Executive Summary

Strong gravitational lensing is a powerful and mature technique for probing galaxies and the Universe as a whole. In the past twenty years, strong lensing observations have enabled unique studies, such as measurements of the dark matter distribution in galaxies and galaxy clusters, detections of substructure in galaxies, measurements of the expansion rate of the Universe with time-delay lenses, and high-resolution analyses of strongly lensed high-redshift galaxies. While these efforts have improved our understanding of galaxy evolution and cosmology, there are still open questions that strong lensing observations can help to address. What is the nature of dark matter and dark energy? Is the history of the Universe well described by a flat Λ cold dark matter model? The answers to these questions have profound fundamental physics implications.

The field of strong lensing is about to be revolutionised by the advent of new observational facilities, such as Euclid, the Rubin Observatory, the Roman Space Telescope and the Chinese Space Station Telescope. These telescopes and their associated surveys are expected to lead to the discovery of around 100 000 new strong lenses, an increase of more than two orders of magnitude with respect to the current sample size of confirmed lenses. Such a large amount of data gives us the potential for carrying out strong lensing studies with very high precision. At the same time, however, it poses new challenges: to fully take advantage of this improvement in precision, it is necessary for the accuracy of the models used to interpret these data to improve as well. Furthermore, traditional analysis methods, based on the detailed study of a few select systems, do not scale well to very large sample sizes. With this symposium, we brought together observational and theoretical researchers in the community to review the progress of the field and develop a roadmap for the new era of strong gravitational lensing.

The goals of the symposium were

- to understand the preparedness of the community to analyse and adapt to forthcoming big data;
- to assess the progress of the field in regard to precision lens modelling and modelling of high-angular-resolution data, and to understand what developments are needed;
- to find synergies between observations and simulations of dark matter and the high-redshift Universe;
- to determine the scientific questions that strong lensing will address over the next decade and foster collaboration.

Four major subjects were covered during the week: cosmology, dark matter, galaxies and galaxy clusters, and high-redshift sources. Each subject had dedicated sessions with invited and contributed talks, as well as posters and discussion sessions. Sessions dedicated to the same subject were spread out over multiple days to encourage synergies between the different science aspects and methodology. The conference itself was oversubscribed, with over 100 submissions for 55 contributed talks and a 20 person

waiting list for registration, demonstrating how much the field of strong lensing has grown over the past few years.

The proposed symposium date of June, 2023, was auspicious as it preceded the first data release from flagship survey facilities. In the past few years, many new astronomers have entered the field, started groups and introduced fresh and innovative ideas. During the symposium, these researchers presented the state-of-the-art techniques they developed to resolve structure in the early Universe, test the nature of dark matter, test fundamental physics and efficiently analyse forthcoming big data sets, demonstrating that the strong lensing community is well-placed to address critical scientific questions in astrophysics. A selection of the work presented is summarised in the proceedings.

Hannah Stacey
Alessandro Sonnenfeld
Claudio Grillo

Photograph of the participants of IAU 381 outside the Castle of Otranto, where the meeting was held

Scientific Highlights

The meeting was divided into five topics: Galaxies, Clusters, Dark Matter, Cosmology and Sources. Each of these topics had 1 review talk, 2 invited talks and 10-13 contributed talks. Days 1 to 4 showcased five different posters and the presenters gave 1 minute elevator pitches to advertise their work. Each topic followed with a 1.5 hr discussion session.

Galaxies

Strong lensing by galaxies is a valuable tool to probe the internal structure of massive galaxies. The internal structure is influenced by mergers, accretion, feedback and dark matter. Thus, the distribution of baryonic and dark matter can allow us to test models of galaxy formation. In his review of the topic, Anowar Shajib discussed several subjects that may be addressed by strong lensing studies, in particular the evolution of stellar and dark matter density profiles over cosmic time and the shape of dark matter profiles as compared to cosmological simulations. Several people presented detailed analyses of these with new data (James Nightingale, Hannah Turner, Chin Yi Tan, Russell Smith). These studies will be revolutionised with the larger sample sizes that could be discovered with forthcoming survey telescopes. Many contributed talks and posters presented viable frameworks to find and catalogue strong lenses in such surveys with machine learning (John McKean, Nan Li, Devon Williams, Karl Glazebrook, Jimena Gonzalez, Karina Rojas, Bharath Chowdhary Nagam, João Paulo França, Timo Anguita, Philip Holloway, Hareesh Thuruthpilly, Alejandra Melo, Kamal Bora). In the discussion led by Alessandro Sonnenfeld and Simon Birrer, semi-automated modelling software such as *PyAutoLens* (Nightingale et al. 2021) and *Lenstronomy* (Birrer and Amara 2018) were discussed and the extent to which the process may be automated. Additionally, was some debate about the possible role of selection bias from machine learning selected samples in constraints on the inner slope and initial mass function.

Clusters

Strong lensing by clusters probes the distribution of matter in the largest structures in the Universe. Despite these large scales, cluster lensing is an important test of structure formation within cosmological models. In his review, Piero Rosati showed how deeper, multi-wavelength surveys of clusters are finding more lensed sources, allowing for more accurate lens models. Whereas cluster lensing was recently achieving only arcsecond accuracy in lensed image fitting, advanced modelling has significantly improved this to fractions of an arcsecond. Meanwhile, cosmological simulations seem to under-predict cluster lensing events, potentially clashing with galaxy evolution models. Several contributors proposed novel techniques to find sources in large survey data (Giuseppe Angora, Lorenzo Bazzanini) or model clusters more accurately (Sangjun Cha, Raven Gassis, Han Wang, Giovanni Granata, Gabriel Bartosch Caminha, Davide Abriola) including the full surface brightness of lensed arcs (Stefan Schuldt). Additionally, several people demonstrated the strength of JWST data in finding new high-redshift lensed sources (Masamune Oguri, Pietro Bergamini).

Dark Matter

According to the cosmological paradigm, dark matter constitutes 85% of the matter in the Universe and is detectable only through its gravitational effect. The nature of dark matter

is a question that strong lensing is well-posed to solve, given that strong lensing is sensitive both to the inner shape of the gravitational potential of the lensing galaxy as well as its granularity due to sub-haloes and line-of-sight haloes. In his review, Massimo Meneghetti delved into the history of dark matter constraints via galaxy-scale and cluster-scale strong lensing. In her invited talk, Giulia Despali discussed how state-of-the-art hydro-dynamical simulations are improving theoretical predictions for lensing phenomena. Anna Nierenberg showed new data from JWST to demonstrate how this new telescope will improve dark matter constraints via four-image lensed quasars. Devon Powell and Wolfgang Enzi showed how powerful lensing can be to constrain dark matter models, with the most stringent constraints yet on fuzzy and warm dark matter. Several contributions touted the importance of machine learning (Sebastian Wagner-Carena, Joshua Fagin, Sergei Gleyzer, Tyler Hughes) and novel approaches to constrain lensing perturbations from dark matter structures (Birendra Dhanasingham, Georgios Vernardos, Dorota Bayer). However, several also emphasised caution in application of machine learning methods and emphasised the need for detailed analysis of individual sources (Daniel Ballard, Chris Fassnacht, Conor O'Riordan, Di Wen). Much of discussion, led by Anna Nierenberg and John McKean, surrounded the problem of degeneracies between dark matter haloes and other systematics, and the importance of detailed, high-angular-resolution follow-up of well-chosen lens systems from large surveys.

Cosmology

In addition to the mass distribution of lenses and clusters, strong lensing can also be applied to calibrate cosmological parameters. In her review, Sherry Suyu discussed how the TDCosmo collaboration has used time-delay distances from galaxy-scale lensed quasars to measure the Hubble constant with 3% precision, in tension with other methods. Additionally, Ana Acebron demonstrated how this may be expanded to cluster-scale lenses, and Tom Collett showed how this parameter may be measured without time-delays for multiple source-plane lenses. Several contributions introduced methods to greatly increase the number of suitable lenses for H0 analysis in large surveys (Sydney Erickson, Raoul Cañameras, Nikki Arendse, Justin Pierel, Satadru Bag, James Chan) and essential tests to correct for systematic biases (Matthew Gomer, Shawn Knabel, Lyne van de Vyvere, Shuaibo Geng). The contributions in this topic were diverse, and included constraints on modified gravity (Martin Makler, Grasiele Romanzini Bezerra), lensed gravitational waves (Dan Ryczanowski), general relativity (Carlos Melo-Carneiro) and other cosmological parameters (Andrea Bolamperti). The discussion was led by Ken Wong and Claudio Grillo, and much discussion involved the sources and magnitudes of systematic bias in cosmological parameter inference: the room was split on the extent to which a <1% precision on H0 is realistic.

Sources

Strong lensing provides a window into the distant Universe by increasing the solid angle through which the source is viewed. This can be applied in different ways, most commonly through investigation of the magnified source surface brightness or by microlensing of quasar accretion discs by stars in the lensing galaxy. In his review, Tommaso Treu discussed the sources in the early Universe that can be resolved with JWST and cluster lensing. In other remarkable discoveries in the distant Universe, Brian Welsch discussed detection of a highly magnified individual star, and Francesca Rizzo reported on the detailed kinematics of rotationally supported galaxies from strong lensing, and several

others resolve distant star clusters and star-forming galaxies (Q.Daniel Wang, Edoardo Borsato, Ashish Kumar Meena, Uros Mestric, Aristeidis Amvrosiadis). Several contributions demonstrated how extremely high precision measurements of AGN may be achieved with detailed modelling of individual lenses (Cristiana Spingola, Matt O'Dowd, Henry Best, Felipe Ávila, Carina Fian, Raquel Forés-Toribio, Dominique Sluse). Much of the discussion, led by Cristiana Spingola and Matt O'Dowd, surrounded the the accessibility of lens modelling tools, and how to enhance the credibility of lens-reconstructed sources within the wider community. There were suggestions that we could do more to provide robust uncertainties and provide more comprehensive data products.

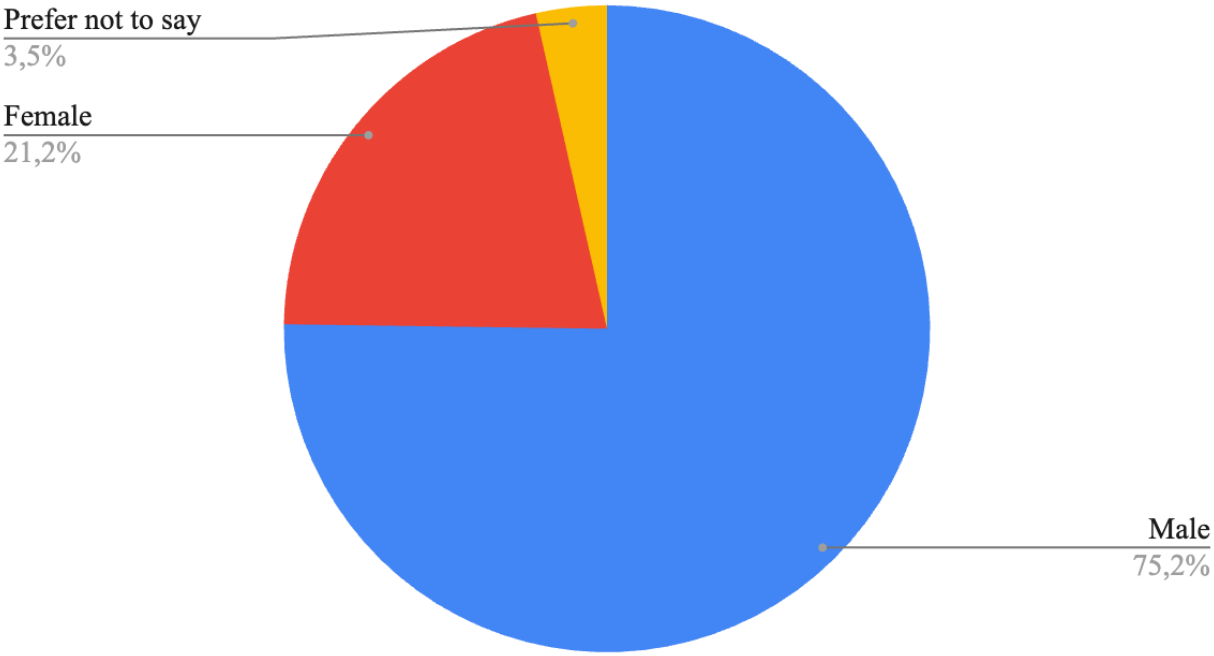
	Monday	Tuesday	Wednesday	Thursday	Friday
9:00-10:30	9:00-9:10 General introduction - Hannah Stacey 9:10-9:15 Local introduction - Fabio Convenga 9:15-9:40: Sherry Suyu (review) 9:40-10:00: Tom Collett (invited) 10:00-10:15: Shawn Knabel 10:15-10:25 Spotlight talks 1	9:00-9:25: Anowar Shajib (review) 9:25-9:45: James Nightingale (invited) 9:45-10:05: Russell Smith (invited) 10:05-10:20: Javier Alejandro Aceveda Barroso 10:20-10:30 Spotlight talks 2	9:00-9:25: Tommaso Treu (review) 9:25-9:45: Francesca Rizzo (invited) 9:45-10:05: Brian Welch (invited) 10:05-10:20: Uros Mestric 10:20-10:30 Spotlight talks 3	9:50-10:05: Karl Glazebrook 10:05-10:20: Tania Barone 10:20-10:30 Spotlight talks 4	Discussion Galaxies (Alessandro Sonnenfeld & Simon Birrer)
10:30-11:00	**Coffee break**	**Coffee break**	**Coffee break**	**Coffee break**	**Coffee break**
11:00-12:30	11:00-11:20: Ana Acebron (invited) 11:20-11:35: Andrea Bolamperti 11:35-11:50: Nikki Arendse 11:50-12:05: Justin Pierel 12:05-12:20: Lyne Van de Vyvere 12:20-12:35: Matthew Gomer	11:00-11:30: Piero Rosati (review) 11:30-11:50: Gabriel Caminha (invited) 11:50-12:05: Hakon Dahle 12:05-12:20: Pietro Bergamini 12:20-12:35: Davide Abriola	11:00-11:15: Ashish Kumar Meena 11:15-11:30: Aristeidis Amvrosiadis 11:30-11:45: Patrick Kamieneski 11:45-12:00: Q. Daniel Wang 12:00-12:15: Edoardo Borsato 12:15-12:30: Irham Taufik Andika	11:00-11:15: Martin Millon 11:15-11:30: Henry Best 11:30-11:45: Dominique Sluse 11:45-12:00: Raquel Forés-Toribio 12:00-12:15: Carina Fian 12:15-12:30: Felipe Ávila	11:00-11:15: Wolfgang Enzi 11:15-11:30: Sebastian Wagner-Carena 11:30-11:45: Conor O'Riordan 11:45-12:00: Birendra Dhanasingham 12:00-12:15: Sergei Gleyzer 12:15-12:30: Chris Fassnacht
12:30-14:30	**Lunch**	**Lunch**	**Lunch**	**Lunch**	**Lunch**
14:30-16:00	14:30-14:55: Massimo Meneghetti (review) 14:55-15:15: Anna Nierenberg (invited) 15:15-15:30: Devon Powell 15:30-15:45: Dorota Bayer 15:45-16:00: Georgios Vernardos	14:30-14:45: Giovanni Granata 14:45-15:00: Giuseppe Angora 15:00-15:15: Sydney Erickson 15:15-15:30: Raoul Cañameras 15:30-15:45: Dan Ryczanowski 15:45-16:00: Martin Makler	14:30-14:50: Masamune Oguri (invited) 14:50-15:05: Stefan Schuldt 15:05-15:20: Han Wang 15:20-15:35: Lukas Furtak 15:35-15:50: Raven Gassis	Discussion Sources (Cristiana Spingola & Matt O'Dowd)	Discussion Dark matter (John McKean & Anna Nierenberg)
16:00-16:30	**Coffee break**	**Coffee break**	**Coffee break**	**Coffee break**	**Coffee break**
16:30-18:00	16:30-16:50: Giulia Despali (invited) 16:50-17:05: Daniel Gilman 17:05-17:20: Di Wen 17:20-17:35: Joshua Fagin 17:35-17:50: Daniel Ballard	Discussion Cosmology (Ken Wong & Claudio Grillo)	Discussion Clusters (Ana Acebron & Masamune Oguri)	16:30-16:45: Hannah Turner 16:45-17:00: Chin Yi Tan 17:00-17:15: Nandini Sahu 17:15-17:30: Devon Williams 17:30-17:45: Nan Li 17:45-18:00: John McKean	16:30-17:00: Summary - Shude Mao

Topics
Cosmology
Dark Matter
Galaxies
Clusters
Sources

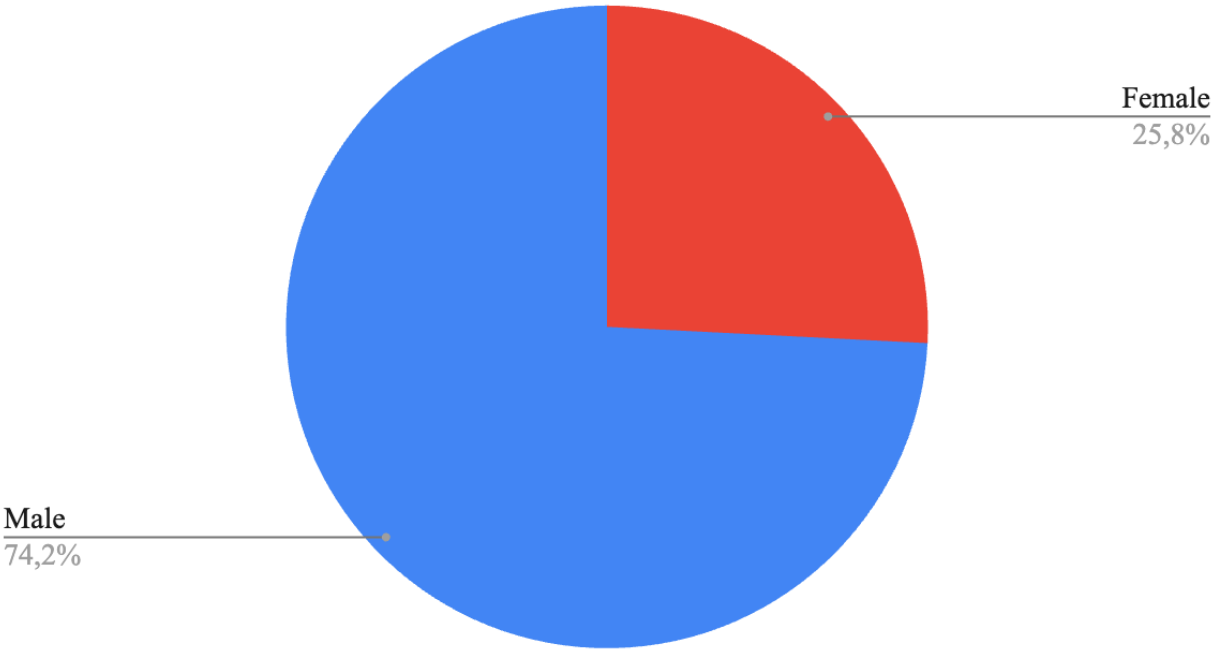
Session chairs
Cosmology 1: Ken Wong
Cosmology 2: Martin Makler
Cosmology 3: Nikki Arendse
Dark matter 1: Simon Birrer
Dark matter 2: Georgios Vernardos
Dark matter 3: Devon Powell
Galaxies 1: Timo Anguita
Galaxies 2: Alessandro Sonnenfeld
Galaxies 3: Cameron Lemon
Clusters 1: Claudio Grillo
Clusters 2: Piero Rosati
Sources 1: Dominique Sluse
Sources 2: Aprajita Verma
Sources 3: Aris Amvrosiadis

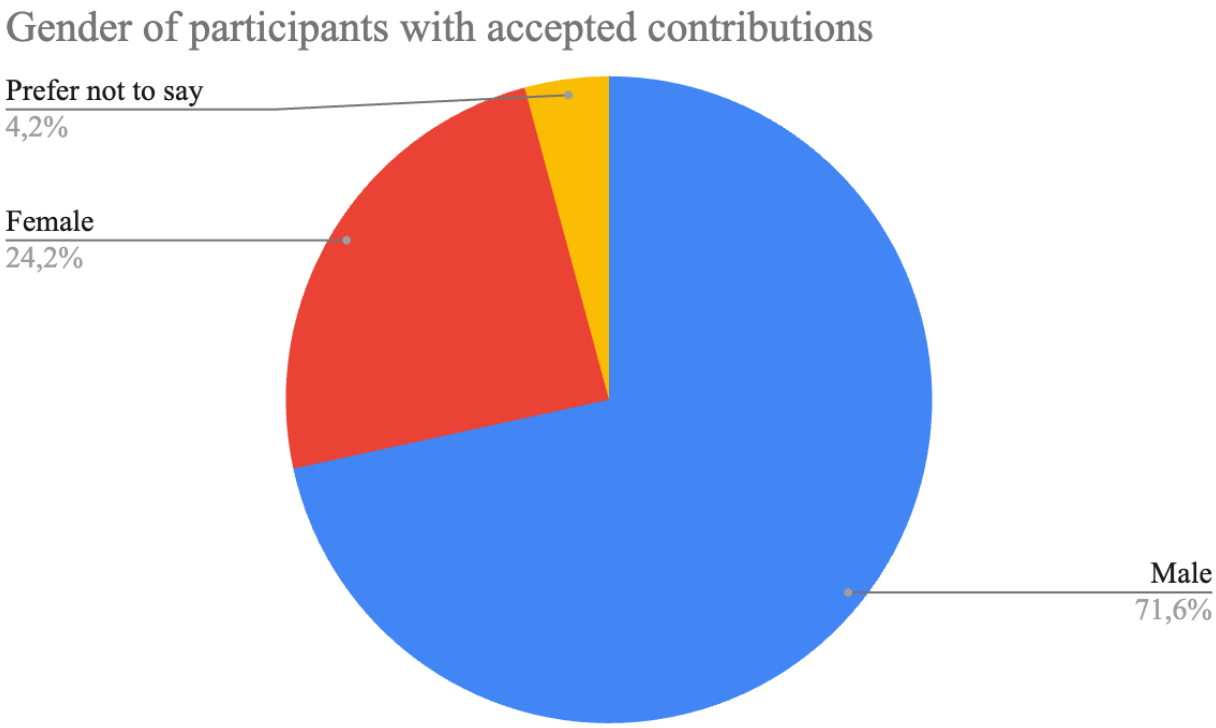
Posters Monday	Posters Tuesday	Posters Wednesday	Posters Thursday
Karina Rojas	Giacomo Queirolo	Cristiana Spingola	Timo Anguita
Hareesh Thuruthipilly	James Chan	Matt O'Dowd	Bharath Chowdhary Nagam
Alejandra Melo	Carlos Carneiro	Tyler Hughes	Kamal Bora
João Paulo França	Grasiele Romanzini Bezerra	Lorenzo Bazzanini	Jimena Gonzalez
Shuaibo Geng	Satadru Bag	Sangjun Cha	Philip Holloway

Gender of all participants (registered and attended)



Gender of invited speakers




Gender of participants with accepted contributions
Prefer not to say
4,2%
Female
24,2%
Male
71,6%