The Pierre Auger Observatory

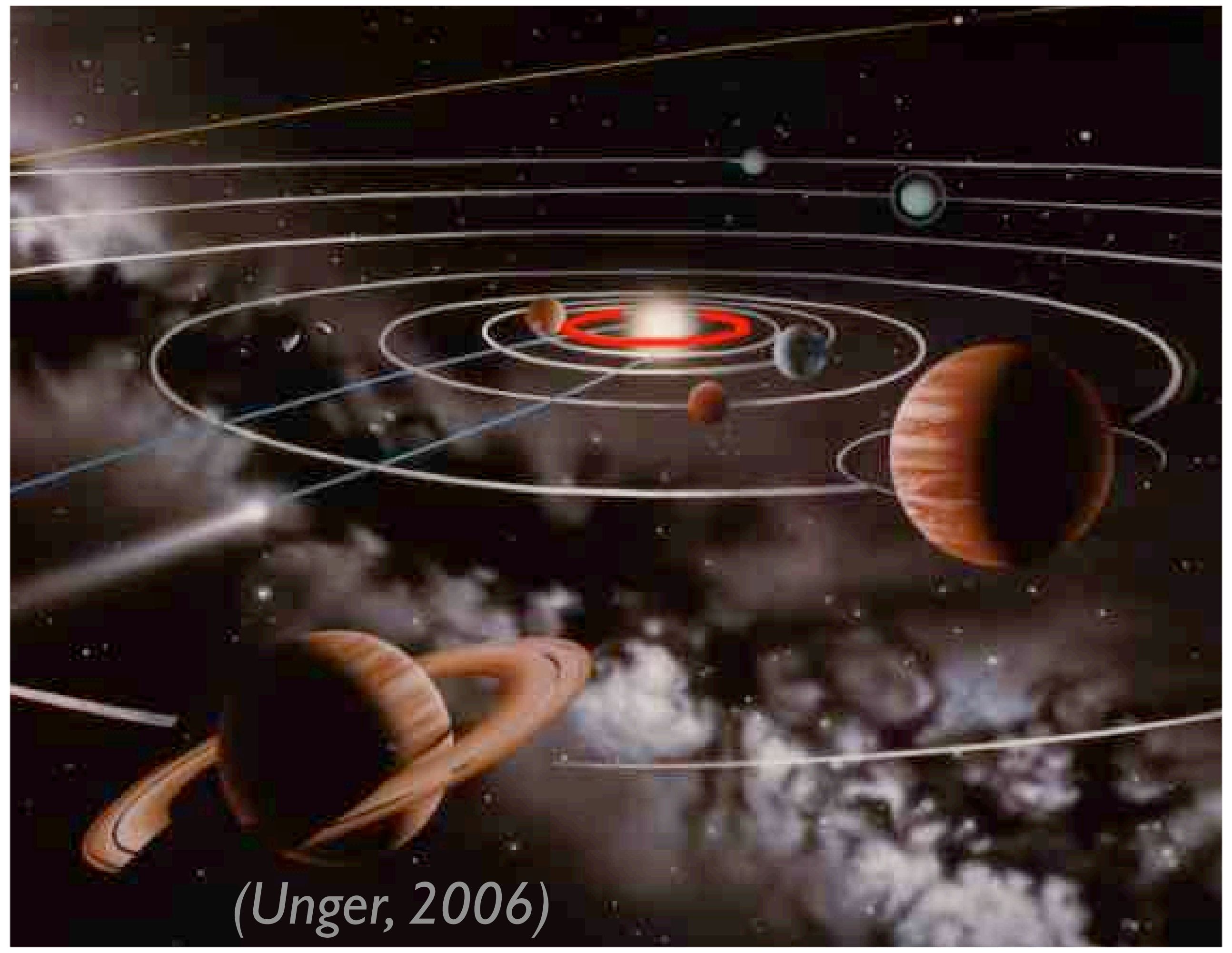
Ralph Engel

Karlsruhe Institute of Technology (KIT)

(picture curtesy S. Saffi)

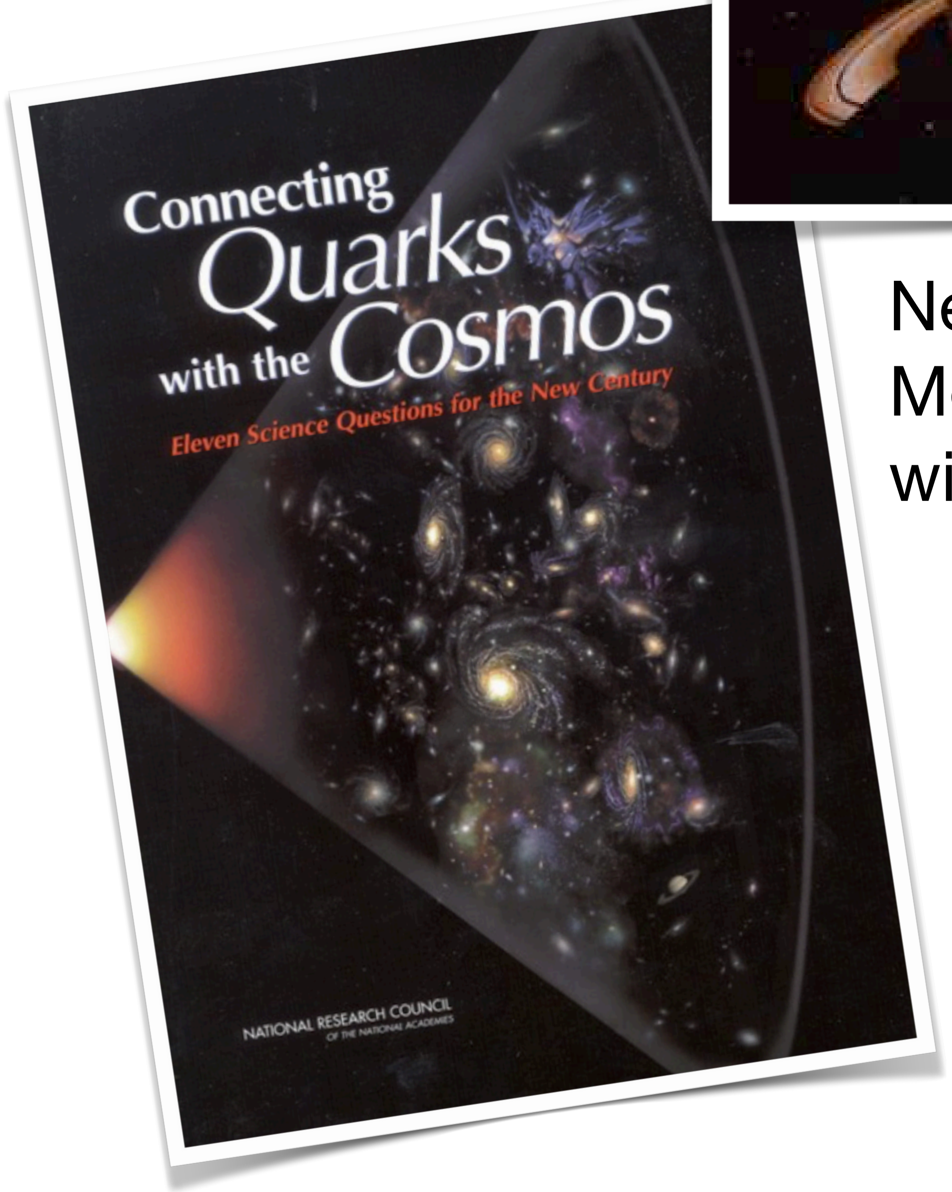
The energy frontier – particles of 10^{20} eV

Large Hadron Collider (LHC), 27 km circumference, superconducting magnets

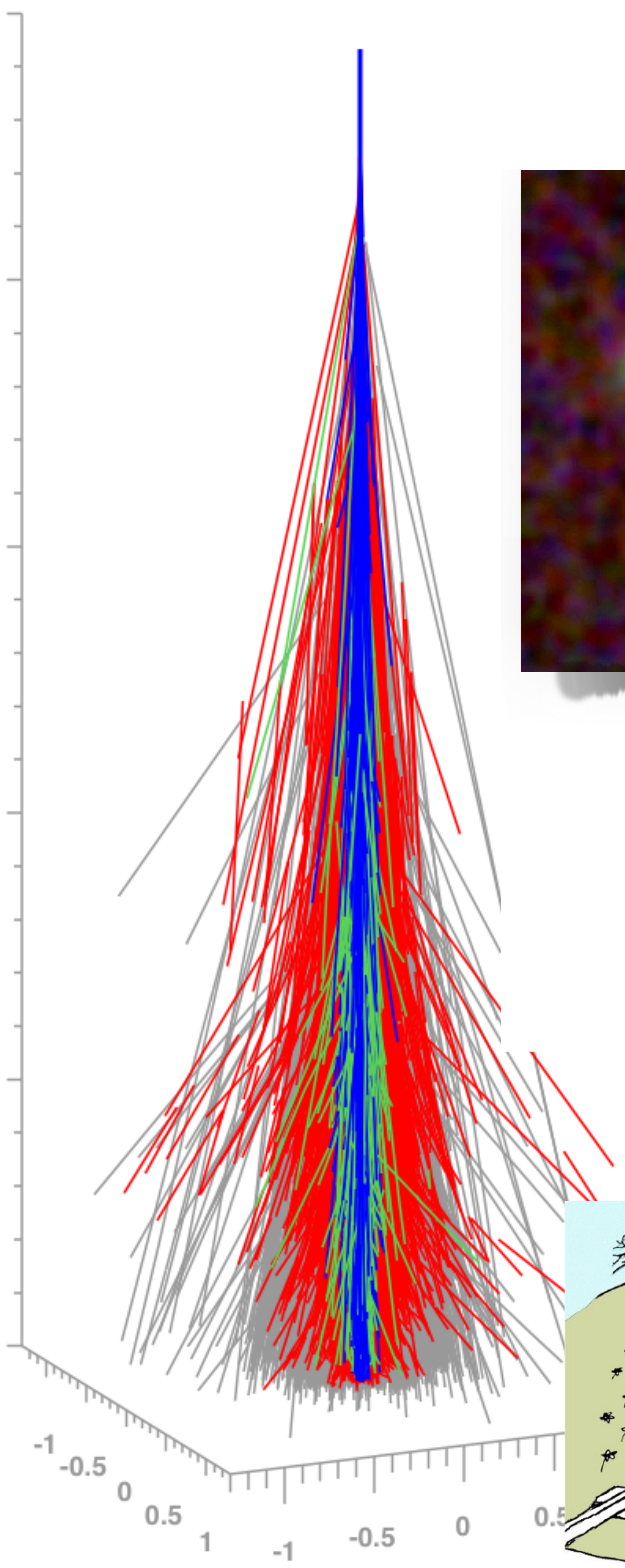


(Unger, 2006)

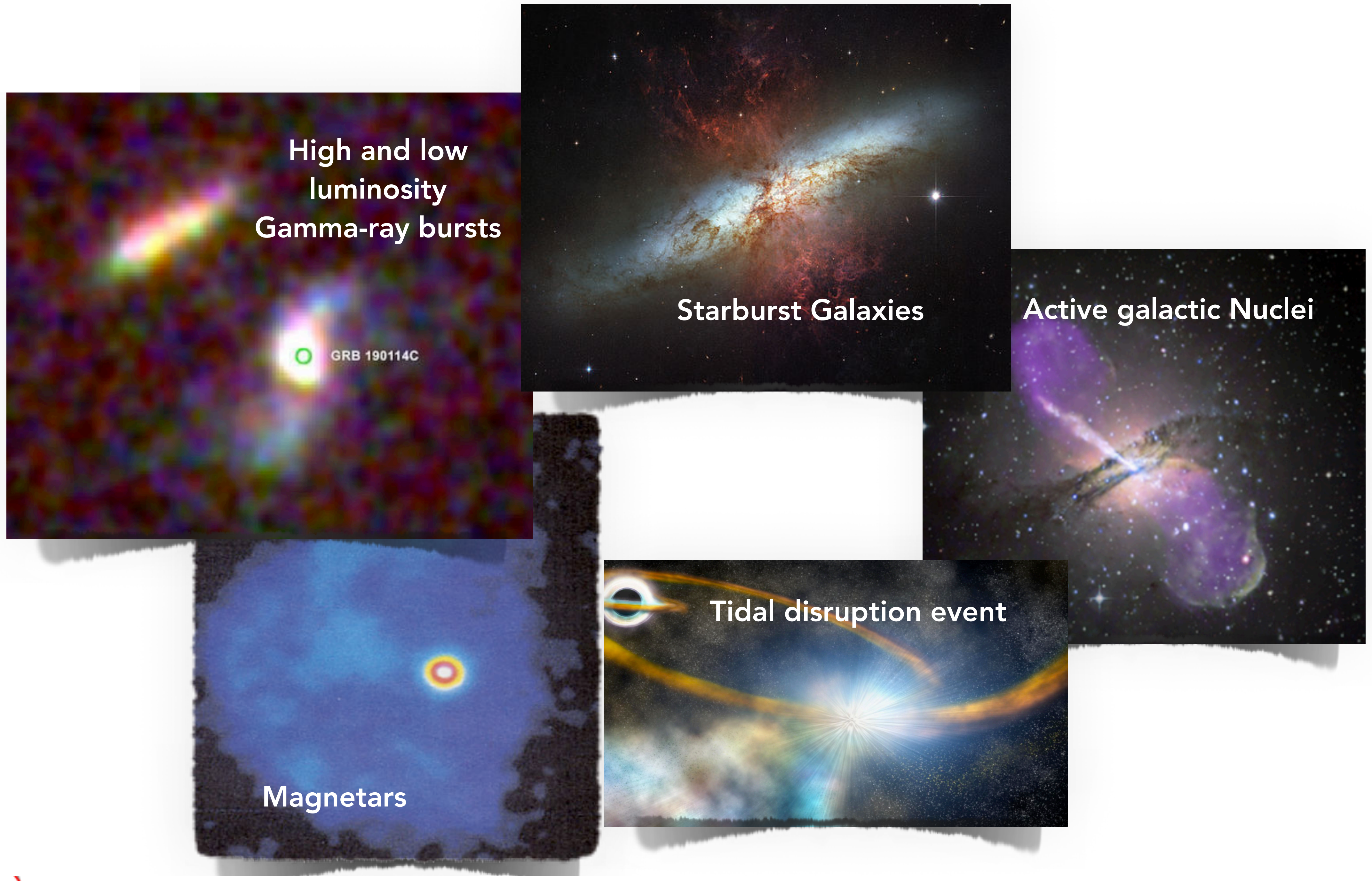
Need accelerator of size of Mercury orbit to reach 10^{20} eV with LHC technology



National Research Council, USA, 2002



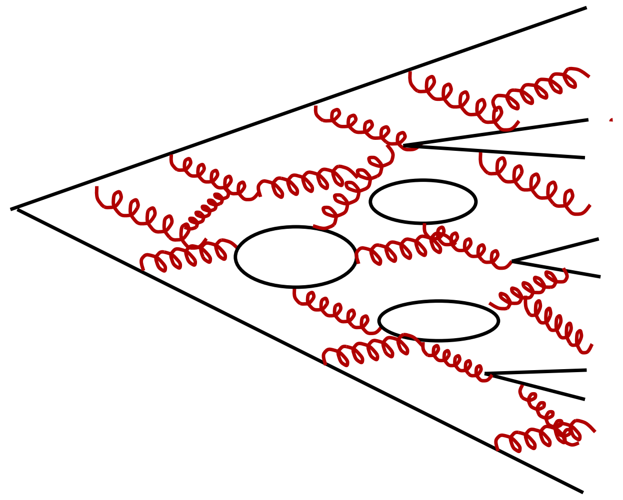
Astrophysical source candidates



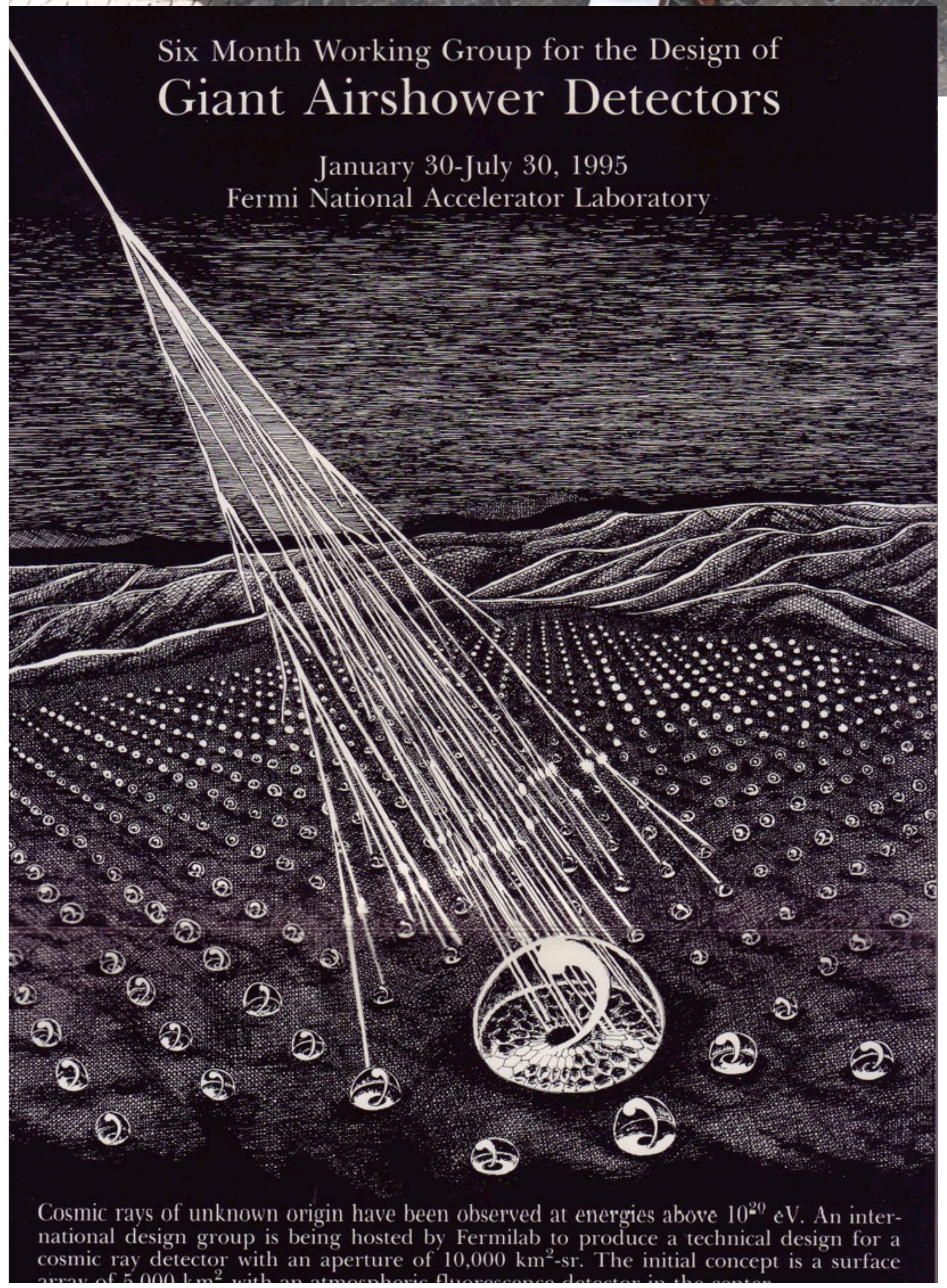
Particle physics source candidates

X particles from:

- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- .....



A really big observatory was needed …



Workshops in

- Paris (1992)
- Adelaide (1993)
- Tokyo (1993)
- Snowmass (1994)
- Fermilab (1995)

Anonymous gift	**$50,000**
Grainger Foundation for site survey	**$100,000**
UNESCO	**$100,000**
NSF	**$30,000**
Universities Research Association	**$50,000**
University of Chicago	**$25,000**

UNESCO

united nations educational, scientific and cultural organization
organisation des nations unies pour l'éducation, la science et la culture
organización de las naciones unidas para la educación, la ciencia y la cultura

7, place de Fontenoy,
75352 Paris 07-SP

telephone: national (1) 45.68.10.00
international + (33.1) 45.68.10.00
telex: 204461 Paris
270602 Paris
telefax: 47.34.85.57

The Director-General

reference: DG/2.4/2121

25 JUL 1994

Dear Professor Cronin,

It was indeed a pleasure for me to receive you at UNESCO and to discuss ways and means by which UNESCO could help promote the development of the international research project to observe the highest energy cosmic rays.

I believe, as you do, that it is important to advance our knowledge of fundamental processes and laws in nature. The project that you are proposing would certainly do that - and more. It would become a focus for international collaboration involving physicists, astronomers, engineers and technical support staff and it would involve both the northern and the southern hemisphere. From our discussions it was clear that UNESCO could contribute significantly to the development and promotion of this project by helping your group ensure that scientists from developing countries can collaborate from the start, and by facilitating discussions and explorations aiming at finding suitable sites for the two detectors.

I confirm that UNESCO is ready to contribute during 1995 some US$100,000 towards the cost of the participation of scientists from developing countries in the Giant Array Design Group that will begin its work early next year at the Fermi National Laboratory.

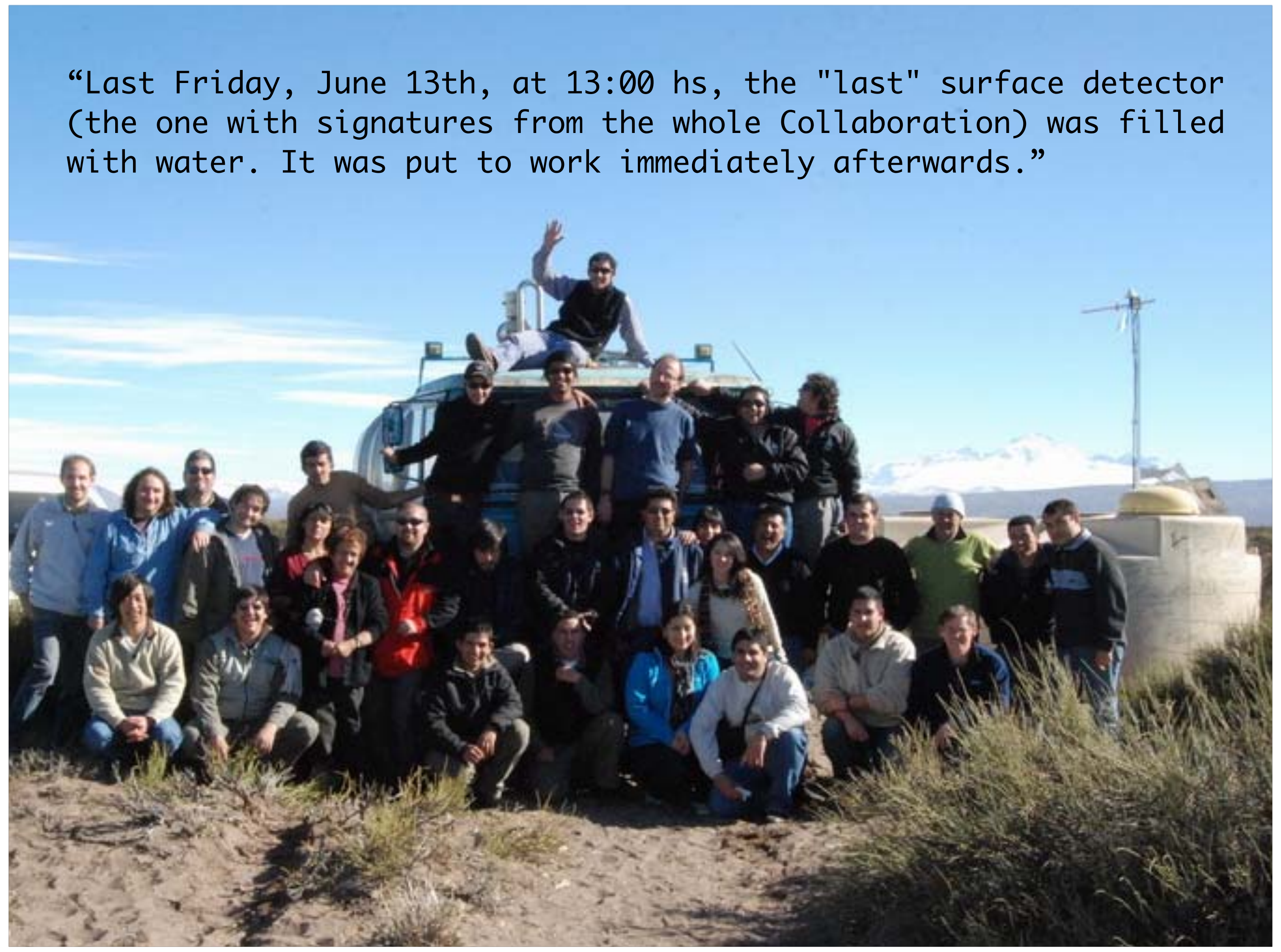
I have asked Dr Siegbert Raither from the Division of Basic Sciences to co-ordinate UNESCO's inputs to your project and to report to me periodically on its progress.

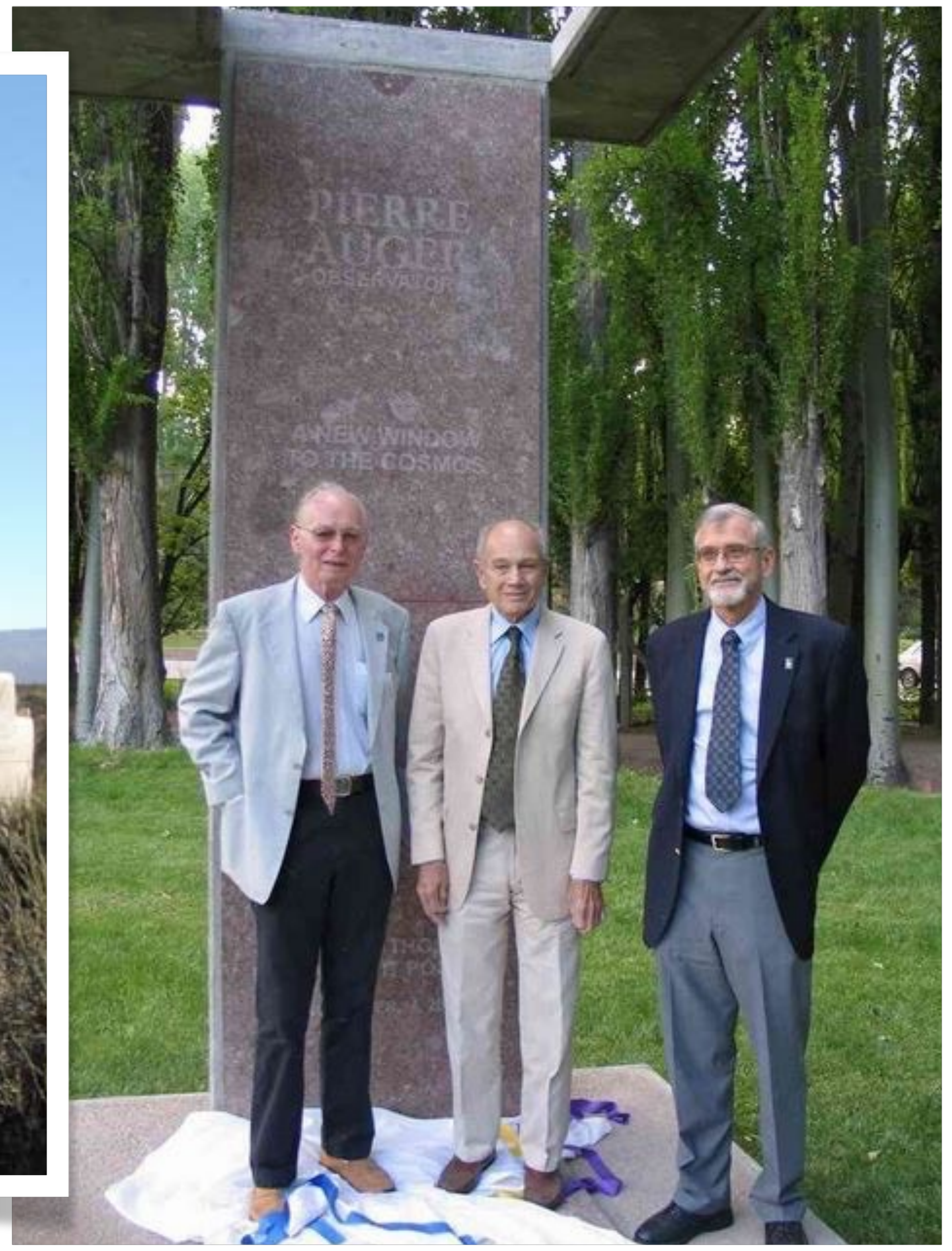
Yours sincerely,

Federico Mayor

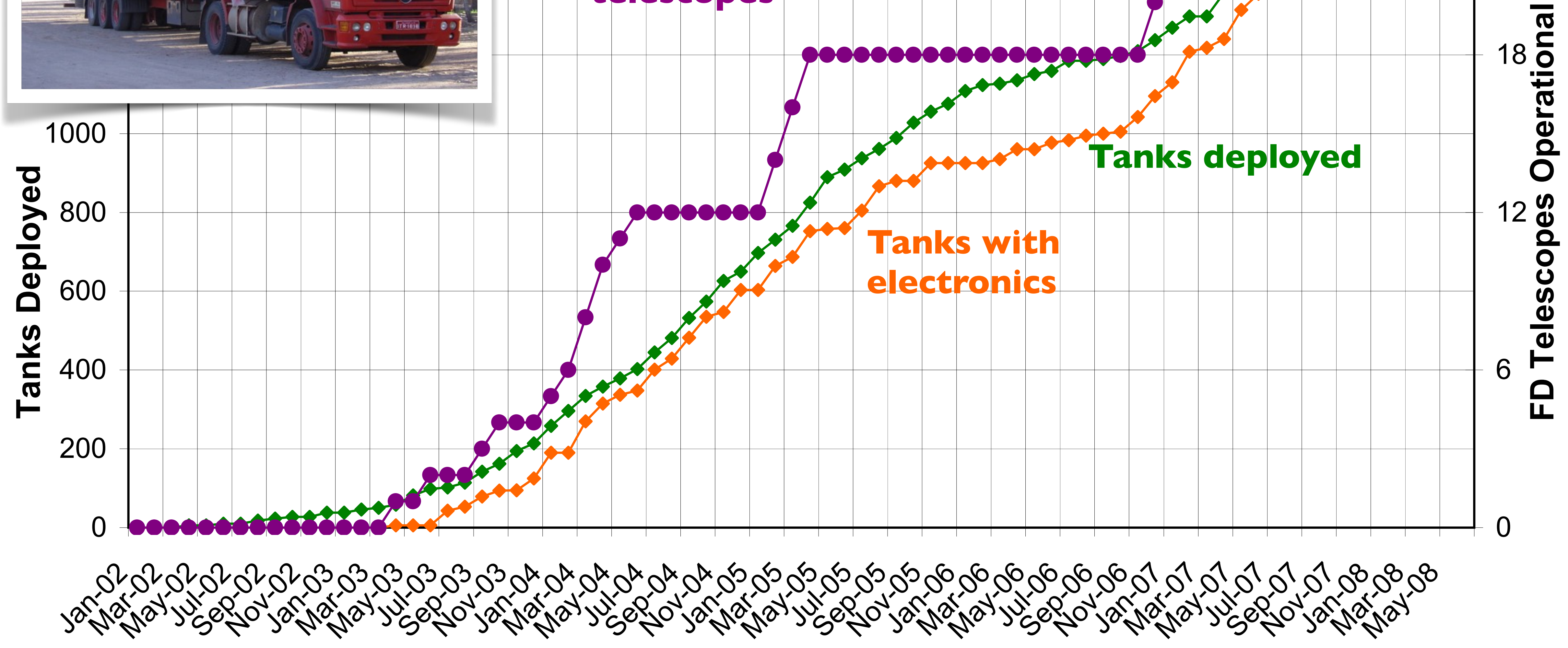
Building the Pierre Auger Observatory

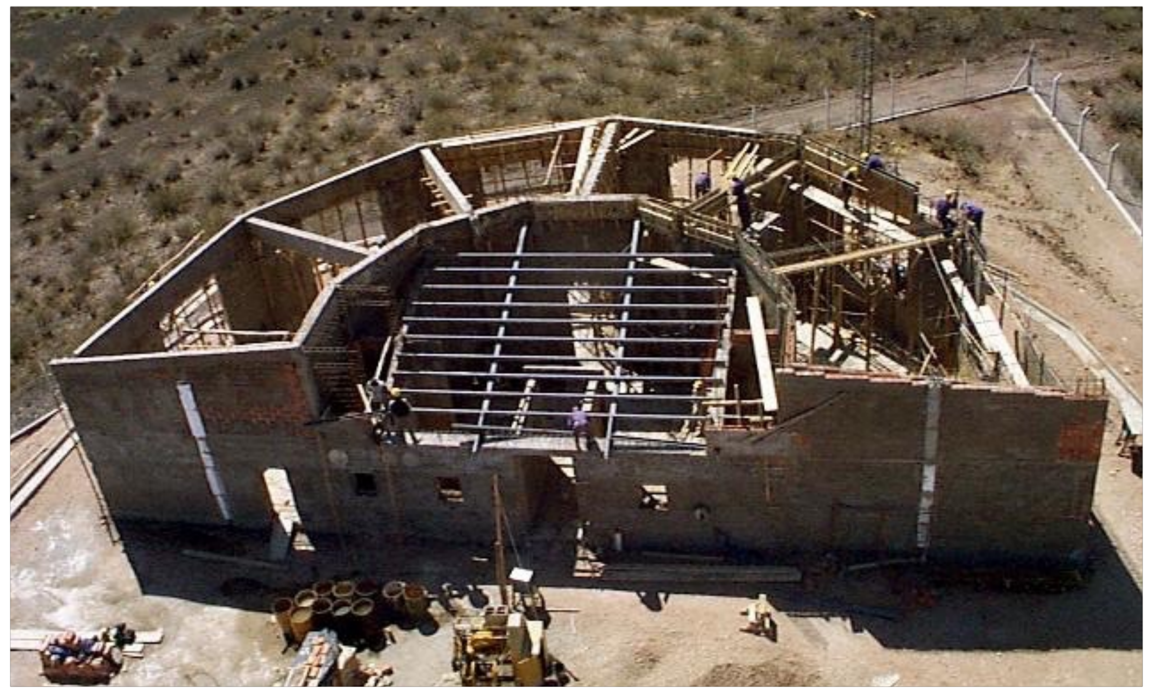
May 2000 – first engineering array station

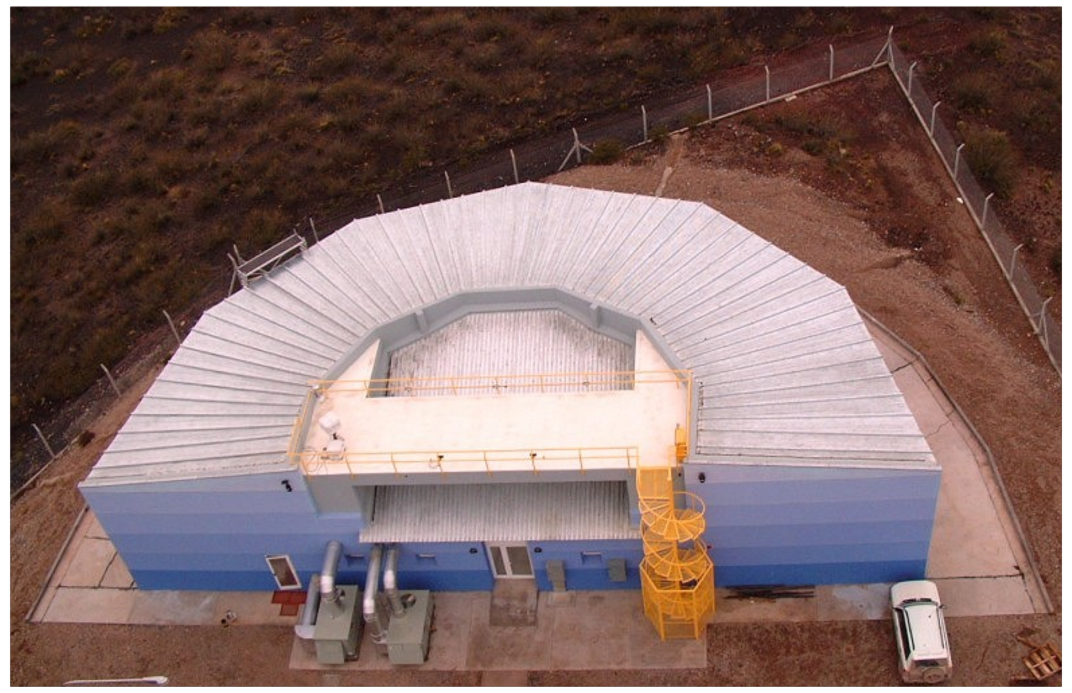




June 2008 – completion of surface array



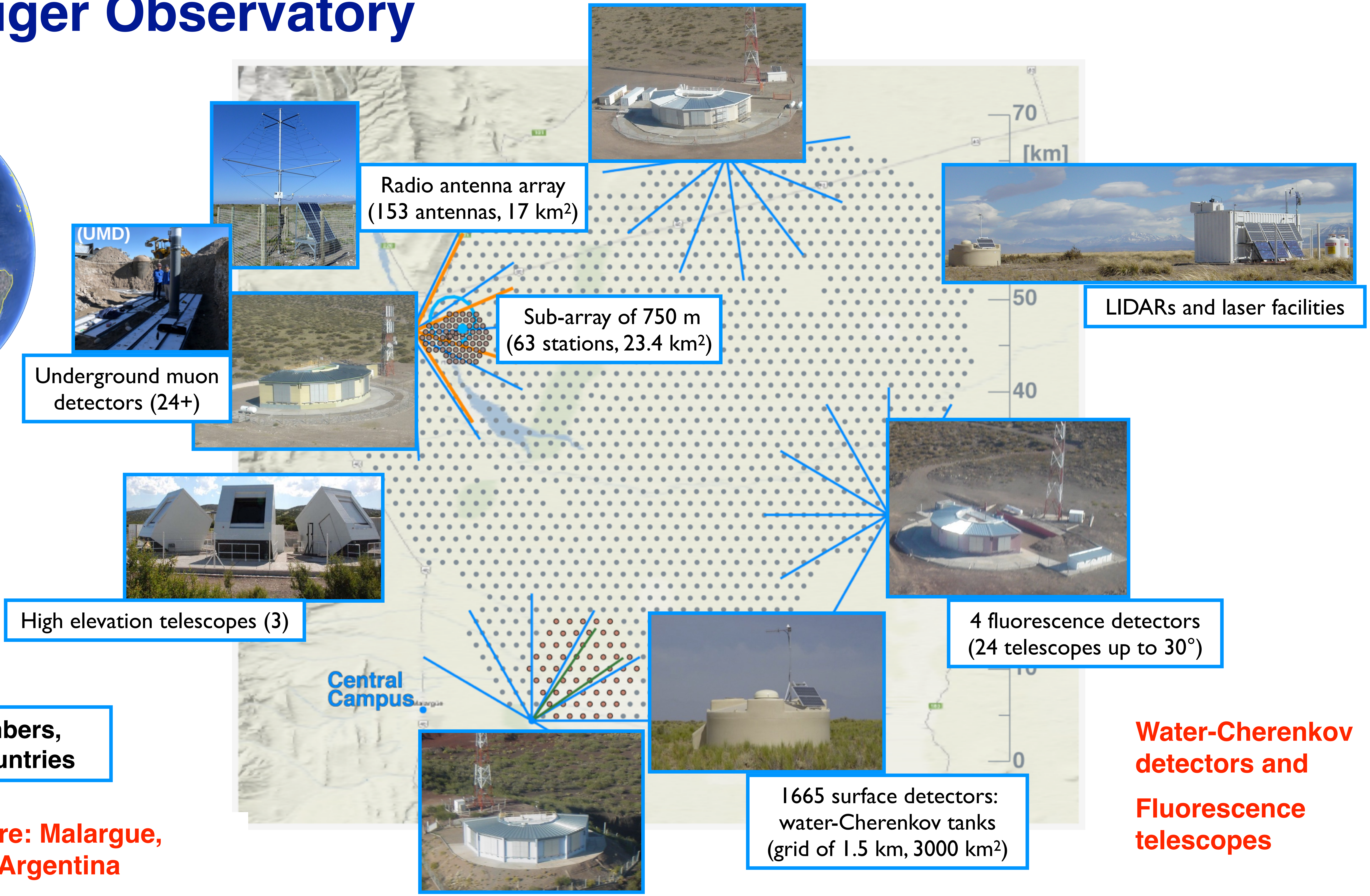




May 2001 – first fluorescence event

The Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina



More than 400 members,
98 institutes, 18 countries

Southern hemisphere: Malargue,
Province Mendoza, Argentina

Water-Cherenkov detectors and

Fluorescence telescopes


Fluorescence telescope
Particle detector
10 m² area, 1.20 m high
12 tons of water
Lidar
FRAM


1.5 km

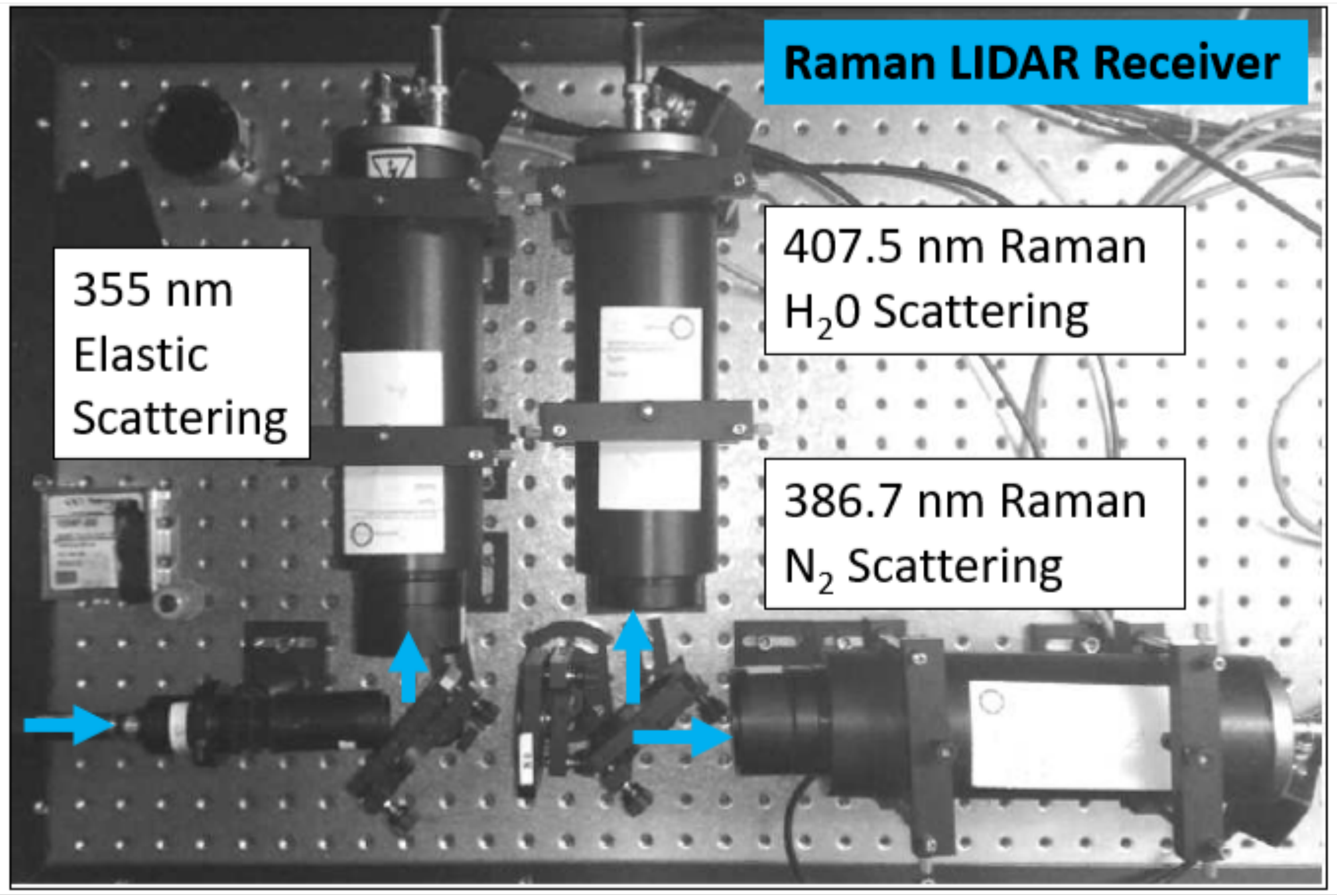

PMT camera with
440 pixels, 1.5° FoV
per pixel, 10 MHz
UV transmitting
filter, corrector
lens, safety curtain
3.4 m segmented mirror
(aluminum alloy, glass)

Central data acquisition building

Supporting instruments

Laser facilities

- 0.1-100 EeV equivalent
- Autonomous Operation Vertical and Steering
- GPS Timing
- Hourly Monitoring of FD
- Aerosol content



Raman Lidar

FRAM – F/Photometric Robotic Atmospheric Monitor

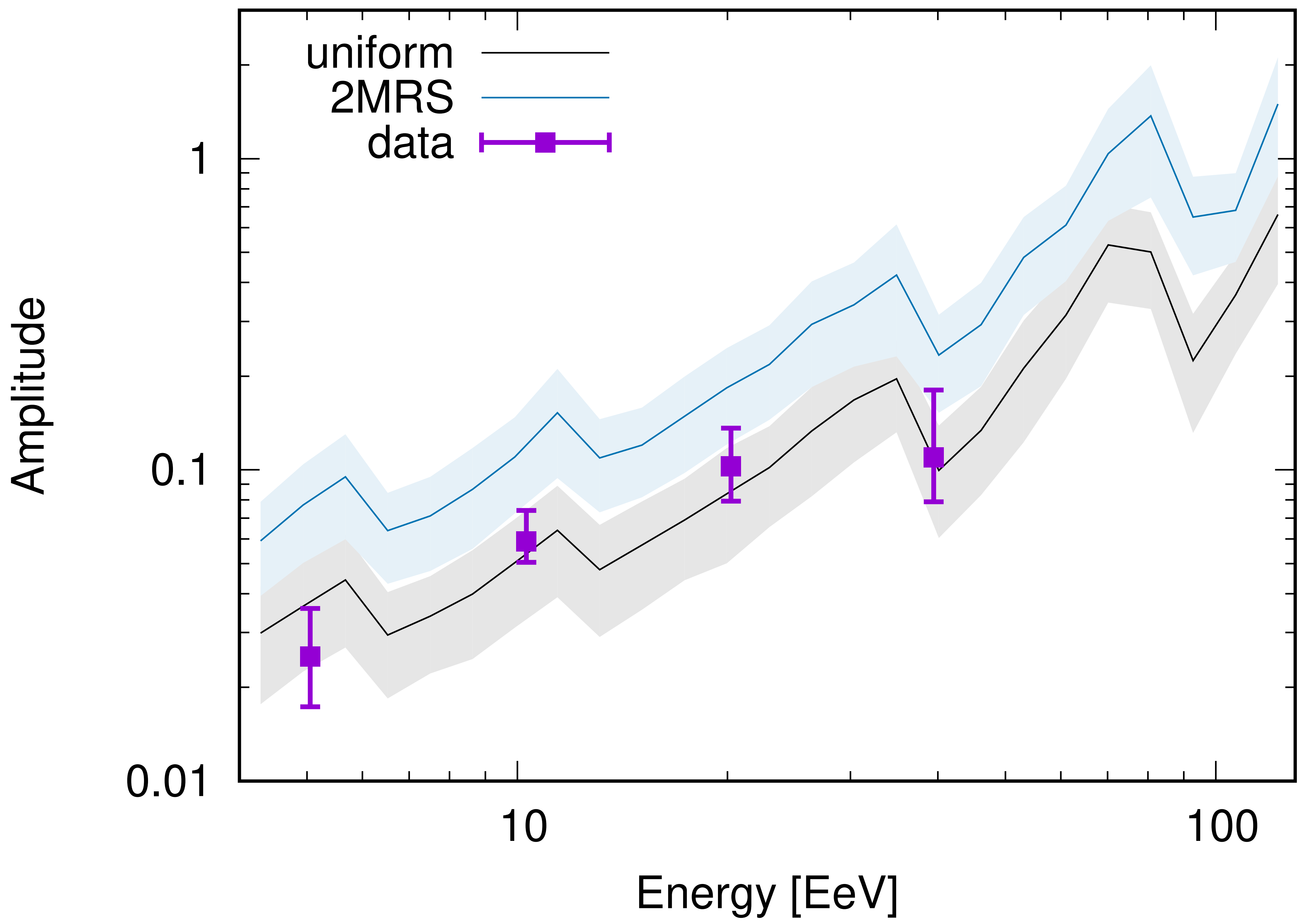
IR cloud cameras

Science highlight: dipole anisotropy

6.5% dipole at 5.2 sigma
Science 357 (2017) 1266

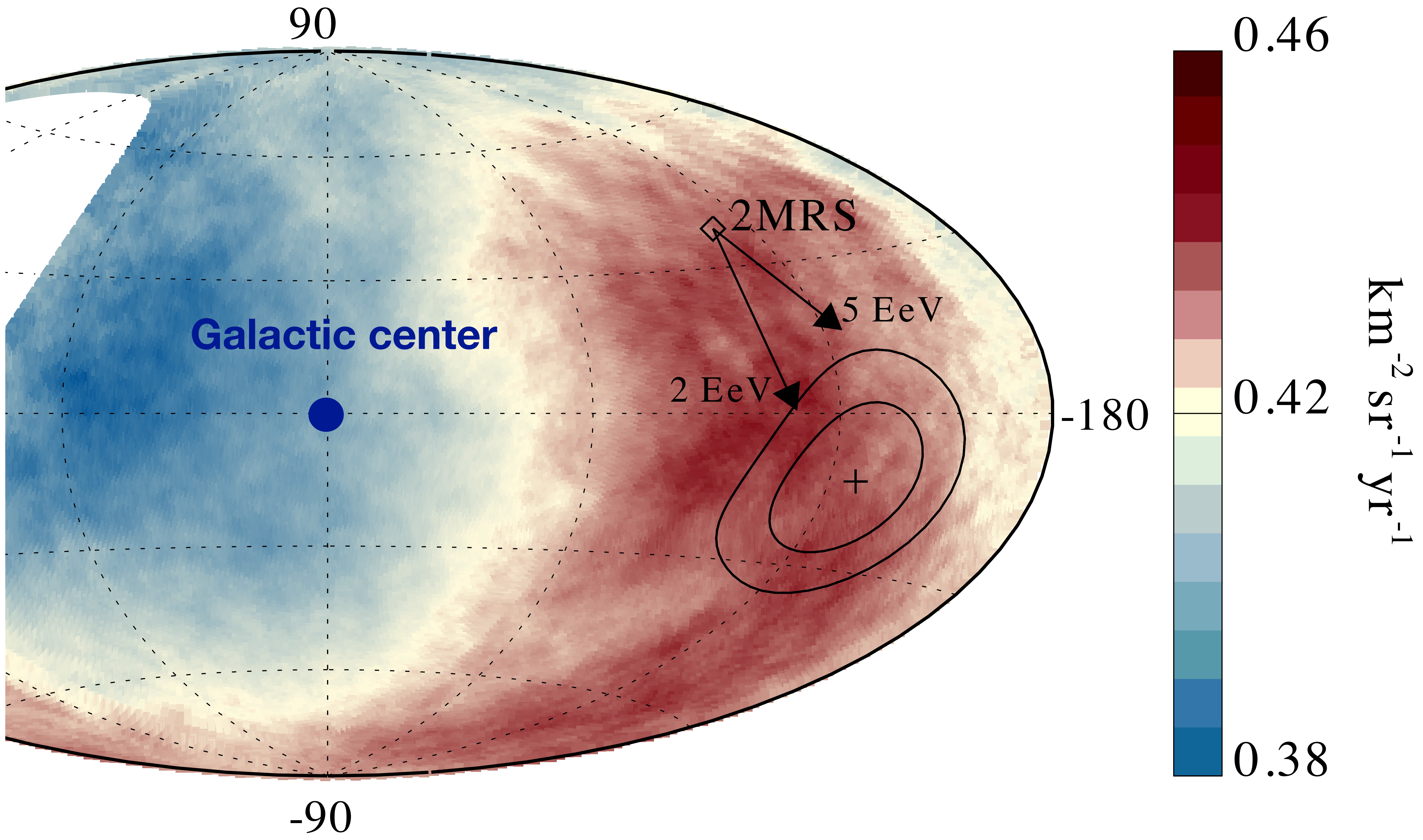
physicsworld TOP 10 BREAKTHROUGH 2017

Energy-dependence of amplitude (ApJ 2018)



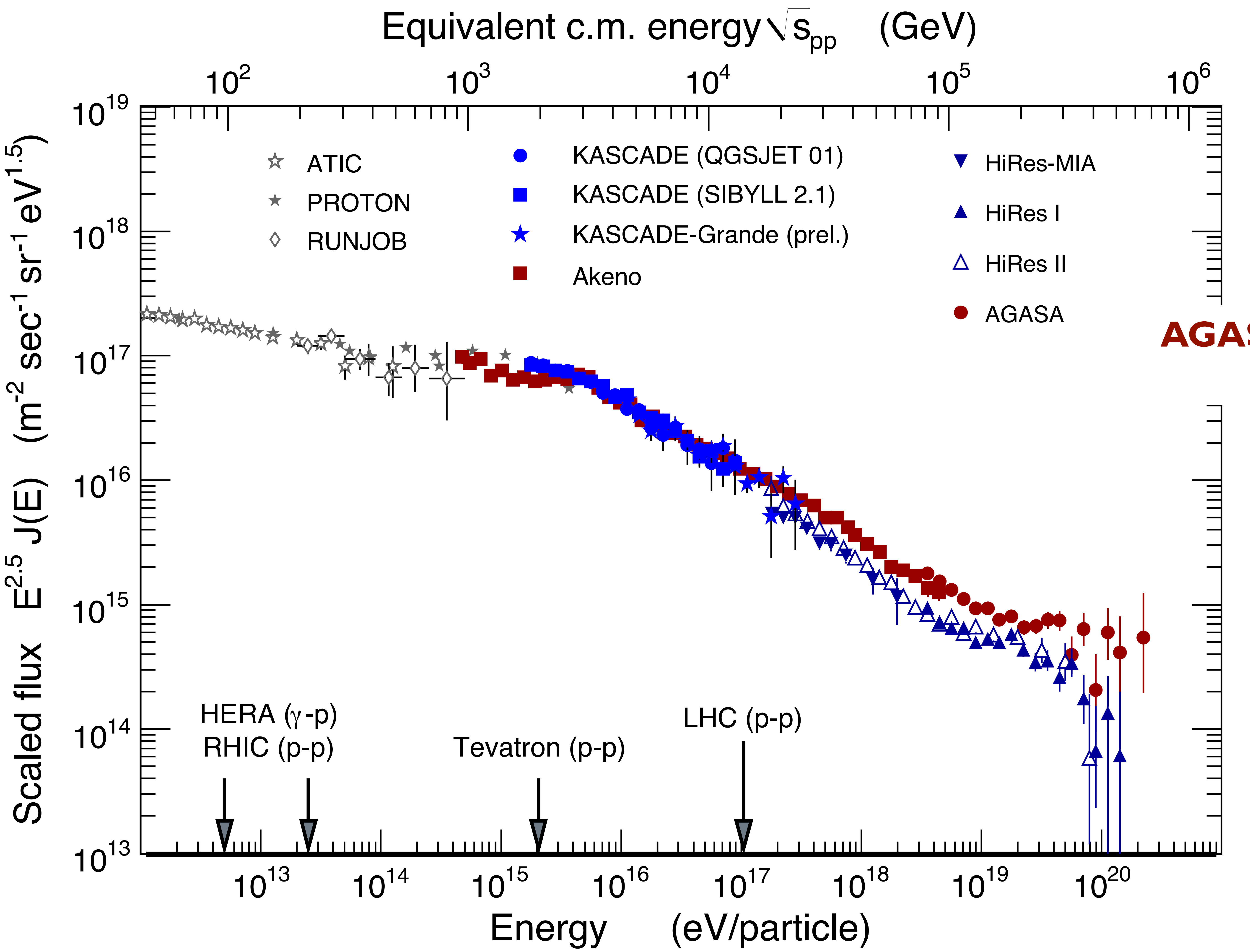
$E > 8 \times 10^{18}\,\mathrm{eV}$

Estimated deflection in galactic mag. field



Arrival directions follow mass distribution of near-by galaxies: **extragalactic origin of sources**

Science highlight: energy spectrum and mass composition

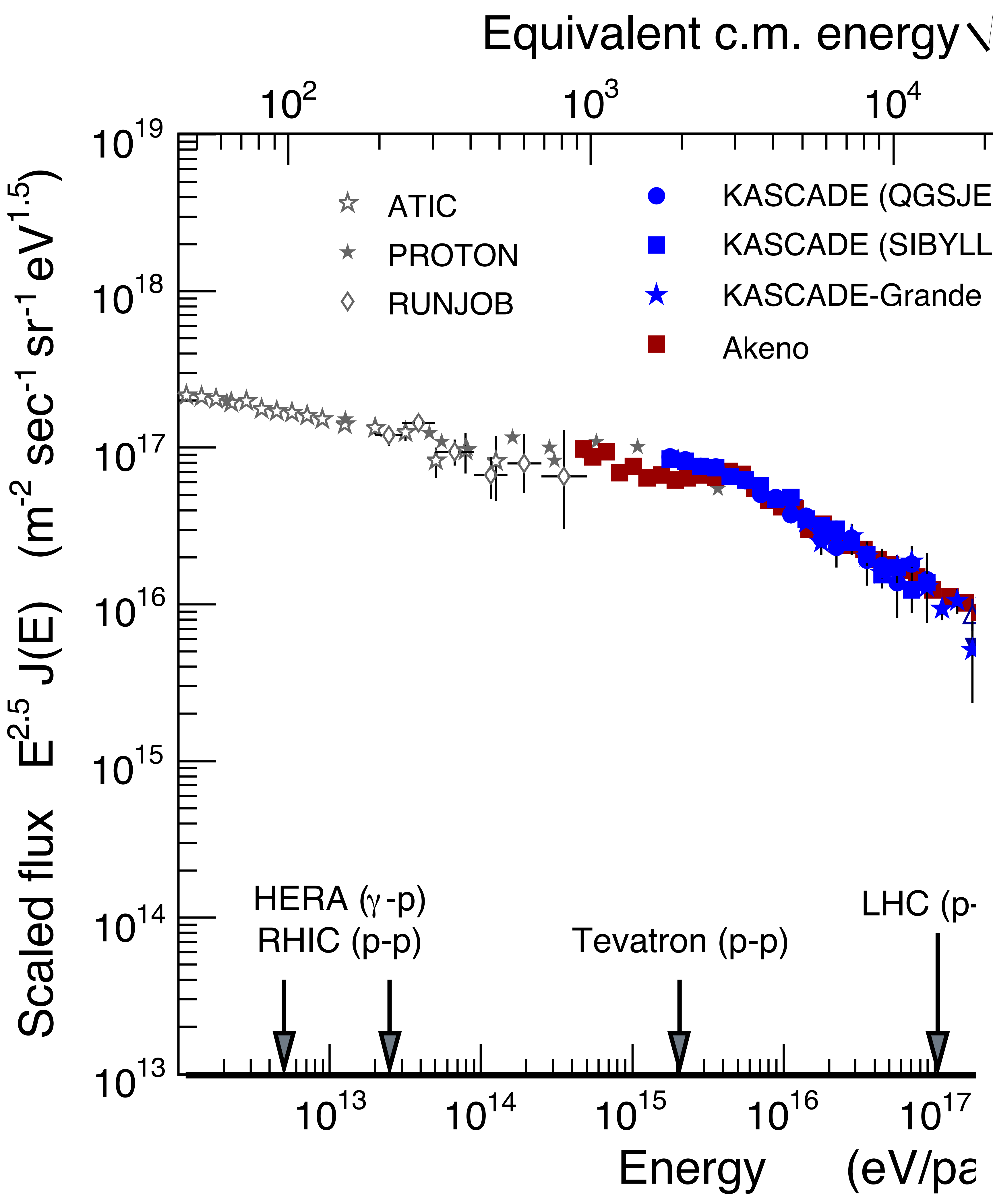


AGASA: particles at ground (scintillator array)

HiRes Fly´s Eye: longitudinal shower profile (fluorescence telescopes)

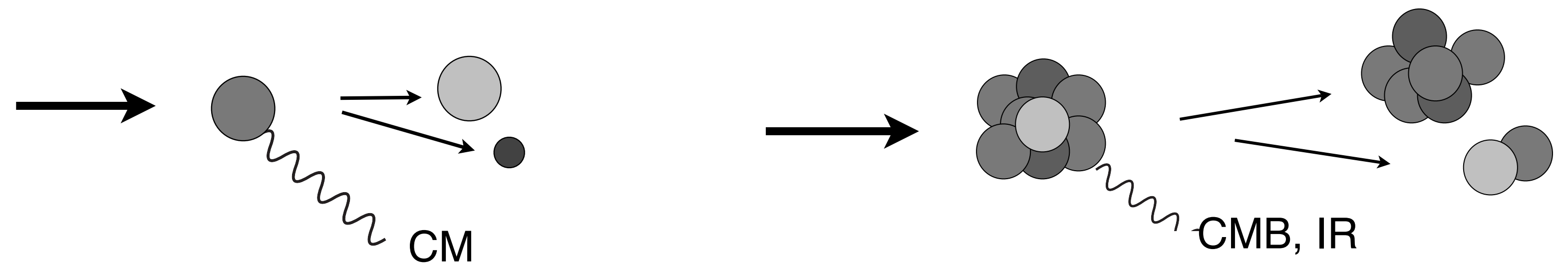
(RE, Nijmegen Summer School, 2006)

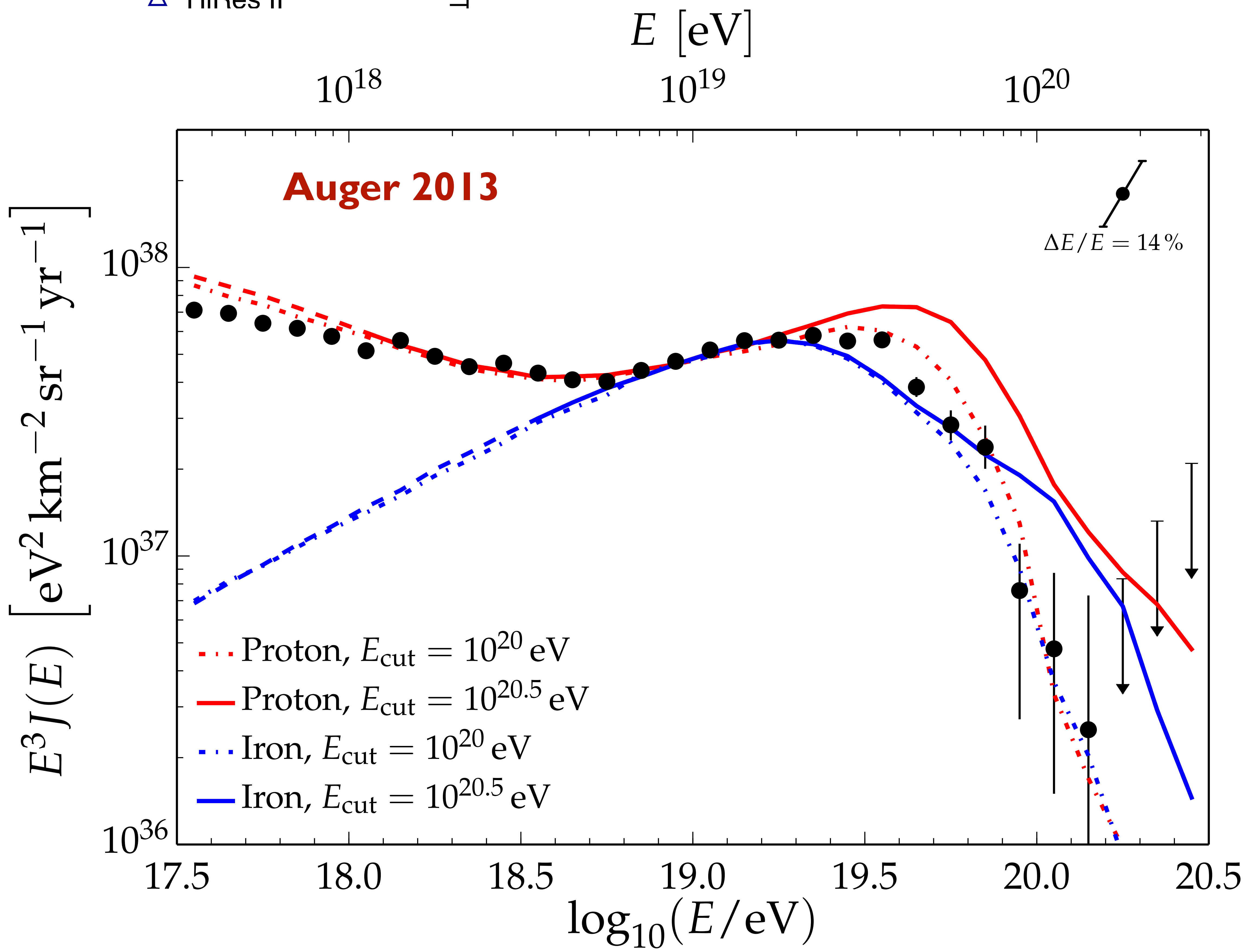
Science highlight: energy spectrum and mass composition



(RE, Nijmegen Summer School, 2006)

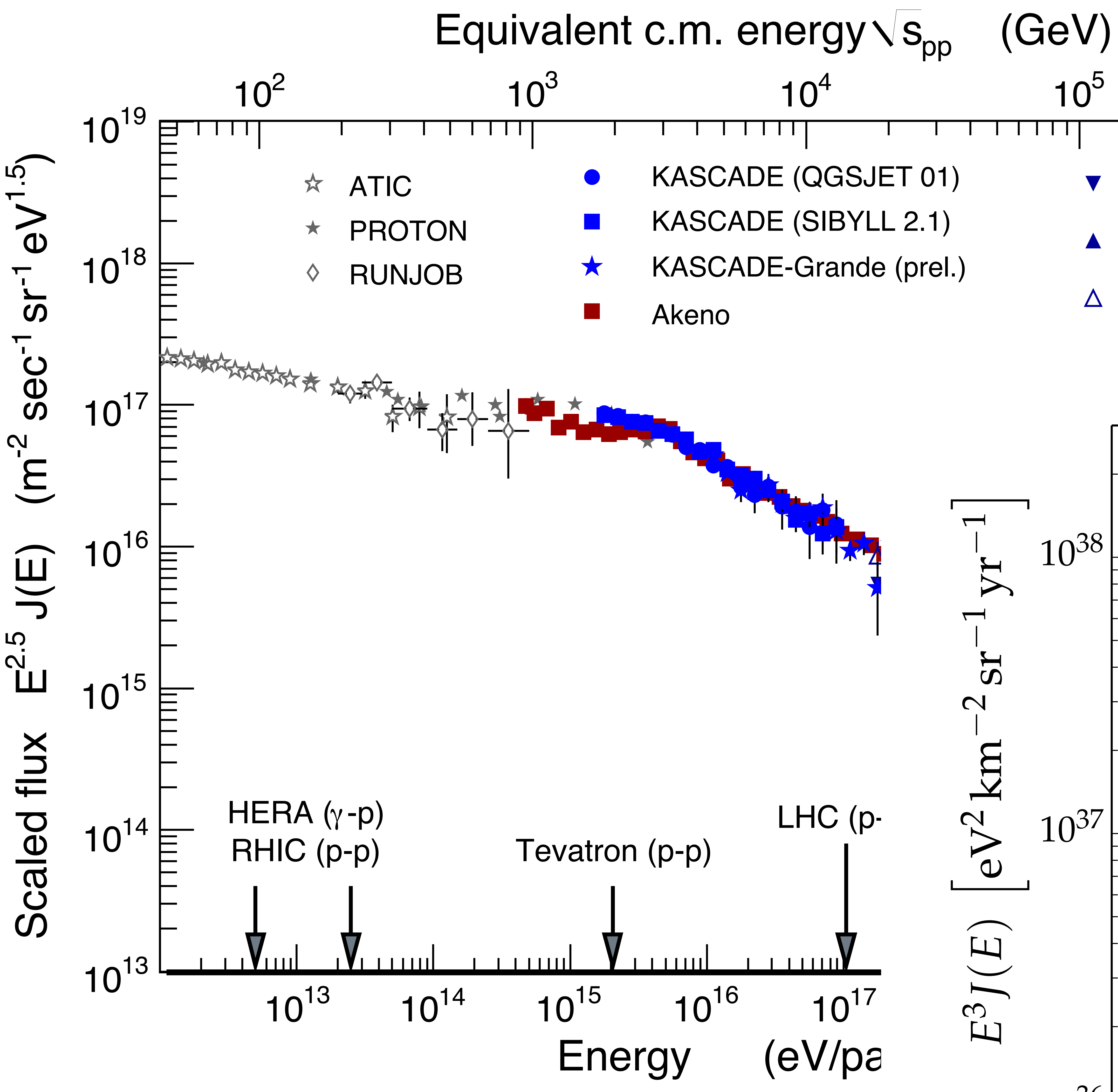
Greisen-Zatsepin-Kuzmin (GZK) effect

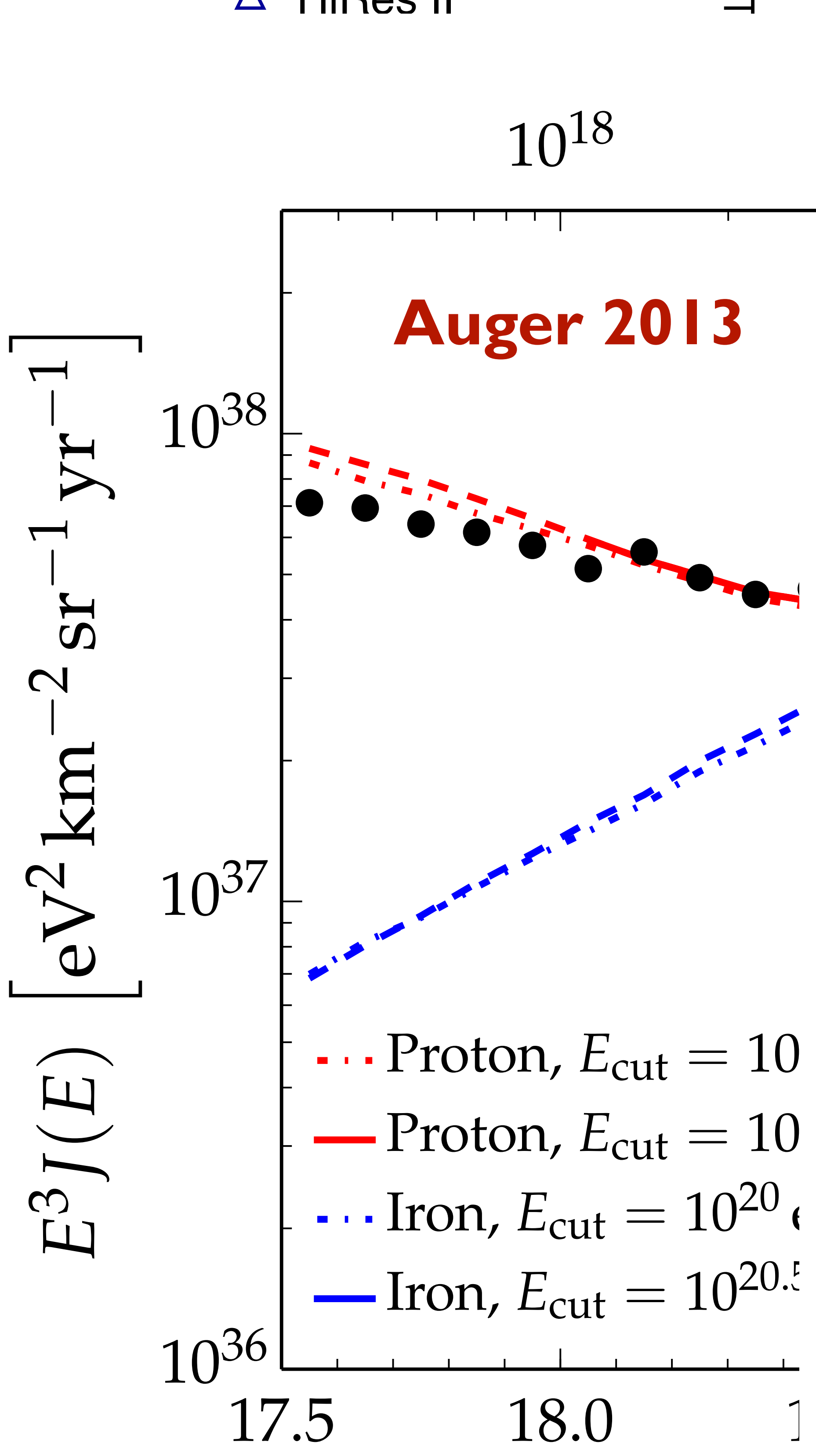


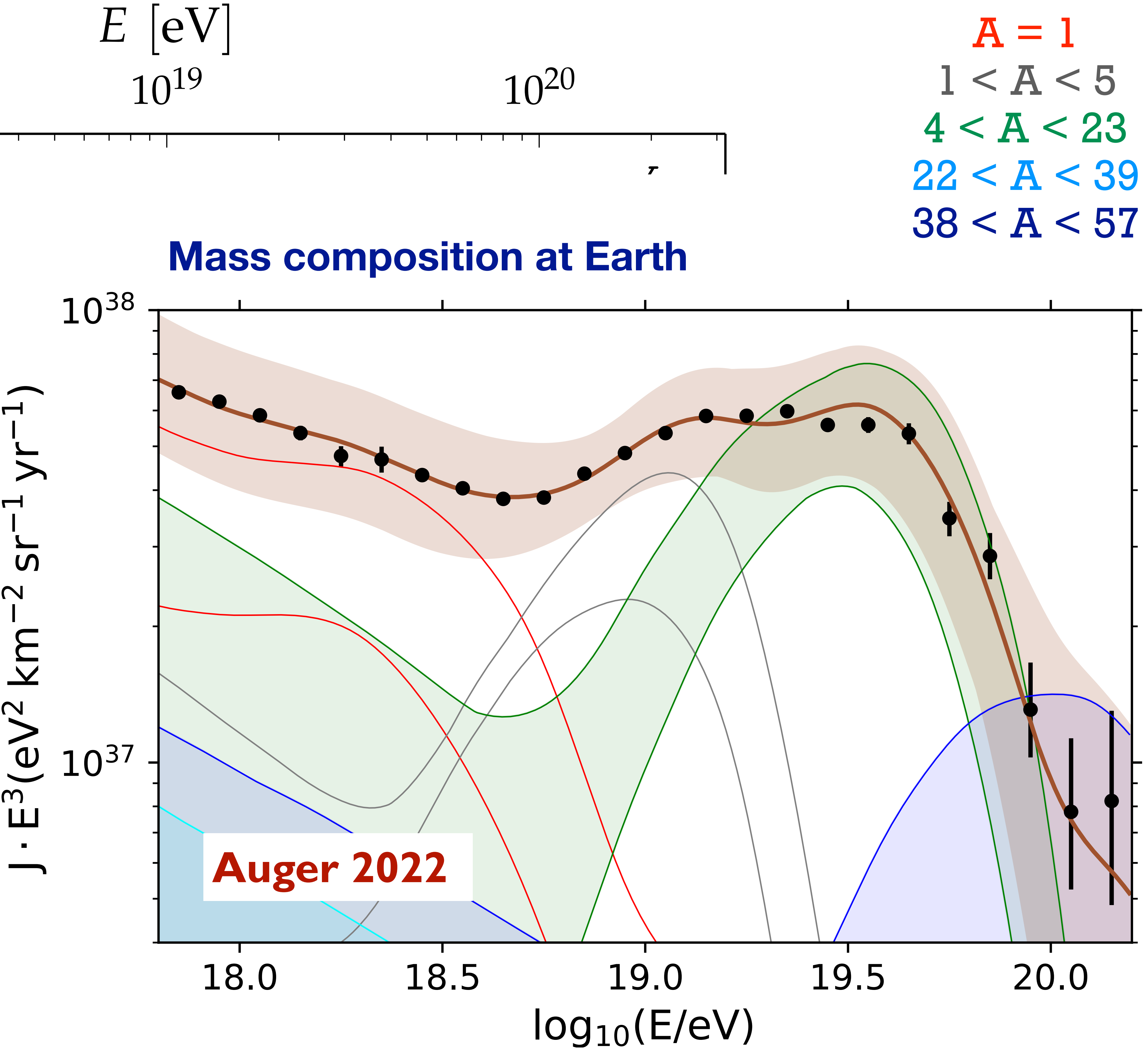


Science highlight: energy spectrum and mass composition

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

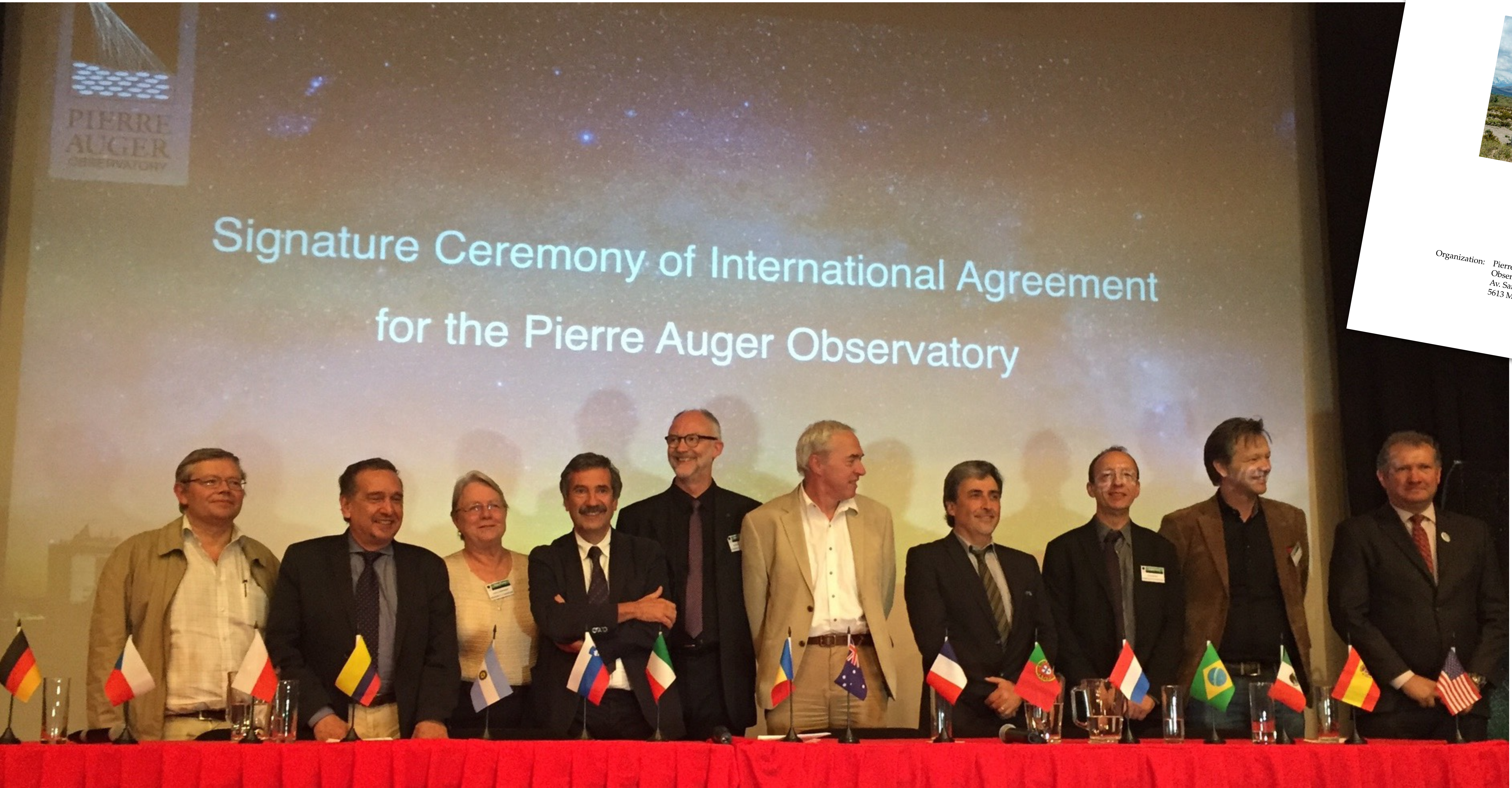


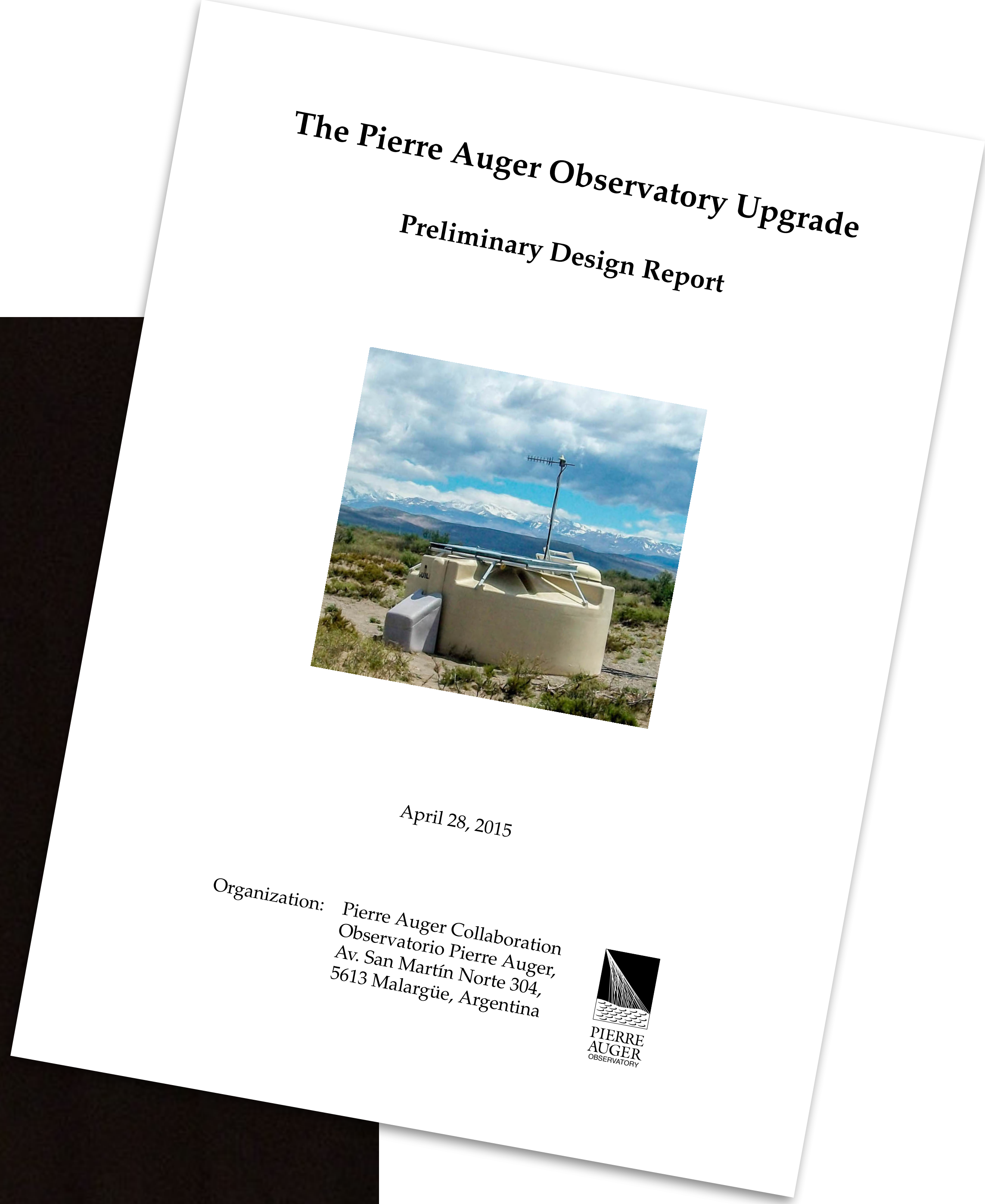




(RE, Nijmegen Summer School, 2006)

Upgrade of Auger Observatory – AugerPrime




The Pierre Auger Observatory Upgrade

Preliminary Design Report

April 28, 2015

Organization: Pierre Auger Collaboration
Observatorio Pierre Auger,
Av. San Martín Norte 304,
5613 Malargüe, Argentina

Science Case Review 2013/2014

Preliminary Design Report April 2015

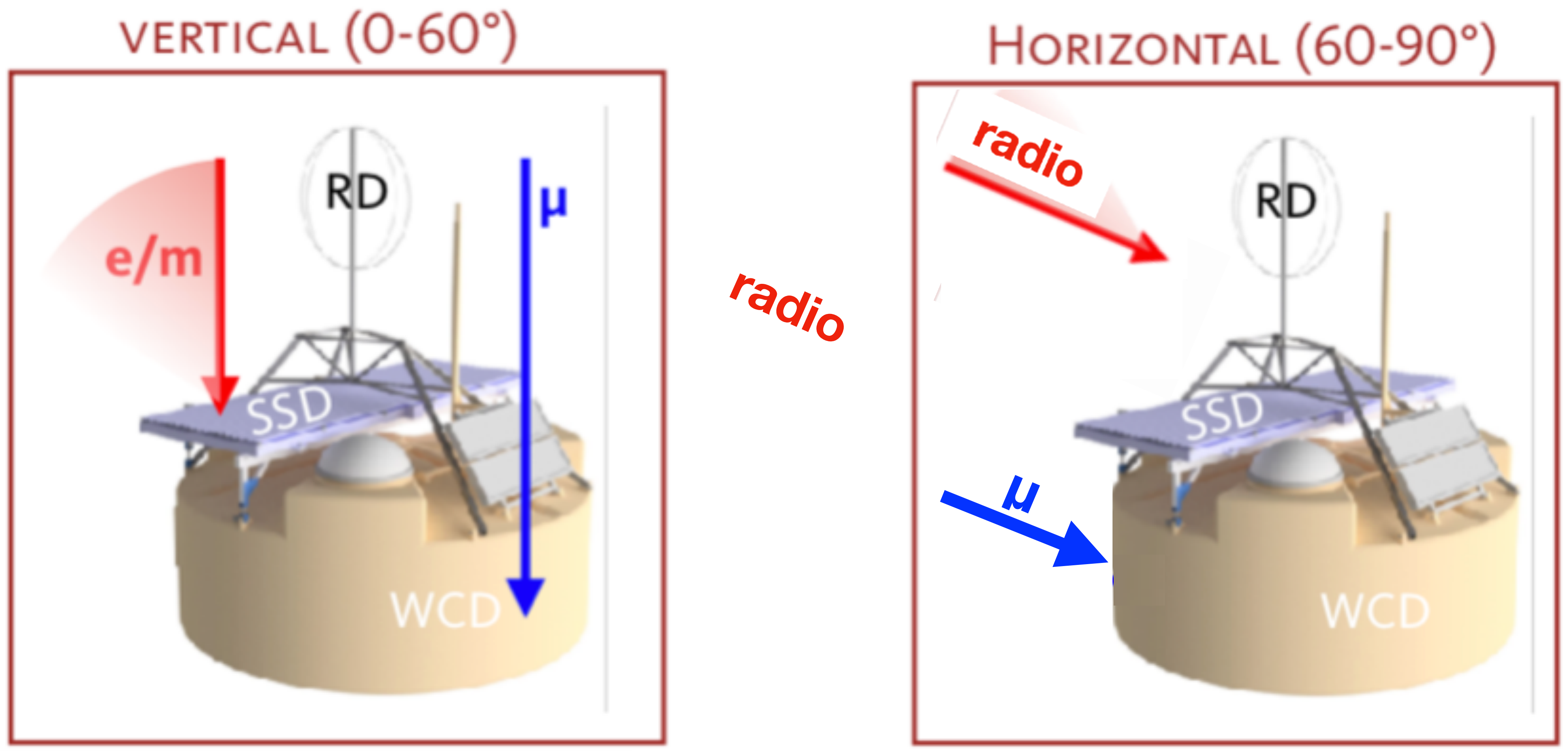
International Agree-ment Nov. 2015

Upgrade of the Observatory – AugerPrime

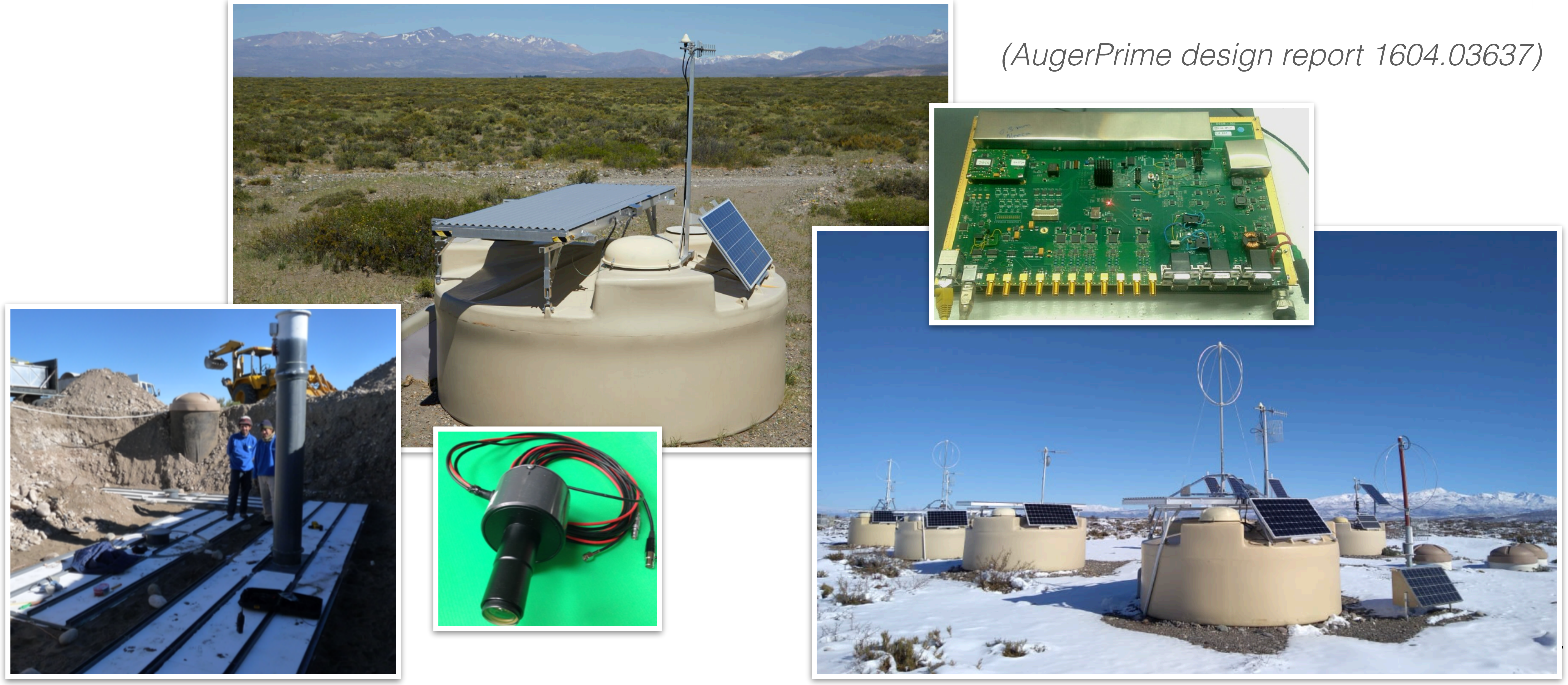
Physics motivation

- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle physics with air showers
- Much better understanding of **new and old** data

Composition sensitivity with 100% duty cycle



(AugerPrime design report 1604.03637)

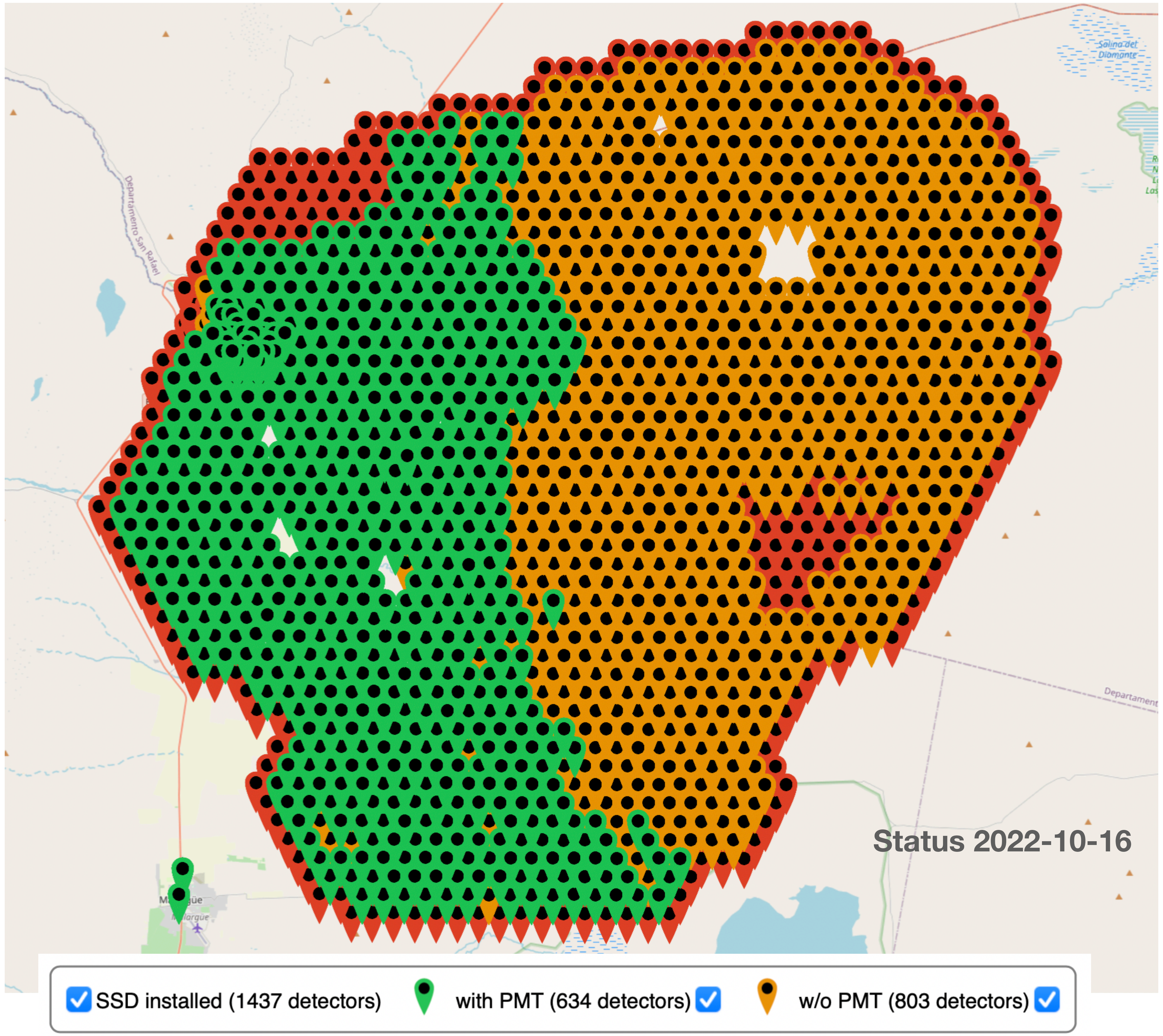


Components of AugerPrime

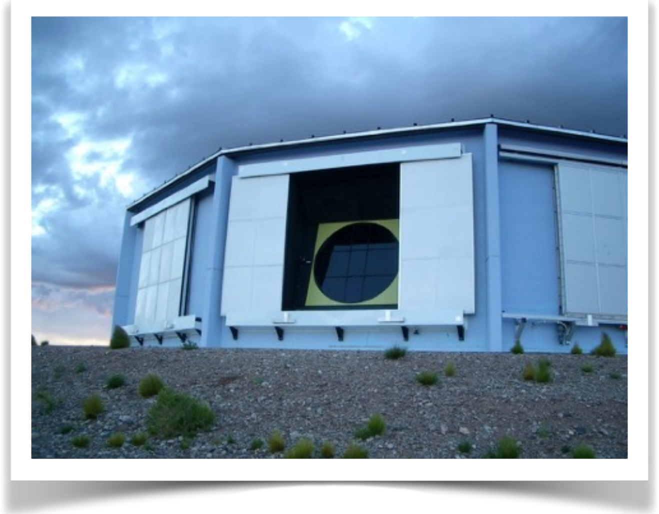
- 3.8 m² scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)
- Enhanced duty cycle of fluorescence tel.

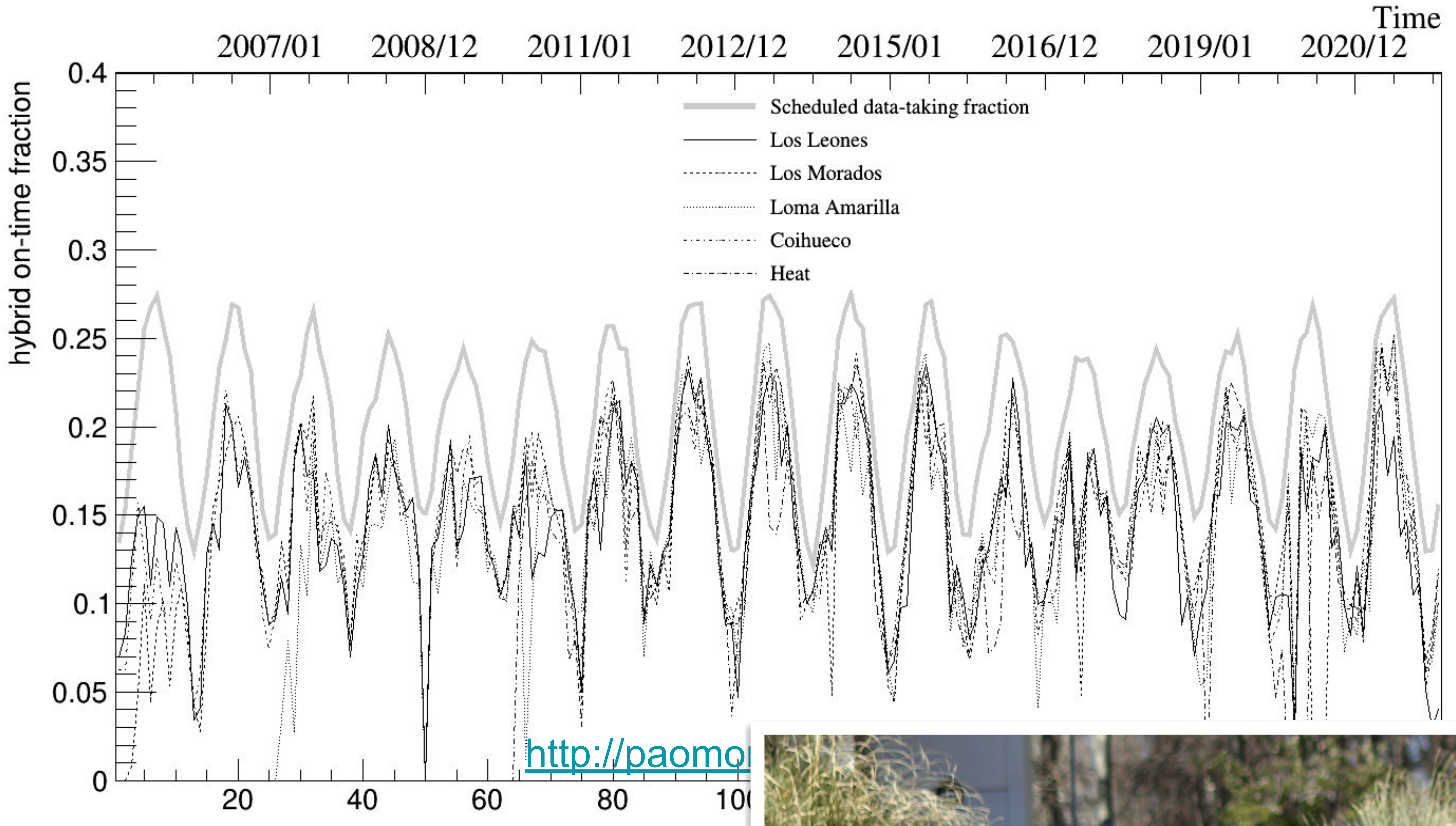
Progress of AugerPrime deployment

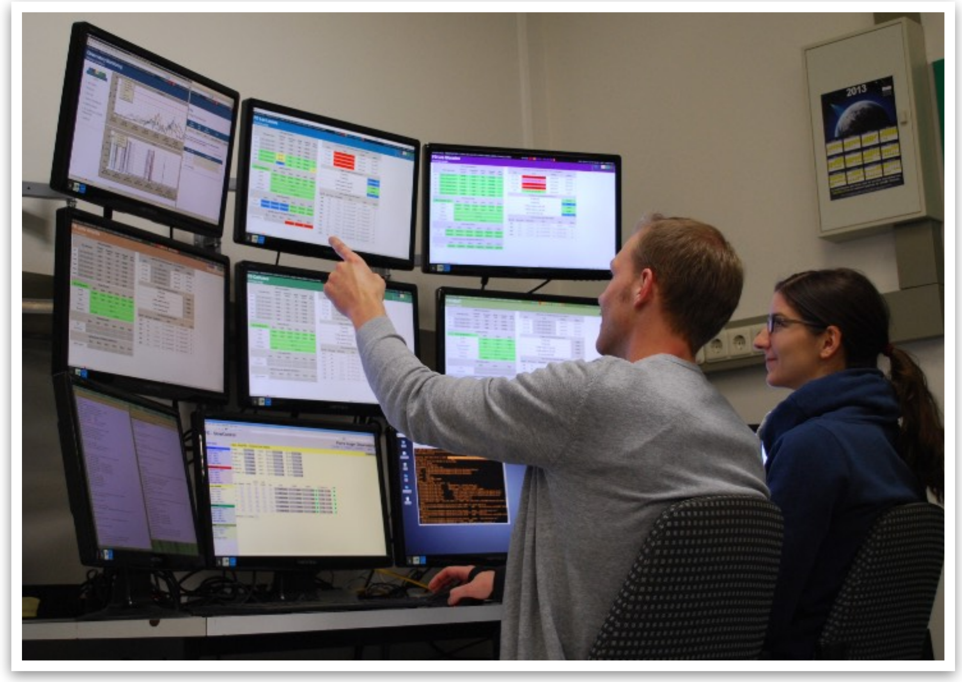
630 detectors completed, radio antennas to follow in 2023



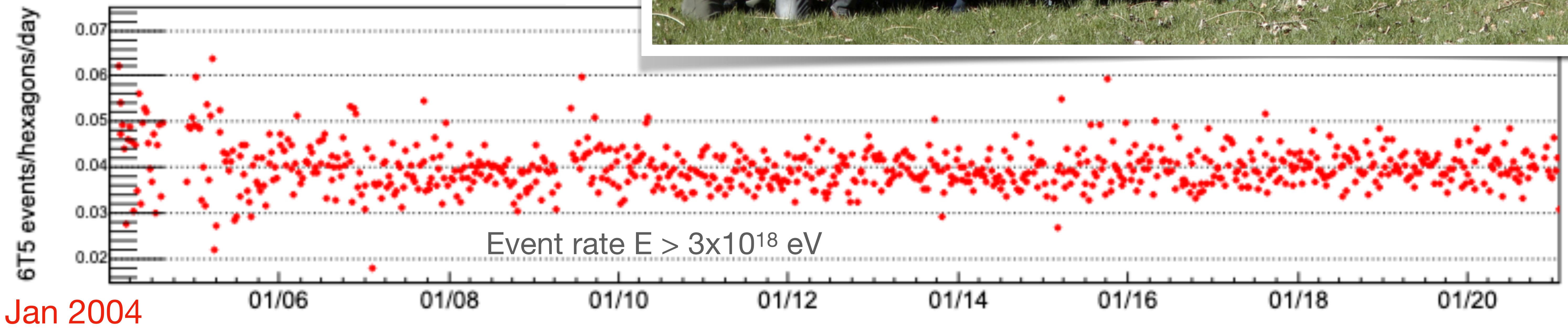
Data taking and deployment – local staff in Malargue







Remote control rooms
(distributed over continents)



31 Staff in Malargue

The Auger Observatory in numbers

Planning phase: 1992 – 1996
Prototyping (engineering array): 1992 – 2002
Construction: 2003 – 2008
Data taking (Phase I): 2004 – 2021

Planning of upgrade: 2015 – 2018
Construction of upgrade: 2019 – 2023
Data taking (Phase II): beyond 2030

Auger Top 10 in INSPIRE

112 Auger papers published

PAPER	INSPIRE (12/03/2022)
APJ 2017 (Multimessenger)	2304
NIM 2004 (Engineering Array)	890
PRL 2008 (Spectrum)	781
Science 2007 (VCV)	752
NIM 2015 (Auger Observatory)	676
PRL 2010 (Xmax)	644
PLB 2010 (Spectrum)	589
APP 2008 (VCV correlation)	496
NIM 2010 (Fluorescence Detector)	431
APP 2010 (VCV update)	426
PRD 2014 Part I (Xmax)	410

22,343 Citations, 10,933 without self-citations

Argentina
Australia
Belgium
Brasil
Colombia
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Peru
Poland
Portugal
Romania
Slovenia
Spain
USA

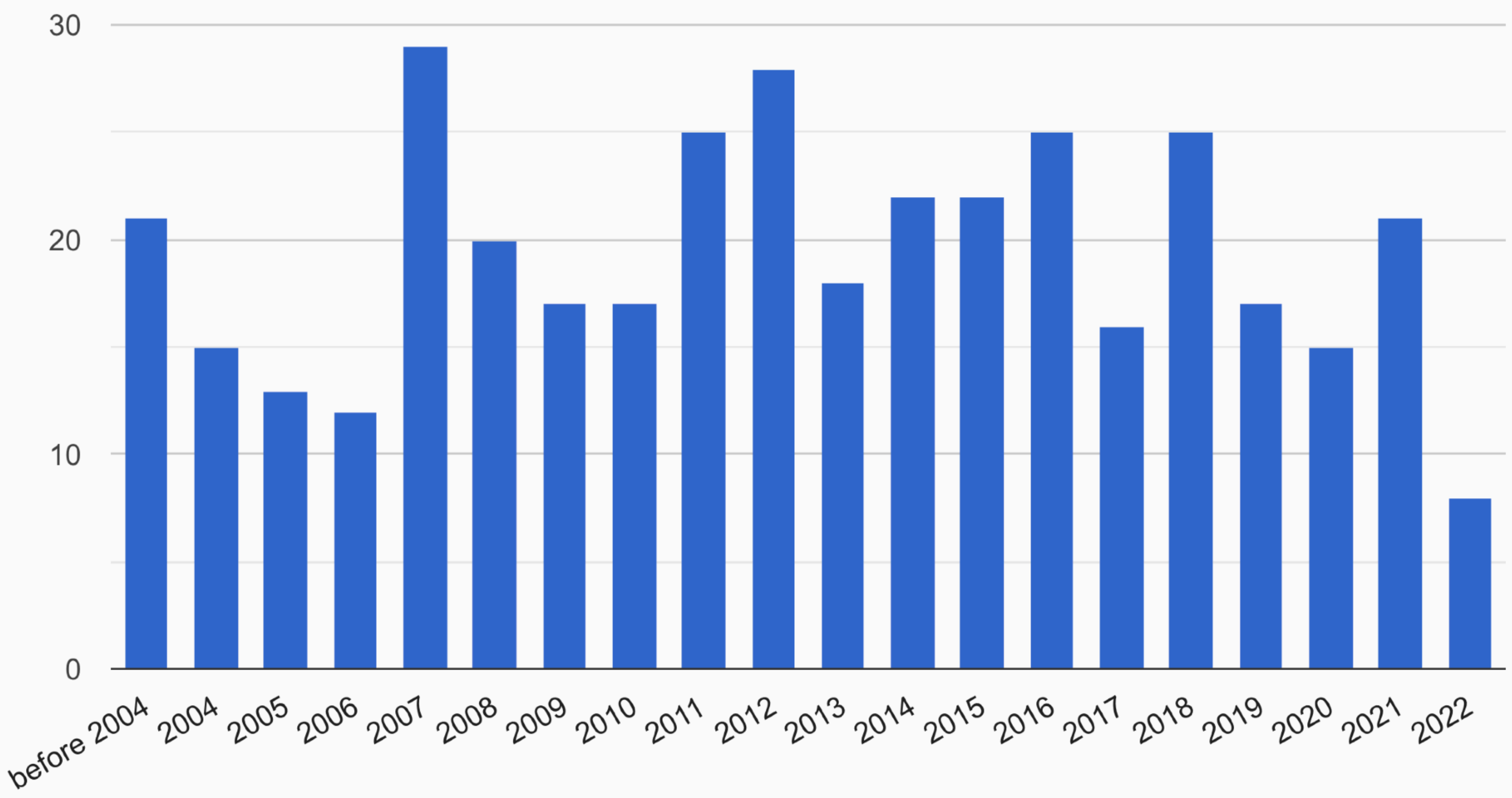
About 400 scientists from more than 90 institutes of 18 countries

Initial construction: ~ 53 MUSD (WBS)
Upgrade (AugerPrime): ~ 16 MUSD
Operating costs (annual): ~ 1.7 MUSD

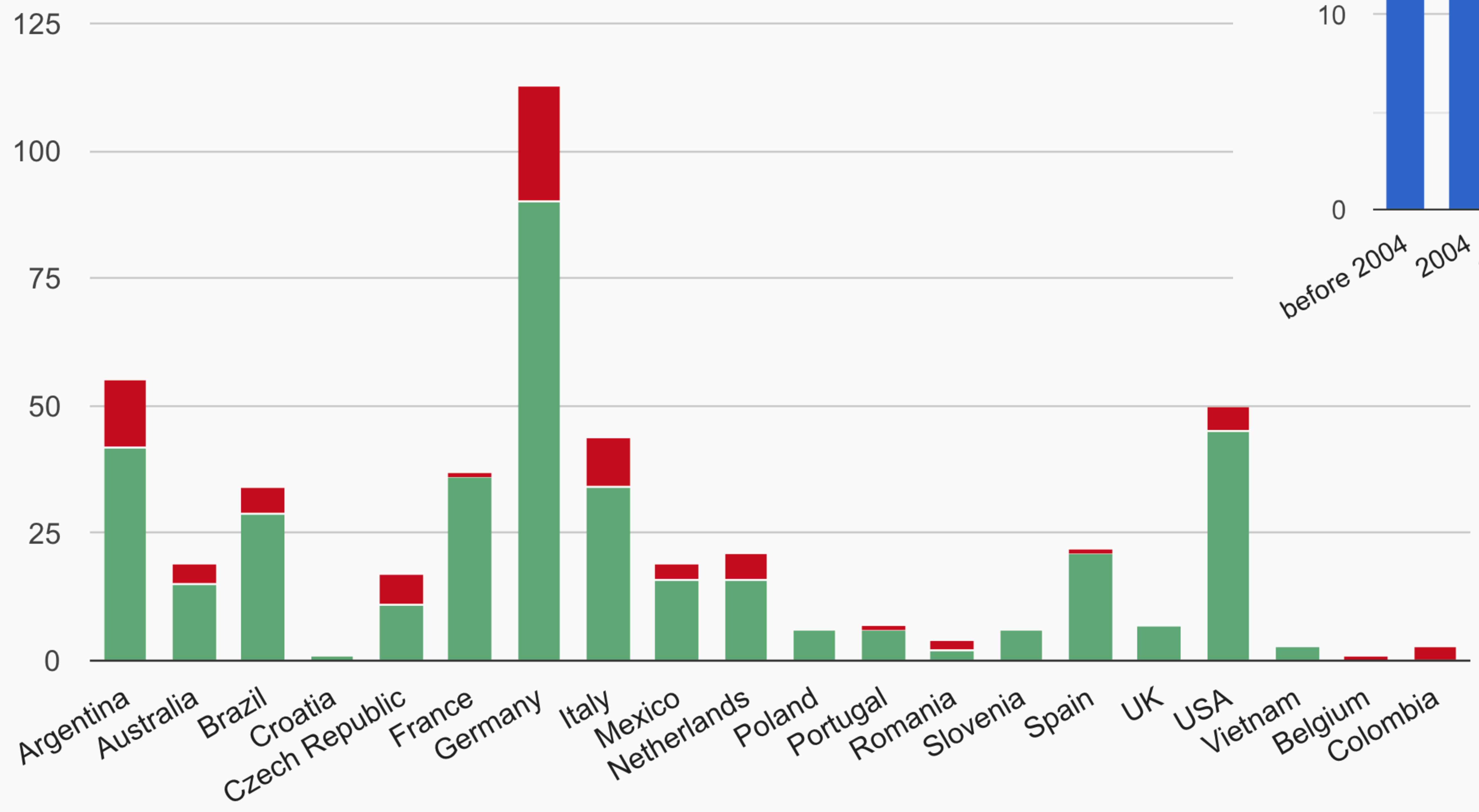
Auger PhD students (doctoral researchers)

Total number of PhD theses: 469
already defended: 386
ongoing: 83

Thesis number by year



Thesis number by country (green: finished)

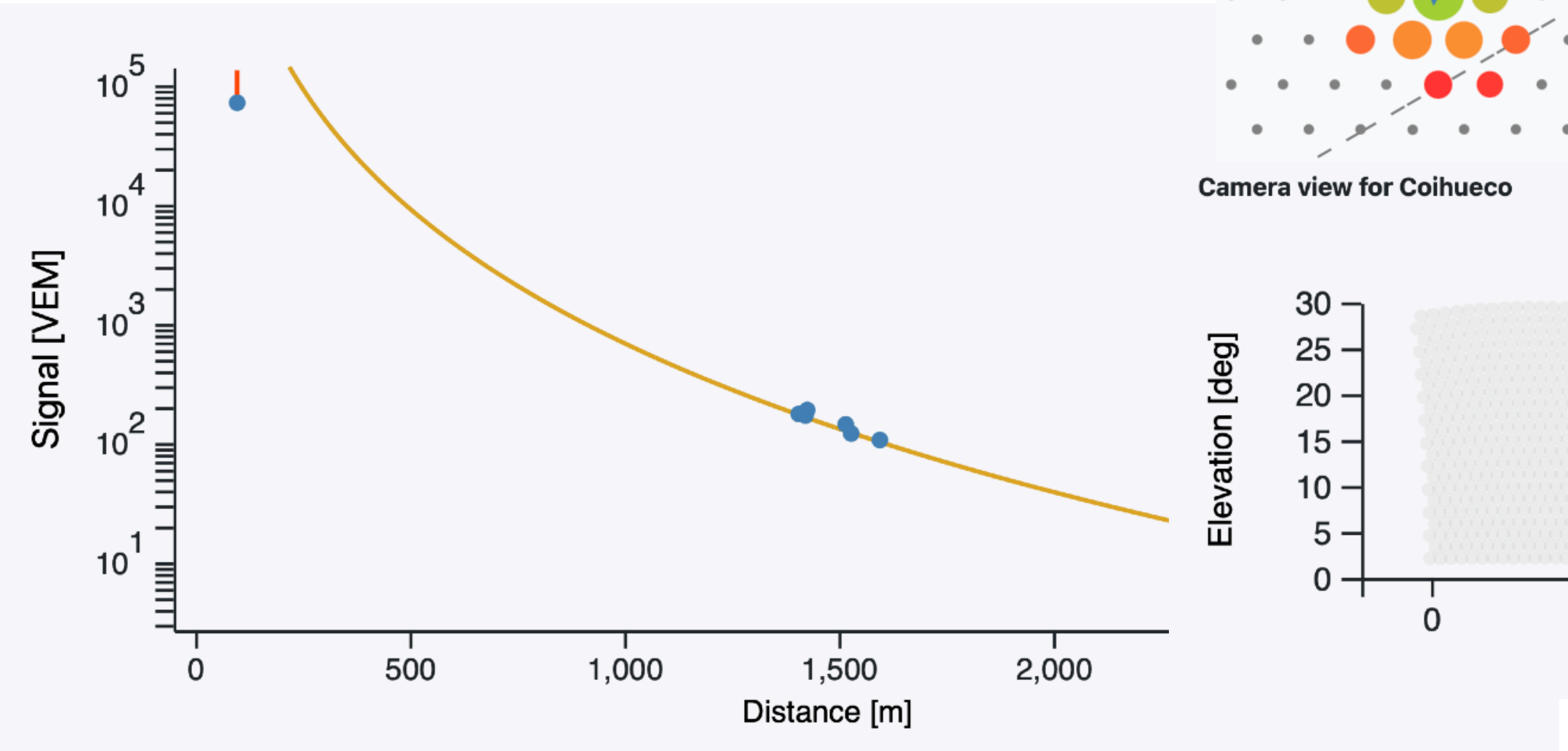


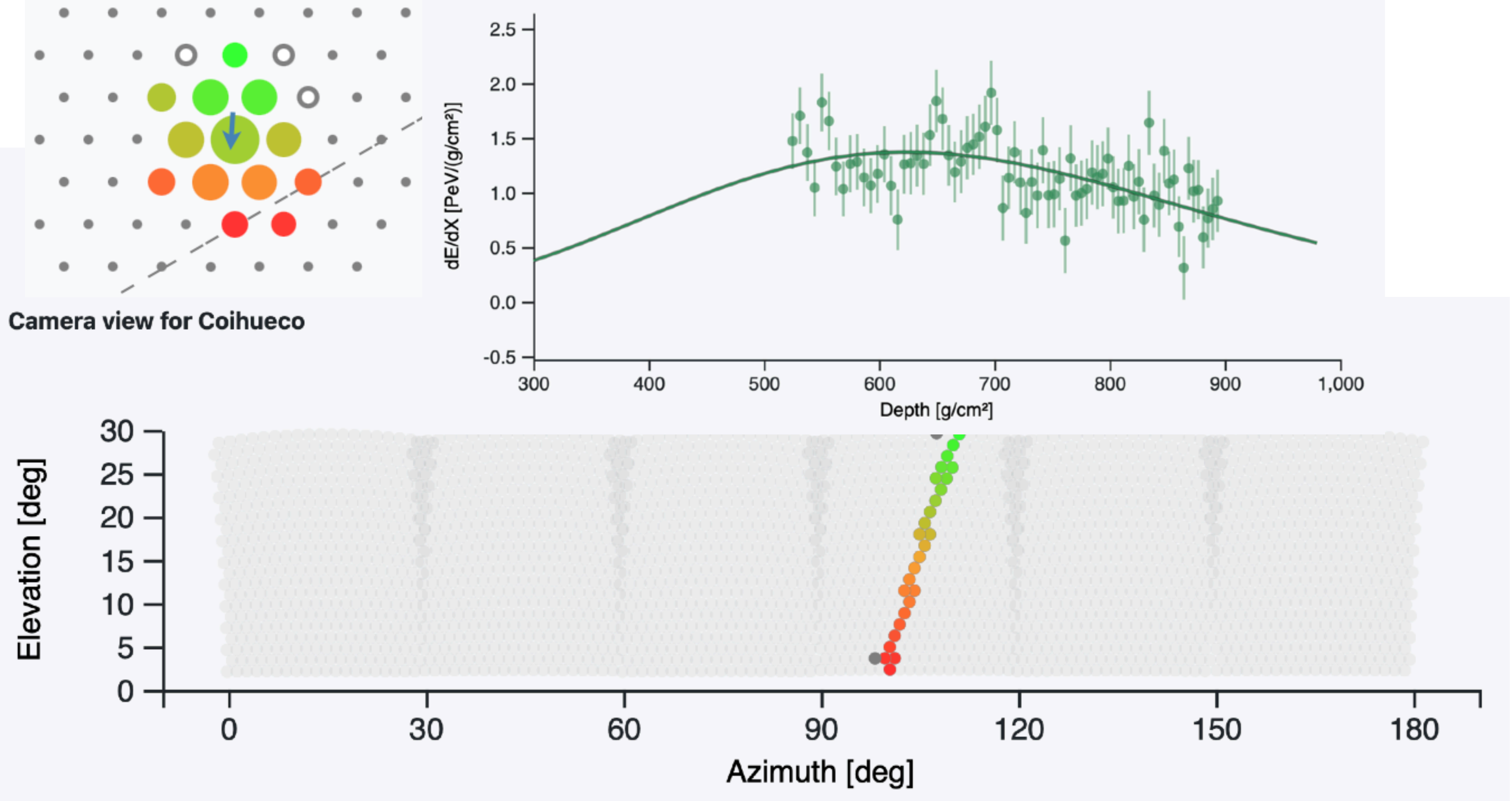
Large impact in field: new generation of skilled scientists

An invitation: Auger Open Data

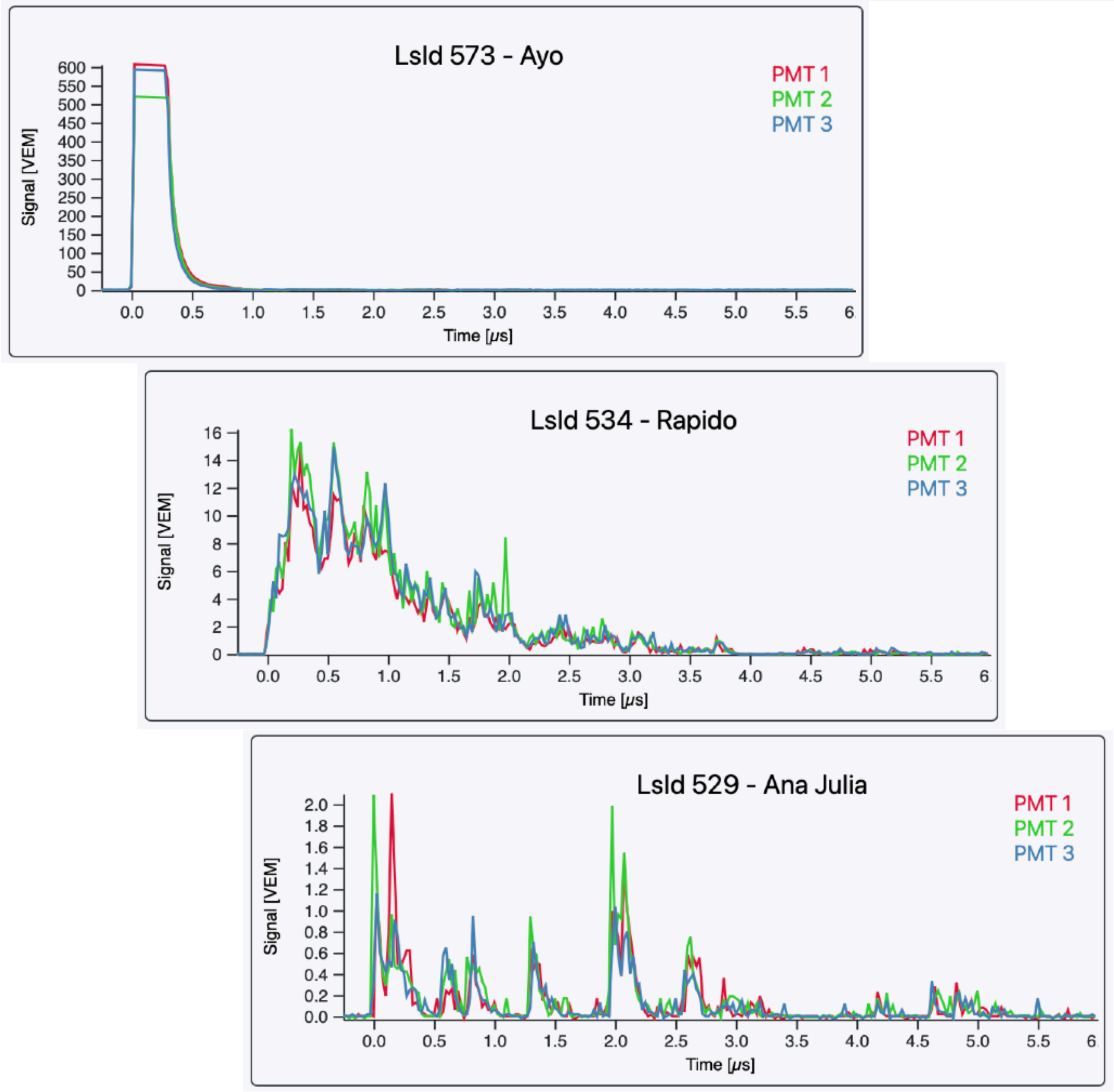
opendata.auger.org

DOI:10.5281/zenodo.4487613





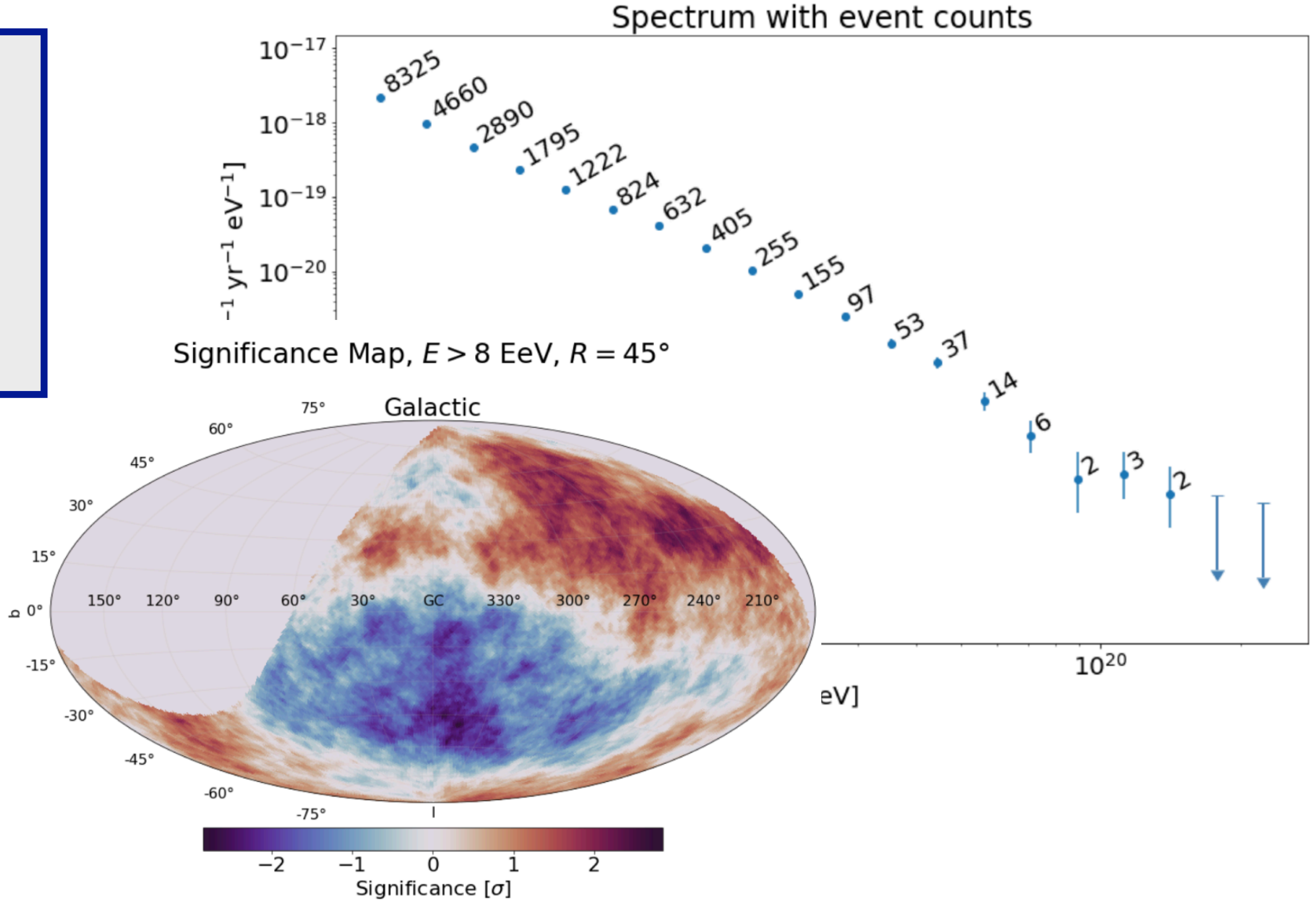

```
In [19]:
Y_0val = FC_CL * 0.9

plt.title("Spectrum with event counts")
plt.errorbar(bin_energy18[cut_nz], flux, [flux_lower, flux_upper], fmt="o")
plt.errorbar(bin_energy18[cut_z], FC_CL, Y_0val, uplims=True, marker="None", color="steelblue",
             markeredgecolor="r", markerfacecolor="r", linewidth=2.0, linestyle="None", capsize
=5)
plt.xscale("log")
plt.yscale("log")
plt.xlabel('E [eV]')
plt.ylabel(r'J$^{Raw}$(E) [km$^{-2}$ sr$^{-1}$ yr$^{-1}$ eV$^{-1}$]')

# expand the range in y to have space for the labels and upper limits
plt.ylim(flux[flux > 0].min()*0.01, flux.max()*7)

# add the counts to the points
for E, J, count in zip(bin_energy18, flux, h):
    if count > 0:
        plt.annotate(count, (E, J), rotation=30, va='bottom')
```



Currently 10% of Auger vertical data
Research-level data in JSON format
Online visualization of events
Data analysis scripts for science plots

You are welcome to use this data

If you have a great idea what to look for we can work with you to apply your analysis also to the full data set

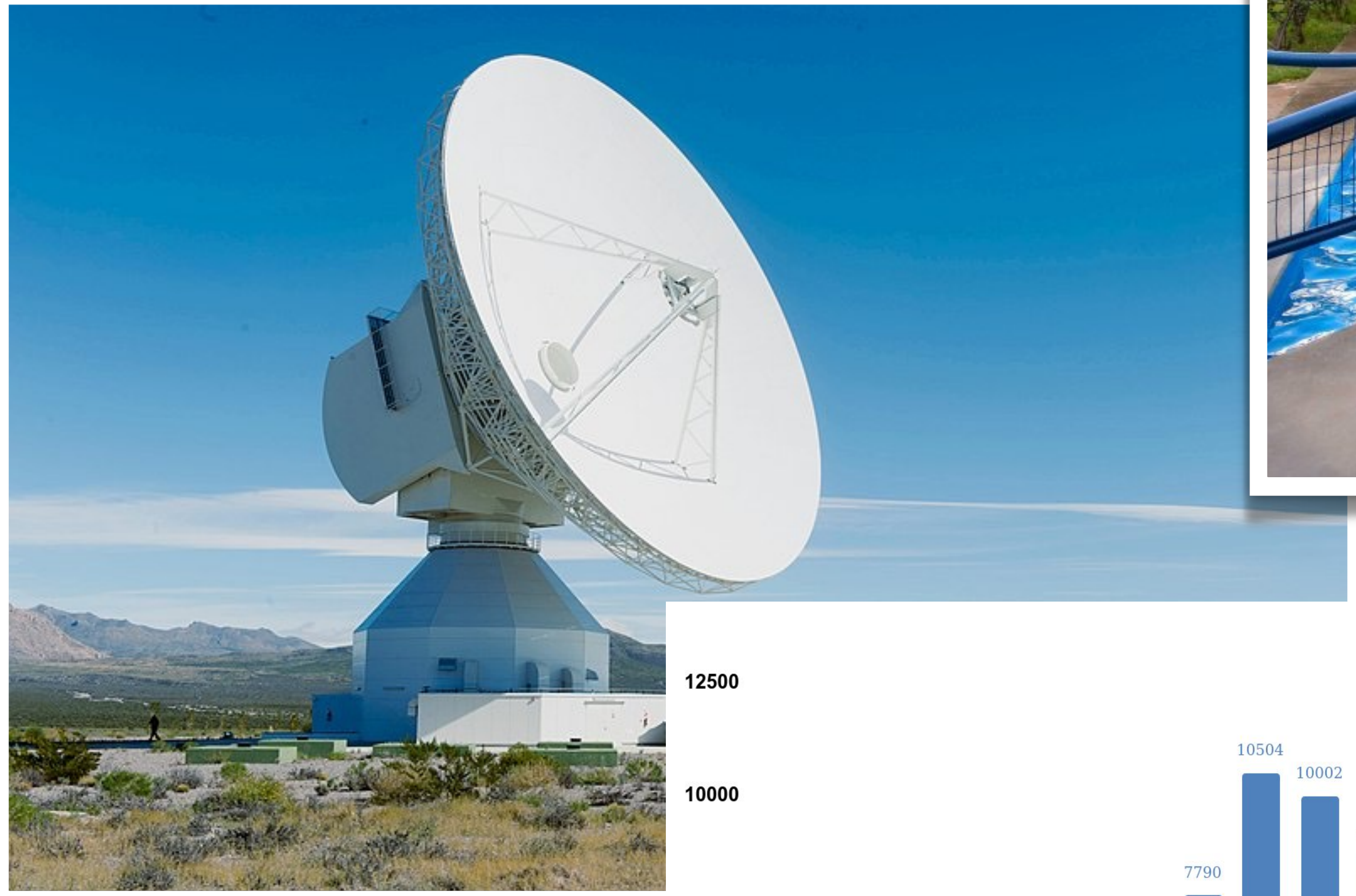


Impact in local area (Malargue) and Argentina

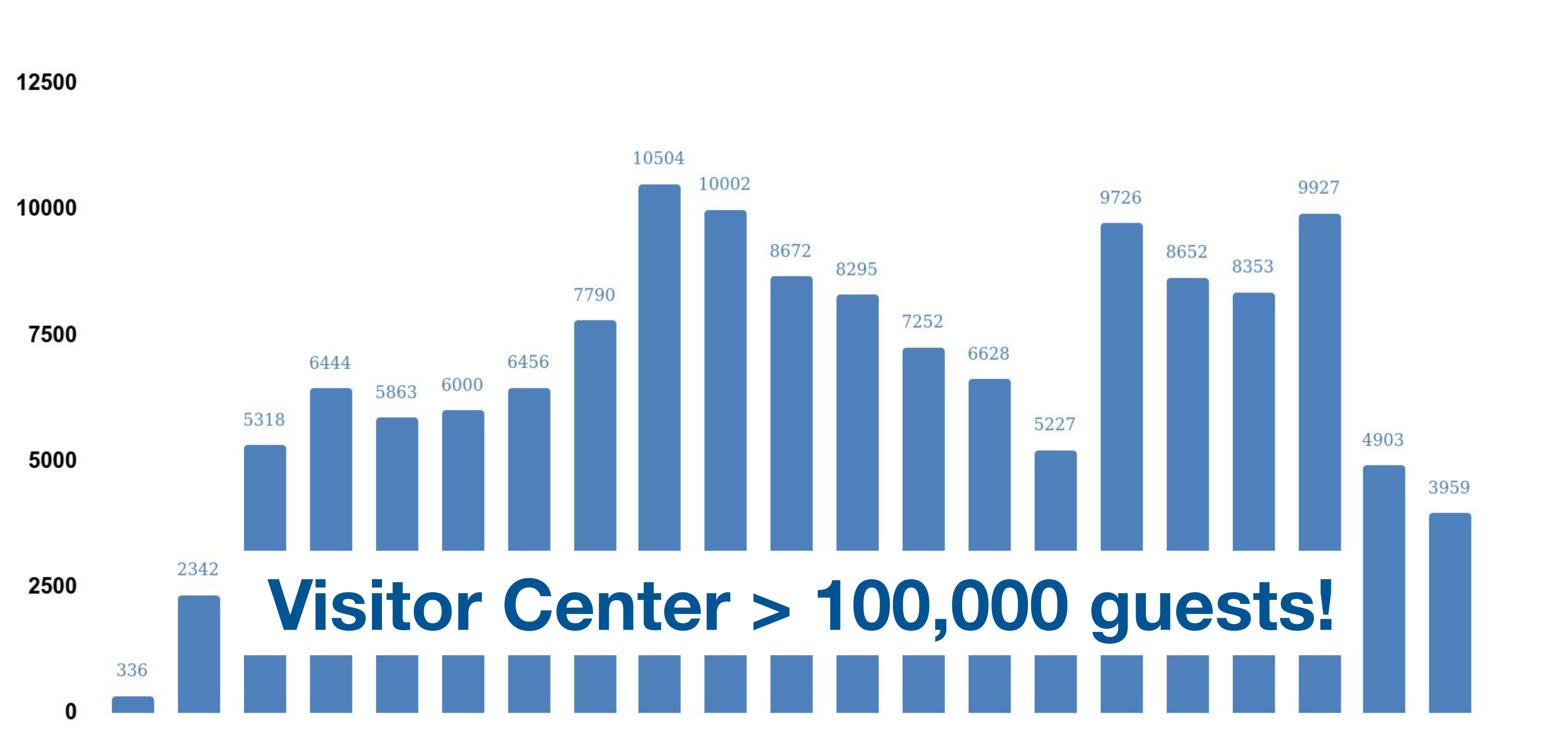
Planetarium

Jim Cronin School

Science Fair



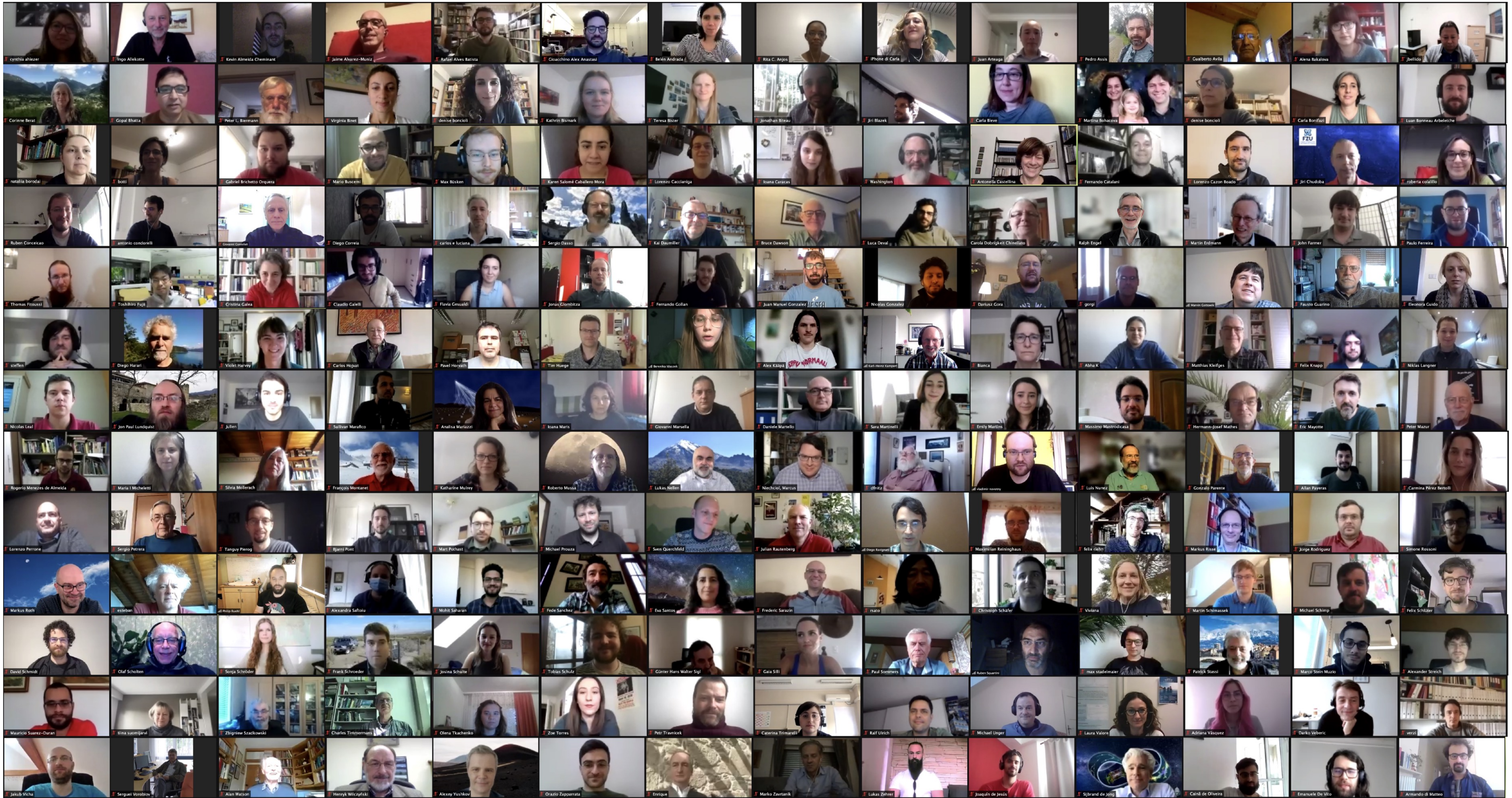
Deep Space 3



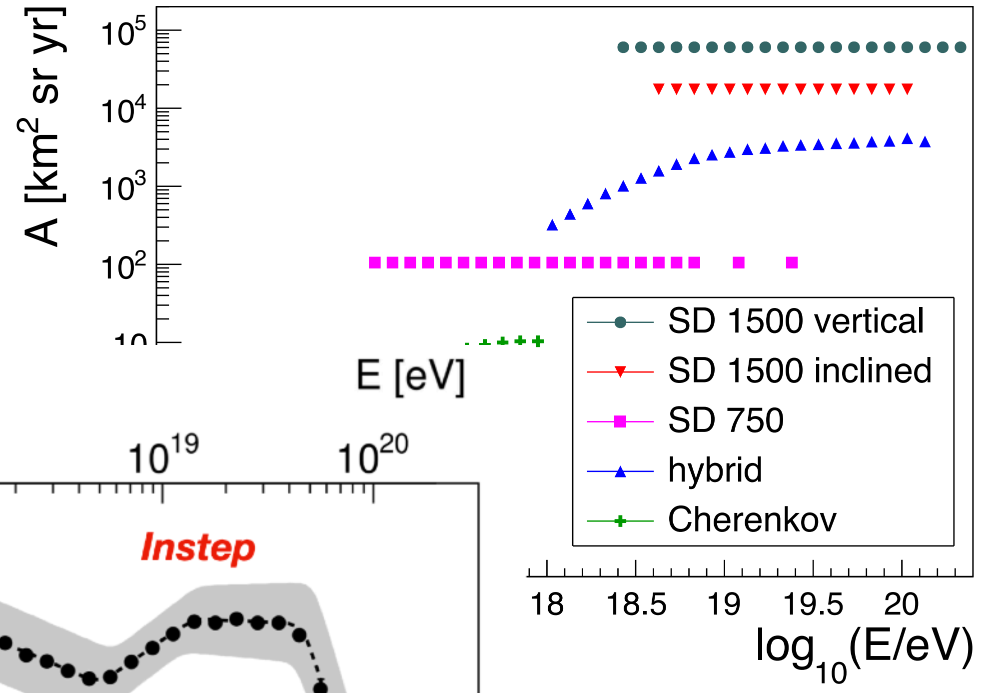
Honorable Senatorship

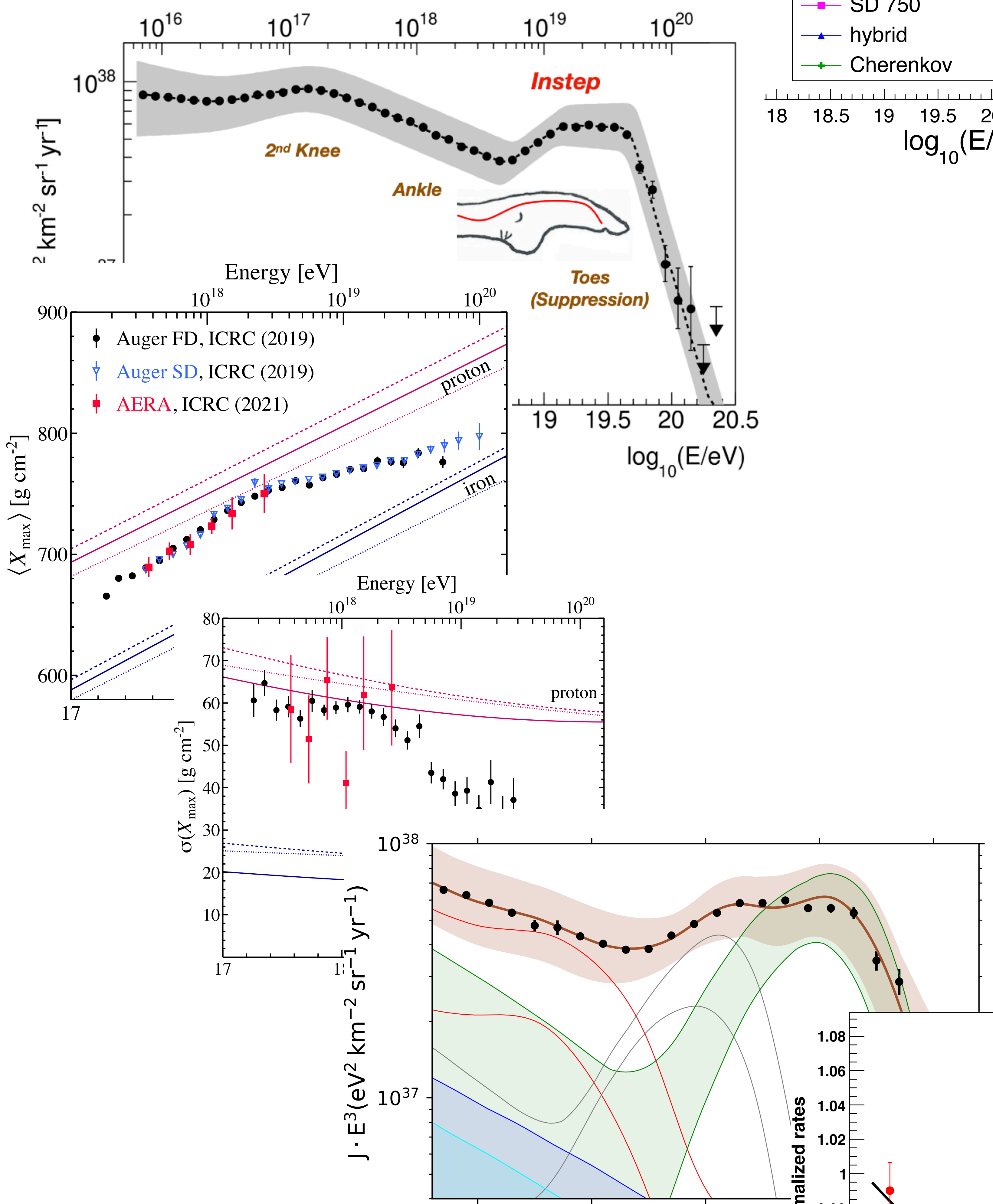
Backup slides

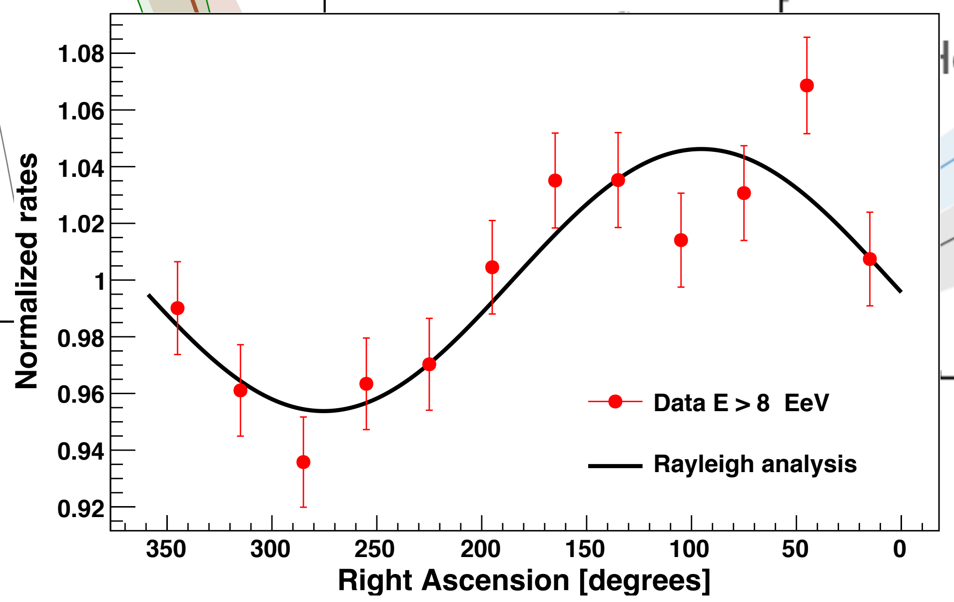
The Pierre Auger Collaboration in March 2021

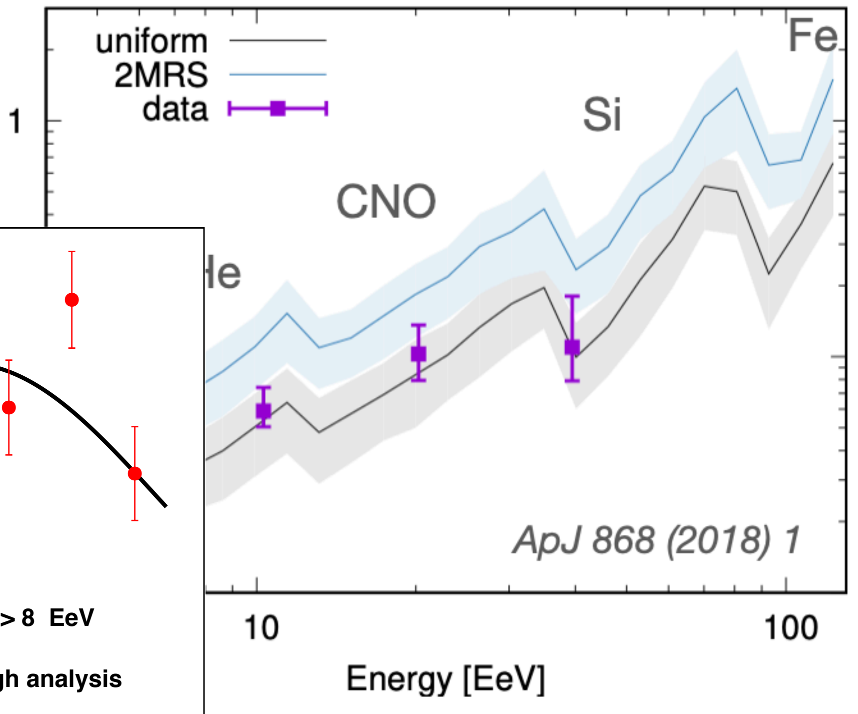


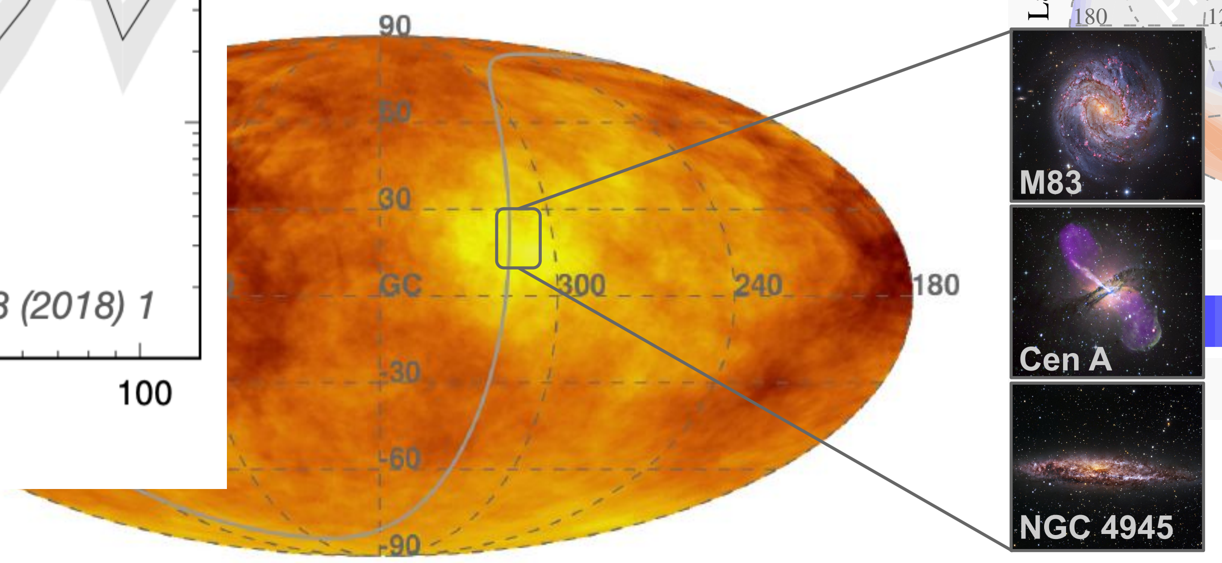
Physics summary

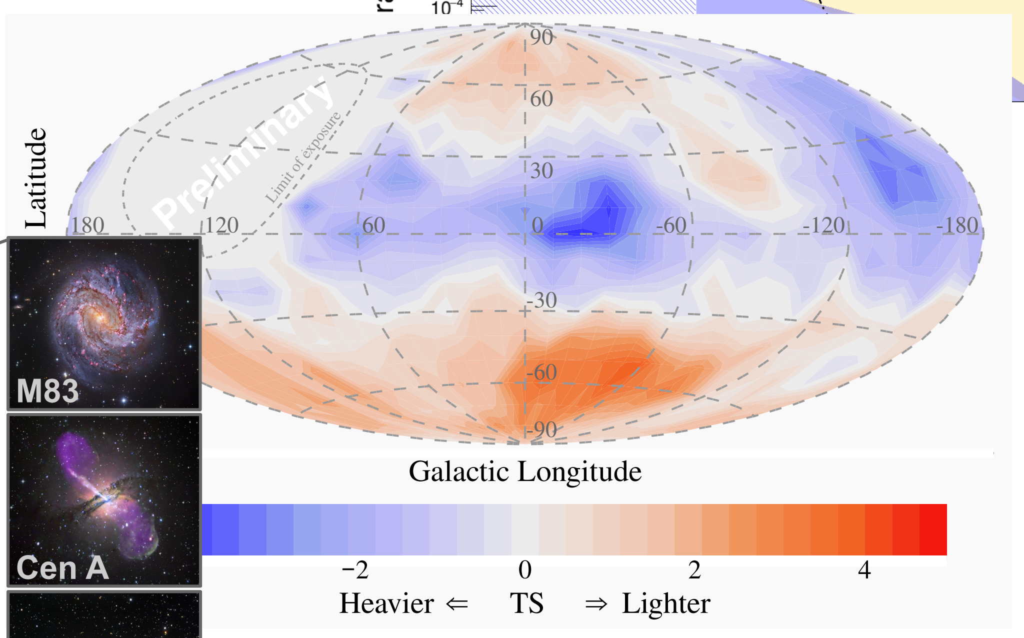










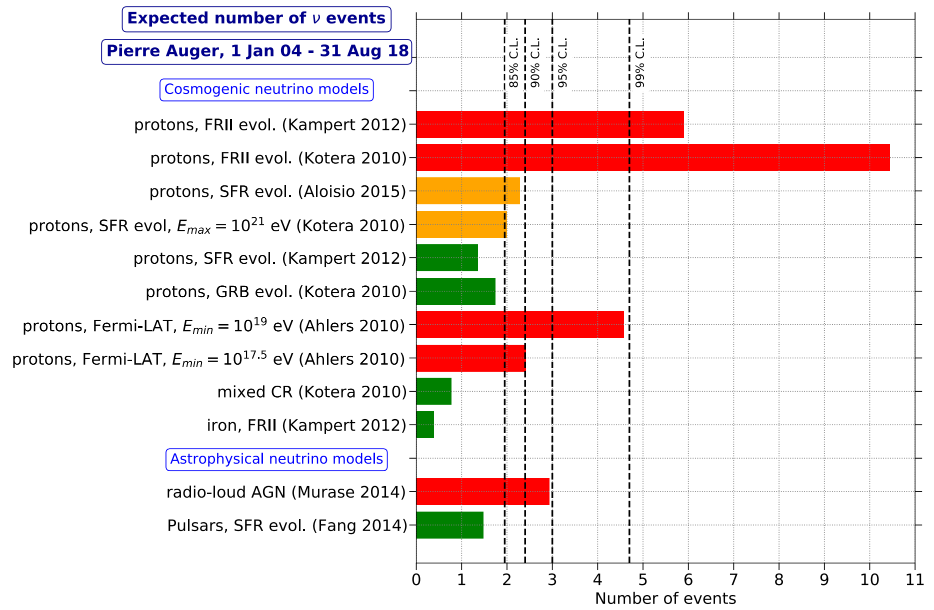


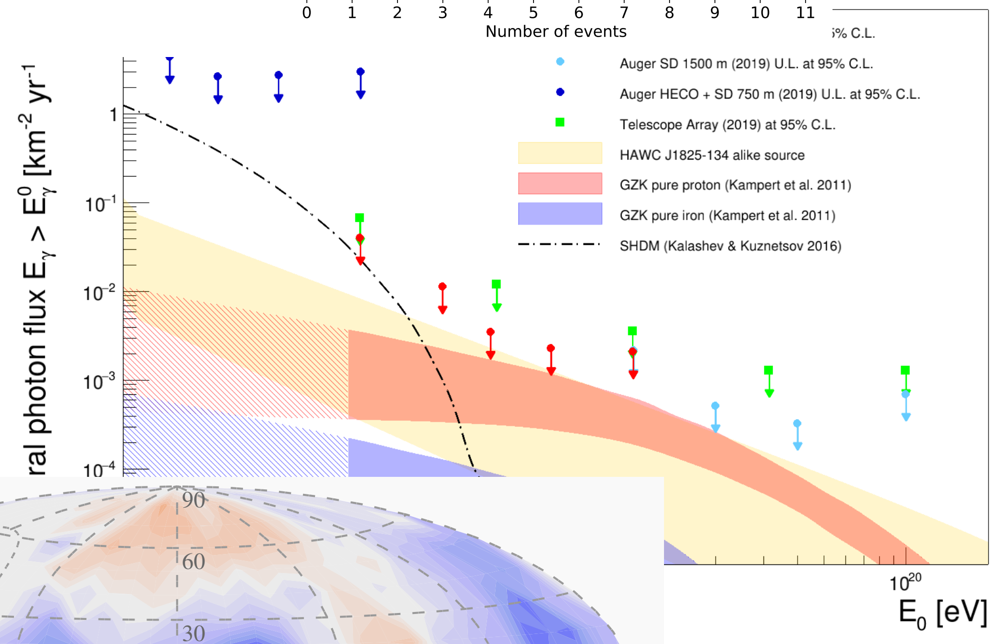
Phase I:

- Exposure 80,000 km² sr yr (vertical, highest quality), up to 120,000 km² sr yr (loose cuts, combined)
- Change of composition established
- Composition tightly linked to hadronic interactions
- Anisotropy observations very promising
- **Increasingly consistent picture is emerging**

Phase II:

- Upgrade AugerPrime in progress
- Additional exposure 40,000 km² sr yr (vertical) expected
- Enhanced composition and hybrid information
- Re-analysis of all data planned





AUGER Organization

(updated 2021-11-30)

PIERRE AUGER OBSERVATORY

Project Oversight

Finance Board
President: S. Bentvelsen (NL)

Collaboration Board
Chair: L. Perrone (Italy)
Co-Chair: F. Sánchez (Argentina)

Project Management

Spokesperson
R. Engel (Germany)

Co-Spokesperson
A. Castellina (Italy)

Spokespersons Emeritus
A. Watson (UK)
J. Cronin (USA, deceased 2016)

Auger South Site Spokesperson
A. Etchegoyen (Argentina)

Technical Board
Chair:
M. Kleifges (Germany)

Project Manager
I. Allekotte (Argentina)
Deputy
P. Stassi (France)

Project Office
Administrative Support, Cost and Schedule Officer, Technical Engineer & Health, Safety and Environment, Webmaster
(KIT, Germany)

Site Administrative Organization (AHUEKNA)
R. Denza (Argentina)

Observatory Site Manager
G. Ávila (Argentina)
Observatory Staff

Data Release
V. Scherini
M. Buscemi

AMIGA
F. Sánchez
M. Platino

Fluores. Det. & HEAT
H.-J. Mathes
M. Boháčová

Central Data Acquisition
D. Schmidt

Fluorescence Detector Electronics
M. Kleifges

Data Processing and Analysis
L. Nellen
F. Schlüter

Surface Detectors
P. Mazur
F. Sarazin

Surface Detector Electronics
T. Suomijärvi
D. Nitz

Monitoring
J. Rautenberg
G. Anastasi

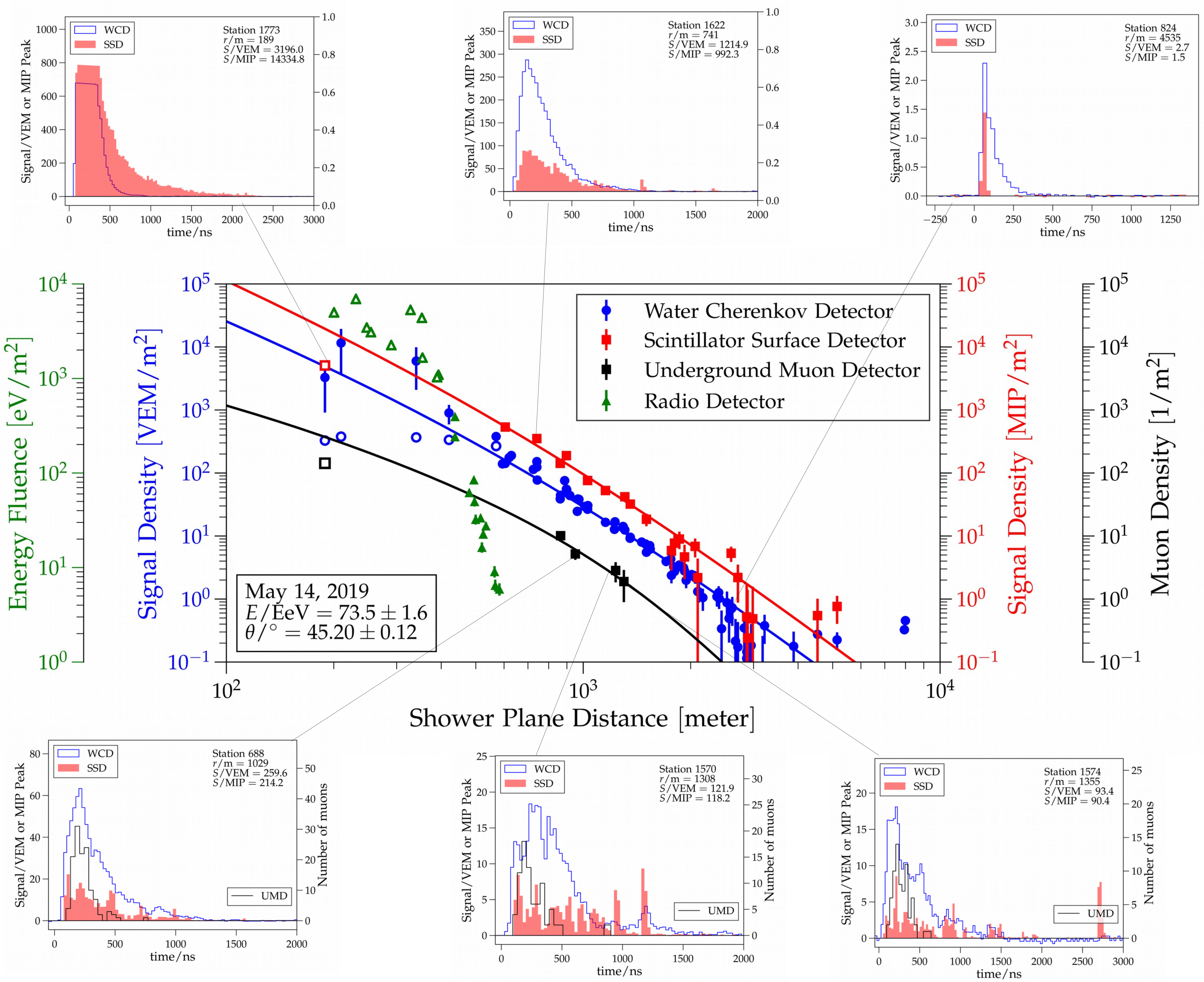
Education - Outreach
B. García
K. Caballero Mora

Communications
C. Covault
D. Nitz

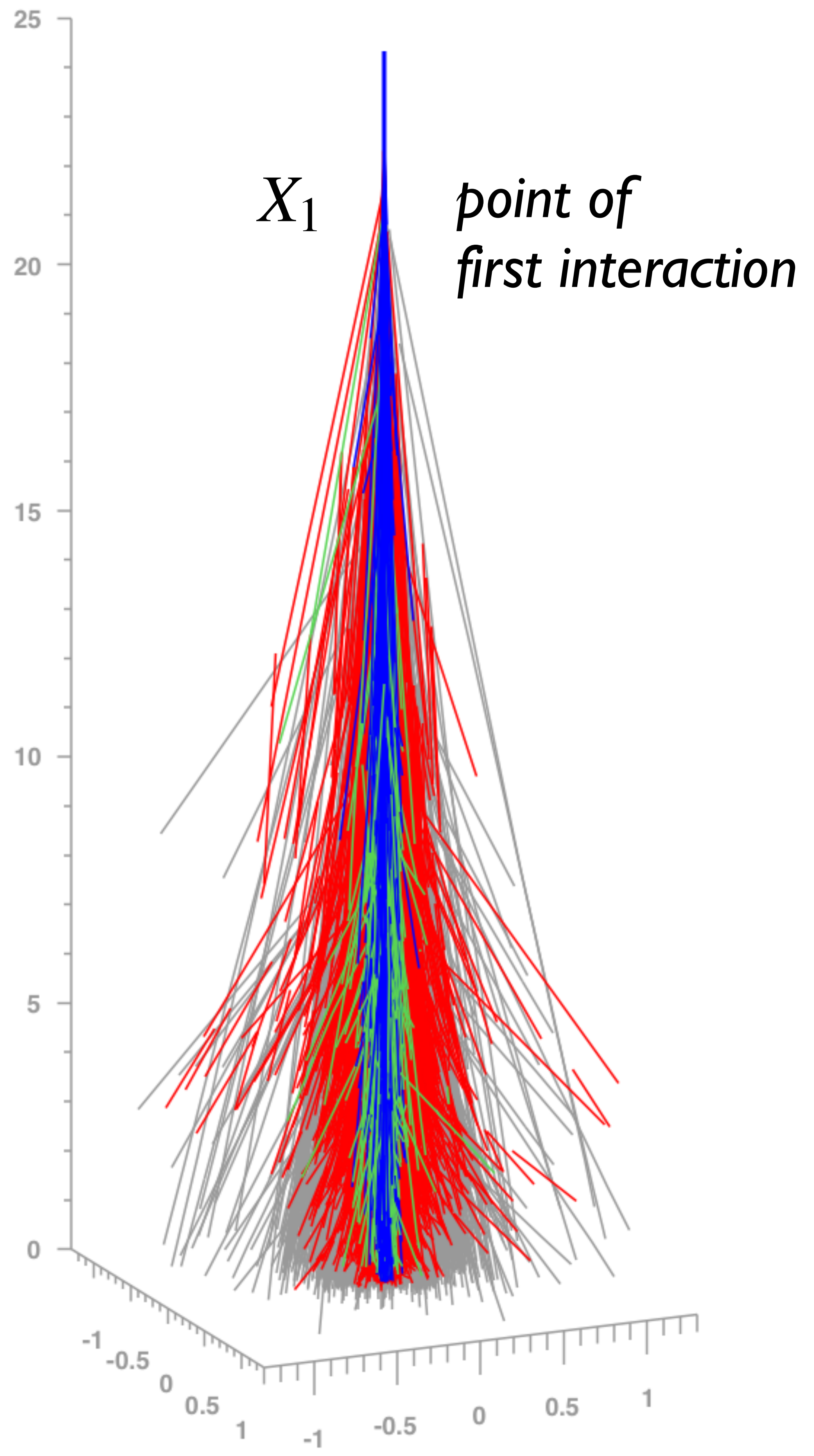
SSD
D. Martello
H. Wilczyński

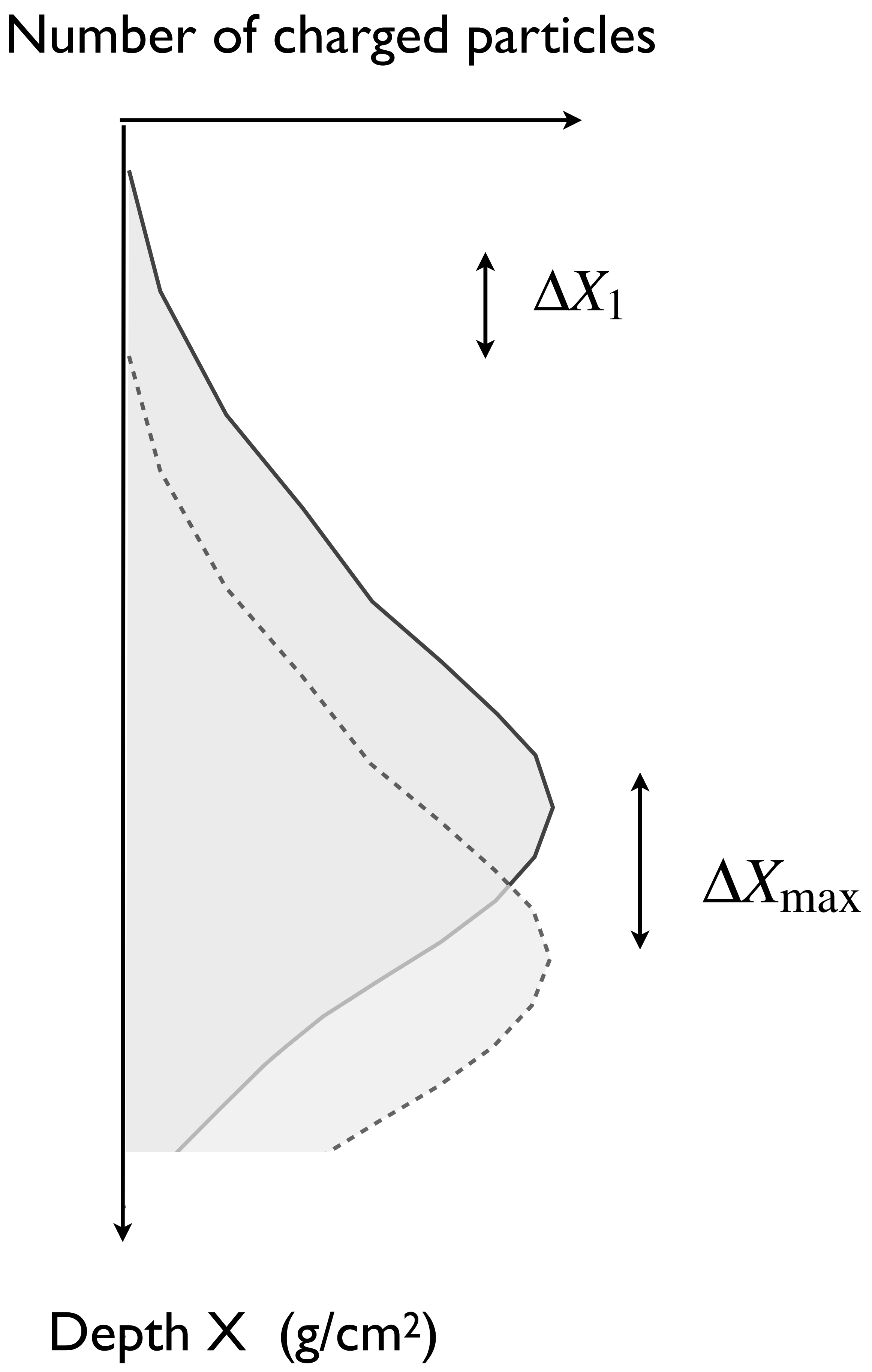
AERA
J. Hörandel
T. Huege

AugerPrime: New quality of data – multi-hybrid measurements



Measurement of proton-air cross section



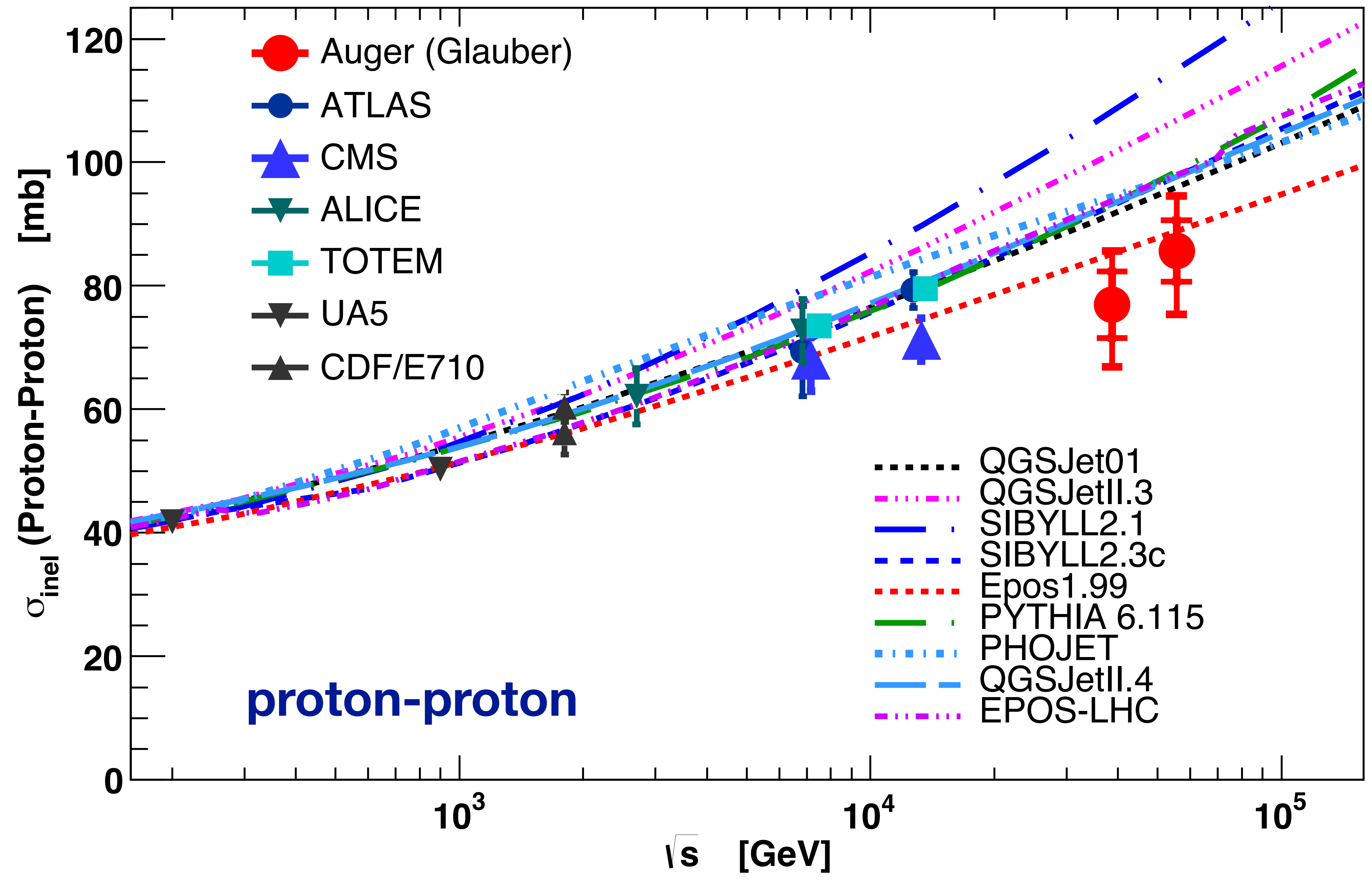


$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\sigma_{p-air} = \frac{\langle m_{air} \rangle}{\lambda_{int}}$$

Difficulties

- mass composition
- fluctuations in shower development (model needed for correction)



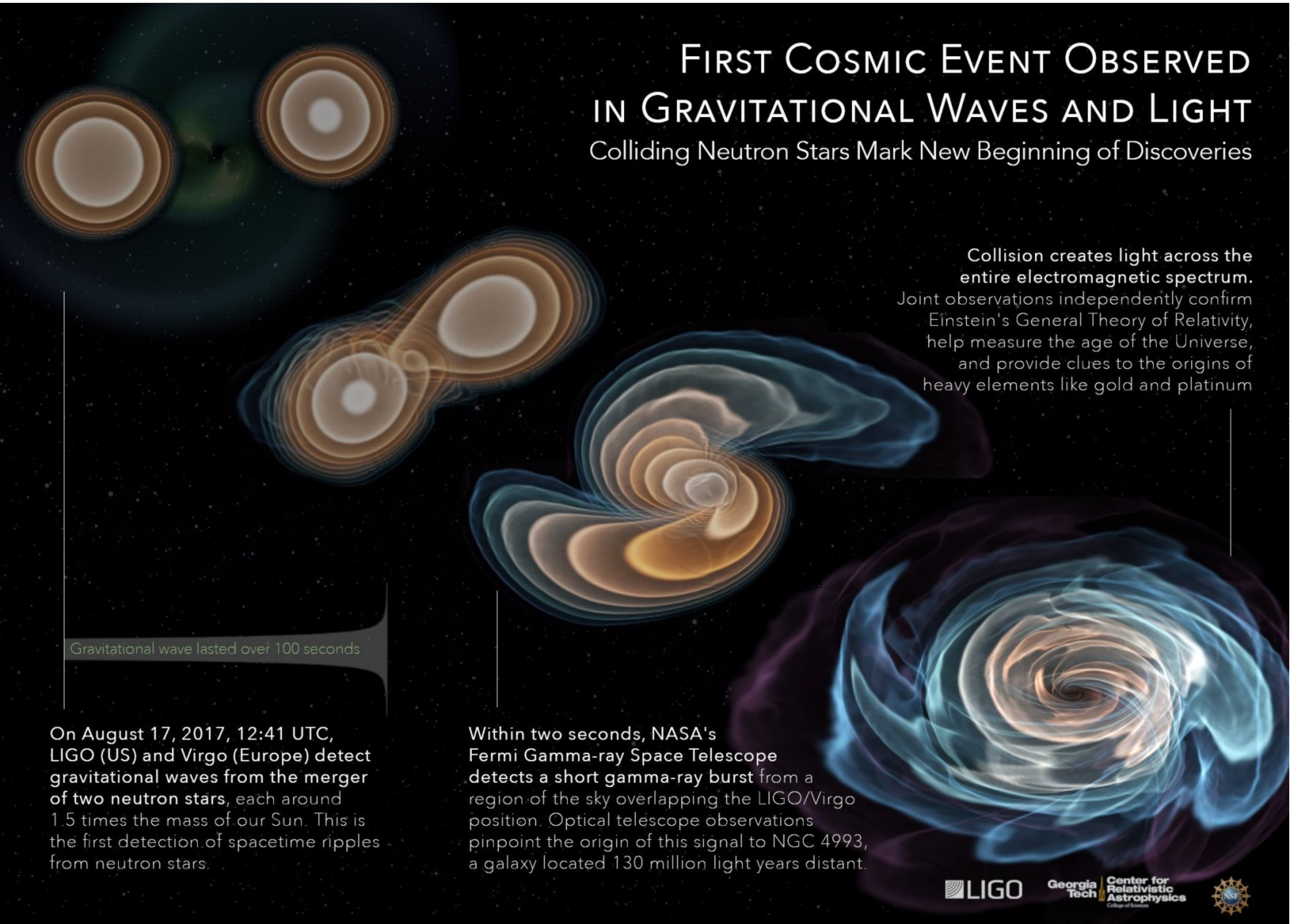
(Auger PRL 109, 2012; Telescope Array PRD 92, 2015)

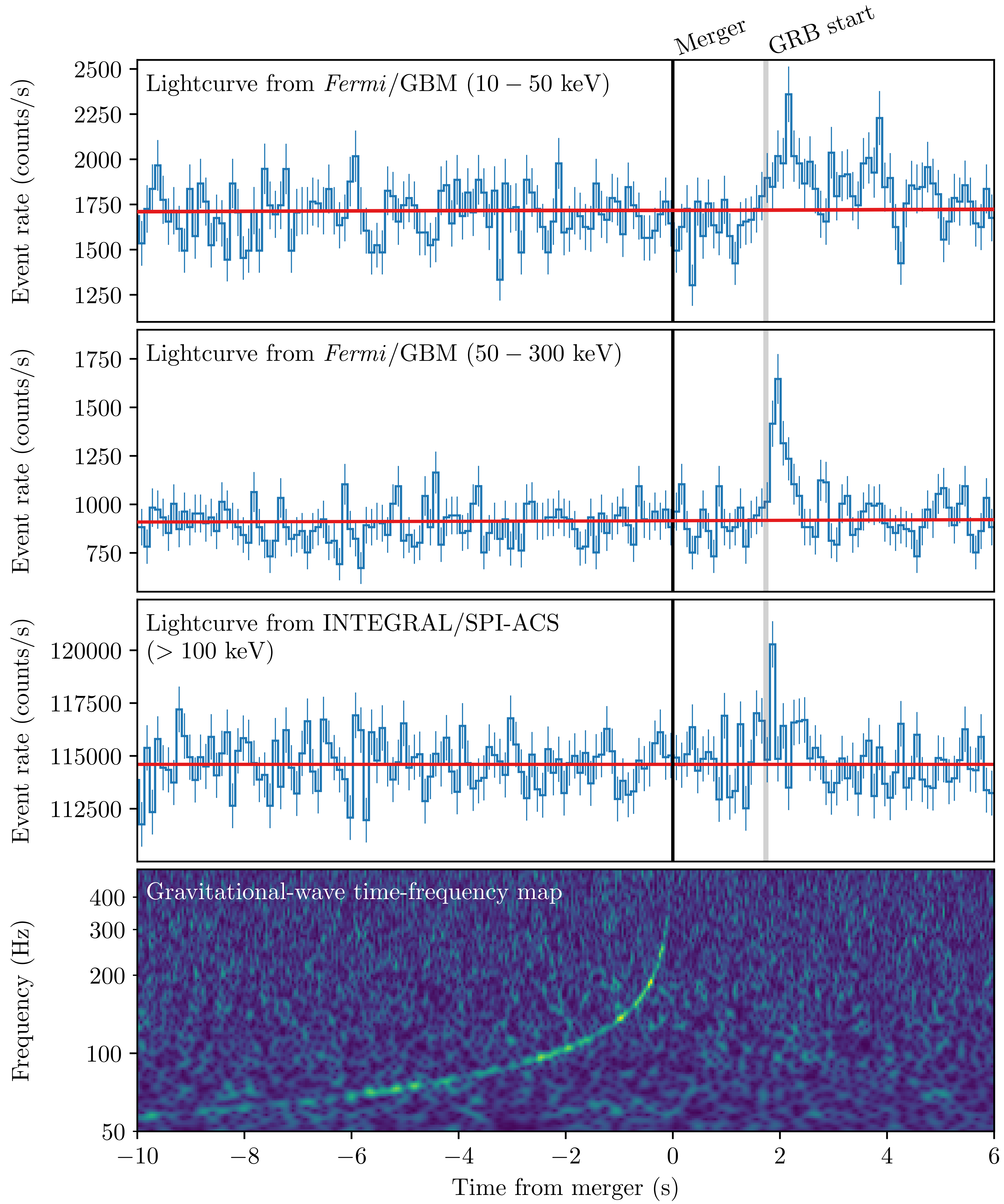
Multi-messenger astrophysics with gravitational waves

Publication 16 Oct 2017 in ApJL

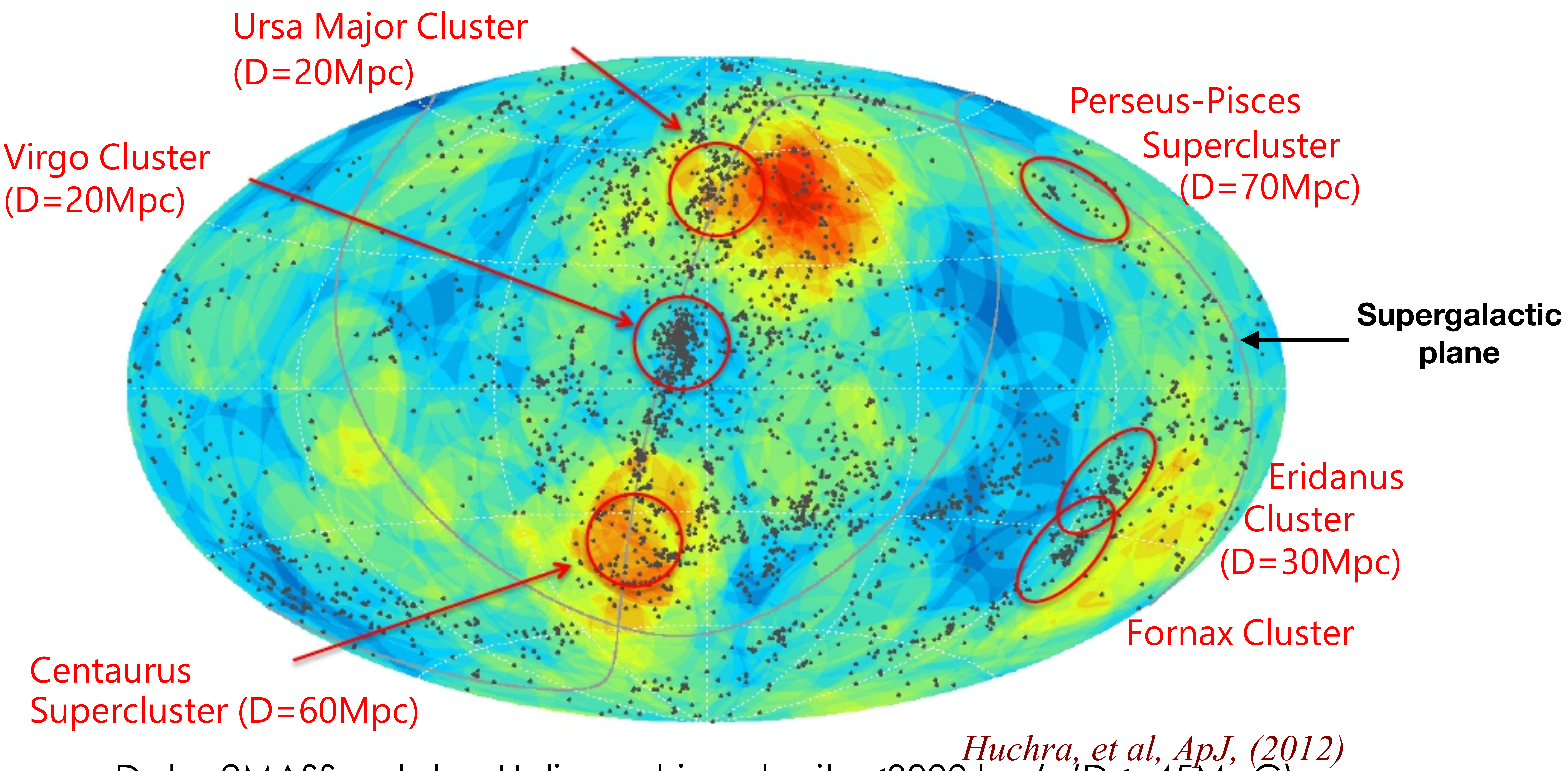
70 collaborations, 953 Institutes, 3500+ Autoren

Auger: limits on neutrinos (and photons)





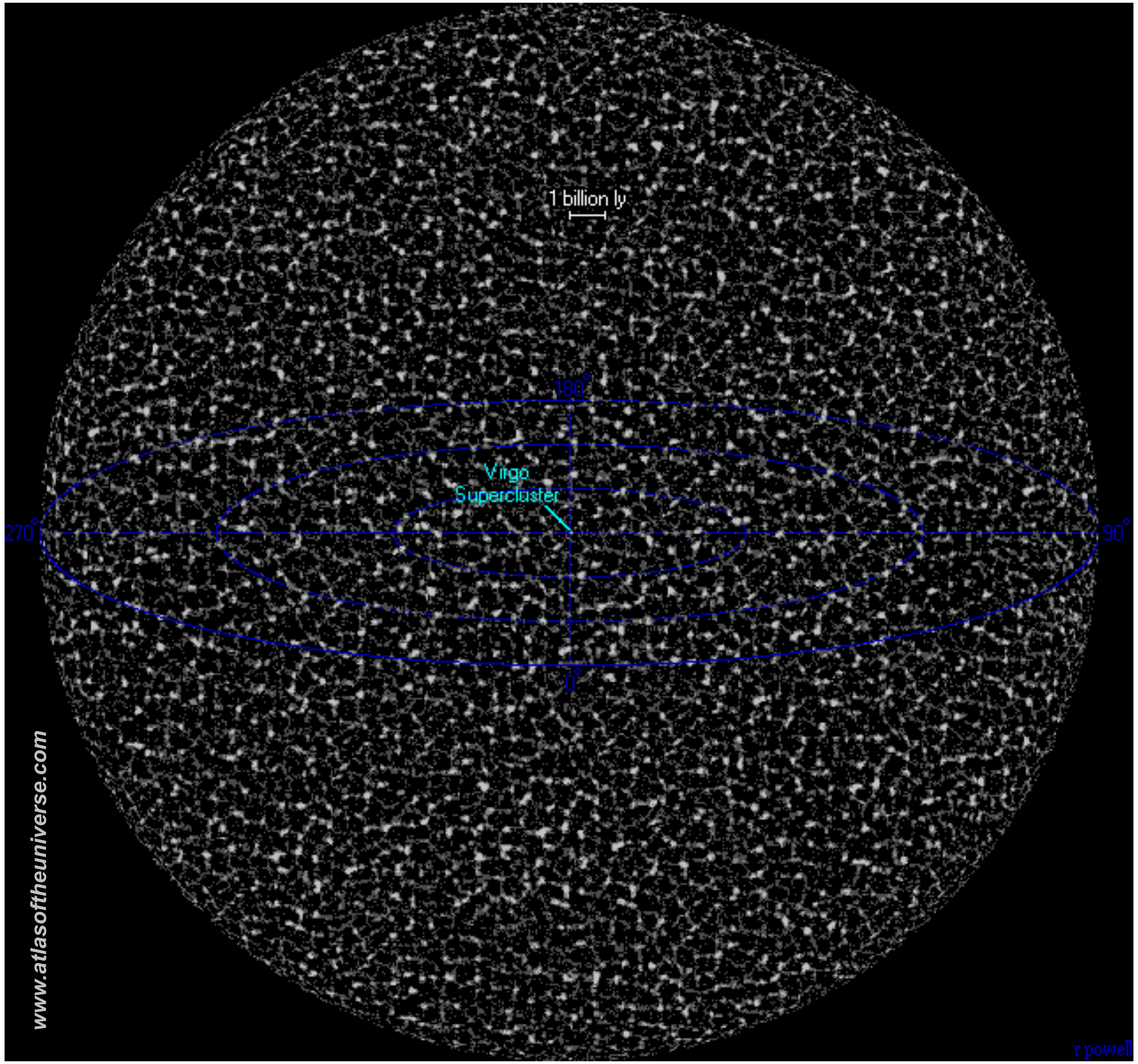
Arrival direction distribution (E > 6 x 10^{19} eV)



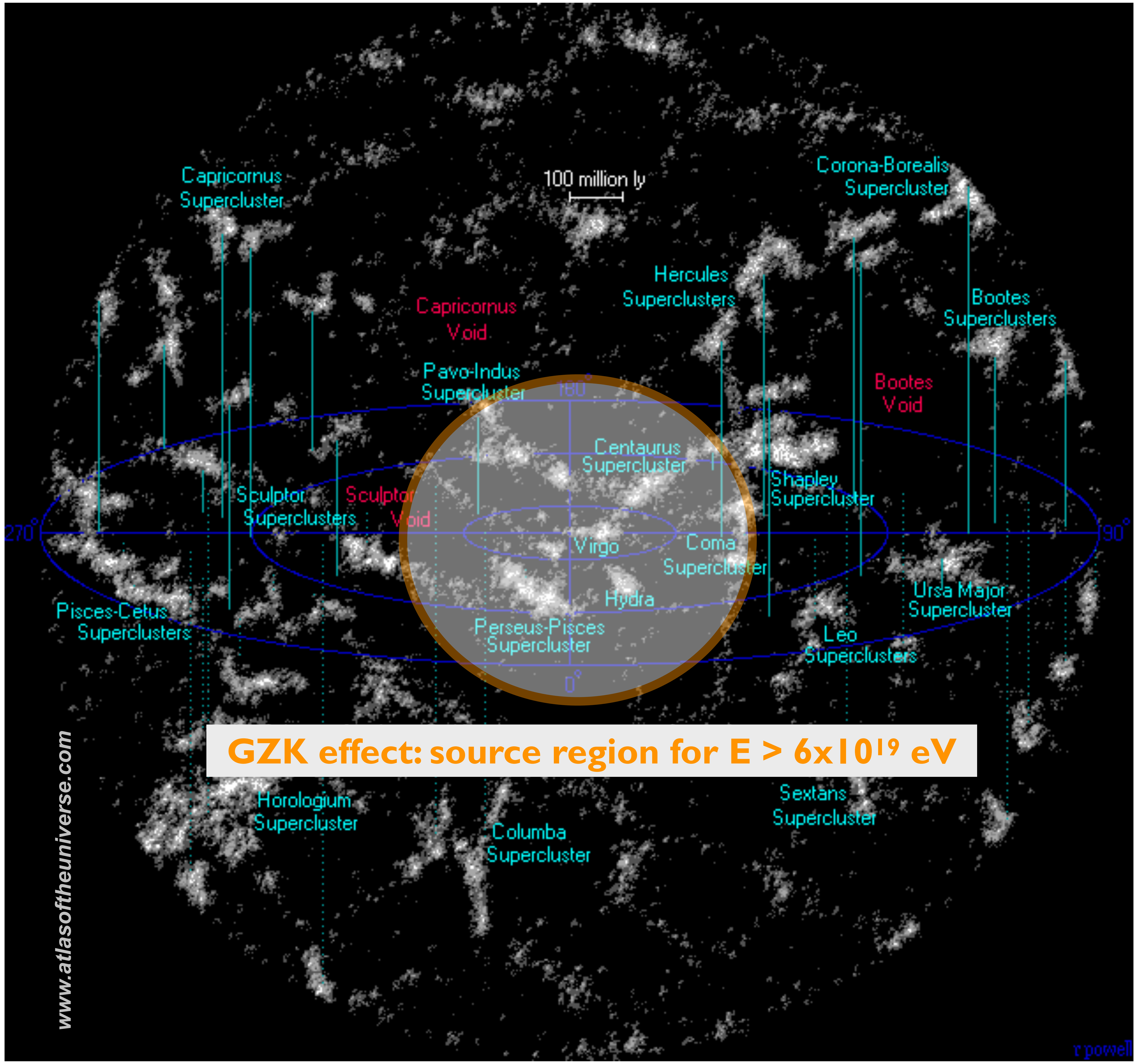
Dots : 2MASS catalog Heliocentric velocity <3000 km/s (D<~45MpC)

(Ogio et al. ISVHECRI 2018, world data set of UHECR)

Distance ranges and matter distribution in the Universe

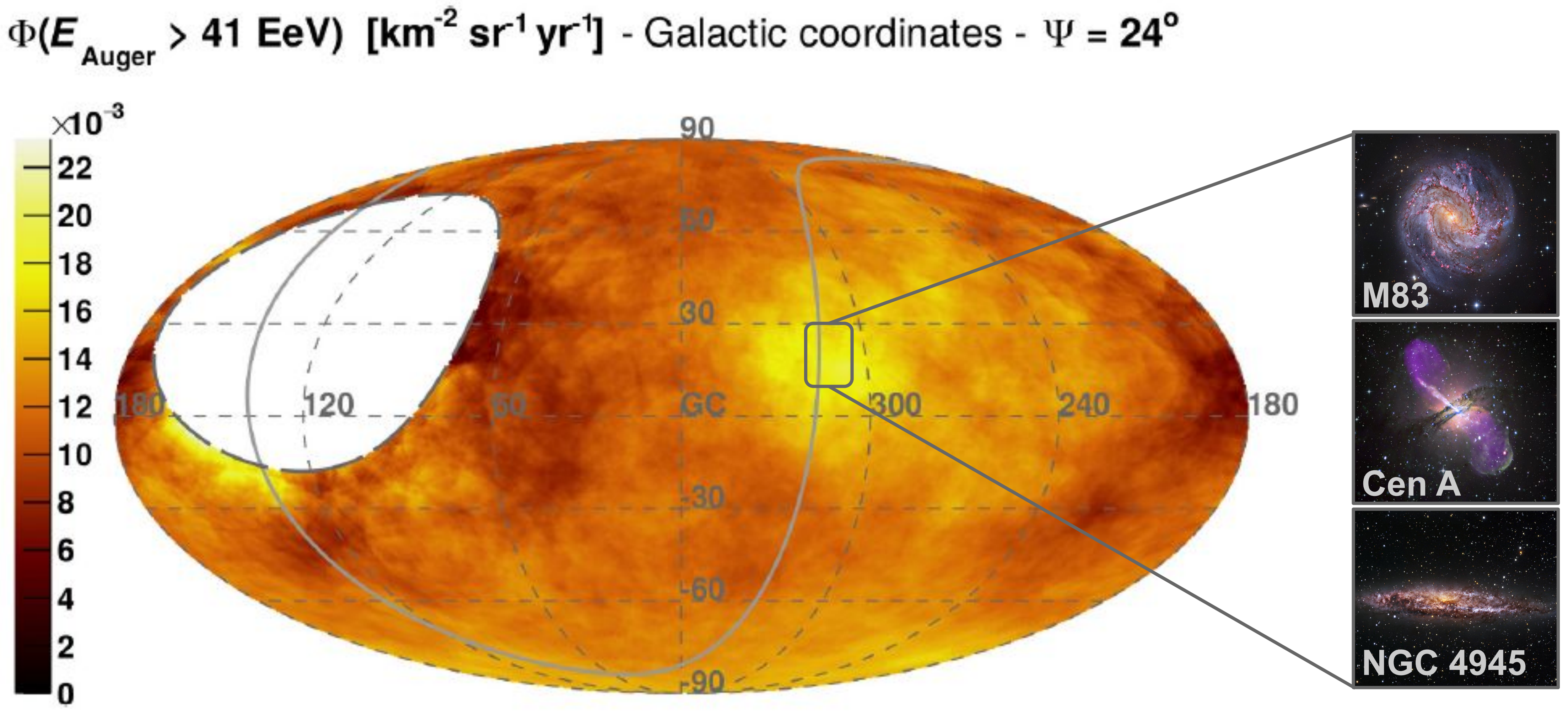


Neutrinos



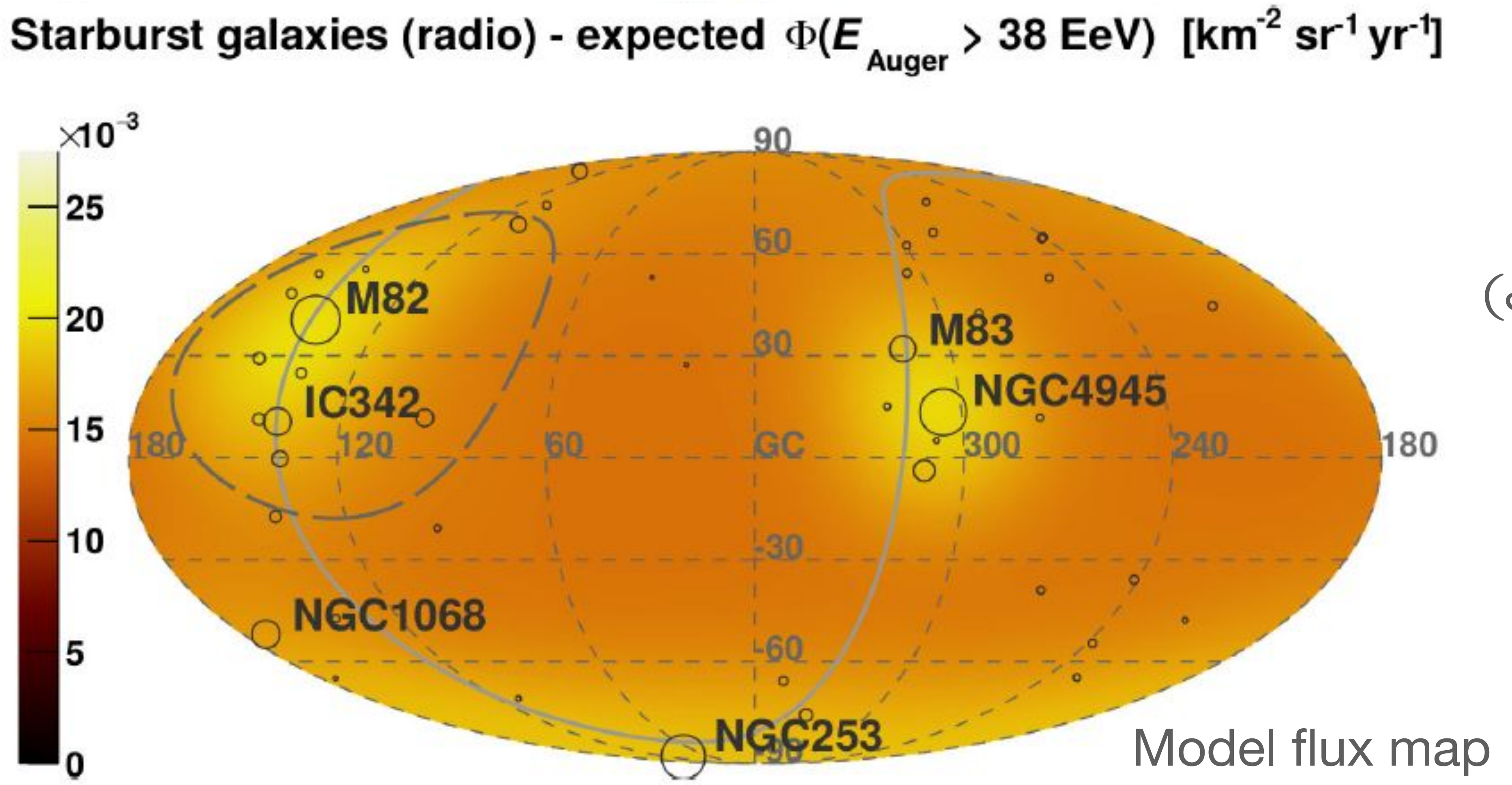
Cosmic rays (gamma-rays)

Anisotropy searches at highest energies – catalogs



Direction fixed to that of Cen A, free E_{th} and Ψ

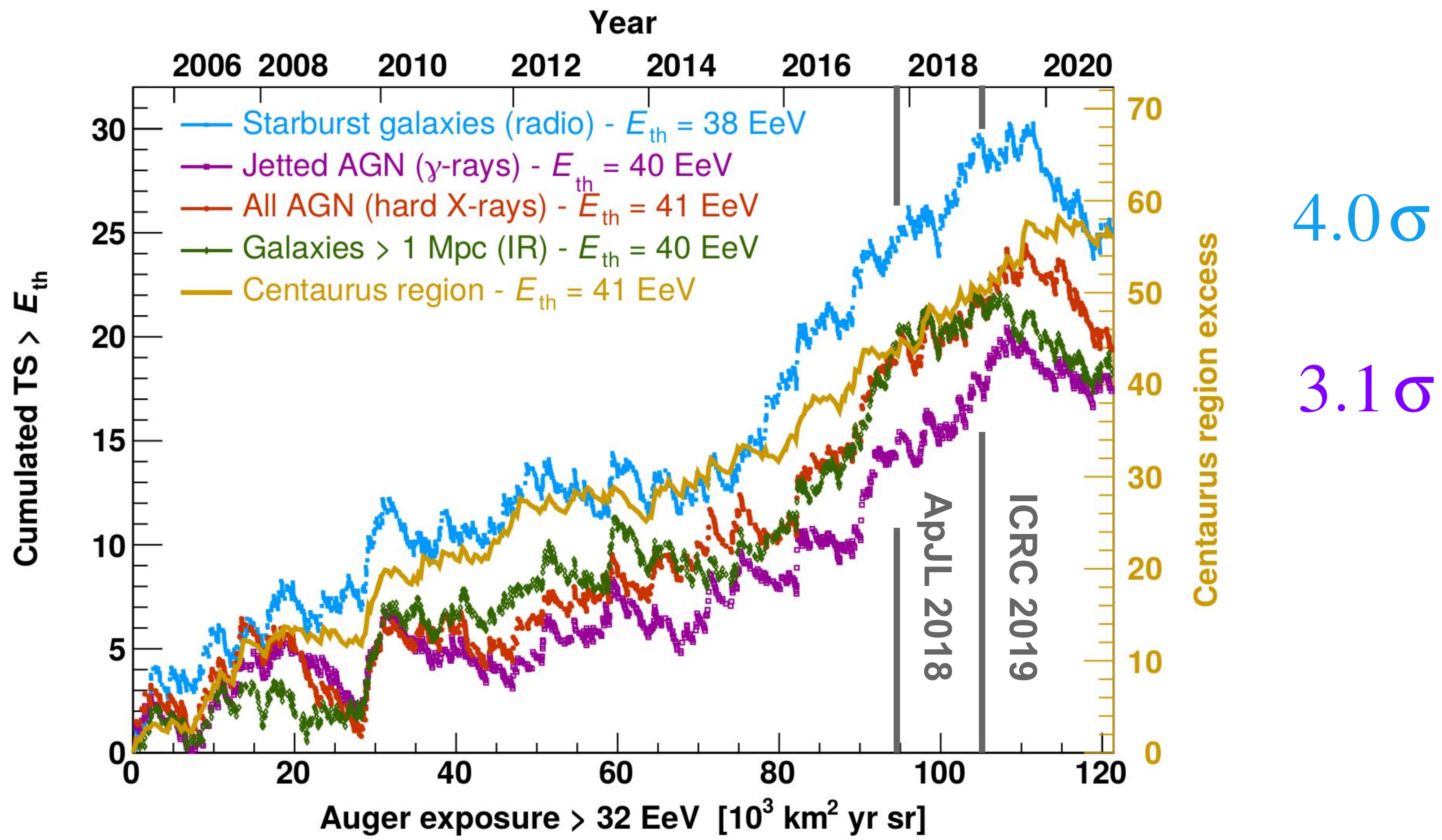
$E_{th} > 41$ EeV, $\Psi = 27°$: **3.9σ post-trial** deviation from isotropy (5% excess)



(Jonathan Biteau)

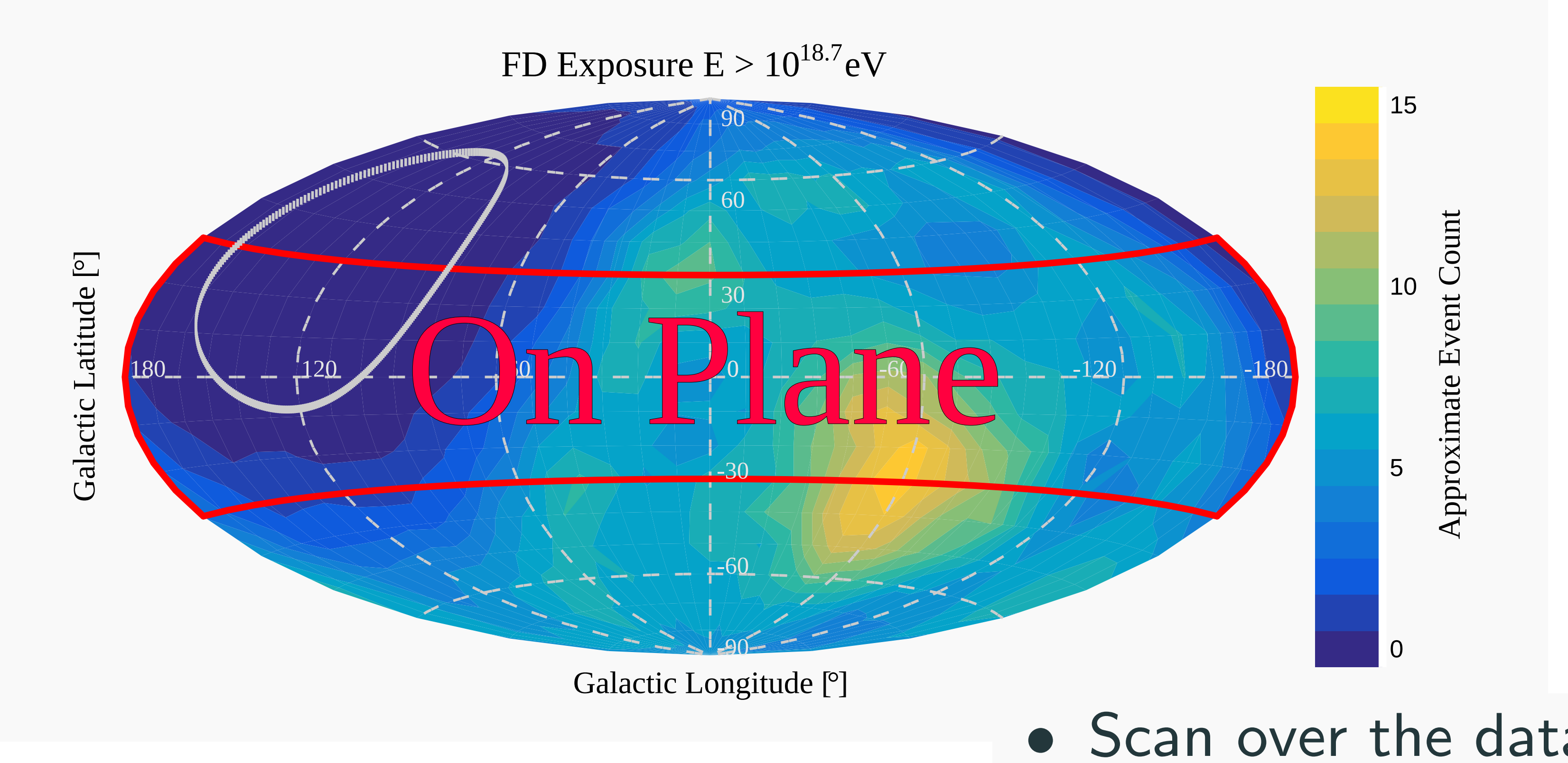
All data until end of 2020, optimized quality cuts: 120,000 km² sr yr

Catalog	E_{th} [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}



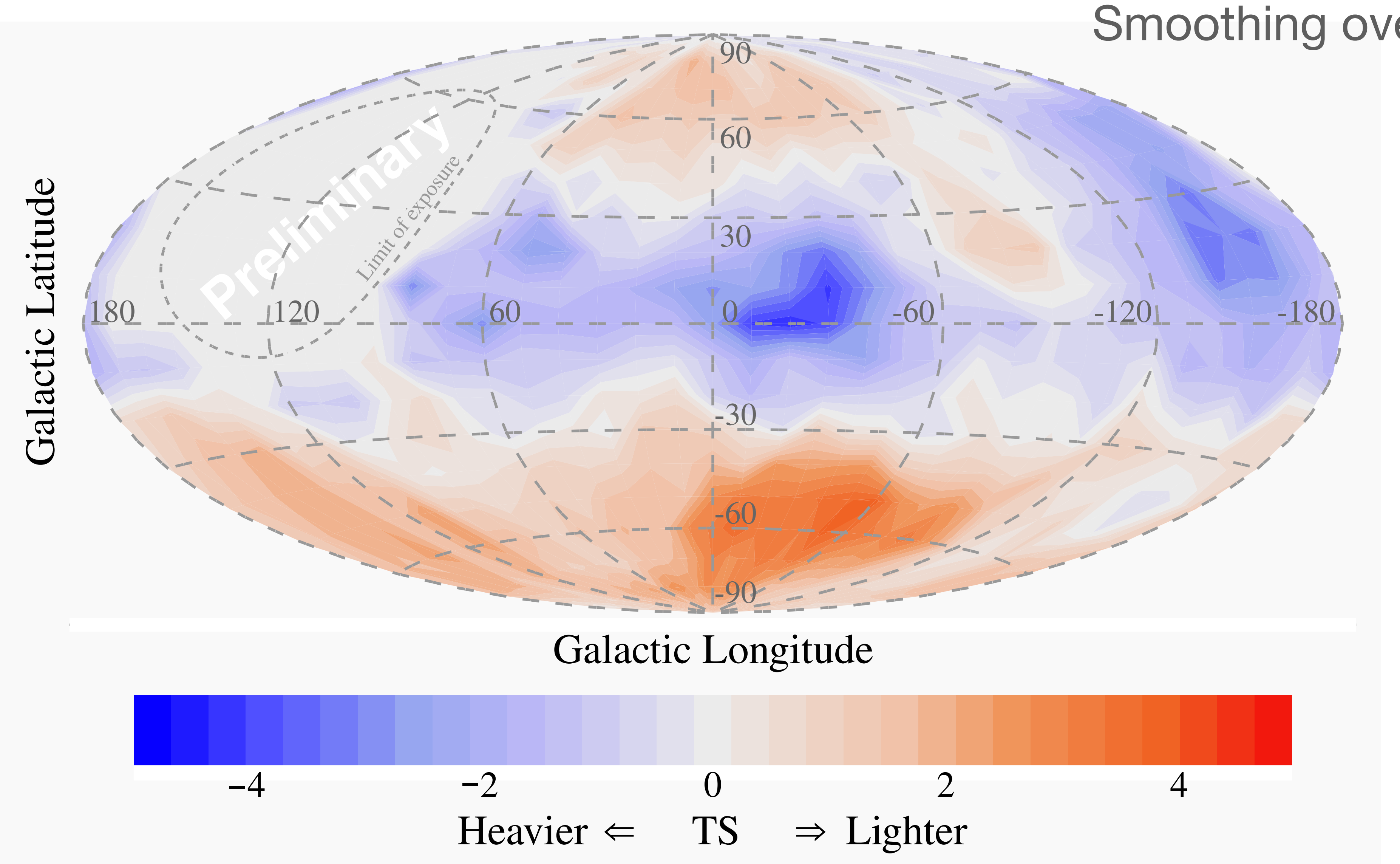
Growth of test statistic (TS) compatible with linear increase
Discovery threshold of 5σ expected in 2025 – 2030 (Phase II)
Other means to increase sensitivity (Auger 85% sky coverage)

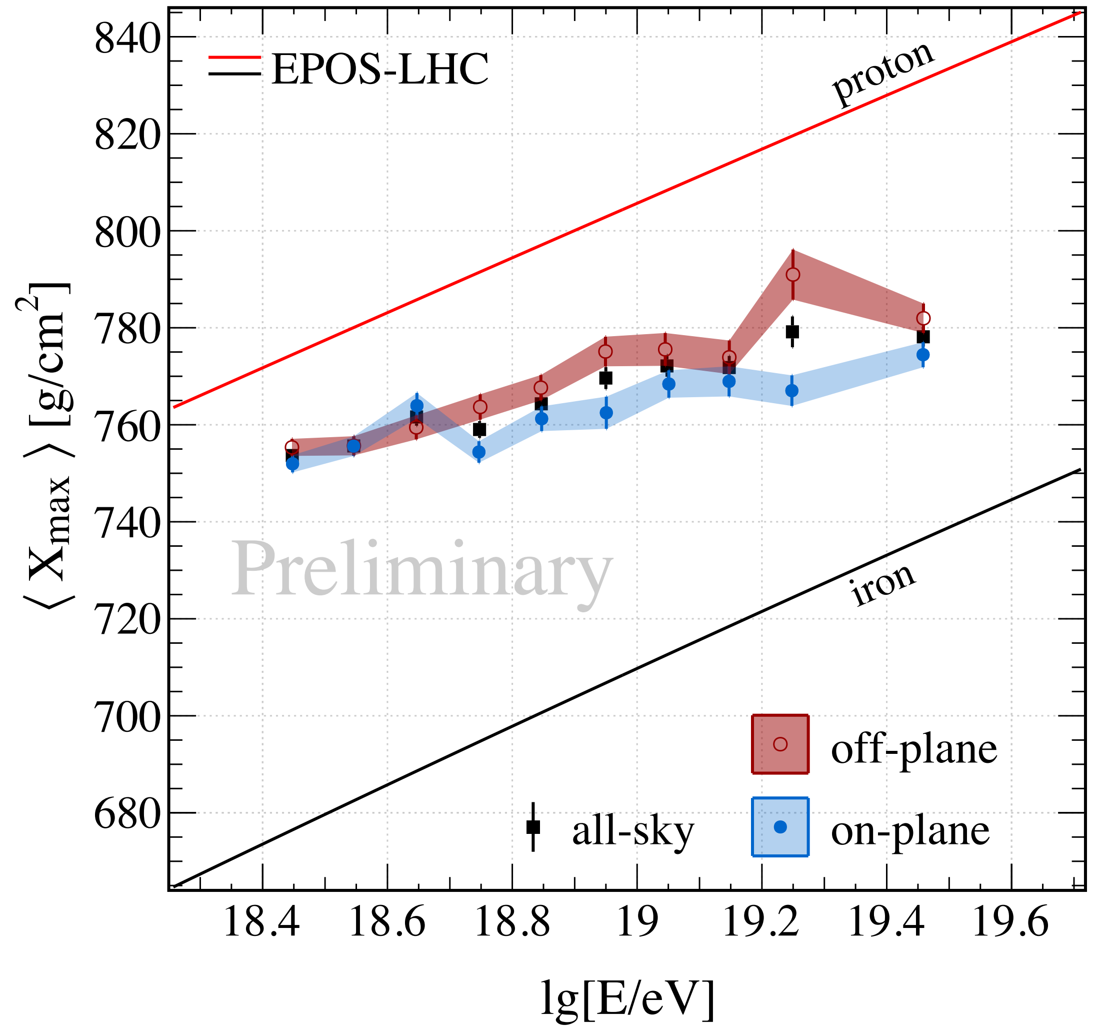
Outlook: Composition-sensitive anisotropy

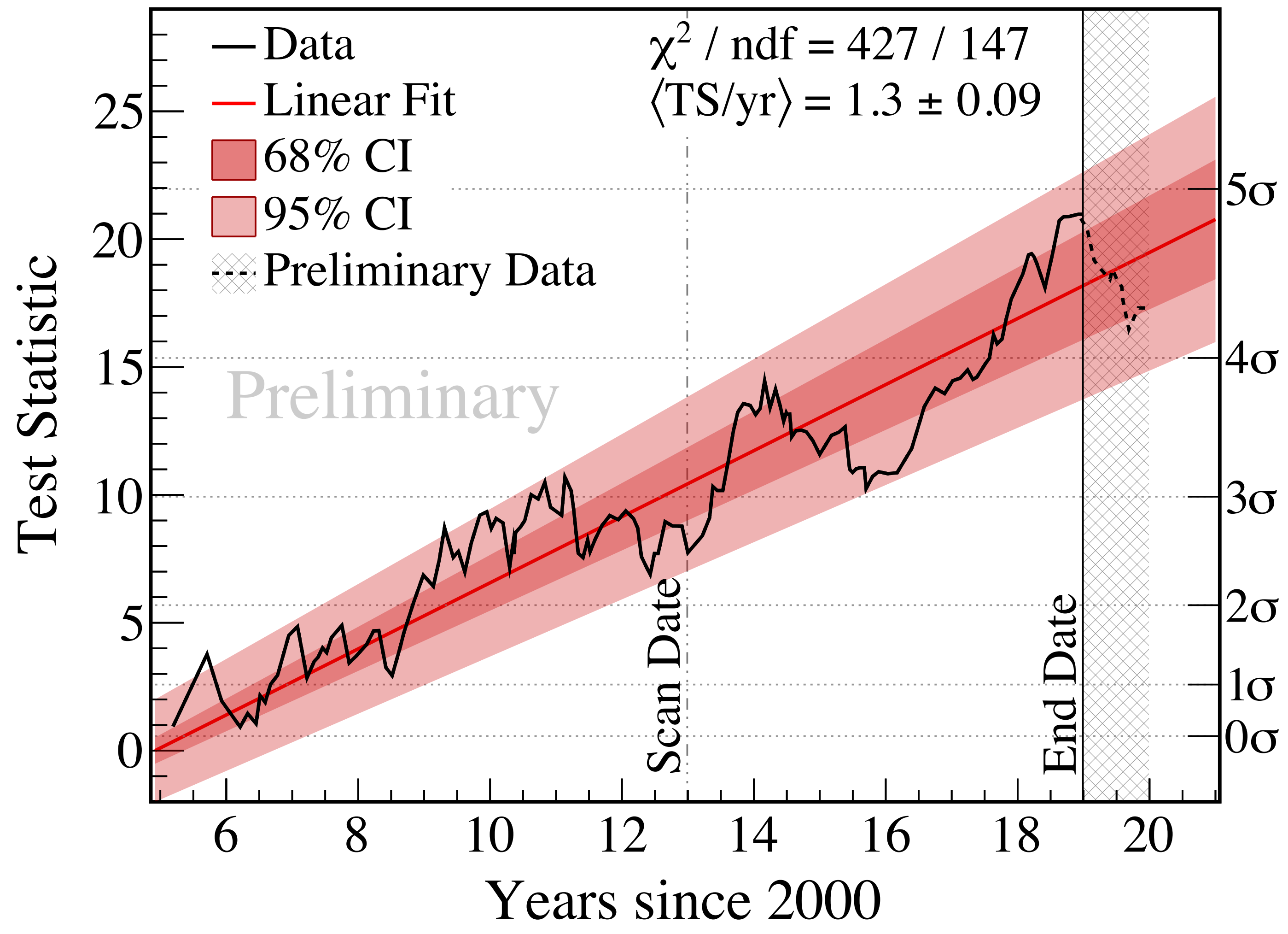


- Scan over the data recorded before 01.01.2013 (54 %)
- 5° steps in b and 0.1 $\lg(E/\mathrm{eV})$ steps in energy
- Highest TS of 8.35 for: $\rightarrow E_{\min} = 10^{18.7}$ eV
  $\rightarrow b_{\mathrm{split}} = 30°$

Smoothing over 30° bins







Not necessarily related to Galaxy

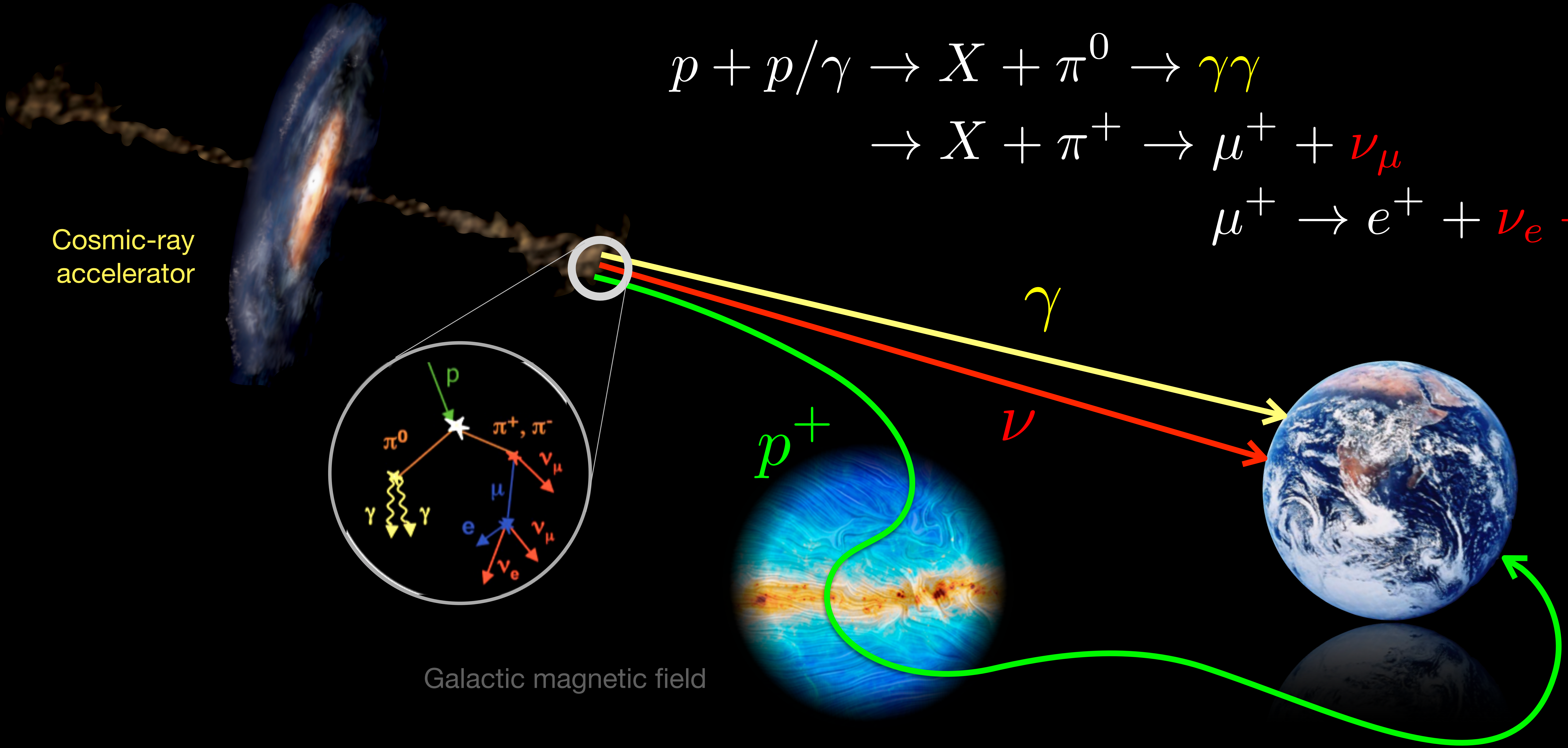
Local source distribution and mass-dependent horizon effect?

No independent confirmation from other data

Phase II data and more statistics really important to make progress

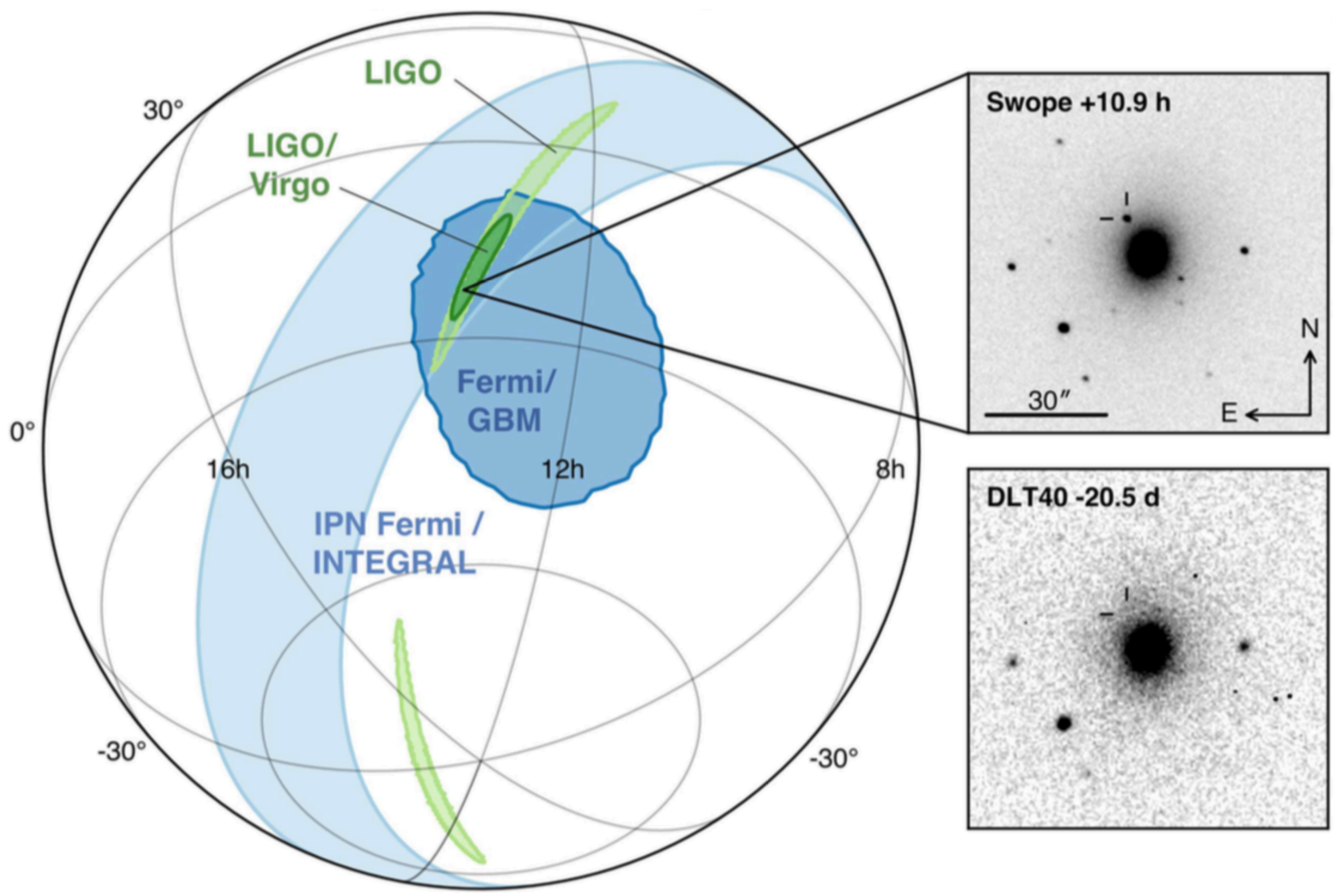
The multi-messenger picture of high-energy astrophysics

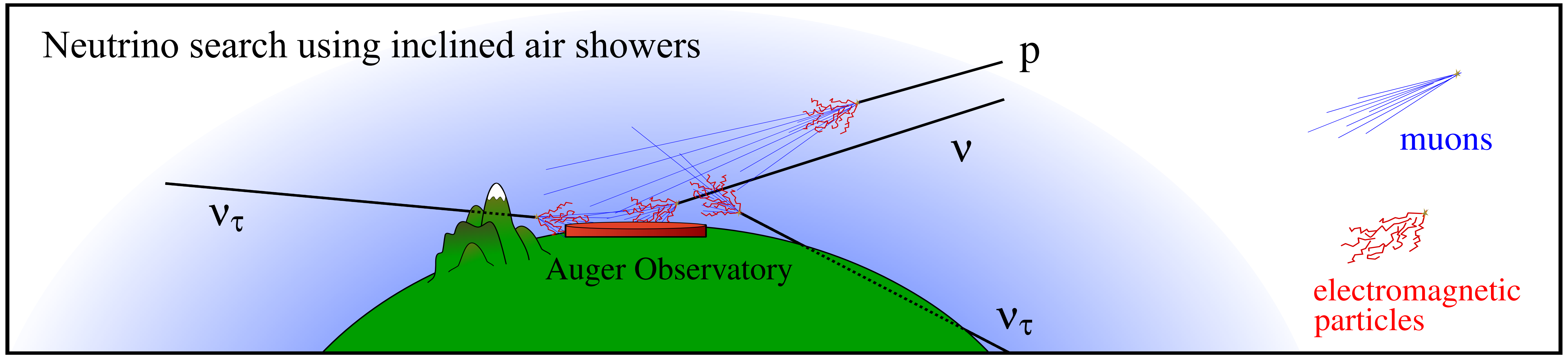
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

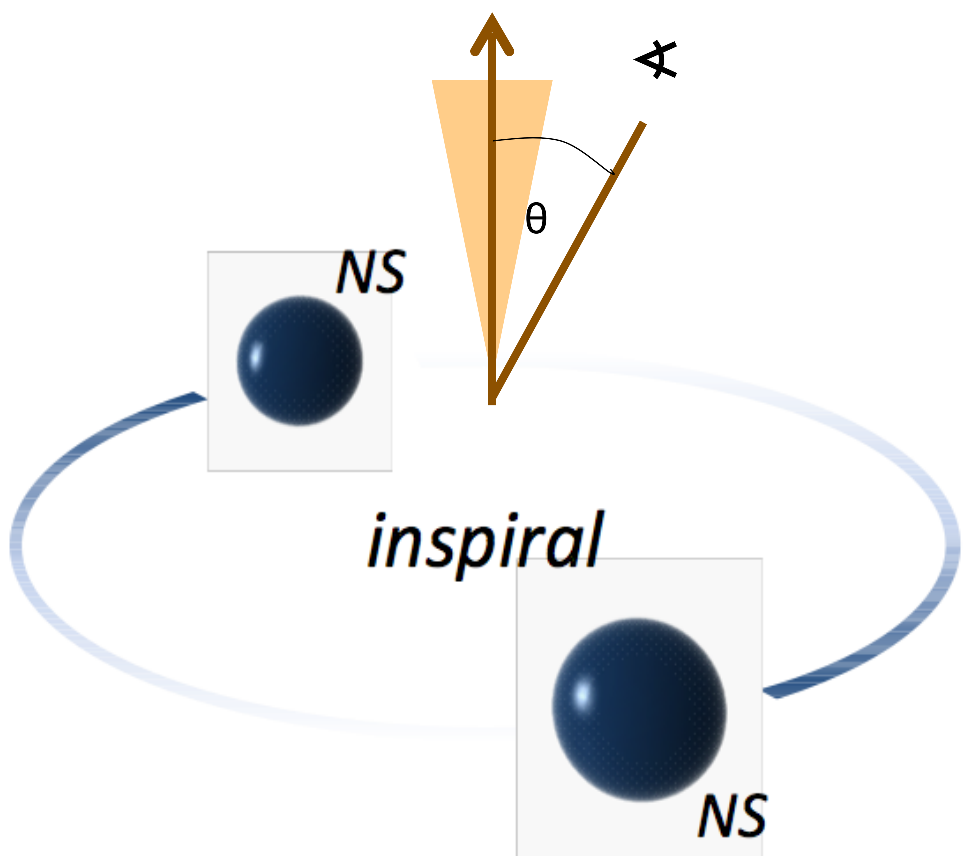


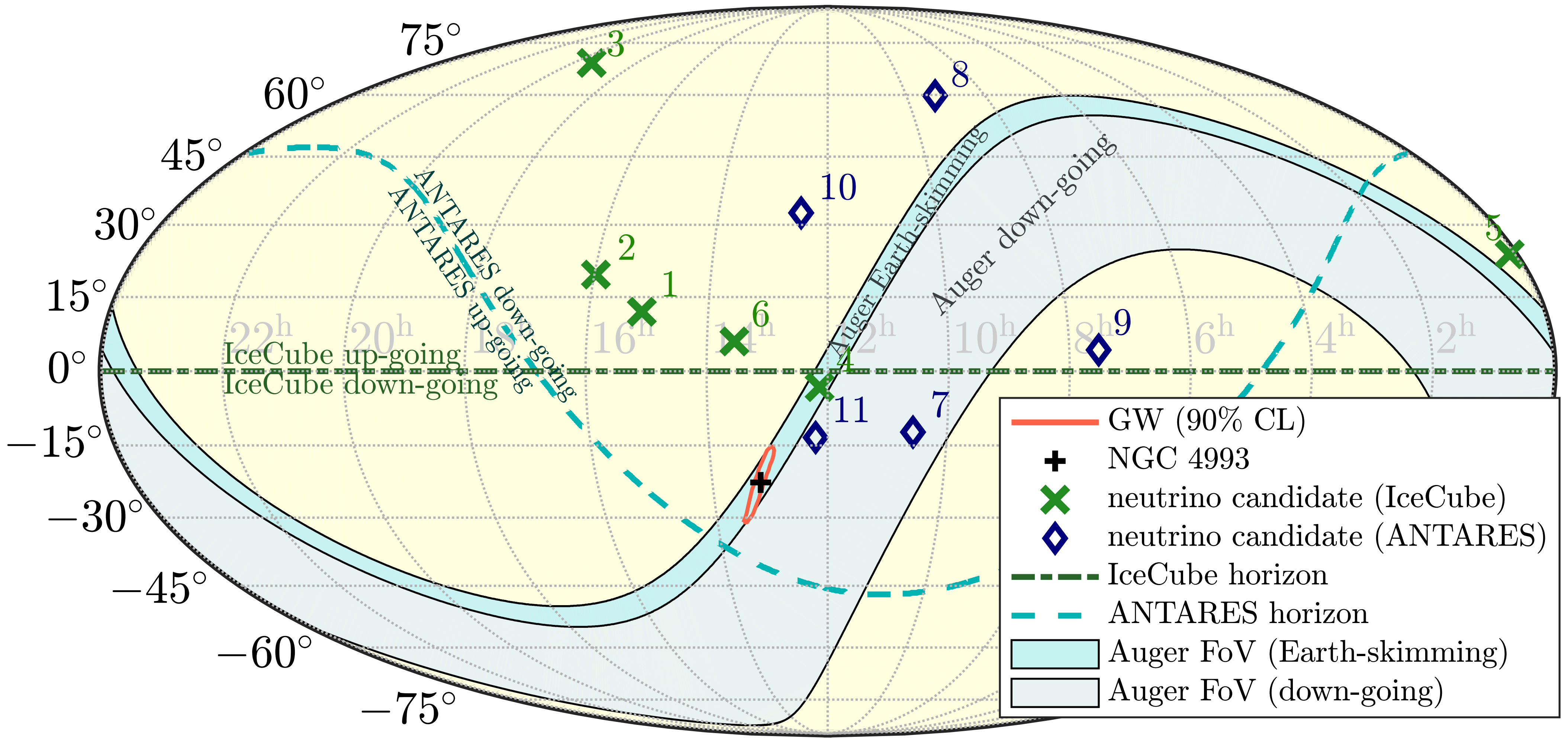
(Santander, ISAPP 2022)

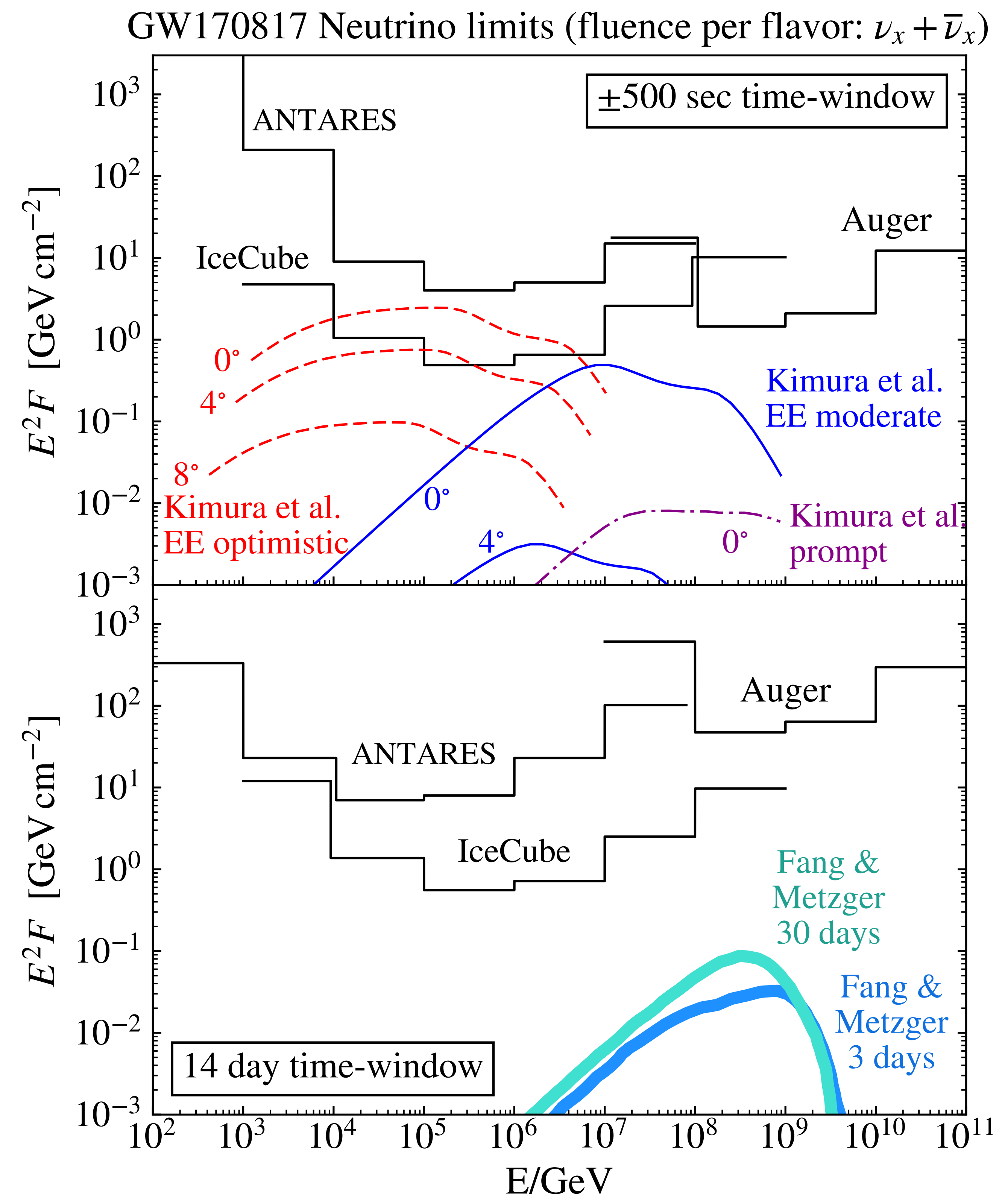
GW170817: Neutrino flux limits by Auger Observatory







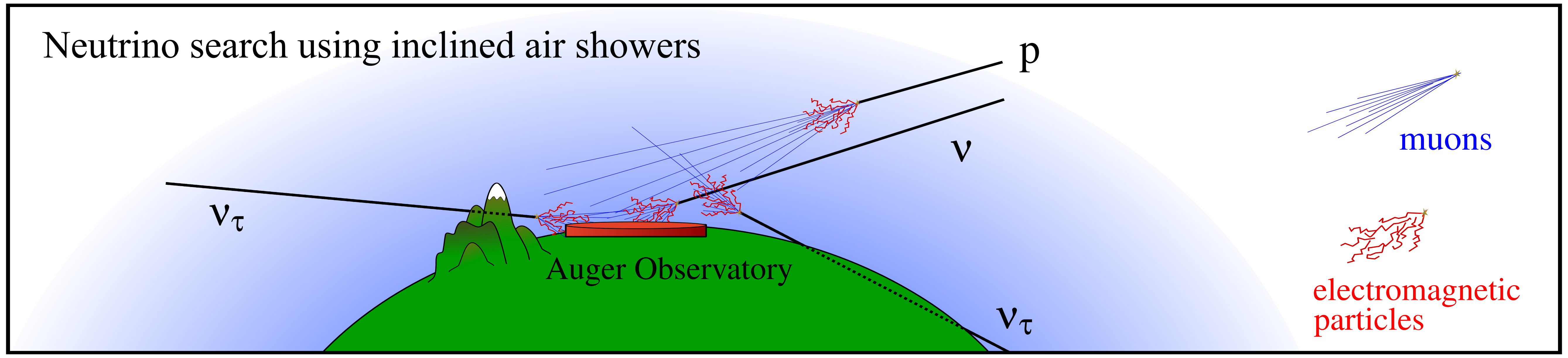




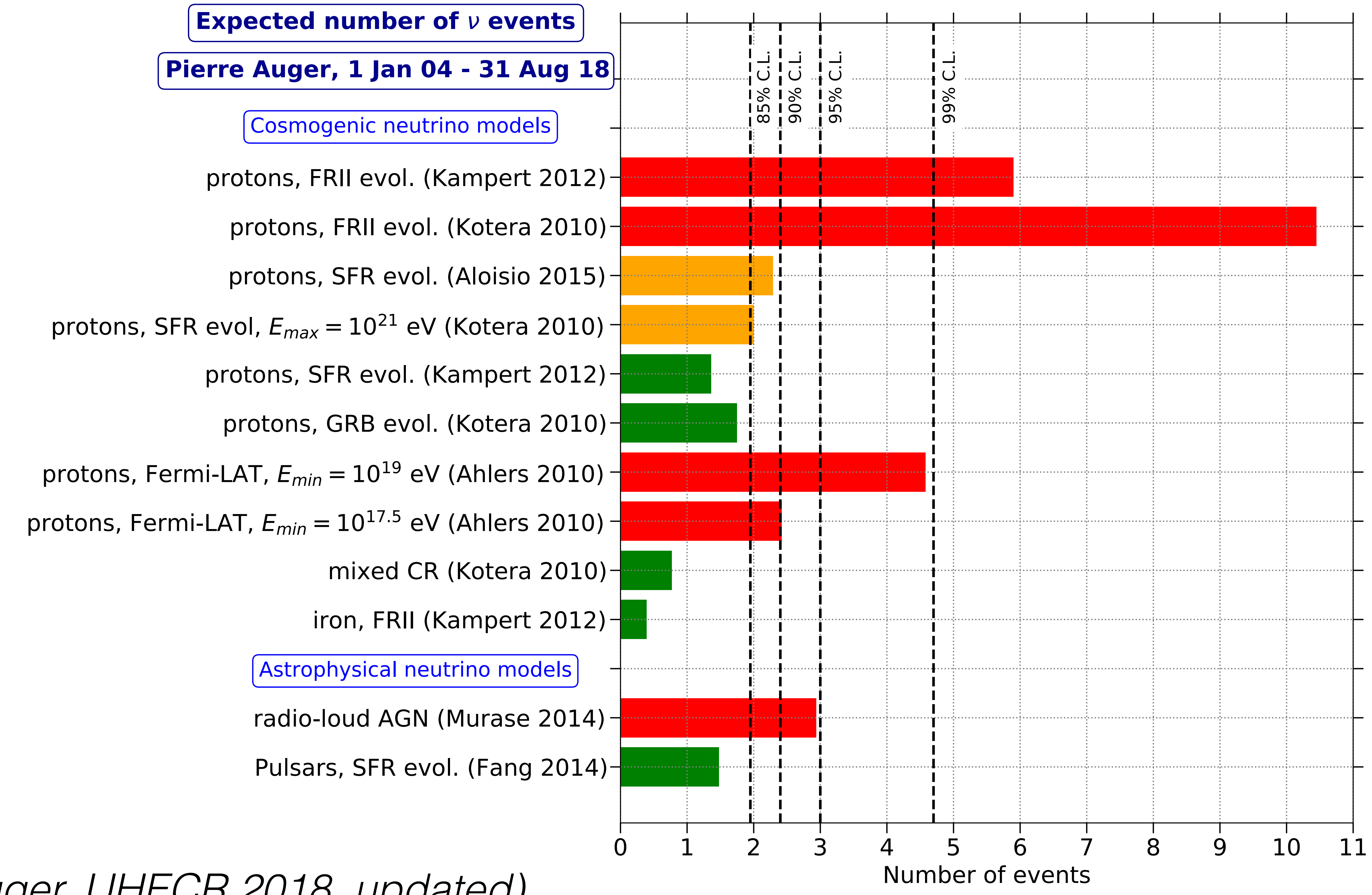
Data of all relevant detectors, including Auger

ApJL (2017), special issue (70 collaborations)

Waiting for the first ultra-high energy neutrino

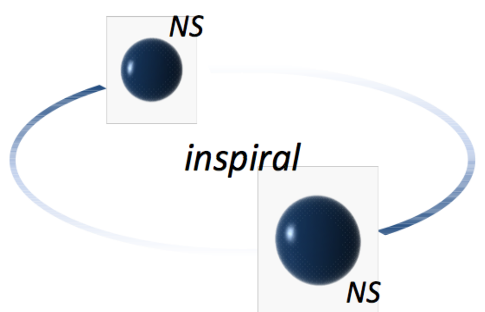


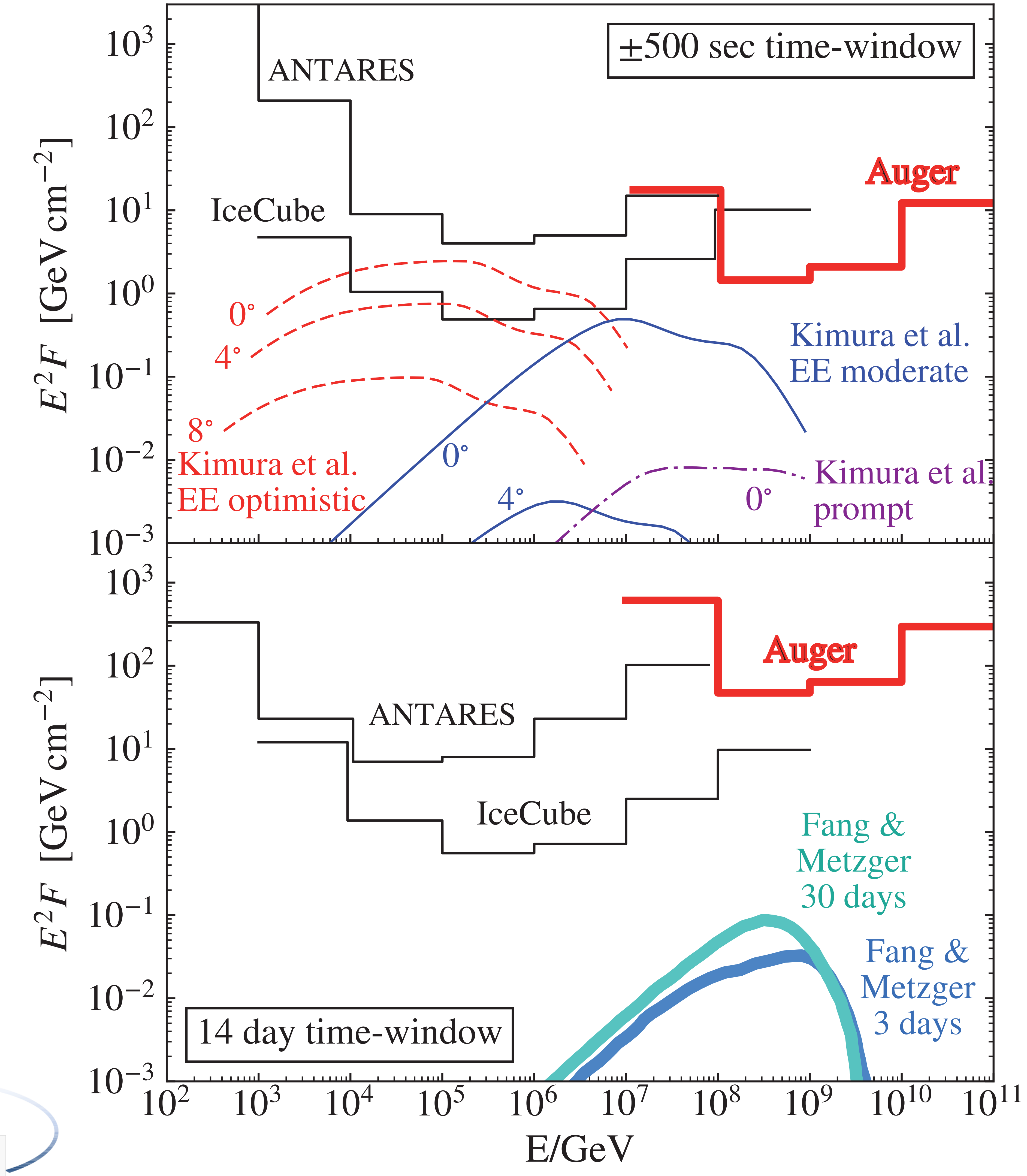
Expected number of events



(Auger, UHECR 2018, updated)

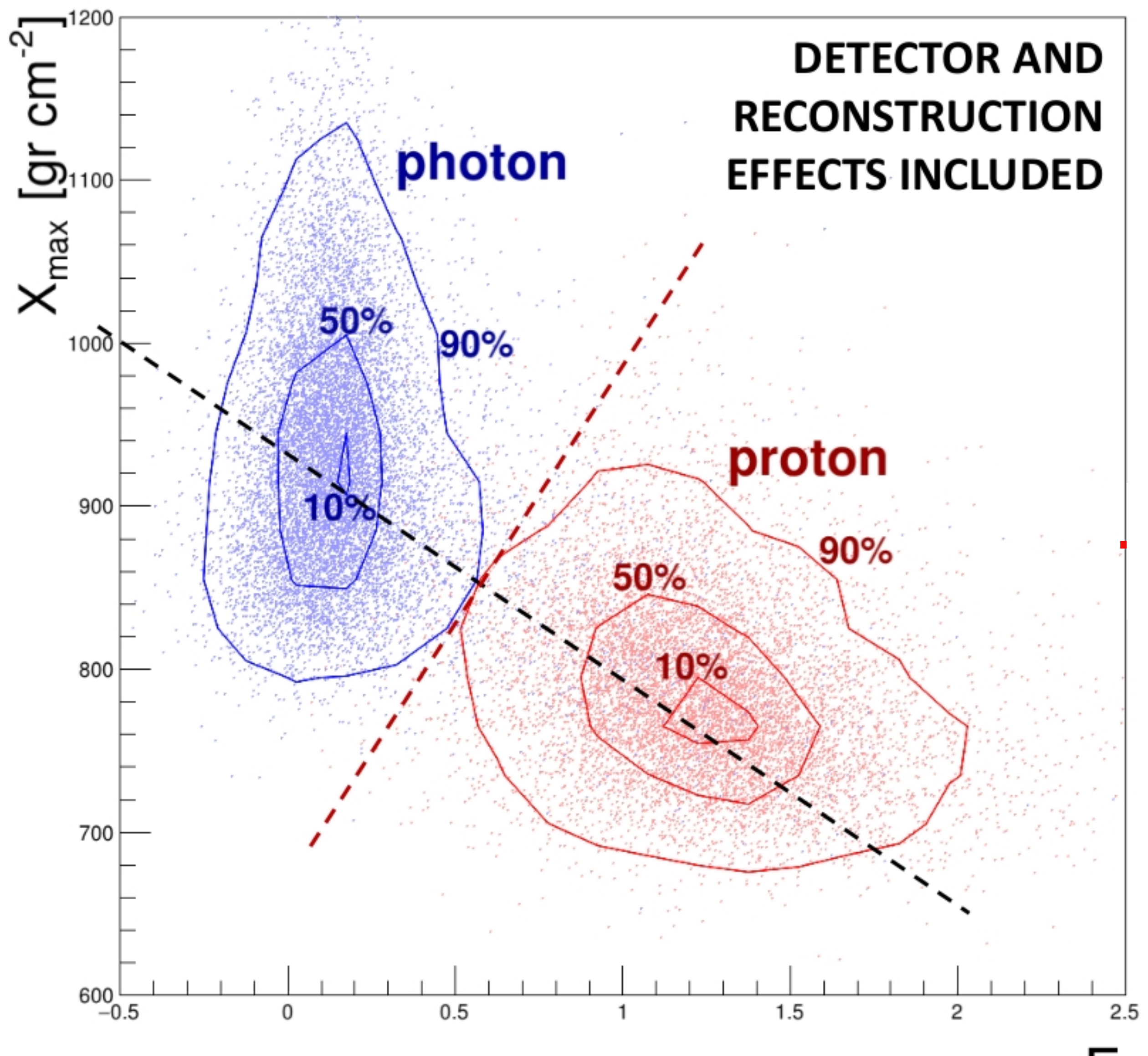
GW170817





ApJL (2017), special issue (70 collaborations)

Searches: Ultra-high energy photons



Muon signal by shower universality

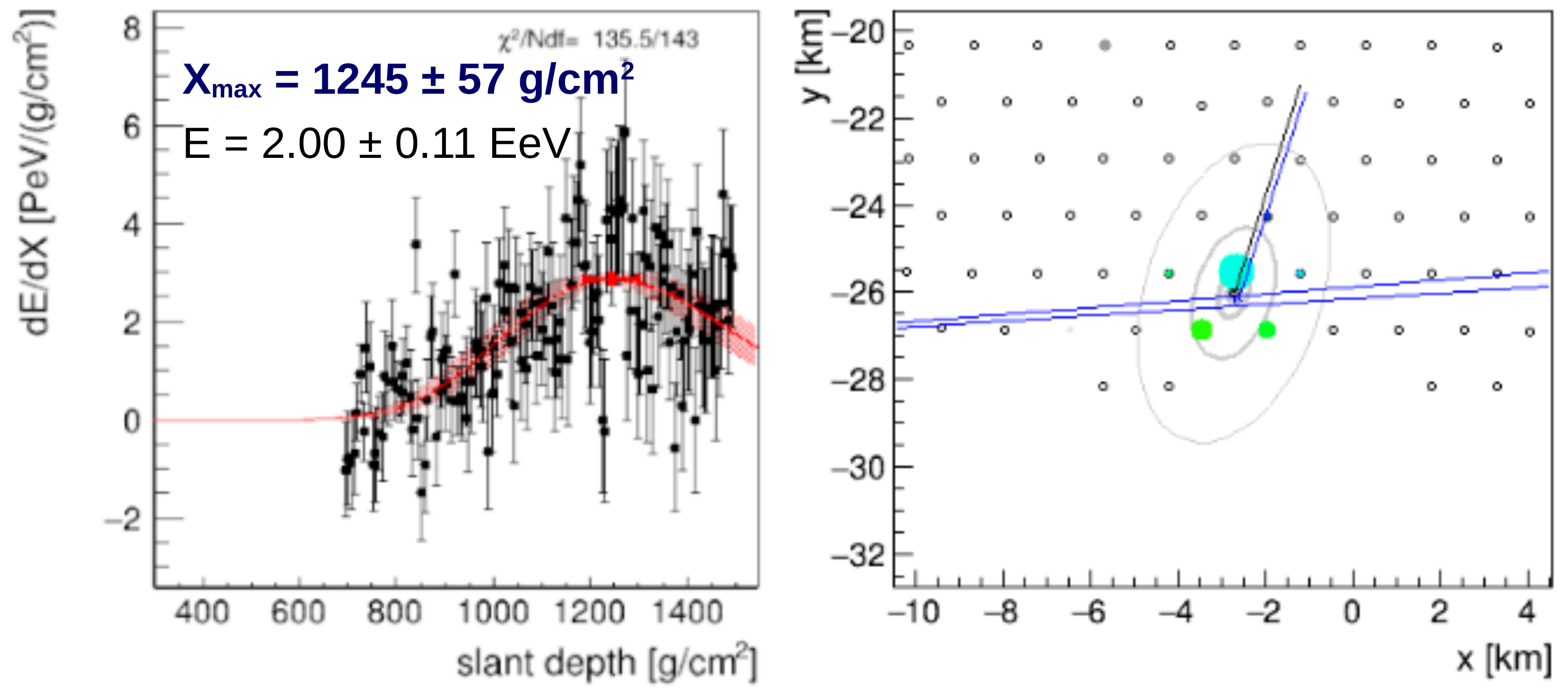
Cut at 50% photon efficiency (median)

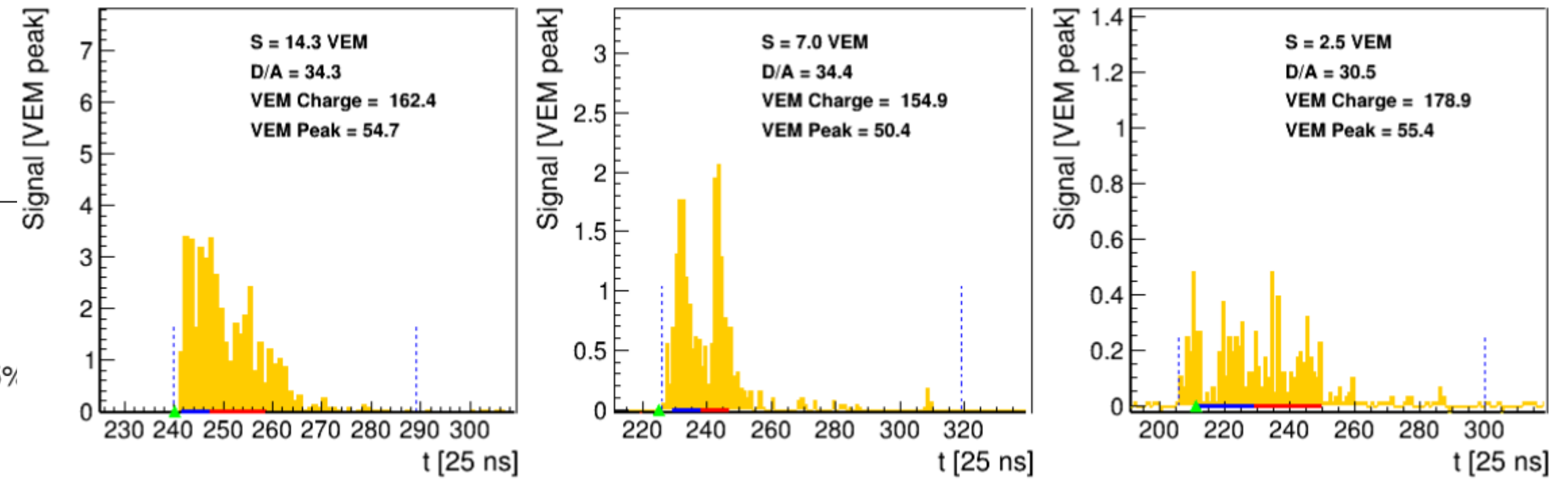
Background compatible with stat. expectation (burn sample of data)

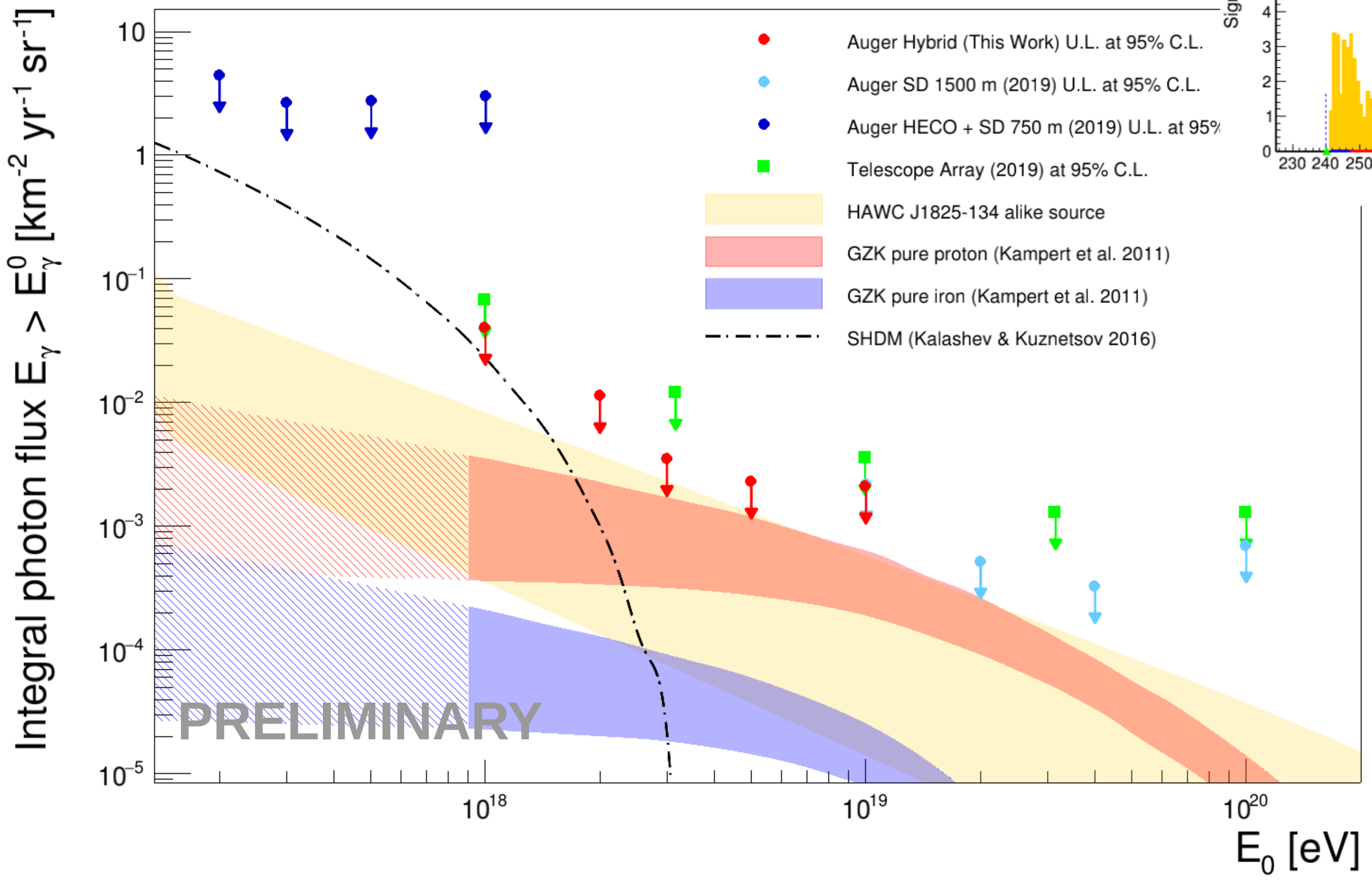
Multi-messenger: searches for photons in coincidence with GW events

estimated events above median:
$N_{exp}(E > 10^{18.0}$ eV) = 30 ± 16

Candidates found:
$N_{obs}(E > 18.0$ eV) = 22





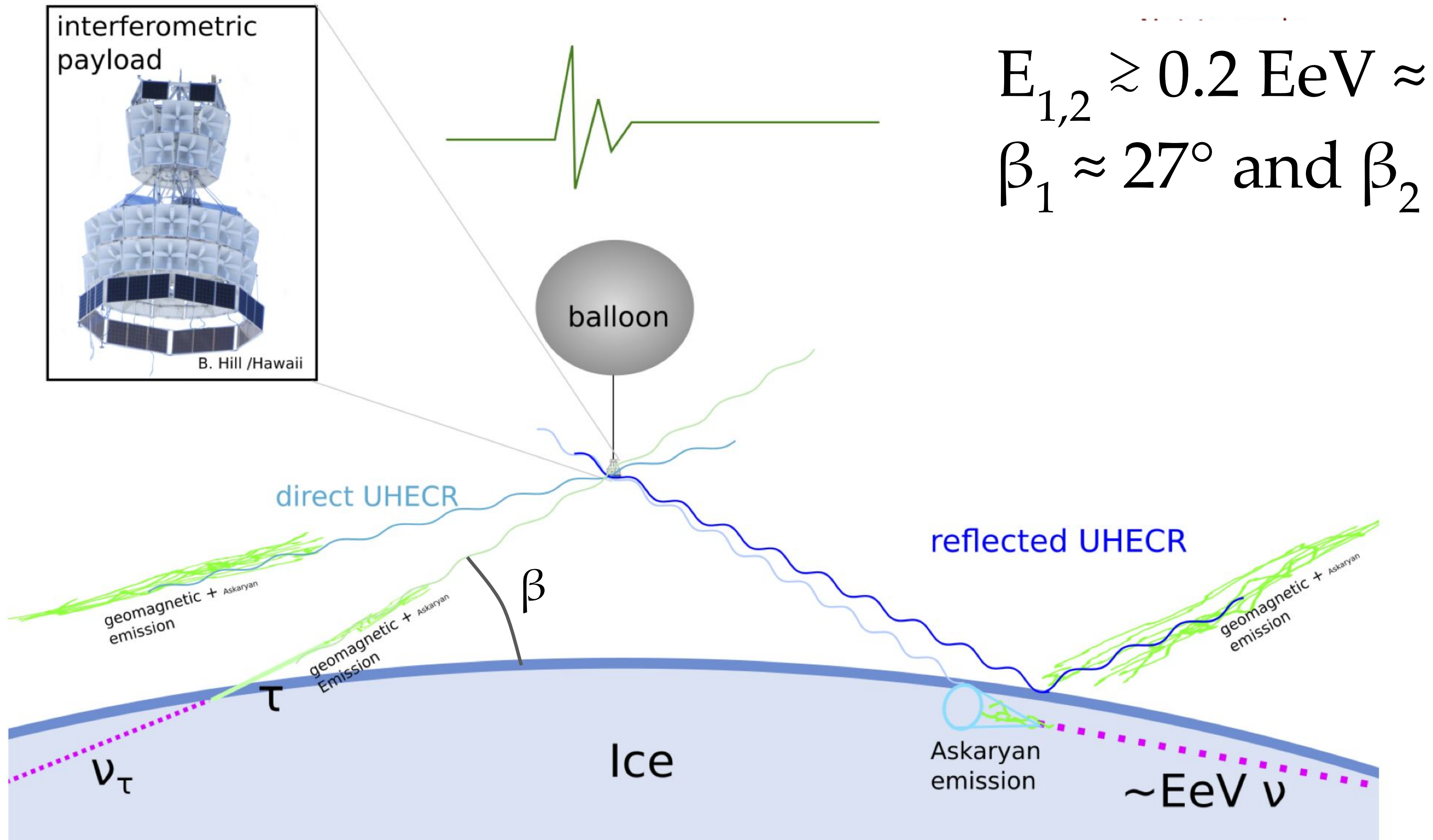


Limits begin being background-dominated

Phase II: additional data for photon/hadron separation or photon discovery

(Philip Ruehl) (Pierpaolo Savina)

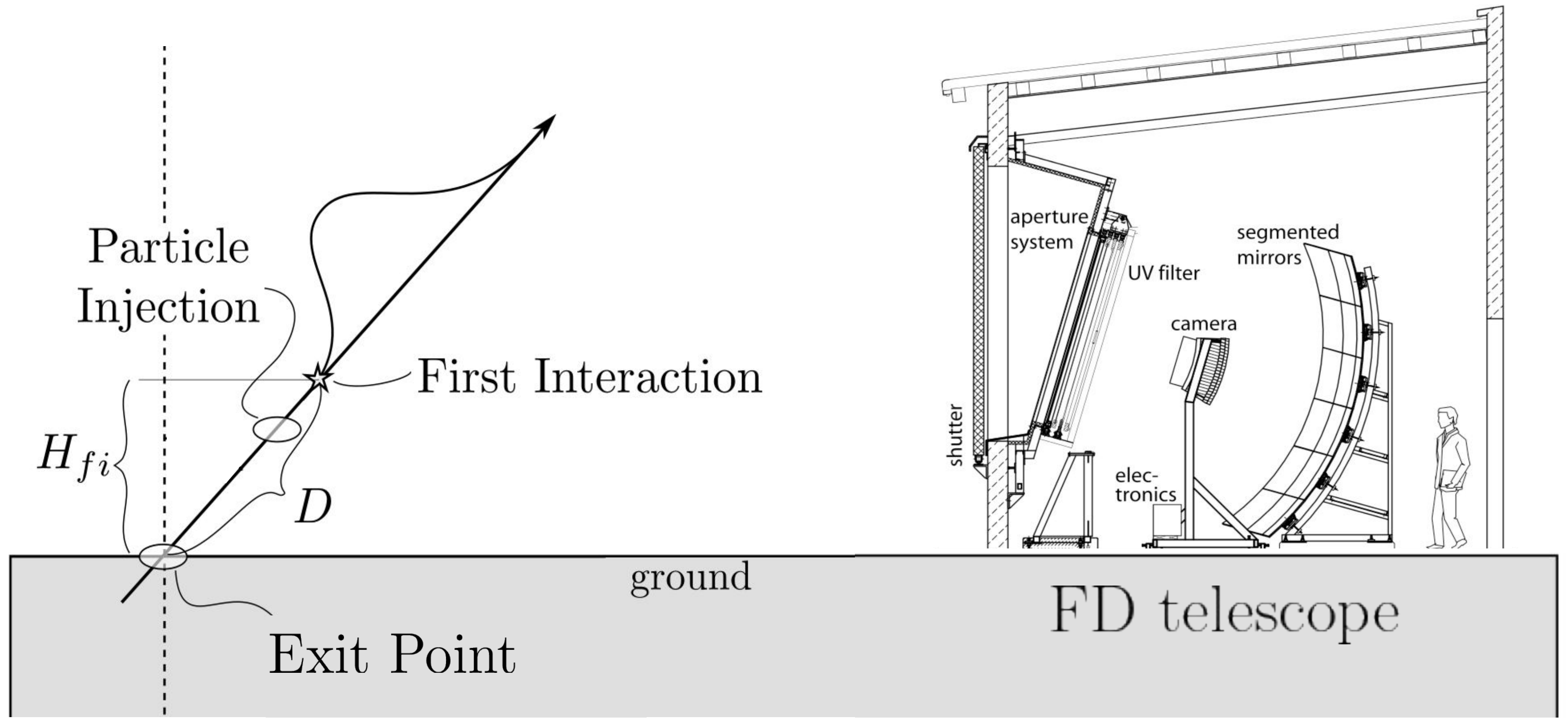
Searches: Upward-going events motivated by ANITA

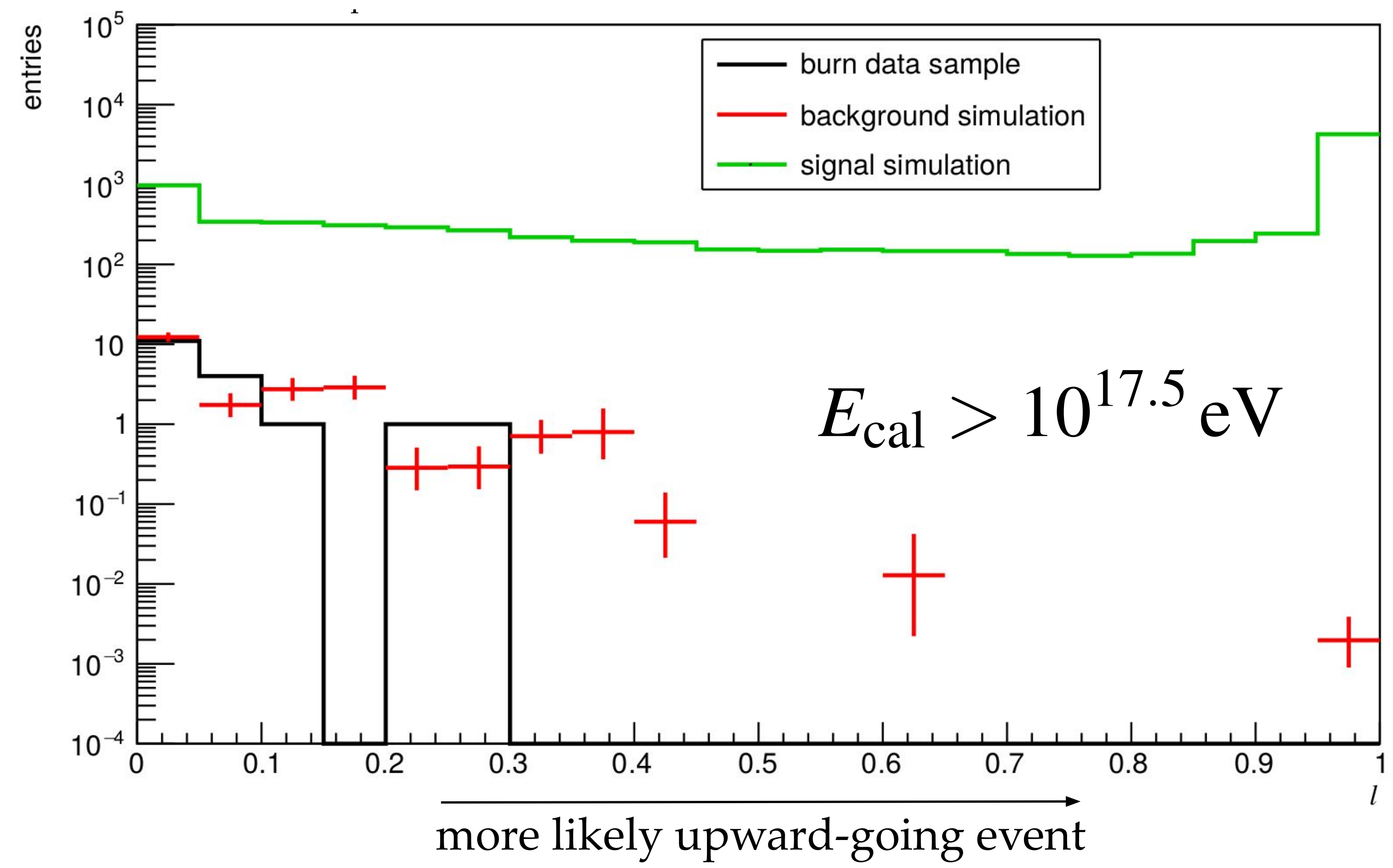


(ANITA, Phys. Rev. Lett. 121 (2018) 161102)

$E_{1,2} \gtrsim 0.2$ EeV $\approx 10^{17.8}$ eV

$\beta_1 \approx 27°$ and $\beta_2 \approx 35°$





(Eva Santos)

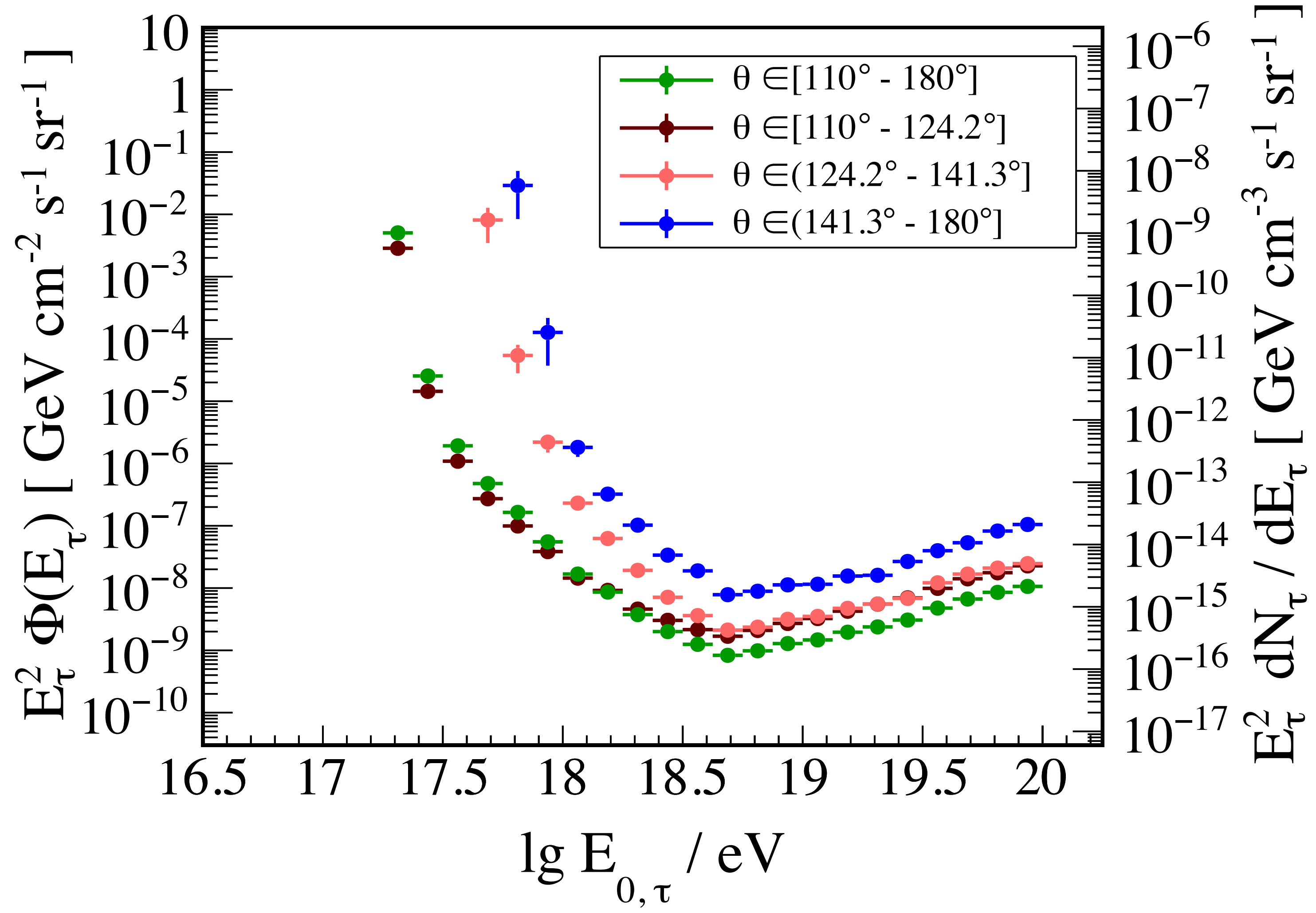
Auger results:

Background 0.45 ± 0.18 expected

One event observed

Flux limits on anomalous events

Tau scenario



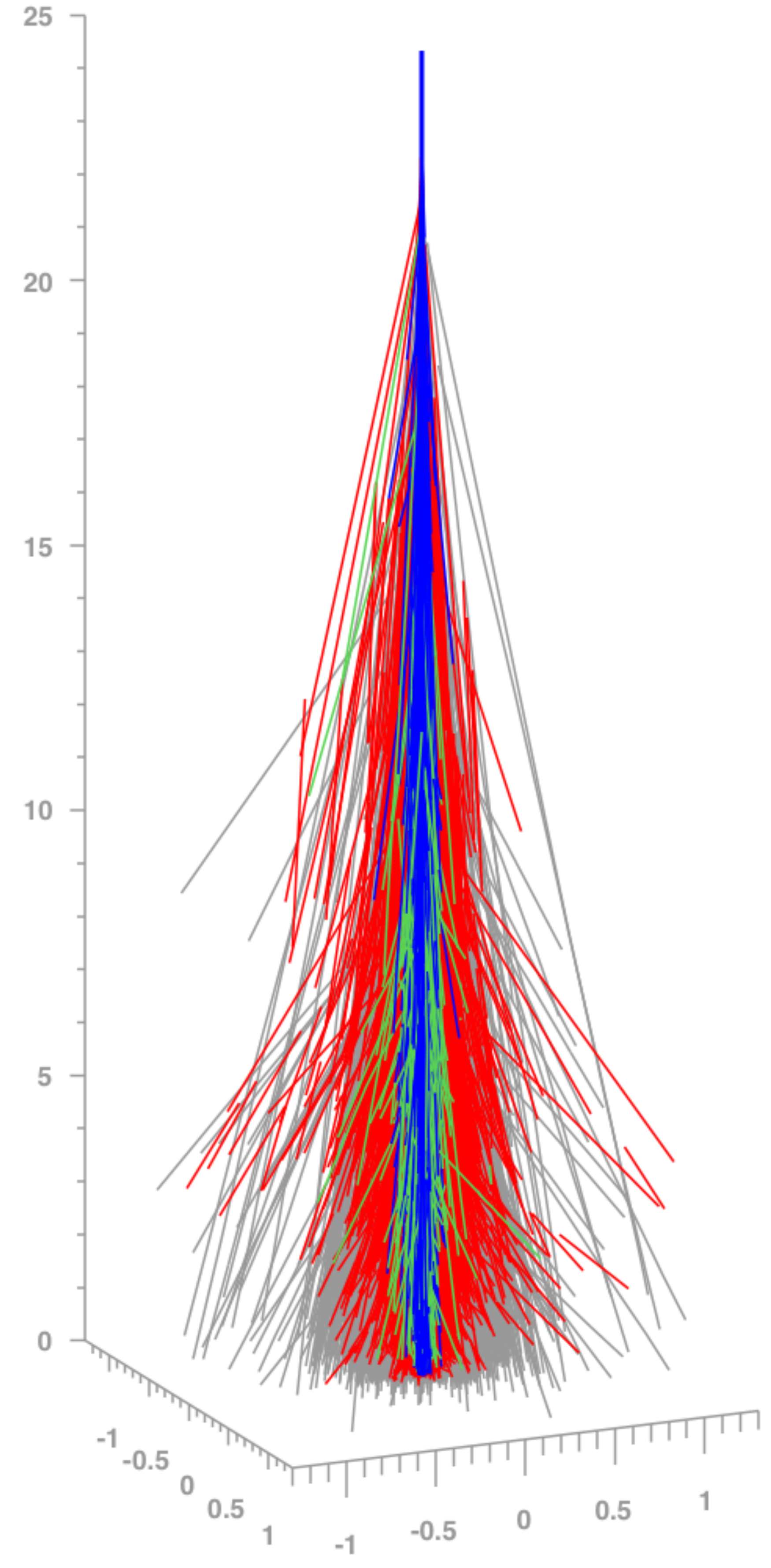
Uniform distribution

3.6×10^{-20} cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with **E^{-1}**

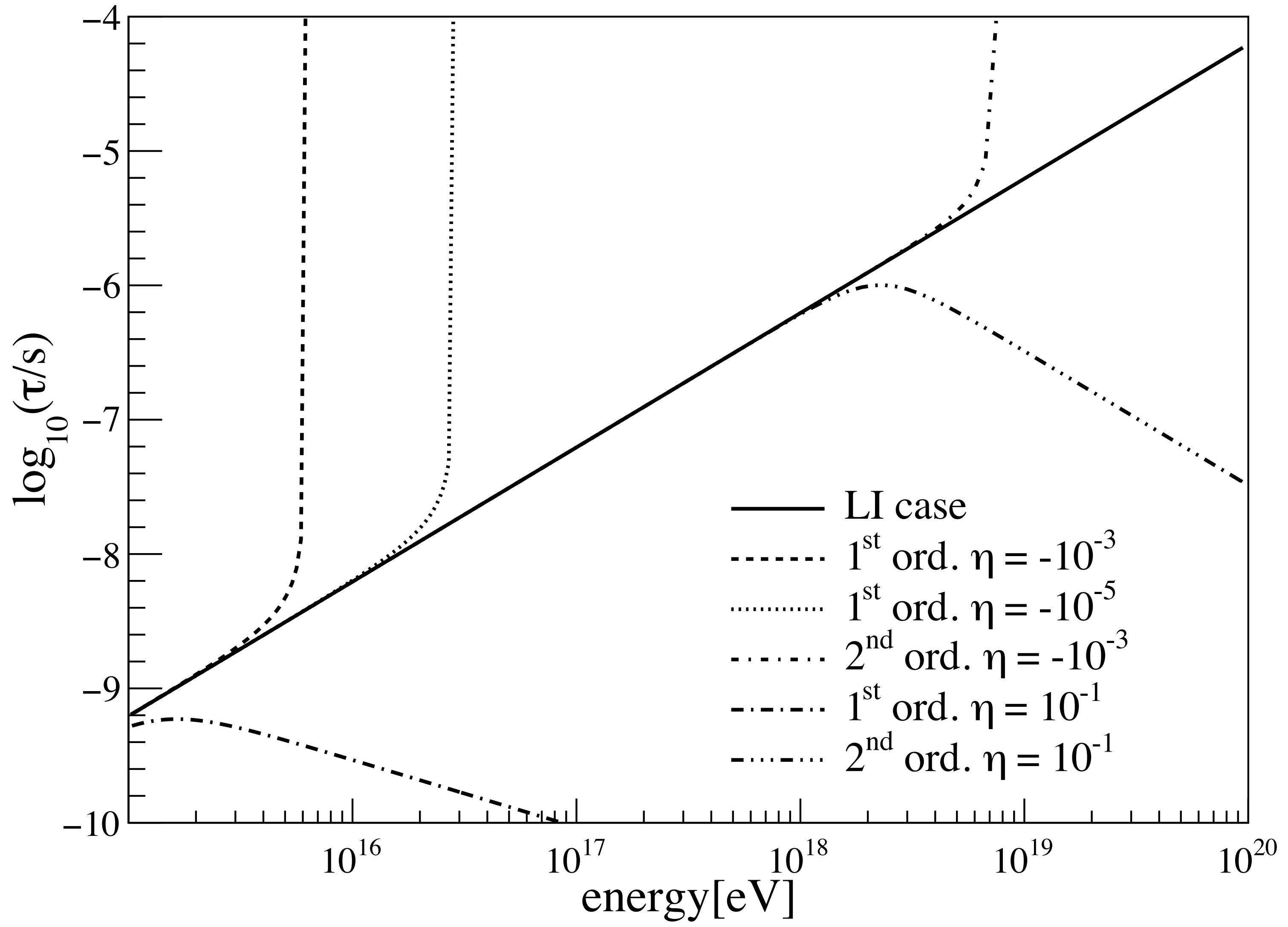
8.5×10^{-20} cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with **E^{-2}**

(Ioana Caracas) (Massimo Mastrodicasa)

Searches: Lorentz invariance violation (LIV)



Lorentz-dilated lifetime of neutral pions



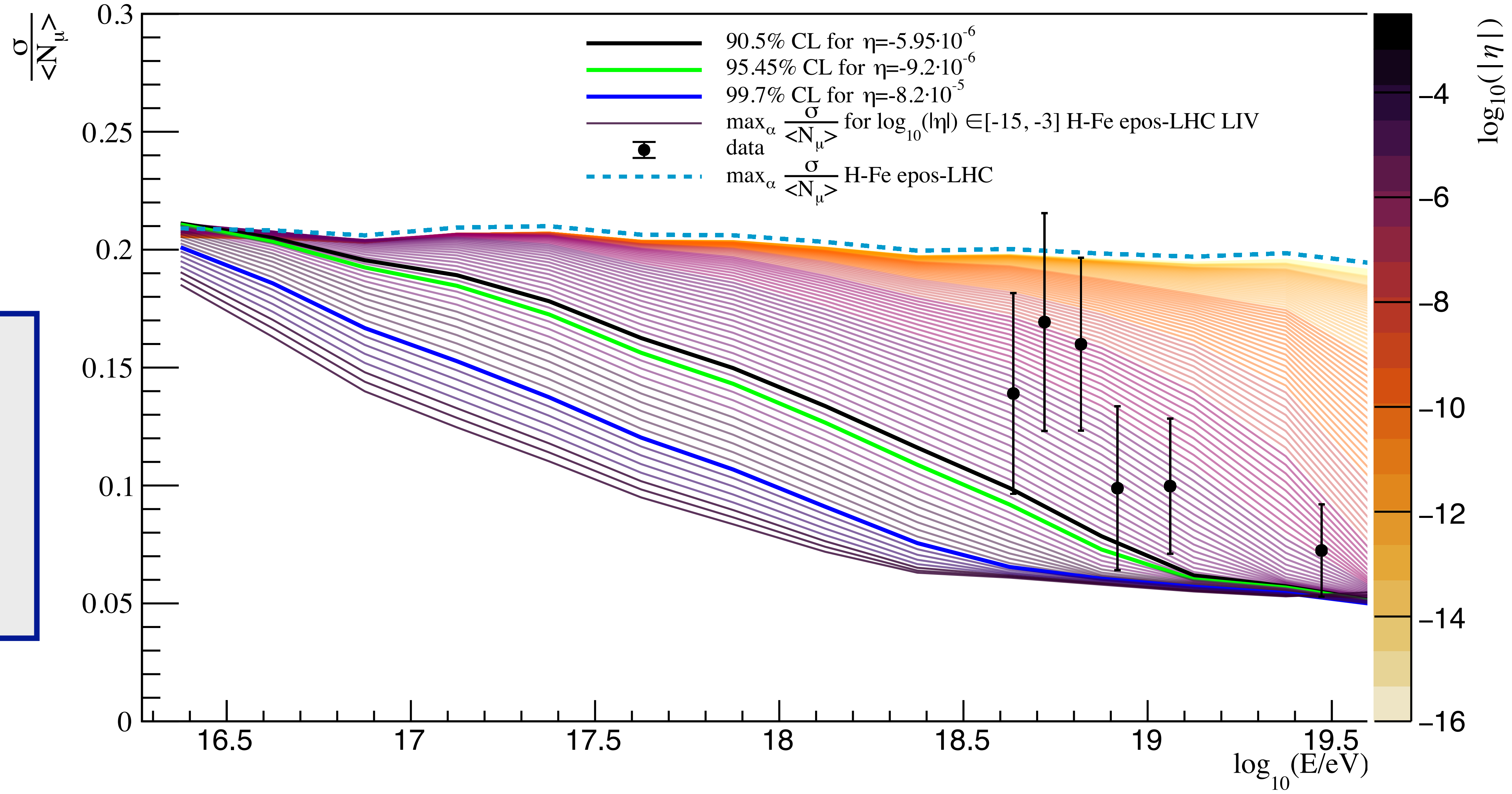
$$E^2 - p^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^n}$$

$$\gamma_{\rm LIV} = E/m_{\rm LIV}$$

$$m^2_{\rm LIV} = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^n}$$

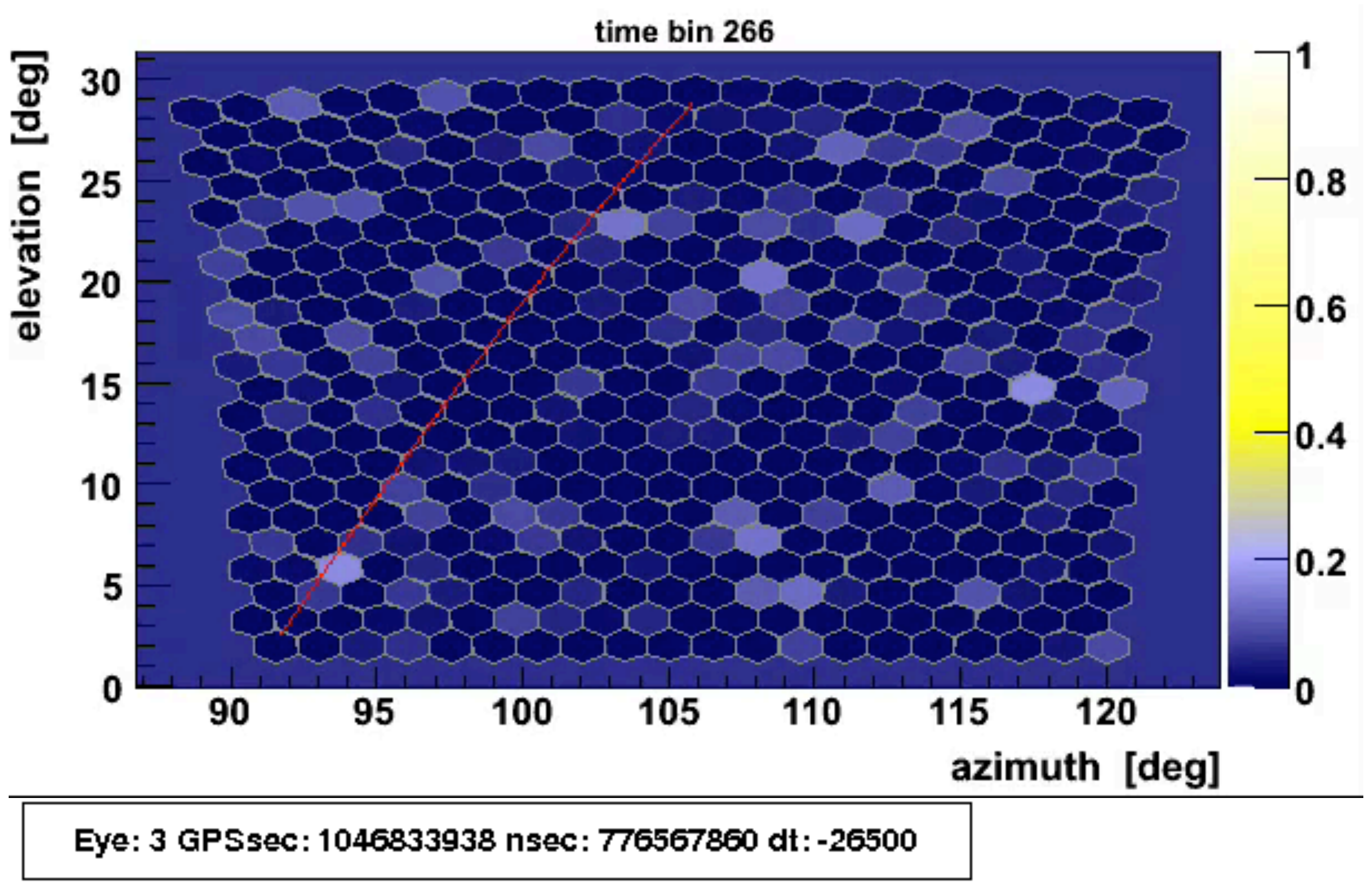
Comparison of model simulations with data on muon number fluctuations

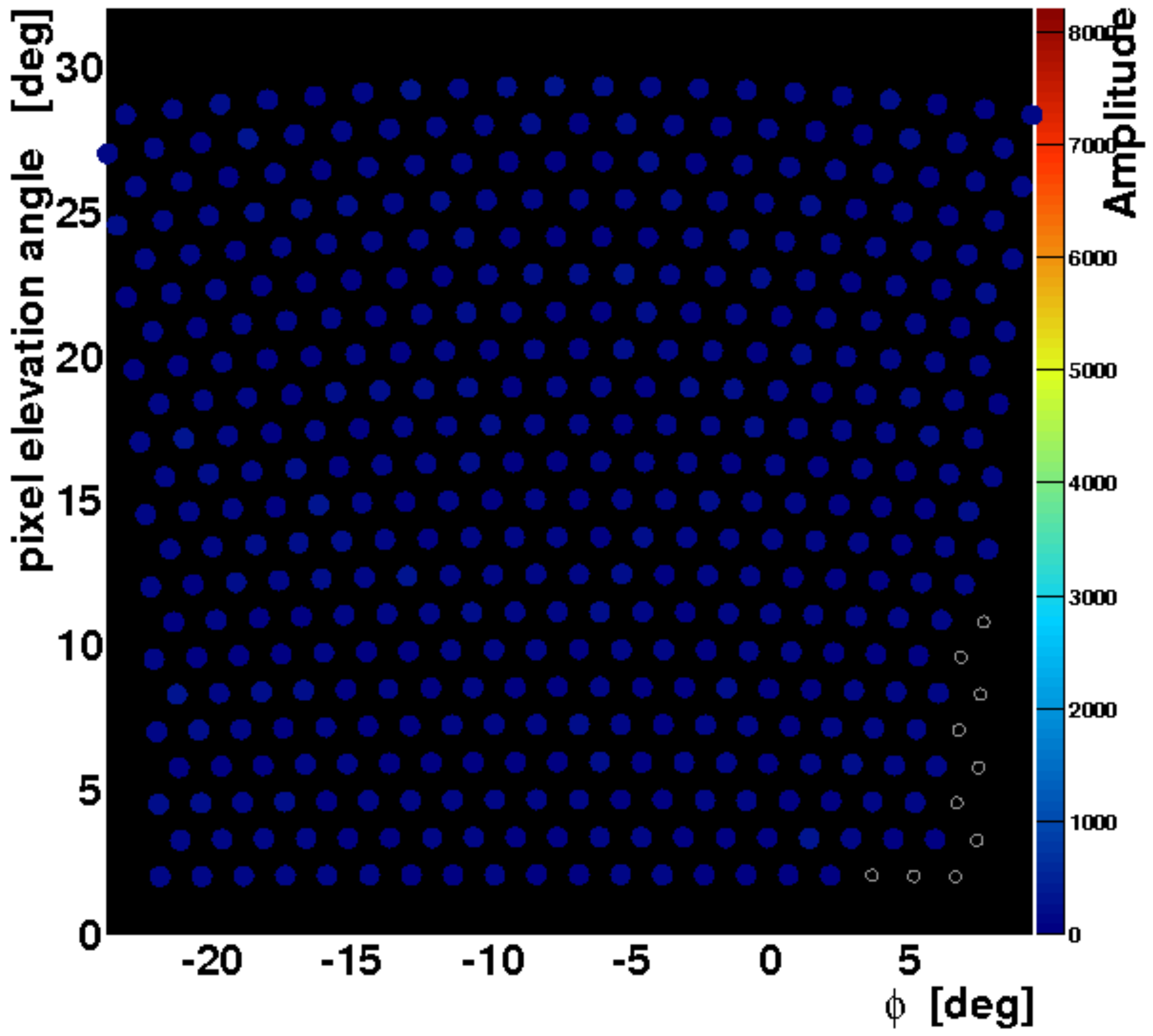
New limits on LIV parameter η

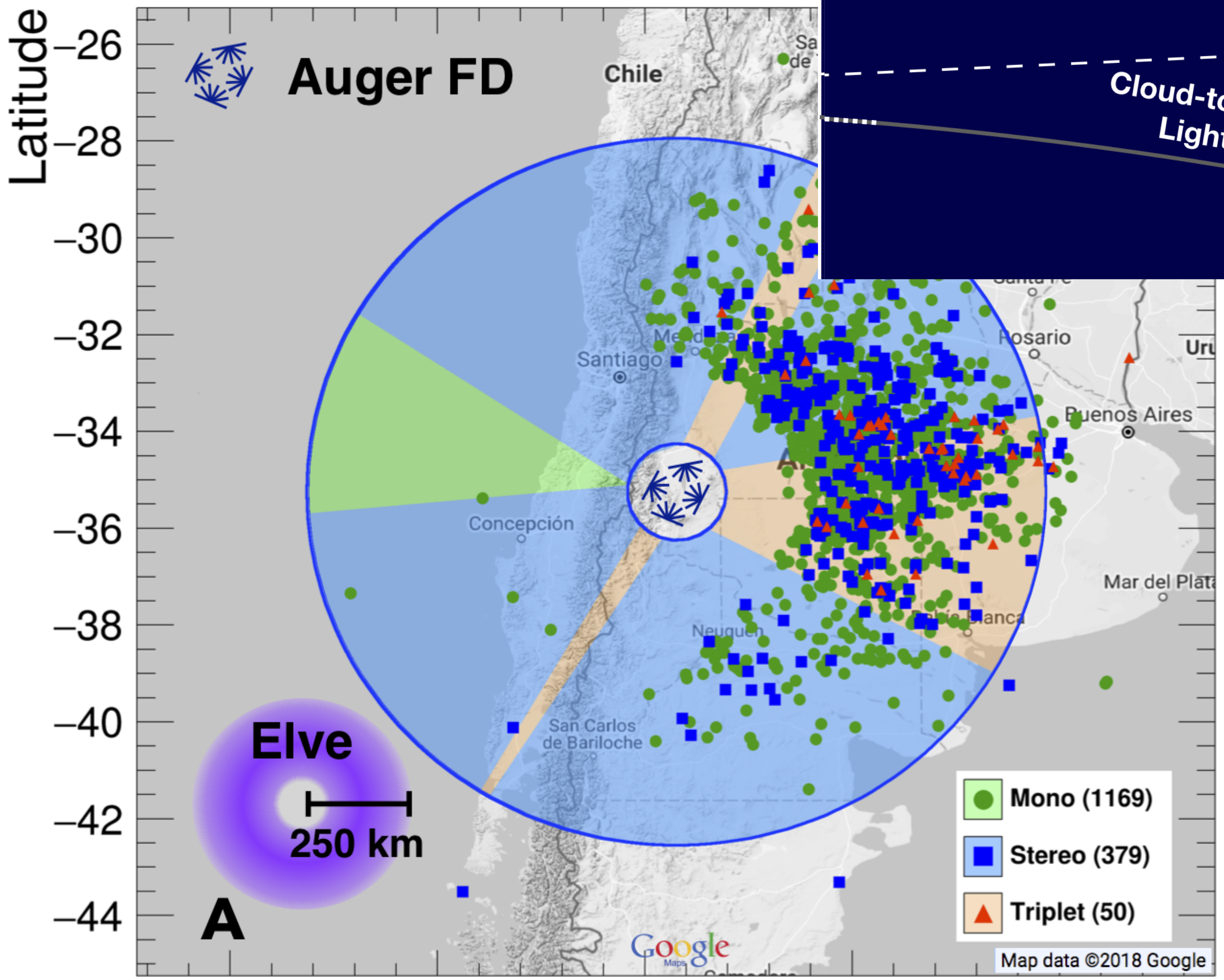


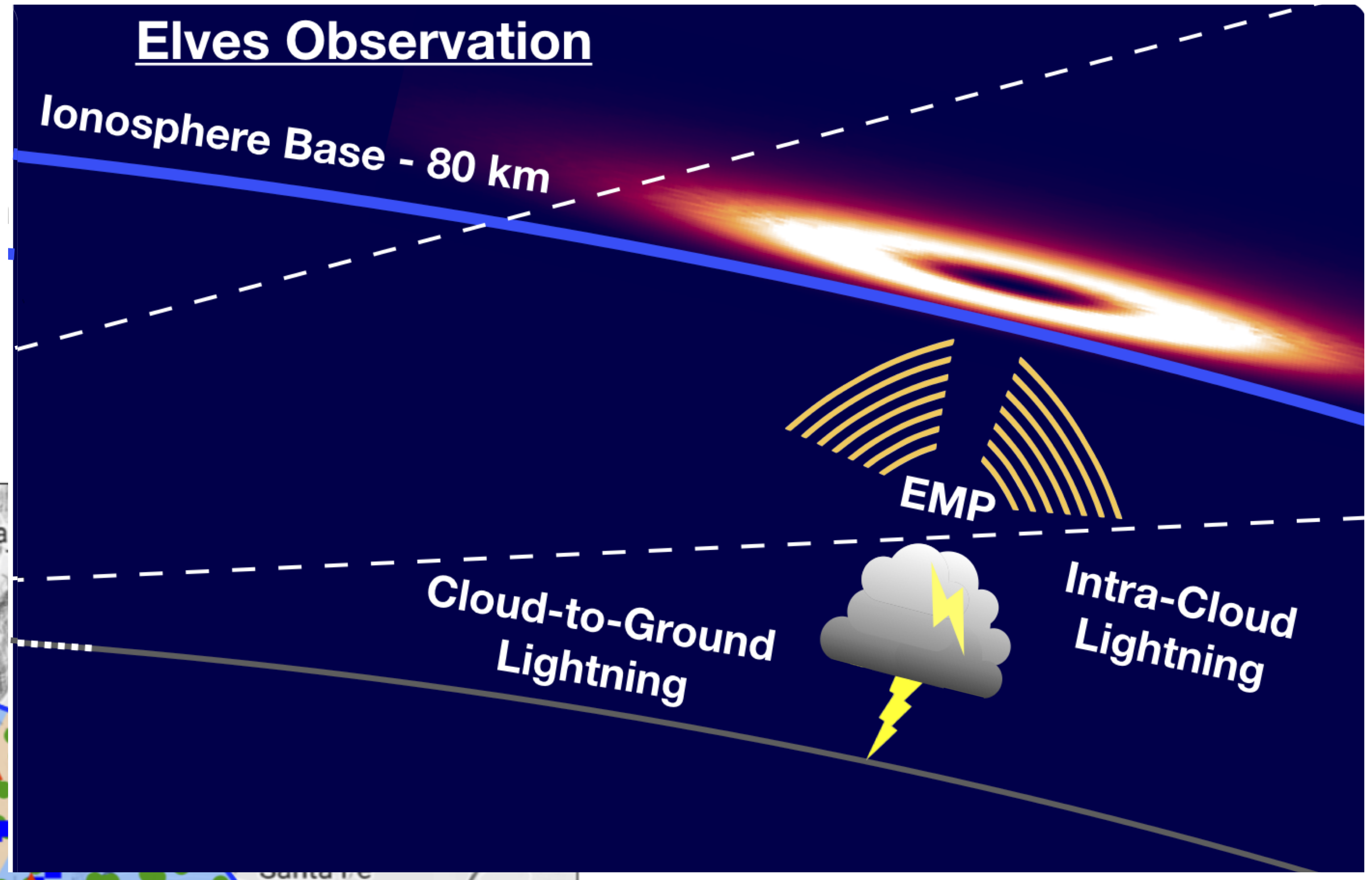
(Caterina Trimarelli)

Atmospheric phenomena: Elves









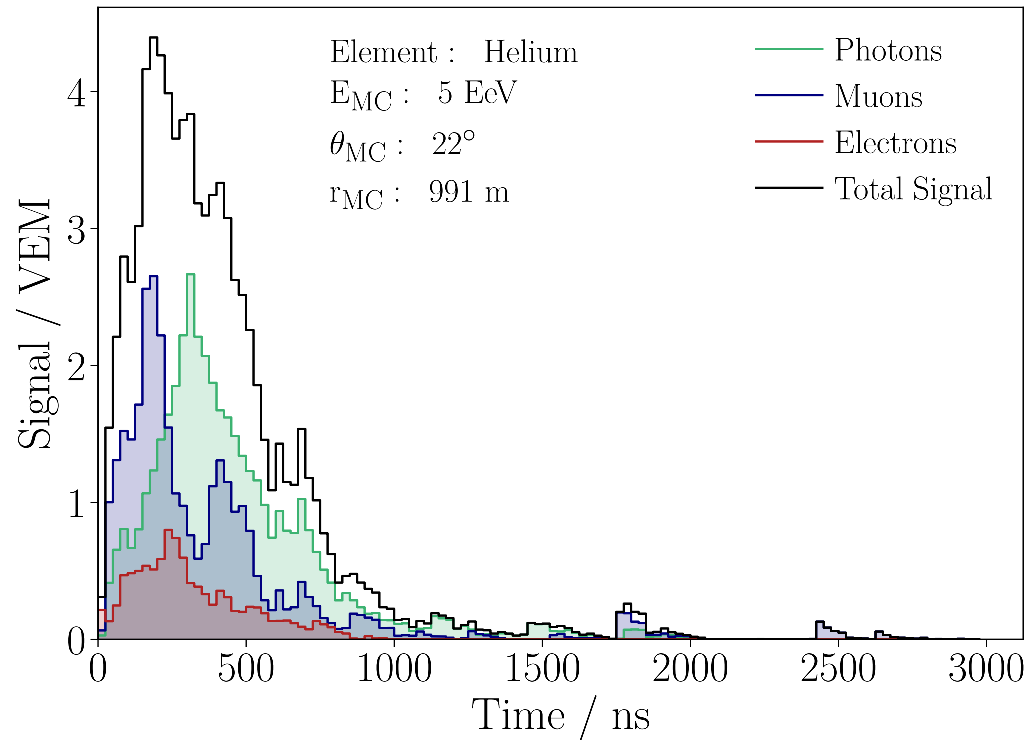
1600 Elves observed

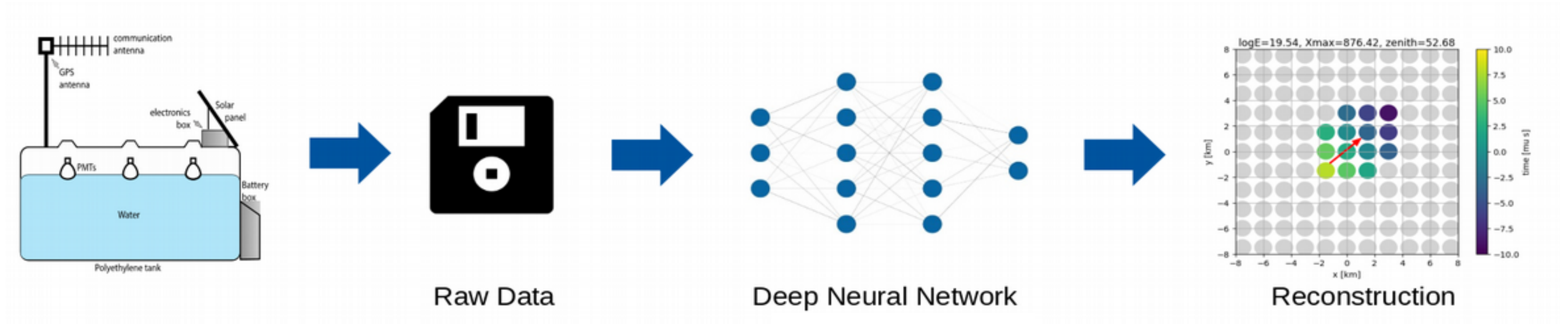
Biggest Elves related to Super-bolts

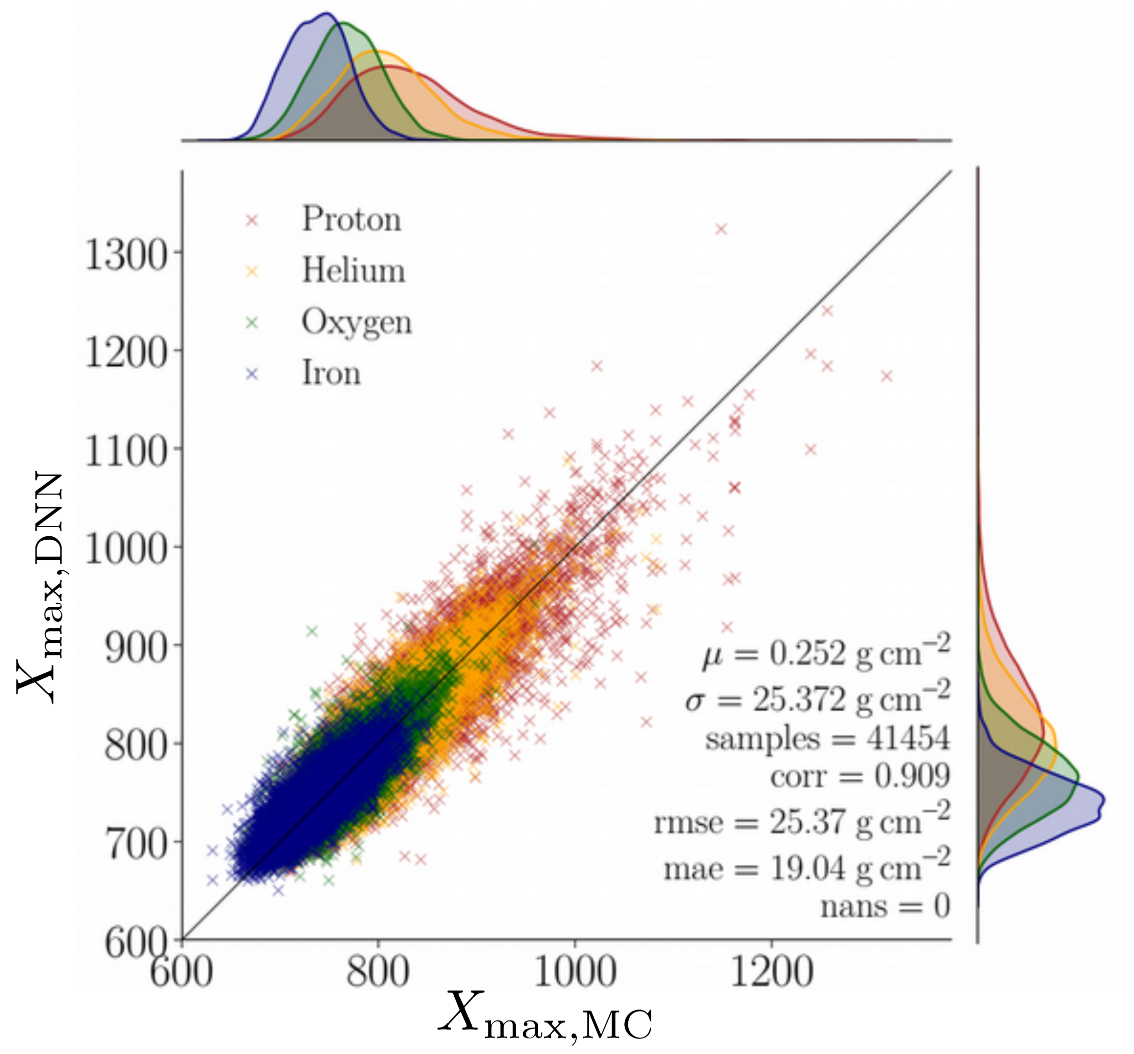
(Submitted to Earth and Space Sciences, 2019)

Outlook: The (r)evolution of machine learning

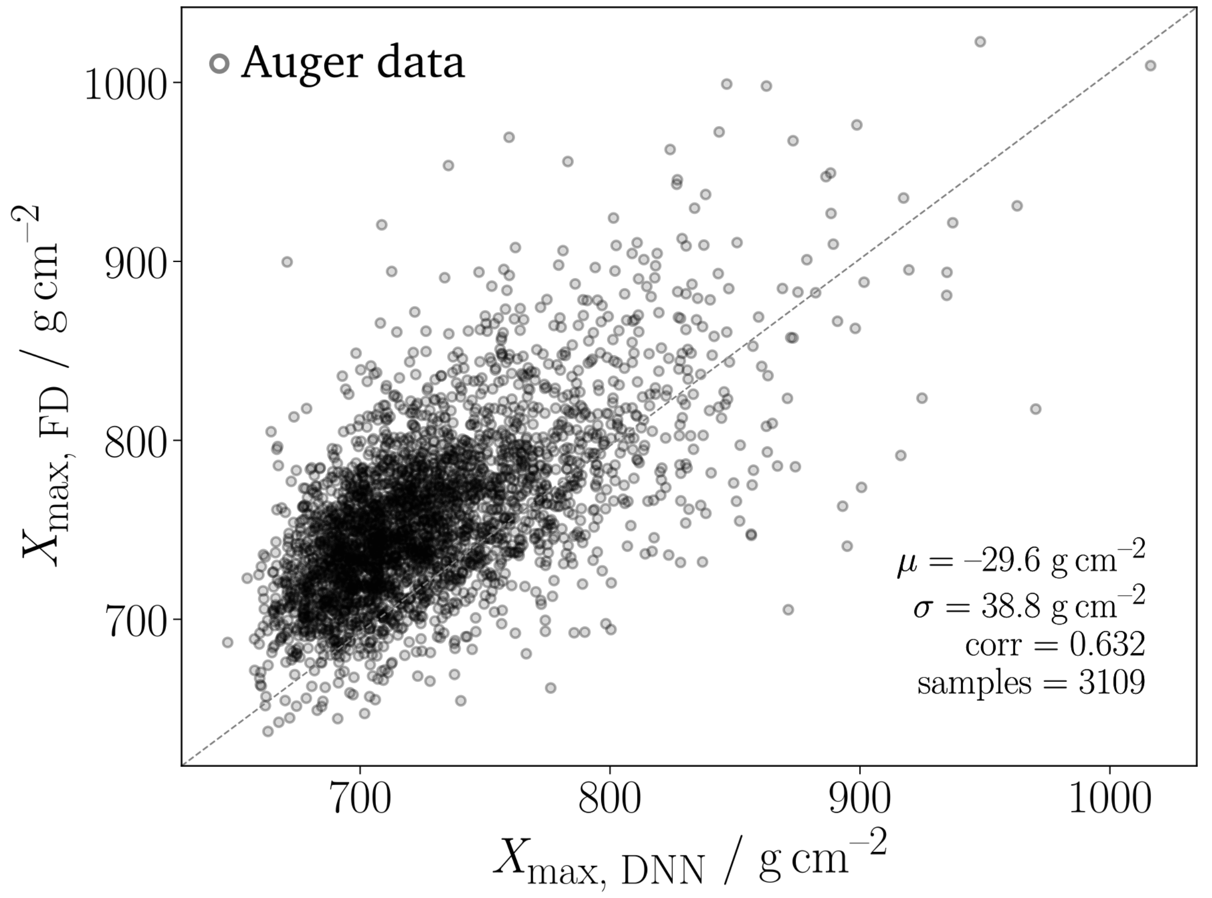
Simulated signal trace of one station

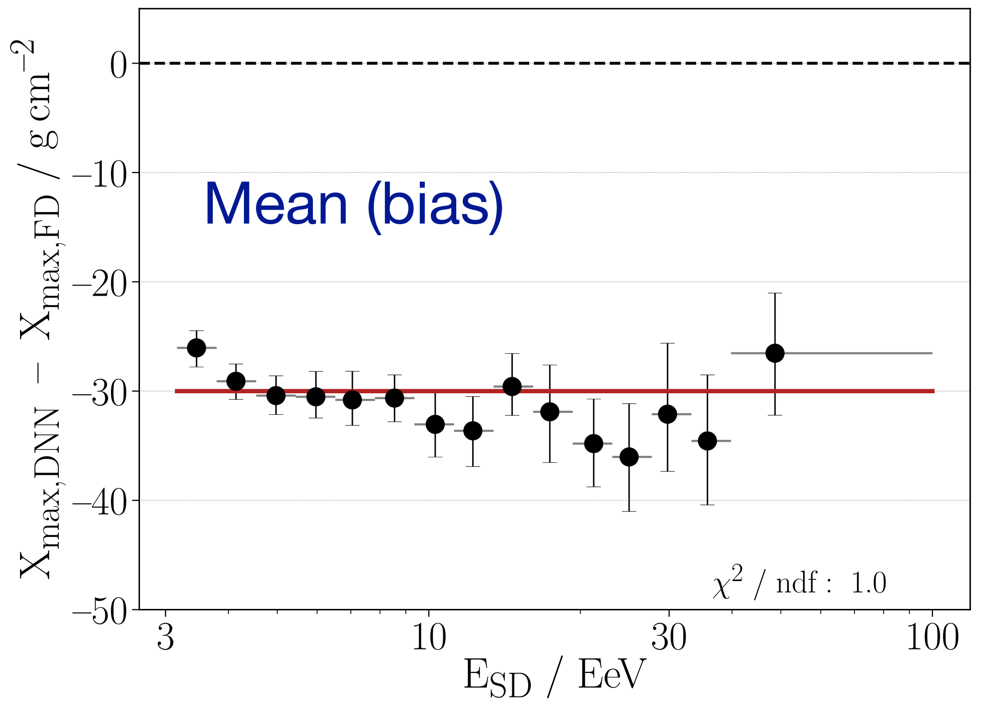


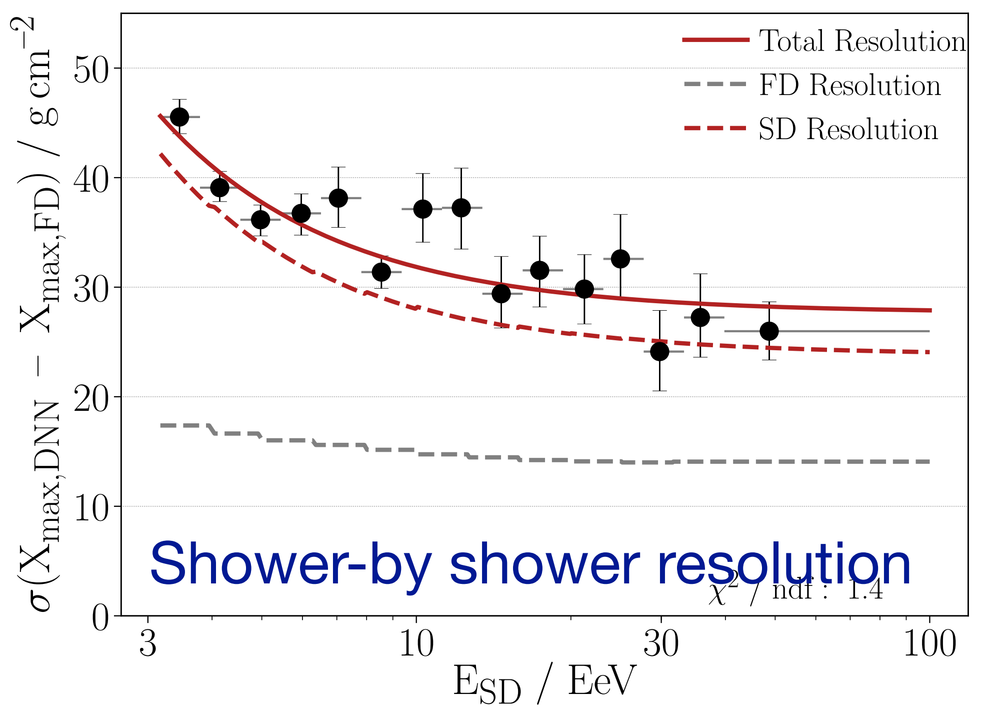




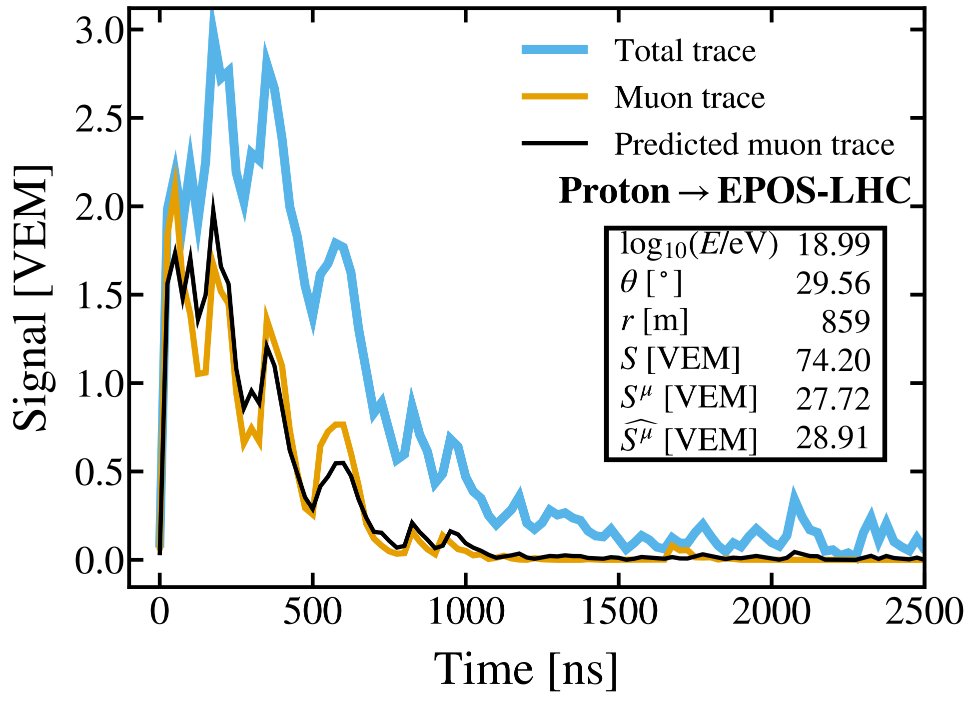
Reconstructing Xmax: ultimate check with data

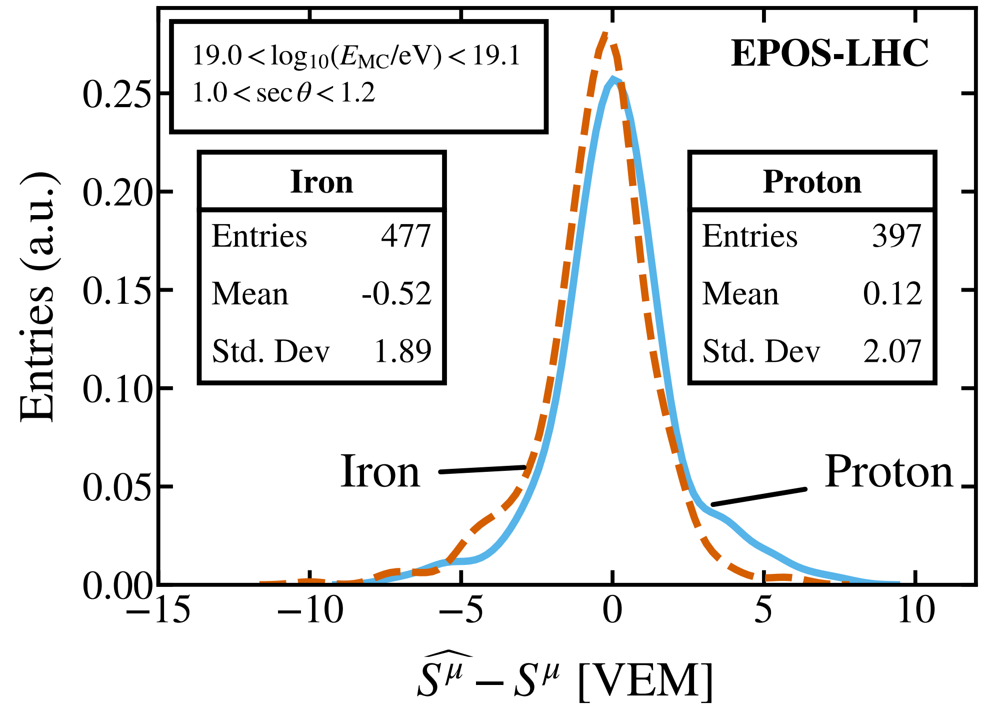






Reconstructing the muon signal of a station (no data available)





Phase II data will allow us to verify and optimize DNN and universality methods