Ultra-high energy cosmic rays in the multi messenger era

Antonella Castellina

INAF, Osservatorio Astrofisico di Torino
INFN, Sezione di Torino, Italy

1- Setting the stage

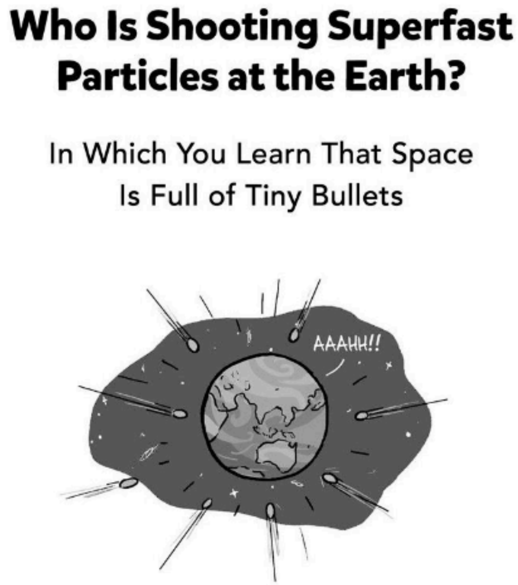
- sources
- acceleration
- propagation from sources to Earth
- extensive air showers

2- Techniques

- surface, fluorescence, radio detectors
- from old to modern Observatories
- the experimental observables
- the energy spectrum

3- What have we learnt?

- mass composition
- anisotropy of UHECRs
- multi-messengers
- the future of the field

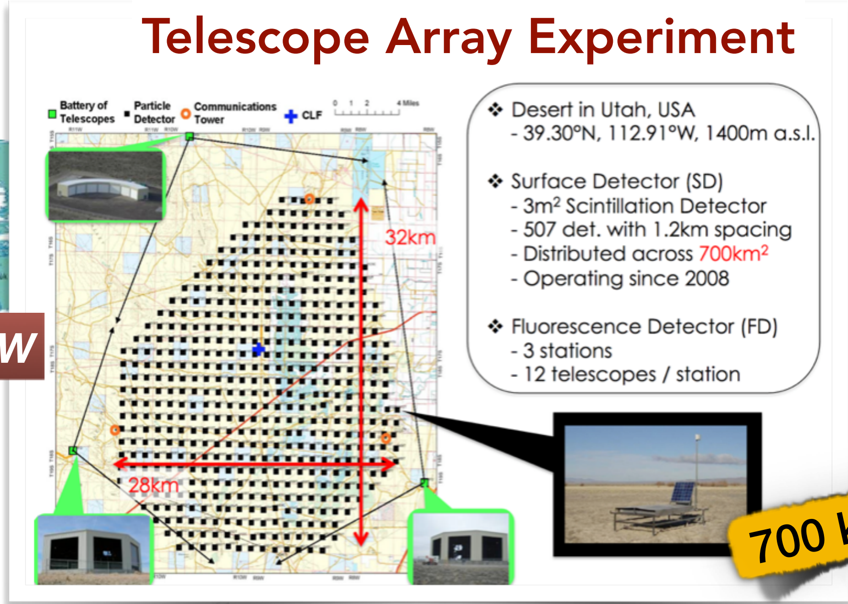


[J.Cham, D.Whiteson]

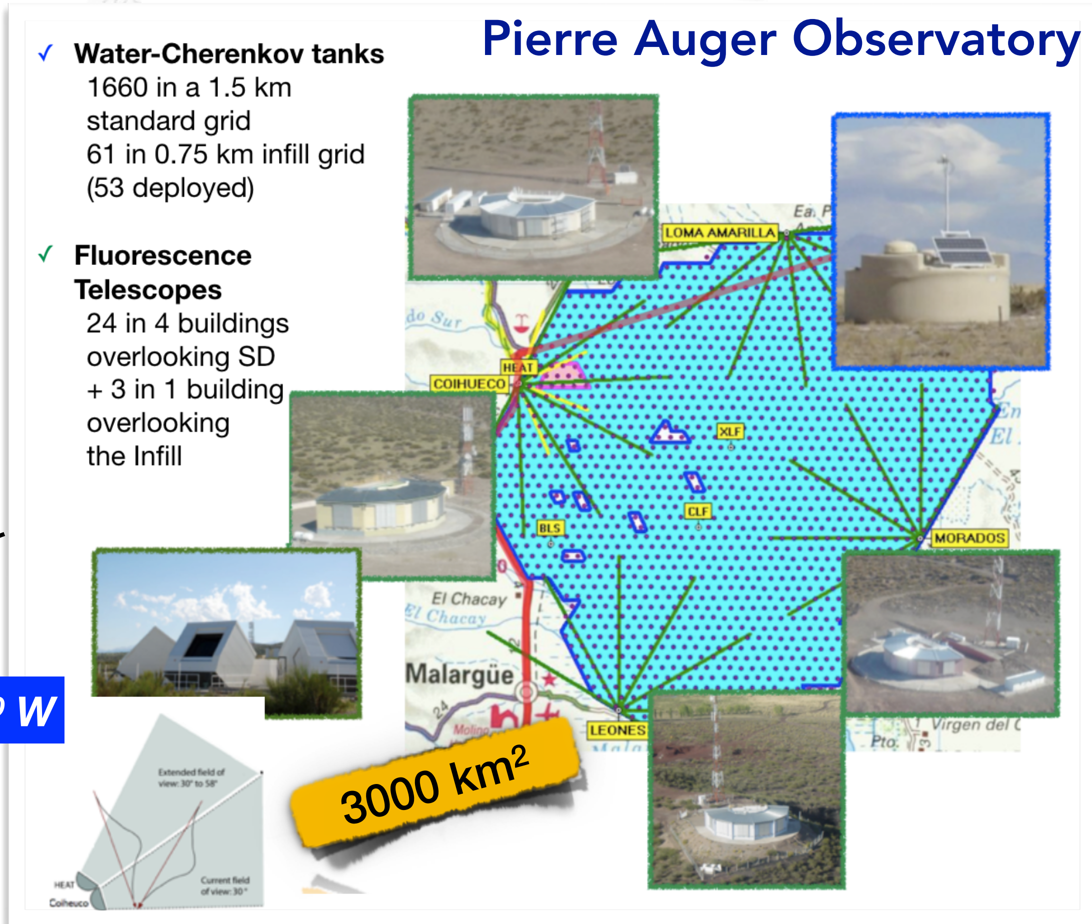
UHECR detectors

34⁰N, -107⁰ W

-35⁰S, -69⁰ W



not in scale !



Anisotropies

J.Miro, Drowned Sun

Anisotropy measurements

Large Scale Anisotropies
- Galactic : diffusion and escape of GCRs
- Transition from Galactic to Extra-Galactic
- extra-Galactic: small dipole due to our motion

Small scale anisotropies
- high rigidity, nearby sources
- clustering of events from the same source
- correlation with a population of sources

Directional exposure

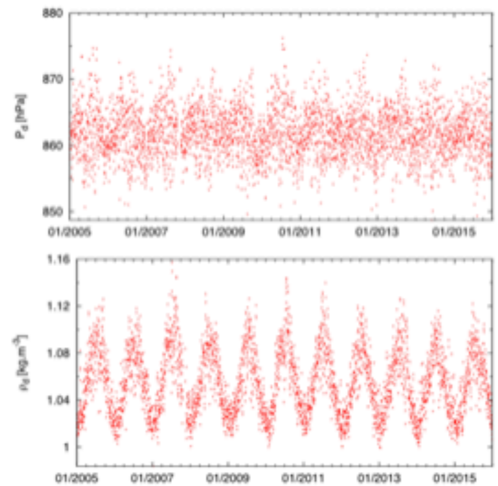
$$\mu(\alpha,\delta;E) = \int_{\Delta t} \mathrm{d}t\; A_0 \cos(\theta(\alpha,\delta,t)) \times \epsilon(E,\tilde{\mathbf{n}}(\alpha,\delta,t),t)$$

Challenge: real conditions (not in lab !)
- uniform exposure in right ascension (thanks to Earth rotation) but not in declination; the FOV is limited by the geographical position, zenith angle dependence of showers and reconstruction
- tiny effect: amplitudes down to 10^{-4}-10^{-3}

Mandatory to:

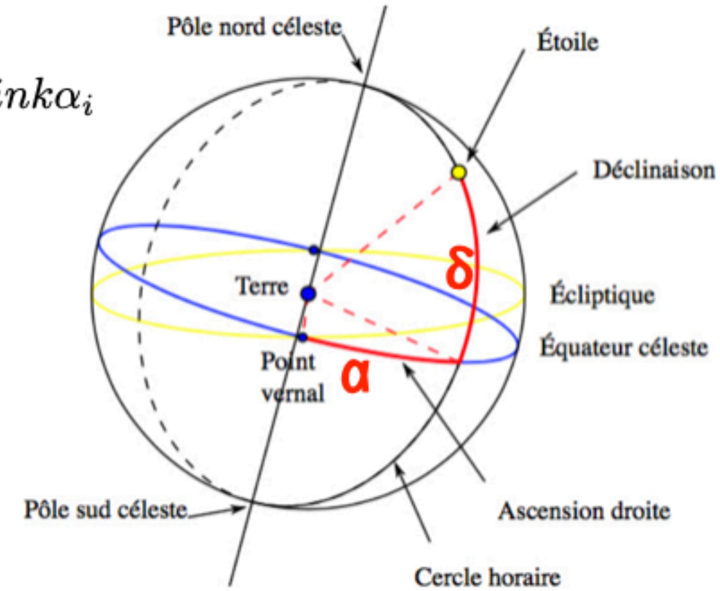
➡ collect a large amount of events
➡ account for systematic uncertainties due to
- ***Exposure:*** <0.6% amplitude due to the non constant number of elementary cells
- ***Atmospheric effects:*** spurious daily and seasonal variations of P and ρ
- ***Geomagnetic effects***: ~0.7% modulation in φ
- ***Tilt of the array:*** ~0.2⁰ SE

➡ probe that the directional exposure μ of the observatory is accurate enough



Large Scale Anisotropy

Rayleigh formalism $a_{\alpha,k} = \frac{2}{N}\sum_{i=1}^{N} w_i cos k\alpha_i, \quad b_{\alpha,k} = \frac{2}{N}\sum_{i=1}^{N} w_i sin k\alpha_i$



Amplitude

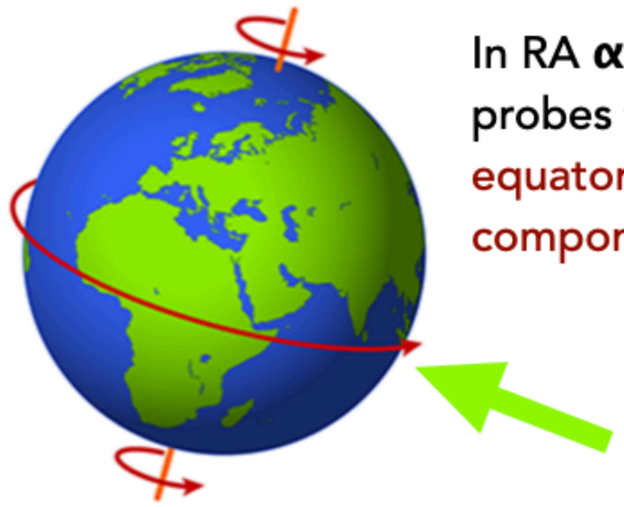
$$r_{\alpha,k} = \sqrt{a_{\alpha,k}^2 + b_{\alpha,k}^2},$$

Phase

$$\Phi_{\alpha,k} = \frac{1}{k} arctan \frac{b_{\alpha,k}}{a_{\alpha,k}}$$

k=1 dipolar modulation

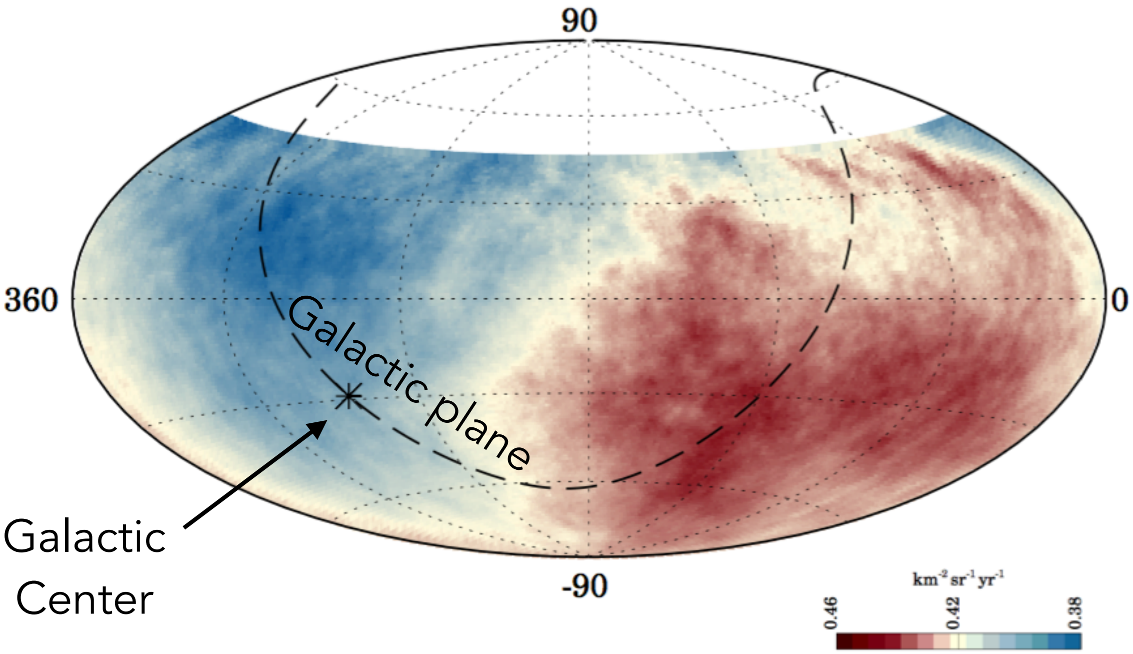
k=2 quadrupole modulation



In RA **α**, k=1 probes the equatorial dipole component

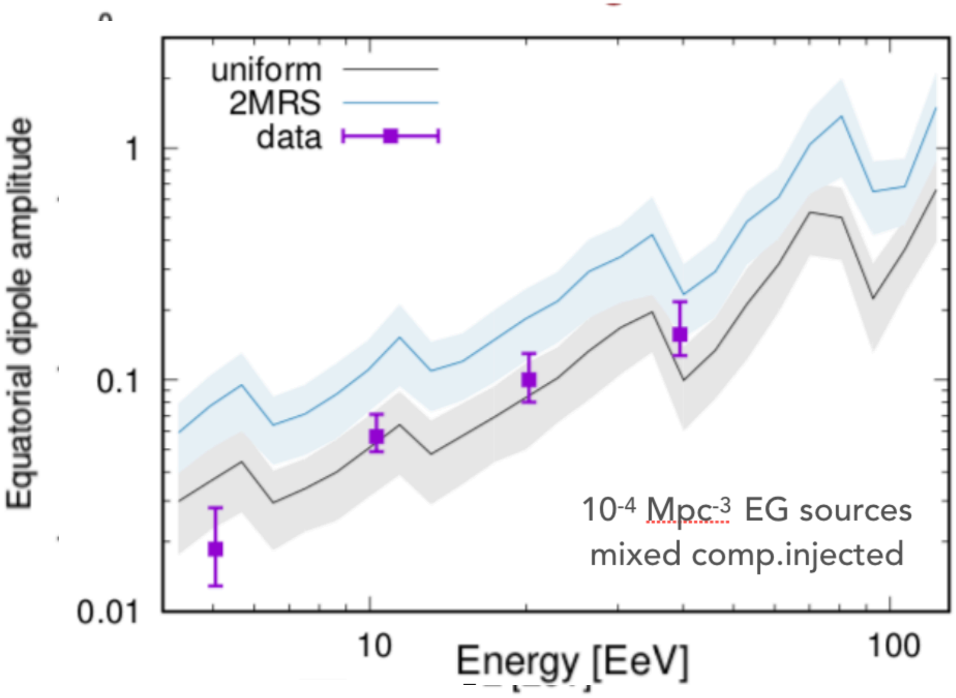
In azimuth **ϕ**, k=1 probes the dipole component along the Earth rotation axis

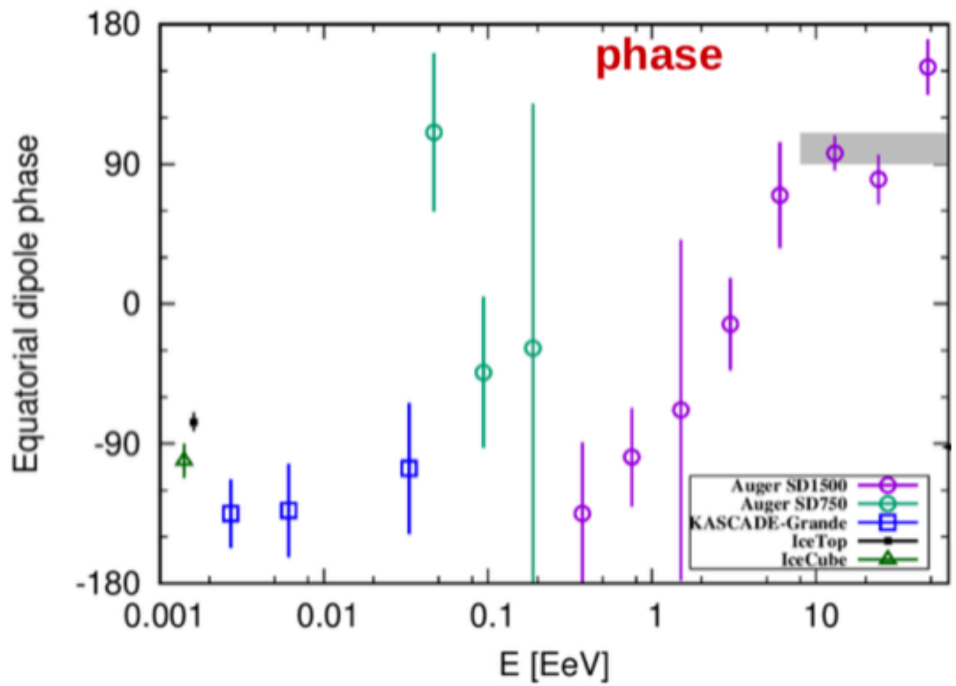
Large Scale Anisotropy - Auger



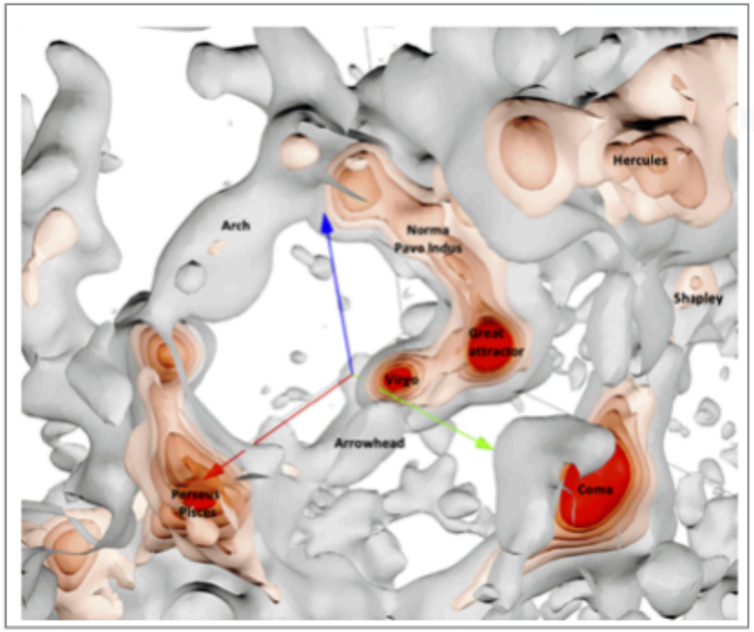
- ➡ exposure ~110000 km^2 sr yr
- ➡ **OBSERVATION (>5σ): 3D dipole above 8 EeV at $(\alpha,\delta)=(98^0,-25^0)$: $(6.6\ ^{+1.2}_{-0.8})$ %**
- ➡ the UHECRs are extra-galactic above 8 EeV, while predominantly Galactic below few EeV

Auger Coll., Science 357 (2017) 1266; ApJ. 891 (2020) 142; R. De Almeida, PoS(ICRC2021) 335





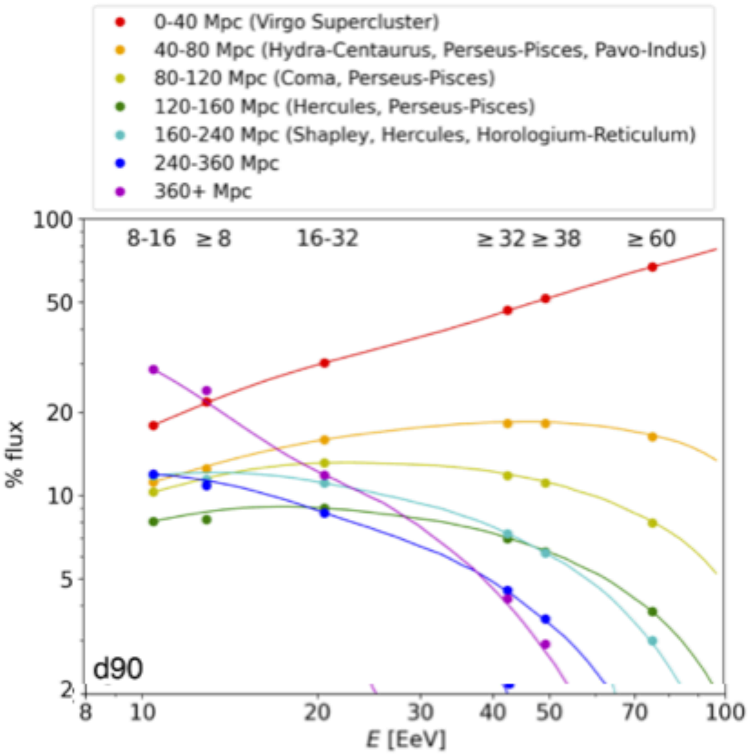
Large Scale Anisotropy - Auger

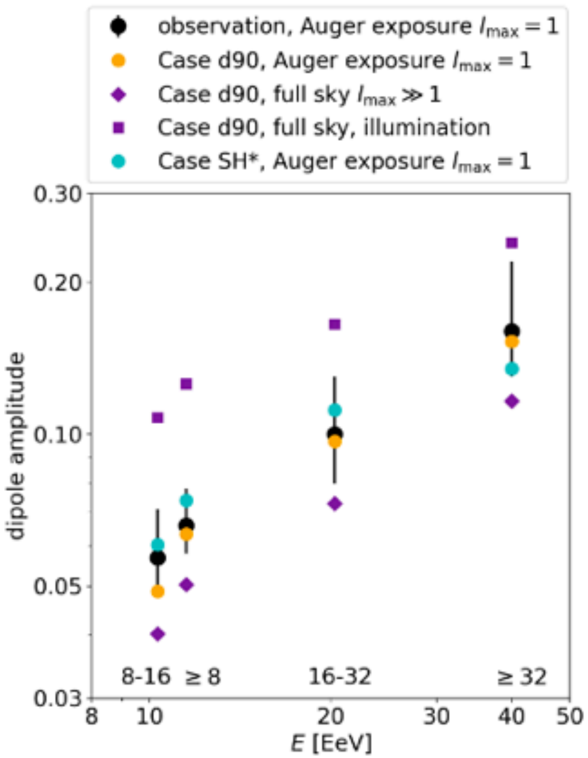


Complex interplay of
- Mass composition
- Source distributions
- Magnetic fields deflections

Attenuation taken into account: a contribution from distance z is weighted in its contribution to the observed spectrum

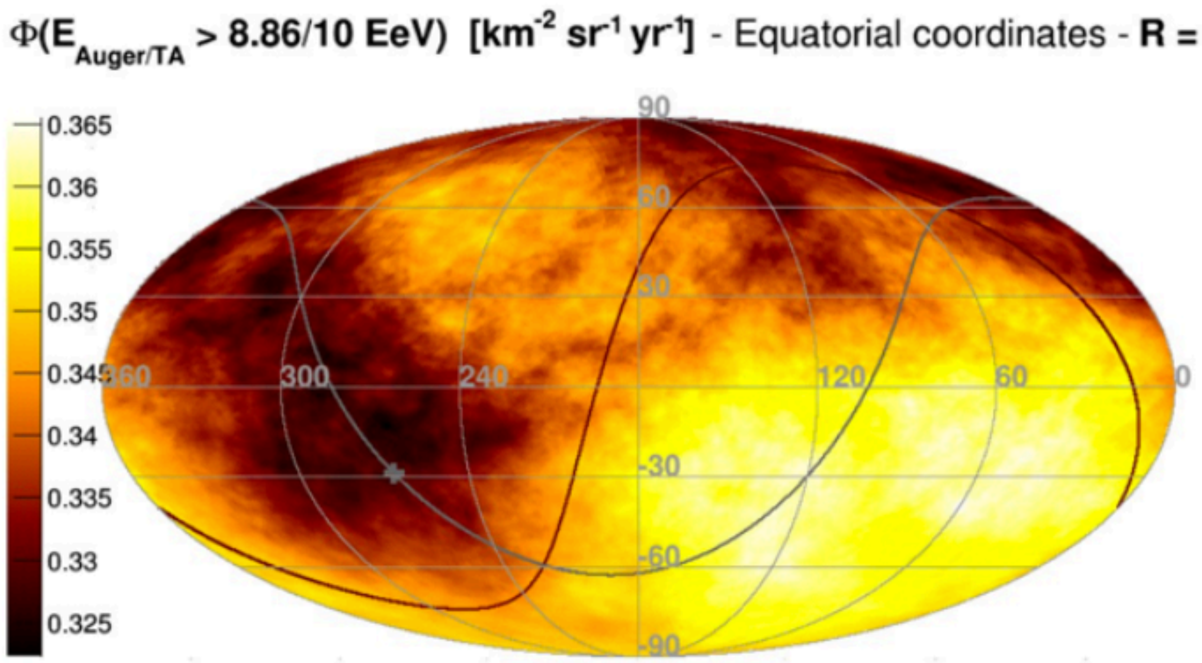
$$\exp\left[-\ln(10)\, p(z, d_{\rm diff})/d_{90}(A, E)\right]$$





Not consistent with pure protons >8 EeV: require mixed composition (unless dipole not due to LSS)

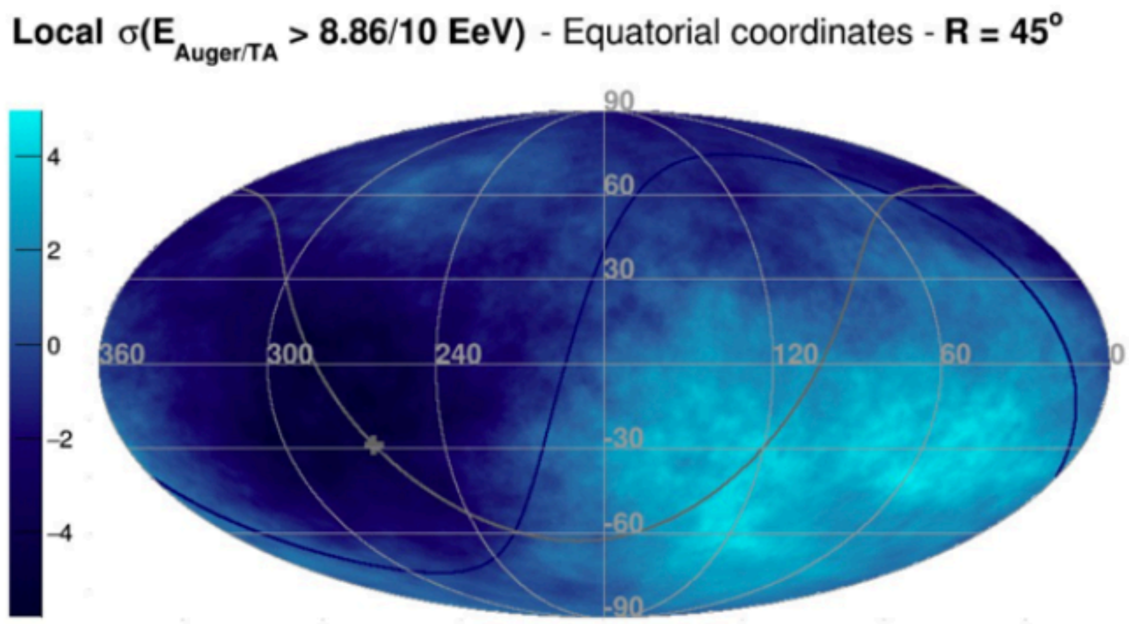
C.Ding et al, ApJ913 (2021) L13

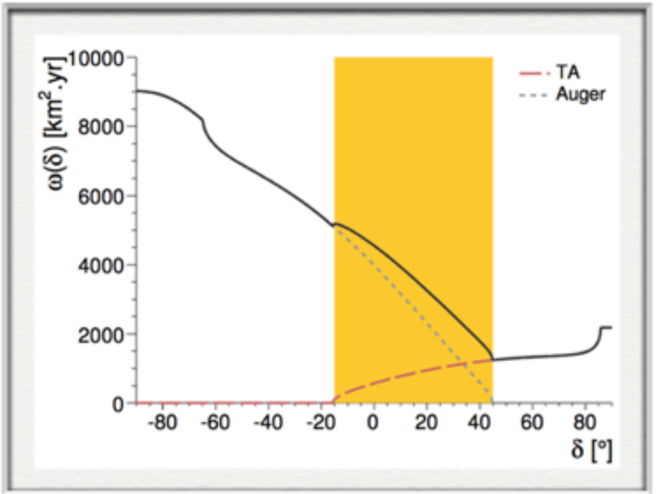


Full sky search for LSA

- scatter plots of arrival directions immediately interpretable
- equal sensitivity anywhere in the sky
- upper limits uniform over the sky
- no need for methods to re-weight individual exposures

Flux

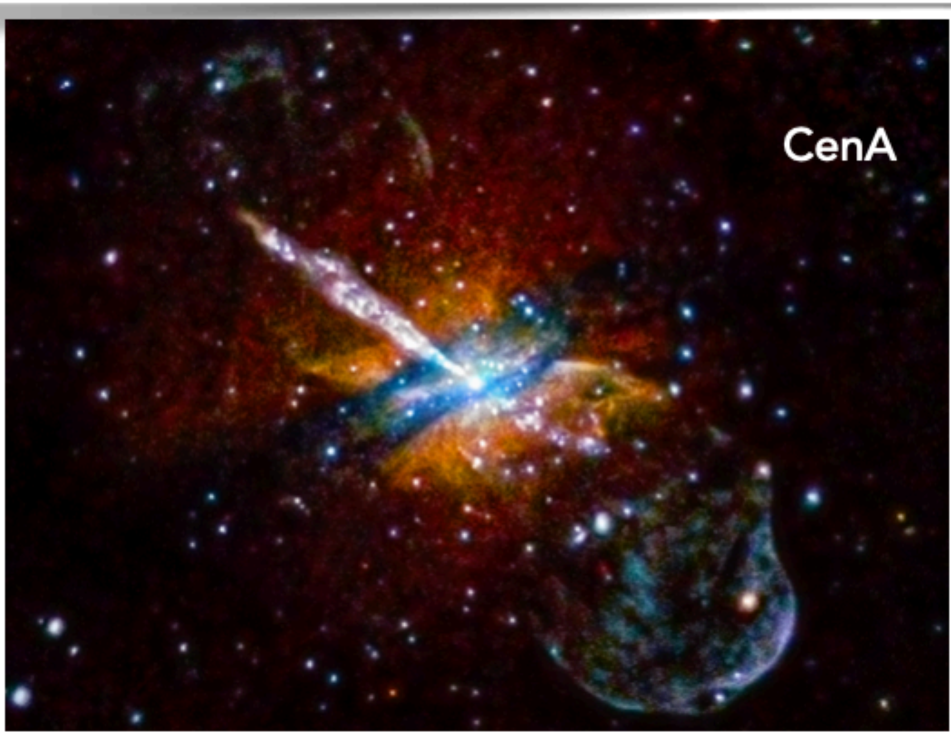




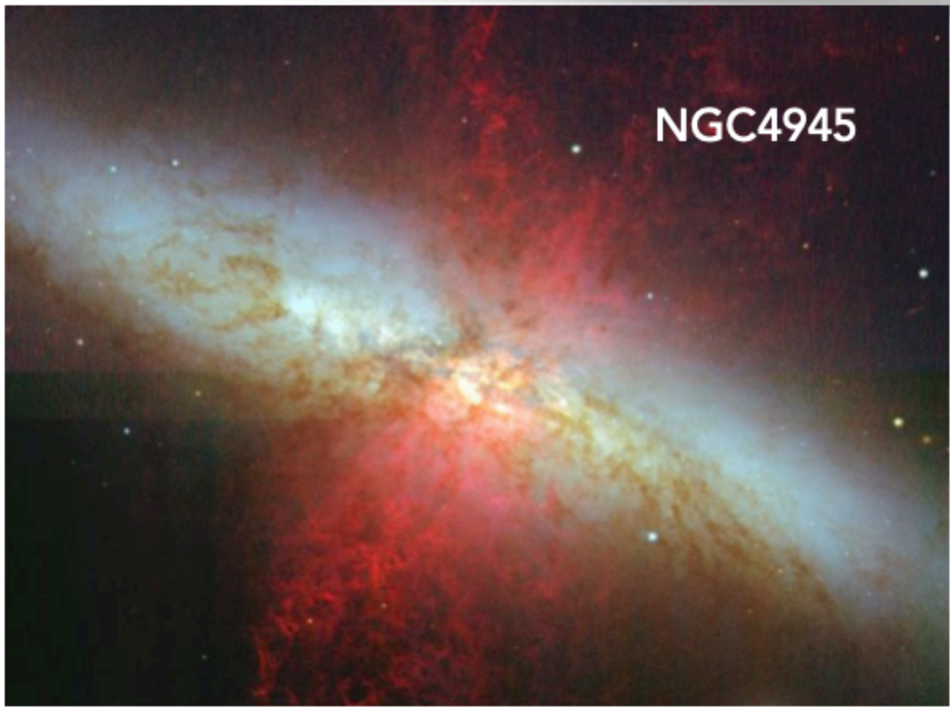
Significance

The UHE sky

Search for excesses of UHECRs from the direction of specific objects from an astrophysical catalog



Active Galactic Nuclei (AGN)
γ-emitting AGNs from Fermi-LAT 2FHL catalog,
$L_{UHECR} \sim L_\gamma(>10\ GeV)$



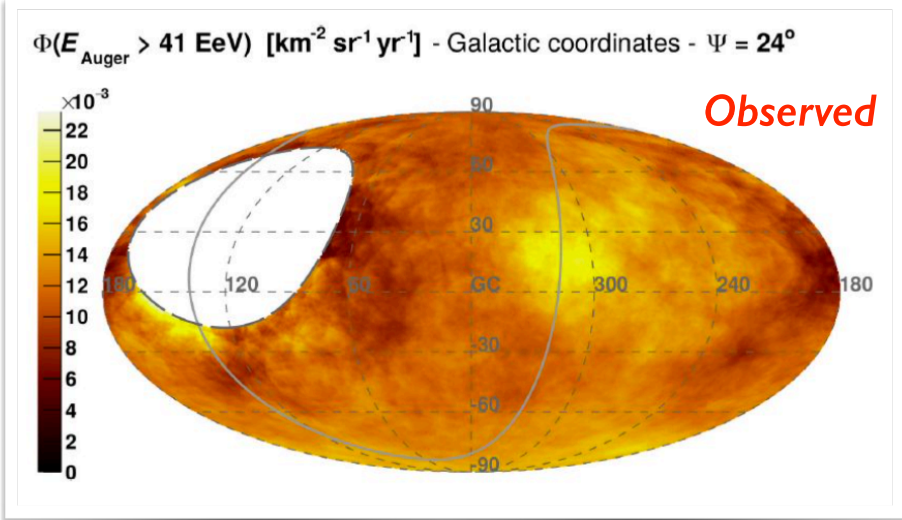
Starburst Galaxies (SBG)
from Fermi-LAT HCN survey,
$L_{UHECR} \sim L_\gamma(1.4\ GHz)$

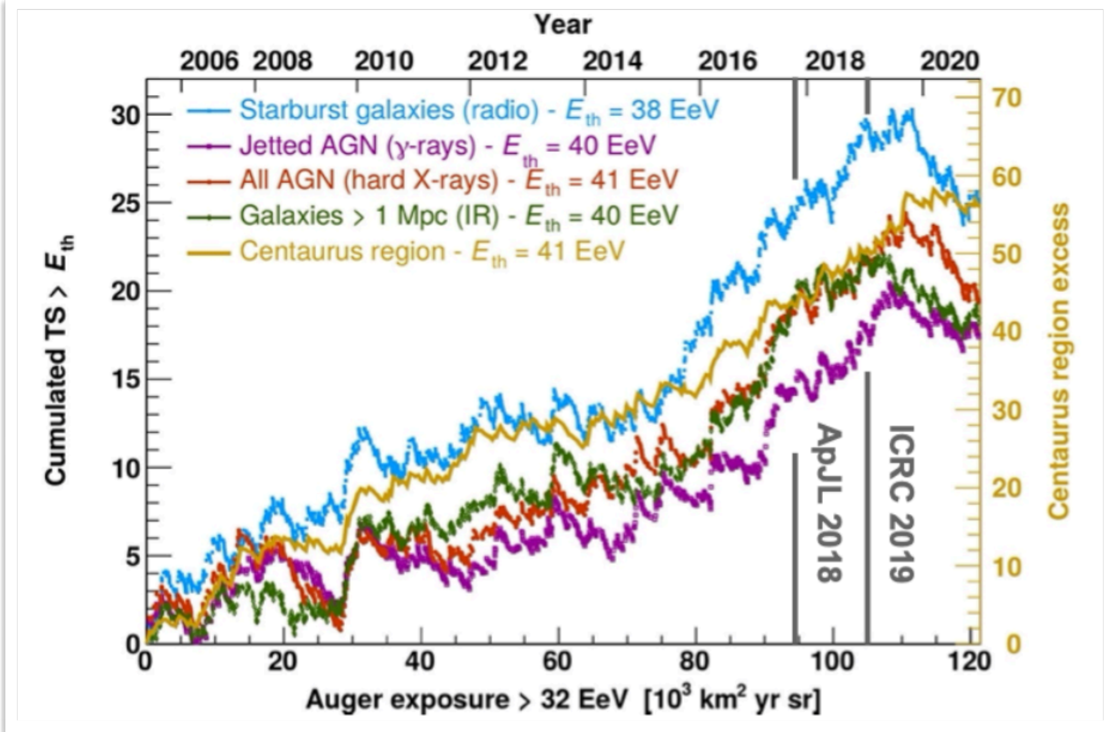
Sources at distances < 250 Mpc

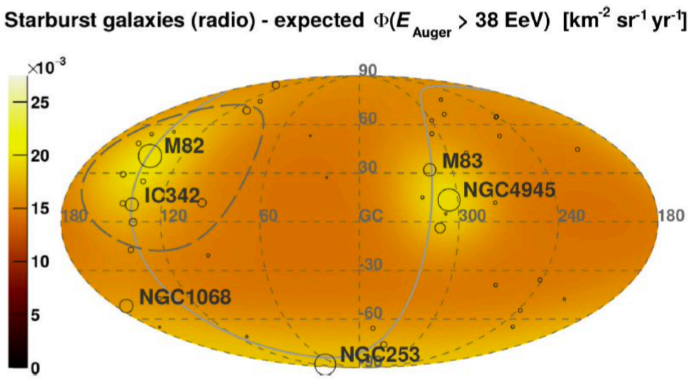
Assumption: UHECR flux ∝ non-thermal photon flux

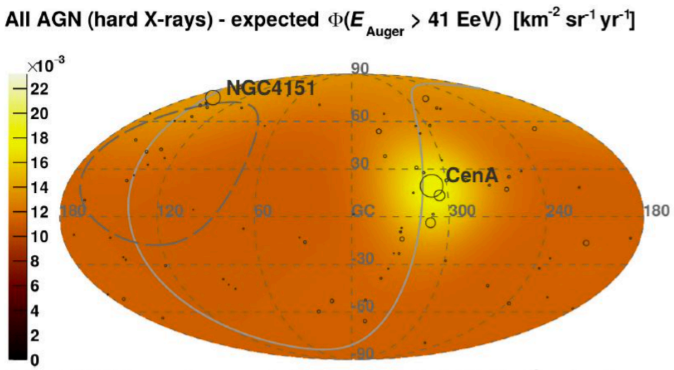
Analysis: unbinned maximum-likelihood analysis vs isotropy

The UHE sky - Auger





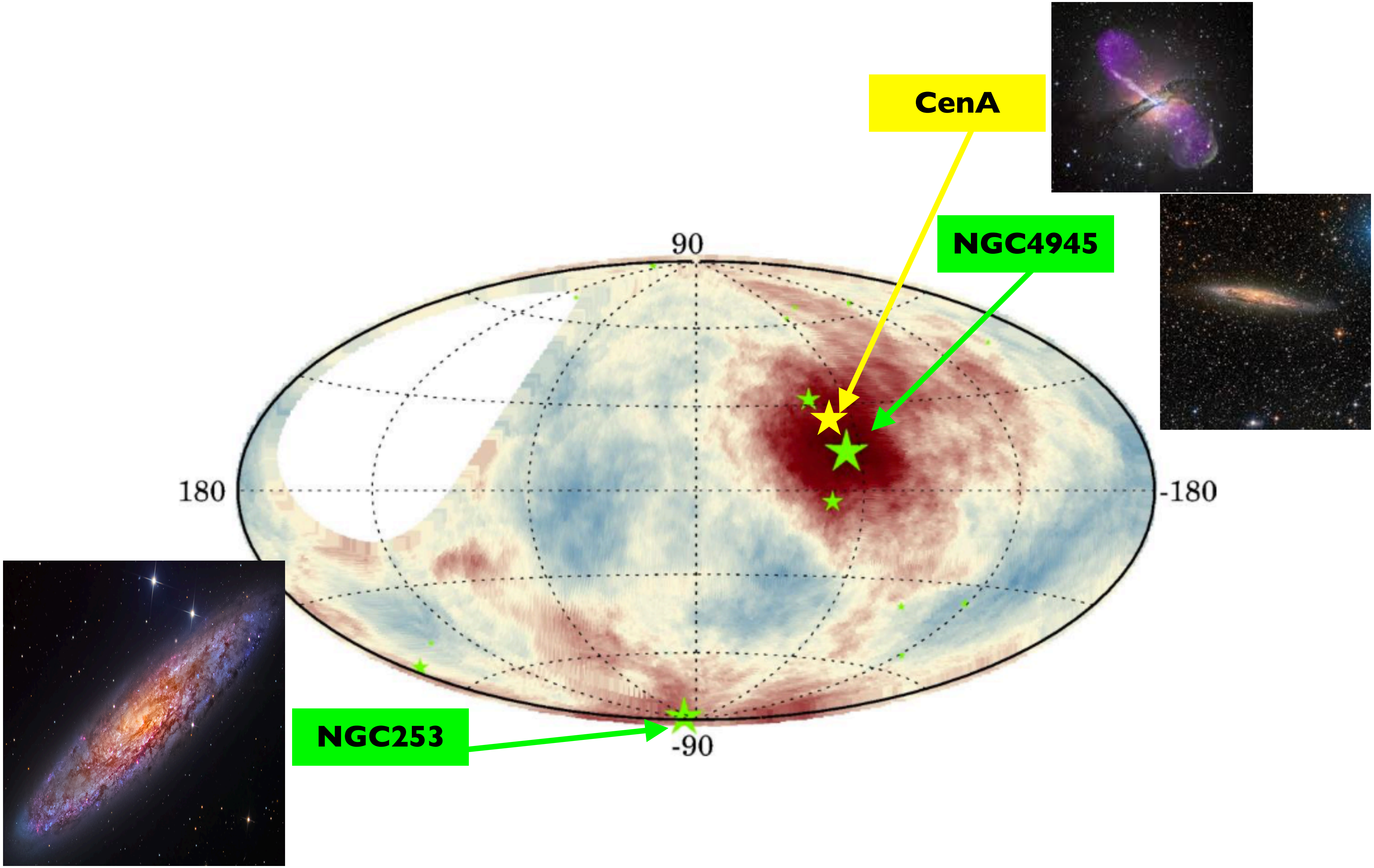




Catalog	$E_{\rm th}$ [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value	
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}	
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}	**4.0 σ**
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}	**3.1σ**
Jetted AGNs (γ-rays)	40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

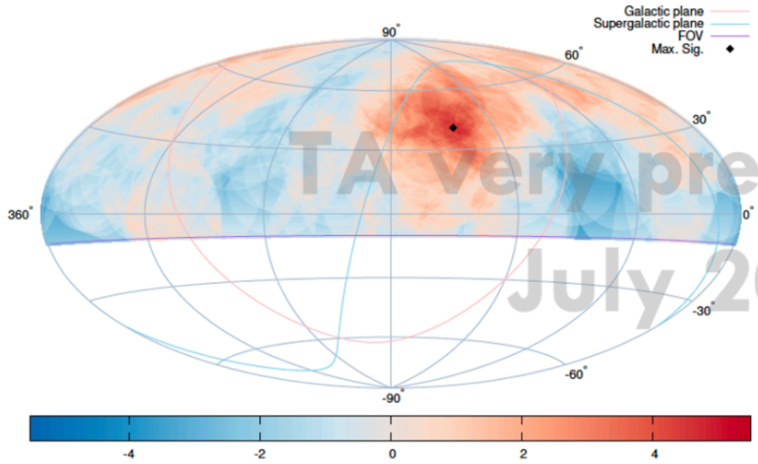
J.Biteau et al. (Auger Coll.) PoS(ICRC2021) 307

The UHECR Sky

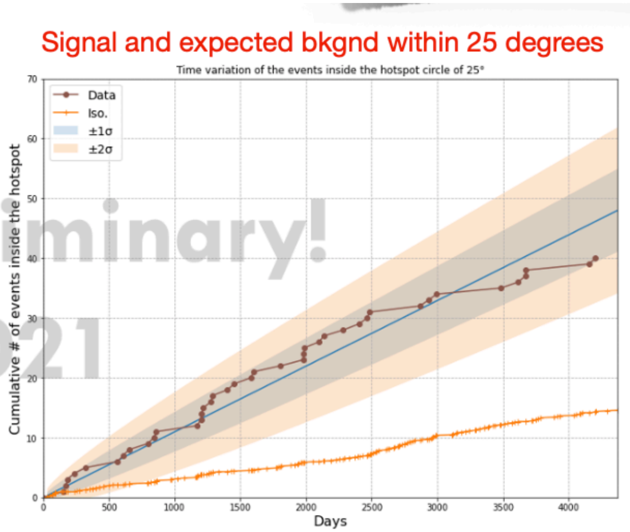


The UHE sky - TA

“Hot” spot

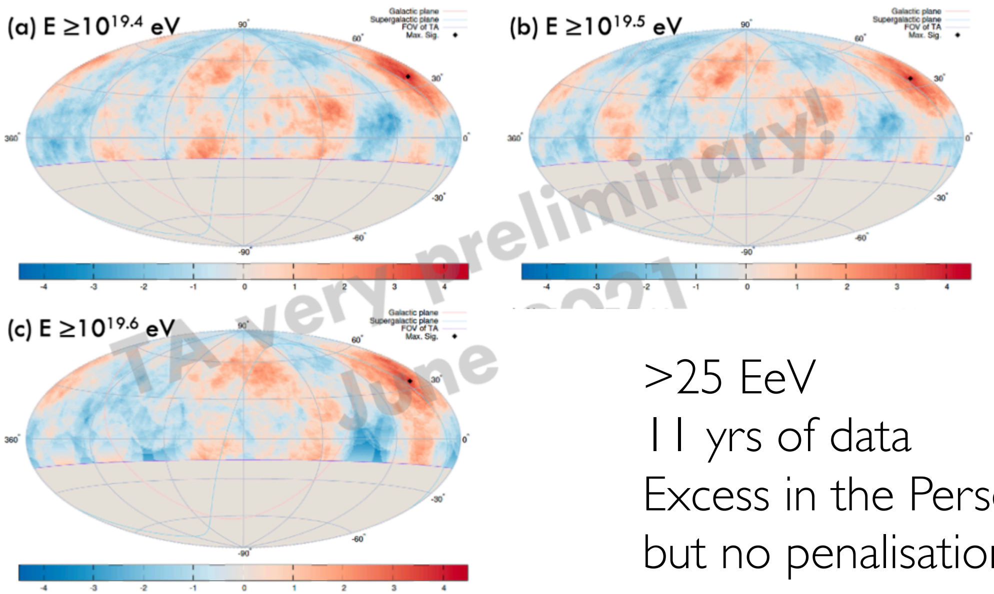


$E > 57$ EeV, 179 events across the sky (2021)



3.2σ post-trial in 25^0 window
Rate of increase constant
within +1σ

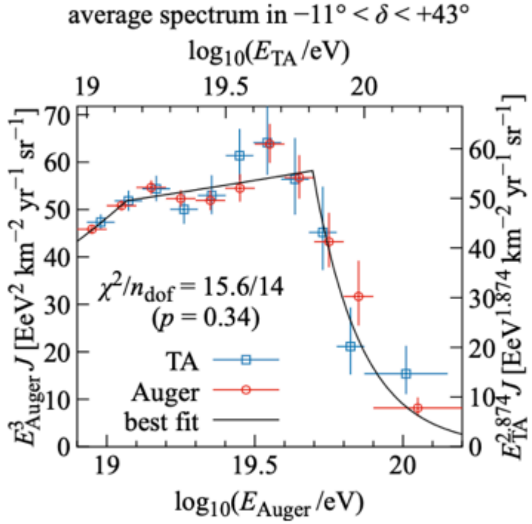
Kim et al. (TA Coll.,) PoS(ICRC2021) 328



>25 EeV
11 yrs of data
Excess in the Perseus-Pisces region, 3.6σ post-trial
but no penalisation for position in the sky

The UHE sky - Auger&TA

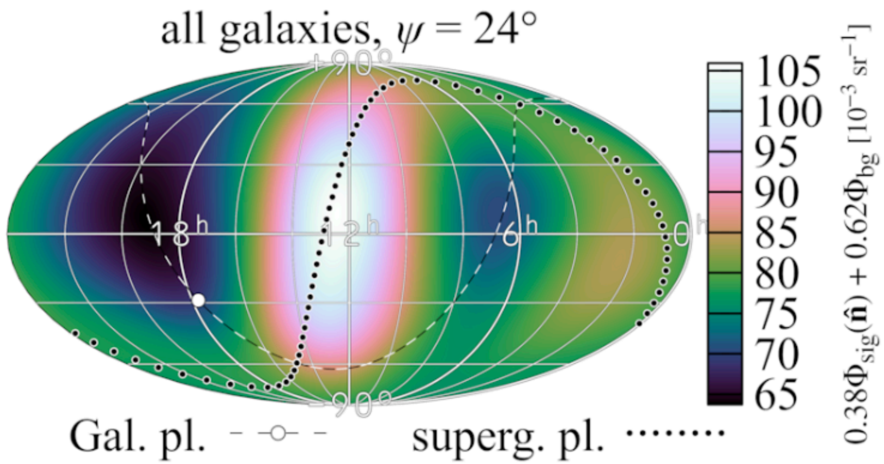
Auger ($\vartheta<80^0$): 120,000 km^2 sr yr
TA ($\vartheta<55^0$): 14,000 km^2 sr yr

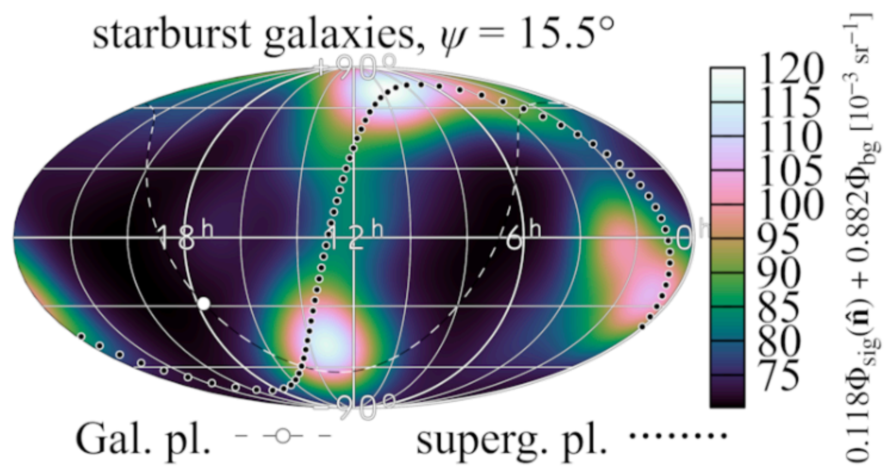


Energy scale conversion

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

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





catalog	E_{min} (Auger)	E_{min} (TA)	ψ	equiv. top-hat radius	f	TS	Post-trial significance
all galaxies	41 EeV	53 EeV	$24^{\circ}{}^{+13^{\circ}}_{-8^{\circ}}$	$38^{\circ}{}^{+21^{\circ}}_{-13^{\circ}}$	$38\%^{+28\%}_{-14\%}$	16.2	2.9σ
starburst galaxies	38 EeV	49 EeV	$15.5^{\circ}{}^{+5.3^{\circ}}_{-3.2^{\circ}}$	$24.6^{\circ}{}^{+8.4^{\circ}}_{-5.1^{\circ}}$	$11.8\%^{+5.0\%}_{-3.1\%}$	27.2	4.2σ

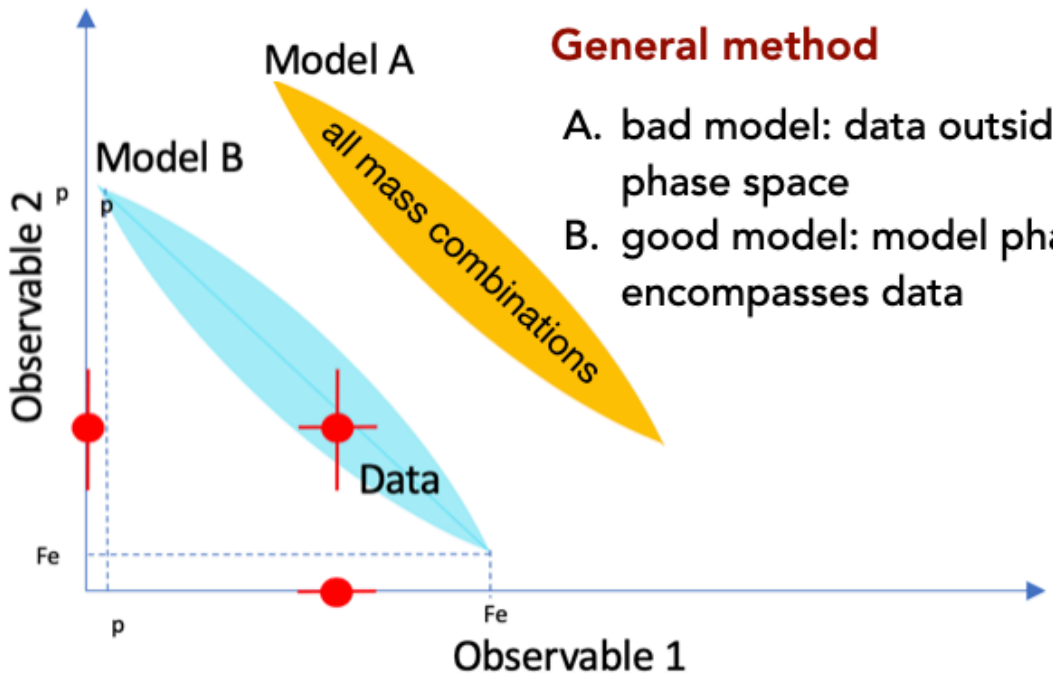
A.di Matteo et al. (Auger-TA working group) PoS(ICRC2021) 308

The mass composition

Air shower+hadronic interaction models are required to convert N_μ and X_{max} to A

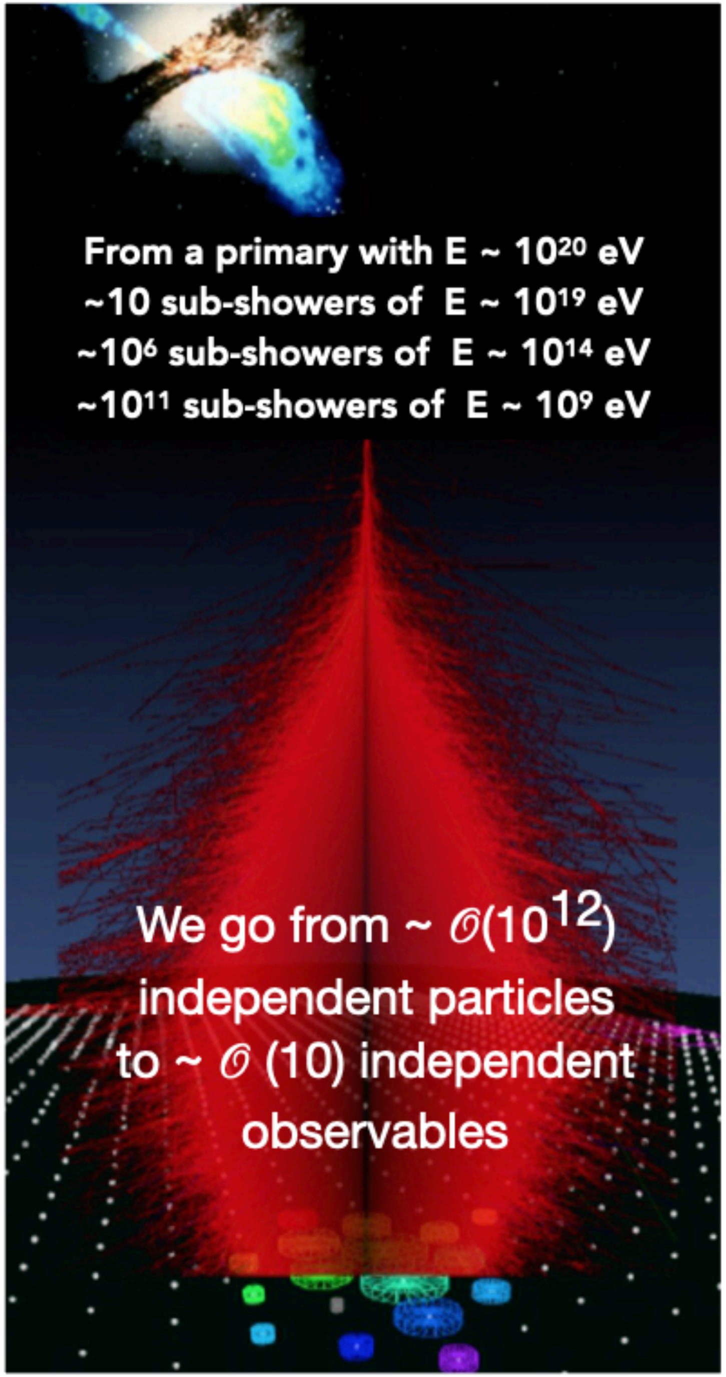
model uncertainty = maximum contribution to systematics

- simulation of different possibilities for the UHECR unknown composition
- check of the compatibility of data with the phase space allowed in a specific model

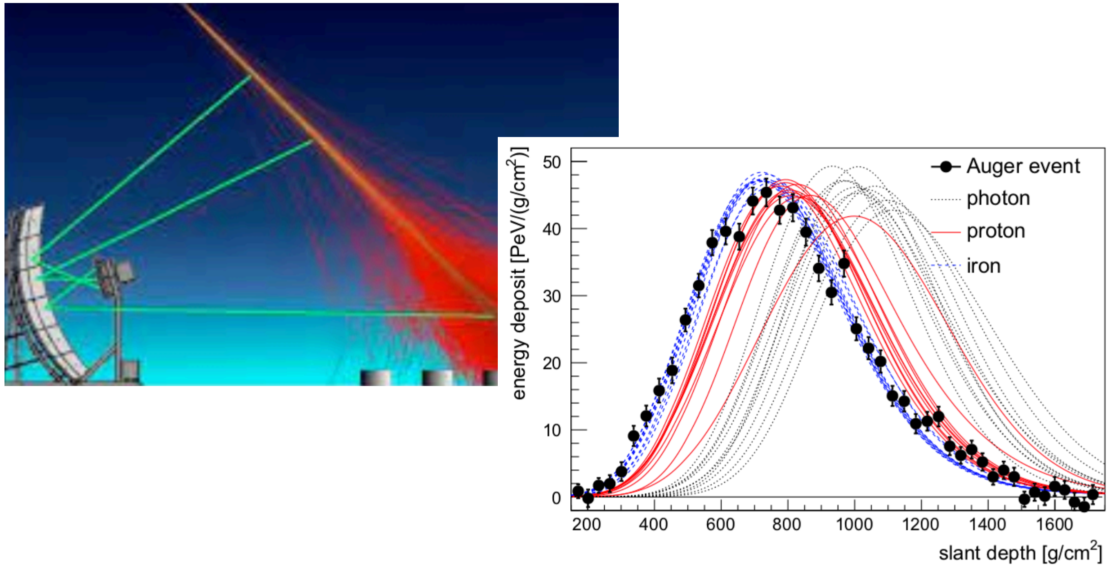


General method

A. bad model: data outside model phase space
B. good model: model phase space encompasses data



The mass composition

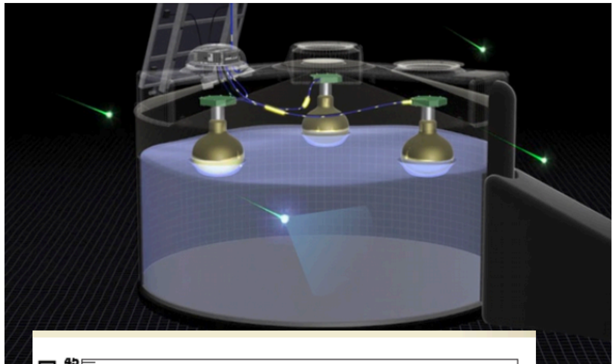


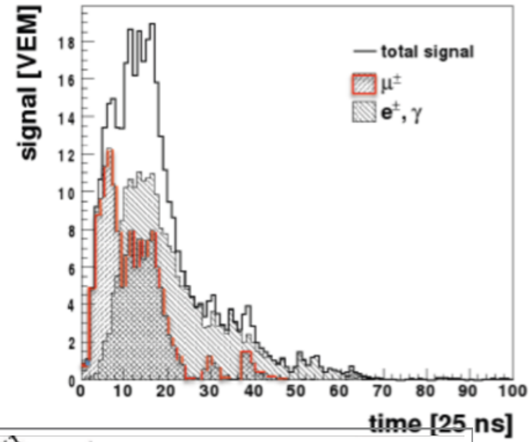
Fluorescence telescopes

- ➡ X_{max} distributions
- ➡ X_{max} moments: $\langle X_{max} \rangle$, $\sigma(X_{max})$
- ➡ X_{max} resolution from 25 to 15 g cm^{-2} for increasing E
- ➡ $\sigma_{sys} \leq 10$ g cm^{-2}
- ➡ Separation p/Fe ~ 100 g cm^{-2}

Surface detectors

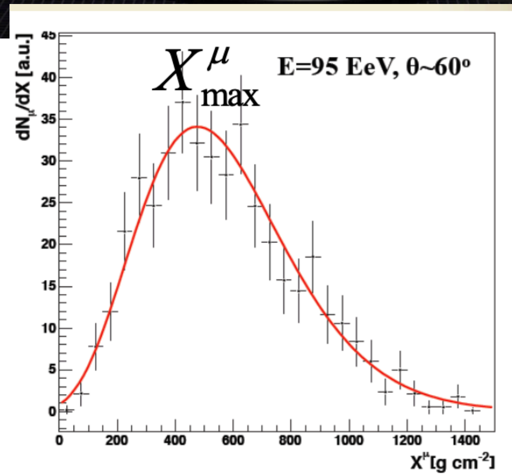
- ➡ no direct observation of X_{max} possible
- ➡ time structure of SD signals
- ➡ muon number distributions (inclined events)

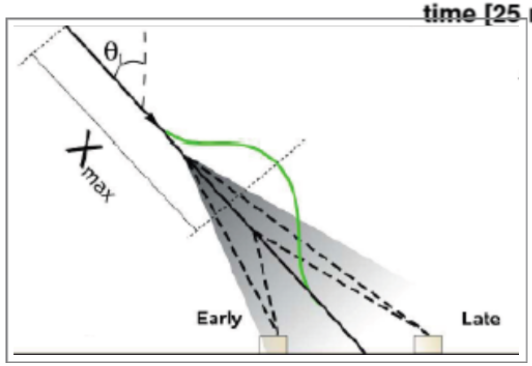




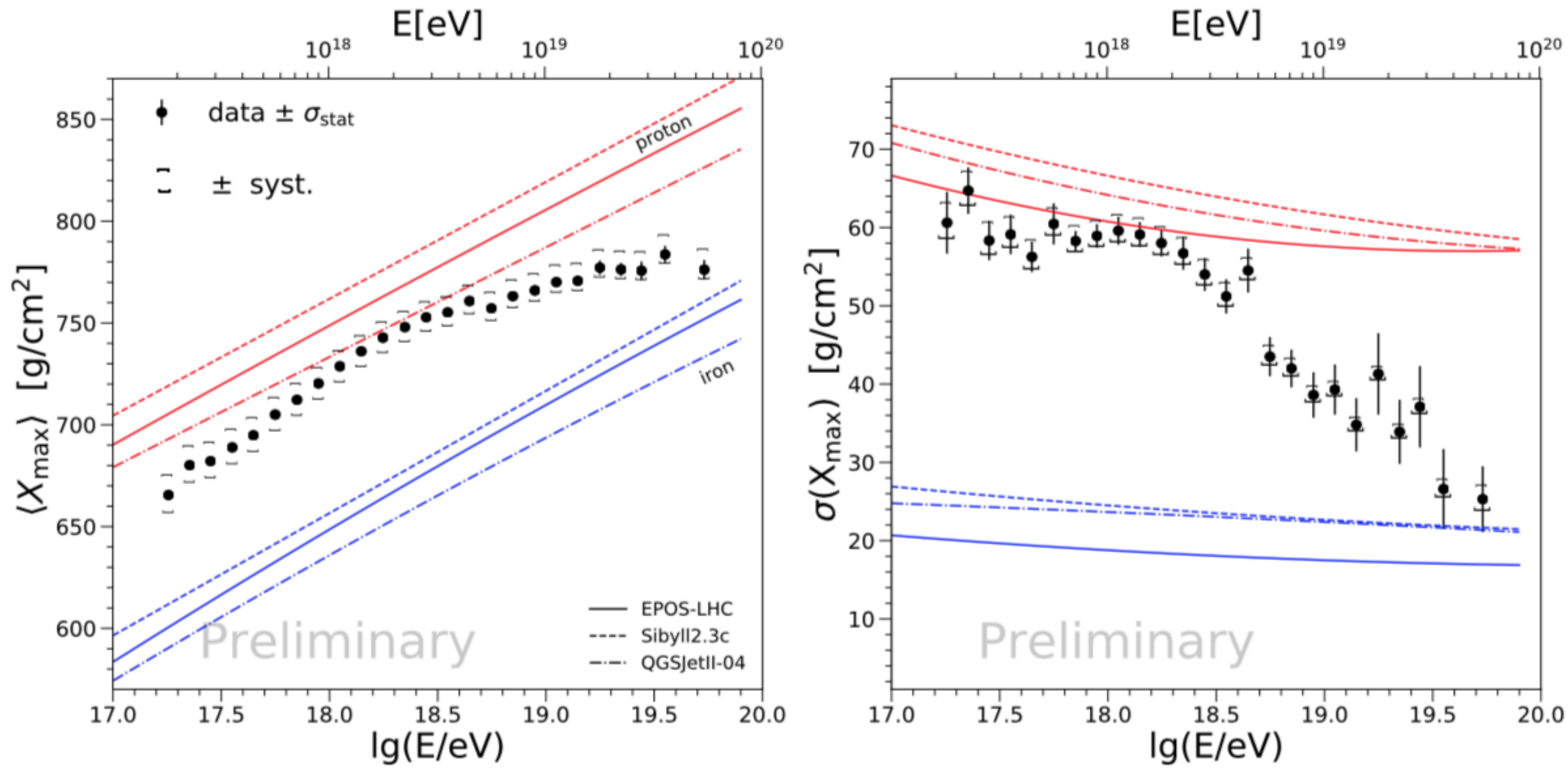
Correlation studies SD-FD

- ➡ cross calibration
- ➡ S1000 - X_{max}
- ➡ use of Deep learning





The mass composition from FD



$$\langle X_{max} \rangle = \langle X_{max} \rangle_p + f_E \langle lnA \rangle$$

$$\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f_E \sigma^2(lnA)$$

X_{max} resolution

~25 g cm^{-2} at $10^{17.8}$ eV

~15 g cm^{-2} for E> 10^{19} eV

$\sigma_{sys} \leq$ 10 g cm^{-2}

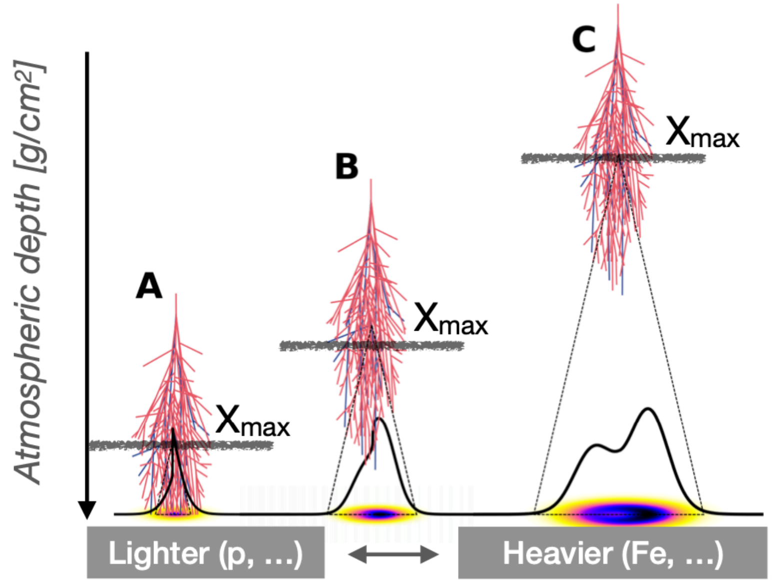
Lighter composition up to ~2 EeV, heavier above this energy

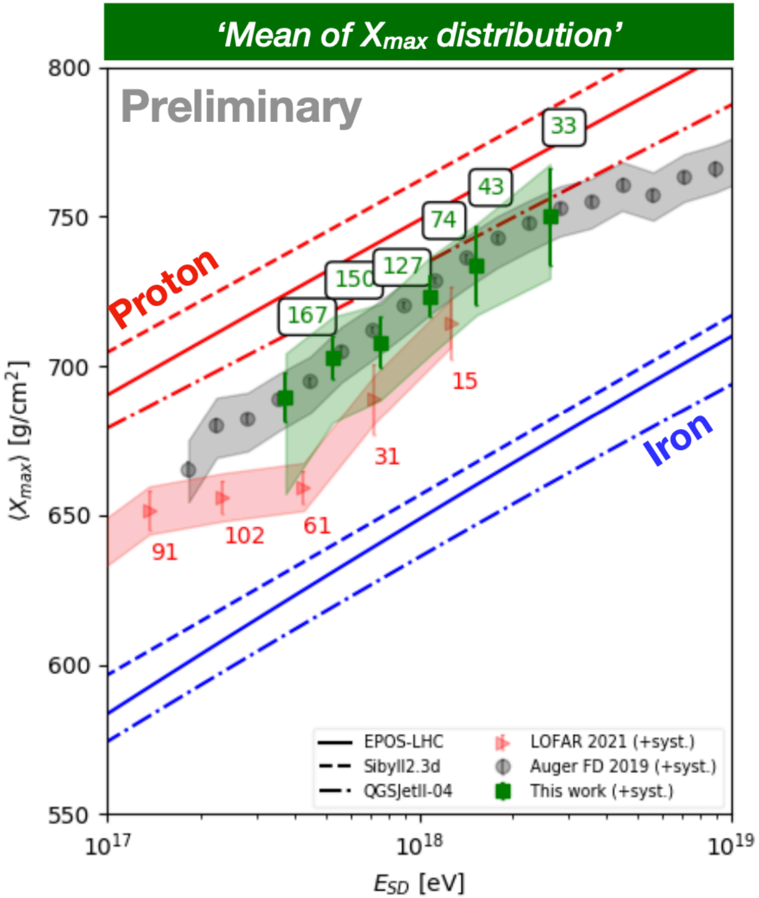
(80±1) g/cm^2/decade up to ~ 2 EeV

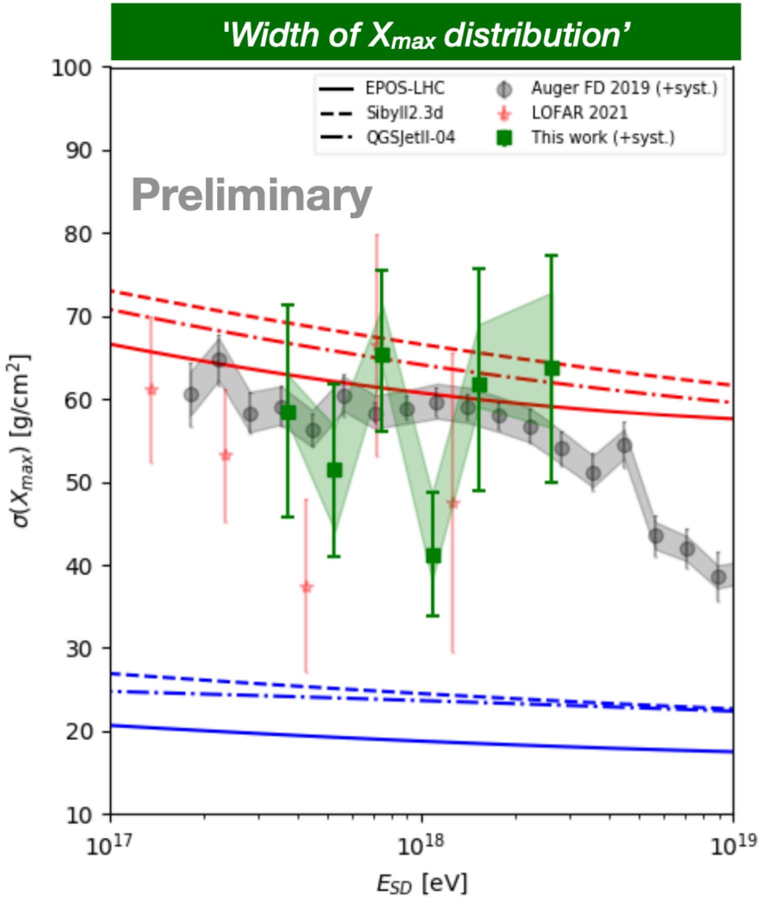
(26±2) g/cm^2/decade above ~ 2 EeV

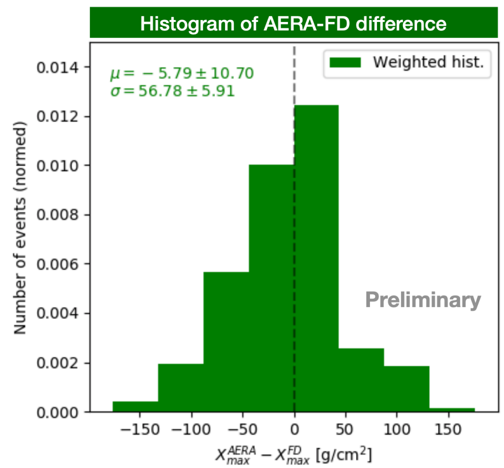
Independent confirmation from radio

- AERA: 153 radio antennas, 27 km²
- general agreement with FD result
- independent measurement wrt FD: checks the consistency of the Xmax method and probes different shower physics
-

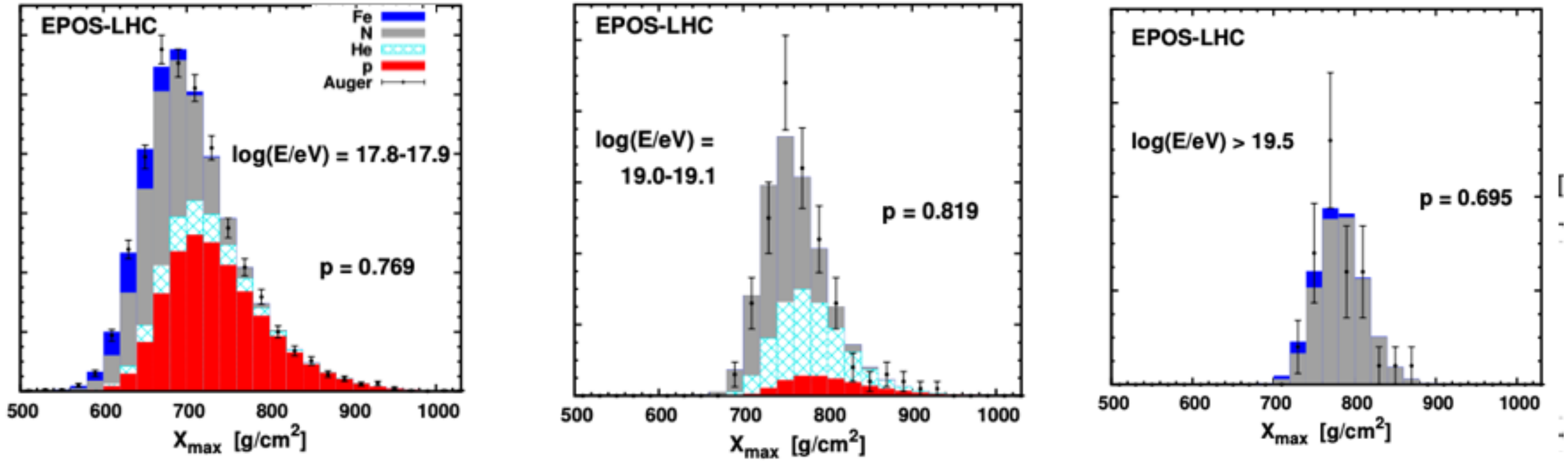


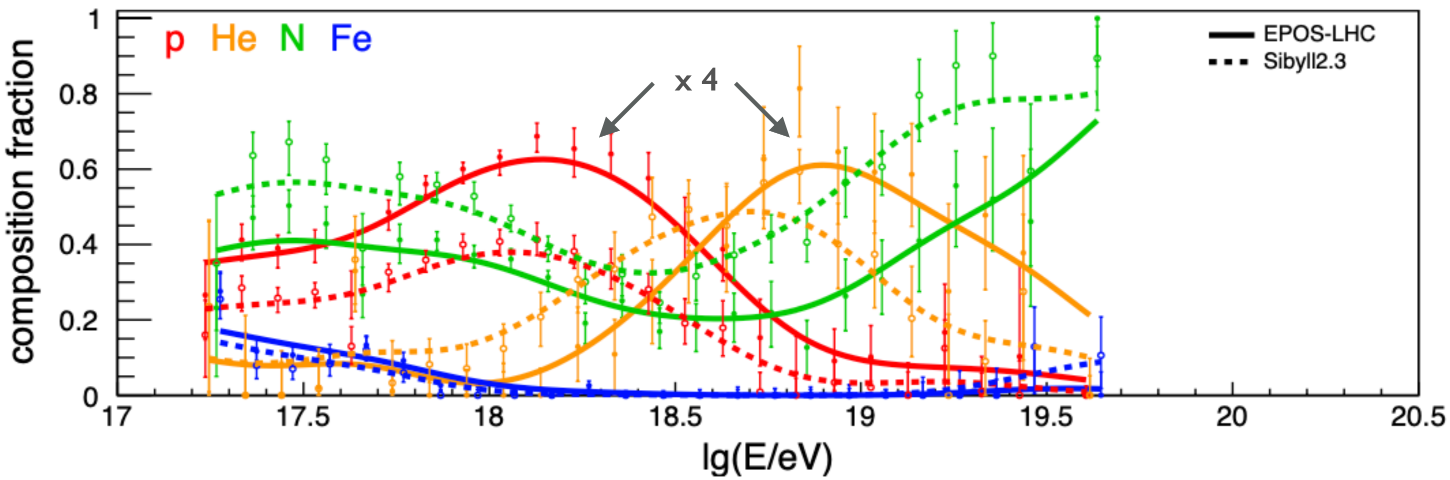






Heavy or light?



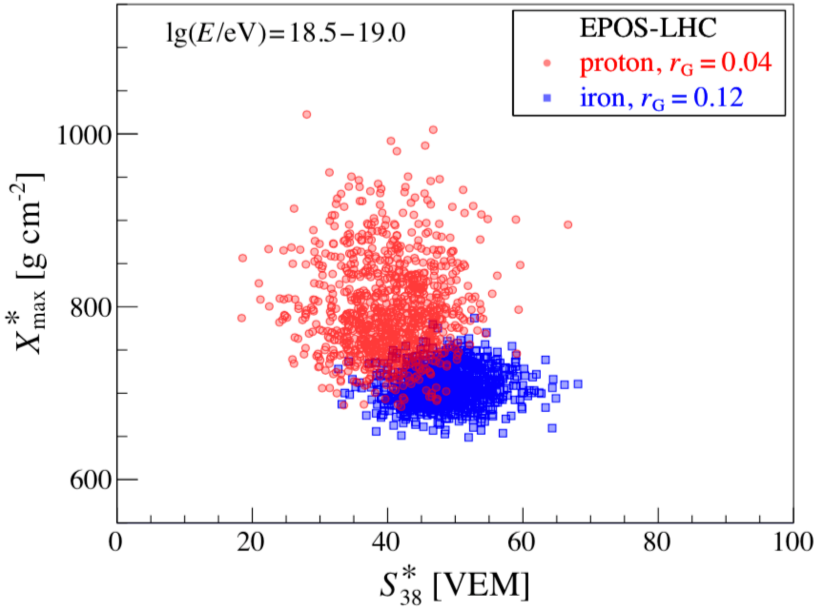


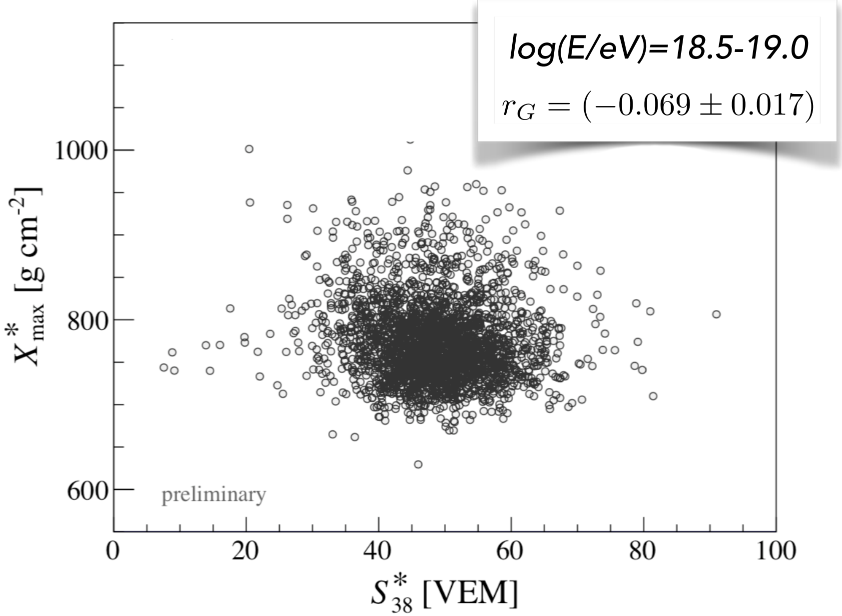
Mass fractions at Earth from fitting templates of 4 mass groups to the measured X_{max} distributions

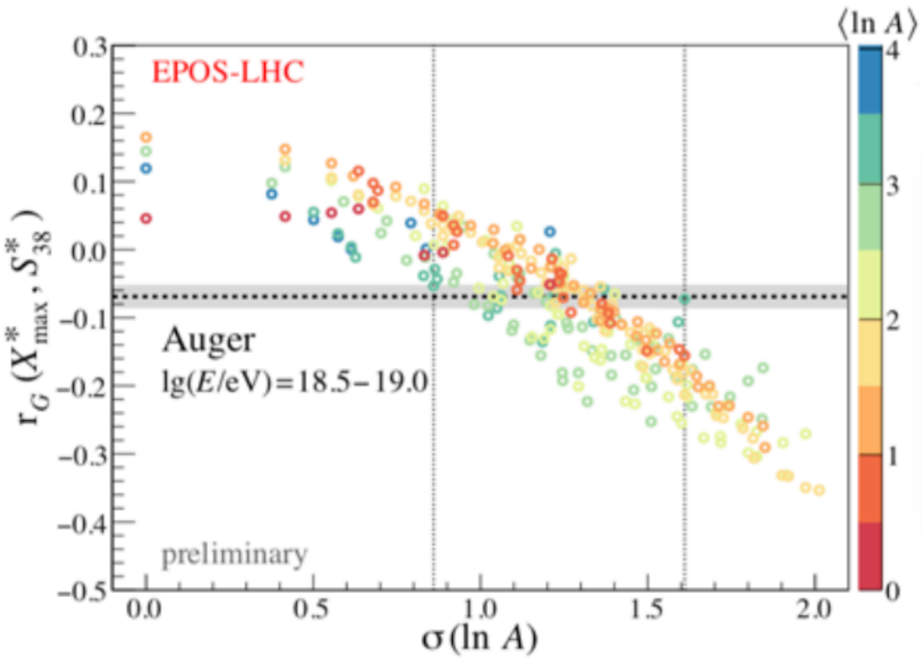
Peter's cycle
or
Spallation ?

Auger Coll., Phys.Rev.D90 (2014) 122005
Auger Coll., Phys.Rev.D96 (2017) 122003
MIAPP Review (2019)
+ Auger Coll. ICRC2021

Heavy or light? an independent measurement







*Data compatible with 0.85 ≲**σ**(lnA)≲1.60*

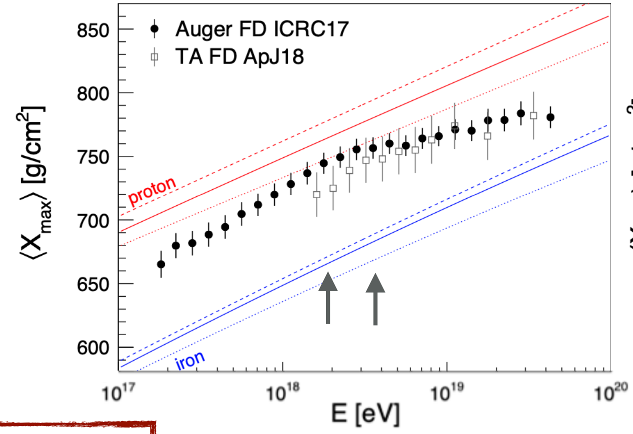
*Around the ankle ($10^{18.5}$-10^{19} eV) the composition is mixed: pure or only light masses excluded at >6**σ** CL*

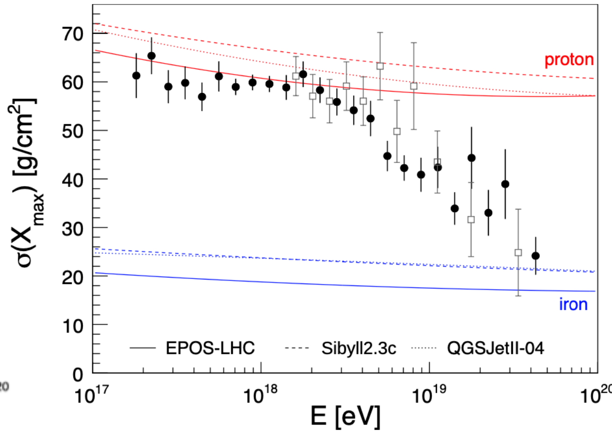
Analysis not affected by detector systematics or by hadronic interaction models uncertainties

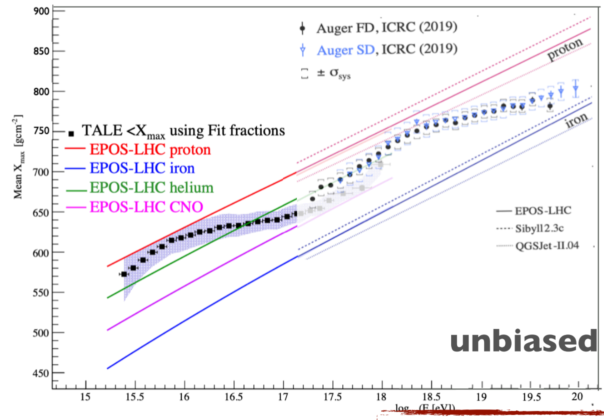
Auger Coll., Phys.Lett. B762 (2016) 288
A.Yushkov, PoS(ICRC2019) 482

Composition differences between Auger and TA?

- Unbiased measurements of the first 2 moments of the X_{max} distributions



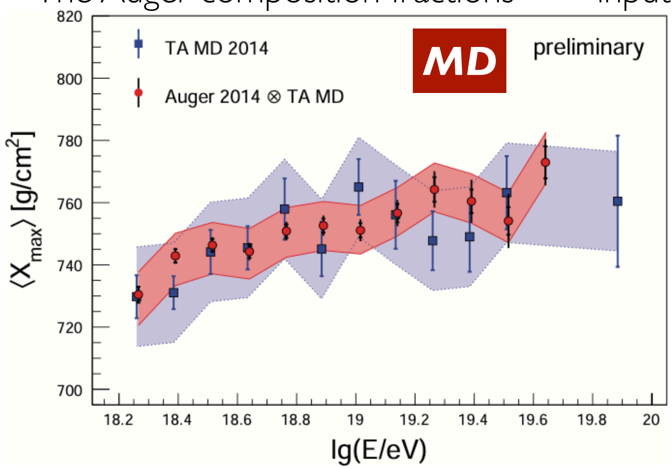


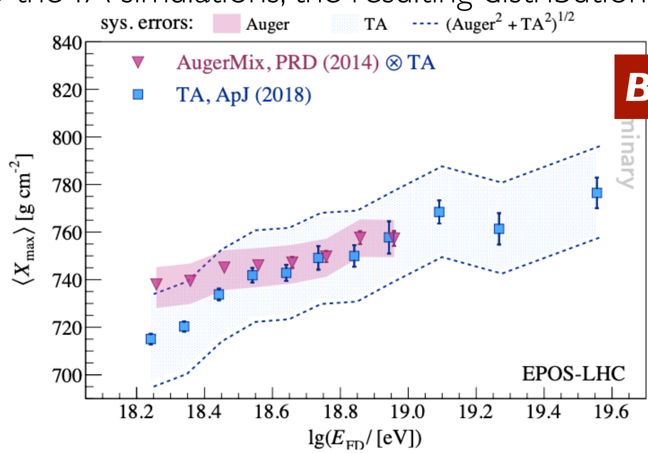


MIAPP review (2019)

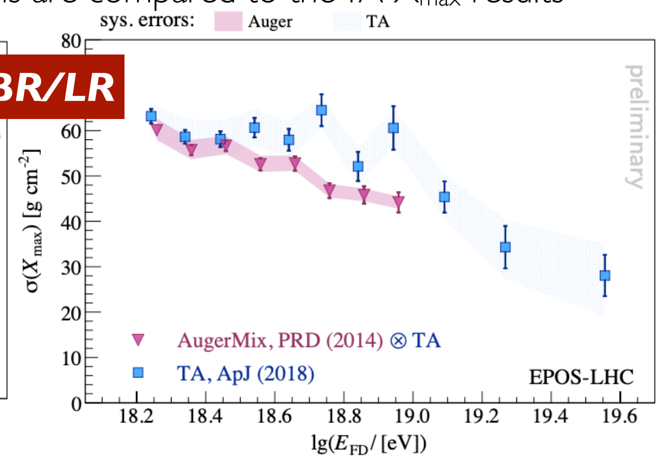
TA Coll., ApJ 909 (2021) 178
Auger Coll. ICRC2019

- The Auger composition fractions —> input to the TA simulations; the resulting distributions are compared to the TA X_{max} results





BR/LR



TA data consistent with proton AND ALSO with Auger-mix composition at least up to 10 EeV due to systematic uncertainties and low statistics

Auger&TA working groups, JPS Conf.Proc. 9 (2016) 010016
Auger&TA working groups, EPJ Web of Conf. 210 (2018) 010009

Combining spectrum and composition

CRs ejected by generic EG accelerators

Assumptions on a simple astrophysical model

CRs considered **at the escape**)
Propagation only

- homogenous and isotropic sources
- different scenarios (Extragalactic / Galactic sources components)
- all emitting particles with the same spectrum

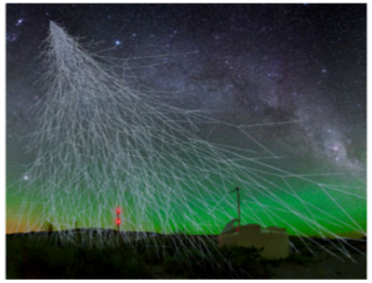
Propagation through the intergalactic medium +

SimProp simulations

Choice of propagation models for uncertain quantities

- Photodisintegration models
- EBL models

Production of showers in the atmosphere



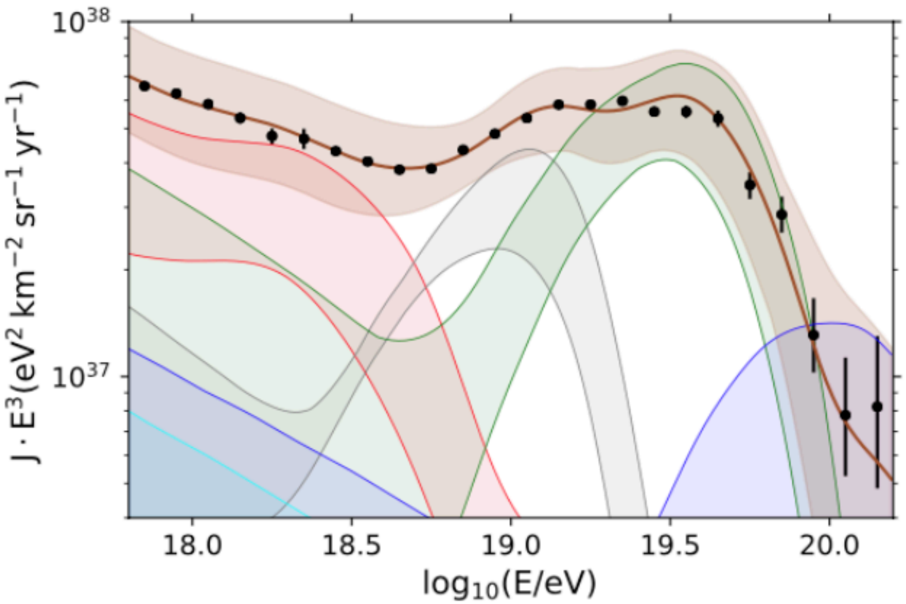
Choice of hadronic interaction models

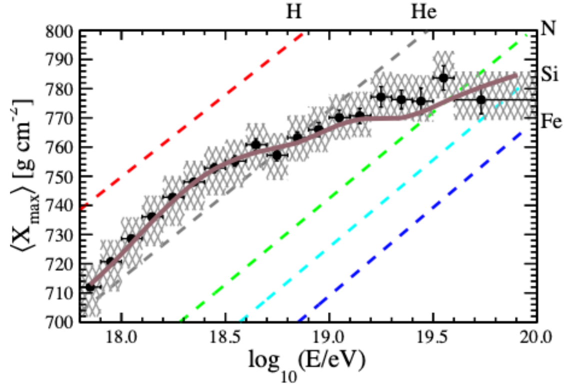
- post-LHC models
  EPOS-LHC
  Sibyll2.3d
  QGSJetII-04

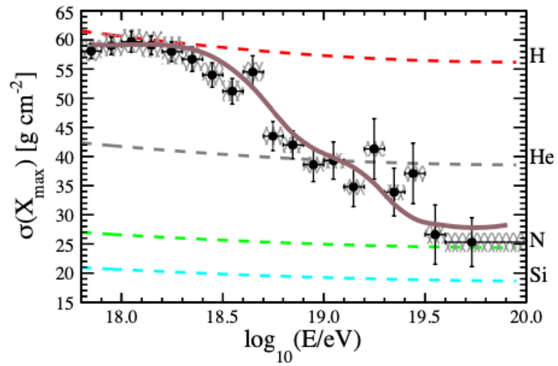
Comparison of
expected spectrum and X_{max} distributions at Earth
measured spectrum and X_{max} distributions
Comparison of expected neutrino and phon fluxes with experimental upper limits

E.Guido et al. (Auger Coll.), PoS(ICRC2021) 311

Combining spectrum and composition







<u>BEST FIT</u>

EG: hard HE component + soft LE component

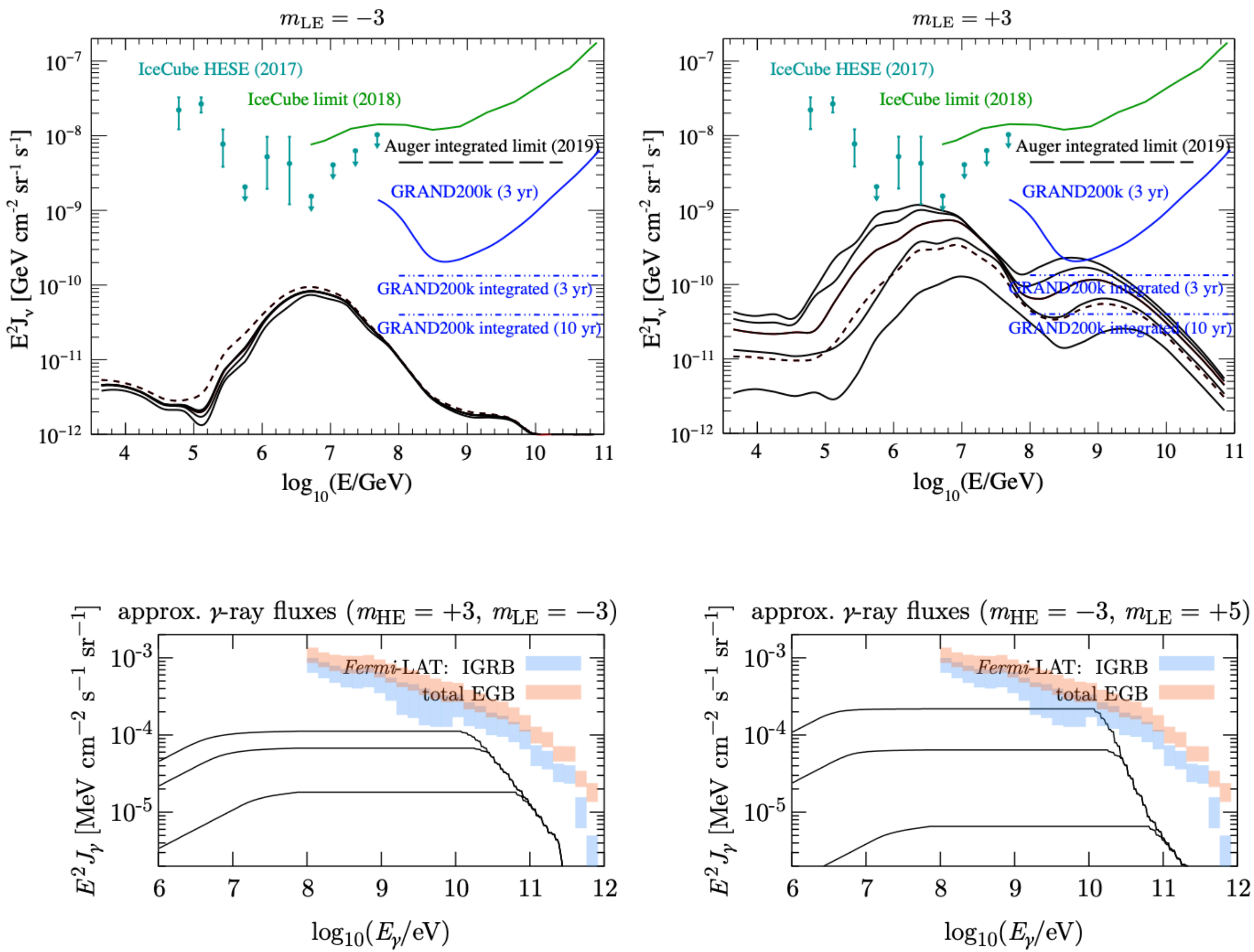
possible Galactic component (N)

- Scenarios compatible within systematics
- AGN Source evolution for the HE component excluded
- dominant systematics uncertainties=experimental (X_{max})

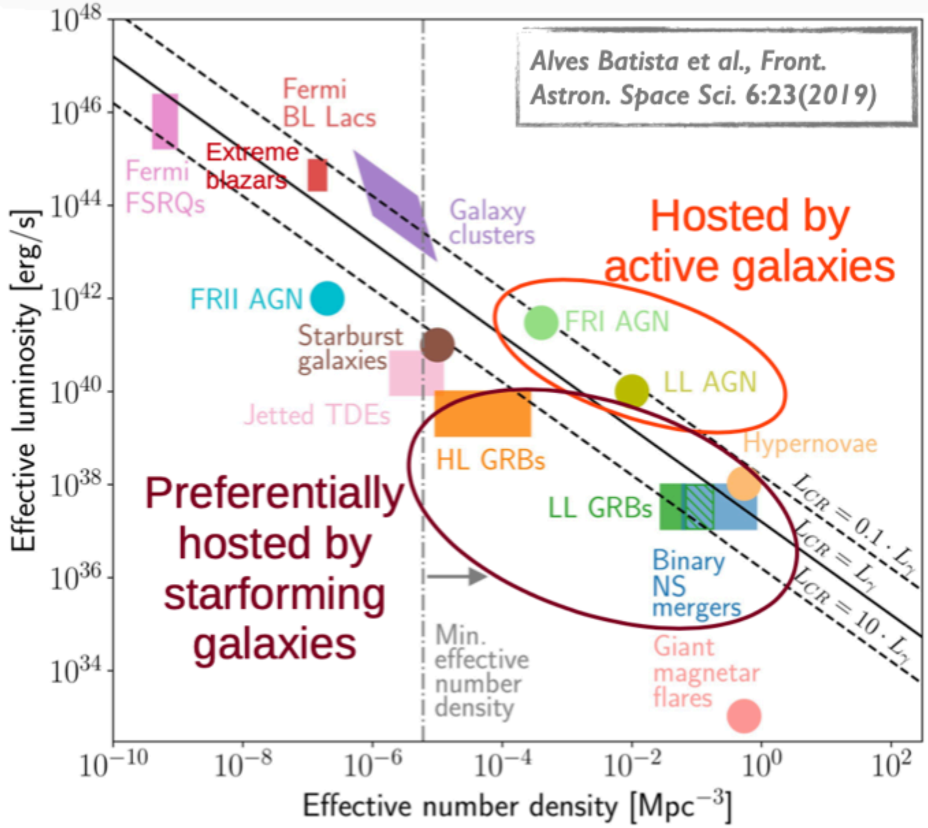
	1st scenario		2nd scenario	
Galactic contribution (at Earth)	N+Si		-	
J_0^{gal} [eV^{-1} km^{-2} sr^{-1} yr^{-1}]	$(1.07 \pm 0.06) \cdot 10^{-13}$		-	
$\log_{10}(R_{cut}^{gal}/V)$	17.48 ± 0.02		-	
f_N (%)	93.0		-	
EG components (at the sources)	Low energy	High energy	Low energy	High energy
$\mathcal{L}_0$ [erg Mpc^{-3} yr^{-1}]	$7.28 \cdot 10^{45}$	$4.4 \cdot 10^{44}$	$1.7 \cdot 10^{46}$	$4.5 \cdot 10^{44}$
γ	3.30 ± 0.05	-1.47 ± 0.12	3.49 ± 0.02	-1.98 ± 0.10
$\log_{10}(R_{cut}/V)$	24 (lim.)	18.19 ± 0.02	24 (lim.)	18.16 ± 0.01
I_H (%)	100 (fixed)	0.0	49.87	0.0
I_{He} (%)	-	27.17	10.92	28.60
I_N (%)	-	69.86	36.25	69.05
I_{Si} (%)	-	0.0	0.0	0.0
I_{Fe} (%)	-	2.97	2.96	2.35
D_J (N_J)	49.5 (24)		60.1 (24)	
$D_{X_{max}}$ ($N_{X_{max}}$)	593.8 (329)		554.8 (329)	
D (N)	643.3 (353)		614.9 (353)	

E.Guido et al. (Auger Coll.), PoS(ICRC2021) 311

Combined fit: expected fluxes of $\boldsymbol{\nu}$ and $\boldsymbol{\gamma}$



Constraints on the UHECR sources

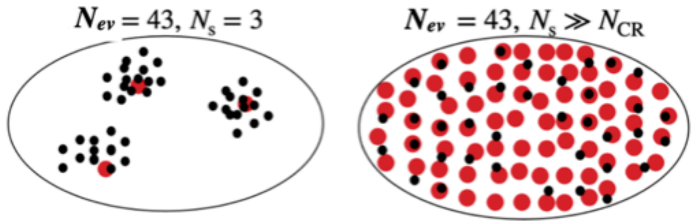


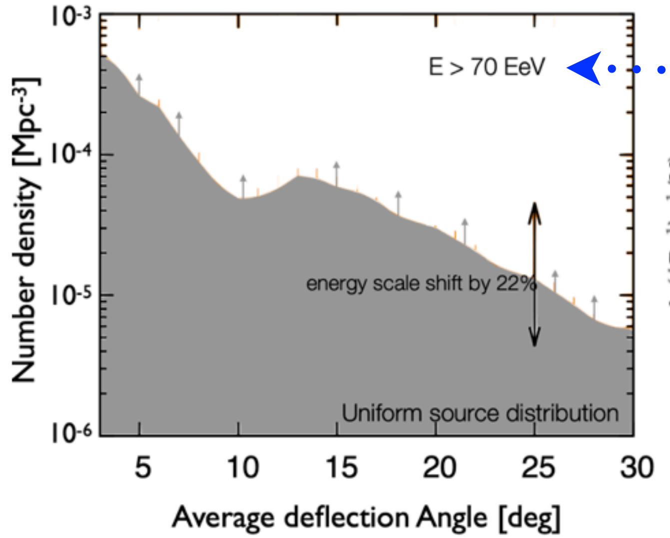
➡ $n_s \gtrsim 10^{-6}$ Mpc^{-3} at least one source within the GZK sphere (r~100 Mpc)

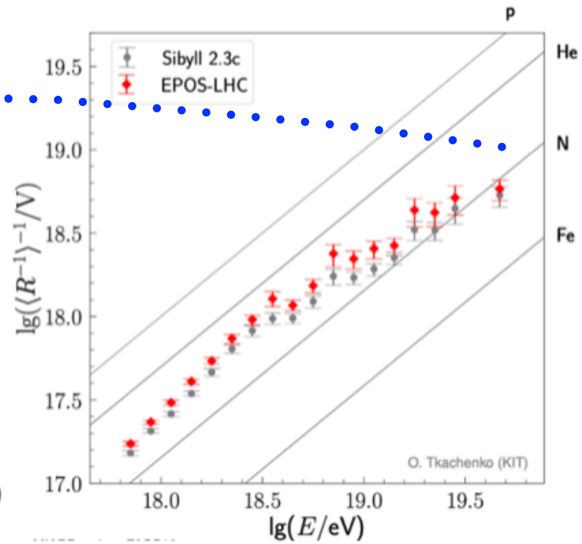
➡ $n_s \lesssim 10^{-4}$ Mpc^{-3}

$$u_{CR} = \frac{4\pi}{\beta c}\int_{E_{min}} E\frac{dN}{dE}dE \qquad \epsilon = \frac{c\, u_{CR}}{L_{loss}} \qquad n_s = L_{min}/\epsilon$$

➡ $n_s \gtrsim 10^{-5}$ Mpc^{-3}: non observation of multiplets in IceCube







Auger CR-CR correlations

Auger Coll., JCAP05 (2013) 009

Multi-messengers at UHE

Neutrinos

- not deflected by GMF/EGMFs
- only messengers along cosmological distances
- can escape from the core of sources
- difficult to detect

Gamma rays

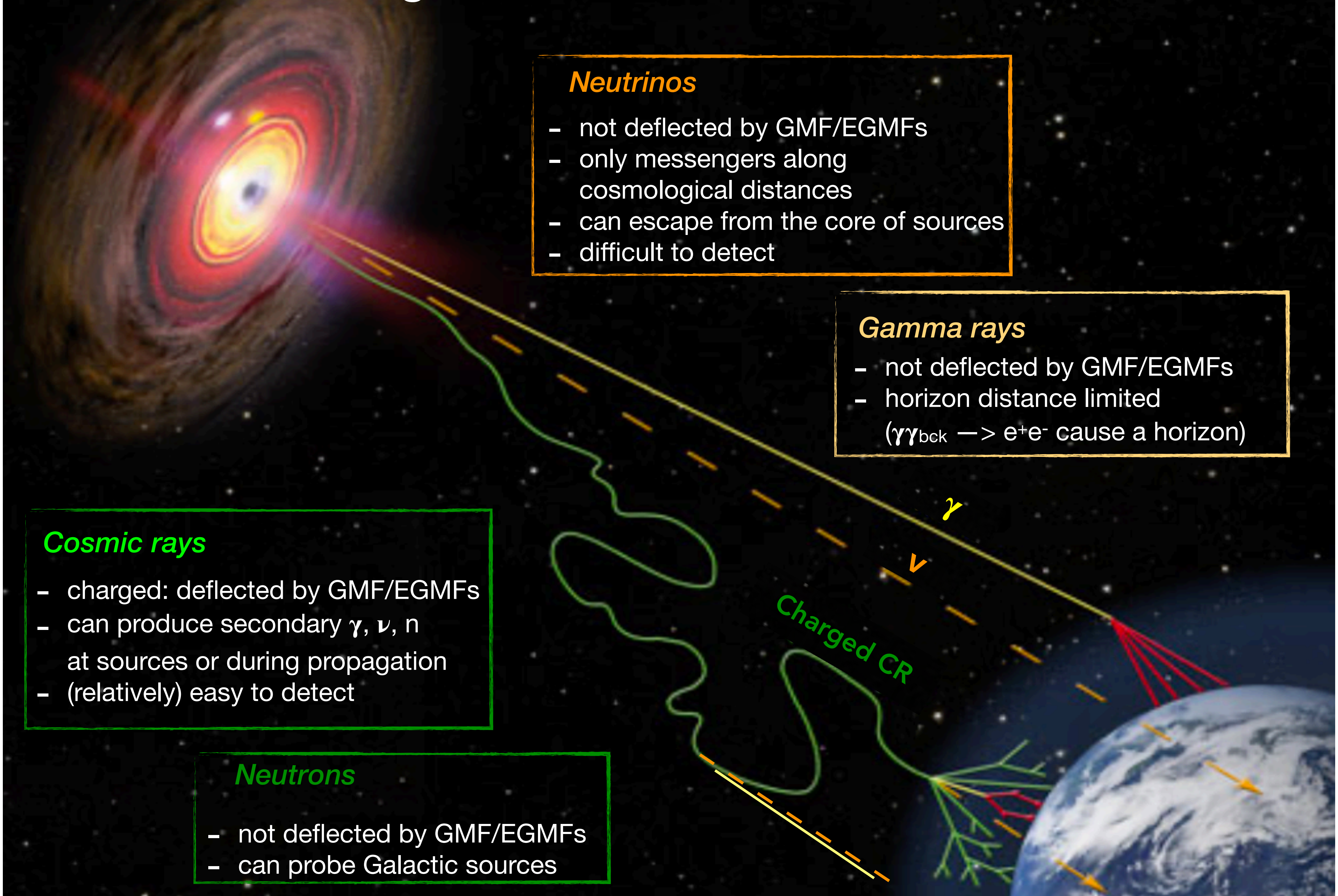
- not deflected by GMF/EGMFs
- horizon distance limited ($\gamma\gamma_{bck}$ —> e^+e^- cause a horizon)

Cosmic rays

- charged: deflected by GMF/EGMFs
- can produce secondary γ, ν, n at sources or during propagation
- (relatively) easy to detect

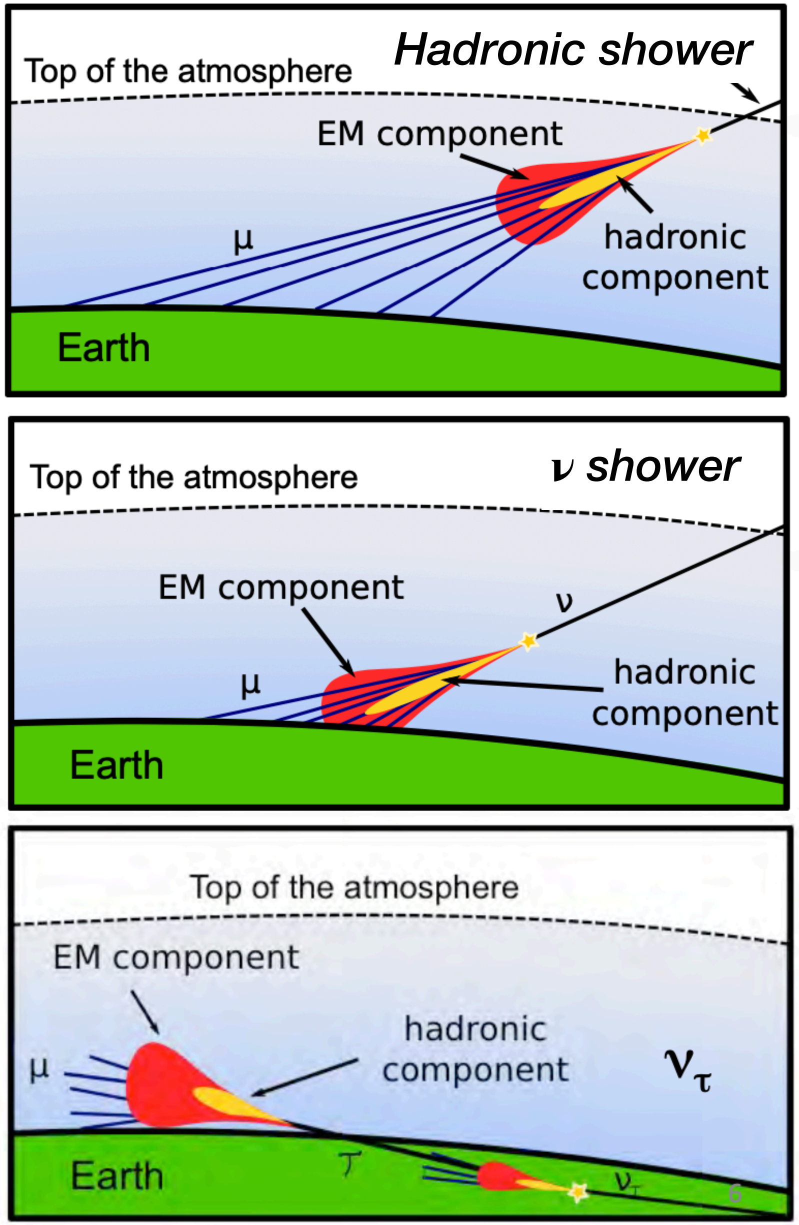
Neutrons

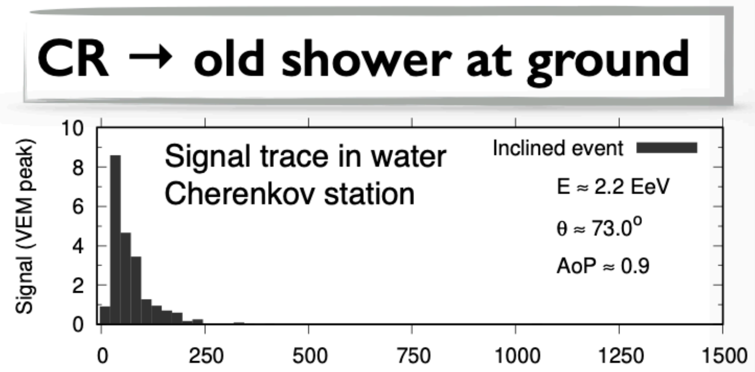
- not deflected by GMF/EGMFs
- can probe Galactic sources

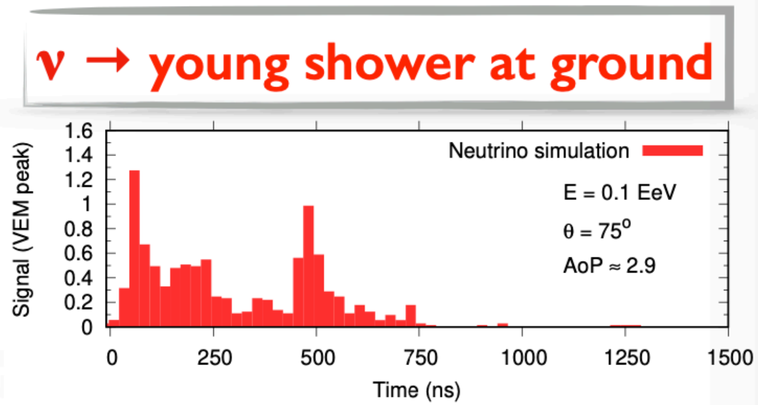


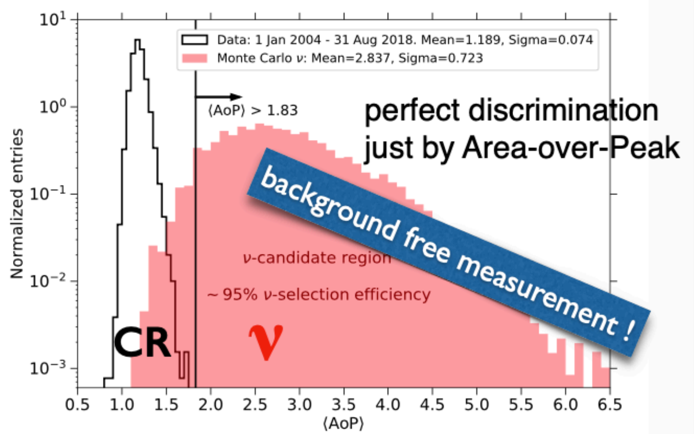
Neutrinos in Auger

Searching for neutrinos = look for inclined showers with em component

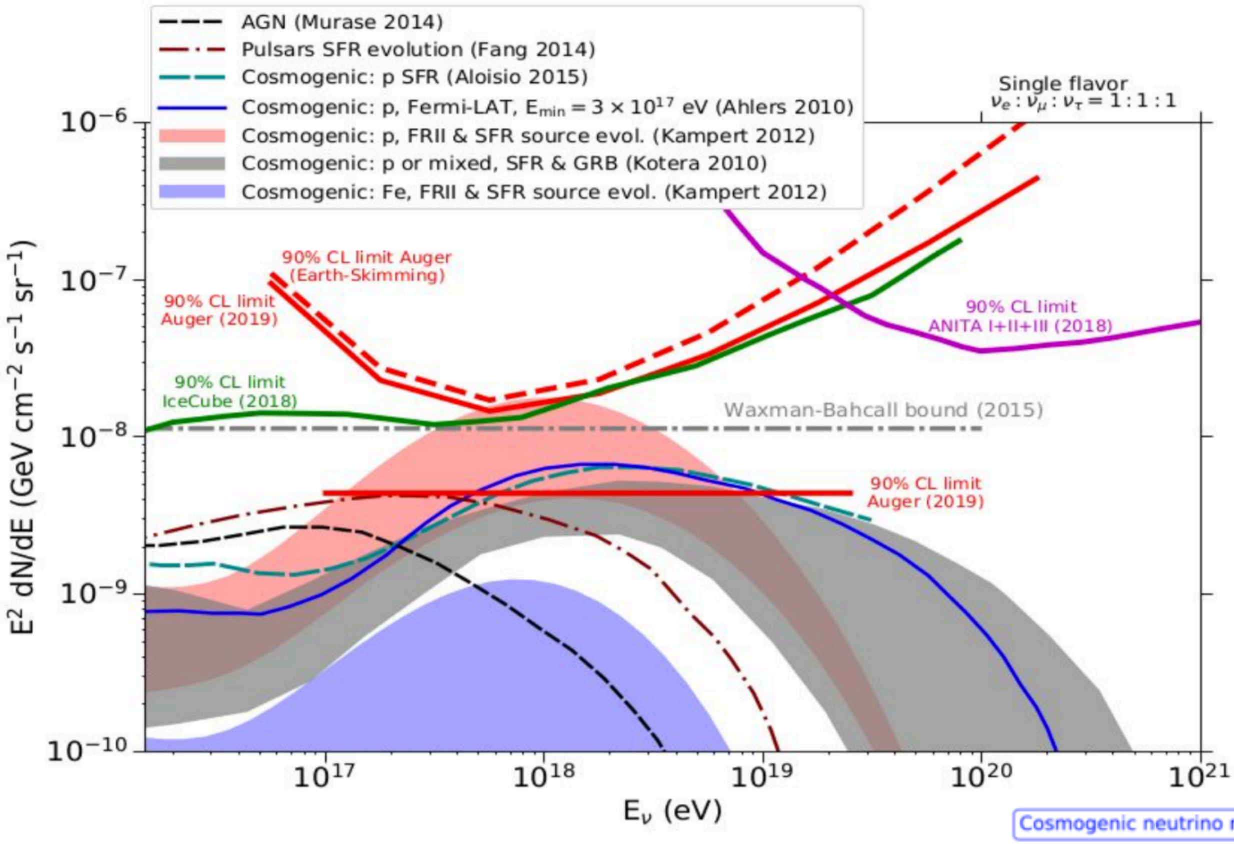






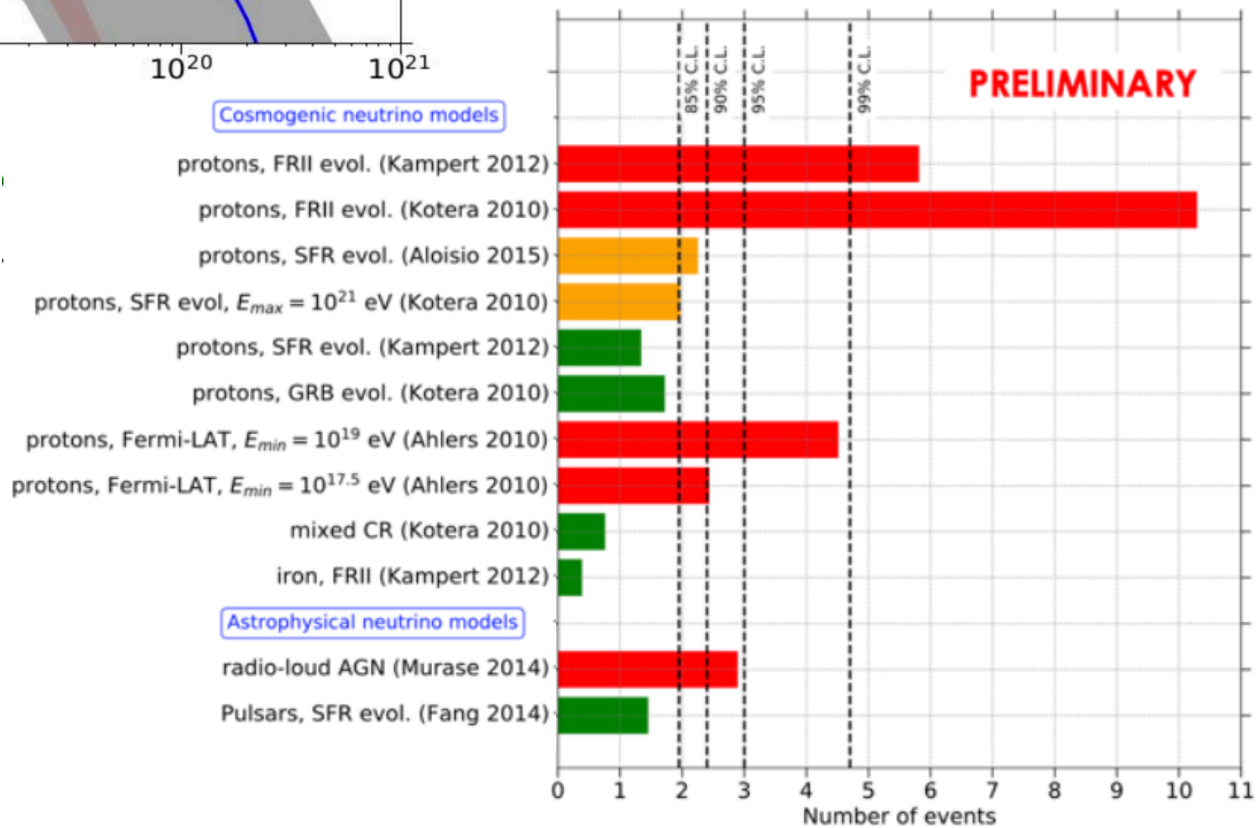


Neutrinos in Auger



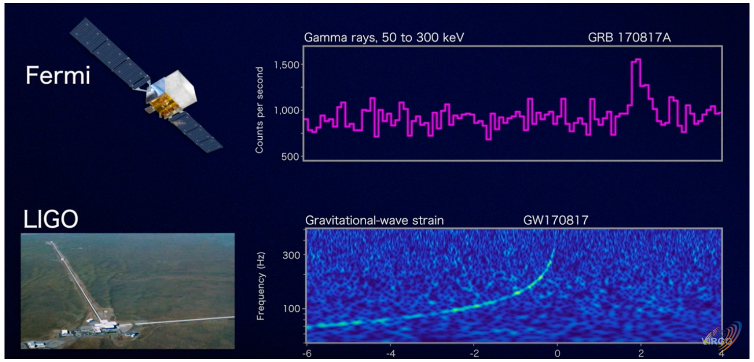
Maximum sensitivity around EeV
k (90% CL) < 4.4. 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

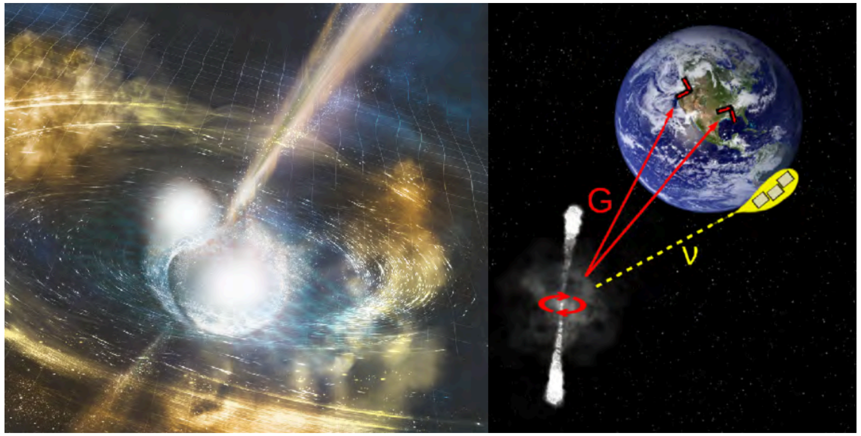
From the expected event rates in Auger, different models of cosmogenic and astrophysical neutrino production are
- excluded (red)
- disfavoured (orange)



NOTE:
*expect up to ~ 0.001 **ν** in Auger from*
a maximum source scenario !

Neutrinos from GW events?



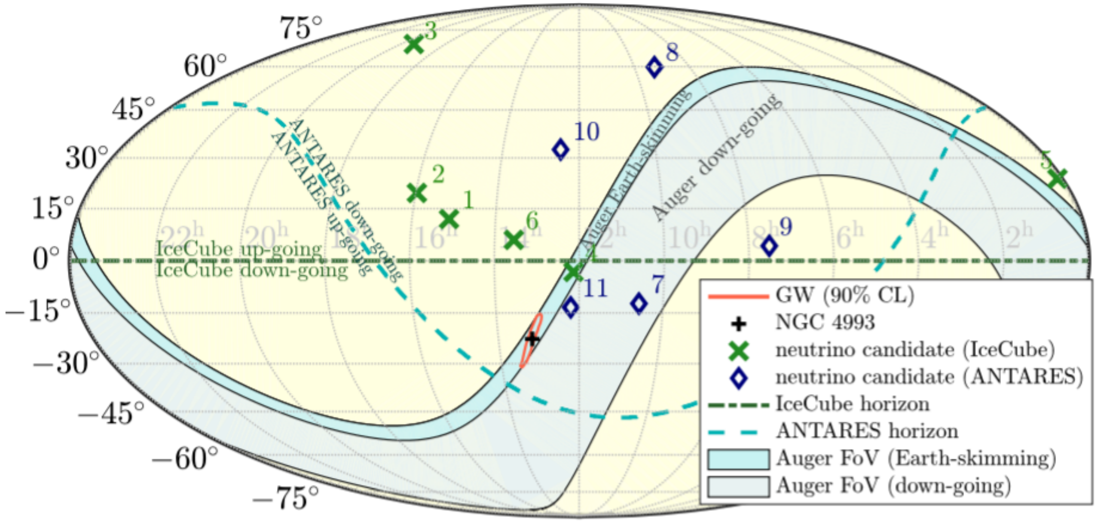


GW170817

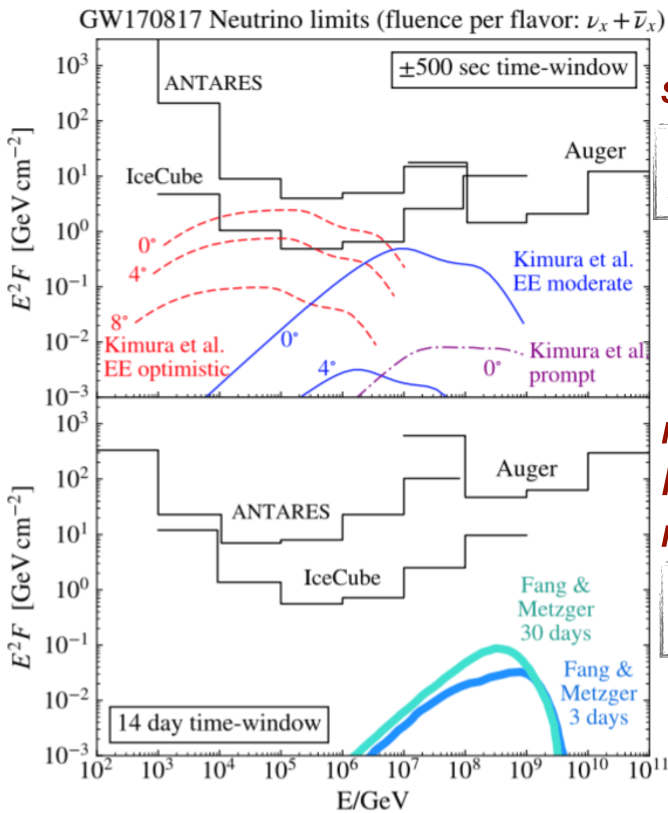
d ~ 40 Mpc [NGC4993]

$M_{components}$: 0.86 and 2.26 $M_\odot$, $M_{total}=(2.82^{+0.47}_{-0.09})M_\odot$

viewing angle <30^0



No UHE neutrino candidate found either in the coincidence window ±500 s around the GW events or in the 14-days search period after it



sGRBs

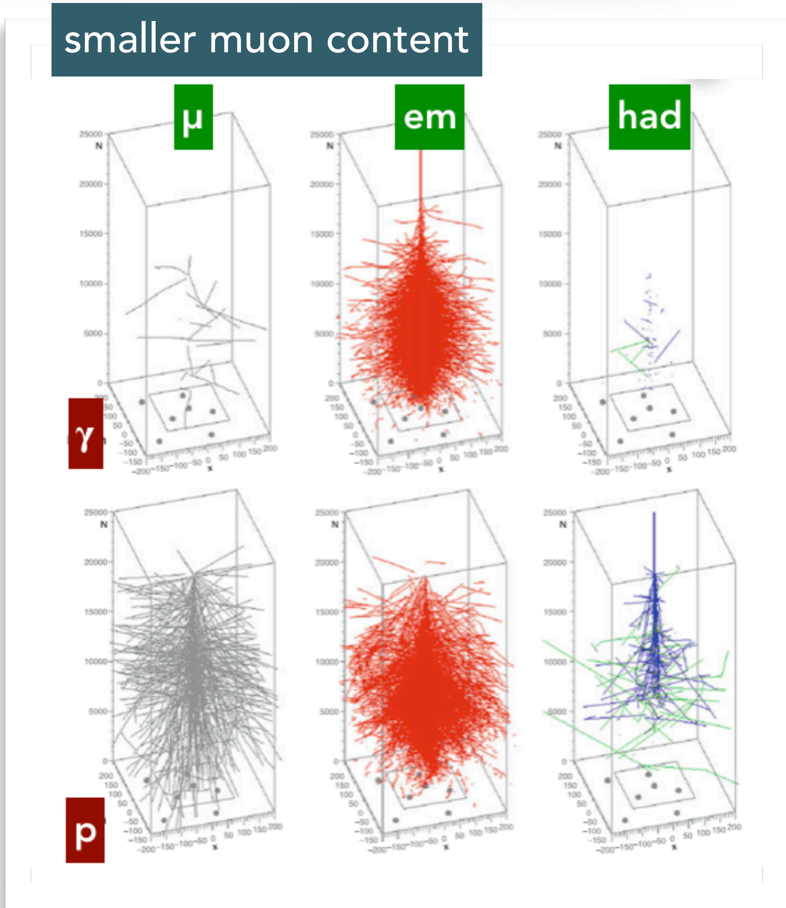
S.Kimura et al., ApJ Lett.848: L4 (2017)

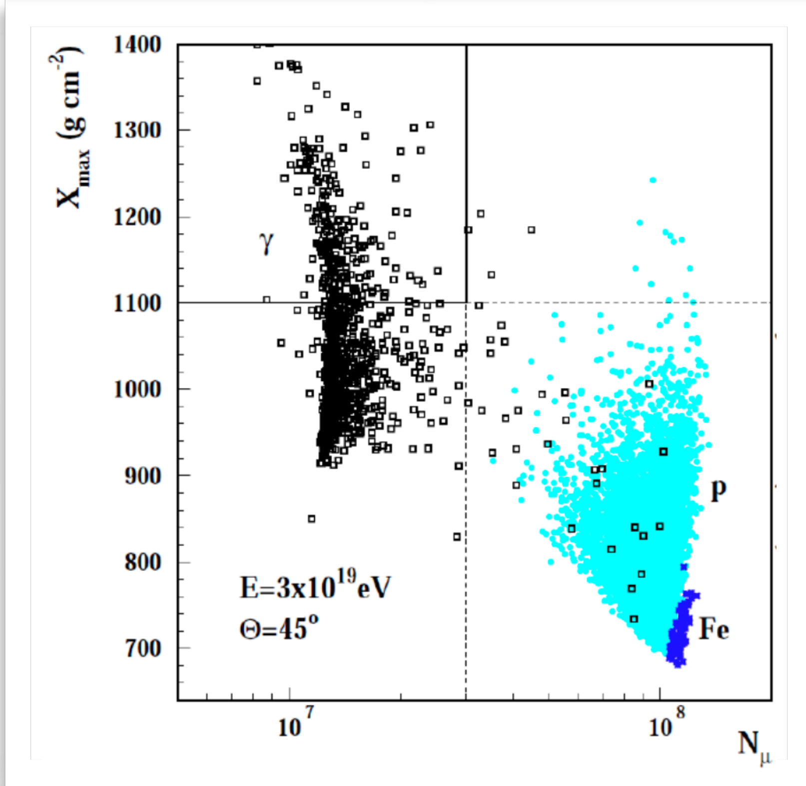
msec Magnetar remnants

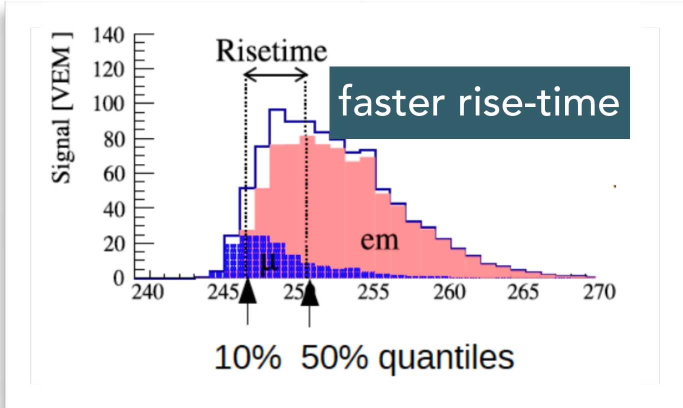
K.Fang, B.Metzger, ApJ 849 (2017) 153

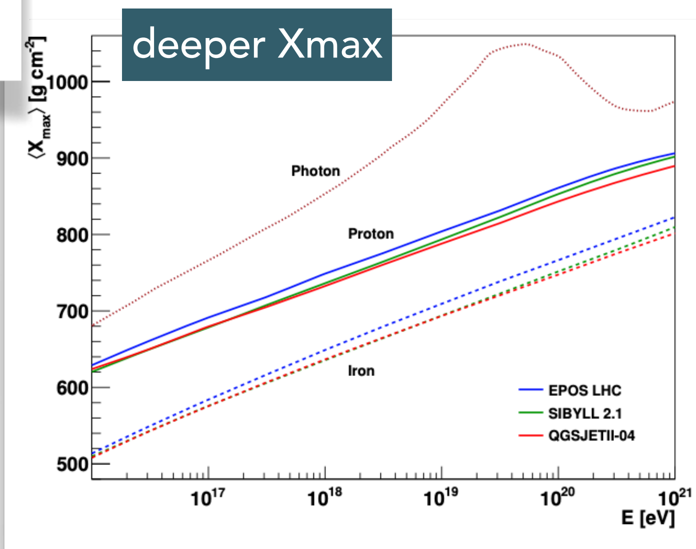
LIGO,Virgo,Auger,IceCube,Antares Coll., ApJ 848 (2017)

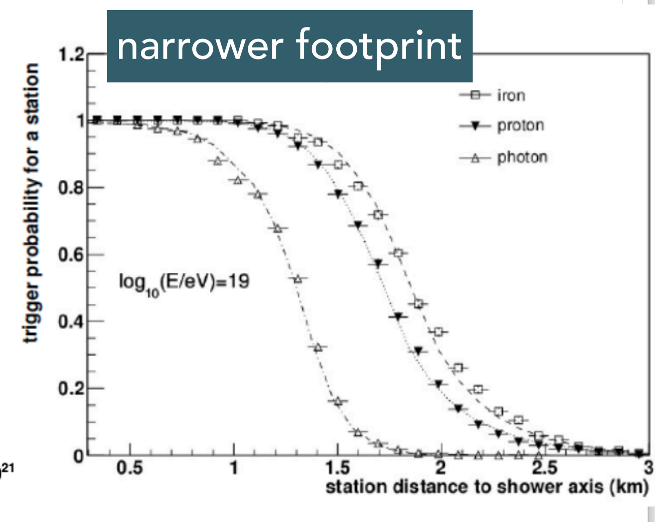
Photons in Auger



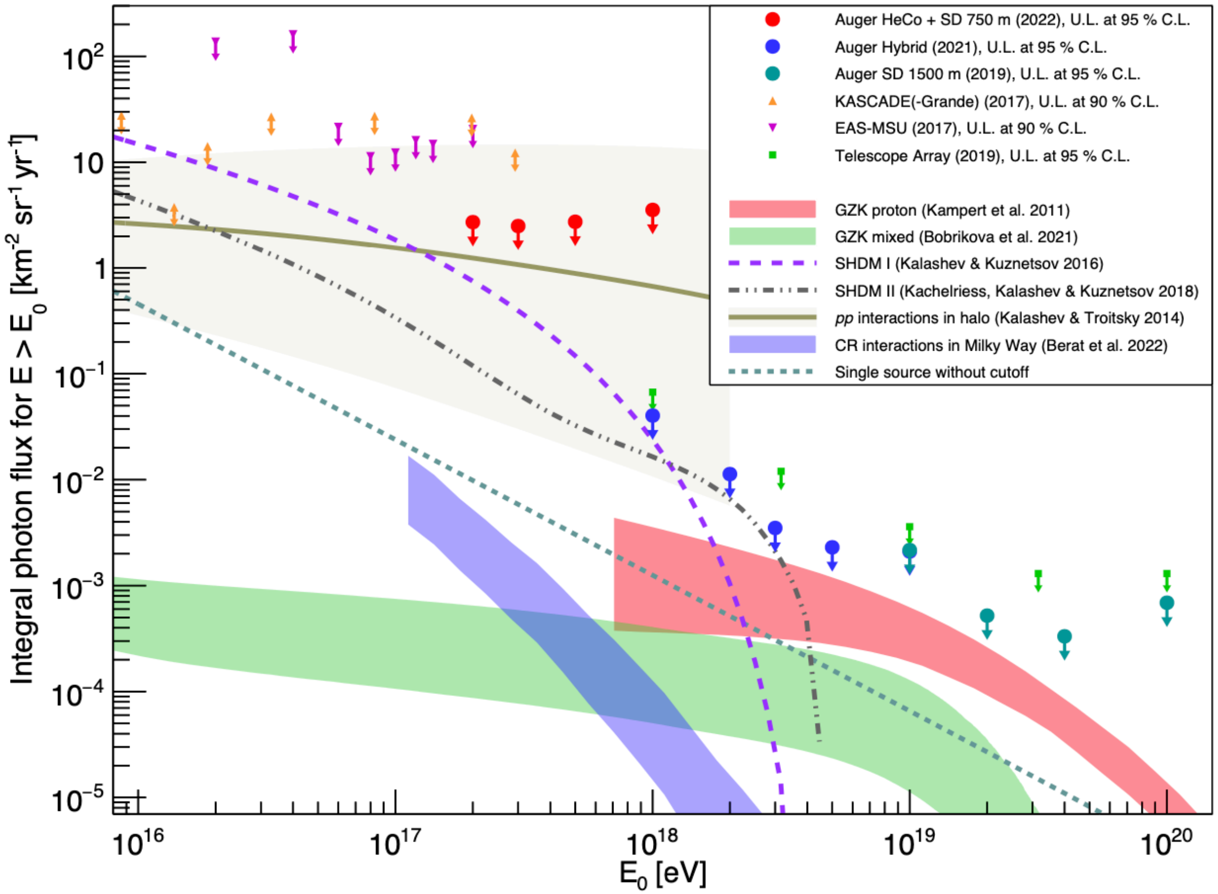








Diffuse Photons



Most stringent limits on UHE photons across three decades in energy

- ✓ sensitivity ~1.5 oom above the expectations from mixed composition models
- ✓ more data for photon/hadron separation needed: AugerPrime
- ✓ an increased sensitivity to photons could reveal unexpected phenomena, like sources in the Galaxy, interaction in the halo, decay of SHDM

Auger Coll., JCAP04 (2017) 009; JCAP09 (2020) E02
P.Savina (Auger Coll.), PoS(ICRC2021) 373
Auger Coll., ApJ (2022)

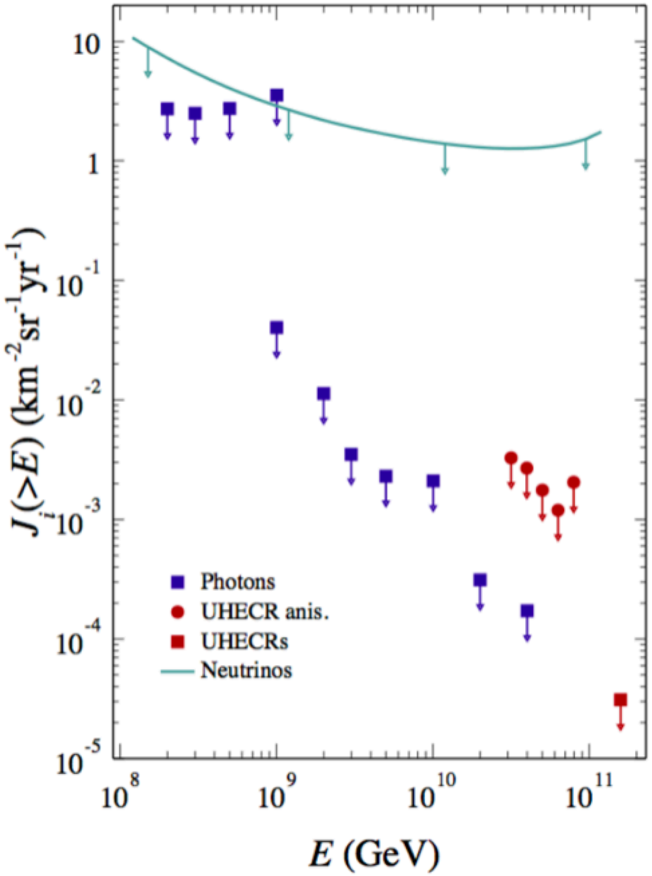
BSM: Super-heavy dark matter searches

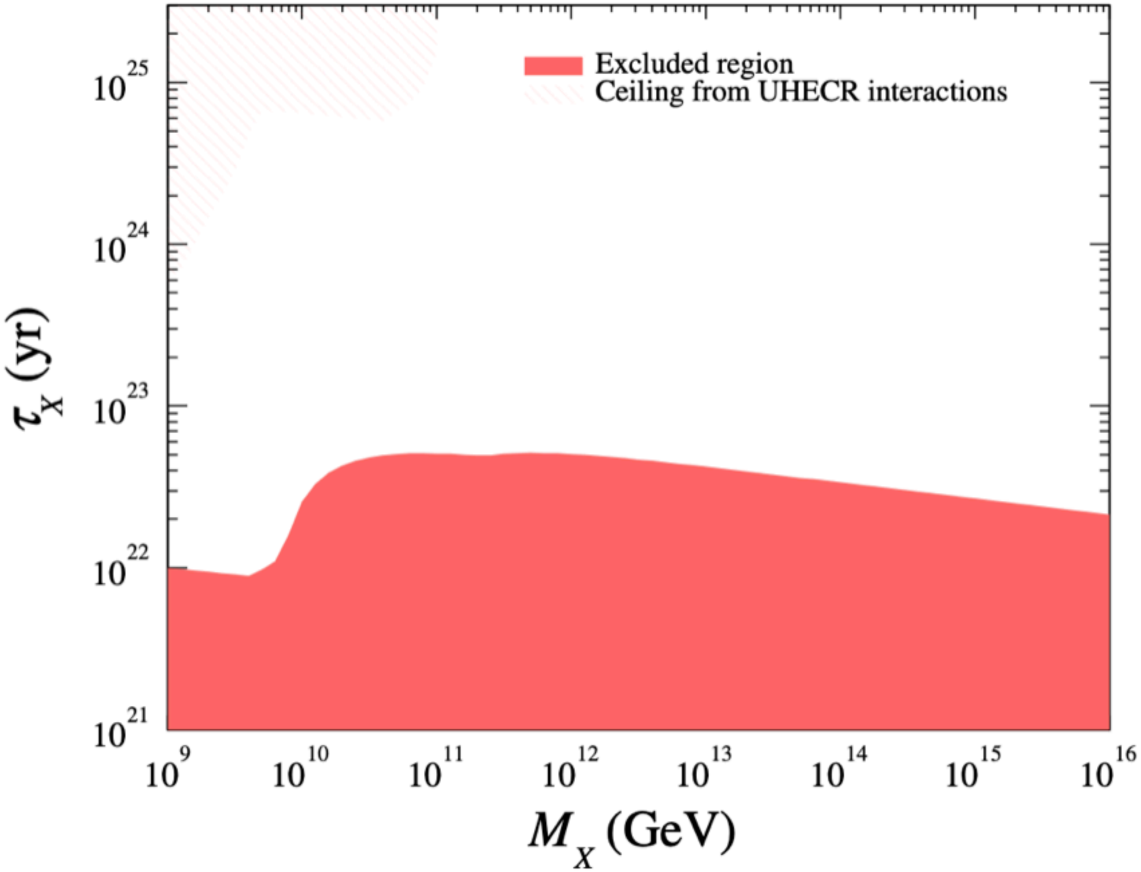
Flux of secondaries from SHDM decay ($i = \gamma, \nu, \overline{\nu}, N, \overline{N}$):

$$J_i^{\rm gal}(E) = \frac{1}{4\pi M_X c^2 \tau_X} \frac{dN_i}{dE} \int_0^\infty ds\ \rho_{\rm DM}(\mathbf{x}_\odot + \mathbf{x}_i(s;\mathbf{n})).$$

Free parameters

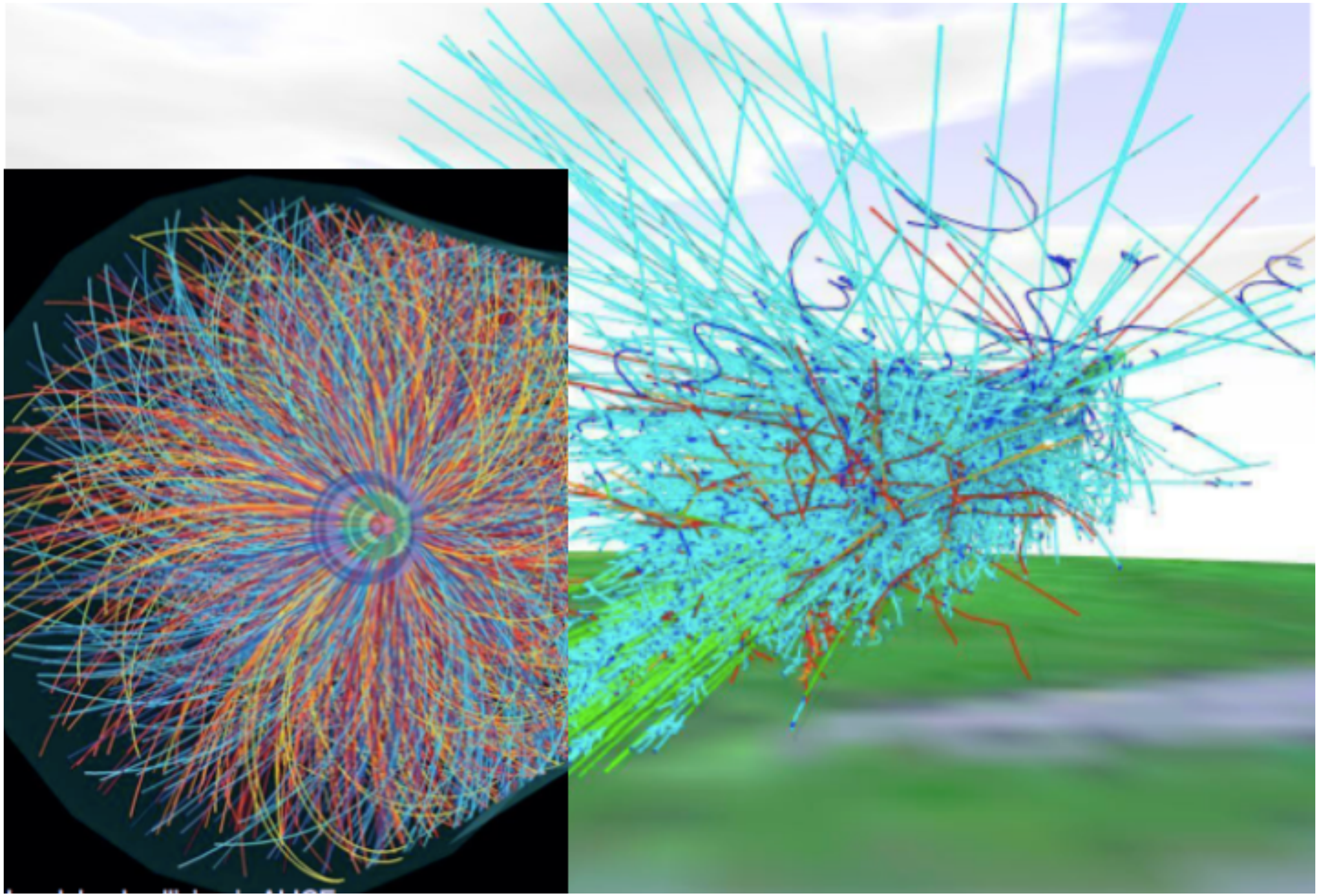
$$\tau_X = \hbar M_X^{-1} \exp(4\pi/\alpha_X)$$



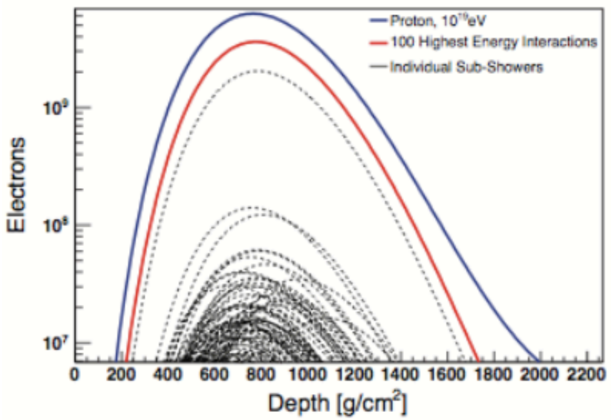


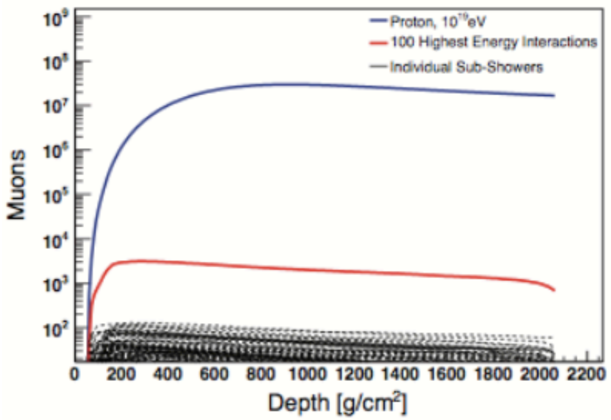
O.Deligny, ISVHECRI2022
L.A. Anchordoqui et al., Astropart. Phys. 132, 102614 (2021)

Hadronic interactions



Uncertainties in HIM





EM shower particles

- ✓ high energy interactions (HE γ from π⁰ decay)
- ✓ profile dominated by the EM particles from secondaries in the first 100 interactions

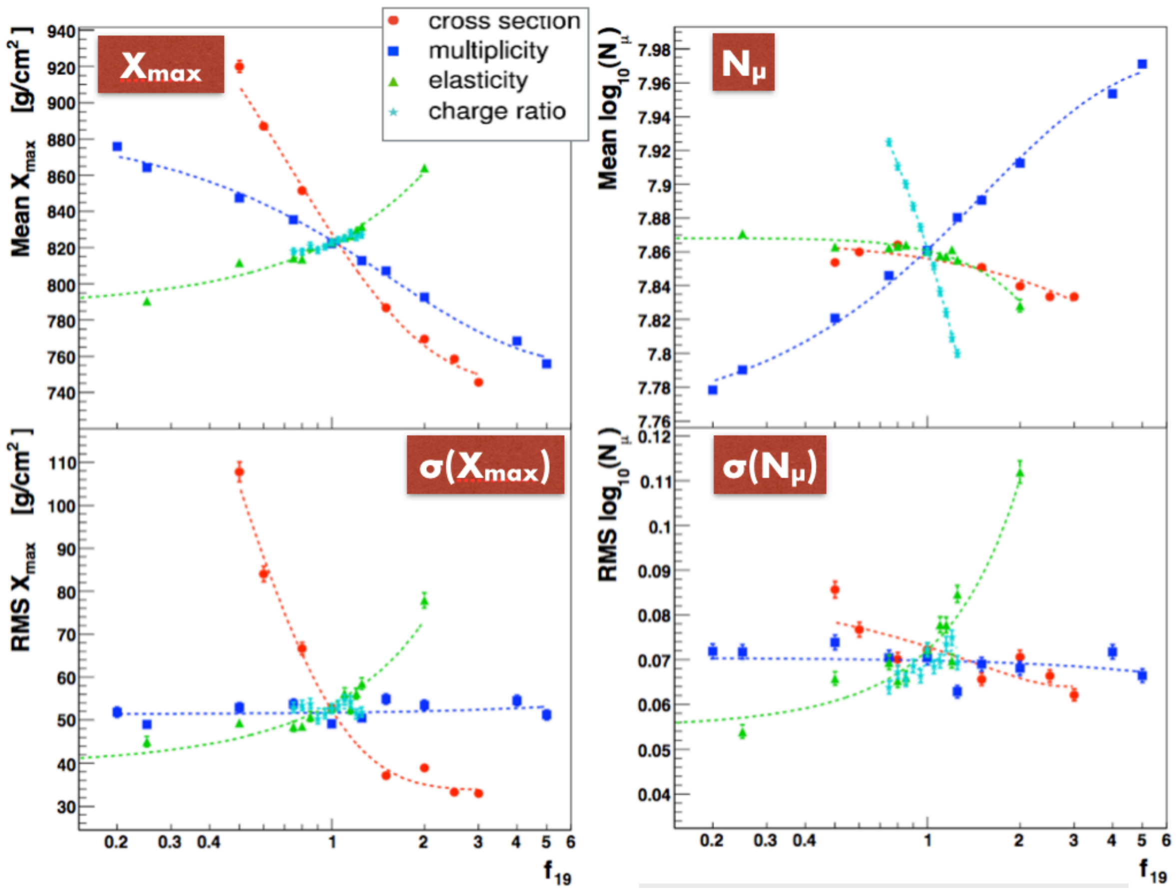
Muons

- ✓ low energy interactions (π± degrade to 30-100 GeV before decaying)
- ✓ negligible fraction from the first interactions

Individual hadronic interaction features can be artificially altered during EAS development :

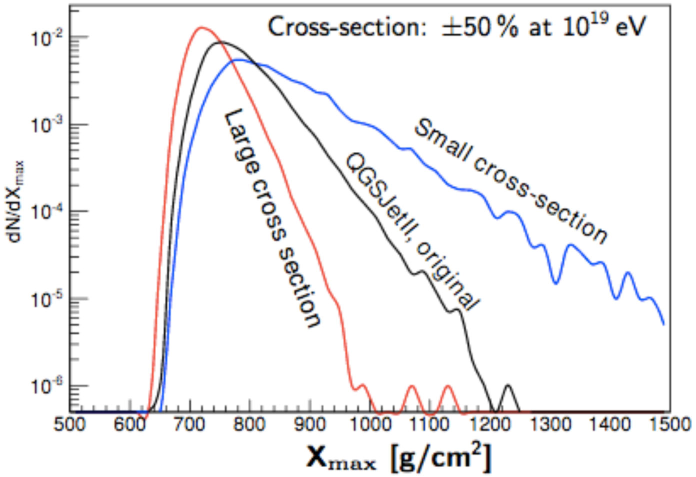
$$f(E,\, f_{19}) = 1 + (f_{19} - 1)\; F(E)$$

$$F(E) = \begin{cases} 0 & E \le 1\,\mathrm{PeV} \\ \dfrac{\log_{10}(E/1\,\mathrm{PeV})}{\log_{10}(10\,\mathrm{EeV}/1\,\mathrm{PeV})} & E > 1\,\mathrm{PeV} \end{cases}$$



The p-Air cross section

The tail of the longitudinal distribution of X_{max} is sensitive to the p-Air cross section.
Select deeply penetrating EAS to enhance the proton fraction

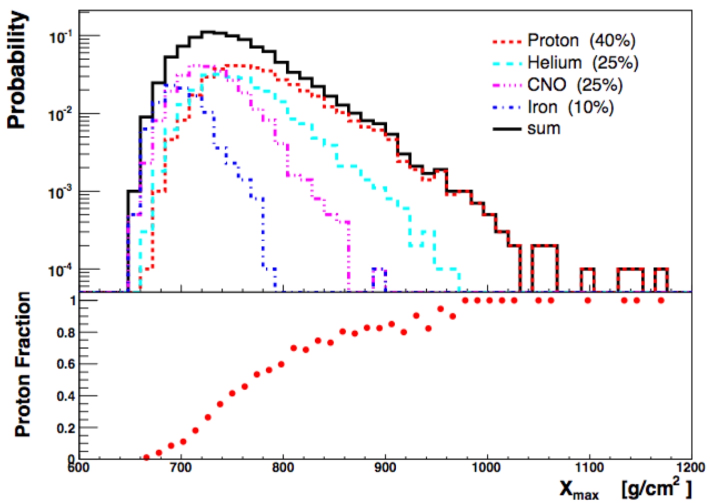


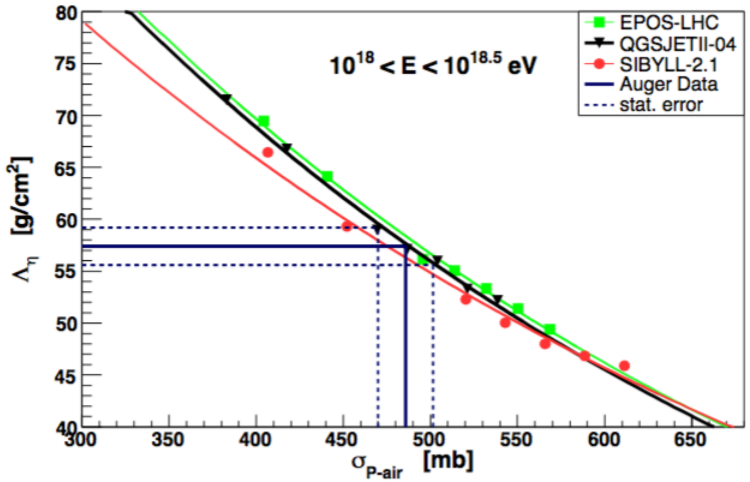
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\sigma_{p-Air} = \frac{< m_{Air} >}{\lambda_{int}}$$

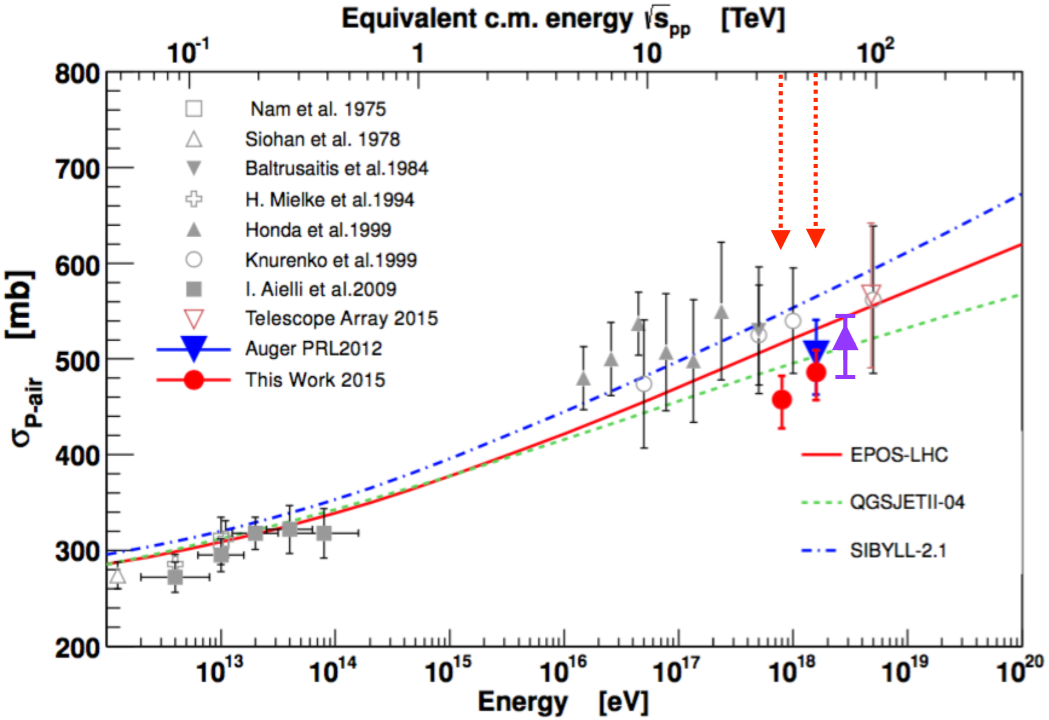
$$\frac{dN_{EAS}}{dX_{max}} \propto e^{-X_{max}/\Lambda_\eta}$$

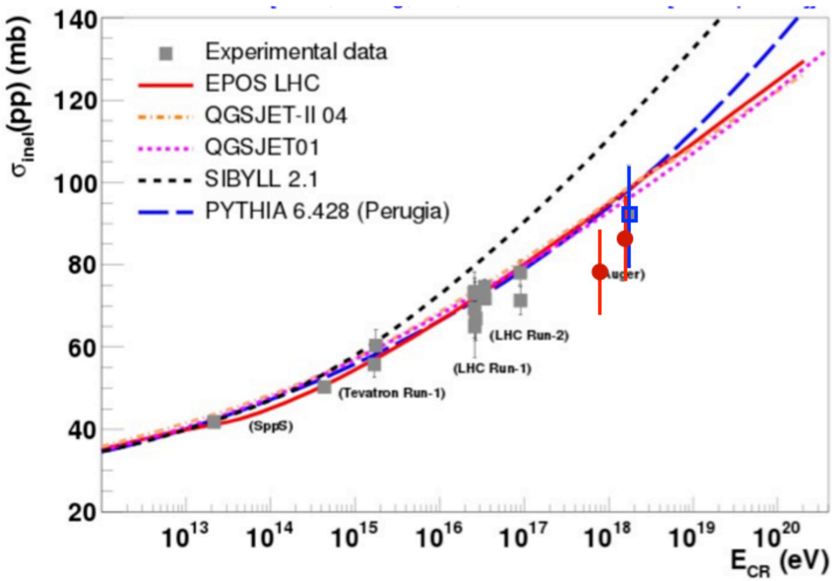
$$\Lambda_\eta = K\lambda_{int}$$



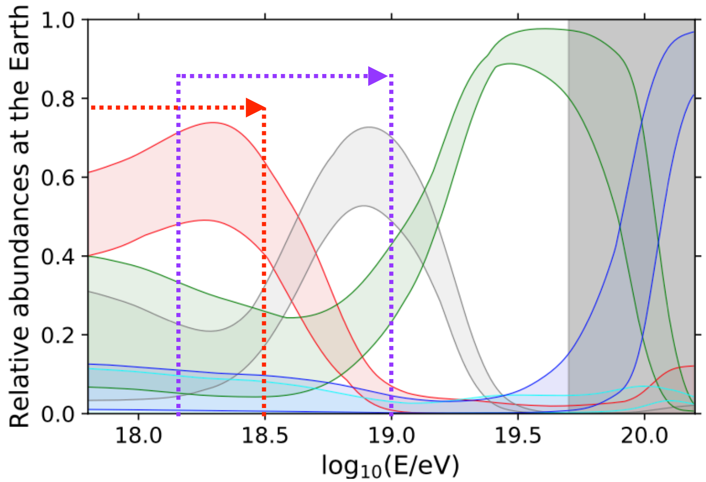


The p-Air cross section





- ➡ different energy ranges covered by Auger and TA due to different evaluation of the heavier nuclei contamination
  - in TA: <44% He [$10^{18.2}$-10^{19} eV] - 1975 events
  - in Auger: <25% He [$10^{17.8}$-$10^{18.5}$ eV] - 4800 and 6900 events
- ➡ the newest Sibyll2.3c predictions are ~ EPOS-LHC
- ➡ the extrapolation from Tevatron to LHC ~ that from LHC(14 TeV) to Auger !



*Auger Coll., Phys. Rev. Lett. **109**, 062002 (2012)*
R.Ulrich for the Auger Coll., PoS(ICRC2015) 401
TA Coll., Phys.Rev.D 102 (2020) 6, 062004

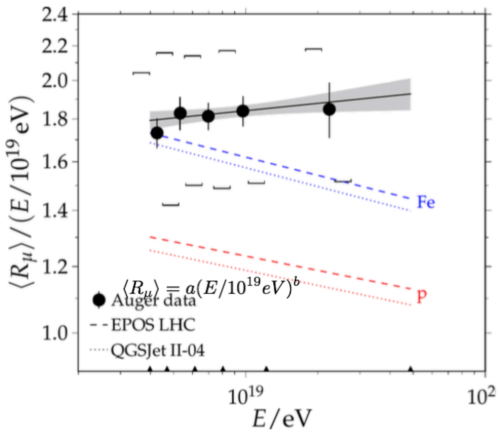
The “muon puzzle”

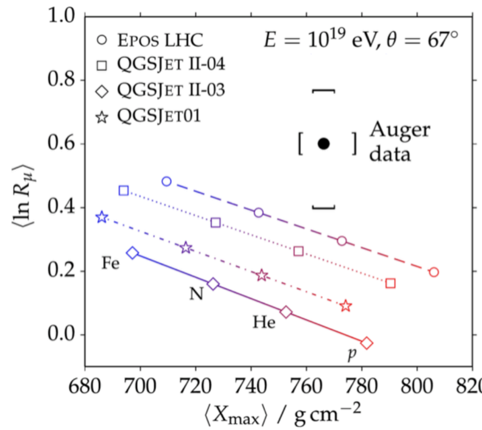
- ## The muon deficit in simulations

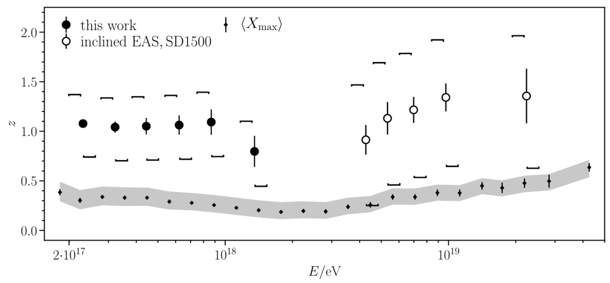
Measurements of the muonic component in inclined EAS @ 10^{19} eV: 30% to 80%$^{+17}_{-20}$ % increase in $<N_\mu>$ needed

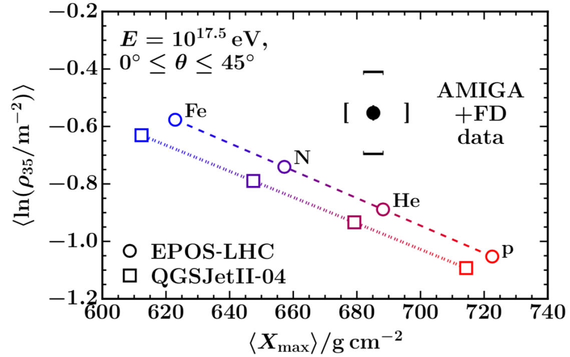
Similar results using the direct measure of the muons

Well established also in different analyses





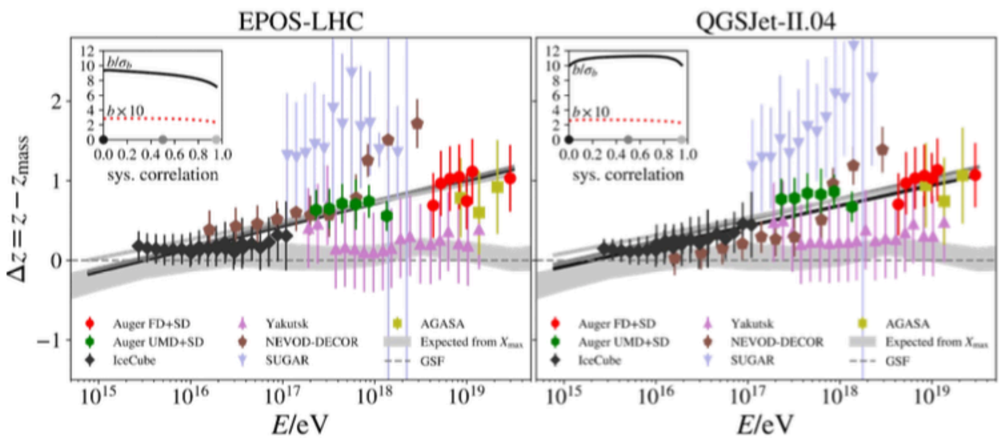




Auger Coll., PRD91 (2015) 032003+059901
Auger Coll., Eur.Phys.J. C80 (2020) 751

- ## The WHISP effort

$$\Delta z = z - z_{\text{mass}} \simeq 3 \ln \frac{N_\mu}{N_\mu^{\text{mass}}} \qquad \Delta z_{\text{fit}} = a + b \log_{10}(E/10^{16}\text{eV})$$



D.Soldin et al. (WHISP), PoS (ICRC2021) 349 (2021)

Slope of the fit: b = 0.23 – 0.29 (EPOS-LHC),
b = 0.22 – 0.25 (QGSJet-II.04)

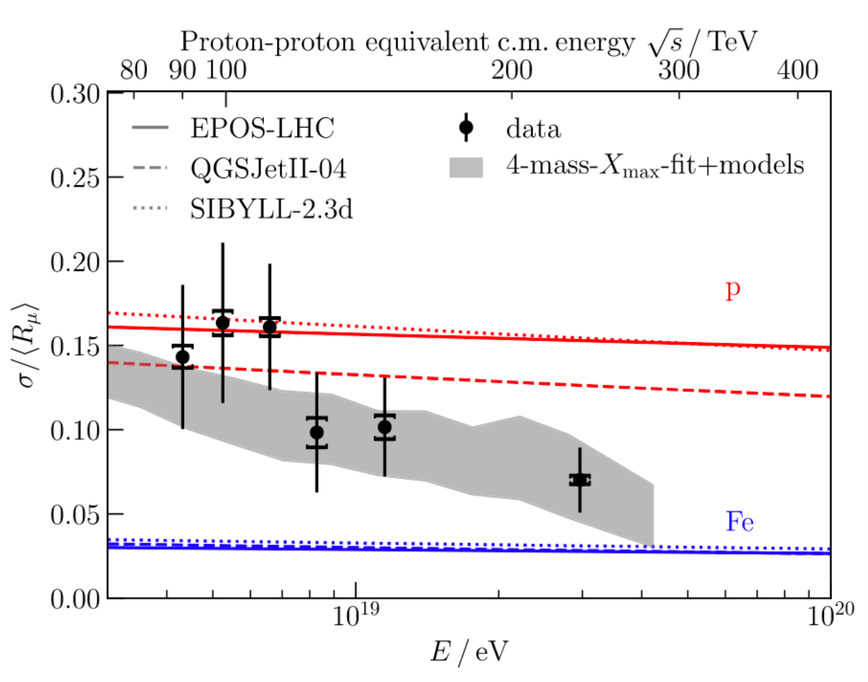
Significance of the slope: ~ 7σ – 9σ (EPOS-LHC),
~ 10σ – 11σ (QGSJet-II.04)

The "muon puzzle"

Intrinsic fluctuations of muons in EAS

Post-LHC models describe well the fluctuations of energy partition in the first interaction up to UHE

Auger Coll., Phys. Rev. Lett. 126 (2021) 152002



Current conclusion

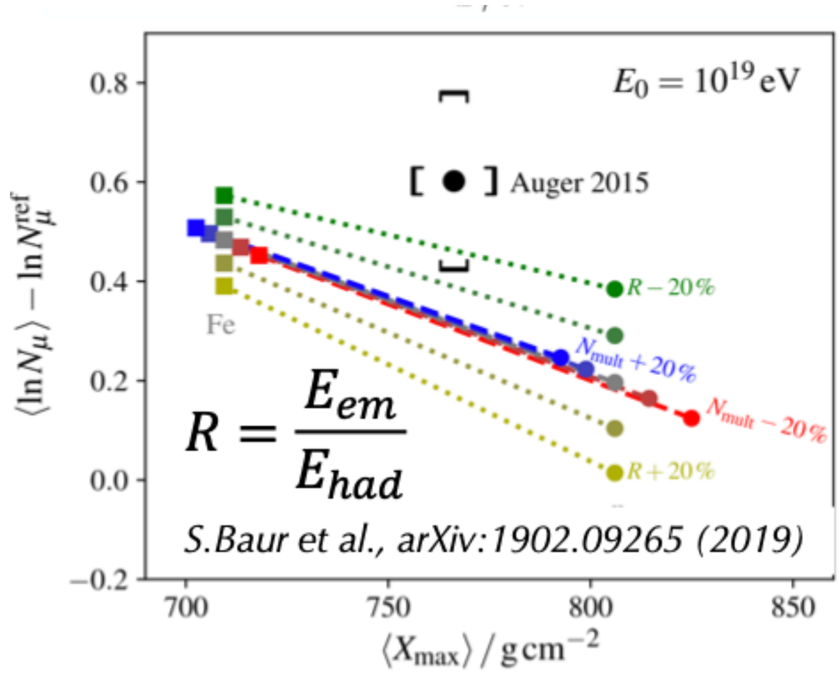
➡ the effect appears above $\sqrt{s_{NN}}$ ~ 8 TeV

➡ observed for GeV μ (perhaps not for TeV μ - IceCube)

➡ different solutions proposed acting on first or few first generations : excluded by the early onset of the discrepancy and by the muon fluctuation measurement

➡ can be fixed by a smooth increment of the hadronic fraction over several generations, reducing the energy fraction carried by π^0s : increases muon production while preserving Xmax

- leading particle effect (π^0 replaced with ρ^0)
- enhancement of strangeness production (ALICE) : to be confirmed in the forward region
- ....

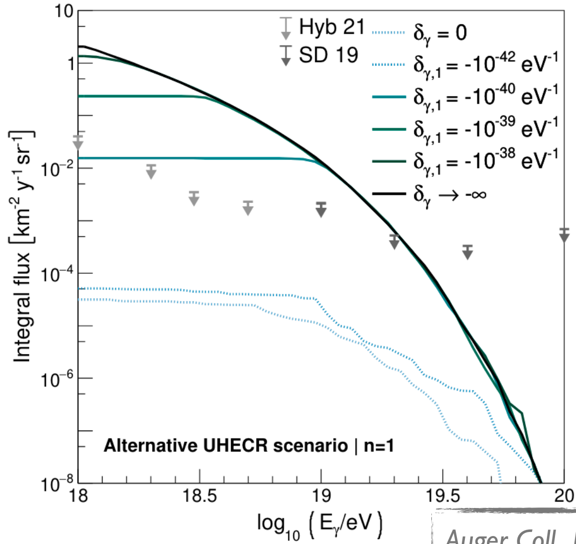


BSM: Lorentz Invariance violation

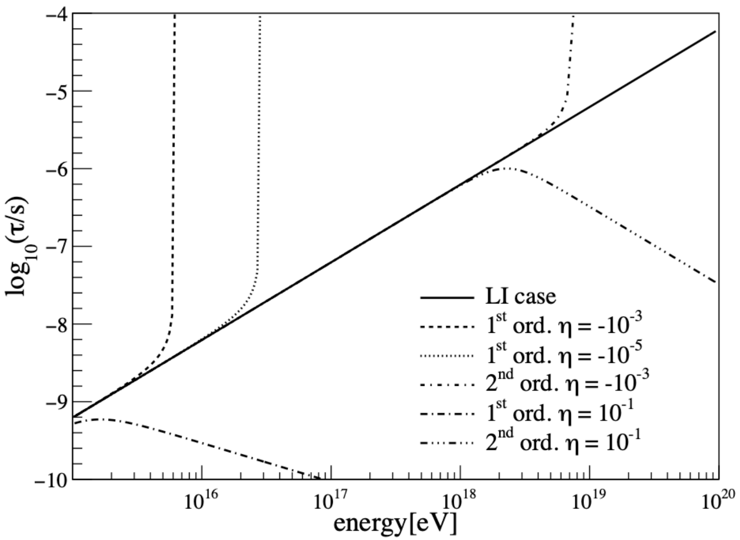
$$E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \delta_i^{(n)} E_i^{2+n} = m_i^2 + \eta_i^{(n)} \frac{E_i^{2+n}}{M_{Pl}^n}$$

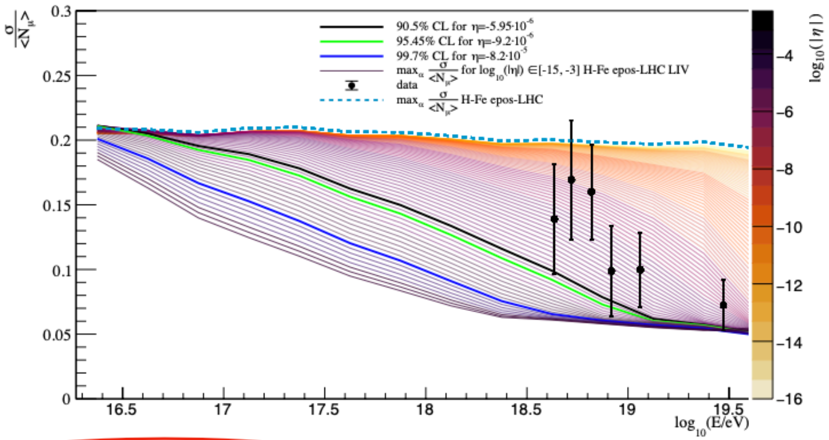
Effects suppressed for low energy and short travel distances : UHECRs !!!

- Propagation - if LIV, the attenuation length of photo-meson production or photo-disintegration may become extremely large: suppression of particle interactions
- Air shower physics - if LIV, for increasing energy and $\eta<0$, π^0 lifetime increases, thus increase in muon number and decrease in the EM component



Auger Coll., JCAP01 (2022) 023

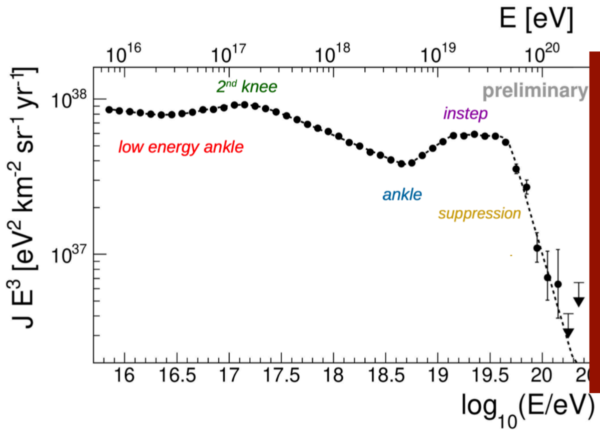




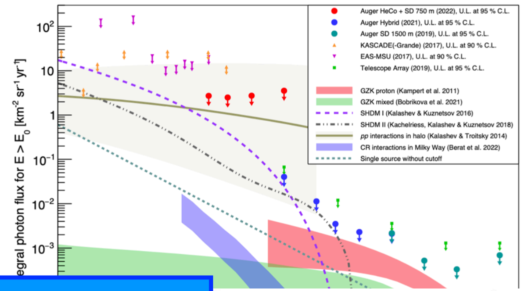
New bound!

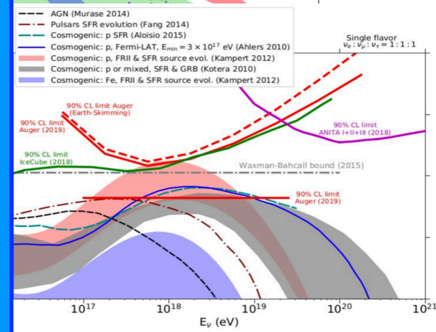
$\eta^{(1)} > -5.95 \cdot 10^{-6}$ with (90.5% C.L.)

What have we learnt from data?

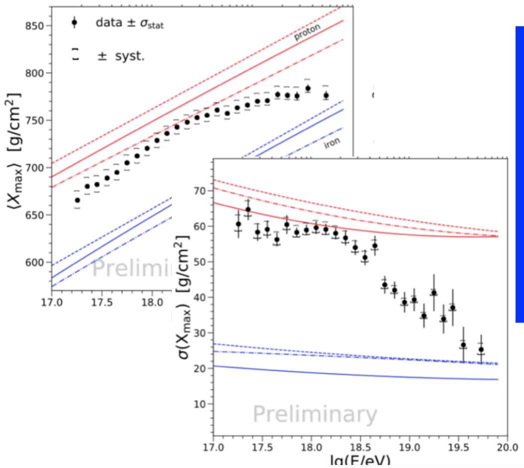


- *Sources must be nearby (<200 Mpc).*
- Hints for source exhaustion
- New feature in the spectrum (the *instep*).
- Limits on the *local density of sources*$^{-3}$

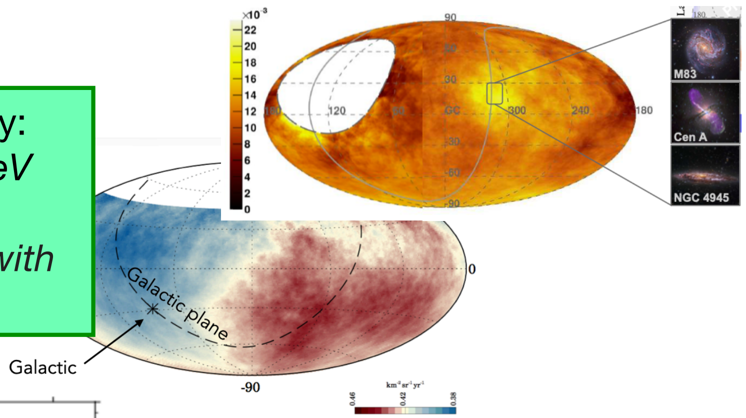




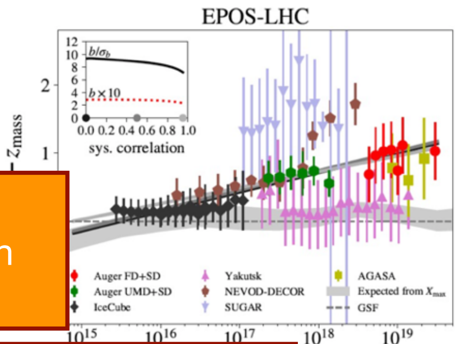
- Strong limits on the flux of ν and γ: ordinary matter !
- Upper limits to ν from GW events and point sources
- constraints to models



- Composition getting light up to ~2 EeV, then going to *mixed and heavier towards UHE*

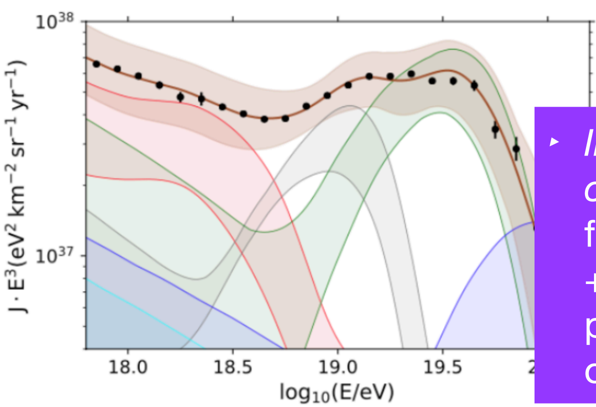


- LS dipolar anisotropy: *UHECR above ~8 EeV are extragalactic*
- *Hints of correlation with SBGs & AGNs*



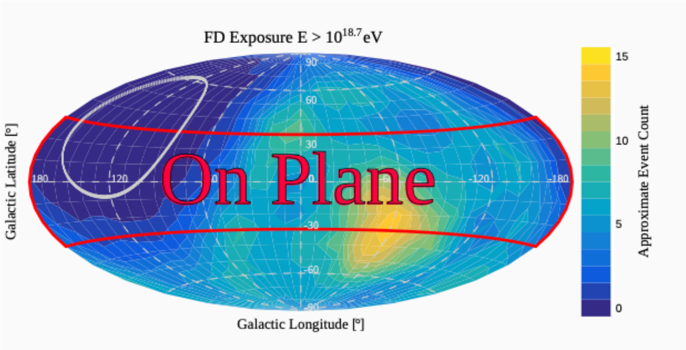
The muon puzzle
p-Air cross section
Separation μ/em

BSM: upper limits on LIV, SHDM …

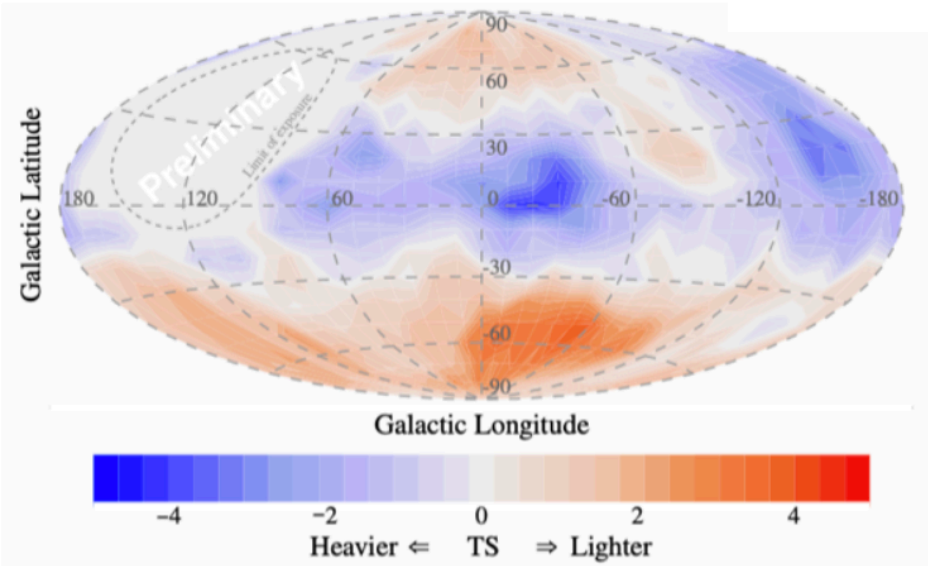


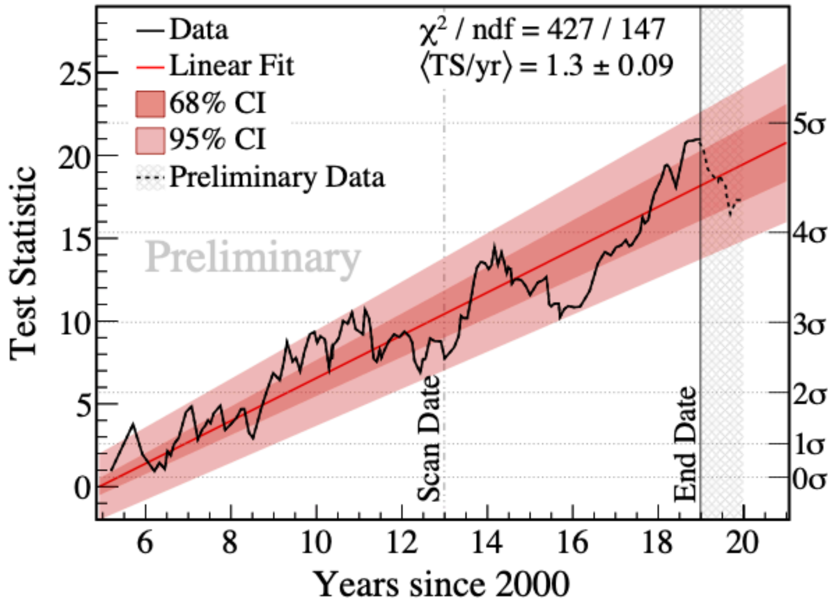
- *Information on Source characteristics & Transition region* from X_{max} distributions + Spectrum + Neutrals: LE and HE EG source populations + secondary Galactic one

Perspectives: composition sensitive anisotropy



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





- Verification of the mixed composition above the ankle
- suggests GMF could be causing composition anisotropies
- May not be related to the GMF
- Local source distribution or mass dependent horizons?
- Still no independent confirmation

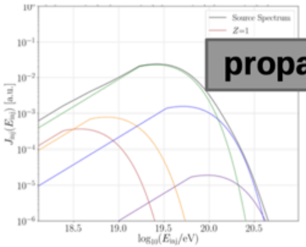
E.Mayotte et al. PoS(ICRC2021) 321

Perspectives: E+X_{max}+ϑ combination

Universe model setup:

injected spectrum:

γ, R_{cut}, a_i

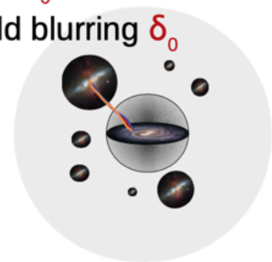


propagation

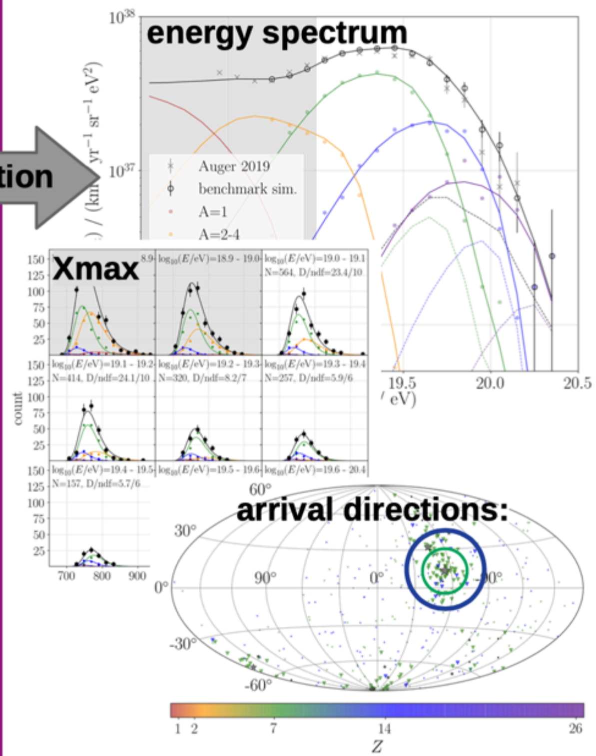
3d setup:

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)

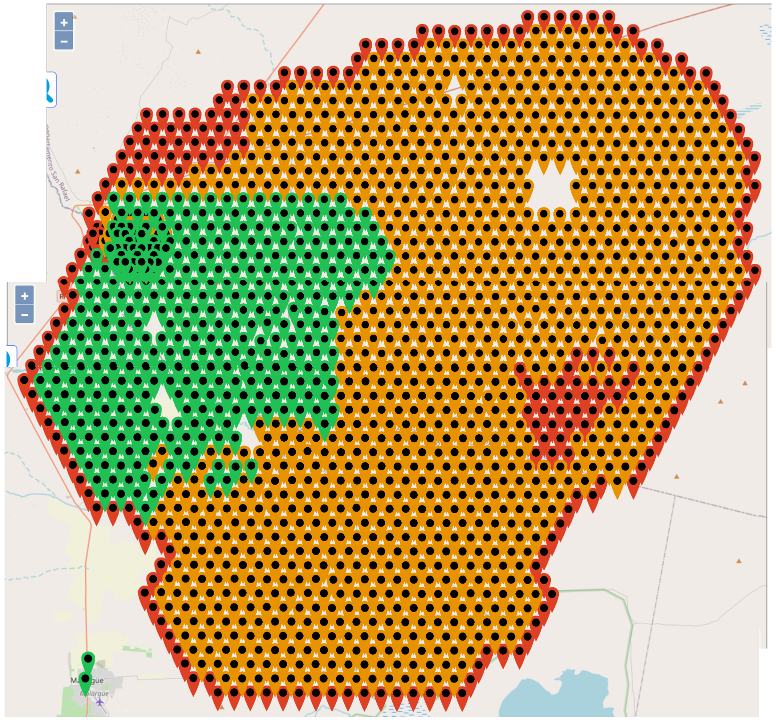
simulation only

	D_E	$D_{X_{max}}$	D_{total}	$2\log\frac{\mathcal{L}_{AD}}{\mathcal{L}_{AD}^{ref,m=3.4}}$	$2\log\frac{\mathcal{L}_{sum}}{\mathcal{L}_{sum}^{ref,m=3.4}}$
SBG model ($m = 3.4$) → *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

T.Bister et al. PoS(ICRC2021) 368

The future: AugerPrime

a large exposure detector with composition sensitivity above ~4 10^{19} eV



- ***Surface Scintillator Detector (SSD)*** to measure the mass composition in combination with the WCD (3.8 m^2, 1 cm thick)
- ***Surface Detector Upgraded Unified Board (UUB)*** to process the signals of all detectors (40 MHz -> 120 MHz, better GPS timing)
- ***small PMT (sPMT)*** to increase the dynamic range of the WCD (≳ 20,000 VEM)
- ***Radio Detector (RD)*** to measure the radio emission of showers in atmosphere (30-80 MHz)
- ***Underground Muon Detector (UMD)*** to have a direct muon measurement (infill area, 30 m^2, 2.3 m underground)

A.Castellina, EPJ Web Conf., 210 (2019) 06002

The AugerPrime science case

Astrophysics

1. Elucidate the origin of the flux suppression, i.e. GZK vs. maximum energy scenario
2. confirm SBG correlations at observation level (>5σ)
3. composition enhanced anisotropy searches
4. improve constraints on UHECR sources
5. particle astronomy if ~10% protons exist above suppression, or study of the Peters cycle
6. Unambiguous EeV γ/ν detection would be a game changer (transient, existence of a proton fraction, decay of SHDM...)
7. secondary Galactic component? galactic vs extragalactic origin

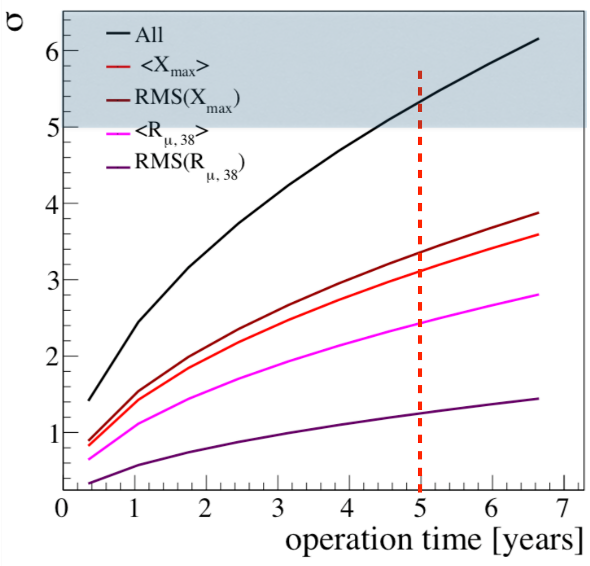
Hadronic physics

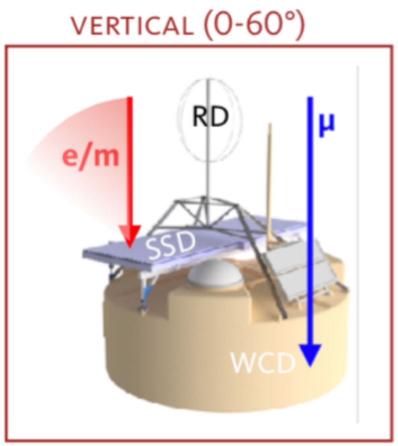
1. event-by-event muon distribution to solve the muon puzzle: better understanding of forward physics and harvest new HEP results (nuclei-air cross sections) or BSM physics?
2. simultaneous measurement of X_{max} and X^{μ}_{max}
3. new measurement of p-Air cross section (improved mass selection)
4. RD extension to improve energy scale systematics
5. BSM: improve limits on LIV and SHDM
6. Upcoming contribution from LHC (p-O run, planned for 2023)

A.Castellina, EPJ Web Conf., 210 (2019) 06002
WhitePaper2002: arXiv:2205.05845v2

The AugerPrime hybrid events

Vertical showers



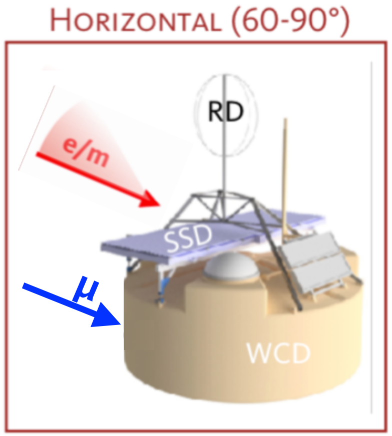


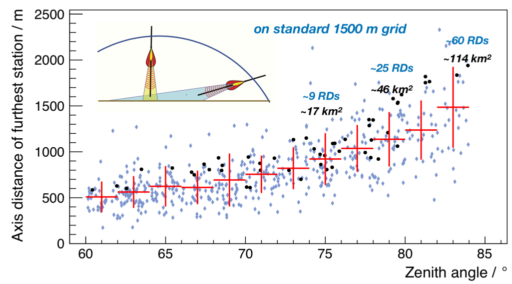
Significance of distinguishing two different realisations of Scenario 1 (maximum rigidity model) :

- as it predicts, i.e. no protons at UHE
- adding 10% protons

>5σ in 5 years of operations

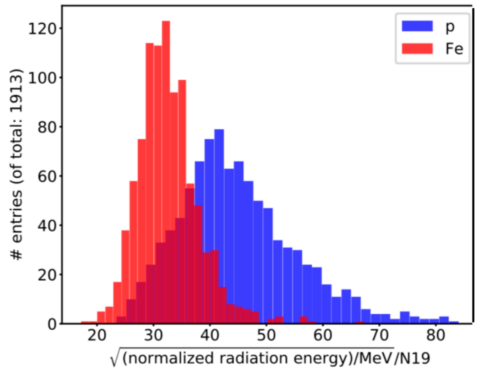
Horizontal showers

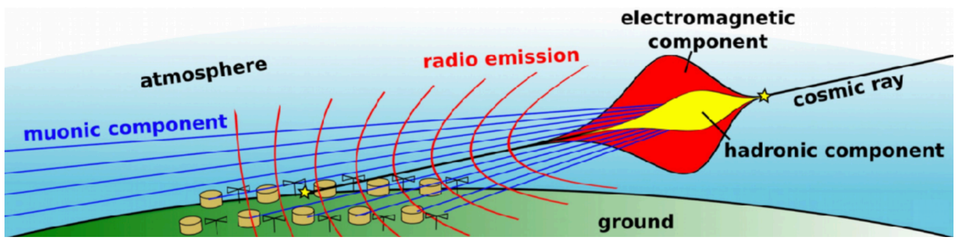


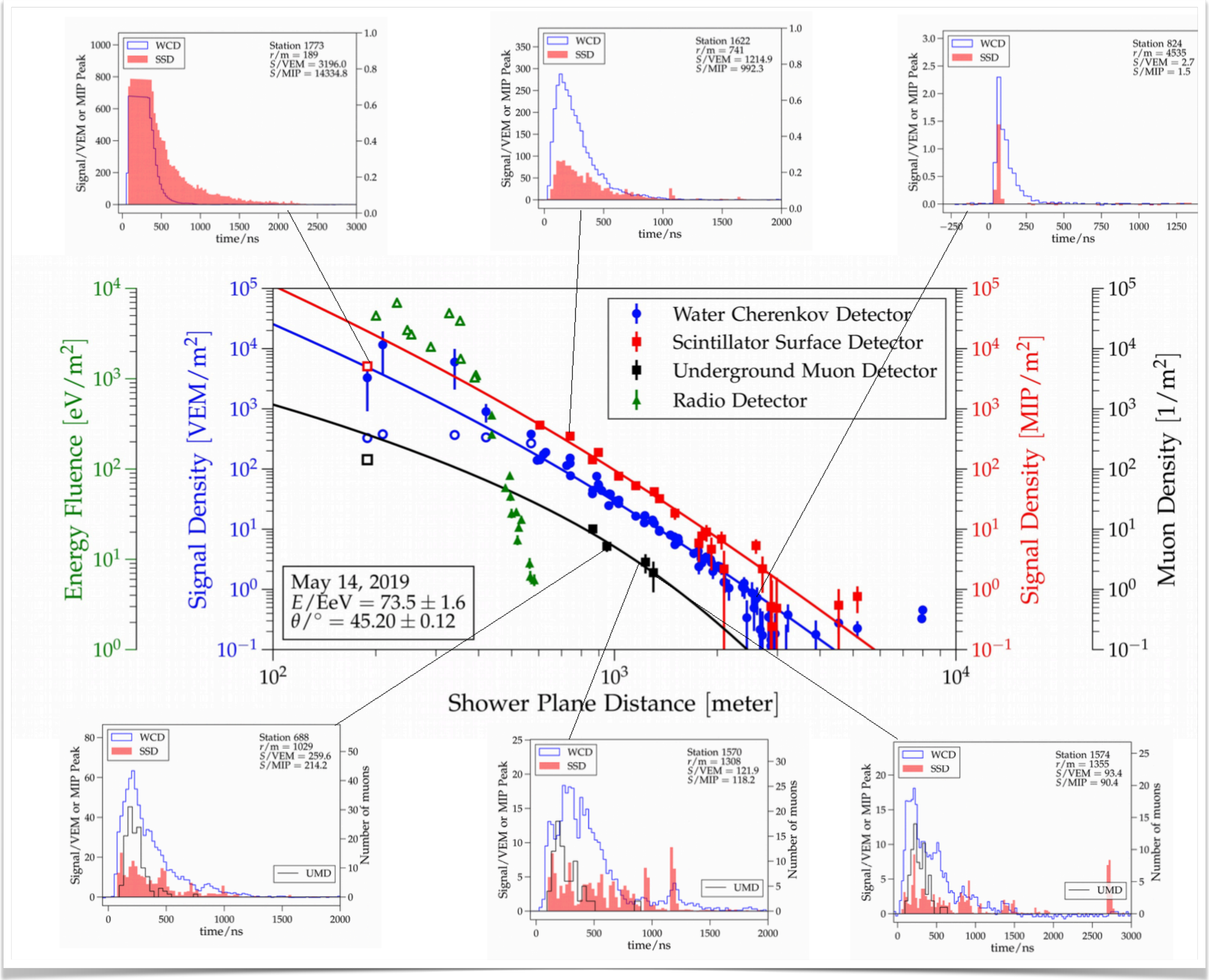


$E_{30-80\ MHz}$ = 15.8 MeV @ 10^{18} eV

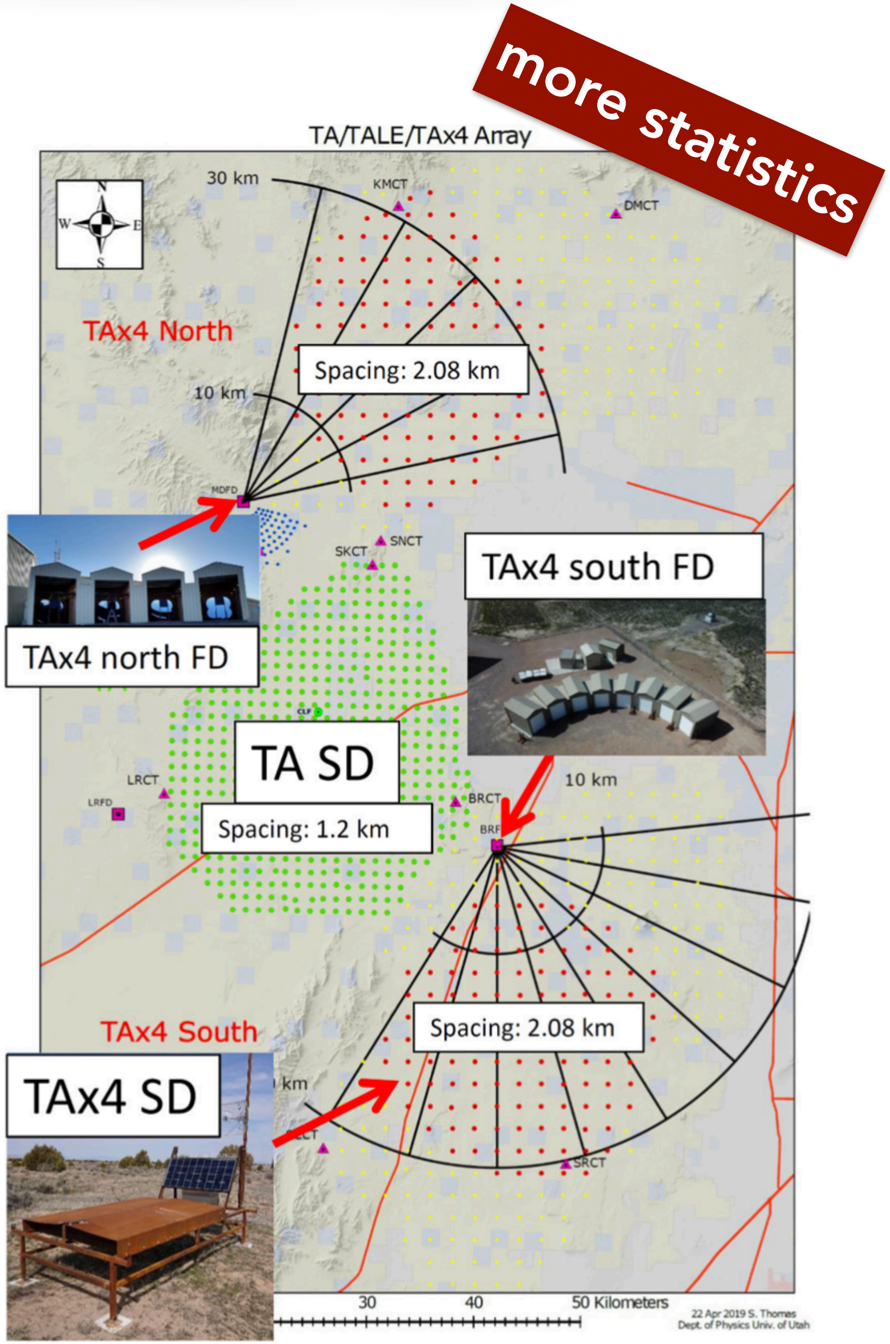
Hybrid:
E_{rad} from radio
muons from WCD






Station 1773
r/m = 189
S/VEM = 3196.0
S/MIP = 14334.8
Station 1622
r/m = 741
S/VEM = 1214.9
S/MIP = 992.3
Station 824
r/m = 4535
S/VEM = 2.7
S/MIP = 1.5
WCD
SSD
UMD
Signal/VEM or MIP Peak
time/ns
Number of muons
Water Cherenkov Detector
Scintillator Surface Detector
Underground Muon Detector
Radio Detector
May 14, 2019
E/EeV = 73.5 ± 1.6
θ/° = 45.20 ± 0.12
Energy Fluence [eV/m²]
Signal Density [VEM/m²]
Signal Density [MIP/m²]
Muon Density [1/m²]
Shower Plane Distance [meter]
Station 688
r/m = 1029
S/VEM = 259.6
S/MIP = 214.2
Station 1570
r/m = 1308
S/VEM = 121.9
S/MIP = 118.2
Station 1574
r/m = 1355
S/VEM = 93.4
S/MIP = 90.4

The future: TAx4

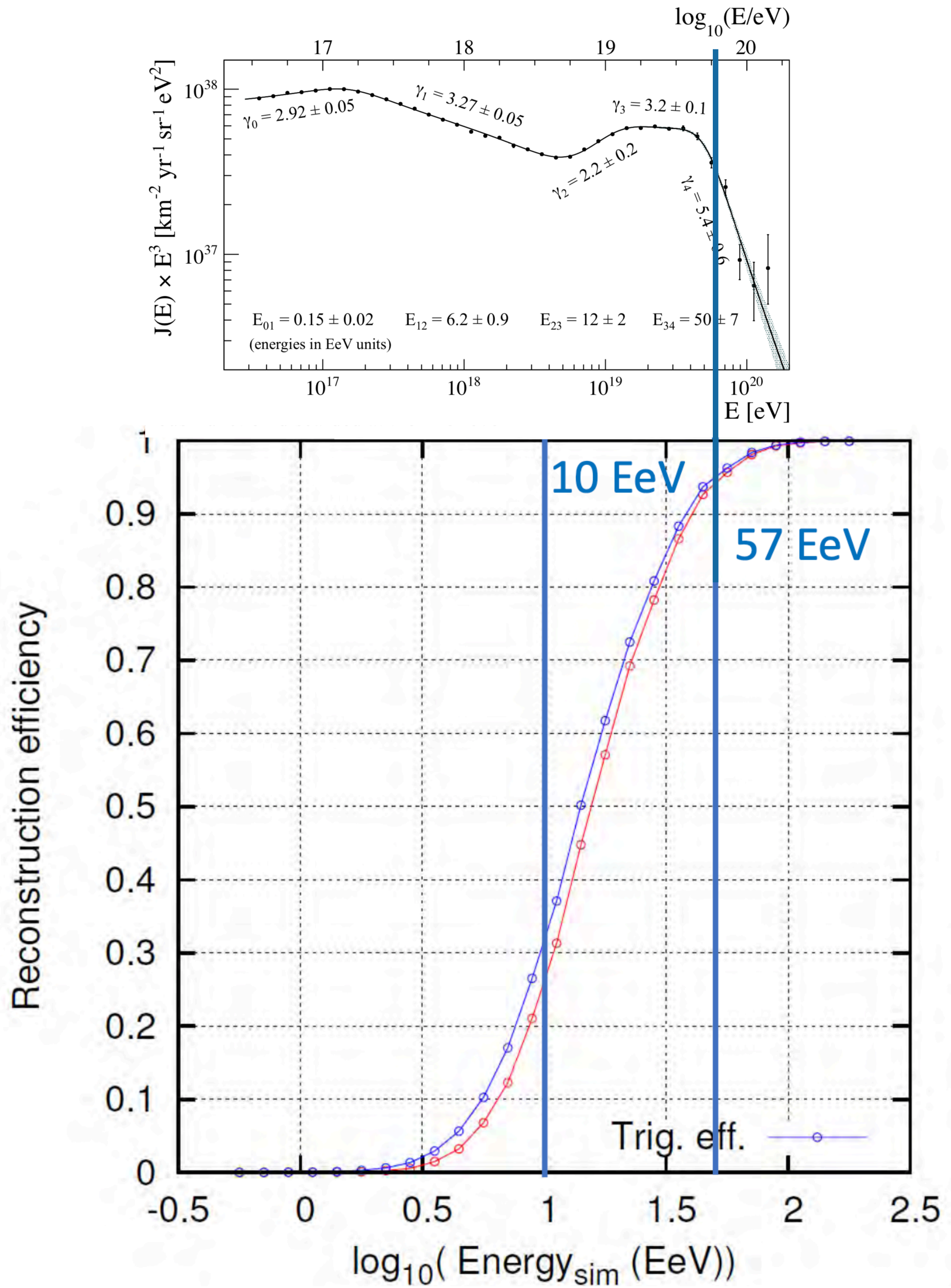


increase the coverage to ~3000 km² to increase the statistics at UHE

- ➡ the SD array: increased by 500 stations with 2 km spacing
- ➡ the FD telescopes: increased by 4 FD in the Northern site, 8 in the Southern site
- ➡ TALE hybrid: low energy extension of TA hybrid sensitivity down to 10^{16} eV

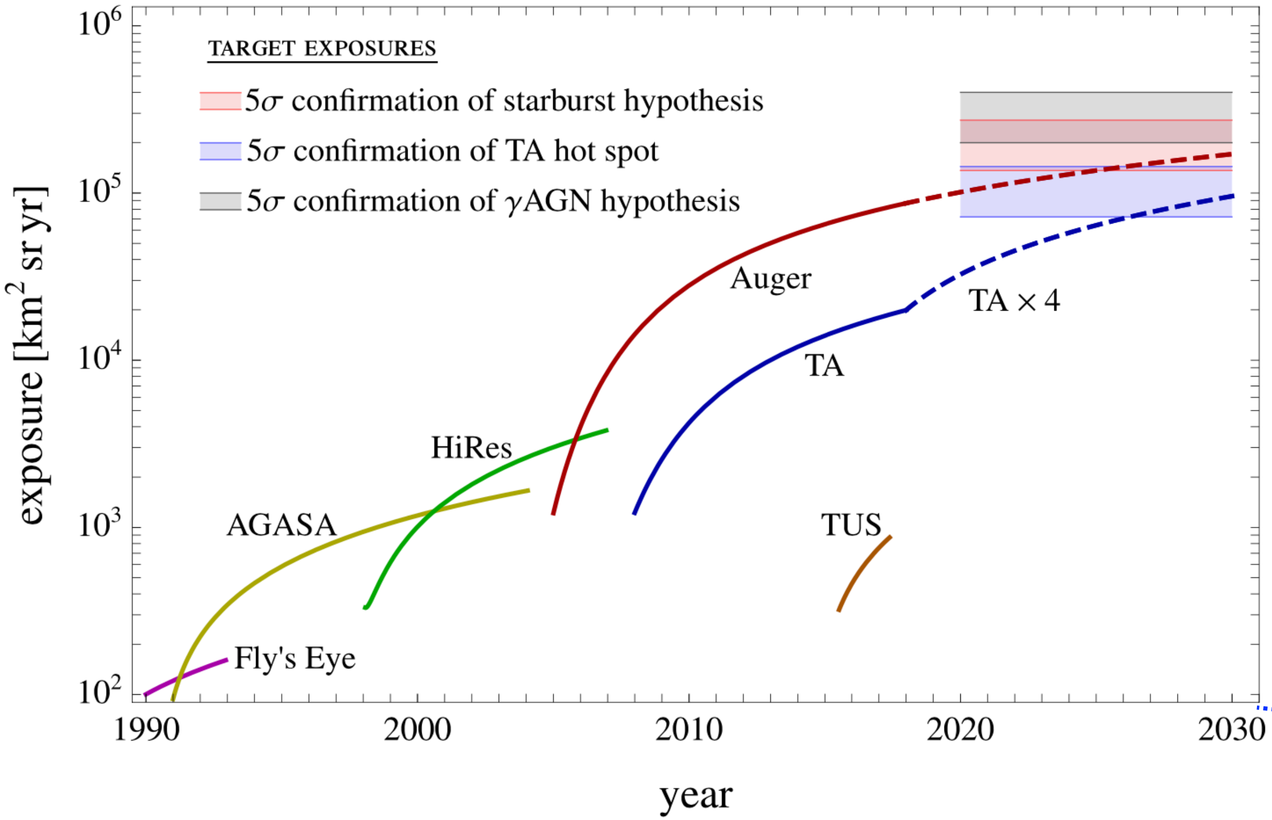
[S.Ogio, Highlight Talk, PoS(ICRC2019) 013]

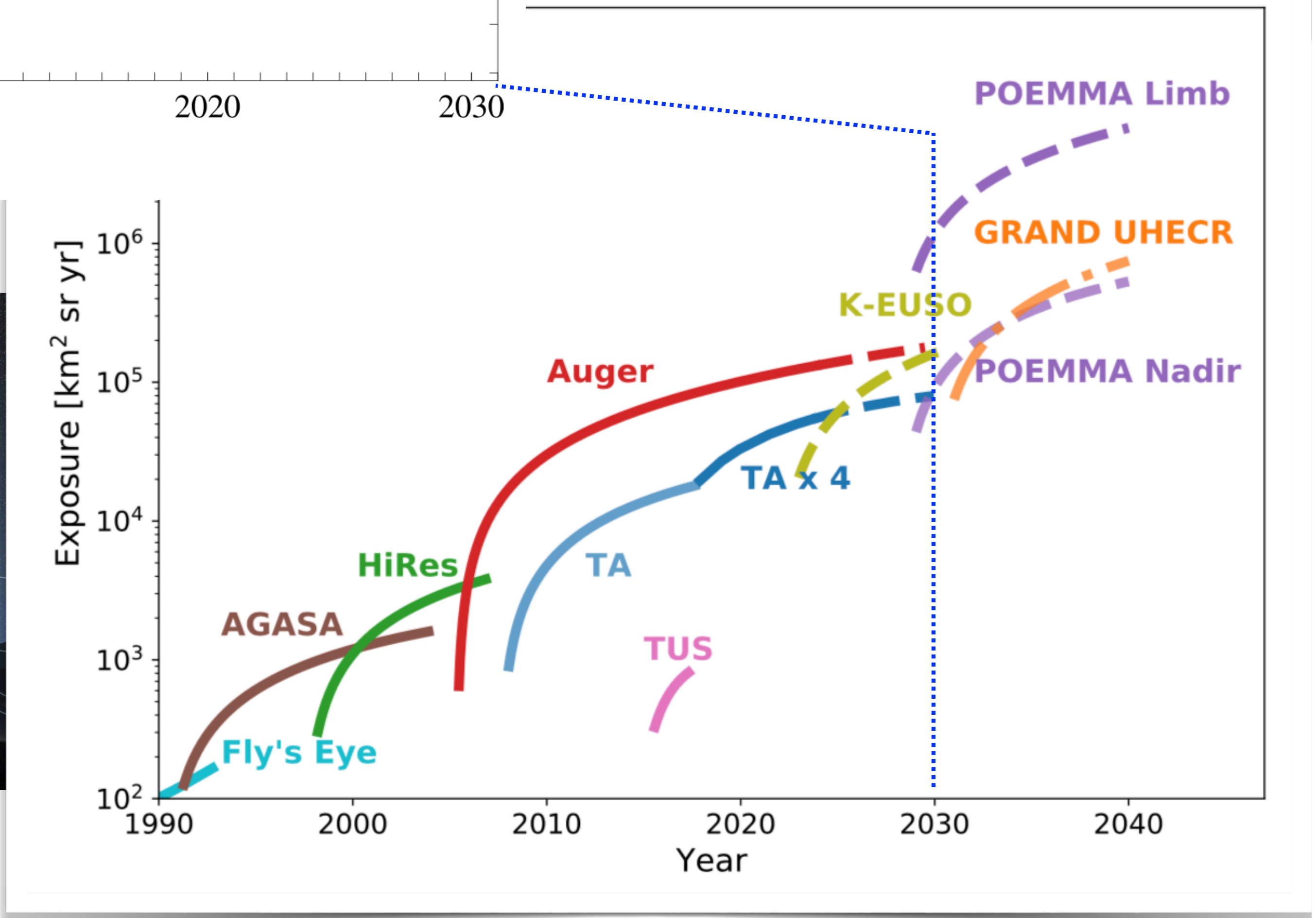
UHECR future: TAx4



Above 57 10^{18} eV

- reconstruction efficiency >95%
- Angular resolution 2.2^{0}
- energy resolution ~25%


TARGET EXPOSURES
5σ confirmation of starburst hypothesis
5σ confirmation of TA hot spot
5σ confirmation of γAGN hypothesis
exposure [km² sr yr]
10⁶
10⁵
10⁴
10³
10²
Auger
TA × 4
TA
HiRes
AGASA
TUS
Fly's Eye
1990
2000
2010
2020
2030
year


POEMMA Limb
GRAND UHECR
K-EUSO
POEMMA Nadir
Auger
TA x 4
TA
HiRes
AGASA
TUS
Fly's Eye
Exposure [km² sr yr]
10⁶
10⁵
10⁴
10³
10²
1990
2000
2010
2020
2030
2040
Year

BACKUP SLIDES

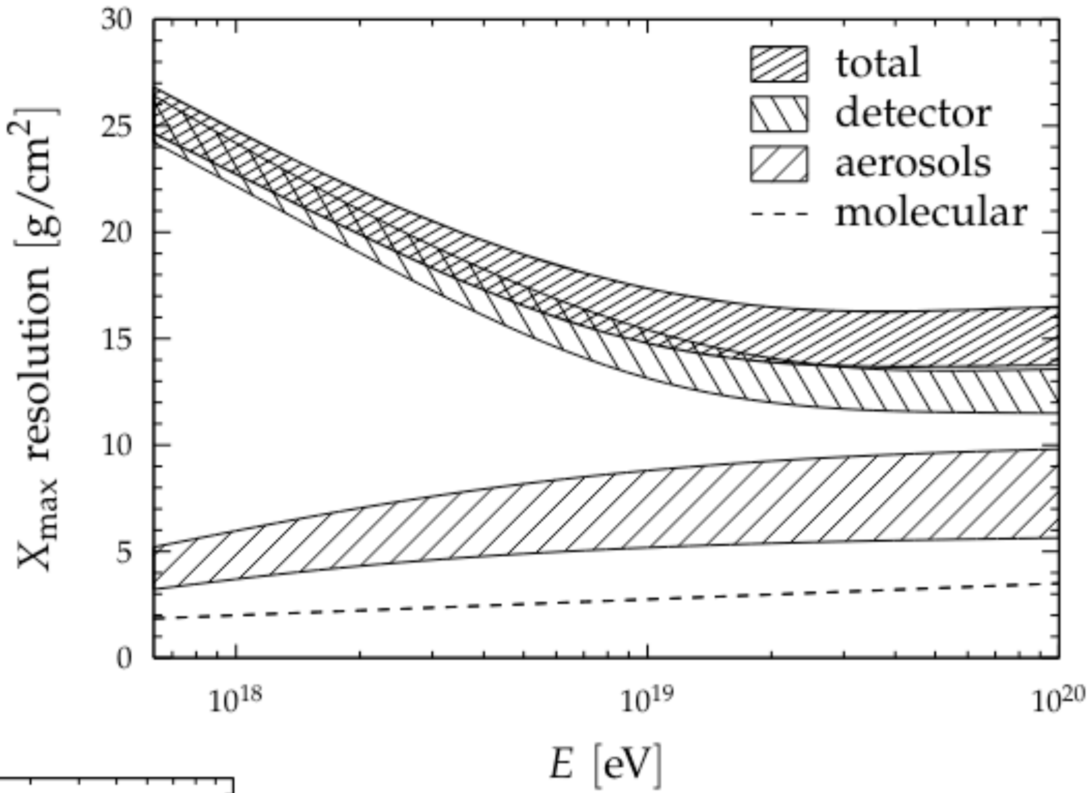
Energy resolution

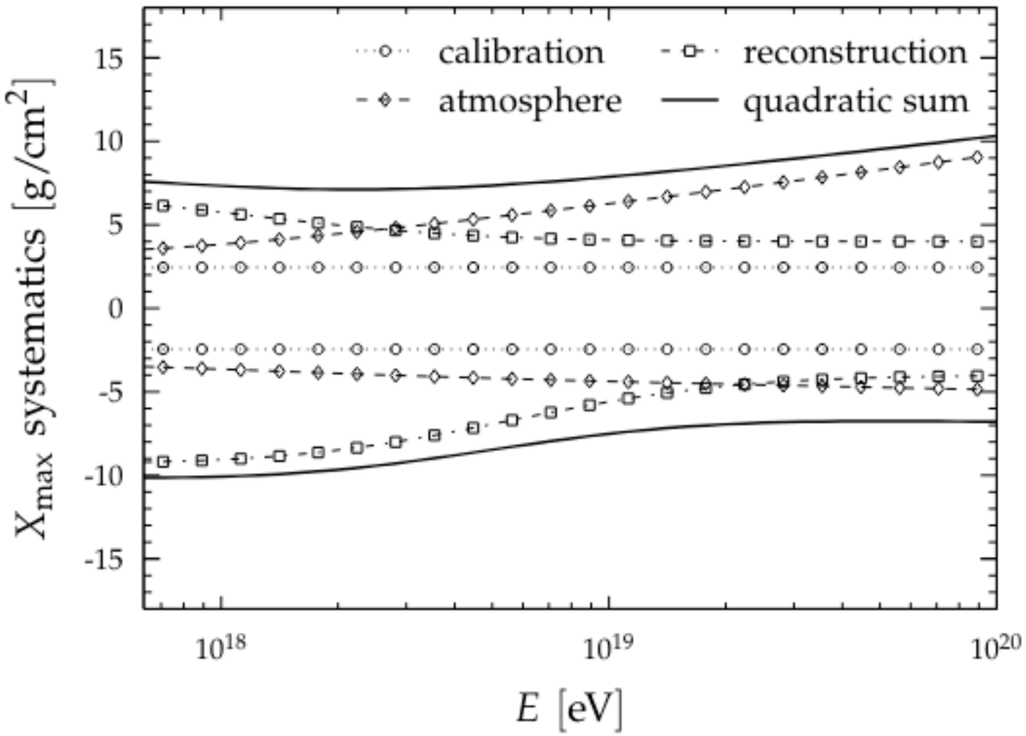
	FD energy resolution	
atmosphere	Aerosol optical depth	1.2% – 3.8%
	Horiz. uniform. of aerosols	1.6% – 5%
	Molecular atmosphere	1%
detector/ reconstruction	Nightly relative calib.	1.3%
	Time drift of FD energies	2.5%
	Mismatch between telescopes	3.5%
	Stat. error from geom. and GH fit	4.6% – 2.8%
	Extrapolation of profile	2.2%
invisible energy	E_{inv} shower-to-shower fluc.	1.1% – 0.6%
	E_{inv} mass uncertainty	2.4% – 0.3%
	TOTAL	7.6% – 8.6%

Systematic uncertainties on the energy scale

Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	**3.4% ÷ 6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec.)	**6.5% ÷ 5.6%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**
TOTAL	**14%**

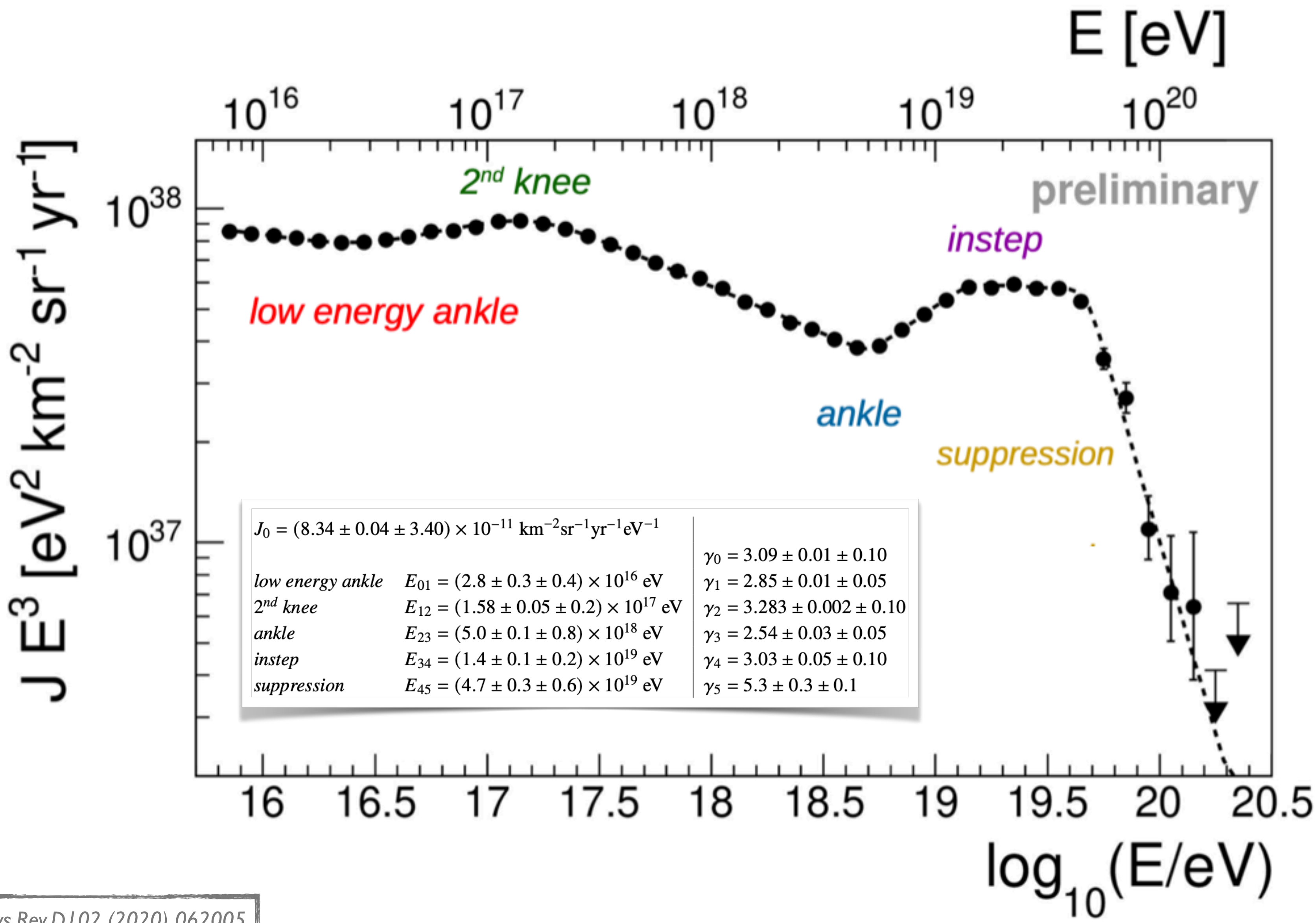
X_{max} resolution





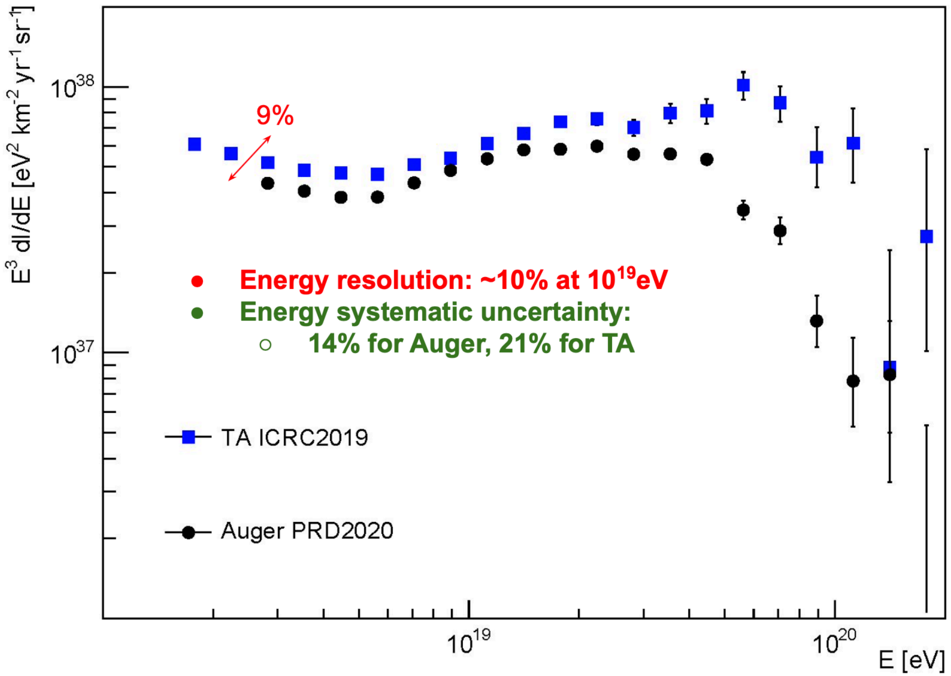
Systematic uncertainties on X_{max}

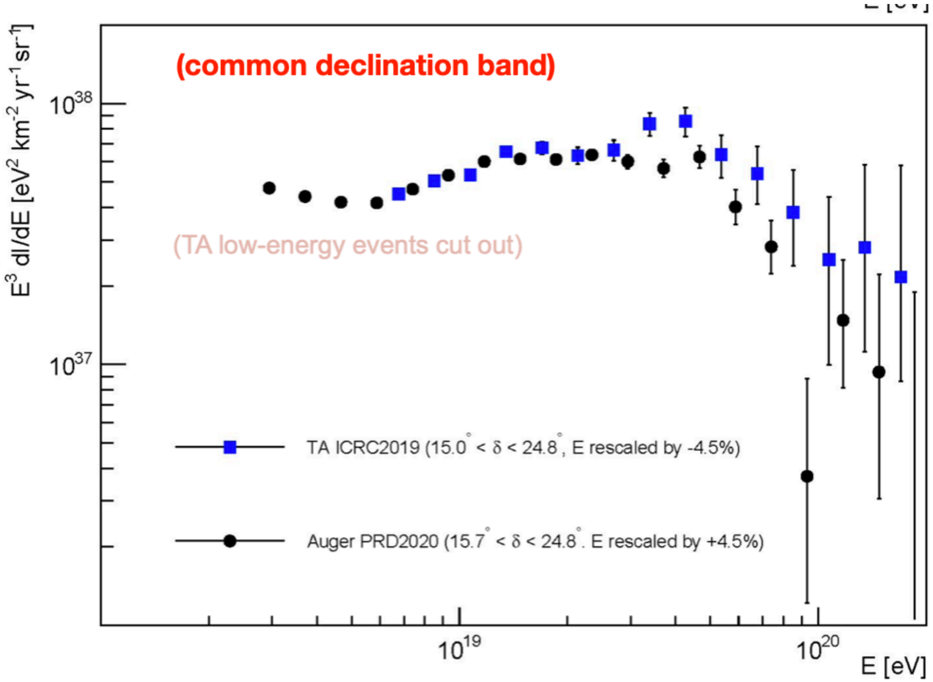
The Auger energy spectrum

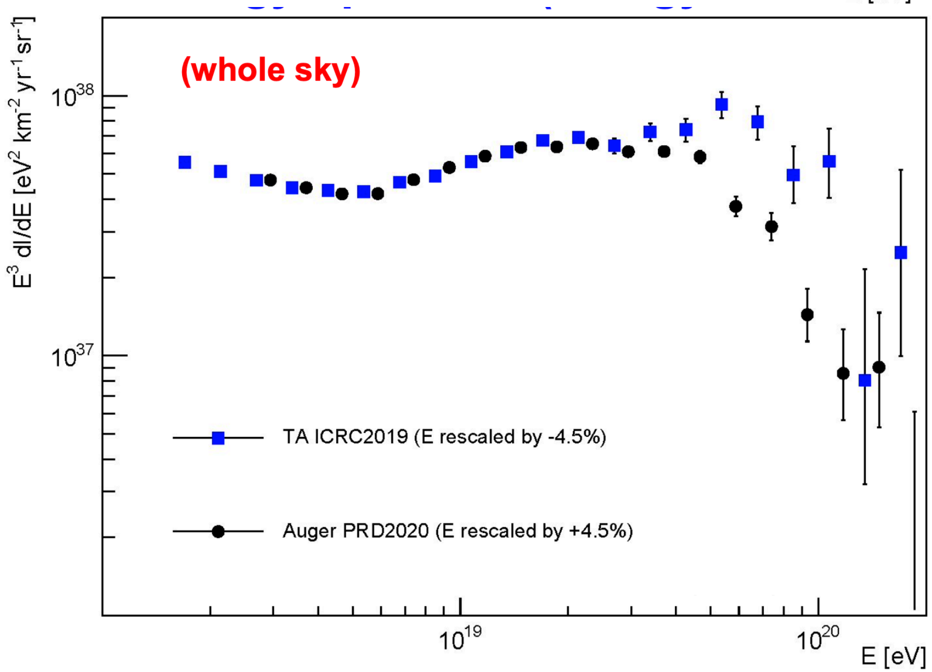


Auger Coll., Phys.Rev.D102 (2020) 062005
Auger Coll., Eur. Phys. J. C 81 (2021) 966
V.Novotny, PoS(ICRC2021) 324

Comparison Auger/TA







good agreement in the common declination band ($-15^0<\delta<24.8^0$) within systematics up to ~30 EeV
further energy dependent rescaling ±10% per decade needed to restore agreement at the UHE - studies ongoing

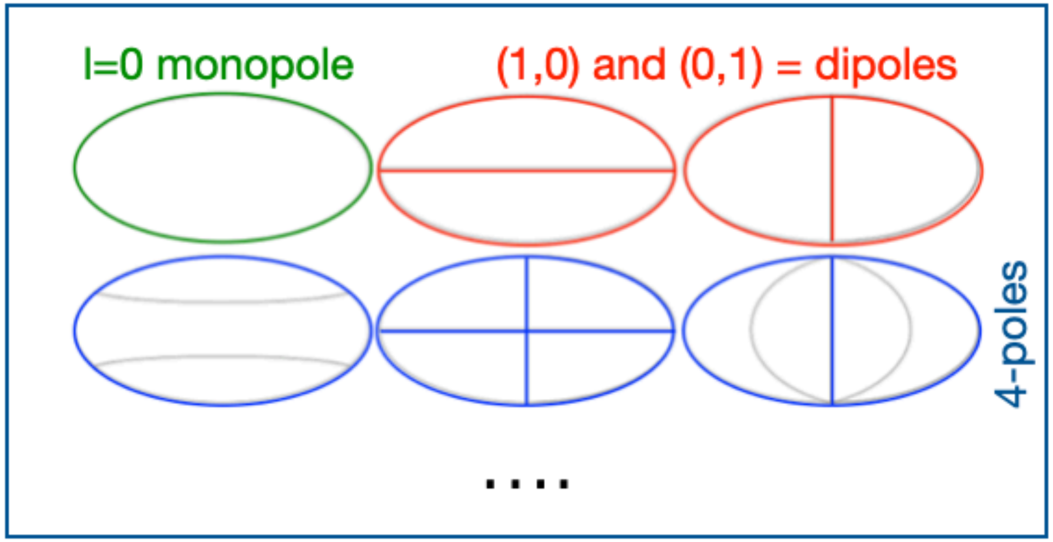
Main differences Auger/TA

- if E_{inv}(Auger) is used in TA : $E_{TA} \times 1.07$
- if FY(Auger) is used in TA : $E_{TA} \times 0.86$
- + differences in the method of correlating the SD observable with E: constant intensity cut in Auger, look-up tables based on QGSJetII-03(proton) for TA

PAO+TA working group, ICRC2021

Spherical harmonics in the sky

Normalised spatial event distribution = $I(\Omega) \equiv \frac{N(\Omega)}{\int d\Omega N(\Omega)} = \sum_{l=0}^{\infty} \sum_{|m| \le l} a_{lm} Y_{lm}(\Omega)$

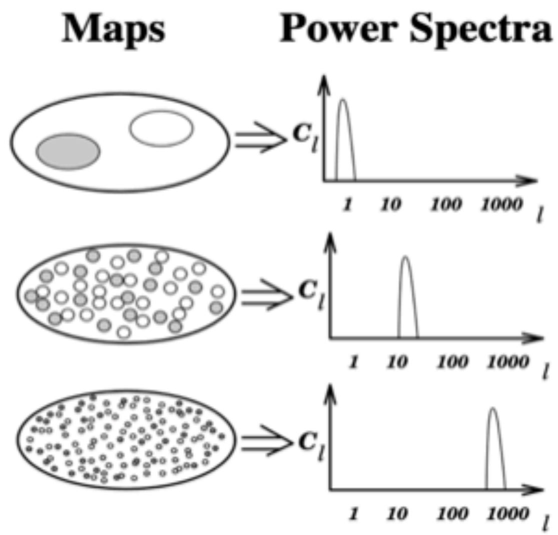


- rigorous expansion in spherical harmonics, complete $\{Y_{\ell m}\}$ set
- N=events seen in the solid angle Ω
- $a_{\ell m}$= spherical harmonics coefficients, include all the information about the event distribution

- l=0 monopole;
- l+1-|m| latitudinal zones
- l-|m| nodal latitudes

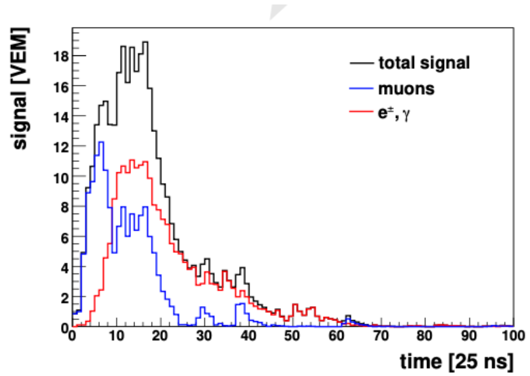
- Expansion coefficients $a_{\ell m}$'s ☞ frame-dependent
- Only $\ell = m = 0$ monopole coefficient is coordinate independent
- To combat problem

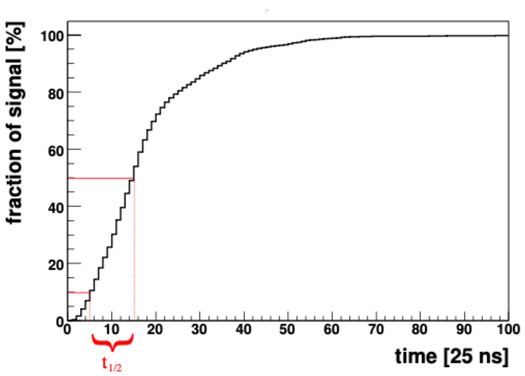
Power Spectrum $C_l \equiv \frac{1}{2l+1} \sum_{m=-l}^{l} a_{lm}^2$

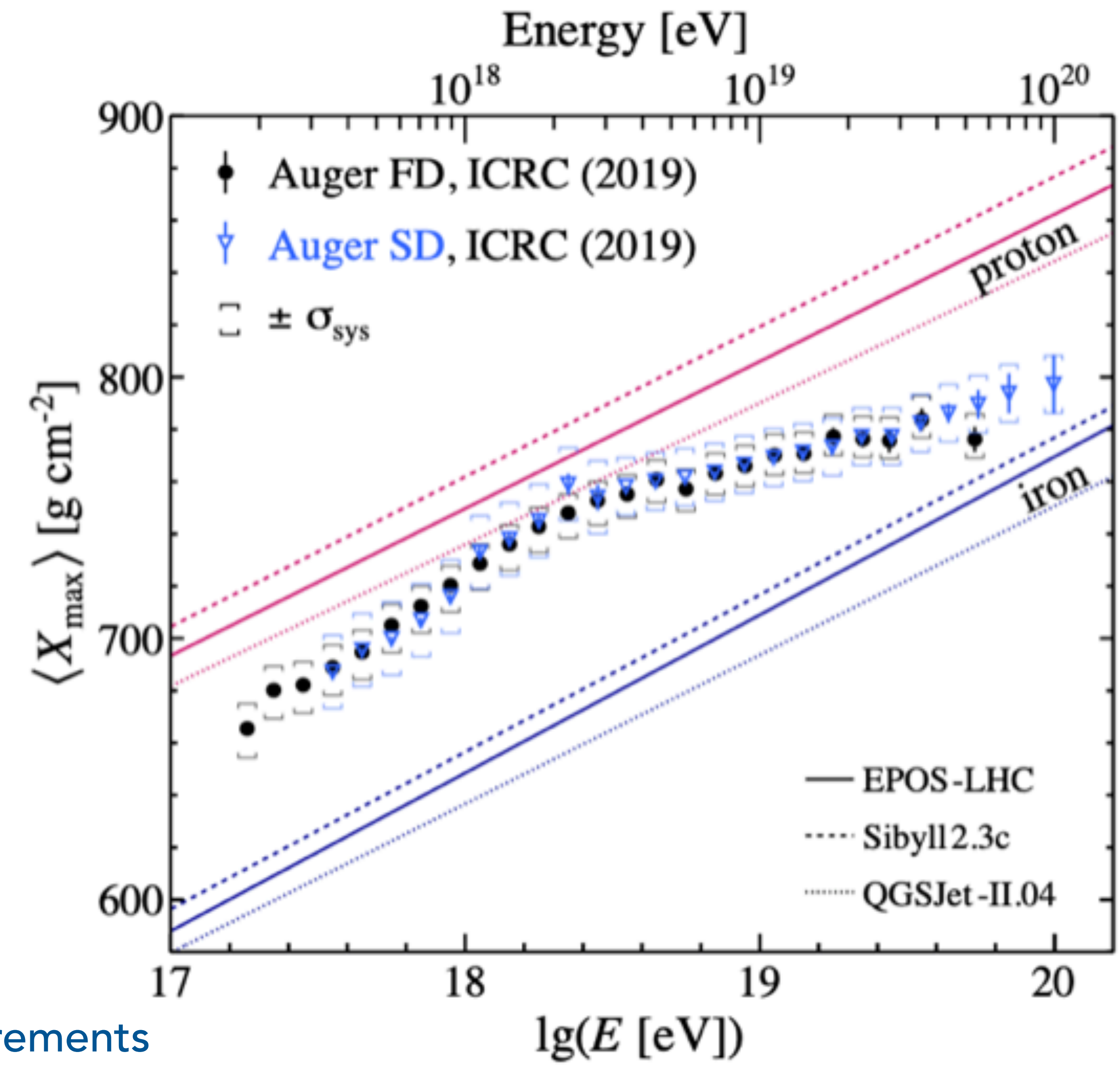


@Anchordoqui, L.

The mass composition from SD

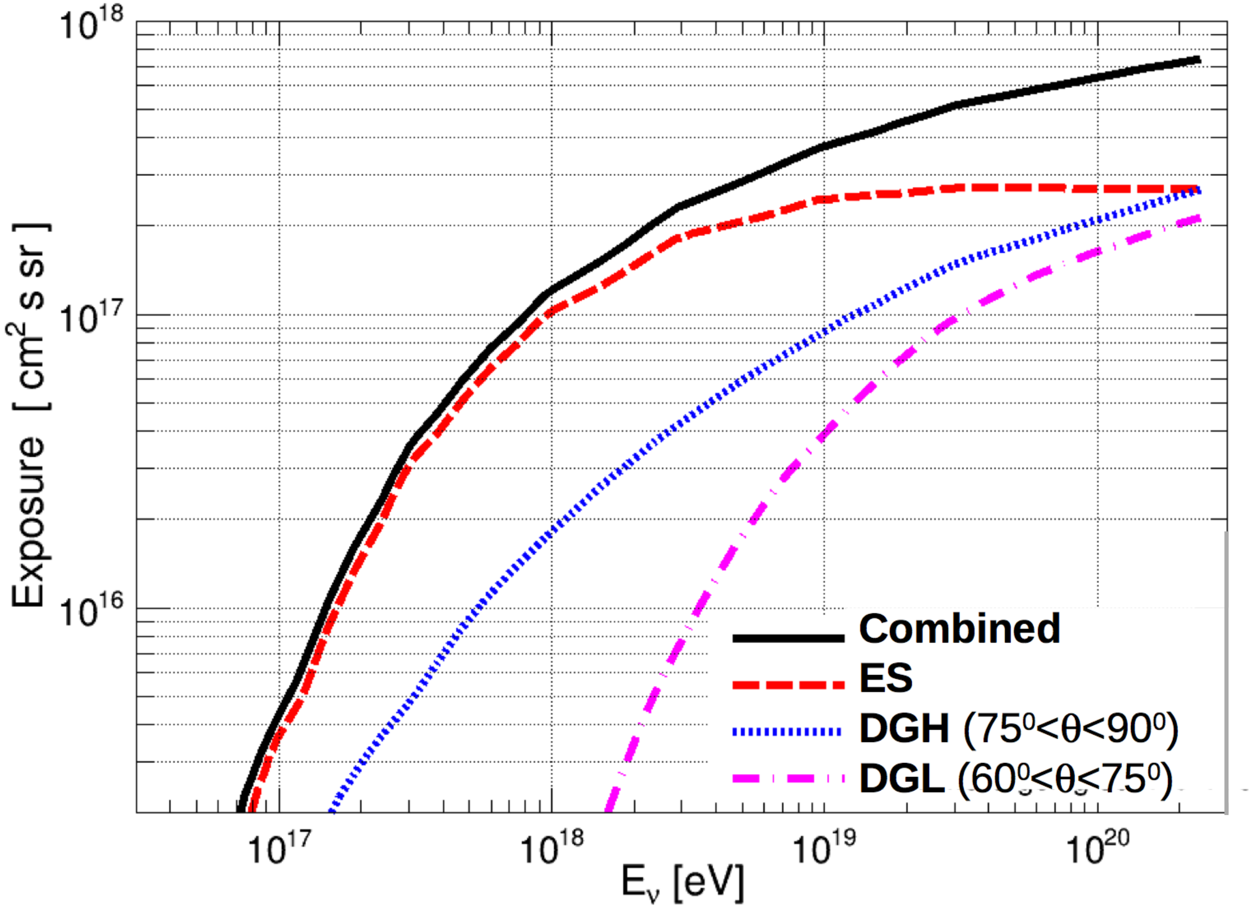






- coherent with the FD measurements
- larger systematic uncertainties but higher energy

Neutrinos in Auger



Relative contribution of channels & flavours to event rate (E^{-2} flux)

ES	79.4%
DGH	17.6%
DGL	3.0%

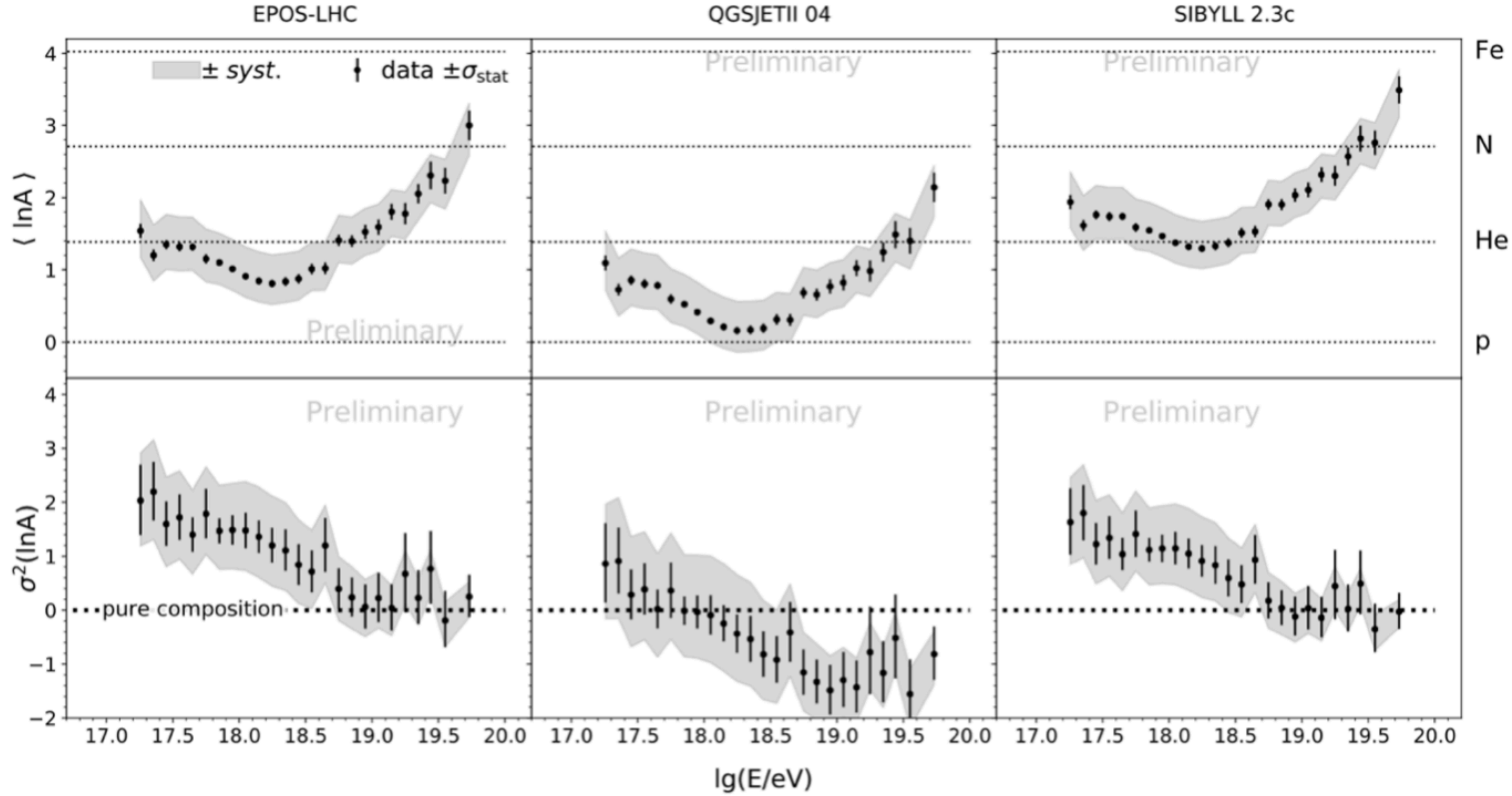
ν_τ

- production is suppressed relative to ν_e or ν_μ
- but ~same fluxes for all flavours after travelling cosmological distances, thanks to ν mixing.
- ES can undergo CC interactions and produce leptons.
- Since a lepton can travel tens of km in the Earth at EeV energies, it can emerge into the atmosphere and decay in flight producing an nearly horizontal extensive air shower (EAS) above the detector.

$$\langle X_{\max}\rangle = \langle X_{\max}\rangle_p + f_E \; \langle \ln A\rangle \qquad f_E = \xi - \frac{D}{\ln 10} + \delta \, \log_{10}\left(\frac{E}{E_0}\right)$$

$$\sigma^2(X_{\max}) = \langle \sigma^2_{\rm sh}\rangle + f_E^2 \; \sigma^2_{\ln A} \; .$$

$$\langle \ln A\rangle = \frac{\langle X_{\max}\rangle - \langle X_{\max}\rangle_p}{f_E} \qquad \sigma^2_{\ln A} = \frac{\sigma^2(X_{\max}) - \sigma^2_{\rm sh}(\langle \ln A\rangle)}{b\;\sigma_p^2 + f_E^2}$$



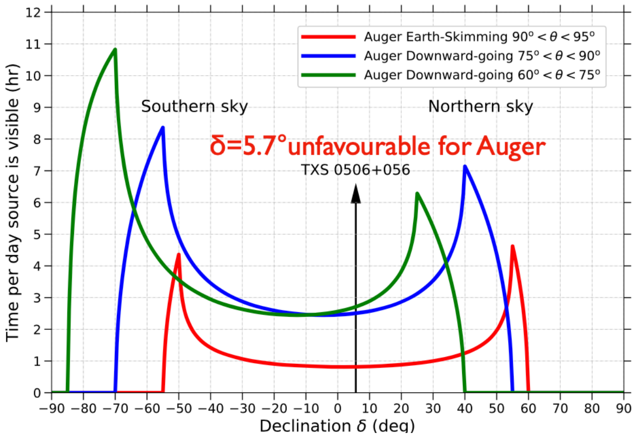
Model-independent decrease of $\sigma(\ln A)$ until $\sim 10^{18.7}$ eV

Less model-dependent constraints on $\sigma(\ln A)$ near the ankle?

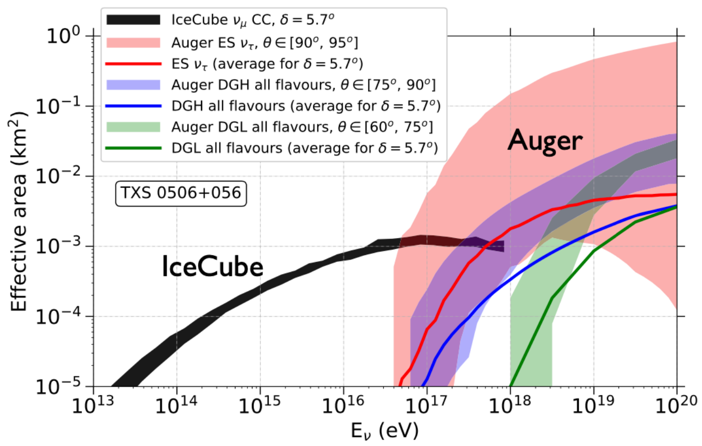
Neutrinos from TXS

In Sept. 2017, IceCube observed a 290 TeV nu from the direction of TXS 0506+59 during a flaring state [Science 361, 146 (2018)]

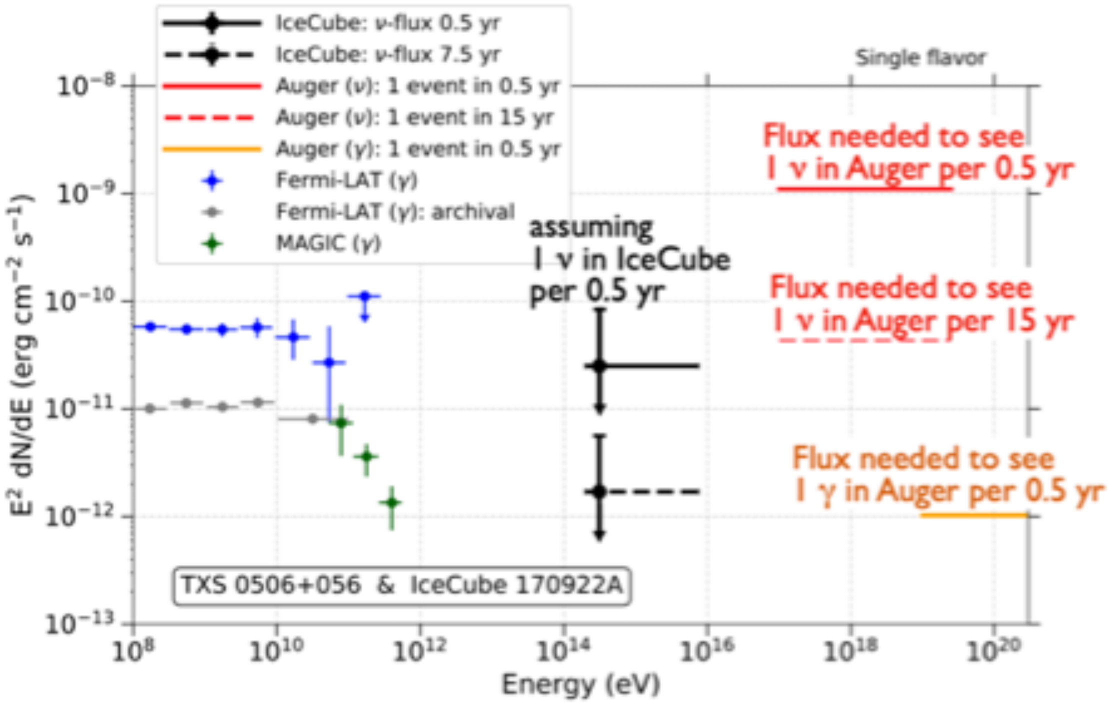
daily visibility in ES channel of Auger: < 1 hrs



effective area in comparison to IceCube



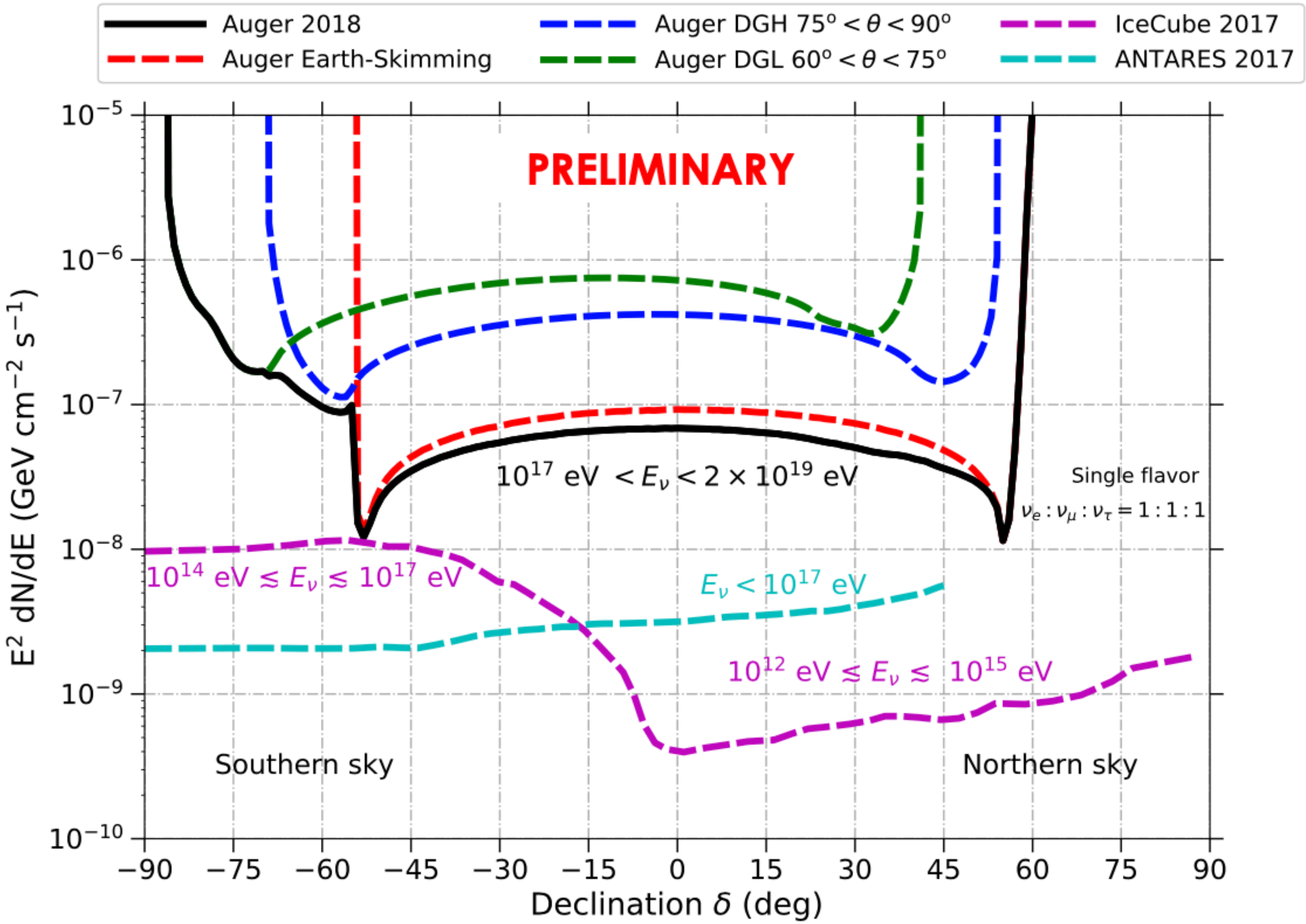
Flux comparison from single event assuming E-2 spectrum

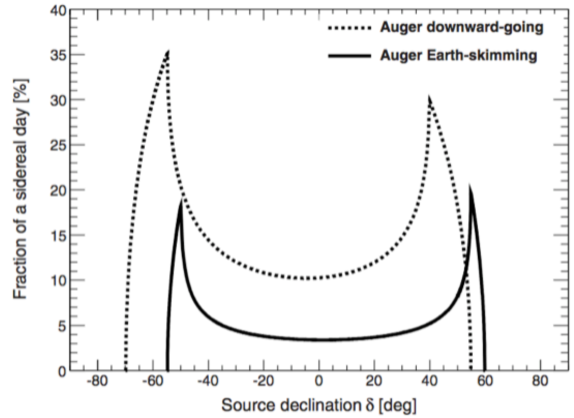


A neutrino in Auger could be seen only in case of hard neutrino spectra (+2σ allowance of IceCube)

Auger Collaboration, ApJ 902 (2020) 105

Steady sources of neutrinos

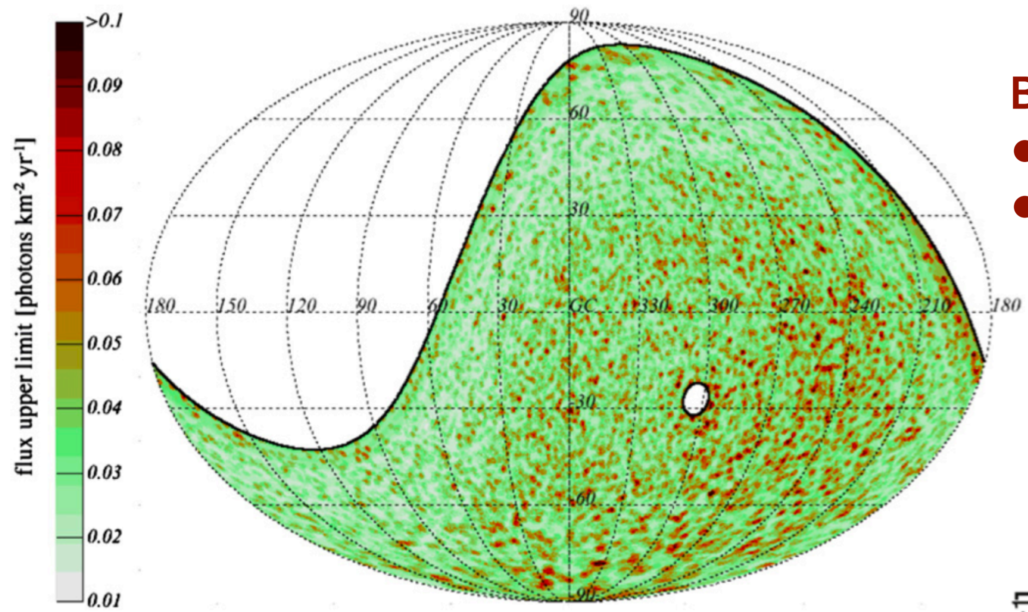




Energy range complementary to that of IceCube and Antares

IceCube, Astrophys.J. **835**, 151 (2017)   ANTARES, PRD **96**, 082001 (2017)

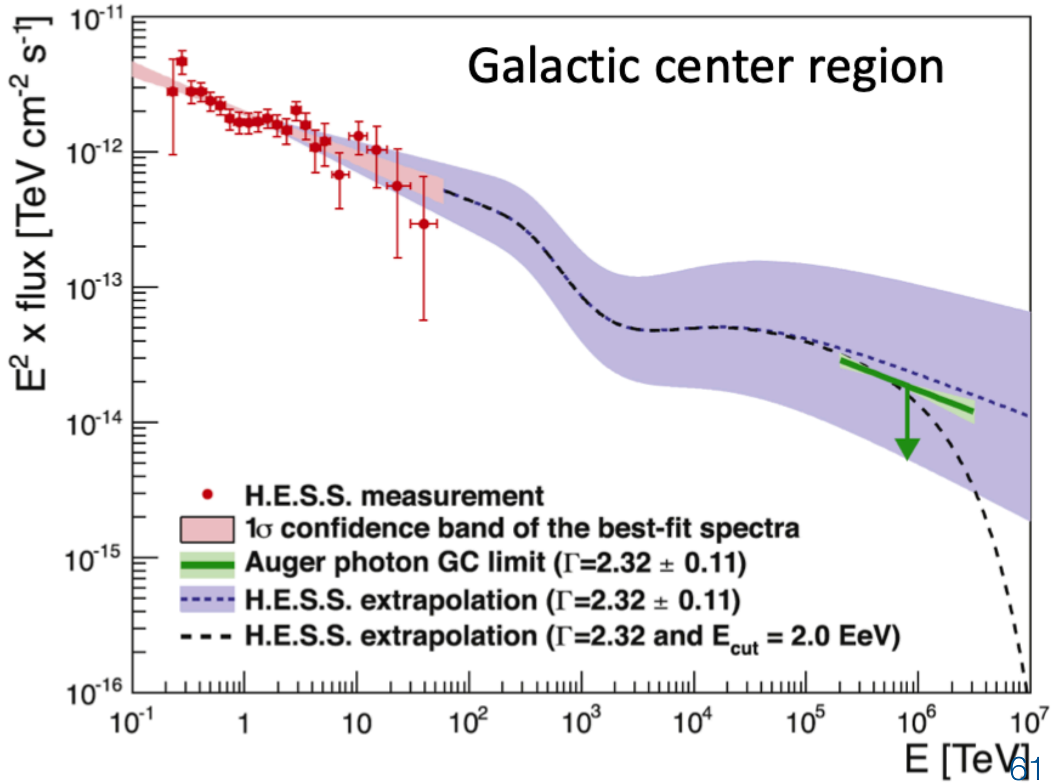
Sources of Photons



Blind search

- no significant excess
- upper limits compatible with different hypotheses
  - EG sources at > 5 Mpc
  - transient or beamed Galactic sources
  - sources inefficient in photon production

Auger Coll., ApJ 789 (2014) 160



Targeted search

- no significant excess
- constrains on the allowed parameter space for the allows the extrapolation of the HESS flux
- upper limit on cut-off at ~ 2 EeV

Auger Coll., ApJ 837 (2017) L25