Cosmic Rays

Astroparticle Physics in Germany: Decadal Strategy Paper 2024

With input from Andreas Haungs, Tim Huege, Philipp Mertsch, Markus Risse, Günter Sigl and others

Markus Roth / Michael Schmelling

October 17, 2024

Studying the high-energy non-thermal universe

Physics questions addressed with charged particle CRs

- ➢ origin and acceleration of galactic and extragalactic cosmic rays
- ➢ combine in multi-messenger astrophysics with UHE neutrinos and photons
- ➢ Ultra-High Energy Cosmic Ray (UHECR) composition and the muon puzzle
- ➢ understanding of hadronic interactions
- ➢ mapping and understanding the CR anisotropy
- ➢ search for BSM physics (e.g. Lorentz invariance violation)

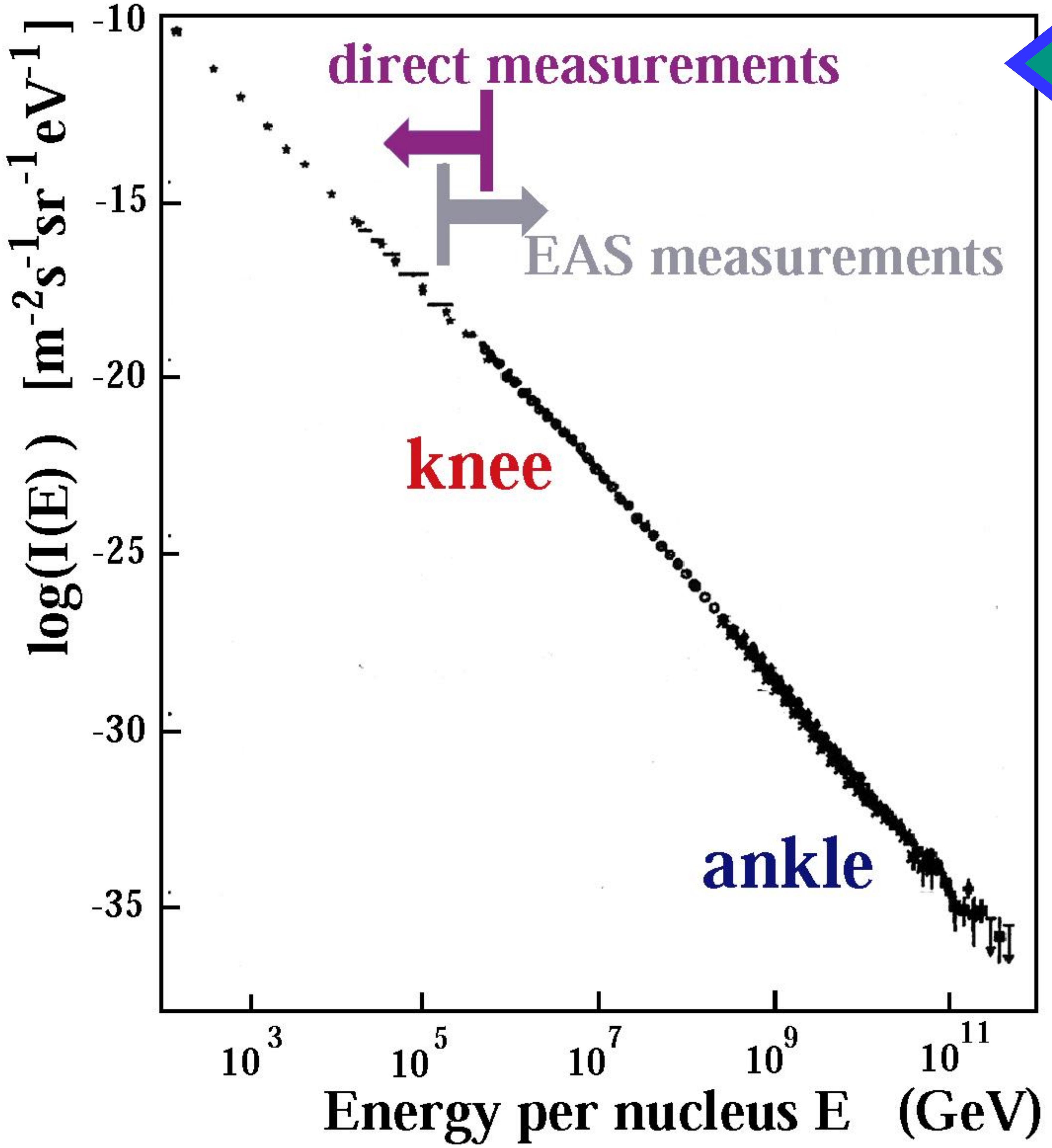
Multi-messenger observations to get the full picture

- ❖ independent measurements of different observables
- ❖ simultaneous observation of different messengers

Ongoing and upcoming projects

- Pierre Auger/ Phase II
- GCOS
- GRAND
- IceCube/IceCube-gen2
- POEMMA
- SKA
- CORSIKA 8

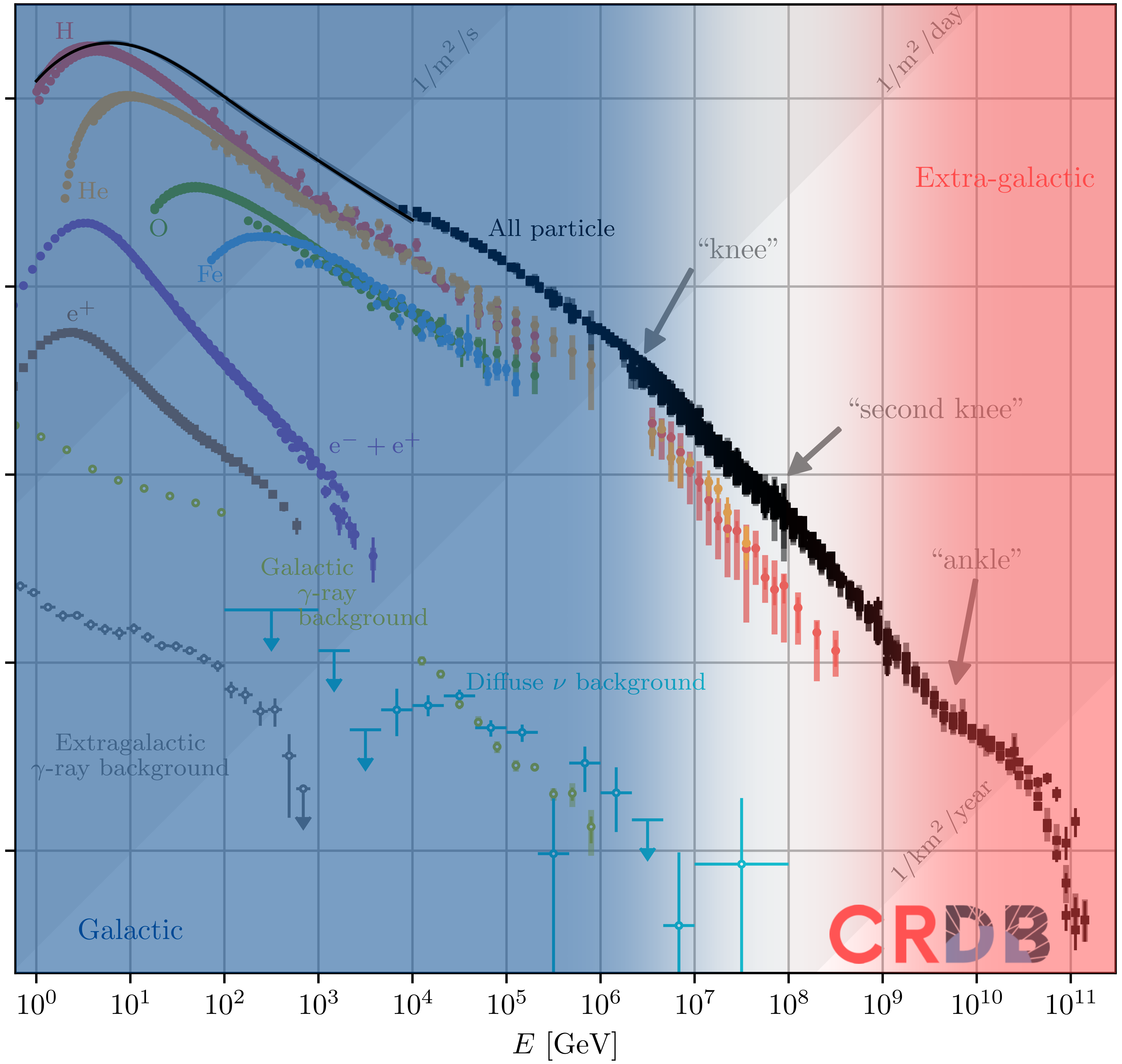
Physics with charged cosmic ray particles



- antimatter, dark matter, single mass spectra
- primary mass composition, anisotropy
- galactic sources, mass composition
- galactic →extragalactic, anisotropies
- CR astronomy, GZK physics, HE neutrinos, γ astronomy, MM, BSM, new physics …

Andreas Haungs

Galactic cosmic rays



Act as messengers of the most extreme environments

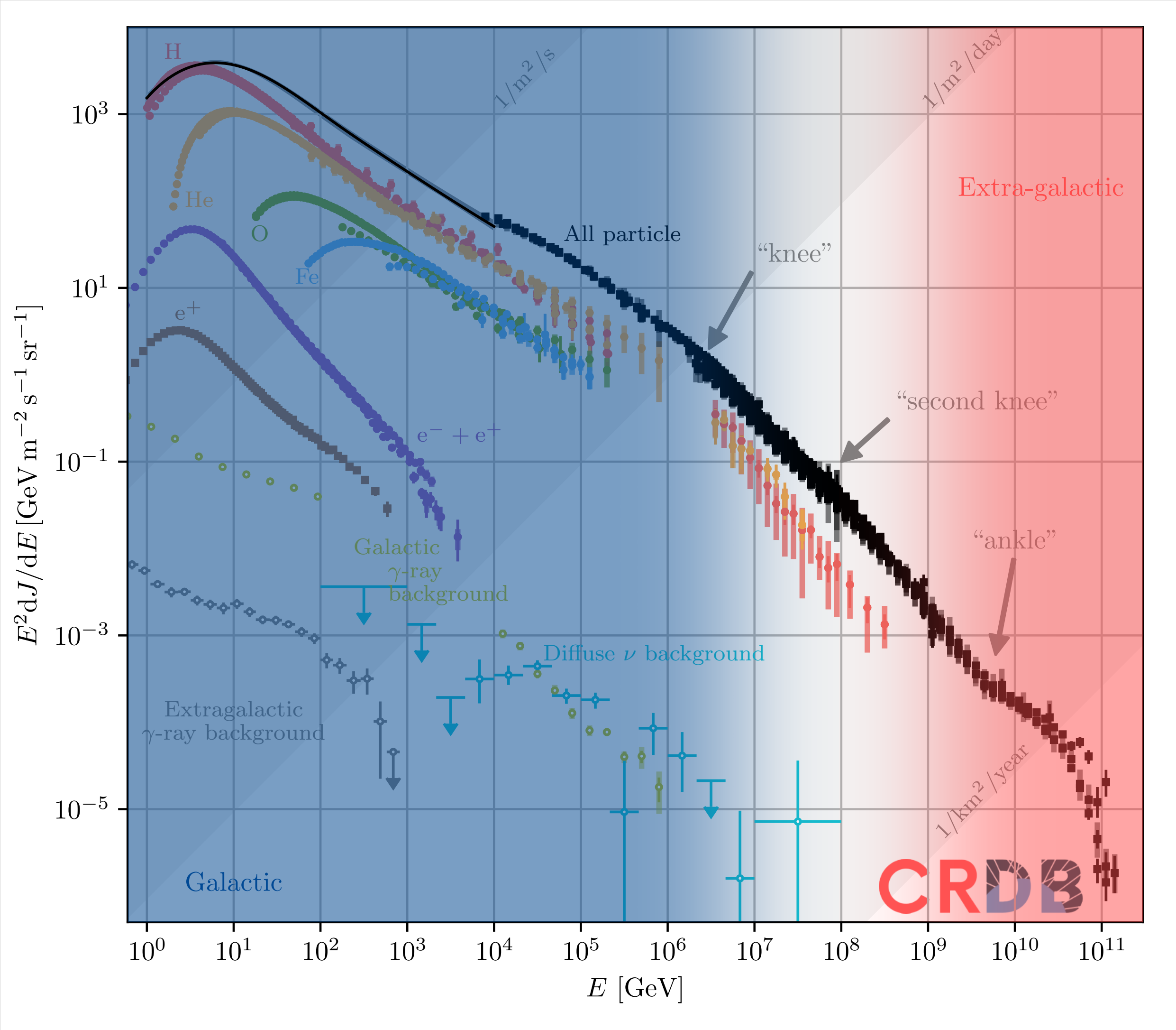
Affect the formation and evolution of galaxies

Probe exotic physics

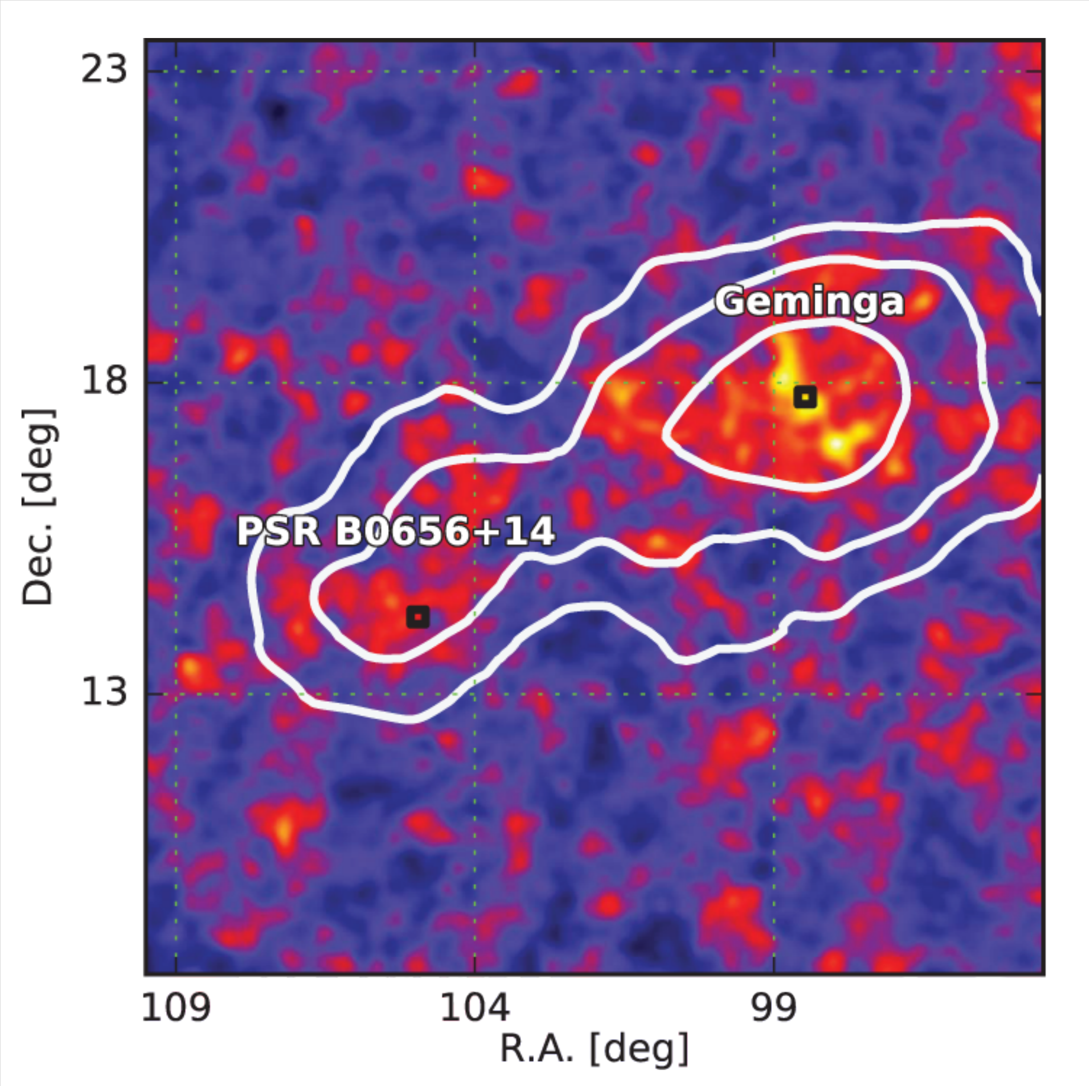
Above 10 PeV … 1 EeV, extra-galactic sources dominate

Philipp Mertsch

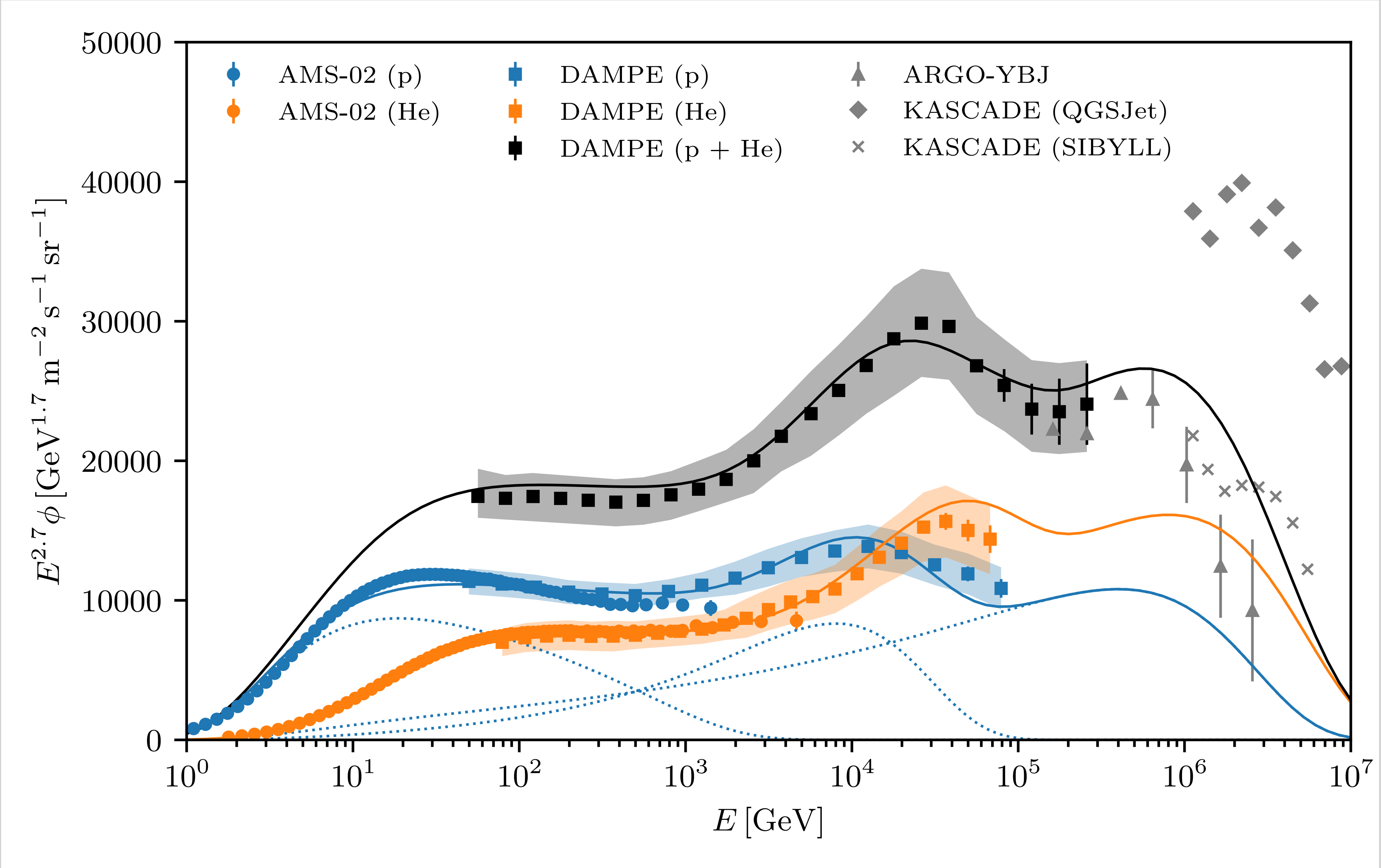
Open questions



How can shocks accelerate up to (at least) a few PeV?



What are the sources of high-energy e+: pulsar wind nebulae?



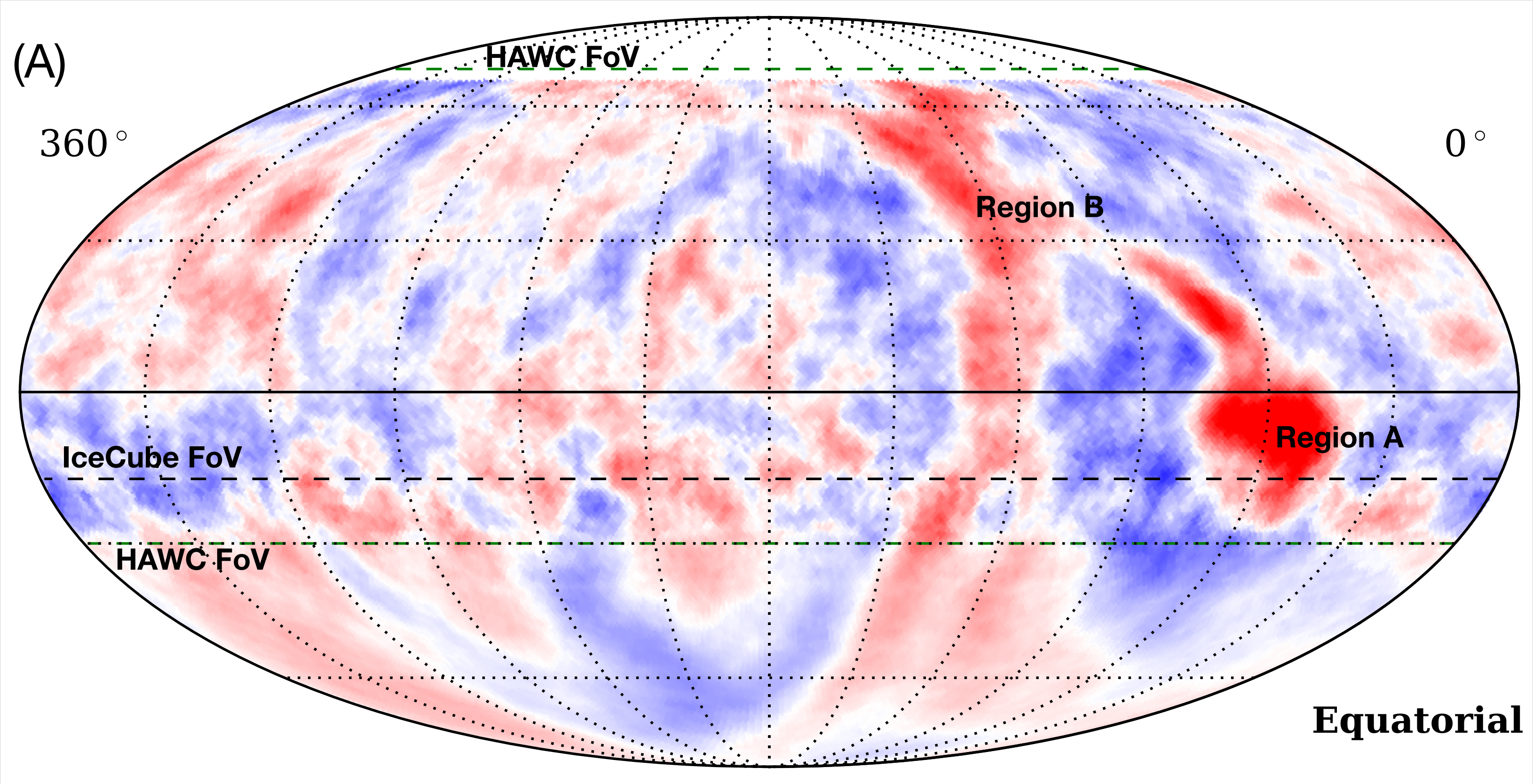
How can transport or source effects explain the various spectral breaks?

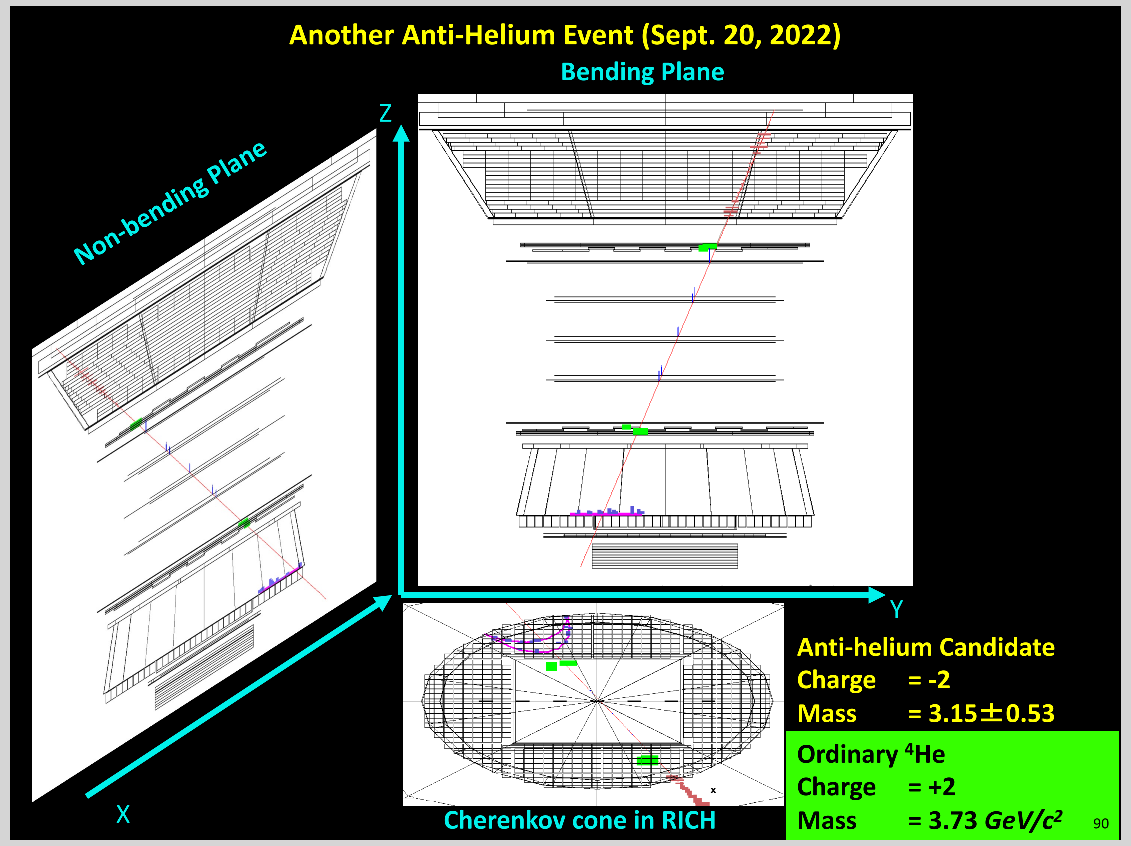
Extreme astrophysics

Galaxy evolution

Philipp Mertsch

Open questions (cont.)





What sources produce the observed anomalous abundances?

How do magnetic fields shape the anisotropies in arrival directions?

Does AMS-02 see primordial anti-helium?

Extreme astrophysics

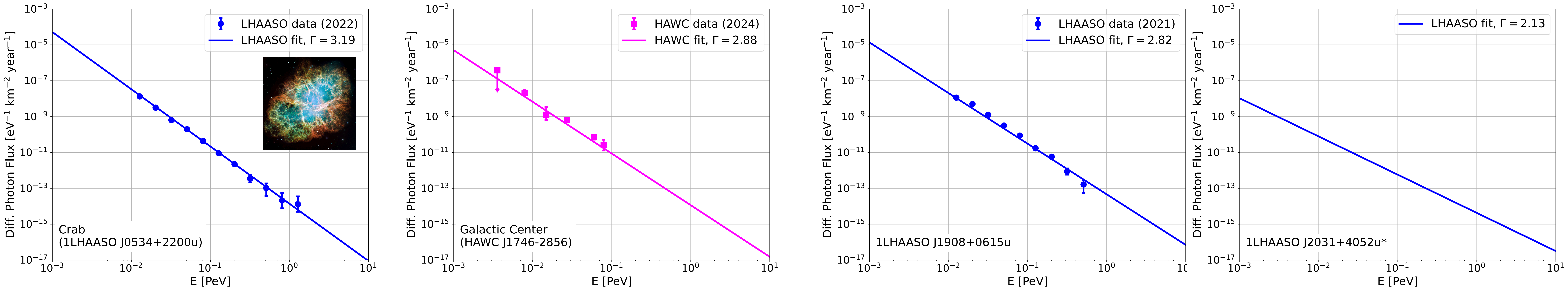
Galaxy evolution

Exotic physics

Searching for PeV Photons from Galactic PeVatrons

- **photons in the PeV range have been observed (LHAASO, HAWC) from galactic sources (“PeV γ-sources”)**
- **measure the UHE ($E \geq 10\ \mathrm{PeV}$) luminosity and study acceleration mechanisms with air shower arrays**

Energy spectra of four exemplary PeV γ-sources

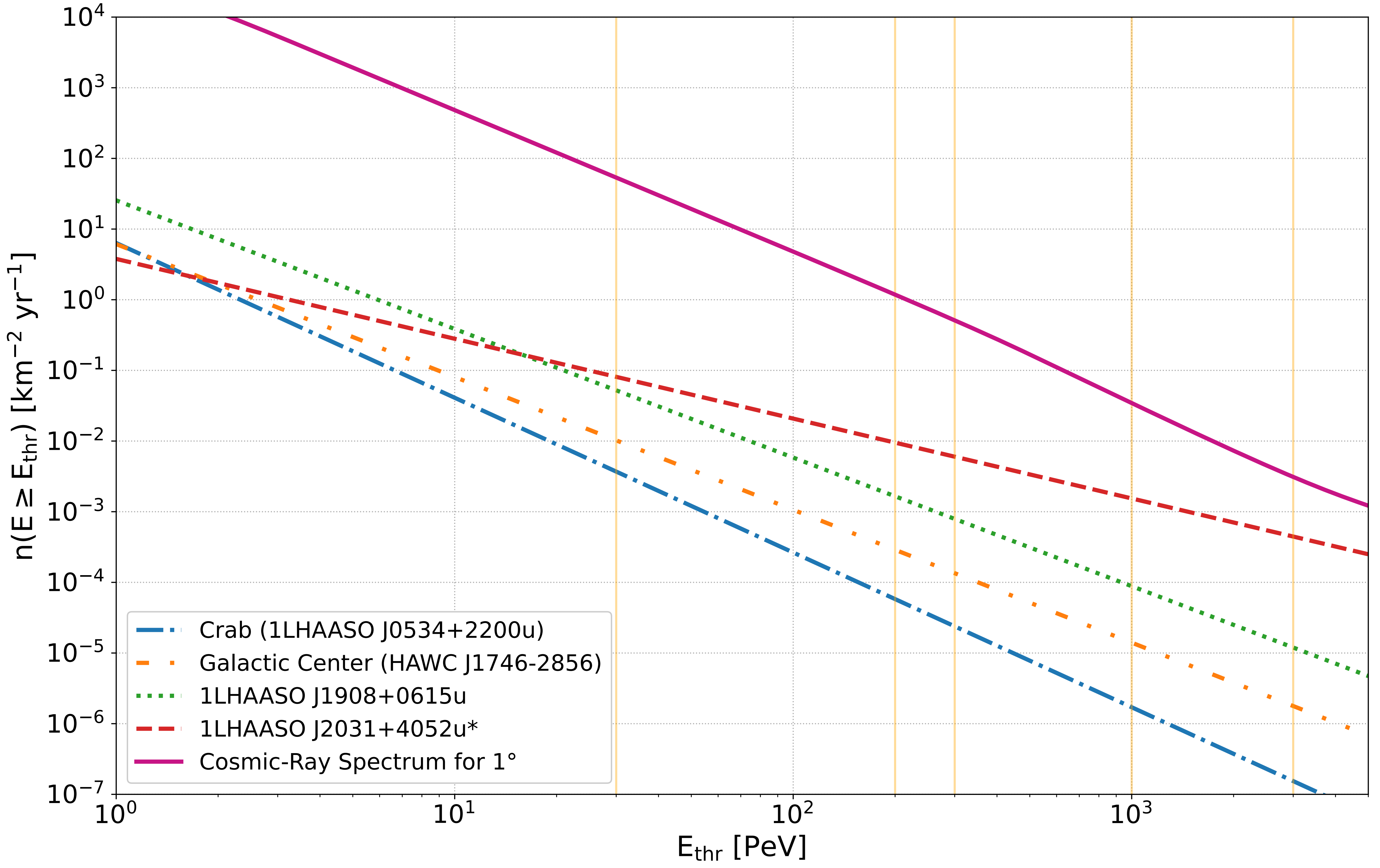


no visible cutoff: extrapolate the power-law spectra to higher photon energies

Funded by
DFG

[M. Niechciol, C. Papior, M. Risse, PoS (ICRC 2023) 557]
[M. Niechciol, C. Papior, M. Risse, publication in preparation]

Integral number of photons n_γ reaching Earth above threshold energy E_{thr}



CRPropa study: interactions with cosmic background fields in the propagation small to negligible

Comparison to cosmic-ray flux: background suppression to a level of about 10^{-3} to 10^{-4} needed

Observing UHE photons from PeV γ-sources seems challenging with current detectors.

Lowering the energy threshold and new dedicated detectors would be very useful.

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[M. Niechciol, C. Papior, M. Risse, PoS (ICRC 2023) 557]

[M. Niechciol, C. Papior, M. Risse, publication in preparation]

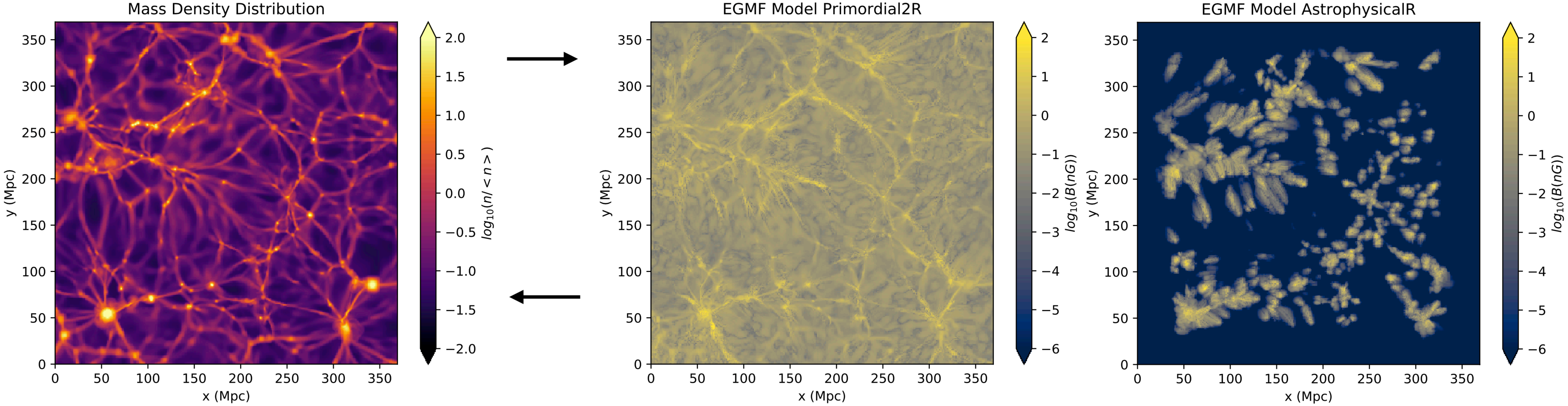
Understanding the CR anisotropy

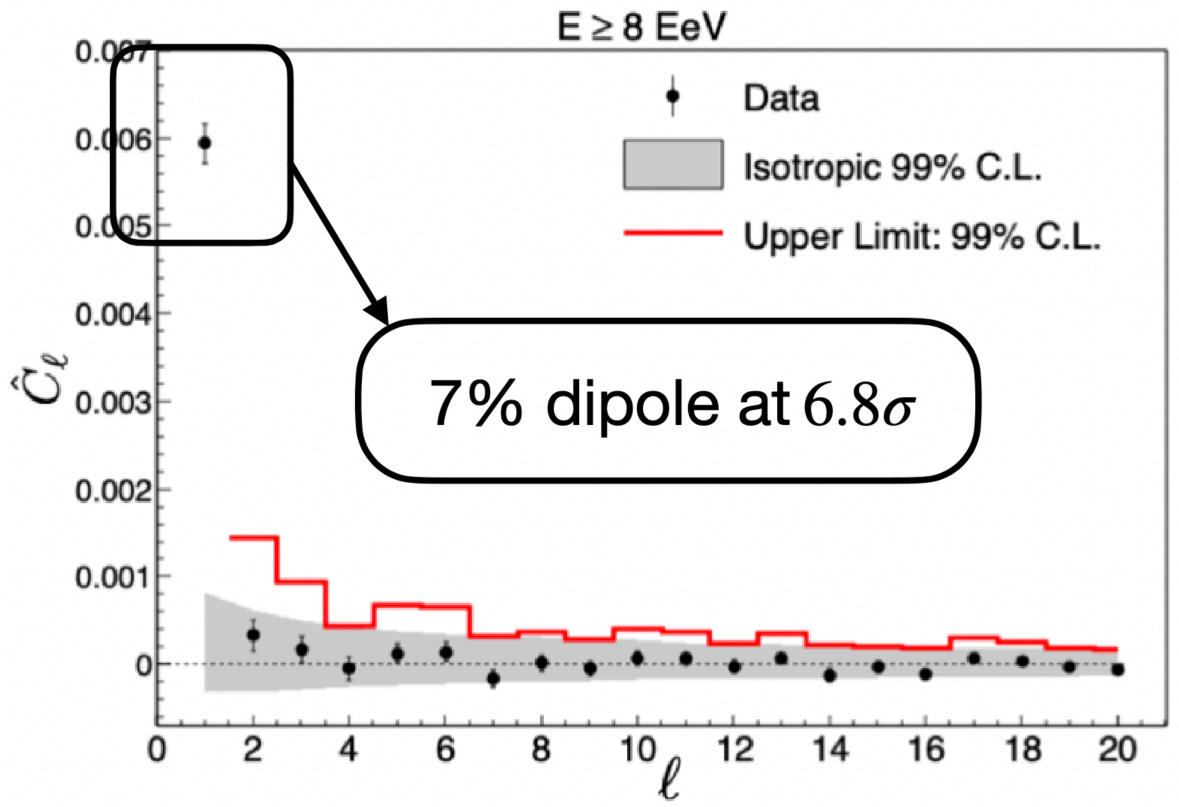
extragalactic UHECR propagation through 2 models of B-fields constrained by baryon distribution at z=60

Baryon distribution

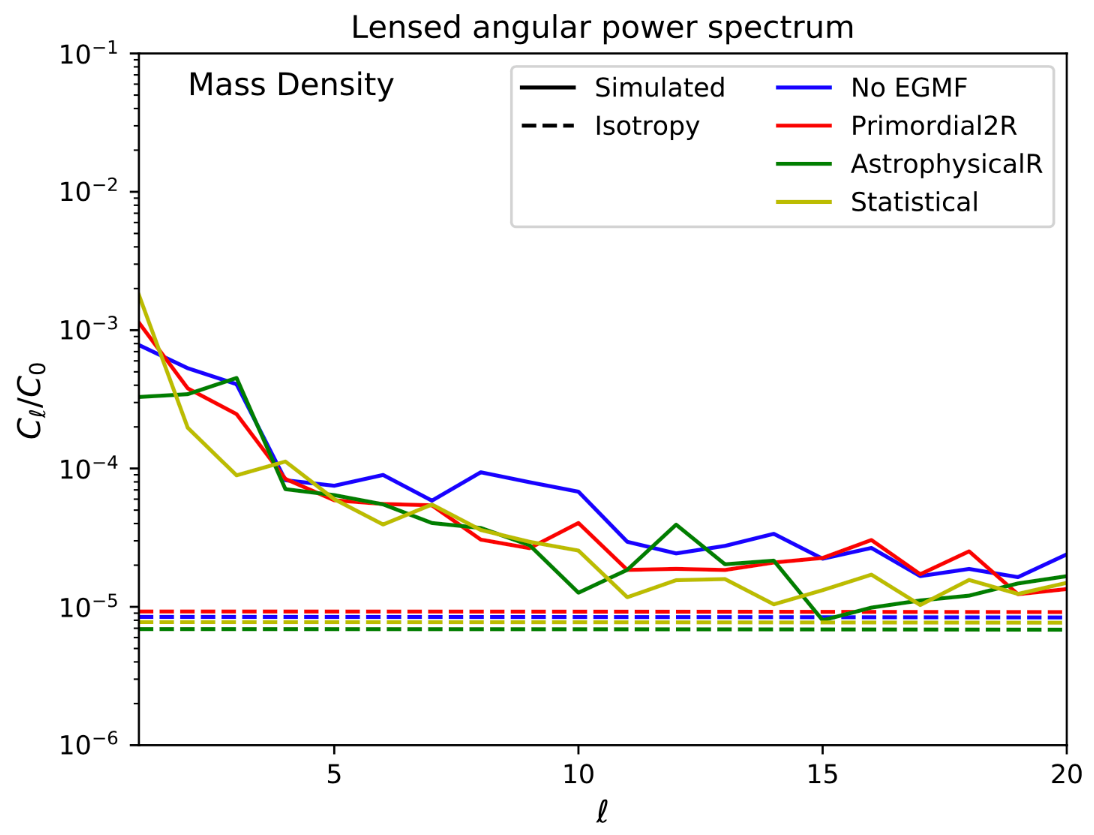
Extragalactic magnetic field

S.Hackstein et al, Mon. Not. R. Astron. Soc. (2017)





Pierre Auger Collaboration, APJ (2024)



GS and S. Rossoni, Hamburg group

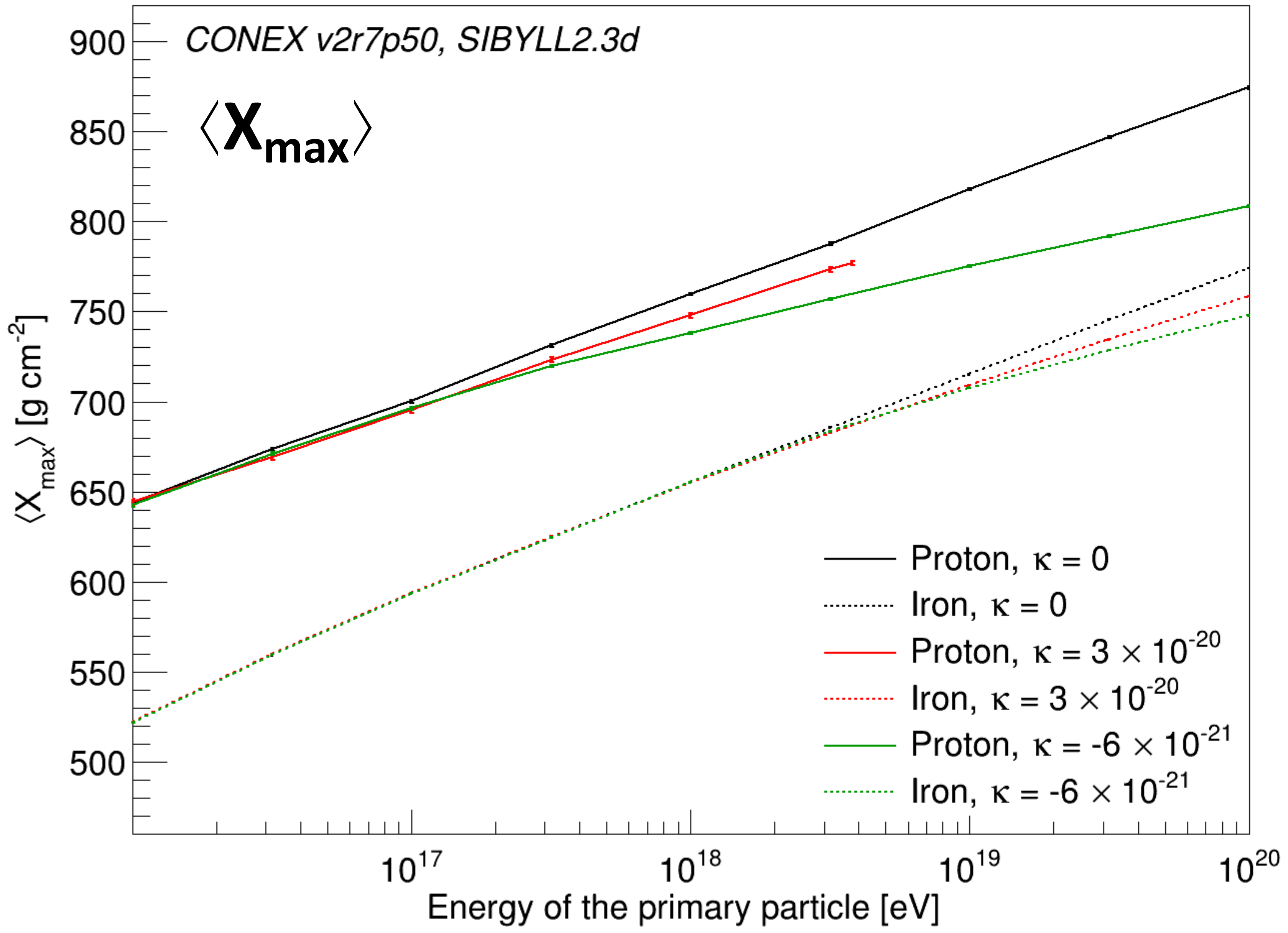
- UHECR simulations can in general reproduce the observed dipole
- Higher multipoles are difficult to reproduce together with the dipole

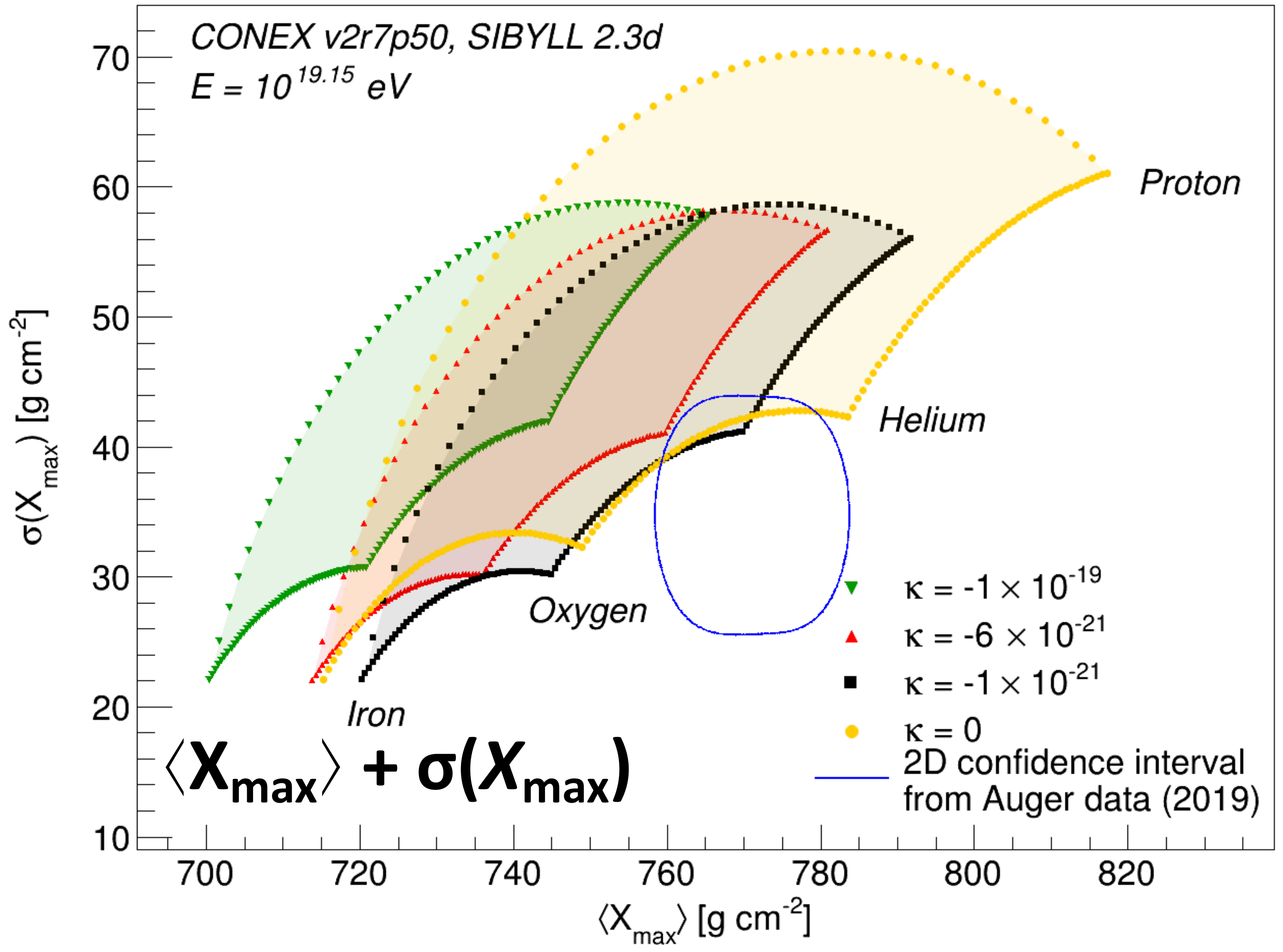
Günter Sigl

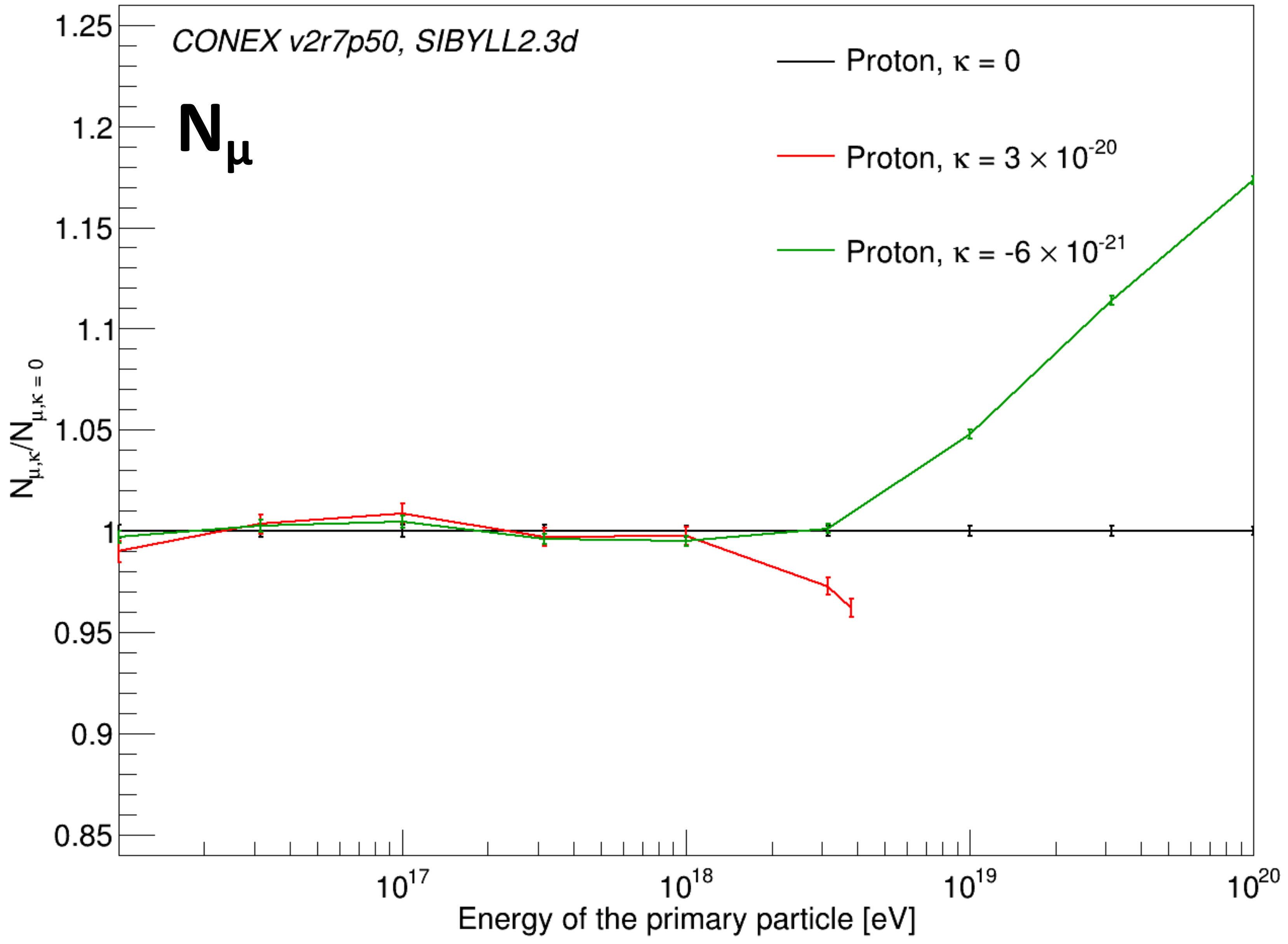
Probing Lorentz violation with UHECR using air showers

Lorentz invariance violation can occur in models combining QM and gravity

- **processes forbidden in the SM like photon decay or vacuum Cherenkov radiation**
- **effect of these processes on the development of an air shower in the atmosphere**



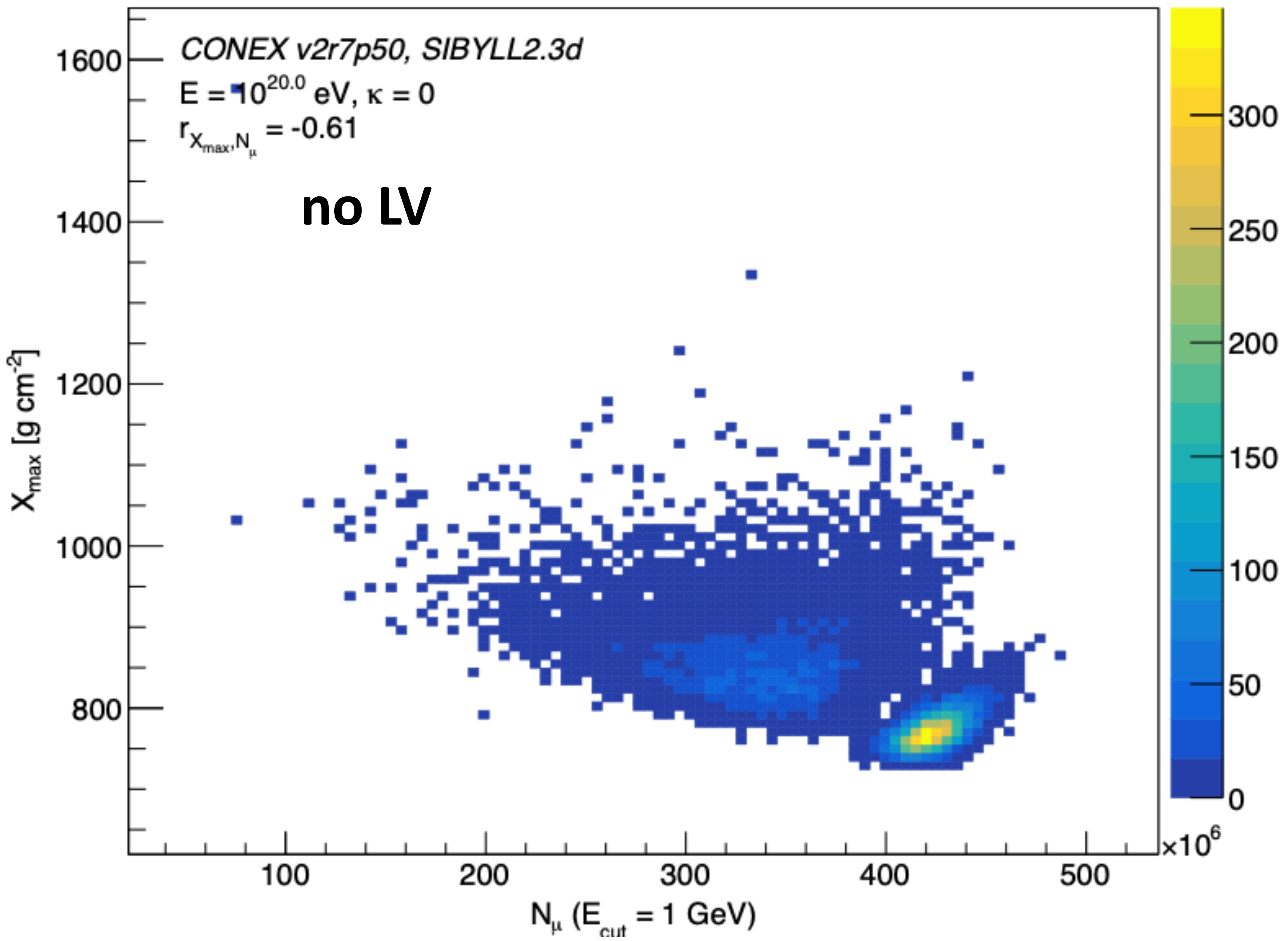


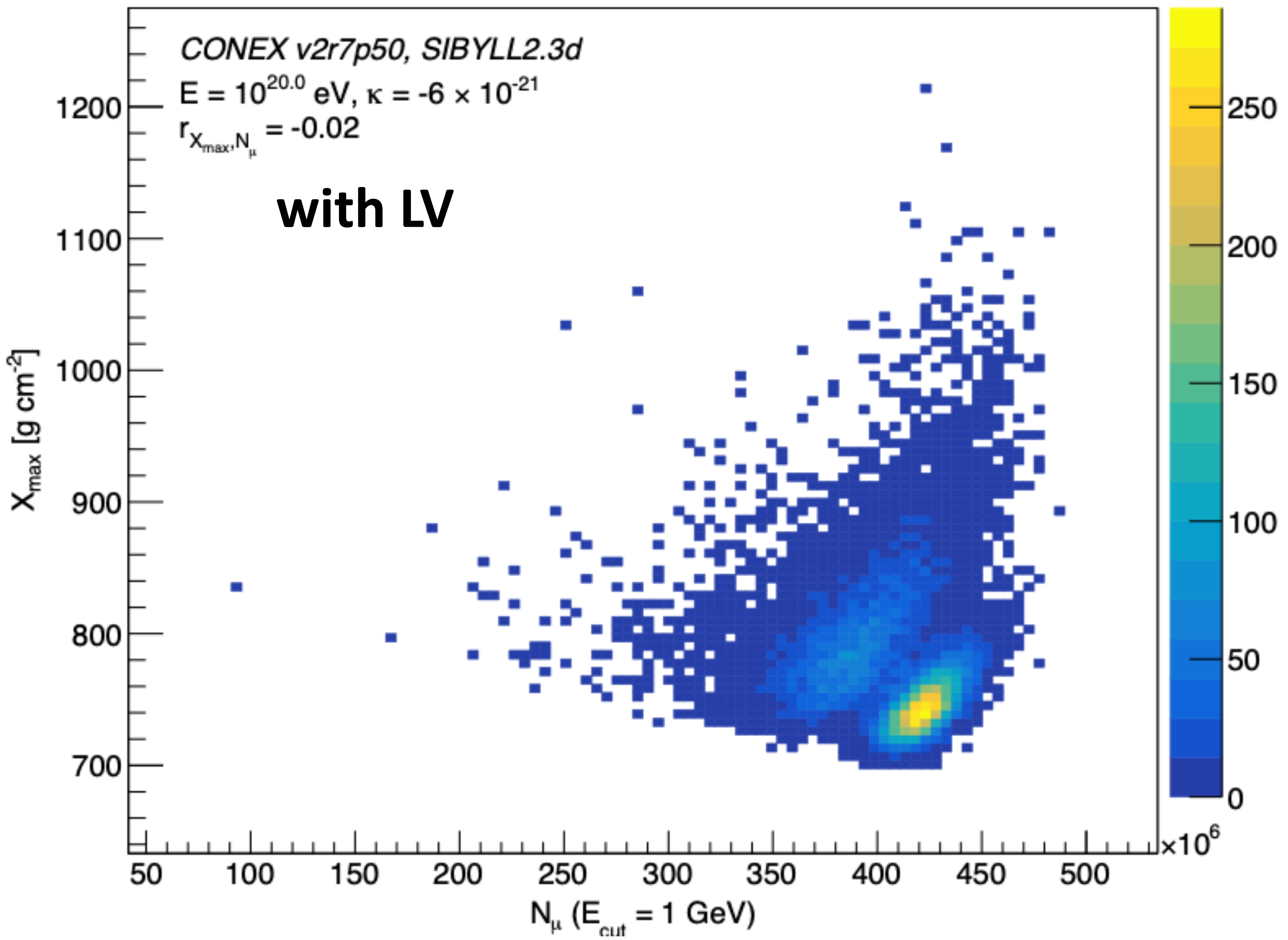


most stringent limits on isotropic, nonbirefringend Lorentz violation in the photon sector from comparing MC with X_{max} data from the Pierre Auger Observatory

future: study correlation between X_{max} and N_μ as a function of A

expectations for proton and iron primaries





Funded by
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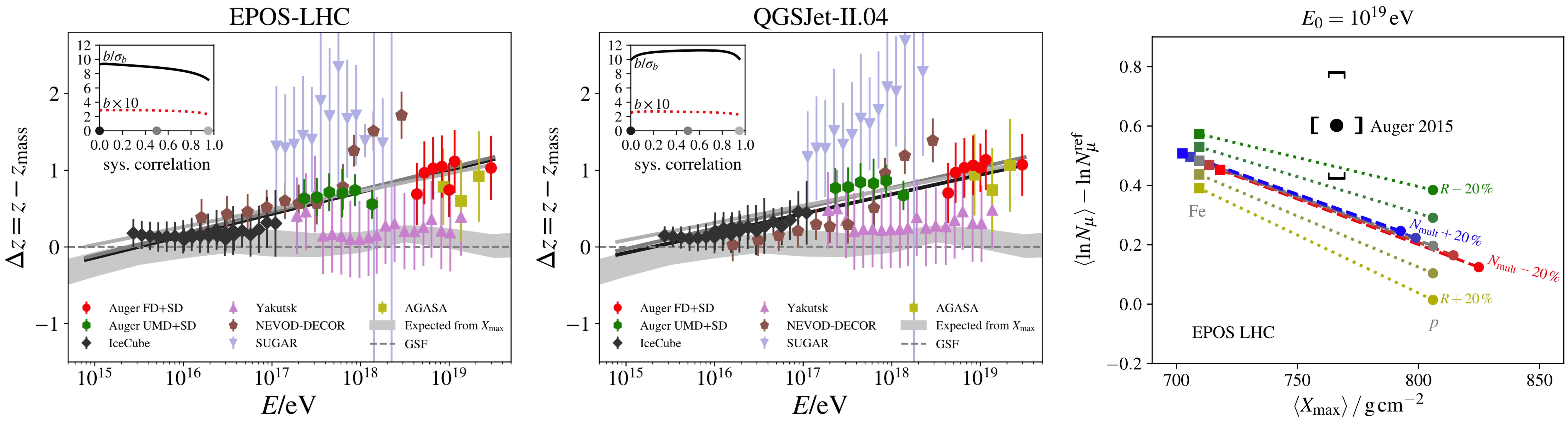
[F.R. Klinkhamer, M. Niechciol, M. Risse, Phys. Rev. D 96 (2017) 116011]
[F. Duenkel, M. Niechciol, M. Risse, Phys. Rev. D 105 (2021) 015010]
[F. Duenkel, M. Niechciol, M. Risse, Phys. Rev. D 107 (2023) 083004]
[F. Duenkel, M. Niechciol, M. Risse, PoS (ICRC 2023) 217]

Hadronic interactions and the Muon Puzzle

Hadronic interactions are not well understood…



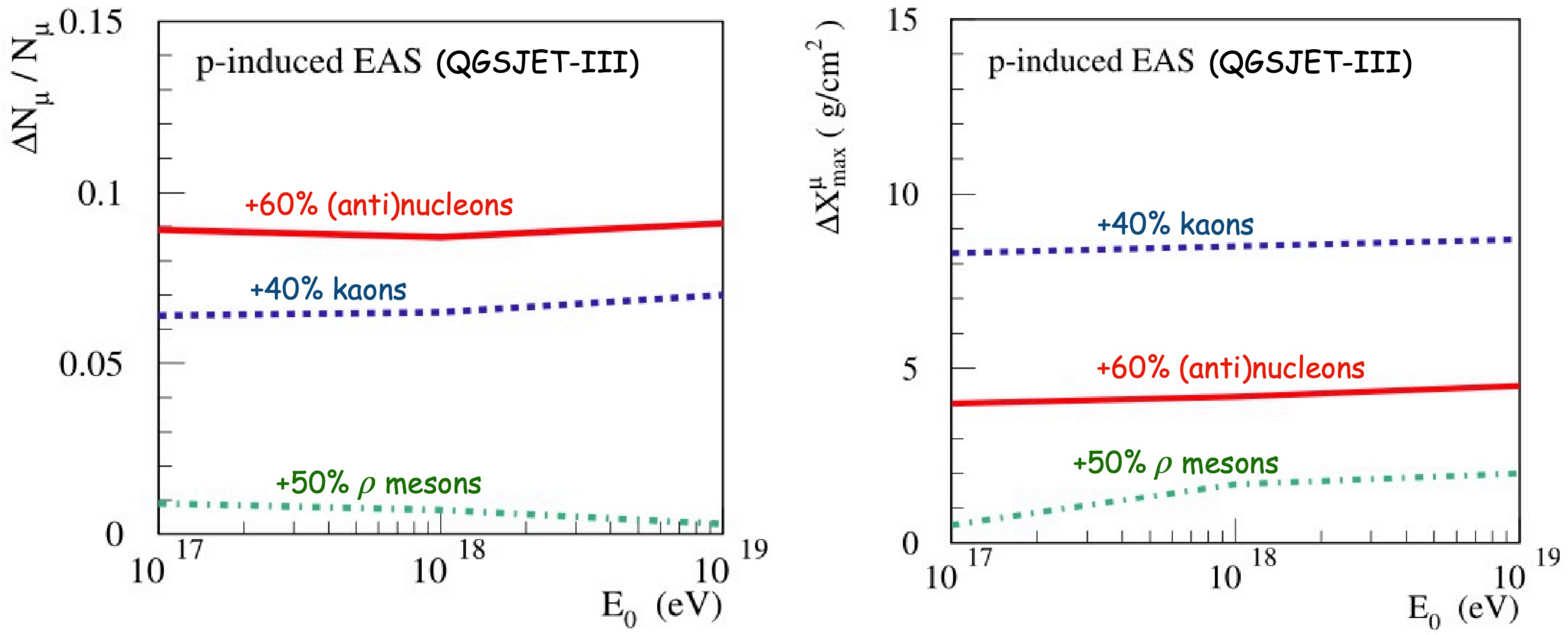
Astrophysics. Space Sci. 367(2022)3

comparing measured and expected muon number

$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p^{MC}}{\ln\langle N_\mu \rangle_{Fe}^{MC} - \ln\langle N_\mu \rangle_p^{MC}}$$

➤ **at high energies all models predict too few muons**

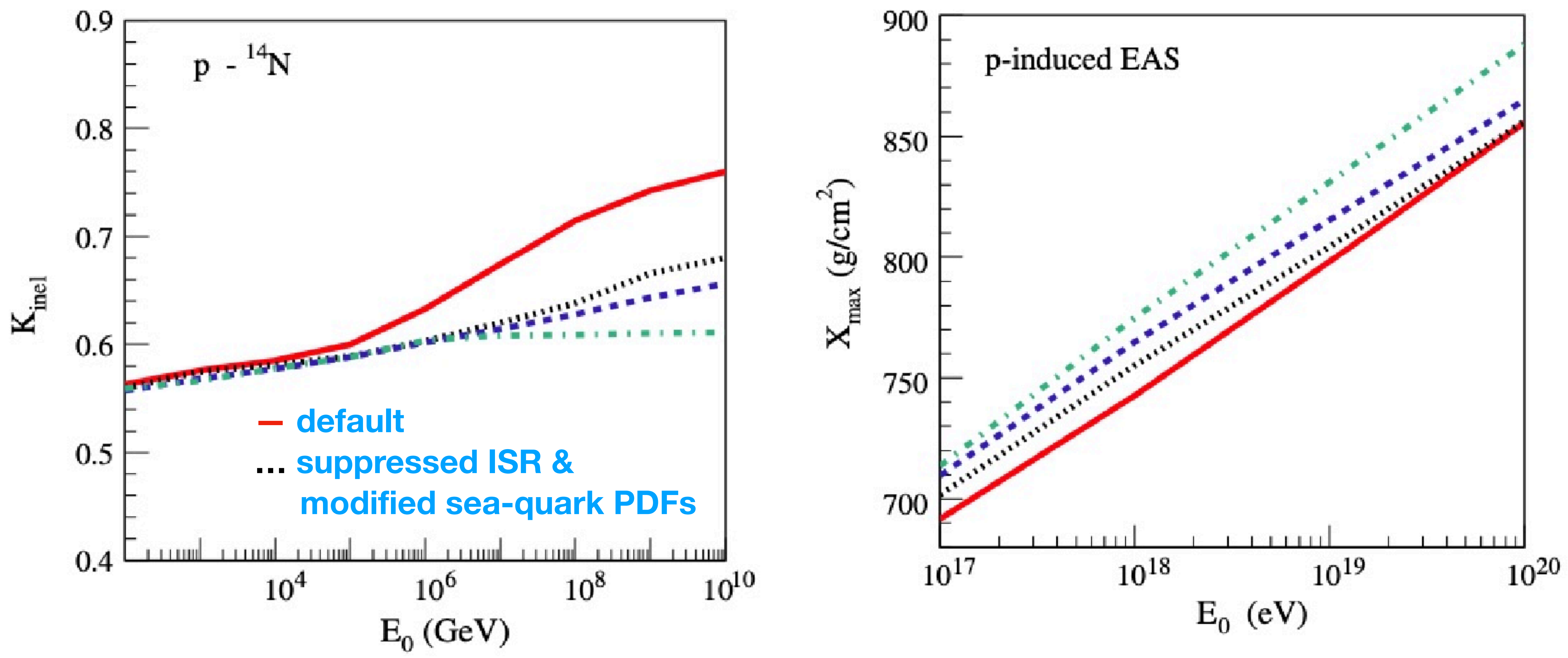
Modifying particle fractions and the modelling of the hard processes



S. Ostapchenko and G. Sigl, Astropart. Phys. 163 (2024) 103004 [arXiv:2404.02085]

muon number can increase by ~ 10% without contradicting accelerator data

all modifcation increase the tension with X_{max} from Pierre Auger data



S. Ostapchenko and G. Sigl, Phys. Rev. D 110 (2024) 063041 [arXiv:2409.05501]

muon deficit from cascade as a whole

study with CORSIKA 8 and new data

➡ p-O and O-O collisions at the LHC

➡ fixed target experiments (NA61/SHINE, LHCb)

➡ new forward physics facilities (FPF)

CORSIKA 8

Heidelberg 2022 workshop:
38 participants

Karlsruhe 2023 workshop:
23 participants on site,
20 via Zoom

- modern re-implementation of CORSIKA in C++
- focus on modularity and more flexibility
- showers in inhomogenous media e.g. from air into ice
- true community effort coordinated by KIT

Status

❖ state-of-the-art models for hadronic interactions:

- QGSJETII-04, Sibyll 2.3d, EPOS-LHC, FLUKA, SOPHIA
- cooperation with HEP community: inclusion of PYTHIA 8

❖ state-of the art model for e/m interactions: PROPOSAL

❖ radio-emission calculation included from the beginning

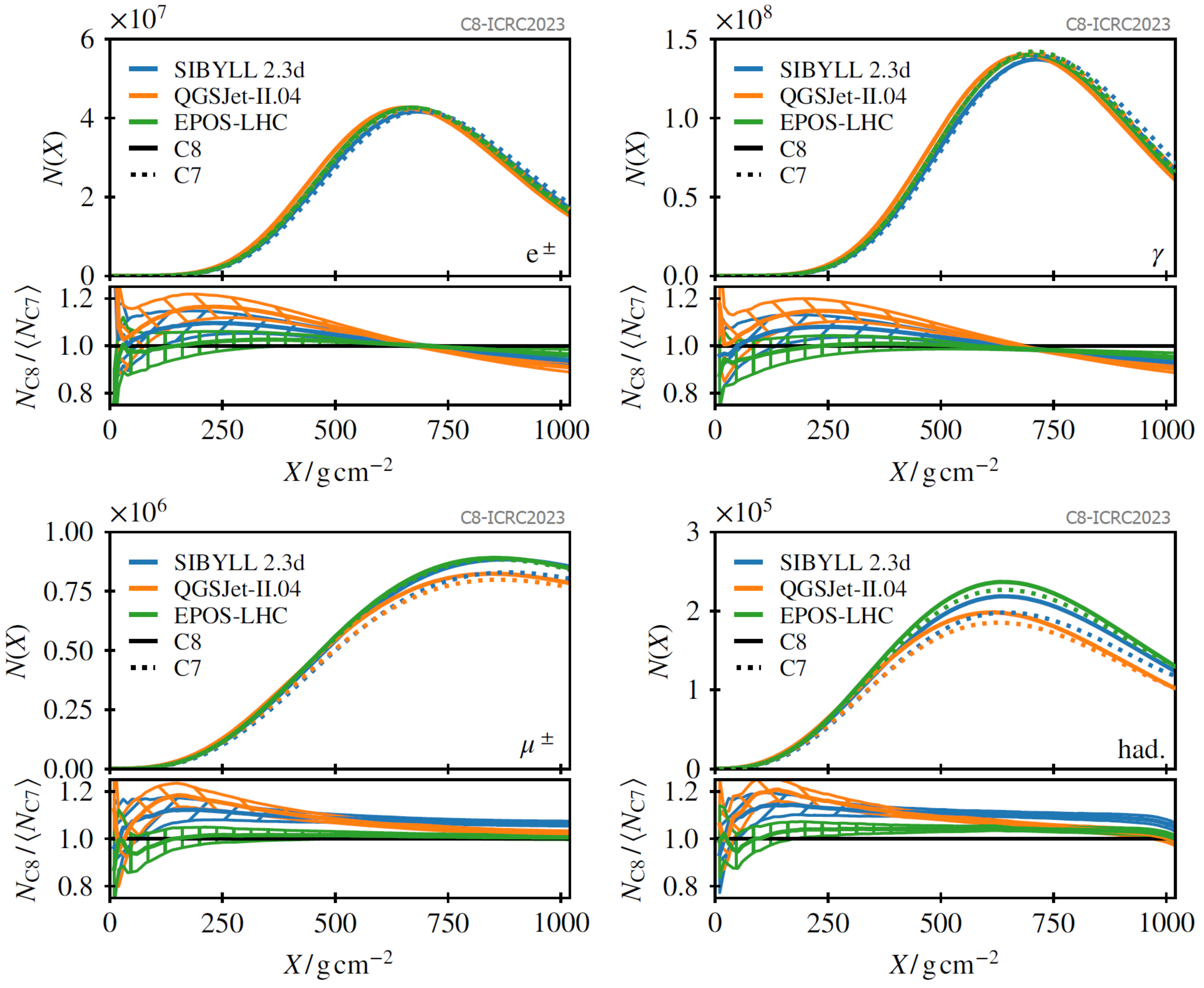
❖ Cherenkov-light calculation included recently

❖ extensive validation against CORSIKA 7 successful

❖ code is „physics-complete“

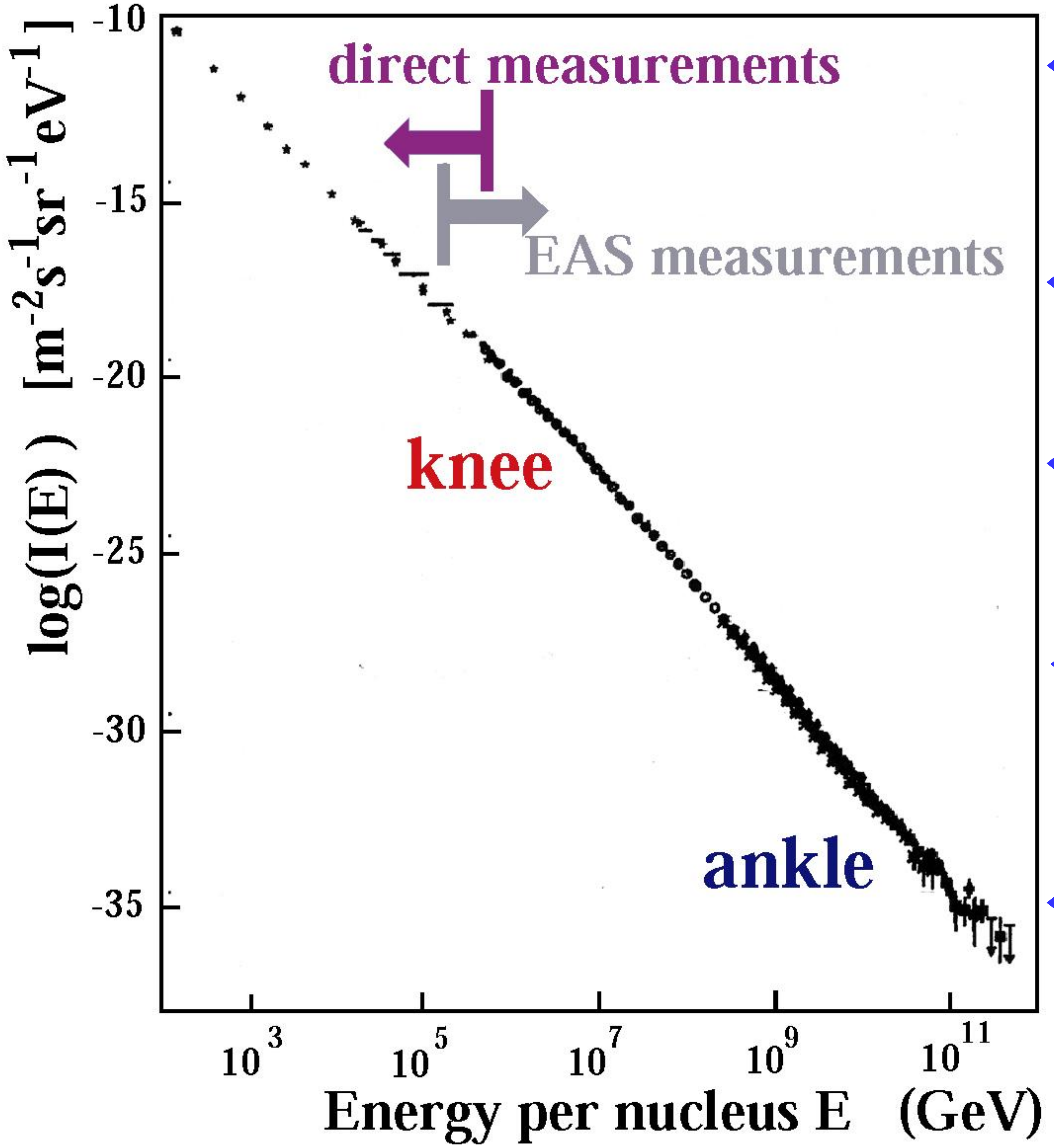
- still needs improvements for end users
- first „expert-level release“ by end of 2024

comparison CORSIKA7 - CORSIKA 8



➤ modelling of hadronic showers agrees at the 5-10% level

Cosmic ray experiments w/ German contribution



ATIC, CREAM, Tiger, …
Pamela, **AMS**

ISS-CREAM

SWGO, LHAASO, GRAPES, **KCDC**, …

IceCube(-Gen2)
Tunka-133 / HiSCORE, **SKA-CR**, …

Auger(Prime), TA,
GCOS, GRAND,
POEMMA

balloon

space

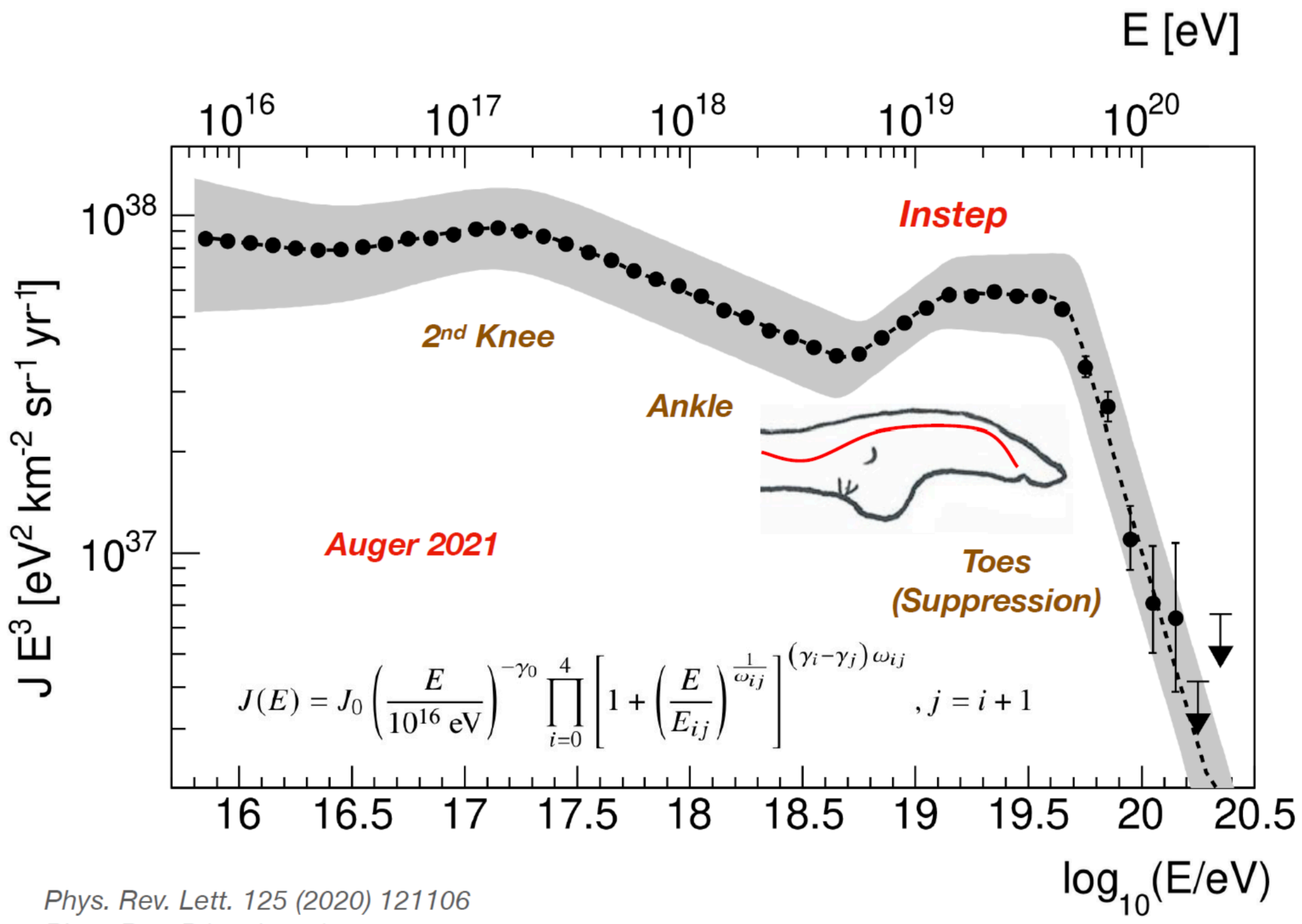
surface

space

Andreas Haungs

Pierre Auger Observatory Phase I - until 2021

All-particle cosmic ray spectrum at the highest energies

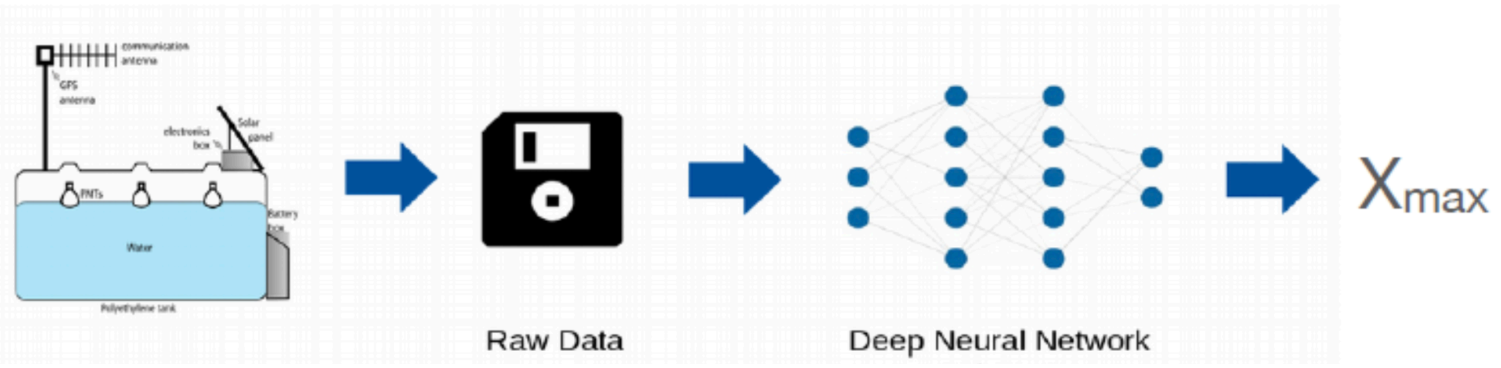


Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
Eur. Phys. J. C81 (2021) 966

Uncertainty dominated by 14% sys. energy scale

Instep not compatible with source models dominated by single mass group (p, …, Fe)

Improved composition analysis using Deep Neural Nets

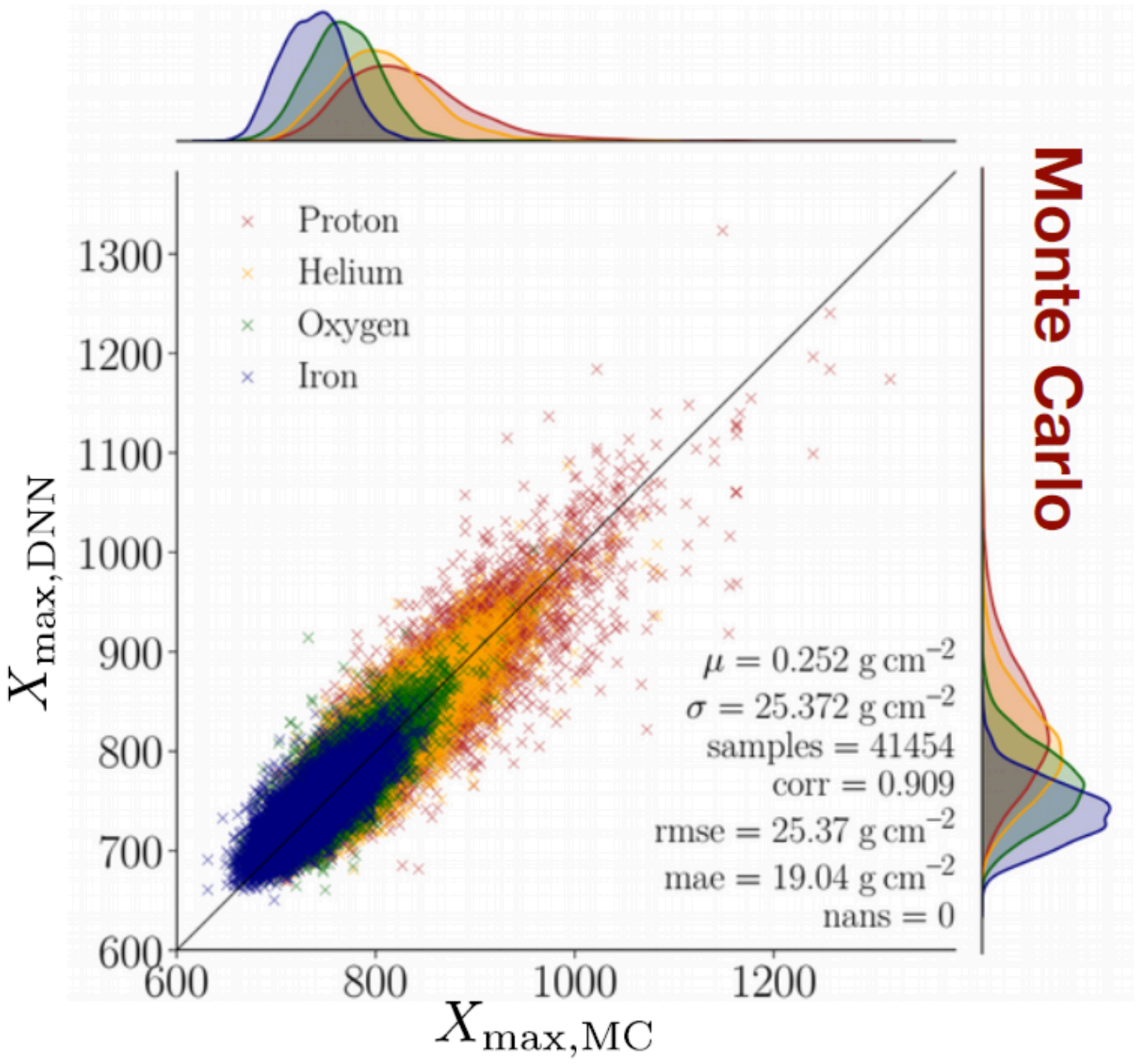


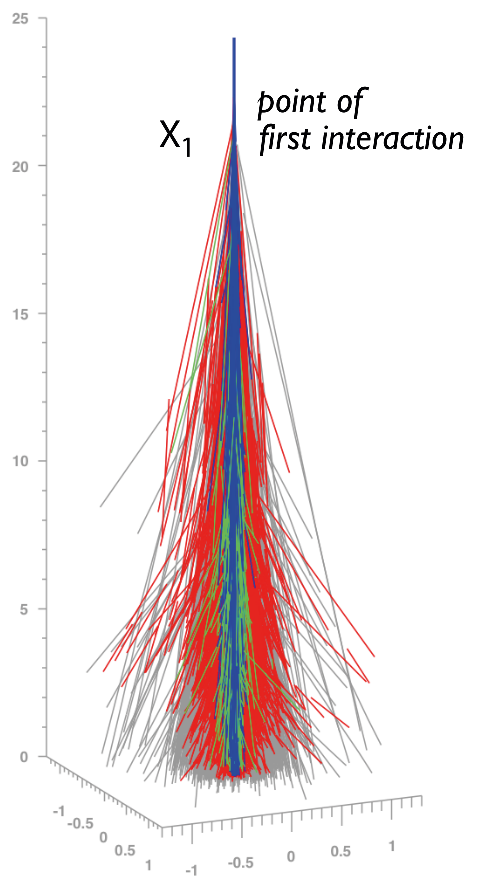
Relation between X_{max} and A

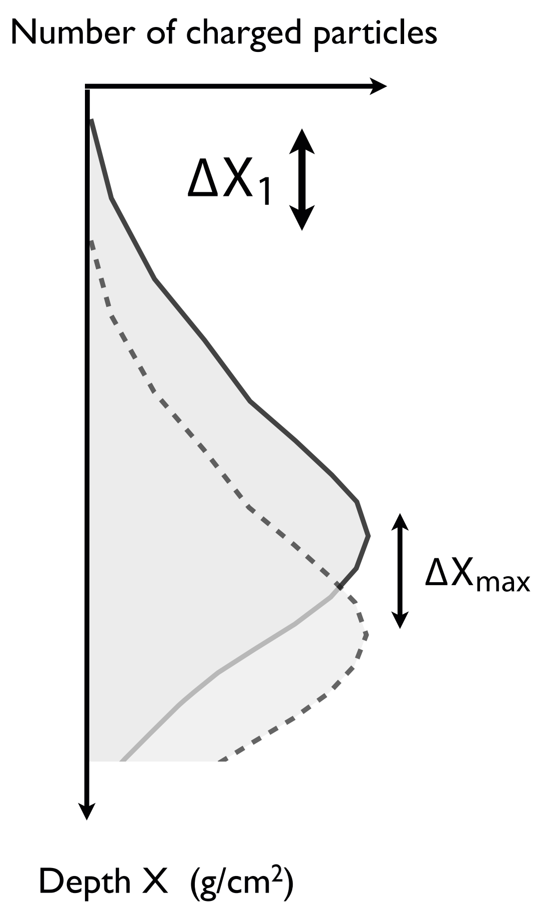
$$\langle X_{max} \rangle \propto \ln A + D \ln \frac{E}{E_0}$$

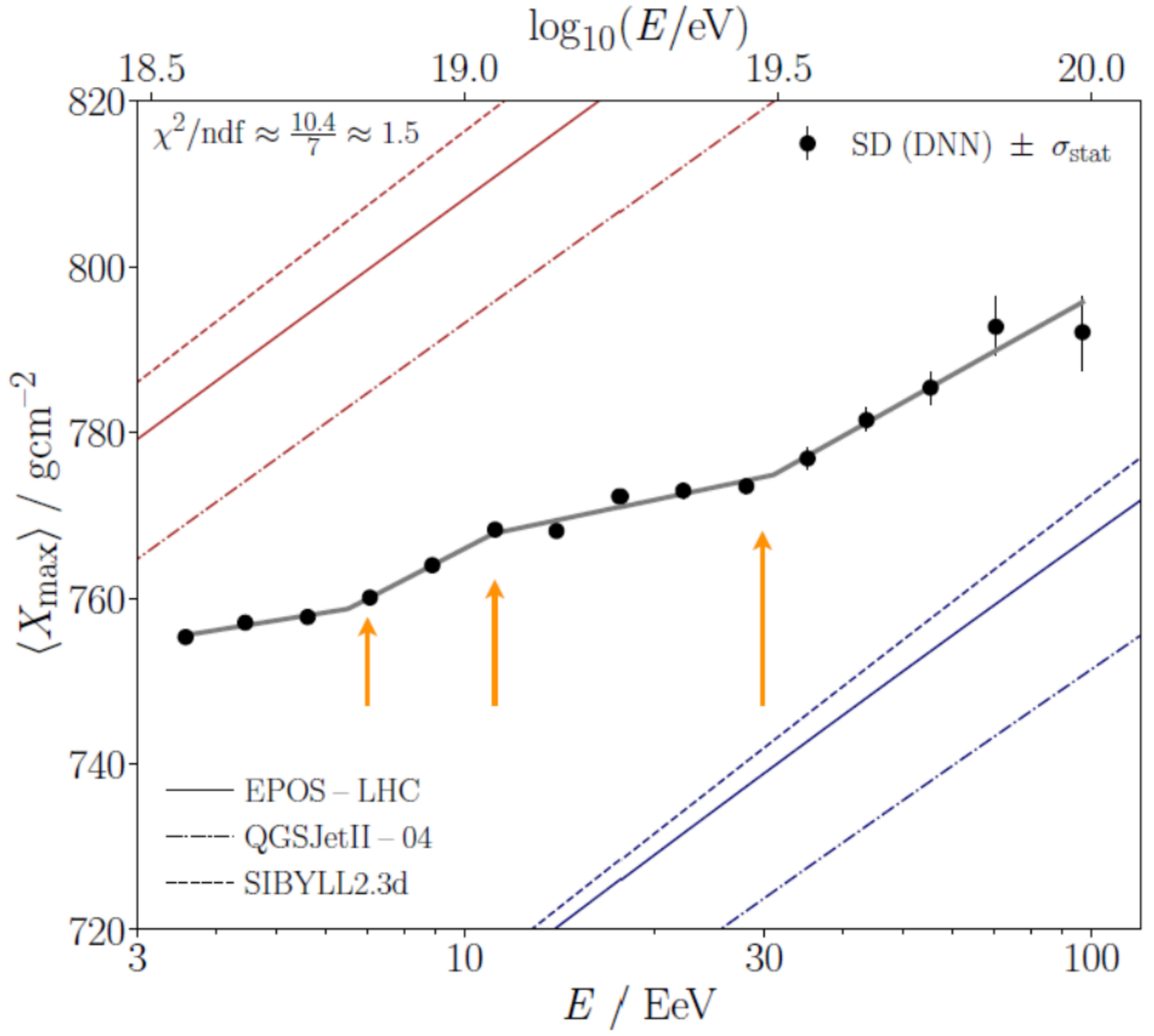
result: breaks in composition which coincide with features of the spectrum

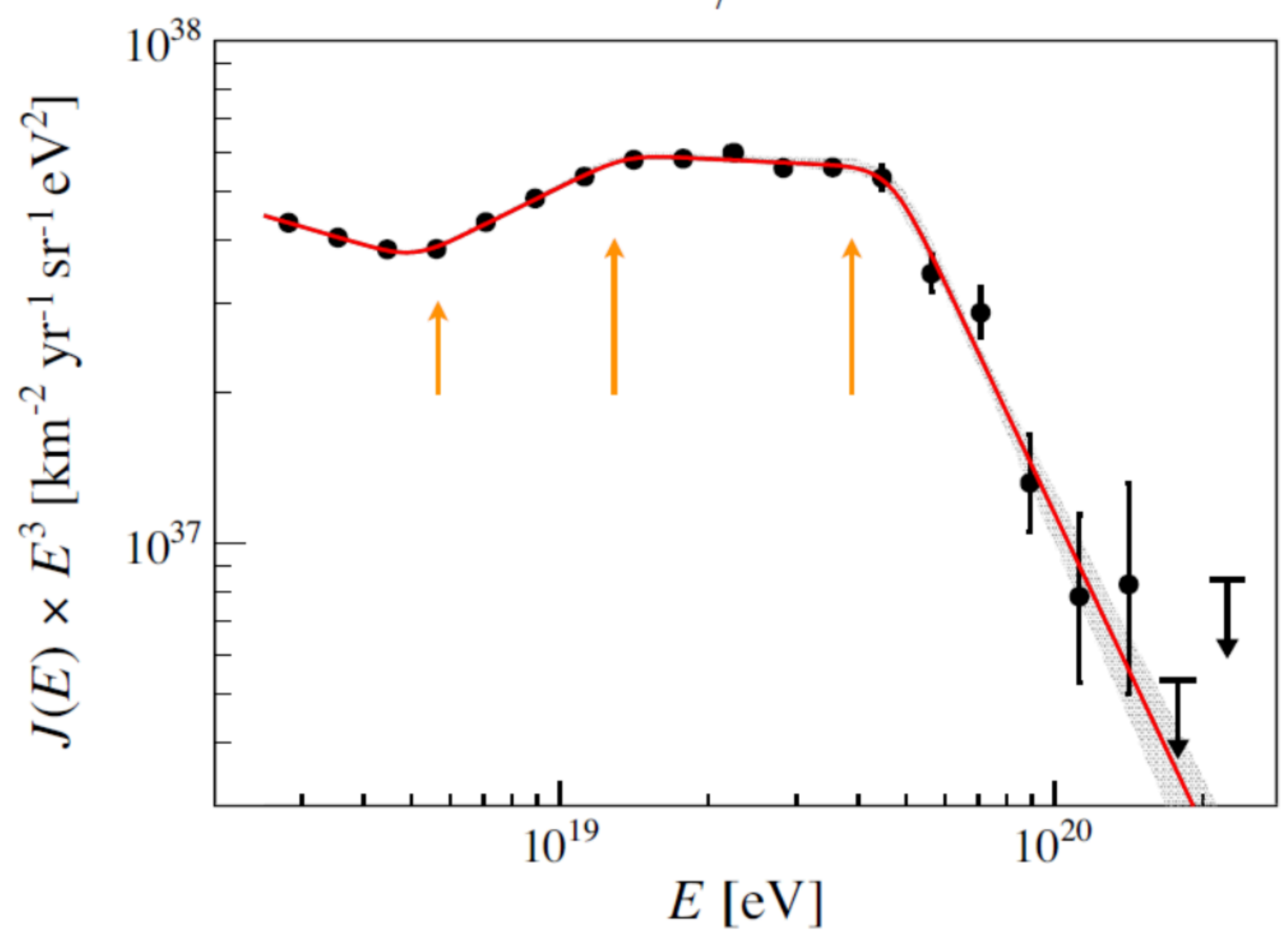
Verification of ML analysis by MC





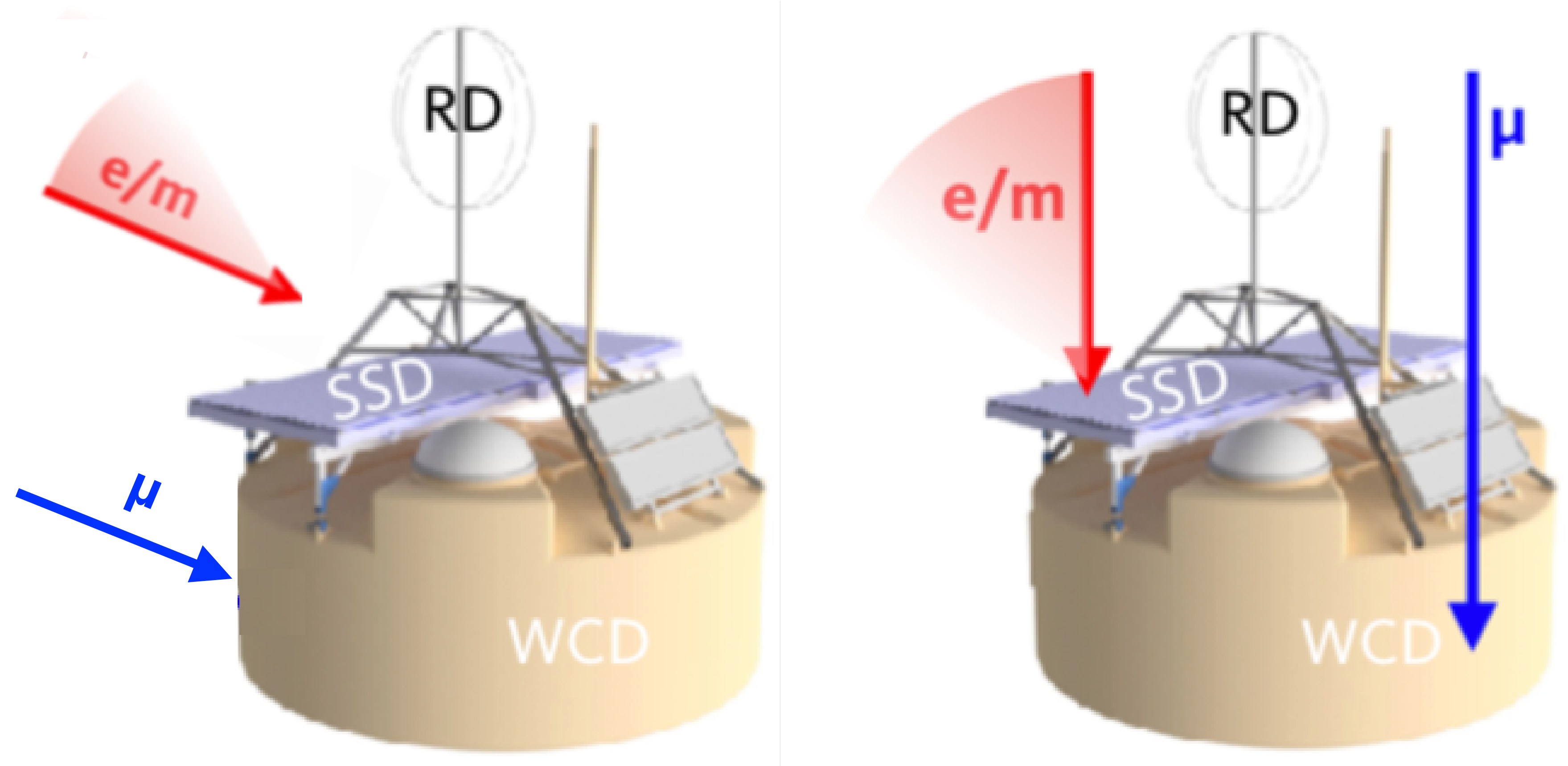






Pierre Auger Observatory Phase II

formal signing ceremony in November 2024

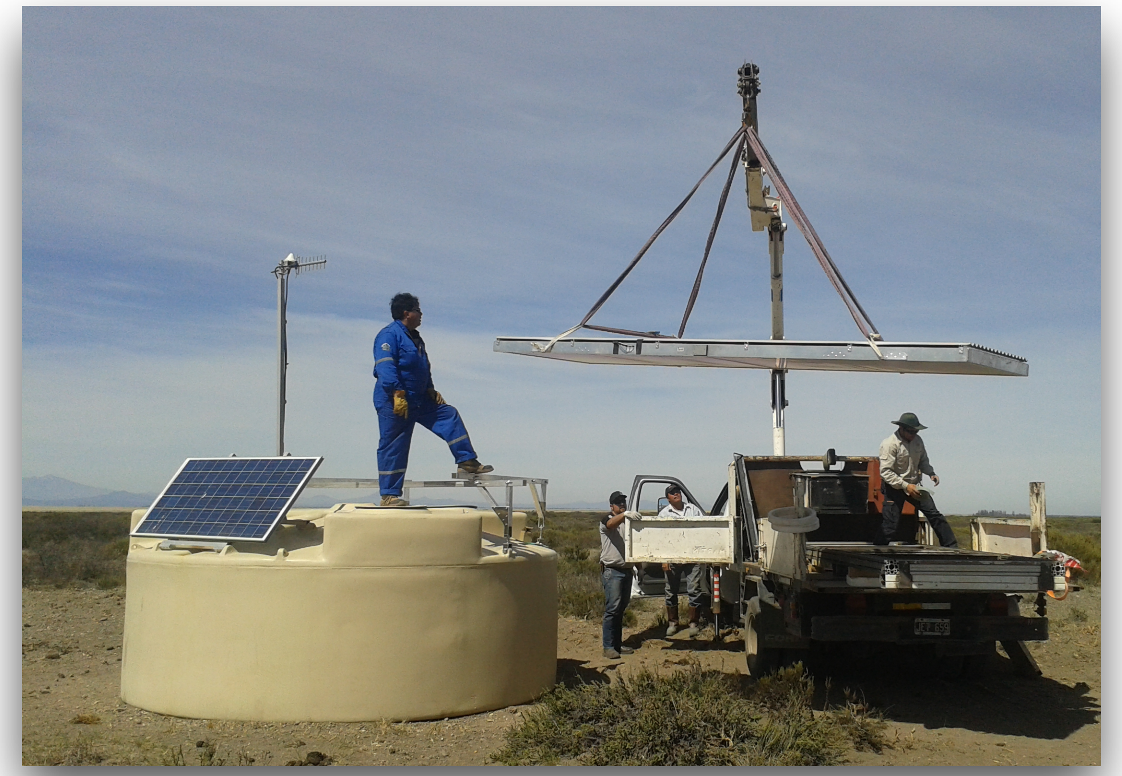


Improve surface detectors to discriminate between e/m and muon component, and to measure zenith angles > 60 deg

- **Scintillator Detector (SSD) < 60 deg**
- **Radio Detector (RD) > 60 deg**

In addition: underground muon detector

Scintillators: 1450 installed

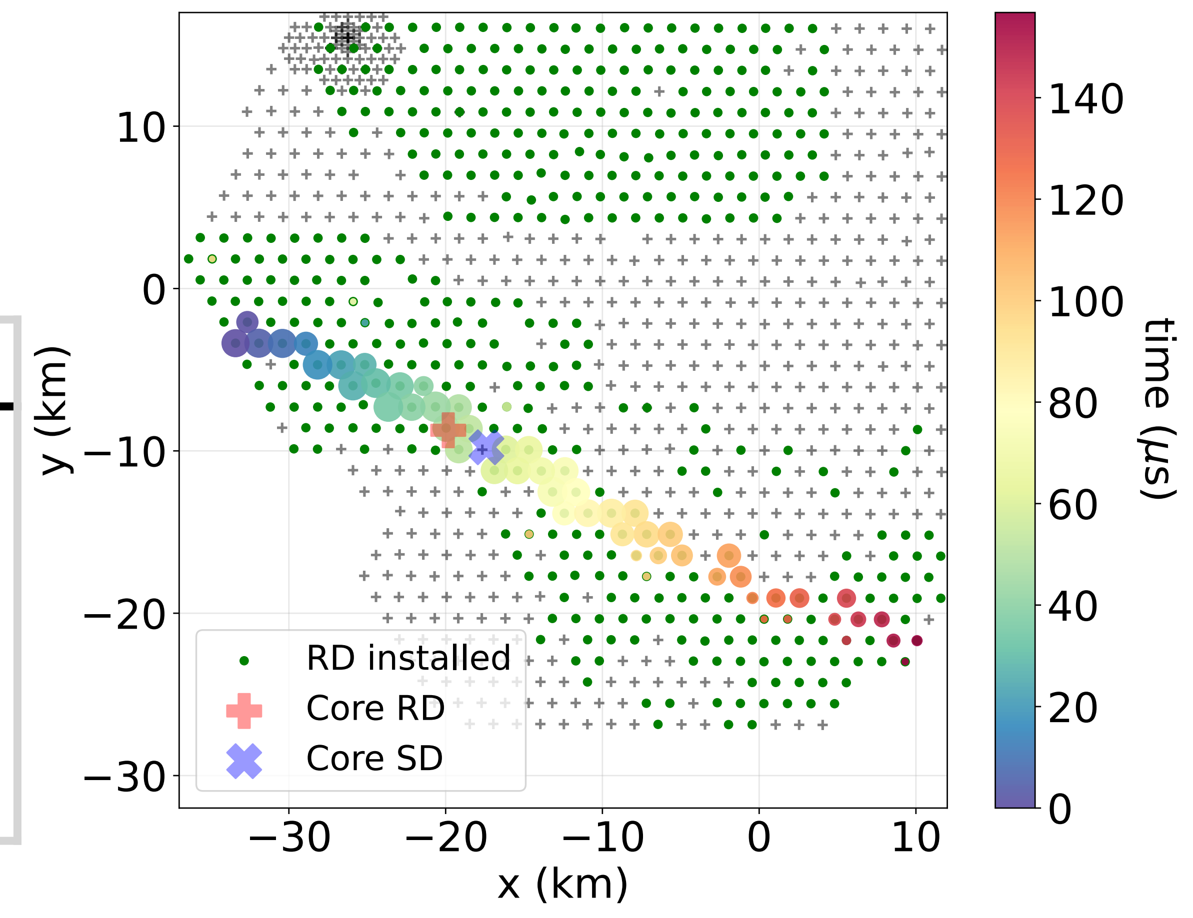


Radio: 1660 installed, 1180 running

Comparing SD and RD

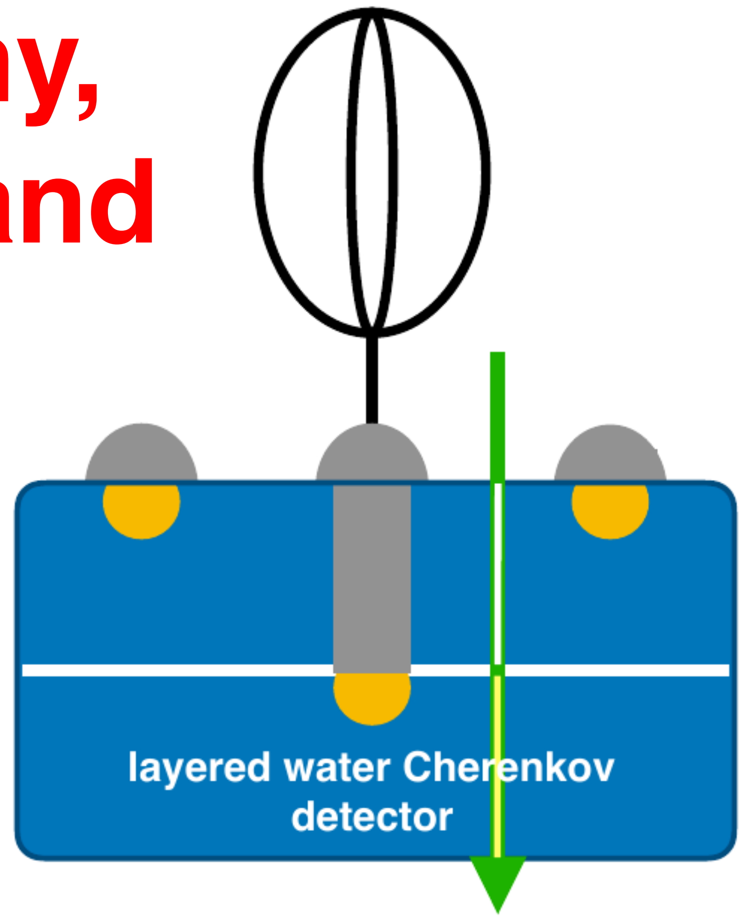
- Recorded in April 2024
- SD and RD data well in agreement

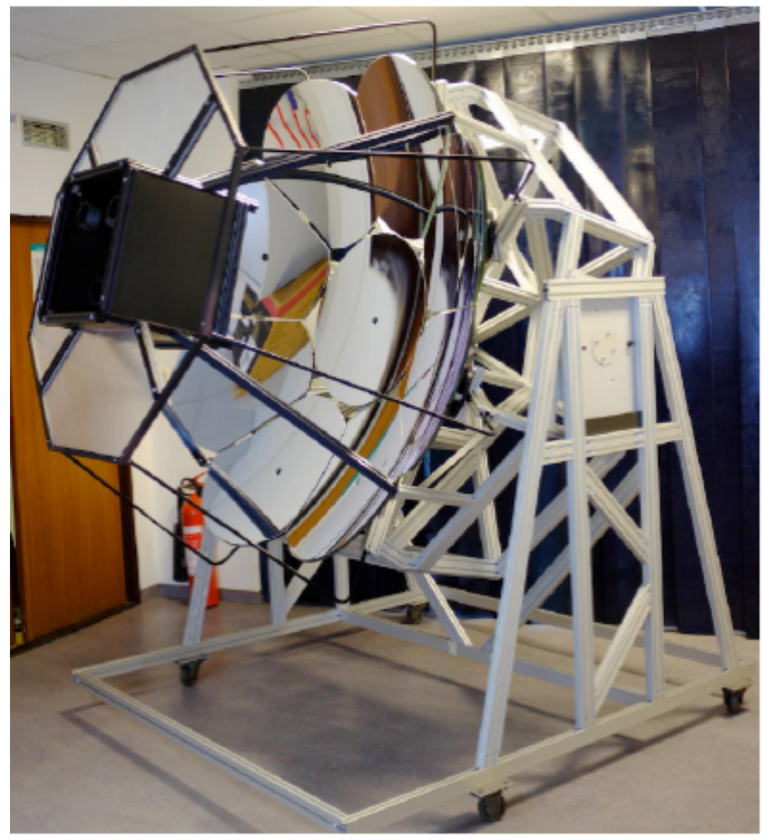
	RD	SD
Azimuth (deg)	156.99±0.01	157±0.1
Zenith (deg)	84.7±0.01	84.7±0.1
Energy (EeV)	36.23 ± 3.34	38.55 ± 2.92
Core X (km)	-19.8	-17.40±0.88
Core Y (km)	-8.73	-9.78±0.45



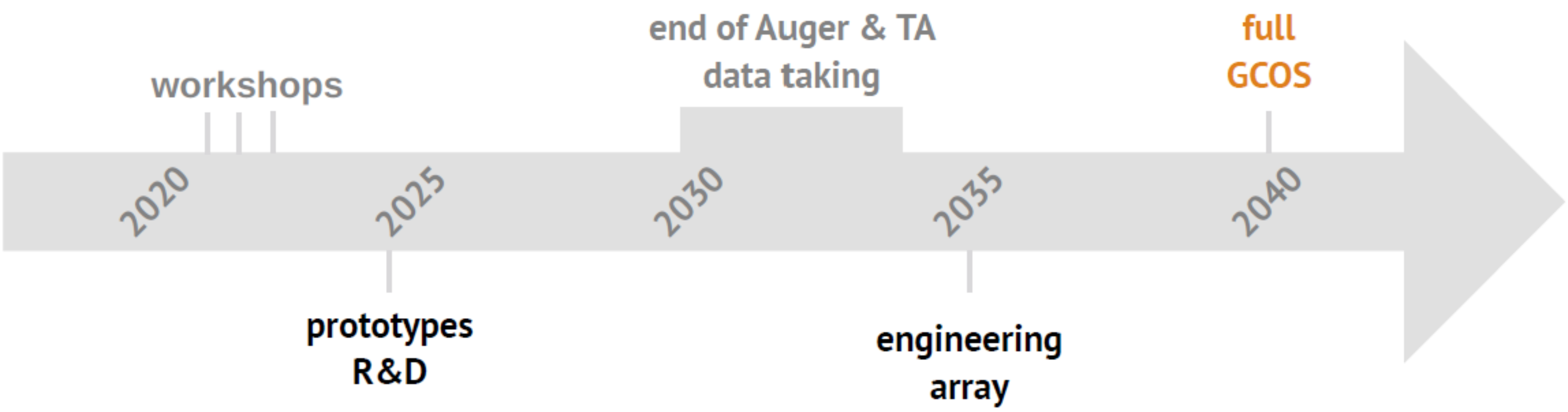
GCOS - The Global Cosmic Ray Observatory

charged-particle astronomy,
multi-messenger studies and
fundamental physics
at ultra-high energies

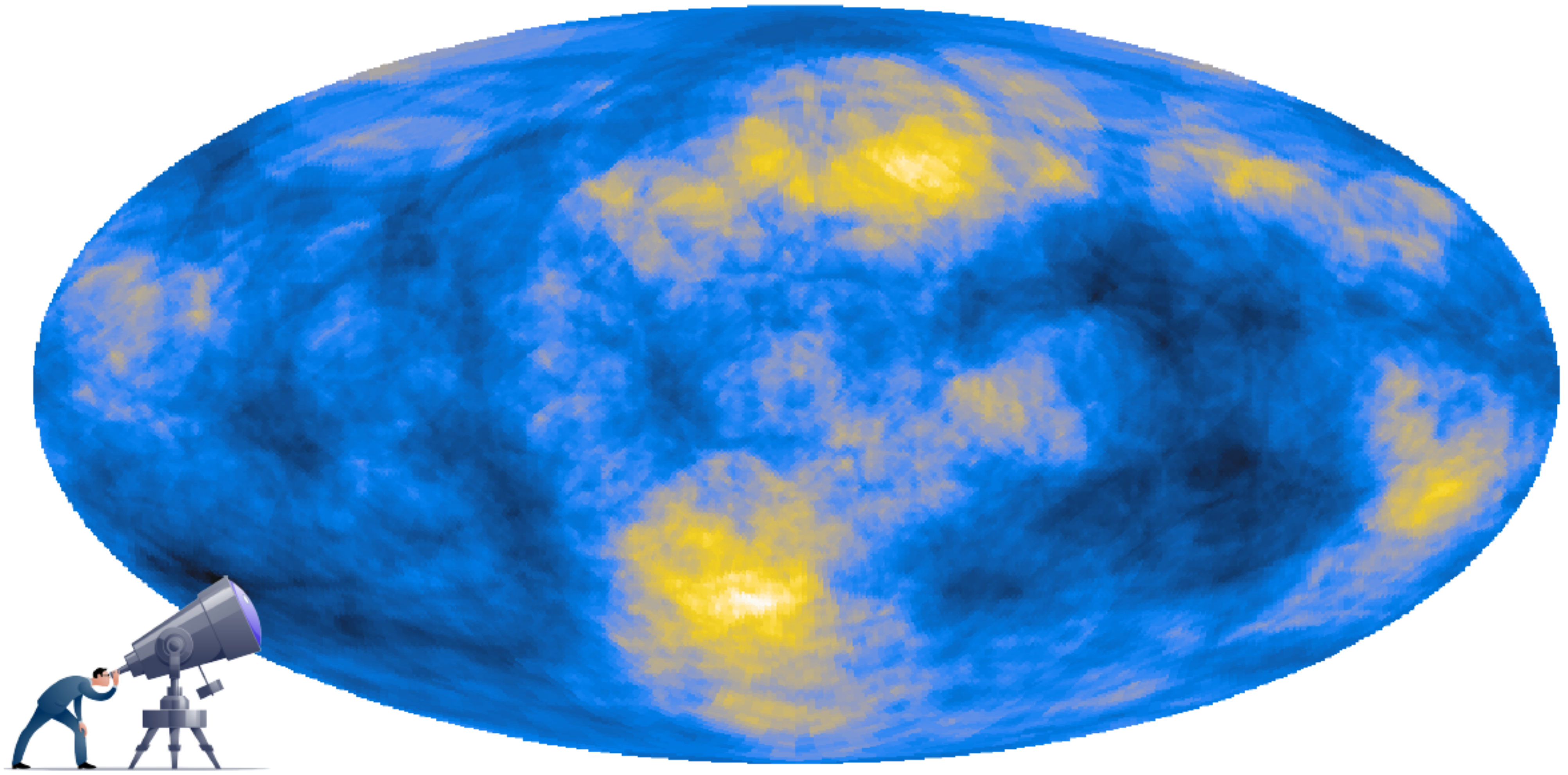




2018 “Future” session at UHECR (Paris)
2021 1st GCOS workshop (online)
2022 2nd GCOS workshop (Wuppertal)
2023 3rd GCOS workshop (Brussels)
two layered WCD prototypes running in Auger
FAST (FD) prototypes running in Auger and TA
UHE WCD+RD detection at AugerPrime

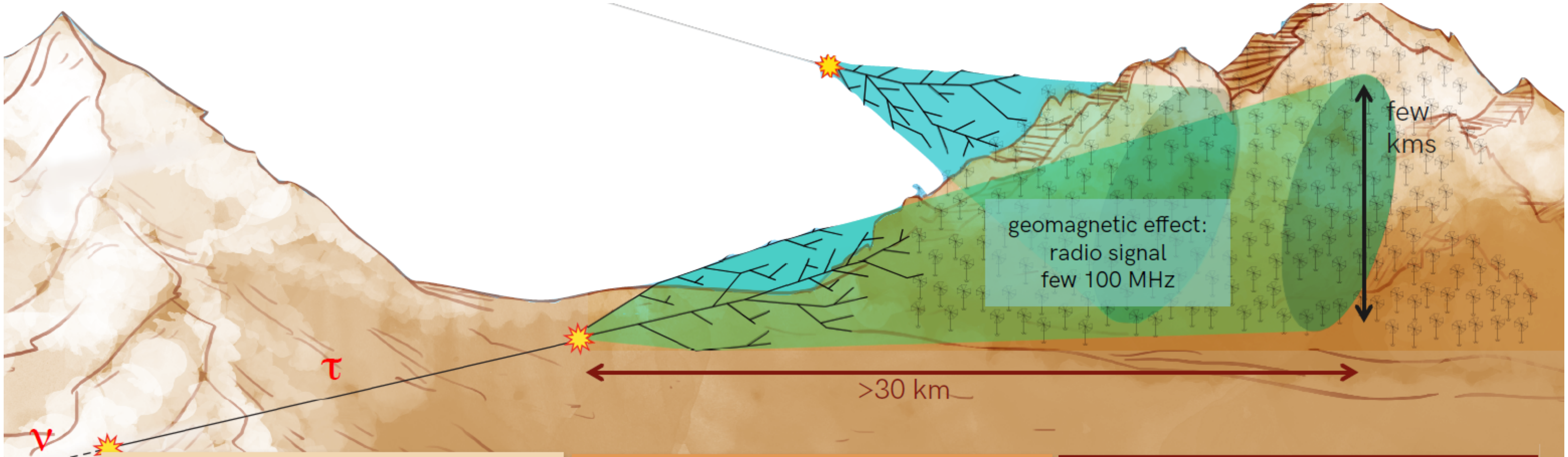


full-sky by 2 sites; 60.000 km²
20k layered WCDs; RD, FD
➔ high quality E and A at 30 EeV



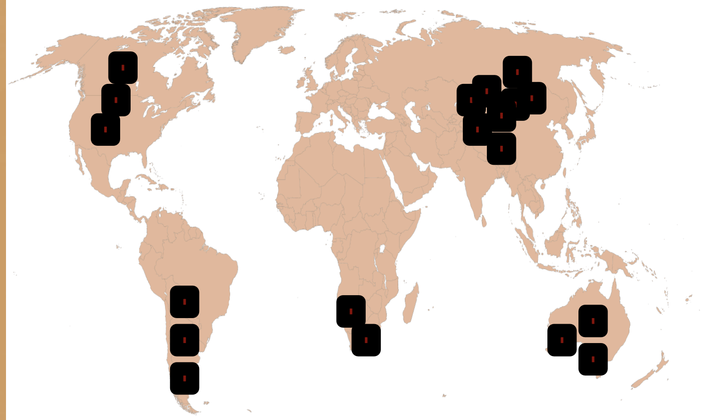
Auger >38EeV: (local) significances of -4.3 (dark blue) to +4.3 sigma

GRAND - Giant Radio Array for Neutrino Detection



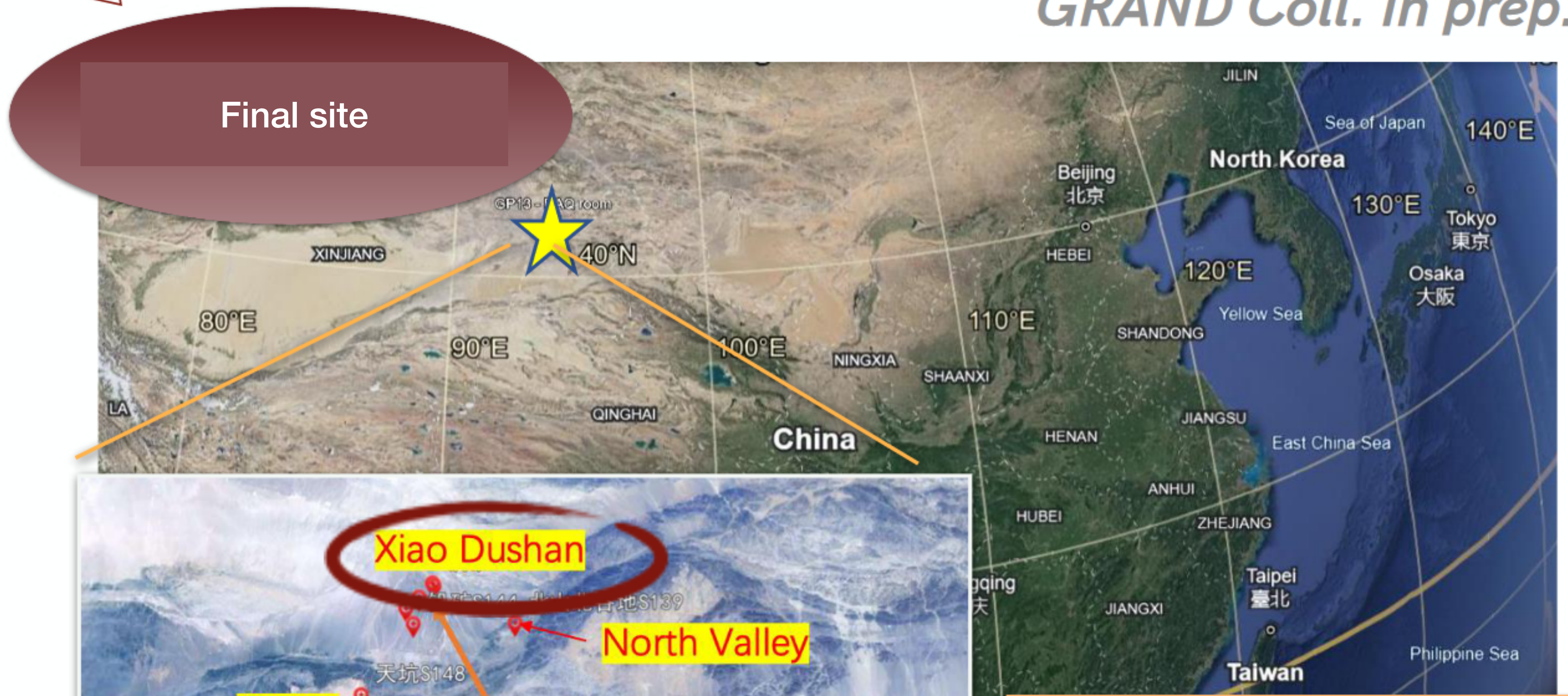
Prototypes	GRAND10k x2 (North/South)	GRAND200k
2023	2028	203X
autonomous radio detection of **very inclined** air-showers **cosmic rays $10^{16.5-18}$ eV** • **GRAND@Nançay**: 4 antennas for trigger testing • **GRAND@Auger**: 10 antennas for cross-calibration • **GRANDProto300**: 13/300 HorizonAntennas over 200 km²	• **discovery of EeV neutrinos** for optimistic fluxes **2 GRAND sub-arrays** • 2x10,000 radio antennas over 2x10,000 km² in China + Argentina • 13 M€ x2	sensitive **all-sky** detector **1st EeV neutrino detection and/or neutrino astronomy!** • 200,000 antennas over 200,000 km² • 20 sub-arrays of 10k antennas • 300 M€

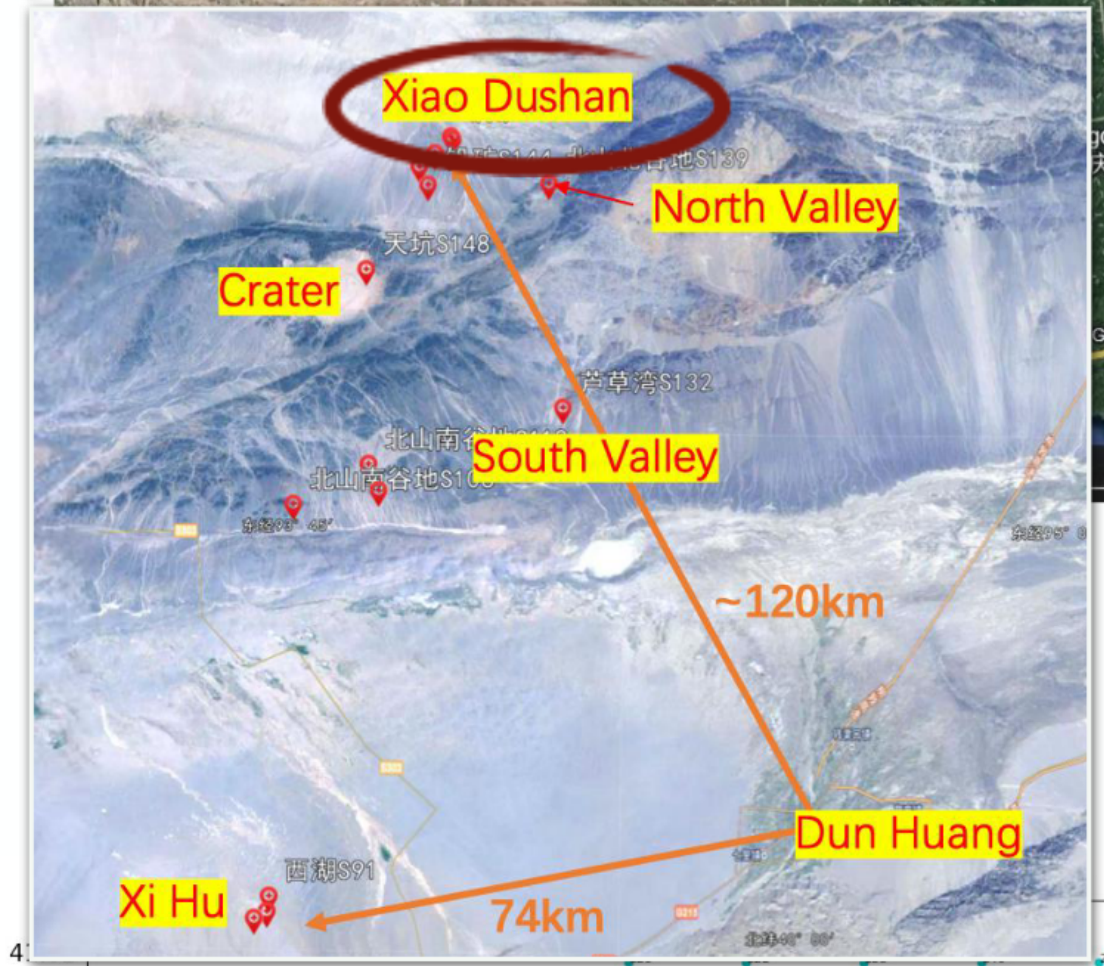
Goals

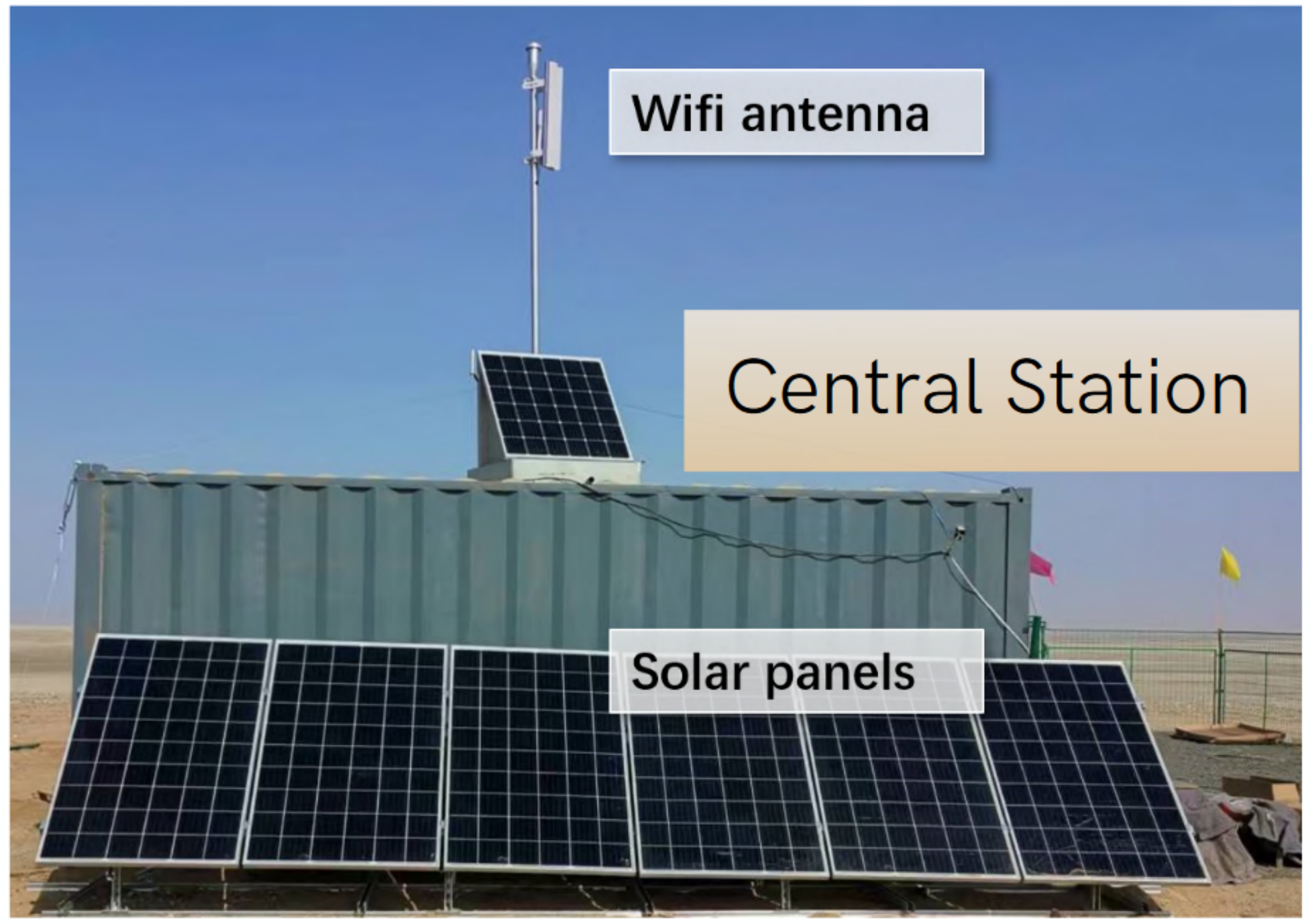


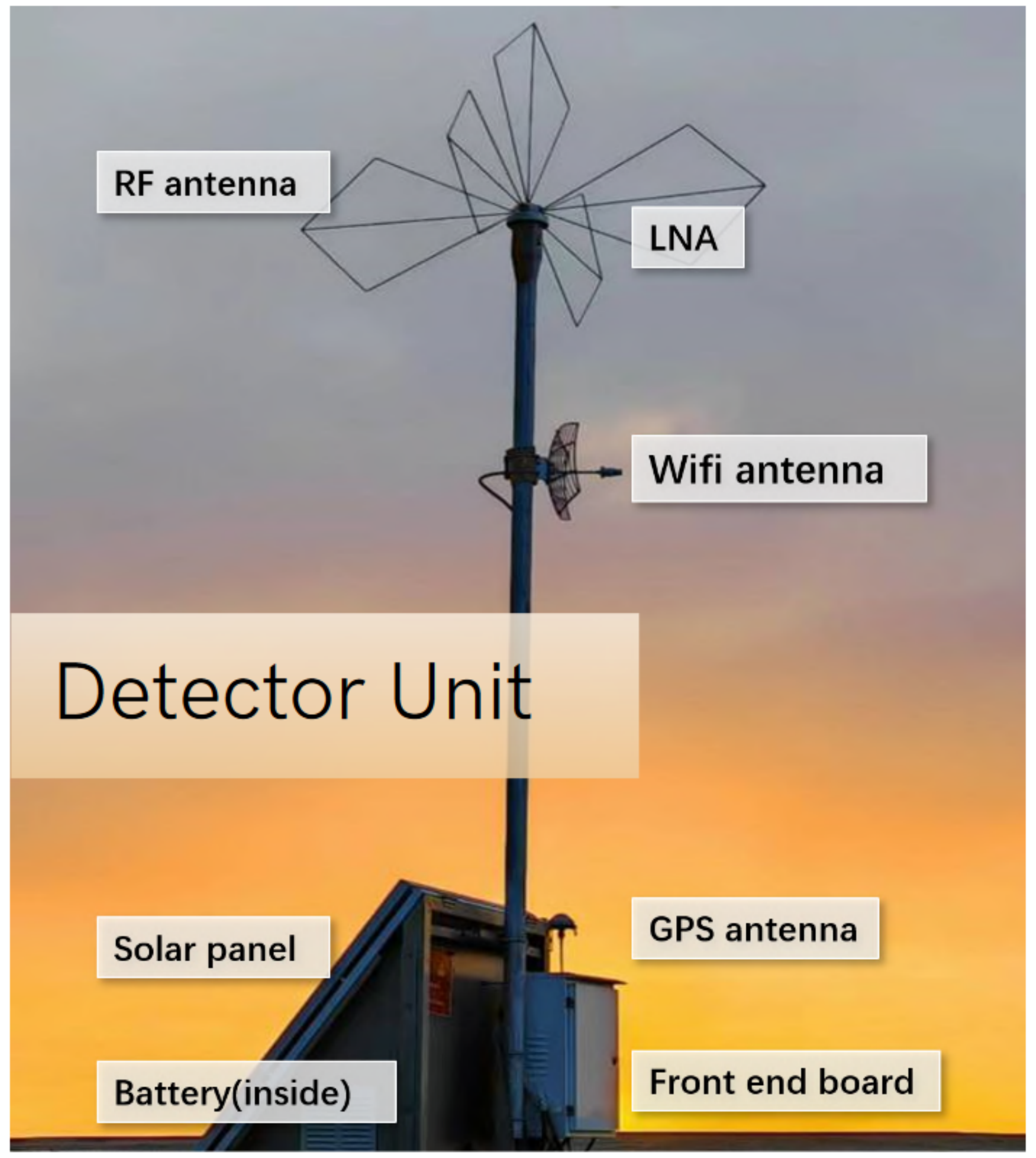
Prototypes: GRANDProto300

GRAND Coll. in prep.

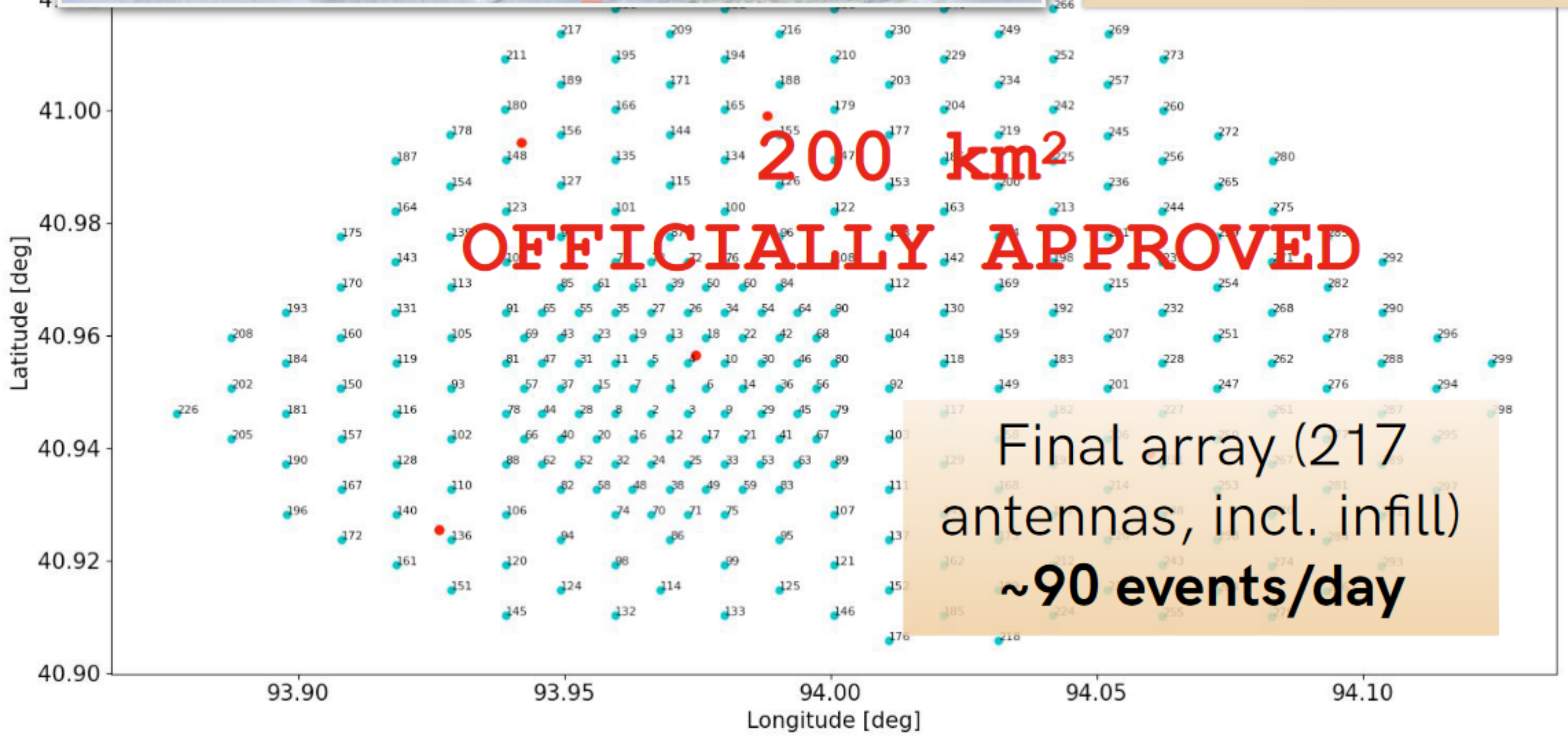


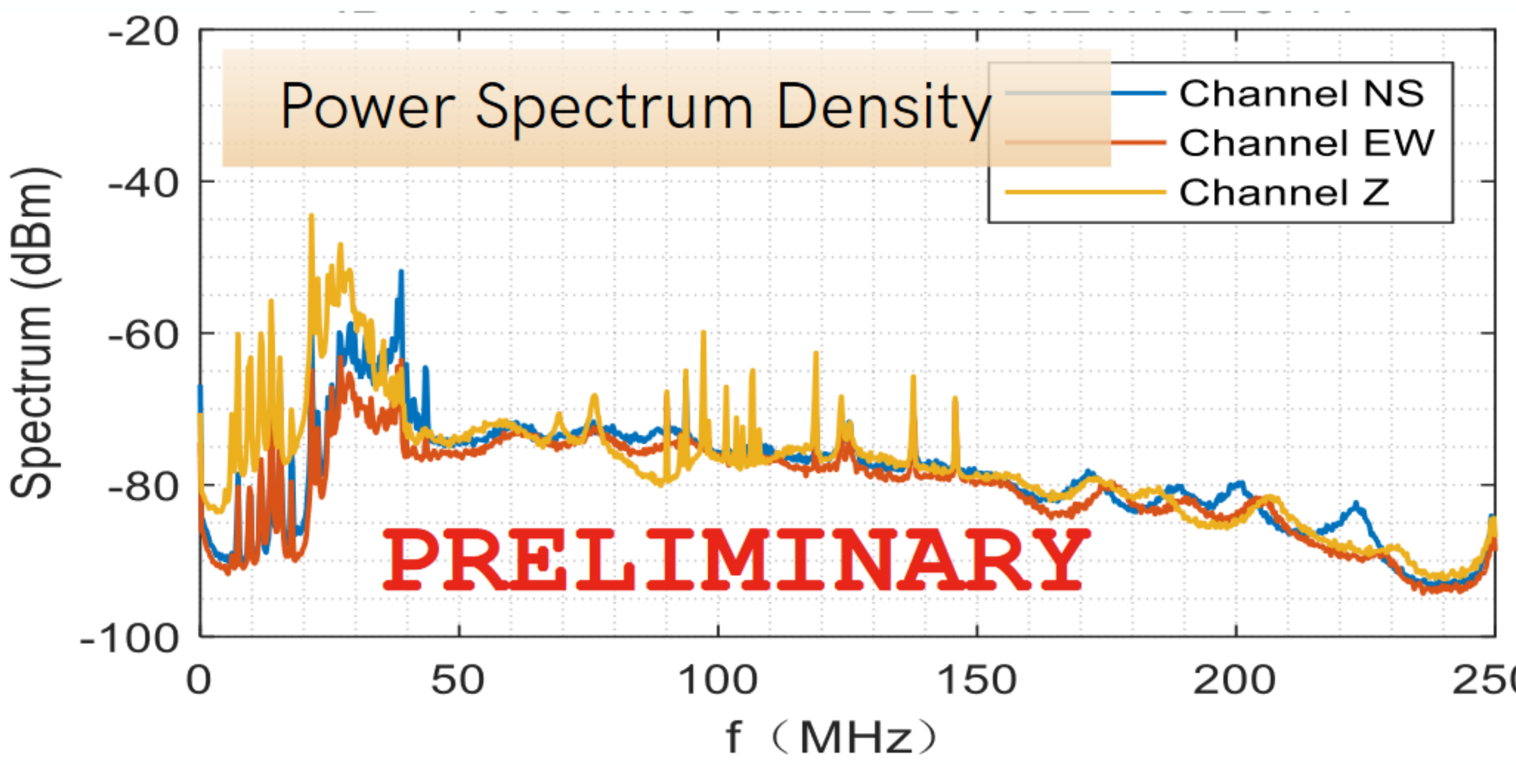


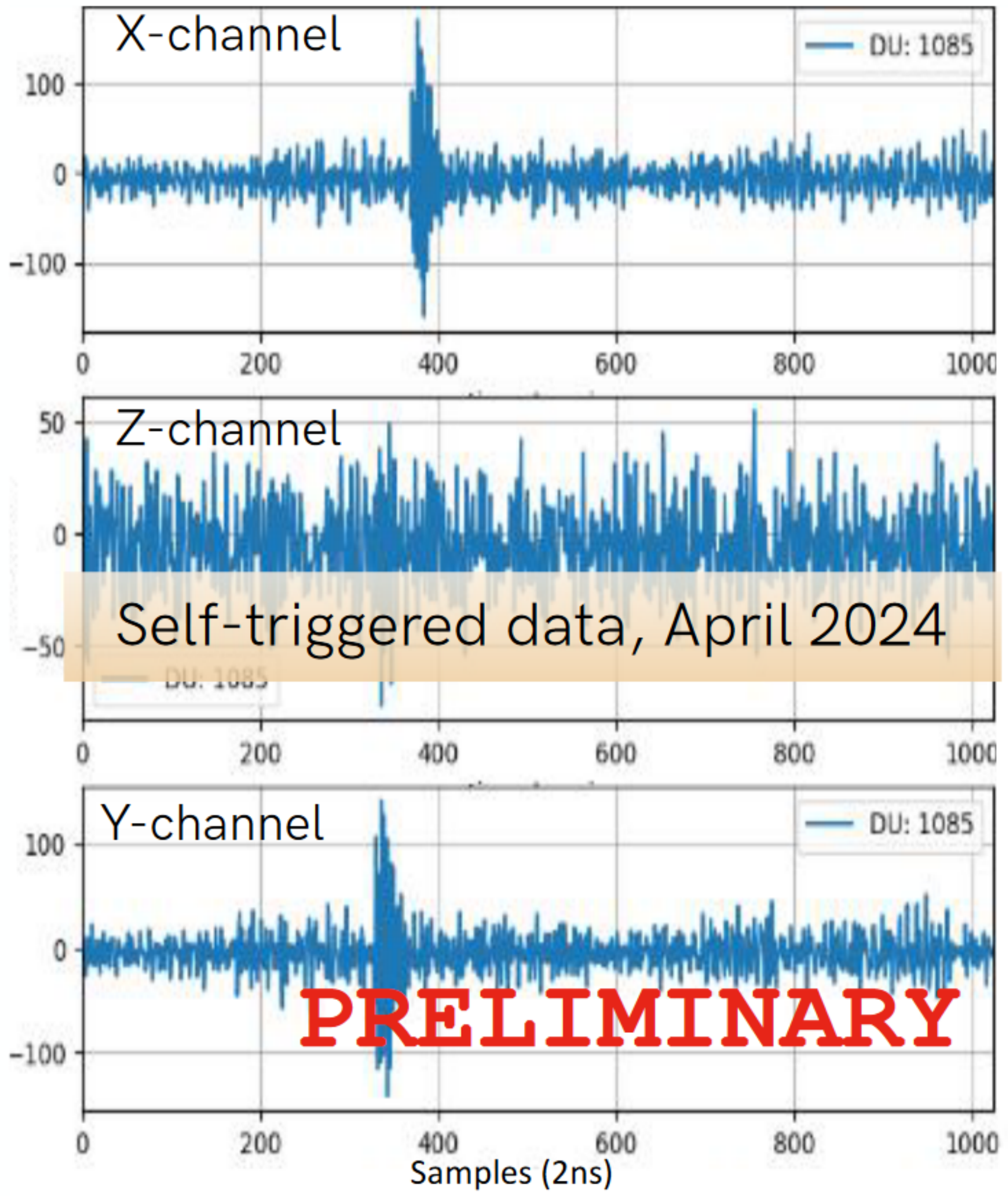




- **GRAND Detection concept validation:** Autonomous triggering & inclined EAS reconstr.
- **13 antennas deployed (80 in Fall 2024)**
- Hardware tests: long-term stability, self-made noise control, LNA optimization
- Firmware tests, trigger / transient detection

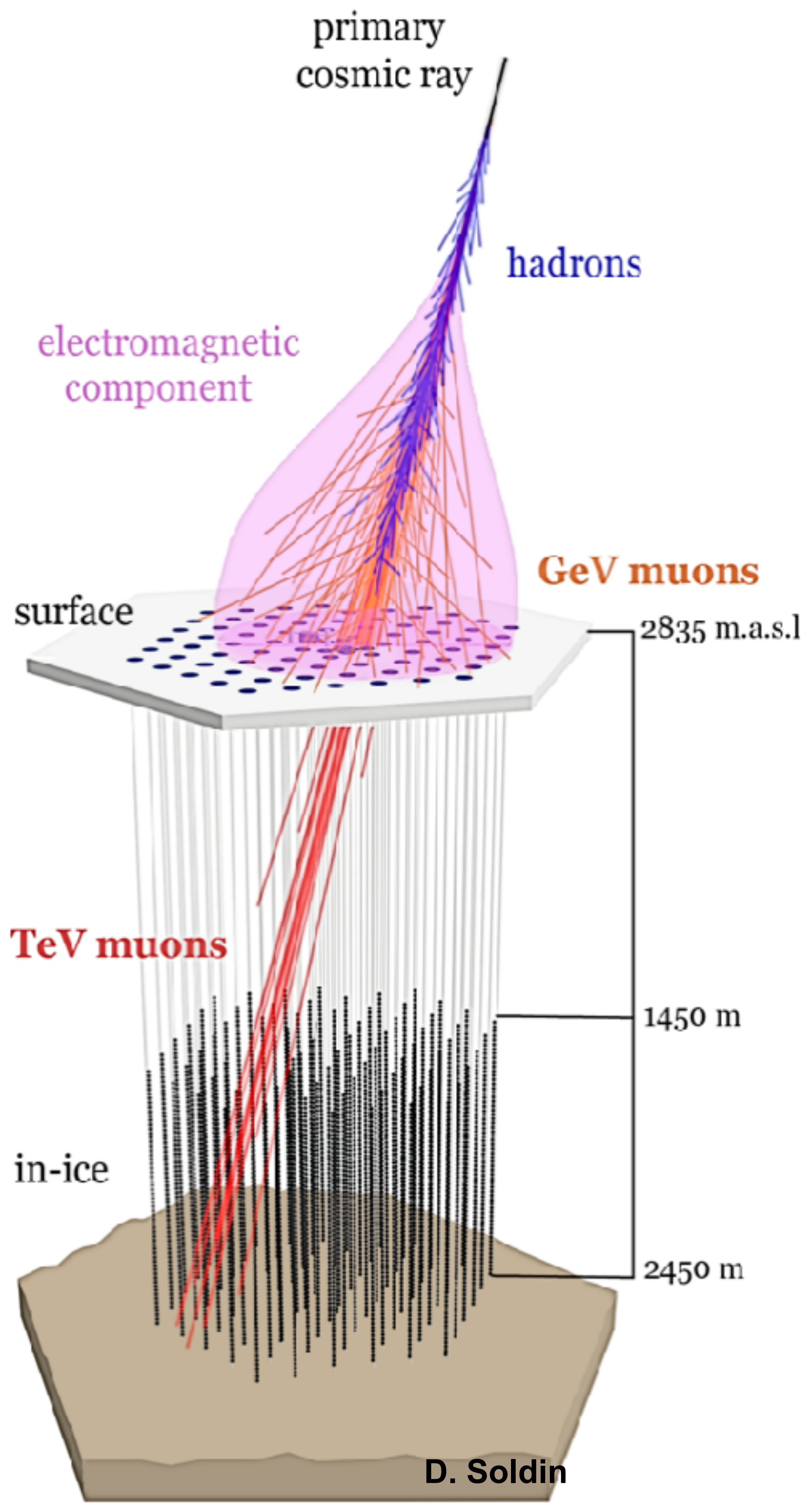






Biggest challenge: pure, efficient and scalable radio self-trigger

IceCube / IceCube-Gen2



❖ Motivation for IceCube surface instrumentation

- veto downgoing neutrinos
- understanding atmospheric neutrinos and muons
- making IceCube a unique instrument also for air showers
- doing galactic multi-messenger astronomy

❖ Surface array of IceCube (IceTop)

- 10^{15} eV – $10^{17.5}$ eV EAS primary energy range
- problem of non-uniform snow coverage increasing with time
- small exposure for IceTop + in-ice coincidences

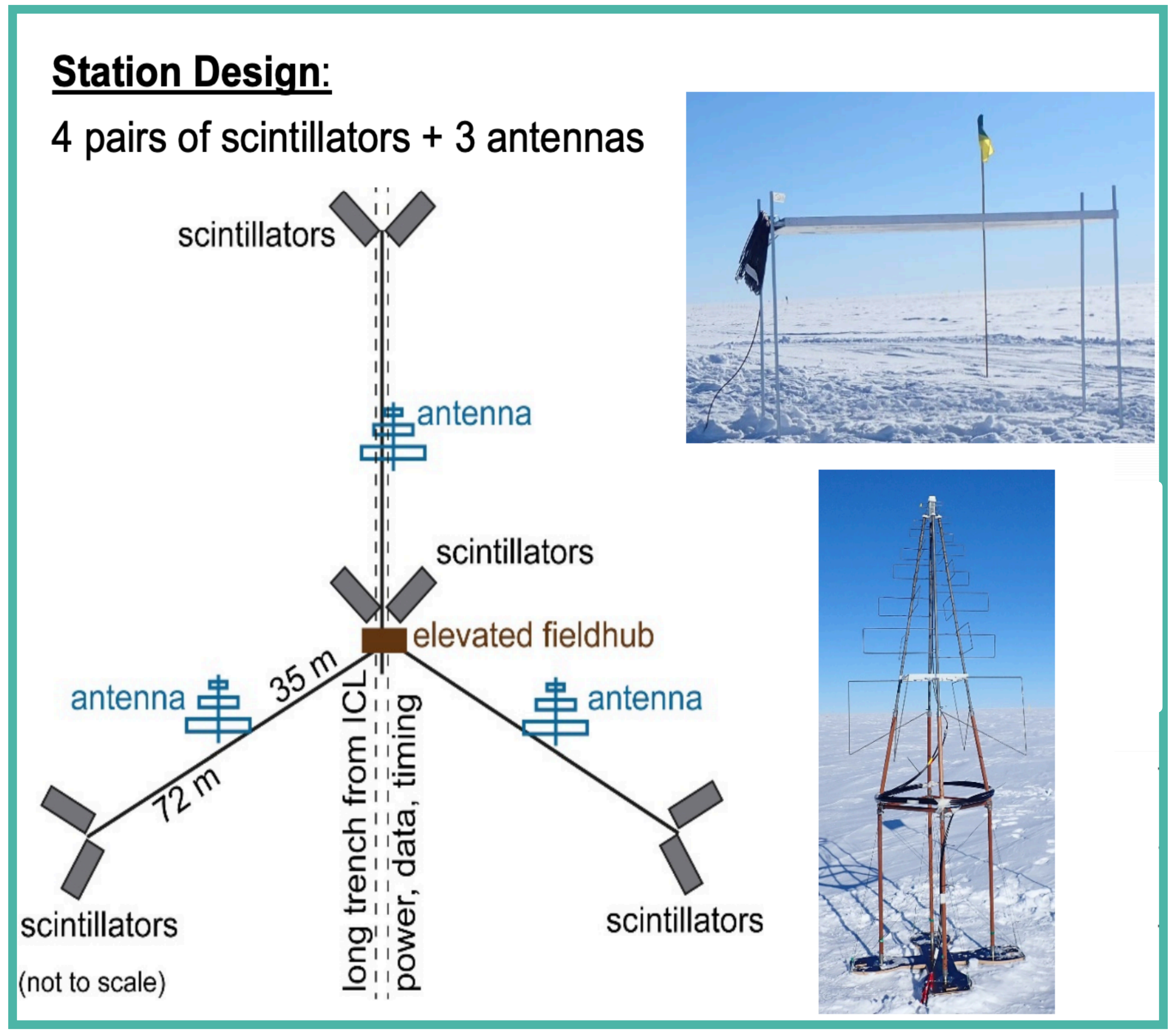
❖ The Multi-Detector IceCube Surface Array Enhancement

- Operating IceTop (and IceCube) + scintillators within IceTop area + Radio antennas + Cherenkov light telescopes (IceACT)
- prototypes operating
- deployment delayed by logistic problems (Covid)
- German initiative (with Madison, Delaware)

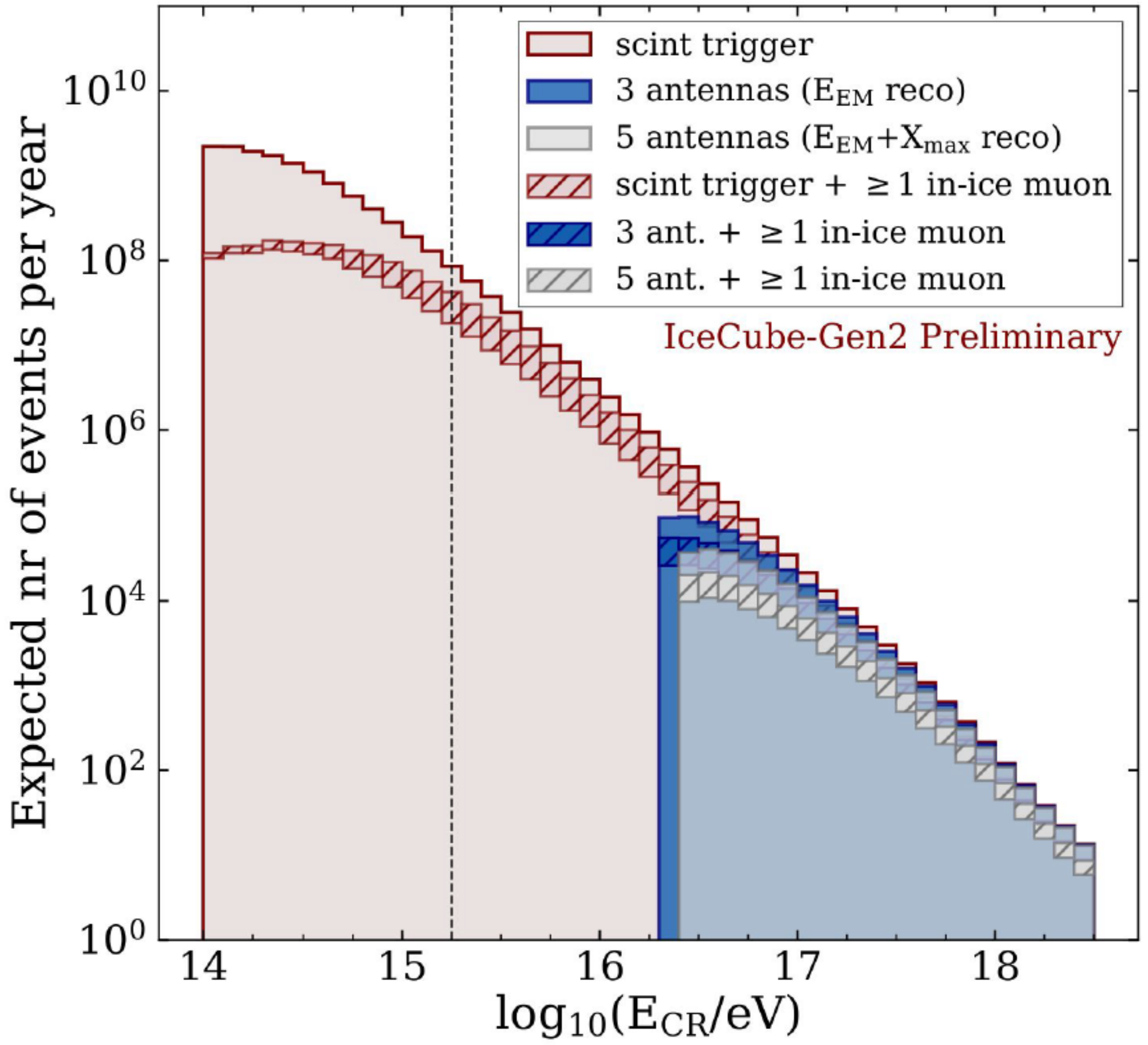
Andreas Haungs

IceCube-Gen2 Surface Array

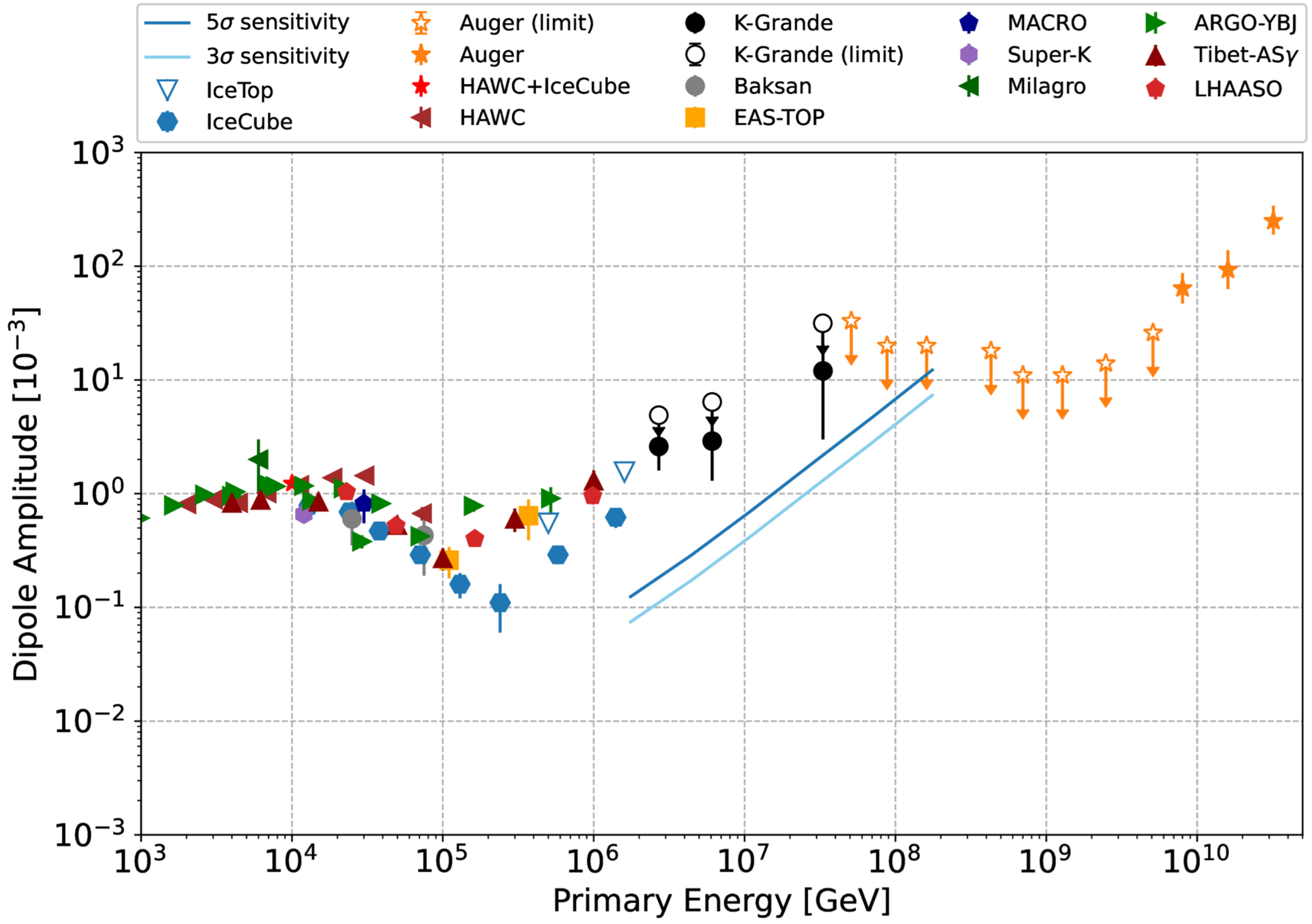
station design



expected number of events/year



sensitivity to cosmic ray anisotropy for 10 years IceCube-Gen2

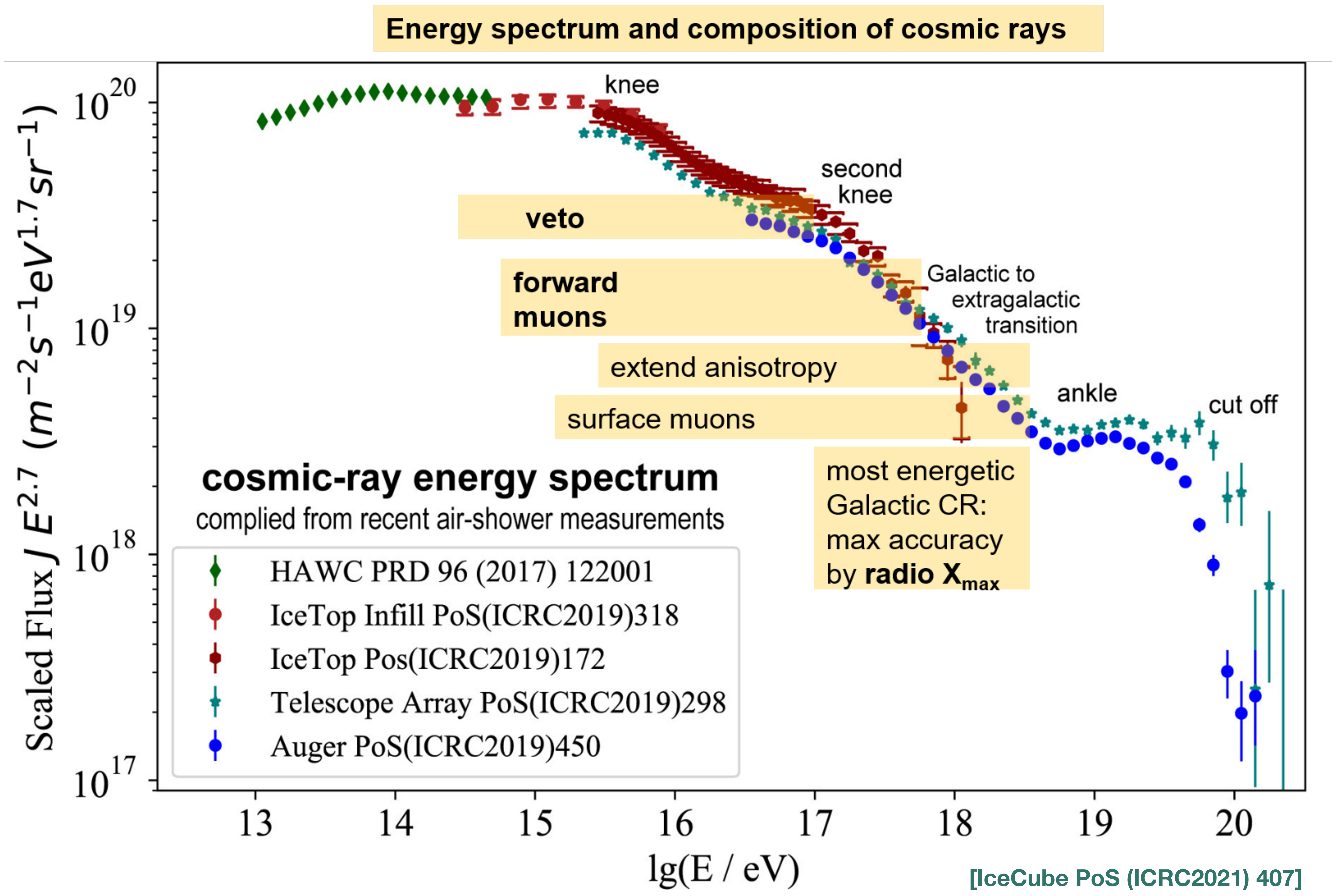


[IceCube PoS (ICRC2023) 205, PoS (ICRC2023) 354]

- ❖ **scientific heritage: IceTop and Surface Enhancement Array in IceCube**
- ❖ **baseline design: 1 hybrid station on top of each new Gen2 string**

The IceCube-Gen2 surface array will be a unique and needed cosmic ray detector in the PeV-EeV primary energy range!

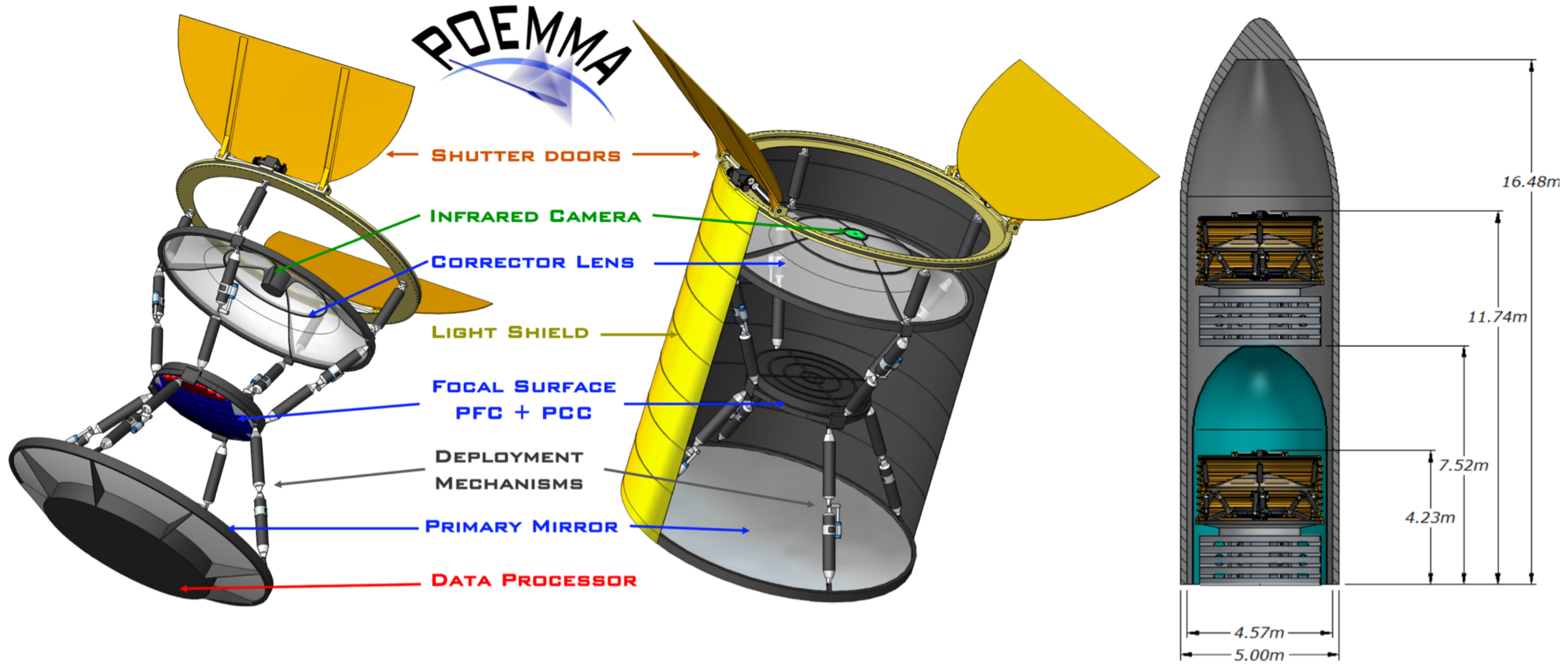
IceCube-Gen2 Surface Array : Physics goals besides veto for neutrino astronomy



Rich physics program!

Not possible with only IceTop or IceCube surface enhancement

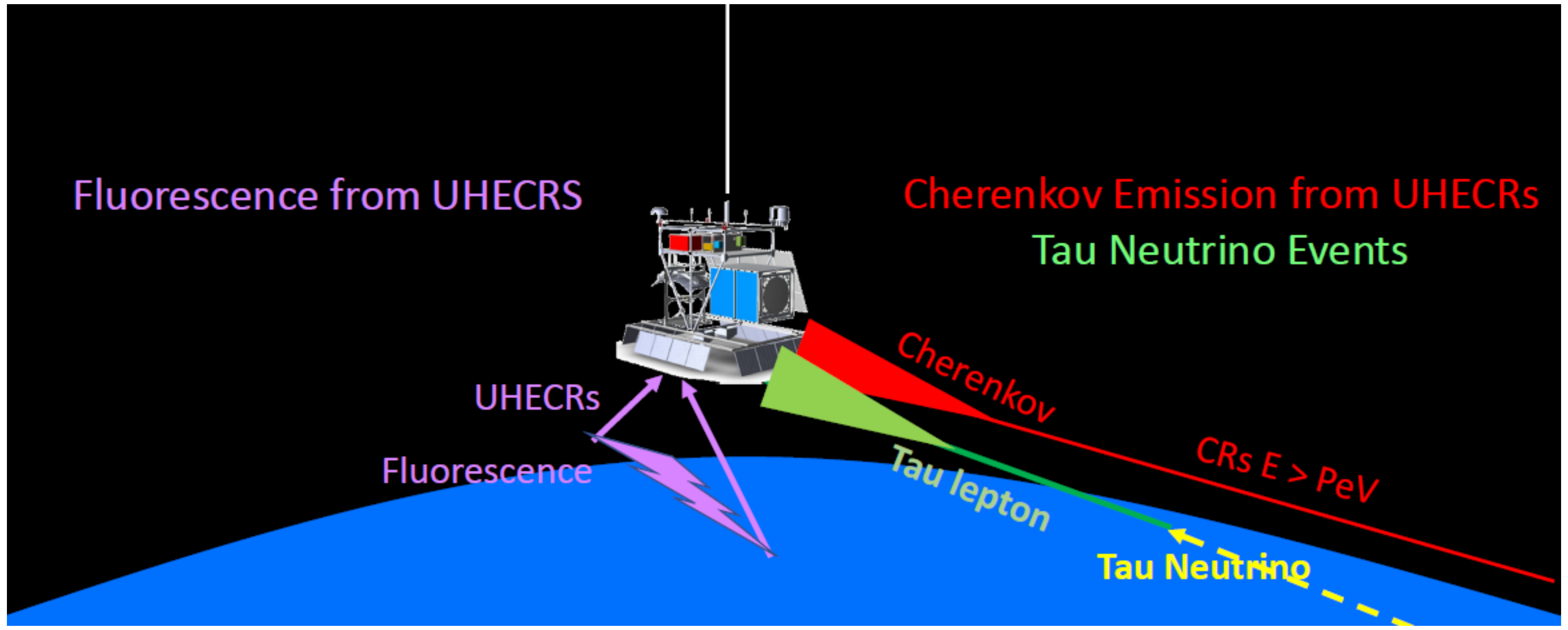
POEMMA - Probe Of Extreme Multi-Messenger Astrophysics

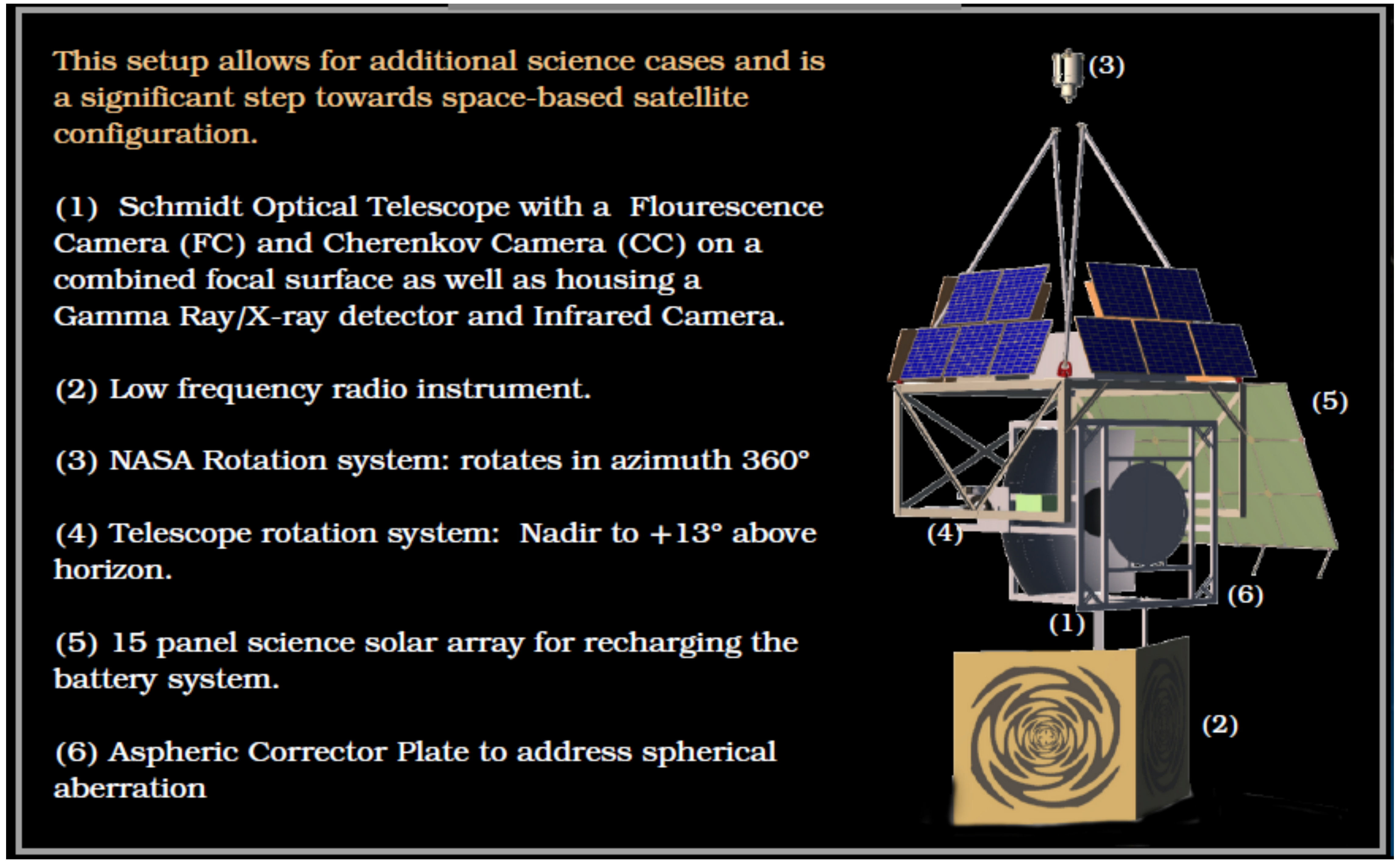


- **POEMMA**
  - **2 satellites with 4 m mirror,**
  - **design study funded by NASA**
  - **launch foreseen mid 2030ies**
- **detection of UHECR and neutrinos:**
  - **find sources of cosmic rays with energies > EeV**
  - **observe cosmic neutrinos with energies > 20 PeV**

POEMMA, PoS (ICRC2023)1159

SPB-PBR: Super Pressure Ballon - POEMMA-Balloon with Radio



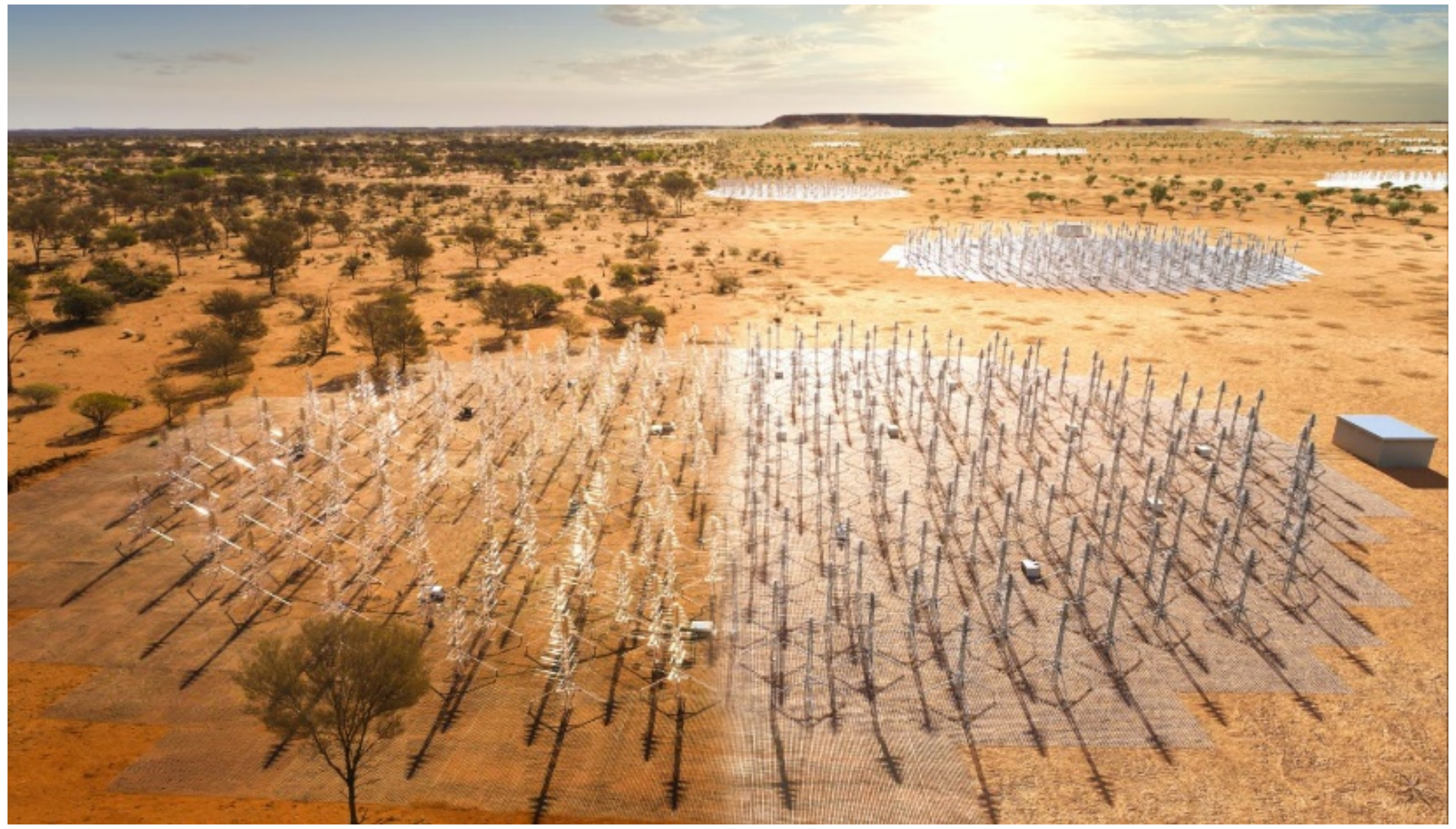


Scientific objectives

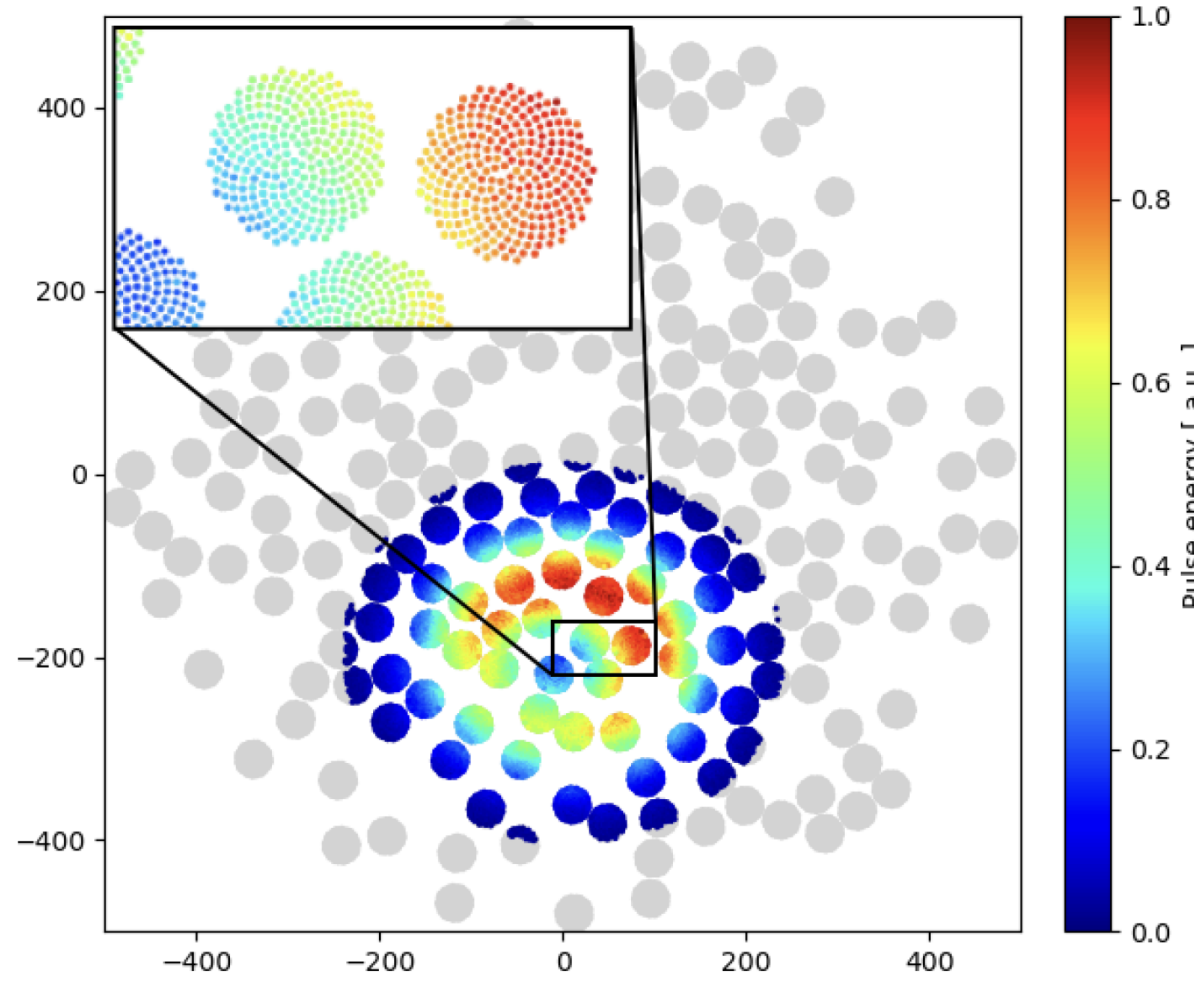
- first observations of UHECR from above with fluorescence light measurements
- measure high-altitude horizontal air-showers to probe the air-shower development at various stages
- search for Earth-skimming astrophysical neutrinos with PeV energies diffuse or from point sources

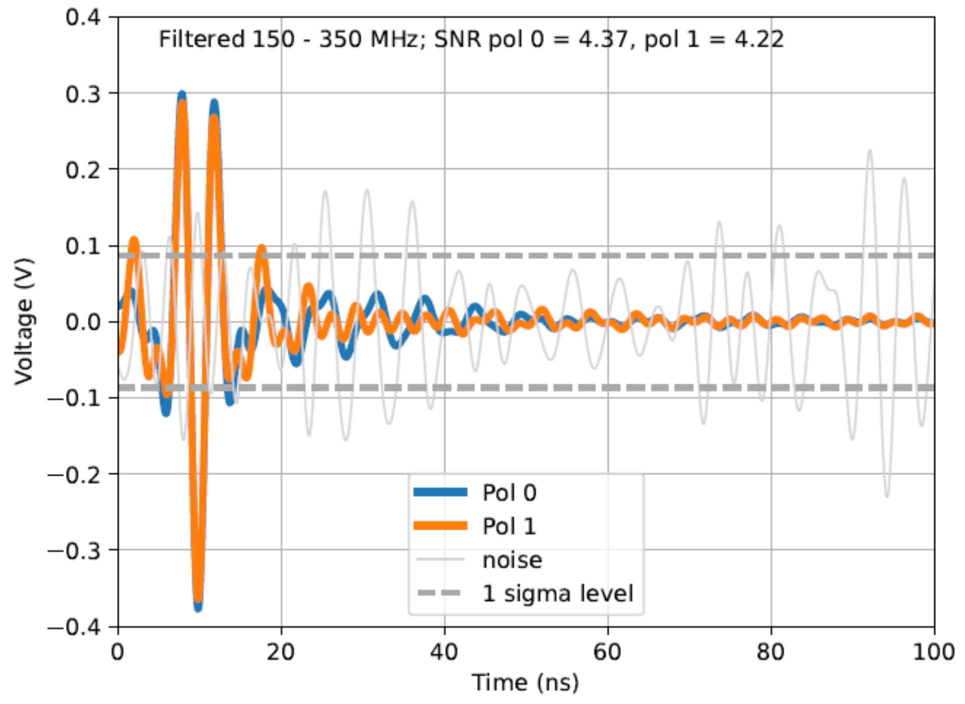
Flight (by NASA around Antarctica) foreseen in 2026

SKA - the Square Kilometer Array as a CR detector

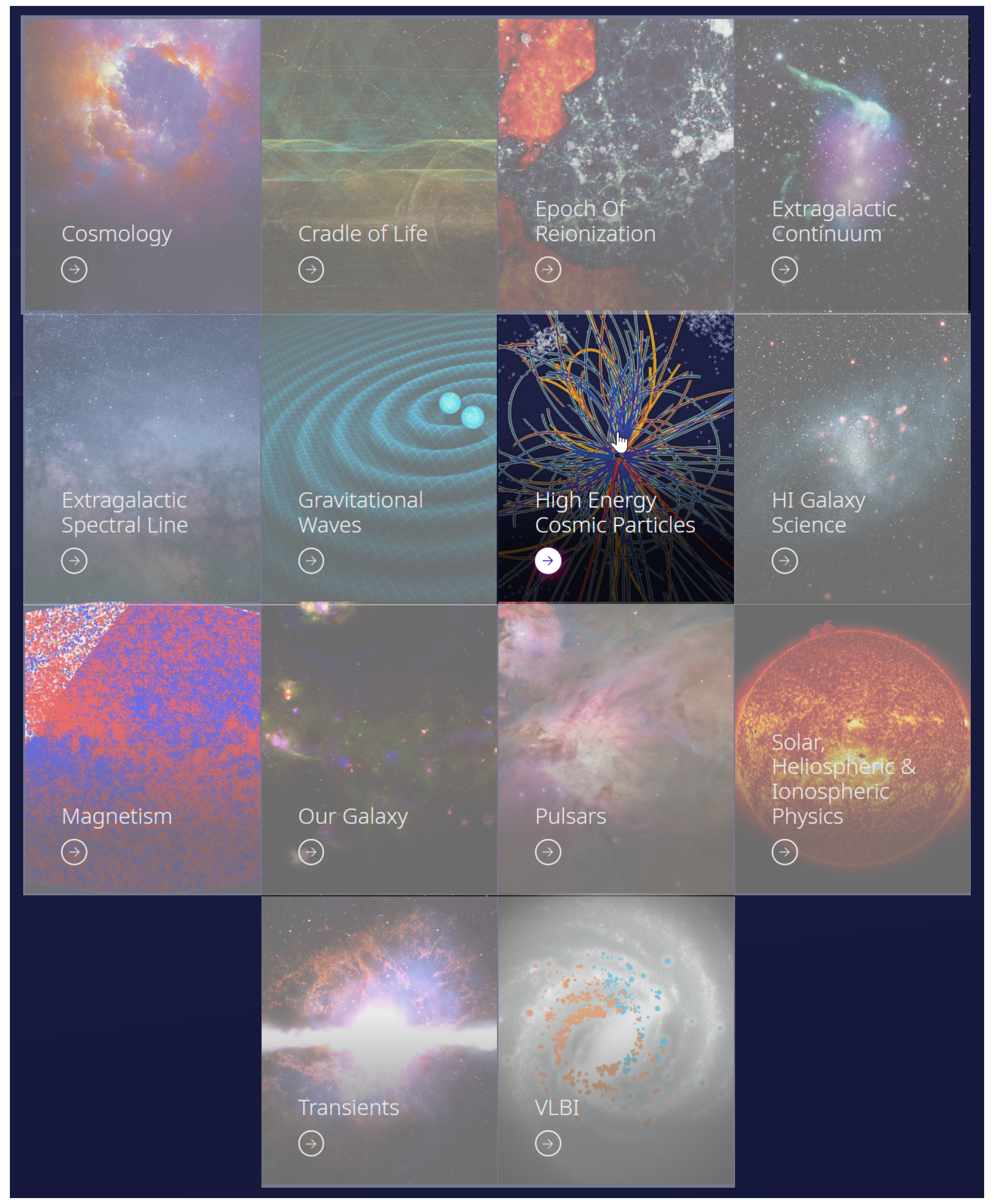


- SKA-Low (Australia): >60,000 antennas in ~1 km² core
- With a particle detector array as trigger, can measure air showers with unprecedented precision at energies of 10 PeV and above
- X_{max} resolution <8 g/cm², potential to measure details of longitudinal profile, test hadronic interaction models
- potential to detect gamma-rays down to PeV energies





1 PeV photon, beam formed with 256 antennas



- strong HECP science working group:
  48 members, 9 from Germany
- acquired ~2 MEUR third-party funding (Belgium, Netherlands, Germany)
- activities ramping up, close coordination with SKA management

Tim Huege

Summary - overview of upcoming projects

Project	CRs	γ	ν
Auger Phase II	$>$ 100 PeV	$>$ 50 PeV	$>$ 10 PeV
GCOS	$>$ 10 EeV	$>$ 10 EeV	$>$ 10 EeV
GRAND	(0.1 PeV-10 PeV)	$>$ 10 EeV	$>$ 100 PeV
IceCube-Gen2	10 GeV-0.1 EeV	0.1 PeV-1 EeV	10 TeV-1 EeV
POEMMA	>20 EeV		>20 PeV
SKA	$>$ 10 PeV	$>$ 1 PeV	
CTA		0.02-300 TeV	
SWGO	$>$ 100 GeV	$>$ 100 GeV	

➡ **measure as many EAS observables as possible**

➡ **radio has become a crucial component**

Summary - tentative timelines