HELMHOLTZ

RESEARCH FOR
GRAND CHALLENGES

TOPIC 3

Matter and Radiation from the Universe

Kathrin Valerius & Christian Stegmann

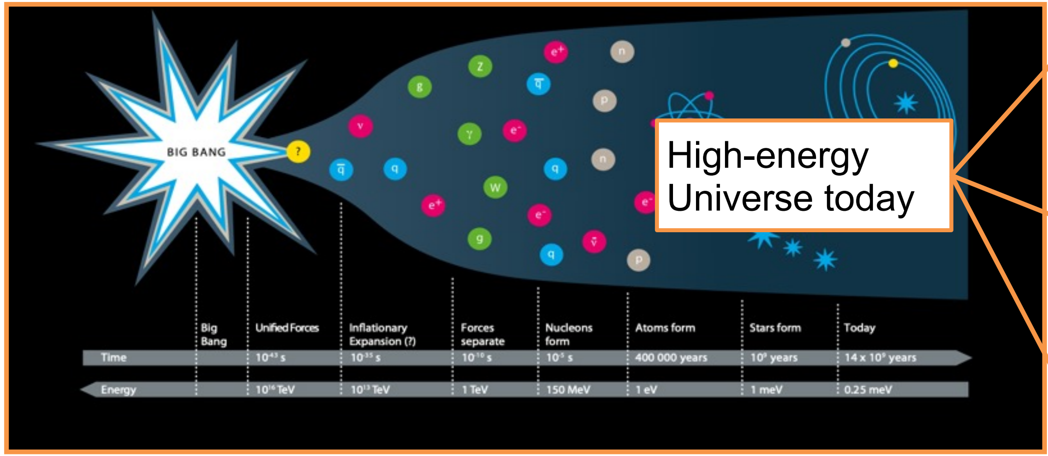
DESY. JÜLICH Forschungszentrum GSI HI JENA HELMHOLTZ Helmholtz Institute Jena HIM HELMHOLTZ Helmholtz-Institut Mainz HZB Helmholtz Zentrum Berlin HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF Helmholtz-Zentrum Geesthacht Zentrum für Material- und Küstenforschung IPP KIT Karlsruhe Institute of Technology

What we want

MATTER AND THE UNIVERSE

Understanding the high-energy Universe and its constituents

A broad but coordinated research program with observatories and in laboratories – a growing field of science



High-energy Universe today

Multi-messenger view of the cosmos

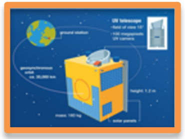
- Gamma-ray astronomy
- Neutrino astronomy
- Cosmic rays
- Gravitational waves

Understand the role of **neutrinos** in the Universe

Search for new physics and **Dark Matter**

Strong interplay between experiments and theory

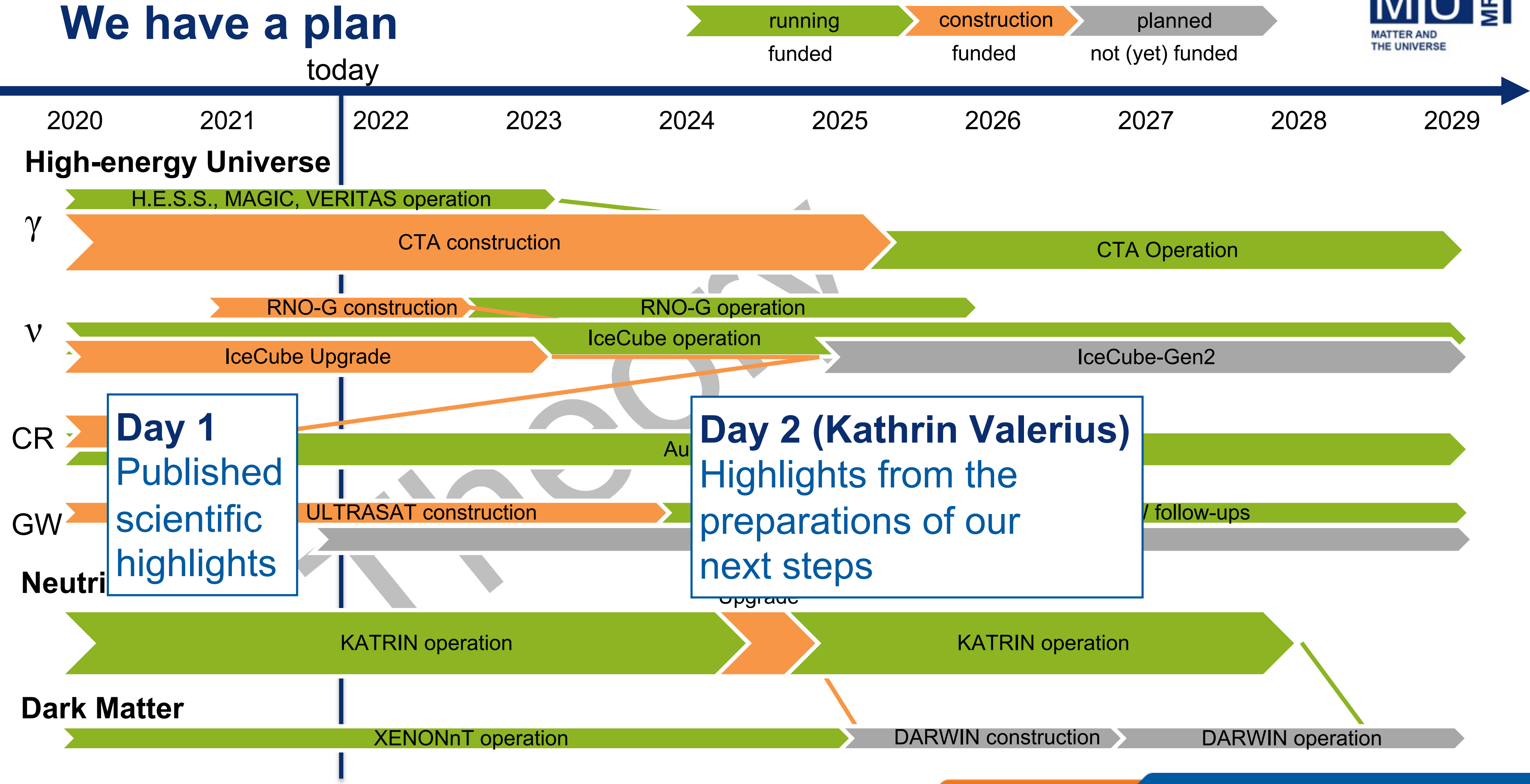
Where we operate



ULTRASAT

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

We have a plan



Day 1
Published scientific highlights

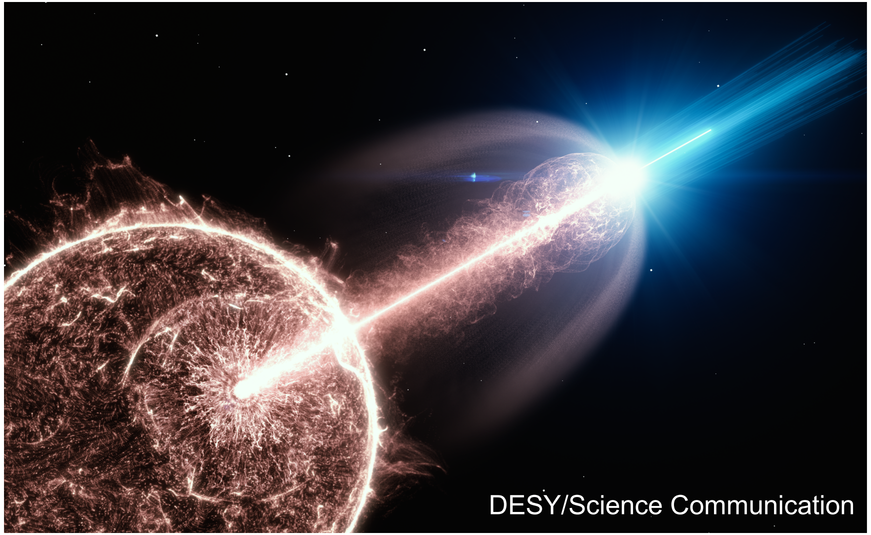
Day 2 (Kathrin Valerius)
Highlights from the preparations of our next steps

Gamma-ray Astronomy

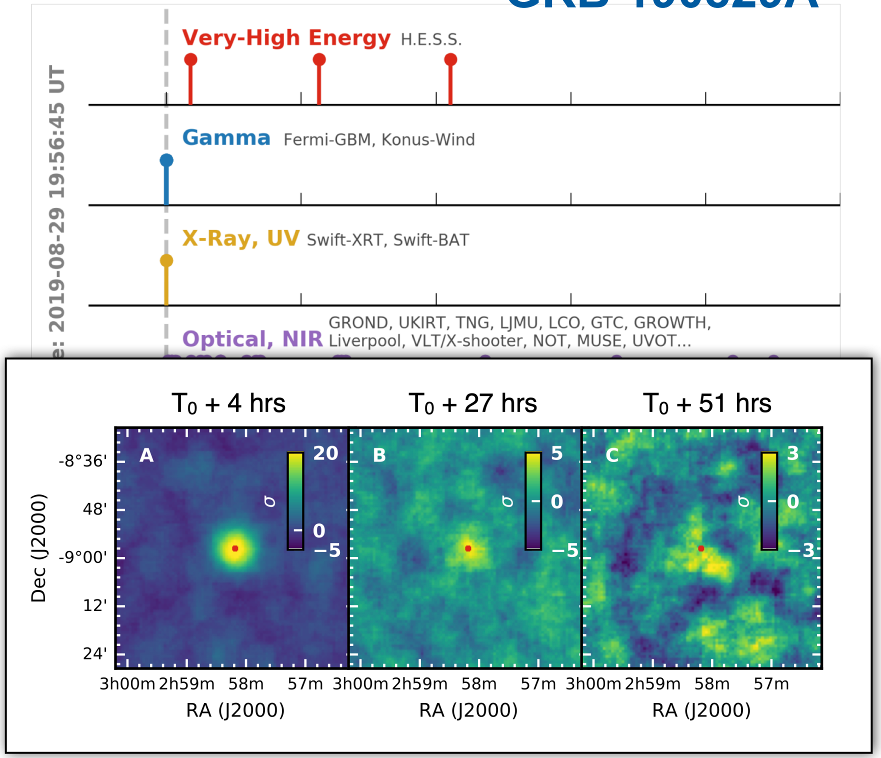
LST 1 collaboration

In the front row at a cosmic explosion

The best view yet of a gamma ray burst (GRB)



GRB 190829A



An increasing sample of detections

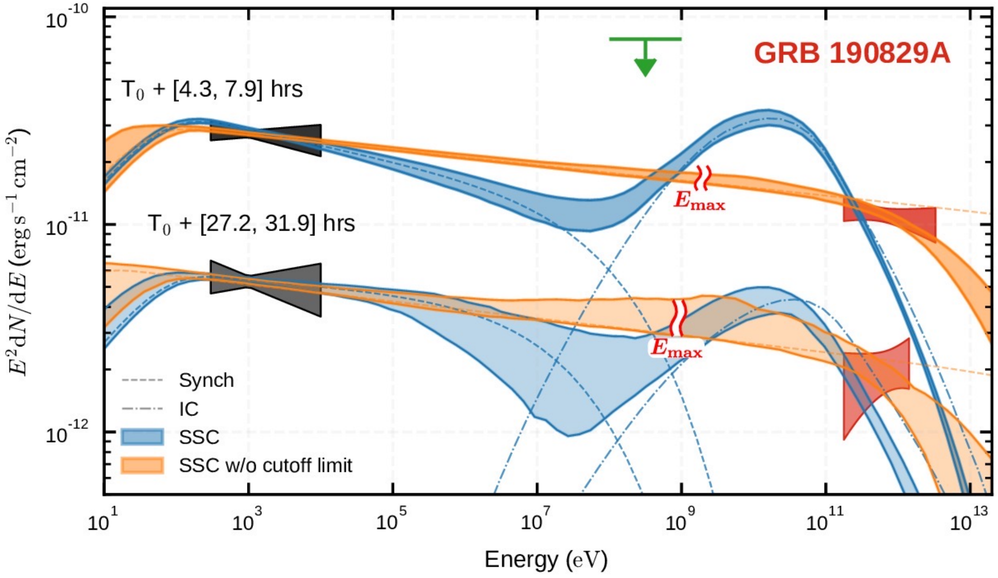
GRB 190114C
MAGIC
Nature 575 (2019) 455
Nature 575 (2019) 459

GRB 180720B
H.E.S.S., Nature 575 (2019) 464
GRB 190829A
H.E.S.S., Science 372 (2021) 1081

The Spectrum of GRB 190829A

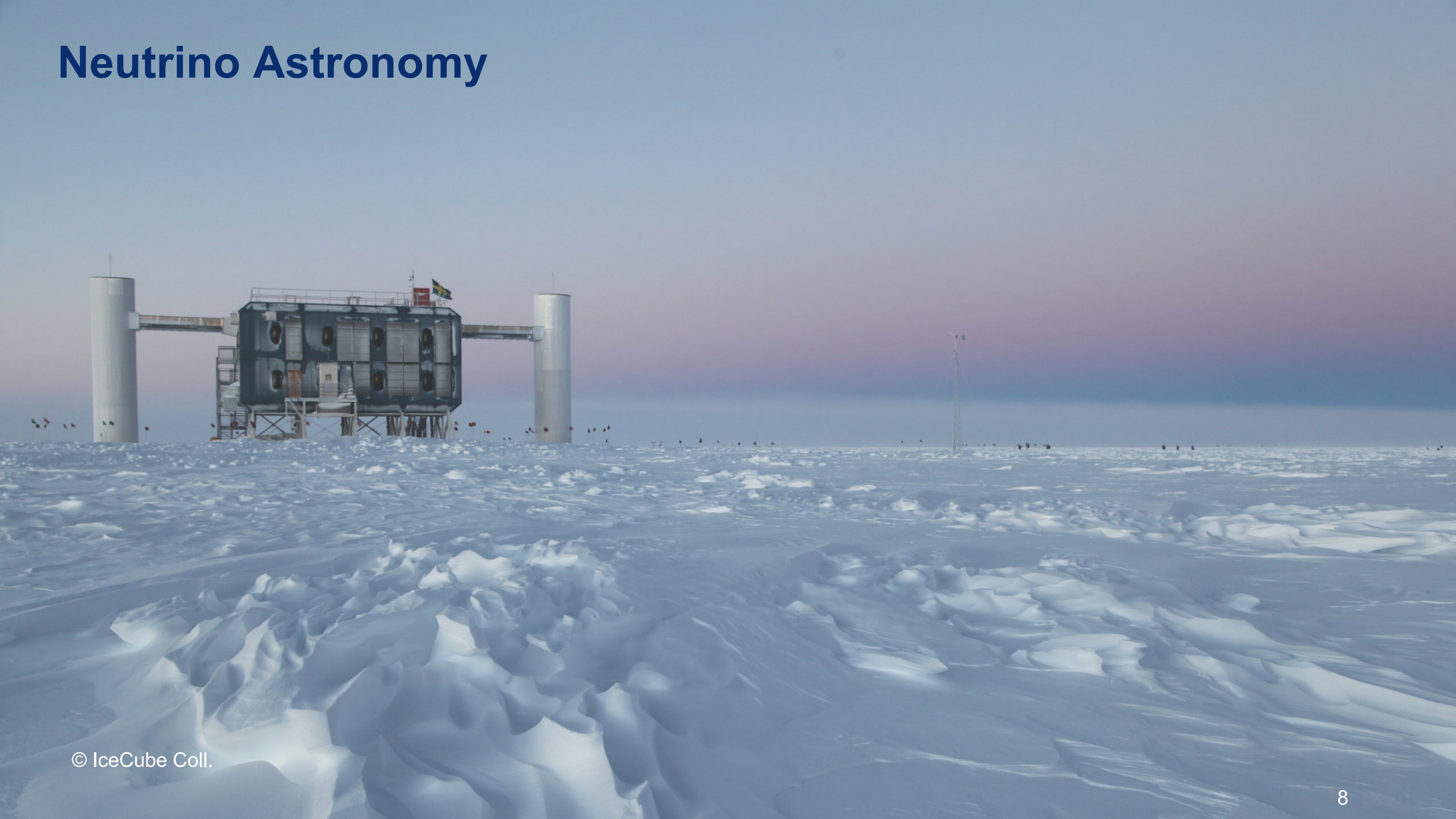
is challenging theory

- Curiously, the most recent HESS GRB detection is compatible with a continuation of the synchrotron emission beyond the expected supposed theoretical limit
- We are finally starting to probe the very high energy (TeV) gamma-ray emission from GRB, allowing us to start probing the magnetic fields in the source



HESS, Science 2021

Neutrino Astronomy



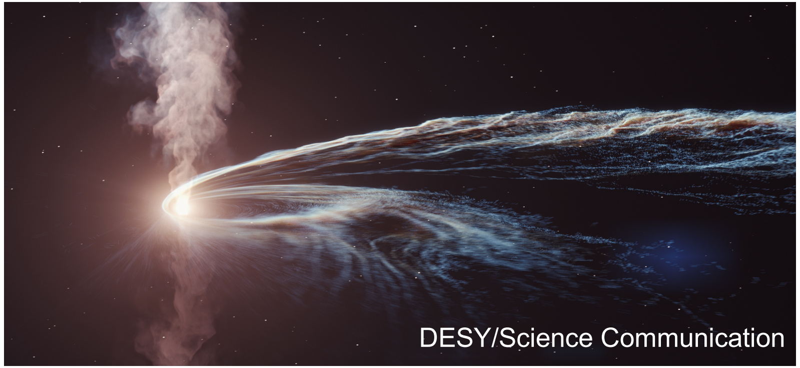
High-energy Neutrinos

in coincidence with the disruption of stars near black holes (TDE)

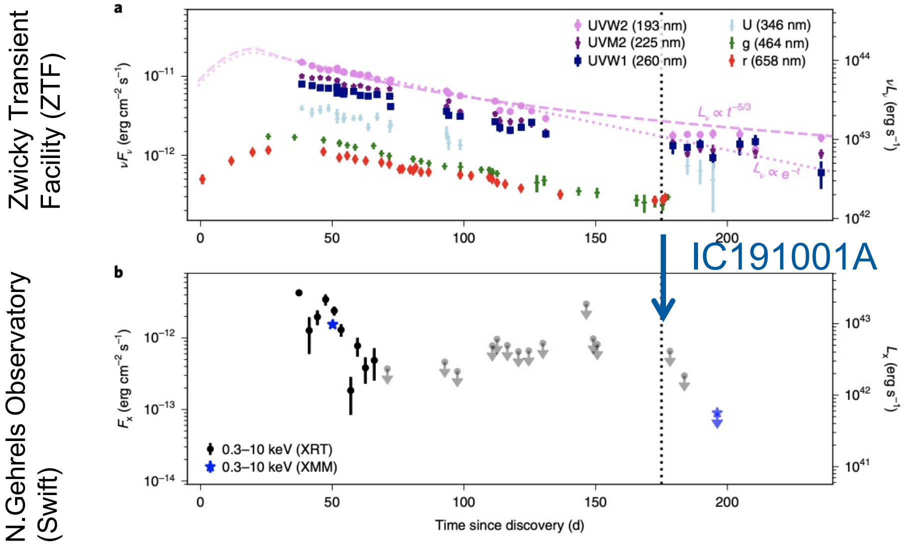
- The **IceCube-191001A-AT2019dsg** association represents the first step in the study of high-energy particle emission from TDEs.
- Possible due to the implementation of realtime alert systems (**AMPEL**)

\+ theoretical modelling (W. Winter, C.Lunardini, Nature Astronomy 5, 472 (2021)

- additional candidates under investigation: e.g. **IC200530A-AT2019fdr**, S. Reusch et al, submitted to PRL https://arxiv.org/abs/2111.09390 and van Velzen et al, submitted to Science https://arxiv.org/abs/2111.09391



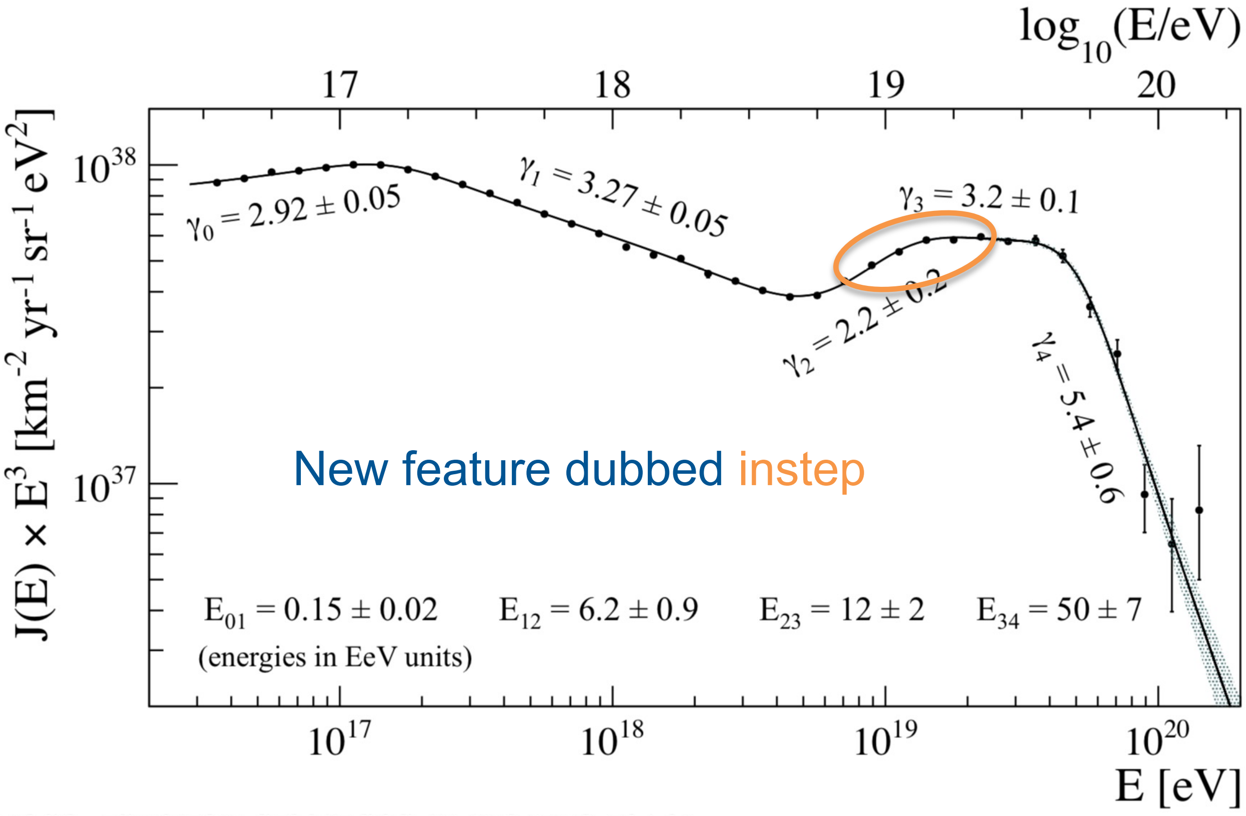
R. Stein, et al., Nature Astronomy 5, 510 (2021)



Cosmic Rays

Energy spectrum of the highest energy particles

allows an unprecedented view of the Universe at the highest energies



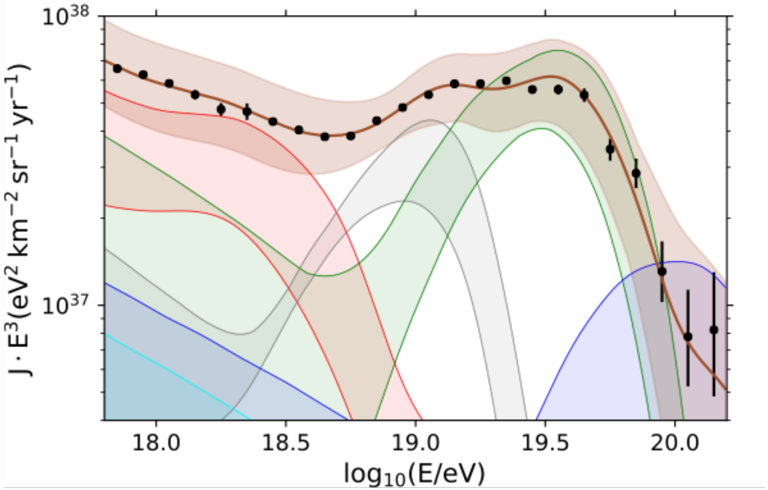
	Exposure [km^2 sr yr]	Events
SD1500 ($\vartheta<60^0$)	60426	215030
SD1500 ($\vartheta>60^0$)	17447	24209
SD750	105.4	569285
Hybrids	2248 (10^{19} eV)	13655
Cherenkov	286 (10^{17} eV)	69793

Stat. uncertainty very small

Sys. uncertainty dominating

Interpretation of flux and composition data

Mass composition at Earth

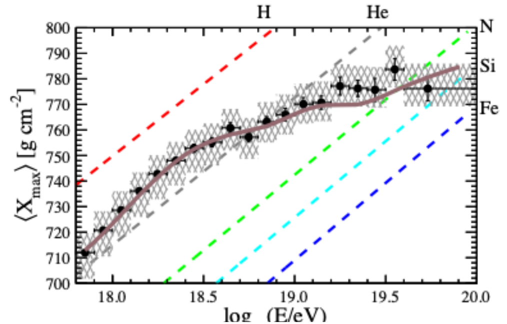


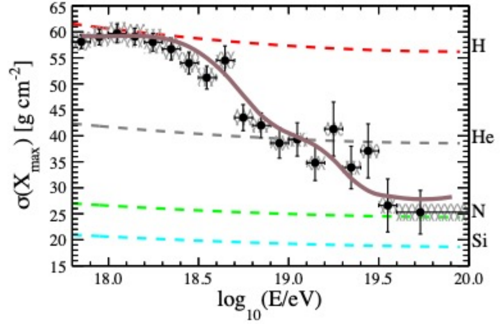
A = 1
1 < A < 5
4 < A < 23
22 < A < 39
38 < A < 57

Bands:
Experimental uncertainties
(model uncertainties smaller)

Energy scale: $\sigma_{sys}(E)/E = 14\,\%$

X_{max} scale: $\sigma_{sys}(X_{max}) = 6 \div 9\ \mathrm{g\,cm^{-2}}$





Different model scenarios considered for low-energy part
(transition to galactic component), similar results for total composition obtained

$$J(E) = \sum_A f_A \cdot J_0 \cdot \left(\frac{E}{E_0}\right)^{-\gamma} \cdot \begin{cases} 1, & E < Z_A \cdot R_{\mathrm{cut}}; \\ \exp\left(1 - \frac{E}{Z_A \cdot R_{\mathrm{cut}}}\right), & E > Z_A \cdot R_{\mathrm{cut}}. \end{cases}$$

$$R_{\mathrm{cut}} = 1.4 \ldots 1.6 \times 10^{18}\,\mathrm{V}$$

Flux suppression superposition of injection maximum energy and propagation energy losses

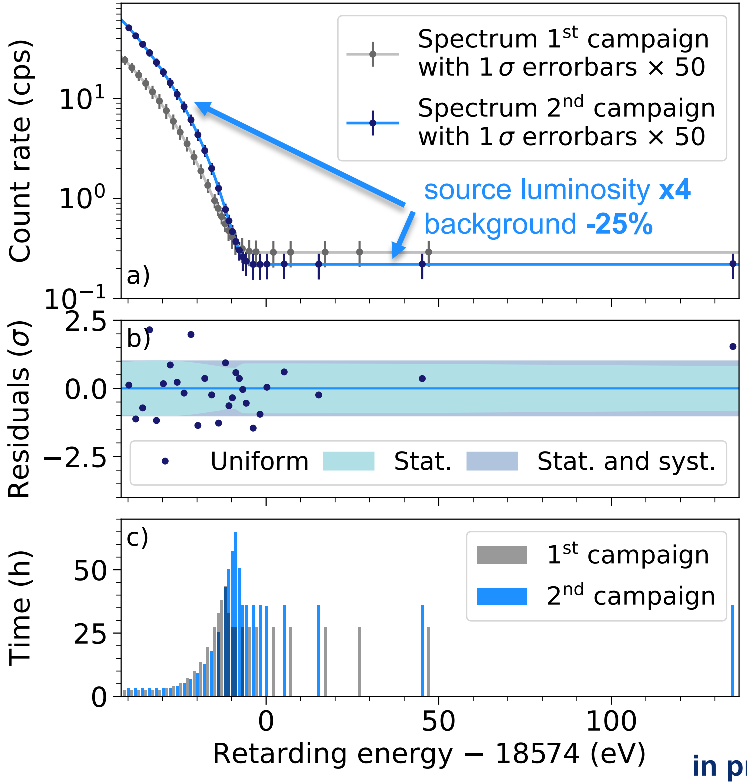
(Guido, Auger ICRC 2021)

Extragalactic index very hard, but no really good handle on this parameter

KATRIN

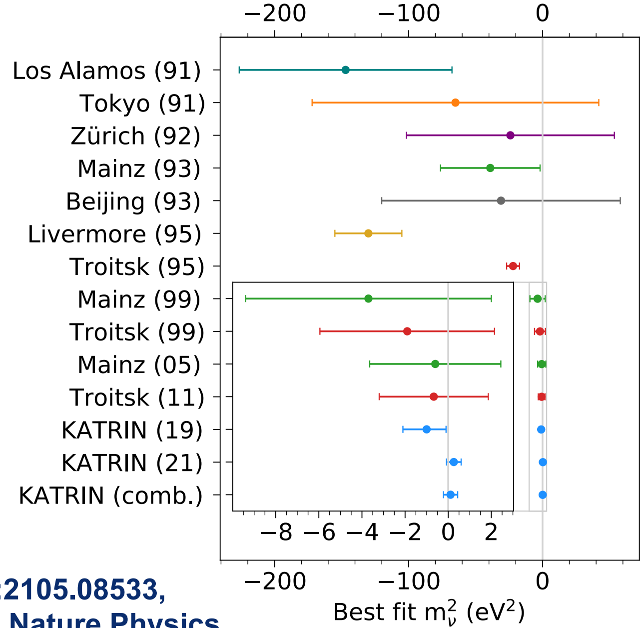
Karlsruhe Tritium Neutrino experiment (KATRIN)

First direct neutrino-mass measurement with sub-eV sensitivity



Best-fit result (2nd campaign): $m_\nu^2 = 0.26 \pm 0.34\ \mathrm{eV}^2$

Upper limit (2019 data combined): $m_\nu < 0.8\ \mathrm{eV}\ (90\%\ \mathrm{CL})$



Only 5% of total anticipated data unblinded.

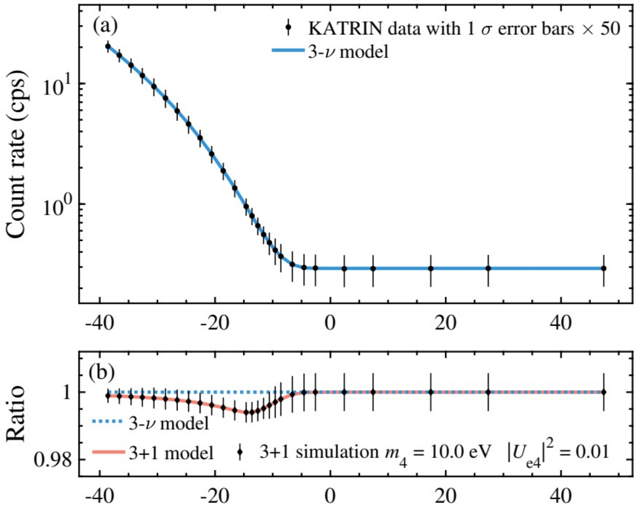
Ca. 1/3 of total anticipated data now on disk.

arXiv:2105.08533, in print at Nature Physics

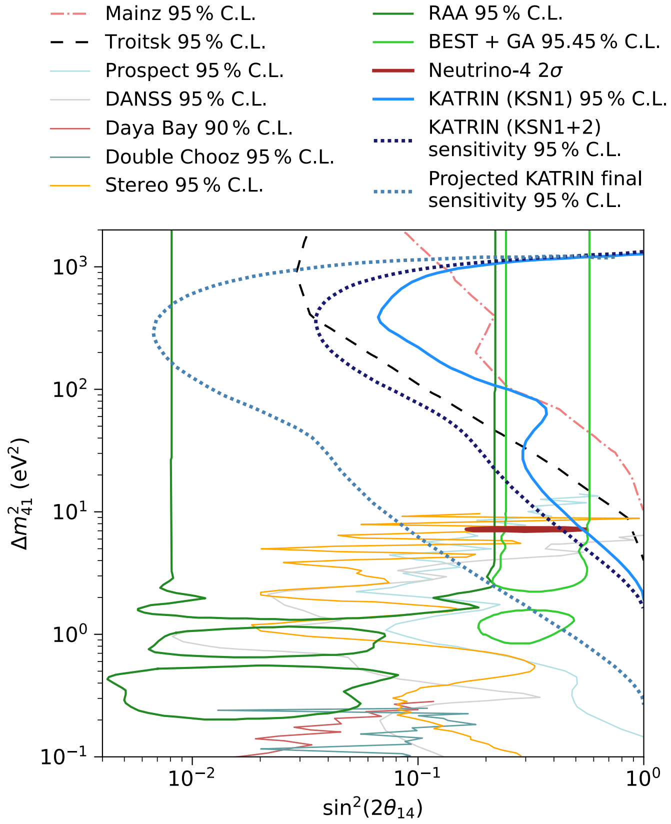
Karlsruhe Tritium Neutrino experiment (KATRIN)

Physics program beyond the neutrino mass

- Test of Lorentz invariance violation in weak decays
- Probe of local overdensities of relic neutrinos
- Probe of non-standard neutrino interactions
- Test of light (eV scale) sterile neutrino hypothesis

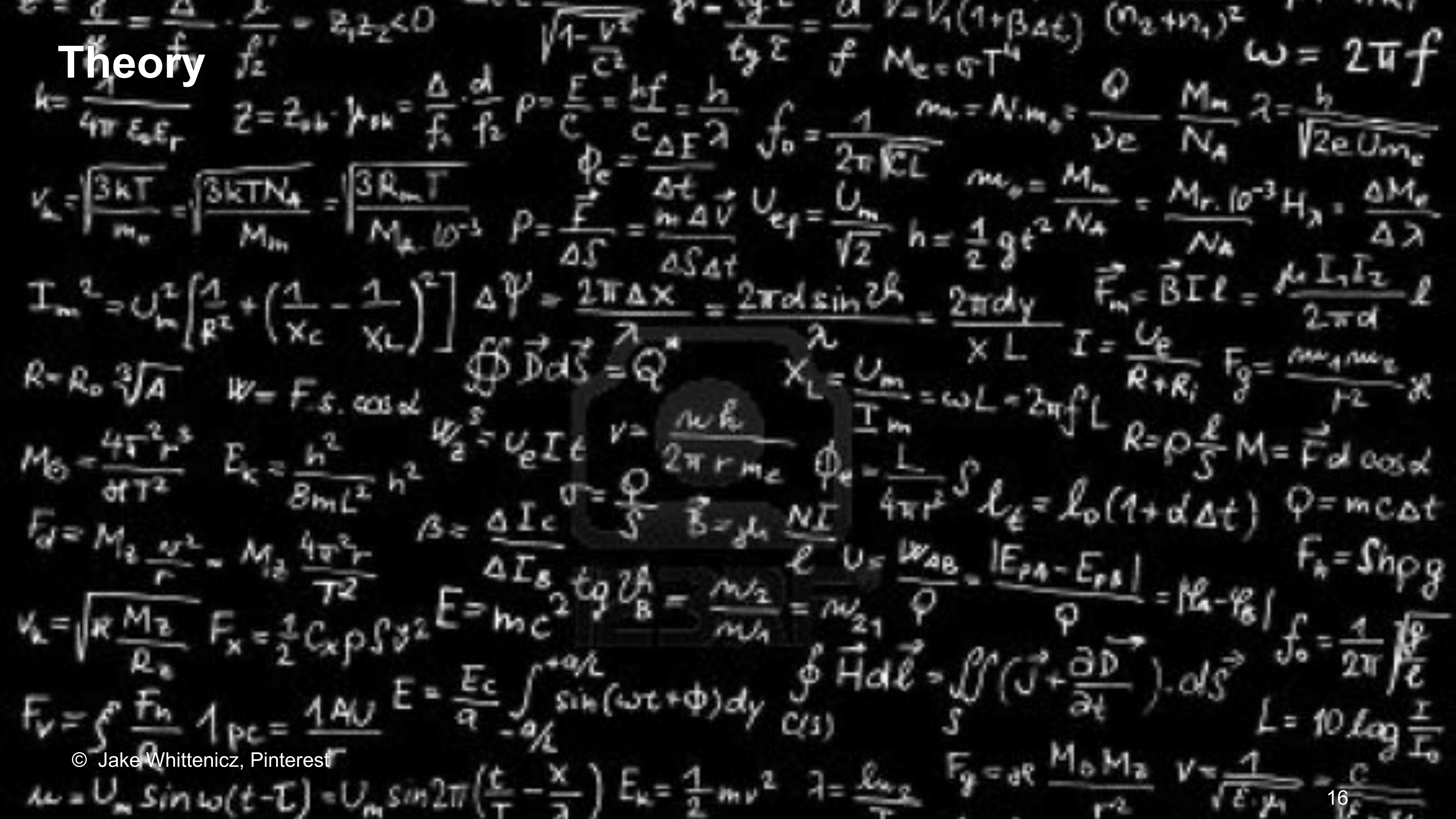


1st campaign:
PRL 126 (2021) 091803



2nd campaign: publication in prep.

Theory

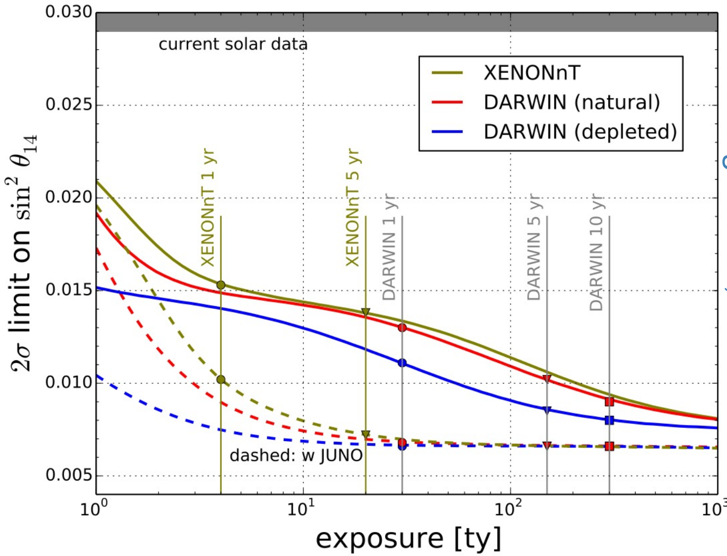


Theoretical Astroparticle Physics @ KIT

Research highlights:

- **Updated global fit of oscillation data**
  Esteban et al. 2007.14792
- **Sterile neutrino searches**
  Coloma, Huber, Schwetz, 2008.06083
  Goldhagen et al., 2109.14898
  Berryman et al., 21 to appear
- **non-standard neutrino properties:**
  non-st. interactions: Chaves, Schwetz, 2102.11981
  magn. moment: Schwetz, Zhou, Zhu, 2105.09699
  model-independent test for T-violation:
  Segarra, Schwetz, 2106.16099
- **neutrino cosmology vs mass measurements vs relic neutrinos** Alvey et al., 21 to appear

Ex.: sensitivity to sterile neutrino mixing from solar neutrino measurements in future Xenon Dark Matter experiments

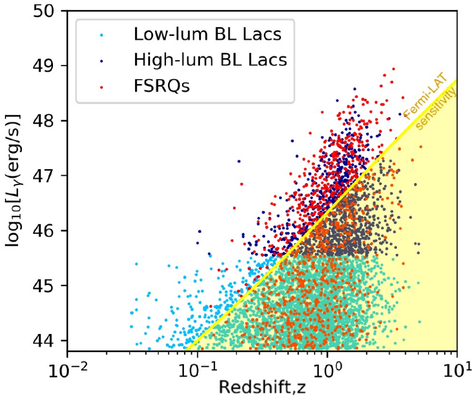


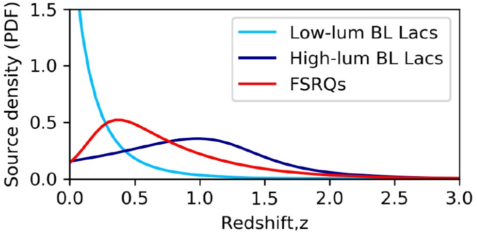
Goldhagen et al., 2109.14898

UHECRs and neutrinos from AGN jets

Hypotheses:

- AGN jets (aligned+mis-aligned) describe UHECR data
- Mis-aligned AGN have same properties as AGN blazars
- Injection compositon fixed (roughly Galactic)
- Population model from **Ajello et al, 2012+2014:**
- Three classes (allowing for different baryonic loadings)
  - LL-BL Lacs
  - HL-BL Lacs
  - FSRQs

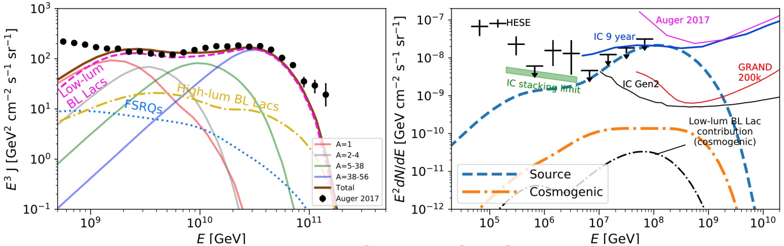




- Neutrino production model and spectral energy distribution model based on **Rodrigues, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018) 54**

Conclusion:

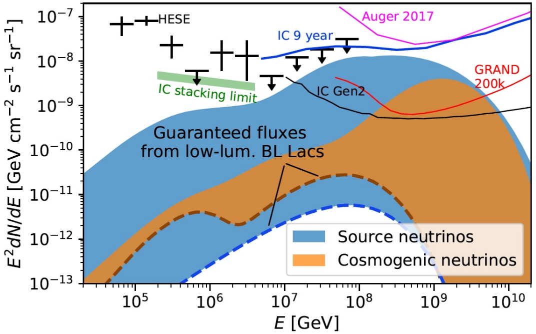
1. UHECR description driven by LL-BL Lacs because of
   - Low luminosity → rigidity-dependent max. energy
   - Negative source evolution



2. Neutrinos mostly come from FSRQs, peak at high energies, and may outshine the cosmogenic flux there

Rodrigues, Heinze, Palladino, van Vliet, Winter, PRL 126 (2021) 191101

Is the cosmogenic neutrino flux really the foreground at EeV energies?



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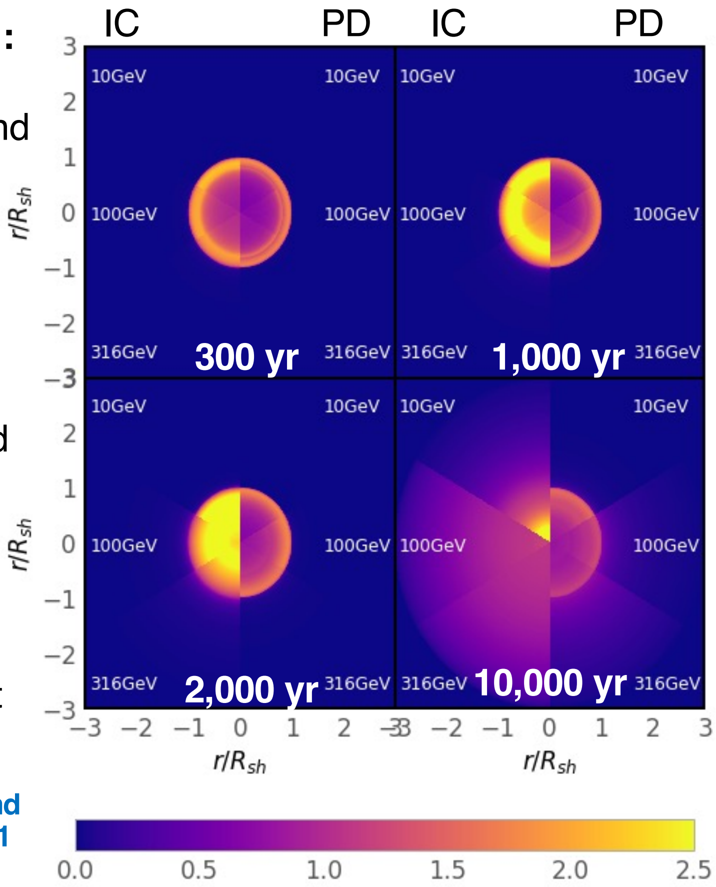
Emission and spectral index maps of supernova remnants

Pion decay (PD)-emission:
- Shell-like morphology throughout all phases and energies
- Faint halo emission

IC-emission:
- Initially shell-like morphology
- Transition to center-filled
- Halo emission already after 2kyr

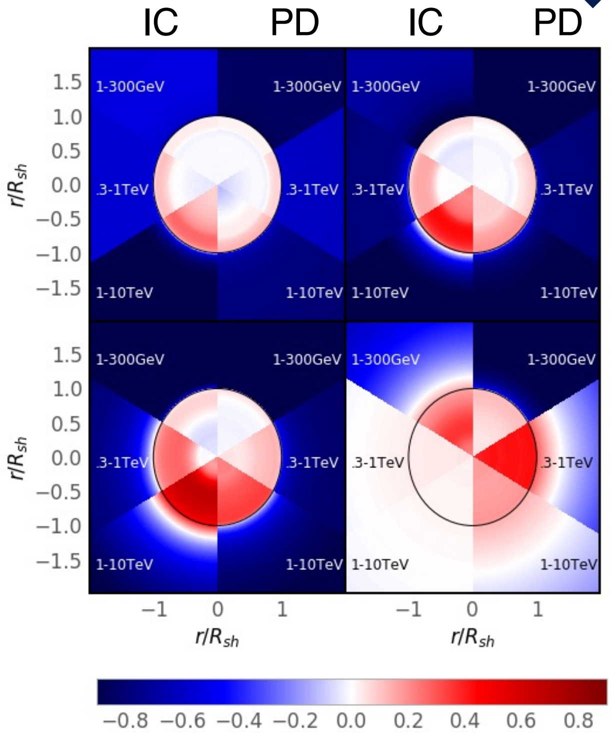
Spectral index distribution:
- No significant deviation from regions of brightest emission

Gamma-ray morphology of SNRs and their halos, Robert Brose, ICRC 2021

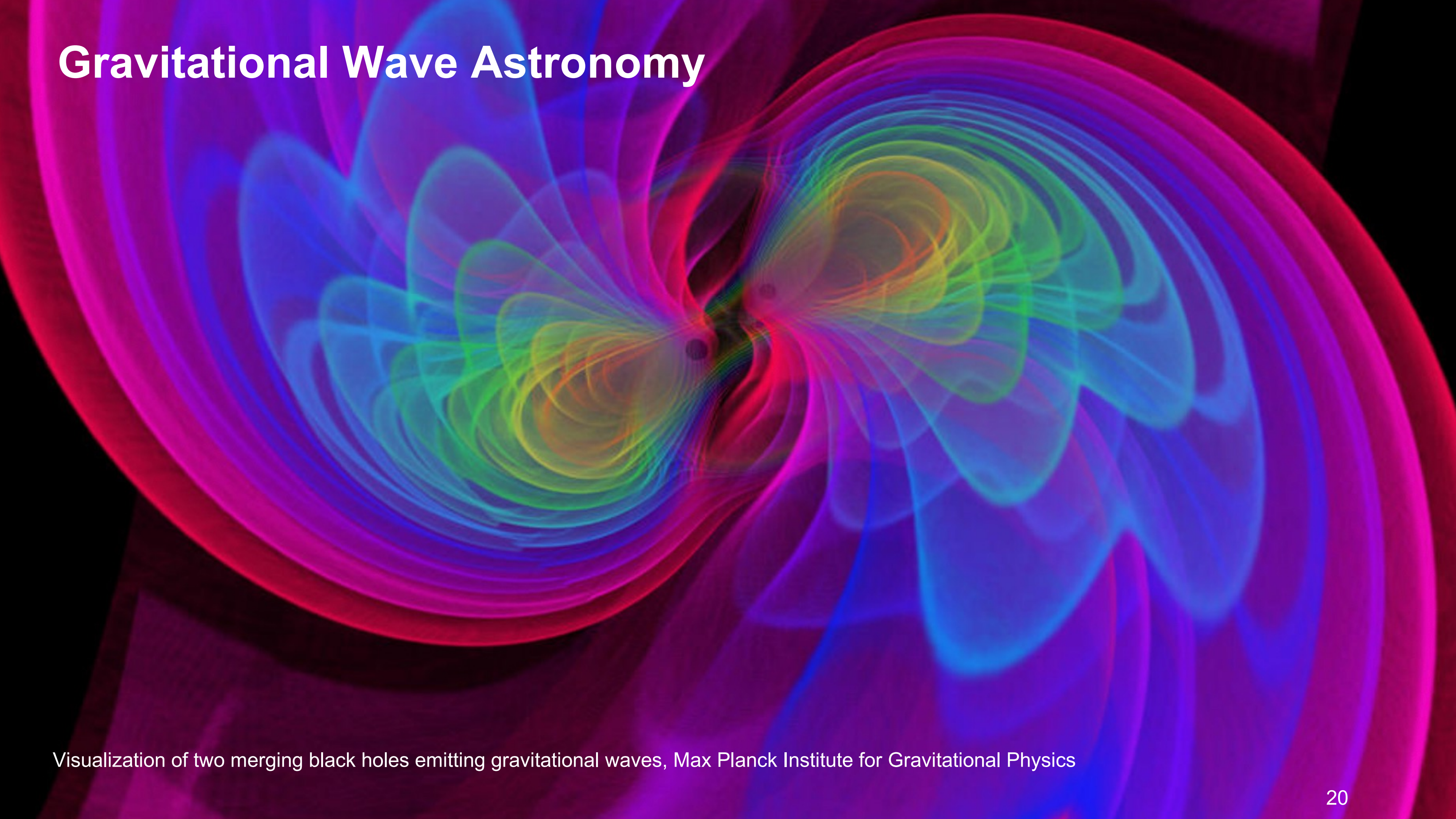


Emission maps

Spectral index deviation maps



Gravitational Wave Astronomy

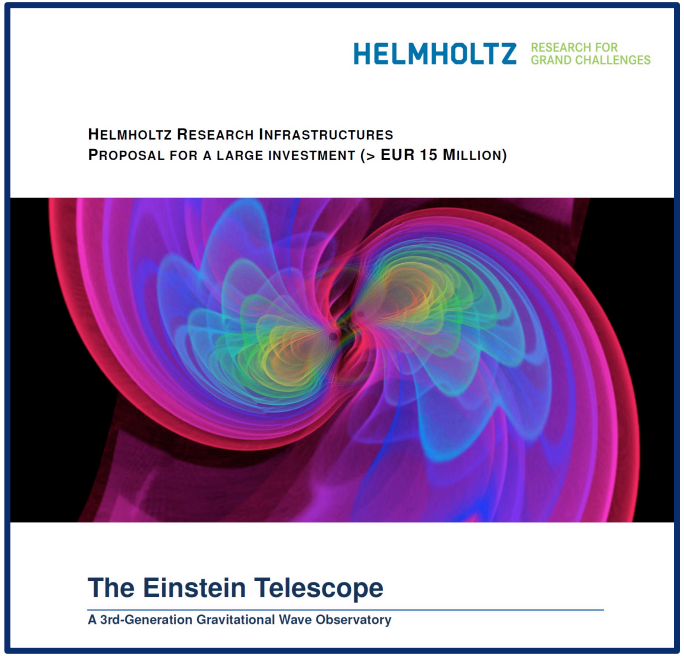


Visualization of two merging black holes emitting gravitational waves, Max Planck Institute for Gravitational Physics

Gravitational Wave Astronomy

with the Einstein Telescope

- Many activites in participating centers started, ranging from theory to contributions to the instrument to coordination
- **Helmholtz-Roadmap:** The FIS Commission recommends the project for full application (2021).
- **DZA in Lusatia:** The proposed German Center for Astrophysics (DZA) – one of its three pillars dedicated to the Einstein telescope – is among the final 6 proposals for two research centers in Saxony.. (https://www.deutscheszentrumastrophysik.de/de)



Thank You!

MATTER AND THE UNIVERSE

This presentation was built with input from

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based on the work of a dynamic team
of motivated people

DESY.

Karlsruhe Institute of Technology