Spectral Synthesis of Phosphorus V Quasars

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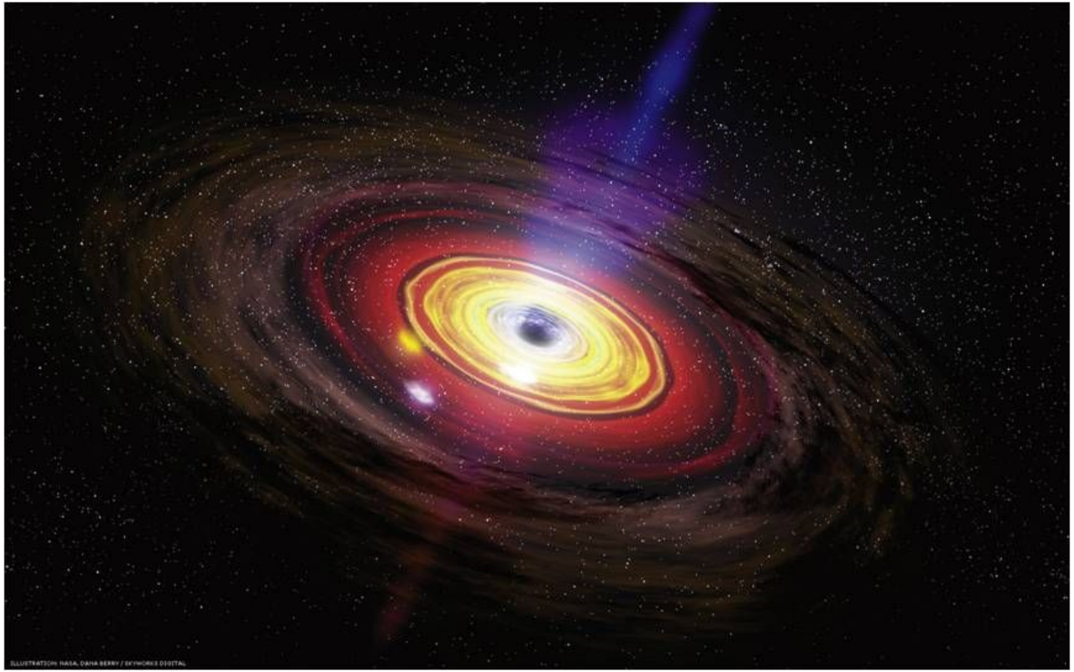
Quasars

-Extremely bright objects made of matter accreting into a supermassive black hole at the centers of galaxies

-Potential energy turned into light

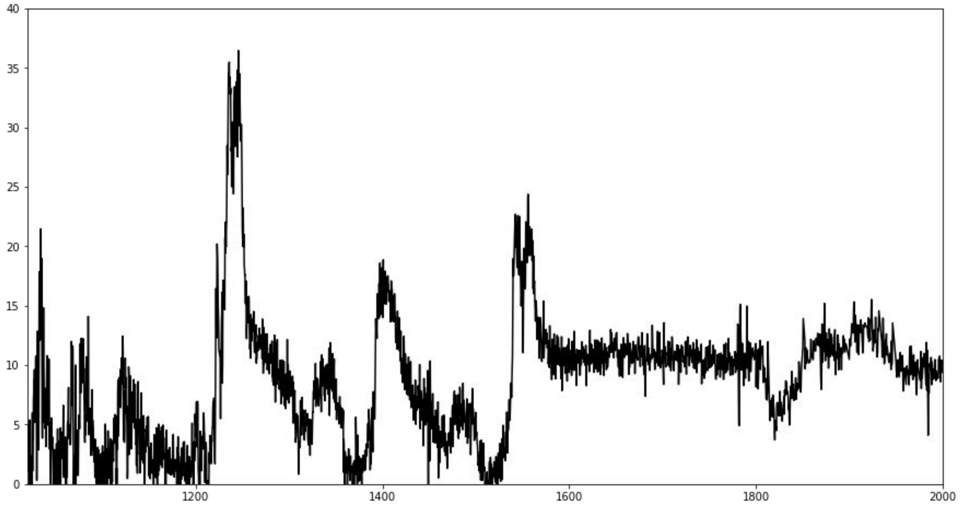


https://www.skyandtelescope.com/astronomy-news/watching-a-quasar-shut-down-122614/

BALs

-Absorption lines come from photoionized gas, powered by the accretion happening in the quasar

-Broad Absorption Lines (BALs) are thought to originate with high velocity outflows, up to 1/10 the speed of light so relativistic formulas are relevant



Ionization

-Photoionization: Photons can transfer energy to electrons in atoms to knock them off the atom, creating ions

-Certain wavelengths of light are known to cause specific transitions

-Ionization parameter describes rate of ionization compared to rate of recombination

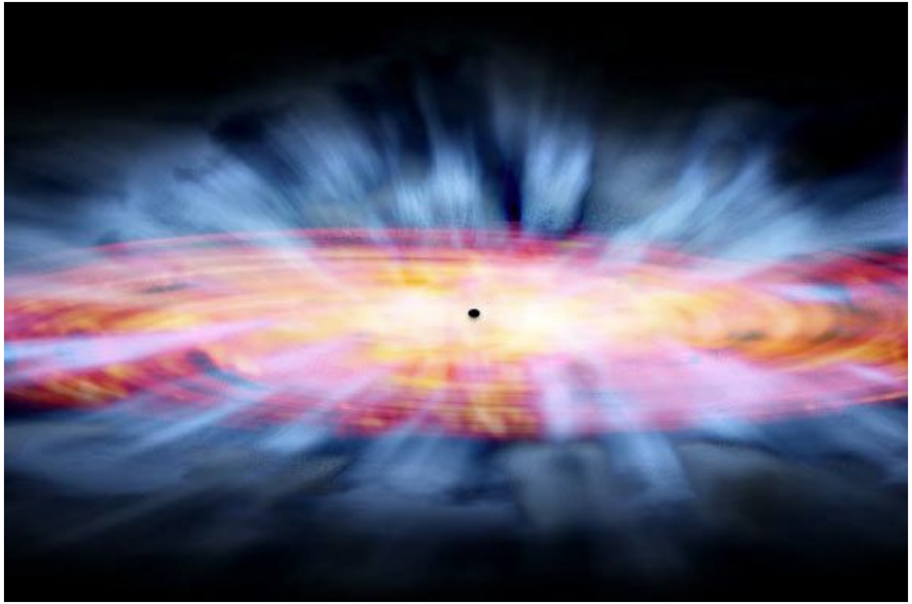
-Radiation pressure - force per area from photons scattering from ions, pushes the gas and creates high velocity outflows

Gas Clouds

-The absorption we see comes from one or several clouds of gas that the light passes through before it reaches us

-Location could be anywhere from near the accretion disk to far out in the galaxy

-We know the clouds only partially cover the continuum emission region but we don't know what exactly that looks like



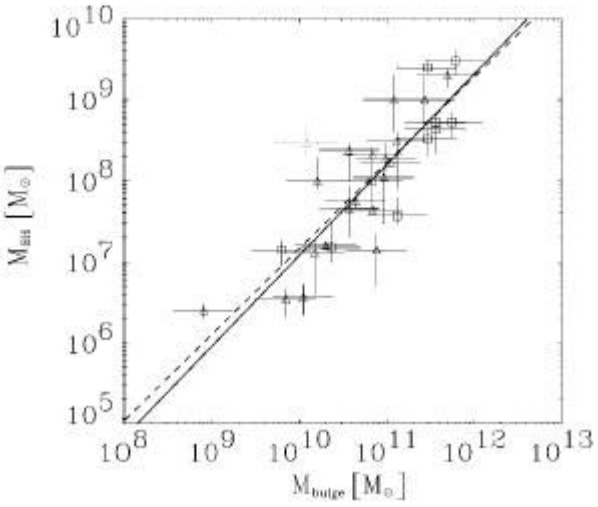
http://www.sci-news.com/astronomy/science-new-class-quasars-01536.html

Feedback

-Models of galaxy formation show many more stars forming than there really are so some sort of feedback is necessary to explain the universe that we see, currently unknown

-There is a close correlation between the size of the supermassive black hole at the center of a galaxy and the size of the bulge of stars in that galaxy

-One way for the black hole to interact with the galaxy is through those high velocity winds



http://atropos.as.arizona.edu/aiz/teaching/a250/distant_galaxies.html

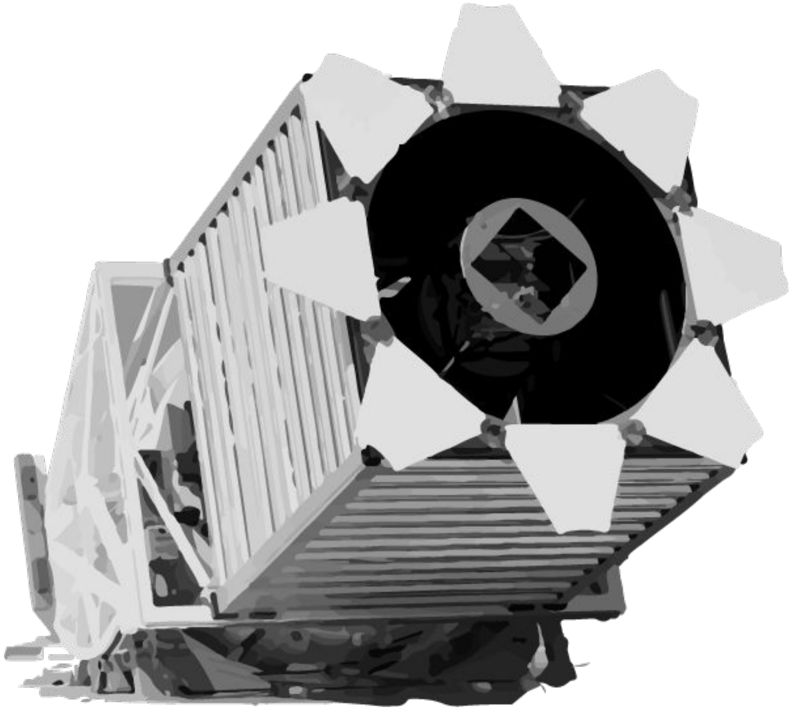
SDSS

-Our data comes from the Sloan Digital Sky Survey (SDSS)

-2.5 m telescope in New Mexico, 10 years of design and construction, regular observations began in 2000

-The Baryon Oscillation Spectroscopic Survey (BOSS) ran from fall 2009 to spring 2014

-BOSS looked at 160,000 quasars



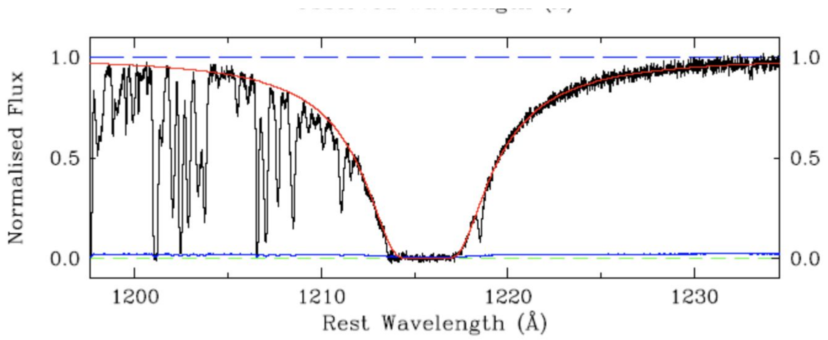
https://www.sdss.org/

Our sample

-Common BALs like Carbon are often saturated, so other lines can give us more information about the outflow

-Ratio of Phosphorus to Carbon of 1 to 1000 in the universe means P v lines indicate massive outflows

-Capellupo et al. (2017) looked through 2694 quasars from the BOSS survey which had BALs and of those found 81 “definite” detections of P v broad absorption, so those were our sample

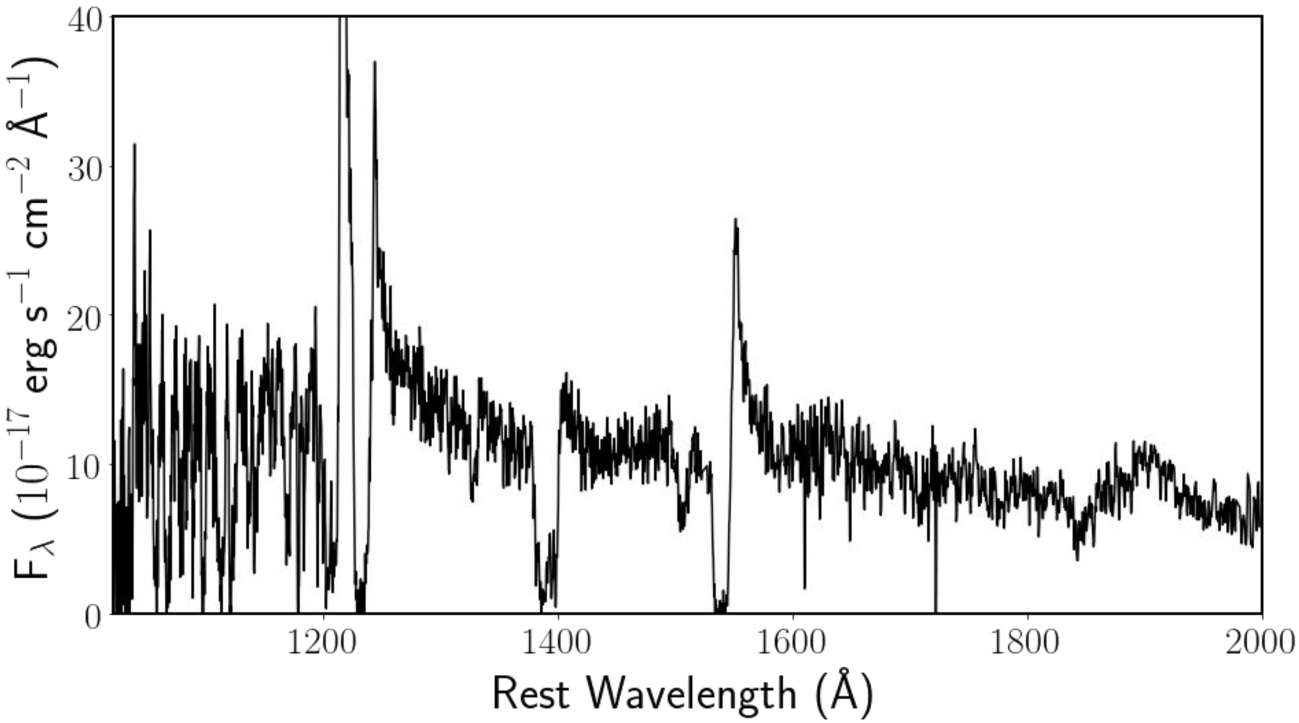


http://spiff.rit.edu/classes/phys443/lectures/gal_dark/play_deuterium.html

-Redshift z=2.5 means light that was emitted around 11 billion years ago and 70 billion light years away, and the universe was 2.6 billion years old then

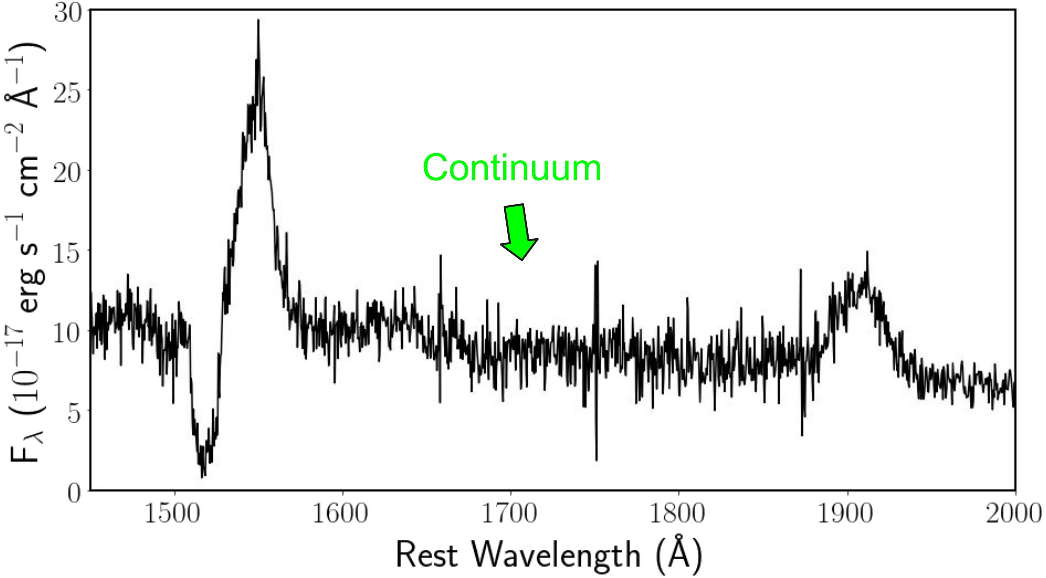
The Physics of Broad Absorption Line Quasars

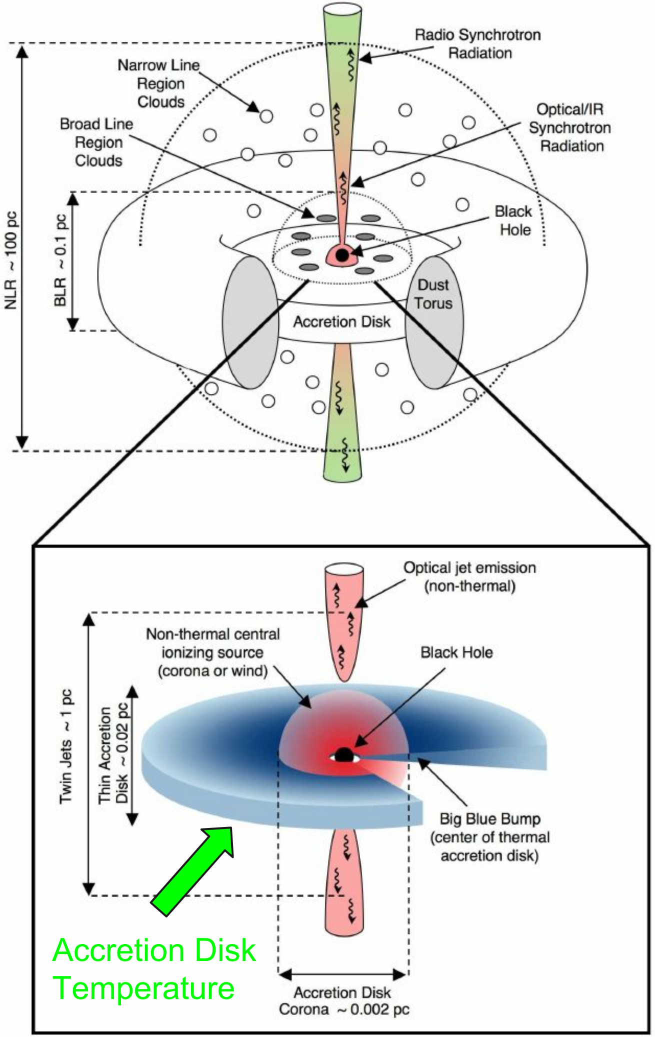
Secrets in the Spectra



- How can we learn about something so far away?
- We use our knowledge of physics to solve the mystery!
- Quasars emit a large amount of E-M radiation.

The Lines... What Do They Mean?

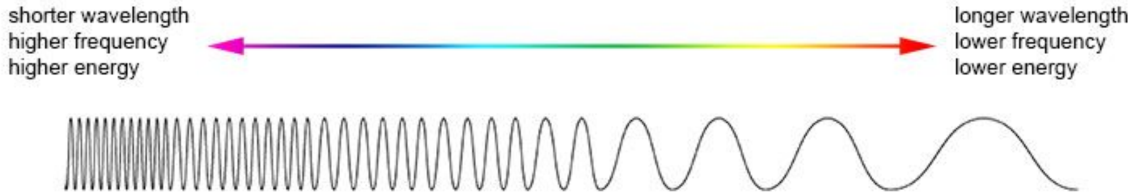




- Star thermal radiation approximated with a blackbody
- Accretion Disk thermal radiation approximated with a wavelength-dependent power law

https://www.researchgate.net/figure/Schematic-diagram-of-the-structure-of-a-typical-quasar-on-scales-from-0-002-100-pc_fig1_235168888

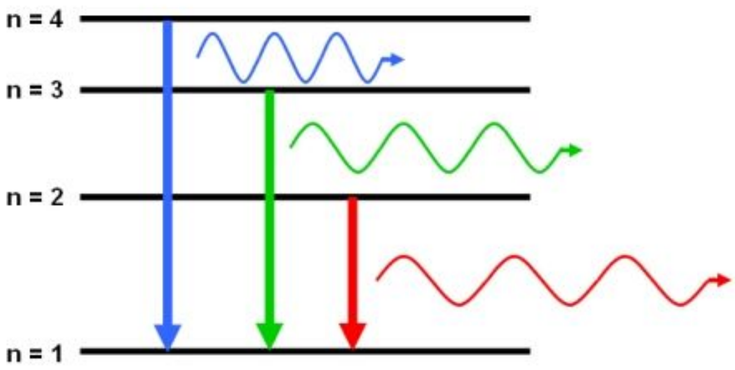
Emission and Absorption Fundamentals

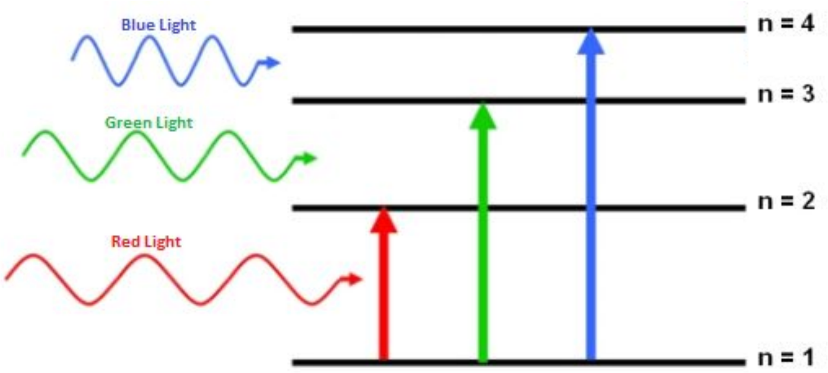


https://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html

http://en.stonkcash.com/emission-of-energy-by-atoms/

http://astronomy.swin.edu.au/cosmos/E/Emission+Line





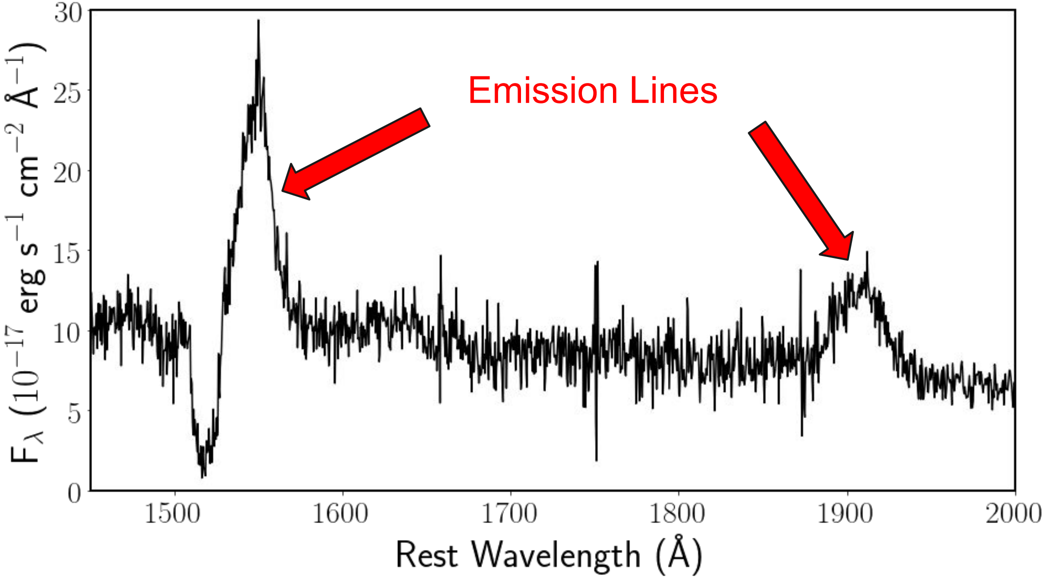
Emission

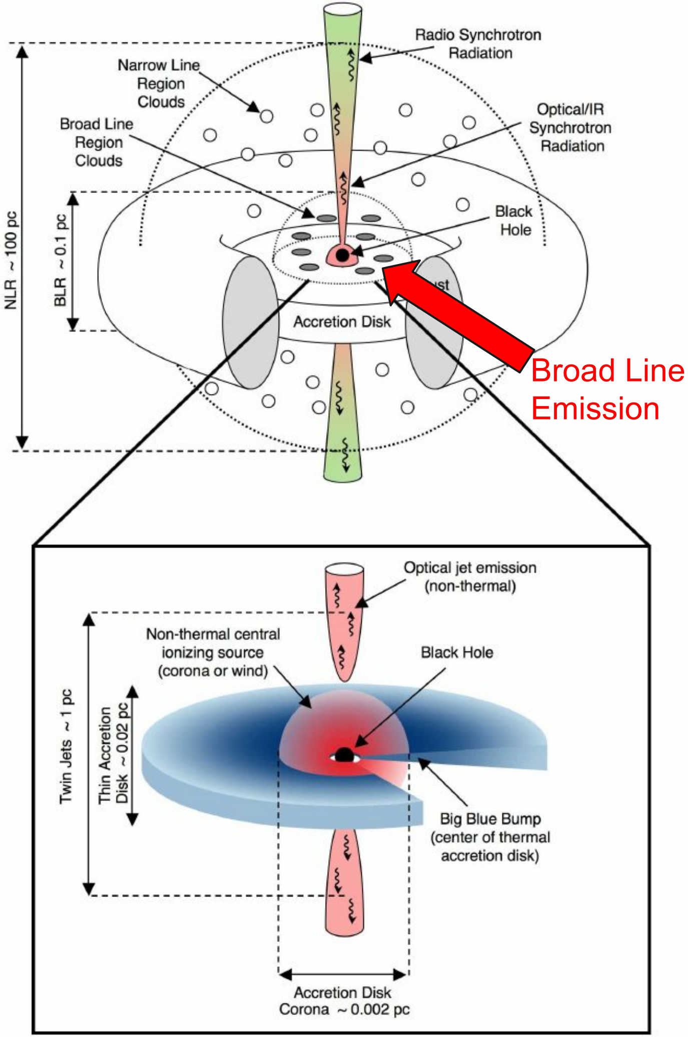
- Excited electron returns to a lower energy ***emitting*** a photon.

Absorption

- A photon is ***absorbed***, exciting an electron to a higher energy.

The Lines... What Do They Mean?

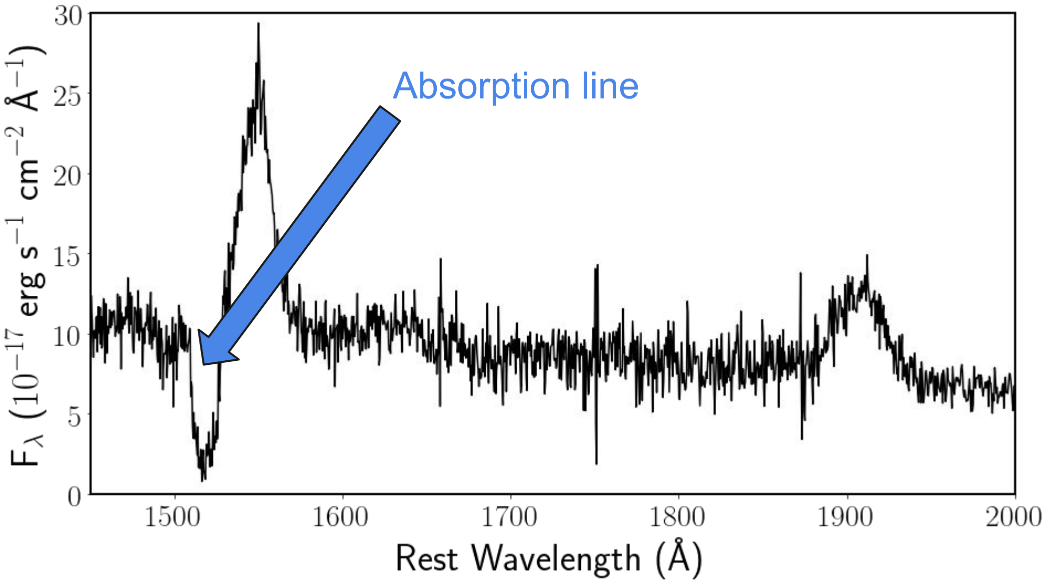


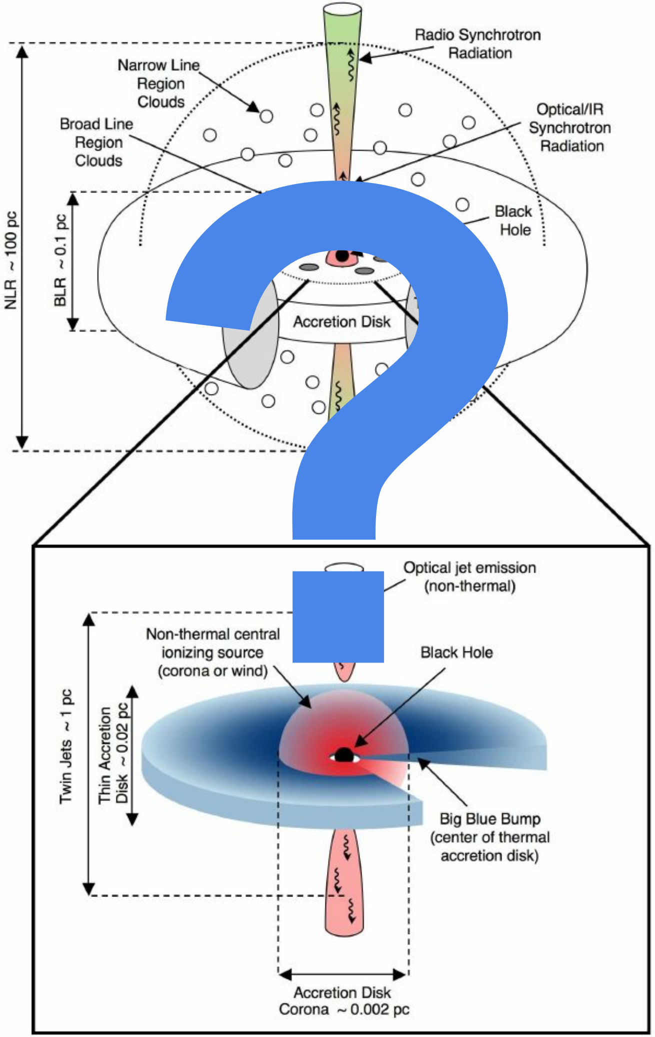


- Emission lines are created by ionized gas in the Broad Line Region.

https://www.researchgate.net/figure/Schematic-diagram-of-the-structure-of-a-typical-quasar-on-scales-from-0-002-100-pc_fig1_235168888

The Lines… What Do They Mean?





- What could be causing absorption lines to appear?
- Could the jets of matter moving at significant fractions of the speed of light be responsible???

https://www.researchgate.net/figure/Schematic-diagram-of-the-structure-of-a-typical-quasar-on-scales-from-0-002-100-pc_fig1_235168888

The Plot *Thickens*... Mysterious Absorption

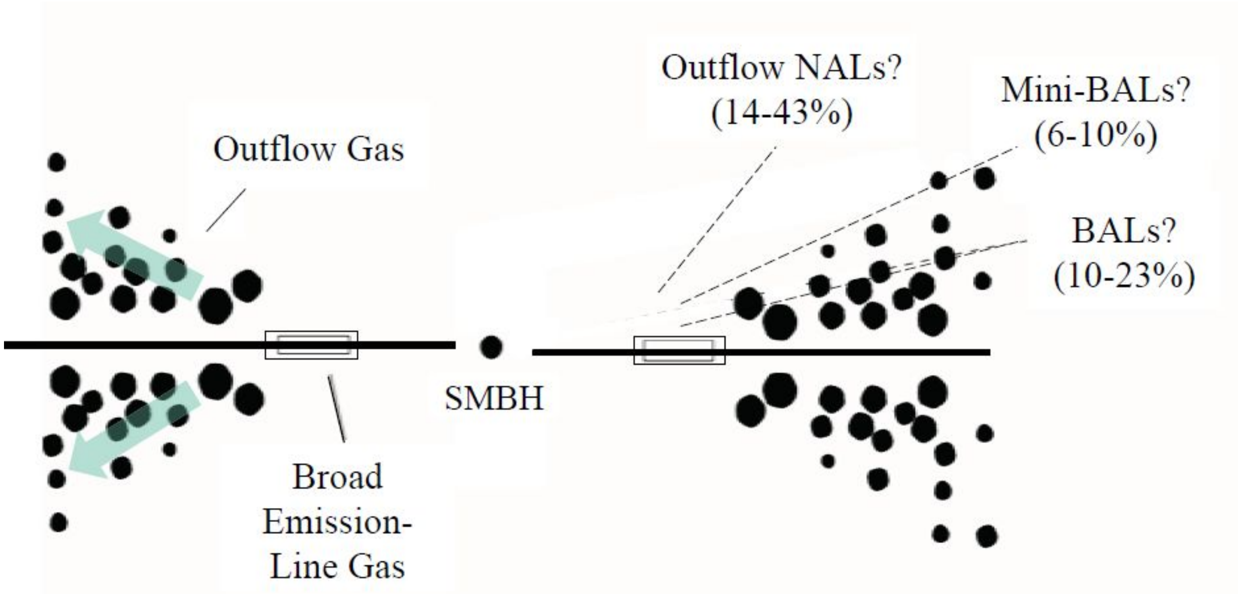
NO!!!

Jets are completely ionized and are incapable of producing absorption lines.

Let’s list observations and what we know

1. Whatever is absorbing the light, is partially optically *thick*/opaque.
2. The absorption lines are only seen in a small fraction of all AGN.
3. The lines can be very *broad*, spanning a large velocity range.
4. The lines can be substantially blue-shifted, the Doppler Effect indicates the absorber is moving outwards(towards Earth) at a high velocity.

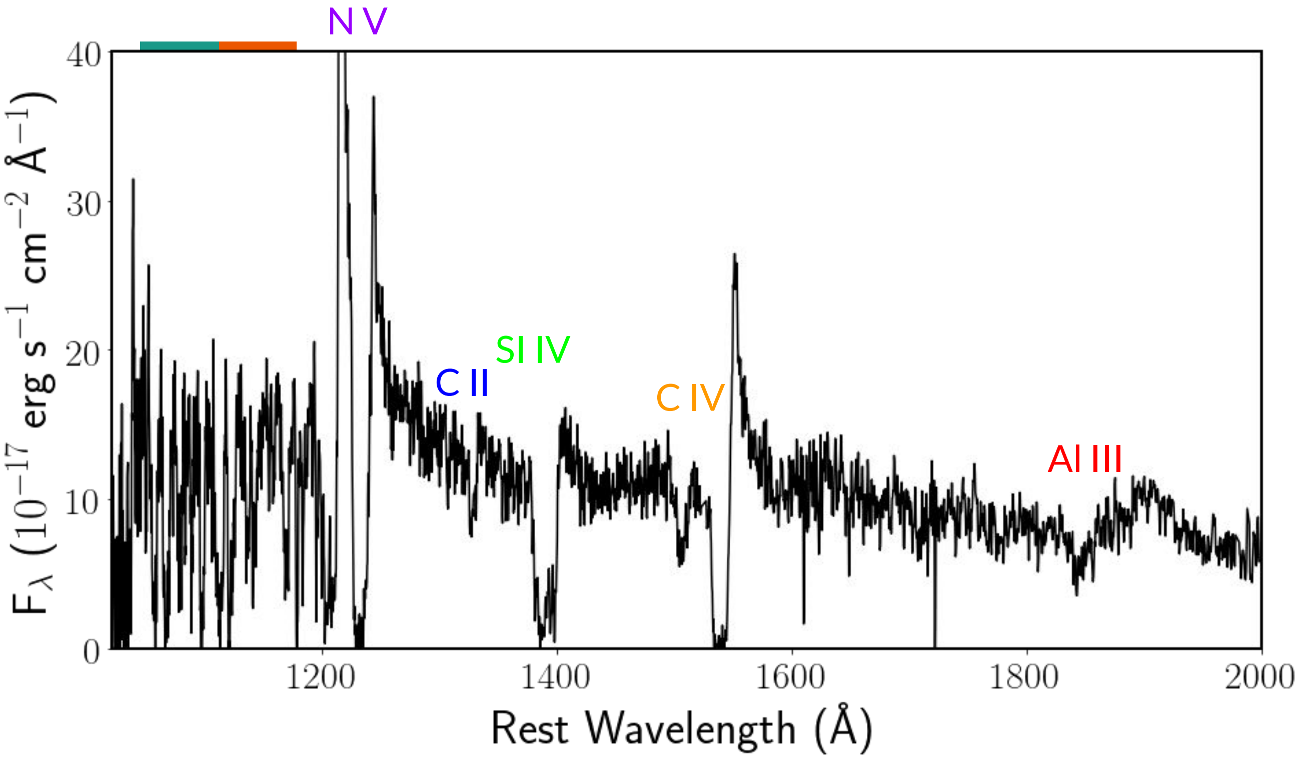
Quasar Outflows



- Opaque gas
- Located over a vast range of distances from the central engine.
- Radiating out
- Observable due to viewing angle or evolution of AGN.

https://www.astro.ufl.edu/~emoravec/UF_Personal_Webpage/Research/Entries/2015/12/11_Toward_a_Complete_Picture_of_Quasar_Outflows__From_Mini-BALs_to_BALs.html

Complex Outflow Absorption Lines



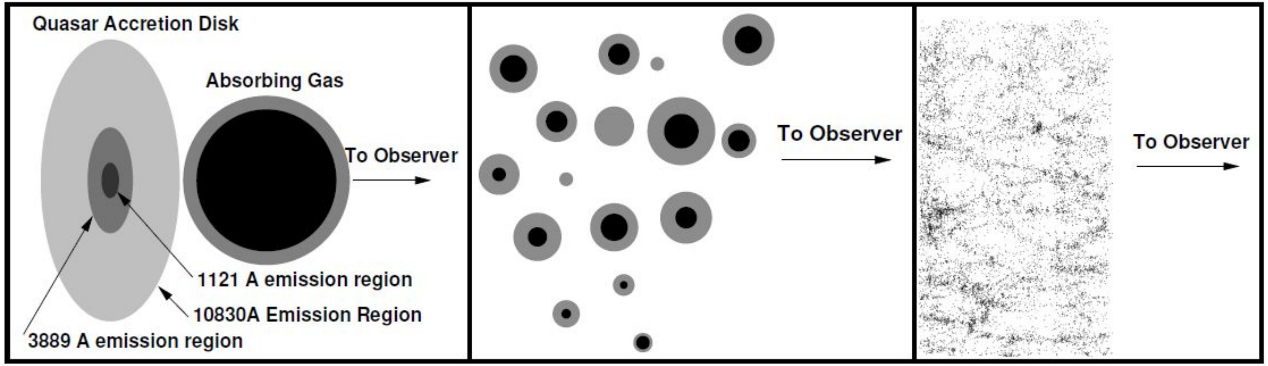
- Absorption lines can be identified using wavelength.

How do the physical aspects of the outflow influence:

- The absorption lines that appear.
- Line Structure
- Opacity of each line.

Important Outflow Physical Properties

1. Partial Covering
2. Density
3. Ionization
4. Column Density



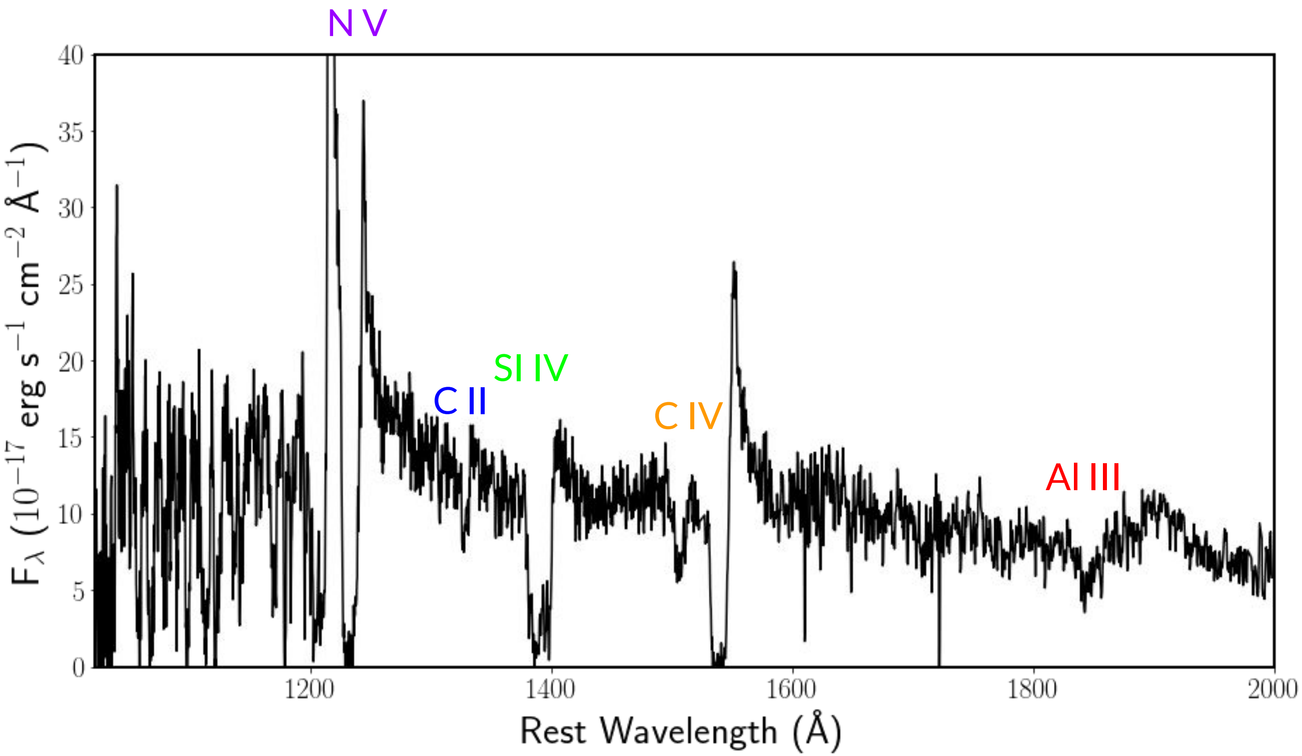
Leighly et al. 2018 (Submitted)

- Only part of the continuum source interacts with the outflow.

Theories to Physically Explain Partial Covering:

- Left: Absorber partially covers emission region.
- Middle: Many small absorbing clouds partially cover.
- Right: Small absorbing clouds clump together.

Complex Outflow Absorption Lines



- Partial covering is a subject of current research.

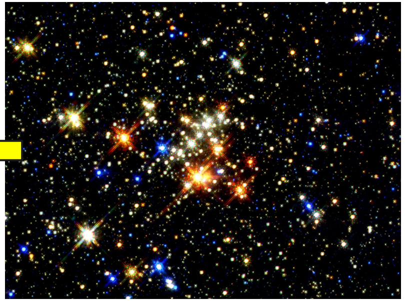
Next

- Why is everything shorter than 1216 angstroms ***appear*** so noisy?
- Maybe it is not noise… Could it be something physical?

The Intergalactic Medium

Earth

Intergalactic Medium



AGN Interstellar Medium

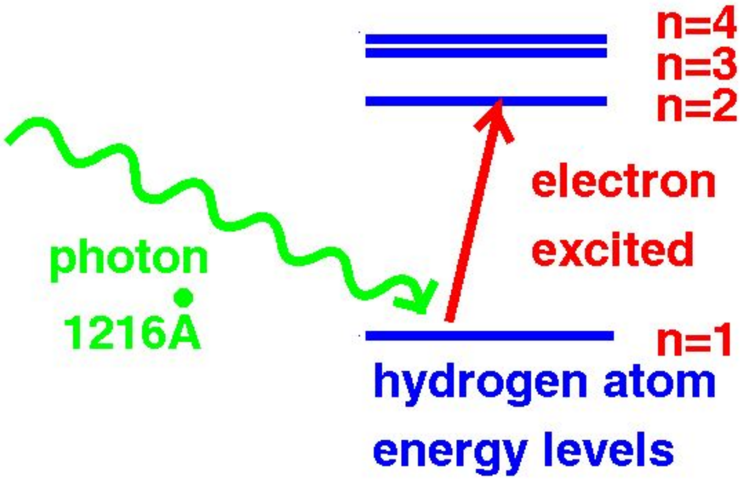
- The space between the Earth and the Quasar is not empty.
- What is the consequence when stuff gets in the way?

http://news.mit.edu/2016/oxygen-first-appearance-earth-atmosphere-0513

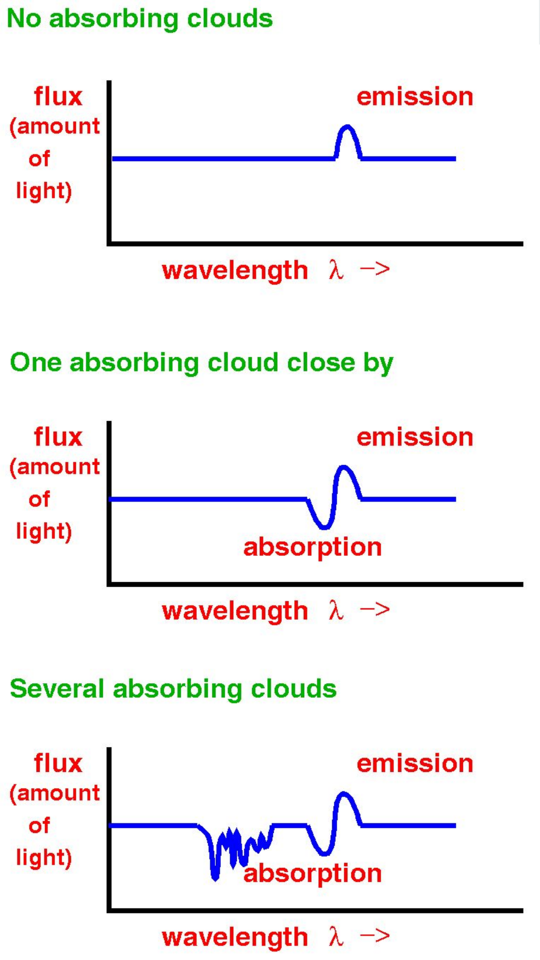
https://www.engadget.com/es/2015/08/11/nuestro-universo-esta-muriendo-lentamente/

https://www.nationalgeographic.com/science/space/universe/stars/

Lyman-α Absorption

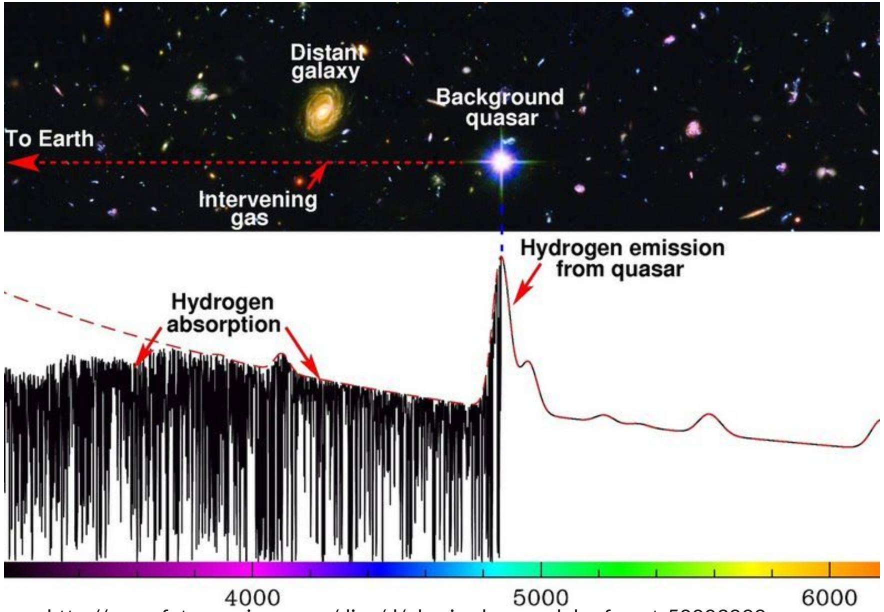


- Filaments of Neutral Hydrogen in the IGM between the AGN and Earth.
- Light redshifted to 1216 angstroms is absorbed by the Hydrogen .



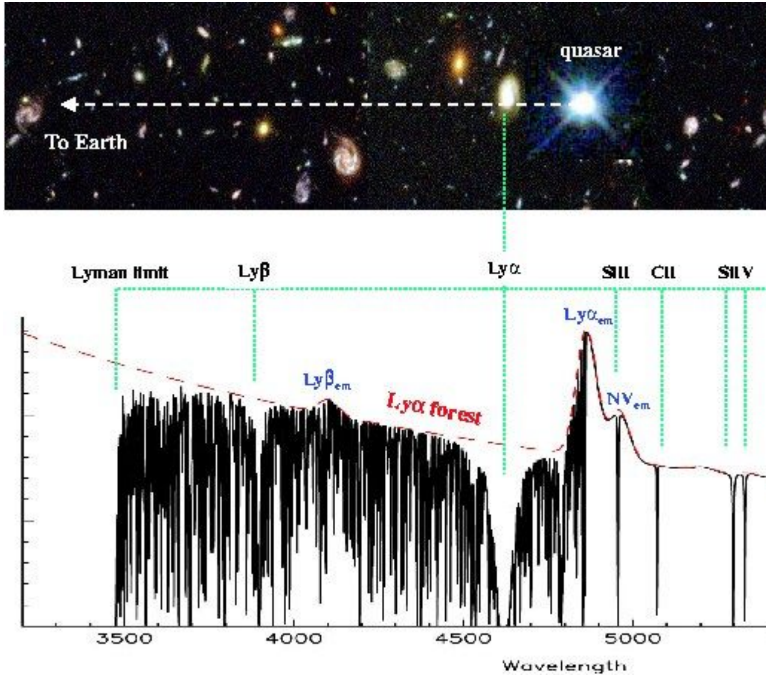
http://w.astro.berkeley.edu/~jcohn/lya.html

The Lyman-α Forest



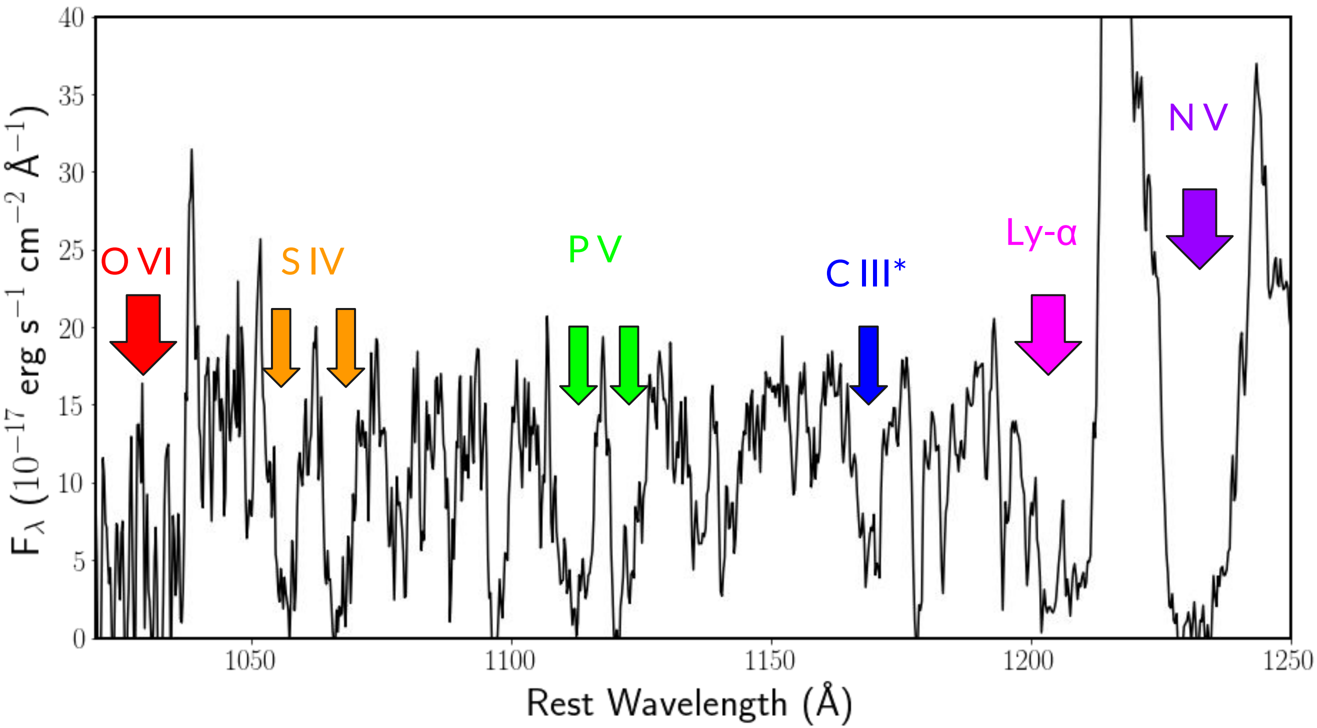
http://www.futura-sciences.us/dico/d/physics-lyman-alpha-forest-50003899/

http://enki.phyast.pitt.edu/qso_abs.html



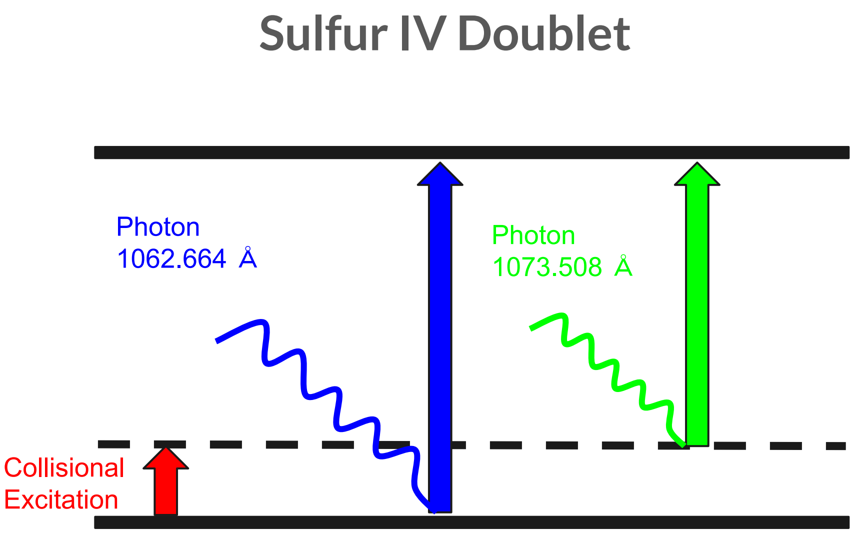
- Ly-α absorption can obscure features shorter than 1216 angstroms

Lost in the Lyman-α Forest



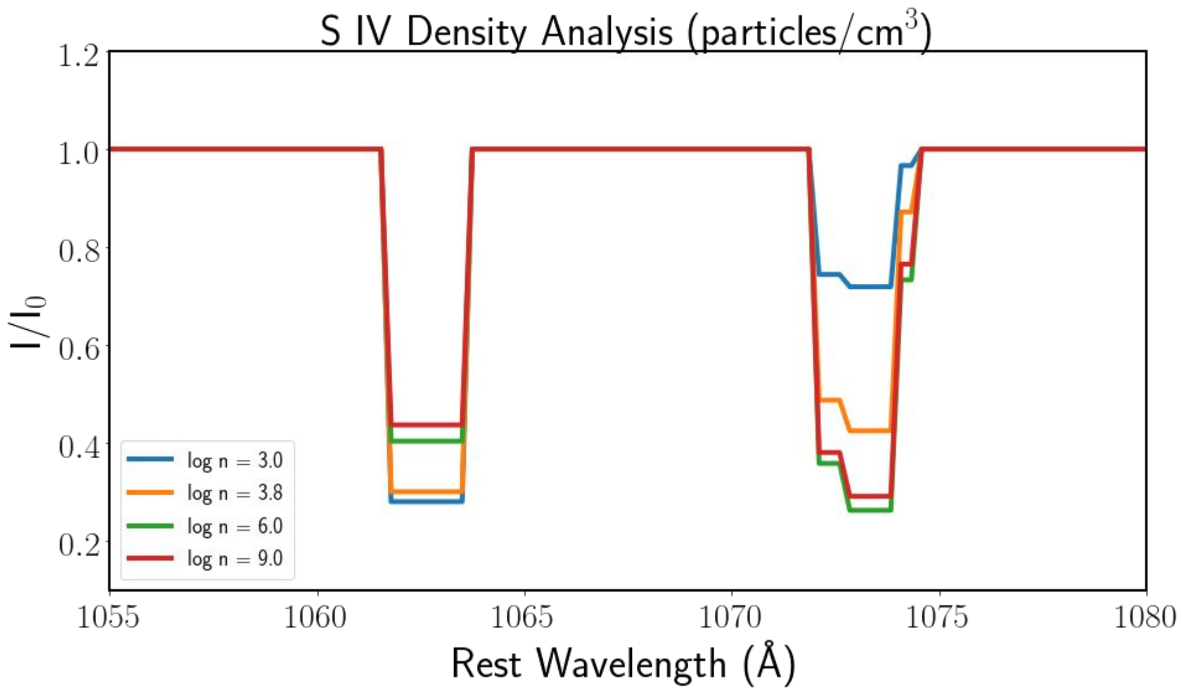
- The Lyman-α Forest often obscures absorption at short wavelengths.
- Developing methods to deal with the forest are ongoing.
- Importance of S IV and C III* will be elaborated on.
- Why is there two S IV absorption lines?

Fine Structure and Collisional Excitation



- Electrons are freed by photoionization.
- Can collide with other atoms.
- Collisions can excite electrons to higher energies.
- Density of the outflow affects amount of collisional excitation.

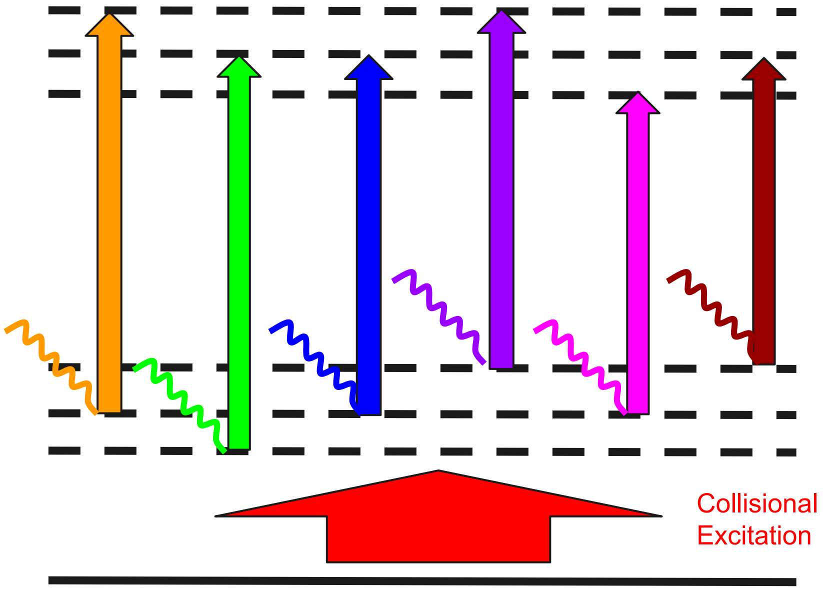
The Ratio of the Sulfur IV Doublet



- At low densities, small amount of collisional excitation.
- Less populating of fine structure.
- Less absorption at the longer wavelength.
- At higher densities, the ratio becomes becomes closer to 1:1
- The ratio of the doublet is an effective density constraint.

Collisional Excitation and Carbon III*

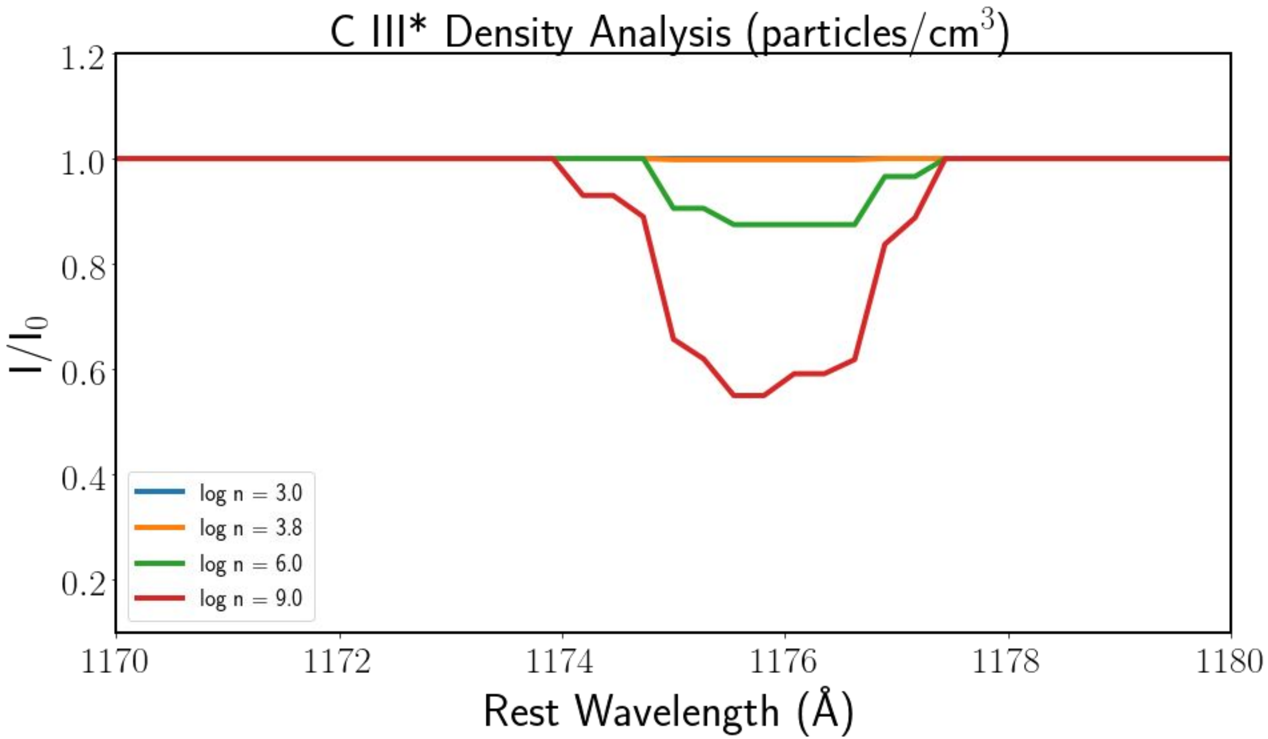
Carbon III* Blended



Carbon III* can be a little complicated…

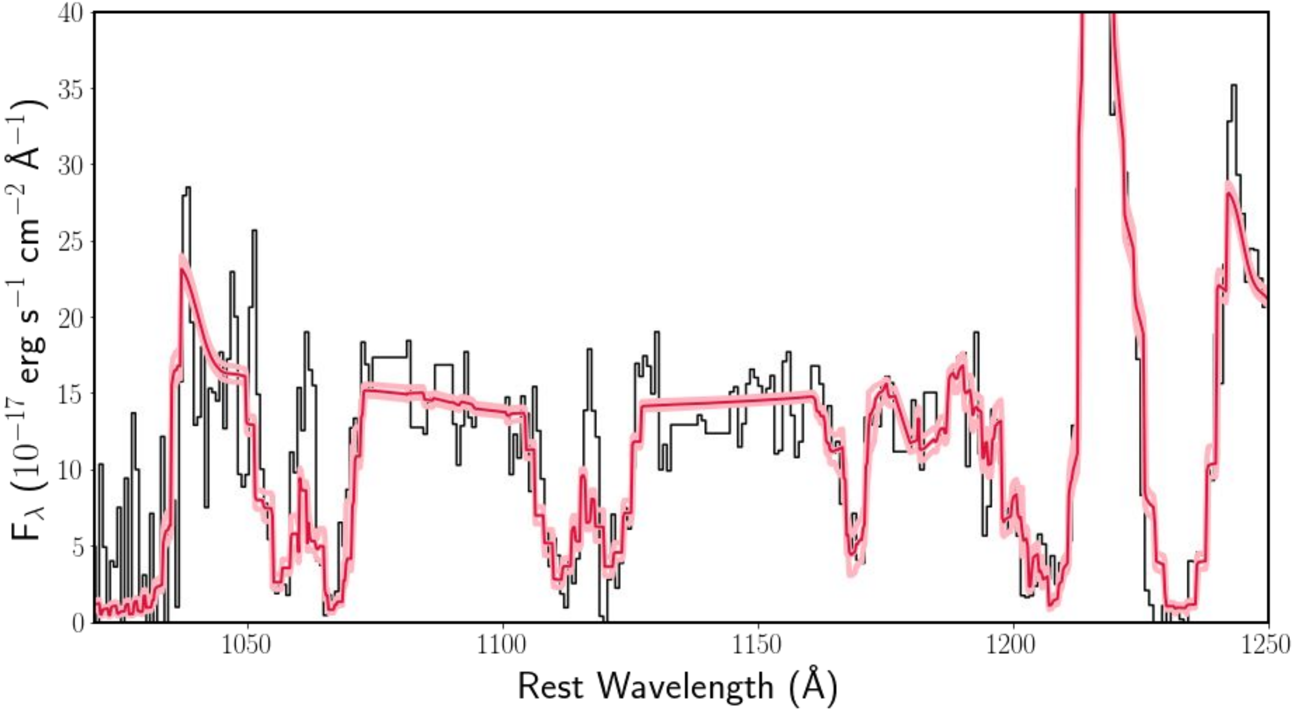
1. Collisional excitation excites electrons into fine structure.
2. Photons are absorbed, exciting the electrons in the fine structure.
3. The electrons are excited into *more* fine structure at higher energies.
4. The 6 absorption lines blend together and are observed as a single absorption line.

Constraining Density Using Carbon III*

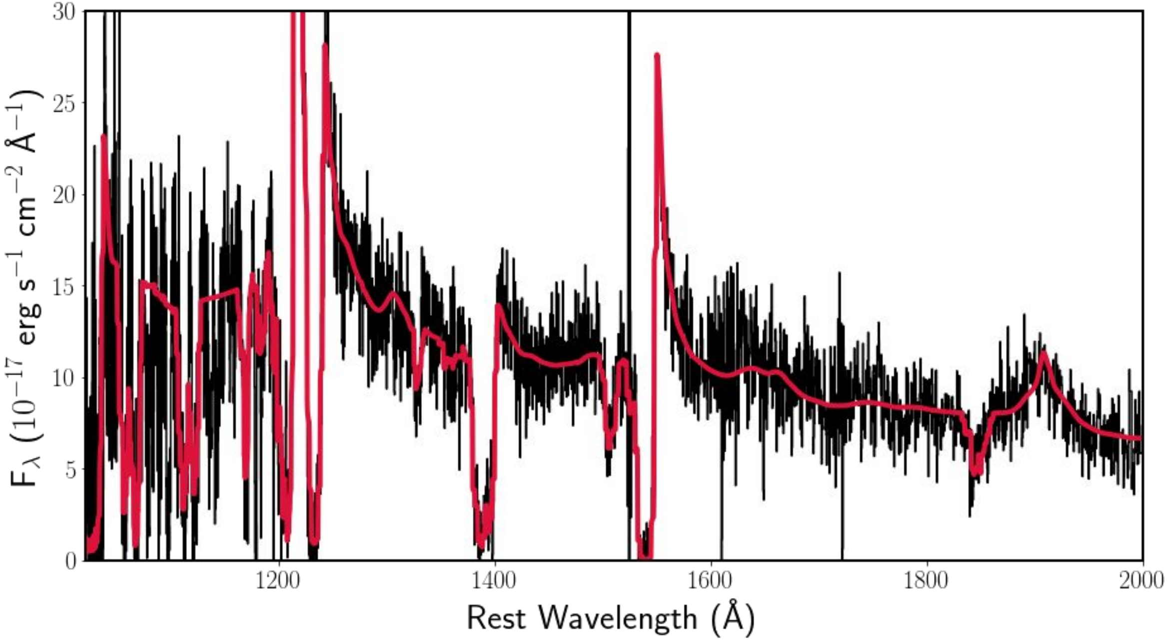


- There is no observable C III* absorption at lower densities.
- All 6 absorption lines depend on collisional excitation.
- Therefore, C III* is an excellent outflow density constraint.

Finding a Reasonable Density



Modeling with *SimBal*

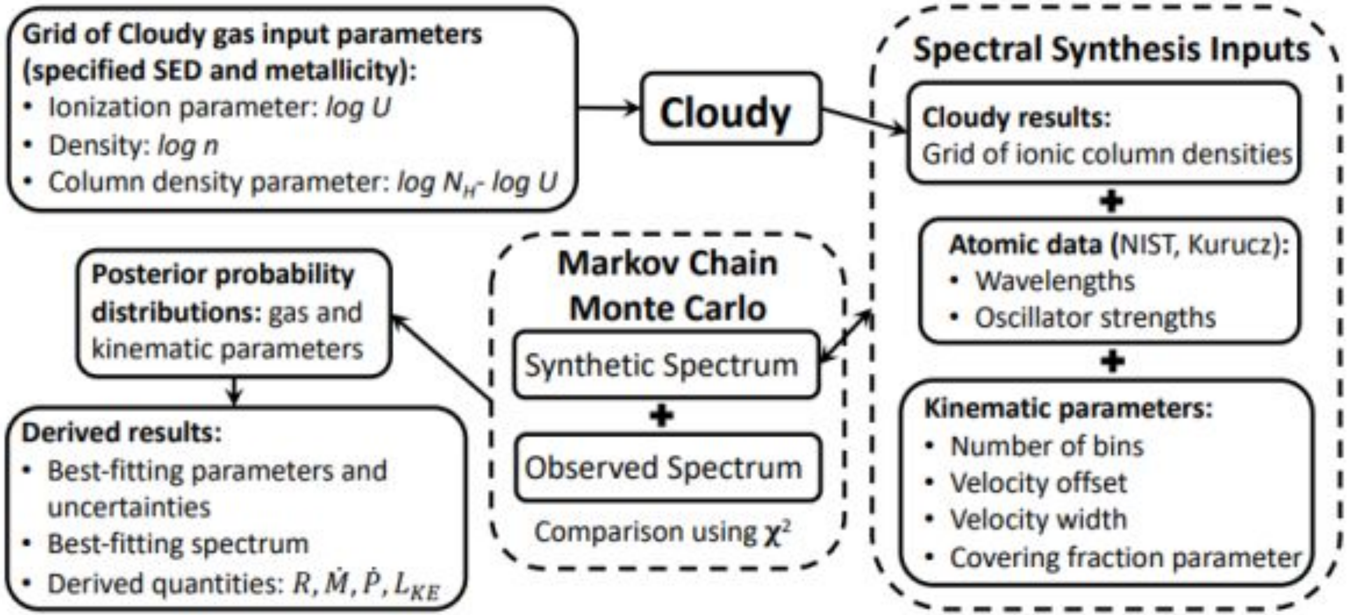


- Density can be difficult to constrain due to S IV blending.
- Also, Lyman-α absorbers can obscure S IV and C III*
- Different lines can constrain parameters other than density.
- *SimBAL* provides physical information from lines we see, and lines we don't see.

Statistics of Quasar Spectrum Models

Finding Best Fit Parameters using simBAL

Path to Best Fit Solutions

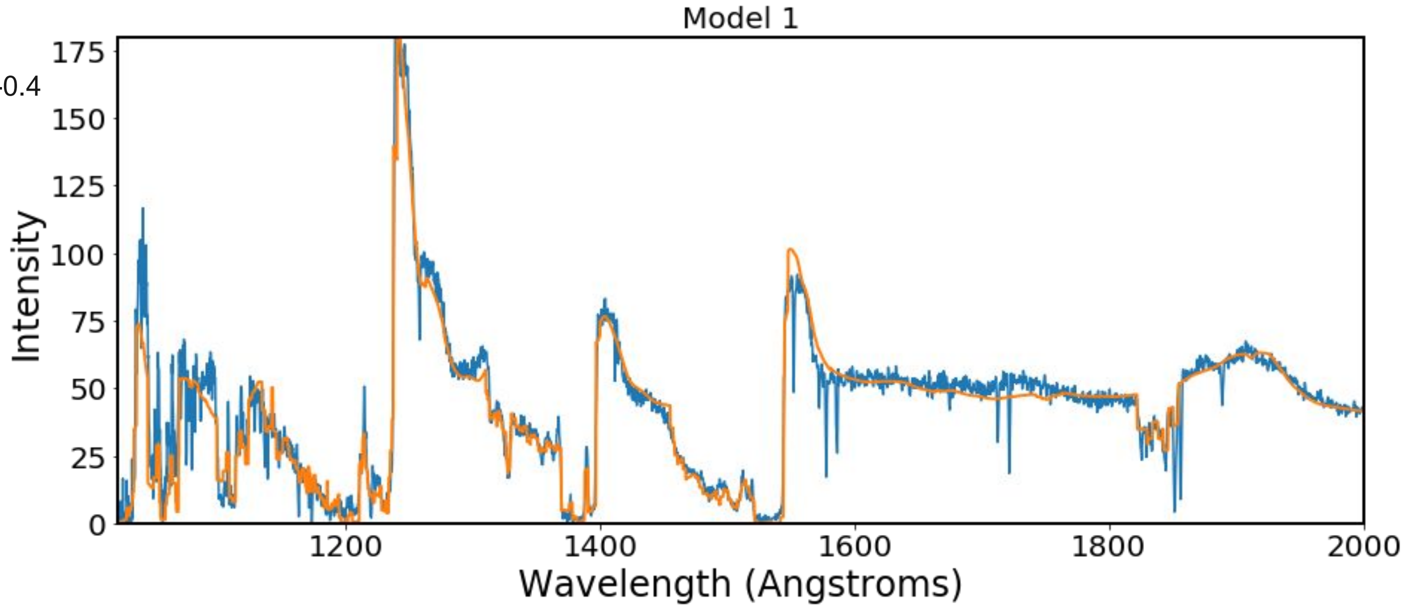


Leighly et al. 2018 (submitted)

Different Models of the Same Spectrum

Model 1 → 2

Ionization Parameter: 1.4 → -0.4
Log Density: 5.1 → 8.3



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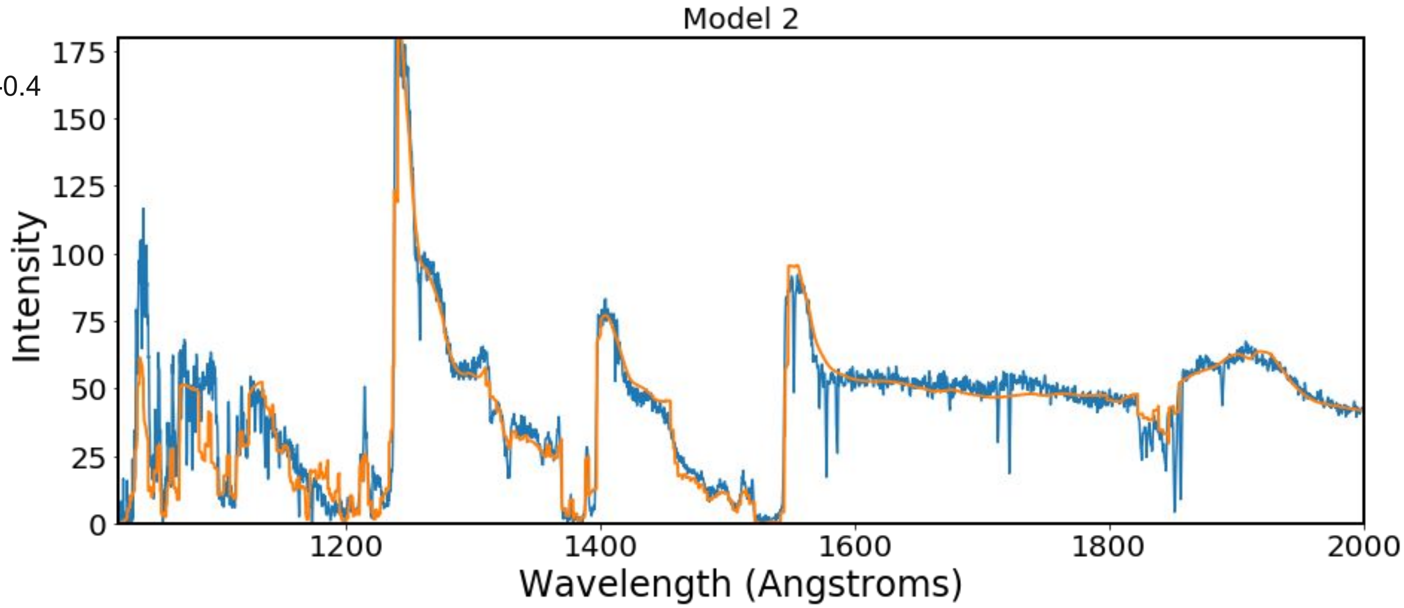


Bayes' Theorem

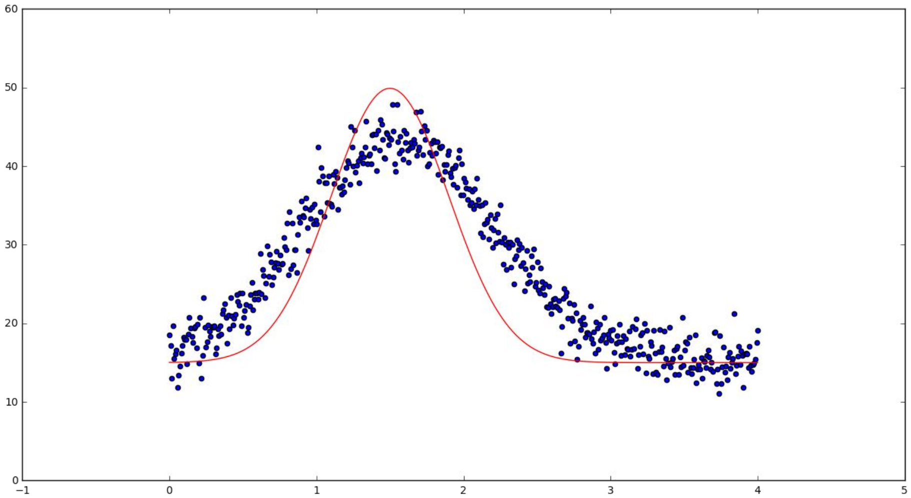
$$P(Model|Data) = \frac{P(Data|Model) * P(Model)}{P(Data)}$$

Likelihood

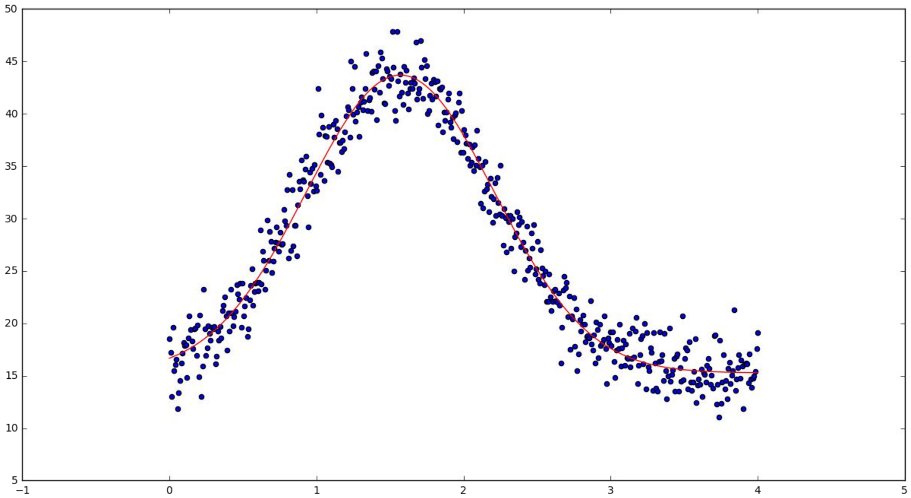
$$P(Model|Data) = \frac{\boxed{P(Data|Model)} * P(Model)}{P(Data)}$$

$$\chi^2 = \sum_{i=1}^{N} \frac{(Data_i - Model_i)^2}{\sigma_i^2}$$

Chi Squared



Chi squared = 531



Chi squared = 84

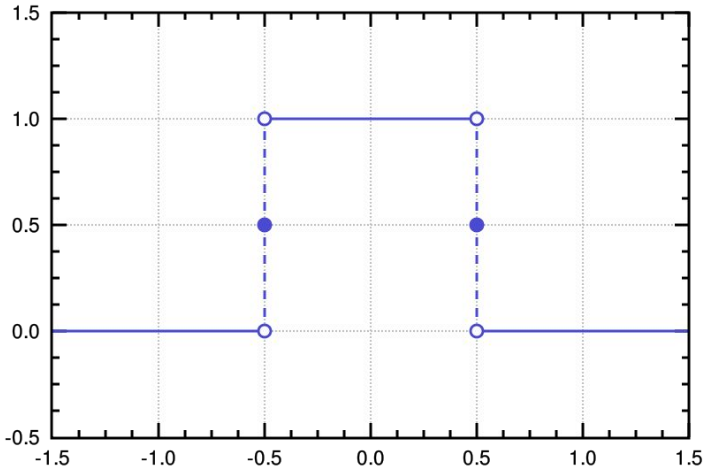
Priors

$$P(Model|Data) = \frac{P(Data|Model) * \boxed{P(Model)}}{P(Data)}$$

Constrain parameter values by physical knowledge:

Flat Priors: min-max

Gaussian Priors: mean-std deviation



Priors

Absorption Parameters: constraints from limits of Cloudy data: based on general quasar observations

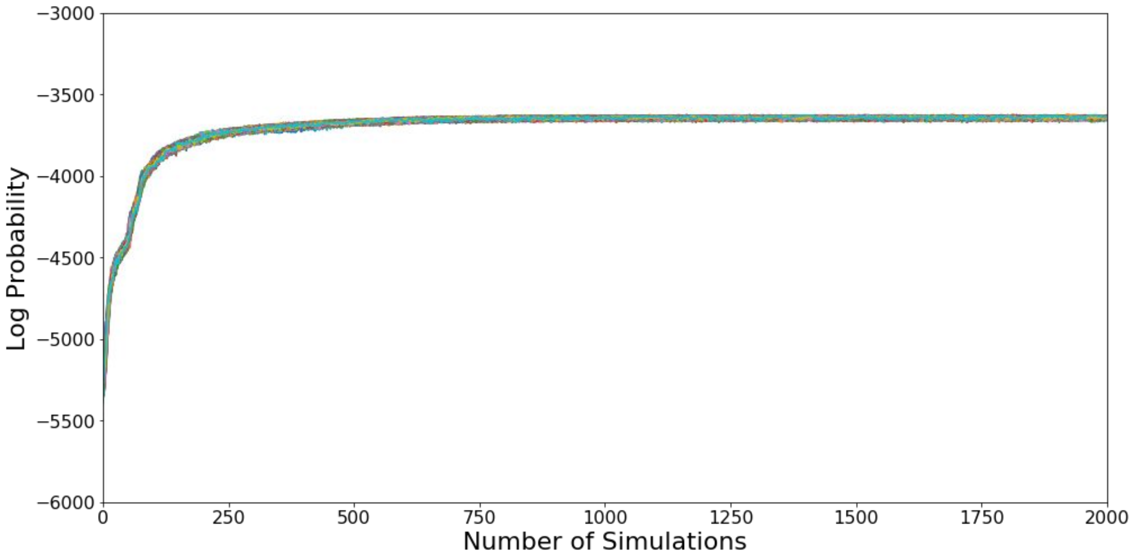
Continuum and Emission Parameters: constraints from analysis of a quasar sample studied by Krawczyk et al. 2015, and from statistical analysis (PCA) of quasar samples

Evidence

$$P(Model|Data) = \frac{P(Data|Model) * P(Model)}{\boxed{P(Data)}}$$

Markov Chain Monte Carlo

- Choose start position in parameter space
- Calculate likelihood (from Bayes' Theorem)
- Take a "random step" in parameter space (methods vary)
- Calculate new likelihood
- Choose to accept or reject new point
- Repeat for a number of simulations



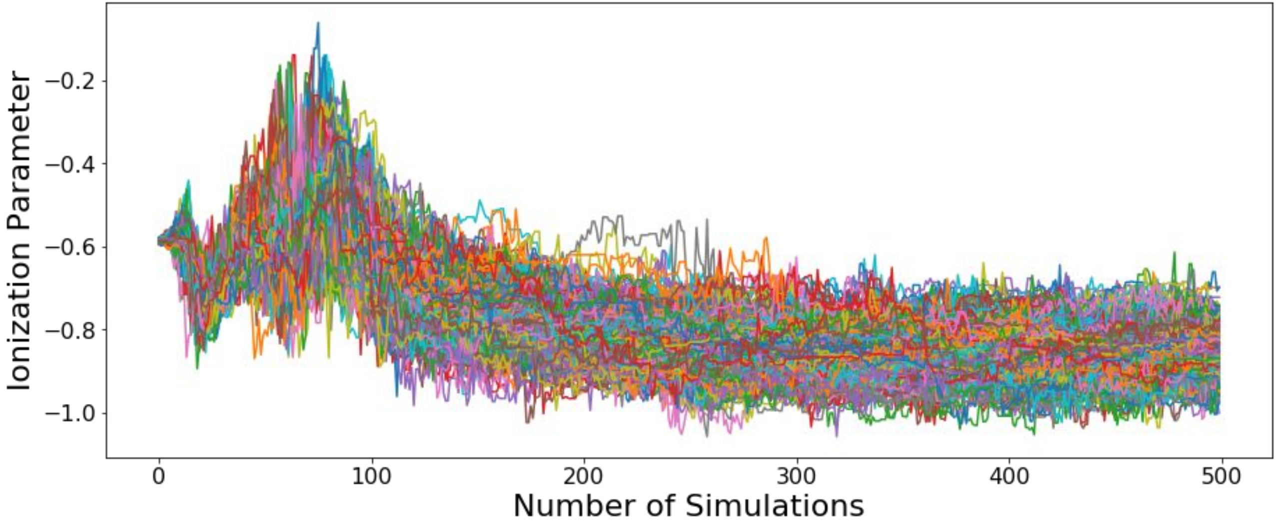
Emcee

From Foreman-Mackey 2013

Markov Chain Monte Carlo method

Uses a number of “walkers”

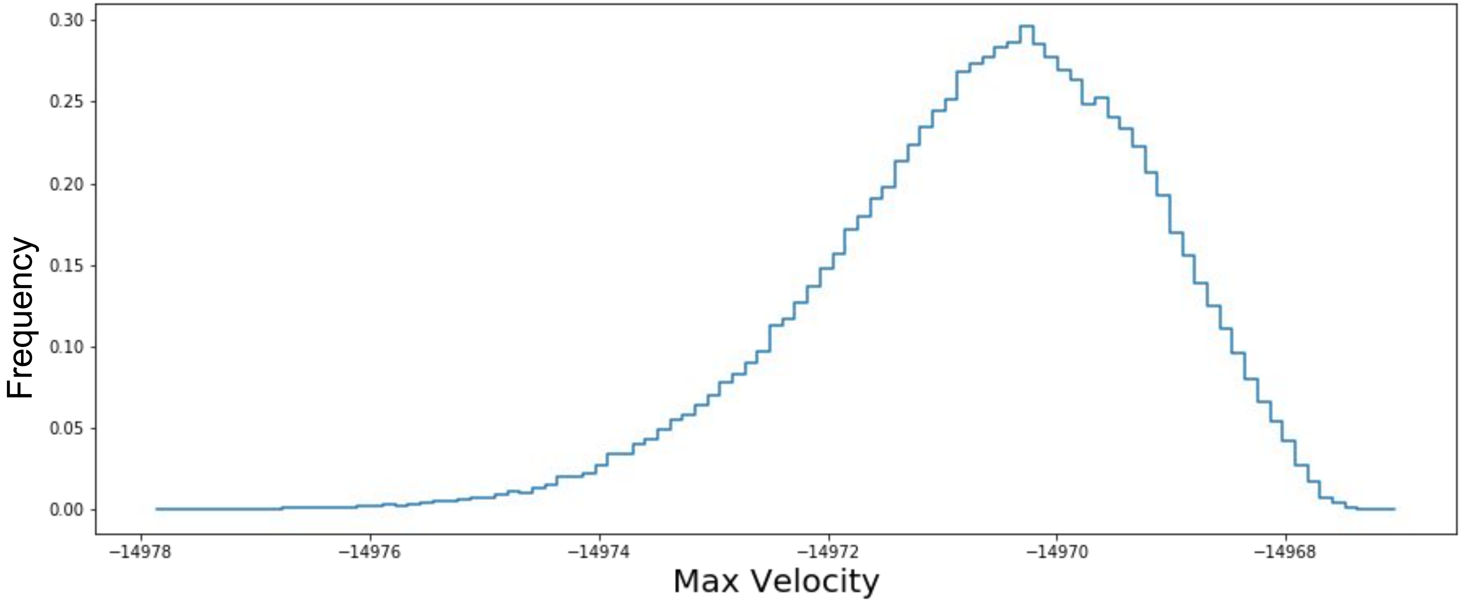
Walkers influence each other



Emcee Results

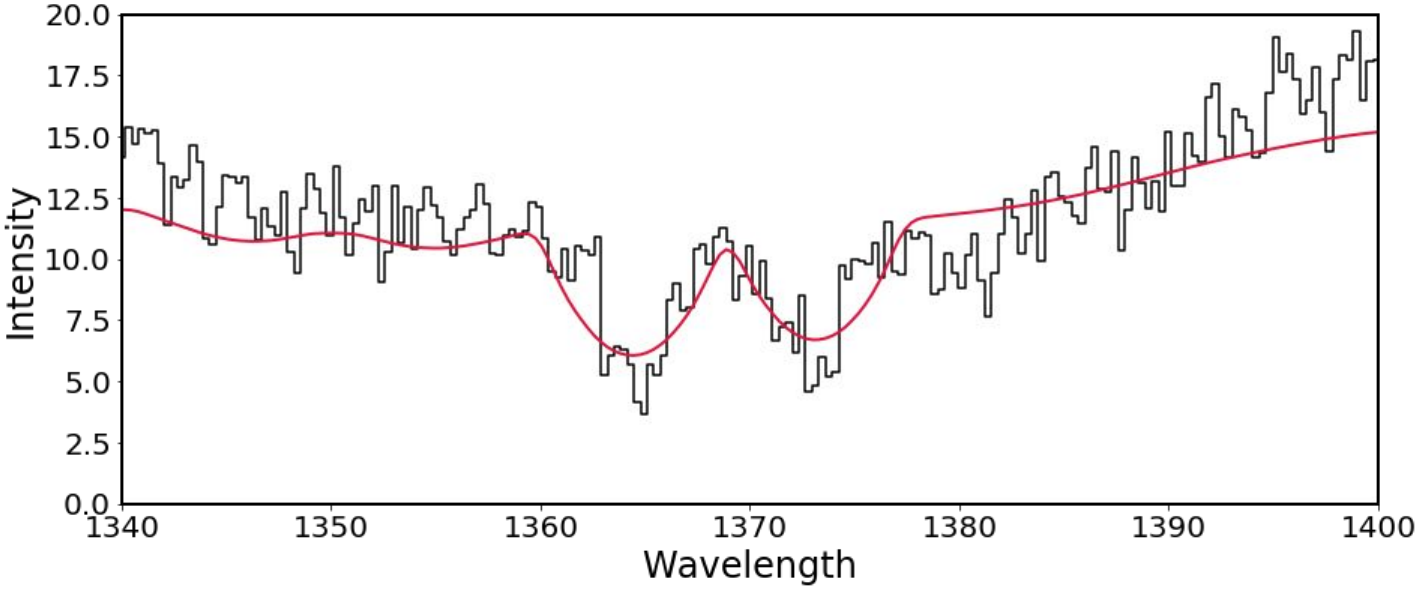
Return Posterior Probability Distributions

P(Model|Data) in Bayes' Theorem



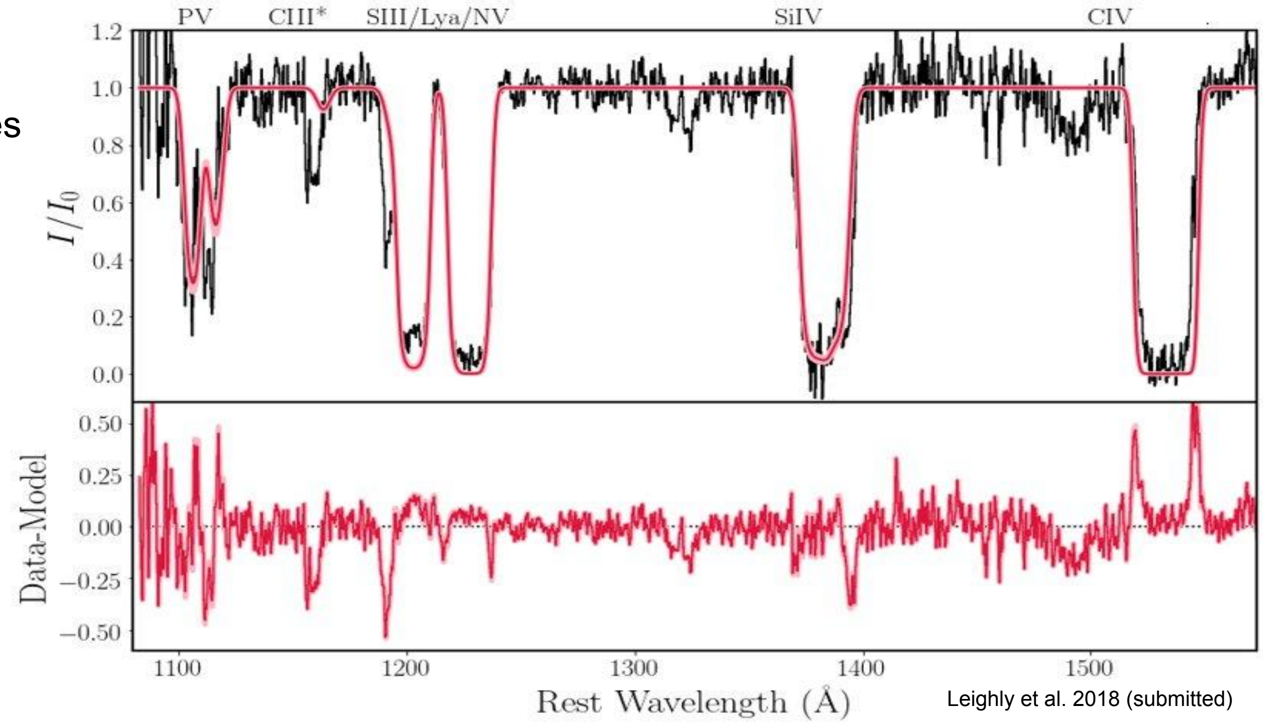
Absorption Structure

Gaussian: max depth, mean, standard deviation (width)



Absorption Structure

More complicated absorption structures require a different model



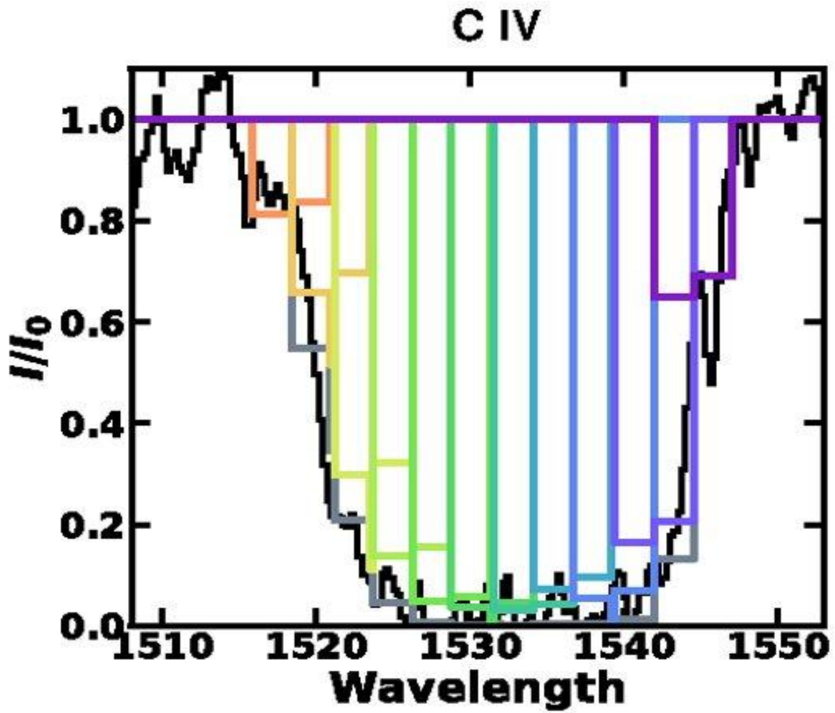
Leighly et al. 2018 (submitted)

Tophat Model

Wavelength change corresponds to velocity by Doppler shift:

$$\lambda' = \lambda * \frac{\sqrt{1+v/c}}{\sqrt{1-v/c}}$$

Categorize tophat "bins" by their velocity (relative to quasar rest frame)



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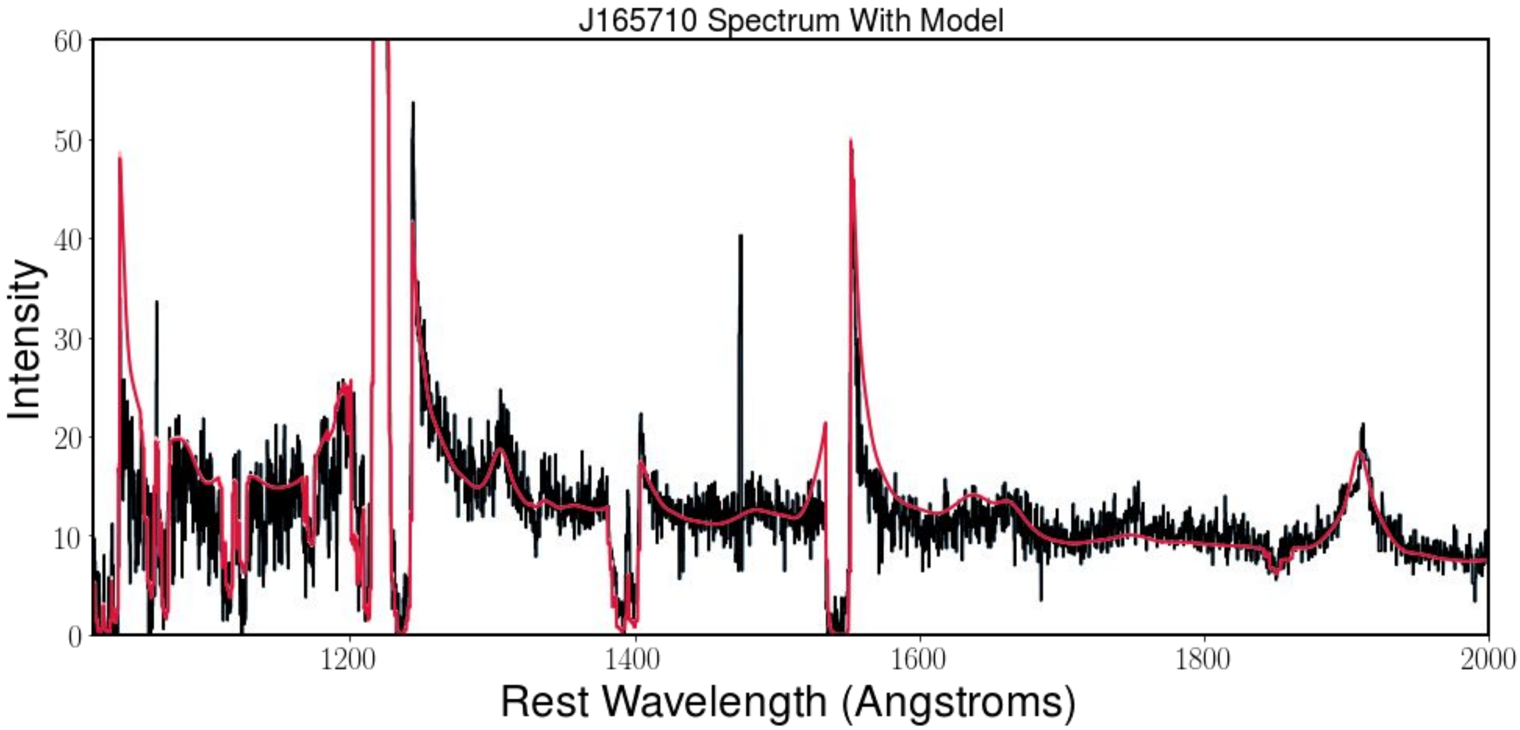
Emcee Results



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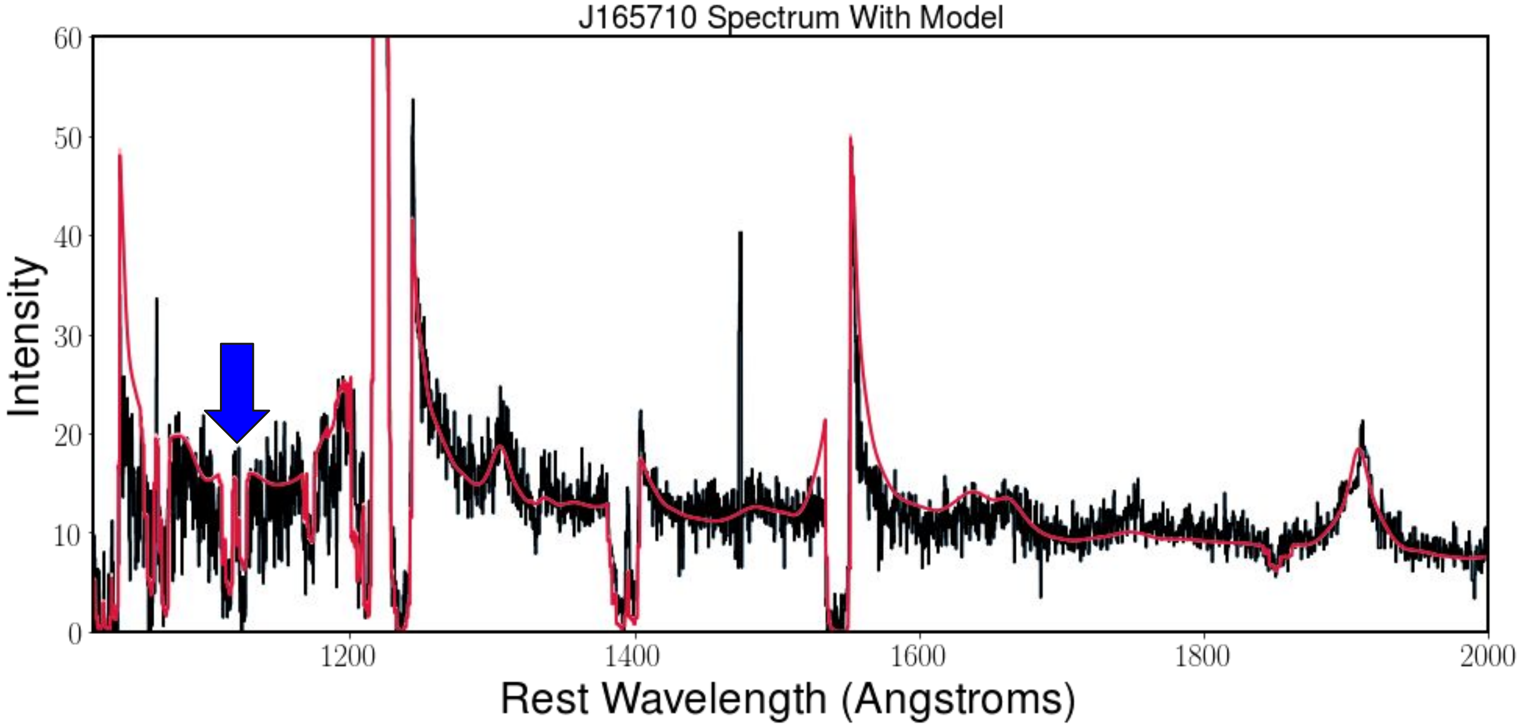
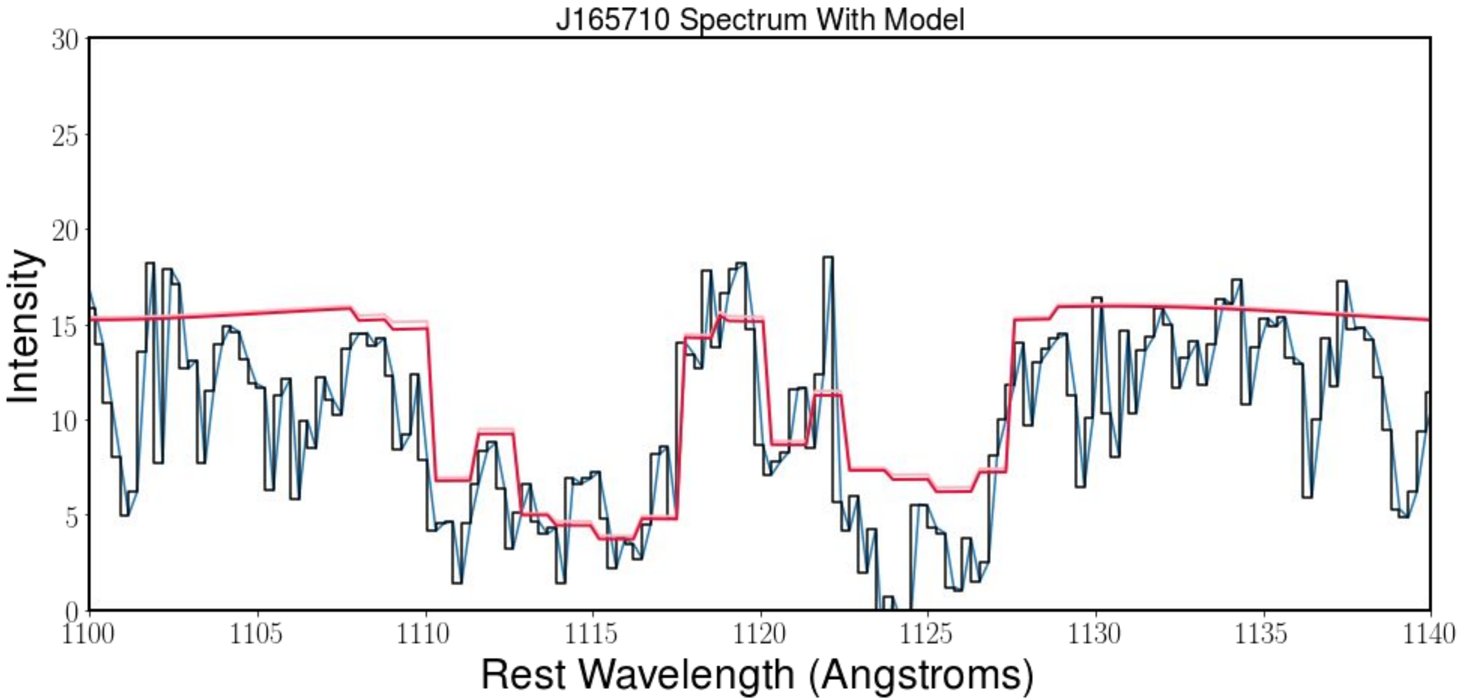
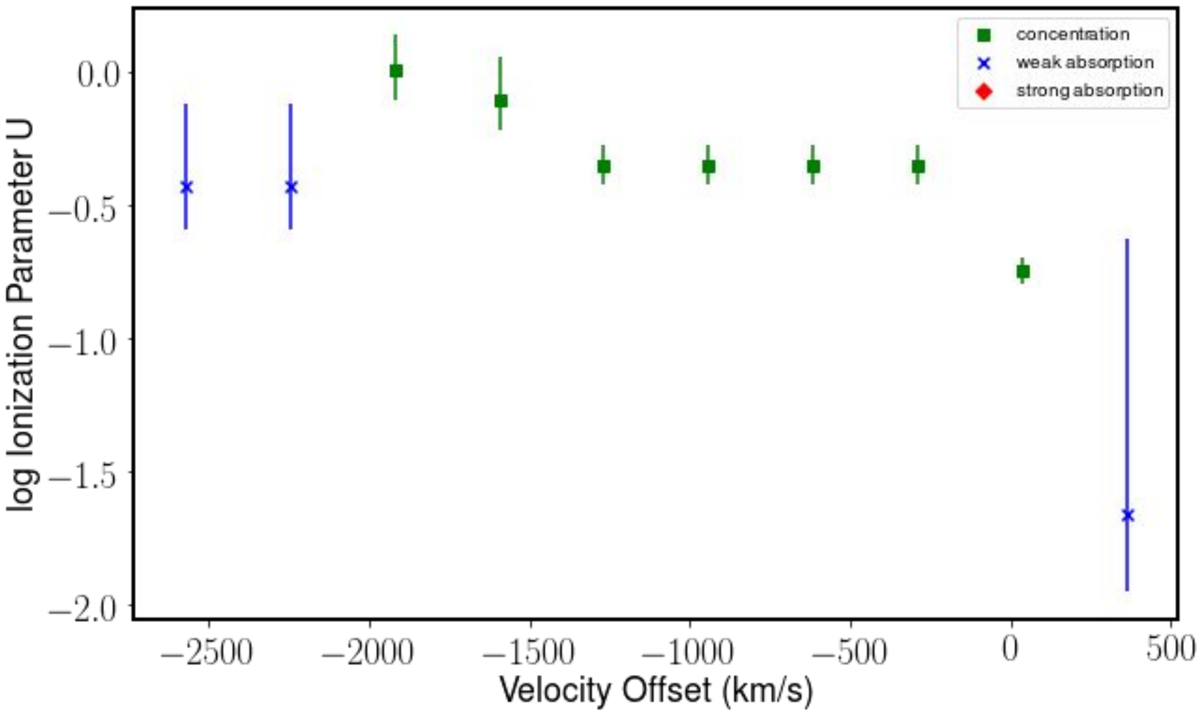


Phosphorus Absorption



Finding Best Values



Extracting Derived Properties

Fit Parameters:

Ionization Parameter: log U

Maxcol: log NH - log U

Density: log n

Covering Fraction: log a

Derived Parameters:

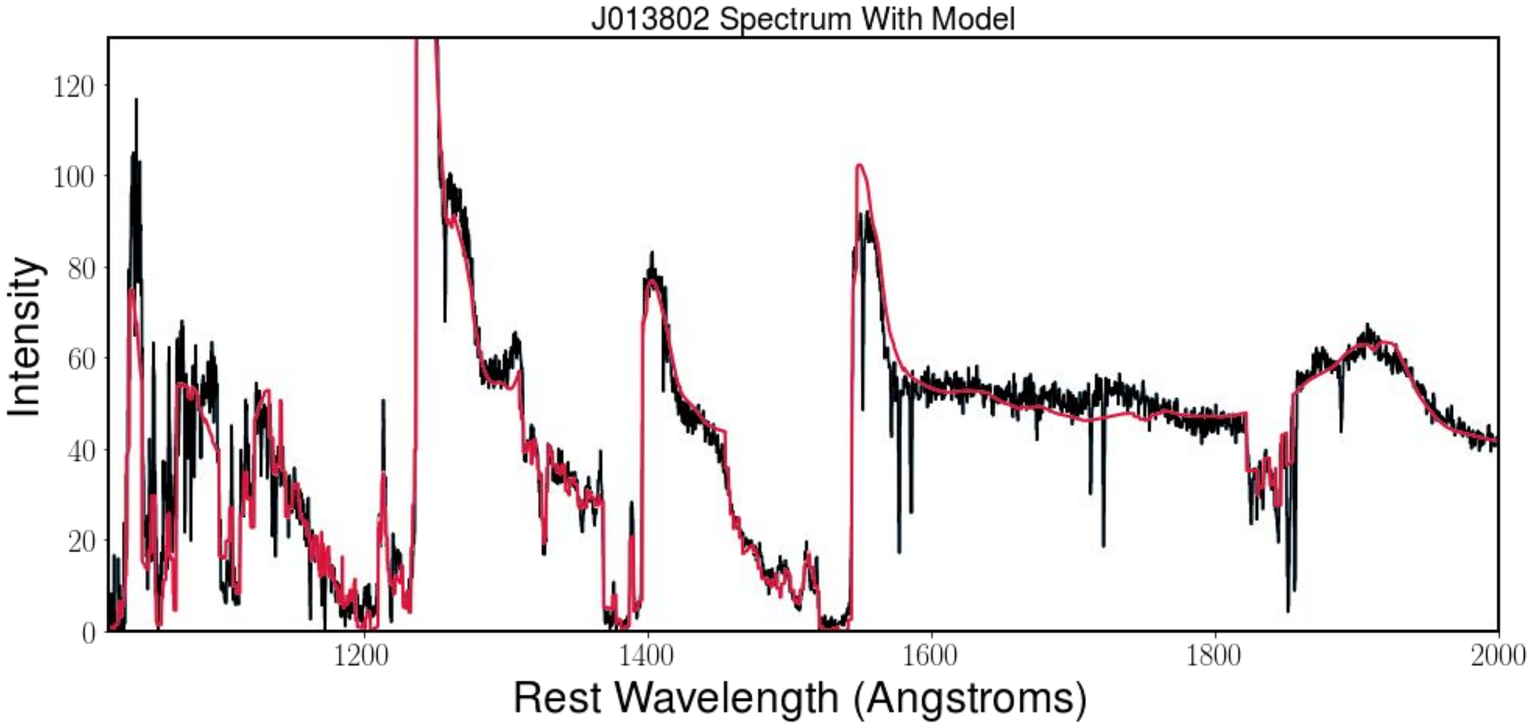
$$\log N_H = \log U + (\log N_H - \log U) + \log\left(\frac{1.0}{1.0 + 10^{loga}}\right)$$

$$\log R = 0.5 * (\log Q - \log 4\pi c - \log n - \log U)$$

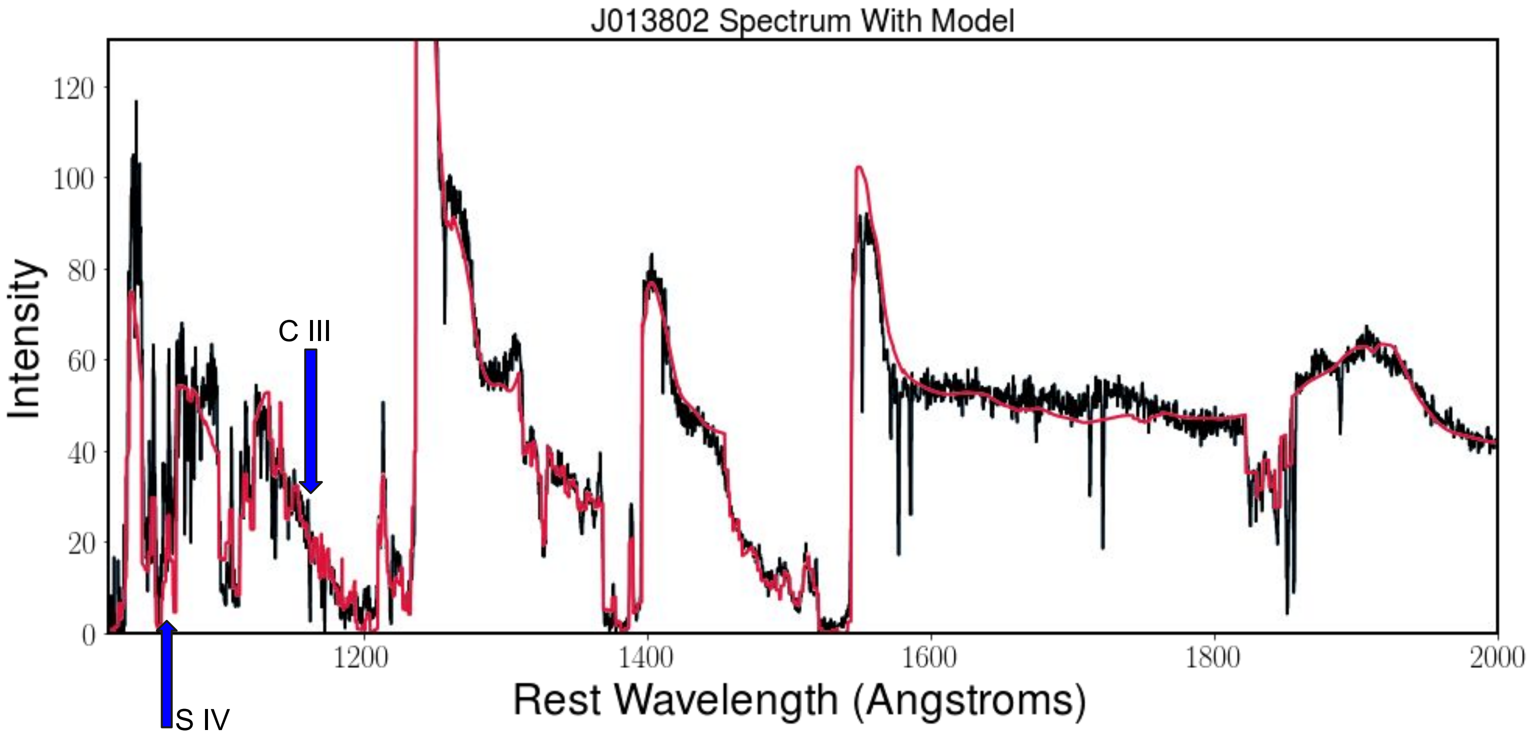
$$\log KE = \log(4.0\pi\mu m_p\Omega) + \log R + \log N_H + 3\log v$$

$$\log M_{dot} = \log(8.0\pi\mu m_p * \Omega) + \log R + \log N_H + log v_{offset}$$

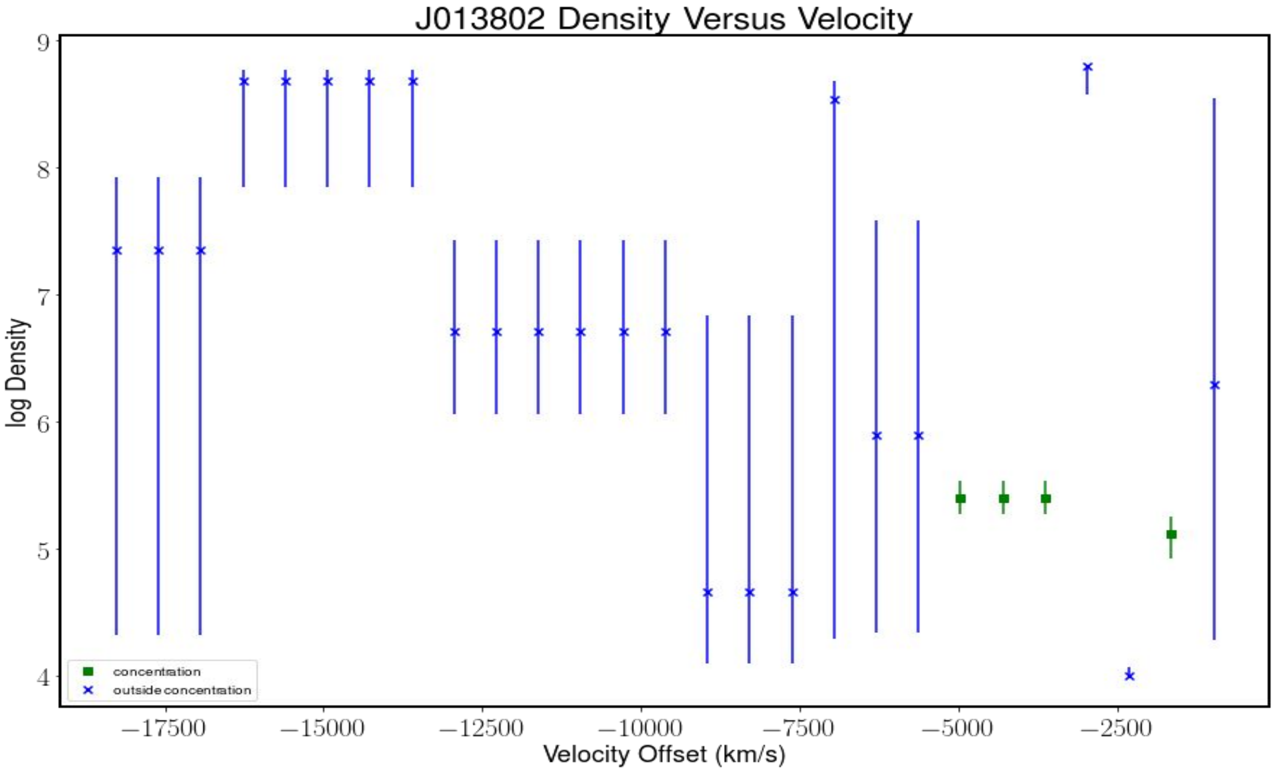
Concentration in Absorption



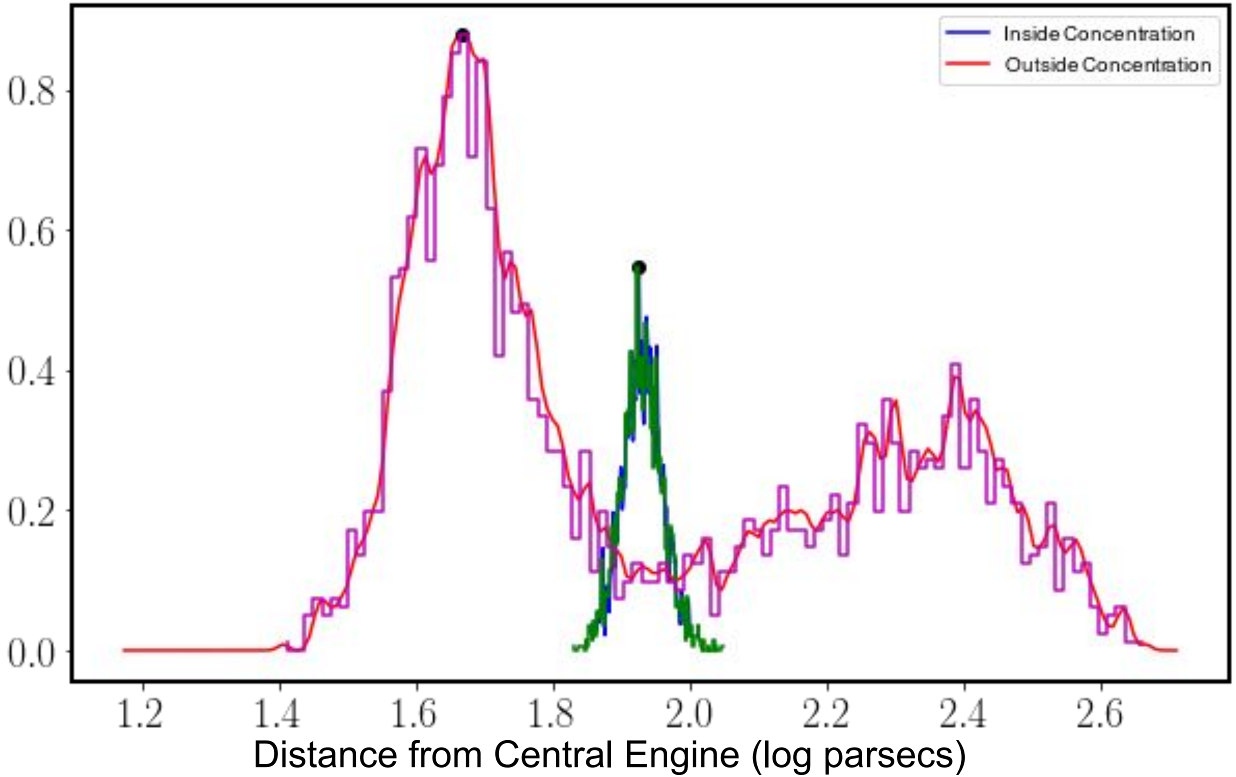
Concentration in Absorption



Concentration in Absorption



Concentration in Absorption

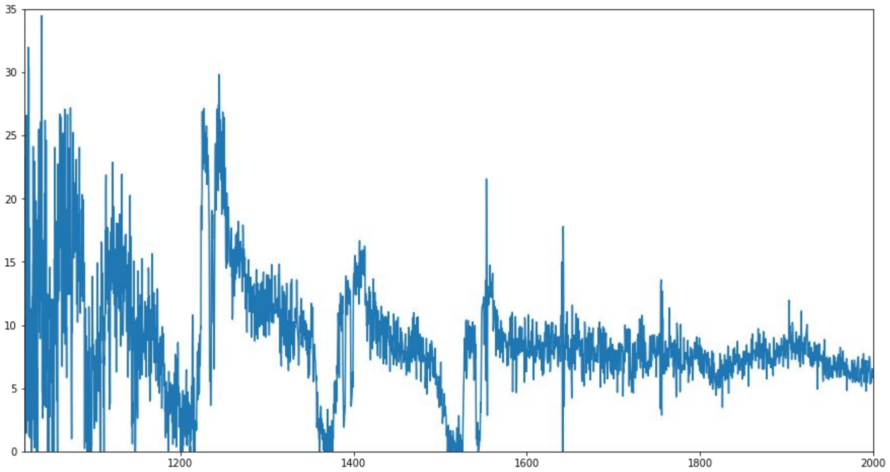


Fitting Long and Short Wavelengths Separately

-Our work this summer was exploratory so we learned what worked and some things that didn't

-The Lyman alpha forest so drastically changes the short wavelength section (less than 1216 angstroms) of the spectrum that it's inaccurate to treat the whole thing as one spectrum

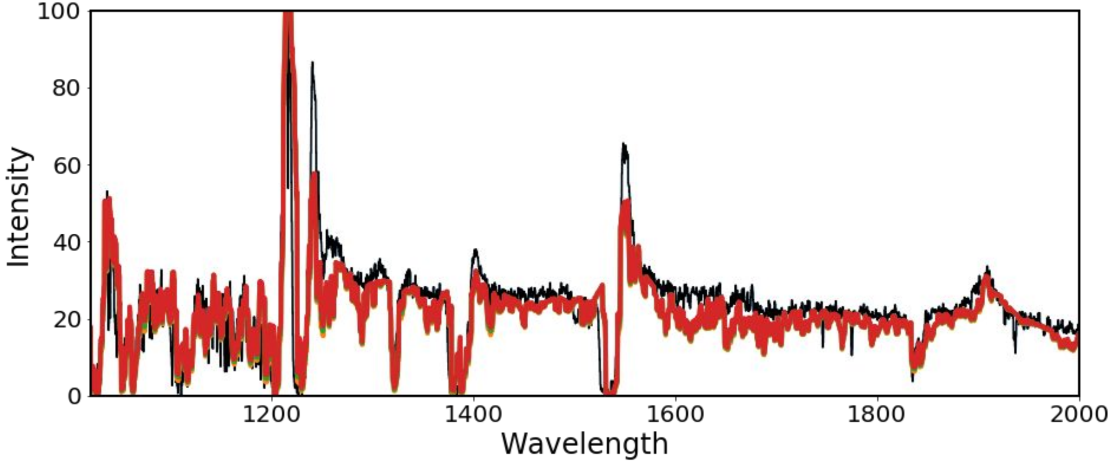
-We've been running simulations of just long wavelengths or just short wavelengths and in each of those included some constraints based on the results of the other simulations



Getting The Right Continuum

-The continuum for the long wavelength simulations was often much too high for the short wavelength ones

-The short wavelength simulations created extra absorption to compensate, leading to inaccurate results and bad extrapolation to long wavelengths

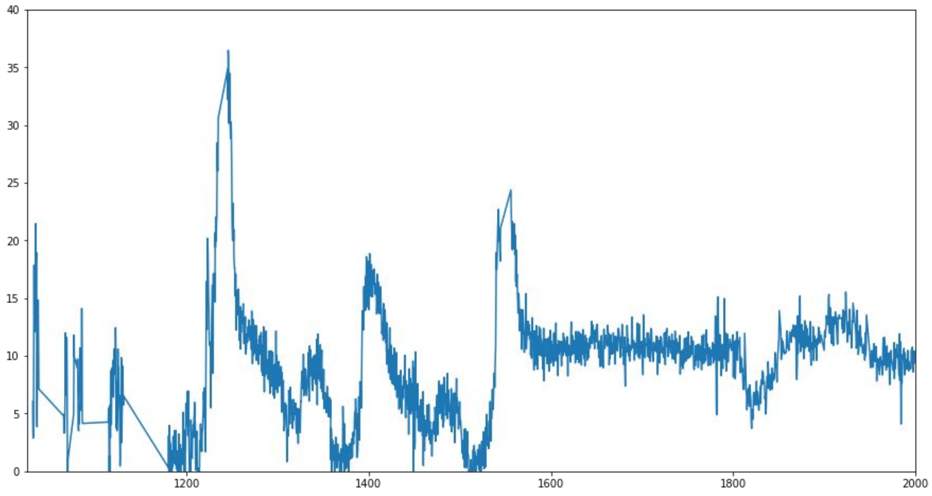


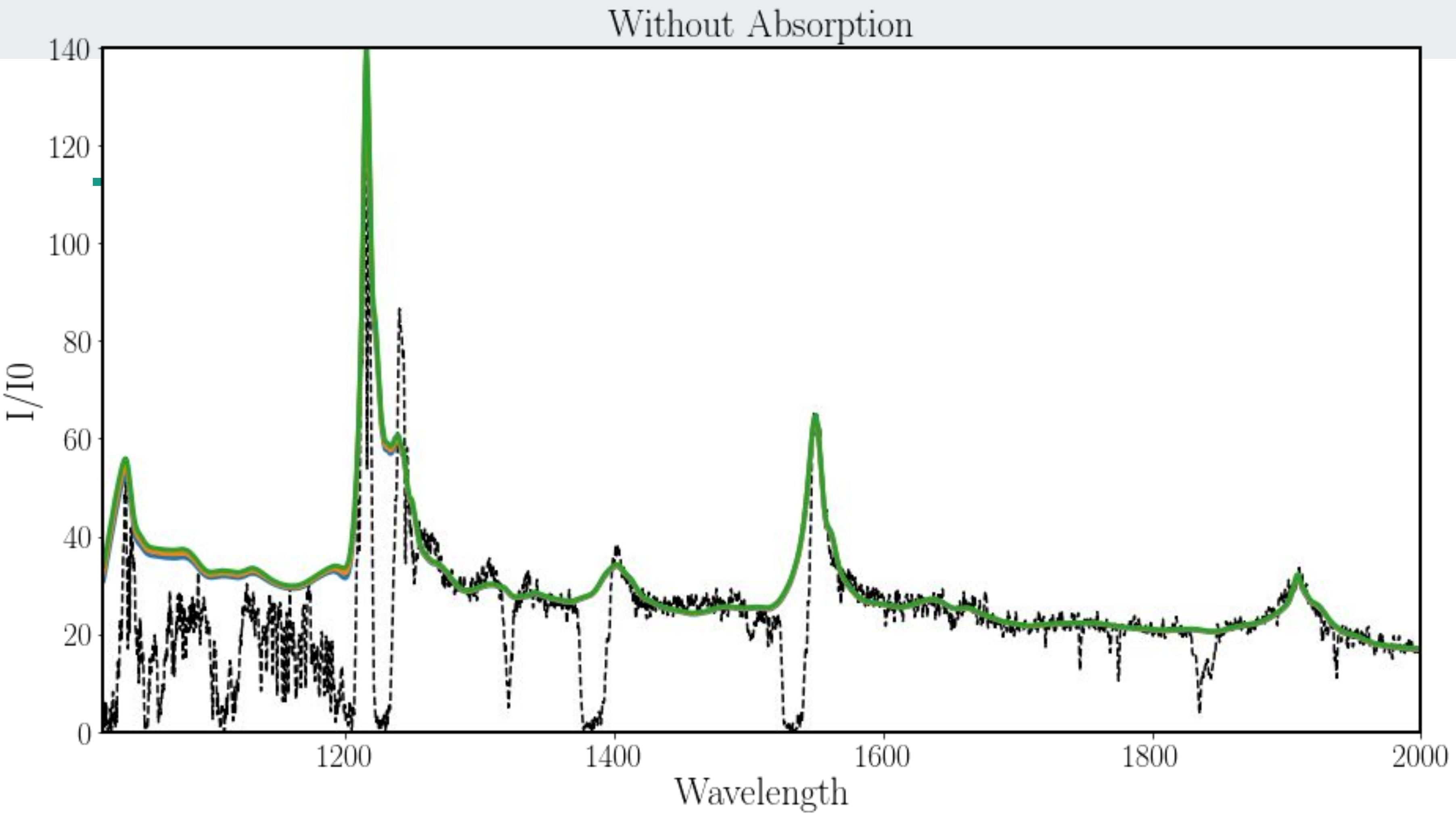
A Possible Solution

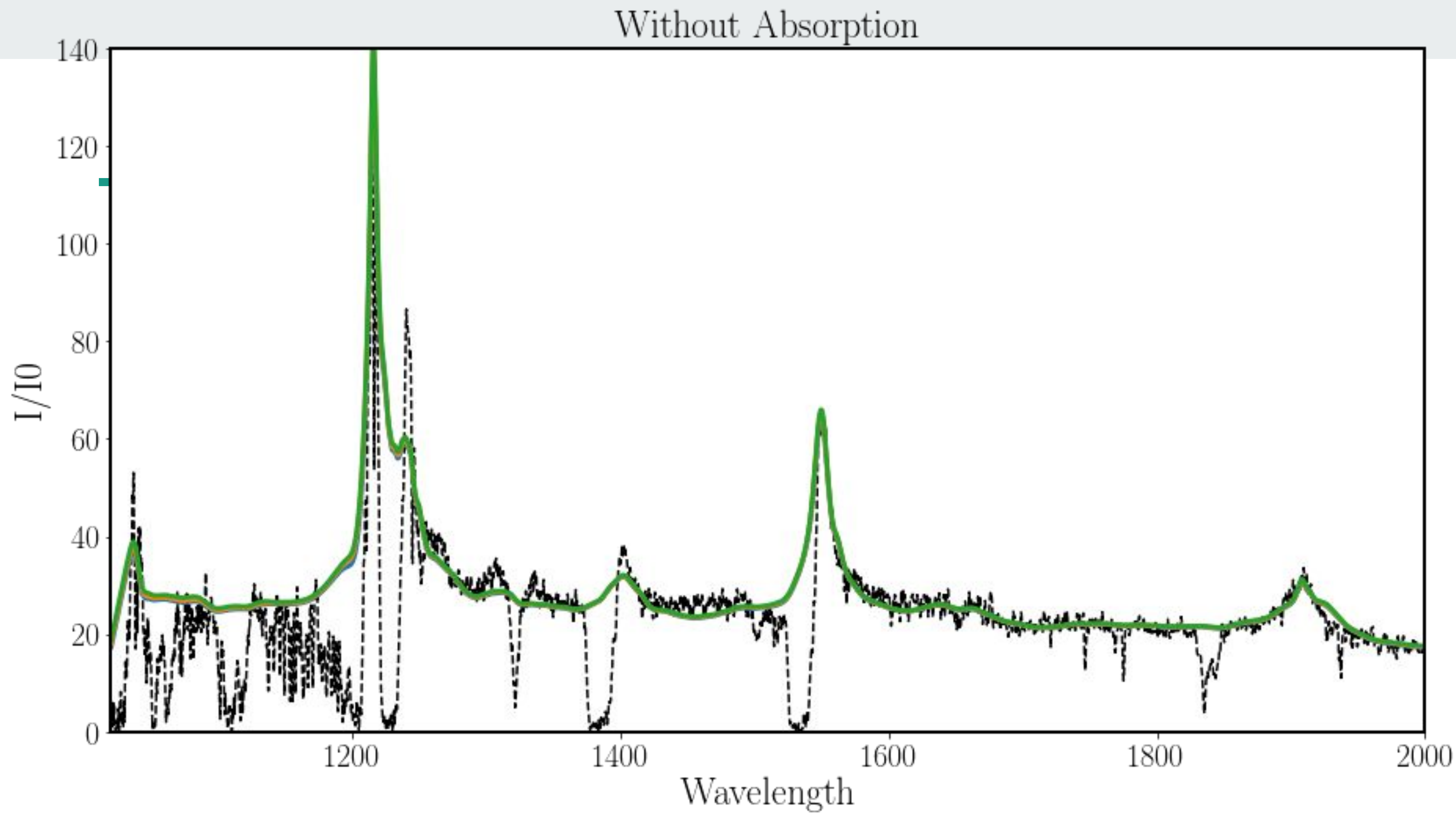
-One thing we tried to fix this was running simulations that included both the long wavelength range and the parts of the short wavelength range that didn't have any absorption

-We can clip out the absorption lines as well as individual Lyman alpha lines

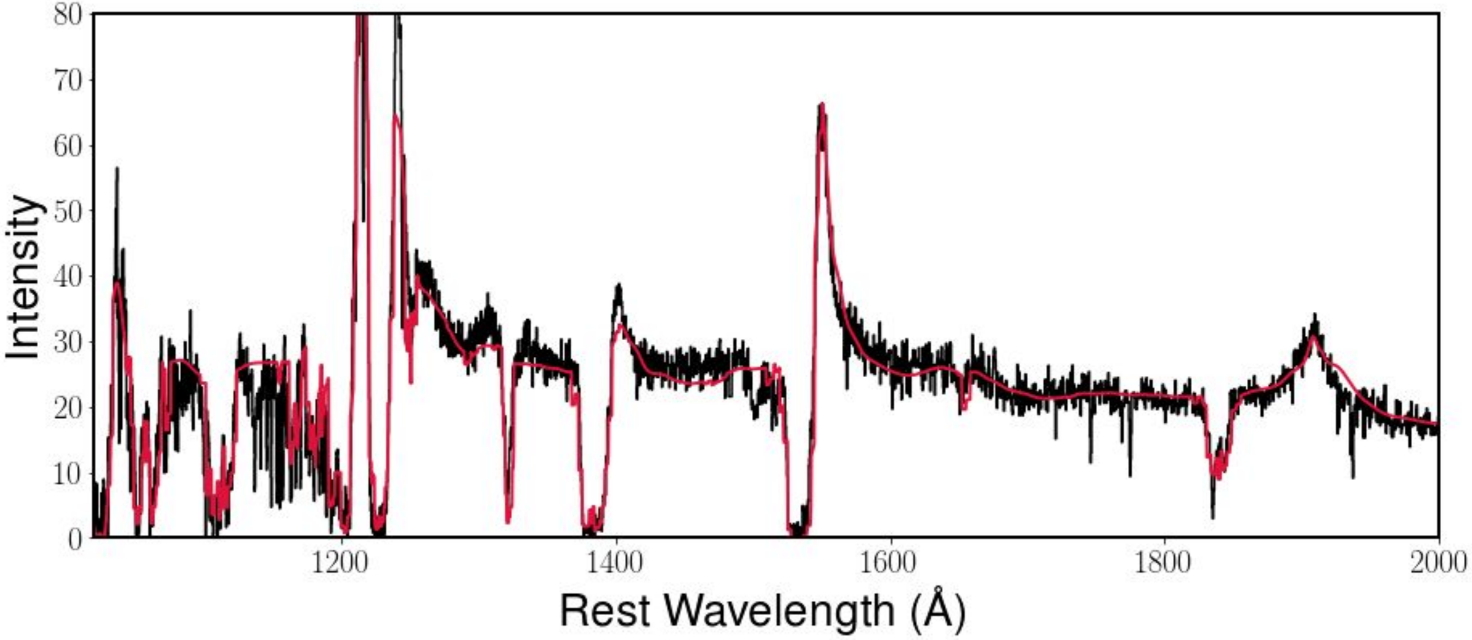
-This often let us get a lower continuum fit, which worked better with the short wavelength simulations

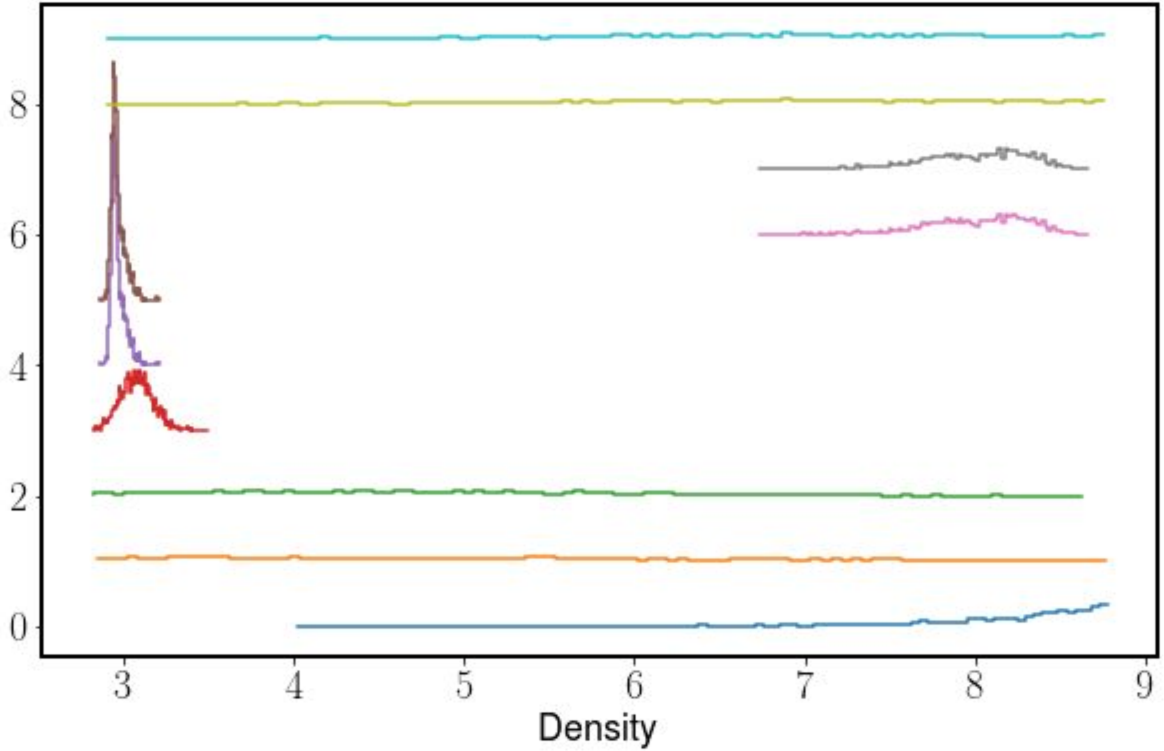



Without Absorption
I/I0
Wavelength
0
20
40
60
80
100
120
140
1200
1400
1600
1800
2000

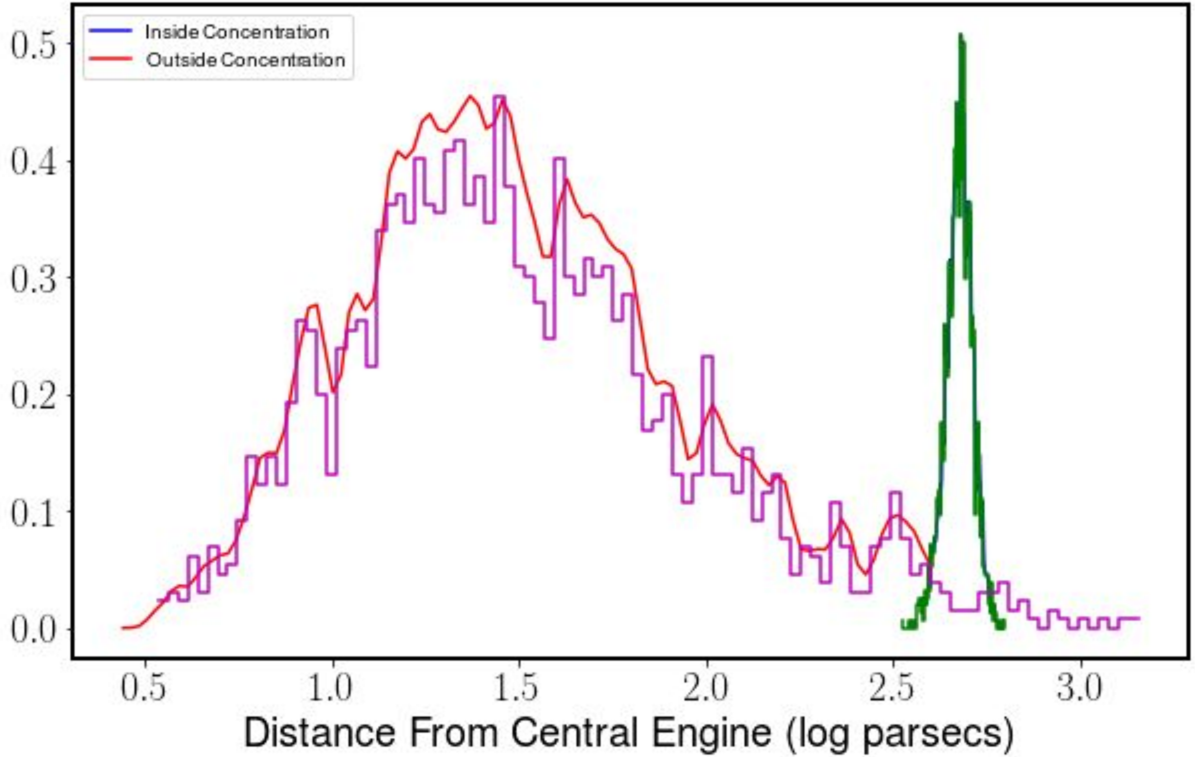

Without Absorption
I/I0
Wavelength
0
20
40
60
80
100
120
140
1200
1400
1600
1800
2000

J230721 Final Fit



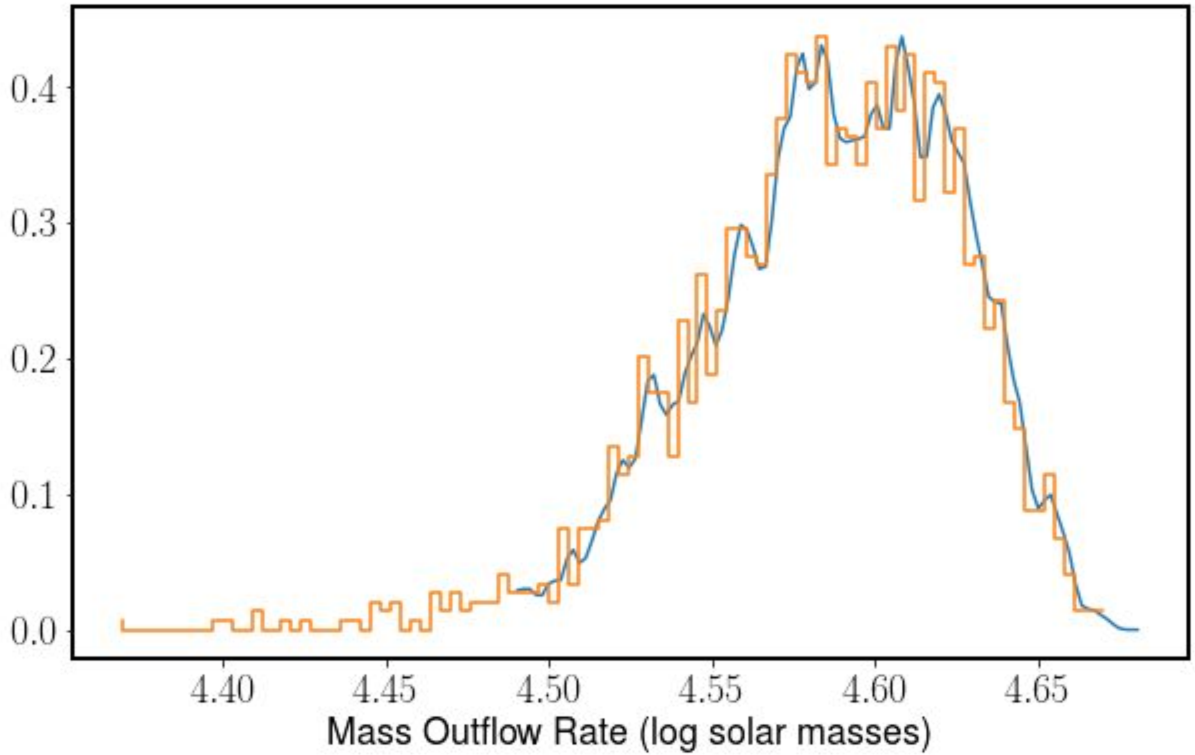


8
6
4
2
0
3
4
5
6
7
8
9
Density

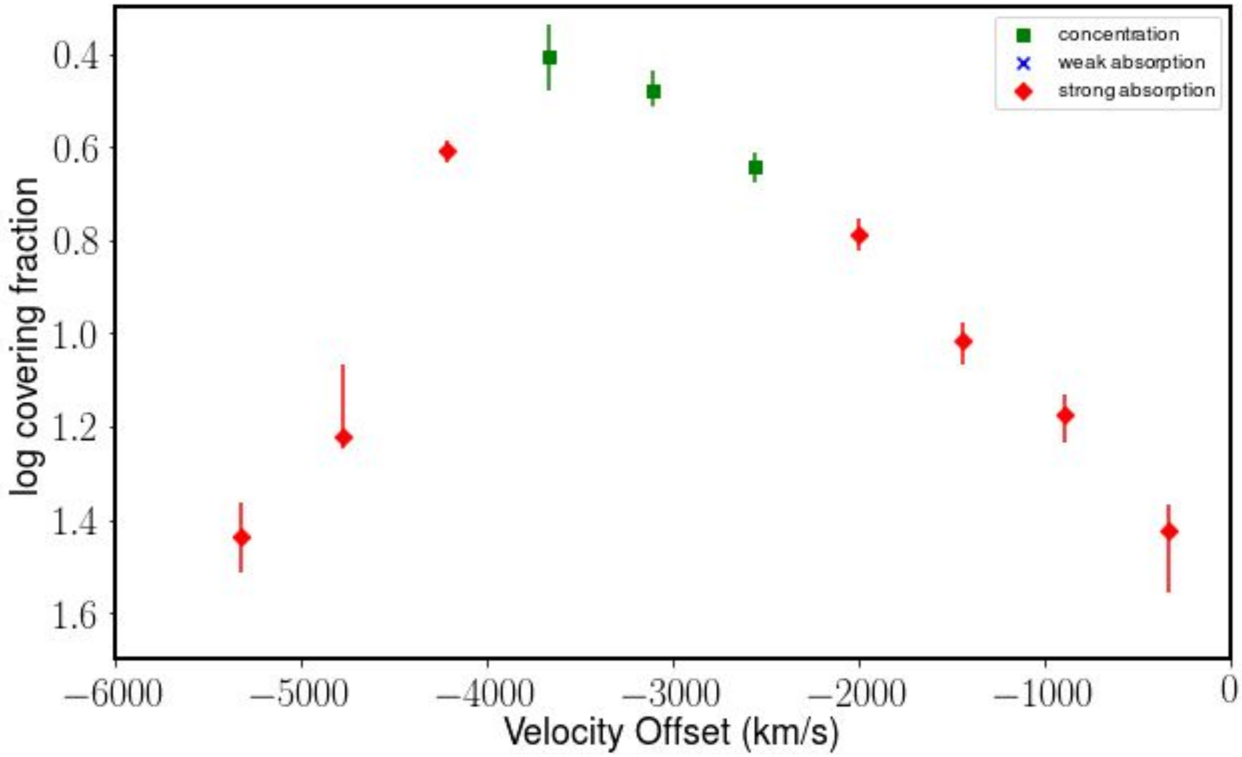


Inside Concentration
Outside Concentration
0.5
0.4
0.3
0.2
0.1
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Distance From Central Engine (log parsecs)

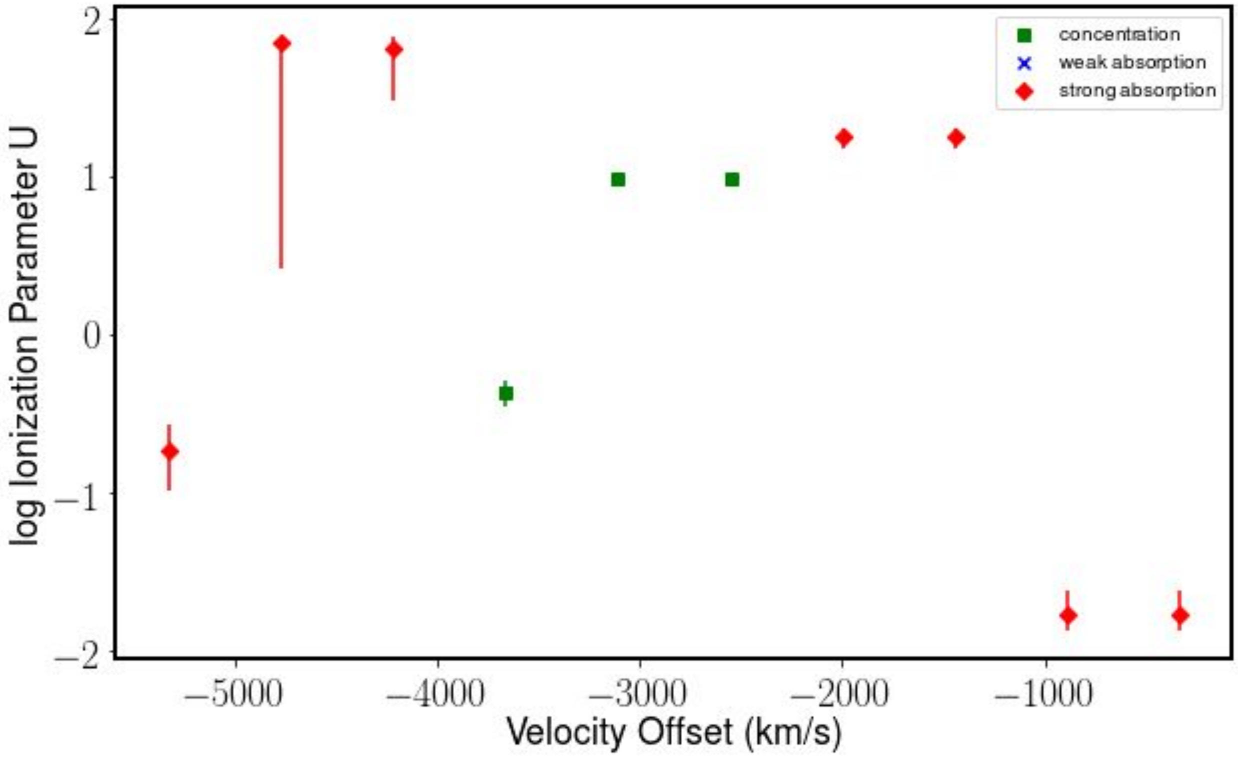
480 pc

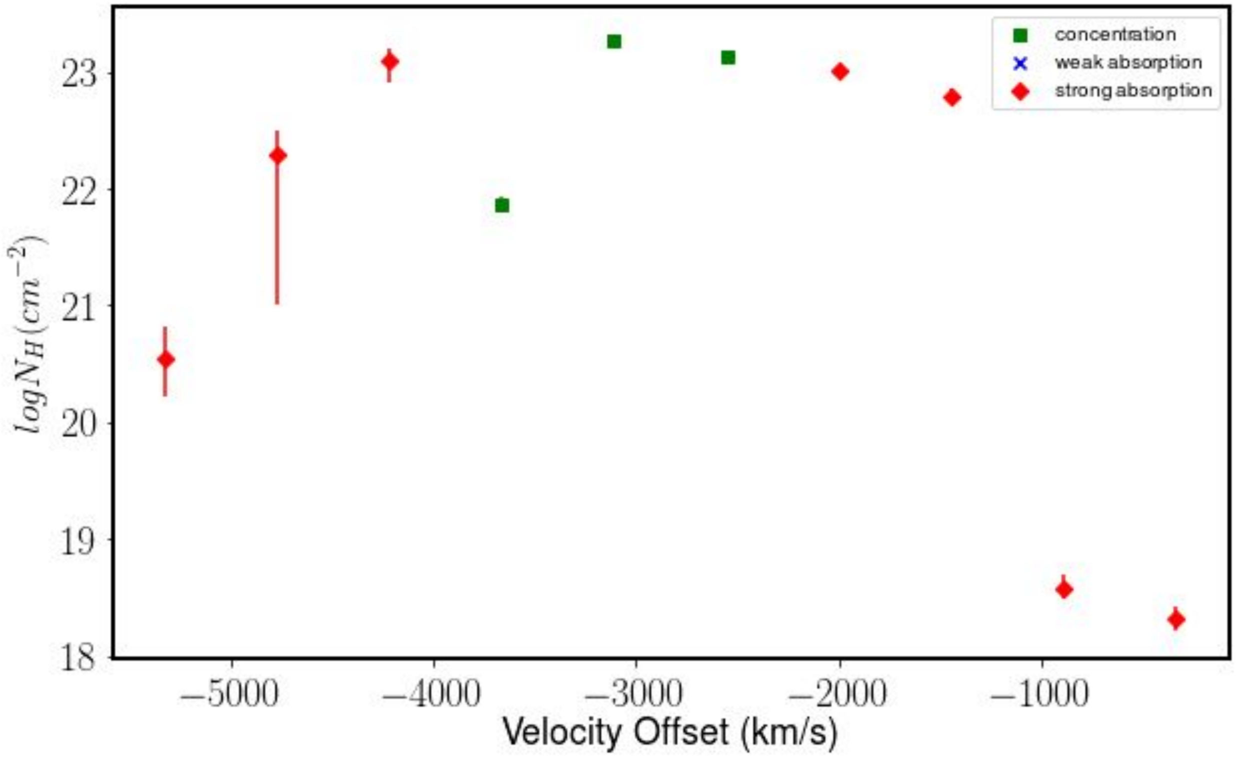


40,580 Solar Masses per Year



concentration
weak absorption
strong absorption
log covering fraction
0.4
0.6
0.8
1.0
1.2
1.4
1.6
−6000
−5000
−4000
−3000
−2000
−1000
0
Velocity Offset (km/s)


concentration
weak absorption
strong absorption
log Ionization Parameter U
2
1
0
−1
−2
−5000
−4000
−3000
−2000
−1000
Velocity Offset (km/s)



concentration
weak absorption
strong absorption
23
22
21
20
19
18
$log N_H (cm^{-2})$
−5000
−4000
−3000
−2000
−1000
Velocity Offset (km/s)

Prioritizing The Sample

-After looking at many quasars this summer we found which ones work the most easily with the program we're using

-Focusing on objects that were low redshift (less than 3) and high signal to noise helped a lot

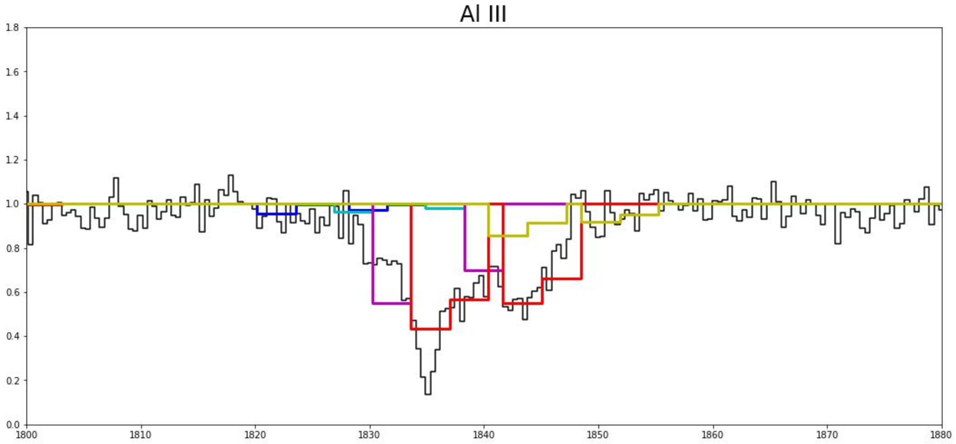
-It was rarer than we expected for objects to have clear C iii lines, so specifically seeking out objects that look like they have a good C iii absorption line and focusing on those objects first is a good idea to get good values for density

Benefits of The Grouping Method

-Makes clear which velocity bins correspond to which absorption lines

-Ties together bins that likely have the same properties while letting the covering fraction be free

-Simpler than previous methods and with improved results



Drawbacks to The Grouping Method

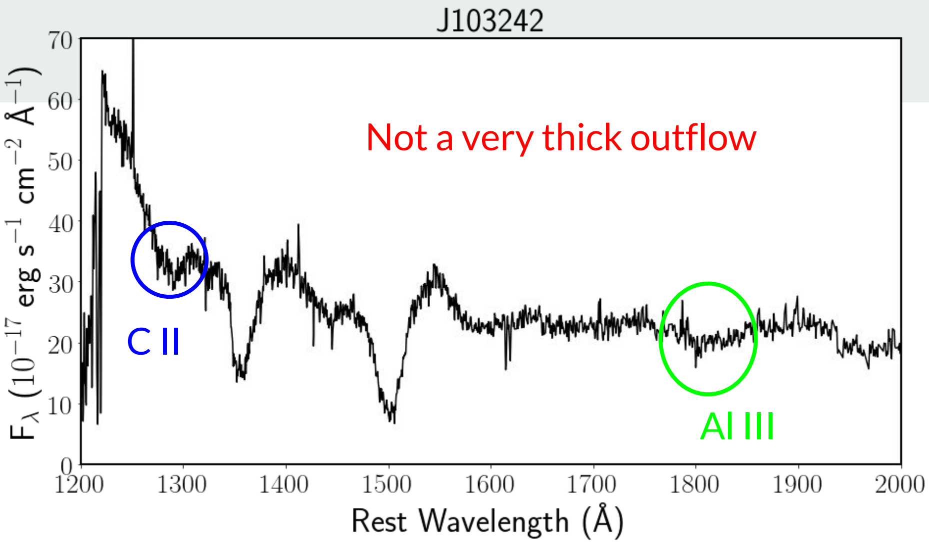
-Exact grouping can be difficult to decide on

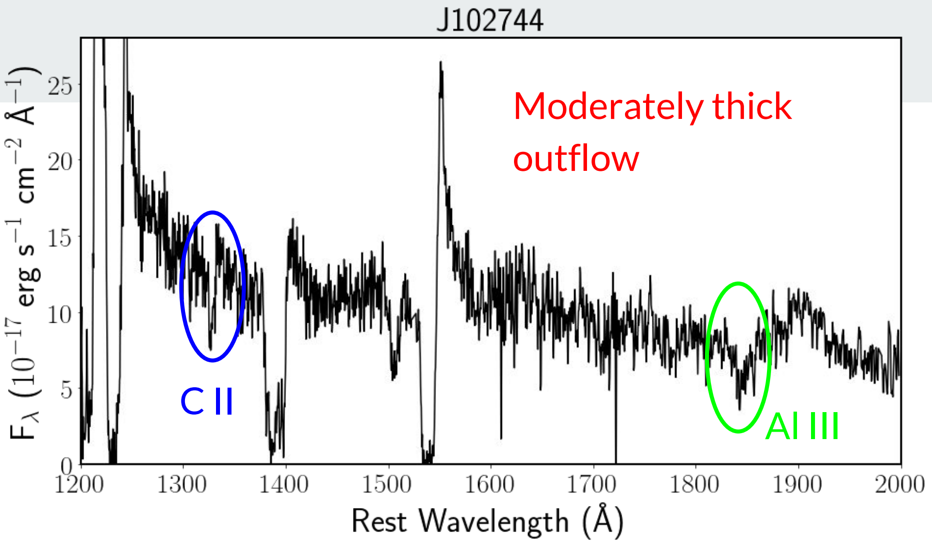
-Not clear how covering fraction and grouping interact

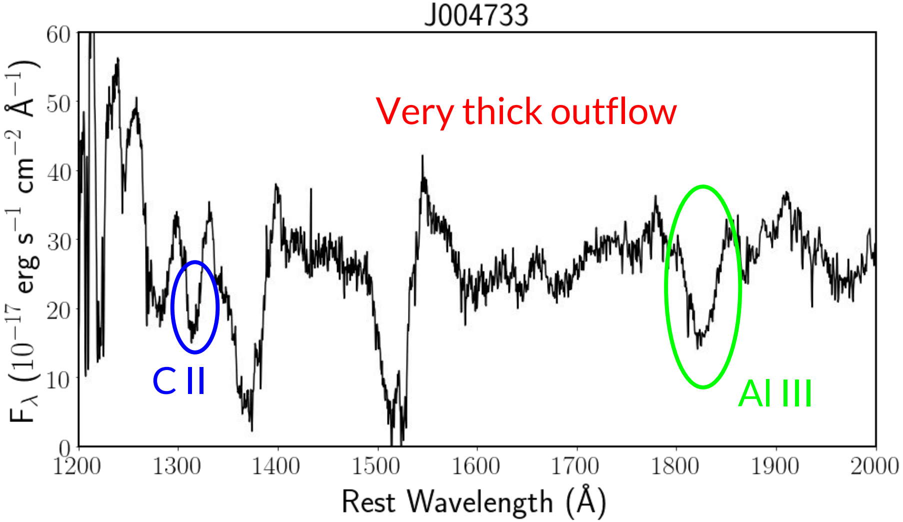
-Unclear how many velocity bins can justifiably be associated together and what the right width for velocity bins to be is

Trends

- **The presence of Al III and C II are good indicators of outflow thickness and are often concentrated at low velocities.**
- **Structure at higher velocities in C IV often do not appear in other ions.**
- Covering Fraction is larger at lower velocities.

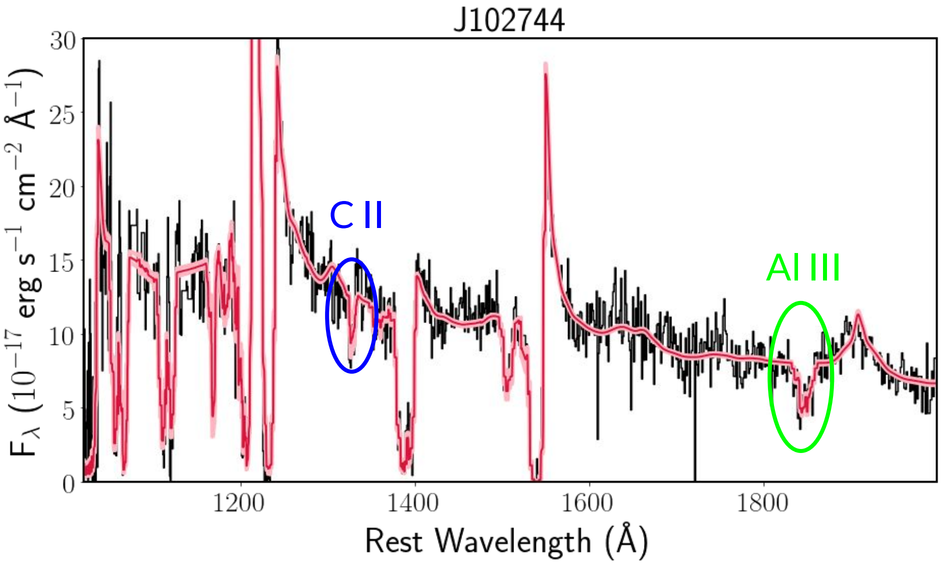


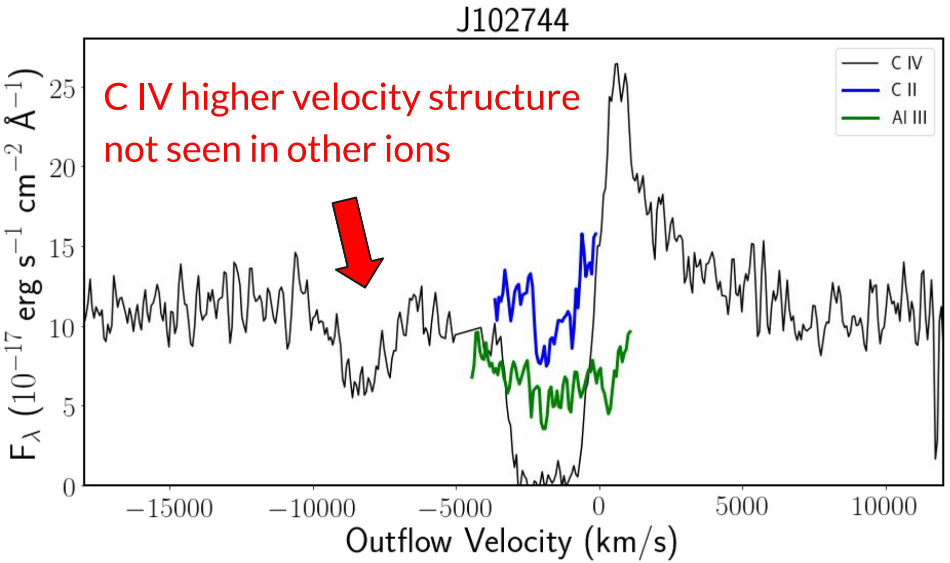




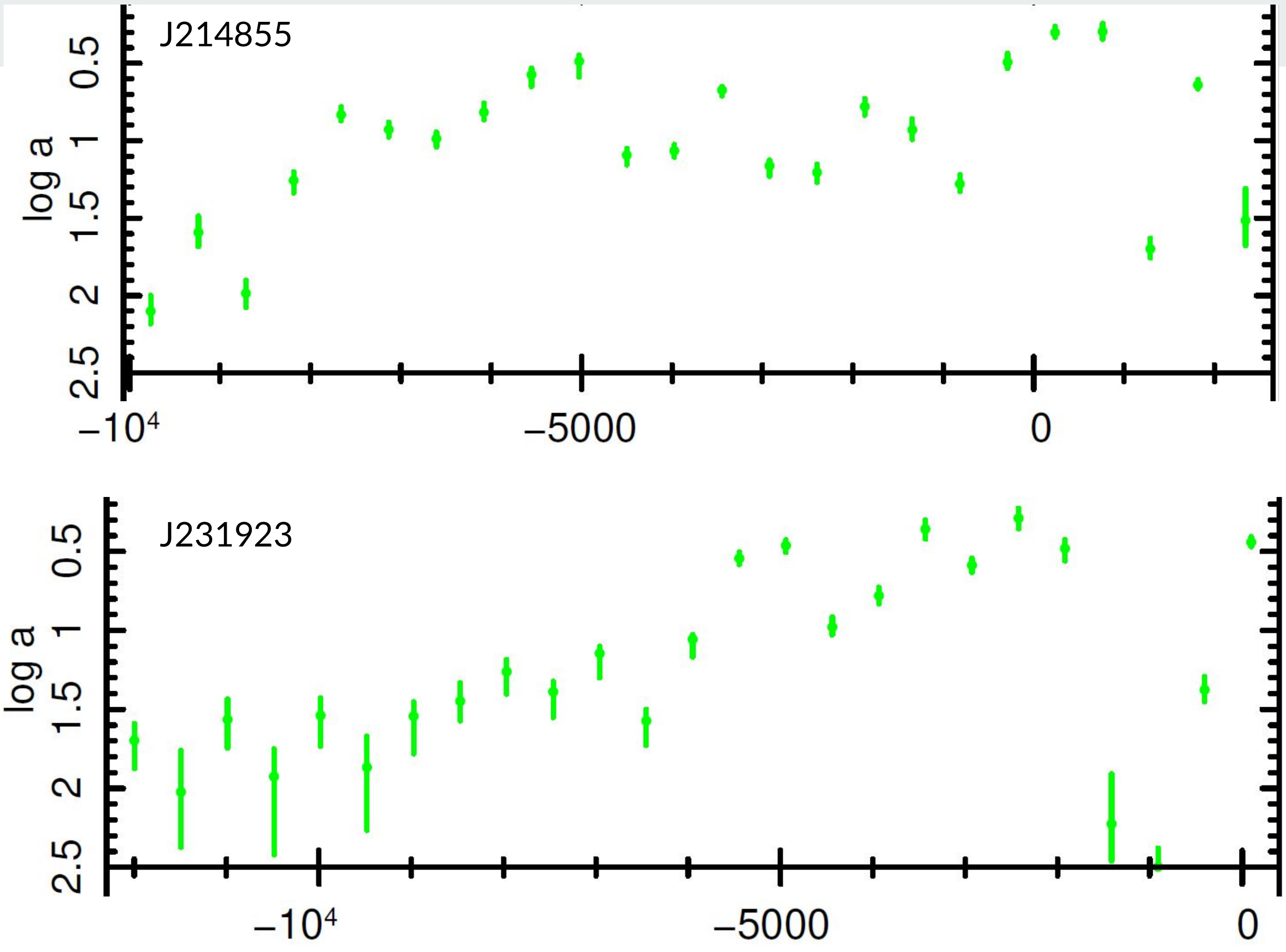
- Found that C II and Al III are better indicators for outflow thickness than P V.
- Si II and possible Fe II absorption begins to occur in very thick outflows.

Outflows and C IV Structure





- C II and Al III represent concentrations and often found at lower velocities.
- Figure on the Right is a comparison of absorption lines in terms of outflow velocity.
- Higher velocity C IV represents thinner gas and has been difficult to model.



Covering Fraction

- An increase in covering fraction for lower outflow velocities has been observed in some objects.

Moving Forward

- Figure out how to model out the Lyman-α Forest.
- Improve methods used in determining grouping of velocity bins.
- Resolve differences in modeling longer wavelengths (1200-2000 Å) with shorter wavelengths (1020-1200 Å).
- Further investigate previously mentioned trends.

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- Leighly, K. M., Terndrup, D. M., Gallagher, S. C., Richards, G. T., & Dietrich, M. (2018). *The z=0.54 LoBAL Quasar SDSS J085053.12+445122.5: I. Spectral Synthesis Analysis*. Submitted for Publication.
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