Refinement of a Semi-Empirical Model to Understand Spectroscopic Indications of Alfvén Waves in the Solar Corona

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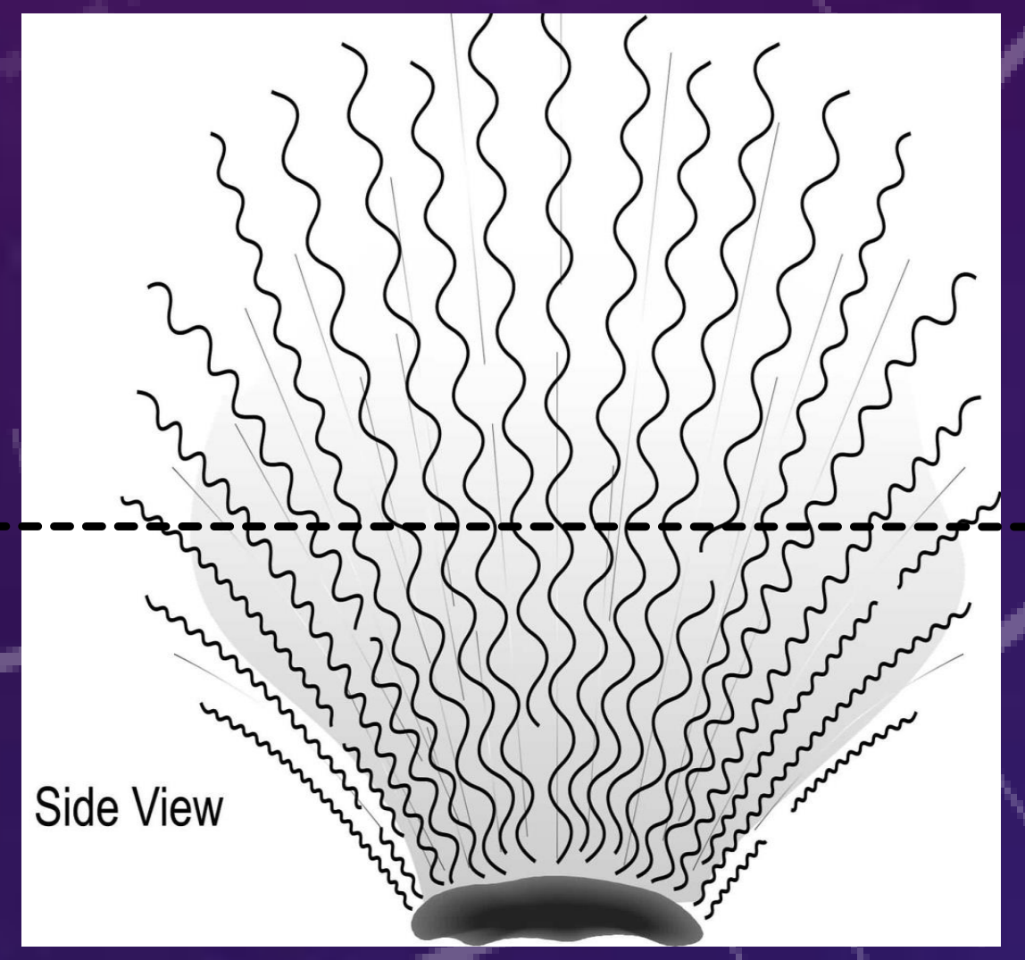
Introduction

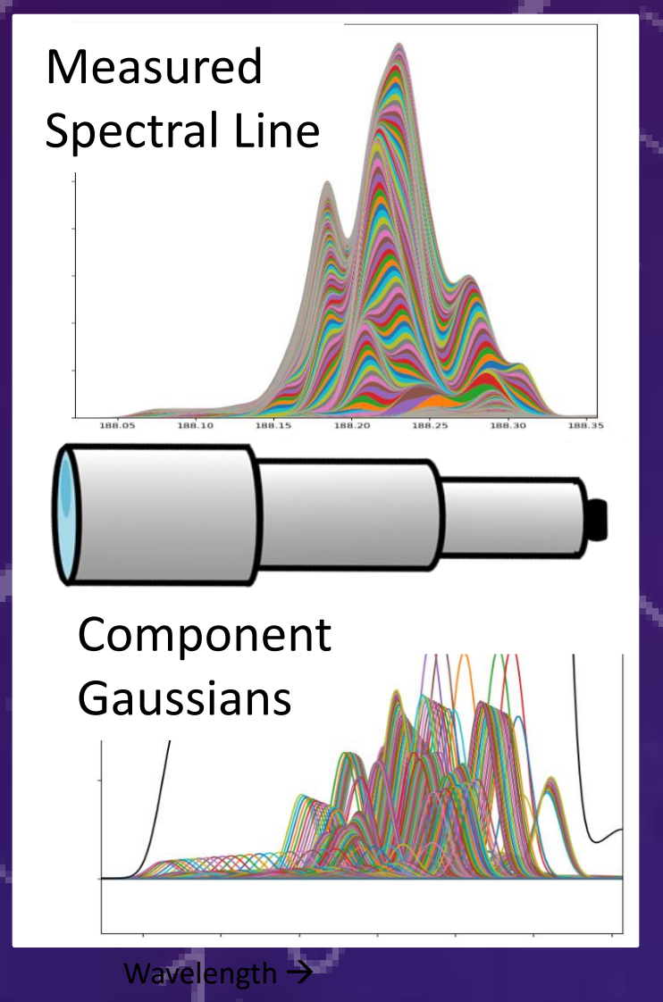
We generate synthetic spectral lines from the solar corona and explore how changes in physics alter the observations. This will help us interpret real observations of the Sun better.

There is much debate in the solar community regarding the precise mechanism by which the corona is heated to millions of Kelvin. Alfvén waves, driven by fluid motion in the photosphere and propagating upwards to dissipate in the corona, are one of several popular hypotheses for the source of the thermal energy. Observations of off-limb spectral lines are in theory able to constrain some properties of these waves as a function of heliocentric altitude, but in practice the interpretation of these measurements is difficult due to the optically-thin nature of the corona. In this work, a forward model (GHOSTS) is developed and refined so that it can be used to generate realistic simulated observations of the Solar Corona. Recent improvements to the model include the addition of resonantly scattered light, refinements in the treatment of photon scattering, and the self-consistent calculation of non-equilibrium ionization states in the corona.

Measuring Alfvén Waves in the Corona

Above the poles of the Sun, open magnetic field lines define **magnetic plumes** which are being **shaken by photospheric convection**. Because these oscillations are transverse, they cause a slight **Doppler shift in the spectral lines** as observed at Earth. Because there are many such flux tubes along a line of sight, measurements are the sum of many individual Doppler-shifted spectral lines.



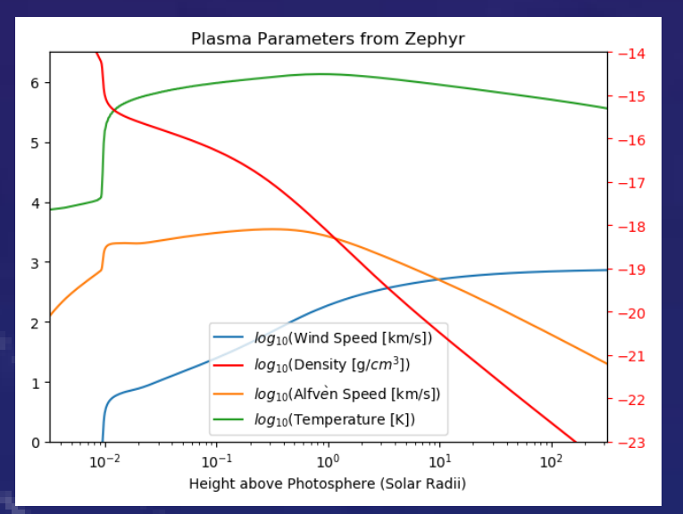


It is not immediately obvious exactly how to extract the properties of the waves from such a profile. One method often used, but little verified, is to simply fit the line with a Gaussian and then **relate the line width to the RMS amplitude**. Care must be taken to subtract out the thermal width to get the true non-thermal (wave/turbulence) width of the line. [3,5,7,8] Usually the remaining width is then assumed to represent the plasma in the Plane of the Sky (POS), which may be misguided. The purpose of this work is to try to better understand how the shape of the spectral lines is related to the Alfvén waves in the corona.

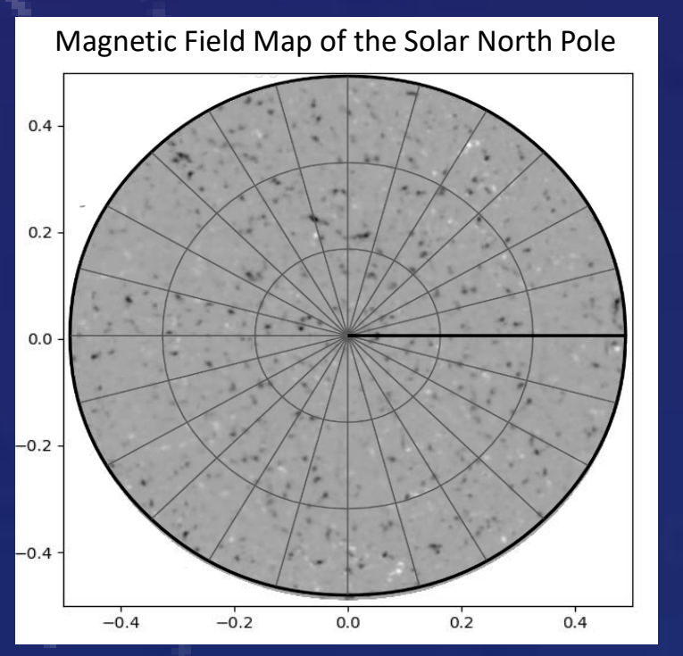
Simulating Coronal Measurements

In order to simulate the spectral lines, three kinds of input are needed:

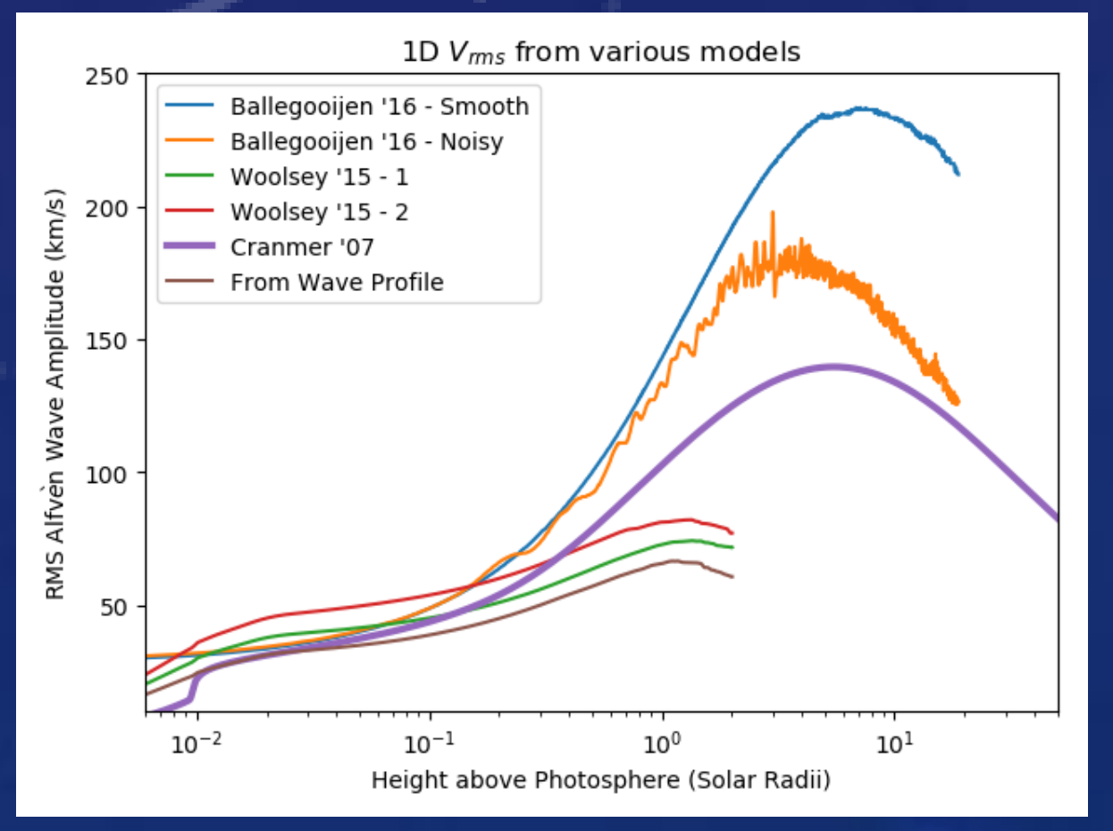
Coronal Plasma Properties: The **ZEPHYR** code is a 1- dimensional code that simulates the time-independent plasma properties of the corona as a function of altitude. [2] It produces tabulated output of the following variables, which are read into the GHOSTS model: **Density, Wind Speed, Alfvén Speed, Temperature.** These values are used as the average background values inside the coronal hole, which are then modified by the magnetic field strength. In the plot, the density uses the red axis.



Polar Magnetic Field Map: This creates the polar plumes. Because we don’t have a line of sight to the solar poles, these maps must be partially synthesized. The magnetic field maps from **SOLIS/VSM** [4] magnetograms taken of large coronal holes between 2010 and 2013 were stitched together to yield polar maps. The magnetic field strength modulates a variety of plasma parameters in the overlying corona, such as density and solar wind velocity.



Alfven Wave Profiles: The **BRAID** code is a simulation of a bundle of flux tubes expanding in the chromospheric network. [1] From that simulation, we are able to draw an average x and y velocity as a function of time. This gives us a **wave profile** that we can draw from in the GHOSTS model. This is then normalized to an RMS of 1, and RMS vs Height info from ZEPHYR is applied to the data.



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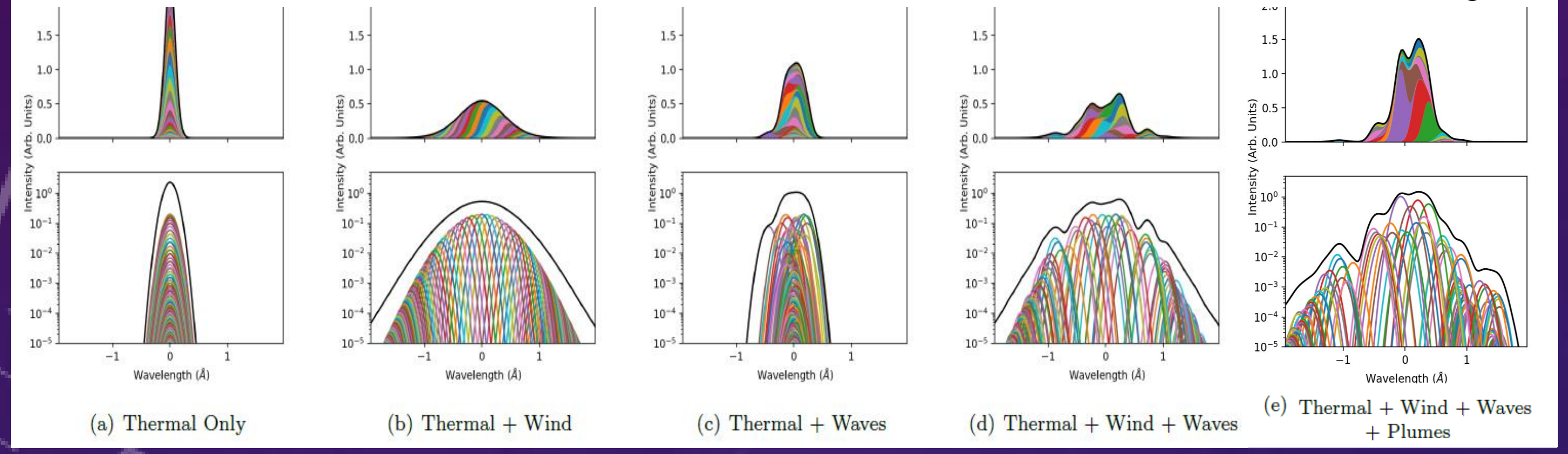
The GHOSTS Model

Generating Spectral Lines

GHOSTS is the **G**lobal **H**eliospheric **O**ptically-thin **S**pectral **T**ransport **S**imulation. This is a semi-empirical forward model which simulates spectral lines coming from the corona. A sightline is established, and the light produced by each point along the sightline is determined based on the local plasma parameters. Because the corona is optically thin, all of this light can simply be summed. Different physics can be turned on and off individually, as shown in this plot:

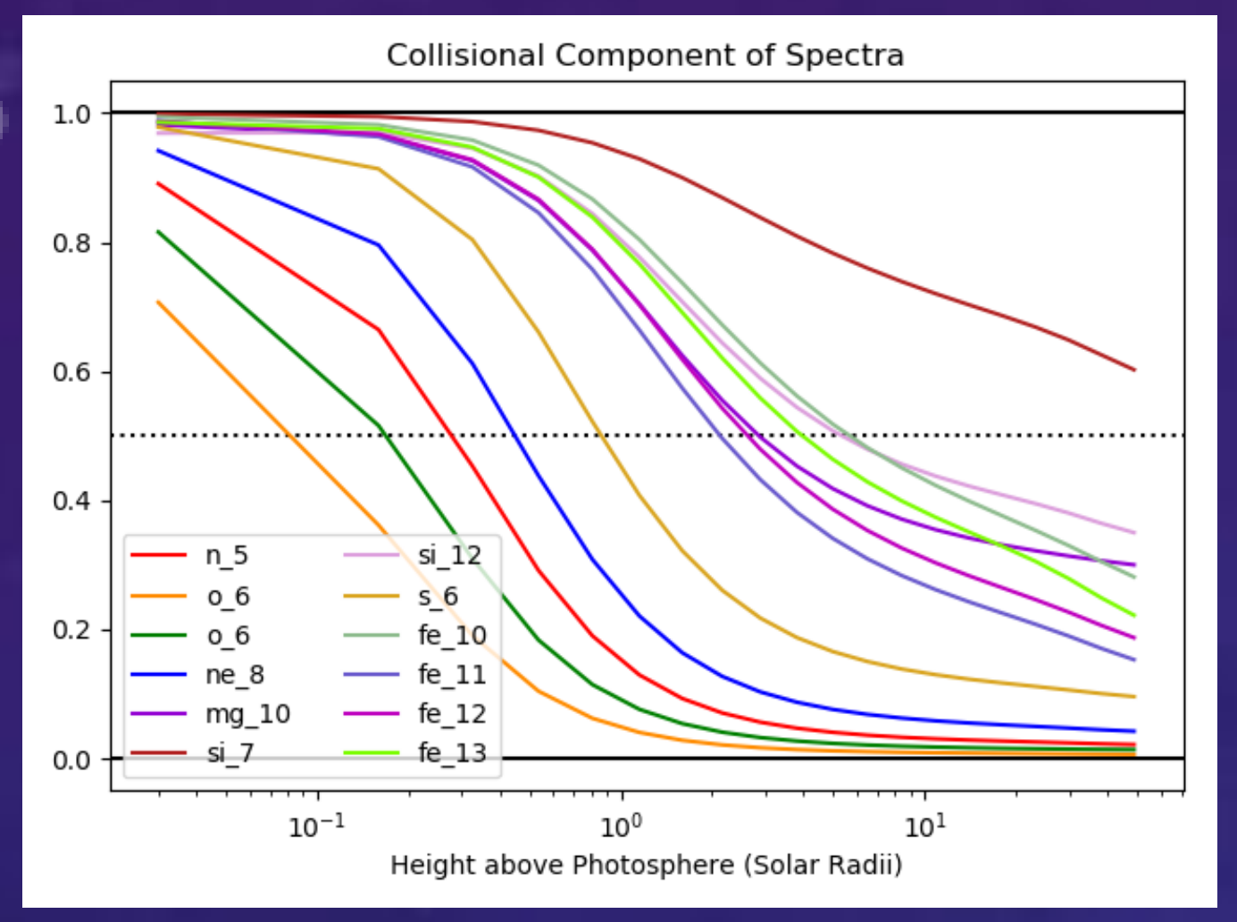
Each of these spectral lines is generated by the same line-of-sight, at an impact parameter of $2R_\odot$



(a) Thermal Only (b) Thermal + Wind (c) Thermal + Waves (d) Thermal + Wind + Waves (e) Thermal + Wind + Waves + Plumes

Recent Upgrades

Two Types of Light



Two different sources of light are now handled by the code: **collisionally excited** lines, and **resonantly scattered** photons from the bright solar disk below, provided by the SUMER Spectral Atlas.

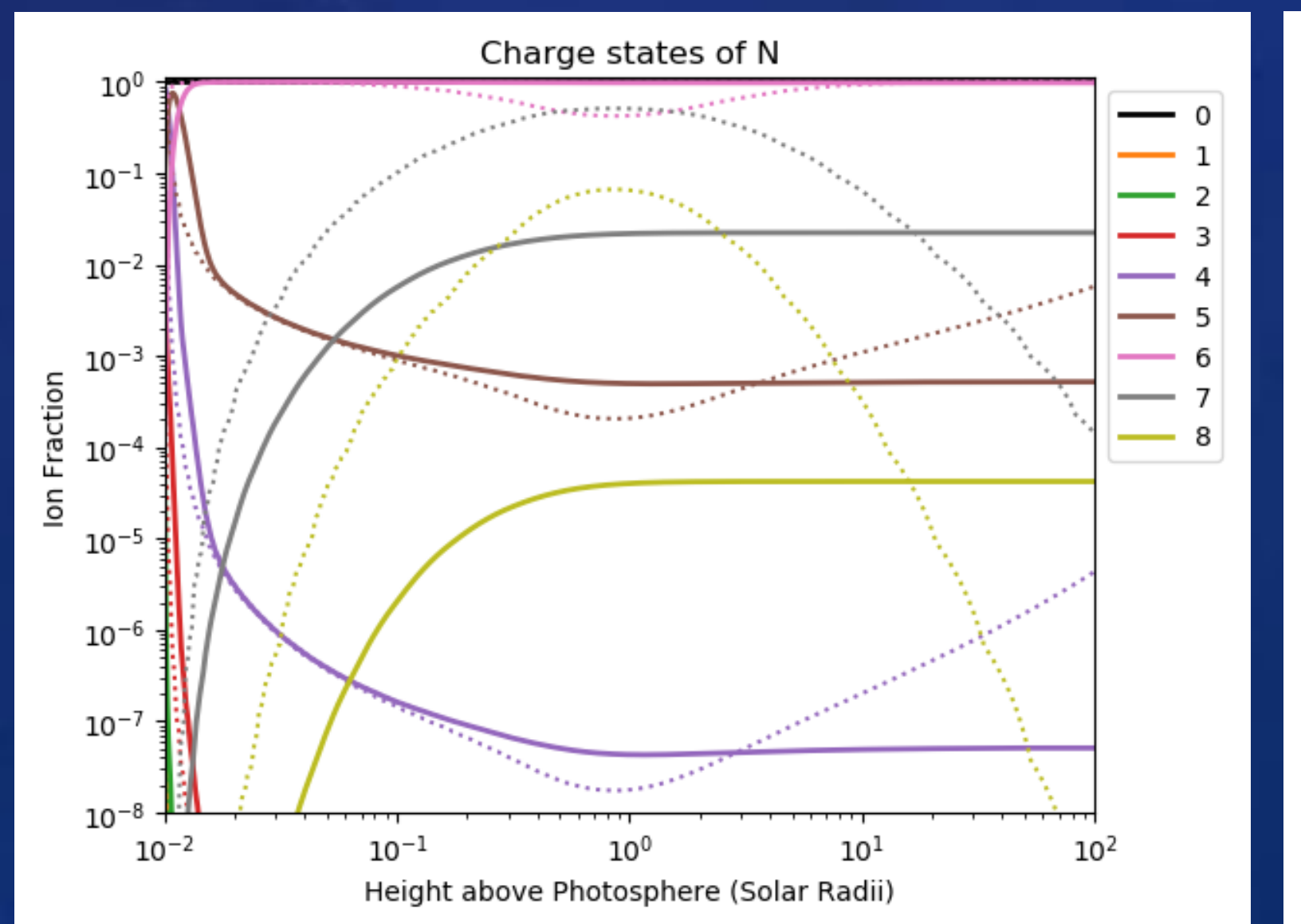
Because there are only two components of the light, we can plot the fraction of the collisionally excited light for each ion line and it contains all of the information about the composition of that line. As can be seen in the panel to the left, the different lines have different fractionalities as a function of Z.

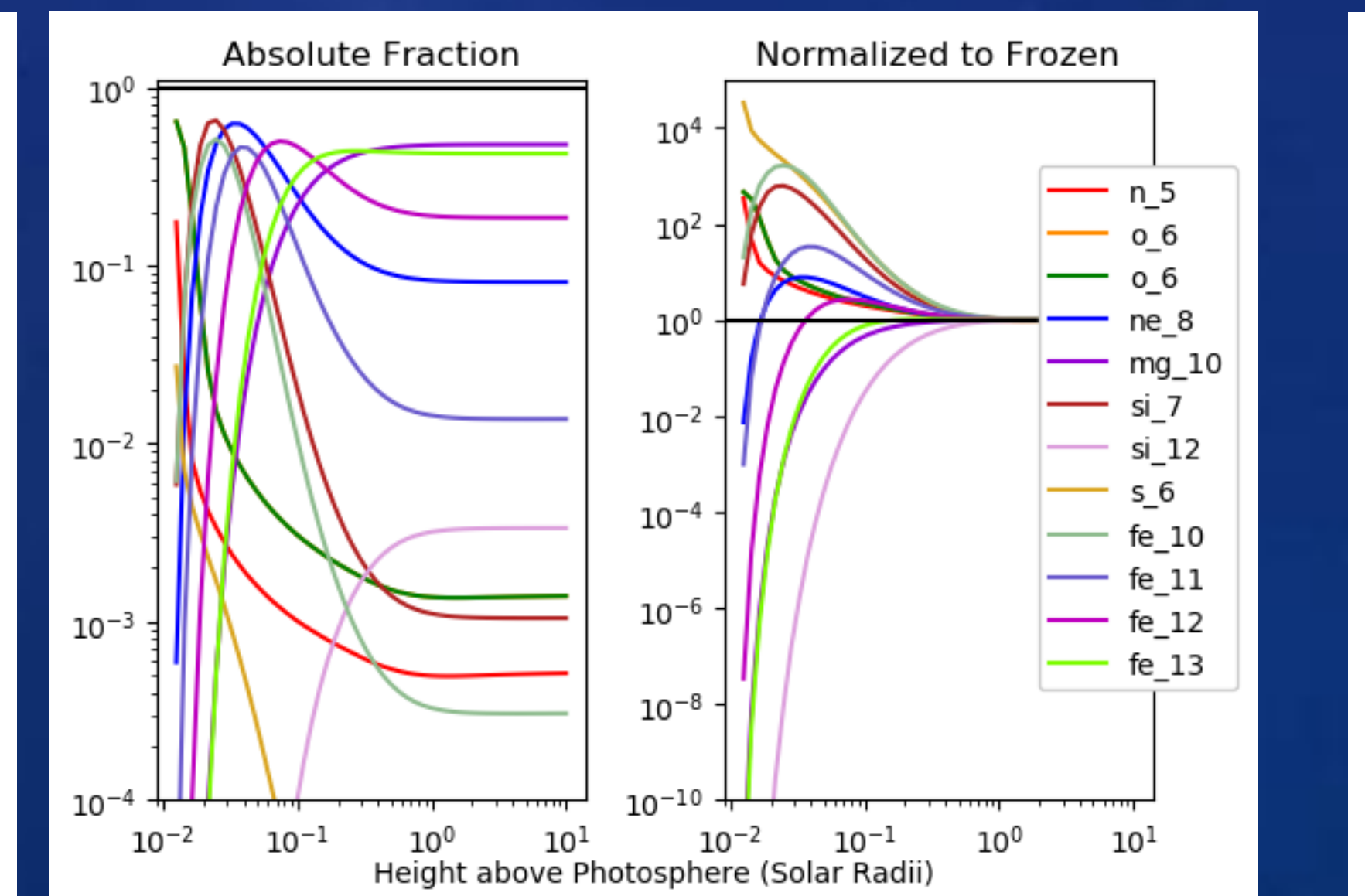
Charge States and Freezing-In

The Zephyr Model (see left panel) provides the density of the corona as a function of height. We need more information if we want to accurately simulate the spectral lines produced in the corona: the abundances and ionization/charge states of the elements. CHIANTI is a database of quantum mechanical information, which provides coronal elemental abundances, as well as temperature-dependent, collisional ionization (C_i) and recombination (R_i) rates for every ion. These rates are input into the following equation [6], which is integrated numerically to find the true, self-consistent non-equilibrium ionization states for each ion of each element.

$$\underset{0}{\cancel{\frac{\partial n_i}{\partial t}}} + \frac{1}{fr^2}\frac{\partial}{\partial r}\left(fr^2 n_i u_i\right) = n_{i-1}C_{i-1} + n_{i+1}R_{i+1} - n_i\left(C_i + R_i\right) \Rightarrow \frac{\partial n_i}{\partial r} = RHS$$

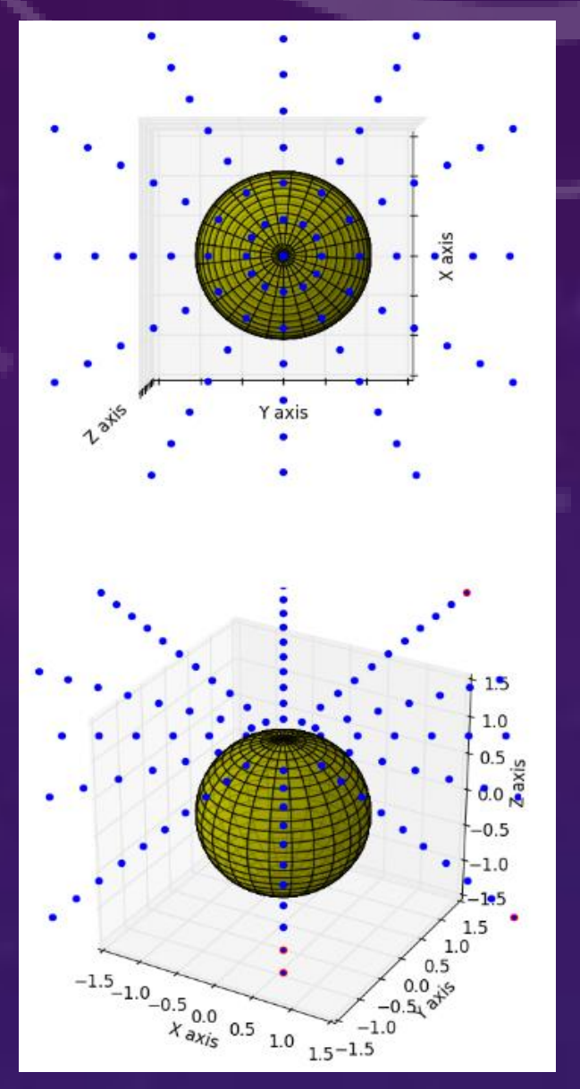
It is important to model these charge states carefully because of the “frozen-in” phenomenon. In general, the charge state fractions are just a function of the local temperature. However, when the solar wind carries the plasma away from the local region before the charge states have a chance to equilibrate, we say that the charge states are frozen-in, and they no longer vary with the temperature above the freezing height, as seen in the first panel below. In this figure, dotted lines show the equilibrium calculation, and solid lines show the results of the above equation, for all of the possible charge states of Nitrogen. In the second panel, just the populations of the ions for the spectral lines we are simulating are shown, as a fraction of the total density at each height.





Analyzing Spectral Lines

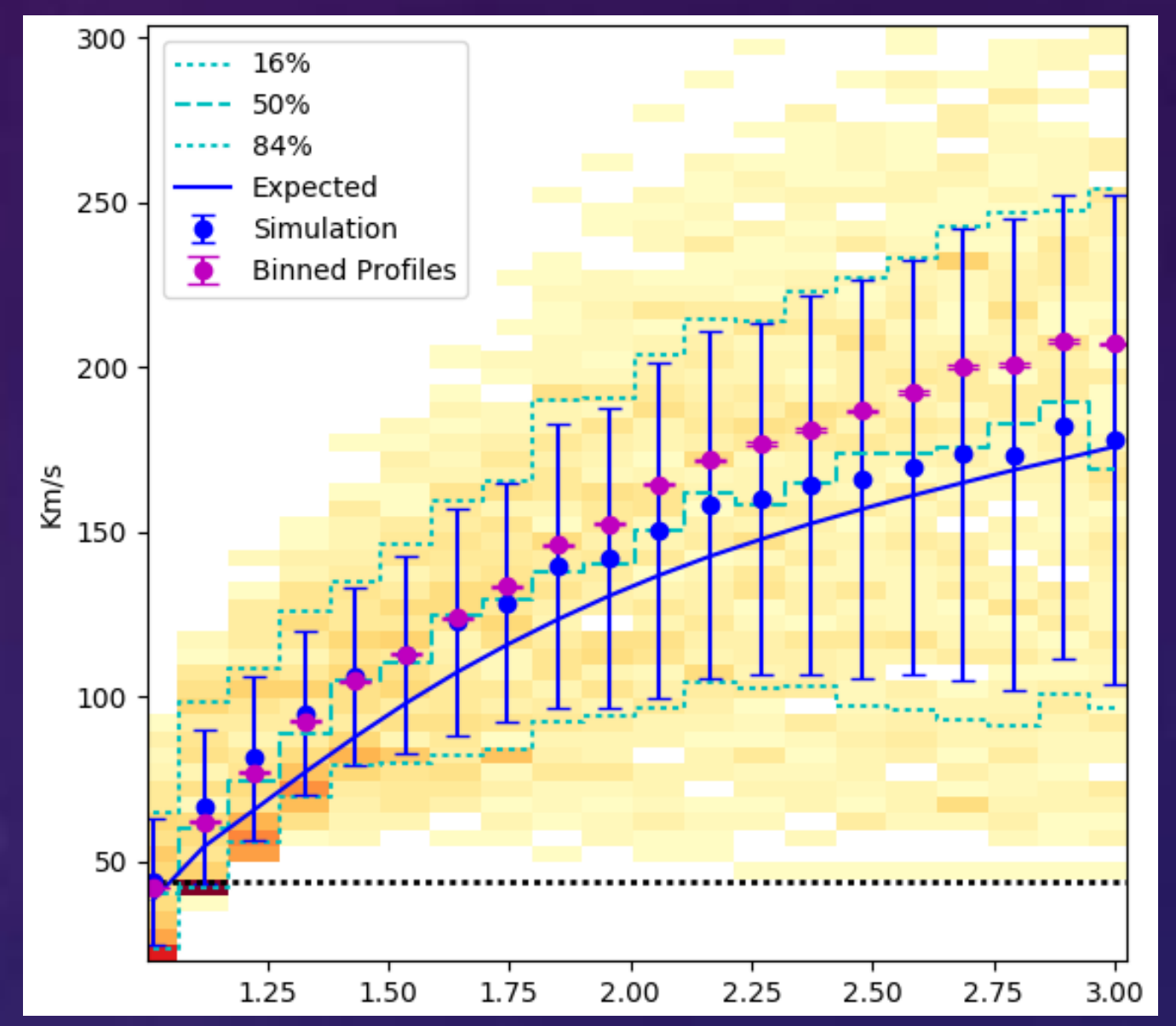
Methodology



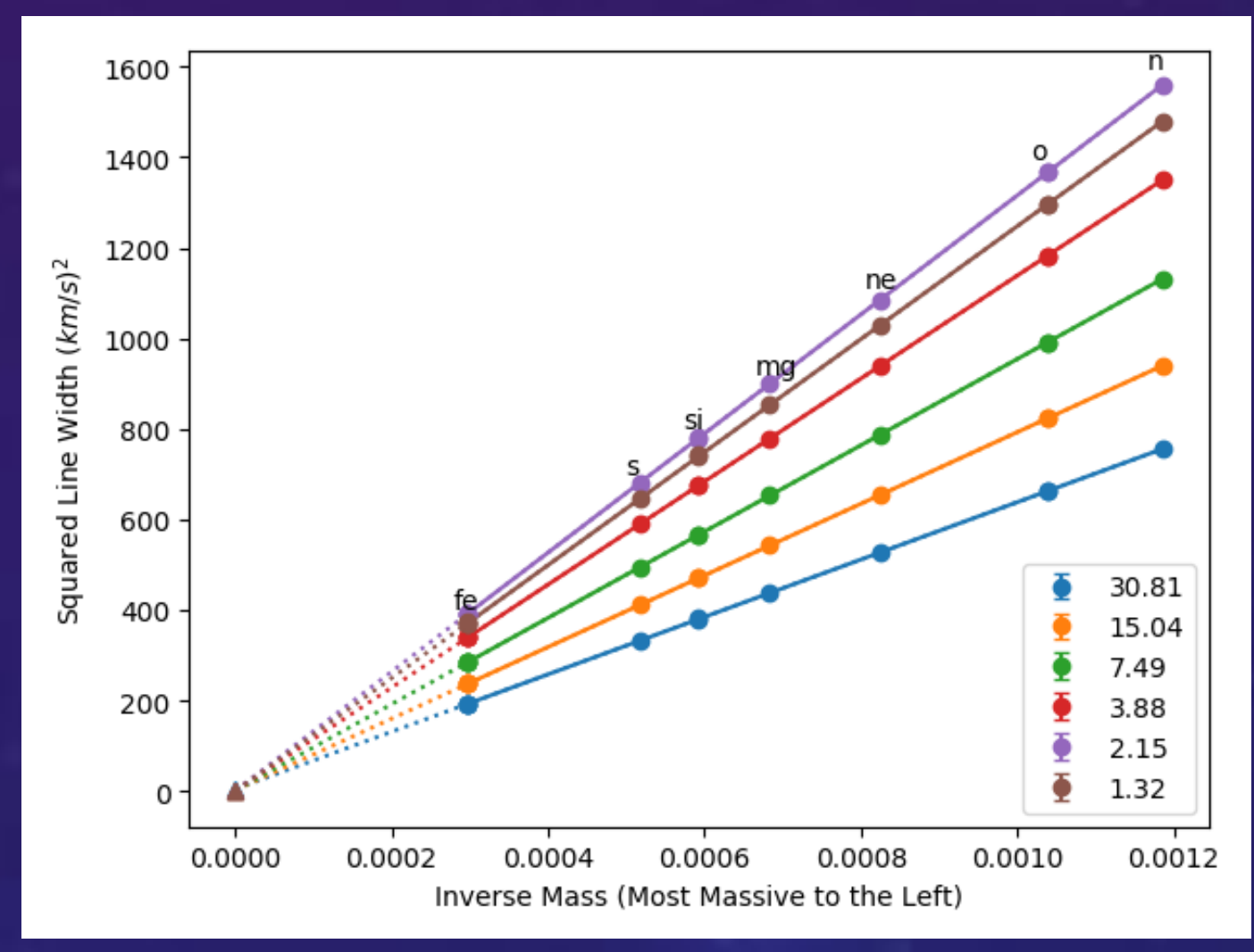
GHOSTS generates many sightlines at a given impact parameter, and fits them with Gaussians to find their width. Statistics can then be performed on the line widths at each height to create a plot like that on the right.

A run generates around 50-100 sightlines at each impact parameter. We use 6 magnetic field maps to create plume structures, and we simulate about 10 different ion lines, with the ability to integrate in time if desired.

These ensembles of lines can then be studied with respect to the known input parameters.



Multi-Ion Fitting

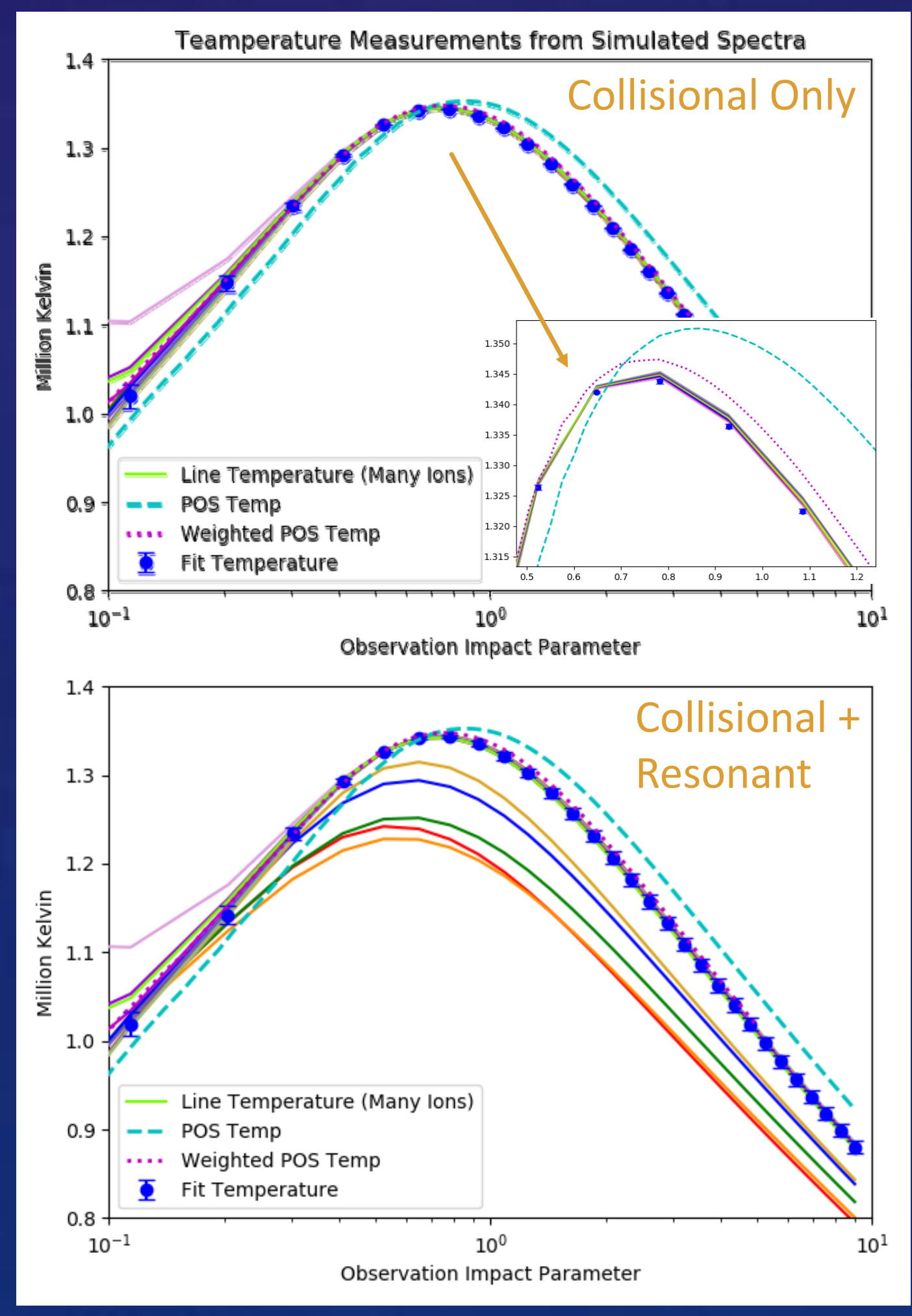


One proposed method to try to determine the thermal and non-thermal parts of an observation involves using measurements of multiple ion lines at the same time [9]. Because the temperature-dependent width is a function of the ion mass, we can use linear fitting to estimate the two components. Each linear fit occurs at a single value of the impact parameter. See results from this method below: The blue line matches the direct inversion very well.

$$v_{1/e}^2 = v_{th}^2 + v_{nt}^2 = \frac{2k_BT_i}{m_i} + v_{\mathrm{nt}}^2$$

$$y = mx + b = \underbrace{2k_BT_i}_{\text{Slope}} \times \frac{1}{m_i} + \underbrace{v_{nt}^2}_{\text{Intercept}}$$

Thermal-Only Observations



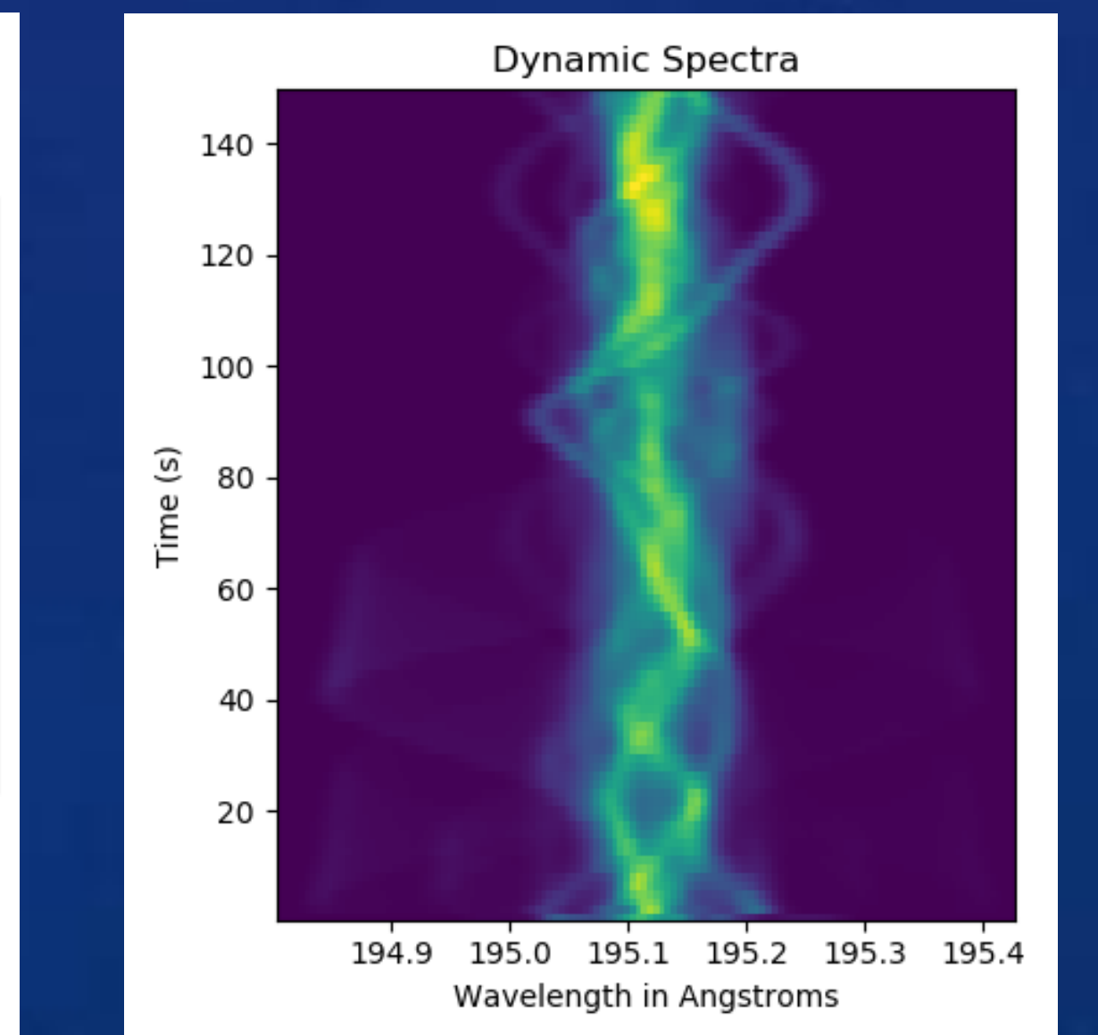
On the left are two panels showing the results of curve fitting the simulated spectral lines and converting the widths to temperatures.

The cyan line is the actual plane of the sky (POS) temperature from the model. The blue line is the results from the multi-ion fitting. The magenta line describes the weighted POS temperature – the temperature we would expect to measure based off of the density-squared weighting of the points along the line of sight. Also plotted, as solid lines, are the results measured by converting the ion line widths directly to temperature using $T = \frac{\Delta\lambda^2 m_{ion}}{2k_B}$.

In the collisional only case, the lines all match up about perfectly, and agree with the muli-ion fitting very well. In the case where resonant light is included, each of the ions has different behavior as a function of height. We expect to see differences: resonantly scattered light is weighted along the line of sight by a factor of rho, and collisionally excited light is weighted by rho^2.

In the future we will invert this problem, allowing us to use line width measurements to recover the plane of the sky temperatures.

Sub-Cadence Dynamics



The instantaneous spectra in cases with waves activated are highly non-Gaussian. Typically the long integration times of these measurements smear out this structure, but faster cadences may be interesting components of future observations, because we could see the effects of the Alfvén waves directly!