
L’Osservatorio Pierre Auger :
fisica astro-particellare di altissima energia
Antonella Castellina - INAF OATo

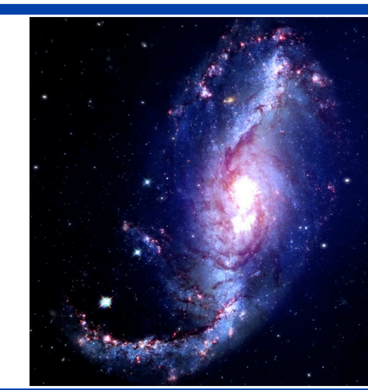
Ultra-High Energy Cosmic Rays

Charged nuclei and neutral particles with energies ≳ 10^{17} eV

the science case

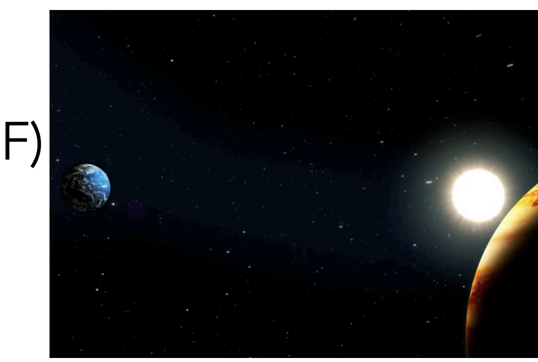
The quest for the sources

- Identification of the sources and/or source regions
- determination of the acceleration mechanism producing UHECRs
- study of the characteristics of the sources
- Multi-messenger studies (neutrinos, gamma-rays)



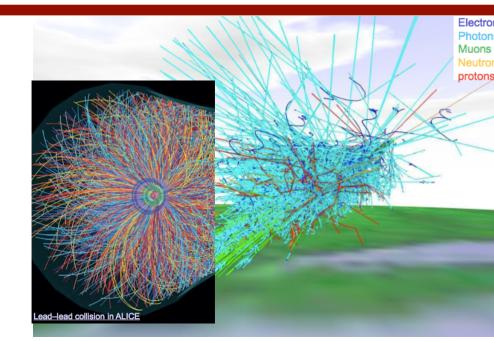
Investigation of the UHECR propagation

- Measurements/limits on magnetic fields (GMF,EGMF)
- Photon background, photonuclear cross-sections
- matter distribution



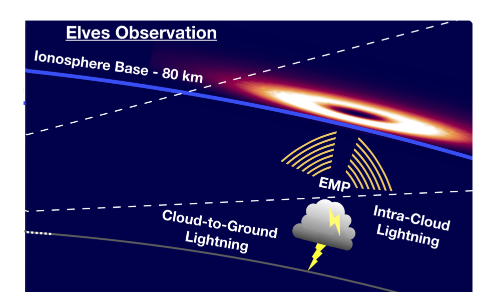
Particle physics at UHE

- Fundamental physics (LIV, Dark matter)
- hadronic interactions at UHE
- study of the characteristics of the sources

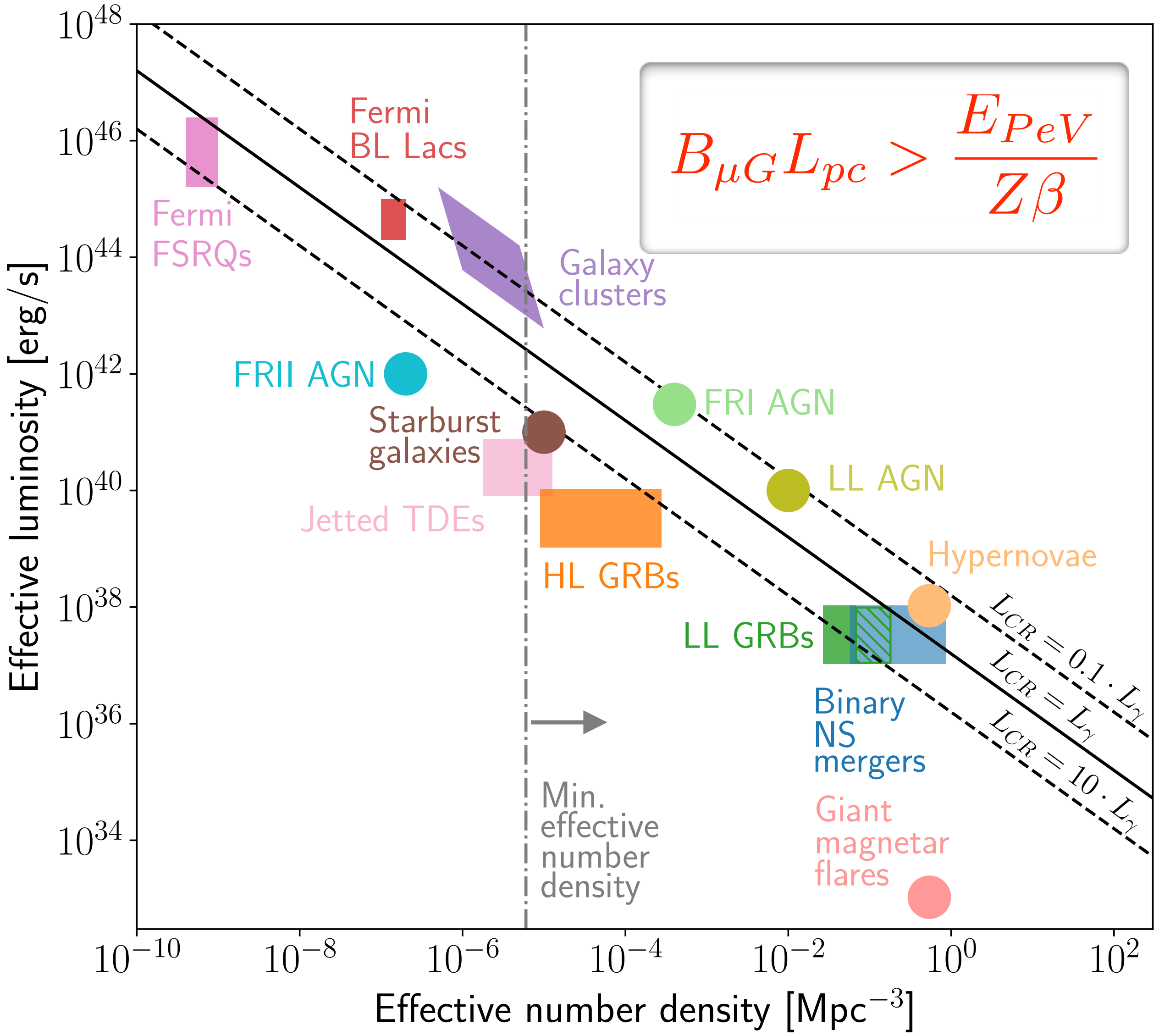


Multi-purpose applications

- atmospheric physics - TGF, Elves
- cosmo-geophysics

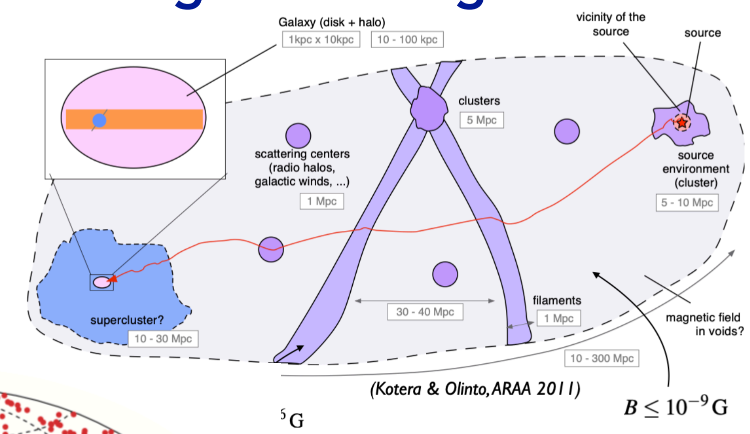


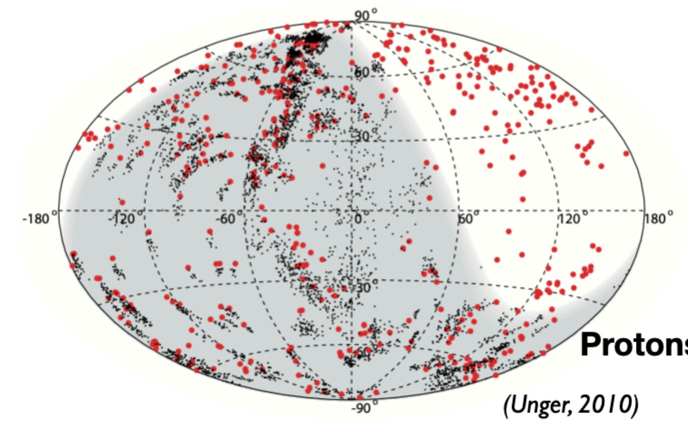
The quest for the sources



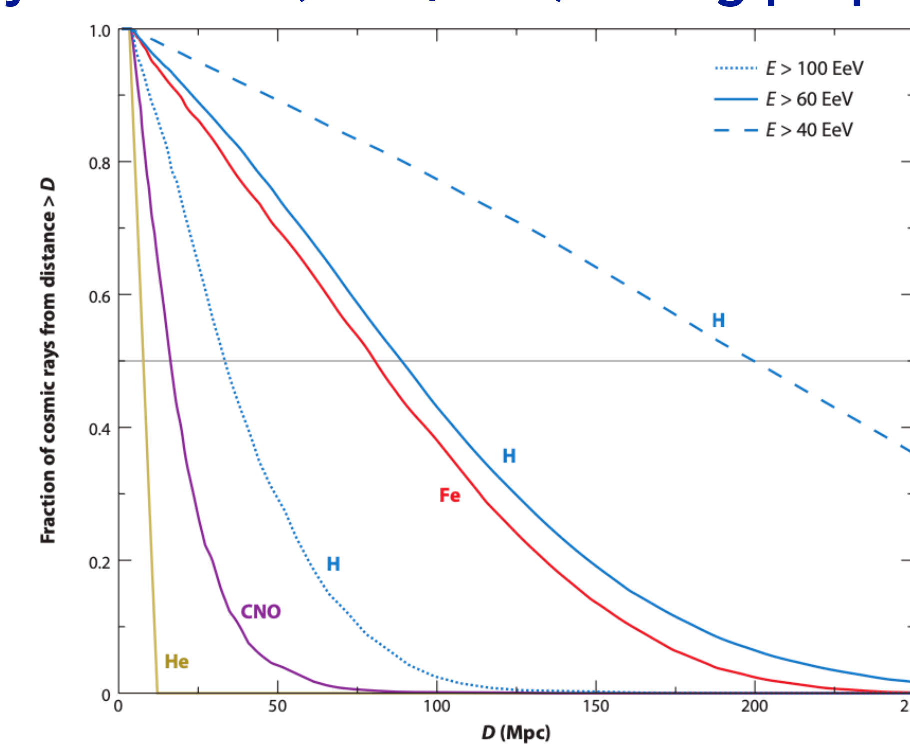
Deflection in Galactic and extragalactic magnetic fields

$$\delta \simeq 3^o \frac{B}{3\,\mu G}\frac{L}{kpc}\frac{6\times 10^{19} eV}{E/Z}$$





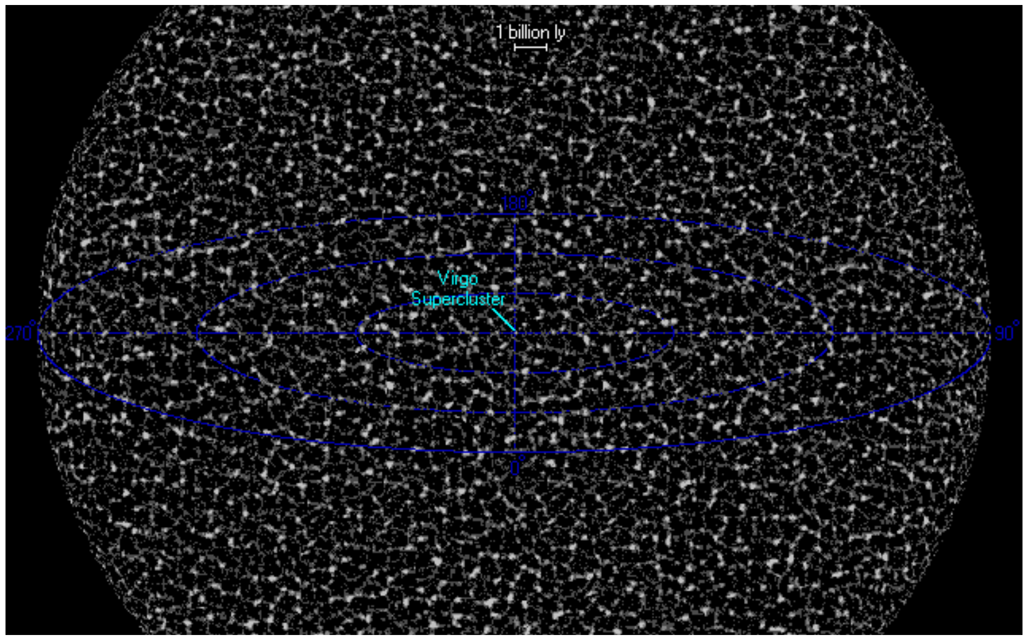
Energy losses on (CMB, EBL) during propagation



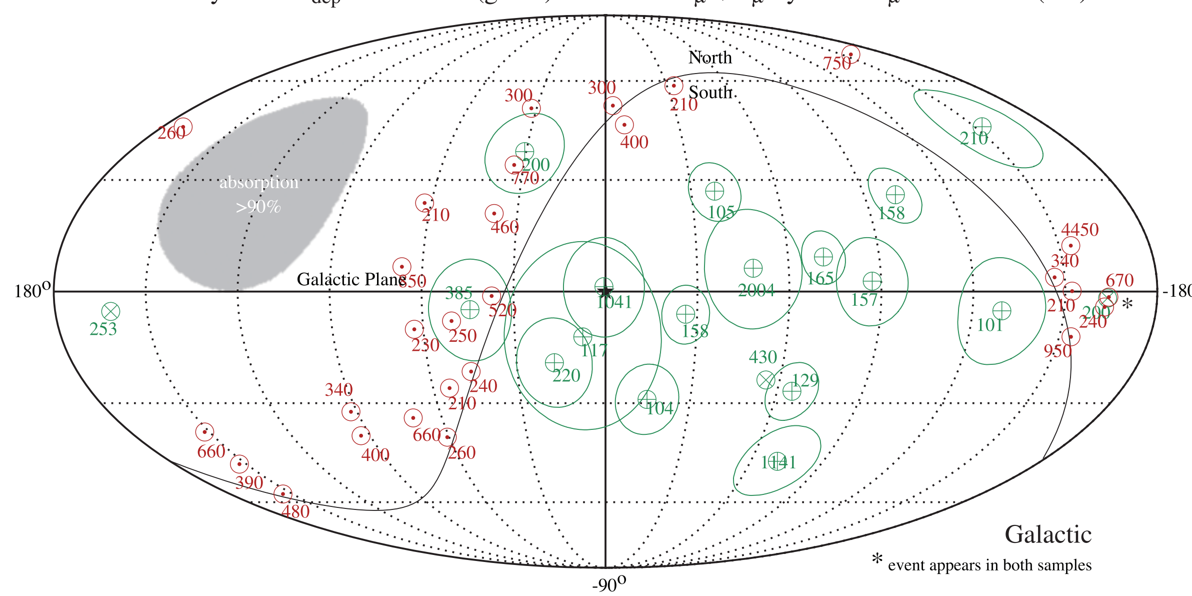
- in the acceleration region
  - $L_{pc} >> r_L$ d
  - ρ_{rad} and ρ_{mat} low
  - $B_{\mu G}$ ⟶ fast t_{acc}

    ⟶ small energy losses
- source power such to reach the observed UHECRs intensities
- acceleration mechanism able to reach $>10^{20}$ eV

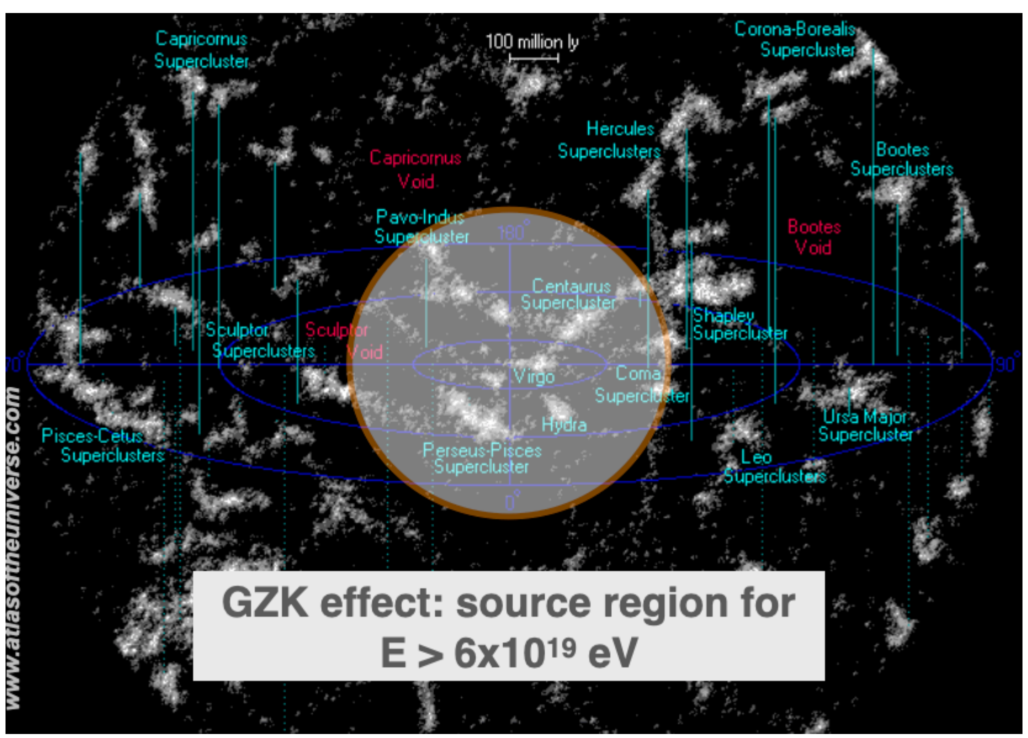
Complementarity of UHECRs and neutrinos



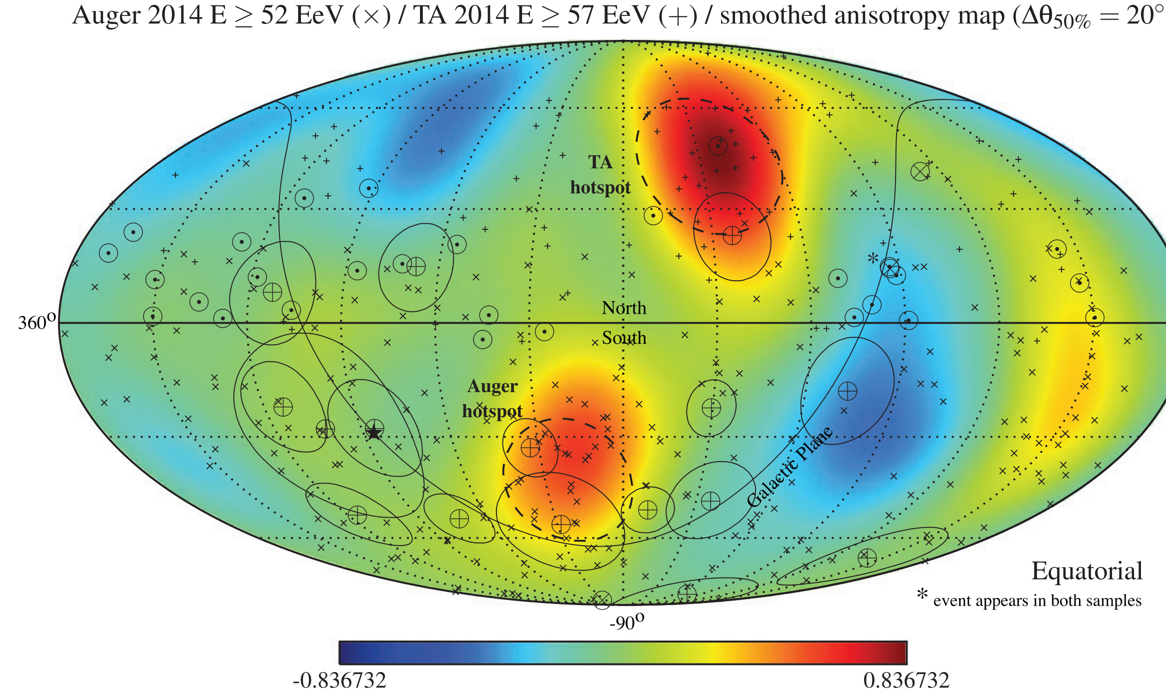
HESE 4yr with $E_{dep} > 100$ TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 6yr with $E_\mu > 200$ TeV (red)



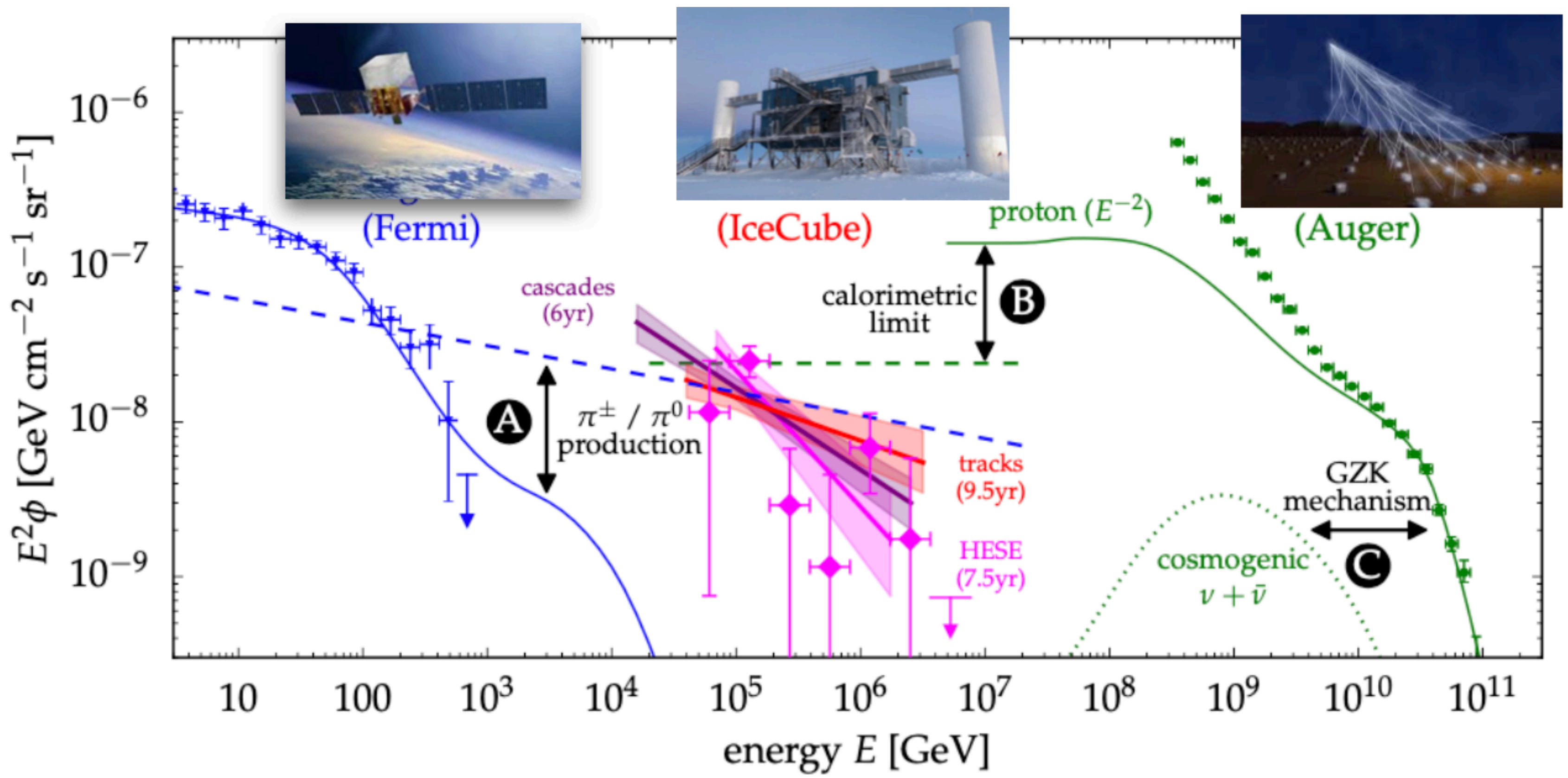
(Ahlers & Halzen, PTEP 2017)



Auger 2014 E ≥ 52 EeV (×) / TA 2014 E ≥ 57 EeV (+) / smoothed anisotropy map ($\Delta\theta_{50\%} = 20°$)



How to make progress



Theory

Model predictions

- Flux of particles
- Mass composition
- Arrival direction distribution
- Secondary particles and multi-messenger observations
- Air shower measurements

- Atmospheric phenomena and geophysics

External input from

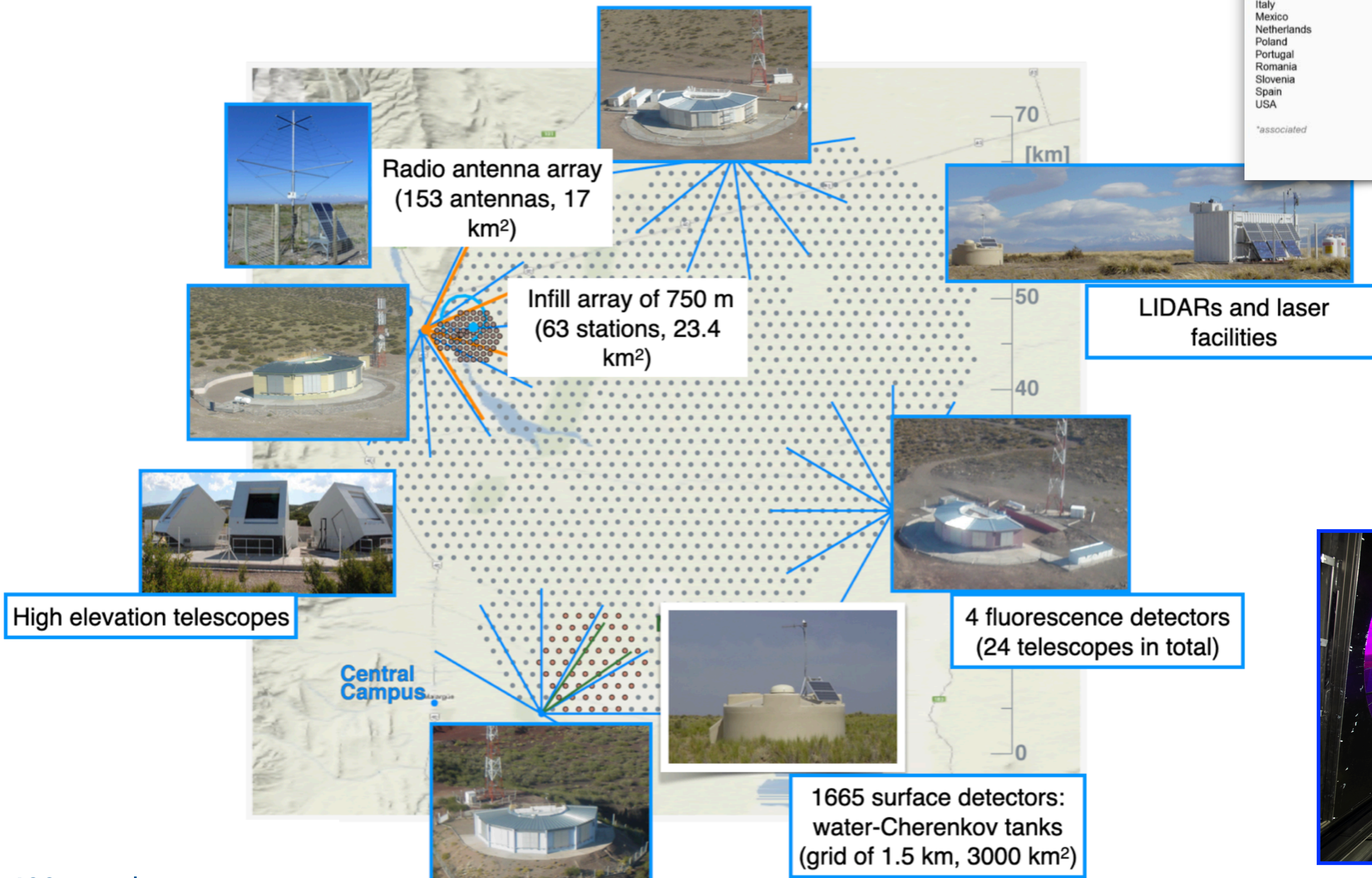
astro and particle physics

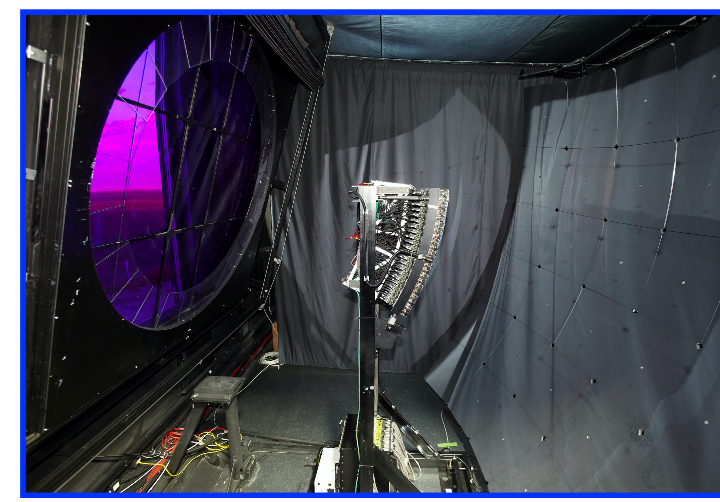
Phenomenological studies

Theory/models vs. data

Combination of different data sets

The Pierre Auger Observatory





~400 members
from 17 Countries, 89 institutions

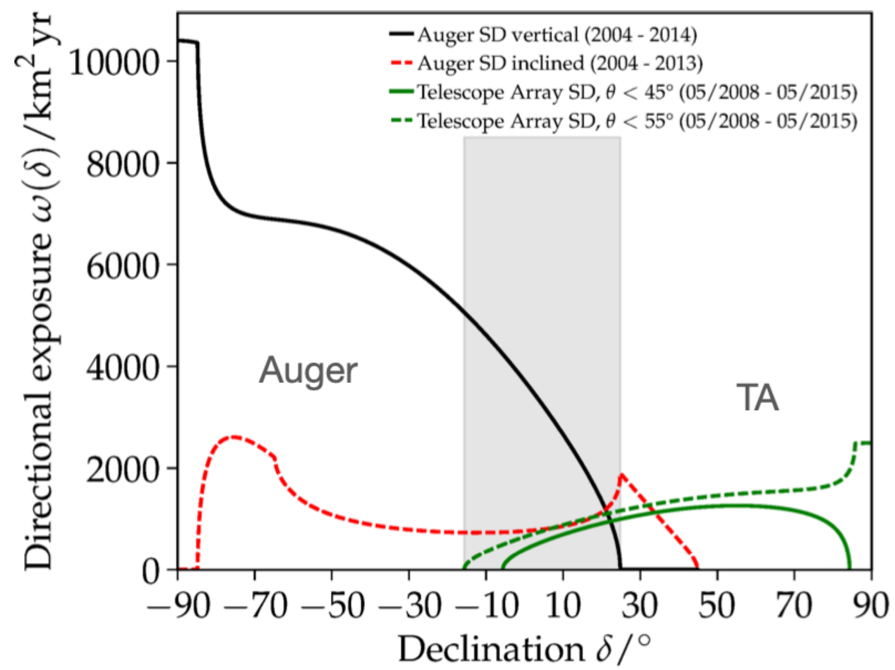
Italy:
38 members from
- 2 INAF (OA-To and IASF-Pa)
- 8 INFN (TO, MI, AQ/GSSI, Roma2, NA, LE, CT, PA)
- 8 Universities

INAF
- co-spokesperson (A.Castellina, OA-To)
- task leader for AugerPrime (Auger upgrade) surface detectors
- task leader for the maintenance of the Auger surface detectors
- analysis task leader for the Spectrum task

The Pierre Auger Observatory

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

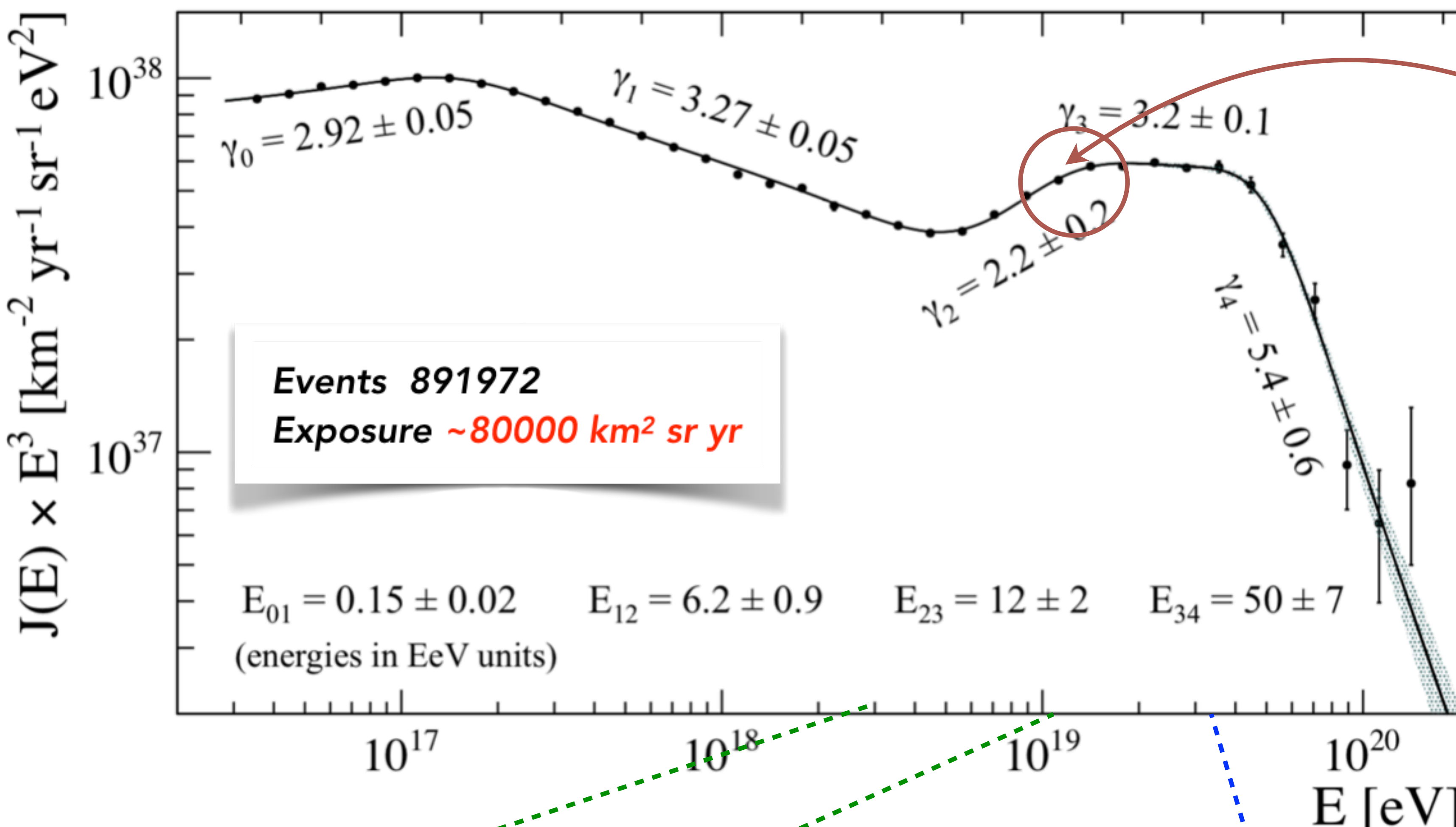


Overlap region can be used for cross-checks and cross-calibration

$\omega(\delta)$

- Main experiments: Auger Observatory (**Southern** Hemisphere) and Telescope Array (**Northern** hemisphere)
- Hybrid detectors (Surface Stations + Fluorescence Telescopes): **100% duty cycle for SD, ~15% for FD**
- Together, **full sky coverage**, but exposures **1:8 - 1:6**
- Area **1:7** (3000 km² for Auger, 680 km² for TA)
- Multi-messenger studies : only Auger can detect neutrinos (horizontal showers)

The energy spectrum



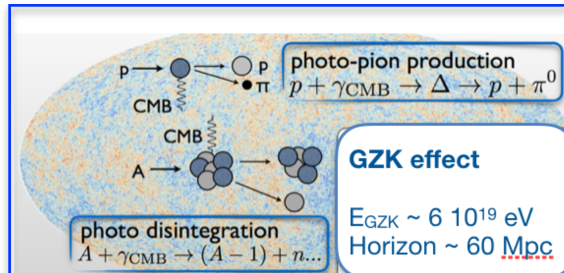
[A.Castellina, Highlight talk, PoS(ICRC2019) 4]

- ☑ New feature
- ☑ He+N ?

Transition region

- ☑ “Ankle” confirmed
- ☑ onset of the extragalactic UHECRs
- ☑ Secondo Galactic component?

Suspression region

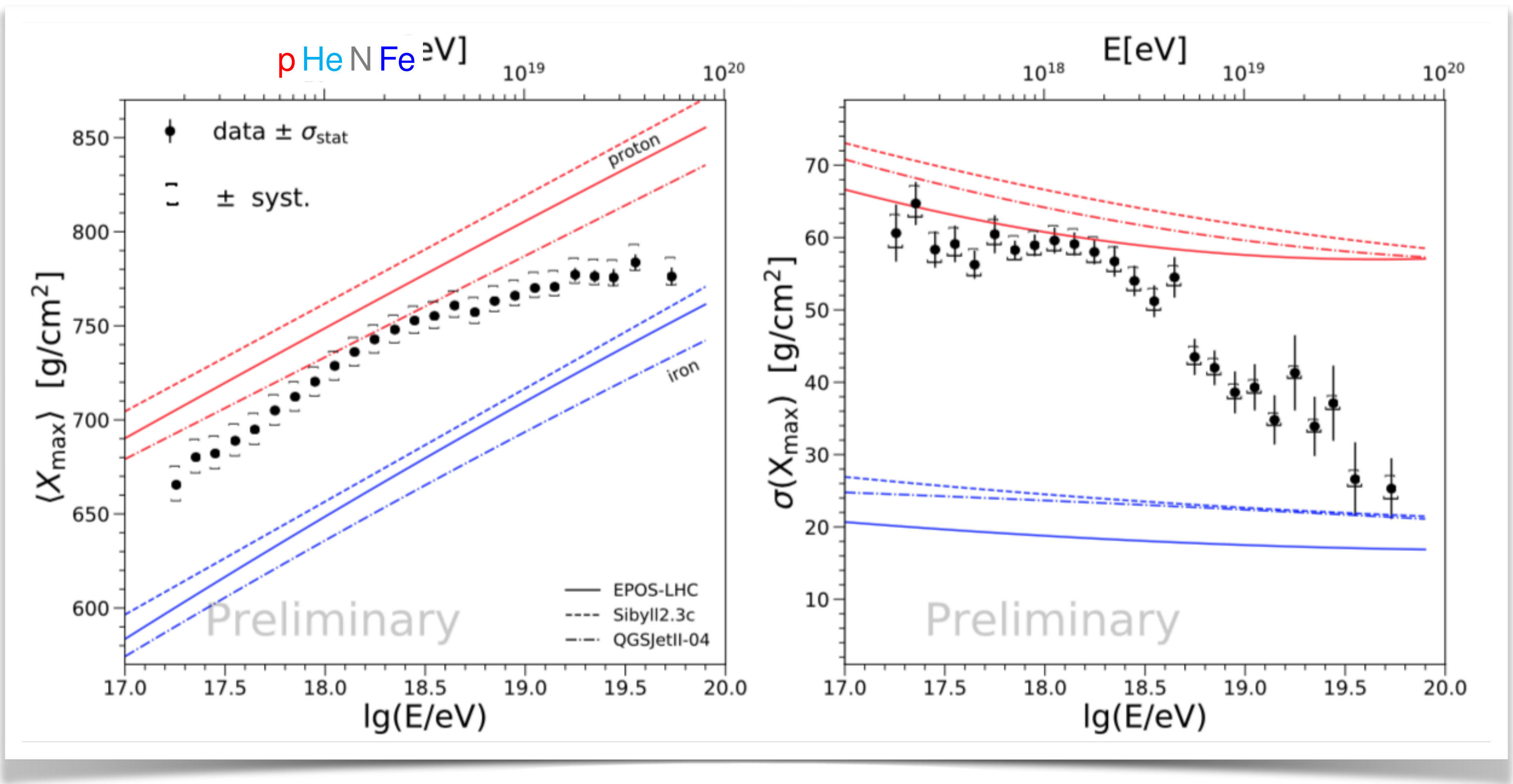


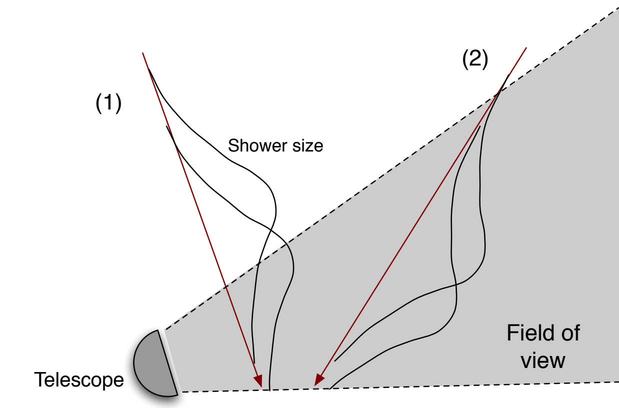
- ☑ light composition (p + <10% heavier)
- ☑ soft injection spectrum (slope ~ 2)
- ☑ copious production of cosmogenic ν

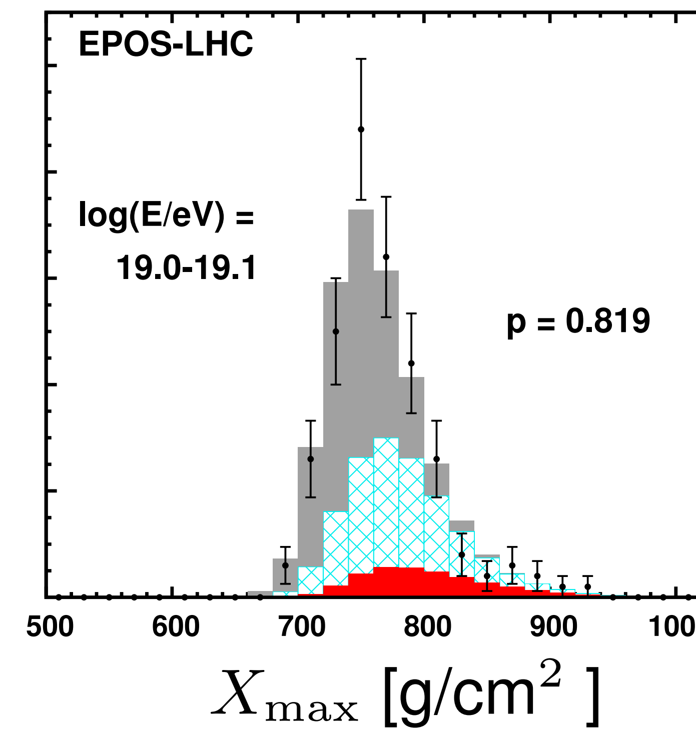
- ☑ mixed composition
- ☑ hard injection spectrum (γ ~ 1)
- ☑ production of cosmogenic ν and γ is suppressed

[Auger, Phys.Rev.D 102, 062005 (2020) (Editor's Suggestion)]

The mass composition







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

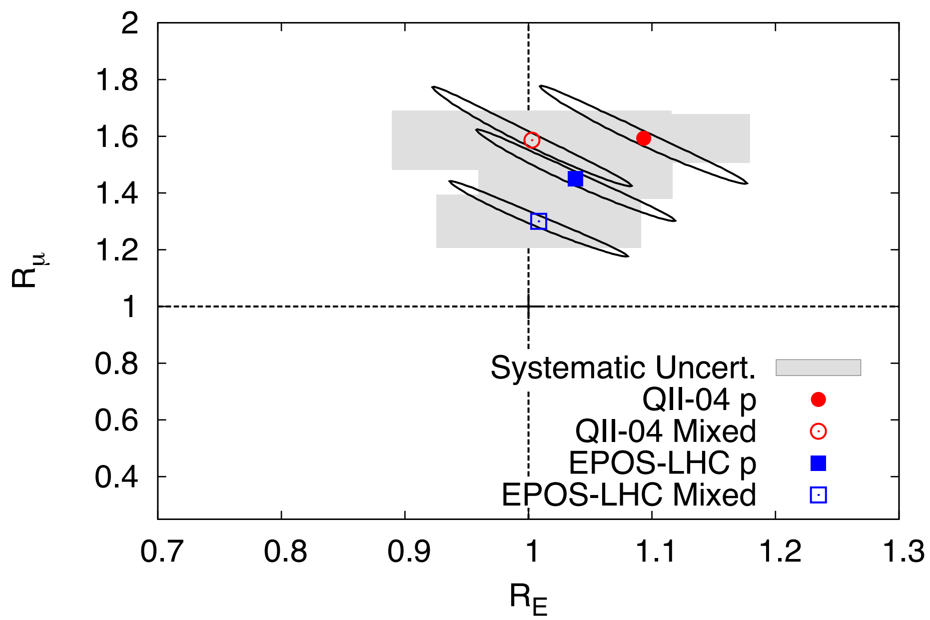
$$\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f_E \sigma^2(lnA)$$

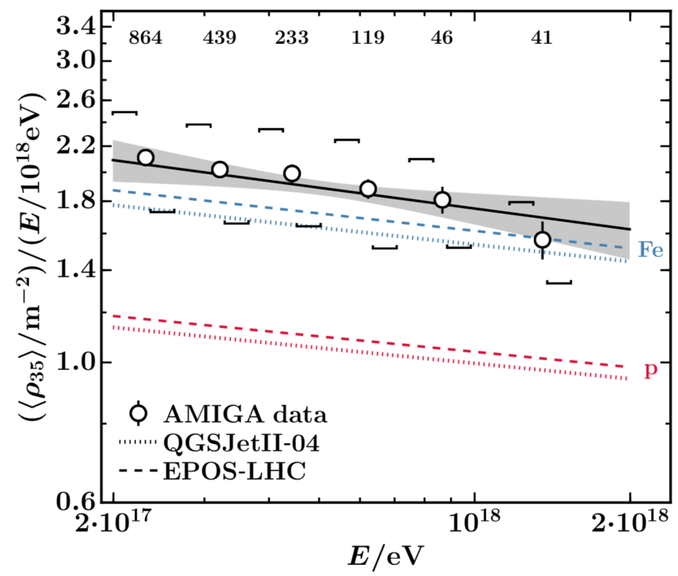
➡Rate of change of primary mass not constant with energy (as expected from constant composition)

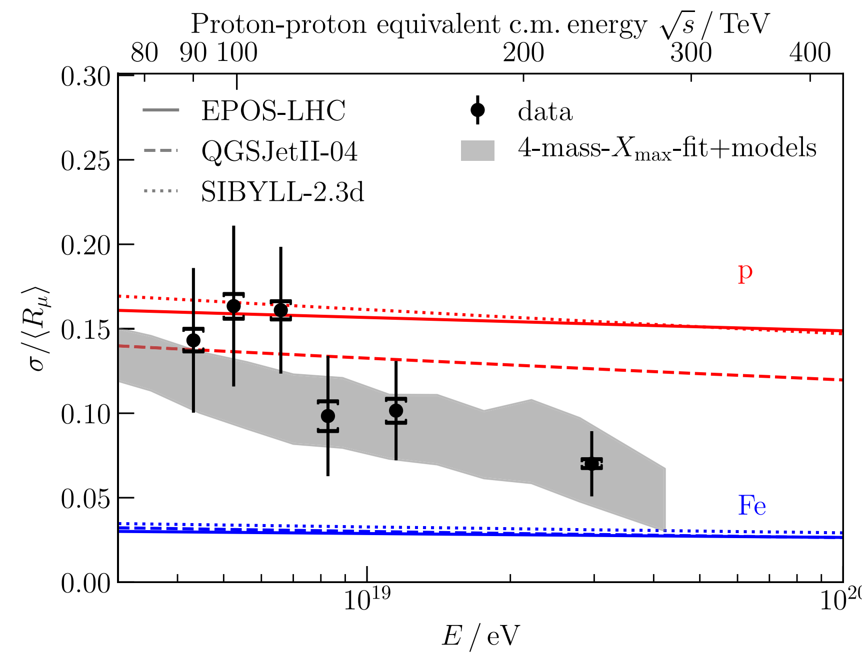
➡IF hadronic interaction models reliable, then the primary composition gets lighter up to ~ 2 10^{18} eV, and then evolves to intermediate masses

Hadronic interactions

Evidence for underestimation of muon production in models

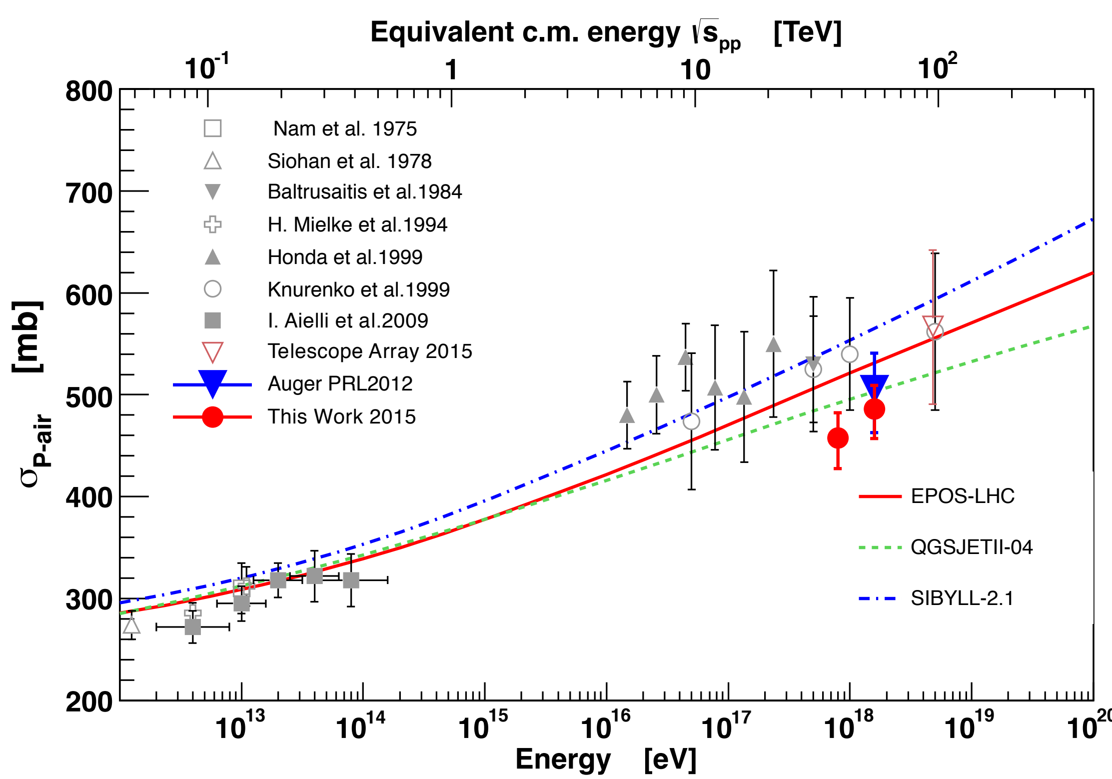


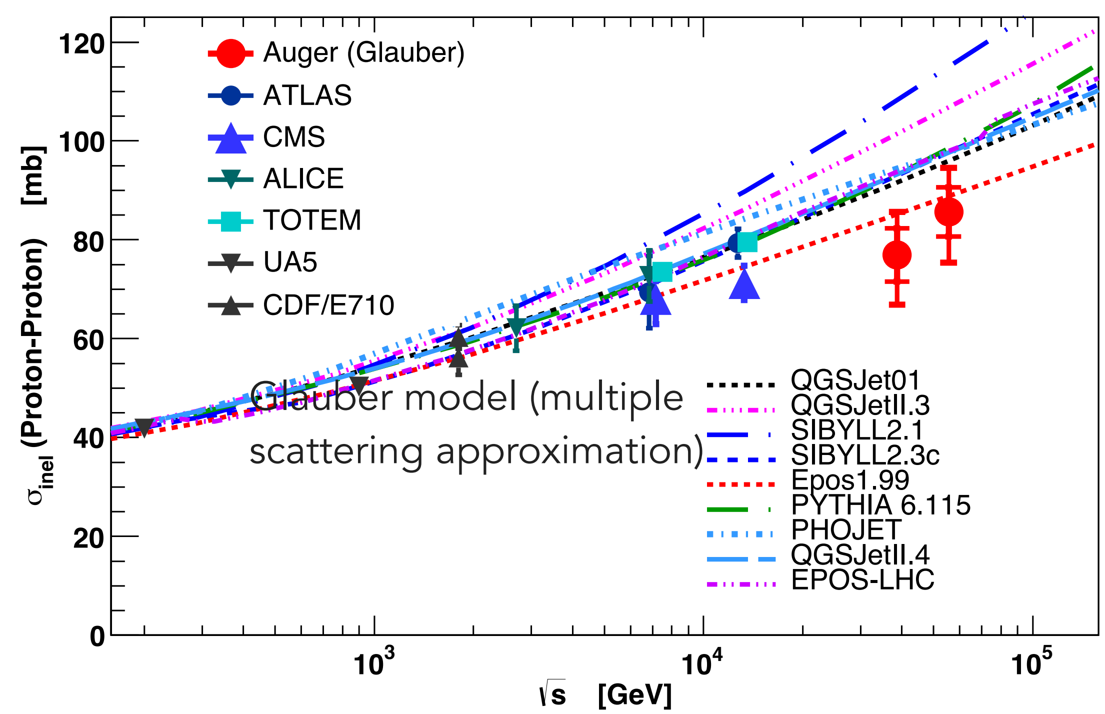




[Auger, Phys. Rev. Lett. 126, 152002 (2021)]

Models, collider data, Auger (derived) cross sections

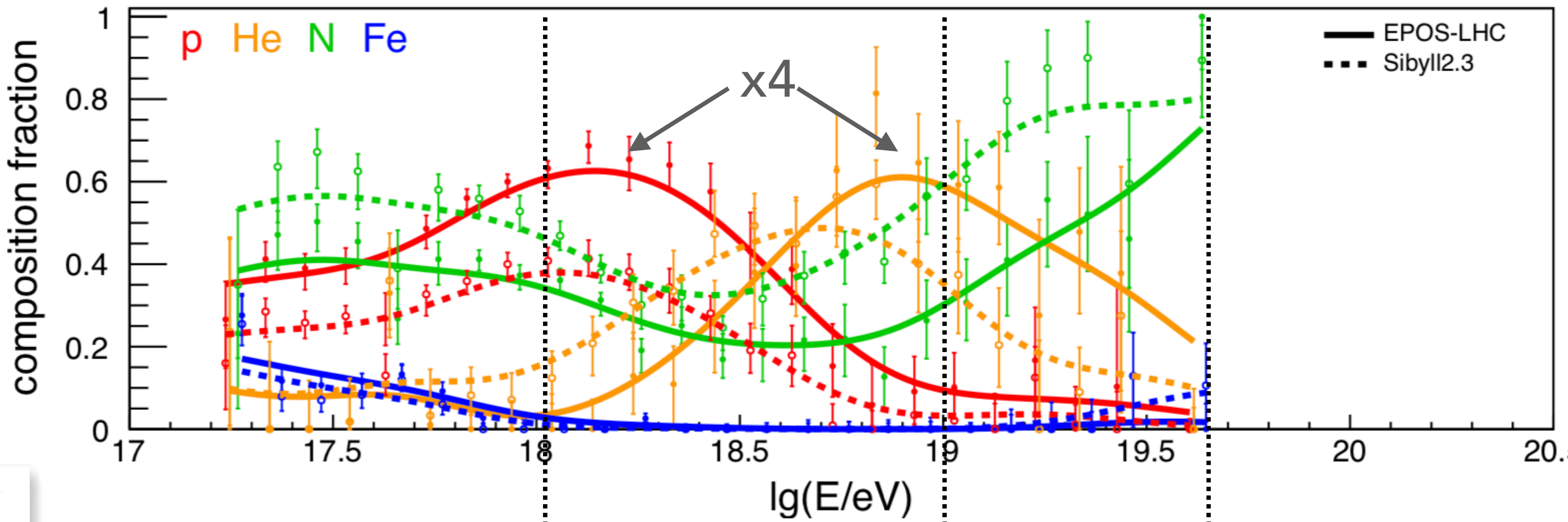




[Auger, Phys. Rev. Lett. 2012, ICRC 2017]

Astrophysical interpretation

∝



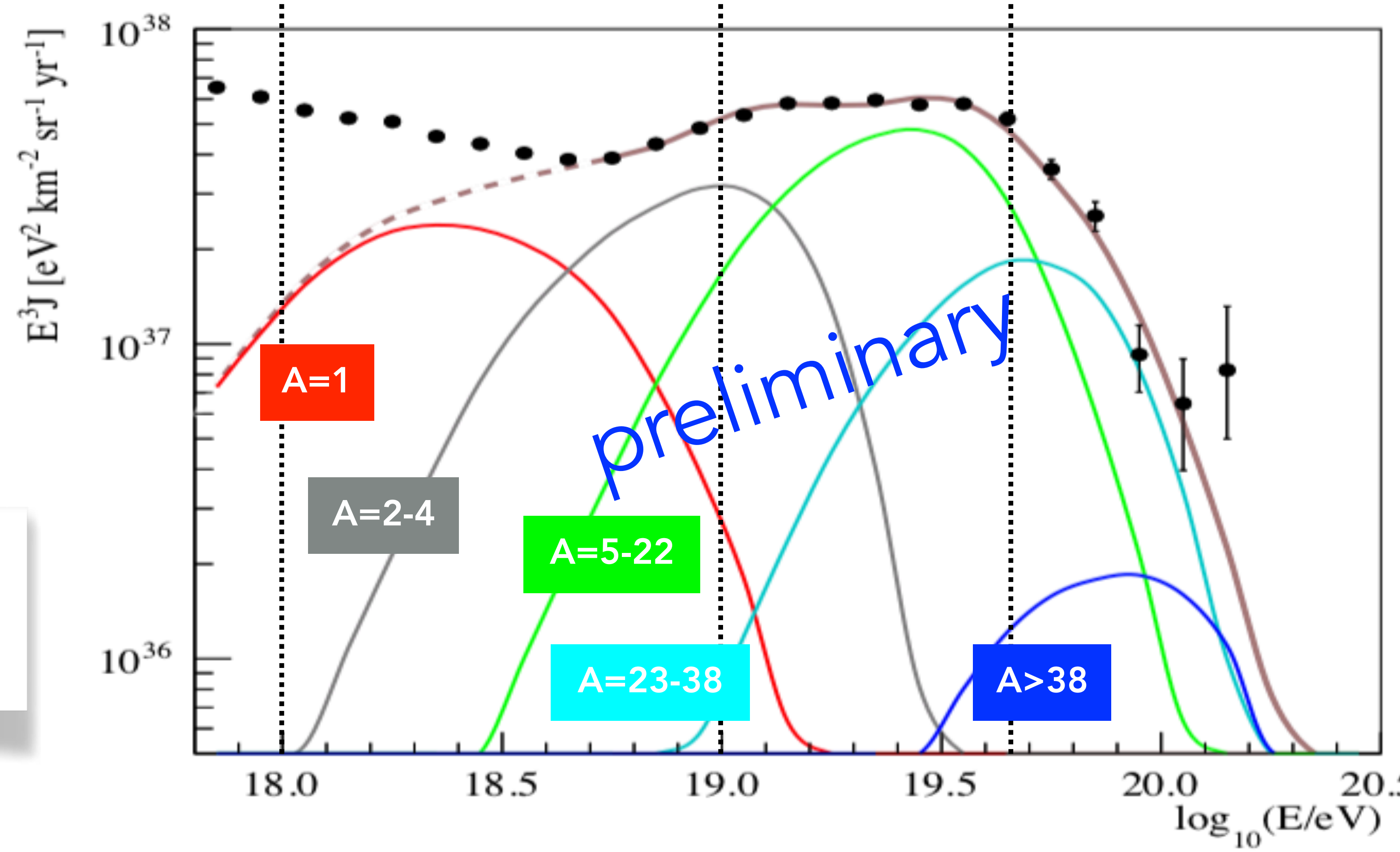
Peter's cycle ∝ E/Z

or Spallation ∝ E/A ?

Combined fit of energy spectrum and X_{max} distribution

Maximum luminosity density needed

~ 6 10^{44} erg Mpc^{-3} yr^{-1} (E>5 10^{18} eV)



[A.Castellina, PoS (ICRC2019) 004, Auger Highlight Talk]

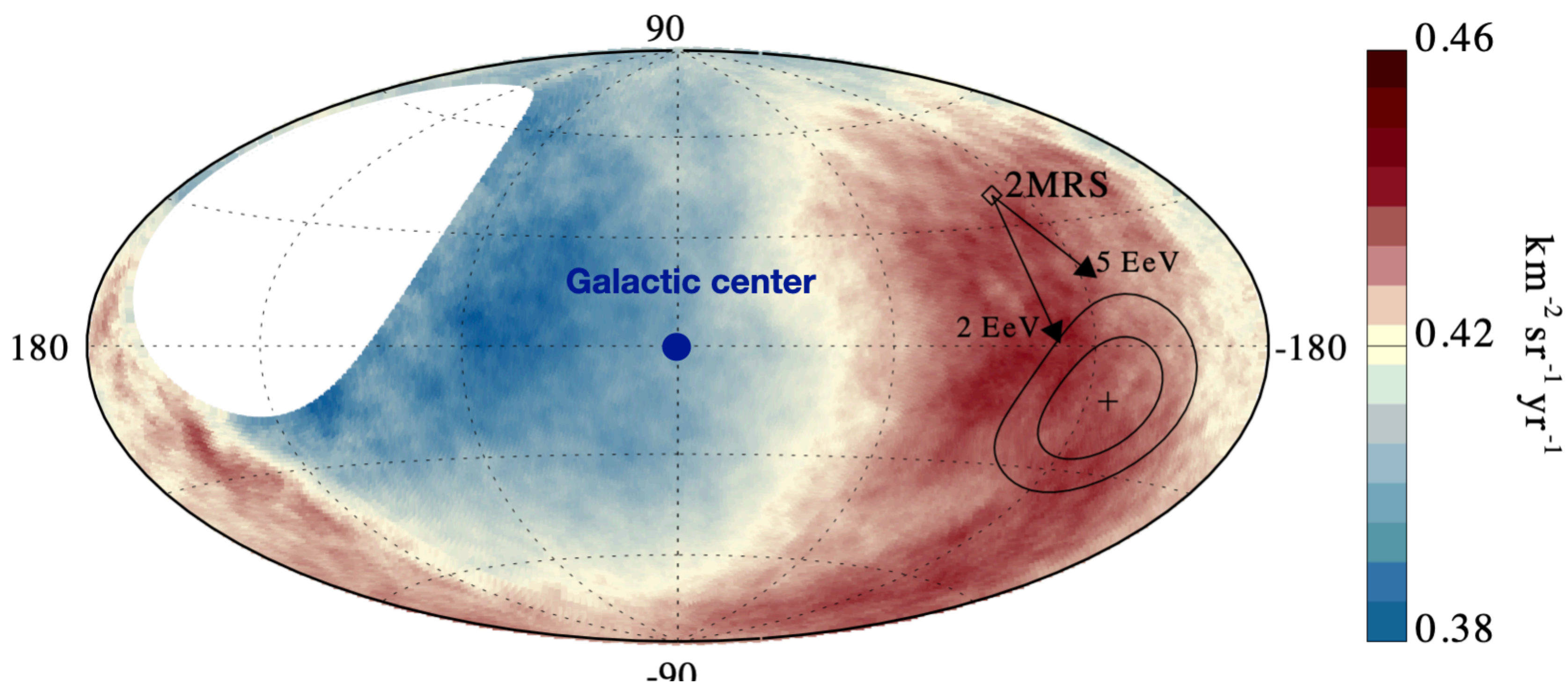
Large scale anisotropy

3-D Dipole above 8 10^{18} eV at $(\alpha,\delta) = (98^0,-25^0)$: $(6.6^{+1.2}_{-0.8})\%$

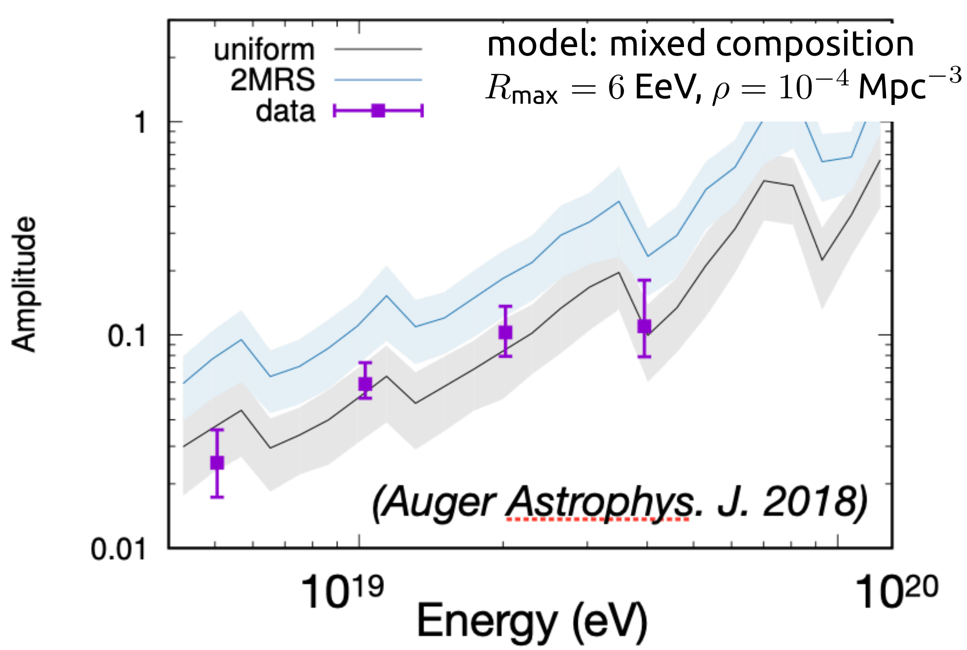
Amplitude increasing with energy

5.2σ significance ⟶ *OBSERVATION*

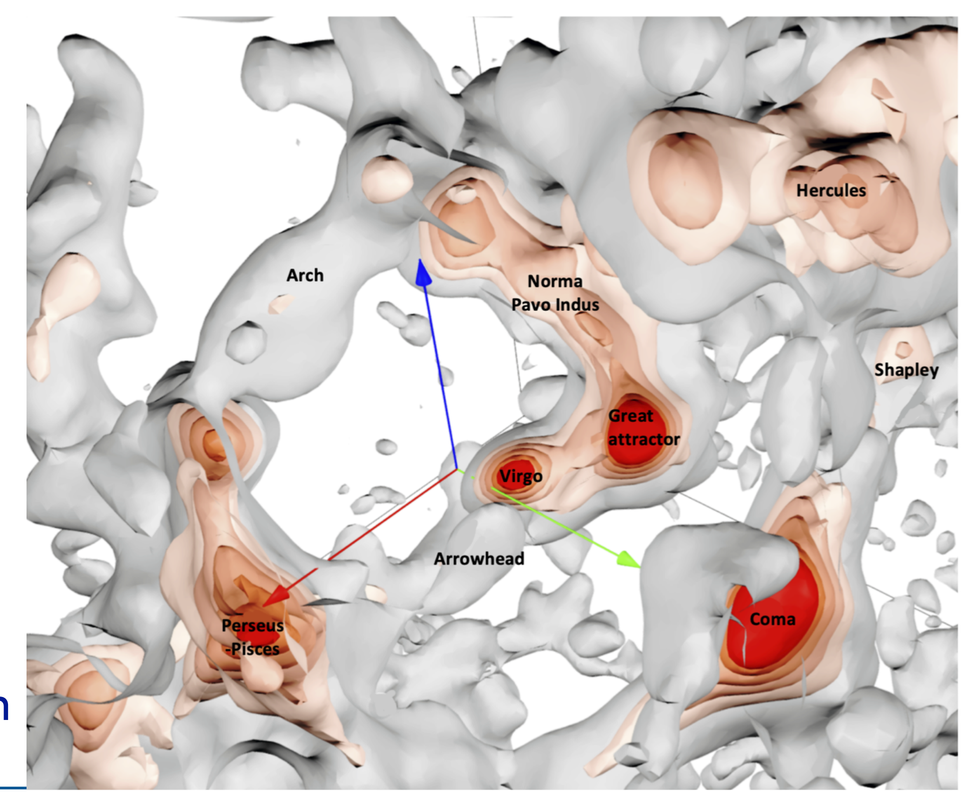
[Auger, Science 357 (2017) 1266]



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



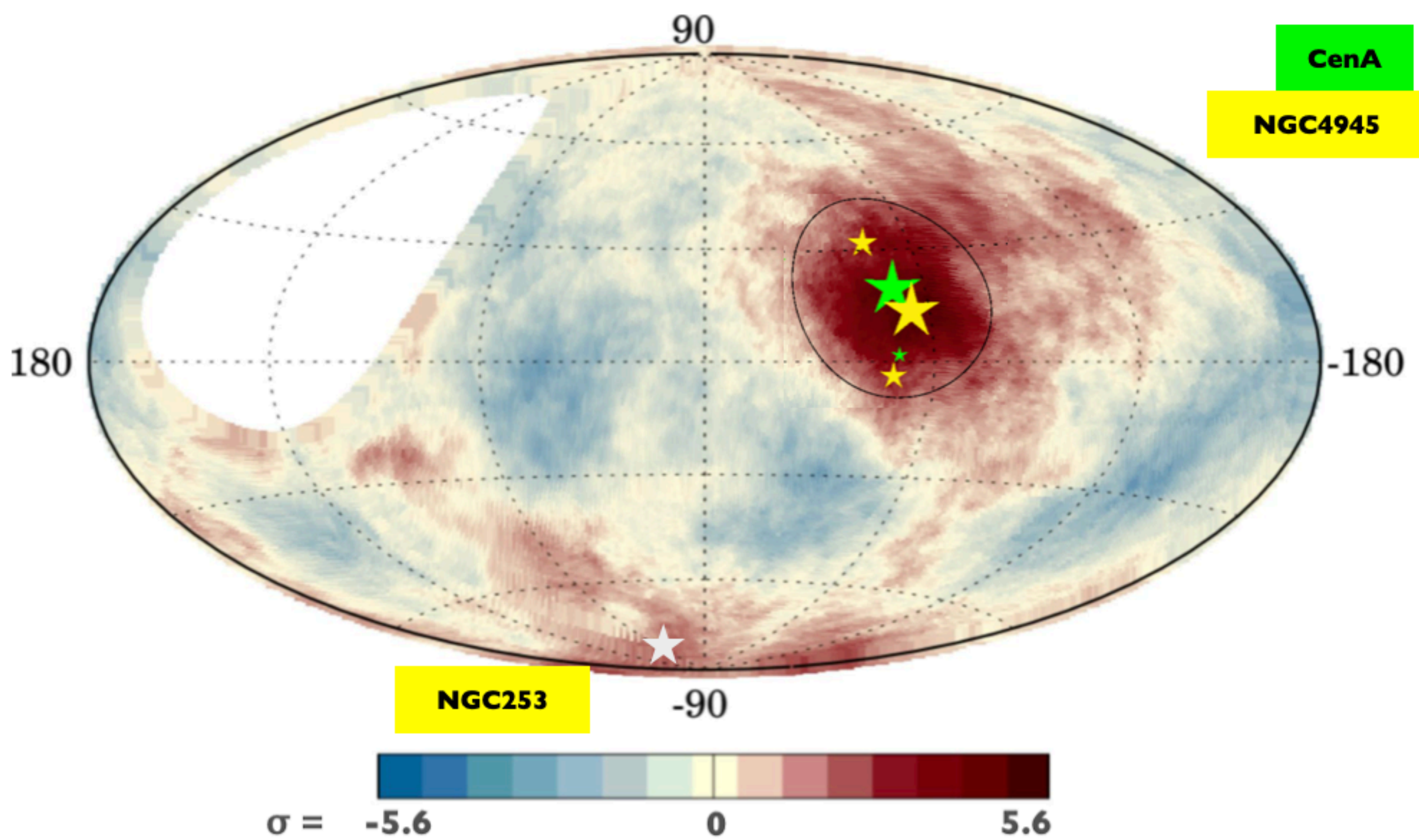
Non-trivial interplay of mass composition, mag. horizon and local source distribution

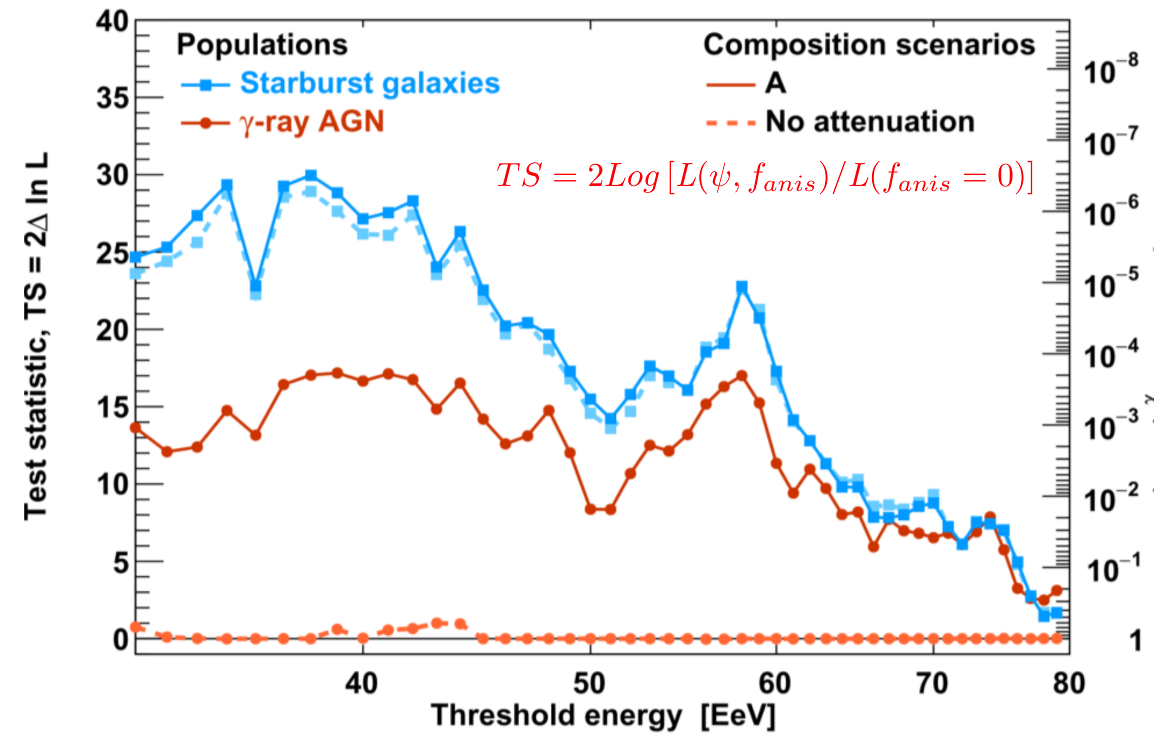


(Ding, Globus & Farrar 2101.04564)

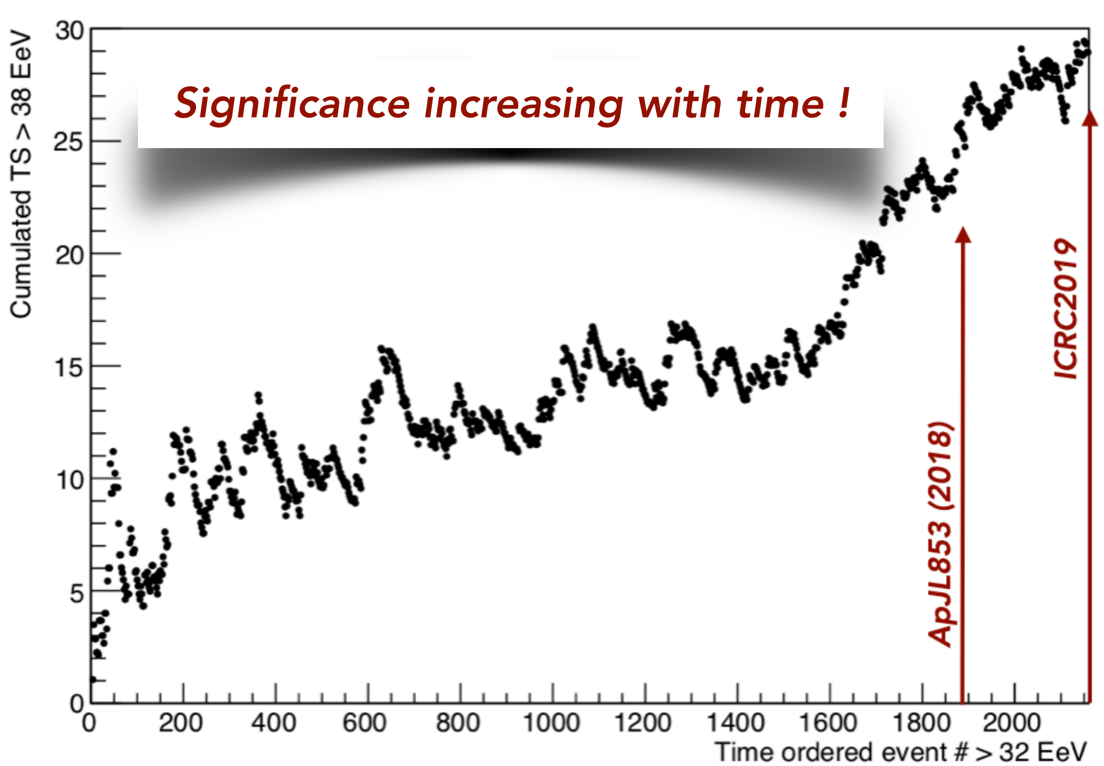
Medium scale anisotropy

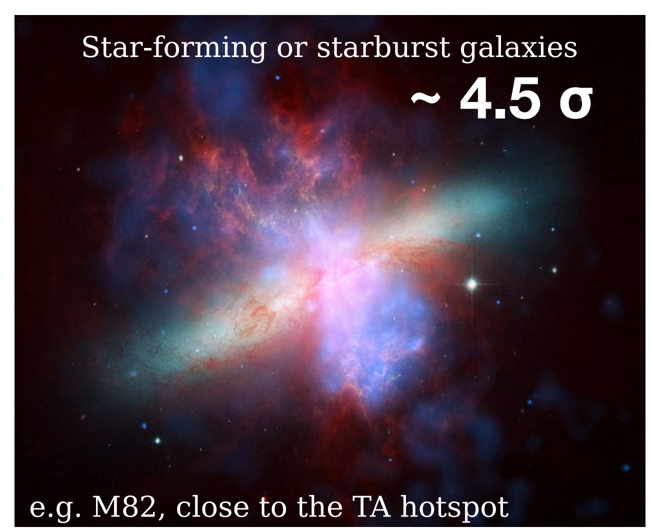
(Auger Astrophys. J.2018, ICRC 2019)

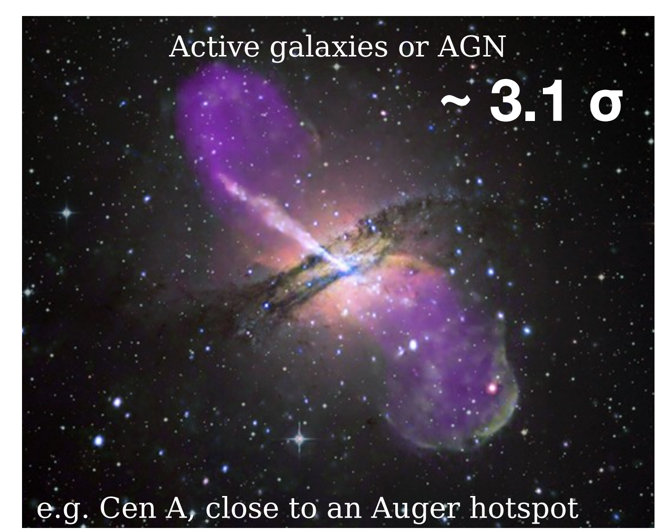




Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	15^{+5}_{-4}°	11^{+5}_{-4}%	29.5	4.5 σ
γ-AGNs	39 EeV	14^{+6}_{-4}°	6^{+4}_{-3}%	17.8	3.1 σ
Swift-Bat	38 EeV	15^{+6}_{-4}°	8^{+4}_{-3}%	22.2	3.7 σ
2MRS	40 EeV	15^{+7}_{-4}°	19^{+10}_{-7}%	22.0	3.7 σ

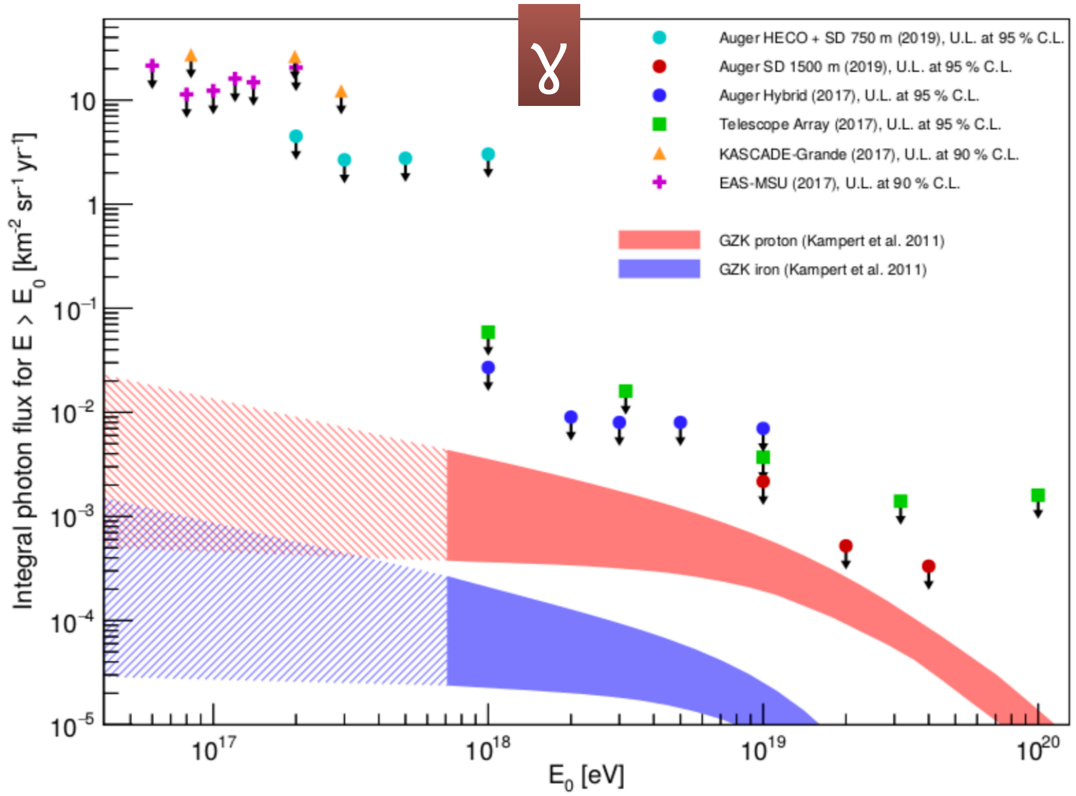




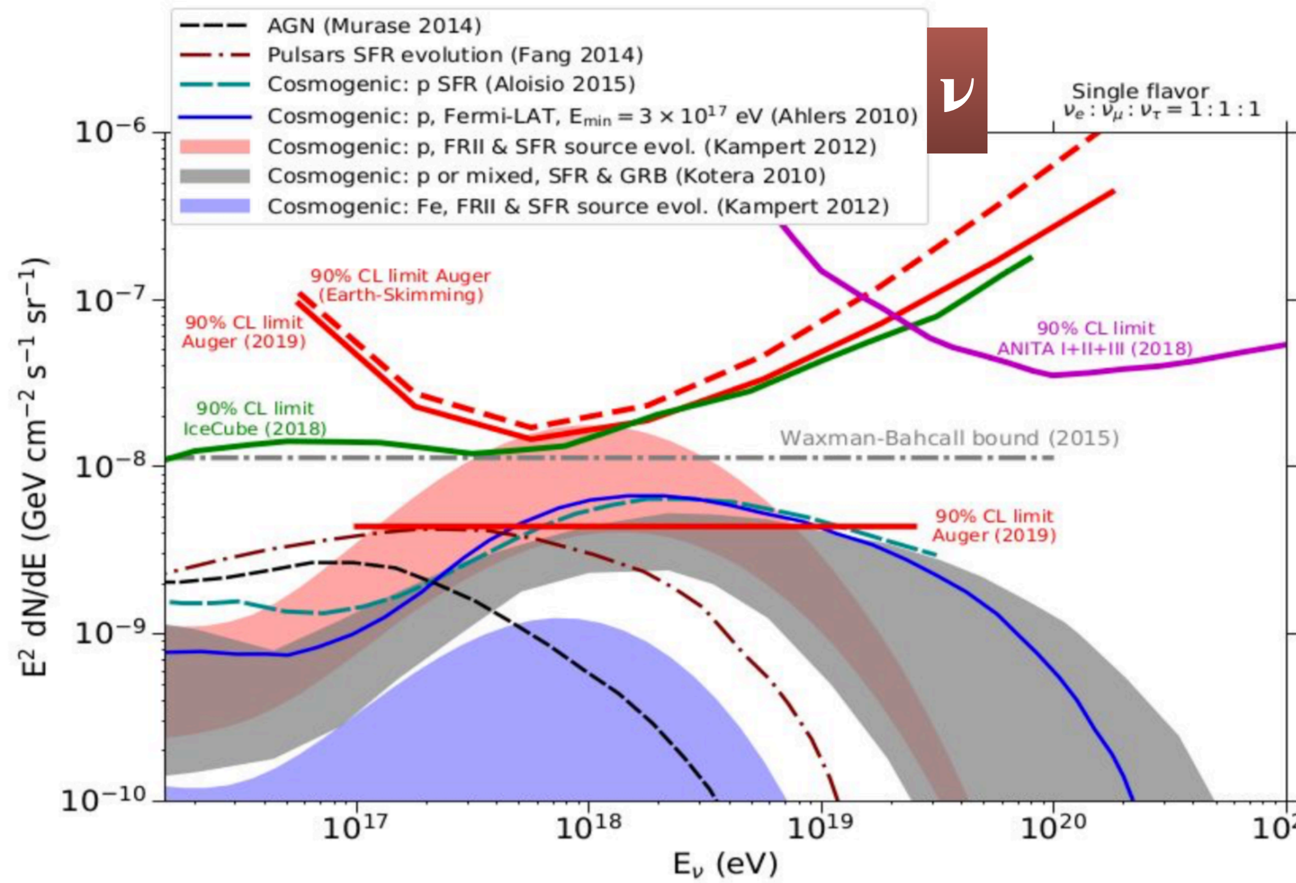


Multi-messengers

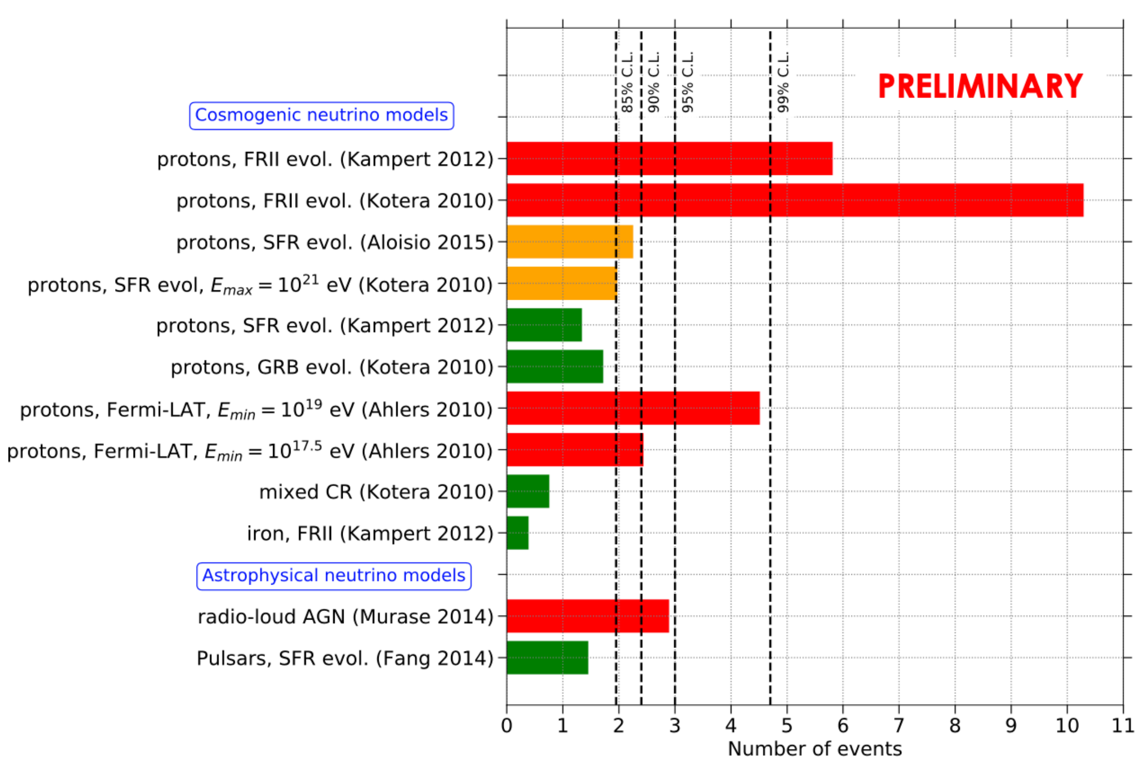
Limits reaching GZK predictions for protons

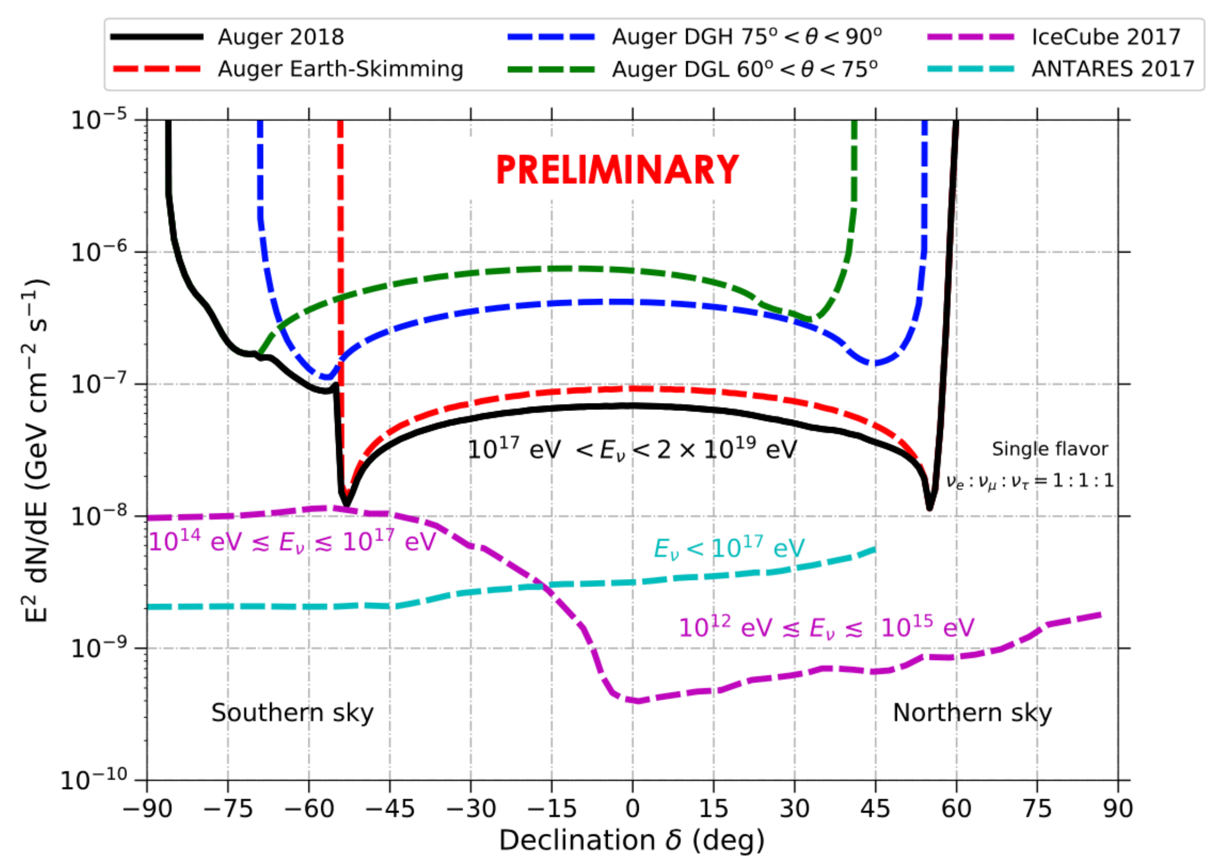


[Auger, JCAP 04 (2017) 009; ICRC2019]



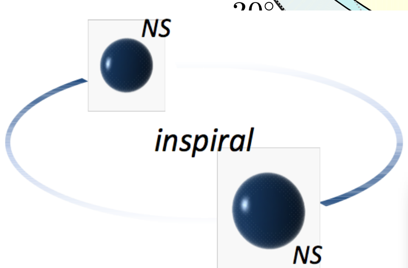
[Auger, Phys. Rev. D 91 (2015) 092008; ICRC2019]

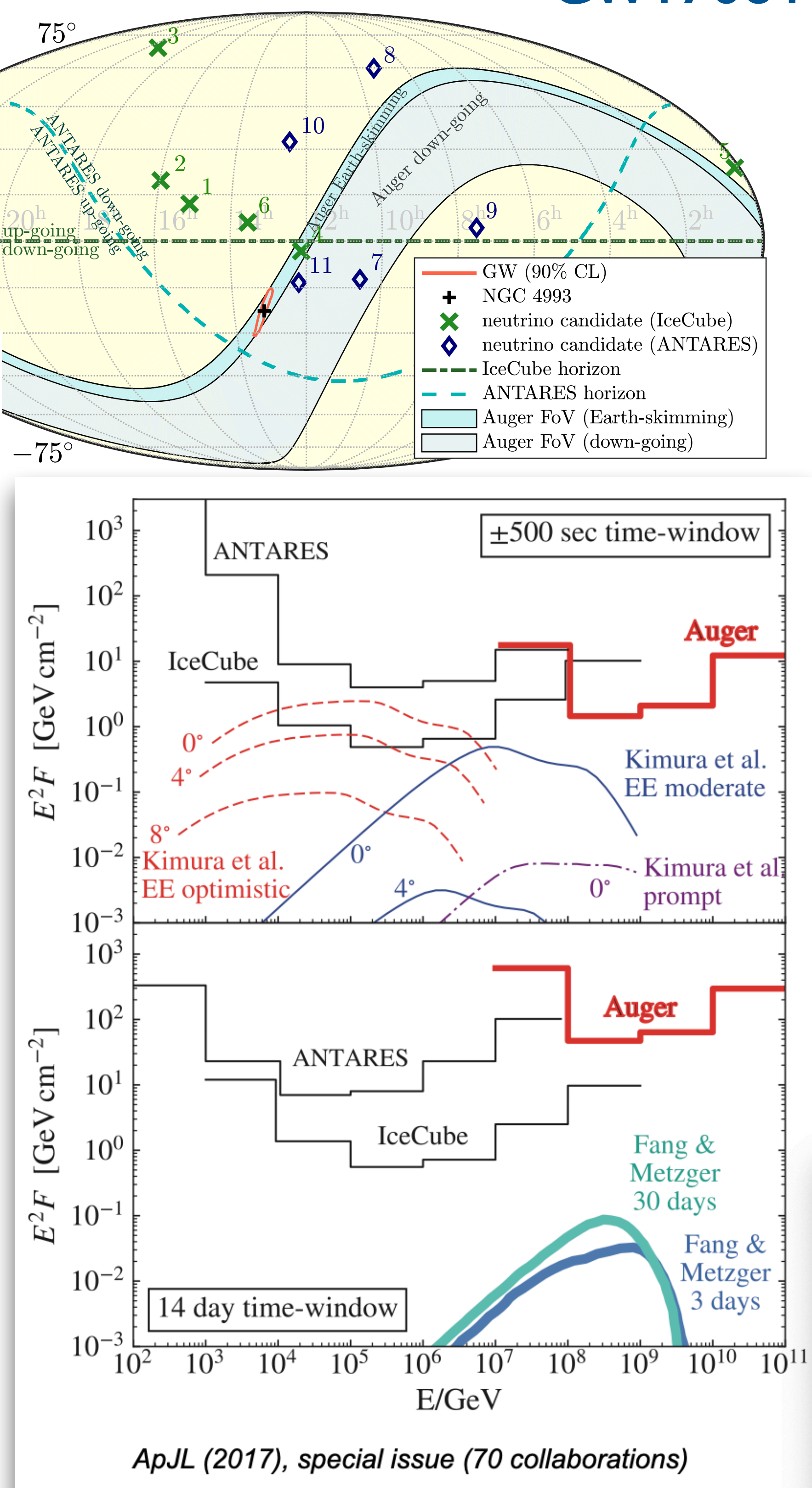




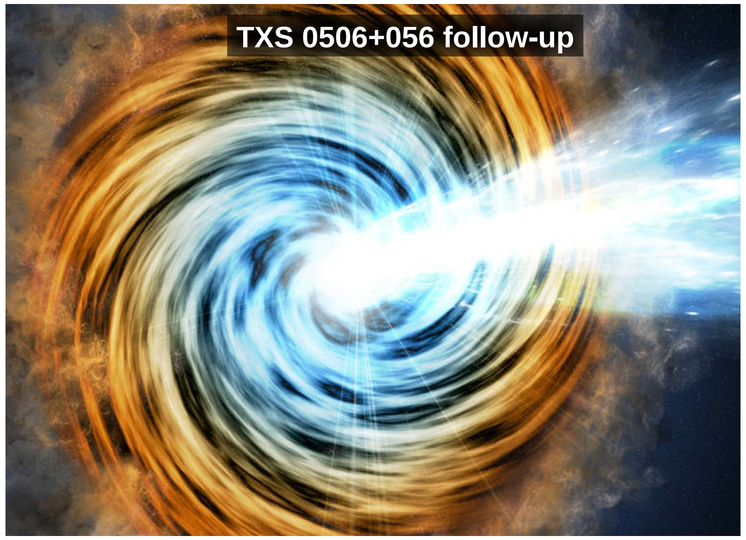
Multi-messengers - transient events

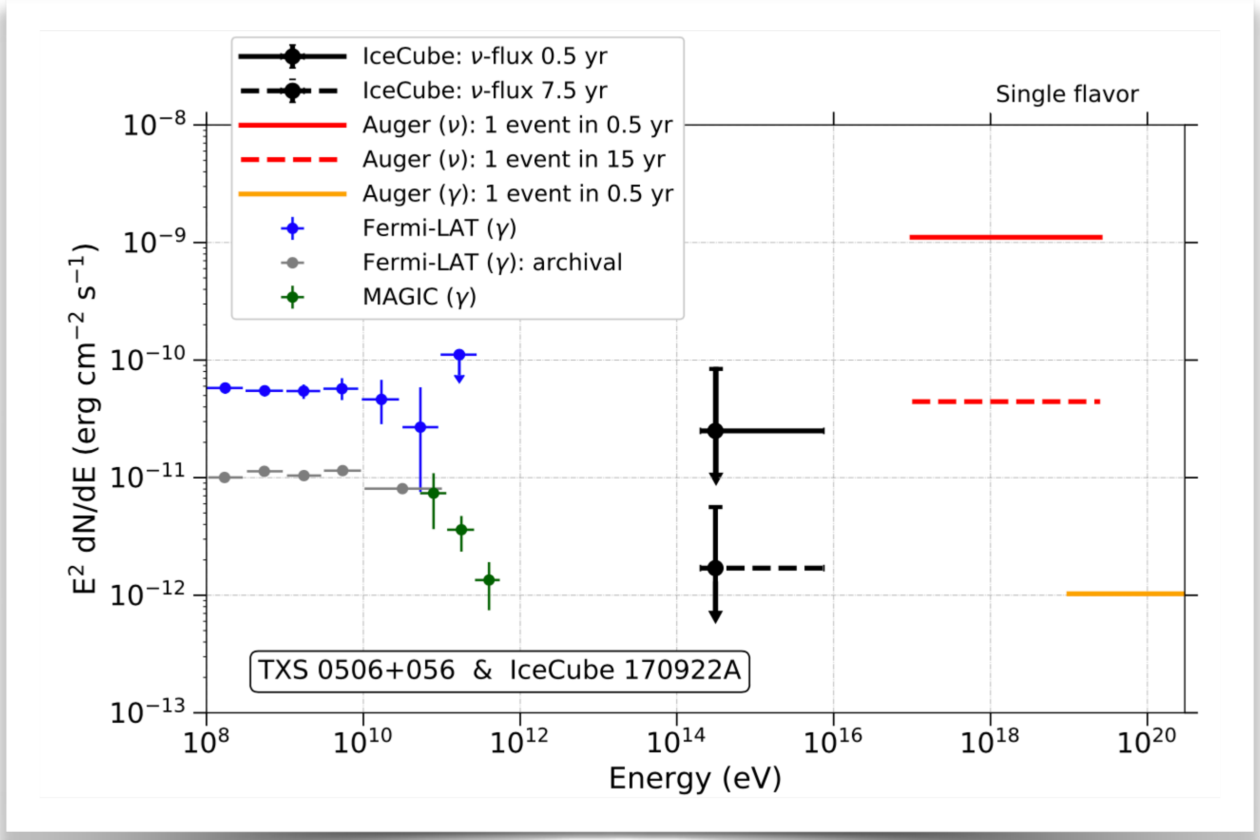
GW170817





TXS 0506+056





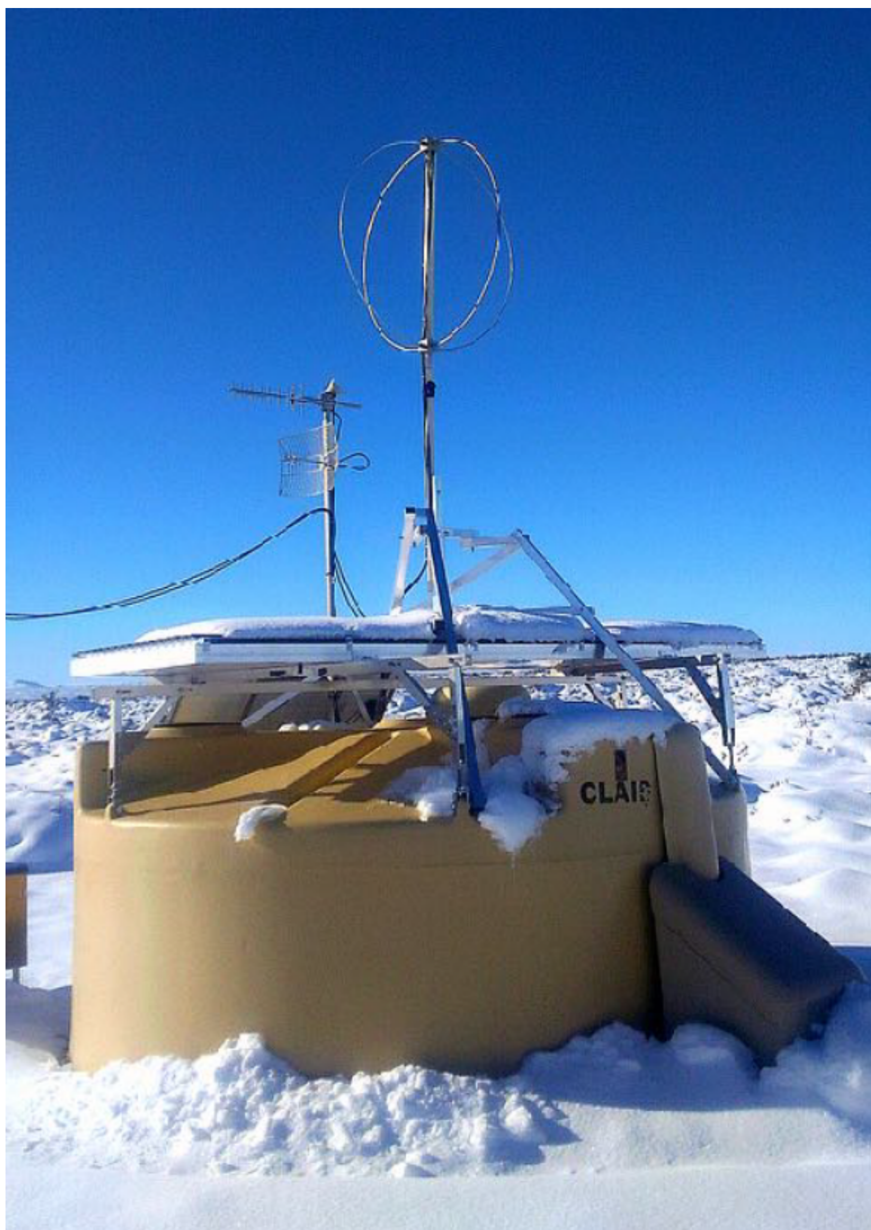
[ApJL (2017), special issue (70 collaborations)]

[Auger, Astrophysical Journal, 902:10, 2020]

AugerPrime upgrade (2022-2025)

Science case

1. Extend **energy range of mass-sensitive measurements** (lower and higher end)
2. New measurements / observables that fully exploit **event-by-event charge/mass** estimates
3. **Multi-hybrid events** to verify our understanding (reconstruction, hadronic interactions)
4. Reduction of **systematic uncertainties** at single event level (fluctuations)
5. Improve our triggers for **neutrinos, exotic events,** atmospheric phenomena
6. Learning for our Phase I data set: **re-analysis of full data** set with new knowledge (DNN, …)



Each of the 1660 surface detectors are being equipped with

◉ **Surface Scintillator Detector (SSD)** to measure the mass composition in combination with the Water Cherenkov Detectors (WCD).

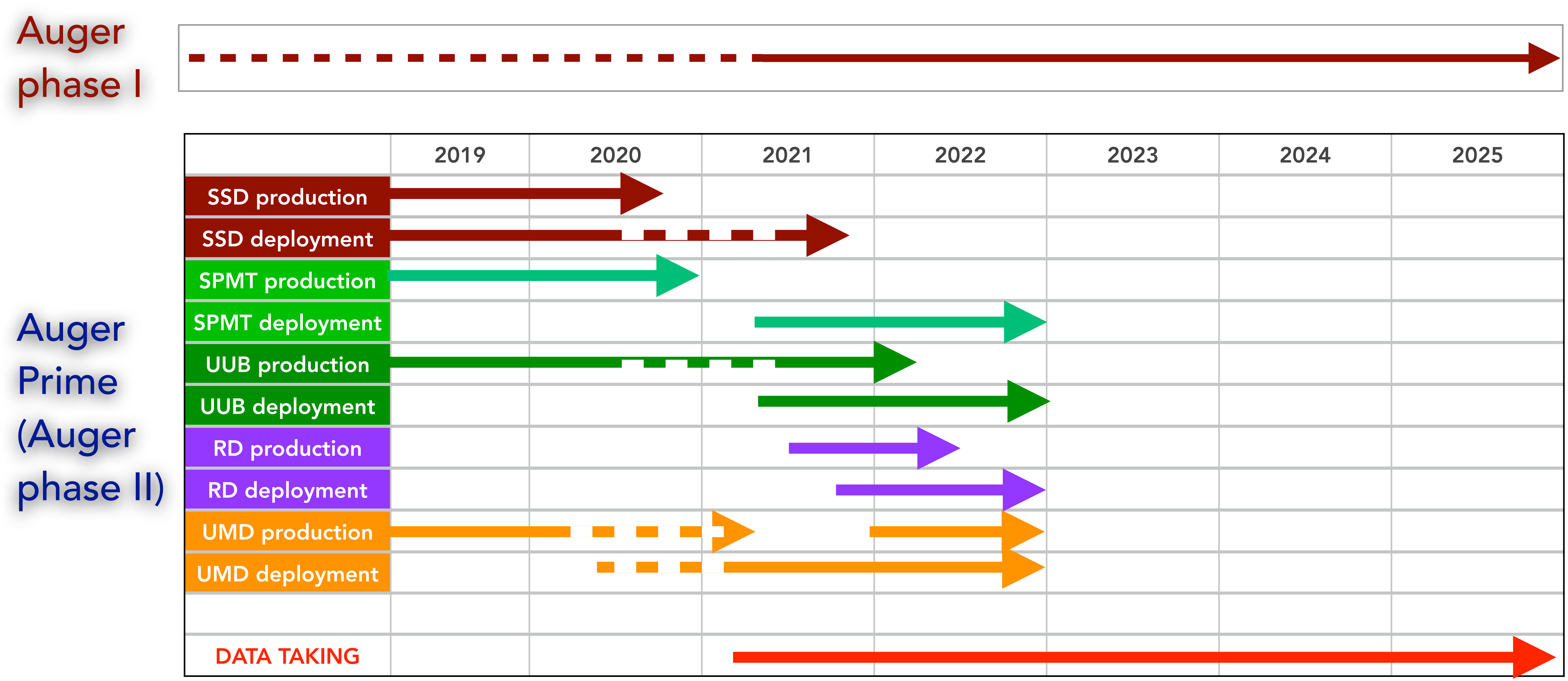
◉ **Surface Detector Electronics (SDEU)** to improve the performance of the WCD

◉ **small PMT** to increase the dynamic range of the WCD.

◉ **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 and cross-check the SSD-WCD combined analysis (infill area)

[A. Castellina, UHECR2018, EPJ Web of Conf. 210 (2019) 06002]



Auger Phase 1

- ➡Deployment started in 2002 —> data taking from 2004
- ➡Completion of Observatory in 2008
- ➡Analysis of Phase 1 data : completion foreseen mid 2022

Auger Phase 2 = AugerPrime

- ➡Deployment started in 2019
- ➡Completion end 2022
- ➡Analysis of Phase 2 data : 2023-2025
- ➡Back to reanalysis of Phase 1+2

end 2023: scientific review by international panel (required by Finance Board)
2025: end of International agreement
2025-2030: extension of international agreement upon positive outcome of review

L’Osservatorio Pierre Auger è completamente finanziato in Italia da INFN attraverso fondi di Progetto di CSN-II [costruzione, maintenance, calcolo, common Funds per INFN e Università
INAF copre i Common Funds per i dipendenti

Criticità

l'Osservatorio e' in fase di deployment dell'Upgrade, che in particolare include la messa in opera di **nuova elettronica**, l’inclusione di **nuovi rivelatori a scintillazione** e il primo utilizzo nella fisica astroparticellare di ultra-high energy di un **apparato radio** (1660 antenne operanti nella regione di frequenza 20-80 MHz, installare su ognuna delle stazioni del rivelatore di superficie).

Essendo conclusa l’attività di progettazione e produzione dei nuovi rivelatori di AugerPrime (upgrade di Auger) non servono figure come ingegneri o progettisti.
Ritardo da Covid-19

Occorrono giovani ricercatori con profilo astrofisico con
- ➡esperienza nel campo dei rivelatori (in particolare fotomoltiplicatori e antenne radio)
- ➡esperienza nell'analisi statistica dei dati
- ➡esperienza in tecniche di analisi tipo Deep Neural Network

➡**Ingresso di ricercatori TI** per avere adeguati profili interni in grado di garantire CON CONTINUITA’ gestione ed analisi dei dati di Auger Fase 1, di AugerPrime e del backtracking

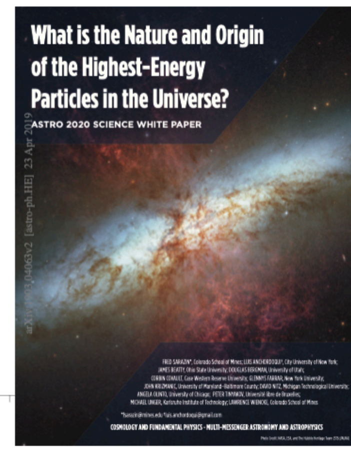
➡Arruolamento di giovani post-Doc con **contratti TD o AdR**

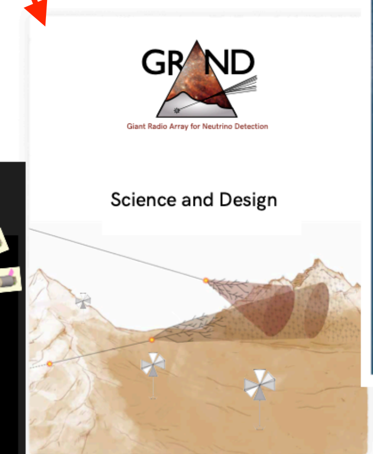
➡Investimento in formazione: finanziamento di **dottorati** rivolti a studi multimessenger

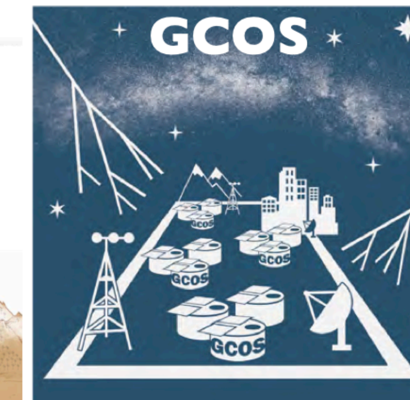
The future of UHECRs

Coinvolgimento di parte dei membri della Collaborazione Auger in progetti e R&D

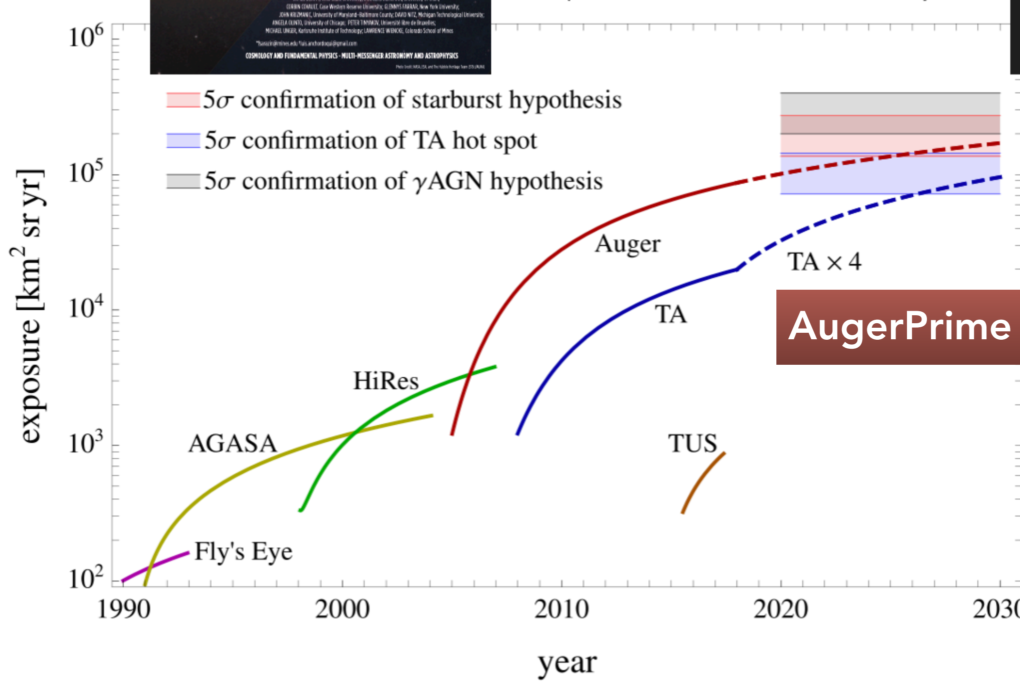
APPEC: European Astroparticle Physics Strategy 2017-2026
Snowmass process 2021-2026

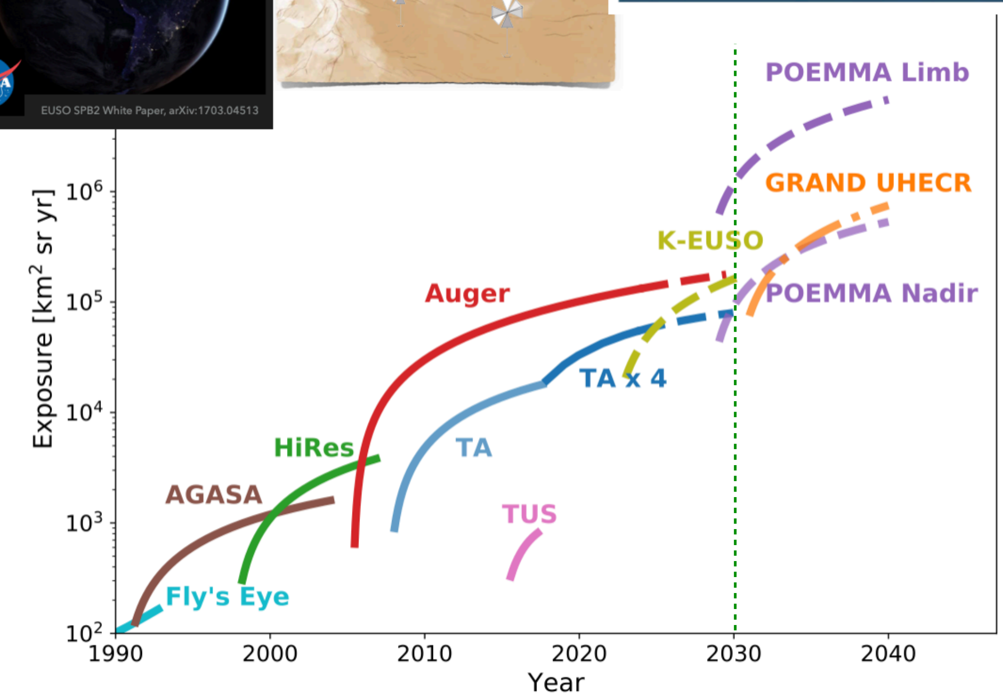






(Sarazin et al, 1903.04063)





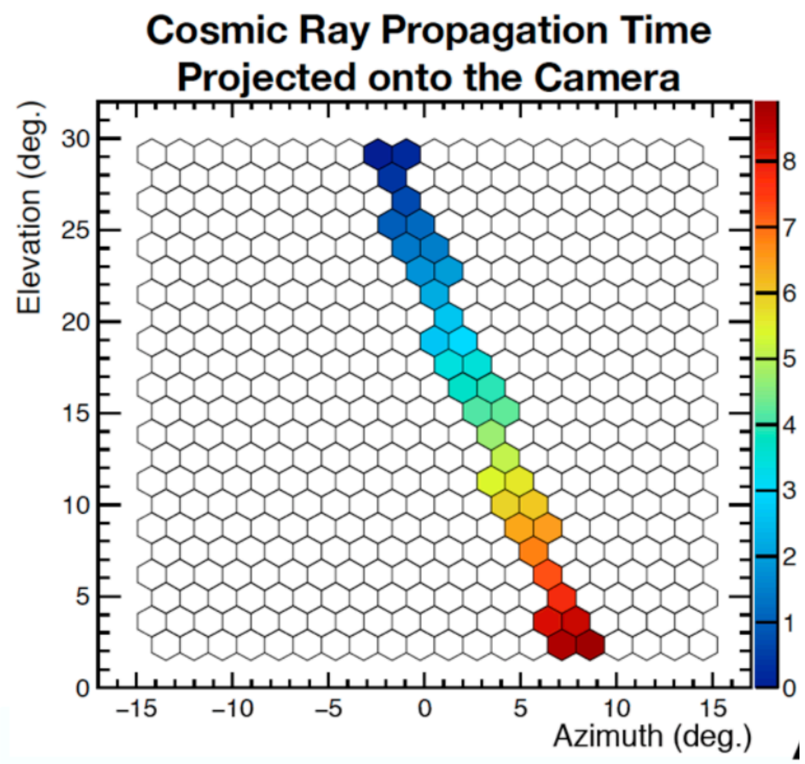
(Alves Batista et al, 1903.06714)

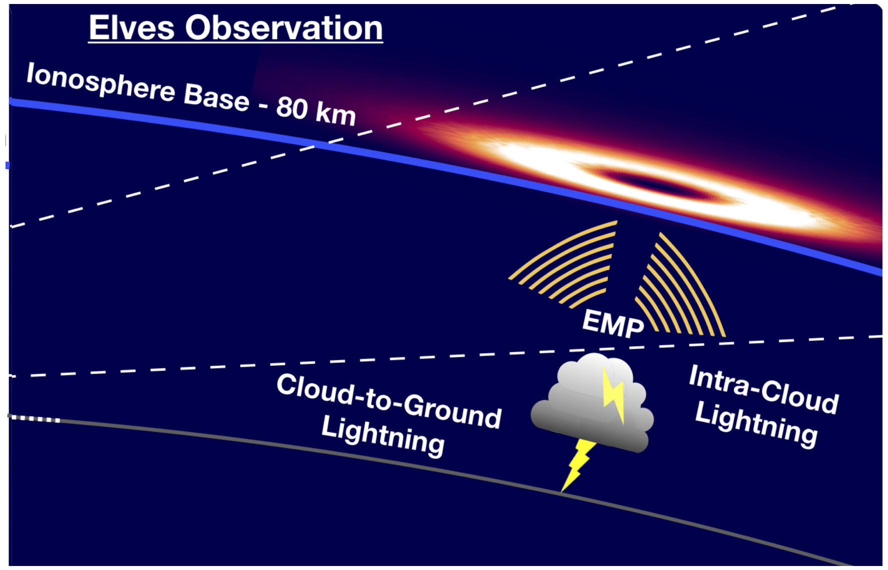
What matters most

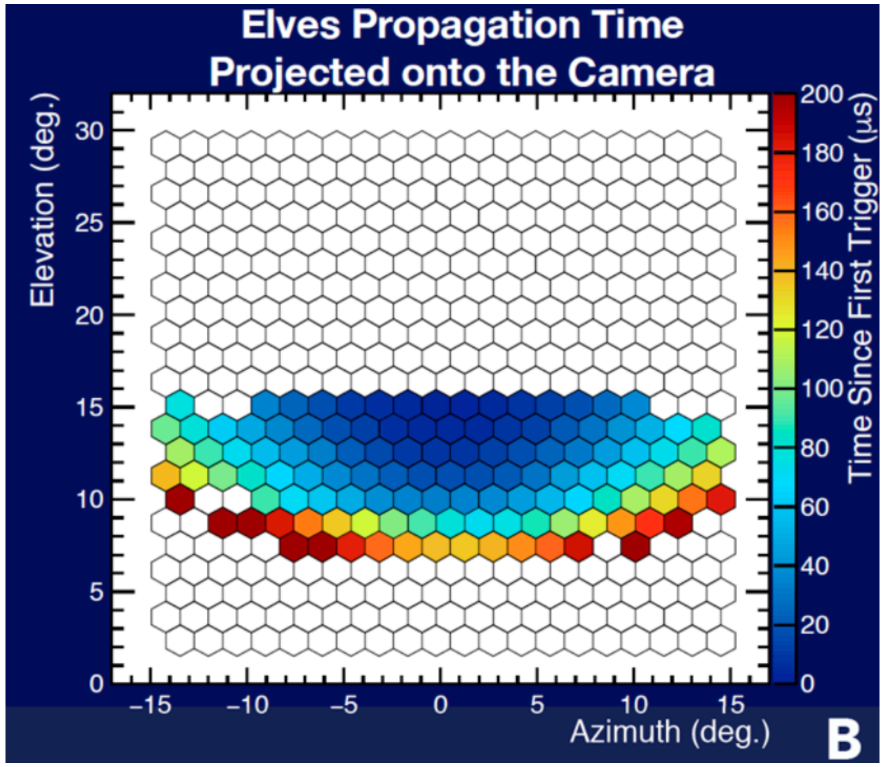
- Statistics (exposure) and energy resolution
- Event-by-event composition sensitivity
- Full sky coverage with <u>one technique and calibration</u>
- Calorimetric and hybrid measurements
- Neutrino and photon aperture

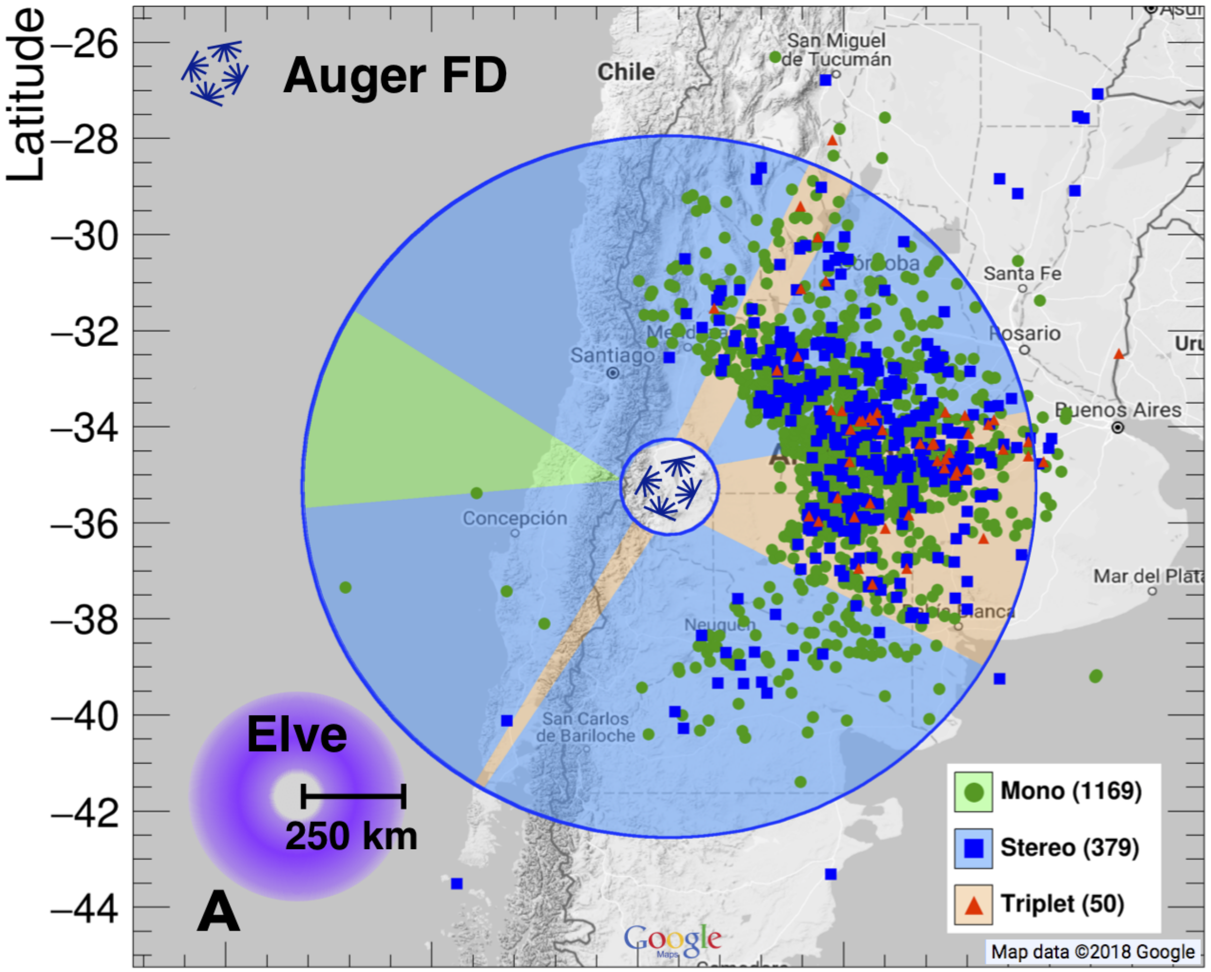
Backup

Atmospheric phenomena





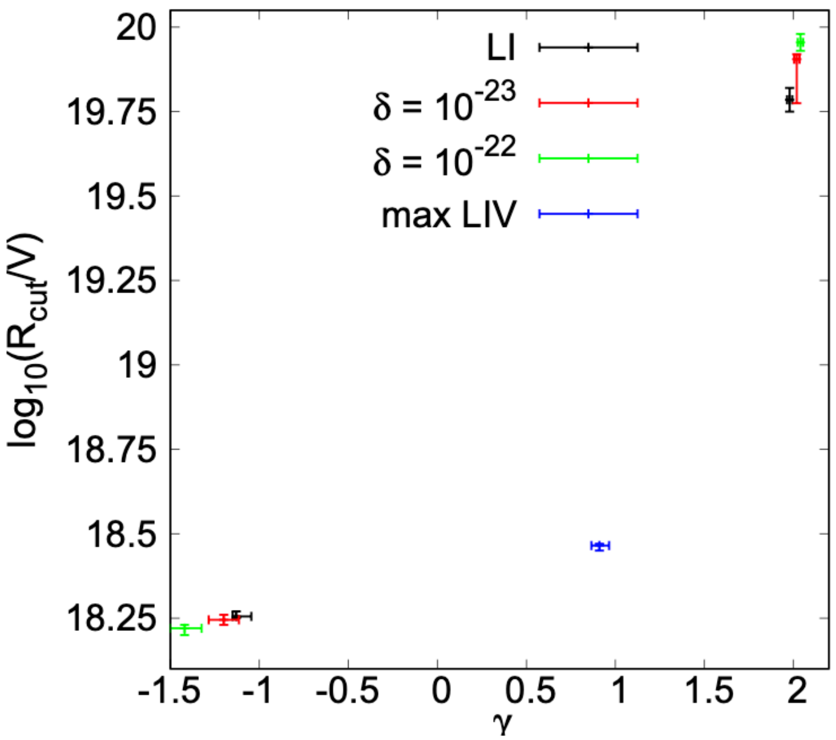


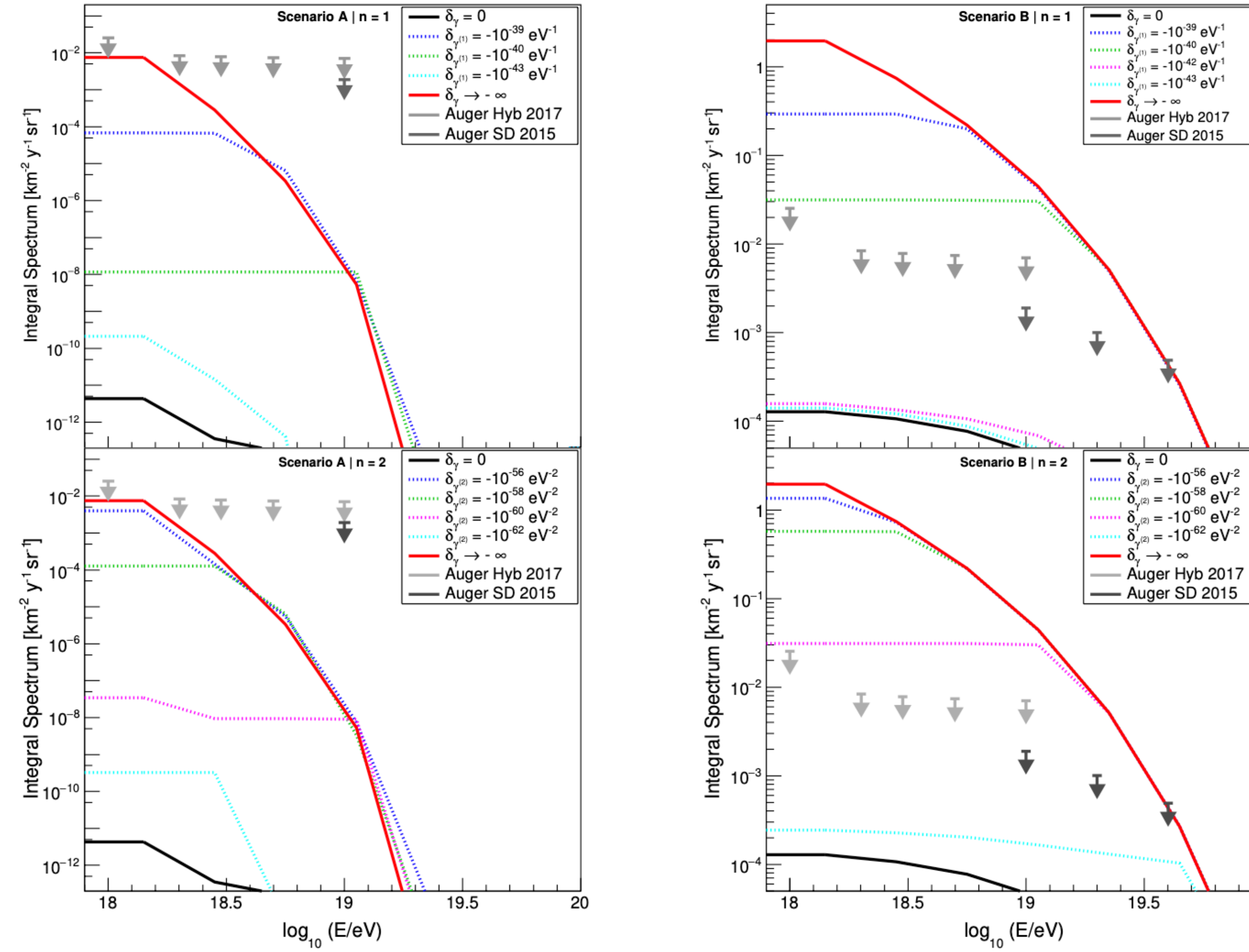


[Auger, Earth Space Sci. 7 (2020) e2019EA000582]

Lorentz Invariance Violation

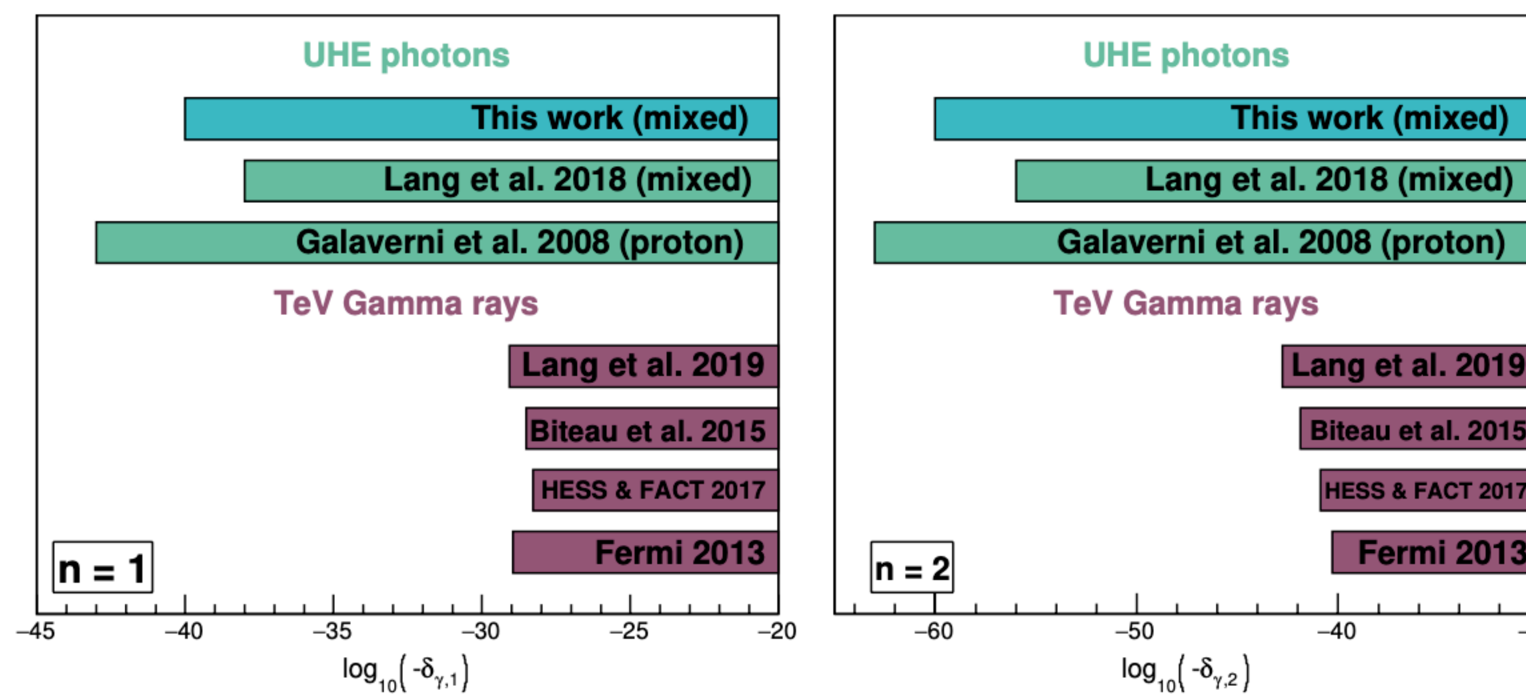
$$E_i^2 = p_i^2 + m_i^2 + \sum_{n=0}^{\infty} \delta_i^{(n)} E_i^{n+2}$$





GZK photons propagated following the two scenarios (A=global and B=local minima)

- A: no limits on LIV can be imposed
- B: $\delta_\gamma^{(1)} \gtrsim -10^{-40}\,\mathrm{eV}^{-1}$ and $\delta_\gamma^{(2)} \gtrsim -10^{-60}\,\mathrm{eV}^{-2}$.



Dark matter

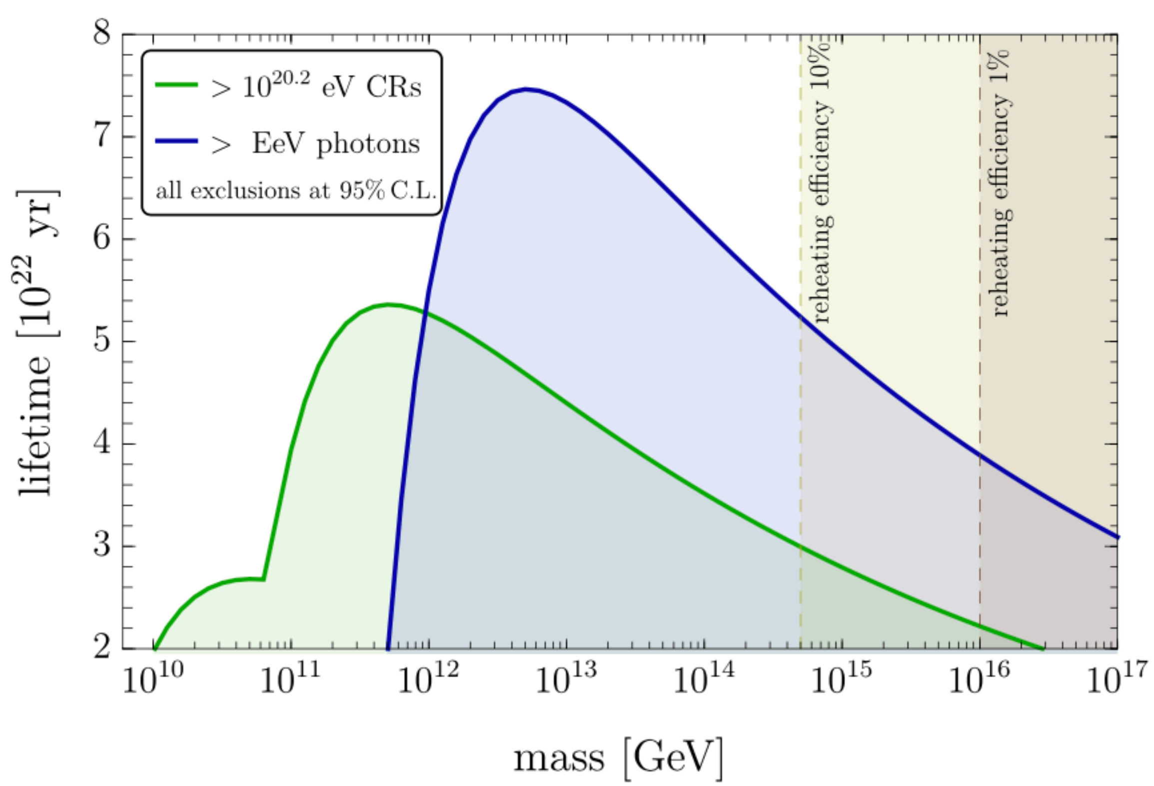
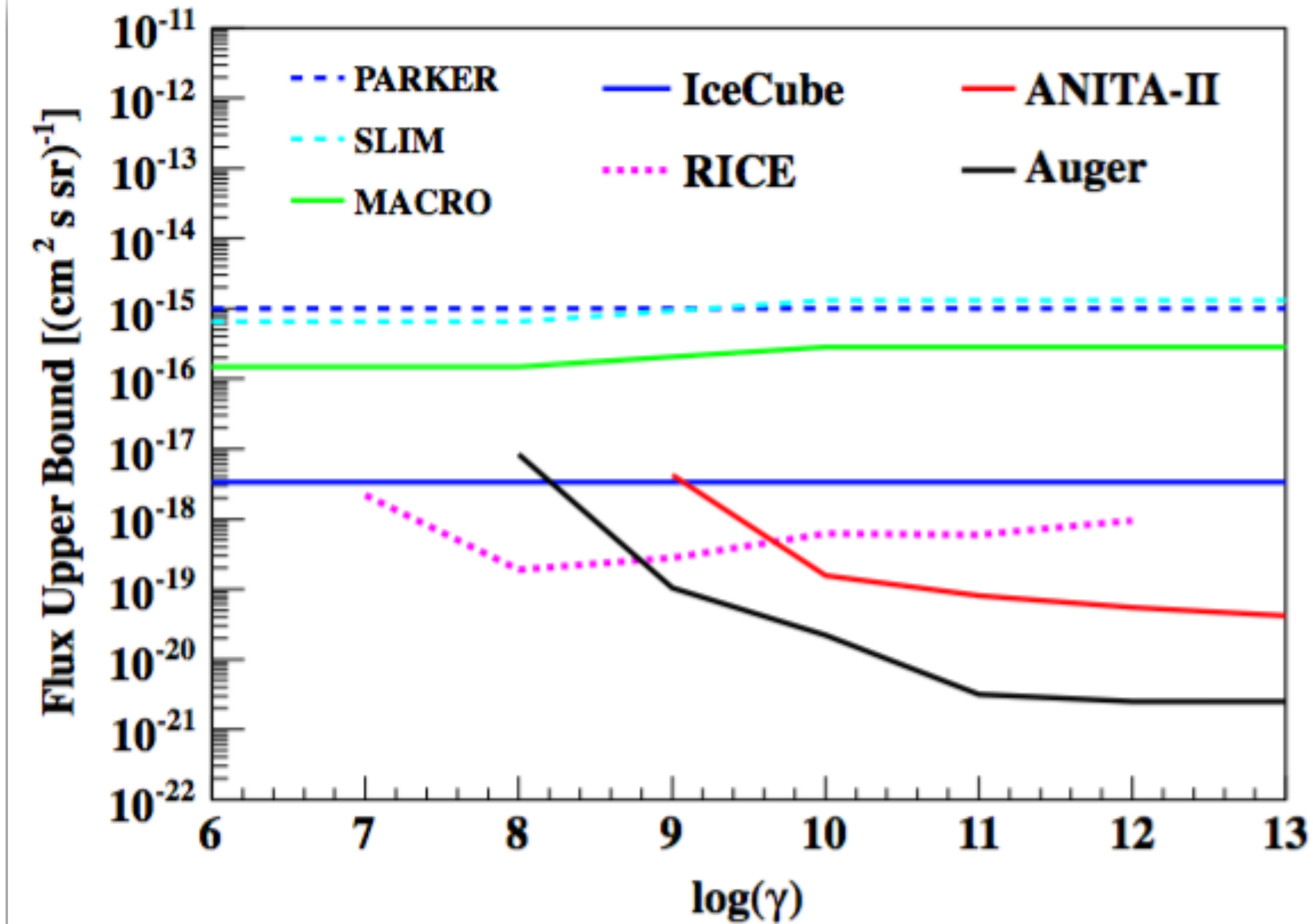


Figure 1: Constraints on the mass and lifetime of super-heavy DM particles from the absence of UHE photons (green) and from the absence of CR with energy above $10^{20.2}$ eV (blue). The allowed region lies above the curves. For illustration purpose, the 95% CL upper limit on mass obtained from the possible value of the Hubble rate at the end of inflation for a reheating efficiency of 1% (10%) is shown as the vertical dashed (dotted) line[11].

[Auger, Snowmass21 CF1-CF7_203, 2021]

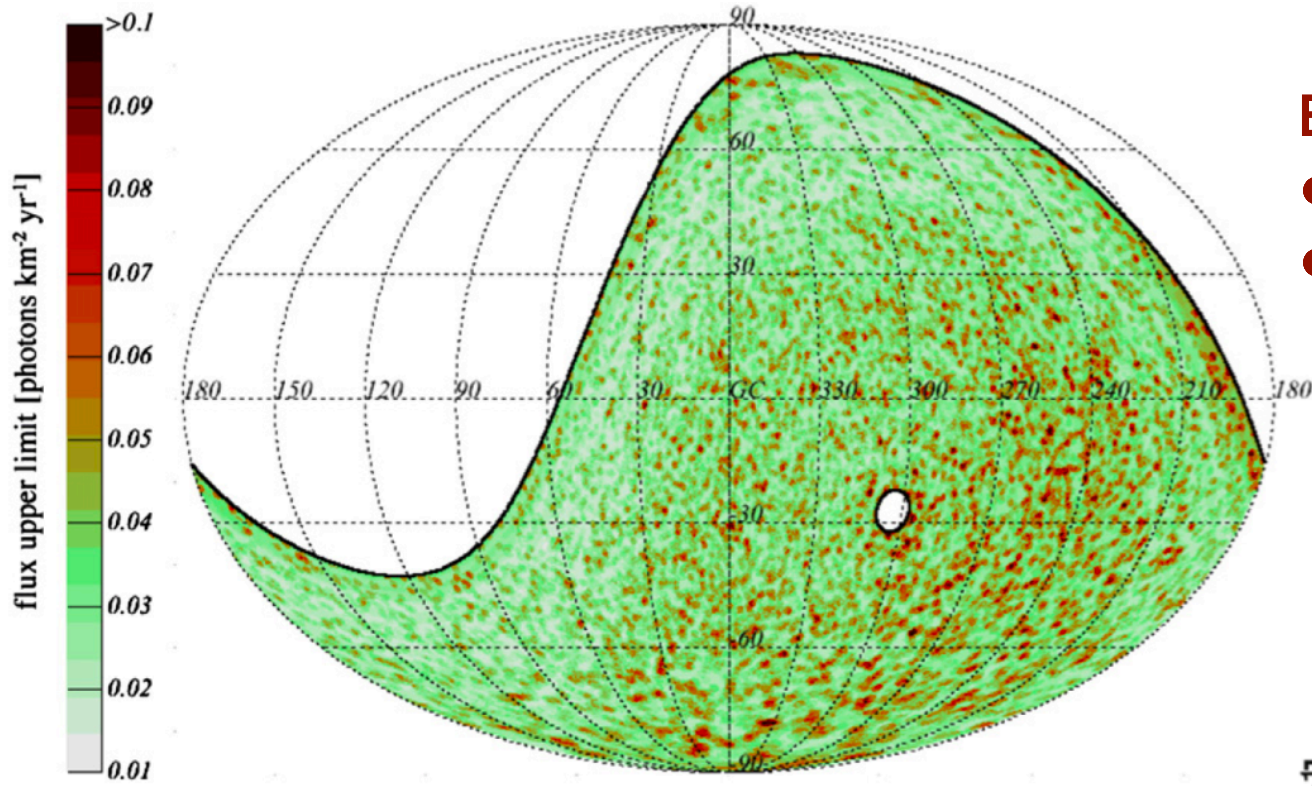
Magnetic monopoles



$\log_{10}(\gamma)$	$\mathcal{E}(\gamma)$ (km^2 sr yr)	$\Phi_{90\%\,\mathrm{C.L.}}$ ((cm^2 sr s)$^{-1}$)
8	1.16	8.43×10^{-18}
9	9.52×10^1	1.03×10^{-19}
10	4.50×10^2	2.18×10^{-20}
11	3.15×10^3	3.12×10^{-21}
≥ 12	3.91×10^3	2.51×10^{-21}

[@A.Aab et al (Auger Coll.) PRD94 (2016) 082002]

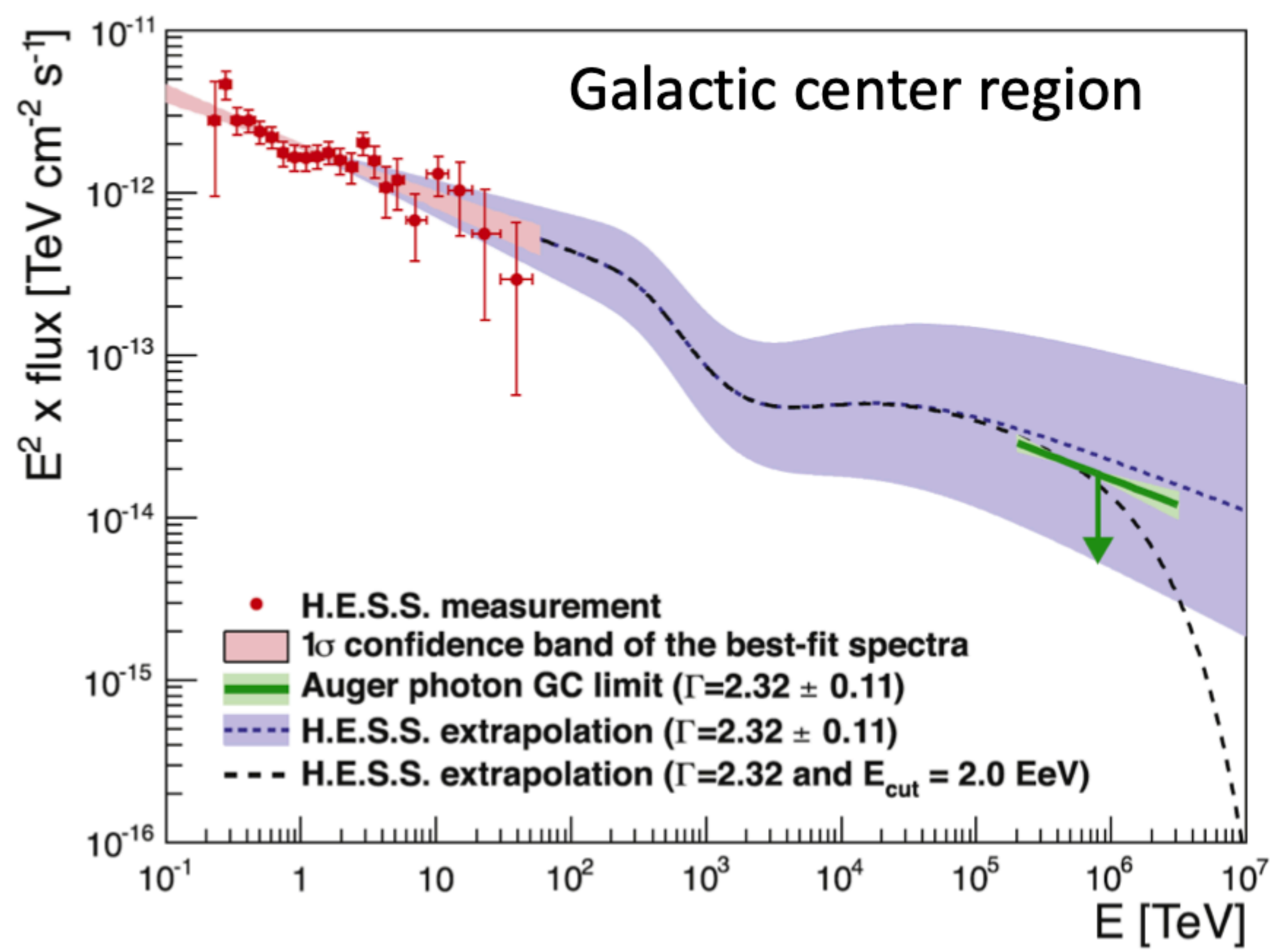
Search for sources of UHE Photons



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

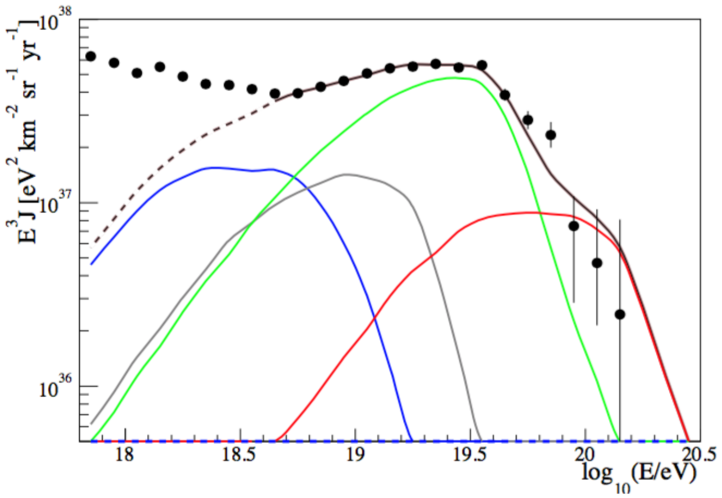


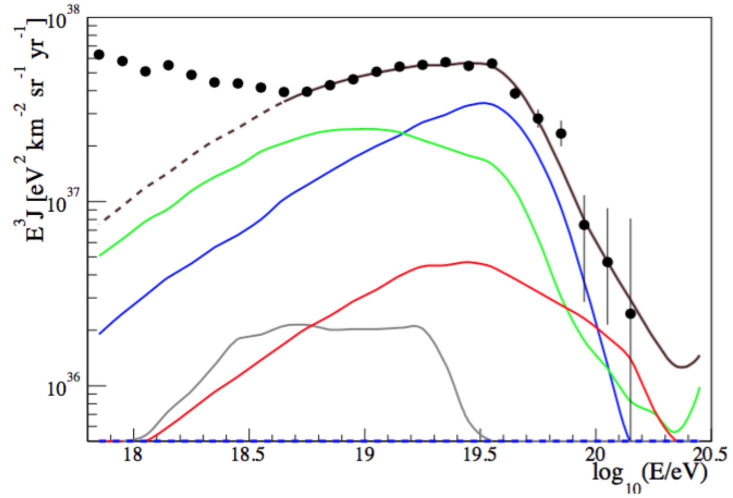
Targeted search

- 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]

Discrimination of astrophysical scenarios with AugerPrime



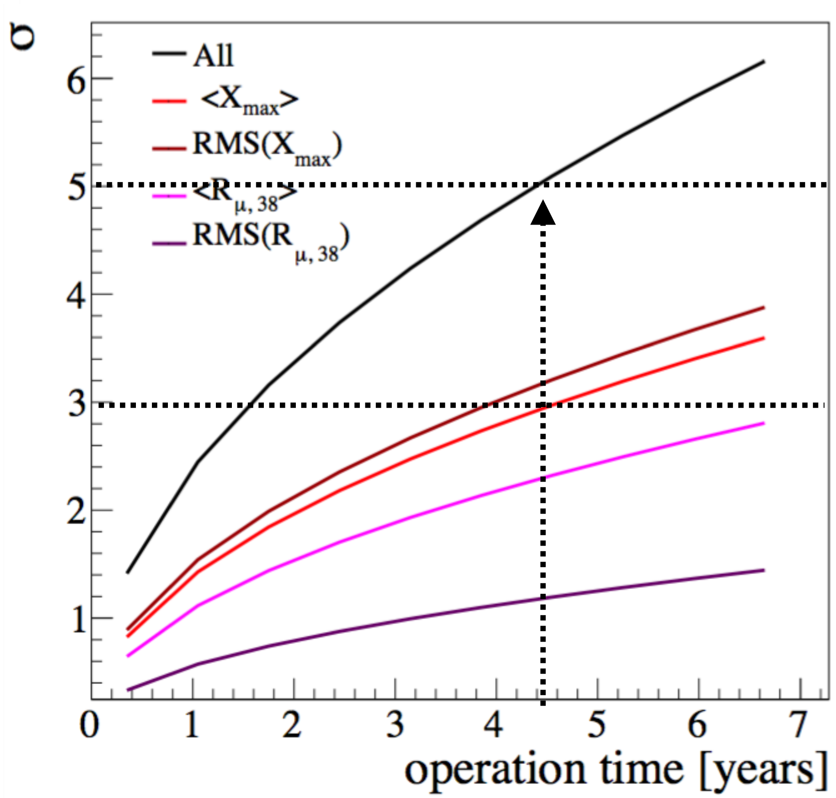


Considering two different benchmark scenarios

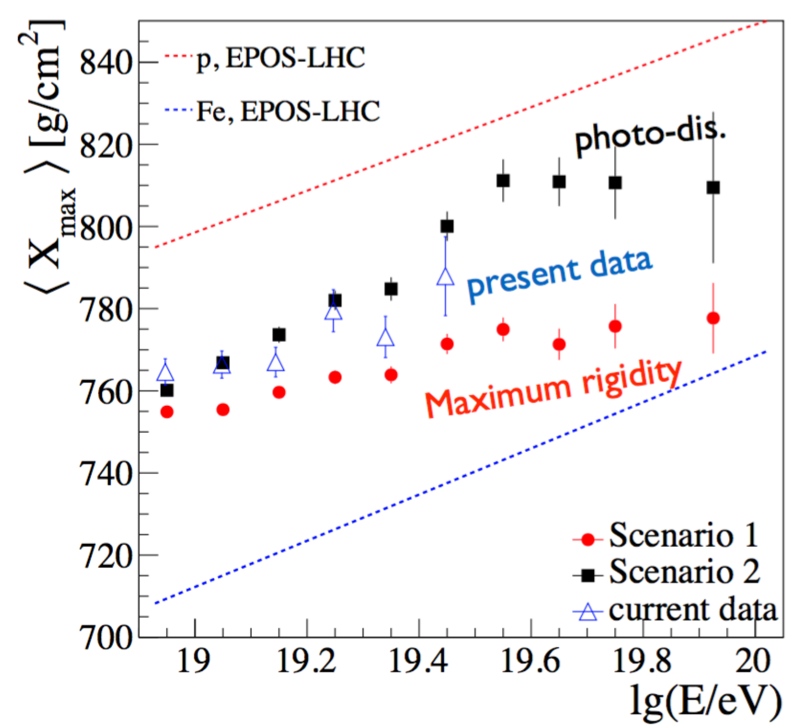
1- maximum rigidity model
2- photodisintegration model

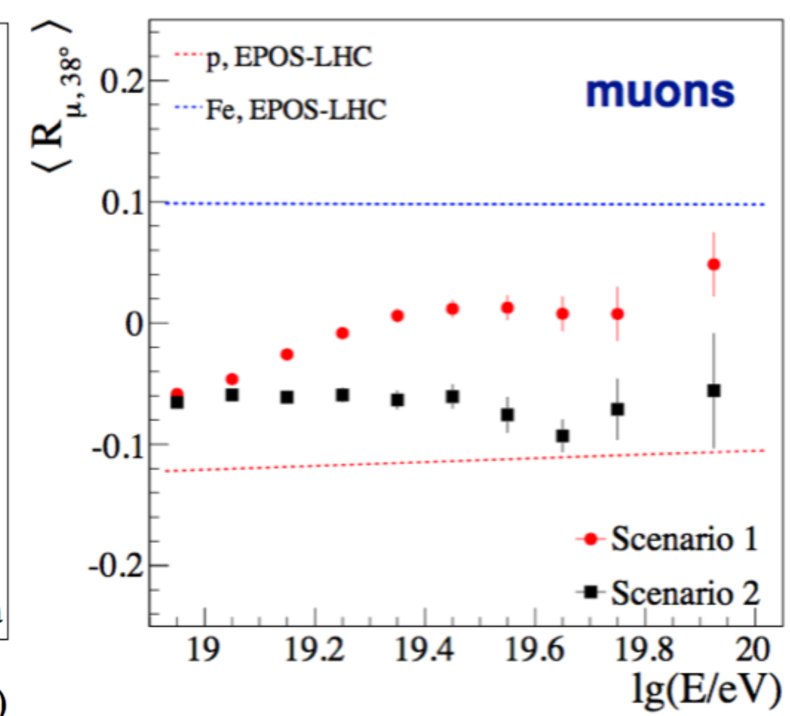
we can

foresee the possibility to tag a fraction as small as 10% of protons at the highest energies with significance σ (scenario 1)



evaluate the discrimination power for the two scenarios with the measure of X_{max}, or of muons





Multimessengers - collaborations

Collaboration, working groups and common papers with

Telescope Array
UHECR spectrum, composition, full sky search for anisotropy

Telescope Array, IceCube, Antares
search for coincidences among CRs and neutrinos

AMON (Astrophysical Multimessenger Observatory Network)
transients and their counterparts

Virgo and LIGO
neutrino follow-up of Gravitational Wave events

DWF (Deeper, Wider and Faster)
>30 collaborations multi-wavelength correlation with fast transients