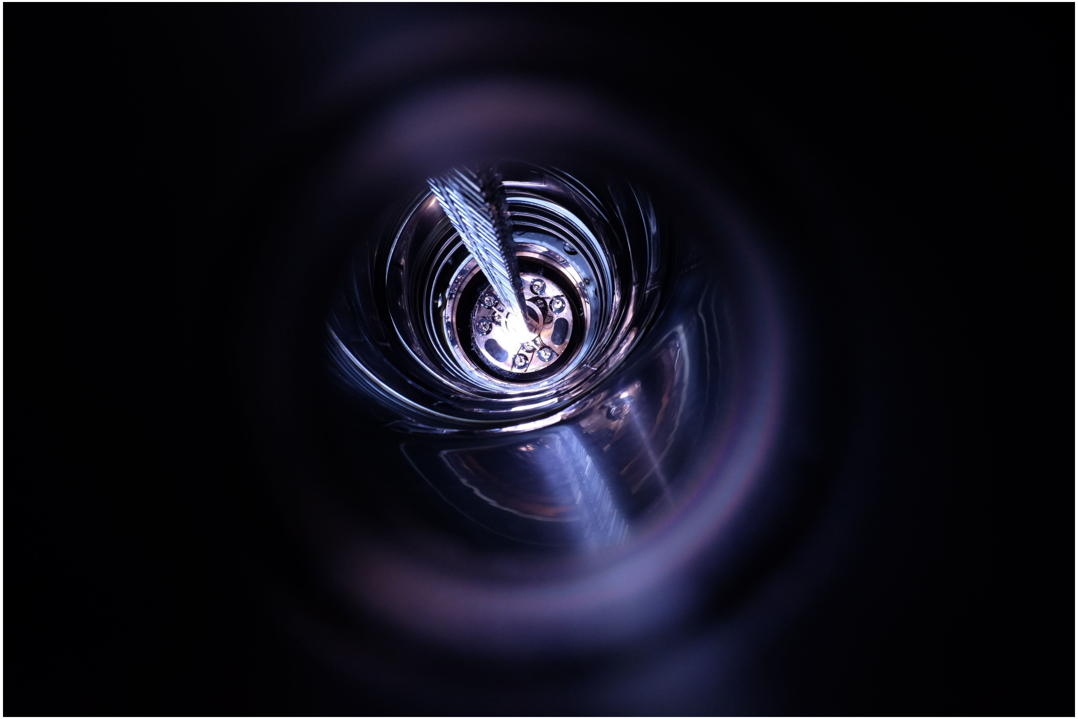
Cosmology, Astro- and Astroparticle Physics



Astrophysics and General Relativity

Prof. Philippe Jetzer

LIGO (Laser Interferometer Gravitational-Wave Observatory) consists of two Earth-bounded instruments together with VIRGO aimed to detect gravitational waves in the frequency range from about 10 to 1000 Hz. In 2015 the first gravitational wave signal has been detected. Since then many more events have been found. Our group has made important contributions to the analysis of LIGO data and also in the modelling of more accurate gravitational waveforms. The latter results will be used in LIGO and for the future LISA mission.

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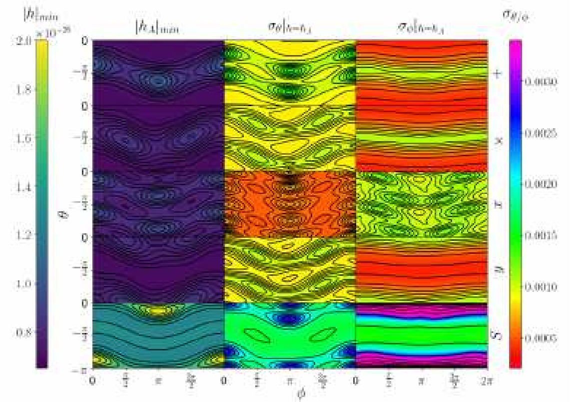
Highlights

The work of the group is focused on the topic of gravitational waves and this both for use with LIGO/Virgo and for the future space mission LISA. Indeed, our group is involved in these collaborations. In the following we briefly describe three main results published in 2018.

In a paper, starting from first principles, Maria Haney and collaborators derived the third post-Newtonian (3PN) accurate Keplerian-type parametric solution to describe PN-accurate dynamics of non-spinning compact binaries in hyperbolic orbits [1]. Orbital elements and functions of the parametric solution were obtained in terms of the conserved orbital energy and angular momentum in both Arnowitt-Deser-Misner type and modified harmonic coordinates. Some elegant checks were discussed that include a modified analytic continuation prescription to obtain our independent hyperbolic parametric solution from its eccentric version. A prescription to model gravitational wave polarization states for hyperbolic compact binaries experiencing 3.5PN accurate orbital motion was presented that employs our 3PN-accurate parametric solution.

Yannick Boetzel and collaborators studied the inspiral waveforms for precessing binaries on eccentric orbits in the Fourier domain [2]. To achieve this, they used a small eccentricity expansion of the waveform amplitudes in order to



Sensitivity of Einstein Telescope, LIGO and DECIGO at 100 Hz towards the different polarizations in the left column. Standard deviation of the Θ and Φ angle for a GW with polarization A and amplitude of $h_A = 2.6 \cdot 10^{-26}$ in the middle and right column respectively. (from [3])

separate the periastron precession timescale from the orbital timescale, and used a shifted uniform asymptotic transformation to compute the Fourier transform in the presence of spin induced precession. They showed that the resulting waveforms can yield a median faithfulness above 0.993 when compared to an equivalent time domain waveform with an initial eccentricity of $e_0 \simeq 0.3$. When the spins are large, using a circular waveform can potentially lead to significant biases in the recovery of the parameters, even when the system has fully circularized, particularly when the accumulated number of cycles is large. This is an effect of the residual eccentricity present when the objects forming the binary have non vanishing spin components in the orbital plane.

In a paper Lionel Philippoz and Adrian Boîtier investigated the sensitivity to additional gravitational wave polarization modes of future detectors [3]. They first looked at the upcoming Einstein Telescope and its combination with existing or planned Earth-based detectors in the case of a stochastic gravitational wave background. They then studied its correlation with a possible future space-borne detector sensitive to high-frequencies, like DECIGO. Finally, they adapted those results for a single GW source and establish the sensitivity of the modes, as well as the localization on the sky.

Highlighted Publications:

1. Gravitational waves from compact binaries in post-Newtonian accurate hyperbolic orbits, G. Cho, A. Gopakumar, M. Haney, H. Mok, Phys.Rev. D**98** (2018) no.2 024039 arXiv:1807.02380
2. Fourier domain gravitational waveforms for precessing eccentric binaries , A. Klein, Y. Boetzel, A. Gopakumar, Ph. Jetzer, and L. de Vittori, Phys.Rev. D**98** (2018) no.10, 104043 arXiv:1801.08542
3. Gravitational wave polarization from combined Earth-space detectors, L. Philippoz, A. Boîtier, and Ph. Jetzer, Phys.Rev. D**98** (2018) no.4, 044025 arXiv:1807.09402

Theoretical Astrophysics

Prof. Prasenjit Saha

Light always takes the path of shortest travel time — except when it doesn't. According to Fermat's principle, light can also take paths that are maxima or saddle-points of the travel time, which can produce multiple images of the same object. In astronomy this phenomenon, known as strong gravitational lensing, can be caused by galaxies warping the spacetime around them. When observed, it offers a way to probe the otherwise invisible dark matter, which makes up most of the mass of a galaxy. Our research is on new ways of extracting the interesting information from the observables, and using it to help understand how galaxies work.

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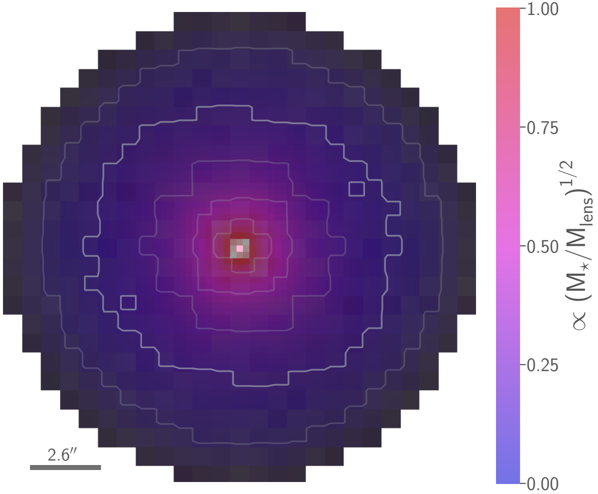
The dark halos of galaxies

An average cubic metre of the universe has about a quarter of an atom, and a little over an atomic mass in the form of dark matter. How then, did condensed matter like us form? The basic process is that small inhomogeneities created by quantum fluctuations grew through gravitational instability. The higher-density regions formed would have been predominantly dark matter, since there is more of it, but because gas unlike dark matter is dissipative, gas would fall into the deepest gravitational potential wells, and increase the density still further. The result: galaxies that are mainly ordinary matter in the inner regions, and almost entirely dark matter in the outer regions.

Our main research has been on mapping the distributions of ordinary matter and dark matter in galaxies using gravitational lensing. A special aspect of this work has been the collaboration with knowledgeable non-professional citizen scientists, four of whom have co-authored papers. This was possible because of a very creative software stack developed by



A reconstruction of the mass distribution in the galaxy J1434+522 from its lensing action on the light of a more distant galaxy. The red/blue scale represents the dark-matter fraction.

Rafael Küng and continued by Philipp Denzel. One interesting conclusion to emerge, which was previously known but only inferred indirectly, is that galaxies similar in mass to the Milky Way are the most efficient at turning their gas into stars.

Together with our collaborators, we are also exploring other exciting optical phenomena in astrophysics. Among them is the granularity in the gravitational field of a galaxy, due to individual stars. This can produce extreme magnification of background objects. If that background object is a quasar, our calculations indicate that the observed image contains tomographic information on the event-horizon scale.

Highlighted Publications:

1. Models of gravitational lens candidates from space warps CFHTLS,
   R. Küng *et al.*, MNRAS 474, 3700–3713 (2018)
2. Microlensing as a possible probe of event-horizon structure in quasars,
   M. Tomozeiu *et al.*, MNRAS 475, 1925–1936 (2018)

Astroparticle Physics Experiments

Prof. Laura Baudis

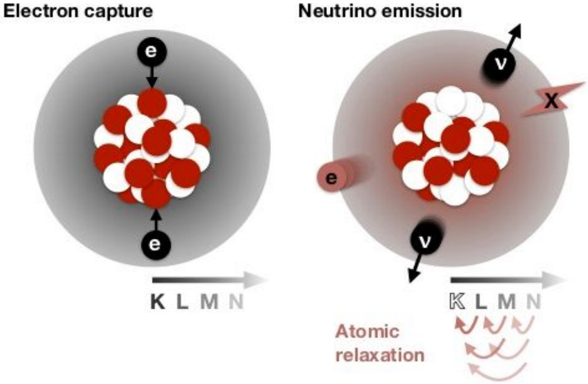
We study the composition of dark matter in the universe and the fundamental nature of neutrinos. We build and operate ultra low-background experiments to detect dark matter particles and to search for the neutrinoless double beta decay, a rare nuclear process which only occurs if neutrinos are Majorana particles.
We are leading members of the XENON collaboration, which operates xenon time projection chambers to search for rare interactions such as from dark matter, and we lead the DARWIN collaboration, with the goal of building a 50 t liquid xenon observatory to address fundamental questions in astroparticle physics.
We are members of GERDA and the future LEGEND experiments, which look for the neutrinoless double beta decay of ^{76}Ge in high-purity Ge crystals immersed in liquid argon, with a sensitivity on the half-life of $T_{1/2}^{0\nu\beta\beta} > 1 \times 10^{26}$ y.

https://www.physik.uzh.ch/g/baudis

Double electron capture in ^{124}Xe with XENON1T

The XENON1T detector was mainly built to detect interactions of dark matter particles, and has recently placed the world's most stringent limits on the coherent elastic scattering of weakly interacting massive particles with xenon nuclei. XENON1T, which was operated underground at Laboratori Nazionali del Gran Sasso, used 3.2 t of ultra-pure liquid xenon, of which 2 t were within the sensitive region of the time projection chamber (TPC): a cylindrical volume that is observed by 248 photomultiplier tubes. The TPC, made out of materials with ultra-low radioactivity levels, allowed for the measurement of the scintillation and ionisation signals induced by a particle interaction - the latter by converting ionisation electrons into light by means of proportional scintillation. It provided a calorimetric energy measurement, a 3D position reconstruction, and the scatter multiplicity of events.

The data recorded between February 2, 2017 and February 8, 2018 as part of the dark matter search, was also analysed for the double electron capture (2νECEC) of ^{124}Xe with emis-



Schematics of the double electron capture in ^{124}Xe.

sion of two neutrinos. This is a very rare process that escaped detection for decades. Two protons in the ^{124}Xe nucleus simultaneously convert into neutrons by the absorption of two electrons, mostly from the K shell, and the emission of two electron neutrinos. After the electron capture, the filling of the vacancies results in a detectable cascade of X-rays and Auger electrons at 64.3 keV. The nuclear binding energy Q =2857 keV released in the process is carried away mostly by the two neutrinos, which are not seen within our detector.

During the analysis process, the XENON1T data in the energy region from 56 keV to 72 keV were blinded, thus inaccessible for analysis, and the energy scale around the expected signal at E_0 = (64.3±0.6) keV was calibrated using mono-energetic lines from injected sources such as ^{83m}Kr, from neutron-activated xenon isotopes as well as γ-rays from radioactive decays in detector materials. Upon unblinding, 126 events from 2νECEC were observed, which - taking into account the isotopic abundance of ^{124}Xe, the fiducial volume containing 1.5 t of natural xenon, and the measurement time, yields a half-life of $T_{1/2}^{2\nu ECEC} = 1.8 \times 10^{22}$ y, the longest half-life ever measured directly. This measurement demonstrates the sensitivity of large xenon TPCs to ultra-rare decays, and sets the stage for 0νECEC searches that can complement double-β-decay experiments in the search for Majorana neutrinos.

Highlighted Publications:

1. Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T
   XENON Collab., Nature Volume **568** Issue 7753 (2019)
2. Dark matter search results from a one ton-year exposure of XENON1T
   XENON Collab., Phys. Rev. Lett. **121** 111302 (2018)
3. Improved limit on neutrinoless double beta decay of ^{76}Ge from GERDA phase II
   GERDA Collab., Phys. Rev. Lett. **120** 132503 (2018)
4. A dual-phase xenon TPC for scintillation and ionisation yield measurements in liquid xenon
   L. Baudis *et al*, Eur.Phys.J. C**78** 351 (2018)

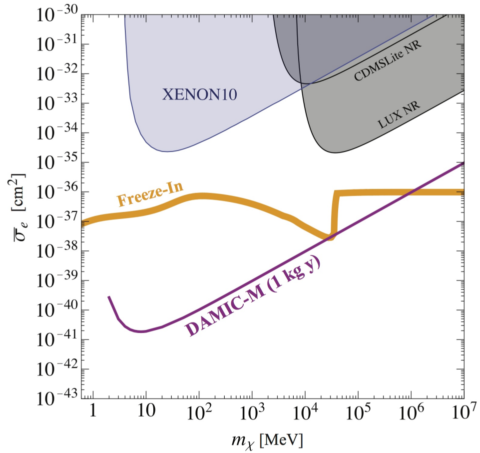
DAMIC Experiment

Prof. Ben Kilminster

DAMIC-M (Dark Matter in CCDs at Modane Underground Lab) is an experiment that searches for the dark matter gravitationally bound in our Milky Way through electrical signals produced from its collisions with silicon CCD detectors. This experiment represents a factor of 10 increase in mass, a factor of 10 decrease in the energy threshold, and a factor of 50 decrease in background rates, as compared to the current DAMIC experiment operating in SNOLAB.

https://www.physik.uzh.ch/r/damic

Our group helped found the DAMIC experiment in 2008. For DAMIC-M, we are currently developing a calibration system based on a radioactive isotope, electronics for digitizing the data, imaging software, the control and safety system, and a prototype of the detector with a vacuum interfacing cabling system.



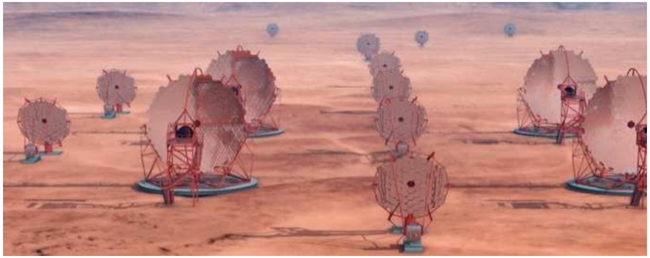
The DAMIC-M experiment tests scenarios of hidden dark matter for the first time. The x-axis is dark matter mass. The y-axis is a measure of the rate of dark matter interactions with matter. The purple line shows the rate down to which DAMIC-M can probe, which is below the theoretical prediction for a type of dark matter that freezes in during the formation of particles in the early universe. The shaded areas are the rates probed by previous experiments.

CTA – Cherenkov Telescope Array

Prof. Florencia Canelli, Prof. em. Ueli Straumann

With more than 100 telescopes located in the northern and southern hemispheres, the Cherenkov Telescope Array (CTA) will extend the currently observable very high gamma ray spectrum by several orders of magnitude.

https://www.physik.uzh.ch/r/cta



Simulated view of part of the CTA telescopes.

The CTA group at UZH has designed essential elements, including the mirror segment actuator system (AMC), light sensor electronics, safety and power control and mechanics for one of the proposed cameras (FlashCam), and contributes to calibration software development.

CTA will search for new very high energy gamma emitters. It will have a great potential for exploring fundamental frontiers in physics including the extragalactic background light, hypothetical dark matter annihilation signals, and the study of the charged cosmic ray acceleration processes.

Highlighted Publications:

1. Science with Cherenkov Telescope Array,
   The CTA consortium, World Scientific, March 2019,
   arXiv 1709.07997
2. Potential for measuring the longitudinal and lateral profile of muons in TeV air showers with IACTs,
   A. Mitchell *et al*, Astroparticle Physics **111** 23-34 (2019)