Recent results and future physics program of the Pierre Auger Cosmic Ray Observatory

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for the Pierre Auger collaboration

PIERRE AUGER OBSERVATORY

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Outline

The Pierre Auger Observatory

Recent results *w/ special attention to the DM physics*
Presented at the ICRC2015 conference in August this year, arXiv:1509.03732

Future plans

Units: 1 EeV = 10^{18} eV = 10^{9} GeV

The FUNK experiment

The Pierre Auger Observatory

The primary goal is a study of the most energetic cosmic rays (10^{18} – 10^{20} eV)

The flux of such particles is extremely rare
(e.g. about 1 CR / km^2 sr century at 10^{19} eV)

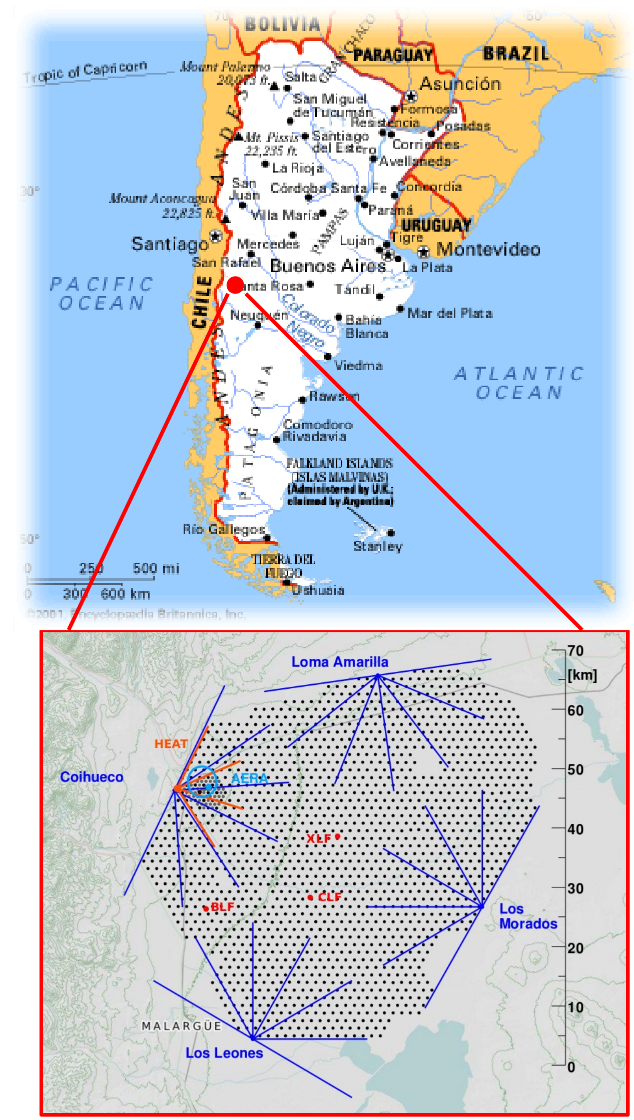
The observatory covers a flat semi-desert area of 3000 km^2

Located next to the Andes mountain at the average elevation of about 1400 m a.s.l.

Located in the southern hemisphere in Argentina,
province Mendoza

Construction started in 2004 and finished in 2008

The hybrid detector: combination of two well tested measurement techniques



Collaboration of 450 scientists from about 80 institutions in 18 countries
(Poland: Institute of Nuclear Physics PAN, Krakow & University of Lodz)

More details: http://www.auger.org/ and Pierre Auger Collab., NIMA 798 (2015)

Surface detector (SD)

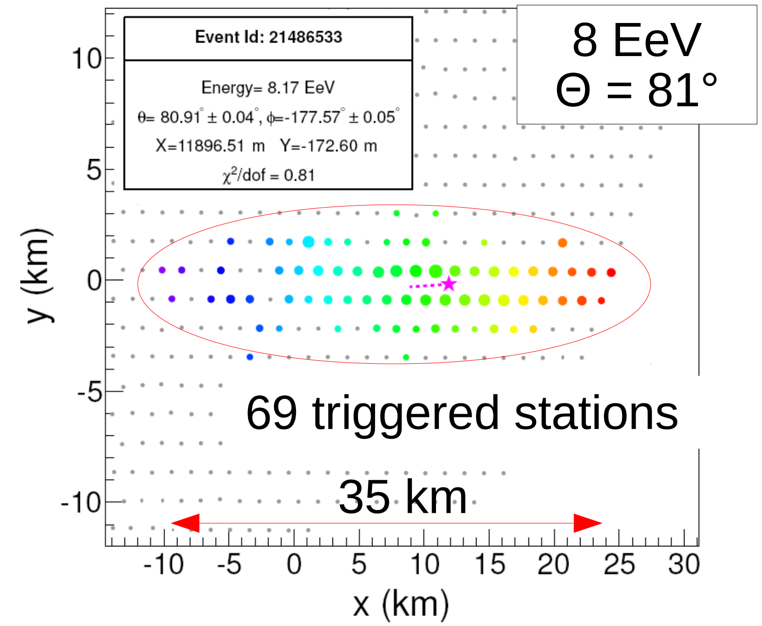
1660 water Cherenkov stations on 1.5 km grid

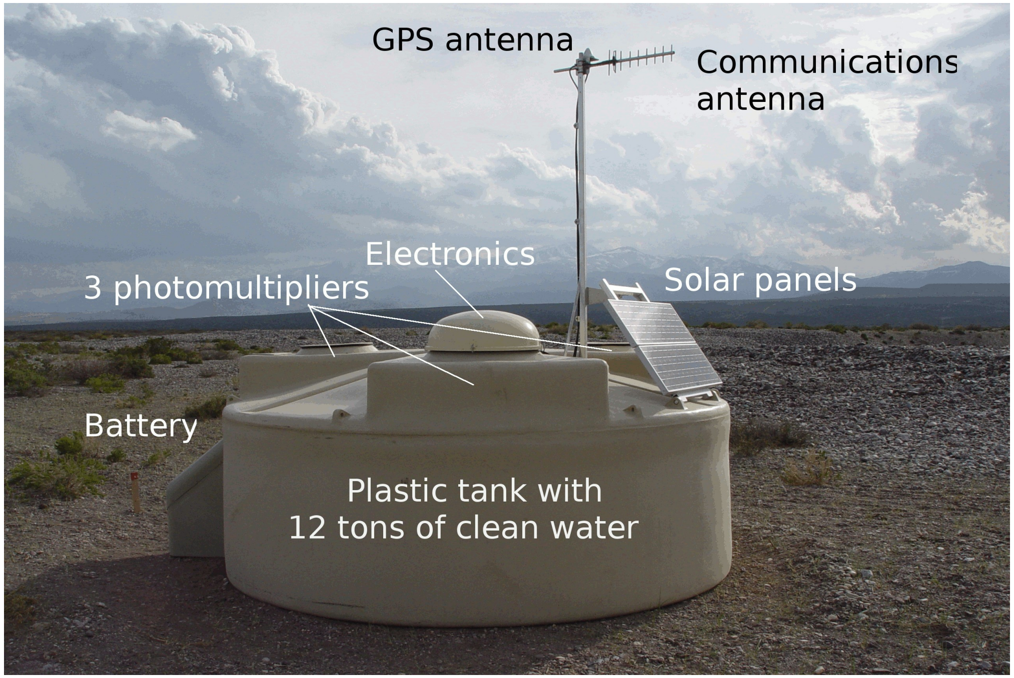
Sampling secondary particles on the ground

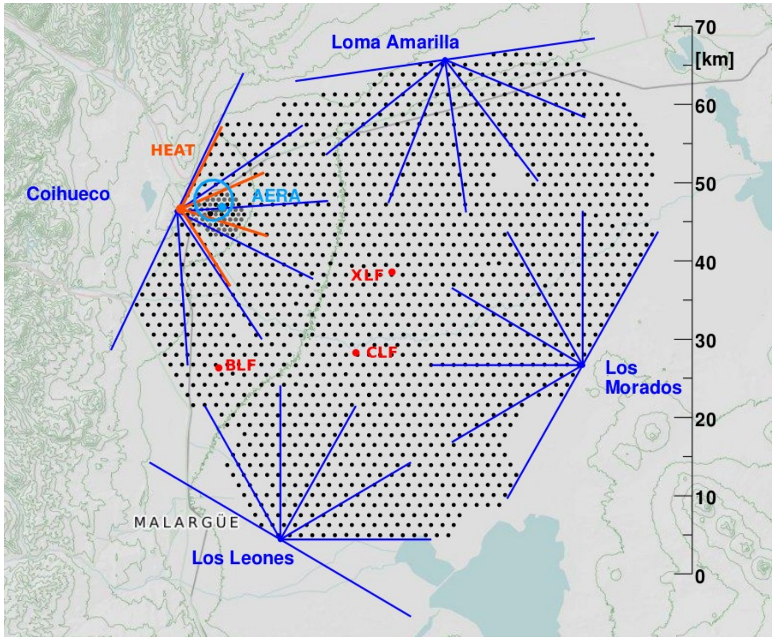
Events with zenith angle up to 80° (!)

Almost 100% uptime and well defined exposure

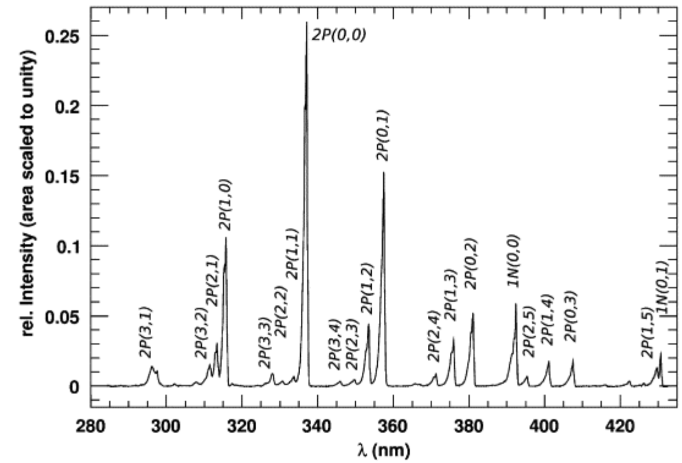
Trigger: 3 or more tanks with a local trigger
or an external trigger







Fluorescence detector (FD)



24 telescopes in 4 buildings

One telescope observes 30° (elevation) x 30° (azimuth)

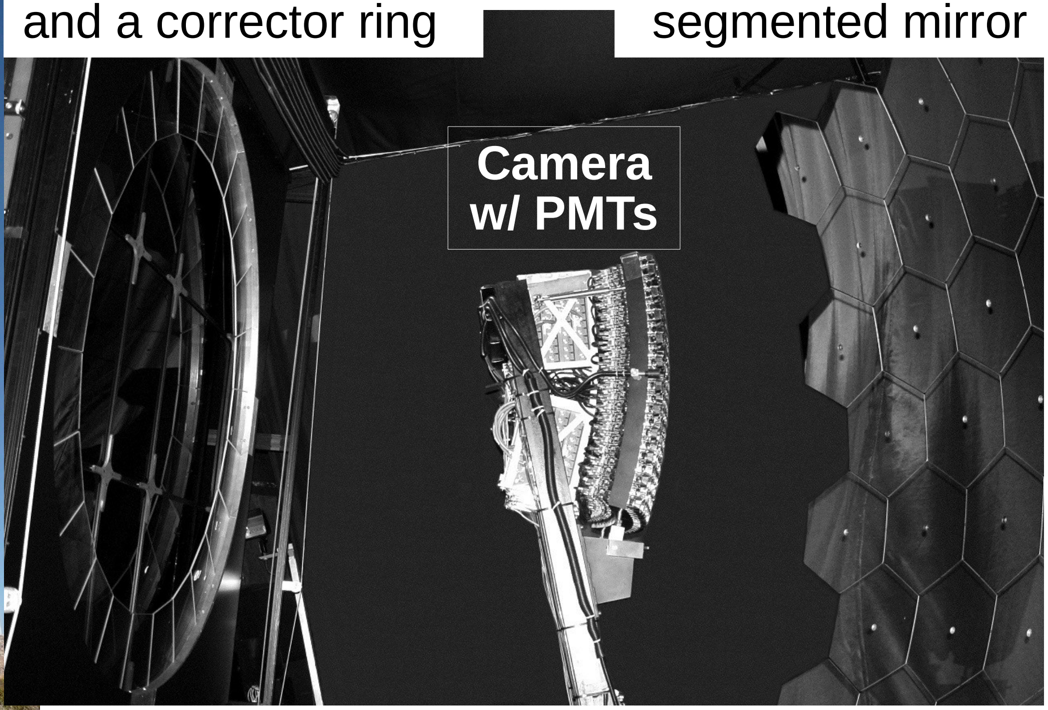
440 PMTs in each camera

Observation is possible only during moonless nights: 12 shifts of ca. 18 nights per yr

15% uptime has been achieved (!)

Aperture w/ UV filter and a corrector ring

Large spherical segmented mirror



Extensive air showers

Ultra-high energy primary particle interacts in the atmosphere and secondary particles (γ, e-, e+, μ, ν, ...) are consequently produced.

Atmosphere can be considered as a part of the detector.

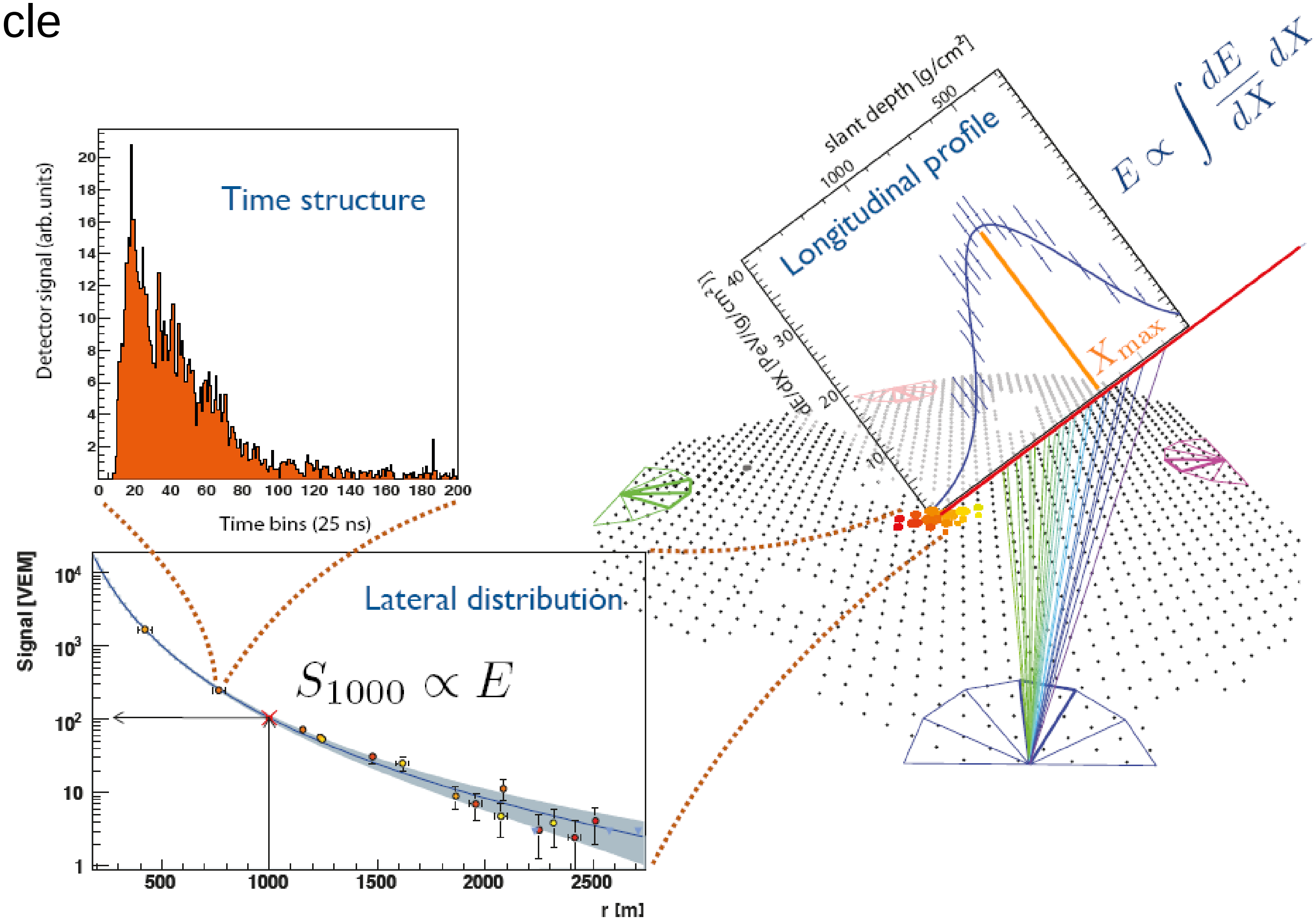
Air shower development (longitudinal and lateral) depends on the energy and type of the primary particle

Reconstruction:

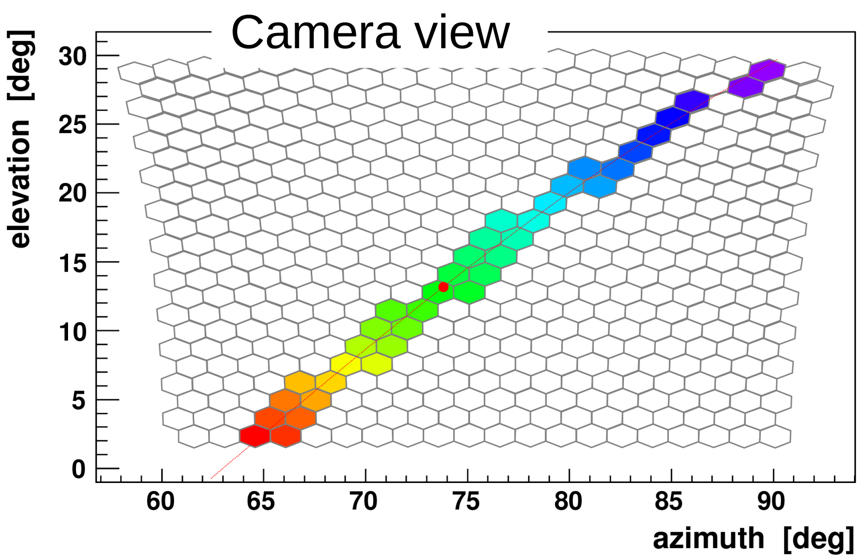
Timing – Arrival direction

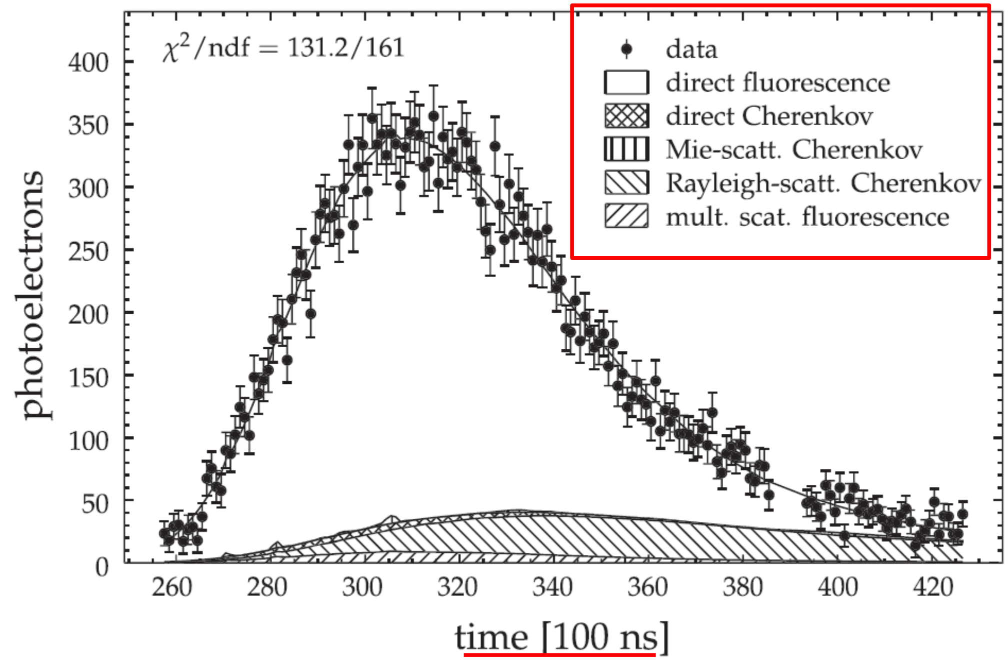
Signal – Energy

Xmax – Mass composition

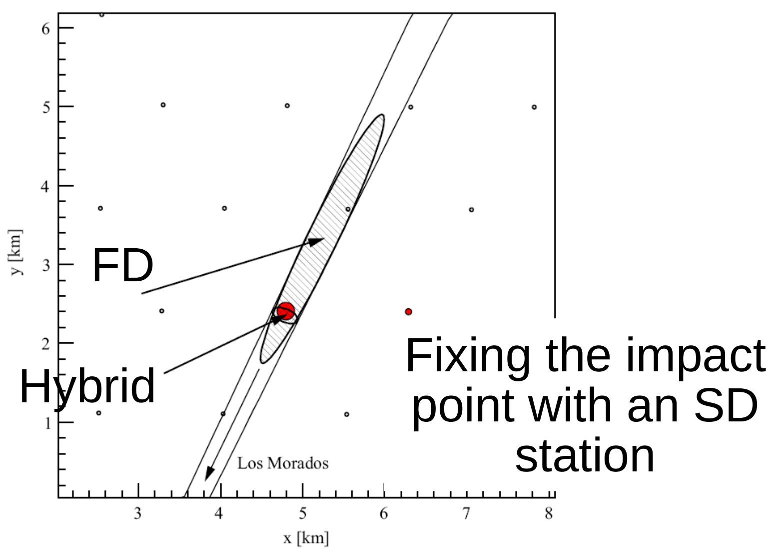


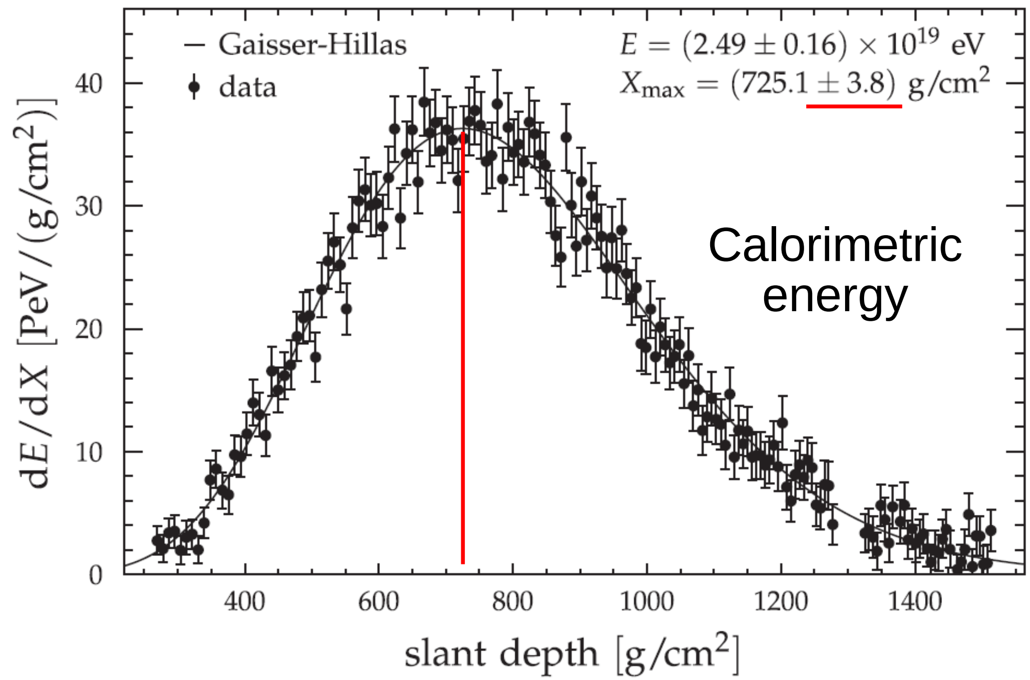
FD reconstruction





Hybrid reconstruction





Atmospheric Monitoring Devices

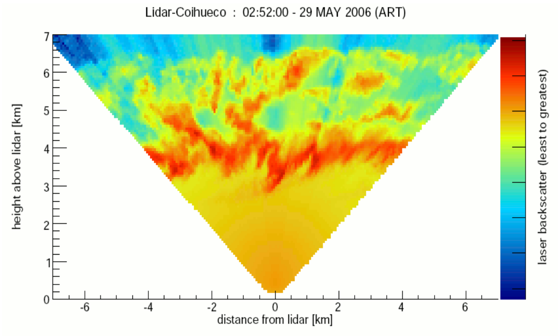
Scattering and attenuation of UV photons between an air shower and a telescope

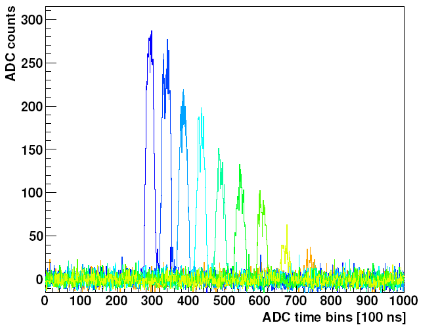
Rapid atmospheric monitoring system

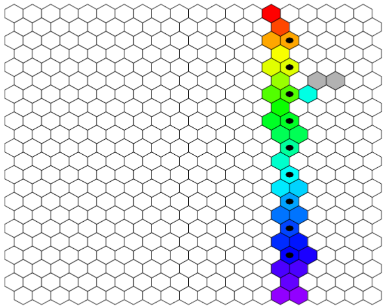
Online reconstruction within a few minutes

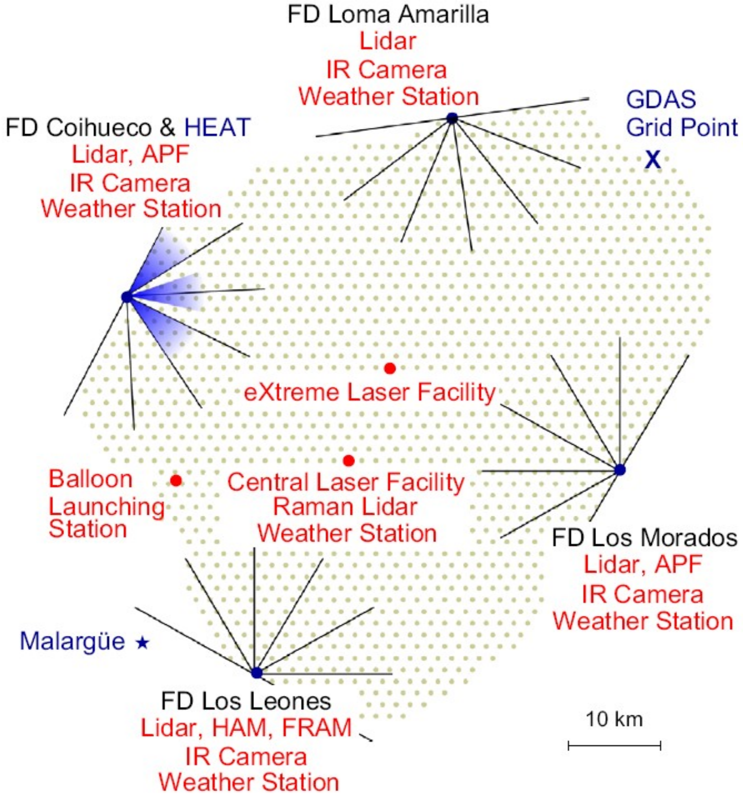
Precise knowledge about the immediate status of the atmosphere for the most interesting events

Many instruments on site







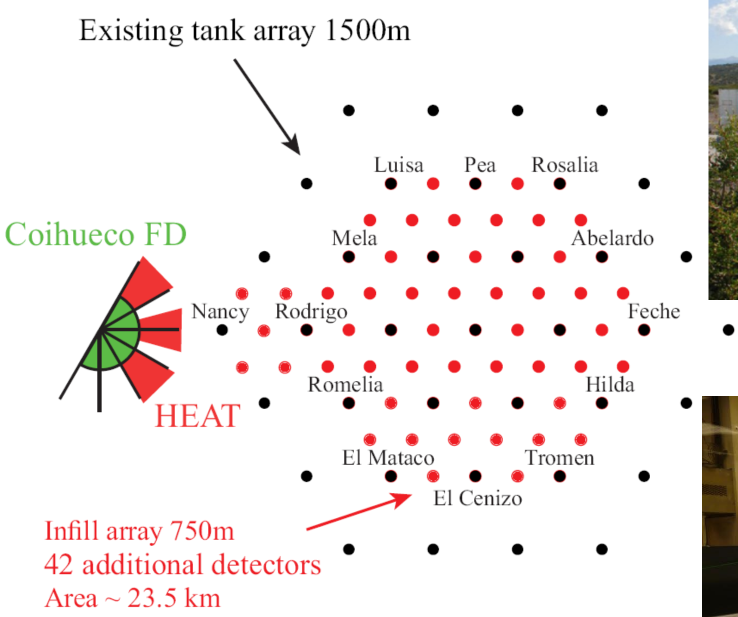


Low-energy extensions – CRs below 3×10^{18} eV

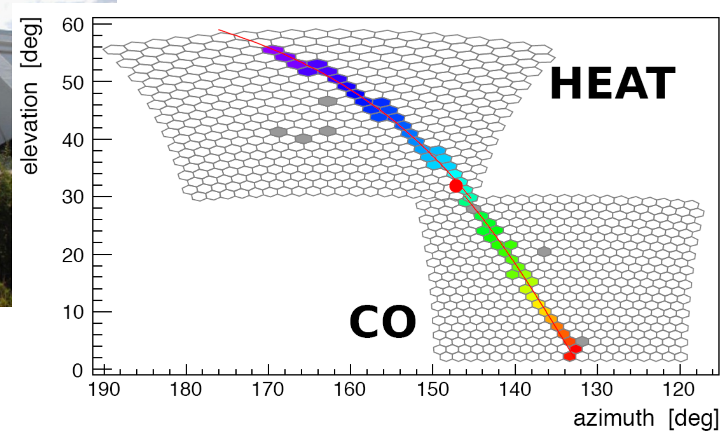
Goals:

1. To test scenarios of a transition from Galactic to extragalactic sources
2. Direct comparison of results obtained by other cosmic-ray experiments
3. Site for testing new detectors (i.e. lower energy, higher event rate)

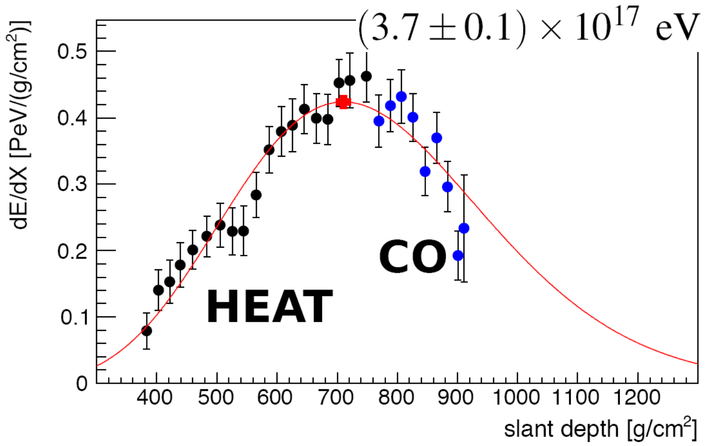
Infill area: 750 m spacing between SD stations



High Elevation Auger Telescopes (HEAT)



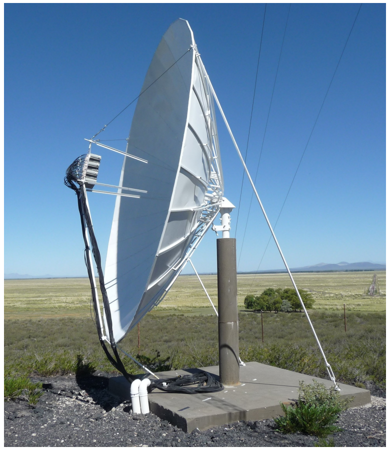
AMIGA – muon detectors underground (under construction)



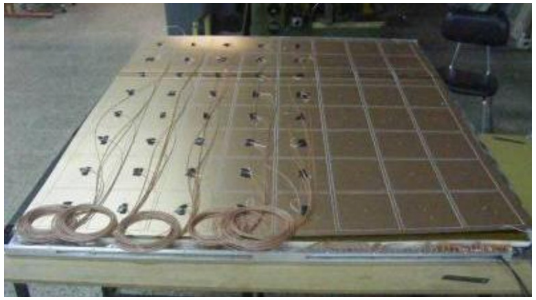
Extensive R&D program

Measurement in MHz

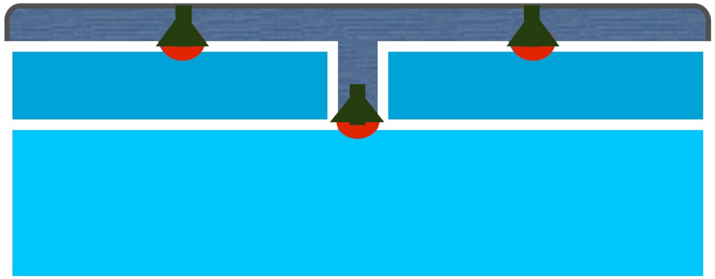
Measurement in GHz



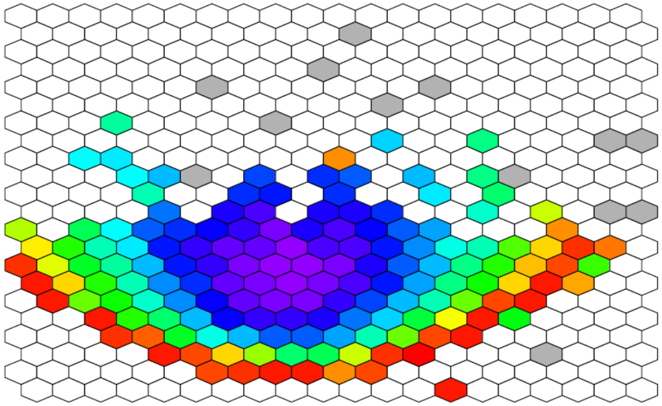
RPC



Layered water Cherenkov detector

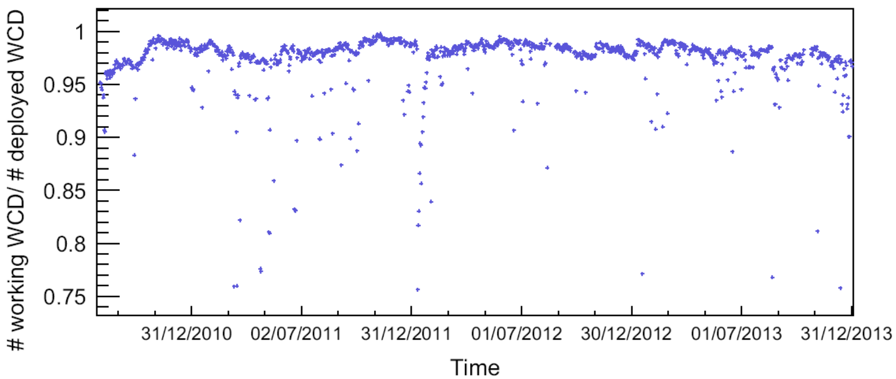


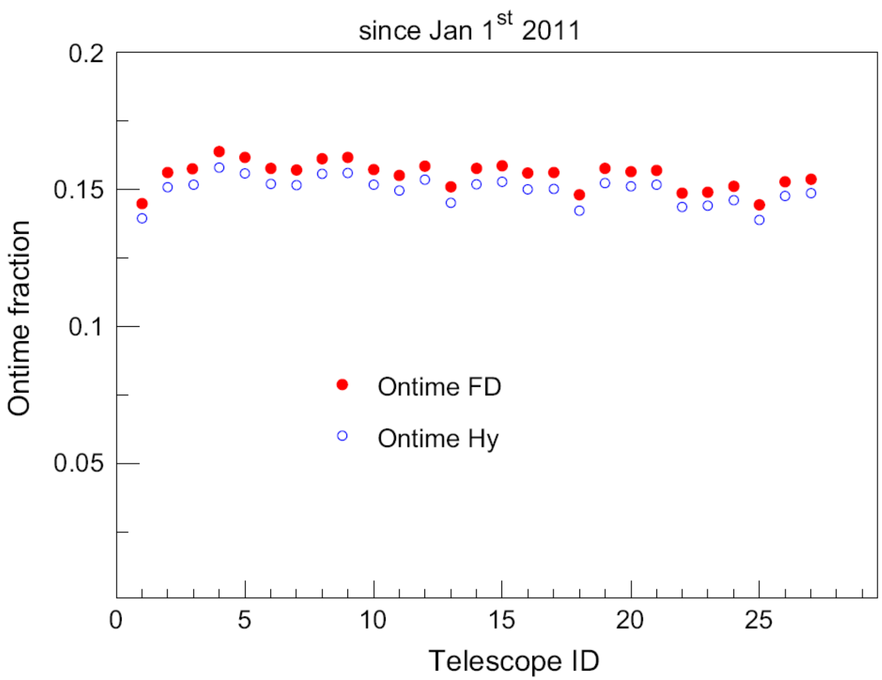
Transient luminous events (TLEs)
ca. 100 km above thunderstorms



Among others...

Performance – long term stability





Key performance parameters for the Auger Observatory.

SD	
SD annual exposure, $\theta < 60^\circ$	~ 5500 km^2 sr yr
T3 rate	0.1 Hz
T5 events/yr, $E > 3$ EeV	$\sim$ 14,500
T5 events/yr, $E > 10$ EeV	$\sim$ 1500
Reconstruction accuracy (S_{1000})	22% (low E) to 12% (high E)
Angular resolution	1.6° (3 stations)
	0.9° ($>$ 5 stations)
Energy resolution	16% (low E) to 12% (high E)
FD	
On-time	$\sim$ 15%
Rate per building	0.012 Hz
Rate per HEAT	0.026 Hz
Hybrid	
Core resolution	50 m
Angular resolution	0.6°
Energy resolution (FD)	8%
X_{max} resolution	< 20 g/cm^2

The energy scale – systematic uncertainties

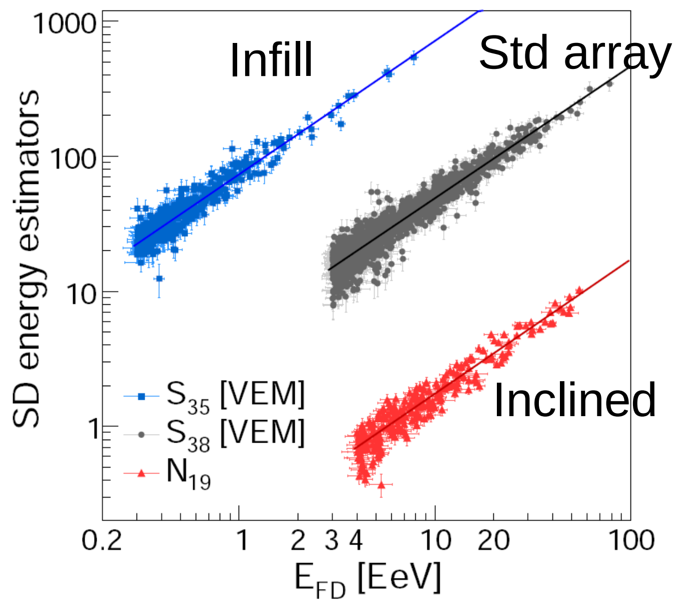
Systematic uncertainties in the energy scale.

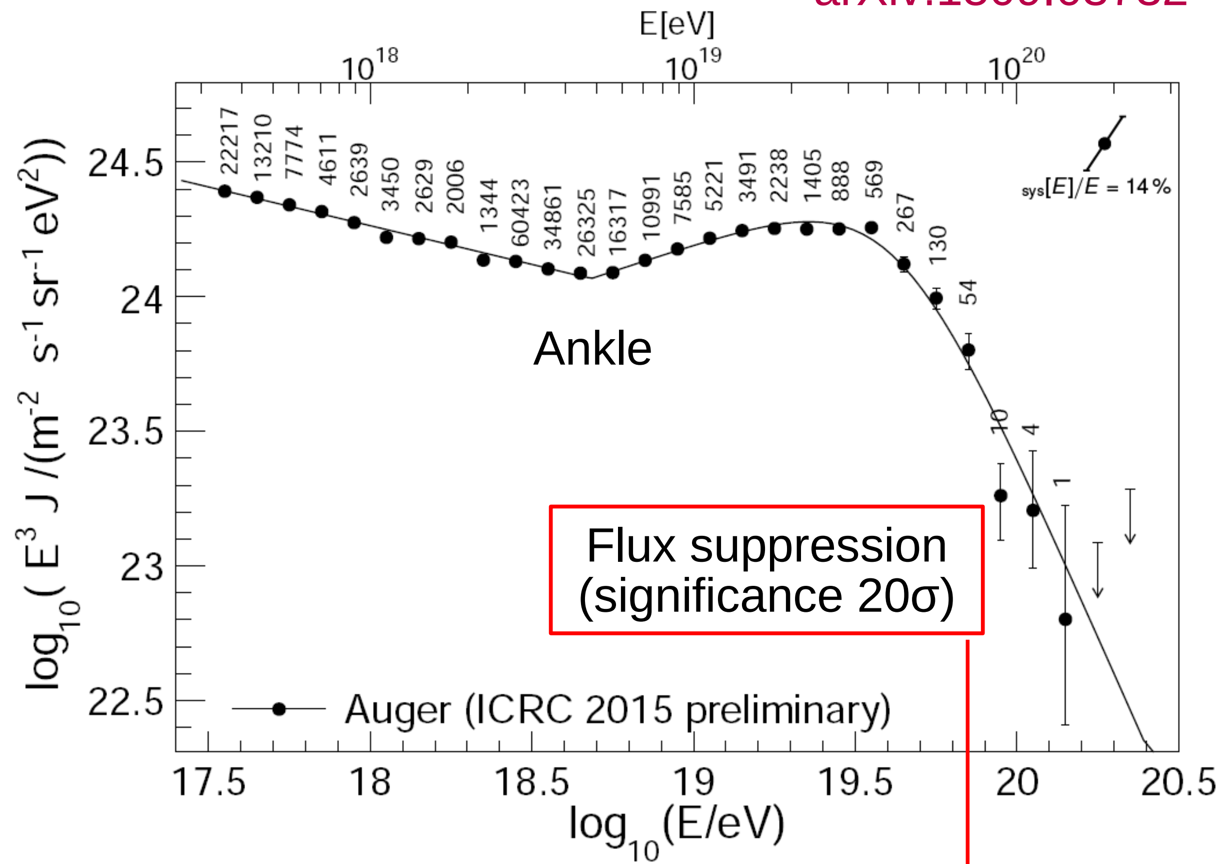
Fluorescence yield	Absolute fluorescence yield	3.4%
	Fluorescence spectrum and quenching parameters	1.1%
	Subtotal, fluorescence yield	**3.6%**
Atmosphere	Aerosol optical depth	3–6%
	Aerosol phase function	1%
	Wavelength dependence of aerosol scattering	0.5%
	Atmospheric density profile	1%
	Subtotal, atmosphere	**3.4–6.2%**
Calibration	Absolute FD calibration	9%
	Nightly relative calibration	2%
	Optical efficiency	3.5%
	Subtotal, FD calibration	**9.9%**
Reconstruction	Folding with point spread function	5%
	Multiple scattering model	1%
	Simulation bias	2%
	Constraints in the Gaisser–Hillas fit	3.5–1%
	Subtotal, FD profile reconstruction	**6.5–5.6%**
Invisible energy (ν)	Invisible energy	**3–1.5%**
	Statistical error of SD calibration fit	**0.7–1.8%**
Long-term stability	Stability of the energy scale	**5%**
	Total	**14%**

It is a tremendous accomplishment!

Energy spectrum

arXiv:1509.03732



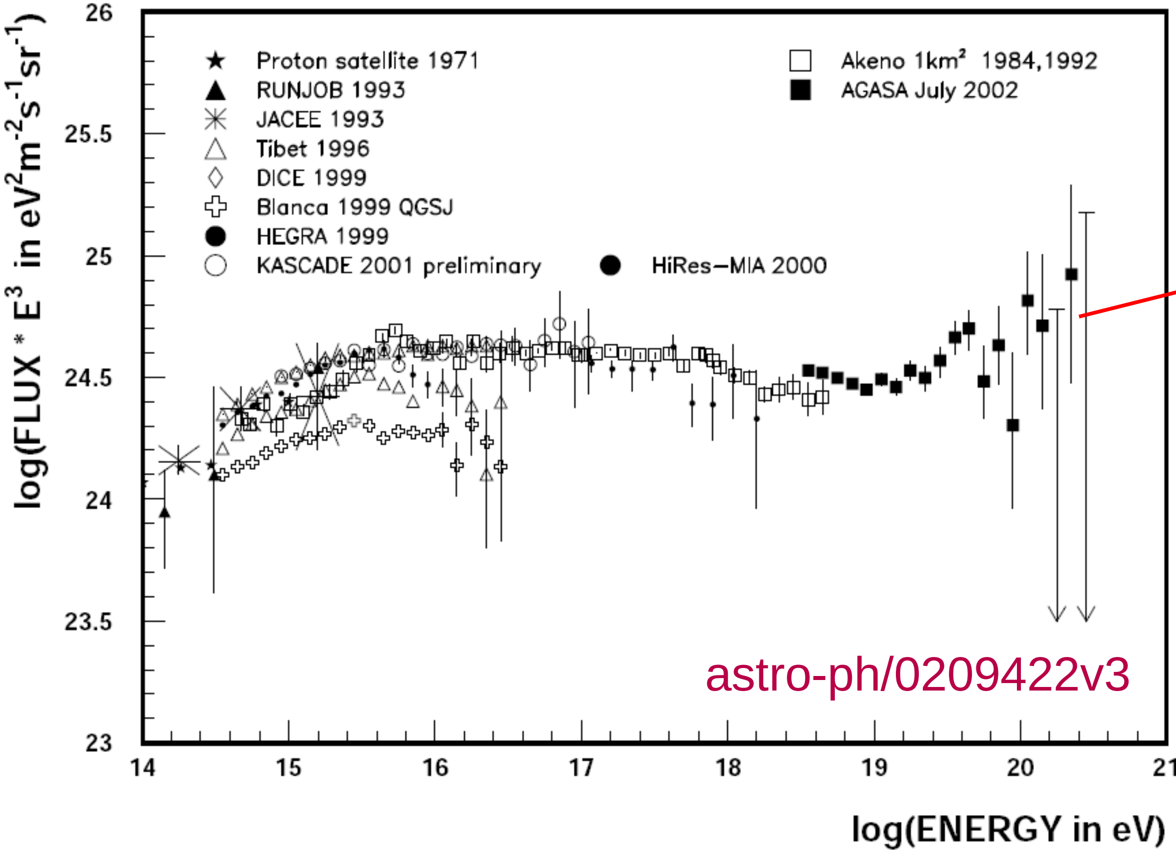


	SD-1500 m		SD-750 m	Hybrid
	vertical	inclined		
Data-taking period	01/2004–12/2014	01/2004–12/2013	08/2008–12/2014	11/2005–12/2013
Exposure [km^2 sr yr]	42500±1300	10900±300	150±5	1500±20 at 10^{19} eV
Zenith angle [deg]	0-60	60-80	0-55	0-60
Threshold energy	3×10^{18} eV	4×10^{18} eV	3×10^{17} eV	10^{18} eV
Number of events	102901	15614	61130	9346
Number of hybrid events	1731	255	469	
Energy scale (A)	(0.1871 ± 0.004) EeV	(5.71±0.09) EeV	(12.87± 0.63) PeV	
Energy scale (B)	1.023 ±0.006	1.01±0.02	1.013±0.013	
Energy resolution [%]	15.3±0.4	19±1	13±1	

GZK cut-off?

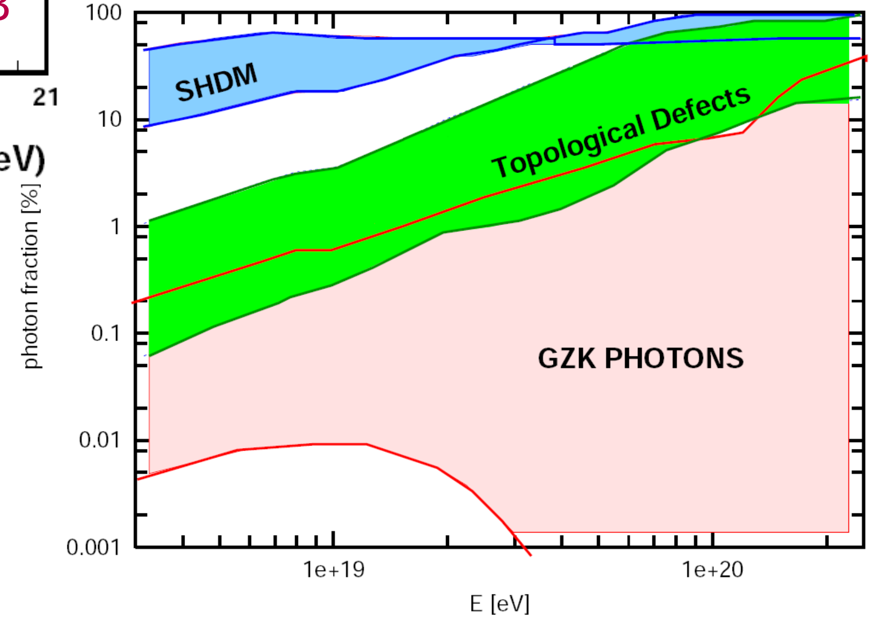
Sources out of power?

AGASA spectrum in 2002



This result has triggered hundreds of papers about decays of super-heavy DM (SHDM) particles...

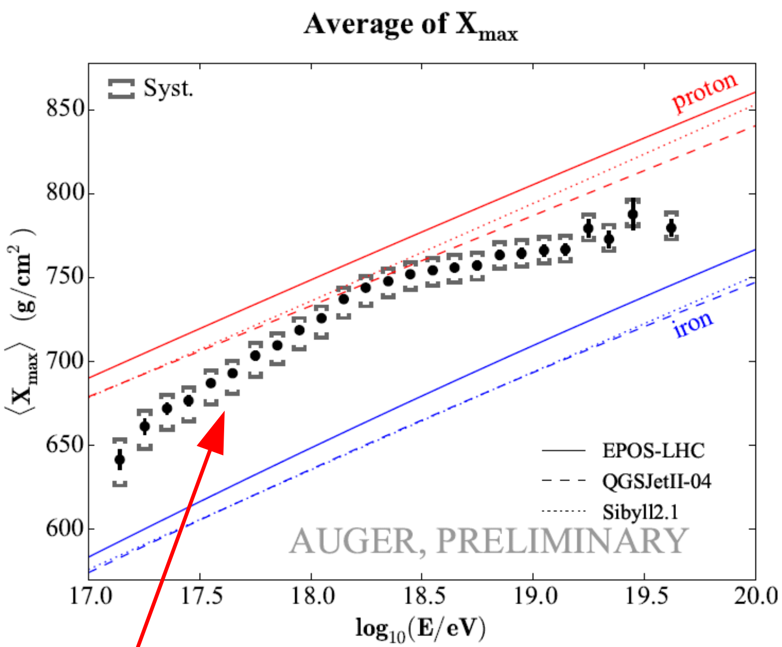
Photons from SHDM decays

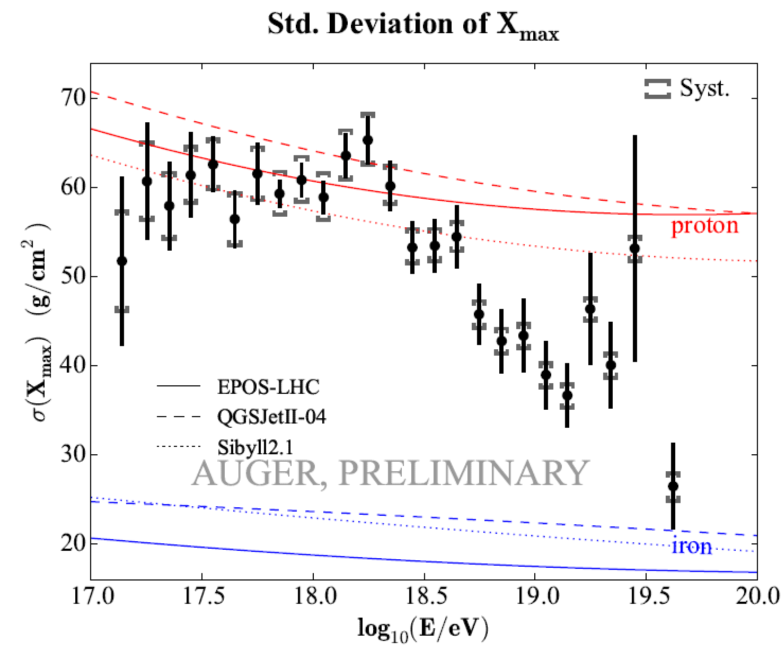


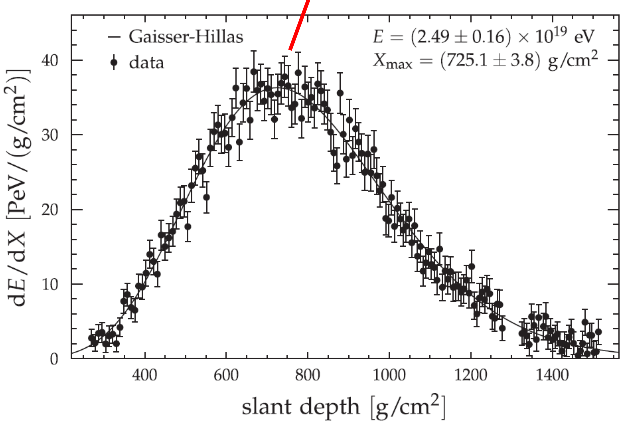
Disproved by Auger results!

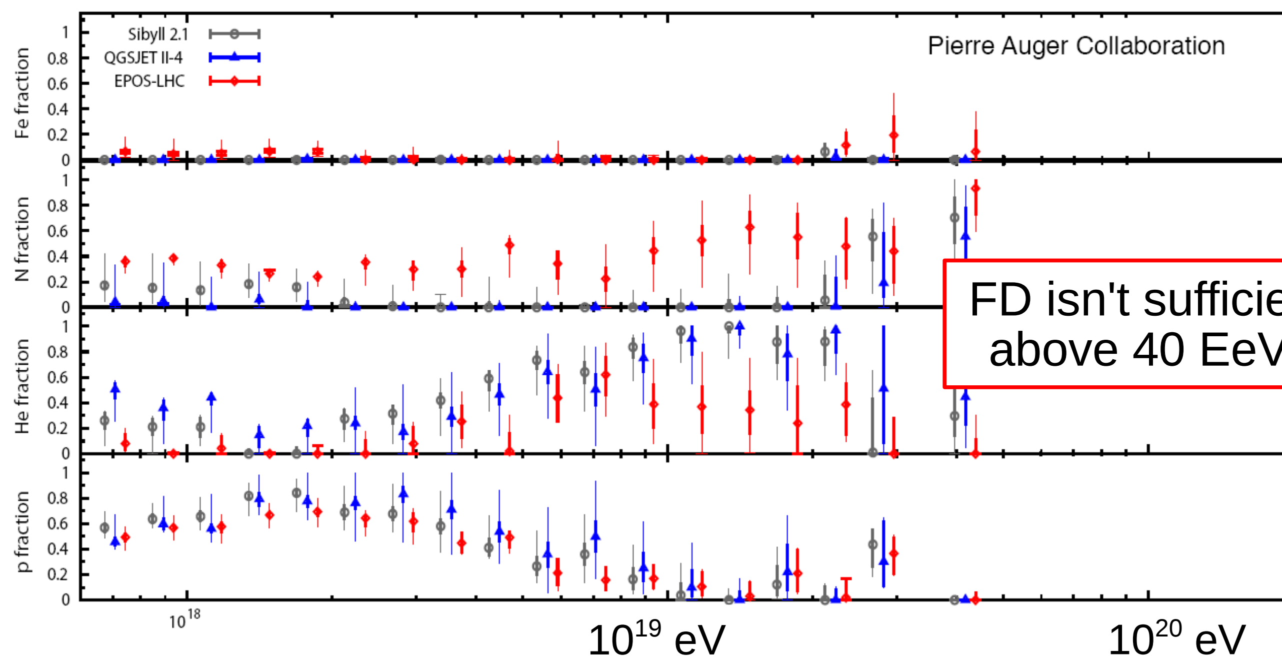
Mass composition by FD

PRD 90 (2014)
arXiv:1509.03732









FD isn't sufficient above 40 EeV.

Inelastic proton-proton cross section

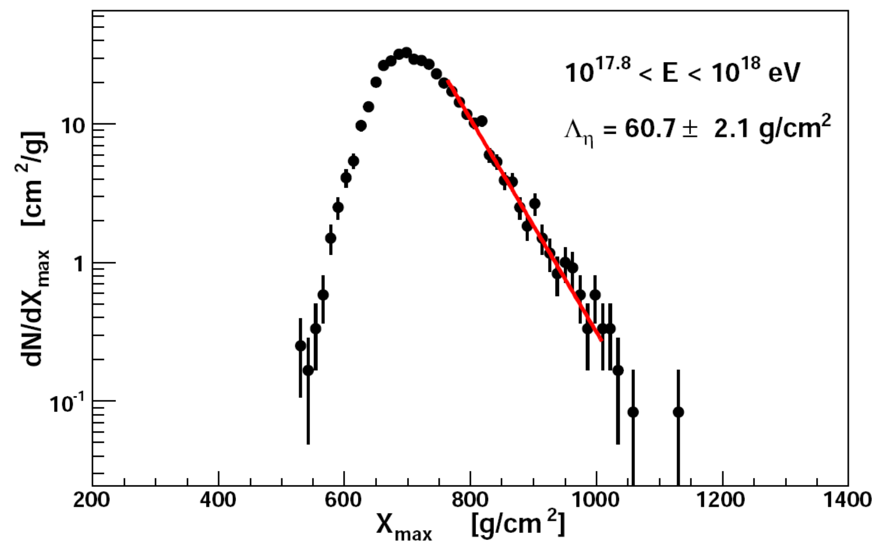
PRL 109 (2012)
arXiv:1509.03732

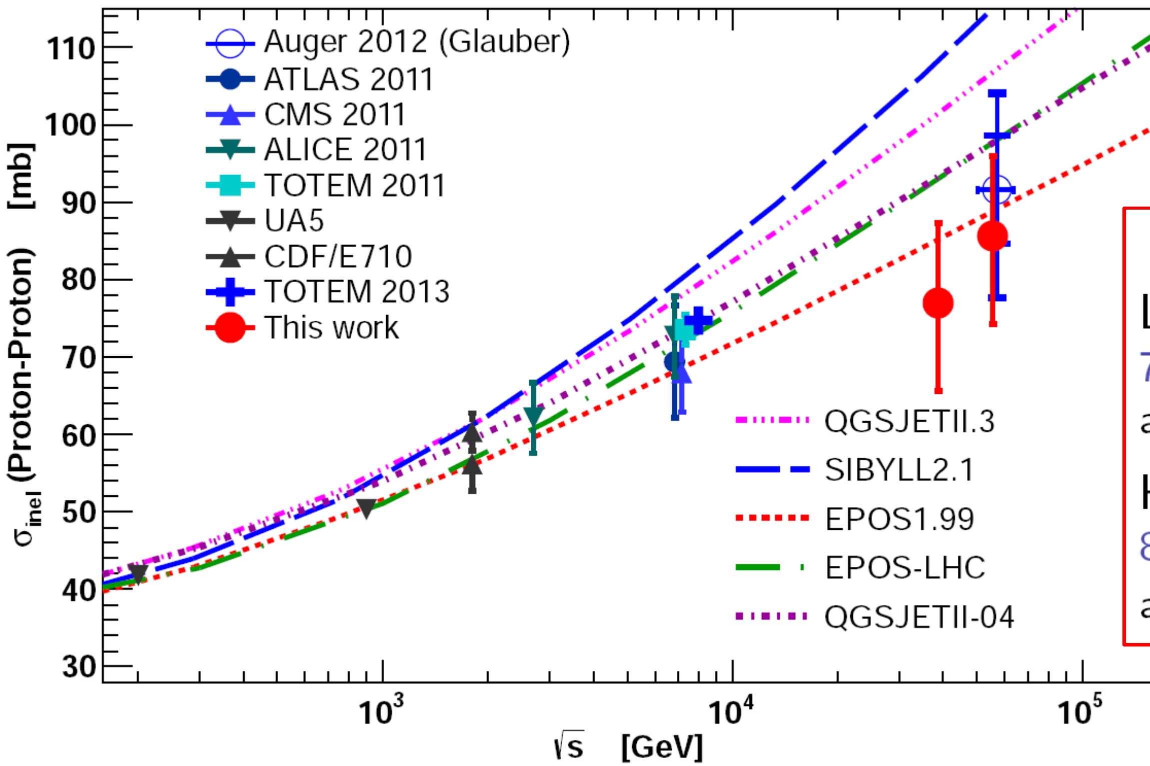
Select deeply penetrating showers to enhance proton fraction

$\Rightarrow$ Tail of $X_{\max}$–Distribution

Ellsworth et al. PRD 1982, Baltrusaitis et al. PRL 1984

$$\mathbf{dN/dX_{max}} \propto \mathbf{exp(-X_{max}/\Lambda_\eta)}$$





Results, σ_{pp}^{inel} in mb

Lower energy point

76.95±5.4(stat)+5.2/-7.2(syst)±7(glauber)

at $\sqrt{s_{pp}} = 38.7 \pm 2.5$ TeV

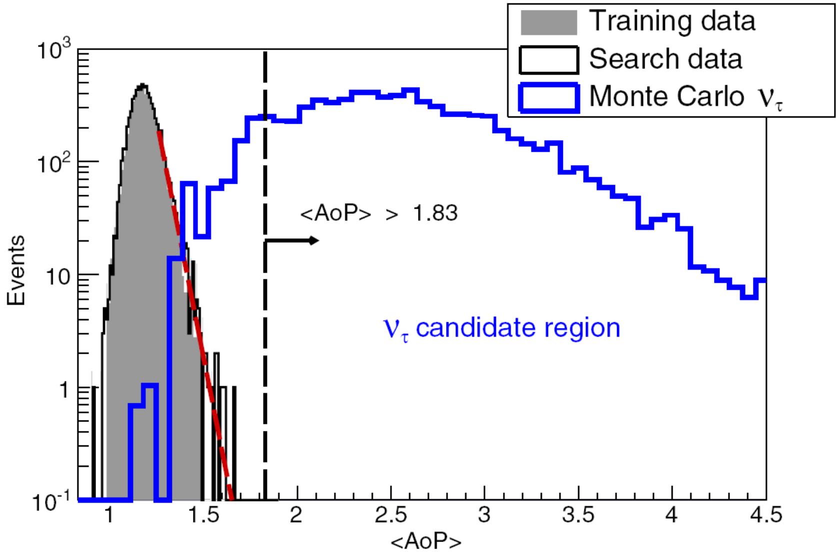
Higher energy point

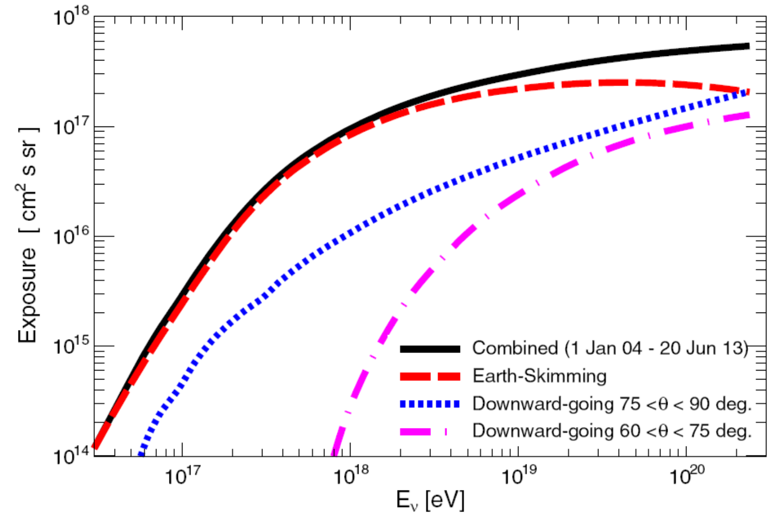
85.62±5(stat)+5.5/-7.4(syst)±7.1(glauber)

at $\sqrt{s_{pp}} = 55.5 \pm 3.6$ TeV

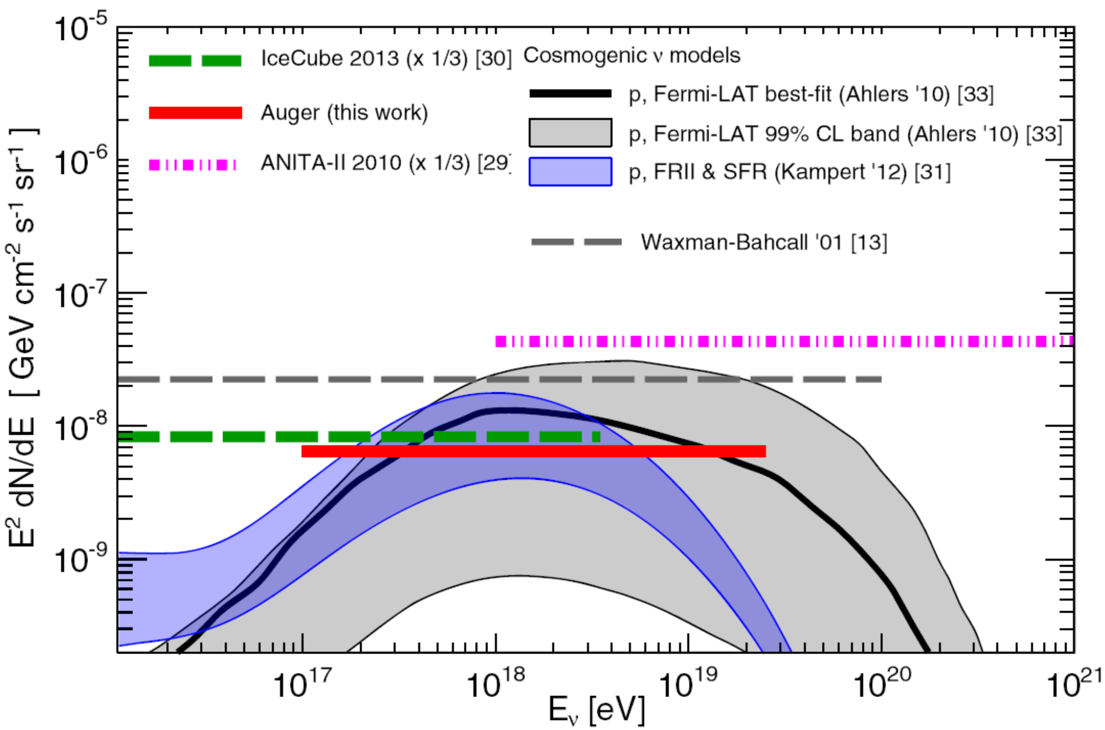
Neutrinos

PRD 91 (2015)





Single flavour, 90% C.L.



No neutrino candidates have been found so far.

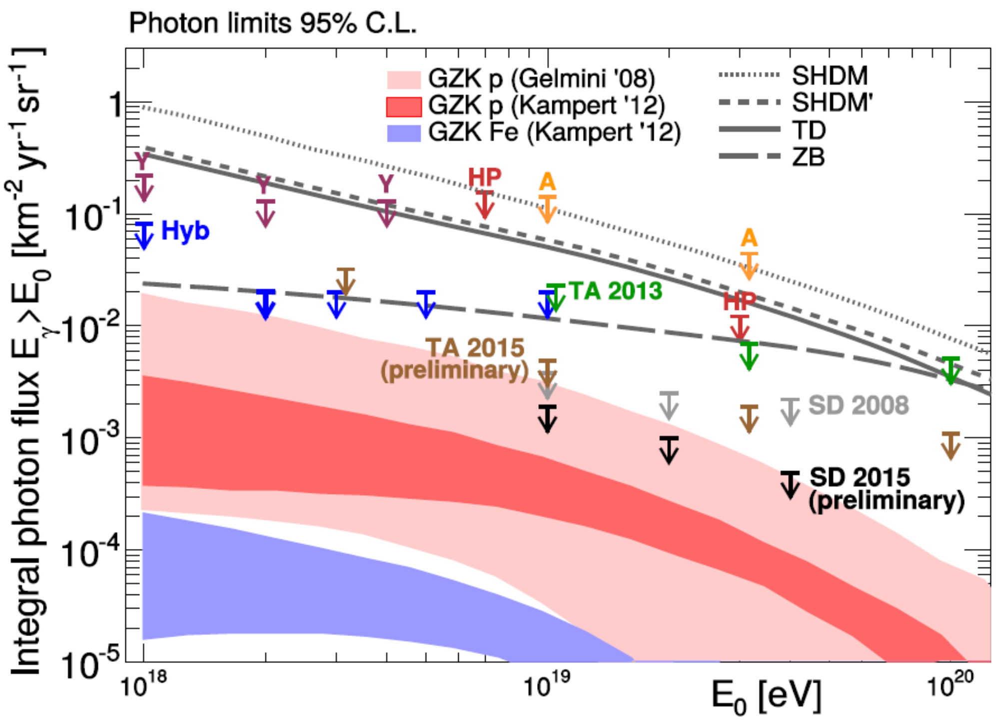
A large range of exotic models of neutrino production are excluded with C.L. larger than 99%.

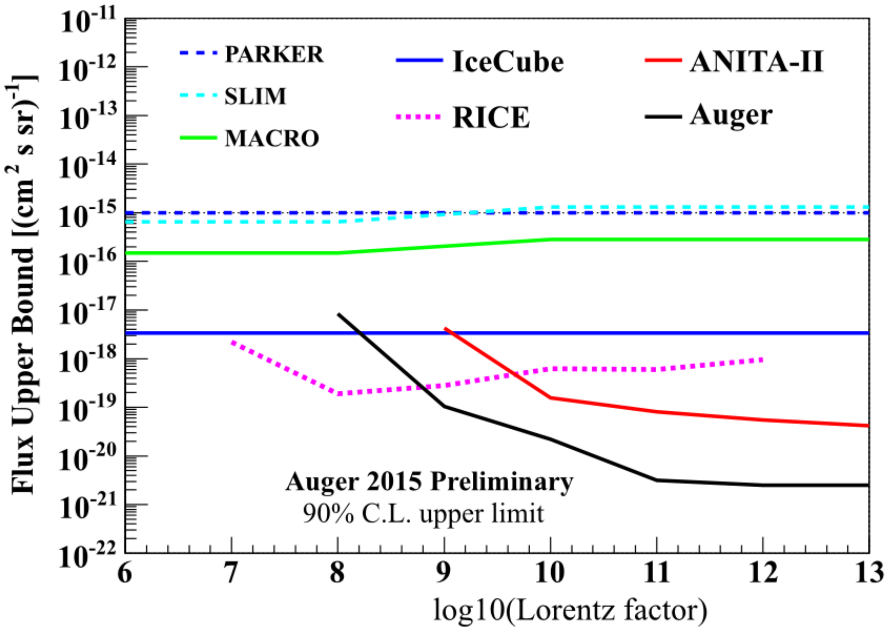
The current limit is a factor 4 below the Waxman-Bahcall bound on ν production in optically thin sources.

Complementary to the IceCube.

Photons and ultra-relativistic magnetic monopoles

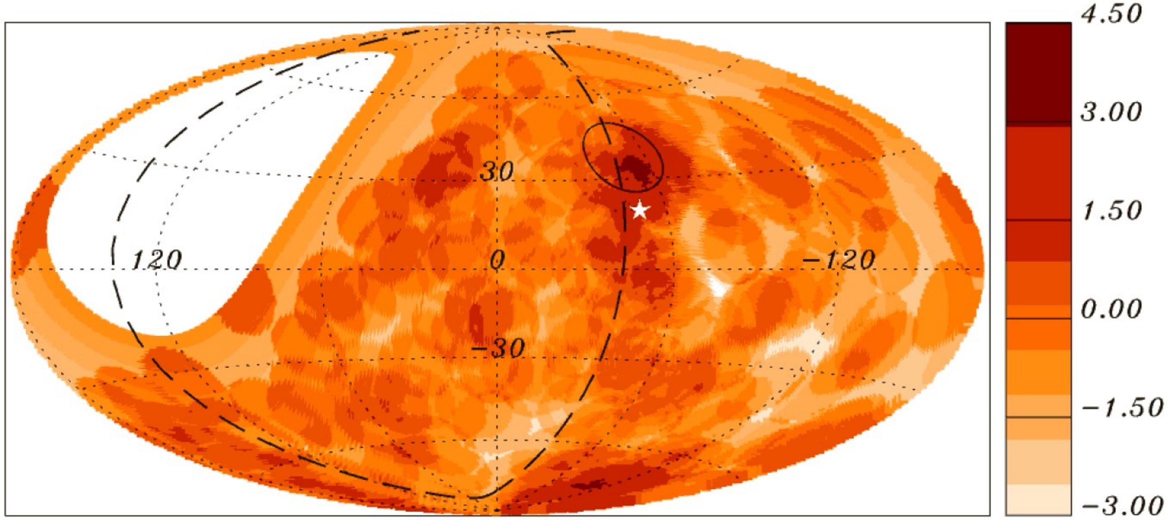
arXiv:1509.03732



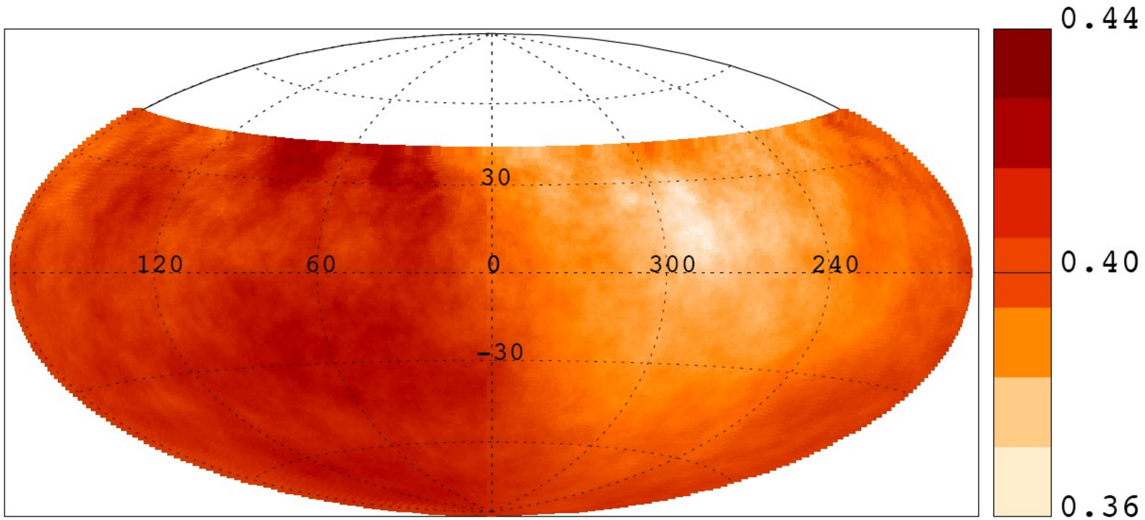


The photon flux limits have further far-reaching consequences by providing important constraints on theories of quantum gravity involving Lorentz invariance violation (LIV), see, for example, [60–63]. Further, identifying a single photon shower at ultra-high energy would imply very strong limits on another set of parameters of LIV theories [64–66].

Arrival Directions



Map in galactic coordinates of the Li-Ma significances of excesses in 12° radius windows for the events with E ≥ **54 EeV**. The Super-Galactic Plane (dashed line) and Centaurus A (white star).
A post-trial probability is not significant.



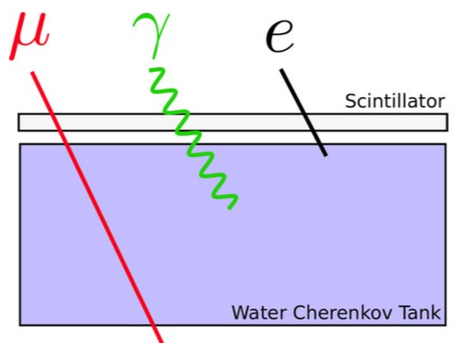
Sky map in equatorial coordinates of flux in $1/km^2/yr/sr$ smoothed in angular windows of 45° radius, for observed events above **8 EeV**.

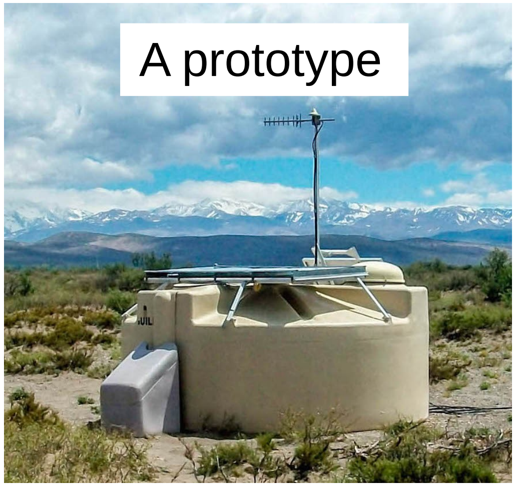
Dipolar anisotropy at the few % level above 8 EeV.

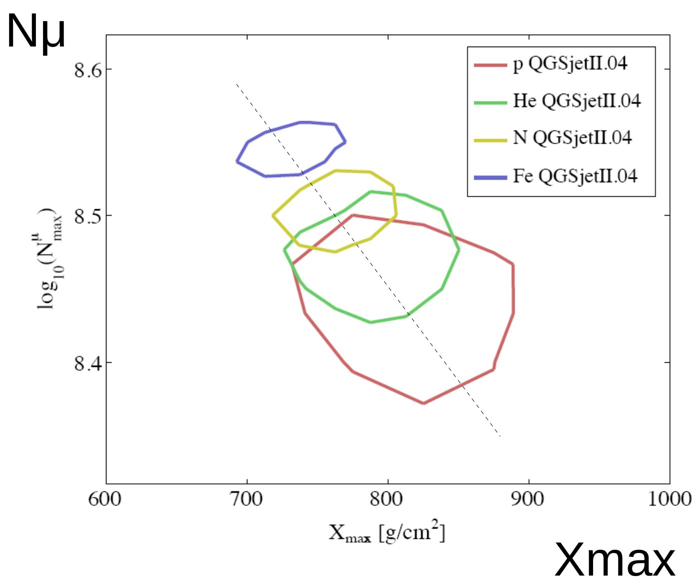
Upgrade – AugerPrime

Mass composition measurement above 40 EeV!

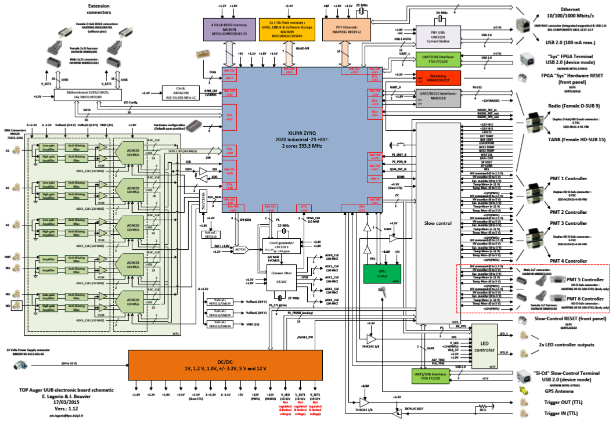
<u>Scintillator</u> (about 4 m^2)







<u>New electronics</u> (faster sampling, more precise timing, higher dynamic range, new triggers, etc.)



<u>Extension of the FD uptime</u>
(higher night sky bgd)

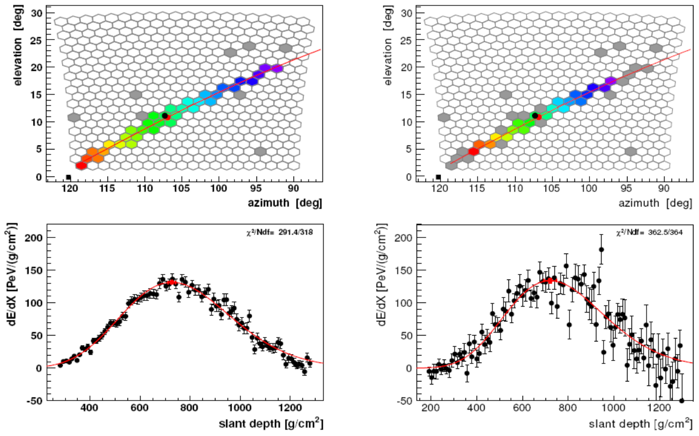


Figure 6.3: A real FD event with reconstructed energy 7×10^{19} eV. In the left panel are measured data (clear sky and no scattered moonlight, a baseline variance of 25 (ADC counts)^2) and in the right panel the same data after adding random noise corresponding to a 40 times higher NSB.

AugerPrime – outlook

arXiv:1509.03732

Main aims of Auger Upgrade

1. Origin of flux suppression (GZK energy loss vs. maximum injection energy)
2. Proton contribution of more than 10% at $E > 6 \times 10^{19}$ eV, particle astronomy?
3. New particle physics beyond the reach of LHC?

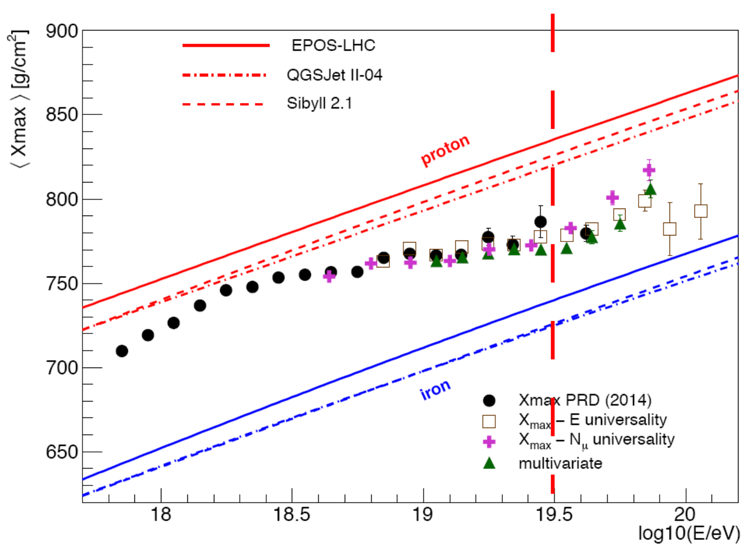
AugerPrime well-suited to address these questions

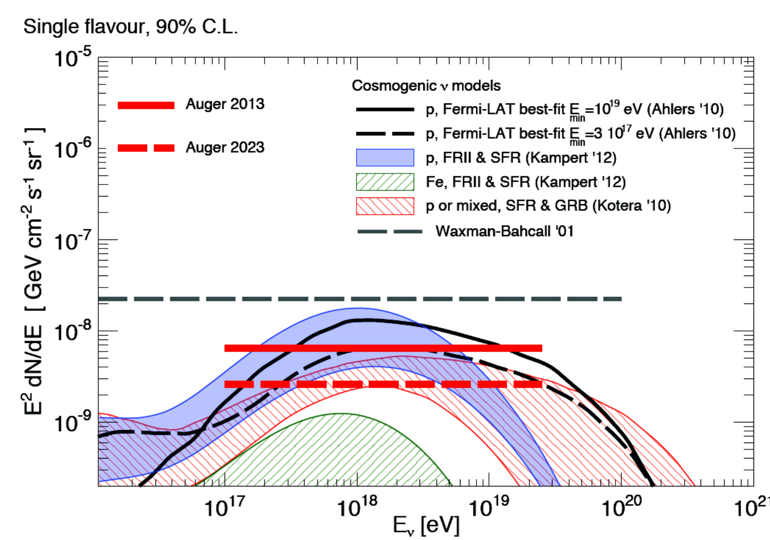
Timeline and exposure

April 2015: preliminary design report
March 2016: engineering array
Fall 2016-17: deployment
2018-24: data taking (40,000 km² sr yr)

Total cost (WBS): $ 15M

$\log_{10}(E/\text{eV})$	$dN/dt\|_{\text{infill}}$ $[\text{yr}^{-1}]$	$dN/dt\|_{\text{SD}}$ $[\text{yr}^{-1}]$	$N\|_{\text{infill}}$ [2018-2024]	$N\|_{\text{SD}}$ [2018-2024]
17.5	11500	-	80700	-
18.0	900	-	6400	-
18.5	80	12000	530	83200
19.0	8	1500	50	10200
19.5	∼1	100	7	700
19.8	-	9	-	60
20.0	-	∼1	-	∼9





Conclusions

Precise measurement of cosmic rays from 0.5 EeV to the highest energies.

- Strong flux suppression above 40 EeV, but itt origin remains unknown

- Mass composition changes from light to heavier above 10 EeV
  Unknown composition at the most interesting energies (i.e. above 40 EeV)

- Proton-proton cross section at $\sqrt{s}$ = 56 TeV

- Strong upper limits on the flux of neutrinos, photons and also monopoles
  Decays of SHDM particles are excluded

- No clear signature of a point source

- Rich R&D program

AugerPrime will allow mass composition study at the highest energies and is well-suited to address the most striking questions of cosmic-ray physics

The FUNK experiment

D. Veberic et al., arXiv:1509.02386

Search for DM in the Hidden-Photon Sector with a Large Spherical Mirror

If dark matter consists of hidden-sector photons which kinetically mix with regular photons, a tiny oscillating electric-field component is present wherever we have dark matter. In the surface of conducting materials this induces a small probability to emit single photons almost perpendicular to the surface, with the corresponding photon frequency matching the mass of the hidden photons.

The Auger mirror prototype @ KIT

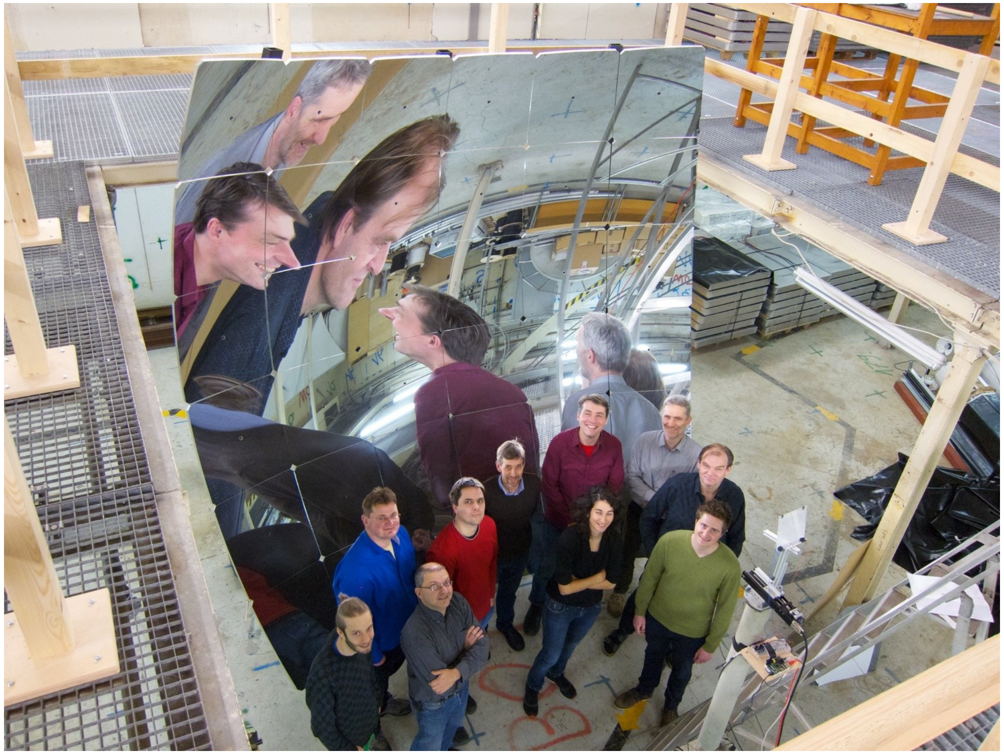
Spherical mirror 14 m^2

Composed of 36 segments

Reflective surface on Alu backing

88% reflectivity in UV

Assembled inside of a windowless air-conditioned experimental hall

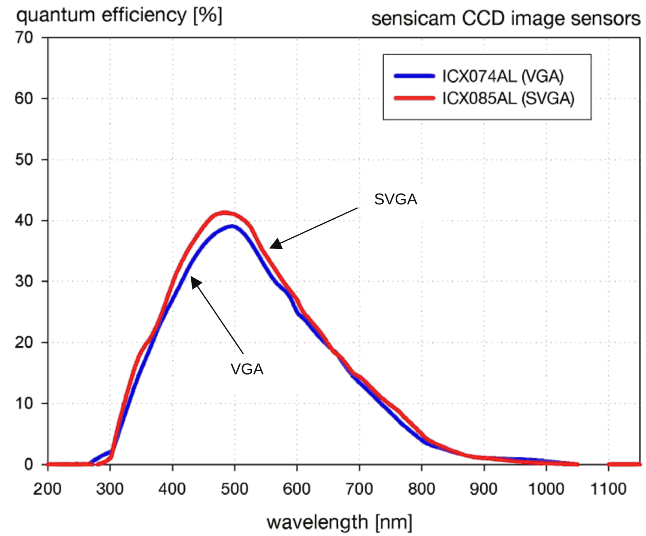


Collaborators from KIT, CERN, DESY, Heidelberg, Berlin, Zaragoza

The FUNK experiment – preliminary results

D. Veberic et al., arXiv:1509.02386

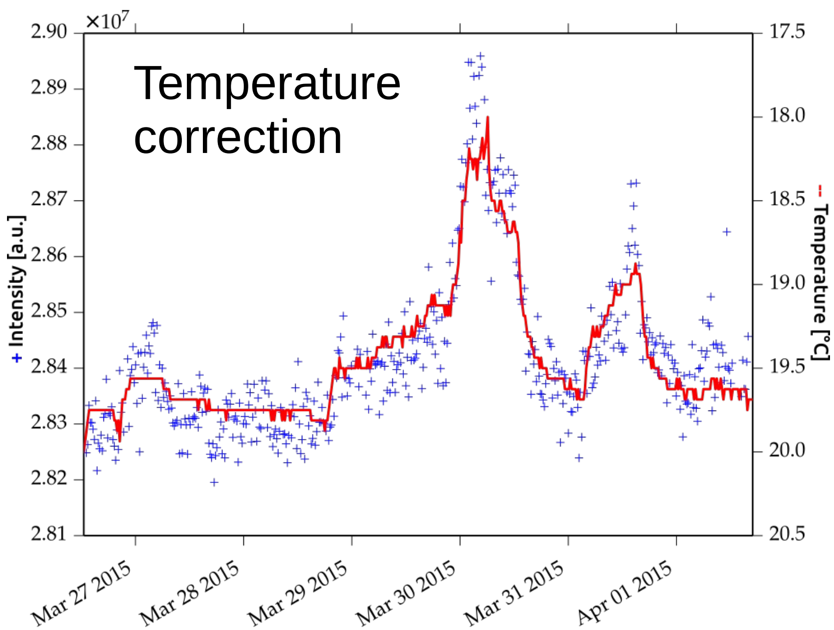
CCD camera

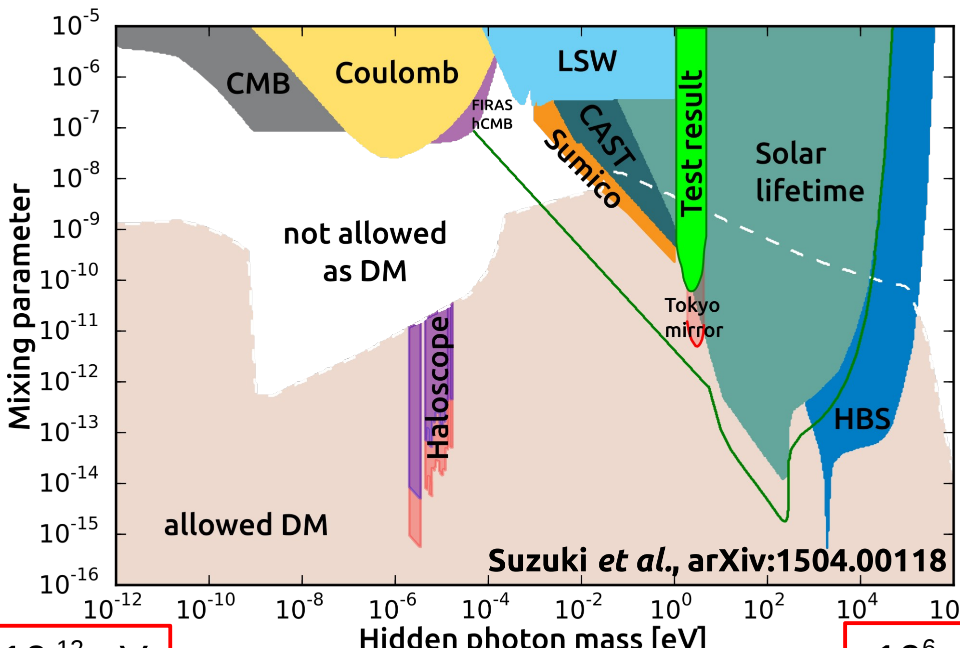


motorized flipper

open/closed images

1000 s exposure





10^{-12} eV

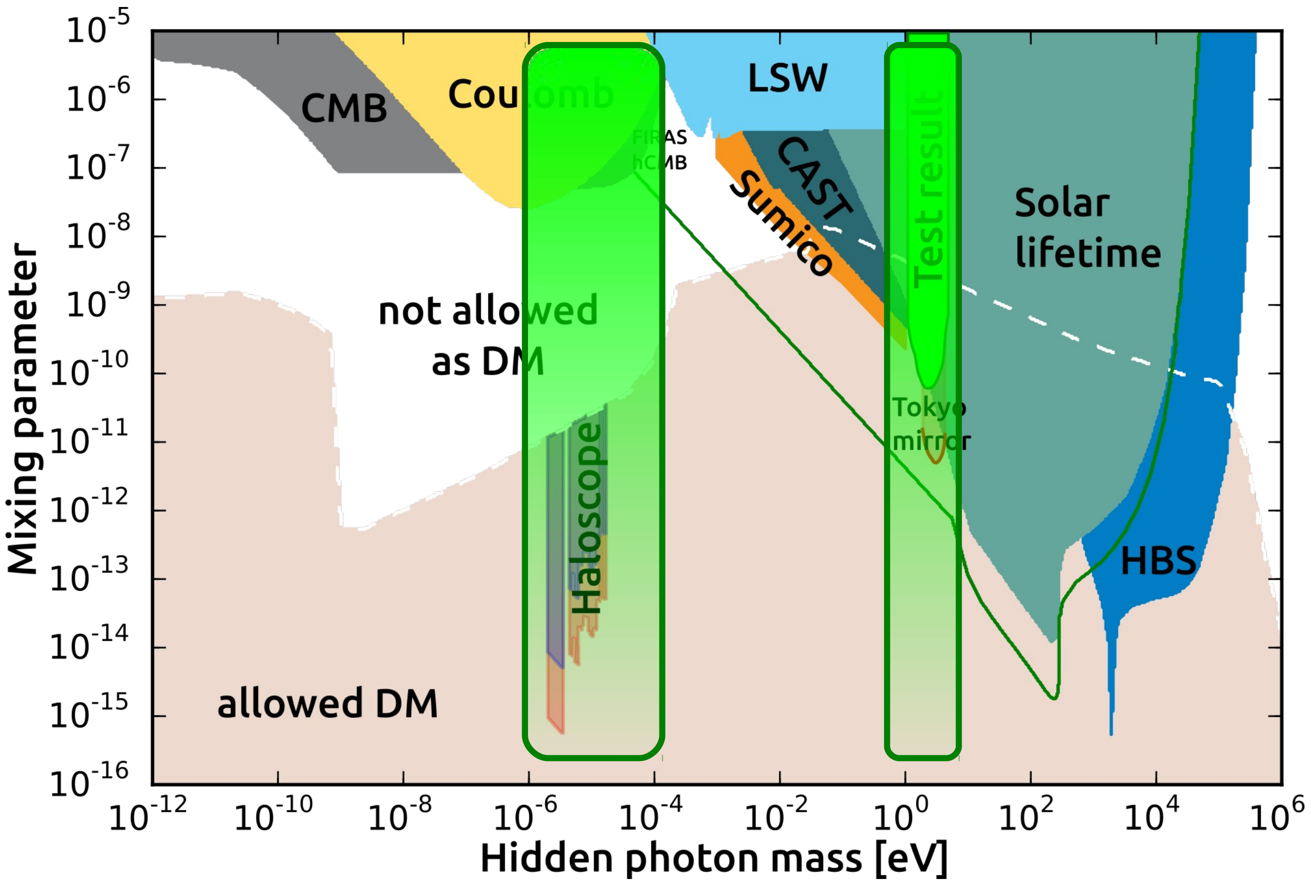
10^{6} eV

Belle II E>10^7 eV (Torben Ferber)

The FUNK experiment – future plans

D. Veberic et al., arXiv:1509.02386

Low noise PMT with far-UV extended sensitivity inside a cooled casing (-50° C)



C band (3-4 GHz) receivers from the CROME exp.

R.Š. et al., PRL 113 (2014)