

2024/2025 Open Day

Part III Astrophysics

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Institute of Astronomy

Students

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Undergraduate

Part III/MASt

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The UG Department

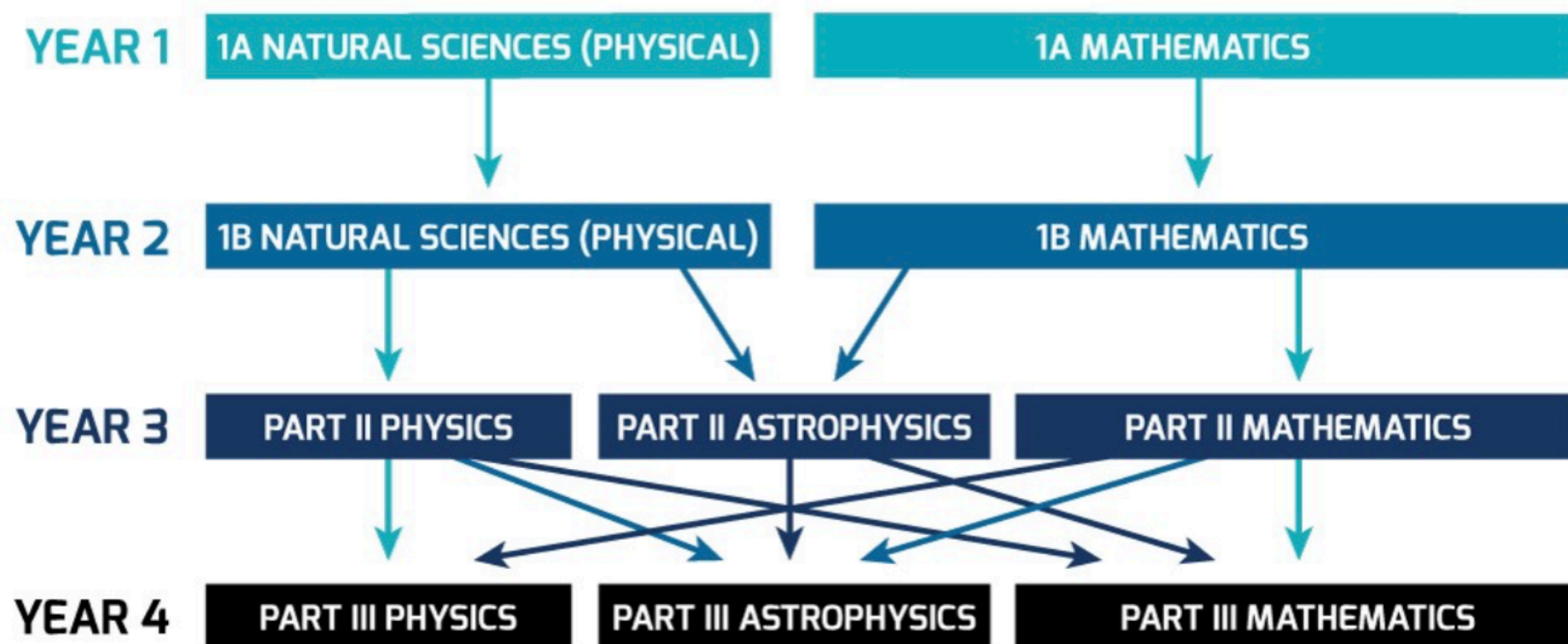
Part III/MASt



Course Aims

Pathways

The Pathway to Astrophysics



Prerequisites are explained here:

<https://www.ast.cam.ac.uk/prospective-students/undergraduate/part-iiimast>

Cohort make-up

- Part III students ($>2/3$) + MAST students ($<1/3$)
- $1/2$ to $2/3$ apply for PhDs but not all here

Course structure

- Courses (2/3 marks) + Project (1/3 marks)

Recommended lecture courses

Note that there are small changes to the recommenced list year to year

Physics

Michaelmas 2024	Lent 2025
Physics of the Earth as a Planet Dr D. Al-Attar & Dr A. Gualandi & Prof. J. Rudge M.W.F. 09:00 Small LT, Cavendish [3 units]	Formation of Structure in the Universe Prof. S. Tacchella W.F. 09:00, IoA HLT [2 units] First lecture on 29-Jan-25
Relativistic Astrophysics and Cosmology Dr S Tacchella M.W.F. 10:00 IoA HLT [3 units]	
Particle Physics Dr C. Lester M.W.F. 12:05 Small LT, Cavendish [3 units]	

Lectures supplied by two departments:
 Physics and Maths
 Courses are taught at three different locations

Mathematics

Michaelmas 2024	Lent 2025	Easter 2025
General Relativity Dr C. M. Warnick M. W. F. 09:00 MR2 [3 units]	Black Holes Prof. J.E. Santos M. W. F. 10:00 MR2 [3 units]	Gravitational Waves and Numerical Relativity Prof. U. Sperhake M. Tu. Th. F. 12:00 MR3 [2 units]
Formation of Galaxies Prof. N.W. Evans M. W. F. 09:00 MR11 [3 units]	Astrostatistics Prof. K. Mandel M. W. F. 11:00am MR4 [3 units]	
Cosmology Prof. B.D. Sherwin M. W. F. 10:00 MR2 [3 units]	Field Theory in Cosmology Prof. E. Pajer M. W. F. 11:00 MR11 [3 units]	
Quantum Field Theory Dr. A. Castro M. W. F. 11:00 MR2 [3 units]	Extrasolar Planets: Atmospheres and Interiors Prof. N. Madhusudhan M. W. F. 12:00 MR11 [3 units]	
Planetary System Dynamics Prof. M. Wyatt M. W. F. 11:00 MR12 [3 units]	Radiative Processes in Astrophysical Plasma* Dr G. Del Zanna Tu. Th. 09:00 MR11 [2 units]	
Structure and Evolution of Stars Prof. C.A. Tout M. W. F. 12:00 MR14 [3 units]	Canonical Gravity Hamiltonian Approach to General Relativity* Prof. M. J. Perry Tu. Th. 10:00 MR13 [2 units]	
Astrophysical Fluid Dynamics Prof. G.I. Ogilvie Tu. Th. S. 10:00 MR12 [3 units]	Dynamics of Astrophysical Discs Prof. H. N. Latter Tu. Th. 11:00 MR12 [2 units]	
	Further Stellar Evolution* Dr A.N. Zytlow Tu. Th. 12:00 MR11 [2 units]	

Two types of courses: Major and Minor
 Major: 3 units, 24 lectures, 3h exam
 Minor: 2 units, 16 lectures, 1.5h exam

All Maths (Major and Minor) exams are in June

Physics Major exams are in January
 Physics Minor exams are in April

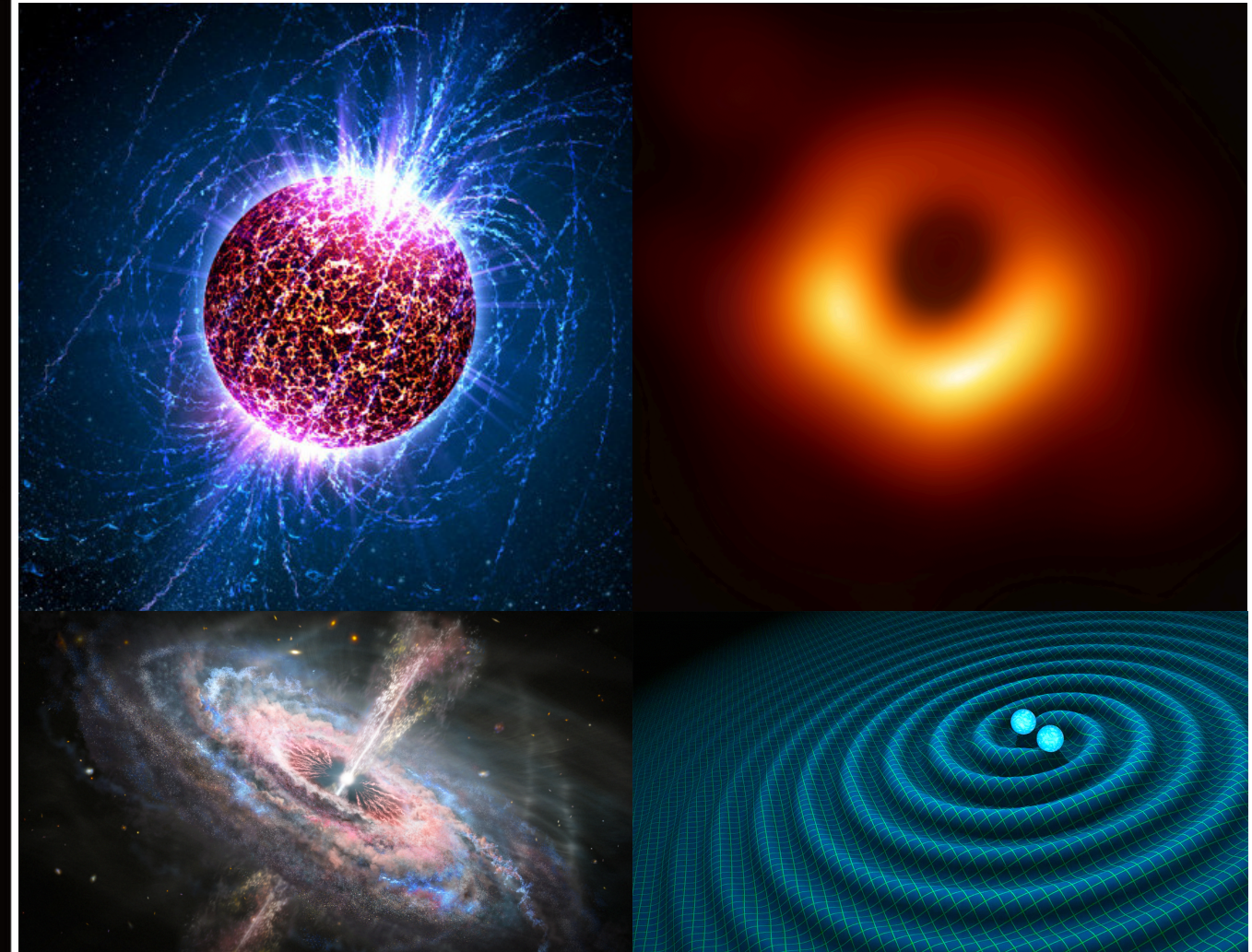
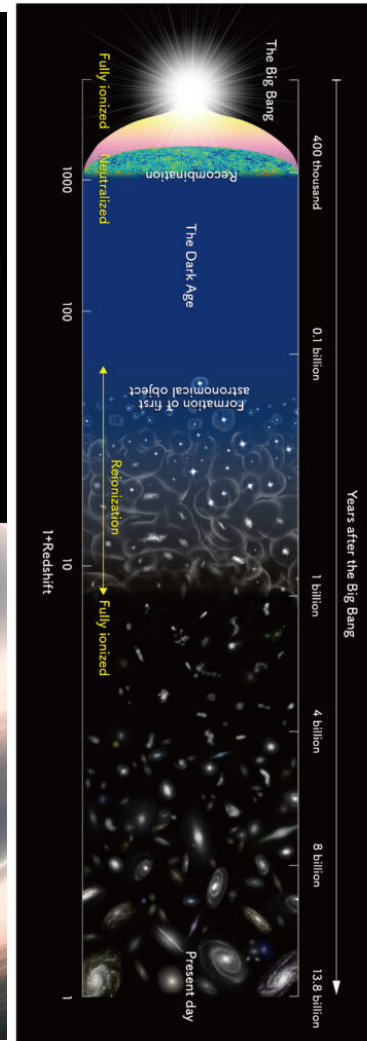
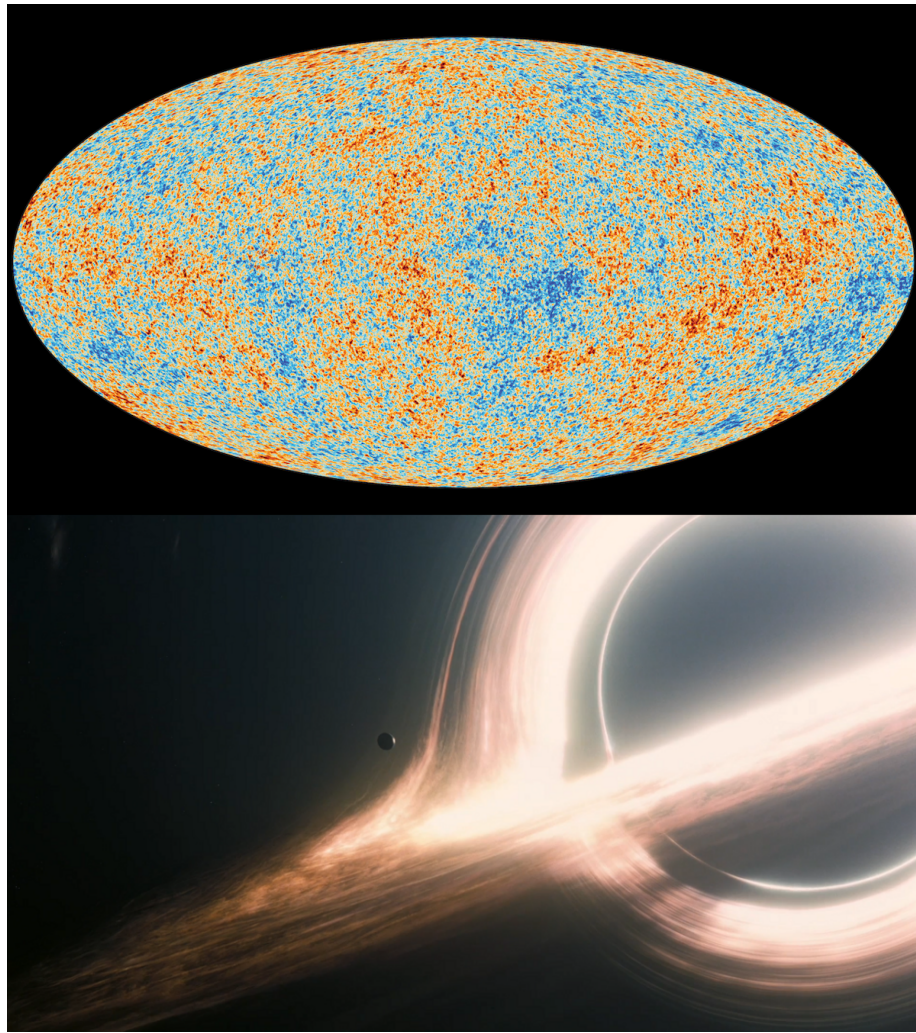
You can take one additional course not from the recommended list to exams

A closer look at some of the courses

Lecturer: **Sandro Tacchella**

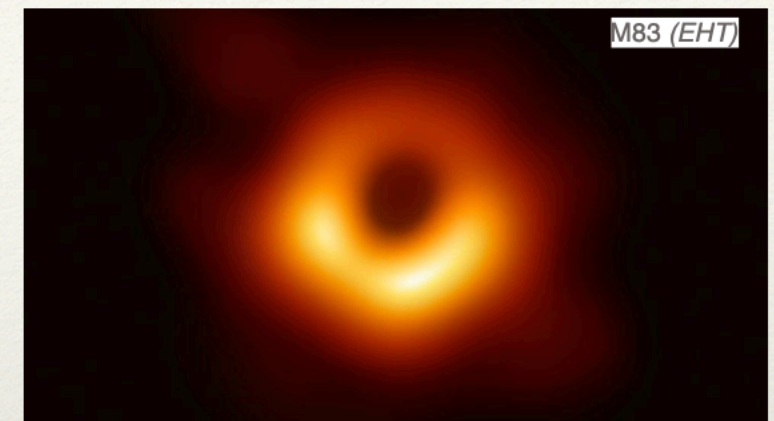
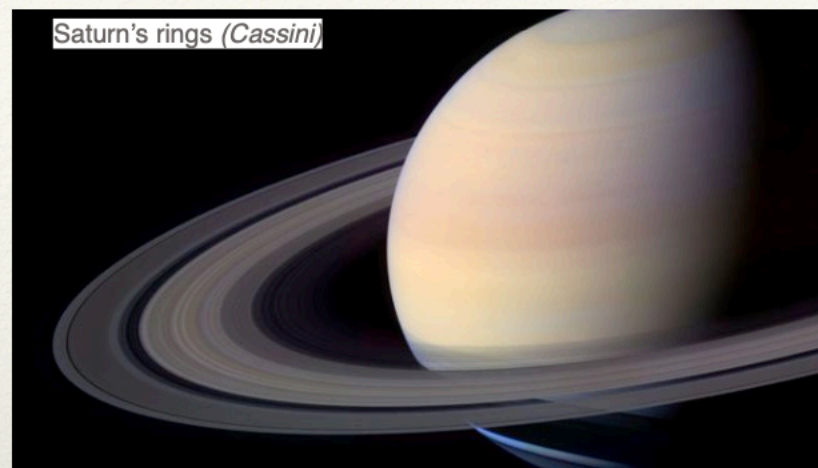
RAC: Relativistic astrophysics and cosmology

Einstein's general relativity across our Universe: gravity & astrophysics from big bang to black holes



Theoretical & Observational: Schwarzschild & Kerr spacetime; Black hole thermodynamics; Gravitational waves; Extreme matter & compact objects; Origin & evolution of the Universe.

Dynamics of Astrophysical Discs

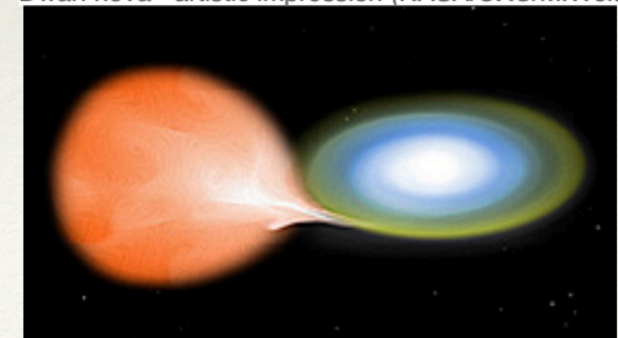


Main Topics

- Classical viscous disk theory (alpha models, etc)
- Waves and gravitational instability
- Vortices and dust dynamics
- Embedded satellites (gap opening, planet migration)
- Magnetic winds and the magnetorotational instability
- Applications to planetary rings, protoplanetary disks, cataclysmic variables, black hole accretion, etc



Dwarf nova - artistic impression (NASA/CXC/M. Weiss)



Astrophysical Black Holes

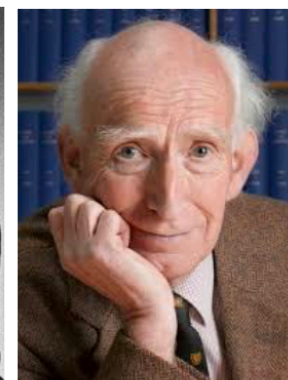
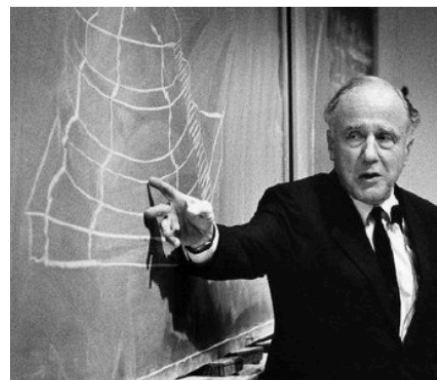
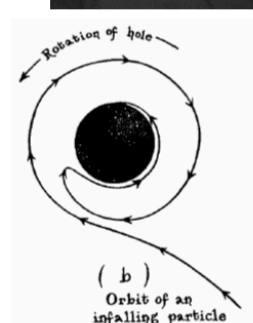
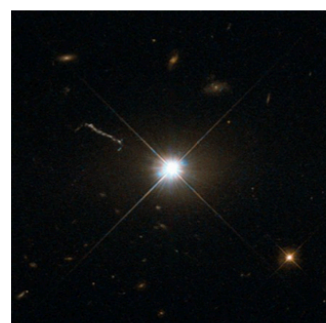
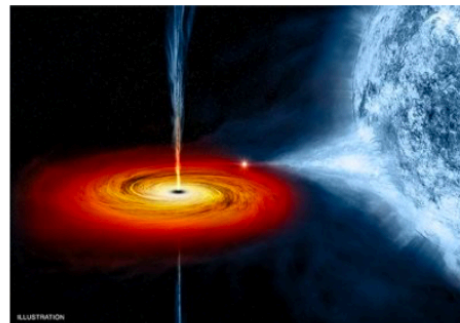
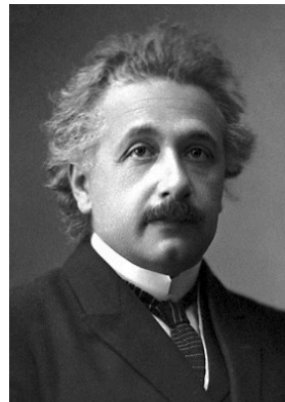
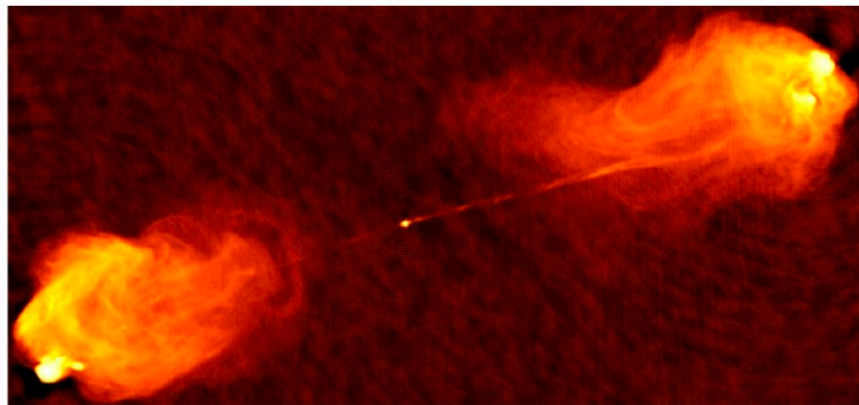
Pre-requisites

Good knowledge of material covered in Part II courses: Astrophysical fluid dynamics, stellar dynamics and structure of galaxies, structure and evolution of stars is required. Some knowledge of (thermo)dynamics, electromagnetism and galaxy formation is advantageous but not strictly necessary.

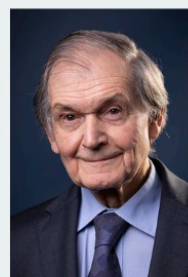
Synopsis

- Basic concepts; observational evidence for dormant and non-dormant objects (SgrA*)
- AGN properties and classification
- Formation pathways for supermassive black holes
- Black hole growth overview
- Fuelling mechanisms from kpc to sub-pc scales
- Bondi-Hoyle solution and limitations
- Accretion disk models: thin, slim and thick discs
- Outflows: basic concepts; collimated wind and jet phenomena
- Energy-, momentum- and radiation pressure-driven outflow solutions
- Impact of outflows on host properties
- Brief overview of black hole binaries and hardening processes

Lecturer: **Debora Sijacki**



The Nobel Prize in Physics 2020



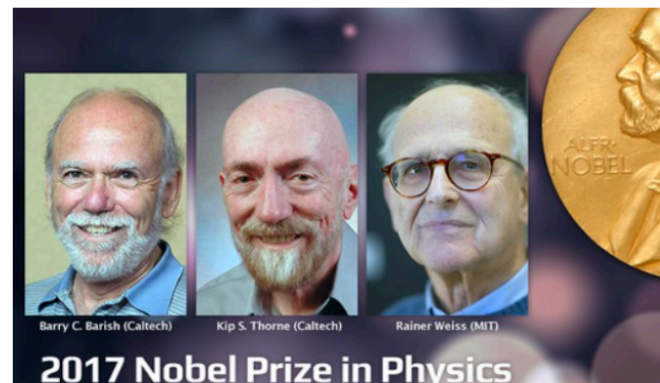
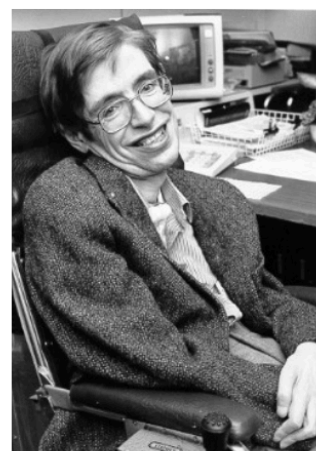
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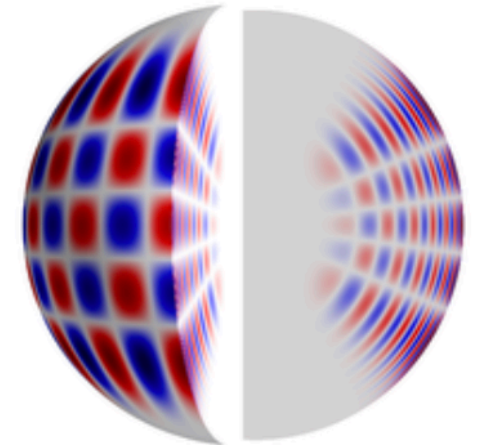
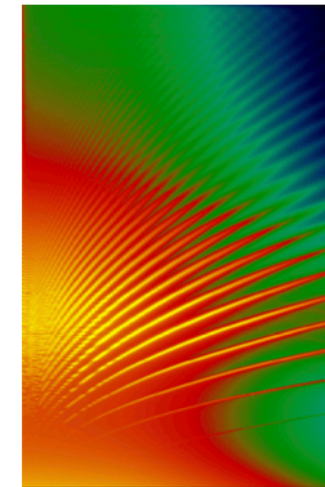
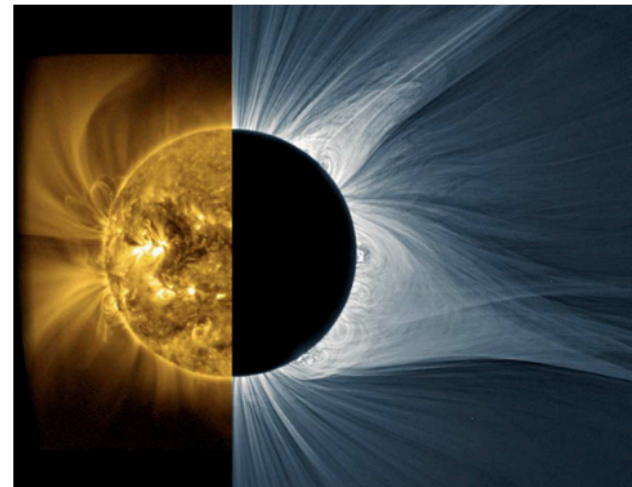
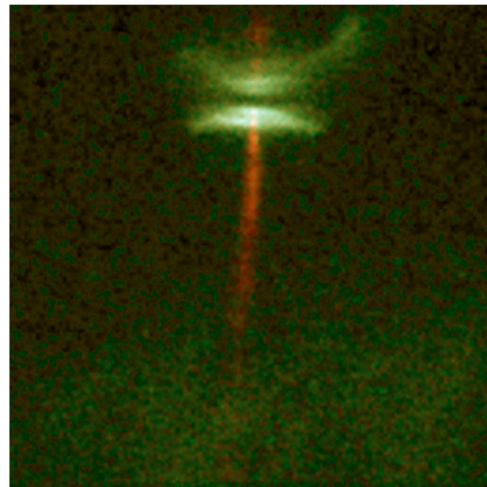
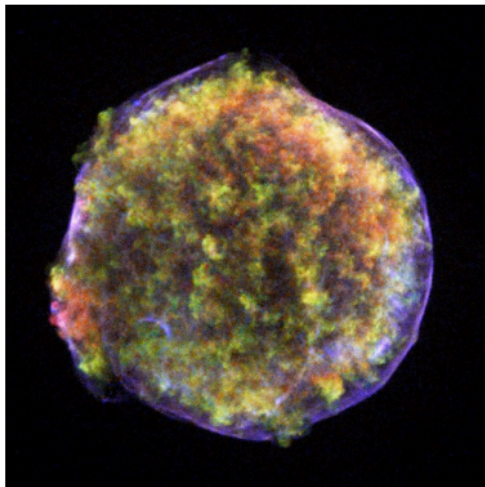
2017 Nobel Prize in Physics

Astrophysical Fluid Dynamics (24 lectures)

Fluid dynamics is involved in a very wide range of astrophysical phenomena, e.g.

- the formation and internal dynamics of stars and giant planets;
- jets and accretion discs around stars and black holes;
- the dynamics of the expanding Universe.

Self-gravitation, compressibility and magnetic fields are often important.

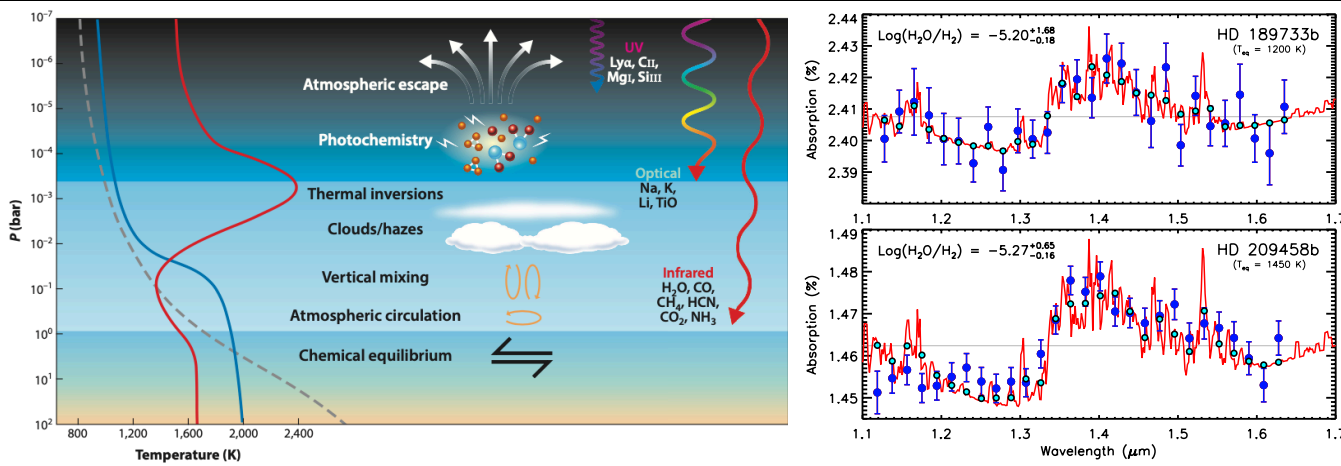


- Gas dynamics and magnetohydrodynamics for an ideal compressible fluid
- Derivation and mathematical properties of the basic equations
- Linear and nonlinear waves, including shocks
- Spherically symmetric flows: supernova blast waves, stellar winds and accretion
- Axisymmetric rotating magnetized flows: astrophysical jets and winds
- Linear perturbation theory: stellar oscillations, tides and instabilities

Extrasolar Planets: Atmospheres and Interiors

24 Unit Course, Lecturer: Prof. Nikku Madhusudhan

1. Theory of Exoplanetary Atmospheres



Madhusudhan et al. 2014, Madhusudhan 2019, Welbanks & Madhusudhan 2019

2. Theory of Exoplanetary Interiors

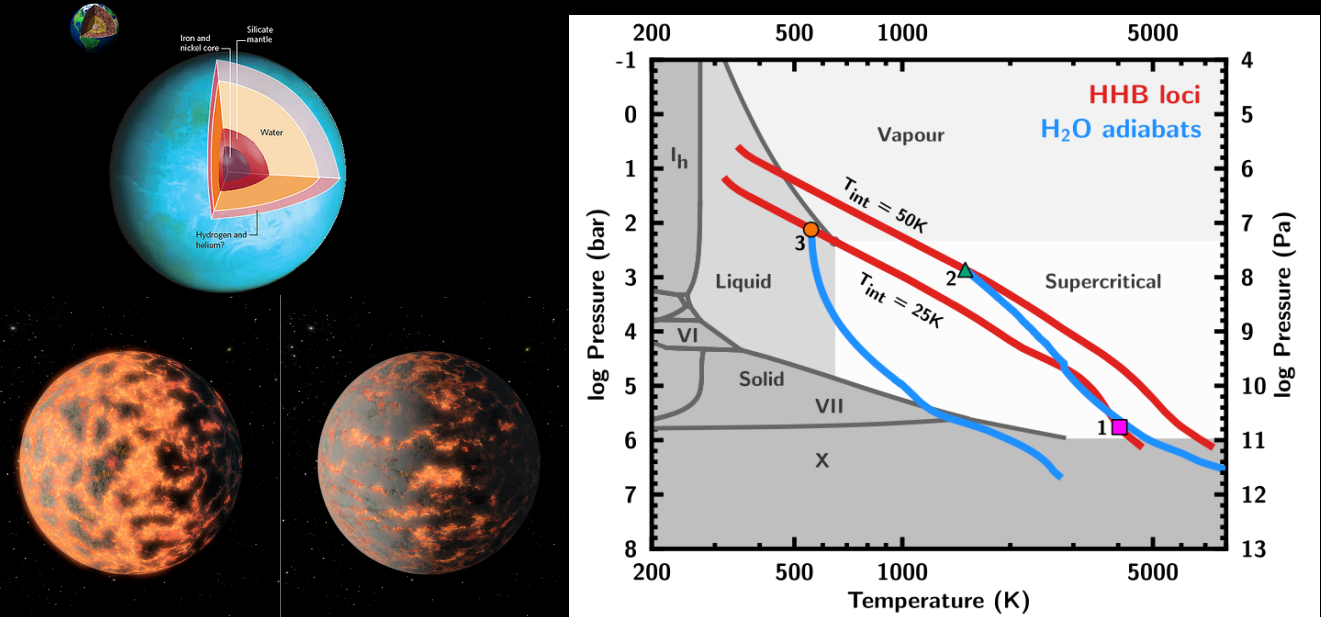


Image Credits: NASA

Madhusudhan et al. 2020, Piette & Madhusudhan 2021

3. Exoplanetary Habitability

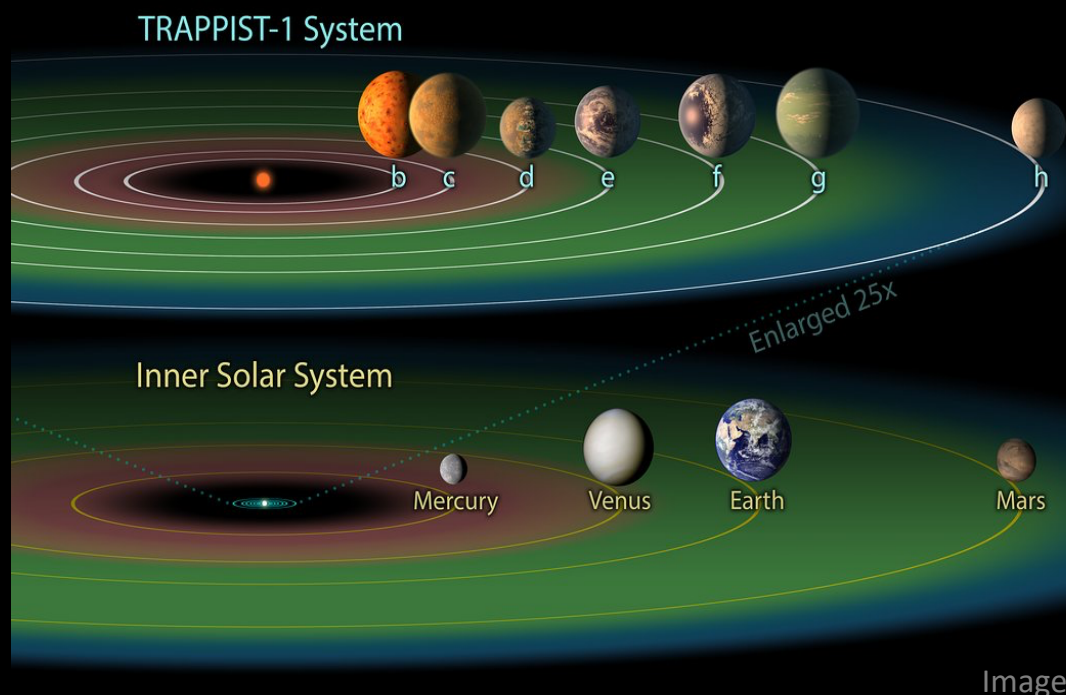


Image Credits: NASA

4. Observations and Retrieval Methods

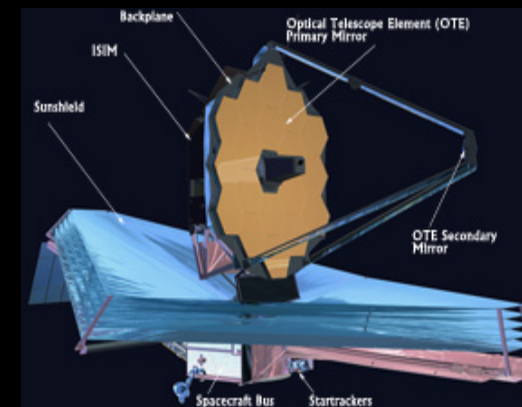
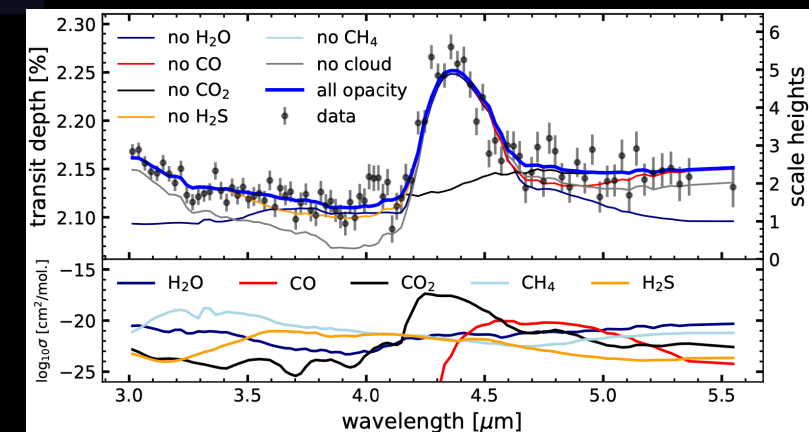


Image Credits: ESO, NASA, ESA
JWST Exoplanet Transit ERS Team

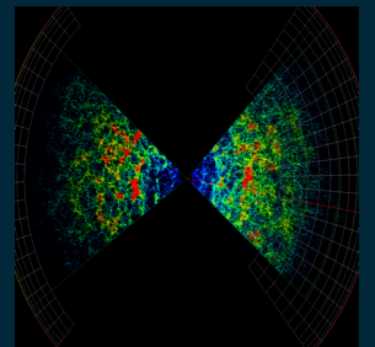
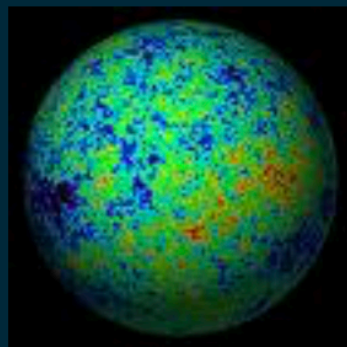
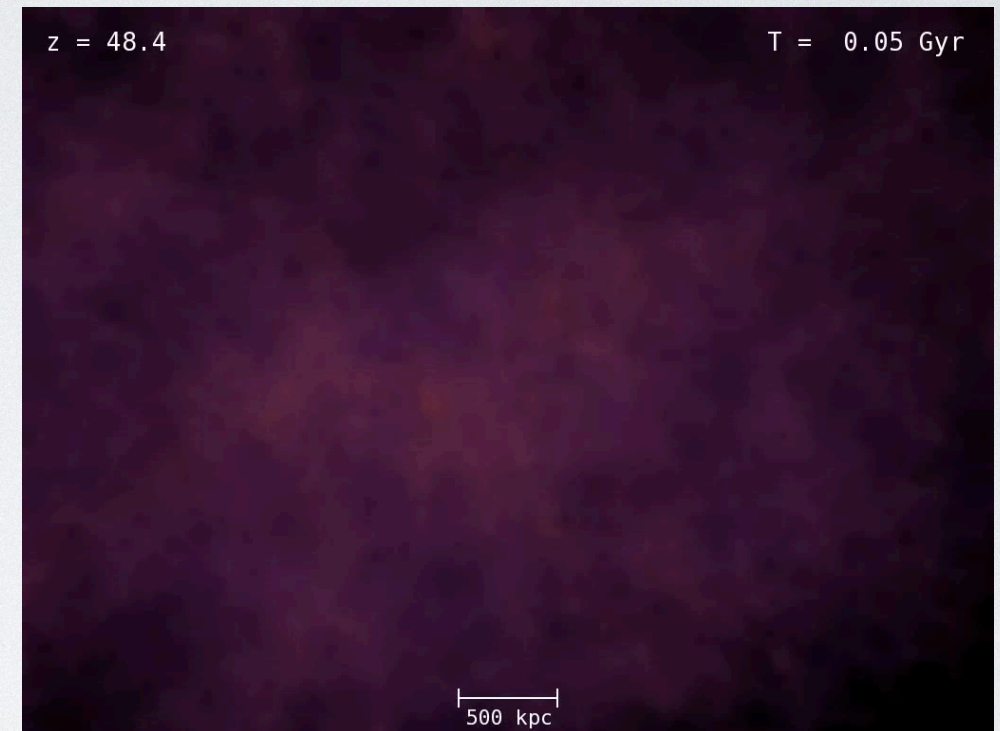


FORMATION OF GALAXIES

This course prepares the student for state-of-the-art research in galaxy formation, galaxy structure and evolution. The course focusses on the physical processes underlying the formation and evolution of galaxies in a Λ CDM cosmology.

Topics include Newtonian perturbation theory, the spherical collapse model, formation and structure of dark matter haloes (including Press-Schechter theory), the virial theorem & Jeans equations, galaxy mergers, dynamical friction, cooling processes, theory of star formation, feedback processes, chemical evolution modelling and supermassive black holes. We end with the formation of spiral galaxies, elliptical galaxies and the Milky Way.

The course assumes that the student has had an introductory cosmology course (& so knows about Friedman-Robertson-Walker universes & the hot big bang. Any of the cosmology courses at Part II in Mathematics or Astrophysics are fine.



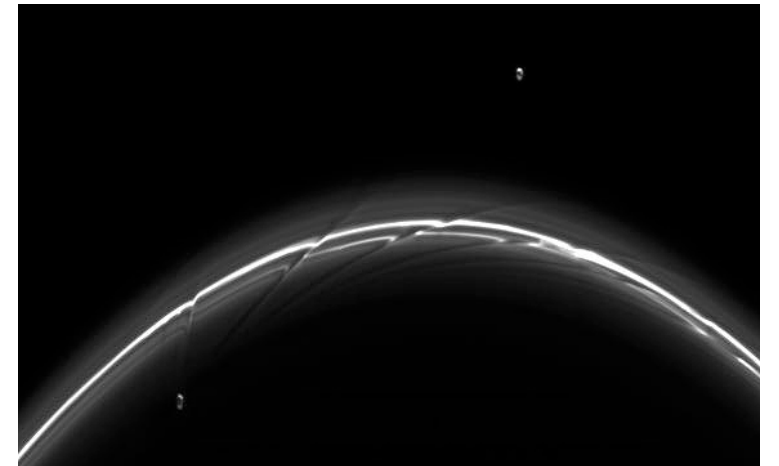
Planetary system dynamics

Lecturer: Mark Wyatt

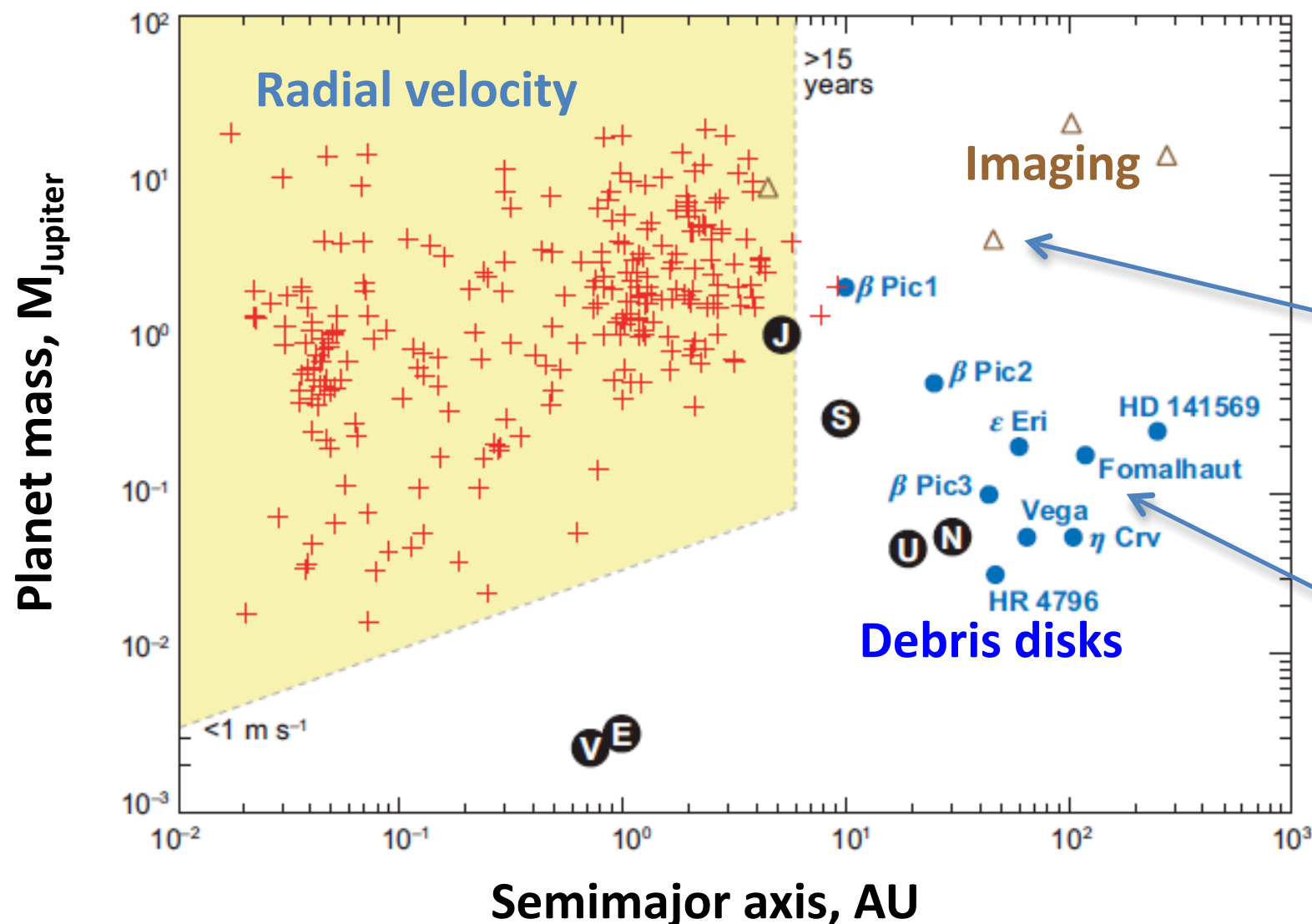
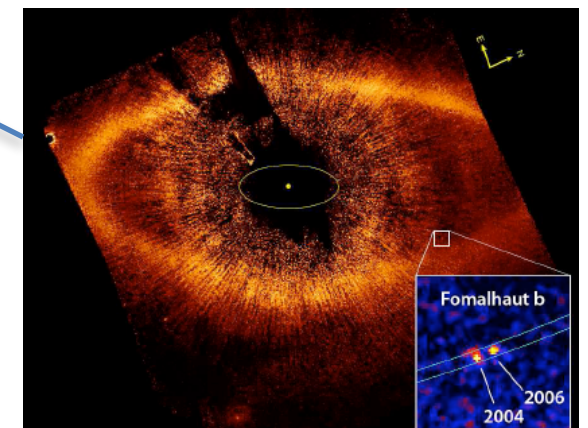
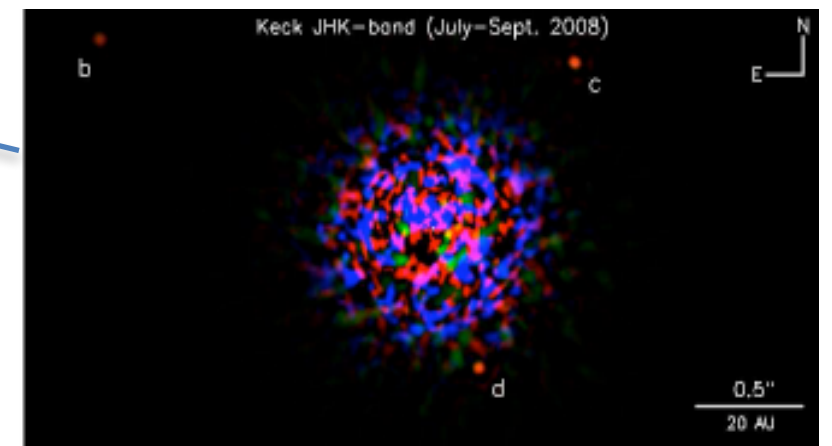
How do planets interact with each other and the system's small bodies, and how do these systems form and evolve? With applications to the Solar System's planets, the 1000s of extrasolar planetary systems, circumplanetary material, debris disks, the asteroid belt, comets, and planet formation in protoplanetary disks.

Topics covered: planetary system, architecture, two body problem, small body dynamics, three body problem, close approaches, collisions, disturbing function, secular perturbations, resonant perturbations.

Cassini image of Saturn's F ring and shepherd moons Pandora and Prometheus



First imaged extrasolar planets



Lecture courses choice

- Follow your interests
- Choose at least some lecture courses that will help you with your Project (normally Astrophysics heavy)
- Consider spreading workload between terms (typically Michaelmas is lecture heavy)
- Read **project descriptions** and look at the notes and past exams questions
- Follow 6-7 courses and sit exams for 4 (max 5)
- Typical load of 9 lectures per week
- Discuss your choices with the course coordinator and the project supervisor

Lecture course preparation

- Strong Astrophysics **Part II** foundation: Structure and Evolution of Stars, Stellar Dynamics and Structure of Galaxies, Astrophysical Fluid Dynamics, Introduction to Cosmology
- Lecture notes, examples and past exams are available online - check them out!

Examples Classes

- Instead of supervisions

Research Projects

- Project should contain [independent](#) and [new](#) research carried out by [you](#)
- You will need to provide a short report before Xmas
- You will need to write a **full report** and give an **oral presentation of your work** in front of a panel in Spring
- Supervisors are there to guide and discuss (at least 12 supervisions scattered over 3 terms)

Research Project Booklet

- The past year's booklet is available online - have a look!
<https://www.ast.cam.ac.uk/current-students/undergraduate/part-iiimast/research-project>

Institute of Astronomy
University of Cambridge

Natural Sciences Tripos
Part III/MASt Astrophysics
Research Project
2024-25

~3 pages per project

Project 5: Constraining Cosmic Dawn with 21-cm Cosmology

Supervisor I: Anastasia Fialkov (afialkov@ast.cam.ac.uk)

Supervisor II: N/A

UTO: Anastasia Fialkov (afialkov@ast.cam.ac.uk)

Project summary:

21-cm cosmology (Furlanetto et al. 2006, Mesinger 2019, Barkana 2016) is anticipated to provide us with a window into the enigmatic cosmic dawn era, the period when the first luminous sources formed in the universe. In this project, the student will produce forecasts for the sensitivity of upcoming 21-cm global signal and power spectrum experiments to the astrophysical properties of these first stars and galaxies. With an extension goal to produce joint forecasts between complementary global signal and power spectrum experiments. Thereby providing insight into what these experiments might teach us about the early universe.

Project description:

Our group and collaborators have developed a semi-numerical simulation code for predicting the 21-cm signal given a set of astrophysical parameters that describe the properties of the first stars and galaxies. This project aims to produce theoretical predictions for the inverse problem, given a hypothetical detection of the 21-cm signal from upcoming experiments what constraints on the properties of these first luminous sources will we achieve.

Projected parameter constraints will be made for a variety of existing and upcoming 21-cm signal experiments, including both global signal experiments (e.g. EDGES, REACH and SARAS, Bowman et al. 2018, de Lera Acedo 2019, Singh et al. 2022), and power spectrum experiments (e.g. HERA, LOFAR and the SKA; HERA collaboration et al. 2022, Mertens et al. 2020, Koopmans et al. 2015). These can then be combined to produce joint forecasts, which are of particular interest given early indications that global 21-cm signal measurements may be able to break parameter degeneracies that exist in power spectrum signal measurements (Gessey-Jones et al. 2022). There exist many methodologies for producing such parameter constraint forecasts, and so the exact approach taken in the project will be decided jointly with the student. An ambitious student may wish to use some or all of neural network emulators, full Bayesian forward modelling, or marginal statistics in producing their parameter forecasts.

Background:

Currently there exists an observational gap in our knowledge of the universe's history. The CMB provides us with a tool to see the very early universe just a few hundred thousand years after the big bang. While deep galaxy surveys can now push back to redshift 8 and above, allowing us to see early galaxies only hundreds of millions of years after the big bang. Between these points in the universe's history, there are two currently unseen epochs, the dark ages and cosmic dawn (Furlanetto et al. 2006). This project concentrates on the latter, the period in the universe when the very first stars and galaxies form. As these stars and galaxies were so distant and so faint, they are outside the realm of direct observation even by JWST. The 21-cm line from neutral hydrogen however provides a promising probe for investigating this epoch via the absorption of CMB photons by the intergalactic medium (IGM) at this spectral line.

The emission and absorption at this line is predicted to be sensitive to the details of the formation of the very first stars (Figure 1, Magg et al. 2021, Gessey-Jones et al. 2022) and

well as the properties of the first black holes and the nature of dark matter. The 21-cm signal would thus potentially provide us with a wealth of knowledge of the first structures to form in the universe. The first tentative detection of the sky-global 21-cm signal was reported in 2018 by the EDGES collaboration (Bowman et al. 2018), though this has since been disputed by the null detection of SARAS3 (Singh et al. 2022). In recent years several interferometers have also published improved upper limits on the 21-cm signal power spectrum including LOFAR (Mertens et al. 2019), MWA (Trott et al. 2022), and HERA (HERA Collaboration et al. 2022). Hence a conclusive detection of the 21-cm signal and/or power spectrum is hoped for in the near future.

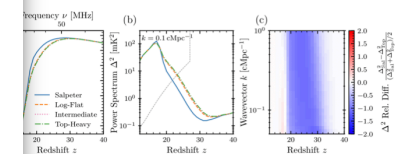


Figure 1: (a) The 21-cm signal for different first-star mass distributions (SFD). Panel (a) shows the global signal, (b) the 21-cm signal power spectrum, and (c) the relative difference between the Salpeter and Top-Henry SFDs. On the middle panel also shown is a gray dashed line, the predicted noise sensitivity of the SKA-Low with sensitivity, showing that the SKA-Low can begin to probe the mass distribution of the first stars via the small differences in ΔT_b it induces. From (Gessey-Jones et al. 2022).

It is increasingly important to consider the question of "if we do detect the 21-cm signal, how do we interpret it?". To this end, theoretical predictions for the 21-cm signal with different models of early universe astrophysics have been developed, and upcoming experiments publish the noise on the signal they hope to achieve. In this project, we will use these theoretical predictions and noise limits and forecast the astrophysical constraints various experiments may achieve. In addition, in one of our recent papers (Gessey-Jones et al. 2022), we found a degeneracy in the 21-cm power spectrum measurements of the formation of the first stars and their mass distribution, but that a future global signal measurement could break this parameter degeneracy. 21-cm global signal and power spectrum measurement may give us significantly tighter constraints by breaking degeneracies, something we hope to investigate in this project.

Skills:

Various existing methods for parameter constraint forecasts and many different for the combination of data sets. Hence the exact plan for this project is flexible and tailored somewhat to the student's interests/strengths. One potential project outline is as follows:

- Literature review into the astrophysics that impacts the 21-cm signal and methods for producing parameter constraint forecasts.
- Generation of a data-set of 21-cm signals via using the high-performance computing facility to run $\mathcal{O}(10000)$ simulations.
- Retrain existing neural network emulators for the global 21-cm signal and power spectrum on the simulated signal dataset.
- Using existing noise models from the literature perform MCMC forecasts for parameter constraints from global signal experiments (REACH, EDGES and SARAS).

MCMC forecasts to produce parameter constraints forecasts for power spectrum experiments (HERA, LOFAR, SKA).

Use the global signal experiment and power-spectrum experiment to perform joint forecasts and investigate the improvement on constraints this grants and whether it breaks degeneracies.

Python and/or MATLAB. Knowledge of Astrostatistics would be useful.

Knowledge of important papers/review articles relevant to the project) 2006, Physics Reports, Volume 433, Issue 4-5, p. 181-301 (Furlanetto et al. 2006). Submitted to MNRAS, arXiv:2202.02099 (Singh et al. 2022). Submitted to MNRAS, arXiv:2110.15948 (Singh et al. 2022).

List of papers referred to in the project description) 2018, Nature, Volume 555, Issue 7694, p. 67-70 (Bowman et al. 2018). 2019, 2019 International Conference on Electromagnetics in Advanced (Singh et al. 2022). Nature Astronomy, Volume 6, p. 607-617 (Singh et al. 2022, APJ, Volume 924, Issue 2 (Mertens et al. 2019). MNRAS, Volume 493, Issue 2, p. 1662-1685 (Mertens et al. 2019). Proceedings of Advancing Astrophysics with the Square Kilometre Array (SKA) 9-13 June 2014 (Trott et al. 2022). MNRAS, Volume 493, Issue 4, p. 4711-4727 (Trott et al. 2022).

Research Projects - Selection

- This year: 47 project choices for 37 students (so project/student ratio is close to but clearly above unity)
- Project booklet available in early September. Before the year starts, investigate and rank, send your ranked list.
- Up to 10 with a minimum of 5 ranked projects is required
- Impossible to rank projects without understanding the topic and the work involved
- Very difficult to understand the work involved without talking with the supervisor
- Projects are allocated based on students' and supervisors' preferences at the beginning of MT

Research Projects - Computing

- **Three computing** courses offered in Michaelmas
- One short compulsory introduction into Linux and the IoA computing infrastructure
- Research Computing course offered as part of Data Intensive Science MPhil, focused on Python and coding best practices
- High Performance Computing

Research Projects - process

- You simply can not do it last minute!
- Start surveying the literature and learning the tools as early as day 1
- Expect finding dead ends
- The bulk of work over Xmas break and in the beginning of Lent

There is more to this Course!

- We expect you to attend Institute talks (Wednesday Seminars and Colloquia on Thursdays)
- You could consider other talk series (find out how to keep up to date)
- It may be wise to go to **group meetings** (related to your Project)
- Journal Club will teach you to read and understand scientific literature

There is more to this Course!

- Public outreach <https://www.public.ast.cam.ac.uk>
get in touch with Matt Bothwell bothwell@ast.cam.ac.uk

There is more to this Course!

- IoA Coffee+Tea, every day twice a day, informal and interactive
- **Talk to our alumni, many former Part II and Part III students are still around and will share a wealth of knowledge if asked**

Have fun!