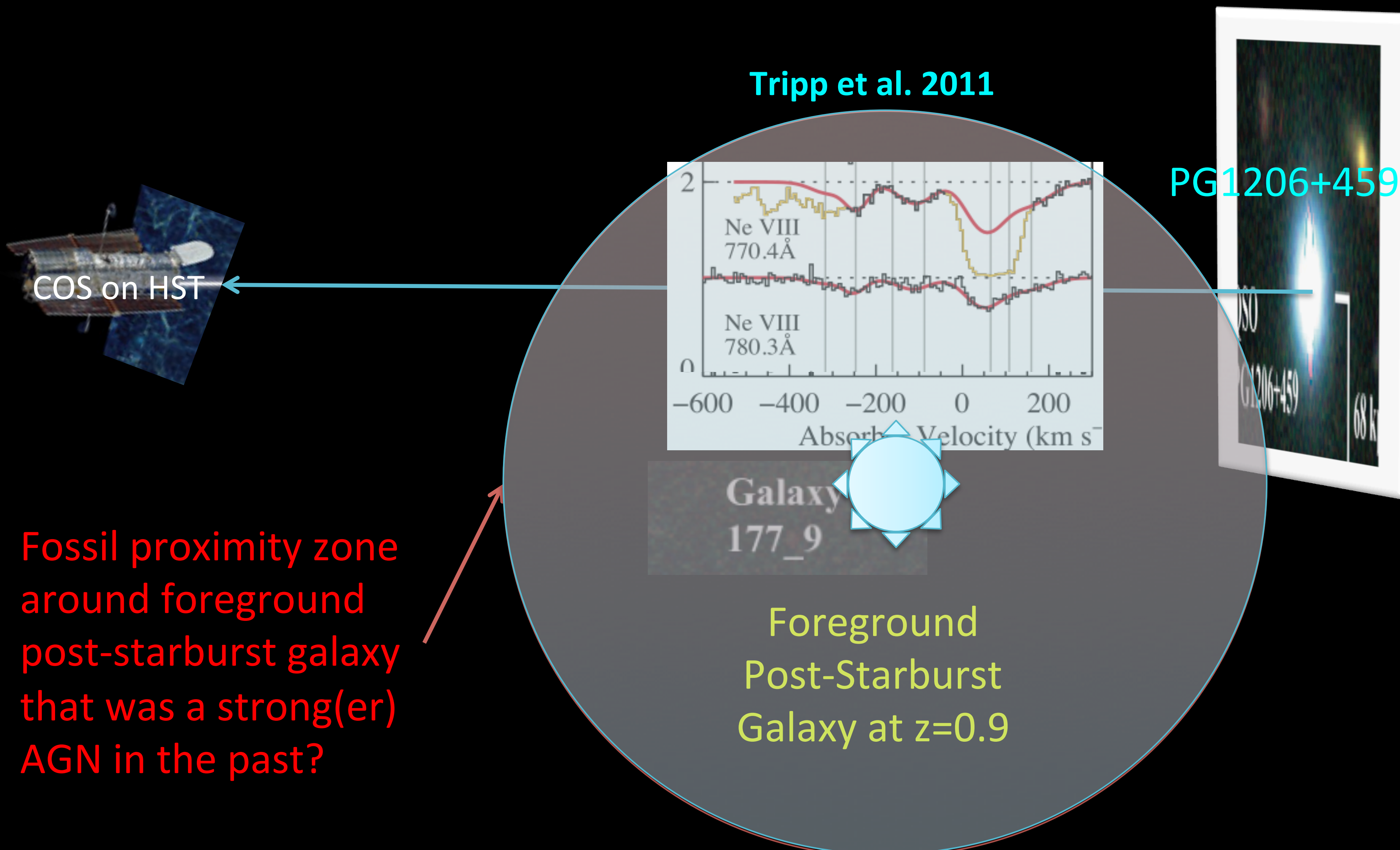
Can Mg II and Ne VIII exist in the same phase?



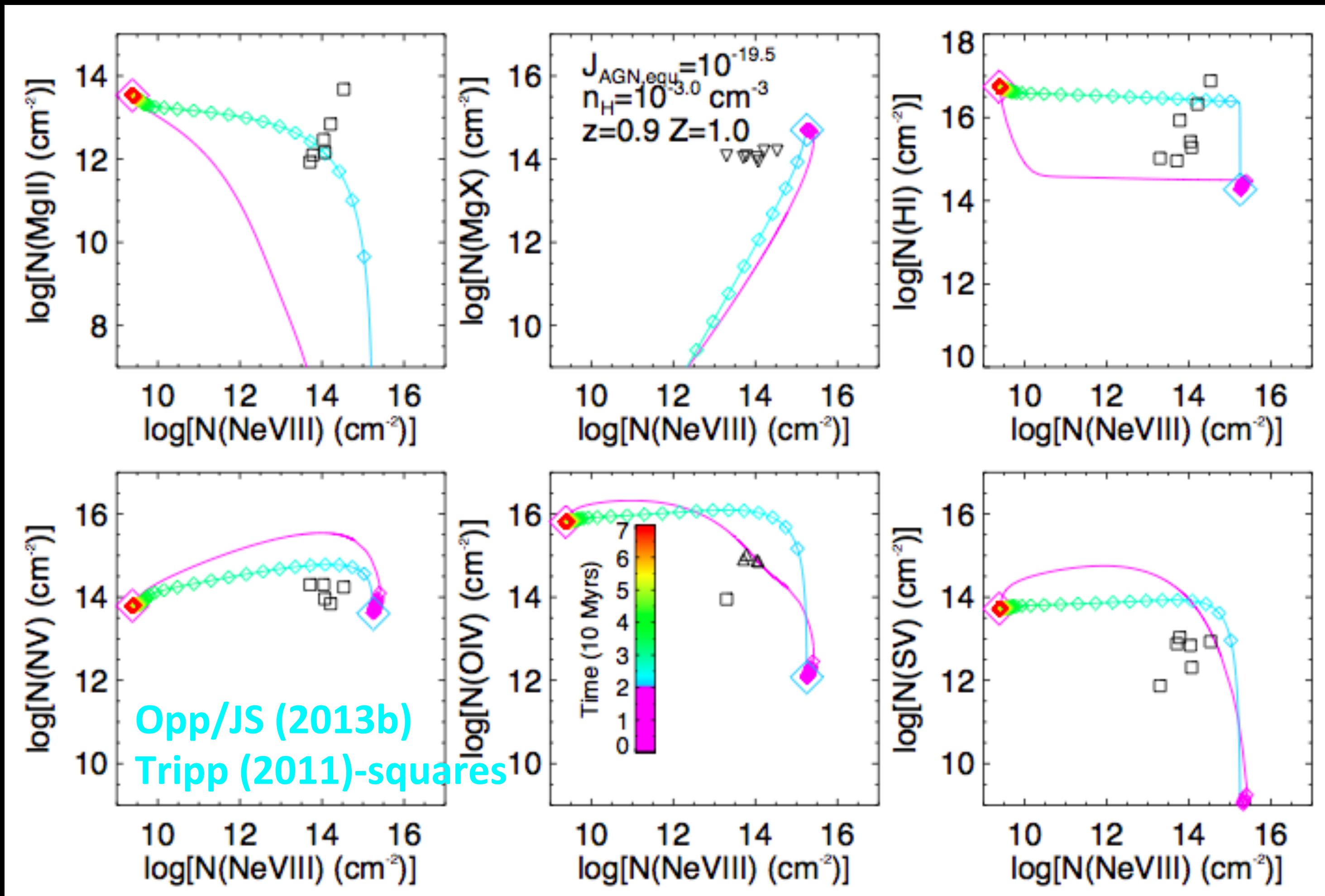


Not according to Ford et al. (2013). Mg II traces much denser and cooler gas than Ne VIII.

Our Model for the PG1206+459: A Quasar Proximity Zone Fossil.



Our Fossil Model: A Single Phase Model at Higher Density, Constraining Mg II and Ne VIII.



Mg II and Ne VIII from the same gas! HI now agrees in the fossil phase.
Nitrogen and Sulfur appear over-abundant using solar ratios.

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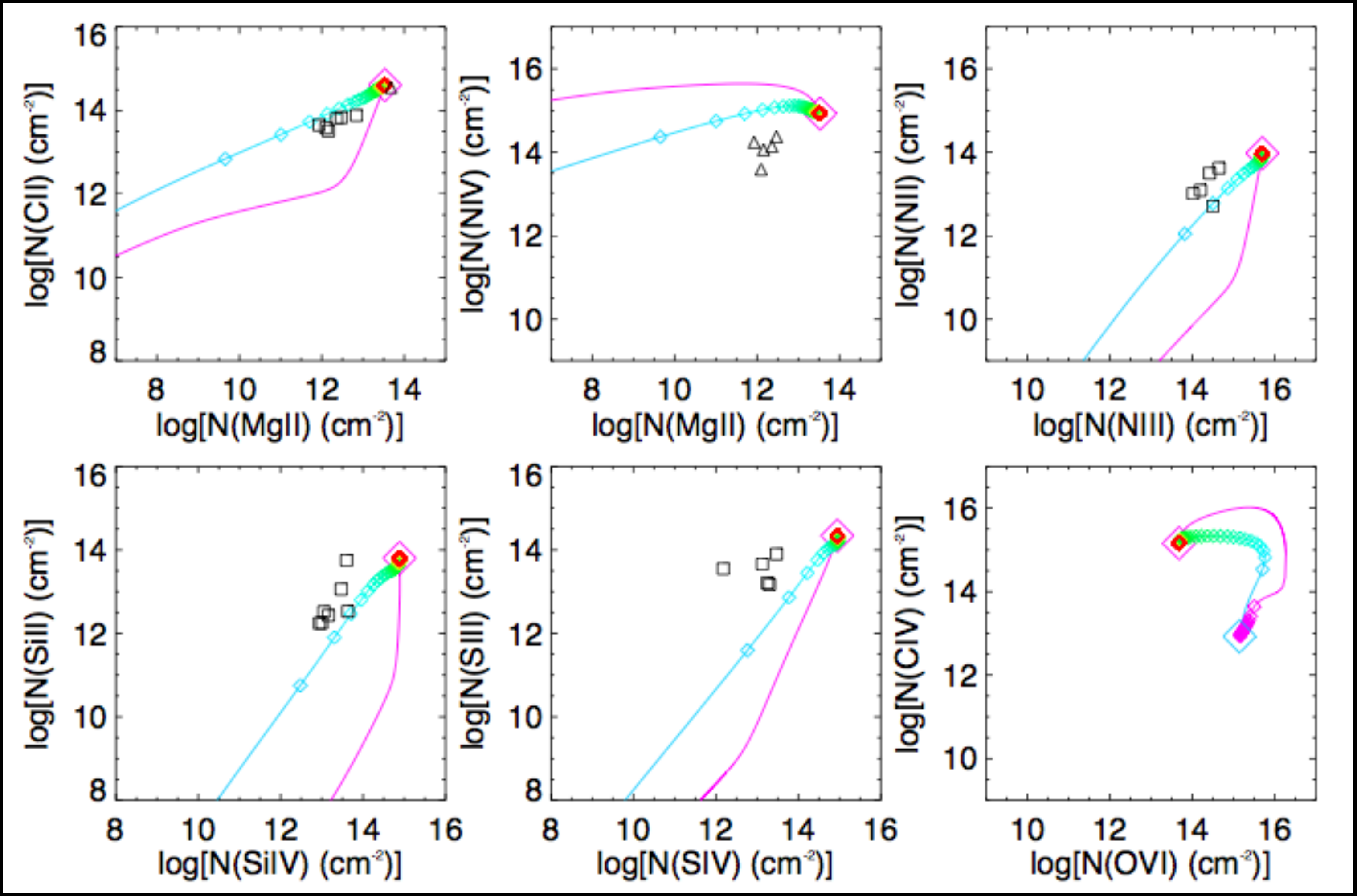
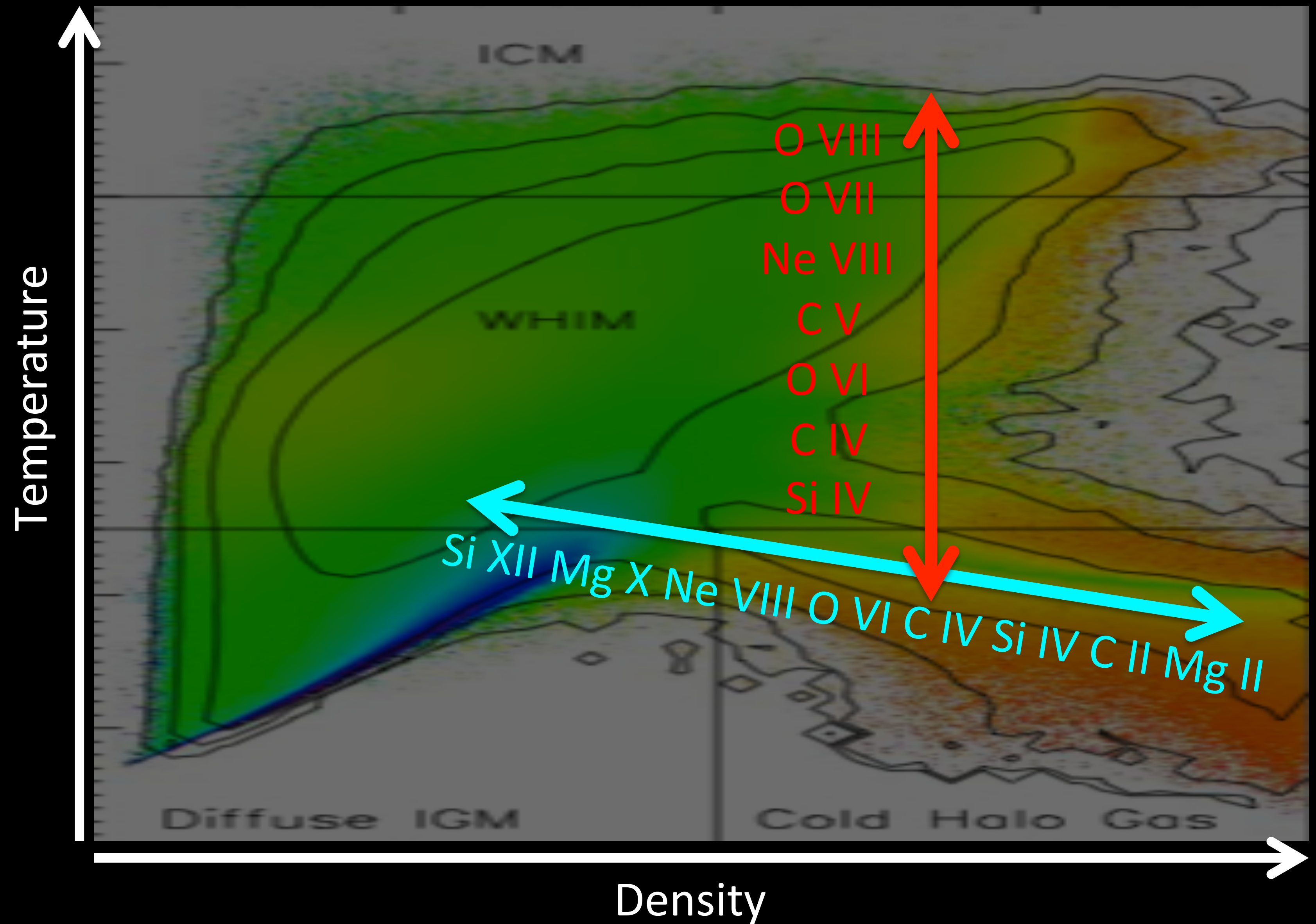


Look now also at other low-ions. And after 3-5 Myrs, the model works very well. Very little dependence on AGN Field Strength.

The Axes of Diffuse Metal Ions



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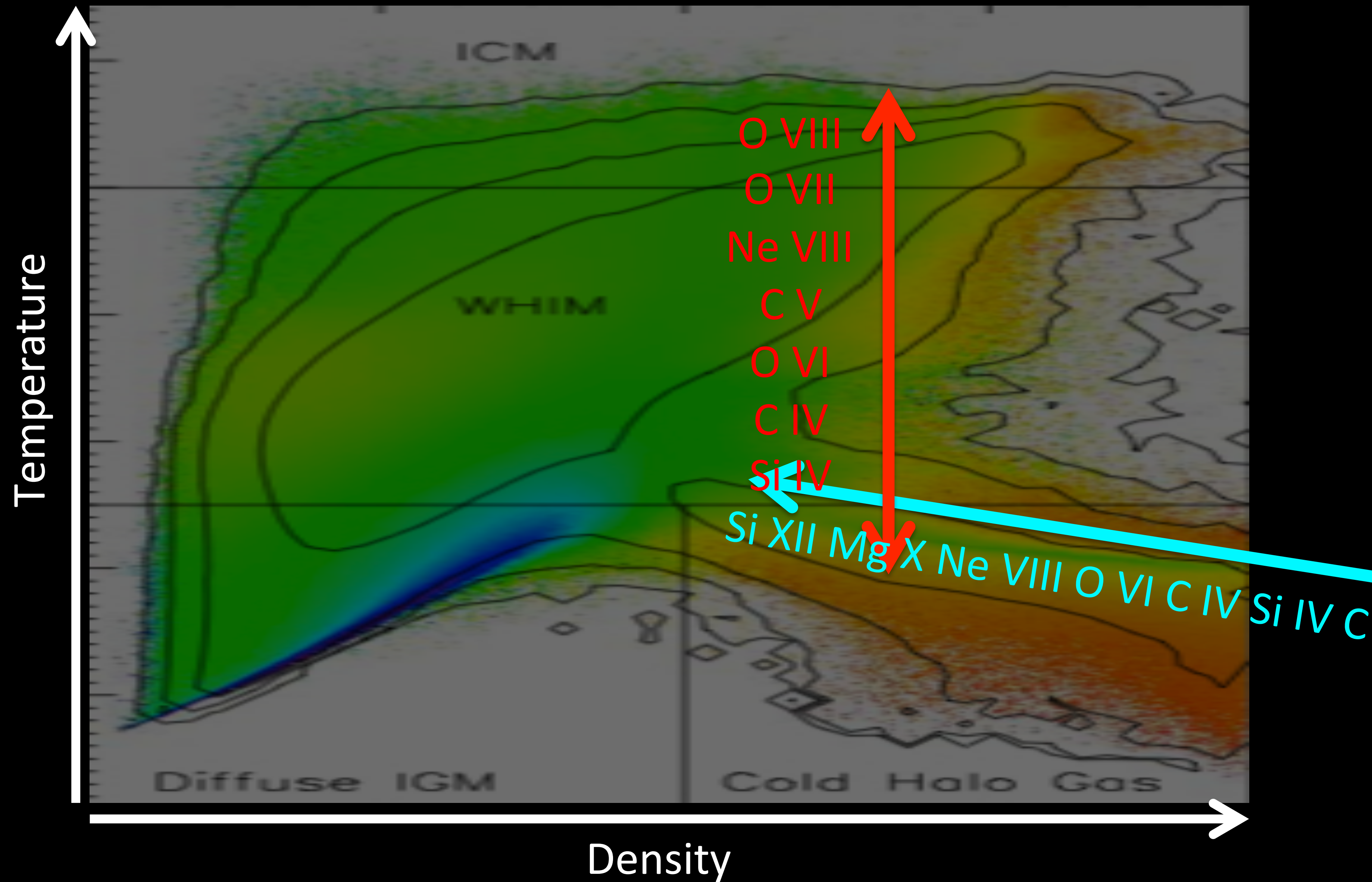
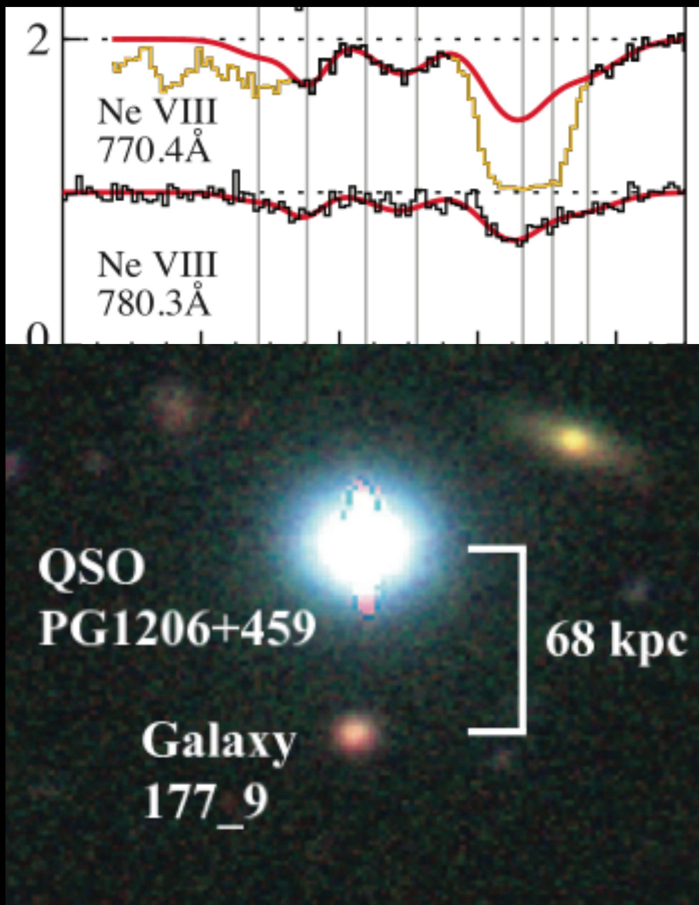


The PG1206+459 Ne VIII Absorber: A Smoking Quasar?



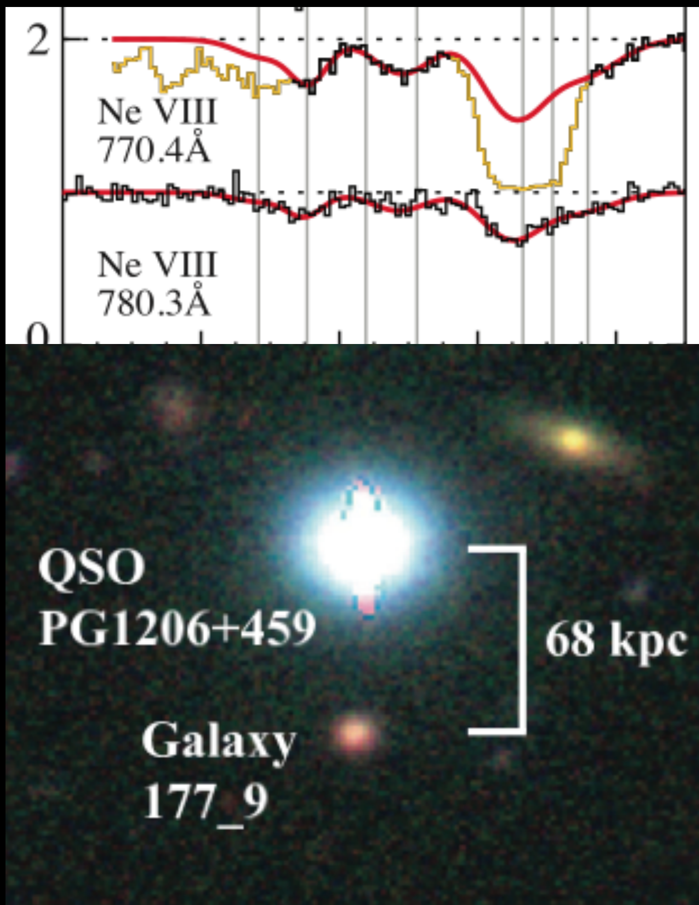
Tripp et al. 2011

Galaxy 177_9 is a 1.8 L* post-starburst galaxy with [Ne V], an AGN signature. Possibly a fluctuating AGN that could have been brighter in the last 3-30 Myr.

Ne VIII in 9 components spread over 1700 km/s, which is 15 Mpc, or the size of a proximity zone around a bright QSO.

Metals along line of sight through proximity zone have different AGN field enhancements, but the recombination timescale is the same for a given density, hence similar metal enhancements.

The PG1206+459 Ne VIII Absorber: Implications and Speculation



Tripp et al. 2011

Could Galaxy 177_9 looked like QSO PG1206+459, 3-30 Myrs ago?

Does this fossil recombination timescale agree with the post-starburst/AGN timescale of the galaxy itself?

Complicated by different densities recombining at different timescales that go as $1/n_H$, plus light travel time effects.

The PG1206 Absorber:
The McKroket of Absorbers

The PG1206 Absorber:
The McKroket of Absorbers

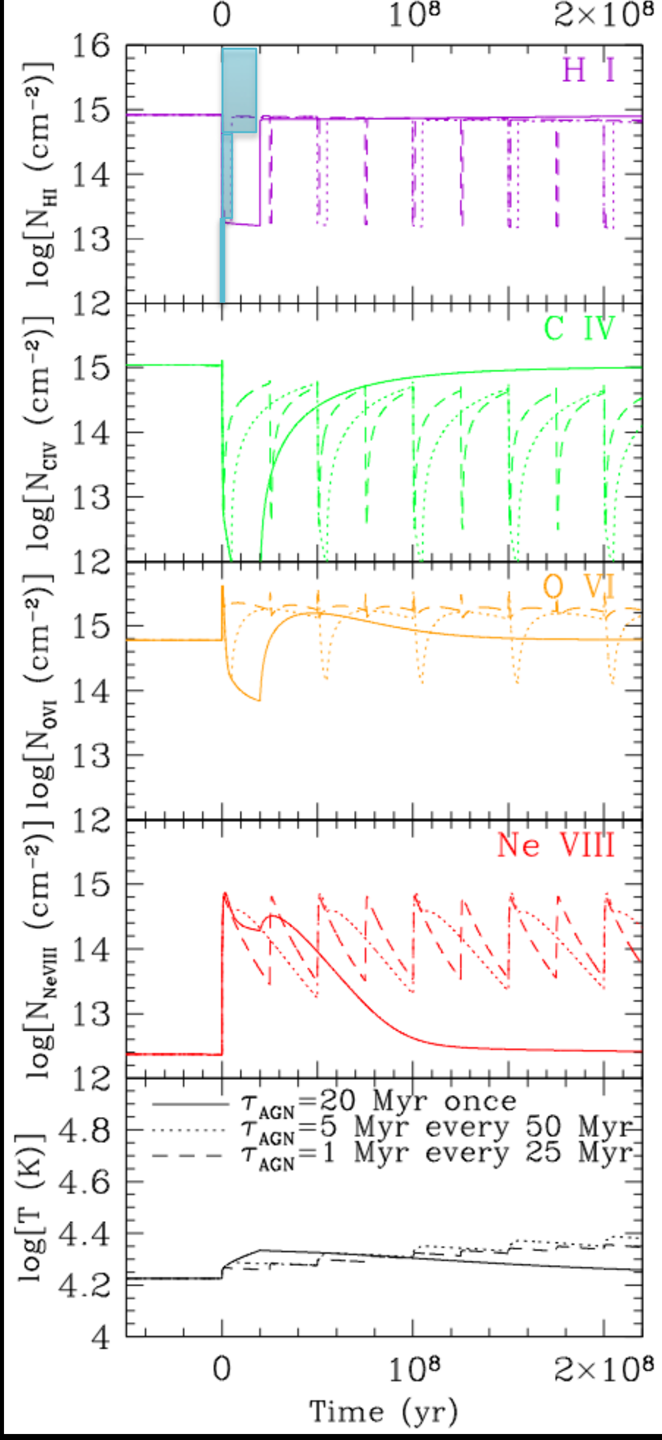
1. A Dutch Concoction
2. A mixture of many, mysterious ingredients in a single phase.
3. If the bun is representative of Dutch bread then it has decayed for a significant timescale since being (photo)-heated.

AGN Proximity Fossil Variations: AGN Lifetime

20 Myrs assumed for fiducial case, however 5 Myrs and even 1 Myr lifetimes cause the same behaviors.

τ_{ion} sometimes shorter than τ_{AGN} meaning it does not take long to achieve ionization equilibrium for AGN phase.

For τ_{AGN}=1 Myr, lower ion state achieved meaning fewer ion states to recombine through. Similar effect as weaker AGN field.

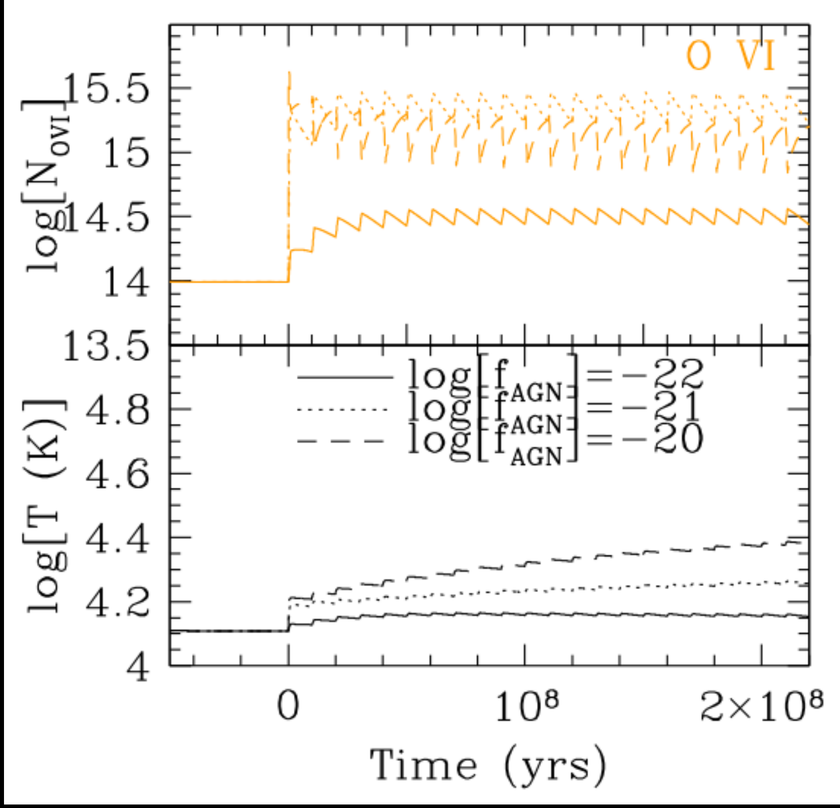


Opp./JS (2013b)

The Duty Cycle Multiplier Effect

Twenty 1 Myr AGN phases have a much greater fossil effect than one 20 Myr AGN phase.

In reality, AGNs fluctuate. AGNs may live for 10-100 Myrs, but strong AGN/QSO phases may be much shorter. The result could be the continual over-ionization in proximity zone fossils.



Opp./JS (2013b)

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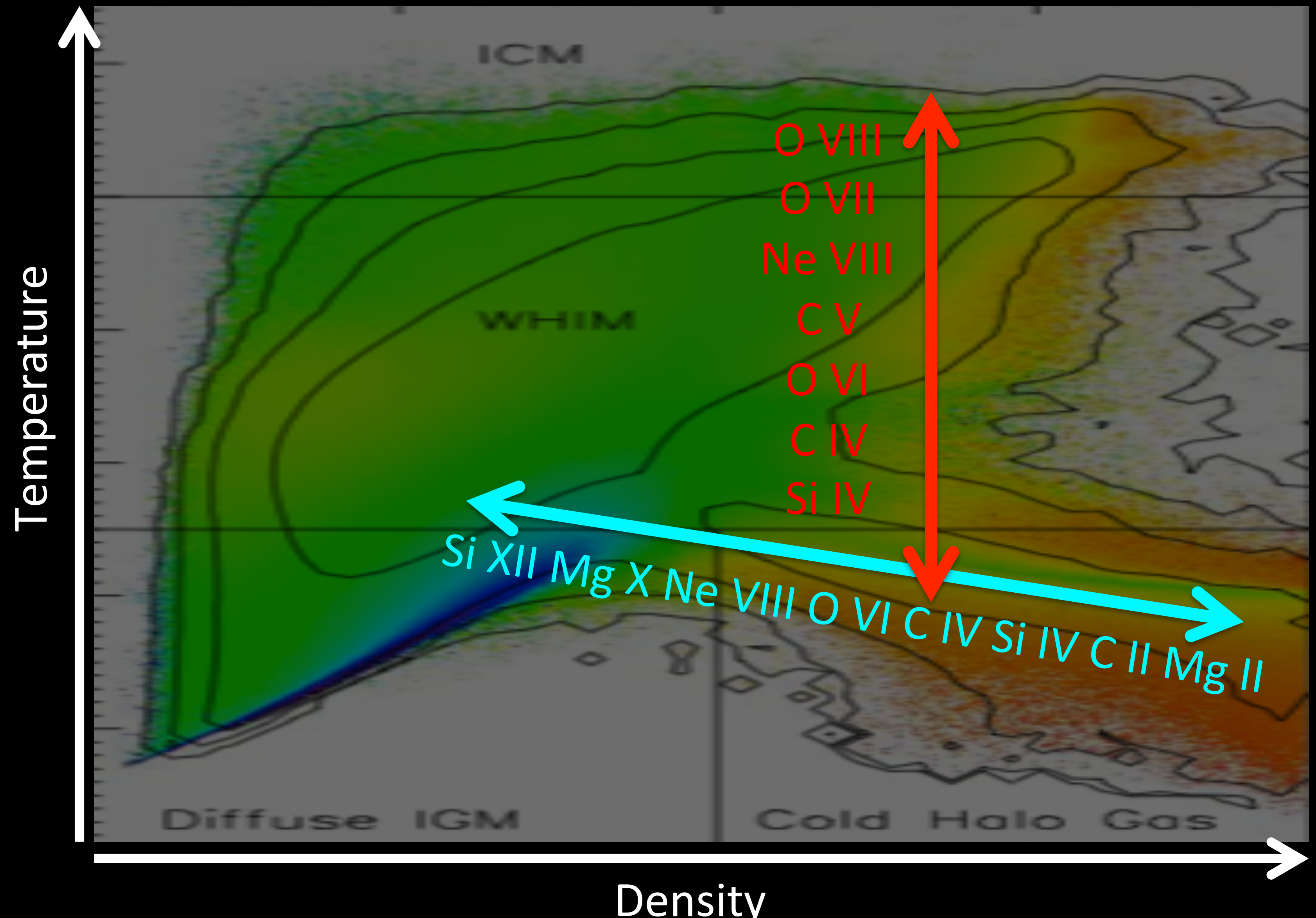

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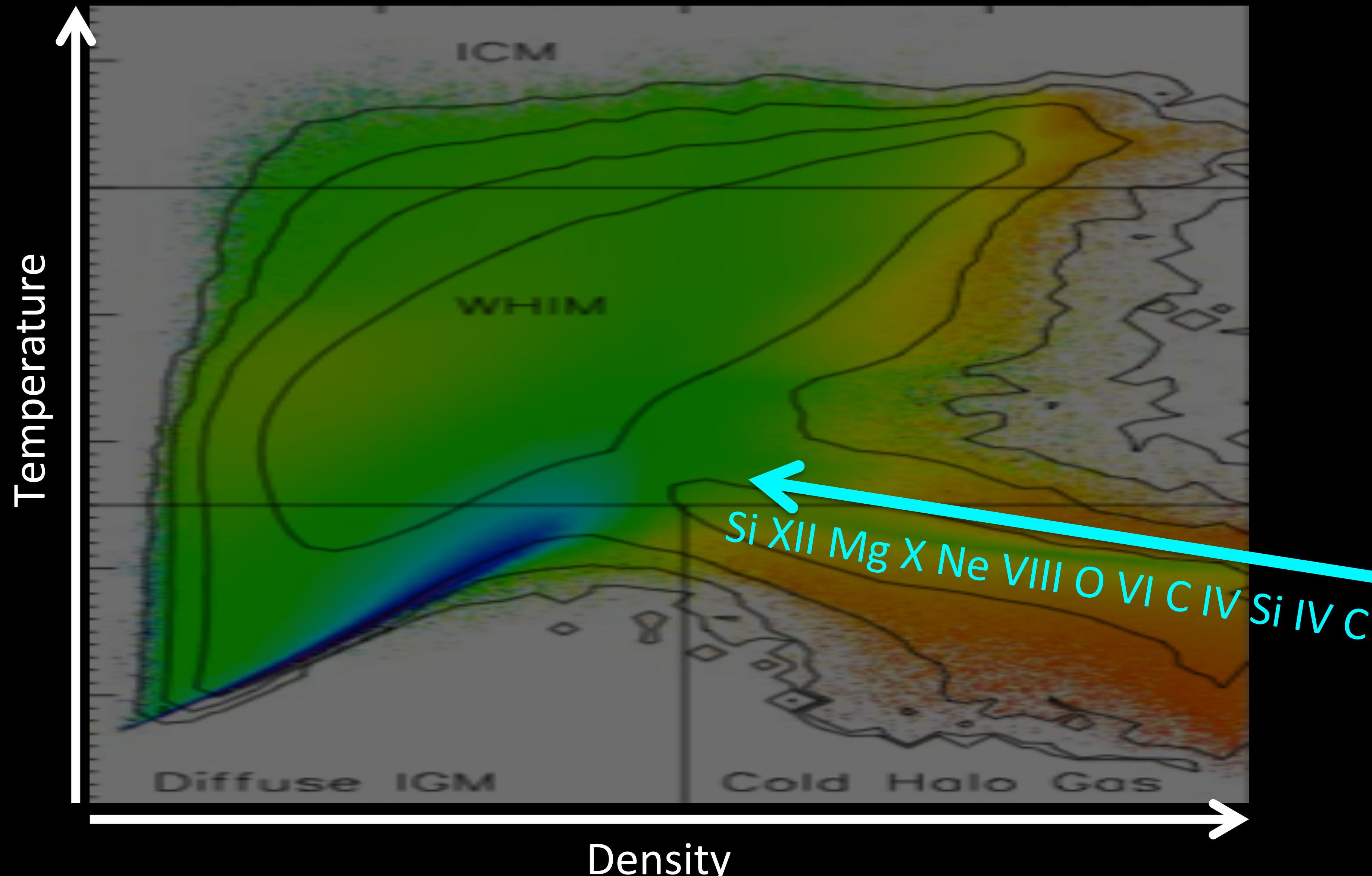


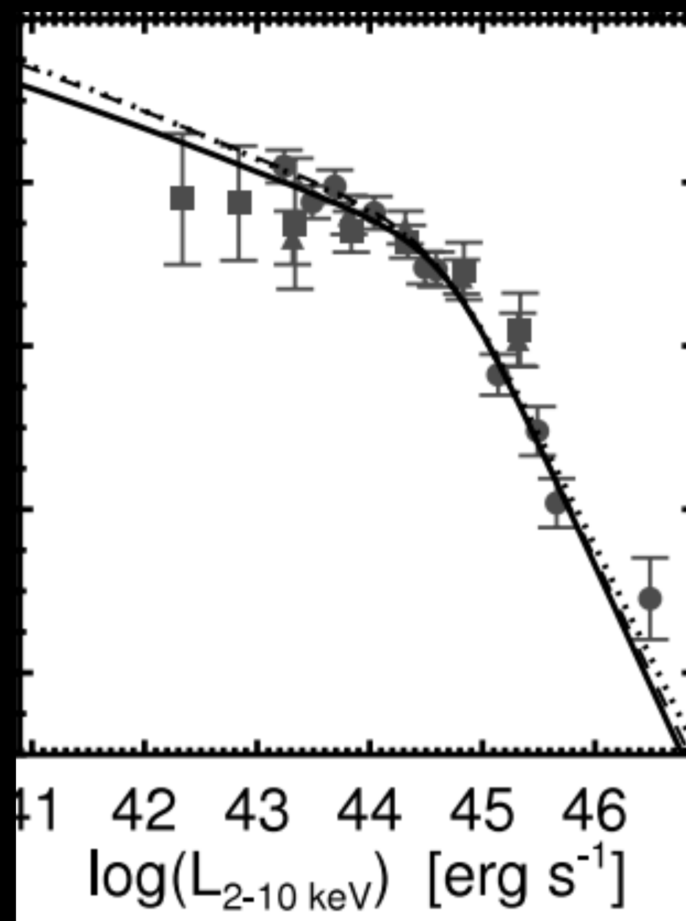
Could Non-Equilibrium Fossil Effects Alter a Significant Fraction of Metal-Line Absorbers?

At z=2.5 that the volume of the Universe affected by proximity zones is of order ~0.1% (integrated over the AGN LF of Hopkins et al. 2007). This may be small, but the effect could be large:

1) Metals live near galaxies, and the *CGM revolution* has told us that there are galaxies almost always found nearby metal lines.

2) The duty cycle multiplier means that AGN proximity zone fossils could affect much more than 0.1% of the volume. If only 3% of LBGs harbor AGN (Steidel 2002), many more LBG CGMs could be affected.

3) If AGN spectra are hard, then even a very weak AGN can enhance the field at CIV, OVI, & NeVIII ionization potentials.



Hopkins et al. (2007)

Take Away Message

A significant fraction of diffuse metals observed in quasar absorption lines may be out-of-equilibrium in quasar proximity zones and, more importantly, their ***fossils***.

See Arxiv:1303.0019 (now accepted in MNRAS)

AGN proximity zone fossils and the delayed recombination of metal lines

Benjamin D. Oppenheimer[1], Joop Schaye[1]

[1] *Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, the Netherlands*

Summary Points

1. The recombination timescales of metals in the CGM are comparable to or longer than an AGN/QSO timescale, meaning metals, unlike HI, can be over-ionized for significant timescales in a proximity zone fossil.
2. Time-dependent single phase models with high and low metal ions and strong HI are possible over the scale of a quasar proximity zone ***fossil***.
3. Metals being close to galaxies combined with fluctuating AGN/QSOs means this could keep a significant fraction of metals out-of-equilibrium and over-ionized.

A Suggested Question:

If you claim that you constrained wind outflows that define galaxy properties by modeling metal lines assuming a uniform background, then don’t proximity zone fossils totally repudiate that line of research?