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# Ernest Rutherford Fellowships PROPOSAL

Document Status: With Owner

STFC Reference:

## Ernest Rutherford Fellowship 2012

**Organisation where the Fellowship would be held**

| | | | |
|---|---|---|---|
| Organisation | Imperial College London | Research Organisation Reference: | TBA |
| Division or Department | Dept of Physics | | |
| | | | |

**Title of Proposed Research** [up to 150 chars]

| |
|---|
| The astroparticle road to new physics |

**Start Date and Duration**

| | | | |
|---|---|---|---|
| a. Proposed start date | 31 March 2014 | b. Duration of the grant (months) | 60 |

**Applicants**

| Role | Name | Organisation | Division or Department |
|---|---|---|---|
| Fellow | Dr Pat Scott | McGill University | Physics |

**Years of Post-Doctoral Experience**

| | |
|---|---|
| Years of postdoctoral experience at 1 September next year | 3 |

If you are returning to research from a career break please tick

**Proposal Classifications**

**Classification Areas:**

Research Areas are the subject areas in which you may have expertise and you should select at least one of these.

To add or remove Research Areas use the relevant link below.

| **Subject** | **Topic** | **Indicator %** | **Keyword** |
|---|---|---|---|
| Astronomy - theory | Computational Methods and Tools | 15 | |
| Astronomy - theory | Extra-Galactic Astronomy & Cosmology | 15 | |
| Particle astrophysics | Direct Dark Matter Detection | 15 | |
| Particle astrophysics | Gamma Ray Astronomy | 15 | |
| Particle physics - theory | Phenomenology | 40 | |

**Qualifiers:**

Qualifiers are terms that further describe your area of expertise and cover aspects such as approach, time period, geographical focus, methodology and materials.

To add or remove Qualifiers use the links below.

| Type | Name |
|---|---|
| Approach | Exploitation of existing datasets |
| Approach | Large new datasets |
| Approach | Modelling |
| Approach | Quantitative |
| Approach | Technique/Method Development |
| Approach | Theory Development |
| Project Engagement by Sector | Academic Users |
| Theoretical Methods | T&M Modelling |
| Theoretical Methods | T&M Monte Carlo |
| Theoretical Methods | T&M Probabilistic Modelling |
| Theoretical Methods | T&M Simulation |
| Theoretical Methods | T&M Stochastic Modelling |

**Keywords:**

Free-text keywords may be used to describe your area of expertise in more detail if appropriate.

To add or remove those previously added use the links below.

| **Free-text Keywords** |
|---|
| beyond the standard model |
| dark matter |
| global fits |
| indirect detection of dark matter |
| statistical methods (Bayesian) |
| statistical methods (frequentist) |
| supersymmetry |

**Choice of Host Institution**

Please explain the choice of your host organisation [up to 4000 characters]

Imperial offers the perfect combination of professional and scientific environments, computational resources and location.

1. An ideal professional environment
I will partake in decision-making and student supervision within the Astrophysics Group at Imperial as if already a permanent member of staff. The group will factor my career path into their long-term strategy, with the intention of retaining me as a lecturer when the Rutherford Fellowship is complete. I will have the opportunity to lecture graduate and undergraduate courses whilst a Rutherford Fellow, and to officially co-supervise PhD and Masters students. I will be supported with extensive feedback from experienced faculty on my applications for further research funding, and on the process of building my own independent research group.

2. Vast expertise relevant to my research
I will collaborate closely and co-supervise students with Roberto Trotta, who has extensive experience in dark matter and global fits. My research program will both enhance the activities of and benefit greatly from the new Imperial Centre for Inference and Cosmology (ICIC), as I work with Alan Heavens, David van Dyk, et al in improving the numerical and statistical optimisation methods that are so central to my global fit research. With Tim Sumner and Henrique Araujo I will ensure that results of LUX and other direct detection experiments are correctly included in my global fits, in the most detailed way possible: at the level of single nuclear recoil events. I will draw on the Imperial CMS group in developing the collider likelihood modules, particularly with respect to optimising fast detector simulations and applying comparable analysis event cuts to the proprietary CMS analyses. Roberto Trotta, Andrew Jaffe, Daniel Mortlock, Carlo Contaldi and Arttu Rajantie will provide excellent cosmological expertise, including strong links to the team operating the Planck satellite. Michael Duff and the Theory Group will be invaluable points of reference as quantum field theory questions arise when I and my new group implement many new particle models in the global fit codes.

3. Priority access to over 10,000 cores of cluster computing power
Imperial's High Performance Computing (HPC) facilities consist of three main computing clusters, boasting over 10,000 processor cores in total, a priority queue on a subset of these for the Astrophysics Group, and the ability to run single jobs on over 3,000 of the latest CPU cores. This sort of computing infrastructure is essential for the highly computationally-demanding, high-dimensional global fits that I will be carrying out in the course of my Rutherford Fellowship. Running code on the Imperial HPC infrastructure will provide a perfect development base and the experience necessary to apply for additional time on the STFC HECToR and/or DiRAC HPC facilities.

4. A productive geographical location
The greater London area also boasts strong cosmology and particle phenomenology groups at University College London and King's College London respectively, leading to good prospects for future collaboration on scientific projects and organisation of conferences and workshops. Finally, my wife works in international development; London is one of only a handful of cities in the world where we can both find positions commensurate with our expertise and interests.

**Objectives**

List the main objectives of the proposed research in order of priority [up to 4000 chars]

Scientific Objectives
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1. Identify the correct theory behind dark matter and TeV-scale BSM physics

Two questions hold a fundamental place in modern physics: What is dark matter, and what physics occurs at the TeV scale? Dark matter (DM) is 80% of the matter in the Universe, yet its identity is unknown. Many theories for particle physics beyond the standard model (BSM - beyond the SM), such as supersymmetry, extra dimensions and phenomenological descriptions of weakly-interacting massive particles, involve a fundamental link between DM and the TeV scale. With the spectacular recent success of the Large Hadron Collider (LHC), particularly in uncovering the Higgs boson, and the construction of high-energy astrophysical experiments like Fermi, IceCube and XENON, astroparticle physics is arriving at the TeV scale; the time to put these disparate pieces together into a cohesive and unified understanding of DM and TeV-scale physics is now.

2. Exclude large classes of other viable and popular dark matter and TeV-scale BSM theories

I propose a cutting-edge 'global fit' research program designed to test a broad range of DM and BSM theories against a similarly large range of experimental datasets, with each theory to be simultaneously compared with every available dataset. The goal is to either uncover the identity of DM and carefully characterise it, or rule out and constrain different BSM theories, drawing deeply on the synergies between experiments. This novel program of holistic analysis will produce far more complete and robust comparisons of experimental data and DM/BSM models than performed to date.

I will employ many more experimental observables than past studies, leveraging UK investment in CMS, ATLAS, LHCb (CERN), ZEPLIN/LUX (Boulby/Sanford), CDF and D0 (FNAL) by amplifying their scientific impacts with additional data from Fermi, HESS, IceCube, PAMELA, XENON, CDMS and others. I will consider far more DM and BSM models than have been subjected to global analysis so far: phenomenological and SUSY-breaking versions of the minimal supersymmetric SM, extra-dimensional, Two Higgs Doublet and effective DM models like Isospin-violating, Inelastic and Exciting DM. This will allow me to determine which theories are favoured over others, and for the first time, to what extent.

3. Distinguish between areas of parameter space giving rise to distinct astroparticle phenomena within single BSM theories

By comparing the performance of a global fit in different parts of the same parameter space, I will determine which parameter areas are favoured, and to what extent. This will tell me which physical processes dominate various observables within that theory; e.g. if the DM relic density is set by DM-DM annihilation or DM coannihilation with another particle.

Community Objectives
------

4. Create a public suite of software tools that allows new theories, observables and datasets to be easily analysed in a global statistical fit

A very timely component of this project is the development of a new, highly flexible 'second-generation' BSM global-fitting code, capable of operating at a degree of computational abstraction that would allow for very fast implementation of future models and datasets. Another is the construction of separate, stand-alone 'likelihood modules' for each set of particle/astroparticle observables. With such tools freely available, activity in BSM global will explode.

5. Enhance cross-disciplinary interaction and awareness between high-energy astronomers, particle experimentalists and particle theorists, via collaboration on global fits

I have unique experience in unifying astronomical and particle perspectives, bringing together theoretical, experimental and statistical techniques, and establishing collaborative links between experts in each of these areas. This experience will be essential to the success of my program, and help forge ongoing links between the different communities.

**Summary**

Describe the proposed research in simple terms in a way that could be publicised to a general audience [up to 4000 chars].

Note that this summary will be automatically published on STFC's website in the event that a grant is awarded.

Imagine living your life in a 5-person household where you don't know the names or faces of your 4 housemates. This is the situation astronomers and particle physicists find themselves in right now with the matter in our own Milky Way Galaxy. Dark matter makes up over 80% of the Milky Way, and the Universe as a whole, but we still don't know what it actually is.

Many theories predict that this mystery is in some way associated with the Higgs boson, the origin of mass, and the existence of an as-yet-undiscovered symmetry about to be unveiled at the Large Hadron Collider (LHC). My research aims to uncover the identity of dark matter, and the broader particle theory responsible for it.

Using cutting-edge statistical techniques only developed in the last few years, my research program will combine the results of searches for dark matter and new symmetries from a huge number of different experiments. These range from the LHC to smaller particle colliders, gamma-ray telescopes, cosmic antimatter probes, ultra-clean experiments in the world's deepest mines, and a neutrino telescope embedded in the Antarctic ice at the South Pole. The result will be the first truly comprehensive analysis of theories for dark matter and new physics, painting a much clearer picture of what dark matter is, and what it isn't. Excitingly, this research program may identify many more new, related particles than just dark matter, and give predictions for others to be discovered in the near future. The statistical and computational tools that I develop for this research program will also serve the broader particle and astrophysics communities during and beyond my fellowship, as they will be available as public, open source projects.

**Summary of Resources Required for Project**

Financial resources

| Summary fund heading | Fund heading | Full economic Cost | STFC contribution | % STFC contribution |
|---|---|---|---|---|
| Directly Incurred | Staff | 228080.00 | 182464.00 | 80 |
| | Travel & Subsistence | 7500.00 | 6000.00 | 80 |
| | Other Costs | 8000.00 | 6400.00 | 80 |
| | **Sub-total** | **243580.00** | **194864.00** | |
| | | | | |
| Directly Allocated | Investigators | 0.00 | 0.00 | 80 |
| | Estates Costs | 0.00 | 0.00 | 80 |
| | Other Directly Allocated | 0.00 | 0.00 | 80 |
| | **Sub-total** | **0.00** | **0.00** | |
| | | | | |
| Indirect Costs | Indirect Costs | 0.00 | 0.00 | 80 |
| | | | | |
| | **Total** | **243580.00** | **194864.00** | |

Summary of staff effort requested

| | Months |
|---|---|
| Investigator | 60 |
| Researcher | 0 |
| Technician | 0 |
| Other | 0 |
| Visiting Researcher | 0 |
| Student | 0 |
| Total | 60 |

**Other Support**

Details of support sought or received from any other source for this or other research in the same field.

| Awarding Organisation | Awarding Organisation's Reference | Title of project | Decision Made (Y/N) | Award Made (Y/N) | Start Date | End Date | Amount Sought / Awarded (£) |
|---|---|---|---|---|---|---|---|
| NSERC | The Banting Fellowship | Discovery and discrimination of models for new physics with combined terrestrial and astrophysical data | Y | Y | 01/10/2012 | 30/09/2014 | 88400 |
| Royal Society of New Zealand | The Marsden Fund, Application 12-UOC-098 | A Neutrino Net for Dark Matter | N | N | 01/01/2013 | 31/12/2015 | 475800 |

## Staff

### Directly Incurred Posts

| | | | EFFORT ON PROJECT | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Role** | **Name /Post Identifier** | **Start Date** | **Period on Project (months)** | **% of Full Time** | **Scale** | **Increment Date** | **Basic Starting Salary** | **London Allowance (£)** | **Super-annuation and NI (£)** | **Total cost on grant (£)** |
| Fellow | Dr Pat Scott | 31/03/2014 | 60 | 100 | 38 | 31/03/2014 | 42960 | 0 | 0 | 228080 |
| | | | | | | | | | Total | 228080 |

**Other Directly Incurred Costs**

| Description | Total £ |
|---|---|
| Relocation expenses, Montreal -> London | 3000 |
| High end laptops and associated peripherals (screen, keyboard, mouse, etc) for developing global fit code (one each at beginning of Year 1 and towards the end of Year 3) | 5000 |
| Total £ | 8000 |

**Classification of Proposal**

**(a) Peer Review Preferences**

Tick one of the following boxes to indicate the STFC fellowships peer review panel you consider most appropriate to review this fellowship.

| | |
|---|---|
| Astronomy Extragalactic | |
| Astronomy Near Universe | |
| Particle Physics Experiment | |
| Particle Physics Theory | |
| Particle Astrophysics and Cosmology | x |
| Nuclear Physics | |

**(b) Types of Activity** (mandatory)

Assign % relevance(in multiples of 5) to the activities listed, totalling 100%

| **Type of Activity** | **Broad Indication of Category** | **%** |
|---|---|---|
| Exploitation and experiment | Data collection, data analysis, experimental research | 50 |
| Investment in new instrumentation, facilities or techniques | For example, design and construction of new facilities and instruments, instruments and technique development and research on underpinning technology | |
| Operation and maintenance of facilities | The recurrent cost of providing facilities | |
| Theory | Theoretical research including modelling | 50 |
| | | **Total = 100%** |

**(c) Facilities**

Please indicate which facilities, if any, apply to this application. Please provide further details if necessary.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| AAO | | AKARI | | ALMA | | Bepi-Colombo | |
| BiSon | | Boulby | x | Cassini Huygens | | CERN LHC | x |
| CERN Other | | CLF | | CLUSTER | | CoRoT | |
| Cross Scale | | CUTLASS | | Diamond | | Double Star | |
| EISCAT | | e-MERLIN | | ESRF | | ExoMars | |
| FAIR | | FMOS | | FNAL | x | GAIA | |
| GAUGE | | Gemini | | Herschel | | Hinode | |
| HPC | x | HST | | ILL | | INT | |
| ISIS | | ISO | | JCMT | | Jupiter Europa | |
| JWST | | KEK | | Kua Fu | | LIGO | |
| LISA / Pathfinder | | Liverpool Telescope | | LOFAR | | Mars Express | |
| MICE | | Newton XMM | | Other | x | Planck | x |
| Samnet | | SDO | | Soho | | Solar Orbiter | |
| SPEAR | | Spitzer | | SRS | | STEREO | |
| SuperDarn | | SuperWasp | | SWIFT | | UKCAN | |
| UKIRT | | UKST | | Ulysses | | Venus Express | |
| VISTA | | VLBI | | VLT | | VST | |
| WHT | | XEUS | | | | | |

Other

| |
|---|
| Fermi-LAT, AMS-02, GAPS, VERITAS, HESS, MAGIC, CTA, LUX, ZEPLIN-III |

**(d) Space or Ground Based** (mandatory)

Please assign relevance (in multiples of 5%) to Ground or Space based activities, entering "0" where there is none.

| Ground or Space | % |
|---|---|
| Ground-based | 50 |
| Space-based | 50 |
| | **Total <= 100%** |

# OTHER INFORMATION

**Reviewers**

| 1 | Name | Organisation | Division or Department | Email Address |
|---|---|---|---|---|
| Professor Joakim Edsjo | | Stockholm University | Physic | edsjo@fysik.su.se |

## Research track record and career vision

My overarching goal is to perform cutting-edge astroparticle research: to discover and characterise new physics and symmetries of nature, and their impacts upon astronomical observations. I ultimately plan to build and lead a large, strong and dedicated research group centred on the interface of particle physics and astronomy. This group will focus on dark matter (DM) and physics beyond the Standard Model (SM) of particle physics, with particular emphasis on quantitative, multi-messenger assessments of the leading theories of the day for new physics. The ERF will give me the opportunity to build this group, providing the stability to apply for further external funding to hire postdocs of my own, and take on students. This will allow me to take my leadership in astroparticle physics to the next level, and eventually run such a group in earnest as permanent faculty.

I have just over 2 years postdoctoral experience, 22 published or submitted articles in refereed journals, 10 refereed proceedings and 1239 citations. My work includes some of the most rigorous global fits for new particle theories to date with data from indirect dark matter searches [1,6,12 in publication list]. This work significantly improved constraints on supersymmetric dark matter, and was only possible through dedicated collaborations between myself and the relevant experiments: first with gamma-ray data from the *Fermi* Large Area Telescope (LAT) [12] and the High Energy Stereoscopic System (HESS) [6], then with IceCube neutrino events [1]. I also played a pivotal role in the recent correction of the chemical composition of the Sun [13], which impacts many areas of astronomy and astroparticle physics.

I have won multiple externally-funded research grants and fellowships: The Banting Fellowship from the Canadian Government (Canada's most sought-after postdoctoral fellowship), the CfA Fellowship from Harvard University (which I declined), two other major grants and 7 smaller competitive travel fellowships. I won The Arrhenius Prize at Stockholm University for my PhD research (in particular my global fit work), the Bok Prize from the Astronomical Society of Australia for the best Honours/Master thesis in astrophysics, and two University Medals for my Honours research at the Australian National University.

I have given 66 talks (19 invited) at international conferences and institutions, and chaired 5 sessions. I convened the Particle Astrophysics and Cosmology Track at the 2012 International Conference on High Energy Physics (ICHEP), organised 2 smaller conferences, and founded the McGill Astroparticle Seminar Series. I am an associate member of the IceCube Collaboration and an affiliated scientist of the *Fermi*-LAT. I collaborate with leading astronomical and particle phenomenology groups all over the world: in the US, Canada, UK, Australia, NZ, Scandinavia and Germany. I have refereed for 6 top-tier journals and authored 4 public astroparticle software packages. I created and lectured an official McGill course in numerical methods, have mentored 4 PhD and 5 Masters students, and am just about to serve on an external PhD defence committee for a student in Lisbon.

## Scientific vision

The identity of dark matter and the nature of physics at the TeV energy scale are two of the most pressing and fundamental questions in modern physics. DM constitutes 80% of the matter in the Universe and was discovered 80 years ago, but its composition remains a mystery. With the activation of the Large Hadron Collider (LHC), discovery of the Higgs boson and construction of high-energy astrophysics experiments like the *Fermi*-LAT, HESS-II, IceCube and SuperCDMS, we now stand on the doorstep of the TeV scale.

Excitingly, many popular DM candidates are intrinsically linked to the appearance at the TeV scale of new physics beyond the Standard Model (BSM). A Higgs mass of 125 GeV itself even compels us to move beyond the SM: theoretically, this value should be orders of magnitude higher if the impact of SM virtual particles is taken into account. If no other particles exist, then the very vacuum of our Universe is also unstable, and might undergo a catastrophic energy transition at any moment. We also know that the SM is incomplete because it does not explain the excess of matter over antimatter in our Universe, nor that fact that neutrinos are massive.

Many different probes are sensitive to BSM physics: direct and indirect searches for DM, accelerator searches, and neutrino experiments. Experiments such as CRESST, *Fermi*-LAT and PAMELA may even already show tantalising hints of DM. To make robust conclusions about the overall level of support for different BSM scenarios from such varied sources, a simultaneous statistical fit of all the data, fully taking into account all relevant uncertainties, assumptions and correlations is an absolute necessity. This 'global fit' approach is what I propose here. Such holistic analyses exploit the synergy between different experimental approaches to its maximum potential, squeezing every last statistical drop of information possible from each source. Robust analysis of correlated signals, in a range of complementary experiments, is *essential* for claiming a credible discovery of DM or new physics at the TeV scale – and indeed, even for definitively excluding theories. This 'win-win' situation is a particular feature of a global fit analysis, as even non-


Case for Support

detections provide crucial physical insight into which theories and parameter regions are disfavoured.

This is an extremely demanding task, existing on the cusp of theory and experiment, astronomy and particle theory – and requiring excellent understanding not only of the theories and experiments involved, but also many specialised statistical techniques and computer codes. I am uniquely placed to lead this endeavour, with the extensive cross-disciplinary background in astrophysics and particle physics, theory and experiment, DM phenomenology, statistical and numerical methods required to make this ambitious proposal a reality. Astroparticle experimental collaborations have so far carried out such global analyses only with my assistance: the examples to date have been my collaborations with the *Fermi*-LAT [12 in publication list], HESS [6] and IceCube [1].

Whilst partial progress has recently been made (by various groups including myself, Roberto Trotta at Imperial, and our respective collaborators), the magnitude of the task and degree of technical difficulty have left global fits largely unexplored for the majority of theories and datasets. With the startup of the LHC, vast amounts of additional data are rapidly becoming available at the TeV scale, making even analyses done in the past year obsolete. *Now* is precisely the time to invest in broadening the application and development of BSM global fits and their related computer codes, in order to deal together, in a consistent and holistic way, with a greatly expanded number of theories and the impending flood of new datasets.

## Scientific Objectives

1. Identify the correct theory behind dark matter and TeV-scale BSM physics
2. Exclude large classes of other viable and popular dark matter and TeV-scale BSM theories
3. Distinguish between areas of parameter space giving rise to distinct astroparticle phenomena within single BSM theories

## Research Framework/Methodology

An example of the utility of a global fit is shown in Fig. 1. Here probability distributions for the mass of supersymmetric DM, and its scattering cross-section with nucleons, are shown for two parameter scans. In one scan (grey), LHC and direct detection data are used to constrain an example supersymmetric theory. Two main regions of high probability exist: a horizontal region with large cross-sections, where the DM also has a large annihilation cross-section and its cosmological density it determined by DM-DM annihilation, and an almost vertical region extending to lower

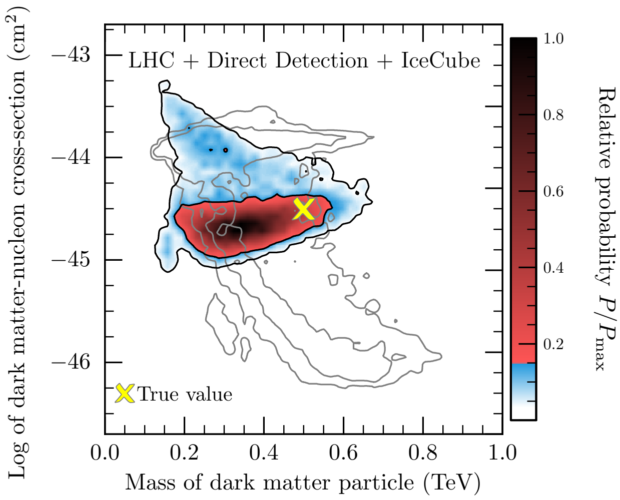


**Figure 1:** An example global fit exploiting the synergy between experiments in the search for BSM physics and DM. Grey contours show the result when LHC and XENON-100 direct detection data are used to constrain supersymmetry, in terms of the mass of the DM and its scattering cross-section with nucleons. Shading shows how the picture changes when a mock detection of DM by the IceCube Neutrino Telescope is considered, corresponding to a specific point in the parameter space. Shading gives the relative probability of the different parts of the parameter space, and contours give $1\sigma$ and $2\sigma$ regions. The fit with IceCube data zooms in markedly on the true point, determining the scattering cross-section with about a factor of 100 better accuracy than without IceCube (at 68% confidence level). Based on [1] in publication list.

cross-sections, where the DM has a much lower annihilation cross-section and its cosmological density is determined mostly by co-annihilation of DM particles with other supersymmetric particles. With LHC and direct detection data alone, there is no way to determine which of these regions is favoured, and therefore what physical process is primarily responsible for determining the amount of DM in the Universe. When data from a future hypothetical detection of DM with the IceCube Neutrino Telescope are added (colour), the degeneracy is lifted, and the parameter space is constrained with high accuracy (a factor of 100 improvement in the cross-section).

The core statistical methodology is that of a composite likelihood-based global fit. One first chooses a BSM physics scenario with some model parameters, and then calculates predicted experimental signatures of the model for arbitrary parameter combinations (gamma-ray fluxes, LHC event rates, etc). Predictions are compared to experimental measurements, and a series of likelihood functions produced. Such analyses have the added advantage of being able to fully deal with uncertainties in modelling assumptions or standard input data, by including them as additional parameters in the fit. The entire exercise can be repeated for different BSM scenarios with different parameterisations, and the results compared to determine if the data strongly favour one scenario over another.


Case for Support

## Core Research Fronts

**Particle and astroparticle datasets:** With Roberto Trotta and accelerator, direct detection and cosmic microwave background (CMB) experts at Imperial, I will include many new and updated observables in my global fits. BSM searches with CMS and ATLAS at the LHC are essential inclusions, but notoriously difficult in all but the simplest BSM theories. In consultation with Tapper, Buchmüller and the Imperial CMS group, I plan to develop approximate but detailed LHC likelihood functions for use in global fits, initially based on the most constraining CMS searches for supersymmetry, including the 'razor' and 'MT2' analyses. Direct searches for DM like XENON-100, ZEPLIN and LUX will also play a pivotal role. In collaboration with Araujo and Sumner at Imperial and the rest of the ZEPLIN/LUX collaboration, I will include full event-level data and detailed background models in the direct detection likelihoods of my global fits. With Jaffe I will include the impacts of DM annihilation on the CMB, as seen by Planck.

I will leverage my contacts in *Fermi*, IceCube and AMS-02 to include searches for cosmic anti-deuterons from Galactic DM annihilation with AMS-02, searches for DM annihilation in the Sun by IceCube, and combined searches for gamma rays from DM annihilation in all Milky Way dwarf satellite galaxies by *Fermi*. Together with the developers of the GALPROP cosmic ray propagation code, Trotta and I will develop a global fit analysis of *Fermi* data from the Galactic centre, utilising nested sampling, Bayesian object detection and detailed diffuse emission templates.

**Theories:** I will investigate the current leading candidates for new physics: 7-, 13-, 19- and 25-parameter phenomenological versions of the minimal supersymmetric standard model (MSSM), specific supersymmetry-breaking schemes such as Planck-scale-mediated, gauge-mediated, anomaly-mediated and gaugino-mediated scenarios, and models of extra dimensions. I will also derive global constraints on more effective DM models, including Effective WIMPs, Sommerfeld-enhanced models, Two Higgs Doublet Models, Asymmetric DM, Isospin-Violating DM, Inelastic and Exciting DM. This will allow me to test, refine and compare the viable regions of these models to a far greater extent than done previously.

**Statistical & Numerical Methods:** A core part of my ERF will be developing a second-generation BSM global-fitting software package, able to dynamically rewrite modules of its own code to implement new theories and adjust to new experimental datasets. This will allow a degree of flexibility not before seen in statistical analyses of BSM theories, facilitating the analysis of vastly more theories and experimental signatures than has been done to date. I intend to make this software, and its component physics codes, freely available to the community.

With the members of the new Imperial Centre for Inference and Cosmology (ICIC; Trotta, Jaffe, van Dyk et al), I will improve on the statistical and numerical aspects of global fit analyses. I have particular expertise in optimisation/scanning algorithms, with extensive experience in both Bayesian and frequentist scanning methods (e.g. genetic algorithms, nested sampling). I will leverage this expertise and the excellence of the ICIC to develop a new alternative scanning code for BSM searches, based on the strategy of differential evolution.

**Additional synergies** with my program exist within Imperial and the general London area. Ellis, Fairbairn and colleagues in High Energy Theory at King's College might contribute to phenomenological aspects of the BSM fit program. As I have shown previously, indirect DM detection also has cosmological implications, via consideration of ultracompact minihalos; my work in this direction would benefit from interaction with Jaffe and Contaldi (inflation and cosmological perturbations), and Rajantie (cosmic strings).

## Timeline

**Years 1–2** Develop:
- core second-generation global fitting code
- first LHC (few channels) likelihood module
- direct detection likelihood modules
- indirect detection likelihood modules
- differential evolution scanner

Publish:
- indirect detection likelihood code package paper
- direct detection likelihood code package paper
- differential evolution code paper

**Year 3**
- Publish phenomenological MSSM analyses
- first public release of code

**Year 4** Add/update observables:
- all LHC channels
- cosmic rays + propagation models
- gamma-rays
- neutrino telescope
- CMB limits on DM annihilation

Add theories:
- supersymmetry-breaking mediation models
- extra dimensions
- Two Higgs Doublet Models
- effective DM models

**Year 5** Complete and publish (for all theories):
- global parameter analyses
- extensive model comparison


Case for Support

Science & Technology
Facilities Council

**IN CONFIDENCE: CURRICULUM VITAE**

| | |
|---|---|
| **Name (title, first name(s), surname):** Dr Pat Scott | |
| **Nationality (Citizenship if appropriate):** Australian | |
| **Address:** 4444 rue Drolet, Montreal, Quebec, Canada H2W2L8 | |
| **Telephone number:** +15145629659 | **Email:** patscott@physics.mcgill.ca |

**Employment: Provide details of your employment in chronological order (most recent first)**

| Dates From | Dates To | Organisation and position held | Type of appointment |
|---|---|---|---|
| 10/12 | 09/14 | NSERC Banting Fellow, McGill University | fixed-term |
| 10/10 | 09/12 | Institute for Particle Theory (Canada) Fellow / Trottier Astrophysics Fellow, McGill University | fixed-term |

**Education: Undergraduate and postgraduate studies**

| Dates From | Dates To | University/College attended | Department | Subject | Class of award |
|---|---|---|---|---|---|
| 2006 | 2010 | Stockholm University | Physics | Theoretical Physics | PhD |
| 2006 | 2008 | Stockholm University | Physics | Theoretical Physics | Licentiate |
| 2001 | 2005 | Australian National University | John Curtin School of Medical Research | Neuroscience | Bsc (Hons, First Class) |
| 2001 | 2004 | Australian National University | Research School of Astronomy & Astrophysics | Astrophysics | Bsc (Hons, First Class) |

**Provide a brief description for the following:**

**Prizes, awards and honours received:**

2012-2014 *The Banting Fellowship*, Government of Canada Tri-Agency / NSERC (£88K)
2010-2012 *Theory Fellowship*, Canadian Institute for Particle Physics (£35K)
2010-2012 *The Trottier Fellowship* in Astrophysics, McGill University (£42K)
2010 *The CfA Fellowship* (declined), Harvard-Smithsonian Centre for Astrophysics (£140K)
2010 *The Sigrid Arrhenius Prize*, Stockholm University, best thesis in Science
2009 *G & E Kobbs Foundation Grant* (£4.7K)
2009 *Helge Axelsson Johnsons Foundation Grant* (£1.3K)
2009 *CF Liljevalchs Foundation Travel Grant* (£0.7K)
2008 *G & E Kobbs Foundation Grant* (£1.3K)
2008 *European Network for Theoretical Astroparticle Physics ILIAS/N6 Travel Grant* (£0.8K)
2008 *Helge Axelsson Johnssons Foundation Grant* (£1.3K)
2007 *IAU Exchange of Astronomers Grant*, Internat. Astronomical Union Commission 46 (£1.2K)
2006-2010 *HEAC (High Energy Astrophysics and Cosmology Centre) Doctoral Fellowship*, AlbaNova University Centre, Stockholm.
2006 *The Sir Grafton Elliot Smith Prize*, Australian Neuroscience Society, best essay on any neuroscience topic by a student yet to submit a doctoral thesis
2005 *The Bok Prize*, Astronomical Society of Australia, best Honours/Masters thesis in astronomy or astrophysics at an Australian university
2004, 2005 *The University Medal* (twice), Australian National University
2001-2005 *National Undergraduate Scholarship and Distinguished Scholar Program*, Australian National University

**Research Interests:**

**Theory and detection of particle dark matter, and phenomenology of particle physics beyond the standard model:** indirect dark matter detection with gamma rays and cosmic rays, dwarf galaxies, the impacts of dark matter upon stars, supersymmetry and its breaking, techniques for scanning supersymmetric parameter spaces, dark matter in the very early universe, collider phenomenology and neutrino telescopes. **Also numerical methods in physics, stellar/solar evolution and the chemical composition of the Sun.**

**Teaching experience (include dates):**

2011 Lecturer, Tutor and Course Responsible, *PHYS606: Practical Numerical Methods in Physics*, McGill University; 13 students, mixed graduate/undergraduate.

2011 Guest Lecturer, *Stellar Evolution*, San Francisco University (Main Lecturer: Aparna Venkatesan); ~20 students, undergraduate.

2008-2009 Tutor, *FK7025: Advanced Relativistic Quantum Field Theory*, Stockholm U.; 6 graduate students

2003 *Residential Tutor in Physics and Mathematics*, Burgmann College, Australian National University; ~ 20 students, undergraduate.

**Student supervision - PhD and undergraduate (include dates):**

Mentoring (unofficial supervision) of

*PhD students*: Yashar Akrami (Stockholm, 2010), Aaron Vincent (McGill, 2012), Elinore Roebber, Grace Dupuis (both McGill, 2016)

*Masters students*: Hamish Silverwood (Canterbury, 2012), Elinore Roebber, Grace Dupuis (both McGill, 2012), Philippe Giguere and Francis Duplessis (both McGill, 2013)

**Scientific responsibilities held (e.g. committee & working group membership, coordinator & convenor roles, space mission involvement):**

Associate member of the IceCube Collaboration (since April 2011)

Affiliated member of the Fermi Large Area Telescope (LAT) collaboration (since 2008)

Member of Stockholm U. Physics Departmental Computing Committee (2009-2010)

**Main Collaborators:**

Imperial: *Roberto Trotta*; King's College: *Malcolm Fairbairn*; Stockholm: *Joakim Edsjö, Lars Bergström, Jan Conrad, Sofia Sivertsson, Erik Zackrisson;* RWTH Aachen: *Antje Putze;* Utah: *Chris Savage, Paolo Gondolo;* McGill; *Robert Brandenberger, Jim Cline, Gil Holder*; Hamburg: *Torsten Bringmann*, Oslo: *Are Raklev, Yashar Akrami*; Auckland: *Richard Easther*; Penn State: *Sarah Shandera*; Canterbury: *Jenni Adams*; ANU: *Martin Asplund*; Barcelona: *Aldo Serenelli*; Liege: *Nicolas Grevesse*; Royal Belgian Observatory: *Jacques Sauval*; The *Fermi-LAT* and *IceCube* Collaborations

**Conference & Seminar organisation (include dates):**

2012 Session chair, *The LHC, Particle Physics and the Cosmos*, Auckland

2012 Co-convenor & session chair, *Particle Astrophysics and Cosmology Track, International Conference on High Energy Physics (ICHEP)*, Melbourne

2012 Co-founder and Committee Leader, *McGill Astroparticle Seminar Series*

2011 Discussion leader, Dark Matter, *Northeast Cosmology Workshop*, Montreal

2011 Chair, Organizing Committee for *Dark Matter From Every Direction*, McGill University, April 1–3, 27 attendees

2010 Co-chair, Organizing Committee for *PROSPECTS Conference*, Stockholm University, September 15–17, 42 attendees

2009 Session chair, Neutrinos, *Dark2009*, Christchurch

**Conference & Seminar talks:** 66 total, 19 invited; see www.physics.mcgill.ca/~patscott/talks

**Refereeing (include dates):**

MNRAS Letters (2012), A&A (2012), JCAP (2012; 2011; 2009), JHEP (2011; 2011; 2010), ApJL (2011), Statistical Analysis & Data Mining (2011)

**Citations - List your top five publications /reports together with the ISI citation rate:**

*(Because ISI citation rates are highly inaccurate, I also give NASA ADS rates below.)*

Asplund M, Grevesse N, Sauval AJ & Scott P, The Chemical Composition of the Sun (2009, *Ann. Rev. Astron. & Astrophys.* 47:481) **Citations: 786** (ADS) / **613** (ISI)

Scott P, Conrad J, Edsjö J, Bergström L, Farnier C & Akrami Y, Direct Constraints on Minimal Supersymmetry from Fermi-LAT Observations of the Dwarf Galaxy Segue 1 (2010, *JCAP* 01:031) **Citations: 61** (ADS) / **38** (ISI)

Scott P, Fairbairn M & Edsjö J, Dark stars at the Galactic Centre - the main sequence (2009, *MNRAS* 394:82) **Citations: 41** (ADS) / **25** (ISI)

Scott P, Asplund M, Grevesse N, Sauval AJ, Line formation in solar granulation. VII. CO lines and the solar C and O isotopic abundances (2006, *A&A* 456:675) **Citations: 39** (ADS) / **29** (ISI)

Akrami Y, Scott P, Edsjö J, Conrad J & Bergström L, A Profile Likelihood Analysis of the Constrained MSSM with Genetic Algorithms (2010, JHEP 04:057) **Citations: 35** (ADS) / **16** (ISI)

**STFC ERF: Public engagement**

I have been involved in a number of outreach activities: I wrote an article on 'dark stars' for the Swedish amateur astronomy magazine *Populär Astronomi*, and gave an interview on the same topic for an article in *New Scientist*. I arranged a public lecture by John Ellis following the PROSPECTS Workshop that I organised in 2010, and have volunteered at various public open days and science festivals over the years.

The Imperial Astrophysics Group has a strong history of innovative outreach activities, and I fully intend to contribute to these both as an organiser and public presenter. I hope to develop an interactive, computer-based exposition of the roles and impacts of different experiments around the world in the hunt for new physics, based on the results of my global fits. This could probably be arranged as a research project for a group of first or second-year undergraduates, and might appear in a science museum, on an Imperial webpage, and/or taken on tour to e.g. schools in disadvantaged areas to promote enthusiasm for physics. I plan to apply for an STFC Public Engagement Small Award to help make this activity a reality.

## List of Publications

**Available from www.physics.mcgill.ca/~patscott/publications**
**Summary (Sep 17 2012, NASA ADS): 32 publications, 1239 citations, h-index: 13**

### Journal articles


[1] E. Zackrisson, *et al.*, *Hunting for dark halo substructure using submilliarcsecond-scale observations of macrolensed radio jets*, *MNRAS* (2012) submitted, [arXiv:1208.5482].

[2] P. Scott, C. Savage, J. Edsjö, and the IceCube Collaboration: R. Abbasi et al., *Use of event-level neutrino telescope data in global fits for theories of new physics*, *JCAP* (2012) accepted, [arXiv:1207.0810].

[3] A. C. Vincent, P. Scott, and R. Trampedach, *Light bosons and photospheric solutions to the solar abundance problem*, *JCAP* (2012) submitted, [arXiv:1206.4315].

[4] P. Scott, *Pippi – painless parsing, post-processing and plotting of posterior and likelihood samples*, *EPJ Plus* (2012) submitted, [arXiv:1206.2245].

[5] C.-E. Rydberg, E. Zackrisson, P. Lundqvist, and P. Scott, *Detection of isolated population III stars with the James Webb Space Telescope*, *MNRAS* (2012) submitted, [arXiv:1206.0007].

[6] P. Scott, A. I. Cowan, and C. Stricker, *Quantifying impacts of short-term plasticity on neuronal information transfer*, *Phys. Rev. E* **85** (2012) 041921, [arXiv:1204.3270].

[7] C. Strege, R. Trotta, G. Bertone, A. H. G. Peter, and P. Scott, *Fundamental statistical limitations of future dark matter direct detection experiments*, *Phys. Rev. D* **86** (2012) 023507, [arXiv:1201.3631].

[8] T. Bringmann, P. Scott, and Y. Akrami, *Improved constraints on the primordial power spectrum at small scales from ultracompact minihalos*, *Phys. Rev. D* **85** (2012) 125027, [arXiv:1110.2484].

[9] P. Scott, A. Venkatesan, E. Roebber, P. Gondolo, E. Pierpaoli, and G. Holder, *Impacts of Dark Stars on Reionization and Signatures in the Cosmic Microwave Background*, *ApJ* **742** (2011) 129, [arXiv:1107.1714].

[10] J. Ripken, J. Conrad, and P. Scott, *Implications for constrained supersymmetry of combined H.E.S.S. observations of dwarf galaxies, the Galactic halo and the Galactic centre*, *JCAP* **04** (2011) 012, [arXiv:1012.3939].

[11] Y. Akrami, C. Savage, P. Scott, J. Conrad, and J. Edsjö, *How well will ton-scale dark matter direct detection experiments constrain minimal supersymmetry?*, *JCAP* **4** (2011) 12, [arXiv:1011.4318].


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[12] Y. Akrami, C. Savage, P. Scott, J. Conrad, and J. Edsjö, *Statistical coverage for supersymmetric parameter estimation: a case study with direct detection of dark matter*, *JCAP* **7** (2011) 2, [arXiv:1011.4297].

[13] E. Zackrisson, P. Scott, C.-E. Rydberg, F. Iocco, S. Sivertsson, G. Östlin, G. Mellema, I. T. Iliev, and P. R. Shapiro, *Observational constraints on supermassive dark stars*, *MNRAS* **407** (2010) L74–L78, [arXiv:1006.0481].

[14] E. Zackrisson, P. Scott, C.-E. Rydberg, F. Iocco, B. Edvardsson, G. Östlin, S. Sivertsson, A. Zitrin, T. Broadhurst, and P. Gondolo, *Finding High-redshift Dark Stars with the James Webb Space Telescope*, *ApJ* **717** (2010) 257–267, [arXiv:1002.3368].

[15] Y. Akrami, P. Scott, J. Edsjö, J. Conrad, and L. Bergström, *A profile likelihood analysis of the Constrained MSSM with genetic algorithms*, *JHEP* **4** (2010) 57, [arXiv:0910.3950].

[16] P. Scott, J. Conrad, J. Edsjö, L. Bergström, C. Farnier, and Y. Akrami, *Direct constraints on minimal supersymmetry from Fermi-LAT observations of the dwarf galaxy Segue 1*, *JCAP* **1** (2010) 31, [arXiv:0909.3300].

[17] M. Asplund, N. Grevesse, A. J. Sauval, and P. Scott, *The chemical composition of the Sun*, *ARA&A* **47** (2009) 481–522, [arXiv:0909.0948].

[18] P. Scott and S. Sivertsson, *Gamma rays from ultracompact primordial dark matter minihalos*, *Phys. Rev. Lett.* **103** (2009) 211301, [arXiv:0908.4082].

[19] P. Scott, M. Asplund, N. Grevesse, and A. J. Sauval, *On the Solar Nickel and Oxygen Abundances*, *ApJ* **691** (2009) L119–L122, [arXiv:0811.0815].

[20] P. Scott, M. Fairbairn, and J. Edsjö, *Dark stars at the Galactic Centre - the main sequence*, *MNRAS* **394** (2009) 82–104, [arXiv:0809.1871].

[21] M. Fairbairn, P. Scott, and J. Edsjö, *The zero age main sequence of WIMP burners*, *Phys. Rev. D* **77** (2008) 047301, [arXiv:0710.3396].

[22] P. Scott, M. Asplund, N. Grevesse, and A. J. Sauval, *Line formation in solar granulation. VII. CO lines and the solar C and O isotopic abundances*, *A&A* **456** (2006) 675–688, [astro-ph/0605116].

### Other refereed contributions (proceedings)

[23] P. Scott, T. Bringmann, and Y. Akrami, *Constraints on small-scale cosmological perturbations from gamma-ray searches for dark matter*, in *Proceedings of TAUP 2011* (G. Raffelt et. al., ed.), *J. Phys. Conf. Series* **375** (2012) 032012, [arXiv:1205.1432].

[24] C. Blázas *et al.*, *DLHA: Dark Matter Les Houches Agreement*, in *Les Houches 2011: Physics at TeV Colliders New Physics Working Group Report* (Brooijmans, G. et. al., ed.) (2012) [arXiv:1203.1488].

[25] P. Scott, *Dark stars: structure, evolution and impacts upon the high-redshift Universe*, in *Cosmic Radiation Fields: Sources in the early Universe* (M. Raue, T. Kneiske, D. Horns, D. Elsaesser, & P. Hauschildt, ed.) (2011) *PoS*(**CRF 2010**)021, [arXiv:1101.1029].

[26] C. E. Rydberg, E. Zackrisson, and P. Scott, *Can the James Webb Space Telescope detect isolated population III stars?*, in *Cosmic Radiation Fields: Sources in the early Universe* (M. Raue, T. Kneiske, D. Horns, D. Elsaesser, & P. Hauschildt, ed.) (2011) *PoS*(**CRF 2010**)026, [`arXiv:1103.1377`].

[27] N. Grevesse, M. Asplund, A. J. Sauval, and P. Scott, *The New Solar Composition and the Solar Metallicity*, in *The Sun, the Solar Wind, and the Heliosphere* (M. P. Miralles and J. Sánchez Almeida, eds.), *IAGA Special Sopron Book Series* **4** (2011) 51–60.

[28] N. Grevesse, M. Asplund, A. Sauval, and P. Scott, *The chemical composition of the sun*, in *10th International Colloquium on Atomic Spectra and Oscillator Strengths for Astrophysical and Laboratory Plasmas*, *Can. J. Phys.* **89** (2011) 327–331.

[29] N. Grevesse, M. Asplund, A. J. Sauval, and P. Scott, *The chemical composition of the Sun*, in *Synergies between solar and stellar modelling*, *Ap&SS* **328** (2010) 179–183.

[30] P. Scott, J. Edsjö, and M. Fairbairn, *The DarkStars code: a publicly available dark stellar evolution package*, in *Dark Matter in Astroparticle and Particle Physics: Dark 2009* (H. V. Klapdor-Kleingrothaus & I. V. Krivosheina, ed.), World Scientific, Singapore (2010) 320–327, [`arXiv:0904.2395`].

[31] P. Scott, M. Fairbairn, and J. Edsjö, *Impacts of WIMP dark matter upon stellar evolution: main-sequence stars*, in *Identification of dark matter 2008* (2008) *PoS*(**idm2008**)073, [`arXiv:0810.5560`].

[32] P. Scott, J. Edsjö, and M. Fairbairn, *Low mass stellar evolution with WIMP capture and annihilation*, in *Dark Matter in Astroparticle and Particle Physics: Dark 2007* (H. K. Klapdor-Kleingrothaus and G. F. Lewis, eds.), World Scientific, Singapore (2008) 387–392, [`arXiv:0711.0991`].

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**STFC ERF: Pathways to Impact**

Whilst searches for particle physics beyond the standard model and astroparticle phenomena are about as 'blue sky' as research comes, I see two potential pathways to impact outside my own academic community:

- Global fits are useful not only for determining the impacts of existing experiments, but for quantitatively comparing the prospective impacts of different proposed experiments and their potential configurations. The results of these comparisons are of direct usefulness for informing upcoming policy decisions by bodies such as STFC itself. I plan to submit such evaluations to the STFC Science Committee where appropriate, and may become involved in the Committee myself at the end of the ERF.

- My differential evolution optimisation code will have some additional features that may make it a commercialisable code package, useful in e.g. finance and engineering. I will explore this possibility with Imperial Innovations, ICL's technology transfer office.