2024/2025 Open Day

# Part III Astrophysics

Vasily Belokurov (Part III Course Coordinator)
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Michelle Fell (Undergraduate Student Co-ordinator )
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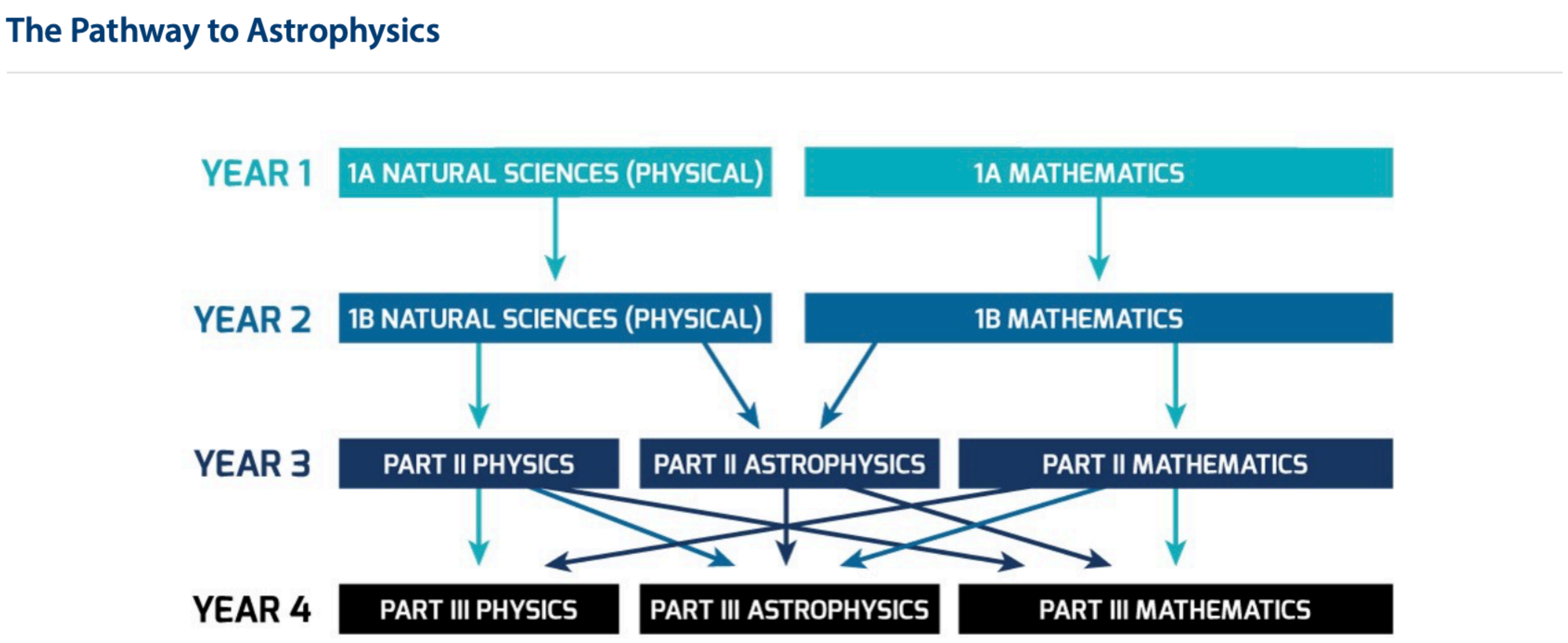
# Consult our website

# Pathways




**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] | |

**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. Zytkow **Tu. Th.** 12:00 MR11 [2 units] | |

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

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

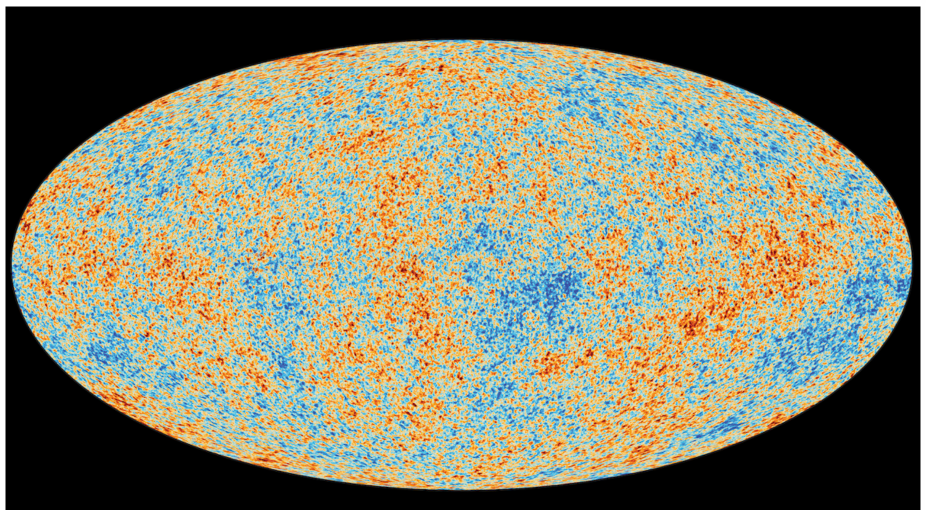
You can take one additional course not from the recommended list to exams

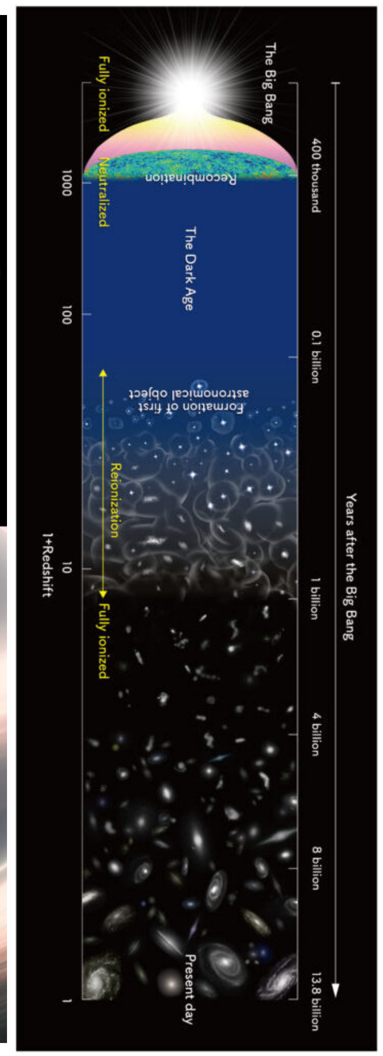
# A closer look at some of the courses

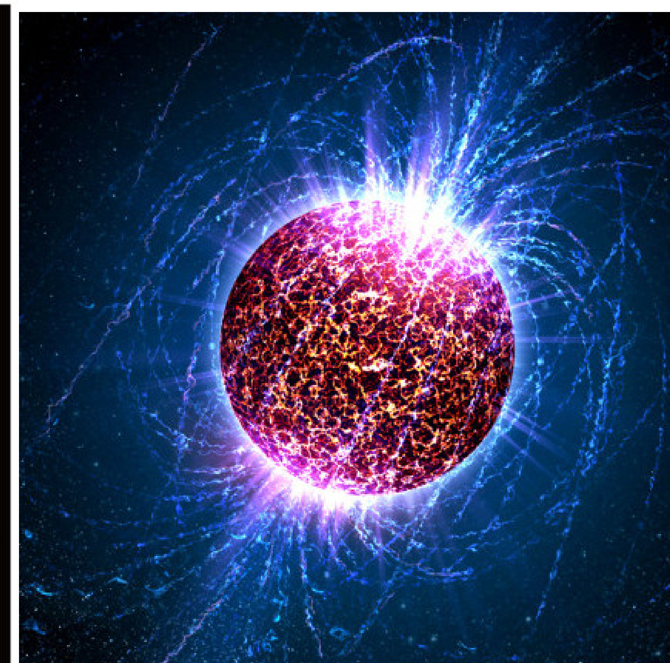
Lecturer**: Sandro Tacchella**

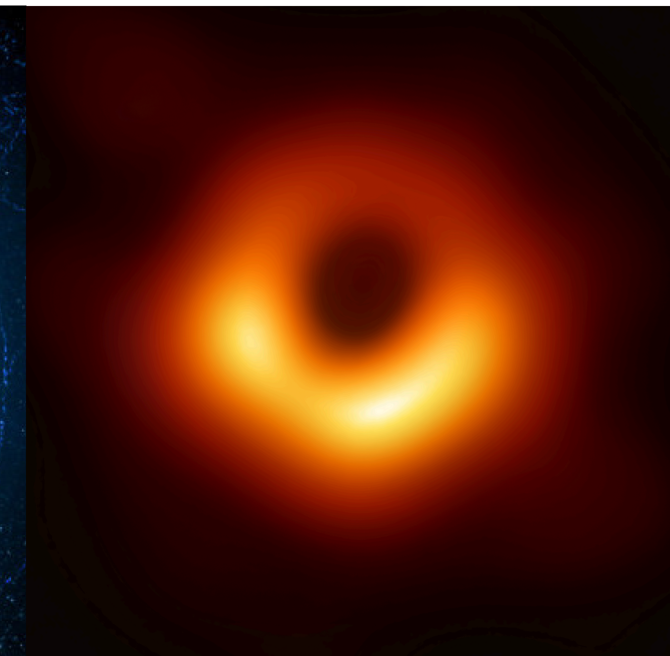
# RAC: Relativistic astrophysics and cosmology

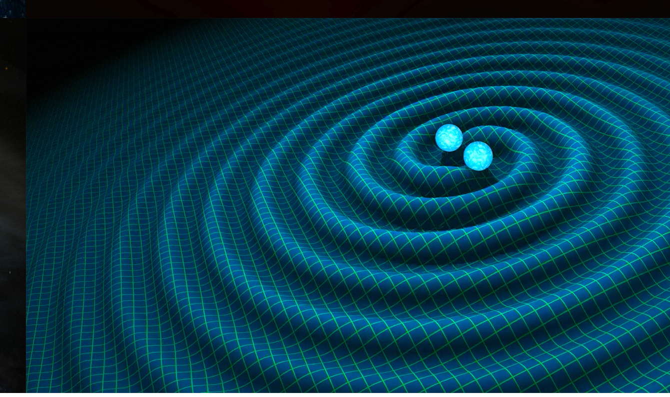
## Einstein's general relativity across our Universe: gravity & astrophysics from big bang to black holes







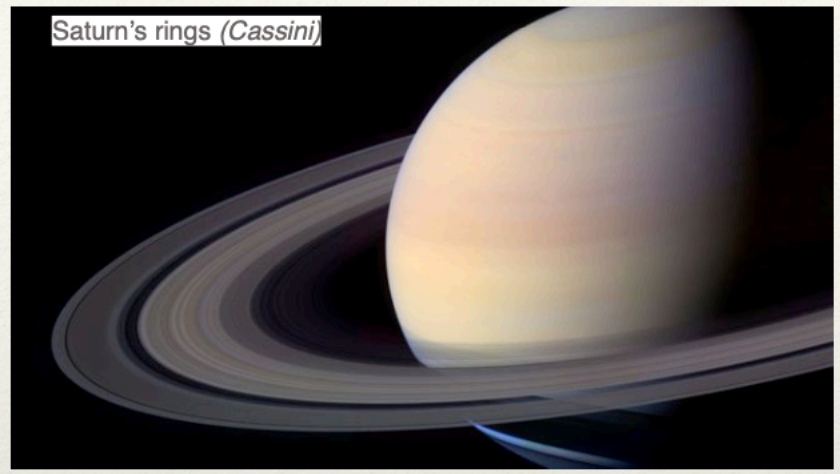


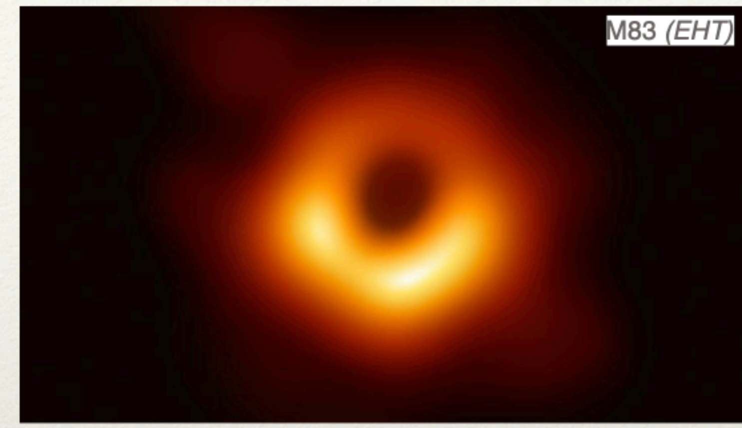
**Theoretical & Observational:** Schwarzschild & Kerr spacetime; Black hole thermodynamics; Gravitational waves; Extreme matter & compact objects; Origin & evolution of the Universe.

Lecturer: **Henrik Latter**

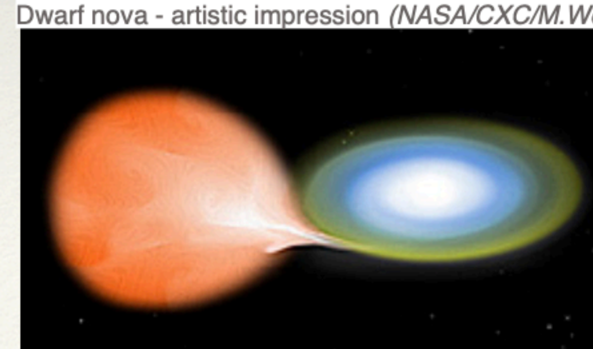
# Dynamics of Astrophysical Discs


HD 163296 *(ALMA)*


Saturn's rings *(Cassini)*


M83 *(EHT)*


Pan in the Encke Gap *(Cassini)*

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


## Main Topics

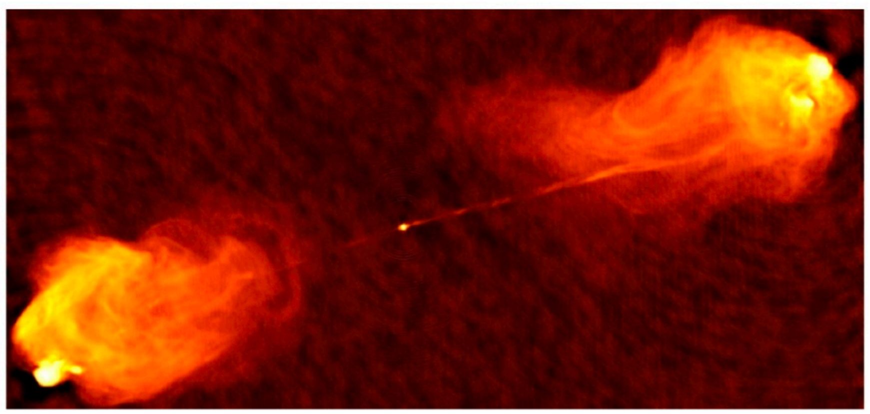
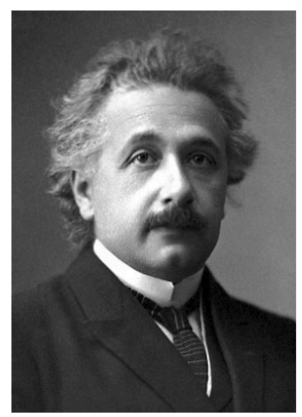
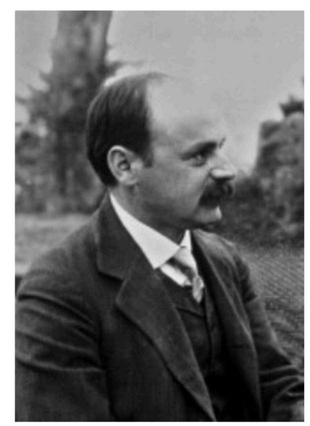
- **Classical viscous disk theory (alpha models, etc)**
- **Waves and gravitational instability**
- **Vortices and dust dynamics**
- **Embedded satellites (gap opening, planet migration)**
- **Magnetic winds and the magnetorotational instability**
- **Applications to planetary rings, protoplanetary disks,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

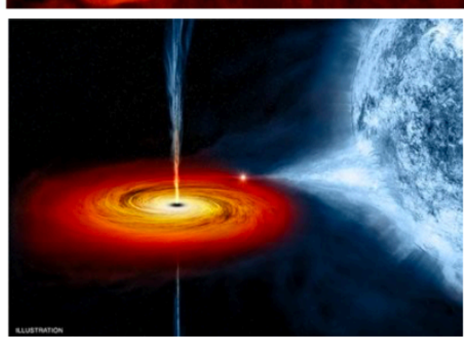
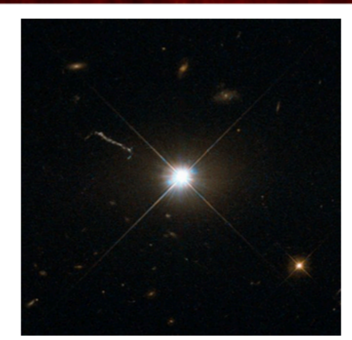
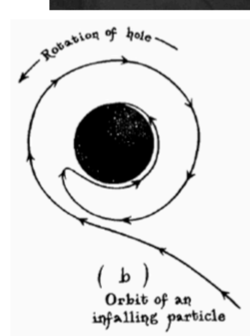
# Astrophysical Black Holes

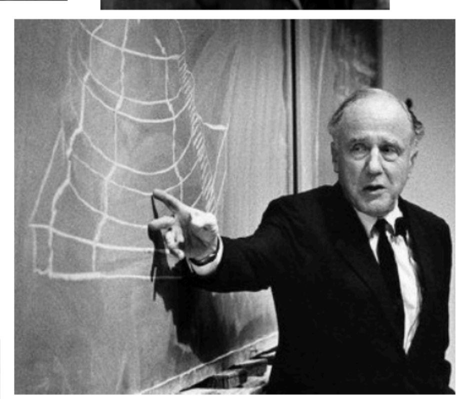
Lecturer: **Debora Sijacki**

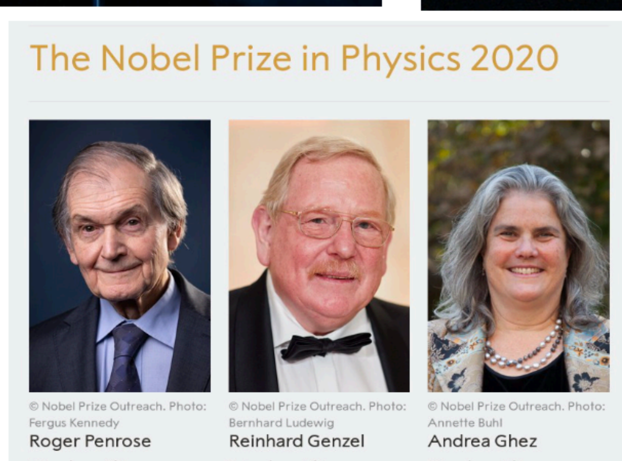
**Pre-requisites**
Good knowledge of material covered in Part II courses: Astrophysical fluid dynamics, stellar dynamics and structure of galaxies, structure and evolution of stars is required. Some knowledge of (thermo)dynamics, electromagnetism and galaxy formation is advantageous but not strictly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

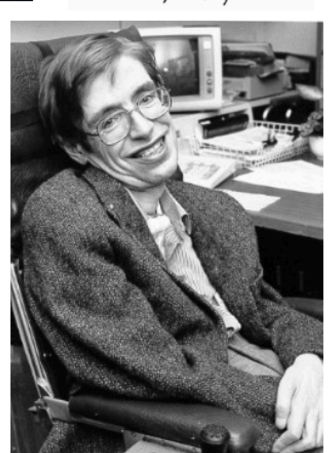
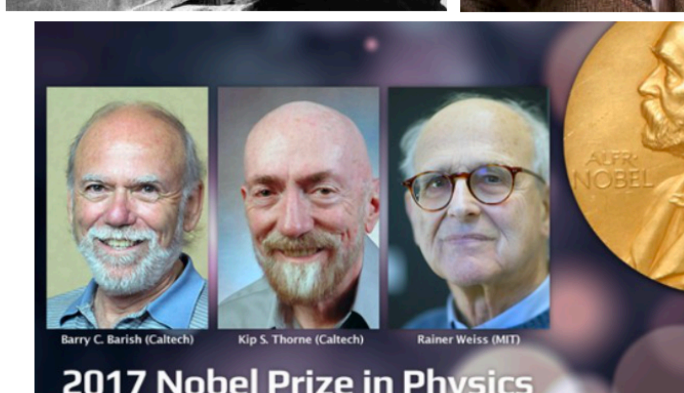
**Synopsis**
- Basic concepts; observational evidence for dormant and non-dormant objects (SgrA*)
- AGN properties and classification
- Formation pathways for supermassive black holes
- Black hole growth overview
- Fuelling mechanisms from kpc to sub-pc scales
- Bondi-Hoyle solution and limitations
- 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





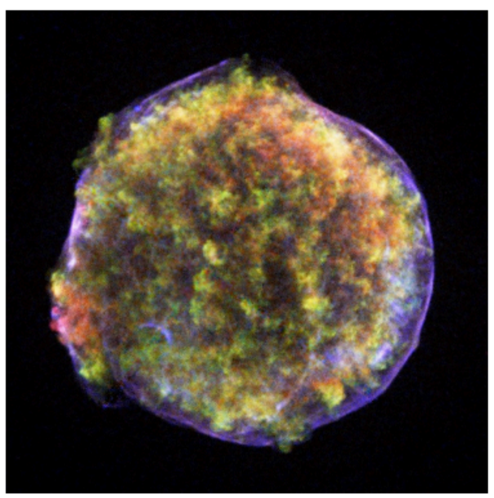
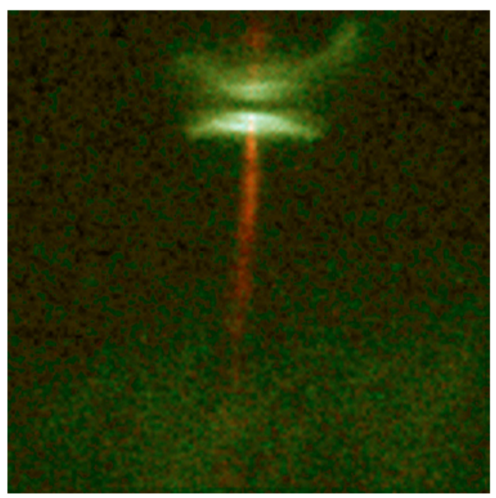
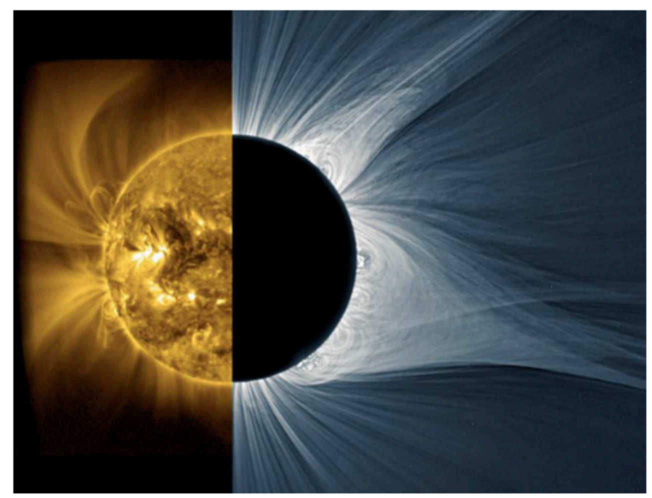
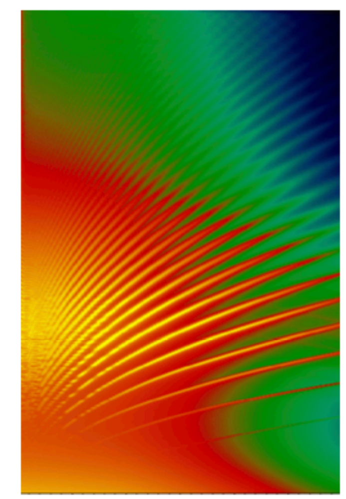
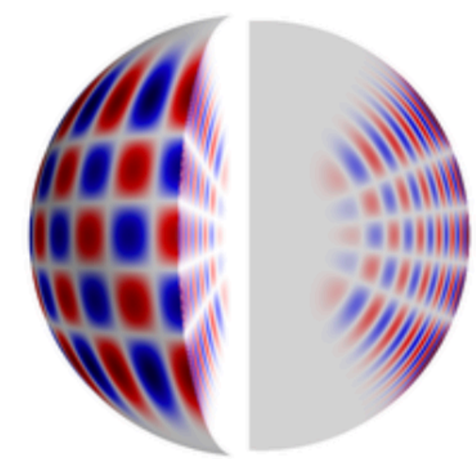
Lecturer: **Gordon Ogilvie**

# 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.**

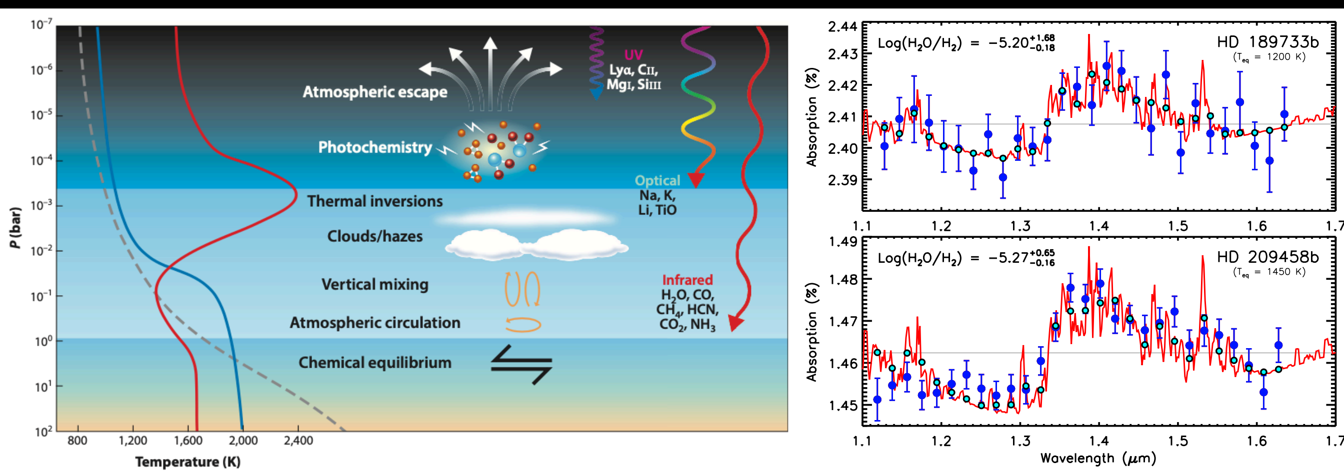






- **Gas dynamics and magnetohydrodynamics for an ideal compressible fluid**
- **Derivation and mathematical properties of the basic equations**
- **Linear and nonlinear waves, including shocks**
- **Spherically symmetric flows: supernova blast waves, stellar winds and accretion**
- **Axisymmetric rotating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

# Extrasolar Planets: Atmospheres and Interiors

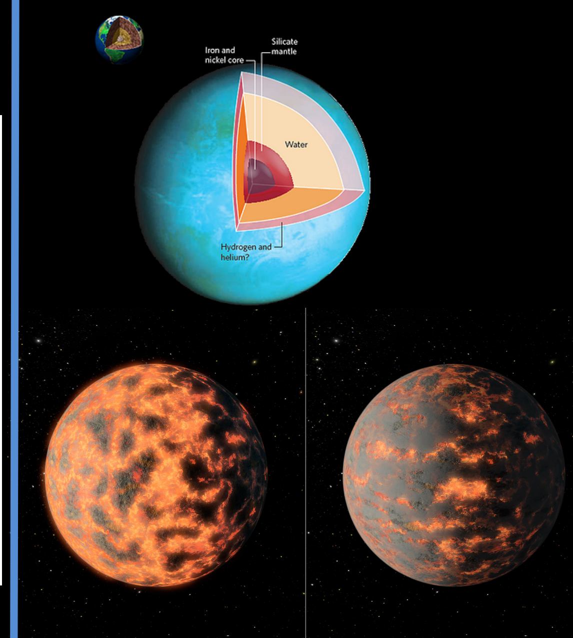
## 24 Unit Course, Lecturer: Prof. Nikku Madhusudhan

## 1. Theory of Exoplanetary Atmospheres




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

## 2. Theory of Exoplanetary Interiors



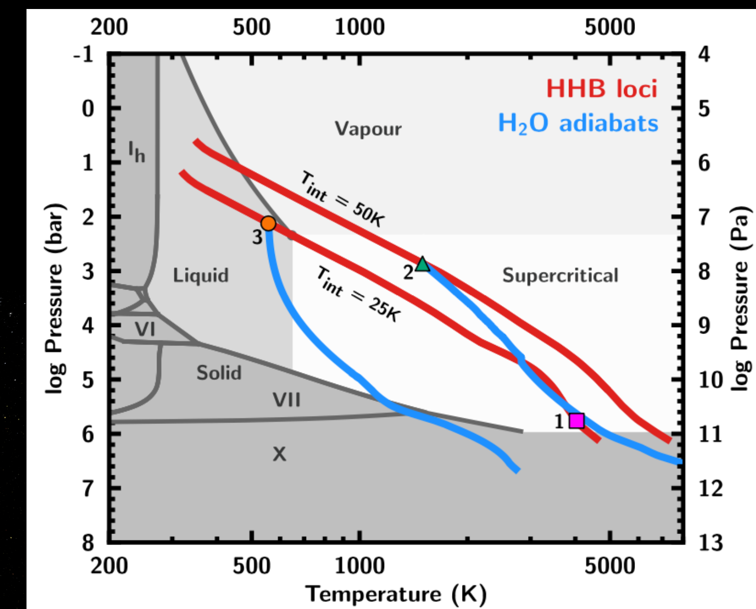




Image Credits: NASA

Madhusudhan et al. 2020, Piette & Madhusudhan 2021

## 3. Exoplanetary Habitability

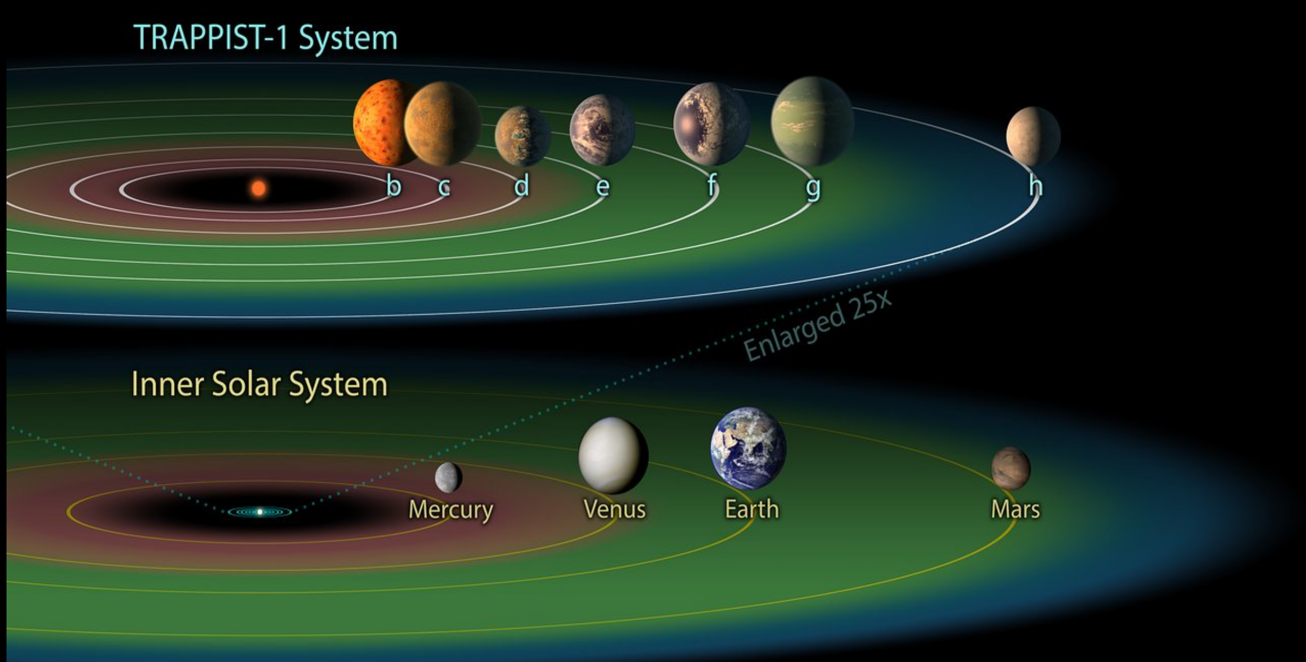
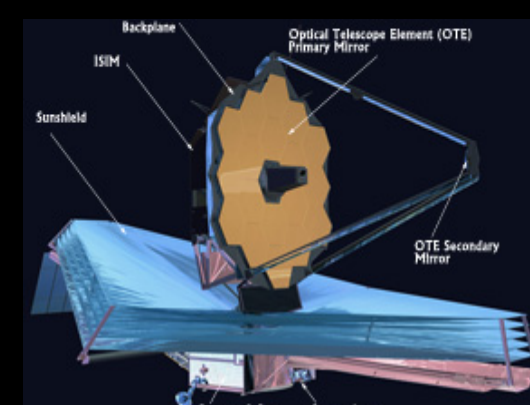



Image Credits: NASA

## 4. Observations and Retrieval Methods



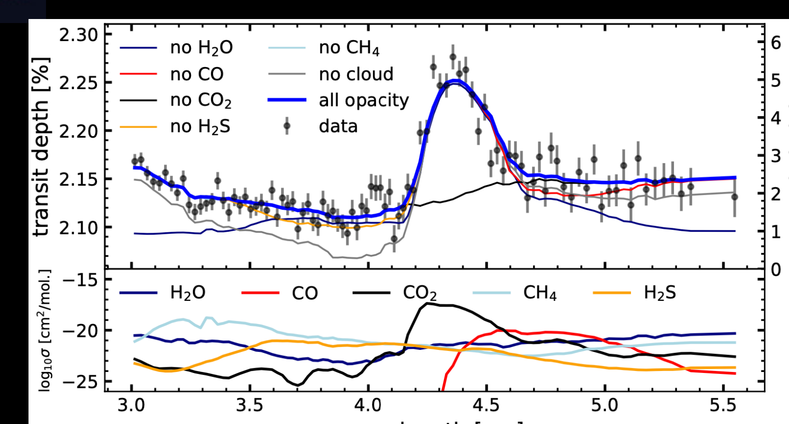
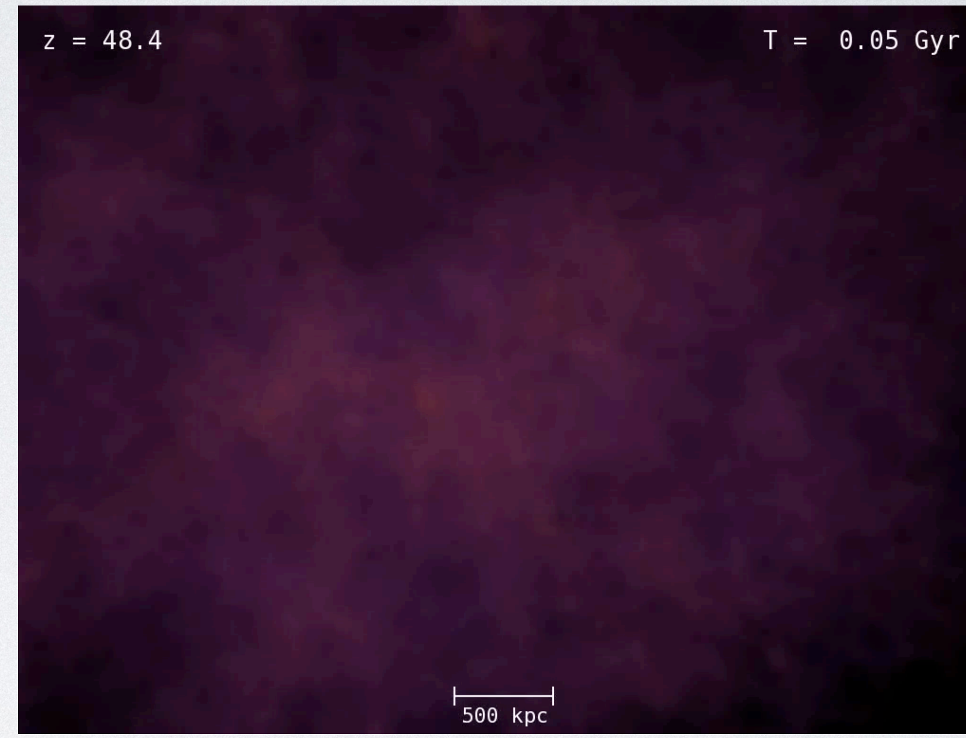




Image Credits: ESO, NASA, ESA
JWST Exoplanet Transit ERS Team

Lecturer: **Wyn Evans**

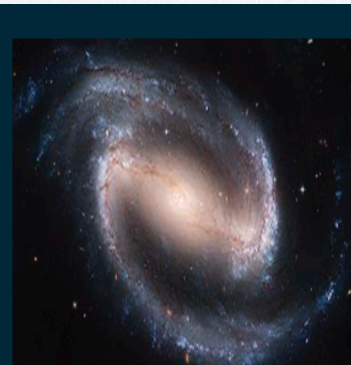
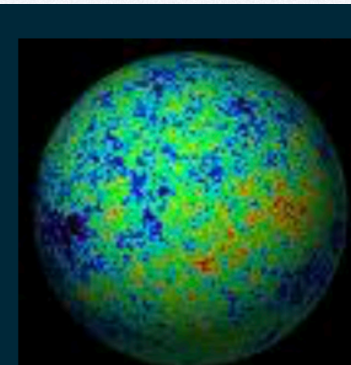
# FORMATION OF GALAXIES

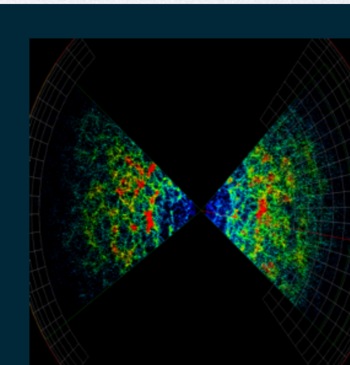
This course prepares the student for state-of-the-art research in galaxy formation, galaxy structure and evolution. The course focusses on the physical processes underlying the formation and evolution of galaxies in a ΛCDM cosmology.




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.

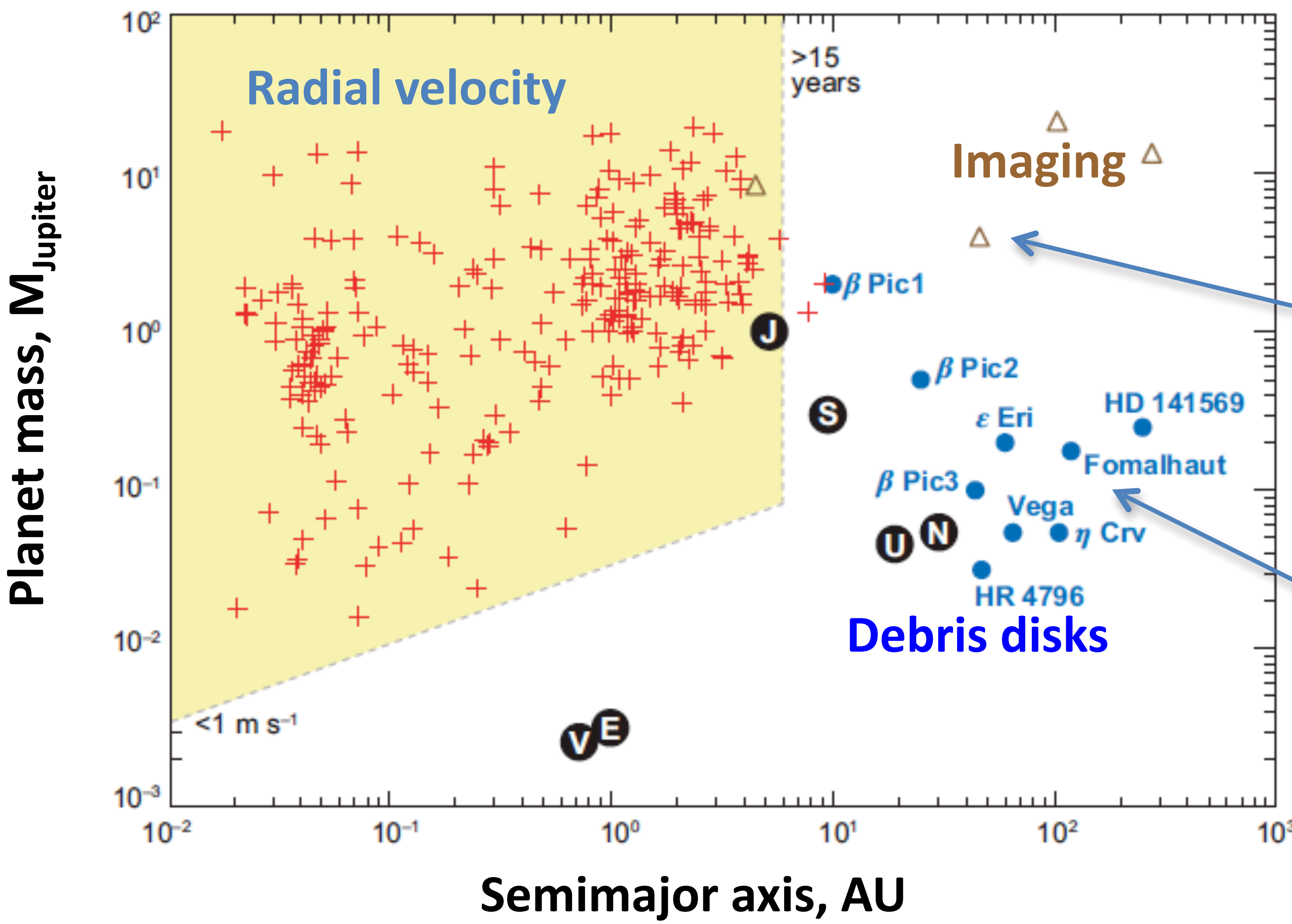


# Planetary system dynamics

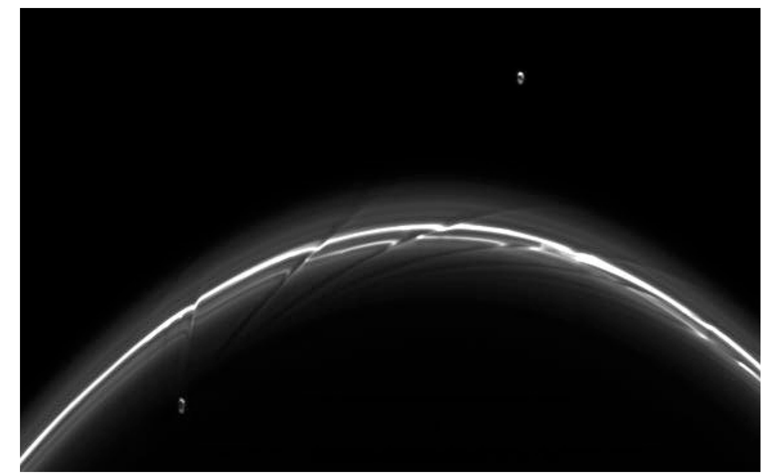
Lecturer: **Mark Wyatt**

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.

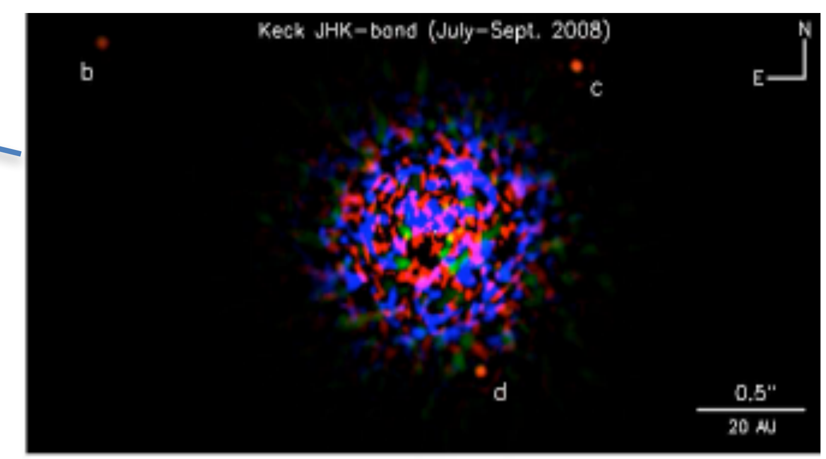
**Topics covered:** planetary system, architecture, two body problem, small body dynamics, three body problem, close approaches, collisions, disturbing function, secular perturbations, resonant perturbations.

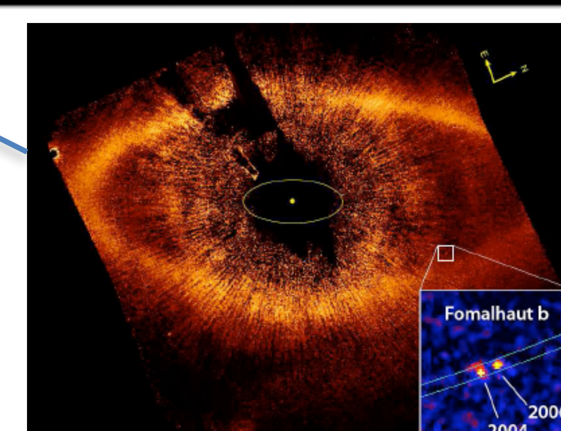



Cassini image of Saturn's F ring and shepherd moons Pandora and Prometheus



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

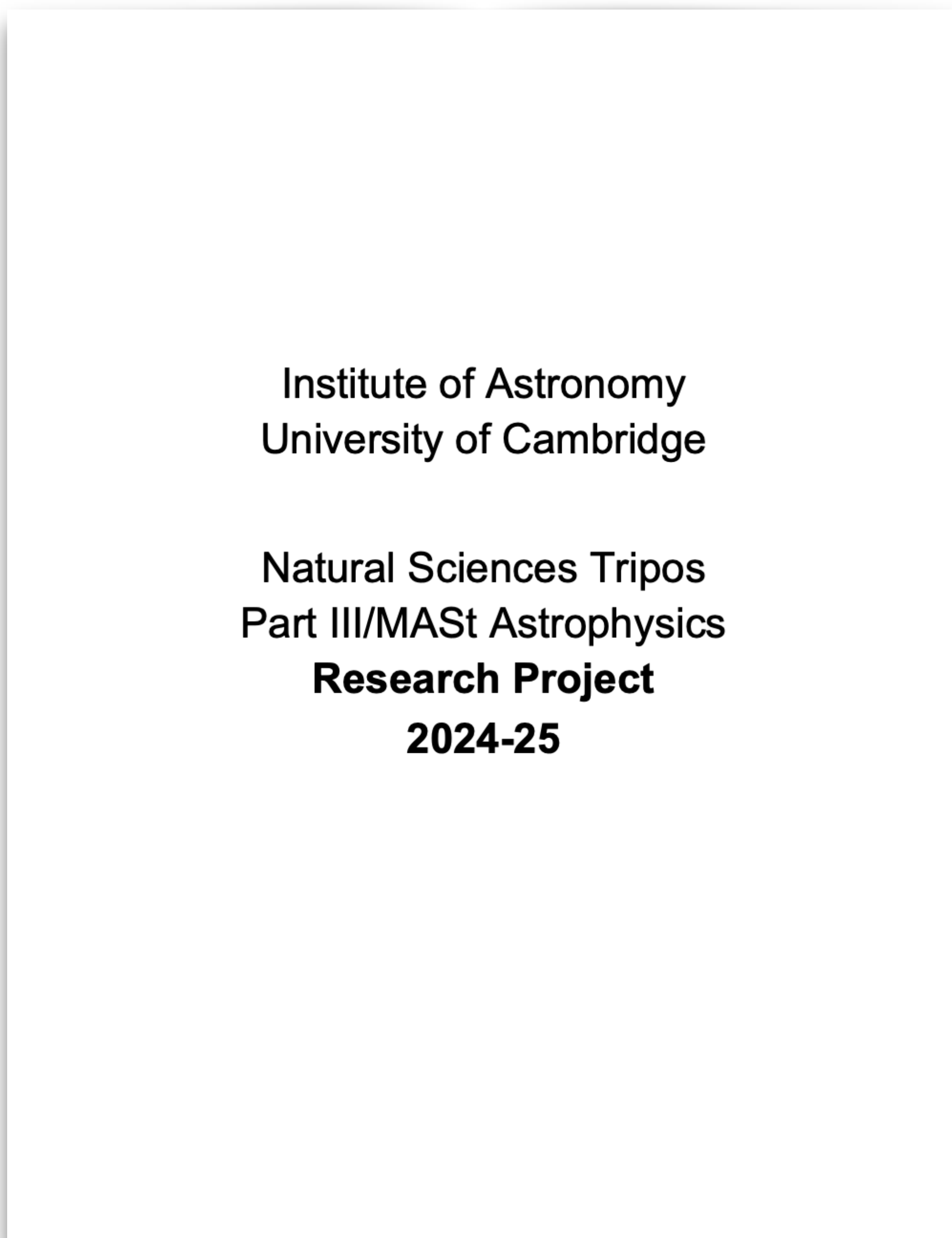
- You will need to provide a short report before Xmas

- 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)

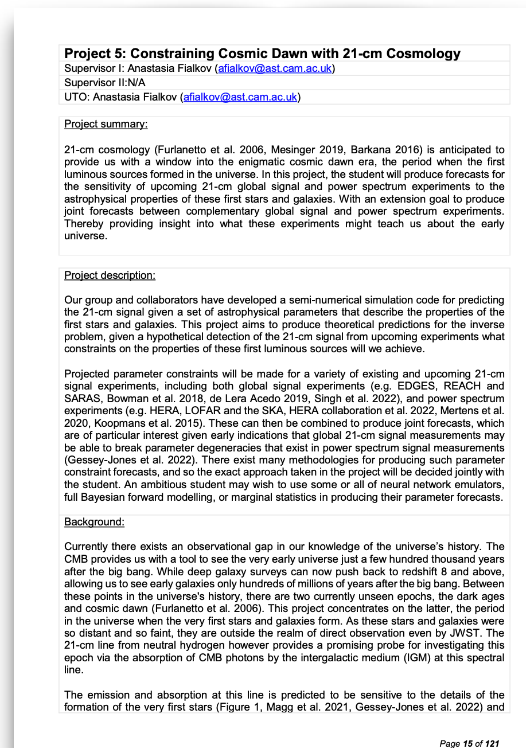
# Research Project Booklet

- 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**



**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

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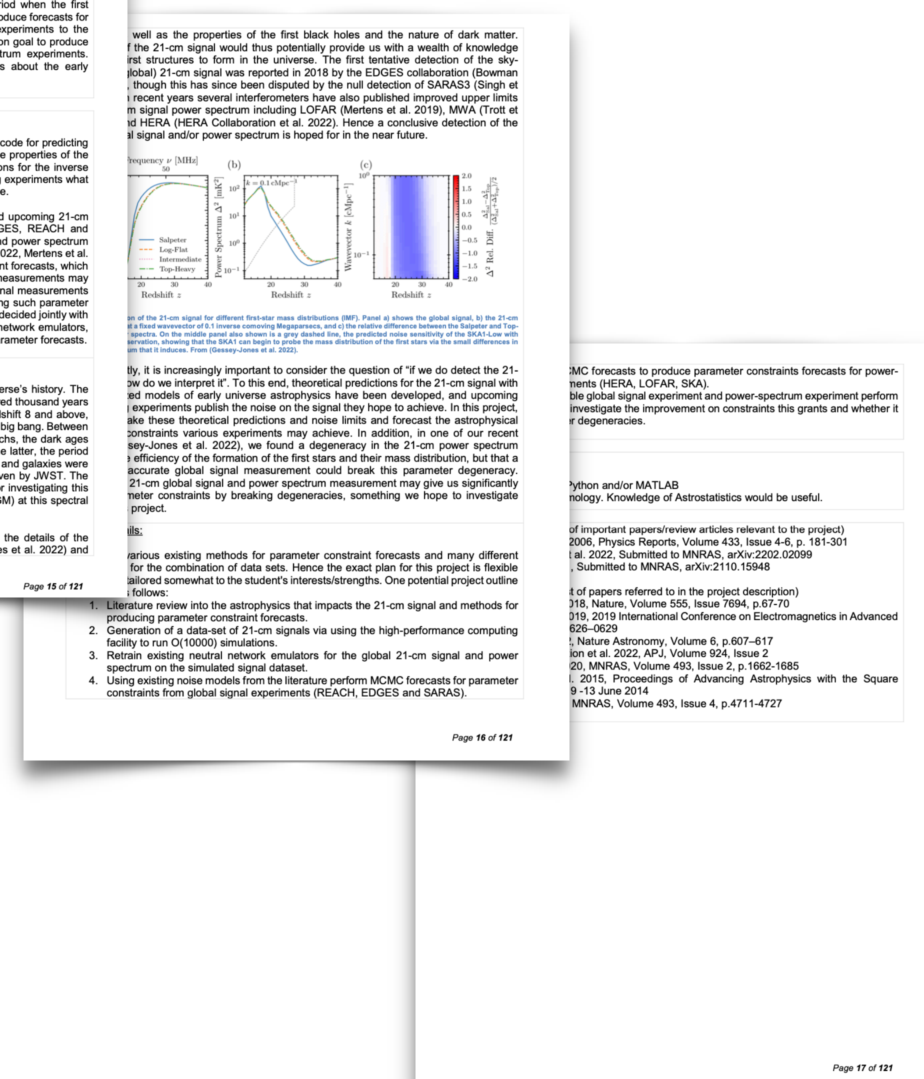


~3 pages per project

# 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 <u>as early as day 1</u>
- 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 <u>other talk series</u> (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!