Abstract
Intergalactic Media Visualization, or *IGM-Vis*, is a novel visualization platform built for the web that enables astrophysicists to identify and analyze galaxies, quasars, and their related absorption spectra. *IGM-Vis* enables astrophysics researchers to investigate the emission spectra given off by quasars, which are very bright galactic cores presumed to be black holes, and analyze the impact nearby galaxies have on absorption. This initial release of *IGM-Vis* has an interactive 3D visualization of galaxies and quasar sightlines contained within the Coma Supercluster, a grouping of nearly twenty thousand galaxies and three hundred and fifty sightlines. *IGM-Vis* facilitates the analysis of astrophysics datasets from the Sloan Digital Sky Survey and the Hubble Space Telescope, and supports a range of presentation and annotation tasks.

Introduction and Related Work

A state-of-the-art review of observational and theoretical CGM research is presented by Tumlinson et al. [TPW17], which emphasizes the importance of the CGM within the larger context of galaxy evolution. *IGM-Vis* seeks to capture and expand upon the observational techniques that built the legacy of work they present. The CGM can be roughly defined as the gaseous envelope surrounding a galaxy, with a size often expressed as the galaxy's virial radius, the approximate maximum distance for which matter is gravitationally bound. Gas flows between the IGM, the CGM, and the interstellar medium, and its characteristics are typically observed by measuring absorption lines in the spectra of light emitting objects behind the gas clouds. Visualizations used in contemporary astrophysics research include spectral plots, which show the data directly and reveal the absorption from material along sightlines, and absorption plots such as equivalent width, which measures the absorption line depth and extent versus the projected distances of nearby galaxies. *IGM-Vis* generates interactive versions of these plots on-the-fly forselected quasar spectra, making it easy to quickly associate galaxies with their imprints upon the absorption spectra.

The landmark COS-Halos survey [TTW∗13a] investigates the CGM of forty-four galaxies at redshift $z=0.15-0.35$. They selected galaxies, both star forming (SF) and quiescent and over arange of mass, and observe distant quasars with projected distances(impact parameters)<150 kiloparsecs from these galaxies. Among key results were that the CGM exhibits strong absorption of neutral hydrogen (HI) emission for both quiescent and SF galaxies[TTW∗12] and that the CGM contains at least half of all the non-dark matter in galaxy. Based on other studies [CPW∗05, PWC∗11], there is a correlation between galaxies as the strongest HIab-sorbers, with the weaker absorbers likely tracing diffuse cosmic filaments and the IGM. IGM-Vis provides a novel interface for interrogating both IGM and CGM data, and enables researchers to investigate the relationships among galaxies, cosmic structure, and absorption patterns.

Cosmological simulations based on the cold dark matter paradigm universally predict that matter in the Universe is organized into a Cosmic Web (also known as large-scale structure), as elongated, interconnected filaments form from dark matter and contain low density IGM gas as well as galaxies and their CGM. Rauchet al. [Rau98] reviewed observational and theoretical studies of theIGM in context with large scale structure. Indeed, most of the non-dark matter mass in the Universe likely resides in the IGM [CO99]. In the nearby Universe, large surveys can reveal the Cosmic Web traced by galaxies [GH89]. A study by Wakker et al. [WHF∗15b] uses HST/COS to probe one Cosmic Web filament and its imprint of Lyα absorption lines. *IGM-Vis* facilitates the analysis of multiple filament structures using quasar sightline data.

A range of visualization tools have been created to mitigate the complexity of astrophysics data. Popular web applications, such as the The Sloan Digital Sky Survey's SkyServer [YAA∗00] and the World Wide Telescope [GS04, RFG∗18], compile and present an enormous amount astronomical image data. The European Space Agency's ESASky [BGR∗16] provides access to data from multiple astronomical archives, and can display the sky at different wavelengths. However, these websites do not provide any tools to analyze the data directly. Similarly, mViewer [BG17] enables a user to merge multiple image layers, using an image mosaic engine to project multiple 2D imagery into common astronomical layouts. AstroShelf [NGH∗12] also facilitates querying multiple datasets, enabling a scalable navigation of data and data annotations. Recent efforts by Sagristà et al. [SJMS18] introduce visualization tools to navigate observations made by the Gaia Spacecraft. Luciani et al. [LCO∗14] introduce an interface that enables users to control the transparency of multiple image layers so that relevant data from multiple datasets can be seen at the same time. A recent approach by Boussejra et al. leverages visual programming techniques to filter and analyze multi-spectral datasets [BMT∗18]. *IGM-Vis* emphasizes the presentation and analysis of spectrum data, and contextualizes these spectra with images for user-selected regions of the Universe on demand.

A number of tools present astrophysical elements as volumes within a 3D view [FH07, Tay17]. For example, Pomarède etal. [PCHT17] make use of images, videos, and derived isosurface structures within a 3D representation to show galaxy position, velocity and density fields, gravitational potential, and velocity shear tensors. Punzo et al. [PVdHR∗15] also note the importance of coupling 3D views with alternative visual representations, and emphasize interactive data filtering data in order to investigate relevant elements. Popov et al. [PCH∗12] explore methods to visualize singularities in cosmological simulation data, showing how 3D plots can be used to compare the resulting outputs from various computational methods. Haroz et al.

[HMH08] use a 2D parallel coordinates plot to emphasize uncertainty inherent to an astronomical dataset or when found through a comparison of datasets. Fujishiro et al. introduce TimeTubes [FSN∗18], which transforms temporal blazar data into an unusual volumetric structure, using ellipses to encode polarization parameters arranged as a 3D "tube" in order to identify patterns of interest. *IGM-Vis* represents galaxies as an interactive 3D scatterplot in which particular regions of the Universe are pierced by cylindrical representations of sightlines, which can then be more thoroughly examined via linked 2D spectral plots.

Visual analytics tools have been used to explore simulation data that models the evolution of the Universe [CKK∗15, HPU∗15]. Almryde and Forbes [AF15] introduce an interactive web application to visualize "traces" of dark matter halos as they move in relation to each other over time, creating tree-like structures when they merge together or split apart, and enabling the interactive comparison of the trees. Preston et al. [PGX∗16] provide a series of integrated panels to display 2D and 3D views of astrophysics data simultaneously. *IGM-Vis* also provides a visual analytics dashboard comprised of integrated panels [DMF17, FBL∗18, MFL∗16,SCB∗19], facilitating a workflow supporting IGM/CGM identification, analysis, and presentation tasks.

Task Analysis Table

Data Tasks **T1: Obtain Sightline Spectra** **T2: Obtain Galaxy Data**	**Description** **T1: Query archives; Make telescope observations** **T2: Derive measurements from spectroscopy and imaging**
Identification tasks **T3: Identify Foreground Features** **T4: Measure Absorption Properties** **T5: Identify Sightline Features**	**Description** **T3: Identify galaxies near sightlines; Identify larger structures** **T4:Find coherent absorption near galaxies or structures** **T5: Find relevant features across multiple sightlines**
Analysis Tasks **T6: Test Correlations** **T7: Discover Absorption Patterns**	**Description** **T6: Quantify relationship between absorption and galaxies** **T7: Compare multiple sightlines; Generate hypotheses from analyzing sightlines**
Presentation Taks **T8: Create Derived Datasets** **T9: Produce Plots**	**Description** **T8: Share data with astrophysics community** **T9: Create plots for presentations; Explore results interactively**

IGM-Vis

In this section, we provide an overview of *IGM-Vis*, and discuss how our design decisions promote the analysis tasks described in Section 3. (Although IGM and CGM research are both enabled by *IGM-Vis*, we chose to title the application *IGM-Vis* as IGM datasets underlie the work in both fields.) By default, *IGM-Vis* provides coverage of the Coma Supercluster and its surroundings to the extent covered by the SDSS. We designed *IGM-Vis* around this dataset as part of the HST Archival Research Program "Surveying the CGM and IGM across 4 orders of magnitude in environmental density"(HST ID 15009), but other datasets can be imported on demand.For the Coma Supercluster data, we used a subset of astrophysical data localizing on galaxies and quasars that fall within a right ascension (RA) range of 115◦and 260◦, a declination (DEC) range between−4◦and 65◦, and a redshift (z) range between 0.018 and0.023. This resulted in nearly 19,268 galaxies and just under 348 quasar sightlines containing HI and CIV absorption data. There are many other quasar spectral lines that can be visualized within *IGM-Vis*, as well as regions with different redshift. *IGM-Vis* is a modular platform that encourages users to begin their analysis from various starting points and to take different paths during an investigation of the Cosmic Web. It was developed through an iterative design process that included multiple rounds of feedback both from astrophysicists and visualization researchers over a 9 month period between February and November 2019.

IGM-Vis is composed of four primary panels, each of which provide a different view of astrophysical data: (1) an interactive 3D visualization of galaxies and QSO sightlines, or "skewers"; (2) image data and metadata from the SDSS for selected galaxies; (3) interactive 2D plots of spectra for selected skewers, and (4) a 2D equivalent width plot that is generated dynamically by user interaction. *IGM-Vis* enables comparisons between multiple emission spectra of a single QSO and its surrounding galaxies, as well as comparison between multiple QSO simultaneously. This is useful for identifying absorption patterns of a spectral line that may be related to particular features of neighboring galaxies. One key use is to quickly visually identify cosmic filaments [WHF∗15b] and inspect the influence these structures may have on their gas.

Universe Panel

The main panel provides an interactive 3D plot of the angular position and distance of all galaxies and quasars sightlines in the dataset, supporting the identification tasks T3 and T5. Galaxies are represented as partly transparent colored spheres, where blue represents star-forming galaxies and red represents quiescent galaxies. Sightlines are represented as cylindrical"skewers" and colored differently along their length to indicate the amount of absorption in the spectrum (by default, neutral hydrogen HI absorption), where dark grey indicates no absorption and white indicates strong absorption. Regions of strong HI absorption appear as white bands on the skewer cylinders, and a user can see at-a-glance which galaxies reside near high-absorption regions.The skewers and galaxies are all rendered over a black background,and skewers are outlined in yellow when they are selected by a user.Both galaxy color maps and skewer color maps can be customized by the user via a drop-down options menu.

When a galaxy is selected, a box with a size proportional to the virial radius is displayed over it. Each galaxy and skewer is positioned according to their angular coordinates in the celestial sphere: right ascension (RA) and declination (DEC). The 3D view is controlled using keyboard shortcuts or via the mouse, where a mouse movement while the left-click button is pressed rotates the view, pans the camera when the right-click button is pressed, andzooms the virtual camera in or out of the 3D plot when the mouse is scrolled. Text displaying the name of each skewer and the visibilityof the skewers themselves can be toggled on or off using either the drop-down menu or a keyboard shortcut.

Several computations are performed on the data in order to be effectively presented in the application. As astrophysical objects are measured in projection on the sky, object redshifts are used in transformations into physical distance. Each galaxy and data point along a skewer has a corresponding redshift, which are converted to physical distances (units of Megaparsecs, or Mpc) via cosmo-logical formulae and plotted in 3D space. We then convert from spherical coordinates by using the RA and DEC angles, look upthe corresponding physical distance for each redshift, and output a 3D position vector that can be interpreted by the WebGL engine.Lookup tables can be generated and saved for redshift regions beyond those in our Coma Supercluster dataset, making *IGM-Vis* very generalizable to other regions of the Universe.

Galaxy Panel

Directly below the Universe Panel, information about selected galaxies is displayed along the bottom of the application window and is updated each time a user hovers over a galaxy is in the Universe Panel. Each galaxy contains a list of attributes: its unique identifier (NSAID), declination (DEC), right ascension (RA), stellar mass (mstars), star formation rate (sfr), star formation rate uncertainty (sfrerr), a log of the specific star formation rate (log_sSFR), redshift, and the virial radius (rvir). When onehovers over a galaxy, this information is displayed along with its corresponding image, retrieved from the Sloan Digital Sky Survey [YAA∗00]. A user can interactively select and store galaxies of interest, which will then continue to populate the Galaxy Paneleven after the user has moved the mouse off of that galaxy. These stored galaxies are also highlighted in the Spectrum Panel, as we discuss below, using either a blue or red tick mark to show the galaxy’s redshift within the spectral plots if it’s impact parameter is within a user-selected threshold of the currently selected skewers. The galaxy panel mainly provides context in support of the identification tasks (especially T3), and relevant galaxy data can be exported for further analysis (T8).

Spectrum Panel

The Spectrum Panel is located on the right side of the application, primarily supporting analysis task T6. When a skewer is hovered over in the 3D view, it appears in the topmost position of the panel. Similar to the Galaxy Panel, multiple spectral plots can be stored by the user and can be quickly retrieved by scrolling up or down. Each skewer can contain multiple spectral plots, representing multiple spectral lines one may study (HI and CIVin the Coma Supercluster dataset). The x-axis of each plot is in units of redshift, and they-axis represents normalized flux.

The range of redshift values displayed can be filtered using an interactive slider, which is mapped to all the spectral plots for easy comparison. Also represented on the spectral plots are tick marks for neighboring galaxies. The maximum radius away from the skewers (impact parameter) for which galaxies are displayed can be filtered using another slider in this panel. By using a keyboard shortcut or double clicking on the slider handle, the user can hide galaxies beyond this radius within the 3D view. When one of these tick marks is hovered over, the line turns green, and a box appears around the galaxy in the 3D view. Likewise, if a galaxy is hovered over in the 3D view, it also changes the tick mark color to green. The relative height and width of these tick marks can be interactively mapped to different attributes in the galaxy data, such as its distance from the skewer, virial radius, stellar mass, or star formation rate. The mapping can be selected via menus below the graphs. The user can also export a file that contains all data within the Spectrum Panel,including the name and spectra for each skewer, along with a list of all nearby galaxies within a specified impact parameter, supporting tasks T8 and T9.

Equivalent Width Profile Panel

Positioned between the Galaxy Panel on the bottom and the Spectrum Panel on the right is a plot for visualizing the projected distance of a quasar sightline-galaxy pair (impact parameter, x-axis) and the absorption strength (equivalent width, y-axis) of a user selected spectral region. This plot is dynamically generated when a user selects three points on a spectral line, pressing ’E’ beforeeach: (1) the left redshift boundary, (2) the right redshift boundary, and (3) a reference point between the two boundaries. Once these points are selected, *IGM-Vis* calculates the equivalent width of the spectral feature. Then, galaxies are dynamically filtered to within the impact parameter range set by the slider in the Spectrum Panel. Galaxies are also filtered to ensure they have redshifts between the user selected left and right boundaries. Once galaxies have been filtered, they are plotted on the graph. An information ‘tooltip’ appears when a point is hovered over, showing the name of the skewer measured, galaxy NSAID, impact parameter, equivalent width, redshift values selected, and velocity transformations of the boundaries. This plot supports identification task T4 and analysis tasks T6 and T7, and these plots can be exported for inclusion in presentations (supportingT9).

Implementation

Galaxy positions and metadata are loaded from `data/galaxies.json` file using the `loadGalaxyData()` function. Once this file has been read, the function `loadSkewerData()` is called and reads the list of QSOs `qsosInSdssSlice_viz.dat` for their name, Right Ascension (RA) and Declination (DEC). The HI and CIV spectra for each QSO listed in `qsosInSdssSlice_viz.dat` is loaded from these folders respectively: `data/spectra_HI_norm` and `data/spectra_CIV_norm`. Calculating the projected distance between every skewer and galaxy can be done using the function `computeProjections()`, which uses the `haversine()` function to calculate an angular distance (impact parameter) between the two objects. In order to do this calculation, redshift must converted to physical units, which is done with the `cosmcalc()` function. In order to save time, a lookup table stored in `data/projections/lookUp.json` is referenced, which was created using the `cosmcalc()` function. If values outside of the range contained in the lookup table are needed, the computation is done on demand. In order to quicken the initial loading time even further, the impact parameter values for this dataset were precomputed in Megaparsecs using the steps outlined above and are stored in the folder `data/projections` as a separate file for each quasar with the function `loadP()`. Data can be downloaded into a .json file using the function `exportData('example.json',JSON.stringify([an array]))`. The data object that is downloaded on the "D" key press can be modified in the `onKeyDown(event)` event handler.

References

[AF15] ALMRYDE K. R., FORBESA. G.: Halos in a dark sky: Interactively exploring the structure of dark matter halo merger trees. *In Proceedings of the IEEE Scientific Visualization Conference (SciVis)* (2015), pp. 73–77.

[BCJ∗16] BOWEN D. V., CHELOUCHED., JENKINSE. B., TRIPP T. M., PETTINI M., YORK D. G., FRYE B. L.: The Structure of the Circumgalactic Medium of Galaxies: Cool Accretion Inflow Around NGC1097. *The Astrophysical Journal 826* (July 2016), 50.

[BFL∗17] BORDOLOI R., FOX A. J., LOCKMAN F. J., WAKKER B. P.,JENKINS E. B., SAVAGE B. D., HERNANDEZ S., TUMLINSON J.,BLAND-HAWTHORN J., KIMT.-S.: Mapping the Nuclear Outflow of the Milky Way: Studying the Kinematics and Spatial Extent of the North-ern Fermi Bubble. *The Astrophysical Journal 834* (Jan. 2017), 191.

[BG17] BERRIMAN G. B., GOOD J.: The application of the montage image mosaic engine to the visualization of astronomical images. *Publications of the Astronomical Society of the Pacific 129, 975* (2017), 058006.

[BGB∗04] BALDRY I. K., GLAZEBROOK K., BRINKMANN J., IVEZIC Z., LUPTON R. H., NICHOL R. C., SZALAYA. S.: Quantifying the bimodal color-magnitude distribution of galaxies. *The Astrophysical Journal 600* (Jan. 2004), 681–694.
[BGR∗16] BAINES D., GIORDANO F., RACERO E., SALGADO J., MARTÍ B. L., MERÍN B., SARMIENTO M.-H., GUTIÉRREZ R., DELANDALUCE I. O., LEÓNI., ET AL.: Visualization of multi-mission astronomical data with esasky. *Publications of the Astronomical Society of the Pacific 129, 972* (2016), 028001.
[BHT∗15] BORTHAKUR S., HECKMAN T., TUMLINSON J., BORDOLOI R., THOM C., CATINELLA B., SCHIMINOVICH D., DAVÉ R., KAUFF-MANN G., MORANS. M., SAINTONGE A.: Connection between the Circumgalactic Medium and the Interstellar Medium of Galaxies: Results from the COS-GASS Survey. *The Astrophysical Journal 813* (Nov.2015), 46.
[BM13] BREHMER M., MUNZNER T.: A multi-level typology of abstract visualization tasks. *IEEE Transactions on Visualization and Computer Graphics 19, 12* (2013), 2376–2385.
[BMBF13] BAHÉ Y. M., MCCARTHY I. G., BALOGH M. L., FONTA. S.: Why does the environmental influence on group and cluster galaxies extend beyond the virial radius? *Monthly Notices of the Royal Astronomical Society 430* (Apr. 2013), 3017–3031.
[BMT∗18] BOUSSEJRA M. O., MATSUBAYASHI K., TAKESHIMA Y., TAKEKAWA S., UCHIKI R., UEMURA M., FUJISHIRO I.: aflak: Pluggable visual programming environment with quick feedback loop tuned for multi-spectral astrophysical observations. *In Proceedings of IEEEVIS* (November 2018).
[BP69] BAHCALL J. N., PEEBLES P. J. E.: Statistical Tests for the Origin of Absorption Lines Observed in Quasi-Stellar Sources. *The Astrophysical Journal Letters 156* (Apr. 1969), L7.
[BS69] BAHCALL J. N., SPITZER JR. L.: Absorption Lines Produced by Galactic Halos. *The Astrophysical Journal Letters 156* (May 1969), L63.
[BTB∗16] BURCHETT J. N., TRIPP T. M., BORDOLOI R., WERK J. K.,PROCHASKA J. X., TUMLINSON J., WILLMERC. N. A., O'MEARA J., KATZ N.: A Deep Search For Faint Galaxies Associated With Very Low-redshift C IV Absorbers: III. The Mass- and Environment-dependent Circumgalactic Medium. *The Astrophysical Journal 832, 124* (Dec. 2016), 124.
[BTP∗15] BURCHETT J. N., TRIPP T. M., PROCHASKA J. X., WERK J. K., TUMLINSON J., O'MEARA J. M., BORDOLOI R., KATZ N., WILLMERC. N. A.: A Deep Search For Faint Galaxies Associated With Very Low-redshift C IV Absorbers: II. Program Design, Absorption-line Measurements, and Absorber Statistics. *The Astrophysical Journal 815, 2* (2015), 91.
[BTW∗18] BURCHETT J. N., TRIPP T. M., WANG Q. D., WILLMER C. N. A., BOWEND. V., JENKINS E. B.: Warm-hot gas in X-ray bright galaxy clusters and the HI-deficient circumgalactic medium in dense environments. *Monthly Notices of the Royal Astronomical Society 475* (Apr. 2018), 2067–2085.
[CFP∗16] CAI Z., FAN X., PEIRANI S., BIAN F., FRYE B., MCGREER I., PROCHASKA J. X., LAUM. W., TEJOS N., HO S., SCHNEIDER D. P.: Mapping the Most Massive Overdensity Through Hydrogen (MAMMOTH) I: Methodology. *The Astrophysical Journal 833* (Dec.2016), 135.
[CKK∗15] CHRISTOUDIAS T., KALLIDONIS C., KOUTSANTONIS L.,LEMESIOS C., MARKOU L., SOPHOCLEOUS C.: Visualising the darksky ieee scivis contest 2015. *In Proceedings of the IEEE Scientific Visualization Conference (SciVis)* (2015), pp. 79–86.
[CO99] CENR., OSTRIKER J. P.: Where Are the Baryons? *The Astrophysical Journal 514* (Mar. 1999), 1–6.
[CPW∗05] CHEN H.-W., PROCHASKA J. X., WEINER B. J., MULCHAEY J. S., WILLIGER G. M.: Probing the intergalactic medium-galaxy connection toward PKS 0405-123. II. a cross-correlation study of Lyα absorbers and galaxies at z<0.5. *The Astrophysical Journal Letters 629*(Aug. 2005), L25–L28.
[DMF17] DANG T., MURRAY P., FORBES A. G.: BioLinker: Bottom-up exploration of protein interaction networks. *In Proceedings of the 10th IEEE Pacific Visualization Symposium (PacificVis)*(Seoul, Korea, April 2017), pp. 265–269.
[EBL∗15] ETEMADPOUR R., BOMHOFF M., LYONS E., MURRAY P.,FORBES A. G.: Designing and evaluating scientific workflows for big data interactions. *In Proceedings of the IEEE Symposium on Big Data Visual Analytics (BDVA)*(2015), pp. 1–8.
[FBL∗18] FORBES A. G., BURKS A., LEEK., LI X., BOUTILLIER P. ,KRIVINE J., FONTANA W.: Dynamic influence

networks for rule-based models. *IEEE Transactions on Visualization and Computer Graphics 24,1* (January 2018), 184–194.
[FH07] FU C.-W., HANSON A. J.: A transparently scalable visualization architecture for exploring the universe. *IEEE Transactions on Visualization and Computer Graphics 13, 1* (2007), 108–121.
[FPH∗17] FLUKE C., PARRINGTON L., HEGARTY S., MACMAHON C., MORGAN S., HASSAN A., KILBORN V.: Sports stars: Analyzing the performance of astronomers at visualization-based discovery. *Publications of the Astronomical Society of the Pacific 129, 975* (2017), 058009.
[FSN∗18] FUJISHIRO I., SAWADA N., NAKAYAMA M., WU H.-Y.,WATANABE K., TAKAHASHI S., UEMURA M.: Timetubes: Visual exploration of observed blazar datasets. *In Journal of Physics: ConferenceSeries* (2018), vol. 1036, p. 012011.
[FWB∗14] FOX A. J., WAKKER B. P., BARGER K. A., HERNANDEZ A. K., RICHTER P., LEHNER N., BLAND-HAWTHORN J., CHARLTON J. C., WESTMEIER T., THOM C., TUMLINSON J., MISAWA T., HOWK J. C., HAFFNER L. M., ELY J., RODRIGUEZ-HIDALGO P., KUMARIN.: The COS/UVES Absorption Survey of the Magellanic Stream. III. Ionization, Total Mass, and Inflow Rate onto the Milky Way. *The Astrophysical Journal 787* (June 2014), 147.
[GFO∗12] GREEN J. C., FRONING C. S., OSTERMAN S., EBBETS D., HEAP S. H., LEITHERER C., LINSKY J. L., SAVAGE B. D., SEMBACH K., SHULLJ. M., SIEGMUND O. H. W., SNOW T. P., SPENCER J., STERN S. A., STOCKE J., WELSH B., BÉLAND S., BURGH E. B., DANFORTH C., FRANCE K., KEENEY B., MCPHATE J., PENTON S. V., ANDREWS J., BROWNSBERGER K., MORSE J., WILKINSON E.: The cosmic origins spectrograph. *The Astrophysical Journal 744* (Jan.2012), 60.
[GH89] GELLER M. J., HUCHRA J. P.: Mapping the universe. *Science 246* (Nov. 1989), 897–903.
[GS04] GRAY J., SZALAY A. S.: The world wide telescope: An archetype for online science. *arXiv preprint cs/0403018* (2004).
[HMH08] HAROZ S., MA K.-L., HEITMANN K.: Multiple uncertainties in time-variant cosmological particle data. *In Proceedings of the IEEE Pacific Visualization Symposium (PacificVis)* (2008), pp. 207–214.
[HPU∗15] HANULA P., PIEKUTOWSKI K., URIBE C., ALMRYDE K., NISHIMOTO A., AGUILERA J., MARAI G. E.: Cavern halos: Exploring spatial and nonspatial cosmological data in an immersive virtual environment. *In Proceedings of the IEEE Scientific Visualization Conference(SciVis)* (2015), IEEE, pp. 87–99.
[IZCC08] ISENBERG P., ZUK T., COLLINS C., CARPENDALE S.: Grounded evaluation of information visualizations. *In Proceedings of the ACM Workshop on Beyond time and errors: novel evaluation methods for Information Visualization* (2008), p. 6.
[JCM15] JOHNSON S. D., CHEN H.-W., MULCHAEY J. S.: On the possible environmental effect in distributing heavy elements beyond individual gaseous haloes. *Monthly Notices of the Royal Astronomical Society 449*(May 2015), 3263–3273.
[KD02] KEWLEY L. J., DOPITA M. A.: Using Strong Lines to Estimate Abundances in Extragalactic H II Regions and Starburst Galaxies. *The Astrophysical Journal Supplement Series 142* (Sept. 2002), 35–52.
[KE12] KENNICUTT R. C., EVANS N. J.: Star Formation in the Milky Way and Nearby Galaxies. *ARAA 50* (Sept. 2012), 531–608.
[LAB∗06] LUDÄSCHER B., ALTINTAS I., BERKLEY C., HIGGINS D.,JAEGER E., JONES M., LEE E. A., TAO J., ZHAO Y.: Scientific workflow management and the kepler system .*Concurrency and Computation: Practice and Experience 18, 10* (2006), 1039–1065.
[LBI∗12] LAM H., BERTINI E., ISENBERG P., PLAISANTC., CARPEN-DALE S.: Empirical studies in information visualization: Seven scenarios. *IEEE Transactions on Visualization and Computer Graphics 18, 9 (*2012), 1520–1536.
[LCO∗14] LUCIANI T. B., CHERINKA B., OLIPHANT D., MYERS S., WOOD-VASEY W. M., LABRINIDIS A., MARAI G. E.: Large-scale overlays and trends: Visually mining, panning and zooming the observable universe. *IEEE Transactions on Visualization and Computer Graphics 20, 7* (2014), 1048–1061.
[LKW∗18] LEE K.-G., KROLEWSKI A., WHITE M., SCHLEGEL D.,NUGENT P. E., HENNAWI J. F., MÜLLER T., PAN R., PROCHASKA J. X., FONT-RIBERA A., SUZUKI N., GLAZEBROOK K., KACPRZAK G. G., KARTALTEPE J. S., KOEKEMOER A. M., LEFÈVRE O., LEMAUX B. C., MAIER C., NANAYAKKARA T., RICH R. M., SANDERS D. B., SALVATO M., TASCA L., TRAN K.-V. H.: First Data Release of the COSMOS Lyα Mapping and Tomography

Observations:3D LyαForest Tomography at 2.05<z<2.55. *The Astrophysical Journal Supplement Series 237* (August 2018), 31.

[LMZ14] LAN T.-W., MÉNARD B., ZHUG.: The Properties of the Cool Circumgalactic Gas Probed with the SDSS, WISE, and GALEX Surveys. *The Astrophysical Journal 795* (Nov. 2014), 31.

[LOF∗14] LEHNER N., O'MEARA J. M., FOX A. J., HOWKJ . C., PROCHASKA J. X., BURNS V., ARMSTRONG A. A.: Galactic and Circumgalactic O VI and its Impact on the Cosmological Metal and Baryon Budgets at 2< z<~3.5. *The Astrophysical Journal 788* (June 2014),119.

[LSR∗07] LEHNER N., SAVAGE B. D., RICHTER P., SEMBACH K. R.,TRIPP T. M., WAKKER B. P.: Physical Properties, Baryon Content, and Evolution of the Lyα Forest: New Insights from High-Resolution Observations at z <~ 0.4.*The Astrophysical Journal 658 (*Apr. 2007), 680–709.

[LTC80] LARSON R. B., TINSLEY B. M., CALDWELL C. N.: The evolution of disk galaxies and the origin of S0 galaxies. *The Astrophysical Journal 237* (May 1980), 692–707.

[LTL∗18] LOPEZ S., TEJOS N., LEDOUX C., BARRIENTOS L. F., SHARON K., RIGBY J. R., GLADDERS M. D., BAYLISS M. B., PESSA I.: A clumpy and anisotropic galaxy halo at redshift 1 from gravitational-arc tomography. *Nature 554* (Feb. 2018), 493–496.

[LWH∗18] LEHNER N., WOTTA C. B., HOWK J. C., O'MEARA J. M.,OPPENHEIMER B. D., COOKSEY K. L.: The COS CGM Compendium. I. Survey Design and Initial Results. *The Astrophysical Journal 866* (Oct.2018), 33.

[MBZL09] MCPHILLIPS T., BOWERS S., ZINN D., LUDÄSCHER B.: Scientific workflow design for mere mortals. *Future Generation Computer Systems 25, 5* (2009), 541–551.

[MFL∗16] MA C., FORBES A. G., LLANO D. A., BERGER-WOLF T., KENYON R. V.: SwordPlots: Exploring neuron behavior within dynamic communities of brain networks. *Journal of Imaging Science and Technology 60, 1* (January 2016), 10405–1–13.

[NCK∗16] NIELSEN N. M., CHURCHILL C. W., KACPRZAK G. G., MURPHY M. T., EVANS J. L.: MAGIICAT IV. Kinematics of the Circumgalactic Medium and Evidence for Quiescent Evolution Around Red Galaxies. *The Astrophysical Journal 818* (Feb. 2016), 171.

[NGH∗12] NEOPHYTOU P., GHEORGHIU R., HACHEY R., LUCIANI T., BAO D., LABRINIDIS A., MARAI G. E., CHRYSANTHIS P. K.: Astroshelf: Understanding the universe through scalable navigation of a galaxy of annotations. *In Proceedings of the ACM SIGMOD International Conference on Management of Data* (2012), pp. 713–716.

[OLH∗15] O'MEARA J. M., LEHNER N., HOWKJ . C., PROCHASKA J. X., FOX A. J., SWAIN M. A., GELIN C. R., BERRIMAN G. B.,TRAN H.: The First Data Release of the KODIAQ Survey. *The Astronomical Journal 150* (Oct. 2015), 111.

[PC05] PIROLLI P., CARD S.: The sensemaking process and leverage points for analyst technology as identified through cognitive task analysis. *In Proceedings of the International Conference on Intelligence Analysis* (2005), vol. 5, pp. 2–4.

[PCH∗12] POPOV U., CHANDRA E., HEITMANN K., HABIB S., AHRENS J., PANG A.: Analyzing the evolution of large scale structures in the universe with velocity based methods. *In Proceedings of the IEEE Pacific Visualization Symposium (PacificVis)* (2012), pp. 49–56.

[PCHT17] POMARÈDE D., COURTOIS H. M., HOFFMAN Y., TULLY R. B.: Cosmography and data visualization *Publications of the Astronomical Society of the Pacific 129, 975* (2017), 058002.

[PGX∗16] PRESTON A., GHODS R., XI EJ., SAUER F., LEAF N., MA K.-L., RANGEL E., KOVACS E., HEITMANN K., HABIB S.: An integrated visualization system for interactive analysis of large, heterogeneous cosmology data. *In Proceedings of the IEEE Pacific Visualization Symposium (PacificVis)* (2016), pp. 48–55.

[PNK∗17] POINTON S. K., NIELSEN N. M., KACPRZAK G. G., MUZAHID S., CHURCHILL C. W., CHARLTON J. C.: The Impact of the Group Environment on the O VI Circumgalactic Medium. *The Astrophysical Journal 844* (July 2017), 23.

[PTF∗17] PEEPLES M., TUMLINSON J., FOX A., ALOISI A., FLEMING S., JEDRZEJEWSKI R., OLIVEIRA C., AYRES T., DANFORTH C., KEENEY B., JENKINS E.: *The Hubble Spectroscopic Legacy Archive.Tech. rep.,* Apr. 2017.

[PVdHR∗15] PUNZO D., VAN DERHULST J., ROERDINK J., OOSTER-LOO T., RAMATSOKU M., VERHEIJEN M.: The role of 3-d interactive visualization in blind surveys of h i in galaxies. *Astronomy and Computing 12* (2015), 86–99.
[PWC∗11] PROCHASKA J. X., WEINER B., CHEN H.-W., MULCHAEY J., COOKSEY K.: Probing the intergalactic Medium/Galaxy connection.v. on the origin of Lyαand O VI absorption at z < 0.2. *The Astrophysical Journal 740* (Oct. 2011), 91.
[Rau98] RAUCH M.: The lyman alpha forest in the spectra of quasistellar objects. *Annual Review of Astronomy and Astrophysics 36* (1998), 267–316.
[RFG∗18] ROSENFIELD P., FAY J., GILCHRIST R. K., CUI C., WEIGEL A. D., ROBITAILLE T., OTOR O. J., GOODMAN A.: Aas worldwide telescope: A seamless, cross-platform data visualization engine for astronomy research, education, and democratizing data. *The Astrophysical Journal Supplement Series 236, 1* (2018), 22.
[ROC∗18] RUBIN K. H. R., O'MEARA J. M., COOKSEY K. L., MA-TUSZEWSKI M., RIZZI L., DOPPMANN G., KWOK S., MARTIN D. C.,MOORE A. M., MORRISSEY P., NEILL J. D.: Andromeda's Parachute: A Bright Quadruply Lensed Quasar at z = 2.377. *The Astrophysical Journal 859* (June 2018), 146.
[RRB∗14] RYKOFF E. S., ROZO E., BUSHA M. T., CUNHA C. E.,FINOGUENOV A., EVRARD A., HAO J., KOESTER B. P., LEAUTHAUD A., NORD B., PIERRE M., REDDICK R., SADIBEKOVA T., SHELDON E. S., WECHSLER R. H.: redMaPPer. I. Algorithm and SDSS DR8 Catalog. *The Astrophysical Journal 785* (Apr. 2014), 104.
[SCB∗19] SARIKAYA A., CORRELL M., BARTRAM L., TORY M., FISHER D.: What do we talk about when we talk about dashboards? *IEEE Transactions on Visualization and Computer Graphics 25, 1* (Jan 2019), 682–692.
[Sch66] SCHMIDT M.: Redshifts of Fourteen Quasi-Stellar Radio Sources. *The Astrophysical Journal 144* (Apr. 1966), 443.
[SJMS18] SAGRISTÀ A., JORDAN S., MÜLLER T., SADLO F.: Gaiasky: Navigating the gaia catalog. *IEEE transactions on visualization and computer graphics* (2018).
[SKD∗13] STOCKE J. T., KEENEY B. A., DANFORTH C. W., SHULL J. M., FRONING C. S., GREEN J. C., PENTON S. V., SAVAGE B. D.: Characterizing the circumgalactic medium of nearby galaxies with HST/COS and HST/STIS absorption-line spectroscopy. *The Astrophysical Journal 763* (Feb. 2013), 148.
[SLF∗15] STEPHENS Z. D., LEE S. Y., FAGHRI F., CAMPBELL R. H., ZHAI C., EFRON M. J., IYER R., SCHATZ M. C., SINHA S., ROBIN-SON G. E.: Big data: astronomical or genomical? *PLoS biology 13, 7* (2015), e1002195.
[Son01] SONGAILA A.: The minimum universal metal density between redshifts of 1.5 and 5.5. *The Astrophysical Journal Letters 561* (Nov.2001), L153–L156.
[Tay17] TAYLOR R.: Visualizing three-dimensional volumetric data with an arbitrary coordinate system.Publications of the Astronomical Society of the Pacific 129, 972 (2017), 028002.
[Tin74] TINSLEY B. M.: Constraints on models for chemical evolution in the solar neighborhood. *The Astrophysical Journal 192* (Sept. 1974),629–641.
[TLS98] TRIPP T. M., LU L., SAVAGE B. D.: The relationship between galaxies and low-redshift weak Lyαabsorbers in the directions of H1821+643 and PG 1116+215. *The Astrophysical Journal 508* (Nov.1998), 200–231.
[TM04] TORY M., MOLLER T.: Human factors in visualization re-search.IEEE Transactions on Visualization and Computer Graphics 10,1 (2004), 72–84.
[TMC∗12] TEJOS N., MORRIS S. L., CRIGHTON N. H. M., THEUNS T., ALTAY G., FINN C. W.: Large-scale structure in absorption: gas within and around galaxy voids. *Monthly Notices of the Royal Astronomical Society 425* (Sept. 2012), 245–260.
[TMP∗11] TRIPP T. M., MEIRING J. D., PROCHASKA J. X., WILLMER C. N. A., HOWK J. C., WERK J. K., JENKINS E. B., BOWEN D. V., LEHNER N., SEMBACH K. R., THOM C., TUMLINSON J.: The hiddenmass and large spatial extent of a post-starburst galaxy outflow. *Science 334* (Nov. 2011), 952.
[TPC∗16] TEJOS N., PROCHASKA J. X., CRIGHTON N. H. M., MOR-RIS S. L., WERK J. K., THEUNS T., PADILLA N., BIELBY R. M.,FINN C. W.: Towards the statistical detection of the warm-hot intergalactic medium in intercluster filaments of the cosmic web. *Monthly Notices of the Royal Astronomical Society 455* (Jan. 2016), 2662–2697.

[TPW17] TUMLINSON J., PEEPLES M. S., WERK J. K.: The circumgalactic medium. *Annual Review of Astronomy and Astrophysics 55* (2017), 389–432.
[TS12] RIPP T. M., SONG L.: The 21 cm "Outer Arm" and the Outer-galaxy High-velocity Clouds: Connected by Kinematics, Metallicity, and Distance. *The Astrophysical Journal 746* (Feb. 2012), 173.
[TSJ00] TRIPP T. M., SAVAGE B. D., JENKINS E. B.: Intervening OVI Quasar Absorption Systems at Low Redshift: A Significant Baryon Reservoir. *The Astrophysical Journal Letters 534* (May 2000), L1–L5.
[TSM∗14] TEMPEL E., STOICA R. S., MARTÍNEZ V. J., LIIVAMÄGI L. J., CASTELLAN G., SAAR E.: Detecting filamentary pattern in the cosmic web: a catalogue of filaments for the SDSS. *Monthly Notices of the Royal Astronomical Society 438* (Mar. 2014), 3465–3482.
[TTW∗11] TUMLINSON J., THOM C., WERK J. K., PROCHASKA J. X., TRIPP T. M., WEINBERG D. H., PEEPLES M. S., O'MEARA J. M.,OPPENHEIMER B. D., MEIRING J. D., KATZ N. S., DAVÉ ., FORD A. B., SEMBACH K. R.: The large, oxygen-rich halos of star-forming galaxies are a major reservoir of galactic metals. *Science 334* (Nov.2011), 948.
[TTW∗12] THOM C., TUMLINSON J., WERK J. K., PROCHASKA J. X.,OPPENHEIMER B. D., PEEPLES M. S., TRIPP T. M., KATZ N. S., O'MEARA J. M., FORD A. B., DAVÉ R., SEMBACH K. R., WEIN-BER G D. H.: Not dead yet: Cool circumgalactic gas in the halos of early-type galaxies. *The Astrophysical Journal Letters 758* (Oct. 2012), L41.
[TTW∗13a] TUMLINSON J., THOM C., WERK J. K., PROCHASKA J. X., TRIPP T. M., KATZ N., DAVÉ R., OPPENHEIMER B. D., MEIR-ING J. D., FORDA. B., ET AL.: The cos-halos survey: rationale, de-sign, and a census of circumgalactic neutral hydrogen. *The Astrophysical Journal 777, 1* (2013), 59.
[TTW∗13b] TUMLINSON J., THOM C., WERK J. K., PROCHASKA J. X., TRIPP T. M., KATZ N., DAVÉ R., OPPENHEIMER B. D., MEIR-ING J. D., FORD A. B., O'MEARA J. M., PEEPLES M. S., SEMBACH K. R., WEINBERG D. H.: The COS-Halos survey: Rationale, design, and a census of circumgalactic neutral hydrogen. *The Astrophysical Journal 777* (Nov. 2013), 59.
[VCBH05] VEILLEUX S., CECIL G., BLAND-HAWTHORN J.: Galactic winds. *ARAA 43* (Sept. 2005), 769–826.
[WGBD11] WALCHER J., GROVES B., BUDAVÁRI T., DALE D.: Fitting the integrated spectral energy distributions of galaxies. *Astrophysics and Space Science 331* (Jan. 2011), 1–52.
[WHF∗15a] WAKKER B. P., HERNANDEZ A. K., FRENCH D. M., KIM .-S., OPPENHEIMER B. D., SAVAGE B. D.: Nearby Galaxy Filaments and the Ly-alpha Forest: Confronting Simulations and the UV Background with Observations.*The Astrophysical Journal 814* (Nov. 2015),40.
[WHF∗15b] WAKKER B. P., HERNANDEZ A. K., FRENCH D. M., KIM T.-S., OPPENHEIMER B. D., SAVAGE B. D.: Nearby galaxy filaments and the lyα forest: Confronting simulations and the uv background with observations. *The Astrophysical Journal 814, 1* (2015), 40.
[WPT∗13] WERK J. K., PROCHASKA J. X., THOM C., TUMLINSON J., TRIPP T. M., O'MEARA J. M., PEEPLES M. S.: The COS-Halossurvey: An empirical description of metal-line absorption in the low-redshift circumgalactic medium. *The Astrophysical Journal Supplement Series 204* (Feb. 2013), 17.
[WTSC86] WOLFE A. M., TURNSHEK D. A., SMITH H. E., COHENR. D.: Damped Lyman-alpha absorption by disk galaxies with large redshifts. I - The Lick survey. *The Astrophysical Journal Supplement Series 61*(June 1986), 249–304.
[YAA∗00] YORK D. G., ADELMAN J., ANDERSON JR. J. E., ANDERSON S. F., ANNIS J., BAHCALL N. A., BAKKEN J. A., BARK-HOUSER R., BASTIAN S., BERMAN E., BOROSKI W. N., BRACKER S., BRIEGEL C., BRIGGS J. W., BRINKMANN J., BRUNNER R., BURLES S., CAREY L., CARR M. A., CASTANDER F. J., CHEN B., COLESTOCK P. L., CONNOLLY A. J., CROCKER J. H., CSABAI I., CZARAPATA P. C., DAVIS J. E., DOI M., DOMBECK T., EISENSTEIN D., ELLMAN N., ELMS B. R., EVANS M. L., FAN X., FEDERWITZ G. R., FISCELLI L., FRIEDMAN S., FRIEMAN J. A., FUKUGITA M., GILLESPIE B., GUNN J. E., GURBANI V. K., DEHAAS E., HALDE-MAN M., HARRIS F. H., HAYES J., HECKMAN T. M., HENNESSY G. S., HINDSLEY R. B., HOLM S., HOLMGREN D. J., HUANG C.-H., HULL C., HUSBY D., ICHIKAWA S.-I., ICHIKAWA T., IVEZIˊC Ž., KENT S., KIM R. S. J., KINNEY E., KLAENE M., KLEINMAN A. N., KLEINMAN S., KNAPP G. R., KORIENEK J., KRON R. G., KUNSZT P. Z., LAMB D. Q., LEE B., LEGER R. F., LIMMONGKOL S., LIN-DENMEYER C., LONG D. C., LOOMIS C., LOVEDAY J., LUCINIO R., LUPTON R. H., MACKINNON B., MANNERY E. J., MANTSCH P. M., MARGON B.,

MCGEHEE P., MCKAY T. A., MEIKSIN A., MERELLI A., MONET D. G., MUNN J. A., NARAYANAN V. K., NASH T., NEILSEN E., NESWOLD R., NEWBERG H. J., NICHOL R. C., NICIN-SKI T., NONINO M., OKADA N., OKAMURA S., OSTRIKER J. P., OWEN R., PAULS A. G., PEOPLES J., PETERSON R. L., PETRAV-ICK D., PIER J. R., POPE A., PORDES R., PROSAPIO A., RECHEN-MACHER R., QUINN T. R., RICHARDS G. T., RICHMOND M. W., RIV-ETTA C. H., ROCKOSI C. M., RUTHMANSDORFER K., SANDFORD D., SCHLEGEL D. J., SCHNEIDER D. P., SEKIGUCHI M., SERGEY G., SHIMASAKU K., SIEGMUND W. A., SMEE S., SMITH J. A., SNEDDEN S., STONE R., STOUGHTON C., STRAUSS M. A., STUBBS C., SUB-BARAO M., SZALAYA. S., SZAPUDI I., SZOKOLY G. P., THAKARA. R., TREMONTI C., TUCKER D. L., UOMOTO A., VANDENBERK D., VOGELEY M. S., WADDELL P., WANG S.-I., WATANABE M., WEINBERG D. H., YANNY B., YASUDA N., SDSS COLLABORATION: The Sloan Digital Sky Survey: Technical Summary. *The Astronomical Journal 120* (Sept. 2000), 1579–1587.

[YMvdB∗07] YANG X., MOH. J., VAN DENBOSCH F. C., PASQUALI A., LI C., BARDEN M.: Galaxy groups in the SDSS DR4. i. the catalog and basic properties. *The Astrophysical Journal 671* (Dec. 2007), 153–170.

[YP13] YOONJ. H., PUTMANM. E.: The Influence of Environmenton the Circumgalactic Medium.The Astrophysical Journal Letters 772(Aug. 2013), L29.

[YP17] YOONJ. H., PUTMAN M. E.: Lyα Absorbers and the Coma Cluster. *The Astrophysical Journal 839* (Apr. 2017), 117.

[ZCR∗16] ZAHEDY F. S., CHEN H.-W., RAUCH M., WILSON M. L., ZABLUDOFF A.: Probing the cool interstellar and circumgalactic gas of three massive lensing galaxies at z = 0.4-0.7. *Monthly Notices of the Royal Astronomical Society 458* (May 2016), 2423–2442.