Ultra-High-Energy Cosmic Rays at the Pierre Auger Observatory: Insights and Future Directions

Markus Roth on behalf of the Pierre Auger Collaboration

RICAP 24

PIERRE AUGER OBSERVATORY

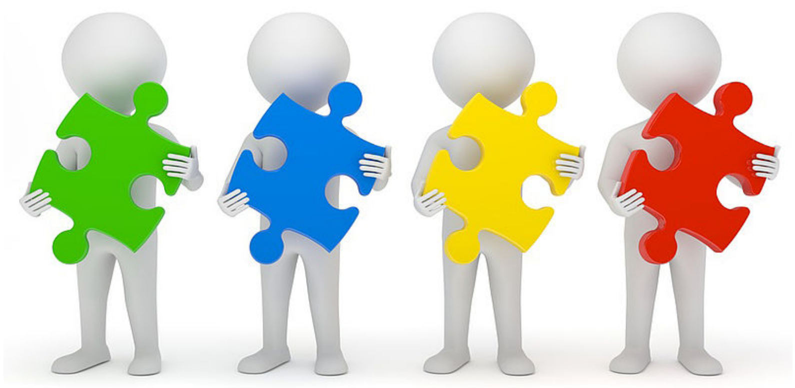
Karlsruhe Institute of Technology

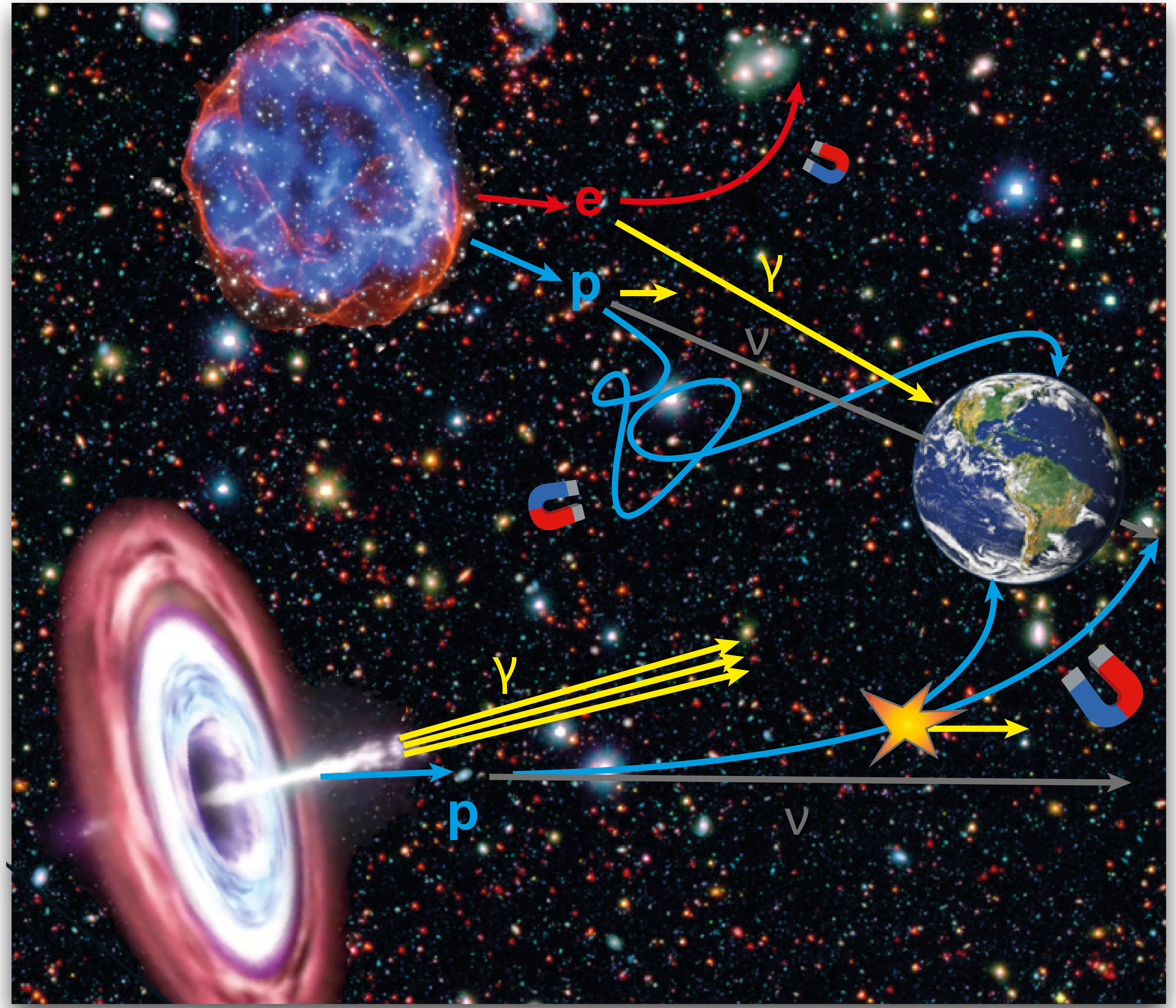
Credit: Steven Saffi

Ultra-high energy cosmic rays above 10^{18} eV

Physics questions:

- What are the **sources**?
- How are they **accelerated**?
- How do they **propagate**?
- How do they **interact** in the atmosphere?





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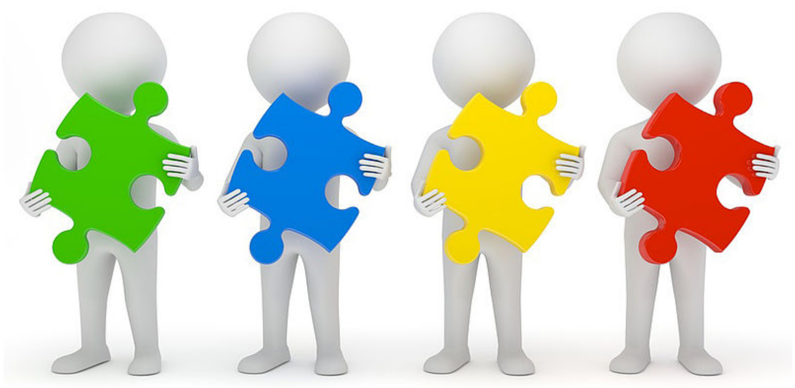
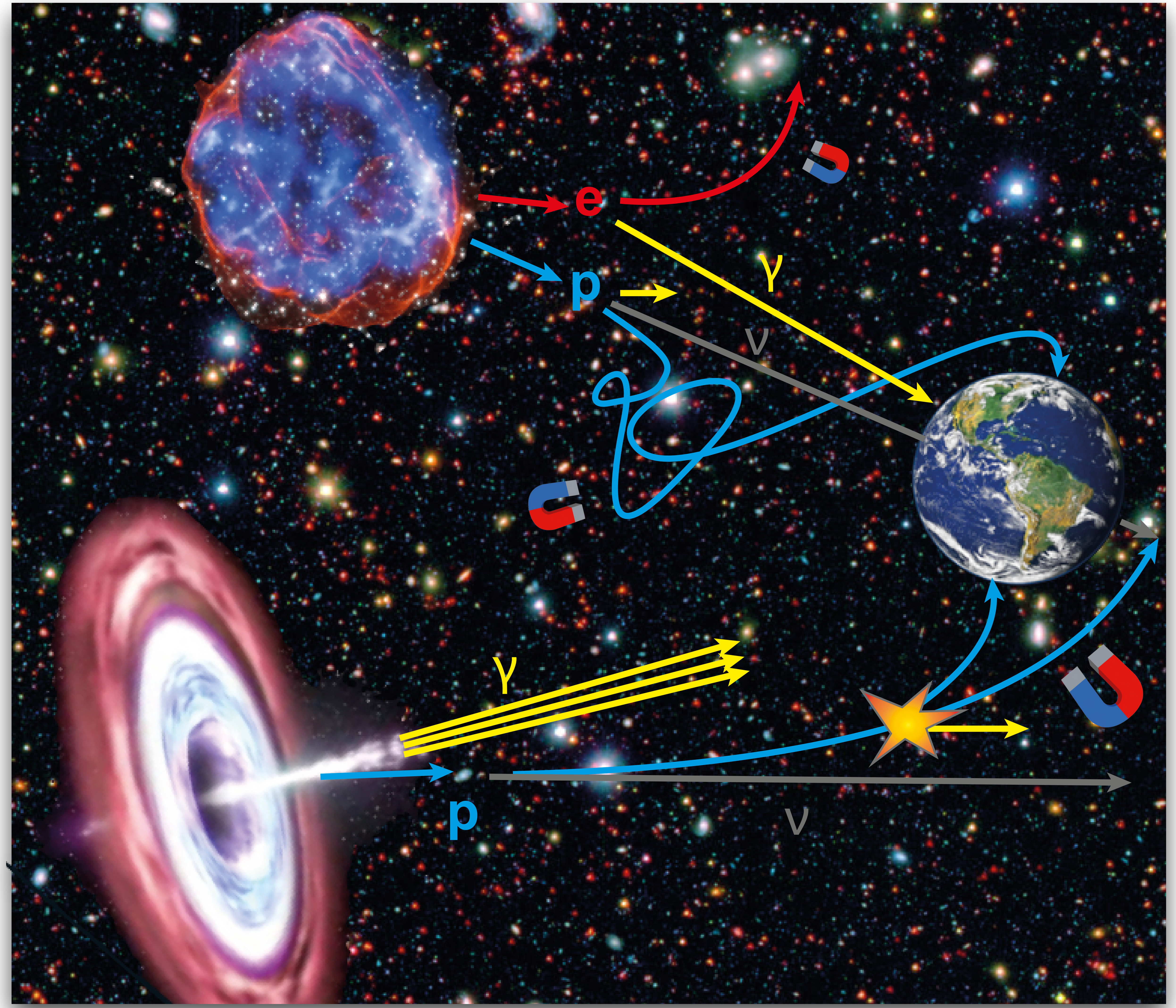


Measured quantities:

- **Energy spectrum**
- **Mass composition**
- **Arrival direction**

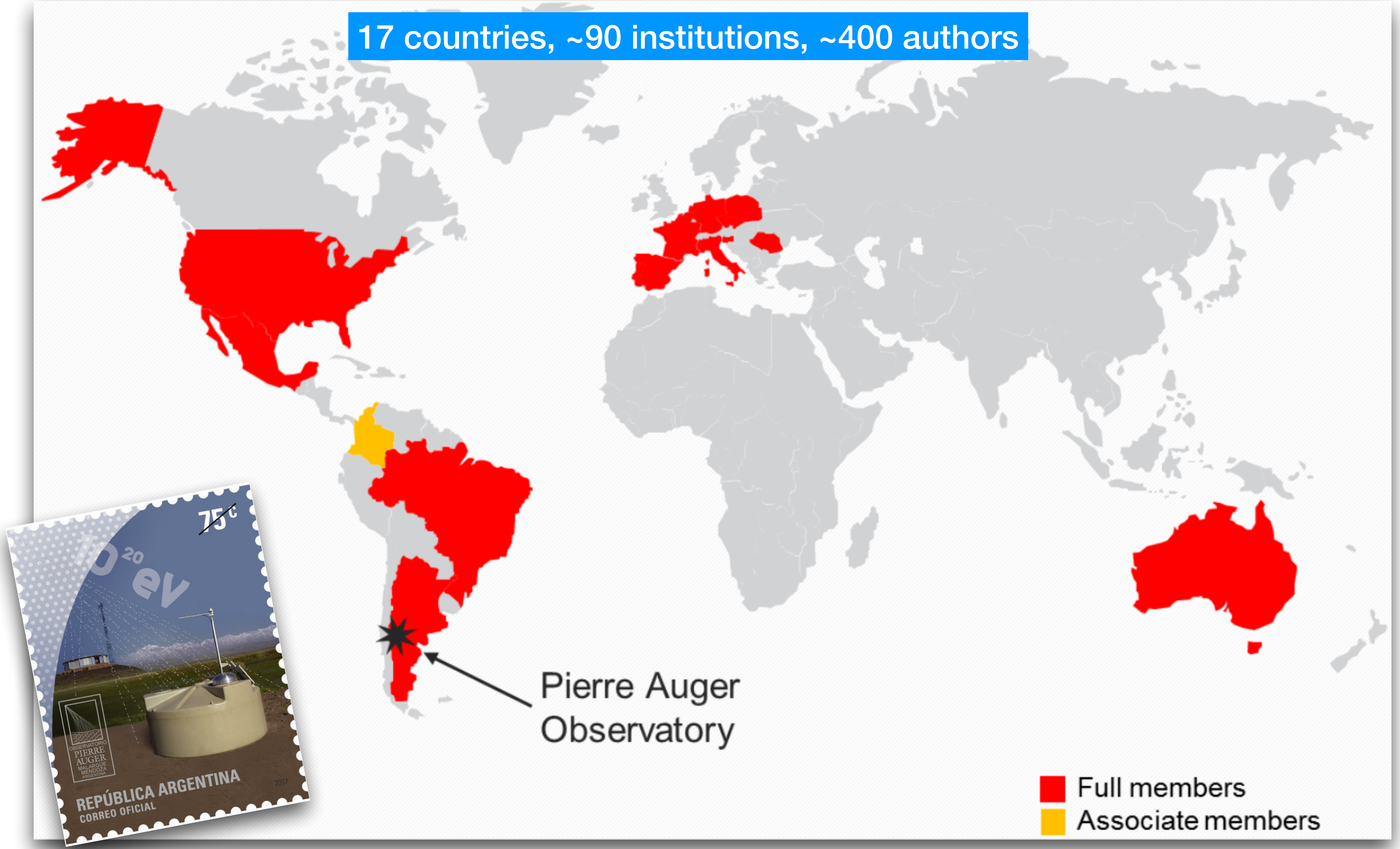
Interpretation



The Pierre Auger collaboration

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

**associated*



PIERRE AUGER OBSERVATORY

Auger contributions at RICAP

- Roberto Aloisio: The Pierre Auger Observatory and Super Heavy Dark Matter
- Marta Bianciotto: Large-scale anisotropies of ultra-high-energy cosmic rays
- Teresa Bister: Global fit of UHECR spectrum, composition, and anisotropies
- Emanuele De Vito: Multi-messenger studies with the Pierre Auger Observatory
- Marvin Gottowik: Update on the Offline Analysis Framework for AugerPrime and integration of the AugerPrime Radio Detector reconstruction
- Federico Mariani: Anisotropy searches at the highest energy cosmic rays with the Pierre Auger Observatory Phase I
- Vladimir Novotny: Energy evolution of cosmic-ray mass and intensity
- Jannis Pawlowsky: The AugerPrime Radio Detector: Enhancing the Sensitivity to UHE Cosmic Rays (poster)
- Julian Rautenberg: The AugerPrime extension of the Pierre Auger Observatory
- Ezequiel Rodriguez: Overview of Machine Learning Applications (poster)
- Pierpaolo Salvina: Latest results from the searches for ultra-high-energy photons

Energy spectrum

Mass composition

Arrival direction

Interpretation

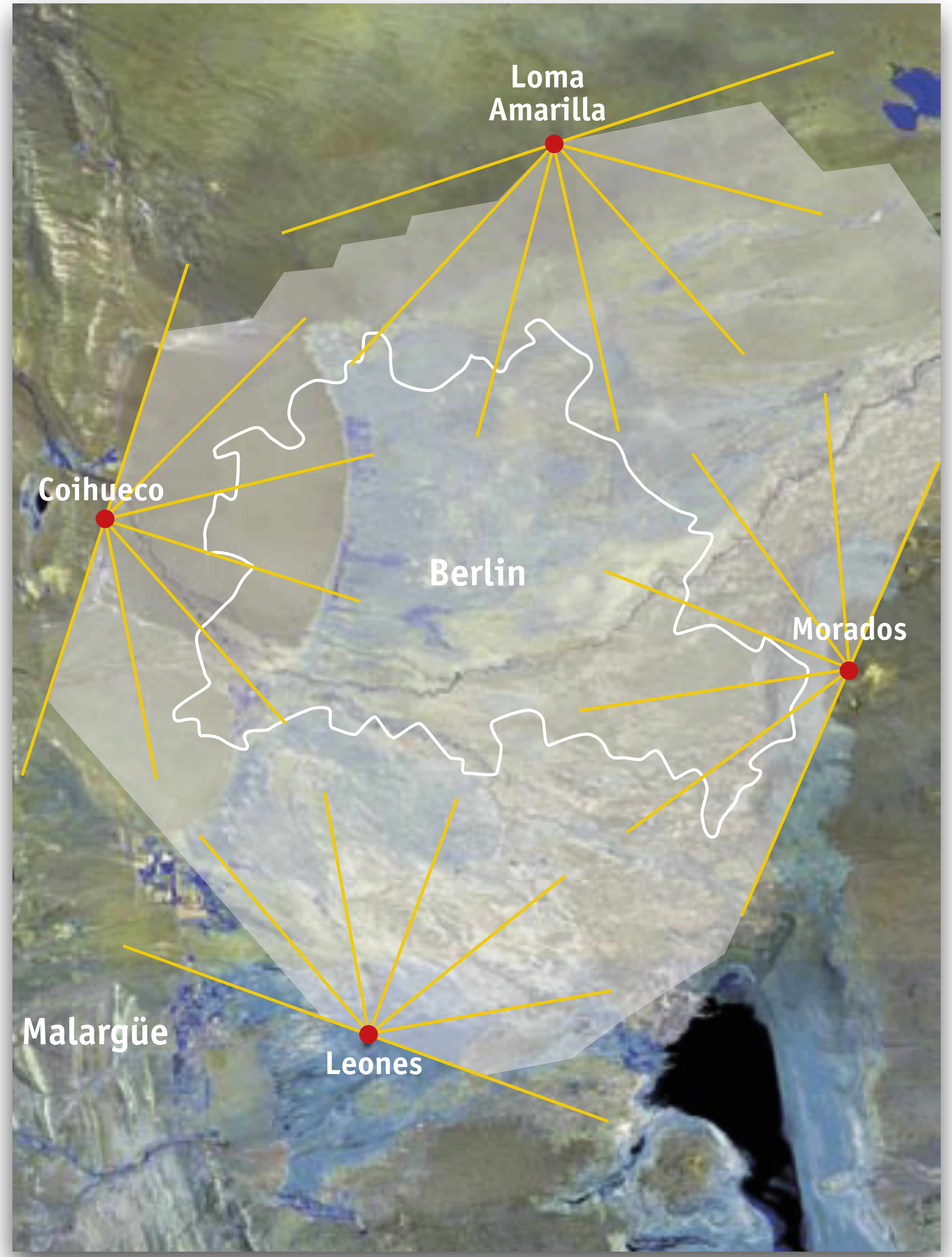
Soft- and hardware improvements

The Pierre Auger Observatory

- East of Andes
- Province of Mendoza, Argentina
- Area 3000 km² (4x Berlin)
- 2000: Engineering Array
- 2004: start...
- 2008: ...end of construction of Auger
- 2024: end of construction of AugerPrime
- Data taking till > 2035

Phase I

Phase II



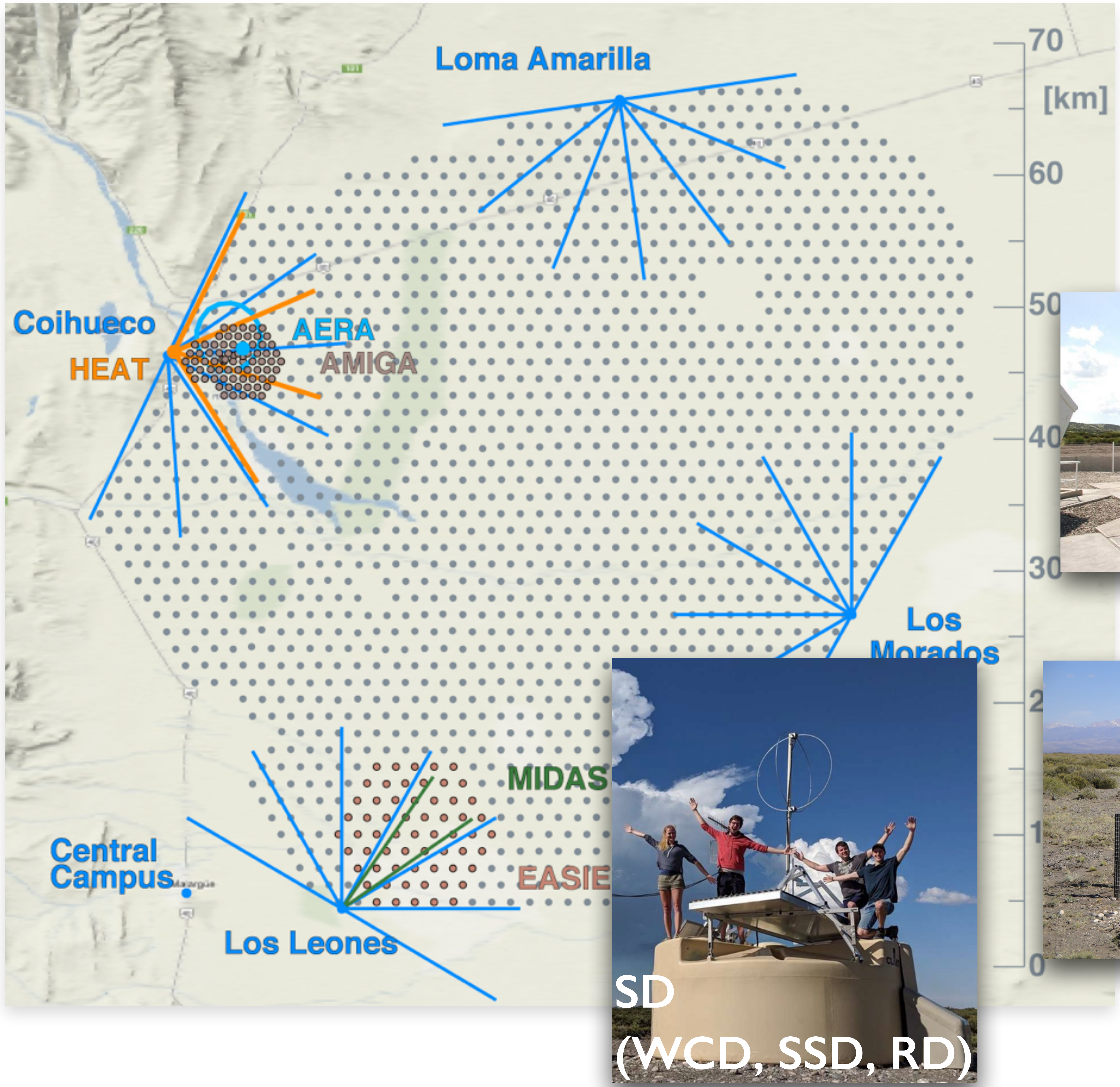
The Pierre Auger Observatory

Fluorescence detector (FD)
- 4 sites
  - 0-30°
  - E>10^{18} eV
- HEAT
  - 30°-60°
  - E>10^{17} eV

Surface detector array (SD)
- Grid of 1500 m / 750 m / 433 m
  - 3000 km^2 / 24 km^2
  - 1660 stations / 61 / 12
  - Water Cherenkov Tanks (WCD)
  - Scintillation Detectors (SSD)
  - Radio Antennae (RD)
  - E>$10^{18.5}$ eV

- Grid of 750 m and 433 m
  - ***Incl. underground muon counters***
  - E>$10^{17.5}$ eV

Radio array (AERA)
- 153 stations
- 17 km^2



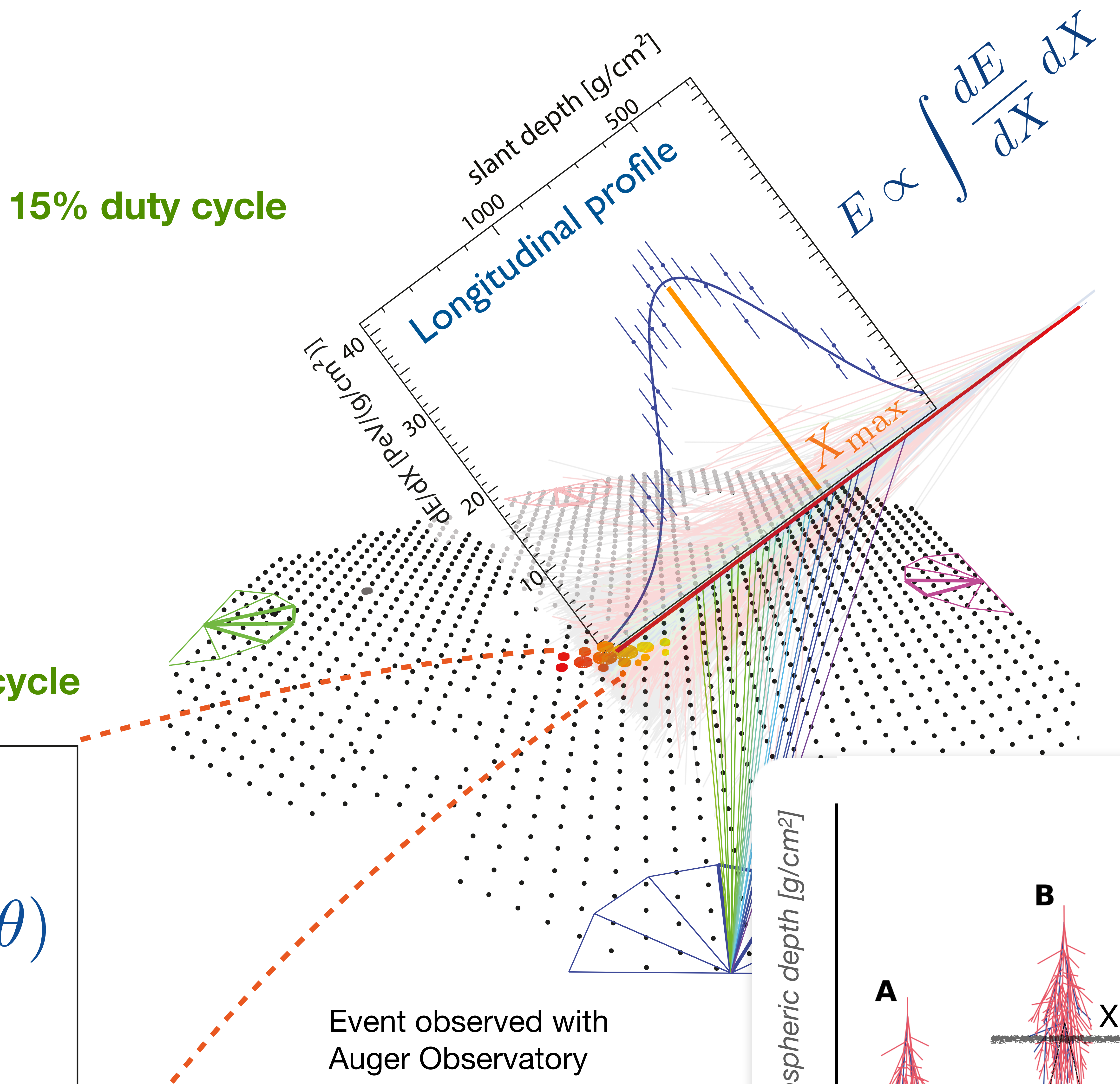
Hybrid detection

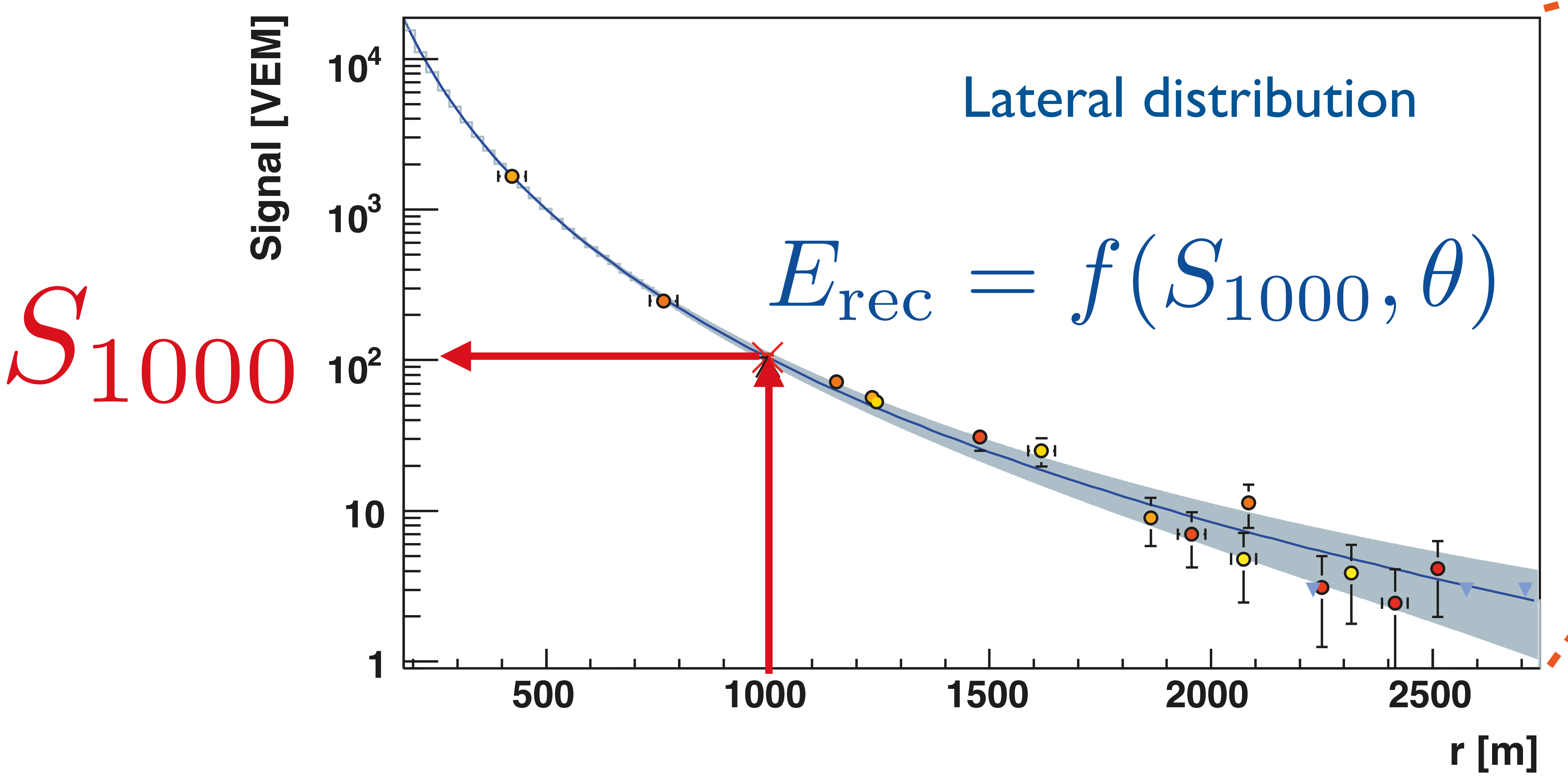
Fluorescence Detector (FD):

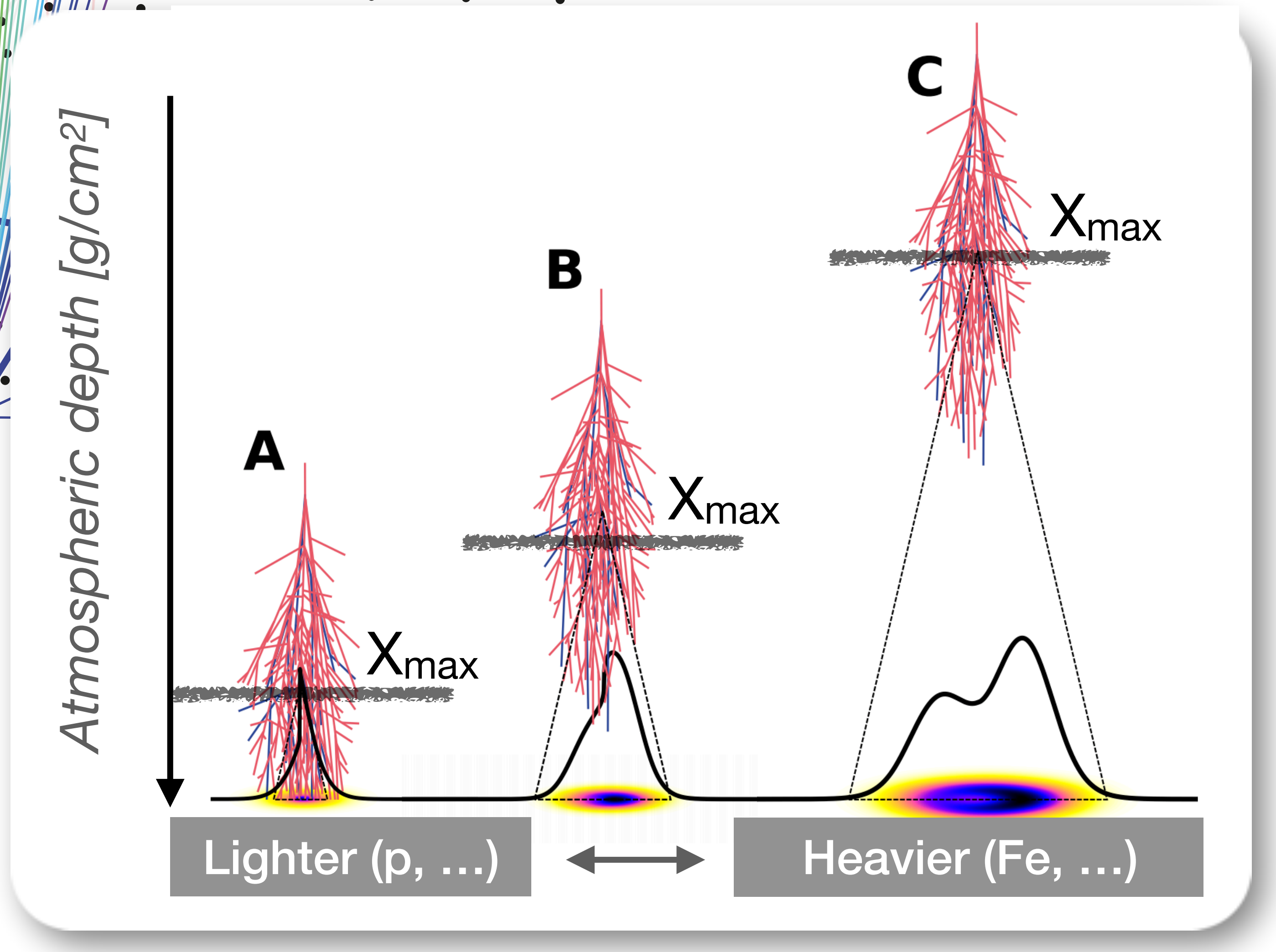
- calorimetric measurement of energy
- ca. 15% duty cycle

Surface Detector (SD):

- data driven shape of Lateral Distribution function (LDF)
- optimal distance at 1000 m
- ca. 100% duty cycle

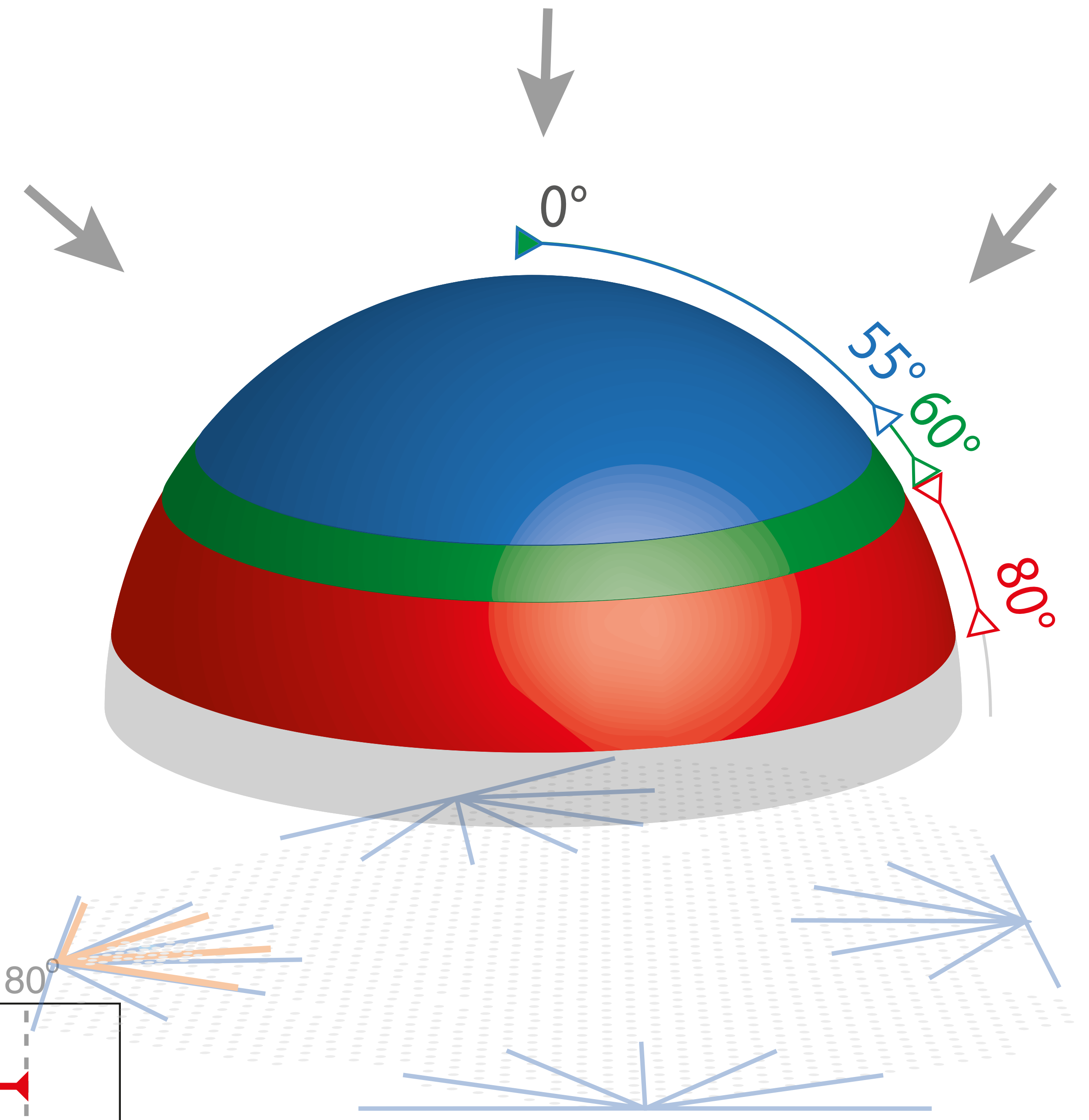






Energy spectrum

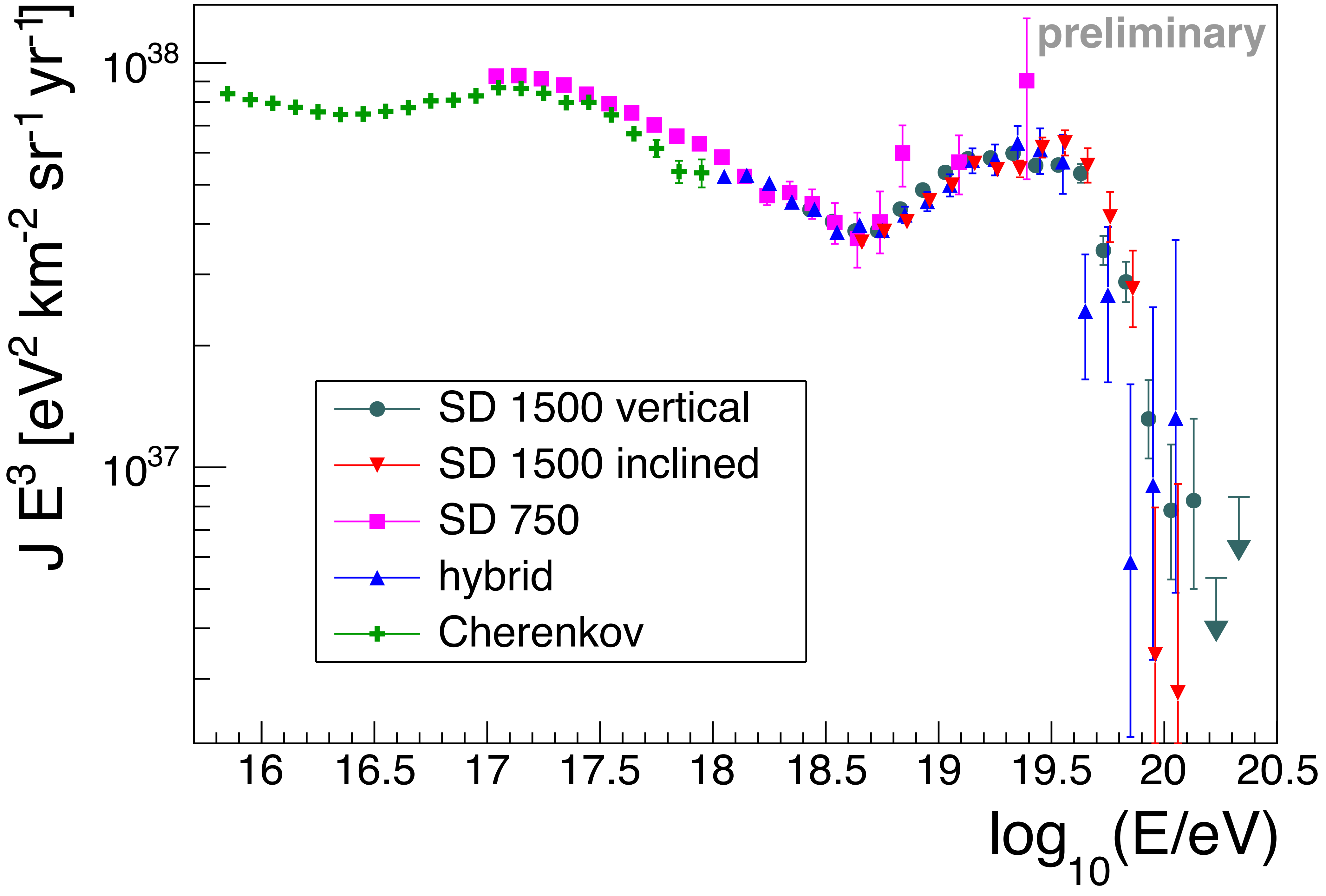
All particle spectrum

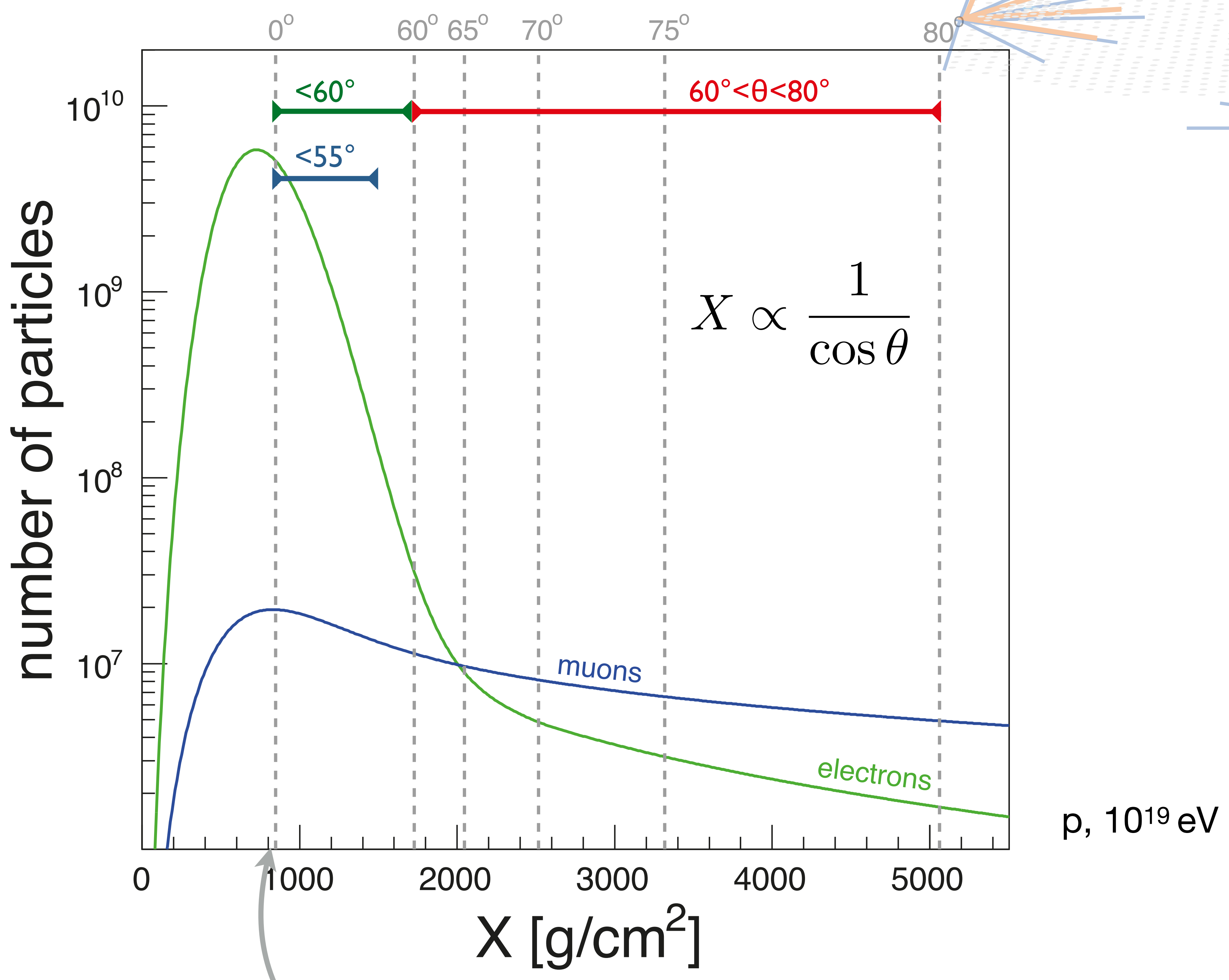


Systematic uncertainty of energy scale

$\Delta E/E = 14\%$

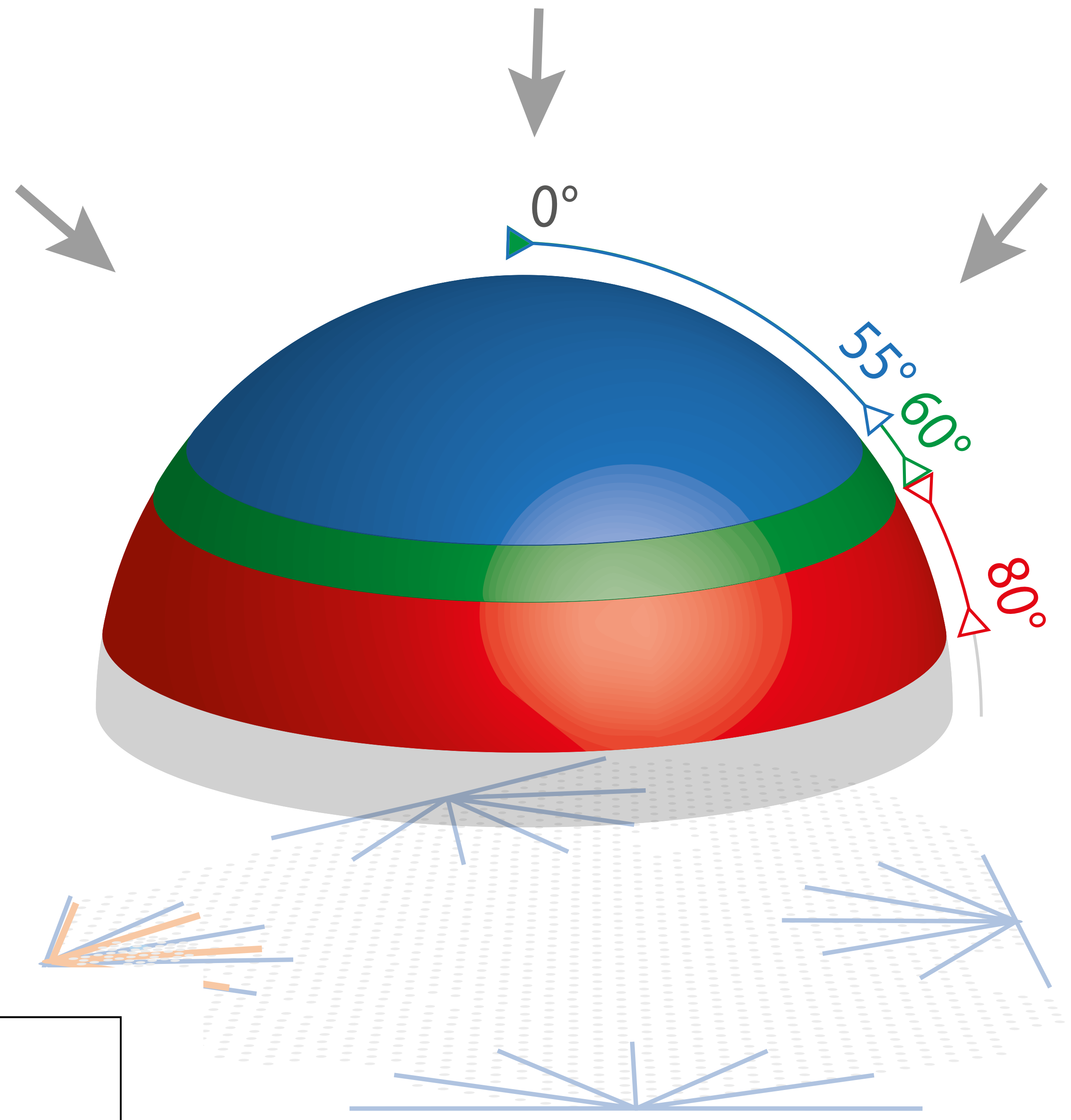
Cherenkov:	$0° < \theta < 60°$	E> 6×10^{15} eV
750m:	$0° < \theta < 55°$	E> 3×10^{17} eV
Hybrid:	$0° < \theta < 60°$	E> 3×10^{18} eV
1500m:	$0° < \theta < 60°$	E> 3×10^{18} eV
1500m:	$60° < \theta < 80°$	E> 4×10^{18} eV





Depth of Malargüe site (870 g/cm²)

All particle spectrum



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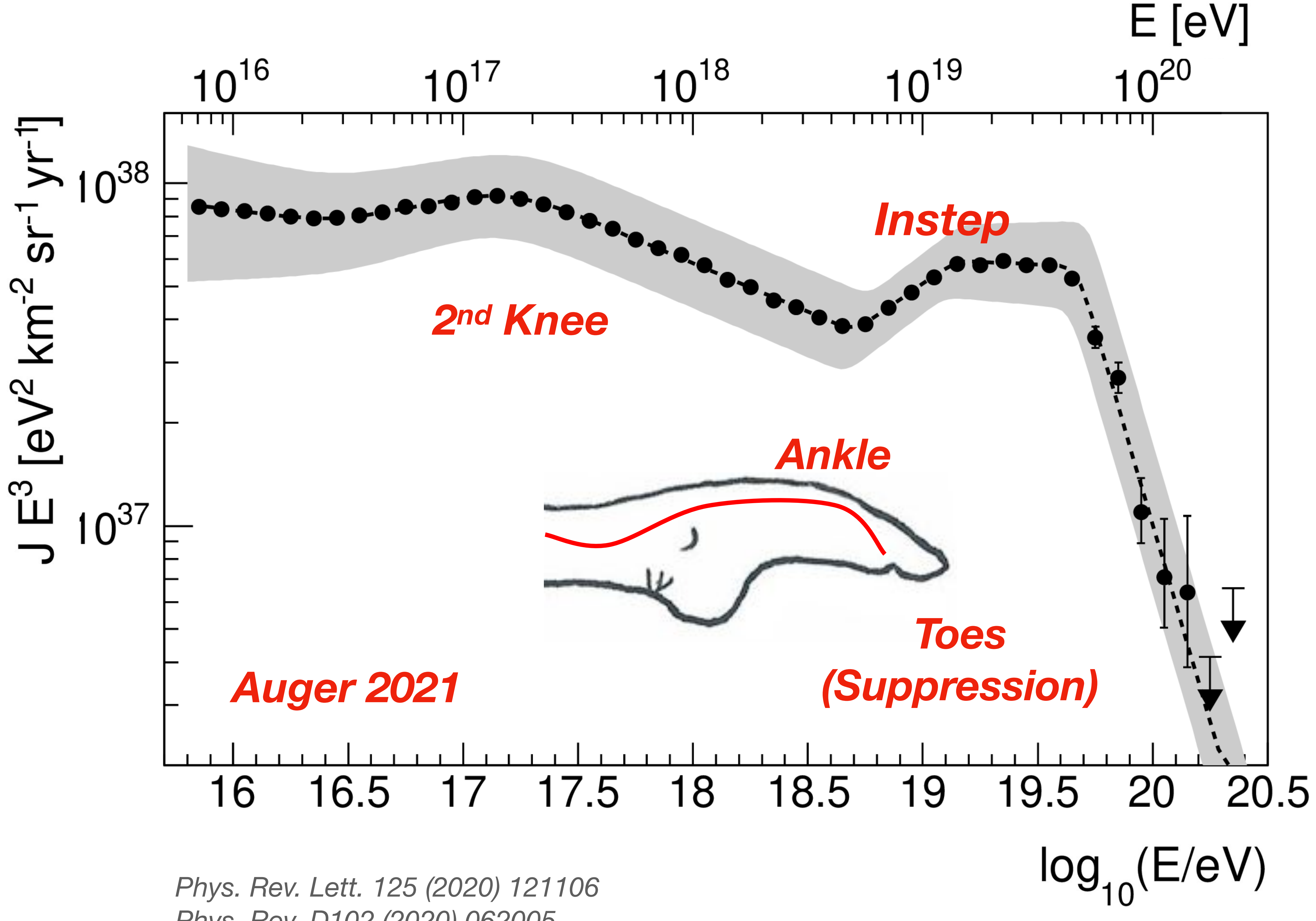
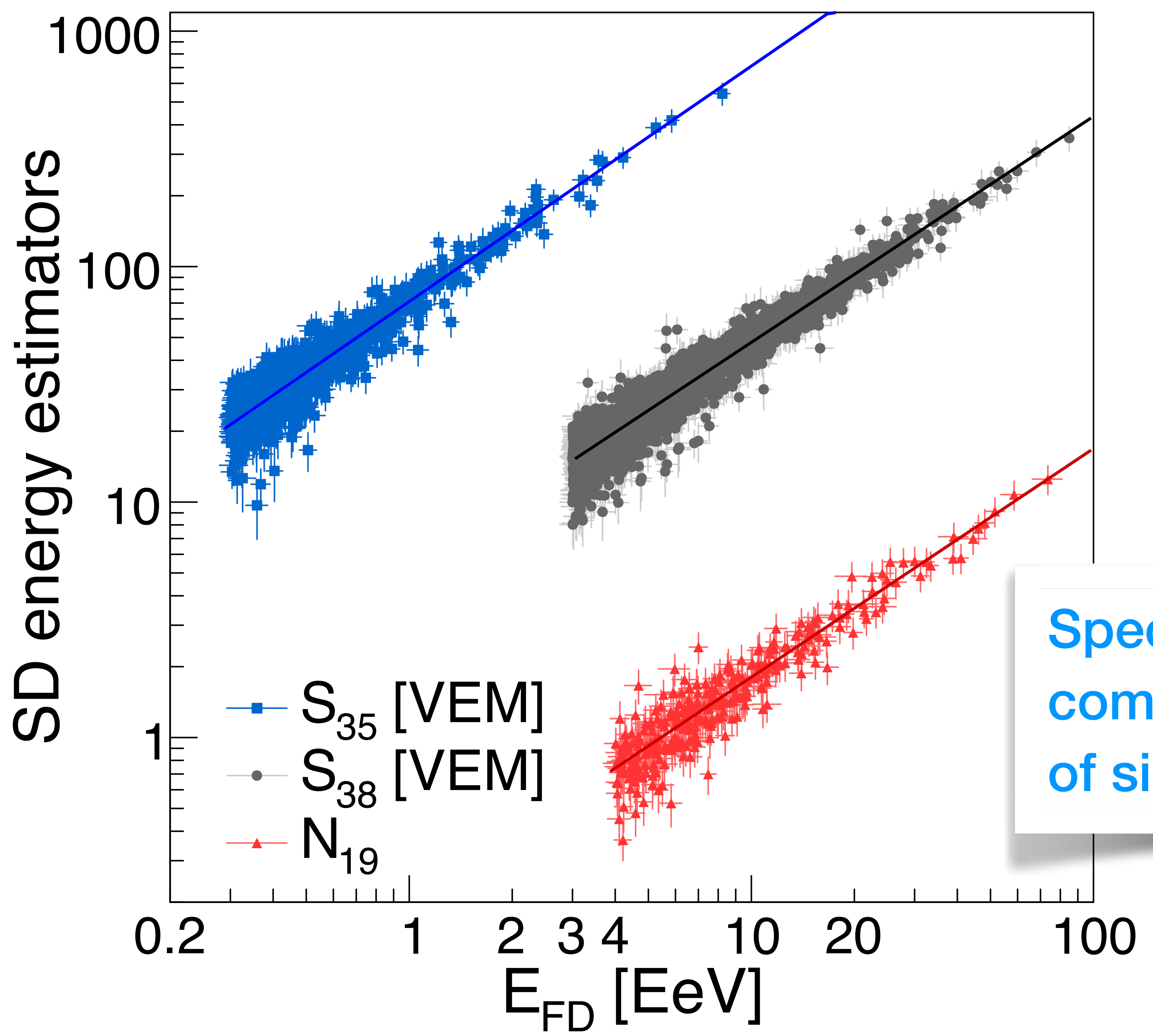
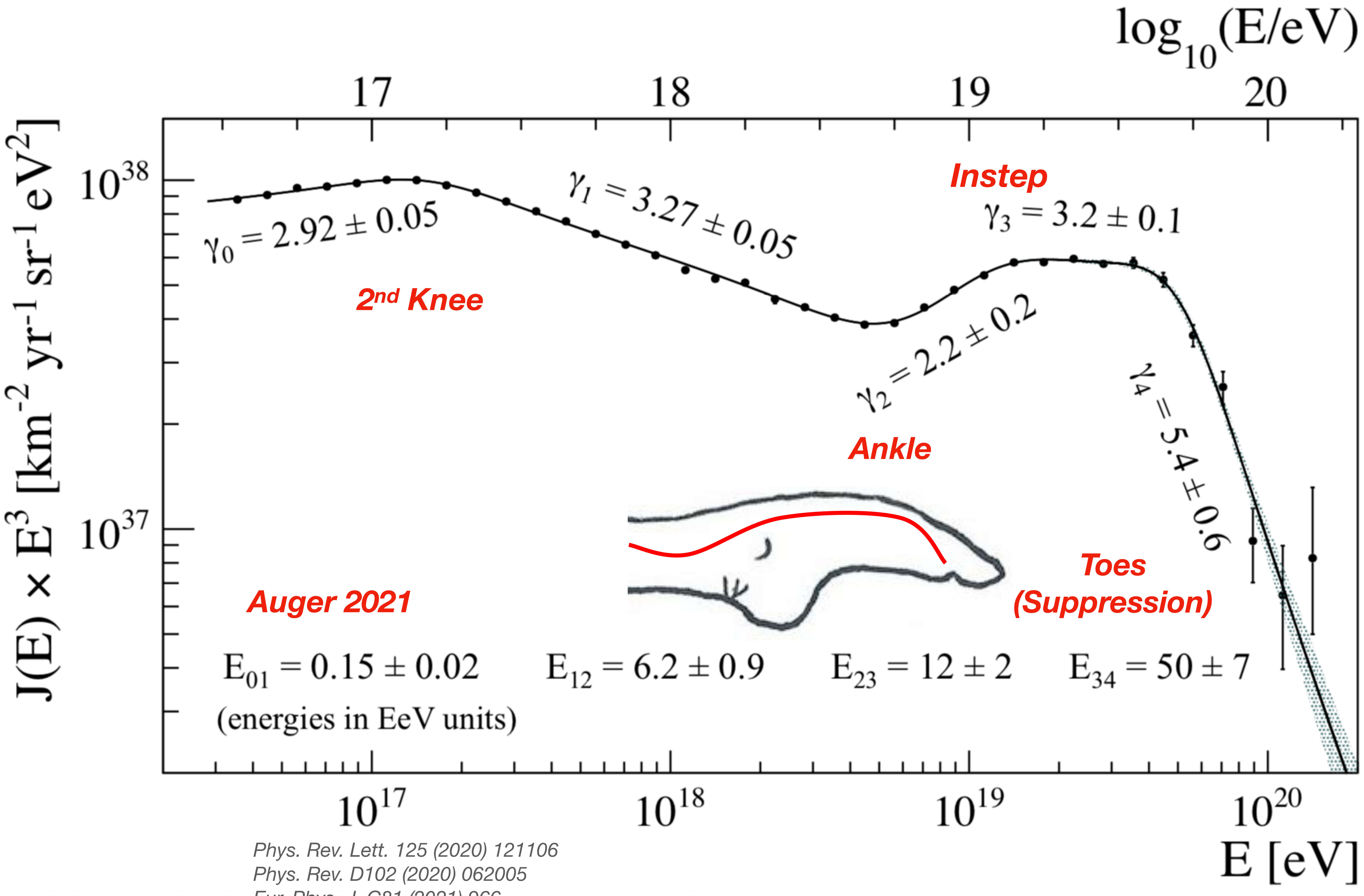




Spectrum shape and Instep not compatible with source models of single mass group (p, ..., Fe)

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

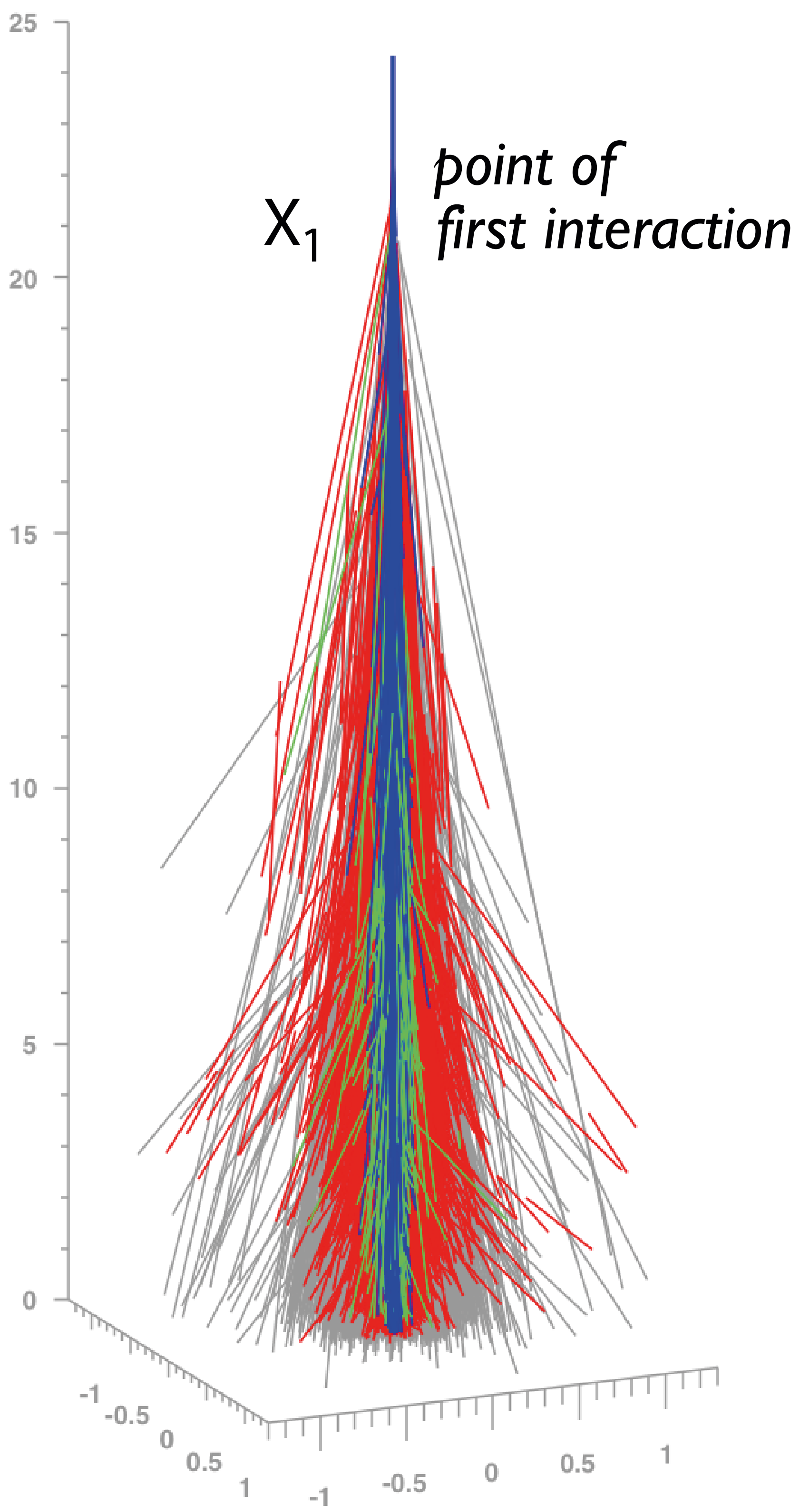
All-particle spectrum

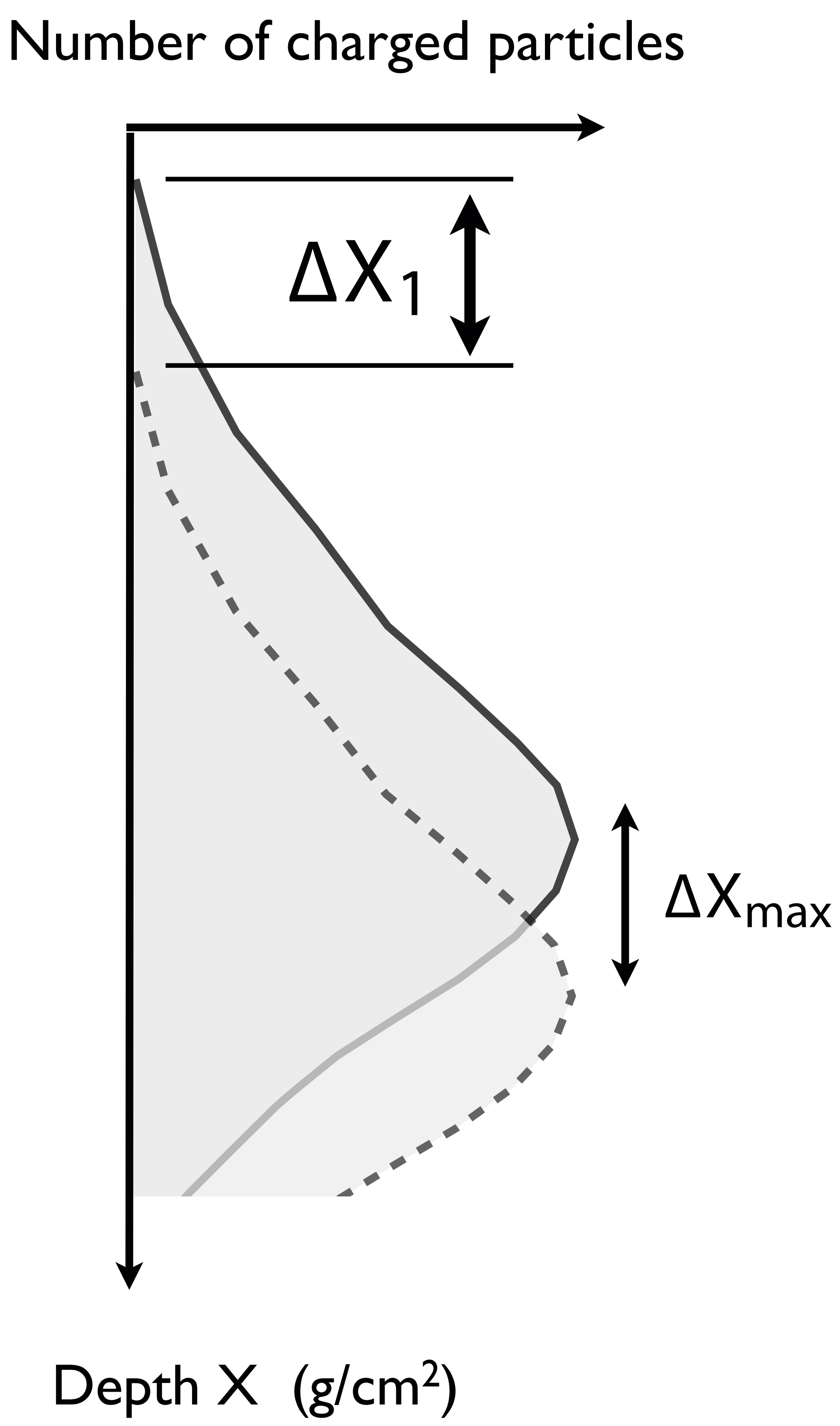


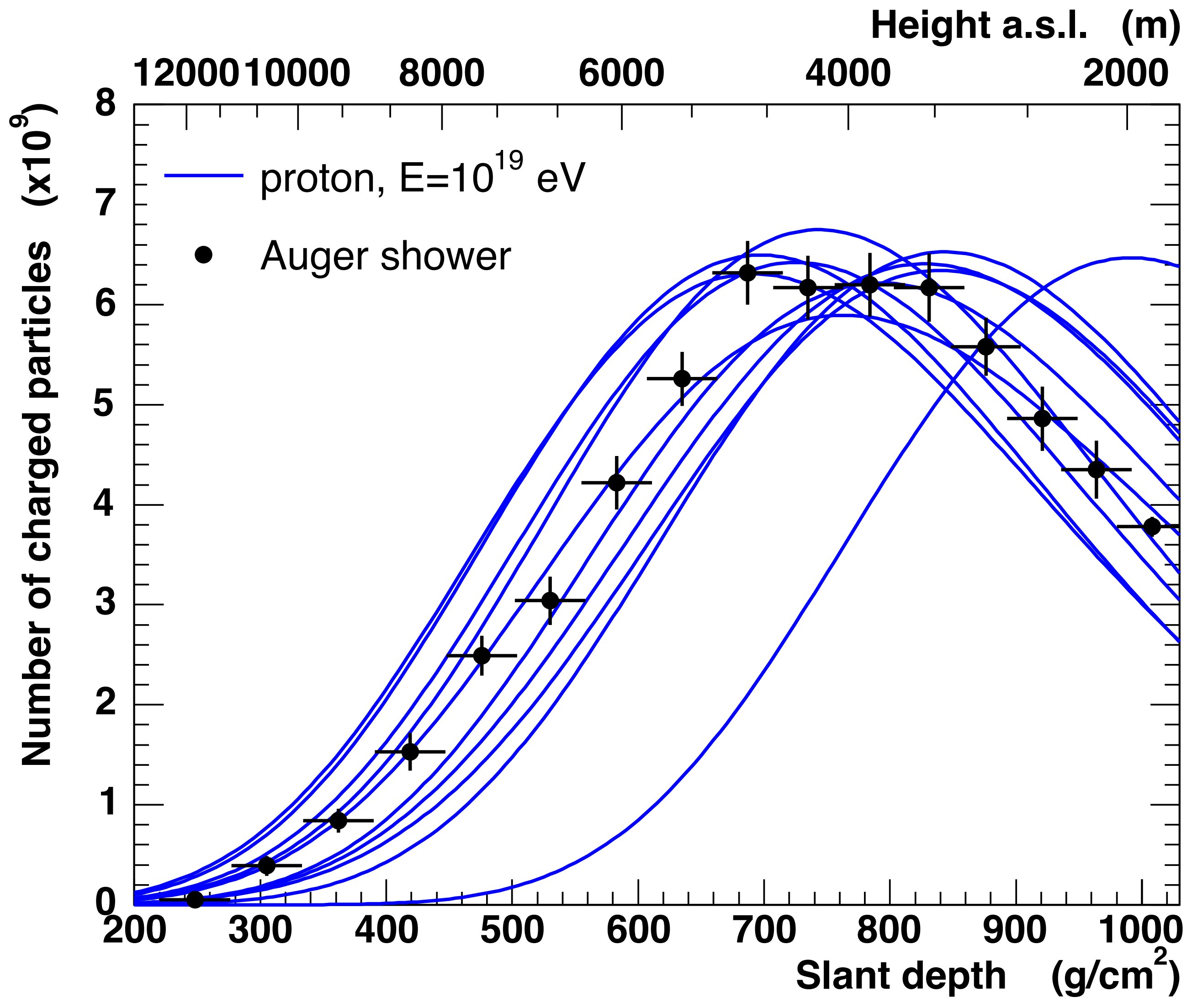
Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
Eur. Phys. J. C81 (2021) 966

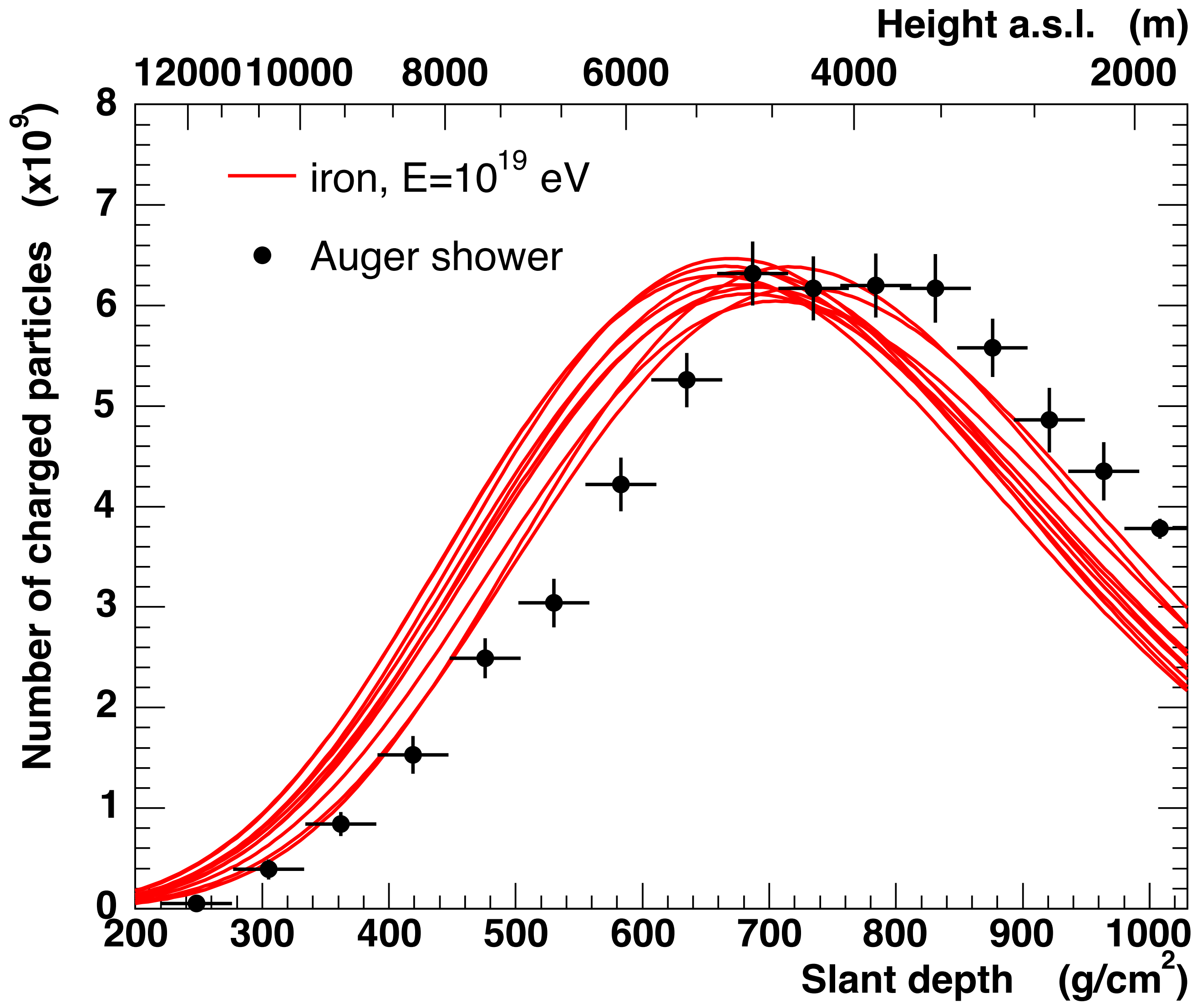
Composition: X_{max}

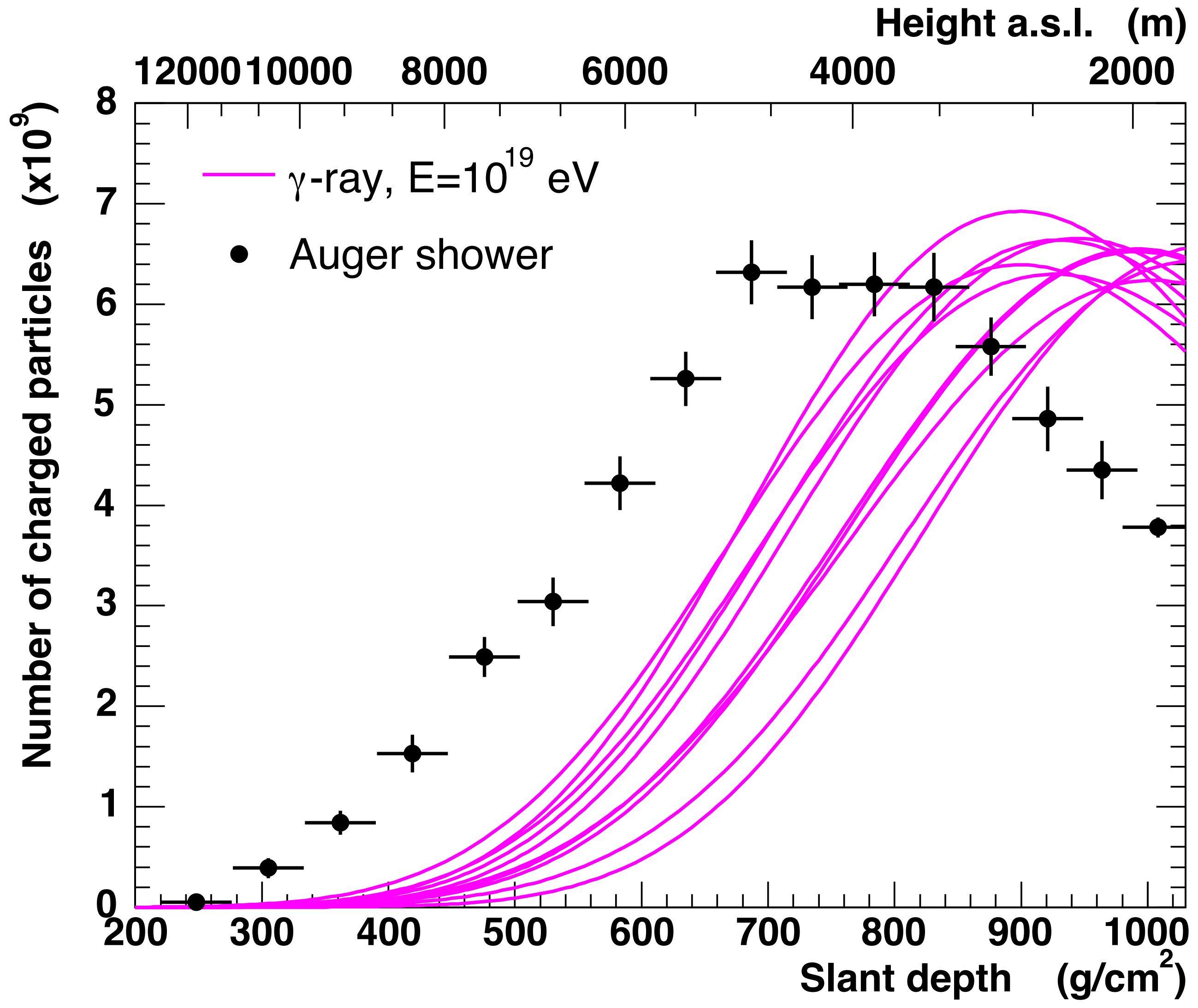
Mass composition: Depth of shower maximum

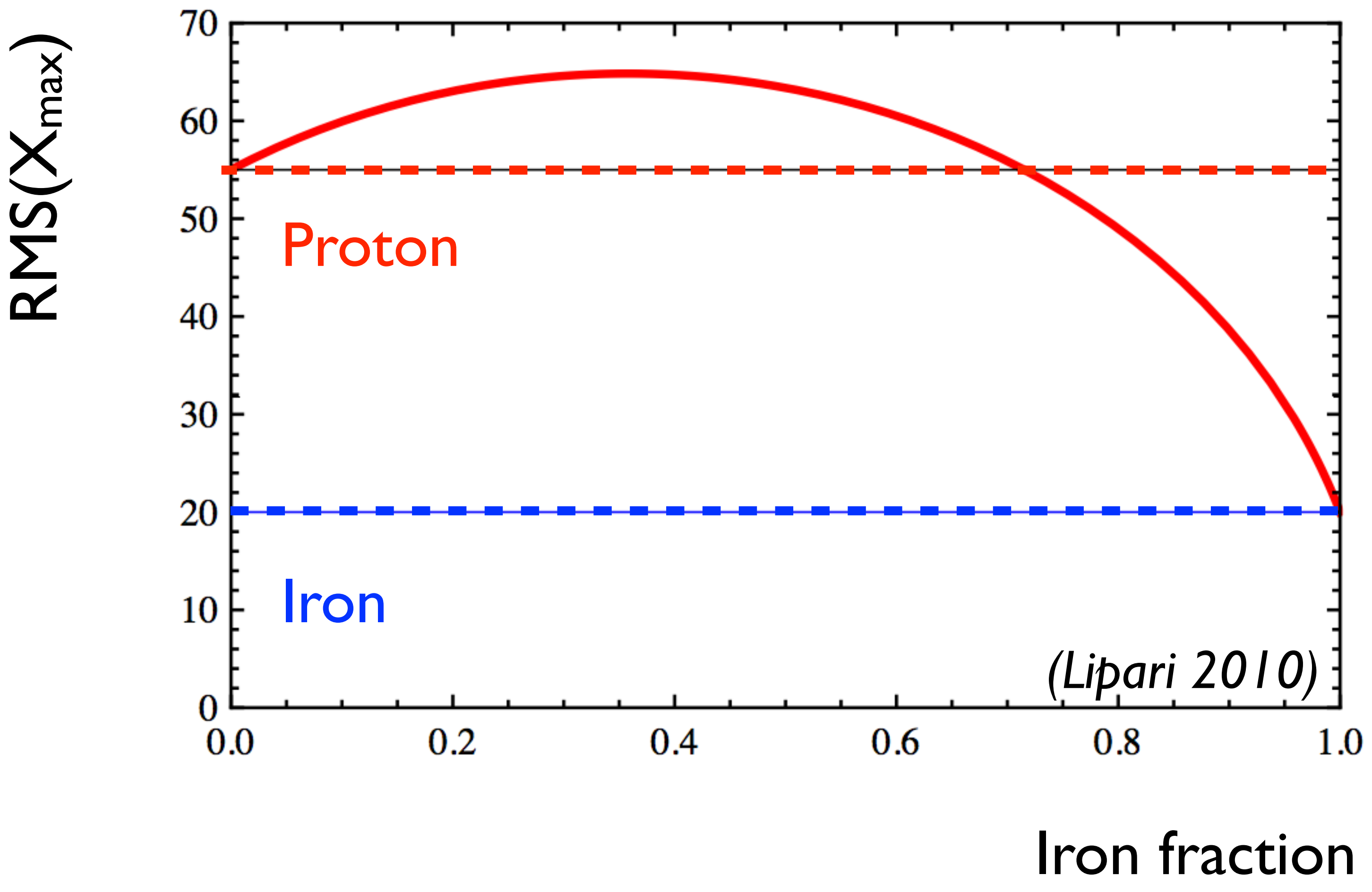




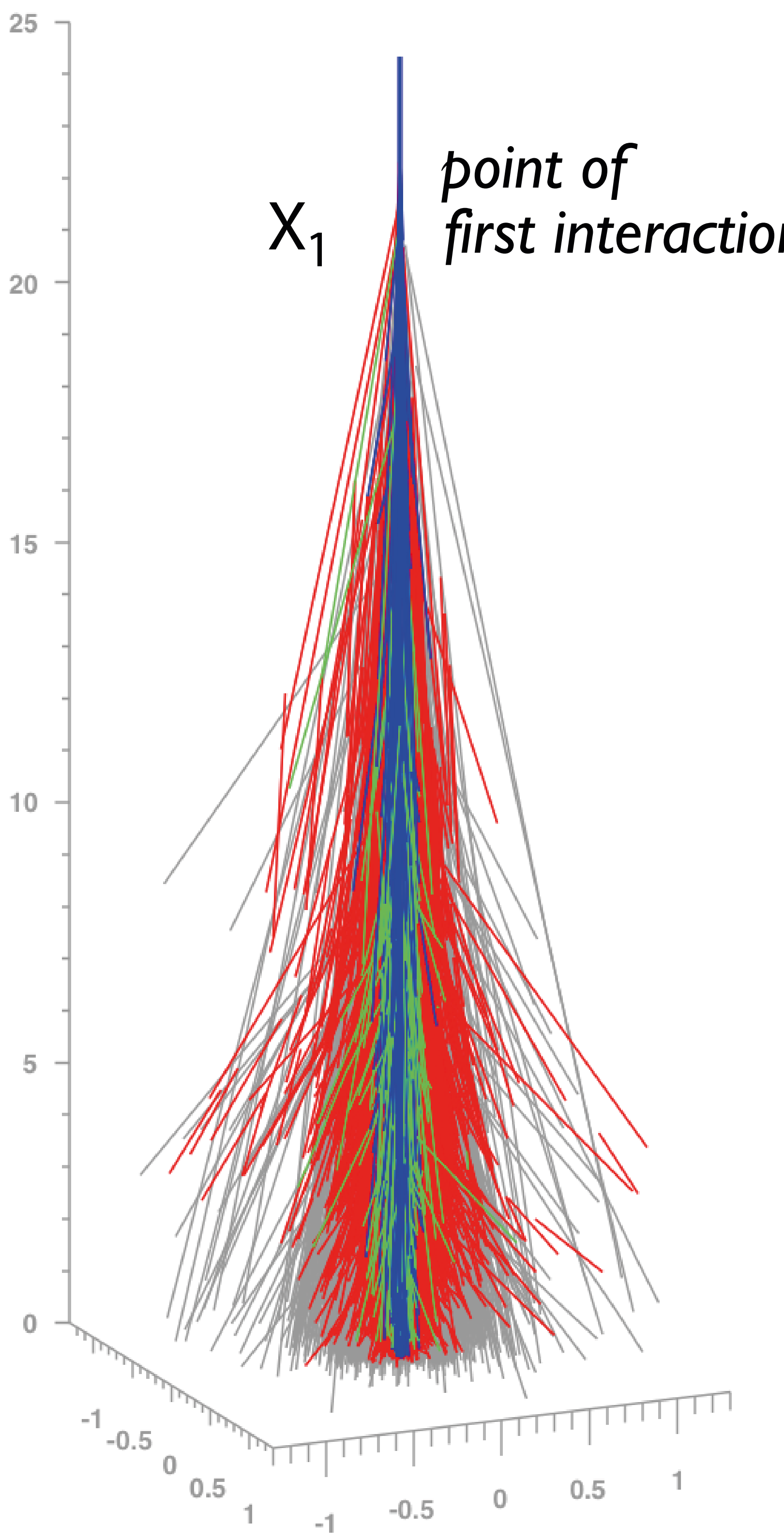


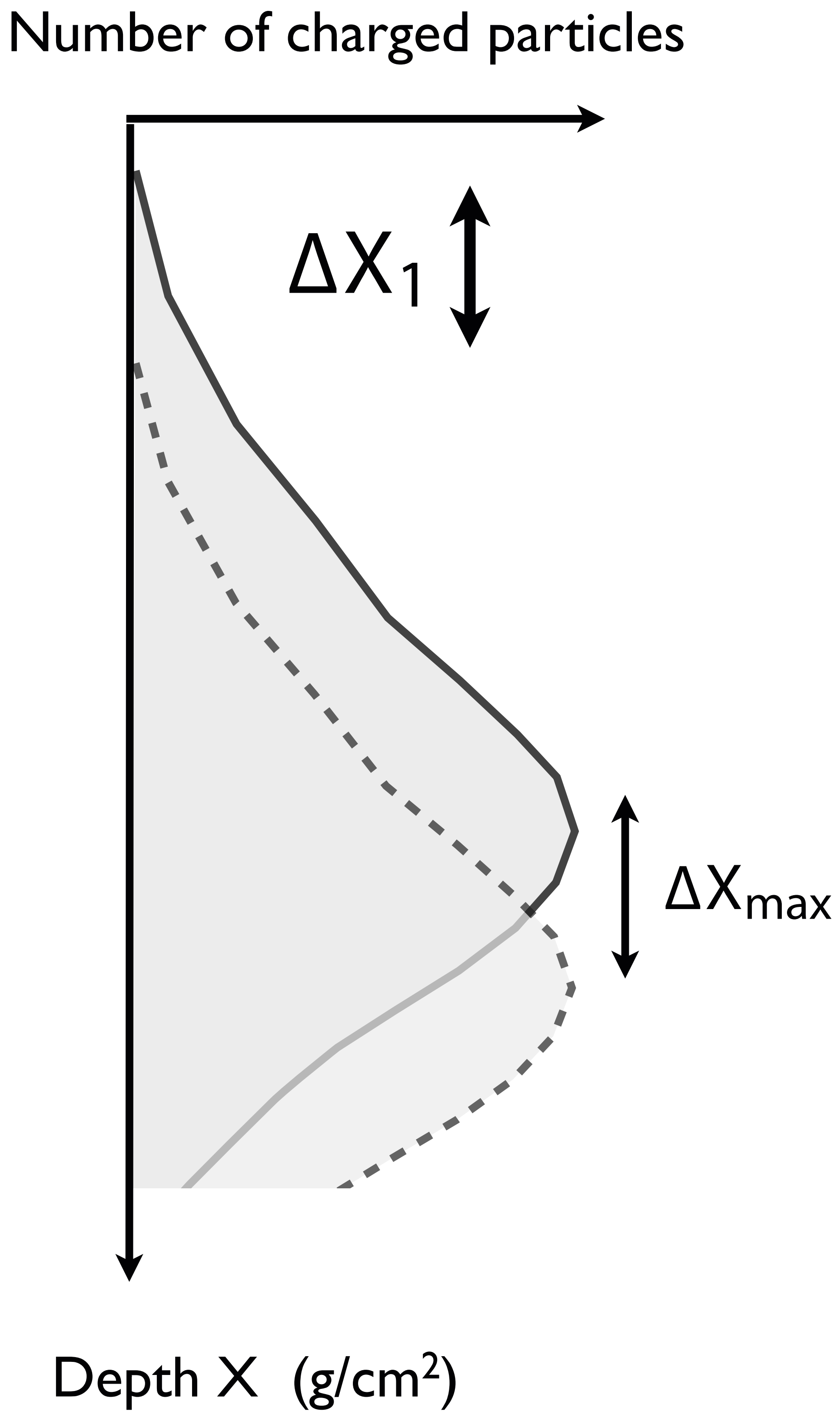






Mass composition



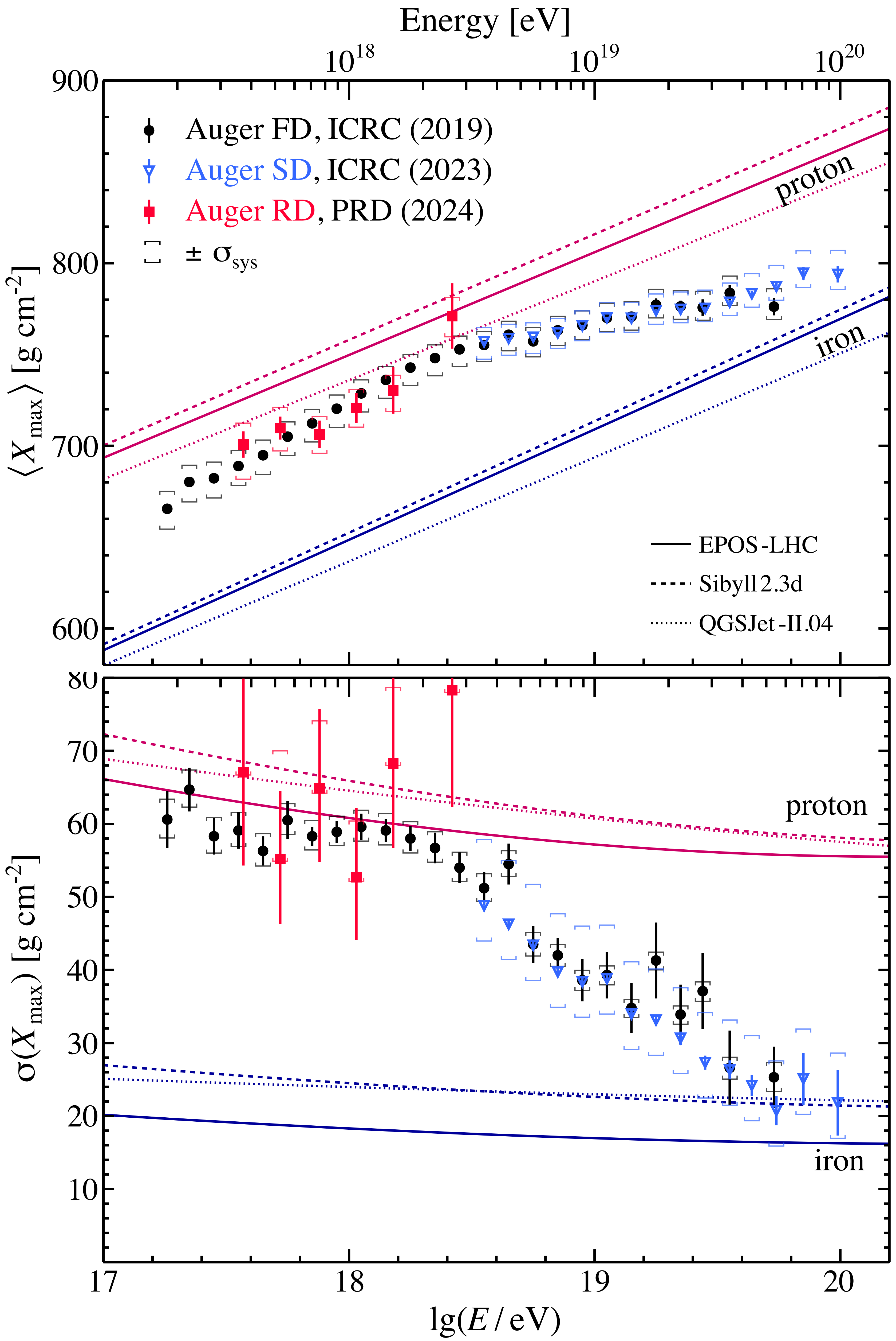


Break(s) in elongation rate *D*?

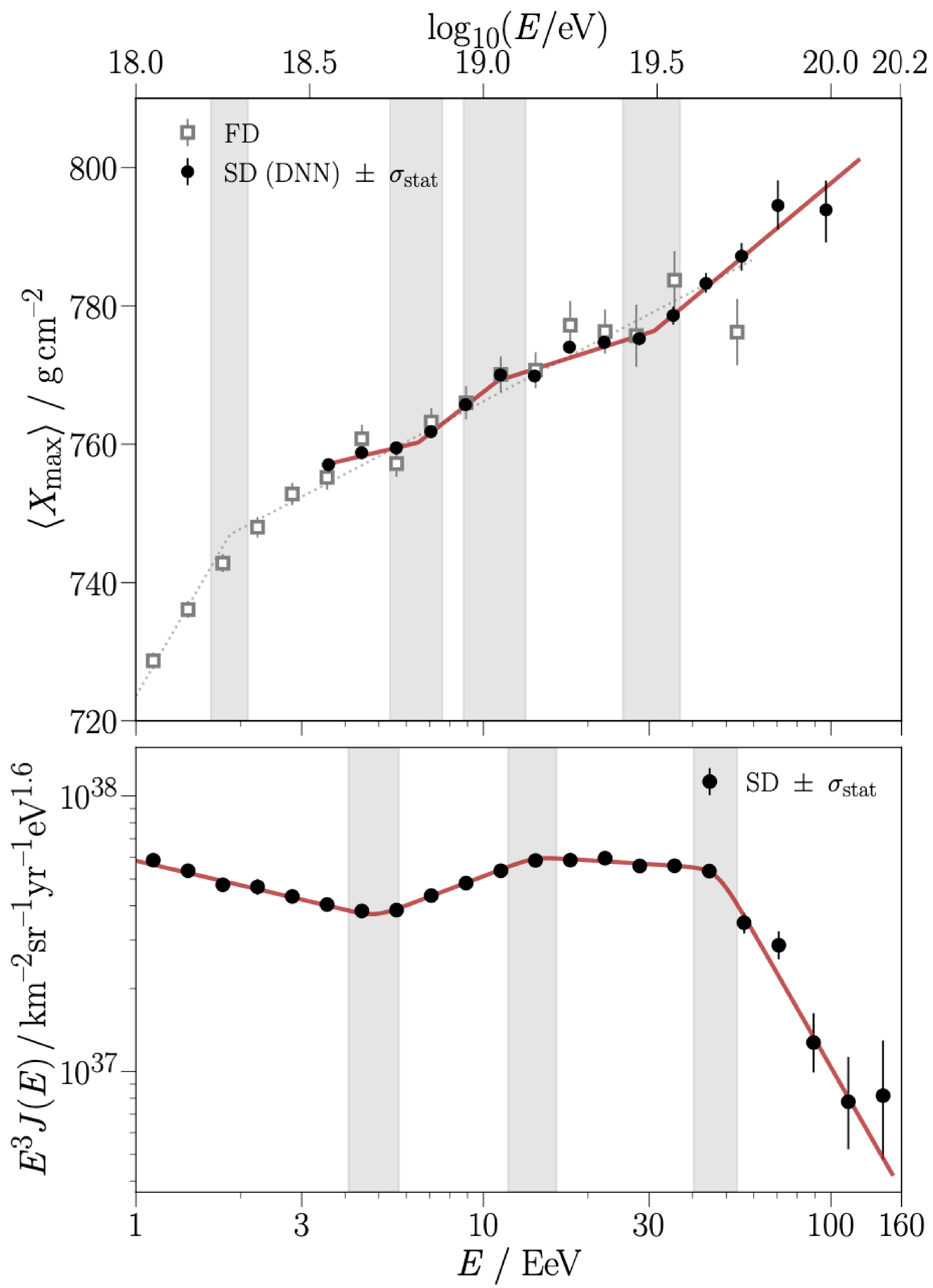
$$\langle X_{\max} \rangle \propto \ln A + D \ln \frac{E}{E_0}$$

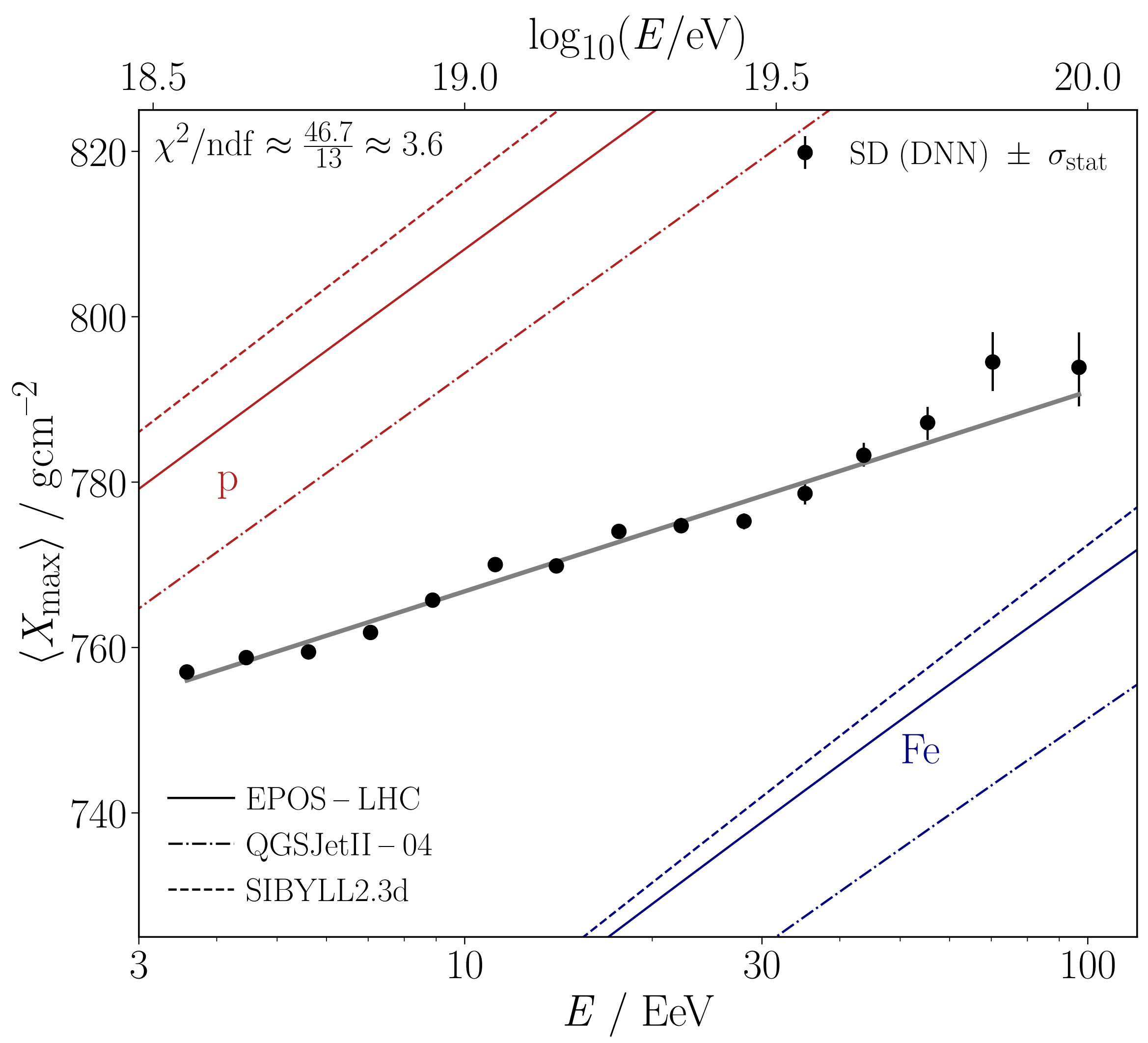
Shower-by-shower fluctuations becoming very small

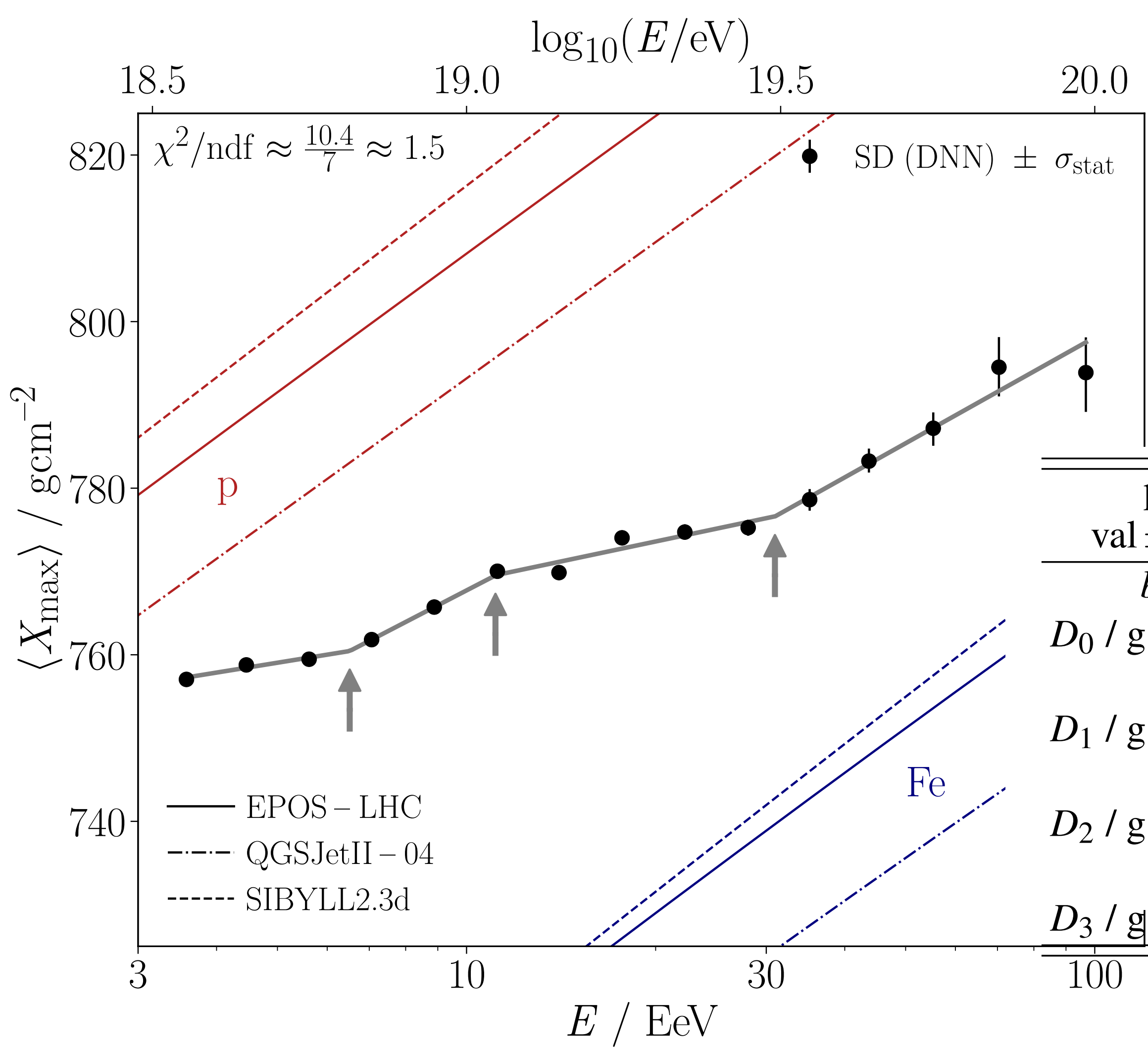
Lines: air shower simulations using LHC-tuned hadronic interaction models



X_{max} from surface detector data using DNNs





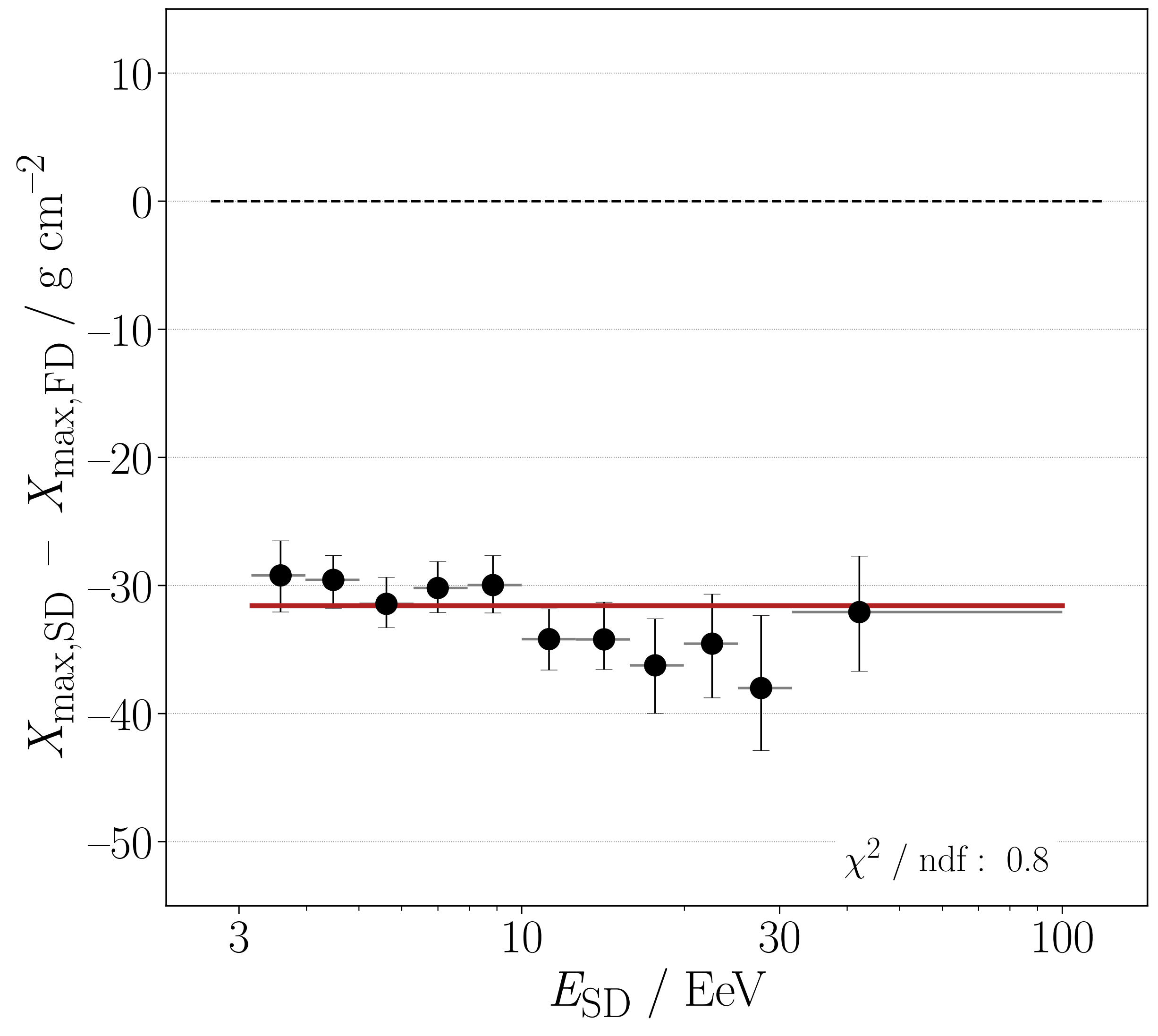


Several breaks identified

parameter val $\pm\sigma_{stat}\pm\sigma_{sys}$	3-break model val $\pm\sigma_{stat}\pm\sigma_{sys}$	energy spectrum val $\pm\sigma_{stat}\pm\sigma_{sys}$
b / g cm^{-2}	$750.5\pm3\pm13$	
D_0 / g cm^{-2} decade^{-1}	$12\pm5\pm6$	
E_1 / EeV	$6.5\pm0.6\pm1$	$4.9\pm0.1\pm0.8$
D_1 / g cm^{-2} decade^{-1}	$39\pm5\pm14$	
E_2 / EeV	$11\pm2\pm1$	$14\pm1\pm2$
D_2 / g cm^{-2} decade^{-1}	$16\pm3\pm6$	
E_3 / EeV	$31\pm5\pm3$	$47\pm3\pm6$
D_3 / g cm^{-2} decade^{-1}	$42\pm9\pm12$	

- Elongation rate agrees with FD
- Clear evidence of structure in ER, best described with three-break model:
  constant ER rejected at 4.4σ

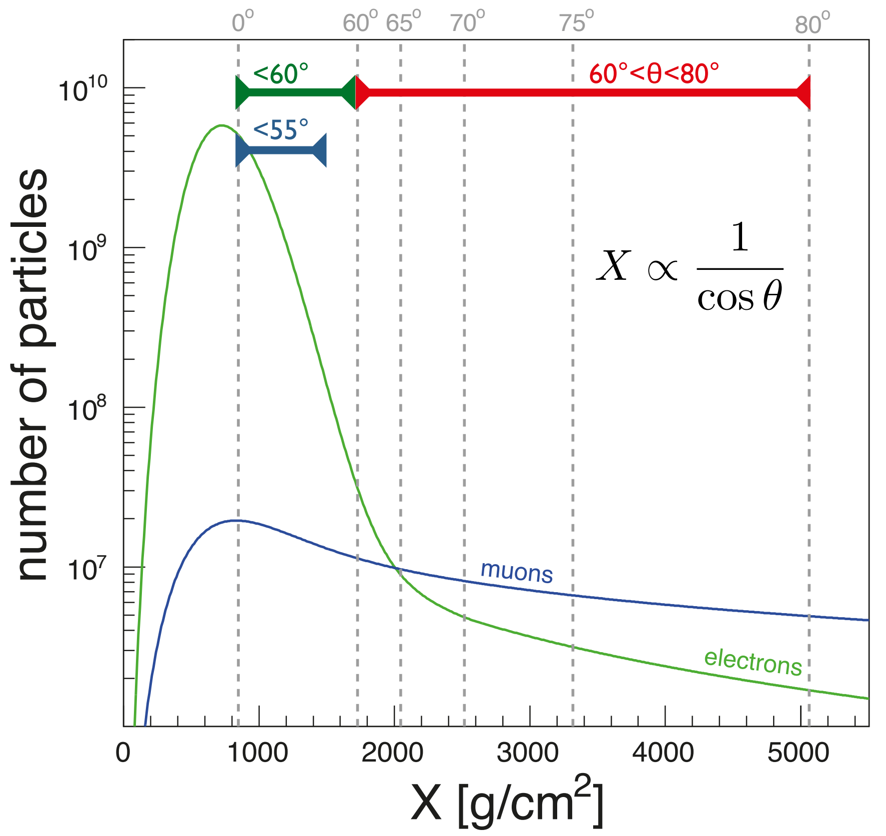
➟ Incompatible with pure composition



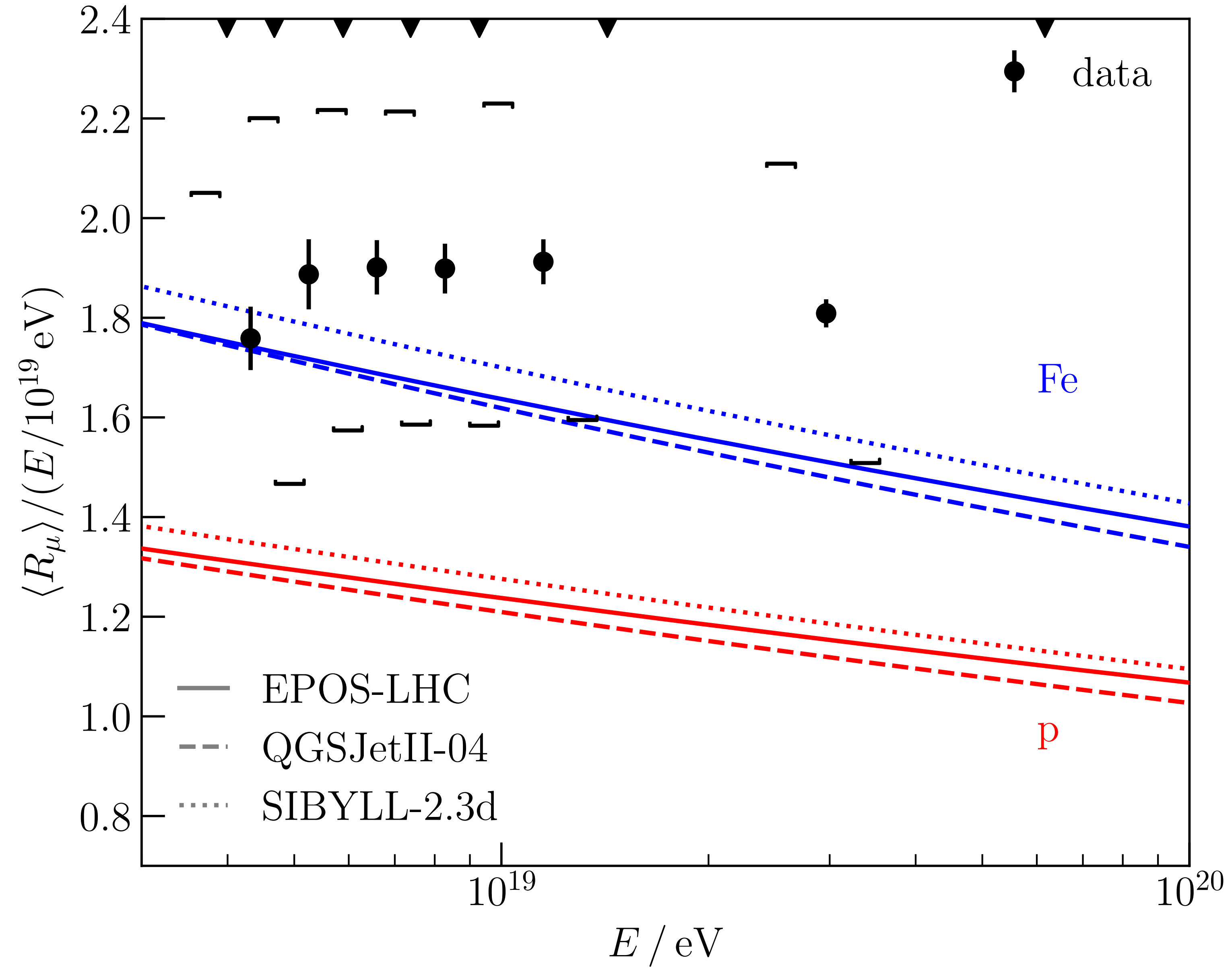
Systematic offset in X_{max}

Composition:
Muon measurements

Muon measurement – inclined showers

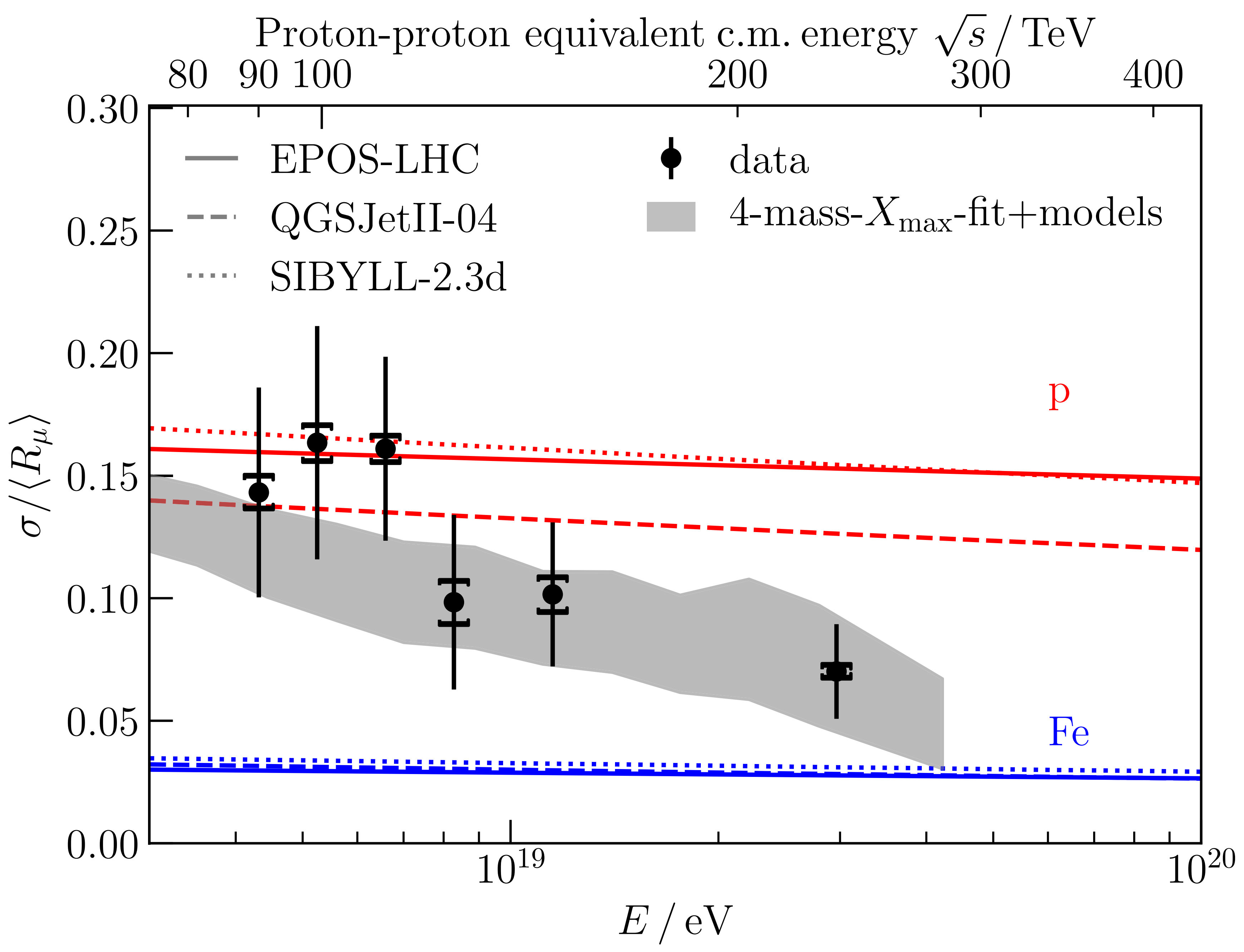


Number of muons in showers with θ>65°

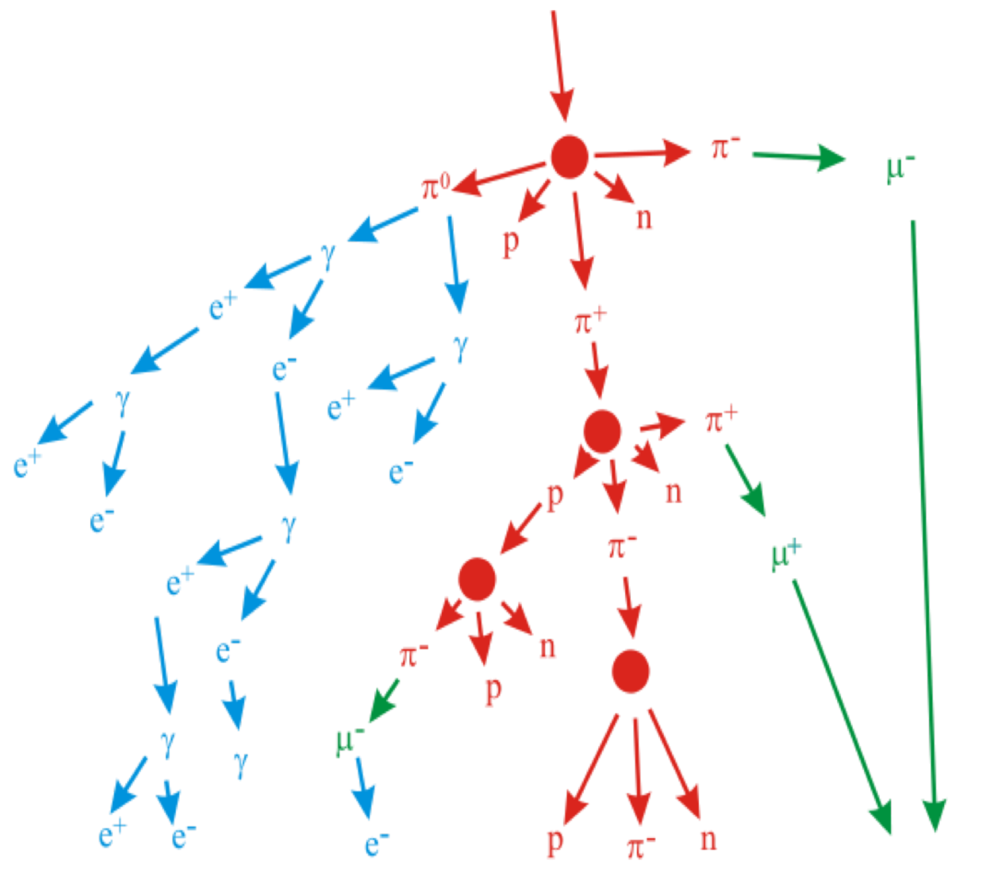


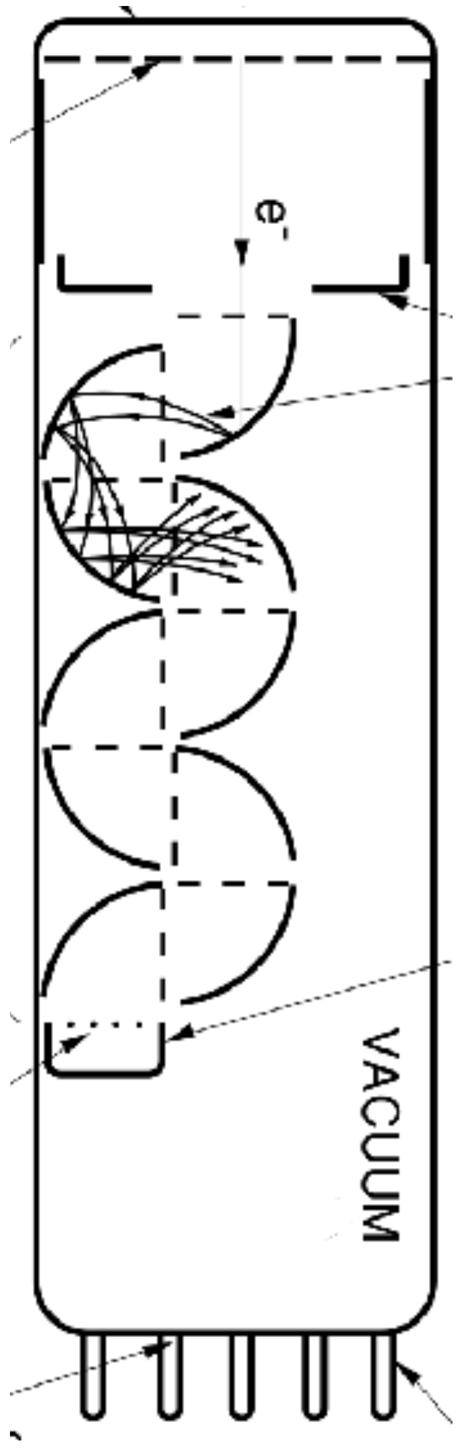
(Auger PRD 2015, PRL 2021)

Shower-to-shower fluctuations



70% of fluctuations from first interaction



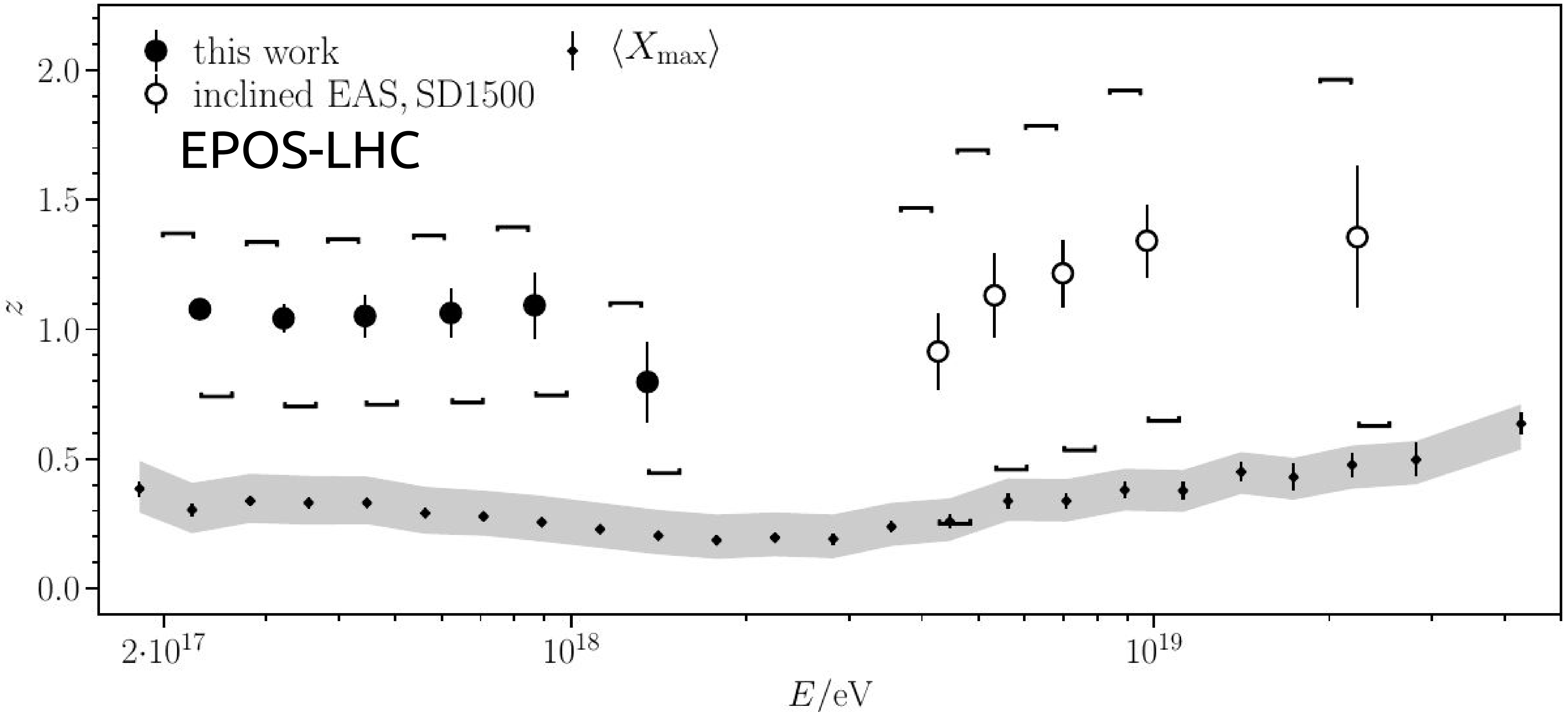


Lorenzo Cazon et al.
Astropart. Phys. 36 (2012) 211
Phys. Lett. B784 (2018) 68
Phys. Rev. D103 (2021) 022001

Discrepancy of muon number (20–30%),
but non in relative shower-to-shower fluctuations

Comparison with other Auger data

$$z = \frac{\langle \ln \rho_{35} \rangle - \langle \ln \rho_{35} \rangle_p}{\langle \ln \rho_{35} \rangle_{Fe} - \langle \ln \rho_{35} \rangle_p}$$

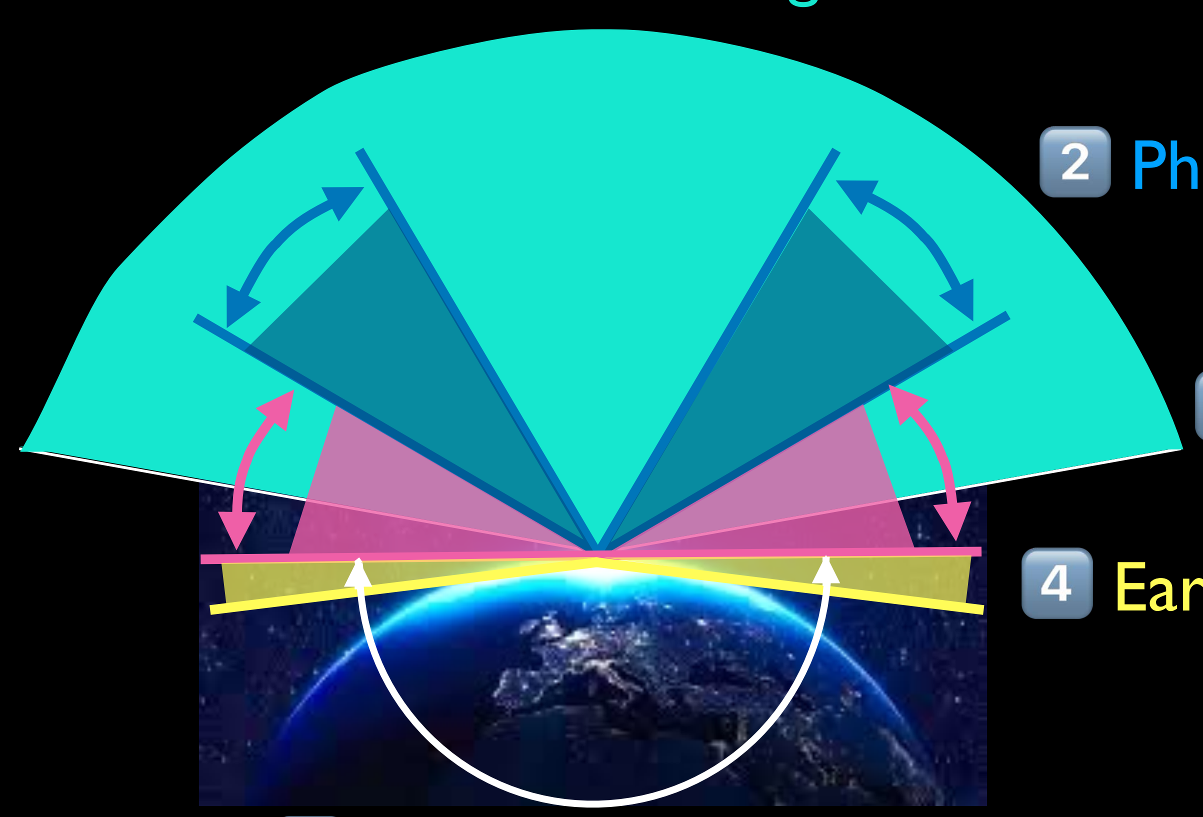


Comparison muon content and X_{max}: Inconsistency

Muon deficit at lower energies: 38% EPOS-LHC, 50% QGSJetII-04

Qualitative agreement with evolution from X_{max}?

Auger as 4π multi-messenger observatory



$$UHECR + matter \rightarrow \pi^{\pm} + \pi^{0} + X$$

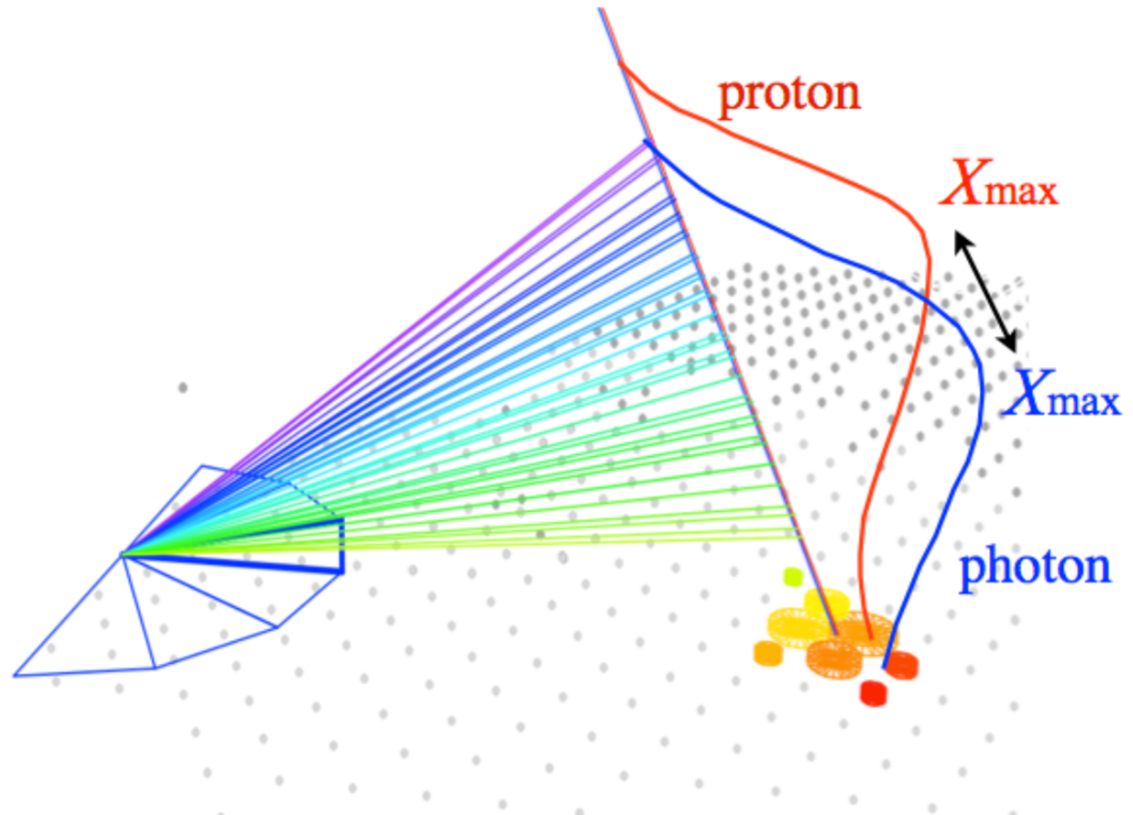
$\pi^{0} \rightarrow \gamma + \gamma$

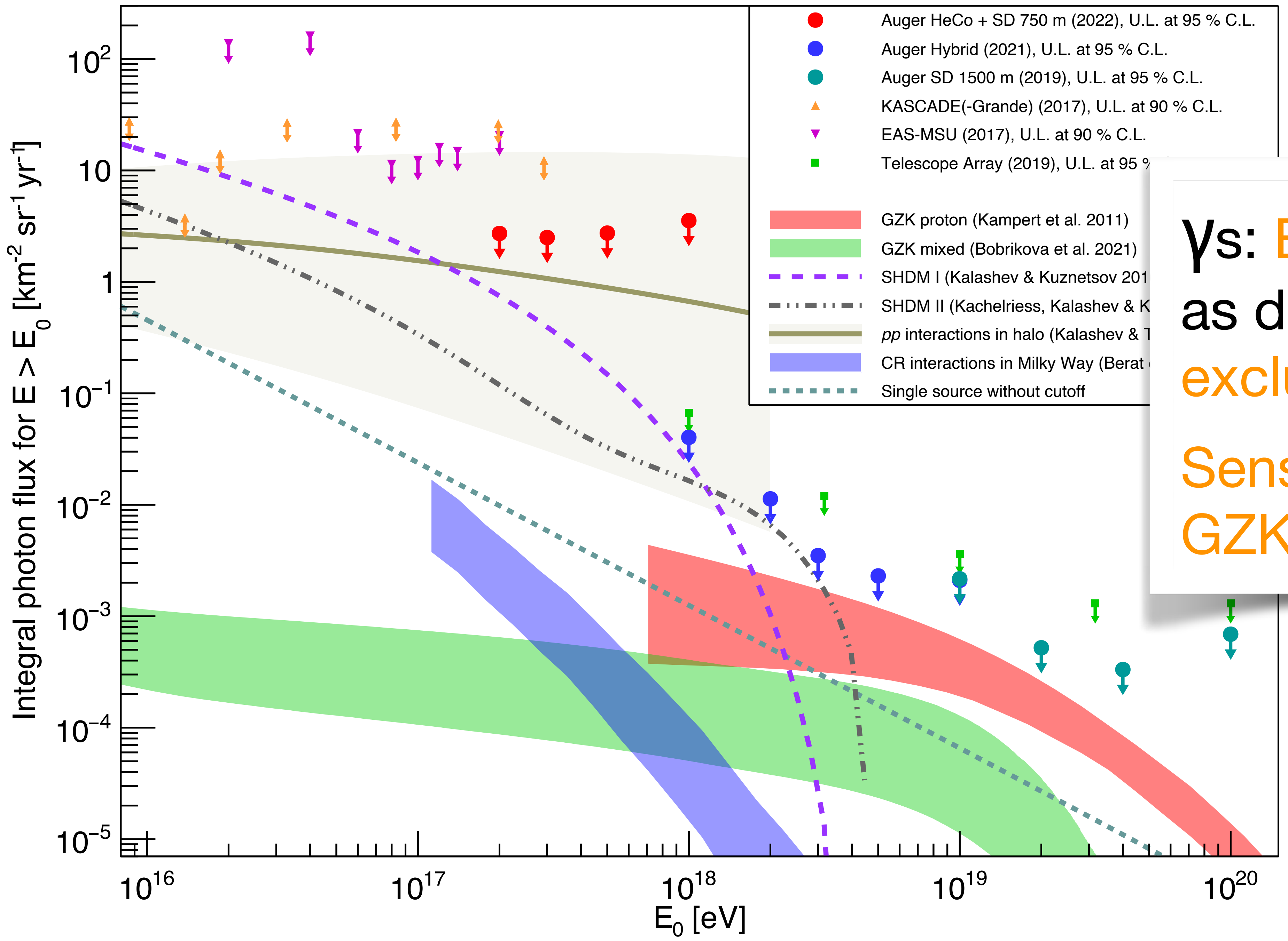
$\pi^{\pm} \rightarrow \mu + \nu_{\mu} + \nu_{e}$

Picture: curtesy KH Kampert

Multimessenger searches: Neutrinos and photons

γ search

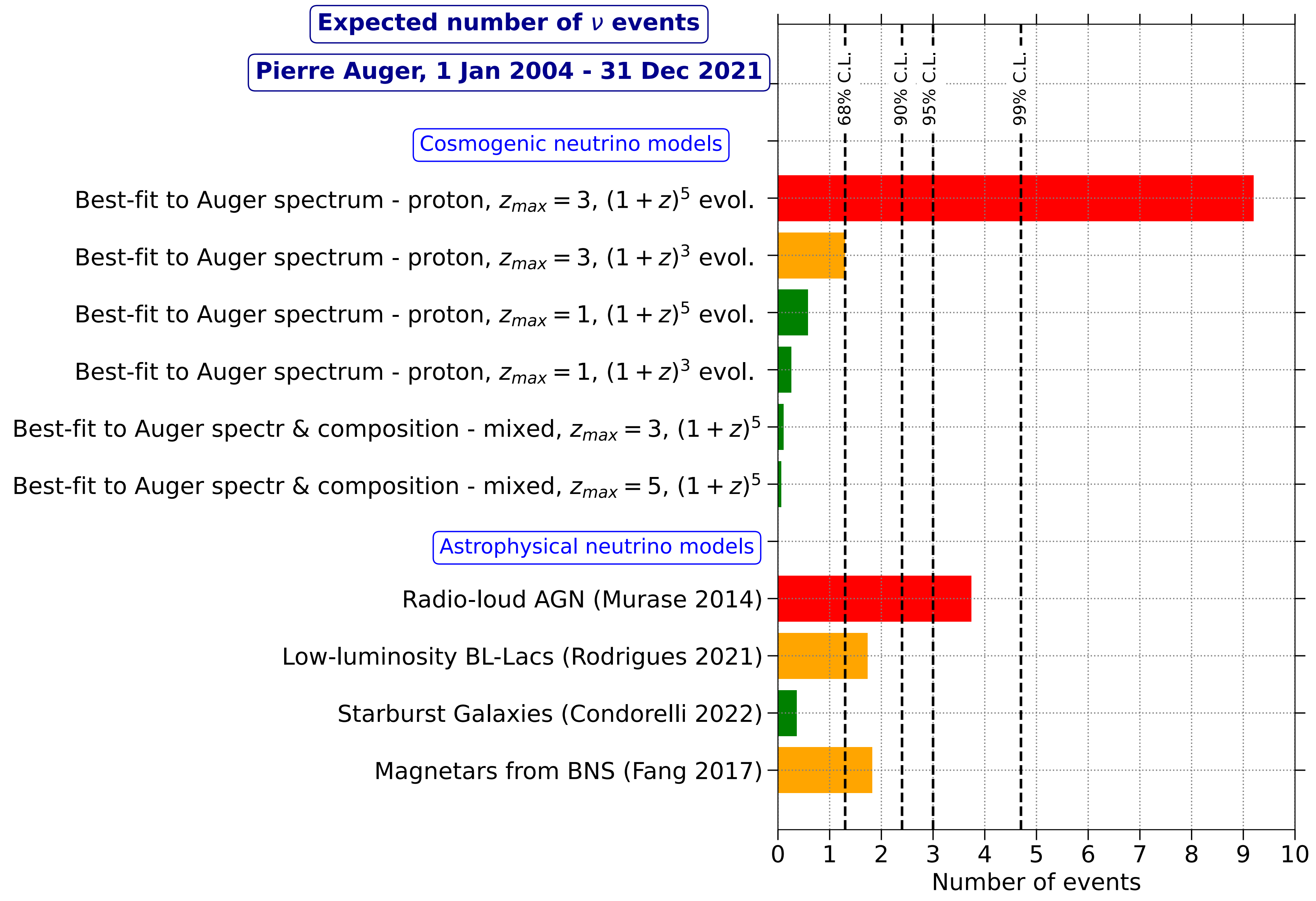


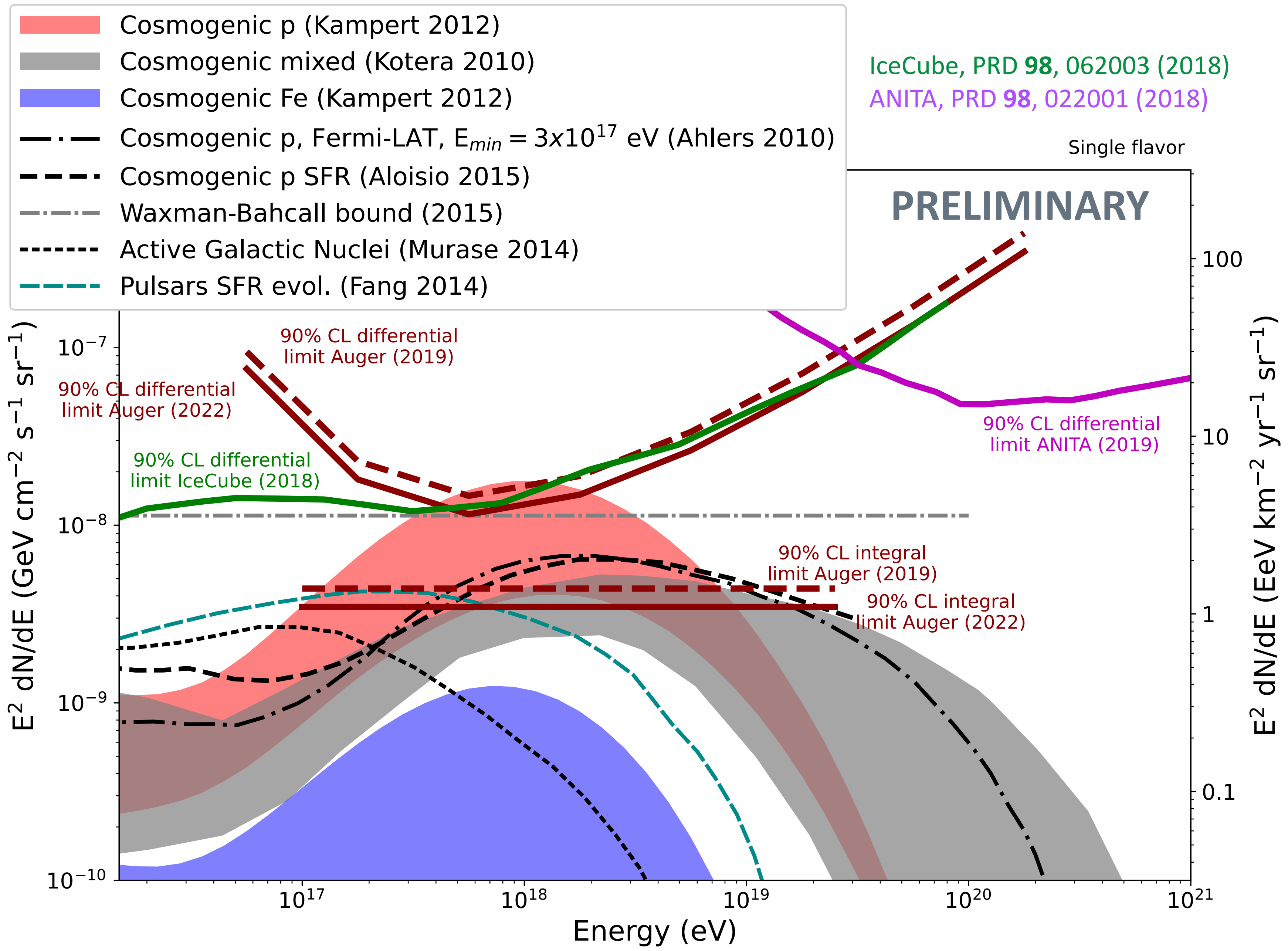


γs: Exotic processes as dominant sources excluded

Sensitivity reaches GZK predictions

ν search





ν: Neutrino sensitivity better than Waxman-Bahcall bound

Limits constrain GZK & astrophysical neutrino models

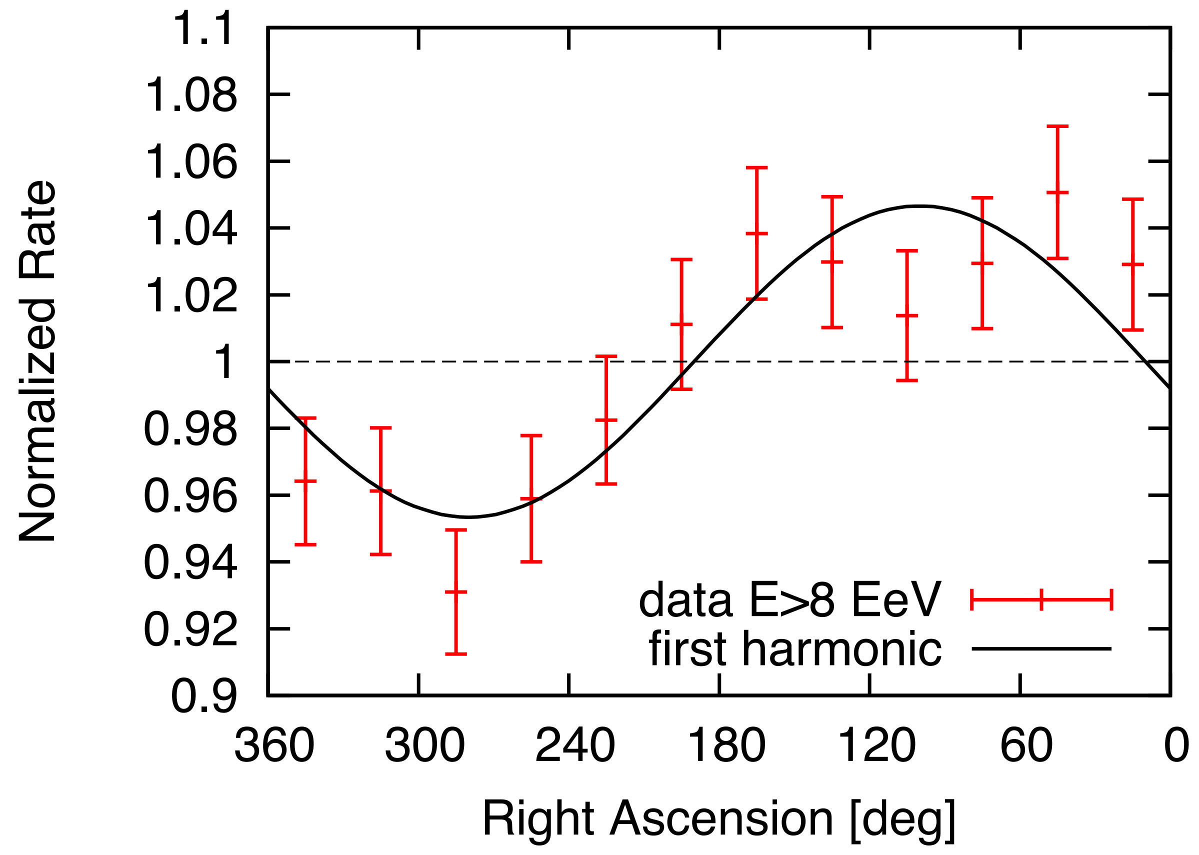
Anisotropy

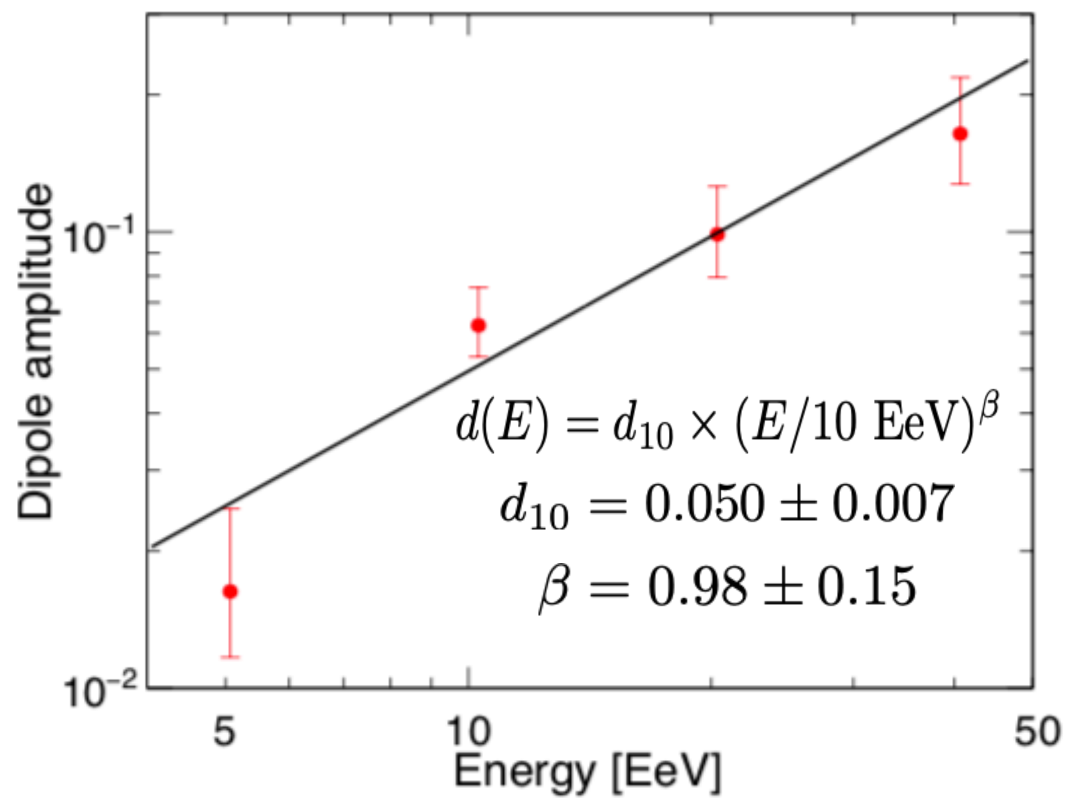
Large scale anisotropy

physicsworld TOP 10 BREAKTHROUGH 2017

Harmonic analysis in right ascension α of SD data

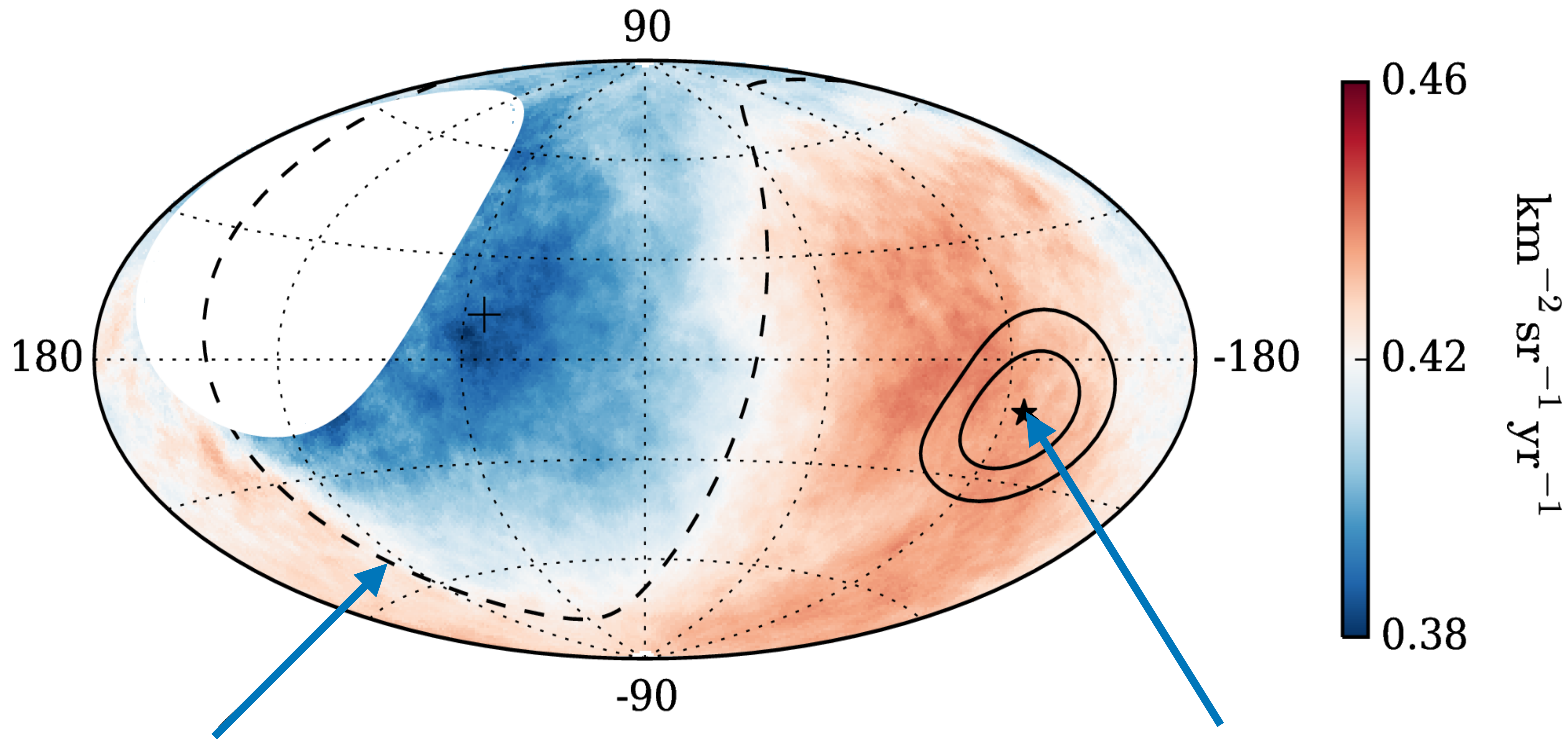
Combination of showers with θ<60° and 60°<θ<80°





Dipole amplitude growing with energy

3D dipole above **8 EeV** in galactic coordinates



Equatorial plane of dipole

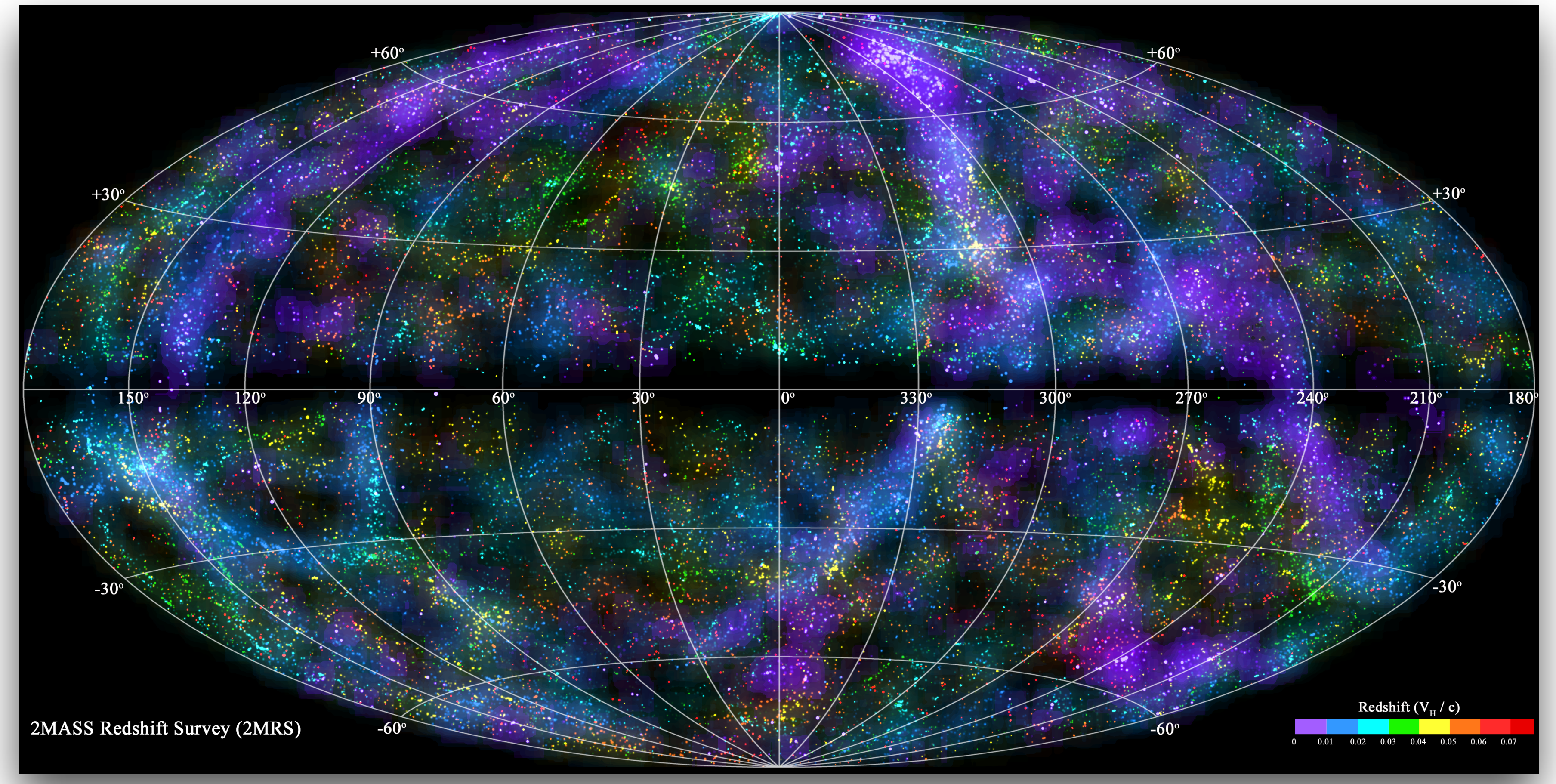
Observed dipole: (l, b) = (233°,-13°)

Significant modulation of $6.5^{+1.3}_{-0.9}$% at 6.9σ level

(Science 357 (2017) 1266, update ICRC 2023)

Large scale anisotropy

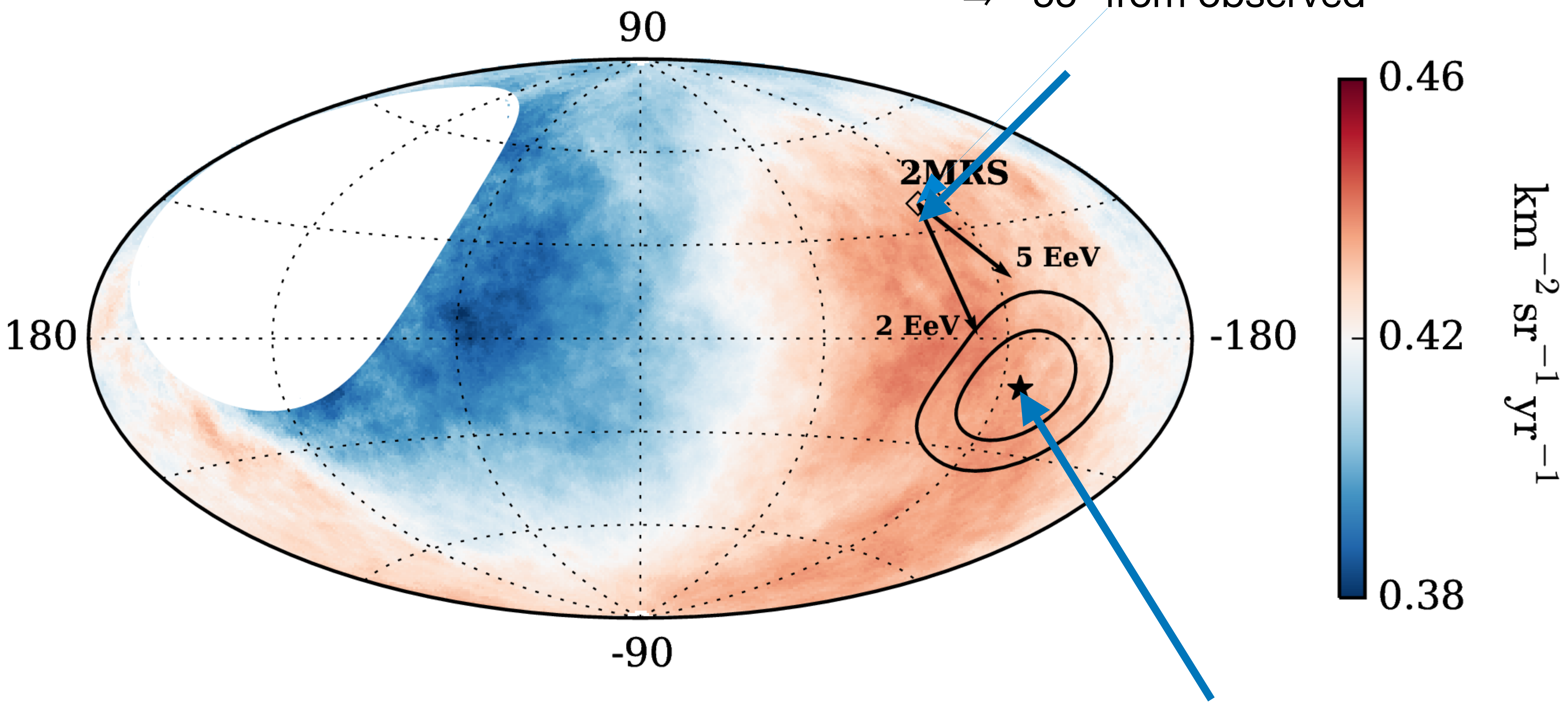
2MASS Redshift Survey



- Expected if cosmic rays diffuse to Galaxy from sources distributed similar to near-by galaxies *(Harari, Mollerach PRD 2015, 2016)*
- Deflection of dipolar pattern due to Galactic magnetic field
- Strong indication for extragalactic origin dipole direction ~ 125° from GC

3D dipole above 8 EeV in galactic coordinates

The flux-weighted dipole from IR galaxy distribution in 2MRS points to (l,b)=(251°,38°) ⇒ ~55° from observed



Observed dipole:
(l, b) = (233°,-13°)

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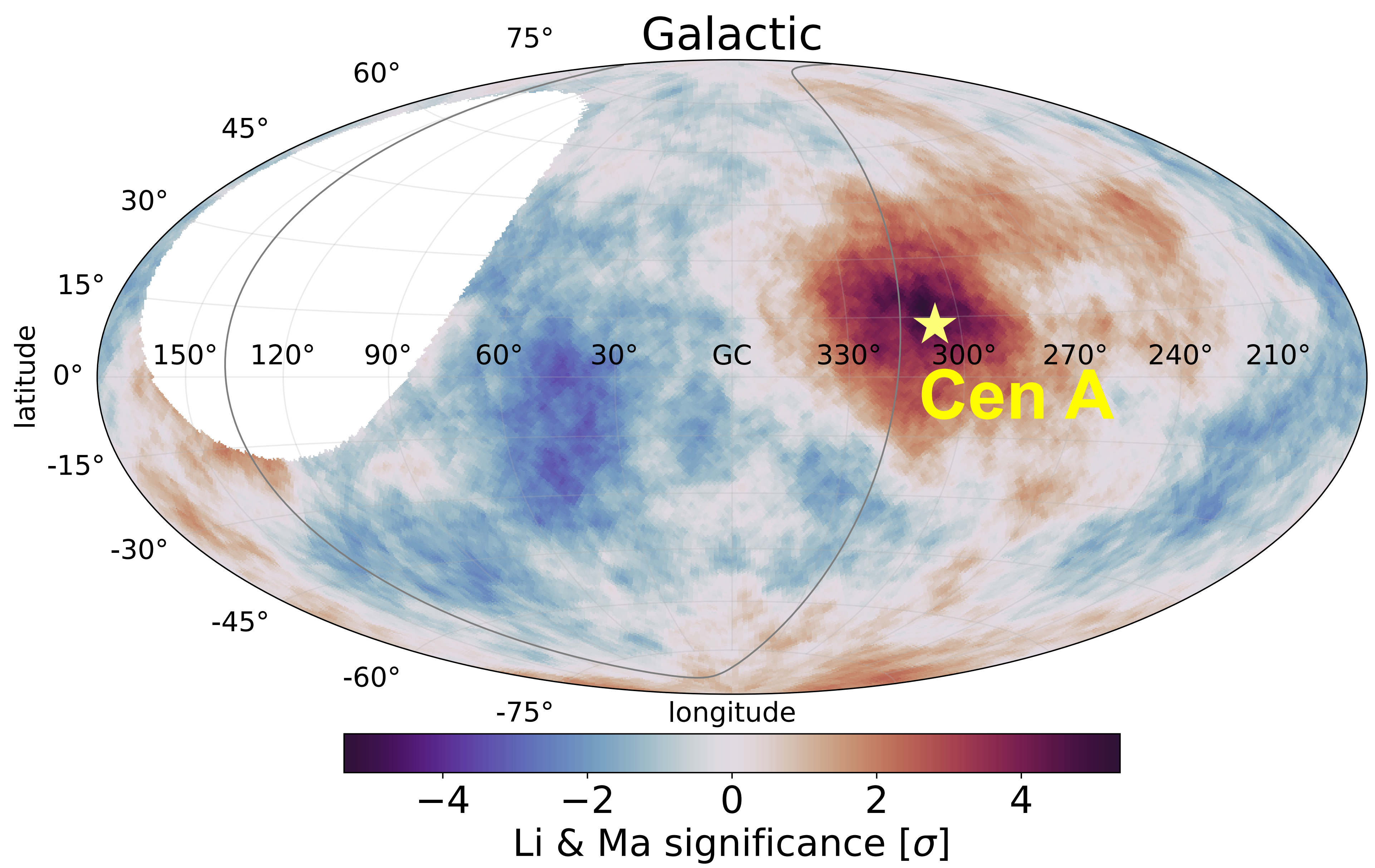
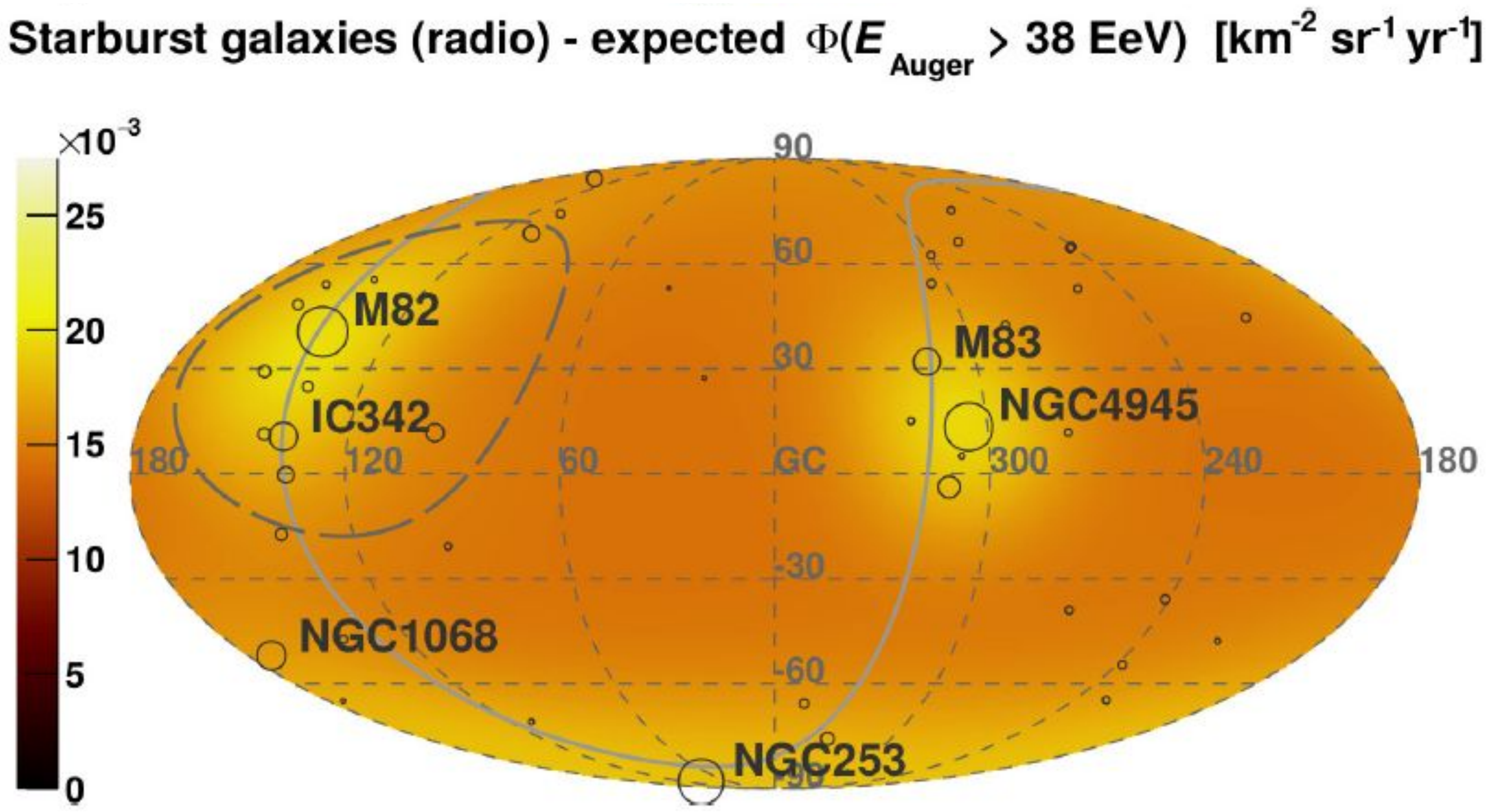
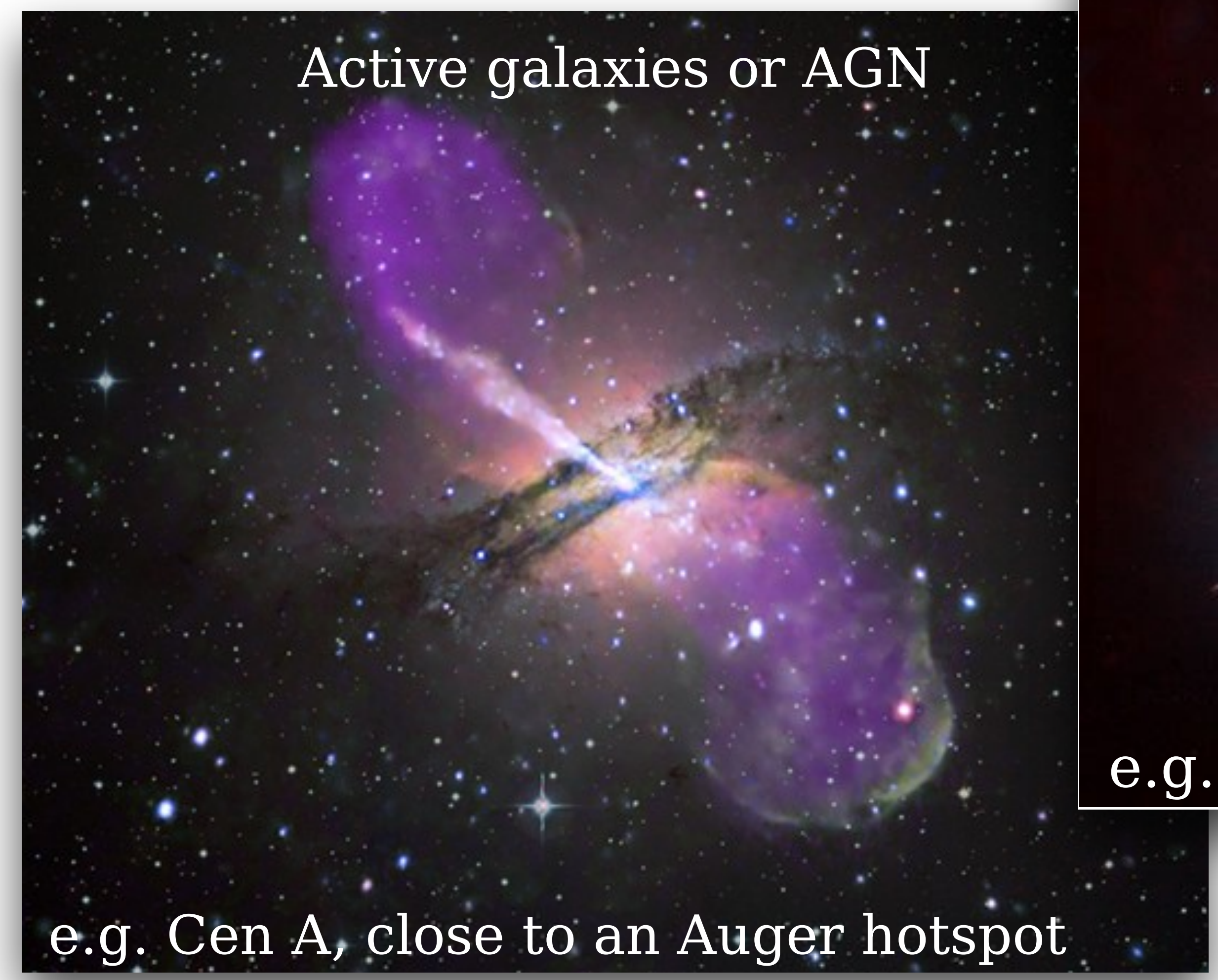
Arrival directions – high-energy anisotropy searches





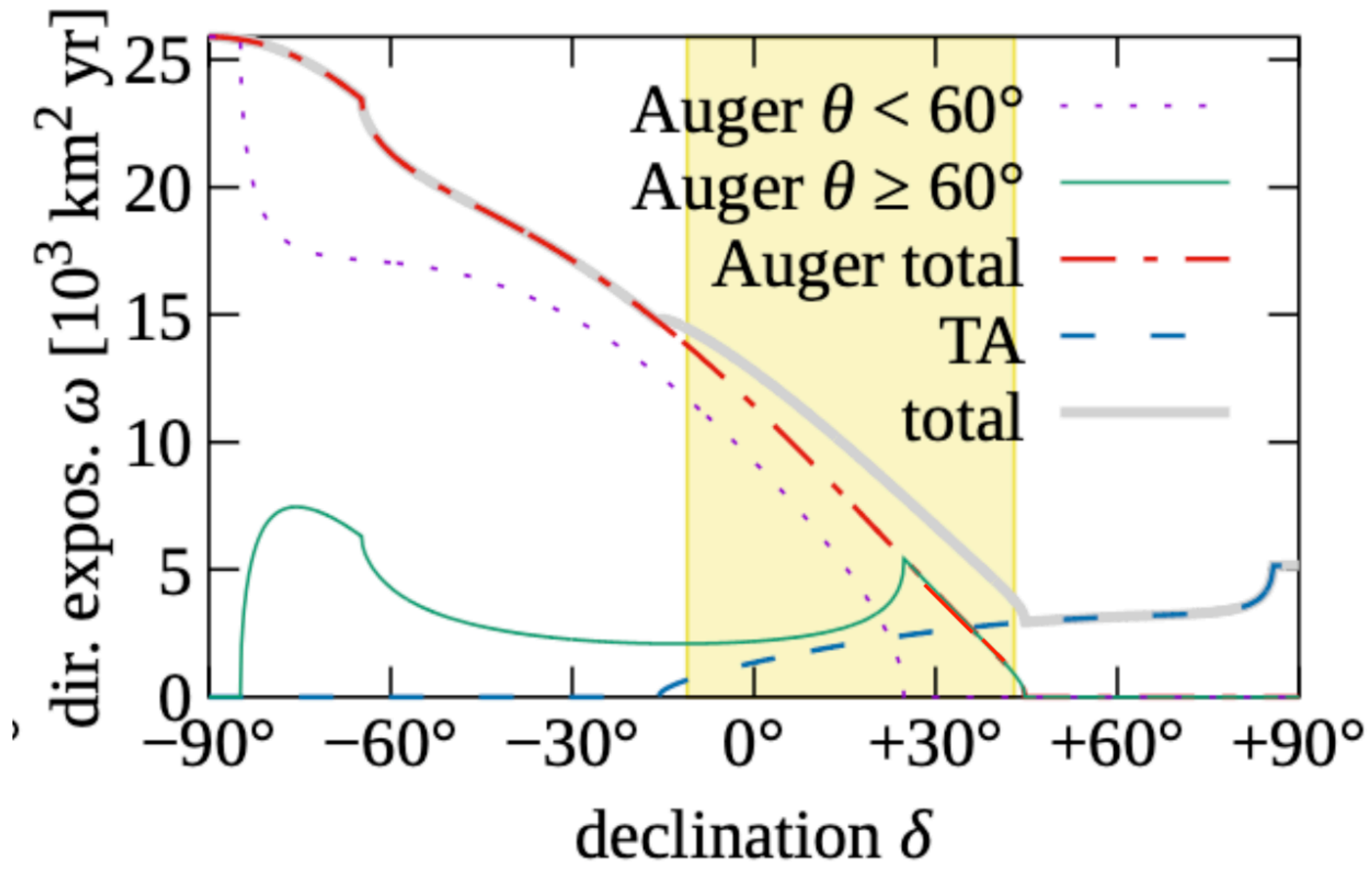


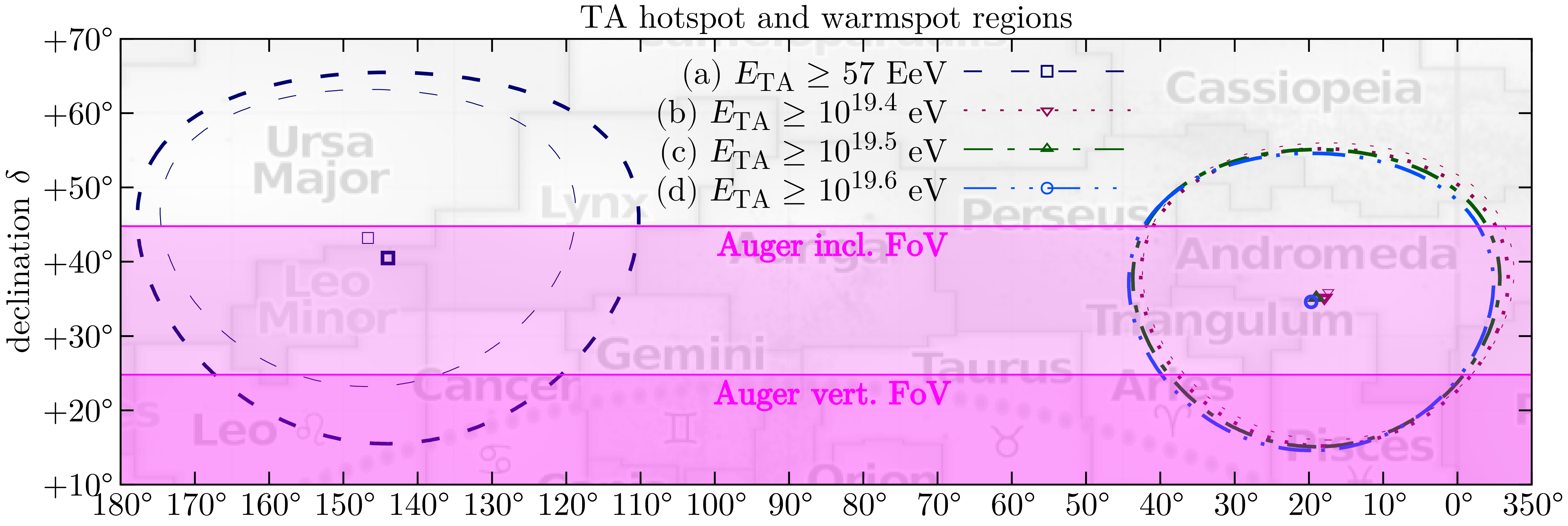
Centaurus A region: E > 38 EeV, ~27° radius, 4.0 σ (post trial)
Starburst galaxies: E > 38 EeV, ~25° radius, 3.8 σ (post trial)

Discovery level of 5σ expected only after 2025

(Astrophysical Journal, 935:170, 2022, update ICRC 2023)

Differences between Northern and Southern sky?





	$(\alpha_0, \delta_0)\,[°]$	E^{TA}	N^{TA}_{obs}	N^{TA}_{exp}	σ^{TA}_{post}	E^{Auger}	N^{Auger}_{obs}	N^{Auger}_{exp}	σ^{Auger}_{Li-Ma}
PPSC	(17.4, 36.0)	25.1	95	61.4	3.1σ	20.1	68	69.3	-0.2σ
	(19.0, 35.1)	31.6	66	39.1	3.2σ	25.3	40	45.2	-0.8σ
	(19.7, 34.6)	39.8	43	23.2	3.0σ	31.8	27	26.5	0.1σ
TA hot spot	(144.0, 40.5)	57	44	16.9	3.2σ	45.6	7	10.1	-1.0σ

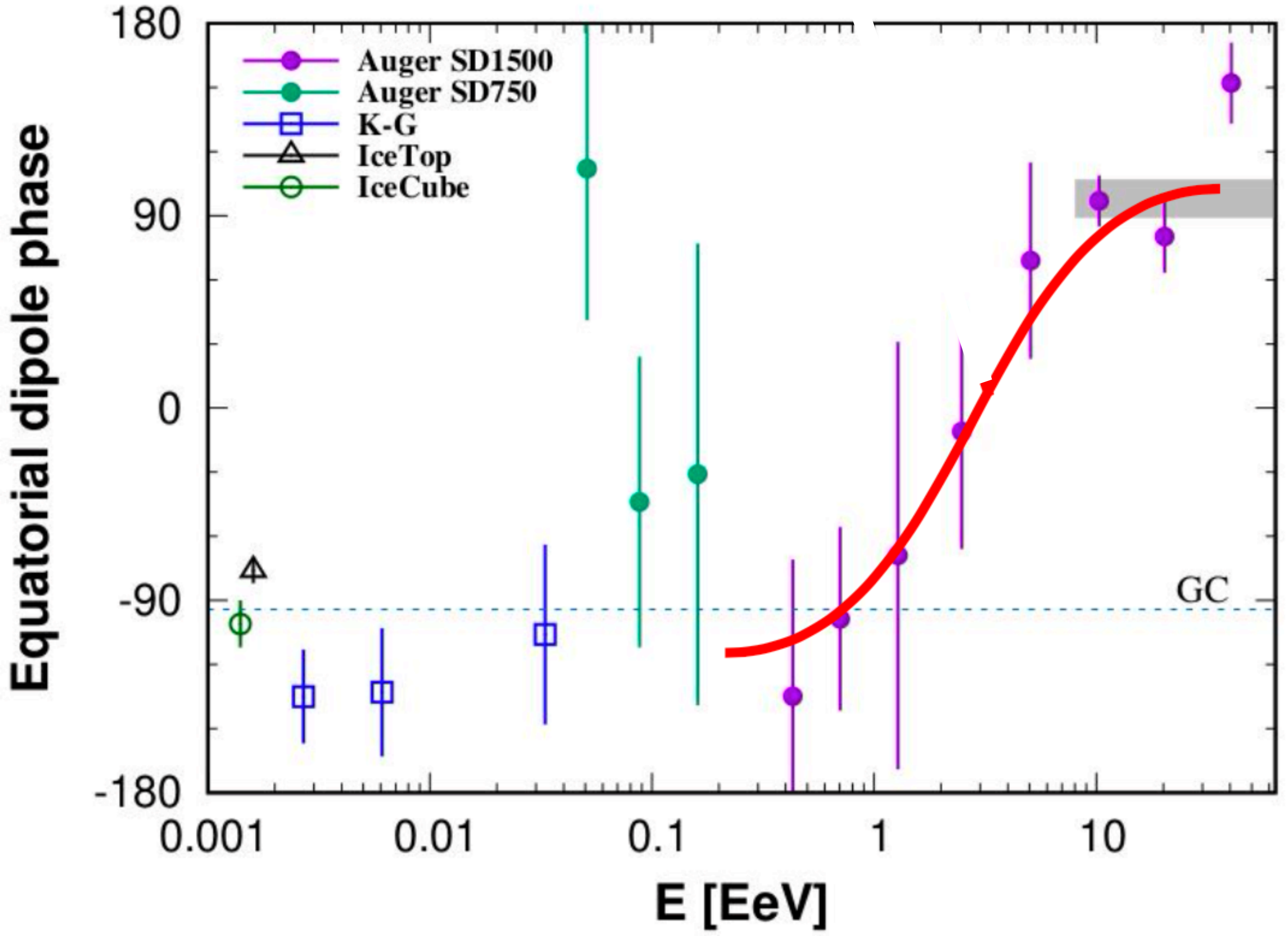
No hint for excesses in TA "spots" with data of comparable size

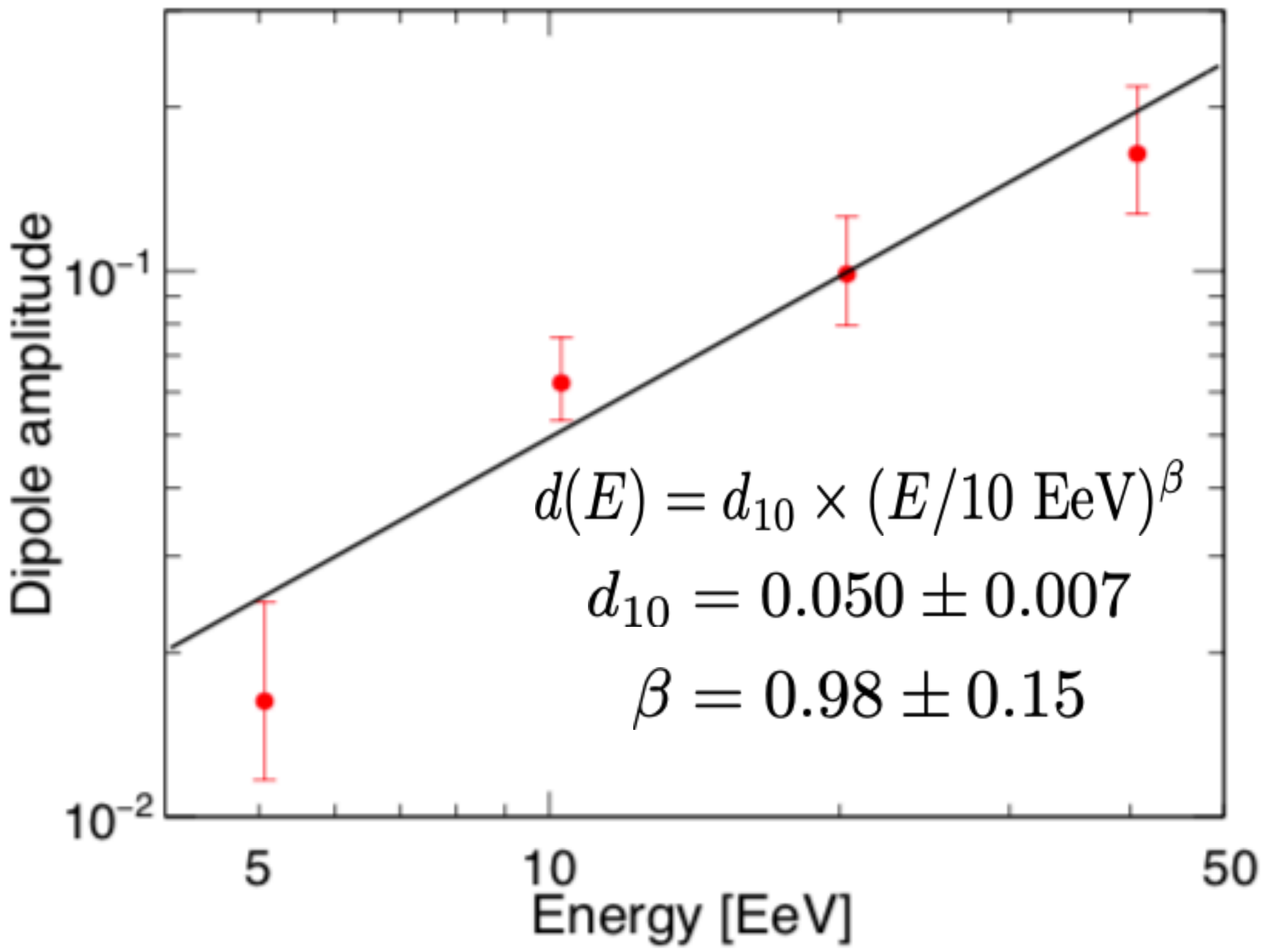
➠ At variance with claim of TA that the declination dependent spectrum due to presence of excesses in particular regions of the Northern sky

How does it all fit together?

Dipole anisotropy of extragalactic origin

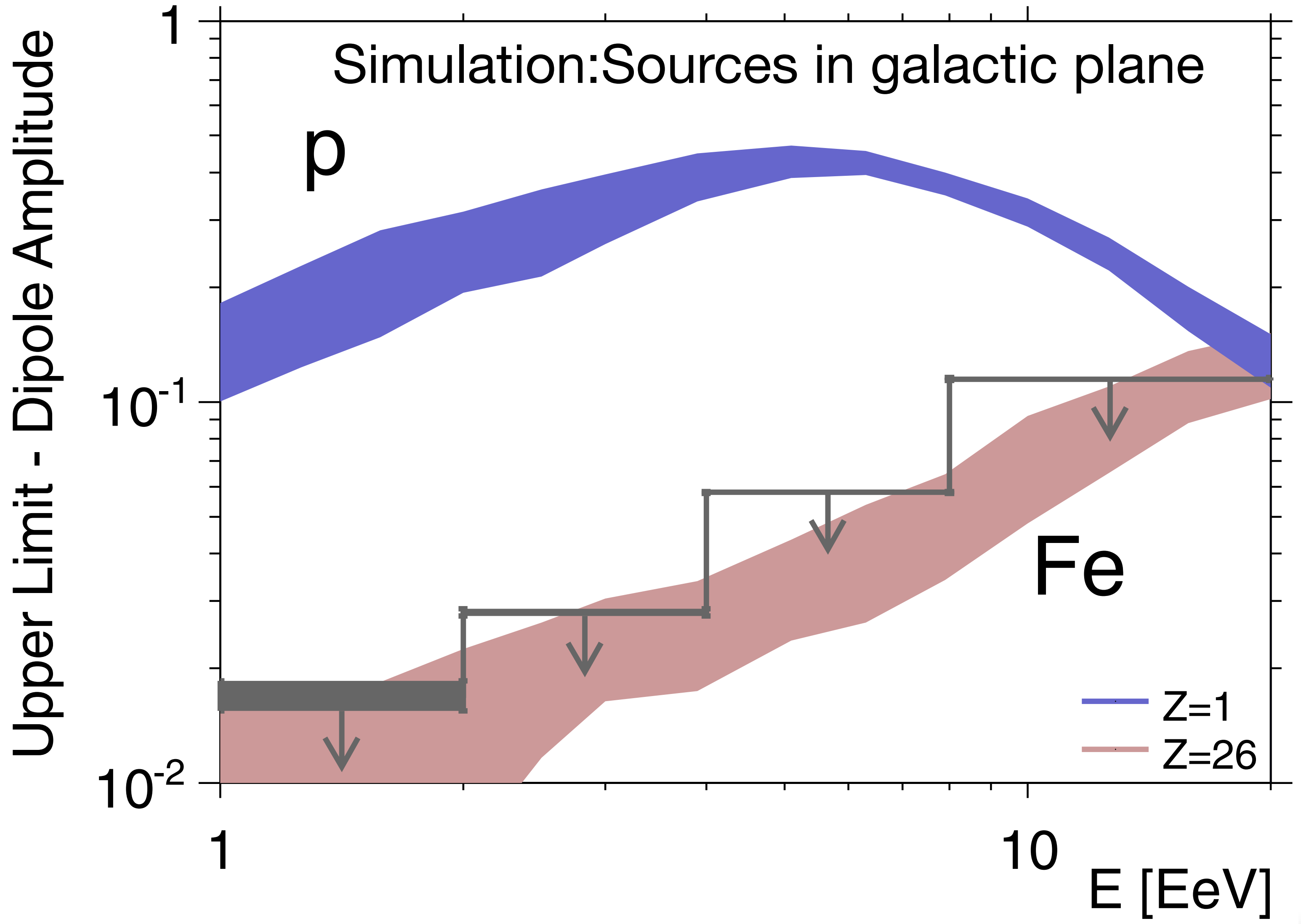
Direction and energy dependence of extragalactic dipole

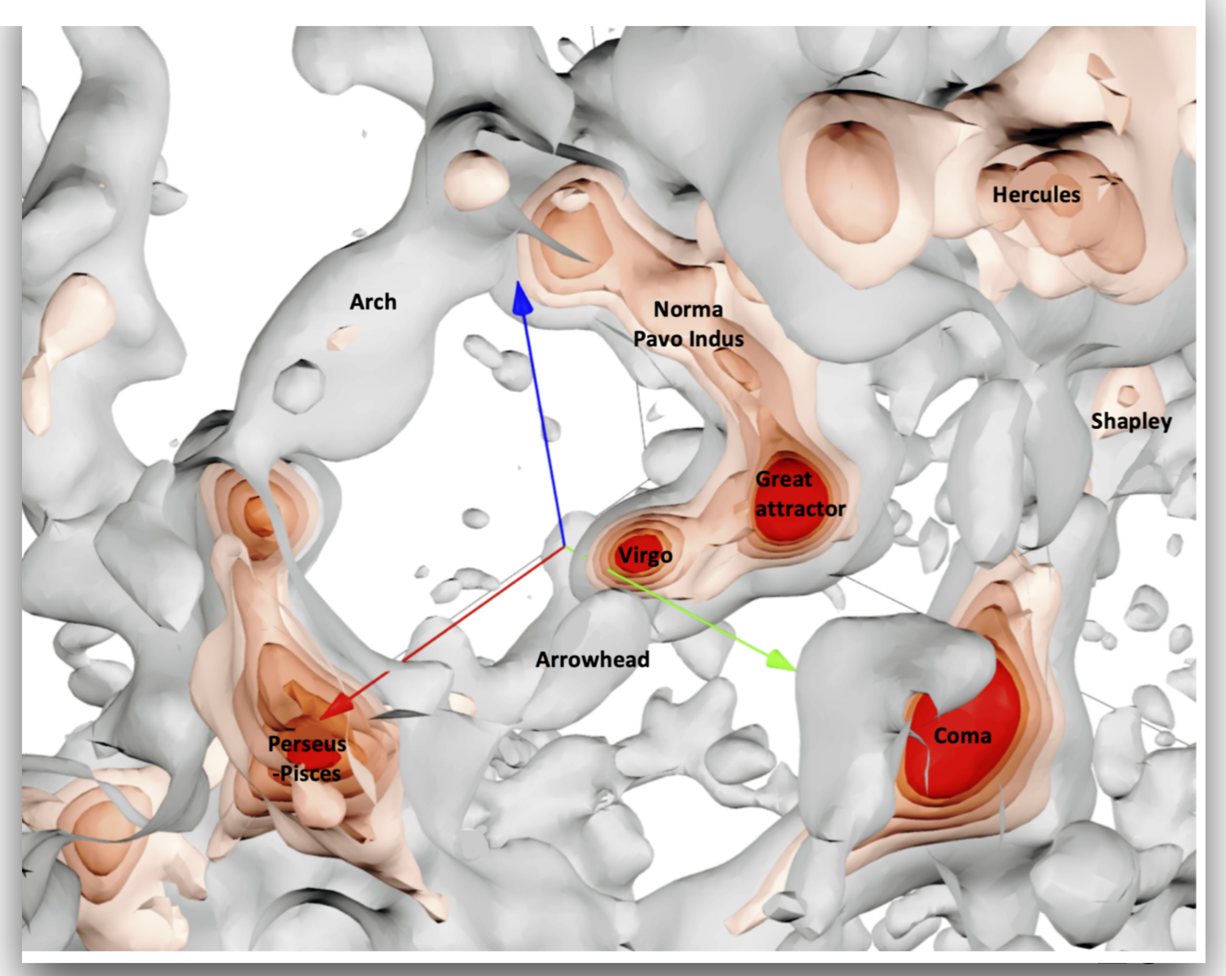




(Auger, ApJ 203, 2012,
Giacinti et al. JCAP 2012, 2015)

(Auger, ApJ 203, 2012,
Giacinti et al., JCAP 2012, 2015)

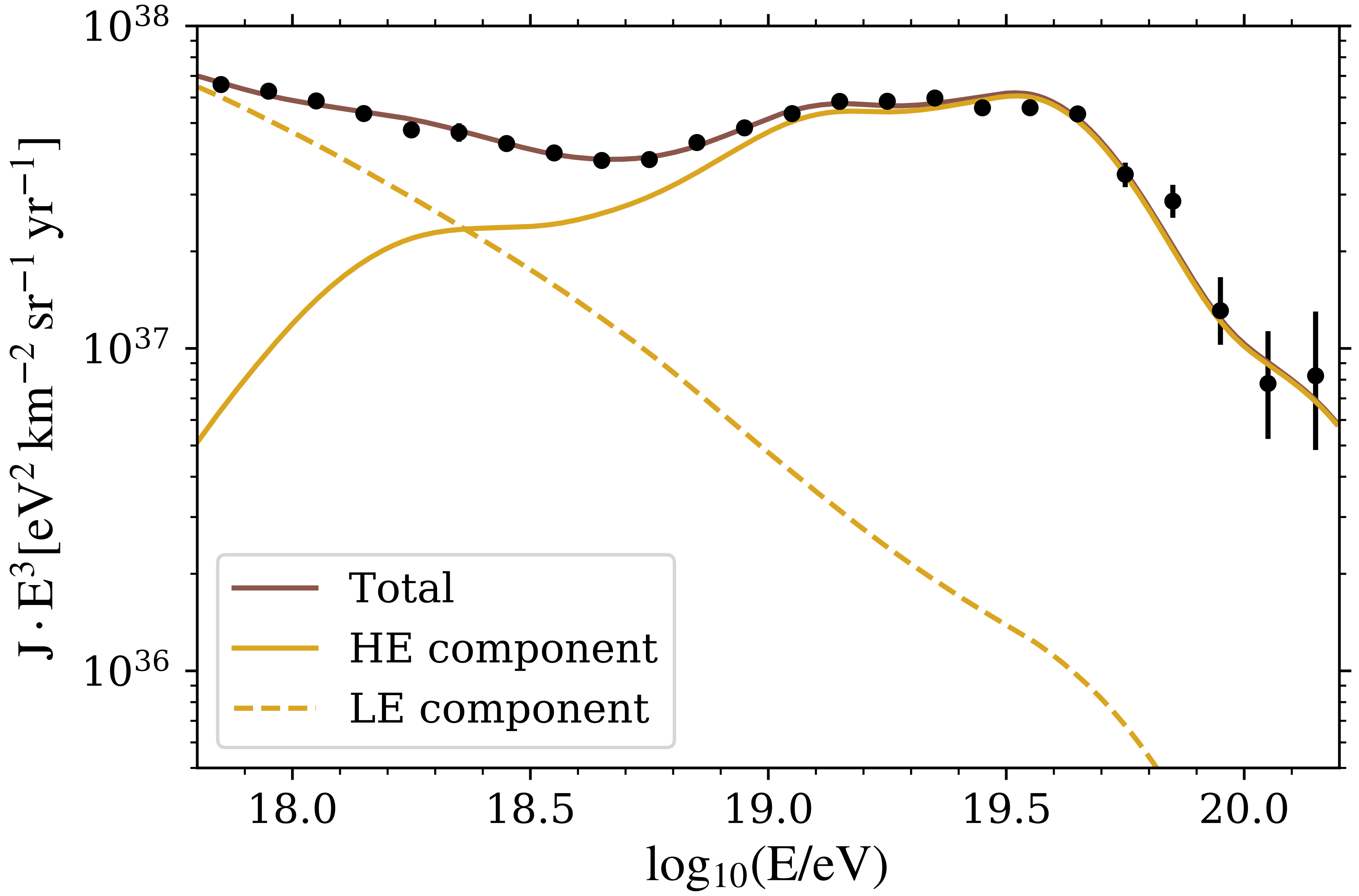


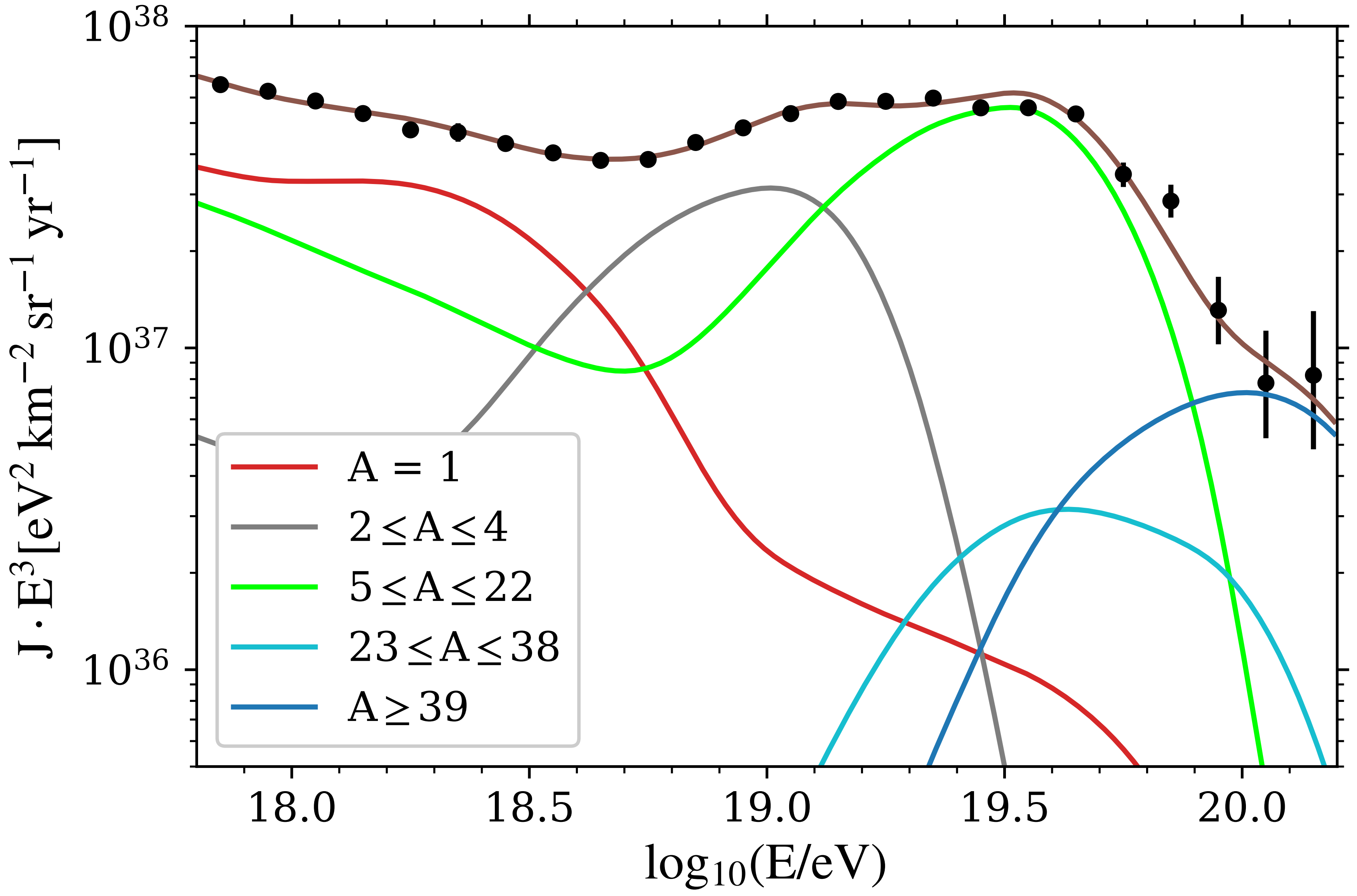


(Ding, Globus & Farrar
ApJ 913 (2021) L13)

Protons below ankle energy are of extragalactic origin
Dipole anisotropy indicates transition to extragalactic sources
Interplay of source distribution, composition, and mag. horizon

Model calculations for mass composition and flux





Ankle ~ 5 EeV
Interplay between the two popolations

Instep ~ 10 EeV
Interplay between He and CNO primary masses

+ Absence of cosmogenic ν and γ
+ Low cutoff

Suppression mainly due to **exhaustion of the sources**

Basic scenario:
- 2 populations of EG identical sources, uniformly distributed
- Power law injected energy spectrum + rigidity cutoff
- Propagation only (no in-source interactions considered)

Best description of the observed energy spectrum and composition at Earth:
- Hard HE component with low rigidity cutoff
- Soft LE component with unconstrained rigidity cutoff

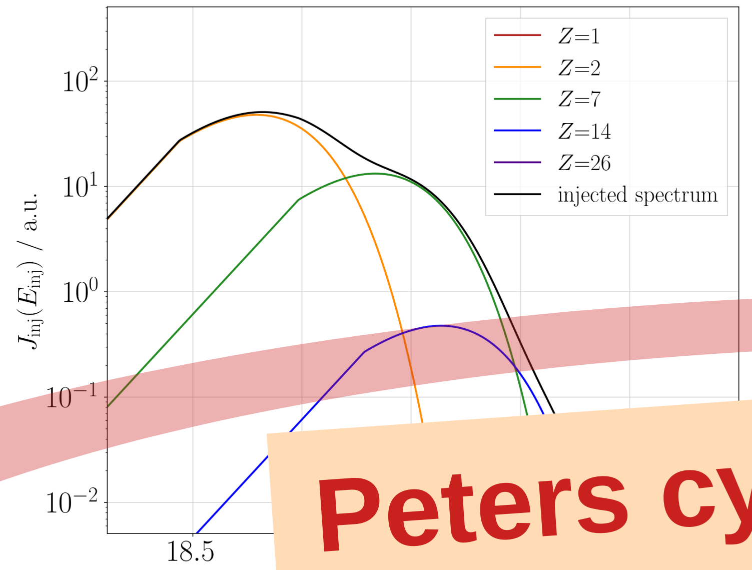
EG magnetic fields between Earth and closest sources affect observed spectrum, reducing low-rigidity particle flux (see arXiv:2404.03533)

Accounting for mass composition, flux and anisotropy

source distribution

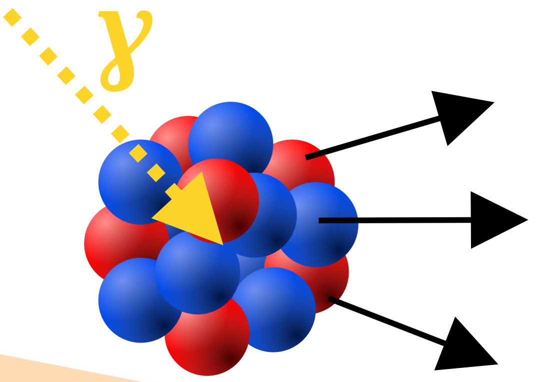
homogeneous + catalog

injection



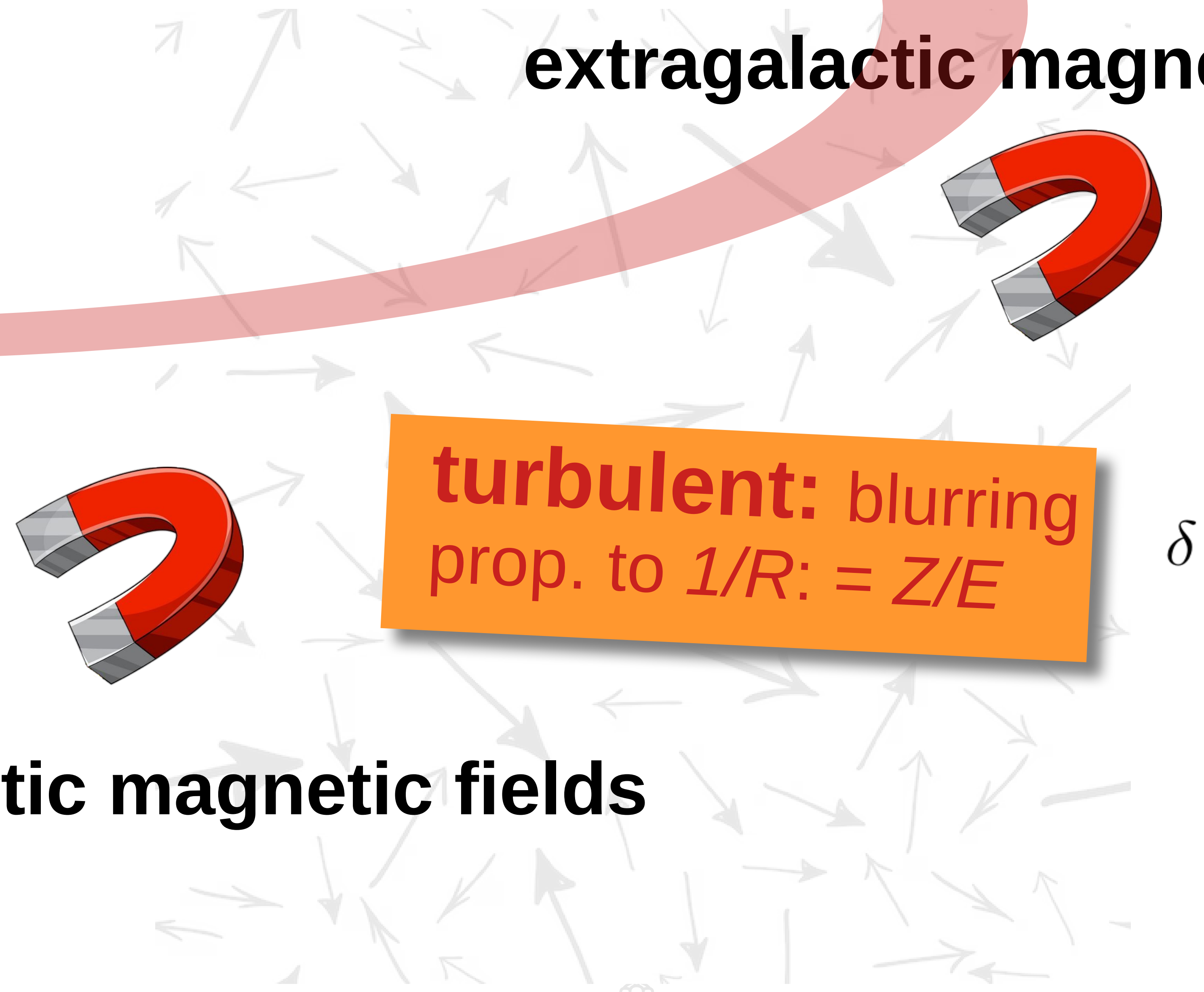
Peters cycle

propagation through extragalactic space



CRPropa

extragalactic magnetic fields

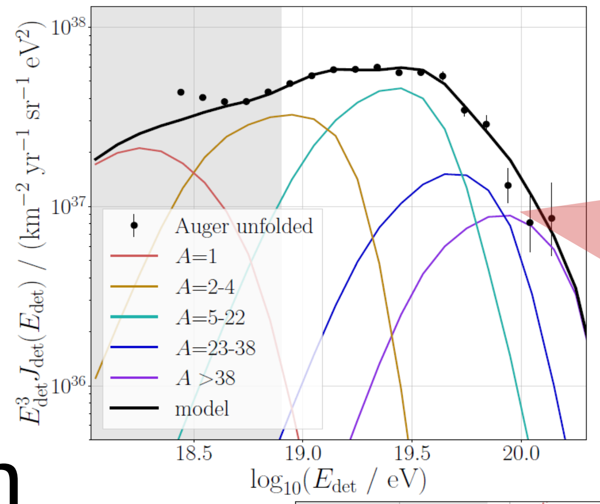


turbulent: blurring prop. to *1/R: = Z/E*

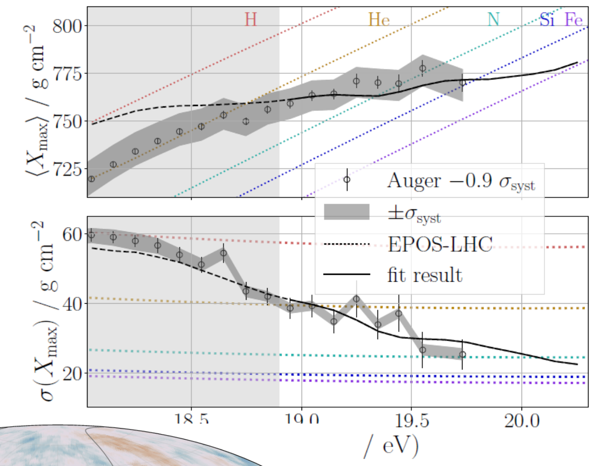
$$\delta = \frac{\delta_0}{R/10\ \mathrm{EV}}$$

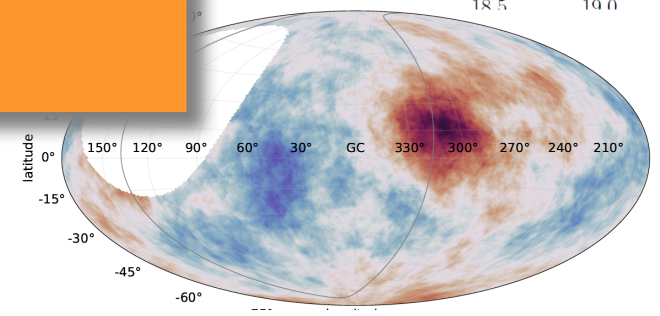
Galactic magnetic fields

compare to data



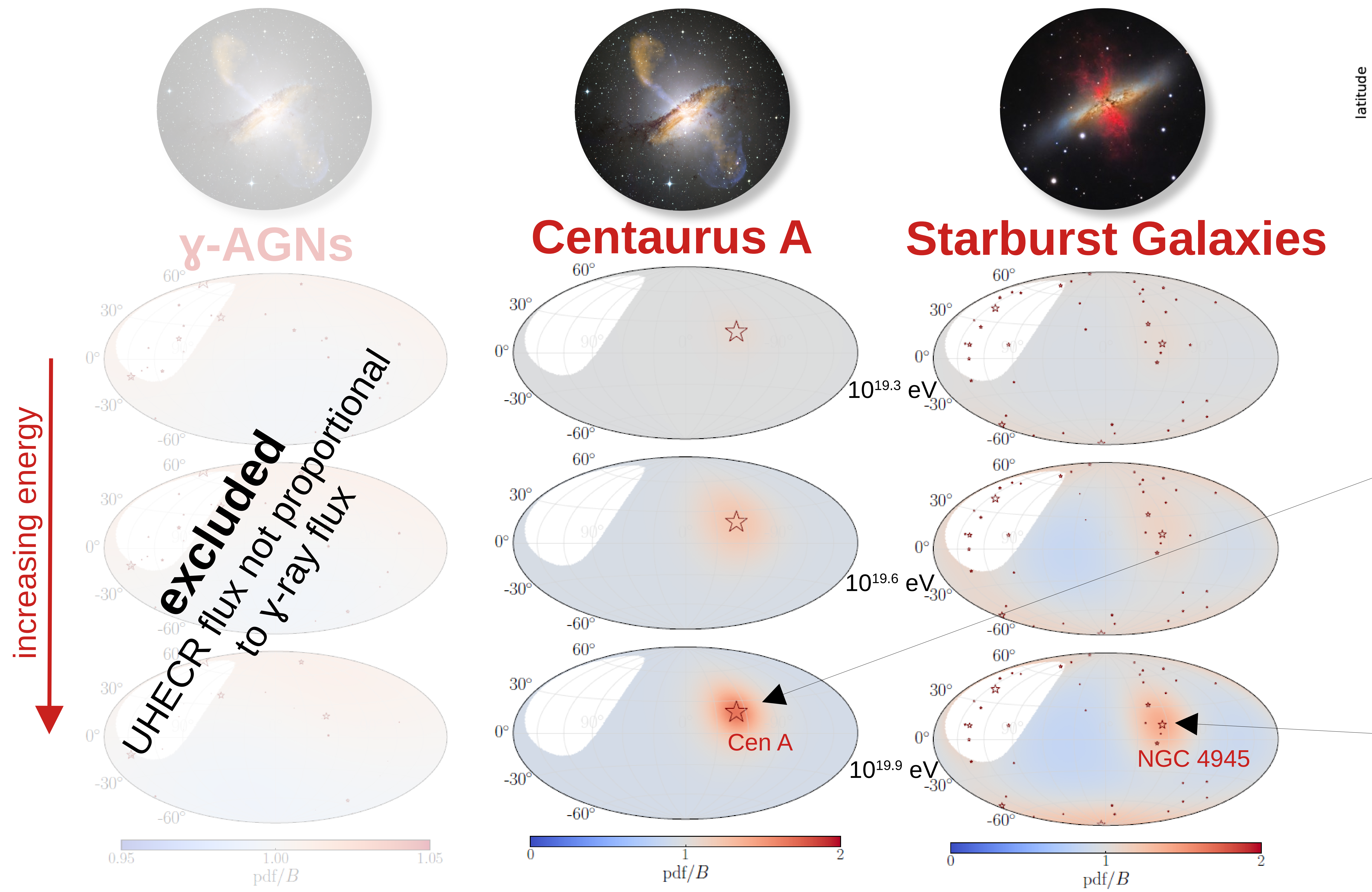
- energy spectrum
- mass composition
- **arrival directions E>20 EeV**

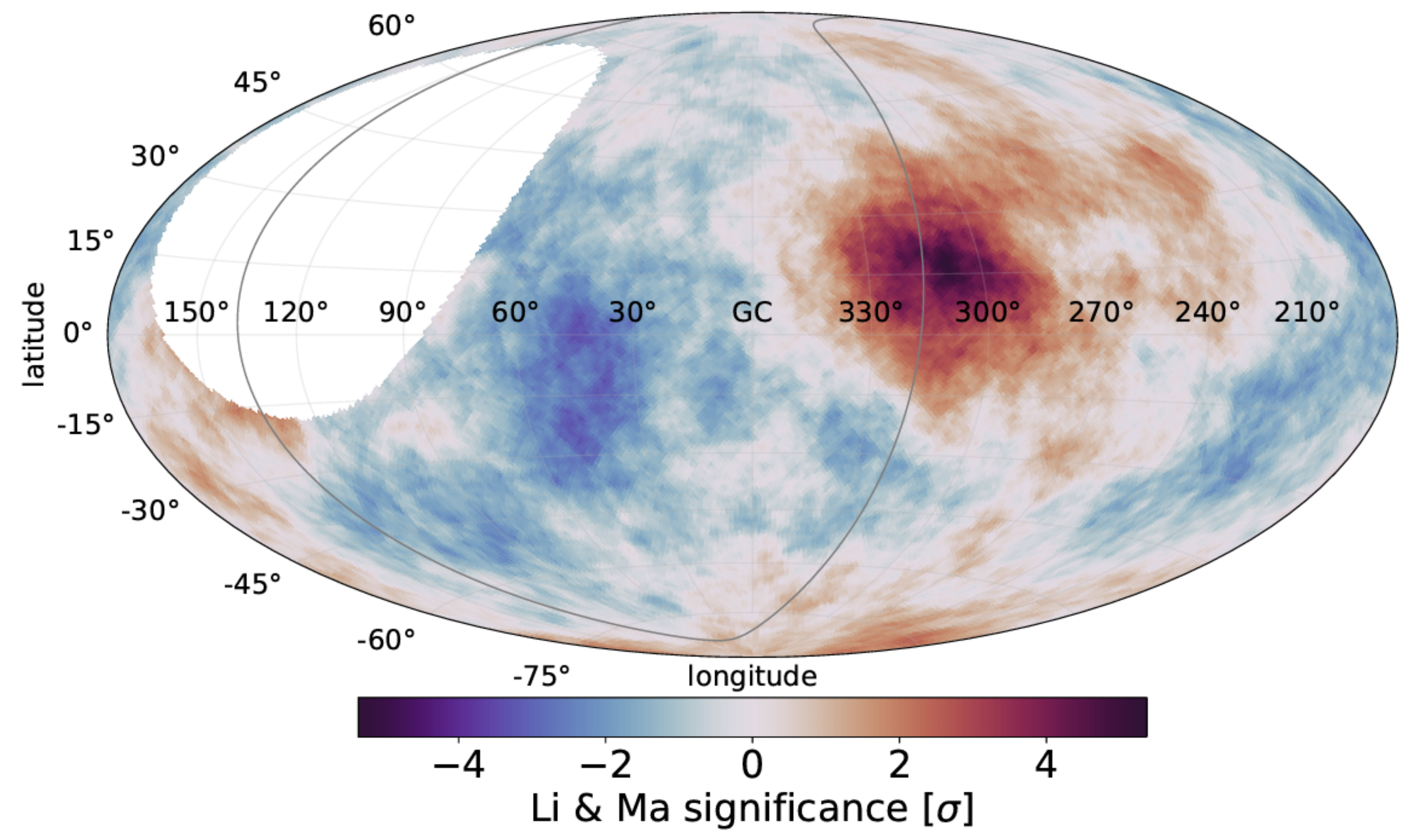




Picture: curtesy T. Bister

Best fit of mass composition, flux and anisotropy



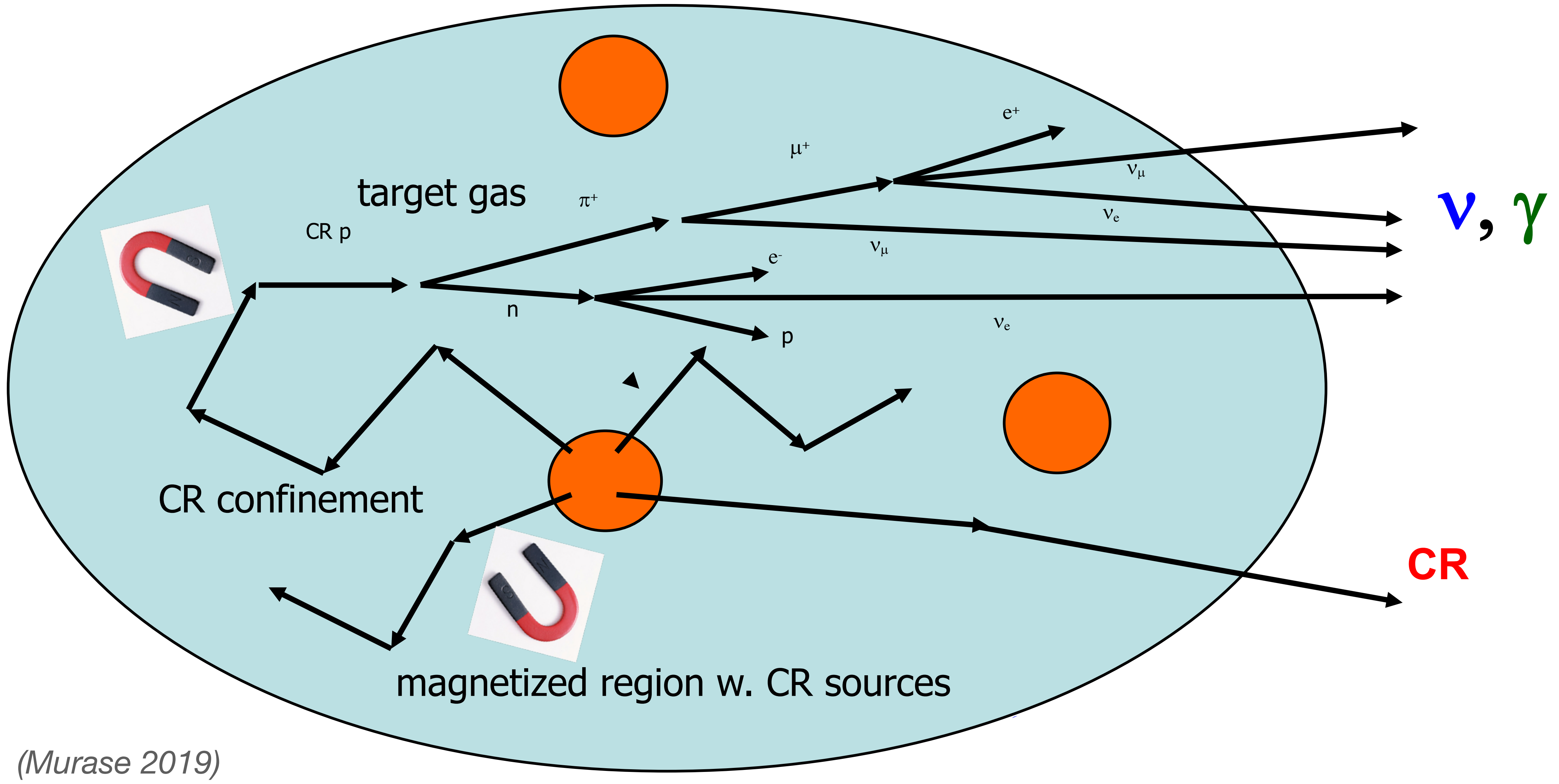


- **starburst galaxy model favored with 4.5σ significance over homogeneous model!**
- mostly due to Centaurus A / NGC 4945 region

PoS ICRC 2023
JCAP01 (2024) 022

Picture: curtesy T. Bister

Source models and challenges



(Murase 2019)

Problem 1: injection of mainly heavy elements

Problem 2: ions have to leave source

Problem 3: hard source spectrum

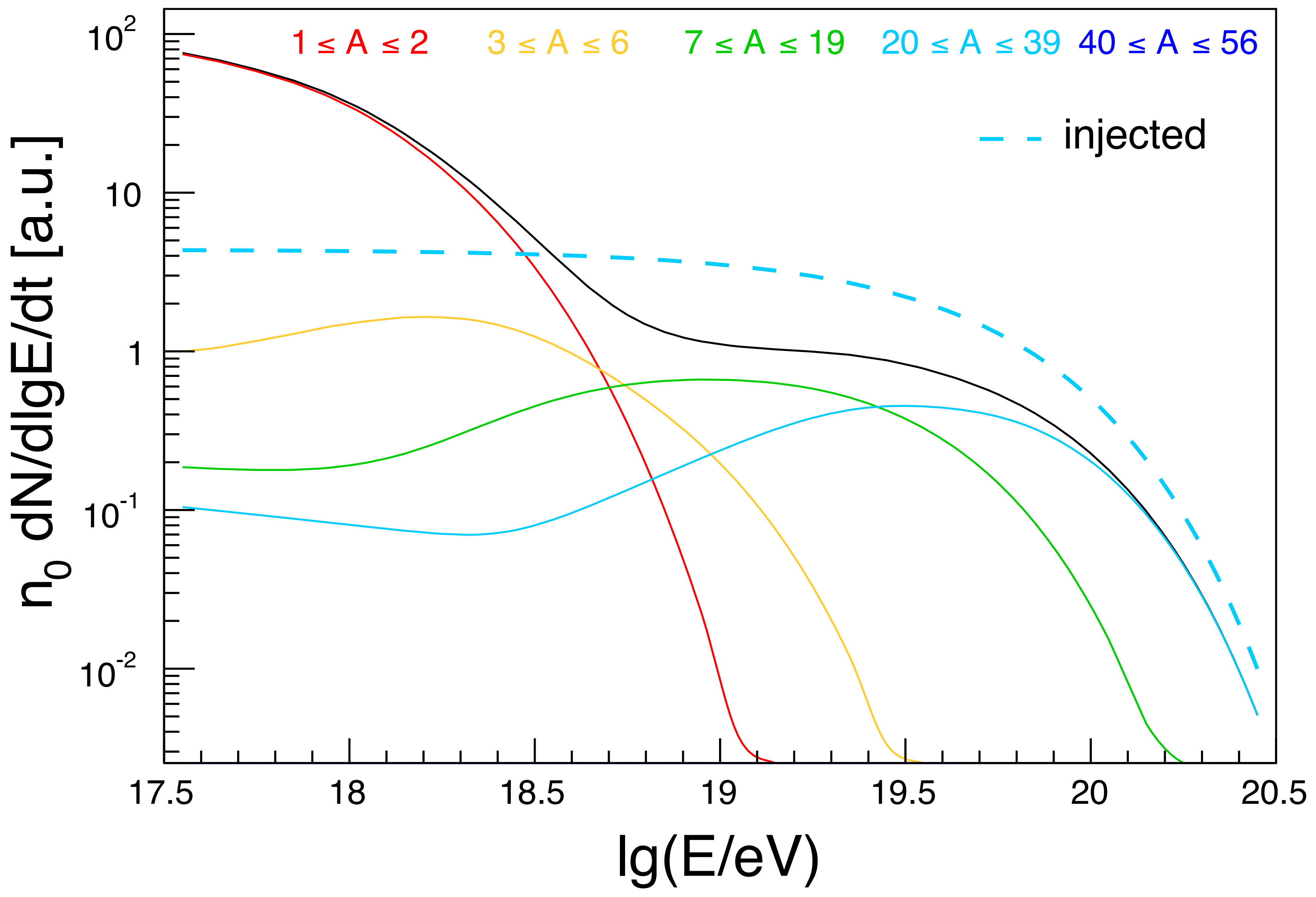
Problem 4: source population diversity

Problem 5: large degree of isotropy

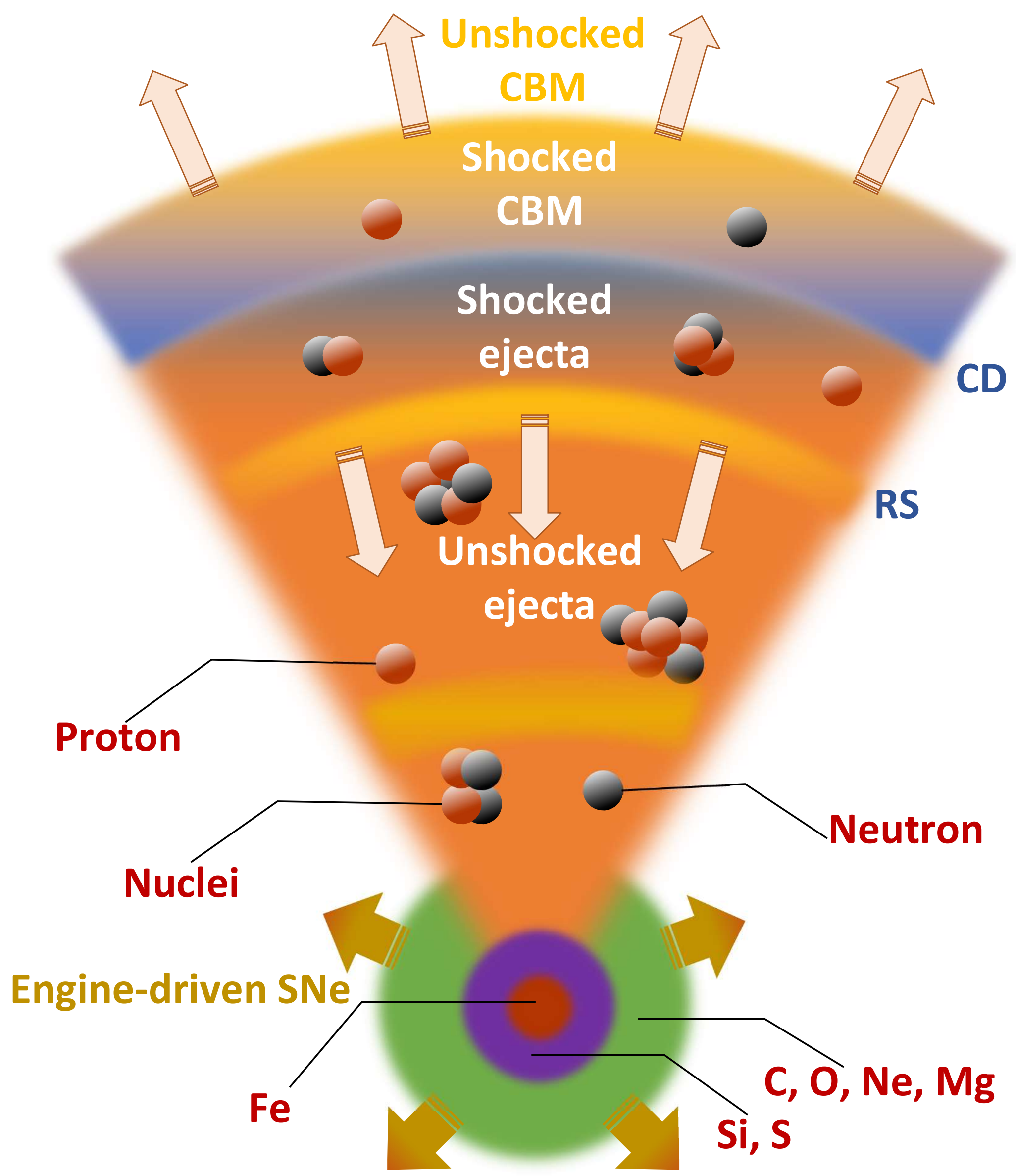
$$\frac{\mathrm{d}N_{\mathrm{ini}}}{\mathrm{d}E} \sim E^{-1}$$

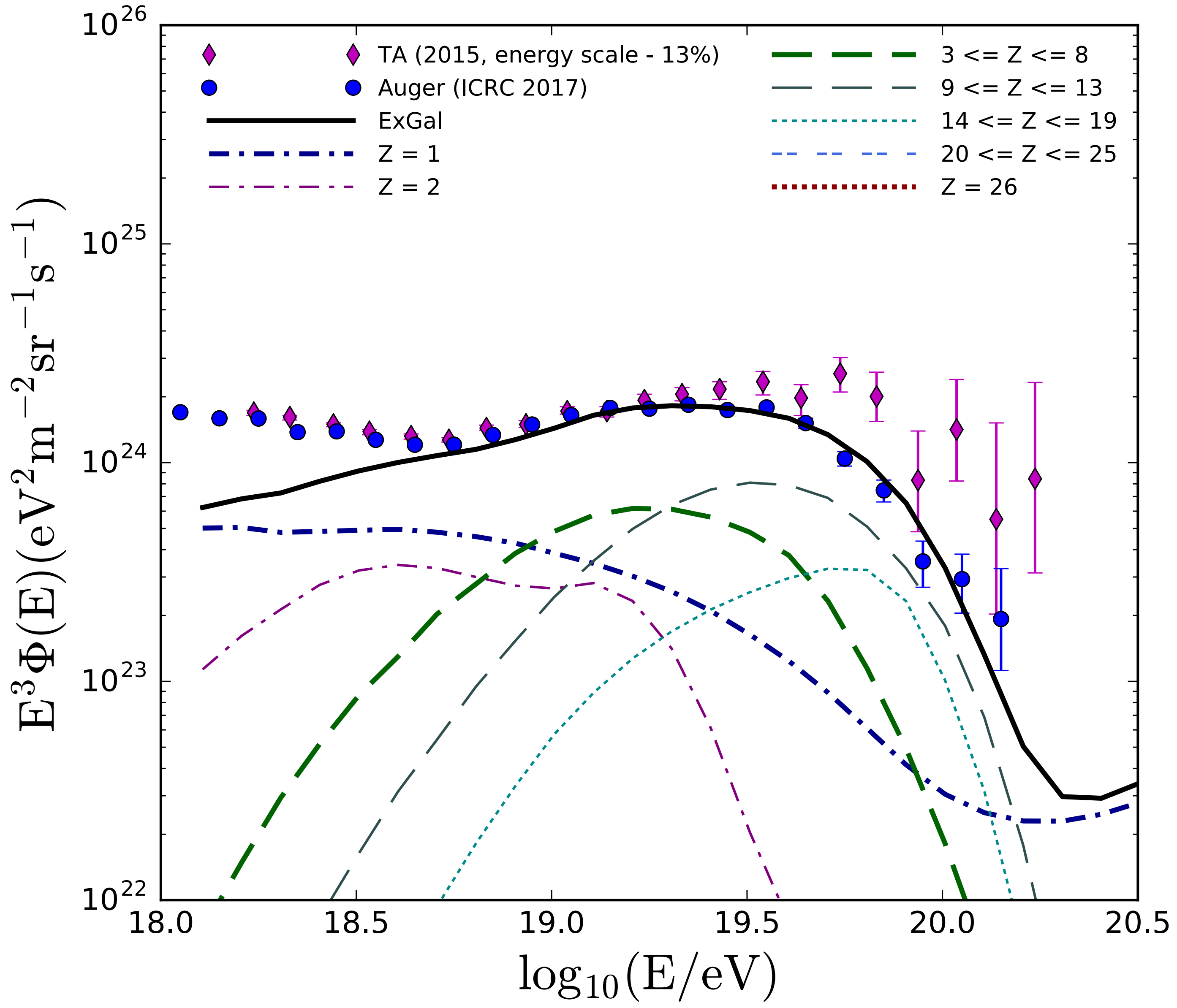
Nuclear disintegration in source region (scaling with mass A)

(Globus et al. 2015, Unger et al. 2015, Fang & Murase 2017)



New generation of complex model scenarios



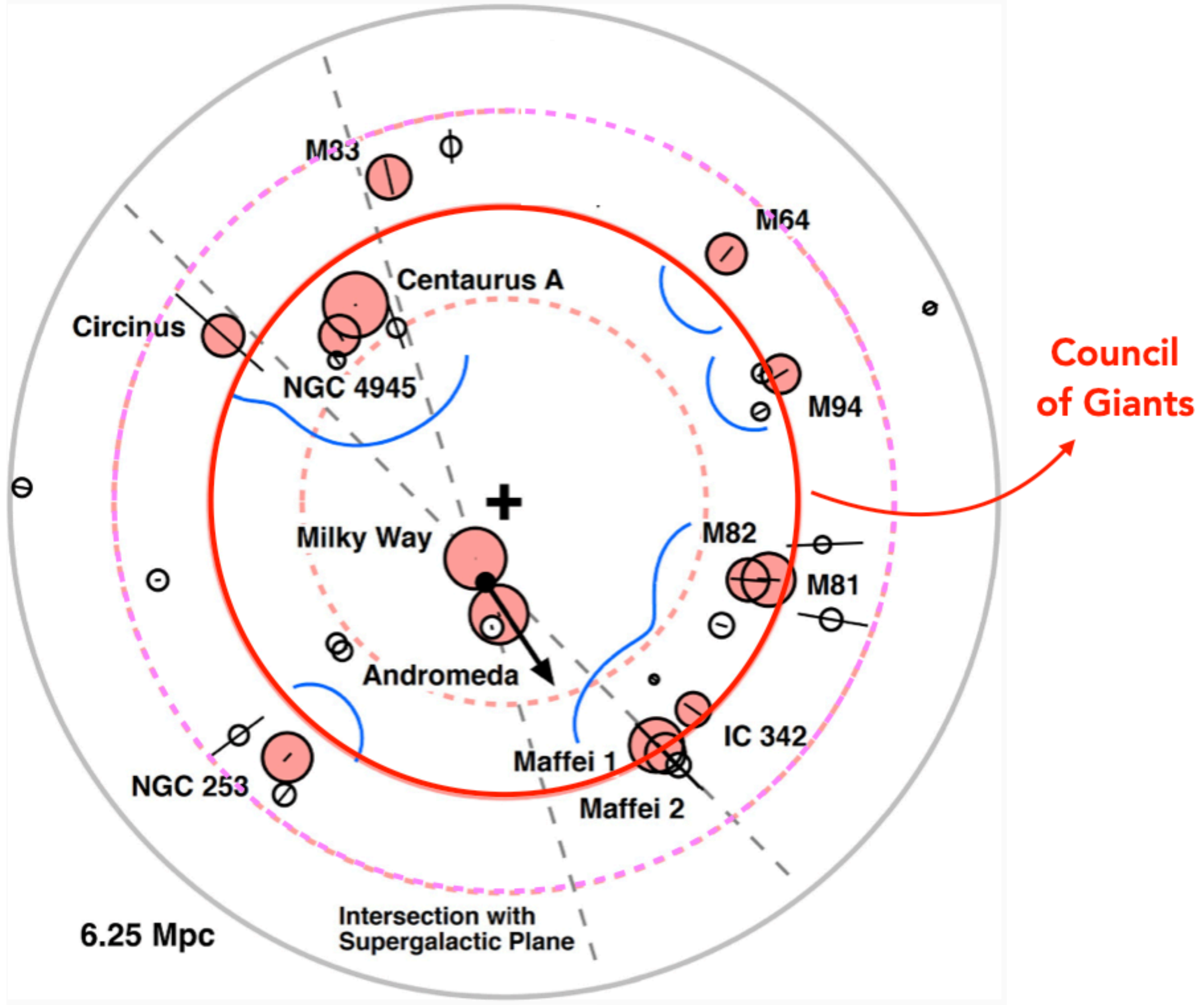


Interplay between
confinement in source
and disintegration of nuclei:
hard energy spectra
(Aloisio et al. 2014, Taylor et al. 2015, Globus et al. 2015, Unger et al. 2015, Fang & Murase 2017)

Reverse shock scenario in
low-luminosity long GRBs
(Zhang, Murase et al 2019+)

Tidal disruption events (TDEs)
of WD or carbon-rich stars
(Farrar, Piran 2009, Pfeffer et al. 2017, Zhang et al 2017)

One-shot acceleration in
rapidly spinning **neutron stars**
(Arons 2003, Olinto, Kotera, Feng, Kirk …)



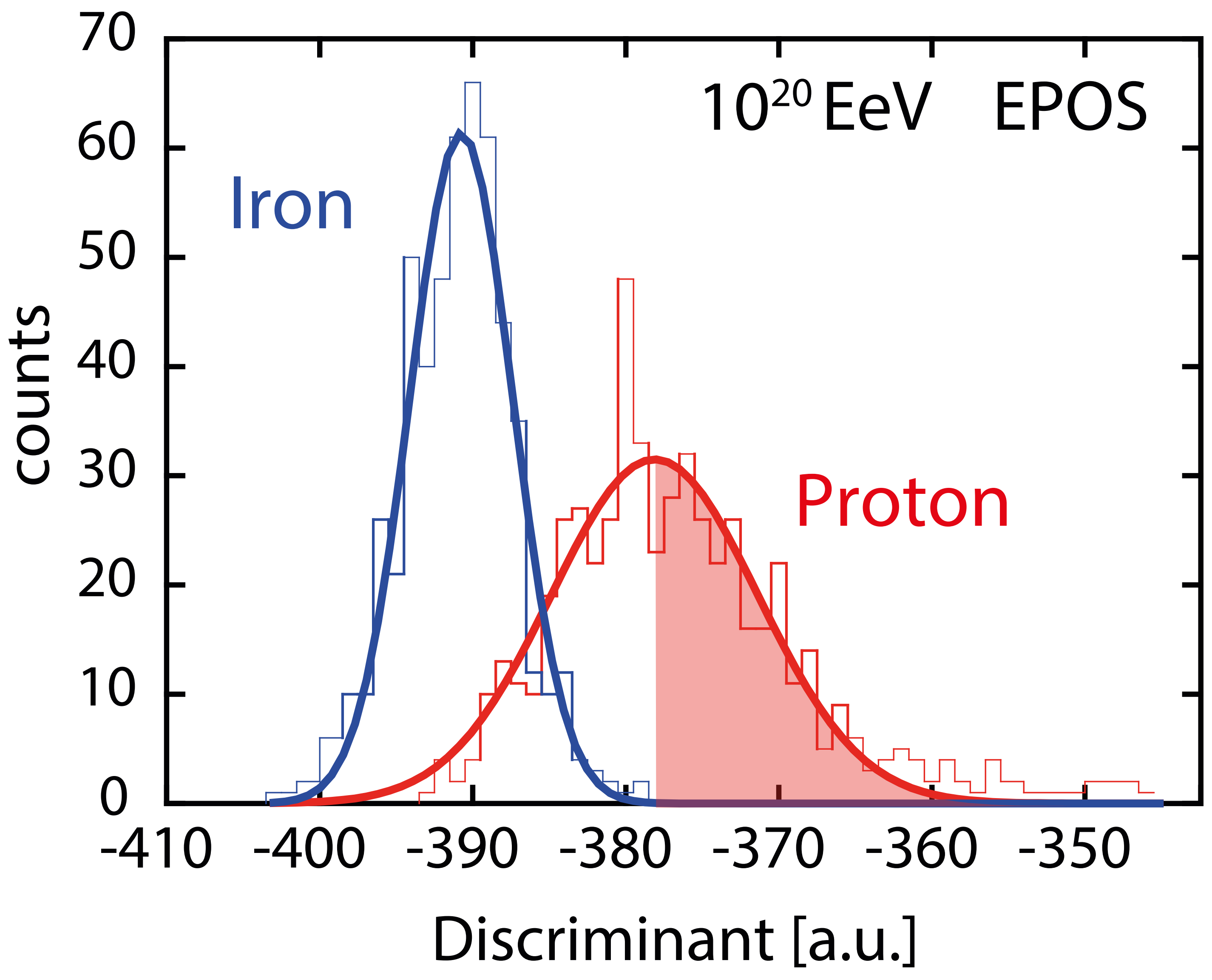
Cen-A bust & **deflection on Council of Giants**, solving isotropy and source diversity problem
(Taylor et al. 2023)

Relativistic reflection of
existing CR population
(Biermann, Caprioli, Wykes, 2012+, Blandford 2023)

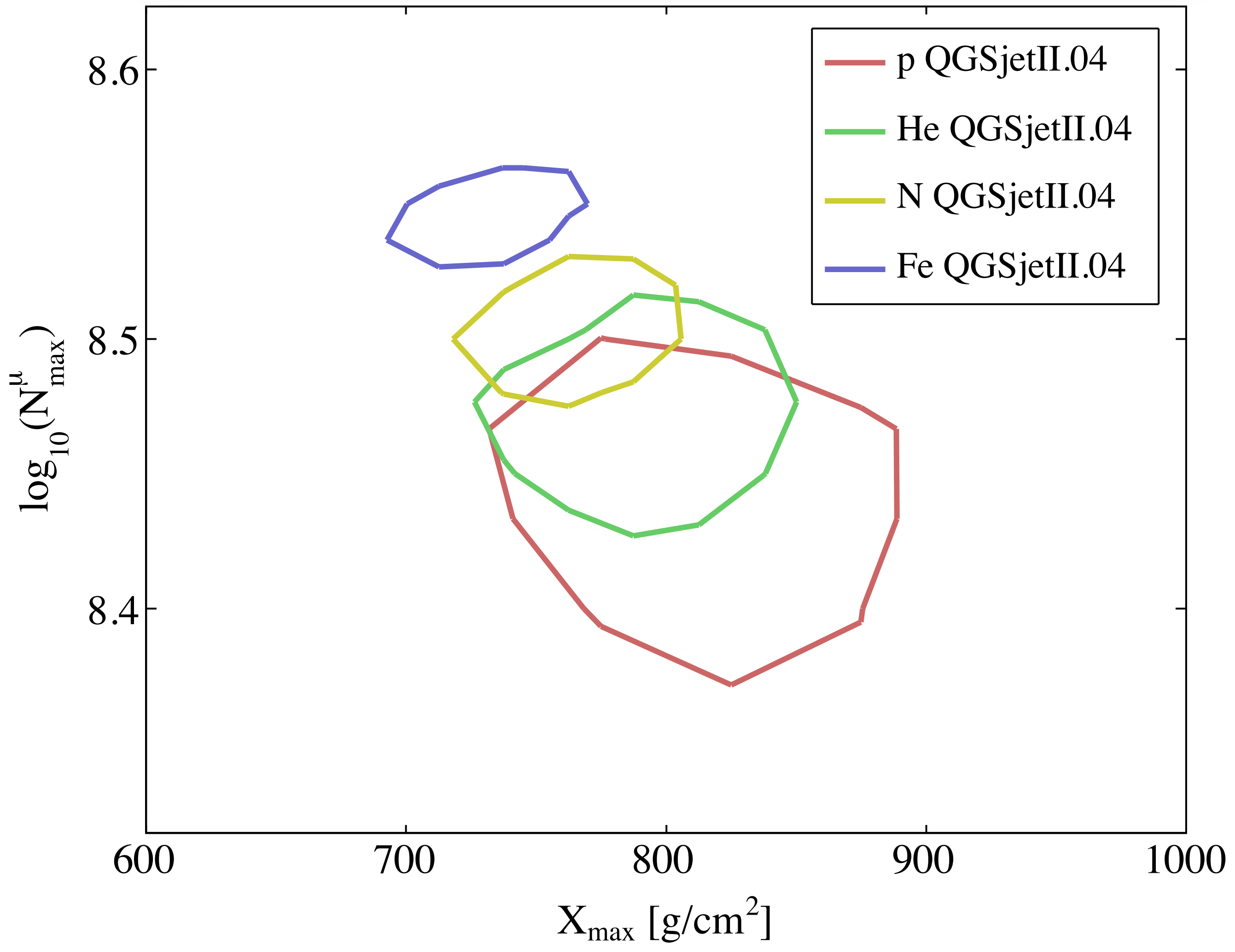
Upgrade of Auger Observatory: AugerPrime

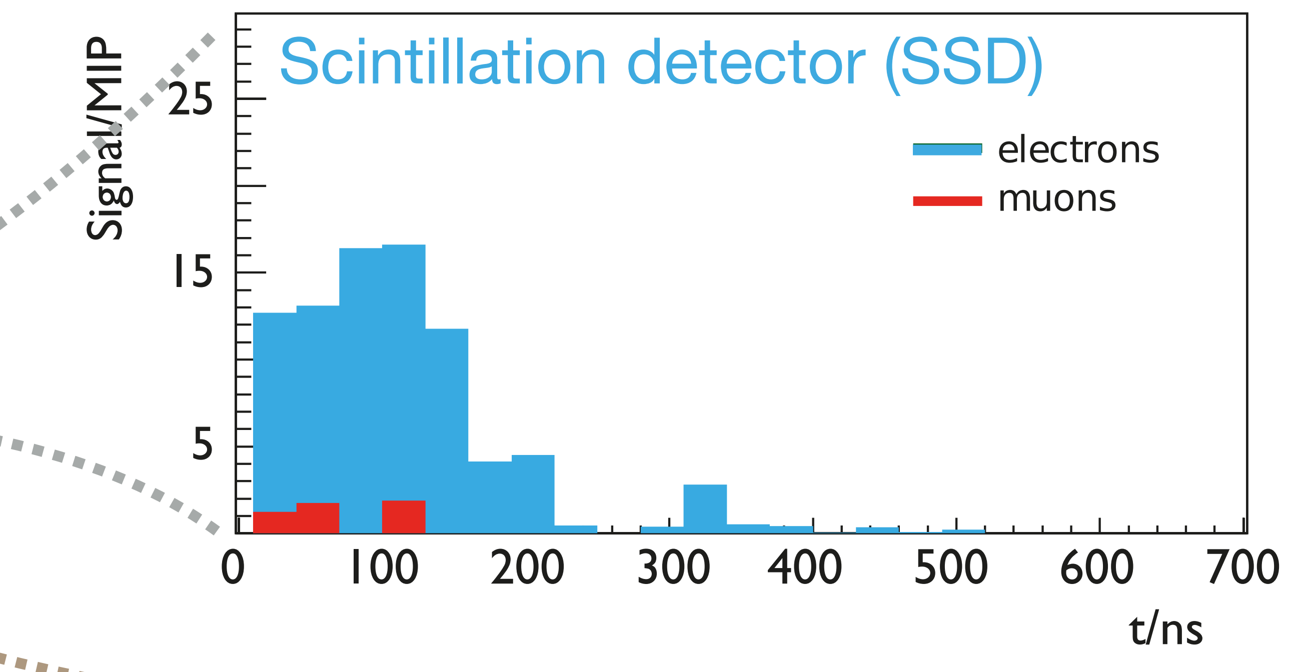
To increase exposure with composition sensitive data Surface array needed!

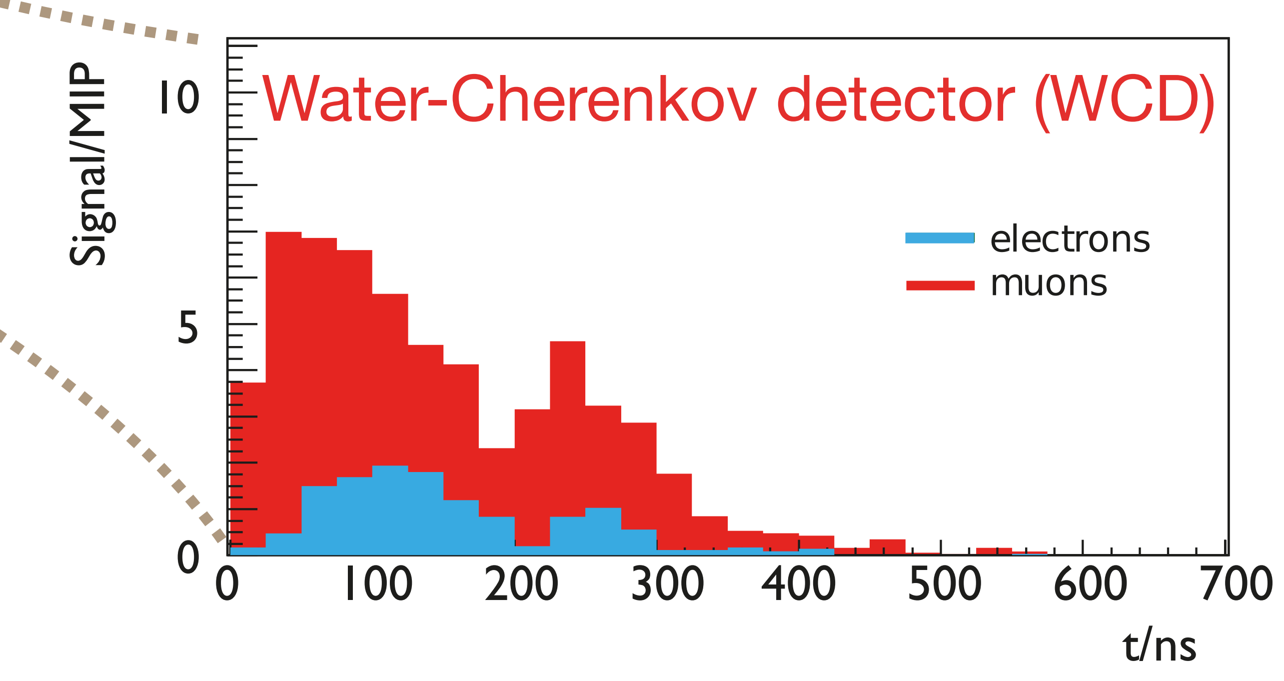
Duty cycle: 100% (SD) vs 15% (FD)



Complementarity of particle response used to discriminate em. and muonic components







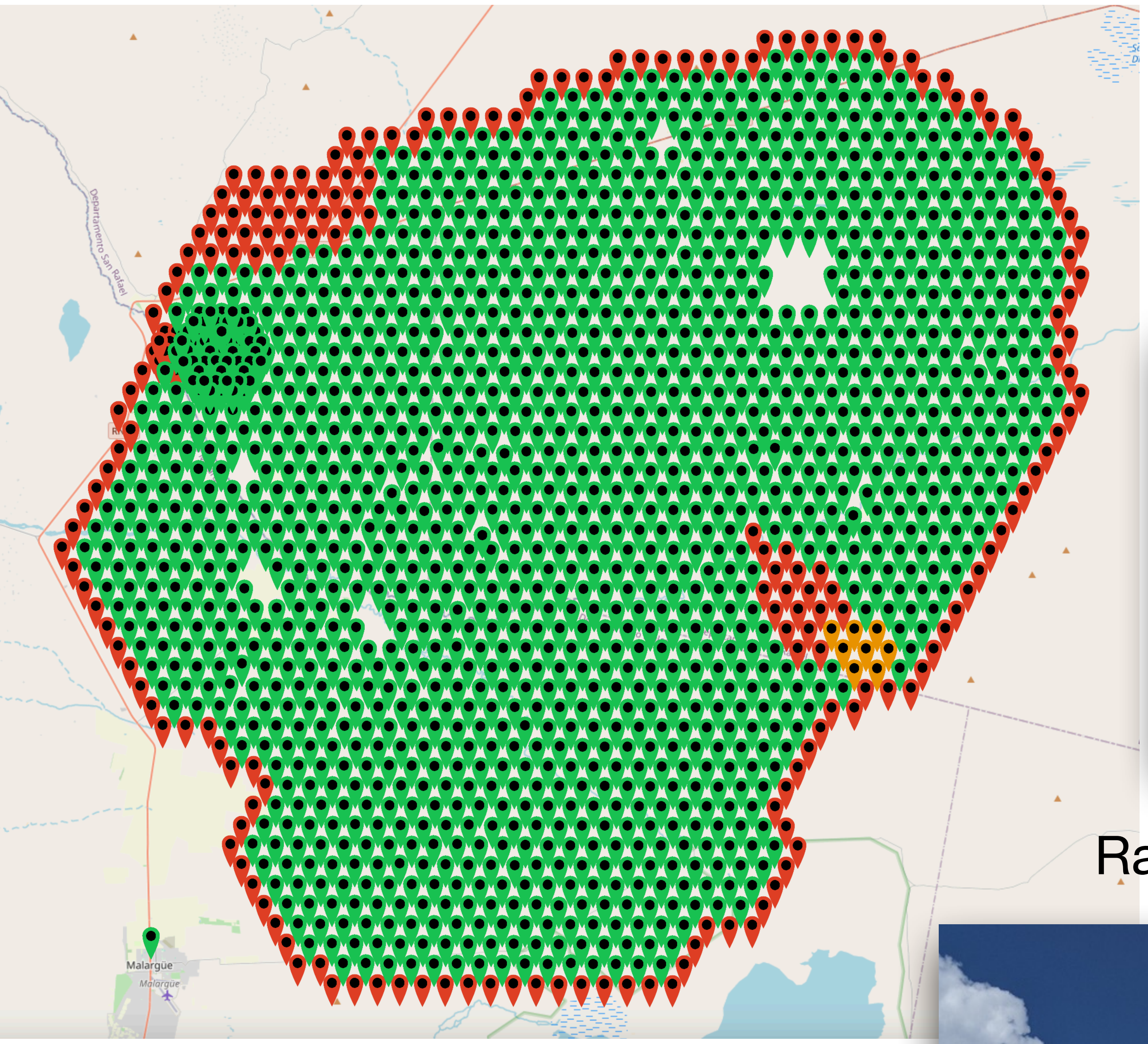
$$S_{\mu,\mathrm{WCD}} = a\, S_{\mathrm{WCD}} + b\, S_{\mathrm{SSD}}$$

$$S_{\mathrm{em},\mathrm{WCD}} = c\, S_{\mathrm{WCD}} + d\, S_{\mathrm{SSD}}$$

(AugerPrime design report 1604.03637)

Status and plans for AugerPrime

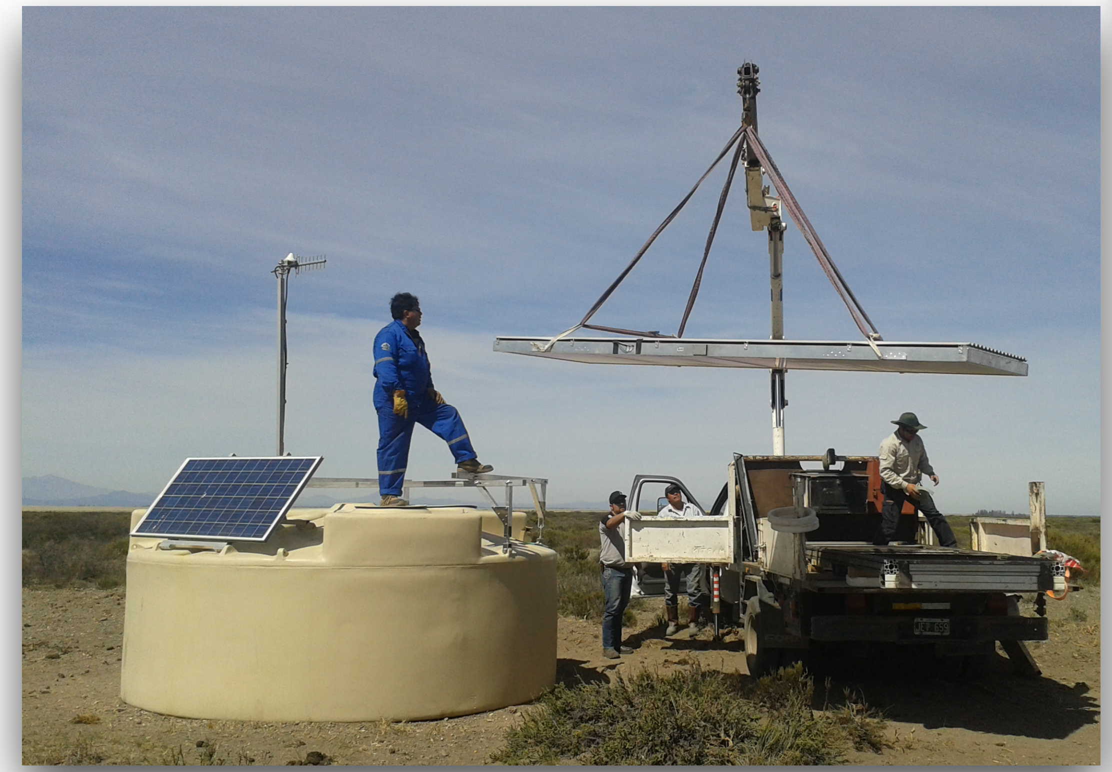
Status 2024-03-04

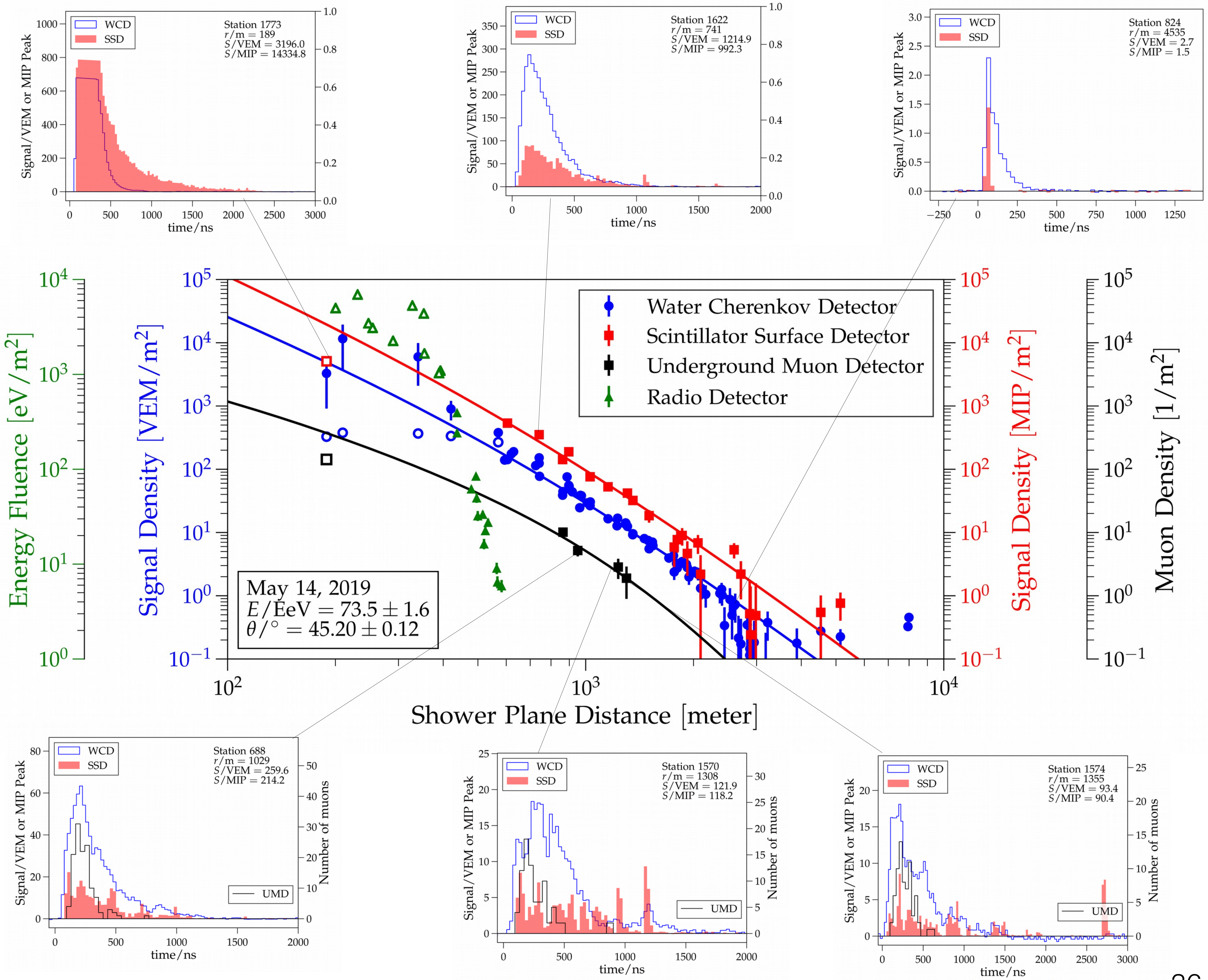


Muon detectors: 41 installed

Radio: 904 (411) installed

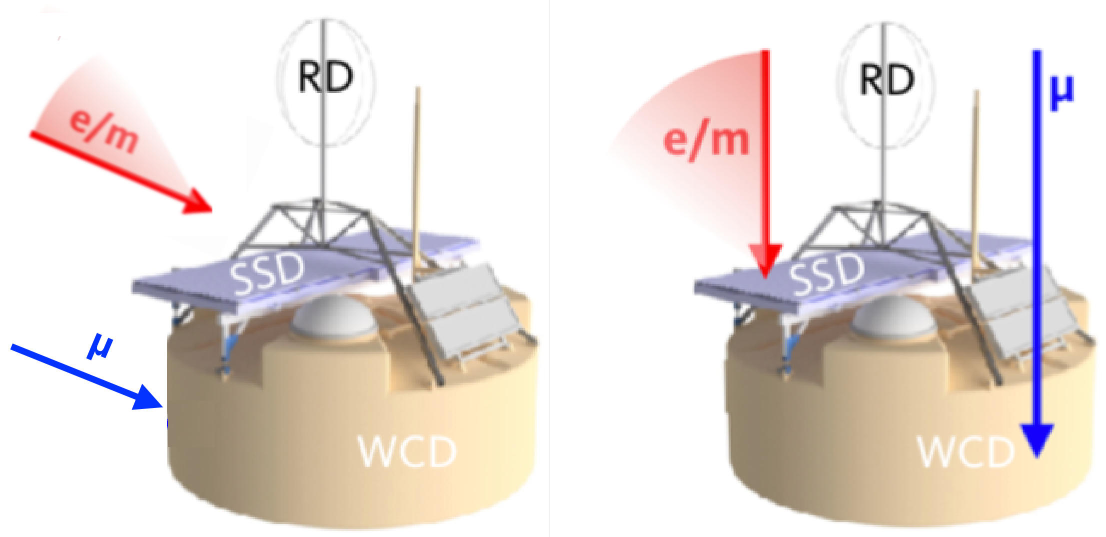
Scintillators: 1450 installed





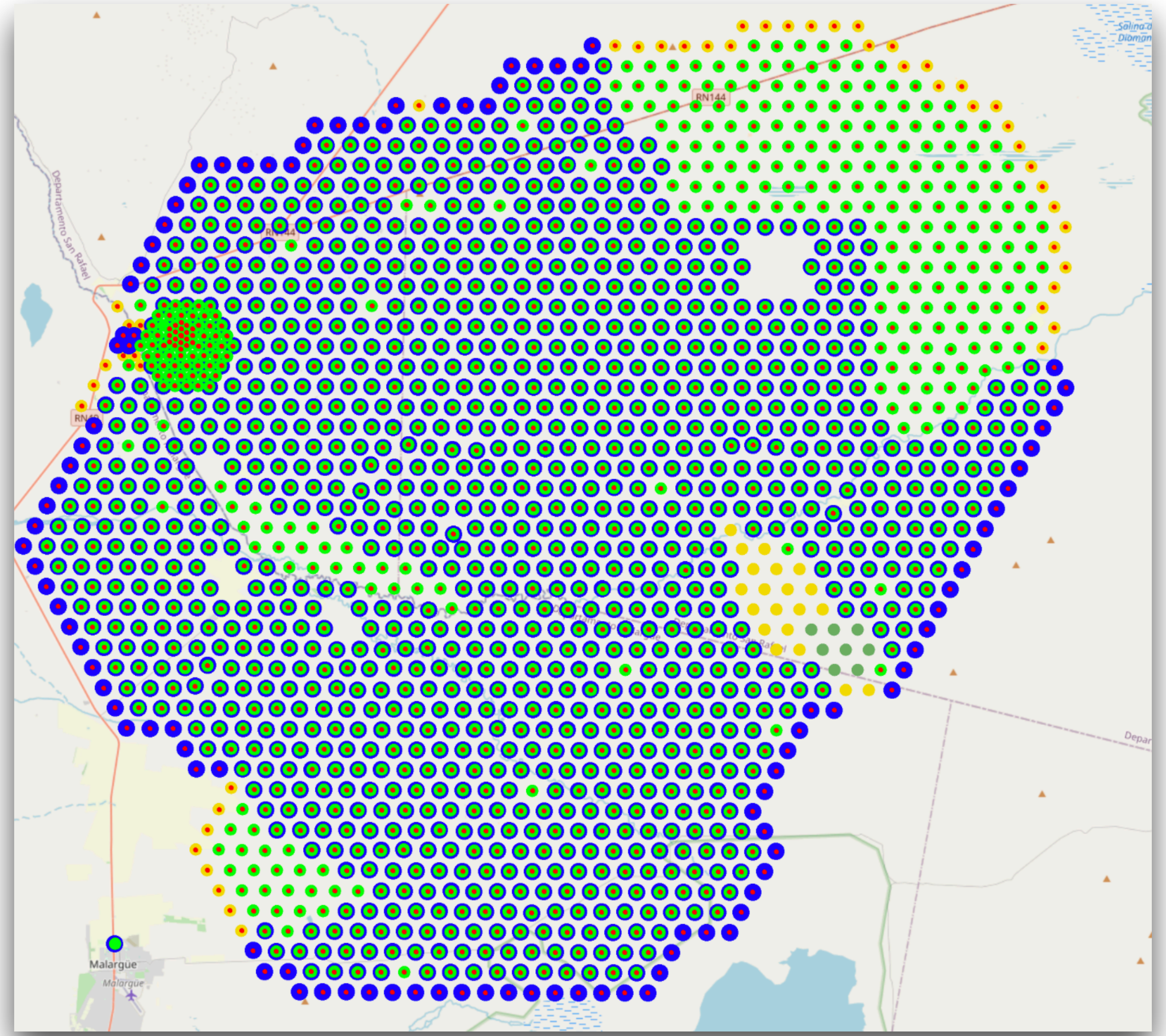
Advent of AugerPrime: data start flowing in

RD: most extended radio event detected so far



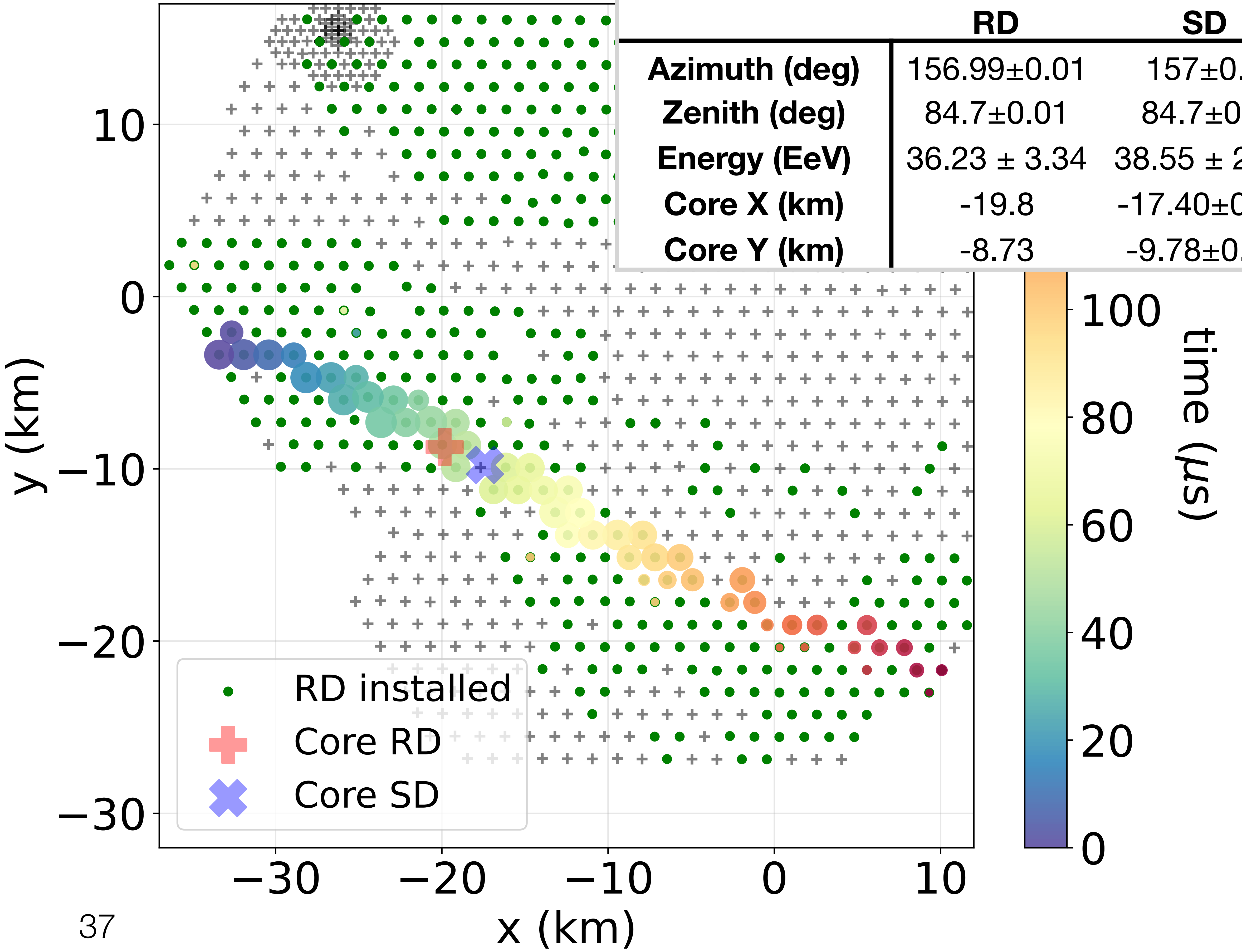
AugerPrime (6/2024)

- 1475 scintillators installed
- 1529 with new electronics (incl. rim)
- 1240 radio antennas (704 with digitizers)



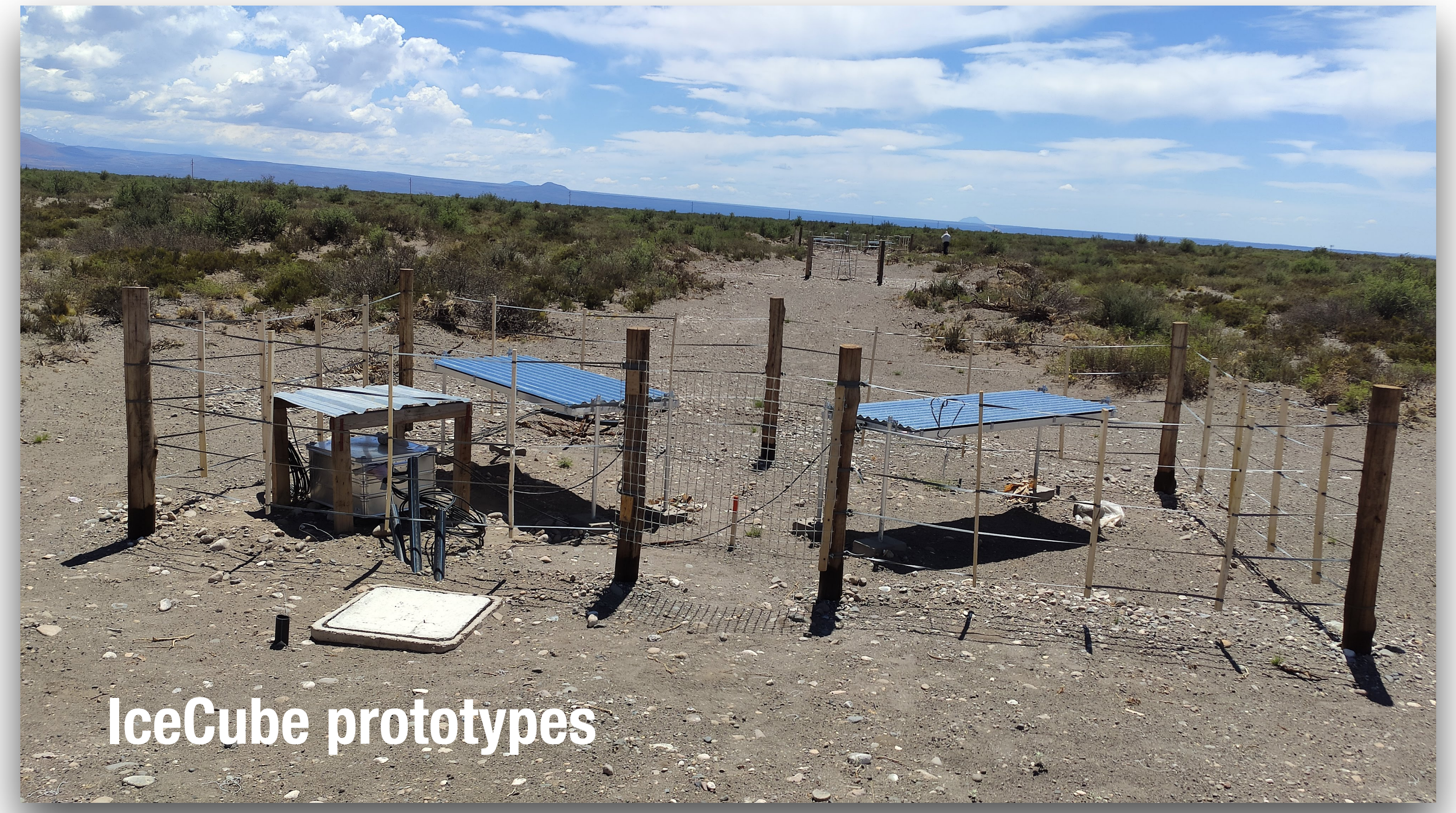
Comparing SD and RD

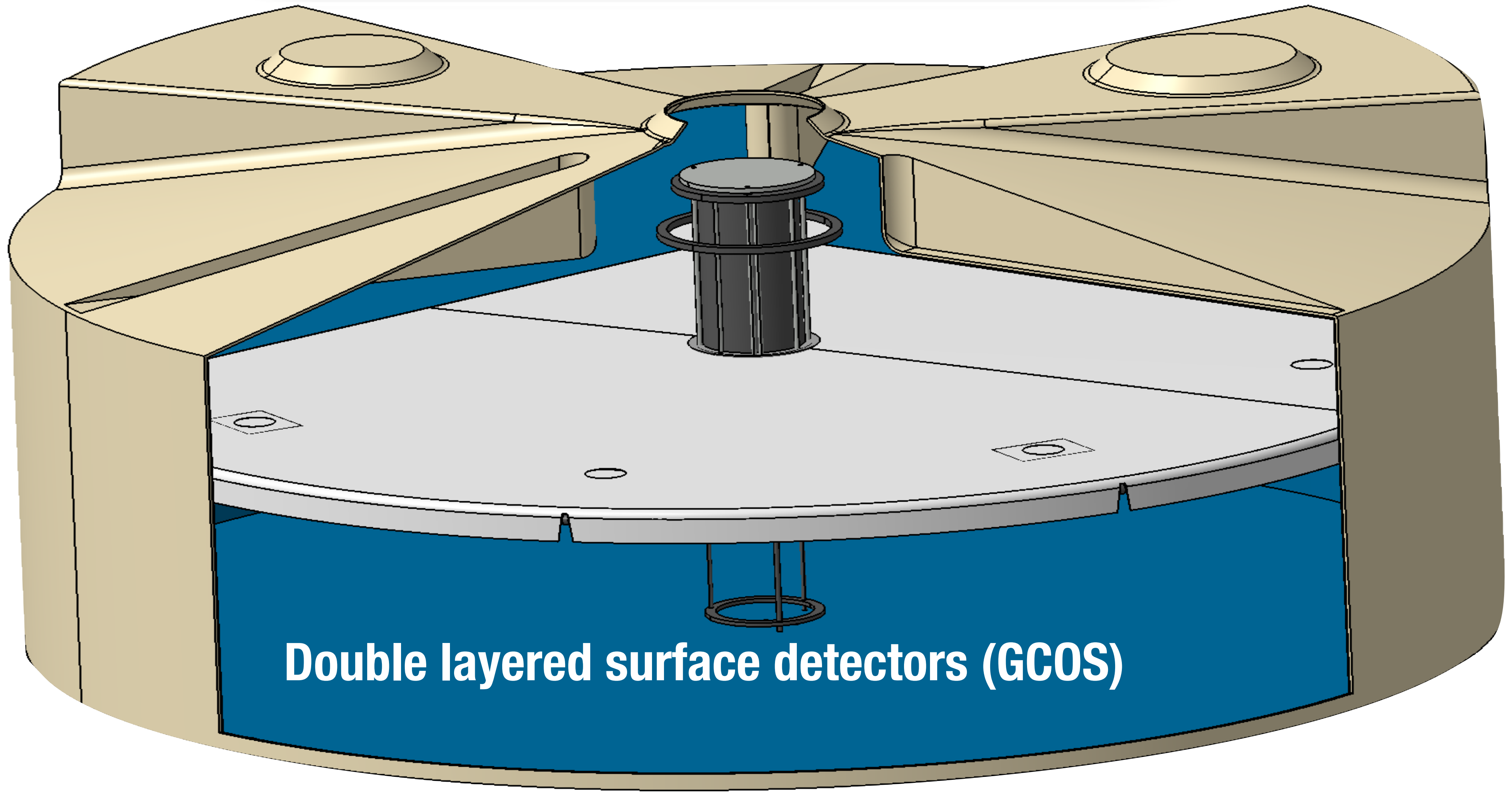
- Recorded in April 2024
- SD and RD data well in agreement



	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

Shaping the future — Auger as testbed for next generation arrays





Conclusions

Measurements are the driving force behind progress in UHECR physics

Complex and unexpected picture of UHECR emerging

Auger data have revolutionized our understanding of UHECRs

Increasingly consistent picture of UHECR emerging

Upgrade AugerPrime implemented, Phase II started

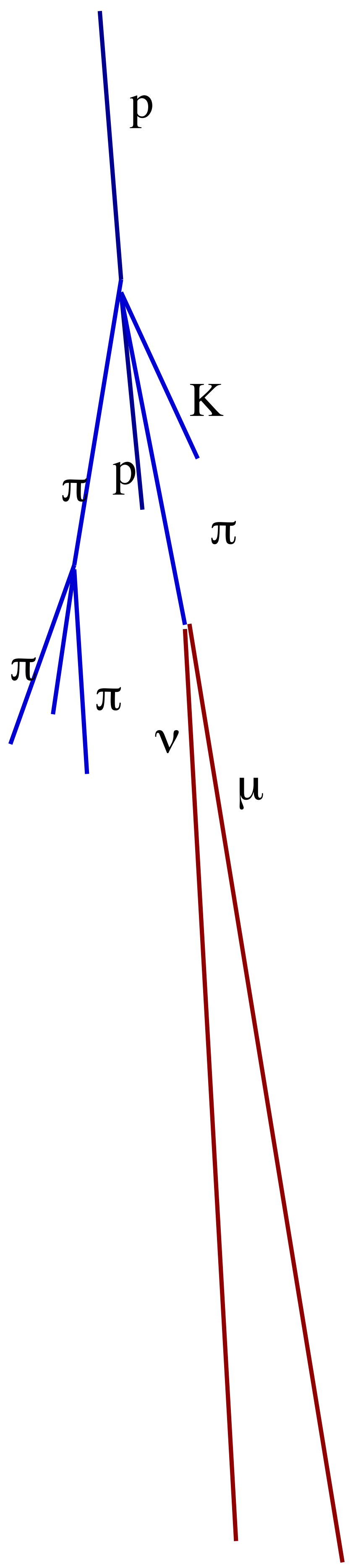
Source models have to be more sophisticated than simple power laws

Nature is completely different from what we thought 20 years ago (prior to Auger)

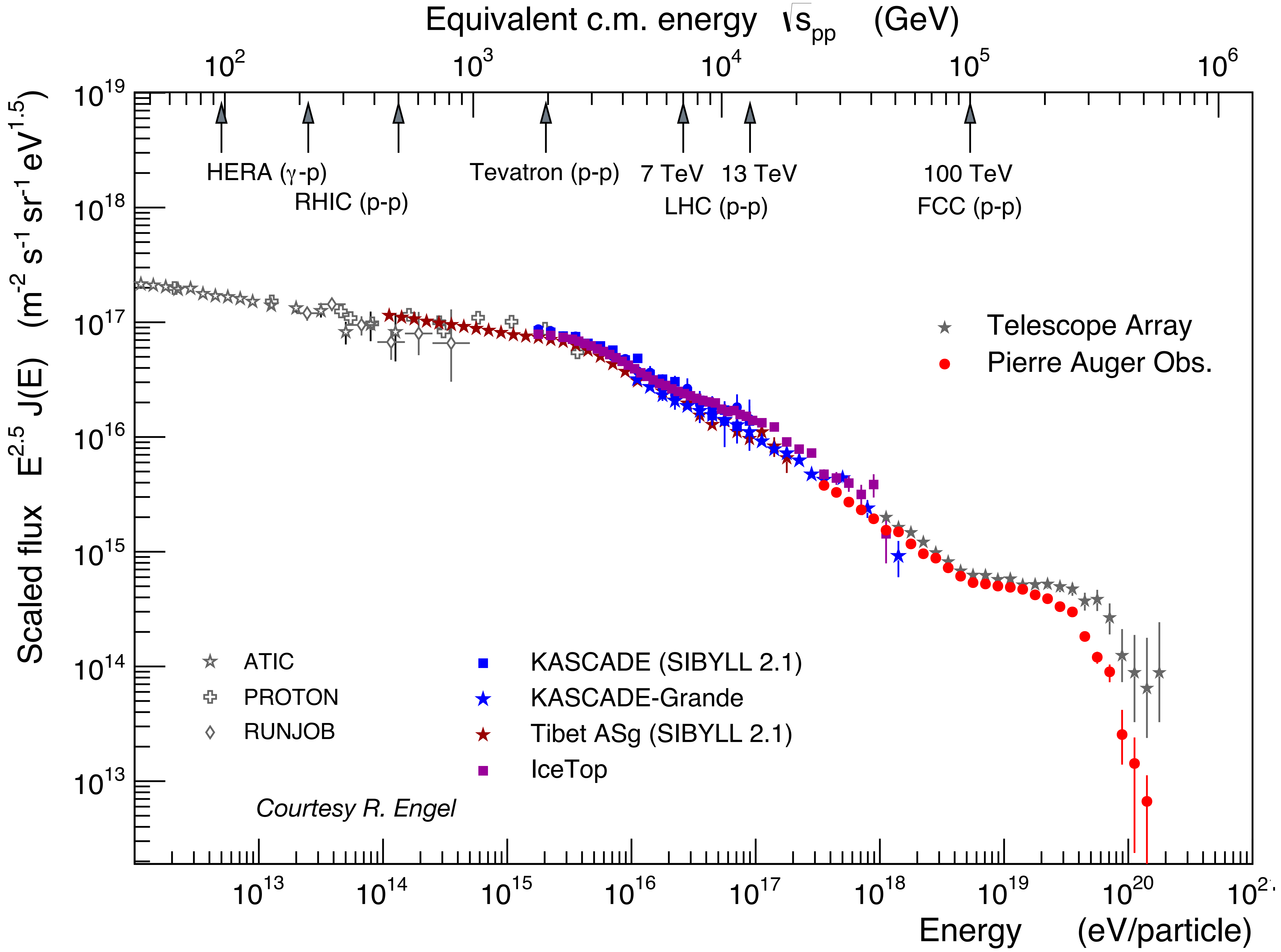
Many new challenges and questions (anisotropy, composition, MM)


THANK YOU
MERCI
GRAZIE
ASANTE
MULTUMESC
MAAKE
KIITOS
OBRIGADO
MATONDO
ARIGATO
SPASIBO
DANK JE
WELALIN
VINAKA
KIA ORA
JUSPAXAR
CHOKRANE
CAM ON BAN
TERMA KASIH
MATUR NUWUN
NIRRINGRAZZJAK
MOCHCHAKKERAM
MAMANA
UA TSAUG RAU KOJ
RAIBH MAITH AGAT
SALAMAT
DANKON

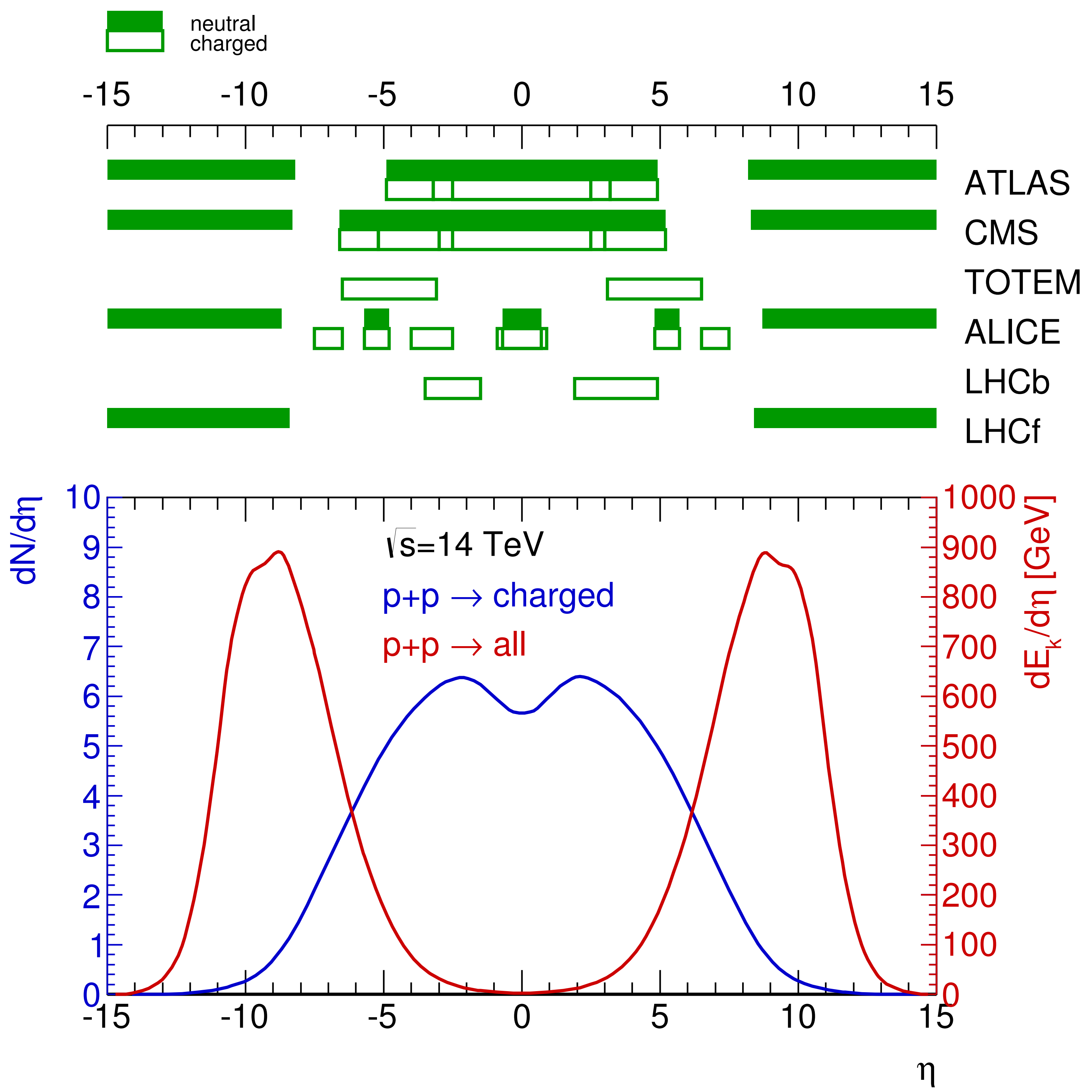
Flux of cosmic rays and interactions



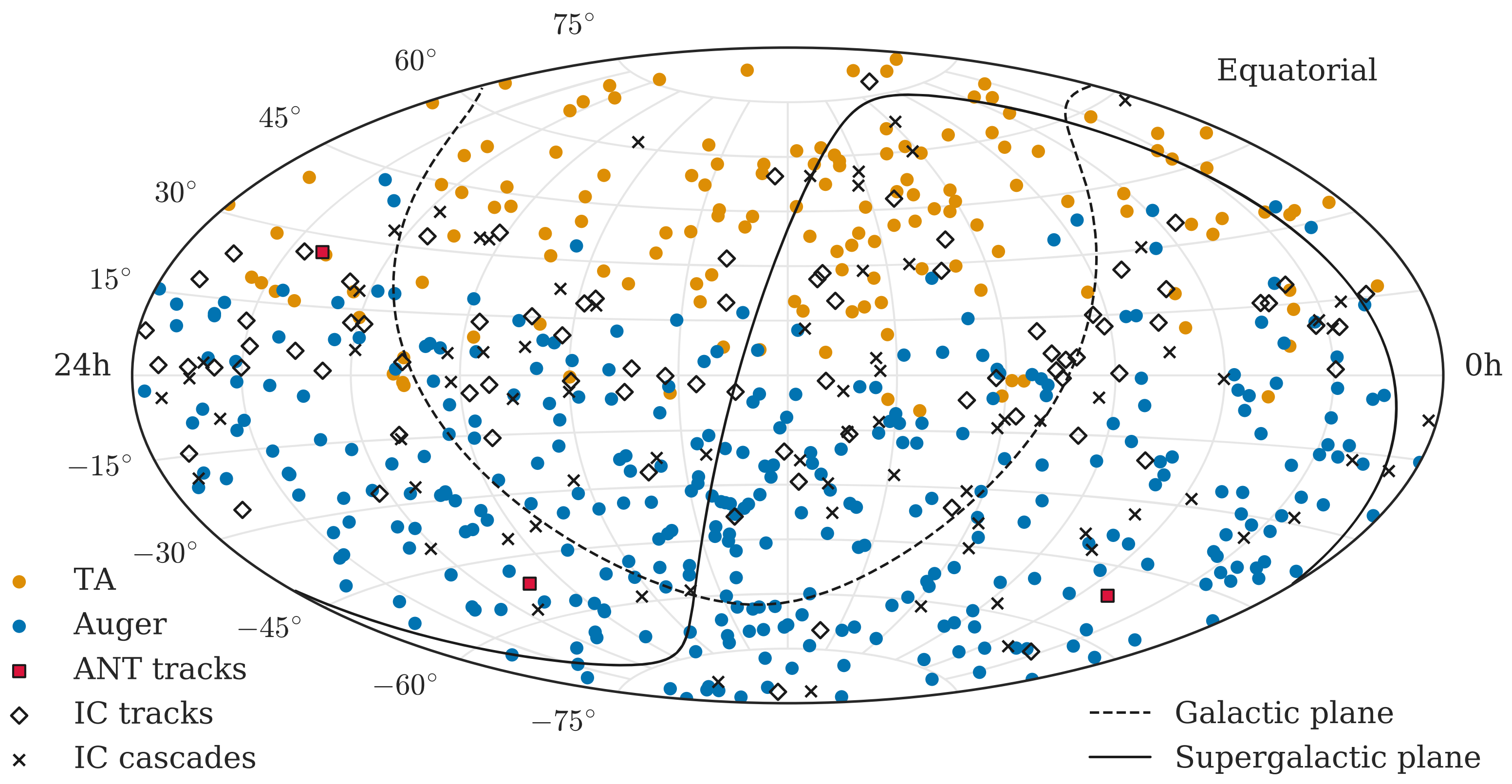
Center of mass energy



Laboratory energy

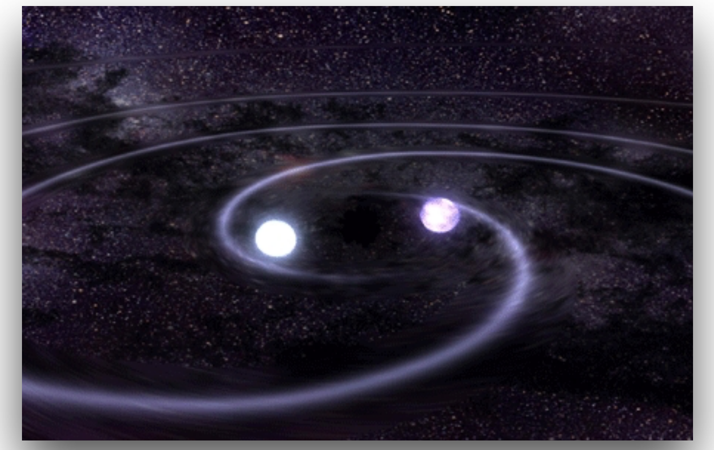


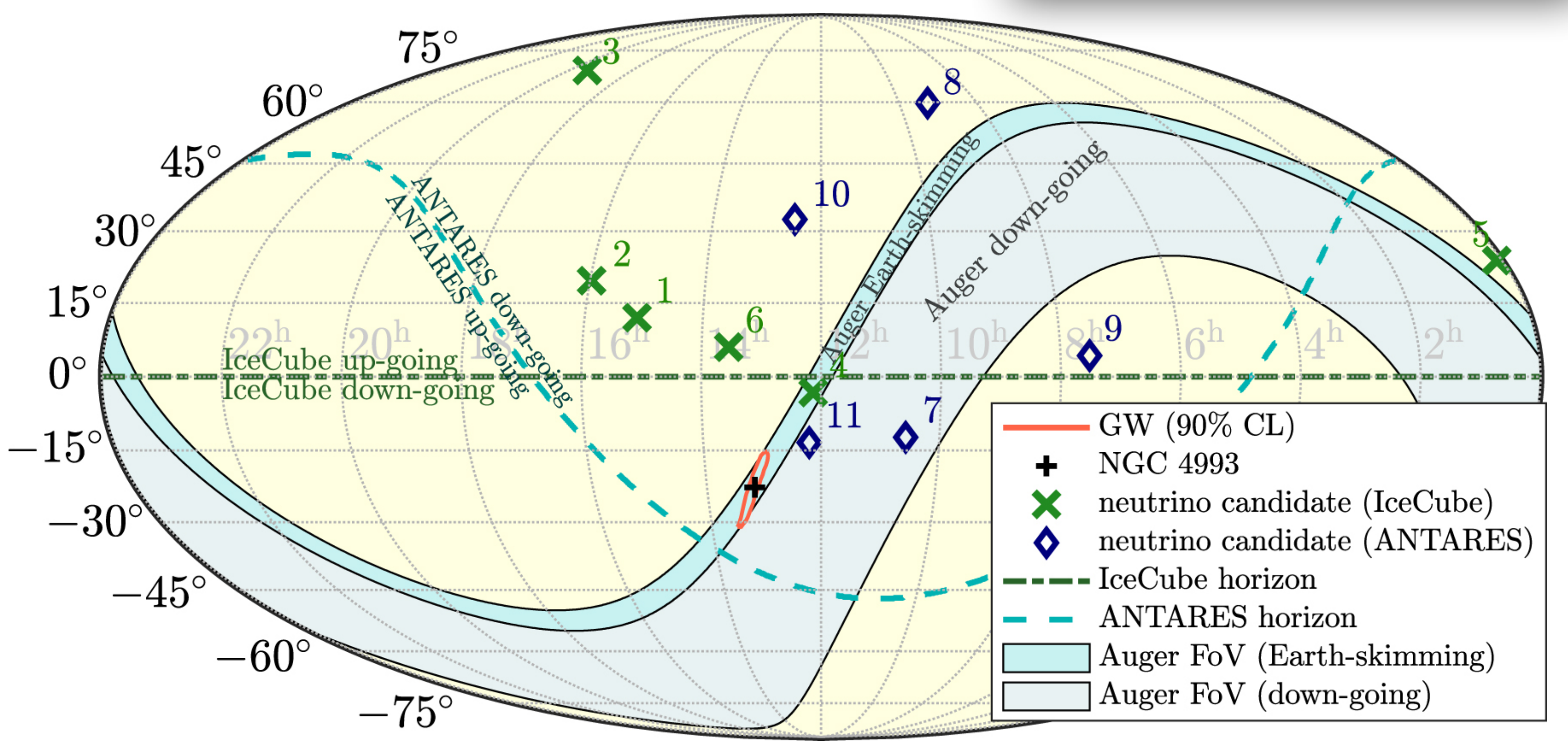
Multi-messenger astronomy with gravitational waves — GW 170817



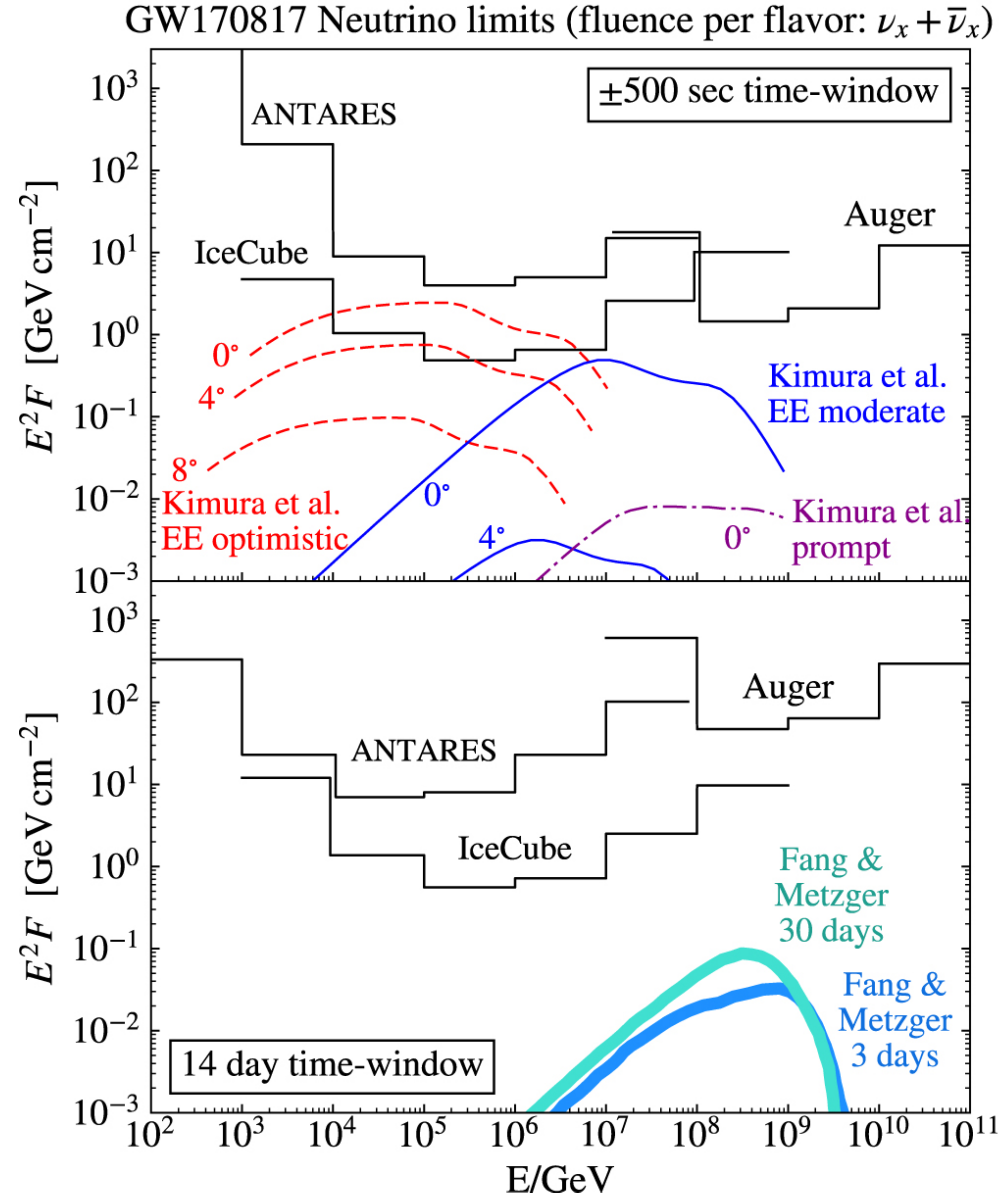
Search for spatial neutrino and UHECR correlations (ApJ 934 (2022) 164)

GW170817





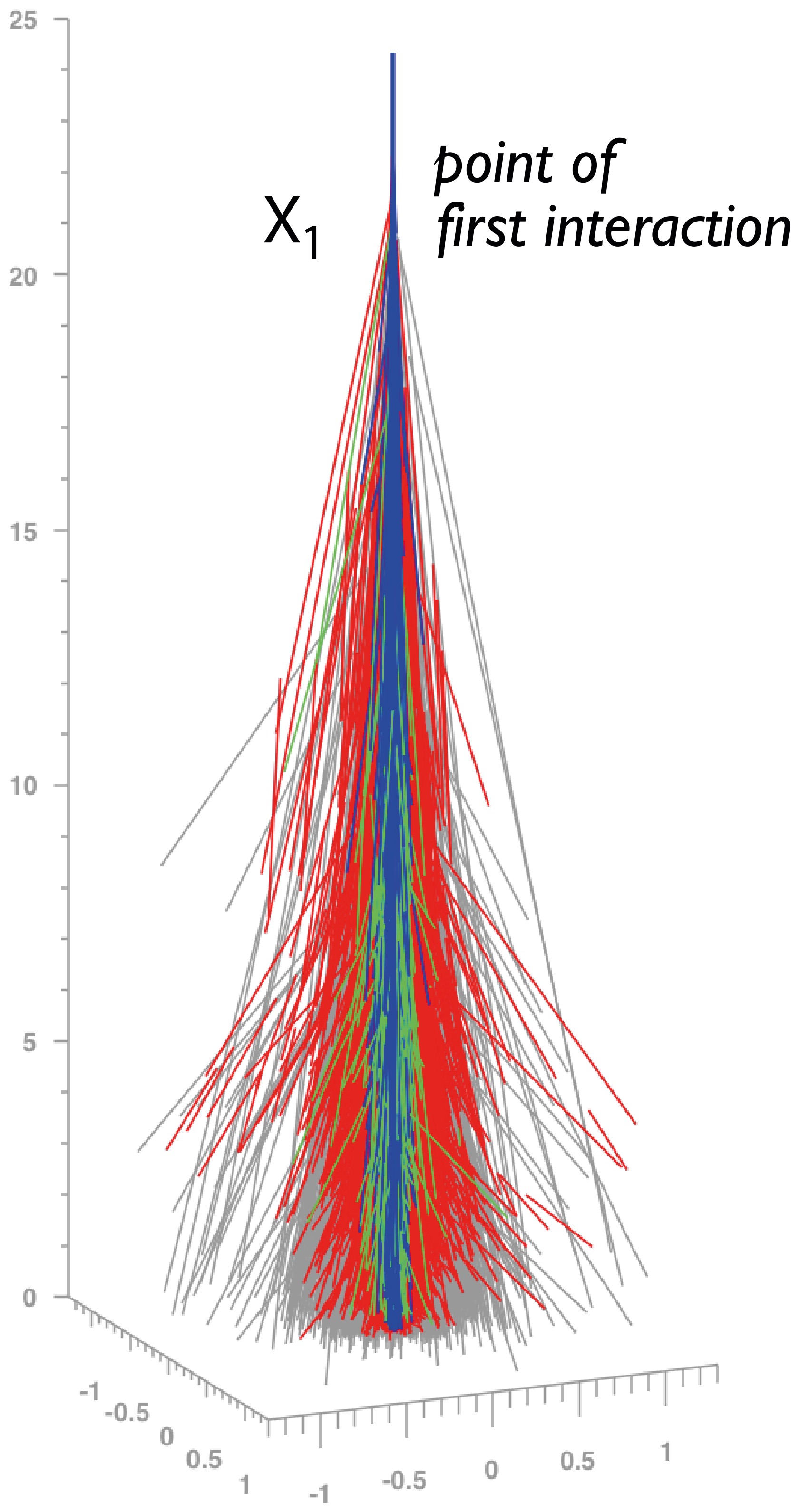
BBH merger; Albert et al. ApJL, 2017

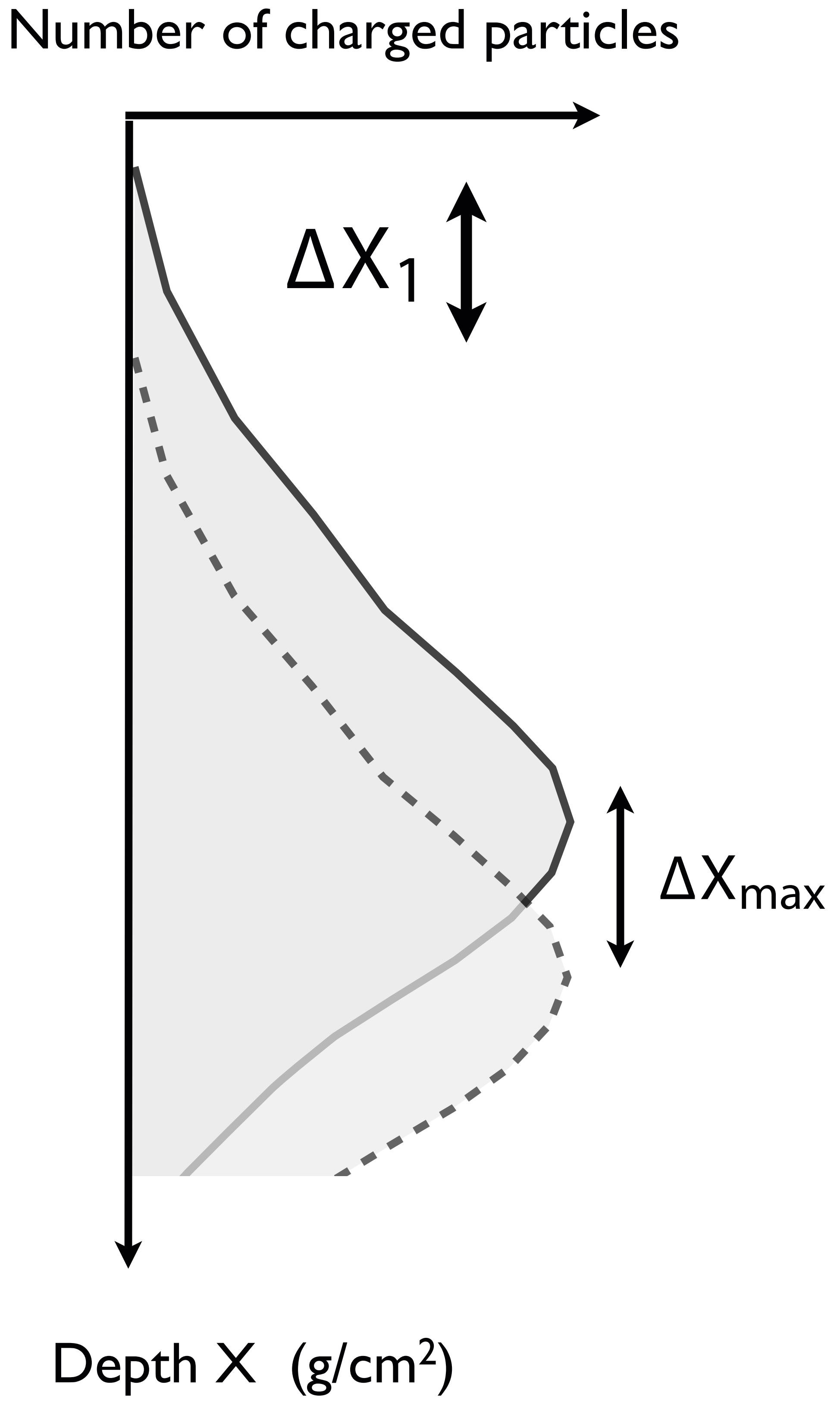


Auger in predefined ± 500s window as sensitive as IceCube

Instantaneous aperture comparable to IceCube if direction of source is favorable
Multi-messenger: searches for neutrinos and photons in coincidence with GW events

Cross section measurement



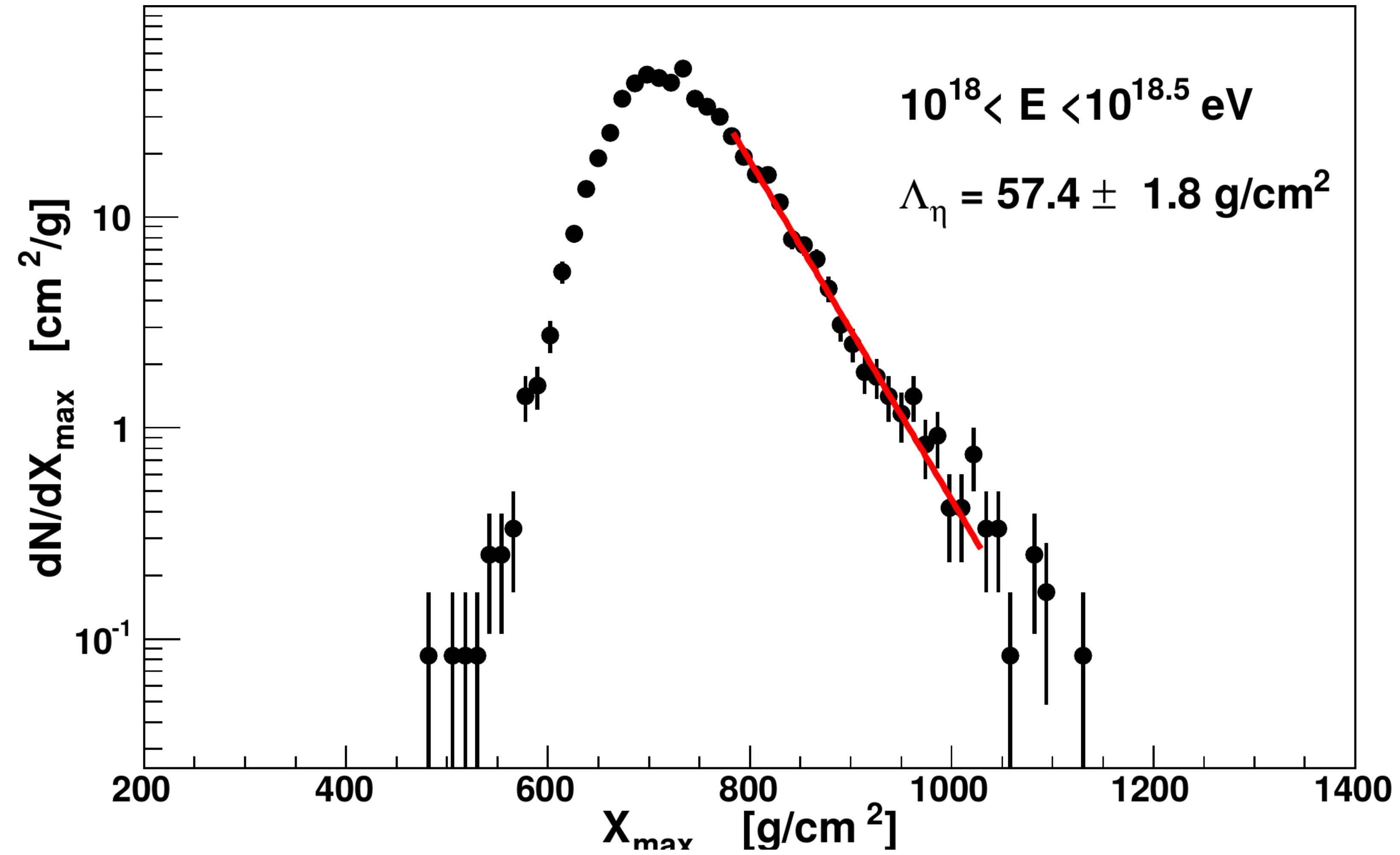


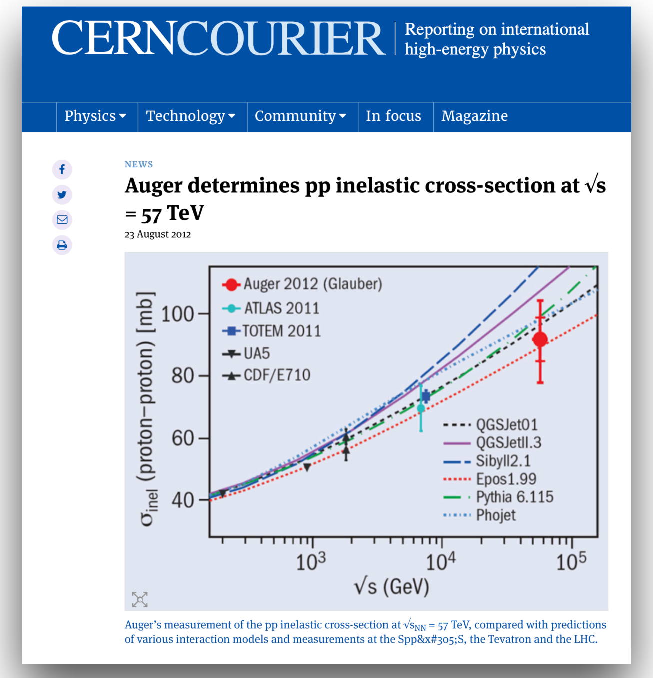
$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

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

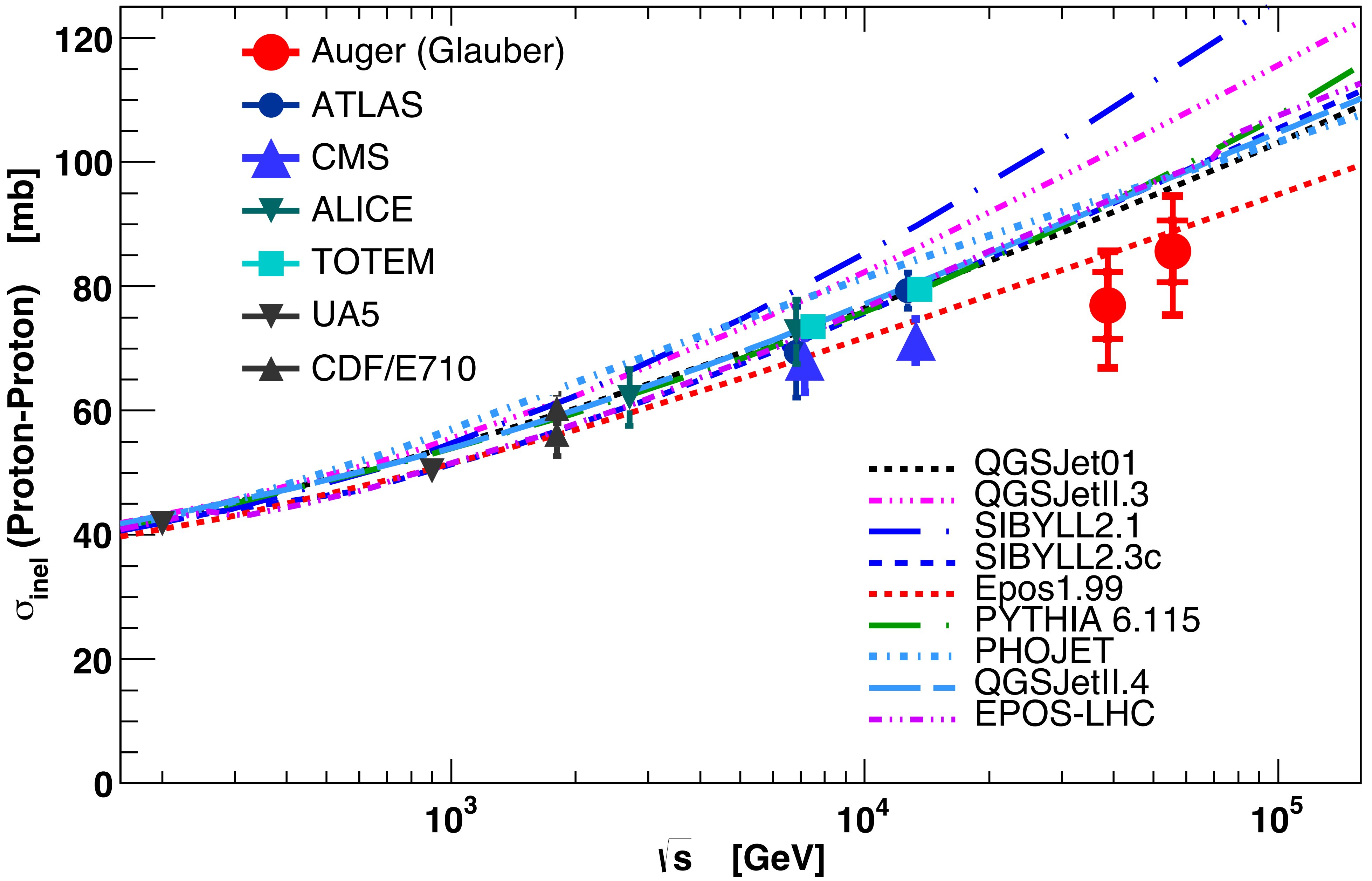
Difficulties

- Mass composition
- Fluctuations in shower development (model needed for correction) $\mathrm{RMS}(X_1) \sim \mathrm{RMS}(X_{max} - X_1)$
- conversion from p-air to p-p
- Experimental resolution ~20 g/cm²



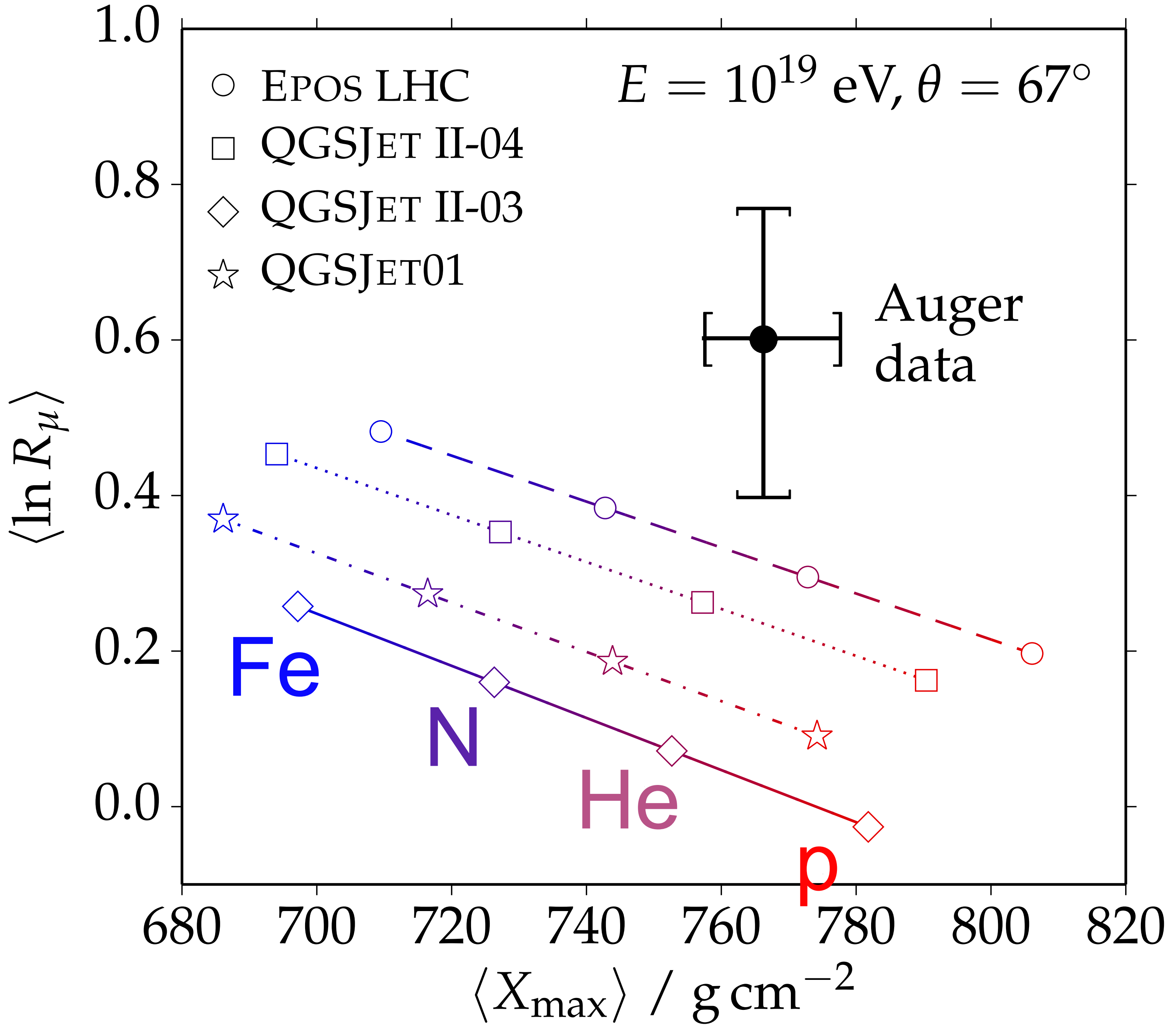

CERNCOURIER Reporting on international high-energy physics

Auger determines pp inelastic cross-section at √s = 57 TeV

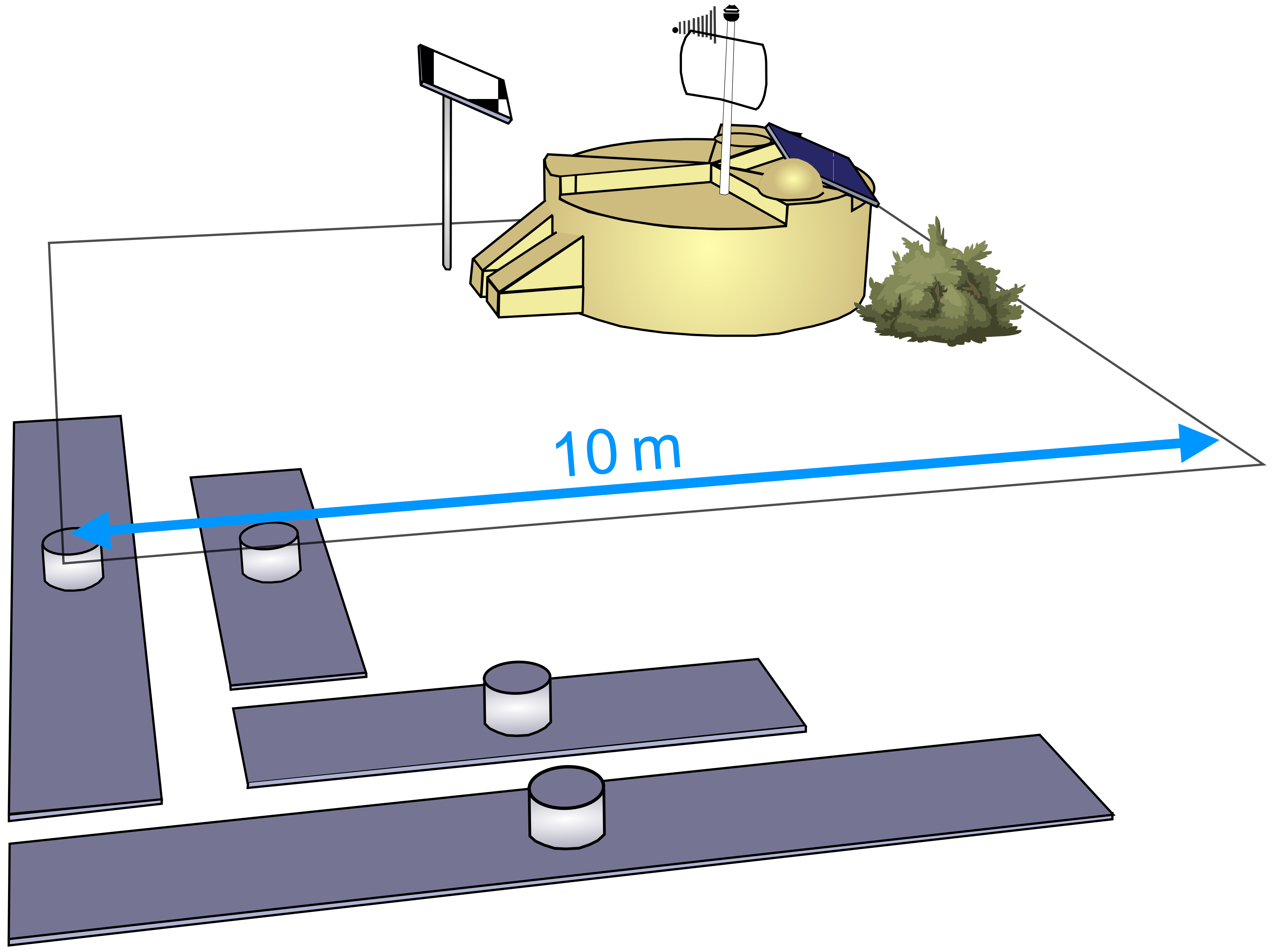


AMIGA (Auger Muons and Infill for the Ground Array)

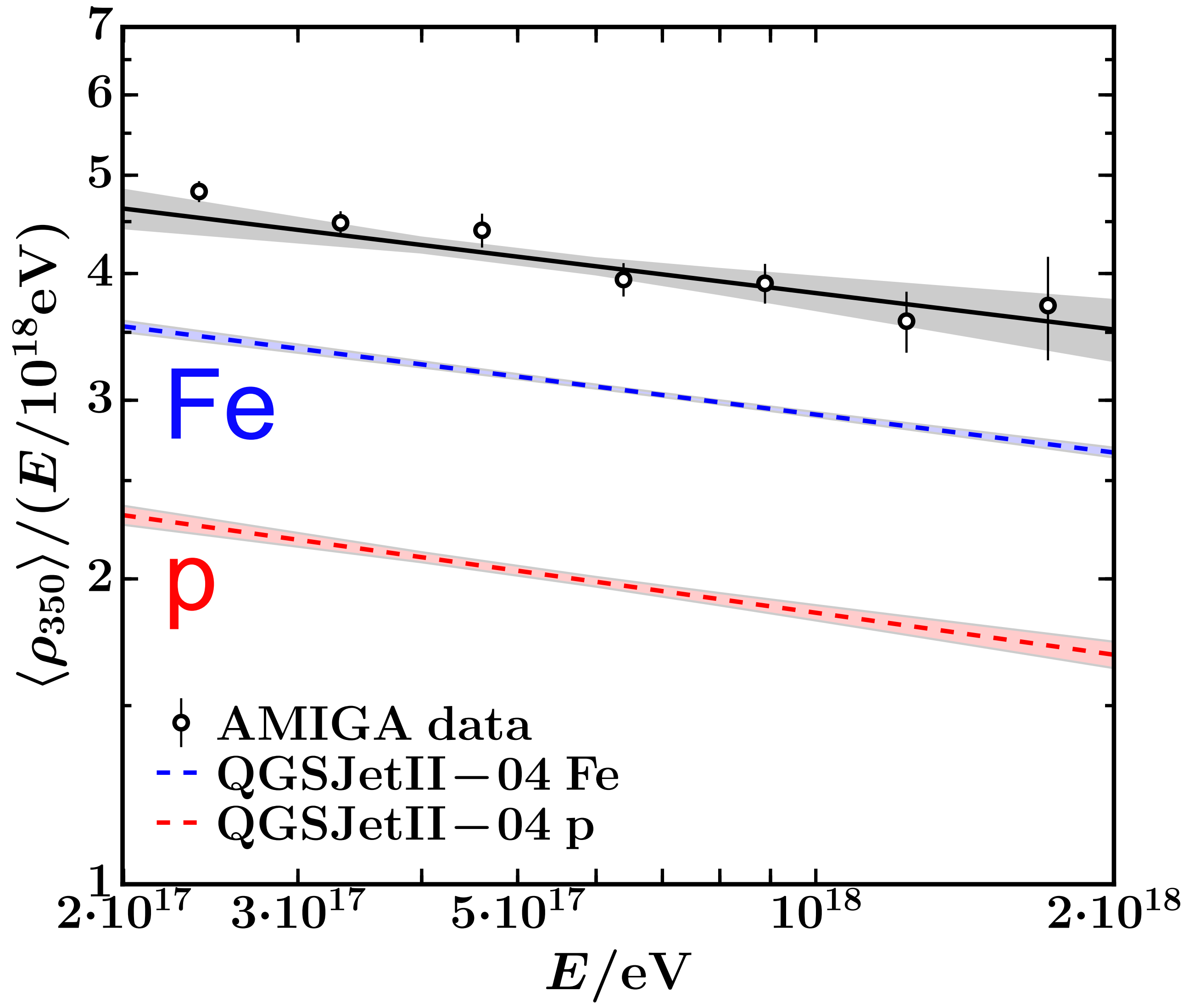
- Muon discrepancy in simulations
- Validation of AugerPrime
- Model tests with direct muon measurement



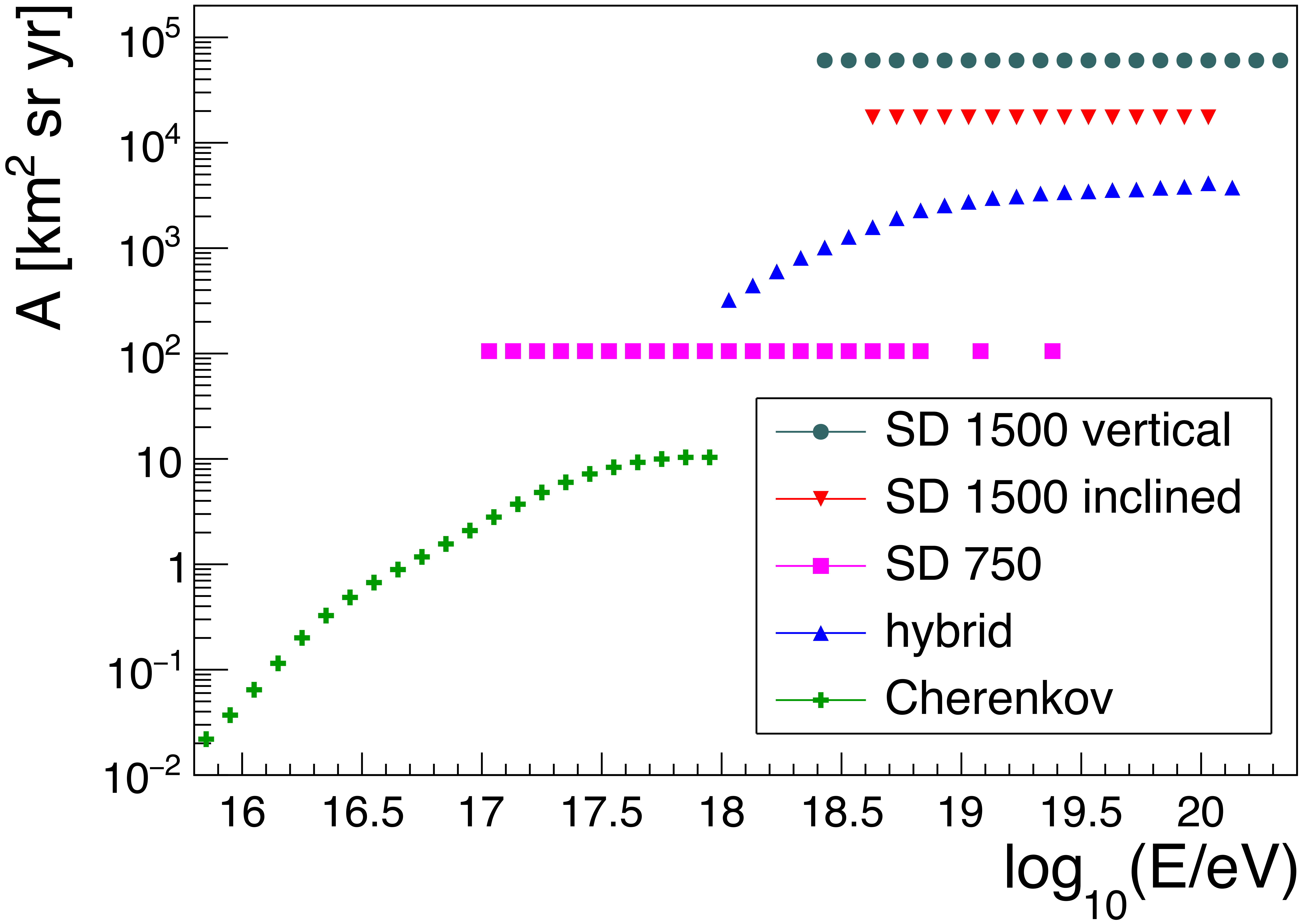
Phys. Rev. D 2015



- 61 positions
- 30 m² each
- 750 m spacing
- 2.5 m of soil

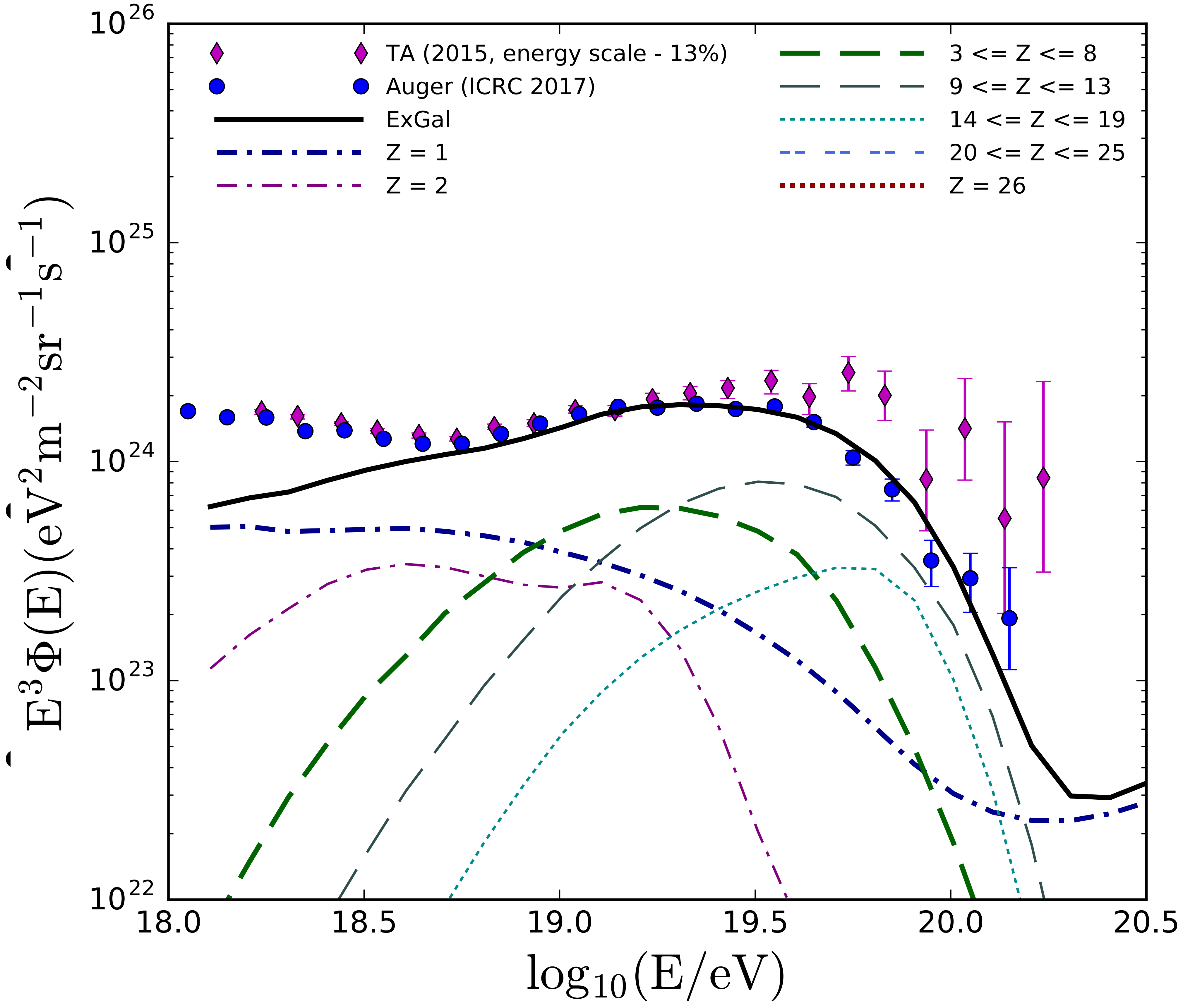


PhD thesis S. Müller

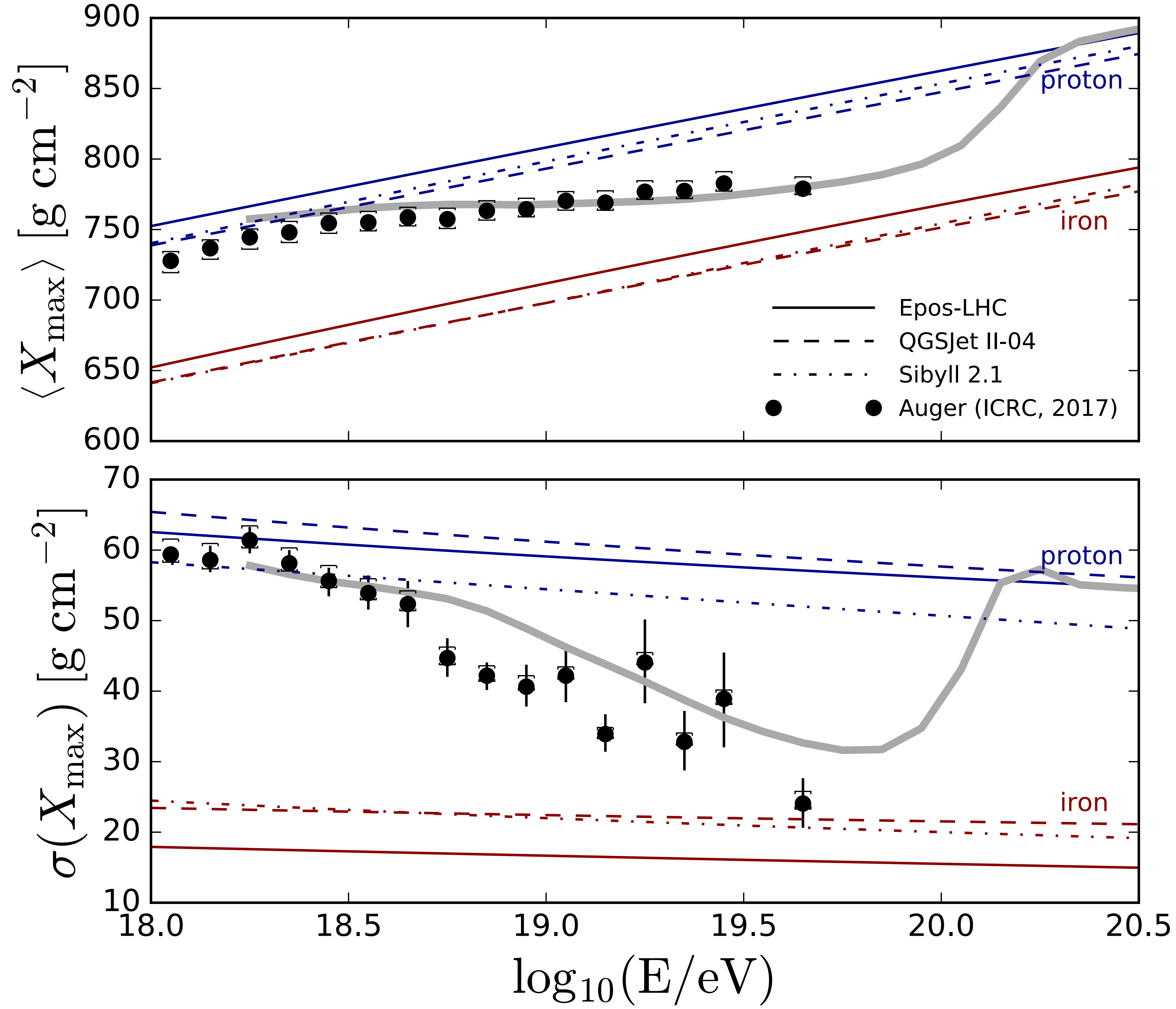

A [km² sr yr]
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
16
16.5
17
17.5
18
18.5
19
19.5
20
log10(E/eV)
SD 1500 vertical
SD 1500 inclined
SD 750
hybrid
Cherenkov

Example of a recent model prediction

Cosmic ray flux



Mass composition



Zhang et al. (1712.09984): GRB (hypernovae), LL GRBs – nuclei escape, HL GRBs – nuclei disintegrate