Division of particle physics and astrophysics 2017-2020

The research fields of PAP form a continuum from experimental and theoretical particle physics through theoretical and observational cosmology, astrophysics, and solar system physics to space physics involving solar activity and its consequences in the solar system.

The PAP research belongs to the University of Helsinki strategic research area *Matter and Materials*. In the Division the fundamental constituents of matter, as well as matter in extreme conditions is studied. Theoretical particle physics belongs also largely to the University spearhead *Mathematics*. Consequently physics department and department of mathematics and statistics have a common university lecturer. Both departments also take part in a common Master's programme, *Theoretical and Computational Methods.* High-luminosity operation of the Large Hadron Collider (LHC), which is the main particle physics infrastructure we use, has been identified as the highest priority in the latest European Particle Physics Strategy (see http://cds.cern.ch/record/1551933/files/Strategy_Report_LR.pdf). Research at CERN is included in the Finnish Research Infrastructure Roadmap.

Within the existing research programme we will exploit the synergy between the groups in particle physics and cosmology. We also aim to strengthen the links between observational cosmology and astrophysics.

The most urgent personnel need is identified to be a university researcher position in observational cosmology (EUCLID). Other positions to be filled, resources permitting, are a tenure-track professorship in particle physics instrumentation, a tenure-track professorship in planetary research, and a tenure track position in particle theory. During next eight years professor positions in experimental particle physics, cosmology, and space physics will become vacant due to retirements. In addition, several of the planned positions in other units in the "Matter and materials" strategic research area will have research links to activities in our division.

The Big Wheel -reorganization of Master's programmes offers new possibilities for strengthening the synergy in Kumpula Campus. Thus, the faculty members will interact more frequently and become familiar with each other's expertise. On the other hand, students graduating from the program will obtain a more unified view of various tools and research directions. This will create an excellent platform for organically growing new creative cross-disciplined research - in addition to coming from top down, from faculty to students, also from bottom up with graduating students initiating new collaborations.

Experimental particle physics

The LHC Run 2 continues until 2019. Our first priority in experimental particle physics is the exploitation of the LHC, where the Run 2 is providing collisions at record energy and record intensity, with potential for new discoveries. Parallel to that we are participating in preparation for further experiment upgrades, with the projected

Run 3 starting in 2021. We take part in the CMS and TOTEM –experiments, as well as forward physics at ALICE, and in the Moedal-experiment. We are involved in the preparations of the Technical Implementation Plan for the future Compact Linear Collider CLIC.

During 2017-2020

- We will exploit the richness of the LHC data. The analysis topics with the CMS data will include Higgs physics, B physics, and physics with jets. The TOTEM data will provide new results on inelastic and diffractive processes.
- We will contribute to the detector operations (CMS tracker, CMS computing, TOTEM T2), as well as to offline and analysis tasks (CMS tracking and alignment, CMS jet calibration, TOTEM physics coordination).
- We will prepare for the high-luminosity phase of the LHC through participation in detector upgrades. Our focus will be on novel tracking technologies.
- We will be involved in R&D for post-LHC energy frontier accelerator options (CLIC, Future Circular Collider FCC).
- ALICE forward physics activities concentrate on space-time structure of hadron interaction, central exclusive production of new particle states.
- In MoEDAL experiment magnetic monopoles, dark matter and other novel physics objects with unusual interactions with matter are searched for.

Background discussion:

CMS - Flagship project in experimental particle physics in Helsinki

The Compact Muon Solenoid (CMS) experiment is a particle physics experiment at the Large Hadron Collider (LHC) at CERN, Geneva. The main scientific goals of CMS are detailed investigations of particles and interactions at a new energy regime, understanding the origin of electroweak symmetry breaking (Higgs bosons), and search for direct or indirect signatures of new physics beyond the standard model of particle physics. The CMS experiment has also a heavy ion research programme, studying the properties of quark-gluon plasma.

The first phase of LHC operation, Run 1 (2010-2012), is completed. About 25 fb^-1 of proton-proton collision data were collected at 7 and 8 TeV centre-of-mass energies. In addition also lead-lead and proton-lead collisions were recorded. Observation of a Higgs boson with a mass of about 125 GeV in 2012 was a major breakthrough and the greatest achievement of Run 1, leading also to a Nobel Prize. After the LHC service break 2013-2014 the Run 2 was started in 2015. The collision centre-of-mass energy was raised to 13 TeV. Run 2 is expected to continue until the end of 2018. The luminosity will be raised successively, facilitating the exploration of a new mass range with improved sensitivity.

The HIP CMS programme is responsible for coordinating the Finnish participation in the CMS and TOTEM experiments. The Finnish groups in CMS are: HIP (currently 14 authors), University of Helsinki (three authors), and Lappeenranta Technical University (two authors). In TOTEM there are nine authors affiliated with HIP, out of which six are also affiliated with University of Helsinki. The HIP CMS programme is currently divided in four projects: the CMS Experiment project, the CMS Upgrade project, the Tier-2 Operations project, and the TOTEM operations project. TOTEM is a separate experiment located near the beam pipe in immediate connection to CMS.

Researchers in Helsinki are involved in CMS and TOTEM experiments in a wide range of experimental activities. The CMS physics analysis topics include Higgs physics, B physics, physics with jets. We contribute to detector operations (CMS tracker, CMS computing), and we are well positioned in view of the detector upgrades.

Upgrade funding has been obtained from the Academy of Finland and Magnus Ehrnrooth foundation to cover the Finnish CMS Phase 1 upgrade contribution, consisting of construction of 250 new pixel detector modules. The construction has taken place 2014-2016 at the Micronova laboratory in collaboration with Advacam (VTT spin-off company).

A major upgrade of the CMS detector, called the Phase 2 upgrade, will take place around 2024-2025. Among other things, the whole tracking detector will be replaced with a new one. We are currently pursuing R&D with novel semiconductor tracking technologies. In the timeframe 2017-2020 the Phase 2 upgrade plans will be frozen and the construction phase will start, implying that new investment funding will be applied for from the Academy of Finland and other sources.

Forward Physics and Diffraction with TOTEM at the LHC

TOTEM is currently the leading forward experiment at the LHC and has published several important physics results, especially related to total and elastic proton-proton cross-section, based on Run I (2010-12) data. Helsinki has had a key role in the building and the operation of the GEM detector based T2 telescope. CMS and TOTEM together provide a unique large angular coverage for tracking and calorimetry that is complemented by leading proton detection making it well suited for studies of diffractive processes, like central diffraction. For Run 2, TOTEM has extended its physics programme to include central diffraction based glueball and QCD studies as well as new physics searches in common data taking with CMS in both special low luminosity and standard high luminosity running.

The Helsinki group is involved in a wide range of activities. The focus of the analysis is on inelastic and diffractive processes, including glueball studies and new physics searches. The hardware contribution include T2 operations and the proton time-of-flight measurement upgrade using diamond sensors. The upgrade is funded by an Academy of Finland grant. The Helsinki group is also responsible for the physics coordination of TOTEM as well as for coordinating the TOTEM side of the common CMS-TOTEM analysis work.

Forward Physics in ALICE at the LHC

The Helsinki forward physics group (two authors in the ALICE and Moedal experiments, also continuing analysis of the data from the CDF experiment at the Tevatron, US) concentrates on studies of the space-time structure of high energy hadron collisions. The ALICE experiment at CERN provides ideal framework for these studies based on the set of central and forward detectors with their excellent tracking, particle identification, rapidity and transverse momentum coverage. Moreover, during the normal high luminosity proton-proton runs at the LHC, ALICE can continue collecting precious forward physics data due to its special optics arrangement while the larger general purpose experiments, ATLAS and CMS, have to cope with large amounts of simultaneous collisions during the same bunch cross-overs (pile-up). The group coordinates ALICE Collaboration's forward physics activities.

The Helsinki group in ALICE is currently finalising two major forward physics analyses based on the 7 and 13 TeV LHC collision data:(1) inclusive diffractive cross sections and (2) an observation of a glueball candidate. In addition, the group has prepared a publication on a novel approach to search for massive new particle states based on the Beam Loss Monitoring (BLM) system of the LHC collider.

The group has actively developed novel particle detection techniques for the benefit of forward physics studies. Composite Scintillation Material (CSM) technologies are used to facilitate position sensitive minimum ionizing particle (MIP) detection. The group actively participates in the detector upgrade plans of the forward spectrometers in ALICE.

The MoEDAL Experiment at the LHC - Looking for magnetic monopoles and dark matter particles at the LHC

The seventh LHC experiment: The Monopole and Exotics Detector at the LHC (MOEDAL) has begun the analysis of its first data collected during the year 2015. The prime motivation of MOEDAL is to search directly for the magnetic monopole – a hypothetical particle with a magnetic charge.

The Helsinki group in MoEDAL concentrates on the potential production processes, Beyond the Standard Model (BSM), of exotic particles, including central exclusive production investigated in ALICE at lower energies.

The technical contributions of the Helsinki group in MoEDAL are based on the usage of the optical scanning facility at the Detector Laboratory. In 2016, a feasibility analysis of scanning MoEDAL's plastic Nuclear Track Detector (NTDs) elements is foreseen.

Future colliders

The Compact Linear Collider (CLIC) is an option for a multi-TeV future electron-positron linear collider for the post-LHC era. The CLIC study develops the CLIC two-beam technology in view of a decision on the future direction of the high energy frontier in the coming years. After the completion of its Conceptual Design Report (CDR) during 2012, the CLIC study is now in a new phase of technical development and optimization leading to a Technical Implementation Plan by 2019. University of Helsinki plays a leading role in the study of the development of a physics model for the phenomena that causes breakdowns in the CLIC RF structures and hence limits the CLIC gradient. Other Helsinki contributions are development of quality assurance methods (dynamic vacuum, internal geometry) for the CLIC RF structures and the integration of all necessary components and systems into the CLIC module.

The Future Circular Collider (FCC) explores hadron-hadron and electron-positron options for the post-LHC era. The targeted collision energy of the proton-proton collider is 100 TeV, almost an order of magnitude larger than LHC, opening up large possibilities for discovery of new physics

Particle theory

We work at the internationally highest level in beyond the Standard Model physics and particle cosmology, which are among the main research directions in theoretical particle physics. The research topics range from the largest scales to the smallest, including inflation, gravitational waves, dark matter, phase transitions, Higgs physics, flavour physics, CP violation.

During 2017-2020

- We study implications of scalar sector for the early universe and dark matter.
- We consider effects of light scalars for vacuum stability.
- We analyse extensions of the Standard Model and their signals at colliders.
- We study extensively composite dynamics, including consequences for cosmology, for collider searches, and in the context of gravity and the early universe. Lattice approach is utilized.
- We study the generation of gravitational waves in phase transitions in the early universe using large-scale numerical simulations. The results are important for the phenomenology of future gravitational wave experiments.
- We determine the properties of the electroweak phase transition in BSM scenarios. The results relevant for electroweak baryogenesis will be applied to understanding the details of the generation of matter-antimatter-asymmetry in the early universe. We will also investigate the possibly common origins between the matter and dark matter abundance.
- We study the role of quantum entanglement and the dynamics of strongly interacting systems with the methods of holographic gauge-gravity duality and quantum information theory.
- Develop further our state-of-the art quantum field theory simulation codes for emerging computer architectures.

Background discussion:

Understanding the theory beyond the Standard Model is one of the main goals of particle physics. The Large Hadron Collider (LHC) is probing the scalar sector of the Standard Model (SM) and providing hints towards its extensions. At the same time, large number of astrophysical and cosmological observations are investigating the nature of dark matter and providing stringent constraints on different model paradigms.

A particularly important research direction is the physics of the Higgs sector. Apart from being the least understood area of the Standard Model, the Higgs boson may provide the link to dark matter and inflation. To this end, the LHC data play a crucial role. Recent tantalizing hints of a further scalar resonance at the LHC make this area all the more exciting.

In light of the current data, the Higgs boson can be an elementary scalar or a composite particle. If it is elementary, new particles may be expected because of naturality. In the case of composite Higgs, one would expect it to be part of a larger composite spectrum analogous to the hadronic states of QCD. Phenomenology studies will parallel the work of the experimental groups at the department.

Composite Higgs models require a new strongly interacting sector. The physics of this sector is non-perturbative, and obtaining quantitative results numerical simulations are required. In Helsinki we are doing leading edge large-scale computer simulations of this class of theories, using supercomputing resources at CSC and PRACE, studying both the phenomenology of the candidate models and their generic theoretical properties.

In cosmology and astroparticle physics light scalar fields lead to interesting cosmological consequences: they leave observational imprints e.g. on non-thermal dark matter production or on the generation of baryon asymmetry. Furthermore, they affect vacuum stability. These, and other cosmological ramifications of beyond Standard Model physics (BSM), provide interesting prospects for research across the different disciplines in the section of particle and astroparticle physics.

Several beyond the Standard Model physics scenarios lead to phase transitions in the early Universe near the electroweak epoch. If the transition is of first order, it will generate gravitational waves, and possibly lead to the origin of the baryon asymmetry of the Universe. The gravitational waves may be observable in future gravitational wave observatories, for example the European eLISA satellite constellation, scheduled for launch in 2034. This will give a unique direct window to the relevant BSM processes. We are studying the generation of gravitational waves using large-scale numerical simulations, obtaining direct relation between the observed signals and the parameters of the BSM models. The results are important input for the physics case of eLISA.

In quantum field theory, the framework of particle physics and particle cosmology, a topical question is how various systems behave in the limit when the interactions become so strong that individual constituents blend into a strongly correlated ensemble. In this limit, computational tools such as the lattice approach can be effectively used to study many physical properties. Another modern tool is the gauge-gravity duality mapping, which translates the physics questions into the language of general relativity. This offers a window to study complicated nonequilibrium phenomena and many body quantum entanglement in strongly interacting systems. The two approaches help to understand various topics, such as the early phase of ultrarelativistic heavy ion collisions producing gauge-gluon matter, quantum critical systems, and technicolor physics which is one of the possibilities to be discovered at LHC in CERN.

A recurring goal in our research is to understand the complicated behavior of extended quantum field theory systems in and out of thermal equilibrium. Here, the toolbox of modern thermal field theory, ranging from weak coupling techniques to lattice Monte Carlo simulations and holography, is applied to study aspects of e.g. the Electroweak symmetry breaking in the early universe, the thermalization dynamics of heavy ion collisions, and the bulk properties of quark matter inside neutron stars.

Cosmology

Using ground base ESO surveys, we participate in characterizing the large-scale structure of the Universe. We participate in the cosmology missions of the European Space Agency, in particular Planck and Euclid, where we are the leading institute in Finland. Planck made observations in 2009-2013, but the data analysis continues. We are preparing for Euclid mission, which will mass-calibrate the Universe. Euclid will be launched in 2020, and we provide one of the nine national Euclid Science Data Centers, SDC-FI.

During 2017-2020:

- We build SDC-FI into a fully functional and capable part of the Euclid Science Ground Segment.
- We secure our role as one of the key teams in Euclid data analysis (as we are in Planck).
- We study the theoretical aspects of the evolution of the large-scale structure of the universe and the role of the inhomogeneities in relation to Euclid and to the nature of dark energy
- We study the models of the primordial perturbations and their possible signatures

Background discussion:

Observational cosmology

One of our themes is structure formation, which also has ramifications for dark matter and the nature dark energy. This topic has a large overlap with extragalactic astrophysics and with beyond the SM particle physics model building. Our main experiment is Planck, which will be followed by Euclid, an ESA mission to be launched in 2020. We are involved in providing the data center for the mission. it is also of critical importance to secure a unique role of Finland in exploration of Euclid data. For that we have engaged in the activity related to upgrading the ESO telescopes (e.g. 4MOST on VISTA). Meanwhile, there we are conducting a number of astrophysical surveys, such as CODEX, which are also important for cosmology. This involves use of Finland's access to telescopes such as Nordic Optical Telescope. We actively seek to be involved in direct dark matter search experiments, such as CTA, which have a high promise for discovery of the annihilation radiation from dark matter particles.

Euclid and Planck complement each other ideally in increasing our understanding of the universe, Planck focusing on the early universe, and Euclid on its later evolution (the last 3/4 of its 13.8 billion year history).

Planck has already led to over 100 publications, with 6 to 7 authors from PAP (2.5 to 3%) on average, with over 10 000 citations. We expect that Euclid will have at least similar impact.

Euclid is one of the national infrastructures in the Academy of Finland infrastructre roadmap and has received 455 000 euros infrastructure funding from the Academy for SDC-FI in 2016-2020. University of Helsinki (PAP) is the leading institute; the other participating institutes are CSC, University of Turku, University of Jyväskylä, and Aalto University. The prototype for SDC-FI exists at the CSC Kajaani data center and is based on virtual machines running on their Pouta cloud service. The Euclid consortium has decided to base the data analysis on virtualization technology to guarantee the same software environment at all national data centers.

In addition to providing the data center, Finnish responsibilities in Euclid include the Data Quality Common Tools work package and contributions to Euclid simulation software and Euclid Level-3 data-analysis software. Level-3 is the last step of Euclid data analysis leading to the science-ready data products including galaxy and weak lensing correlation functions and power spectra. PAP participates in the Euclid Science Working groups of Theory (cosmological and gravitation), Cosmology simulations, Weak gravitational lensing, CMB cross correlation, Galaxy clustering, and Clusters of galaxies.

The teaching program leading to participation in Euclid starts with the Bachelor/Master level courses Cosmology I, Cosmology II, Galaxies and Cosmology, and General Relativity; and continues with graduate level courses Cosmological Perturbation Theory, and a new course, to be introduced in 2017 on Physical Cosmology (name not yet fixed, will deal with topics related to Euclid Level-3 data)

Possibilities for participation in future space missions are WFIRST (NASA-led mission where ESA participates, successor to Euclid, launch on 2024 or later) and the next CMB satellite (working name COrE+), successor to Planck, but optimized for polarization measurements (we participate in the preparation of a proposal for such a mission for the ESA M5 launch slot in 2029).

Theoretical cosmology

One of our main objectives is to develop consistency tests of homogeneous and isotropic cosmological models, which is one area of interest in Euclid Theory Science Working Group. We aim to further develop precision cosmology; one example is the assessment of the role of relativistic effects when relating perturbation theory and observations. Euclid is sensitive to small corrections, and it is necessary to check whether neglecting relativistic corrections biases the estimation of cosmological parameters. These considerations are also important for understanding dark energy.

The nature of the primordial perturbations is theoretically most often related to cosmological dynamics of light scalar fields. On one hand we will focus on building and testing models of inflation and curvaton models that make use of the Planck data, and in the near future, of other (ground based) forthcoming experiments. On the other hand we will continue studying the cosmological consequences of the scalar sectors in the Standard Model and its extensions. Here there is considerable overlap with theoretical particle physics as is obvious from the items listed under "Particle theory".

Regarding models of the origin of the primordial perturbations, we will focus on the magnitude and spectrum of the primordial gravitational waves, as well as on the induced spectral distortions of the black body form, which may be observable in the near future. Modified theories of gravity are also relevant and may also have an impact on studies of dark energy.

Astrophysics

We aim to understand the role of black holes in the evolution of galaxies and the role of environment. Similarly our goal is to understand the physical and chemical composition of interstellar matter, the formation of dense interstellar molecular clouds, and the final evolution leading to cloud collapse and the formation of new stars in the Milky Way.

In theoretical astrophysics, our main priorities will include 1) accurately modelling the dynamics of supermassive black holes in both merging and cosmologically evolving massive galaxies and to understand the influence of the black holes on galactic evolution; 2) developing the most accurate simulated model of the local Universe to date by running a very high-resolution full physics simulation of the Local Galaxy group and its immediate neighbourhood; and 3) simulating the formation of massive elliptical galaxies using both merger and cosmological simulations in order to understand the assembly of their stellar components both as a function of time and environment.

During 2017-2020

- Complete the analysis of observations from the Herschel key programme "Galactic Cold Cores", regarding the evolution of interstellar dust grains and the role of environmental effects on Galactic star formation
- Complete the analysis of Planck polarisation data to reach final conclusions on the effects of Galactic magnetic fields on cloud structure and star formation
- In collaboration with other European teams, create the first global models of interstellar medium in the Milky Way (complete with radiative transfer modelling)
- Expand our participation in follow-up projects on Planck-detected cold clumps, especially in ground-based interferometric and polarimetric observations
- Update our simulations codes for polarised dust emission, for enhanced analysis of Planck and ground-based observations and for predictions of future missions
- Complete the next generation of radiative transfer codes for the modelling of line transfer on hierarchical grids and in heterogeneous computing environments
- Complete the development and testing of our new and unique simulation code that combines accurate small-scale force calculations in the neighbourhood of the black hole with a global tree code that simulates the large-scale environment in the wider galaxy.
- Complete the simulations of the SIBELIUS (Simulations Beyond the Local Universe) project using the Sisu supercomputer. The final simulation data products will be made publicly available to the wider astronomical community after a proprietary period.
- Setup and run a large set of cosmological and merger simulations to study the formation and assembly of elliptical galaxies. With the help of these simulations we can understand how the redshift two elliptical galaxy population evolved into the present-day massive ellipticals.
- Complete the code development of the Helsinki workhorse simulation code by adding low temperature cooling routines necessary for studies of high-density gas found in very high-resolution simulations.
- Strengthen collaboration links with observational astrophysics groups both internationally and nationally by targeting the simulation work towards answering unsolved observational questions.

Background discussion:

Observational astrophysics

The European Southern Observatory (ESO) is a 16-nation intergovernmental research organisation for ground-based astronomy. Created in 1962, ESO has provided astronomers with state-of-the-art research facilities and access to the southern sky. The organisation employs about 730 staff members and receives annual member state contributions of approximately €131 million with Finnish contribution of €2.2 million. ESO observatories are located in northern Chile.

ESO has built and operated some of the largest and most technologically advanced telescopes. These include the New Technology Telescope, an early pioneer in the use of active optics, and the Very Large Telescope (VLT), which consists of four individual telescopes, each with a primary mirror 8.2 metre across, and four smaller auxiliary telescopes. The Atacama Large Millimeter Array observes the universe in the millimetre and submillimetre wavelength ranges, and is the world's largest ground based astronomy project to date. It was completed in March 2013 in an international collaboration by Europe (represented by ESO), North America, East Asia and Chile.

Currently under construction is the European Extremely Large Telescope. It will use a 39.3-metre-diameter segmented mirror, and become the world's largest optical reflecting telescope when operational in 2024. Its light-gathering power will allow detailed studies of planets around other stars, the first objects in the universe, supermassive black holes, and the nature and distribution of the dark matter and dark energy which dominate the universe. Department of Physics is involved in the construction of the multi-Object spectrograph for E-ELT, MOSAIC.

The European Space Agency (ESA) is an intergovernmental organisation dedicated to the exploration of space, with 22 member states. Established in 1975 and headquartered in Paris, France, ESA has a worldwide staff of about 2,000 and an annual budget of about €5.25 billion with Finnish contribution of €20 million, with €7 million contribution to science payload.

ESA's space flight programme includes human spaceflight, mainly through the participation in the International Space Station programme, the launch and operations of unmanned exploration missions to other planets and the Moon, Earth observation, science, telecommunication as well as maintaining a major spaceport, the Guiana Space Centre at Kourou, French Guiana, and designing launch vehicles. The main European launch vehicle Ariane 5 is operated through Arianespace with ESA sharing in the costs of launching and further developing this launch vehicle. Department of physics has been involved in preparation and conduction of several missions, Planck, GAIA, Euclid, Athena.

Extragalactic observations are concentrated on understanding on the co-evolution of galaxies and black holes and the role of environment on this process. We use the ground-based data from ESO and the data obtained by the ESA space missions, such as HST, Herschel. To define the environment, we use the data of ESA space mission XMM-Newton, which also provides the insights on the physics of intergalactic medium.

Research is conducted to understand the physical and chemical composition of interstellar matter, the formation of dense interstellar molecular clouds, and the final evolution leading to cloud collapse and the formation of new stars in the Milky Way. Current emphasis is on the interpretation of data from the recent Planck and Herschel satellite missions. Ground-based follow-up observations are pursued at optical, near-infrared, and radio wavelengths. The ESO telescopes (VLT, APEX, ALMA) have a central role but are complemented with observations with NOT and through our collaboration in international surveys conducted on telescope in the USA (JCMT, SMT) and Southeast Asia (KVN, Nobeyama). We are developing methods for data analysis and numerical modelling of both continuum and line observations. In particular, we are participating in studies where magnetohydrodynamical simulations of cloud evolution are compared to observations using radiative transfer programs developed by us.

Theoretical astrophysics

The main goal is to numerically model the various physical processes that are relevant for the formation and subsequent evolution of galaxies. Currently we are studying the cosmological formation of elliptical galaxies, the birth of the first supermassive black holes in the Universe, the formation and evolution of the local group of galaxies, relativistic dynamics near supermassive black holes and black hole accretion physics, and finally the formation of tidal dwarf galaxies in galaxy mergers. Within the group we use both sophisticated particle based and adaptive mesh refinement simulation codes, in addition to analytic modeling techniques. The key infrastructure enabling this research is the CSC supercomputer facilities, namely the Sisu and Taito supercomputers. The astrophysical modeling is carried out in close collaboration with leading theoretical astrophysics teams in the United Kingdom and Germany giving the group access to state-of-the art simulation codes that are required in order to remain at the forefront of the international astrophysics scene. Researchers in the group also collaborate closely with observational teams as data from recent observations serve as both input and motivation for the theoretical studies.

Space physics

The space physics research group studies the solar-terrestrial physics and space weather. The emphasis of our research is on understanding the formation of solar eruptions and their evolution in the heliosphere and consequences in the near-Earth space and at other planets of our solar system.

During 2017-2010

- Develop an advanced modeling scheme of coronal mass ejections (CMEs) from their formation out to Mars orbit.
- Establish a prediction scheme based on remote-sensing solar observations for estimating the magnetic field configuration of CMEs and their early evolution
- Make significant progress in understanding of the initiation and evolution of CMEs using the above mentioned modeling and empirical schemes
- Make significant improvements in long-lead time space weather predictions by combining the above mentioned modeling and empirical schemes
- Characterize solar wind – magnetosphere-ionosphere interactions during large-scale solar wind drivers and extend the analysis to planetary

magnetospheres of the solar system (in particular Mercury) and beyond (exoplanets)
- Combine state-of-the art inner magnetospheric and solar wind observations to make breakthroughs in understanding the complex dynamics of the Van Allen radiation belts

Background discussion:

The UH space research group research tackles one of the most prominent open questions in the field. Coronal mass ejections (CMEs) are huge eruptions of solar plasma and magnetic field and their importance ranges from their paramount impact on solar cycle evolution to being key drivers of strong space weather disturbances at the Earth and at other planets of our solar system. In particular one key problem in the field is the lack of realistic knowledge of CME magnetic fields from remote-sending observations or modelling relying on solar observations. This significantly limits our understanding of CME initiation and evolution as well as providing accurate long-lead time space weather predictions. UH group studies the whole chain from Sun to Earth with the main focus being on predicting magnetic fields in CMEs and their early evolution by combining advanced simulations and state-of-the-art observations. Our simulation scheme couples a data-driven inner coronal magnetofrictional model, an outer coronal MHD model and an inner heliospheric MHD model Euhforia. Another major question we study is the dynamics of the Van Allen radiation belts. The variations of the fluxes of high-electrons in the belts are still largely unpredictable, and one of the long-standing puzzles in the field. In particular, we aim at establishing a solid connection between structured large-scale solar wind drivers, conditions in the inner magnetosphere and processes that govern electron acceleration, loss and transport.

Space research group studies the solar-terrestrial physics and space weather in collaboration with the Finnish Meteorological Institute and Aalto University within the Kumpula Space Centre. The observational data comes from international satellite projects involving spacecraft of ESA and NASA, such as SOHO, STEREO, Solar Dynamics Observatory and Van Allen Probes). The relevant future observatories include Solar Orbiter, BebiColombo, Solar Probe+ and Proba-3. The space research group is also involved in the development and scientific planning of several space-borne instruments. The most recent one being the SIXS instrument on-board BepiColombo that will measure solar X-rays, electrons and protons. BepiColombo is an ESA-led mission to Mercury scheduled for launch in 2018.

Planetary research

Planetary research focuses in on deriving the physical properties and dynamical evolution of small Solar System bodies, such as near-Earth objects, asteroids and comets at large, and planetary satellites, as well as on the physical and chemical properties of meteorites. Theoretical and experimental studies are carried out on the interaction of electromagnetic radiation (scattering, absorption, and emission) with cosmic dust in planetary regoliths and elsewhere, from Solar System objects through the interplanetary medium to the interstellar medium and extrasolar planetary systems.

During 2017-2020

- Scattering research within the ERC Advanced Grant project SAEMPL (Scattering and Absorption of ElectroMagnetic waves in ParticuLate media) will be completed, resulting in novel numerical methods for dense systems of particles and laboratory instrumentation for their validation.
- X-ray fluorescence emission studies ramp up in view of the BepiColombo mission to Mercury (launch in 2018; Co-Principal Investigator status in MIXS, the Mercury Imaging X-ray Spectrometer).
- Scattering by systems of large, solid, inhomogeneous particles will be studied as a natural continuation to SAEMPL, with key questions arising from the boundary conditions.
- Experimental instrumentation will be extended by combining the integrating-sphere optics and ultrasonic levitation, allowing for integrated radiation studies for samples.
- UV-Vis-NIR spectroscopic measurements on lunar, asteroid, and cometary samples returned by space missions will shed light on the evolution of matter and materials in the Solar System.
- Studies will be launched on the integrated Earth radiation balance and spherical albedo using space geodesy.
- The near-Earth-object population studies will be extended to encompass the entire small-body population of the Solar System.
- Research will be initiated on interstellar dust and extrasolar planetary systems in the fields of radiation and dynamics.
- Public outreach and commercialization efforts assume an increasingly important role.

Background discussion:

Excellence is the guiding principle in planetary research at the Dept. Physics. Research on electromagnetic scattering progresses steadily with the help of funding from the European Research Council and the Academy of Finland. Theoretical methods are maturing and allowing for extensive application to astronomical and space science data. Research on inverse methods allow for advances in statistical orbital inversion for both natural and artificial celestial bodies. Research on populations of Solar System objects are resulting in key paradigm changes in the evolution of near-Earth objects (NEOs) and asteroids at large. Research in planetary geophysics will focus on physical properties of planets, Moons, and small solar system bodies. The work will incorporate both experimental and theoretical modeling methods. One of the main goals is to deliver a reliable link between composition of planetary bodies, their spectral signature, and meteorites recovered on the Earth. As the Solar System hosts the Earth, the research is intimately related to the prosper of the human kind (e.g., NEO and space-debris impact hazard, space geodesy, atmospheric radiation balance). Relevant future ground-based observing facilities include the ESO VLT (Very Large Telescope) and E-ELT (European Extremely large Telescope), the NOT (Nordic Optical Telescope), as well as the space geodetic instrumentation at the Metsähovi Fundamental Station of the Finnish Geospatial Research Institute (FGI; Satellite Laser Ranging, Very Large Baseline Interferometry). Relevant ongoing and future space missions include Gaia (groundbased follow-up at the NOT), Rosetta, BepiColombo, Dawn, Hayabusa II, and OsirisREx. In atmospheric Earth observation, collaboration is foreseen, in particular, with the Finnish Meteorological Institute, Aalto University, and University of Jyväskylä.

Research equipment of astronomy and space physics

Telescopes of ESO: VLT, ALMA, E-ELT (in the future)
Nordic optical telescope NOT

Current satellite missions with UH participation:
- Rosetta (ESA cometary mission)
- Gaia (ESA astrometry mission)

Future satellite missions with UH participation:
- BepiColombo (ESA mission to Mercury, launch 2016)
- Euclid (ESA cosmology mission, launch 2020)

Potential participation further along the road:
- JUICE (ESA mission to Jupiter icy moons, launch 2022; potential participation?)
- Athena (ESA high-energy astronomy mission, launch 2028)