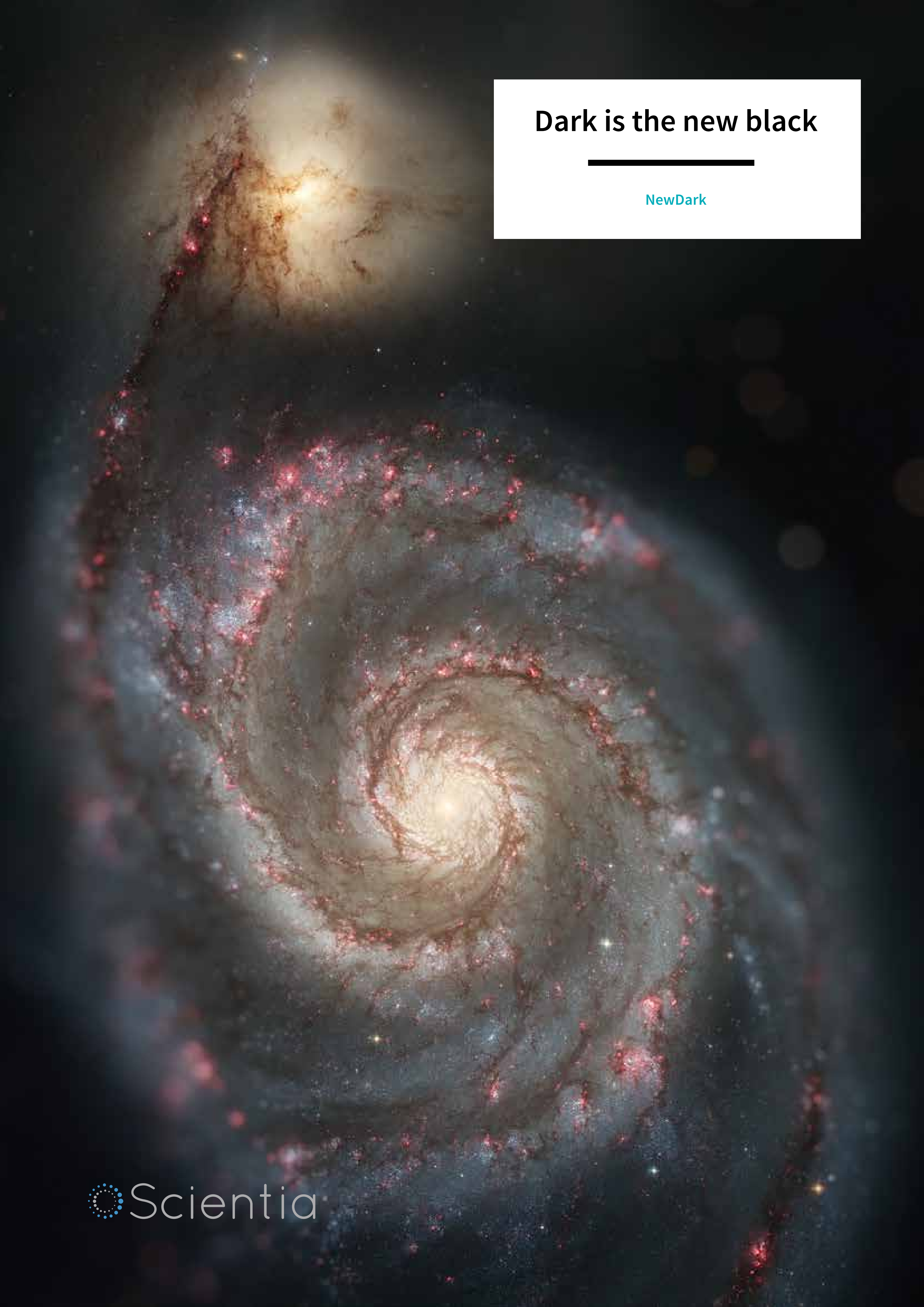
Dark is the new black

NewDark



Scientia

DARK IS THE NEW BLACK

Eighty-four percent of the matter in the universe is made of something we cannot see, cannot detect, can only guess at based on the gravitational shadows it leaves in the visible universe. Sounds crazy? Welcome to the world of dark matter, where teams of researchers collaborate to catch this most elusive of prey. Here, we meet the NewDark group, at the Laboratory of Theoretical and High Energy Physics, CNRS, France, whose ambitious quest is to uncover the true nature of this mysterious substance.

We live in a vast and terrifying universe in which our homes and citie s are, quite literally, infinitesimal. Our eyes can perceive a tiny fraction of a spectrum which ranges from energetic gamma rays to ground-penetrating sub-radio frequencies; we complain of unseasonably warm and cold temperatures in a climate which makes up a tiny, tiny fraction of a universe ranging from the almost absolute zero of deep space to the million-plus degrees inside stars. And even when we bring out our best equipment, our sensors and telescopes and large hadron colliders, then we still cannot see the majority of the universe. Eighty-four percent of the matter in the universe is hidden, undetectable, seen only by its gravitational interactions with other objects. Known as Dark Matter, this mystery has galvanised the attention of physicists for many, many years.

Dark what?

You think this sounds interesting, but are unsure as to what, exactly, Dark Matter is? Well, you aren't alone. We asked members of the NewDark group, at the Laboratory of Theoretical and High Energy Physics in France, who are quite frank about humanity's almost complete lack of knowledge: 'Dark Matter is most probably a particle – as opposed to some sort of fluid – which doesn't interact with light. It is stable, heavy – enough to catalyse galaxy formation – and, last but not least, different in nature from the stuff of everyday matter. A quick check shows that none of the known particles can fit the bill.'

The question then is – how do we know anything about dark matter at all? The first clues popped up in the last century, as astronomers noticed that galaxies were able to spin faster than should be possible – the amount of visible mass simply could not provide enough gravitational force to hold everything together. More detailed experiments followed, studying stellar movement and gravitational lensing, in which gravity bends the light of stars behind the object to act as a colossal magnifying glass. The gravitational effects of dark matter can be seen far from the visible stars and gases we are used to; indeed, dark matter forms a vast network throughout space which we can detect from measurements of the cosmic microwave background radiation. Dark matter filaments (if we can use a word so dainty for macrostructures larger than our galaxy) and their crossings seem to have acted as gravitational cores to seed the very starting locations of galaxies themselves.

So we know that it is out there, we can see the shadows which dark matter casts in our safely visible space-time pond. However, as the NewDark team know too well, the very same features that make Dark Matter cosmologically important also make it extremely difficult to detect. Many attempts have been made to spot the offshoots of dark matter – highly sensitive detectors buried deep in the earth watch for the slightest spark of interacting particles, satellites in high orbits watch for the curious fluxes of subatomic particles associated with dark matter annihilations or decay, vast

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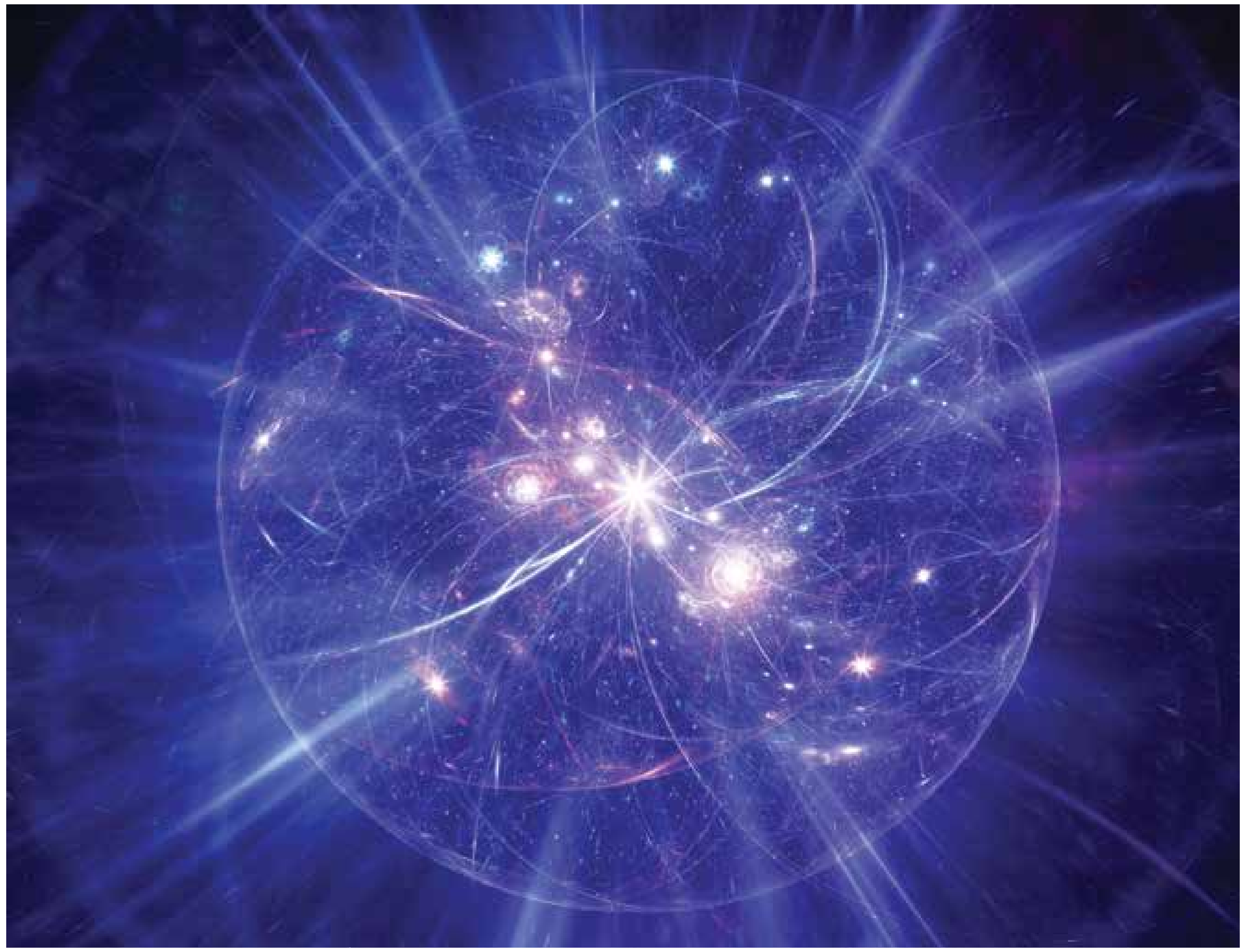

accelerators smash particles together at very respectable percentages of the speed of light. All glimpse at the hidden features of dark matter, none have provided definitive proof.

A matter of shadows and gravity

All our experiments have shown pieces of the many-faceted puzzle that is dark matter. Clever interpretation of the available evidence has led to the deductions that dark matter must be a particle (as the density of dark matter decreases as the universe expands), stable enough to last for billions of years without decaying, heavy enough to cluster gravitationally, yet weak enough to barely interact with itself or the other 'standard' particles in the universe. A complex set of properties, which cannot be fulfilled by the particles we know of at the moment.

So what could dark matter be? Physicists have thought up many ideas for dark matter particles over the years. Many of these particles fall under the broader category of 'WIMPs' (Weakly Interacting Massive Particles). WIMPs are so named for their meagre interactions with the 'standard' atoms and subatomic particles we are used to, passing in their millions through each of us with barely a twitch of interaction. Theoretical extensions to the standard model of particle physics independently predicted a WIMP particle whose properties matched calculations derived from dark matter studies, a fact which managed to excite a number of physicists – at least until results from the Large Hadron Collider seemed to put the idea under tension. This was unfortunate both for the resulting disappointment and for the fact that one of the many hypothesised candidates was the *higgsino* – the super-symmetric partner of the Higgs boson. The Higgs boson is often hyperbolically referred to as the 'god particle' in the media, which would theoretically make the *higgsino* somewhat satanic – perfect for those aspiring sci-fi/horror writers out there.

Luckily dark matter research is in no way short of excellent names. Directly contrasting the WIMPs is the MACHO hypothesis (for massive astrophysical compact halo object). In this hypothesis, dark matter is actually just standard matter in forms which we can't see (brown dwarves, neutron stars, special black holes and the like), although recent work has indicated that there cannot be enough of these objects to make up all the missing matter. What else? We could try looking for axions, slow moving hypothetical particles with a low mass (in contrast to the 'massive' WIMPs), which could theoretically

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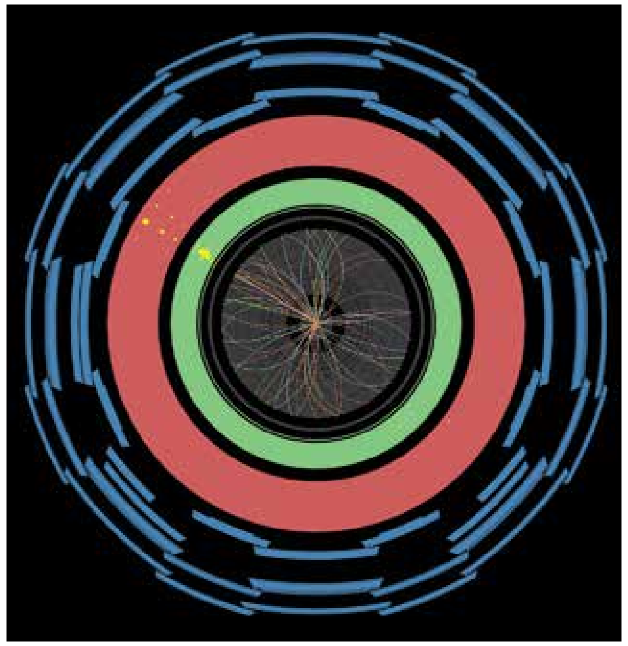


ATLAS Experiment © 2016 CERN

Dark matter could be made of particles 1000 times heavier than the proton or as light as a millionth of an electronvolt, or of sterile neutrinos, cousins of the known neutrinos but insensitive to ordinary forces. Or even more exotic possibilities.

be detected as they transmutate into photons. Or we could embrace the Kaluza-Klein theories, which bring us the concept of a 4th spatial dimension (in addition to length, width and height), which is curled up at sub-atomic scales in a way which we could never detect, save for the particles left behind as they decay and the gravitational interactions they leave behind themselves.

The problem, however, is that none of these particles have actually been detected. Even multinational collaborations consisting of billions in funding such as the Large Hadron Collider have so far failed to detect signs of these hypothesised pieces of exotic matter. In the words of Dr Marco Cirelli, the head of the NewDark group, this lack of success has allowed 'theorists' minds to start wandering in less explored territories. Dark matter could be made of particles as light as a millionth of an electronvolt, or of sterile neutrinos, cousins of the known neutrinos but insensitive to ordinary forces. Or even more exotic possibilities.'

Even more exotic?

More exotic than the reflections of tightly wound-up higher dimensions? Welcome to the world of theoretical physics and dark matter! The NewDark project was set up in an effort to make some sense of this field, by bringing together expertise from the multiple overlapping fields involved in dark matter research. The project covers theory, the particular physical signals detected from particle colliders, direct and indirect methods, and astrophysical observations. The hope is that by blending the information found in multiple different fields, with their associated strengths and weaknesses, a clearer picture of the mysterious particle will be formed.

The Laboratory of Theoretical and High Energy Physics, where the NewDark group is based, is a joint research venture between the French national research body known as the Centre National de la Recherche Scientifique (CNRS) and the renowned University Pierre et Marie Curie, one of the largest scientific complexes in France. Its overarching goal is to conduct research into quantum field theory, a method of modelling all subatomic particles (from electrons to quarks) as excitations of an underlying 'quantum field.' These approaches allow us to explain the strange manner in which subatomic particles are able to act as both a discrete particle and a continuous wave *at the same time.*

Energetic researchers in a field of data

The aims of the NewDark project fit perfectly into this overarching goal, with their scientific interests and varied backgrounds allowing them to effectively study the many facets of dark matter research. The NewDark group is highly international, in keeping with physics research itself, having members from Italy, France, England, Greece, Switzerland and Germany. Born in Italy but based in Paris for over 10 years, Dr Cirelli has a long history of high-energy physics behind him, a history which has slowly led him over the last few years into the complex world of dark matter. He is supported by several postdoctoral researchers, including Dr Mathieu Boudaud (who is examining cosmic rays for signs of dark matter interactions); Dr Bradley Kavanagh (who follows results from dark matter signal detectors buried deep under the ground); Dr Kallia Petraki (who studies the microscopic nature of dark matter interactions); and Dr Filippo Sala (who covers both theoretical and experimental aspects of particle physics). Previous members of the team include Dr Marco Taoso and Dr Gaëlle Giesen, both experts in the field of dark matter research. The group also assists in the training of up-and-coming scientists, with PhD student Marta Perego rounding out the group – her focus lying in the field of particle colliders and associated dark matter production.

This sounds like a lot of different methods for one group, but Dr Cirelli is convinced that it is the only practical approach. 'A multi-faceted attack at the problem is necessary,' he muses, 'because the tools at our disposal are powerful but only partial. For instance, the LHC is a machine which, in its first years, will not easily provide precision measurements; the astroparticle experiments, by nature, are plagued by astrophysical backgrounds. Only via cross-correlating partial information from different fields will progress be made.' Their hope is that these multiple avenues of research will lead to better results than specialising in one field alone.

'The ultimate goal,' comments Dr Cirelli, 'as a part of the larger global effort with a long timescale, is the identification of the nature of the Dark Matter.' No minor goal this one, but given the quality of the team on the case, one with potential.

Meet the researchers

Marco Cirelli

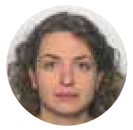
Dr Marco Cirelli obtained his PhD from Scuola Normale Superiore in Pisa and went on to perform postdoctoral research at Yale University, CEA Saclay and CERN. Since 2015 he has held a position at the Laboratory of Theoretical and High Energy Physics at Sorbonne University in Paris. In 2011 he was assigned a Starting Grant from the European Research Council for the NewDark project: 'New Directions in Dark Matter Phenomenology at the TeV Scale', and in 2014 he was awarded the Prix Thibault from the Academy of Arts and Letters in Lyon. In the last few years his research revolves around solving the Dark Matter problem. He enjoys the challenge and the excitement of working at the intersection among particle physics, astrophysics and cosmology, juggling between the infinitely small and the extremely large frontiers of our current fundamental understanding of the Universe.

Mathieu Boudaud

Dr Mathieu Boudaud received his PhD in 2016 from University of Savoie in France. During the fall of 2016, he moved to the Laboratory of Theoretical and High Energy Physics in Paris where he currently works as a postdoctoral researcher. Dr Boudaud's research focuses on the propagation of charged cosmic rays in the Galaxy and on the indirect detection of astrophysical dark matter from antiparticle cosmic rays.

Bradley Kavanagh

Dr Bradley Kavanagh obtained his PhD in particle astrophysics from the University of Nottingham in 2014, and soon after moved to Paris to join the NewDark group as a postdoc. Dr Kavanagh's current focus is in studying possible dark matter signals in dedicated underground detectors. He aims to understand what information about the particle physics and astrophysics of dark matter could be extracted from a future signal. A key aspect of this lies in studying how different models of dark matter might be distinguished from one another. Bradley is also interested in looking for new 'Smoking Gun' signatures of dark matter, aiming to open up new directions in the hunt for these ever-present but ever-elusive particles.



Kallia Petraki

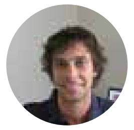
Dr Kallia Petraki received her PhD from the University of California Los Angeles in 2009, where she investigated possible connections between dark matter and neutrinos. She continued working on dark matter as a postdoc, at the University of Melbourne and at the National Institute for Subatomic Physics in the Netherlands. She is currently a researcher at the Laboratory of Theoretical and High Energy Physics in Paris. In her work, she aims to understand the microscopic nature of dark matter, and in particular how the fundamental properties of dark matter may reveal themselves in the way our universe is structured.

Filippo Sala

Dr Filippo Sala obtained his PhD in physics at Scuola Normale Superiore, Pisa, and has been a postdoctoral researcher in the NewDark group, since December 2013. Before joining the group, he was also a long term visitor at CERN and the Lawrence Berkeley Laboratory. He is curious about how Nature works at a fundamental level, at the smallest and largest scales of length and time. These domains still hide the answers to some fascinating mysteries, like what constitutes dark matter. Dr Sala's research activity explores theoretical ideas that address these issues, for example by studying how they can be best probed using current and future collider experiments, as well as using telescopes. His approach is characterised by the cross-fertilisation of a broad set of neighbouring domains, in both particle and astroparticle physics.

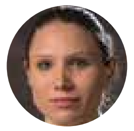
Marta Perego

Marta Perego is currently a PhD student in particle physics at CEA Saclay. She is part of the ATLAS collaboration of the Large Hadron Collider at CERN, where her main interest is searching for dark matter production at colliders. She works both with the ATLAS group and with NewDark on collider dark matter searches. She performs data analysis to look for dark matter produced in vector boson fusion processes in the high energy proton collisions collected by the ATLAS detector in 2015 and 2016.



Marco Taoso

Dr Marco Taoso is an Italian physicist working on dark matter, astrophysics and particle physics. After his PhD, obtained from University of Padova in Italy and in co-tutorship with Université Paris Diderot, he has held several post-doctoral appointments. In 2013, he moved to Paris, to join the NewDark group. As well as helping him to find new ideas and interesting directions for his scientific career, his post with the NewDark group was also a lot of fun for many reasons: friendly collaborators, a chance to live in Paris, delicious macarons and chocolate tastings to brighten up workshops and scientific meetings, as well as travelling to wonderful and exotic places to attend conferences! Now, Marco Taoso is working at the Instituto de Fisica Teorica in Madrid, Spain.



Gaëlle Giesen

Dr Gaëlle Giesen graduated from École polytechnique fédérale de Lausanne with a Master's degree in Physics, and soon after joined the NewDark group in 2012. Here, she completed a thesis on indirect detection of Dark Matter using charged cosmic rays and received her PhD from the University Paris-Sud in 2015. Also passionate about space technologies, she is now working at the launchers directorate at the Centre National d'Etudes Spatiales (CNES). Photo credit: Gislain Mariette