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Research Statement

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1. MY MOTIVATIONS

1.1. *Accurately Measuring Galaxies*

From the beginning of my research career, I have been motivated to study black hole mass scaling relations. Inspired by the work of Seigar et al. (2008), I explored the relationship between supermassive black holes (SMBHs) and the geometry of their host spiral galaxies. This pursuit led first to an improved software tool for measuring the winding angle of spiral arms (Davis et al. 2012, 2016; Seigar et al. 2018), followed by an updated relation (Berrier et al. 2013) and its application to the black hole mass function (Davis et al. 2014; Mutlu-Pakdil et al. 2016; Fusco et al. 2022). My work on logarithmic spiral-arm pitch angle also yielded papers on dark matter (Seigar et al. 2014), density wave theory (Davis et al. 2015; Pour-Imani et al. 2016; Miller et al. 2019; Abdeen et al. 2020, 2022), and an alternative measurement method (Shields et al. 2015, 2022). I completed my Ph.D. with a dissertation that encapsulated this body of work on pitch angle and black holes (Davis 2015).

1.2. *Subsequent Scaling Relations and Related Discoveries*

During my first postdoctoral appointment, I extended my research on pitch-angle correlations (Koliopanos et al. 2017; Davis et al. 2017) to broader investigations of galaxy structure. My focus turned to measuring accurate light profiles of galaxies, decomposing their components, and developing new black hole mass scaling relations for spiral galaxies (Davis et al. 2018, 2019a,b). This work led to several studies that used these scaling relations to identify intermediate-mass black hole candidates (Graham et al. 2019, 2021a,b; Davis & Graham 2021). We subsequently decomposed early-type galaxies and combined their scaling relations with those of spirals (Sahu et al. 2019a,b, 2020, 2022a,b), work that contributed to the *LISA* Consortium white paper (Amaro-Seoane et al. 2023). We also explored the potential disc cloaking of compact red-nugget galaxies (Hon et al. 2022).

In my second postdoctoral position, I joined a galaxy formation group focused on numerical simulations of galaxies (Waterval et al. 2024). We also used direct N-body simulations to investigate current topics such as "little red dots" (Khan et al. 2025). This period marked my entry into artificial intelligence (AI) and machine learning (ML). Adopting these tools led to several interdisciplinary studies (Pasquato et al. 2023; Jin & Davis 2023; Jin et al. 2024, 2025; Davis & Jin 2023; Davis et al. 2024, 2025a,b). From spiral-arm morphology to causal discovery, my research has consistently pursued the fundamental links between black holes and galaxies.

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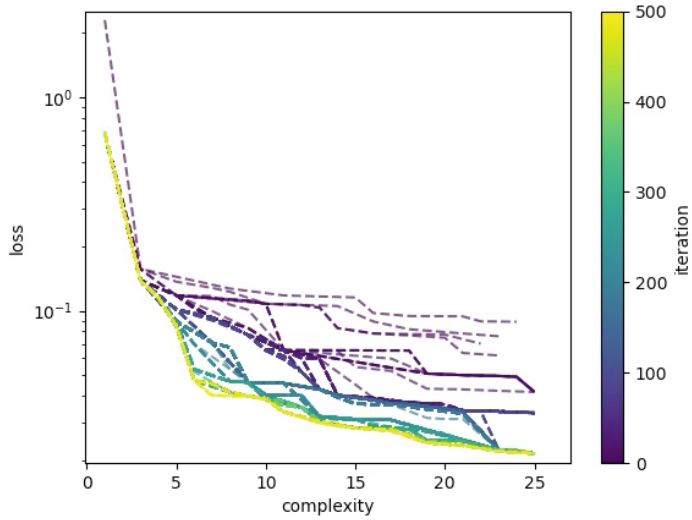

Figure 1. Evolution toward the Pareto front. The plot shows the loss (mean squared error) in predicted black hole mass versus formula complexity (number of variables plus operators). Each run of `PySR` (Cranmer 2023) evolves 2000 mutations and produces a front of ∼10 formulas sampling the population. We perform 500 recursive iterations of `PySR` to migrate (from --- to ---) toward the true Pareto front. Formulae from the final iteration (---) are selected and refined via our Bayesian framework to derive optimal black hole mass scaling relations.

2. WHERE MY MOTIVATIONS HAVE LED ME

2.1. *Finding Better Correlations with Symbolic Regression*

As described above, my career has been motivated by the study of scaling relations. Given their abundance, the challenge lies in identifying improved relations by leveraging multi-dimensional data. Symbolic regression (SR), a subfield of ML, provides an ideal framework for this task. SR searches for the mathematical expressions that best describe a dataset, optimizing the trade-off between model complexity and accuracy based on Occam's razor.

Many classical scaling relations exist in astrophysics, including the Tully–Fisher, Faber–Jackson, and M–σ relations, as well as higher-dimensional analogs such as the fundamental plane of elliptical galaxies. SR enables the discovery of novel, higher-dimensional relations that can offer deeper insight into the astrophysical processes underlying them. Figure 1 illustrates an example from a work in preparation that uses SR to identify Pareto-optimal black hole mass scaling relations.

2.2. *Understanding Correlations via Causal Discovery*

Astrophysics, as an observational science, relies heavily on correlations. While controlled experiments allow causal inference in other disciplines, such interventions are impossible in astrophysics. Causal discovery offers a statistical solution: inferring causal relationships from observational data by analyzing conditional independence among variables, represented through causal graphs. I am working to integrate causal discovery into astrophysics to understand the mechanisms driving observed correlations. Figure 2 shows a recent example addressing the long-standing debate over the causal interpretation of correlations between SMBH mass and host-galaxy properties (Jin et al. 2025).

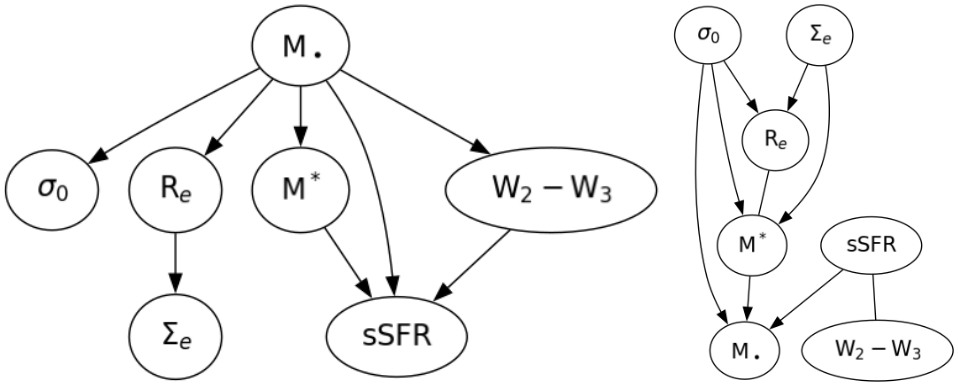

Figure 2. Example causal relationship identified in spiral (left graph) and elliptical (right graph) galaxies, represented as directed acyclic graphs (DAGs). With black hole mass ($M_\bullet$) positioned at the top of the DAG for spiral galaxies, this analysis suggests that $M_\bullet$ causally influences host-galaxy properties: central stellar velocity dispersion (σ_0), spheroid effective radius (R_e), galaxy stellar mass (M^*), W_2–W_3 color, projected stellar density within R_e (Σ_e), and specific star-formation rate (sSFR). Conversely, black hole mass is positioned at the bottom of the DAG for elliptical galaxies, indicating that the black hole is a passive passenger that is influenced by its host galaxy's properties.

3. WHERE MY MOTIVATIONS CONTINUE TO LEAD ME

3.1. *Cross-Pollination of Astrophysics and Computer Science*

To date, causal discovery has seen limited adoption in astronomy. Because its advances arise largely from AI and computer science, I have sought to bridge these disciplines. Over the past several years, I have presented papers at leading computer science conferences (Pasquato et al. 2023; Jin & Davis 2023; Jin et al. 2024; Davis et al. 2025a). My objective is to facilitate bidirectional exchange: enabling astronomers to adopt powerful computational tools, and helping computer scientists recognize astrophysical data as fertile ground for discovery.

3.2. *Fertile Ground for Discovery*

With these tools in hand, I am pursuing problems across multiple astrophysical domains. Ongoing work employs causal discovery and N-body simulations to identify causal reversals during the temporal evolution of galaxies (Figure 3). I am also extending these methods to planetary science. Our recent study (Davis et al. 2025b) revealed the causal origin of color diversity among trans-Neptunian objects (Figure 4), and ongoing projects explore causal links between exoplanets and their host stars.

4. MY DESIRED FUTURE IN A TENURE-TRACK FACULTY POSITION

My research journey has been guided by a desire to uncover the fundamental mechanisms that connect cosmic structure to physical law—from the evolution of galaxies to the causal processes that govern their dynamics. This pursuit has led me from observational astronomy to the frontiers of computational science, where I have focused on developing and applying novel machine learning and causal discovery methods to astrophysical data. The next phase of my career will center on building an independent, externally funded research group that bridges astrophysics, statistics, and computer science to reveal the causal relationships underlying the observed Universe.

My future research plans are centered on fertile ground for new discoveries. With the new Vera C. Rubin Observatory online, the amount of new data will flood astronomy and my methods will be

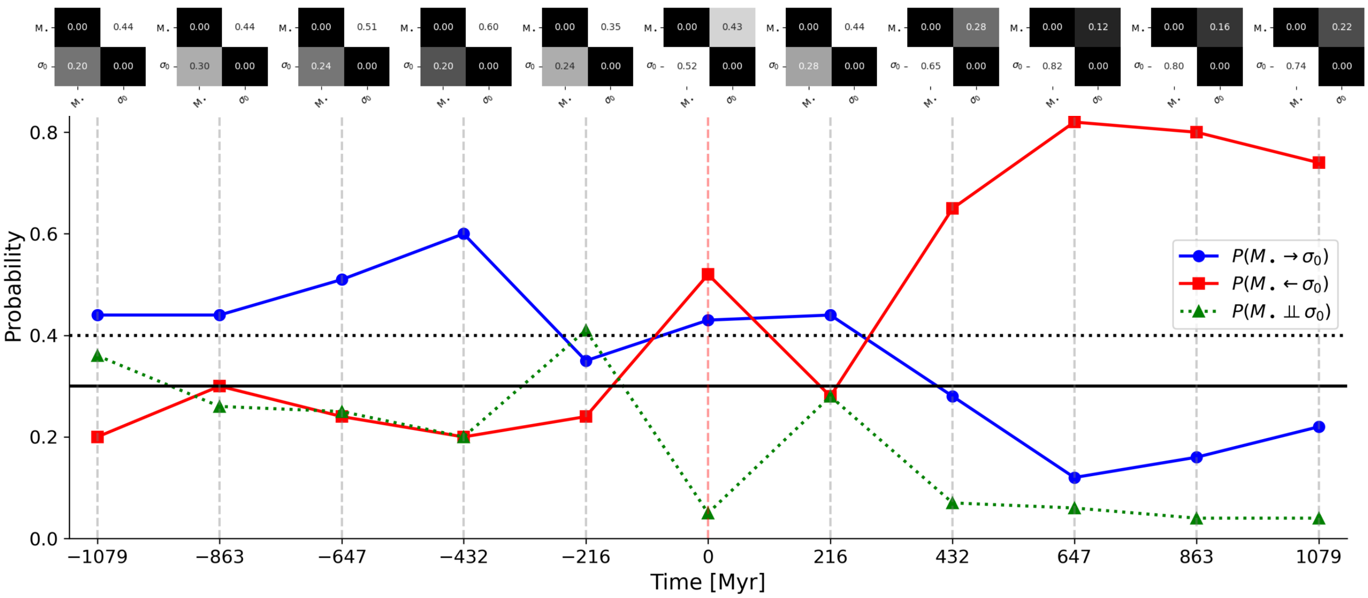

Figure 3. Time evolution of the causal $M_\bullet$–σ_0 relation. Here, we reduce the full 5×5 edge marginal matrices to only the 2×2 matrices concerning SMBH mass and central stellar velocity dispersion for our simulated galaxies, with 27 galaxies in our sample completing their evolution from star-forming to quenched by $z = 0$. These marginal matrices are listed across the top of the plot, with x-axes depicting causal children and the y-axes depicting causal parents. We select eleven matrices from successive snapshot, centered at the peak of star formation at 0 Myr the vertical . The plot below the matrices connects the snapshot times of the matrices via the vertical . For each snapshot, we illustrate the probabilities of the $P(M_\bullet \rightarrow \sigma_0)$ causal direction (● connected by), its opposing $P(M_\bullet \leftarrow \sigma_0)$ represented by ■ connected by , and the probability, $P(M_\bullet \perp\!\!\!\perp \sigma_0)$, that $M_\bullet$ and σ_0 are independent (▲ connected by);$P(M_\bullet \rightarrow \sigma_0) + P(M_\bullet \leftarrow \sigma_0) + P(M_\bullet \perp\!\!\!\perp \sigma_0) = 1$. The horizontal lines at $P = 0.4$ () and $P = 0.3$ () represent the null probabilities for the independency case and causal directional cases, respectively. Thus, significance occurs when the plotted solid lines are further away from the solid horizontal line and the plotted dotted line is significantly different from the horizontal dotted line. For example, the snapshot at -216 Myr demonstrates a period of transition that lacks any meaningful causal information because all values are near their null values.

well-positioned to take advantage of this era of rapid growth in astronomical data. I will leverage the powerful tools of symbolic regression and causal discovery to not only uncover new, higher-dimensional scaling relations but to understand their physical origins. This research program is perfectly suited for mentoring students. My projects naturally lend themselves to student engagement, from developing AI tools to applying them to galaxy and exoplanet data. This approach has a proven track record of producing high-impact publications and is well-positioned to attract the extramural funding necessary to build and sustain a vibrant research group.

In addition to my research, I am enthusiastic about teaching, mentoring, and advising students/postdocs. My broad background, spanning observational techniques, numerical simulations, and ML, prepares me to teach a wide range of courses across the physics and astronomy curriculum. I am eager to share my passion for discovery with the next generation of scientists and to become a valued faculty member. I am excited by the prospect of becoming a professor and establishing a legacy of excellence in research and education.

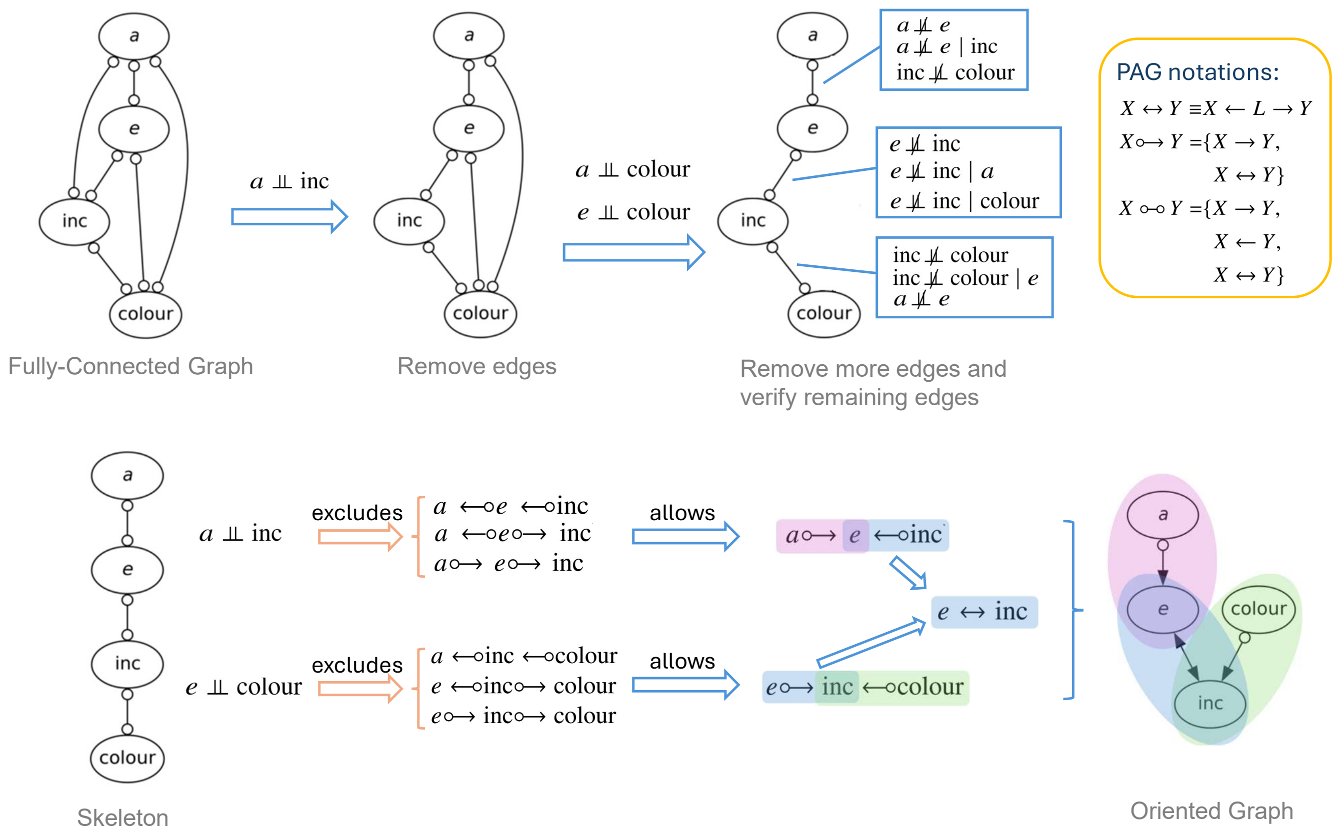

Figure 4. Visualization of the Fast Causal Inference (FCI) algorithm. In FCI stage i (upper panel), the algorithm begins with a fully connected graph ($\circ\!\!-\!\!\circ$) and iteratively removes edges as independence and conditional independence relations are detected. In FCI stage ii (lower panel), the remaining edges are oriented according to the discovered conditional independencies, constraining their directional endpoints.

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