Tutorial on Multiphase Cloudy Modeling

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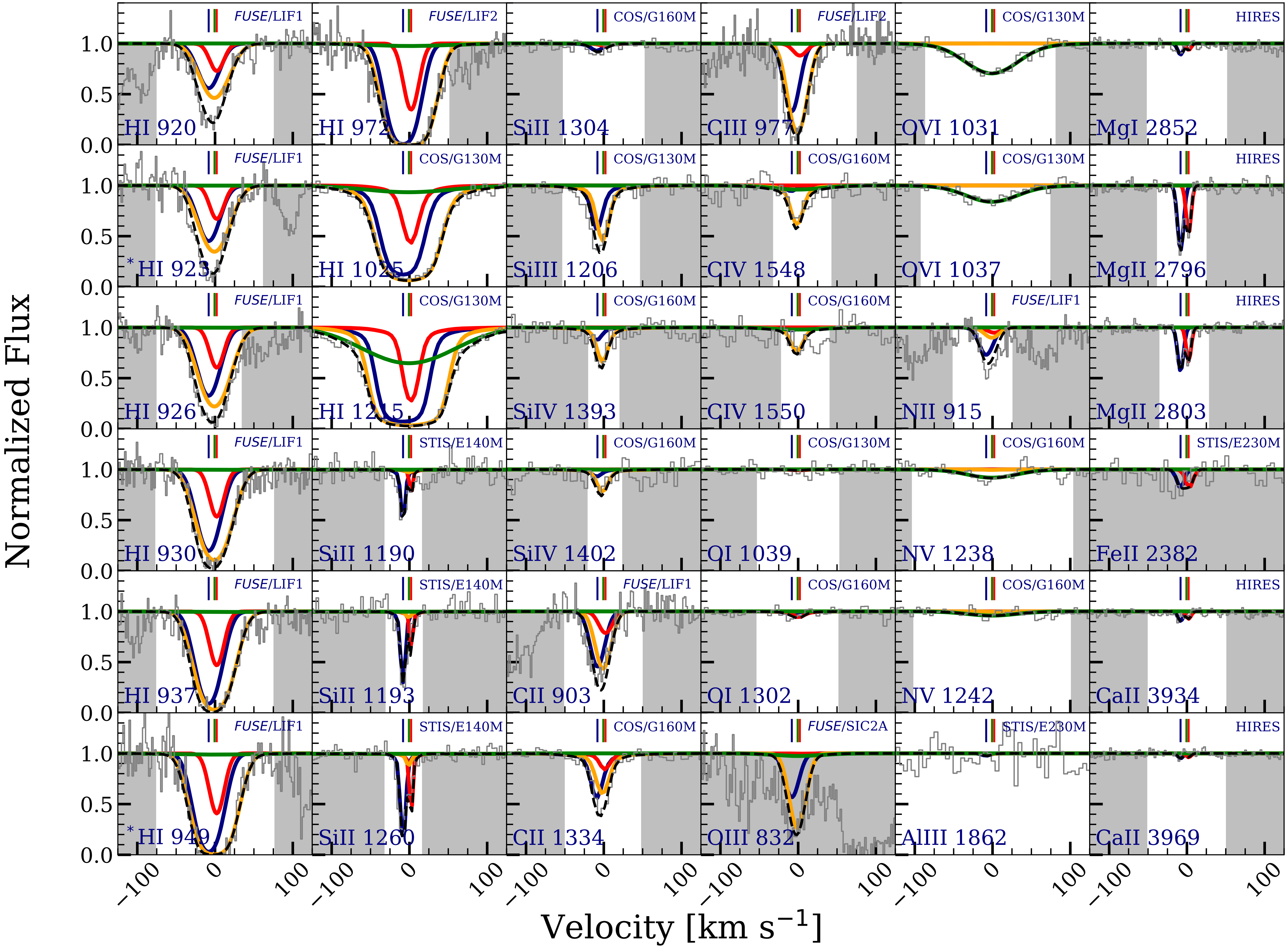


When we see a quasar absorption line system, how are the profiles of multiple chemical transitions spanning a wide range of ionization states shaped by the physical conditions of the multiphase gas?

Each component cloud in each phase is described by:

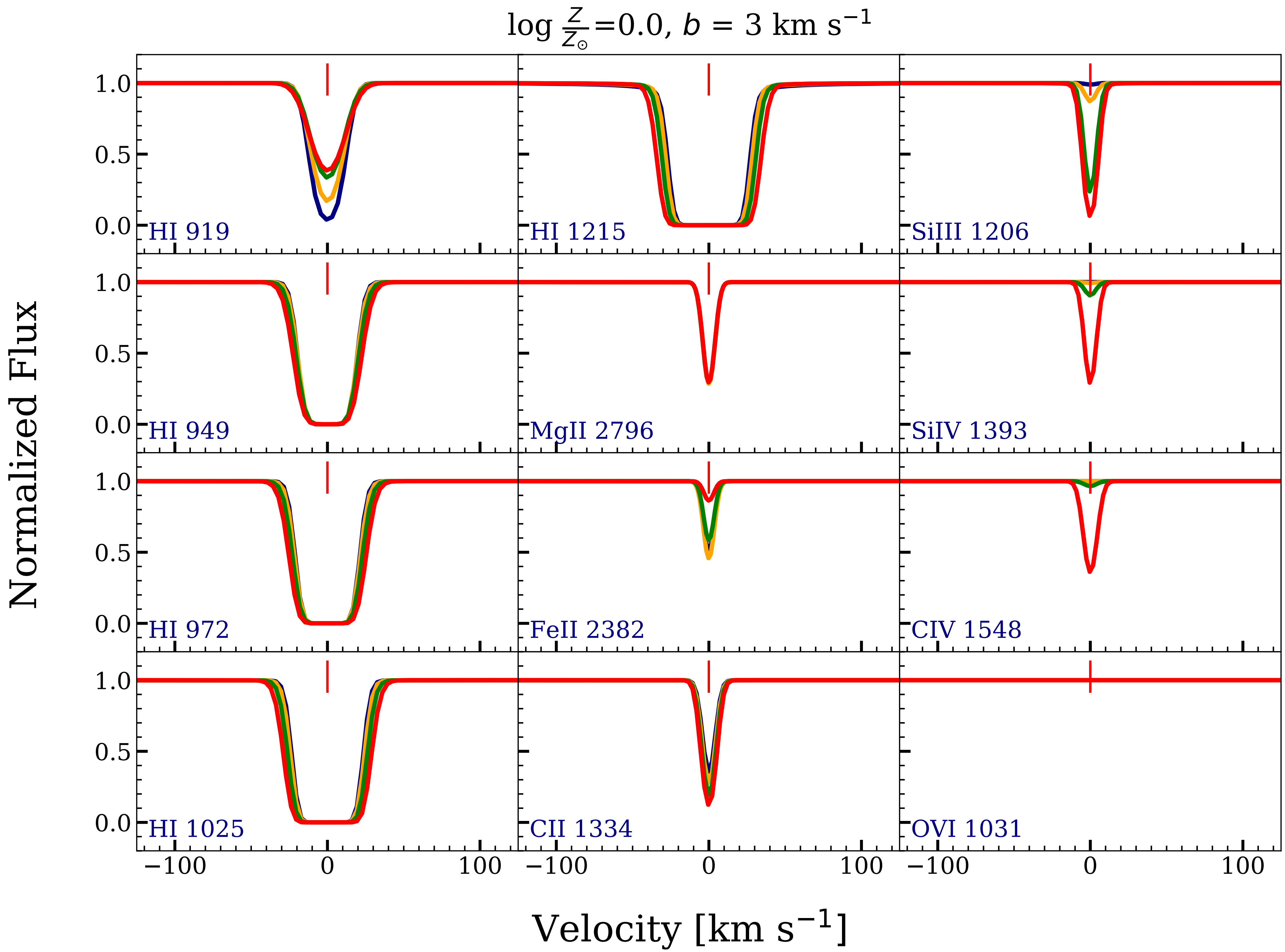
- Number density log n_e
- Metallicity log Z (relative to solar so log Z = 0 is solar value)
- Temperature log T (if not in photoionization equilibrium)
- Turbulent b parameter
- (abundance pattern)
- Thickness = $N(H)/n_e$

Main Insights:

- Shapes of the Lyman-alpha and Lyman series lines are sensitive to the phase structure, with different contributions from different phases.

- An absorber traced by a particular ion (eg. MgII, CIV, OVI) is not necessarily produced by the same type of structure (process) at different redshifts. This is due to the evolving extragalactic background radiation.

Low Ionization Phase log N(MgII)=12.5 at z=1



Varying log n = -2, -1.5, -1, -0.5 log U = -3, -3.5, -4, -4.5

Thicknesses = 50pc - 0.1pc

Procedure for Thought Experiment:

- The EBR (KS18) at z=1 is incident on a constant density slab with an assumed metallicity (and abundance pattern)
- N(MgII) and b(Mg) are specified as the optimized transition for the phase
- Cloudy yields a temperature, T, and column densities of all other transitions.
- $b(Mg)^2 = 2kT/m(Mg) + bturb^2$ $b(H)^2 = 2kT/m(H) + bturb^2$

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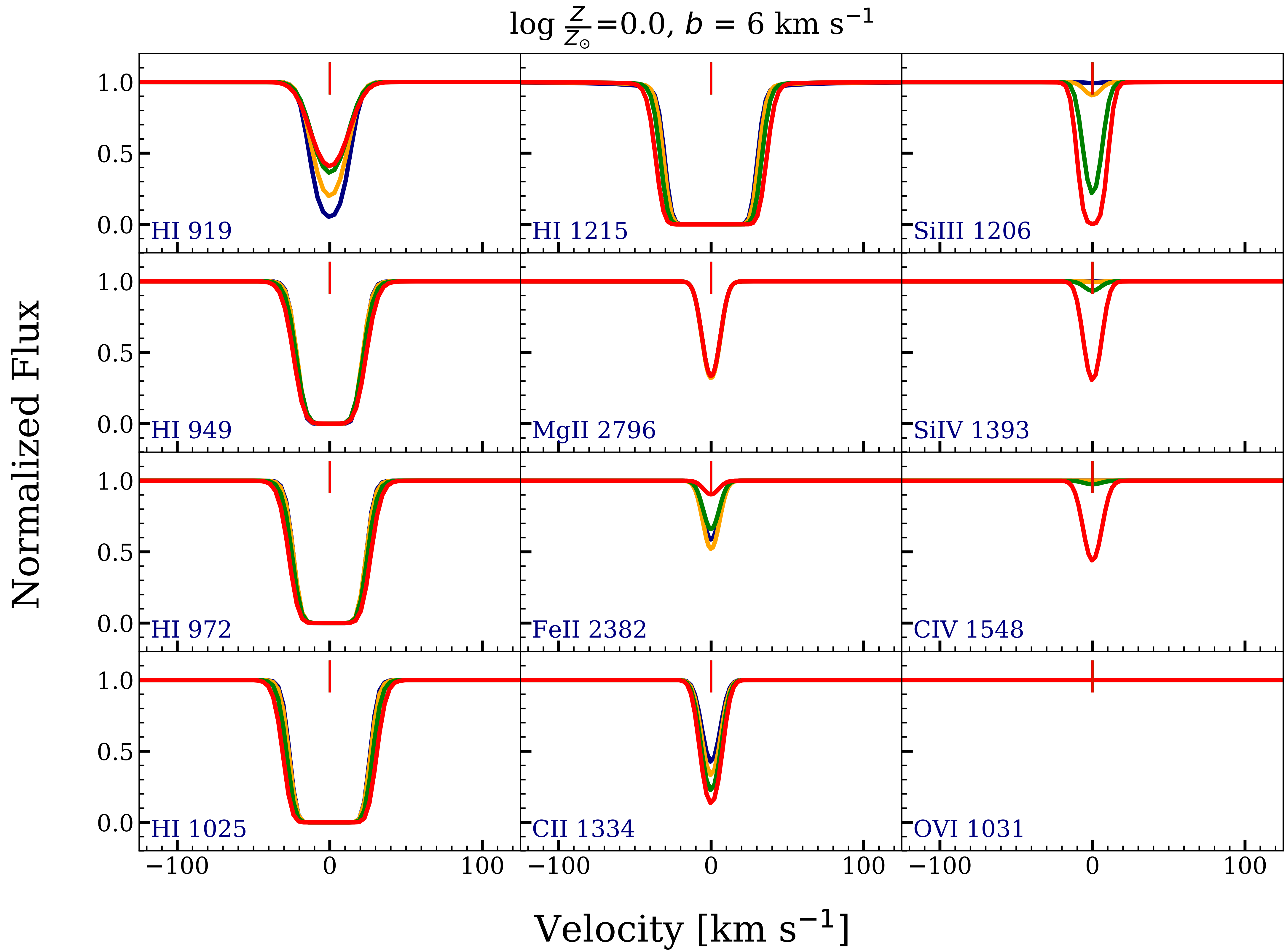

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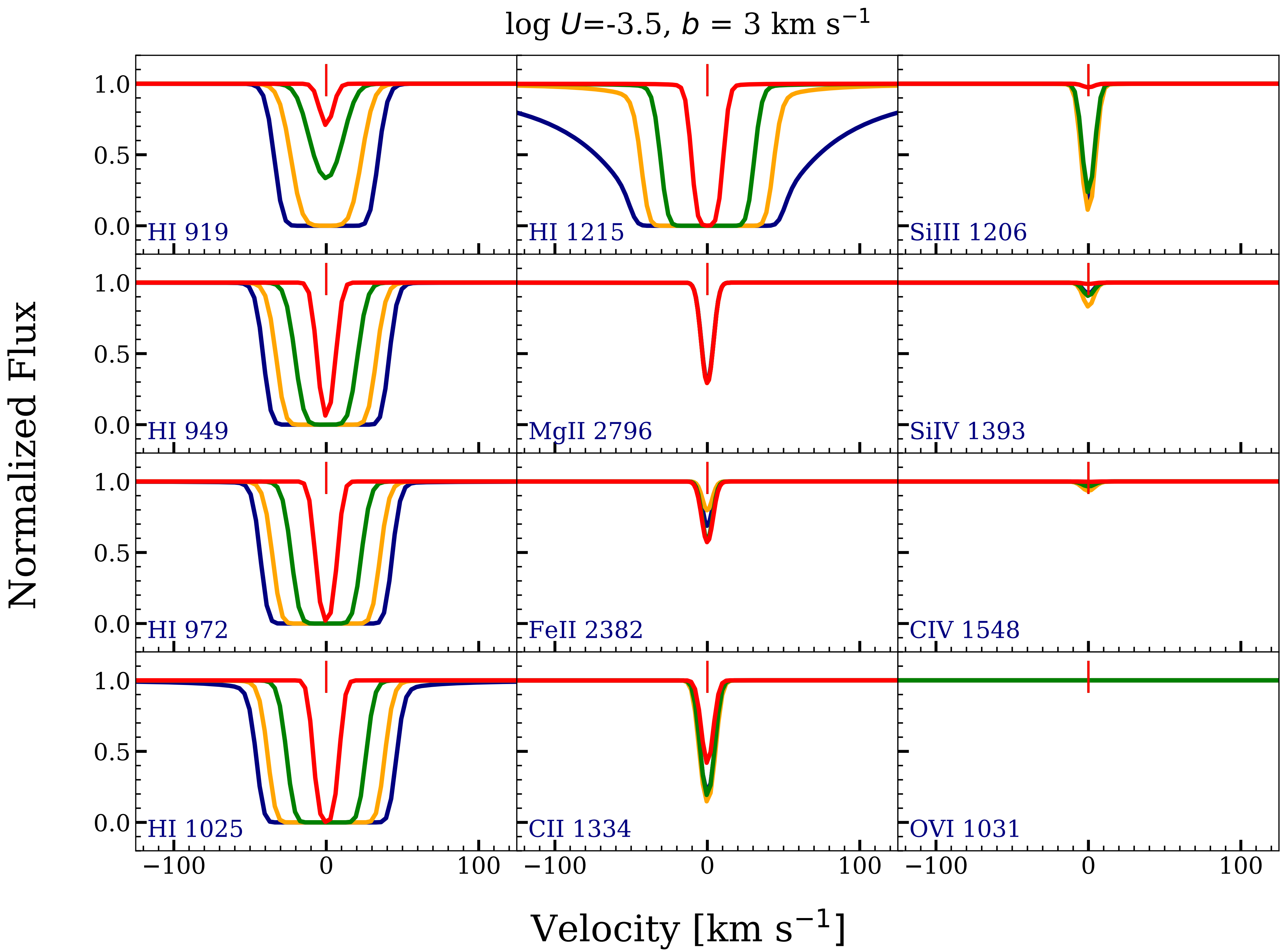


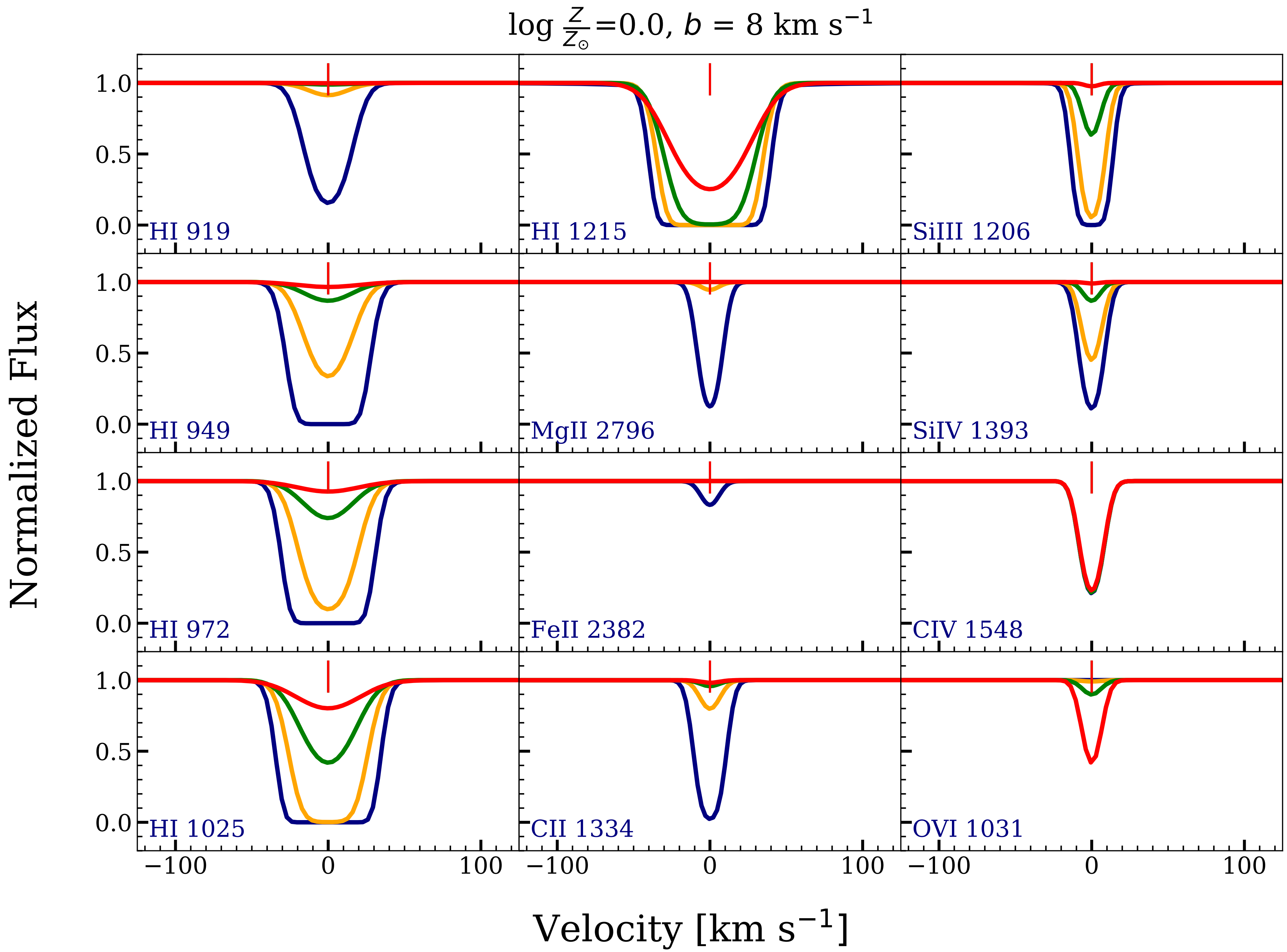
log n = -1.5 log U=-3.5 Thickness = 400pc - 0.1pc

varying metallicity log Z = -2, -1, 0, 1

Thoughts about low ionization phase:

- The degeneracy between b(H) and log Z can be broken by using observed b of optimized transition metal line along with Cloudy temperature to derive turbulent b.
- Contributes to higher order Lyman series lines and square bottom of Lyman-alpha.
- b parameters small at z=1. 2-8km/s common.
- No OVI can come from this phase.
- Some cloud thicknesses quite small (parsec scale). Smaller than cells in most simulations - a different kind of structures than produce some low ionization absorption in simulations

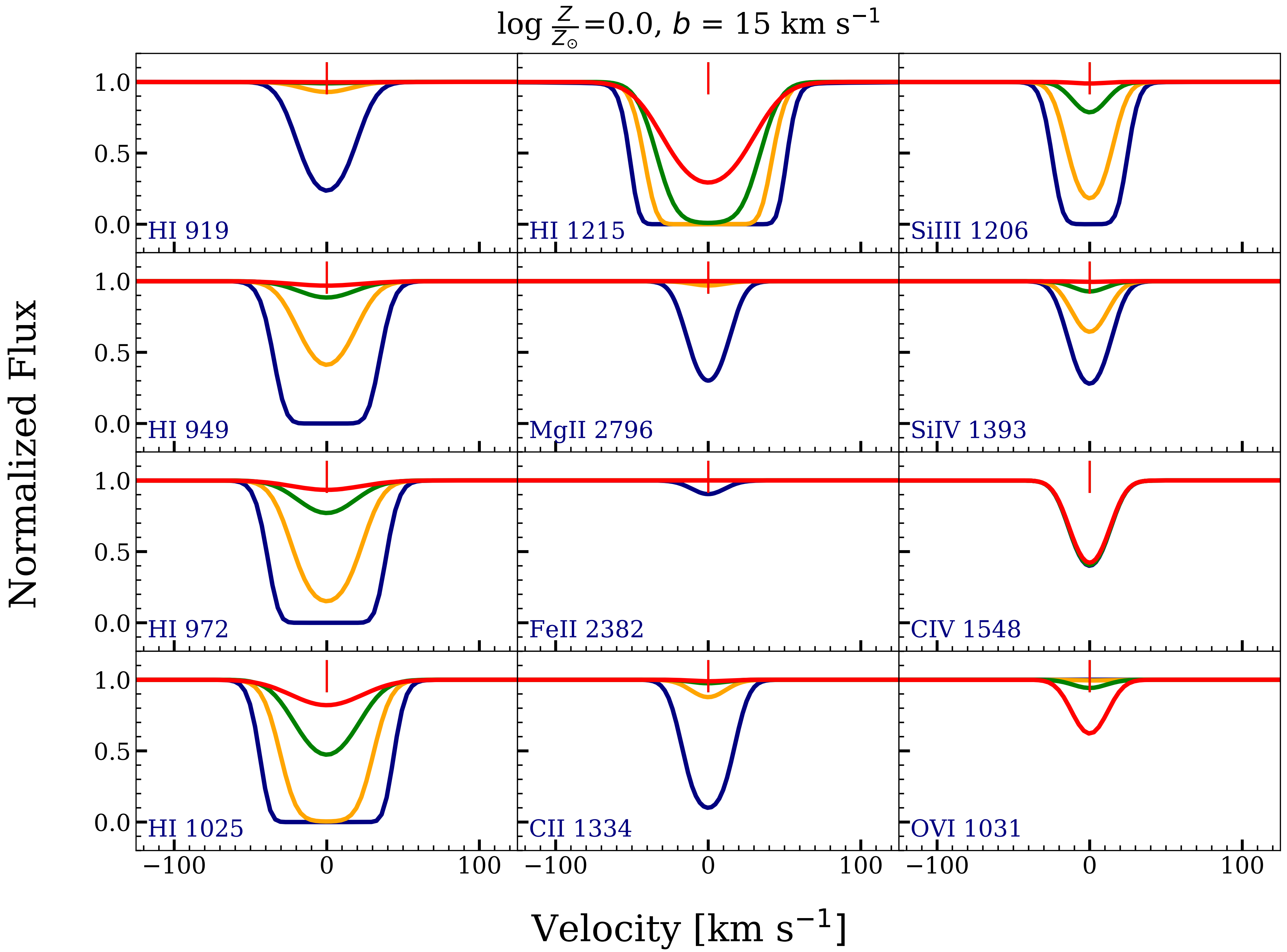
Intermediate Ionization Phase
log N(CIV)=13.5 at z=1



varying log n = -3.5, -3, -2.5, -2   log U = -1.5, -2, -2.5, -3

Thicknesses 100pc - 1kpc

Intermediate Ionization Phase
log N(CIV)=13.5 at z=1



varying log n = -3.5, -3, -2.5, -2 log U = -1.5, -2, -2.5, -3

Thicknesses 100pc - 1kpc

Intermediate Ionization Phase
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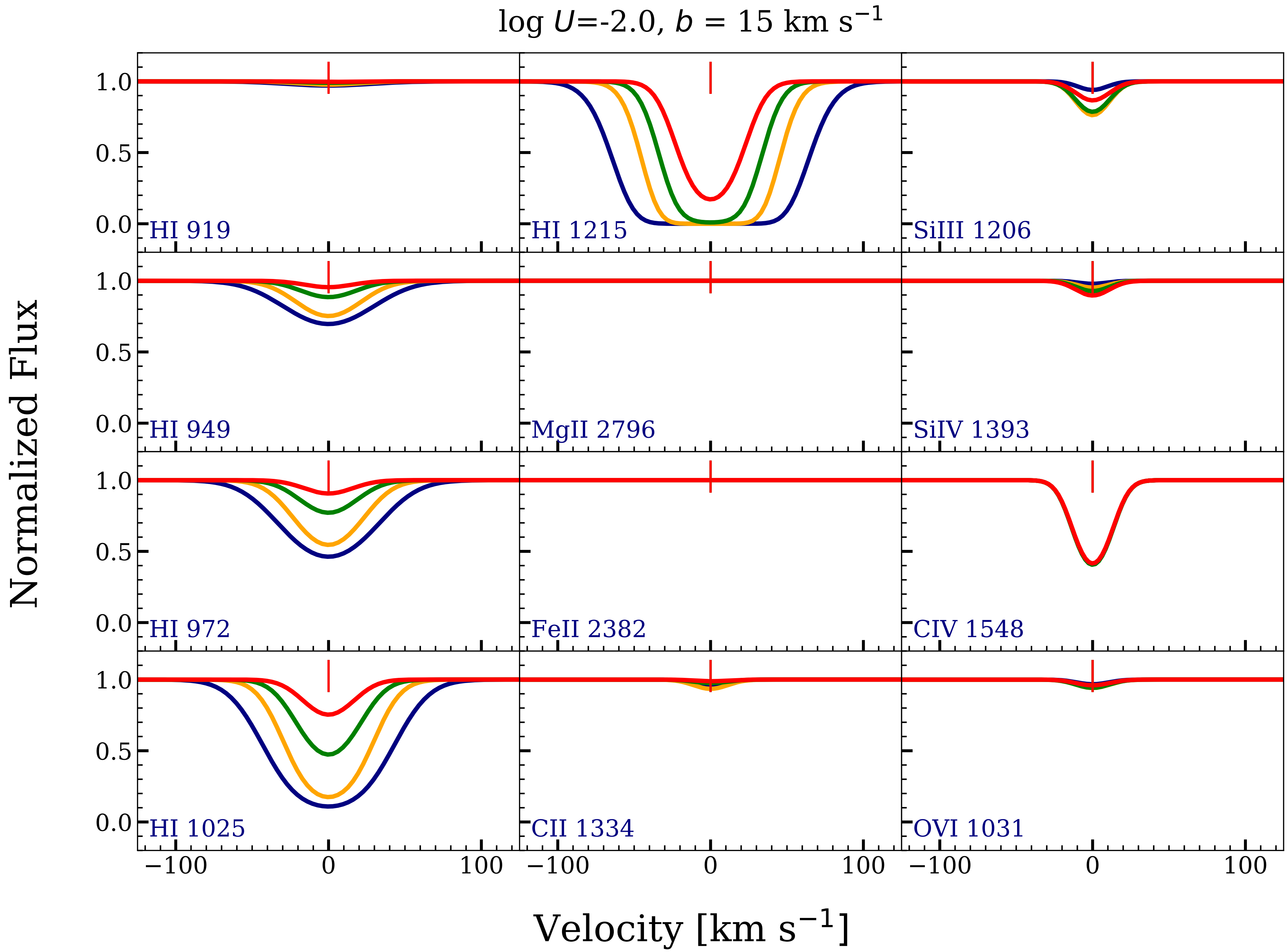


log n = -3.0   log U = -2.0   Thicknesses 8kpc - 40pc

varying log Z = -1.5, -0.5, 0, 0.5

Thoughts about intermediate ionization phase:

- Some MgII and OVI can arise from this phase at z=1; Photoionized OVI is possible at this redshift.

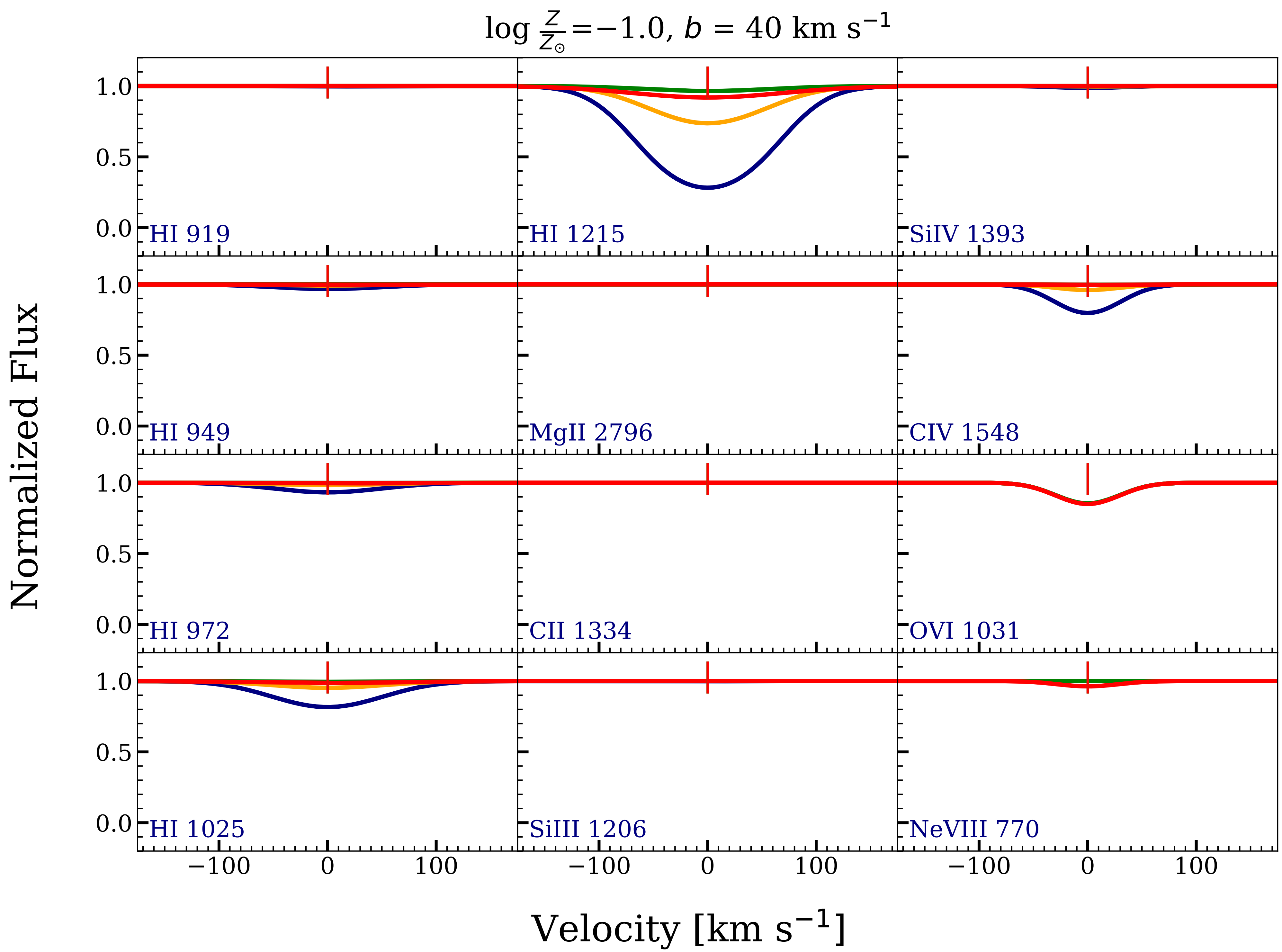
- Often broader than low ionization phase 6-20km/s for CIV.

- Contributes to upper edges of Lyman-alpha but often not much to Lyman series.

- Typical N(HI) is smaller compared to low ionization phase but contribution to Lyman-alpha can be large due to larger b parameter.

- Cloud thicknesses can range from pc to kpc scale depending on metallicity. Larger than low ionization phase.

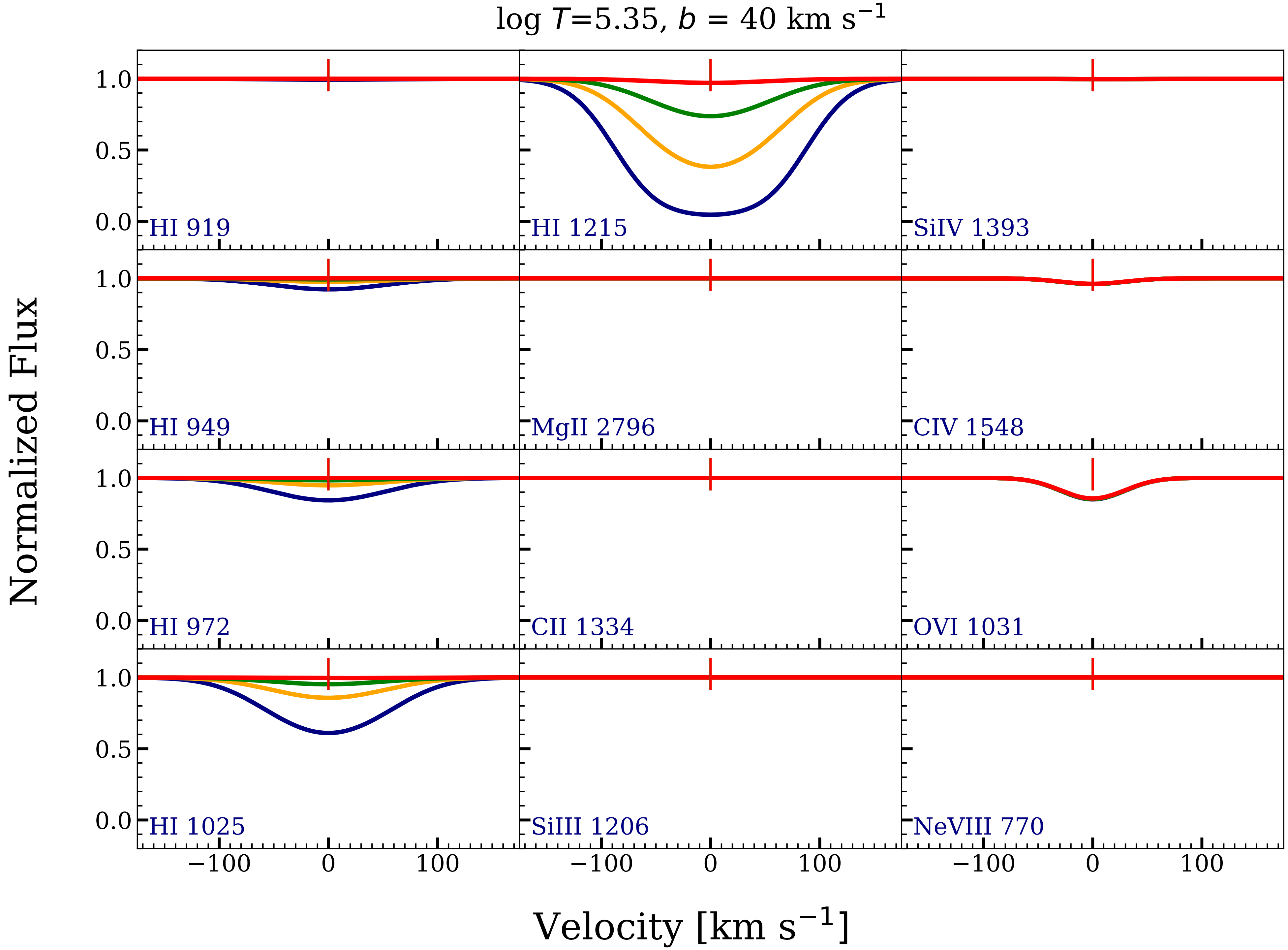
High Ionization Collisional Phase
log N(OVI)=13.5 at z=1



b = 40 km/s and log Z = -1

varying log T = 5.3, 5.35, 5.5, 5.7

High Ionization Collisional Phase
log N(OVI)=13.5 at z=1

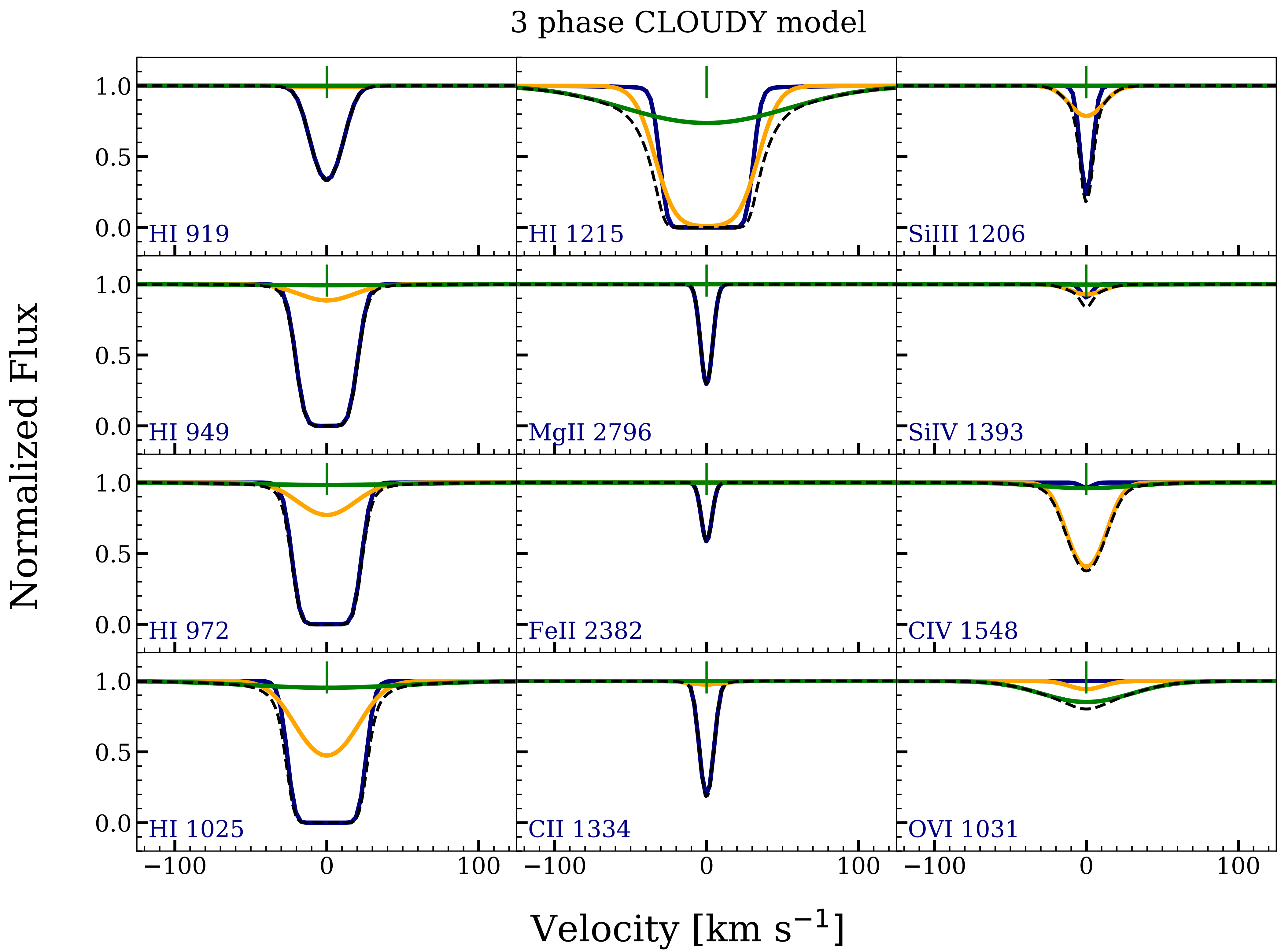


b = 40 km/s and log T = 5.35
varying log Z = -2, -1.5, -1, 0

Thoughts about high ionization phase:

- Depending on the temperature, CIV, NV, and NeVIII can arise from this phase at any redshift.
- Typical N(HI) is quite small compared to other phases.
- Density likely to be small, but cloud thickness depends on assumed density - likely kpc scale
- Pressure balance with this phase would require it to have density about 10 times smaller than low or intermediate phases.

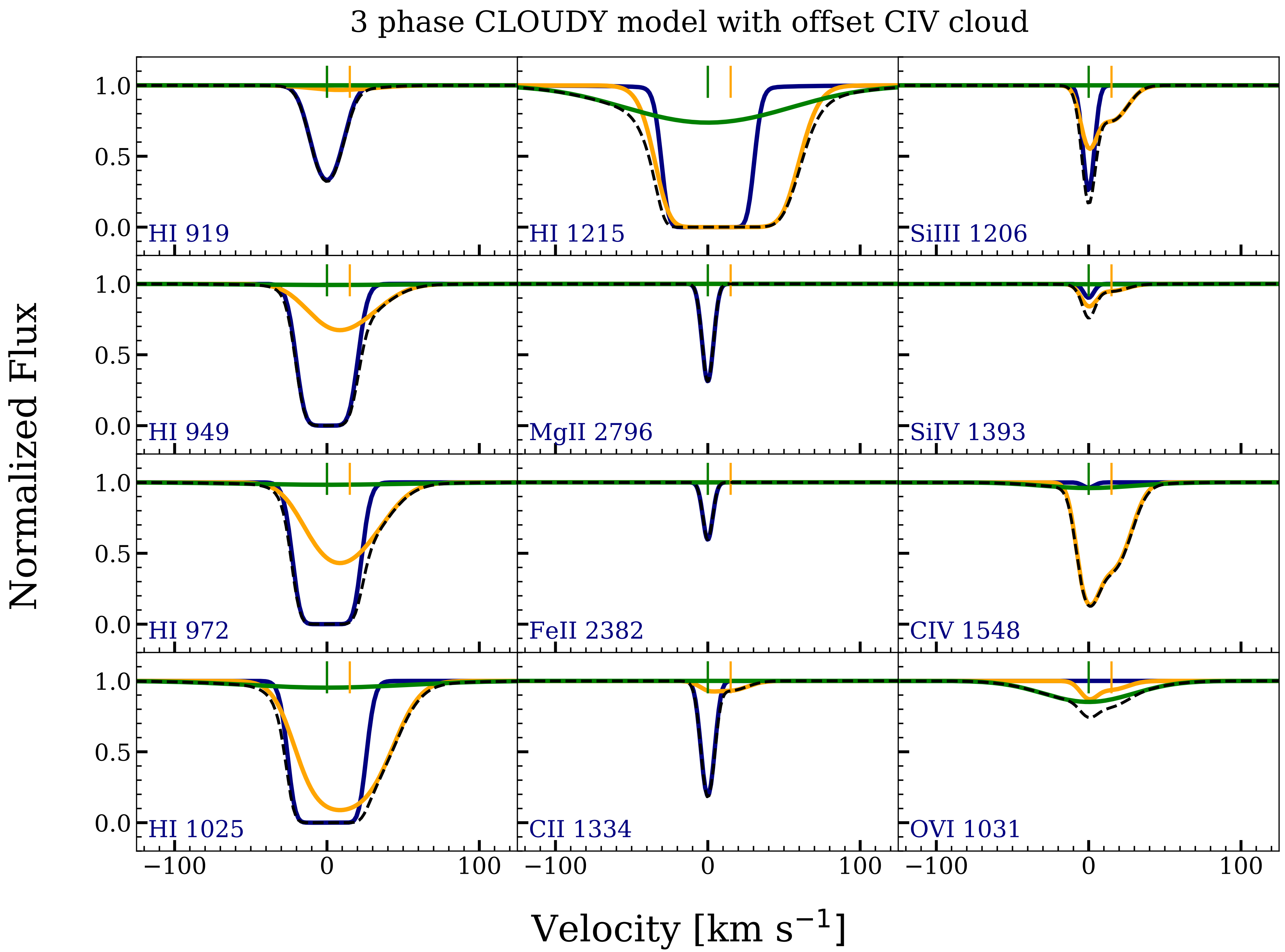
Combining the Phases at z=1: Example 1



logZ=0 logn=-1.5 b=3 4pc; logZ=0 logn=-3 b=15 160pc;

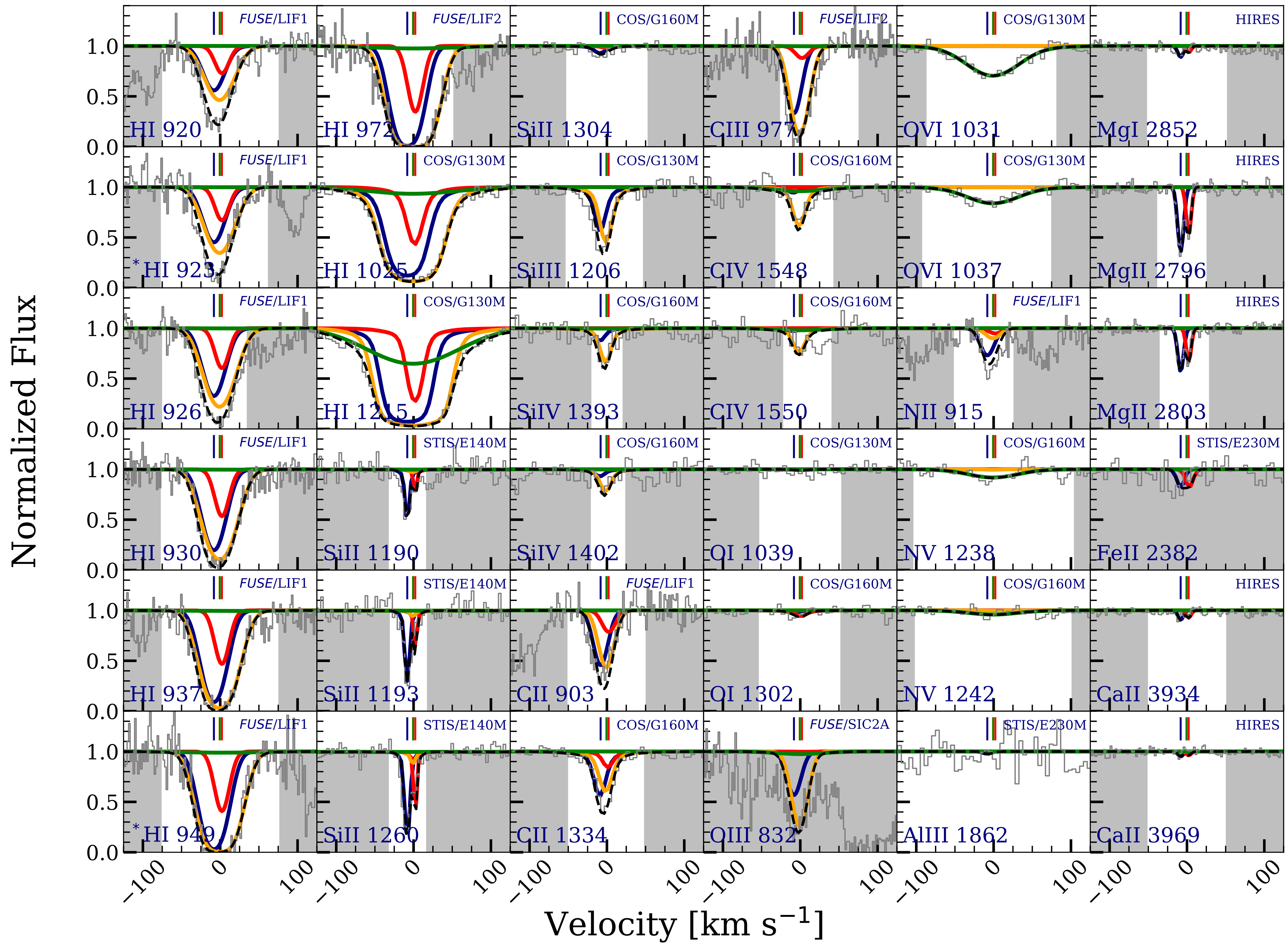
logZ=-1 logT=5.35 b=40

Combining the Phases at z=1: Example 2



logZ=0 logn=-1.5 b=3 4pc; logZ=0 logn=-3 b=8 160pc;
v=+15 logZ=-0.5 logn=-3 b=15 670pc; logZ=-1 logT=5.35 b=40

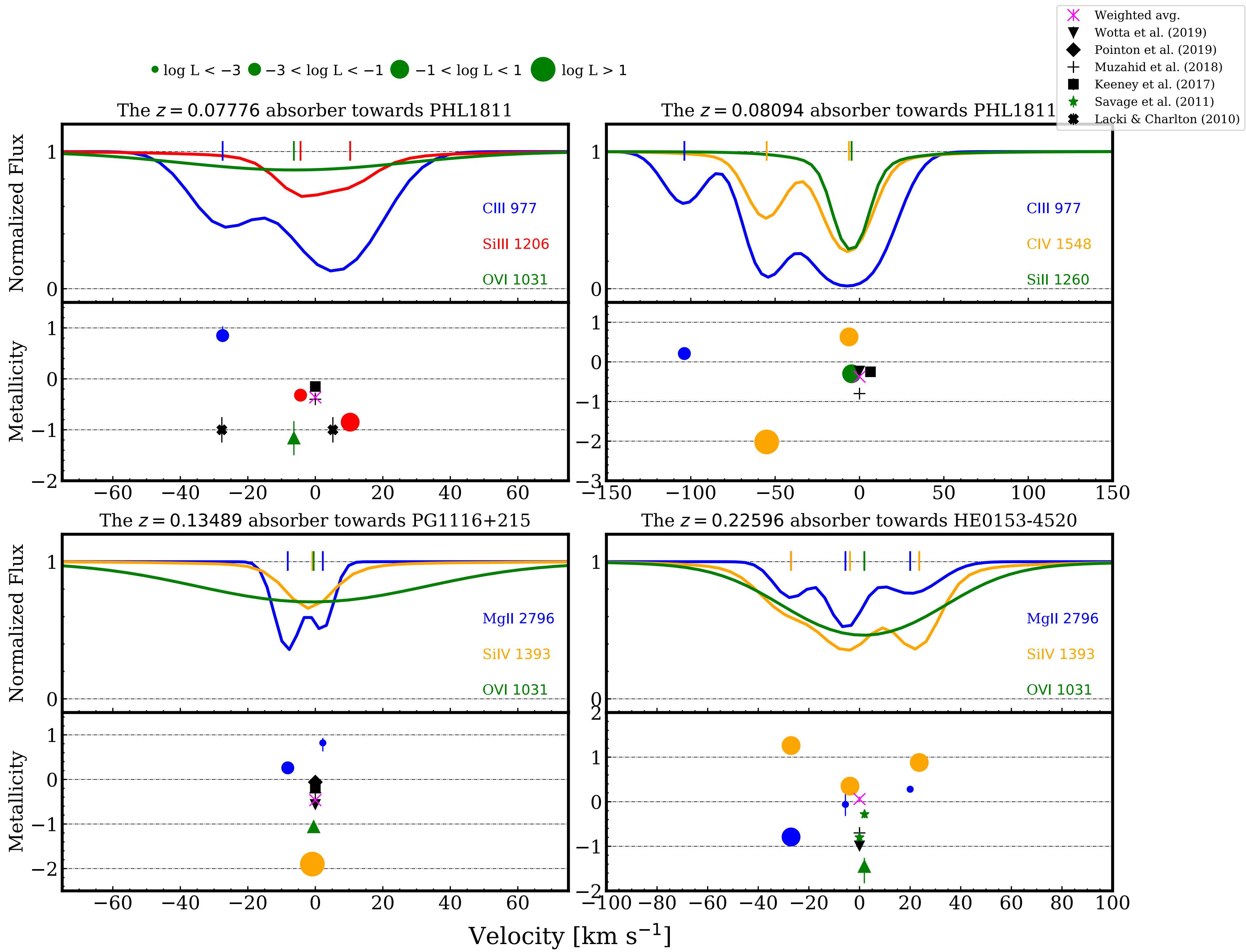
Extracting Multiphase Conditions in Practice



- Several groups finding variation of metallicity across a system and between multiple phases.

  Lehner+2019, Zahedy et al. 2019, Sankar et al. 2020, Chen et al. 2020, Haislmaier et al. 2021, Sameer et al. 2021

Extracting Multiphase Conditions in Practice



- For more information on Cloud-by-cloud, multiphase Bayesian modeling see the 4 minute presentation on YouTube or the MNRAS paper Sameer et al. 2021

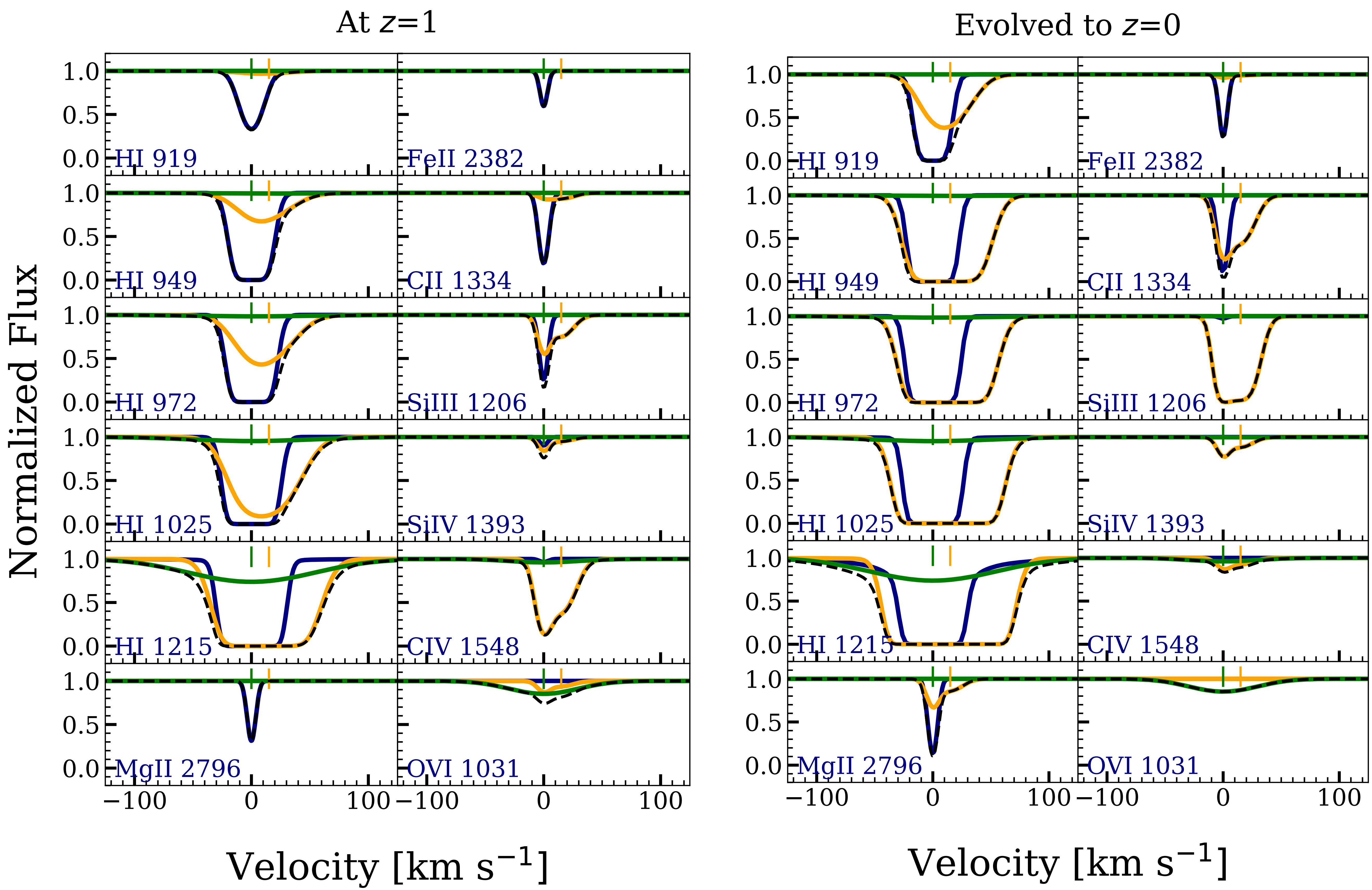
How will same structure appear at different redshift?

- Fix the density, metallicity, NHtot, bturb for each component/phase.

- Subject the same structure (same size, density, and metallicity) to a different EBR corresponding to different redshift and predict profiles.

- Keep collisionally ionized gas the same.

How will same structure appear at different redshift?



Lessons from Evolving Structure Thought Experiment

- MgII absorbers at higher z are higher density and narrower than at low z.

- Some low z MgII absorbers would have been CIV absorbers at higher redshift. Multiple clouds appear in MgII at low redshift.

- Photoionized OVI absorbers at high redshift would become CIV absorbers at low redshift.

- OVI collisional phase could be hidden in photoionized OVI profiles at higher redshift but might still be apparent in Lyman-alpha wings.

- Should consider the halo covering factors for gas of a certain density and how that changes with time. For example, CIV covering factor changing does not necessarily mean a change in density.

Closing Thoughts

- The shapes of the line profiles, particularly the Lyman series, are important diagnostics of physical conditions in Bayesian, component-by-component modeling.

- Often the metallicities can be derived even for superimposed phases by looking carefully at line shapes. Resolution is important.

- This can be formalized and errors determined from a Bayesian cloud-by-cloud approach with human intervention to assign phases and optimizing transitions, carefully considering effect of possible unresolved components.