HELMHOLTZ

RESEARCH FOR
GRAND CHALLENGES

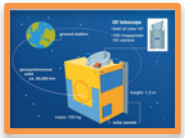
Matter and Radiation from the Universe

Highlights

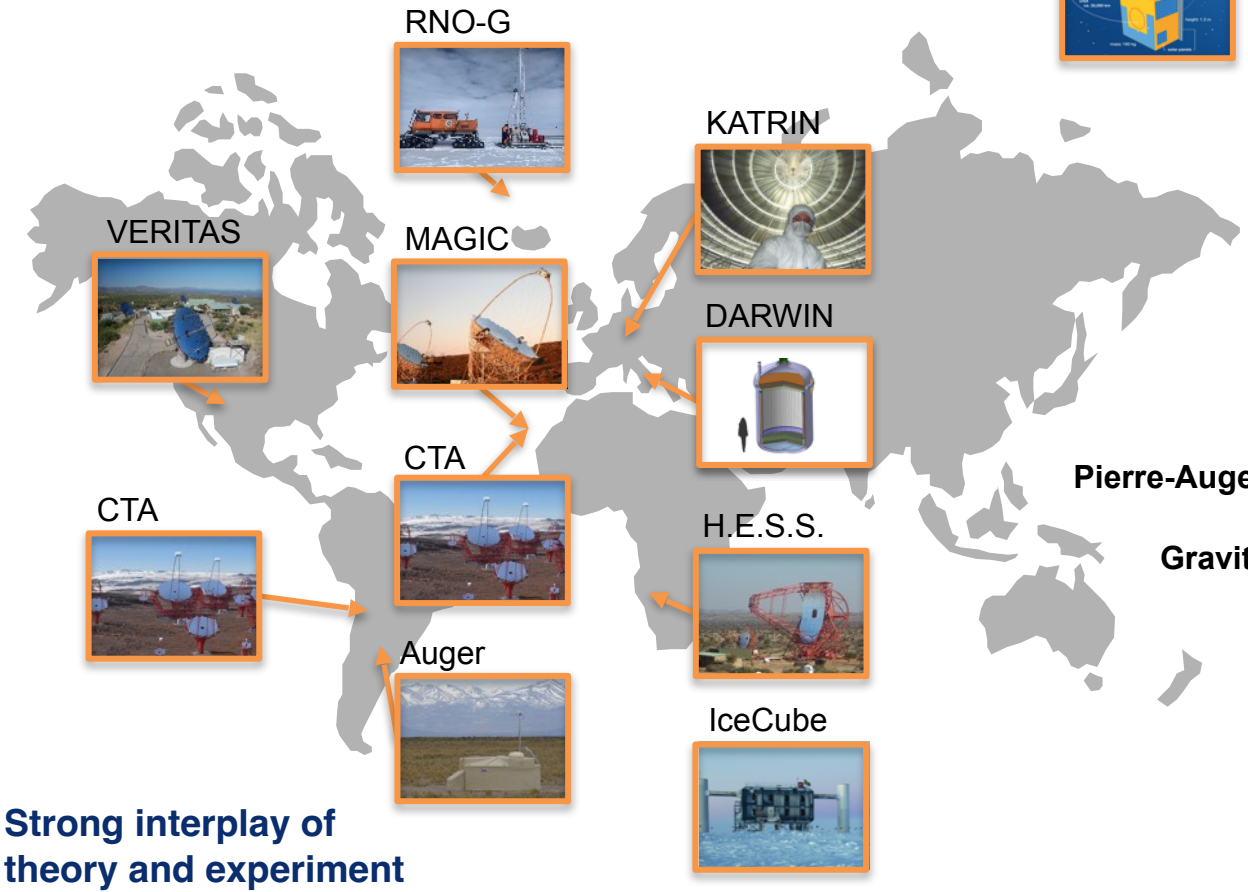
Kathrin Valerius & Christian Stegmann

MU Days, Oct. 20-21, 2022

Research program in a nutshell



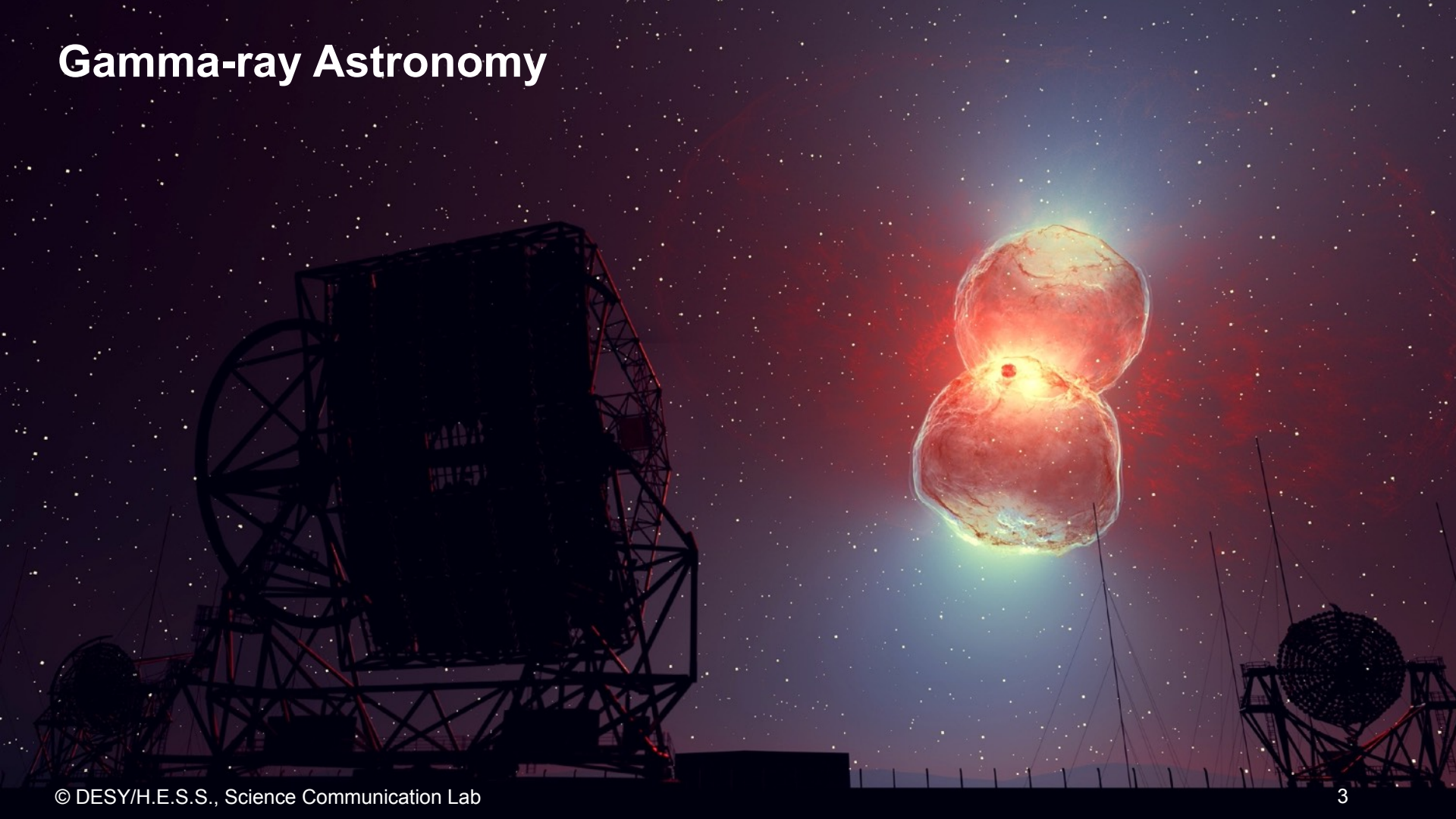
ULTRASAT



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

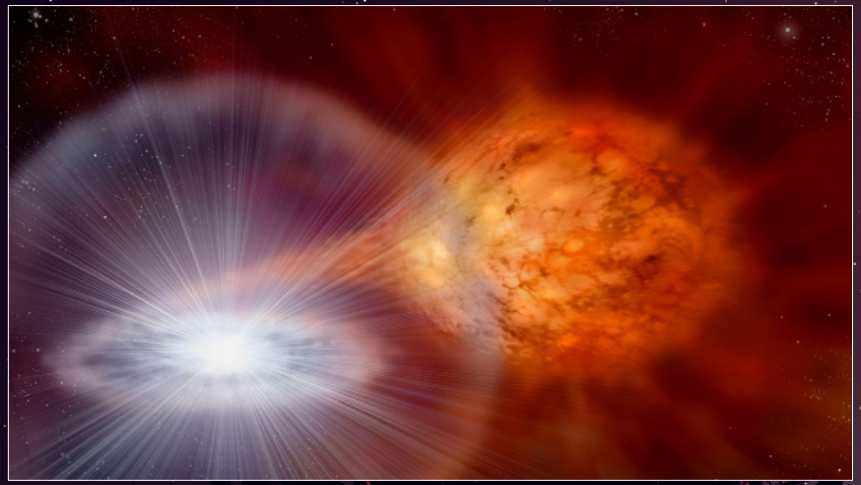
Strong interplay of theory and experiment

Gamma-ray Astronomy



Gamma-ray Astronomy

Efficient particle acceleration in a recurrent nova



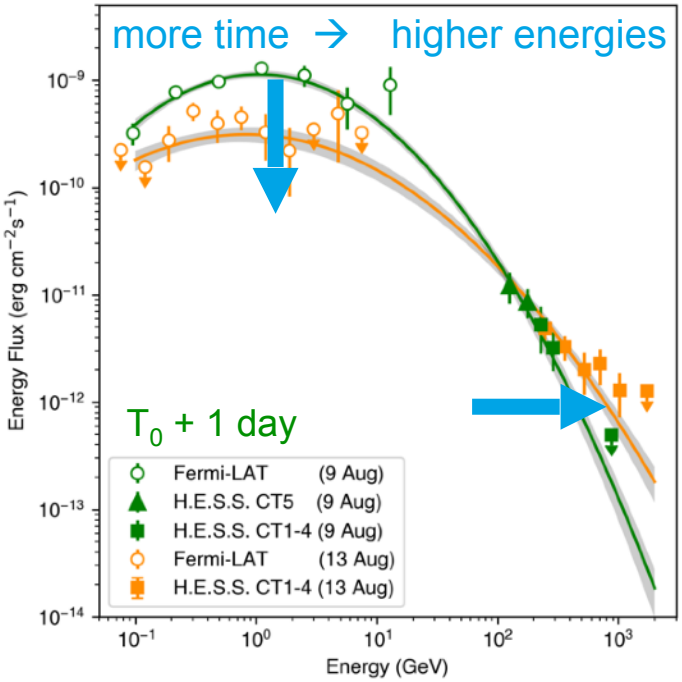
RS Ophiuchi: White Dwarf matter accretion leads to recurrent nova from thermo-nuclear explosion every 9-26 years

H. E. S. S. Collaboration et al., Science 376, 6588, 77-80, 2022

Gamma-ray Astronomy

Efficient particle acceleration in a recurrent nova

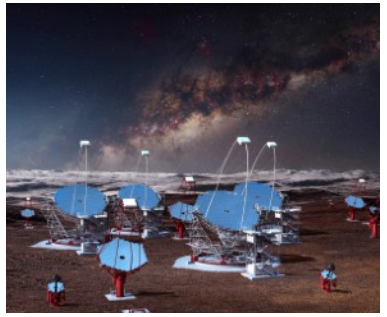
- 2021: Discovery of VHE gamma rays (> 100 GeV) with H.E.S.S.
- Observation of acceleration over time scale of a month
- Spectral evolution with time points to cosmic hadron (not lepton) accelerator
- Particle acceleration at theoretical limit in astrophysical shocks, support for supernova remnant paradigm of cosmic rays



H. E. S. S. Collaboration et al., Science 376, 6588, 77-80, 2022

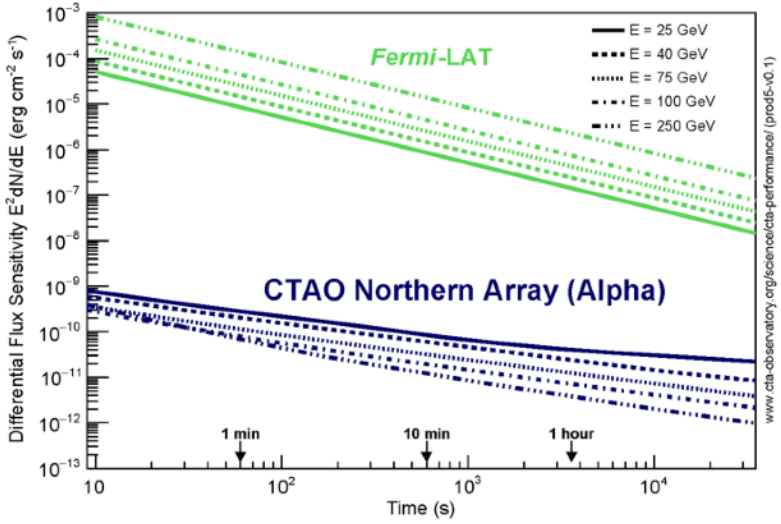
Gamma-ray Astronomy

CTA: The future global open observatory



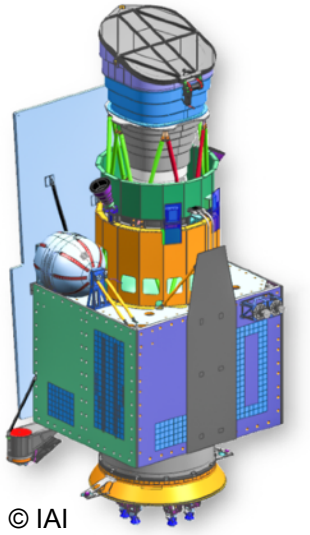
- La Palma (N) and Paranal (S), 5-year construction to start in 2023
- The funded Alpha Configuration meets many of the original requirements
- Low-energy extension of Southern array recently funded (Corona recovery funds, Italy)

- Science Data Management Center under construction at DESY Zeuthen (from 2024 on: up to 30 persons)
- SDMC hosts data and software services of CTA and will provide user support and data access



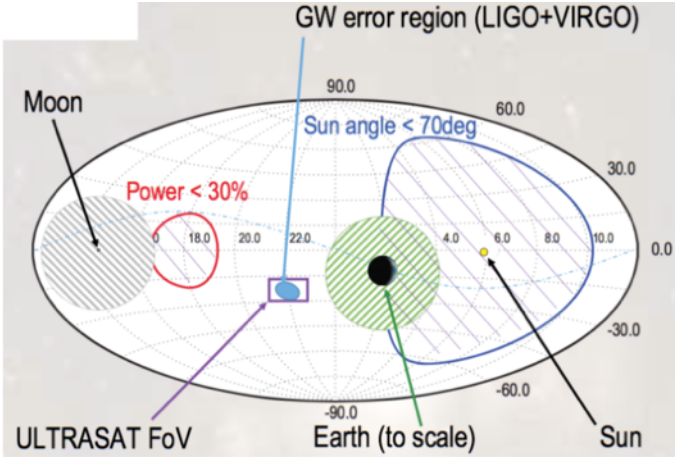
Ultraviolet Transient Astronomy Satellite

Exploring the dynamic ultraviolet sky



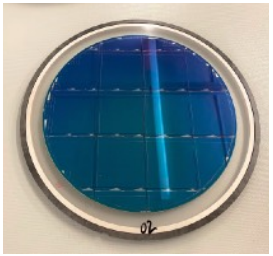
© IAI

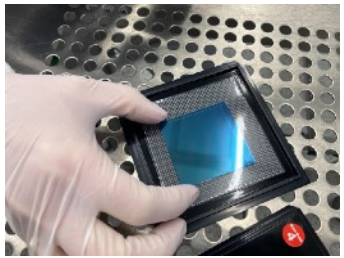
- 200 deg² field of view
- 5 min transients published within < 30 min
- Mission by Israel Space Agency, Weizmann Institute, DESY (camera) and NASA (launch)
- In orbit for O5 of LIGO-VIRGO-KAGRA (2025)

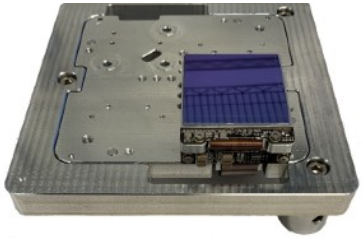


See > 50% of the sky at any time, rapid localisation of NS mergers and SNe for alerts

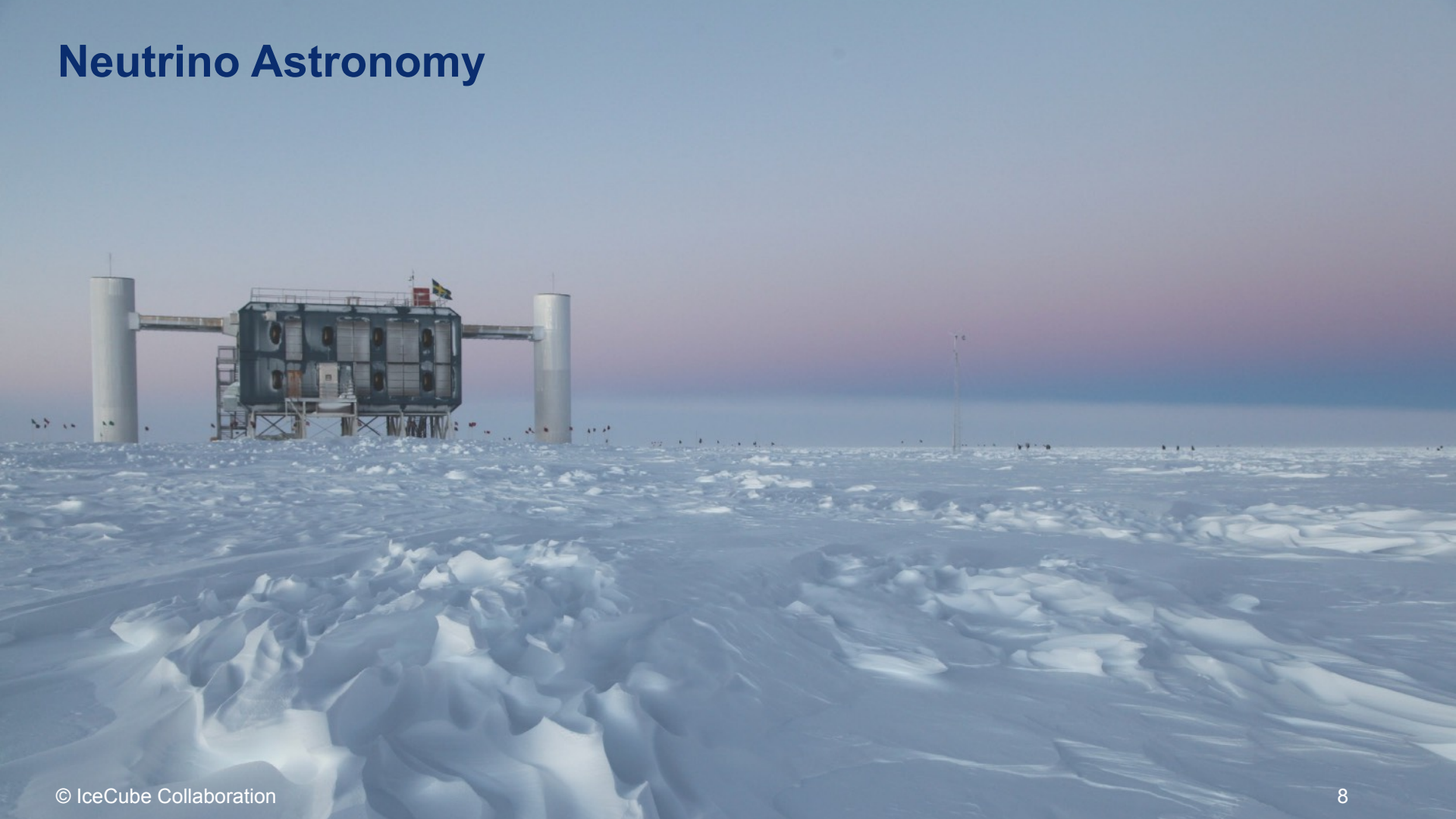
UV sensors ULTRASAT camera:







Neutrino Astronomy



IceCube & Multimessenger Astronomy

Highlight: Tidal Disruption Events (TDEs)

Candidate Tidal Disruption Event AT2019fdr Coincident with a High-Energy Neutrino

Reusch et al., PRL 128 (2022) 221101

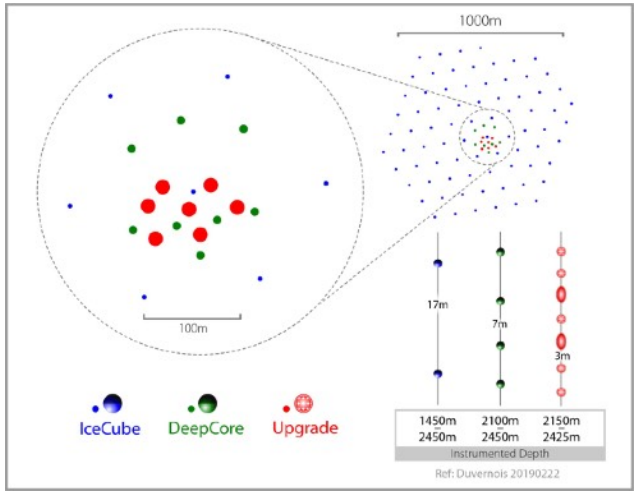
- **Recap:** First TDE discovered in coincidence with an IceCube neutrino *(Stein et al., Nature Astronomy, 2021)*.
- **Now:** Second TDE in coincidence with a high-energy neutrino ➜ data from **IceCube & Zwicky Transient Facility** (ZTF), along with **AMPEL** multi-messenger framework operated at DESY.
- Close collaboration between theory and experiment (see MU Days 2021).

IceCube Upgrade

Extending the GeV neutrino physics programme

- Seven new, densely instrumented strings inside the DeepCore volume:
  - GeV neutrino physics (unitarity of PMNS matrix, search for sterile neutrinos, neutrino mass ordering)
  - Improved calibration for re-analysis of 10+ years of IceCube data
  - R&D for IceCube-Gen2
- Field seasons 2020/21, 21/22, and 22/23 canceled due to COVID, but the project has been successfully re-baselined for deployment in 2025/26.
  - Main sensor (mDOM) now being produced in a collaboration of German Universities with DESY and KIT.

See talk by **Summer Blot** (Fri)



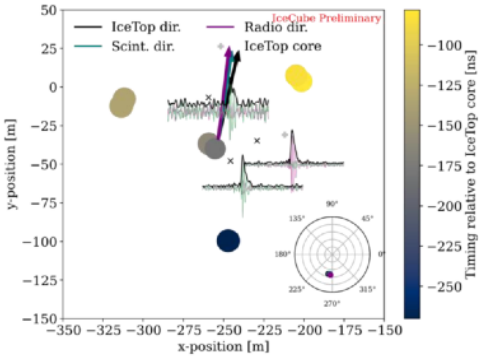
IceCube surface instrumentation

Enhancing IceTop with hybrid stations of scintillation detectors and radio antennas

Goals:

- Improve cosmic ray physics (0.1 PeV – 1 EeV)
- Calibrate IceCube and improve veto capabilities
- Test hadronic interaction models
- R&D surface array for IceCube-Gen2

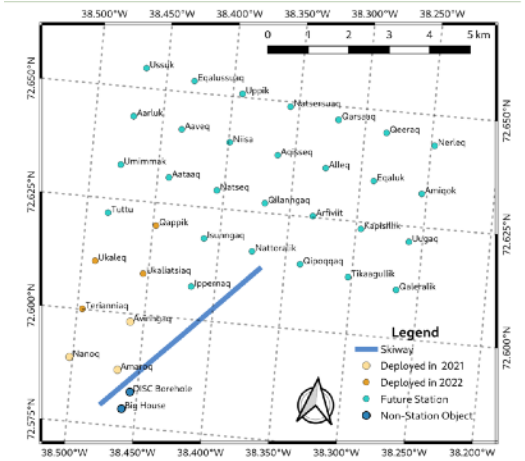
- Plan 30 stations: each 8 scintillation detectors, 3 radio antennas and hybrid DAQ
- Fully funded; one third now produced
- First station in operation at South Pole, 6 further stations are on site
- Due to COVID delays we installed one station at the Pierre Auger Observatory in Argentina and one station at the Telescope Array in Utah, US.



Radio Neutrino Detection

RNO-G - now already the world's largest neutrino detector

- A "small" project (for astroparticle physics): < 70 authors
- Lead institutions: U Chicago, DESY, VU Brussels
- Pathfinder mission for IceCube-Gen2



Progress as of now:

- Second installation season just finished, 7 stations (of 35) running
- 2 stations equipped with wind-turbines, very promising, success will add 35% more live time
- Hardware availability will determine schedule for 2023 and onwards, 35 stations anticipated for 2025
- Factor 10 sensitivity gain over current instruments!

RNO-G will have the sensitivity to detect high-energy neutrinos at ~10^{18} eV

Cosmic Rays

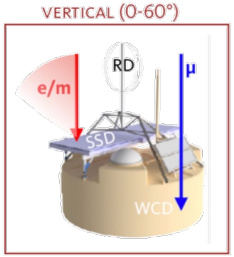
CORSIKA 8 – the next-generation simulation framework

Complete rewrite of CORSIKA in modern C++

- Community effort coordinated by KIT
  - ~35 on-site participants at recent workshop
  - for details see GitLab webpage
- Many milestones have been reached, such as
  - full hadronic and electromagnetic cascades
  - radio-emission simulation
  - Cherenkov-light simulation
  - cross-media showers
  - multi-threaded simulations
- Experts are very welcome to join us already now, first beta release ideally before ICRC2023

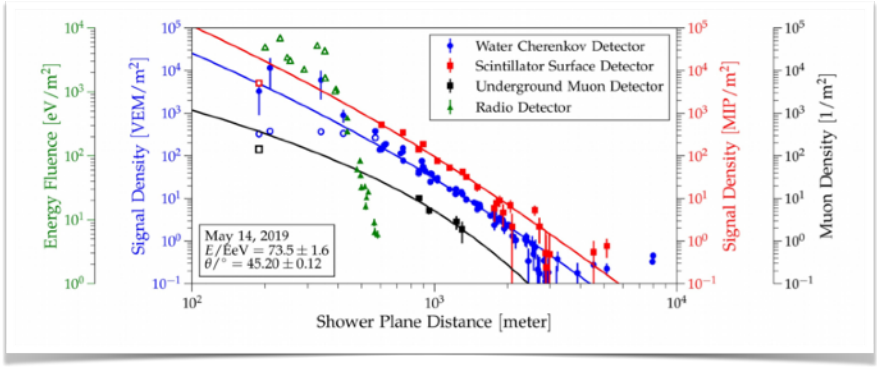
AugerPrime

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)

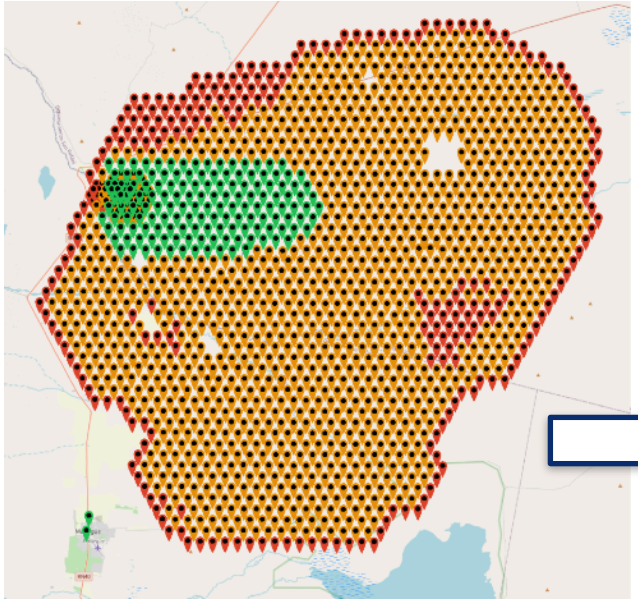
Plus:

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

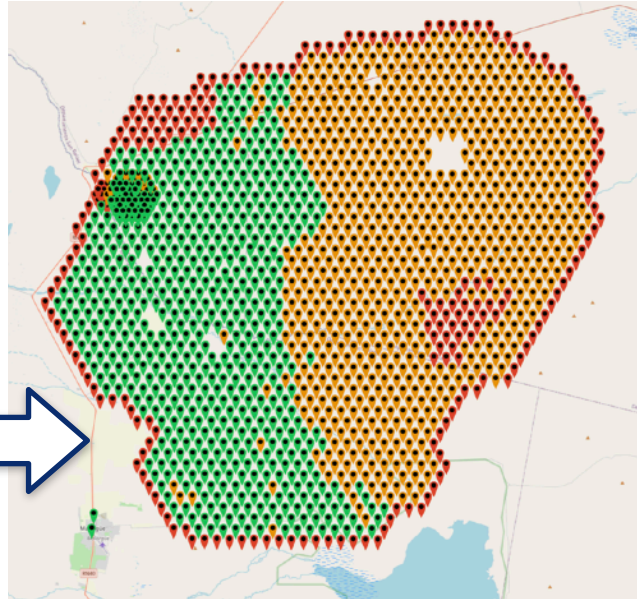
AugerPrime

Goal: 8 years of operation starting in 2022/23

Status MU Days **2021**



Status MU Days **2022**



Legend:

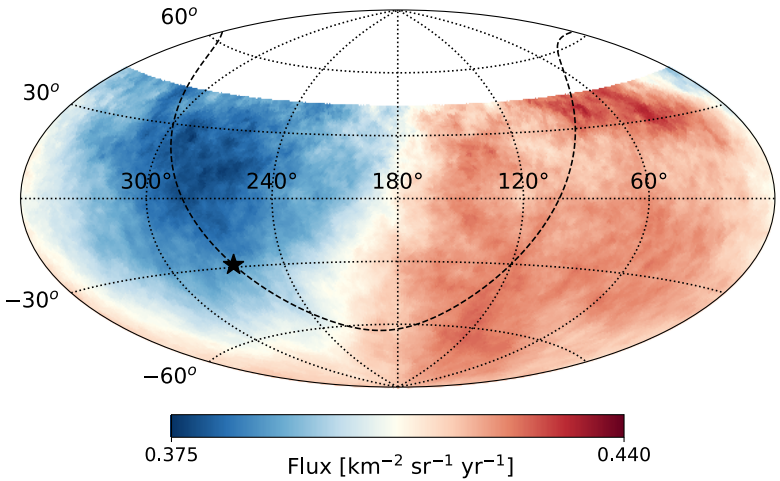
Scintillator deployed
+ acquiring data

Radio array *(not shown)*:
full 3000 km^2
(1660 antennas)
to be completed in 2023

Anisotropies

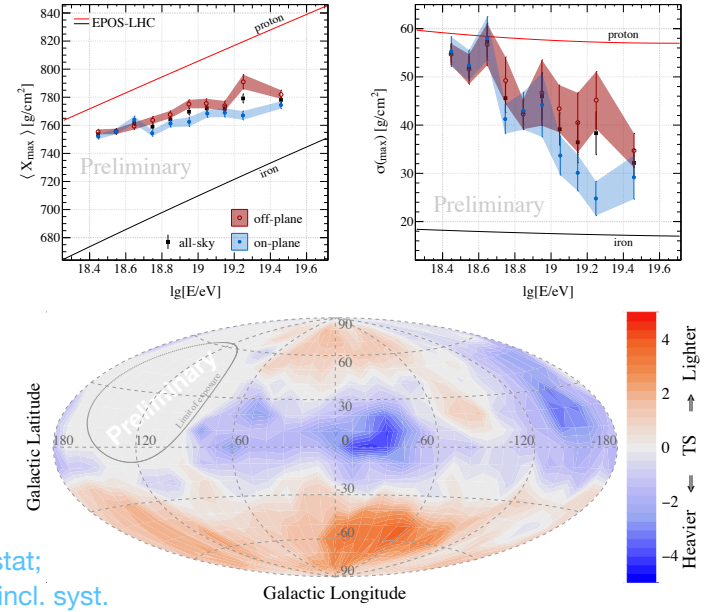
E. Mayotte for the Pierre Auger Collaboration, ICRC 2021 #321
Paper to be submitted to JCAP

Dipolar anisotropy at 6.6 σ (E > 8 EeV)



- Increase of the dipole amplitude as function of energy. No evidence for quadrupolar structure.
- Dipole structure remains centered in same region.
- Location of the dipole is consistent with mixed composition deflected by galactic magnetic fields.

Composition-enhanced anisotropy using FD data



4,9σ stat;
3.3.σ incl. syst.

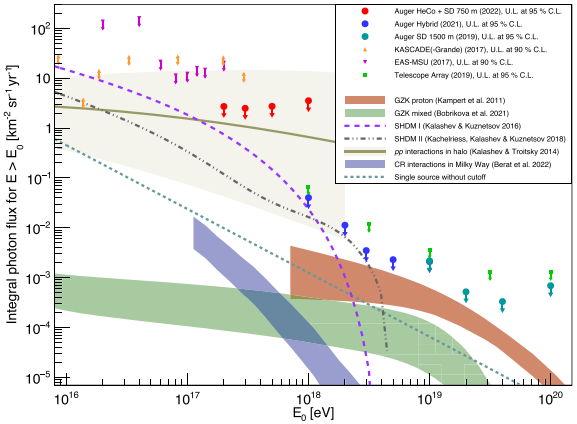
- Indication of lighter composition far from galactic plane (|b|>30°).
- Interpretation is likely complex. Local source distribution, mass-dependent horizons, propagation effects may all play a role.

Photons and neutrinos and super heavy Dark Matter

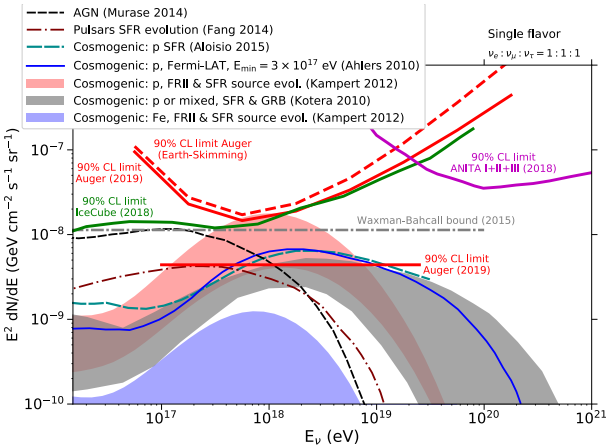
Auger is also a UHE photon and neutrino detector, placing competitive limits

- Unambiguous detection of one UHE photon or neutrino can be a game changer
- Photon and neutrino limits strongly constrain pure proton models in particular
- SHDM limits derived from photon limits

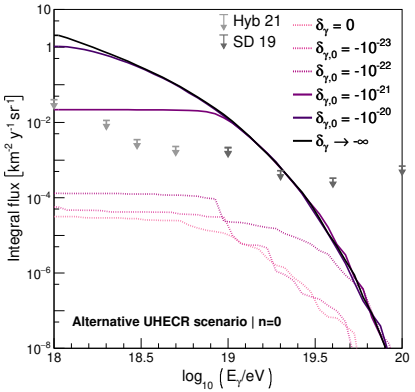
Photons



Neutrinos



Estimated photon fluxes for particular SHDM model assumptions



Phase II: Event-by-event primary mass information allows for tighter cuts for photons especially.

Photons: Pierre Auger Collaboration, Astrophys. J. 933 (2022)
Neutrinos: Aab et al., JCAP 10 (2019), JCAP 11 (2019)
SHDM: Pierre Auger Collaboration, JCAP 23 (2022)

KATRIN

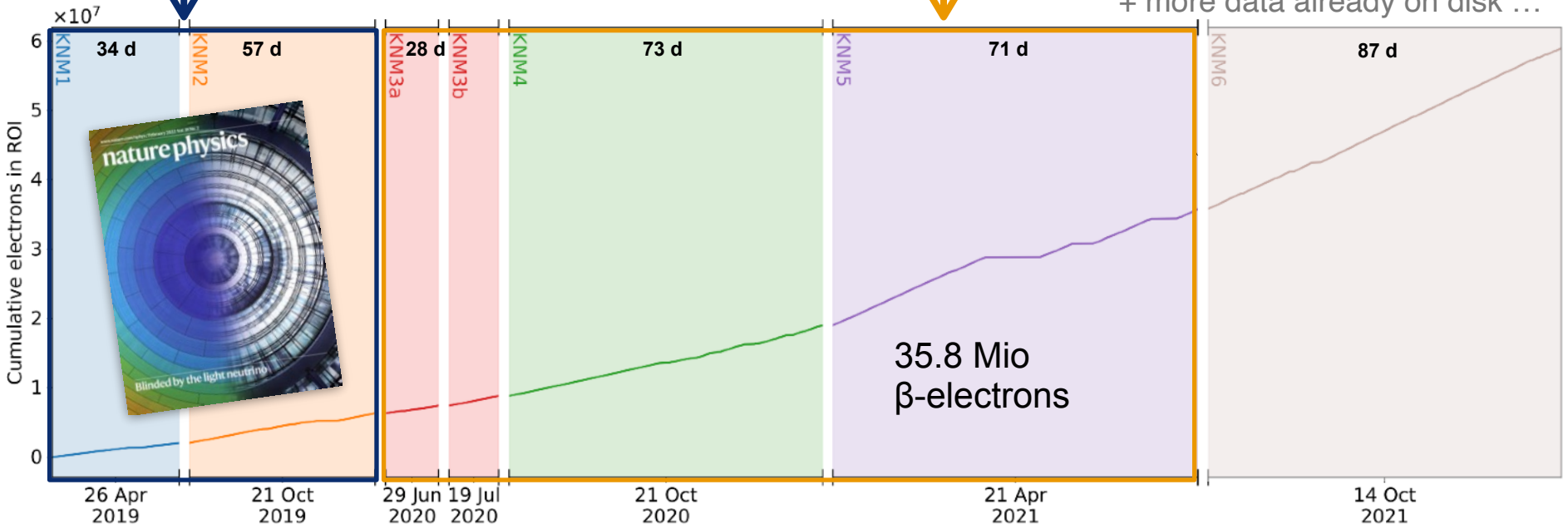
Karlsruhe Tritium Neutrino experiment (KATRIN)

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

2022: analyzed first 91 days ➜ $m_\nu < 0.8$ eV (90% CL)
KATRIN Coll., Nat. Phys. 18 (2022) 160

Now: Combining runs 1-5 (total 263 days) for expected sensitivity ~0.5 eV

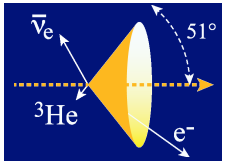
+ more data already on disk …

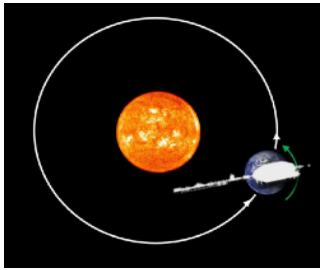


Karlsruhe Tritium Neutrino experiment (KATRIN)

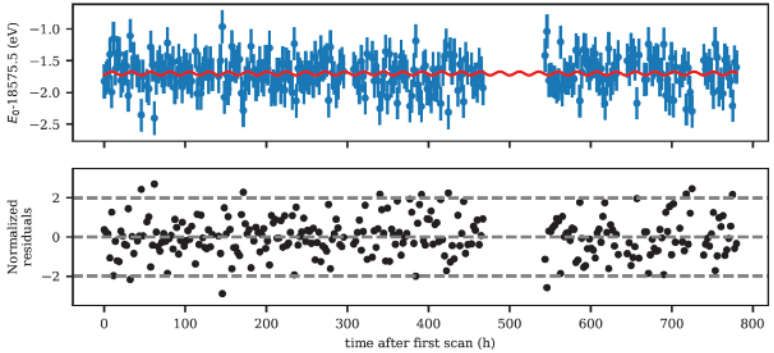
Physics program beyond the neutrino mass

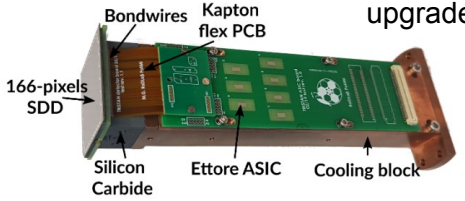
- Test of light (eV scale) sterile neutrino hypothesis:
  Phys. Rev. D 105 (2022) 072004
- Probe of local overdensities of cosmic relic neutrinos:
  Phys. Rev. Lett. 129 (2022) 011806
- Test of Lorentz invariance violation in weak decays:
  arXiv:2207.06326
- Probe of non-standard neutrino interactions (in prog.)
- Search for keV sterile neutrinos in first KATRIN data:
  arXiv:2207.06337



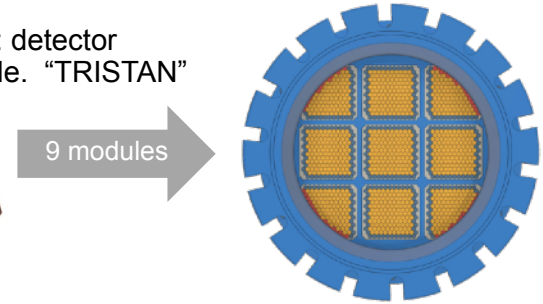


"oscillation-free" parameters only accessible through kinematics:
search for sidereal oscillation of endpoint E_0



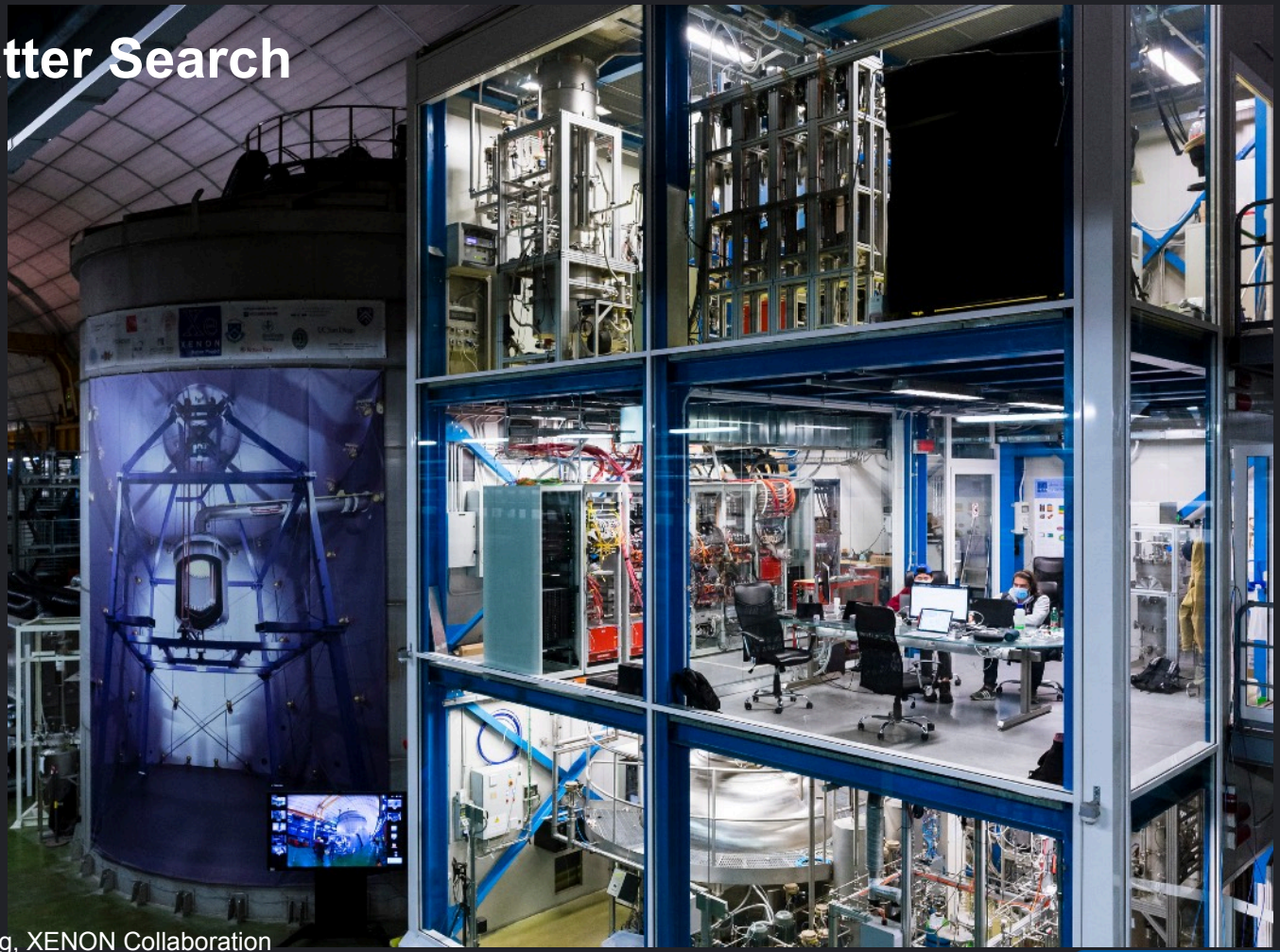


2025+: detector upgrade. "TRISTAN"



Snowmass report - "KATRIN: Status and prospects for the neutrino mass and beyond", J. Phys. G 49 (2022) 100501

Dark Matter Search

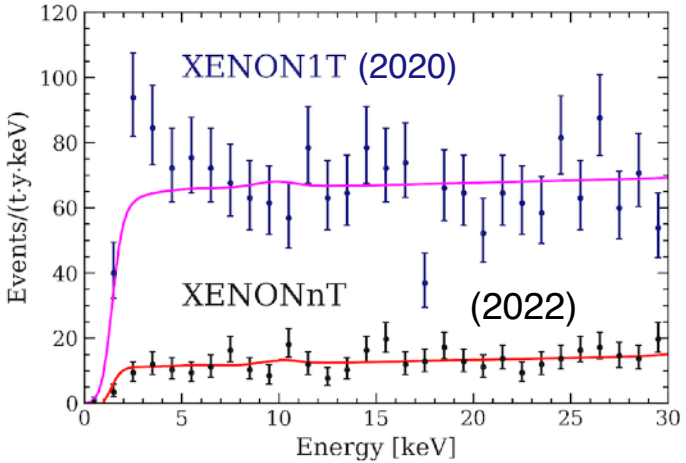


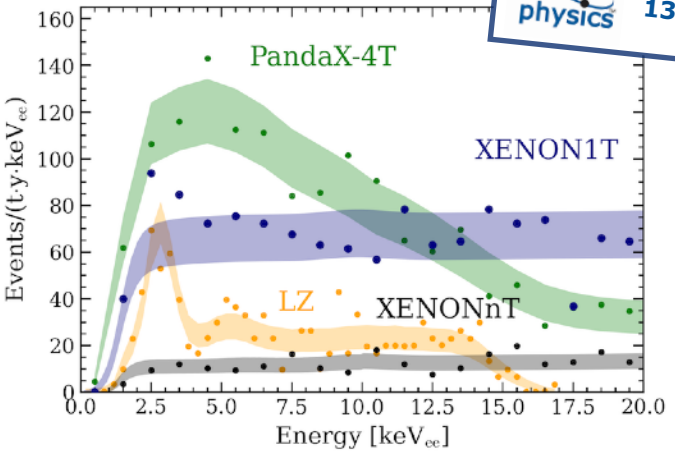
© H. Schulze-Eißing, XENON Collaboration

Direct Dark Matter Search

Search for new physics in electronic recoil data from XENONnT

XENON Collaboration, PRL 129 (2022) 161805





APS physics Research News, 13.10.22

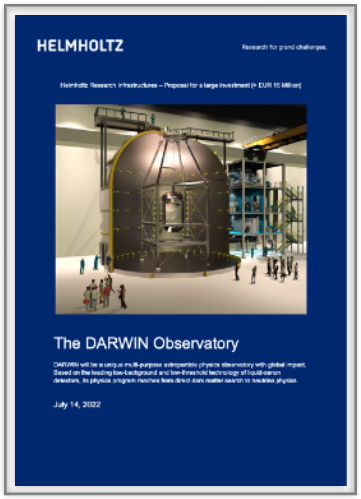
- First science run of XENONnT demonstrates lowest background ever reached by a xenon TPC in low-energy electronic recoil region (5x lower compared to XENON1T)
- New results do not confirm low-energy excess seen in 2020 and set stringent constraints on solar axions, enhanced neutrino magnetic moment, bosonic dark matter

Direct Dark Matter Search

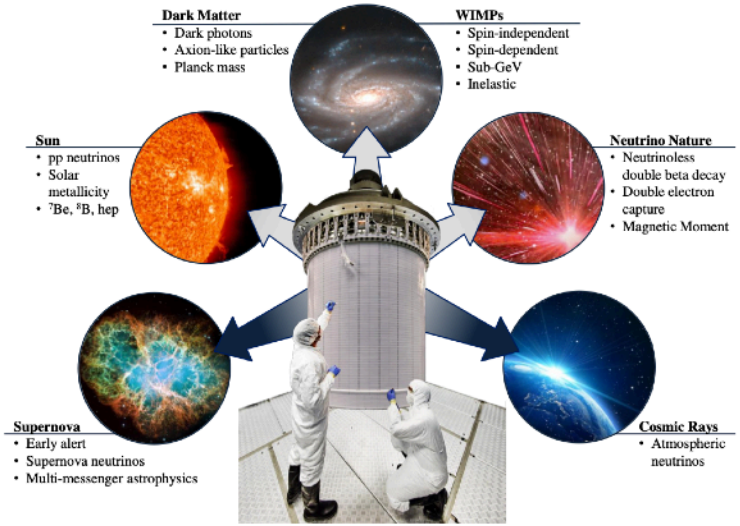
Towards the future observatory for rare-event searches

The challenge: go from ~6 tonnes active xenon mass to 40+ tonnes at ultra-low background to extend sensitivity down to the “neutrino fog”

DARWIN: First-stage research infrastructure proposal submitted to Helmholtz in July 2022



Community white paper (600+ authors), 2203.02309, acc. in J. Phys. G
“A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics”



Meeting of the XLZD Consortium at KIT, June 2022

Theory

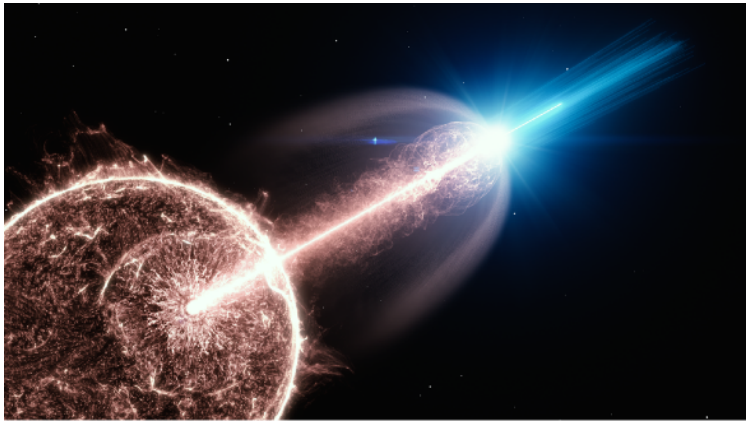
image found on wallpapersafari.com

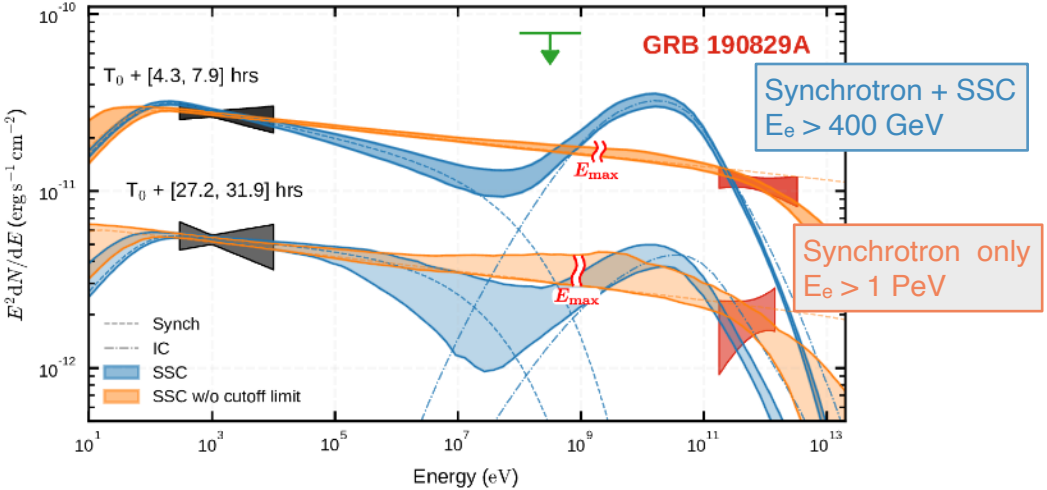
Evidence for new gamma-ray burst physics

Detection of a local GRB (d < 350 Mpc) by H.E.S.S. over 3 days

… demands a change to the one-zone acceleration/emission description used for GRB physics

New results appear consistent with an extension of the synchrotron emission up to the VHE range, possible if the magnetic field possesses small-scale structure





H.E.S.S. Collaboration, A. Taylor et al., ***Science 2021***

D. Khangulyan, A. Taylor, F. Aharonian, ***Astrophys. J. 2021***

Theoretical Astroparticle Physics (cont'd)

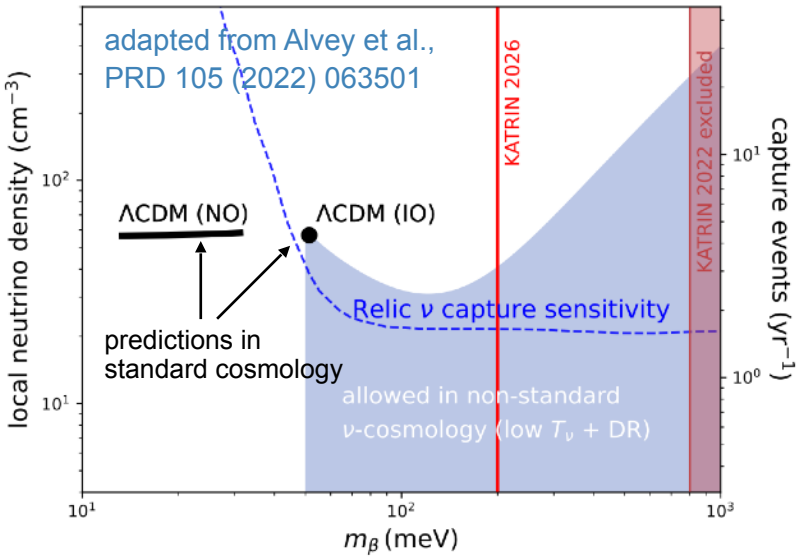
Recent research highlights:

- **Axion/ALP dark matter**
  Axion minicluster in our galaxy:
  Dandoy, Schwetz, Todarello, JCAP'22
  ALP DM freeze-in from lepton-flavor violation:
  Panci, Redigolo, Schwetz, Ziegler, arXiv:2209.03371

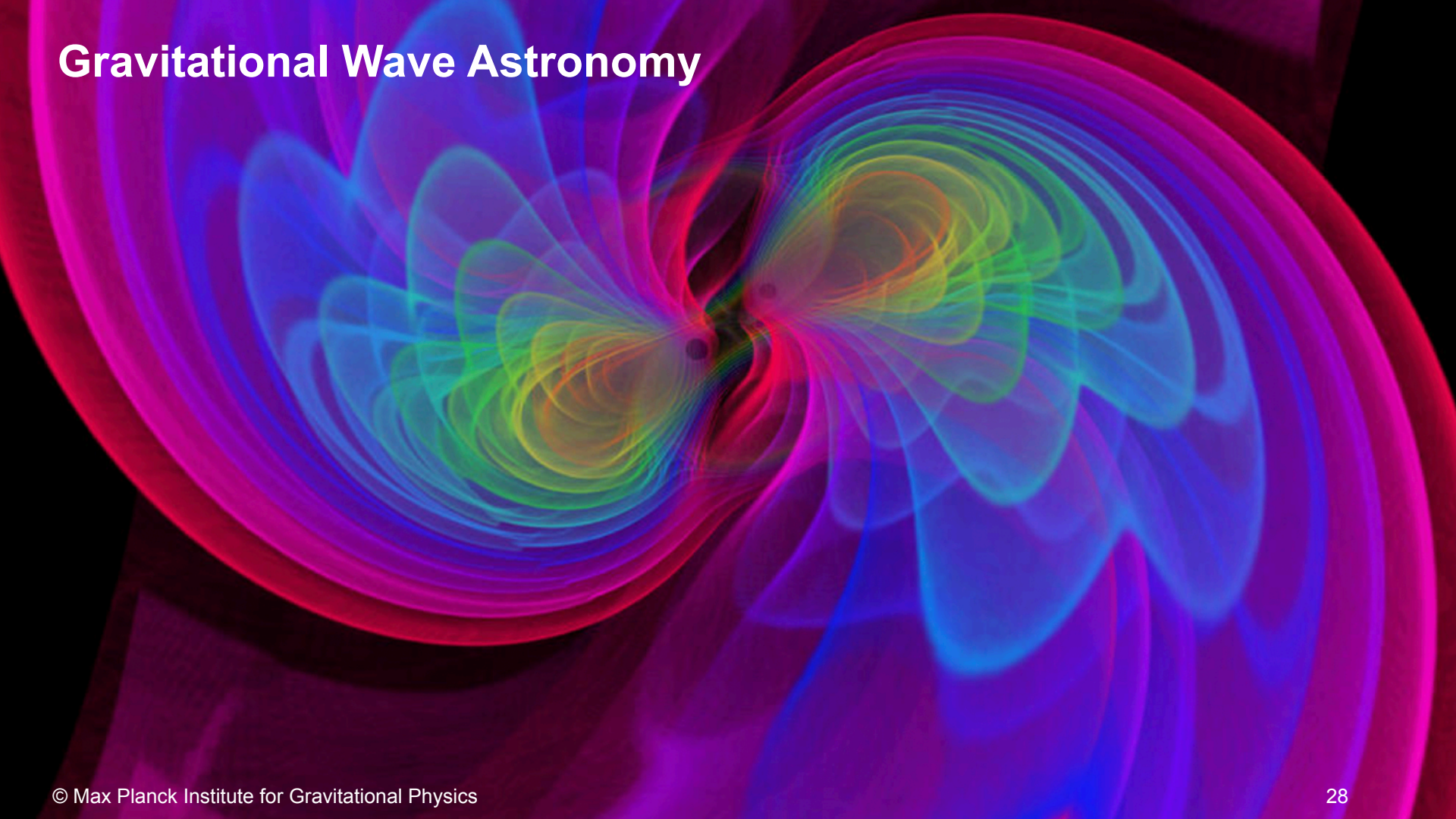
- **Neutrino oscillations**
  Model-independent test for T-violation:
  Segarra, Schwetz, PRL'22, PRD'22

- **Neutrino cosmology**
  Mass measurements & relic neutrinos:
  Alvey, Escudero, Sabti, Schwetz, PRD'22
  Neutrino mass ordering:
  Gariazzo, Gerbino, Schwetz, et al., JCAP'22

Ex.: potential of neutrino mass measurements and future relic neutrino search ideas in a non-standard cosmological scenario



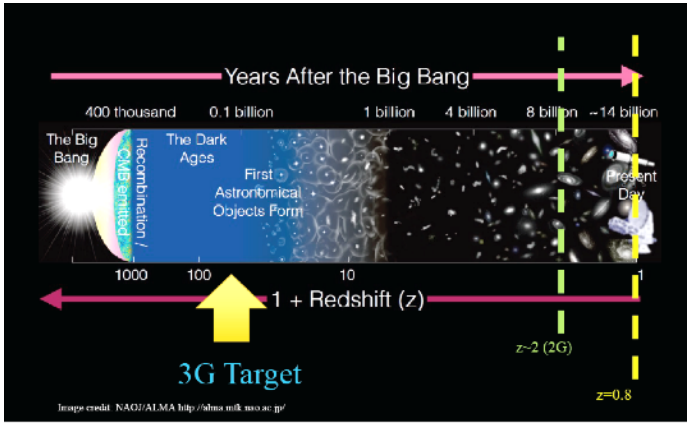
Gravitational Wave Astronomy

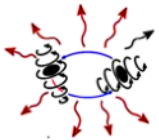


Gravitational Wave Astronomy

Science case - very interdisciplinary!

- Formation of Black Holes at the center of galaxies?
- Is General Relativity (GR) right or do we need new physics?
- Is Dark Energy the cosmological constant?
- Understanding the dynamics of ultra dense matter!
- *… and many more questions!*





Recent works by GW Theory Group (R. Porto, DESY)

PHYSICAL REVIEW LETTERS **128,** 161104 (2022)

Conservative Dynamics of Binary Systems at Fourth Post-Minkowskian Order

Christoph Dlapa, Gregor Kälin, Zhengwen Liu, and Rafael A. Porto
Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

Dynamics of binary systems to fourth Post-Minkowskian order from the effective field theory approach

Christoph Dlapa [a,b], Gregor Kälin [a], Zhengwen Liu [a], Rafael A. Porto [a,*]

[a] *Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
[b] *Max-Planck-Institut für Physik, Werner-Heisenberg-Institute, 80805 Munich, Germany*

Physics Letters B 831 (2022) 137203

- Discovery potential: High-precision waveform models for present and future detectors
- Transfer of methods from high-energy physics (ERC grant “LHC to LISA *and ET*”)
- Physics programme raises experimental challenges: luminosity and frequency frontiers

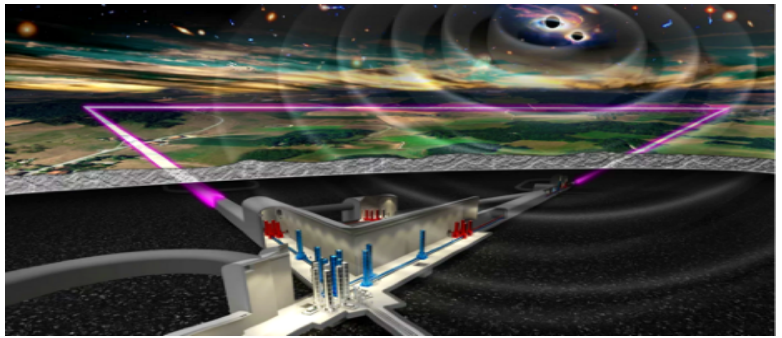
Gravitational Wave Astronomy

Towards the Einstein Telescope

- **ESFRI Roadmap:** ET is listed in the June 2021 Update (I, NL, B, E, Pl).
- **Organisation:**
  - Due to science case, the interest on ET is rapidly growing.
  - Boards have been formed: Instrument Science (ISB), Observational Science (OSB), Site Preparation (SPB), E-Infrastructure (EIB).
  - The ET collaboration had its kick-off meeting in July 2022 (79 Research Units).
  - KIT is one of the RU with activities in all four boards (cryo & vacuum; seismic; computing; MM), DESY is about to join ET.
- **R&D:**
  - Helmholtz active in adv. Virgo (I) and ETpathfinder (NL)
  - MoU with CERN on common vacuum R&D
  - Foreseen cooperative activity with the DZA (D)

ET EINSTEIN TELESCOPE

http://www.et-gw.eu



More news on Fri, live from the ET meeting in Hannover!

Thank You!

MU MRU
MATTER AND THE UNIVERSE

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

D. Berge
A. Haungs
T. Huege
M. Kowalski
A. Nelles
R. Porto
M. Roth
M. Schlösser
Th. Schwetz-Mangold
W. Schubotz
M. Steidl
A. Taylor
W. Winter

Find out more in the Flash Talks on Friday:

Dennis Soldin
Pavlo Plotko
Francesco Zappon
Martin Schimassek
Tim Holch
Maksym Ovchynnikov

DESY.

KIT Karlsruhe Institute of Technology

Supplementing material

The Multimessenger School

- up and running!

- Topics: Gamma rays, neutrinos, gravitational waves, and theory
- … spanning from fundamental physics to particle acceleration to plasma physics, compact objects, dark matter, particle cosmology, …
- Core partners: DESY, Weizmann Institute of Science (WIS), HU Berlin, U Potsdam
- Associated partners since 2021:
  U Erlangen-Nürnberg and U Bochum

IceCube H.E.S.S. RNO-G ULTRASAT CTA LAST

The Multimessenger School

- Key elements:
  - i) supervision by international group of supervisors
  - ii) research stays at WIS
  - iii) broad range of transferable skills courses
  - iv) many scientific and social events
- 4 application rounds concluded: currently 34 doctoral candidates and 5 alumni
- **Call for applications** for new PhD projects open until Nov. 6, 2022 → **web link**
- 2019-25: Funded through Helmholtz Initiative and Networking Fund (1.8 M€)
  Agreement on keeping the established structures after funding ends
- Future plan: extension to international partners that meet the scientific scope of the school (especially gravitational wave physics)
- For questions, contact Wiebke Schubotz (DESY)