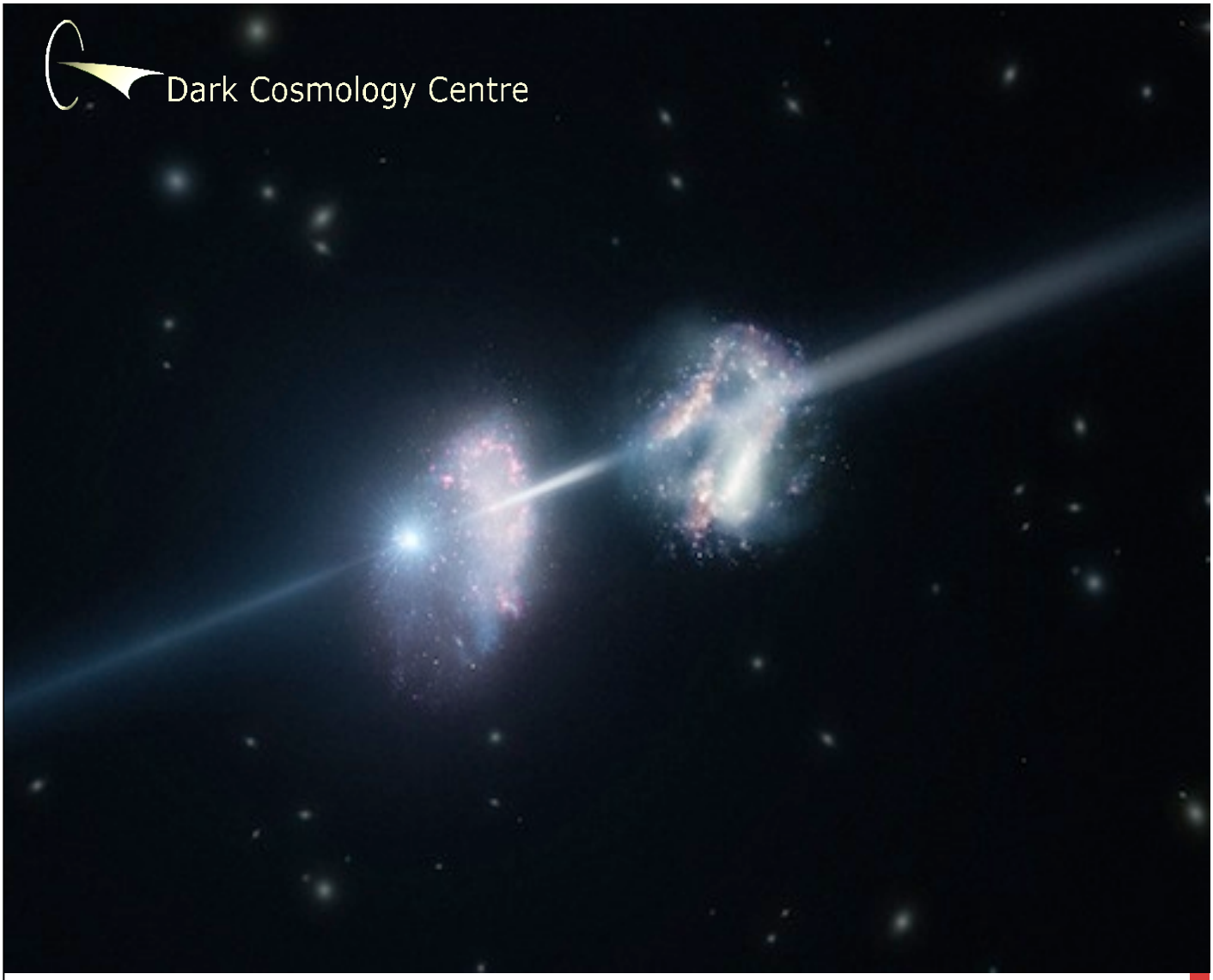

ANNUAL REPORT 2011

THE DANISH NATIONAL RESEARCH FOUNDATION'S
DARK COSMOLOGY CENTRE (DARK)
AT THE NIELS BOHR INSTITUTE
UNIVERSITY OF COPENHAGEN

Cover Photo:

This artist's impression shows two galaxies in the early Universe. The brilliant explosion on the left is a gamma-ray burst. The light from the burst travels through both galaxies on its way to Earth.

Credit: ESO/L. Calçada

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Organization

In 2011, year two of the Centre's 2nd funding period (DARK2), we welcomed new PhD students, including Karen Pardos Olsen, Johannes Zabl and Andreas Skielboe, as well as Kristen Jones, who visited DARK from the University of Virginia as a National Science Foundation Nordic Fellow. New research staff joined the Centre: Marie Curie Fellow Thomas Krühler, FREJA and Carlsberg Fellow Lise Christensen, and Space Science Fellow Stefania Pandolfi.

DARK Fellow Antonio de Ugarte Postigo left the Centre for a position at the Astrophysics Institute of Andalucía, Berian James took up the second part of his Brahe Fellowship at the University of California at Berkeley, DARK Fellow Stefano Zibetti started an INAF permanent position at the Astrophysics Observatory in Arcetri, Brahe Fellow Justyn Maund left DARK for a 5-year Royal Society Research Fellowship at the University of Belfast, and Brahe Fellow Johan Richard started a permanent CNRS position at the Observatory in Lyon.

A permanent associate professor position was posted internationally this year. The search process will be completed sometime in 2012. Marianne Vestergaard, who came to DARK in 2009 with FREJA and Marie Curie Fellowships, was tenured.

A new meeting group, called Senior Staff, was created in the fall, consisting of the DARK2 Co-Is, new faculty member Lise Christensen, and Coordinator Michelle Cumming Løkkegaard. The group meets monthly to review issues related to the Institute, like teaching, and the Centre, like research, fund-raising and hiring. A key topic for this group will be planning for the Centre after the DNRF funding period.

Research

In this section we briefly address progress on the 2011 targets we set in 2010. We next provide some a description of progress on the Centre's key projects, and finally we list 2012 milestones.

2011 MILESTONES

Observe the highest redshift supernovae and their host galaxies

A program to observe very high-redshift supernova host galaxies was initiated and so far has resulted in record redshifts. The project will form the basis for Teddy Frederiksen's PhD thesis.

Obtain new insight into the nature of faint high-redshift galaxies from spectra of galaxies lensed by galaxy clusters

Our X-shooter guaranteed time program on galaxies lensed by clusters of galaxies was completed. More than 10 galaxies were observed and are the subject of two papers near completion.

Model the expected distribution of time delays of lensed supernovae behind lensing clusters

This project is part of Xue Li's PhD thesis. A paper is near completion.

Publish first results from near-infrared (NIR) spectroscopic observations of compact, old massive galaxies at high redshift (SEED galaxies)

Two papers with NIR spectroscopic observations of SEED galaxies were submitted. Two more papers are in preparation.

Lead the X-shooter gamma-ray burst (GRB) Target-of-Opportunity program

Fynbo remains principal investigator of the program. The program has been progressing slowly, due to a low rate of detected GRBs from the satellite.

Make the first public release of UltraVISTA data and publish the first paper describing the survey and presenting the first catalogs

The first UltraVISTA data have been publicly released. Two publications are in preparation, but not yet submitted for publication.

Submit analysis of HST data on massive starforming quasar systems at redshifts of 4 for publication

Preliminary analysis shows that extended UV emission from massive young stars is consistent with the high star-formation rate inferred from far-infrared emission.

Become integrated into the *Euclid* consortium and initiate studies leading up to scientific exploitation of the *Euclid* mission

Through the Space Science Center, DARK is now leading Danish integration into the *Euclid* consortium. Through the hire of a PhD student and a postdoc, studies leading up to scientific exploitation are underway.

Measure the infall velocity of galaxies in clusters

The theoretical foundation was established, including the expansion of the Universe (the Hubble parameter). The theoretical study, led by PhD student Martina Falco, is planned for submission in April 2012.

Establish the spectral energy distributions of 10 local AGNs with robust black hole masses

This was achieved as part of Ece Kilerci Eser's PhD project and results are being prepared for publication. An extensive analysis of the epoch dependent implications of these energy distributions for quasar physics is on-going.

Measure the non-sphericity of galaxy clusters using a novel method involving purely X-ray observations

The new method was established, and a paper led by PhD student Johan Samsing has been published.

Use high-energy sources to determine fundamental parameters of the Milky Way interstellar medium: the dust-to-gas ratio and the metallicity

This was achieved using gamma-ray bursts. New values were determined for the dust-to-metals and metallicity ratios in the Milky Way and published.

Investigate the newly identified dark matter attractor for more realistic systems

This was studied together with our Scottish collaborators, and a paper is currently under review.

Make the first detection of gravitational redshift in clusters of galaxies

This project was completed and published in *Nature* as discussed elsewhere in this annual report.

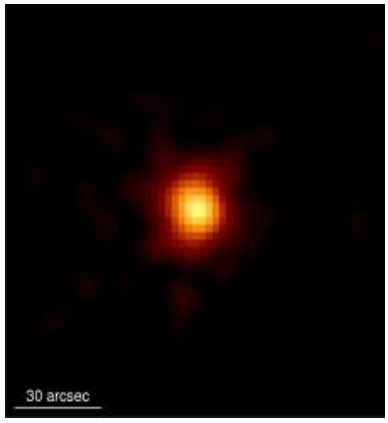
KEY PROJECT 1: GAMMA-RAY BURSTS AND QUASARS IN THE ERA OF REIONIZATION

Investigating the epoch of reionization is fundamentally important for structure formation and cosmology as a whole, because it is during this phase that the first black holes grew into quasars and the first star-forming galaxies took shape, enriching the intergalactic medium. The highest redshift GRBs, quasars, and galaxies have allowed us to probe the intergalactic medium and the history of star formation at the very end of this period, at redshifts of 6–10.

1.1 High-redshift gamma-ray bursts (GRBs) and quasar (QSOs)

Darach Watson, Kelly Denney, Marianne Vestergaard and former DARK post doc Tamara Davis (U Queensland) developed a groundbreaking method for measuring distances in the Universe using light from QSOs. The team used the tight relationship between the luminosity of an active galactic (AGN) and the radius of its broad-line region established via reverberation mapping to determine the luminosity distances to a sample of 38 AGNs. All reliable distance measures up to now have been limited to moderate redshift, AGNs will, for the first time, allow distances to be estimated to redshifts (z) of about 4, where variations of dark energy and alternate gravity theories can be probed (Watson et al, ApJ 740, L49).

In the continuing efforts to detect and eventually obtain spectroscopic observations of high-redshift GRBs, a record photometric redshift of 9.4 was reported by a large collaboration, including several members of the DARK GRB team (Cucchiara et al, ApJ 736, 7).



Swift X-ray image of z~9.4 GRB 090429B. Credit: NASA

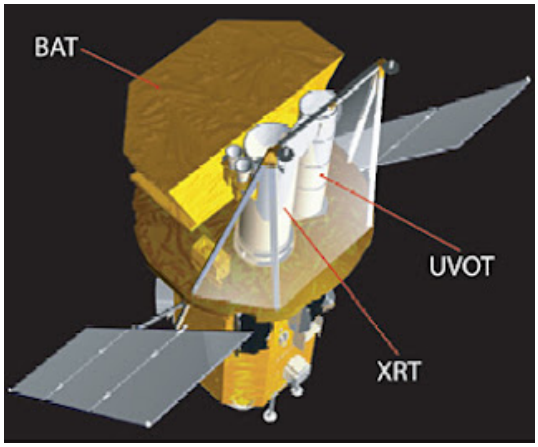
Strong expertise has been built up on X-shooter observations of GRBs by a number of DARK scientists. A few QSOs have also been observed and more will be observed leading up to the 2-year milestone in 2012. Significant progress was made on studying well-defined samples of GRB afterglows for studying dust extinction up the epoch of reionization by Tayyaba Zafar (Zafar et al, A&A 532, A143).

Darach Watson and DARK Affiliated Scientist, Peter Laursen calculated the values required to determine a limit on the metallicity of a star-forming region in the early Universe using only the high energy data from a GRB at high redshift, using GRB 050904 at z~6.3 as an example (Watson et al, A&A 527, A104). Stefania Pandolfi pointed out that the inclusion of astrophysical data sets, such as QSO absorption line data, are important for determining accurate cosmological parameters (Pandolfi et al, PhysRevD 84,123522). Darach Watson reported *Spitzer* and X-shooter observations of a low-redshift GRB host galaxy and pointed out its importance as a prototype for very high-redshift galaxy spectral energy distributions (Watson et al, ApJ 741, 58).

In parallel works Christa Gall and Lars Mattsson reported in several papers models of dust formation at high redshift, addressing the inferred very large dust masses in high-redshift QSOs (see also *Key Project 4.2 Origin of cosmic dust in the early Universe*).

1.2 Proposing the JANUS Mission

The proposed JANUS mission was not selected for further studies by NASA. Consequently, the Centre has re-focused space instrumentation efforts towards the European Space Agency's *Euclid* mission, which was selected for launch in 2019. Through the Space Science Center, the Centre has become a central partner in the *Euclid* mission. In collaboration with DTU Space, the Space Science Center will contribute the telescope simulator for testing the Near Infrared Spectrometer (NISP) instruments and participate in testing the NISP detectors. On the science side, many DARK researchers are members of the *Euclid* Science Working Groups. In addition, the Space Science Centre hired Andreas Skielboe and Stefania Pandolfi to help prepare the Danish scientific exploitation of *Euclid*.



Swift's three telescopes work together to learn as much as possible about gamma-ray bursts: X-ray (XRT), ultraviolet and optical (UVOT) and burst alert (BAT). Credit: NASA

1.3 Other projects related to the transient Universe

One of the key 2-year milestones for DARK2 is to build up a significant sample of GRBs with X-shooter spectroscopy coming from the *Swift* satellite. The X-shooter project utilizes guaranteed time using X-shooter granted due to DARK's contribution to building the instrument. The GRB project has progressed slower than planned due to fewer well-placed bursts from the *Swift* satellite in the latest few years, but the program still produces very interesting results. In 2011 the highlights were the detection of a supernova related to a GRB (Sparre et al, ApJ 725, L24) and the measurement of a good afterglow spectrum for a very distant GRB at z~5.

KEY PROJECT 2: GALAXY CLUSTERS AS GEOMETRY PROBES, DARK-MATTER LABS AND GRAVITATIONAL TELESCOPES

Clusters of galaxies provide the opportunity to study the properties of dark matter and its link with ordinary matter. The main aim of this project is to obtain a high-precision mass model of a galaxy cluster in order to look into the properties of dark matter and to use the mass model to address a range of cosmological issues.

2.1 A 'Cluster Ultra Deep Field' as dark-matter lab

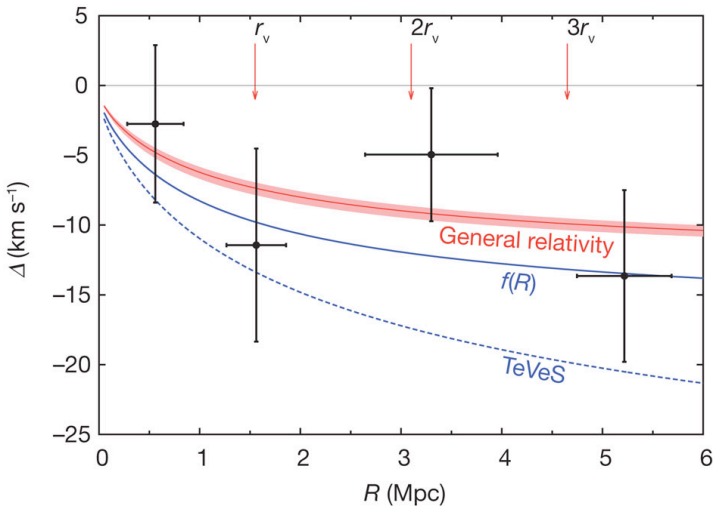
Following the approval of the Hubble Space Telescope Multi Cycle Program CLASH (Cluster Lensing And Supernova survey with Hubble) the idea of proposing for a very deep field has been put on hold for the time being with more than 500 orbits already allocated to cluster lensing science. Two post-doctoral fellows who will join DARK in 2012, Claudio Grillo and Ole Høst, are members of CLASH, and collaboration continues with former DARK Fellows Marceau Limousin (Laboratory of Astrophysics of Marseille) and Andrea Morandi (U Tel Aviv) (Morandi et al, ApJ 729, 37), and former Brahe Fellow Johan Richard (Observatory of Lyon).

2.2 Precision cosmology

With current data inadequate for making significant progress on cluster lensing cosmography we have focused our efforts on high-redshift supernovae, including lensed supernovae. The highest redshift supernova so far discovered was reported (Amanullah et al, ApJ 742, L7) in observations of the lensing cluster Abell 1689. Darach Watson and Jens Hjorth contributed the measurement of the redshift of z~1.70 from X-shooter. Teddy Frederiksen, Justyn Maund and Jens Hjorth used X-shooter to obtain redshifts for supernova host galaxies discovered in the CLASH and Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS). This project will form the basis for Frederiksen's PhD thesis and we are well on track for reaching the 2-year milestone of finding our first high-redshift supernovae. Work on time delays of lensed supernovae was reported (Riehm et al, A&A 536, A94) and is also the subject of the thesis of PhD student Xue Li.

New X-ray data available has helped to better determine dark matter profiles. Traditionally the mass profiles of galaxy clusters have been fitted using the same density slope. A new analysis shows that the density profiles vary from structure to structure (Høst et al, ApJ 736, 52). This is important because it indicates that the effects of gas, star formation, supernovae and active galactic nuclei may be relevant for the evolution of the dark matter mass profile.

Finally, as described in the highlights section, Radek Wojtak, with Steen Hansen and Jens Hjorth, reported the first detection of gravitational redshift in clusters of galaxies and used this to set constraints on alternative theories of gravity (Wojtak et al, Nature 477, 567). With this breakthrough detection the predictions of the theory of general relativity on very large scales were confirmed for the first time.



Detection of gravitational redshift in galaxy clusters (Wojtak et al. 2011)

KEY PROJECT 3: HIGH-REDSHIFT GALAXY FORMATION

Galaxies at redshifts z > 5 carry information about reionization, the properties of dark matter and the formation of the first supermassive black holes. By studying how they formed, their properties and the properties of their central black holes as a function of redshift, we can begin to understand the timing and process of reionization, galaxy formation and evolution.

3.1 UltraVISTA: Finding galaxies in the reionization epoch

Observational progress in 2011 was slowed by external factors. The primary mirror of the VISTA telescope was dismounted in March and the telescope was offline for more than a month, exactly at the time when the target field of the survey, the COSMOS field, would be best observed. As a result, less than 10% of the planned observations were executed in 2011, which will cause a delay of the completion of the survey. The quality of the data that is secured is fortunately very high, and the first public release of data from the UltraVISTA survey is planned for 2012.

3.2 Unveiling the nature of massive, quiescent, compact high-redshift galaxies

Andrew Zirm and Sune Toft completed a study showing for the first time that the sizes of SEED galaxies at high redshift are influenced by environment. In proto clusters at z~2 massive quiescent galaxies are found on average to be less compact than galaxies in lower density environment. PhD student Allison Man, Sune Toft and Andrew Zirm also completed a study of the frequency of major mergers to the highest redshift yet, investigating the importance of these for the build up of the size and mass of galaxies with cosmic time, which will constitute a major part of Allison Man's PhD thesis. The team is well on track for making the 2-year milestone for this project, which is to obtain and describe a deep, near-infrared spectrum of a prototype z~2.5 compact quiescent galaxy.

3.3 Quasars and their role in galaxy formation and evolution

Investigations of the properties of host galaxies of distant quasars and their relationships with 'normal' galaxies with non-active central black holes are underway. One study shows that quasars at *z*~4, based on their far-infrared emission, appear to have vigorous star formation.

The first studies aimed at improving mass measurements of central black holes are underway, with a focus on characterizing the velocity field of the line-emitting gas used for these mass measurements. The first analysis of the potential effects of radiation pressure on this gas shows mixed results, where this effect is only strong for a small fraction of objects and thus cannot be generalized. Recent work shows that the emission line shape used for velocity measurements changes with the nuclear luminosity colors (Assef et al, ApJ 742, 93). New observations are planned to examine this effect and its origin further, since it may hold important clues to the inter-relationship between the gas velocity and the black hole accretion physics that affect the mass estimates.

An important aspect of the accuracy and precision in mass estimates of black holes is the ability to characterize the velocity field based on the spectral data available. A systematic study has been initiated, partly to characterize and map the uncertainties associated with the standard velocity measurements, and partly to seek a robust line width measure that will not be sensitive to damaging effects such as signal-to-noise and spectral resolution of the data.

KEY PROJECT 4: THEORETICAL INVESTIGATIONS OF DARK MATTER AND DUST

One of the goals of Key Project 2 is to accurately measure the spatial distribution of dark matter. Key Project 4 will complement this study with a theoretical attempt to explain the origin of the cluster dark-matter mass profile.

Spectroscopic observations of GRBs, QSOs, and high-redshift galaxies provide substantial information about the presence and properties of dust in the early Universe. Numerical modeling complements these observations to better understand how dust formed and evolved in this era.

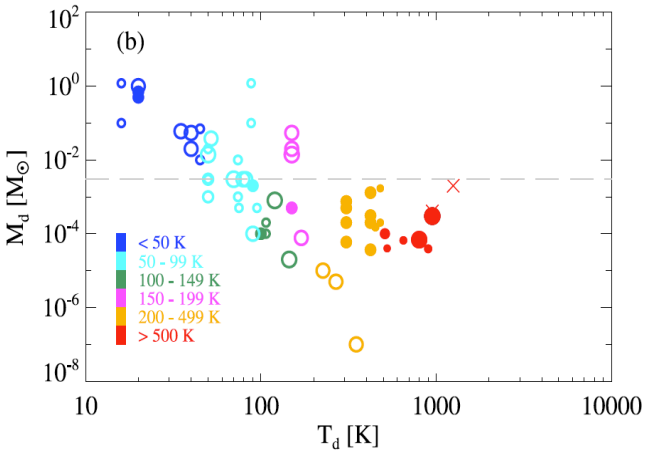
4.1 Cosmological structures

One milestone, understanding of the gas profile, is within reach. A series of earlier studies considered the gas profiles in large galaxy clusters. However, the gas profile in galaxies is much more difficult to model, because they are smaller and therefore the effect of radiation is more important. A range of advanced high-resolution numerical simulations test the profile of the gas in galaxies, and indeed the gas is dancing to the tune of dark matter, in the sense that all the gas properties (density and temperature) are determined by the gravitationally dominating dark matter (Hansen et al, ApJ 734, 62). This provides strong support for previous theoretical suggestions.

Another milestone was reached, namely to investigate the turbulence in gas in clusters. The signal is very low, and it therefore is much too difficult to measure turbulence with the techniques under development. While this result was not published, it formed a major part of Catarina Fernandes' master's thesis.

4.2 Origin of cosmic dust in the early Universe

Work toward understanding dust production from supernovae progressed this year. In a series of papers, Christa Gall, Jens Hjorth, and Anja Andersen reported models of dust formation at high redshift, in particular the inferred very large dust masses in high-redshift QSOs. The papers argue that observations of supernova remnants are likely to have overlooked significant amounts of dust as the dust might be cold and therefore only can be observed in the far-infrared. This would explain the apparent difference between the observations of supernovae in the local Universe and the considerable amounts of dust seen in the early Universe at high redshift. (Gall et al, A&A 528, A13 and Gall et al, A&A 528, A14). A comprehensive review paper outlining dust production by massive star sources at high redshift was also published (Gall et al, A&ARv 19, 43).



This figure shows the dust mass (M) as a function of temperature (T) in supernovae and supernova remnants (Gall et al, 2011)

In parallel work, Lars Mattsson also reported models of dust formation at high redshift. A significant uncertainty regarding supernovae as the major contributors of the dust observed in early galaxies at high redshifts, is whether or not the dust formed by the supernovae actually survives the reverse shock when the supernova ejecta interacts with the interstellar medium. Mattsson investigated how such reverse shocks would influence the efficiency of dust formation significantly, and how the observationally derived dust-to-gas-ratios for these high-redshift galaxies are remarkably high if any significant dust destruction in connection with supernova occurs (Mattsson, MNRAS 414, 781).

Work toward the 2-year milestone to construct of template of synthetic extinction curves for galaxies at different redshift is on track.

2012 MILESTONES

Researchers at DARK will strive to meet the following milestones:

- Organize and host international *Euclid* conference
- Secure funding for the Danish hardware contribution to *Euclid*
- Establish the origin of X-ray absorption in gamma-ray bursts
- Complete the The Optically Unbiased Gamma-ray burst Host (TOUGH) survey (4 additional papers to be completed)
- Publish first paper on high-redshift supernova host galaxies
- Complete a series of papers on dust extinction in z~6 quasars and supernovae
- Get two papers on gravitationally lensed galaxies accepted for publication
- Find an attractor for hot gas in galaxy clusters
- Complete the first statistical study of the properties of the galaxies hosting Damped Lyman-α Absorbers at $z > 2$
- Make the first public release of UltraVISTA data
- Submit paper reporting spectroscopic investigations of a z~3.3 massive galaxy
- Publish paper testing if the origin of the quasar narrow absorbers is a disk wind near the central black hole
- Submit first paper on the effects of spectral quality and line shape on the accuracy of quasar black hole mass determinations
- Publish properties of particles ejected during dark-matter mergers
- Establish how the dark-matter velocity anisotropy depends on direction in dark-matter halos
- Publish two papers on modeling the growth and destruction of dust grains in the interstellar medium

External relations

The Centre is engaged in several high-profile international collaborations. This year Kristian Pedersen was named the Danish National Representative in the *Euclid* Consortium Board and Project Manager for the Danish Hardware contributions to *Euclid*. Several DARK researchers are active in *Euclid* Science Working Groups.

DARK is responsible for the narrow-band of the UltraVISTA survey, a collaboration within the European Southern Observatory between University of Edinburgh, Leiden Observatory, University of Marseilles, and DARK. Thomas Greve was active in the MASTER (Molecules AS Tools for Extragalactic Research) collaboration. Steen Hansen leads the Nordic Particle Physics and Cosmology Network, which supports interaction among young Nordic researchers. Johan Fynbo leads the Nordic Network of Astrophysics and Cosmology (NNAC), a network of centres of excellence. Marianne Vestergaard is part of the management committee, and the representative for Denmark for the European Cooperation in Science and Technology (COST) Action MP0905: Black Holes in a Violent Universe, as well as a member of COST 's international working group on supermassive black holes.

DARK organized and hosted a successful 5-day workshop in August, with 60 prominent researchers form all over the world. *Current and Future Challenges of the Dark and Early Universes* (DEUS) featured presentations and discussion focused on a critical examination of the challenges that theoretical and observational cosmologists currently are facing in the study of dark energy, dark matter, and gravity.

Darach Watson, along with former DARK PhD student Danuta Paraficz (Laboratory of Astrophysics of Marseille) and former DARK post doc Páll Jakobsson (now Professor, U Iceland), organized *Dust In Space: Consequences and Origins,* an international workshop on the topic of cosmic dust, funded in part by NNAC. The workshop was held at the Institut d'Etudes Scientifiques de Cargèse in Corsica.

Research conducted at the Centre continues to be highly international. In 2011, DARK produced 89 refereed publications, and all except five were written in concert with researchers outside of Denmark. Many of these papers are a result of informal networks, and some more formal ones, especially in the cases where observational data from many facilities are combined in a collaborative work.

The Centre continues to support and benefit from a busy visitors programme, hosting more than 100 visitors in 2011. More about the visitor's programme: http://www.dark-cosmology.dk/visitors.

International Talent Recruitment Programme

The Centre has received two supplementary grants from the DNRF through the ITRP to enhance recruitment of international students and collaborators. DARK continues to strengthen its collaboration with leading international institutions through the *Sophie and Tycho Brahe Research Programme*. Berian James left DARK for the second part of his Brahe Fellowship, working with Professor Joshua Bloom (U California at Berkeley). In 2011, Stanford University Professor Steve Allen was appointed the new Brahe Professor and we recruited Anja von der Linden, who will start in a 3-year joint DARK/Stanford fellowship in 2013. Brahe Professor Enrico Ramirez-Ruiz (U California at Santa Cruz) led a 3-week workshop at DARK in the summer, *Relativistic Jets in the Universe*. The program included projects for PhD students and a lecture series featuring both DARK and visiting researchers. Brahe Professor Eiichiro Komatsu (U Texas at Austin) visited with 5 of his PhD students to attend the DEUS workshop, and the group stayed 2 additional weeks to collaborate with DARK staff and students. In addition, Brahe Professor Priya Natarajan (Yale U) attended the DEUS workshop and also served on its International Organizing Committee.

The *Research Excellence Programme* funded a workshop for international master's students in 2007 and the PhD of Tayyaba Zafar (Pakistan), 2008-2010. Zafar defended her thesis in April, as the first Pakastani woman to earn a PhD in astrophysics. She started a post doc position at the Laboratory of Astrophysics of Marseille in the summer, so this part of the ITRP officially – and successfully – finished in 2011.

Nordic Fellows Programme

University of Virgina PhD student, Kristen Jones, was funded by the U.S. National Science Foundation and the DNRF as a Nordic Fellow at DARK. Jones worked for 6 months with Thomas Greve mainly on radio astronomy, including radio instrumentation to study galaxy evolution and quasars. She also presented her work in a poster, *Morphology and Star Formation Rates of 5 LIRGs at z~0.01*, at the *Through the Infrared Looking Glass* conference at the California Institute of Technology in October 2011.

Educational activities

Centre staff led or contributed significantly to six University bachelor's courses in 2011, and supervised bachelor projects for 15 students. Four master's courses were given with DARK faculty as lead lecturer, and four master students finished their theses, among the 10 who were in progress at different points throughout the year.

The Centre arranged two elite PhD courses funded by the Faculty of Science, *Advanced Statistical Methods* and *PhD School in Space Science*. Both courses were co-taught by DARK faculty and featured internationally prominent lecturers. In addition, several DARK PhD students completed projects during the *Relativistic Jets in the Universe* and DARK-Berkeley *Time-domain Astrophysics workshops*.

External funding

DARK's researchers continue to win external funding, and the Centre is actively using external funding possibilities to attract high quality post-doctoral researchers. As detailed further in Appendix D and the Personnel Overview, DARK's external funding accounted for over 11 MDKK in spending in 2011, mostly on research staff and PhD salaries.

Marie Curie Fellow Thomas Krühler started in 2011, as did Carlsberg-funded post-doctoral researchers Giorgos Leloudas and Lise Christensen.

Johan Fynbo was awarded a €1M 'Starting Grant' from the European Research Council (ERC). The 4-year grant started in 2011 and will support Fynbo and 2 post-doctoral researchers combining three different methods to study the first galaxies formed in the early Universe.

The Space Science Centre (SSC) was particularly successful in 2011, securing 3-year funding from FNU to work on preparing *Euclid* science and instrumentation. This grant funded a PhD student and post-doctoral fellow who both started in 2011. FNU also funded the Instrument Centre for Danish Astrophysics, a project to support Danish research and instrumentation that has been administered by DARK since the beginning of the Centre.

Johan Fynbo was awarded €1M from the European Research Council, ERC to research galaxies in the early Universe

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By signing I confirm that this annual report and the accounts therein, including notes and summaries, contain all relevant information relating to this year's main activities in the Danish National Research Foundation's Dark Cosmology Centre.

Jens Hjorth
Professor and Director
1 April 2012