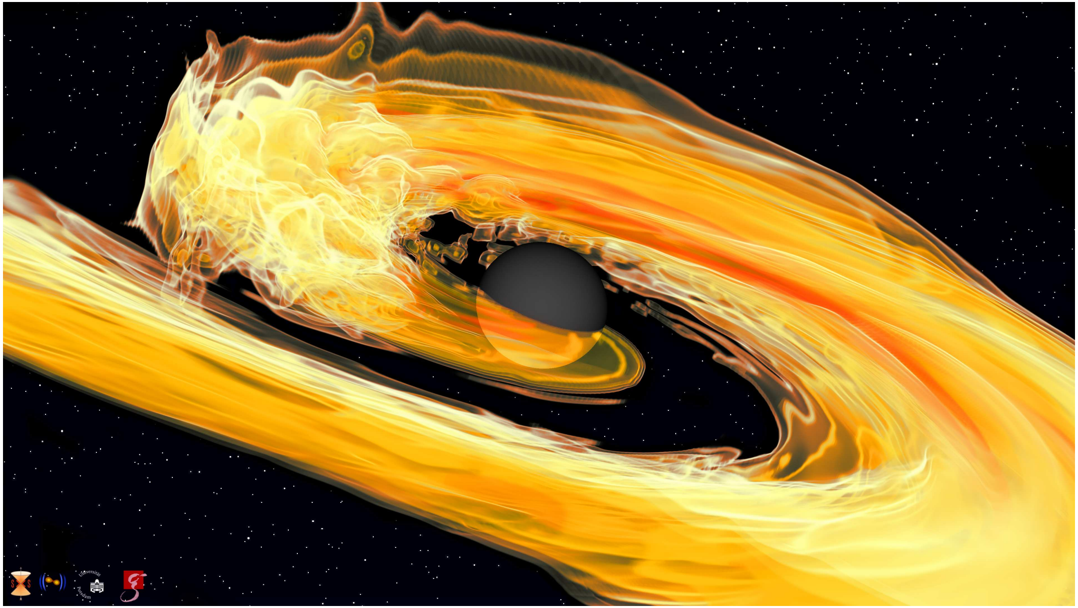
# Cosmology, Astro- and Astroparticle Physics



# 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 about 90 events have been found. Our group has made important contributions to the analysis of LIGO/Virgo data and in the modelling of more accurate gravitational waveforms. The latter results will be used in LIGO/Virgo and for the future LISA mission and the Einstein Telescope project.

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

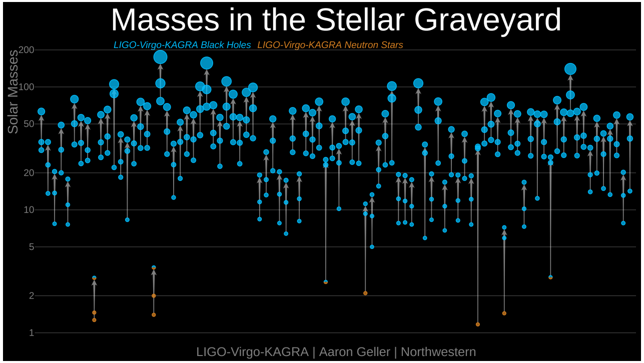


### Highlights

The work of the group is focused on the topic of gravitational waves in the framework of the LIGO Scientific Collaboration and for the future space mission LISA, since our group is involved in both these international collaborations. In the following we briefly describe some results published in 2021, besides all the works appeared in the framework of the LIGO/Virgo and LISA Pathfinder collaborations.

S. Tiwari, M. Ebersold and E. Hamilton developed a method to distinguish between binary-black-hole and neutron-star-black-hole systems by studying the effect of tidal disruption on the non-linear memory of the gravitational wave signal. This method is complementary to other methods of distinguishing these sources and is of particular relevance in cases where the observation of an electromagnetic counterpart from a neutron-star black-hole merger is unlikely. It will be most useful for observations made by third generation gravitational wave detectors, such as Einstein Telescope and Cosmic Explorer.

E. Hamilton and collaborators produced a model of the gravitational waves emitted by binary-black-hole systems in which the spins are oriented in an arbitrary direction. This is the first such model applicable to the complete inspiral-




*Black holes of all shapes and sizes in the new gravitational-wave catalog (https://www.ligo.org/science/Publication-O3bCatalog/)*

merger-ringdown signal where the spin effects have been tuned to numerical relativity. This model will be particularly relevant for the next observing run of the LIGO-Virgo-Kagra collaboration as we anticipate detecting a number of spinning binaries.

S. Tiwari and D. Lopez led the analysis and paper writing of the search for short duration generic transients for the LIGO-Virgo-Kagra collaborations.

A. Boitier, S. Tiwari and P. Jetzer derived a generic expression for the pulse redshift, the main observable for the Pulsar Timing Array (PTA) experiment for detection of gravitational waves for all possible polarizations induced by modifications of general relativity. In particular, we provided a generic expression of the overlap reduction function for PTA without using the short wavelength approximation for tensorial polarization. We derived a series expansion to calculate the integral exactly and investigated the behavior of the series for short wavelength values via numerical evaluation of the analytical series.

**Highlighted Publications:**

1. Leveraging gravitational-wave memory to distinguish neutron star-black hole binaries from black hole binaries,
   Phys. Rev. D**104** (2021), 123024, arXiv:2110.11171
2. Model of gravitational waves from precessing black-hole binaries through merger and ringdown,
   Phys. Rev. D**104** (2021), 124027, arXiv:2107.08876
3. All-sky search for short gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run,
   Phys. Rev. D**104** (2021), 122004, arXiv:2107.03701
4. Analytic series expansion of the overlap reduction function for gravitational wave search with pulsar timing arrays,
   Phys. Rev. D**103** (2021), 064044, arxiv:2011.13405

# Theoretical Astrophysics

## Prof. Prasenjit Saha

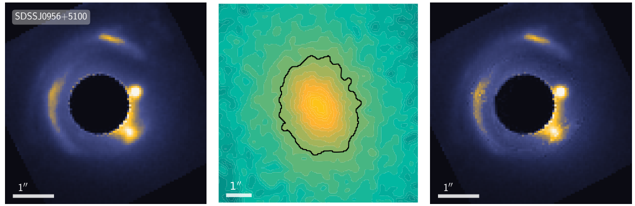
Our research has been on diverse astrophysical phenomena involving light and gravity, especially multiple-image gravitational lenses, but also spacecraft ranging as gravitational-wave sensors.

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



Galaxies that create multiple mirages of background galaxies through gravitational lensing have long been understood as a probe of dark matter and indeed the process of galaxy formation. As part of our long-running research in this area, we have now shown that it is possible to find simulated galaxies arising in galaxy-formation simulations that are plausible matches to observed lensing galaxies (see Figure).

In other work we explored the possibility of detecting the strongest LISA gravitational-wave events separately using spacecraft ranging, which would greatly improve sky localization compared to LISA alone.




*The left panel shows four gravitationally-lensed images of a background galaxy. (The lensing galaxy itself has been cut out.) The middle panel shows a simulated candidate for the lensing galaxy, while the right panel shows the simulated lensed image.*

**Highlighted Publications:**

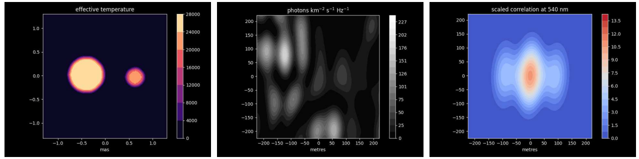
1. A new strategy for matching observed and simulated lensing galaxies, P. Denzel, S. Mukherjee, P. Saha, MNRAS **506**, 1815–1831 (2021)
2. Searching for gravitational waves via Doppler tracking by future missions to Uranus and Neptune, D. Soyuer, L. Zwick, D. J. D'Orazio, P. Saha, MNRAS **503**, L73–L79 (2021)

# CTA – Cherenkov Telescope Array

## Prof. Prasenjit Saha

The Cherenkov Telescope Array (CTA) is a next-generation facility to observe high-energy sources in the Milky Way and beyond. It is designed especially for gamma-ray photons from 10 GeV to above 100 GeV, which it will detect indirectly, through optical Cherenkov showers in the atmosphere. Fortuitously, the facility will also have the capacity to operate in a completely different mode, as an optical intensity interferometer, which can image stellar-scale phenomena.

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




*Simulated interferometry of a binary star (Spica). The left panel shows the effective temperature, the middle panel its (not directly observable) interference fringes, while the right panel shows the observable auto-correlation of the fringes.*

**Highlighted Publications:**
Radius measurement in binary stars: simulations of intensity interferometry,
K.N. Rai, S. Basak, P. Saha, MNRAS 507, 2813–2824 (2021)

# Theoretical Astrophysics

## Prof. Aurel Schneider (Institute for Computational Science)

Research interests lie within the fields of cosmology and theoretical astrophysics, working on nonlinear structure formation as well as the astrophysical aspects of different dark matter models.

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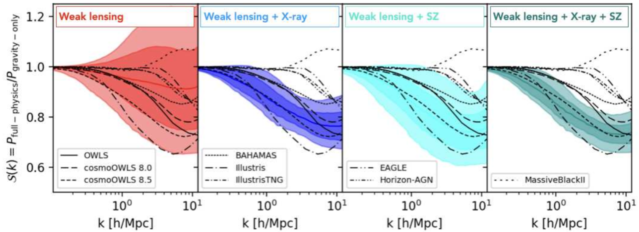
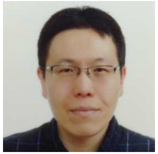





The observed shapes of galaxies contain information about the underlying matter distribution via the weak-lensing (light-deviation) effect. We use observations from the Kilo-Degree Survey (KiDS) to investigate how much the weak-lensing signal is affected by the black-hole driven ejection of gas from galaxy clusters. This so-called baryonic feedback effect consists of a very serious systematic for cosmological surveys (threatening their success in constraining fundamental physics). In our recent work, we show that the uncertainties from baryonic feedback can be overcome with the help of additional data from the distribution of gas around galaxy clusters (obtained via X-ray and kinematic Sunyaev-Zeldovich observations). Combining direct gas and weak-lensing observations, we find that baryonic feedback effects lead to a 20-30 percent suppression of the matter power spectrum, which is more than predicted by most simulations. The results are illustrated in the Figure , where the black lines show the results from various simulations, while the coloured bands indicate our constraints from observations.

Constraining baryonic feedback and cosmology...
Aurel Schneider *et al.* arXiv:2110.02228



# Theoretical Cosmology


## Prof. Jaiyul Yoo (Institute for Computational Science)


The group is interested in large-scale structures of the Universe and focuses on developing gauge-invariant relativistic descriptions of the cosmological observables, performing numerical computations for their predictions in Einstein gravity or modified gravity theories.

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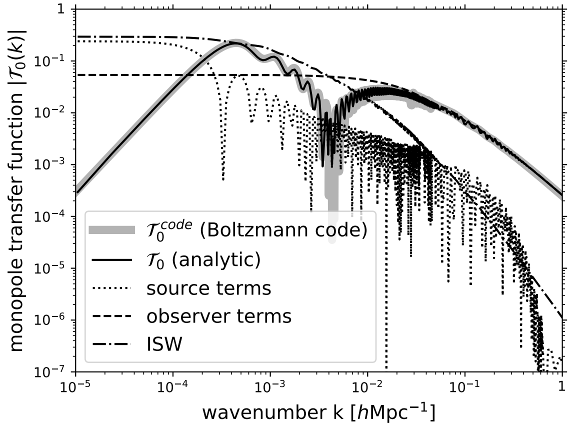
In the standard model, the monopole fluctuation of the observed cosmic microwave background (CMB) temperature anisotropies is gauge dependent, and its power is infinite due to the infrared divergences, while the observations show the contrary. Here we resolved the theoretical issues associated with the infrared divergences and computed the finite monopole power. By recognizing that the background CMB temperature is in fact one of the fundamental cosmological parameters, we removed the ambiguity in defining the hypersurface and showed that the monopole fluctuation can be unambiguously defined and measured. Adopting simple approximations for the anisotropy formation, we derive a gauge-invariant analytical expression for the observed CMB temperature anisotropies to study the CMB monopole fluctuation and the cancellation of the uniform gravitational potential contributions on large scales.

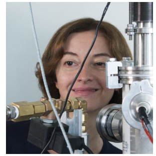



*Gauge-invariant calculations (solid) show that all contributions to the CMB (dashed) are needed to cancel the infrared divergences.*


Physical Review D **103**, 063516 (2021)

# 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, to search for the neutrinoless double beta decay, a rare nuclear process which only occurs if neutrinos are Majorana particles.

We are 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 the **GERDA** and **LEGEND experiments**, which look for the **neutrinoless double beta decay of $^{76}$Ge** in high-purity Ge crystals immersed in liquid argon, with an unprecedented sensitivity.

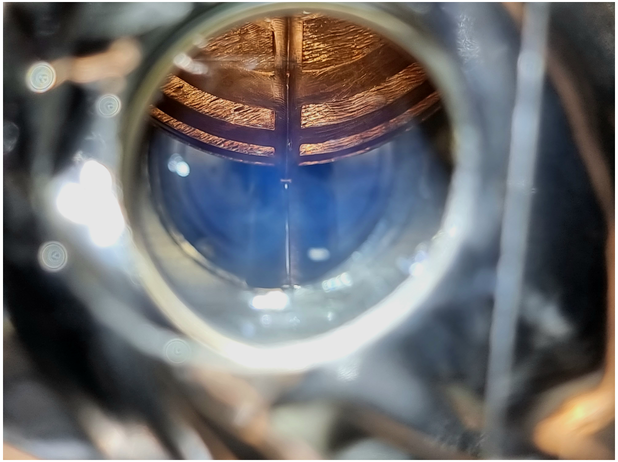
https://www.physik.uzh.ch/g/baudis



### Highlight: Xenoscope

The DARWIN observatory is a proposed next-generation experiment to search for particle dark matter and other rare interactions. It will operate a 50 t liquid xenon detector, with 40 t in the time projection chamber (TPC). When a particle interacts with the liquid xenon target in a TPC, both scintillation and ionisation are produced. The scintillation photons are collected by arrays of photosensors, whereas the electrons produced from the ionisation process are drifted across the length of the TPC by an applied electric field. The electrons are then amplified via electroluminescence and collected as photons at the top of the detector. Achieving such an electron drift for the DARWIN TPC requires both high xenon purity to minimise electron capture along the anticipated 2.6 m length of the detector as well as the application of high voltage, on the order of -50 kV. To this end, a full-scale demonstrator in the vertical dimension, Xenoscope, was constructed in the assembly hall of the University of Zurich.

The design and construction of the facility infrastructure,



*Liquefaction of xenon gas at -100 C and ∼2 bar, as viewed in Xenoscope during the system commissioning phase.*

including the cryostat, cryogenic and purification systems, the xenon storage and recuperation system, as well as the slow control system, were completed in 2021, resulting in a technical design report published in the Journal of Instrumentation [1]. The publication details the system design and operation as well as the successful commissioning of the cryogenics and purification systems. Shown in Figure is the liquefaction of xenon as seen through a viewport in the system during the commissioning run. We demonstrated the nominal operational reach of Xenoscope and benchmarked the components of the systems, demonstrating reliable and continuous operation over 40 days.

Following the commissioning phase, a 50 cm purity monitor was designed, constructed, and installed inside the cryostat in order to benchmark the survival probability of electrons in the xenon. The purity monitor will be succeeded by a 1 m drift TPC, then followed by the full 2.6 m tall detector. In the future, the facility will also be a platform for testing several key technologies necessary to the realisation of the proposed DARWIN experiment.



**Highlighted Publications:**


1. Design and construction of Xenoscope – a full-scale vertical demonstrator for the DARWIN observatory,
   L. Baudis et al, JINST **16** (2021) P08052

2. A measurement of the mean electronic excitation energy of liquid xenon,
   L. Baudis, P. Sanchez-Lucas, K. Thieme,
   Eur. Phys. J. C **81** (2021) 1060

3. Calibration of the GERDA experiment
   GERDA collaboration (M. Agostini et al.),
   Eur. Phys. J. C **81** (2021) 8

# DAMIC Experiment

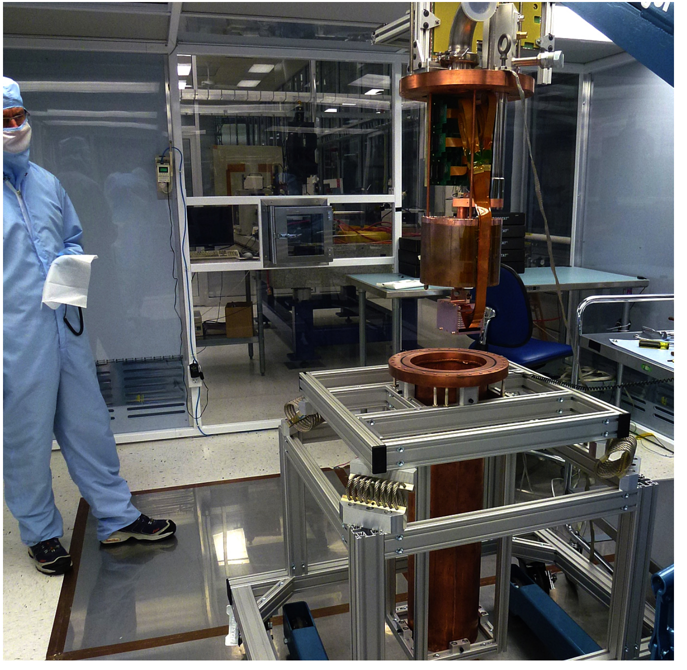
## Prof. Ben Kilminster

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 have built mechanical components and a detector control and safety system for a prototype that has successfully collected data at the end of 2021. We have also developed and tested analog to digital electronics for the readout.

*The new prototype DAMIC experiment, being installed in the Modane underground laboratory in France in November 2021. Shown are the copper box housing the CCD detectors, as well as lead and polyethylene shielding.*



*The copper box hosting the CCDs, top lead shield and in-vacuum electronics being inserted in the copper vacuum vessel.*