**Institution: Imperial College London**

**Unit of Assessment: 10 Mathematical Sciences**

**1. Context, Structure, and Strategy**

**A.     Context.** The Department of Mathematics at Imperial College is large and diverse. We are returning 103 staff (94.63FTE): 46 Professors (*P*); 11 Readers (*R*); 17 Senior Lecturers (*SL*); 14 Lecturers (*L*); 8 Senior Research Investigators (*SRI*); and 7 Independent Fellows. 24 are Early-Career Researchers. Over the REF2021 period we hosted 323 postdocs/fellows and enrolled 372 new PhD students. With external funding exceeding £53M, we have sufficient scale to:

- make world-leading and discipline-defining contributions across the breadth of Mathematics and Statistics;
- identify key challenges where Mathematics can *impact* science, the economy, and society; and
- solve outstanding mathematical problems by developing fundamental new tools and, where appropriate, apply these tools to diverse real-world problems.

Central to this vision is fostering a creative, inclusive, and supportive culture where research students receive excellent training, postdoctoral researchers develop into outstanding independent scientists, and staff at all levels realise their full potential.

Our research strategy aligns synergistically with Imperial's academic strategy and its research ethos, which emphasises working across disciplines, quantitative approaches to research, translating ideas into impact, and collaboration with stakeholders locally, nationally, and internationally (REF5a). These principles permeate our research culture. Along with horizon scanning and UKRI and national priorities (see §4E), they steer the new research directions we choose. Our international leadership is fortified by recent high-level initiatives including the CNRS-Imperial de Moivre Research Laboratory (1-of-37 CNRS International Laboratories worldwide across all subjects, only one in UK, §4A), the CFM-Imperial Institute for Quantitative Finance (with French institutions, §1E), and the Imperial-TU Munich Mathematical Sciences Hub.

To deliver our overarching research strategy, we appoint outstanding individuals into coherent research groups (§1C) of sufficient scale and international standing that they attract both world-class researchers and substantial funding from research councils, charities and industry (§3A). We strongly believe that diversity drives innovation, and strategically invest to diversify the pipeline into research mathematics and to foster an inclusive research culture for staff and students (§2K). All of this guides our strategic planning and choices regarding the research groups we grow, always ensuring academic excellence by hiring the very best talent.

Departmental leadership is provided by the Head of Department (HoD), van Dyk, advised by a Management Committee (11 academics, meeting fortnightly) that sets policies on resources, appointments, and research directions. The Department has dedicated Directors of Research (Degond[†])[1] and Enterprise (Muhle-Karbe[†]), and a Diversity Champion (Coates). Degond[†] chairs the Research Committee, which coordinates bids for strategic and College funding, and oversees the Department's own internal research-funding schemes (§2A).

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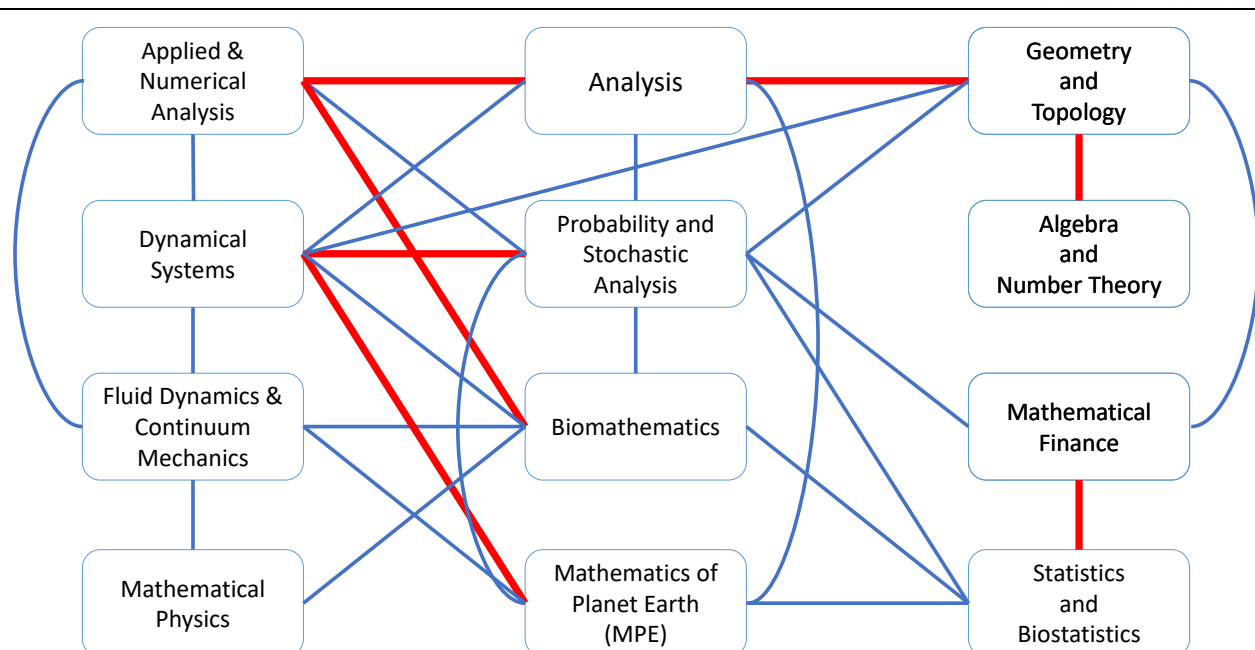[1] REF2021-period academic appointments are marked[†].

*Fig.1: Our overlapping network of research groups. Links strengthened through significant collaboration, appointments and funded projects are indicated; *REF2014 strategic aims in red.*

**B.     Research position relative to REF2014.** We are submitting 94.63FTE (85.23FTE permanent), compared to 100.3FTE (76.9FTE permanent) in REF2014. (Changes to Imperial's Code of Practice resulted in reduced non-permanent FTE, e.g., not including Marie Skłodowska-Curie Fellows.) Comparing averages over the REF2014 and REF2021 periods, our academic-staff FTE increased **13%**; both PhD-student and research-staff FTE increased **77%.** We appointed 39 permanent staff (8 Professors, 2 Readers, 8 SLs, 21 Lecturers) to provide leadership, top talent, succession planning, continuity, and growth. Substantial strategic hiring in Number Theory, Geometry and Stochastic Analysis, the latter two under the respective leadership of Fields Medallists Donaldson and Hairer[†], strengthened our world-leading fundamental mathematics. (Sir Martin Hairer[†] is a new appointment.) Other strategic hiring focused on high-impact and interdisciplinary areas including biomathematics/biostatistics, machine learning, and industry-facing mathematicians in fluids, finance, and data-centric engineering.

Relative to REF2014, annual research income increased **69% (£4.5M/year to £7.6M/year**); per FTE it grew by 80%. Annual EU funding nearly tripled (**£0.76M/year to £2.0M/year**). We won 14 research grants over £1M (e.g., €10M ERC Synergy Grant, $8.5M Simons Collaboration, 2 Royal Society (RS) Research Professorships) and 3 new EPSRC-funded CDTs. This strategic growth has strengthened our world-leading and internationally excellent research (100% 4* environment in REF2014) while further increasing our potential for impact.

**C.     Research structure, objectives, and strategy.** Research staff are organized into a network of twelve overlapping thematic groups, a design that encourages diverse collaboration across the breath of mathematics, see Fig.1, and promotes highly interactive and open research communities for staff and students. Specific REF2014 objectives centred around developing the international profiles of our research groupings and strengthening interactions, both within the Department and with other groups at Imperial and elsewhere. These objectives have all been exceeded. Below, we summarize how we accomplished current goals (specific achievement of REF2014 objectives are marked*) and list future strategic aims.

*Fig.1 summarizes the strengthened links among our research groupings.

**Algebra & Number Theory.**
*P:* Buzzard, Evans[†], Gee, Ivanov, Liebeck, Skorobogatov; *R:* Caraiani[†], Helm[†], Schedler[†];
*SL:* Pal.

Algebra & Number Theory has gone from strength to strength. Buzzard, Caraiani[†], Gee, Helm[†], Pal and Skorobogatov form a coherent world-class group in Algebraic Number Theory with particular expertise in the arithmetic aspects of the Langlands program; Caraiani[†], Gee and Helm[†] (SL, promoted to R) are three of 10 authors of a 192-page 2019 paper proving the Ramanujan conjecture for weight 2 Bianchi modular forms. Caraiani[†] (RS URF and SL, promoted to R), recruited from postdocs at Princeton and Bonn, has won LMS Whitehead and EMS prizes and a €1.5M ERC Starting Grant. This grant, along with Buzzard and Gee's £620k EPSRC grant and Gee's €1.1M ERC Starting Grant (and soon-to-begin €2.2M Advanced Grant), funded a stream of postdocs, complemented by five Heilbronn Fellows. In Algebra, Schedler[†] (SL, promoted to R, André Lichnerowicz Prize) brings new expertise in geometric representation theory, *strengthening connections with **Geometry**, while Evans[†] (P) opens new directions in algebraic aspects of model theory. Number Theory benefits from close interactions with strong groups at King's and UCL, in particular via our back-to-back CDTs in Geometry and Number Theory (£10.7M). London now rivals Paris as the world's leading centre in automorphic forms.

**Analysis.**
*P:* Crisan, Hairer[†], Holzegel, Laptev, Zegarlinski; *R:* Krasovsky; *SL:* Cheraghi[†];
*L:* Taylor[†].

Bringing Hairer[†] (Field medalist, FRS, €1.5M ERC grant) to Imperial was a spectacular boost to Analysis, particularly strengthening its links to **Stochastic** and ***Applied Analysis**. *The interface between Analysis and **Geometry** was strengthened with the appointments of Li[†] (P, see Probability) who brings expertise in stochastic differential geometry, Cheraghi[†] (SL, EPSRC Early Career Fellow) who works at the interface with **Dynamical Systems**, and Taylor[†] (RS-Tata URF and L), who joined the general relativity group led by Holzegel. Working at the interface of **Geometry** and Analysis (nonlinear hyperbolic PDEs), Holzegel was awarded the LMS Whitehead Prize, a Blavatnik Award, and two consecutive ERC grants (totalling €3.3M).

**Applied & Numerical Analysis**.
*P:* Cotter[†], Degond[†], Pavliotis; *R:* Olver[†]; *SL:* Coti-Zelati[†], Nurnberg.

Our Applied and Numerical Analysis group complements our excellence in **Stochastic Analysis** with leading expertise in stochastic differential equations, numerical analysis, and PDEs for fluid mechanics, biology and social sciences. Measures of success include Degond's[†] invited talk at ICM 2018; EPSRC and Leverhulme grants (totalling £2.2M[2], Pavliotis, Carrillo, Degond[†], Olver[†]); a JPMorgan Faculty Award (Pavliotis); and Coti-Zelati's[†] RS URF. Addressing the call for "considerable growth in [UK capacity in] nonlinear PDEs" in the 2016 EPSRC Mathematical Sciences Community Overview, we prioritized PDEs, hiring Olver[†] (R), who works on numerical methods for PDEs, Coti-Zelati[†] (RS URF and SL), who studies PDEs in **Fluid Mechanics** and stochastic **Dynamical Systems**, and Degond[†] (P), who uses PDEs to model self-organization in biology and *built connections with life and social sciences (notably via the Crick Institute),

Looking forward, the group will enhance links with the life and social sciences, and expand into burgeoning areas in optimisation and control, with applications to fluids and data science.

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[2] Total values of grants are given, except in research-group funding totals, where only department income is included.

**Biomathematics.**
*P:* Barahona, Jones; *R:* Keaveny, Shahrezaei; *L:* Monod[†], Thomas, P[†].

*Biomathematics fulfilled its aim of establishing an internationally leading profile with its £2.1M EPSRC Centre for Mathematics of Precision Healthcare (Barahona, PI), one of only five Mathematics-in-Healhcare UK Centres. With wide-ranging expertise in network analysis, data-driven modelling, stochastic processes, and mathematical biophysics, research focuses on developing methods for data-rich biological and medical systems delivering both foundational and high-impact publications. Biomathematics benefits from tight links with **Biostatistics** (Evangelou[†], Filippi[†], Flaxman[†], Monod[†], Ratmann[†]), **Fluid Dynamics** (Keaveny), **Applied/Stochastic Analysis** (Degond[†], Pavliotis), and **Mathematical Physics and Complexity** (Pruessner, Jensen). In addition to individual grants and fellowships (totalling £8.9M), the group's heightened profile enabled co-applications (Barahona, co-I) in major national initiatives: HDR-UK Substantive London Centre (£6.9M); BHF Research Excellence Centre (£7M); MRC Discover NOW (£4.4M). The group co-leads three cross-disciplinary PhD programmes funded by Wellcome Trust, UKRI and Leverhulme (totalling £11.3M, §1D). Its research attracts prestigious independent fellowships (James S. McDonnell Foundation, MRC Skills Development (2), MRC Research, 1851 Royal Commission, Imperial Research (2), Sir Henry Wellcome), and a soon-to-begin UKRI FLF (P Thomas[†]).

With high demand for quantitative bioscience research, strategic aims include: fortifying its international profile in network theory and stochastic systems in biology with further appointments, and continuing to expand precision healthcare through ongoing collaborations with industrial, biomedical, and clinical partners, the NHS, and leading UK and overseas institutions (§4A).

**Dynamical Systems.**
*P:* Holm, Lamb, Turaev, van Strien; *R:* Rasmussen.

Dynamical Systems continues to strengthen and extend its international leadership. Along with other grants (totalling £3.5M), funded projects included two ERC Advanced Grants (Holm, Van Strien, totalling £4.0M), and an EU Innovative Training Network (Lamb, €3.9M). Cutting-edge research in Hamiltonian, low-dimensional, stochastic and random dynamical systems and bifurcation theory ranges from pure mathematics to interfaces with physics, ecology, climate, and finance. The group has specifically *strengthened links with **Mathematics of Planet Earth (MPE)** and **Stochastic Analysis** through work on ocean dynamics (Holm, Crisan, ERC Synergy Grant) and on random dynamical systems approaches to Stochastic (P)DEs. Recent research highlights include Turaev's Séminaire Bourbaki (2019) and Van Strien's ICM 2014 invited talk.

Along with extending leadership in its areas of strength, the group will continue developing interfaces with ocean dynamics (Holm), non-ergodic physics (Turaev), and machine learning (Lamb, Rasmussen, Van Strien).

**Fluid Dynamics & Continuum Mechanics.**
*P:* Craster, Cotter[†], Crowdy, Holm, Mestel, Papageorgiou, Schmid[†], Wu;
*SRI:* Atkinson, Gibbon, Ruban; *R:* Berloff, Keaveny; *SL:* Schnitzer[†], Walton; *L:* Mughal[†].

This highly productive group specializes in dynamics across scales, from microfluidics, plasmonics and micro-swimming to aerodynamics and geophysical fluid dynamics. With a track record of impact-oriented collaboration with the aerospace and defence industries (§1E), the group is central to our cross-disciplinary research, linking mathematics with Imperial Engineering and Physics (*REF2014 priority, §1F). In addition to other grants (totalling £5.7M), large projects

include an EPSRC Programme Grant on Laminar Flow Control (Hall, £4.2M, with Aeronautics) and a CDT on Fluid Dynamics Across Scales (£4.3M, with Engineering). Along with collaborations with UK Research Centre in Non-Destructive Evaluation (e.g., Craster's industrial funding with MechEng totaling £1M, §1E), these create a vibrant cross-disciplinary environment with active co-supervision of PhDs and postdocs.

Complementing strengths in asymptotic and analytical fluid mechanics, future directions will further strengthen industrial collaboration (e.g., Airbus, metamaterials) and expand into modern data-centric fluid dynamics.

**Geometry.**
*P:* Cascini, Coates, Corti, Donaldson, Holzegel, Nicaise[†], Thomas, R; *R:* Schedler[†];
*SL:* Cheraghi[†], Sivek[†]; *L:* Taylor[†].

Our world-leading Geometers continue to thrive under the leadership of Donaldson (awarded $3M Breakthrough prize, AMS Veblen prize, Wolf prize) and R Thomas (awarded FRS, Academia Europaea, £1.3M RS Research Professorship). Appointments of Nicaise[†] (R, promoted to P, ERC Starting Grant, Ferran Sunyer i Balaguer Prize) and Schedler[†] (SL, promoted to R, André Lichnerowicz Prize) strengthened algebraic geometry and *increased interactions with **Algebra and Number Theory**, a great benefit to the CDTs in Geometry and Number Theory (250 applicants/year). Three EPSRC Programme Grants (£5M, Corti, R Thomas, Neves), various ERC grants (€6.3M, Coates (2), Donaldson, Neves, Nicaise[†]), large EPSRC grants (£2.7M, Cascini, Cheragi[†], Nicaise[†], R Thomas) and an $8.5M Simons Collaboration (Donaldson, Haskins, §4A) enabled a dynamic community of postdocs.

Looking forward, we aim to leverage our pre-eminent algebraic geometry and analysis groups under Donaldson's leadership by strengthening differential geometry, geometric analysis, and topology. We have appointed Cheragi[†] (SL, EPSRC Early Career Fellow, linking to **Analysis** and **Dynamical Systems**), Taylor[†] (L, see **Analysis**), and Sivek[†] (L). R Thomas' RS Research Professorship enables a further hire in symplectic topology.

**Mathematical Finance.**
*P:* Brigo, Muhle-Karbe[†], Zheng; *SRI:* Bingham; *R:* Cass, *SL:* Jacquier, Pakkanen[†];
*L:* Neumann[†], Siorpaes[†].

This group is a leading centre for research in volatility modelling, risk measurement, valuation, hedging, market microstructure, statistical learning in finance, rough paths, **Stochastic Analysis,** and **Geometry**. The recruitment of Muhle-Karbe[†] (P), Pakkanen[†] (L, promoted to SL), Siorpaes[†] (L) and Neumann[†] (L) strengthened expertise in emerging areas including market microstructure and statistical finance. Pakkanen[†] is joint with **Statistics**, building *links planned in REF2014. The group has a leading role in two successful EPSRC-funded CDTs (£10.2M, financial computing, random systems).

Highly effective industrial engagement is the group's hallmark. Top practitioners from companies such as Deutsche Bank, IHS-Markit, Macquarie Bank, and Banca IMI are visiting faculty and collaborate with staff, steering research toward impact and industry. Created in 2014, the CFM-Imperial Institute (£2.4M from Capital Fund Management, director Muhle-Karbe[†], §1E) provides an array of conferences, seminars, and exchanges of researchers with Ecole Polytechnique, *strengthening ties with Paris (the other leading European centre in Quantitative Finance). *Our annual Imperial-ETHZ workshop similarly strengthens ties with Zurich.

**Mathematical Physics & Complexity**.
*P:* Craster, Jensen, Parry; *SRI:* Edwards, Hewson; *R:* Graefe[†]; *SL:* Barnett, Pruessner.

This leading group for research in quantum mechanics, statistical mechanics, hard condensed matter theory and complexity enjoys strong links with Imperial Physics and our **Fluid Dynamics** and **Biomathematics** groups, funded e.g., via a EPSRC Programme on Metamaterial for Multiscale Physics (Craster, £2.6M, with physics). The appointment of Graefe[†] (RS URF and SL, promoted to R, €1.3M ERC Starting Grant, LMS Anne Bennett prize) brings new expertise in theoretical quantum dynamics.

Adding to our strengths in quantum and condensed-matter theory, we will leverage the newly funded Borland Fellowship (£950k legacy gift from Dr Borland, former National Physical Laboratory head of theory) to bring outstanding ECRs to the group over the next decade.

**Mathematics of Planet Earth (MPE).**
*P:* Cotter[†], Crisan, Gandy, Holm, Jones, Veraart; *SRI:* Bingham; *R:* Berloff, Rasmussen;
*SL:* Ham[†], Kantas.

*Developing MPE into a world-class research group was a strategic achievement. The group's international profile was boosted by its *leadership of a highly successful CDT in MPE (Crisan, £5.5M, with Reading). The recruitment of Cotter[†] (SL, promoted to P) and Ham[†] (NERC Fellow and SL, promoted to R effective September 2020) led to close links with the European Centre for Medium Range Weather Forecasting and the UK Met Office, e.g., Cotter[†] and Ham[†] develop computational methods underpinning next-generation atmospheric models for the Met Office. *The group plays a significant role in the NERC DTP in Science for a Changing Planet (supervising 7 PhDs, Cotter[†] on Board). Research focuses on computational models, **Statistics** models, geophysical **Fluid Dynamics**, stochastic parameterisation and data assimilation, and ***Dynamical Systems** tools. MPE benefits from a College-wide prioritization led by the Grantham Institute for Climate Change and holds significant funding from EPSRC (£1.8M), NERC (£2.3M). and a €10M ERC Synergy Grant (Crisan, Holm, §4D).

Looking forward, the group will further strengthen international links (e.g., IFREMER, France) to lead computational modelling of Planet Earth with observational data, further pursuing numerical and software strategies for massively parallel ocean, weather and climate models under EPSRC-funded Platform (PRISM) and UKRI Excalibur programme grants.

**Probability & Stochastic Analysis.**
*P:* Brigo, Crisan, Gandy, Hairer[†], Li[†], Muhle-Karbe[†], Pavliotis, Veraart; *SRI:* Bingham;
*R:* Cass, Rasmussen; *SL:* Jacquier, Kantas, Pakkanen[†]; *L:* Neumann[†]. Rodriguez[†].

*Following a long-term strategic goal, we have grown Probability and Stochastic Analysis into a world-class centre with top experts in stochastic PDEs, regularity structures, stochastic geometry, stochastic homogenization, rough paths, stochastic filtering, and branching processes. Recruiting 2014 Fields Medalist Hairer[†] (P) was a massive boost. Six additional appointments – Li[†] (P), Muhle-Karbe[†] (P), Pakkanen[†] (L, promoted to SL), Chandra[†] (Leverhulme Early Career Fellow, appointed L effective September 2020), Neumann[†] (L), and Rodriguez[†] (L) – joined a coherent team that now spans the breadth of the Department (Fig.1) and enjoys strong interactions with Imperial's Grantham Institute and the CNRS-Imperial de Moivre Laboratory (§4A). The group attracted significant funding, including Cass (£4.1M EPSRC Programme Grant on Mathematics of Data Science, aforementioned EPSRC CDT), Crisan (aforementioned EPSRC CDT, Synergy Grant), Hairer[†] (£1.4M RS Research Professorship, ERC grant), Pavliotis (£1.6M EPSRC Platform Grant).

In future, the group will capitalize on its world-leading expertise in SPDEs (Hairer[†], Li[†], Crisan, Chandra[†], Coti-Zelati[†]) and expand ties with **MPE** (Crisan, stochastic geophysical fluids), ATI (Cass, rough paths theory), Bath (Neuman[†], Hairer[†], Chandra[†], super-processes) and TU-Munich (Pavliotis, homogenization).

**Statistics.**

*P:* Adams, Gandy, Heard, McCoy, Nason[†], van Dyk, Veraart, Young; *SRI:* Hand, Walden;
*SL:* Cohen, Evangelou[†], Filippi[†], Flaxman[†], Kantas, Pakkanen[†];
*L:* Battey[†], Bodenham[†], Duncan[†], Lau[†], Monod[†], Pike-Burke[†], Ratmann[†], Ray[†].

The Statistics group is committed to rigorous interdisciplinary research, developing methods for applied problems, and the statistical theory underpinning these methods. Particular expertise in statistical learning, Bayesian, computational, spatio-temporal, and applied-probabilistic methods is deployed to a rich array of interdisciplinary collaborations, ranging from cyber-security, to astrostatistics, **MPE**, **Biomathematics**, medicine and epidemiology, public policy, energy, **Finance**, and data-centric engineering. Along with other funding (totalling £4.9M), collaborative work was supported by an Alan Turing (ATI) Data-Centric Engineering Programme (£2.9M, Girolami, McCoy, §4B) funded by Lloyd's Register Foundation, an EPSRC Programme (£3M, Girolami), and secondments to ATI (Duncan[†], Lau[†]) and the Heilbronn Institute (Adams, Heard). An array of industrial partners includes those associated with the EPSRC-funded CDT in Statistics and Machine Learning (£6.2M + £610k industrial funding, with Oxford). The group's world-class researchers (e.g., Battey's[†] back-to-back EPSRC Fellowships, Hand's 2016 ENBIS George Box Prize, van Dyk's 2019 ASA Founders Award) are augmented by engaged long-term visitors from government and industry (§2E). *A strategic decision to expand and diversify enabled the appointments of Battey[†], Ray[†], Nason[†] (Theory/Methodology); Bodenham[†], Flaxman[†], Pike-Burke[†] (Learning); Duncan[†], Lau[†] (Data-Centric Engineering); Evangelou[†], Filippi[†], Monod[†], Ratmann[†] (*Medicine and Epidemiology, REF2014 strategic aim), and Pakkanen[†] (*Finance, REF2014 strategic aim).

Future strategic aims include: further growth to enhance international leadership in statistical learning and methods for high-dimensional and complex data, and strengthening research activity with public policy and government through links to the ONS Data Science campus and the Government Statistical Service (e.g., Hand, Allin, Pullinger, Nason[†], Flaxman[†]).

**D.      CDTs.** The UoA took a leading role in 7 **EPSRC-funded CDTs:** 4 in the 2014-22 round (Financial Computing, Fluids Across Scales, Geometry and Number Theory, Mathematics of Planet Earth, totaling £18.6M); 3 in the 2019-27 round (Geometry and Number Theory, Random Systems, Statistics and Machine Learning, totaling £18.8M). Together they foster diverse research collaborations with our partners (Oxford, Reading, Kings, UCL), with Imperial Departments (spanning Engineering, Medicine, Computing, Physics, and Life Sciences), and across the Department (e.g., Random Systems links applied analysis, biomathematics, dynamical systems, mathematical finance, statistics, probability and stochastic analysis, see Fig.1). This is **further supplemented by cross-disciplinary, cross-departmental PhD programmes**, e.g., an Imperial-led Marie Skłodowska-Curie ITN (€3.9M, PI Lamb) combining mathematics, climate research, ecology and finance; the Wellcome Trust PhD in Theoretical Systems Biology (£2.4M, Barahona co-I, co-director); the UKRI CDT AI4Healthcare (£7.8M, Barahona co-I); and a Leverhulme PhD Programme in Cellular Bionics (£1.1M, Jones co-I, co-director). 126 UoA students studied in these CDT/ITNs. As per Recommendation 22 of the Bond Report, our CDT/ITNs are engines of impact and knowledge exchange via their array of cross-disciplinary, industrial, SME, and government partnerships. Partners provide student co-

supervision, embedded research opportunities, and access to data (e.g., Airbus, Amazon, ATI, DeepMind, EDF, JPMorgan, Met Office, ONS, NPL). The CDT/ITN successes attest to strength across the Department's research areas, and to strong collaborations between research groups within the UoA, in College, and externally.

**E.     Enabling and facilitating impact.** The "application [of our research] in industry, commerce and healthcare" forms the core of Imperial's mission statement and is central to the Department's vision and strategy. Because advanced mathematics is fundamental to the modern technology that drives everyday life, our impact is broad and diverse. Pathways for non-academic impact involve both direct interaction with end-users and collaboration with implementation-oriented academic disciplines, thus enabling access to other groups of end-users. Impact of our high-quality research persists beyond REF's twenty-year timeframe, often forming the generic methodology of a field, e.g., Cash-Karp ODE solvers, Davis' piecewise stochastic dynamics, Smith's Bayesian computation. Imperial's world-leading Engineering, Medical, Business and Science faculties, our proximity to the City of London, government, and national institutes such as ATI and Francis Crick, and our diverse range of CDTs are all opportunities that inform our strategic vision toward impact.

To leverage these opportunities for non-academic impact, we prioritize engagement with the health, finance, tech, and public sectors as well as industrial, engineering, environmental, defence, and security applications. As detailed below, *the effectiveness of this impact strategy is demonstrated by our impact case studies:*

> **C1**: *Informing Public Policy to Control Covid19.*
> **C2**: *Safety and Quality of Healthcare Delivery.*
> **C3:** *General-Purpose Bayesian Software.*
> **C4**: *Laminar-Flow Wing Design for Next-Generation Aircraft.*
> **C5**: *Characterizing Defects for Nuclear Safety*.
> **C6:** *Vaccine Coverage and Confidence.*
> **C7**: *Statistical Cybersecurity*.

***Engagement with health sector***.  Our Biomathematics and Biostatistics research is used to effect in Public Health, Medicine, and the pharmaceutical industry, aiding the analysis of clinical and epidemiological studies and NHS performance monitoring. Impact-enabling collaborations are fostered by close links with biostatisticians in Imperial Public Health, our Mathematics in Medicine Group (§4A), and our EPSRC-funded Centre for Mathematics of Precision Healthcare (CMPH, §1F). This enables mathematical research leading to impact, carried out both by UoA staff and our collaborators in Public Health (e.g., Aylin, Bhatt, Bottle, Ferguson, Holmes, Larson). Immediate worldwide impact in the fight against Covid19 stemmed from widespread use of our Bayesian hierarchical methods, guiding the imposition/lifting of non-pharmaceutical interventions (e.g., school closures, stay-at-home orders) and saving many lives [C1]. Working with Dr Foster Ltd, we developed mortality alerts that were major triggers of interventions that improved poor-performing hospitals [C2]. Barahona carried out funded work with Syngenta (developing biomarkers for early detection of carcinogenic toxicity of herbicides); GSK (producing software using graph-theoretic methods to detect druggable allosteric targets in proteins); and Biogen (predicting patient response to a drug aimed at slowing degenerative disease). UoA staff (led by Best) provided the mathematical underpinning for WinBUGS software, an inspiration for the later Stan package; both are widely used in Bayesian analyses, including clinical trials and public-health decision making [C3].

***Engagement with financial sector.*** We have a long record of developing advanced mathematical tools, often using stochastic analysis, for direct and immediate impact in banks, hedge funds, insurance, and investment companies (e.g., Davis' work). Jacquier's "Surface Stochastic Volatility Inspired" parameterization provides robust arbitrage-free inter/extrapolation of option prices and has been widely adopted by banks, clearing houses, hedge funds and financial-software companies for their Equity desks. Brigo's CEPIX model (developed in consultation with the European Stability Mechanism, published in 2015) led to the creation of a Euro exit probability index for EU countries. The **CFM-Imperial Institute for Quantitative Finance** (£2.4M from CFM, 2014-24) facilitates industrial links leading to impact, e.g., work on non-performing loans (Brigo), crowding and optimal trading (Neuman with CFM), limit orders for hedging (Muhle-Karbe[†] with Citadel), cross-price impact and alternative trading venues (Muhle-Karbe[†] with Goldman Sachs). Industrial collaborators include JPMorgan, Lloyd's, Macquarie Bank, Nomura, Deutsche Bank, Banca IMI.

***Engagement with industry and tech sector.*** Standing alongside Imperial's world-class engineering and science departments enables long-term interdisciplinary collaborations (§1F) resulting in sophisticated Mathematics with direct industrial impact. Airbus' "Blade" laminar-flow-control wing demonstrator took flight in 2017, showing that wing drag could be reduced by 10% and $CO_2$ by 5% [C4], and is a tangible product of our collaborative aerospace research (total funding £5.3M). Our multidisciplinary CDTs (§1D), CASE, and iCASE studentships (§2J) incubate dozens of industrial partnerships, providing funded internships, collaborative projects, student inroads to careers in industry, and mechanisms for staff engagement on problems with direct industry impact; this multipronged strategy has produced new mathematics impacting manufacturing (via Rolls-Royce), energy markets (EDF, Edison Energy), AI/ML (JPMorgan, Deep Mind), voice-activated devices (BP). Our long-term interaction with the **National Research Centre for Non-Destructive Evaluation** at Imperial produces numerous industrially sponsored joint grants and studentships (totaling £983k) and a pipeline for mathematical modelling that reaches directly into industry with commercialized software (e.g., DISPERSE); a recent project involves scattering from, and detection of, rough cracks in the nuclear-power industry [C5], enabled by matching funding from BAE systems, Rolls-Royce, National Nuclear Laboratory, EDF, and Amec Foster Wheeler. The UK is a world-leader in non-destructive modelling partially due to the direct relationship between mathematics and engineering at Imperial. [C2,C4,C7] also involve engagement with industry (Dr Foster, Airbus, Microsoft).

***Engagement with public sector, government, and international bodies.*** We actively encourage staff to accept public-sector roles and to collaborate with policy-making bodies. Hand is a non-executive director of UK Statistics Authority (2013-21), which oversees the ONS and Office for Statistics Regulation. He also serves on the European Statistical Advisory Committee, which advises the European Commission. Such roles directly impact public policy: Hand's work with the ONS's Technical Advisory Group influenced the UK's *Measuring National Wellbeing* programme, which produces influential annual statistics. Hand was made "Companion of the Commonwealth Partnership for Technology Management", for his advice to central-bank governors and ambassadors of Commonwealth countries about national-data strategies.

Cotter[†] and Ham[†] develop weather, climate, and ocean models (£500k NERC funding); their numerical methods were adopted by the Met Office for next-generation UK forecasting. This is part of our broader engagement with climate and environment, e.g., Crisan and Holm's ERC Synergy Grant on Upper Ocean Dynamics (§4E).

Jones's work on large-scale surveys on vaccine attitudes worldwide was critical to WHO warnings on "vaccine hesitancy" and impacted French vaccine policy which saved lives [C6]. Engagement with government decision makers influenced Covid19 responses [C1, see above]. Flaxman[†] works with the World Food Program on food security and WHO on vision-loss prevention; Ratmann[†] works with UNAIDS on HIV prevention in Africa ($5.6M, Gates Foundation).

[C2,C5] involved engagement with the NHS and government regulators, respectively.

***Engagement with defence and security.*** Our expertise is actively sought by defence and security institutions, including GCHQ, MoD, and in the US by Los Alamos National Laboratory and USAF. (We are not reporting details of confidential work.) Heard and Adams' work identifying unusual patterns in large computer networks is critical for early warning of fraud or cyberattacks [C7]. This timely work is relevant both to government bodies where we have assigned staff to long-term secondments (via Heilbronn) and to the private sector where staff collaborate with Microsoft and QinetiQ. Staff provided direct advice to MoD through its Defence Science and Technology Strategy (Dstl), and obtained MoD funding via defence companies (e.g., Thales, Atlas Elektronik, QinetiQ) through Progeny and Centre for Defence Enterprise processes. Total REF2021-period funding exceeded £2.6M.

***Quantitative Sciences Research Institute (QSRI) and impact-enabling workshops****. To create new collaborations and provide mathematical input directly into problems identified by industry and applied scientists, the Department launched its QSRI in 2017. After an initial investment of £50k, the QSRI is now self-sustaining. Ten workshops focused on strategic growth areas (AI/ML, Mathematics in Medicine, collaborations with industry and/or engineering), e.g., *Data Science for Cybersecurity* (2017), *Field Theories come to Life* (2018), *Data-Centric Engineering: Instrumented Infrastructure* (2019), *Assessing the Impacts of Public-Health Policies* (2020). These interactions have significant benefits; for example, the 2018 *Acoustics & Metamaterials* workshop led directly to £1.3M UKRI Strategic Priority Fund (Physics of Life) and €3M EU FET Grants (Craster co-I). QSRI Workshops were complemented by 47 other Imperial-based Department-funded mathematics workshops (§2A).

***Staffing, sabbaticals, and secondments.*** The Department actively uses appointments, promotions, sabbaticals, and secondments (§2D-2F) to encourage staff to achieve impact. Adams (2011-16) and Heard's (2013-19) long-term secondments to Heilbronn established our international profile in ***defence and security,*** see above. Lau[†] (2017-19) and Duncan's[†] (2018-current) secondments to ATI led to new data-centric engineering research with Autodesk, MX3D and Rolls-Royce (§4B). Hand reduced his Imperial FTE to serve as Chief Scientific Advisor at Winton Capital (2010-18) to advise 150 researchers on statistics, machine learning, and data science.

***Enabling Enterprise.*** Knowledge transfer and research commercialization are central to our impact strategy, supported by Imperial's *White City Incubator* and *Imperial Enterprise* (REF5a)*.* We exercise maximum flexibility to support enterprise, e.g., 20% of staff's time can be devoted to consultancy, often mediated by *Imperial Consultants* (helping 12 staff consult with 14 companies on 29 projects). Gould (RA, mathematical finance) launched the start-up Sonalytic, a 2016 finalist in *Imperial Enterprise's* Venture Catalyst Challenge, to deploy his next-generation ML-based audio-identification technology to identify, monitor, and discover music. Sonalytic was sold to Spotify in 2017 for an undisclosed sum.

The Department takes advantage of Imperial funds devoted to enabling impact via enterprise, (e.g., UKRI Impact Acceleration Funds, SME Engagement Fund, travel grants for industrial partnerships, Covid-19 Research Fund). The EPSRC Impact Acceleration Account provided £380k to seed what, over the REF2021 period, became Imperial's Advanced Hackspace (Jones, co-I, then co-Director), an innovative community of 2000+ staff and students from all backgrounds, disciplines and levels of expertise developing prototypes and research ideas. The hackspace has earned substantial external/industrial funding (totalling £3.85M), supported 3 of Forbes 30 Innovators under 30, and supported dozens of spinouts (e.g., award-winning Mitt, Aergo, Gravity Sketch, Fresh Check, Entia).

With industrial partners Airbus, Bombardier, Crossword Cybersecurity, CONTEXT, and Rolls-Royce, we won six Innovate UK Grants (totaling £19.3M), funding a wide range of impact-producing activities. For instance, Mughal[†] provides methods to predict performance of laminar-flow wing designs to Airbus [C4].

Our Impact Case Studies were enabled by industry-facing workshops [especially C4,C5,C7], secondments [C7, Heard and Adams to Heilbronn], hiring [C1, Flaxman[†]; C4, Mughal[†]], sabbaticals [C5, Craster], and enterprise activities [C5-C6, consultancy; C7, patents].

***Evolving strategy for impact.*** Investing in areas with clear pathways to impact is paramount and we will do so by growing biomathematics, data-centred research, statistical learning, and MPE. We have already leveraged ***Imperial's 2020 Academic Strategy*** for College investment in statistical learning (300m$^2$ of new space, 8 new academic appointments by 2025) and biomathematics (2 appointments by 2022). ***Imperial X,*** a major new collegewide initiative, will allow us to co-locate data-science-oriented staff and students with industrial partners and like-minded multi-disciplinary Imperial colleagues. Imperial's state-of-the-art White City Campus will serve as an incubator for this new model of co-discovery and co-creation, thus enabling growth of our core activities.

Evolving ***Topical Groupings*** enable us to mobilize staff into recognizable foci of impact-oriented research. We recently formed *Mathematics in Medicine* (§4A), and *MPE* (§1C) and are actively shepherding *Mathematics of Machine Learning* (spanning applied/stochastic analysis, biomathematics, dynamical systems, statistics). A ***Knowledge-Exchange Committee*** with dedicated funding has been approved to facilitate impact-generation via software development (an identified bottleneck for impact), industry-engaging workshops, staff exchanges with industrial partners, and seed funding for impact-generating research.

**F.     Support for interdisciplinary research.** We place mathematics at the centre of a diverse array of collaborative research, continually enhancing and extending our interdisciplinary reach within Imperial's world-class Departments in Engineering, Natural Sciences, Business, and Medicine. Support for this strategy mirrors our support for impact: engaging with researchers in life, physical, and social sciences, engineering and business; designing strategic workshops to build new multidisciplinary collaborations; and equipping staff for these collaborations via sabbaticals, joint appointments, and recruitment.

Our **Quantitative Sciences Research Institute** (§1E) creates new interdisciplinary collaborations across Imperial. A series of workshops (2014, 2015, 2018) co-funded by CMPH and QSRI spawned a variety of interdisciplinary collaborations between UoA and MRC London Institute of Medical Sciences (LMS) researchers, including an on-going position as "Mathematician in Residence" for Shahrezaei at the MRC-LMS leading to funded research (£250k Leverhulme, £1.5M Brain Tumour Charity).

Our commitment to interdisciplinary research is evidenced by new cross-disciplinary and joint **appointments** across strategic areas, including at the interfaces with biomedicine/public health (P Thomas[†], Evangelou[†], Filippi[†], Monod[†], Ratmann[†]), engineering (Duncan[†], Lau[†]), physics (Graefe[†], Taylor[†]), and machine learning (Bodenham[†], Flaxman[†], Pike-Burke[†]). Placement agreements with the **Crick Institute** support staff development; Pruessner's 2016 Crick **sabbatical** led to new projects and PhD-student funding, enabling him to branch into work with experimentalists and data analysis. To maximise interdisciplinary links, Jones and Shahrezaei (Biomathematics) are co-located with Life Sciences and the Complexity group (Jensen) is co-located with Physics collaborators.

The result is exceptionally successful **engagement with research in other disciplines**: 35.4% of REF2021-period research grants had formal cross-disciplinary collaboration with other Departments or UK/overseas institutions. We further strengthened our interface with Physics through links between Geometry and Theoretical Physics (R Thomas's RS Research Professorship; Holzegel's back-to-back ERC grants and Adams Prize; Taylor's[†] URF; and a Simons Collaboration Grant, §4A), a £2.6M Metamaterials Programme Grant (Craster), and an international Astrostatistics collaboration partially funded by back-to-back Marie Skłodowska-Curie RISE Grants (€1.1M, van Dyk, Mortlock – joint appointment). Collaborations with Engineering have been fortified with, e.g., new initiatives in Data-Centric Engineering (Girolami, McCoy, Duncan[†], Lau[†]) through a £3M EPSRC Programme Grant and a £2.9M Lloyd's Register project (§4B); participation in an EPSRC Programme on Low-Carbon Energy Systems (Flaxman[†], led by Electrical Engineering); and through EPSRC Programme and Platform Grants (totaling £7.4M, Cotter[†], Craster, Hall, Ham[†], Papageorgiou, Pavliotis, Parry) with Chemical Engineering and Aeronautics. We act as quantitative leads within Imperial's cross-cutting initiatives, from the top-level Global Institutes (Data Science, Grantham Climate Change, Global Health, Infection) to 18 of its Centres/Networks in emergent areas (e.g., leadership roles in Complexity, AI/ML, ChemBio, Neurotechnology). Mathematics for Planet Earth has led a rich array of collaborations, e.g., with Grantham, including substantial funding (e.g., NERC awards totalling £2.3M; €10M Synergy Grant, Holm, Crisan, §4D). These interdisciplinary links with engineering, computing, AI/ML, climate, and biomedical sciences are reinforced with an array of **cross-cutting PhD programmes and CDTs** (§1D).

Our interdisciplinary research is a **proven path to impact**: Hall's Programme Grant with Aeronautics facilitated [C4] and Craster's collaboration with Mechanical Engineering led to [C5], see §1E. The **EPSRC-funded Centre for Mathematics of Precision Healthcare** (£2.1M, Barahona, Jones), awarded to deepen and extend collaborations with data-rich biomedical and healthcare problems, facilitated [C6] and co-funded work with clinicians at Oxford and The Gambia to improve diagnosis of childhood malaria, with Imperial NHS Trust medics to extract information from free text in hospital incident reports, and with NHS personnel to analyse patient-sharing between hospitals and the implications of patient choice on inequality and efficiency.

Together, these interdisciplinary links embed mathematics into the fabric of the University, providing a lively interplay of research, strengthening the UoA, directing it toward external challenges, and thus enabling the impact that is vital to its sustainability.

**G.     Progress toward open and reproducible research.** Staff actively promote open and reproducible research in the broader community: Ham's[†] Firedrake project enables researchers to archive the exact versions of their code, citable with a DOI on the CERN science-data repository Zenodo.org; Ratmann[†] helped revise the data-sharing procedures of the PANGEA

consortium to enable sharing of HIV-sequence data; Gee, as a MathOA board member, lobbies journals to adopt a "fair-open-access" model.

Staff are required to post all publications on a REF-compliant open-access repository. Aligning with the *Concordat on Open Research Data,* staff must, whenever possible, publish data and computer codes necessary to make their research reproducible. Our software quantifying the effectiveness of non-pharmaceutical interventions on the Covid19 pandemic [C1] is opensource, as is Firedrake; WinBUGS [C3] is freely available. Barahona's opensource SC3 package for single-cell analysis (Nature Methods 2017) is on Bioconductor (34k downloads, 615/month).

**H.      Proactive support for research integrity.** The UoA not only follows Imperial's data-management policy for data access and protection, but also takes measures to guarantee compliance with GDPR via a dedicated Data-Protection Coordinator. All PhD students take courses on plagiarism and researchers involved with confidential data (e.g., medical) undergo specific training. All staff must undertake unconscious-bias training and the UoA enforces balanced interviewing and examination panels. Staff are leaders in research integrity in the College, UK, and internationally. Parry is Deputy Chair (2015-21) of Imperial's Research Ethics Committee. As a member of the UK Statistics Authority's Board, Hand helped revise its Code of Practice for Statistics (2019), and also publishes extensively on Data ethics.

## 2. People
## Staffing Strategy and Staff Development

**A.      Staff-development strategy.** *New academic staff* are supported with: 50% teaching for one year, no administrative duties for 3 years (lecturers), a Department-funded PhD studentship, tailored research funds (travel, equipment), relocation, housing, and visa allowances. Total awarded start-up funds (excluding teaching/admin reductions) were £2.8M, twice that of REF2014 (per appointment).

We assign all new staff a mentor who provides support and guidance; (Senior) Lecturers undertake a 3-year probation (with formal midterm review). The Department provides full support for grant applications (informal mentoring from group members, formal internal review coordinated by Research Committee, internal mock panels, and external interview coaching, as appropriate); this support is also available for established staff. This support is effective: 81% of incoming staff (with 1+ year in post) were already awarded external grant funding.

The Department-funded **Cecilia Tanner Schemes** provide flexible small-scale research funding for ECRs as seed funding and stepping-stones to external grant funding (and to other staff transitioning to new research areas or during "funding gaps"). These schemes (and their precursive EPSRC Platform Grant, Lamb, £526k) supported numerous short-to-medium term research visits (102 incoming; 211 outgoing/conferences), provided underpinning funding for 47 Imperial-based workshops, and funded public engagement.

Nurturing younger staff and enabling career progression is key to maintaining our research strength. Nomination for promotion is by a diverse committee (female and pre-professorial staff are always represented) that *considers all pre-professorial staff for promotion every year.* Informal external references are sought, and strong cases are progressed. Self-nomination is also possible. Interviews are mandatory for promotion to Reader and Professor and follow the appointment format (§2B, externals replaced by Assistant Provost); mock interviews are provided and exit interviews give feedback. In the rare event of failure (2% over REF2021 period), a concrete action plan, monitored at annual-review meetings, is launched to ensure

successful re-application. Of 39 pre-professorial staff submitted to REF2014, 26 are still in post, of which 20 were since promoted: 11 are now Professors, 6 Readers and 3 Senior Lecturers. Of 18 REF2021-period pre-professorial appointments with 2+ years in post, 11 have been promoted.

*Established staff:* The Department places considerable emphasis on reducing administrative burden to enable research. We appointed eight permanent Teaching Fellows who take on administrative roles (e.g., UG Admissions, Senior Tutor) and work on curriculum review and development. Academic teaching is capped at two (30-hour) courses/year. Staff actively participate in high-quality training (e.g., academic leadership, management, industrial engagement) and *all* academics (joining before October 2019) either have a current PhD student or completed one during the REF2021 period.

The HoD (or deputy, in alternating years) meets all academic staff for annual Personal Review and Development Planning. These meetings facilitate constructive dialogue regarding promotions, teaching, research, impact, staff development, implementation of strategies, and funding opportunities. This enables HoD engagement with a large and diverse mathematical community and understanding of the needs of individuals and groups when coordinating and interacting with College.

We enable our most capable staff to continue their research after reducing from full-time (as Senior Research Investigators with part-time salary, office space, §1C); SRIs participate in seminars, supervise MSc/PhD students, and mentor junior staff.

**B.    Staffing and recruitment strategy.** Our priority is to attract and retain top mathematicians and statisticians, from diverse backgrounds (§2K) and from around the world, who will become international research leaders and to provide them with the best possible research environment. Only SRIs and postdoc/fellows (§2C) are appointed on fixed-term contracts (15% of staff, §1A).

Research strategy drives staffing: considerable thought is given to appropriate staff numbers within groupings and the level of appointments to account for exciting new research developments.  Informed by Recommendations 12 and 17 of the Bond Report, recent academic appointments have focused on impact and interdisciplinary research (Duncan[†], Filippi[†], Flaxman[†], Monod[†], Taylor[†], P Thomas[†]). With our demographics (52% Professors, §1A), we generally recruit (Senior) Lecturers (29 of 39 REF2021-period academic appointments), but take advantage of exceptional opportunities, e.g., Hairer[†]. Succession planning is deployed where necessary, e.g., appointing Coti-Zelati[†] and Zatorska[†] in Applied Analysis.

Space does not constrain staffing: physical expansion since 2013 (§3C) allowed growth and development. Imperial's outstanding interdisciplinary-research structures allow leveraging space in other Departments (Life Sciences and Physics, §1F).

Academic appointments are only made to those deemed able to rise to the Professorial level. Rigorous recruitment involves a seminar, one-to-one meetings, and an interview with an EDI/HR-trained panel of diverse academics with appropriate expertise, academically elected College Consul, and (for Reader/Professor appointments) external Professors. If not absolutely satisfied with quality and fit, we restart the process.

**C.    Support and contribution of Postdocs/Fellows.** Our large population of high-quality **postdocs and fellows** (323 over REF2021 period) plays a vital role in Departmental life, organizing workshops and seminars, mentoring and (with appropriate training) supervising PhD students, pursuing outreach activities, facilitating impact, and (where appropriate for their career

development) lecturing. We fully implement the *Concordat to Support Career Development of Researchers* (REF5a). Each is assigned an academic mentor who regularly meets them informally and annually to formally discuss career development. We fund an annual self-organized postdoctoral workshop to foster community. Dedicated academic champions (Battey[†], Rasmussen) advise ECRs on all aspects of transitioning from postdocs to permanent academic positions. Imperial's Postdoc and Fellows Development Centre (REF5a) provides tailored career-development courses including fellowship-proposal writing, funder showcases, one-to-one support, and mock interviews.

Funders for our 323 postdocs/fellows include, e.g., EPSRC (123 ECRs), EU (87), Leverhulme (17), ATI (6), CFM-Imperial Institute (4). In addition to hosting prestigious externally funded Fellows, each year we appoint 3+ department-funded highly competitive **Chapman Fellows** (2-years, light teaching) selected from 250+ applications from around the world. Over the REF2021 period we employed 28 Chapmans (£2.3M investment) originating from, e.g., Bern, Cambridge, Edinburgh, Johns Hopkins, Oxford, Sorbonne, Stanford, Technion, and Toronto. **Imperial's (Junior) Research Fellowships** (3-4 years, generous research funds, no obligatory teaching or administration) follow a highly competitive University-wide selection; we have hosted 11. Many of our former Fellows now hold prestigious permanent academic appointments (§2L).

**D.**      Staff are eligible for one term of **Sabbatical Leave** for every 6 worked (all academic levels, including part-time and short-term staff). Leave is discretionary, reliant upon a strong coherent research plan, awarded after discussion by the Management Committee, and (given the quality of proposals) almost invariably granted. Leave designed to facilitate impact (§2E) or cross-disciplinary research (§1F) is especially encouraged. 41 REF2021-period sabbaticals were granted: destinations included the Crick, Ecole Polytechnique, EPFL, ETH, Harvard-Smithsonian Astrophysical Observatory, IMPA, Kyoto, Mittag-Leffler, MPI Bonn, MRC-LMS, MSRI-Berkeley, Princeton, and TU-Munich.

**E.**      **Staff exchanges with other sectors** are actively encouraged to drive impact. §1E details secondments (totalling 158 months) and Hand's position at Winton Capital. We hosted 5 Heilbronn Fellows working 50% with GCHQ; encourage public-sector roles (§1E), particularly in education (§4C); and host numerous non-academic visitors (e.g., from Spotify, RBS, LANL).  In addition to those from the financial industry (§1C-mathematical finance), honorary staff include Anagnostopoulos (data scientist at Quantum Black), Briers (ATI Defence and Security Director), Allin (retired from ONS), and Pullinger (UK National Statistician, 2014-19), all of whom collaborate closely with staff and students.

*Visiting Scholars.* Our location makes us an international hub, hosting 600+ international visits longer than one week since August 2013, and many more for shorter periods. We have dedicated programmes to enable scientific exchanges: our Cecilia Tanner Fund (§2A) supports short-term visitors, and our prestigious **Nelder Visiting Fellowships** and Imperial-CNRS Fellowships (§3E, §4A) facilitate longer-term visitors. These encourage new collaborations and larger-scale external funding as they mature. We choose visitors who complement our expertise, interact actively, and extend our ECR's research networks. Nelder Fellows visit for at least a month and are expected to present a postgraduate-level Lecture Series and Colloquium (§2J); we hosted 17 (e.g., Colonius, Ghil, Kurtz, Rosenbaum).

**F.**      The Department is strongly proactive in **recognizing and rewarding excellence in research and impact**, e.g., through promotions (43 during REF2021 period, §2A) and research/impact merit-pay increases (36 instances). In line with Recommendation 12 of the Bond Report, impact is recognized in hiring (e.g., Duncan[†], Flaxman[†], Lau[†], Mughal[†]), release from probation, and promotion (e.g., Cotter[†], Ham[†], Heard, Jones). Imperial's President's

Awards publicly recognized outstanding research and impact (Battey[†], Caraiani[†], Crisan, Girolami, Graefe[†], Jones, Shahrezaei) and our nominations of staff for major international prizes are successful (e.g., Hairer's $3M Breakthrough Prize, §4F).

§1E describes our **support for achieving impact**. In annual staff appraisals (§2A), the HoD reviews staff contributions and discusses how the Department can facilitate and support staff in developing impact. An annual one-day cross-Faculty workshop offers Strategic Training in External Partnerships. The Department has a Director of Enterprise, who oversees impact development strategy, and a dedicated Research-Development Manager, who negotiates contacts and facilitates engagement with non-academic partners.

**Research Students**

**G.    Recruitment of doctoral students.** PhD students are central to the research life of the Department and are a strategic priority. Our PhD-student population grew significantly, by 85% (from 139FTE in 2012-13 to 258 in 2019-20). This was a strategic choice, achieved by winning numerous CDTs (§1D) and making a large departmental investment in studentships (£11.6M), enabled by substantial growth in our research (§3A) and teaching income. The Department funded ninety-six highly competitive Roth Studentships, enlarging our pool of highly qualified applicants, particularly outstanding non-UK students with limited access to UKRI funding.

Students are selected from a large pool of top applications from around the world. We received 268 applications (63/73/132, Home/EU/Overseas) for roughly 60 places starting in 2019-20.  The vast majority of successful applicants achieved first-class honours, MSc with distinction, or both (91% in 2019-20). We take proactive steps to increase applications/enrolment of *students from under-represented populations*; we fund an LML-Roth PhD studentship for an African Institute of Mathematical Sciences graduate (§2K), and part-time study enables mature PhD students. Our recently launched McDermott Scholarships and McCammon Fellowships encourage women into PhD study (§2K). Our female PhD-student population grew by 80% over the REF2021 period. To attract strong applicants, the UoA and its CDTs arrange open days and individual research groups welcome potential students to visit. A stream of students enters via our MSci and four MSc courses, providing top students with excellent training in advanced areas strongly aligned with PhD study in the Department.

Top PhD applicants are interviewed by at least two academics and ranked by our Postgraduate Committee and/or CDT committee, based on academic merit, eligibility for various funding streams, and needed skill spread. All staff involved with admissions are EDI-trained. The very top candidates are nominated for Imperial's prestigious President and Schrödinger Scholarships.

**H.    Studentships from major funders.** Our 372 PhD students starting since 2013-14 received funding from wide-ranging sources, including: 152 EPSRC (including CDTs), 96 department (Roth), 23 self-funded, 13 EU, and 39 College funded (President/Schrödinger Scholars). Other funders included Wellcome, Crick, NERC, BBSRC, CRUK and numerous private-sector institutions (§2J).

**I.    Student monitoring and support, linked to progress.** The Director of Postgraduate Studies (Barnett) provides oversight that is augmented by a Postgraduate Welfare Tutor and academic Postgraduate tutors overseeing research groups. New lecturers take the Imperial course "Supervising PhD Students", and all active supervisors undergo continued development by participating in half-day PhD-supervision workshops every six years, delivered by Imperial's Graduate School and tailored to the Department. Inexperienced supervisors always have an

experienced co-supervisor who advises on student selection and actively engages with supervision.

*Progress monitoring.* A comprehensive monitoring and review system of PhD milestones is used to identify potential problems early, provide support, and monitor progress. All students submit a 4-page Research Plan at 3 months and are twice examined in person (at 9 and 18-24 months) by two independent academics who provide detailed feedback on written reports and progress. These meetings allow students to self-report on their progress and relationship with their supervisor. Any issues are flagged and followed up by the Postgraduate Welfare Tutor or Director of Postgraduate Studies, allowing problems to be quickly caught. During the REF2021 period, 90% of PhD students completed within 48 months.

Other support mechanisms include: PG-student representation on Staff/Student Committee; a dedicated PGR-student committee; prizes for top PhD theses; an annual PG-research forum (with poster competition and prizes), and department-funded networking and social activities. The Department ensures all PhD students (including self-funders) have an annual research allowance of at least £1k. The Department continually improves the physical environment for research students through refurbishment and new space for student offices (§3B).

**J.      Research culture, training, and preparation for future research.** Imperial's Graduate School offers award-winning and sector-leading **career-development training**. Our PhD students complete its Professional-Development Programme, selecting from 50+ courses to form a programme tailored to their specific needs and interests. Many courses are aligned with the Bond Report's Recommendation 7 on training in knowledge exchange and innovation, including research communication, industry & enterprise, research impact, and research integrity. The Graduate School also offers courses in research computing (C++, Python, HPC), thesis writing, career planning, and academic English.

Discipline-specific training consists of 100 hours of taught PG courses, through our extensive masters programmes, and PhD-specific programmes offered through the Taught Course Centre (TCC), London Taught Course Centre (LTCC), and London Graduate School in Mathematical Finance (LGSMF). The EPSRC-funded TCC focuses primarily on Pure and Applied Mathematics and is run jointly by Bath, Bristol, Imperial, Oxford, and Warwick.  It uses streaming technology (2019 upgrade, £42k) to enable real-time lectures across these institutions.  Eleven London-area institutions participate in LTCC; its offerings span mathematics with a strong representation in Statistics. LGSMF offers tailored PhD-level courses in advanced Mathematical Finance and related disciplines.

The Department hosts numerous focused workshops (57+, §1E-QSRI, §2A) and 25+ weekly research-group seminars. Along with Nelder-Lecture Series (§2E), these complement formal courses and are well-attended by PhD students.  PhD students run several seminar series, including "junior seminars" in geometry, number theory, analysis, applied mathematics, and fluids. The Departmental Colloquium, held bi-monthly, provides a venue for the whole Department to come together and meet world-leading mathematicians. Colloquia are accessible to PG students in all areas of mathematics and post-Colloquia receptions encourage interactions across all levels and groups in the Department. Recent Colloquium speakers include Gelman, Caffarelli, Diaconis, Villani, Kühn, Stuart, Dafermos, Figalli.

The UoA's commitment to impact via industry-facing and interdisciplinary research extends to PG training. This aligns with Recommendations 6, 7, and 11 of the Bond Report which call for dedicating more PhD studentships to impact in partnership with government, industry, and national-level initiatives. Twenty-eight CASE, iCASE, and other studentships were funded by such companies as Airbus, ASOS, BP, Capital Fund, Cervest, Citigroup, EDF, GCHQ,

JPMorgan, Nataxis, Nomura, PWC, QinetiQ, RBS, Schlumberger, and Shell. Our CDTs (§1D) and CNRS-Imperial de Moivre Laboratory (§4A) encourage interdisciplinary and cross-institutional PhD research projects.

**Equality and Diversity**

**K.** We are strongly **committed to equality and diversity** as drivers for innovation. Academic recruitment is key to promoting diversity; we always appoint search committees to encourage applicants from diverse communities and require hiring panels to undergo EDI and HR-training. This resulted in 29% of 28 academic hires since Autumn 2016 being women. Since 2013, female academics in the Department more than doubled in number (from 4 to 10) as did our academics from ethnic minorities (from 4 to 10 excluding white minorities). Our promotions procedure (§2A, refined in 2017) encourages transparency and equity, resulting in 4 of 5 academic women appointed in 2013-17 being nominated for and successfully promoted. Shahrezaei serves as Diversity Champion for the Faculty of Natural Sciences, e.g., organizing workshops on diversifying PhD-student populations. The UoA has held a Bronze Athena SWAN award since 2010, expanded its EDI committee remit to include teaching and administrative staff in 2017, and requires all staff to be EDI-trained annually (e.g., unconscious bias, active bystander). REF5a describes College-level initiatives and achievements supporting EDI.

We foster diversity by developing new pathways into mathematics. In 2019 the Department launched its **Mary Lister McCammon Summer Research Fellowship Programme**, a ten-week program for final-year female undergraduates that provides generous bursaries, supervised research projects, advice on postgraduate applications, and network building towards pursuing a PhD. The UoA funds an LML-Roth PhD studentship for a master's graduate of the African Institute of Mathematical Sciences, and recently hosted two LMS Grace Young Fellows (after family-related career breaks). In 2019 we launched the Marjorie McDermott Scholarship to encourage top female undergraduates to pursue postgraduate study. Imperial has approved a new departmental scholarship for black undergraduates. Ramsden leads our **mA*ths Programme**, developing MOOC and SPOC support for able A-level students (45,000 participants in Jan 2021). College and ongoing philanthropic funding (Hg Foundation) enable tailored online support and mentoring for 200 participants from under-represented groups. These resources were particularly useful for isolating students during COVID19. In partnership with Woodhouse College, Imperial recently received government backing for a **new sixth-form mathematics college** with the aim of attracting more female, BAME, and other under-represented students to Imperial (Craster, Trustee). Our efforts to diversify pathways into mathematics have been recognized by Graefe's[†] 2019 Anne Bennett Prize for "the inspirational role she has played among female students" and black undergraduate Vanessa Madu's 2019 Women of the Future Award.

**L. Career pathways for part-time and fixed-term staff.** Our PhD students, postdocs, and fellows are in high demand in industry and have excellent records of permanent placements at top research universities, including Imperial, attesting to the quality of both the staff we attract and the success of our career-development support (§2C).

Of 28 REF2021-period Chapman Fellows, 19 are now permanent (or tenure-track) academics, 3 hold further fellowships, and 4 remain in post (e.g., Groechenig, Assistant Professor, Toronto; Huang, Lecturer, Manchester; Liokumovich, Assistant Professor, Toronto; Ottobre, Reader, Heriot Watt; Sirignano, Associate Professor, Oxford; Wang, Professor, Caltech; Cheraghi[†], Schnitzer[†], Coti-Zelati[†], all SLs, Imperial).

Of 11 Imperial College Research Fellows. 9 are now permanent (or tenure-track) academics (e.g., Ben-Artzi, Reader, Cardiff, EPSRC Early Career Fellowship; Graefe[†], Reader, Imperial, URF, ERC Starting Grant; Ouldridge, SL, Imperial (Bioengineering), ERC Starting Grant; Oyarzún, Reader, Edinburgh; Gongyo, Associate Professor, Tokyo).

Other postdocs/fellows have excellent placements in industry (e.g., Beguerisse, Spotify; Gould, Head of Product, Spotify; McMurray, Vice-President, JPMorgan; Winckler, Deep Mind) and top universities (e.g., Thompson, SL, Manchester; Johnston, Associate Professor Bergen, ERC Starting Grant; Merino-Aceituno, Assistant Professor, Vienna, €1.5M grant from City of Vienna).

**M.      Staff and postgraduate-student support.** The UoA employs a variety of flexible mechanisms to support staff/students with special needs. **Flexible and remote working** are supported whenever possible. Those with caring responsibilities or health concerns can schedule work commitments accordingly and/or work remotely where possible. Before the Covid19 shutdown, most staff/students took advantage of flexible/remote working, now all do. **Travel for those with caring responsibilities or ill-health** is facilitated by an internal scheme that funds family-member travel, hiring a babysitter, or other creative travel-enabling solutions. Elsie Widdowson Fellowships provide **study leave** for academics **returning from maternal/paternal/adoption leave** so they can concentrate on research for 12 months; 9 have been awarded since 2015. Similar arrangements have been made whenever possible for **staff/students with long-term illness or returning from ill health.** Some **staff with caring responsibilities** choose to temporarily reduce their FTE, others choose flexible/remote working or a rebalancing of their work responsibilities. In all cases the UoA works with them to find workable solutions. The UoA takes a pragmatic approach to **support those with disabilities**, e.g., via flexible/remote working and providing taxi fares on a long-term basis when necessary. **Postgraduate-student welfare support** includes a dedicated academic welfare tutor and research-group tutors, College counselling and career advice, workshops on professional skills and wellbeing, regular Department-funded social events, and financial hardship support.

**N.      Equality and diversity in rewards, research support, and leadership.** All staff are EDI-trained to ensure our processes are fair, transparent, and equitable. This has improved our diversity, doubling our BAME academics (§2K). 8 of 39 (21%) REF2021-period appointments were women, doubling the Department's proportion of female academics to 11.5%. Among 18 pre-professorial staff appointed during 2014-17, 4 of 5 women (80%) were promoted after an average of 29 months, compared with 7 of 13 men (54%) after 36 months. Of our 25 academic staff with the fastest growing salaries, 7 (28%) are women. Since 2017, 20% of research/impact related pay increases went to women and women's increases were 65% higher. Female academics are encouraged to seek funding and are successful (e.g., Caraiani[†] and Graefe[†] each hold ERC Starting Grants and URFs; Battey[†] won back-to-back EPSRC Fellowships, McCoy is PI of a £2.9M LRF Data-Centric Engineering Programme Grant).

We encourage staff from underrepresented groups to take on leadership roles if personally rewarding or serves their career/professional goals. Academic women in the Department include a Vice-Provost, QSRI Director, Director of a highly successful MSc, and two with CDT leaderships roles. Other examples include our Deputy HoD (BAME), Faculty Diversity Champion (BAME), and HoD (LGBT).

**O.      Equality and diversity in REF submission.** The UoA REF committee was trained in unconscious-bias awareness. Output selections were cross-checked at multiple levels to ensure REF criteria were applied. The committee followed Imperial's code-of-practice in all aspects, particularly regarding the selection of outputs and declared circumstances affecting research productivity. After selection, Imperial's REF Equality Committee and the UoA committee

conducted separate assessments. The output-count distributions for men and women are indistinguishable (men averaged 2.15 papers submitted, women averaged 2.09; 14% of men and 9% of women had 4+ papers submitted).

## 3. Income, Infrastructure, and Facilities

**A.** Our **research-funding strategy** aims to provide staff with resources to enable success (§2A); to build a diverse overall portfolio of funders; to maintain a balance of smaller responsive-mode grants, individual fellowships and larger-scale grants; and to pursue significant and diverse funding for interdisciplinary research (§1F). This strategy has generated significant funding.

Over the REF2021 period, research income totalled £53.5M. Top funders were:

1. Research Councils £26.5M (e.g., £21.5M EPSRC, £2.4M Royal Society, £2.0M NERC)
2. European Commission, £14.0M
3. Industry, £4.1M (£2.3M UK, £1.8M EU/Overseas).

Despite a 22% decrease in EPSRC Mathematics funding nationally from 2010-11 to 2017-18, the average annual research income of the UoA grew by 69% (£4.5M to £7.6M/year) compared with REF2014. (Per FTE, it grew by 80%, from £45k to £81k/FTE/year.) Growth was driven by a near tripling of European funding (£0.76M/year to £2.0M/year), a 33% increase in Research Council funding, 52% increase in industrial funding, and quadrupling of Government research grants (£79k/year to £333k/year). As of July 2020, our active research grants totalled £46.1M, with £28.1M yet to be spent. An additional £10.2M was awarded by January 2021.

Our longer and larger grants from various funders continued to grow in number. Leadership roles in 6 EPSRC Programme grants (totalling £17.3M, 5 Imperial-led):

- New Methods in Geometry (£2.2M, Corti PI, with Cambridge, Warwick),
- Mathematics of Metamaterials (£2.6M, Craster PI, with Liverpool),
- Laminar Flow Control (£4.2M, Hall PI, plus £518k from industry),
- Applied Derived Categories (£1.2M, R Thomas PI),
- Inference, Computation, Numerics for Cities (£3M, Girolami PI, with Edinburgh, Cambridge, Manchester),
- Mathematics of Data Science (£4.1M, Cass, with Oxford, UCL)

and key participation in 3 others (Flaxman[†], Holm, Neves) were complemented by similar large-scale Imperial-based projects:

- ERC Synergy Grant on Upper Ocean Dynamics (€10M, Holm, Crisan PIs, with Ifremer, Inria),
- EPSRC Centre for Mathematics of Precision Healthcare (£2.1M, Barahona PI, 1-of-5 in UK),
- ATI Data-Centric Engineering Programme (£2.9M, Girolami PI, then McCoy) funded by Lloyd's Register,
- CFM-funded Institute of Quantitative Finance (£2.4M, Cont PI, then Muhle-Karbe[†]),
- EPSRC Chemical Engineering/Mathematics Platform (£1.6M, Pavliotis),
- EPSRC Simulation Methods Platform (£1.6M, Cotter[†]).

Together these enabled world-leading research groups to flexibly address significant challenges, e.g., dramatic progress classifying Fano manifolds using mirror symmetry and Gromov-Witten theory (Coates, Corti); proving KKV conjecture (string theory) and first rigorous definition of Vafa-Witten invariants (R Thomas); sophisticated mathematics underpinning reduced airplane-wing drag (Hall, Mughal, impact case C4); network-theoretic measures for clustering and graph-based learning in healthcare (Barahona, Jones).

We co-lead numerous major (inter)national initiatives, including 3 major biomedical Centres (totalling £18.3M, Barahona co-I, see §1C-Biomathematics), a Brain Tumour Charity Grant (£1.5M, Shahrezaei co-I), and a Simons Foundation Collaboration on *"Special Holonomy in Geometry, Analysis, and Physics"* ($8.5M, PI Haskins, co-I Donaldson).

Staff have been successful in winning competitive long-term fellowships:

- **6 EPSRC:** *Career Acceleration* **(**Rasmussen); *Early Career* (Colijn, Cascini, Cheraghi[†]); *Established Career* (Crowdy, Girolami).
- **7 Royal Society:** *Research Professorships* (Hairer[†], R Thomas); *URFs* (Caraiani[†], Coti-Zelati[†], Graefe[†], Taylor[†]); *Dorothy Hodgkin* (Manolache).
- **6 Others: MRC** Biostatistics (Johnston); **NERC** Independent (Ham[†]); **Leverhulme** Early Career (Chandra[†]); **Leverhulme** Research Leadership (Hairer[†]); **Royal Commission 1851** Research **(**P Thomas[†]); **RAEng** Research Chair (Girolami).

and **13 sole-investigator ERC Grants**: Advanced (Donaldson, Holm, van Strien), Consolidator (Coates, Hairer[†], Holzegel) and Starting (Caraiani[†], Coates, Gee, Holzegel, Graefe[†], Neves, Nicaise[†]).

Together, these fellowships and ERC grants totalled £24.3M. Looking forward, additional awards starting in October 2020 include 3 UKRI/EPSRC Fellowships (P Thomas[†], Flaxman[†], Battey[†]) and an ERC Advanced Grant (Gee), totalling £5M.

Early-career staff won 12 EPSRC Doctoral Prizes, 3 EPSRC Postdoctoral, 23 Marie Skłodowska-Curie, 2 McDonnell Foundation, 1 Sir Henry Wellcome, and 5 Heilbronn Fellowships.

§1D describes an array of CDTs (exceeding £42M).

**B.     UoA, HEI, and cross-HEI Infrastructure.** Our directly employed research-support and technical staff (10.1FTE) include full-time managers for Research Development (Sood, §2F) and Research Computing (A Thomas). Thomas oversees 200+ CPU-based servers, 38 of which comprise the 340-processor NextGen cluster (upgraded in 2017), and several GPU servers, acquired as recently as 2020. Since 2014, NextGen alone hosted over 1M jobs (4.3M CPU hours).  Most of the servers are inhouse in a bespoke air-conditioned server room (upgraded in 2016).  Data storage (1 petabyte) is mirrored locally and on remote tape drives. The Department's REF2021-period investment in upgrading and maintaining its extensive computational resources exceeded £250k. Additionally, Imperial invests £3M/year centrally in Research Computing, including consultancy on project execution. The Department makes heavy use of these facilities (1.8M jobs, totalling 15.4M CPU hours) for large-scale computing with up to 15000 processors, as well as ARCHER and cloud computing (ATI, Azure, AWS, e.g., impact case C1). Researchers enjoy effortless access to a library of proprietary software (e.g., Mathematica, MATLAB, VMWare) and to virtually any scholarly reference (via Imperial's Library and a dedicated librarian).

**C.     UoA Facilities.** A 17% increase in UoA space since 2014 (now 5,565m$^2$, half research space) has enabled increased research capacity. Lecture space used for colloquia, seminars, workshops and conferences benefitted from a £404k refurbishment, while an ongoing renovation programme of staff/student offices has created facilities for new appointments and growing research teams. An £8.8M conversion of Weeks Residence Hall into academic space provided offices for our Mathematical Finance group. The Department has recently refurbished a further 130m$^2$ (£383k) for new data-science staff. An extensive £5M reconfiguration of the main Library houses 6 of our EPSRC-funded CDTs (2013 and 2018 calls) enabling expanded research activity in Department space. **Equality, diversity, and safety** are always at the forefront**.** Our

Infrastructure Chair (Adams) coordinates individual plans to help disabled staff acquire research funding and access infrastructure and facilities safely.

**D.      Our infrastructure, facilities, and expertise enable impact.** In-house expert ICT support (A Thomas) is easily accessible to researchers. With EPSRC funding, A Thomas and Mughal† built a dedicated cluster enabling specialized code to optimize next-generation laminar-flow wings for Airbus [C4]. Again, relying on A Thomas' expertise, Heard used in-house infrastructure to collect and process large network-flow datasets, enabling his development of cyber-security tools, e.g., for Microsoft [C7]. Imperial's mathematical modelling of the Covid19 pandemic relies on Imperial HPC and commercial cloud computing [C1]. Our facilities host impact-enabling workshops (§1E-QSRI) and organizations like the UK Acoustics Network [C5] to enable impact.

**E.      Benefits-in-kind** (including cash/sponsorships) from corporate and public-sector partners contribute substantially to the UoA's research environment. EADS/Airbus, ARA, and BAE contributed secondments and flight data (£1.5M), that were critical to the success of [C4] and our Laminar Flow Control Programme Grant (Hall PI). MPE CDT (Crisan PI) partners (e.g., National Centre for Earth Observations, Climate-KIC, Met Office, NCAR, NPL) provided studentships, project co-creation/supervision, internships, and data (£4M). Since 2015, CNRS has provided salaries for 16 French mathematicians hosted by the UoA as CNRS-Imperial Fellows (totalling 67.5 months, about £304k, §4A).

**4. Collaboration and Contribution to Research Base, Economy and Society**

**A.      The UoA strongly supports research collaborations, networks, and partnerships.**
48.7% of our REF-period research grants included formal collaboration with other departments or institutions. Support for collaboration includes: sabbatical leave and teaching cover to facilitate long-term secondments (§2D); flexible Cecilia Tanner Funding for travel grants, visitors and workshops (§2A); and the QSRI (§1E-1F).

The Department actively encourages collaborative interdisciplinary groupings such as **Mathematics in Medicine.** This tight new topical grouping was initiated strategically from our EPSRC-funded Centre for Mathematics of Precision Healthcare by a series of workshops and pilot projects to galvanise the broad interest in applications to biomedicine, public health, and data science among UoA staff spanning Biomathematics, Statistics, Complexity, and Applied Analysis. The Centre's profile enabled a research focal point with several high-profile Fellows joining biomathematics (§1C-biomathematics), and numerous collaborations within Imperial and through a network of national (Cambridge, Oxford, Edinburgh) and international (Simons-Flatiron, Harvard, MIT) institutions.  This *informed UoA research activity and strategy* leading to participation in major national initiatives (totalling £18.3M, §1C-biomathematics) and new appointments (Filippi†, Monod†, P Thomas†).

The UoA leads a host of *local research collaborations,* including several CDTs involving co-supervision with Kings, Oxford, Reading, and UCL (§1D), an array of collaborative activities with ATI (e.g., Data-Centric Engineering Programme, £2.9M, §4B) and Programme grants in partnership with Cambridge, Oxford, UCL, and Warwick (§3A).

The £4.1M Programme Grant (Mathematics of Data Science, 2019-24, with Oxford, UCL) exemplifies large-scale strategic collaboration with academic and industrial partners *at the national level.* Working with domain experts from INRIA (Grenoble) and Cambridge, the Programme uses high-order mathematical signatures of multi-modal data to solve data-science challenges in computer vision, human-computer interaction, radioastronomy and mental-health diagnostics. Partnerships with ARM, Costain, and ATI enable industrial and societal impact.

The UoA's coordinated approach to *international partnerships* is illustrated by its **Imperial-CNRS Abraham de Moivre International Research Laboratory** (IRL), the only UK-based IRL and one of 37 worldwide (across all subjects). IRLs are the highest strategic level of French CNRS international engagement. The IRL hosted 16 CNRS-Imperial Fellows (§3E) and provided support for joint UK-French colloquia, seminars and events (UoA+CNRS+Others investment totaling £480k). A 2019 Research England I3 Grant (£500k) extended this collaboration with Imperial-CNRS PhD studentships, annual summer schools, and a short-term visitor programme. As a full-fledged CNRS laboratory, the IRL can have permanent French staff; reflecting CNRS's commitment, Sebastian Guenneau, a Director of Research, started in 2019.

In 2016 Donaldson and Haskins won a four-year $8.5M Simons Collaboration Grant on *"Special Holonomy in Geometry, Analysis, and Physics"* with 10 institutions worldwide. Focusing on the interdisciplinary interface of geometry and string theory, this project underpins international activity, centred around 25 meetings, including 8 at Imperial -- drawing in staff from fields from algebraic geometry (Corti, R Thomas) to string theory (Hanany, Hull). Strategic international capacity building includes the *"Brazilian-European partnership in Dynamical Systems"* (Lamb, €700k), Lamb, Ruzhansky, and Kestner's participation in African Institute for Mathematical Sciences programmes, and Crowdy's Visiting Professorship in Brazil's "*Science without Borders*".

**B.**     §1E describes the UoA's coordinated **engagement with key research users** in the financial, health, tech, industrial, environmental, defence, and public sectors **and how this develops impact and enriches our research environment** with a diverse portfolio of collaborators, funded projects, workshops, secondments, sabbaticals, and visitors from other sectors.

Interaction with industrial partners influences research strategy within the Department and Imperial. With funding from the Lloyd's Register Foundation at ATI (£2.9M, 2017-22), for example, we launched a large-scale programme in data-centric engineering that facilitated a range of engineering-based academic-industrial data-science collaborations within ATI (e.g., co-located staff). Working with industrial collaborators and funders (totalling £604k, e.g., MX3D, QinetiQ, GCHQ, Autodesk, Crossword Cybersecurity, Mentat, EDF, Shell, Microsoft, Rolls-Royce), this programme developed statistical methodologies in a range of projects, spanning instrumented infrastructure, digital twins, and monitoring complex systems, all with direct applications in civil engineering, transportation, and cybersecurity. Together, this provides a rich environment of multi-disciplinary collaboration fostered by impact-oriented PhD studentships and QSRI-funded workshops where staff and students mix with industrial partners. Impact has been swift and significant: new ML-based solar forecasts have enabled National Grid to improve forecasting accuracy by 30%; predictive monitoring for nuclear infrastructure have enabled EDF to extend the lifetime of aging nuclear plants; and ongoing work with Rolls-Royce uses rigorous Bayesian modelling to assess efficiency within the gas path of aero-engines.

**C.**     The UoA's **contributions to the economy and society** abound. Hand's numerous public-sector roles (§1E) allow him to translate his administrative-data research into societal impact. On the ONS's *Measuring National Wellbeing* Technical Advisory Group, he helped develop broader measures of wellbeing (beyond GDP) and advised on their presentation, leading to a new public ONS dashboard that provides a visual overview supporting the ONS Measuring National Wellbeing programme. Our work on "vaccine hesitancy" [C6] and on the impact of non-pharmaceutical interventions on Covid19 [C1] impacted public policy; our mortality alerts improve poor-performing NHS hospitals [C2] (§1D).

The Department actively engages with ***mathematics education***, influencing policy, and upskilling students and teachers nationally. Craster chaired the mathematics A-level Content Advisory Board reporting to DfE (2014-16), and subsequently the A-level group for the Royal Society Advisory Committee on Mathematics Education (2017-present); McCoy chairs its statistics assessment sub-group. These committees influenced the DfE into increasing funding for Further Mathematics and to delay the reformed Mathematics A-levels (administered to 90,000+ annually). Our educational outreach portfolio is broad: Ramsden and McCoy participate in the Royal Institution masterclass programme; McCoy in the Training Partnership Maths in Action GCSE and A-level days (900 students in each sitting).

**D.** The UoA actively encourages ***public engagement and outreach to diverse communities through its research.*** Holzegel leads a dedicated team overseeing activity. Staff regularly give Royal Institution, LMS, Maths in Action, Pint of Science, London Science Museum, Café Scientifique, and other popular lectures (some posted on youtube, viewed by tens of thousands) and deliver 50+ presentations to schools each year and to scientific Olympiads. The Mathematics of Planet Earth CDT hosted three biennial, week-long exhibitions with physical models and interactive demonstrations of the mathematics behind Planet Earth. Each welcomed thousands of visitors, guided by CDT students, including schools visits and public talks. UoA staff organized an evening public *"Imperial Lates"* event entitled Xmaths in 2018 that attracted 1000+ visitors and 250 school children for games, puzzles, demonstrations, and hands-on activities promoting and celebrating mathematics. It was the best-attended event in the history of *Imperial Lates.*

**E. Sustainability.** Our investments in department-funded PhD studentships (£11.6M, §2G) and Chapman Fellowships (£2.3M, §2C) were strategic choices aimed at ***sustaining the discipline***. A post-Brexit UoA initiative will top-up 20 PhD studentships starting each year to pay overseas fees. Our numerous ***contributions to diverse interdisciplinary research***, the wider economy and society (§1E, §1F, §4B, §4C) also bolster UK mathematics. Another exemplar: Since 2017, the EPSRC-funded UK Acoustics Network (UKAN, Craster co-Director) has brought together an internationally leading, but disparate acoustics research community, providing a single access point for industry and government. Half of UKAN's 800+ members are from industry, with academic members from physics, engineering and mathematics. Its original 9 Special Interest Groups (SIGs) have expanded to 15; two SIGS (acoustic metamaterials, early career researchers) are coordinated from the UoA. UKAN has run 70+ events, including industry-academia engagement workshops, ECR summer schools, and specialist meetings including two major European metamaterial meetings at Imperial, each with 100+ participants.

A series of recent reports (2016 CMS Report, 2018 Bond Report, 2019 LMS Report) highlight the importance of mathematics to the information economy, emphasizing its key role in knowledge exchange (KE). The UoA fully ***engages with these UK priorities*** and contributes to sustainability by: appointing an Enterprise Director (Muhle-Karbe[†]); strengthening priority areas including number theory, biomathematics, statistics, and industrial/engineering mathematics (§1C); integrating KE and industrial engagement into CDTs (§1D); incentivizing staff exchanges with industry/government (§2E); considering impact, KE, and cross-disciplinary work for appointments and promotions (§2F); and expanding PhD programmes/projects undertaken in partnership with government, industry, and national-level initiatives (§2J). We responded to the 2017 independent report *"Growing the AI Industry in the UK"* recommendation of "200 more PhD places in AI" with new CDTs (Statistics and Machine Learning, AI4Healthcare) and four new academic positions in statistical learning (plus four more by 2025) to increase PhD-training capacity in the area.

Individual research projects similarly align with *UK and international priorities*. Our €10M ERC Synergy grant, *Stochastic Transport in Upper Ocean Dynamics,* (2020-26) responds to the EPSRC's 2019 Strategy and Delivery Plan (R5: Build new tools to mitigate climate change) and EU commitments for clean, healthy, and safe oceans. Worldwide, this research responds to the urgent climate change challenges emphasized at the 2019 UN Climate Change Conference.

## F.  Indicators of influence and recognition during REF2021 period.

*Leadership in academic community (selection):*

*Donaldson,* Clay Institute Scientific Committee;

*Craster,* IMA Council (2017-20);

*Evans*[†], LMS Council (2014-16);

*Gandy,* Royal Society Covid19 DELVE action team (2020-);

*Hairer*[†], REF 2021 Mathematics Subpanel, Institut Henri Poincaré and Oberwolfach Scientific Committees;

*Laptev,* ERCOM Chair (2015-18), Mittag-Leffler Director (2011-18);

*McCoy,* RSS Council (2017-21);

*Nason*[†]*,* REF 2021 Mathematics Subpanel, CMS Board (2016-20), RSS Vice-President (2016-19), International Statistics Prize Foundation (2020-23, chair);

*R Thomas,* Newton Institute Steering Committee (2012-15);

*van Dyk,* American Statistical Association Board (2015-17), EPSRC Mathematical Sciences Advisory Board (2020-);

*Veraart,* EPSRC Mathematics SAT (2017-19);

*Young,* Institute of Mathematical Statistics Council (2019-22).

*Leadership in industry and government (selection):*

*Brigo,* Director Capco Institute (2012-15), Academic advisory board Credit Benchmark (2015-17) and HIS Markit (2017-);

*Hand,* Royal Society/British Academy Data Governance Group (2016-17), ATI mid-term review panel (2018-19), UK Statistics Authority, non-executive Director (2013-21);

*McCoy,* Royal Society ACME (2017-21) and Dynamics of Data Science Steering Group (2017-19).

*Collaborative PGR training:*

UoA staff lead numerous collaborative CDTs and cross-disciplinary PhD programmes (§1C).

*Editorship (main editors, not large boards, selection):*

*Craster,* Joint Executive Editor, Quarterly Journal Mechanics Applied Mathematics (2002-17);

*Barahona*, 1-of-5 Editors-at-Large, IEEE Transactions (Network Science Engineering, 2014-);

*Donaldson,* main co-Editor: Duke Mathematical Journal, Journal of Differential Geometry, Geometric and Functional Analysis, Journal American Mathematical Society.

*Gee,* Editor (Number Theory), Mathematische Annalen (2013-18);

*Ham*[†]*:* 1-of-6 Executive Editors, Geoscientific Model Development (2016-);

*Holm*: 1-of-7 Senior Editors, Journal of Nonlinear Science;

*Laptev:* Editor in Chief, Acta Mathematica (2011-18) and Arkiv für Matematik (2014-18);

*Papageorgiou:* 1-of-2 co-Editors, IMA Journal of Applied Mathematics;

*van Dyk:* Reviews Editor, Journal American Statistical Association (2014-16).

*Participation on grants panels (selection):*

*Royal Society URF* (Hairer[†], 2015-20);

*EPSRC Prioritization* (x4, Lamb, McCoy; and Nason[†], **chair 2015**), *Fellowship* (Nason[†] 2014 and **chair** 2017**);**

*ERC Starting Grants* (Laptev, **chair,** 2014, 2016) *Synergy Grant* (Holm, 2014);
*Marie Skłodowska-Curie Fellowship* (Laptev 2017-18 and **vice-chair** 2019).

**Invited keynotes (selection):**

*Caraiani*[†] and *Gee*, both at Journees Arithmetiques 2017;
*Donaldson,* AMS Summer Institute on Algebraic Geometry 2015, IAS Marston-Morse Lecture Series 2019;
*Hairer*[†]*,* IMS Medallion Lecturer 2014, Sciences Switzerland Einstein Lecture Series 2016;
*Holzegel*, International Conference on General Relativity and Gravitation 2016;
*Jacquier* and *Veraart,* both at Vienna Congress on Mathematical Finance 2019;
*van Dyk,* COMPSTAT 2019.

**Invitations to address major international congresses:**

International Congress of Mathematics: 2014 Hairer[†], Neves, van Strien, 2018 Degond[†], Donaldson (plenary).
European Congress of Mathematics (postponed): 2021 Hairer[†] (Hirzebruch Lecture).
International Congress of Mathematical Physics: 2018 Laptev.
World Economic Forum: 2017 Flaxman[†].

**Scientific organization and conference chairs (selection):**

*Hairer*[†]*:* Chair of ICM 2022 Programme Committee;
*R Thomas:* ICM 2014 Algebraic Geometry Program Committee;
*Buck, Cont, Crisan, Crowdy, Hand, Liebeck, and Veraart* each co-organized INI programmes (totalling 30 months);
*McCoy*: MaxEnt 2018 Programme Chair.

**ERC grants:**

*3 Advanced Grants:* Donaldson (2010-16), Holm (2011-17), van Strien (2014-19)
*3 Consolidator Grants:* Coates (2016-21), Hairer[†] (2014-19), Holzegel (2018-23)
*7 Starting Grants:* Caraiani[†] (2018-23), Coates (2009-14), Gee (2012-17), Holzegel (2013-18), Graefe[†] (2018-23), Neves (2011-16), Nicaise[†] (2013-18).

**Election member/fellow of learned societies:**

*Caraiani*[†]*,* AMS Fellow 2019;
*Donaldson,* Russian Academy of Science 2019;
*Gee,* AMS Fellow 2014;
*Hairer*[†]*,* FRS 2014, AMS Fellow 2015, Austrian Academy of Sciences 2015, Academy of Sciences Leopoldina 2015, Academy of Europe, 2015, Polish National Academy of Sciences 2018;
*Liebeck,* AMS Fellow 2019;
*Nason*[†]*,* International Statistical Institute 2015;
*Papageorgiou*, American Physical Society Fellow 2016;
*Skorobogatov,* AMS Fellow 2019;
*R Thomas,* FRS 2015; AMS Fellow 2018, Academy of Europe 2019.
*van Dyk,* International Astrostatistics Association Fellow 2016*.*

**Visiting Fellowships (selected):**

*Olga Taussky Pauli Fellowship, Vienna:* Veraart (2014-19).
*Simons Foundation Visiting Fellows at INI*: Veraart (2019), Chandra[†] (2018), Degond[†] (2017)
*MSRI:* Liebeck (2017-18), Hairer[†] (2015-16).
*von Neumann Visiting Professorships (TUM):* Nicaise[†], Rasmussen (2021, postponed), Pavliotis (2019).

*Awards & Prizes:*

*Atkinson,* ASCE Maurice Biot Medal 2020;

*Caraiani[†],* Whitehead Prize 2018, EMS Prize 2020;

*Cascini,* Moore Research Article Prize 2016;

*Coates,* Whitehead Prize 2014, Adams Prize 2015;

*Donaldson,* Breakthrough Prize 2015, Oswald Veblen Prize 2019, Wolf Prize 2020;

*Graefe[†],* L'ORÉAL Women in Science Fellowship 2014, Anne Bennett Prize 2019;

*Hairer[†],* Fields Medal 2014; Fröhlich Prize 2014;

*Ham[†],* Wilkinson Prize 2015;

*Hand,* ENBIS George Box Prize 2016, International Federation of Classification Societies Research Medal 2019;

*Holzegel,* Whitehead Prize 2016, Adams Prize 2018, Blavatnik Prize 2018;

*Liebeck,* Pólya Prize 2020;

*Neves,* New Horizons Prize 2016, Oswald Veblen Prize 2016;

*Nicaise[†],* Ferran Sunyer i Balaguer Prize 2017;

*Schedler[†],* André Lichnerowicz Prize 2016;

*van Dyk,* ASA Founders Award 2019.

*Wolfson Merit:* Carrillo, Crowdy, Degond[†], Donaldson, Gee, Thomas, van Dyk, Zegarlinski.

*National honours:*

*Hairer[†],* Knight Commander honorary 2015, substantiated 2019.