Highlights of the Pierre Auger Observatory

– The Present and the Future –

Ralph Engel, for the Pierre Auger Collaboration

(picture curtesy S. Saffi)

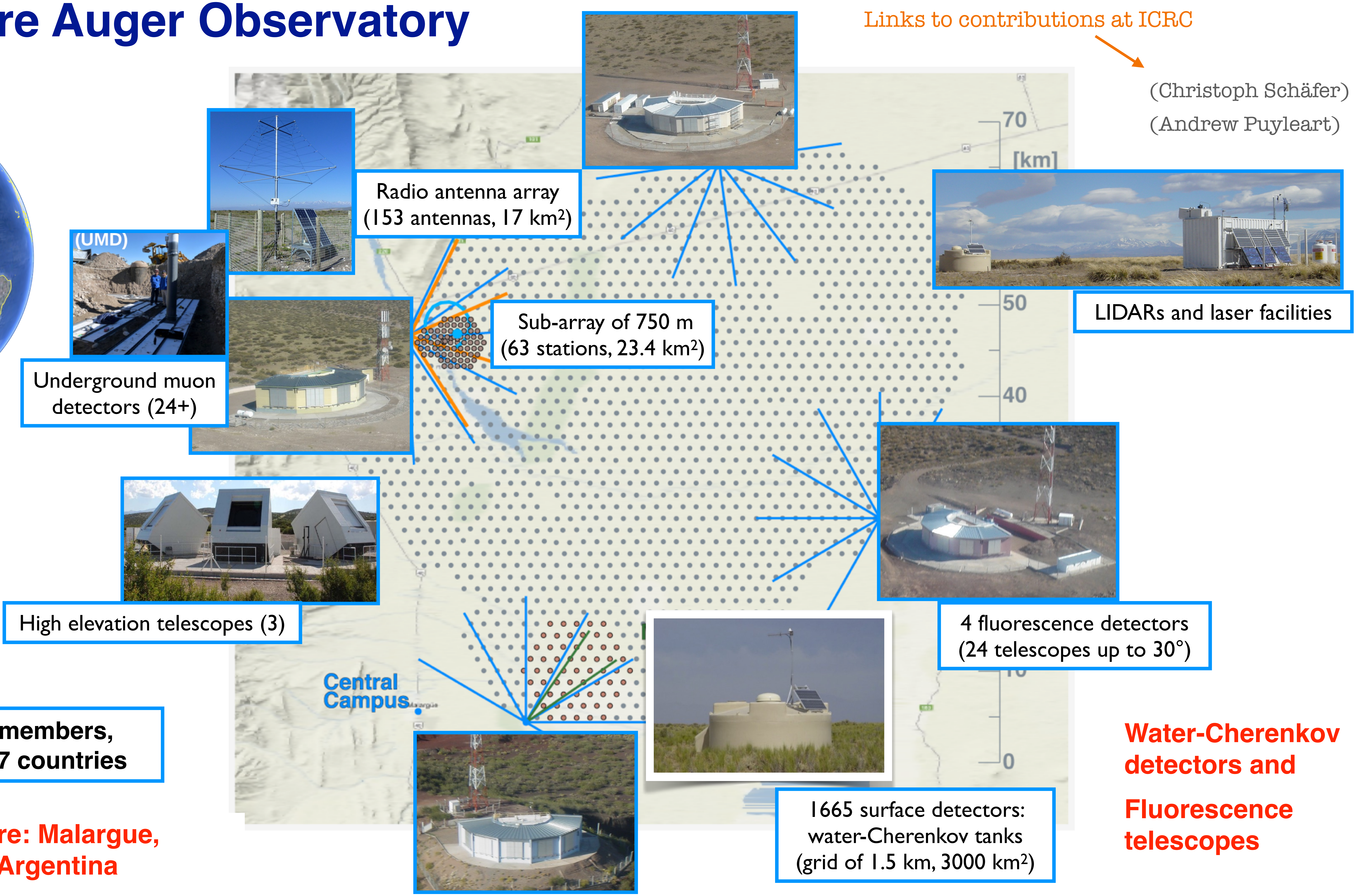
The Pierre Auger Observatory

Links to contributions at ICRC

(Christoph Schäfer)

(Andrew Puyleart)

Pierre Auger Observatory
Province Mendoza, Argentina



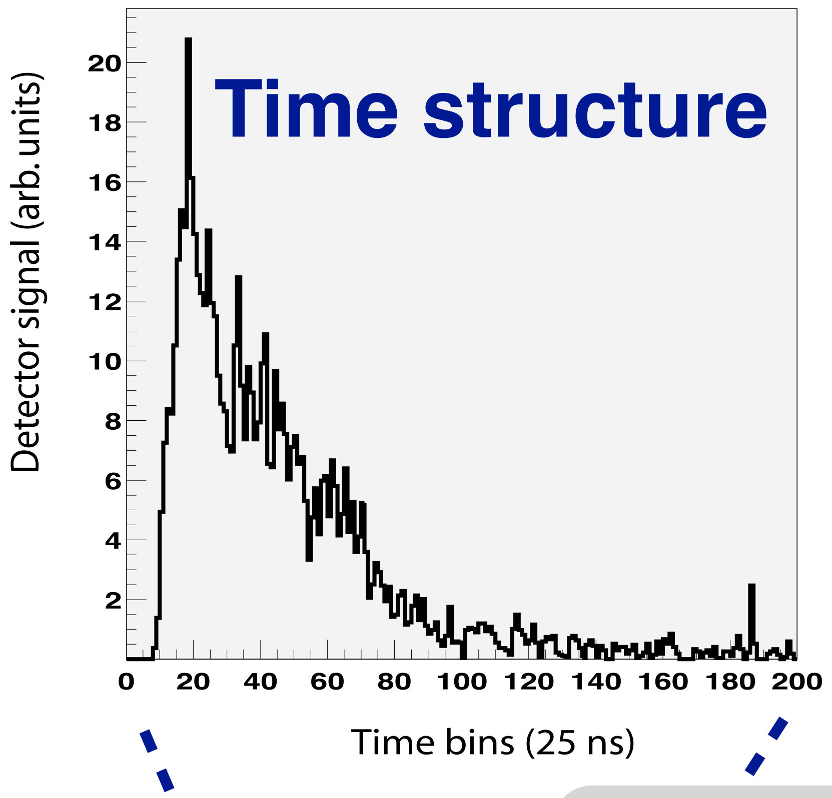
More than 400 members, 98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

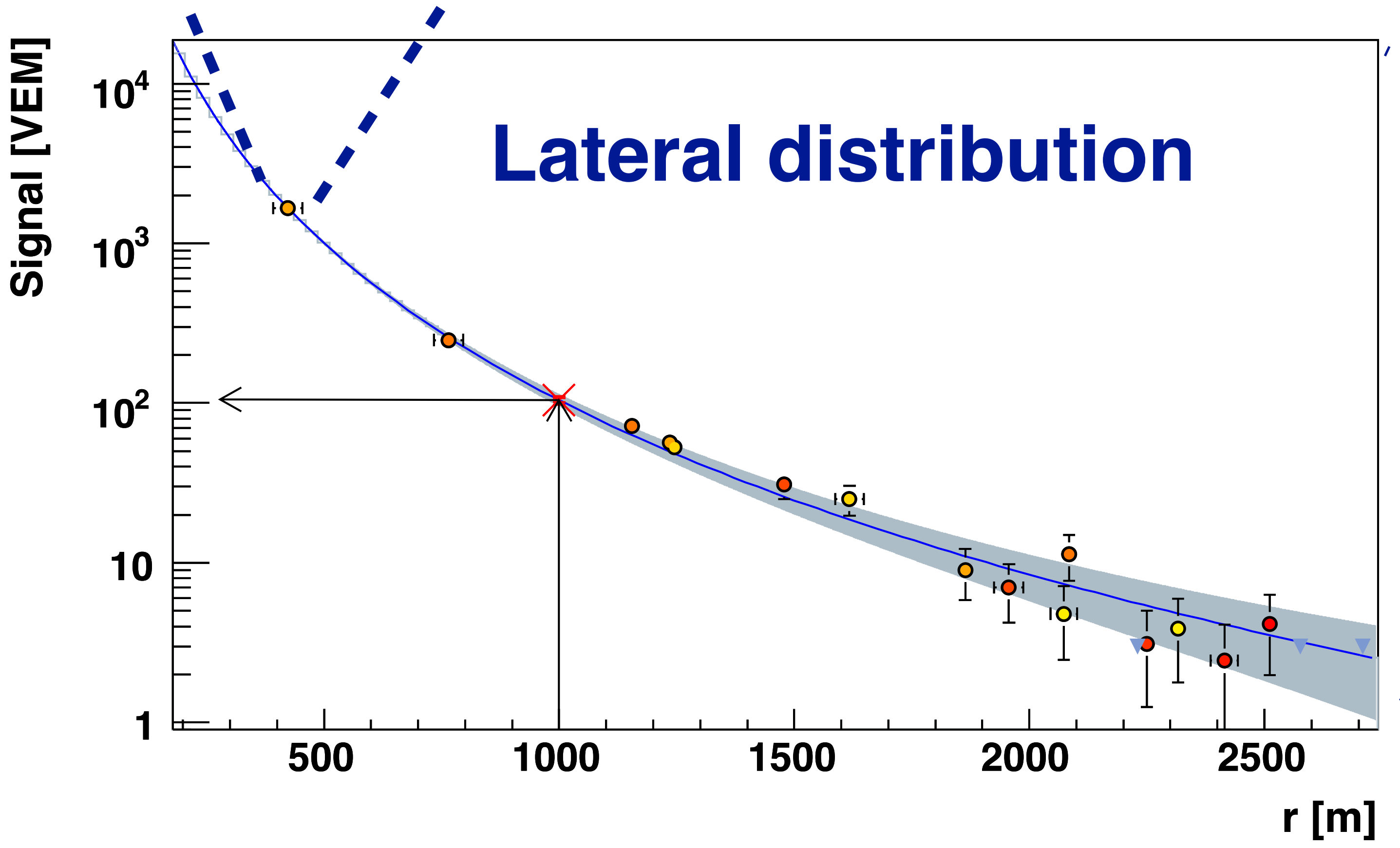
Water-Cherenkov detectors and

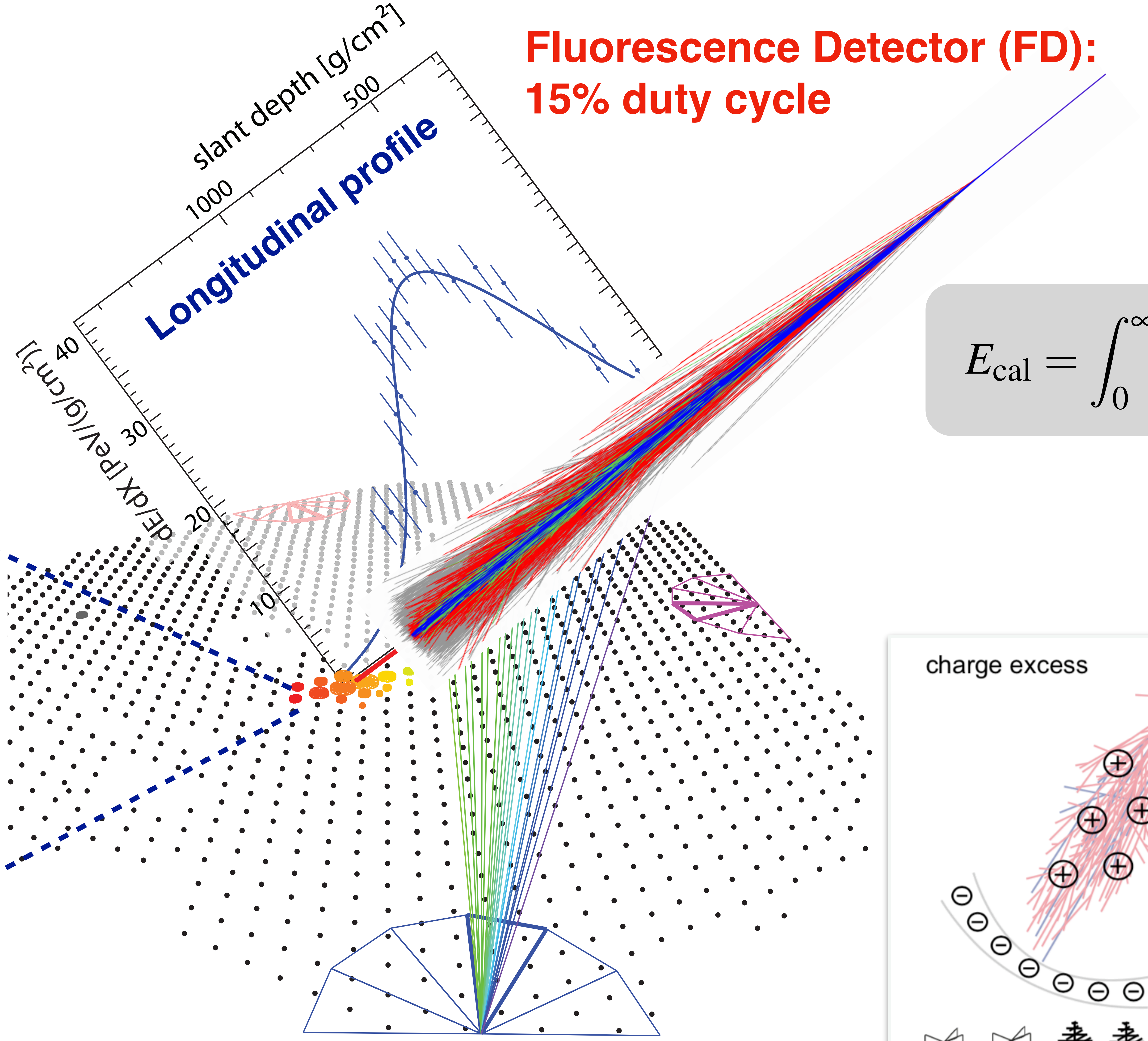
Fluorescence telescopes

Air shower observables (hybrid observation)



$$E_{\rm rec} = f(S_{1000}, \theta)$$

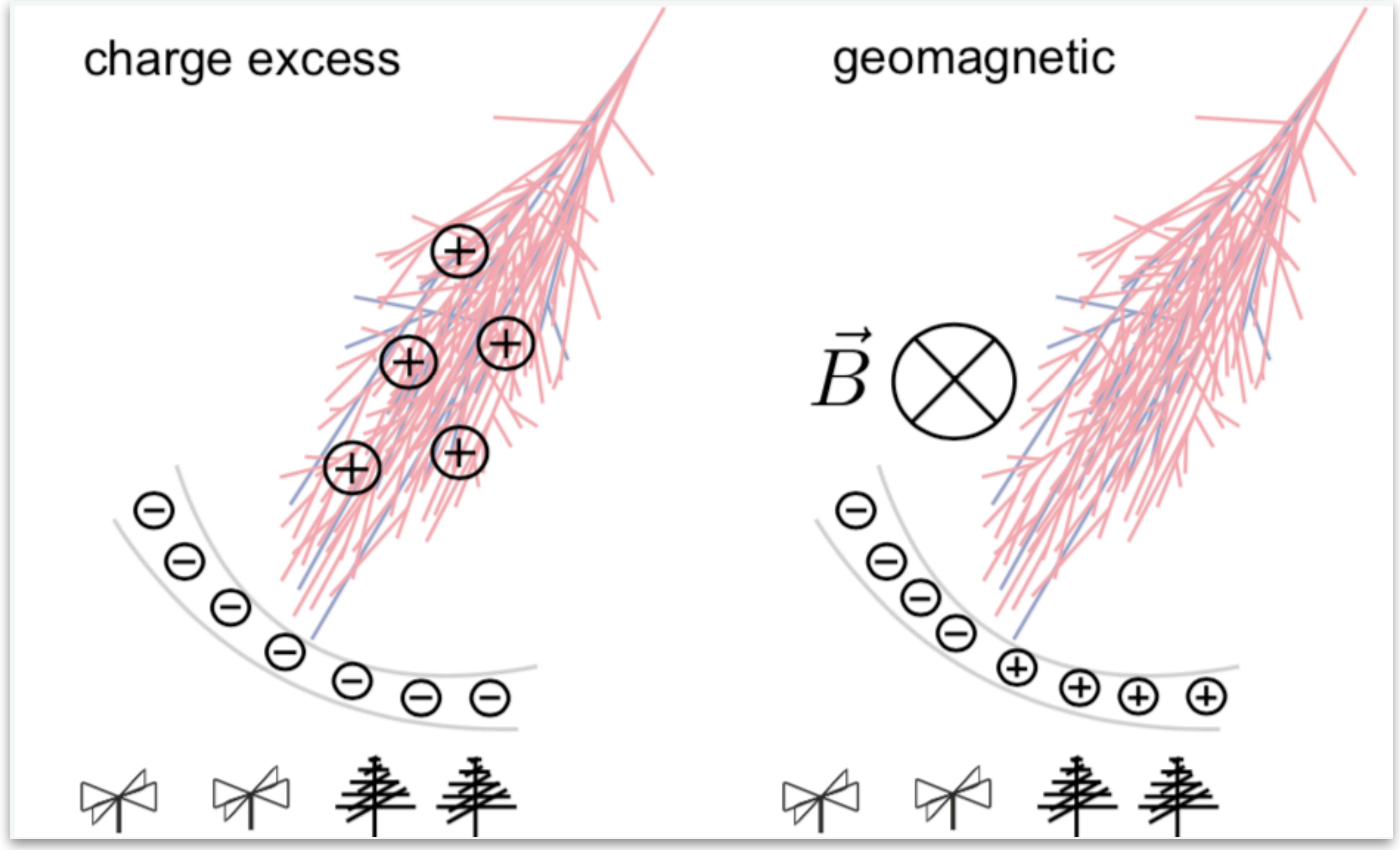




Fluorescence Detector (FD):
15% duty cycle

$$E_{\rm cal} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\rm obs} dX$$

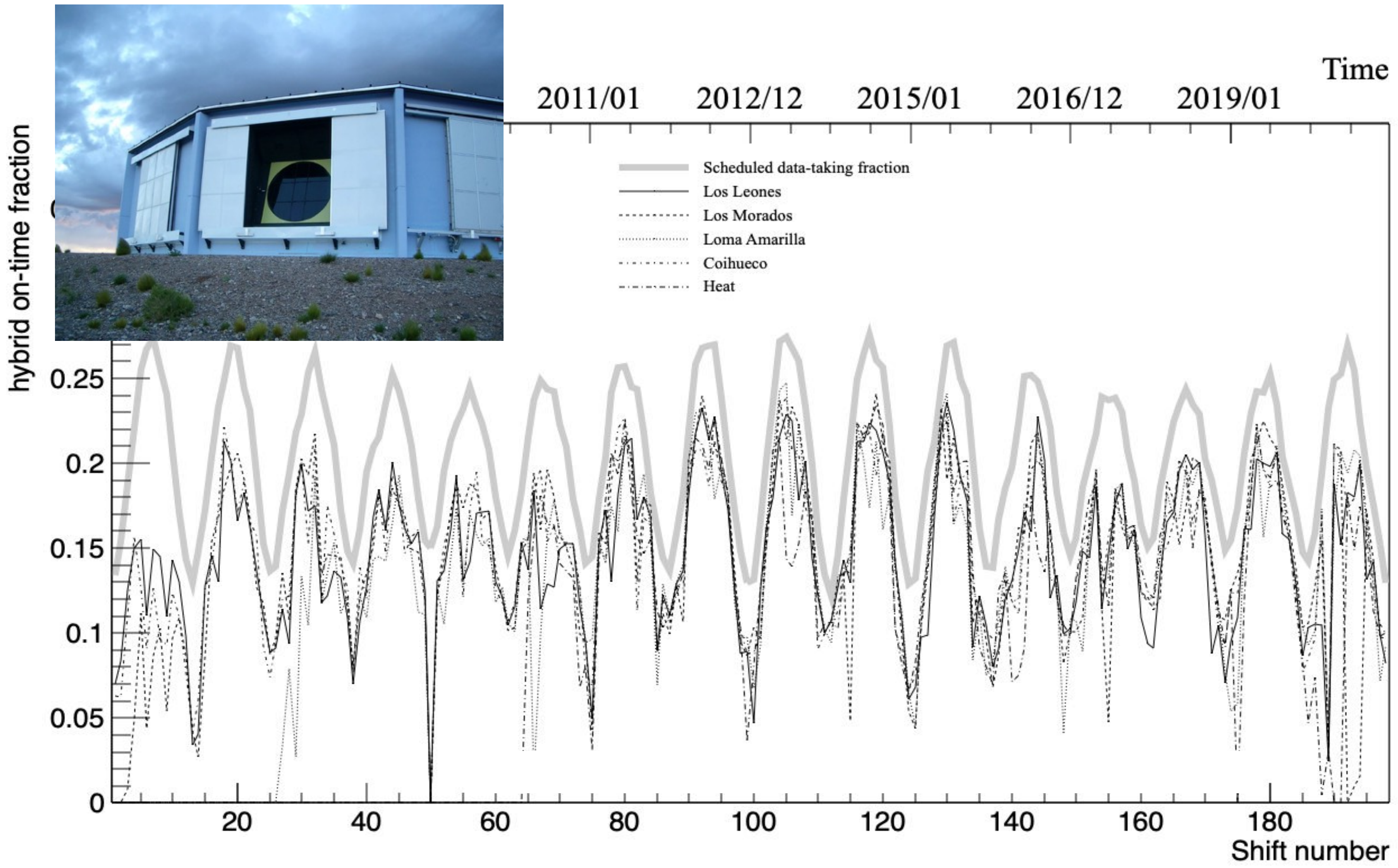
Radio Detector (RD):
100% duty cycle

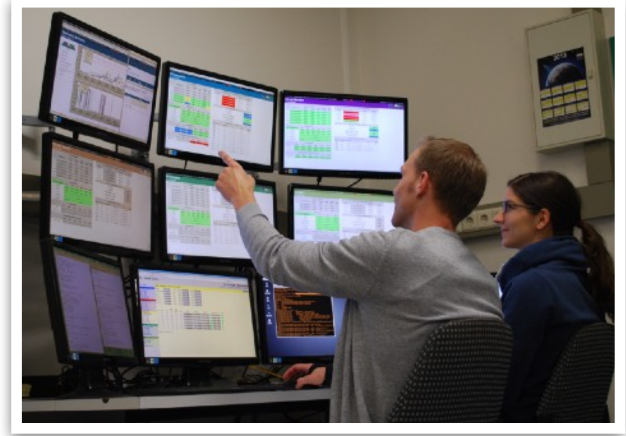


Surface Detector (SD)
100% duty cycle

Phase I of the Pierre Auger Observatory

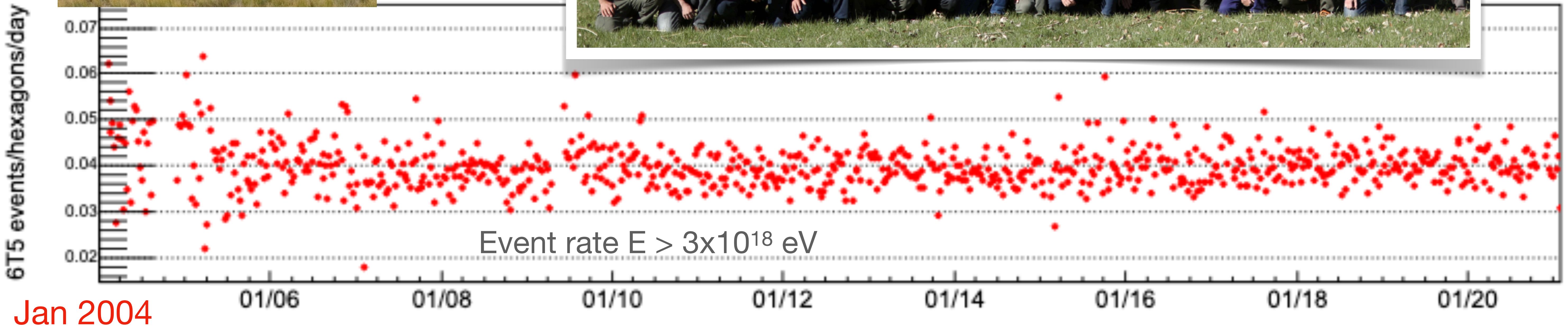
(Karen Mora)



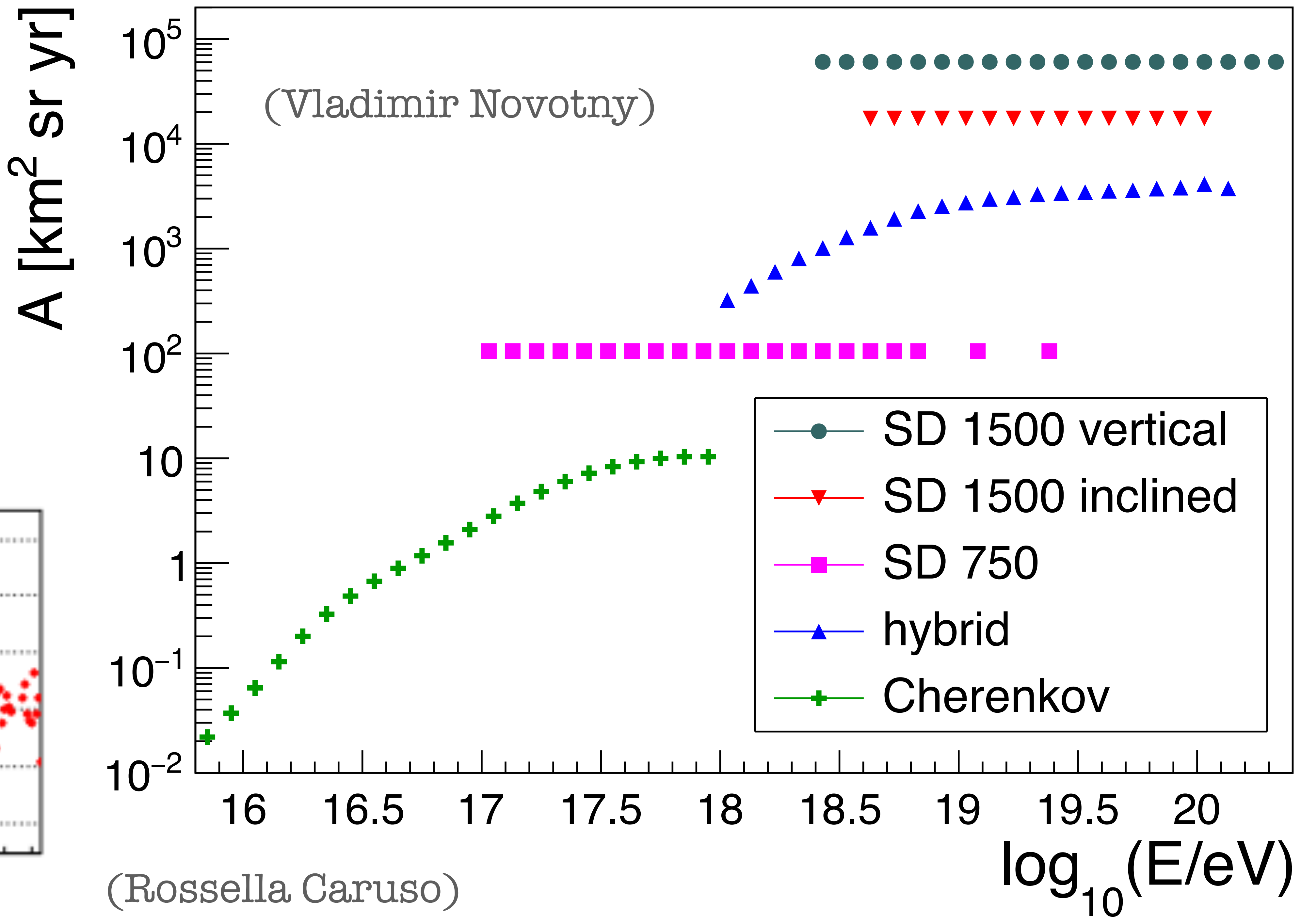


Remote control rooms

Staff in Malargue



Jan 2004



(Rossella Caruso)

Upgrade of the Observatory – AugerPrime

Physics motivation

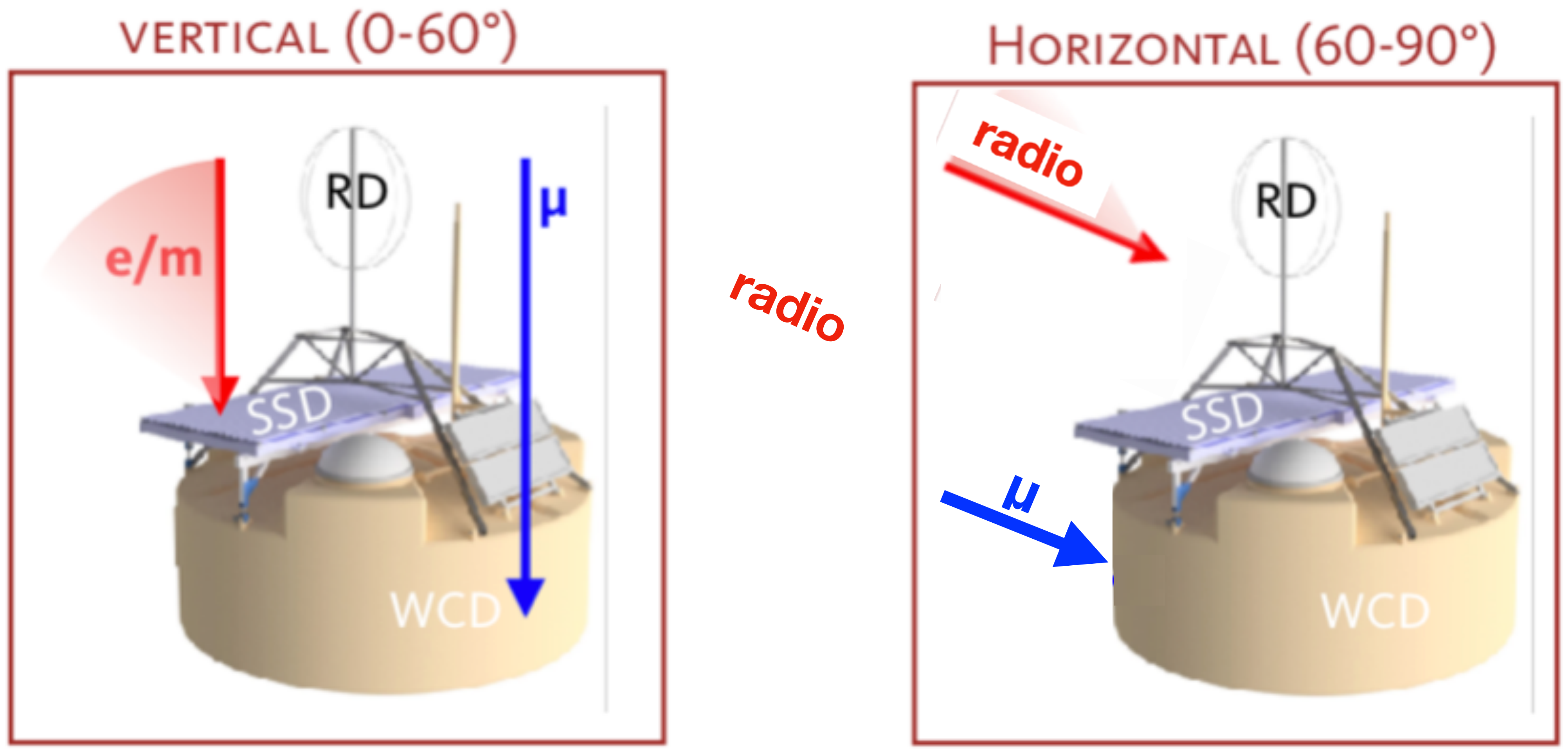
- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle physics with air showers
- Much better understanding of **new and old** data

Components of AugerPrime

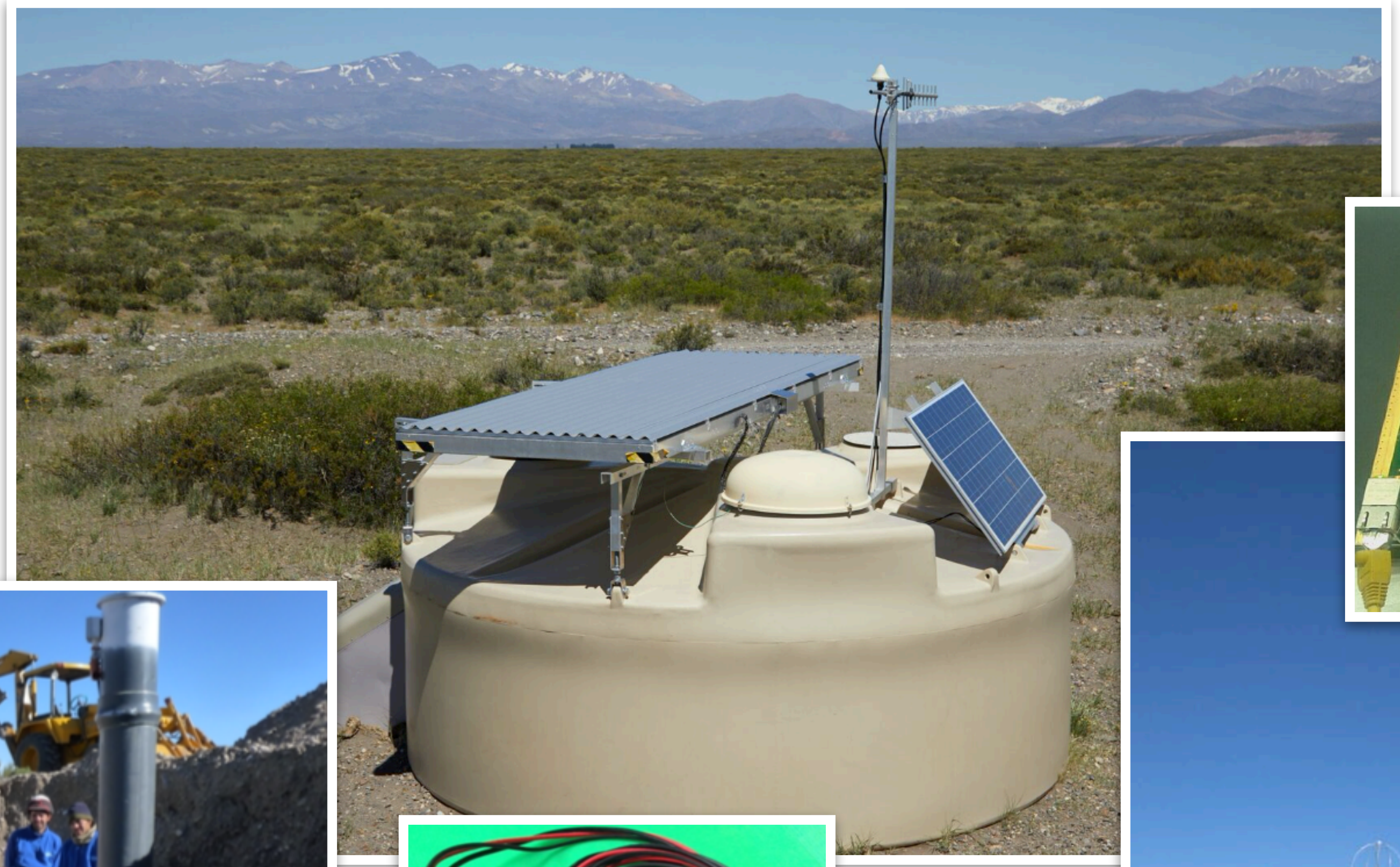
- 3.8 m^2 scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)
- Enhanced duty cycle of fluorescence tel.

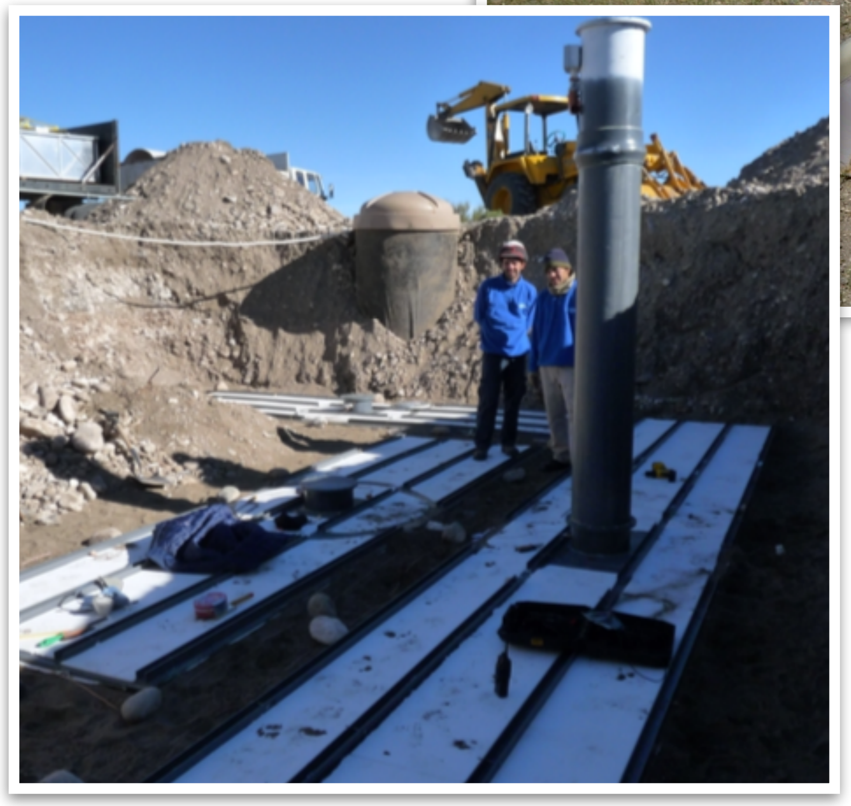
(Gabriella Cataldi) (Giovanni Marsella) (Ana Botti)
(Tomas Fodran) (Felix Schlüter) (Gaia Silli)

Composition sensitivity with 100% duty cycle

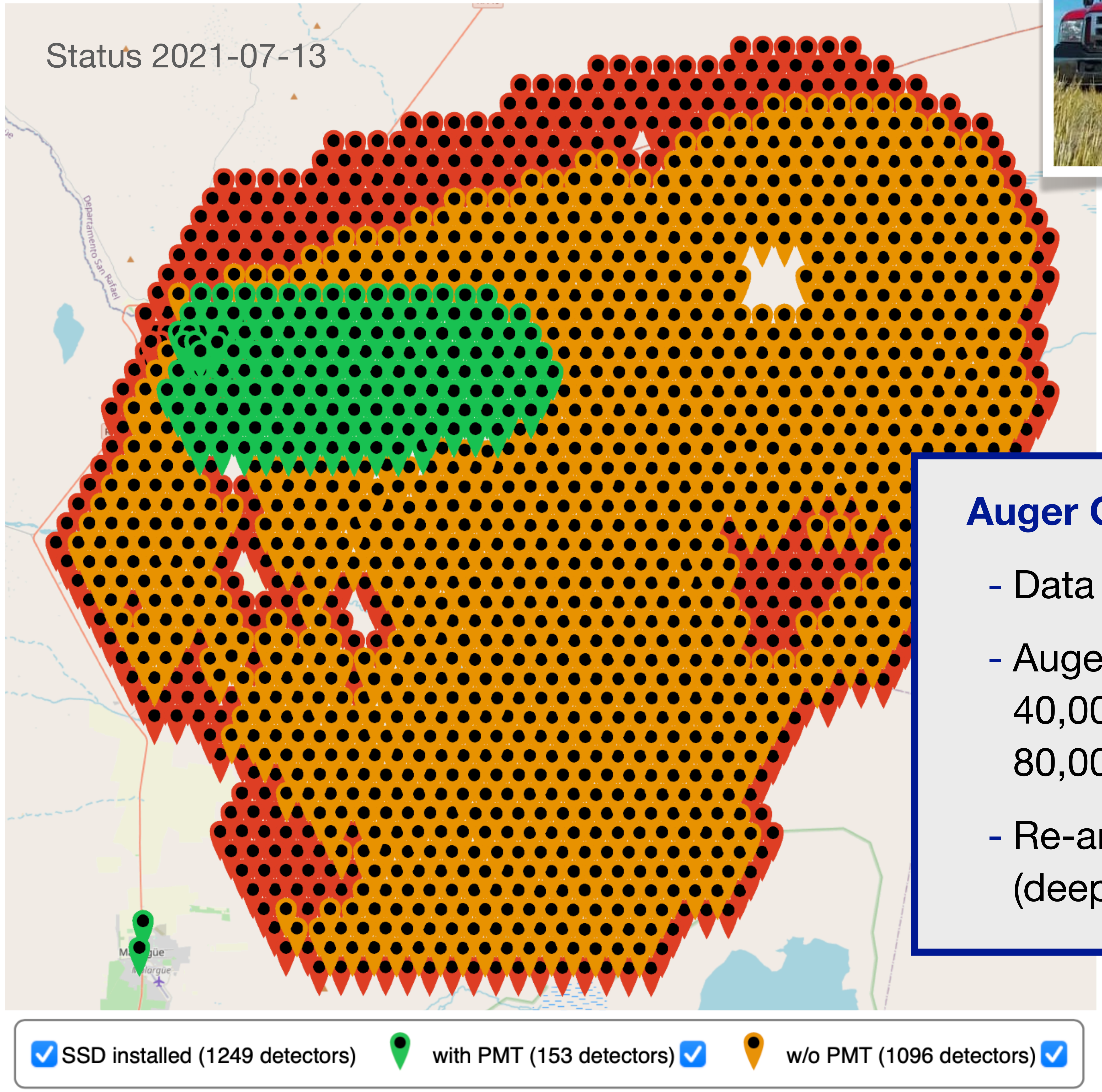


(AugerPrime design report 1604.03637)





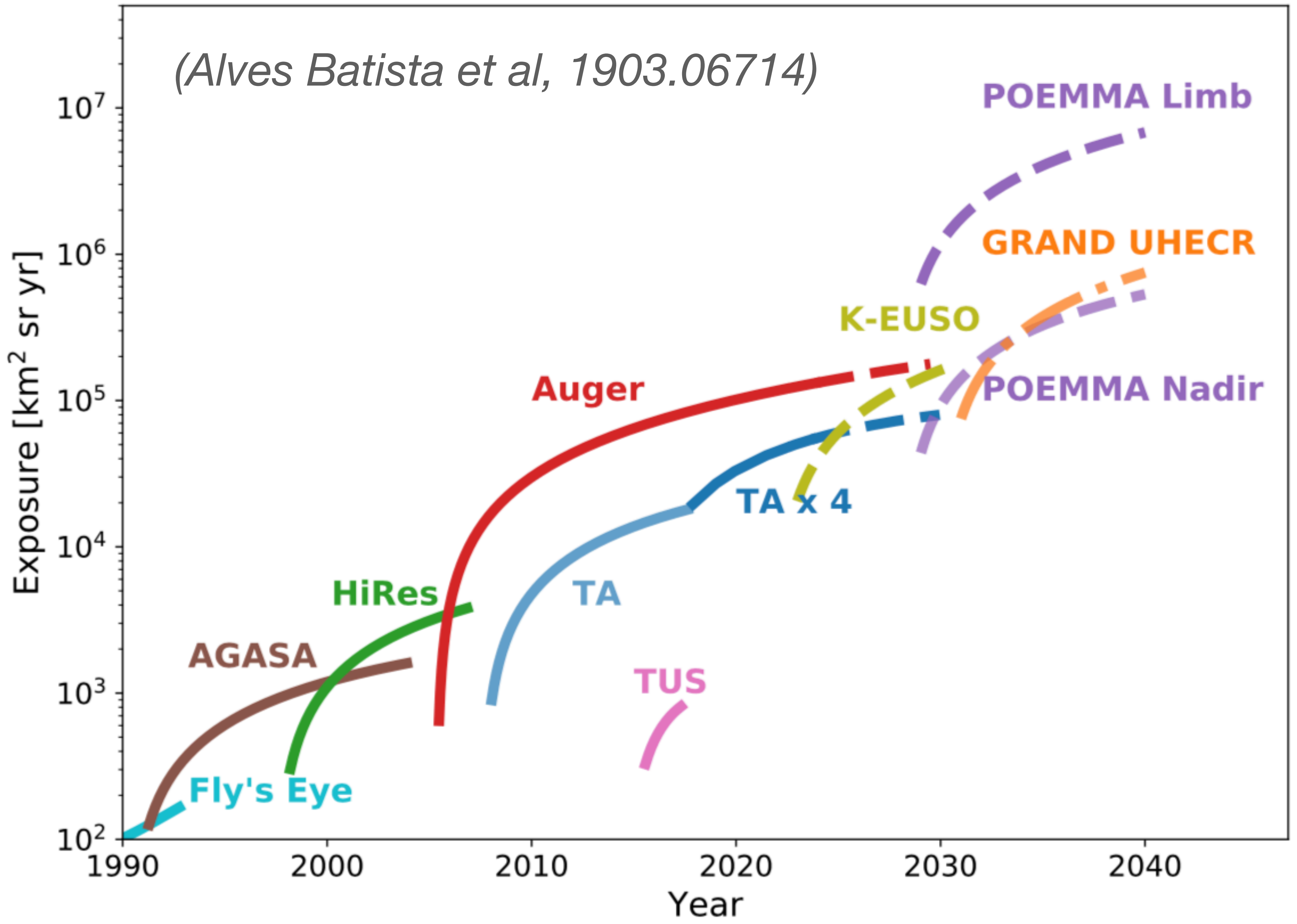
Status of AugerPrime – Transition to Phase II of the Observatory



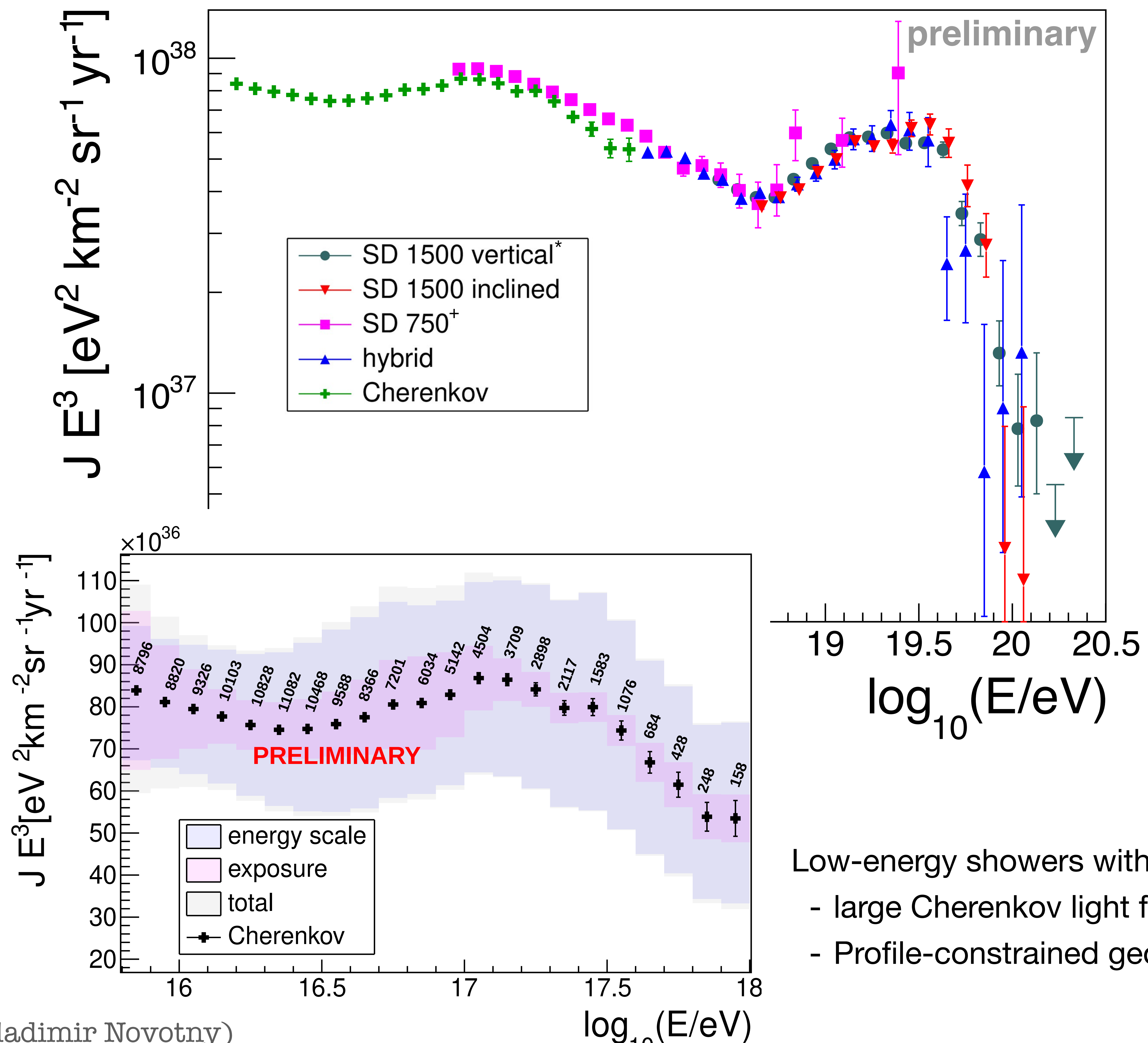
Deployment team working continuously in Malargue

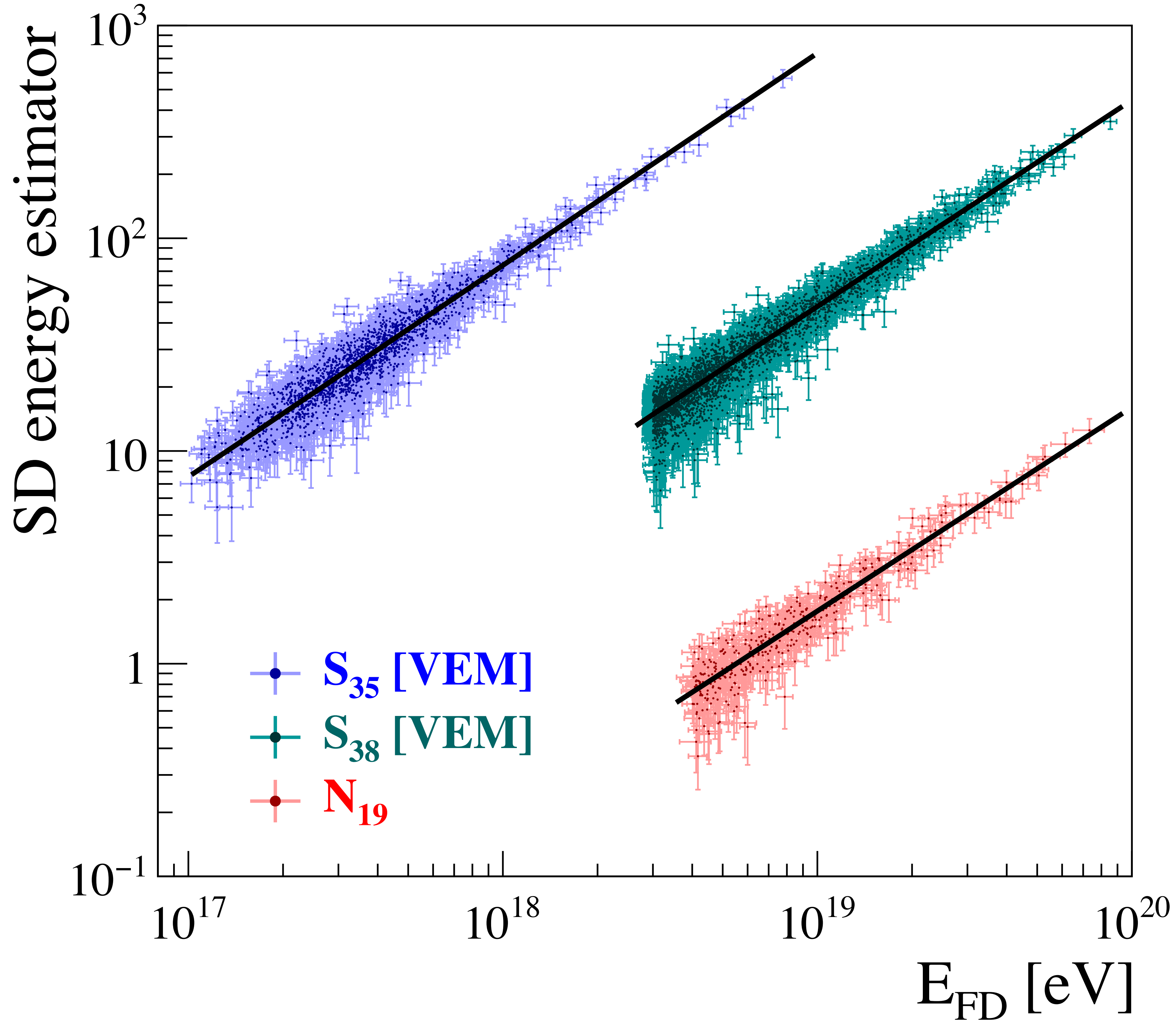
Auger Observatory Phase II

- Data taking 2022/23 – 2030
- AugerPrime (8 years, θ < 60°): 40,000 km² sr yr (Phase II), 80,000 km² sr yr (Phase I)
- Re-analysis of old data set (deep learning)



Energy spectrum (i)





SD 1500 m vertical – S_{38}
- S(1000)+CIC
- threshold 2.5 EeV

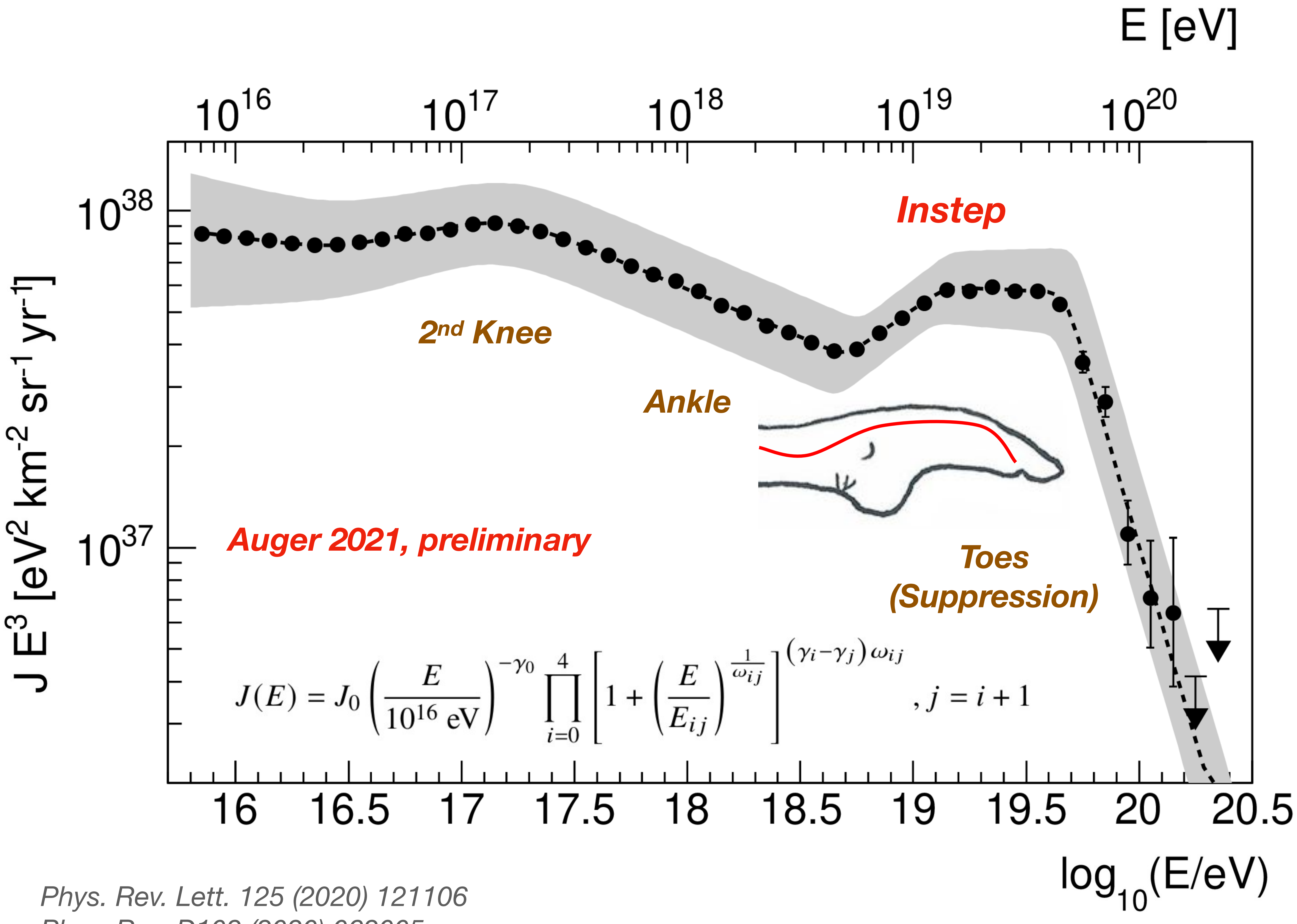
Low-energy showers with FD
- large Cherenkov light fraction
- Profile-constrained geometry fit

SD 750 m – S_{35}
- S(450)+CIC
- threshold 0.1 EeV

SD 1500 m inclined – N_{19}
- scaling parameter
- threshold 4 EeV

(Vladimir Novotny)

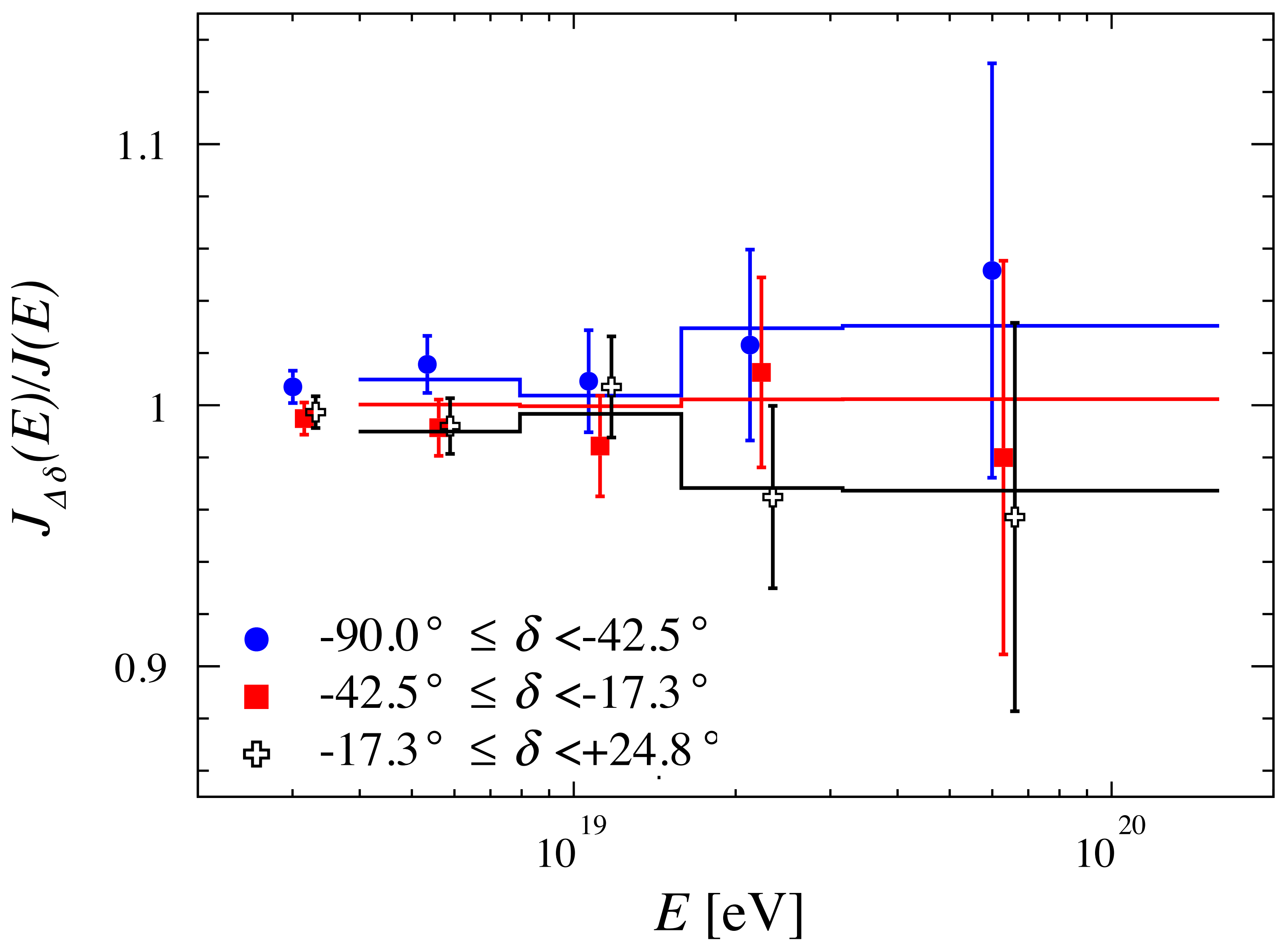
Energy spectrum (ii)



Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
submitted to Eur. Phys. J. C (2021)

(Vladimir Novotny)

Declination dependence of spectrum

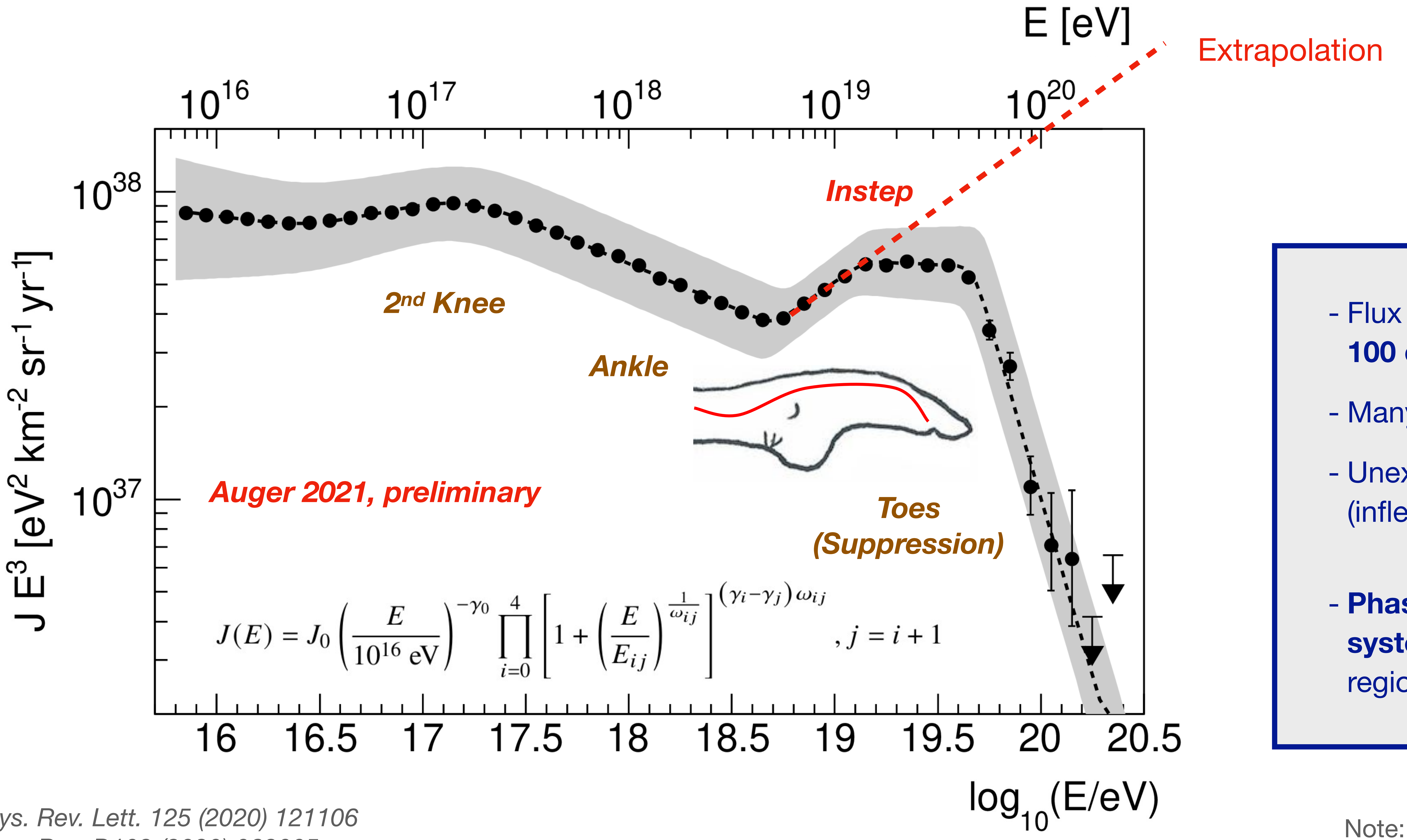


Lines: Expectation from observed dipole

Uncertainty dominated by 14% sys. energy scale

γ_0 = 3.09 ± 0.01 ± 0.10
E_{01} = (2.8 ± 0.3 ± 0.4) x 10^{16} eV
γ_1 = 2.85 ± 0.01 ± 0.05
E_{12} = (1.58 ± 0.05 ± 0.2) x 10^{17} eV
γ_2 = 3.283 ± 0.002 ± 0.10
E_{23} = (5.0 ± 0.1 ± 0.8) x 10^{18} eV
γ_3 = 2.54 ± 0.03 ± 0.05
E_{34} = (1.4 ± 0.1 ± 0.2) x 10^{19} eV
γ_4 = 3.03 ± 0.05 ± 0.10
E_{45} = (4.7 ± 0.3 ± 0.6) x 10^{19} eV
γ_5 = 5.3 ± 0.3 ± 0.1
J_0 = (8.34 ± 0.04 ± 3.40) x 10^{-11} km^{-2} sr^{-1} yr^{-1} eV^{-1}

Energy spectrum (ii)



$$J(E) = J_0 \left(\frac{E}{10^{16}\ \mathrm{eV}}\right)^{-\gamma_0} \prod_{i=0}^{4} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\,\omega_{ij}}, \quad j = i+1$$

- Flux suppression by factor of **100** observed
- Many features well established
- Unexpected feature of **instep** (inflection point) at 1.4×10^{19} eV
- **Phase II:** further reduction of **systematics**, in particular in regions of mixed composition

Phys. Rev. Lett. 125 (2020) 121106
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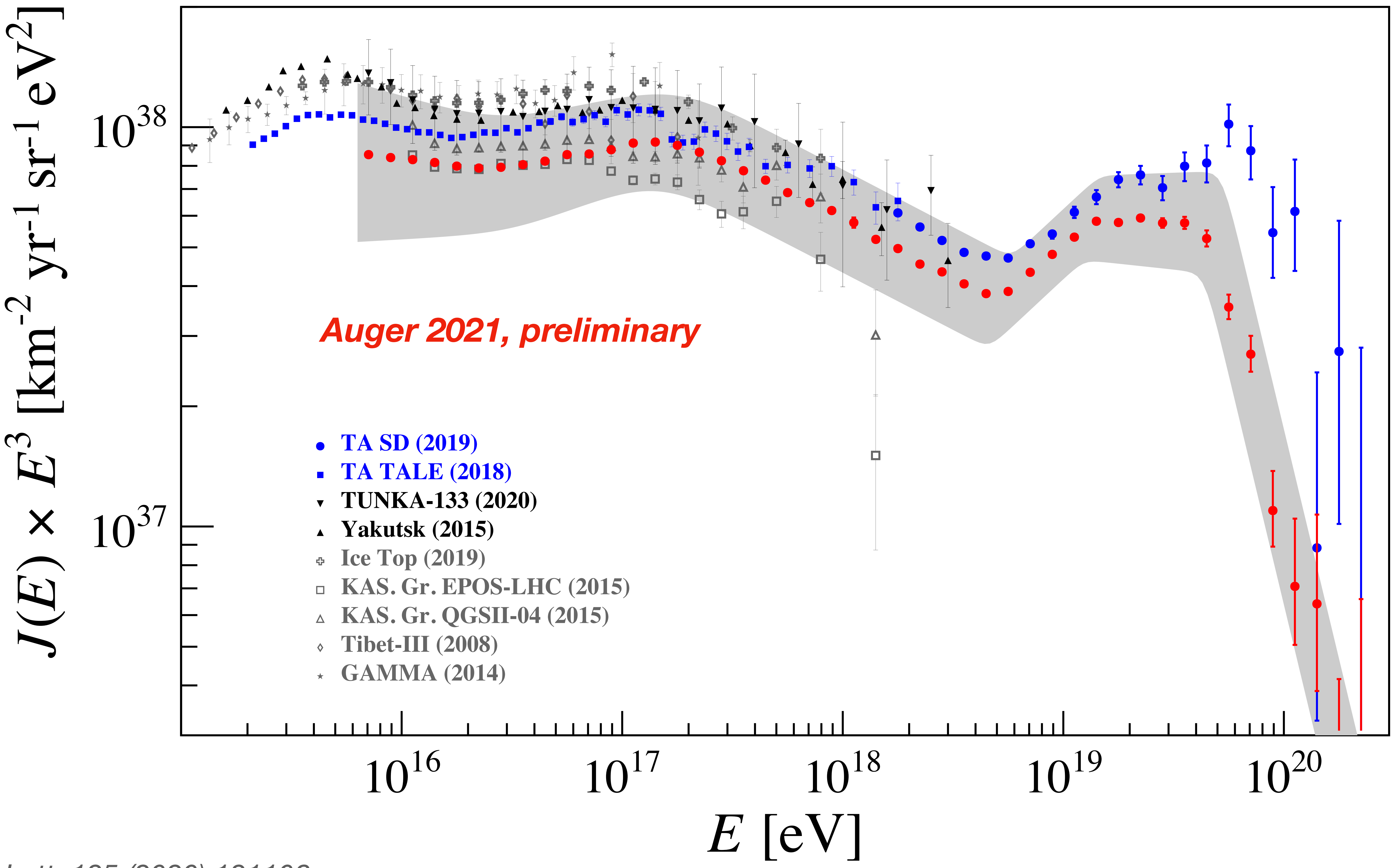
(Vladimir Novotny)

Note: A foreground source of protons leads to flux recovery

Energy spectrum – comparison with other data



- Other experiments shown without sys. uncertainties
- Auger has smallest sys. uncertainty on energy scale (14%)

Auger-TA comparison: see presentation of joint working group (Tsunesada et al.)

Phys. Rev. Lett. 125 (2020) 121106
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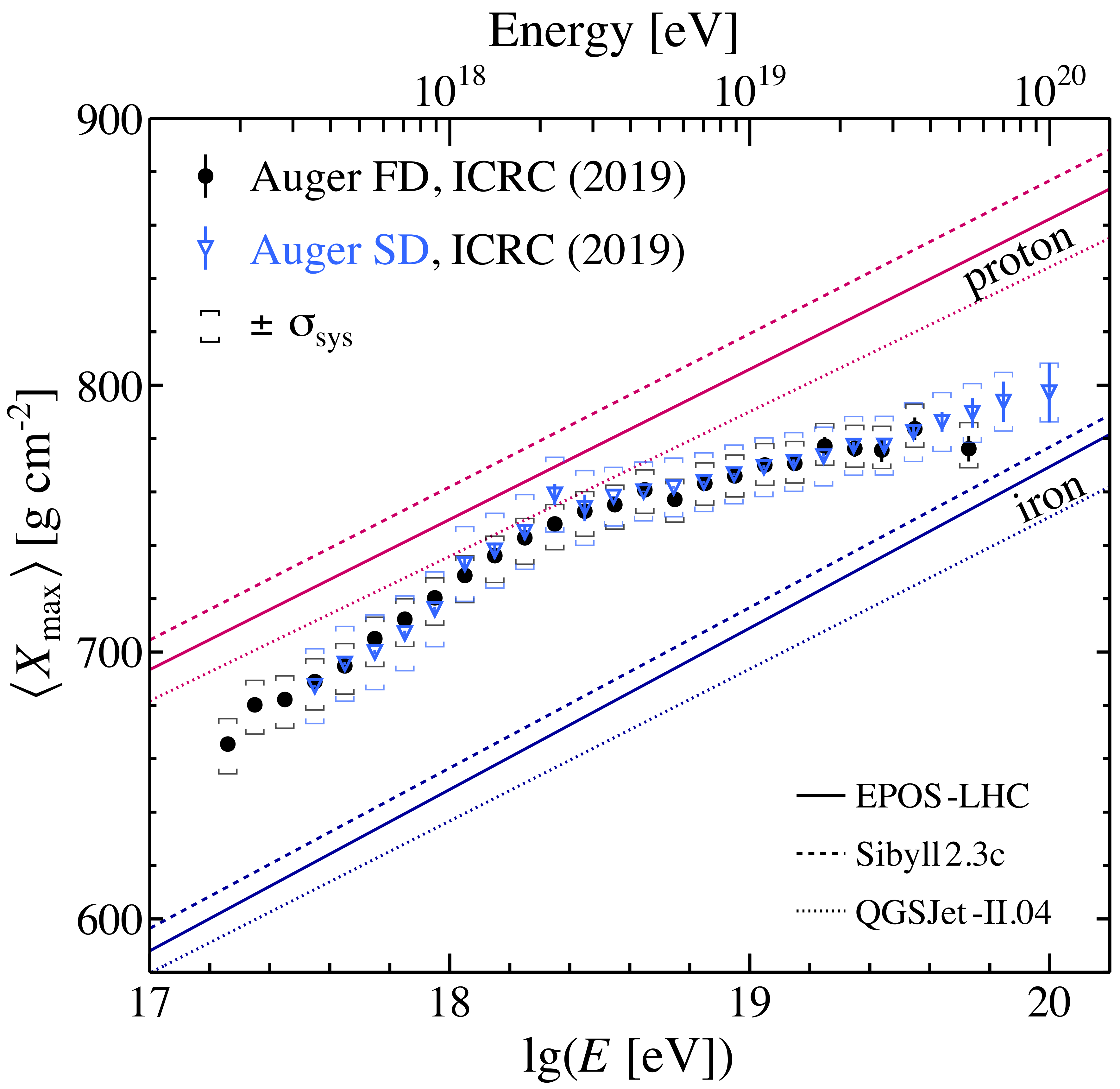
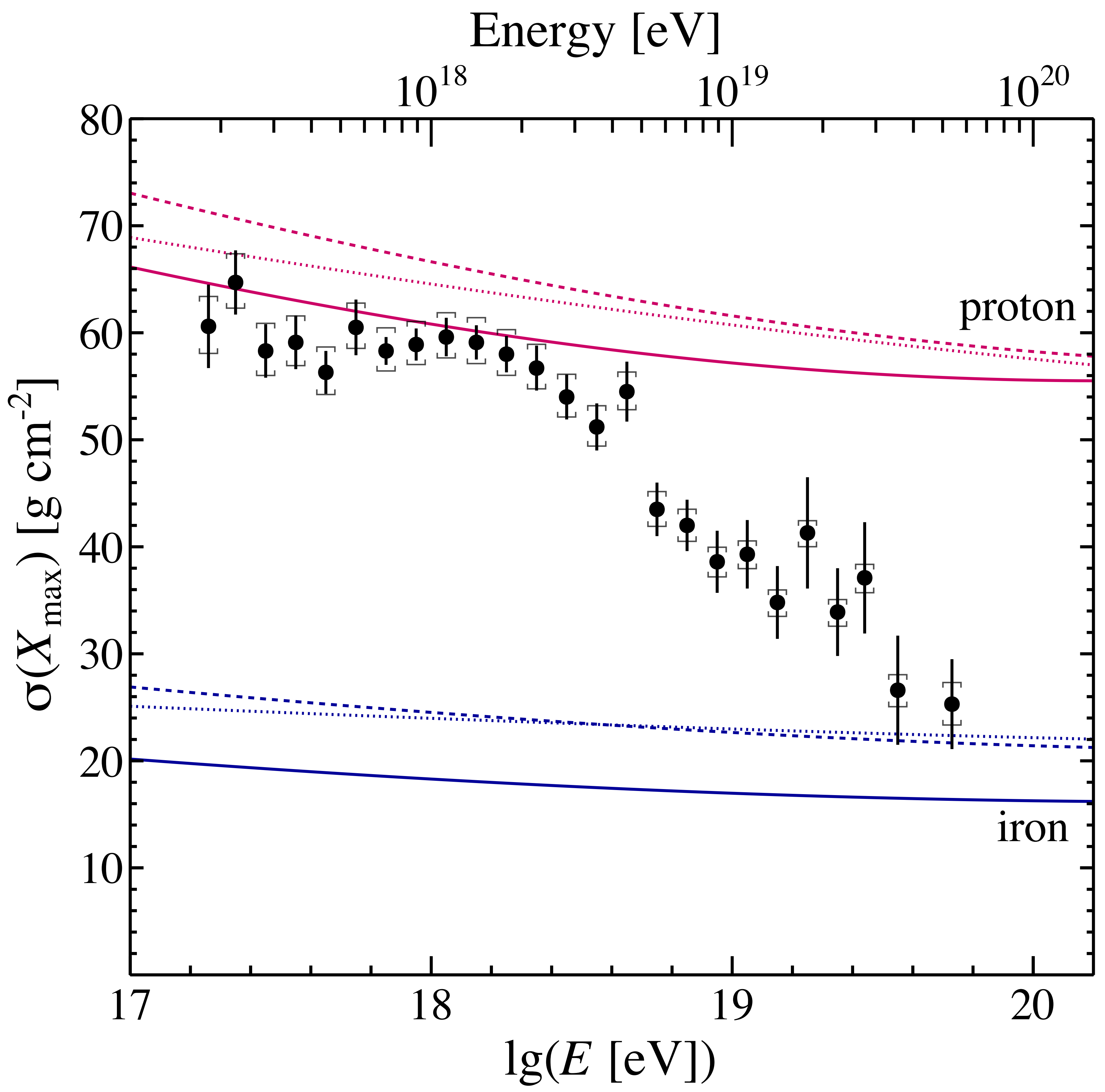
submitted to Eur. Phys. J. C (2021)

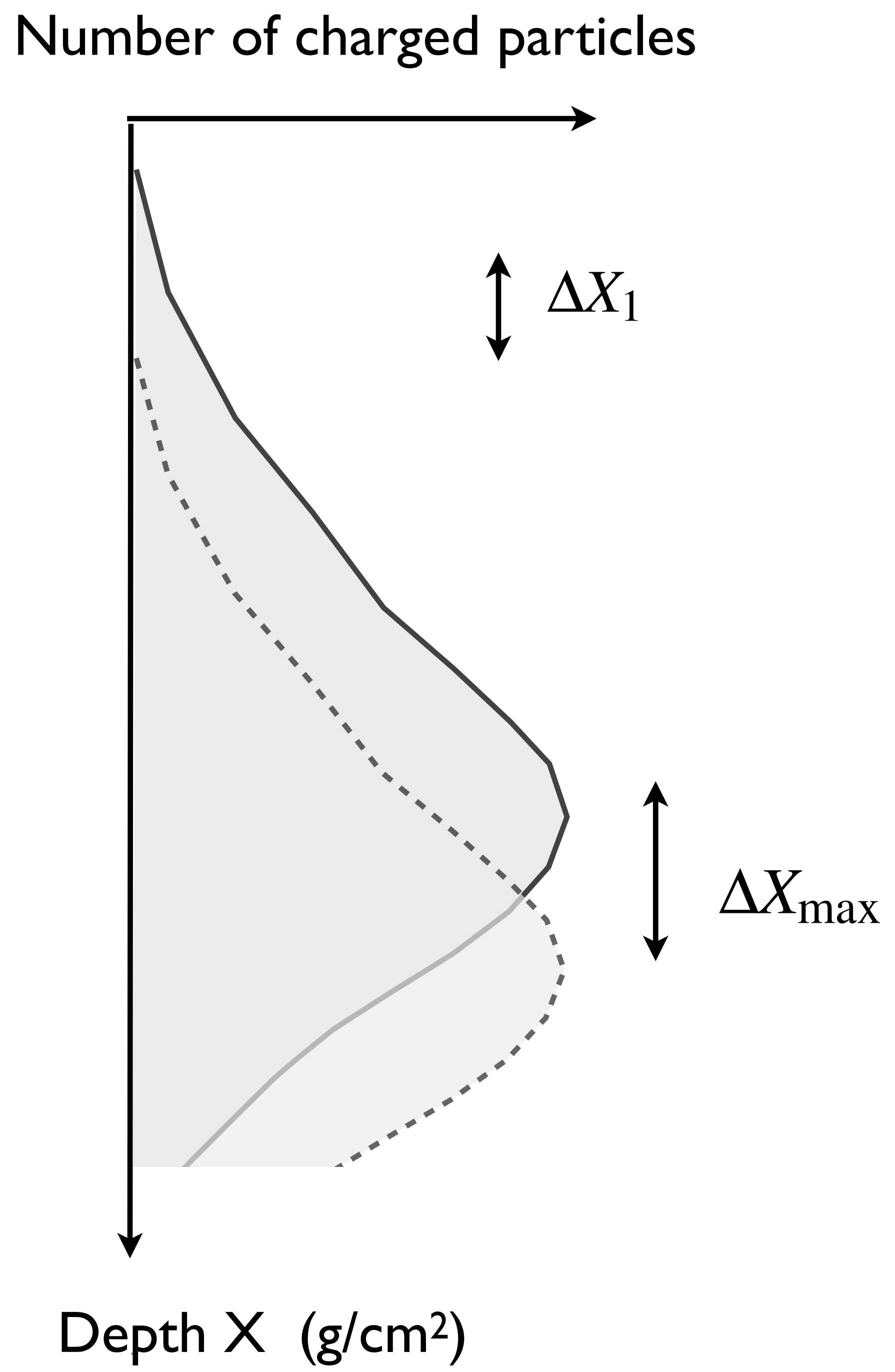
(Vladimir Novotny)

(Yoshiki Tsunesada)

Mass composition results







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

$$\sigma_{X_1,p} \sim 45 - 55\,g/cm^2$$
$$\sigma_{X_1,Fe} \sim 10\,g/cm^2$$

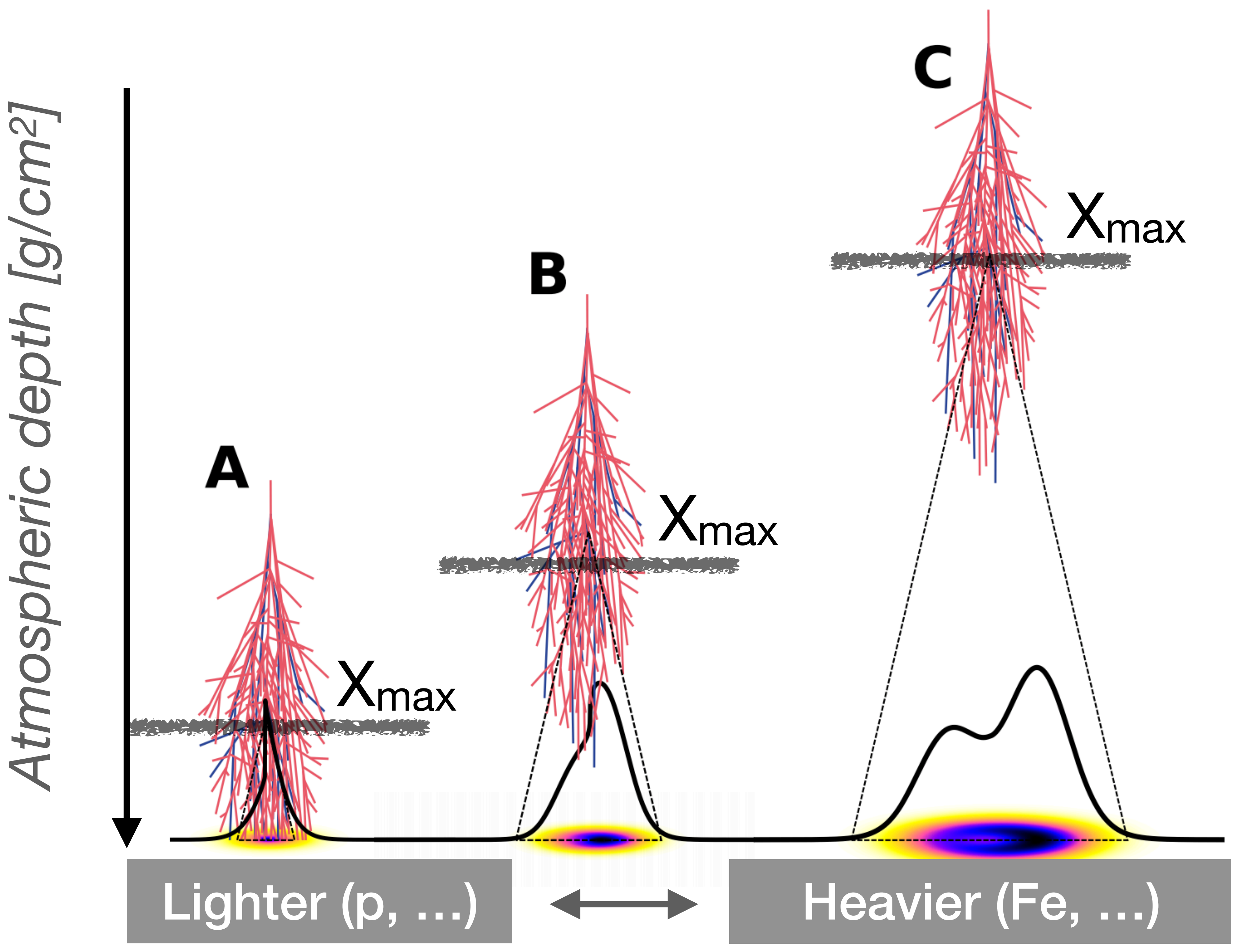
$(E \sim 10^{18}\,eV)$

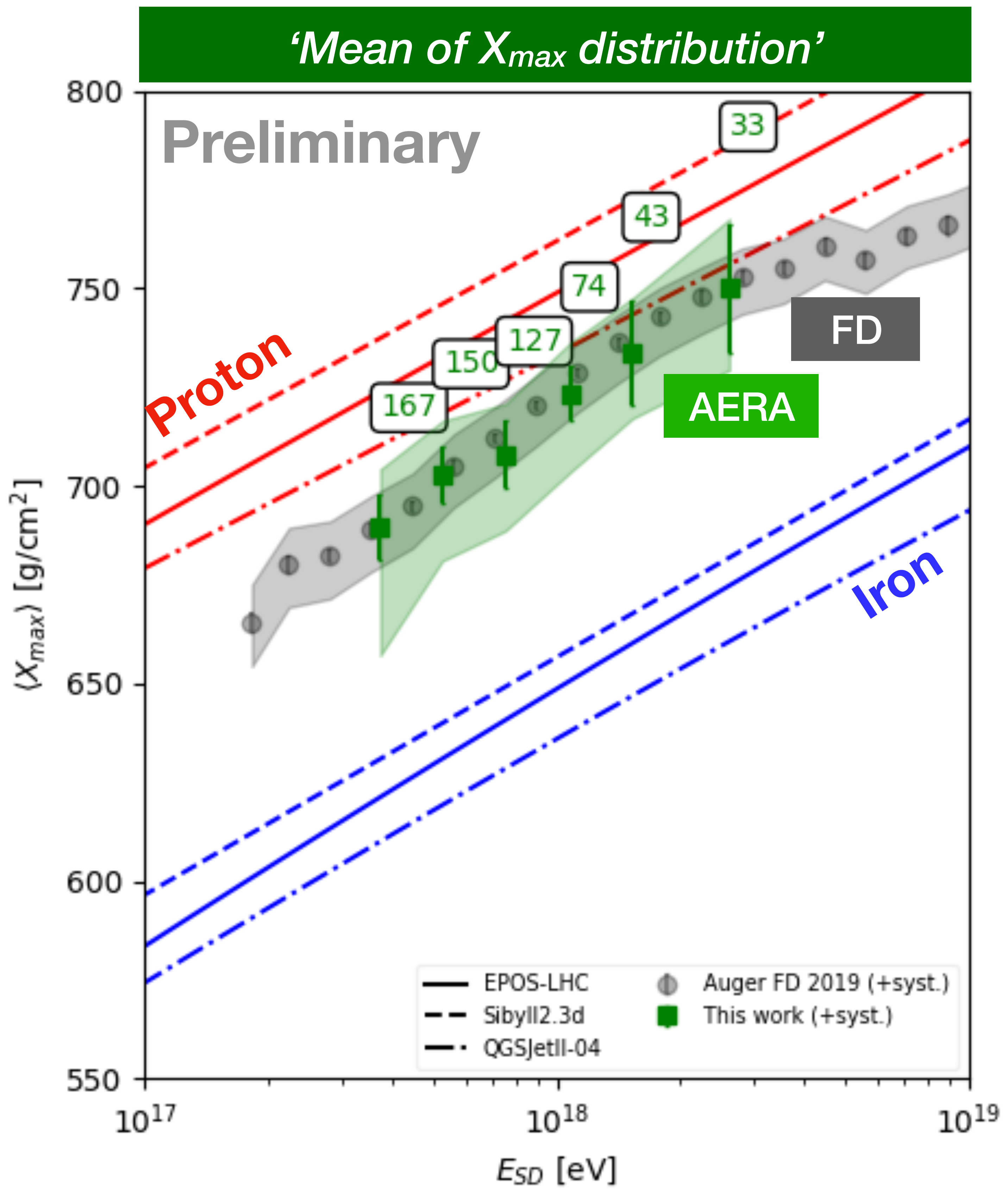
Important: LHC-tuned interaction models used for interpretation

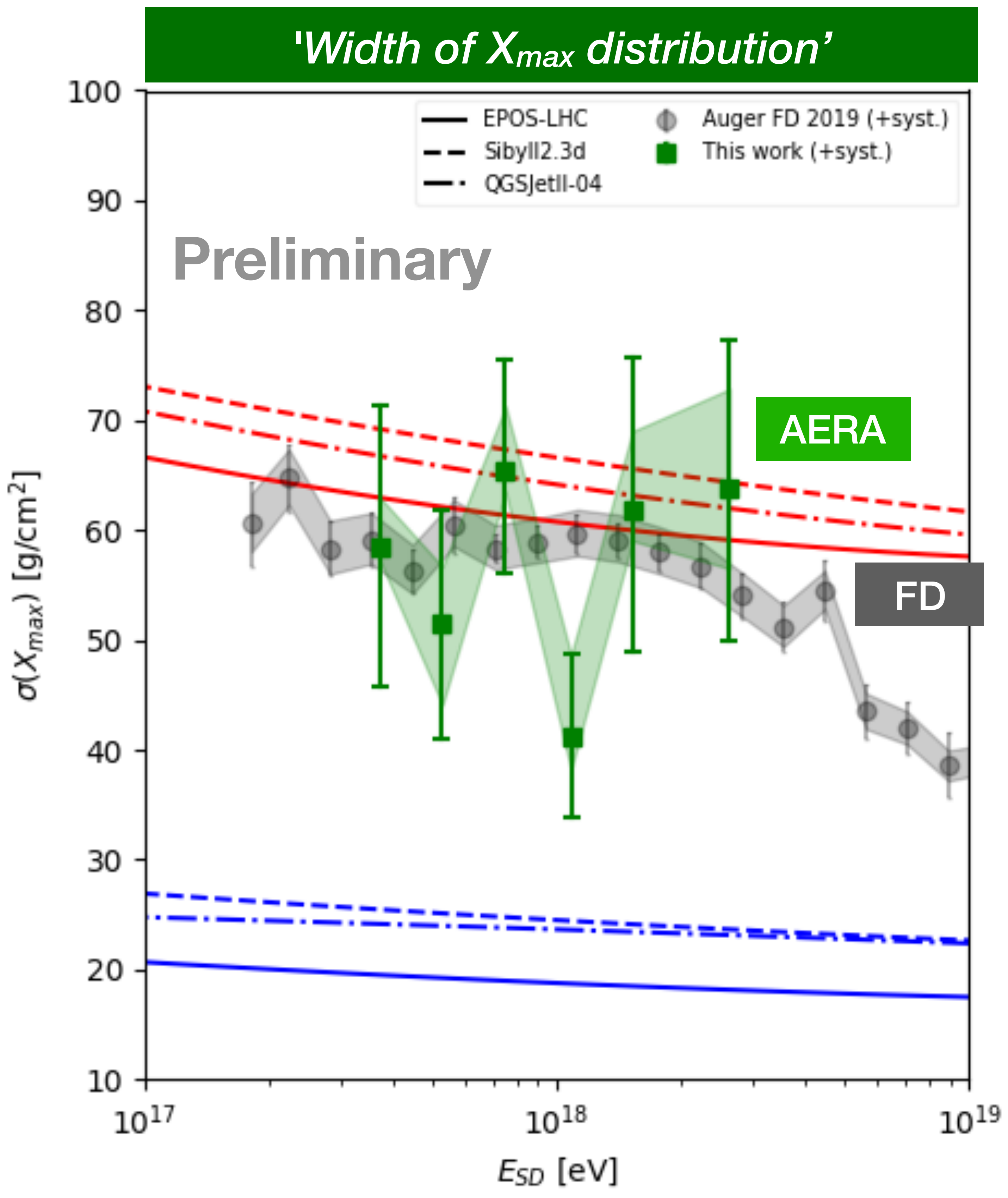
(Phys. Rev. D90 (2014), 122005 & 122005, updated ICRC 2019)

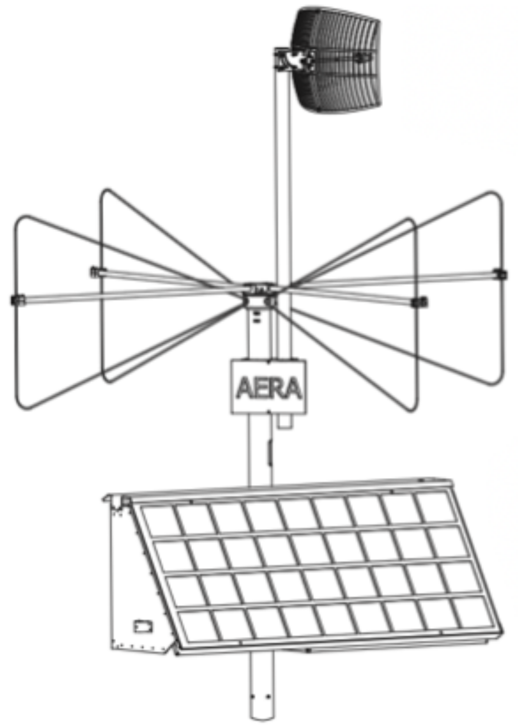
(Phys. Rev. D96 (2017), 122003)

Mass composition results (ii)







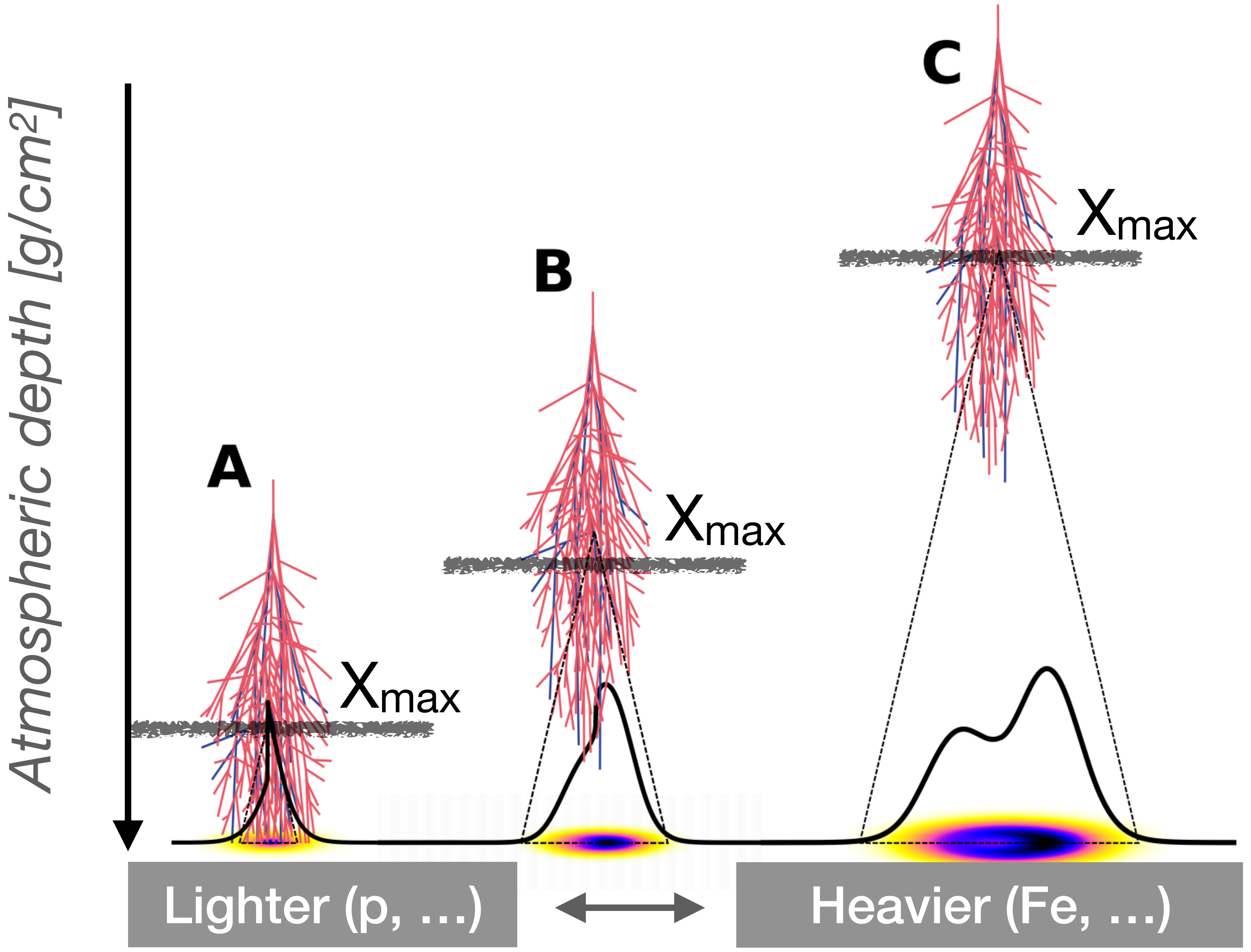


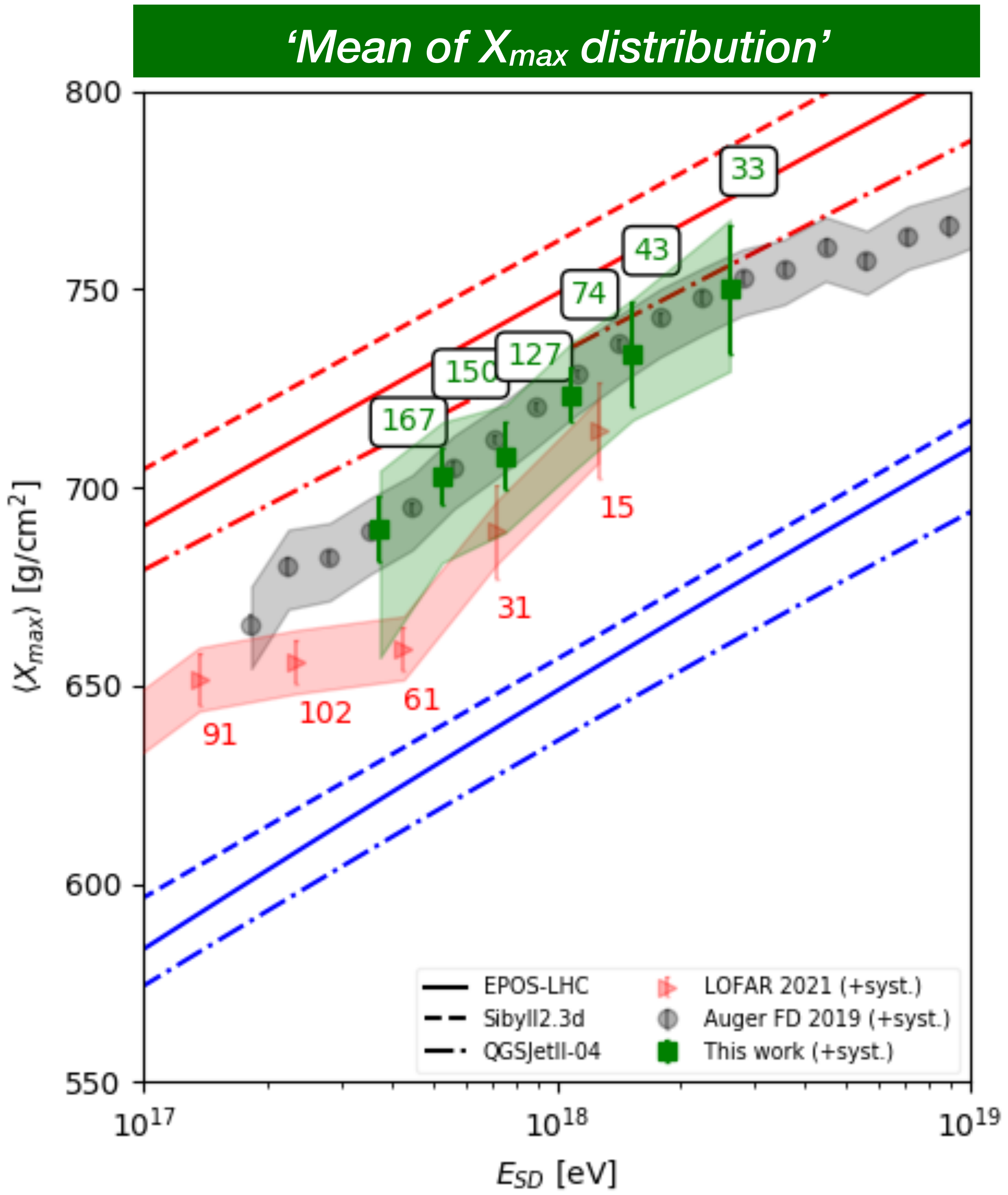
Independent confirmation of earlier Auger results

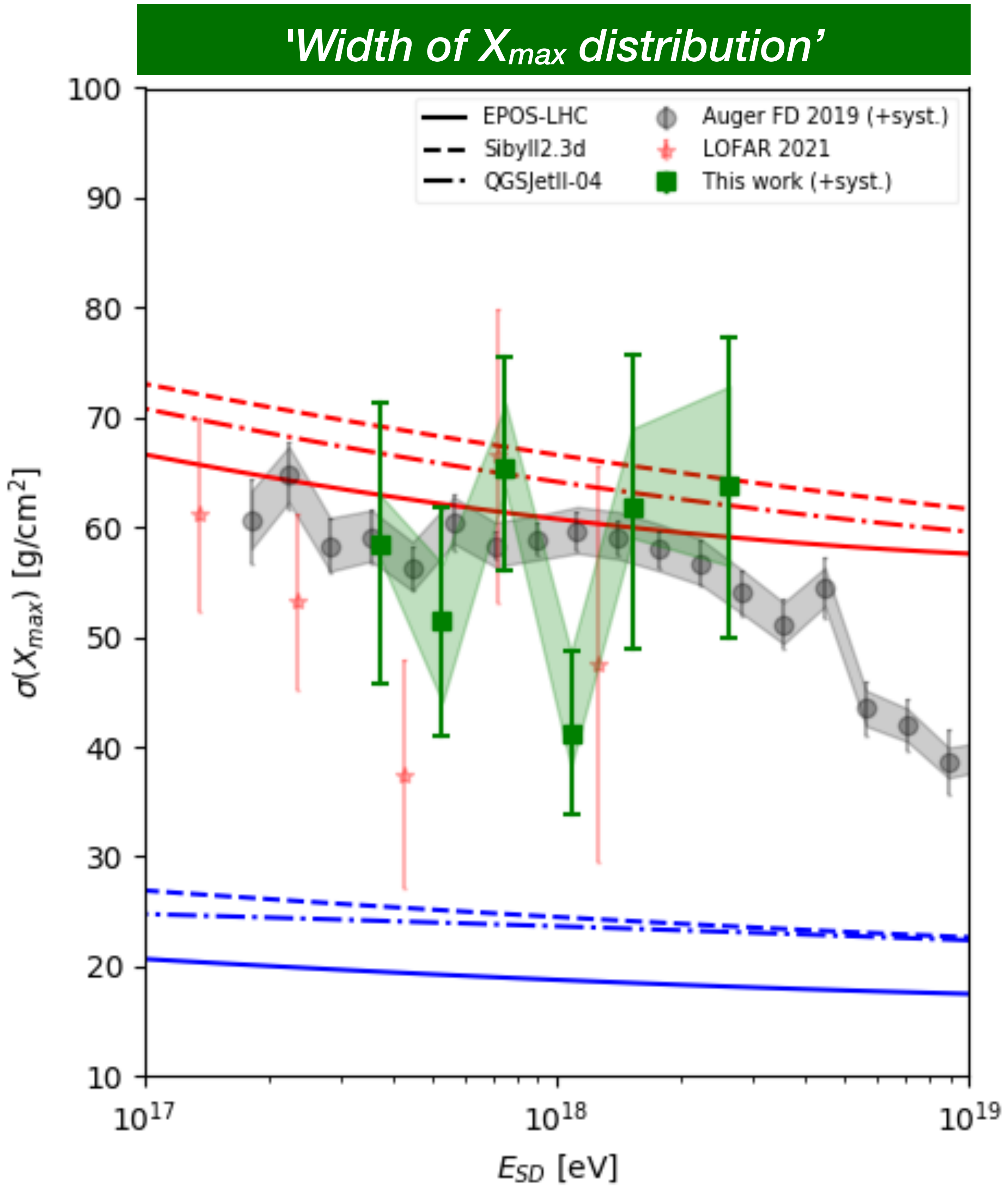
Auger Engineering Radio Array (AERA)

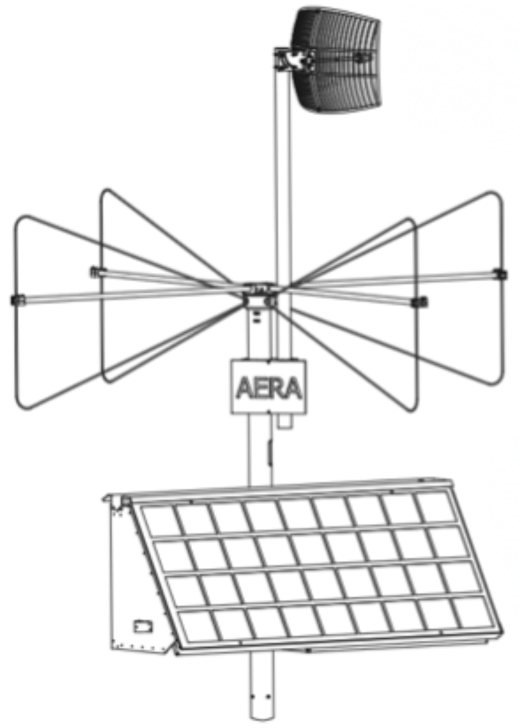
(Bjarni Pont)

Mass composition results (ii)







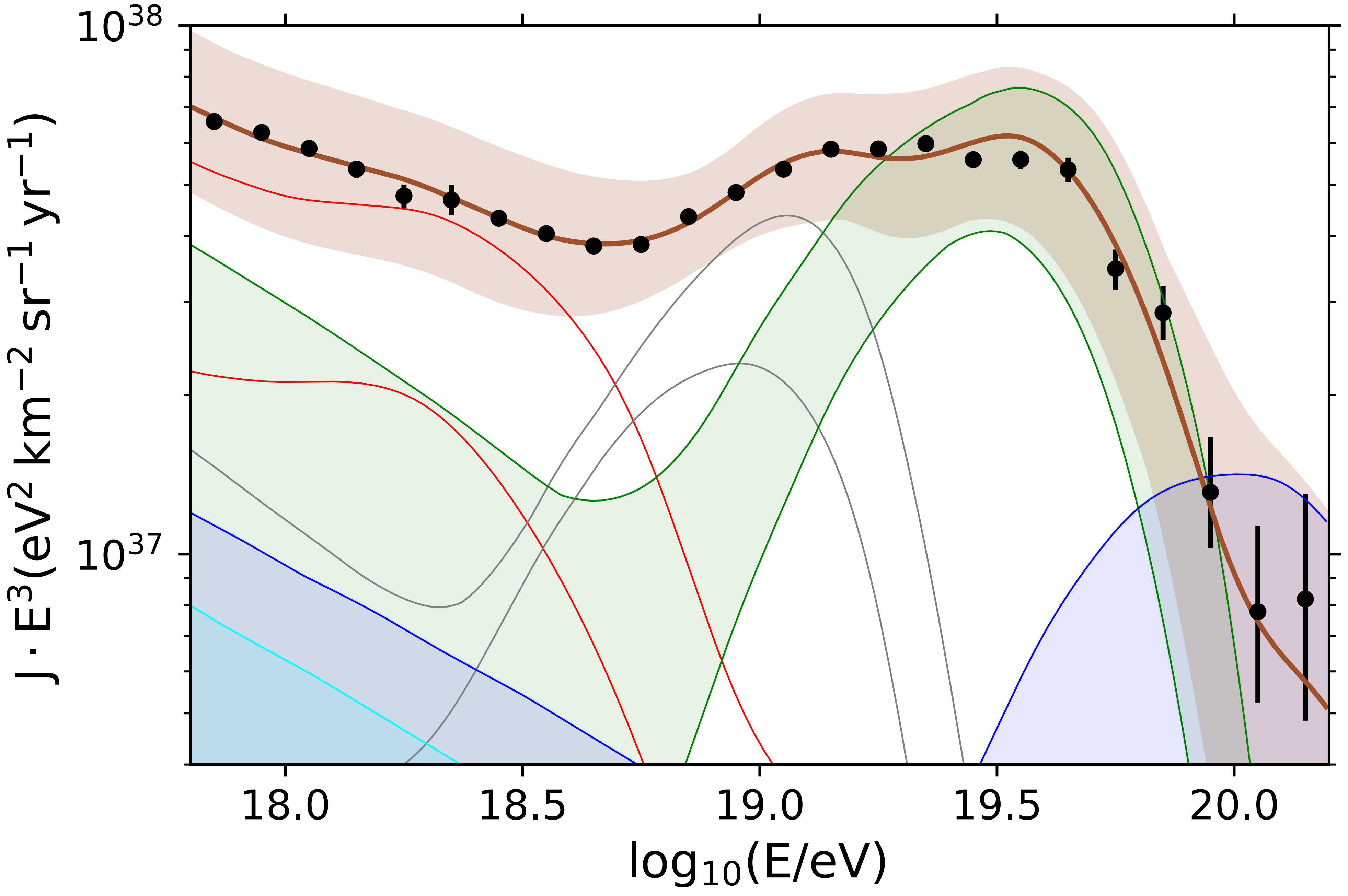


Auger Engineering Radio Array (AERA) (Bjarni Pont)

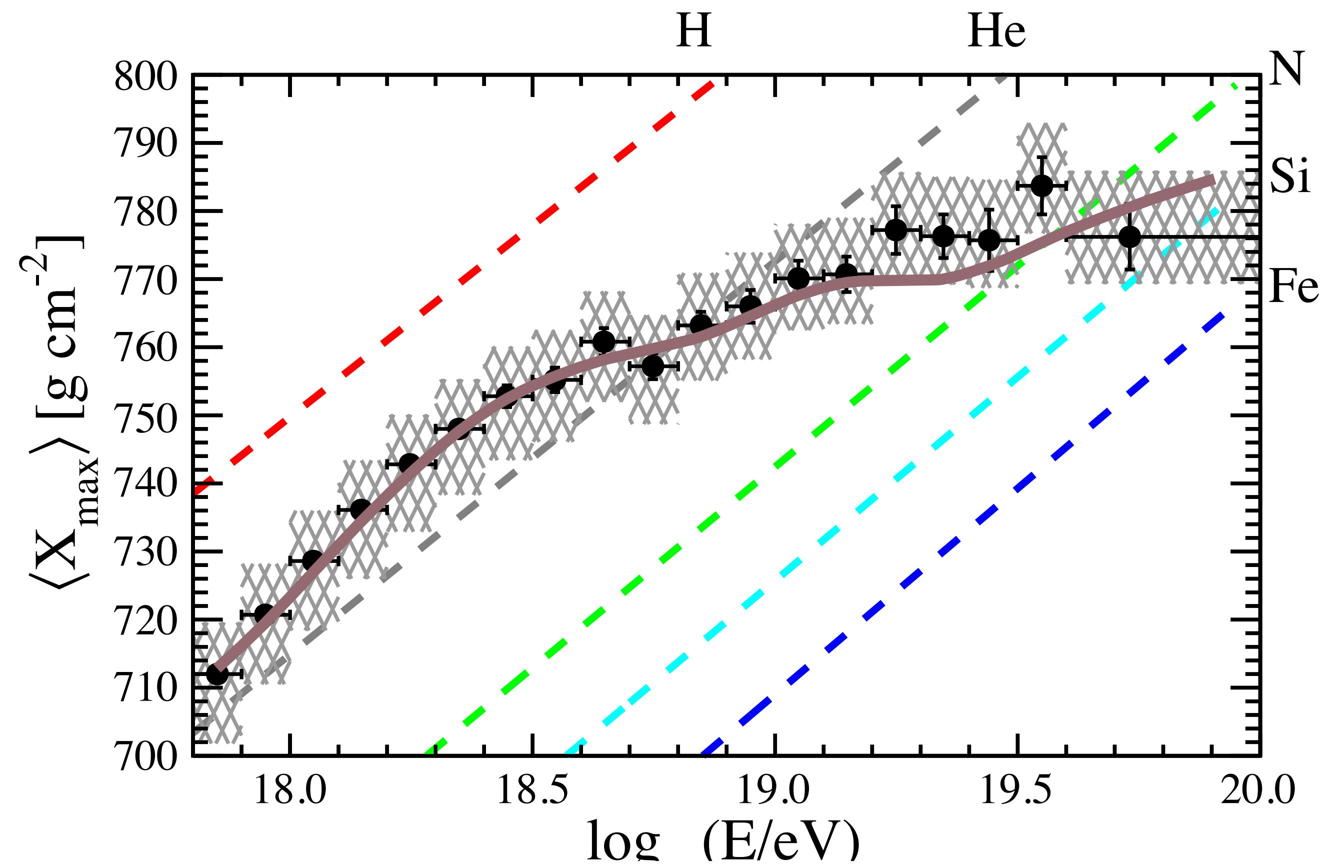
Independent confirmation of earlier Auger results

Interpretation of flux and composition data (i)

Mass composition at Earth



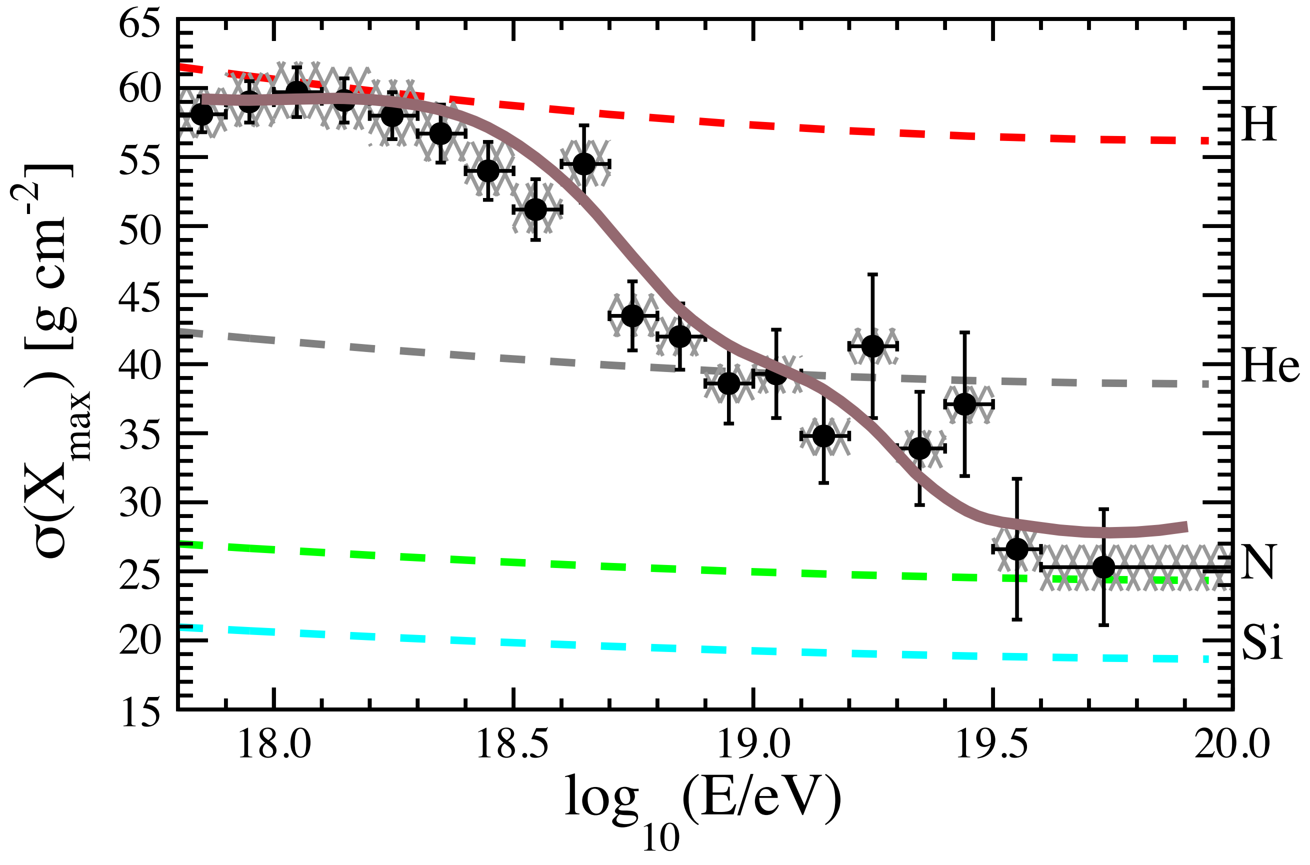
A = 1
1 < A < 5
4 < A < 23
22 < A < 39
38 < A < 57



Bands:
Experimental uncertainties
(model uncertainties smaller)

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

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



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

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

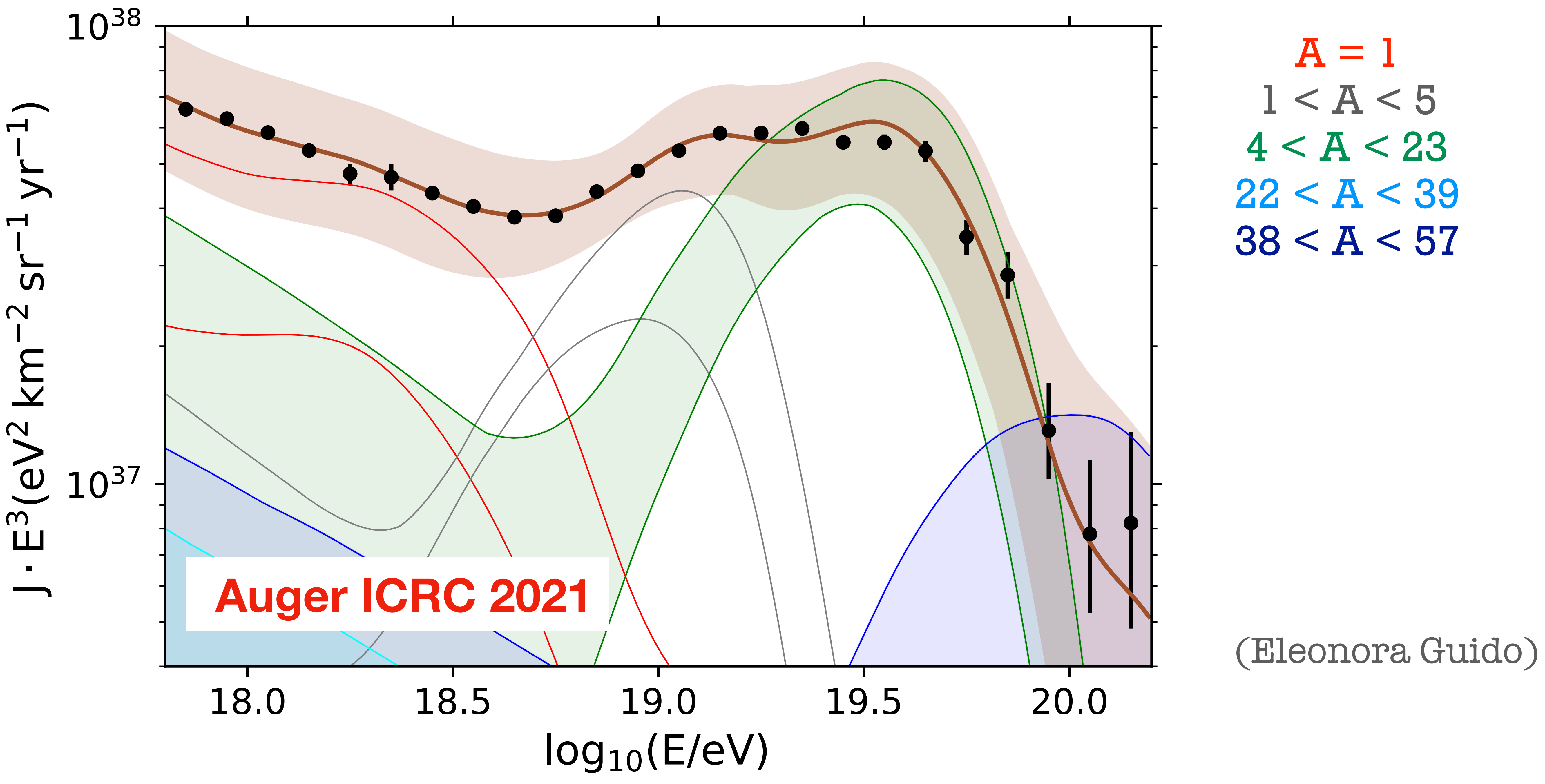
$$R_{cut} = 1.4 \ldots 1.6 \times 10^{18}\,\mathrm{V}$$

Flux suppression superposition of injection maximum energy and propagation energy losses

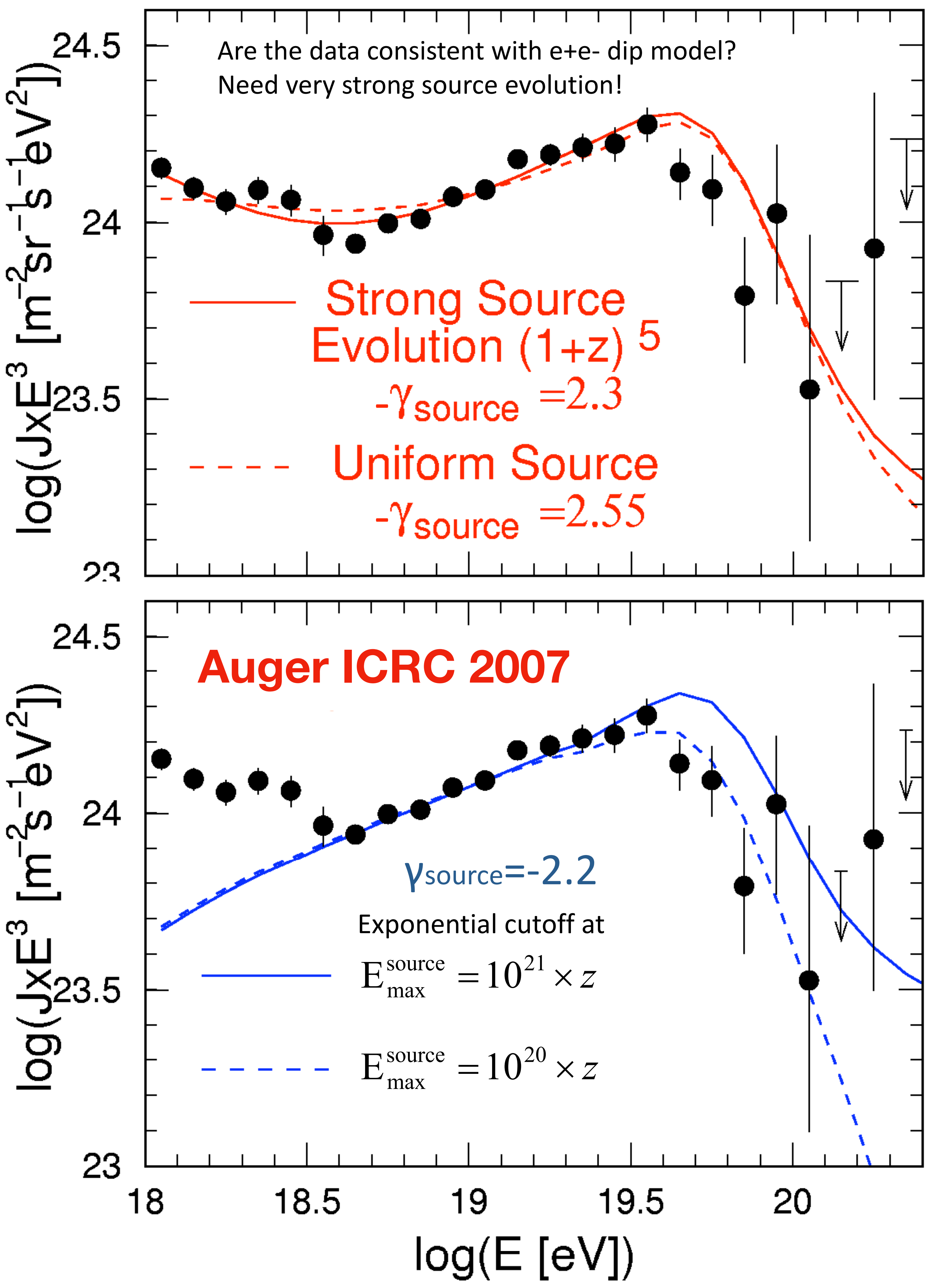
Extragalactic index very hard, but no really good handle on this parameter

(Eleonora Guido)

Interpretation of flux and composition data (ii)



(Eleonora Guido)

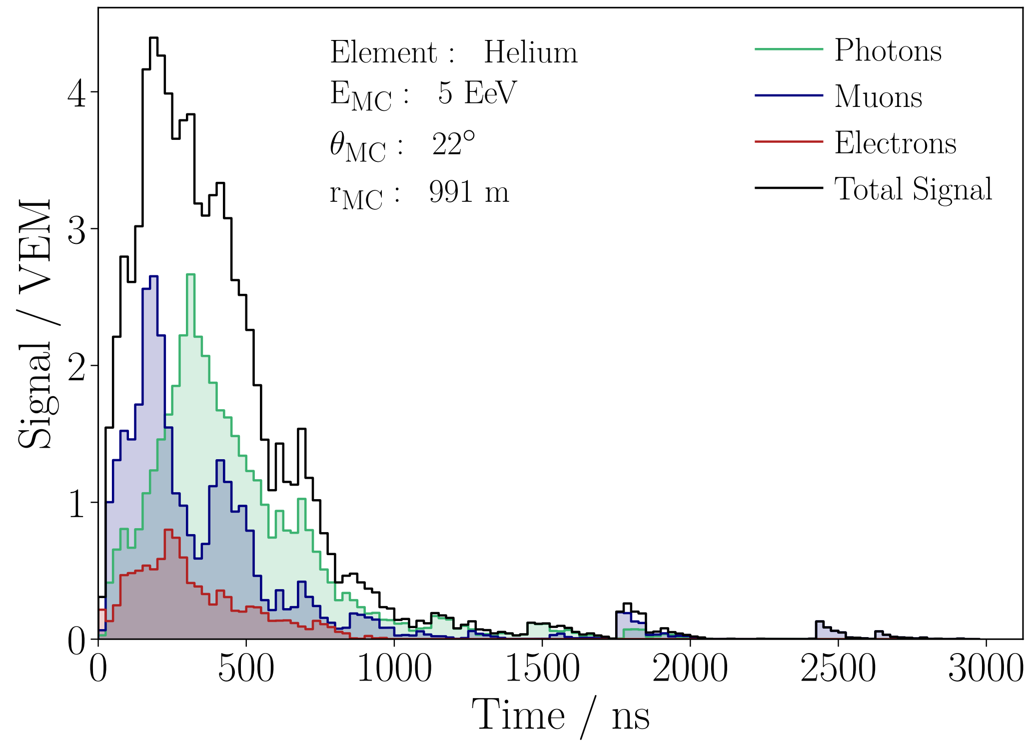


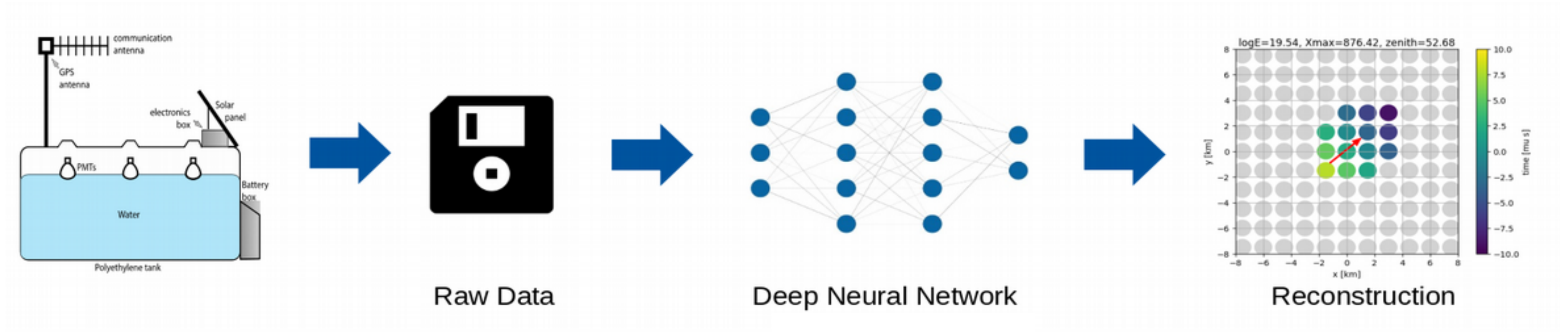
- **Instep** as new feature is of **fundamental importance** (composition!)
- Watch region between 10^{18} and $10^{18.5}$ eV (another feature?)

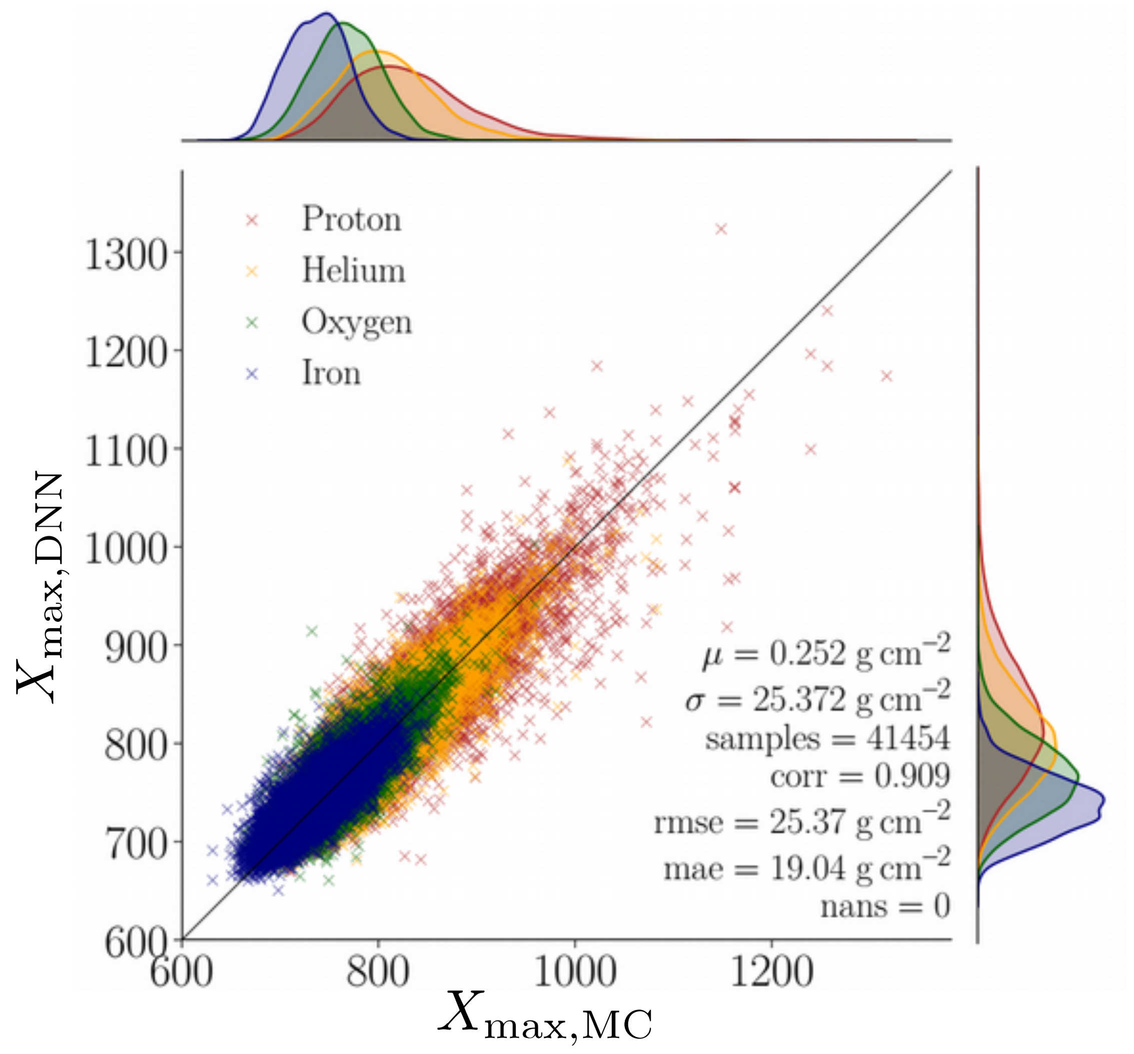
Phase II: composition information
for all high-energy events (old and new)

Outlook: The (r)evolution of machine learning

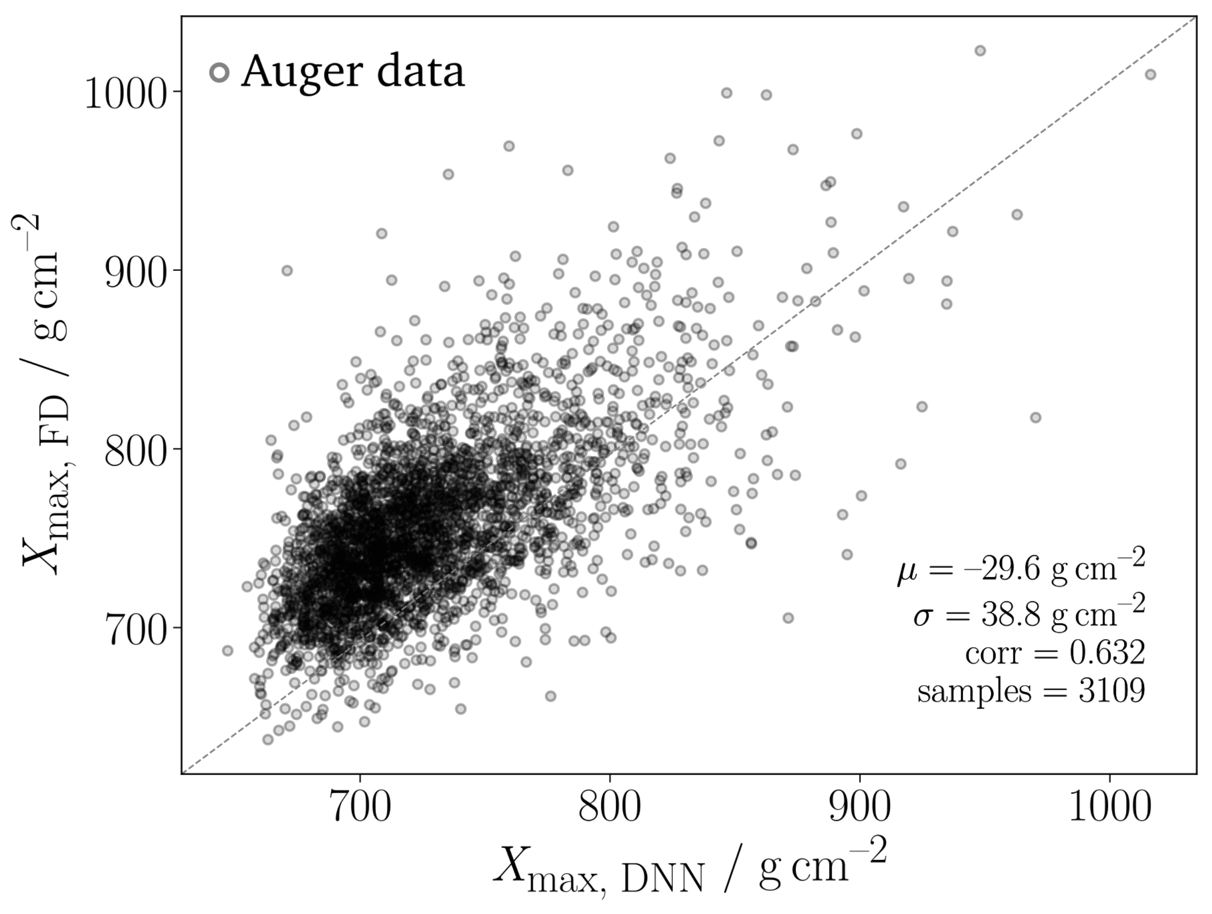
Simulated signal trace of one station

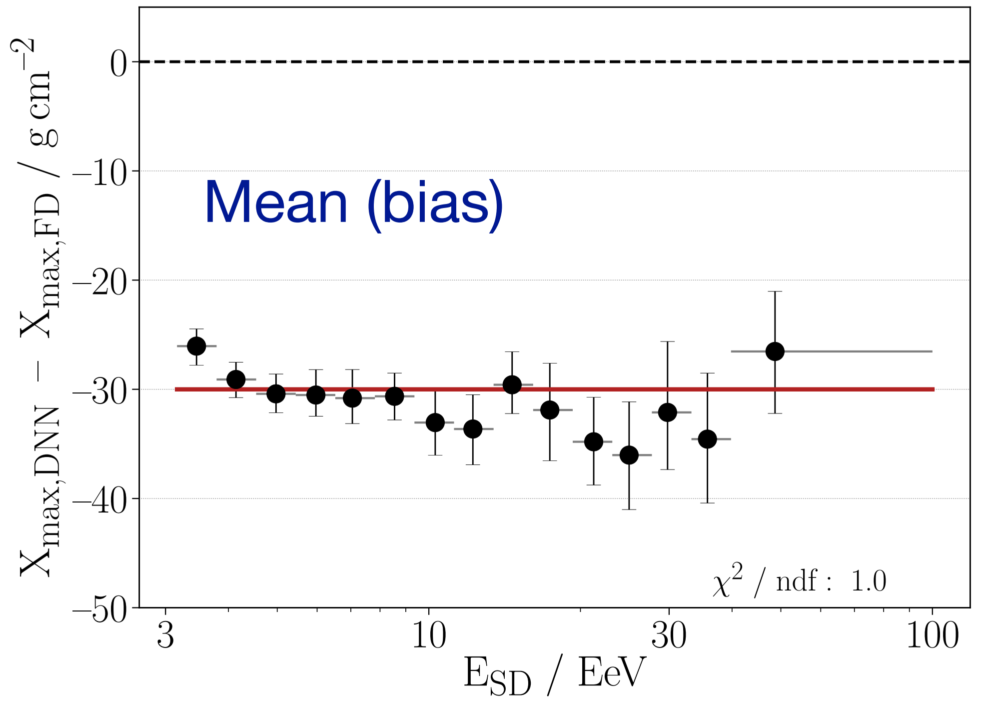


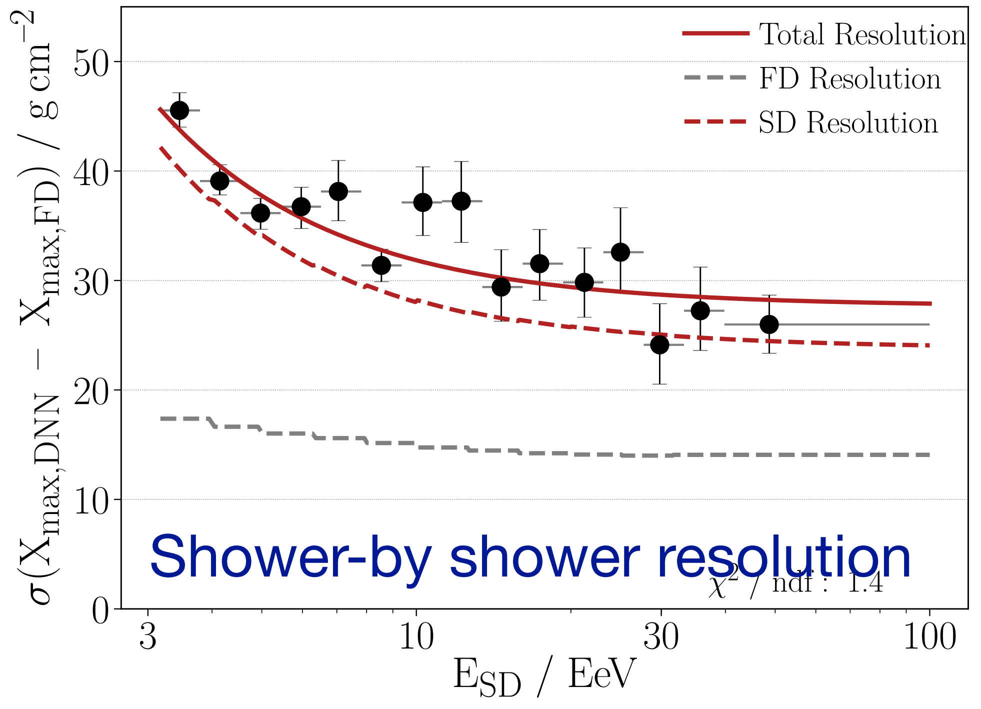




Reconstructing Xmax: ultimate check with data

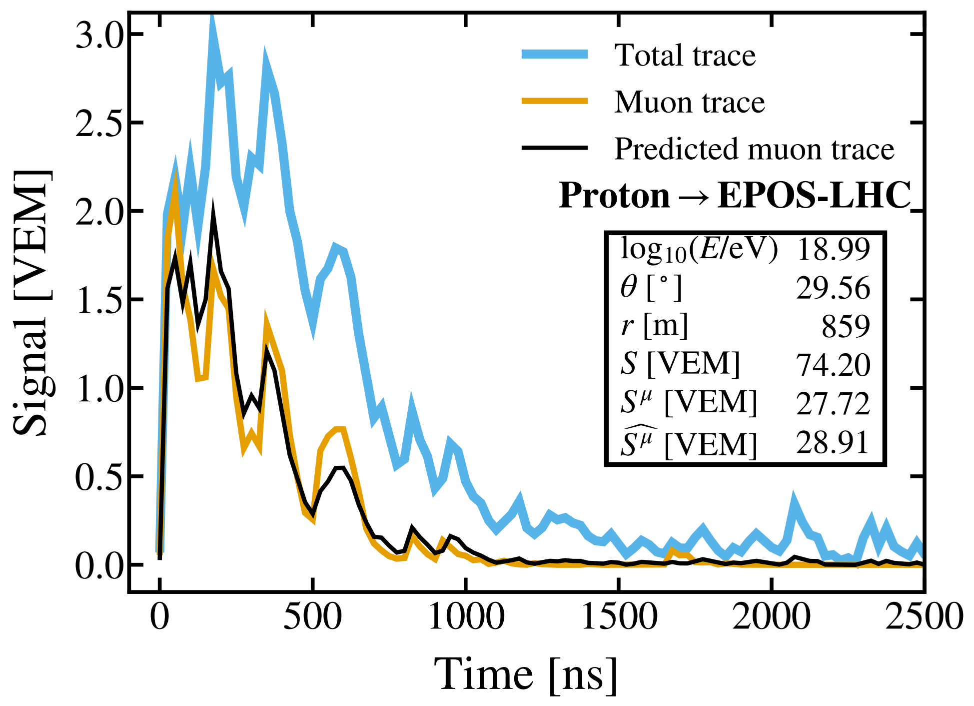


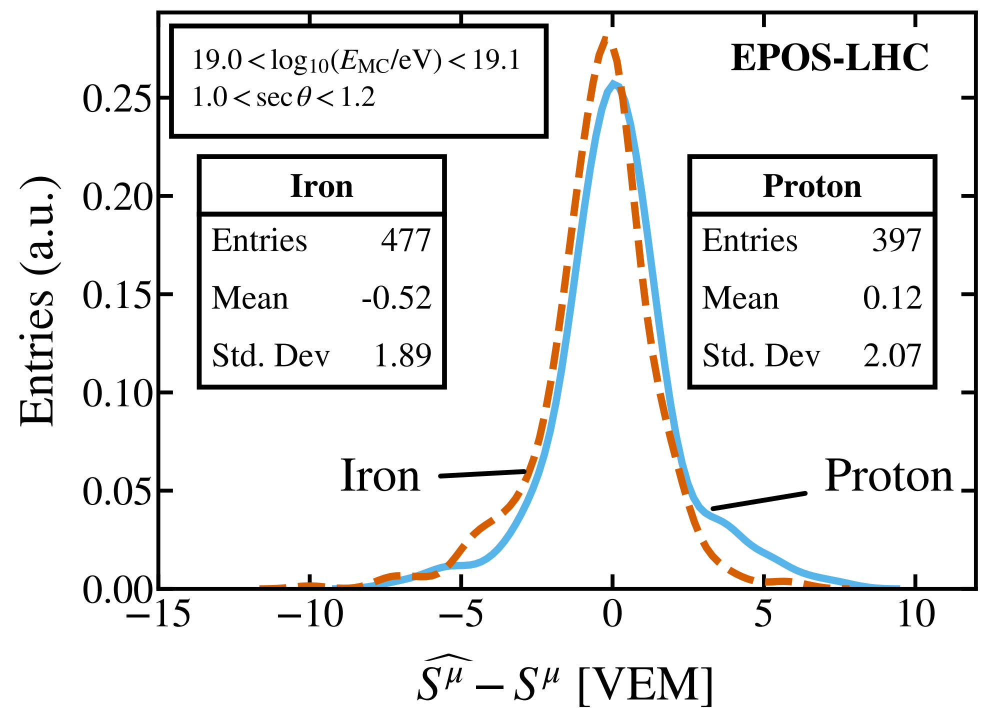




(Jonas Glombitza) (Juan Miguel Carceller)

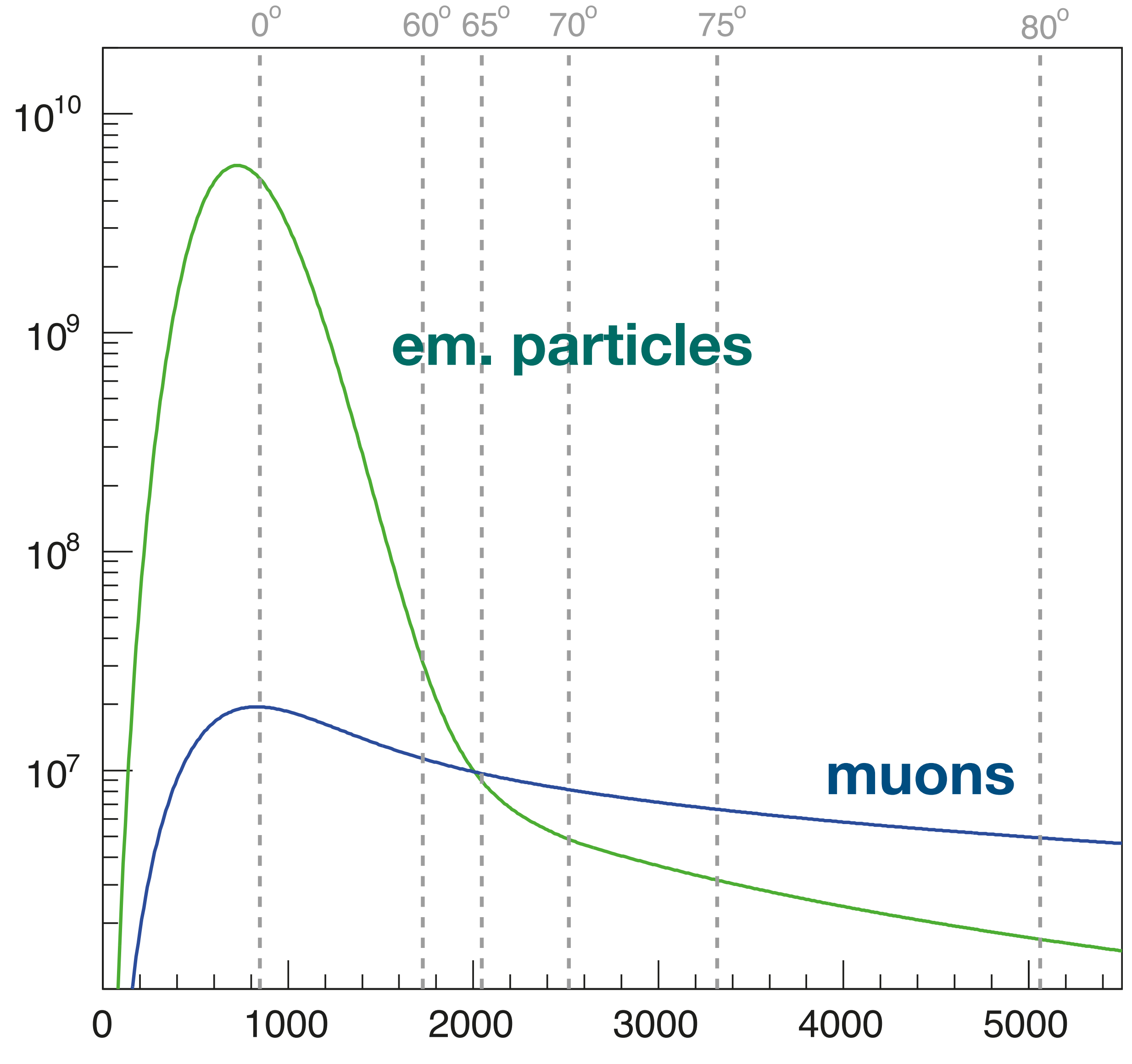
Reconstructing the muon signal of a station (no data available)



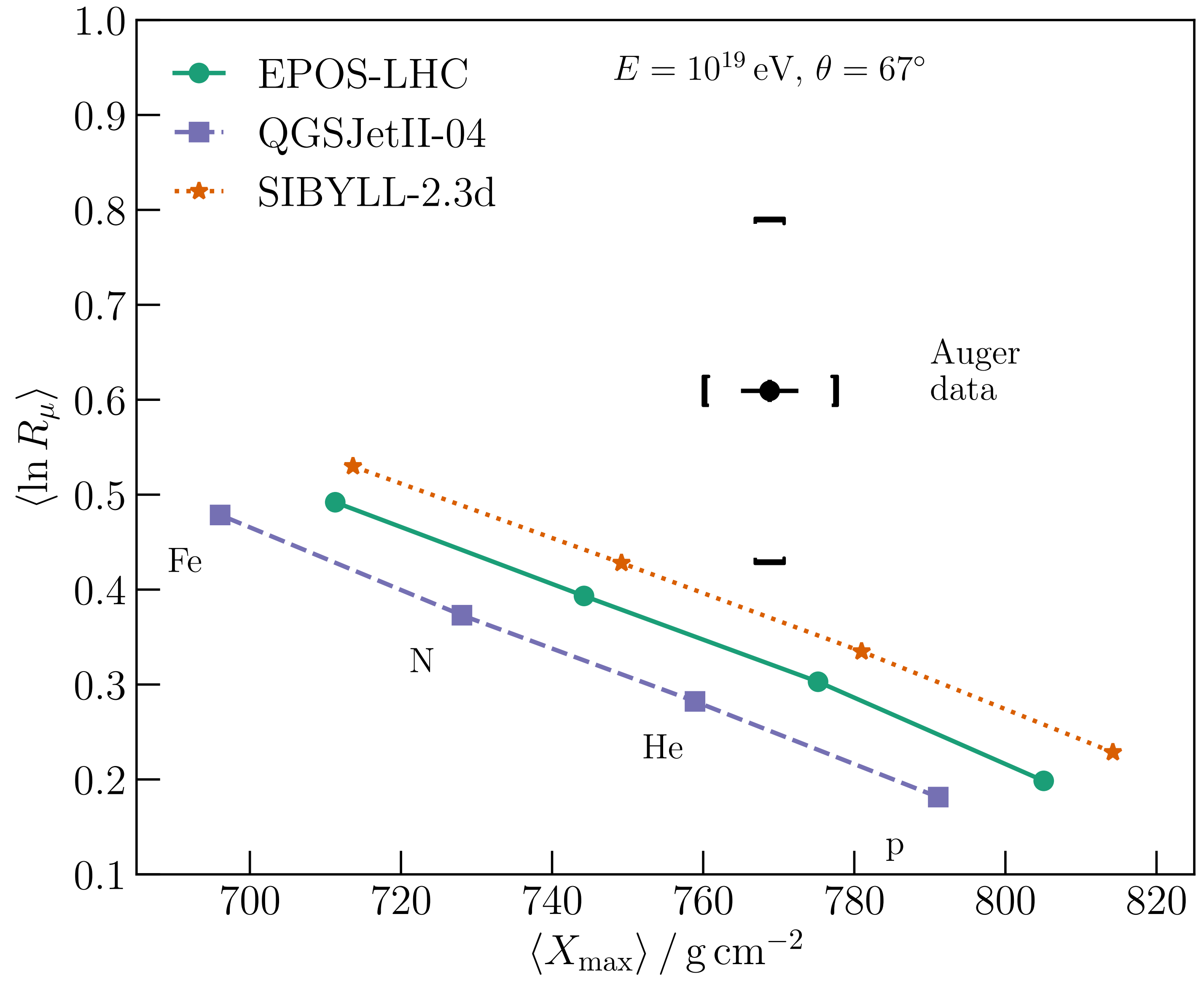


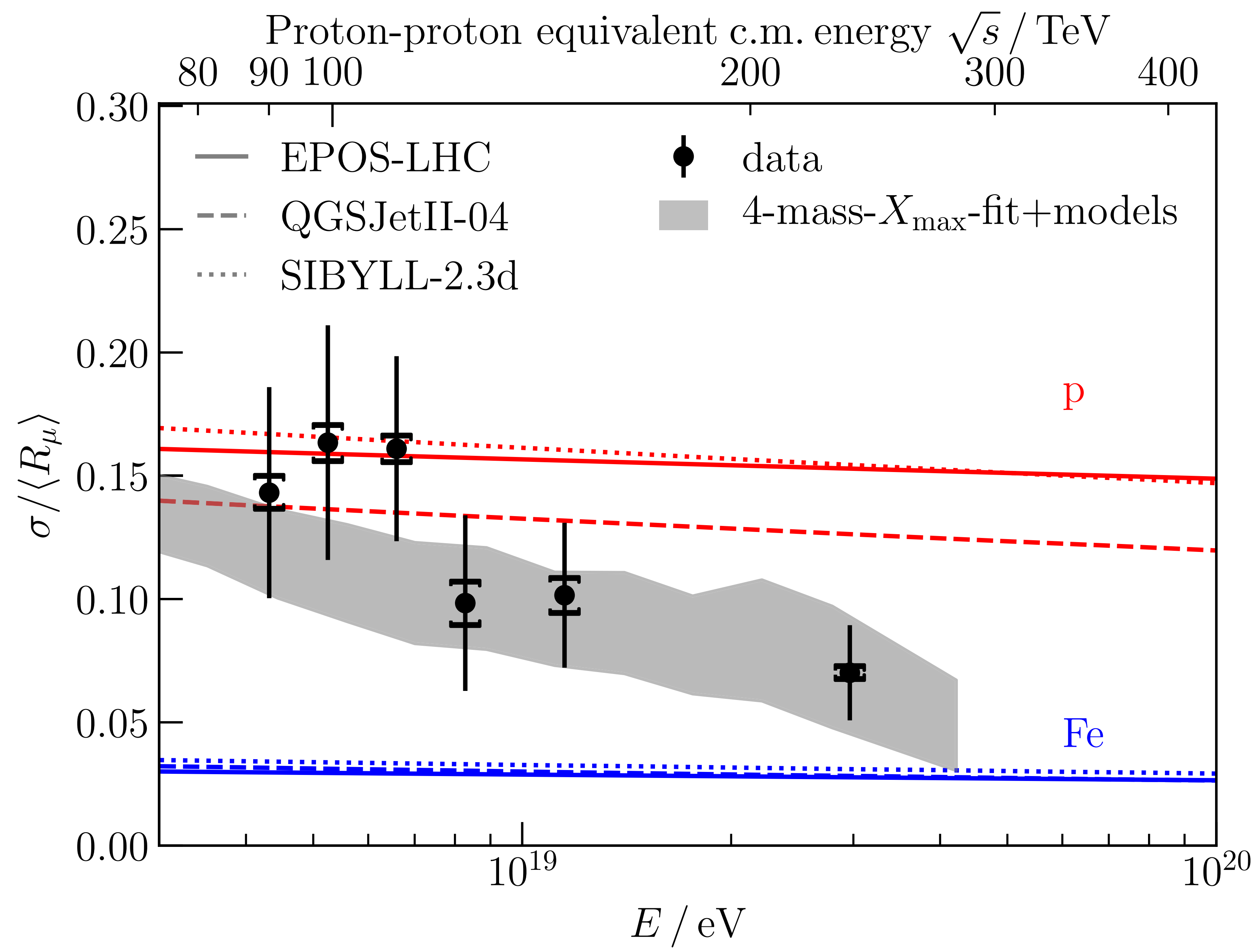
Phase II data will allow us to verify and optimize DNN and universality methods

What could be the origin of the problem?

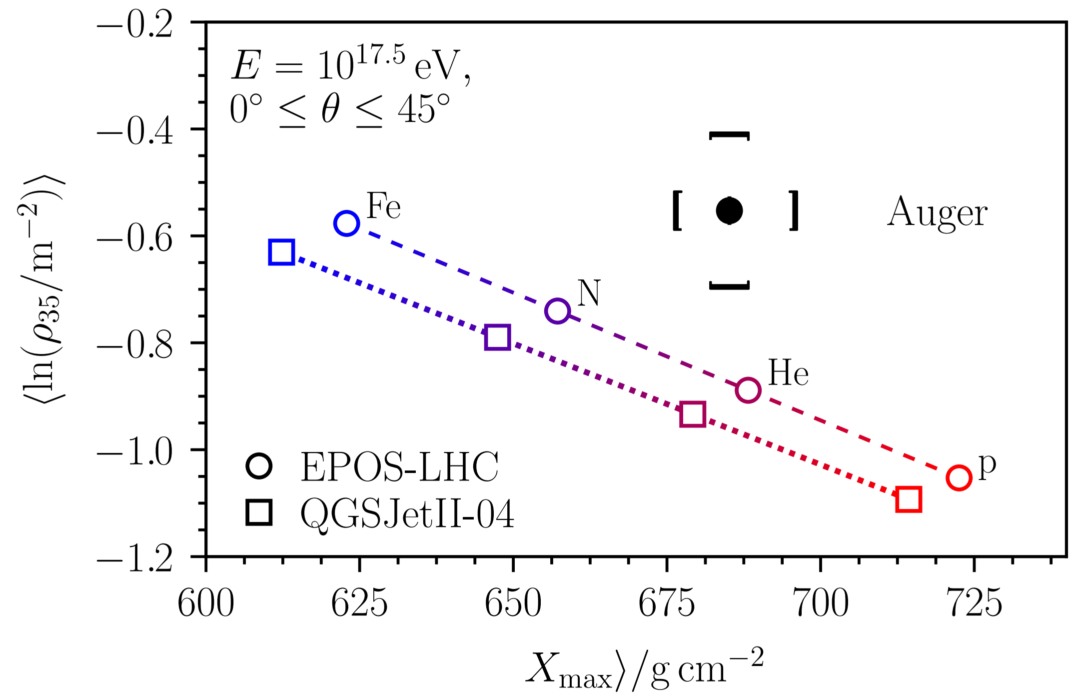


Hybrid events and inclined showers





Muon counters and vertical showers



(Eur. Phys. J. C80 (2020) 751)

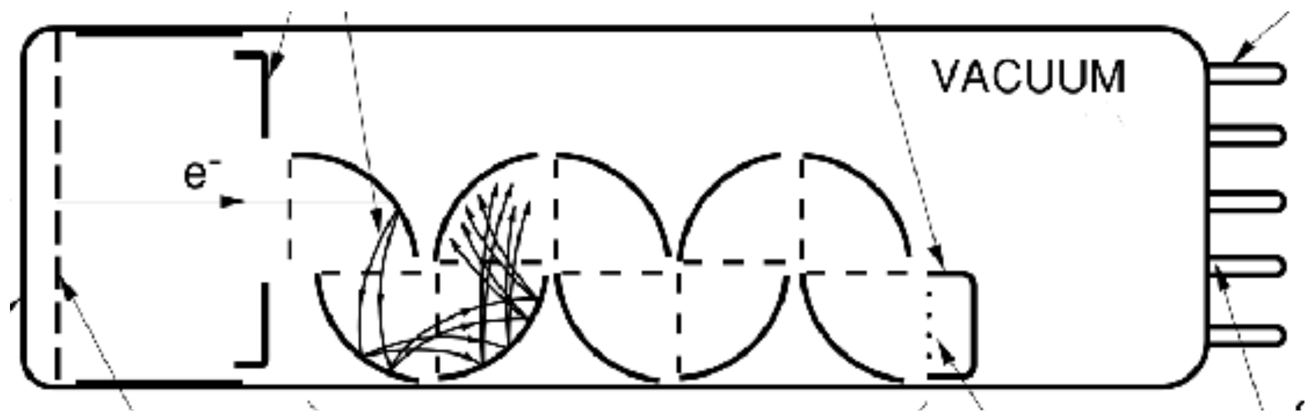
(Phys. Rev. Lett. 117 (2016) 192001, Phys. Rev. D91 (2015) 032003)

Discrepancy in number of muons

Relative fluctuations in agreement

(Dennis Soldin)

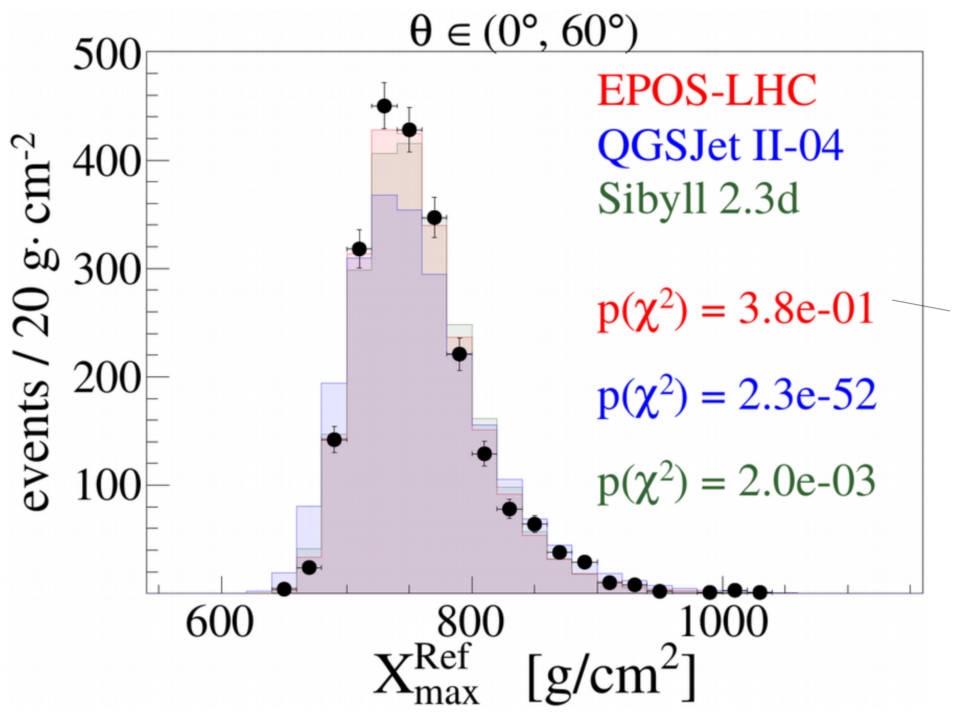
PMT analogy of air shower



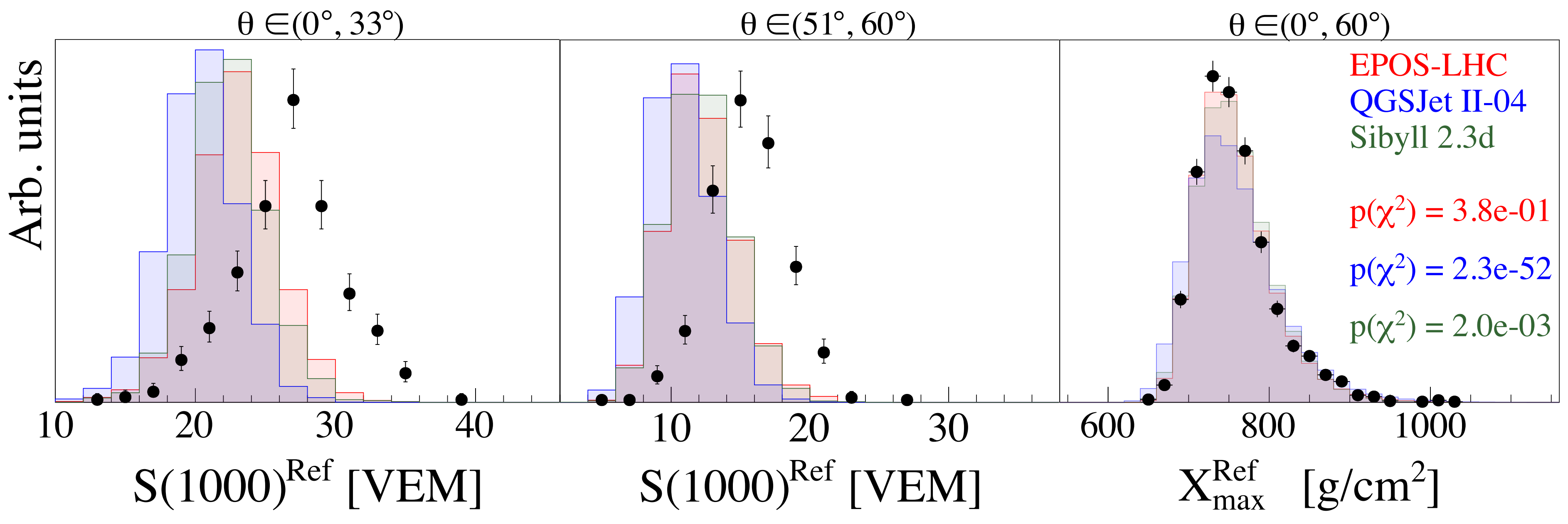
Muon fluctuations driven by first interactions

(Phys. Rev. Lett. 126 (2021) 152002)

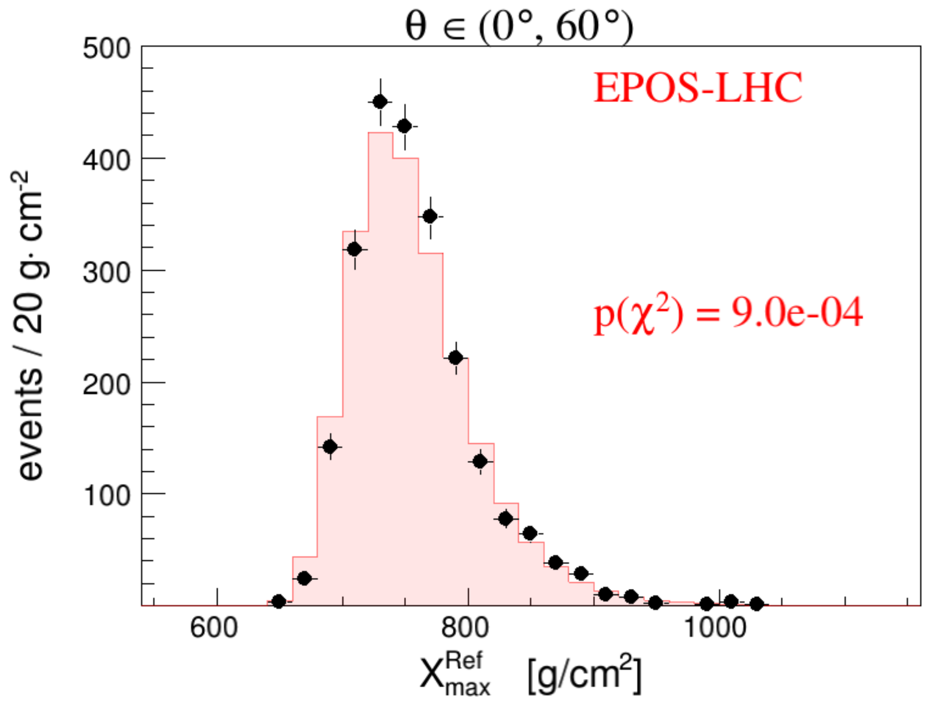
Test: modification of hadronic interaction models



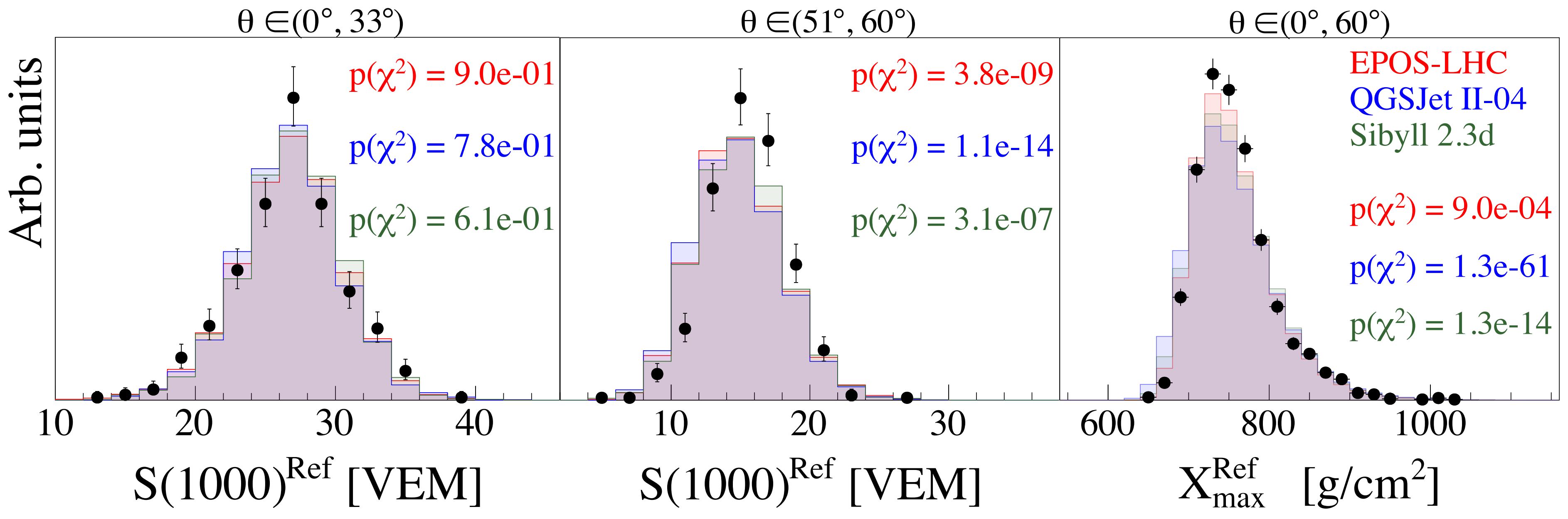
Combined fit of correlated Xmax distribution and S(1000) signal at ground



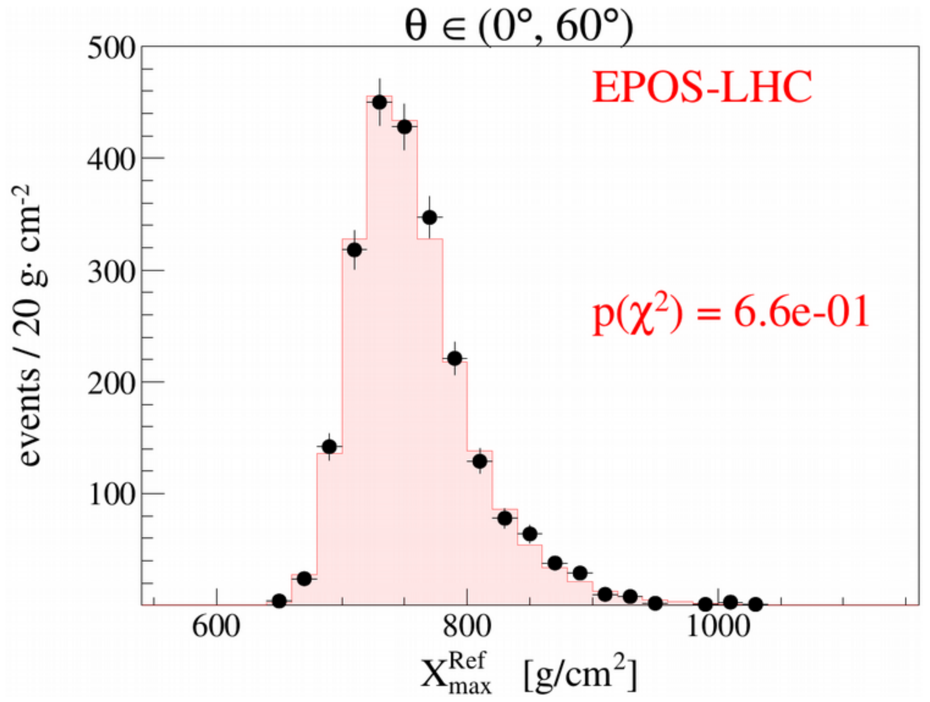
(a) No MC corrections



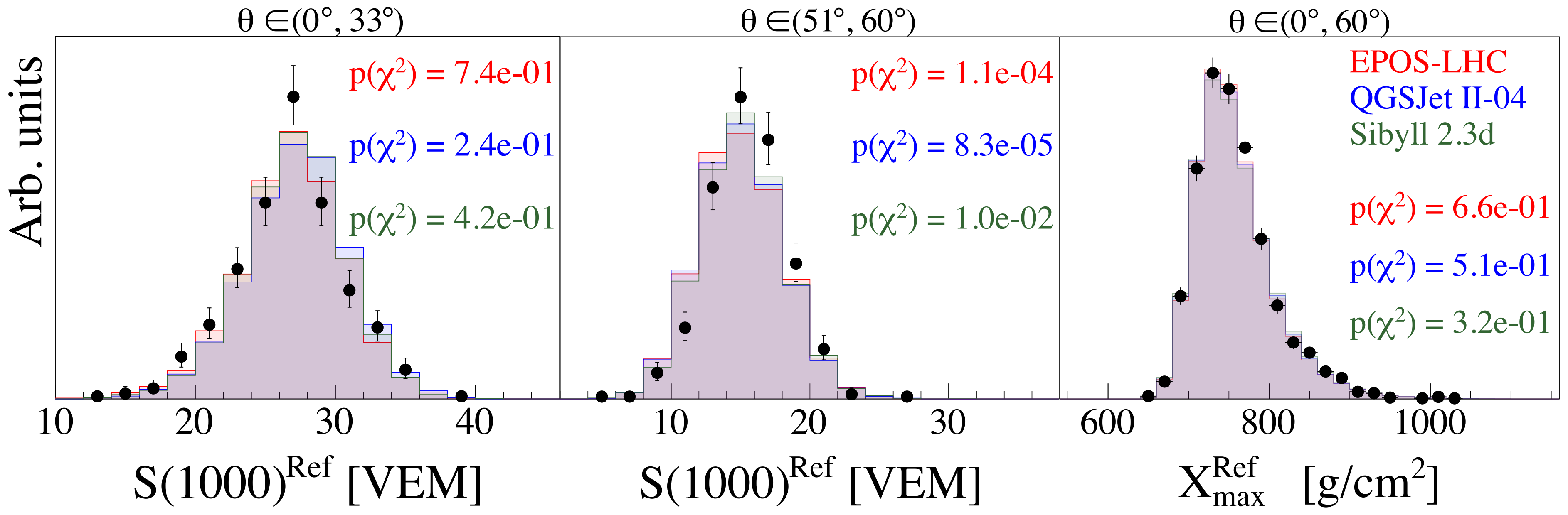
Combined fit of correlated Xmax distribution and S(1000) signal at ground allowing for an **angular-dependent muon re-scaling** (only mean muon number changed)



(b) MC corrections: $R_{\mathrm{Had}}(\theta)$



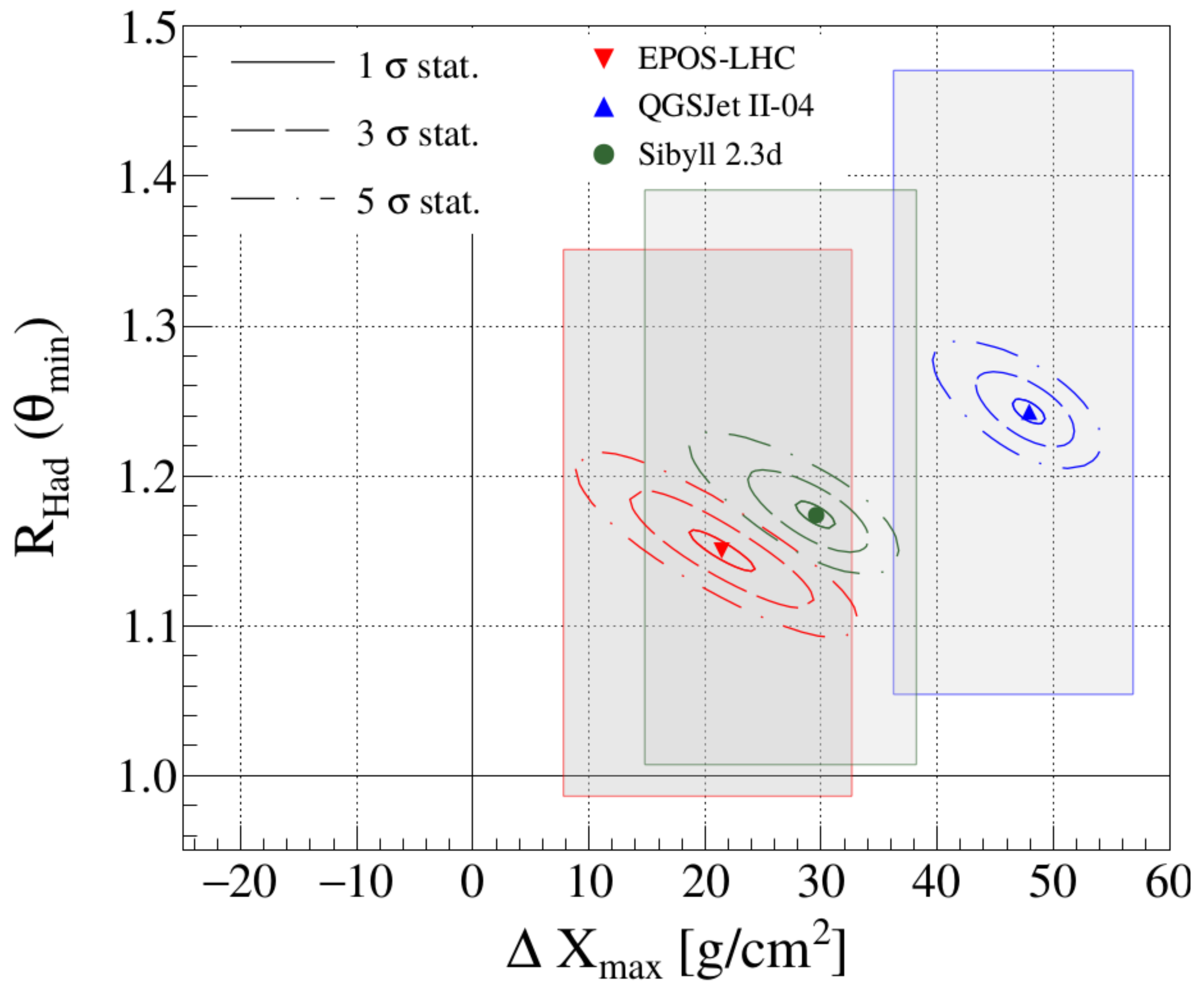
Combined fit of correlated Xmax distribution and S(1000) signal at ground allowing for an **angular-dependent muon re-scaling** (only mean muon number changed) and **shifting Xmax** of all primaries by fixed value

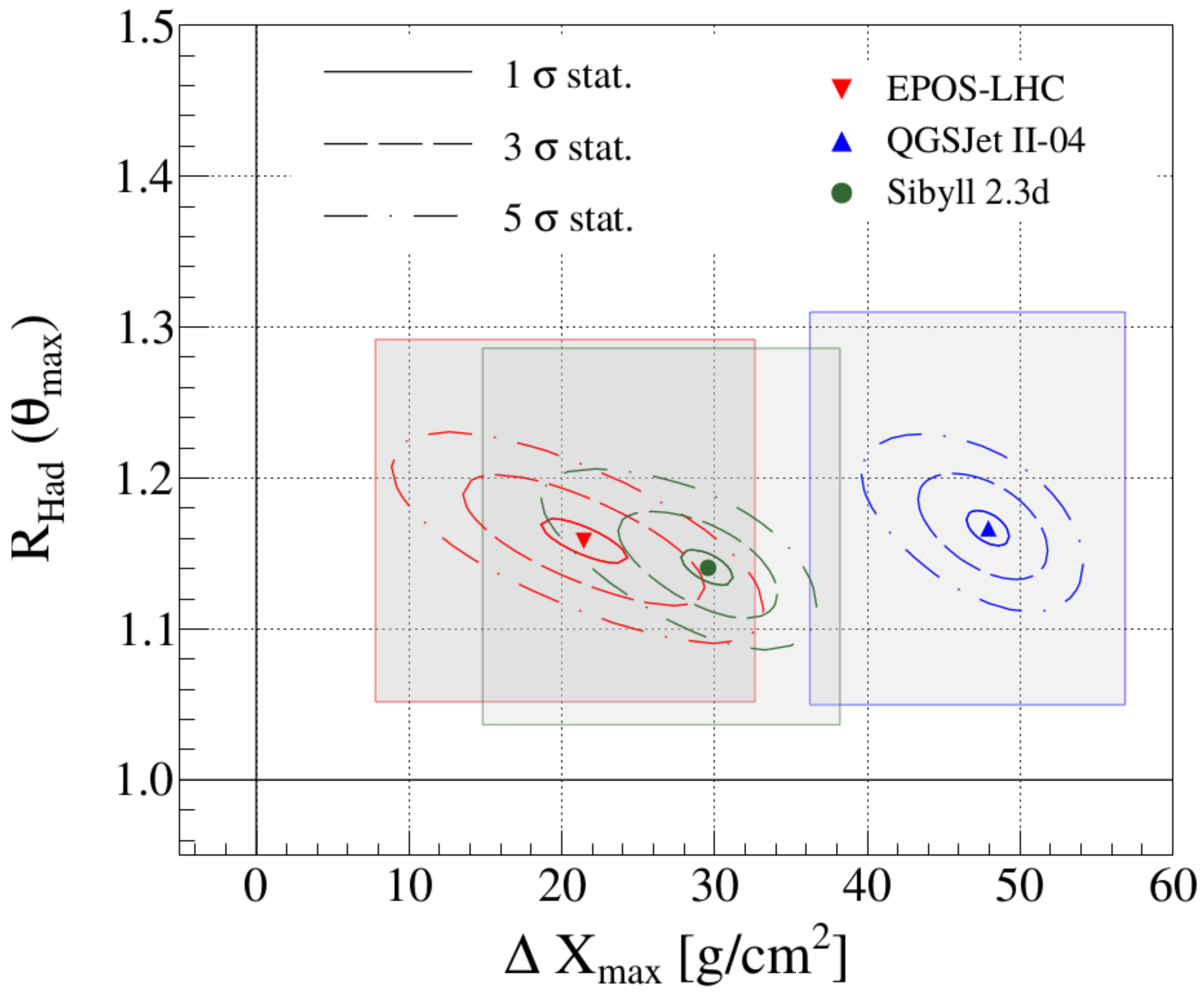


(c) MC corrections: ΔX_{max} and $R_{\mathrm{Had}}(\theta)$

(Jakub Vicha)

Test: modification of hadronic interaction models (ii)





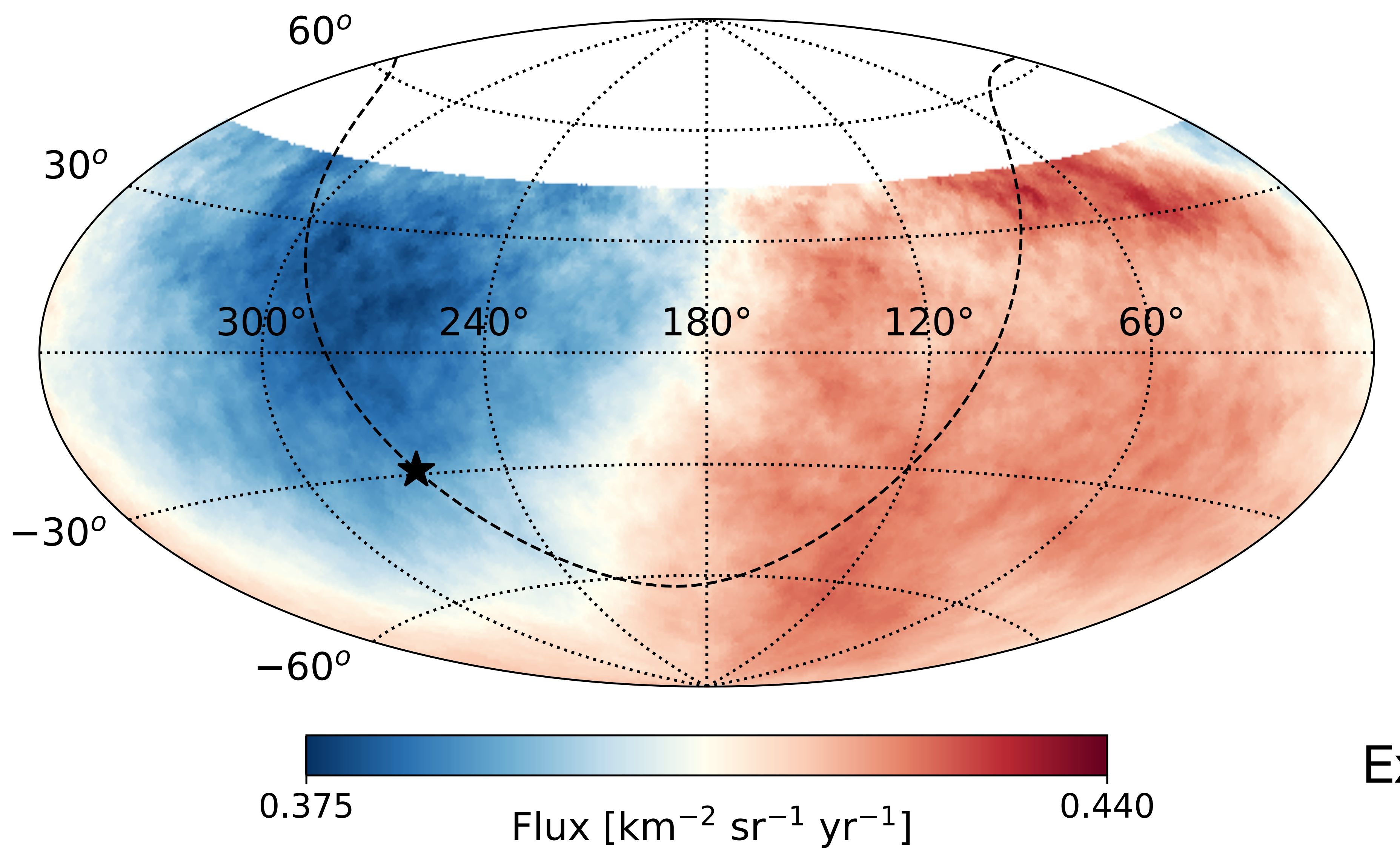
(Jakub Vicha)

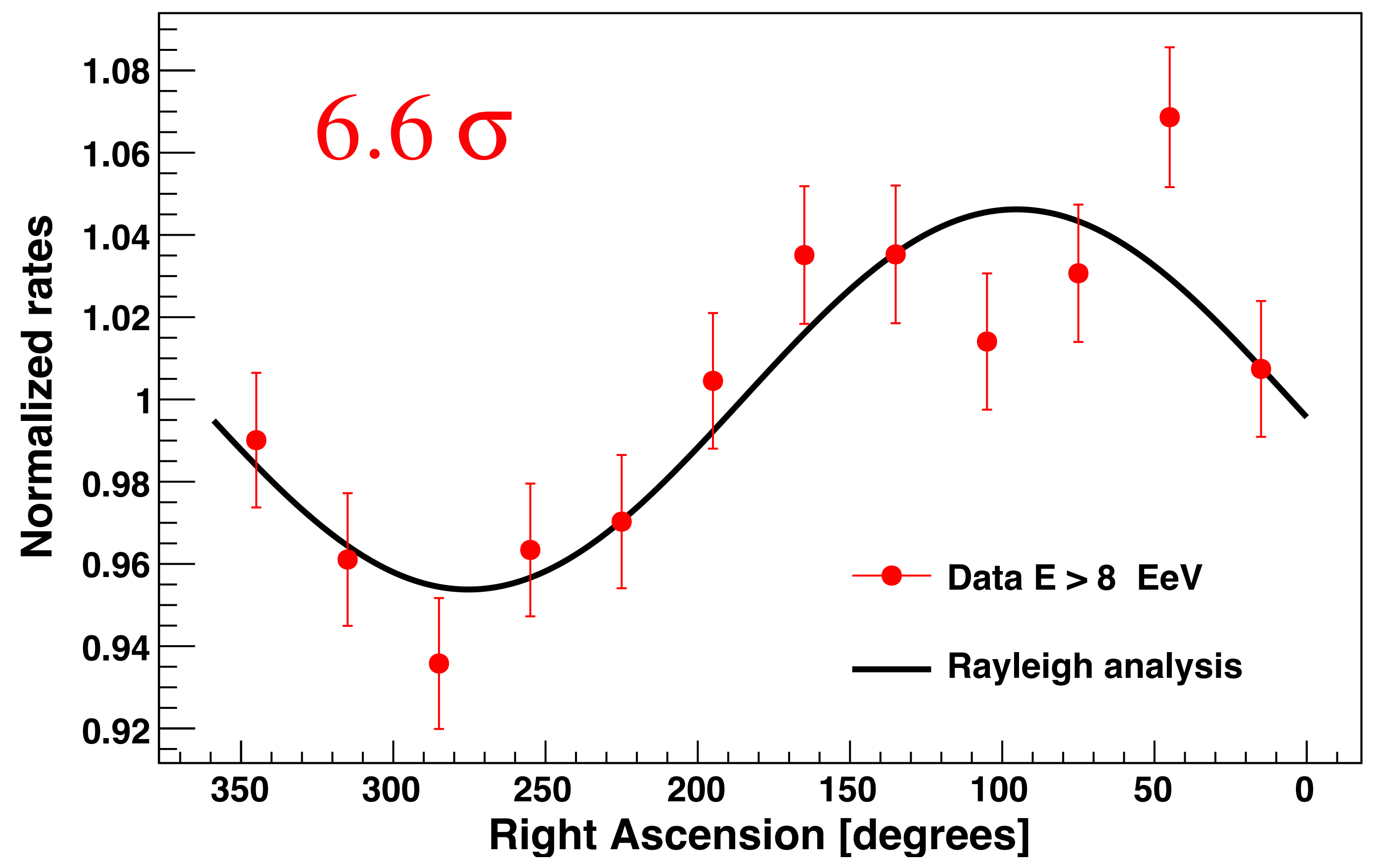
Assumption: relative fluctuations not changed

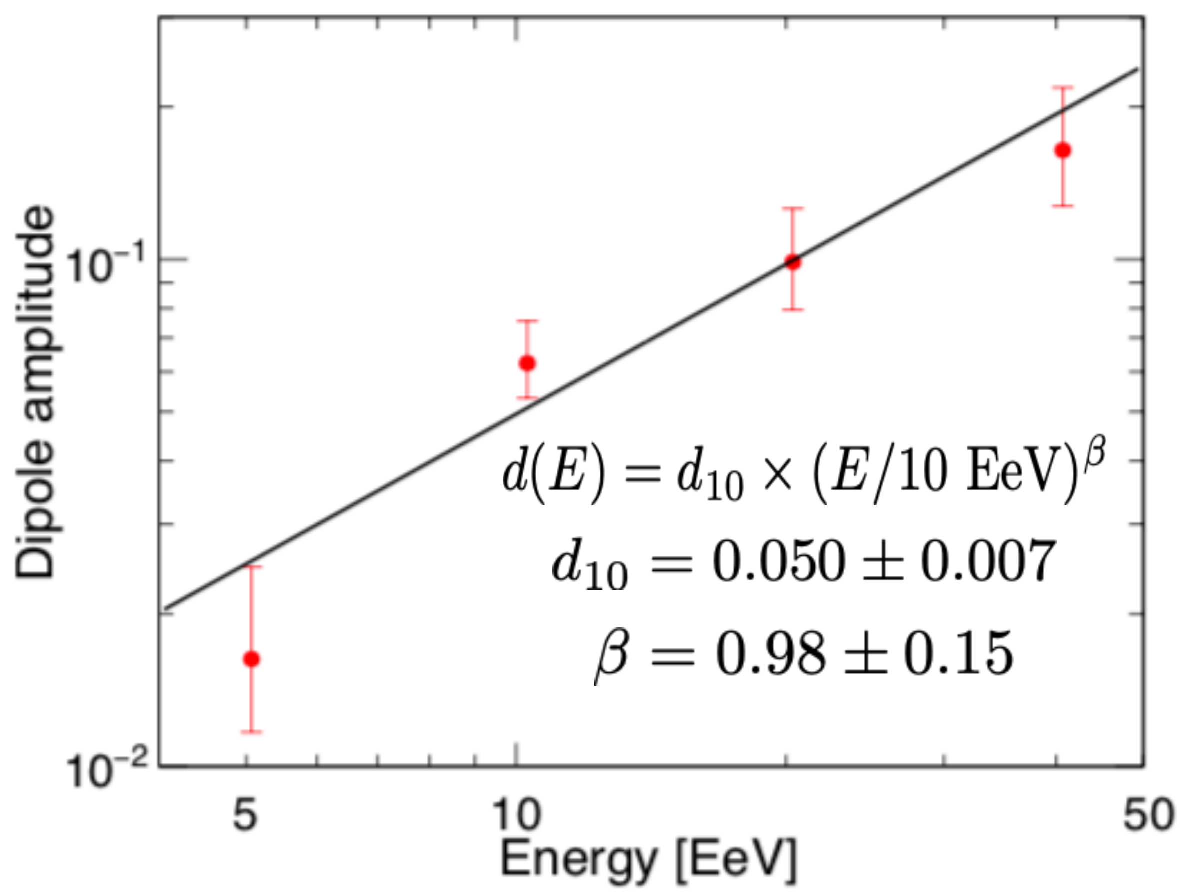
Main improvement by re-scaling muon component by angle-dependent factors (attenuation)

Further improvement by shifting Xmax of models to larger depth (heavier composition)

Anisotropy on large angular scales – dipole



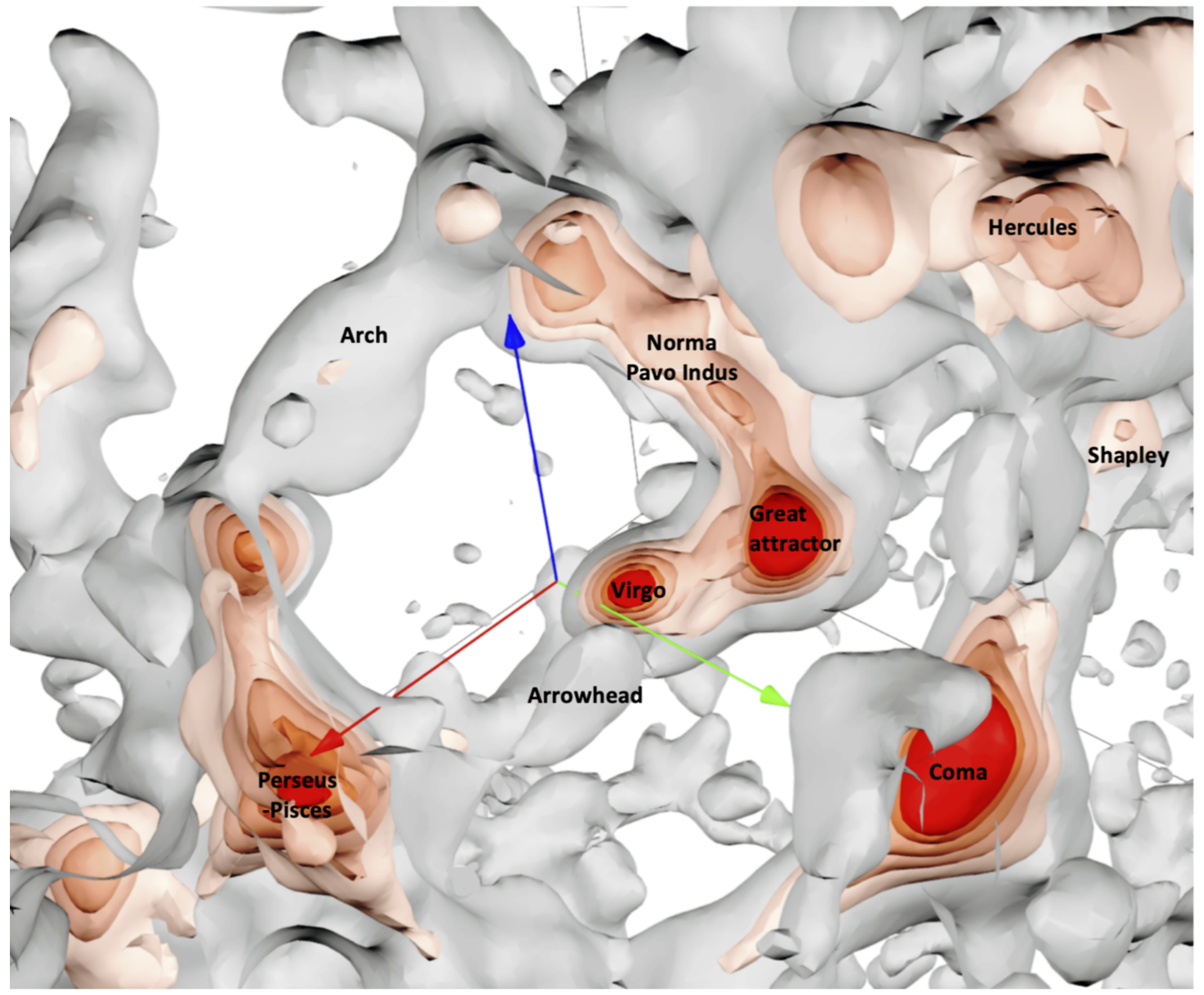




Exposure until end of 2020 (θ < 80°): 110,000 km² sr yr

$p \sim 5 \times 10^{-11}$

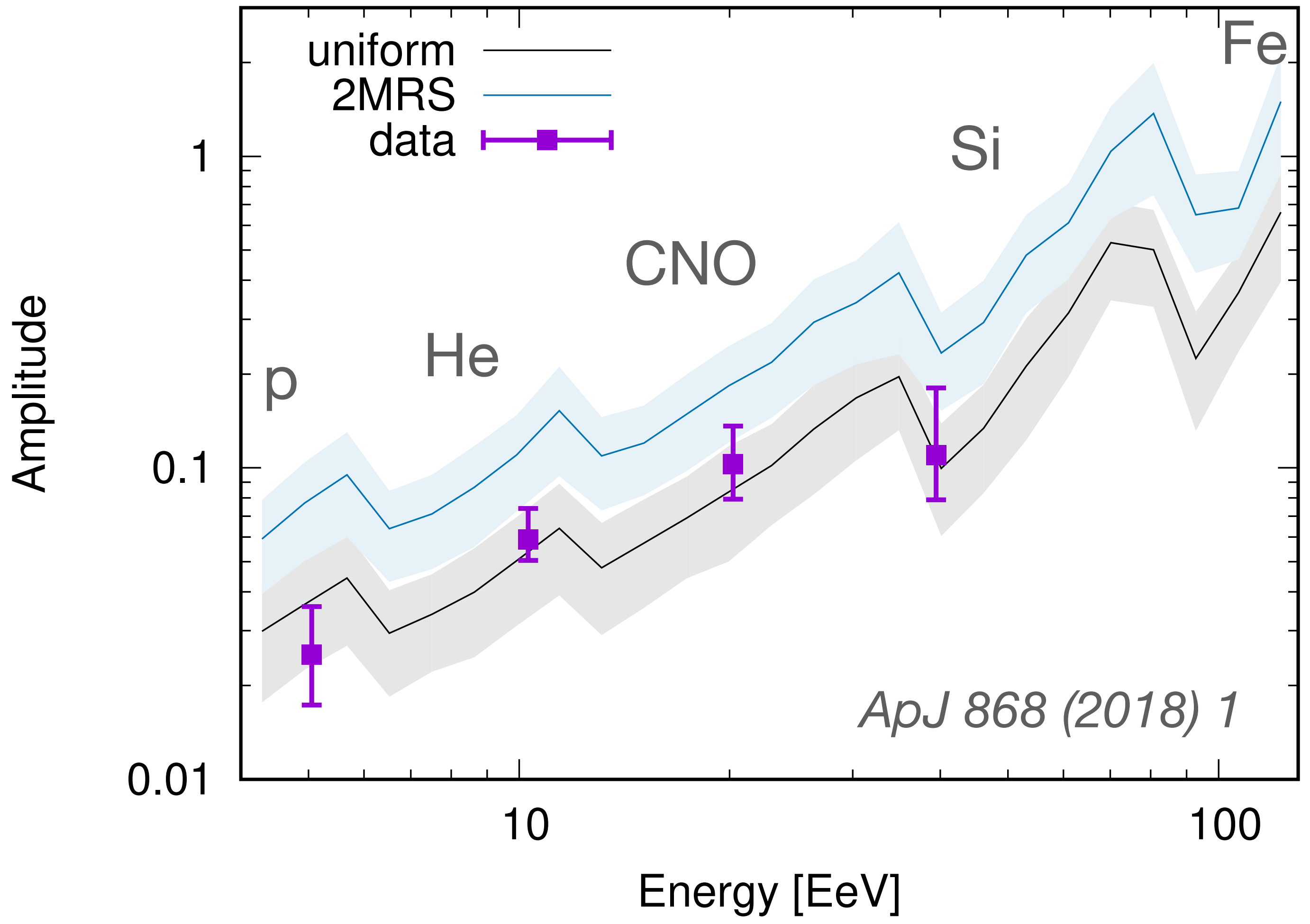
(Rogerio Menezes)



(Ding, Globus & Farrar 2101.04564)

Fundamental observation:
non-trivial interplay of

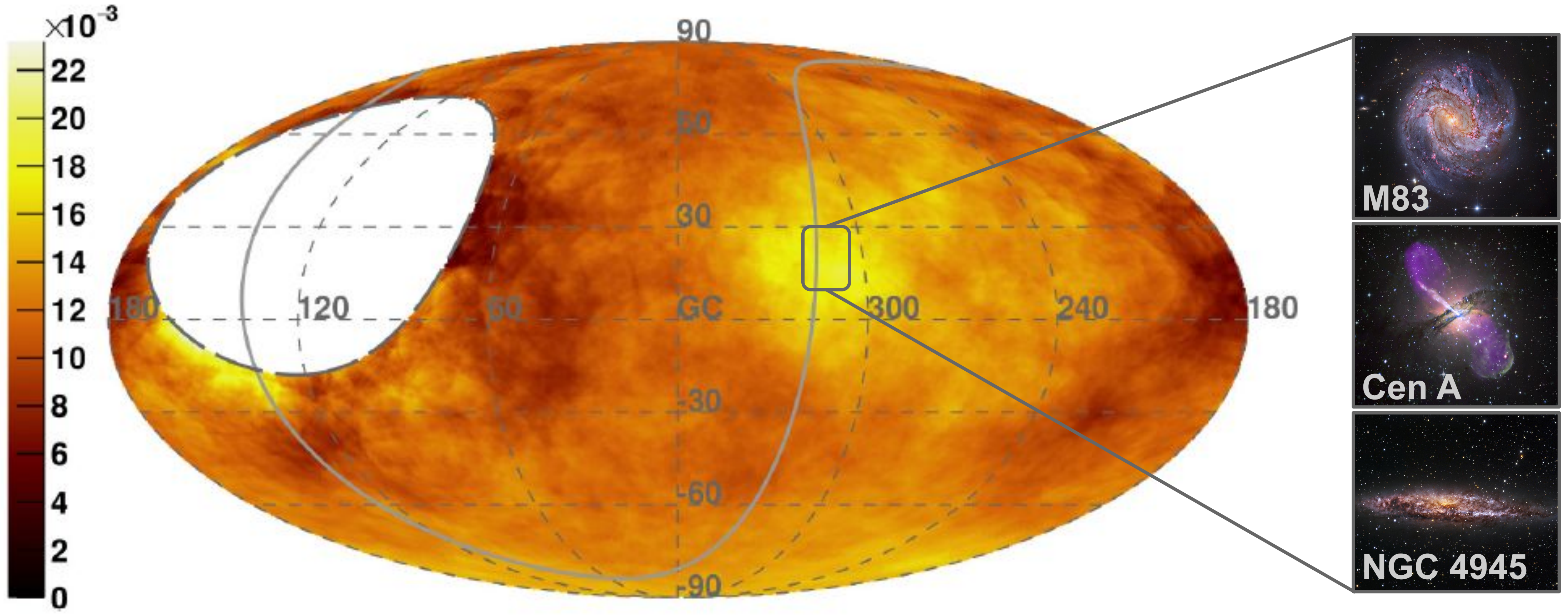
- **mass composition,**
- **magnetic horizon and**
- **local source distribution**



(Harari, Mollerach, Roulet PRD92 (2015) 06314)

Anisotropy searches at highest energies – catalogs

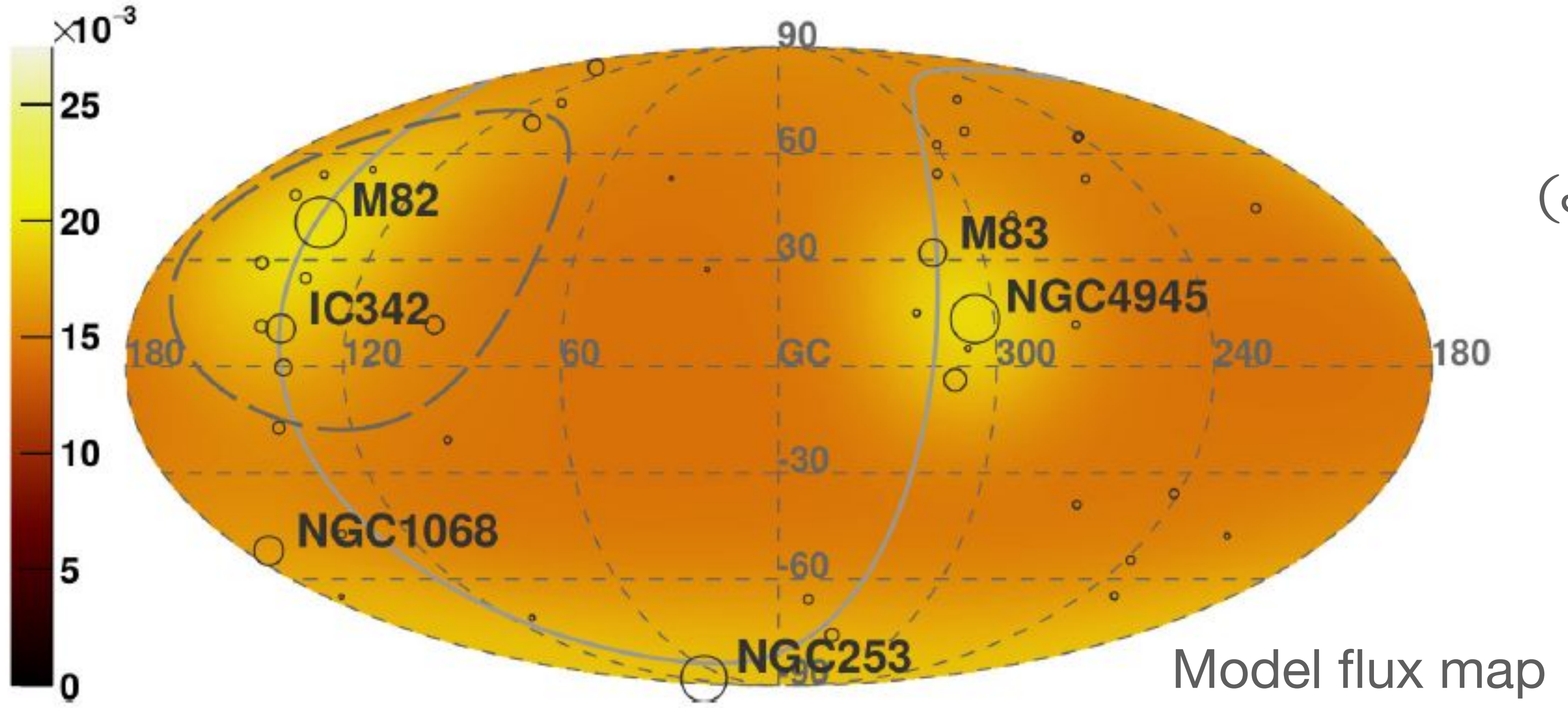
$\Phi(E_{Auger} > 41\ \mathrm{EeV})$ [km^{-2} sr^{-1} yr^{-1}] - Galactic coordinates - $\Psi = 24°$



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)

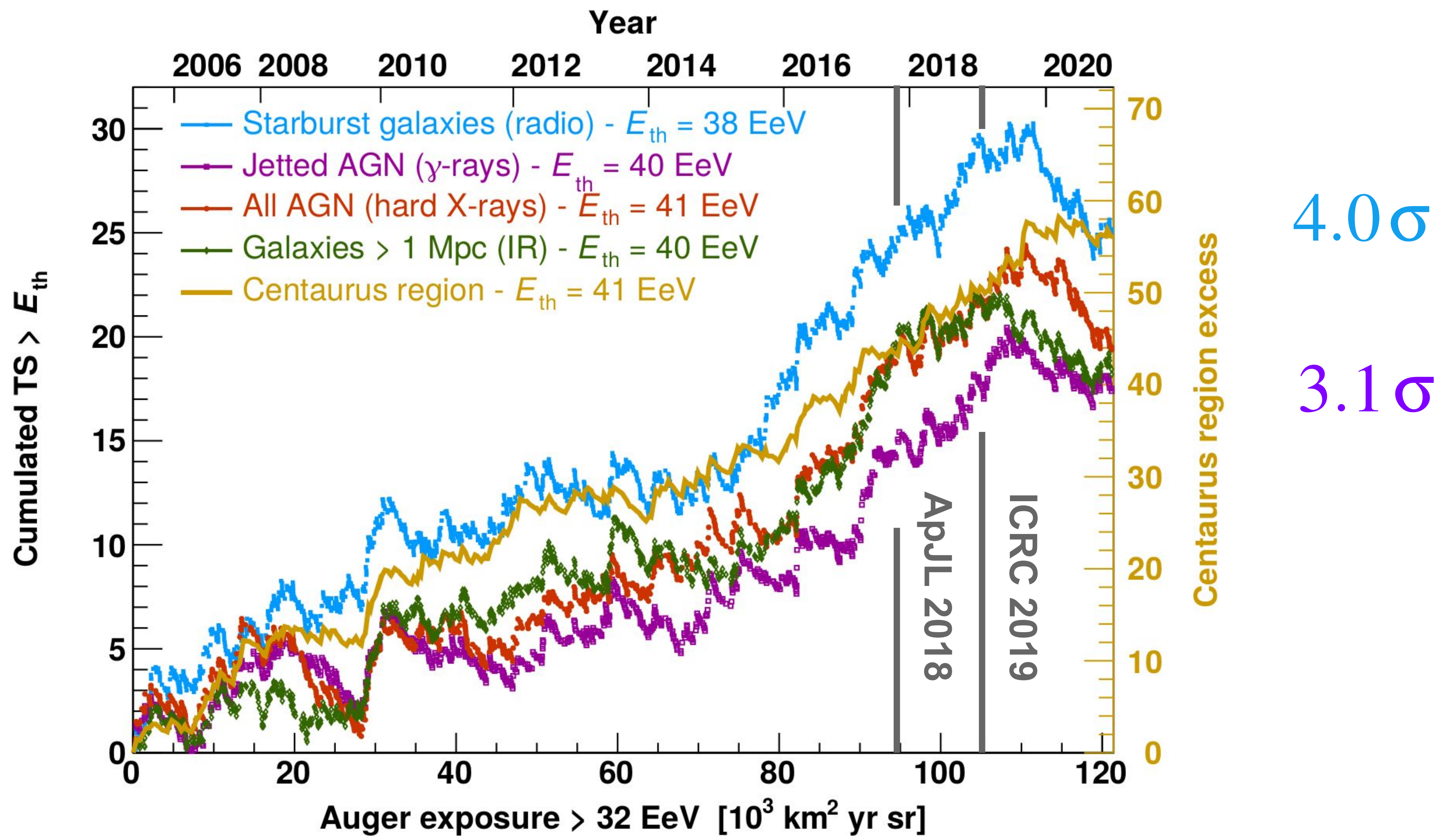
Starburst galaxies (radio) - expected $\Phi(E_{Auger} > 38\ \mathrm{EeV})$ [km^{-2} sr^{-1} yr^{-1}]



(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}



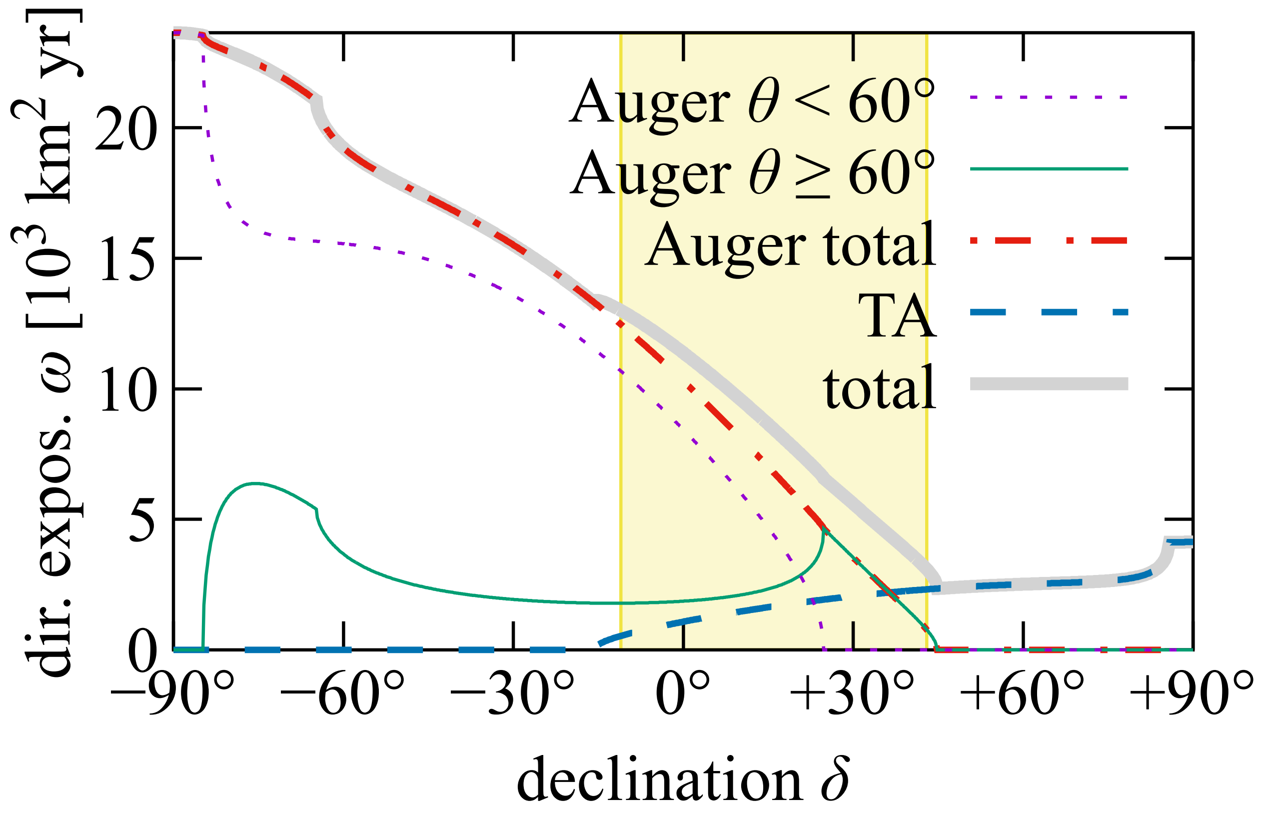
Growth of test statistic (TS) compatible with linear increase

Discovery threshold of 5σ expected in 2025 – 2030 (Phase II)

Other means to increase sensitivity (Auger 85% sky coverage)

Joint Auger-TA anisotropy working group

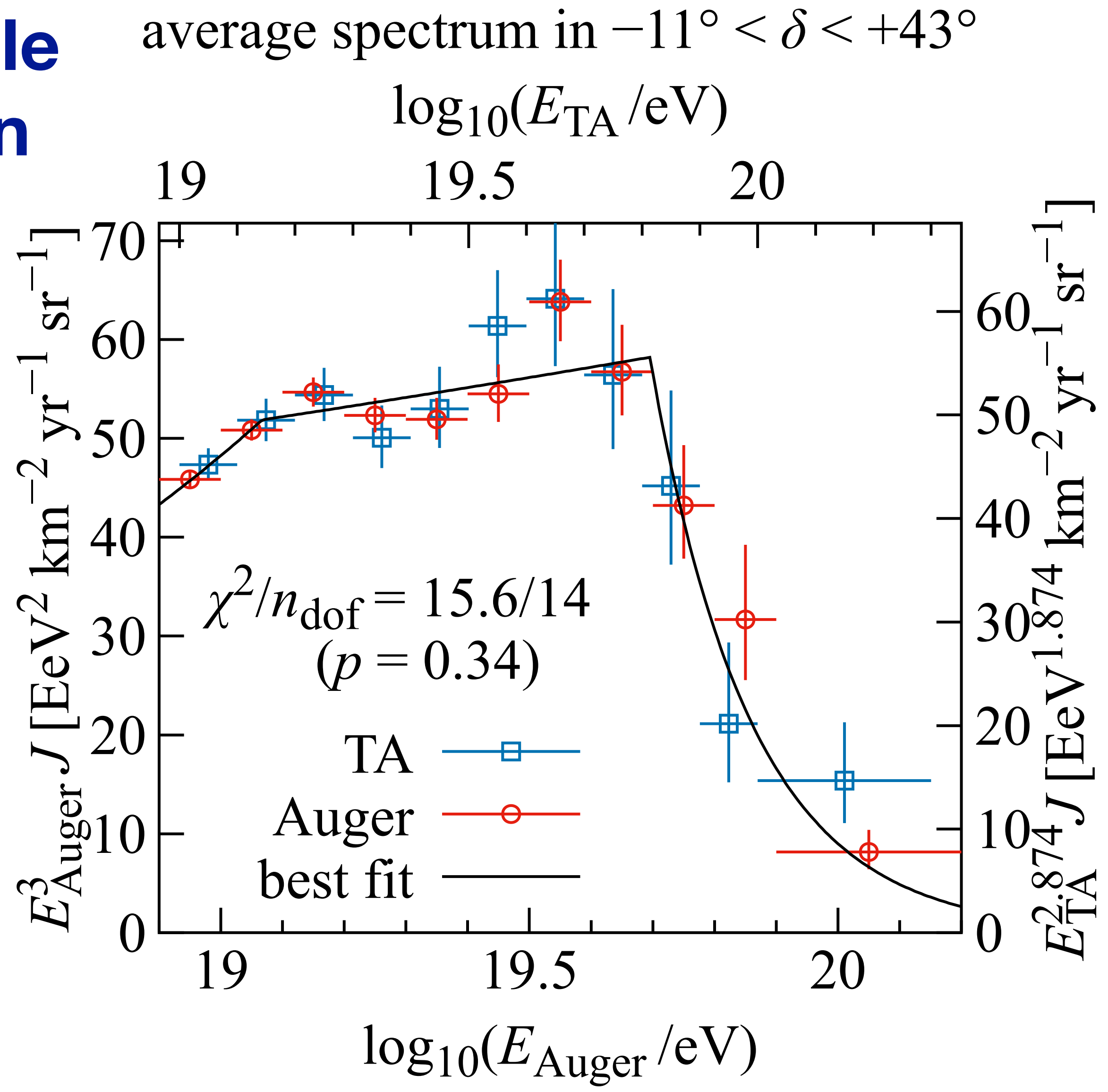
Sky coverage



Auger (θ < 80°): 120,000 km² sr yr

TA (θ < 55°): 14,000 km² sr yr

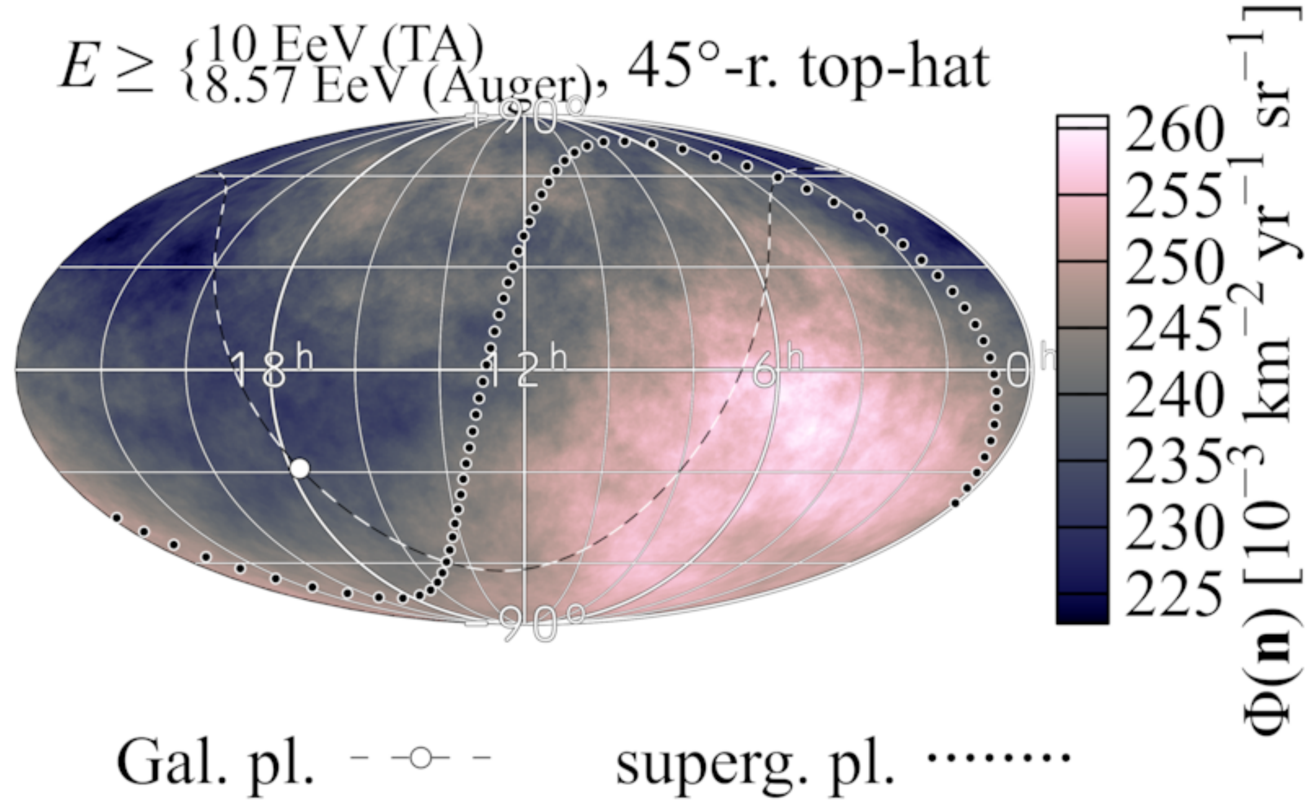
Energy scale conversion



$$\frac{E_{Auger}}{10\ \text{EeV}} = 0.857 \left(\frac{E_{TA}}{10\ \text{EeV}}\right)^{0.937}$$

$$\frac{E_{TA}}{10\ \text{EeV}} = 1.179 \left(\frac{E_{Auger}}{10\ \text{EeV}}\right)^{1.067}$$

Large angular scales

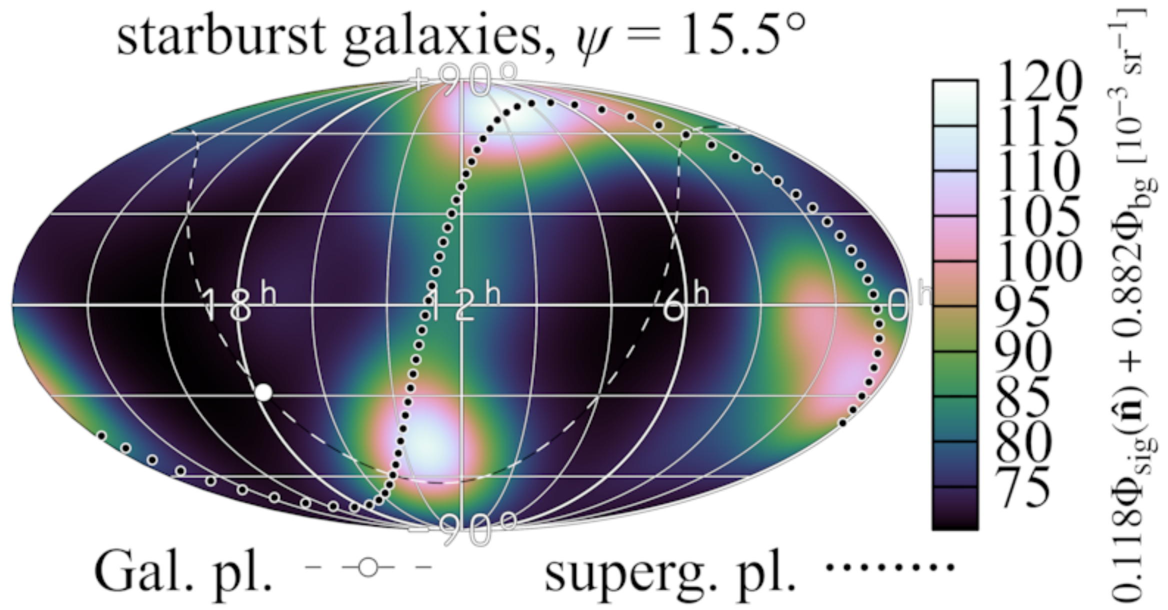


(Peter Tinyakov)

Dipole direction better constrained, compatible with Auger-only result

Catalog correlation searches

(Armando di Matteo)



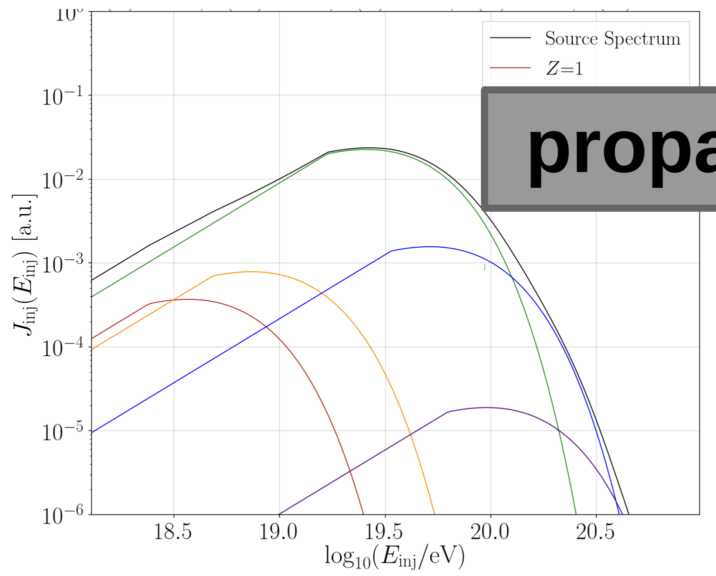
catalog	E_{min} (Auger)	E_{min} (TA)	ψ	equiv. top-hat radius	f	TS
all galaxies	41 EeV	53 EeV	$24°^{+13°}_{-8°}$	$38°^{+21°}_{-13°}$	$38\%^{+28\%}_{-14\%}$	16.2
starburst galaxies	38 EeV	49 EeV	$15.5°^{+5.3°}_{-3.2°}$	$24.6°^{+8.4°}_{-5.1°}$	$11.8\%^{+5.0\%}_{-3.1\%}$	27.2

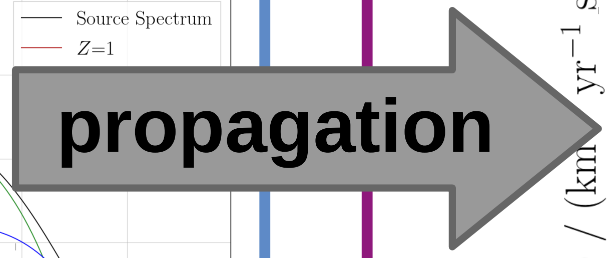
4.2σ for the starburst galaxy catalog $\quad$ 2.9σ for the all-galaxy catalog

Outlook: How to gain sensitivity to distinguish source scenarios

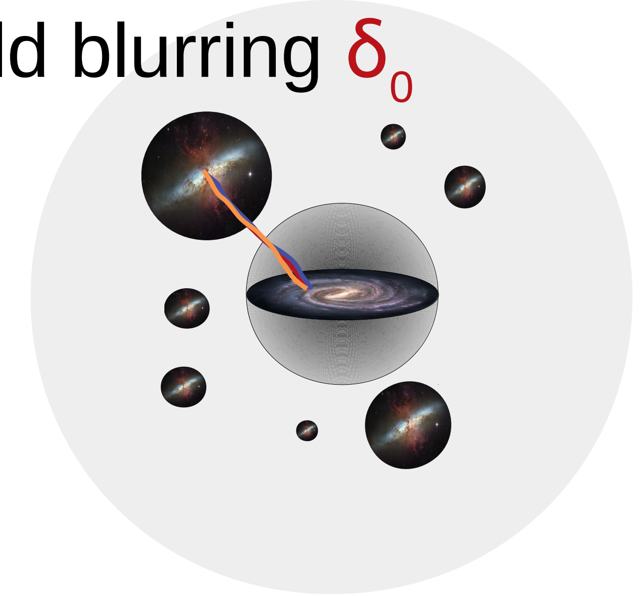
Universe model setup:

injected spectrum:
γ, R_{cut}, a_i

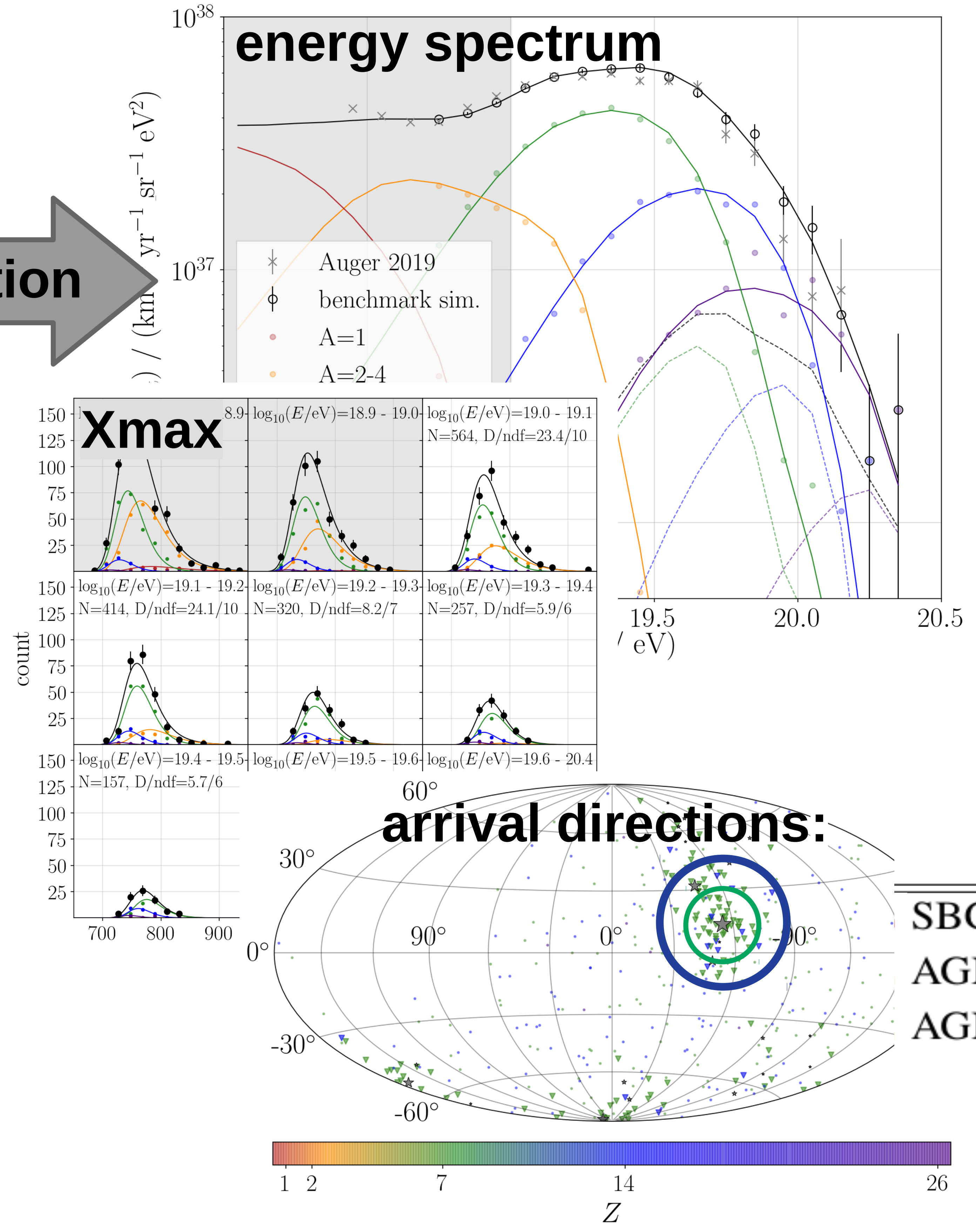




3d setup:
signal fraction f_0,
magnetic field blurring δ_0



Simulated observables:



Fit of model parameters to

- energy spectrum,
- Xmax distribution
- arrival direction distribution

Flux and Xmax data:
fluxes of different mass groups at Earth

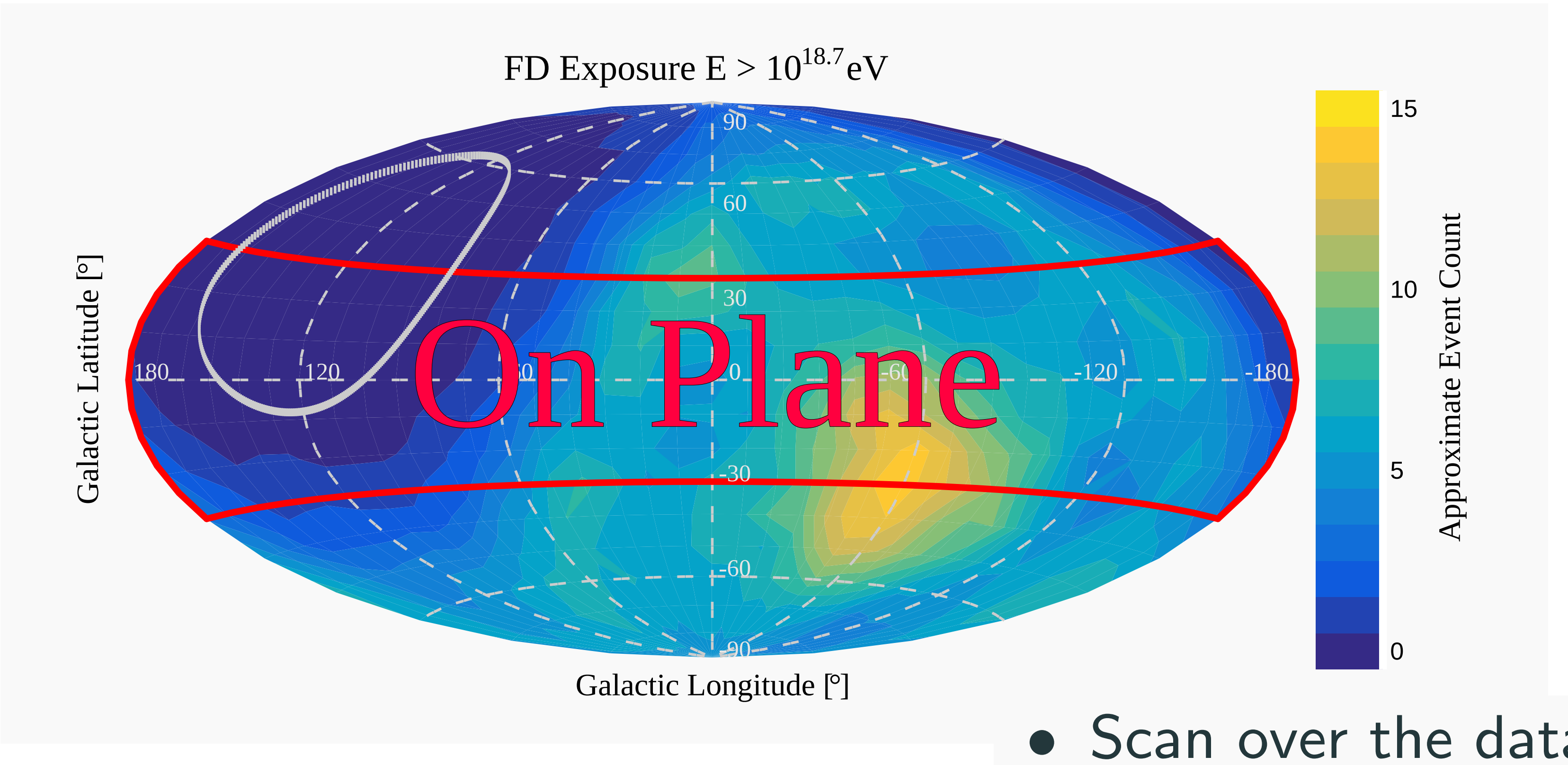
Arrival direction distribution:
distance sensitivity (deflection, production of secondaries)

	Deviance			Likelihood	
	D_E	$D_{X_{\max}}$	D_{total}	$2\log\frac{\mathcal{L}_{\text{AD}}}{\mathcal{L}_{\text{AD}}^{\text{ref},m=3.4}}$	$2\log\frac{\mathcal{L}_{\text{sum}}}{\mathcal{L}_{\text{sum}}^{\text{ref},m=3.4}}$
SBG model ($m = 3.4$) $\rightarrow$ *sim. truth*	5.5	80.2	85.7	30.6	32.4
AGN model ($m = 3.4$)	6.0	81.8	87.8	11.2	10.8
AGN model ($m = 5.0$)	5.6	84.1	89.9	1.4	−1.0

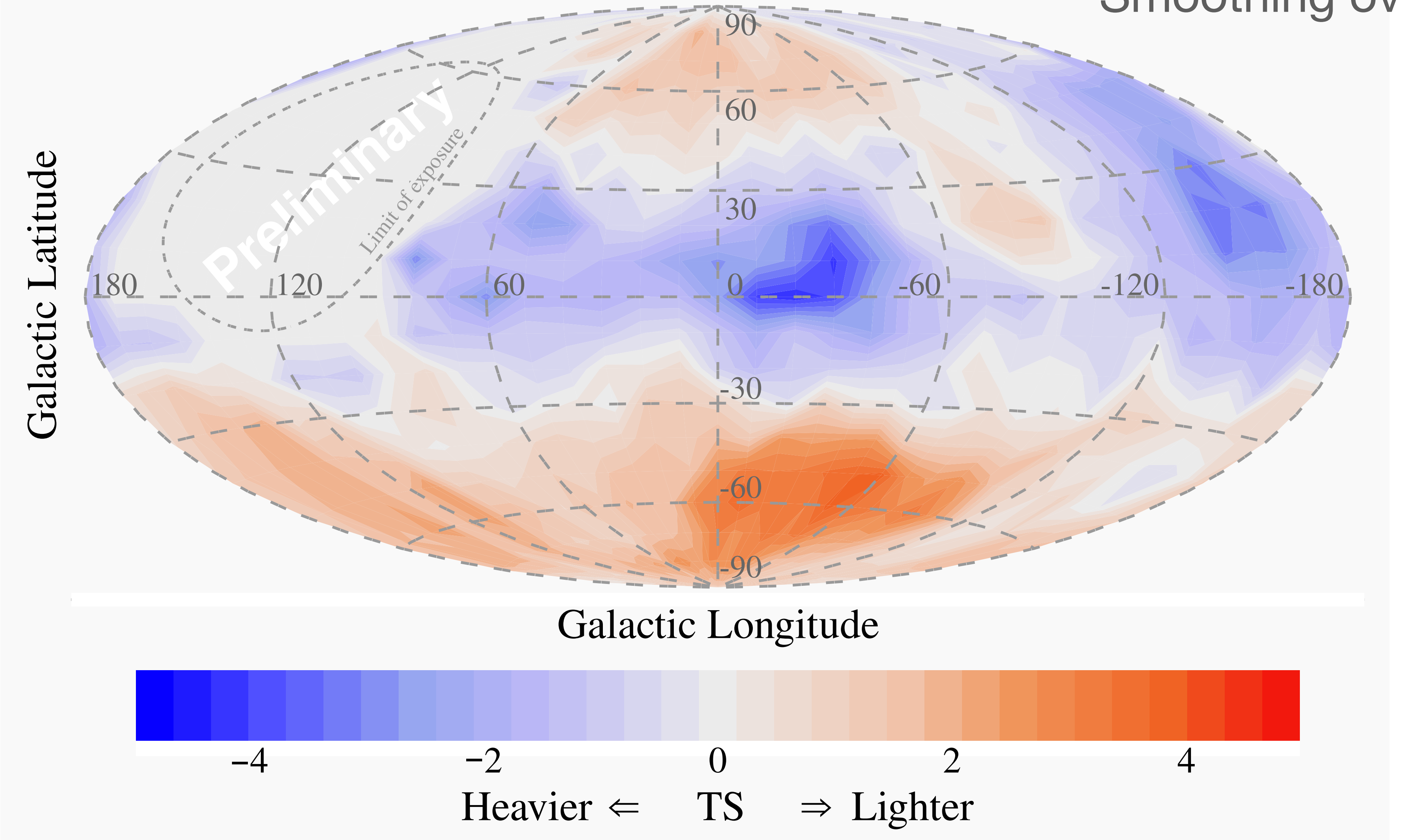
(Teresa Bister)

Monte Carlo study: Scenarios with similar catalog correlations can be clearly distinguished

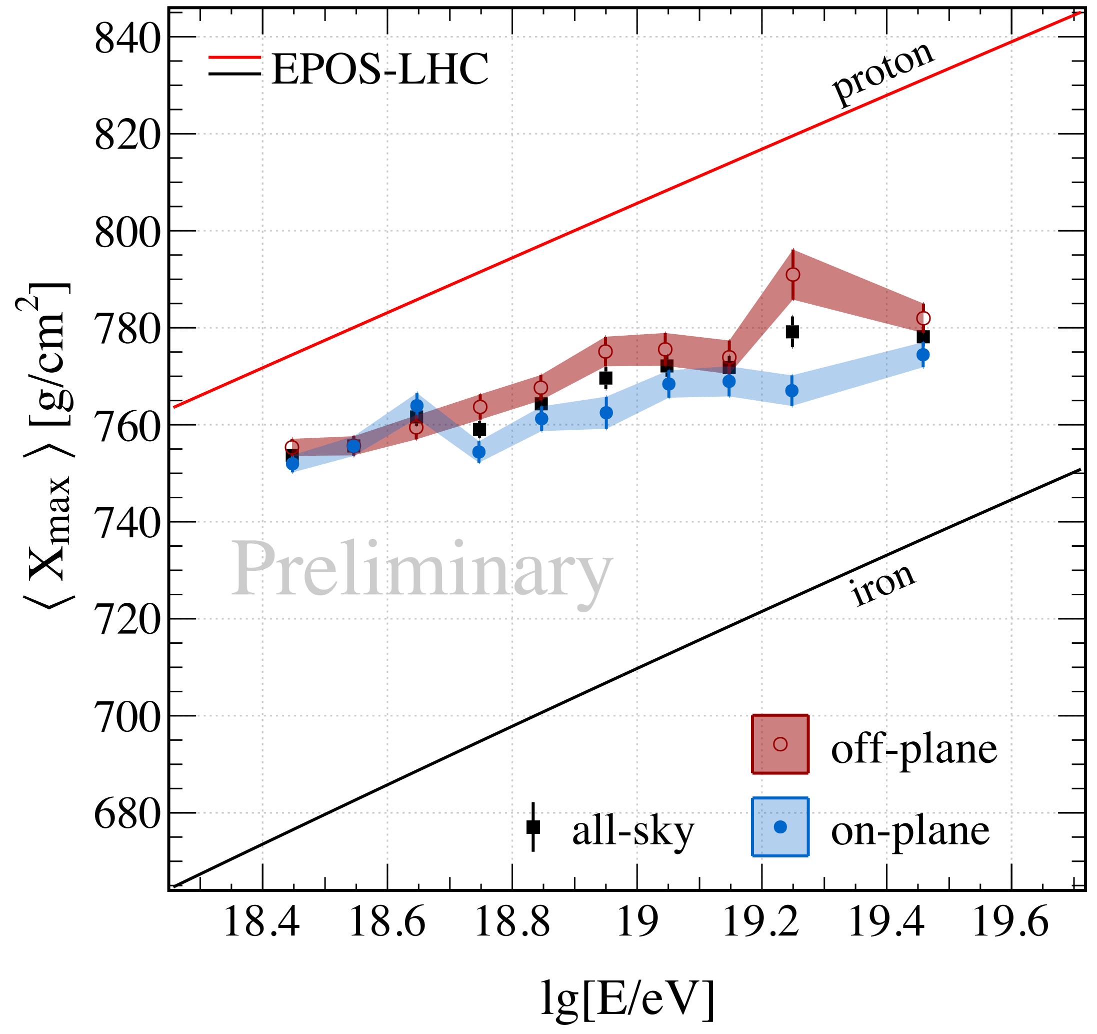
Outlook: Composition-sensitive anisotropy

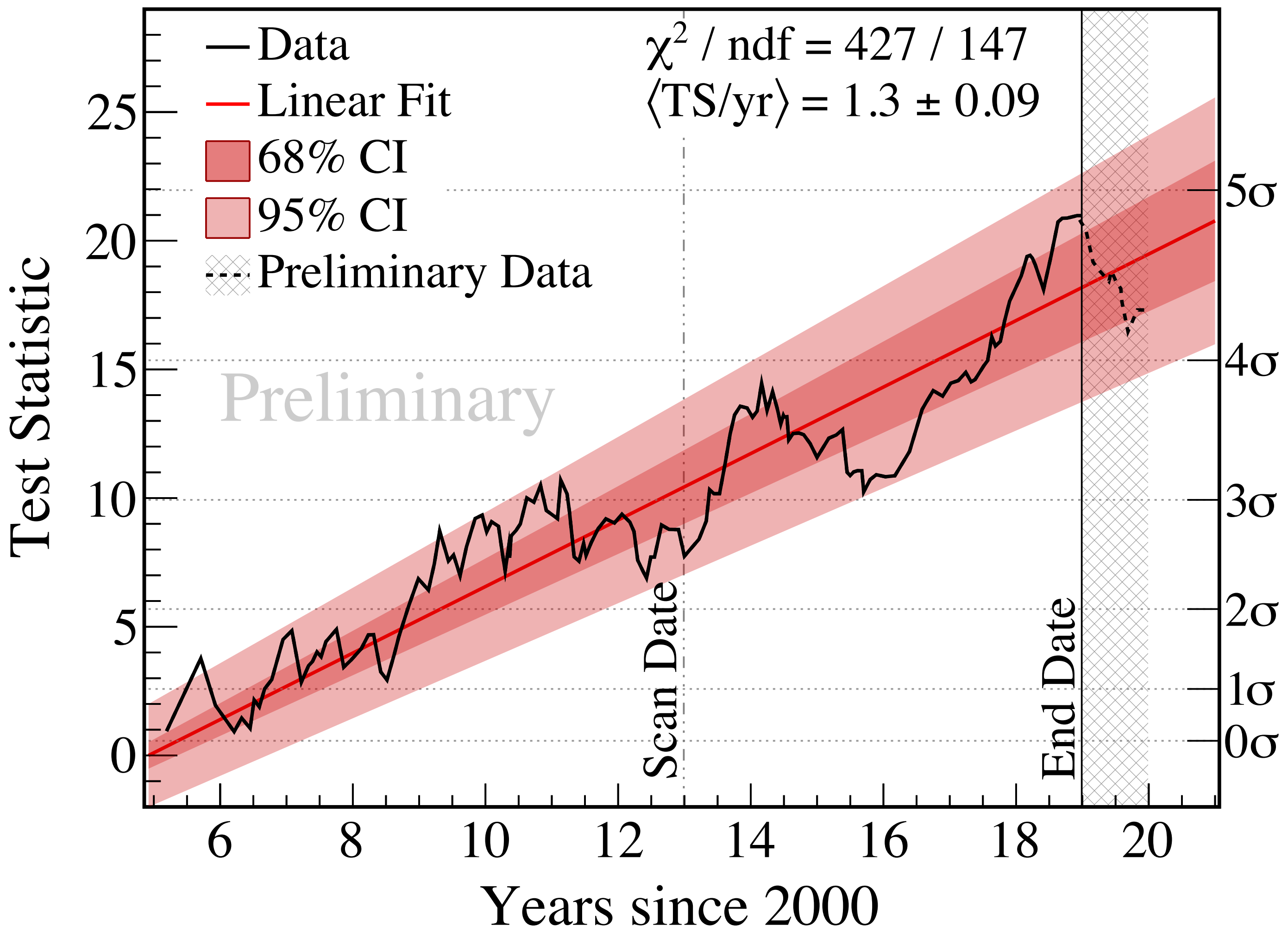


Smoothing over 30° bins



- 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: $\rightarrow E_{\mathrm{min}} = 10^{18.7}$ eV
  $\rightarrow b_{\mathrm{split}} = 30°$





Not necessarily related to Galaxy

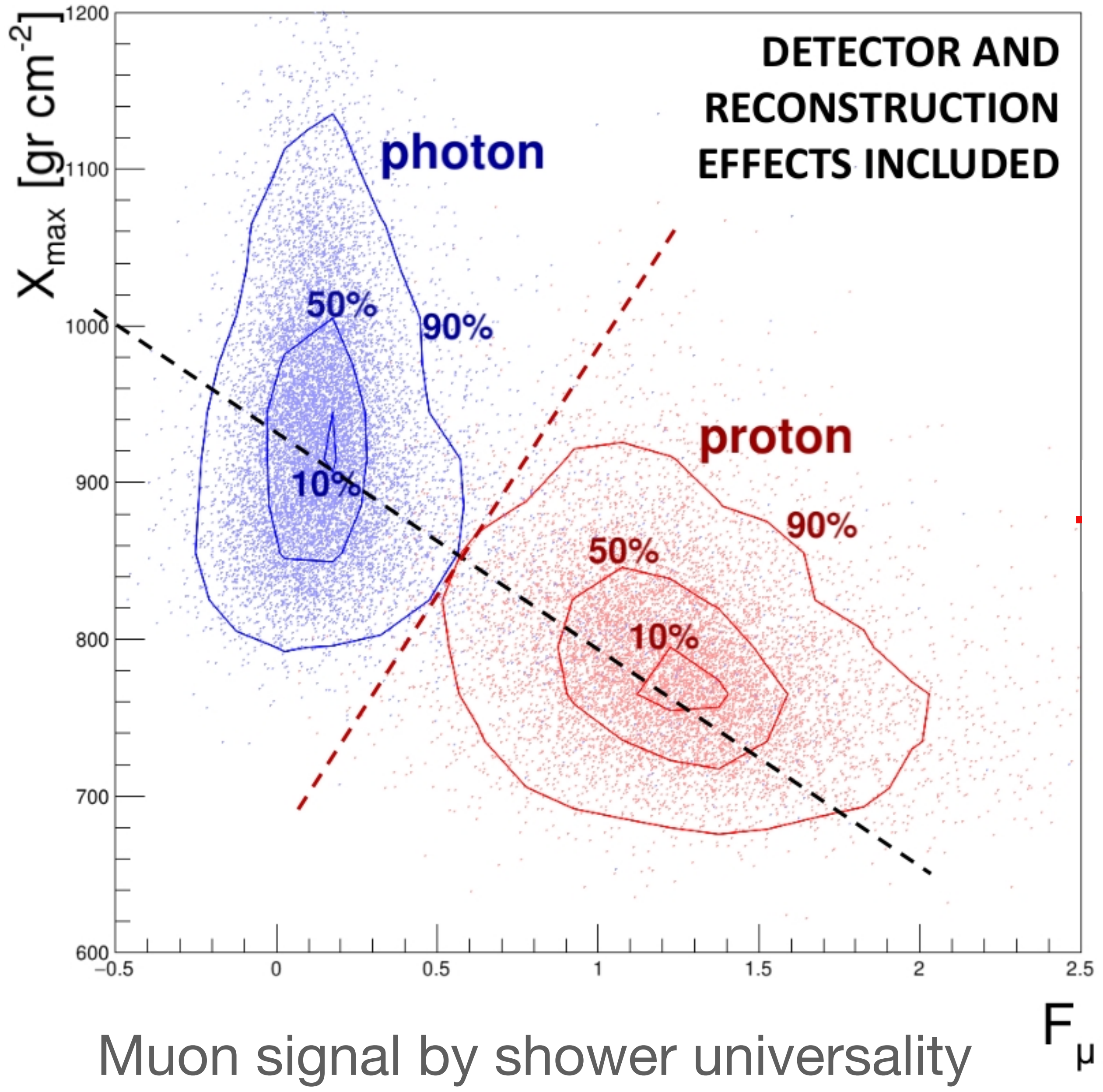
Local source distribution and mass-dependent horizon effect?

No independent confirmation from other data

Phase II data and more statistics really important to make progress

(Eric Mayotte)

Searches: Ultra-high energy photons



Muon signal by shower universality

Cut at 50% photon efficiency (median)

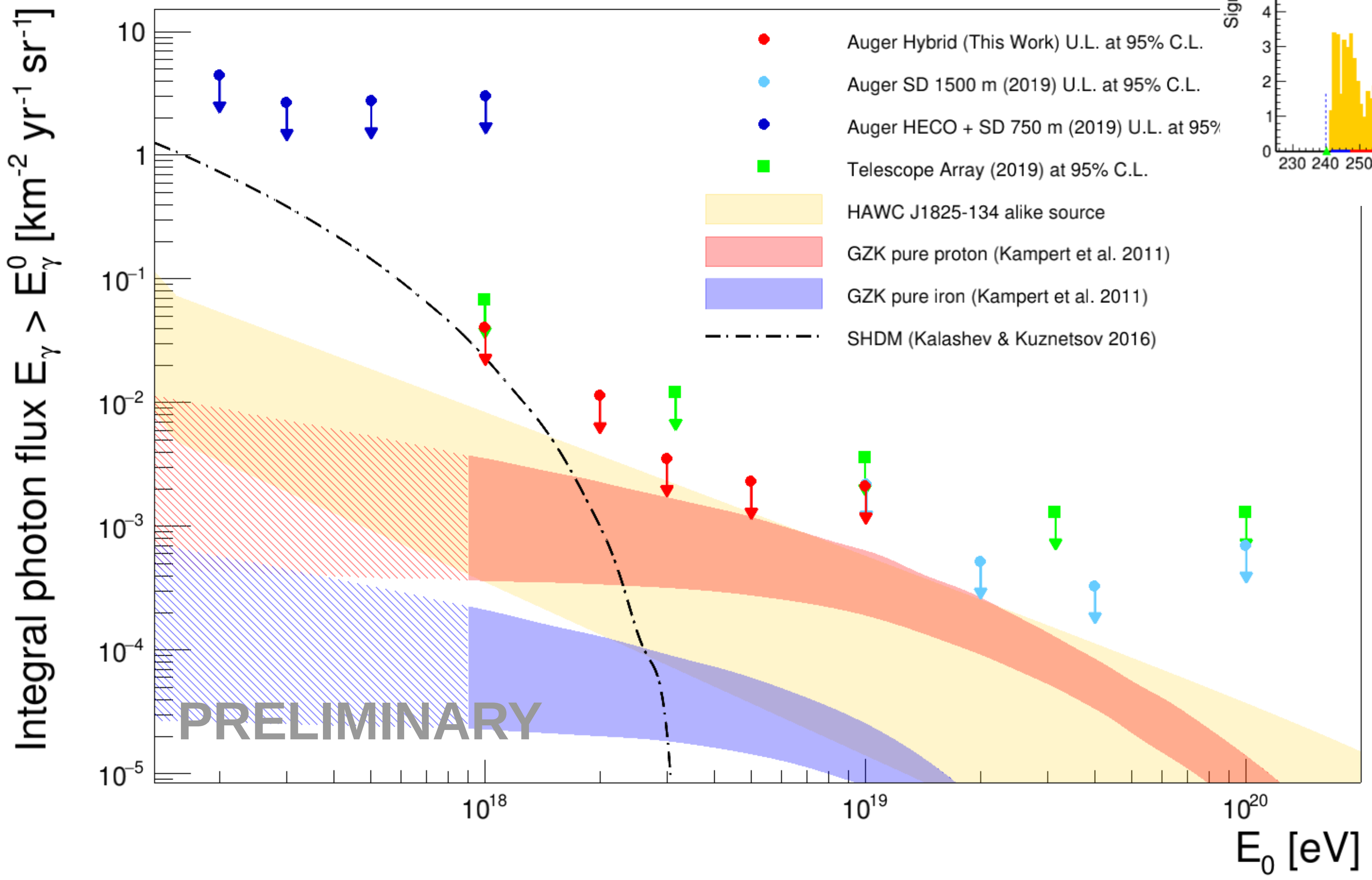
Background compatible with stat. expectation (burn sample of data)

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

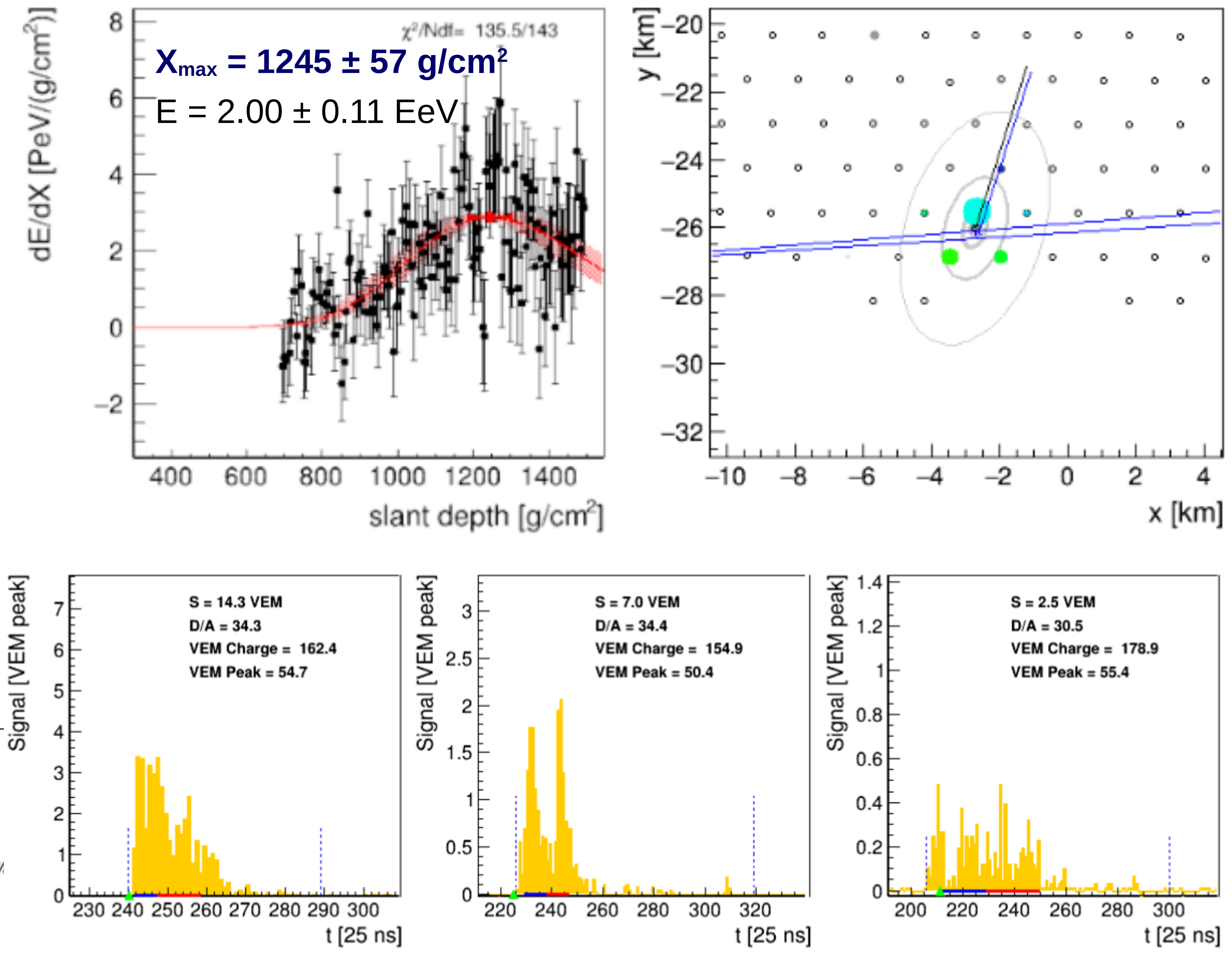
(Philip Ruehl)

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

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



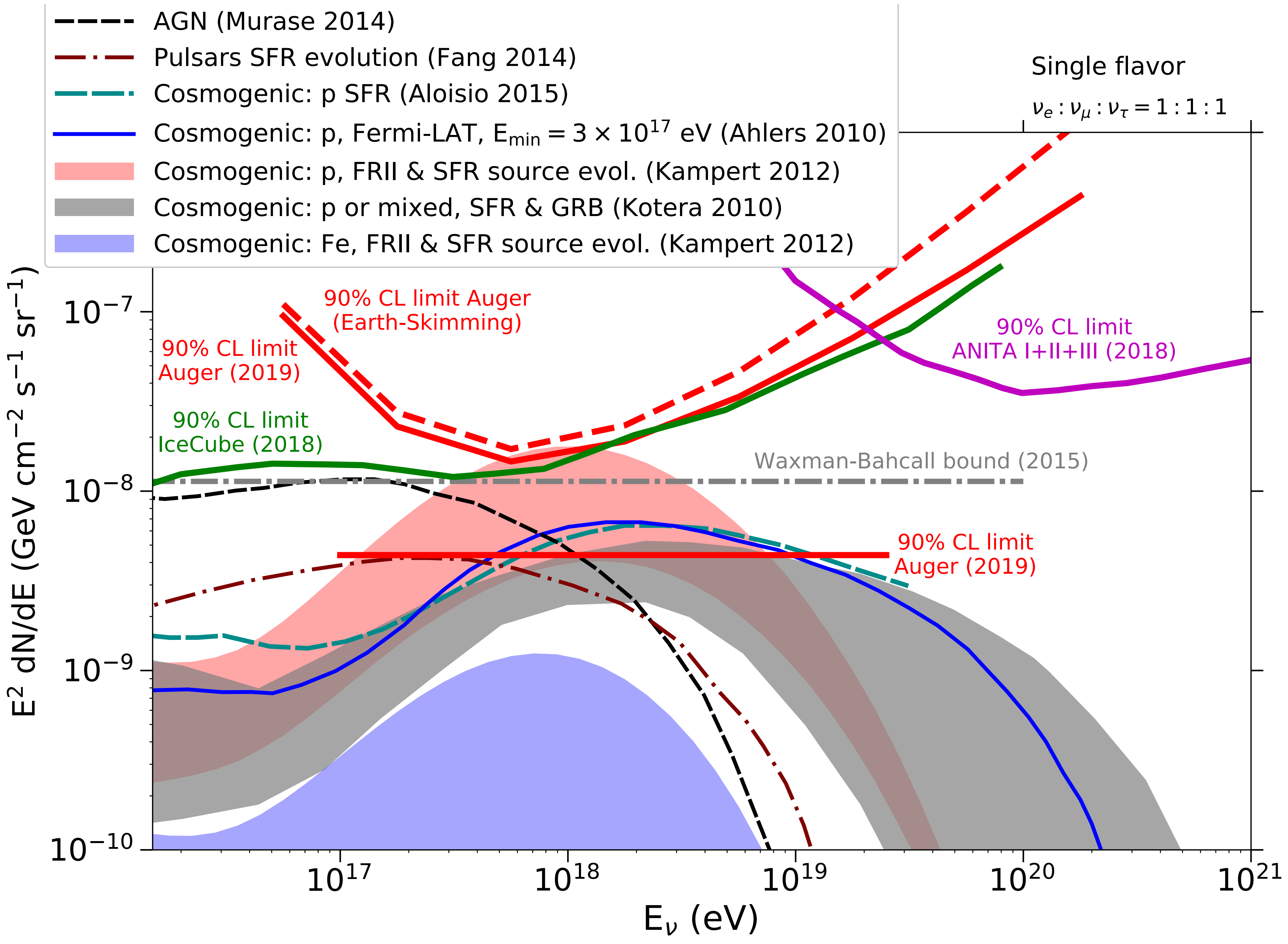
(Pierpaolo Savina)

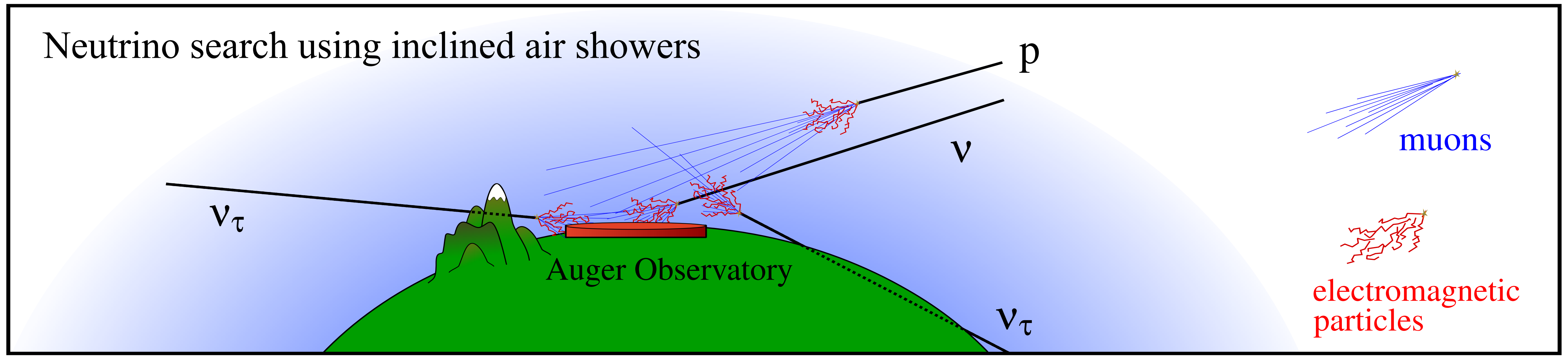


Limits begin being background-dominated

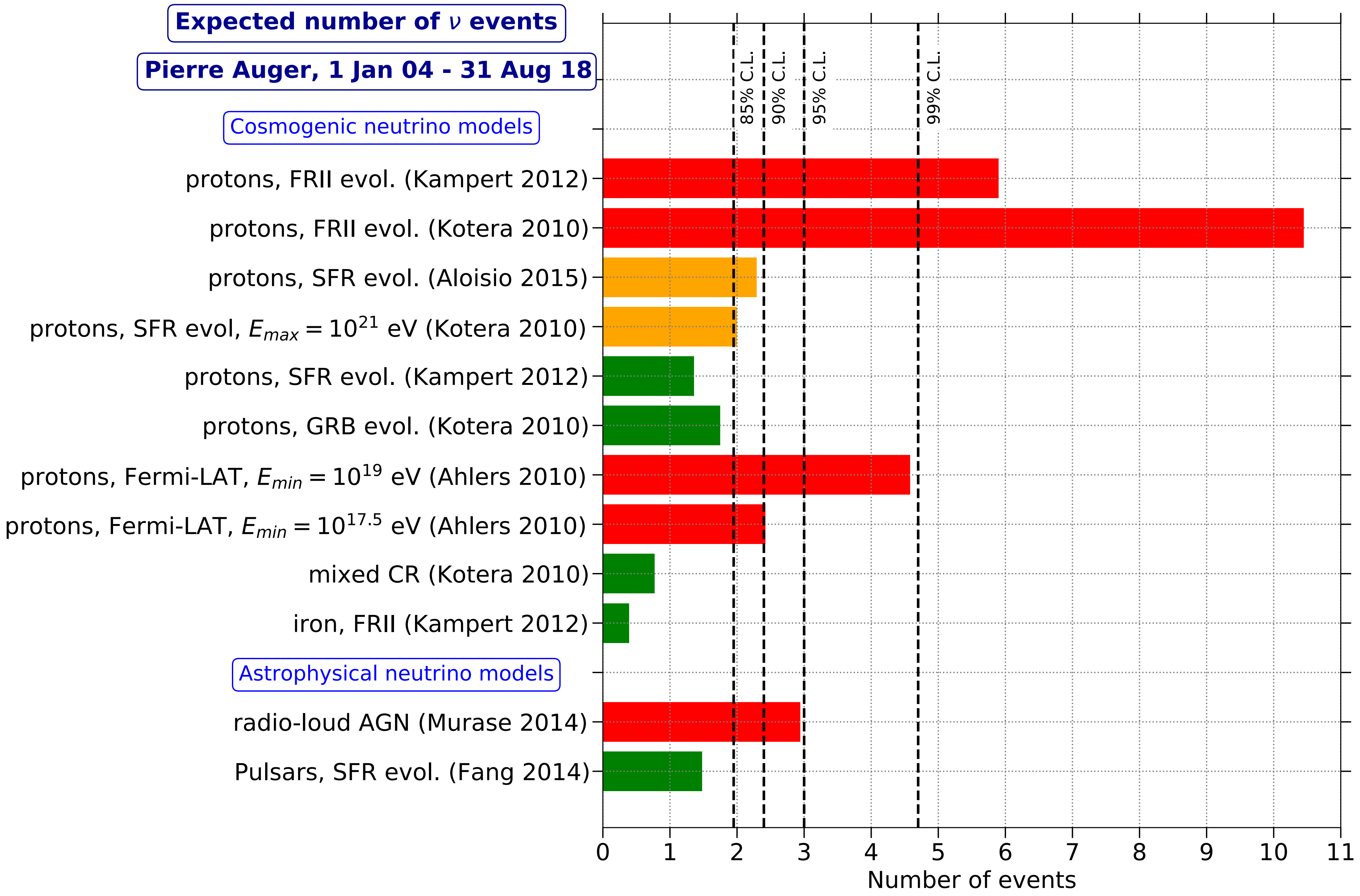
Phase II: additional data for photon/hadron separation or photon discovery

Searches: Ultra-high energy neutrinos





(JCAP 10 (2019) 022,
JCAP 11 (2019) 004)

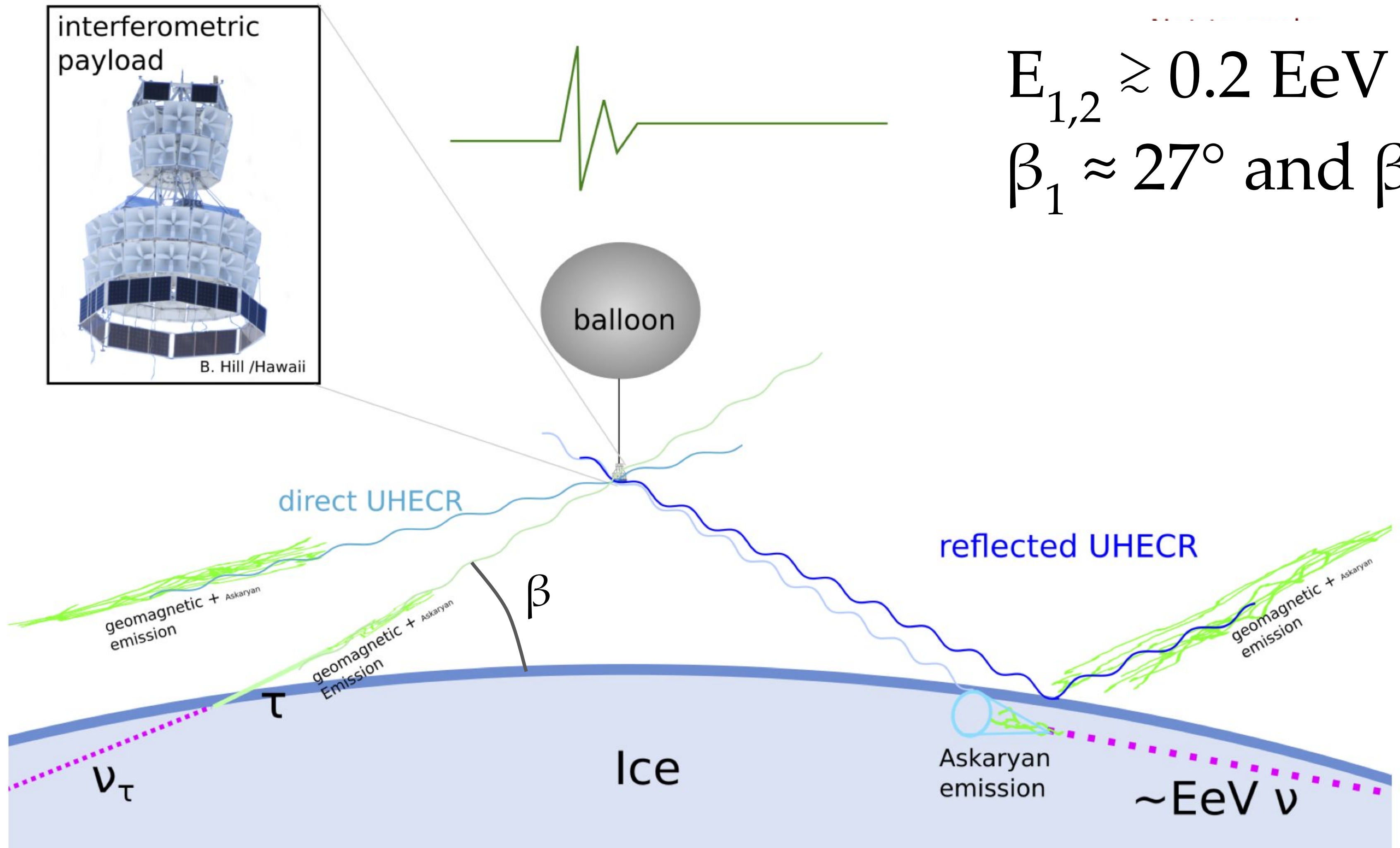


Aperture comparable to IceCube if direction of source is favorable
Multi-messenger: searches for neutrinos in coincidence with GW events
Phase II: lowering of detection threshold (new electronics)

(Michael Schimp)

(UHECR 2018, updated)

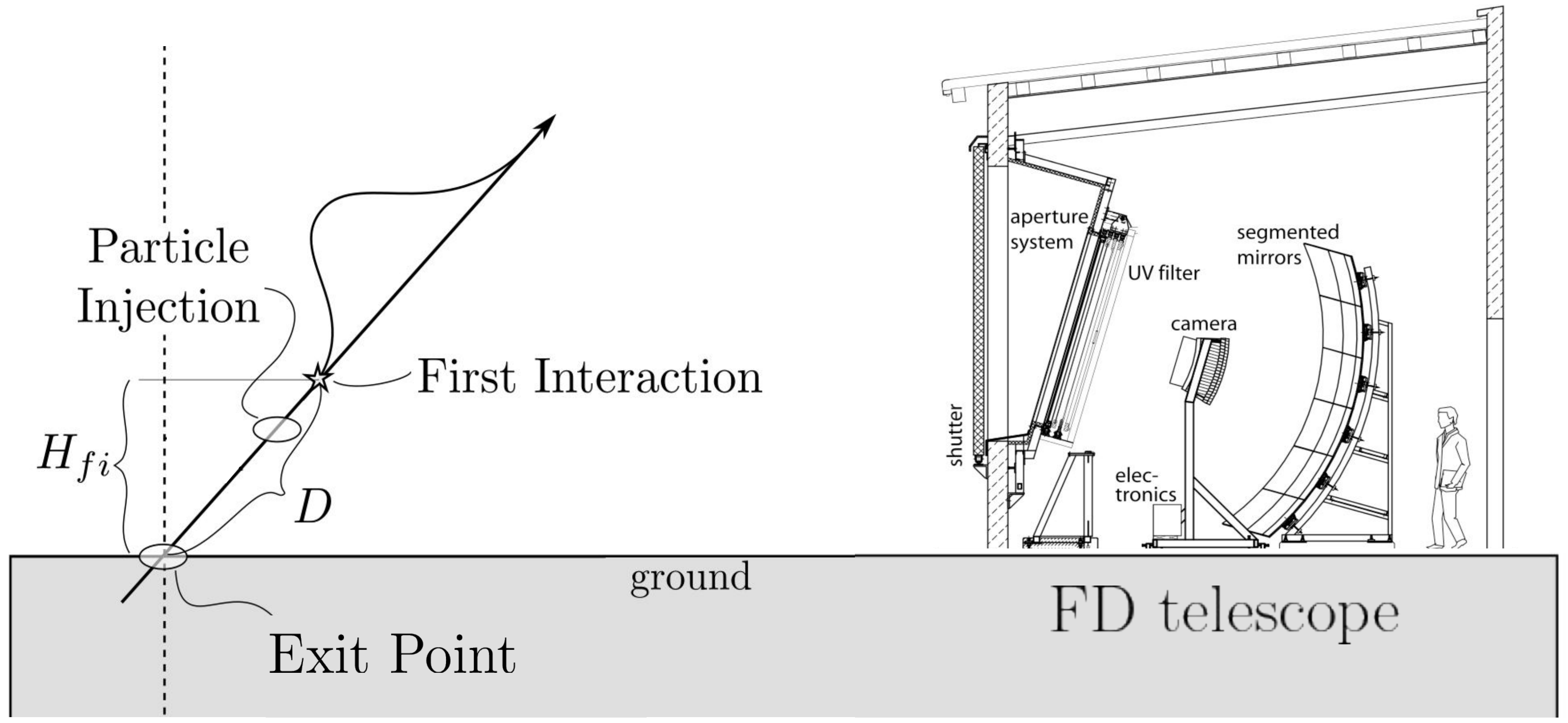
Searches: Upward-going events motivated by ANITA

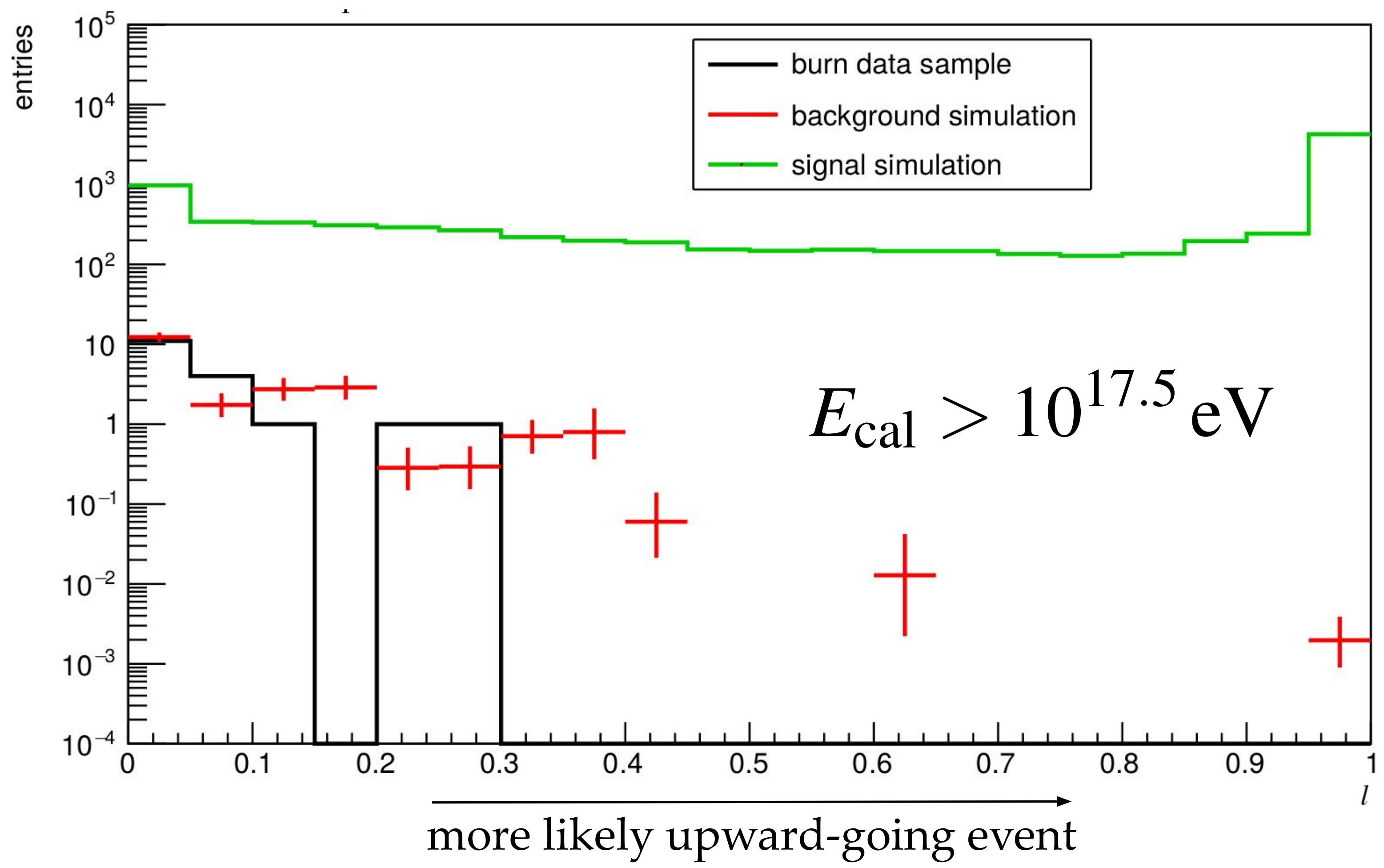


(ANITA, Phys. Rev. Lett. 121 (2018) 161102)

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

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





(Eva Santos)

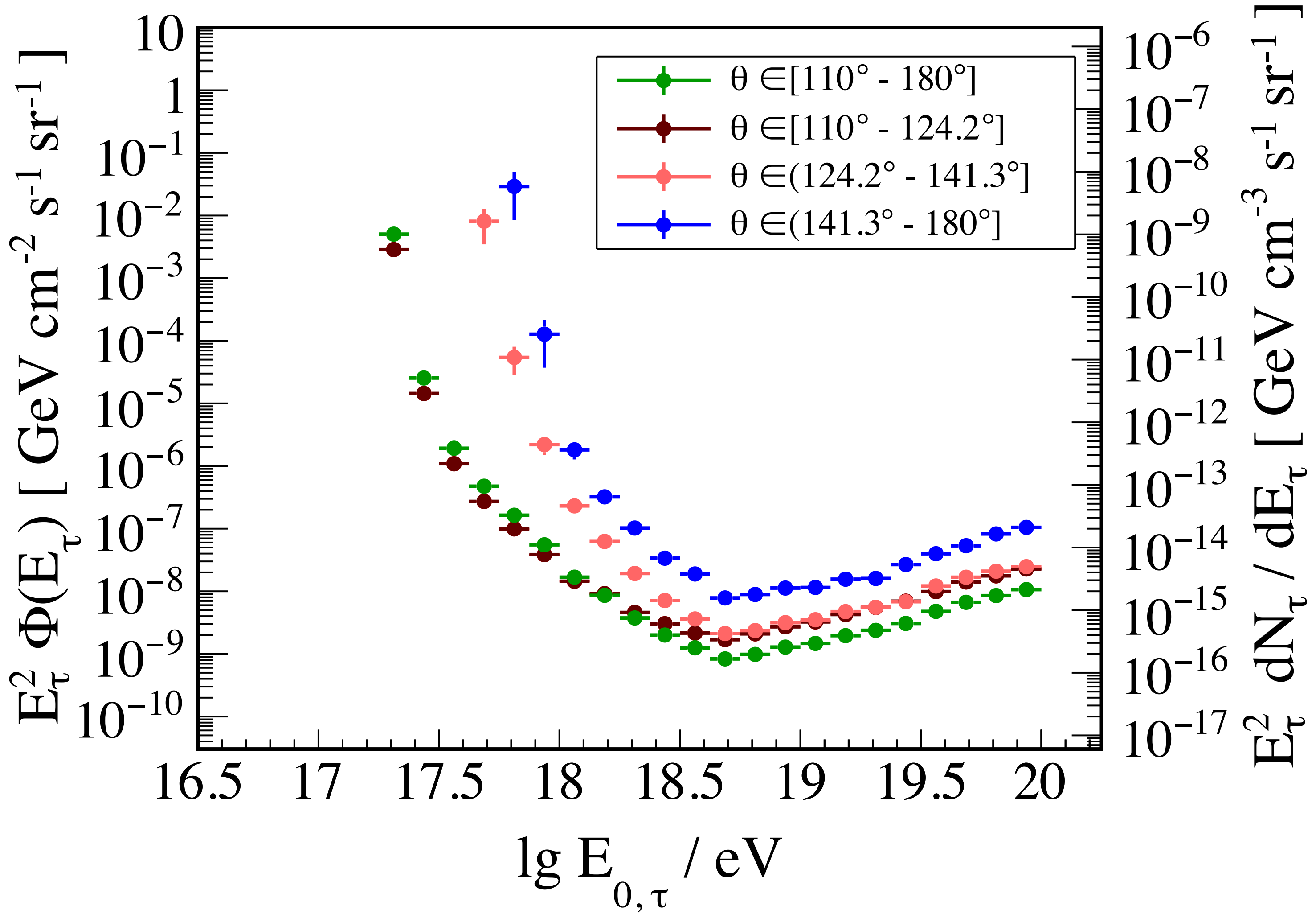
Auger results:

Background 0.45 ± 0.18 expected

One event observed

Flux limits on anomalous events

Tau scenario



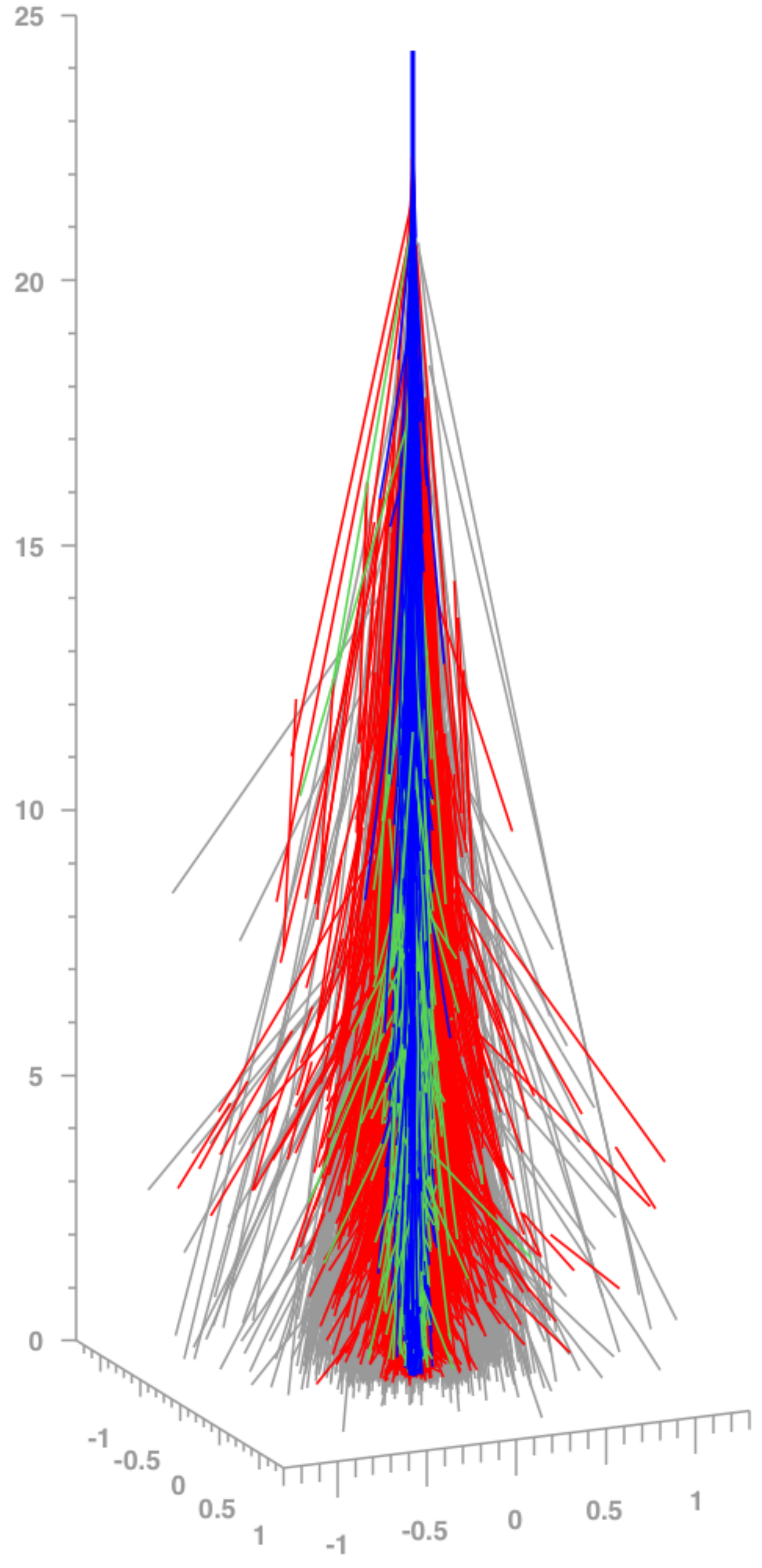
Uniform distribution

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

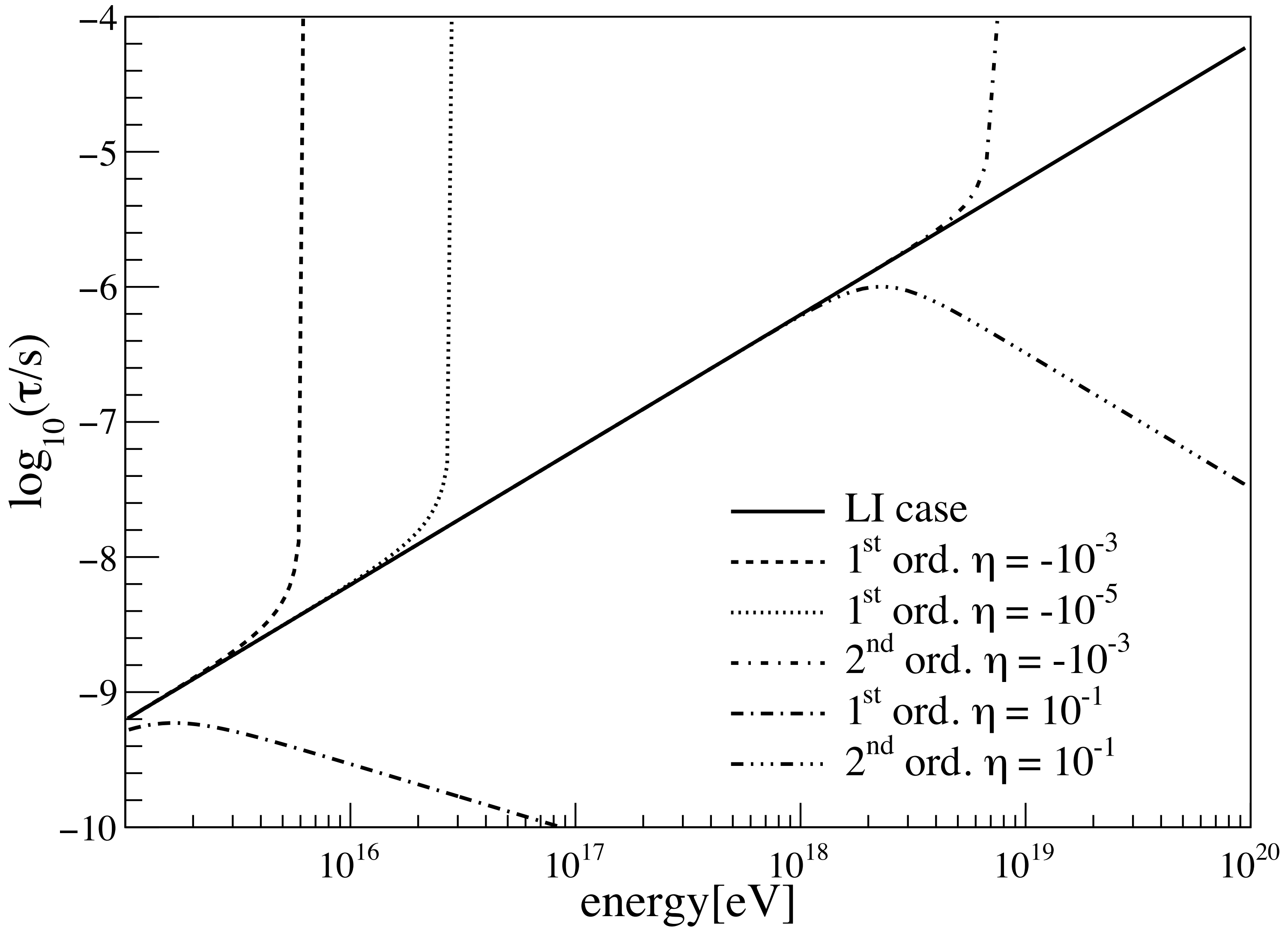
8.5×10^{-20} cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with E^{-2}

(Ioana Caracas) (Massimo Mastrodicasa)

Searches: Lorentz invariance violation (LIV)



Lorentz-dilated lifetime of neutral pions



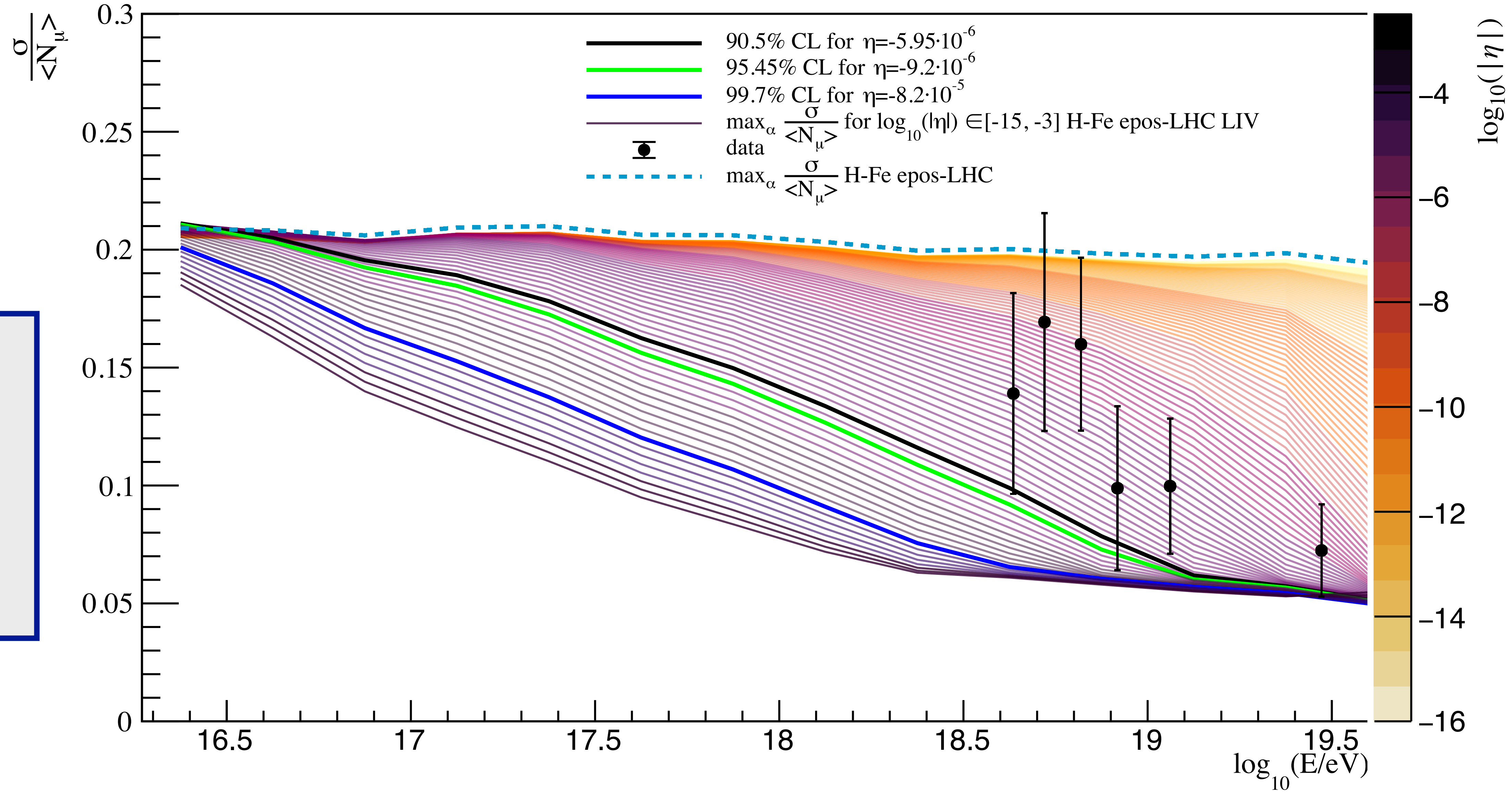
$$E^2 - p^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^n}$$

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

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

Comparison of model simulations with data on muon number fluctuations

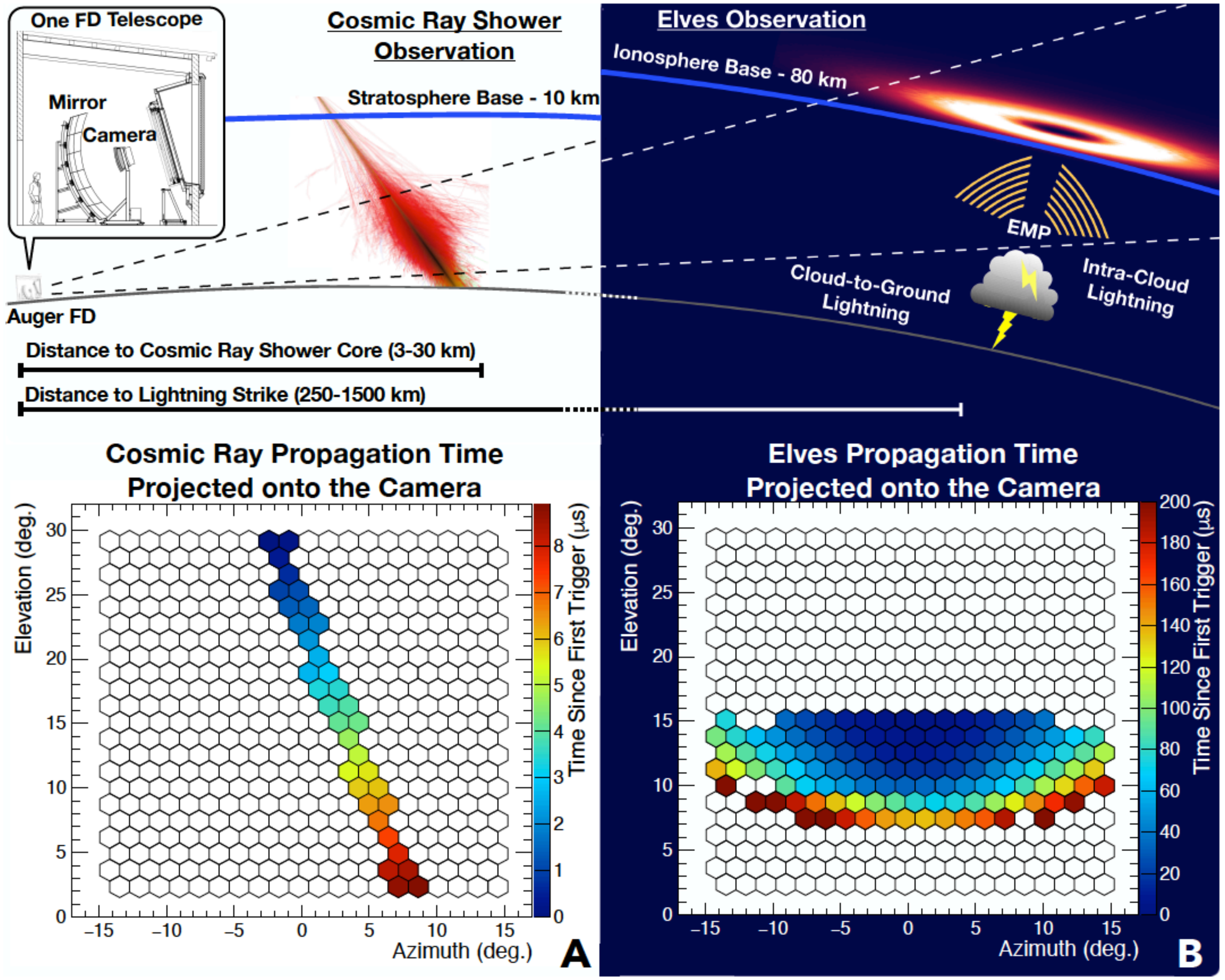
New limits on LIV parameter η



(Caterina Trimarelli)

Atmospheric phenomena – Elves and other beasts

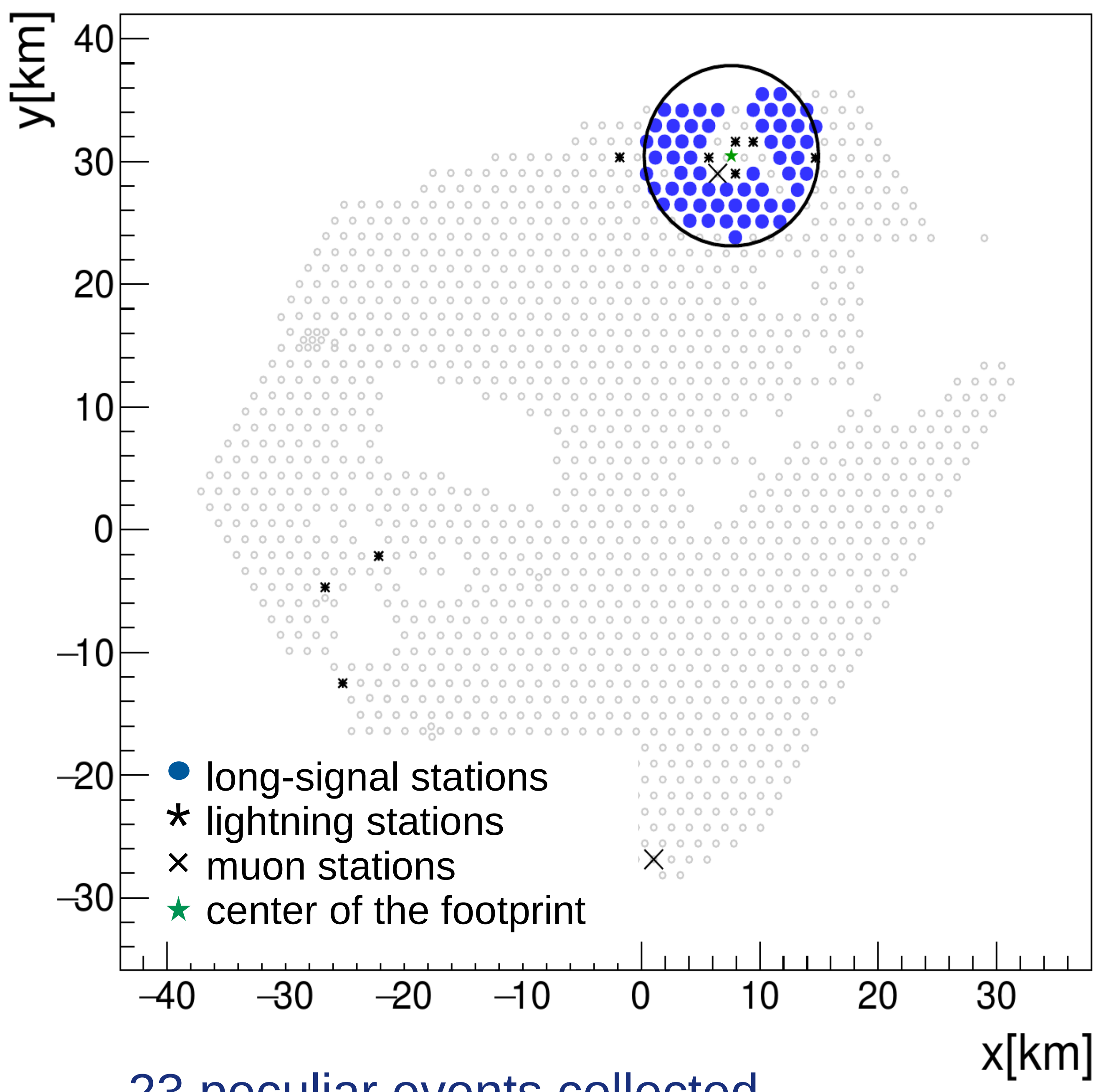
1600 Elves observed with fluorescence telescopes



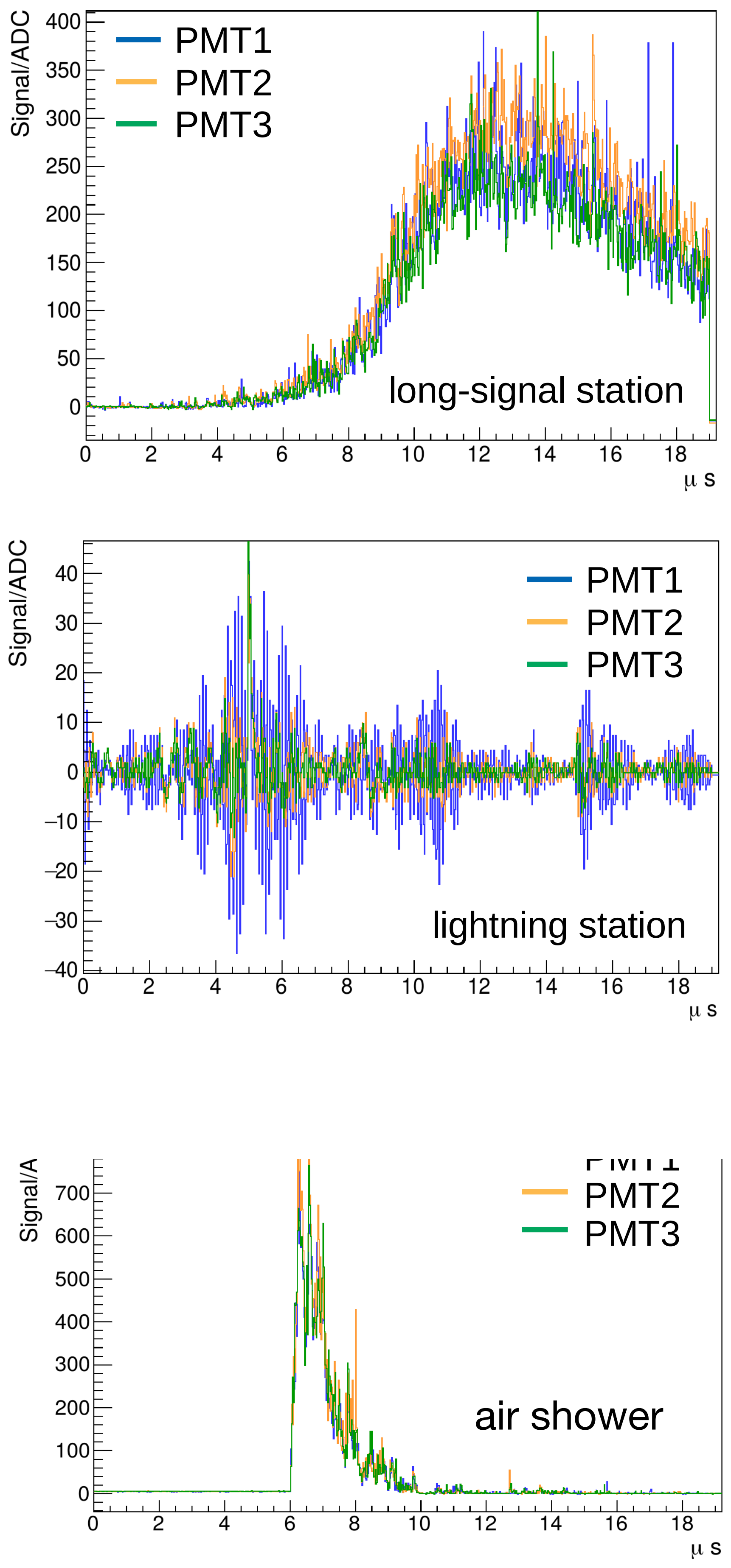
CRs ~ 8 μs

ELVES ~ 200 μs

Downward-going Terrestrial Gamma Ray Flashes (TGFs) ?

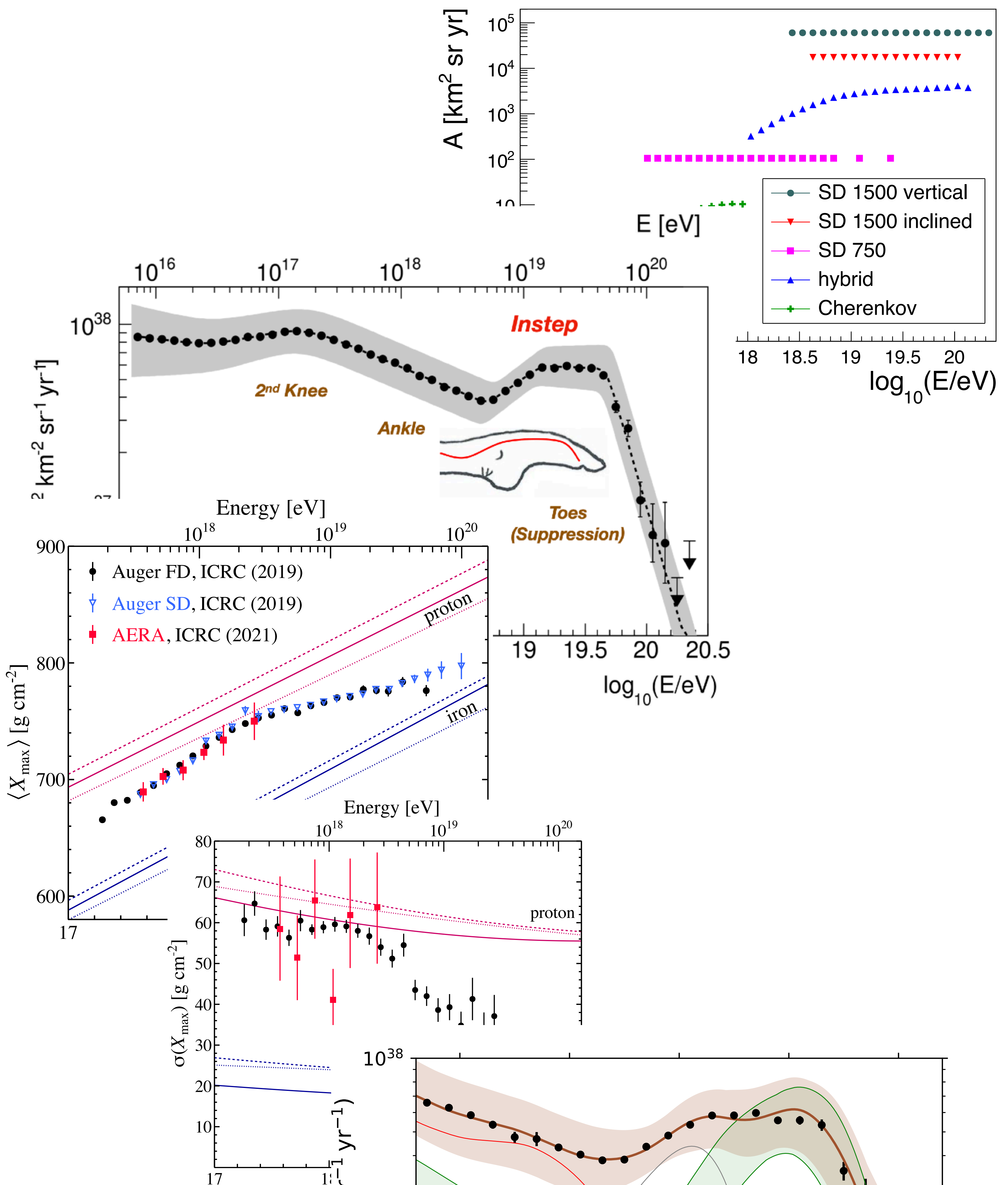


23 peculiar events collected.



Rich physics of additional phenomena still at the beginning of exploration

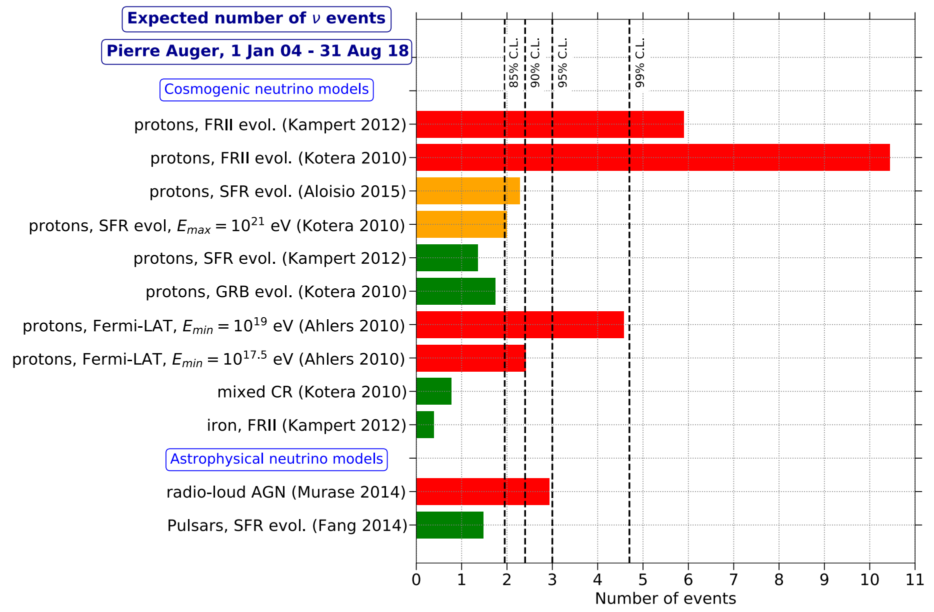
(Adriana Vazquez) *(Earth Space Sci. 7 (2020) 4)* (Roberta Colalillo)



Summary

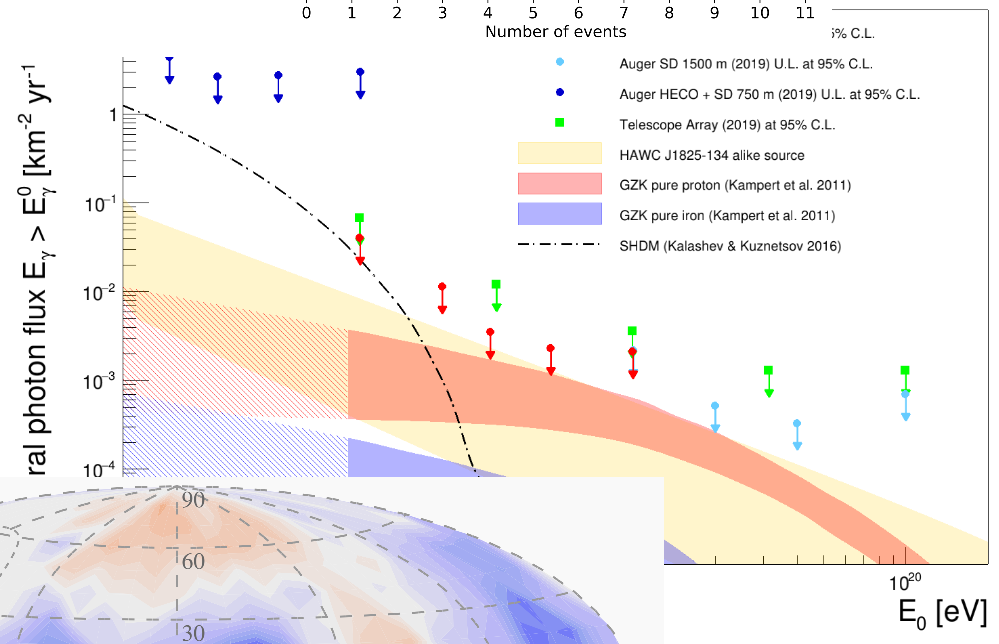
Phase I:

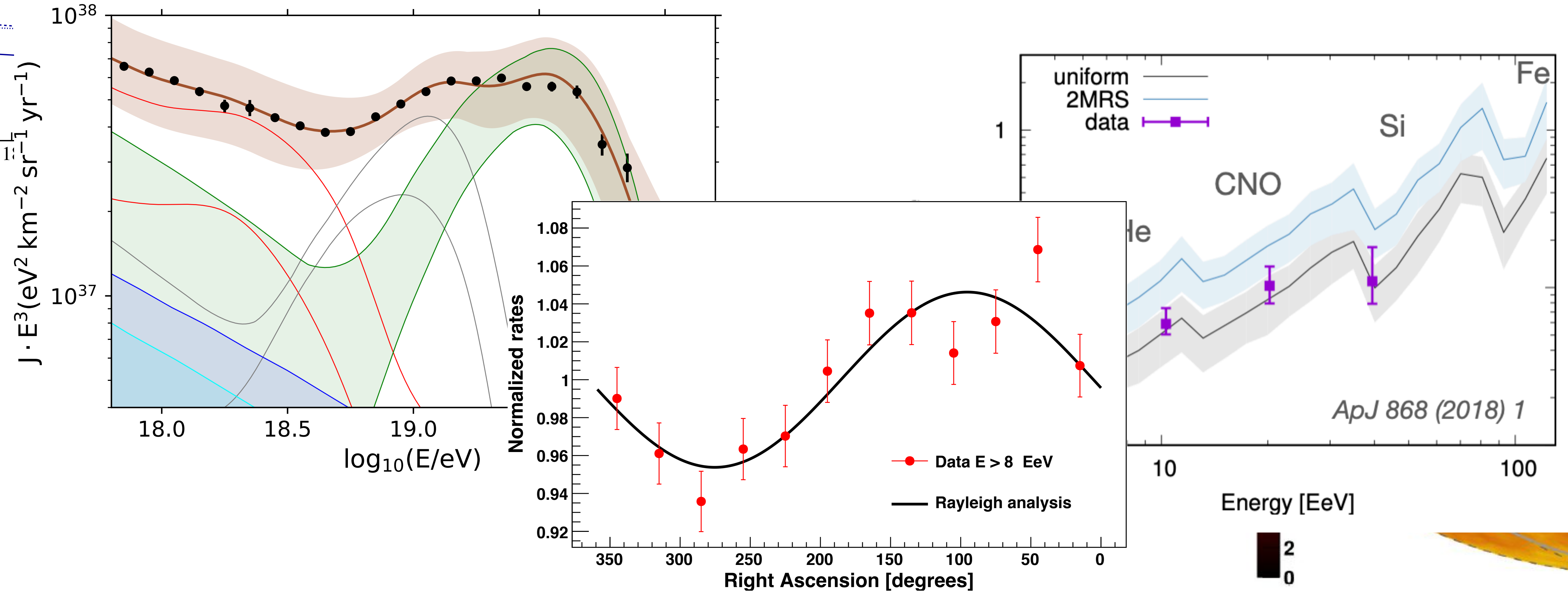
- Exposure 80,000 km² sr yr (vertical, highest quality), up to 120,000 km² sr yr (loose cuts, combined)
- Change of composition established
- Composition tightly linked to hadronic interactions
- Anisotropy observations very challenging
- **Increasingly consistent picture is emerging**

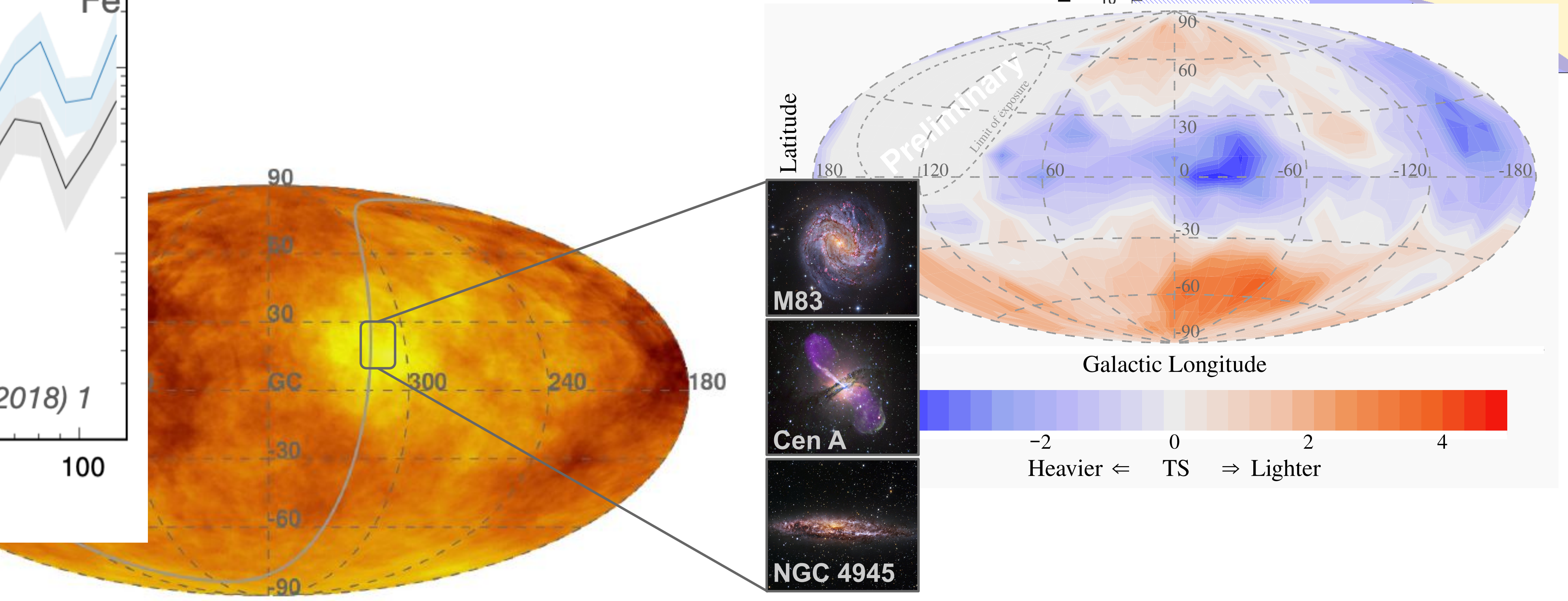


Phase II:

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



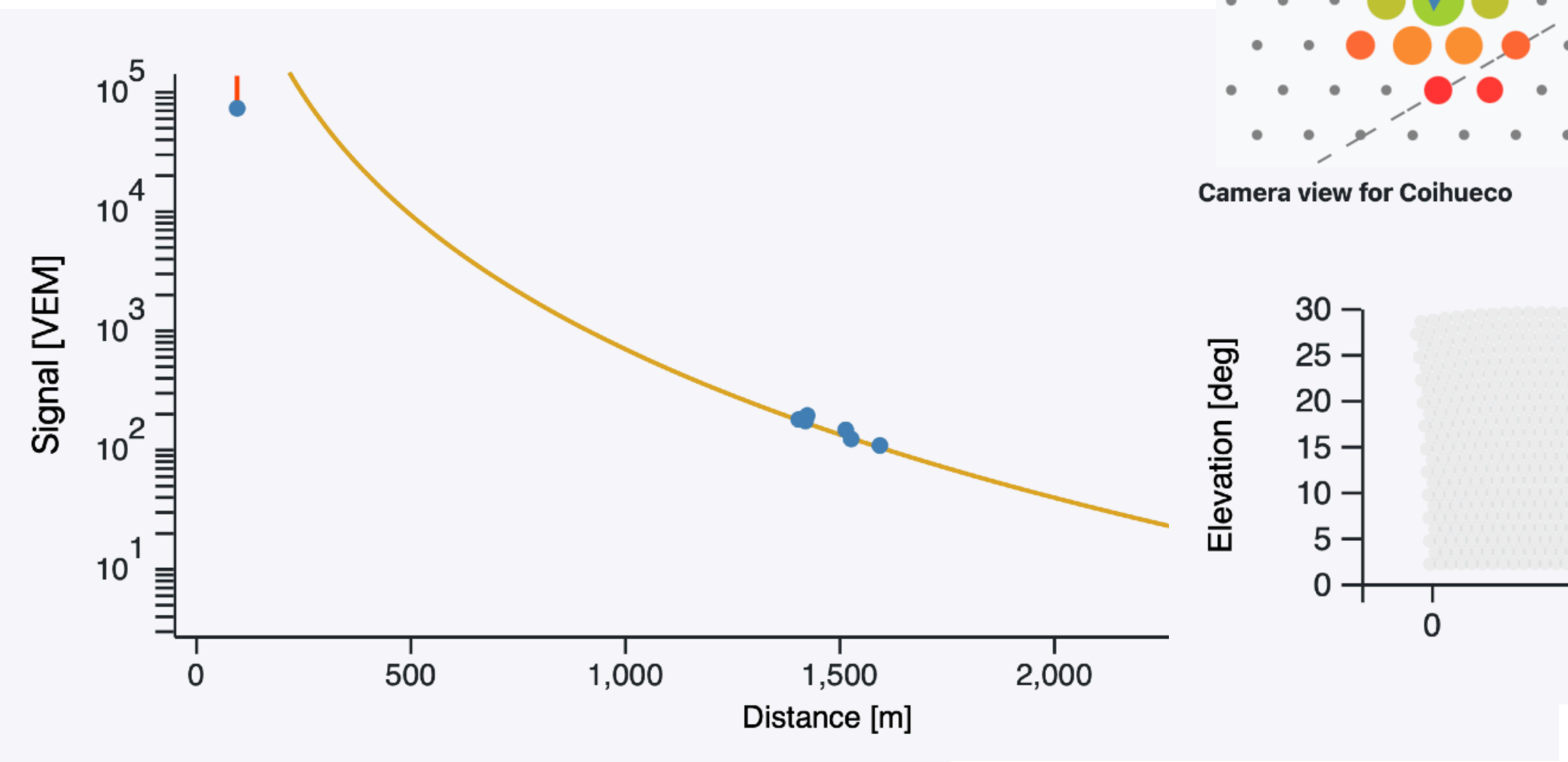


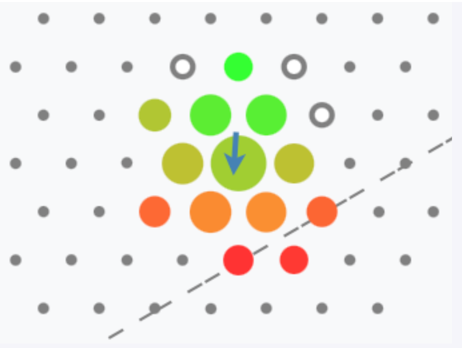


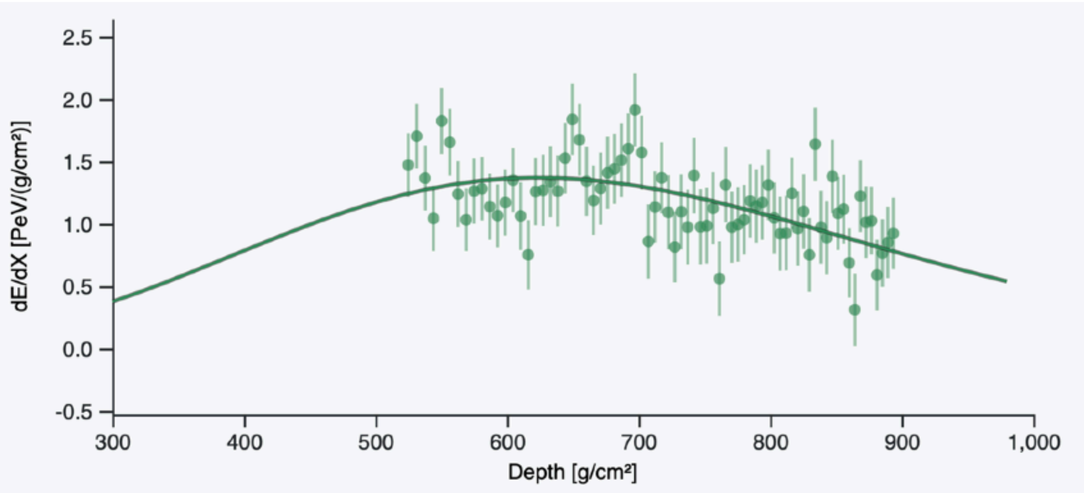
An invitation: Auger open data

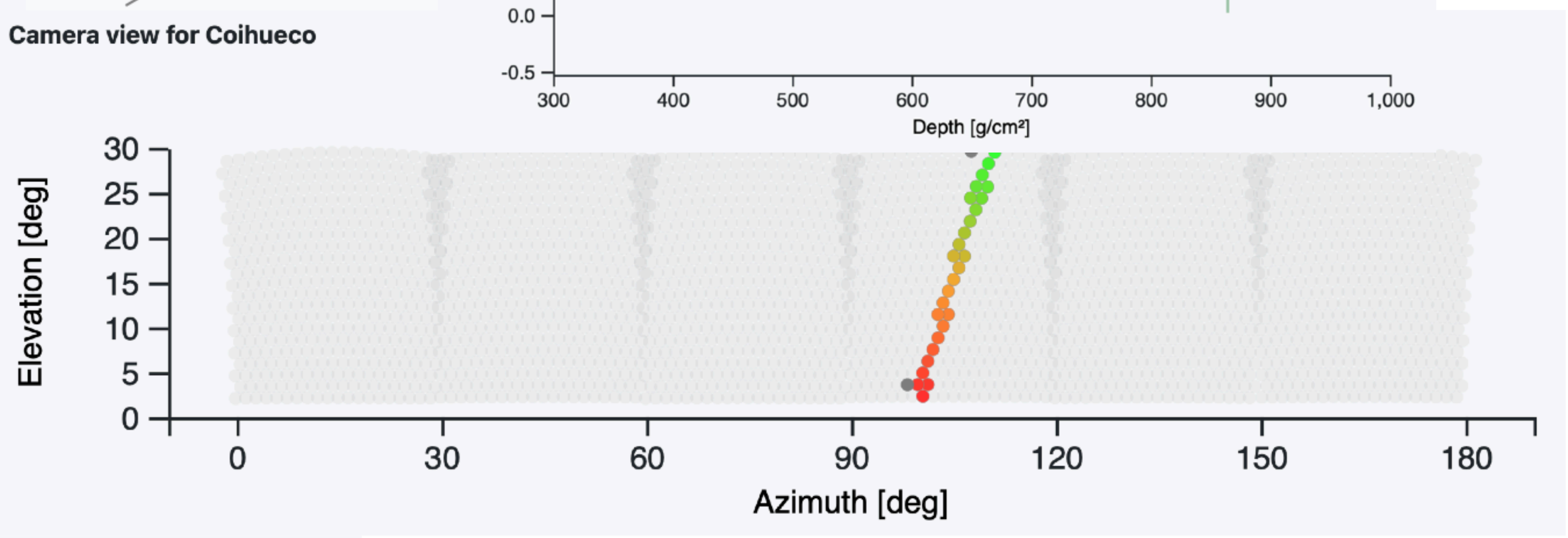
opendata.auger.org

DOI:10.5281/zenodo.4487613

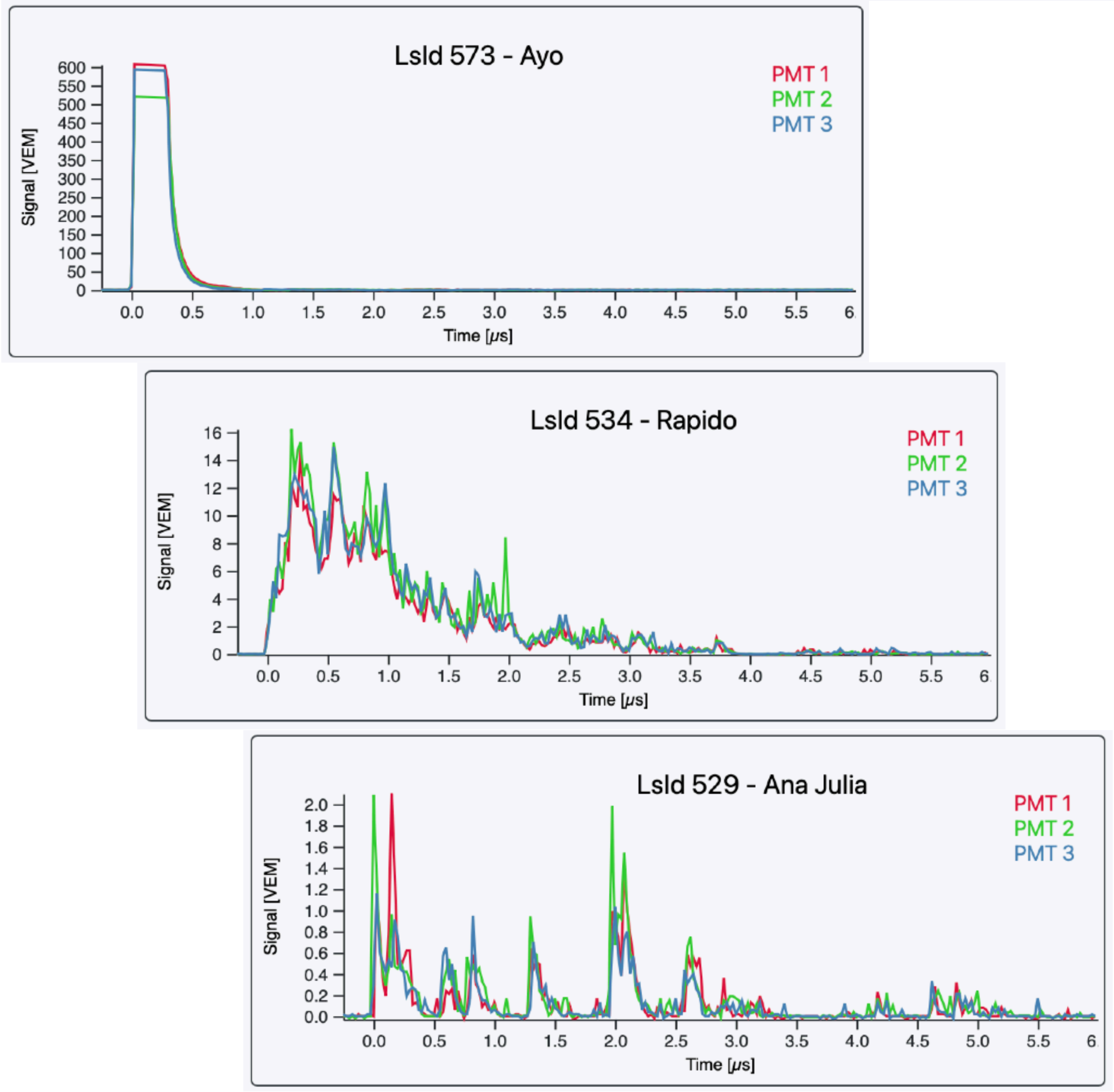



Camera view for Coihueco





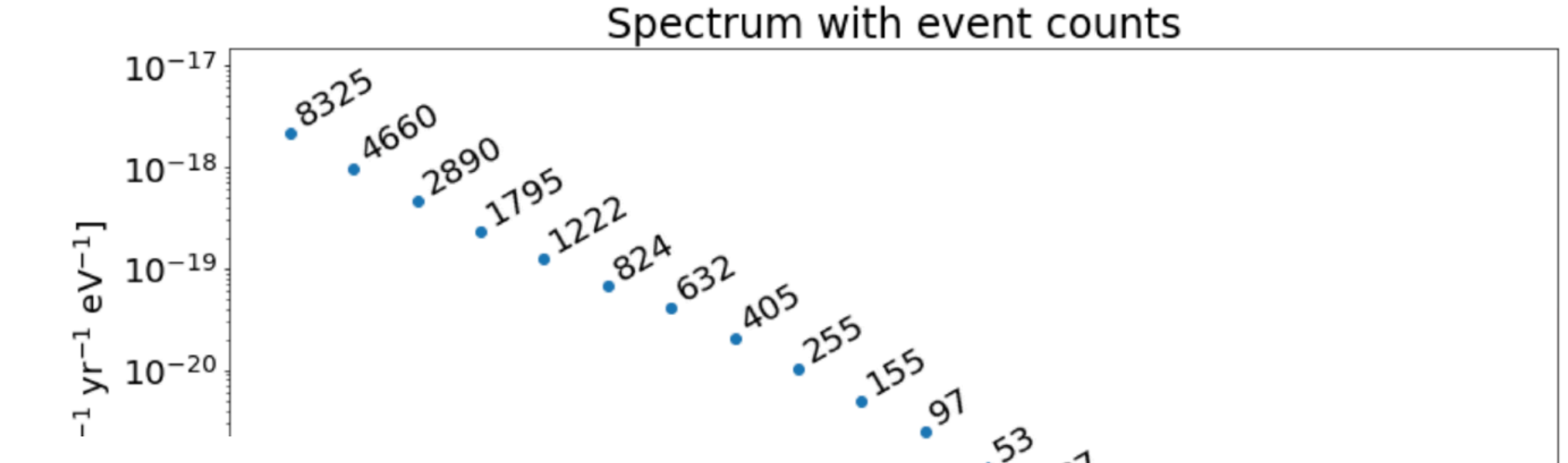

```
In [19]:
Y_0val = FC_CL * 0.9

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')
```

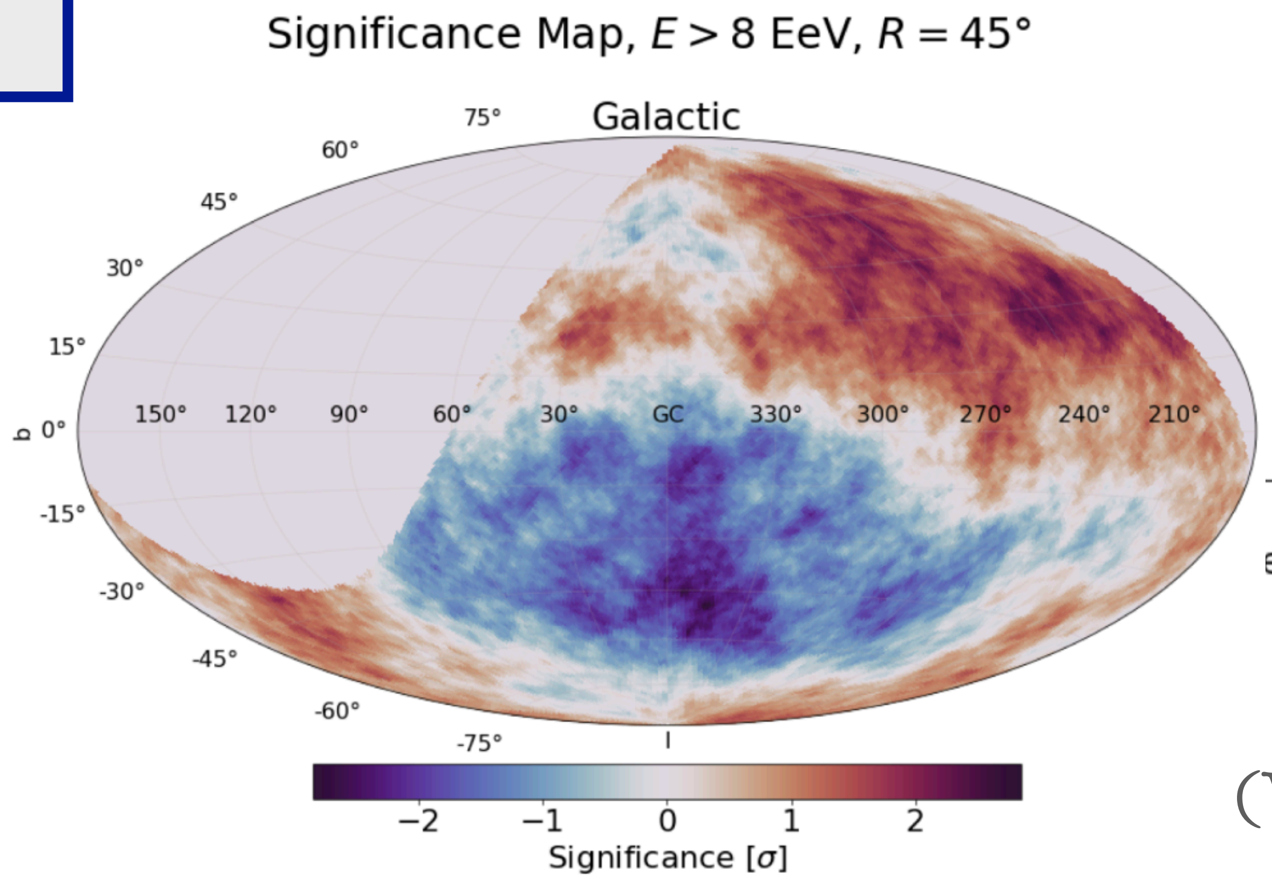


Currently 10% of Auger vertical data
Research-level data in JSON format
Online visualization of events
Data analysis scripts for science plots

You are welcome to use this data

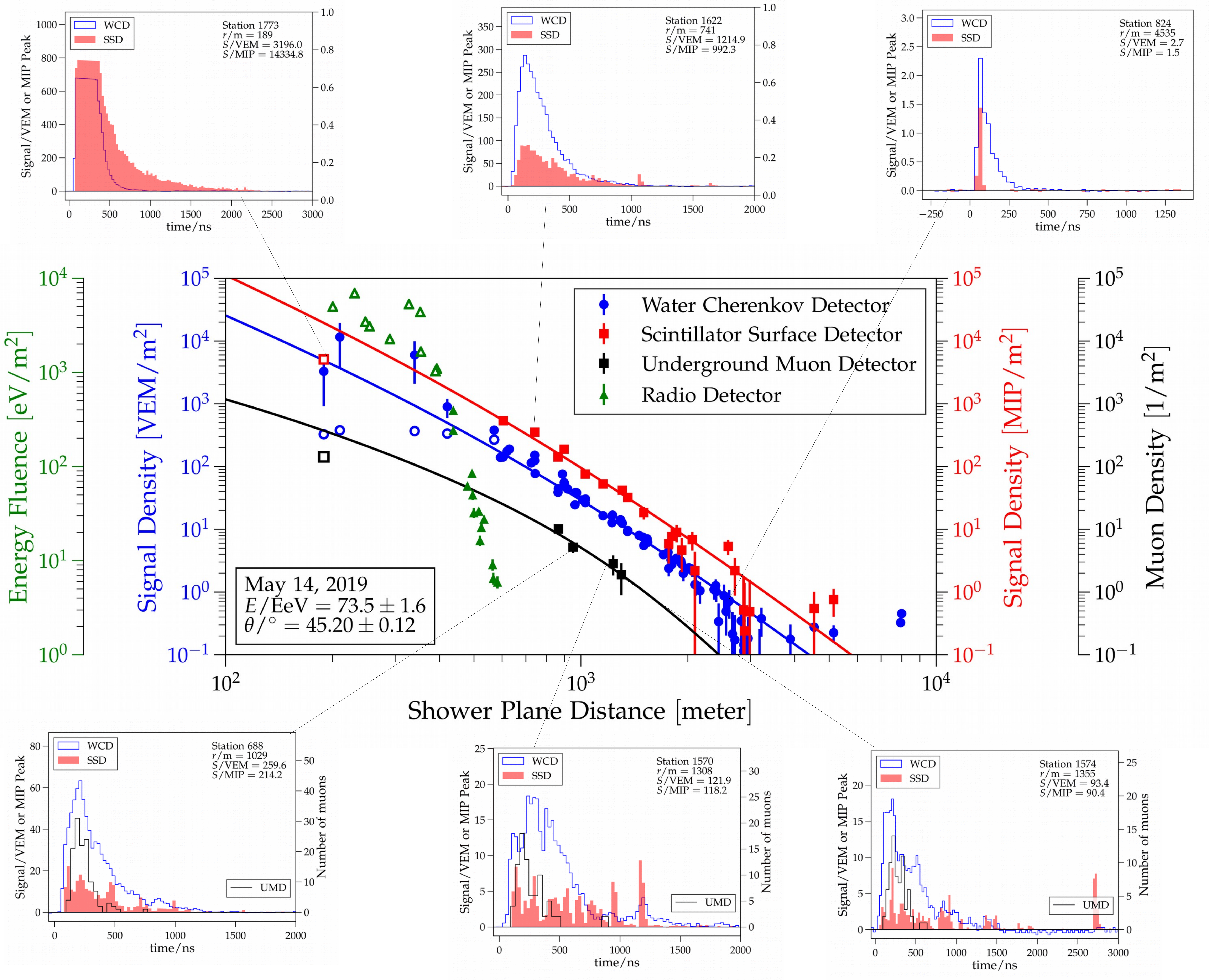
If you have a great idea what to look for we can work with you to apply your analysis also to the full data set





(Viviana Scherini)

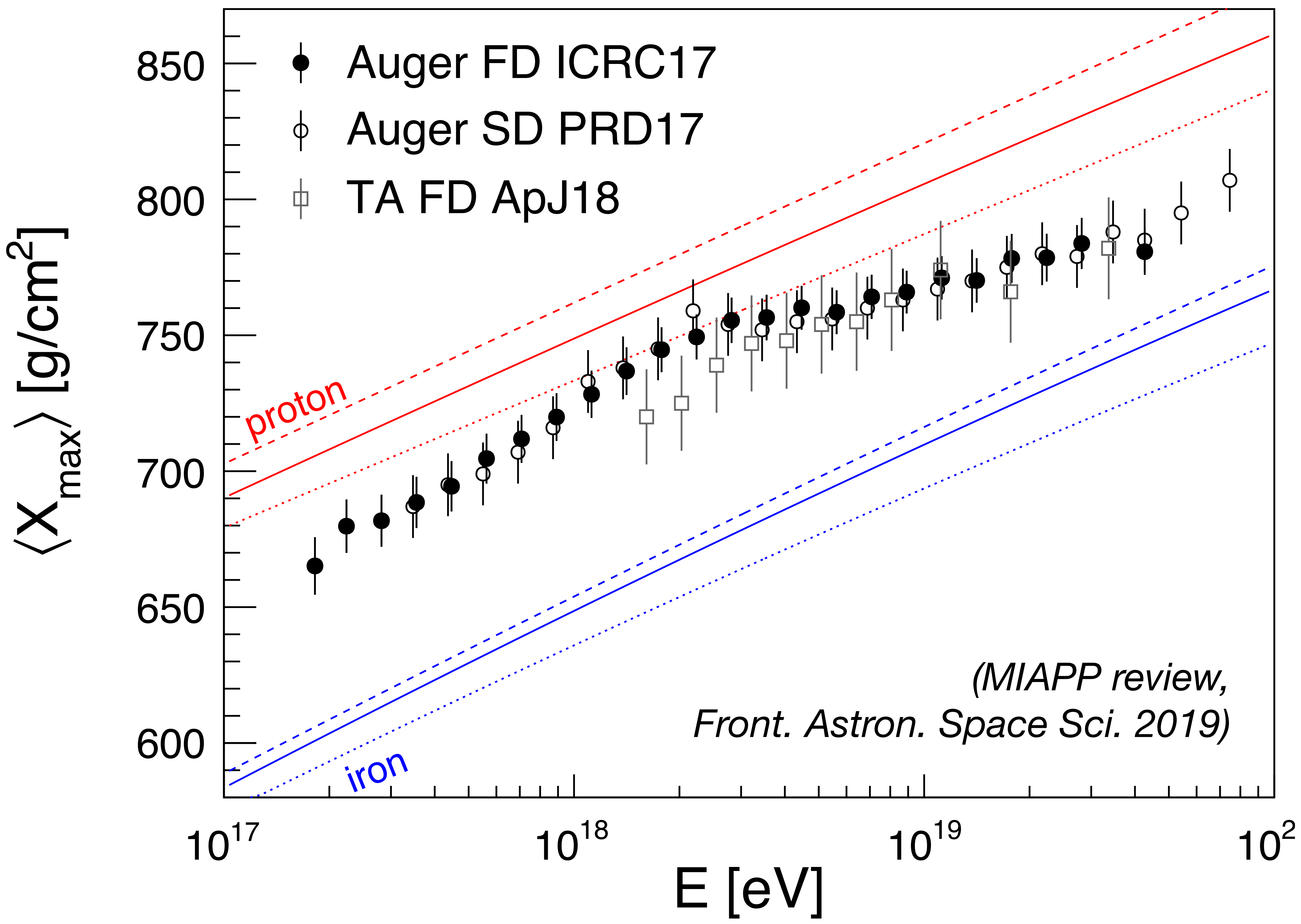
AugerPrime – multi-hybrid measurements

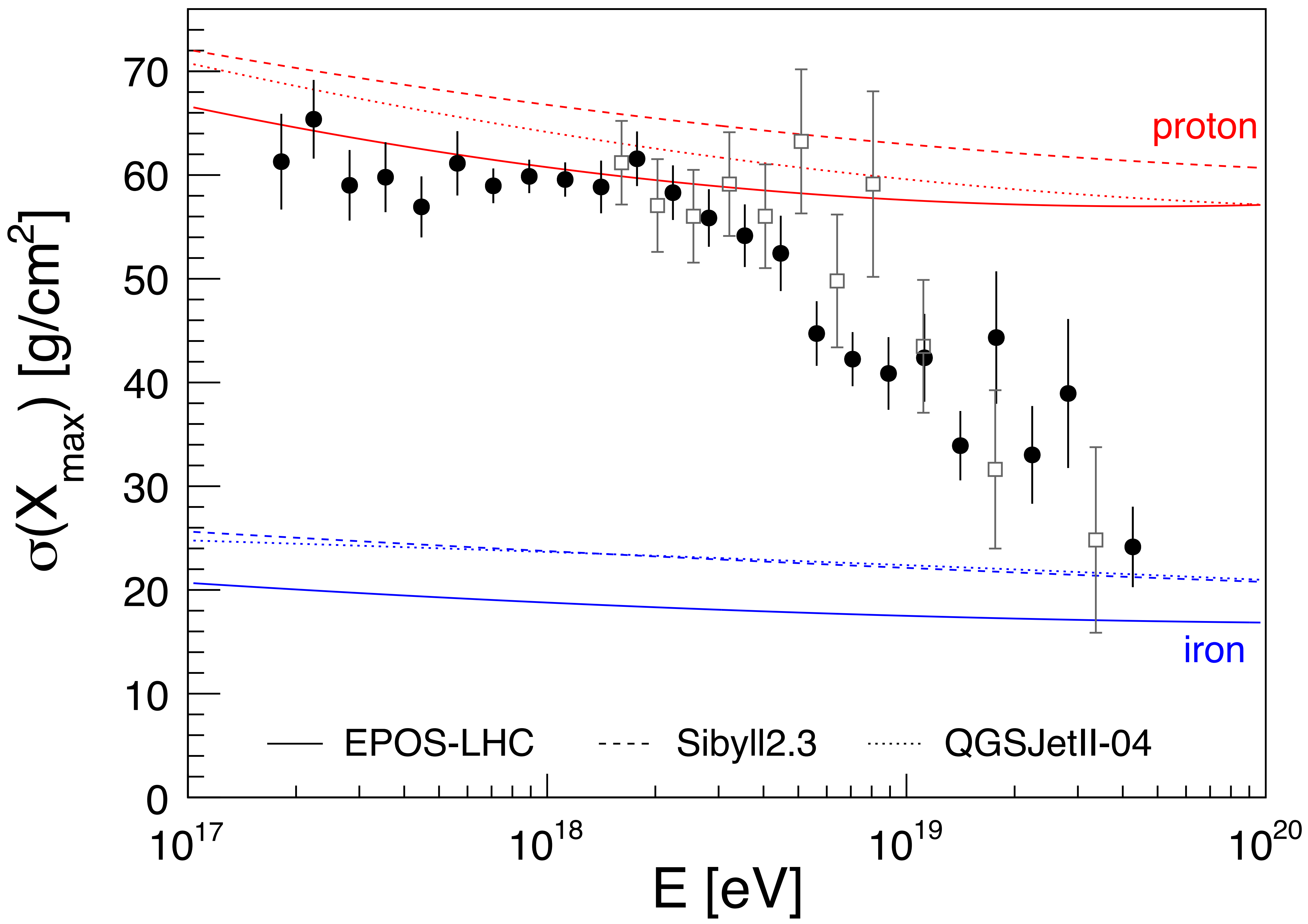


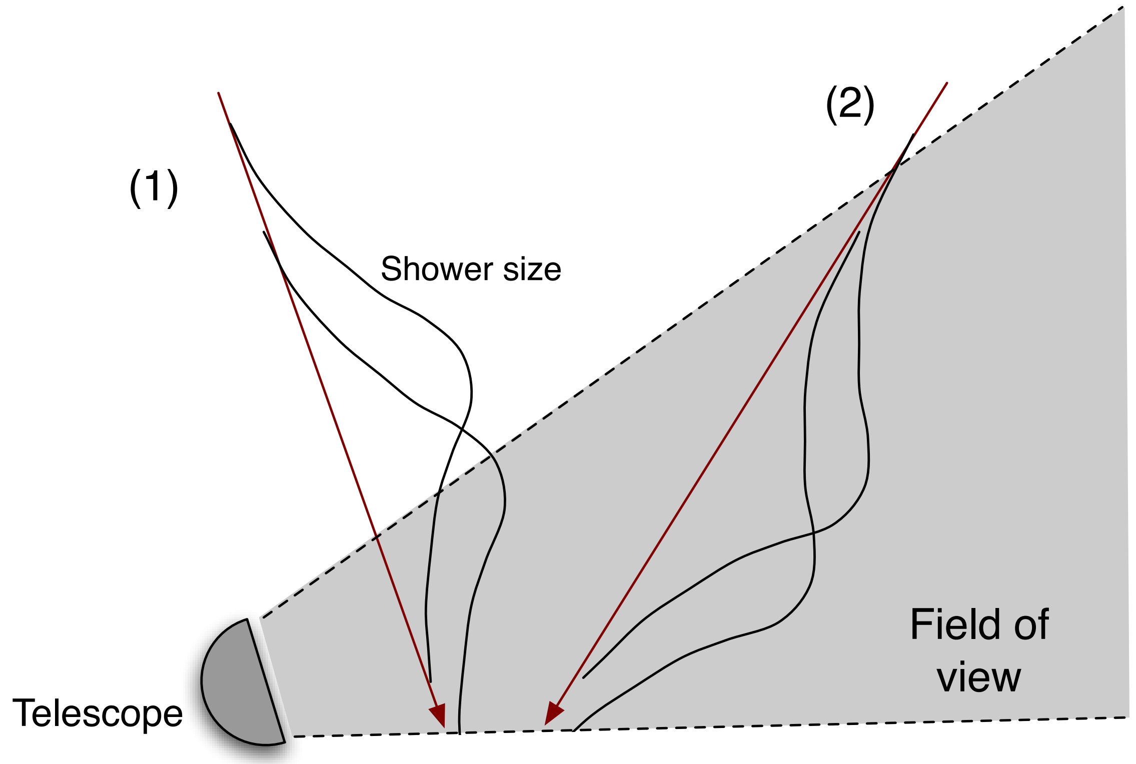
(David Schmidt) (Lukas Nellen)

Backup slides

Comparison of Xmax data of Auger and TA



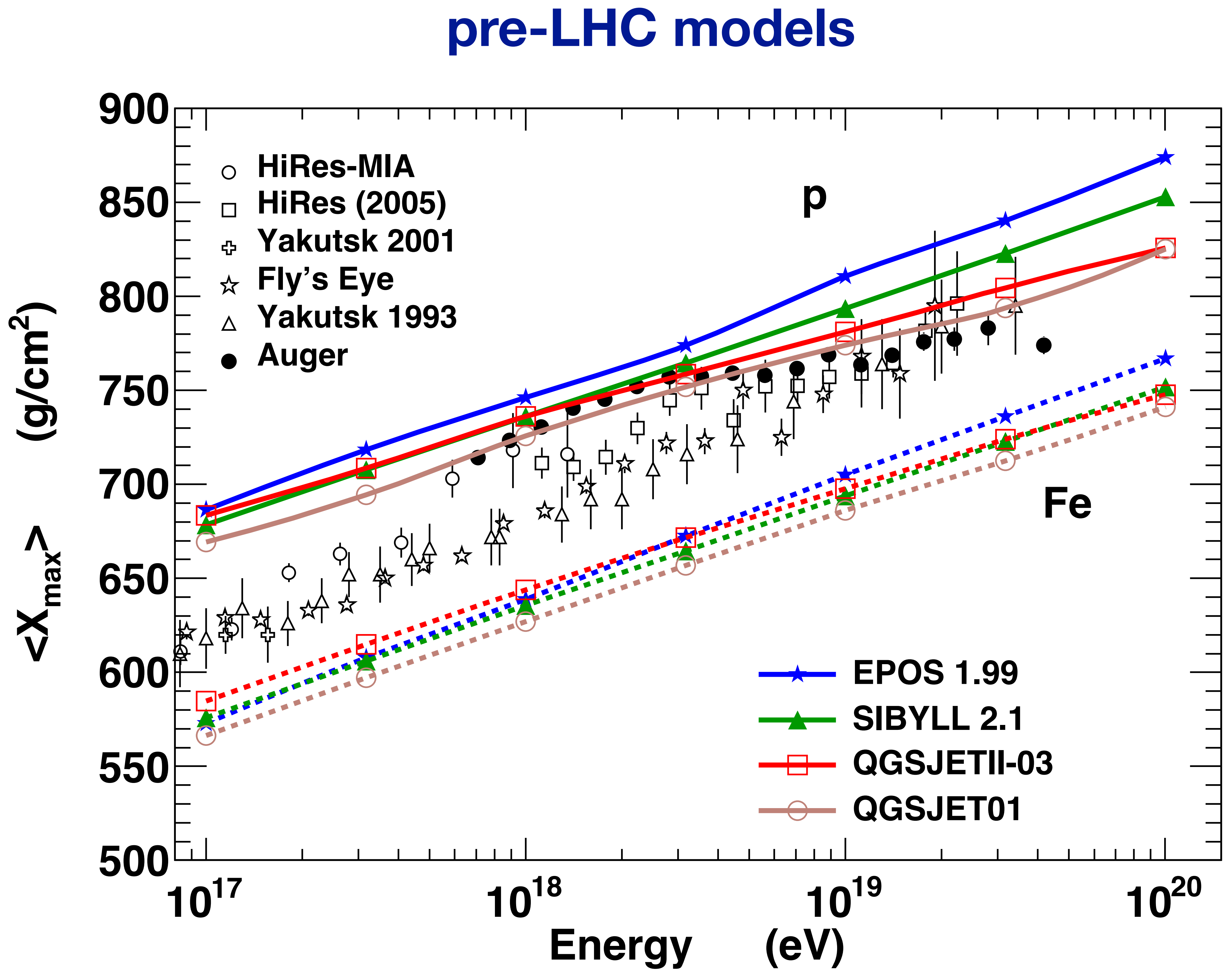


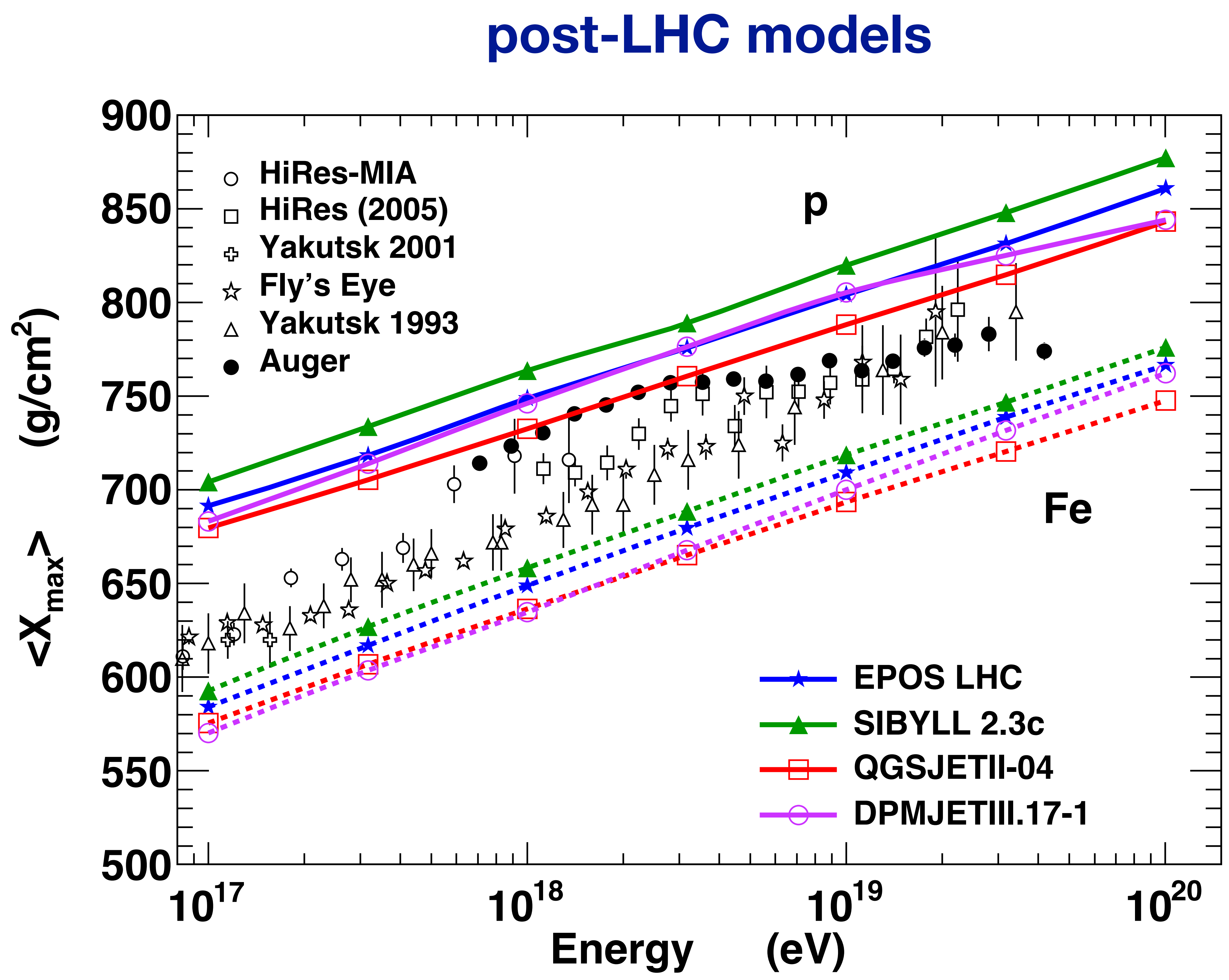


Work in progress:
data consistent in energy range with sufficient statistics

(Auger-TA Xmax Working Group, UHECR 2018)

Change of model predictions thanks to LHC data





(Pierog, ICRC 2017)

Sys. X_{max} uncertainty Auger: $\Delta X_{\rm max} = -10\,{\rm g/cm^2}\ +8\,{\rm g/cm^2}$

TA: $\Delta X_{\rm max} = \pm 20\,{\rm g/cm^2}$

LHC-tuned models should be used for data interpretation

(see also discussion Lipari, Phys.Rev.D 103 (2021) 103009)