Automating the detection of strong gravitational lenses in large-scale surveys using deep learning

Nagam, Bharath Chowdhary

DOI:
10.33612/diss.1187888207

Publication date:
2025

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Summary

Strong Gravitational Lensing

Strong gravitational lensing is based on Einstein's General Theory of Relativity. This phenomenon occurs when a massive foreground object, such as a galaxy or galaxy cluster, acts as a lens, deflecting light rays from a background source. This can result in multiple images, arcs, or even complete Einstein rings of the background object appearing around the foreground lensing mass.

One of the most powerful applications of strong lensing is in measuring the mass distribution of the lensing object. By carefully modelling the positions and magnifications of lensed images, one can reconstruct the gravitational potential of the lens, providing insights into dark matter distribution and deviations from General Relativity on cosmological scales. Moreover, strong lensing serves as a natural telescope, magnifying distant sources that would otherwise be too faint to observe. This has proven invaluable insight in studying high-redshift galaxies and quasars, pushing the boundaries of our observable universe. The time delay between multiple images of a time-variable source, such as a quasar, provides a unique probe of cosmology. The time delay depends on the Hubble constant and the mass distribution of the lens, allowing for independent measurements of H_O, crucial for addressing the tension between early and late-universe measurements of its value.

The advent of large-scale surveys like the Euclid Wide and Deep Surveys, the Dark Energy Survey and the upcoming Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) promise to increase the number of known strong lensing systems by orders of magnitude. This wealth of data will enable statistical studies of lens populations, providing insights into galaxy evolution and large-scale structure formation. These strong lenses, however, are rare and difficult to find in large survey datasets. Machine learning offers significant help in this process.

Convolutional Neural Networks

Neural networks are a type of artificial intelligence that processes information similar to how our brains work. Convolutional Neural Networks (CNNs) are a special type designed specifically for understanding images. They work by breaking down images into smaller pieces and looking for important patterns, much like how our eyes and brain work together to recognize objects. Think of CNNs as having different layers that each serve a specific purpose. The first layer might look for simple patterns like edges or colours, while deeper layers combine these simple patterns to recognize more complex features like shapes or textures. Between these layers are special filters that help the network focus on the most important information while ignoring less relevant details. What makes CNNs particularly powerful is their ability to learn and improve automatically from examples, without being explicitly programmed with rules. The more images they process, the better they become at recognizing patterns and making accurate predictions. This makes them extremely valuable for tasks like identifying objects in photos, detecting faces, or analyzing medical images.

Teaching a neural network is like training a student - it learns by practising and correcting its mistakes. When the network makes a prediction, it compares its answer to the correct one and adjusts its internal settings to do better next time. This process happens automatically through a method called gradient descent, which helps the network gradually improve its accuracy. One of the biggest advantages of CNNs is that they're efficient learners unlike simpler AI systems that try to remember everything, CNNs share their learning across different parts of an image, similar to how we use the same skills to recognize objects regardless of where they appear in our vision. They can also build upon existing knowledge - much like how a student might use basic math skills to learn advanced concepts, CNNs can use features learned from millions of images to quickly adapt to new, specific tasks. Recent improvements have made these networks even more powerful. For example, scientists have developed ways to build deeper networks that can learn more complex patterns and added special connections that help the network focus on the most important parts of an image - similar to how we naturally focus on specific details when looking at a scene.

The applications of CNNs extend far beyond image classification. They have proven highly effective in object detection, semantic segmentation, and even in domains outside computer vision, such as natural language processing and speech recognition.

Despite their success, CNNs face challenges. They can be vulnerable to adversarial attacks – small, carefully crafted perturbations to input data that can cause misclassification. Understanding and mitigating these vulnerabilities is an active area of research. The interpretability of CNNs remains another significant challenge.

This Thesis

In this thesis, we have developed an algorithm to automate the finding of strong lenses in large-scale surveys such as Euclid. We have introduced DenseNet architecture which produces fewer false positives compared to ResNet architecture. We explored ways to define a parameter that can rank-order strong lenses based on how big and bright the lensing features are. We introduced segmentation to find the number of source pixels present in each candidate. We have experimented with using this number of classified pixels as an additional metric in classification. We have investigated methods to combine these metrics to reduce false positives in large-scale surveys such as KiDS and Euclid.

In Chapter 2, I develop a DenseNet-121 architecture for strong gravitational lens detection, improving upon ResNet models. This ensemble approach outperforms previous methods, particularly in reducing false positives. I introduce an Information Content (IC) metric for ranking lens candidates and create a pipeline combining classification and regression CNNs to filter and rank-order candidates.

In Chapter 3, I implement a U-Net segmentation algorithm to complement the DenseLens classifier, further enhancing lens detection in large surveys. This integrated approach, using classification scores, IC metrics, and segmentation results, significantly improves the purity of lens candidates. Applied to KiDS data, this method leads to the discovery of fourteen new strong lensing candidates.

In Chapter 4, I investigate how Denoising Diffusion Generative Adversarial Networks (DDGAN) can create simulated gravitational lenses. This generative modelling technique shows promise in producing images that closely resemble those from the Kilo-Degree Survey (KiDS), potentially serving as a valuable tool for creating mock datasets in future research.

In Chapter 5, I apply the Denselens and U-Denselens algorithms to Euclid Early Release Observations data. Across all ERO fields, we discover 46 strong lens candidates, including 12 high-confidence detections. U-Denselens consistently outperforms Denselens, identifying nearly all candidates while substantially reducing false positives. These results highlight the potential of U-Denselens to enhance the efficiency of gravitational lens searches in large-scale surveys like Euclid.

In summary, this thesis advances our understanding of automated gravitational lens detection by developing an intelligent algorithm that combines DenseNet neural networks and image segmentation. Our approach demonstrates a marked improvement over existing methods, successfully identifying several new gravitational lens candidates in the KiDS and Euclid surveys with notably higher confidence levels and fewer false positives. The novel integration of generative AI for synthetic data creation further strengthens our ability to train these detection systems, ultimately enhancing our capacity to efficiently discover these cosmic phenomena in the vast datasets produced by modern astronomical surveys. This work represents a significant step forward in automating the search for gravitational lenses, contributing to our broader understanding of our Universe.

Samenvatting

Sterke Zwaartekrachtlenzen

Sterke zwaartekrachtlenzen zijn gebaseerd op Einsteins Algemene Relativiteitstheorie, waarbij de kromming van ruimte-tijd door massieve objecten het pad van licht van verre bronnen aanzienlijk verandert. Dit fenomeen treedt op wanneer een massief voorgrond object, zoals een sterrenstelsel of cluster van sterrenstelsels, als een lens fungeert en licht van een achtergrondbron buigt en vergroot. Dit resulteert in meerdere beelden, bogen, of zelfs complete Einstein-ringen van het achtergrond object die rond de voorgrond lensmassa verschijnen.

Een van de krachtigste toepassingen van sterke lenswerking is het meten van de massaverdeling van het lenzende object. Door zorgvuldig de posities en vergrotingen van gelensde beelden te modelleren, kunnen onderzoekers de zwaartekrachtpotentiaal van de lens reconstrueren, wat inzicht geeft in de verdeling van donkere materie en afwijkingen van de Algemene Relativiteitstheorie op kosmologische schalen. Bovendien dient sterke lenswerking als een natuurlijke telescoop, die verre bronnen vergroot die anders te zwak zouden zijn om waar te nemen. Dit is van onschatbare waarde gebleken bij het bestuderen van sterrenstelsels en quasars met hoge roodverschuiving, waardoor de grenzen van ons waarneembare universum worden verlegd. De tijdsvertraging tussen meerdere beelden van een tijdsvariabele bron, zoals een quasar, biedt een unieke kosmologische sonde. De tijdsvertraging hangt af van de Hubble-constante en de massaverdeling van de lens, wat onafhankelijke metingen van H mogelijk maakt, cruciaal voor het aanpakken van de spanning tussen vroege en late universum metingen.

De komst van grootschalige zoek programma's zoals Euclid, Dark Energy Survey en het aankomende Legacy Survey of Space and Time (LSST) van het Vera C. Rubin Observatorium belooft het aantal bekende sterke lenssystemen met ordes van grootte te vergroten. Deze schat aan gegevens zal statistische studies van lenspopulaties mogelijk maken, wat inzicht zal geven in de evolutie van sterrenstelsels en de vorming van grootschalige structuren. Deze sterke lenzen zijn echter zeldzaam en moeilijk te vinden in grote onderzoeksdatasets. Machine learning biedt hierbij een belangrijke hulp.

Convolutionele Neurale Netwerken

Neurale netwerken zijn een vorm van kunstmatige intelligentie die informatie verwerkt op een manier die vergelijkbaar is met hoe onze hersenen werken. Convolutionele Neurale Netwerken (CNN's) zijn een speciaal type dat specifiek is ontworpen voor het begrijpen van afbeeldingen. Ze werken door afbeeldingen op te delen in kleinere stukjes en te zoeken

naar belangrijke patronen, vergelijkbaar met hoe onze ogen en hersenen samenwerken om objecten te herkennen.
Zie CNN's als netwerken met verschillende lagen die elk een specifiek doel dienen. De eerste laag zoekt naar eenvoudige patronen zoals randen of kleuren, terwijl diepere lagen deze eenvoudige patronen combineren om complexere kenmerken zoals vormen of texturen te herkennen. Tussen deze lagen bevinden zich speciale filters die het netwerk helpen zich te concentreren op de belangrijkste informatie en minder relevante details te negeren.
Wat CNN's bijzonder krachtig maakt, is hun vermogen om automatisch te leren en te verbeteren aan de hand van voorbeelden, zonder expliciet geprogrammeerd te worden met regels. Hoe meer afbeeldingen ze verwerken, hoe beter ze worden in het herkennen van patronen en het maken van nauwkeurige voorspellingen. Dit maakt ze uiterst waardevol voor taken zoals het identificeren van objecten in foto's, het detecteren van gezichten of het analyseren van medische beelden.
Het trainen van een neuraal netwerk is vergelijkbaar met het opleiden van een student - het leert door te oefenen en fouten te corrigeren. Wanneer het netwerk een voorspelling doet, vergelijkt het zijn antwoord met het juiste antwoord en past het zijn interne instellingen aan om het de volgende keer beter te doen. Dit proces gebeurt automatisch via een methode die gradiëntafdaling wordt genoemd, waardoor het netwerk geleidelijk zijn nauwkeurigheid verbetert.
Een van de grootste voordelen van CNN's is dat ze efficiënte leerlingen zijn. In tegenstelling tot eenvoudigere AI-systemen die proberen alles te onthouden, delen CNN's hun leerproces over verschillende delen van een afbeelding, vergelijkbaar met hoe wij dezelfde vaardigheden gebruiken om objecten te herkennen, ongeacht waar ze in ons gezichtsveld verschijnen. Ze kunnen ook voortbouwen op bestaande kennis - net zoals een student basiswiskunde gebruikt om gevorderde concepten te leren, kunnen CNN's kenmerken die ze hebben geleerd uit miljoenen afbeeldingen gebruiken om zich snel aan te passen aan nieuwe, specifieke taken.
Recente verbeteringen hebben deze netwerken nog krachtiger gemaakt. Wetenschappers hebben bijvoorbeeld manieren ontwikkeld om diepere netwerken te bouwen die complexere patronen kunnen leren en hebben speciale verbindingen toegevoegd die het netwerk helpen zich te concentreren op de belangrijkste delen van een afbeelding - vergelijkbaar met hoe wij ons natuurlijk concentreren op specifieke details bij het bekijken van een scène.
De toepassingen van CNN's reiken veel verder dan beeldclassificatie. Ze zijn zeer effectief gebleken bij objectdetectie, semantische segmentatie en zelfs in domeinen buiten computervision, zoals natuurlijke taalverwerking en spraakherkenning.

Ondanks hun succes kennen CNN's uitdagingen. Ze kunnen kwetsbaar zijn voor vijandige aanvallen - kleine, zorgvuldig geconstrueerde verstoringen van invoergegevens die kunnen leiden tot misclassificatie. Het begrijpen en verminderen van deze kwetsbaarheden is een actief onderzoeksgebied. De interpreteerbaarheid van CNN's blijft een andere belangrijke uitdaging.

Dit proefschrift

In dit proefschrift hebben we een algoritme ontwikkeld om het vinden van sterke zwaartekrachtlenzen in grootschalige surveys zoals Euclid te automatiseren. We hebben de DenseNet-architectuur geïntroduceerd, die minder valse positieven oplevert in vergelijking met de ResNet-architectuur. We hebben manieren onderzocht om een parameter te definiëren die sterke lenzen kan rangschikken op basis van hoe groot en helder de lenskenmerken zijn. We introduceerden segmentatie om het aantal bronpixels in elke kandidaat te bepalen. We hebben geëxperimenteerd met het gebruik van dit aantal geclassificeerde pixels als een extra maatstaf bij classificatie. We hebben methoden onderzocht om deze maatstaven te combineren om valse positieven te verminderen in grootschalige surveys zoals KiDS en Euclid.

Hoofdstuk 2
In Hoofdstuk 2 ontwikkel ik een DenseNet-121 architectuur voor de detectie van sterke zwaartekrachtlenzen, een verbetering ten opzichte van ResNet-modellen. Deze ensemble-aanpak presteert beter dan eerdere methoden, met name bij het verminderen van valse positieven. Ik introduceer een Information Content (IC) metriek voor het rangschikken van lenskandidaten en creëer een pijplijn die classificatie- en regressie-CNN's combineert om kandidaten te filteren en rangschikken.

Hoofdstuk 3
In Hoofdstuk 3 implementeer ik een U-Net segmentatie-algoritme als aanvulling op de DenseLens classifier, wat de detectie van lenzen in grote surveys verder verbetert. Deze geïntegreerde aanpak, die gebruik maakt van classificatiescores, IC-metingen en segmentatieresultaten, verbetert de zuiverheid van lenskandidaten aanzienlijk. Toegepast op KiDS-data leidt deze methode tot de ontdekking van veertien nieuwe sterke lenskandidaten.

Hoofdstuk 4
In Hoofdstuk 4 onderzoek ik hoe Denoising Diffusion Generative Adversarial Networks (DDGAN) kunnen worden gebruikt om gesimuleerde zwaartekrachtlenzen te creëren. Deze generatieve modelleertechniek toont veelbelovende resultaten in het produceren van beelden die sterk lijken op die van de Kilo-Degree Survey (KiDS) en kan mogelijk dienen als een waardevol instrument voor het creëren van gesimuleerde datasets in toekomstig onderzoek.

Hoofdstuk 5
In Hoofdstuk 5 pas ik de DenseLens- en U-DenseLens-algoritmen toe op Euclid Early Release Observations data. In alle ERO-velden ontdekken we 46 sterke lenskandidaten, waaronder 12 detecties met hoge betrouwbaarheid. U-DenseLens presteert consequent beter dan DenseLens, identificeert bijna alle kandidaten en vermindert tegelijkertijd aanzienlijk het aantal valse positieven. Deze resultaten benadrukken het potentieel van U-DenseLens om de efficiëntie van zwaartekrachtlenszoektochten in grootschalige surveys zoals Euclid te verbeteren.

Dit proefschrift verbetert ons begrip van geautomatiseerde detectie van zwaartekrachtlenzen door een intelligent algoritme te ontwikkelen dat DenseNet neurale netwerken combineert met beeldsegmentatie. Onze aanpak toont een duidelijke verbetering ten opzichte van bestaande methoden en identificeert met succes verschillende nieuwe zwaartekrachtlenskandidaten in de KiDS- en Euclid-surveys met aanzienlijk meer vertrouwen en minder valse positieven. De innovatieve integratie van generatieve AI voor het creëren van synthetische data versterkt verder ons vermogen om deze detectiesystemen te trainen, wat uiteindelijk onze capaciteit vergroot om deze kosmische fenomenen efficiënt te ontdekken in de enorme datasets die door moderne astronomische surveys worden geproduceerd. Dit werk vormt een belangrijke stap voorwaarts in het automatiseren van de zoektocht naar zwaartekrachtlenzen en draagt bij aan ons bredere begrip van het Universum.

Acknowledgments

Mother and Father

I thank my Mother for nurturing me, and providing me moral, financial and emotional support throughout my life and without her I would not have achieved anything in my life. We are always at the mercy of nature and no human being has the liberty to choose his / her parents. So, Dear Ma: I thank God that I am lucky and fortunate to have you as my mother. I am eternally grateful. I thank my Father for helping me to aspire and take a career path in astronomy.

Teachers

In Sanskrit, Guru (teacher) means a person who removes the darkness (ignorance) of a student. I love this word as it has a profound meaning. I bow down to all my teachers from a young age till now who have transformed my ignorance into a righteous one. I would like to say thanks to both my academic and spiritual teachers.

There is a well-known saying that you are the average of the people around you. Reflecting on my journey, I see a noticeable difference between the young adult stepping into Kapteyn four years ago and the individual now writing this thesis. The most significant change is my improved ability to approach problems and make well-informed decisions. This skill—highly valued globally and what makes CEOs successful—is, in my view, more crucial than data science itself.

I often joke that "decision science" is more important than “data science”. I’ve developed this skill simply by being in the company of Leon, Edwin, and Gijs, learning from their experience and observing their decision-making processes. These insights cannot be taught in a classroom but are absorbed through proximity to those who make critical decisions daily. I am deeply grateful to Leon, Edwin, and Gijs for this wisdom, which will guide me throughout my life.

Leon

When I realized that Leon is not only my supervisor but also holds other critical responsibilities, such as being the director of the institute, I initially thought that I might receive replies only once every two weeks or even once a month. However, over the past four years, despite the countless emails I’ve sent, I have received a response 99.99% of the time by 9 a.m. the next morning. Such amazing discipline is what makes great leaders. I often tell myself that if I could adopt even half of Leon’s discipline, I would achieve great success in my own life.

Some might think this isn’t a big deal, but for a PhD student, small actions from a supervisor can have a significant impact. Quick responses from supervisors send a message that our work is being noticed and we are being supported.

To me, a leader shouldn’t be too strong or too weak. If they’re too weak, chaos ensues, with everyone doing what they please, turning the journey into a directionless ship. If they’re

too strong, they risk coming across as overly controlling, losing the trust of the team, and only getting what they want. A true leader knows when to command and when to listen, allowing each individual to contribute their unique perspectives. I've consistently seen this quality in Leon, where he clearly communicates his expectations but also encourages students to achieve those goals in their own way.
I wish Leon all the best in his future endeavors, and I sincerely hope he leads many successful science missions in the future, both for European and Dutch astronomy.

Edwin
Whenever I speak with Edwin, I immediately feel his fatherly love and affection. Once, when I was struggling with a personal situation, he kindly invited me to join him for a bike ride to help me feel better. He often shares fondly his experiences with data collection, and how it has benefitted various tech giants in the industry. Where else could I get such first-hand knowledge, if not from Edwin? After each of our regular progress meetings, he would tap me on the shoulder, reassuring me that I was doing well. These small gestures carry profound meaning for any PhD student, and through all his actions, I have felt nothing but love. More than a supervisor, I have always seen you as a fatherly figure, and I bow to your compassion and kindness!

Gijs
I am very fortunate to have encountered many spiritual masters up close, who have dedicated themselves to spiritual service and practiced meditation for several decades. The common thread among all of them is the absence of ego and a childlike laughter filled with pure innocence. As the saying goes, 'The mind is the index of the soul, and the face is the index of the mind.' When the soul is pure, it is reflected in the mind, which in turn is mirrored in the face. In the presence of Gijs, I observed a similar joyous and heartfelt nature, reminiscent of a child's. Additionally, your sharp acumen and clarity of thought are qualities I will always reflect on and carry with me for the rest of my journey. I wish you all the very best in your future endeavours!

Spiritual teacher
I moved to the Netherlands from India about nine years ago. In my view, India is the spiritual capital of the world, and people often journey to the East in search of spiritual wisdom. However, my destiny felt deeply connected with the Netherlands, as I was fortunate enough to find spiritual wisdom here. My life transformed completely after being introduced to Kriya Yoga by my master, and through the few days I spent at his hermitage in the village of Sterksel, near Eindhoven. I would like to humbly bow to my saintly spiritual master, Shri Rajarshi Peter van Breukelen, whose grace allowed me to experience the true meaning of my 'self'. Without him, this profound realization would not have been possible. I highly recommend the book *Autobiography of a Yogi* by the beloved master Sri Paramahansa Yogananda, as reading it completely transformed my perspective on life.

About India and Netherlands
A nation is just a piece of land without its people. What makes a nation truly great are its people. I have spent about two-thirds of my life in India and one-third in this wonderful

country, the Netherlands. What follows is my unbiased reflection on my life in these two nations.
India: First, I would like to express my gratitude for the ancestral wisdom that India possesses. The mind is just a tool—ideas arise as though they come from the mind. However, the mind is also the source of worries and the origin of much of human mischief. What amazes me most is the technique of meditation, which was practiced extensively by the ancient masters of India. These practices continue to serve as a beacon of light to the world in the form of yoga (for the body) and meditation (for the mind). I am deeply thankful for all the experiences I had in this great country and for its spiritual wisdom, which I will carry with me for the rest of my life.
Righteousness is the most important quality any human can possess. In nature, or in God's design, freedom is limited. Whether it is planets or other celestial bodies, they are bound by laws and must act accordingly. Even animals have very little, if any, freedom. I fondly recall a joke from a spiritual master: "God became bored with all His manifestations. So, He decided to manifest as humans and gave them a little more freedom. Since then, He's had all the fun and has never been bored again." I remember this joke because it highlights the importance of righteousness. Righteousness is the most important guide that can help us use the freedom given by nature (or God) in a responsible and meaningful way. With great power comes great responsibility.
Nederland: Zoals hierboven vermeld, ben ik al negen jaar in dit land. Overal zag ik alleen maar liefde en rechtvaardigheid in de harten van de mensen. Een natie met rechtvaardigheid kan nooit ten onder gaan. Ik ben erg trots dat dit gevoel overheerst bij de meeste mensen. Ook is liefde een zeer sterke universele emotie. Ik kwam naar Nederland als student en later, door jullie liefde, vriendelijkheid en medeleven, hebben jullie me veroverd en tot een van jullie gemaakt. Ik weet niet wat ik kan teruggeven voor de enorme hoeveelheid liefde die ik heb ontvangen. Deze liefde zal ik nooit vergeten, zolang ik leef. Waar ik ook ben in de wereld, wat ik ook doe, ik zal mijn best doen om door mijn daden de vlag hoog te laten wapperen.

Lang leve de koning! Lang leve Nederland!

Friends and Family

I would like to thank all my friends at Kapteyn for all the help they have provided. I would like to thank my wife for her continued support throughout this PhD journey.

God

God is love, and love is God. It's like two ends of a string—if you start at one end (love), you will inevitably reach the other (God). It's deeply ironic that humanity has a long history of fighting over the concept of God without truly understanding what God is. To me, God (or nature) is present in everything, everywhere, and in everyone. Can anyone point to something and say, 'Look, I've found this special thing that doesn't belong to nature (God)'? I see nothing that is untouched by God (nature). Everything is cared for and nurtured. For atheists and agnostics, you may still view all things as embodiments of nature. In my view, by cultivating this perspective, kindness and compassion will naturally flow from each person toward all life on this planet—from plants and trees to animals and humanity. As selflessness grows, hatred will diminish. Slowly, as the ego dissolves, you will eventually recognize yourself as part of the whole. I am grateful to God for nurturing all things, including myself, and for being the embodiment of everlasting love.

with unconditional love,
Bharath