IceCube and Ultra-High Energy Cosmic Ray Physics at IoP

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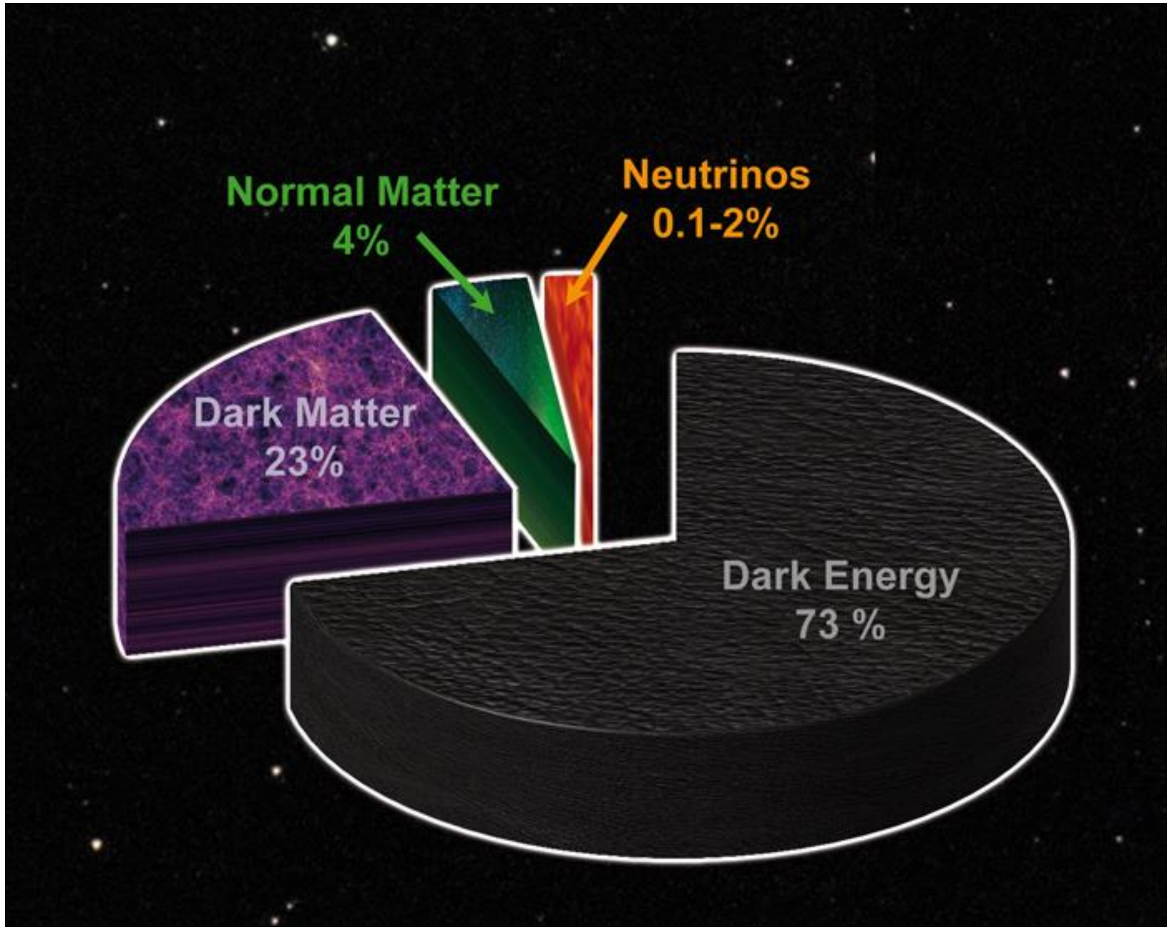
ASIoP AAC mini-workshop, 2023/08/02

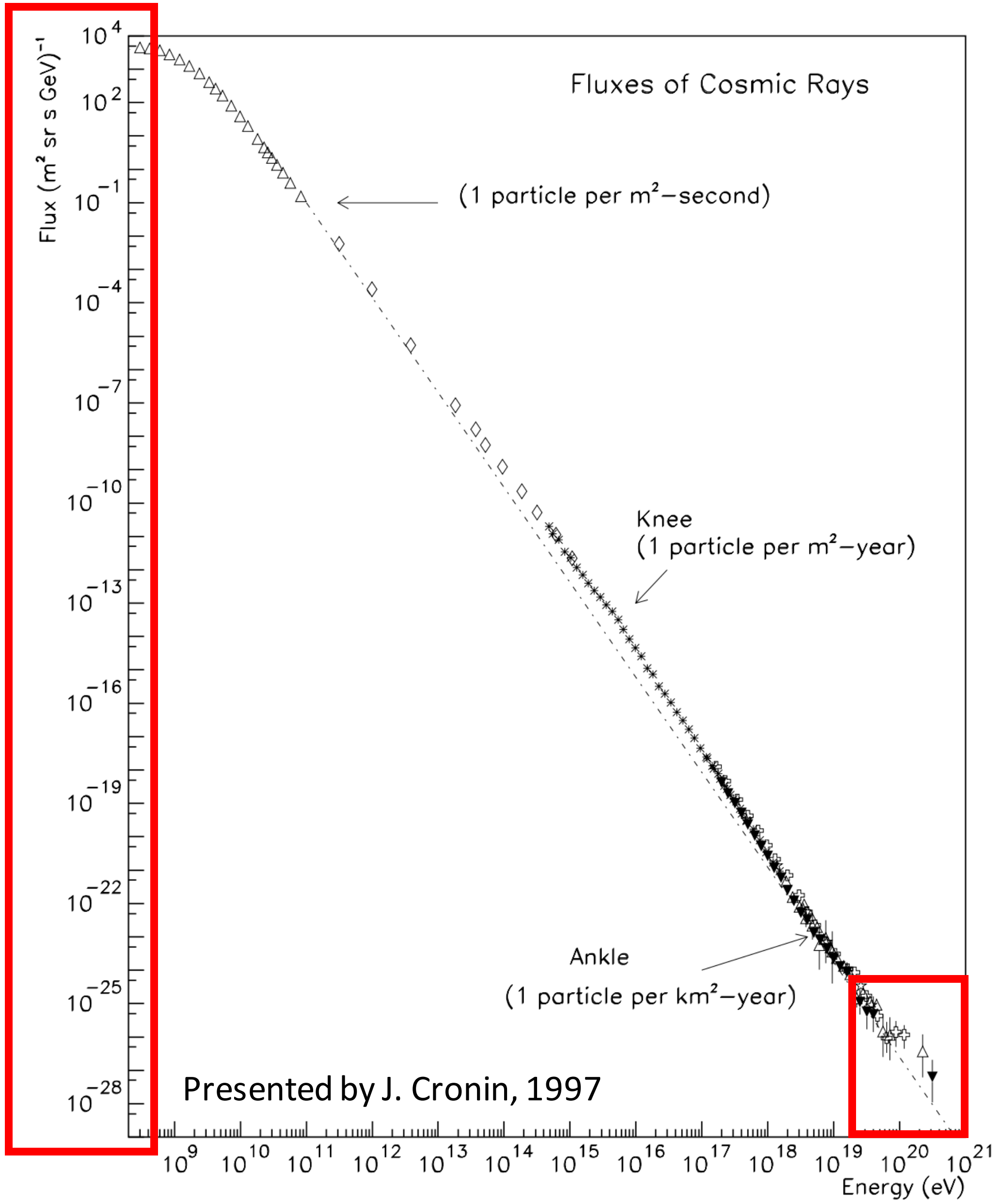
The universe seems to be made of

- "Normal matter":
  - Radiation (EM)
  - Non-relativistic: stars, gas, dust
  - Relativistic: e^{+-} plasma, protons & nuclei → cosmic rays (CR)
- Some of the neutrinos are produced in CR interaction with gas or radiation

	Energy density
Cosmic rays	**0.8 eV / cm^3**
CMB	0.3 eV / cm^3
Starlight	0.5 eV / cm^3
Magnetic fields	~ 0.3 eV / cm^3
Gas pressure	~ 0.5 eV / cm^3



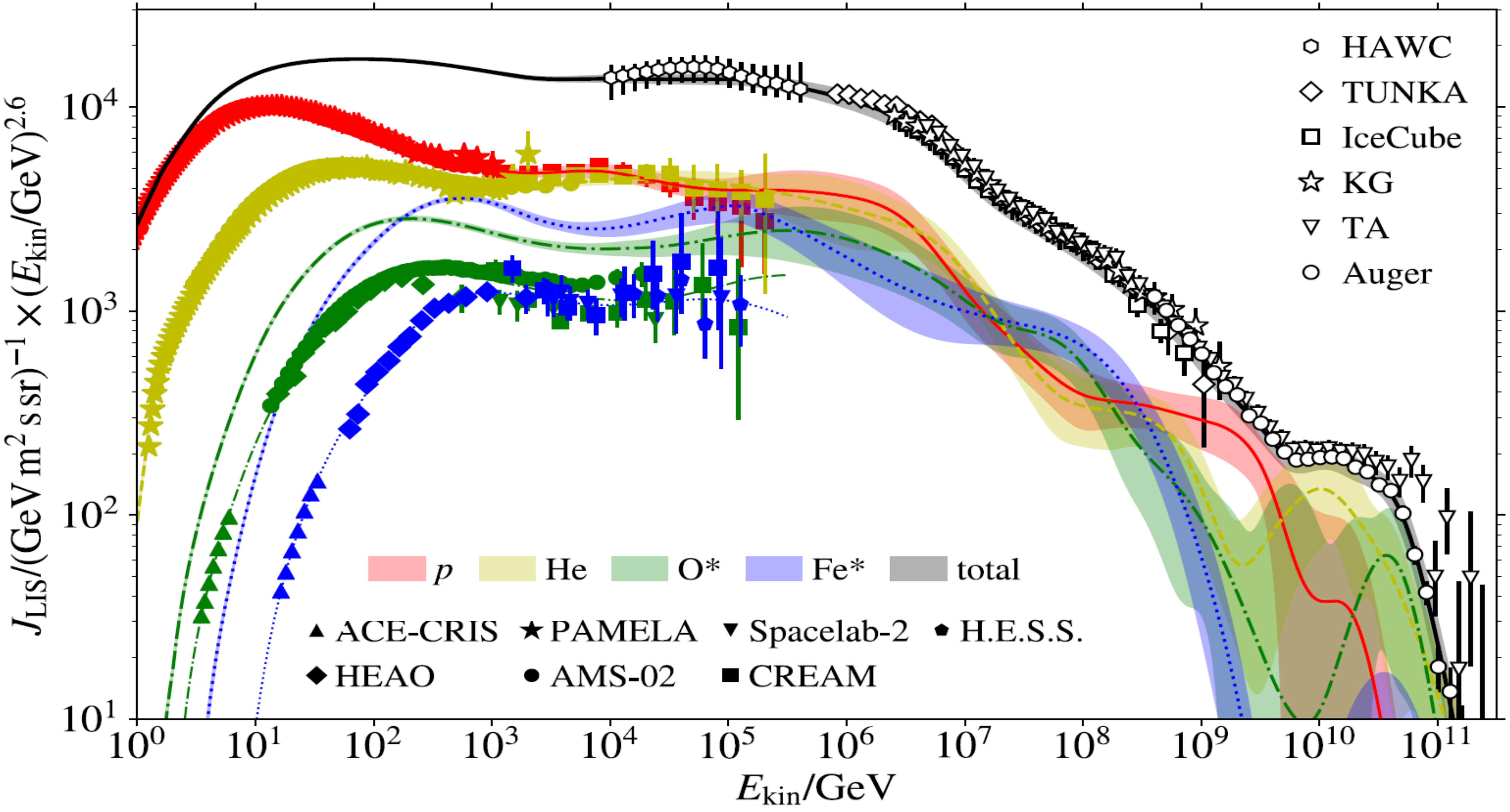
Spectrum of Cosmic Rays : a question of scale (→ multiple origins)



Ultra-High Enegy Cosmic Rays (UHECR):
1 particle/km2/century

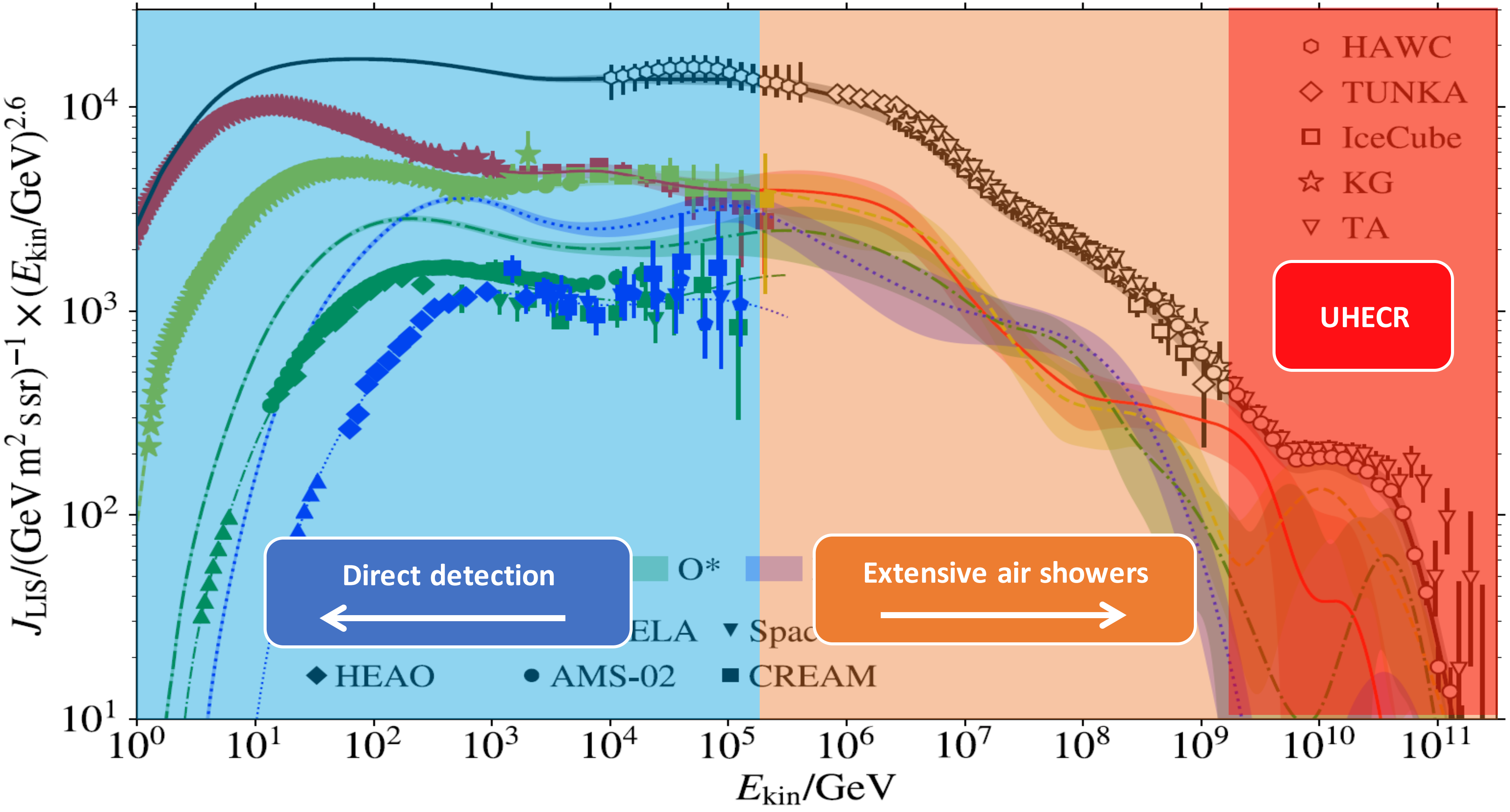
Resolving the details of CR spectrum…

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533



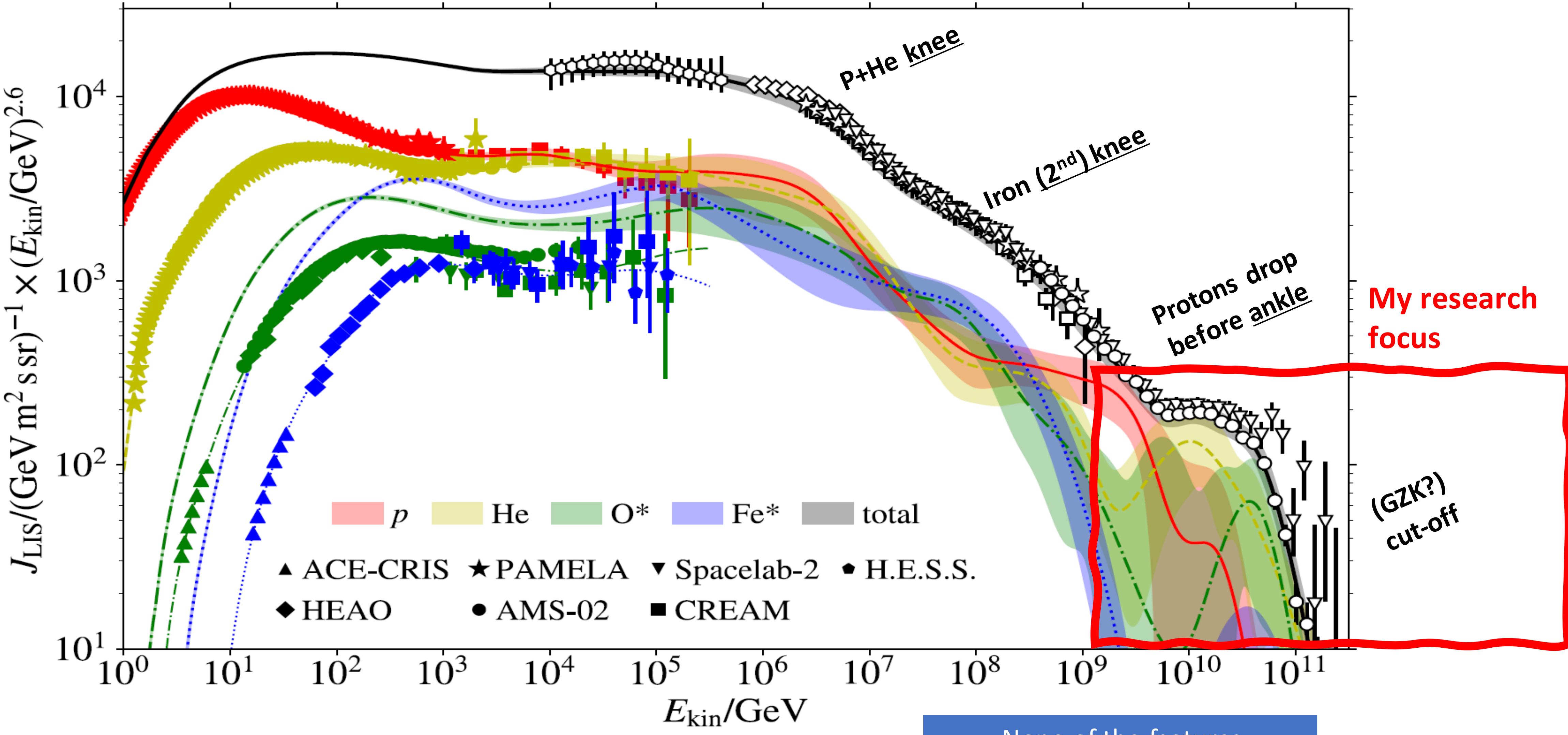
…requires a broad variety of detection techniques

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533

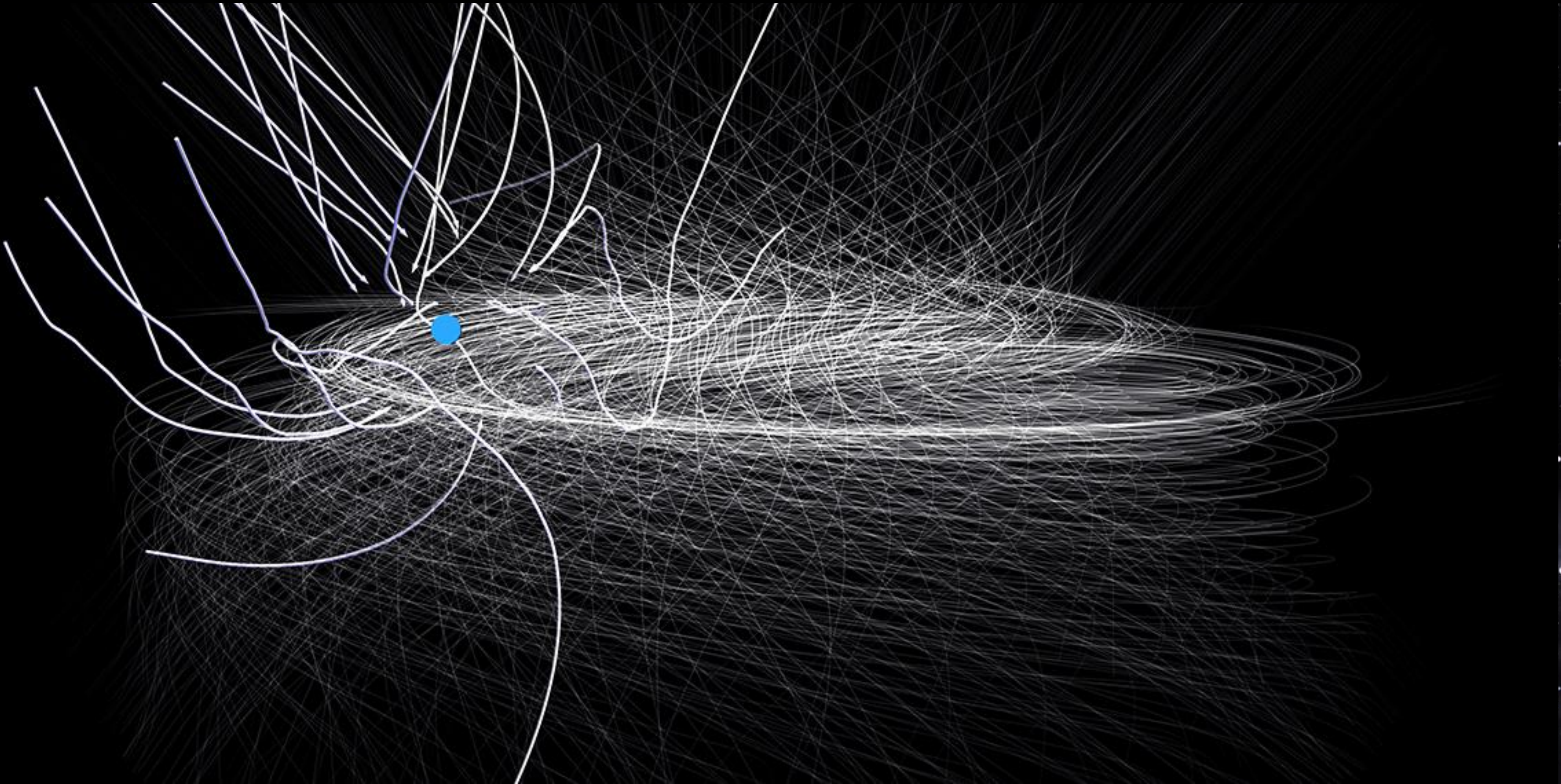


Many unexplained spectral features

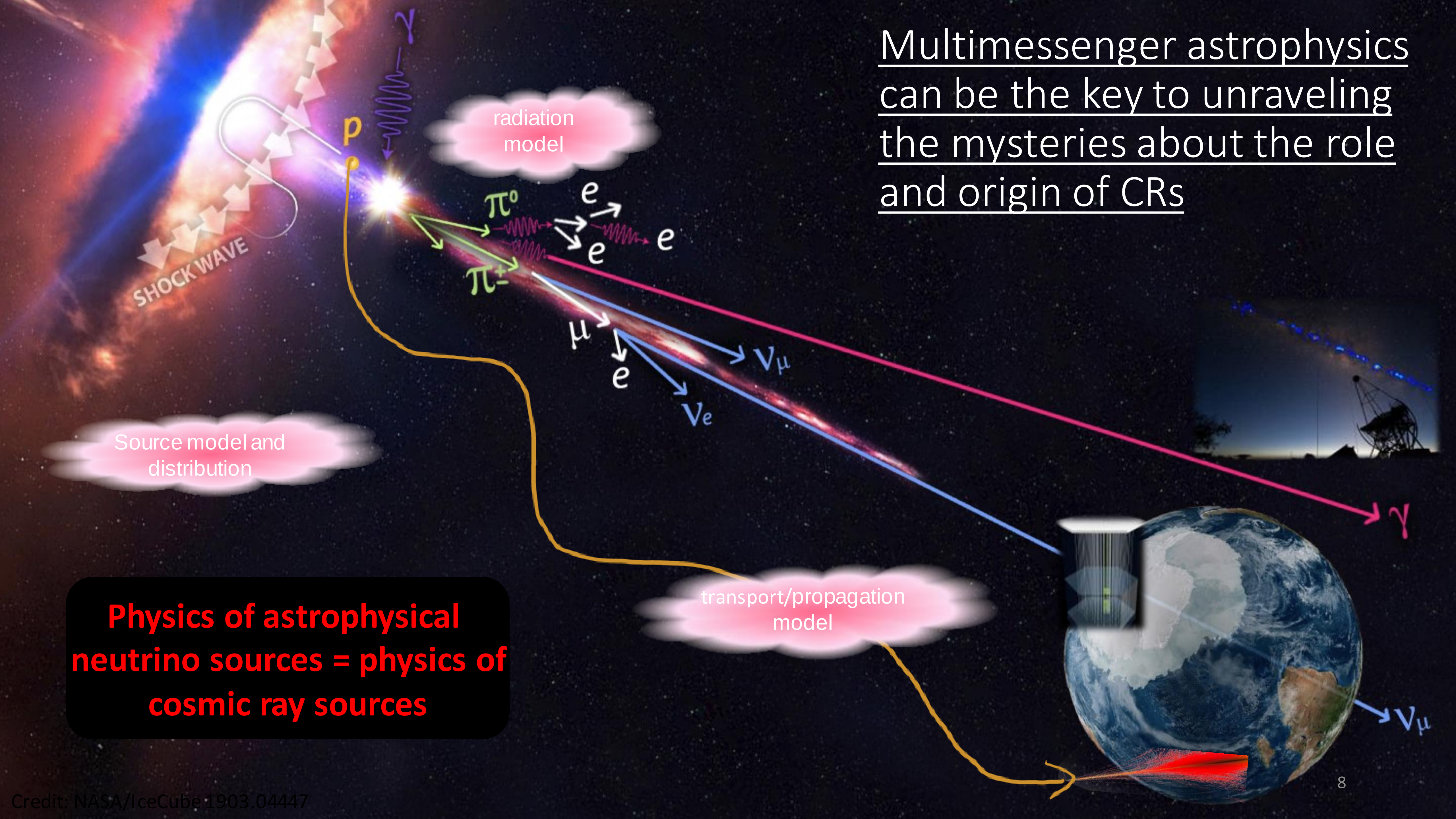
Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533



None of the features unambiguously explained!



Multimessenger astrophysics can be the key to unraveling the mysteries about the role and origin of CRs

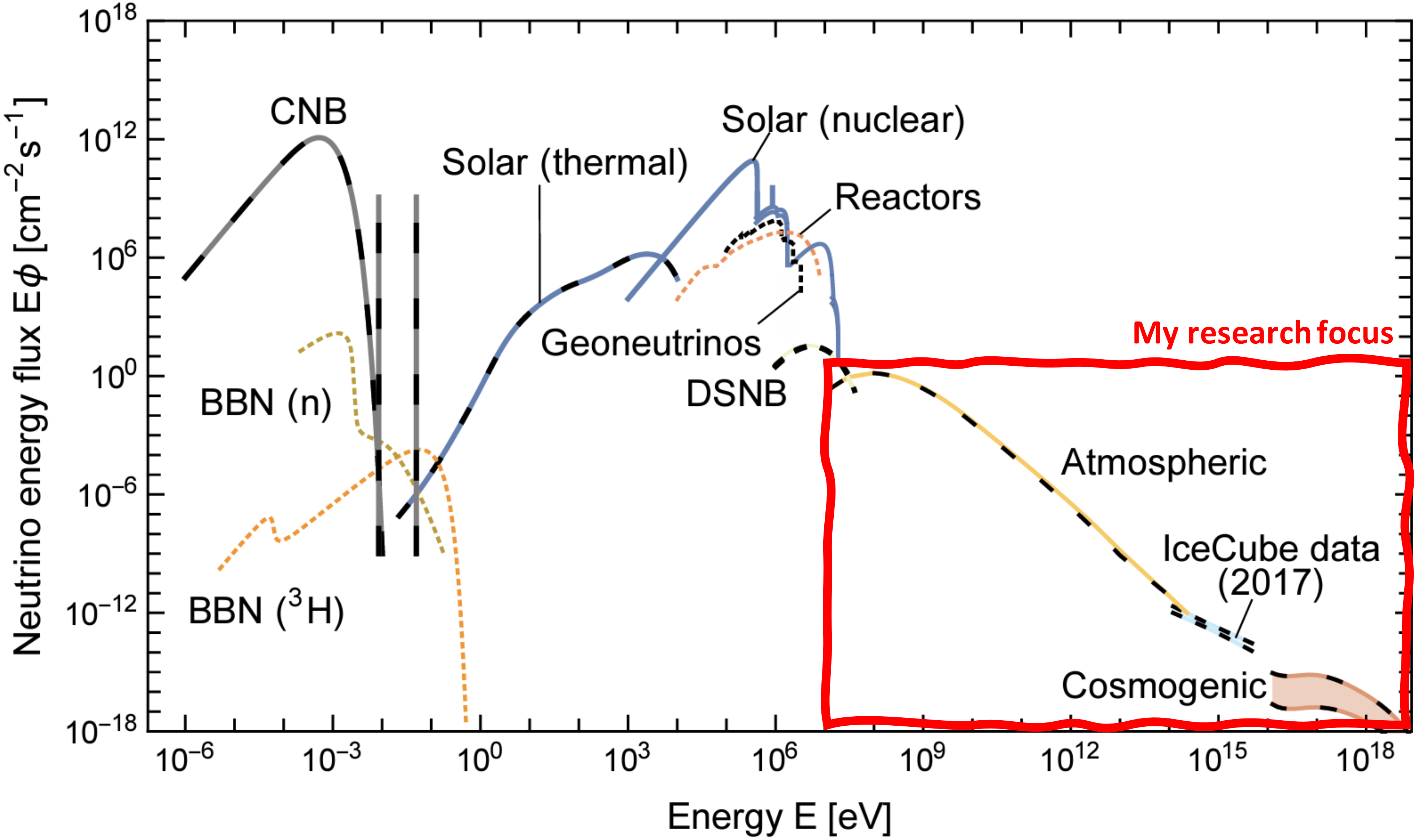


Physics of astrophysical neutrino sources = physics of cosmic ray sources

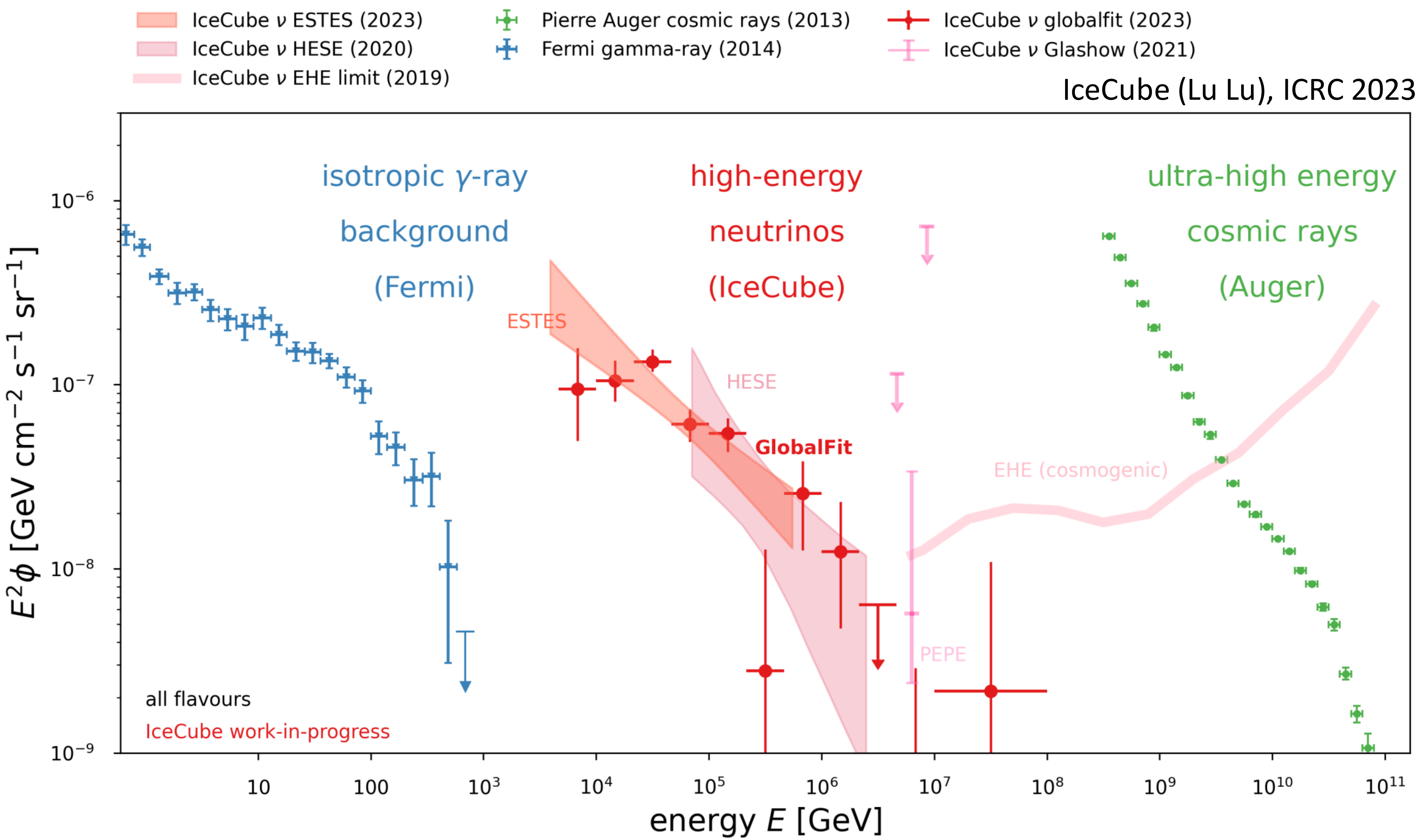
Credit: NASA/IceCube 1903.04447

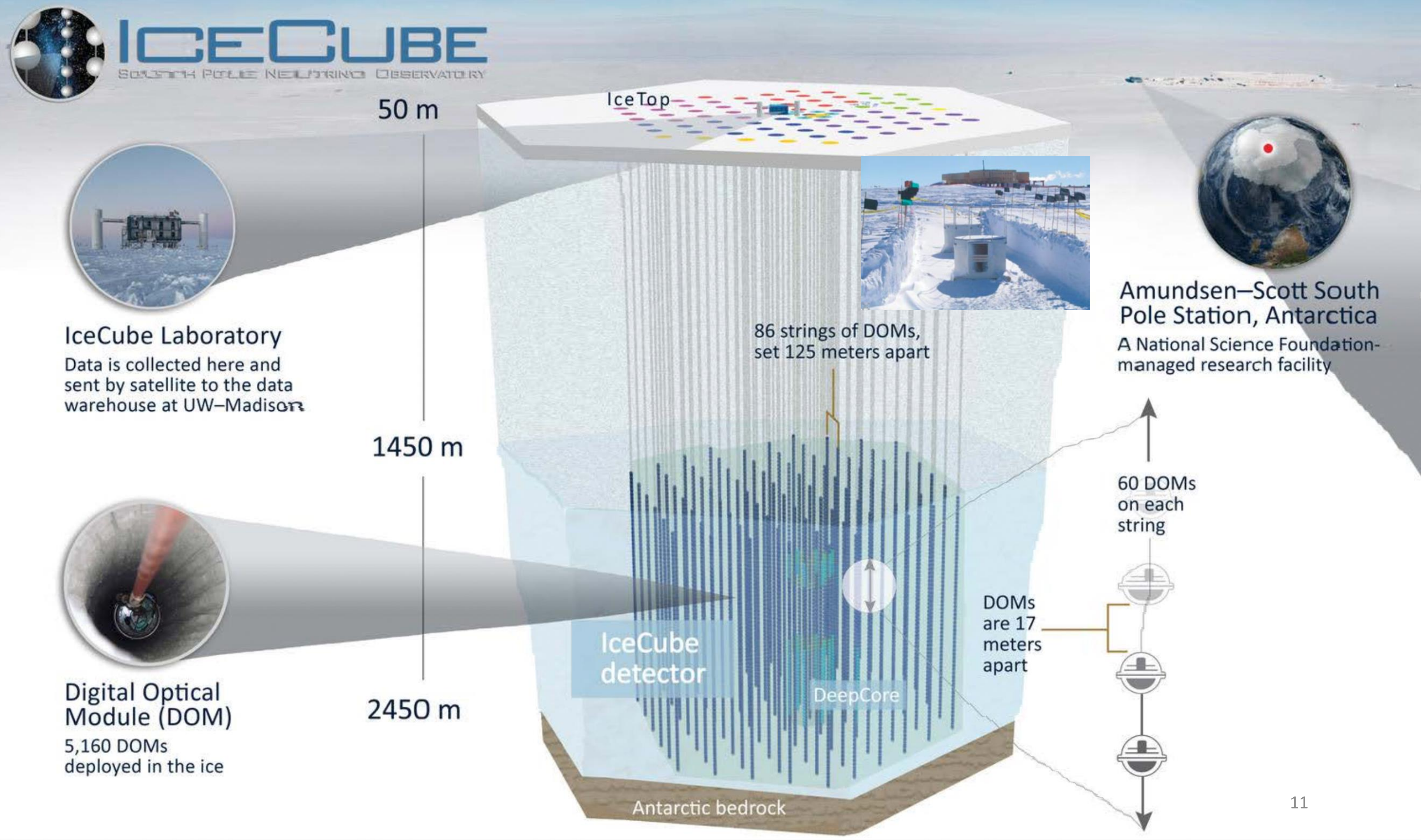
Neutrino spectra at Earth

Vitagliano, Tamborra, Raffelt 2019, 1910.11878



Comparable energy density in gamma rays, neutrinos and UHECR. Connection?




ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
2450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock

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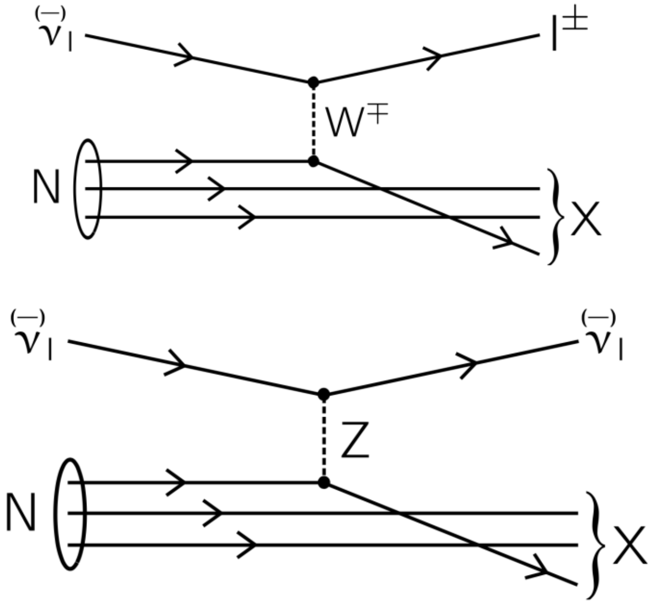
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

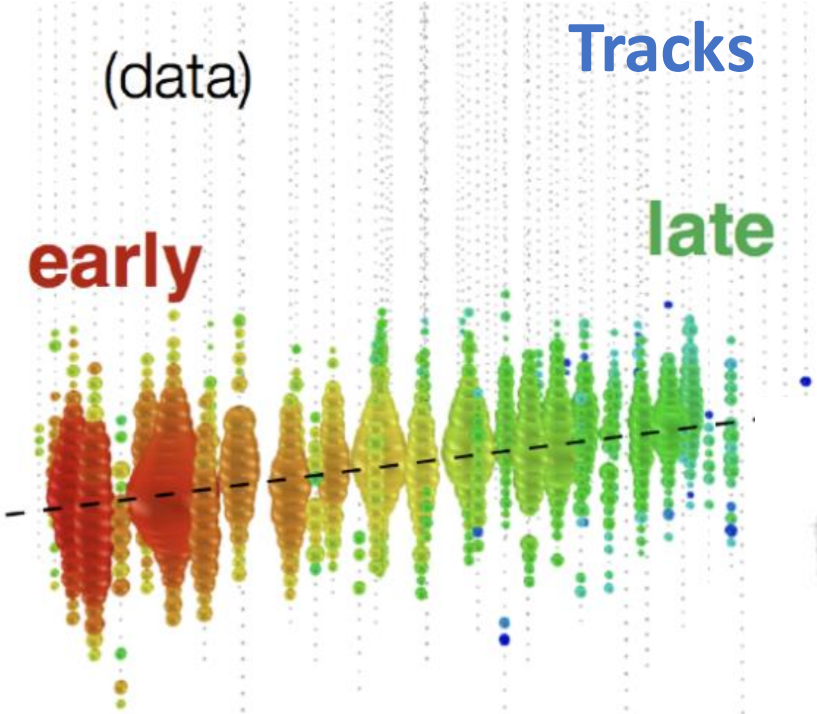
ICECUBE NEUTRINO OBSERVATORY

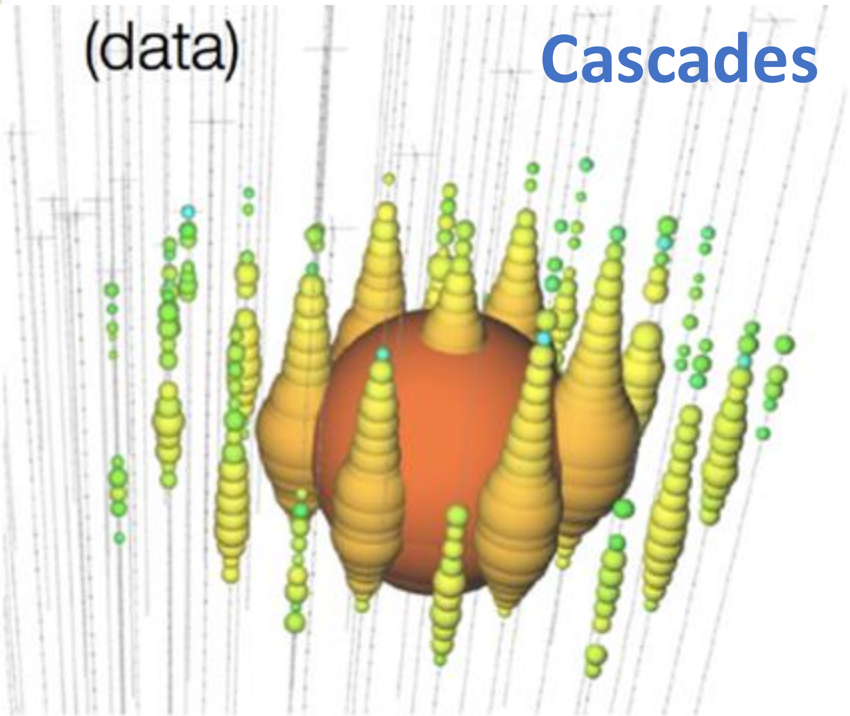
icecube.wisc.edu

Neutrino topologies seen by IceCube



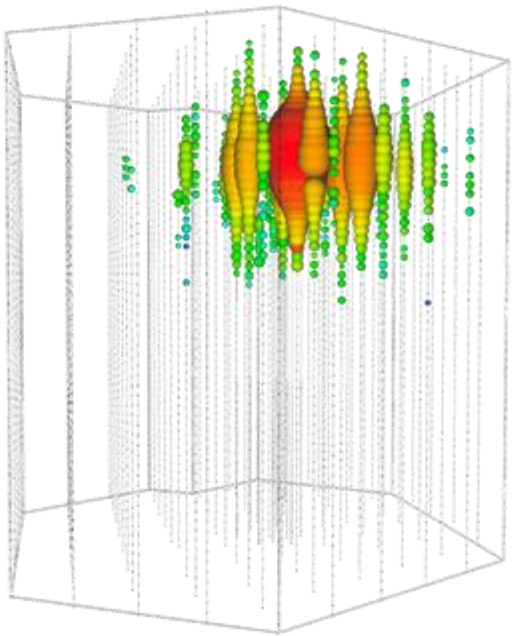
- Deep-inelastic scattering
- Tracks deposit significant energy outside of the fiducial volume
- Showers length ~ few metres -> direction reconstruction challenging

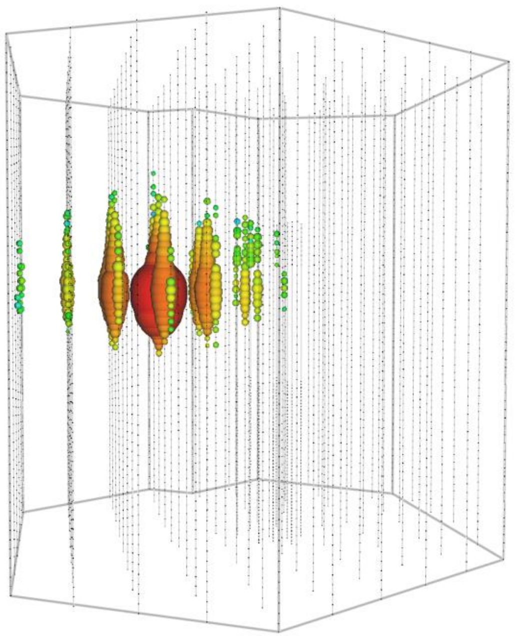


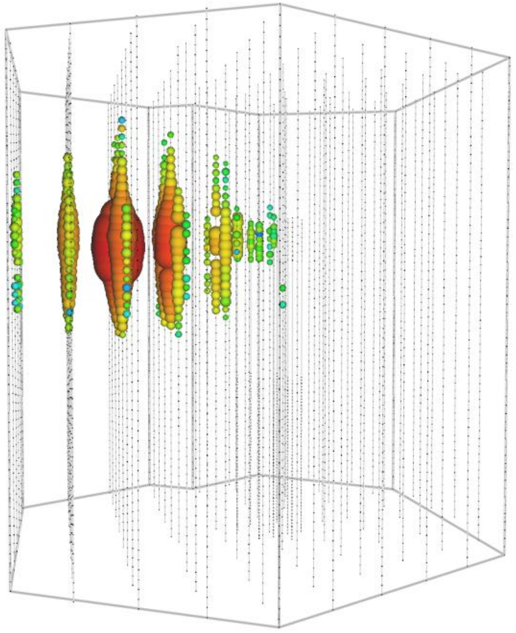


PeV events in IceCube

Deposited energy > PeV

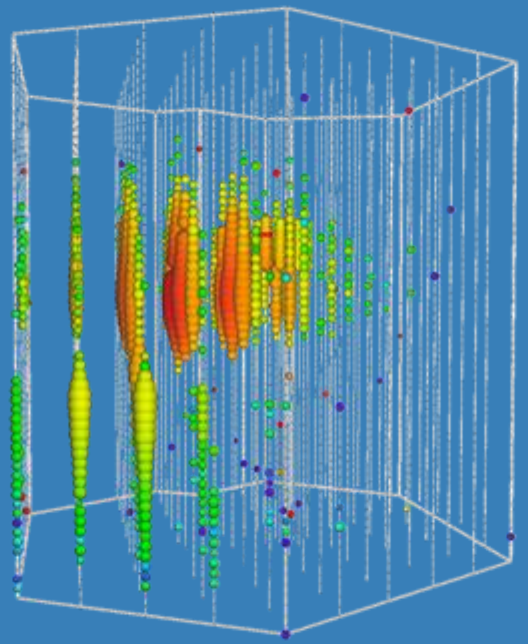


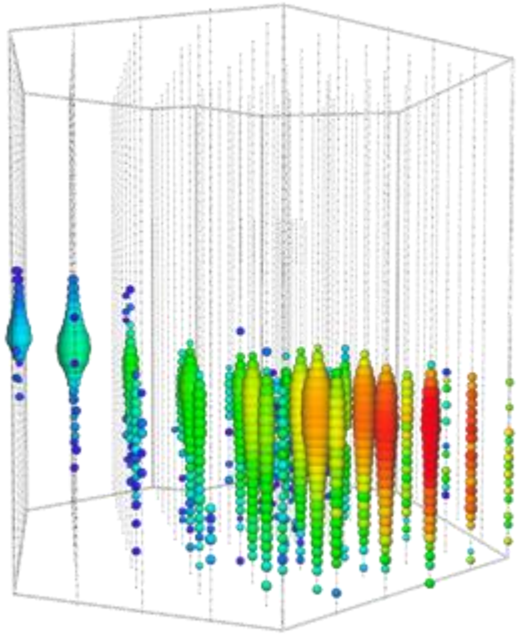


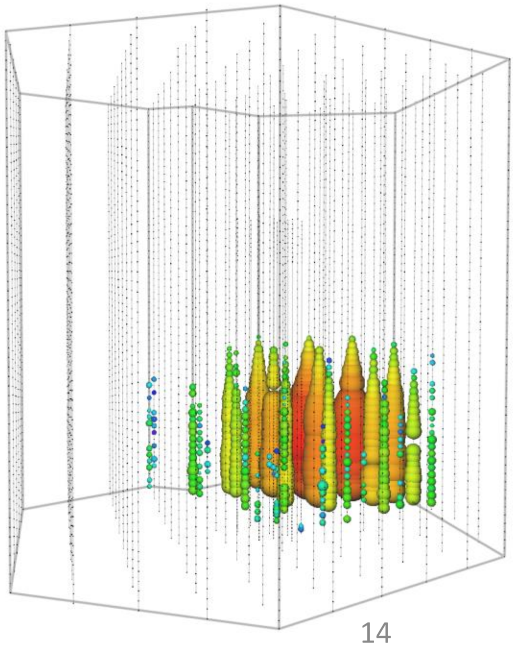


- Newest PeV+ event
- 4.8 PeV deposited energy
- Neutrino energy ≈ 13 ± 5 PeV (analysis on-going)

T. Yuan’s talk at ICRC2023
PoS-ICRC2023-1030







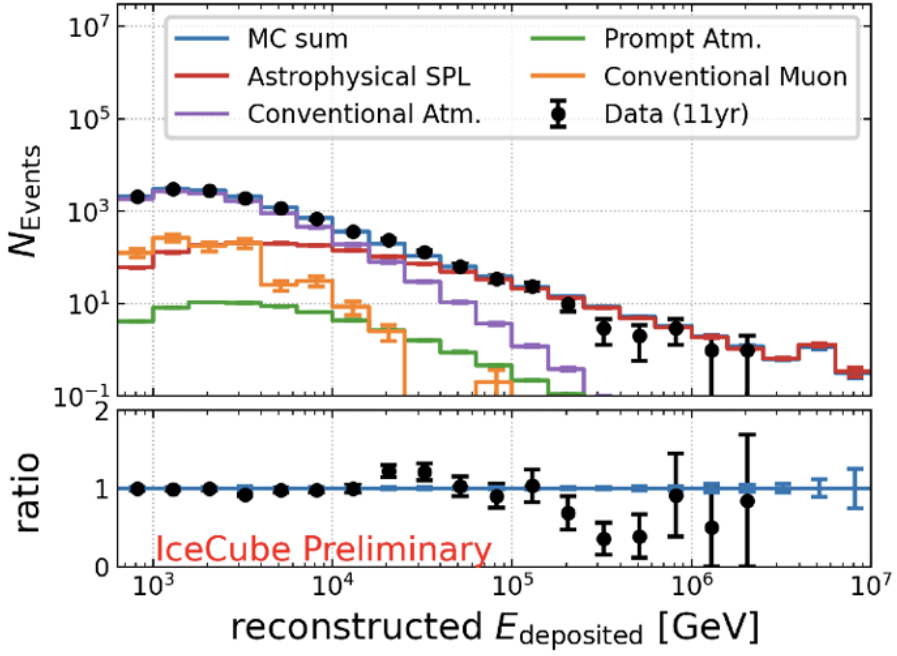
Challenges of the astrophysical diffuse flux measurement

Astrophysical single power law (SPL)

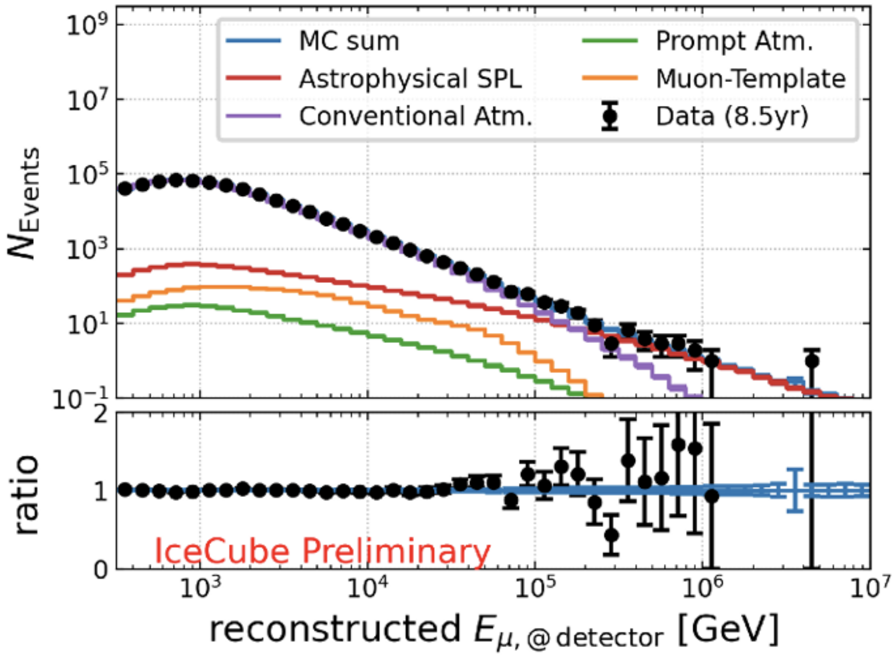
- Fit $\gamma = 2.52^{+0.04}_{-0.04}$ and $\Phi^{\nu+\bar{\nu}}_{@100\mathrm{TeV}} = 1.80^{+0.13}_{-0.16}$
- Sensitive from 2.5 TeV to 6.3 PeV, assuming unbroken single power law

- Measurement comprised of the **sum of atmospheric + astrophysical flux components**
- **Indication of spectral features** around the transition energy between atmospheric and astrophysical neutrinos
- **Sophisticated modeling of systematics** required

Cascade histogram

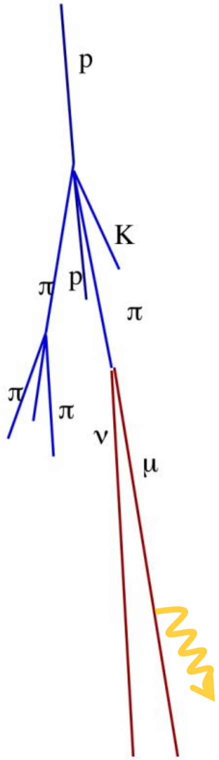


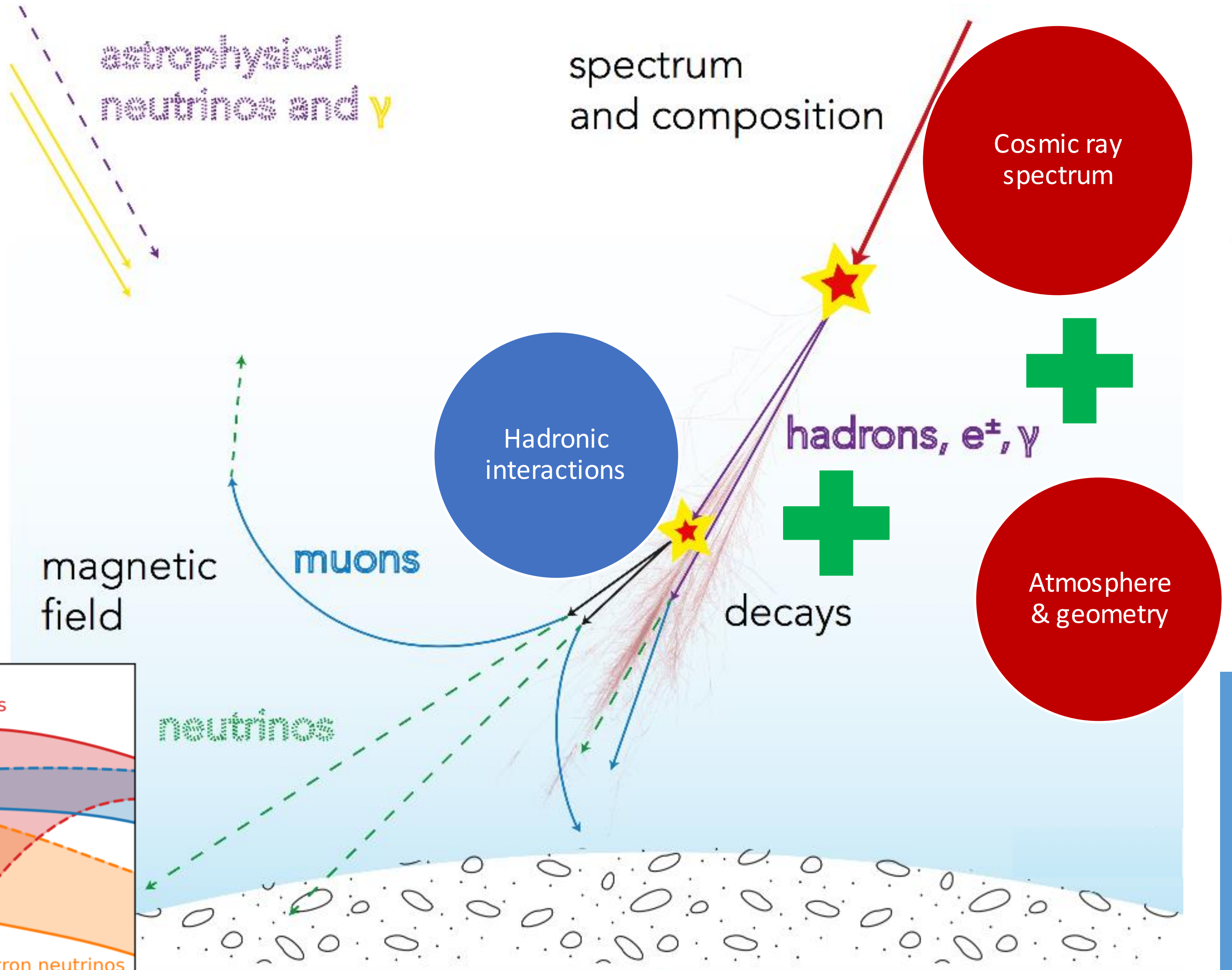
Track histogram

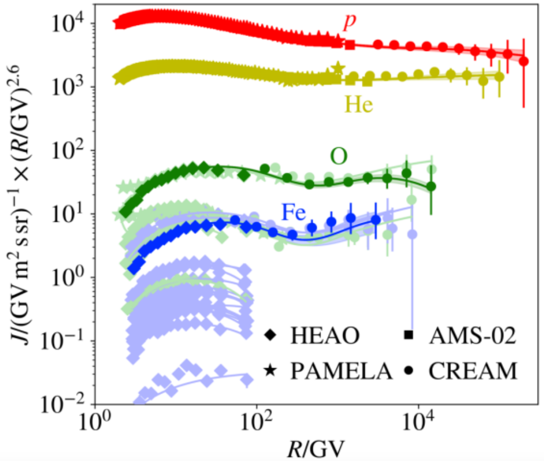


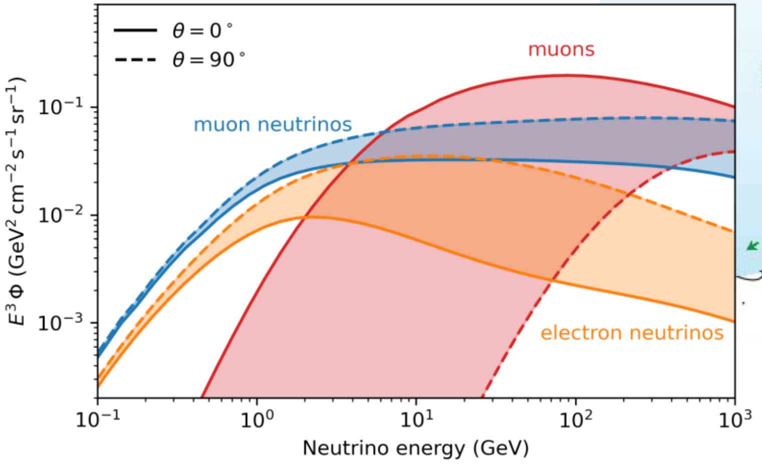
IceCube Diffuse GlobalFit (presented by Richard Naab), ICRC 2023

Modeling atmospheric lepton fluxes







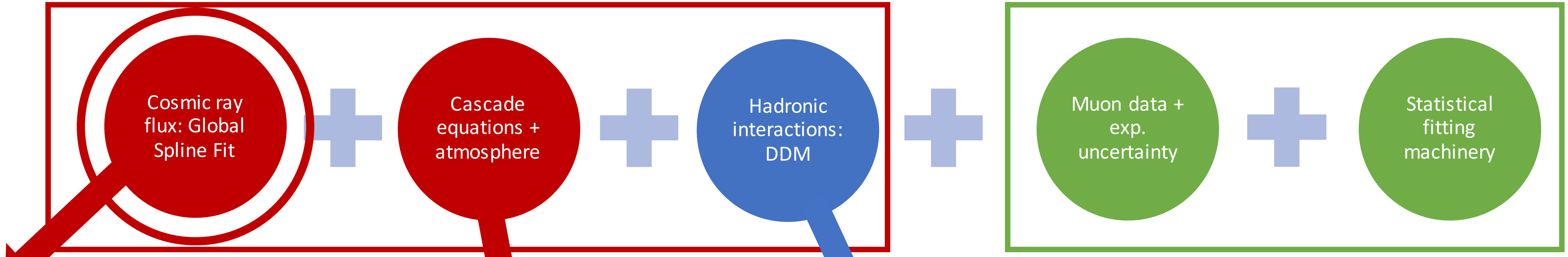


No model is founded on a "fundamental" theory/framework.

All are "theory-motivated", "data-driven", or empirical.

The road to a bleeding edge atmospheric flux model

”Flexible” flux model with uncertainty priors from data



Cross-calibration with atmospheric muons

GSF: Dembinski, AF, Engel, Gaisser, Stanev PoS(ICRC2017)533

- Representation of CR flux and mass composition **measurements and uncertainties**
- Fit global fit to data
- High-quality data requirements (systematics)
- Fitting ~100 parameters
- On the market since 2017, so far good feedback and no obvious flaws.

MCEq code

(AF, arXiv:1503.00544, 155 cites):

- Mature code (since 2014)
- **Baseline in high-energy neutrino physics**
- Solves coupled cascade equations
- Contains many models
- **Fast & userfriendly**

DDM model

(AF + Huber PRD107, 2022):

- Study connection between accelerator data and atmospheric leptons
- **Data-driven model and error estimate for hadronic interactions**
- Describes other data well

daemonflux

(Yanez + Fedynitch PRD107, 2022):

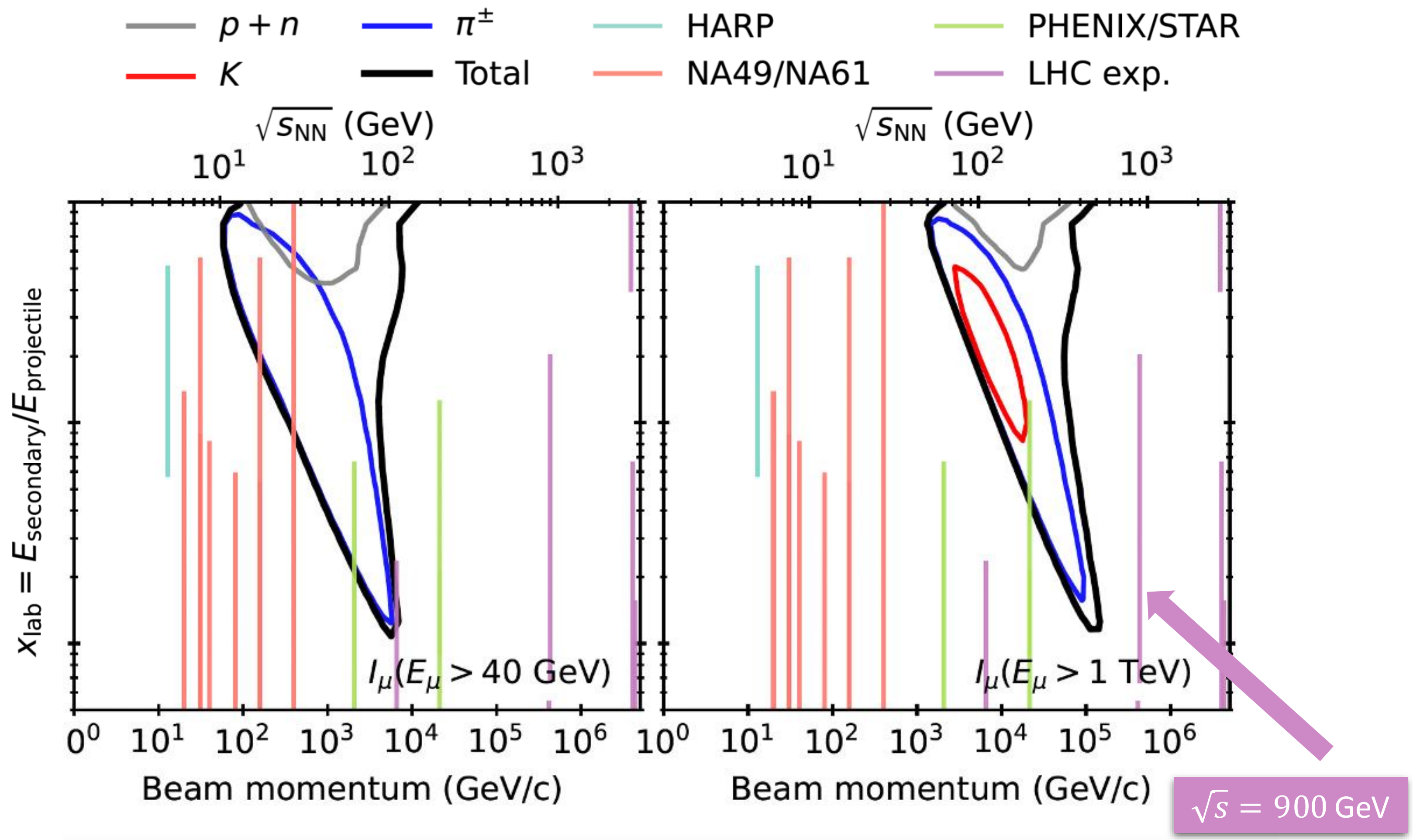
- DAta-drivEn MuOn-calibrated atmospheric Neutrino Flux
- **Global Fit of free params to surface muon data**
- Reduction of error x10 wrt previous models

Hadron production phase space seen by neutrino detectors

See also Albrecht et al., Muon Puzzle review, 2105.06148

AF & M. Huber, arXiv:2205.14766

- Oscillation target energies covered by data from fixed target experiments
- IceCube energies not well covered by data
- LHC energies too high
- Shared production phase-space for parent mesons of muons and neutrinos
- Optimizal description of atm. Muon data → imporved atm. neutrinos



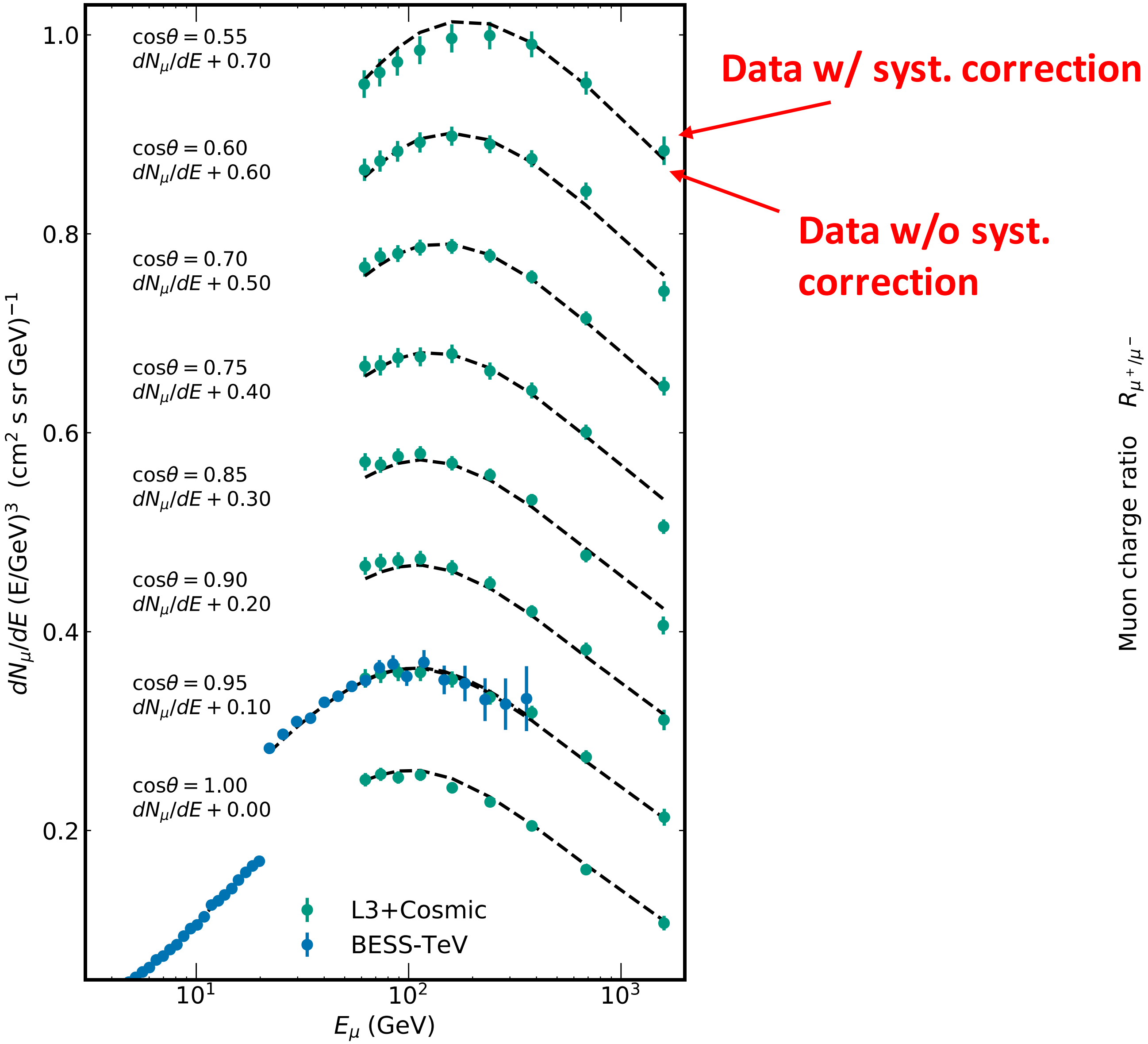
Integrated muon flux at the surface: E > 40 GeV

Integrated muon flux at the surface: E > 1 TeV

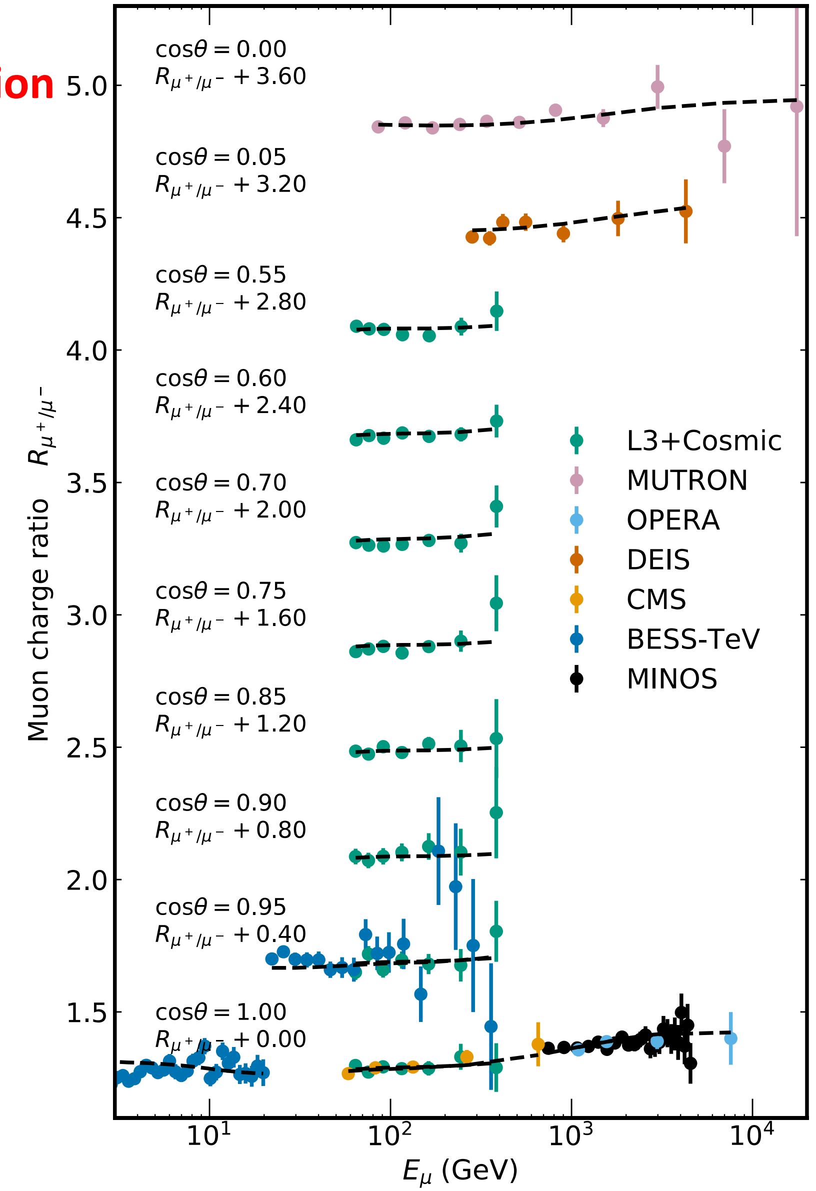
Contours = 90% of ν_μ events

Resulting muon fluxes and cross-calibrated data

Muon flux

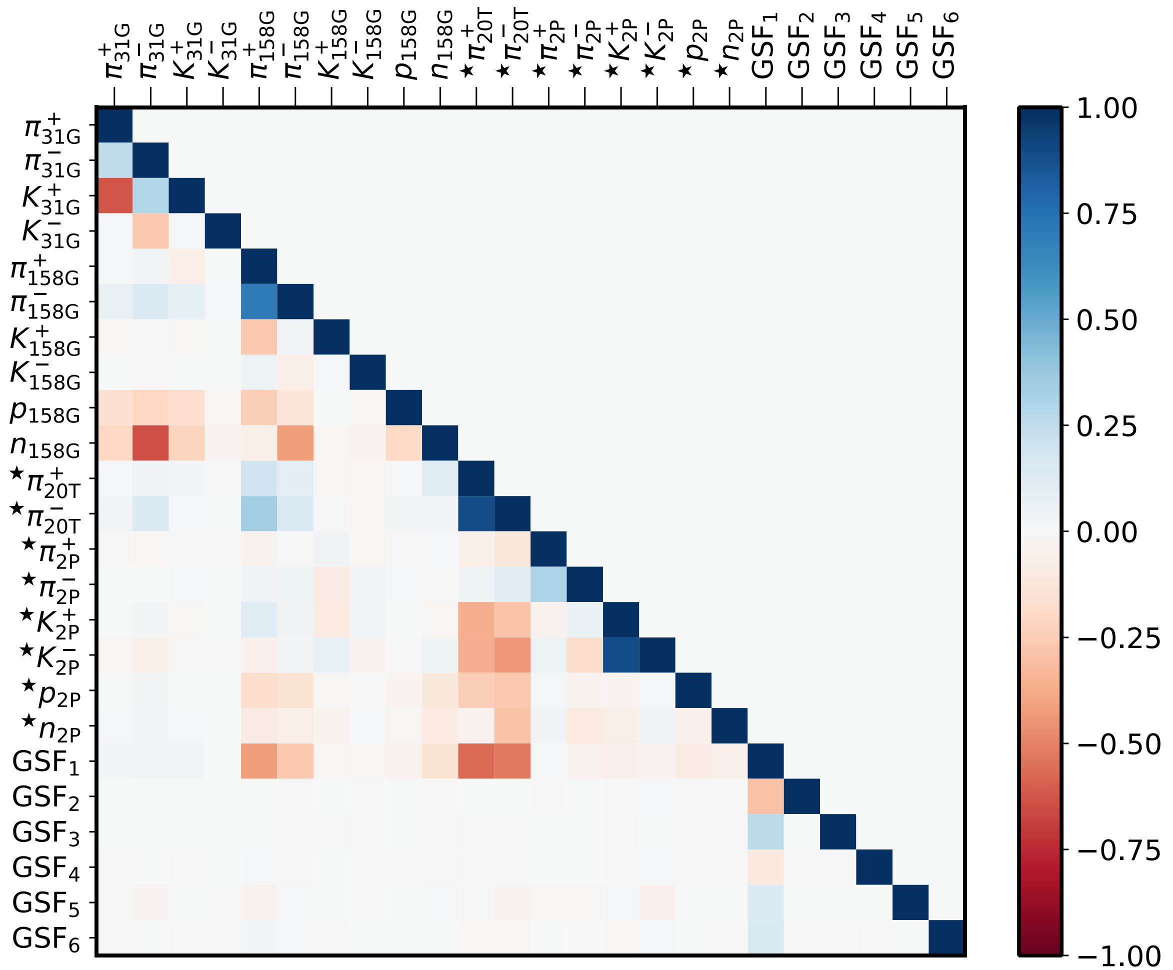


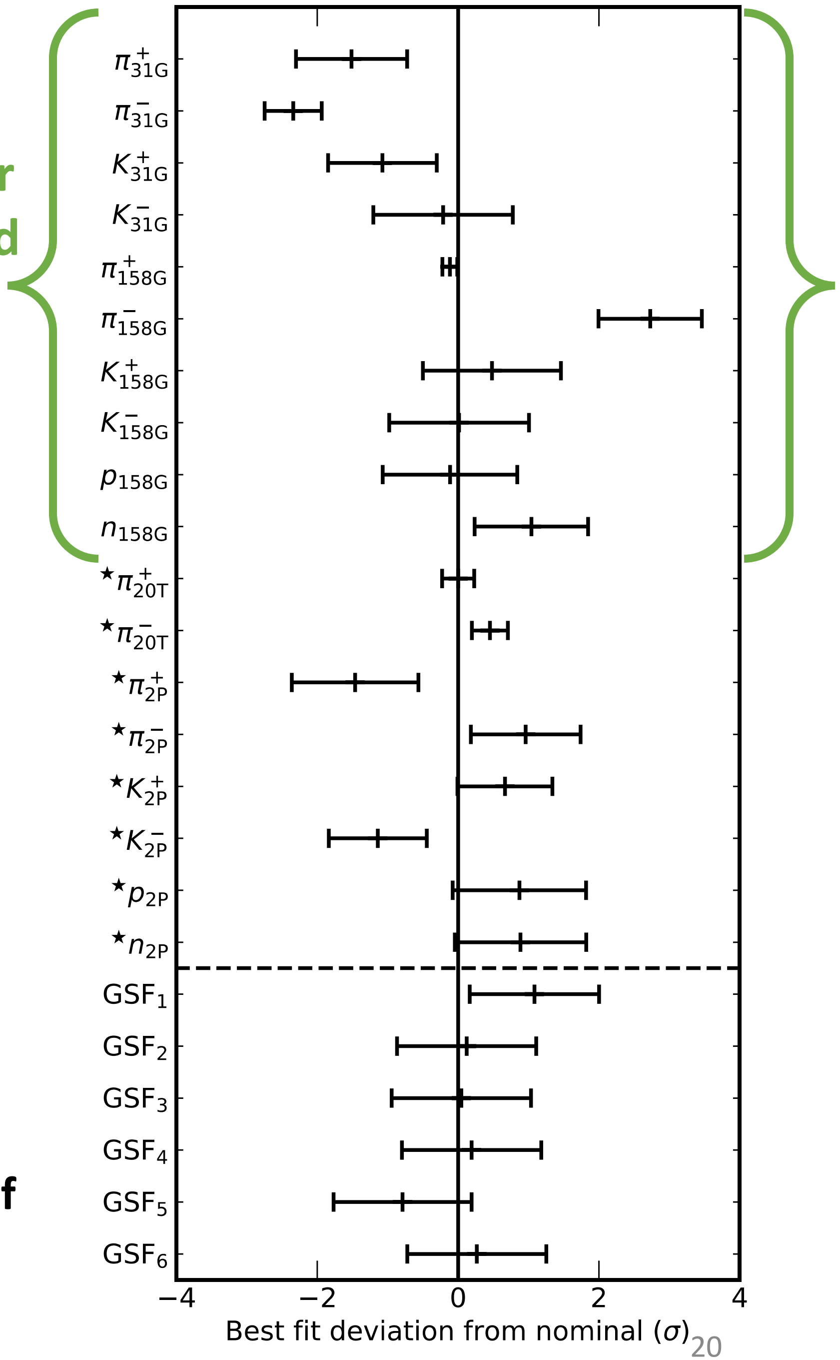
Muon charge ratio



J. P. Yanez & AF, arXiv:2303.00022

Fitted parameter values





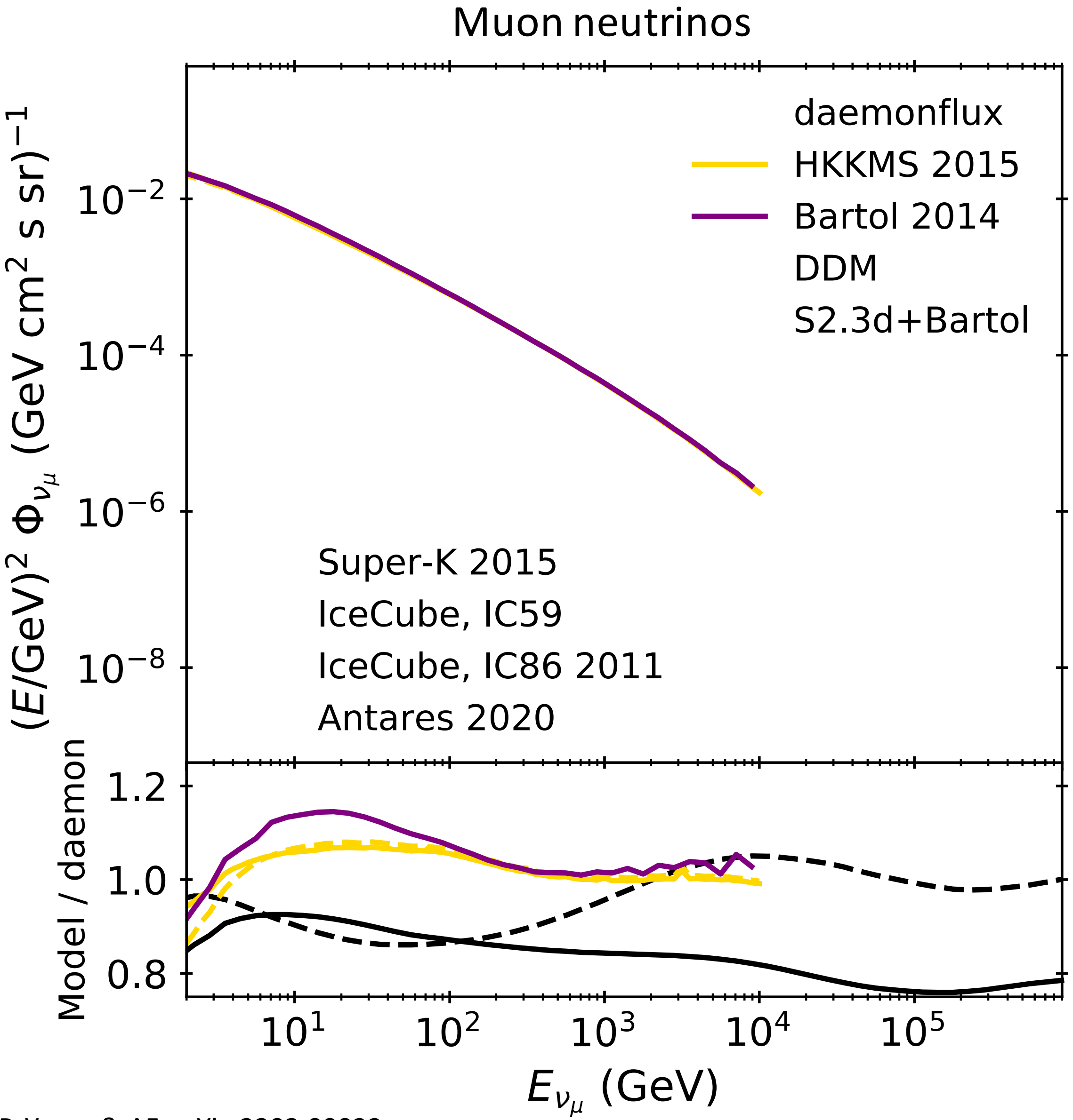
Physics parameter part of the correlation matrix: Total 34 parameters: 18 hadrons + 6 GSF + 10 experimental

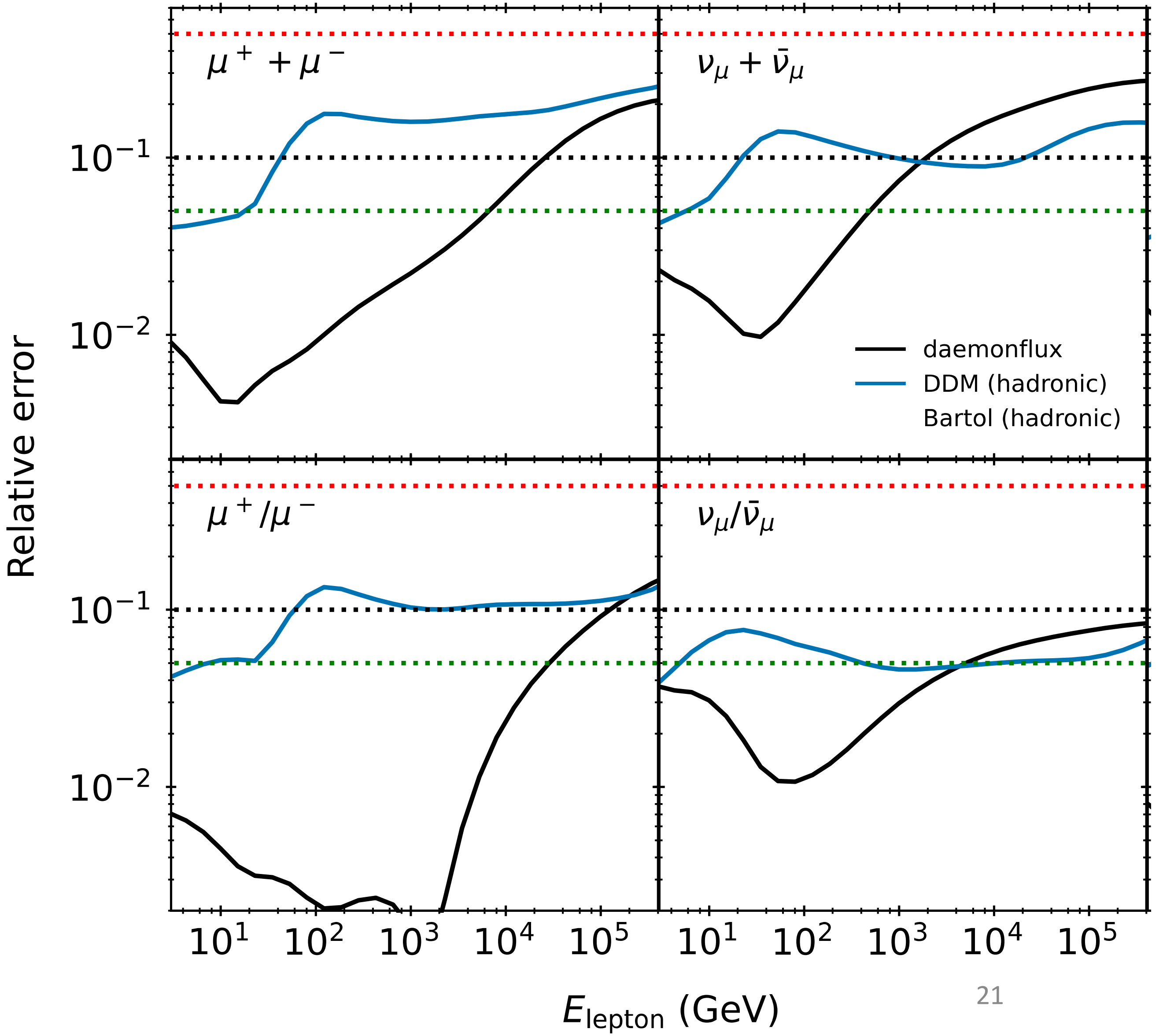
Chi[2] 199/ 217 dof (approximate)
P-value = 81%

Neutrino fluxes

hatched area: previous reference uncertainty estimation

Barr et al. PRD74, 094009 (2006) & AF, Huber PRD (2022)



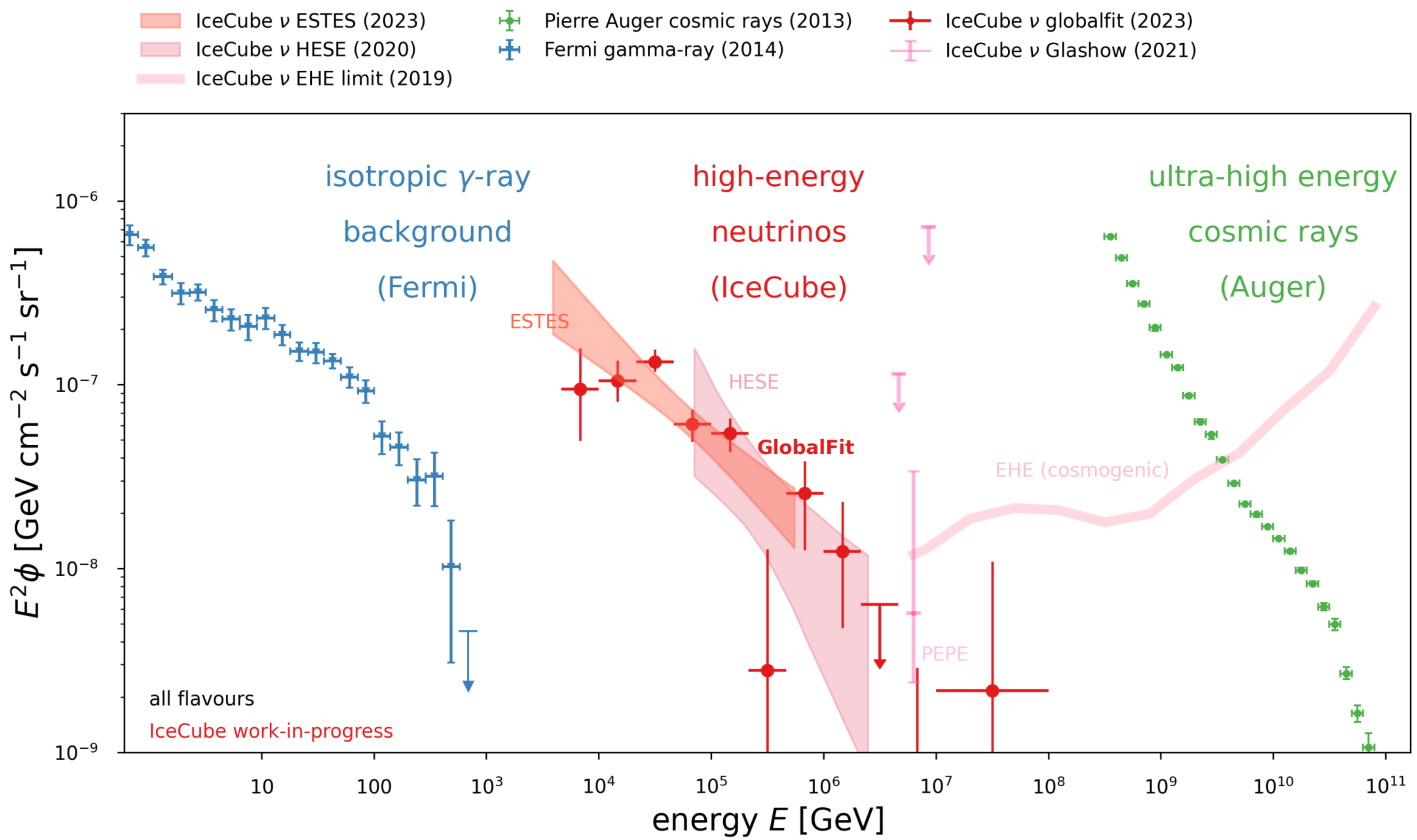


J. P. Yanez & AF, arXiv:2303.00022

Takeaways from my IceCube and atmospheric neutrino activities

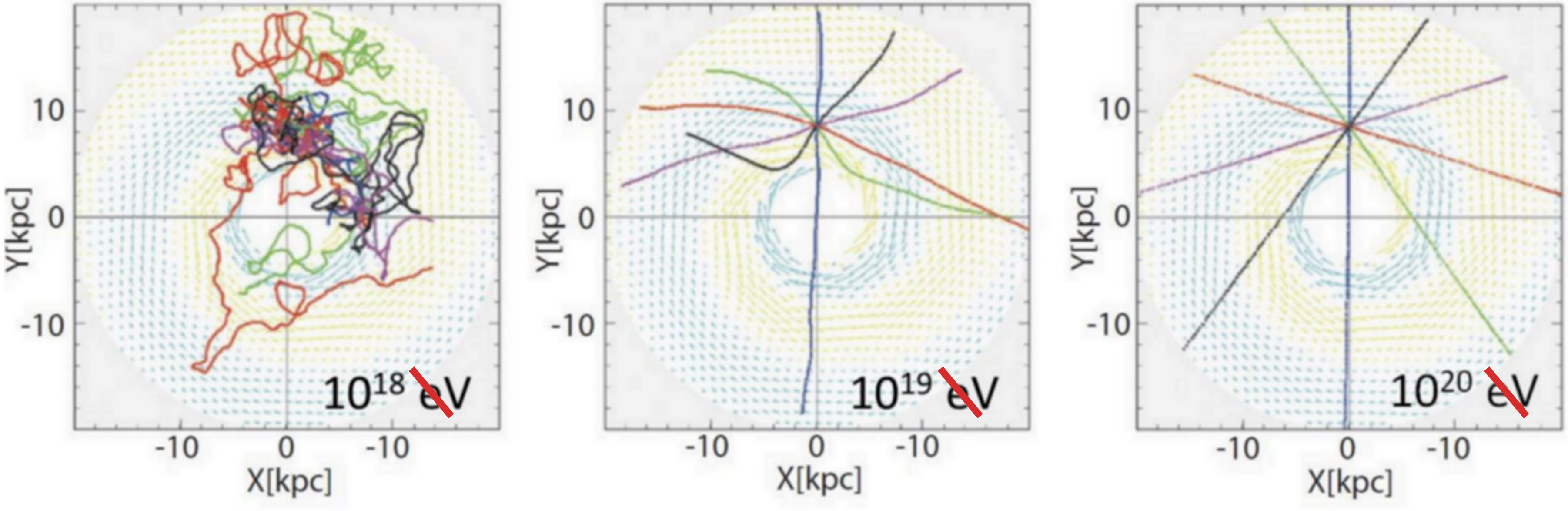
1. After 12 years of datataking **IceCube as a detector has unprecendented statistical power** to reveal details about the majority of neutrinos (diffuse fluxes)
2. Key developments recently happened in systematics, such as ice model, fitting machinery (Snowstorm + GlobalFit), and now also the new atmospheric model daemonflux
3. The key **observation targets** (for me) are the flux of **prompt neutrinos from decay of heavy flavor** mesons, energy dependence of the **astroph. flavor ratio** and **evidence for substructure**, all of which require a pedantic approach to systematics
4. It is likely that in October 2023, the collaboration will award me the **leadership of the diffuse working group**, drive the **science output of ~50 very actively** engaged members.
5. **IceCube as a collaboration has reliably produces discoveries**, published in high profile journals (**Science publications recently in 2022 and 2023**). Further exceptional results are expected to come.
6. Among several planned improvements and upgrades **the flux modeling**, I plan to **maintain the leadership** and engage with other collaborations as an expert, such as **KM3NeT, Baikal, P-ONE and TRIDENT**.
7. I envision my >10 year long journey to **a satisfactory set of flux modeling tools** become a more **stable business**.

If astrophysical neutrinos are connected to UHECR, how do we find their sources?



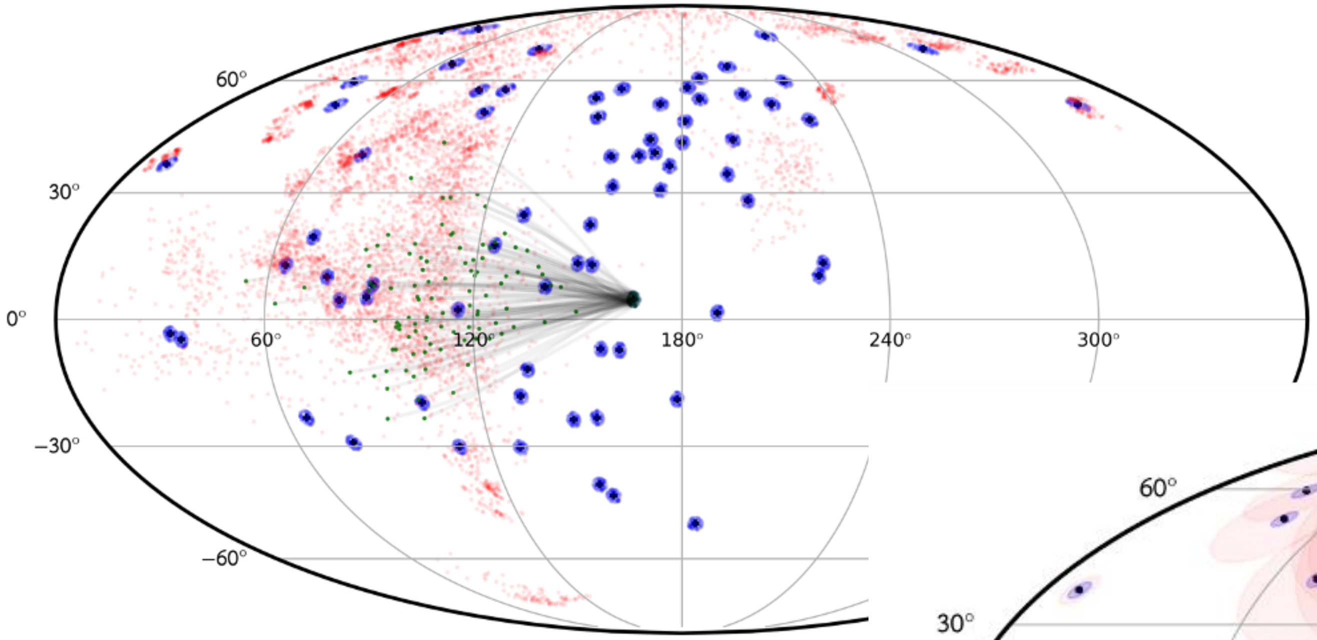
Key physics challenge: missing identification of charge at high energies

Credit: Ebisuzaki (RIKEN)

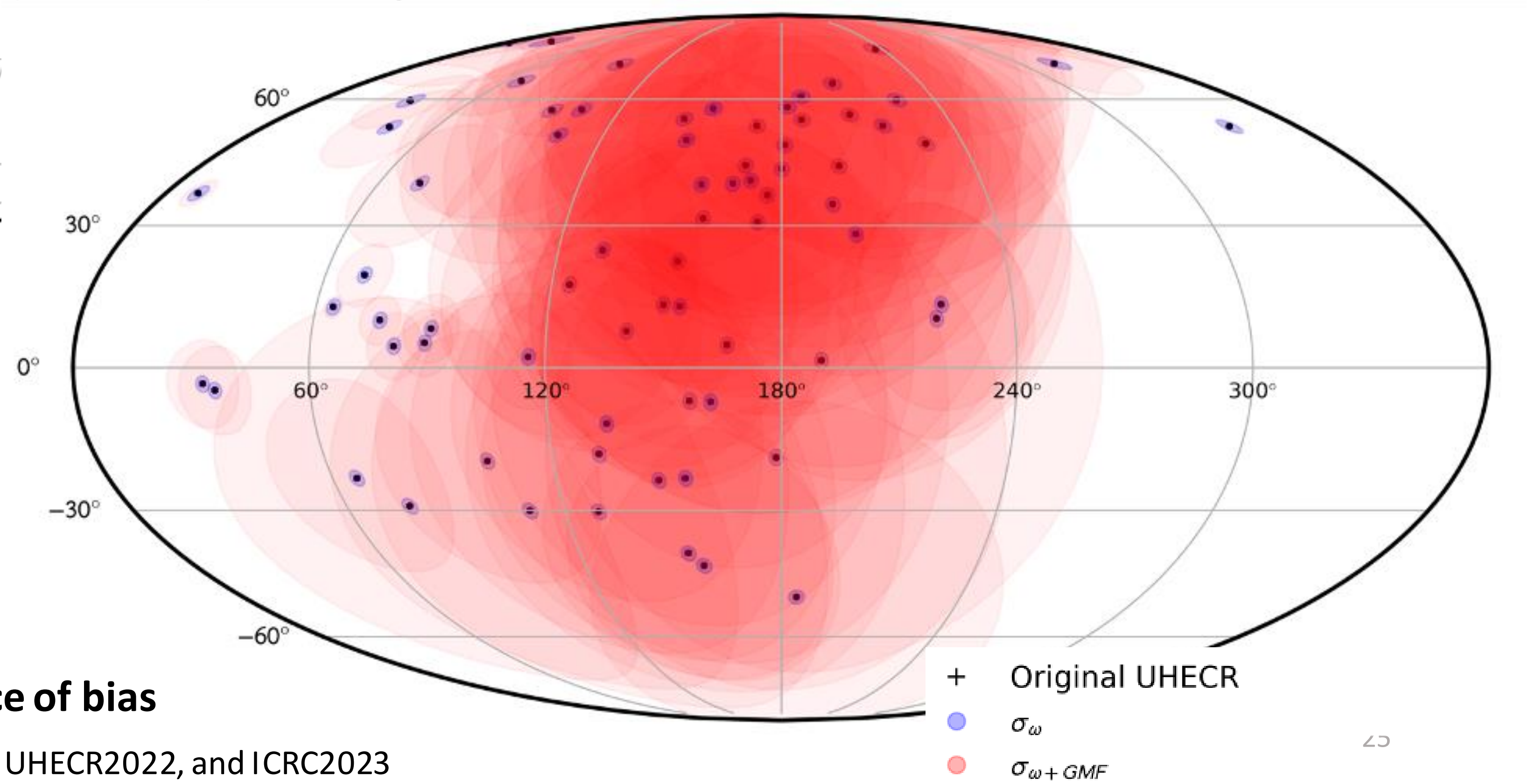


- Magnetic deflection in galactic and extragalactic magnetic fields is a function of **RIGIDITY (E/Z)**
- Anisotropic “by design”
- If an experiment measures the CR energy but not the charge (or mass number)
  - → Divide the energy by your favorite integer number between 1 and 20 😅 😉

Deflections are anisotropic, energy and composition dependent



TA 2015 data, nitrogen assumption, JF12

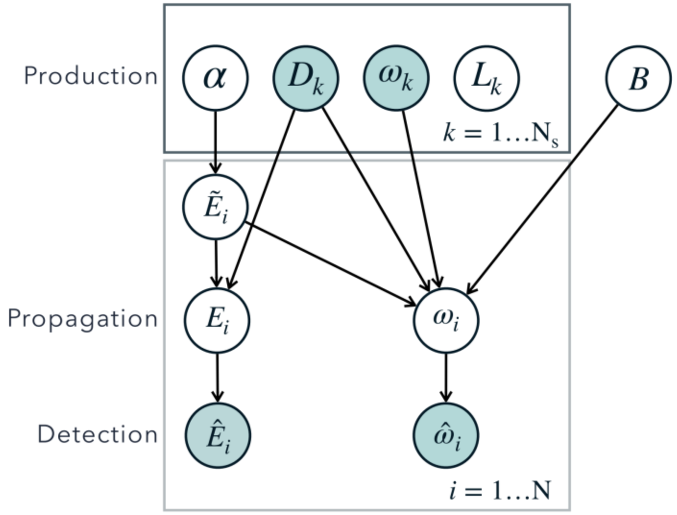


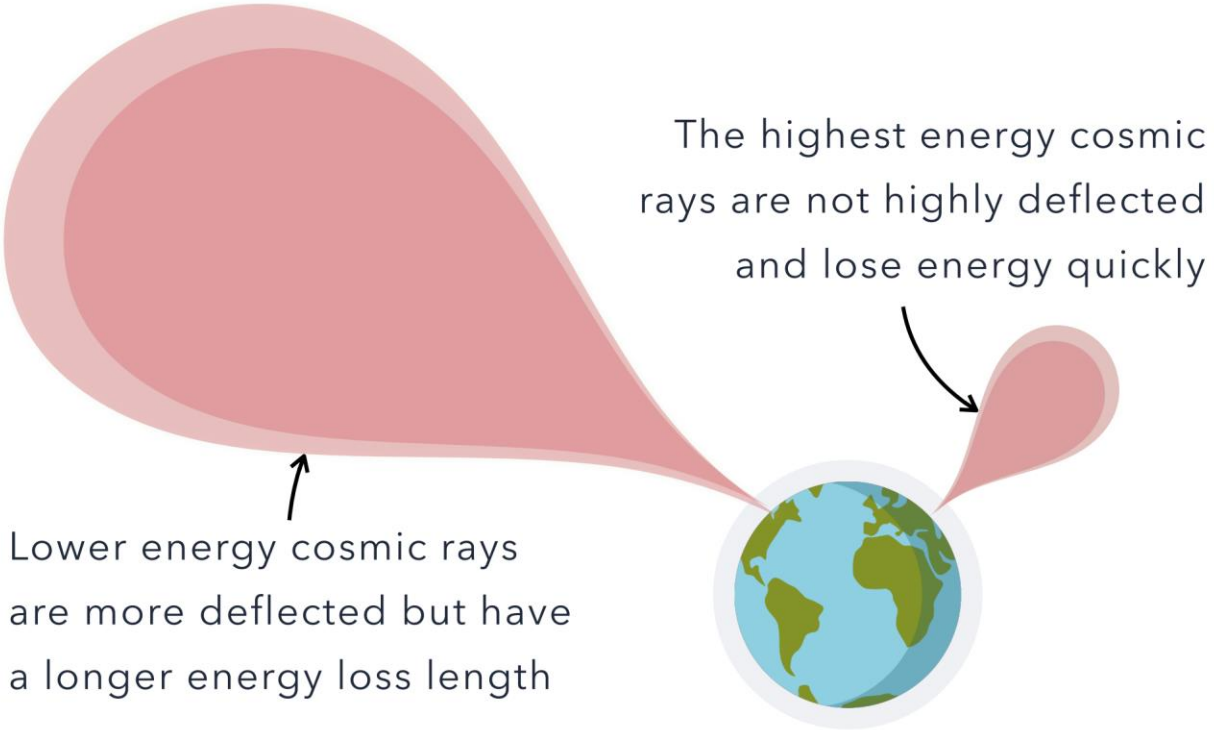
A simple, "circular search range" is a source of bias

Keito Watanabe, AF, Francesca Capel, Hiroyuki Sagawa, UHECR2022, and ICRC2023

Road: Bayesian inference and detailed physics model input

Bayesian Hierarchical Model
(implemented in Python + STAN, Hamiltonian MCMC)

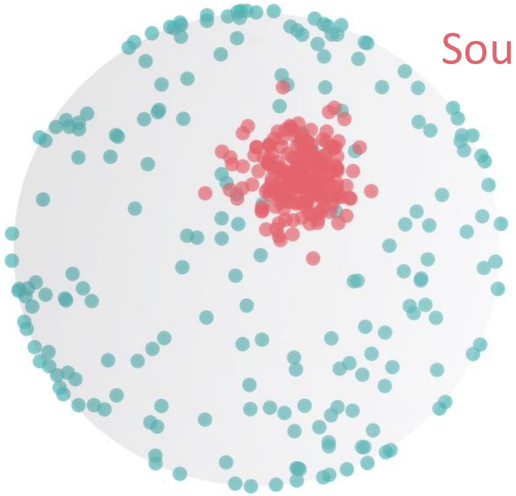




Source fraction:

$$f = \frac{F_s}{F_0 + F_s}$$

Source Flux



Background Flux

Evolution of:

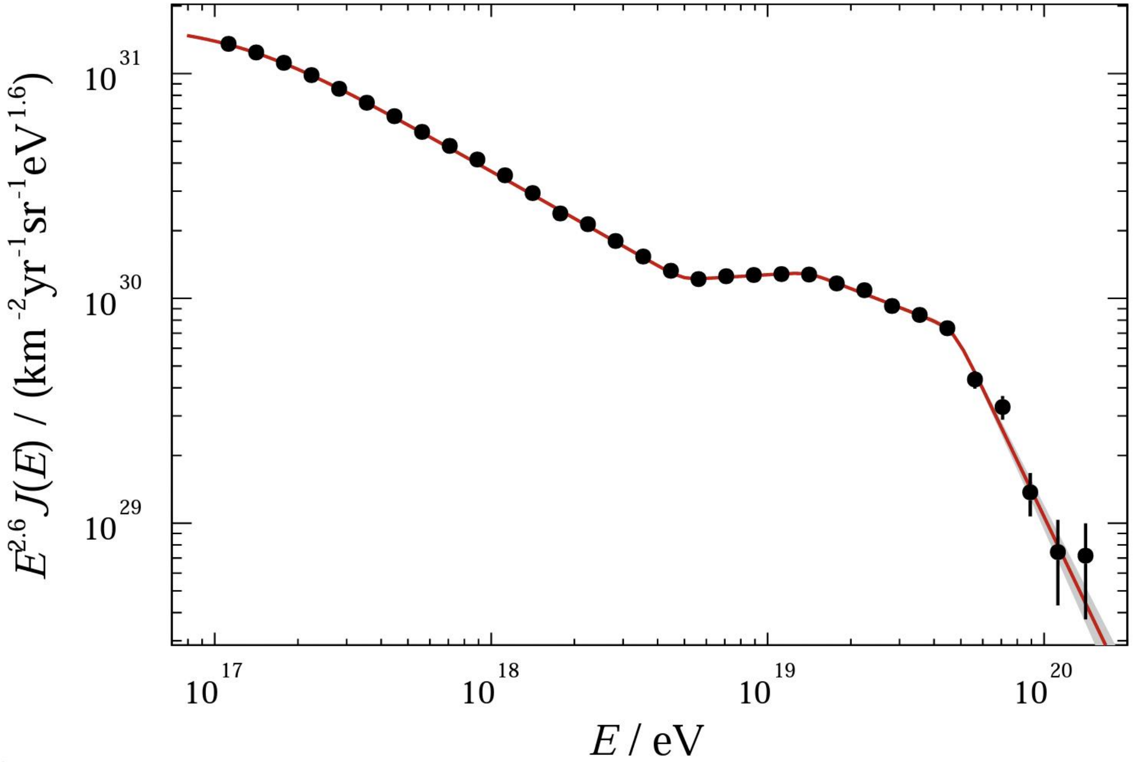
Francesca Capel & Mortlock, 1811.06464

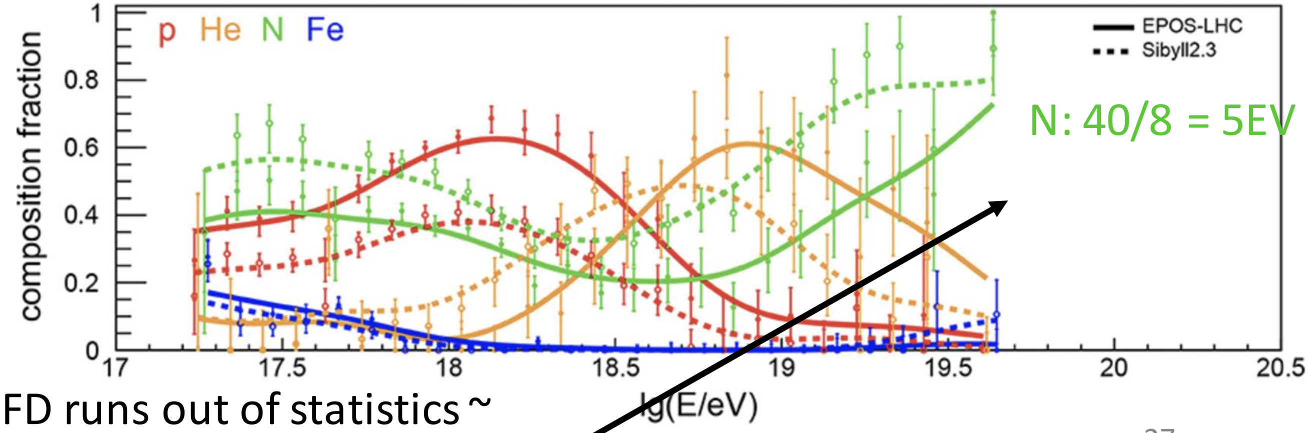
Keito Watanabe, AF, Francesca Capel, Hiroyuki Sagawa, UHECR2022, ICRC2023

Current mass measurements not good enough

O. Deligny (PAO), CRIS 2022

- Template method (backup) gives "all-sky average" of masses, **not the mass of each event**
- The errors are still large ~lnA=1, because the impact on the shift of mean X_{max} is quite small
- The conversion from <Xmax> to <lnA> is model dependent (dashed vs solid line)
- Needs Fluorescence Detector FD (for X_{max})
  - Small duty cycle
  - Smaller exposure





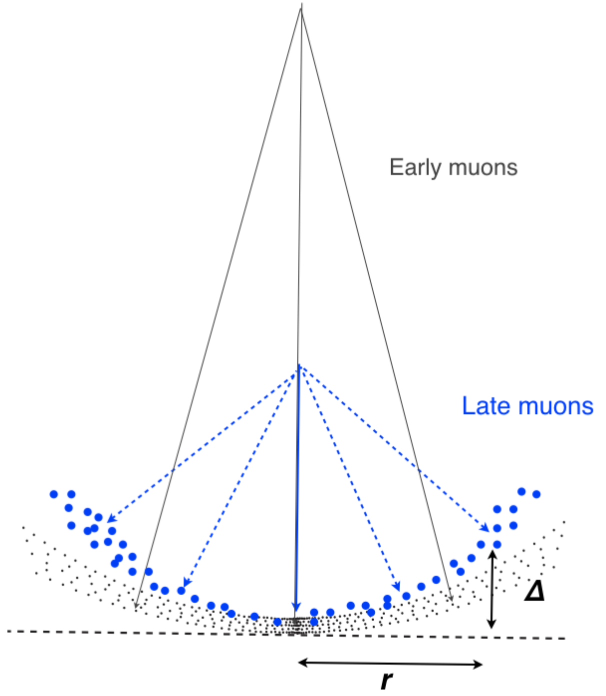
N: 40/8 = 5EV

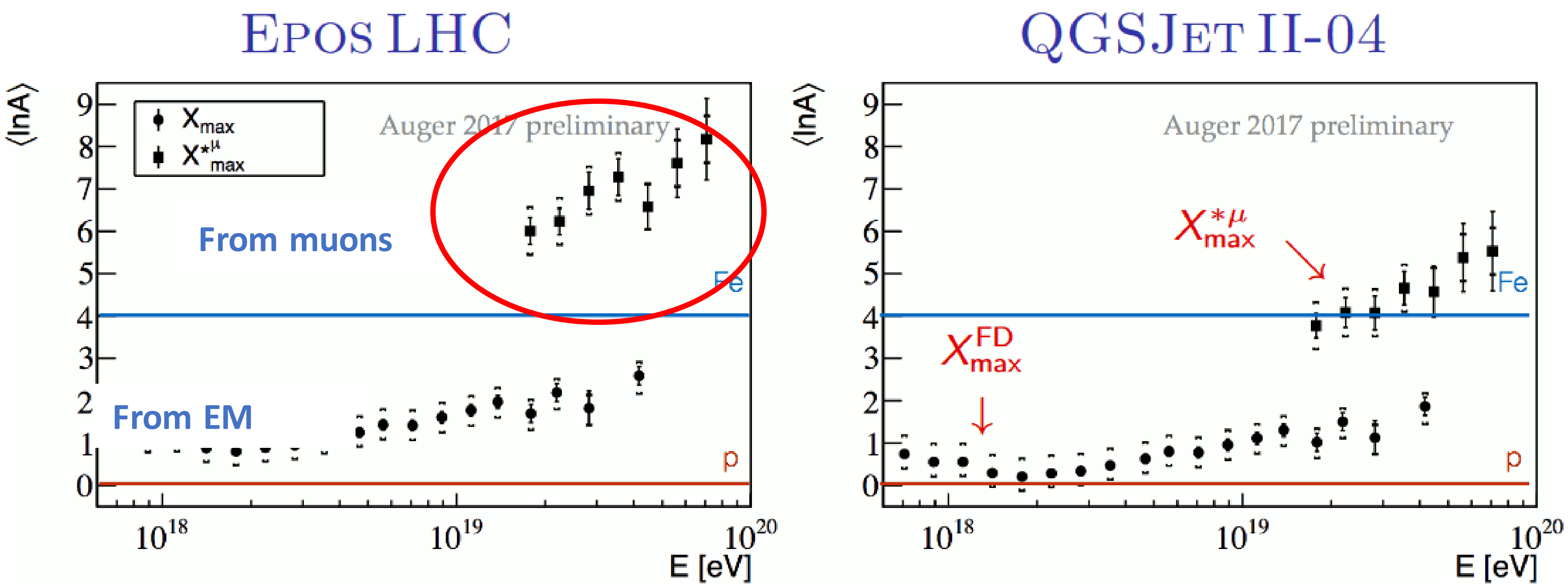
FD runs out of statistics ~ 40 EeV (PAO), 10 EeV (TA)

See also Albrecht et al., Muon Puzzle review, 2105.06148

Other means of mass determination

R. Prado, ISVHECRI 2018



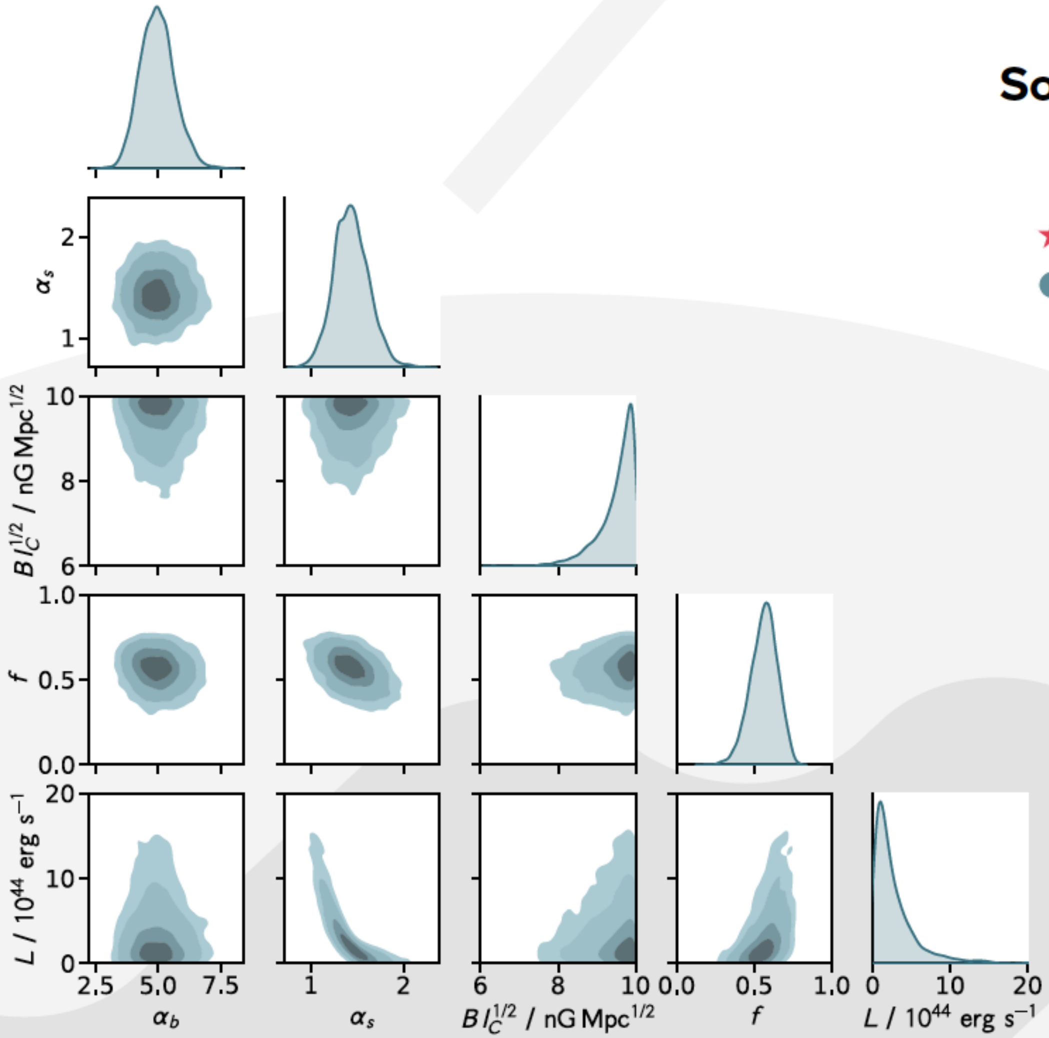


- Identify mass by surface detectors → higher energies
- Several issues, like the Muon Excess (review by Albrecht et al. 2105.06148)
- Big improvements expected soon but work in progress
- Auger Prime Upgrade in construction to solve some of these problems
- In 5 - 10 years?

Partial solution: Brute Force -- Explore higher energies.
High EeV = high EV?

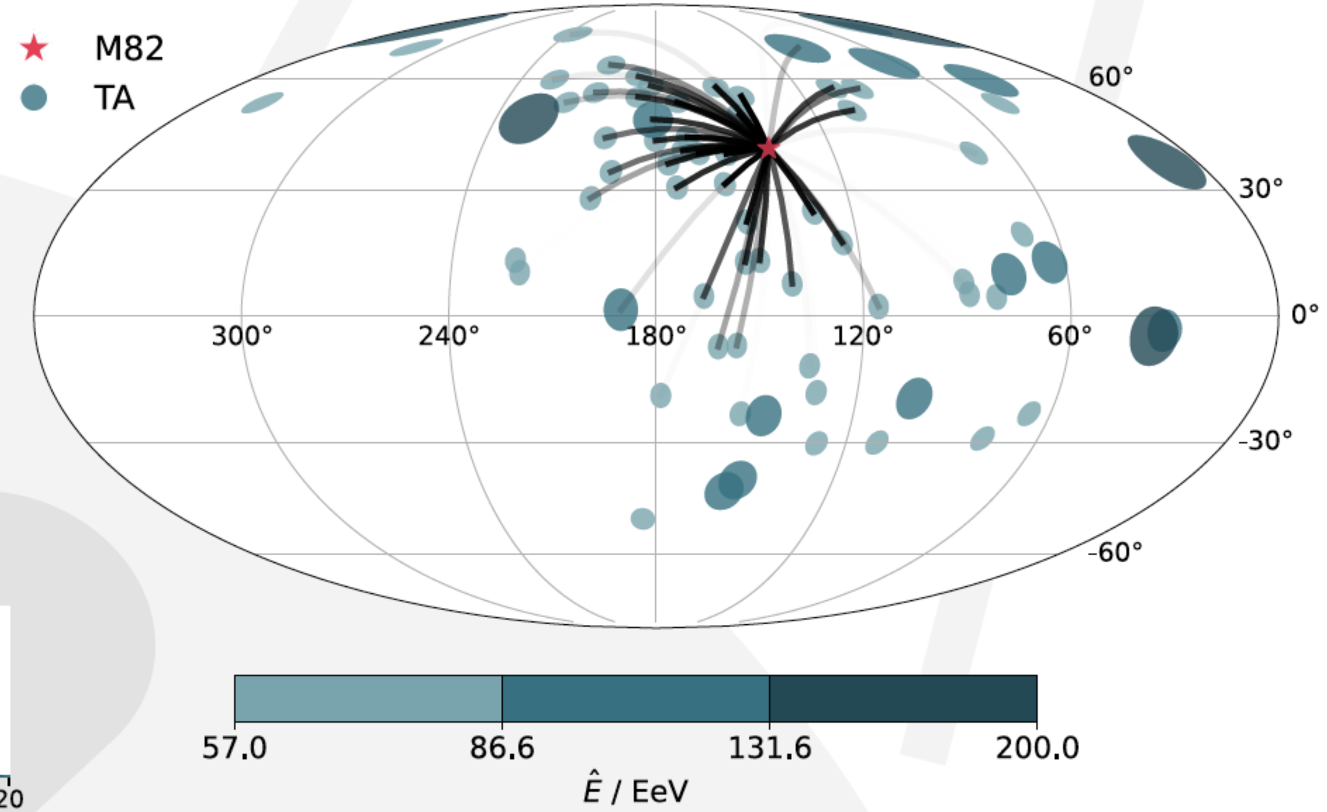
See also Albrecht et al., Muon Puzzle review, 2105.06148

An example result: Which events are likely to originate from M82 (starburst)



Joint marginalised posterior distribution for fitted source parameters.

Source-association probabilities in Galactic coordinates.



Please come and see our ICRC2023 poster next ot my office at P712

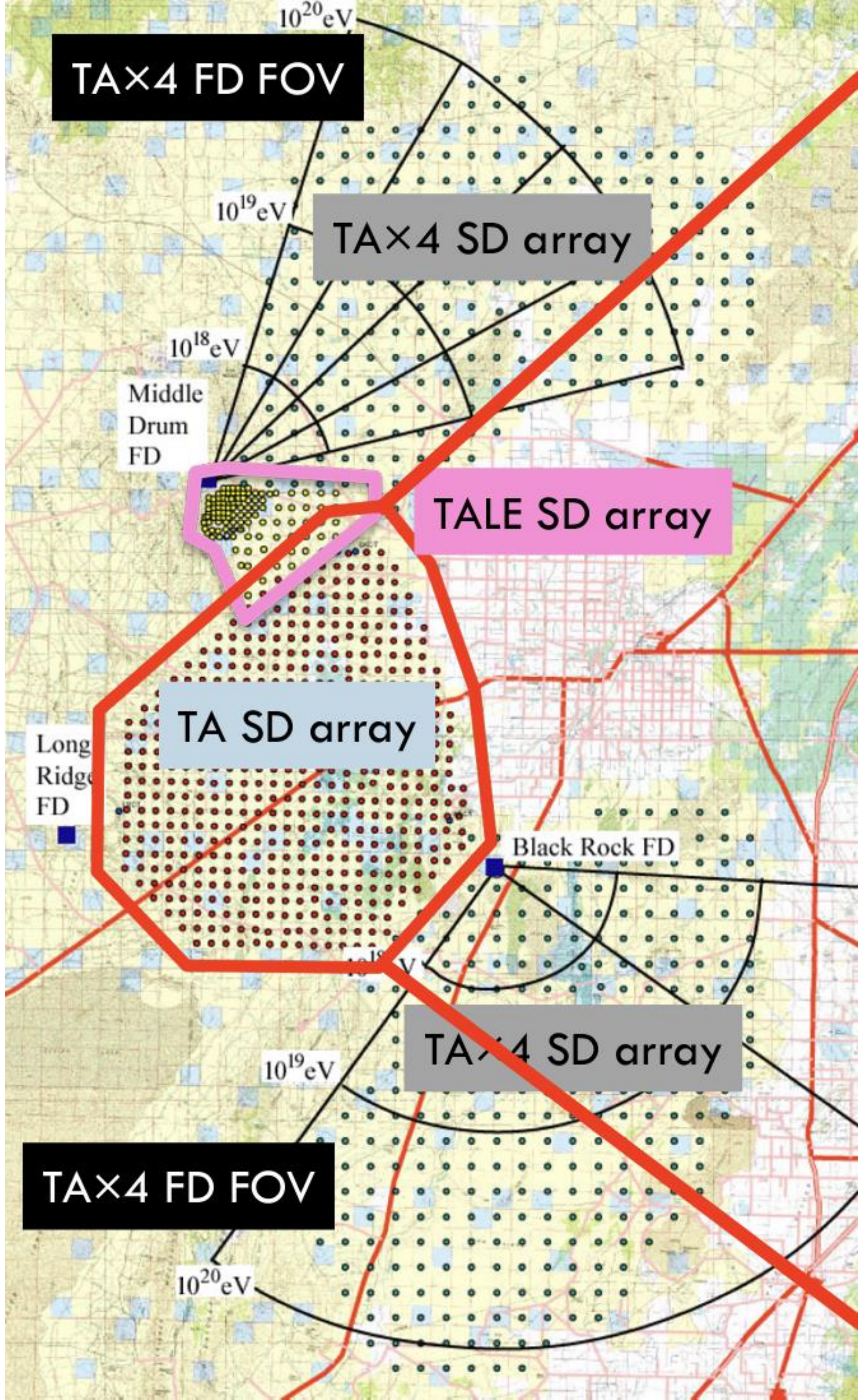
This Bayesian inference model solves some conceptual issues

- **No need to invent oversimplified assumptions**
- The **likelihood takes care of physically motivated reduction of weights** of events that are too far deflected off source, or reconstructed with too small uncertainty
- Allows to **test all kinds of theoretical hypotheses** about source, propagation, magnetic fields, once sufficient data available and base modeling work is done.
- **Physical models of the** magnetic field, detector uncertainties, source model, etc. is incorporated directly into the framework, **and are marginalized over**
- However, the most striking show-stopper is the lack of event-by-event mass measurements, i.e.
  we only know energy not rigidity

--> Need to obtain data

Toward CR rigidity (E/charge) measurement using the Telescope Array

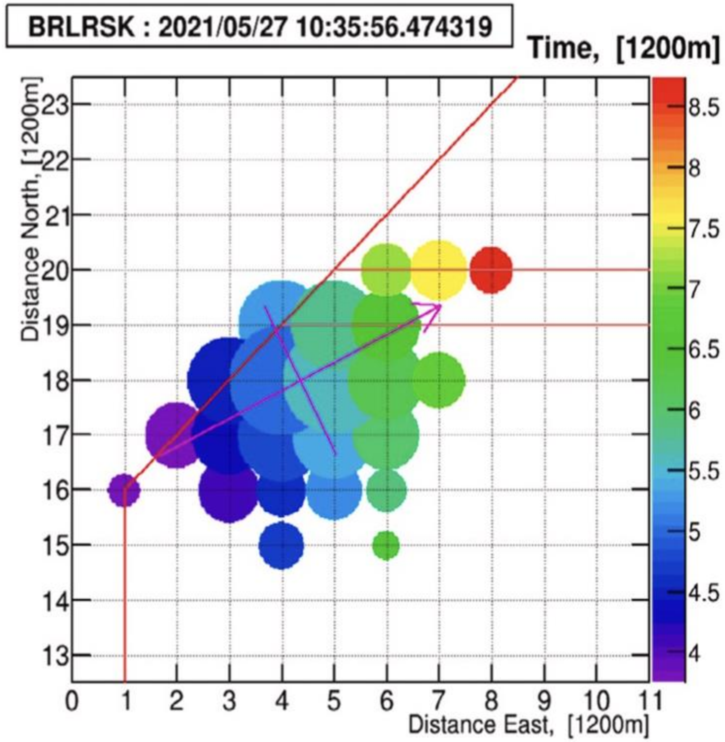
- The Telescope Array is an airshower array, comprised of **surface and fluorescence detectors**, located in Utah.
- Area is about 700km^2 (TA) + 3000km^2 (TAx4)
- TA collected about **15 years of data** in the northern hemisphere
- Competitor of the much larger Pierre Auger Collaboration with a detector in Argentina (south)
- Suficient funding for M&O but **insufficient manpower to develop modern data analyses**
- I was asscociate member of TA since 2019 and **author since 2023**
- Plan of developing a **machine-learning-based mass reconstruction** for surface detector data (manpower + computing)
- Use PMT waveforms from scintillators (first time in TA!)

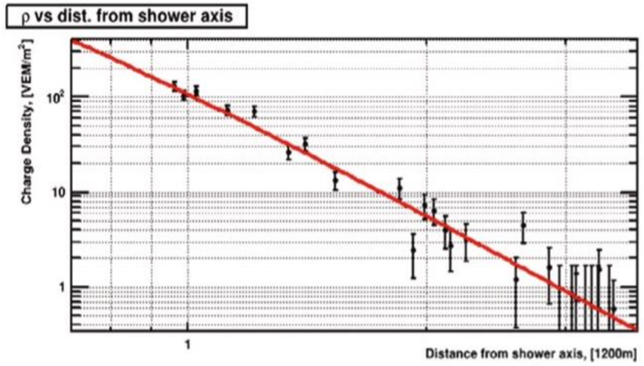


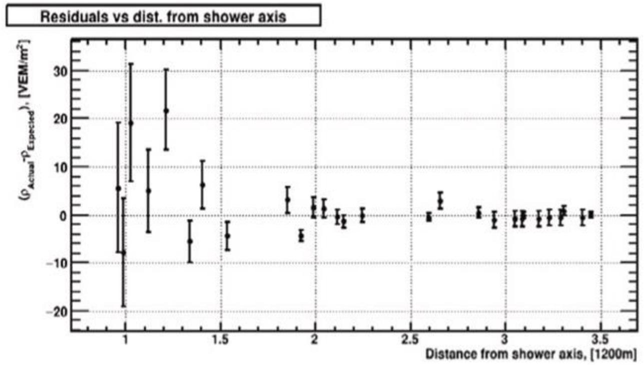
Events and waveforms in TA

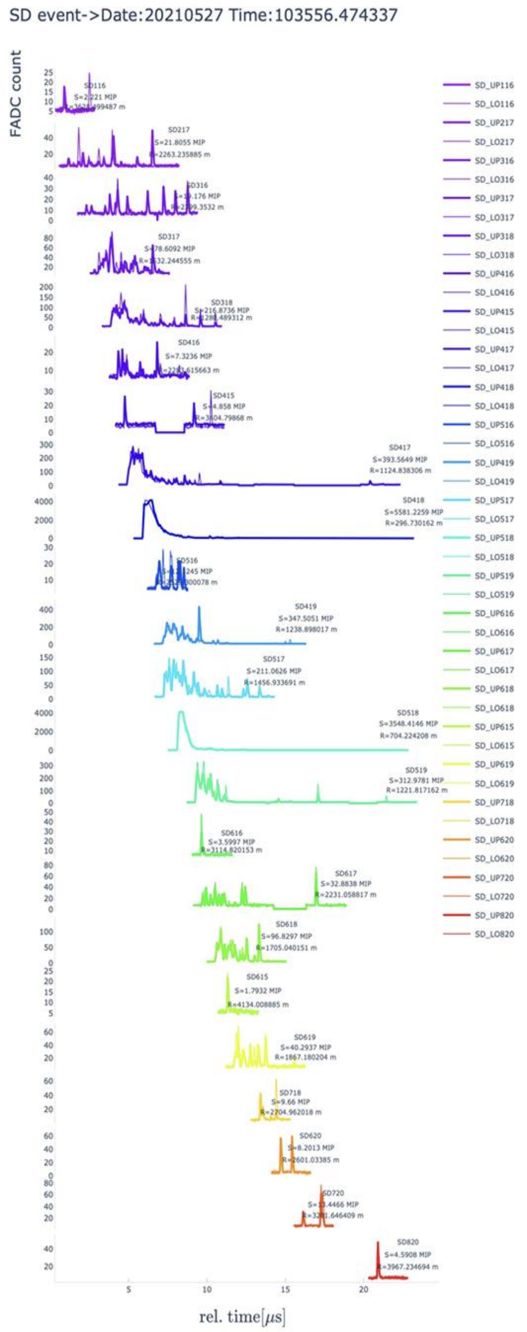
J. Kim, Telescope Array Highlights, ICRC2023

- 2021-05-27 10:35:56.47, No FD observation
- E > ~240 EeV, More details will be coming up soon

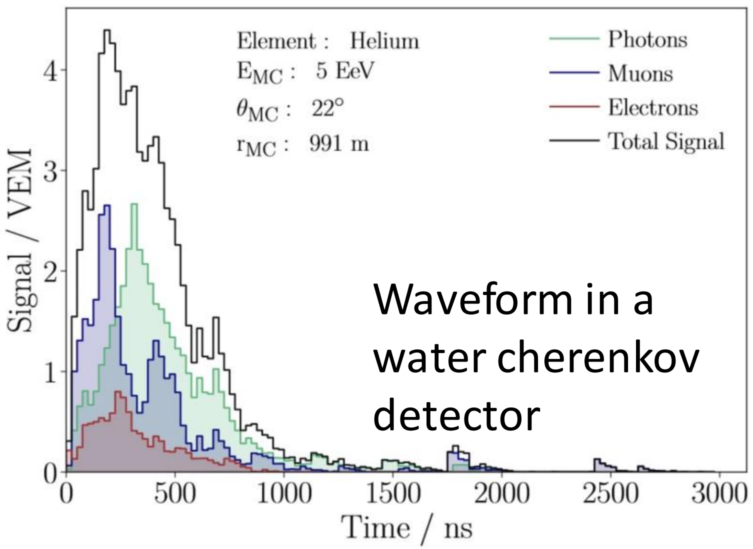




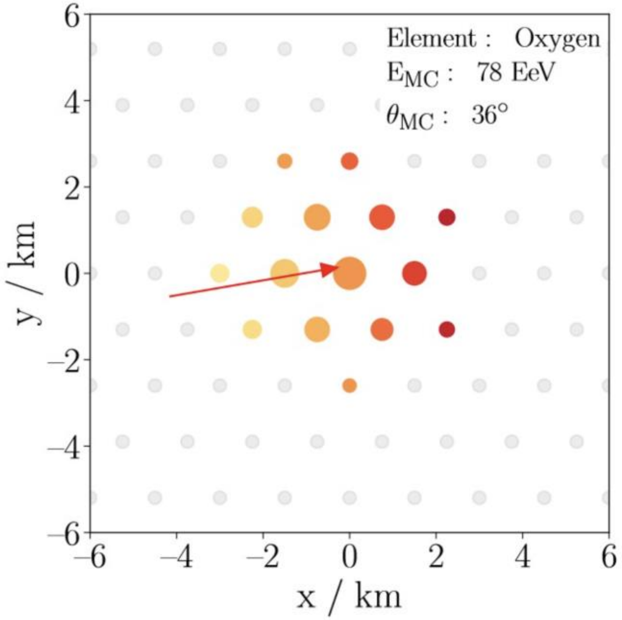




Approach



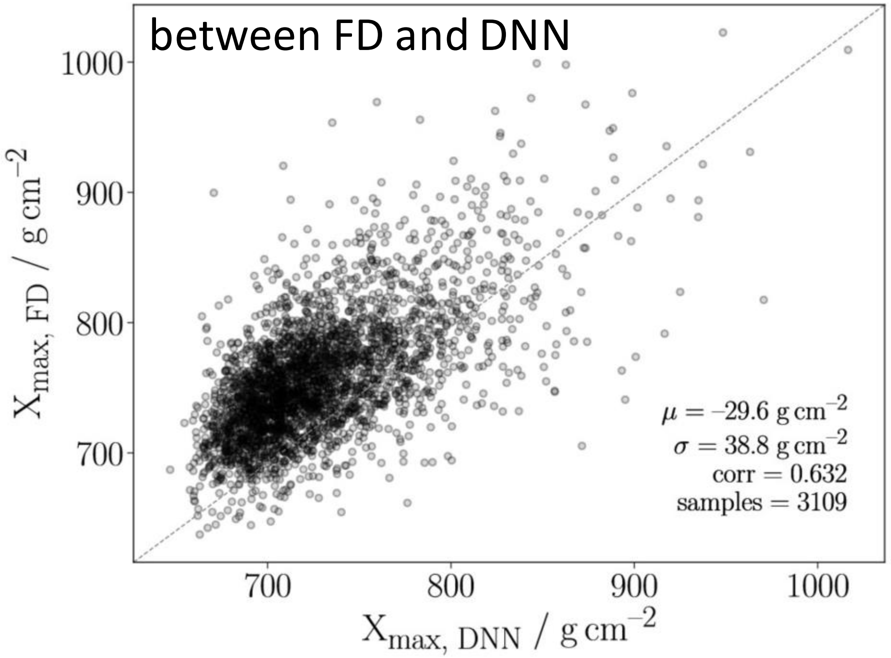
Waveform in a water cherenkov detector



Ongoing research with exisiting methods and successes

1. Erdmann, M., et al. A Deep Learning-based Reconstruction of Cosmic Ray-induced Air Showers. Astroparticle Physics 97, 46–53 (2018).
2. Kalashev, O. et al. Deep learning method for identifying mass composition of ultra-high-energy cosmic rays. J. Inst. 17, P05008 (2022).
3. A. Aab et al. Deep-learning based reconstruction of the shower maximum Xmax using the water-Cherenkov detectors of the Pierre Auger Observatory. J. Inst. 16, P07019 (2021).
4. Aab, A. et al. Extraction of the muon signals recorded with the surface detector of the Pierre Auger Observatory using recurrent neural networks. J. Inst. 16, P07016 (2021).
5. Ivanov, D. et al. Using deep learning to enhance event geometry reconstruction for the telescope array surface detector. Mach. Learn.: Sci. Technol. 2, 015006 (2020).

Observed bias in Xmax reco between FD and DNN

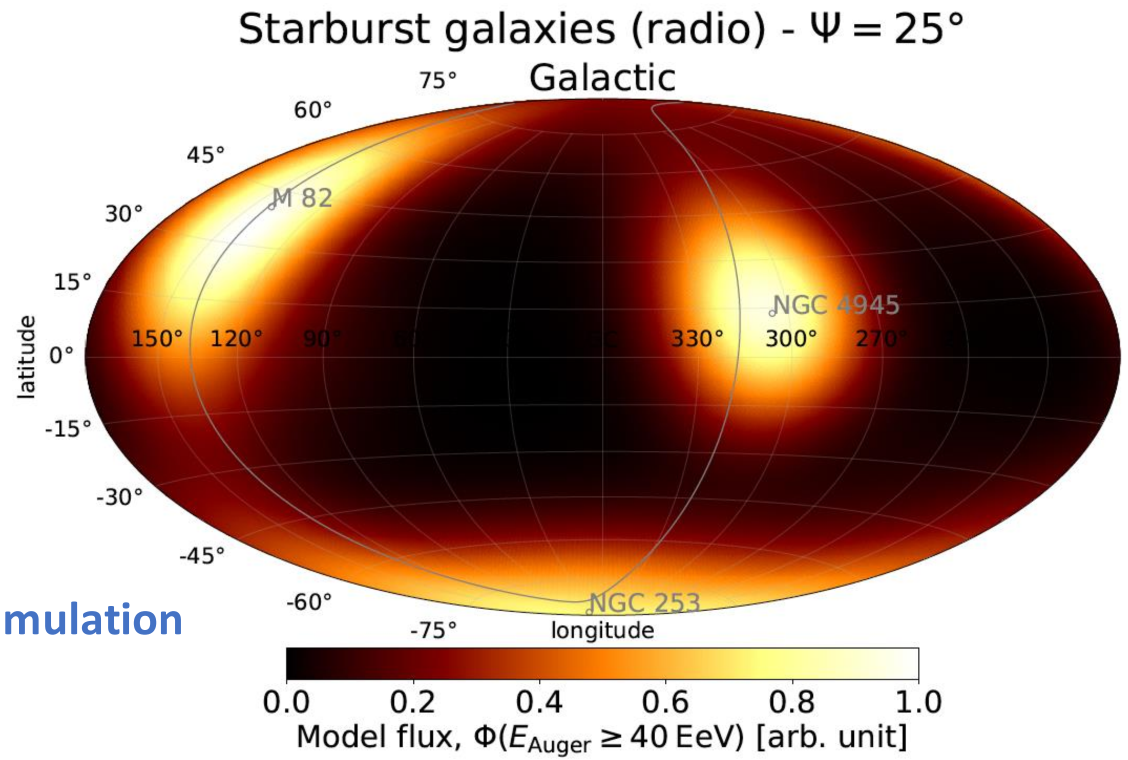


- **Support from** ICRR, U. Tokyo and Utah (**spokespersons**)
- Goal is to develop **the algortihms for mass determination** at highest energies
- Simultaneously:
  - Improve the Bayesian Methods to make use of event-by-event information
  - **Many project pieces suitable for student work**

Summary and outlook

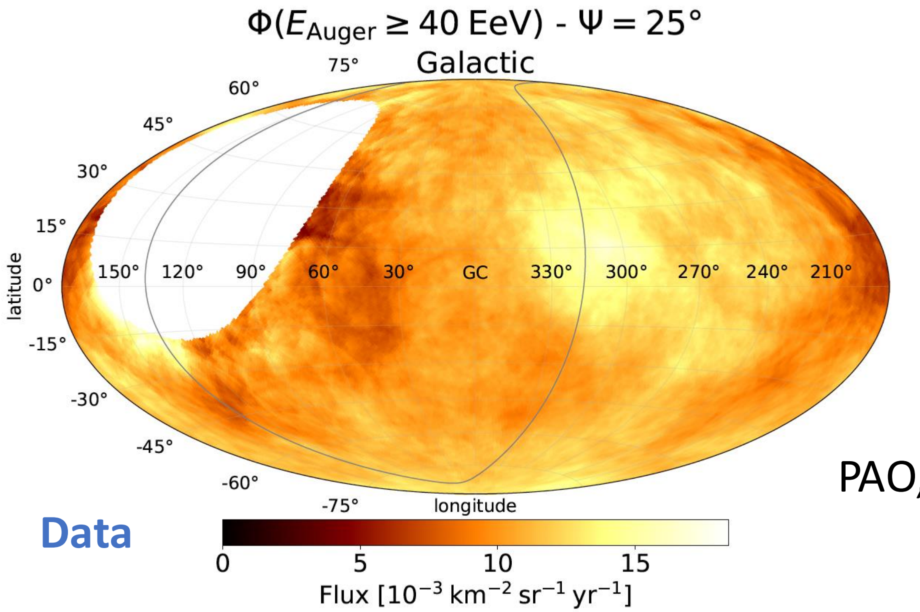
1. Many of other projects with international students and collaborators could not be highlighted today ☹
2. Now is the best chance is to test my modeling work on real data, and **chance for providing a key element for a new discovery**
3. **My IceCube contribution** initially suffered from lack of qualified manpower but **is now on track**. More executive/management roles that I have hoped for but good for the **reputation of IoP** and personal development.
4. **Leadership in high-energy atmospheric neutrino flux modeling is established**, will be maintained, and expanded to lower energies relevant for DUNE and Hyper-K
5. There are 3 neutrino telescopes (KM3NeT, P-ONE, Baikal GVD) under construction and 2 more are planned (TRIDENT, IceCube Gen2) → **future should be bright**.
6. **UHECR phenomenology is challenging but also very exciting**. New bayesian methods are life-changing but require more manpower
7. **Crucial element for source identification** or any extended type of anisotropy identification is the event-by-event mass, or at least, average **mass determination**.
8. No serious result for the northern hemisphere → **engage in TA, make use of 15 years of data**, use AI --> **find clues or contribute to science goal of future observatory, such as GCOS.**

Searching for clustering in the direction of potential sources



Simulation

1. Assume that a catalog of sources astrophysical objects are the sources (here Starburst galaxies)
2. Assume isotropic and circular deflection scale here 25deg and an energy threshold
3. Assume that all sources have the same brightness (or so)
4. Test the compatibility of simulated pattern with observed one



Data

PAO, 2206.13492

Common search radius at low rigidities misleading

THE ASTROPHYSICAL JOURNAL LETTERS, 833:L17 (5pp), 2016 December 20 GLOBUS & EICHLER

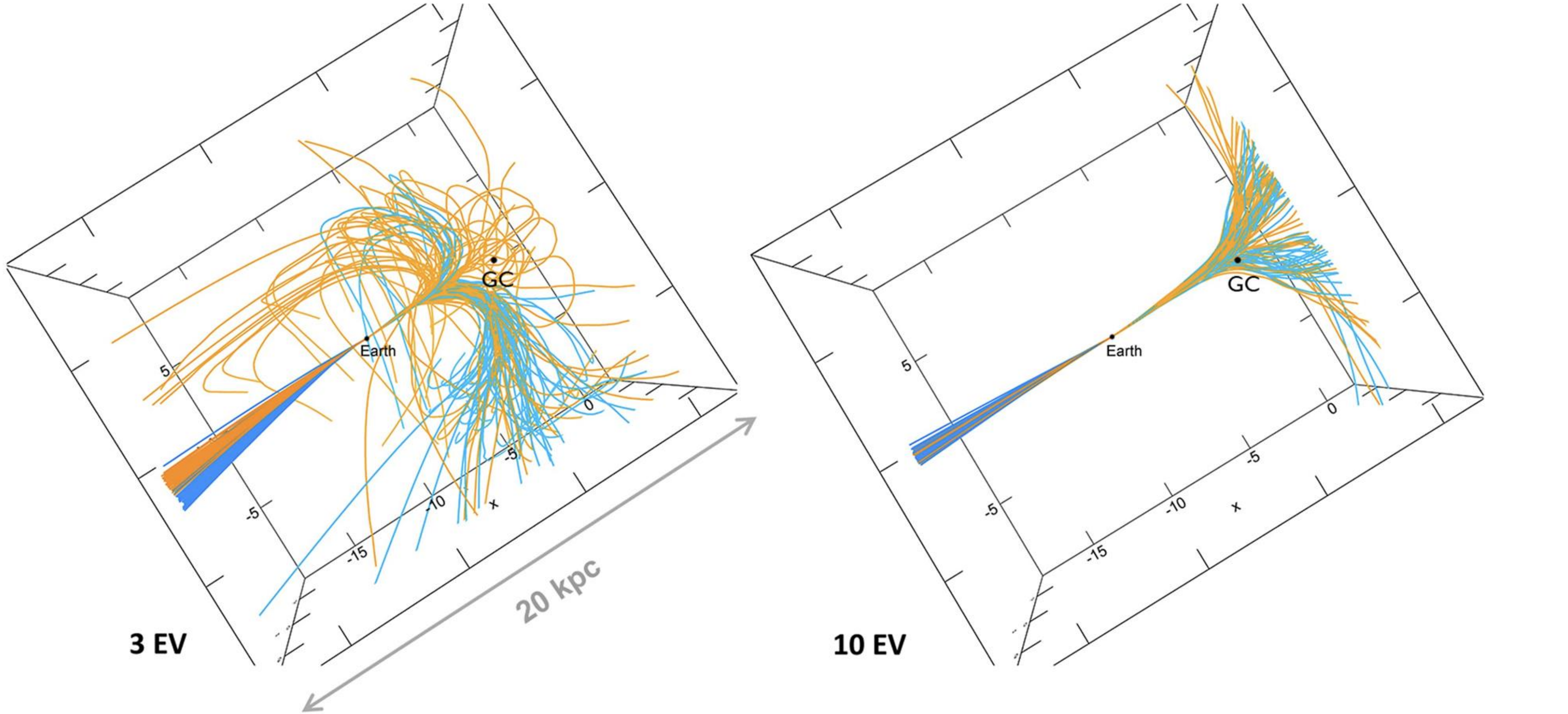
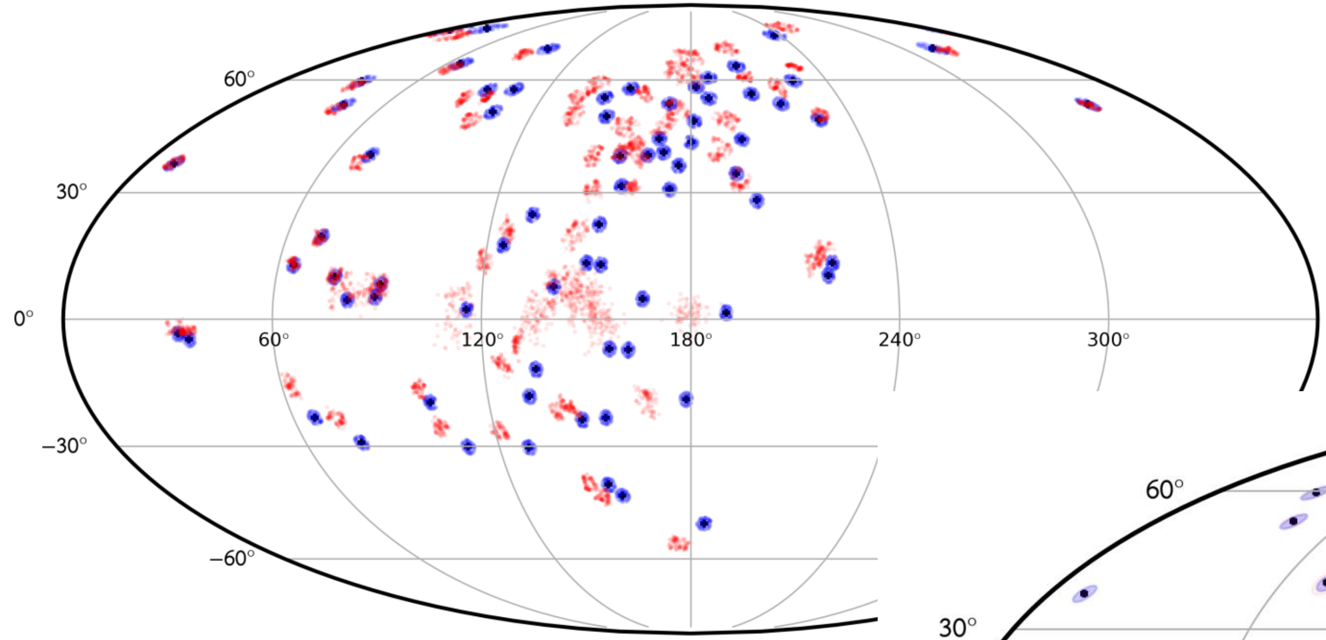
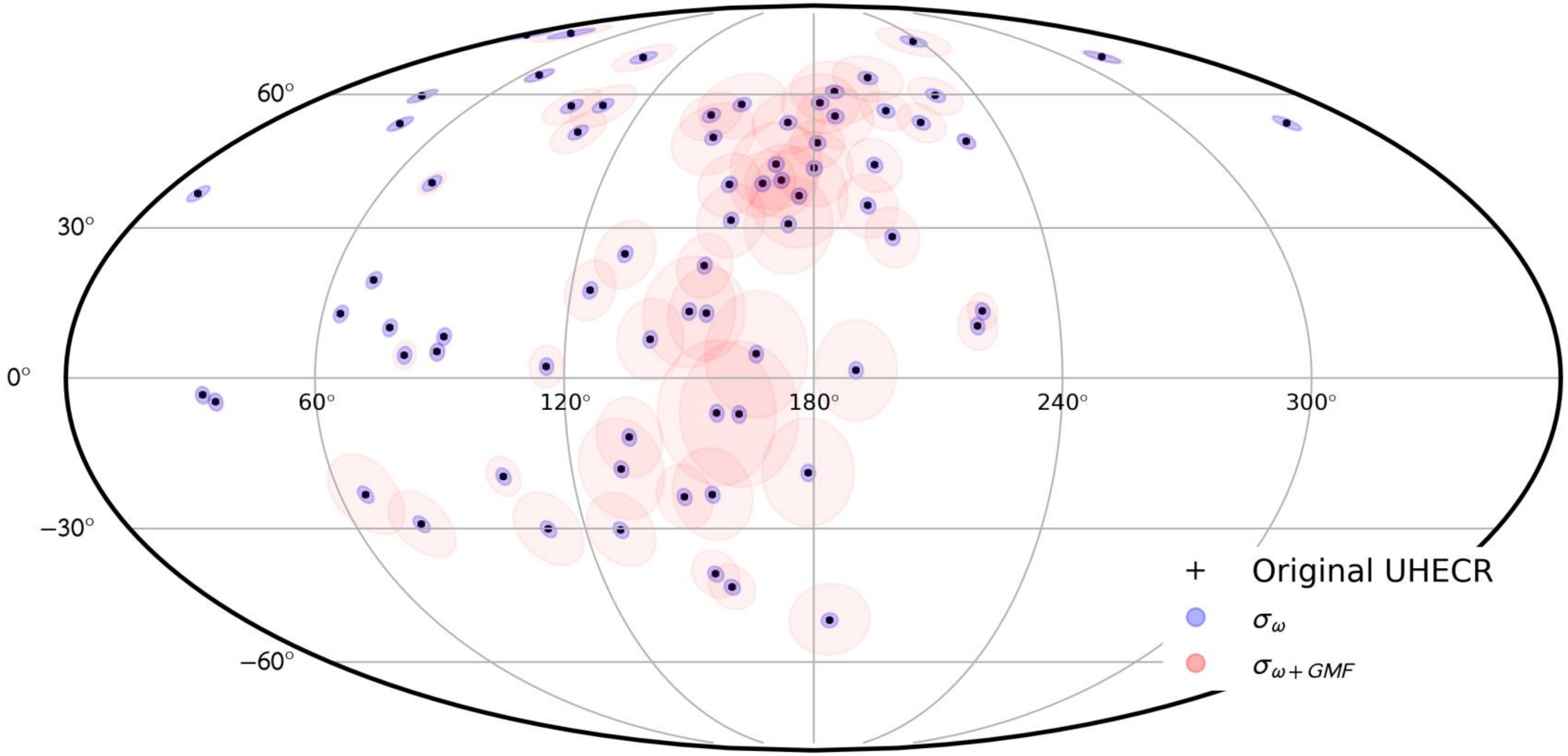


Figure 1. Trajectories of antiparticles corresponding to a spot of 3° square, after a backward propagation in the GMF in two different configurations of the magnetic turbulence (in orange and blue, respectively).

Deflections are anisotropic, individual, energy and composition dependent



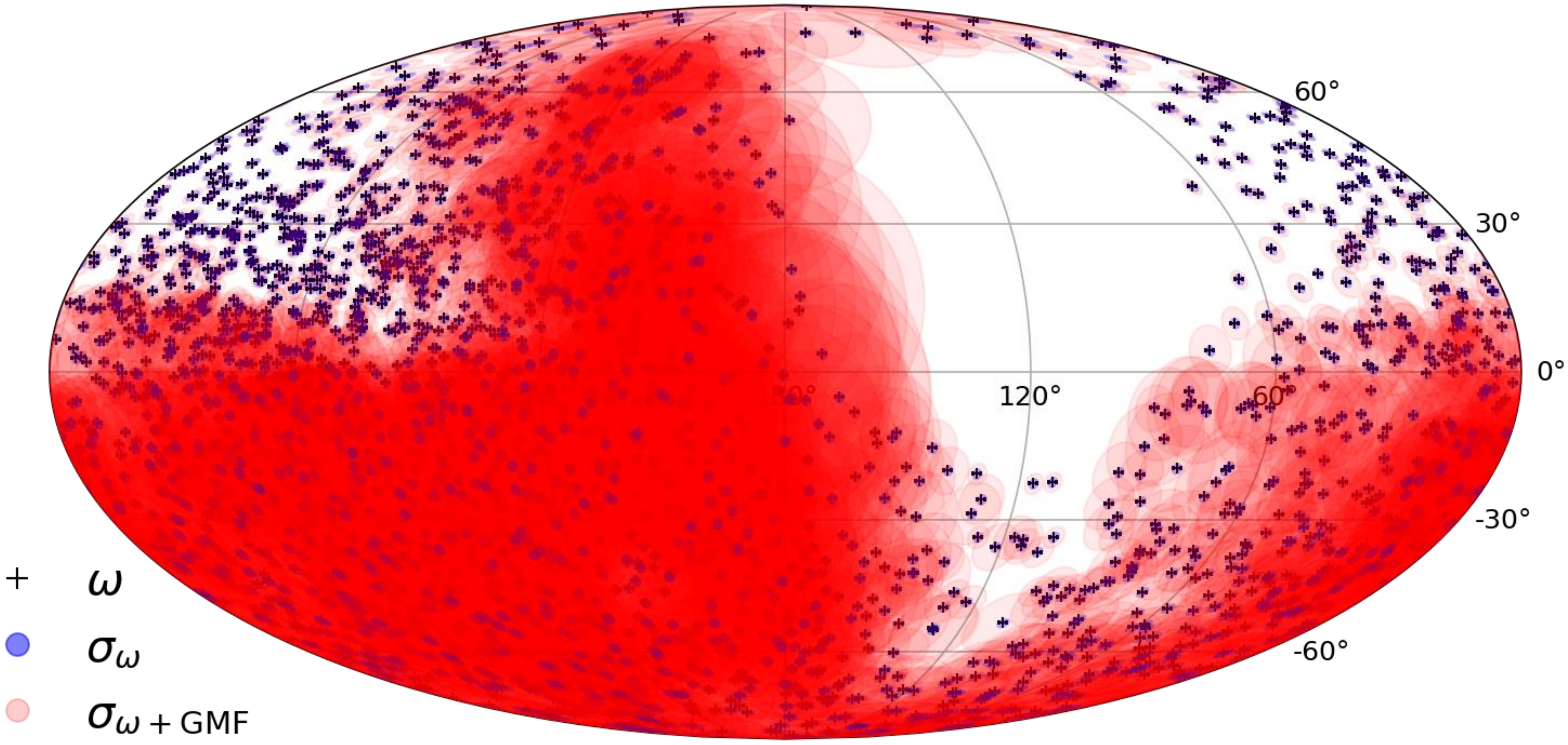
TA 2015 data, proton assumption, JF12



Keito Watanabe, Francesca Capel, AF, Hiroyuki Sagawa, UHECR2022, in prep.

Deflections are anisotropic, individual, energy and composition dependent

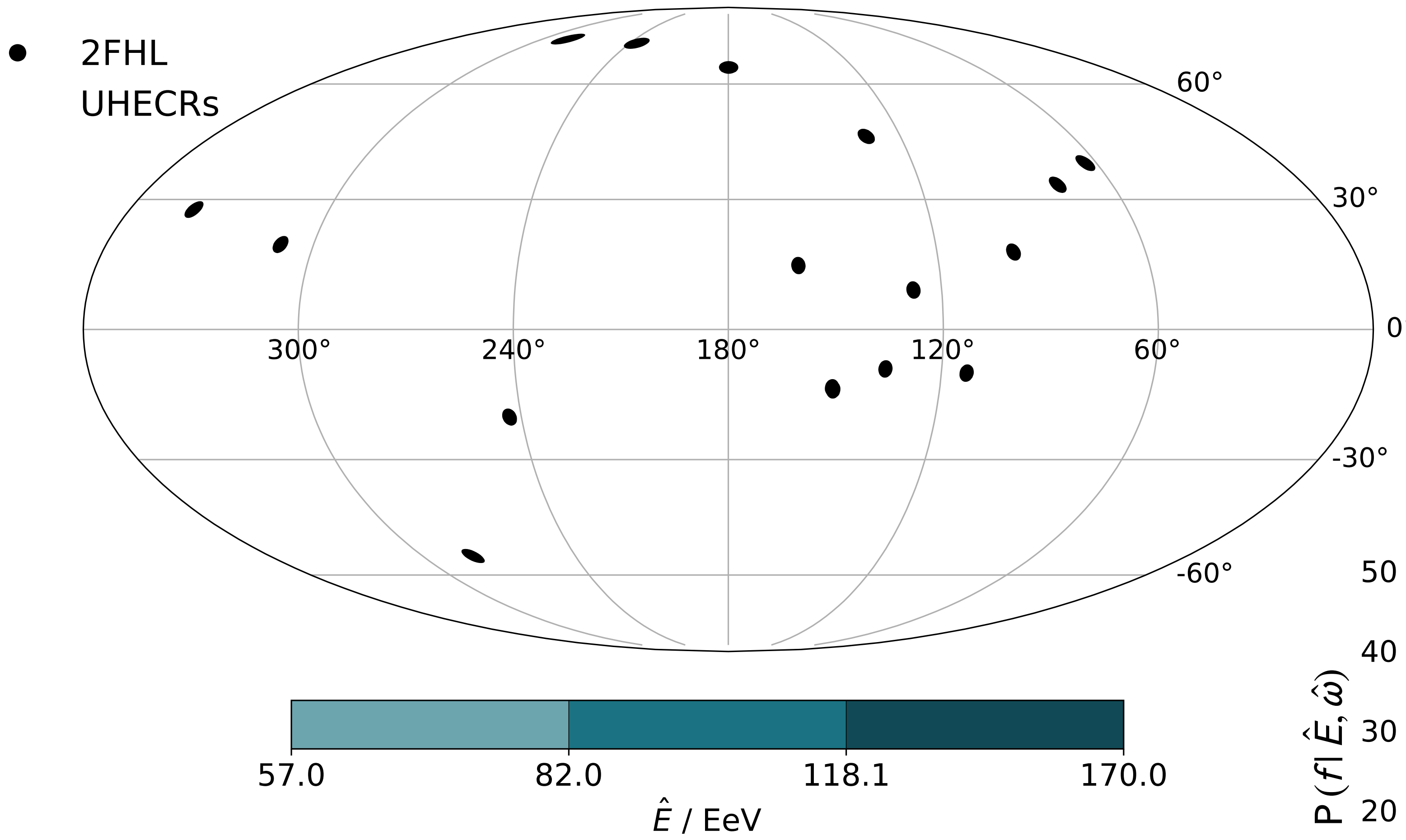
PAO 2022, <u>proton</u> assumption, JF12



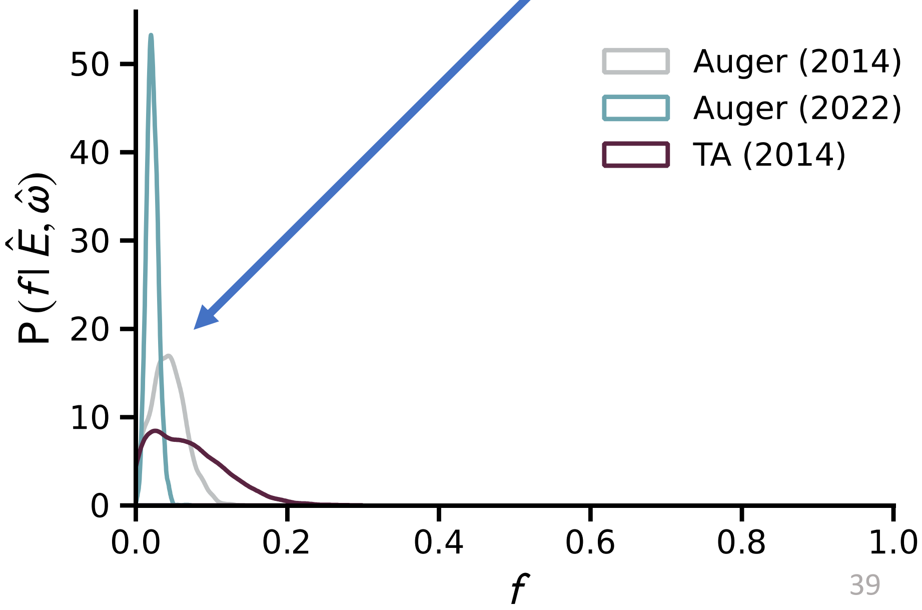
A simple, “circular” search radius is misleading

Keito Watanabe, Francesca Capel, AF, Hiroyuki Sagawa, UHECR2022, in prep.

Are source fraction and catalog searches really the right tool?



- Source association search using **2FHL catalog** < 250 Mpc
- Same physics model as Capel & Mortlock, 2018
  - simple deflection model, no GMF
  - assumes pure proton composition
  - **same per-source luminosity**
- "Clear source" (CenA) by eye but source fraction is small

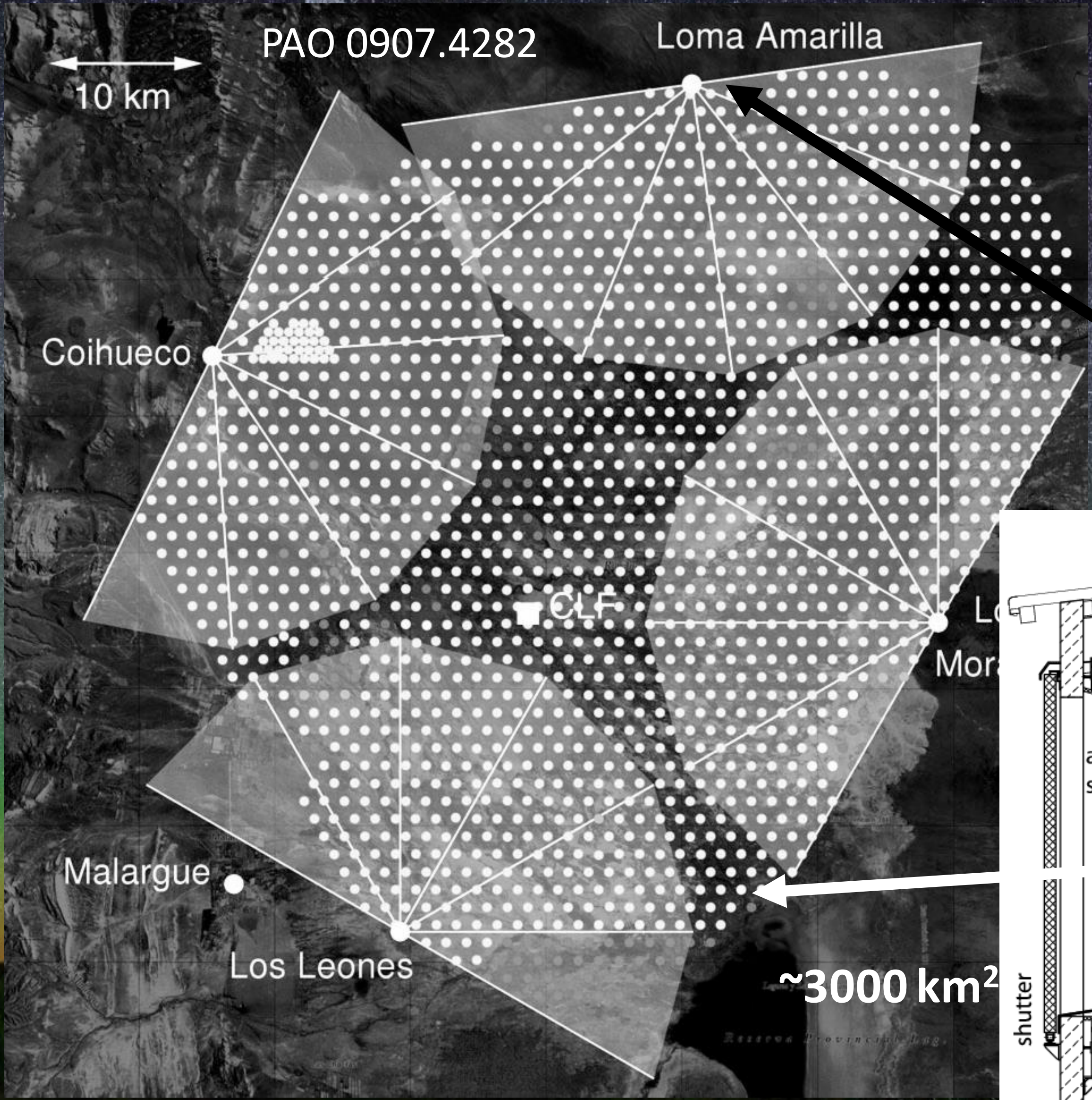


More at ICRC… stay tuned

Keito Watanabe, Francesca Capel, AF, Hiroyuki Sagawa, UHECR2022, in prep.

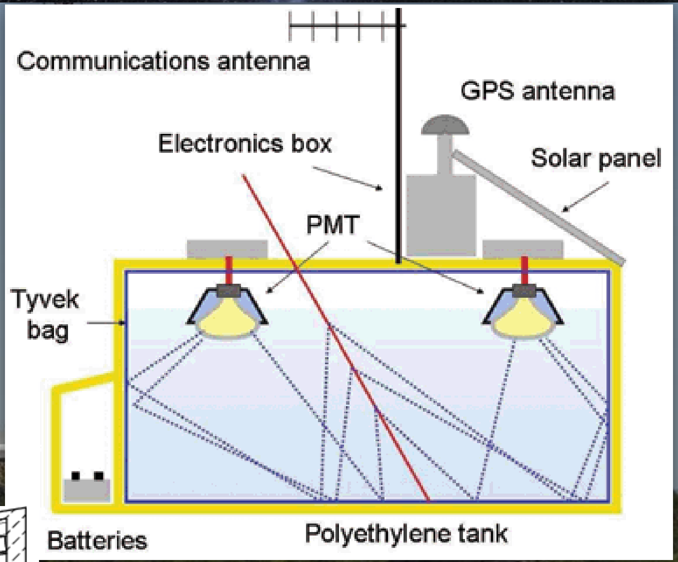
Pierre Auger Observatory in Malargüe (Argentina)

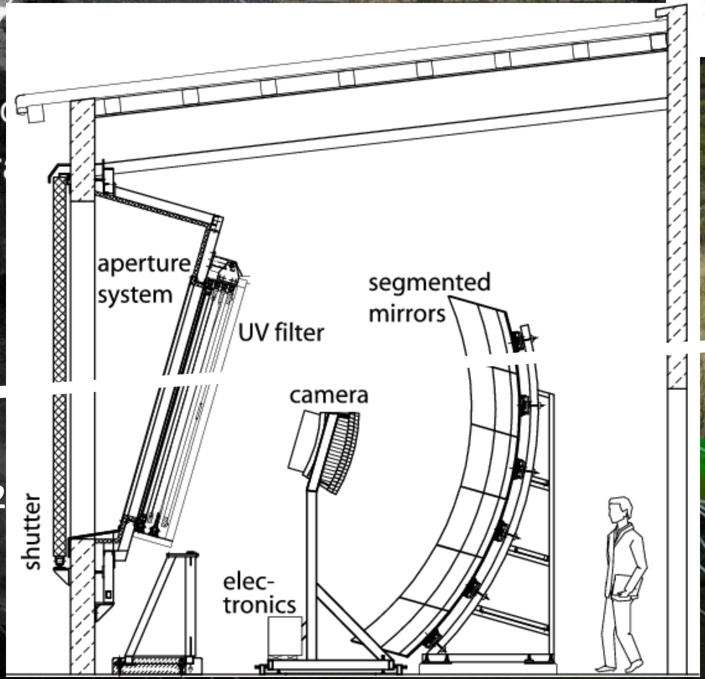
70 km



~3000 km²

Fluorescence detector (FD)

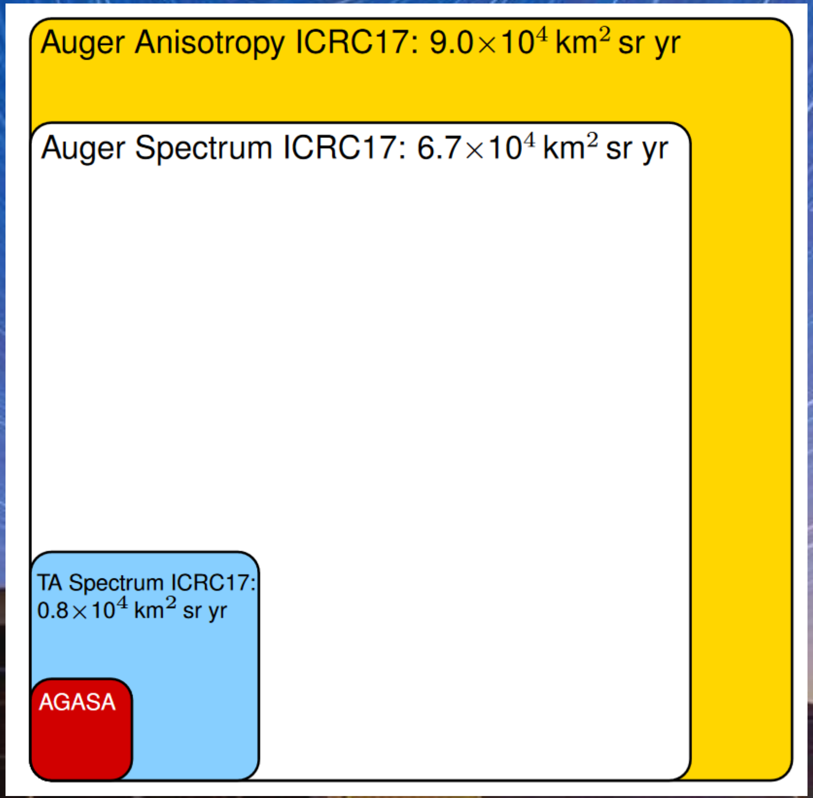




Surface detector (SD)

Photo & artwork by © Steven Saffi 2014 & Pierre Auger Observatory

Exposure



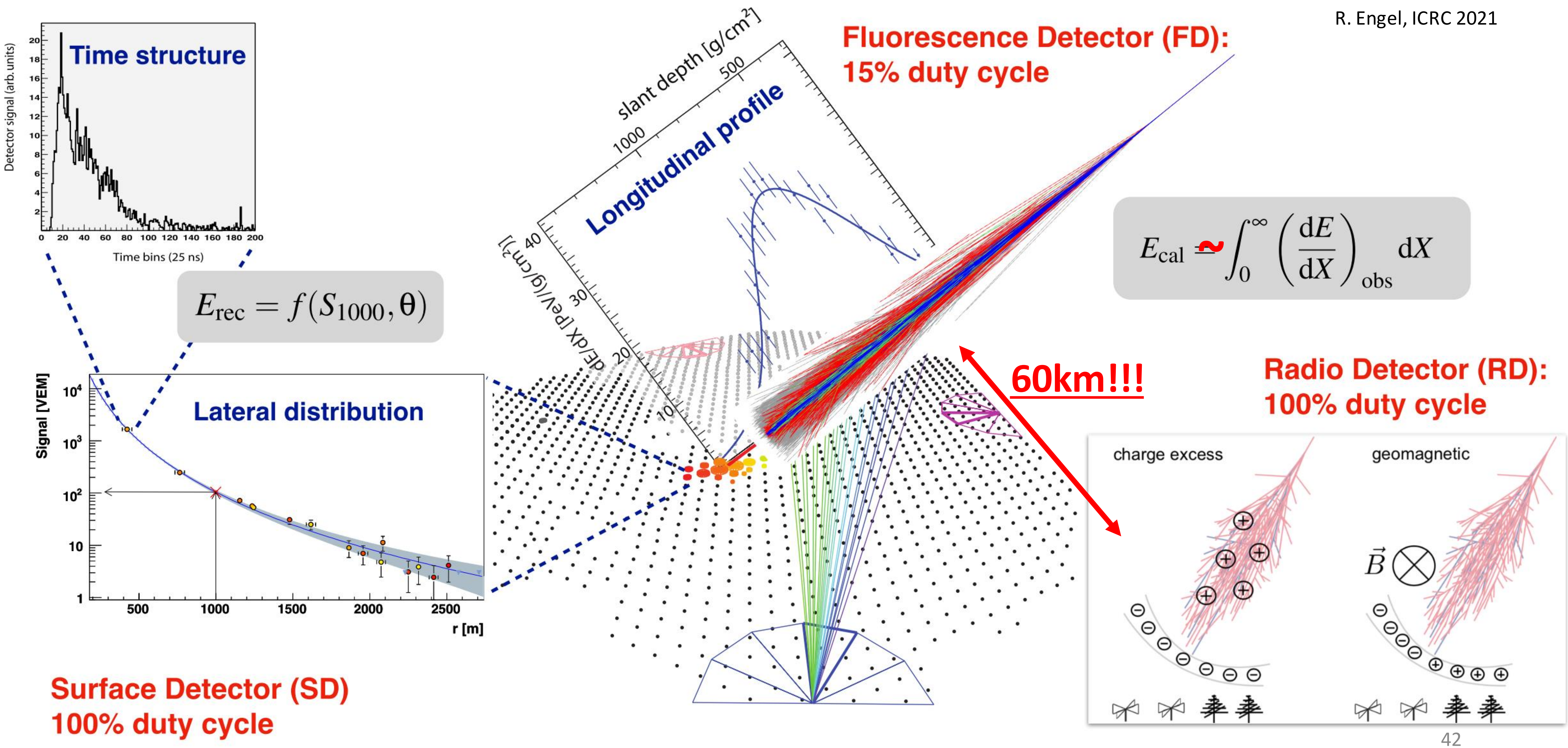
M. Unger, ICRC2017

Telescope array in Utah (USA)

Photos courtesy of the Telescope Array Collaboration

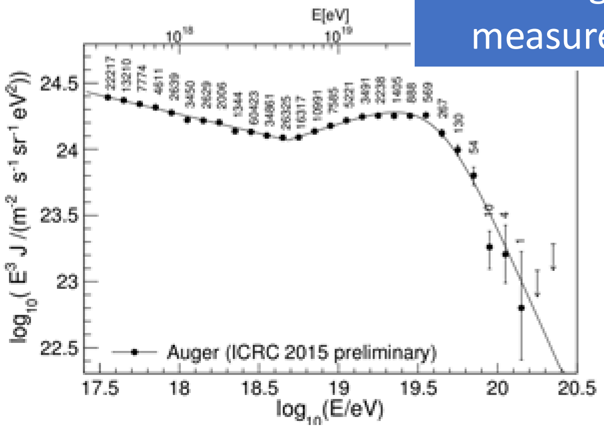
Hybrid air shower detection (Pierre Auger Observatory)

R. Engel, ICRC 2021

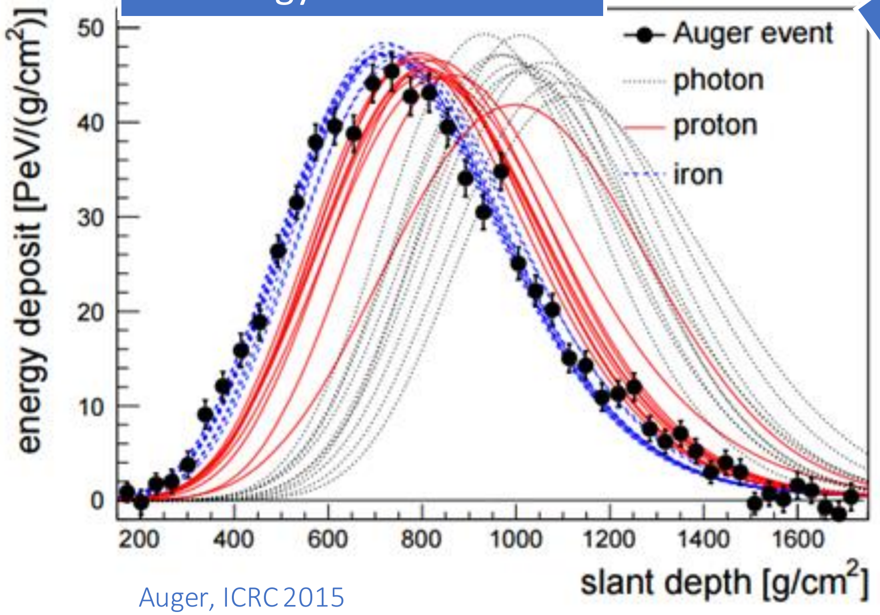


Template method for measuring average UHECR mass composition

Energy and spectrum measured calorimetrically

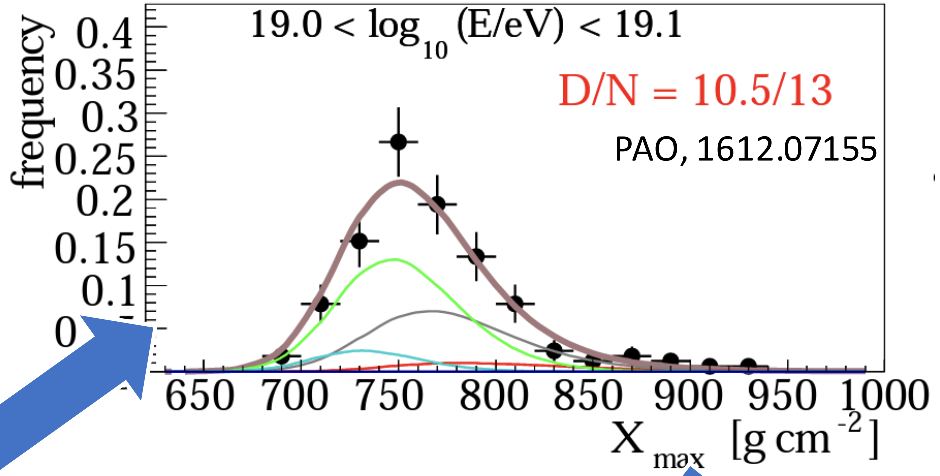


Simulated events of same energy + real event



Auger, ICRC 2015

Group events in energy and histogram X_{max}



Conversion from Xmax dist to mass using models