# PART C1 - Description of Project/Program of Research

PROJECT TITLE: Discovery and discrimination of models for new physics with combined terrestrial and astrophysical data

## AIMS AND BACKGROUND

We aim to answer the following questions:

- What is the correct theory of matter beyond the Standard Model of particle physics?
- What is dark matter?

### Background

We are living in the golden age of particle physics. The Standard Model (SM) explains, in the language of gauge field theory, what the basic building blocks of the universe are and how they interact. The recent discovery of a Higgs-like boson [1] in the proton–proton collisions of the Large Hadron Collider at CERN, Geneva, gives us for the first time an experimental probe of the origin of mass, and ranks as one of the greatest scientific achievements in history. This tremendous progress in our measurements of the smallest scales in Nature is matched by outstanding leaps forward in our understanding of the universe as a whole. Astrophysicists have combined observations of galaxy rotation curves, gravitational lensing measurements and precision measurements of the cosmic microwave background to discover that 80% of the matter in the universe is composed of a strange form of "dark matter".

Unfortunately, dark matter and the Higgs boson *both severely challenge the SM.* In the former case, the theory contains no particles that fit the properties of dark matter unless we extend it. In the latter case, the size of the Higgs mass is many orders of magnitude below that expected by the structure of the theory, requiring a significant fine tuning of the underlying parameters in order to reproduce the observed value of 125 GeV (the so-called "hierarchy problem" [2]). It is widely assumed, therefore, that the SM is a low energy effective theory, and at higher energy scales one will observe new particle content and new physics capable of providing a natural explanation for the low energy behaviour. Many candidates exist in the literature (e.g. supersymmetry [3], extra dimensional theories), and it is sufficient for our purposes to learn one startling fact: new physics at the TeV scale can simultaneously solve the dark matter and hierarchy problems, whilst also dramatically increasing the elegance of our theories by, for example, ensuring that the three forces we see at low energies were in fact unified as a single force in the early universe.

***The biggest challenge in particle physics today is to determine which, if any, TeV-scale theory of Beyond the Standard Model (BSM) physics is true.*** **The central theme of this Project is to address this challenge.**

**Aims**

BSM physics at the TeV scale will show up in lots of places, including accelerator searches (such as the LHC and previous experiments), neutrino mass and mixing data, and direct and indirect DM search experiments. Many experiments already show tantalizing hints of DM or other TeV-scale BSM physics [914]. 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. The same is true for determining the preferred regions of parameter space within a particular scenario. This is a highly non-trivial 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 a raft of specialized statistical techniques and computer codes. Whilst partial progress has recently been made in this direction (by various groups including the authors and their collaborators; [1533]), the magnitude of the task and degree of technical difficulty have left it 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, quickly making even the analyses that have been done in the past year obsolete.

The research in this proposal will revolutionize this emerging field, by taking the publicly available data from the LHC and astrophysics experiments, and vastly expanding the scope of models to which it is applied. We will develop the methods that make it possible to explore *any* model of BSM physics with almost all of the particle and astrophysical data recorded up to, and including, the period of the project. We will apply these methods to the leading examples of physics at the TeV scale to place recent and future discoveries in their proper context. We will use the strong experimental connections of our named researchers to feed this information back to the leading particle and astrophysics experiments, directly influencing the course of future research.

# RESEARCH PROJECT

**Significance:**

The origin of dark matter is arguably the greatest unsolved mystery in fundamental physics. Tens of thousands of physicists worldwide are engaged in performing direct or indirect searches for dark matter, or analysing particle accelerator data for evidence of dark matter production. Finding the correct theoretical explanation for dark matter and other fundamental phenomena is the ultimate goal of thousands of international theorists. We will make the most robust and general statements of the ability of BSM physics at the TeV scale to explain dark matter at a time when the profile of particle astrophysics research has never been higher. The outcomes of this project will determine the future direction of international physicists.

**Advancing the Knowledge Base with Novel and Innovative Aims and Concepts:**

The first statistically rigorous global fits for BSM physics analysis (not counting neutrino oscillations) were performed just 5 (CHECK NUMBER) years ago [18, 19], in the context of very simple versions of the minimal supersymmetric standard model (MSSM) [4]. Subsequent analyses painstakingly improved the statistical and computational tools involved [20, 23, 3436], examined small theoretical departures from the simplest models [37, 38], more general MSSM parameterizations [24], alternative supersymmetry-breaking schemes [25] or extensions of the MSSM [39], and added other astrophysical data to the fits [21, 26]. Recent efforts have focused on adding new data from the LHC [2729], and from direct detection experiments [30, 31] hunting for nuclear scattering of DM on highly radio-pure target materials in deep underground labs, such as SNOLAB in Sudbury. In all of these directions (observables, techniques and models), existing analyses are only just beginning to explore what can and must be done, and the limiting factor is the considerable computational expense of accurately modelling observables, and repeating calculations millions of times in large parameter spaces.

This proposal will *advance the knowledge base* by providing the most general body of statistical inferences ever made on BSM physics models, including a supersymmetric model with 5 times as many parameters as those commonly used in the literature, non-trivial extensions of the minimal supersymmetric model, and non-supersymmetric models. Our work will rely on several *innovative aims and concepts*. The primary challenge in our research is to solve the computational challenges in exploring large parameter spaces that are holding the field back. We will:

- develop a fast and general method for applying LHC data in parameter fits, building on the work of CI Dr Martin White who has published the two most advanced techniques for applying LHC data to generic BSM physics models

- develop new sampling technology to explore large parameter spaces more efficiently

- develop new techniques for calculating astrophysical observables

The second challenge in particle astrophysics is to ensure that we use as much of the current collider and astrophysical data as possible to build a truly unique inventory of knowledge. We will:

- apply flavour physics data in a much more detailed fashion than has previously been attempted, building on the experience of CI Dr Paul Jackson
- use a wide selection of observables from the LHC, rather than relying on one or two flagship particle searches as is standard in the literature
- extend the number of astrophysical observables used in BSM physics studies

Any one of these innovations would be sufficient to place us at the front of the field. By accomplishing all of them, we will be the preeminent team in particle astrophysics data interpretation.

### Conceptual framework, Design and Methods

Our core methodology is that of a composite likelihood-based global fit (see e.g. [20, 21, 23]). 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, event rates at the LHC, etc). Predictions are compared to experimental measurements, and a series of likelihood functions produced. The likelihood describes the probability of obtaining the observed data if the BSM physics scenario is correct, given some combination of the model parameters. Each experimental dataset has an associated likelihood function. The individual likelihoods are multiplied to obtain a single combined likelihood. By sampling the likelihood function at a number of different parameter combinations, one can map the overall likelihood surface. This step is highly non-trivial and computationally intensive, even with sophisticated optimization algorithms [23, 34]; traditional grid and random scans are woefully inadequate even for simple versions of the MSSM. The samples are analysed with established statistical methods to produce likelihood maps and probability distributions for the different parameters and observables. These results then form our bank of knowledge about that particular BSM model and its allowed parameter space, and this information is highly sought after by experimental researchers wishing to focus their analyses on viable physics models.

We will use a wide range of available data, including Higgs and supersymmetry searches at the LHC and its predecessors [1, 5, 6], low-energy accelerators [13, 12, 14, 15, 16, 17], the magnetic moment of the muon [53], beam dump/fixed target searches for light bosons [54, 55], electroweak precision tests [56], DM direct detection experiments [46, 5760], searches for antimatter in cosmic rays [8, 40, 41, 6164], nuclear cosmic ray ratios [65], radio data [66, 67], effects of DM on reionisation [68, 69], recombination [70, 71] and helioseismology [72], the observed DM cosmological abundance [73], neutrino masses and mixings [13, 14, 74], and other indirect DM searches [11]. Standard tools exist to calculate ~~likelihoods based on some of~~ these data sets, yet others remain unwritten. Even once this step is completed, one needs to develop the computational methods by which one can take a generic physics model, plug in data sets and evaluate likelihood maps.

To facilitate the completion of these tasks, CI Dr Martin White recently formed an international collaboration (GAMBIT) to develop a general, modular computer code that interfaces likelihood calculations with generic BSM physics theories via sampling technology. All CIs and PIs of this proposal are GAMBIT members, and this proposal will ensure Australian dominance of this collaboration. The work in this proposal will be accomplished as a series of (parallel) stages, and much of it involves the development of *new methodologies or technologies*:

**1. Development of the GAMBIT computational framework:** We will write a modular C++ code to take generic physics models, scan them using novel sampling techniques, and apply physics constraints by calculating the likelihood based on LHC and astrophysical observables. This will be made available as a standard tool which is itself an important research outcome.

**2. Development of tools to calculate LHC likelihoods:** Calculating a model likelihood based on LHC observables can be done using standard tools in a two step process. First, one uses a Monte Carlo event generator to simulate the physics of new particle production in proton–proton collisions, before passing the results through a simulation of an LHC detector. This currently takes approximately 1 hour per likelihood, which is far too slow to obtain convergent fits in large parameter spaces, where one requires millions of likelihood calculations. We will reduce this calculation time to ¡10 s by parallelising the simulation code using high performance computing. Previous examples have been developed by CI Dr Martin White, including a second method that uses machine learning algorithms to interpolate grids of previously simulated data. These will be extended further during this project. We will also develop a fast simulation of an LHC detector based on the published detector response. These novel techniques will provide the most advanced solutions for calculating LHC likelihoods, and the only methods that will allow us to explore parameter spaces of high dimension. Both of our CIs combine phenomenology work with high profile experimental work on the ATLAS collaboration of the Large Hadron Collider.

**3. Development of tools to calculate astrophysical likelihoods:** There are three broad categories of astrophysical observable relevant for BSM physics studies: the relic density of dark matter derived cosmic microwave background observations, the limits placed on the rate of interaction of WIMP dark matter with Earth bound targets by direct search experiments, and limits on the flux of objects reaching the Earth from dark matter annihilation in space. The preeminent computer code for calculating these observables for supersymmetry models was developed by PIs Joakim Edsjo [7] and Jan Conrad of Stockholm University. This project will extend the range of observables considered, to include searches for cosmic anti-deuterons from DM annihilation [40, 41], searches for DM annihilation in the Sun by IceCube (with the IceCube Collaboration, and combined searches for gamma rays from DM annihilation in all Milky Way dwarf satellite galaxies by the FERMI experiment.

**4. Development of tools to calculate flavour physics quantities:** Important, will have new data from LHCb, will add new calculations...

**5. Development of new sampling technology:** A key component of staistical fits is the sampling algorithm used to explore the parameter space of the BSM theory of interest. The crudest method of doing this is simply to scan along each axis of the space and evaluate the likelihood at each point; this is also *precisely* the slowest method. There now exist a host of sampling algorithms that offer large increases, essentially by concentrating the search in regions of high likelihood. Examples include Markov Chain Monte Carlo techniques such as the Metropolois Algorithm, and nested sampling which is more robust with multimodal likelihood functions. We will include these techniques in GAMBIT, and will also develop new ones based on novel combinations (e.g. nested sampling with MCMC applied in each iteration rather than a random scan), or on entirely novel techniques (e.g. differential evolution). The net result will be a substantial decrease in the time required to explore a given BSM physics model.

**6. Development and deployment of interface to local high performance computing cluster:** Sufficient computing will be crucial to extracting the optimal performance from the sampling techniques developed in step 5. Local support in Adelaide will benefit from our close links with *eResearch SA* and computing resources requested herein. The GPU-based setup will provide the testbed for new computing which can then be deployed on local resources or shared with international partners.

These goals can be accomplished in parallel, by different members of our team (see section LIST OF PEOPLE). Having developed the code, we will use it to make a studies that significantly extend our knowledge of particle theory, and the particle physics of dark matter in particular. These include:

- A convergent statistical fit that applies all current LHC and astrophysical data to a minimal supersymmetry model with 25 parameters, 5 times as many as the simple models typically considered in the literature. This will tell us directly which distinct supersymmetric theories, if any, are still capable of providing solutions to the dark matter and hierarchy problems.

- A series of fits in well-motivated extensions of the simplest supersymmetric framework. More complex supersymmetric models include the Next-to-Minimal Supersymmetric Standard Model (MSSM) and the E6-MSSM. We will develop tools to explore these models, and compare which model is the most favoured, and should thus be prioritised in LHC searches.

- A series of fits of the leading non-supersymmetric scenarios. Very little attention is paid to non-supersymmetric models in statistical studies, and we will provide the first solid body of

Table 1: A selection of key milestones to be met by the project

| Milestone | Date Commenced | Date Achieved | Outcome |
|---|---|---|---|
| First convergent fits achieved | January 2014 | April 2014 | First physics exclusion paper from GAMBIT |
| Addition of newest astrophysical data to early 2012 8TeV LHC analyses | March 2014 | September 2014 | A more complete understanding of SUSY DM exclusions |
| Framework in place to run with first high-energy LHC constraints | August 2014 | March 2015 | Publish first global BSM constraints with high energy LHC data |
| Addition of first data from SuperKEKB flavour factory | December 2015 | August 2016 | A paper detailing the precise exclusion from low- and high-energy collider studies in tandem with astrophysics |

results that constrains the physics of extra dimensional theories, simple effective dark matter models, inert Higgs doublet models, asymmetric dark matter models, inelastic/exciting models, and isospin-violating dark matter models.

GAMBIT will be sufficiently general that it can be interfaced to new models with ease, and we will make selections based on which study will have the highest impact at the time of publication.

In order to accomplish the physics goals of this proposal, the technical work must be accomplished early. A suggested list of milestones is provided in Table 1. It is important to note that *some* physics papers can be completed with earlier versions of the code whilst it is still being extended, since not every observable is relevant for every BSM physics model. It is also worth noting that the LHC undergoes a two year shutdown period between February 2013 and February 2015, and we should therefore aim to present compelling physics results by the start of the second LHC run to maximise the international impact of our findings.

**Summary of Approach & Outcomes** This Discovery Project will use novel techniques and new data from particle and astrophysics experiments to systematically evaluate which models of TeV scale BSM physics can explain dark matter. The outcomes will include a series of standard tools for performing particle astrophysics calculations, and a series of groundbreaking studies that apply these tools to the most popular theories in the literature. Should nature provide new particles in the mass range ~~of 1TeV – ≈4TeV~~ these techniques will provide direct evidence and, if not, we will have the most robust exclusion of TeV scale physics models ever obtained. Either outcome will drive the direction of the field for years to come. *Furthermore, no other experimental particle physics program or proposal in the country is based on the outcomes of variables and techniques invented by the proponent.*

**National Benefit** Adelaide plays a leading role in high profile international collaboration, formed with the aim of solving one of the longest standing problems in physics. Through Australia's monetary contributions and our intellectual input, we have access to the output of data from these observatories. This strengthens Australia's involvement in high-energy (astro)particle physics, an extremely vibrant area of study worldwide, and an increasingly important part of the Australian academic scene.

RESEARCH ENVIRONMENT

**Adelaide**

The University of Adelaide is a research intensive university and a member of the Group of Eight. It is consistently ranked within the top 1% of universities worldwide, based on the Times Higher Education, QS and Jiao Tong Rankings. For example, in the Times rankings or 2010-11, Adelaide ranked thirty-fourth in the world in the area of this research proposal, Physical Sciences. These rankings are based on metrics covering teaching, and on research income, quality and reputation.

The University has identified major strengths in strategic areas relating to National Research Priorities. These include the Fundamental Disciplines with **specific emphasis on discipline of Physics.** In the recent Excellence in Research Australia (ERA) rankings administered by the ARC, Physical Sciences (FoR 02) at the University of Adelaide received the highest ranking of 5, which included a ranking of 5 for Astronomical & Space Sciences (FoR 0201). With the reinvigoration of nuclear and particle physics in Adelaide with the Centre for Complex Systems and the Structure of Matter and the Centre of Excellence in Particle Physics at the Terascale these research strengths will continue to grow with particular focus on particle physics phenomenology. The physics department in Adelaide boasts current or former members of the ATLAS, Auger, BaBar, Belle, Fermi-LAT, HESS and Ice Cube experimental collaborations, providing the *breadth of knowledge and unique collection of expertise* that make Adelaide the ideal location to perform the physics outline in this program. This confirms that the University of Adelaide has achieved "outstanding performance well above world standard" in the research area of the current proposal.

The research in this proposal will benefit from the support of the University and the School of Chemistry & Physics. The school hosts a University research institute, The Institute for Photonics and Advanced Sensing. Through the School we have access to a wide range of state-of-the-art research equipment, and IT infrastructure supported by technical and workshop staff. Supercomputing is supported by eResearch South Australia founded by members of the School. We are also fortunate to have access to a pool of talented and enthusiastic potential research students, mostly via the and HPCP (High Performance Computational Physics) B.Sc. and Space Science & Astrophysics B.Sc. degrees at the University.

**Stockholm**

Stockholm University and the "Oskar Klein Centre for Cosmoparticle physics"

**Edinburgh**

The University of Edinburgh School of Physics & Astronomy is one of the leading Physics departments in the UK. In the most recent Research Assessment Exercises (RAE2008) they were ranked 6th, with 45% of our research rated 3* (internationally excellent), and a further 20% rated 4* (world-leading). Research is carried out n a broad range of areas such as Astronomy, Cosmology, Particle

Physics and Nuclear Physics The School has more than 300 researchers, each belonging to one or more of its research institutes: the Institute for Astronomy (IfA); the Institute for Particle Physics and Nuclear Physics (IPPNP) and EPCC, the University's supercomputing centre which is home to some of the world's most advanced high-performance computer systems. Of the schools research centres the "Higgs Centre for Theoretical Physics" brings together researchers from different institutes involved in high-impact work related to measurement of the Higgs Boson and investigating the nature of the "dark matter" and "dark energy".

**Communication of Results** We communicate our research to the scientific community through the usual channels of refereed publications, conference publications and colloquia. In addition we are active in communicating our research to the general public, through talks to schools and community groups. Public Lectures for Jack and Martin. All kinds of presentations and things.....

ROLE OF PERSONNEL

**Jackson CI: Tasks:** *(see "Approach & Methodology" above): Joint responsibility for tasks 1 and 2; prime responsibility for task 4* Dr Jackson is a World Leader in collider searches for new physics beyond the Standard Model and designer of new techniques that provide unique and sensitive methods to search for new processes. He leads the flavour physics and precision observables area of GAMBIT and is responsible for all aspects of physics related to that. .

**White CI: Tasks:** *(see "Approach & Methodology" above): Joint responsibility for task 1; prime responsibility for task 2 and 5; strong contribution to task 3* Dr White is a sought after figure in the cross-over between phenomenological constraints, experimental data measurement and computational statistical techniques, a combination of skills that are central to modern global astroparticle fitting needs. Dr White is the leads high-energy collider constraints with GAMBIT and brings a history of collider particle phenomenology and particle physics code development to the project.

**Edsjo PI: Tasks:** *(see "Approach & Methodology" above): Prime responsibility for task 3; strong contribution to task 1* Professor Edjso is *one of the World's most distinguished particle astrophysicists* with a special interest in Weakly Interacting Massive Particles, in particular neutralinos. He will make key contributions to task 3 in developing astrophysical tools to calculate likelihoods to input to GAMBITs computational framework. Through this task he will also make considerable contributions to the standard tool used by the modular inputs. As one of the major contributors to the preeminent code for performing Supersymmetric Dark Matter calculations for observables he is the best international partner available for this task.

**Conrad PI: Tasks:** *(see "Approach & Methodology" above): Prime responsibility for tasks 3; strong contribution to tasks 1 & 5* Professor Conrad is a World leader in experimental astroparticle physics. He is the *Principal Investigator of the Swedish HESS, FERMI and CTA consortia*, has served as Co-leader of the FERMI Working group for Dark Matter/New Physics and a member of the Swedish National Committee for Astronomy, Royal Swedish Academy of Sciences. Professor Conrad will contribute his expertise to producing likelihood functions based on astrophysical observables addressing task 3. His expertise in the experimental observations of these quantities will be combined with PI Edsjo to provide the best possible team to write these modular inputs to GAMBIT. Through the development and running of these likelihoods PI Conrad will also making telling contributions to the computational framework (task 1) and the tools used to speed up the overall performance (task 5).

**Buckley PI:** **Tasks:** *(see "Approach & Methodology" above): Prime responsibility for tasks 2; strong contribution to tasks 1 & 5* Dr Buckley is an expert in the design, writing and performance of Monte Carlo generators for collider particle physics. PI Buckley is a member of the ATLAS collaboration and has the roles of *Working group convener of the MC Generators group.* PI Buckley will provide exceptional abilities to task 2 in the development of tools for calculating LHC likelihoods given his unique position within one of the LHC experiments. His knowledge of modern computational techniques, and the vast array of available tools, will improve the core aspects of tasks 1 and 5.

**Research Associate:** **Tasks:** *(see "Approach & Methodology" above): Prime responsibility for task 6, strong contributions to tasks 1,3,4,5& 8.* We will seek a research associate with strong skills and experience in....

**Postgraduate students:** The project in Adelaide provides opportunities to postgraduate students. In particular....

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