HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

MU Topic 3: Matter and Radiation from the Universe

Topic Highlights | MU Days 2023

Kathrin Valerius & Christian Stegmann

Research program in a nutshell

	High-energy Universe	Neutrino properties	Dark Matter
CTA	■		■
IceCube	■	■	■
Pierre-Auger Observatory	■		■
Gravitational Waves	■		■
KATRIN		■	■
XENON & DARWIN		■	■
Theory	■	■	■

Cosmic Rays

CORSIKA 8 – the next-generation simulation framework

The work horse for air shower simulations (25 yrs!) is receiving an overhaul

- Modern, modular re-implementation in C++ (see https://gitlab.iap.kit.edu/AirShowerPhysics)
- True community effort (support letters from 17 collaborations), led & coordinated by KIT

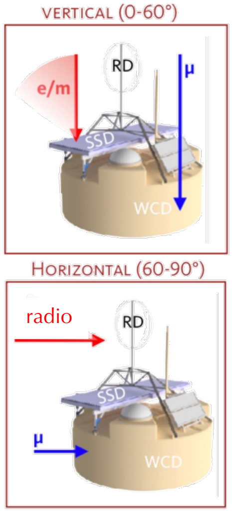
Status of the project:

- Updated models for hadronic & electromagnetic interactions to state of the art
- Added new use cases, such as cross-media showers and radio emission
- Many recent improvements (e.g. Cherenkov-light calculation, photohadronic int., photo-effect, multiple scattering, thinning, FLUKA, …)
- Extensive validation against CORSIKA 7 (found bugs in C7 …)
- First “physics-complete” release planned in 2023

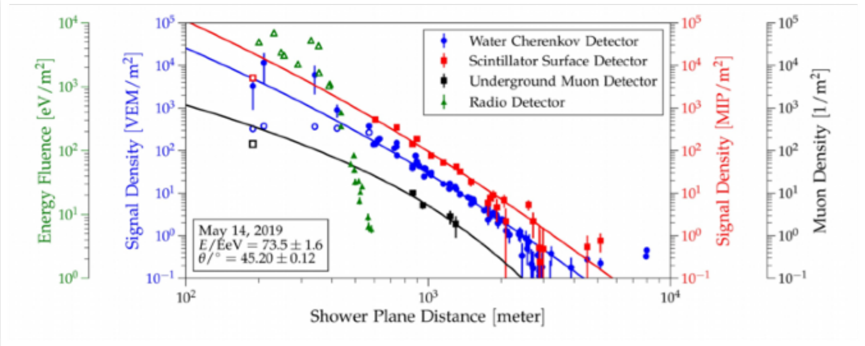
Karlsruhe workshop, June 2023

AugerPrime

The upgrade (= phase II) of the Pierre Auger Observatory



Key goal: Event-by event primary mass information
- Composition-enhanced anisotropy studies
- Improved test of hadronic interactions



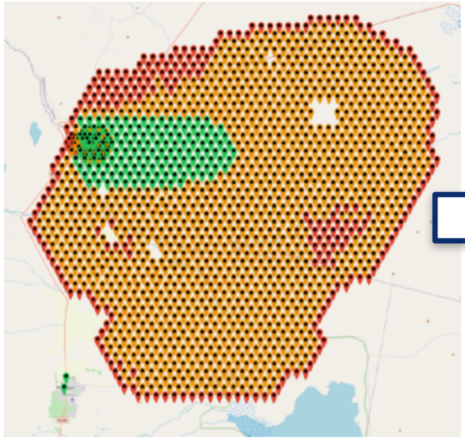
Water Cherenkov Detectors enhanced by
- Surface Scintillation Detector (SSD, <60°)
- Radio antenna (RD, inclined showers >60°)
- Small PMTs to increase dynamic range
- New electronics (faster, more channels)

Plus:
- Underground muon counting array
- Increased duty cycle of Fluorescence Detectors

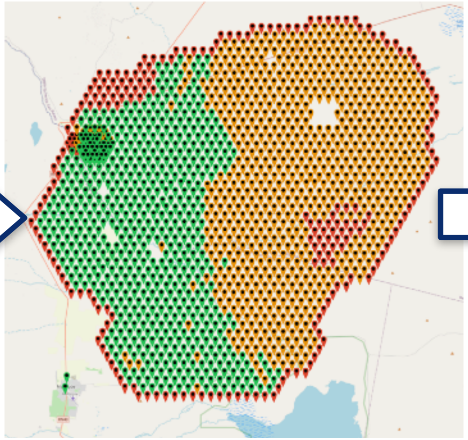
AugerPrime

Goal for Phase II: 8 years of operation starting in 2022/23

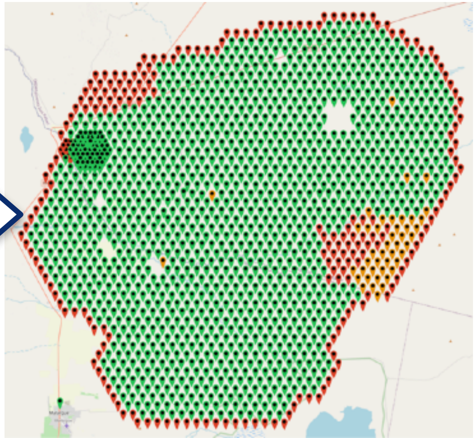
Status MU Days **2021**



Status MU Days **2022**



Status MU Days **2023**



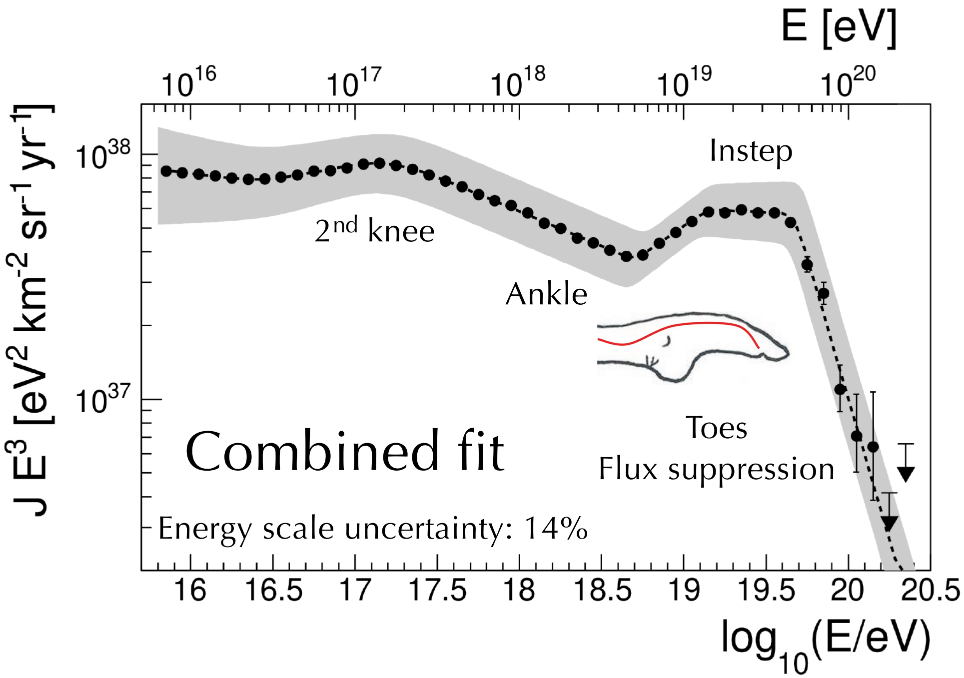
- 1436 stations with surface scintillators installed
- 1529 stations equipped with new electronics
- 40 radio antennas deployed

The cosmic-ray energy spectrum

… revealing new features:

- 2nd knee
- Ankle
- Instep (new!)
- Flux suppression

A. Aab et al., PRL 125, 121106 (2020)
A. Aab et al., PRD 102, 062005 (2020)
A. Aab et al., Eur. Phys. J. C81 (2021)
V. Novotny for the Pierre Auger Coll., ICRC 2021, #324

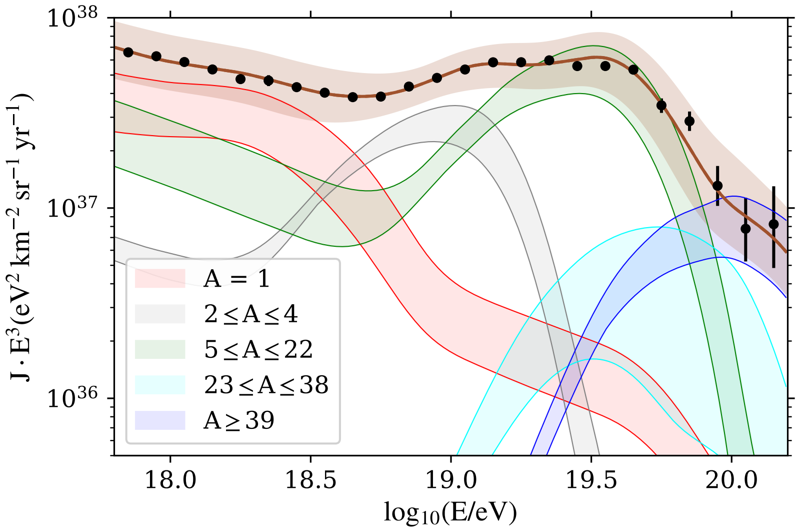


- AugerPrime (Phase II) will have TA-like detectors (SSDs) to mimic their detector response.
- Cross-check of energy estimates possible.

Combined energy spectrum and mass composition

What is the origin of ultra-high-energy cosmic rays?

Auger Coll., *JCAP* 05 (2023) 024



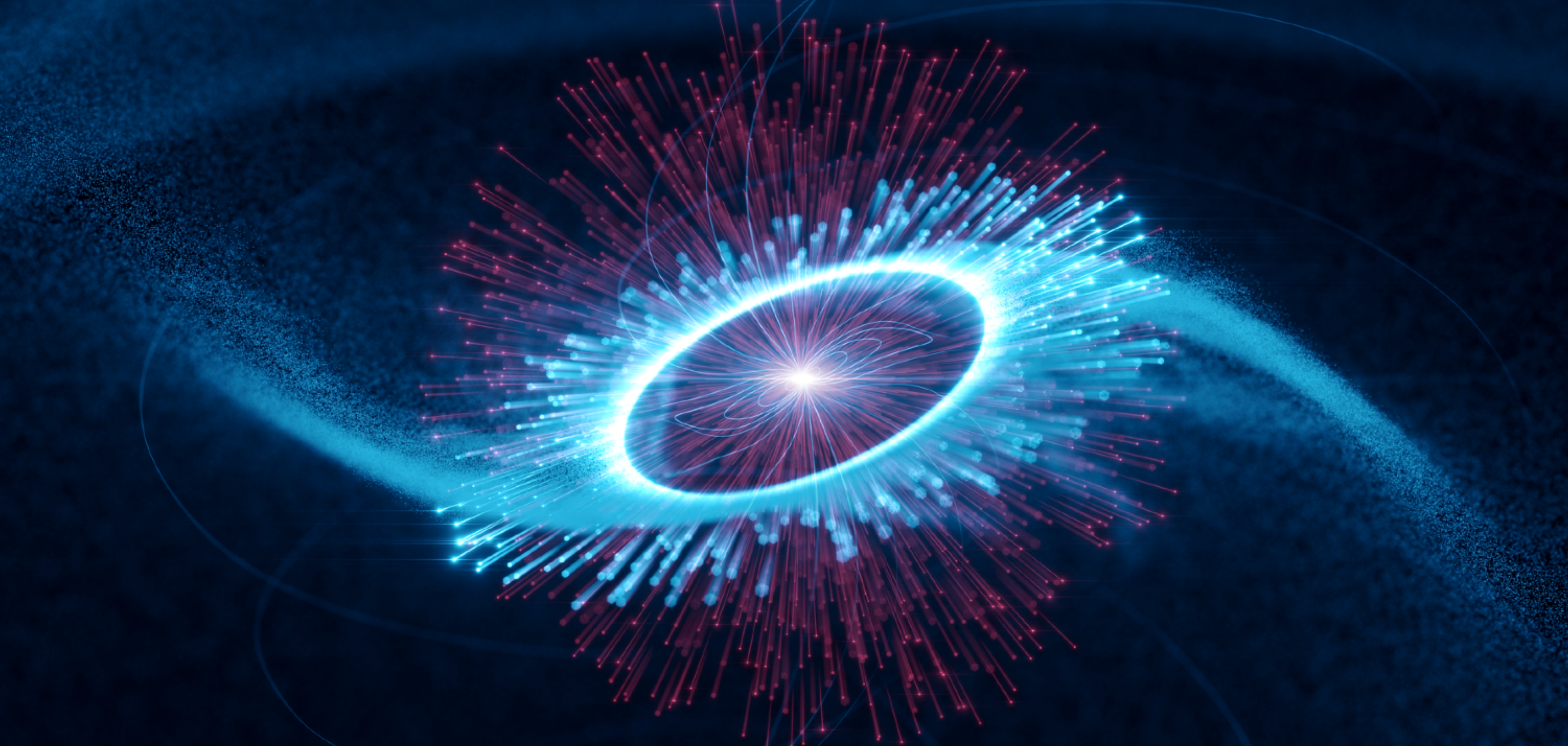
Extension of previous work to below the ankle.

A. Aab et al., PRL 125, 121106 (2020)
E. Guido for the Pierre Auger Collaboration, ICRC2021 #311

- Chance of significant proton fraction at highest energy appears dim.
- Similar work also including anisotropy under development.

▸ AugerPrime (Phase II) will have event-by-event primary mass information to help identify spectral features of different mass groups.

Gamma-ray Astronomy

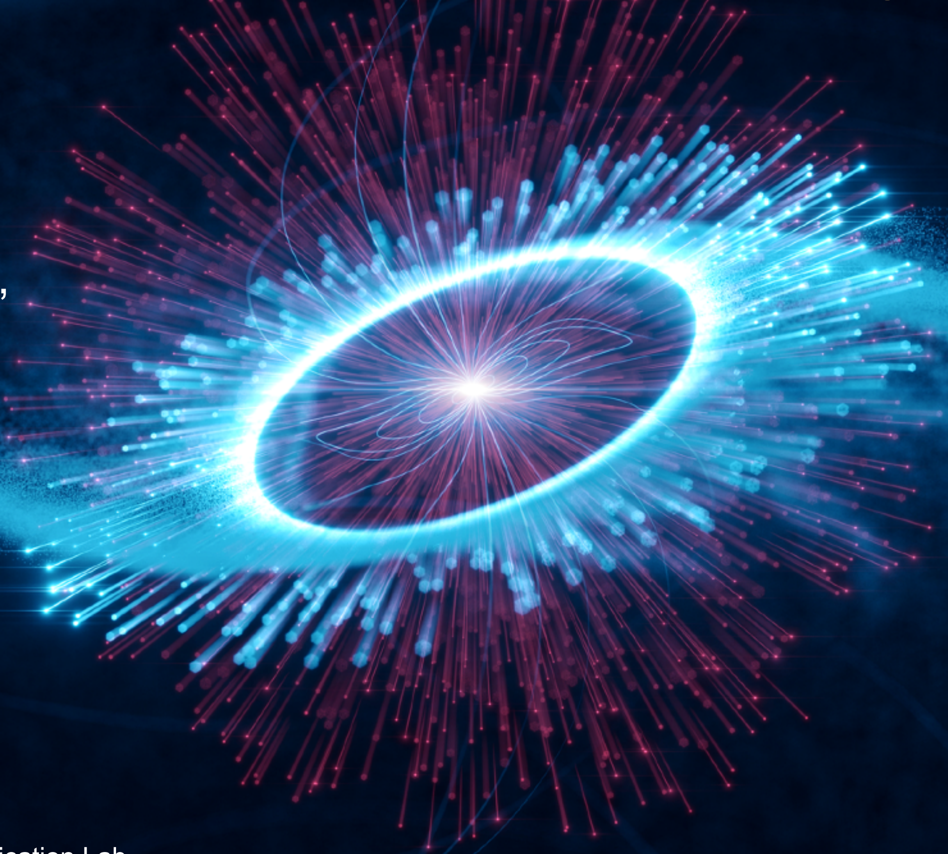


Gamma-ray Astronomy

Discovery of a radiation component from the Vela pulsar reaching 20 TeV

The Vela Pulsar, the brightest radio and GeV persistent source, holds a new record:

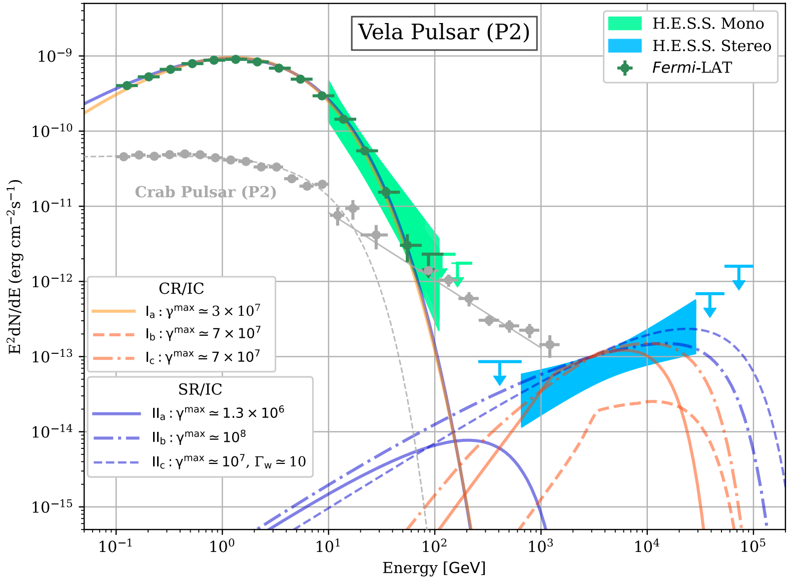
the first pulsar detected at 20 TeV with the H.E.S.S. telescopes



Gamma-ray Astronomy

Discovery of a radiation component from the Vela pulsar reaching 20 TeV

- The first proof of pulsed inverse Compton component in the TeV regime
- One of the hardest spectra detected in TeV range, powered by particles with Lorentz factors $\Gamma > 4 \times 10^7$
- The high energy requires emission regions beyond the pulsar magnetosphere!
  … but still keeping the light curve coherence: extended gaps or relativistic wind?
- Leads way towards a new understanding of pulsars

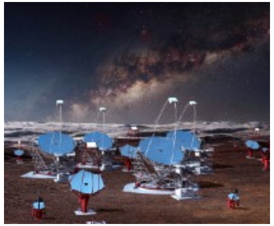


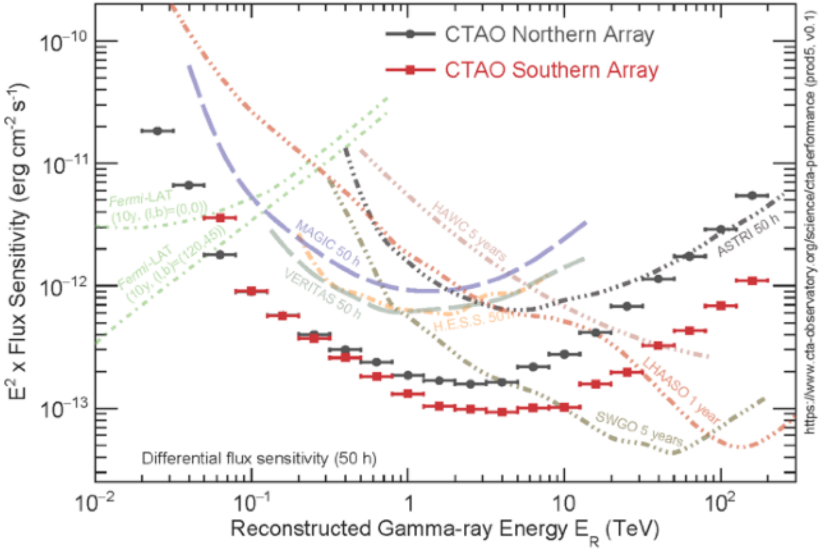
H. E. S. S. Collaboration et al., *Nature Astronomy, to appear 21.09.2023*

Gamma-ray Astronomy

CTA: The future global open observatory

cherenkov telescope array





- Science Data Management Center at DESY ready by Q3 2024
- Will host data and software services, user support and data access of CTAO

- CTAO construction start imminent
- Northern array in La Palma, Southern array in Paranal

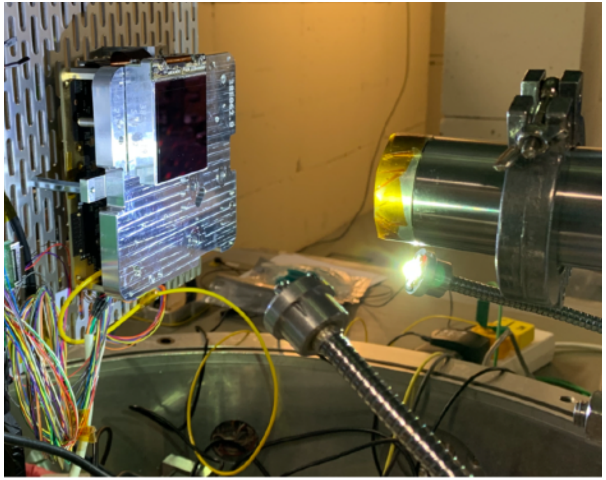
Ultraviolet Transient Astronomy Satellite

Key science goals: hot explosive transients*

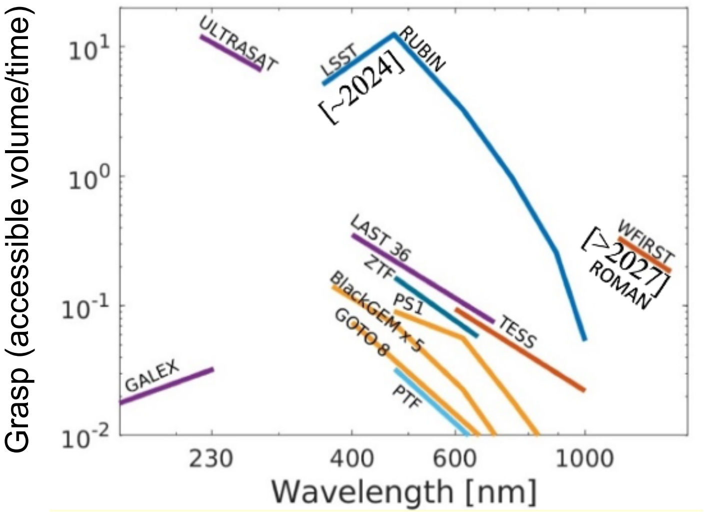
* Merging neutron stars, supernovae, GRBs, TDEs, AGN, etc etc

- Large 200 deg^2 field of view
- Transients published within < 30 min
- UV sensitivity 1.5 x 10^{-3} ph/cm^2 s (900s, 5σ), limiting magnitude m=22.4
- UV camera by DESY
- In orbit for O5 GW science run (2026-27)

Radiation test beam of UV sensor:

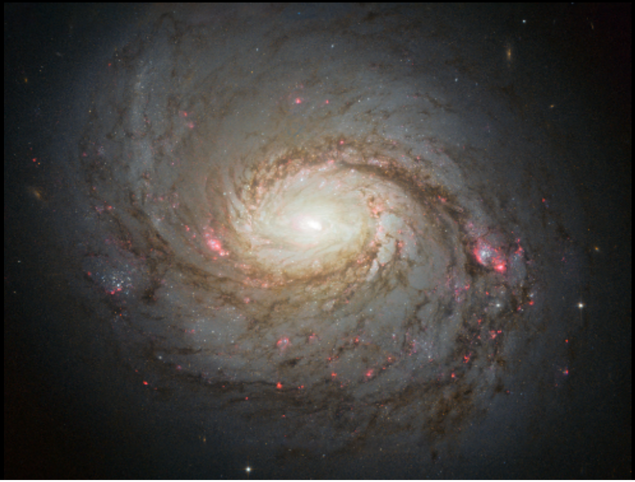


Transients detection rates of leading surveys:



Neutrino Astronomy

M77 seen by HTS
(NASA & ESA, A. van der Hoeven)

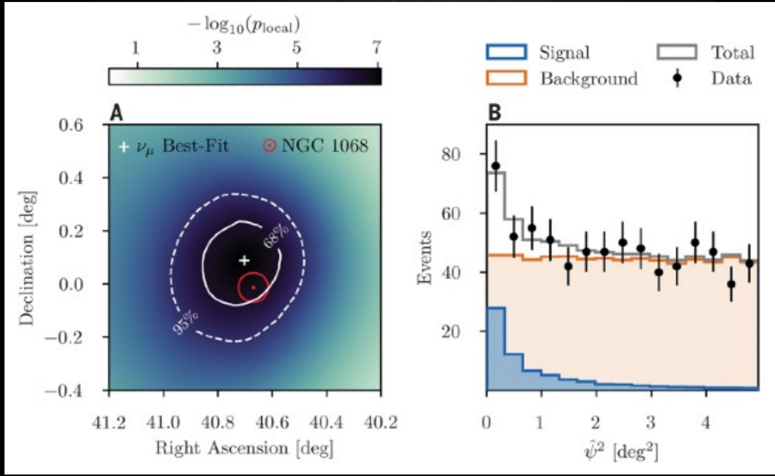



ASTRONOMY

Science

Neutrinos unveil hidden galactic activities

An obscured supermassive black hole may be producing high-energy cosmic neutrinos



- IceCube detects neutrino emission from nearby (d~43 mio. lightyears) active galaxy NGC 1068 (M77)
- Analysis of 10-year data set yields excess of 79^{+22}_{-20} neutrinos at TeV energies (4.2σ)
- Properties different from previously detected (flaring) AGN TXS 0506+056
  ➜ distinct source classes?

IceCube Collaboration, *Science* 378 (2022) 538

ASTRONOMY

Science

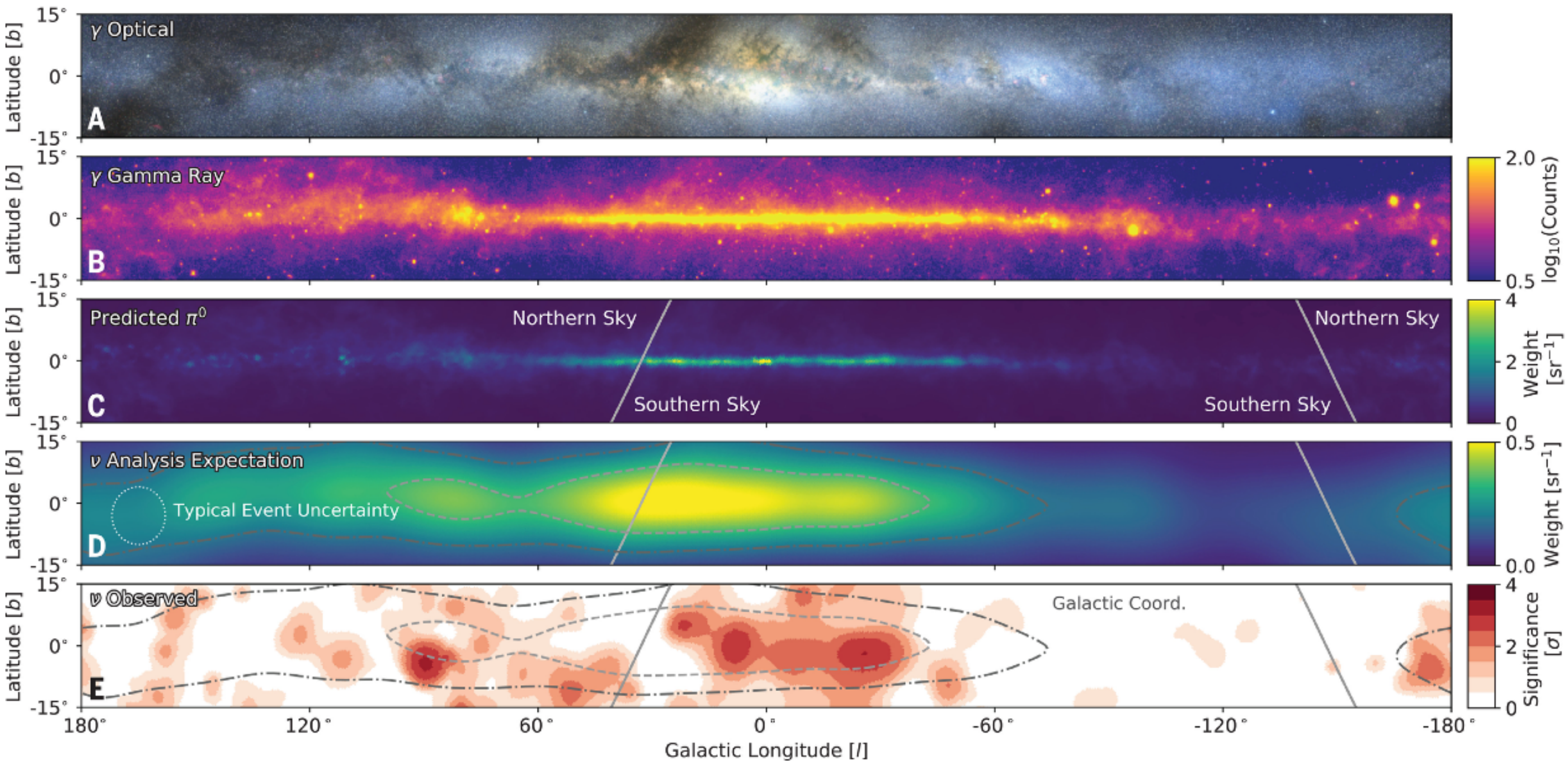
Galactic neutrinos in the Milky Way

A source of neutrinos may lie within the midplane of the Galaxy

- 60,000 neutrinos from 10 years of data
- Highly pure cascade event sample
- Advanced machine-learning reconstruction

IceCube Collaboration, *Science* 380 (2023) 1338

Milky Way in electromagnetic radiation … and in neutrinos!



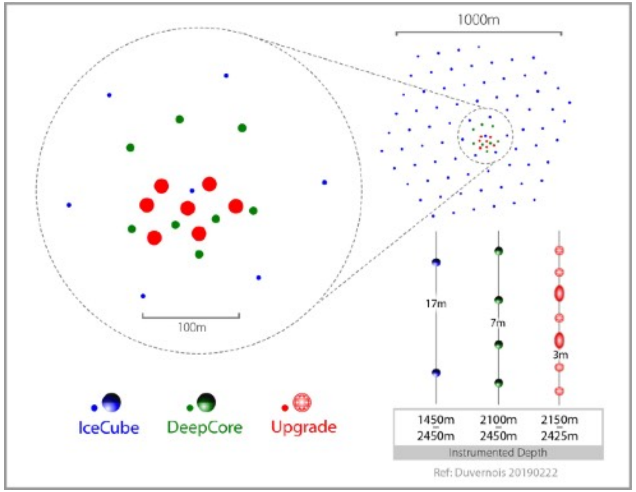
IceCube Collaboration, *Science* 380 (2023) 1338

IceCube Upgrade

Turning IceCube into a GeV neutrino detector

- **Seven new**, densely instrumented **strings** inside the DeepCore volume
  - Main sensor (mDOM) produced in a collaboration of German Universities with DESY and KIT

- **Surface Array Enhancement**
  - Plan 30 stations: each 8 scintillation detectors, 3 radio antennas and hybrid DAQ
  - Station 0 is at the Pole, taking valuable data; 6 more stations at Madison, ready for deployment; 5 stations assembled in summer 2023
- Covid-Delays: 5y-project (2019) → 8 years; drilling/deployment season 2025/26



Radio detection of neutrinos

RNO-G under construction

- A “small” project (for astroparticle physics): < 70 authors
- At least a factor of 10 improvement over existing experiments targeting EeV neutrinos
- Lead institutions: DESY, Penn State, Chicago, Brussels

Funding news:

- ERC Starting Grant for Anna Nelles (DESY, 2023 - 2028)
- US: NSF funding secured for remaining installation seasons

Experiment progress:

- Due to part shortages: 2023 calibration and maintenance season, no new stations
- On-going glaciological studies and reconstruction methodology
- Installation seasons on schedule for 2024, 2025, 2026 to complete array

Melting probe in field 2023 to study refractive index

2023 Ground penetrating radar for antenna positioning

KATRIN

Karlsruhe Tritium Neutrino experiment (KATRIN)

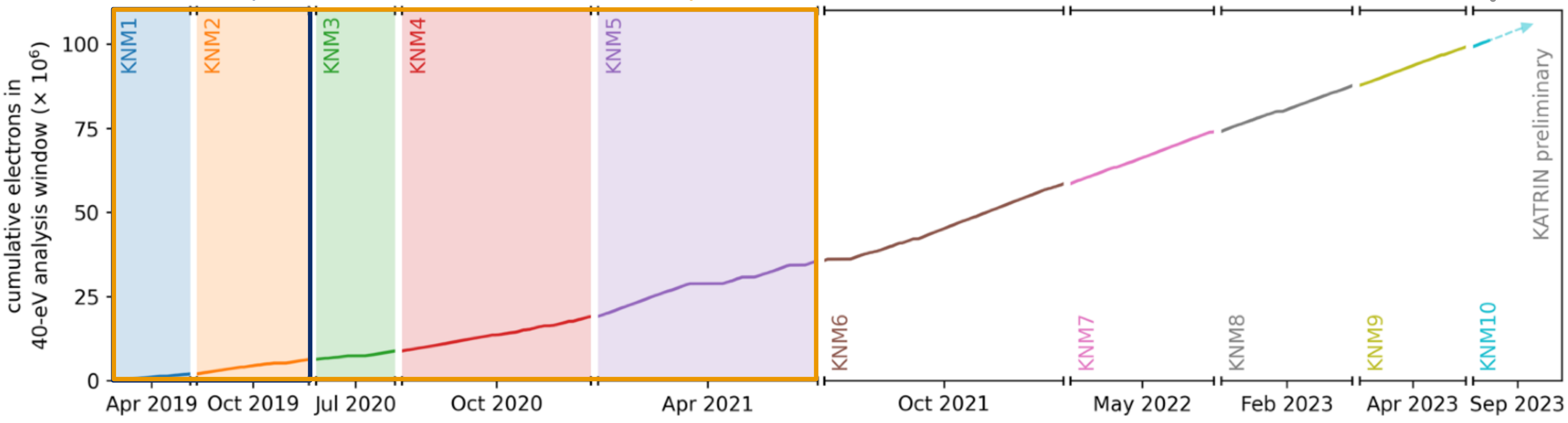
Karlsruhe Institute of Technology

Direct neutrino-mass measurement at endpoint of tritium β-spectrum

Now: best direct bound from runs 1 & 2
$m_\nu < 0.8$ eV (90% CL), Nat. Phys. 18 (2022) 160

Soon: Combination of runs 1-5
(20% of expected total data)
with sensitivity ~0.5 eV

Data-taking: approaching
100 million β-electrons



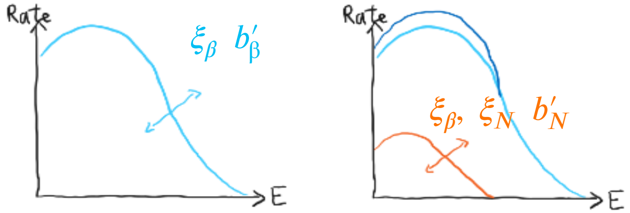
Karlsruhe Tritium Neutrino experiment (KATRIN)

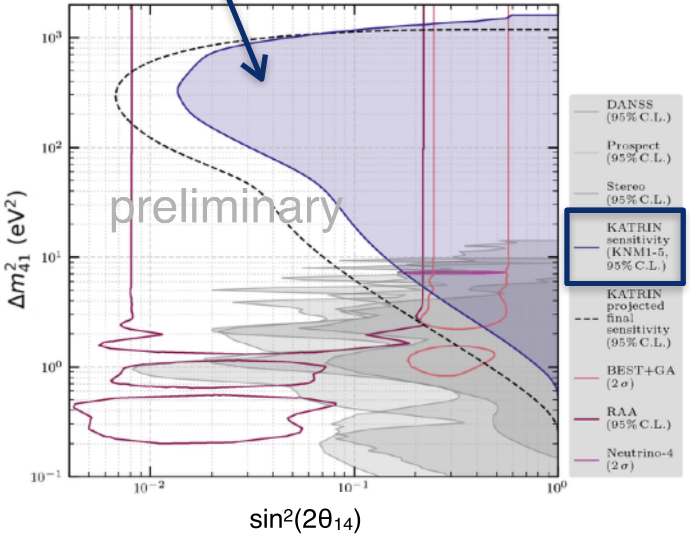
Physics program beyond the neutrino mass

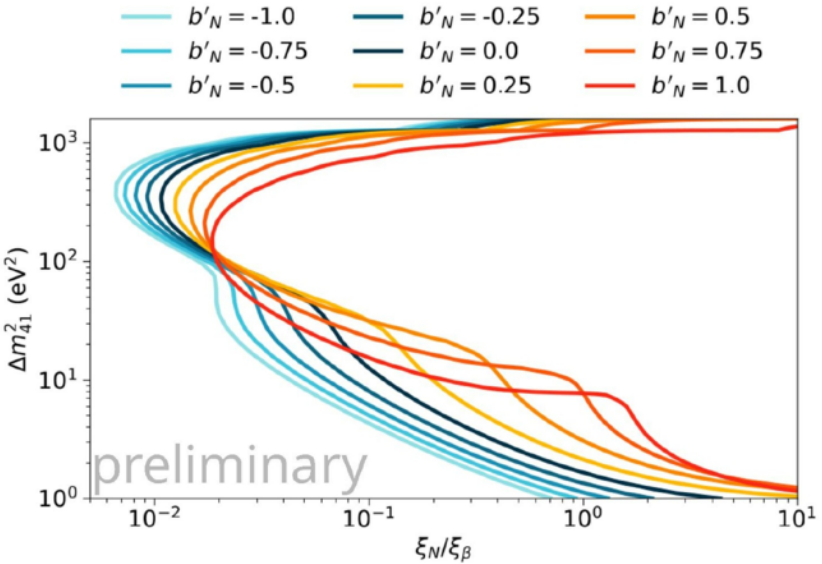
Many analyses under way:

- search for light extra bosons
- non-standard neutrino interactions
- update on local neutrino overdensities
- update on eV-scale sterile neutrino search, …

see parallel talk C. Fengler

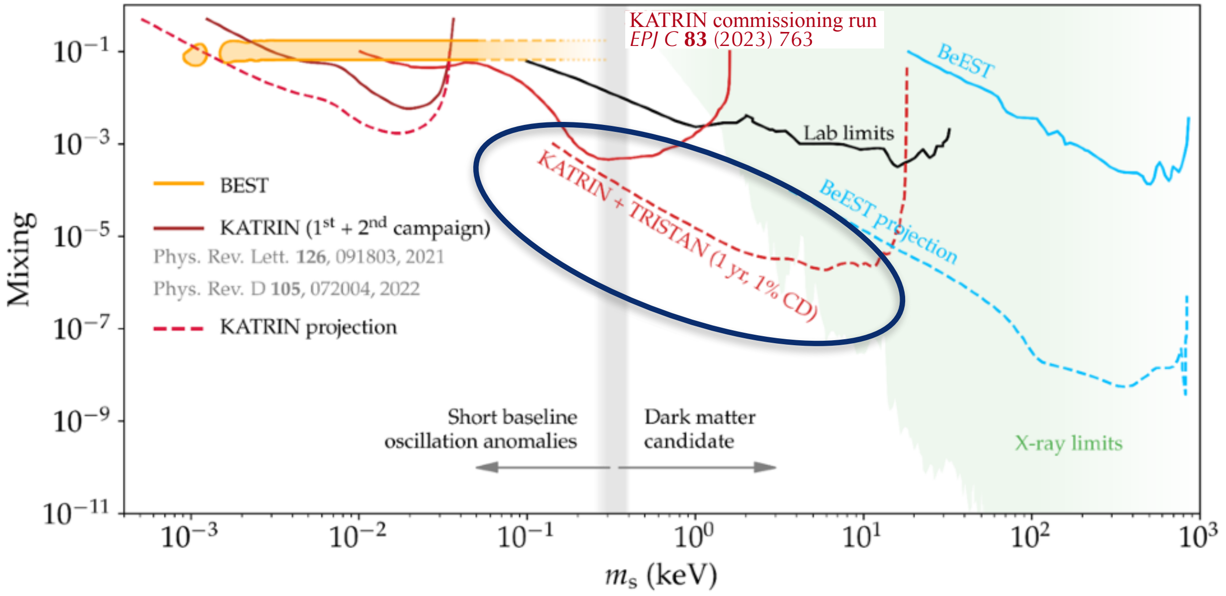




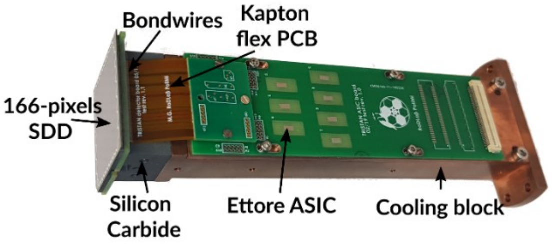


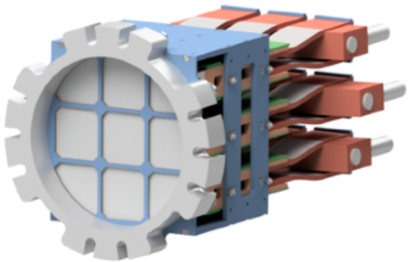
Karlsruhe Tritium Neutrino experiment (KATRIN)

Kinematics-based search for sterile neutrinos: eV to keV masses



Leading direct bounds on eV- and keV-scale steriles from KATRIN





Detector upgrade **"TRISTAN"**: ~1500-pix Silicon Drift Detector array prepared for beamline installation in 2026 → probe keV sterile ν at ppm mixing

Anniversary: 30 years of TLK

neutrino physics with tritium

novel source technologies

tritium interactions

fusion fuel cycle & blanket

tritium processing & analytics

tritium in industry

Dark Matter Search

© H. Schulze-Eißing, XENON Collaboration

The Search for WIMPs Continues

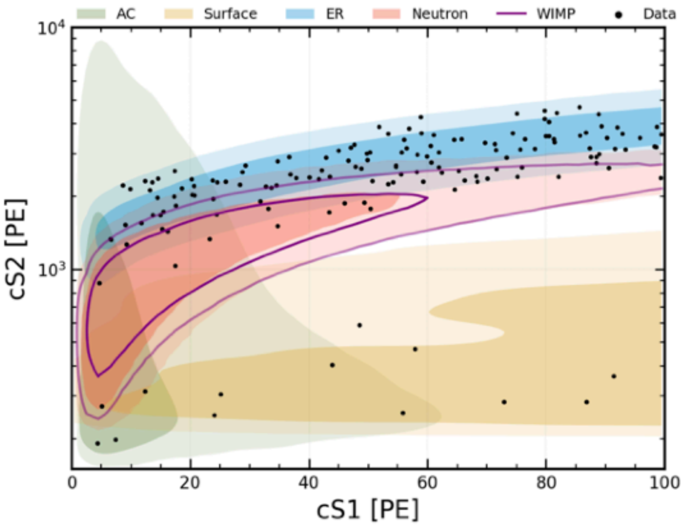
APS physics

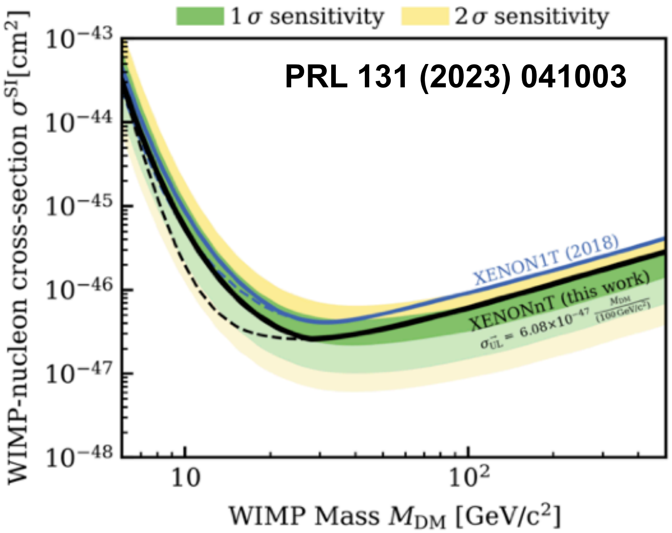
July 28, 2023 • *Physics* 16, s106

Two mammoth underground detectors have delivered more stringent upper limits on how strongly a putative dark matter candidate interacts with normal matter.

XENON

Karlsruhe Institute of Technology





XENONnT:

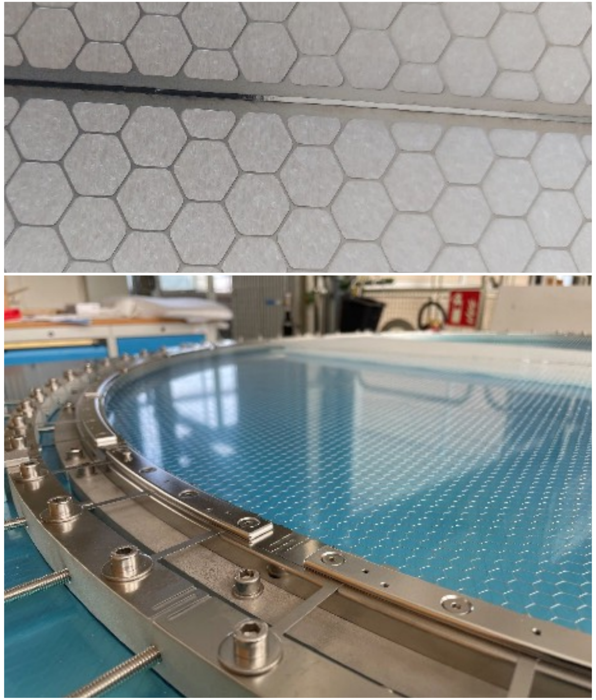
- First blinded WIMP dark matter search (SR0) with **1.1 t × yr** exposure
- More data acquired with **further reduced back-ground** through improved radon distillation
  ➜ analysis in progress

Physics harvest phase of detectors using ~10 tons of liquid xenon
➜ preparing for 40+ ton scale with DARWIN/XLZD

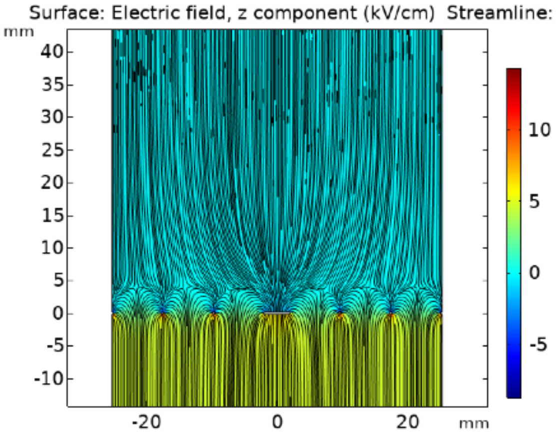
➜ See talk by Marc Schumann (Friday)

R&D for large high-voltage electrodes

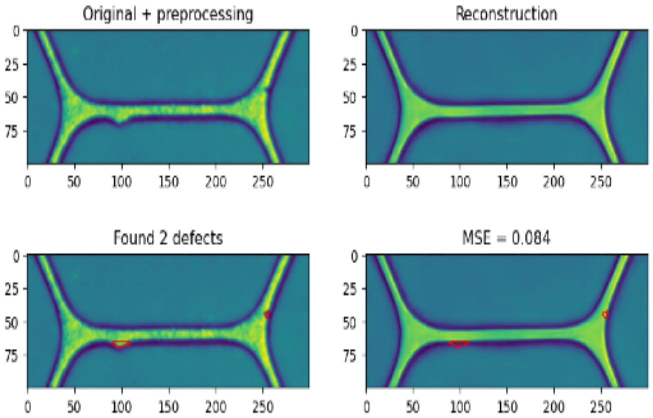
Laser welding (KIT-TEC) allows to construct mesh electrodes of large size



Field simulations show that welding effects are local



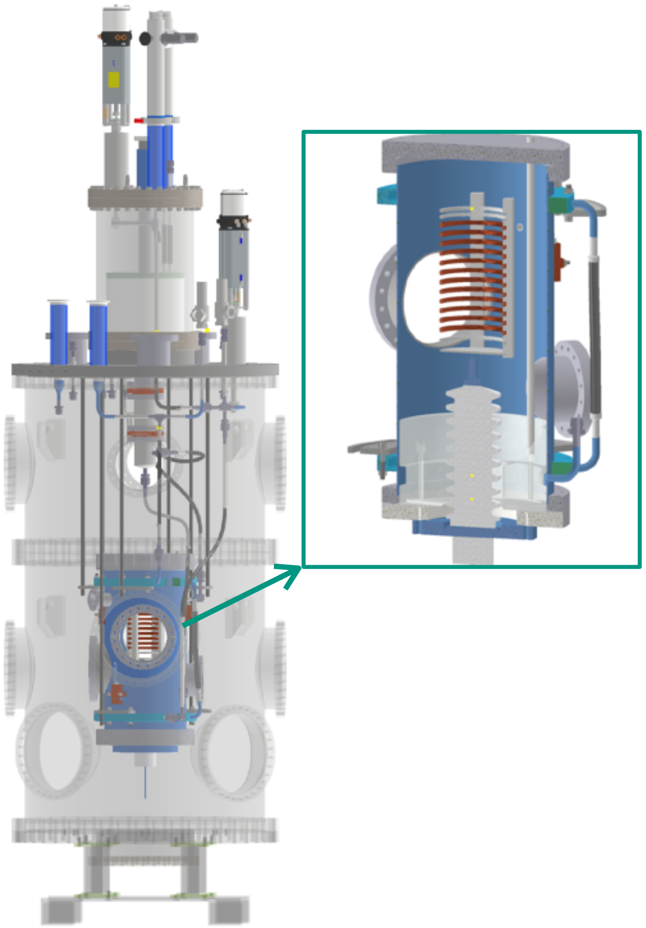
Automated search for mesh defect using machine learning



R&D for large high-voltage electrodes

Setup for high-voltage tests in liquid xenon

- Study of type of discharge: bubble streamers, cosmic rays, …
- Continuous monitoring of supplied current, purity of the xenon and thermodynamical parameters
- Camera + photosensors and liquid level control: fully functional dual-phase TPC
- Design for cryostat and gas systems completed, detector design on-going

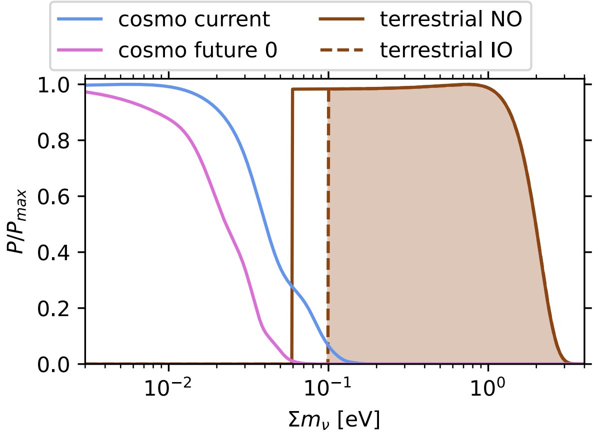


Theory

image found on wallpapersafari.com

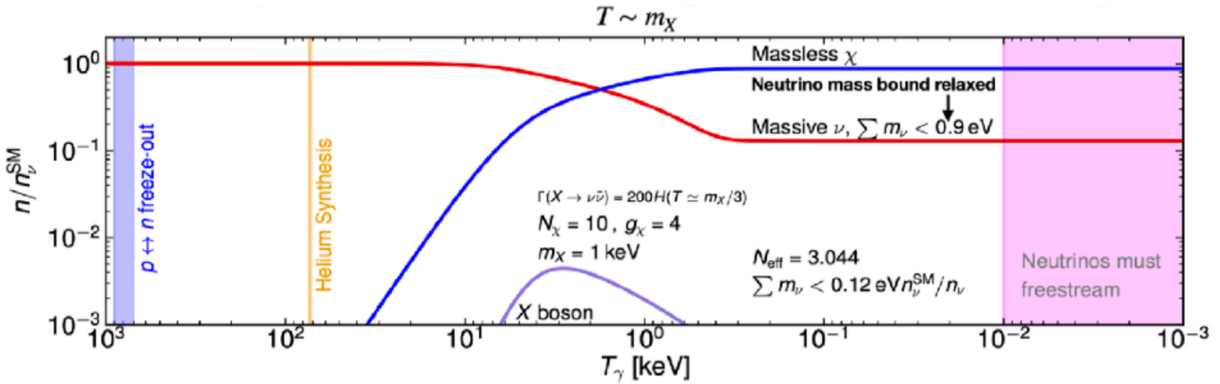
Neutrino mass — terrestrial vs. cosmological bounds

Determination of neutrino mass ordering from cosmology & oscillation / cosmo tension:



Gariazzo et al., *JCAP* (2022) [2205.02195]
Gariazzo, Mena, Schwetz, *Phys. Dark Univ.* (2023) [2302.14159]

How to make „large“ neutrino mass (within KATRIN sensitivity) consistent with cosmology?



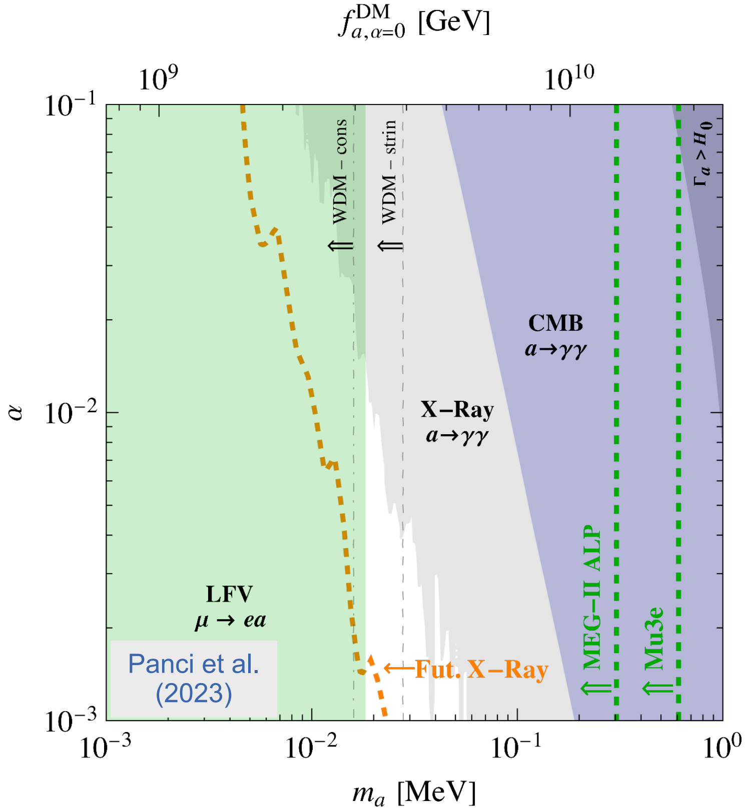
Escudero, Schwetz, Terol-Calvo, *JHEP* (2023) [2211.01729]

Dark Matter and Axions

- Search for scalar induced gravitational waves in the International Pulsar Timing Array Data Release 2 and NANOgrav 12.5 years dataset [Dandoy, Domcke, Rompineve, 2302.07901]

see parallel talk V. Dandoy

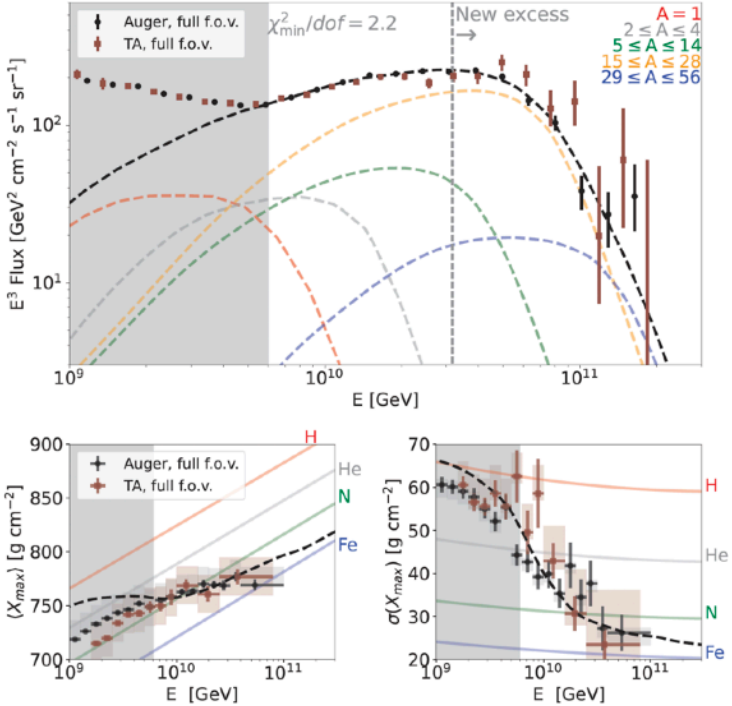
- Axion Dark Matter from lepton flavor-violating decays: testing the DM production mechanism with LFV experiments [Panci, Redigolo, Schwetz, Ziegler, Phys. Lett. B 841 (2023) 137919]

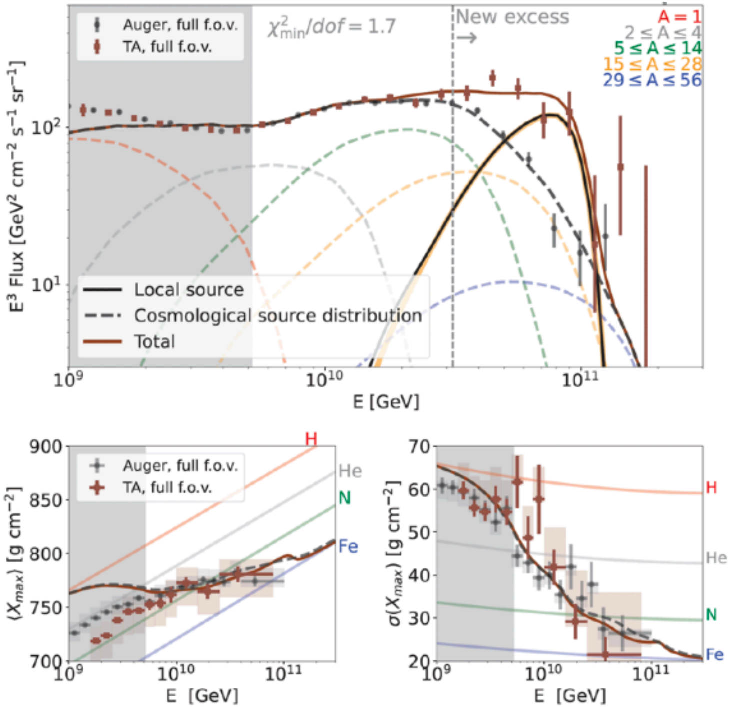


Interpretation of UHECR data

Is the long-standing discrepancy between PAO and TA data an astrophysical or a systematic effect?

Special energy-dependent systematics vs. **Local astrophysical source (D < 23 Mpc)**

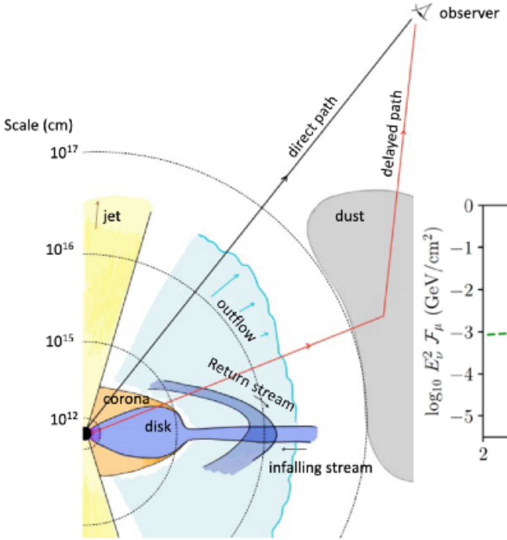


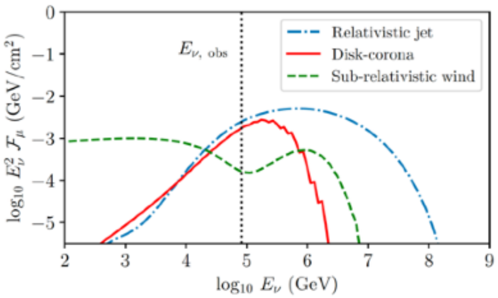


Plotko, van Vliet, Rodrigues, Winter, *Astrophys. J. 953* (2023) 2, 129

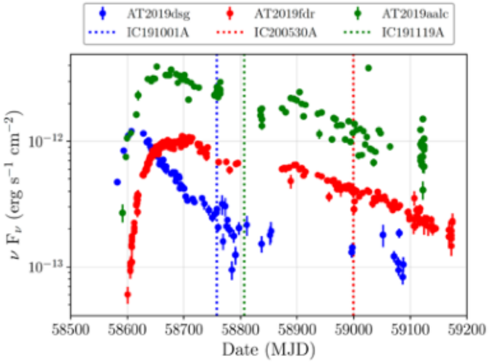
Multi-messenger mission from Tidal Disruption Events

Model computations in support of an experimental discovery paper for AT2019fdr:

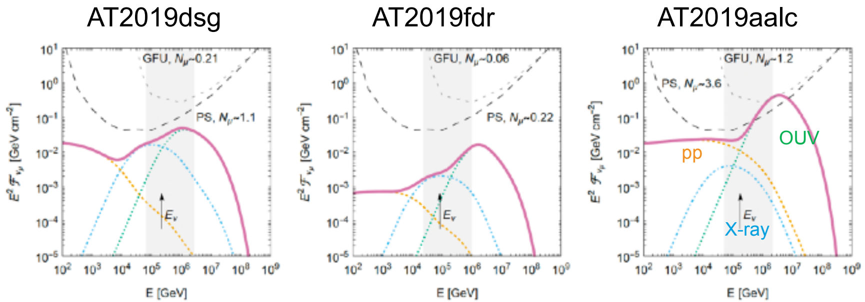




Comparison of neutrino emission from three TDEs:



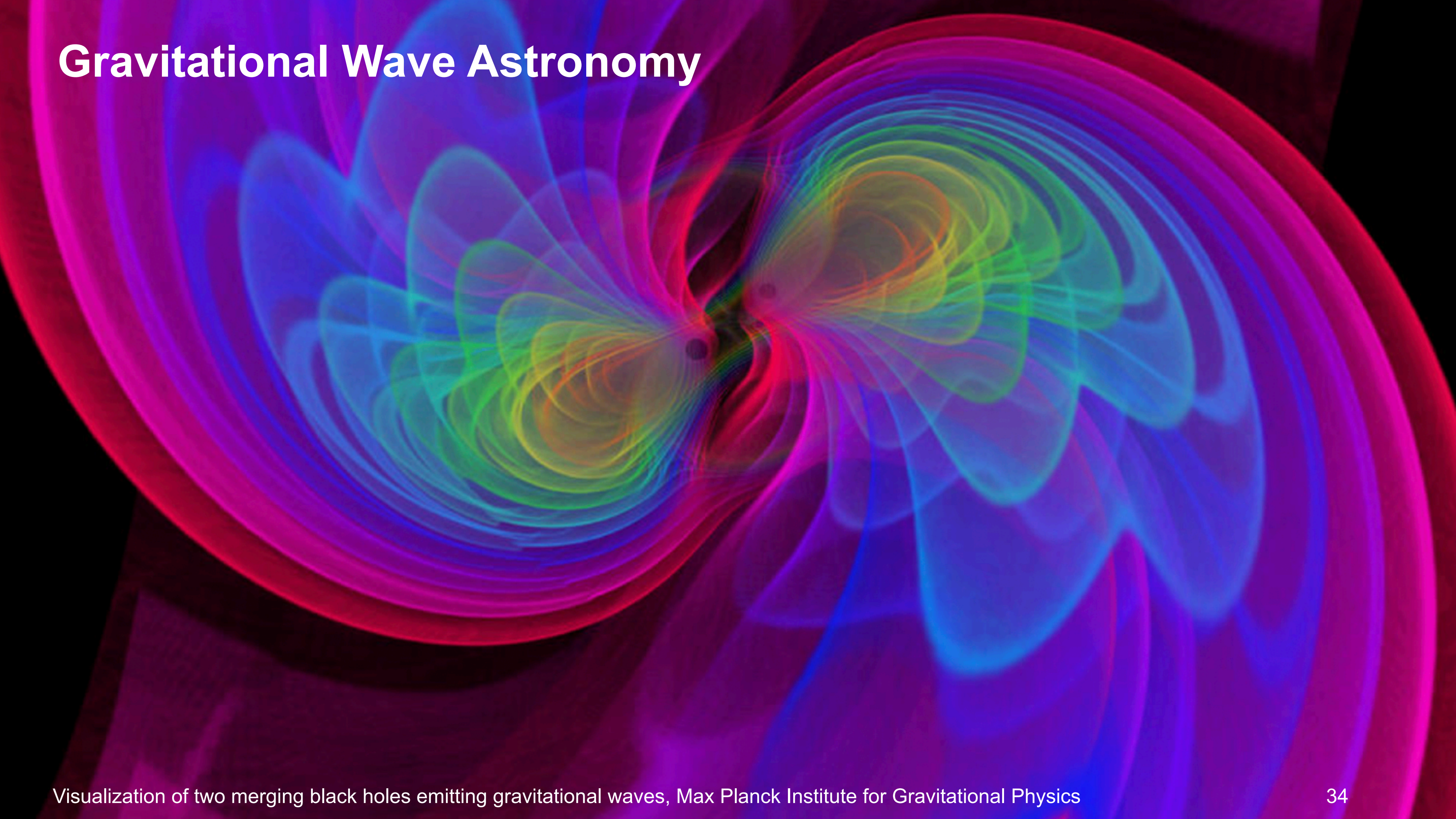
Simeon Reusch @ ECRS 2022



Reusch, Kowalski, Winter, et al., *PRL 128* (2022) 22

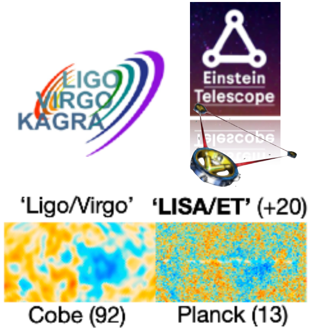
Winter, Lunardini, *Astrophys. J. 948* (2023) 1, 42 / Model M-OVU

Gravitational Wave Astronomy

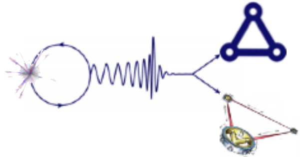


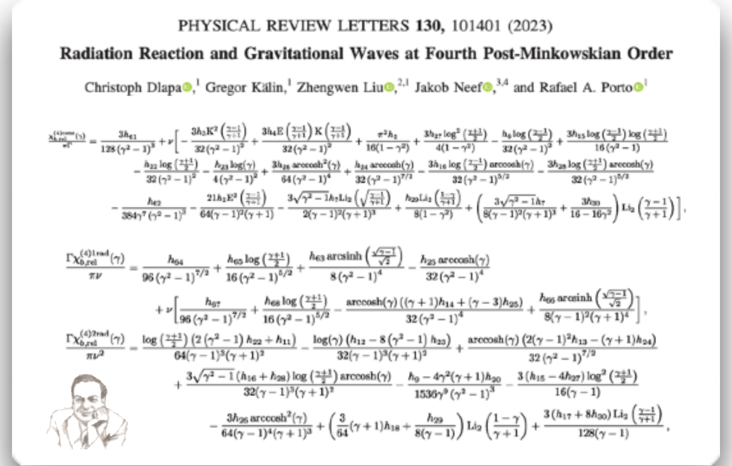
Visualization of two merging black holes emitting gravitational waves, Max Planck Institute for Gravitational Physics

Gravitational Wave Astronomy



- Discovery potential: GW experiments on ground and in space require more accurate waveform models: new theoretical challenges and opportunities.
- Transfer of methods from collider physics to GW science
  ERC project R. Porto: "LHC to LISA *and ET*"



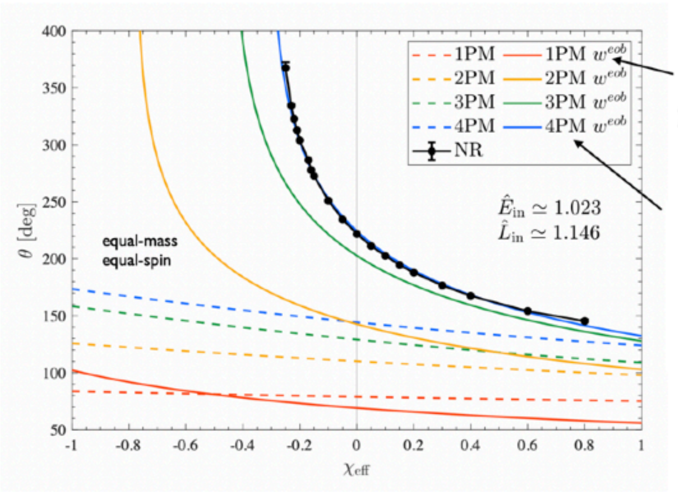


PHYSICAL REVIEW LETTERS **130**, 101401 (2023)

Radiation Reaction and Gravitational Waves at Fourth Post-Minkowskian Order

Christoph Dlapa,[1] Gregor Kälin,[1] Zhengwen Liu,[2,1] Jakob Neef,[3,4] and Rafael A. Porto[1]

(Rettegno, Pratten, Thomas, Schmidt & Damour 23)



$w^{\rm EOB}$ is similar to the resummation à la Firsov.
(Kälin & Porto 20; Dlapa, Kälin, Liu & Porto 23)

Best fit with Numerical Relativity to date!

Gravitational Wave Astronomy

Towards the Einstein Telescope

- Cryogenic design for cooling mirrors
  - Novel He II cooling; different ET interferometer designs
- Seismic evaluation of candidate sites
  - Coordination of seismic measurements in Lusatia
  - Lead author of ET site comparison paper
  - Funding support by DZA starting June 2023
- ETpathfinder vacuum system slow control
  - Design of slow control based on KATRIN experience
  - Setup of vacuum pumps at KIT for tests
- Multi-messenger analysis GW data and IceCube
- Gitlab mirror of global GW network

Cooperation with
EU Interreg project
ETpathfinder (Maastricht)

At KIT: several institutes
ITTR/IBPT, IGP, ITEP,
ETP, IAP, SCC

German Center for Astrophysics (DZA)

PROJECT PHASE (2023-2026):

Project funding by BMBF through TU Dresden and DESY/ Zeuthen

⇒ If site good, then enter the bid for ET site

⇒ Low Seismic Lab for diverse (GW and also EM astronomy related) research

first hires (5 profs, 60 staff and support)

"FULL FUNDING" PHASE (2026 ONGOING):

Buildings and underground lab construction, full ramp-up of personnel and research & science

- DZA will conduct technology development for gravitational wave astronomy and in particular for ET

2023 – 1
- Hasinger and his team start in Görlitz in rented rooms on the Kahlenbaum Areal. The DZA project is implemented at the TU Dresden.

2024 – 2
- The appointments of 5 professorships at TU Dresden are underway, the first research groups are starting.

2026 – 3
- We found the association DZA e.V. The administration is in place. We have temporary space for all employees. Plans for the construction of the campus on the Kahlbaum site, the data centre in Görlitz and the Low Seismic Lab in Lusatia have been completed.


Warum die Astrophysiker nach Görlitz wollen

Günther Hasinger ist Professor für Astrophysik und will ein Großforschungszentrum aufbauen. Ob es gelingt, steht noch in den Sternen.

Unterstützt durch:

Thank You!

MATTER AND THE UNIVERSE

This presentation was built with input from many people, including:

M. Ackermann
D. Berge
K. Eitel
A. Haungs
T. Huege
M. Kowalski
A. Nelles
E. de Oña Wilhelmi
M. Pohl
R. Porto
M. Roth
M. Schlösser
Th. Schwetz
W. Schubotz
M. Steidl
A. Taylor
W. Winter

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Find out more in the talks … and posters!

A. Elykov
T. Mukherjee
F. Toschi
J. Saffer
S. Mohanty
S. Untereiner
F. Ellwanger
V. Wu
Ch. Schäfer
L. Busch
N. Kovac
S. Hahn
M. Venugopal
R. Größle
N. Karasthatis
Th. Thümmler
S. Balan
F. Pompa
L. Gülzow
P. Plotko
L. Hasselmann
J. Köhler